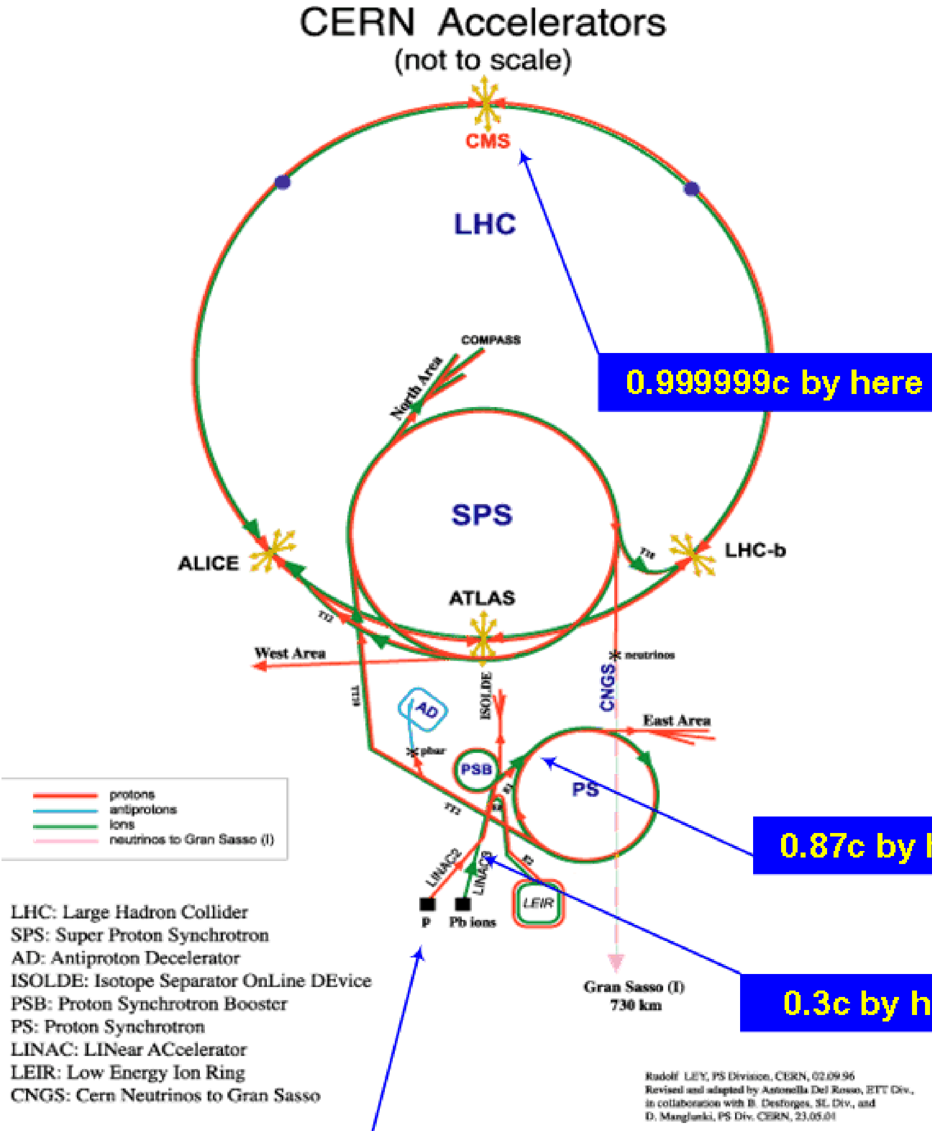
S. Stone
June 24, 2010

SYRACUSE UNIVERSITY FOUNDED AD 1870

LHCb Physics

CERN Accelerator Complex

- Protons are obtained by removing electrons from hydrogen atoms. They are injected from the linear accelerator (LINAC2) into the PS Booster, then the Proton Synchrotron (PS), followed by the Super Proton Synchrotron (SPS), before finally reaching the Large Hadron Collider (LHC).



LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Rudolf LEY, PS Division, CERN, 02.09.96
Revised and adapted by Antonella Del Rosso, ETT Div.,
in collaboration with B. Desforges, SL Div., and
D. Manglunki, PS Div. CERN, 23.05.01

0.999999c by here

0.87c by here

0.3c by here

Start the protons out here

The LHC

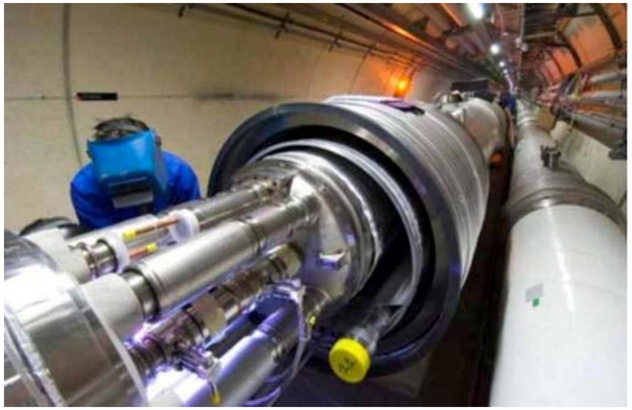
- pp collider maximum energy of 14 TeV, luminosity goal of $\mathcal{L}=10^{34}$ cm^{-2}/s
- http://hepoutreach.s

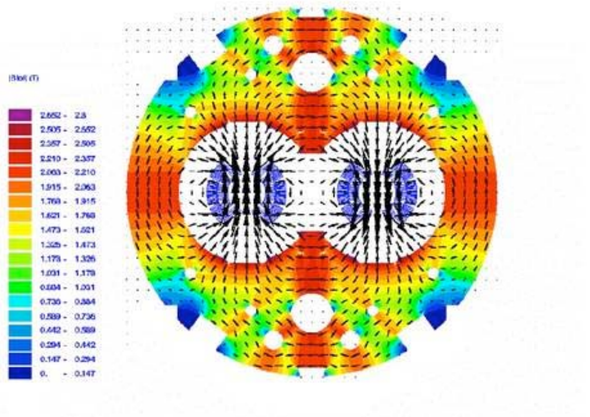
- Achieves high $\mathcal{L}$

by colliding many bunches at 25 ns intervals. At 10^{34} there are 23 interactions/crossing

Short Description of LHC

- Need to bend beam in a circle to keep it in the machine. For the “LEP” tunnel, 27 km circumference, B = 8.3 Tesla
- To lower operating costs use superconducting Ni-Tn magnets operating at 1.9 ^{o}K
- Numbers: 1232 two-in-one dipole magnets, 14.3 m long
- Also other “optical” magnets





Bunch Structure & Luminosity

- High luminosity is achieved by colliding 2808 bunches. At design L each bunch has 1.1x10^{11} particles, making for a total energy per beam of 350 MJ. (TNT is 2.7 MJ/kg)
- The luminosity in a collider is given by

$$L = f\,\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

where f is the collision frequency, n_1 & n_2 are the # of protons/bunch, & σ_x, σ_y are the beam widths

- Special magnets near the interaction region (quadrapoles) “squeeze” the beam
- The entire physics of the machine is quite complicated and important

Machine Physics

- Particles move in a magnetic field and energy is provided to make up for synchrotron radiation losses due to circular motion. In terms of motion along the radial arc of the machine, we have

$$x(s) = A\sqrt{\beta(s)}\cos\left[\psi(s)+\delta\right]$$

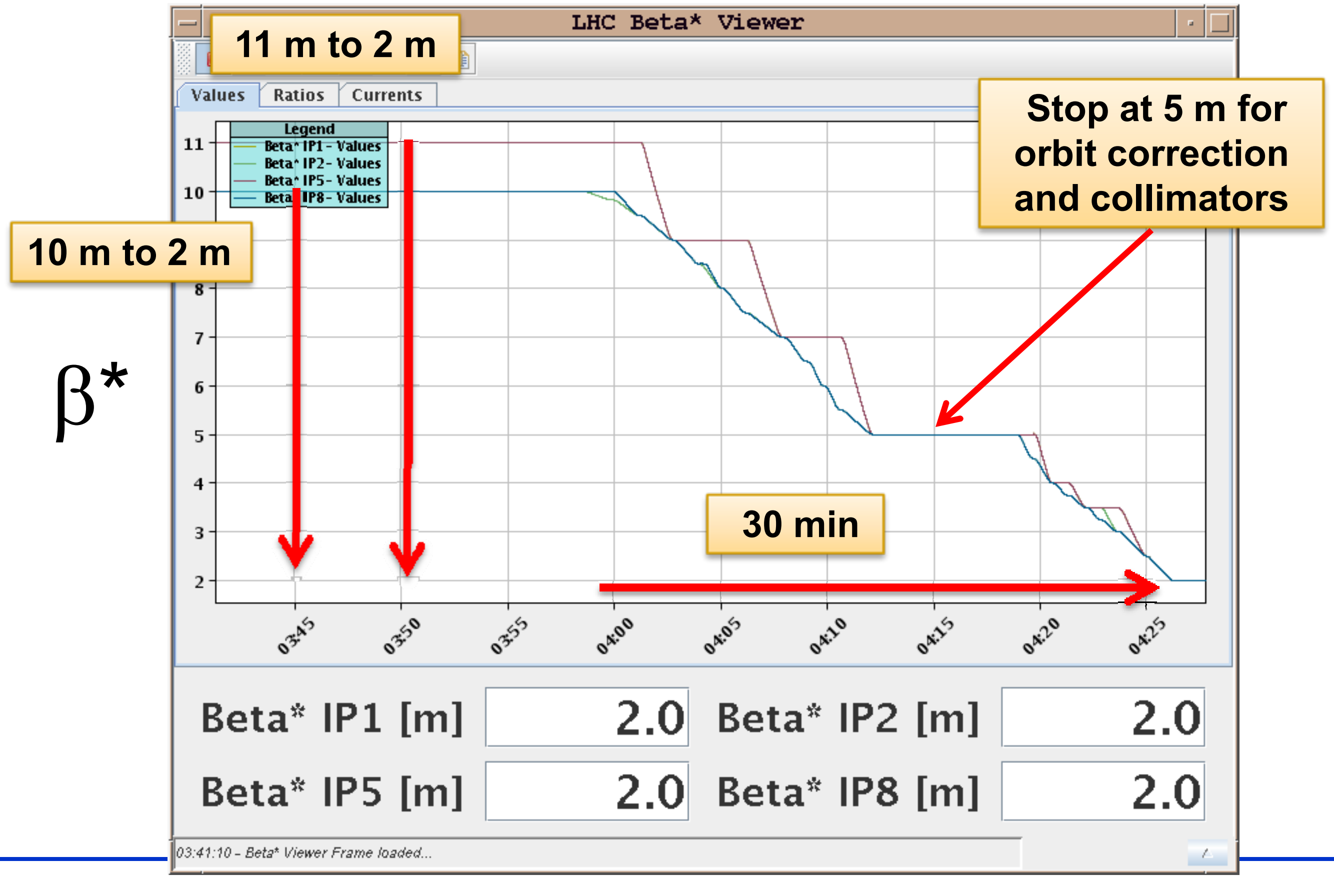
- The β function describes the motion & is made small where the beams collide. The emittance is defined as $\varepsilon_x \equiv \pi \frac{\sigma_x^2}{\beta_x}$ (same for ε_y)

Luminosity Limitations

- We can write $L = f\dfrac{n_1 n_2}{4\sqrt{\varepsilon_x \beta_x^* \varepsilon_y \beta_y^*}}$
- Idea to make β's and ε's small at interaction point
- Limitations
  - Imperfections in magnetic guide file
  - One beam acts like a magnetic lens on the other
  - Resonant oscillations can disrupt beam

Optics and β*

- For several weeks we routinely squeeze β* at the IPs all in parallel to 2 m.
- One intermediate stop for orbit correction & final collimator (tertiary collimators near IRs) adjustment.



11 m to 2 m

10 m to 2 m

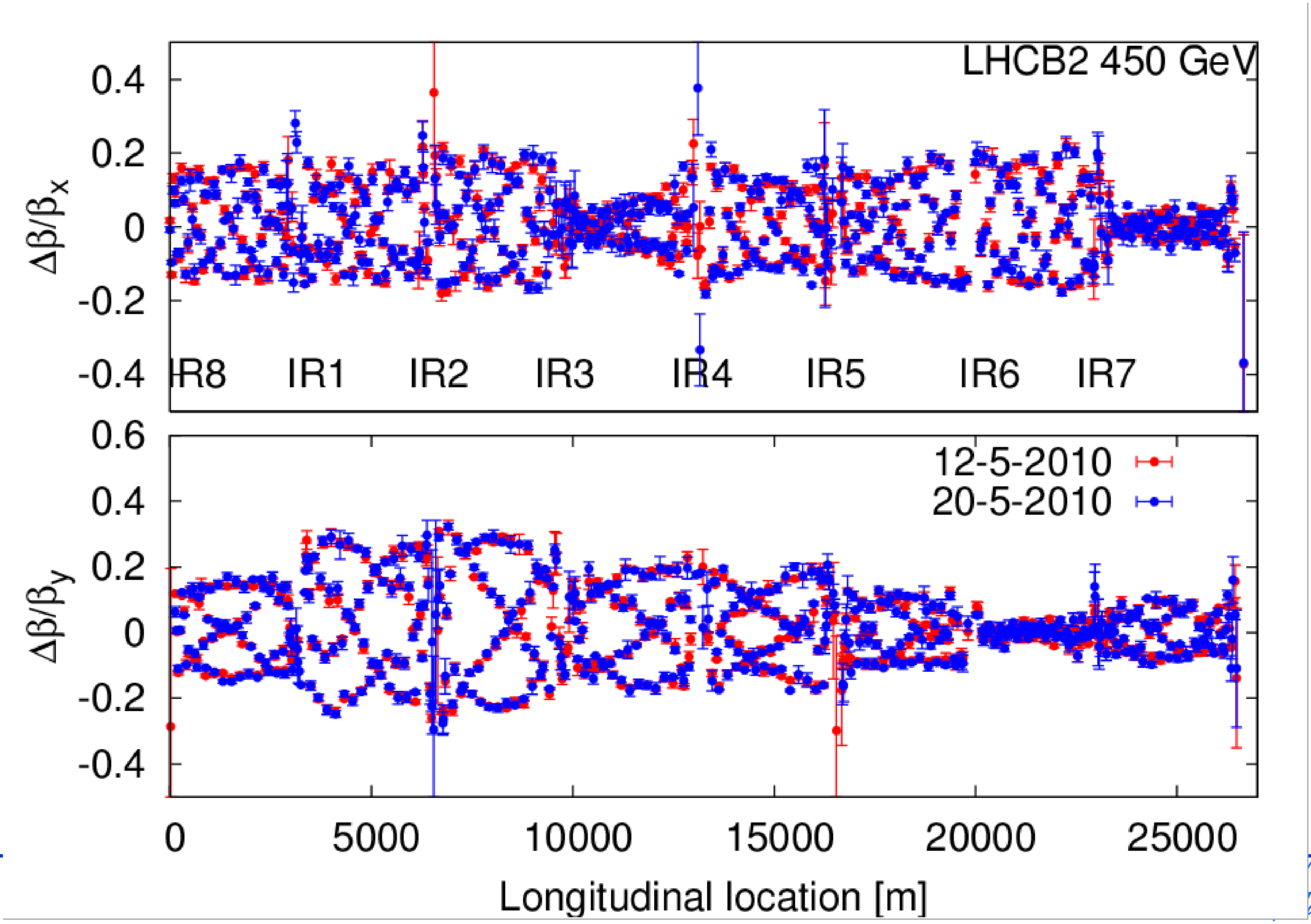
Stop at 5 m for orbit correction and collimators

30 min

Beta* IP1 [m] 2.0
Beta* IP2 [m] 2.0
Beta* IP5 [m] 2.0
Beta* IP8 [m] 2.0

03:41:10 - Beta* Viewer Frame loaded...

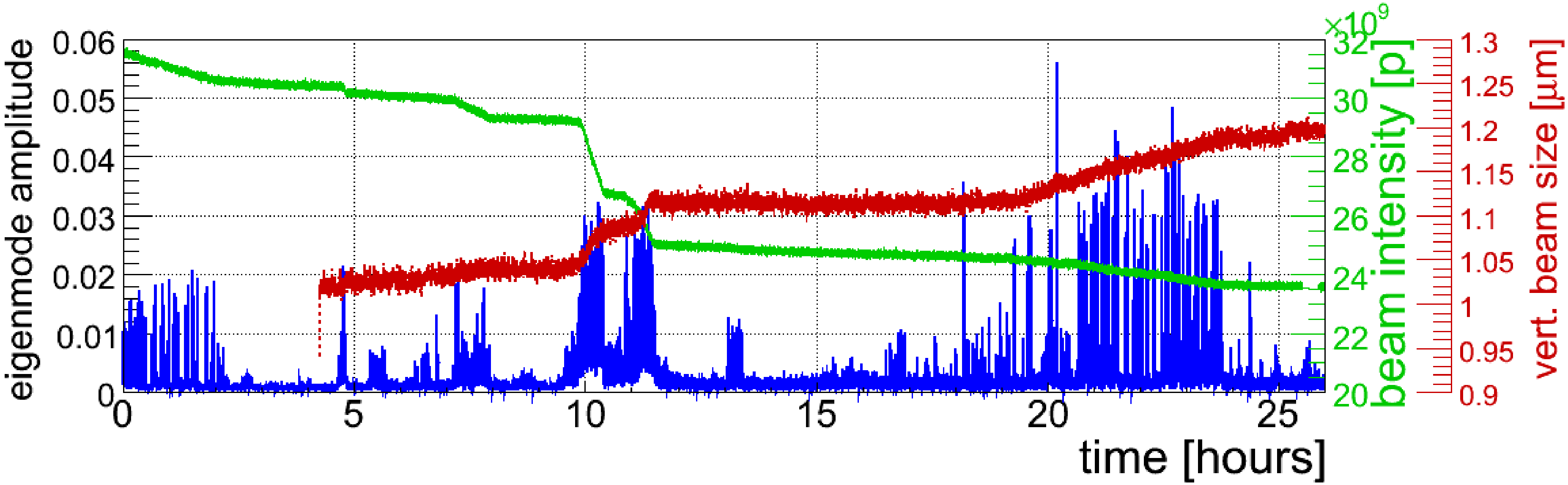
Optics reproducibility



The hump…

- Fast (but low amplitude nm to μm) vertical oscillation of the beams.
- Sometimes it is present, sometimes it is not.
- Beam 2 is more affected…
- The frequency changes slowly (7-8 minute period), and when the frequency coincides with the tune it leads to emittance blow-up.

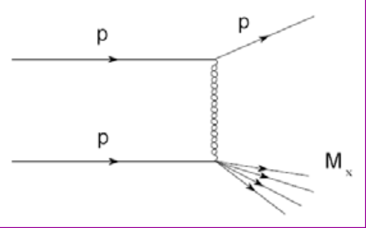
>> we are still hunting for the source….



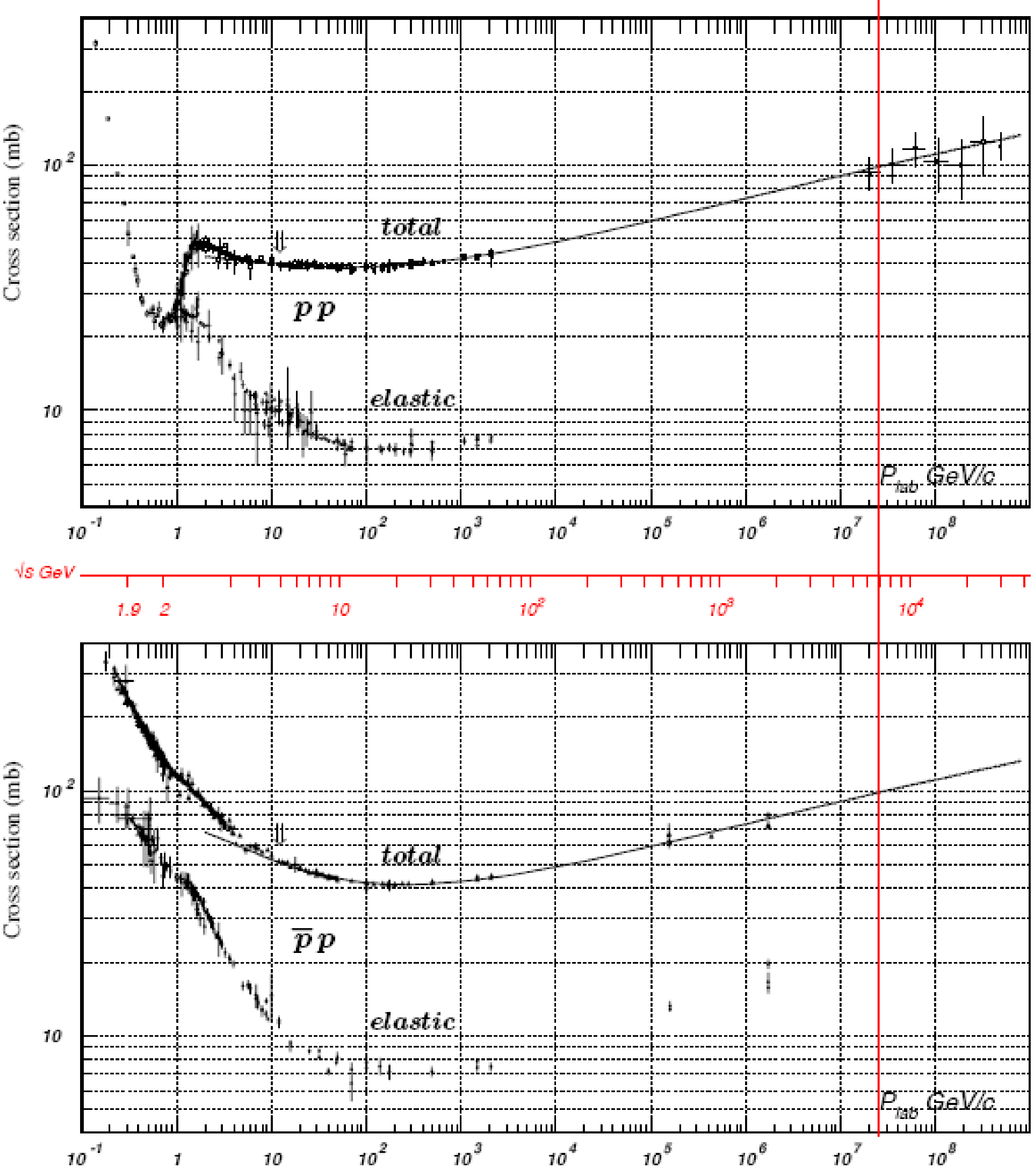
Courtesy R. Steinhagen

Cross Sections

- Def: “Effective area for scattering by a target particle of a beam particle.” Related to the probability of an interaction
- Cross sections at 7 TeV (1 barn = 10^{-24} cm^2)
  - Total 90 mb, Elastic 26 mb
  - Single Diffractive 9 mb, Double Diffractive 9 mb
  - “Hard Inelastic” ≈50 mb
- At L=10^{34} cm^{-2}/s there are ≈20 inelastic collisions per crossing (30 MHz of filled bunch collisions)
- LHCb plans to run at 2x10^{32}

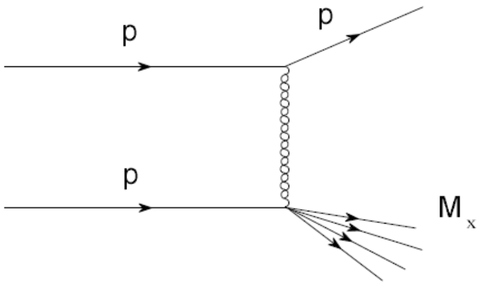

Single diffractive

- Measured X-section
- Froissart bound: $<A\ln^2(s/s_o)$

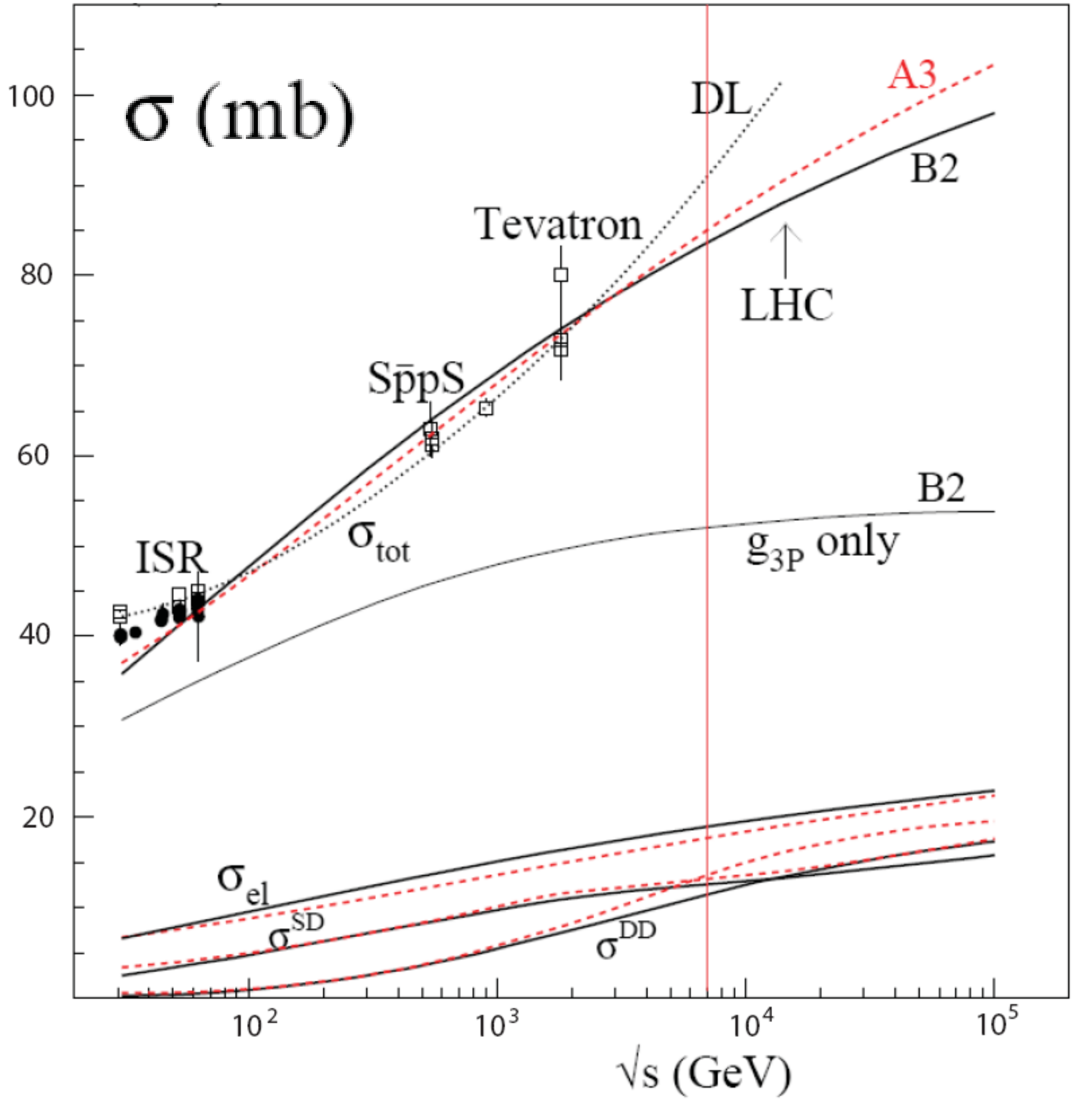


Components of the Cross-Section

Single Diffraction (SD)

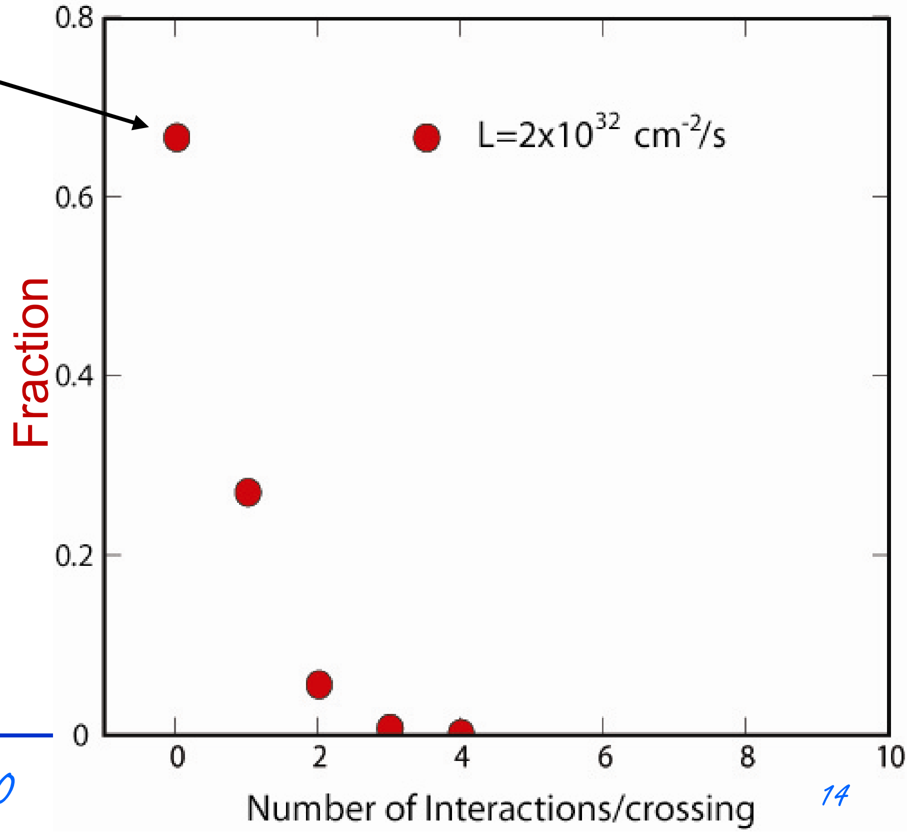


Also, Double Diffraction (DD)



Expected Running Conditions

- Luminosity 2x10^{32} cm^{-2}/s at beginning of run
- Take σ = 60 mb, [σ(total)-σ(elastic)-σ(diffractive)/2]
- Account for only 29.5 MHz of two filled bunches
- Most xings don't have an interaction
- Need 1st level trigger "L0" to reduce data by factor~30 to 1 MHz
- Higher Level Triggers reduce output to 2 kHz



Recent Running Conditions

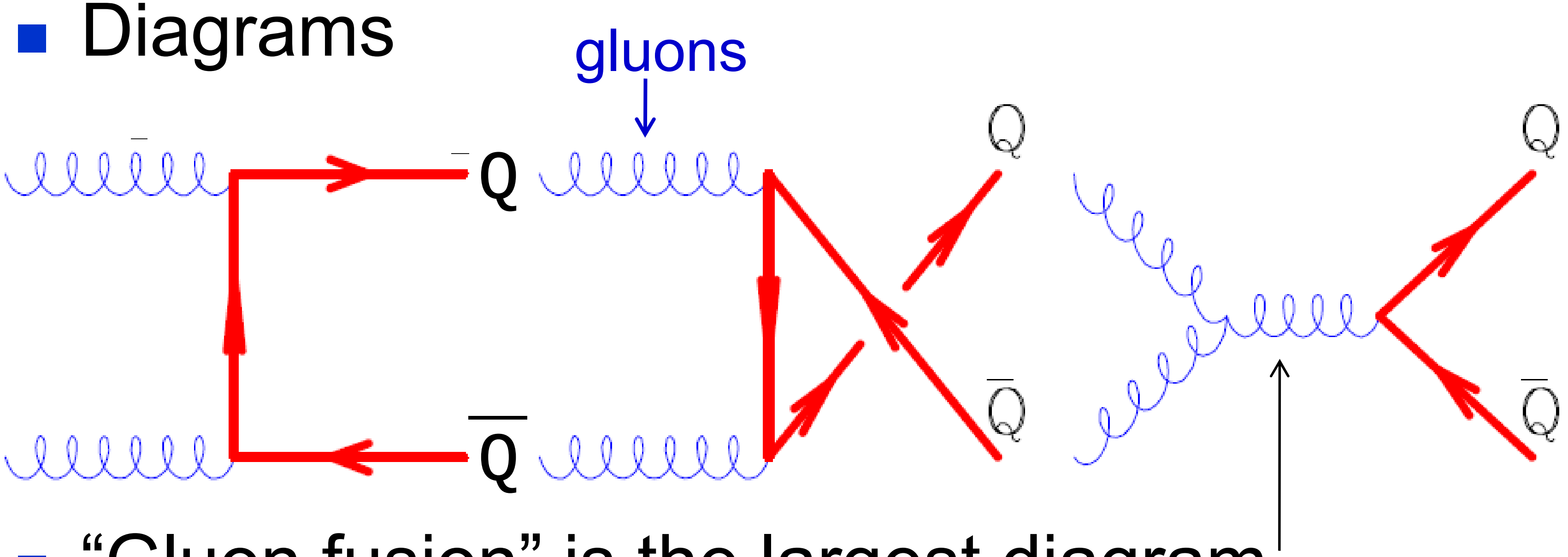
- Much fewer bunches, so lower luminosity
- BUT current in the bunches is close to or even higher than expected at nominal LHCb conditions
- SO if you subtract out the bunch crossings where nothing happens, you have ~20% of the bunch crossing with interactions having more than one interaction!
- Why is this a problem?

Machine Status

- Running at 7 TeV (3.5 TeV/beam). Many fewer bunches so far but luminosity is increasing according to plan
- Past problems
- Current worry: beam is lethal to both experiments & magnets

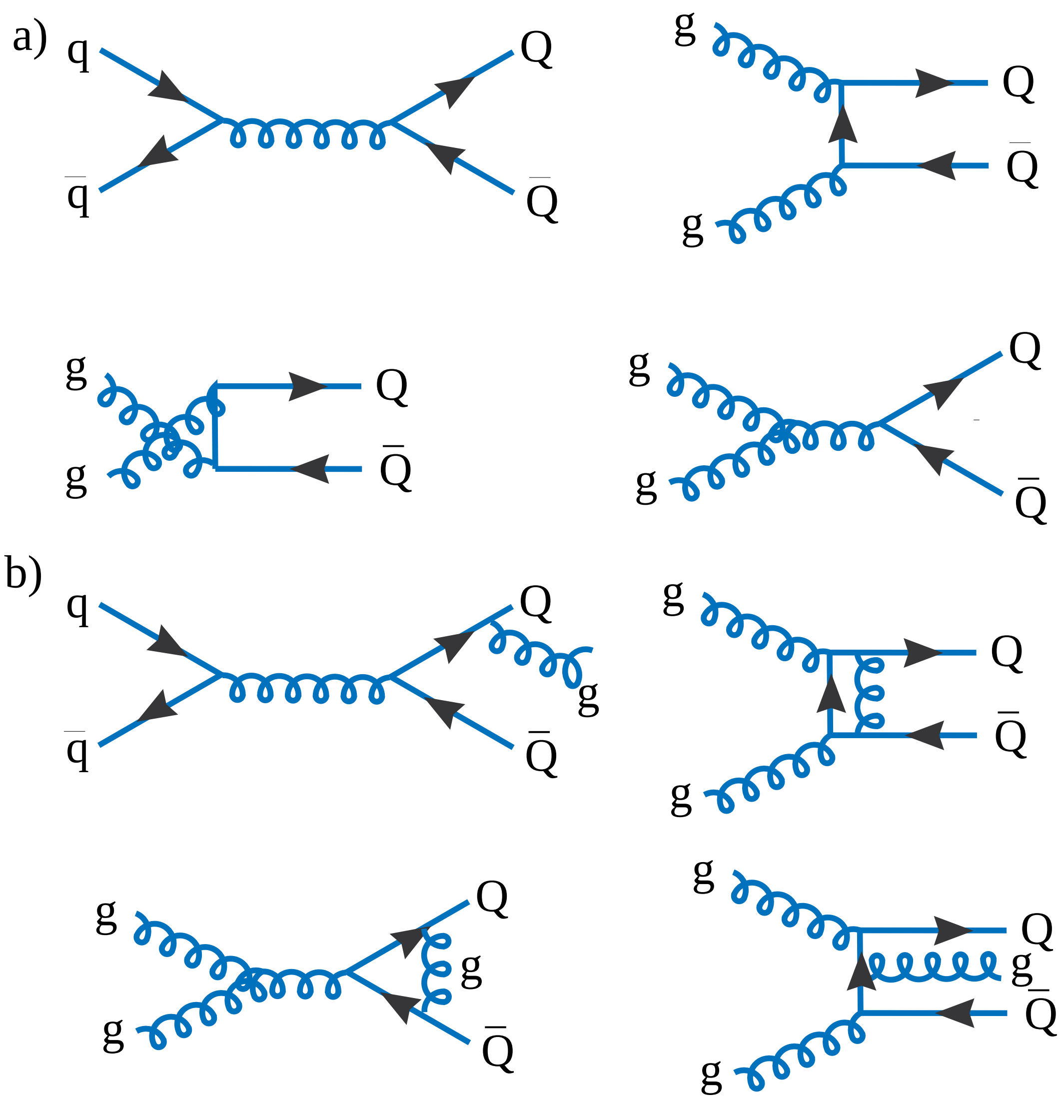
How are b quarks produced

- Diagrams



- "Gluon fusion" is the largest diagram
- Calculations are difficult, done in perturbative expansion to NLO. In LO Ellis et al predict $\sigma(pp\rightarrow b\bar{b}X)$ = 111 mb, and 332 mb at NLO

Really lots of diagrams!

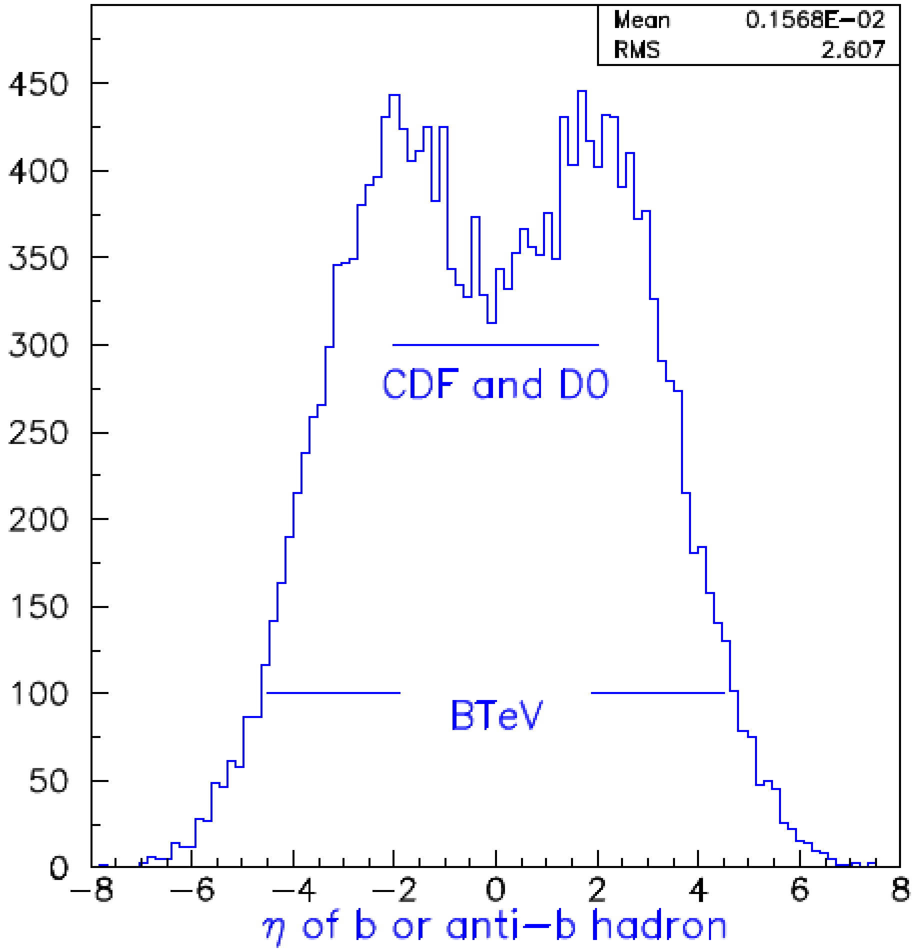


- For details see: P. Nason, S. Dawson and R. K. Ellis, Nucl. Phys. B303, 607 (1988), ibid., B327. 49, (1989);
- M. Cacciari, M. Greco and P. Nason, J. High Energy Phys., 9805 (1998) 007.

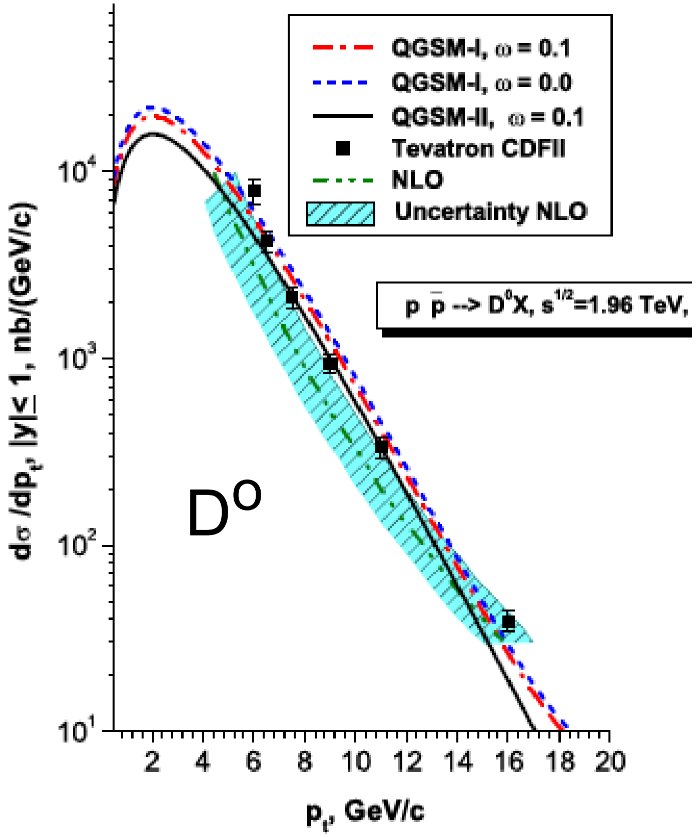
Past Measurements

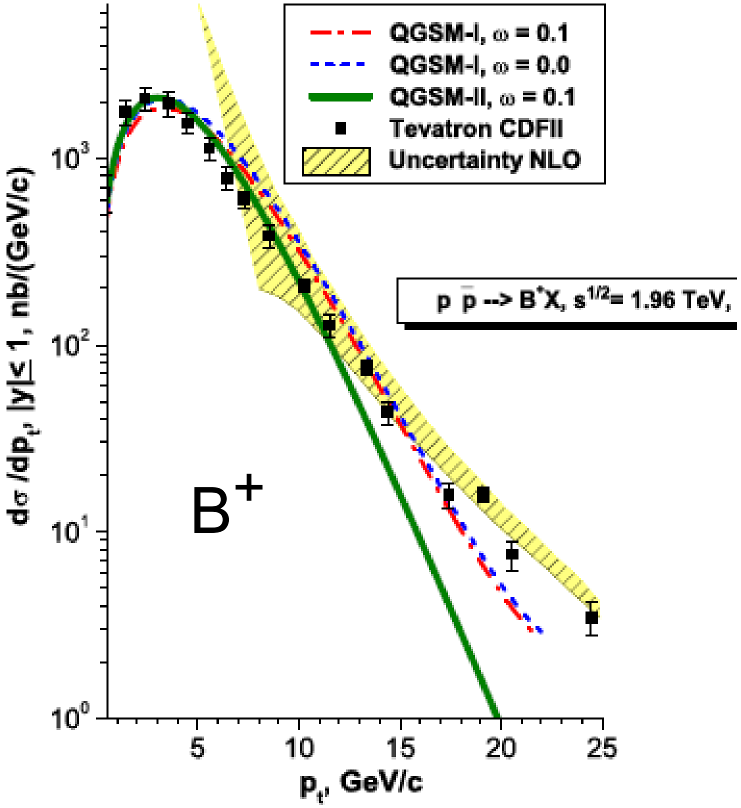
- Highest energy at 1.96 TeV in p$\bar{\text{p}}$ collisions
- Generally results available for limited rapidity ranges.
  - Def. Rapidity: $y = \frac{1}{2}\ln\left(\frac{E + p_\ell}{E - p_\ell}\right)$, where ℓ refers to the beam direction. Generally refers to a reconstructed B meson
  - Other variable used would be p_t
  - Also use η = -ln(tan(θ/2))
  - Idea is that particle production is flat in η and exponential in p_t

Flat in η?


Mean 0.1568E−02
RMS 2.607
450
400
350
300
250
200
150
100
50
0
−8
−6
−4
−2
0
2
4
6
8
CDF and D0
BTeV
η of b or anti−b hadron

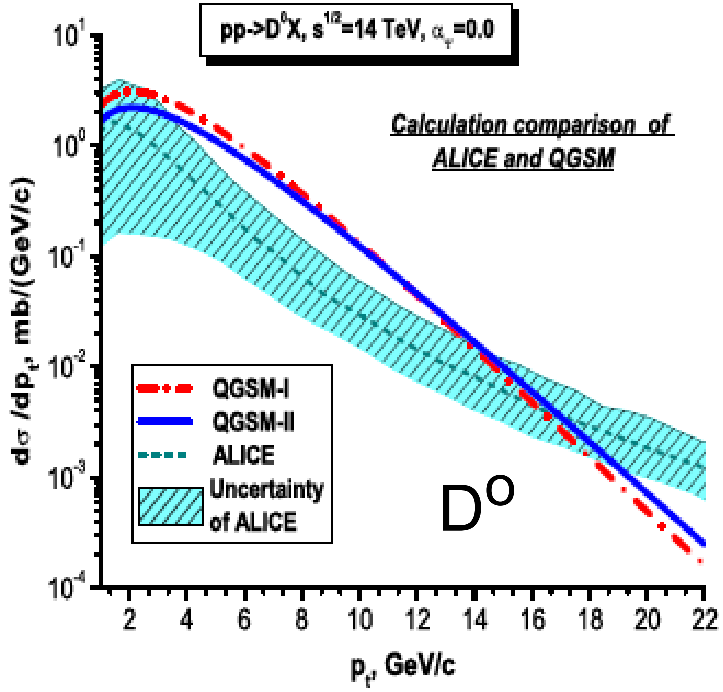
p_t (Tevatron)

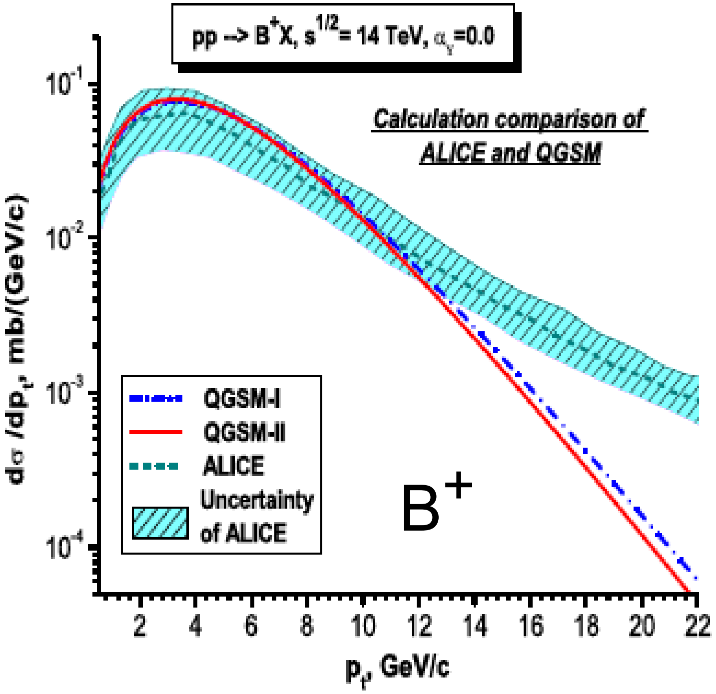




Peak of distributions is approximately at particles Mass

p_t LHC





7 times the energy, yet not very different

Comparisons with Theory

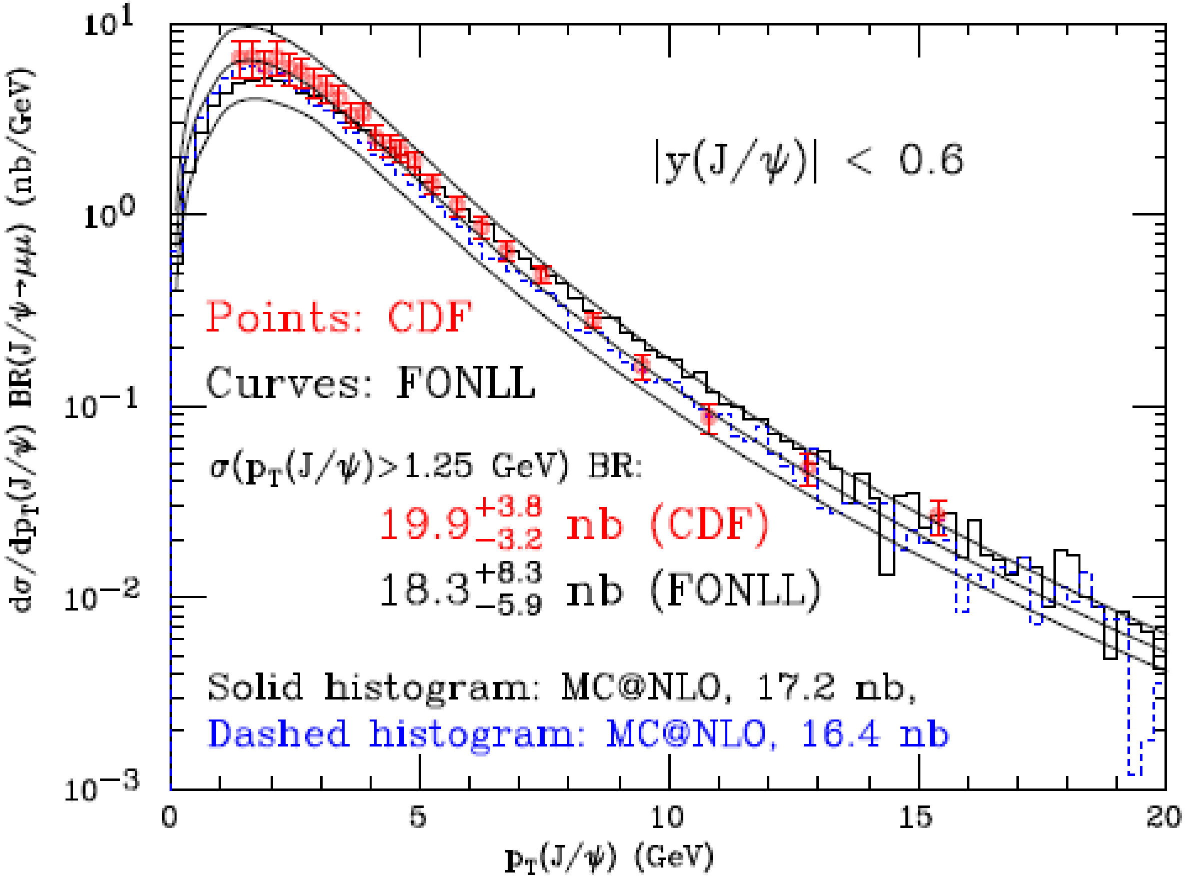


FIGURE 9. CDF J/ψ spectrum from B decays. The theory band represents the FONLL systematic uncertainties, as described in the text. Two MC@NLO predictions are also shown (histograms).

The Standard Model & B Decays

- Theoretical Background
  - Physical States in the Standard Model

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L ,\ldots\ldots u_R,\ d_R,\ c_R,\ s_R,\ t_R,\ b_R$$

  - The gauge bosons: $W^{\pm}$, γ & Z^{o} and the Higgs H^{o}
  - Lagrangian for charged current weak decays

$$L_{cc} = -\frac{g}{\sqrt{2}} J^{\mu}_{cc} W^{\dagger}_{\mu} + h.c.$$

  - Where

$$J^{\mu}_{cc} = \left(\overline{\nu}_e, \overline{\nu}_{\mu}, \overline{\nu}_{\tau}\right)\gamma^{\mu}\begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} + \left(\overline{u}_L, \overline{c}_L, \overline{t}_L\right)\gamma^{\mu} V_{CKM}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

VMNS

The CKM Matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Unitary with 9*2 numbers → 4 independent parameters
- Many ways to write down matrix in terms of these parameters

Parameterization of the CKM Matrix

- *Wolfenstein parameterization good to λ^3 in real part & λ^5 in imaginary part*

$$V_{CKM}= \begin{array}{cc} & \begin{array}{ccc} d & s & \\ \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \left(\begin{array}{ccc} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 - \text{[redacted]} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 + \text{[redacted]} & 1 - \text{[redacted]} \end{array} \right) \end{array}$$

- λ, A, ρ & η are fundamental constants of nature!

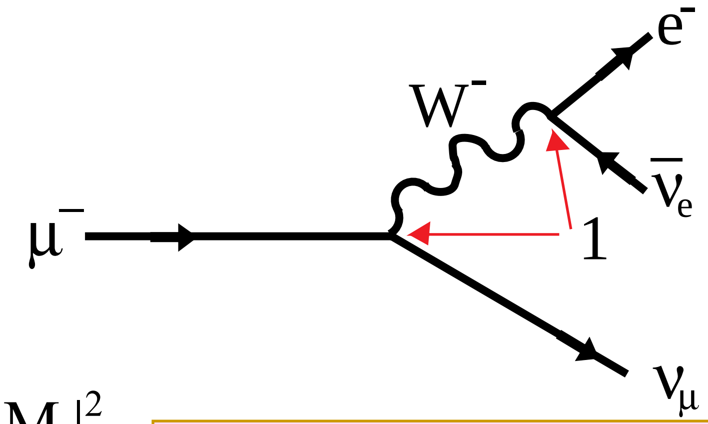
Weak Charged Current Decays

- It all starts with muon decay

$$M=\frac{G_F}{\sqrt{2}}\bar{u}_2\gamma_\lambda\left(1-\gamma_5\right)u_\mu\bar{u}_e\gamma^\lambda\left(1-\gamma_5\right)v_1$$

$$d\Gamma_\mu=(2\pi)^4\delta^4(p_e+p_1+p_2-p_\mu)\times$$

$$\frac{m_e}{E_e}\frac{m_\mu}{E_\mu}\frac{m_{\nu_e}}{E_1}\frac{m_{\nu_\mu}}{E_2}\frac{d^3\vec{p}_e}{2\pi^3}\frac{d^3\vec{p}_1}{2\pi^3}\frac{d^3\vec{p}_2}{2\pi^3}|M|^2$$



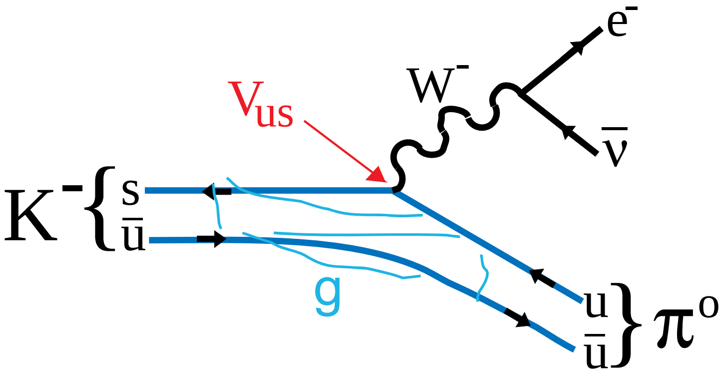
A "tree level" diagram

$$\Gamma_\mu=\frac{G_F^2}{192\pi^3}m_\mu^5\times(\text{phase space})\times(\text{radiative corrections})$$

- Since $\Gamma_\mu \bullet \tau_\mu = \hbar$, (why?) measuring the muon lifetime gives G_F

Semileptonic K^- Decay

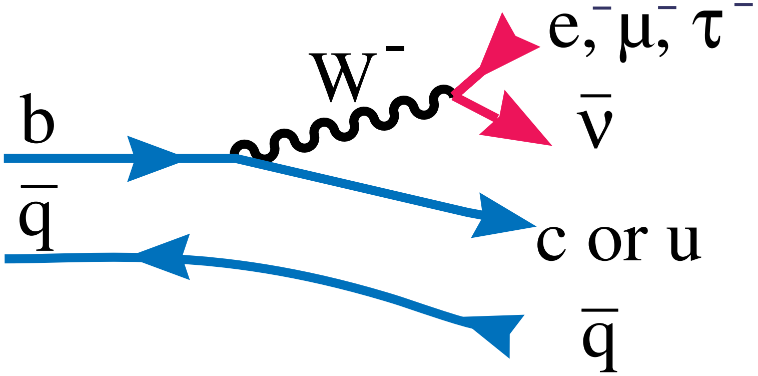
- s quark charged current decay



- If we didn't have to worry about the fact that the s quark is paired with a $\bar{u}$ quark to form a K^- & that a $u\bar{u}$ forms a π^o, we could measure the decay rate for $K^- \rightarrow \pi^o e^- \nu$ by measuring the K^- lifetime & the branching ratio & then find $|V_{us}|$
- Taking into account the hadronic physics we find $|V_{us}|=\lambda=0.2205\pm0.0018$

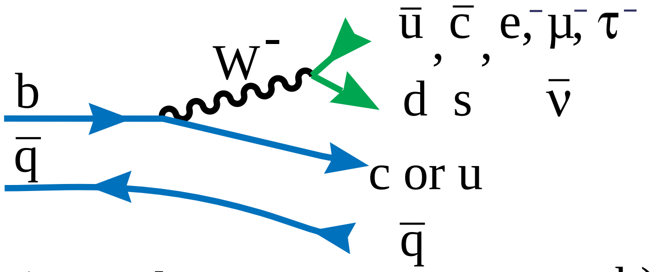
Semileptonic B Decays

- Two CKM elements can be measured, V_{cb} & V_{ub}
- Necessary ingredients
  - B lifetimes
  - Branching fractions
  - Theory or Model to take care of hadronic physics

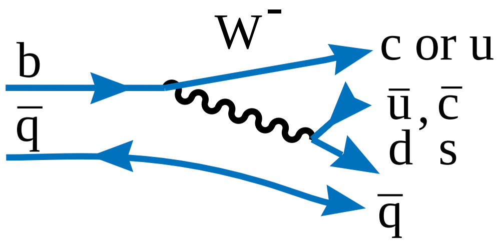


B Decay Diagrams

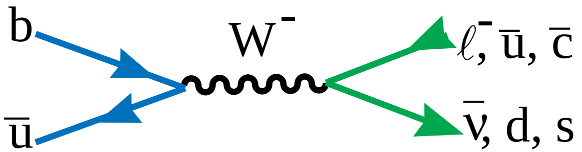
- Each diagram contributes to the decay width
- a) is dominant
- No direct evidence for c) or d)
- More diagrams for baryons



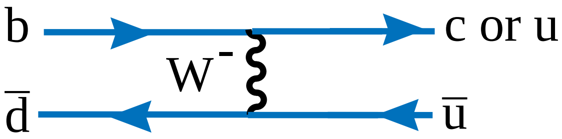
a) simple spectator



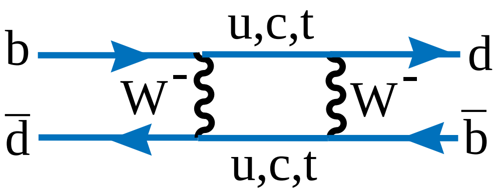
b) hadronic: color suppressed



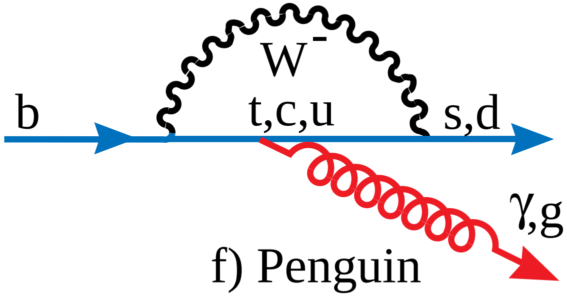
c) annihilation



d) W exchange



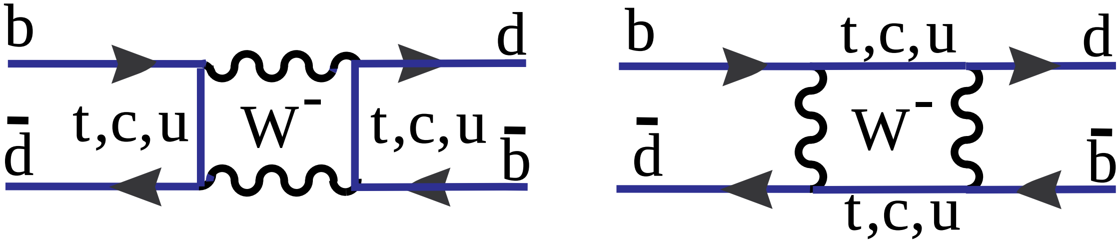
e) box: mixing



f) Penguin

B^o-$\overline{B}^o$ Mixing

- B^o can transform to B^o, like neutral K's

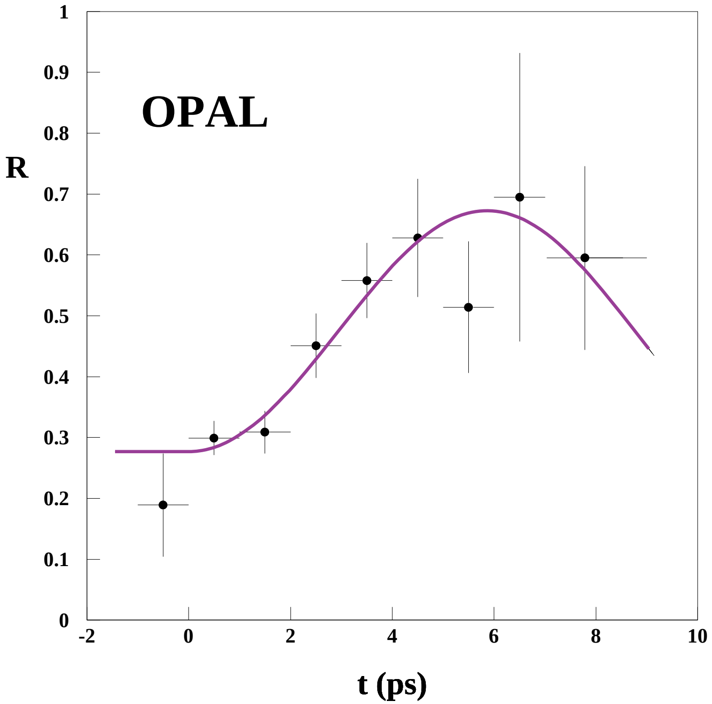


- The eigenstates of flavor, degenerate in pure QCD mix under the weak interactions. Let QM basis be $\{|1>,|2>\} \equiv \{|B^o>,|\overline{B}^o>\}$, then

$$H = M - \frac{i}{2}\Gamma = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}$$

More on Mixing

- R= prob $B^o \rightarrow \overline{B}^o$/ prob $B^o \rightarrow B^o$
- First seen by ARGUS
- $P(B^o \rightarrow \overline{B}^o) = 0.5\Gamma e^{-\Gamma t} \bullet$
  $[1+\cos(\Delta m t)]$
- Where Δm=is the mass difference given after diagonalizing H, between the Heavy & Light eigenstates



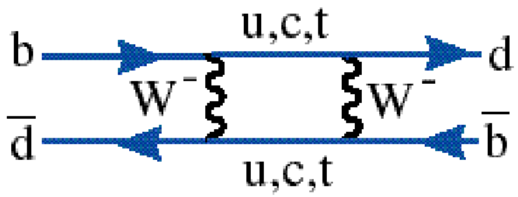
B_d Mixing in the Standard Model

- Relation between B mixing & CKM elements:

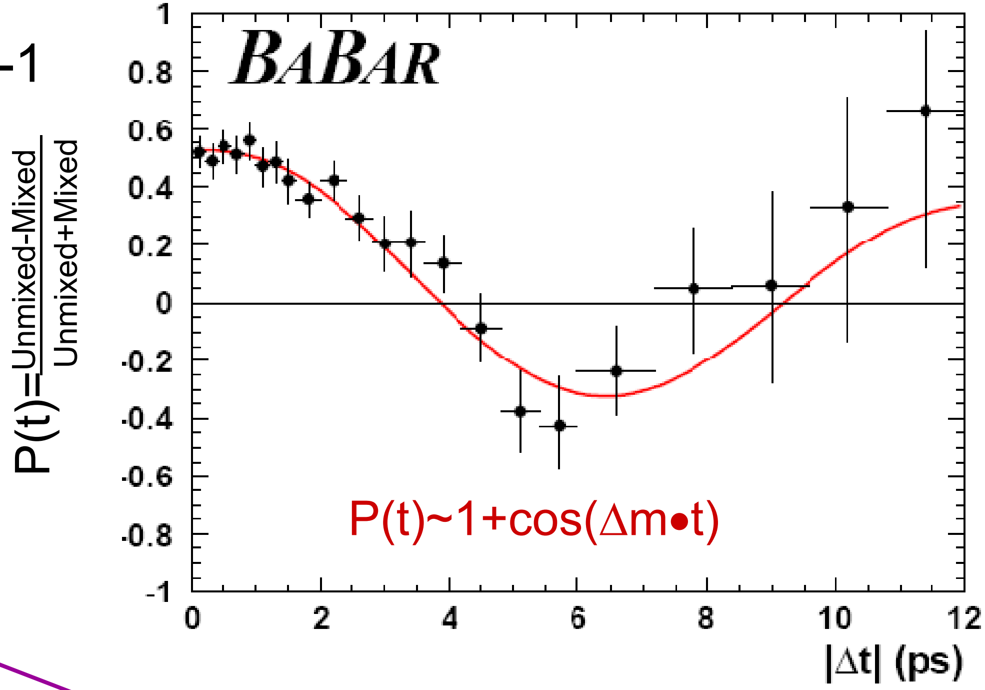
$$x \equiv \frac{\Delta m}{\Gamma} = \frac{G_F^2}{6\pi^2} B_B f_B^2 m_B \tau_B \left|V_{tb}^* V_{td}\right|^2 m_t^2 F\left(\frac{m_t^2}{m_W^2}\right) \eta_{QCD}$$

- F is a known function, η_{QCD}~0.8
- B_B and f_B are currently determined only theoretically
  - in principle, f_B can be measured, but its very difficult, need to measure $B^o \rightarrow \ell\nu$
  - Current best hope is Lattice QCD

More on B^o Mixing



- B^o mixing measured by ARGUS in 1987
- $\Delta m = 0.507 \pm 0.004$ ps^{-1} (current world avg)



P(t)~1+cos(Δm•t)

What we are interested in

- $$x_d \equiv \frac{\Delta m}{\Gamma} = \frac{G_F^2}{6\pi^2} B_{B_d} f_B^2 m_B \tau_B \left|V_{tb}^* V_{td}\right|^2 m_t^2 F\left(\frac{m_t^2}{M_W^2}\right) \eta_{QCD}$$

Theoretically determined parameters

B_s Mixing in the Standard Model

$$x_s \equiv \frac{\Delta m_s}{\Gamma_s} = \frac{G_F^2}{6\pi^2} B_{B_S} f_{B_S}^2 m_{B_S} \tau_{B_S} \left| V_{tb}^{*} V_{ts} \right|^2 m_t^2 F\left(\frac{m_t^2}{m_W^2}\right) \eta_{QCD}$$

- B_s mixing is measures the ratio of V_{td}/V_{ts} which gives the same essential information as B_d mixing alone, with smaller theory errors
  - $|V_{td}|^2 = A^2\lambda^4[(1-\rho)^2+\eta^2]$
  - $|V_{td}|^2 / |V_{ts}|^2 = [(1-\rho)^2+\eta^2]$
  - Circle in (ρ,η) plane centered at (1,0)
- Lattice best value for

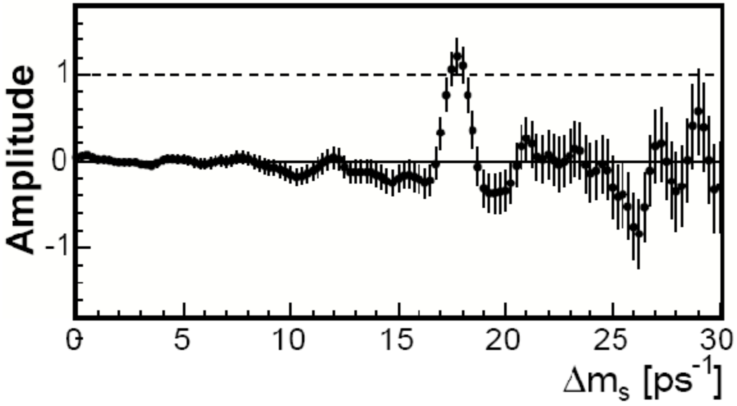
$$\xi = \frac{f_{B_S}\sqrt{B_{B_S}}}{f_{B_d}\sqrt{B_{B_d}}} = 1.13 \pm 0.12$$

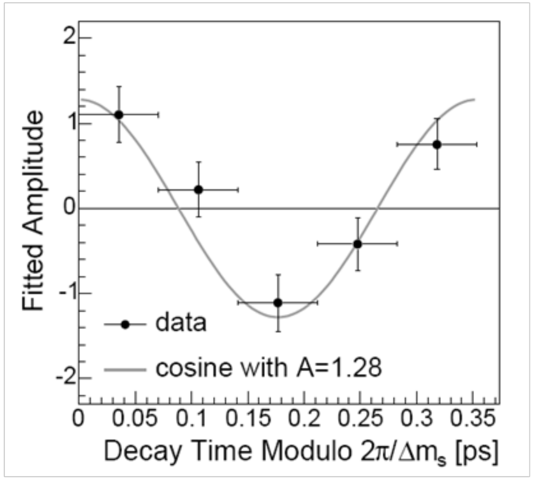
Unquenched
arXiv:1001.2023

More on B_s Mixing

- Measured by CDF in 2006

P(t)~1+cos($\Delta m_s \bullet t$). A=1 is signal, A=0 elsewhere





$$\Delta m_s = 17.31^{+0.33}_{-0.18} \pm 0.07 \text{ ps}^{-1}$$

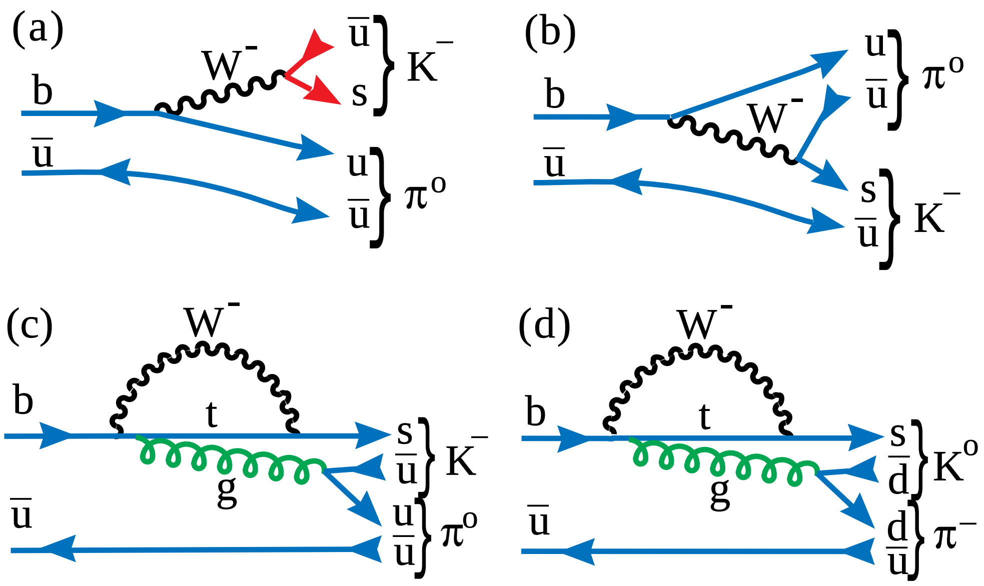
- Note $$\lambda \frac{|V_{td}|}{|V_{ts}|} = (\rho - 1)^2 + \eta^2 = \lambda \frac{B_B}{B_{B_s}} \frac{f_B^2}{f_{B_s}^2} \frac{m_B}{m_{B_s}} \frac{\tau_B}{\tau_{B_s}}$$

a circle in the ρ–η plane centered at (1,0)

CP Violation in b decay

- C takes particle to antiparticle, P takes **r** to **-r**
- Complex phase in CKM matrix ⇒ CP Violation
    - Consider the case of a process B→f that goes via two amplitudes a & b.
        - $\Gamma(B\rightarrow f)=(|a|e^{i(s_a+w_a)}+|b|e^{i(s_b+w_b)})^2$
        - $\overline{\Gamma}(\overline{B}\rightarrow \overline{f})=(|a|e^{i(s_a-w_a)}+|b|e^{i(s_b-w_b)})^2$
        - $\Gamma-\overline{\Gamma}=2|ab|\sin(s_a-s_b)\sin(w_a-w_b)$
        - Note, it's only the complex part of V_{ckm} that causes this
    - One of the two amplitudes could be from mixing

CPV in Charged B decays



- Consider charged $K\pi$ decays
- For $K^-\pi^o$, there are 3 diagrams, but only 1 for $K^o\pi^-$
- Therefore, we expect CP violation in $K^-\pi^o$ but not in $K^o\pi^-$
- However, because we don't know strong phases its difficult to get useful info on weak phases

~~CP~~ in B^o Decays: Formalism

- Consider B^o & $\overline{B}^o$ states (either B_d or B_s)
- These obey a Schrodinger equation

$$i\frac{d}{dt}\begin{pmatrix}a\\ b\end{pmatrix} = H\begin{pmatrix}a\\ b\end{pmatrix} = \left(M-\frac{i}{2}\Gamma\right)\begin{pmatrix}a\\ b\end{pmatrix}$$

with M & Γ being 2x2 Hermitian matrices

- Diagonalizing M-(i/2 Γ) yields Mass eigenstates

$$\begin{pmatrix} M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12} \\ M_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*} & M_{22}-\frac{i}{2}\Gamma_{22} \end{pmatrix}$$

$$\left|B_L^o\right\rangle = p\left|B^o\right\rangle + q\left|\overline{B}^o\right\rangle, \left|B_H^o\right\rangle = p\left|B^o\right\rangle - q\left|\overline{B}^o\right\rangle, |p|^2+|q|^2=1$$

- Note the physical quantities related to oscillations are $|M_{12}|$, $|\Gamma_{12}|$ & $\phi_d = \arg(-M_{12}/\Gamma_{12})$

B^o CP Formalism II

- For CP not being conserved

$$|B_L\rangle = p|B^o\rangle + q|\bar{B}^o\rangle, \ |B_H\rangle = p|B^o\rangle - q|\bar{B}^o\rangle$$

- where $p = \frac{1}{\sqrt{2}} \frac{1+\varepsilon_B}{\sqrt{1+|\varepsilon_B|^2}}, \quad q = \frac{1}{\sqrt{2}} \frac{1-\varepsilon_B}{\sqrt{1+|\varepsilon_B|^2}}$

- CP is violated if $\varepsilon_B \neq 0$ or $|q/p| \neq 1$

$$a_{sl} = 2\left(1 - \left|\frac{q}{p}\right|\right), \quad a_{sl} = \frac{4\mathrm{Re}(\varepsilon_B)}{1+|\varepsilon_B|^2}$$

- Time dependence is given by

$$|B_L(t)\rangle = e^{-\Gamma_L t/2} e^{i m_L t/2} |B_L(0)\rangle, |B_H(t)\rangle = e^{-\Gamma_H t/2} e^{i m_H t/2} |B_H(0)\rangle$$

B^o CP Formalism III

- This leads to the time evolution of flavor as

$$\left|B^o(t)\right\rangle = e^{-(i\Delta m+\Gamma/2)t}\left(\cos\frac{\Delta mt}{2}\left|B^o(0)\right\rangle + i\frac{q}{p}\sin\frac{\Delta mt}{2}\left|\bar{B}^o(0)\right\rangle\right)$$

$$\left|\bar{B}^o(t)\right\rangle = e^{-(i\Delta m+\Gamma/2)t}\left(i\frac{p}{q}\sin\frac{\Delta mt}{2}\left|B^o(0)\right\rangle + \cos\frac{\Delta mt}{2}\left|\bar{B}^o(0)\right\rangle\right)$$

- $\Delta m = m_H - m_L$, $\Gamma \approx \Gamma_L \approx \Gamma_H$ *(true for B_d, not for B_s)*
- Probability of a B^o decay is given by $<B^o(t)|B^o(t)^*>$

a_{sl}

- These are related to the measurable quantities $2|M_{12}| = \Delta M = M_H - M_L$

$$2|\Gamma_{12}|\cos\phi = \Delta\Gamma = \Gamma_L - \Gamma_H$$

- Another quantity of interest is

$$a_{sl} = \text{Im}\frac{\Gamma_{12}}{M_{12}} = \frac{|\Gamma_{12}|}{|M_{12}|}\sin\phi = \frac{\Delta\Gamma}{\Delta M}\tan\phi$$

- Which characterizes CPV in flavor specific B→f. Generally $\bar{B}^o \to X\ell^- \bar{\nu}$, $B^o \to X\ell^+ \nu$
- Here $|A(B\to f)|=|A(\bar{B}\to \bar{f})|$, which is not always true (Homework: Give an example when it isn't)

a_{sl} II

- Then
$$a_{sl} = \frac{\Gamma\left(\overline{B} \rightarrow f\right) - \Gamma\left(B \rightarrow \overline{f}\right)}{\Gamma\left(\overline{B} \rightarrow f\right) + \Gamma\left(B \rightarrow \overline{f}\right)}$$
- Which is the asymmetry in wrong-sign decays & measures the CP violation in mixing
- As an example take f to be a semileptonic decay such as $B_s \rightarrow D_s^- \mu^+ \nu$. The measurement is to see an asymmetry between $D_s^+ \mu^- \nu$ and $D_s^- \mu^+ \nu$. Can use other decays.
- Homework: What are ΔM, $\Delta\Gamma$ & for B_d & B_s systems? Any guesses as to a_{sl}?

Dilepton asymmetry and a_{sl}

- First of all, an experimental quantity of interest is the dilepton asymmetry

$$A_{\mathrm{SL}} \equiv \frac{\Gamma(b\bar{b} \to \mu^+\mu^+X) - \Gamma(b\bar{b} \to \mu^-\mu^-X)}{\Gamma(b\bar{b} \to \mu^+\mu^+X) + \Gamma(b\bar{b} \to \mu^-\mu^-X)}$$

$$= \frac{\Gamma^+_{\mathrm{RS}}\Gamma^+_{\mathrm{WS}} - \Gamma^-_{\mathrm{RS}}\Gamma^-_{\mathrm{WS}}}{\Gamma^+_{\mathrm{RS}}\Gamma^+_{\mathrm{WS}} + \Gamma^-_{\mathrm{RS}}\Gamma^-_{\mathrm{WS}}},$$

- Since $\Gamma^-_{\mathrm{RS}} = \Gamma^+_{\mathrm{RS}}$, we have

$$A_{\mathrm{SL}} = \frac{\Gamma^+_{\mathrm{WS}} - \Gamma^-_{\mathrm{WS}}}{\Gamma^+_{\mathrm{WS}} + \Gamma^-_{\mathrm{WS}}}$$

so can measure either single or dimuon asymmetry

New Physics and a_{sl}

- Since $$a_{sl}=\frac{\Delta\Gamma}{\Delta M}\tan\phi=\frac{\Delta\Gamma}{\Delta M}\tan\left(\phi_{SM}+\phi_{NP}\right)$$
- We know $\Delta\Gamma/\Delta M$, & can predict ϕ_{SM},
  - for B_d $\phi_{SM}(d)=-0.09\pm0.03 \Rightarrow a_{sl}=(-4.8\pm1.1)\times10^{-4}$
  - for B_s $\phi_{SM}(s)= 0.0042\pm0.0014 \Rightarrow$

    $a_{sl}=(-2.06\pm0.57)\times10^{-5}$
- Same ϕ_{NP} would appear in CP violation in $B_s\to J/\psi\ \phi$.
- Many theoretical papers on NP have appeared

~~CP~~ in B^0 Decays

- Use the mixing amplitude
  - For B_d generates an asymmetry ~sin(2β), where $\sin(2\beta) = -2(1-\rho)\eta/[(1-\rho)^2+\eta^2]$
  - Asymmetry means

$$a \equiv \frac{\Gamma(B^o \to f)-\Gamma(\bar{B}^o \to \bar{f})}{\Gamma(B^o \to f)+\Gamma(\bar{B}^o \to \bar{f})}$$

  - For a CP *eigenstate* f = f
  - Homework: Which of these is a CP eigenstate
    - $B^o \to \pi^+\pi^-$
    - $B^o \to \pi^+\pi^-\pi^o$
    - $B_s \to J/\psi\ \eta'$
    - $K^o \to \pi^+\pi^-$
    - $K^o \to \pi^+\pi^-\pi^o$
    - $B^o \to \rho^o\pi^o$
    - $B^o \to J/\psi\ K_s$
    - $B_s \to J/\psi\ \phi$
    - $B^o \to \rho^o\rho^o$

CP violation using CP eigenstates

- We will use the direct decay for one amplitude and mixing for the other one
- Define
  - $A=\langle f|H|B^o\rangle$
  - $\bar{A}=\langle f|H|\bar{B}^o\rangle$
  - $|\bar{A}/A|\neq 1$ is evidence of CP violation in the decay amplitude ("direct" CPV)

- With mixing included, we can have CPV if

$$\lambda=\frac{q}{p}\frac{\bar{A}}{A}\neq 1$$

CP violation using CP eigenstates

- CP asymmetry $a_f(t) = \dfrac{\Gamma\left(B^o(t) \to f\right) - \Gamma\left(\overline{B}^o(t) \to f\right)}{\Gamma\left(B^o(t) \to f\right) + \Gamma\left(\overline{B}^o(t) \to f\right)}$
- for q/p = 1

$$a_f(t) = \frac{\left(1-|\lambda|^2\right)\cos(\Delta m t) - 2\,\mathrm{Im}\,\lambda \sin(\Delta m t)}{1+|\lambda|^2}$$

- When there is only one decay amplitude, λ=1 then $a_f(t) = -\mathrm{Im}\,\lambda \sin(\Delta m t)$
- Time integrated

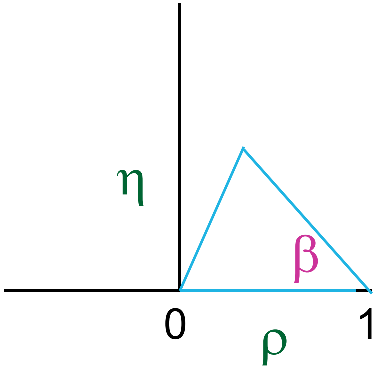
$$a_f(t) = -\frac{x}{1+x^2}\,\mathrm{Im}\,\lambda = -0.48\,\mathrm{Im}\,\lambda$$

good luck, maximum is –0.5

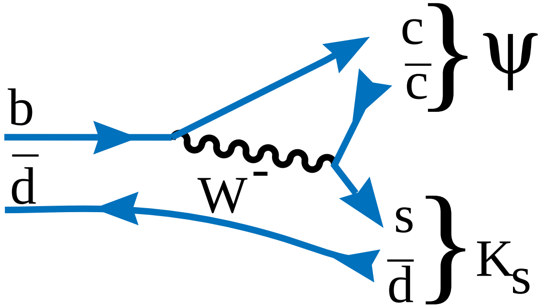
CP violation using CP eigenstates II

- For B_d, $$\frac{q}{p}=\frac{\left(V_{tb}^{*}V_{td}\right)^2}{\left|V_{tb}^{*}V_{td}\right|^2}=\frac{\left(1-\rho-i\eta\right)^2}{\left(1-\rho+i\eta\right)\left(1-\rho-i\eta\right)}=e^{-2i\beta}$$

$$\mathrm{Im}\left(\frac{p}{q}\right)=\frac{2(1-\rho)\eta}{\left(1-\rho\right)^2+\eta^2}=\sin(2\beta)$$



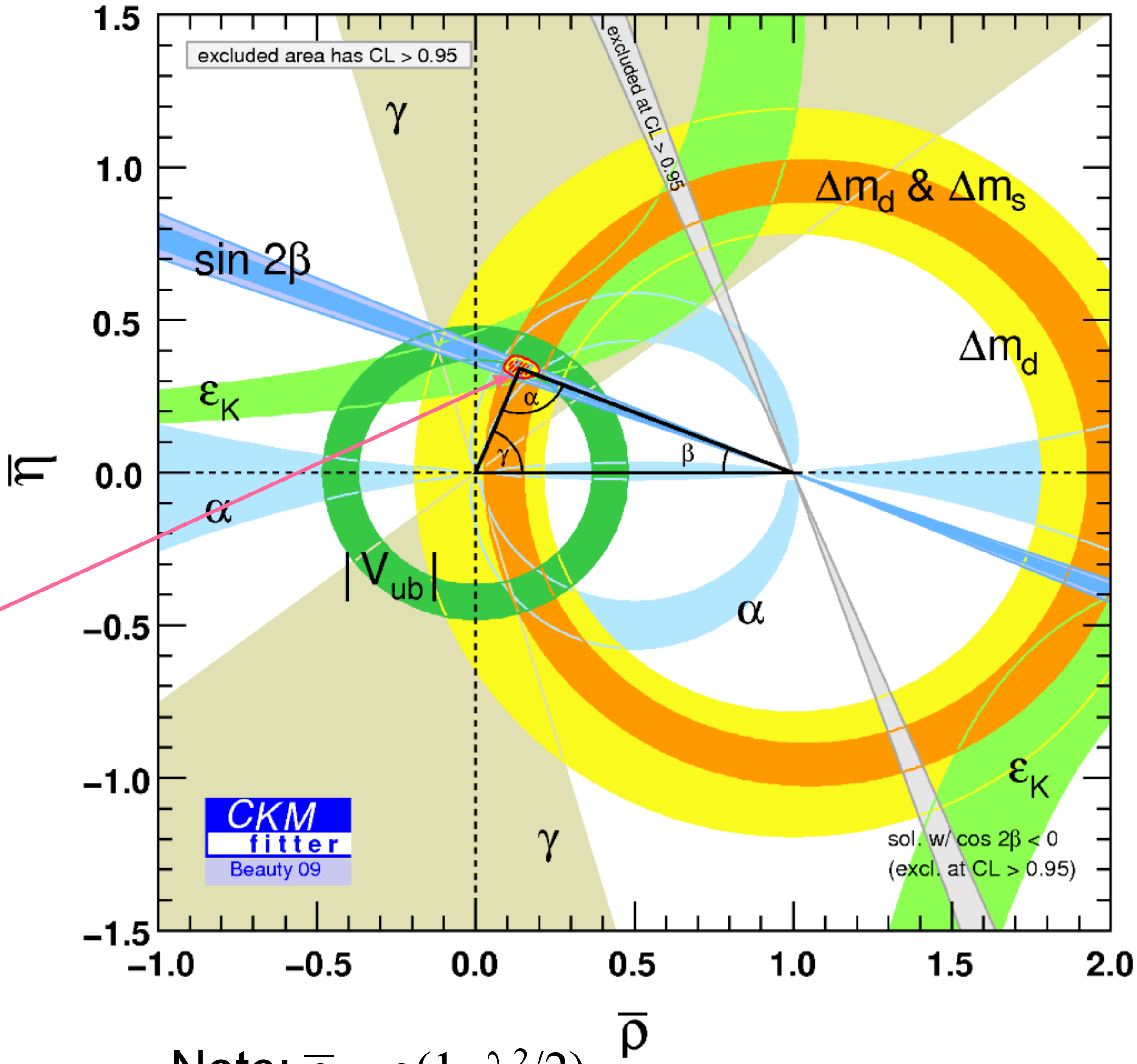
- Homework, what is q/p for B_s?
- Now need to add $\bar{A}/A$
  - for $J/\psi\ K_s$: $$\frac{\bar{A}}{A}=\frac{\left(V_{cb}V_{cs}^{*}\right)^2}{\left|V_{cb}V_{cs}^{*}\right|^2}\approx 1$$



HW: what is $\bar{A}/A$ for $\pi^+\pi^-$?

Current Status of CP & Some Other Measurements

- SM CKM parameters are: A~0.8, λ=0.22, ρ & η
- CKM Fitter results using CP violation in $J/\psi\ K_S$, $\rho^+\rho^-$, DK^-, K_L, & V_{ub}, V_{cb} & ΔM_q
- The overlap region includes CL>95%
- Similar situation using UTFIT
- Measurements "consistent"



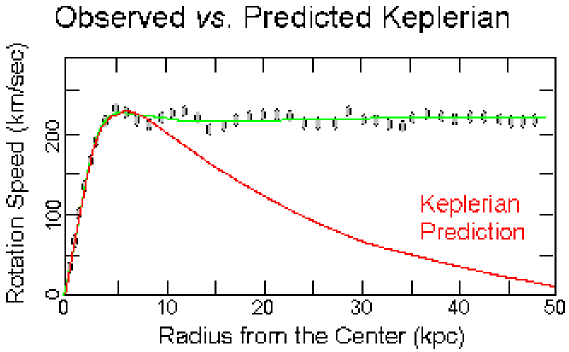
Note: $\bar{\rho} = \rho(1-\lambda^2/2)$

$\bar{\eta} = \eta(1-\lambda^2/2)$

What don't we know: Physics Beyond the Standard Model

Physics Beyond the Standard Model

- Baryogensis: CPV measurements thus far indicate $(n_B-n_B)/n_\gamma = \sim 6\times10^{-10}$, while SM can provide only $\sim10^{-20}$. Thus New Physics must exist
- Dark Matter



Gravitational lensing

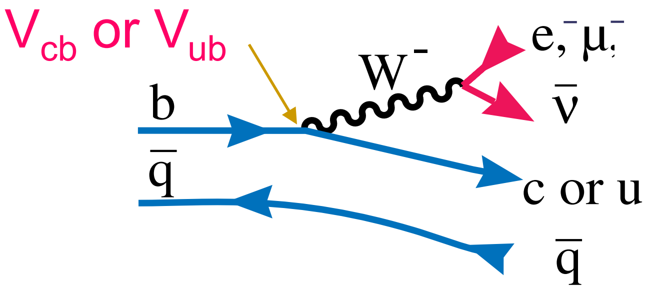
- Hierarchy Problem: We don’t understand how we get from the Planck scale of Energy $\sim10^{19}$ GeV to the Electroweak Scale ~100 GeV without “fine tuning” quantum corrections

Flavor Problems

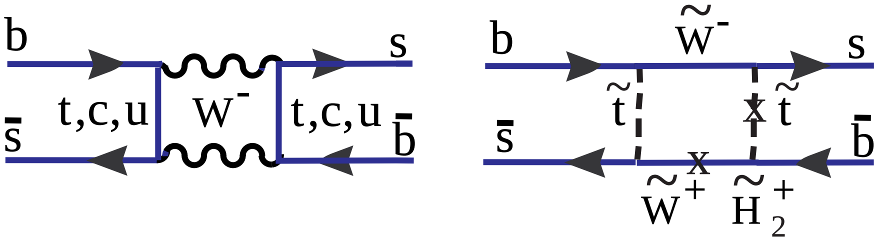
- Why do the fermions have their specific masses? Why are the masses in general smaller than the electroweak scale?
- Why do the mixing angles (the CKM matrix elements) have their specific values?
- Is there a new theory that relates the CKM matrix elements to masses?
- What is the relationship between the CKM matrix and the neutrino mixing matrix?

Limits on New Physics

- What we observe is the sum of Standard Model + New Physics. How to set limits on NP?
- Assume that tree level diagrams are dominated by SM and loop diagrams could contain NP



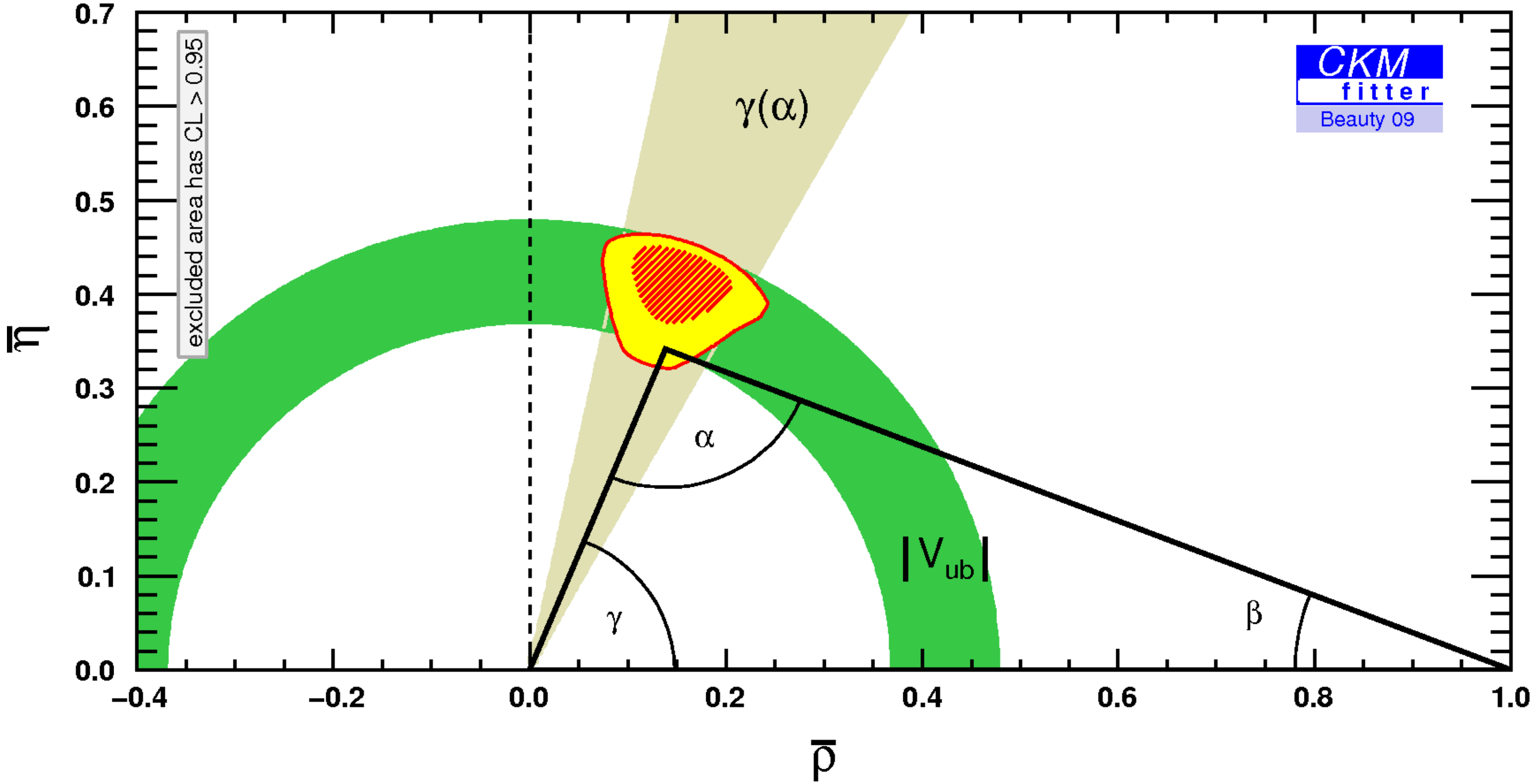
Tree diagram example



Loop diagram example

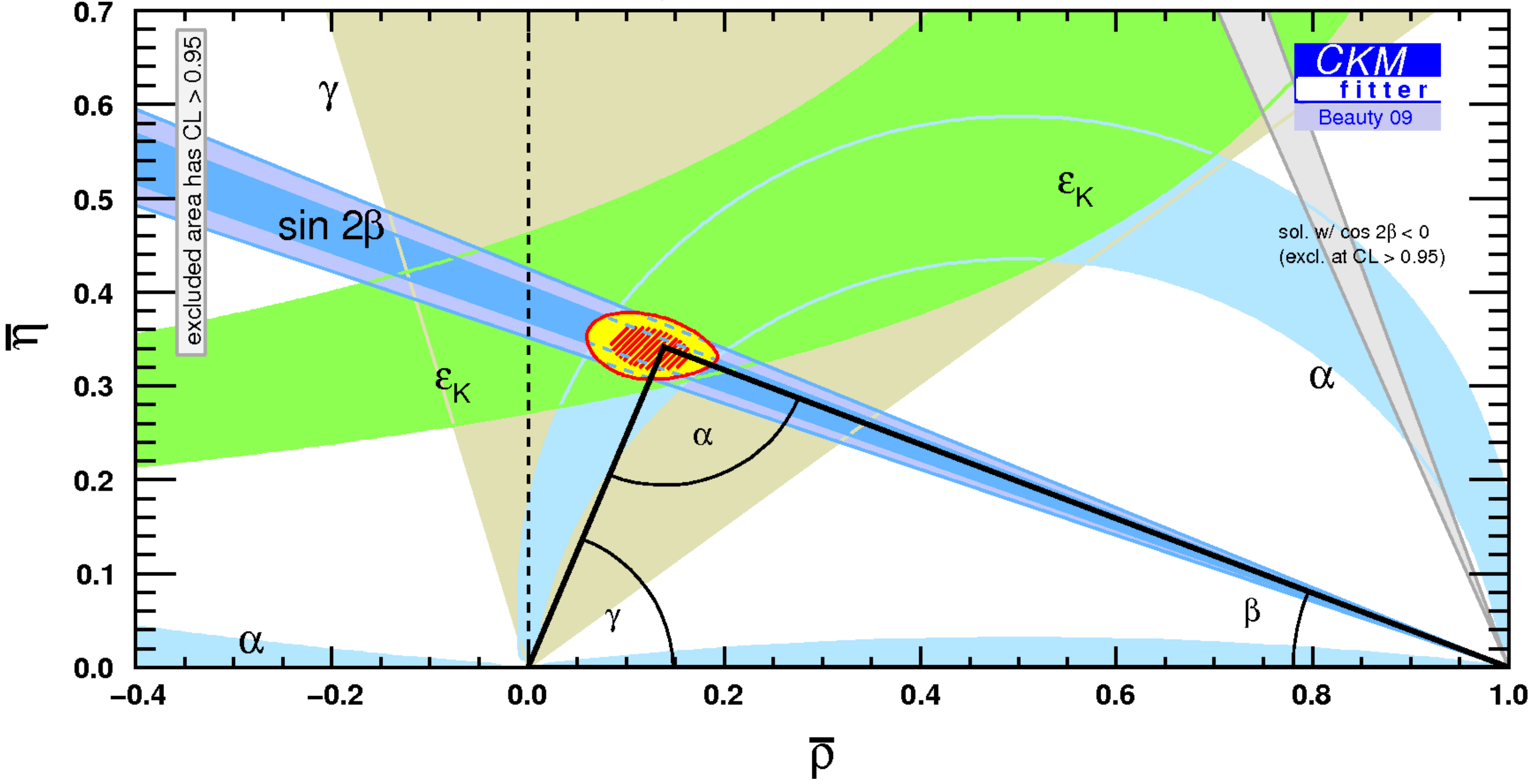
Tree Level Only

- Tree diagrams are unlikely to be affected by physics beyond the Standard Model

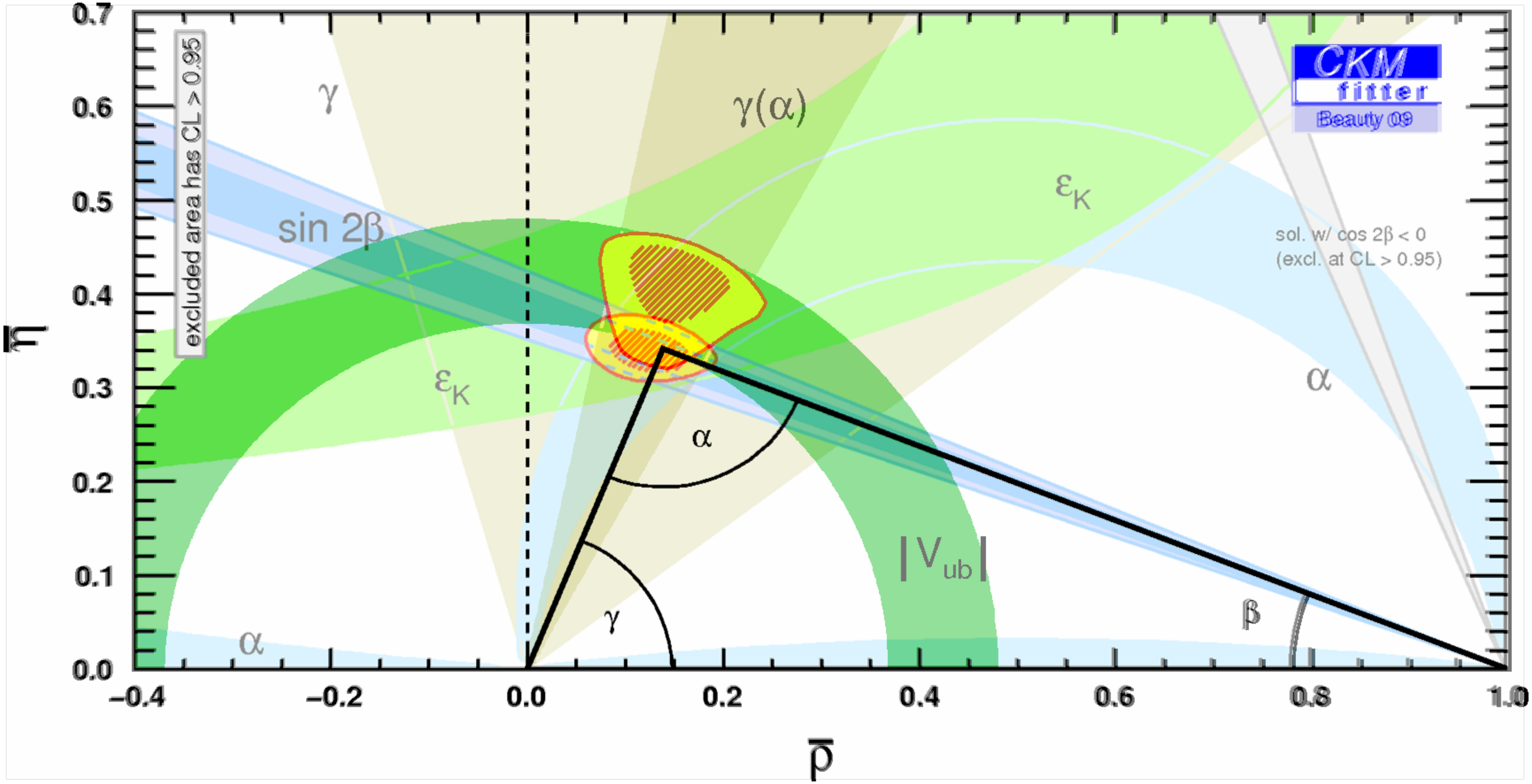


CP Violation in B^0 & K^0 Only

- Absorptive (Imaginary) of mixing diagram should be sensitive to New Physics

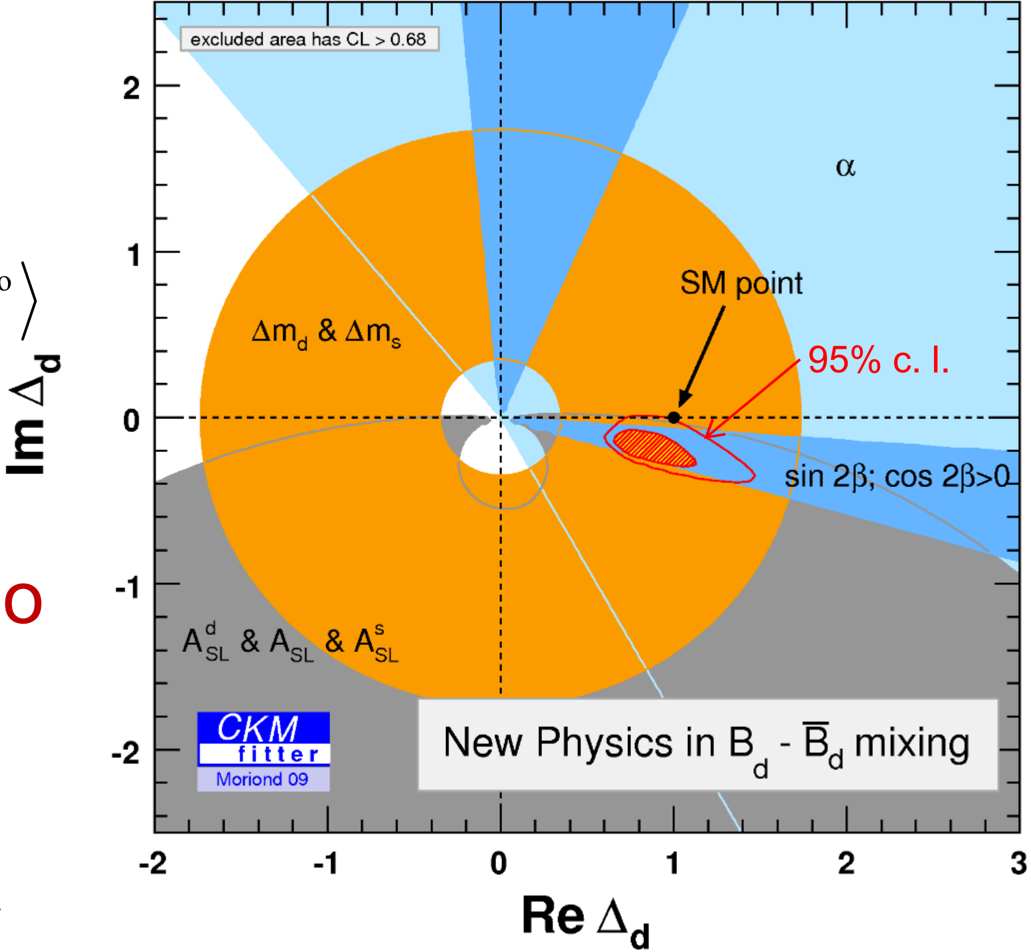


They are Consistent



Limits on New Physics From B^o Mixing

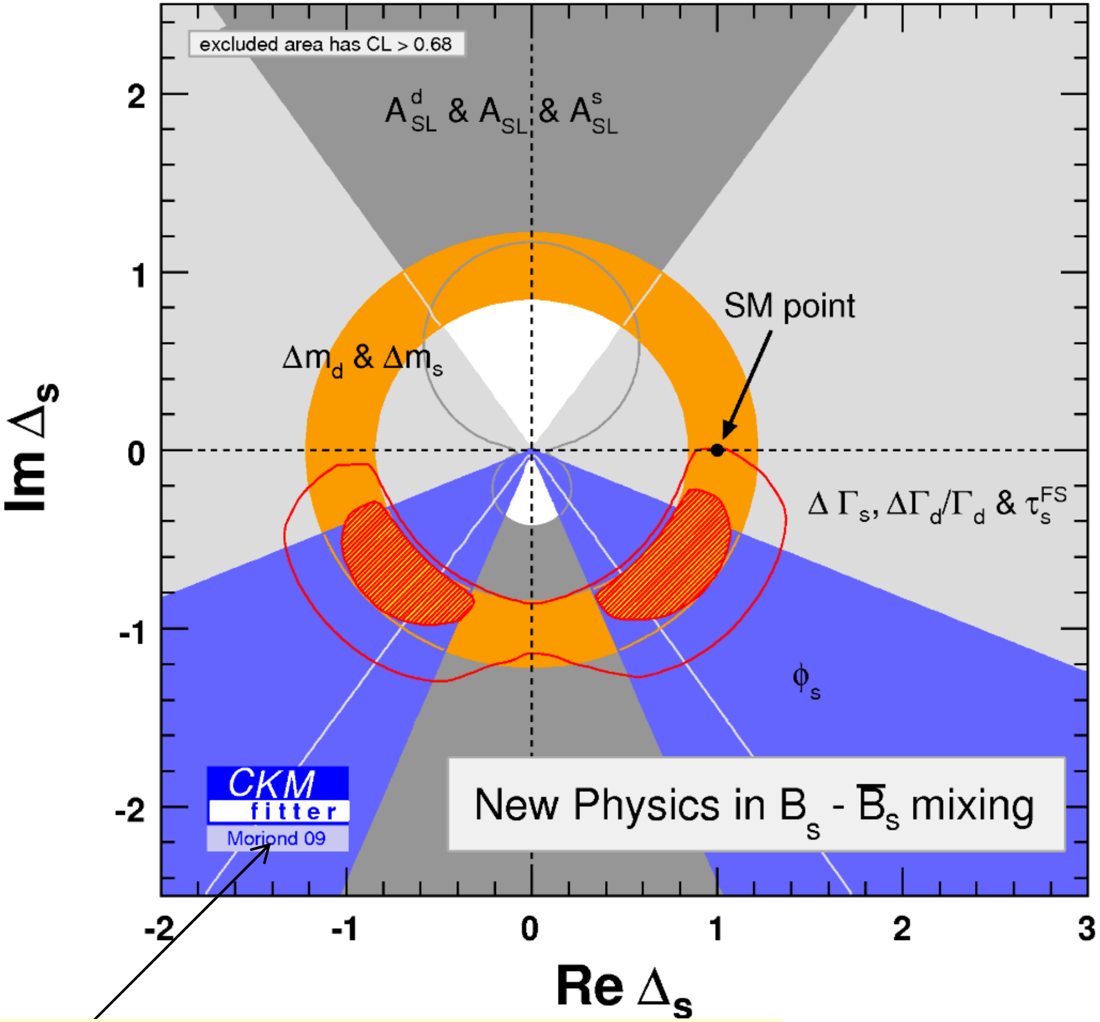
- Is there NP in B^o-$\bar{B}^o$ mixing?
- $$\left\langle B^o | H^{SM+NP}_{\Delta B=2} | \bar{B}^o \right\rangle = \Delta_d^{NP} \left\langle B^o | H^{SM}_{\Delta B=2} | \bar{B}^o \right\rangle$$
  $$\Delta_d^{NP} = \mathrm{Re}\,\Delta_d + i\mathrm{Im}\Delta_d$$
- Assume NP in tree decays is negligible, so no NP in $|V_{ij}|$, γ from $B^- \rightarrow D^o K^-$.
- Allow NP in Δm, weak phases, A_{SL}, & $\Delta\Gamma$.



- Room for new physics, in fact SM is only at 5% c.l.

Limits on New Physics From B_S Mixing

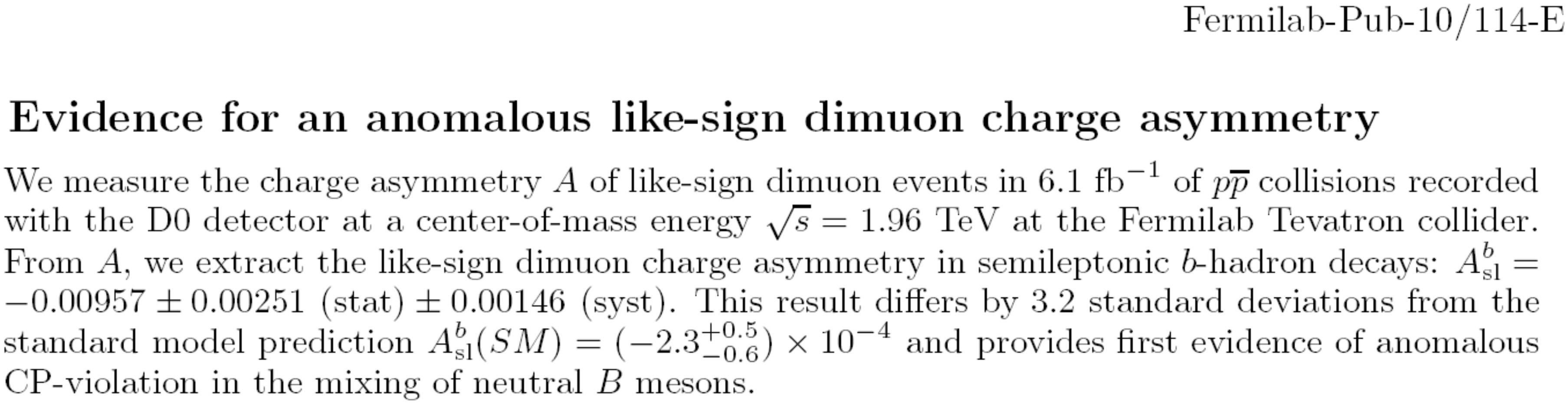
- Similarly for B_S
  - One CP Violation measurement using $B_S \to J/\psi\ \phi$
- Here again SM is only at 5% c.l.
- Much more room for NP due to less precise measurements



Note date, much has changed! or has it?

Hint of New Physics: a_{sl}

- New D0 measurement
- Idea here is to use dilepton asymmetry



Fermilab-Pub-10/114-E

Evidence for an anomalous like-sign dimuon charge asymmetry

We measure the charge asymmetry A of like-sign dimuon events in 6.1 fb^{-1} of $p\overline{p}$ collisions recorded with the D0 detector at a center-of-mass energy $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. From A, we extract the like-sign dimuon charge asymmetry in semileptonic b-hadron decays: $A^b_{\rm sl} = -0.00957 \pm 0.00251\ (\text{stat}) \pm 0.00146\ (\text{syst})$. This result differs by 3.2 standard deviations from the standard model prediction $A^b_{\rm sl}(SM) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$ and provides first evidence of anomalous CP-violation in the mixing of neutral B mesons.

- Only 3.2 σ, therefore a hint to be pursued by LHCb

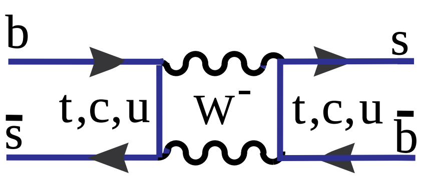
New Physics Models

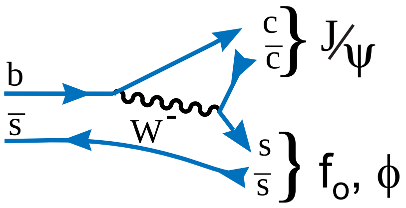
- There is, in fact, still lots of room for "generic" NP
- What do specific models predict?
  - Supersymmetry: many, many different models
  - Extra Dimensions: "
  - Little Higgs: "
  - Left-Right symmetric models "
  - 4th Generation models "
- NP **must** affect every process; the amount tells us what the NP is ("DNA footprint")
- Lets go through some examples, many other interesting cases exist

Supersymmetry: MSSM

- MSSM from Hinchcliff & Kersting (hep-ph/0003090)
- Contributions to B_s mixing

$B_s \rightarrow J/\psi f_o$ or ϕ



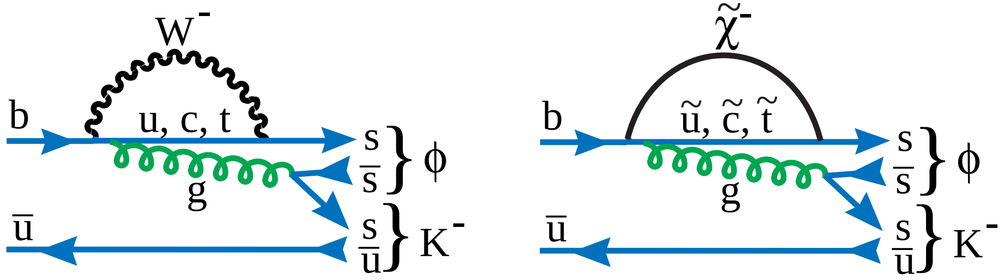


measures CP violating $\angle -2\beta_s$

CP asymmetry ≈ $0.1\sin\phi_\mu\cos\phi_A\sin(\Delta m_s t)$, ~10 x SM

- Contributions to direct CP violating decay

$B^- \rightarrow \phi K^-$

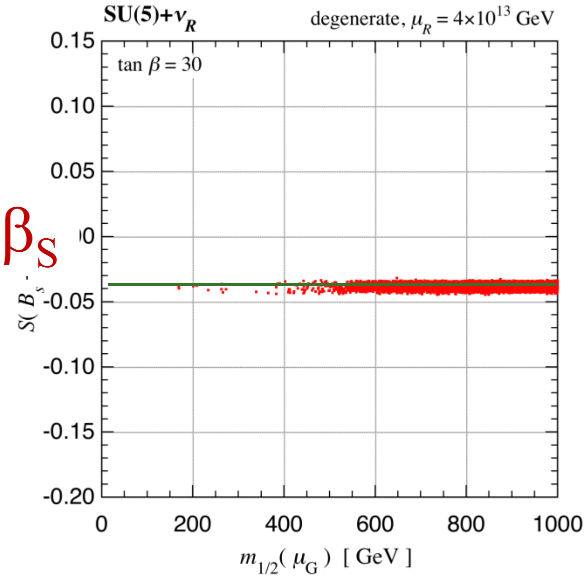


Asym=$(M_W/m_{squark})^2\sin(\phi_\mu)$, ~0 in SM

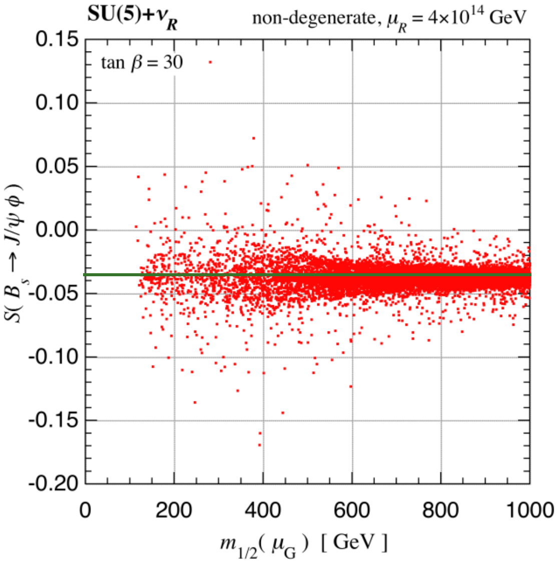
Supersymmetry: SU(5) &U(2)

SU(5) GUT
Degenerate

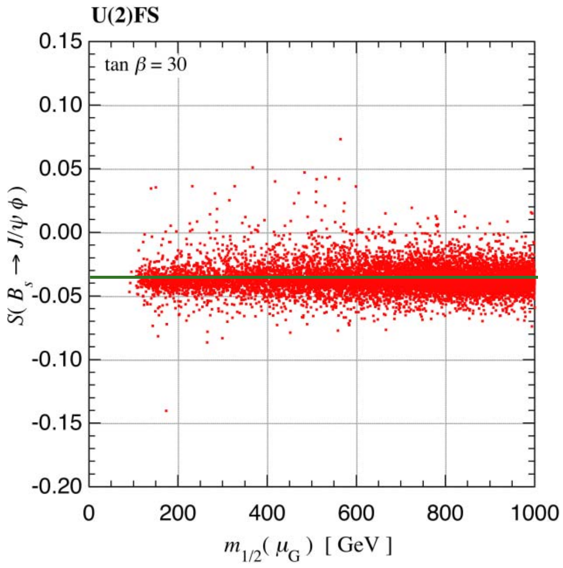
$-2\beta_s$



SU(5) GUT
Non-degenerate



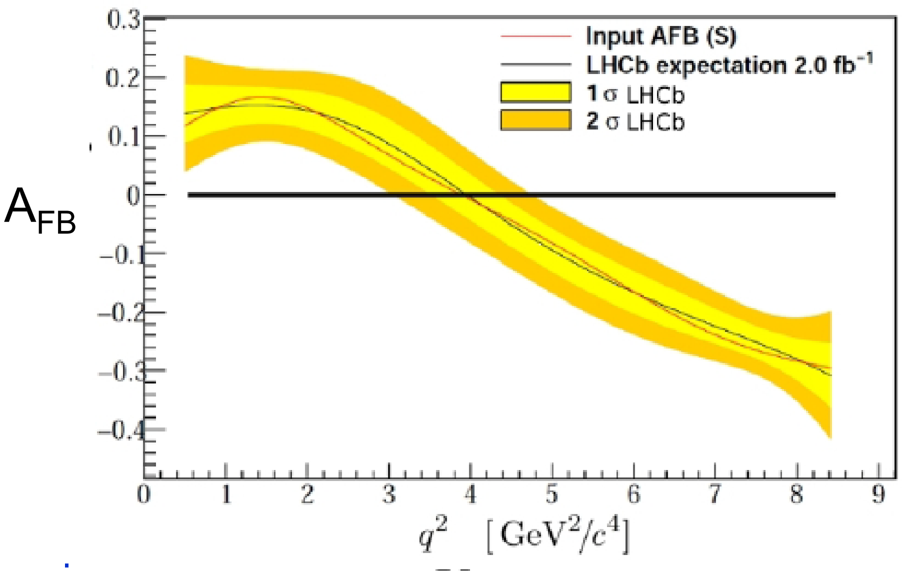
U(2) FS

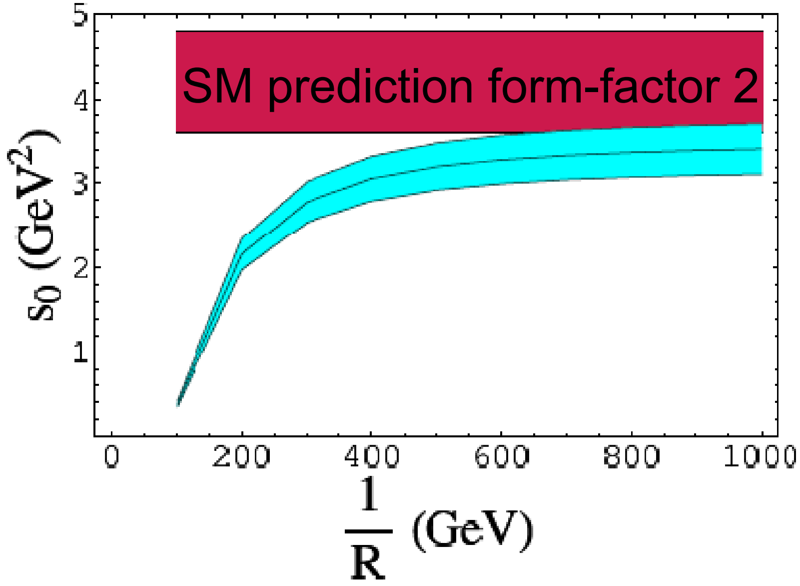


- $-2\beta_s$ can deviate from the "SM" value of -0.036 in SU(5) GUT non-degenerate case, and the U(2) model. From Okada's talk at BNMII, Nara Women's Univ. Dec., 2006

Extra Dimensions

- Using ACD model of 1 universal extra dimension, a MFV model, Colangelo et al predict a shift in the zero of the forward-backward asymmetry in $B \to K^{*}\mu^{+}\mu^{-}$
- *Insensitive to choice of form-factors. Can SM calculations improve?*





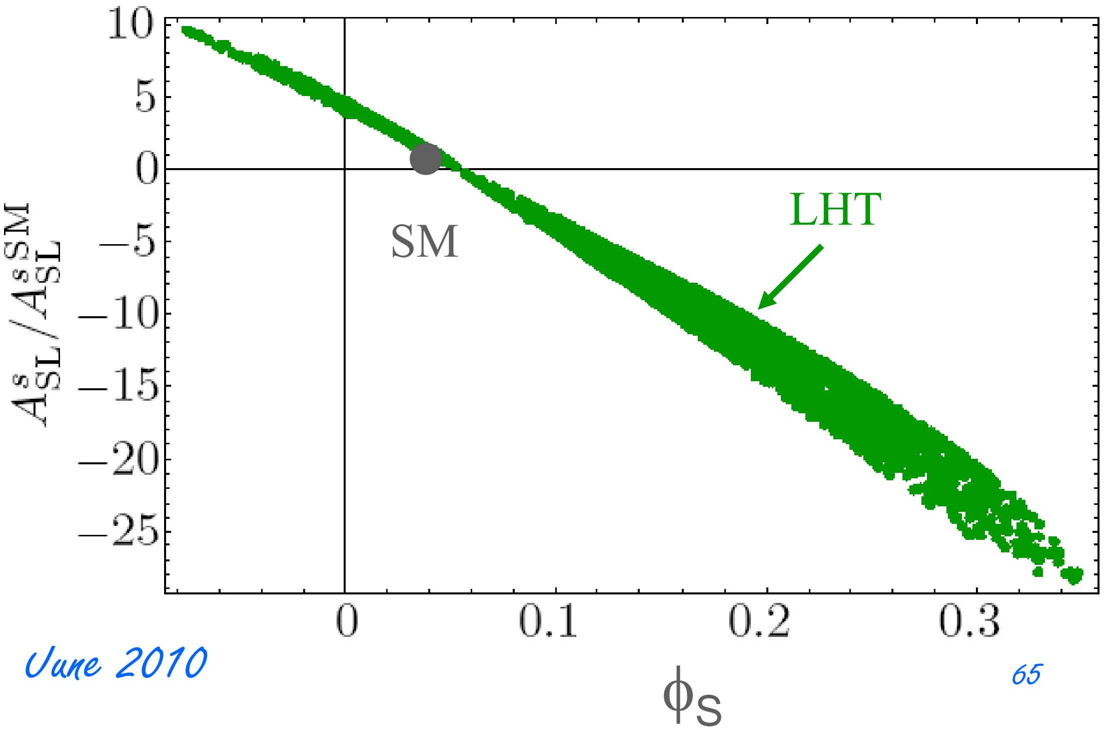
SM prediction form-factor 2

Little Higgs Model with T Parity

- There exist regions of parameter space consistent with measurement where large ϕ_S is predicted & ΔM_S is found somewhat smaller than in the SM.
- In particular, significant enhancement of ϕ_S & the semileptonic asymmetry $a_{SL}(S)$ relative to the SM are found

•From Blanke & Buras, [hep-ph/0703117]

- Need precision measurements of CP asymmetry in $B_S \to J/\psi\phi$ & $\mathcal{B}(B_S \to D_S^+ \ell^- \nu)$- $\mathcal{B}(B_S \to D_S^- \ell^+ \nu)$



The LHCb Detector

The LHCb Collaboration

- 800 Physicists
- 54 Institutes
- 15 Countries
  - 1 Group from USA
- Basking in light of 2008 Nobel Prize to Kobayshi & Maskawa, “for the discovery of the origin of the broken symmetry which predicts the existence of at least 3 families of quarks”

Detector Requirements – General

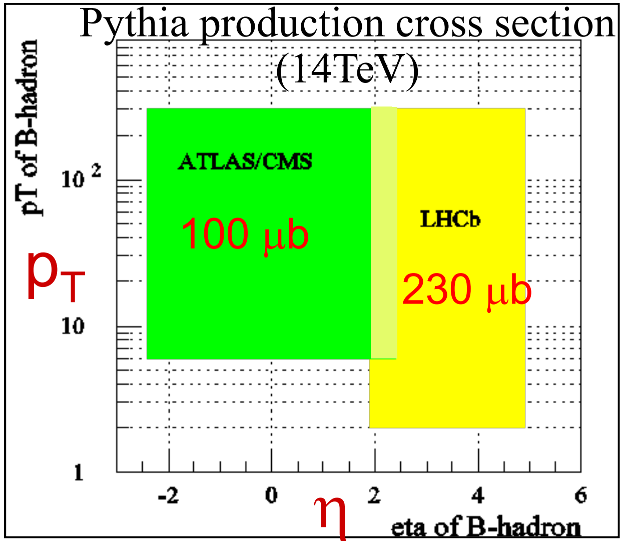
- Every modern heavy quark experiment needs:
  - Vertexing: to measure decay points and reduce backgrounds, especially at hadron colliders
  - Particle Identification: to eliminate insidious backgrounds from one mode to another where kinematical separation is not sufficient
  - Muon & electron identification because of the importance of semileptonic & leptonic final states including J/ψ decay
  - γ, π^o & η detection
  - Triggering, especially at hadronic colliders
  - High speed DAQ coupled to large computing for data processing
  - An accelerator capable of producing a large rate of b's

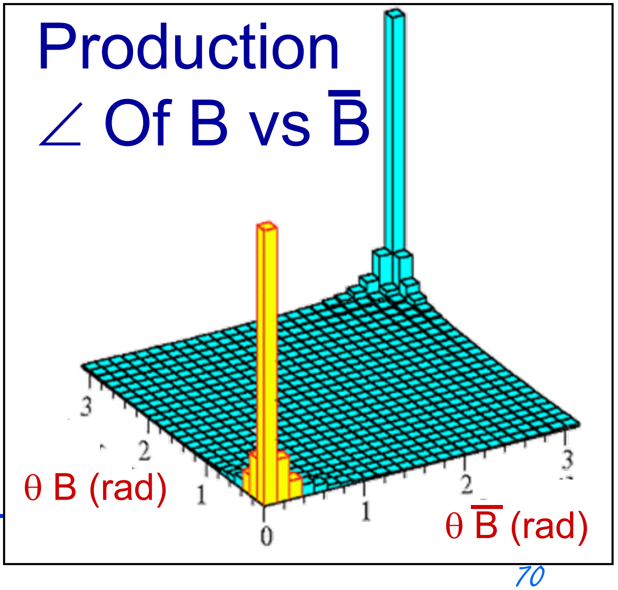
Basics For Sensitivities

- # of b’s into detector acceptance
- Triggering
- Flavor tagging
- Background reduction
  - Good mass resolution
  - Good decay time resolution
  - Particle Identification

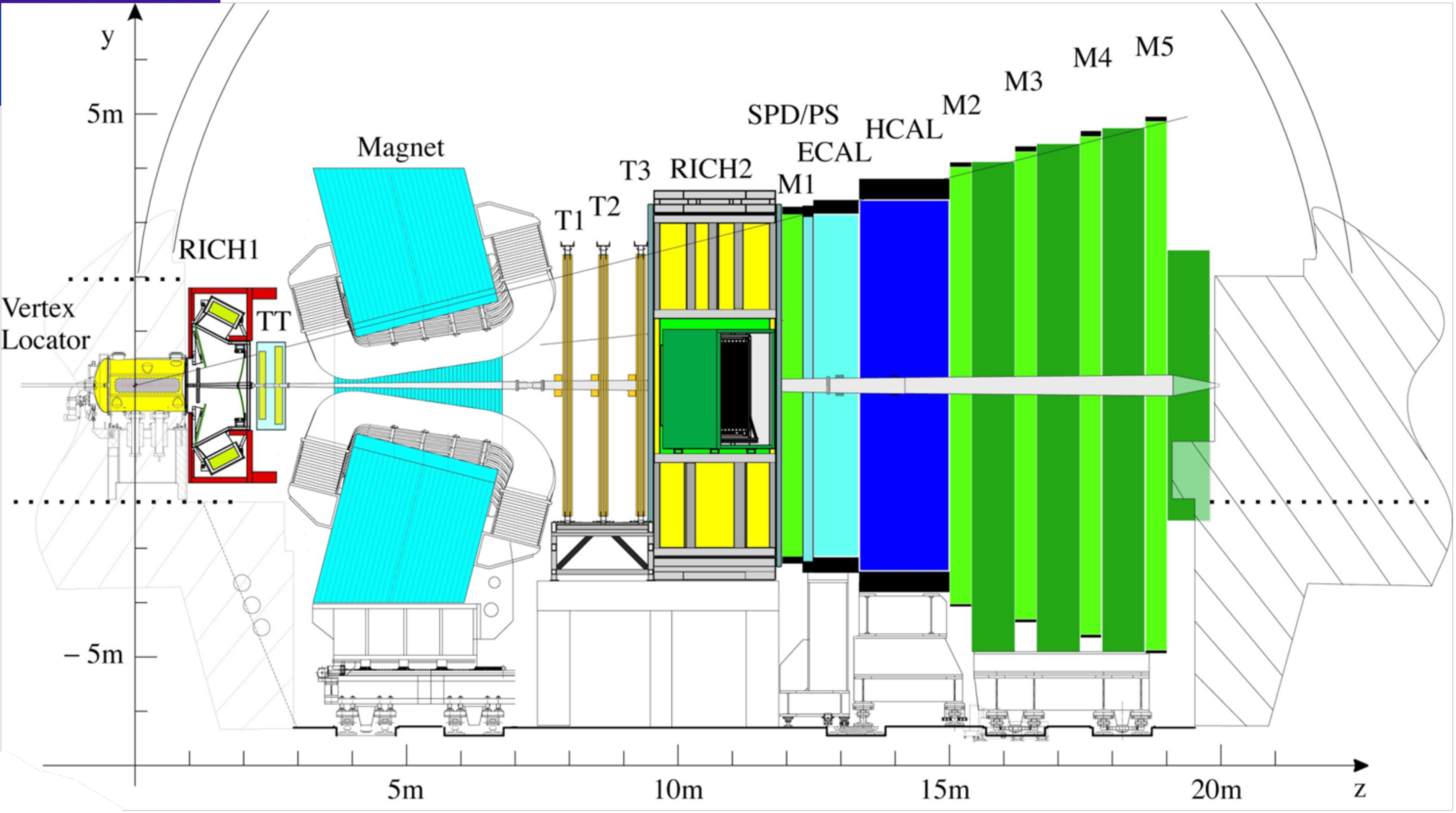
The Forward Direction at the LHC

- In the forward region at LHC the $b\bar{b}$ production σ is large
- The hadrons containing the b & $\bar{b}$ quarks are both likely to be in the acceptance
- LHCb uses the forward direction, $4.9 > \eta > 1.9$, where the B's are moving with considerable momentum ~100 GeV, thus minimizing multiple scattering
- At $\mathcal{L}=2\times10^{32}/cm^2$-s, we get 10^{12} B hadrons in 10^7 sec

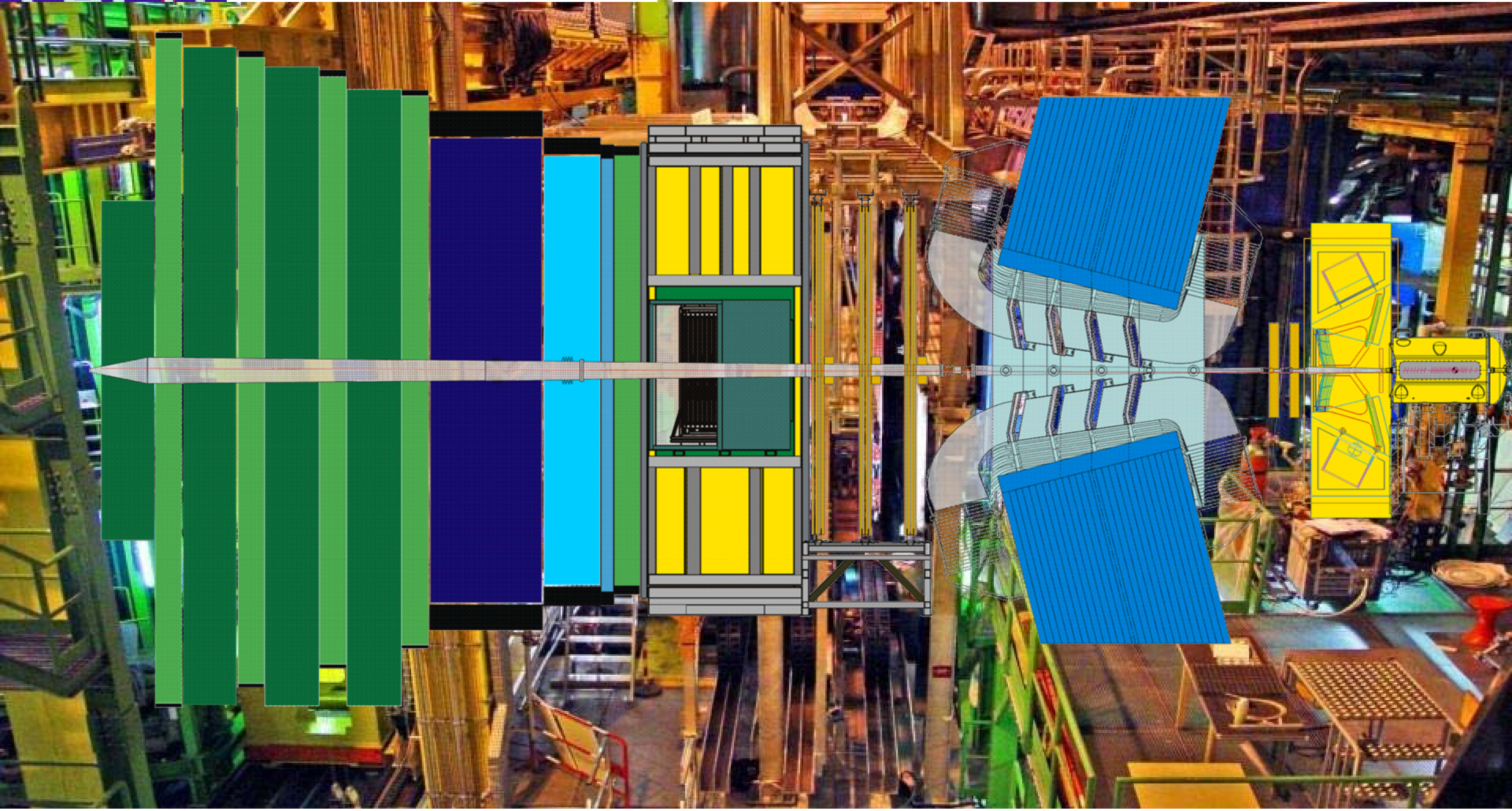




The LHCb Detector

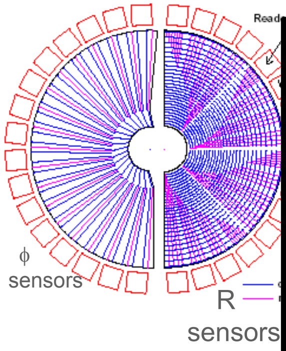


Detector Workings

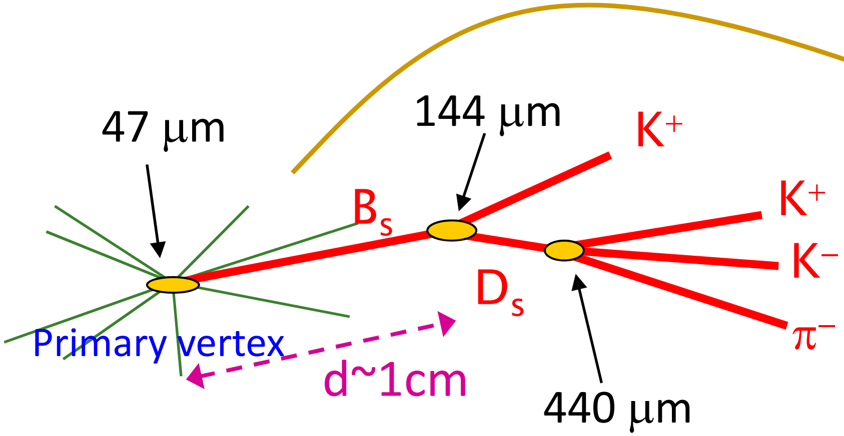


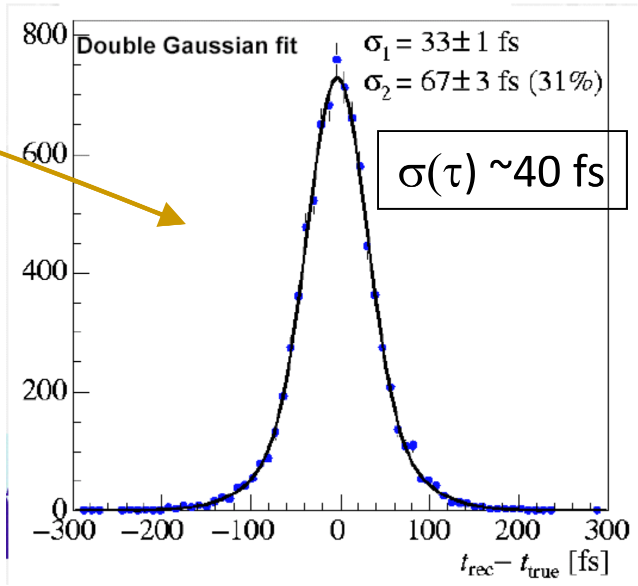
LHCb detector ~ fully installed and commissioned → walk through the detector using the example of a $B_s \rightarrow D_s K$ decay

B-Vertex Measurement



Example: $B_s \rightarrow D_s K$





σ(τ) ~40 fs

Decay time resolution = 40 fs

Vertex Locator (Velo)

Silicon strip detector with

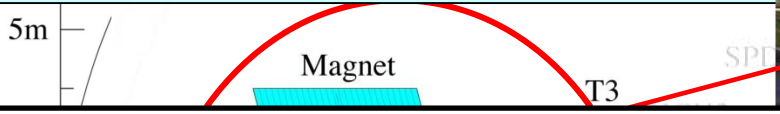
~ 5 μm hit resolution

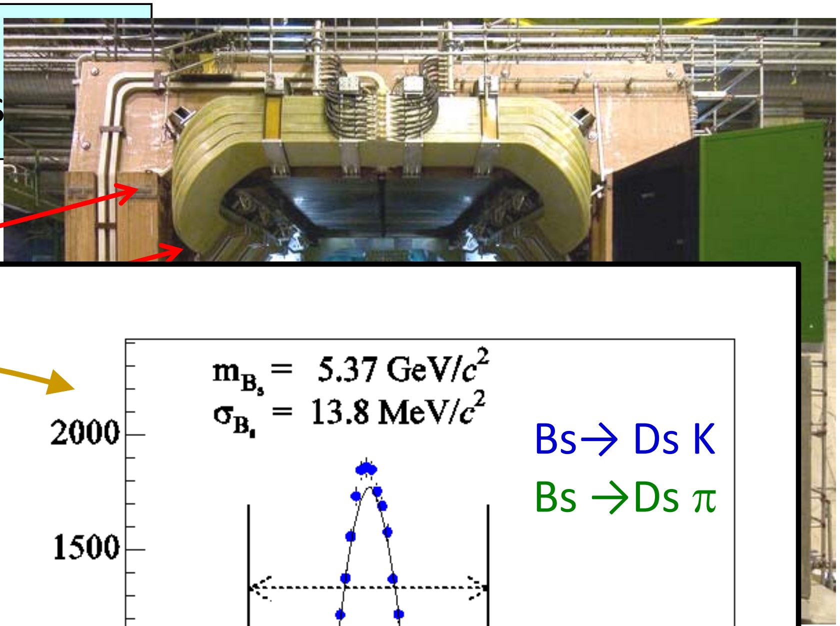
→ 30 μm IP resolution

Vertexing:
- trigger on impact parameter
- measurement of decay distance (time)

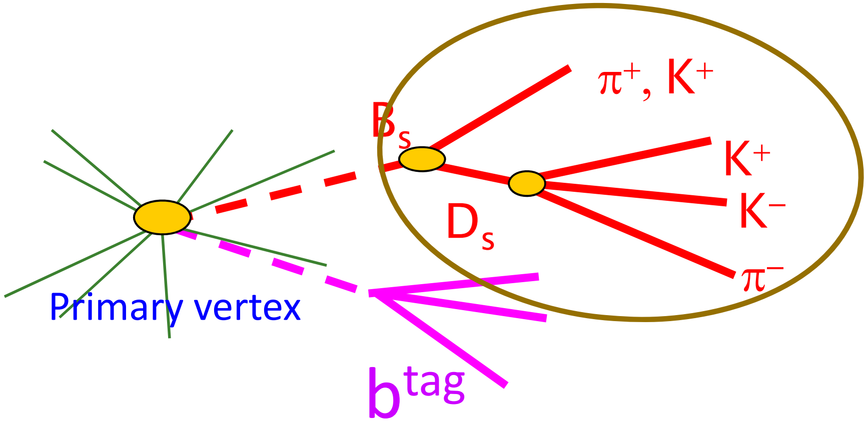
Momentum and Mass measurement

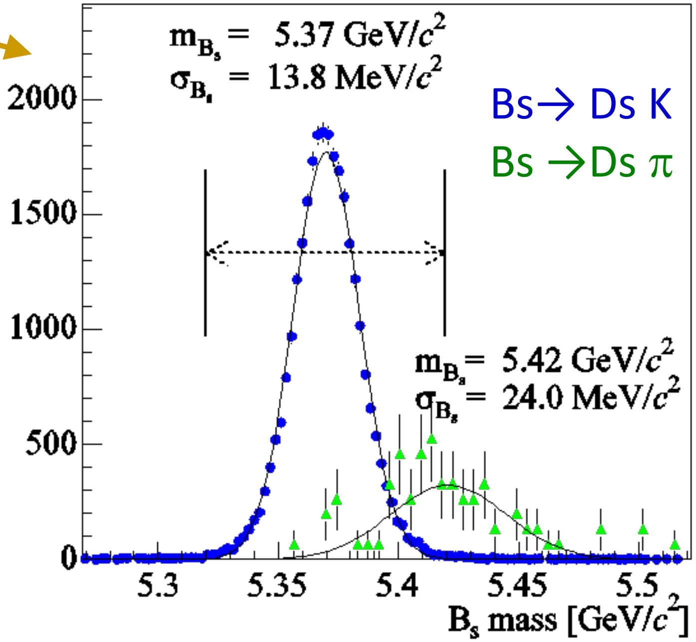
Momentum meas. + direction (VELO):
Mass resolution for background suppres





Mass resolution
σ ~14 MeV





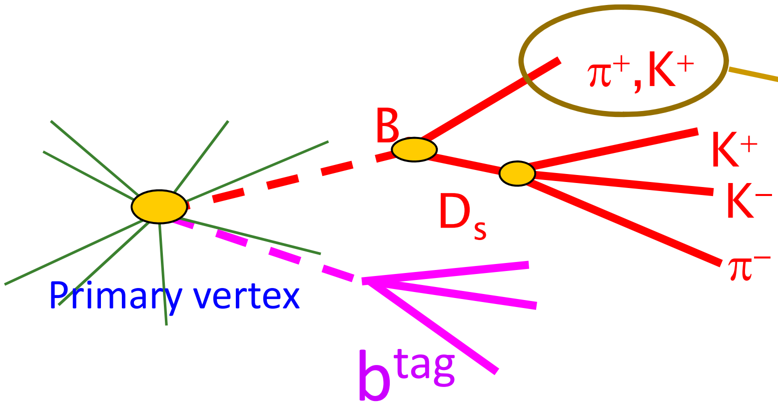
Bs→ Ds K
Bs →Ds π

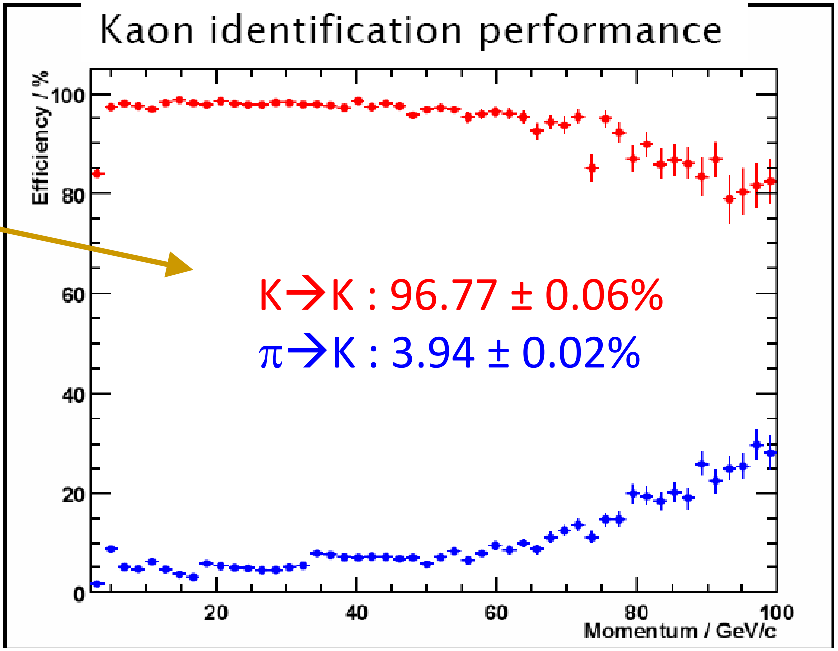
Hadron Identification

RICH: K/π identification using Cherenkov light emission angle

$B_s \rightarrow D_s K$

SS flavour tagging





K→K : 96.77 ± 0.06%

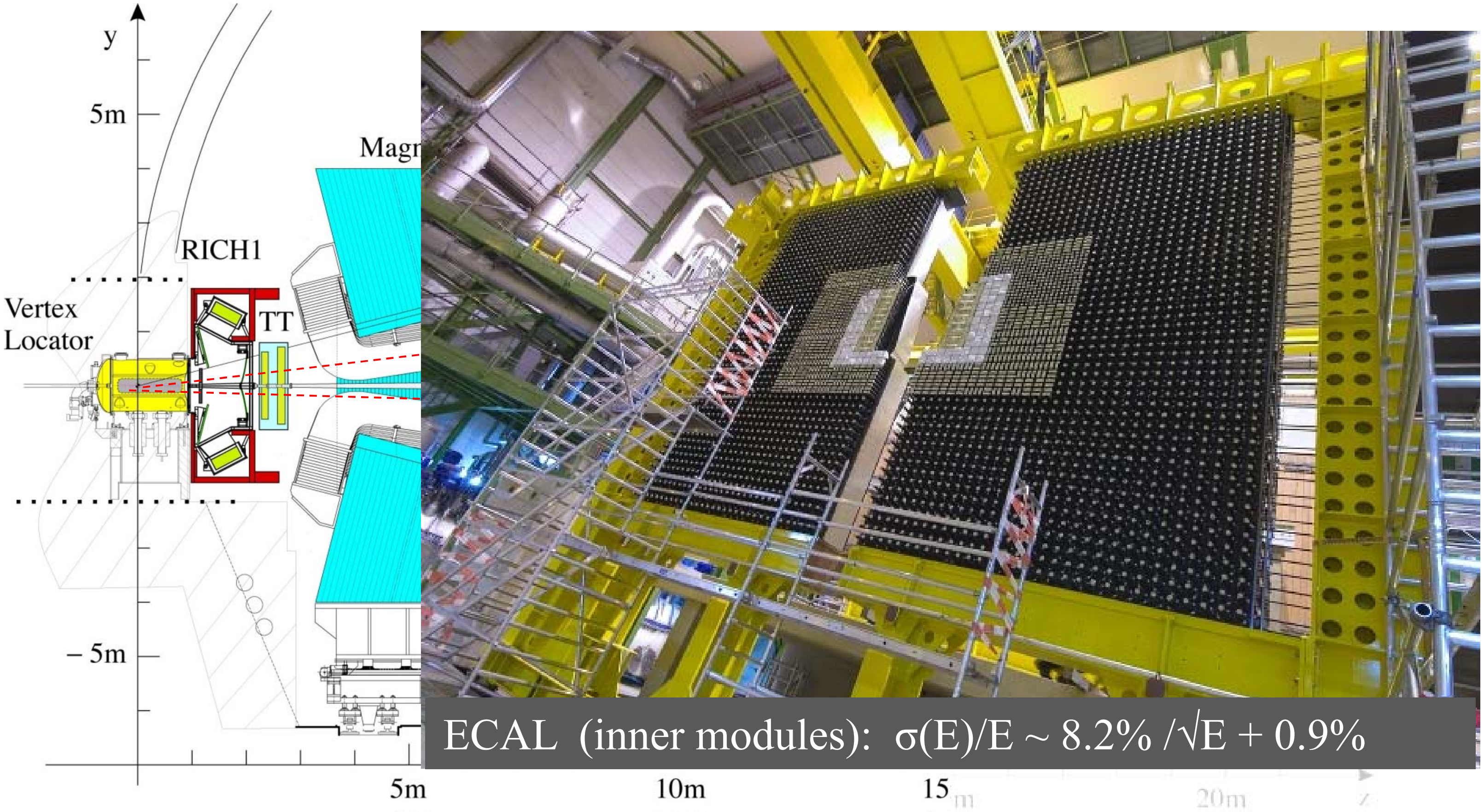
π→K : 3.94 ± 0.02%

RICH1: 5 cm aerogel n=1.03

4 m^3 C_4F_{10} n=1.0014

RICH2: 100 m3 CF_4 n=1.0005

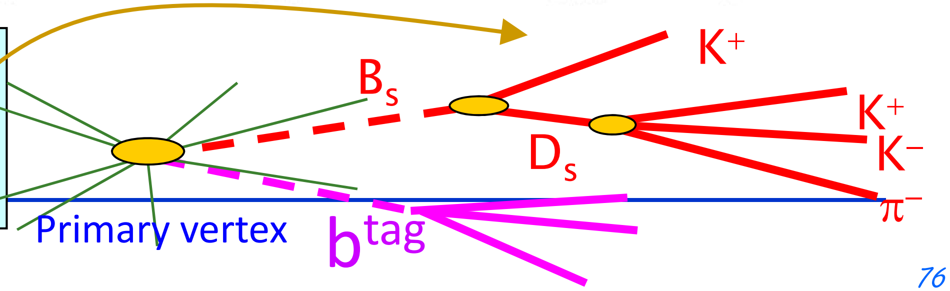
Particle identification and L0 trigger



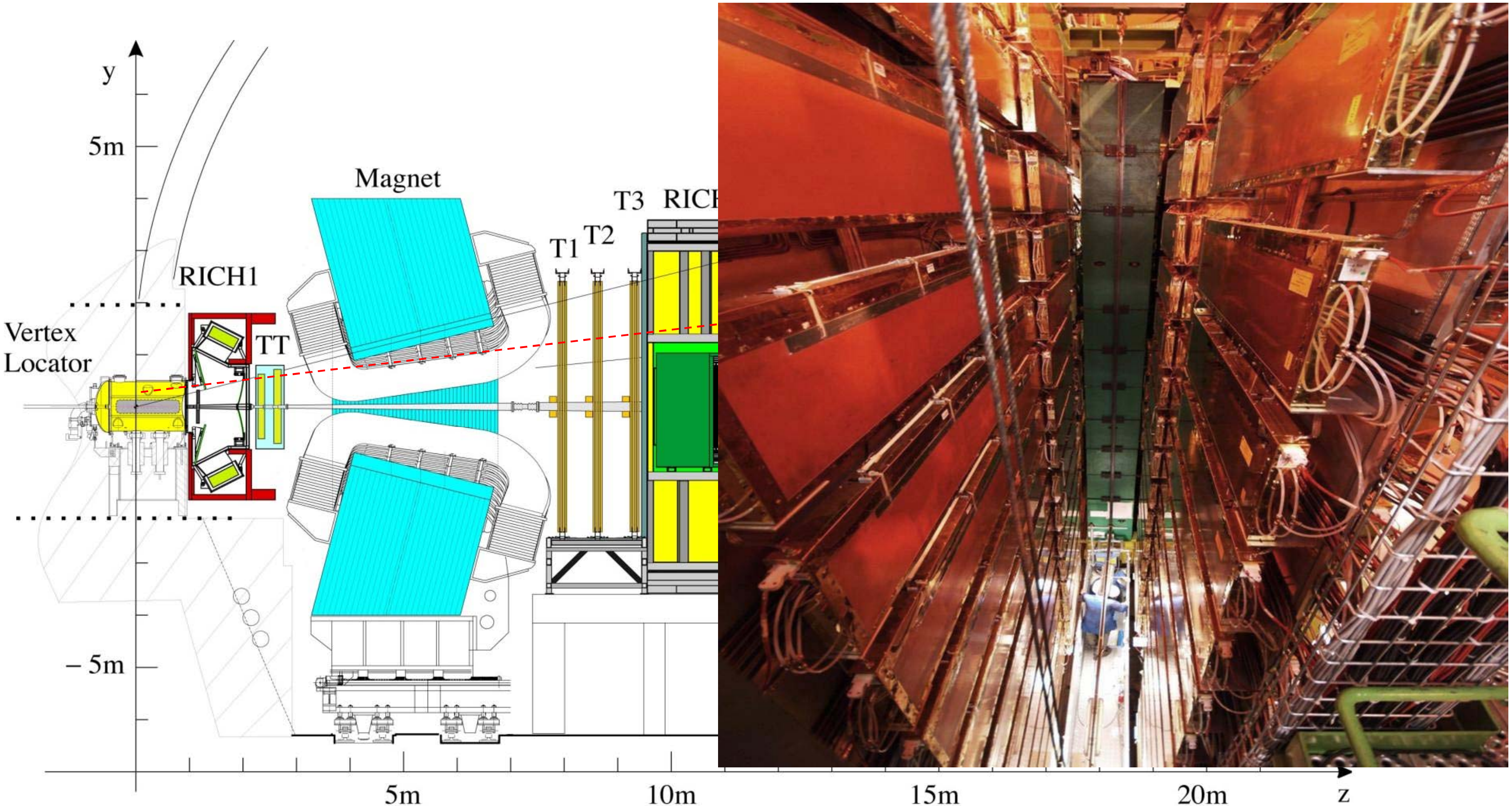
ECAL (inner modules): $\sigma(E)/E \sim 8.2\% /\sqrt{E} + 0.9\%$

Calorimeter system :

- Identify electrons, hadrons, π^0 ,γ
- Level 0 trigger: high E_T electron and hadron

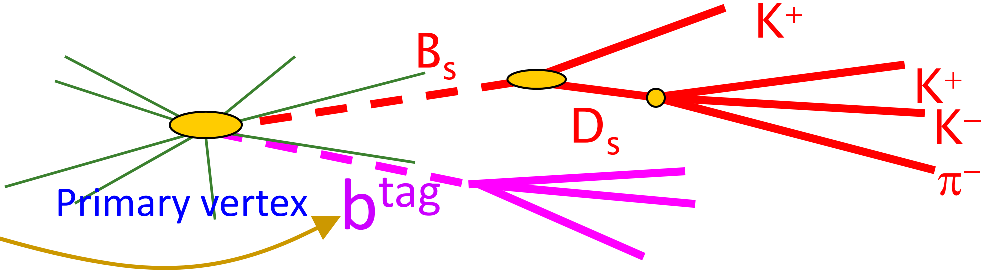


Particle identification and L0 trigger

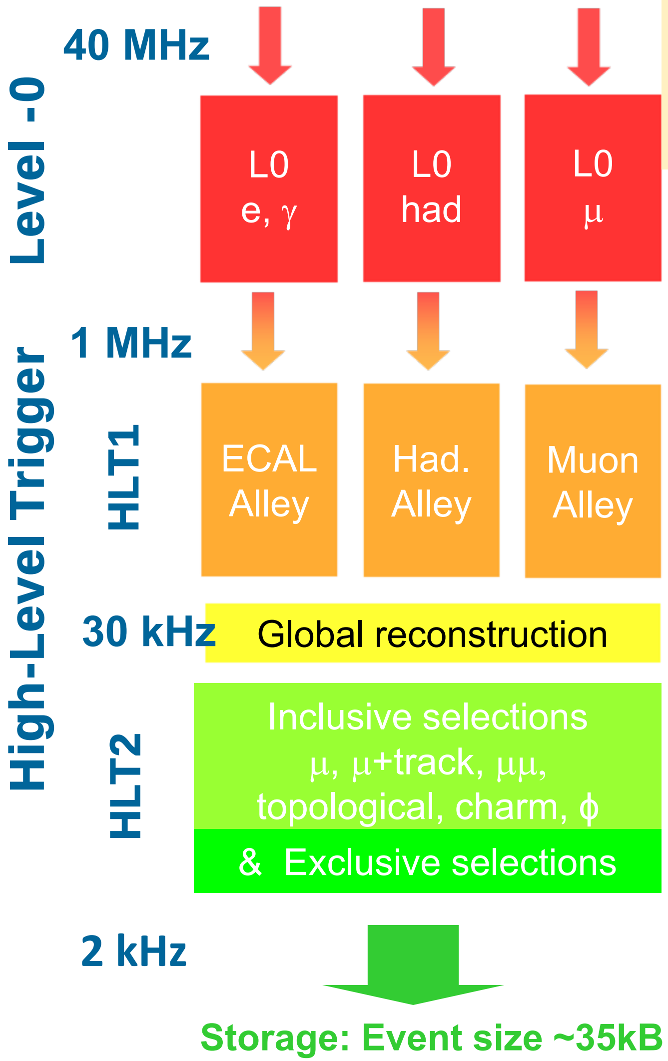


Muon system:

- Level 0 trigger: High P_t muons
- OS flavour tagging



Triggering



Level -0

40 MHz

L0 e, γ

L0 had

L0 μ

1 MHz

High-Level Trigger

HLT1

ECAL Alley

Had. Alley

Muon Alley

30 kHz

Global reconstruction

HLT2

Inclusive selections μ, μ+track, μμ, topological, charm, ϕ

& Exclusive selections

2 kHz

Storage: Event size ~35kB

Trigger is crucial as $\sigma_{b\bar{b}}$ is less than 1% of total inelastic cross section and B decays of interest typically have $\mathcal{B} < 10^{-5}$

- **Hardware level (L0)**

  Search for high-p_T μ, e, γ and hadron candidates

- **Software level (High Level Trigger, HLT)**

  Farm with $\mathcal{O}(2000)$ multi-core processors

  HLT1: Confirm L0 candidate with more complete info, add impact parameter and lifetime cuts

  HLT2: B reconstruction + selections

	ε(L0)	ε(HLT1)	ε(HLT2)
Electromagnetic	70 %	> ~80 %	> ~90 %
Hadronic	50 %		
Muon	90 %		

Stripping

- Even with the trigger most of the events are uninteresting
- Typical interesting branching fraction $\mathcal{B}(B_s \to J/\psi\ \phi)\mathcal{B}(J/\psi \to \mu^+\mu^-)\mathcal{B}(\phi \to K^+K^-) = 1.3\text{x}10^{-3}$ $\text{x}0.059\text{x}0.5 = 4\text{x}10^{-5}$.
- Rate of events 2 kHz. Rate of $J/\psi\ \phi$ $=2^*\sigma(pp \to b\bar{b})^*\mathcal{L}^*\text{accept}^*\text{recon}^*\text{trigger}^*B$

$=2^*500\ \mu b^*2\text{x}10^{32}\text{cm}^{-2}/\text{s}^*0.18^*0.6^*0.9^*4\text{x}10^{-5}$

$=10^3{}^*10^{-30}\text{cm}^*10^{32}\text{cm}^{-2}/\text{s}^*4\text{x}10^{-6}$

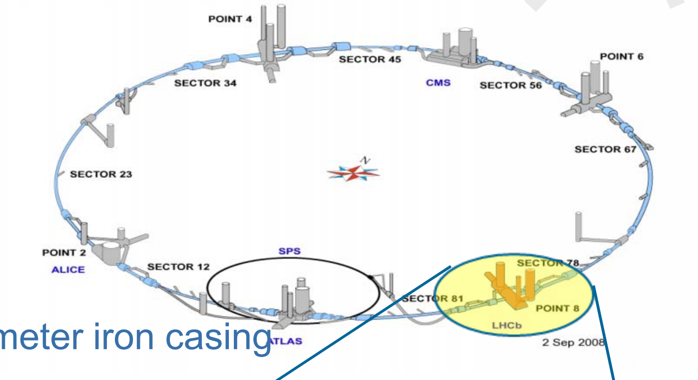
=0.4/second

Stripping II

- Many interesting final states
- Each final state stripping line is limited to accept only 10^{-3} – 10^{-2} of minimum bias simulated events that passed the trigger
- This means that you need to understand what you want to look at before you take the data!

Commissioning

A First Glimpse of LHC Protons

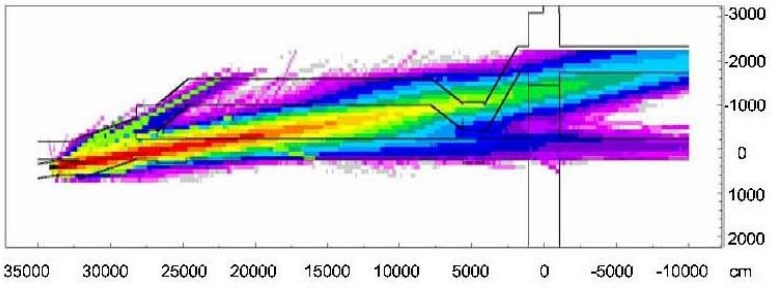


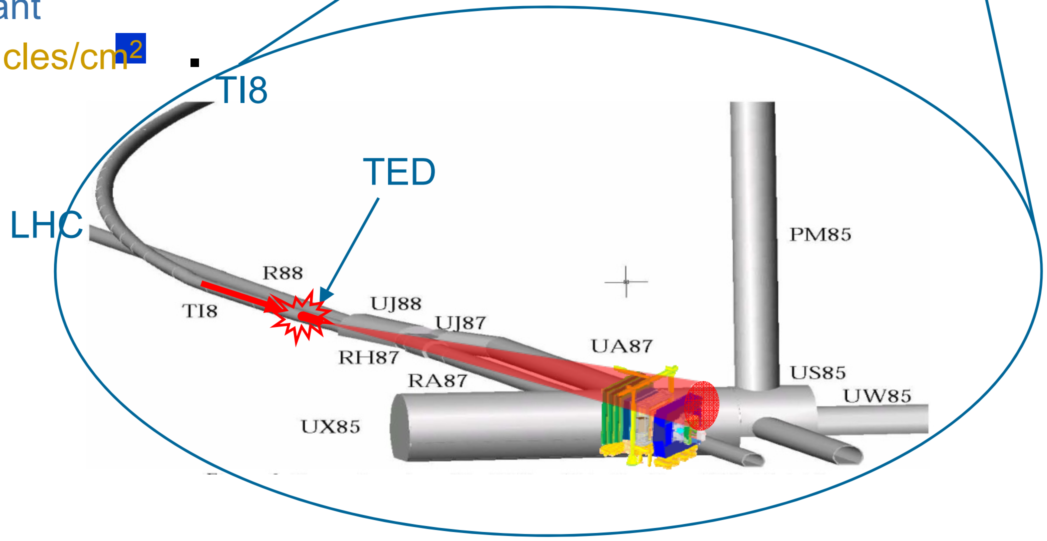
LHCb@LHC Sector Tests

- ☐ Beam 2 dumped on injection line beam stopper (TED)
  - 4 m tungsten, copper, aluminium, graphite rod in a 1m diameter iron casing
  - 340 m before LHCb along beam 2

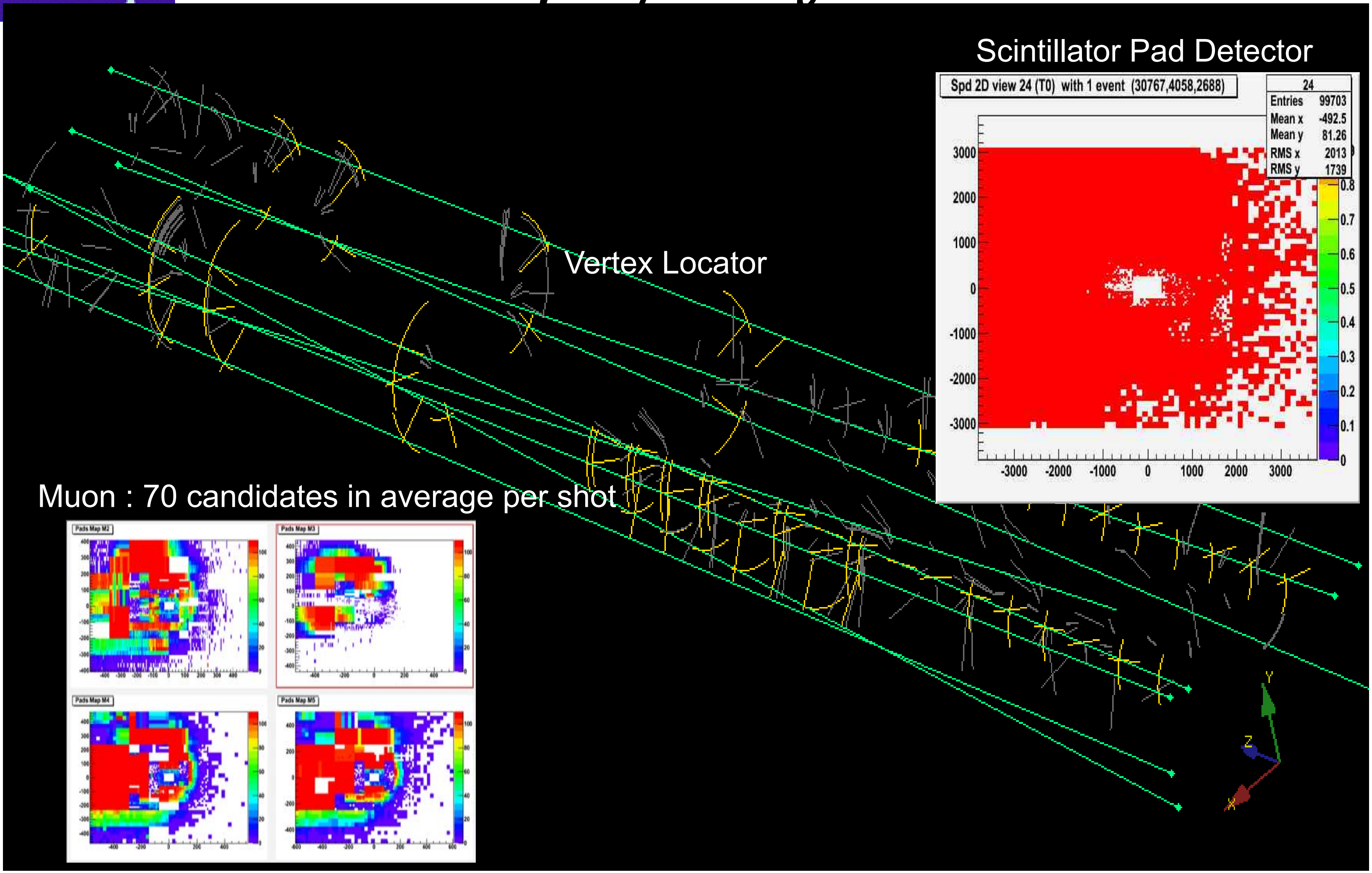
→

  - "Wrong" direction for LHCb
  - Centre of shower in upper right quadrant
  - High flux, centre of shower $\mathcal{O}(10)$ particles/cm^2
  - Vertex Locator $\mathcal{O}(0.1)$ particles/cm^2





A First Glimpse of LHC Protons



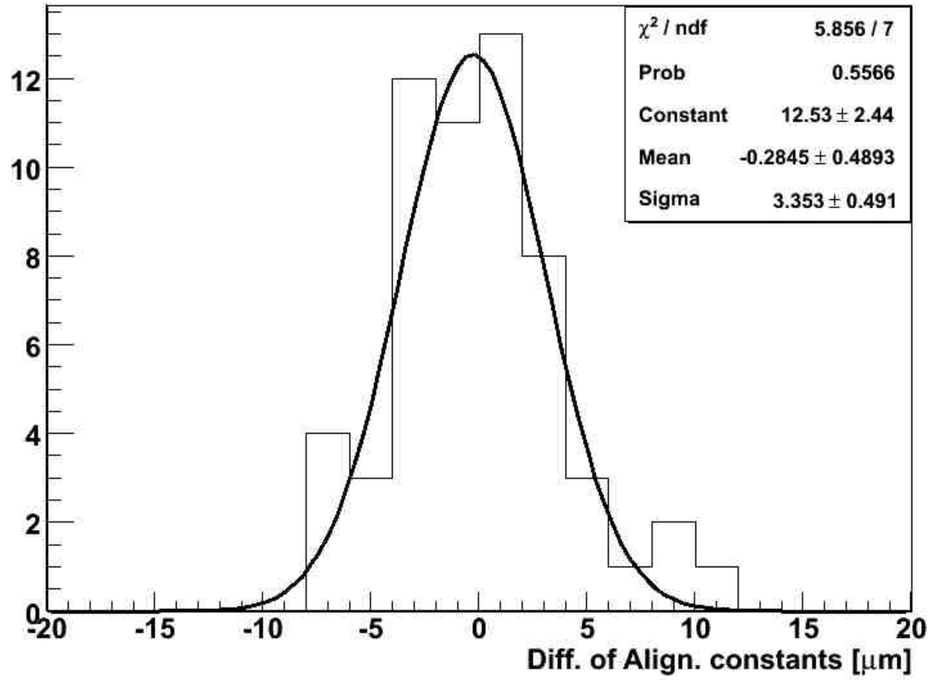
Scintillator Pad Detector

Vertex Locator

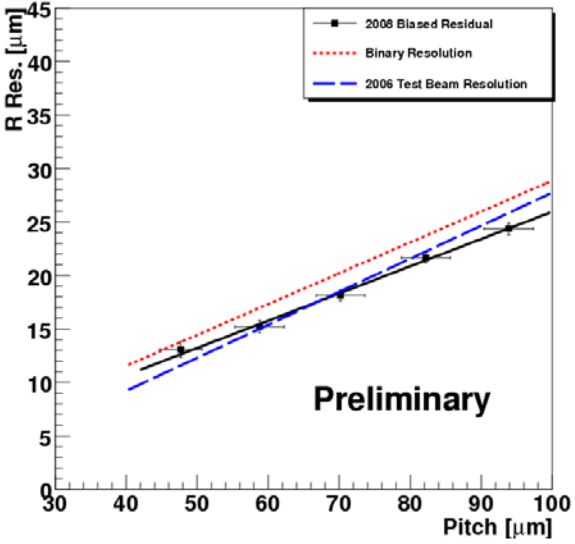
Muon : 70 candidates in average per shot

VELO Space Alignment with TED

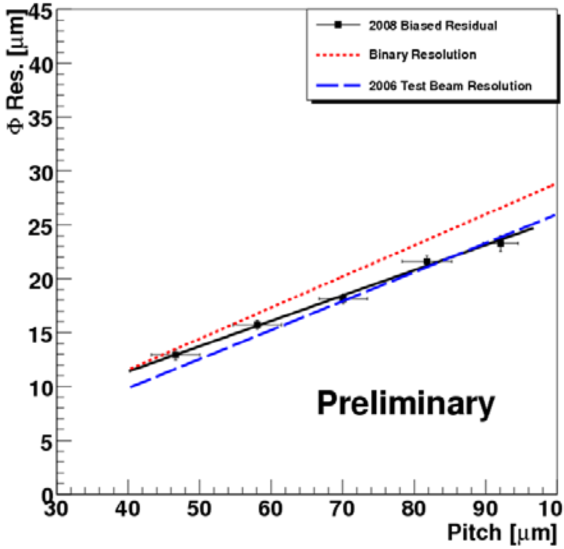
- The detector displacement from metrology usually is less than 10 μm
- Module alignment precision is about 3.4 μm for X and Y translation and 200 μrad for Z rotation



R residuals

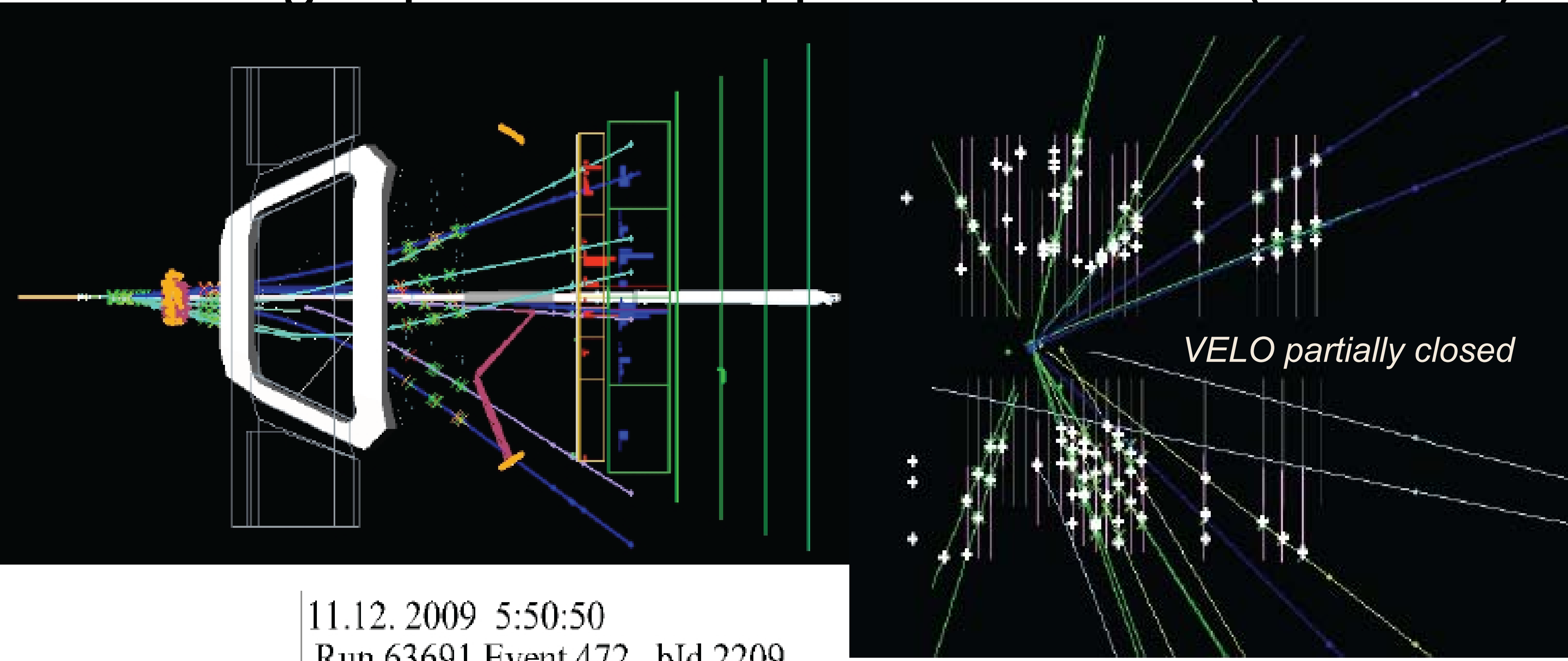


Φ residuals



LHCb Data

- A few glimpses of real pp collision data (0.9 TeV)

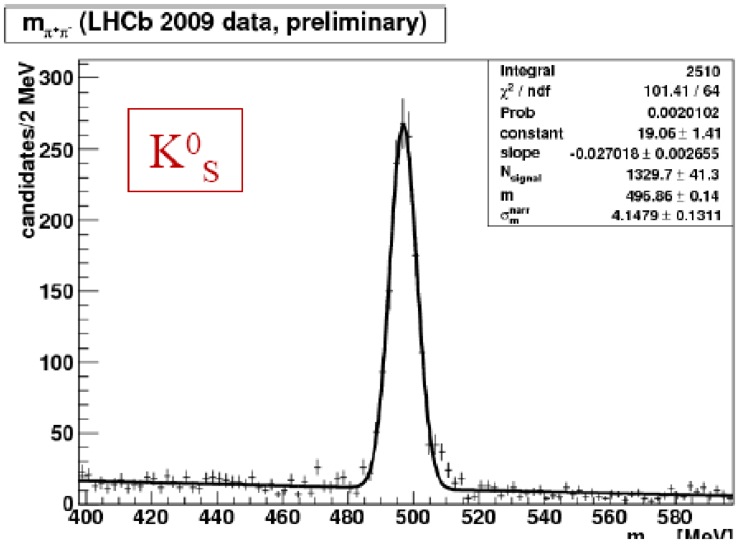


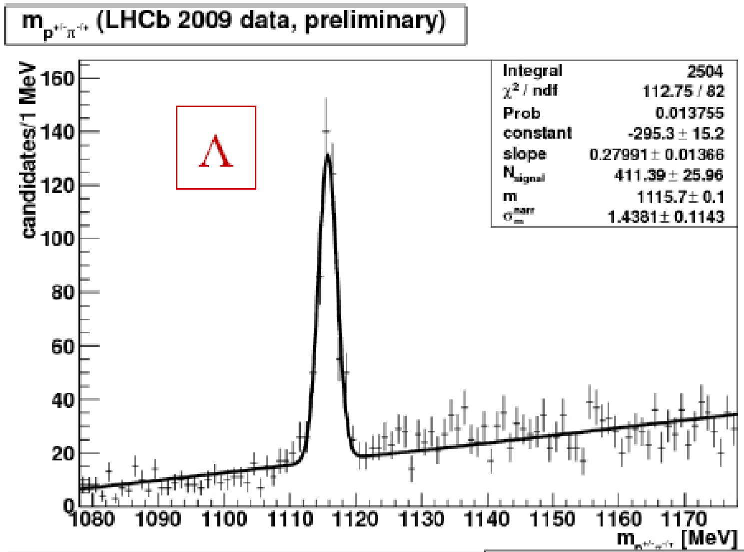
11.12. 2009 5:50:50
Run 63691 Event 472 bId 2209

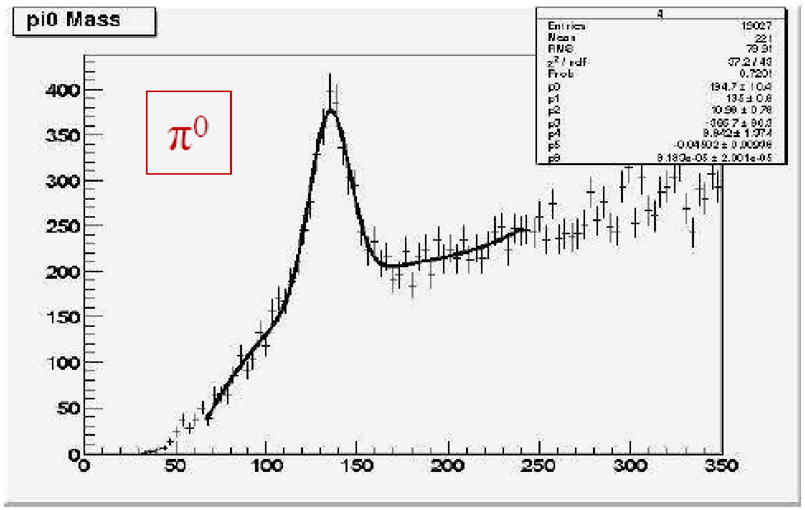
VELO nominally at ~8 mm from beam
kept at 15 mm due to beam hazards

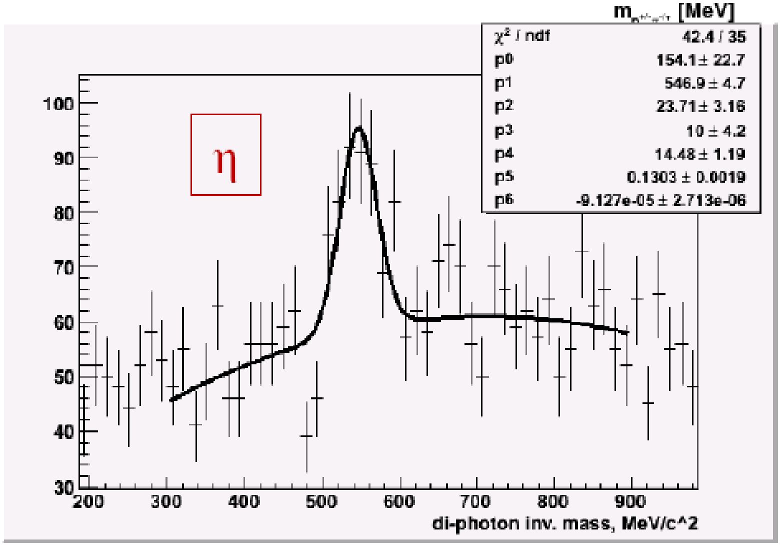
Tracking & Calorimetry

LHCb preliminary

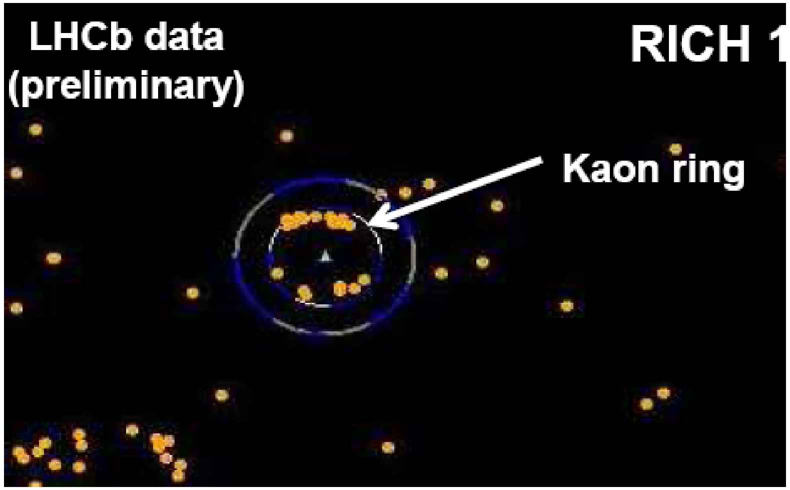


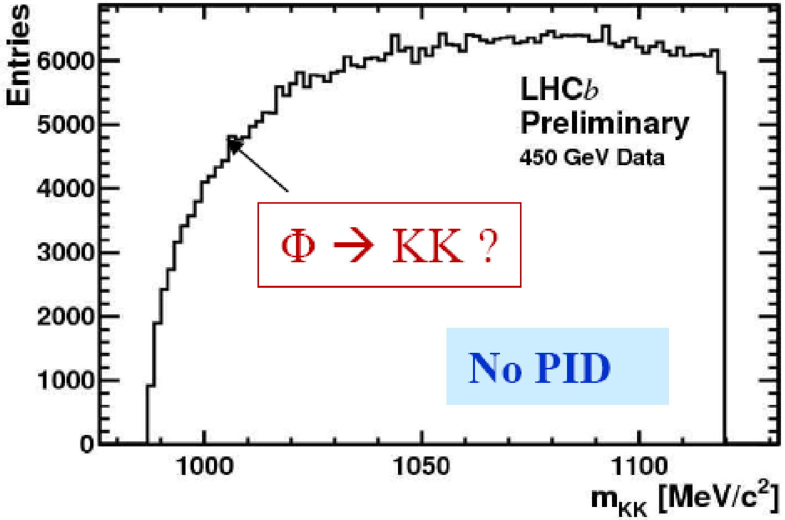


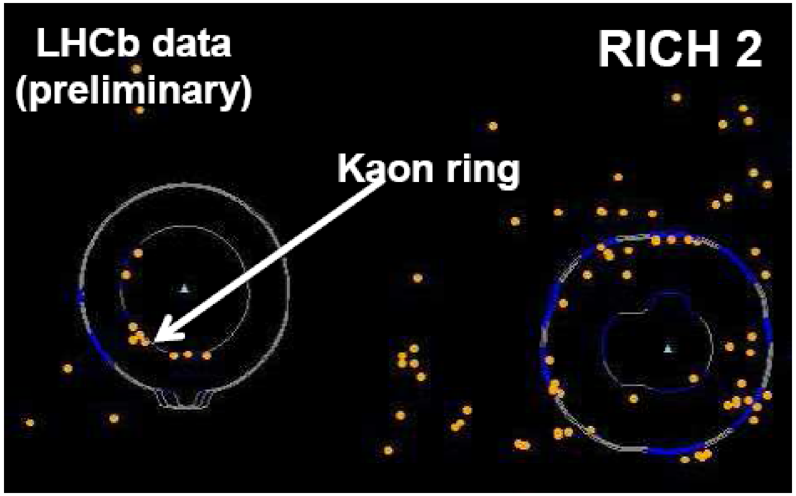


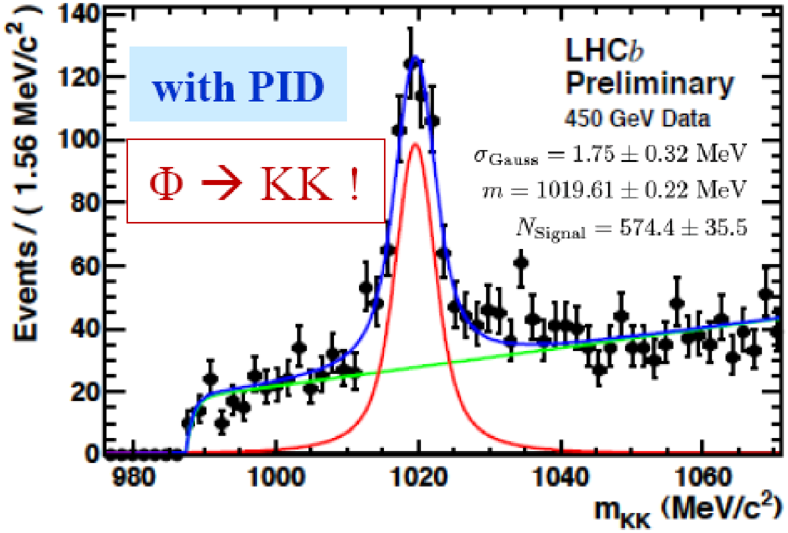


Particle Identification



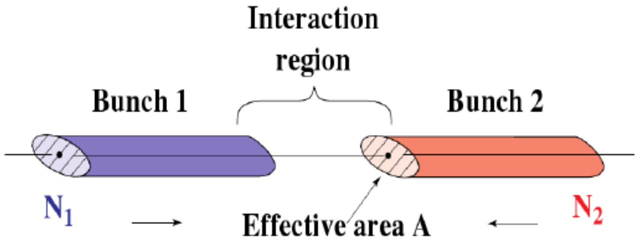






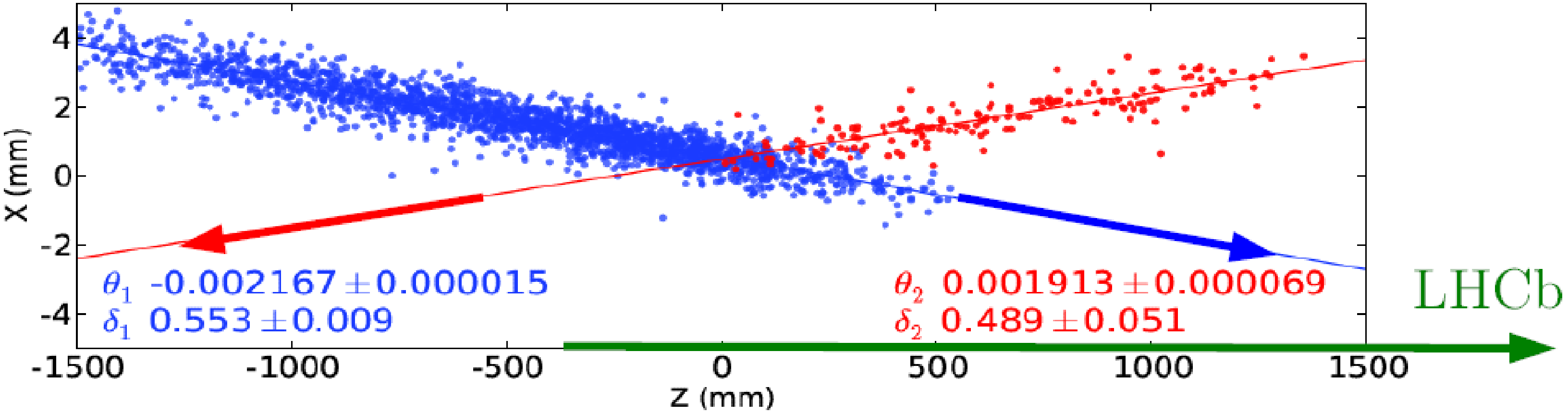
Luminosity

- $$\boxed{\mathcal{L} = \frac{N_1\, N_2\, f}{A_{\text{eff}}}}$$



$$\frac{1}{A_{\text{eff}}} = \underbrace{\int g_1(x,y)\, g_2(x,y)\; dx\, dy}_{\text{overlap integral}} \quad \Rightarrow \quad \text{Gaussian shape beams: } \mathcal{L} = \frac{N_1\, N_2\, f}{4\pi \sigma_x \sigma_y}$$

- Profile from beam-gas collisions

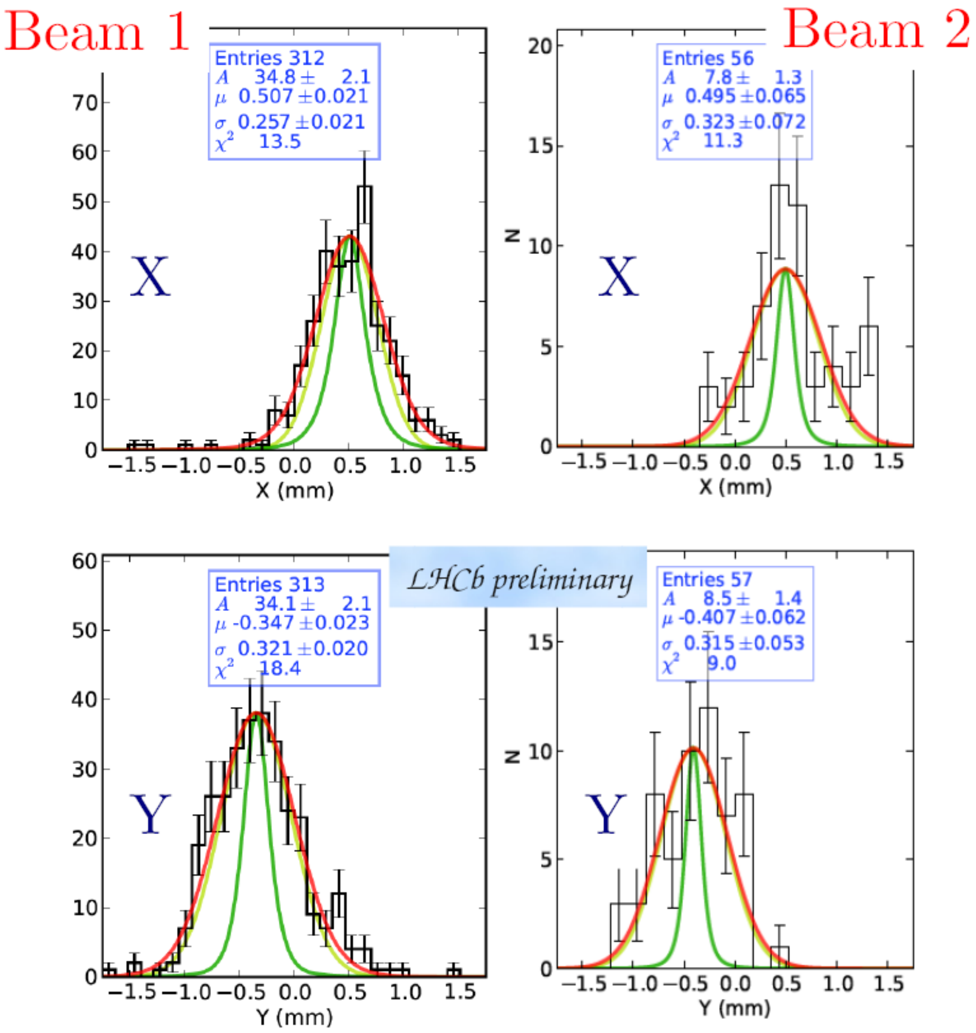


Beam Sizes from Beam-Gas

Fit with VELO resolution added
in quadrature for every bin
in Z and #tracks

Green – overall VELO resolution

Yellow – unfolded beam profile



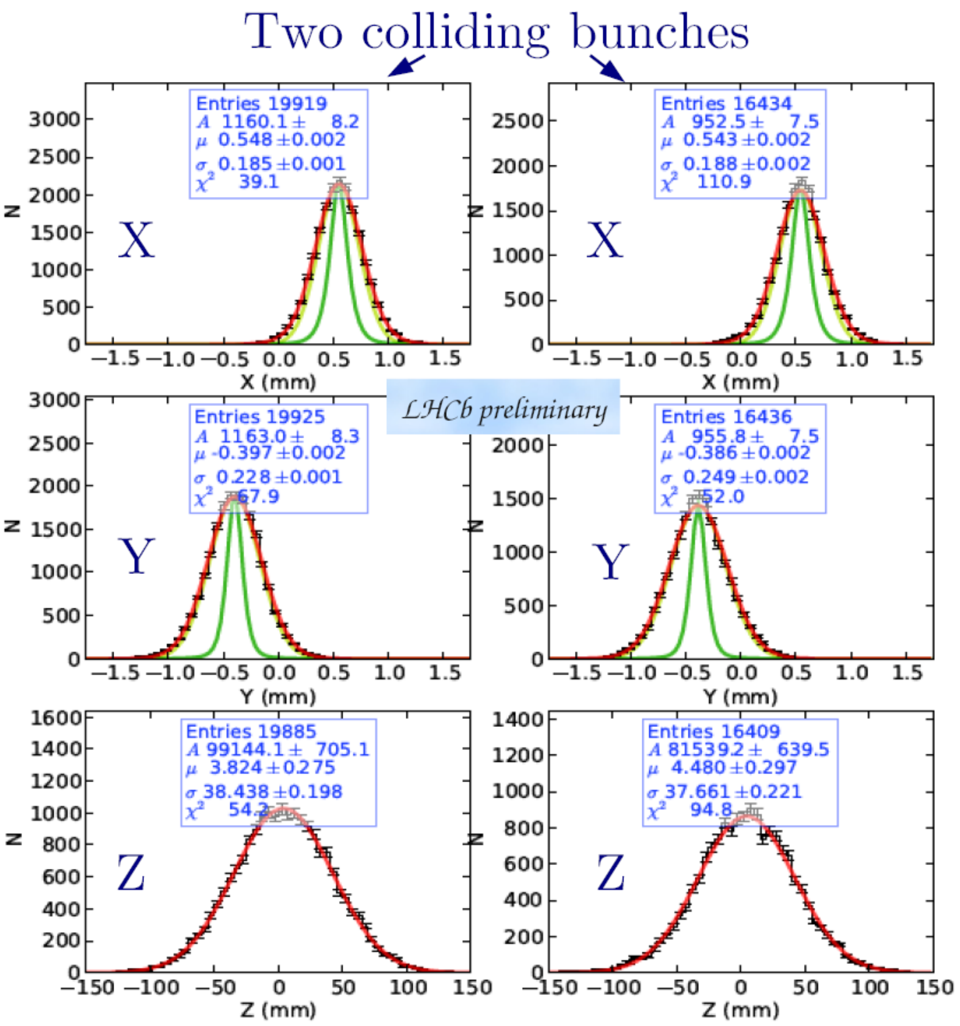
Size of Luminous Region

$$\sigma^2_{beam-beam} = \frac{\sigma_1^2\sigma_2^2}{\sigma_1^2+\sigma_2^2} \quad for\ X, Y$$

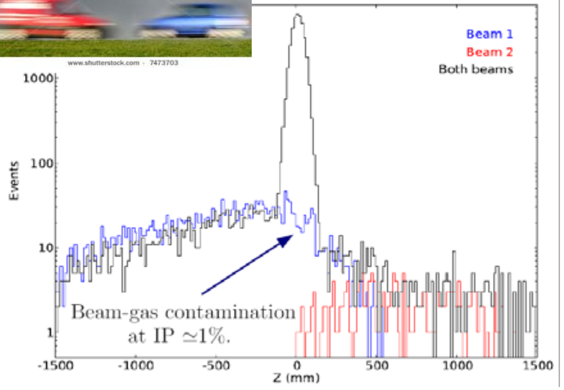
correlated

$$Lumi \propto \frac{1}{2\pi\sqrt{\sigma_{1x}^2+\sigma_{2x}^2}\sqrt{\sigma_{1y}^2+\sigma_{2y}^2}}$$

Strong constraint on overlap integral


Two colliding bunches

LHCb preliminary

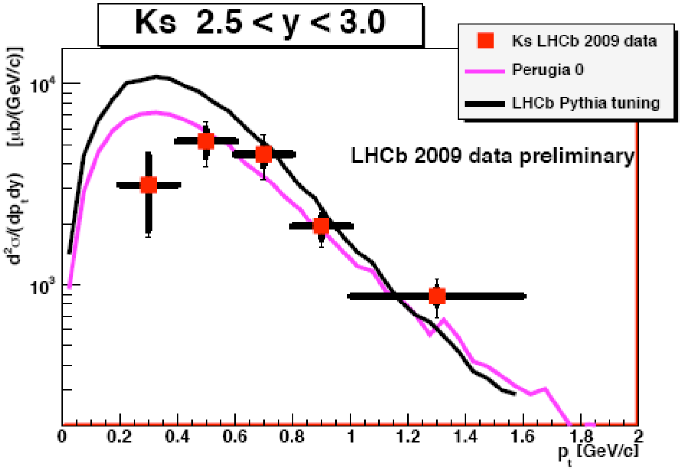


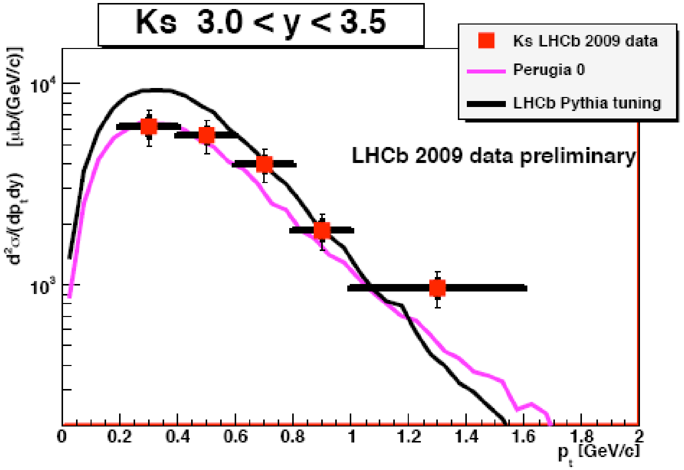
Beam-gas contamination at IP ≃1%.

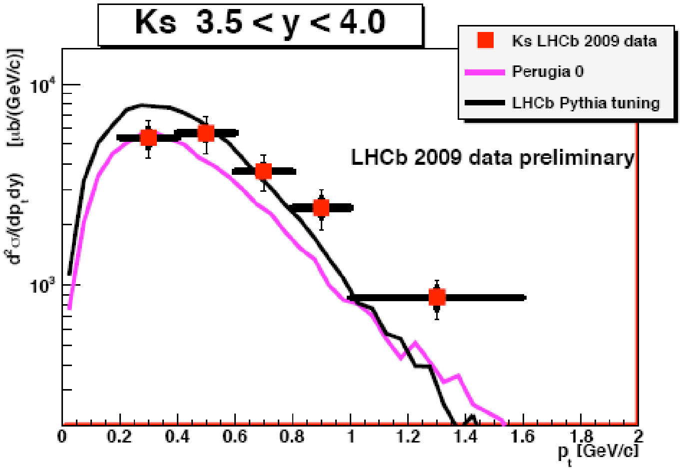
K^0 Yields

- ☐ Including L_{int}=6.8±1.0 μb^{-1}

Preliminary
More data
taken







-Crosses: LHCb DATA 2009 Preliminary

-Bold error bars: statistical errors

-Thin error bars: syst. including 15% on lumi

-BLACK curve: LHCb PYTHIA tuning

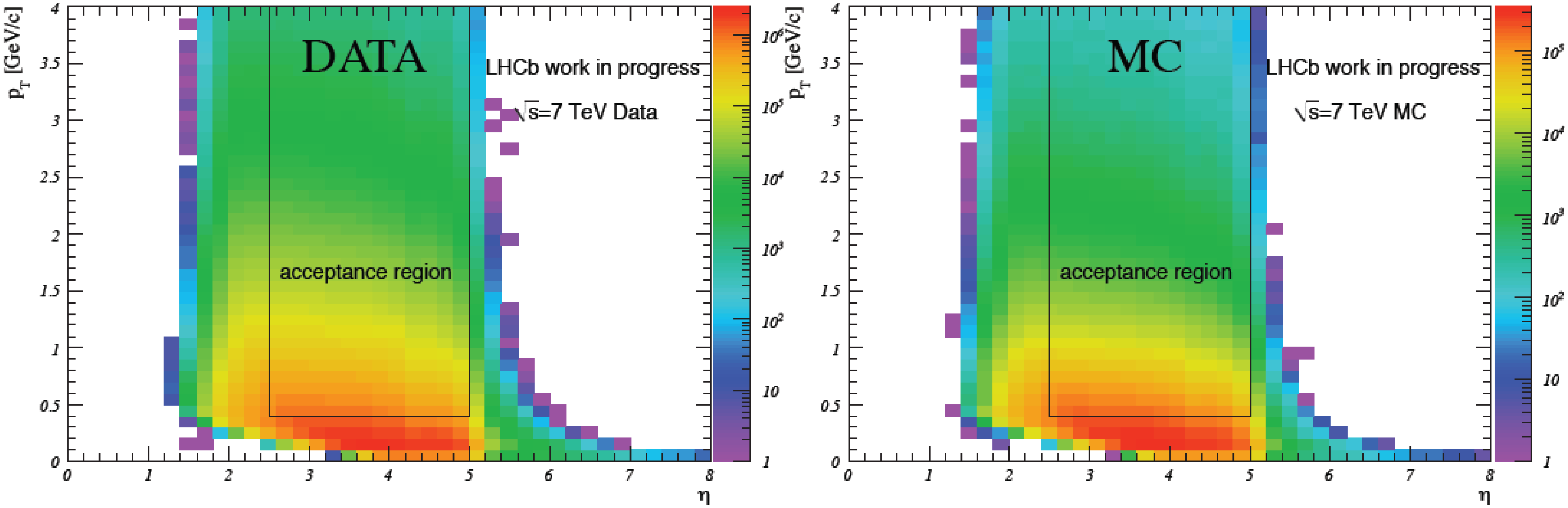
-PINK curve: Perugia 0 PYTHIA tuning

Cross-sections reasonably consistent with PYTHIA predictions

3.5 TeV x 35 TeV Collisions

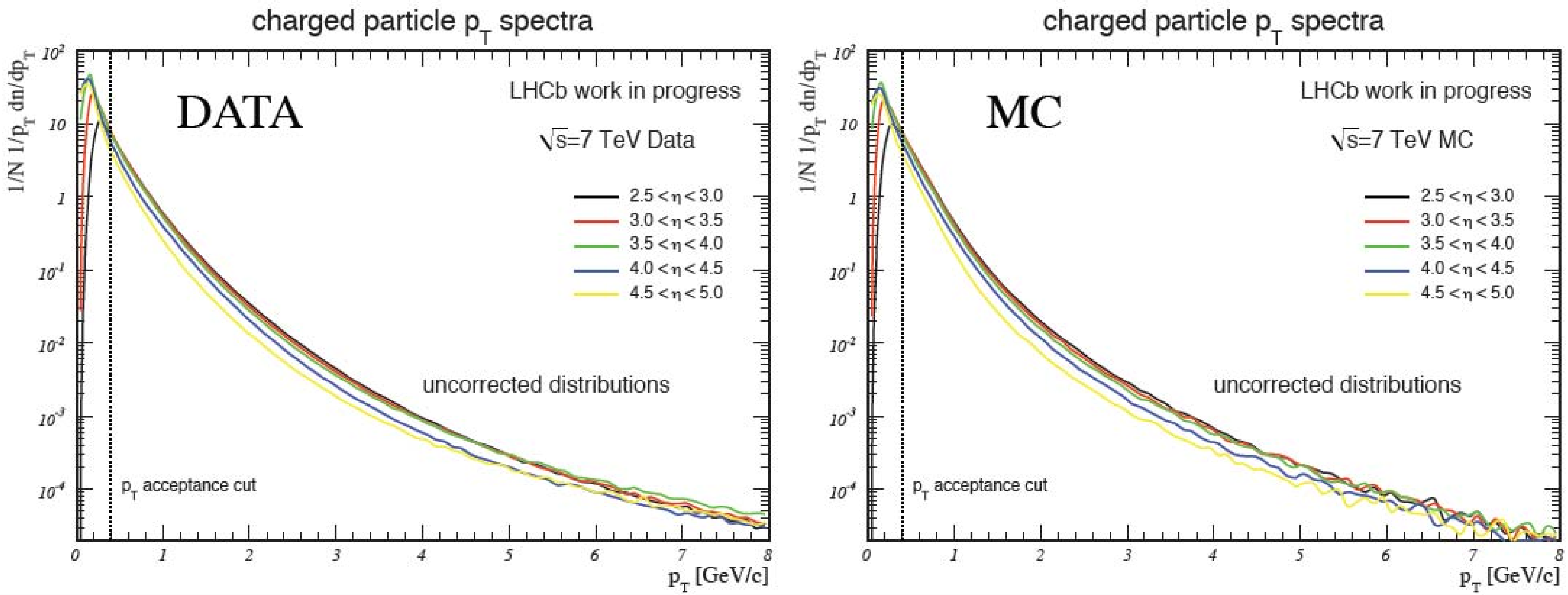
Charged Particle Tracking

- 7 TeV data (~10M events):
  - — use “micro-bias” trigger: at least one charged track seen in the detector
  - — select events with one reconstructed primary vertex (PV)
  - — look at distribution of charged tracks traversing VELO and tracking stations
- 7 TeV full simulation MC:
  - — determine region of ~flat acceptance in p_T and η (pseudo-rapidity)



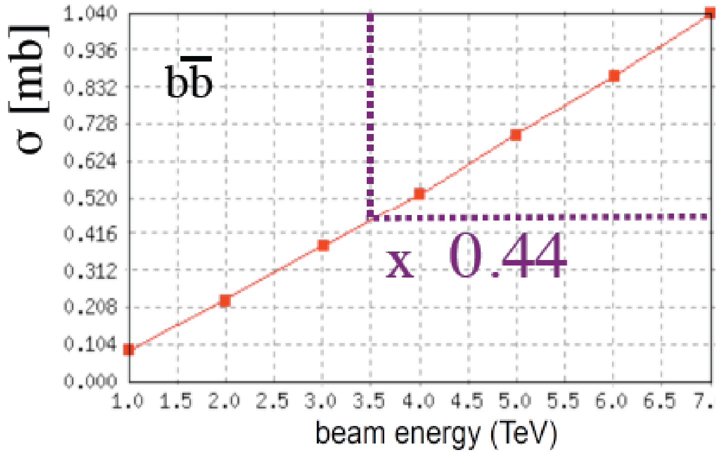
P_t of Charged Tracks

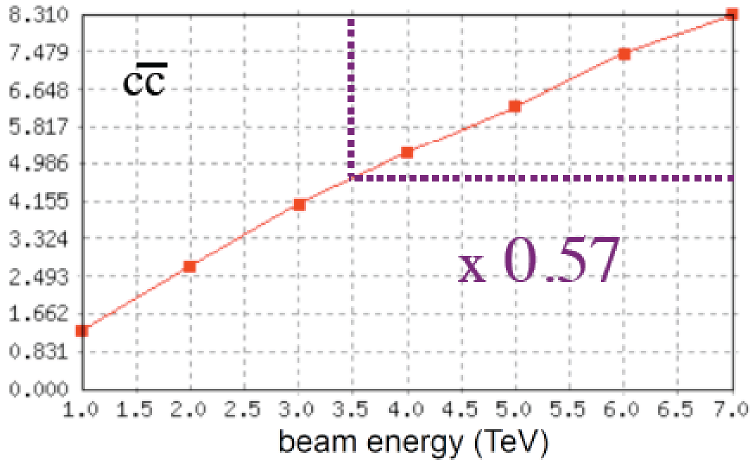
- Raw p_T distributions in bins of η:
  - normalized by $1/p_T$ and $1/N$,
    where N = number of events with one reconstructed PV
  - clear acceptance drop at low p_T



Effects of 7 TeV

- Energy at half of design ⇒ $b\bar{b}$ & $c\bar{c}$ cross-sections approximately halved according to Pythia 6.4



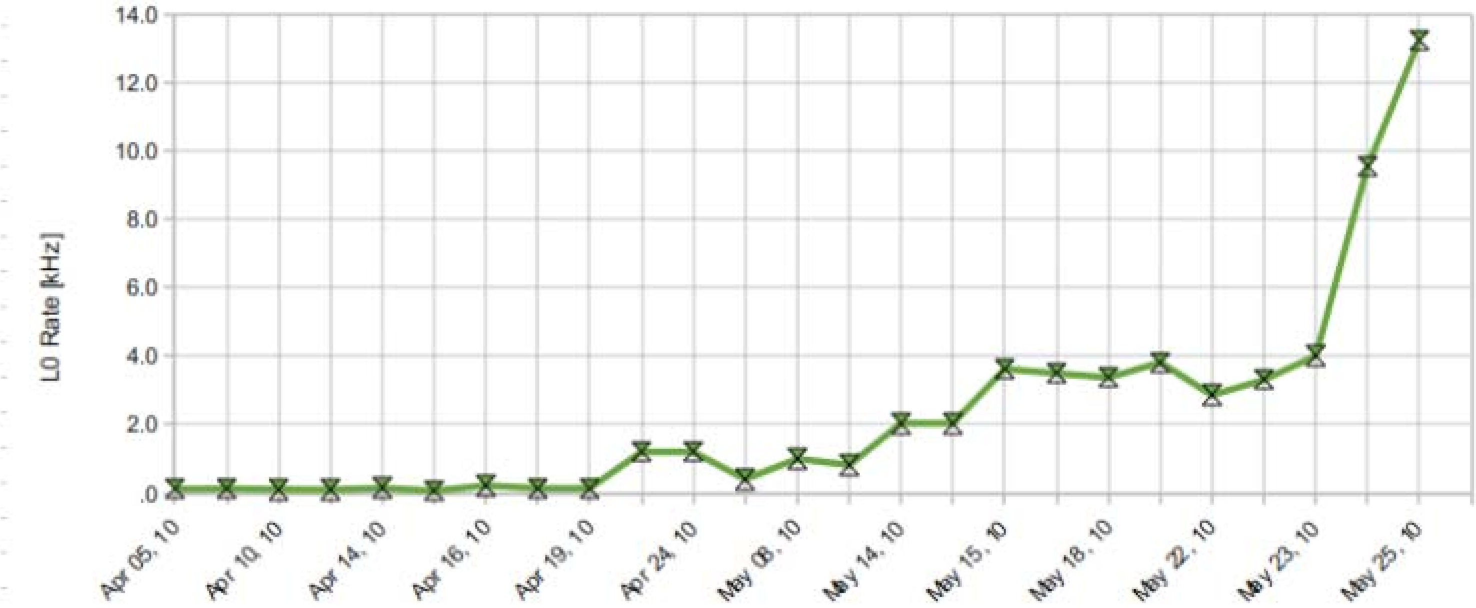


- But Pythia 6.4 larger than others. LHCb assumed $\sigma(b\bar{b})$=0.5 mb
- Lower $\mathcal{L}$ leads to increased trigger efficiencies

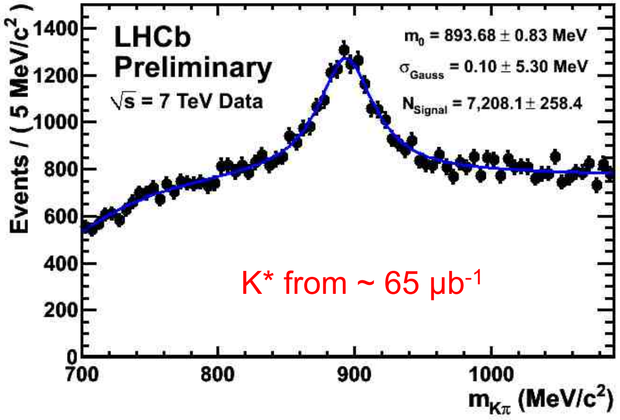
Triggering with first data

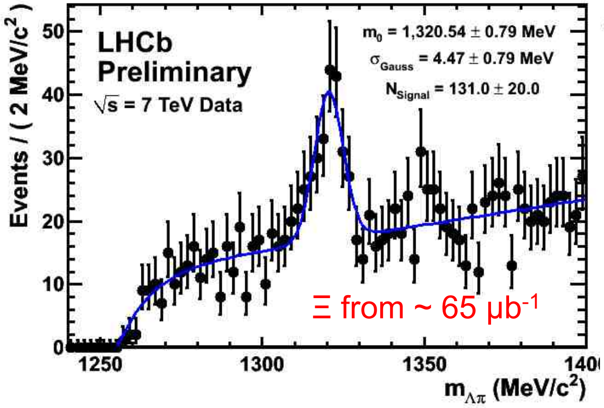
Interaction rate	L0 output rate	HLT1 output rate	HLT2 output rate
< 2 kHz	< 2 kHz		
< 25 kHz	< 25 kHz	2 kHz	
< 300 kHz	< 300 kHz	10 kHz	2 kHz

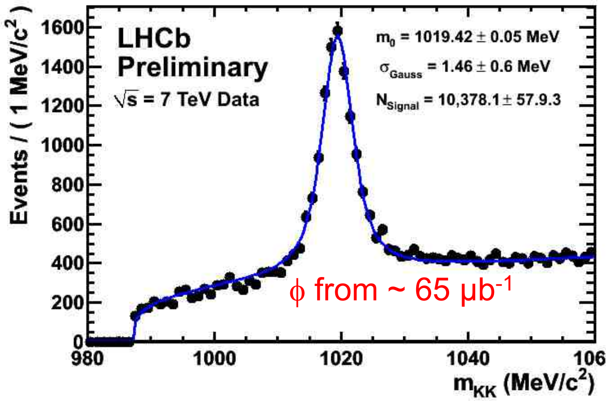
- First 3/nb trigger almost unbiased
- Then next 11/nb HLT1 reduces rates (~80% ε on charm)



Some Nice Mass Plots

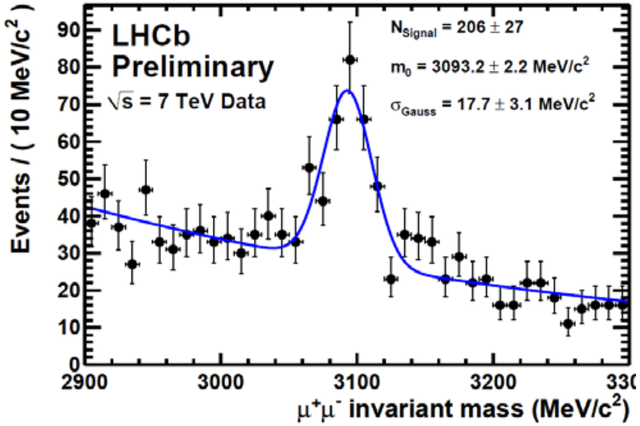




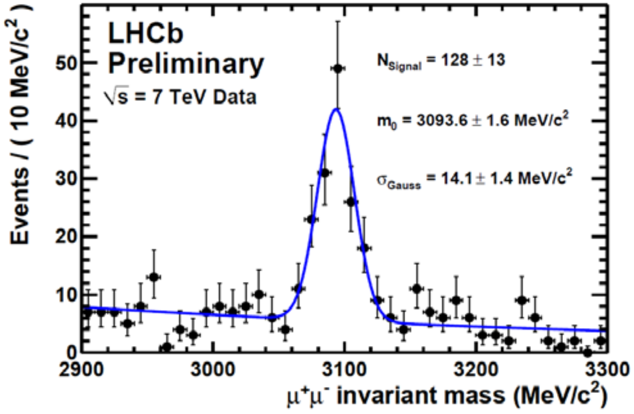


J/ψ from ~ 800 μb^{-1}

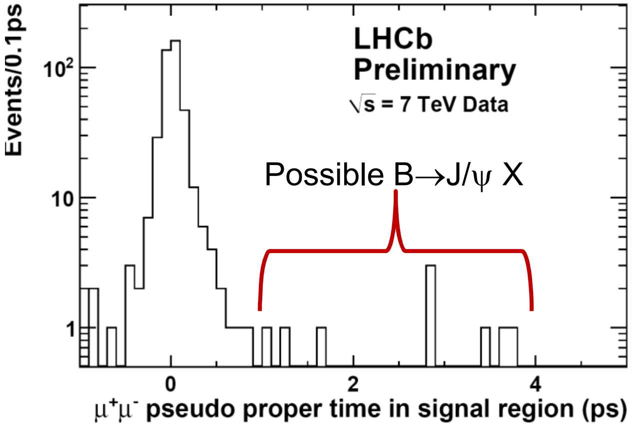
Loose selection



Tight Selection

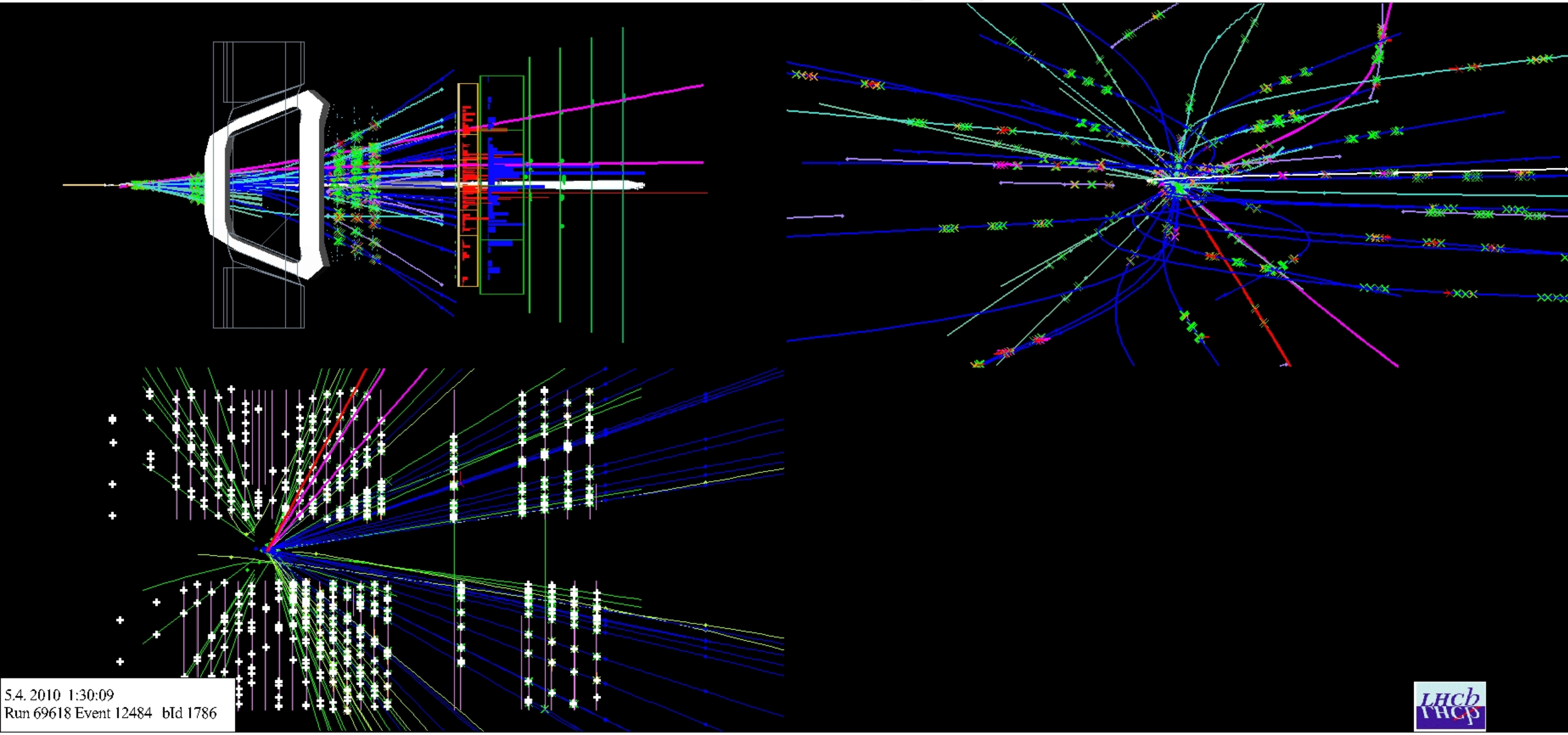


Time Resolution

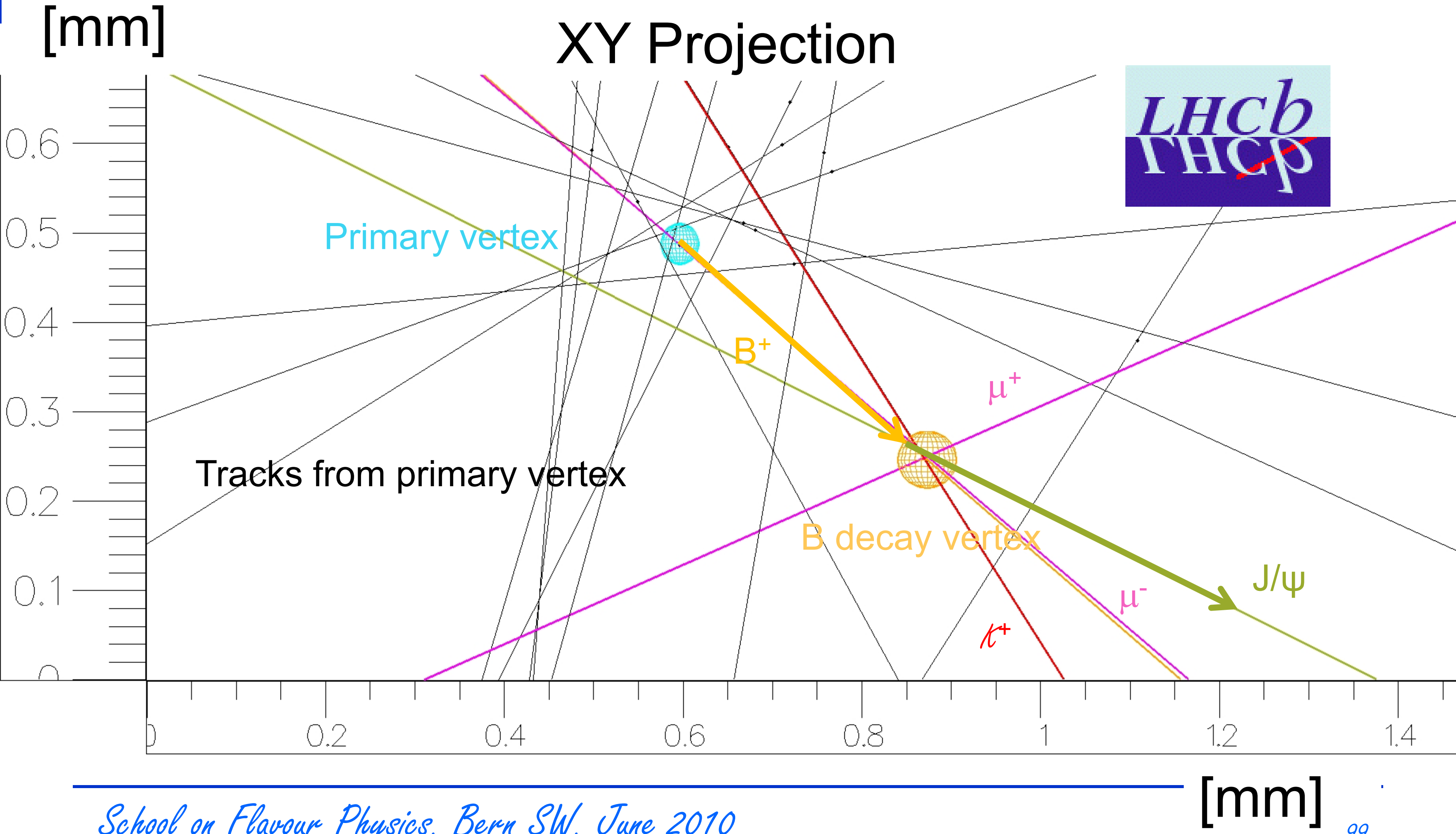


B→J/ψK candidate: global view (muons are magenta, kaon is red)

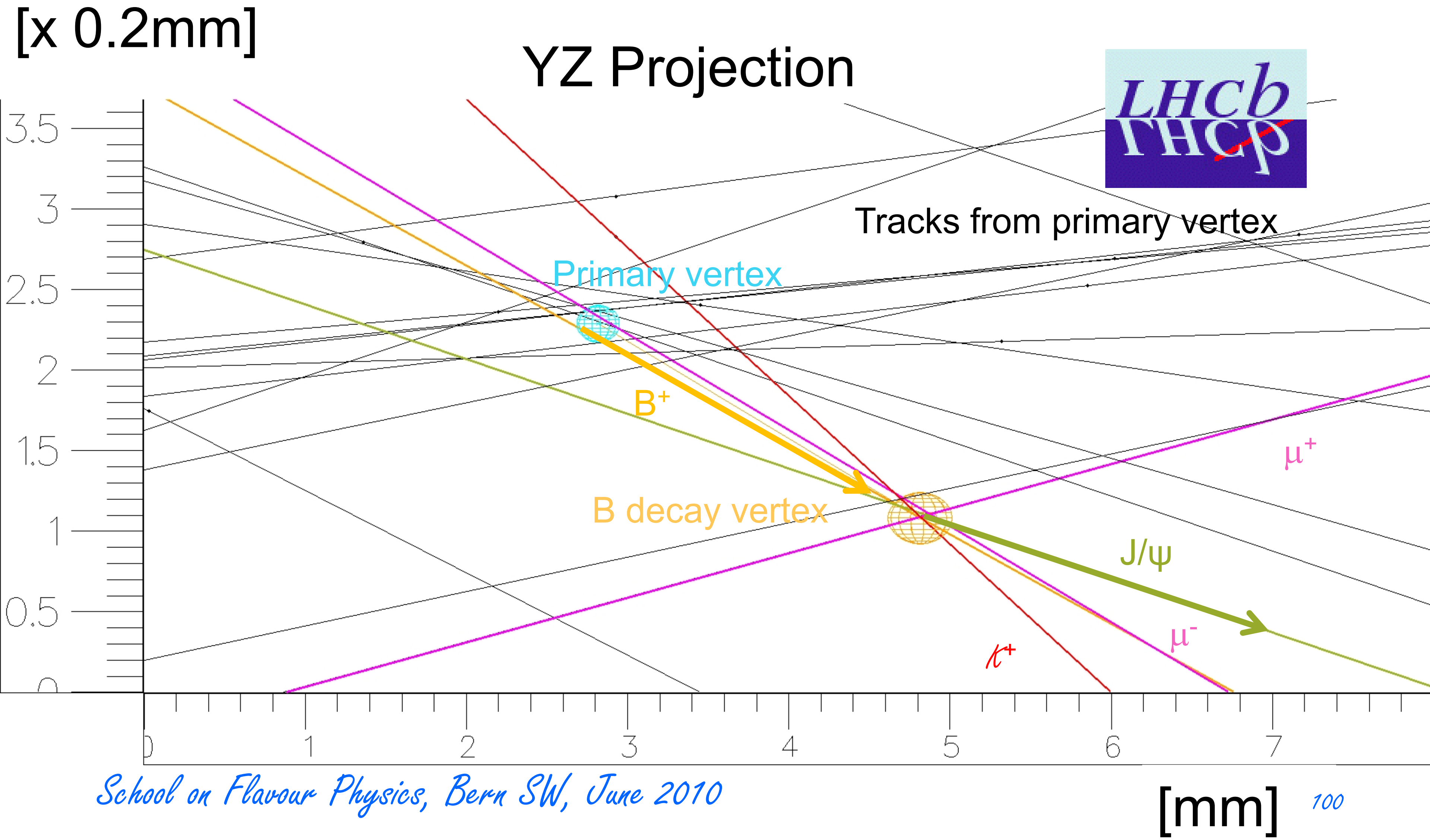
LHCb Event Display



B→J/ψK candidate: XY vertex zoom



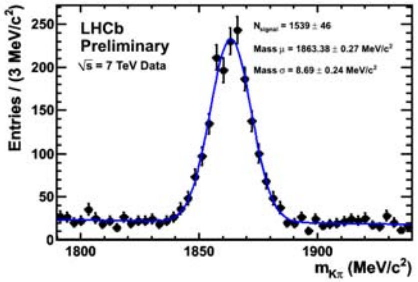
B→J/ψK candidate: YZ vertex zoom



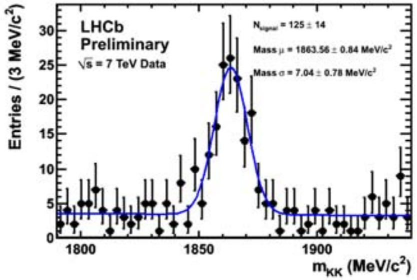
Charm Signals

- Useful for detector calibration & eventual measurements of charm mixing & CPV

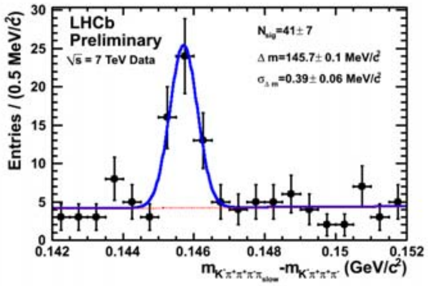
$D^0 \to K\pi$



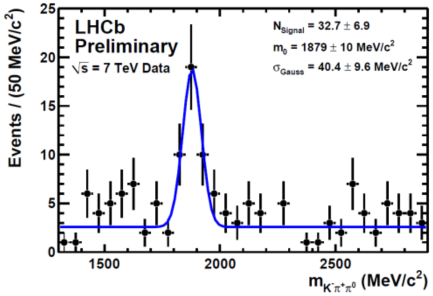
$D^0 \to KK$



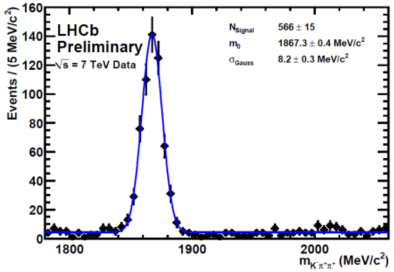
$D^* \to D^0\pi$, $D^0 \to K\pi\pi\pi$



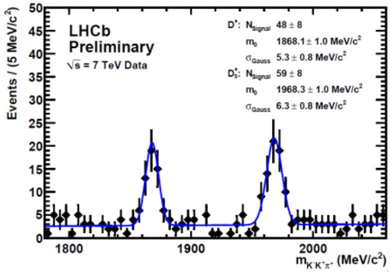
$D^0 \to K\pi\pi^0$



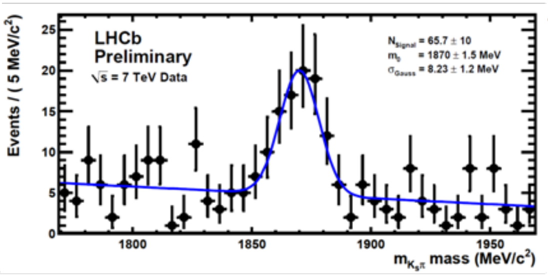
$D^+ \to K\pi\pi$



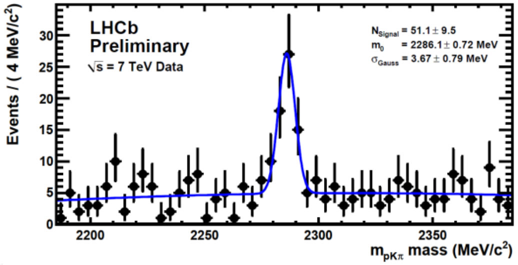
$D^+, D_s \to KK\pi$



$D^+ \to K_S\pi$

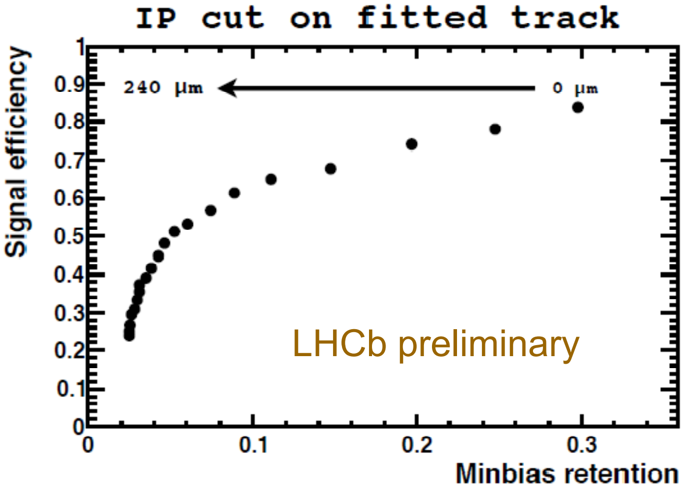


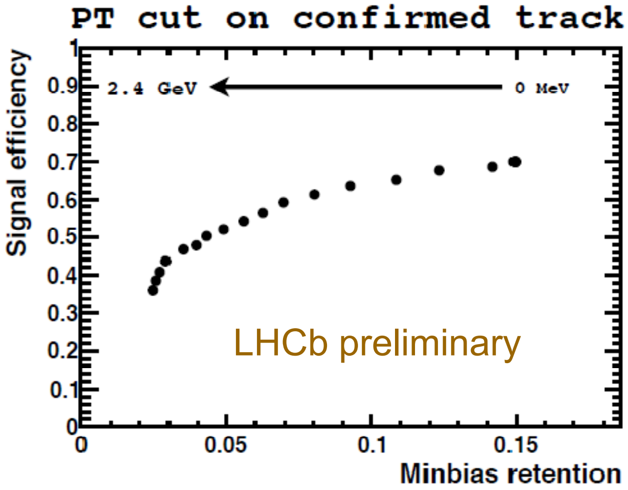
$\Lambda_c \to pK\pi$



Hadron Trigger Checks

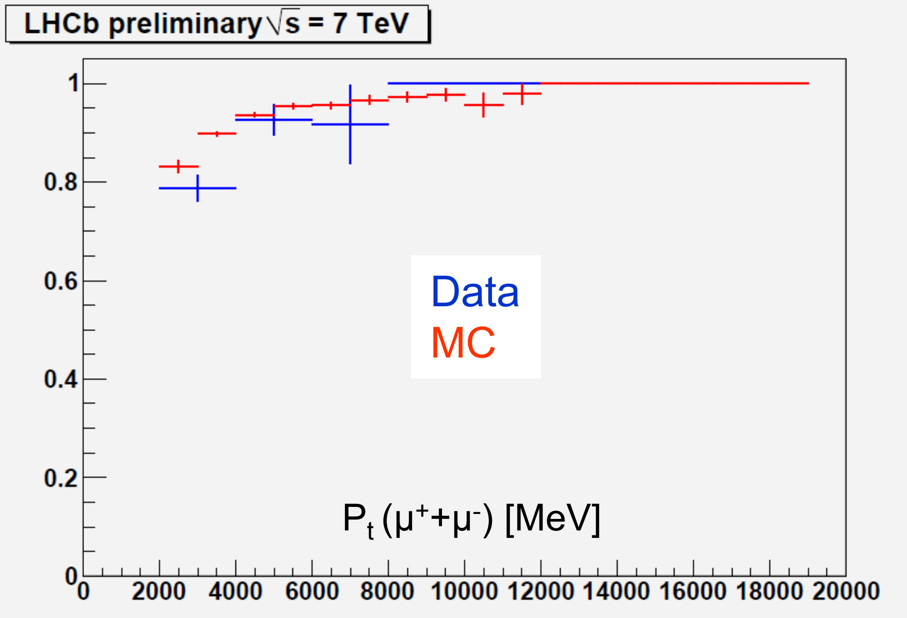
- Take D*, $D^0 \to K\pi$ signal collected in minimum bias events & evaluate preliminary L0*HLT1 performance
- Performance curves of single-hadron HLT1 line on data: $\varepsilon_{trigL0*HLT1}(\text{data}) = 60 \pm 4\ \%$ vs MC 66%

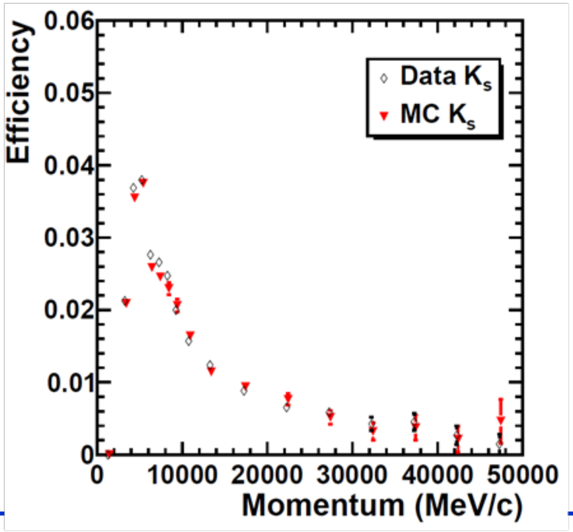




Muon Checks

- Measure performance of L0*HLT1 trigger for J/ψ→μμ
- Data = (82±1) %
- MC = 91%
- fake rate





Detector Performance Summary

- All parts working with resolutions conquerable to expectations
- Exceptions
  - Vertex resolution perhaps 1.5 x poorer, seems to be due to optimistic resolution assumptions and inadequate material in simulation
  - Aerogel resolution is much worse due to absorption of gas; plans are being formulated to fix
  - Some alignments are taking more time than expected

LHCC Comments (May 8)

- “Congratulations for the excellent state of the detector and of the analysis
- - With current luminosity projections LHCb is the only detector capable to achieve almost completely its full physics potential during the 2010-11 run!!! “

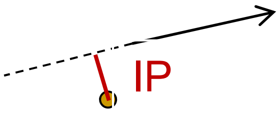
Some Early Measurements

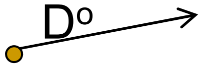
Initial LHCb $\sigma(b\bar{b})$ Measurement

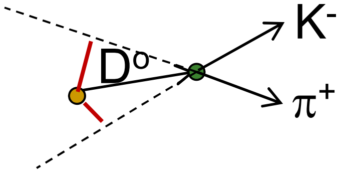
- How can we determine $\sigma(pp\to b\bar{b})$ with small amount of data?
- Note that $B(b\to D^o X\mu^-\nu)=(6.82\pm0.35)\%$ as measured at LEP. Assuming the fraction of B^-, B^o, B_s and Λ_b doesn't change too much at the LHC, we can use this
- Need to reconstruct decays with a D^o & μ^- coming from the same vertex
- Important concept: Impact parameter (IP). Def: minimum distance between track & vertex

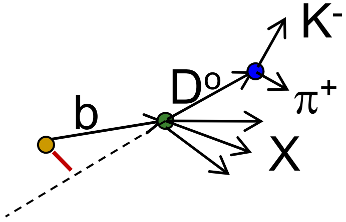
Impact Parameter

- Consider $pp \to c\bar{c}X$, $c \to D^o X$
  - The D^o should point at the vertex, so IP should = 0
  - Now suppose $D^o \to K^-\pi^+$, then $K^-\pi^+$ have large IP's, in general, i.e. distributions are not peaked at zero
- Consider $pp \to b\bar{b}X$, $b \to D^o X$
  - Now the D^o has significant IP
  - The $K^-\pi^+$ even larger than before



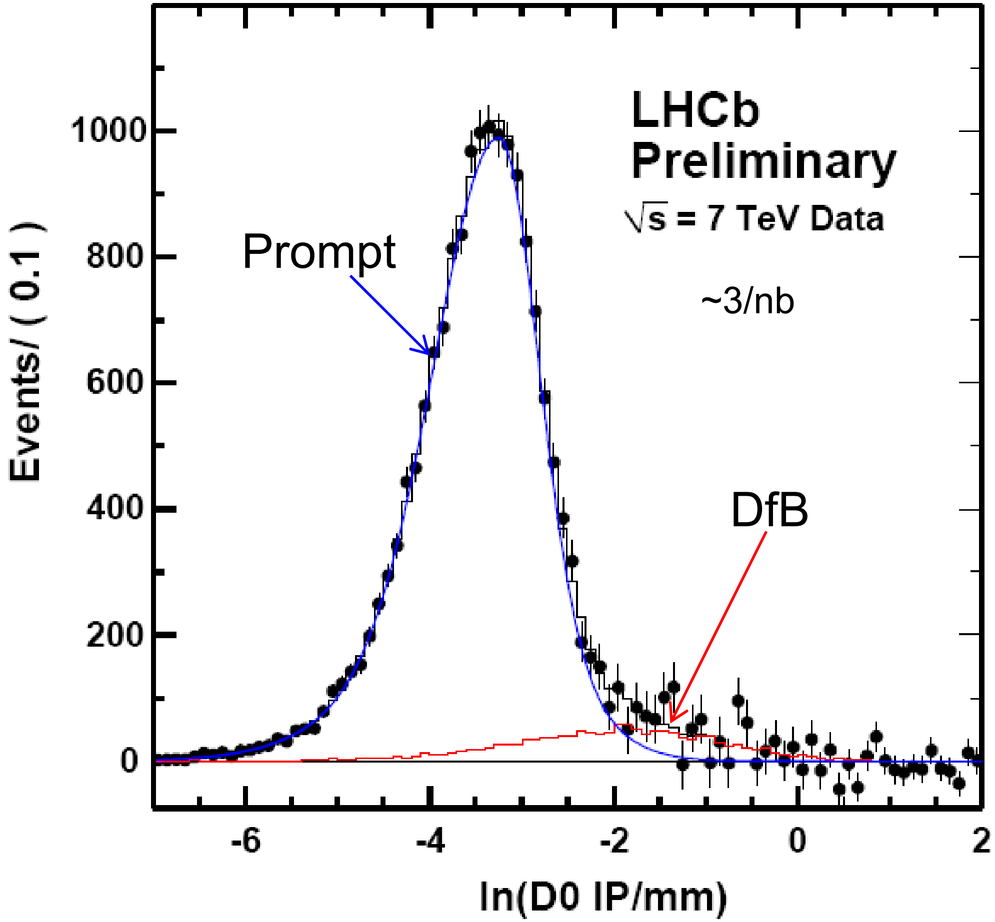






D^0 Impact Parameter in Data

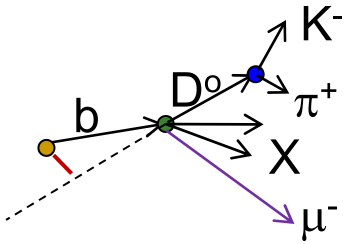
- Select on $K^-\pi^+$ with large IP's
- Fit prompt component with double bi-furcated Gaussian letting parameters float & DfB component using MC shape



- Find 15827±262 prompt D^o, 1331±354 DfB

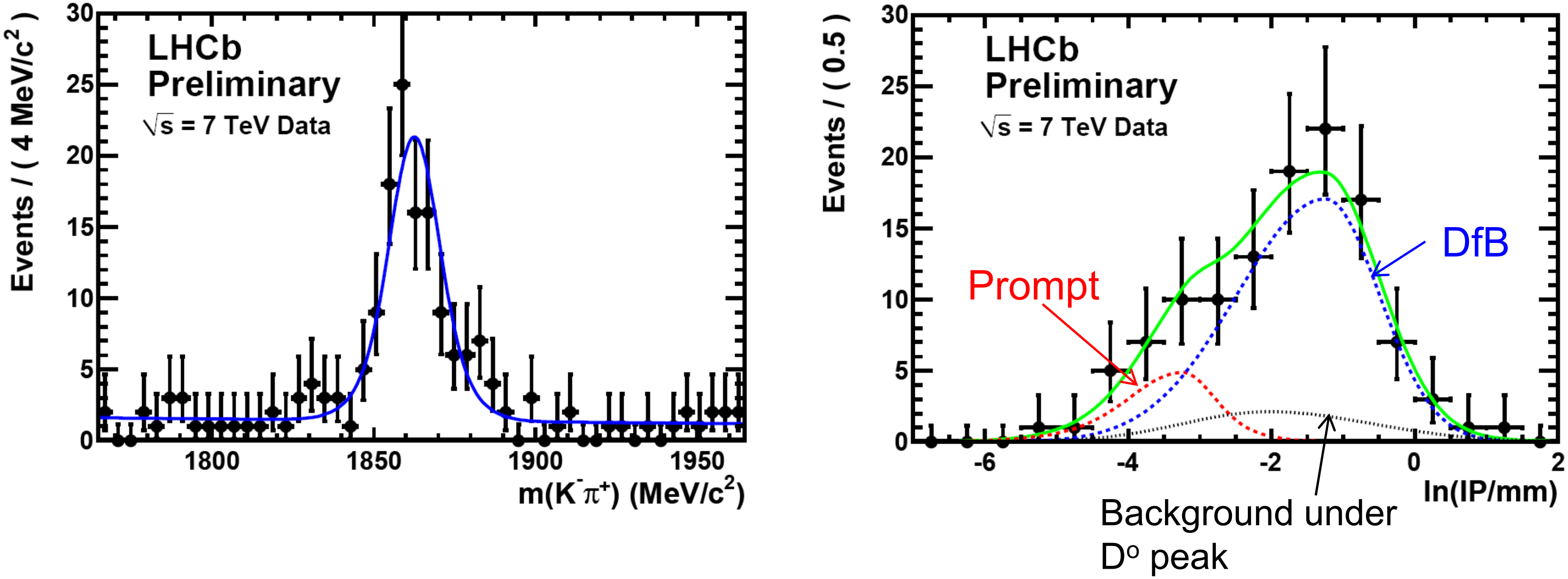
$B \rightarrow D^o X \mu^- \nu$

- We want to use a sample enriched in B decays so that the error related to prompt component is minimized
- Accomplished by adding finding events with a track that is identified as a μ^- & forms a common vertex with the D^o. Thus prompt D^o from $c\bar{c}$ production are greatly suppressed



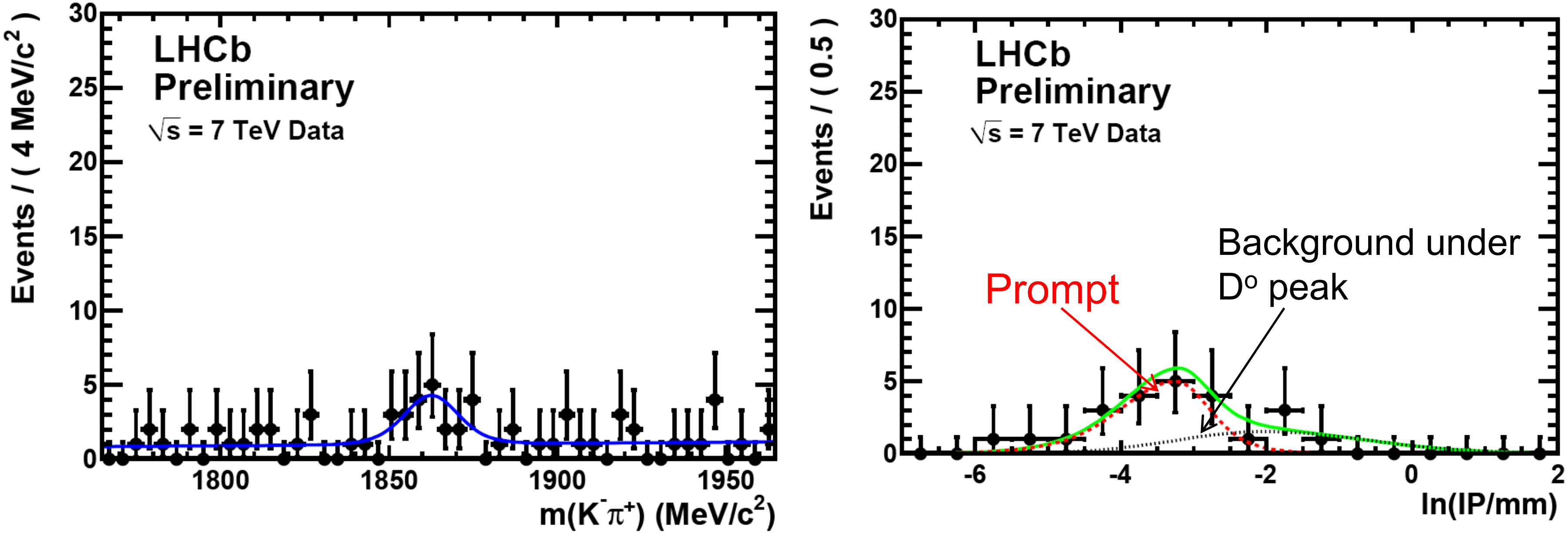
- Right-Sign (RS) combos are $D^o\mu^-$ or $\bar{D}^o\mu^+$, while-Wrong Sign (WS) are $D^o\mu^+$ or $\bar{D}^o\mu^+$

RS $B \rightarrow D^0 X \mu^- \nu$



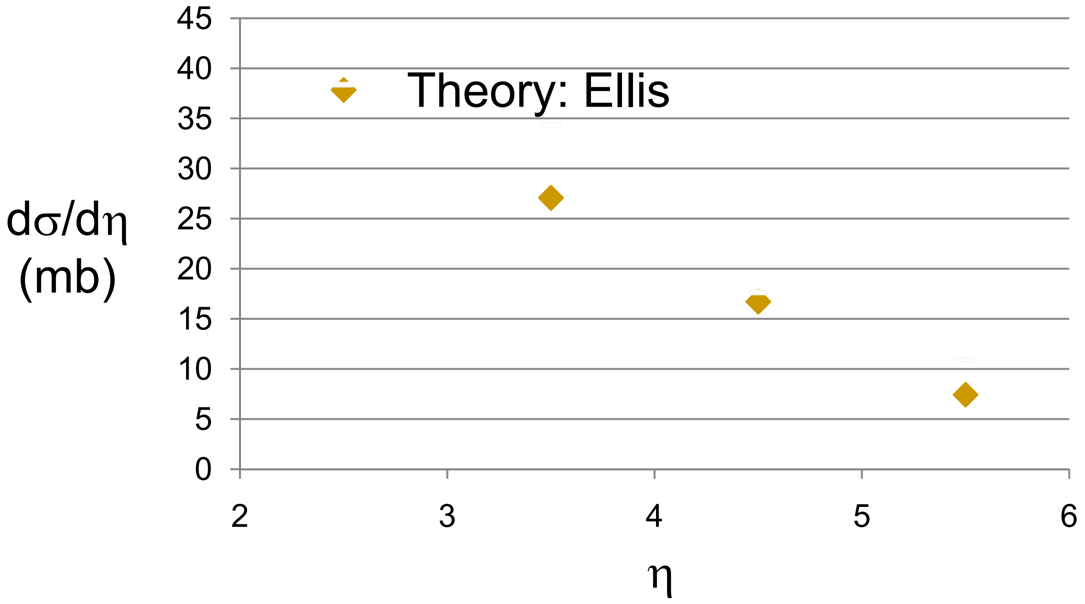
- Find 85.3±10.6 DfB events, 8σ
- 16.2±5.7 prompt
- 14.0 ± 1.9 sideband bkgrd, determined directly

RS $B\rightarrow D^0 X \mu^+ \nu$



- Find 0±1.1 DfB events
- 16.7±4.9 prompt
- 10.2 ±1.5 sideband bkgrd

Comparison with theoretical σ

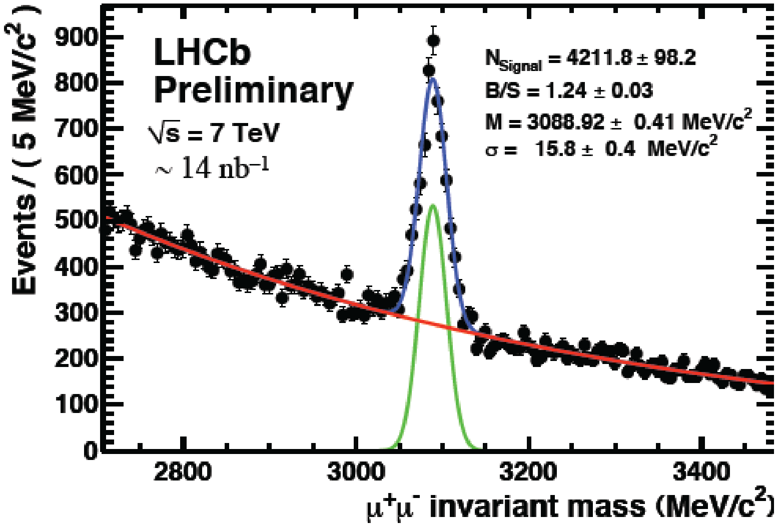


- Come to ICHEP to see results

$J/\psi \to \mu^+\mu^-$ studies

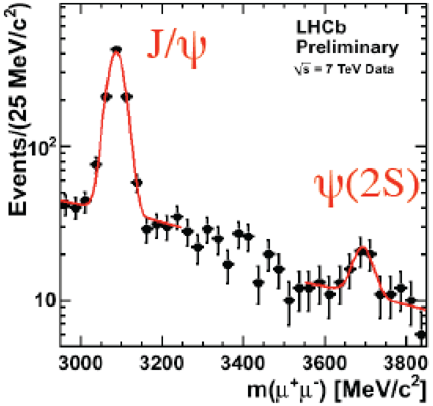
❑ Abundant J/ψ signal = gold mine:

- data-MC and data-PDG differences (in bins of many variables) provide many crucial calibration handles, to be exploited to improve performance:
  - alignment, tracking studies
  - material effects (dE/dx)
  - B-field systematic effects
  - momentum resolution, mass scale
  - lepton identification



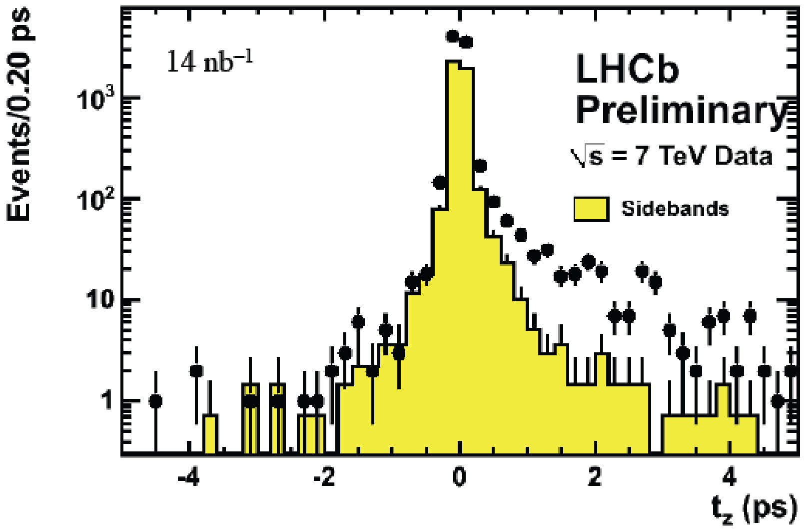
❑ J/ψ, ψ(2S), … signals open large parts of the physics program:

- quarkonium production, polarization, spectroscopy, …
- bottom physics with both incl. and excl. b → J/ψ modes

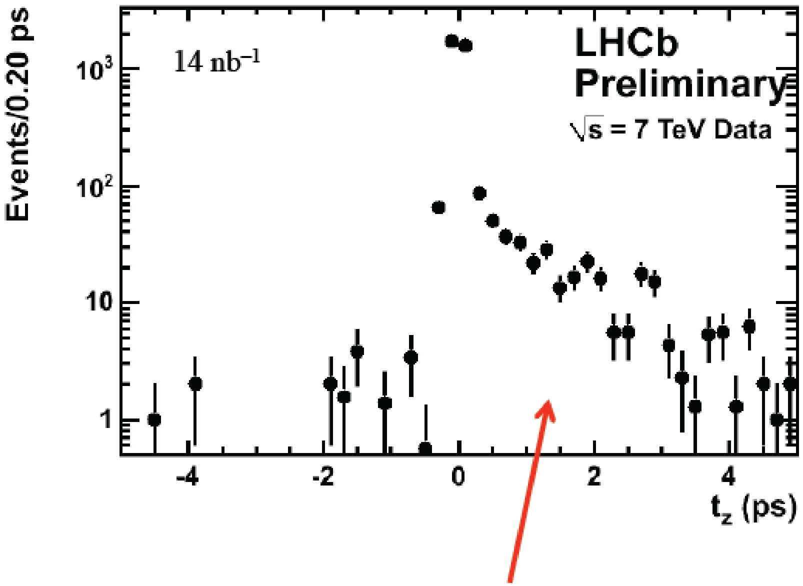


J/ψ Pseudo-proper-time (t_z)

Signal window & normalized sideband



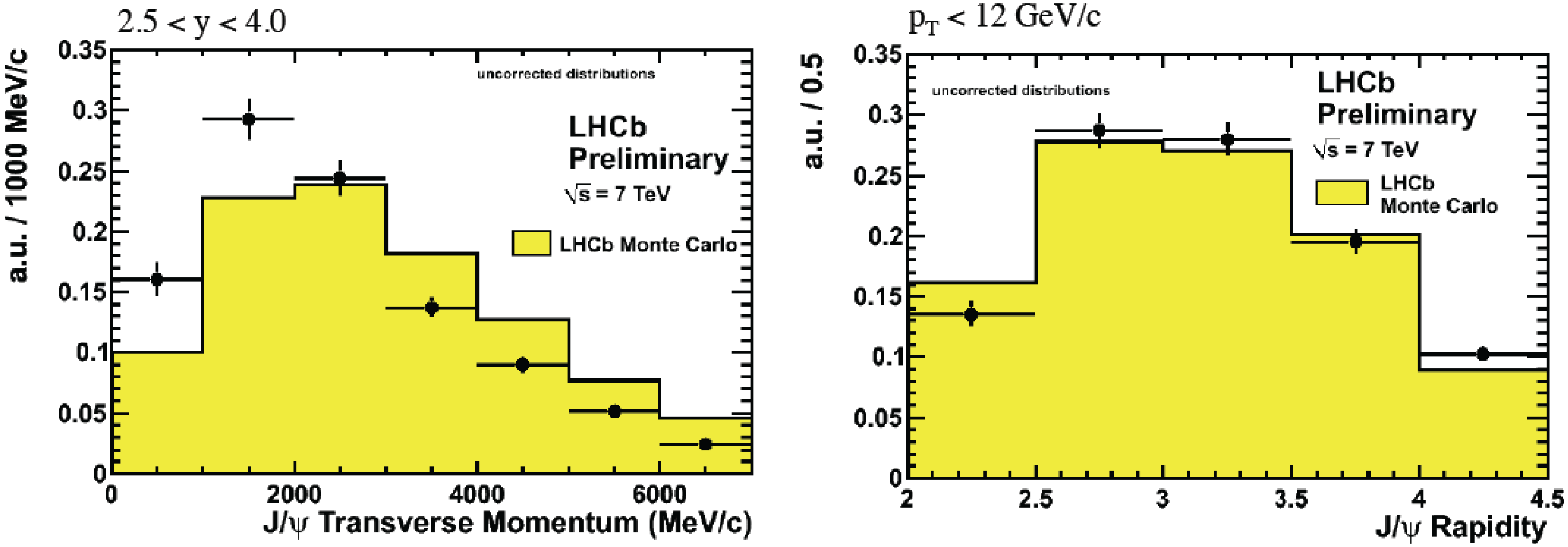
Sideband-subtracted distribution (pure signal)



- ❑ Asymmetric distribution with clear long-lived signal from b-hadron decays

J/ψ Rapidity and p_t

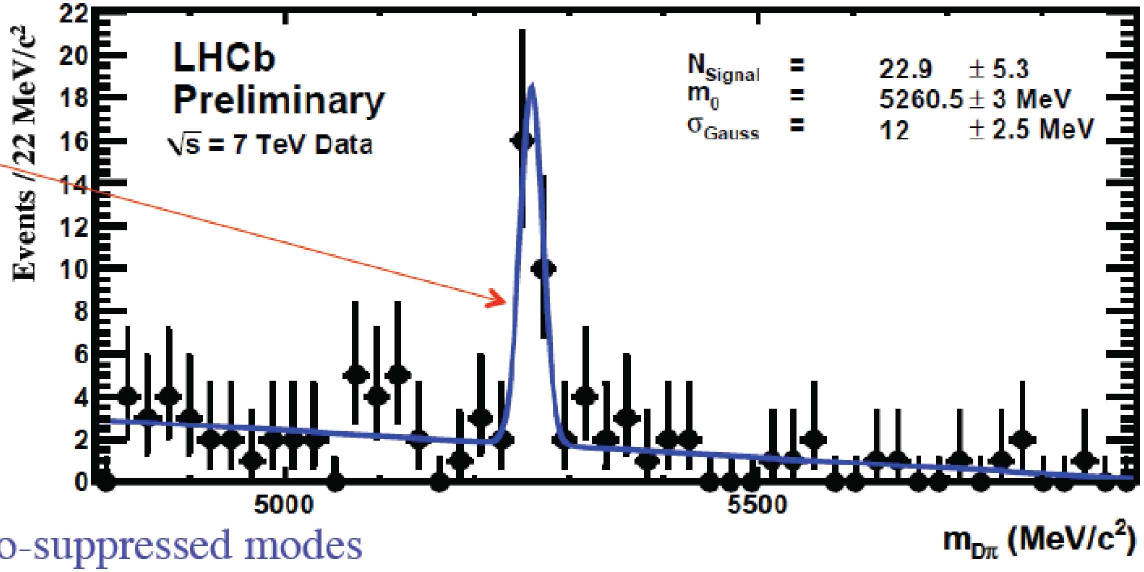
- In each p_T or y bin, J/ψ yield extracted from mass distribution
  - shown before any correction (e.g. efficiency correction)
  - spectrum contains prompt J/ψ and $b \to J/\psi$



  - above is illustrative of the capability, preliminary measurement expected soon

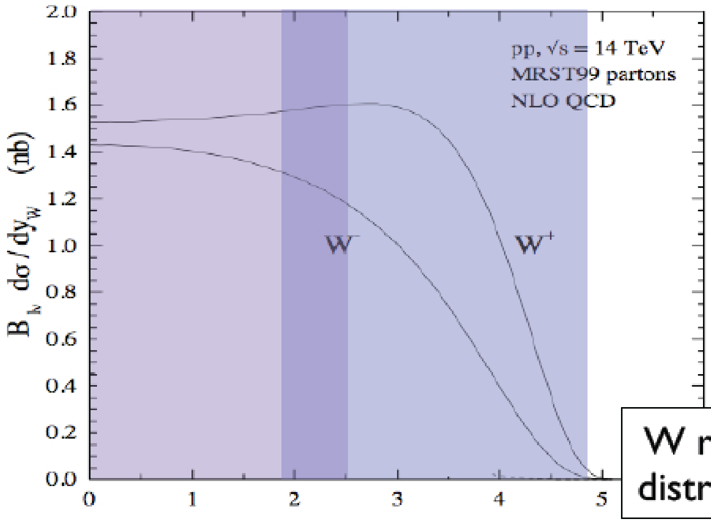
First exclusive hadronic decays

- First signal combining two modes:
  - $B^0 \to D^+\pi^-$
  - $B^+ \to D^0\pi^+$
- Expect soon:
  - $B_s \to D_s\pi^-$
  - $B \to DK$ Cabibbo-suppressed modes

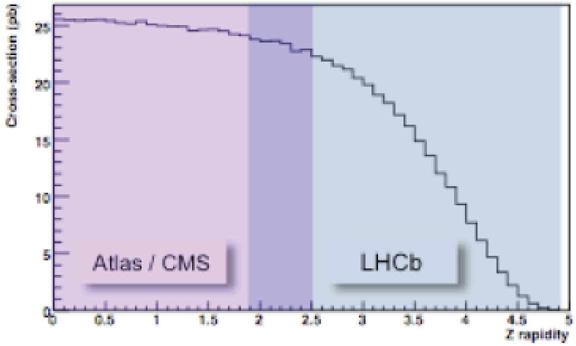


Electroweak Boson Production

- ❑ LHCb coverage:
  - — interesting rapidity region where W^+/W^- ratio is very different from 1
  - — small y overlap with ATLAS/CMS
  - — unique area of (Q^2,x) plane
- ❑ Measurements of interest:
  - — $Z^0/W^\pm$ ratio
    - precisely predicted (< 1%)
    - should aim at 1% measurement with 0.1 fb^{-1} → test SM
  - — W^+/W^- ratio
    - sensitive to d/u ratio
    - expect to measure ≠ 1 very soon
  - — W, Z production cross sections
    - can constrain PDFs, down to ~6×10^{-4} at $\sqrt{s}$= 7 TeV



W rapidity distribution



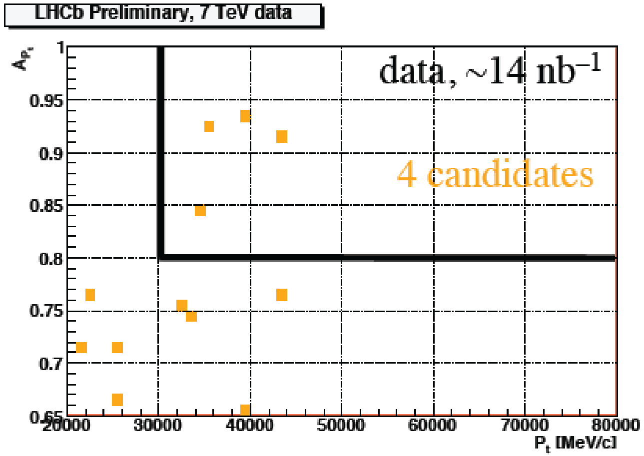
Z rapidity distribution

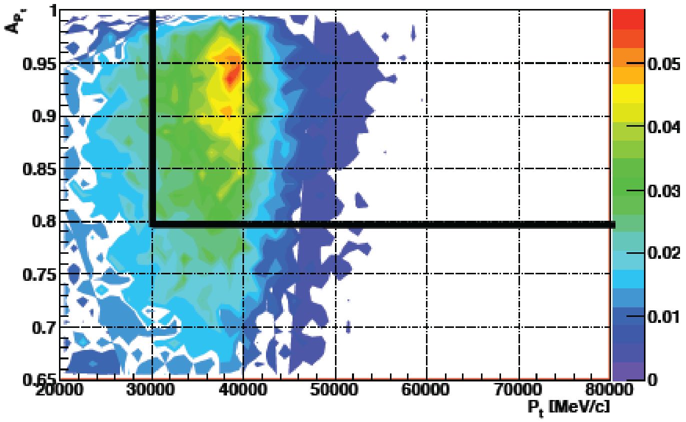
Selecting W→$\mu\nu$ events

- Selection:
  - — good track (χ^2, $\sigma_p/_p$, …) identified as muon
  - — $p_T > 30$ GeV/c and $A_{pT} > 0.8$

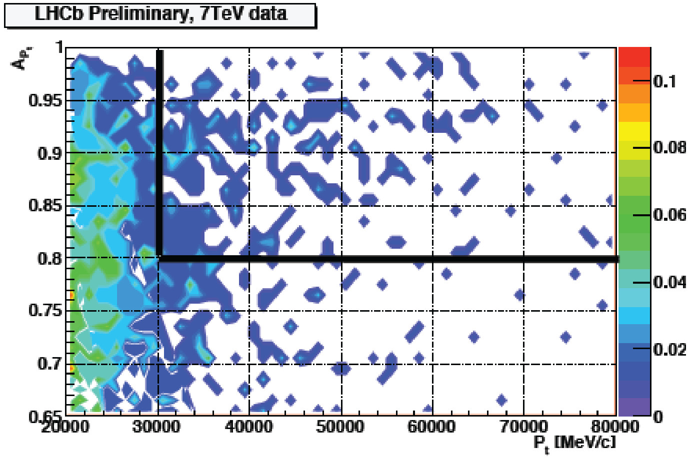
$$A_{pT} = \frac{p_T - p_T^{rest}}{p_T + p_T^{rest}}$$

p_T^{rest} = transverse momentum of vector sum of all charged tracks, excluding the selected track



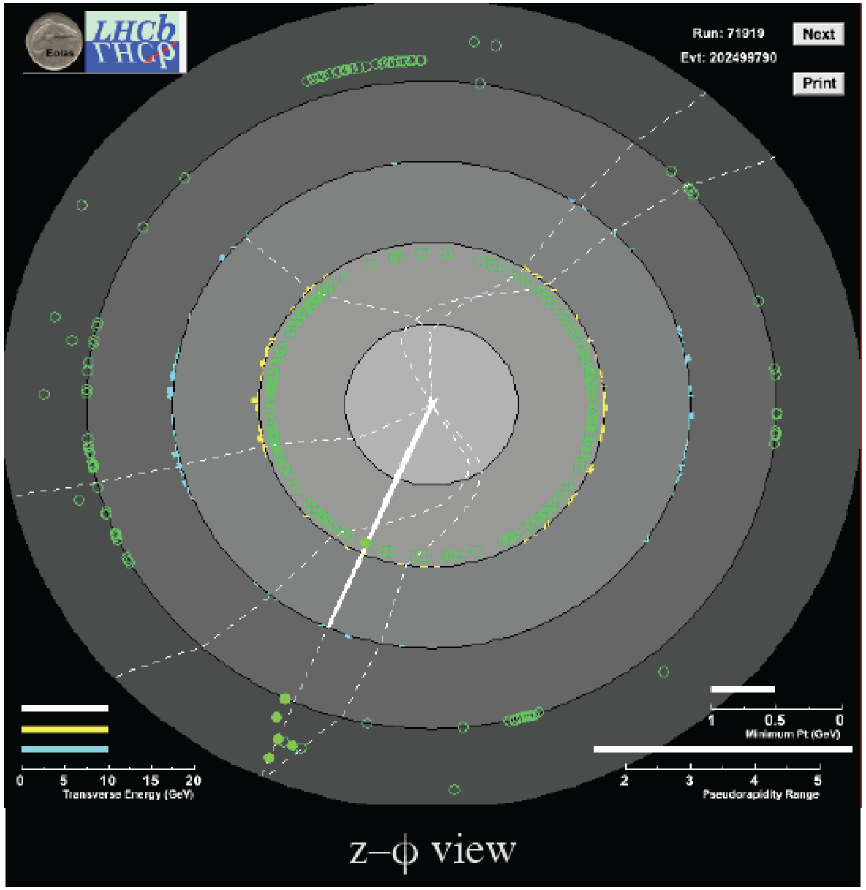


MC, W→ $\mu\nu$ signal



data, ~8 nb⁻¹, without muID cut

$W \rightarrow \mu\nu$ event candidate

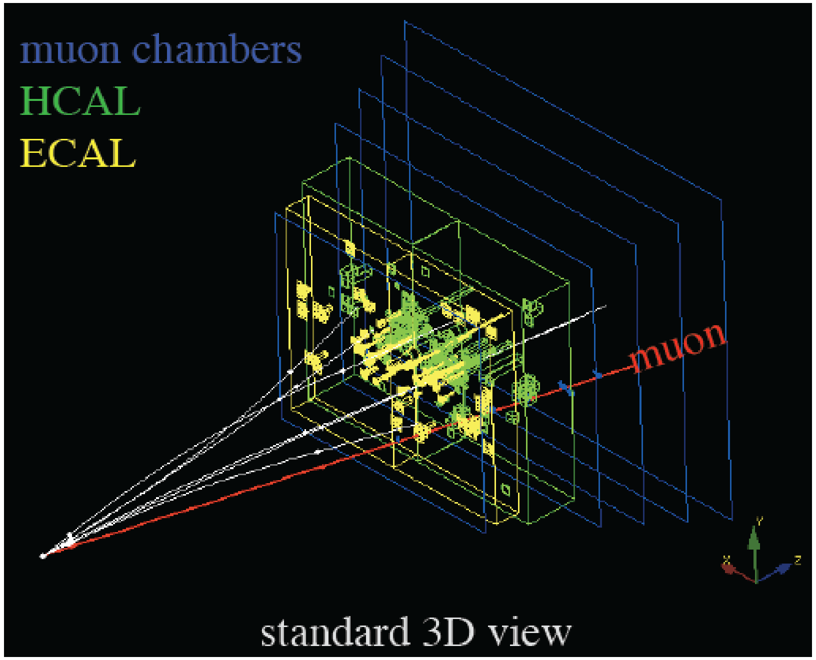


z–φ view

$\eta = 2.51$

$p_T = 35.4$ GeV/c

$A_{pT} = 0.92$



standard 3D view

Some Interesting Measurements & Sensitivities

LHCb expectations: $\geq$ 300 fb^{-1} in 2010

~ 2 fb^{-1} for nominal yr

~ 10 fb^{-1} for "1st run"

~100 fb^{-1} for upgrade

2010

LHC Luminosity Projections

- Two years at 3.5 TeV
- 2010: should peak at 10^{32} and yield up to 0.5 fb^{-1}
- 2011: ~1 fb^{-1} at 3.5 TeV
- 2012: splice consolidation (and cryo collimator prep.)
- 2013: 6.5 TeV - 25% nominal intensity

Aggressive

Year	Months	energy	Beta*	ib	#b	Peak Lumi x10^{32}	Lumi per month	Int Lumi Year GPD's (LHCb)	Int Lumi Cul GPDs (LHCb)
2010	8	3.5	2.5	7 e10	720	1.2	-	0.5 (0.5)	0.5 (0.5)
2011	8	3.5	2.5	7 e10	720	1.2	0.1	0.8 (0.8)	1.3 (1.3)
2012									
2013	6	6.5	1	1.1 e11	720	14	1.1	7 (2)	8 (3.8)
2014	7	7	1	1.1 e11	1404	30	2.3	16 (2)	24 (5.8)

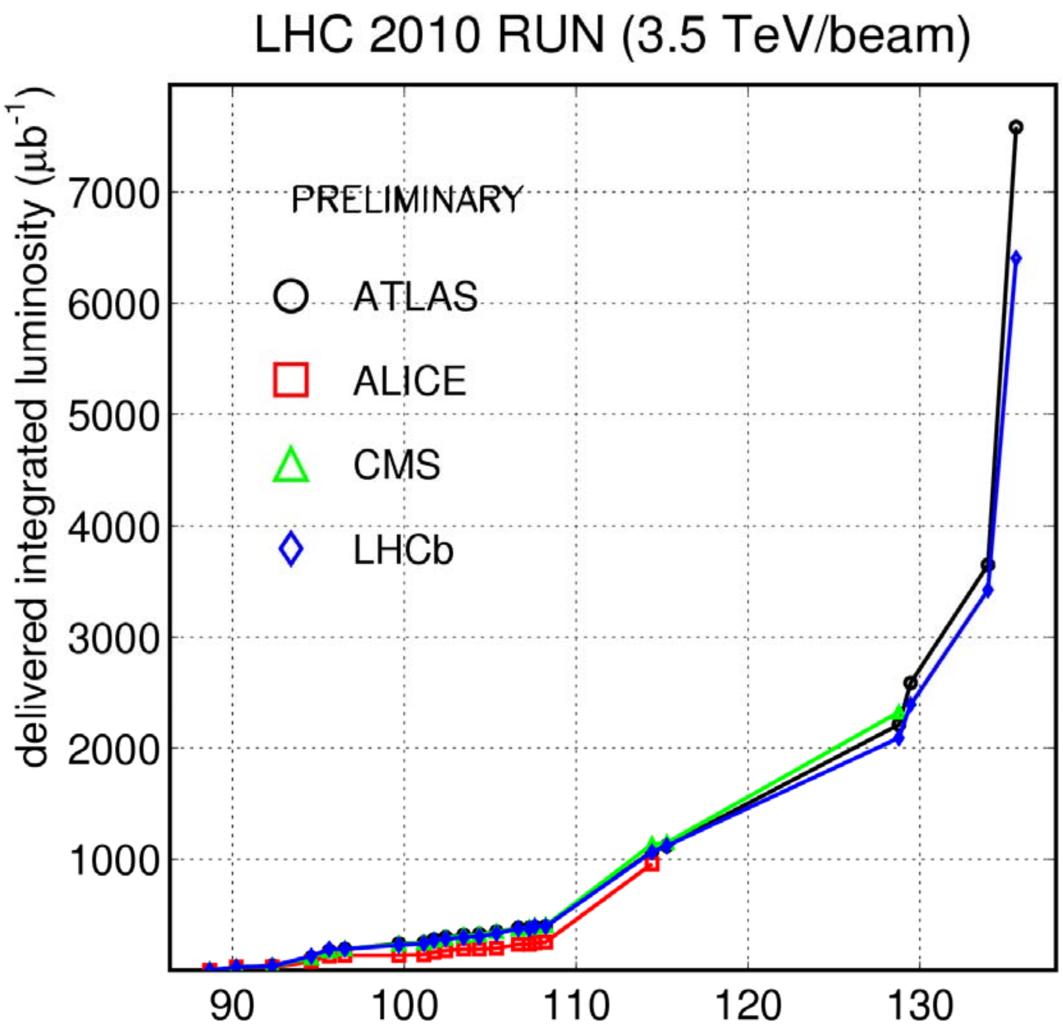
Independent estimate

Courtesy of a rather pessimistic but perhaps more realistic Massi Ferro-Luzzi

Year	**Months**	**energy**	**Beta***	**ib**	**#b**	**Peak Lumi x10^{32}**	**Lumi per month**	**Int Lumi Year GPD's (LHCb)**	**Int Lumi Cumlative GPD's (LHCb)**
2010	8	3.5	2.5	7 e10	720	1.2	-	0.1 (0.1)	0.1 (0.1)
2011	9	3.5	2.5	9 e10	720	1.2	0.1	1.0 (1.0)	1.1 (1.1)
2012									
2013	6	6.5	1	9 e10	720	9	0.45	2.7 (2)	3.8 (3.1)
2014	9	6.5	1	9 e10	1404	17	0.6	5.3 (2)	9.1 (5.1)

At least in the same ball park

Current Integrated Luminosity



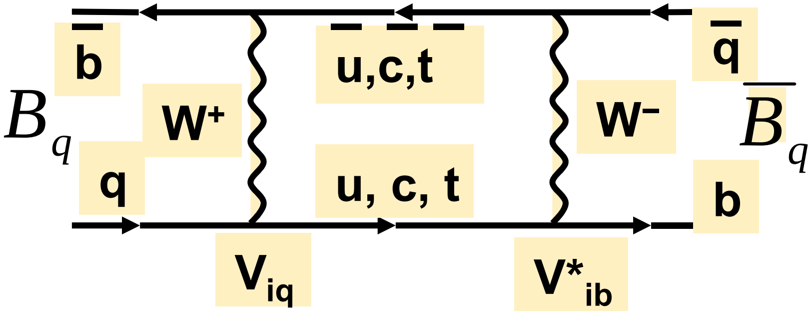
Days since Jan. 1, 2010 (from M. Ferro-Luzzi)

Better Trigger Efficiencies at Low L

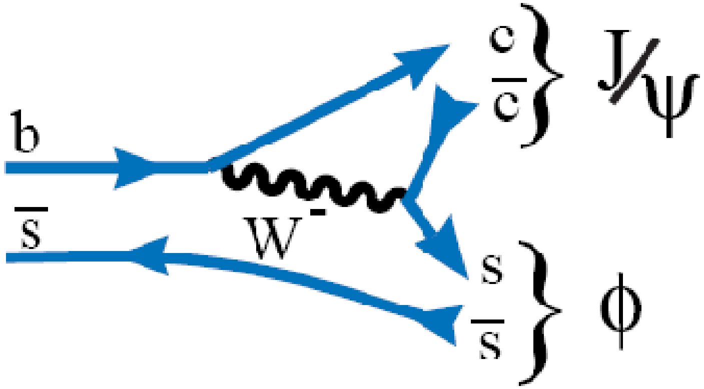
- At LHCb design luminosity (2 x 10^{32} cm^{-2} s^{-1}) all thresholds are optimised for B-physics, and consequently ε_{trig} for D decays from prompt-production is low, typically ~ 10%
  - Still adequate for accumulating very large samples, but corresponding efficiencies for hadronic B-decays ~4x high
- At low $\mathcal{L}$ we boost trigger efficiencies for hadronic decays of promptly produced D's by factor 4-5 w.r.t. nominal settings
  - ε_{trig} for hadronic B decays now 75-80%, those for leptonic decay modes >90%.

General Strategy

- Measure experimental observables sensitive to New Particles through their interference effects in processes mediated by loop diagrams, e.g.
  - CP violation via mixing

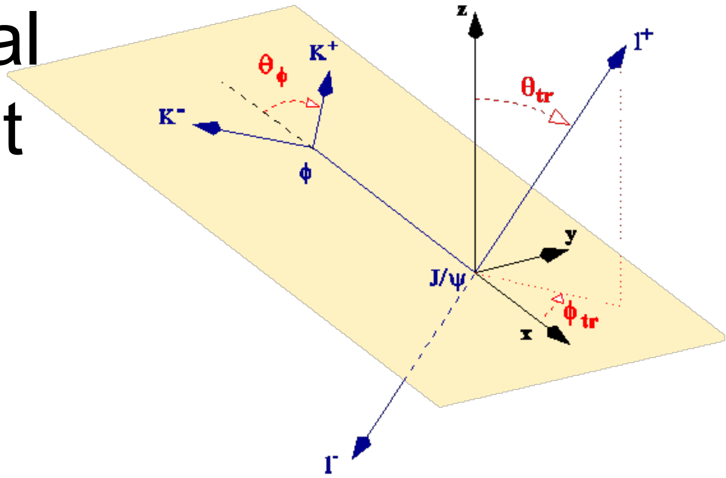


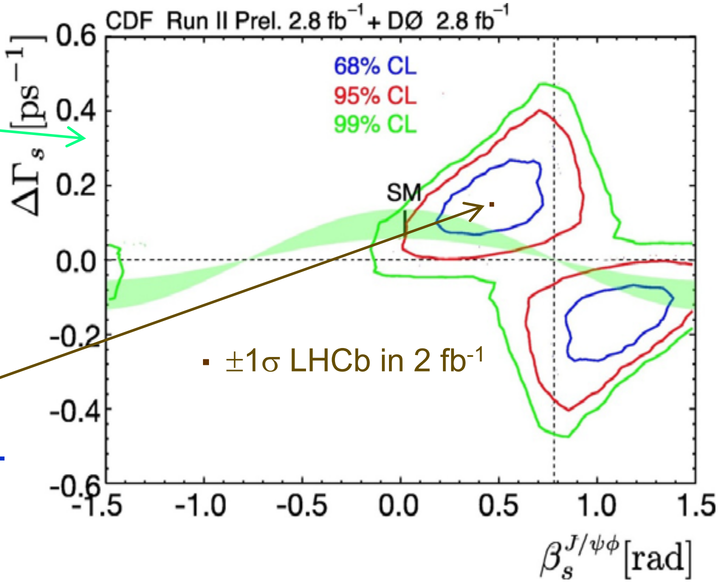
  - Example



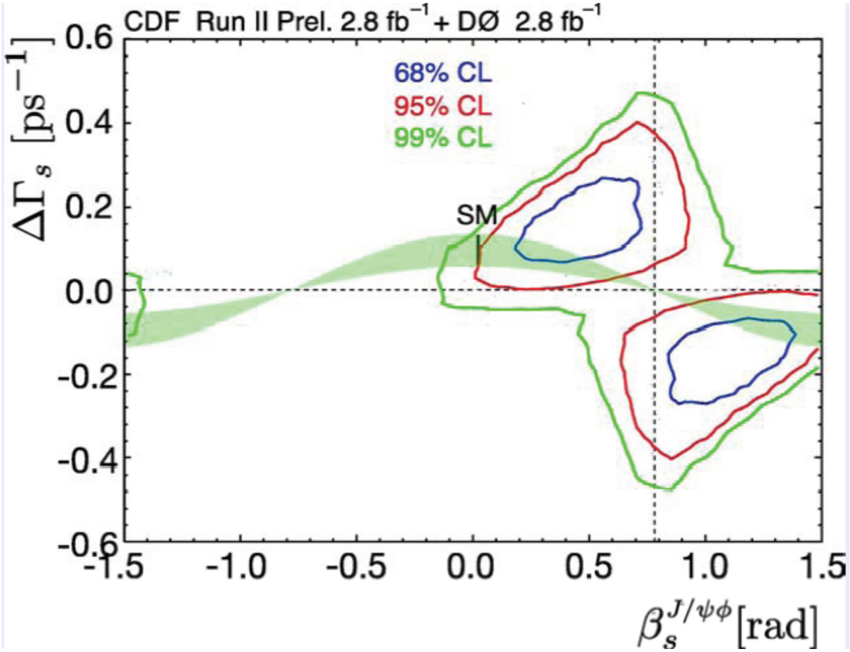
CP Asymmetry in $B_S \to J/\psi\ \phi$

- Just as $B^o \to J/\psi\ K_S$ measures CPV phase 2β $B_S \to J/\psi\ \phi$ measures CPV B_S mixing phase $-2\beta_S$
- Since this is a Vector-Vector final state, must do a time dependent angular (transversity) analysis
- The width difference $\Delta\Gamma_S/\Gamma_S$ also enters in the fit
- Combined current CDF & D0 results
- LHCb will get 60,000 such events in 2 fb^{-1}. Projected errors are ±0.07 rad in $2\beta_S$ & ±0.026 in $\Delta\Gamma_S/\Gamma_S$. [Will also use $J/\psi\ f_o(980)$]

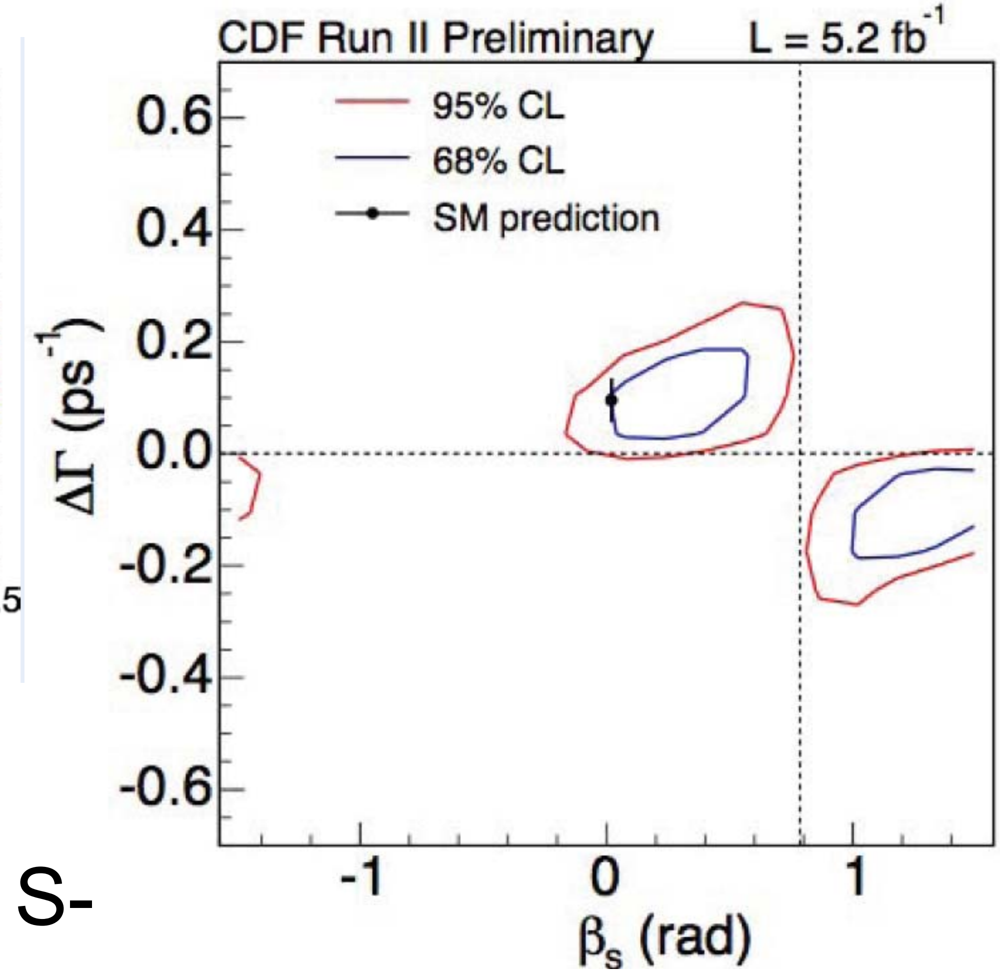




New CDF measurement of β_s



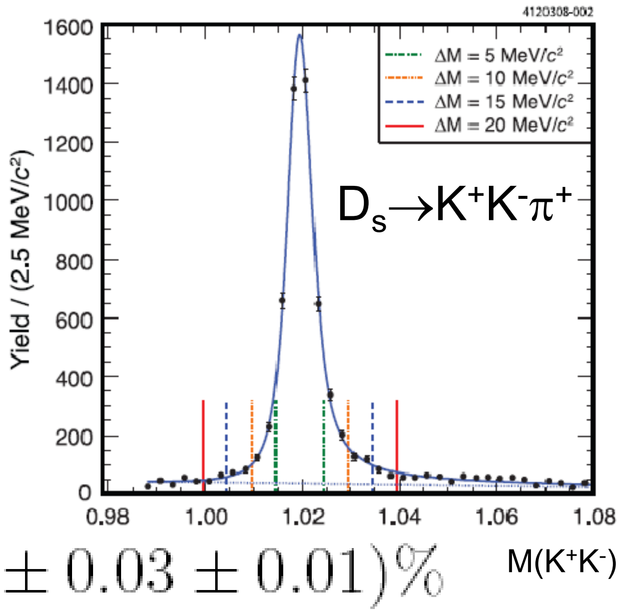
Tevatron combination: probability of observed deviation from SM = 3.4% (2.12 σ)



- CDF now allows for S-wave in fit

P-value for SM point: 44% (0.8σ deviation)

β_s Using $B_s \to J/\psi\, f_0(980)$



- Problem with $J/\psi\ \phi$: S-wave
- Stone & Zhang estimate 10%, can be dealt with, but increases complexity and error (arXiv:0812.2832)
- CLEO also measures

$$\mathcal{B}(D_s^+ \to f_0(980)e^+\nu,\ f_0 \to \pi^+\pi^-) = (0.20 \pm 0.03 \pm 0.01)\%$$

$$\mathcal{B}(D_s^+ \to \phi e^+\nu,\ \phi \to K^+K^-) = (1.16 \pm 0.11 \pm 0.06)\%$$

- Estimate: $\mathcal{B}(B_s \to J/\psi\ f_o \to J/\psi\ \pi^+\pi^-)/\mathcal{B}(B_s \to J/\psi\ \phi \to J/\psi\ K^+K^-)$ =20-40% [Note $M(B_s)-M(J/\psi) \approx M(D_s)$]
- This is a CP Eigenstate, so can get independent measurement of somewhat worse accuracy

Mystery of Scalar Mesons

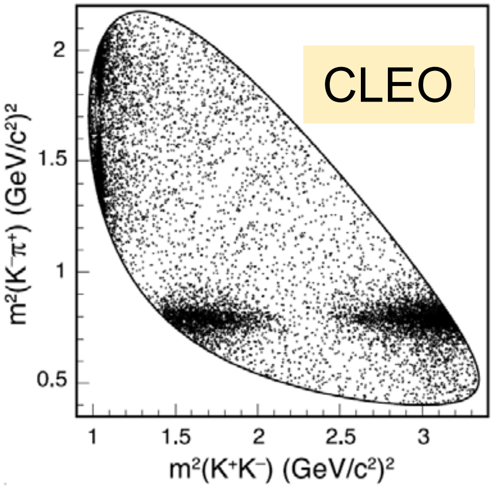
- 0^+ nonet is not ~~well~~ understood
- Compare 0^- versus 0^+

Quarks	Pseudoscalar		Scalar	
	Particle	Mass (MeV)	Particle	Mass (MeV)
$1/\sqrt{2}(u\bar{u}+d\bar{d})$	π^o	135	σ ?	~600
$u\bar{d}$	π^+	139	a_o^+	980
$u\bar{s}$	K^+	495	κ^+ ?	~900
$\sim s\bar{s}$	η'	960	f_o	980

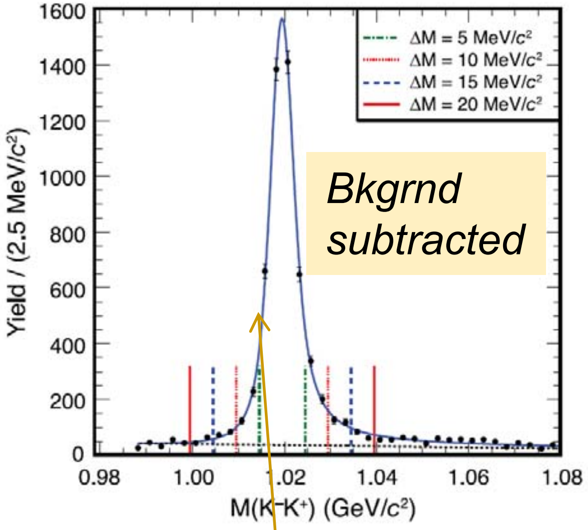
  - For 0- nonet, the mass increases by ~400 MeV for each s quark. Why isn't this true for the 0+ nonet?
  - Why aren't the a_o & the σ degenerate in mass?
- Suggestions that the 0^+ are 4-quark states

S-waves in $D_s \to K^+K^-\pi^+$ decays

- Dalitz analyses (also E687)



Particle	J^P	Fit Fraction (%) (sums to 130%)
K*(892)	1^-	47.4±1.5
ϕ(1020)	1^-	42.2±1.6
f_o(980)	0^+	28.2±1.9
f_o(1370)	0^+	4.3±0.6
K_o*(1430)	0^+	3.9±0.5
f_o(1710)	0^+	3.4±0.5



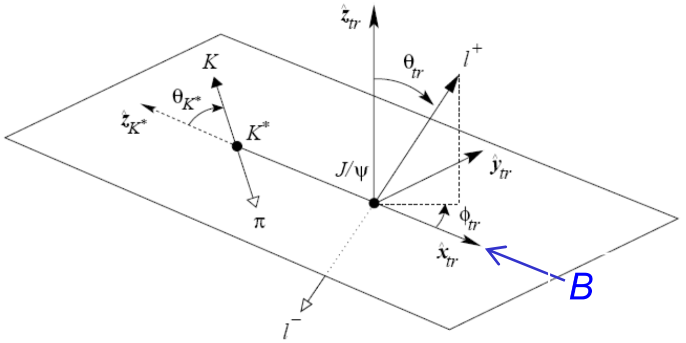
Bkgrnd subtracted

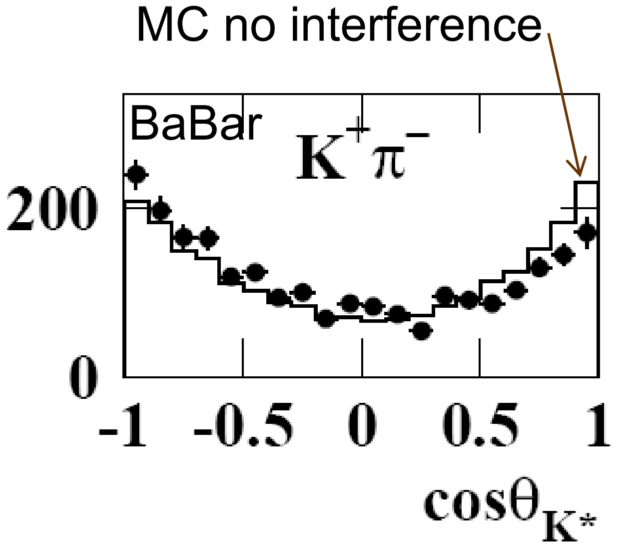
- Fit using a linear S-wave + Breit-Wigner convoluted with Gaussian for the ϕ. Find 6.3% (8.9%) S-wave for ±10 MeV (±15 MeV)

The S-Wave in $B \to J/\psi K^*$

- Two Vectors in final states so a transversity analysis is required
- BaBar & Belle measure interference between S & P waves in K* decay angle
- The fraction of S-wave intensity is (7.3±1.8)% for

  $0.8 < m(K\pi) < 1.0$ GeV
- BaBar uses this interference to remove ambiguities in the measurement of $\cos(2\beta)$




MC no interference

Decay rate for $B_s \rightarrow J/\psi\ \phi$

- Without S-waves & $\Delta\Gamma$=0

$$A(B_s \to J/\psi\phi) = A_0(m_\phi)/E_\phi \boldsymbol{\epsilon}^{*L}_{J/\psi} - A_{\|}\boldsymbol{\epsilon}^{*T}_{J/\psi}/\sqrt{2} - iA_\perp \boldsymbol{\epsilon}^*_\phi \cdot \hat{\mathbf{p}}/\sqrt{2},$$

- A_0 P=+ longitudinal, $A_{||}$ P=+ trans, $A_\perp$P= - trans

$$\frac{d^4\Gamma[B_s \to (\ell^+\ell^-)_{J/\psi}(K^+K^-)_\phi]}{d\cos\theta\ d\phi\ d\cos\psi\ dt} = \frac{9}{32\pi}[2|A_0|^2\cos^2\psi(1-\sin^2\theta\cos^2\phi)$$

$$+\sin^2\psi\{|A_{\|}|^2(1-\sin^2\theta\sin^2\phi)+|A_\perp|^2\sin^2\theta-\mathrm{Im}(A_{\|}^*A_\perp)\sin 2\theta\sin\phi\}$$

$$+\frac{1}{\sqrt{2}}\sin 2\psi\{\mathrm{Re}(A_0^*A_{\|})\sin^2\theta\sin 2\phi+\mathrm{Im}(A_0^*A_\perp)\sin 2\theta\cos\phi\}] \quad .$$

- For $\overline{B}_s$ replace $A_\perp$ by $-A_\perp$.
- Strait-forward to add finite $\Delta\Gamma$
- S-Wave term cannot be ignored (Stone & Zhang [arXiv:0812.2832])
- So must add in S-wave amplitude

All terms [Xie et al, arXiv:098.3627]

- Time dependence (for ex.)

$$|A_0(t)|^2 = |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi \sin(\Delta m_s t)\right]$$

- Can write $\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\, d\cos\theta\, d\cos\psi\, d\varphi} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega)$

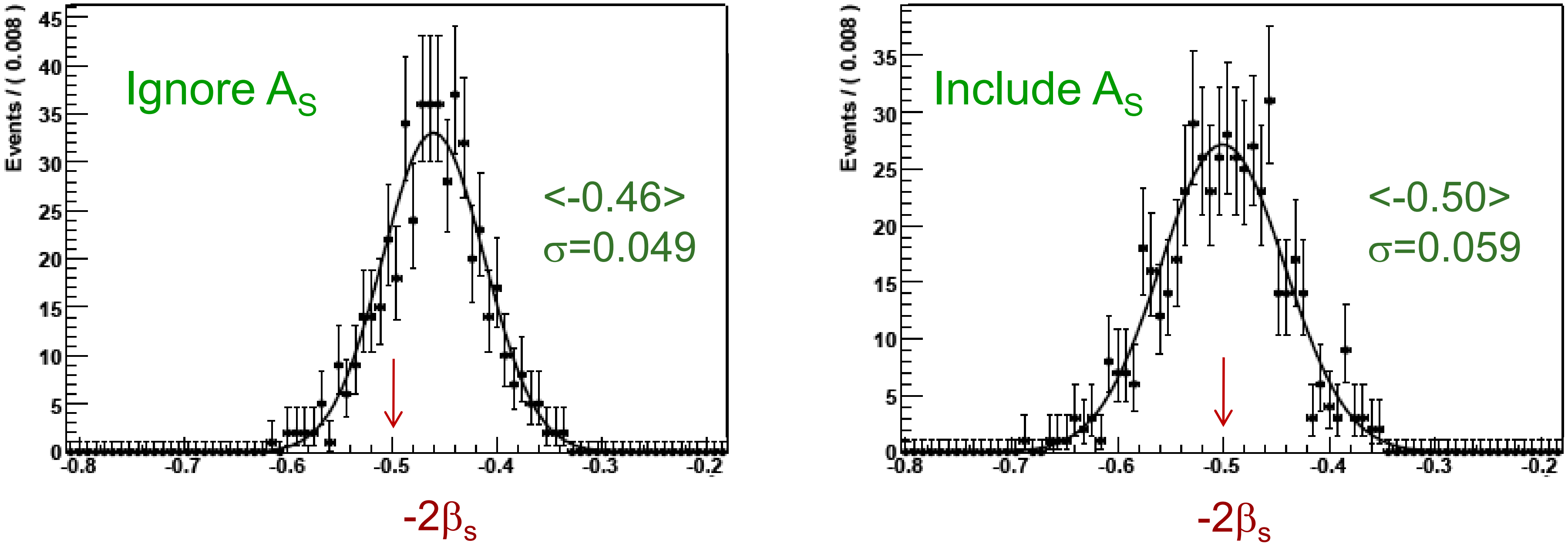
k	$h_k(t)$	$\bar{h}_k(t)$	$f_k(\theta_l, \theta_K, \varphi)$
1	$\|A_0(t)\|^2$	$\|\bar{A}_0(t)\|^2$	$4\sin^2\theta_l \cos^2\theta_K$
2	$\|A_{\|\|}(t)\|^2$	$\|\bar{A}_{\|\|}(t)\|^2$	$(1+\cos^2\theta_l)\sin^2\theta_K - \sin^2\theta_l \sin^2\theta_K \cos 2\varphi$
3	$\|A_{\perp}(t)\|^2$	$\|\bar{A}_{\perp}(t)\|^2$	$(1+\cos^2\theta_l)\sin^2\theta_K + \sin^2\theta_l \sin^2\theta_K \cos 2\varphi$
4	$\Im\{A_{\|\|}^*(t) A_{\perp}(t)\}$	$\Im\{\bar{A}_{\|\|}^*(t) \bar{A}_{\perp}(t)\}$	$2\sin^2\theta_l \sin^2\theta_K \sin 2\varphi$
5	$\Re\{A_0^*(t) A_{\|\|}(t)\}$	$\Re\{\bar{A}_0^*(t) \bar{A}_{\|\|}(t)\}$	$-\sqrt{2}\sin 2\theta_l \sin 2\theta_K \cos\varphi$
6	$\Im\{A_0^*(t) A_{\perp}(t)\}$	$\Im\{\bar{A}_0^*(t) \bar{A}_{\perp}(t)\}$	$\sqrt{2}\sin 2\theta_l \sin 2\theta_K \sin\varphi$
7	$\|A_S(t)\|^2$	$\|\bar{A}_S(t)\|^2$	$\frac{4}{3}\sin^2\theta_l$
8	$\Re\{A_S^*(t) A_{\|\|}(t)\}$	$\Re\{\bar{A}_S^*(t) \bar{A}_{\|\|}(t)\}$	$-\frac{2}{3}\sqrt{6}\sin 2\theta_l \sin\theta_K \cos\varphi$
9	$\Im\{A_S^*(t) A_{\perp}(t)\}$	$\Im\{\bar{A}_S^*(t) \bar{A}_{\perp}(t)\}$	$\frac{2}{3}\sqrt{6}\sin 2\theta_l \sin\theta_K \sin\varphi$
10	$\Re\{A_S^*(t) A_0(t)\}$	$\Re\{\bar{A}_S^*(t) \bar{A}_0(t)\}$	$\frac{8}{3}\sqrt{3}\sin^2\theta_l \cos\theta_K$

Estimate of S-wave Effect

- Adding A_S can only increase the experimental error. The size of the effect depends on many factors including the magnitude & phase of the S-wave amplitude, β_s, values of the strong phases, detector acceptances, biases…
- One simulation for LHCb by Xie et al
  - Assumes either 5% or 10% S-wave with phases either 0 or 90°.
  - Simulates many Pseudo experiments

Results of ignoring S-wave

Generate $-2\beta_s = -0.5$



- ❑ Find bias of -10%
- ❑ Error increases by ~20%.
- ❑ Can also use to eliminate δ_s ambiguity

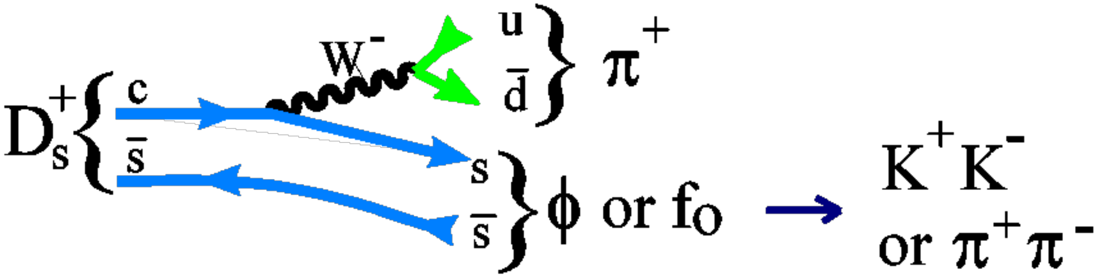
Estimates of J/ψ f_0(980)

- Can use S-wave materializing as f_o(980) for CP measurements (Stone & Zhang [arXiv:0812.2832])
- The final state J/ψ f_o is a CP+ eigenstate
- No angular analysis is necessary! This is just like measuring J/ψ K_s. The modes J/ψη & J/ψ η′ can also be used, but they involved γ's in the decay & thus have lower efficiency at hadron colliders
- Define:

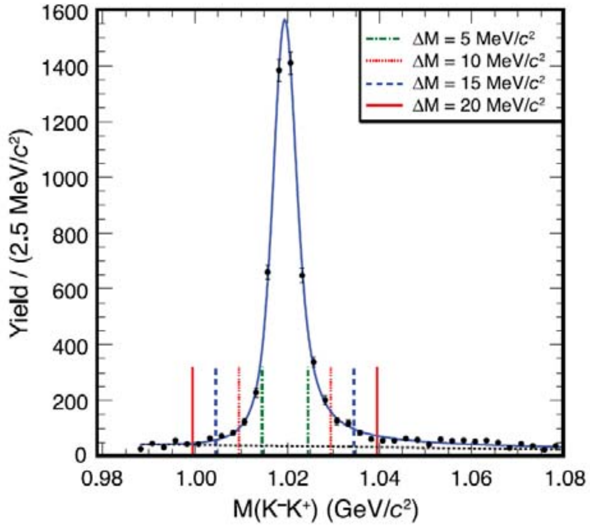
$$R_{f/\varphi} = \frac{\Gamma\left(B_s \to J/\psi f_0; f_0 \to \pi^+\pi^-\right)}{\Gamma\left(B_s \to J/\psi\phi; \phi \to K^+K^-\right)}$$

Estimate Using Hadronic D_s Decays

- $M(B_s)-M(J/\psi)=5366-3097 = 2270$ MeV
- $M(D_s)-M(\pi) = 1830$ MeV, not too different

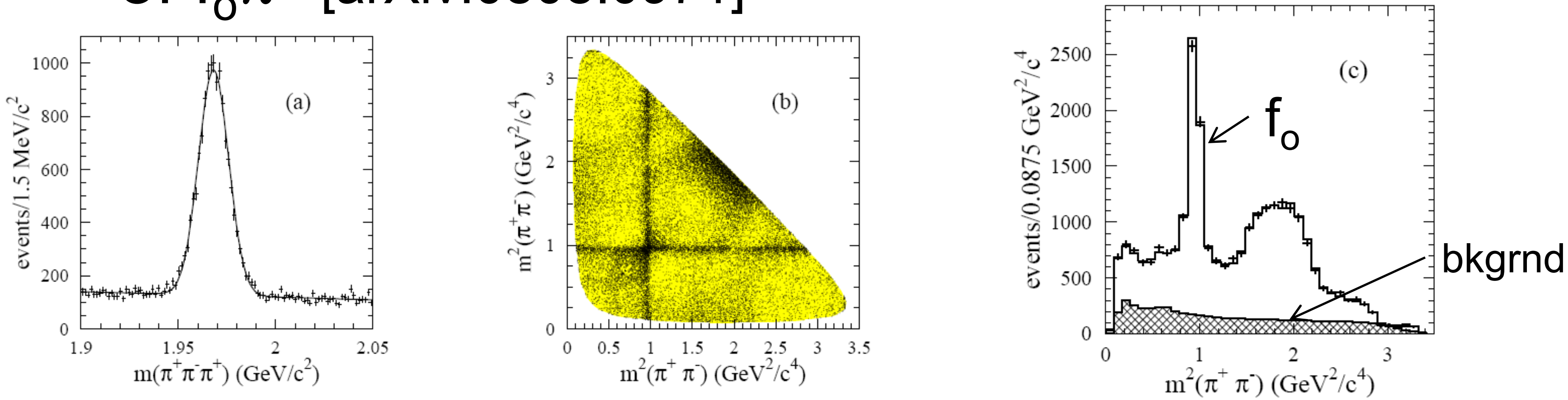


- Use CLEO result for $D_s \to K^+K^-\pi^+$ extrapolated to zero ϕ width to extract $\mathcal{B}(D_s \to \phi\pi^+, \phi \to K^+K^-) = (1.6\pm0.1)\%$ (only for comparison)



Estimate from $D_s \to h^+h^-\pi^+$

- CLEO: $\mathcal{B}(D_s \to \pi^+\pi^+\pi^-) = (1.11 \pm 0.07 \pm 0.04)\%$
- Use BaBar Dalitz analysis to estimate fraction of $f_o\pi^+$ [arXiv:0808.0971]



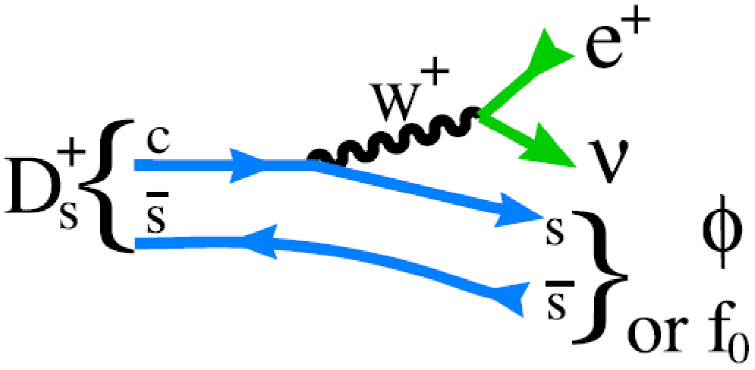
- Estimate (27±2)% of final state is in narrow f_o peak

$$R'_{f/\varphi} = \frac{\Gamma\left(D_s \to f_0\pi^+; f_0 \to \pi^+\pi^-\right)}{\Gamma\left(D_s \to \phi\pi^+; \phi \to K^+K^-\right)} = (19 \pm 2)\%$$

Estimate from $D_s \to (\phi/f_0)\, e^+ \nu$

- Compare semileptonic rates near $q^2=0$ to get maximum phase space

CLEO [arXiv:907.3201]



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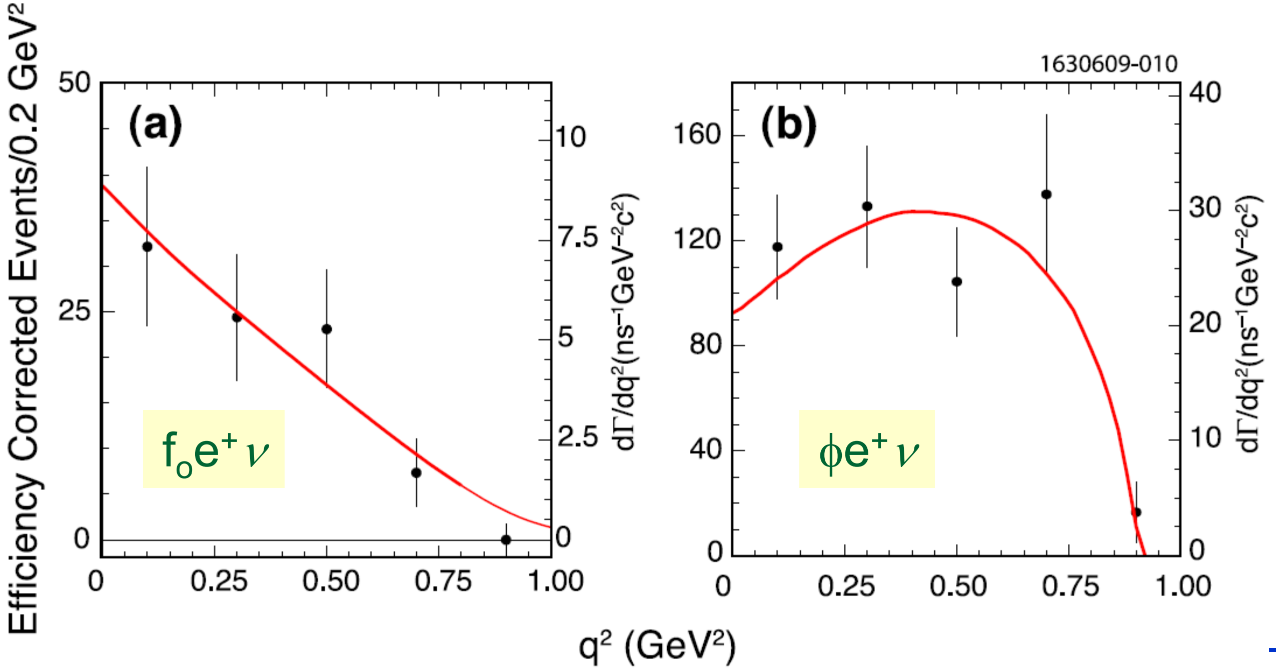
$$\frac{d\Gamma}{dq^2}$$



Semileptonic estimate

- At q^2=0, where phase space is closest to $B_s \to J/\psi(\phi/f_o)$
- $$R_{f/\phi} \equiv \frac{\frac{d\Gamma}{dq^2}(D_s^+ \to f_0(980)e^+\nu,\ f_0 \to \pi^+\pi^-)\mid_{q^2=0}}{\frac{d\Gamma}{dq^2}(D_s^+ \to \phi e^+\nu,\ \phi \to K^+K^-)\mid_{q^2=0}} = (42 \pm 11)\%$$
- Note that at q^2=0 and in the case of $D_s \to \phi\pi$, the ϕ is forced into a longitudinal polarization state
- CDF measures only 53% ϕ_L, so these ratios may be too large by x2

Theory Estimates of $R_{f_0/\phi}$

- Colangelo, De Fazio & Wang [arXiv:1002.2880]
- Use Light Cone Sum Rules at leading order
- Prediction 1: Using measured $\mathcal{B}(J/\psi\ \phi) = (1.3 \pm 2.4) \times 10^{-3}$
  - $\mathcal{B}(J/\psi f_o) = (3.1 \pm 2.4) \times 10^{-4}$ (0th order), R=24%
  - $\mathcal{B}(J/\psi f_o) = (5.3 \pm 3.9) \times 10^{-4}$ (leading order), R=41%
- Prediction 2: Using ff for ϕ from Ball & Zwicky [arXiv:hep-ph/0412079]

$$R_L = \frac{B(B_s \to J/\psi f_0)}{B(B_s \to J/\psi \phi_L)}$$

R_L =0.13±0.06 (0th order),

=0.22±0.10 1st order

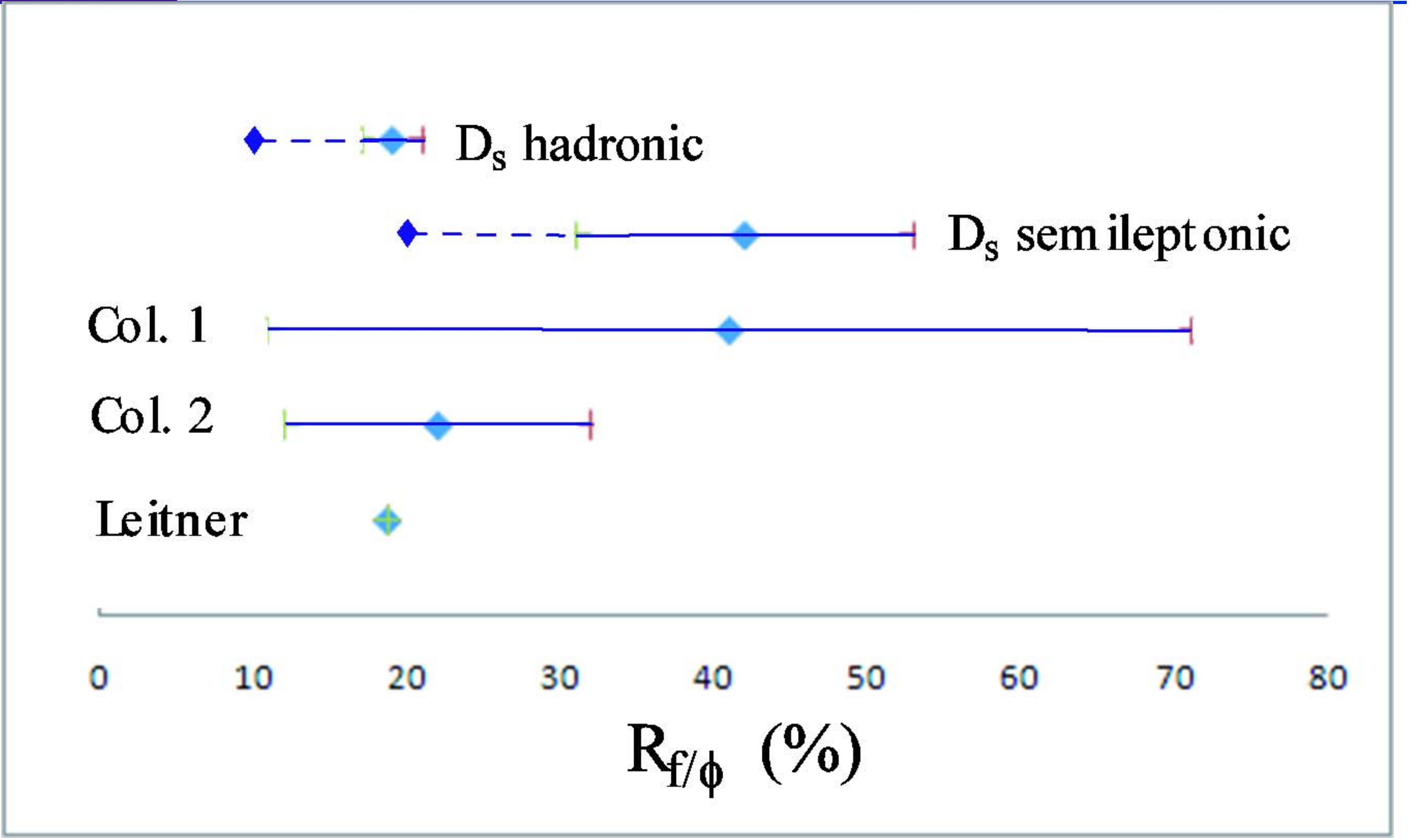
Check on Prediction

- Note that Colangelo et al predict
- $\mathcal{B}(D_s \rightarrow f_o e^+ \nu) = \left(2.0^{+0.5}_{-0.4}\right) x 10^{-3}$,
- While CLEO measures
- $\mathcal{B}(D_s \rightarrow f_o e^+ \nu) = (4.0 \pm 0.6 \pm 0.6) \times 10^{-3}$,
- Which implies that the calculated form-factor is low by a factor of 2, thus compensating for $\Gamma \phi_L / \Gamma_{total} = 0.53$

QCD Factorization

- O. Leitner etal [arXiv:1003.5980]
  - Assume f_{Bs} = 260 MeV, f_{fo} = 380 MeV
- Predict $\mathcal{B}(B_s \to J/\psi\ f_o) = 1.70 \times 10^{-4}$.
- $\mathcal{B}(B_s \to J/\psi\ \phi) = 9.30 \times 10^{-4}$.
- $R_{fo/\phi}$ = 0.187. They show small variation with $B_s \to f_o$ form factor; “annihilation” effects important and decrease f_o rate.
- “S-wave kaons or pions under the ϕ peak in $J/\psi\phi$ are very likely to originate from the similar decay $J/\psi f_o$. Therefore, the extraction of the mixing phase from $J/\psi\phi$ may well be biased by this S-wave effect which should be taken into account in experimental analysis”

Summary of R estimates

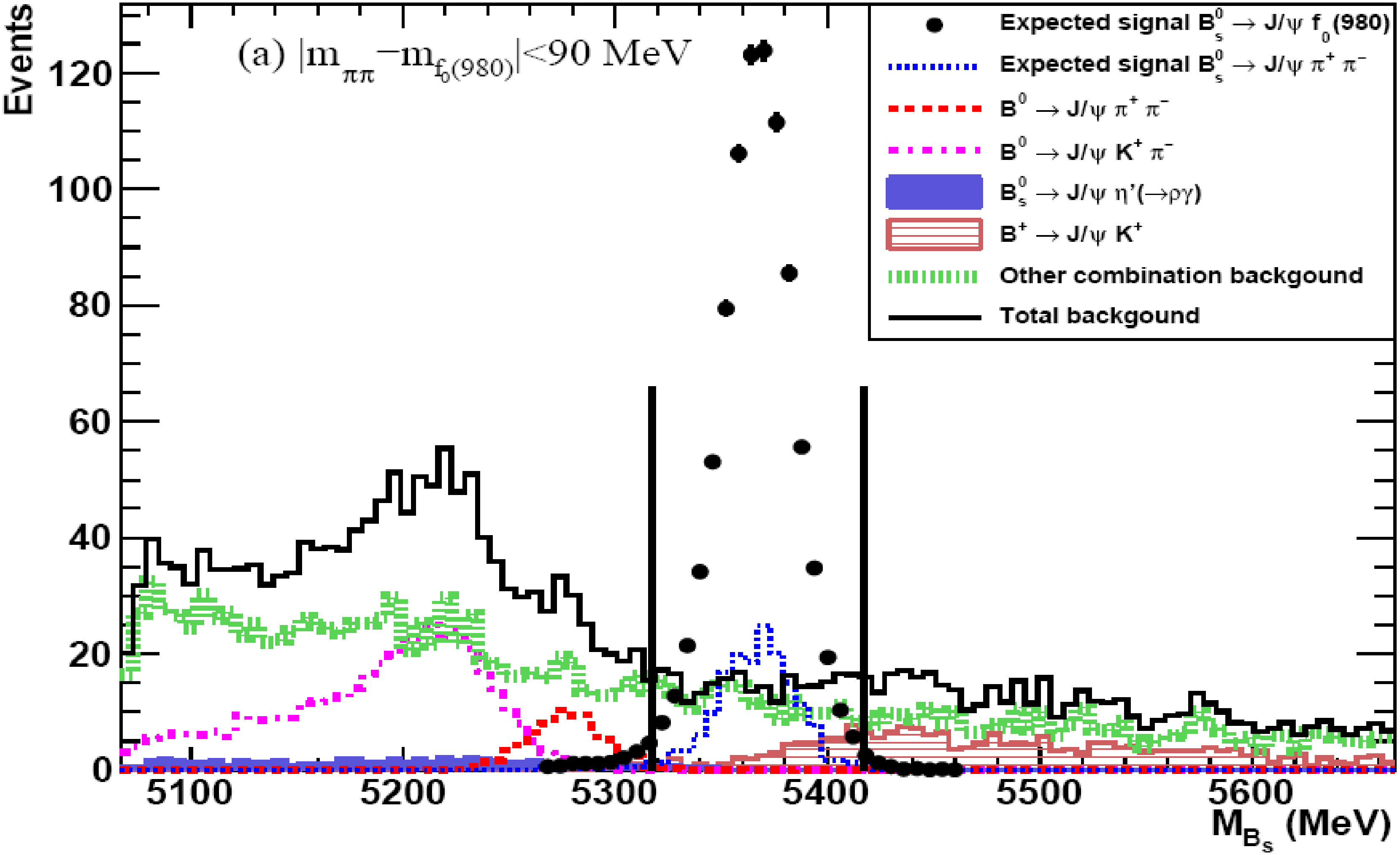


- Measurement will constrain theories

β_s Sensitivity Using $J/\psi\, f_o$

- From Stone & Zhang [arXiv:0909.5442] for LHCb
- Assume $R_{fo/\phi}$ = 25%
- Assume 2 fb^{-1} at 14 TeV (~4 fb^{-1} at 7 TeV)
- Error in $-2\beta_s$
  - $J/\psi\ \phi$: ±0.03 rad (not including S-wave)
  - $J/\psi\ f_o$, $f_o \rightarrow \pi^+\pi^-$: ±0.05 rad
  - $J/\psi\ f_o + J/\psi\ \eta'$, $\eta' \rightarrow \pi^+\pi^-\gamma$: ±0.044 rad
- The f_o mode should be useful

$B_s \to J/\psi f_0$ Signal Selection



$B_s \to \phi\gamma$: Right-Handed currents

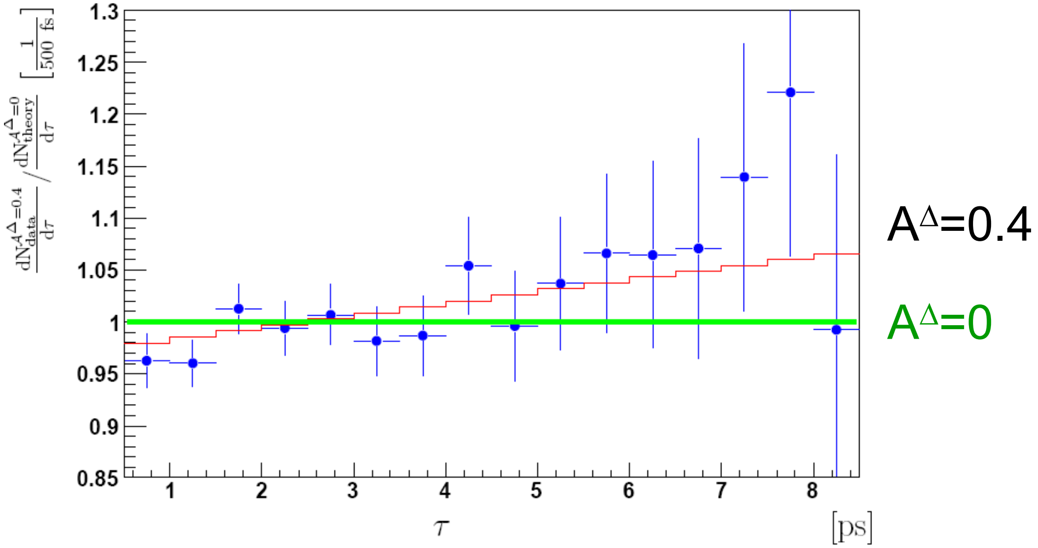
- Define $\tan\psi \equiv \left|\frac{\mathcal{A}\left(\bar{\mathrm{B}}_{(\mathrm{s})} \to \Phi^{\mathcal{CP}}\gamma_{\mathrm{R}}\right)}{\mathcal{A}\left(\bar{\mathrm{B}}_{(\mathrm{s})} \to \Phi^{\mathcal{CP}}\gamma_{\mathrm{L}}\right)}\right|$, zero in SM
- Theory

$$\Gamma_{\mathrm{B}^0_s \to \Phi^{\mathcal{CP}}\gamma}(\mathrm{t}) \approx |\mathrm{A}|^2 \mathrm{e}^{-\Gamma_s \mathrm{t}}\left(\cosh\frac{\Delta\Gamma_s \mathrm{t}}{2} - \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma_s \mathrm{t}}{2}\right)$$

$$\Gamma_{\bar{\mathrm{B}}^0_s \to \Phi^{\mathcal{CP}}\gamma}(\mathrm{t}) \approx \Gamma_{\mathrm{B}^0_s \to \Phi^{\mathcal{CP}}\gamma}(\mathrm{t})$$

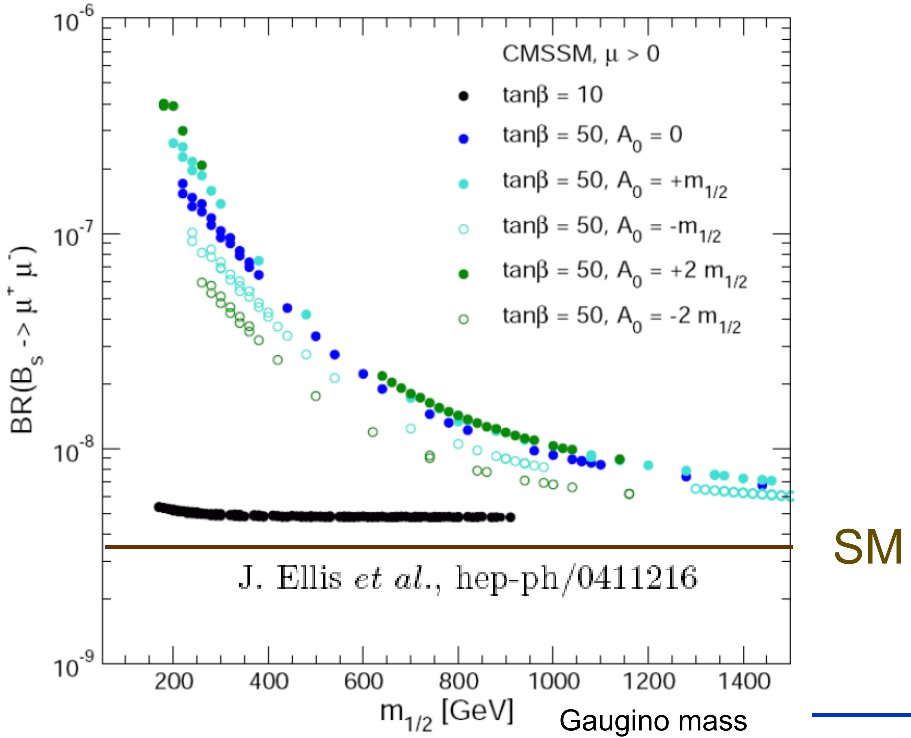
where $A^{\Delta}=\sin 2\psi$

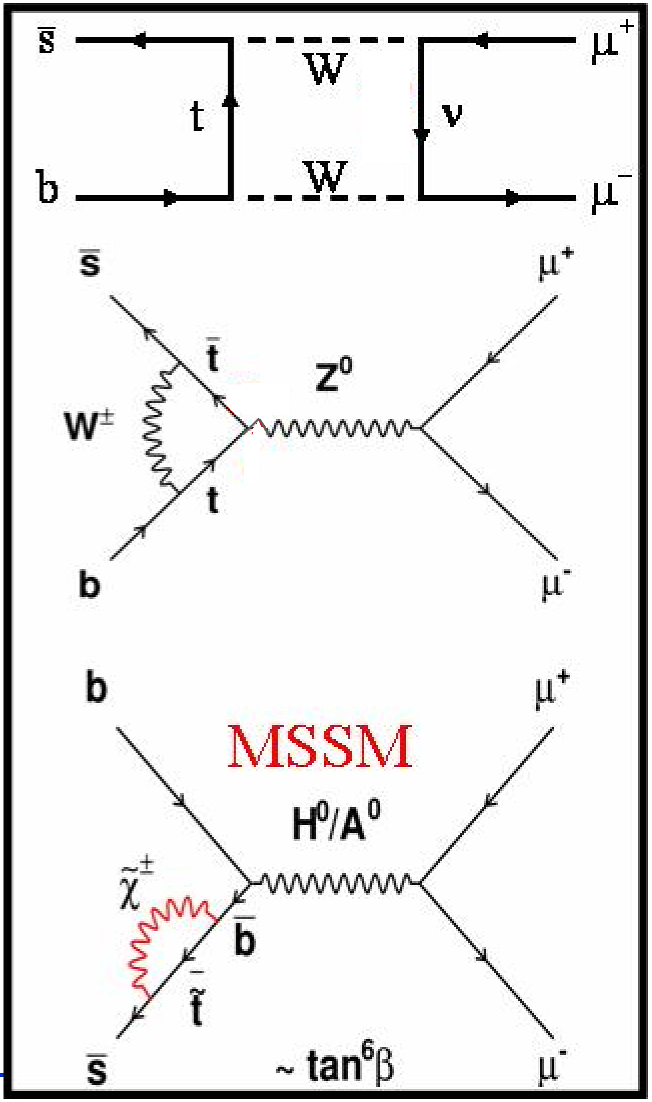
- Sensitivity (assume $\Delta\Gamma_S/\Gamma_S=0.12$)
- $\sigma(\sin 2\psi)=0.22$ 2fb^{-1}
- $\sigma(\sin 2\psi)=0.10$ 10fb^{-1}
- $\sigma(\sin 2\psi)=0.02$ 100fb^{-1}



$B_s \rightarrow \mu^+\mu^-$ & Supersymmetry

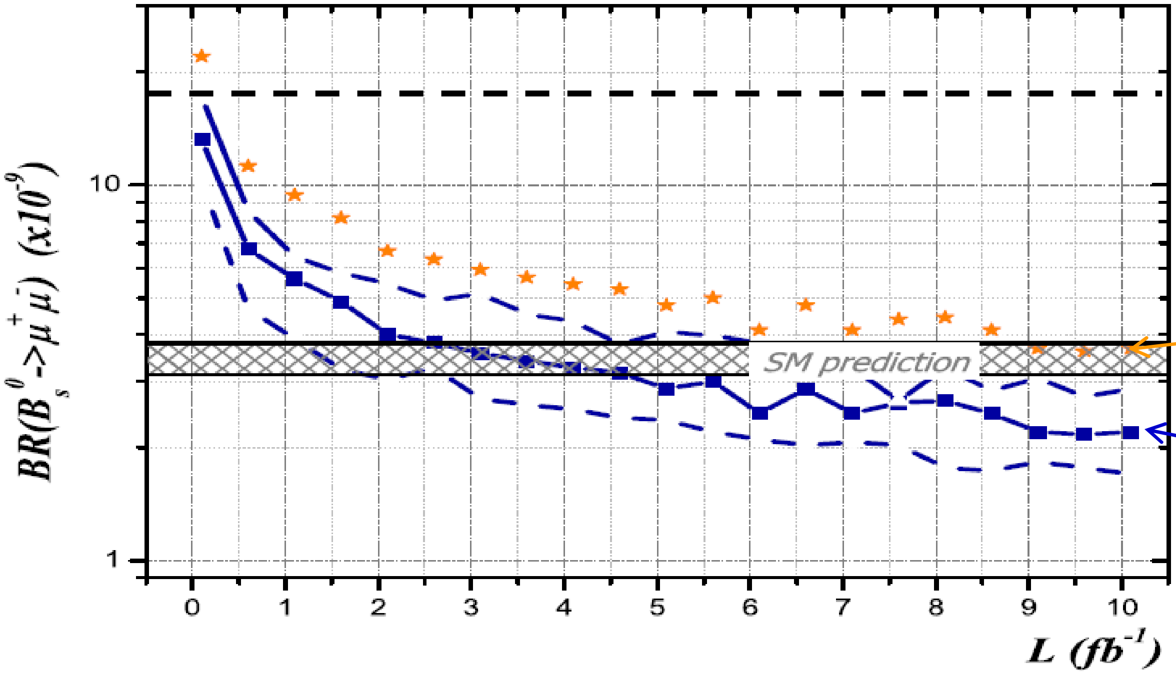
- Branching Ratio very sensitive to SUSY
- In MSSM goes as $\tan^6\beta$





$B_s \to \mu^+\mu^-$

- With 10 fb^{-1} barely able to make significant SM level measurement
- Precision measurement requires 100 fb^{-1}



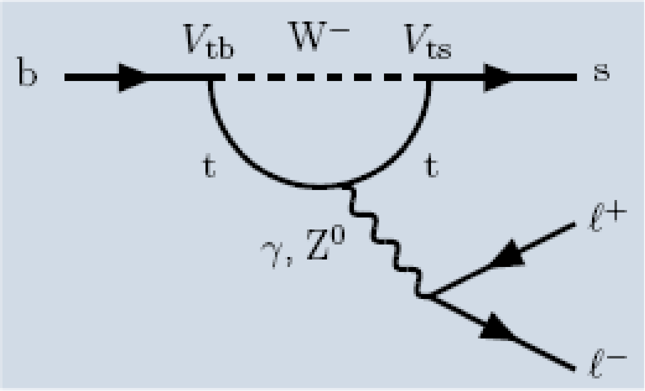
CDF+D0 expected 9 fb^{-1}

5σ measurement

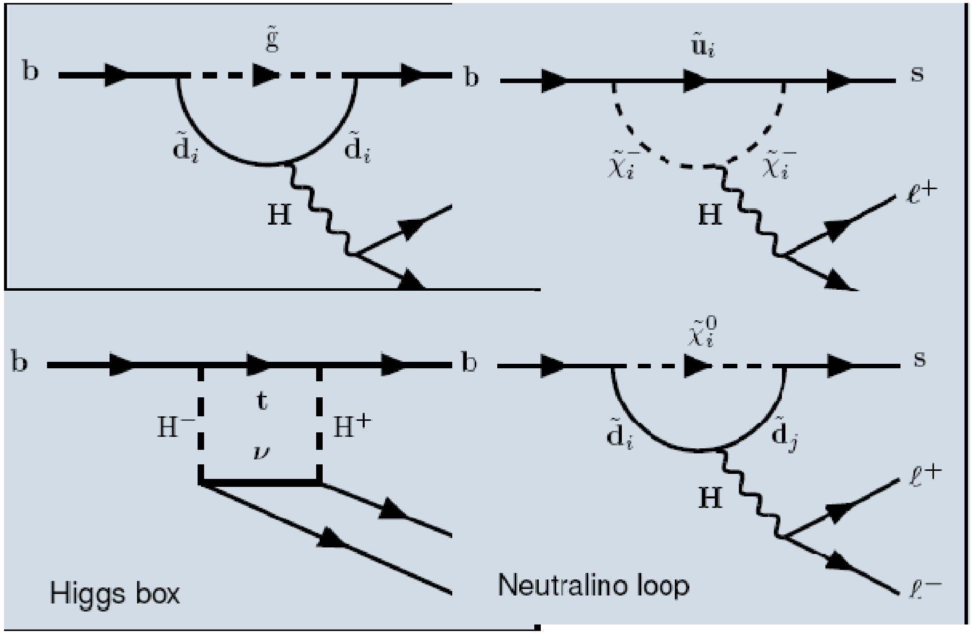
3σ measurement

$B \rightarrow K^{*}\mu^{+}\mu^{-}$

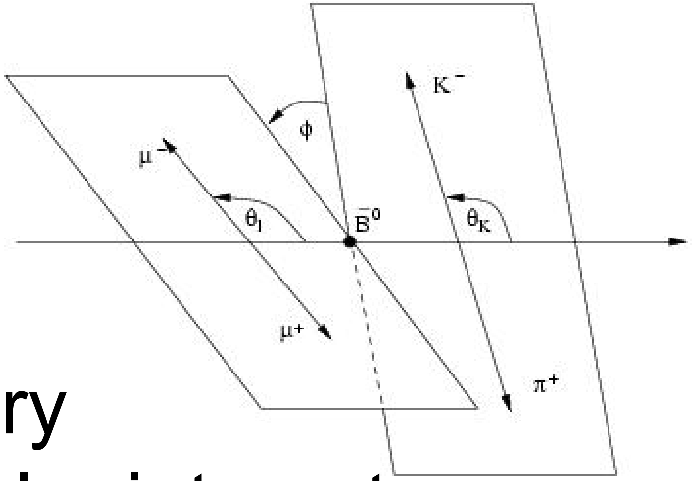
- Standard Model:



- Supersymmetry:



$B \rightarrow K^{*}\mu\mu$



- Described by three angles (θ_l, ϕ, θ_K) and di-μ invariant mass q^2
- Forward-backward asymmetry A_{FB} of θ_l distribution of particular interest:
  - Varies between different NP models →
  - At $A_{FB} = 0$, the dominant theoretical uncertainty.from $B_d \rightarrow K^*$ form-factors cancels at LO

$$A_{FB}\left(q^2\right) = \frac{N_F - N_B}{N_F + N_B}$$

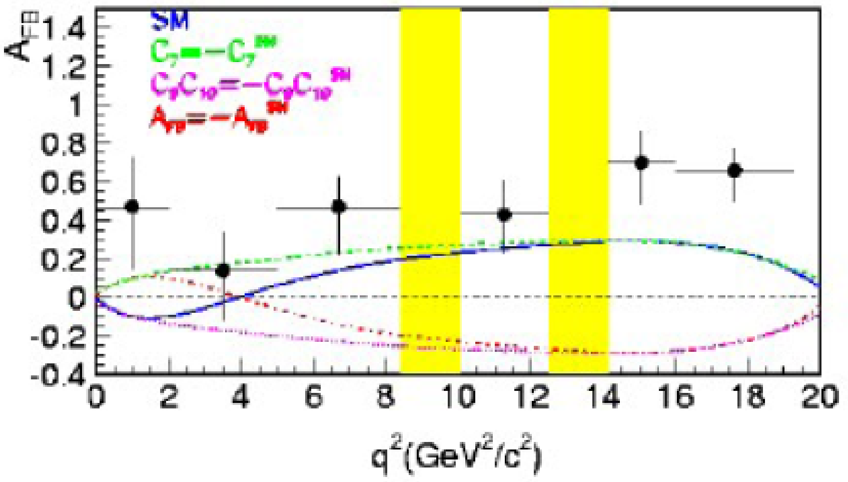
$B\rightarrow K^*\mu^+\mu^-$

- State-of-the art is recent 625 fb^{-1} Belle analysis ~ 250 K*$\ell\ell$ arXiv:0904.07701
- CDF have ~20 events

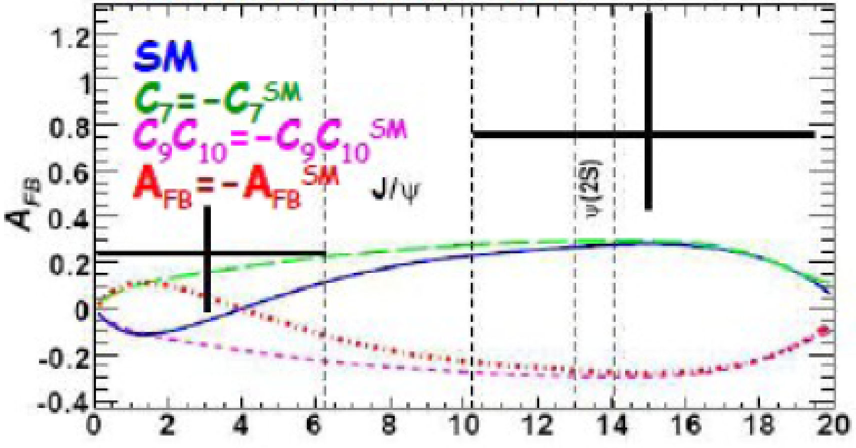
in 1 fb^{-1} arXiv:0804.3908

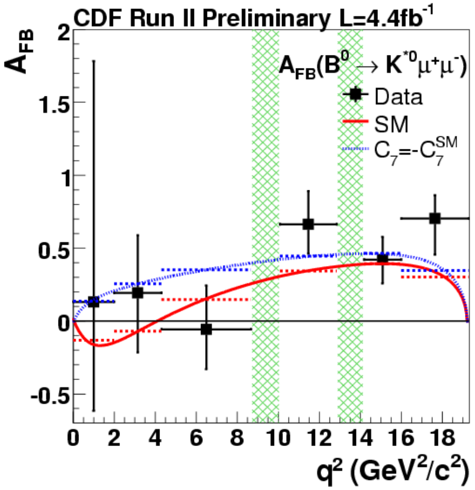
- LHCb expects ~360 in 300 pb^{-1}(with $\mu^+\mu^-$ only)

Belle (ICHEP '08)



BaBar (ICHEP '08)





Other Angular Variables in $K^*\mu^+\mu^-$

- Supersymmetry (Egede, et al... arXiv:0807.2589)
- Use functions of the transverse polarization

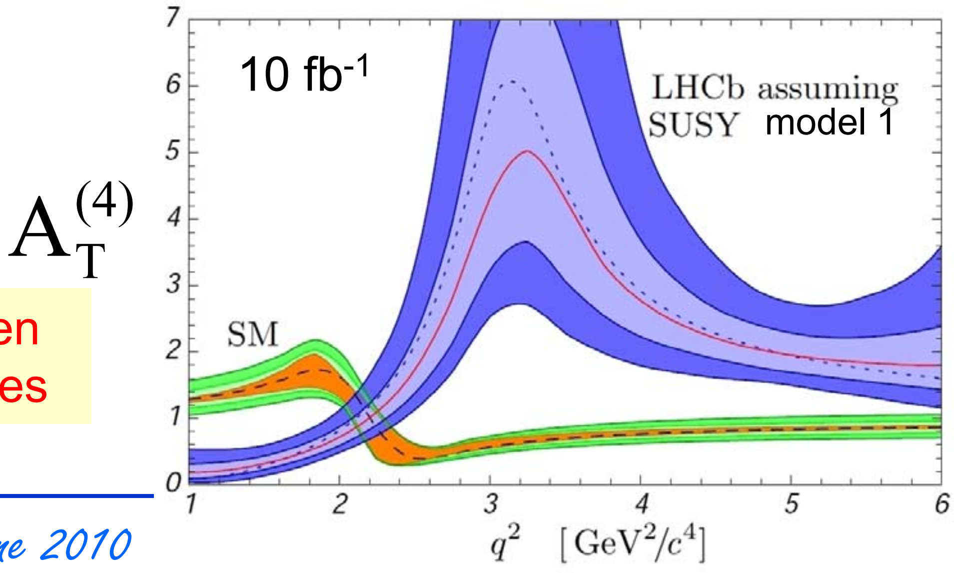
$$A_{\perp L,R} = \sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{(\mathrm{eff})} \mp \mathcal{C}_{10}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{(\mathrm{eff})} + \mathcal{C}_7^{\prime(\mathrm{eff})}) \right] \xi_\perp(E_{K^*}),$$

$$A_{\parallel L,R} = -\sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{(\mathrm{eff})} \mp \mathcal{C}_{10}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{(\mathrm{eff})} - \mathcal{C}_7^{\prime(\mathrm{eff})}) \right] \xi_\perp(E_{K^*}),$$

ξ_i are form factors

$$A_{0L,R} = -\frac{N m_B}{2\hat{m}_{K^*}\sqrt{\hat{s}}} (1-\hat{s})^2 \left[(\mathcal{C}_9^{(\mathrm{eff})} \mp \mathcal{C}_{10}) + 2\hat{m}_b (\mathcal{C}_7^{(\mathrm{eff})} - \mathcal{C}_7^{\prime(\mathrm{eff})}) \right] \xi_\parallel(E_{K^*}),$$

$$A_T^{(4)} = \frac{|A_{0L}A_{\perp L}^* - A_{0R}^* A_{\perp R}|}{|A_{0L}^* A_{\parallel L} + A_{0R} A_{\parallel R}^*|},$$



With more ∫L can distinguish between different SUSY models in some cases

What Can LHCb do on a_{sl}?

- Recall

$$a_{sl} = \frac{\Gamma\left(\overline{B} \to f\right) - \Gamma\left(B \to \overline{f}\right)}{\Gamma\left(\overline{B} \to f\right) + \Gamma\left(B \to \overline{f}\right)}$$

- D0 measurement used dimuons, but this is a difficult measurement sensitive to the sum $a_{sl}(s)+a_{sl}(d)$. It is very sensitive to muon fakes since K^+ and K^- have very different fake rates due to different interaction cross-sections & the detector has a significant amount of material

LHCb a_{sl} II

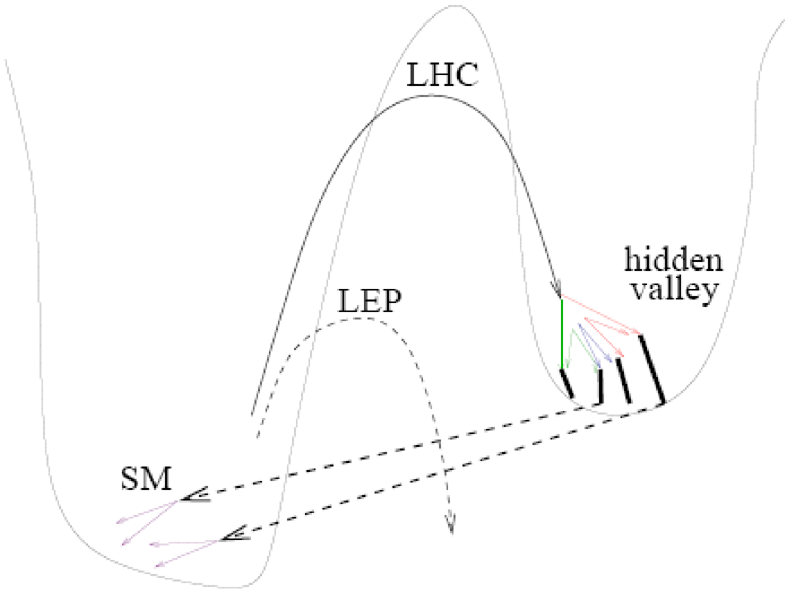
- Easiest to measure the difference between $a_{sl}(s)$-$a_{sl}(d)$
- Consider $B_s \rightarrow D_s^- \mu^+ \nu$ & $B_d \rightarrow D^- \mu^+ \nu$ with both D_s & $D^- \rightarrow \phi\pi^-$. Look for difference here between B_s-B^o & B_s-B^o, the asymmetry between $D_s^+\mu^-\nu$–$D^+\mu^-\nu$ & $D_s^-\mu^+\nu$–$D^-\mu^+\nu$. (Can use other decays.)
- Since B-factories have limits on $a_{sl}(d)$, this method can confirm or deny D0 result.
- Must worry about B production asymmetries

Exotic Searches

- LHCb complements the ATLAS/CMS solid angle by concentrating at large η and low p_t
- Sensitive to "Exotic" particles decaying into lepton or quark jets, especially with lifetimes in the range of $500>\tau>1$ ps.
- We will show one example, that of "Hidden Valley" Higgs decay

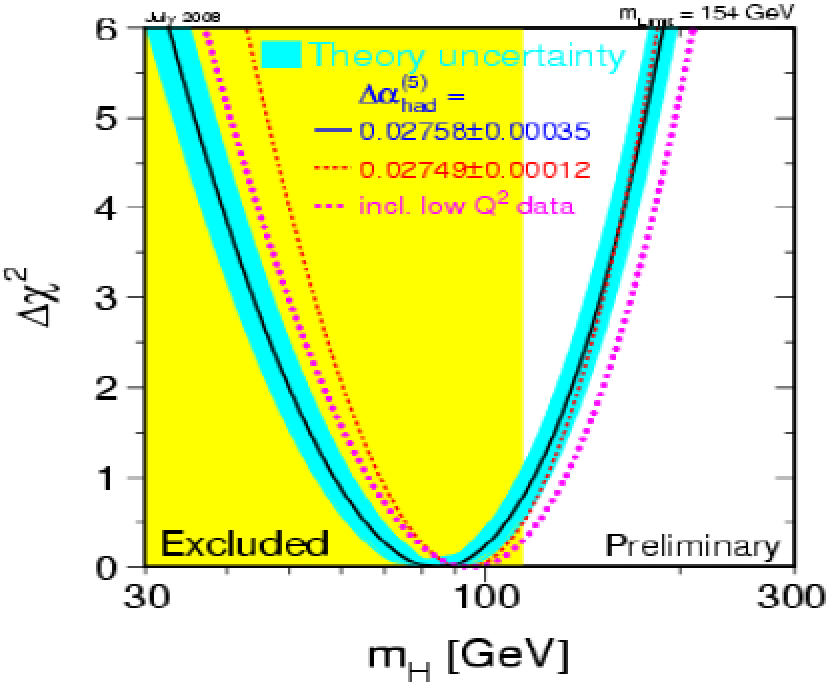
Search for Hidden Valleys

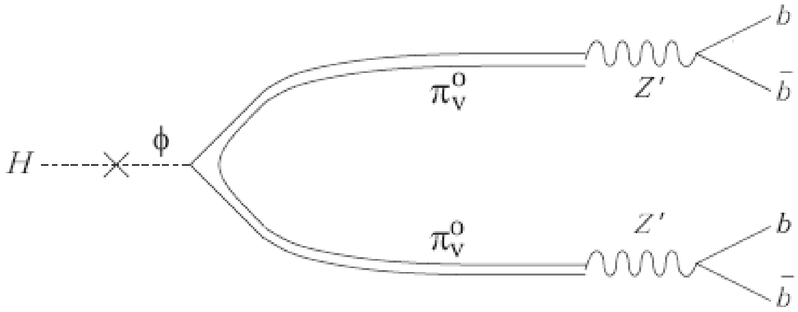
- New heavy Gauge sectors can augment the Standard Model (SM) as well SUSY etc..
- These sectors arise naturally in String theory
- It takes Energy to excite them
- They couple to SM via Z′ or heavy particle loops
- From Strassler & Zurek [hep-ph/604261]



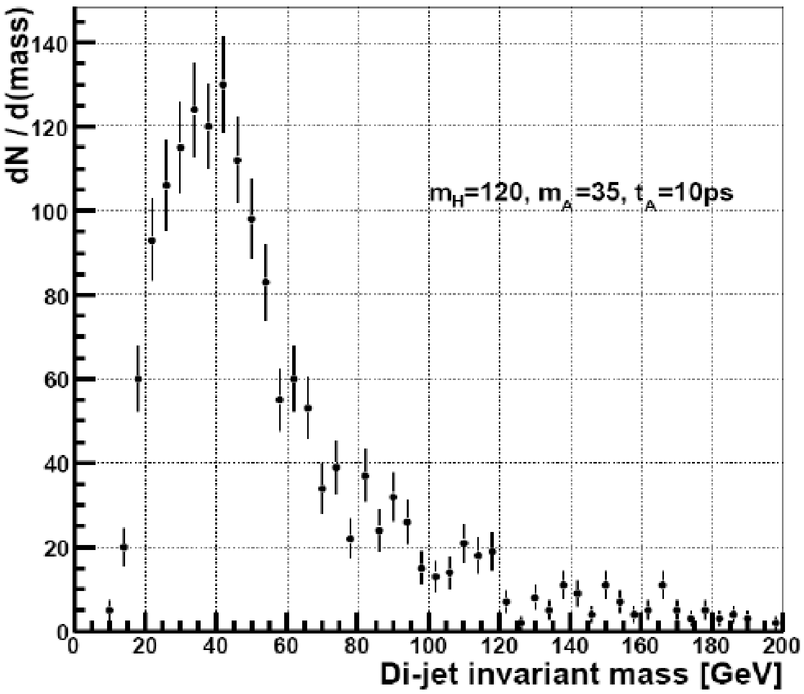
Search for Exotic Higgs Decays

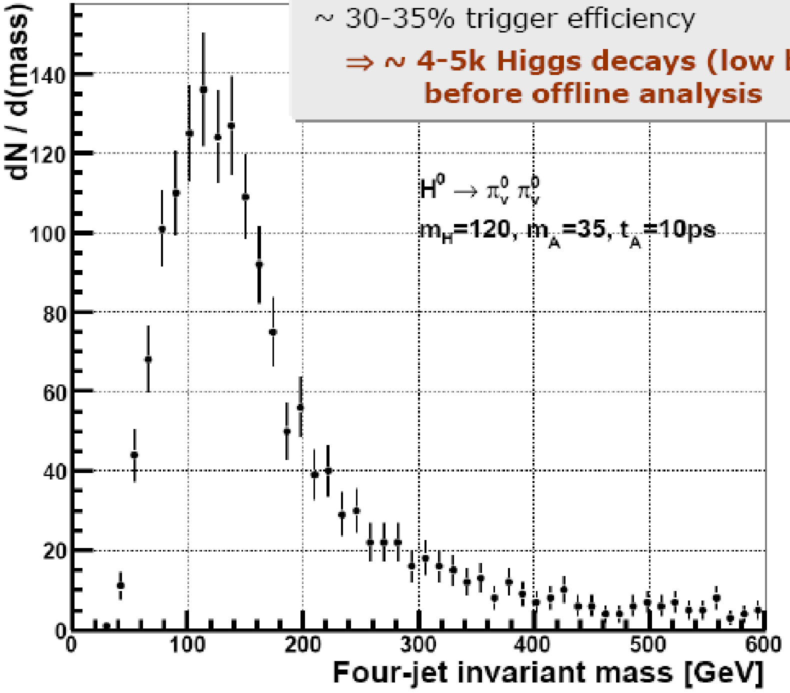
- Recall tension between predicted SM Higgs mass using Electroweak data & direct LEP limit
- Limit is based on SM decays, would be void if there were other modes
- Hidden Valley provides new scalars π^o_v, allowing $H^o \rightarrow \pi^o_v\ \pi^o_v \rightarrow b\bar{b}$, with long lifetimes possible.





Mass Resolutions





~ 14k Higgses in LHCb acceptance for 2fb^{-1}
~ 30-35% trigger efficiency
⇒ ~ 4-5k Higgs decays (low bckgrd) before offline analysis

- Expect a few thousand reconstructed decays in 2 fb^{-1}

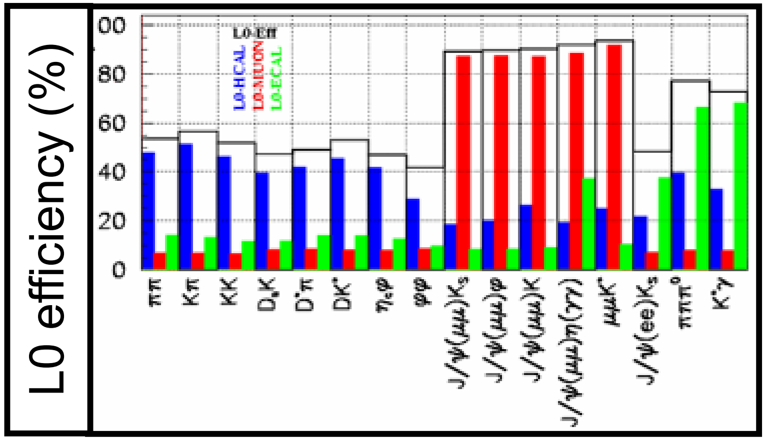
The LHCb Upgrade

How We Can Upgrade

- Run at higher luminosity
- Improve efficiencies
  - especially for hadron trigger
  - Photon detection
  - Tracking, e.g. reduce material
- Improve resolutions
  - Photon detector
  - RICH
- Basically build a better magnifying glass!
  - New VELO, etc…

Current Trigger Efficiency

- As usual define trigger ε= # events accepted by trigger / # of events found after all other analysis cuts



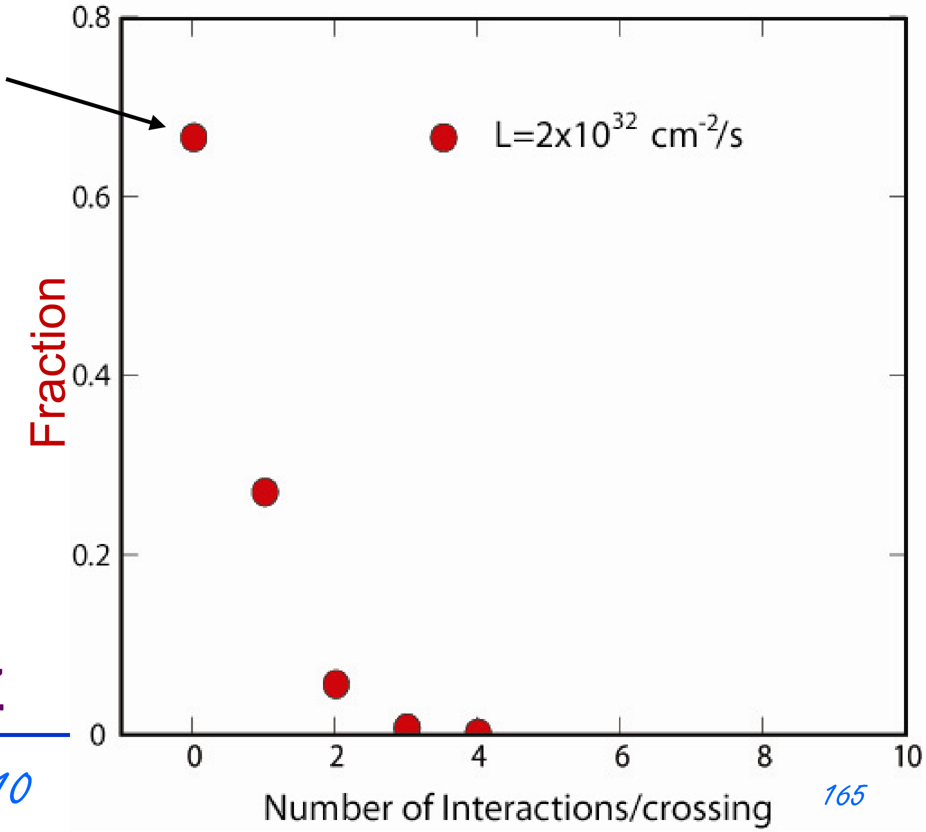
- L0 typically is 50% efficient on fully hadronic final states
- HLT1 is 60% on $D_S K^-$
- HLT2 is 85% on $D_S K^-$
- Product is 25%, room for improvement

Our Goal

- To collect signal at >10 times current rate, then we will possess the most powerful microscope known to man to probe certain physical processes
  - We will use specific channels and show rates can be increased, but the idea is to be able to increase data on a whole host of channels where new ones may become important
- We are taking into account possible changes due to the LHC schedule…

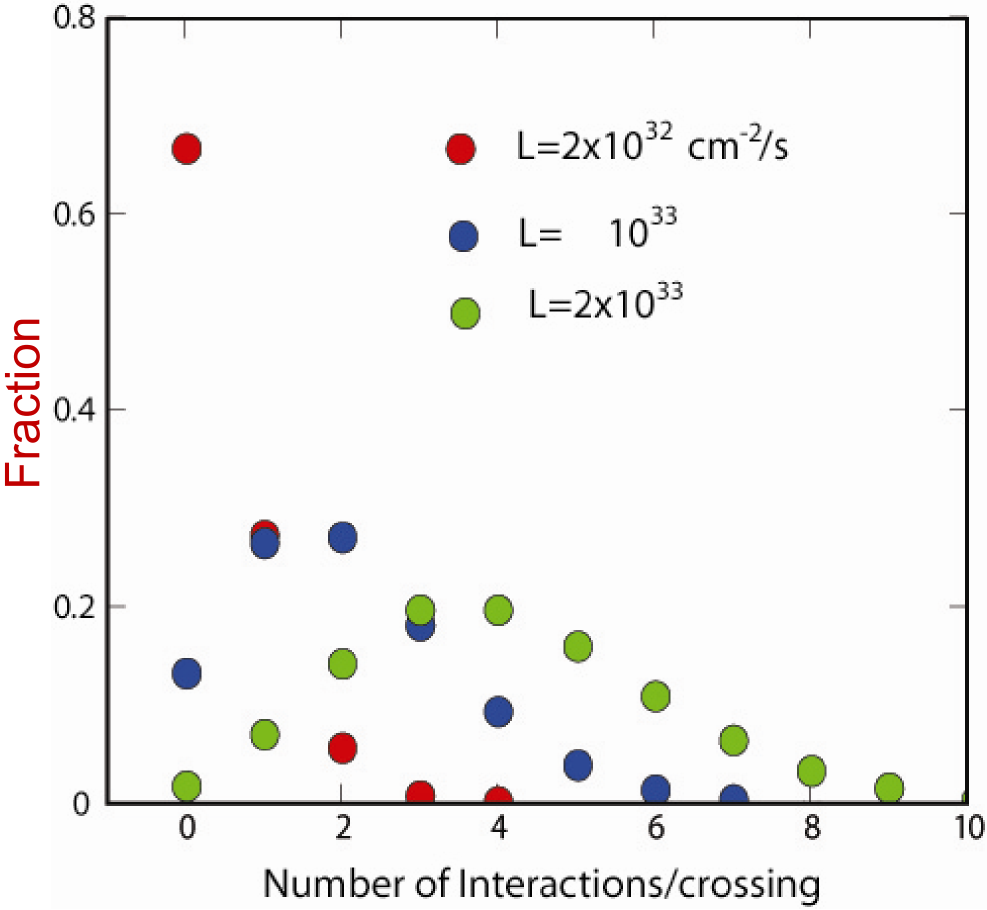
Current Running Conditions

- Luminosity 2×10^{32} cm^{-2}/s at beginning of run
- Take σ = 60 mb, [σ(total) - σ(elastic) - σ(diffractive)]
- Account for only 29.5 MHz of two filled bunches
- Most xings don't have an interaction
- Need 1st level trigger "L0" to reduce data by factor~30 to 1 MHz
- Higher Level Triggers reduce output to 2 kHz



Upgrade Running Conditions

- First step run to 10^{33} increases average # of int/crossing to only ~2.3
- Second step to $2\text{x}10^{33}$ increases to ~4.6
- Trigger change: will readout entire detector each crossing & use software to select up to 20 kHz of events



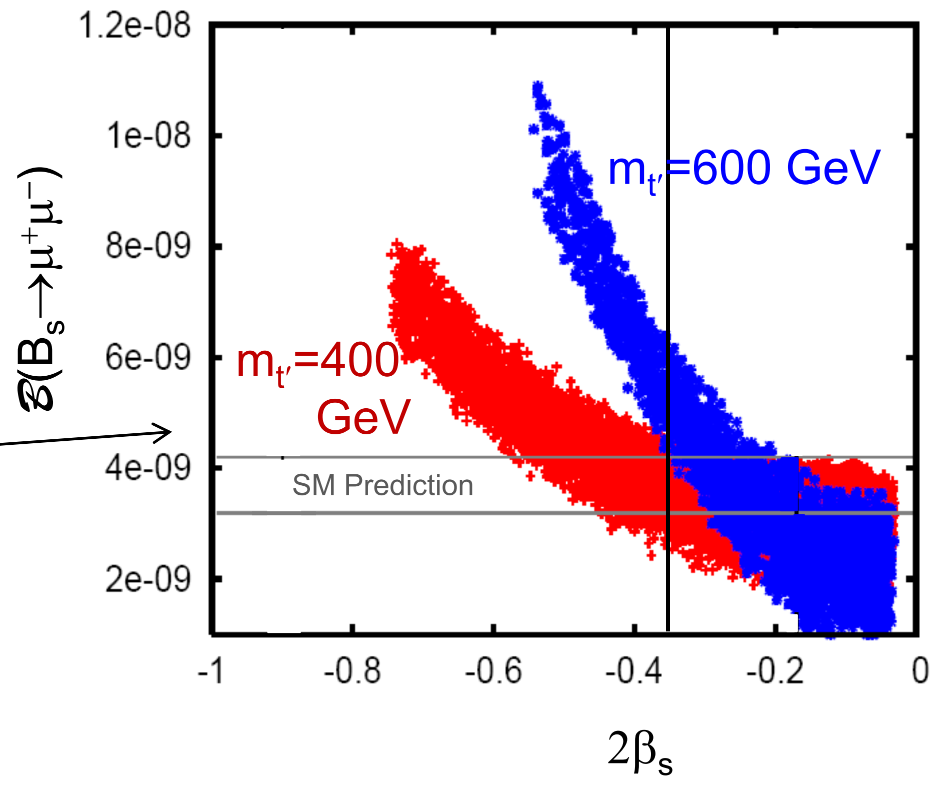
One Ex: LHCb Sensitivities for $2\beta_s$

	0.3 fb^{-1}	2.0 fb^{-1}	10 fb^{-1}	100 fb^{-1}
Error in $-2\beta_s$	±0.08	±0.03	±0.013	±0.004
#σ wrt SM value: -.0368	0.5	1.3	2.8	8.8

- With 100 fb^{-1} (LHCb upgrade) error in $-2\beta_S$ decreases to ±0.004 (only $\mathcal{L}$ improvement), useful to distinguish among Supersymmetry (or other) models (see Okada slide), where the differences are on the order of ~0.02

4th Generation Model

- New heavy t′ quark
- Changes many rates & CPV in many modes
- Ex.
- Soni et al arXiv:1002.0595
- Likely to need 100 fb^{-1} to distinguish among models



Conclusions

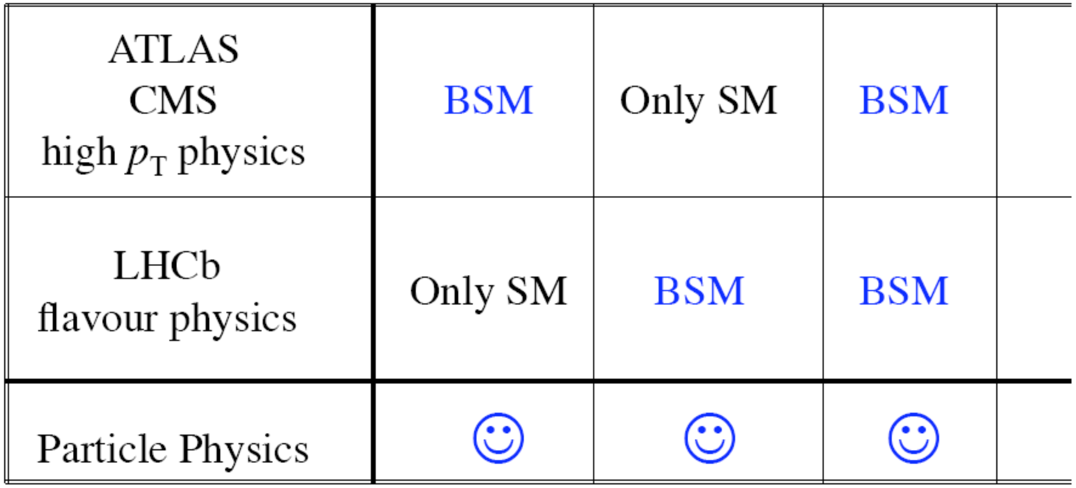
- We hope to see the effects of new particles observed by ATLAS & CMS in "flavor" variables in 10 fb^{-1}
- Upgrading will allow us to precisely measure these effects

Upgraded Sensitivities (100 fb^{-1})

Observable	Sensitivity
CPV($B_s \to \phi\phi$)	0.01-0.02
CPV($B_d \to \phi K_s$)	0.025-0.035
CPV($B_s \to J/\psi\phi$) ($2\beta_s$)	0.003
CPV($B_d \to J/\psi K_s$) (2β)	0.003-0.010
CPV($B \to DK$) (γ)	<1°
CPV($B_s \to D_s K$) (γ)	1-2°
$\mathcal{B}(B_s \to \mu^+\mu^-)$	5-10% of SM
$A_{FB}(B \to K^*\mu^+\mu^-)$	Zero to ±0.07 GeV^2
CPV($B_s \to \phi\gamma$)	0.016-0.025
Charm mixing x'^2	2×10^{-5}
Charm mixing y'	2.8×10^{-4}
Charm CP y_{CP}	1.5×10^{-4}

The Future

- Yogi Berra: “Its difficult to make predictions, especially about the future”
- Possibilities:



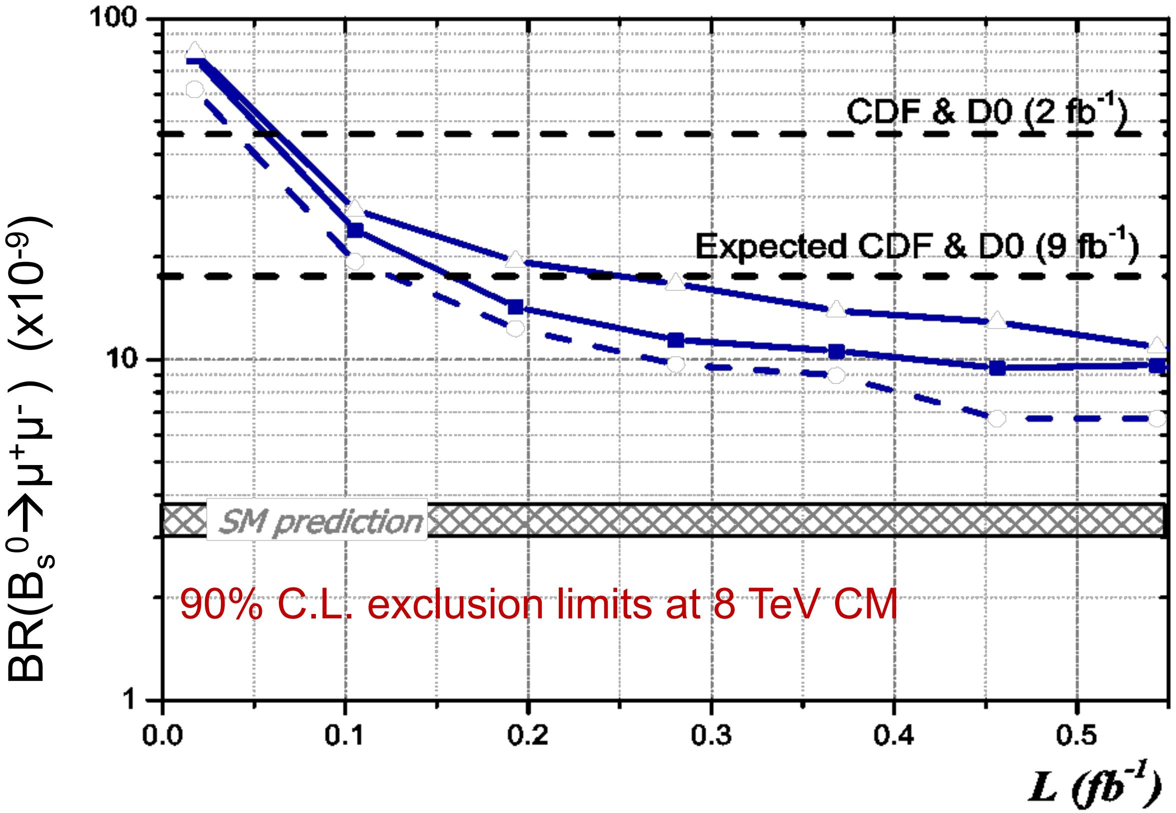
ATLAS CMS high p_T physics	BSM	Only SM	BSM
LHCb flavour physics	Only SM	BSM	BSM
Particle Physics	☺	☺	☺

- Fourth possibility too depressing to list, but LHCb measurements could set the scale of where we would have to go next

The End

LHCb Expectations 300 pb^{-1}

- Upper limit on $B_S \to \mu^+\mu^-$



Physics Case for Upgrades

- One view: Most major discoveries have been not "planned."

Grape Juice

Left undisturbed →

Left undisturbed →

Examples of Serendipitous Discoveries

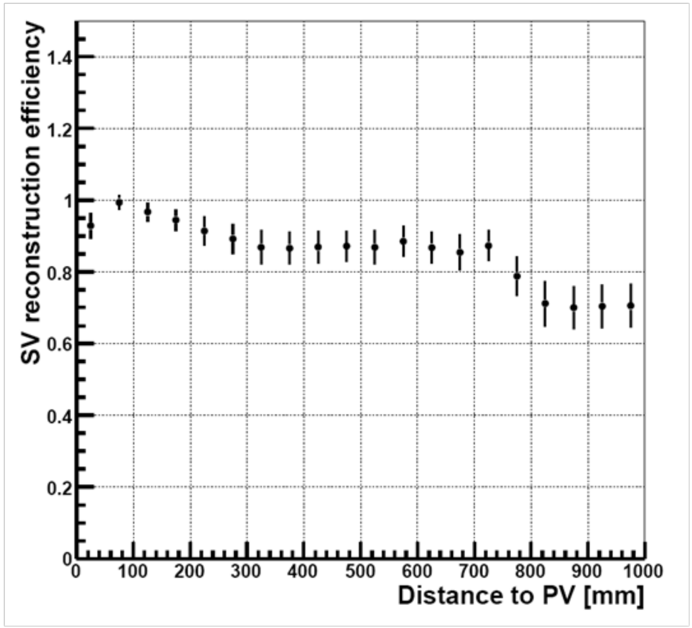
Device	User	date	Intended Use	Actual use
Optical Telescope	Galileo	1608	Navigation	Moons of Jupiter
Compound Microscope	Hooke	1650	Magnification	Bacteria, Cells…
Optical Telescope	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
Super Kamiokande	Koshiba	1996	Proton Decay	Neutrino oscillations
Spear, BNL	Richter, Ting	1974	Hadron production	J/ψ
Tevatron	CDF, D0	2007	Find Higgs Boson	B_S oscillations

Trigger Specifications

- Projected online farm is 16,000 cores. Original spec was 1 GHz, but now getting 2.8 GHz
- For 16,000 processors we have 25 ns *16,000 = 0.4 ms to make a decision (probably will have >10 GHz cores)
- We need a trigger strategy that executes in $\langle 0.4$ ms$\rangle$ that is maximally efficient on signal and reduces the background to an acceptable level
  - Minimum bias must be reduced from 100 MHz interaction rate to <10 kHz, reduction factor is 100,000 to get 1 kHz background rate (~same as now)
  - We specify ε_{trig}>50% on hadronic events, but aim higher

Complementarity with ATLAS/CMS

- We are sensitive for lifetimes shorter than a few hundred picoseconds



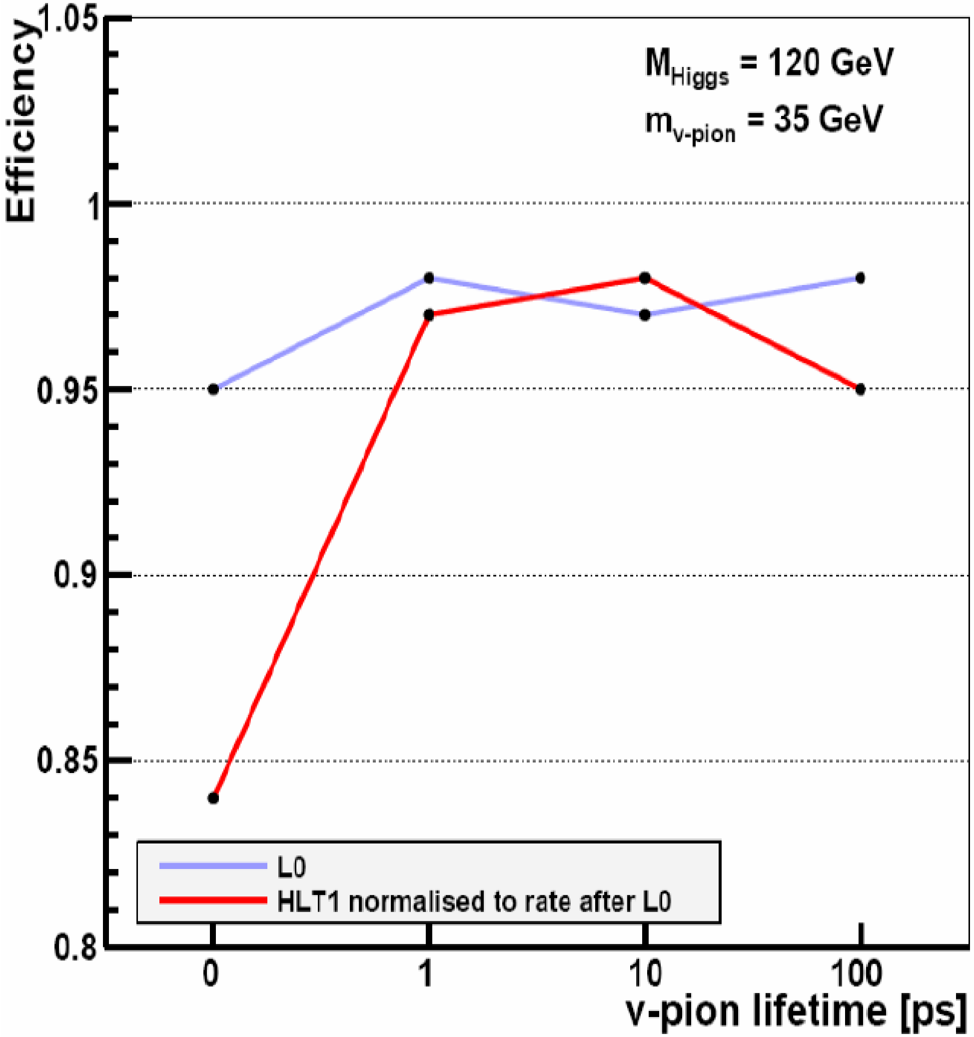
- ATLAS/CMS are designing triggers to see these decays if they occur in their calorimeters or muon system, sensitive to much longer lifetimes. See S. Giagu “Search for long-lived particles in ATLAS and CMS,“ arXiv:0810.1453v1 [hep-ex].

Higgs Studies

- Many different kinds of exotic decays possible, but we have studied only two so far
- We know H° production cross-section as function of H° mass, e.g. gg → H° is 30 pb for m(H)=120 GeV at 14 TeV
- We must show
    - Efficient triggering
    - Efficient b-jet and mass reconstruction
    - Sensitivity to short & long lifetimes of the π^o_v or other intermediate objects
    - Background rejection, e.g. 4b σ is 5.5 μb

Hardware & 1st Level Trigger

- L0 is hardware trigger, uses calorimeters & μ
- HLT1 is 1st level software
- Efficiencies are quite high, as expected



Higher Level Trigger

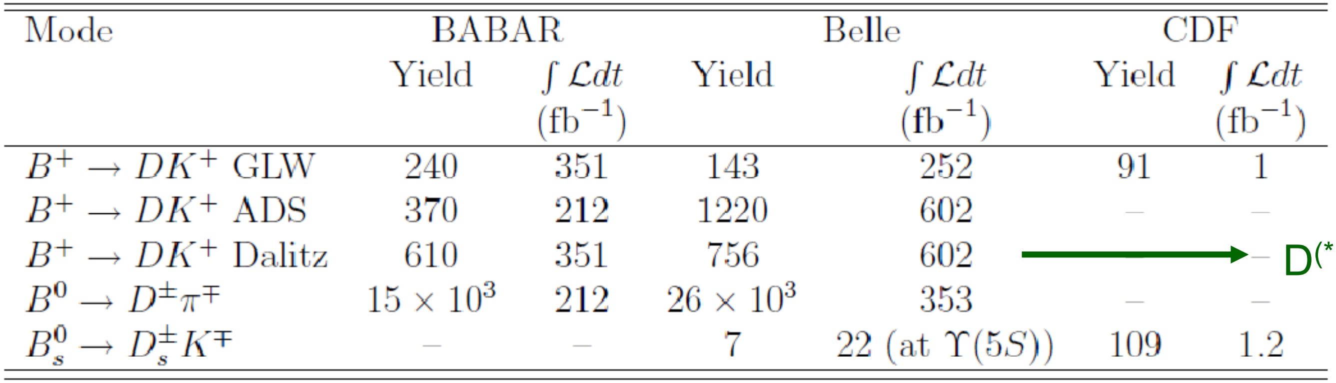
- More software cuts. Also high efficiency

t_v (ps)	ε_{GEOM} (%)	ε_{L0} (%)	ε_{Hlt1} (%)	ε_{Hlt2} (%)	ε_{TOT} (%)
0	14	95	84	7	0.8
1	14	98	97	29	3.9
10	14	97	98	37	4.9
100	15	98	95	30	3.9

- Also reduces 4b background to a negligible level, since the energies of the b's are much lower

γ from trees

Current experimental status in key channels:



Mode	BABAR		Belle		CDF	
	Yield	$\int \mathcal{L}dt$ (fb^{-1})	Yield	$\int \mathcal{L}dt$ (fb^{-1})	Yield	$\int \mathcal{L}dt$ (fb^{-1})
$B^+ \to DK^+$ GLW	240	351	143	252	91	1
$B^+ \to DK^+$ ADS	370	212	1220	602	–	–
$B^+ \to DK^+$ Dalitz	610	351	756	602		–
$B^0 \to D^\pm \pi^\mp$	15×10^3	212	26×10^3	353	–	–
$B_s^0 \to D_s^\pm K^\mp$	–	–	7	22 (at $\Upsilon(5S)$)	109	1.2

Totals

D(hh)K ~ 2k

$D^{(*)}(K_S hh)K^{(*)}$ ~ 2k

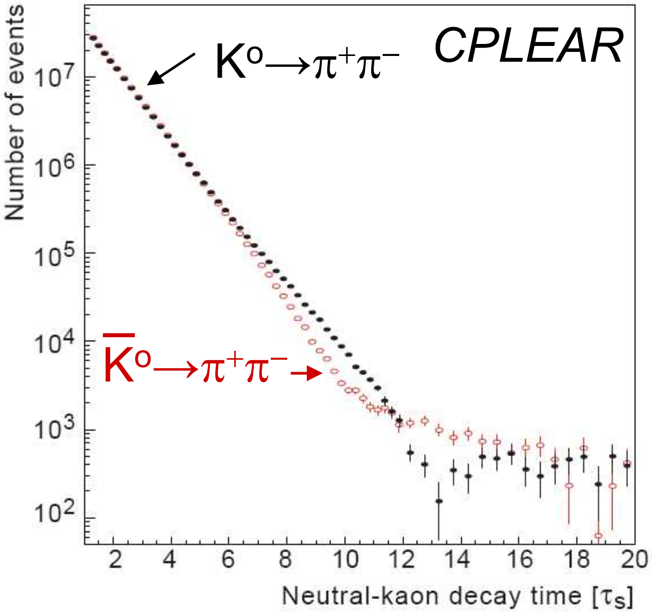
LHCb expectations with 100 pb^{-1}
(but including no HLT, and
assuming 14 TeV xsec)

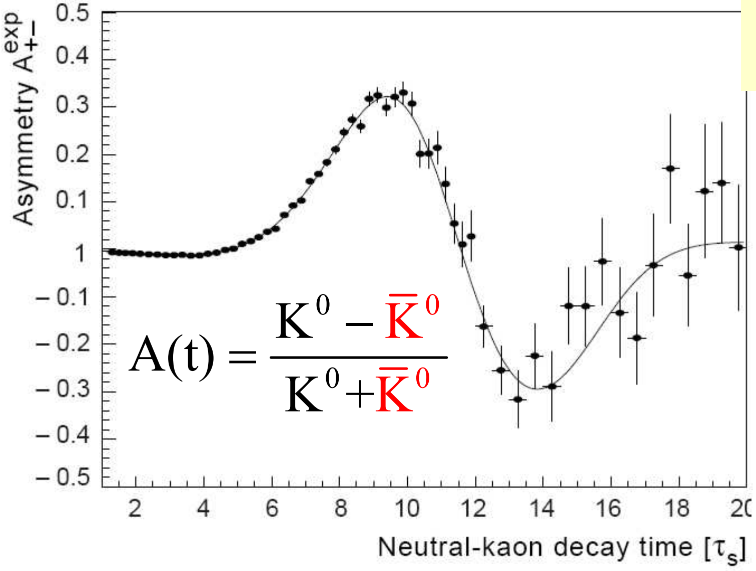
D(hh)K	4.8k
$D(K_S\pi\pi)K$	340
$D\pi$	80k
D_sK	450

The Enigma of Baryogenesis

- When the Universe began, the Big Bang, there was an equal amount of matter & antimatter
- Now we have most matter. How did it happen?
- Sakharov criteria
  - Baryon (B) number violation
  - Departure from thermal equilibrium
  - C & CP violation
    - C is charge conjugation invariance (particle – antiparticle)
    - P is mirror reflection $P[\psi(\mathbf{r})]=\pm\psi(-\mathbf{r})$
    - So one way of viewing CP violation is left-handed particles behave differently than right-handed anti-particles

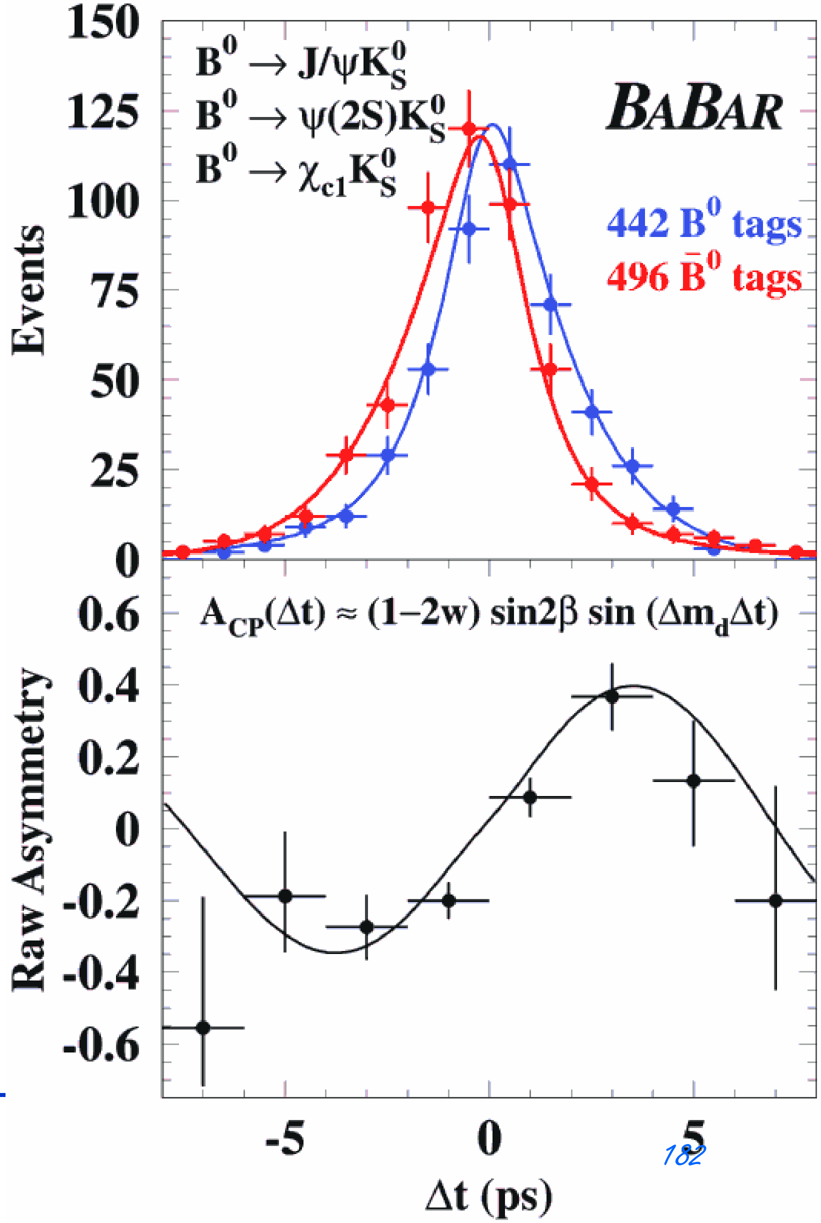
Physical Evidence for CP Violation





$$A(t) = \frac{K^0 - \bar{K}^0}{K^0 + \bar{K}^0}$$

For B's measure Δt between B^o & $\bar{B}^o$ decay in $e^+e^- \to B^o\bar{B}^o$



Sakharov Criteria All Satisfied

- B is violated in Electroweak theory at high temperature, B-L is conserved (need quantum tunneling, powerfully suppressed at low T)
- Non-thermal equilibrium is provided by electroweak phase transition
- C & CP are violated by weak interactions. However the violation is too small!
  - $(n_B - n_{\bar{B}})/n_\gamma = \sim 6\text{x}10^{-10}$, while SM can provide only $\sim 10^{-20}$
- Therefore, there **must** be new physics

Hierarchy Problem

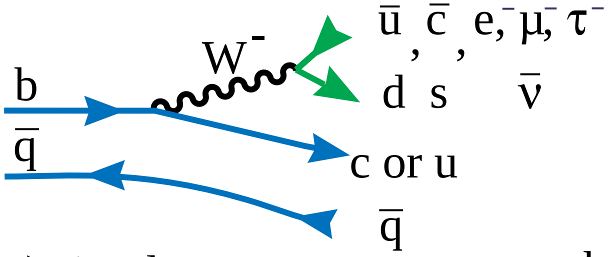
- We don't understand how we get from the Planck scale of Energy ~10^{19} GeV to the Electroweak Scale ~100 GeV without "fine tuning" quantum corrections

General Justification for Flavor Physics

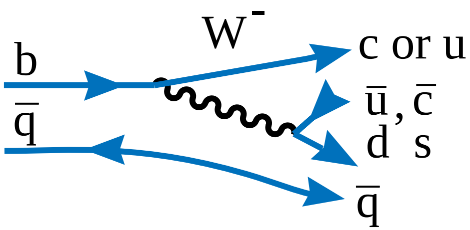
- Expect New Physics will be seen at LHC
  - Standard Model is violated by the Baryon Asymmetry of Universe & by Dark Matter
  - Hierarchy problem (why $M_{Higgs} << M_{Planck}$)
- However, it will be difficult to characterize this physics
- How the new particles interfere virtually in the decays of b's (& c's) with W's & Z's can tell us a great deal about their nature, especially their phases

B Decay Diagrams

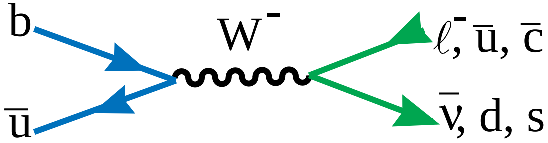
- a) is largest "tree" level diagram
- e) & f) contain "loops," other intermediate particles could contribute



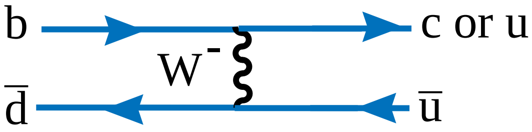
a) simple spectator



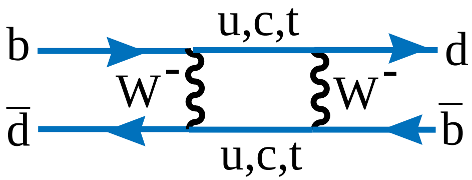
b) hadronic: color suppressed



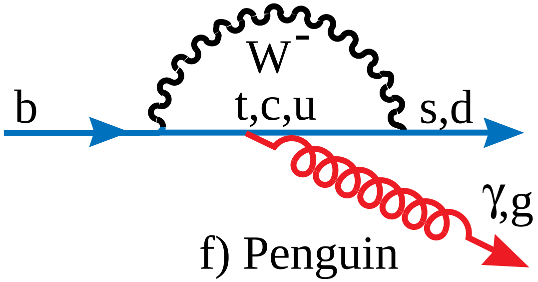
c) annihilation



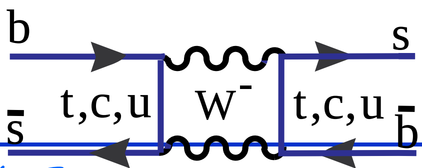
d) W exchange

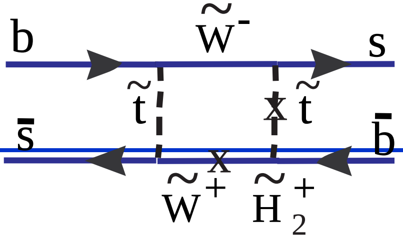


e) box: mixing



f) Penguin





Flavor in the Standard Model

Conclusions

- While much has been learned about flavor in the last decades, even more questions have been raised including:
  - Why 3 families?
  - What is the relationship between quark mixing & neutrino mixing
  - Why haven't we seen the affects of new heavy particles?
- Flavor decays are an essential way of establishing the identities of anything new that is found
- Congratulations to Kobayashi & Maskawa for their Noble Prize!

The Standard Model

- Theoretical Background
  - Physical States in the Standard Model

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L ,\ldots\ldots u_R, d_R, c_R, s_R, t_R, b_R$$

  - The gauge bosons: $W^{\pm}$, γ & Z^o and the Higgs H^o
  - Lagrangian for charged current weak decays

$$L_{cc} = -\frac{g}{\sqrt{2}} J^{\mu}_{cc} W^{\dagger}_{\mu} + h.c.$$

  - Where

$$J^{\mu}_{cc} = \left(\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau\right)\gamma^{\mu} V_{MNS} \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} + \left(\bar{u}_L, \bar{c}_L, \bar{t}_L\right)\gamma^{\mu} V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

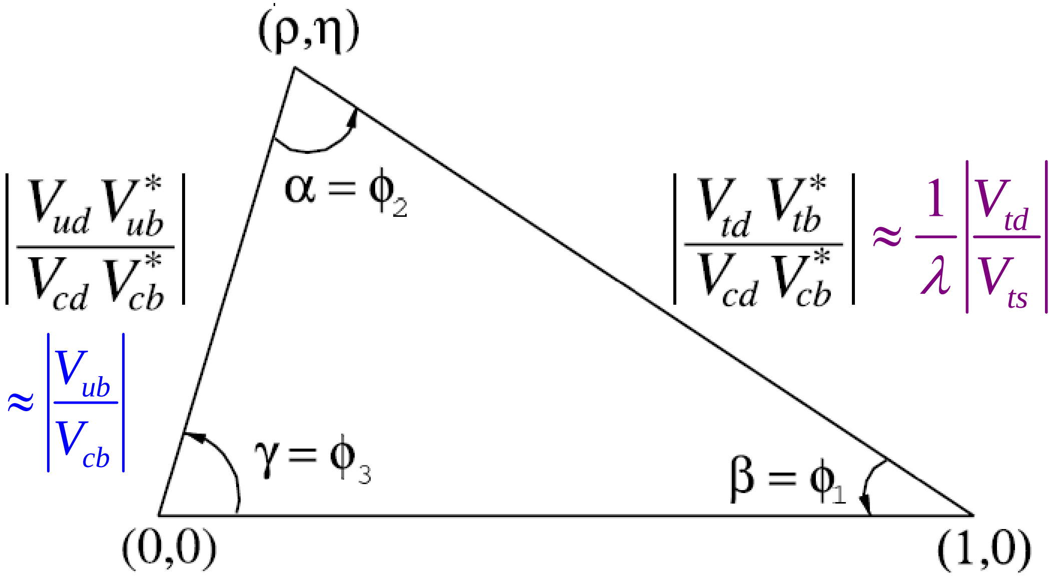
The CKM Matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Unitary with 9*2 numbers → 4 independent parameters
- Many ways to write down matrix in terms of these parameters

The Unitarity Triangle

- From unitarity: $V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$
- Divide by $V_{cd}V_{cb}^{*}$ to get a triangle in the complex plane whose base is 1

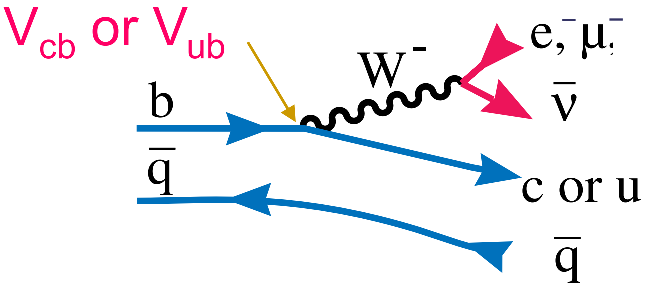


All side & ∠ measurements can be expressed as functions of ρ & η

The Role of QCD

- Interpreting fundamental quark decays requires theories or models than relate quarks to hadrons in which they live and die
- In some measurements the QCD effects cancel completely, in others QCD accounts for small corrections, and yet in others it is the dominant error
- Some experimental studies in b & c decays serve to check the theory

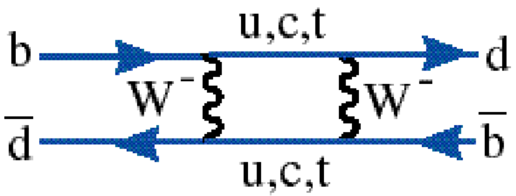
Existing Constraints on ρ & η



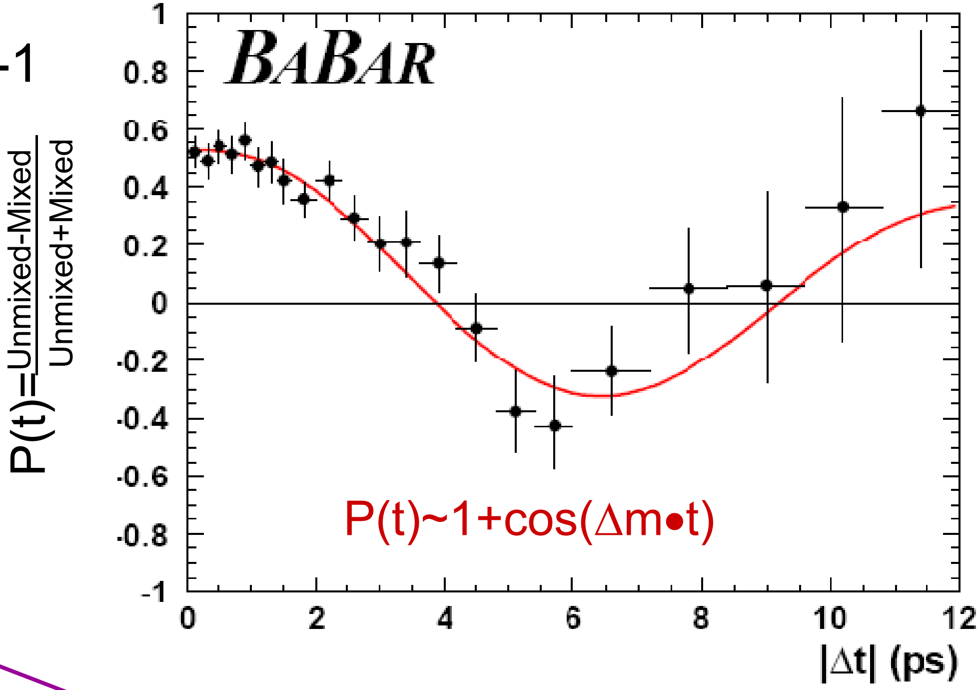
- Consider $V_{ub}/V_{cb} = \lambda(\rho+i\eta)$, we measure the ratio of rates $b\rightarrow u\ell\nu / b\rightarrow c\ell\nu \propto$ $|V_{ub}/V_{cb}|^2 = \lambda^2(\rho^2+\eta^2)$, a circle
  - Unfortunately, there are theoretical errors due to the fact that the b quark is paired with a light quark in the B meson, so error on $|V_{ub}/V_{cb}|$ is ~ 5-10% & is fiercely debated
- Another important ratio is $|V_{td}/V_{ts}|$ which is related to the ratio of the frequency of B^o/B_S mixing. *The dominant error here also is theoretical*

More on B⁰ Mixing

- B⁰ mixing measured by ARGUS in 1987



- Δm=0.507±0.004 ps^{-1} (current world avg)



What we are interested in

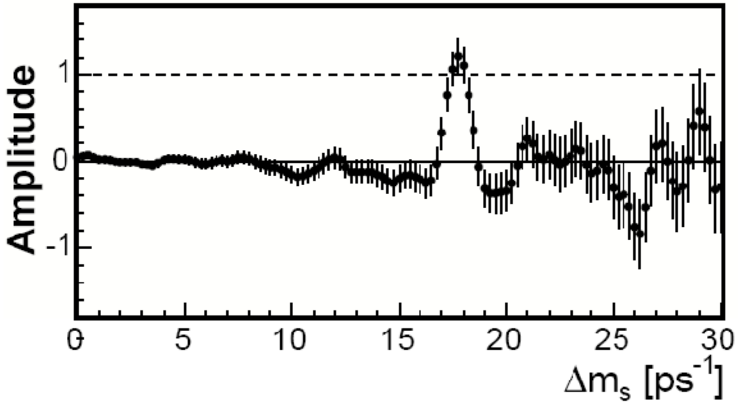
- $$x_d \equiv \frac{\Delta m}{\Gamma} = \frac{G_F^2}{6\pi^2} \boxed{B_{B_d} f_B^2} m_B \tau_B \boxed{|V_{tb}^* V_{td}|}^2 m_t^2 F\left(\frac{m_t^2}{M_W^2}\right) \eta_{QCD}$$

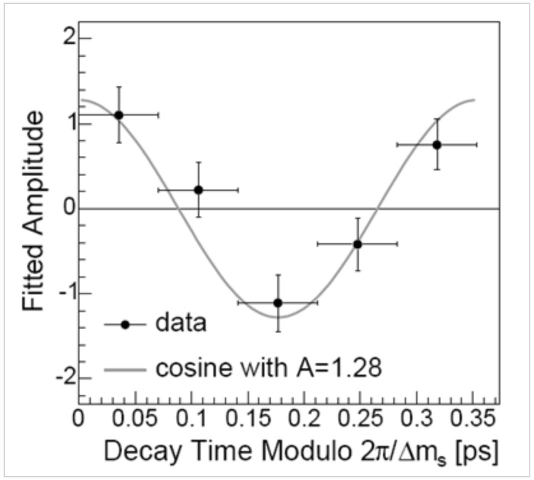
Theoretically determined parameters

More on B_s Mixing

- Measured by CDF in 2006

P(t)~1+cos($\Delta m_s \bullet t$). A=1 is signal, A=0 elsewhere





$$\Delta m_s = 17.31^{+0.33}_{-0.18} \pm 0.07 \text{ ps}^{-1}$$

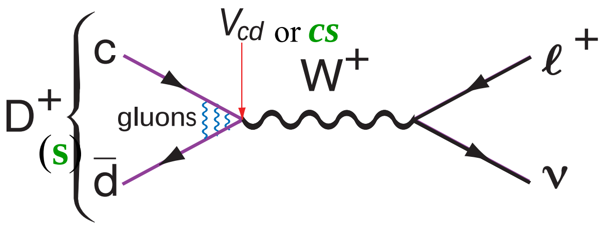
- Note

$$\lambda \frac{|V_{td}|}{|V_{ts}|} = (\rho-1)^2 + \eta^2 = \lambda \frac{B_B}{B_{B_s}} \frac{f_B^2}{f_{B_s}^2} \frac{m_B}{m_{B_s}} \frac{\tau_B}{\tau_{B_s}}$$

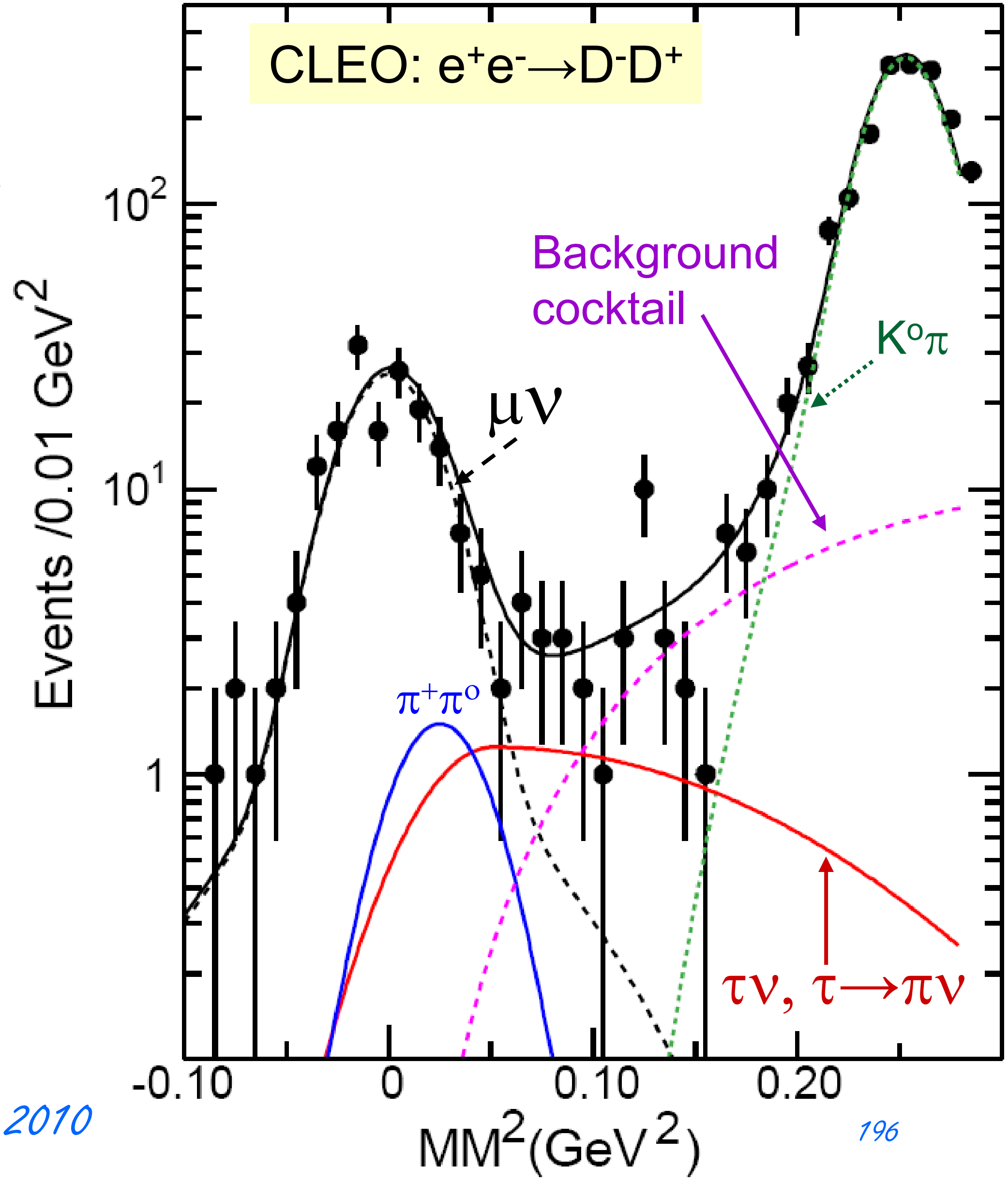
a circle in the ρ–η plane centered at (1,0)

Lattice QCD & Determination of f_B

- Cannot measure f_{B^o} & f_{Bs}
- We can measure f_{D^+} & f_{Ds}



- f_{D^+} CLEO results
  f_{D^+}=(205.8±8.5±2.5) MeV
- Calculation of Follana et al
  208±4 MeV
- Excellent agreement!

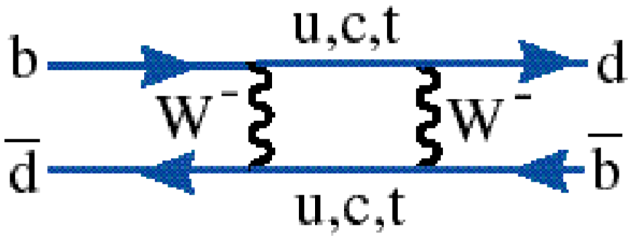


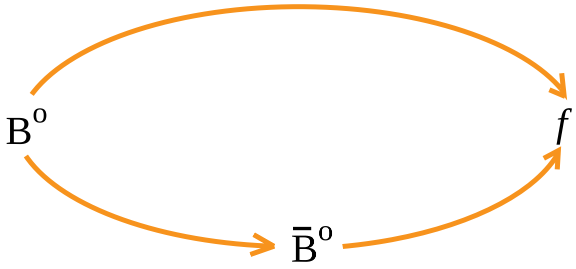
Problem with f_{Ds}?

- Weighted Average CLEO + Belle: f_{Ds}=270.4±7.3±3.7 MeV
- Follana et al: 241±3 Mev
- May be a problem here, but errors still large
- In any case take f_{Bs}=268±17±20 MeV & f_{Bs}/f_B=1.20±2±5 from average of several results (see Tantalo hep-ph/0703241)

Angles: Use ~~CP~~ in B^o Decays

- For CPV we interfere two decay amplitudes, one the direct decay and the decay via mixing. Consider what happens if $B^o \rightarrow f$ and $\overline{B}^o \rightarrow \overline{f}$, with $f = \overline{f}$





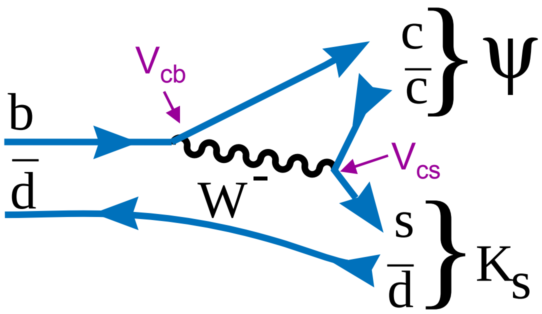
- The mixing amplitude for B_d generates an asymmetry ~sin(2β), where

  $\sin(2\beta) = -2(1-\rho)\eta/[(1-\rho)^2+\eta^2]$

  - Asymmetry means

$$a \equiv \frac{\Gamma(B^o \rightarrow f) - \Gamma(\overline{B}^o \rightarrow f)}{\Gamma(B^o \rightarrow f) + \Gamma(\overline{B}^o \rightarrow f)}$$

~~CP~~ in Decay



- Must also consider effect of CKM matrix elements in specific decay channel
- For $B^o \rightarrow J/\psi\ K_S$, this phase = 0, since the decay proceeds via V_{cb} & V_{cs}
- The result is $a_f(t) = -\sin(2\beta)\sin(\Delta m t)$

What we don't know about Flavor

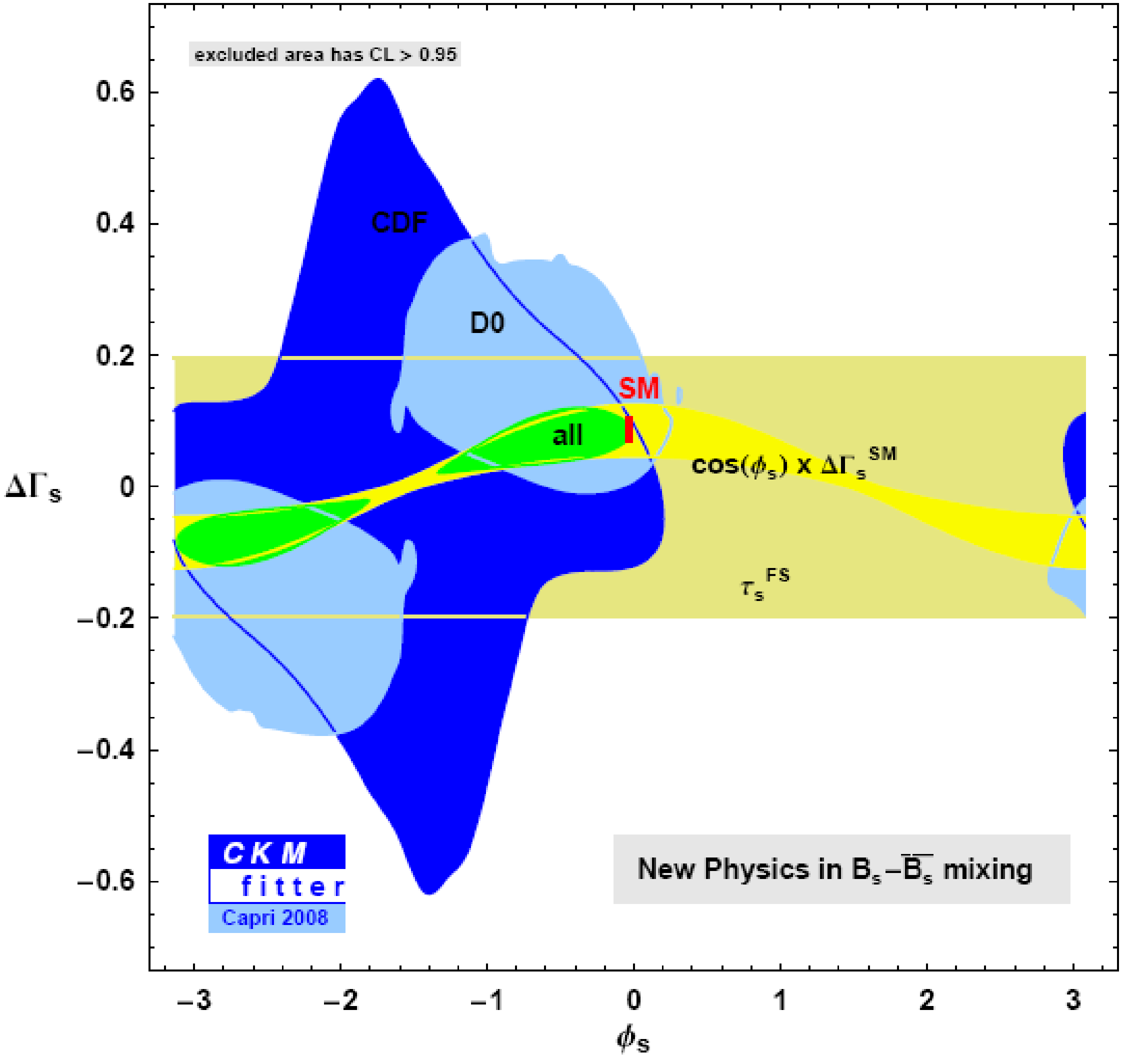
Flavor as tool for understanding NP

Future Experiments

B Experiments

- Recently Completed
  - CLEO
  - BABAR
  - BELLE
- Ongoing
  - CDF (B_S)
  - D0 (B_S)
- New
  - LHCb (B_S)
  - BELLE Upgrade
- Proposed
  - Super B (at Frascati) & higher lumi Belle Upgrade
  - LHCb Upgrade (B_S)

Current Status



- Combined data are 2.4σ from SM prediction
- We shall see…
- From Jérôme Charles, Capri, June 2008
- Similar results from UTfit, Silverstrini

Physics Goals of B Decay Studies

- Discover, or help interpret, New Physics found elsewhere - There is New Physics out there: Standard Model is violated by the Baryon Asymmetry of Universe & by Dark Matter
- Measure Standard Model parameters, the “fundamental constants” revealed to us by studying Weak interactions
- Understand QCD; necessary to interpret CKM measurements.

CP violation using CP eigenstates

- CP asymmetry $$a_f(t) = \frac{\Gamma\left(B^o(t) \to f\right) - \Gamma\left(\bar{B}^o(t) \to f\right)}{\Gamma\left(B^o(t) \to f\right) + \Gamma\left(\bar{B}^o(t) \to f\right)}$$
- for q/p = 1 $$a_f(t) = \frac{\left(1 - |\lambda|^2\right)\cos(\Delta m t) - 2\,\mathrm{Im}\,\lambda \sin(\Delta m t)}{1 + |\lambda|^2}$$
- When there is only one decay amplitude, λ=1 then $$a_f(t) = -\mathrm{Im}\,\lambda \sin(\Delta m t)$$
- Time integrated

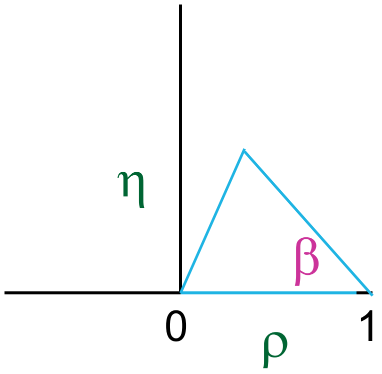
$$a_f(t) = -\frac{x}{1+x^2}\,\mathrm{Im}\,\lambda = -0.48\,\mathrm{Im}\,\lambda$$

good luck, maximum is –0.5

CP violation using CP eigenstates II

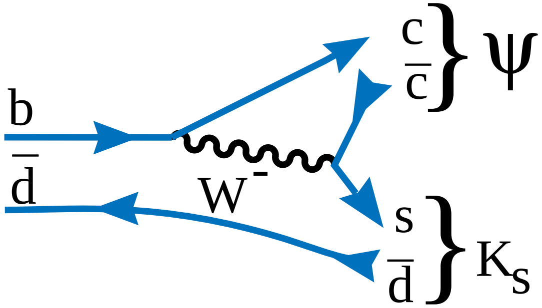
- For B_d, $$\frac{q}{p}=\frac{\left(V_{tb}^{*}V_{td}\right)^{2}}{\left|V_{tb}^{*}V_{td}\right|^{2}}=\frac{\left(1-\rho-i\eta\right)^{2}}{\left(1-\rho+i\eta\right)\left(1-\rho-i\eta\right)}=e^{-2i\beta}$$

$$\mathrm{Im}\left(\frac{p}{q}\right)=\frac{2(1-\rho)\eta}{\left(1-\rho\right)^{2}+\eta^{2}}=\sin(2\beta)$$

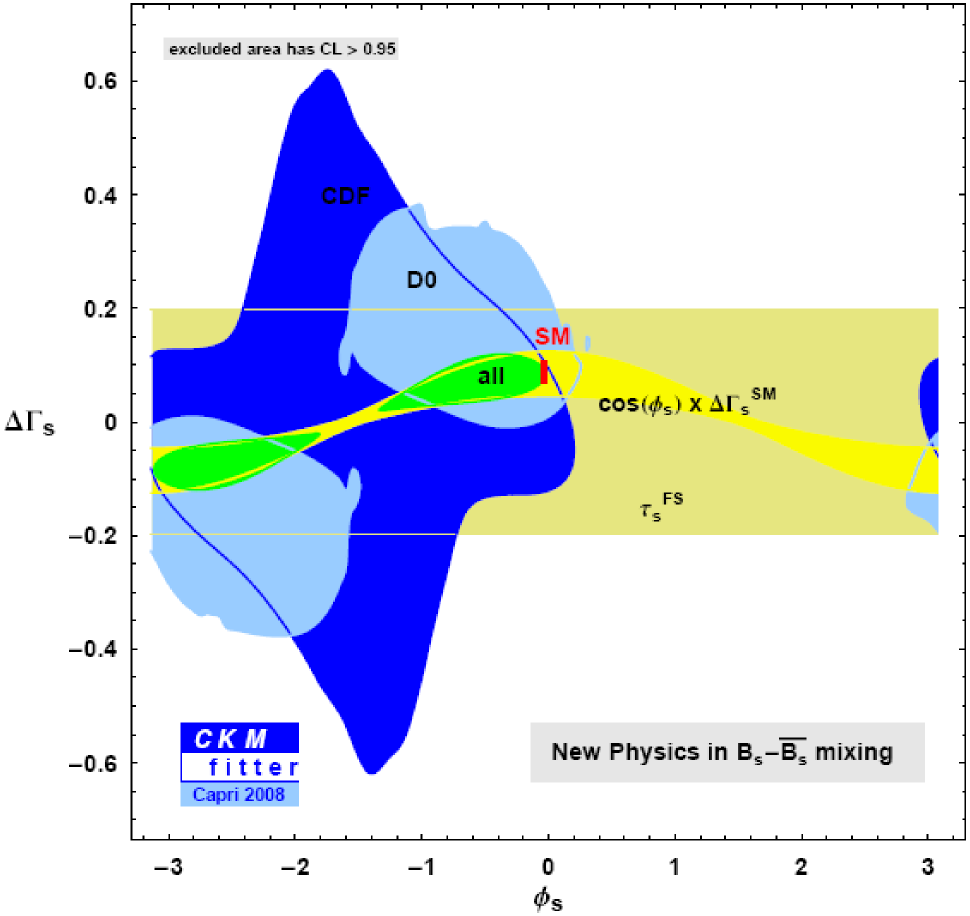


- Now need to add $\bar{A}/A$
  - for $J/\psi\ K_s$:

$$\frac{\bar{A}}{A}=\frac{\left(V_{cb}V_{cs}^{*}\right)^{2}}{\left|V_{cb}V_{cs}^{*}\right|^{2}}=1$$



CDF & D0 May See Something

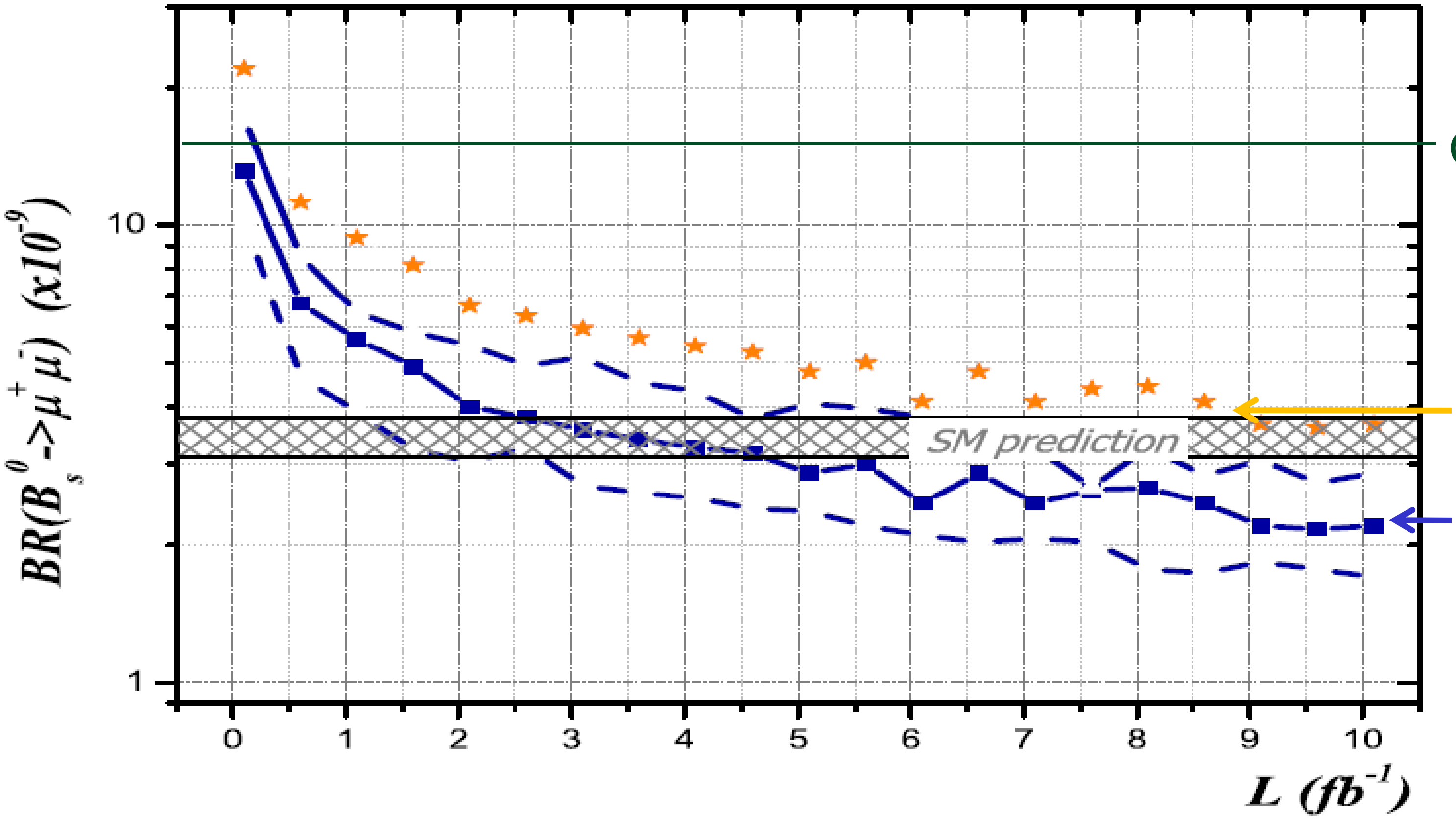


using all $(\phi_s, \Delta\Gamma_s)$ inputs, $\phi_s = -2\beta_s$ is excluded at 2.4σ, while the 2D hypothesis $\phi_s = -2\beta_s$, $\Delta\Gamma_s = \Delta\Gamma_s^{SM}$ is excluded at only 1.9σ (wrt to 1.4σ from FC treatment by CDF)

very transparent analysis: all theoretical uncertainties are contained in the SM prediction $\Delta\Gamma_s^{SM} = 0.090^{+0.017}_{-0.022}$ ps (red line)

- From Jérôme Charles, Capri, June 2008
- Similar results from UTfit, Silverstrini

LHCb Reach for $\mathcal{B}(B_s \to \mu^+\mu^-)$



Current CDF Limit

5σ discovery

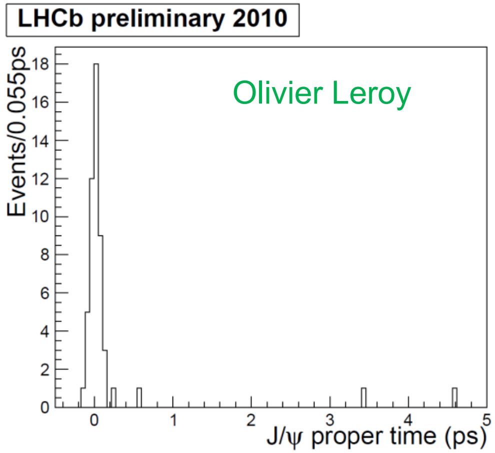
3σ observation, 90% probability Range from MC statistics

Observation by LHCb expected in 10 fb^{-1}, but 100 fb^{-1} needed for precise measurement

Info on B candidate

Leroy, Ruf et al.

- Studies of J/ψ vertices in sample showed that some not consistent with PV
- Example: plot of J/ψ pseudo proper-time showing suggestion of ~ 4 non-prompt candidates →
- This is about the fraction we would expect from MC (assuming the cross-sections in the MC)



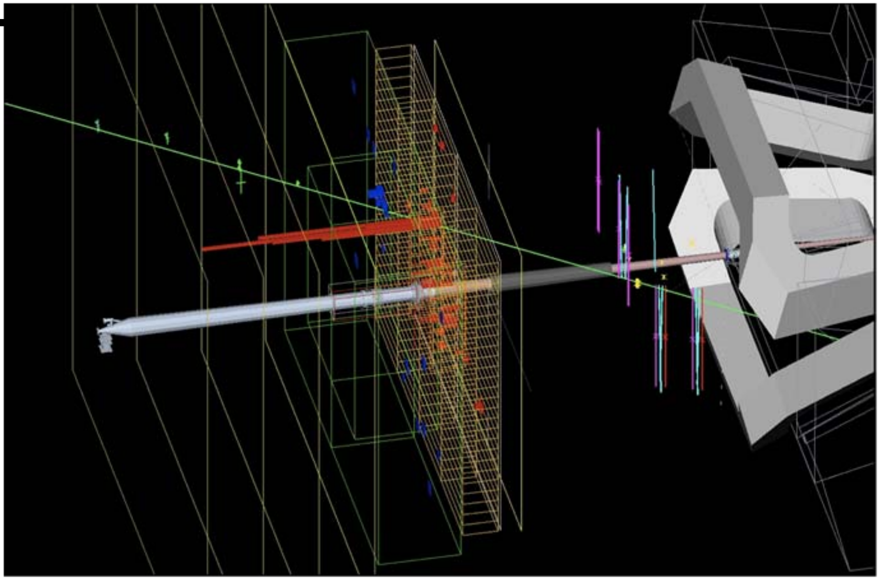
- Displaced candidates have been scanned in Panoramix, to check in particular whether vertex looks truly displaced, or whether it is in an unreconstructed PV
- One event is of particular interest: 69618 12484. The J/ψ vertex has another track well associated with it which is identified by the RICH as a good kaon candidate. The invariant mass of the vertex is 5315 MeV, which would be within 2 sigma of the B mass assuming the resolution in the MC. The kinematics and topology of the event look 'normal'. It passes the established B→J/ψK selection.
- With the MC cross-sections, we would expect ~0.15 B→J/ψK events.
- More details on: http://lhcb-reconstruction.web.cern.ch/lhcb-reconstruction/Panoramix/PRplots/2010/bees/

Okada Models Summary

Possible deviations from the SM prediction

	B_d - unitarity Triangle test	T-dep CPV in $B \to \phi K_s$, $B \to K^* \gamma$	$b \to s\gamma$ direct CP	T-dep CPV in $B_s \to J/\psi \phi$	LFV
mSUGRA	-	-	-	-	-
SU(5)SUSY GUT + ν_R (degenerate)	—	—	—	—	$\mu \to e\gamma$
SU(5)SUSY GUT + ν_R (non-degenerate)	—	<~0.05	—	<~0.05	$\mu \to e\gamma$ $\tau \to \mu\gamma$
U(2) Flavor symmetry	< a few %	<~0.05	< a few %	<~0.05	$\mu \to e\gamma$ $\tau \to \mu\gamma$

Commissioning with Cosmics



- Challenge: LHCb is NOT suited for cosmics
  - “Horizontal” cosmics well below a Hz
  - Still 1.6x10^6 good events (July – September 2008) recorded for Calorimeters

    & Muon
- Alignment in time and space was done
- L0 trigger parameters were set