S. Stone
April 7, 2010

The Status of LHCb

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"

Quark Mixing & the CKM Matrix

$\longrightarrow$ mass

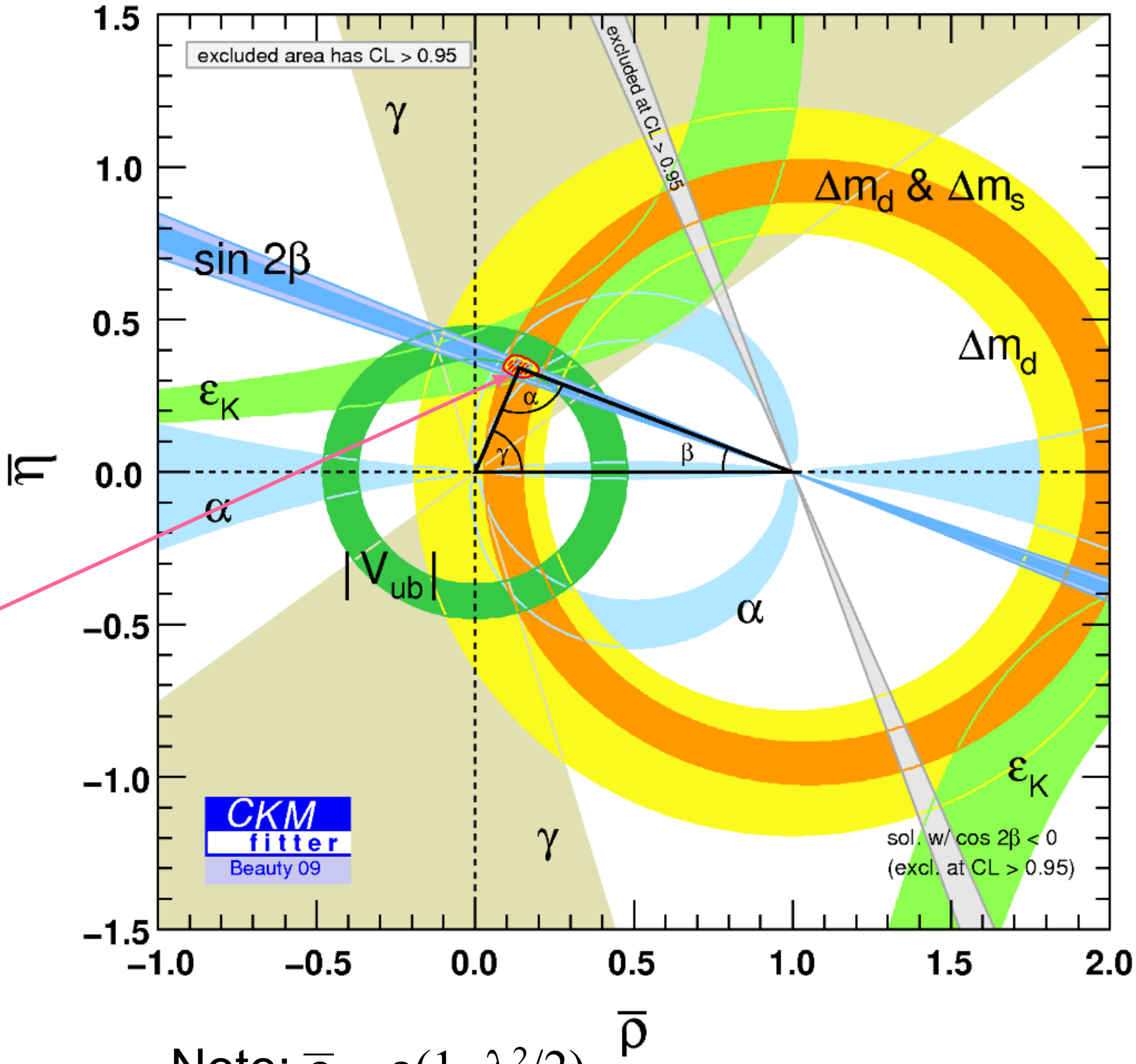
$$\begin{array}{ccc} & & \begin{array}{ccc} d & \qquad s & \qquad b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & V= & \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array}$$

$\downarrow$ mass

- A, λ, ρ and η are in the Standard Model fundamental constants of nature like G, or α_{EM}
- η multiplies i and is responsible for CP violation
- We know $\lambda=0.22$ (V_{us}), A~0.8; constraints on ρ & η

Current Status of CP & 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"



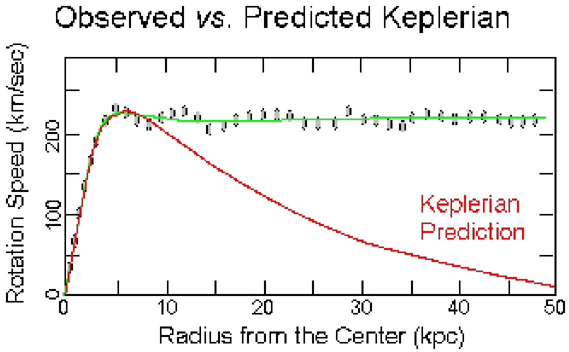
Note: $\bar\rho = \rho(1-\lambda^2/2)$

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

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

Physics Beyond the Standard Model

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



Gravitational lensing

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

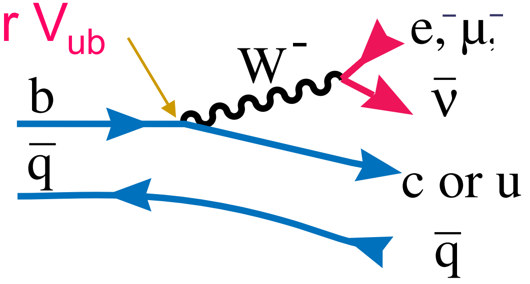
Flavor Problems

- 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?

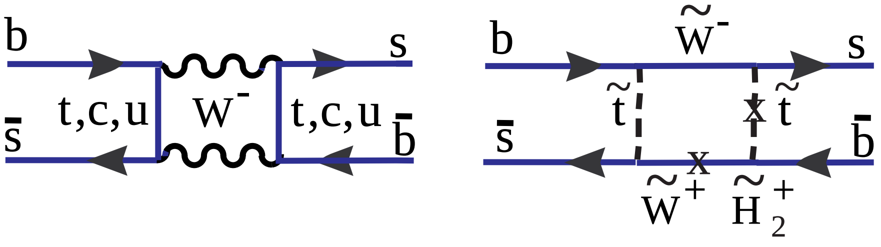
Limits on New Physics

- 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

V_{cb} or V_{ub}



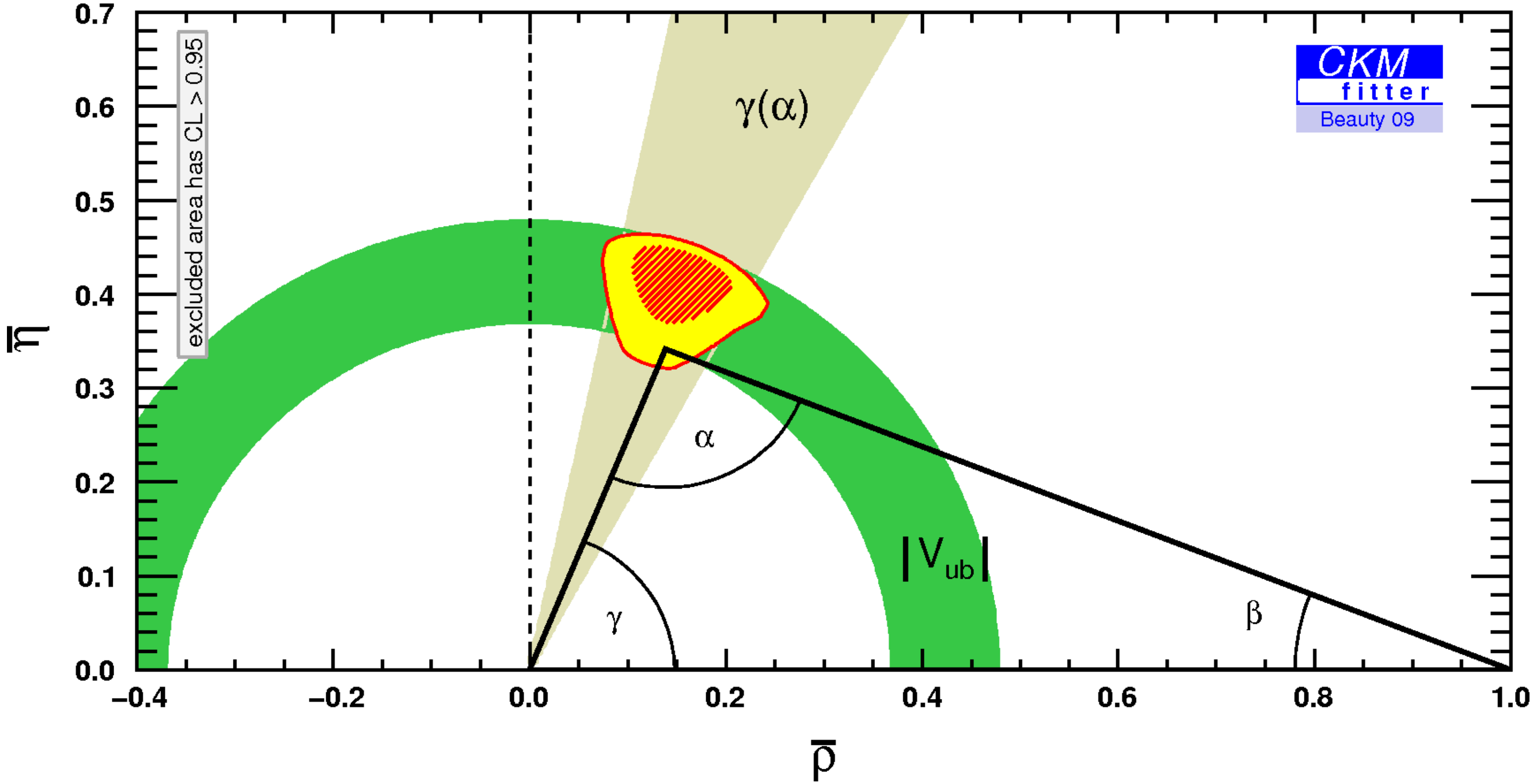
Tree diagram example



Loop diagram example

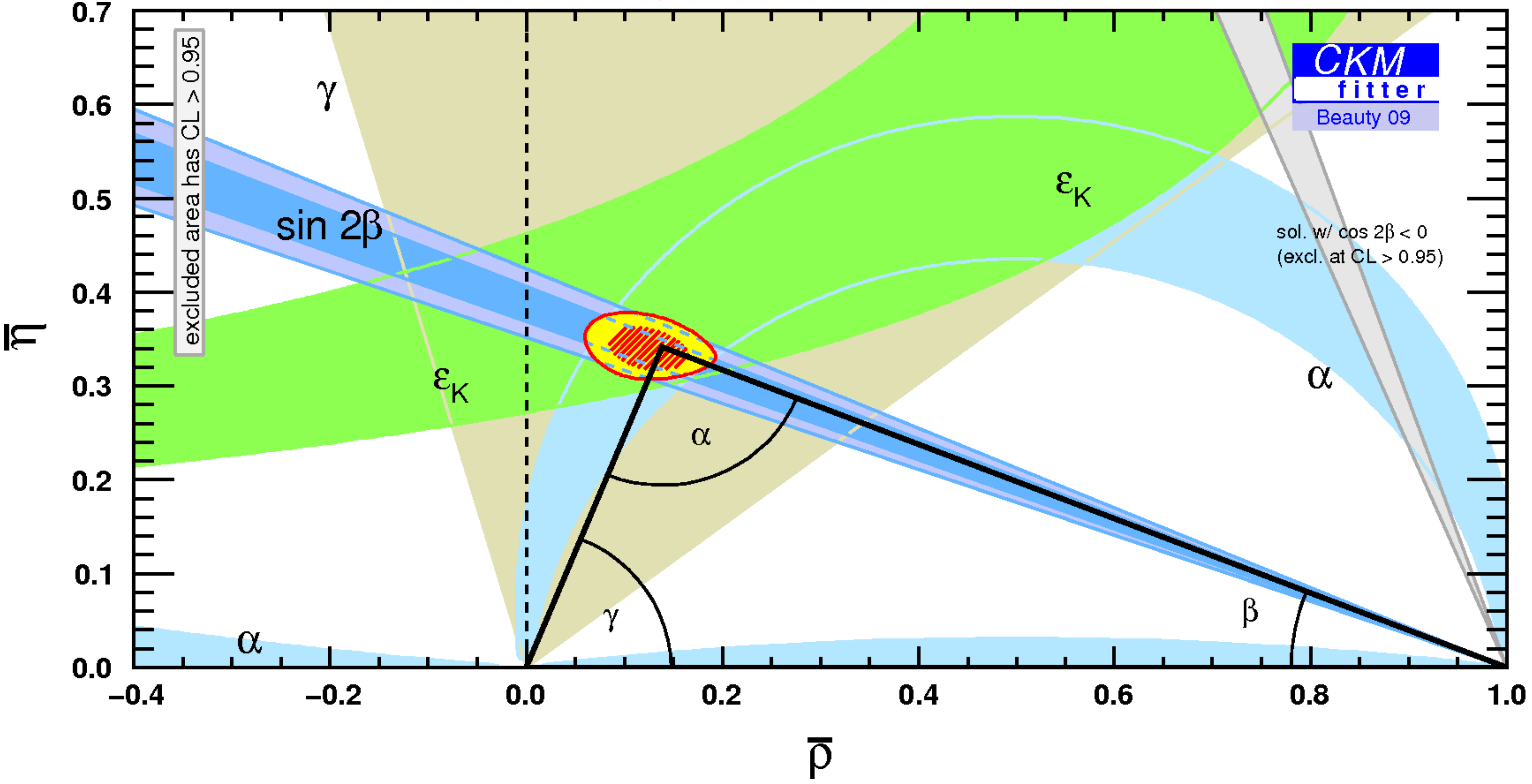
Tree Level Only

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

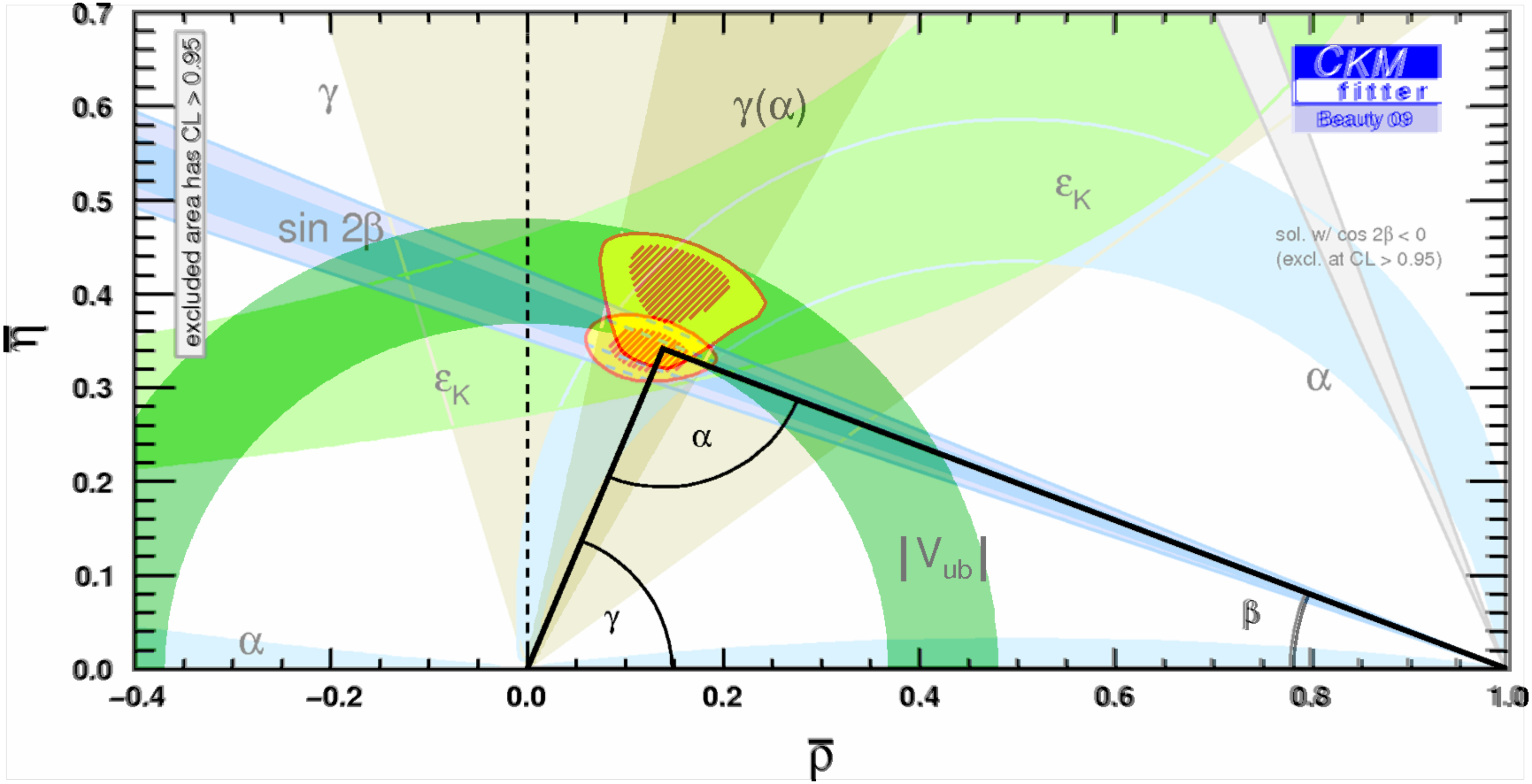


CP Violation in B^0 & K^0 Only

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



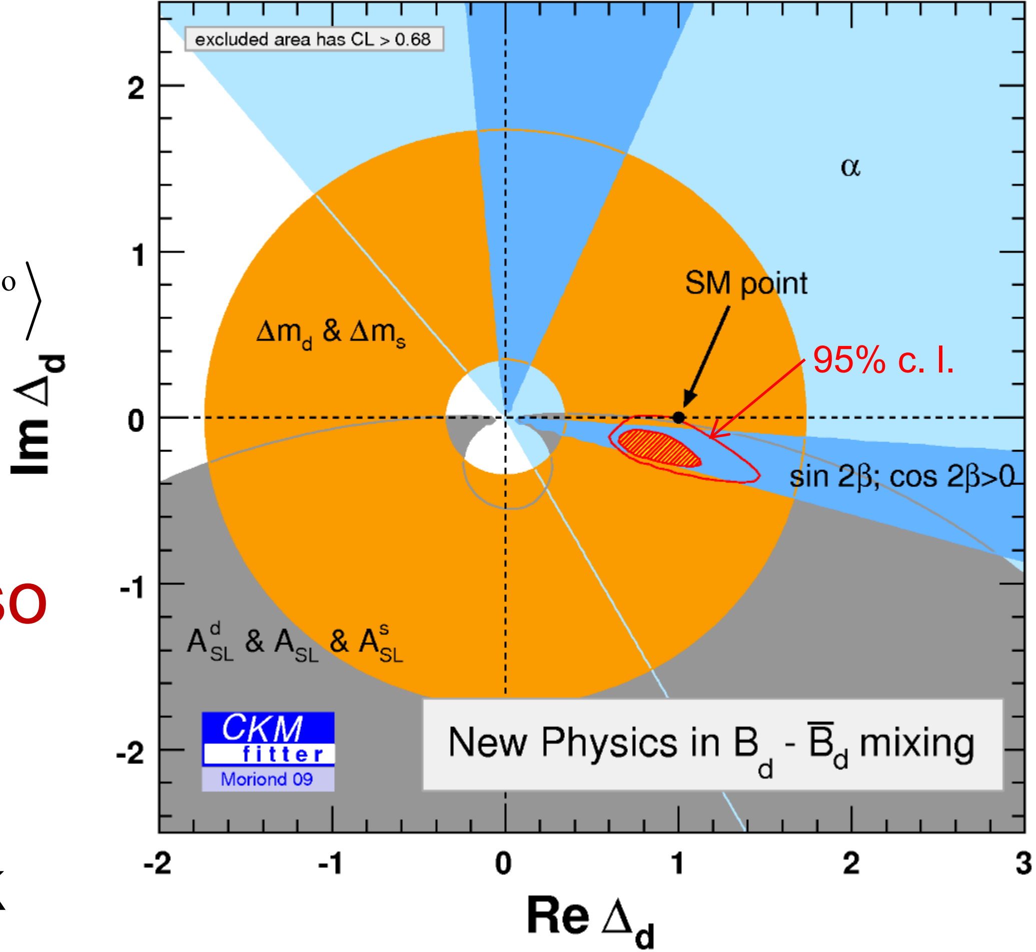
They are Consistent



Limits on New Physics From B^o Mixing

- Is there NP in B^o-$\bar{B}^o$ mixing?
- $\langle B^o | H^{SM+NP}_{\Delta B=2} | \bar{B}^o \rangle = \Delta_d^{NP} \langle B^o | H^{SM}_{\Delta B=2} | \bar{B}^o \rangle$

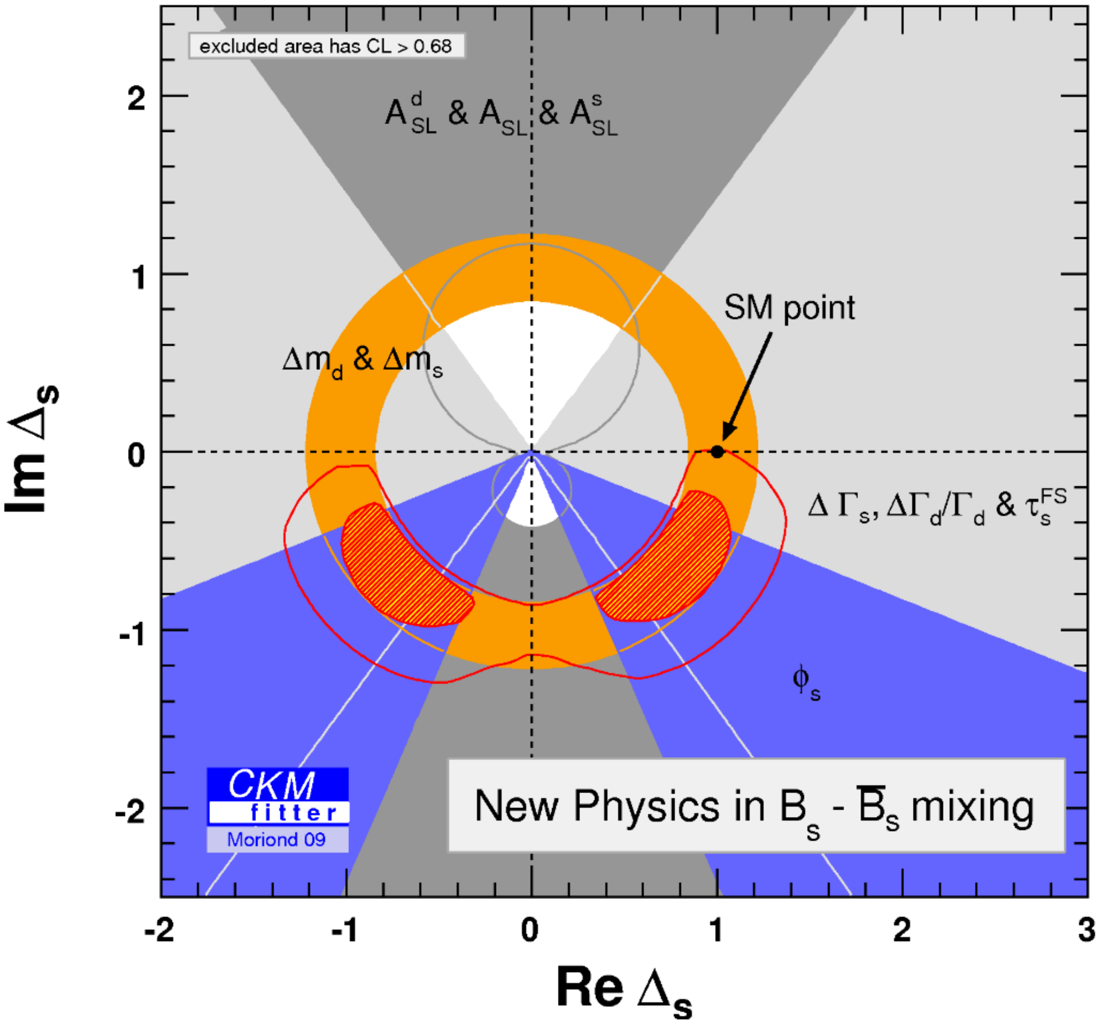
  $\Delta_d^{NP} = \mathrm{Re}\,\Delta_d + i\mathrm{Im}\Delta_d$
- Assume NP in tree decays is negligible, so no NP in $|V_{ij}|$, γ from $B^- \rightarrow D^o K^-$.
- Allow NP in Δm, weak phases, A_{SL}, & $\Delta\Gamma$.



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



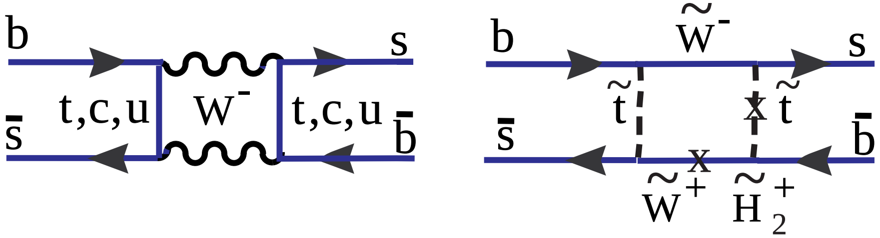
New Physics Models

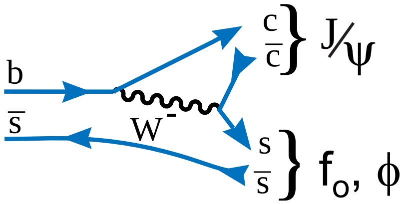
- There is, in fact, still lots of room for "generic" NP
- What do specific models predict?
  - Supersymmetry: many, many different models
  - Extra Dimensions: "
  - Little Higgs: "
  - Left-Right symmetric models "
  - 4th Generation models "
- NP **must** affect every process; the amount tells us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



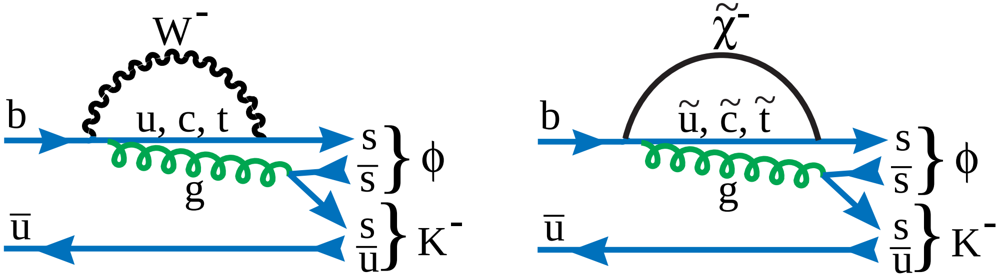


measures CP violating $\angle$ -2β_s

CP asymmetry $\approx$ 0.1sin$\phi_\mu$cos$\phi_A$sin(Δm_st), ~10 x SM

- Contributions to direct CP violating decay

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

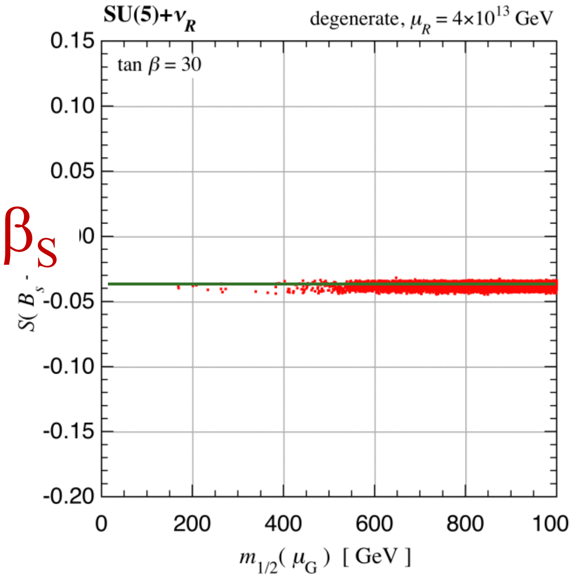


Asym=$(M_W/m_{squark})^2$sin(ϕ_μ), ~0 in SM

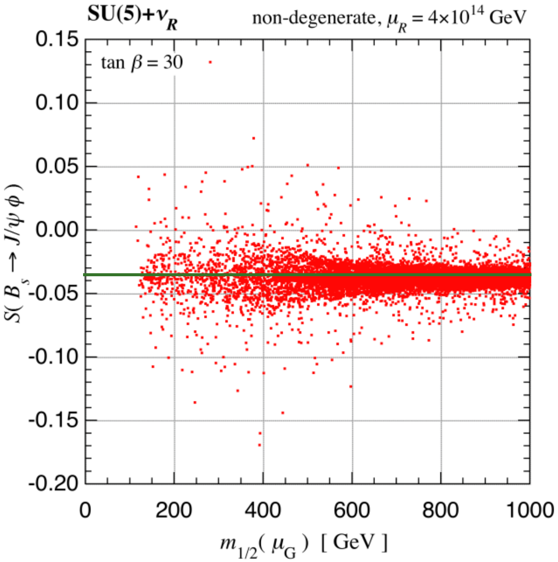
Supersymmetry: SU(5) &U(2)

SU(5) GUT
Degenerate

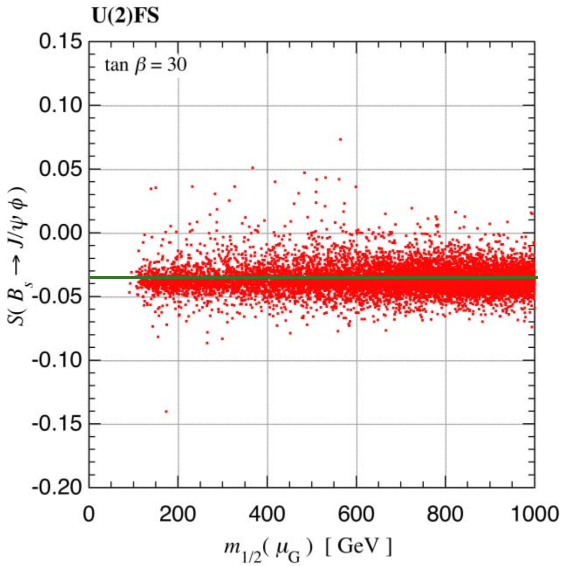
$-2\beta_s$



SU(5) GUT
Non-degenerate



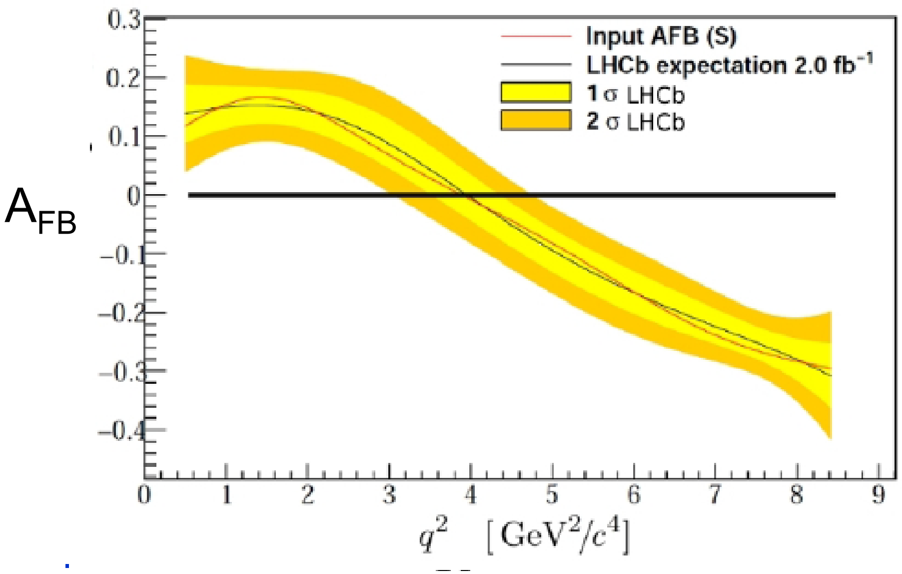
U(2) FS

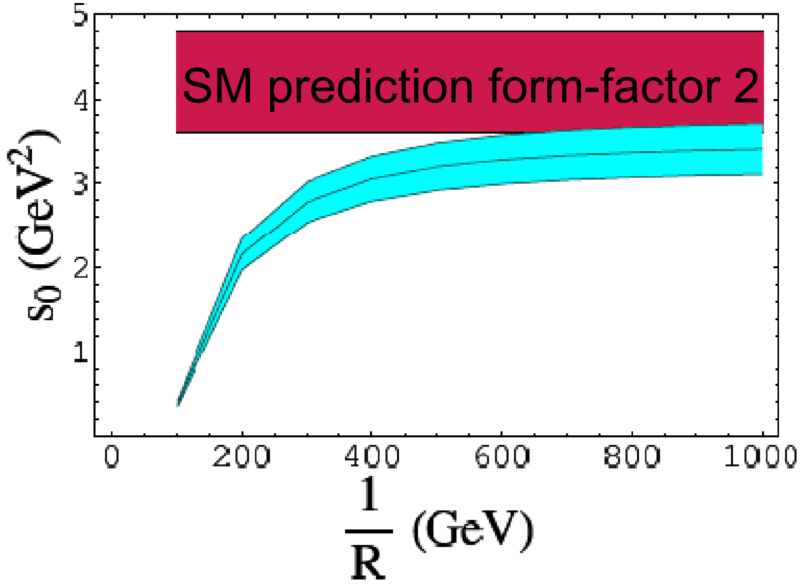


- $-2\beta_s$ can deviate from the “SM” value of -0.036 in SU(5) GUT non-degenerate case, and the U(2) model. From Okada’s talk at BNMII, Nara Women’s Univ. Dec., 2006

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 $B \rightarrow K^{*}\mu^{+}\mu^{-}$
- *Insensitive to choice of form-factors. Can SM calculations improve?*





The LHCb Detector

Detector Requirements – General

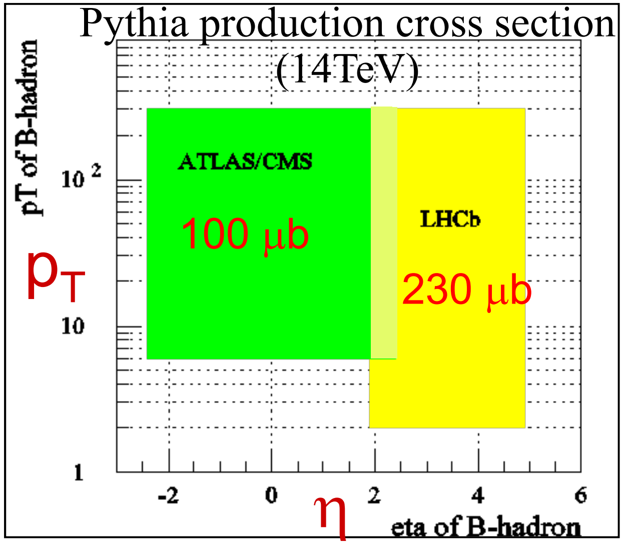
- Every modern heavy quark experiment needs:
  - Vertexing: to measure decay points and reduce backgrounds, especially at hadron colliders
  - Particle Identification: to eliminate insidious backgrounds from one mode to another where kinematical separation is not sufficient
  - Muon & electron identification 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

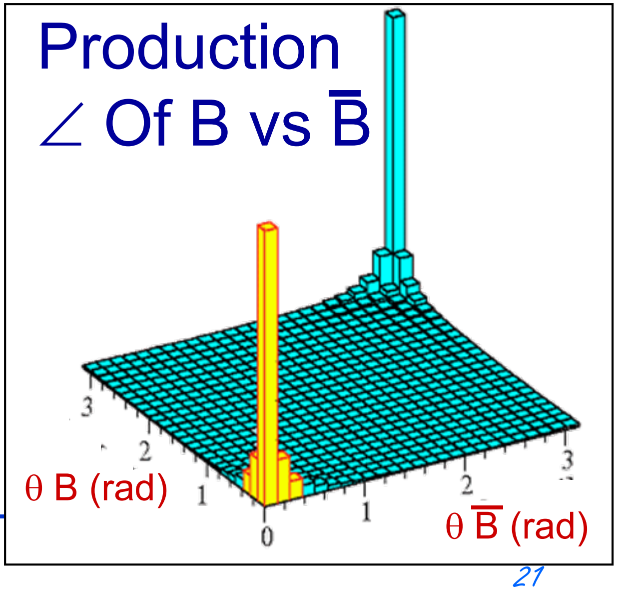
Basics For Sensitivities

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

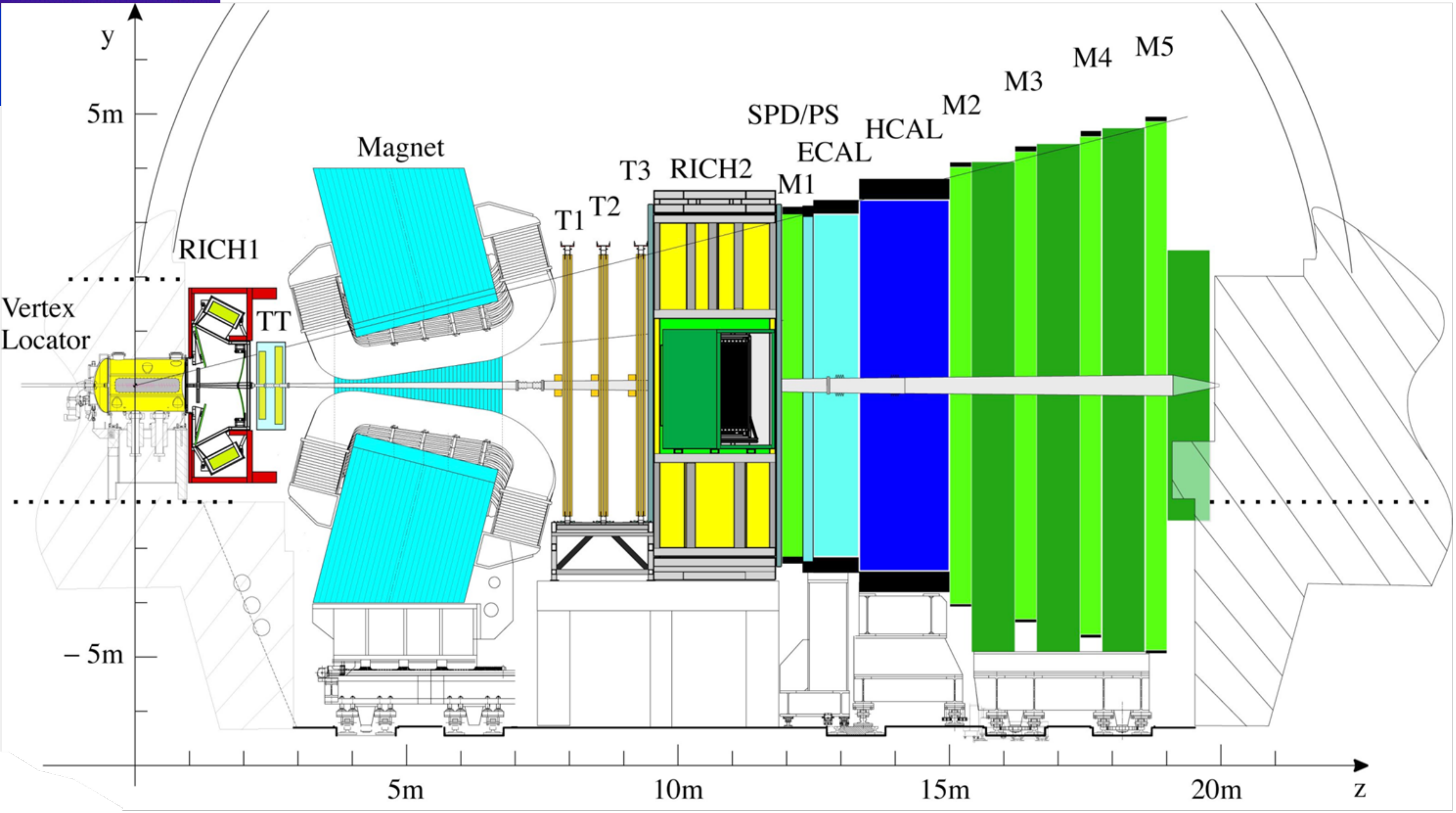
The Forward Direction at the LHC

- 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 > η >1.9, where the B's are moving with considerable momentum ~100 GeV, thus minimizing multiple scattering
- At $\mathcal{L}=2\text{x}10^{32}/\text{cm}^2$-s, we get 10^{12} B hadrons in 10^7 sec

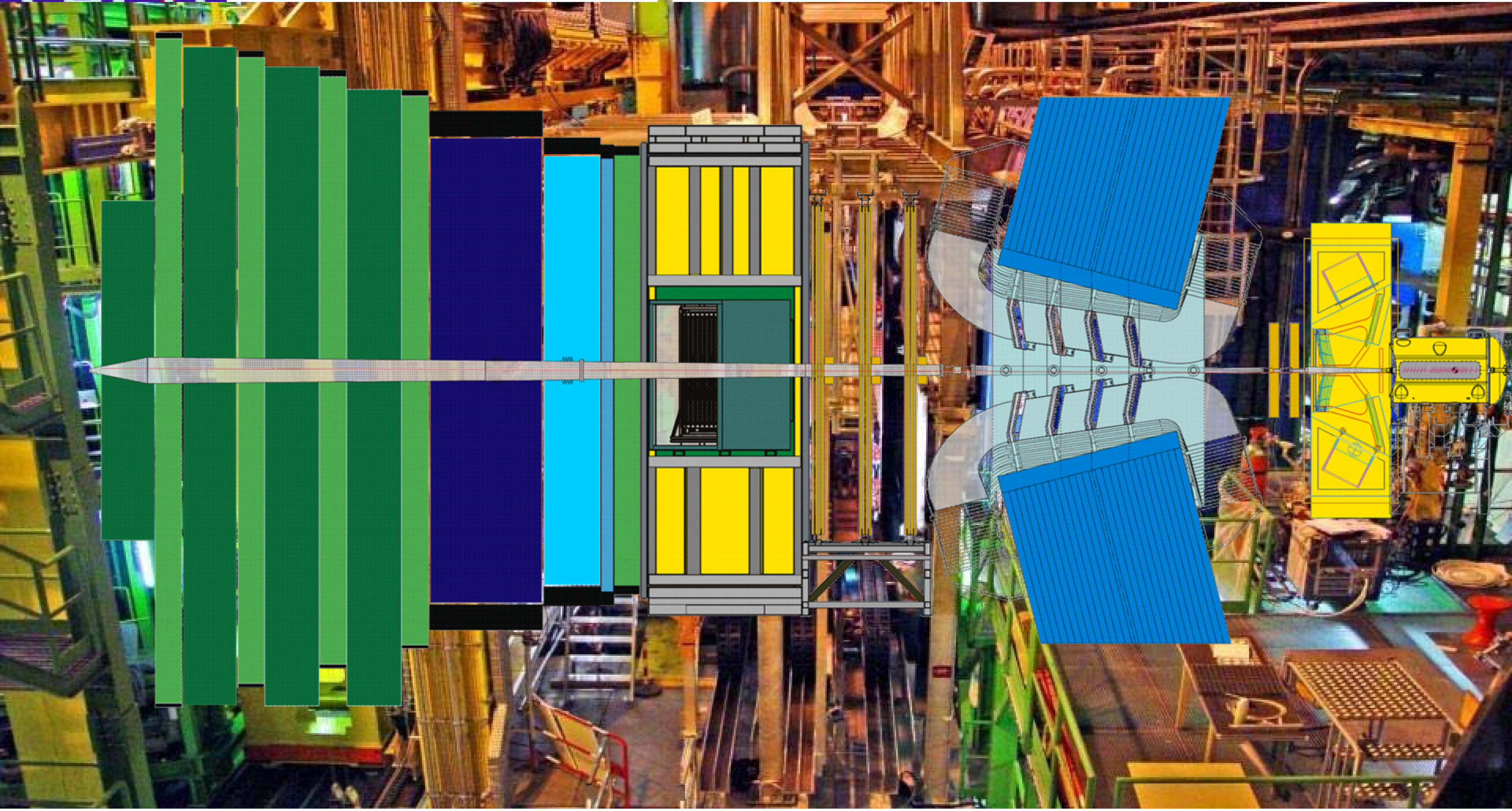




The LHCb Detector

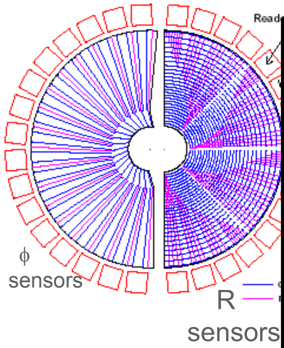


Detector Workings

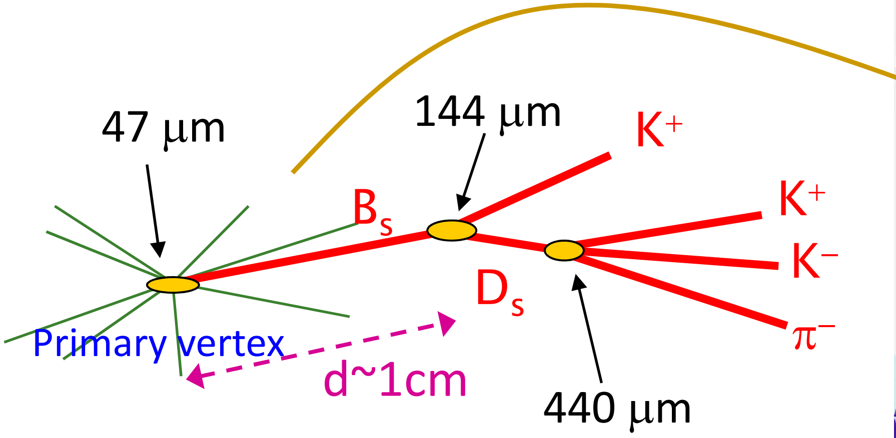


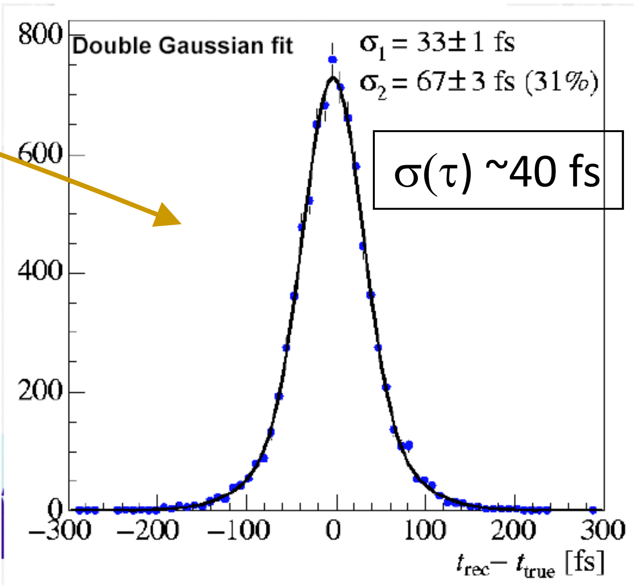
LHCb detector ~ fully installed and commissioned → walk through the detector using the example of a $B_s \rightarrow D_s K$ decay

B-Vertex Measurement



Example: $B_s \rightarrow D_s K$





Decay time resolution = 40 fs

Vertex Locator (Velo)

Silicon strip detector with

~ 5 μm hit resolution

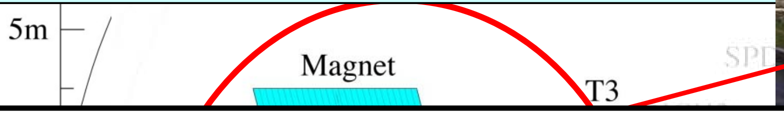
→ 30 μm IP resolution

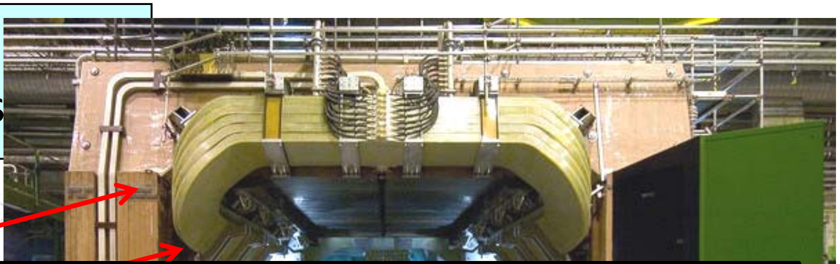
Vertexing:

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

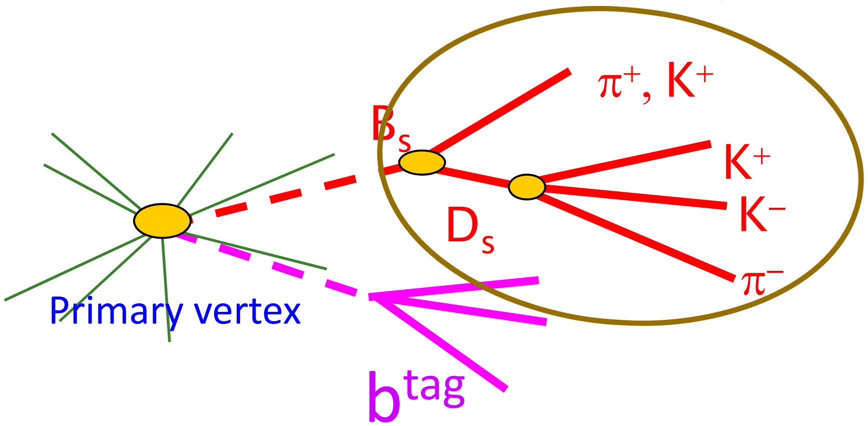
Momentum and Mass measurement

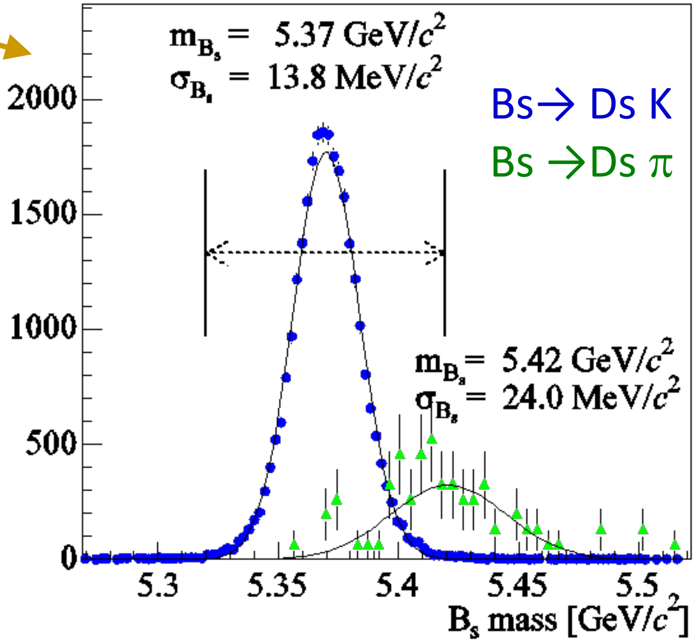
Momentum meas. + direction (VELO):
Mass resolution for background suppres





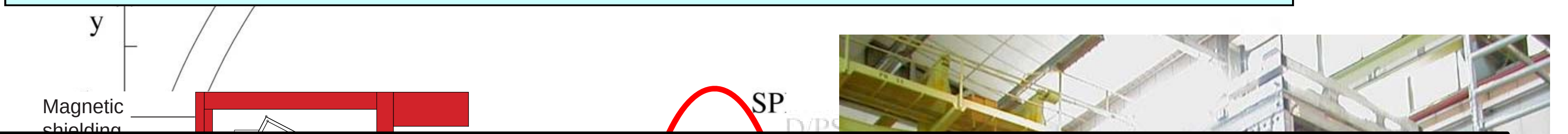
Mass resolution
σ ~14 MeV





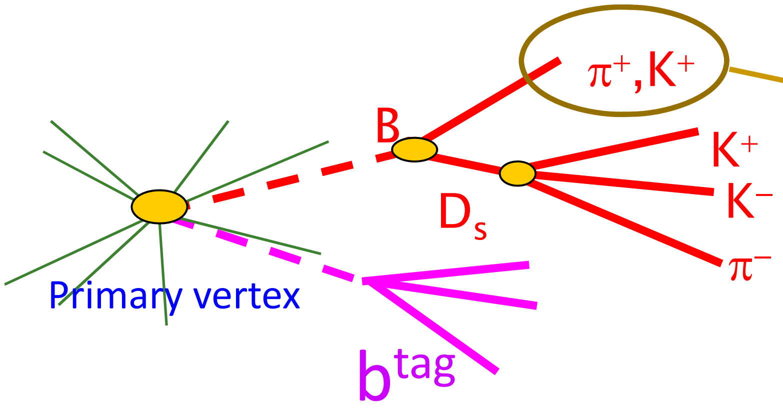
Hadron Identification

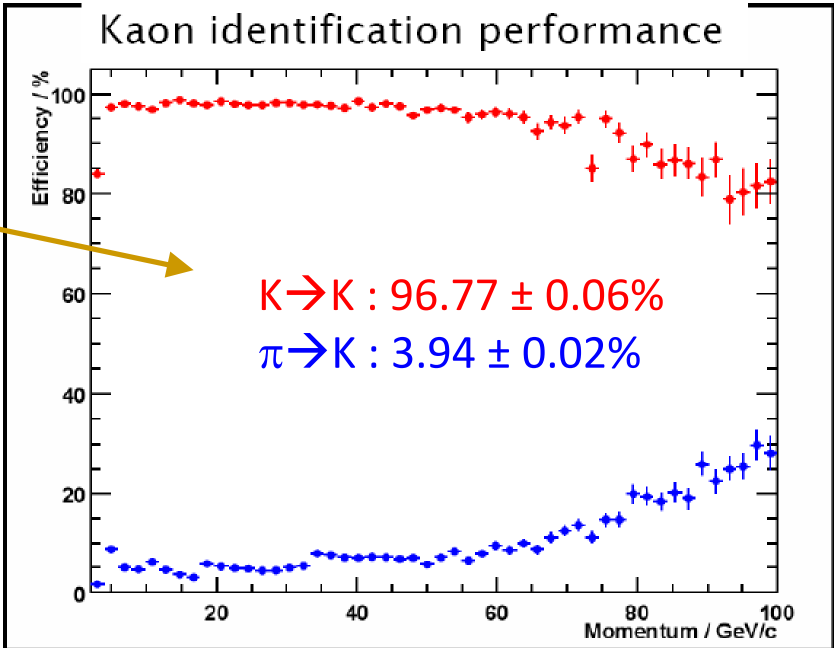
RICH: K/π identification using Cherenkov light emission angle



Bs → Ds K

SS flavour tagging





K→K : 96.77 ± 0.06%

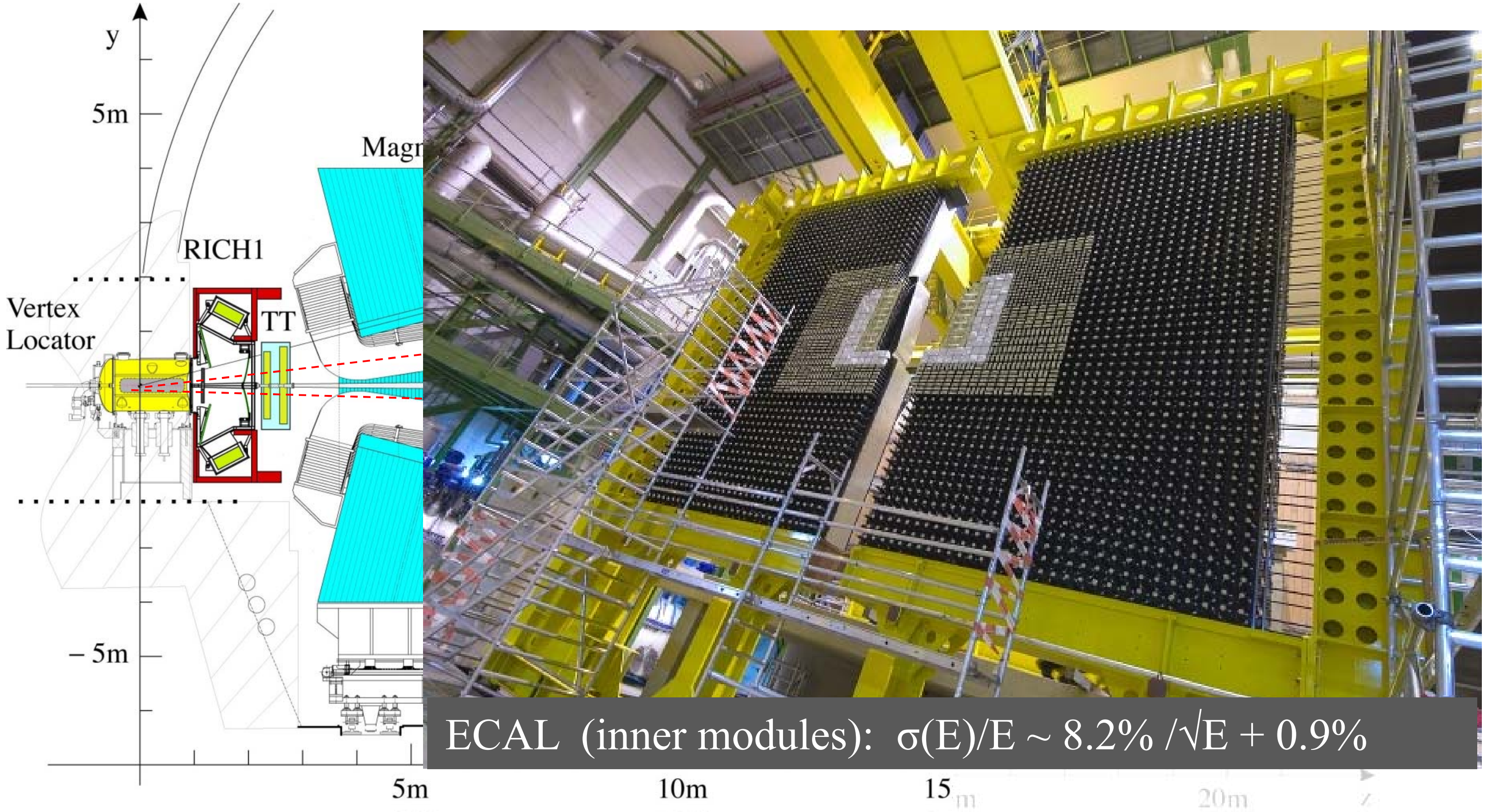
π→K : 3.94 ± 0.02%

RICH1: 5 cm aerogel n=1.03

4 m^3 C_4F_{10} n=1.0014

RICH2: 100 m3 CF_4 n=1.0005

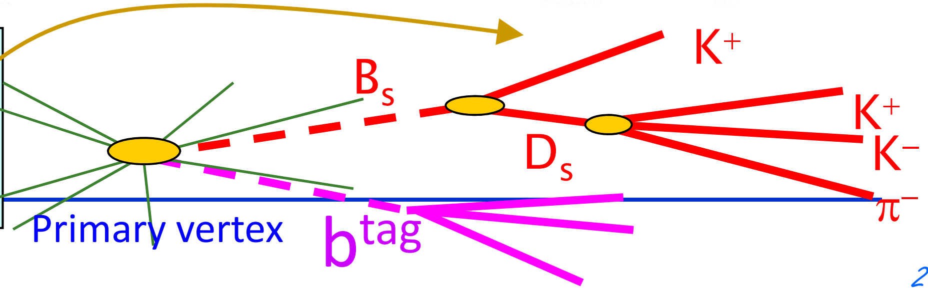
Particle identification and L0 trigger



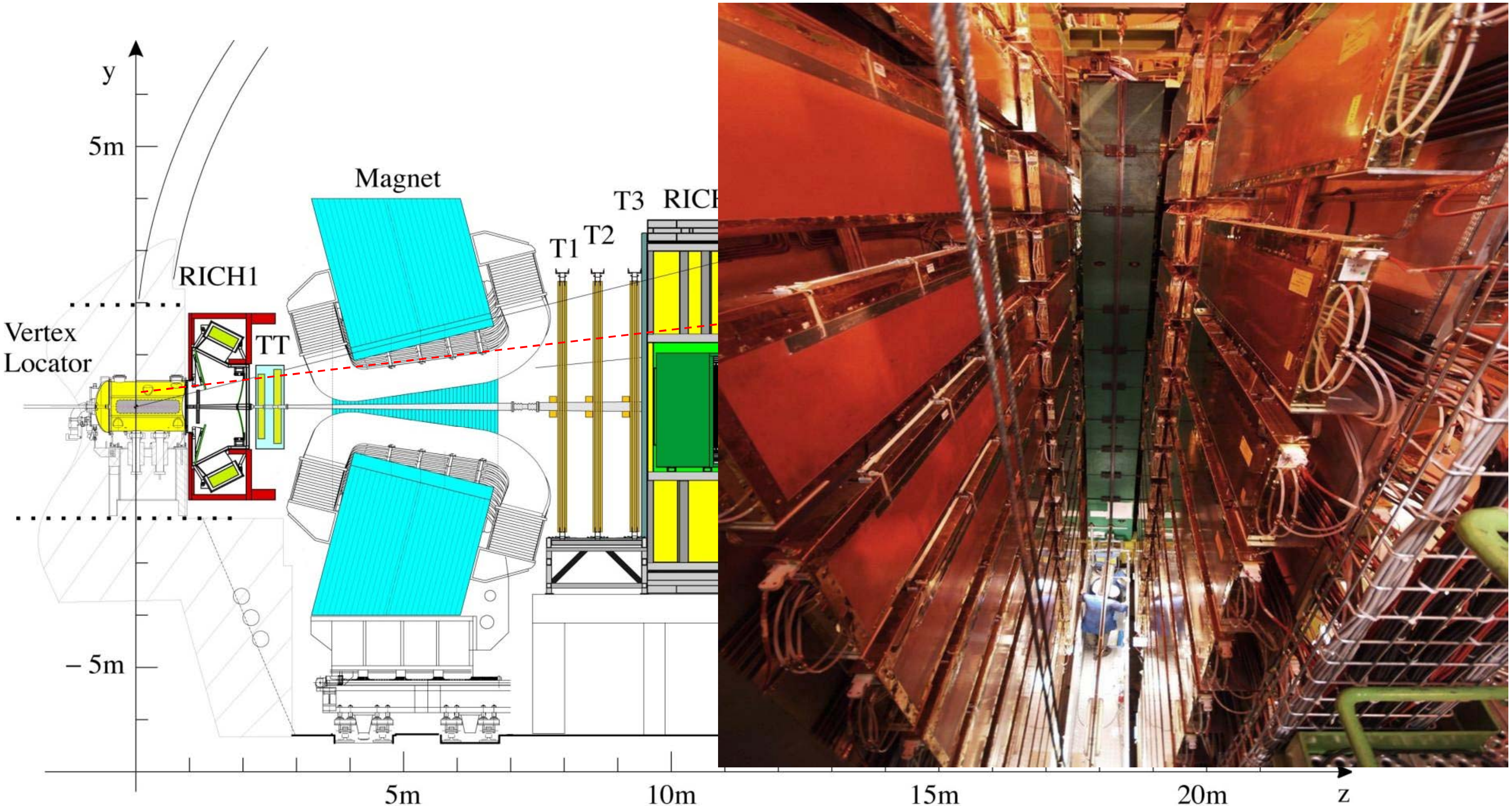
ECAL (inner modules): σ(E)/E ~ 8.2% /√E + 0.9%

Calorimeter system :

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

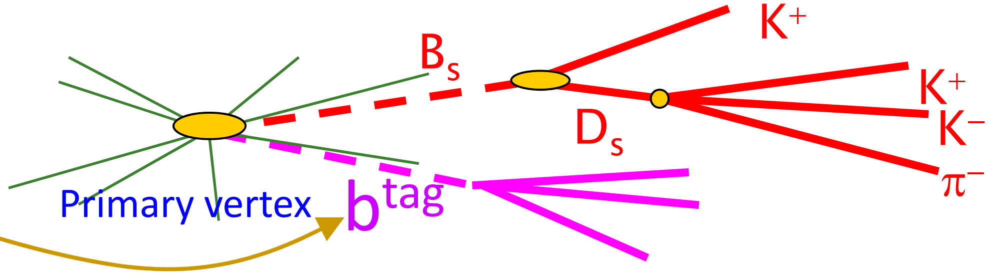


Particle identification and L0 trigger

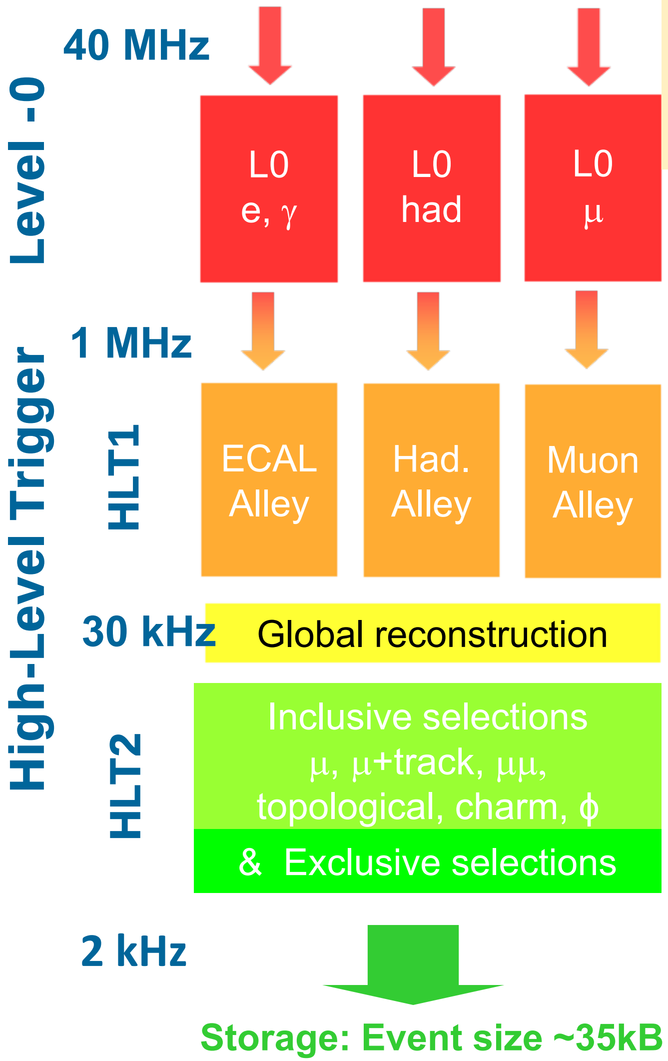


Muon system:

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



Triggering



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

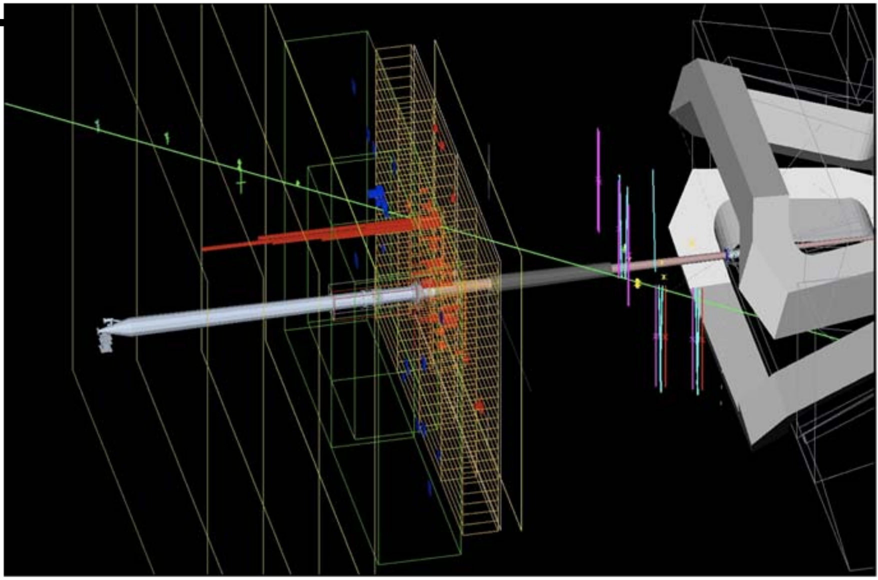
  HLT1: Confirm L0 candidate with more complete info, add impact parameter and lifetime cuts

  HLT2: B reconstruction + selections

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

Commissioning

Commissioning with Cosmics

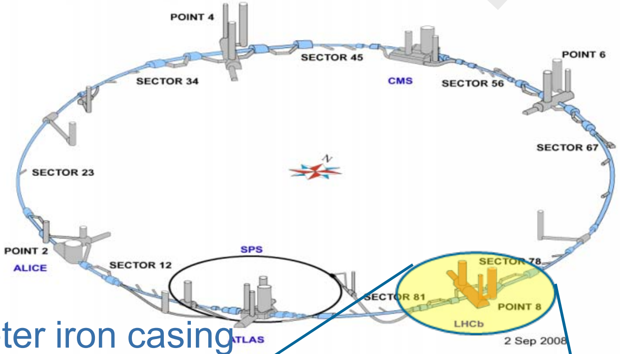


- Challenge: LHCb is NOT suited for cosmics
  - "Horizontal" cosmics well below a Hz
  - Still 1.6x10^6 good events (July – September 2008) recorded for Calorimeters

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

A First Glimpse of LHC Protons

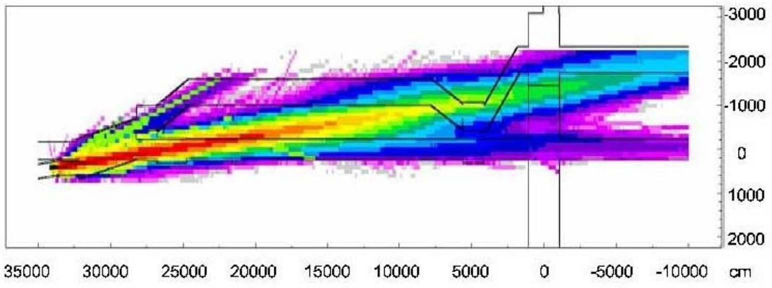
LHCb@LHC Sector Tests

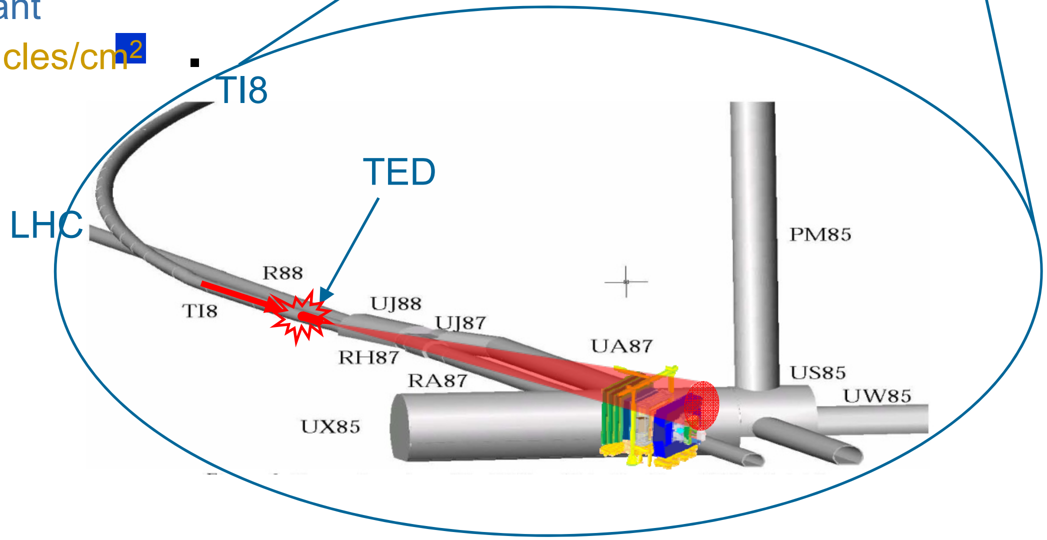


- Beam 2 dumped on injection line beam stopper (TED)
  - 4 m tungsten, copper, aluminium, graphite rod in a 1m diameter iron casing
  - 340 m before LHCb along beam 2

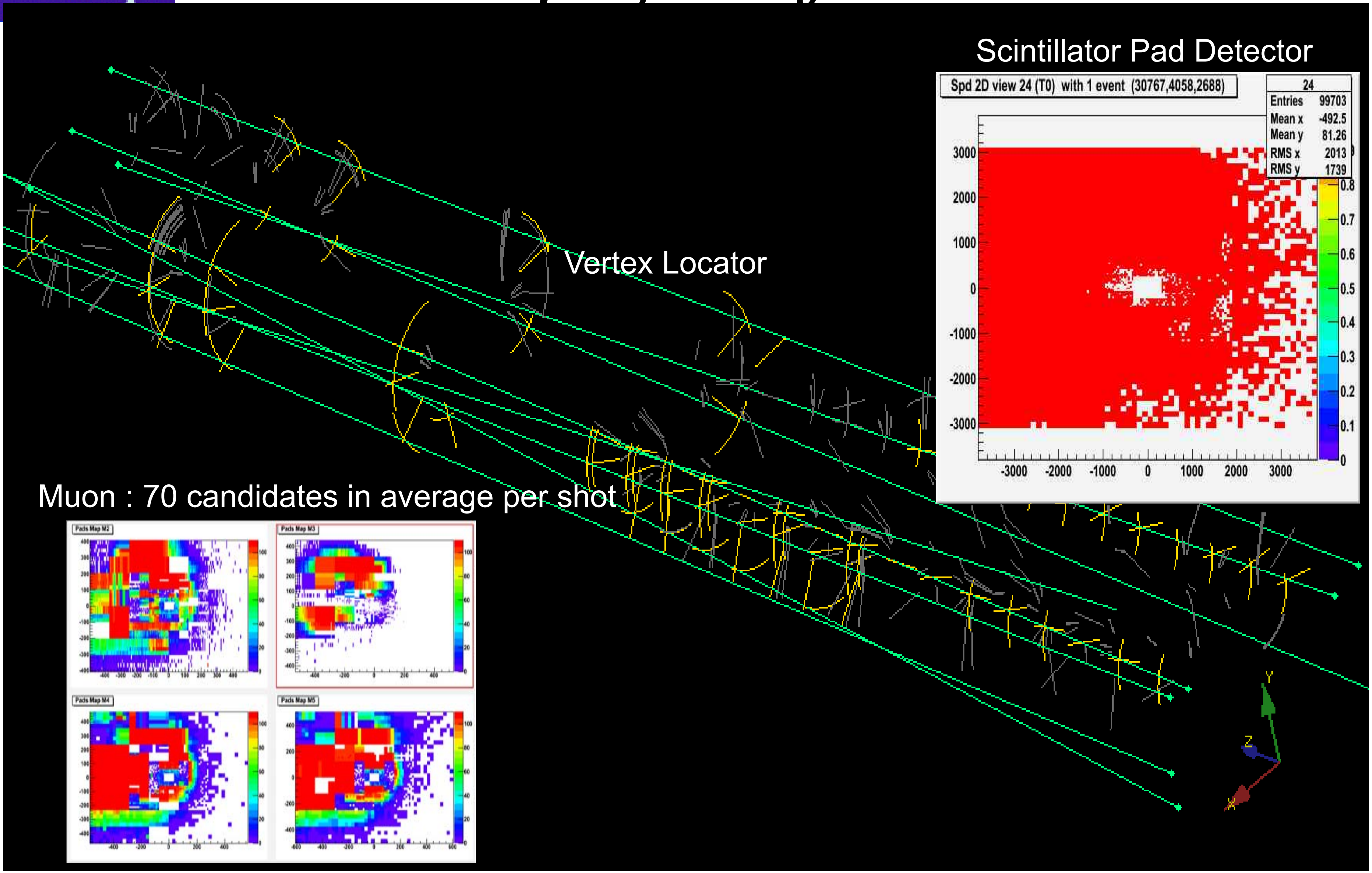
→

  - “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

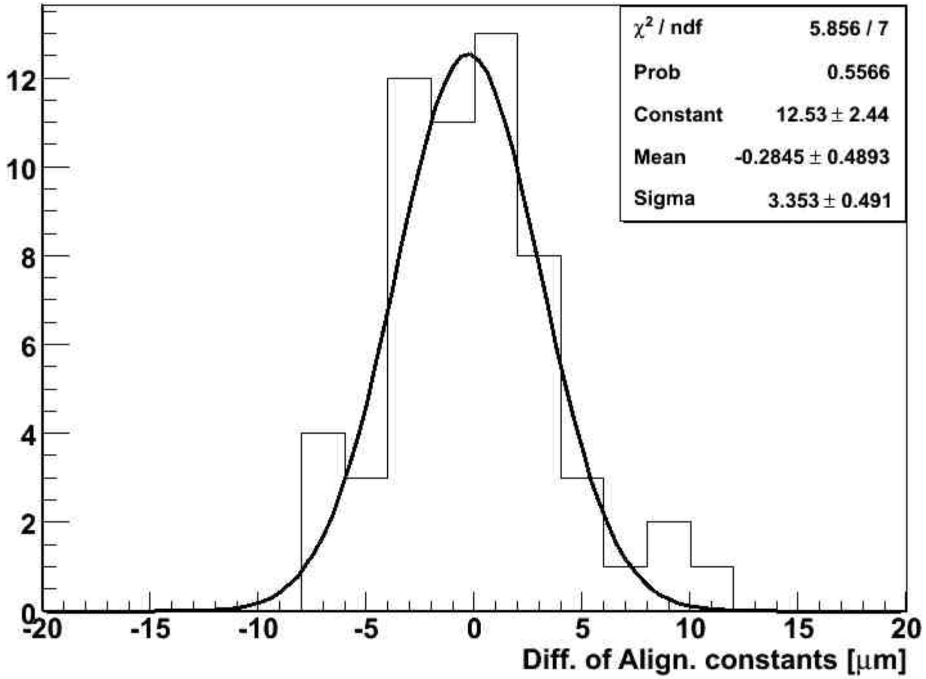

Scintillator Pad Detector

Vertex Locator

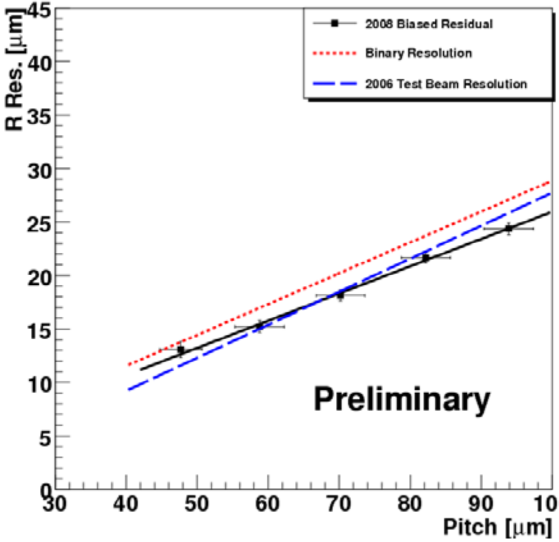
Muon : 70 candidates in average per shot

VELO Space Alignment with TED

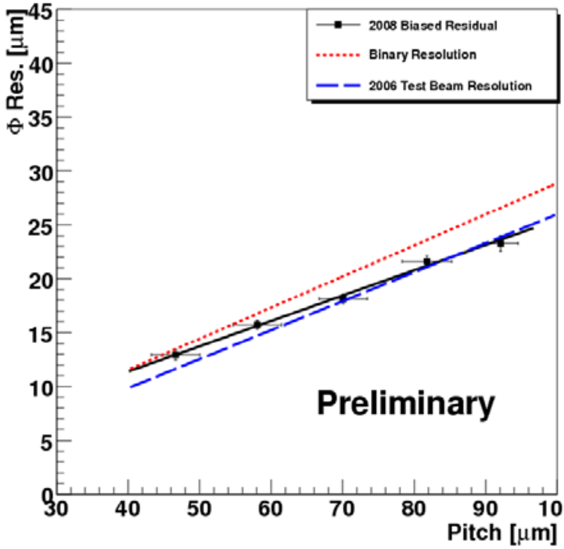
- The detector displacement from metrology usually is less than 10 μm
- Module alignment precision is about 3.4 μm for X and Y translation and 200 μrad for Z rotation



R residuals

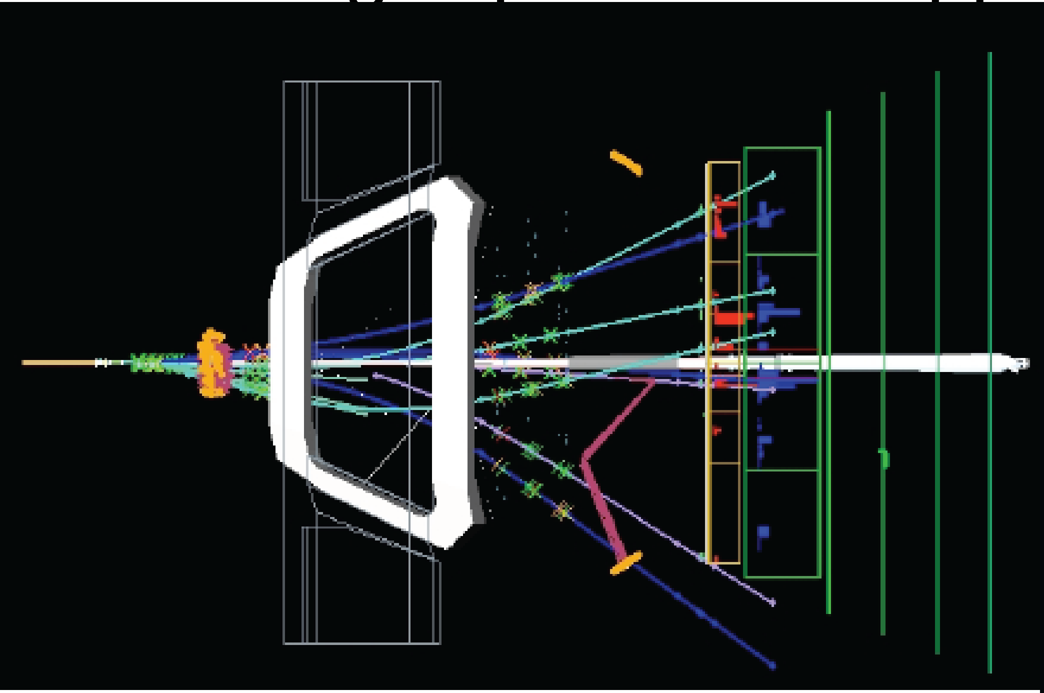


Φ residuals

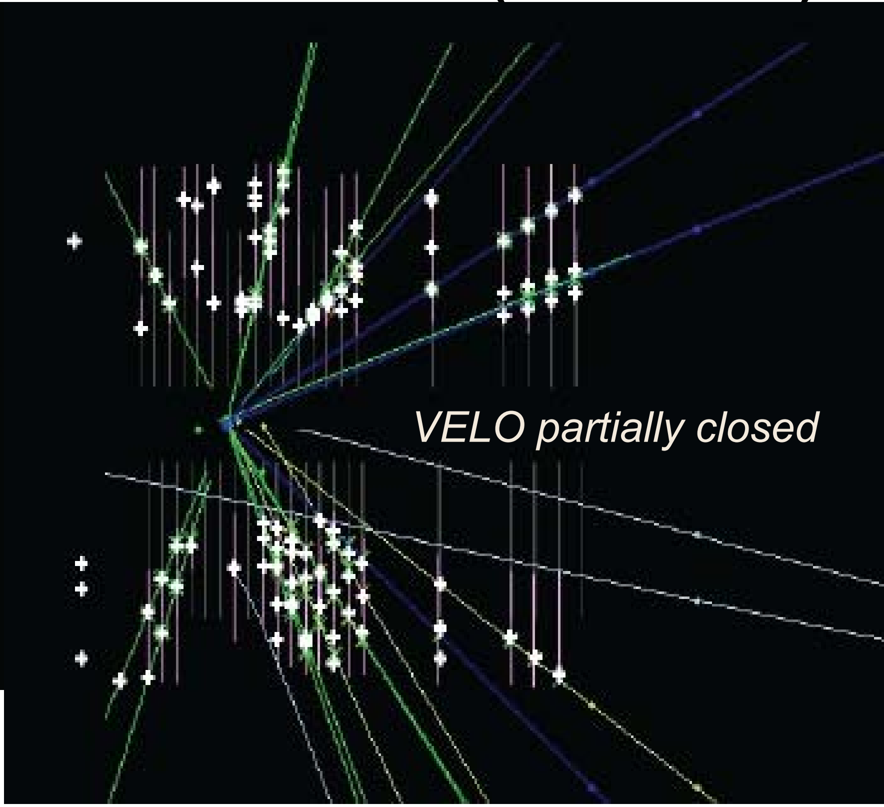


LHCb Data

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



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

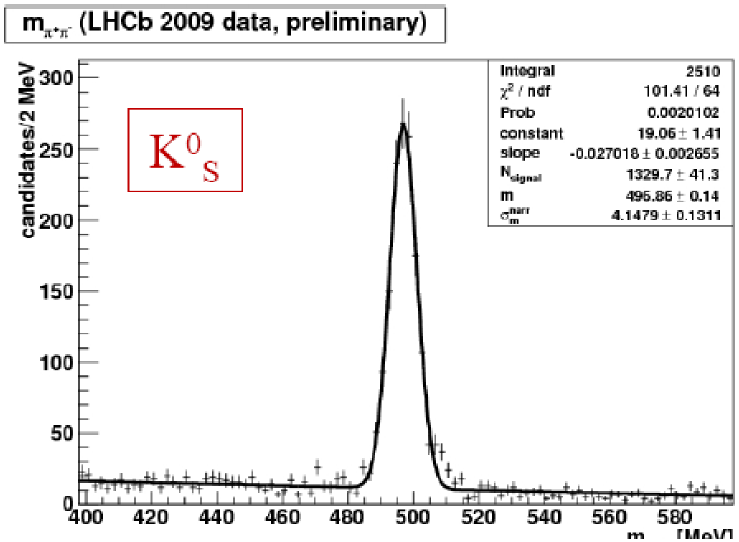


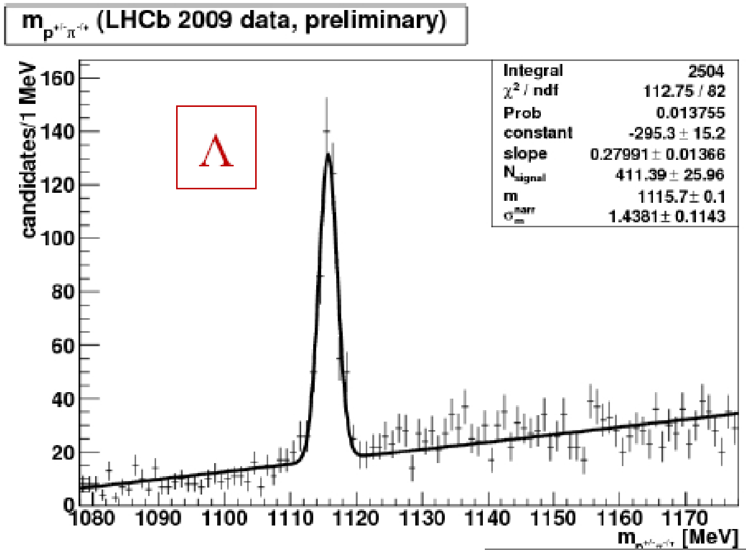
VELO partially closed

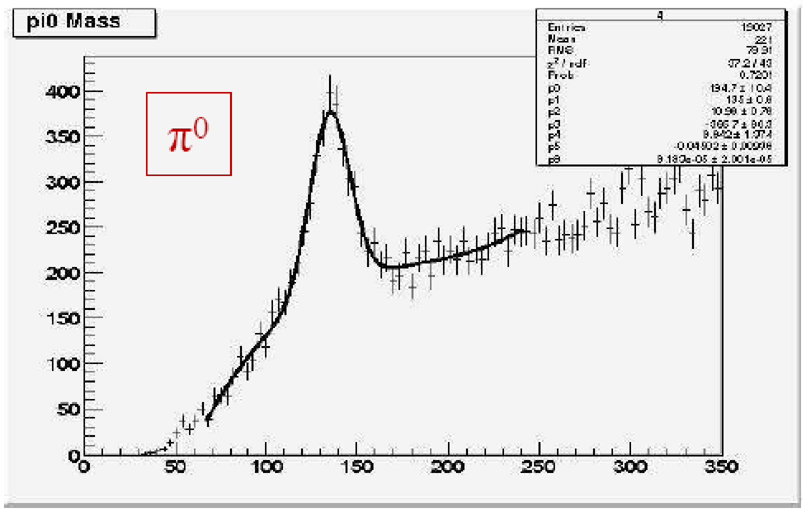
VELO nominally at ~8 mm from beam kept at 15 mm due to beam hazards

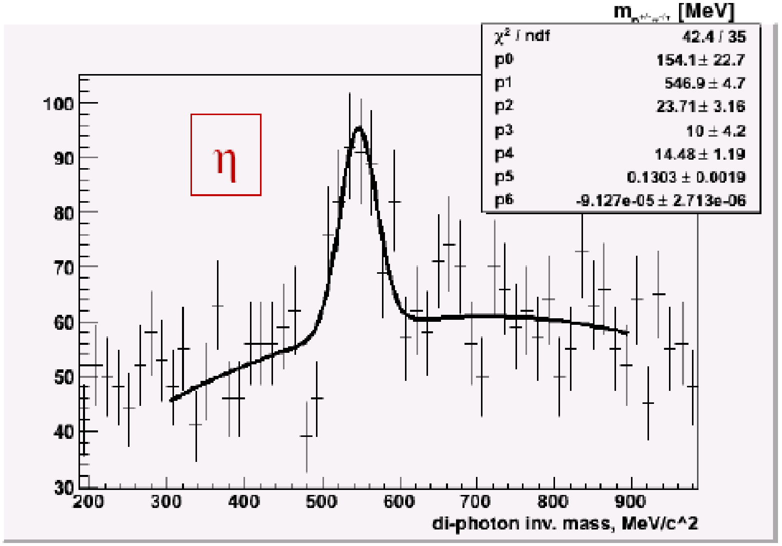
Tracking & Calorimetry

LHCb preliminary

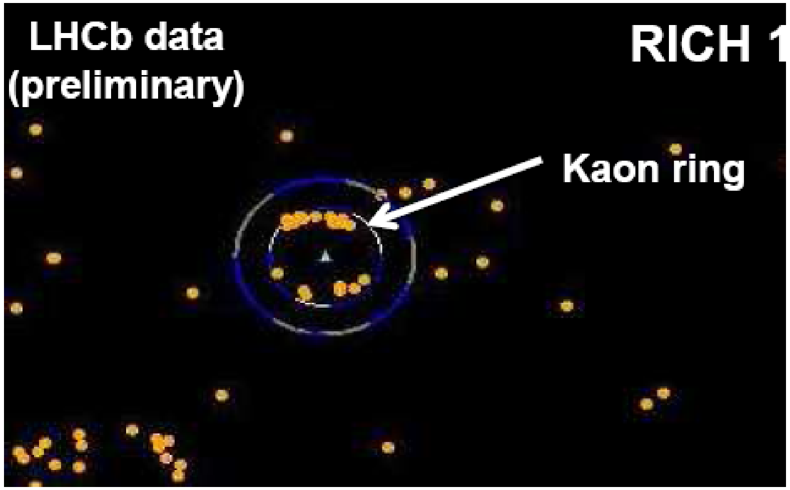


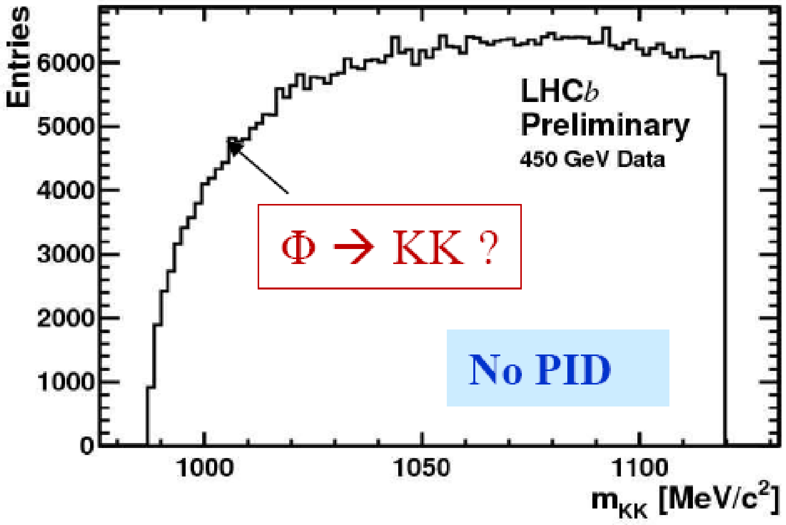






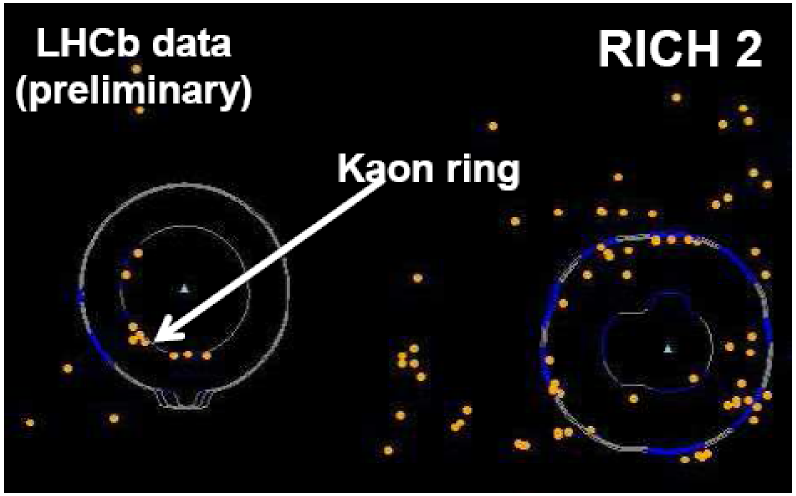
Particle Identification

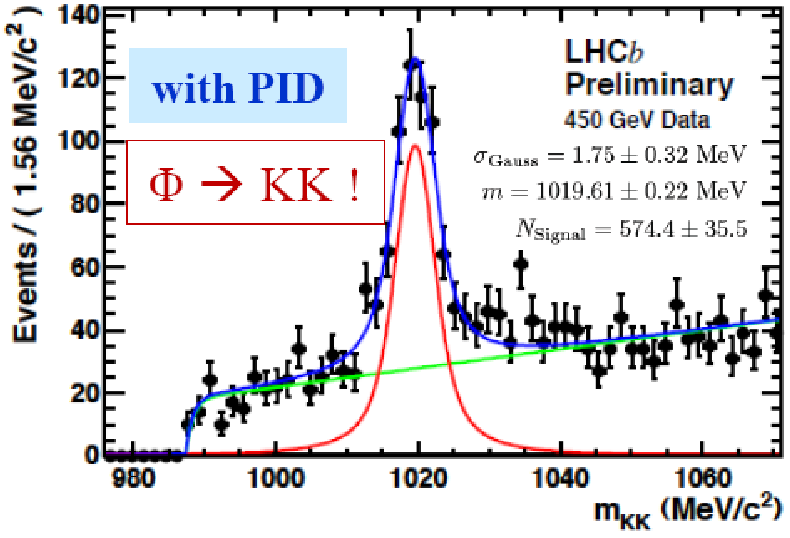




$\Phi \rightarrow KK$?

No PID





$\sigma_{\mathrm{Gauss}} = 1.75 \pm 0.32$ MeV

$m = 1019.61 \pm 0.22$ MeV

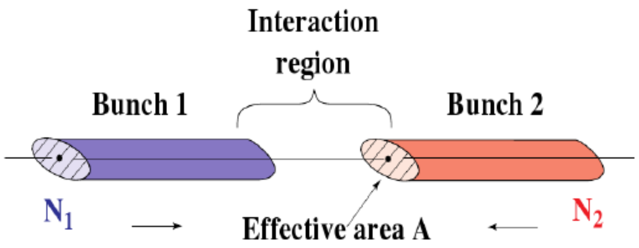
$N_{\mathrm{Signal}} = 574.4 \pm 35.5$

with PID

$\Phi \rightarrow KK$!

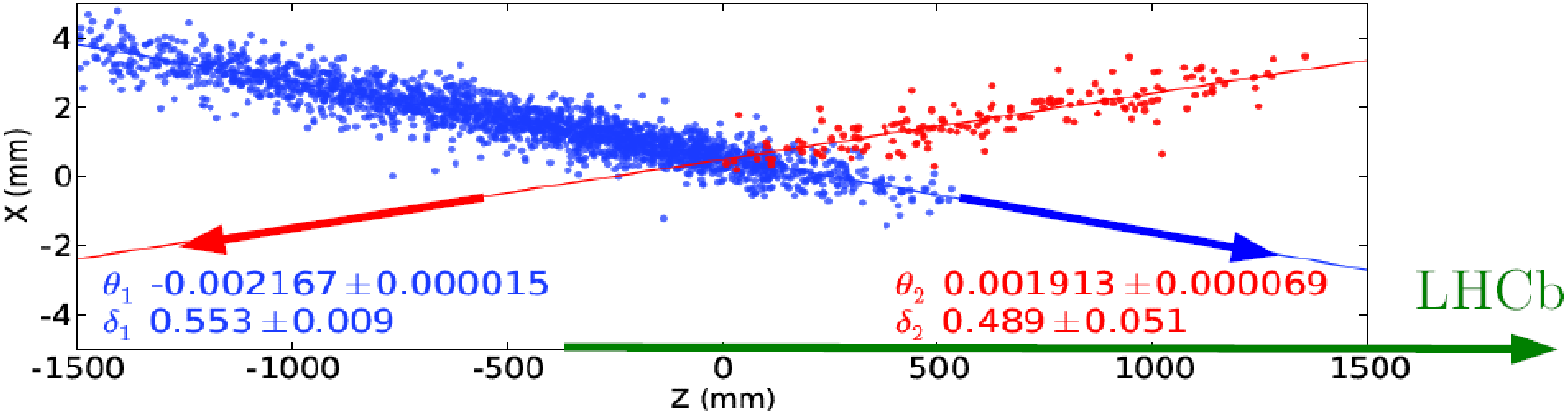
Luminosity

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



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

- Profile from beam-gas collisions

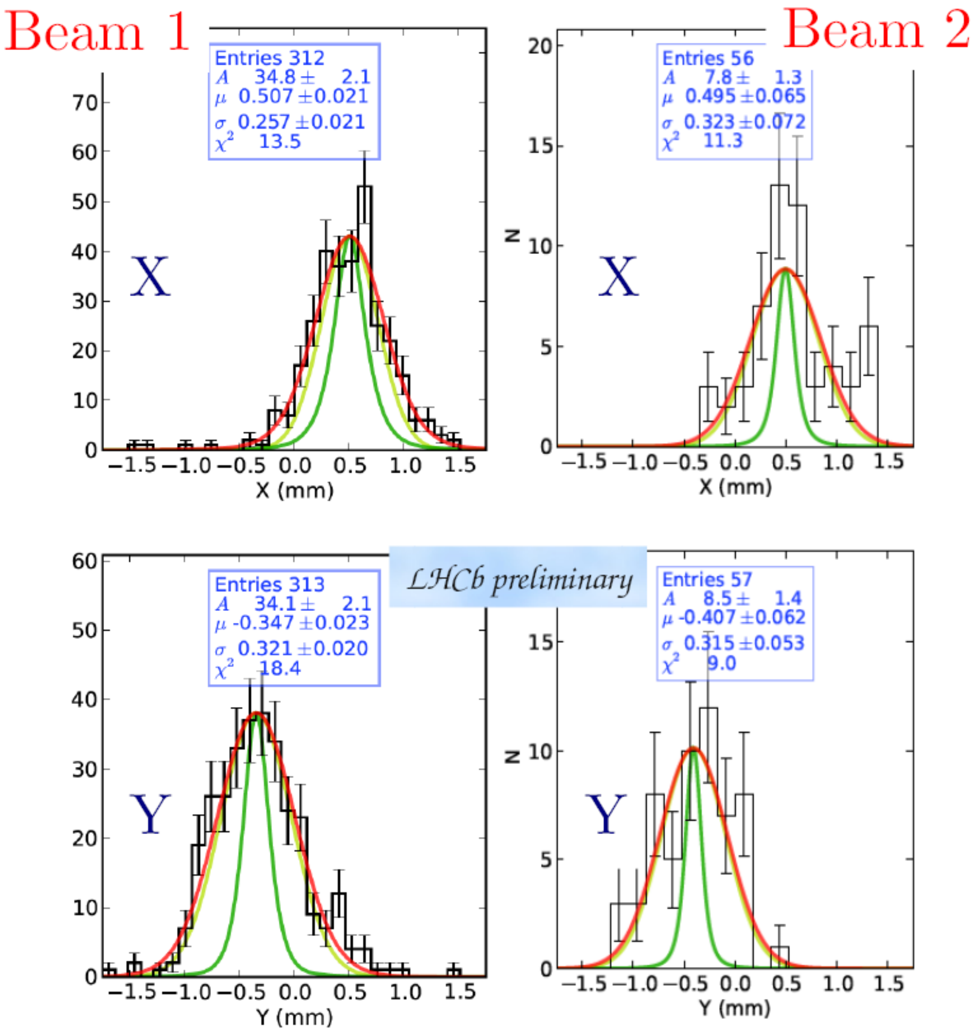


Beam Sizes from Beam-Gas

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

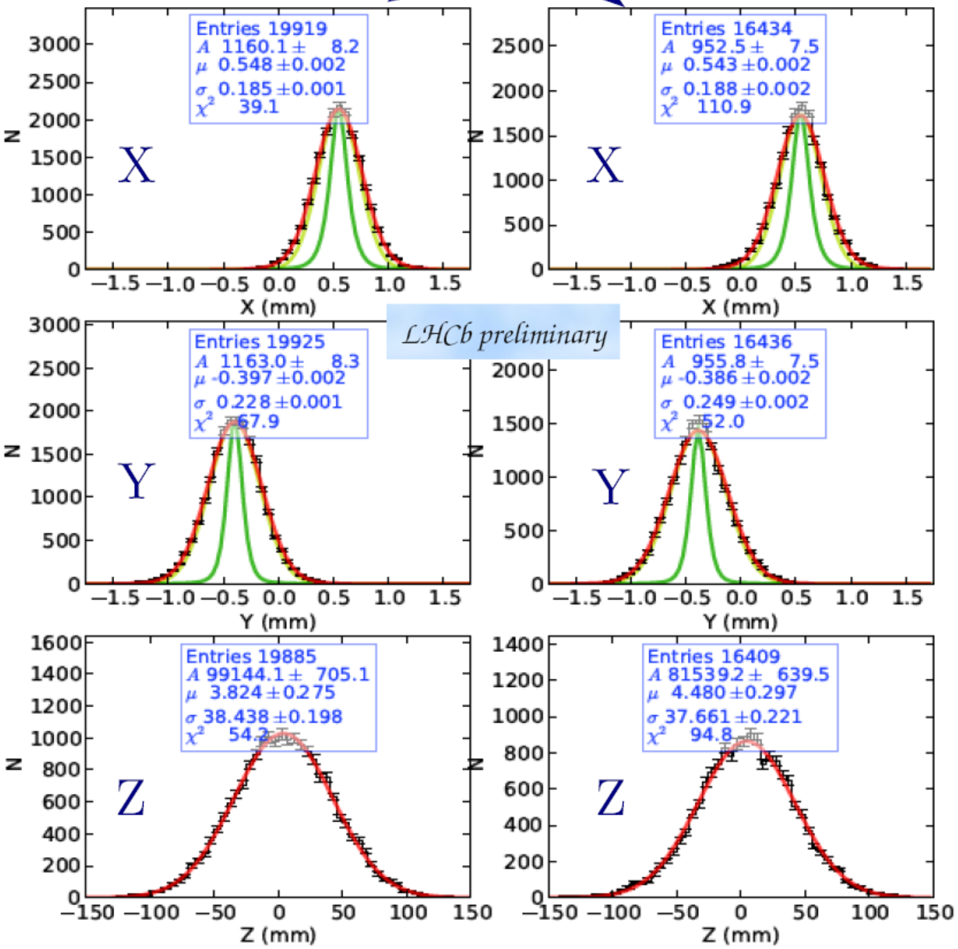
$$\sigma^2_{beam-beam} = \frac{\sigma_1^2\sigma_2^2}{\sigma_1^2+\sigma_2^2} \qquad for\ X, Y$$

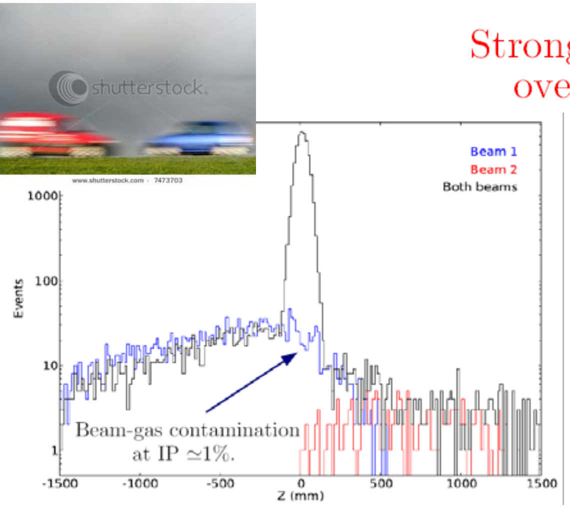
correlated

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

Strong constraint on overlap integral

Two colliding bunches

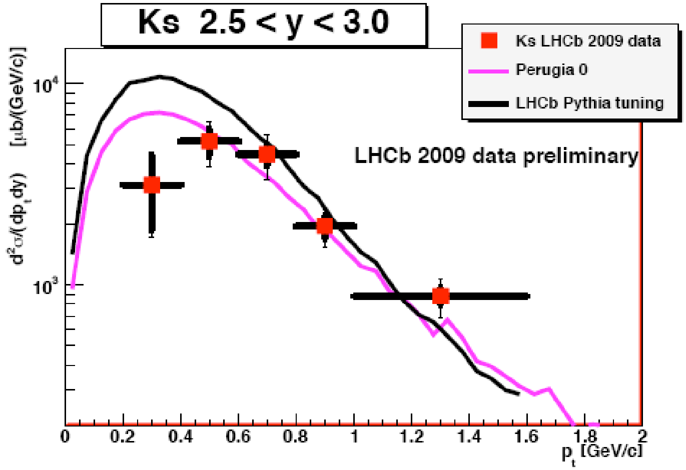


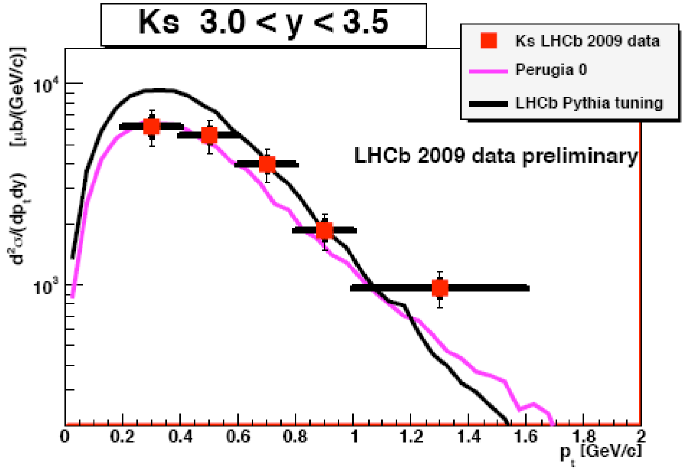


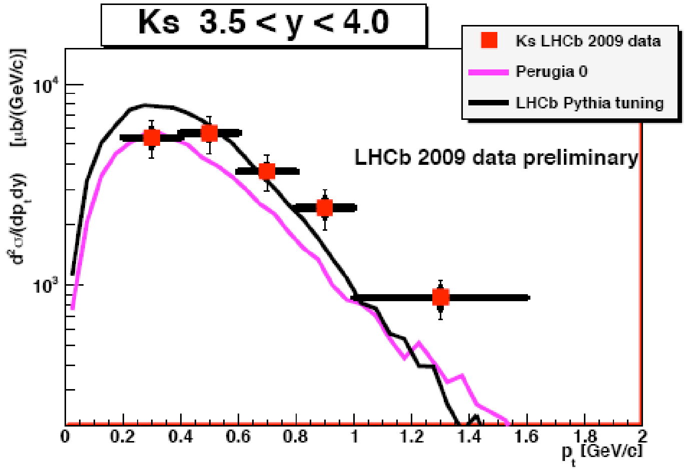
Beam-gas contamination at IP ≃1%.

K^0 Yields

- Including $L_{int}=6.8\pm1.0\ \mu b^{-1}$







-Crosses: LHCb DATA 2009 Preliminary

-Bold error bars: statistical errors

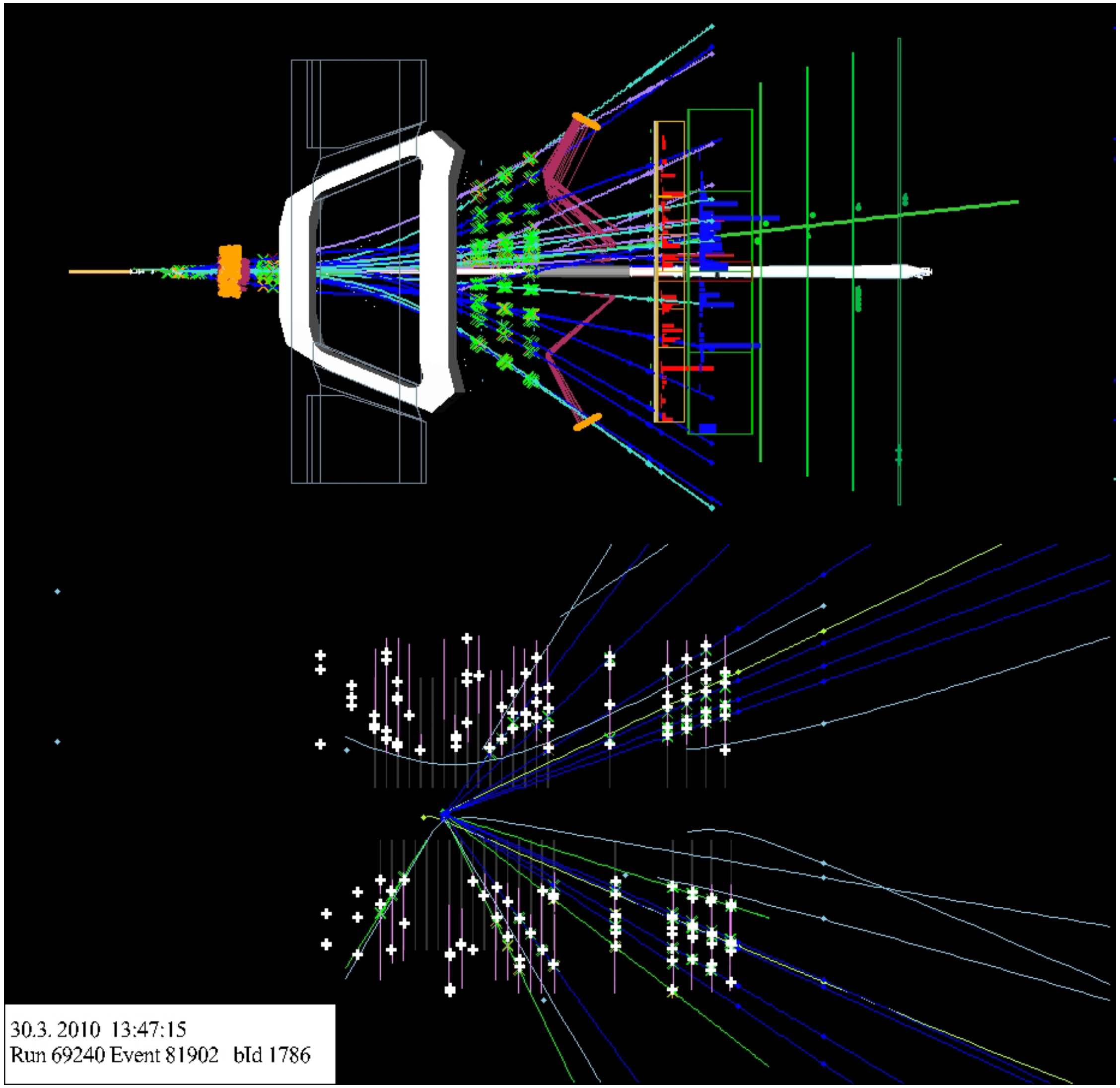
-Thin error bars: syst. including 15% on lumi

-BLACK curve: LHCb PYTHIA tuning

-PINK curve: Perugia 0 PYTHIA tuning

Cross-sections reasonably consistent with PYTHIA predictions

Start at 7 TeV


30.3. 2010 13:47:15
Run 69240 Event 81902 bId 1786

http://lhcb-public.web.cern.ch/lhcb-public/

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

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

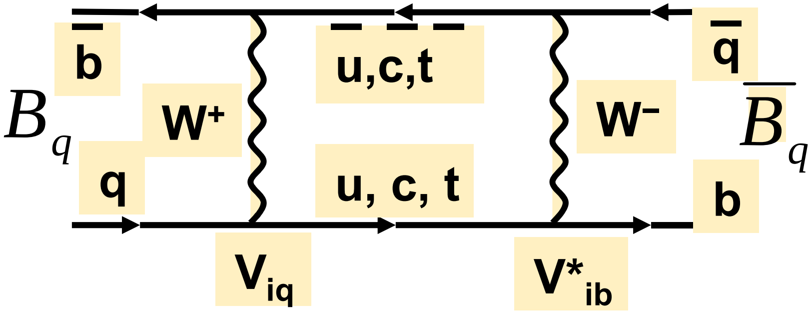
Courtesy of a rather pessimistic but perhaps more realistic Massi Ferro-Luzzi

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)

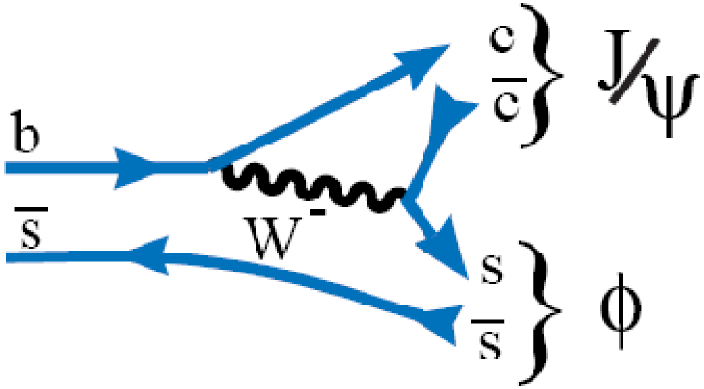
At least in the same ball park

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

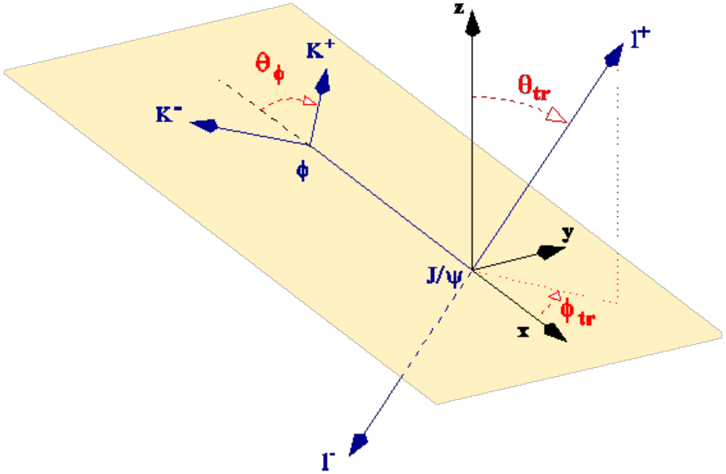


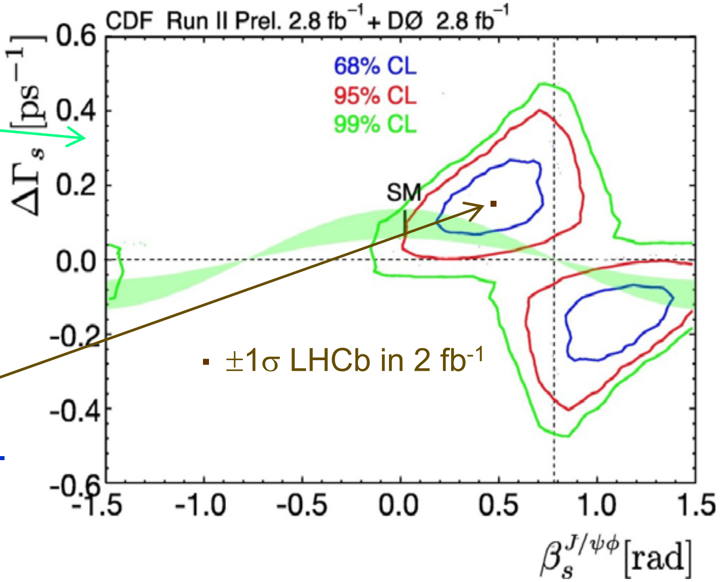
  - Example



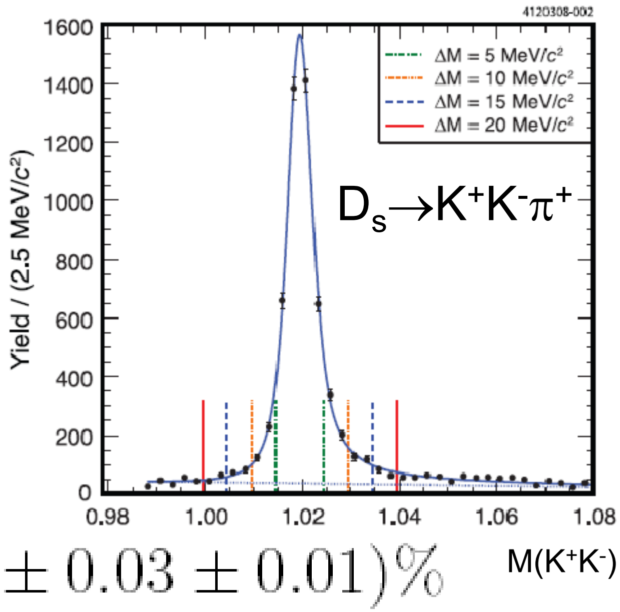
CP Asymmetry in $B_S \rightarrow J/\psi\ \phi$

- Just as $B^o \rightarrow J/\psi\ K_S$ measures CPV phase 2β $B_S \rightarrow J/\psi\ \phi$ measures CPV B_S mixing phase $-2\beta_S$
- Since this is a Vector-Vector final state, must do an angular (transversity) analysis
- The width difference $\Delta\Gamma_S/\Gamma_S$ also enters in the fit
- Combined current CDF & D0 results
- LHCb will get 131,000 such events in 2 fb^{-1}. Projected errors are ±0.03 rad in $2\beta_S$ & ±0.013 in $\Delta\Gamma_S/\Gamma_S$. [Will also use $J/\psi\ f_o(980)$]





β_s Using $B_s \rightarrow J/\psi\ f_0(980)$



- 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

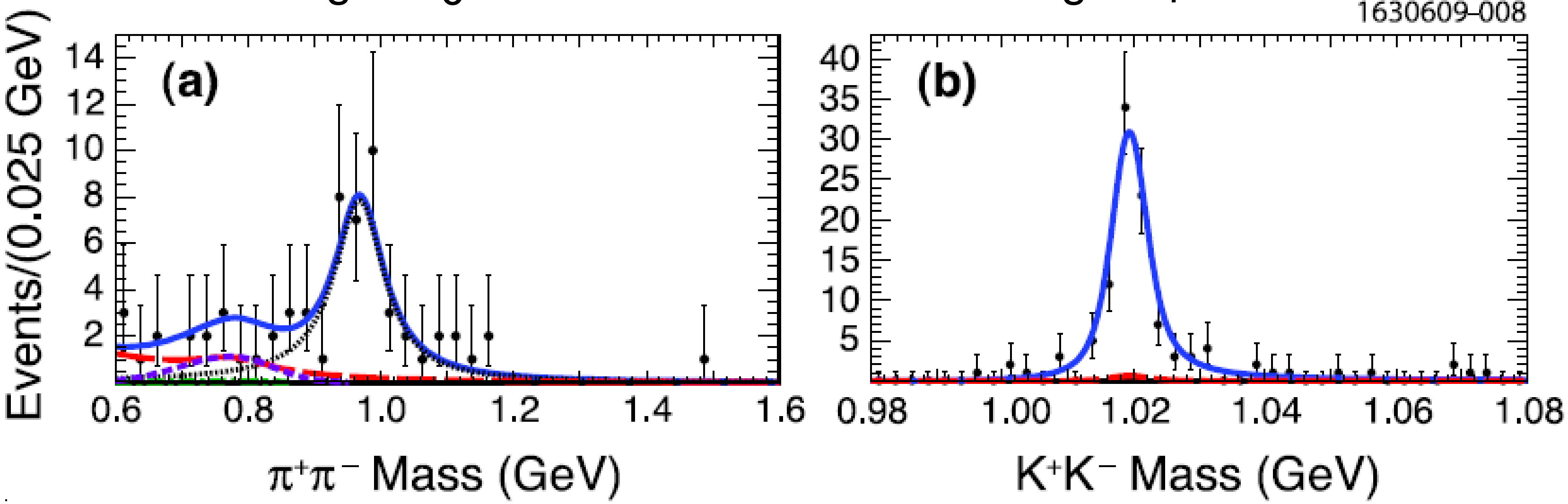
$$\mathcal{B}(D_s^+ \rightarrow f_0(980)e^+\nu,\ f_0 \rightarrow \pi^+\pi^-) = (0.20 \pm 0.03 \pm 0.01)\%$$

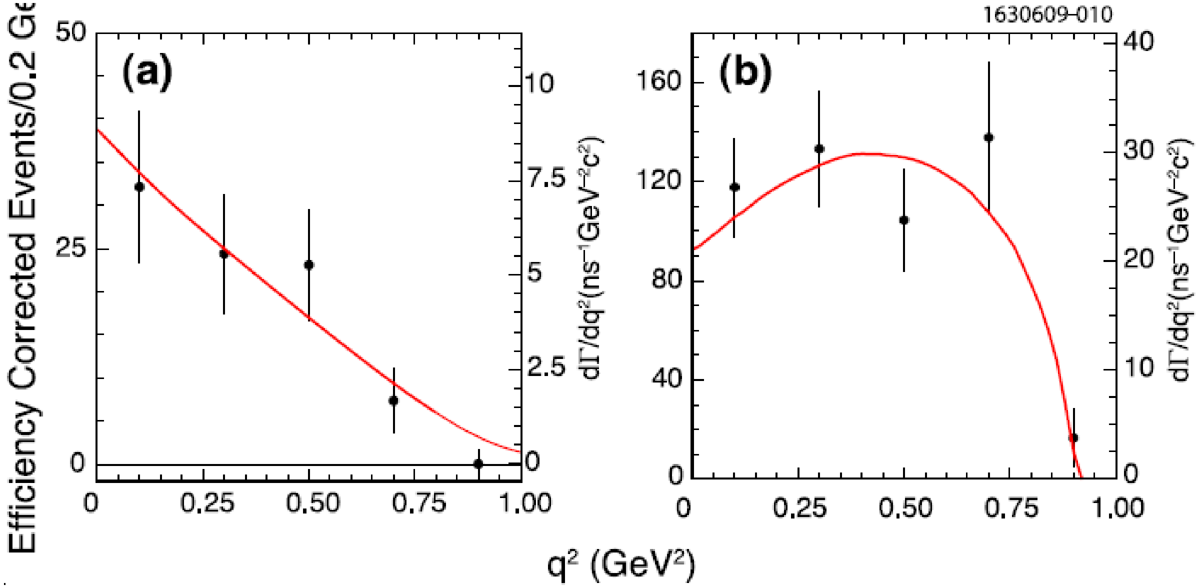
$$\mathcal{B}(D_s^+ \rightarrow \phi e^+\nu,\ \phi \rightarrow K^+K^-) = (1.16 \pm 0.11 \pm 0.06)\%$$

- Estimate: $\mathcal{B}(B_s \rightarrow J/\psi\ f_o \rightarrow J/\psi\ \pi^+\pi^-)/\mathcal{B}(B_s \rightarrow J/\psi\ \phi \rightarrow J/\psi\ K^+K^-)$ =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

CLEO Data arXiv:0907.3201

- $D_s \to f_0 e^+ \nu$ $D_s \to \phi e^+ \nu$





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

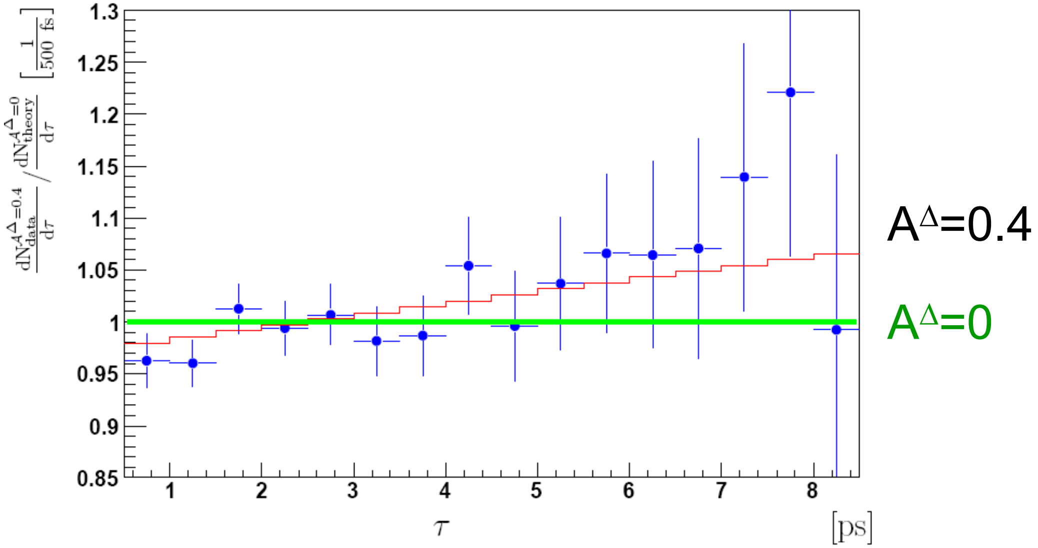
- Define $\tan\psi \equiv \left|\frac{\mathcal{A}\left(\bar{B}_{(s)} \to \Phi^{CP}\gamma_R\right)}{\mathcal{A}\left(\bar{B}_{(s)} \to \Phi^{CP}\gamma_L\right)}\right|$, zero in SM
- Theory

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

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

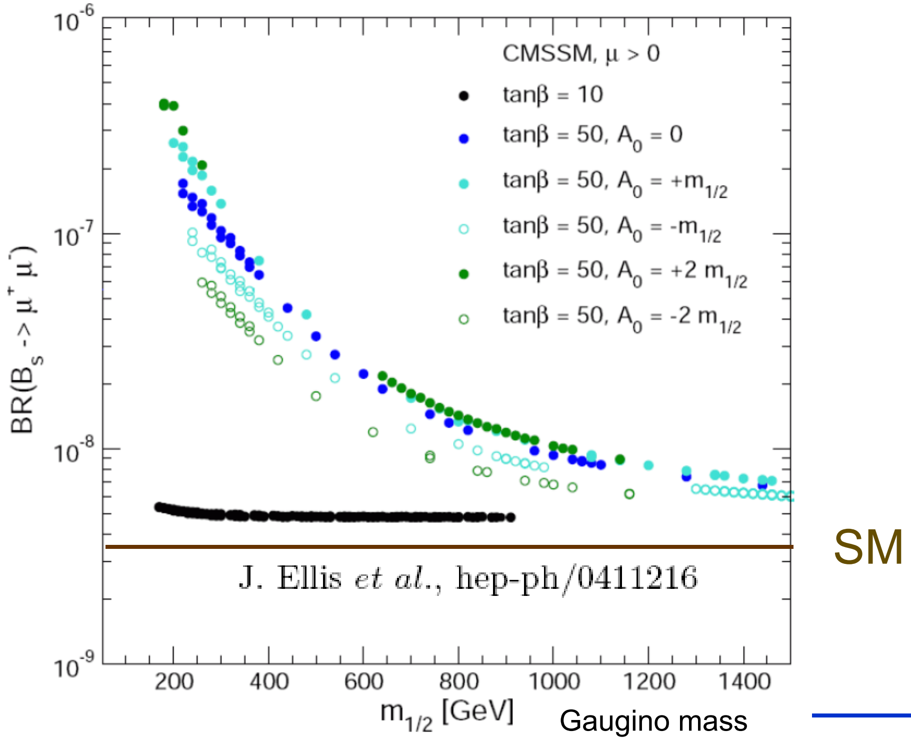
where $A^\Delta = \sin 2\psi$

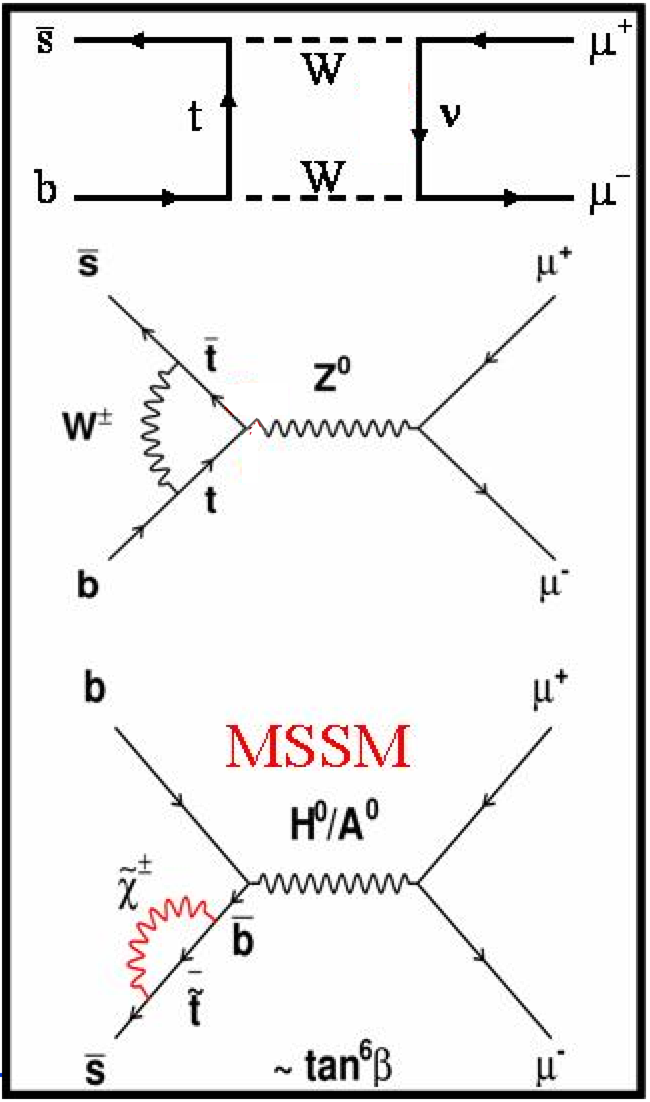
- Sensitivity (assume $\Delta\Gamma_S/\Gamma_S = 0.12$)
- $\sigma(\sin 2\psi) = 0.22$ 2fb^{-1}
- $\sigma(\sin 2\psi) = 0.10$ 10fb^{-1}
- $\sigma(\sin 2\psi) = 0.02$ 100fb^{-1}



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

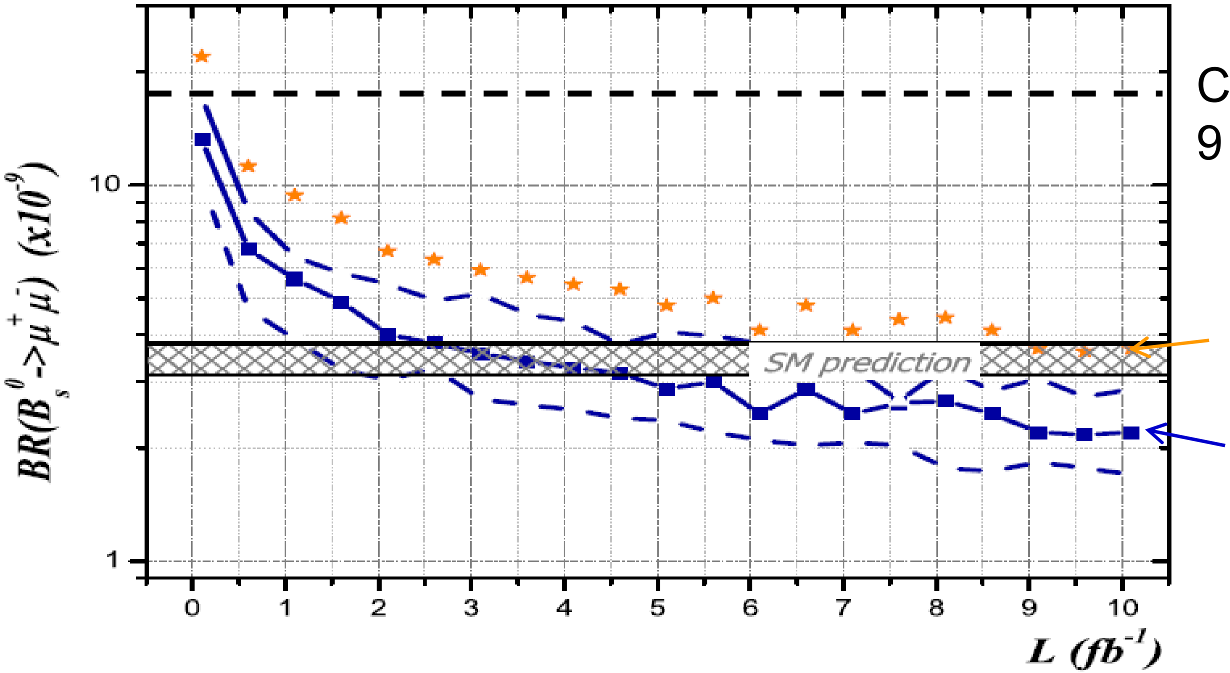
- Branching Ratio very sensitive to SUSY
- In MSSM goes as $\tan^6\beta$





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

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



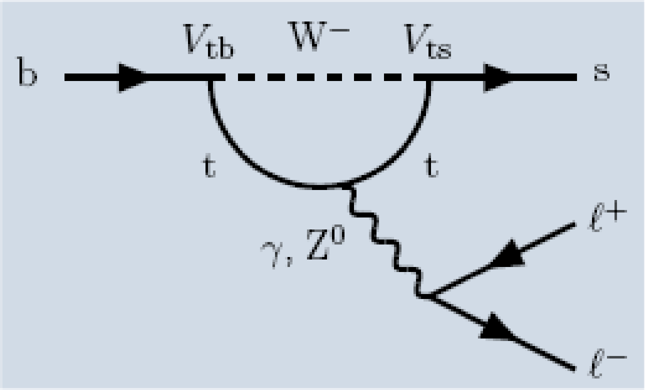
CDF+D0 expected
9 fb^{-1}

5σ measurement

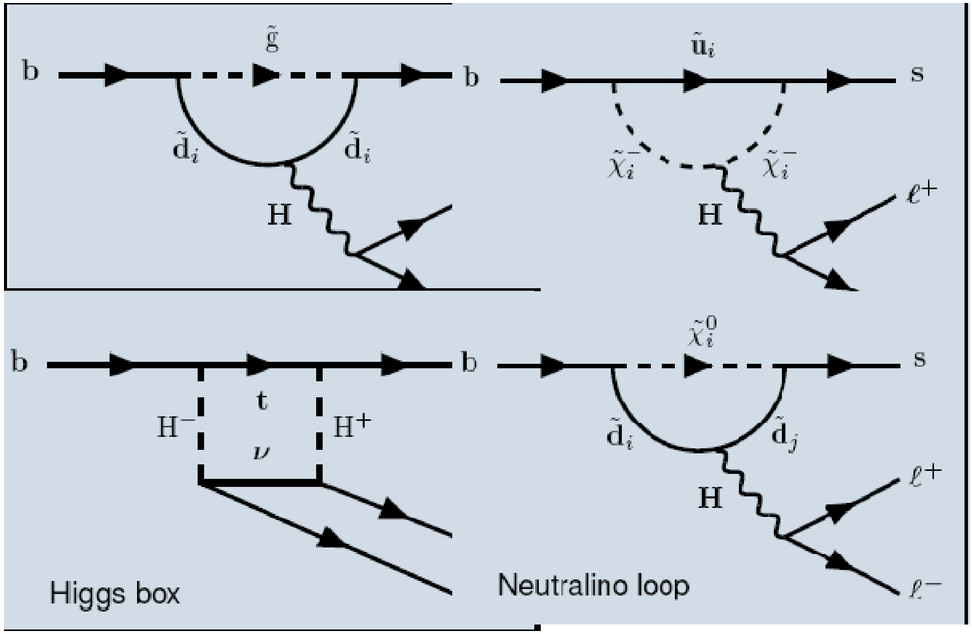
3σ measurement

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

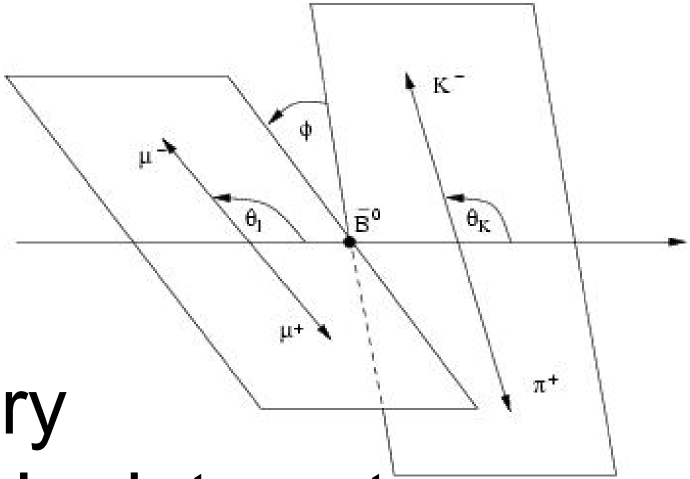
- Standard Model:



- Supersymmetry:



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



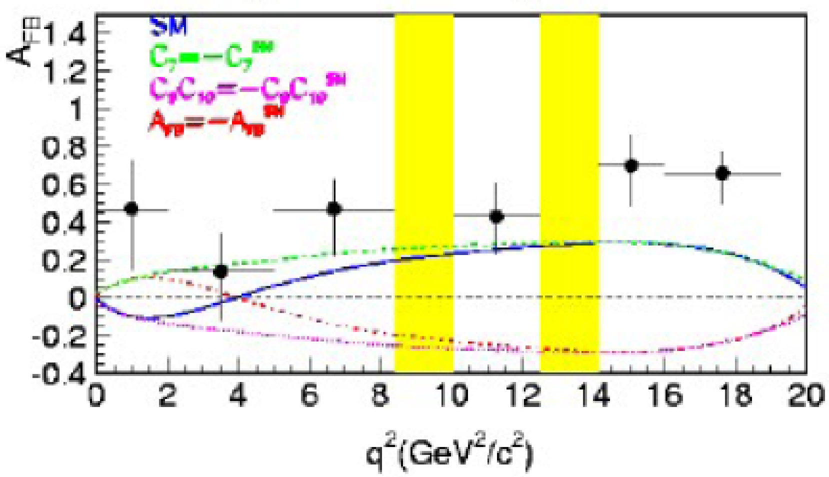
- Described by three angles (θ_l, ϕ, θ_K) and di-μ invariant mass q^2
- Forward-backward asymmetry A_{FB} of θ_l distribution of particular interest:
  - Varies between different NP models →
  - At $A_{FB} = 0$, the dominant theoretical uncertainty.from $B_d \rightarrow K^*$ form-factors cancels at LO

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

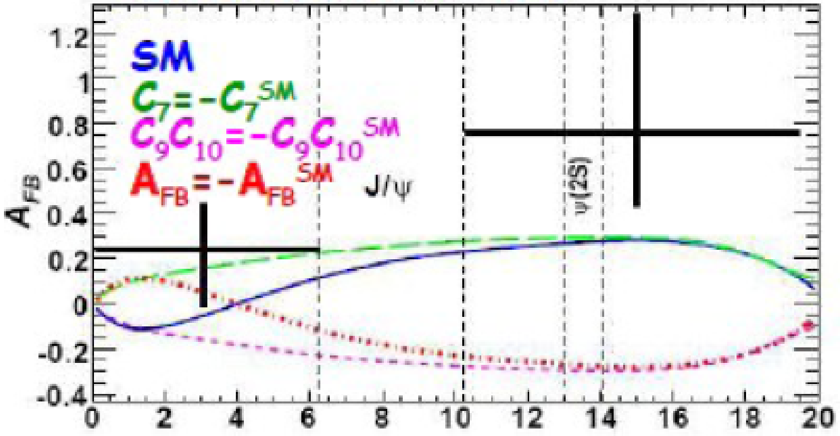
$B \to K^{*}\mu^{+}\mu^{-}$

- 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 ~750 in 300 pb^{-1}(with $\mu^{+}\mu^{-}$ only)
- *~7k events / 2fb^{-1} with B/S ~ 0.2. After 10 fb^{-1}zero of A_{FB} located to ±0.28 GeV^2*

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

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

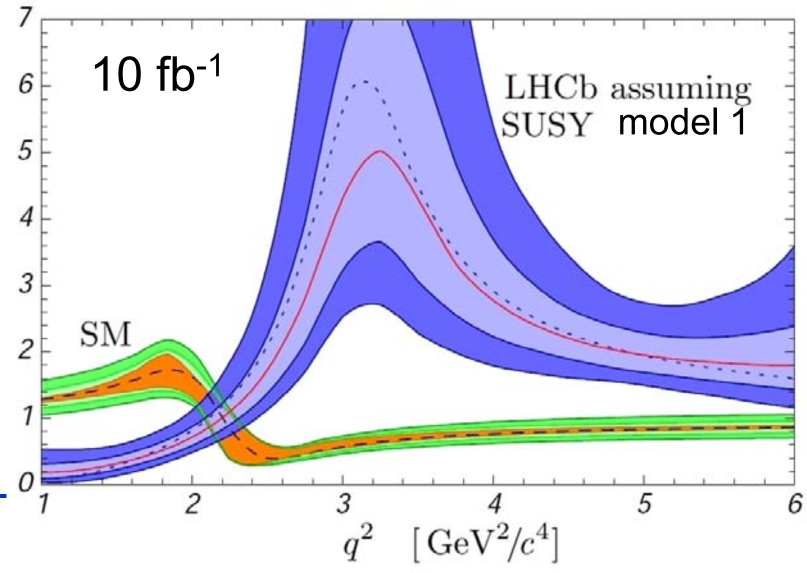
$$A_{\parallel L,R} = -\sqrt{2} N m_B (1-\hat{s})\left[(\mathcal{C}_9^{(\mathrm{eff})} \mp \mathcal{C}_{10}) + \frac{2\hat{m}_b}{\hat{s}}(\mathcal{C}_7^{(\mathrm{eff})} - \mathcal{C}_7'^{(\mathrm{eff})})\right]\xi_\perp(E_{K^*}),$$

ξ_i are form factors

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

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

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

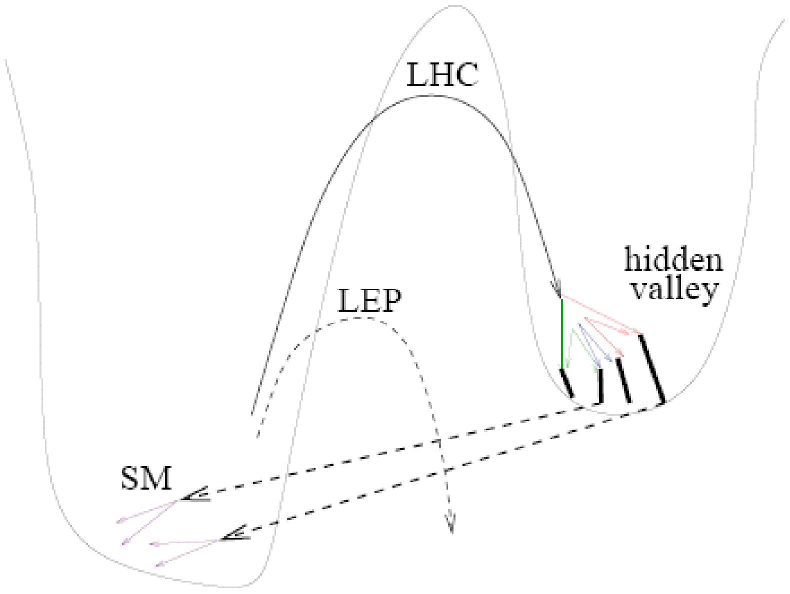


Exotic Searches

- 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

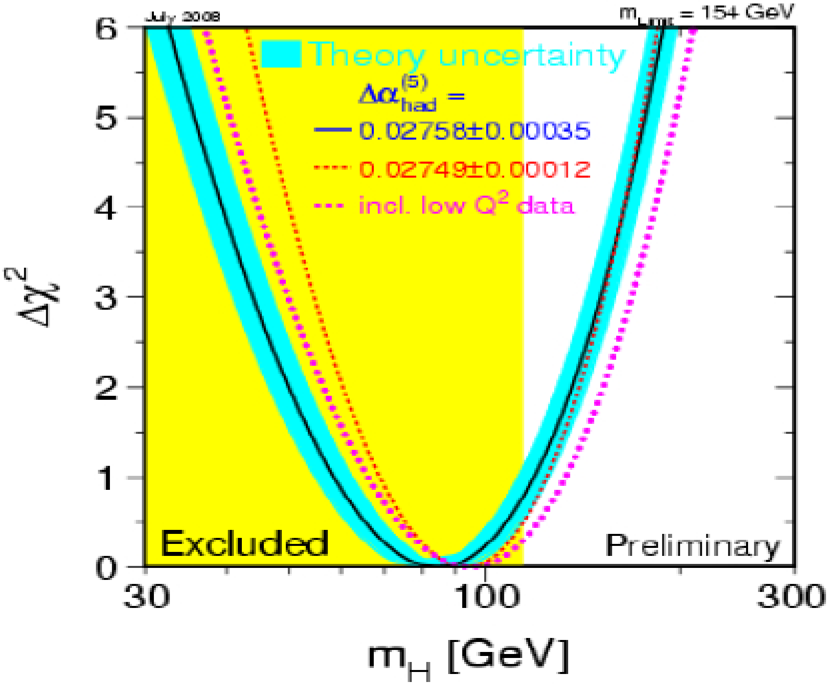
Search for Hidden Valleys

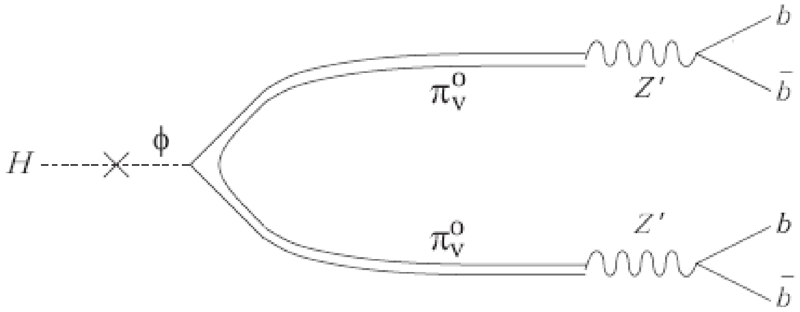
- New heavy Gauge sectors can augment the Standard Model (SM) as well SUSY etc..
- These sectors arise naturally in String theory
- It takes Energy to excite them
- They couple to SM via Z′ or heavy particle loops
- From Strassler & Zurek [hep-ph/604261]



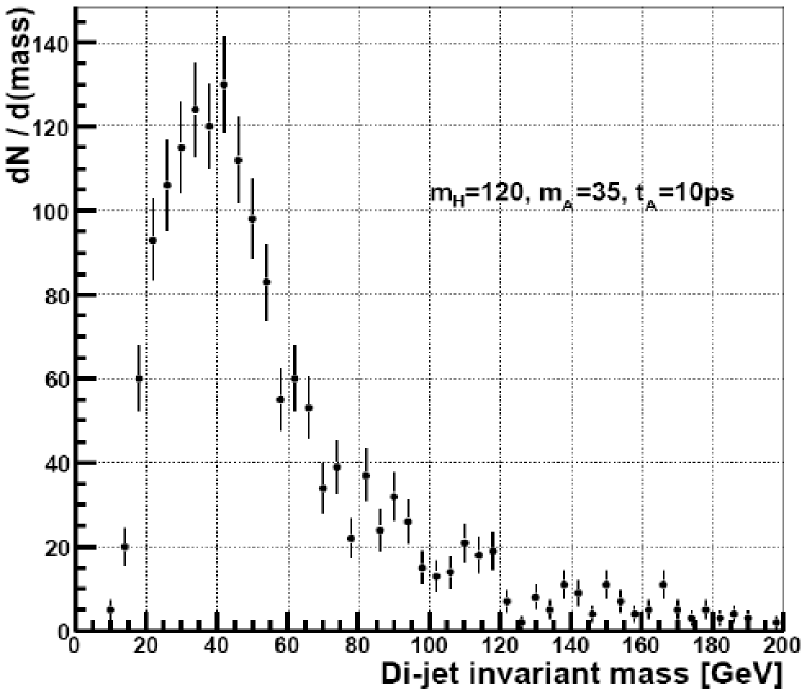
Search for Exotic Higgs Decays

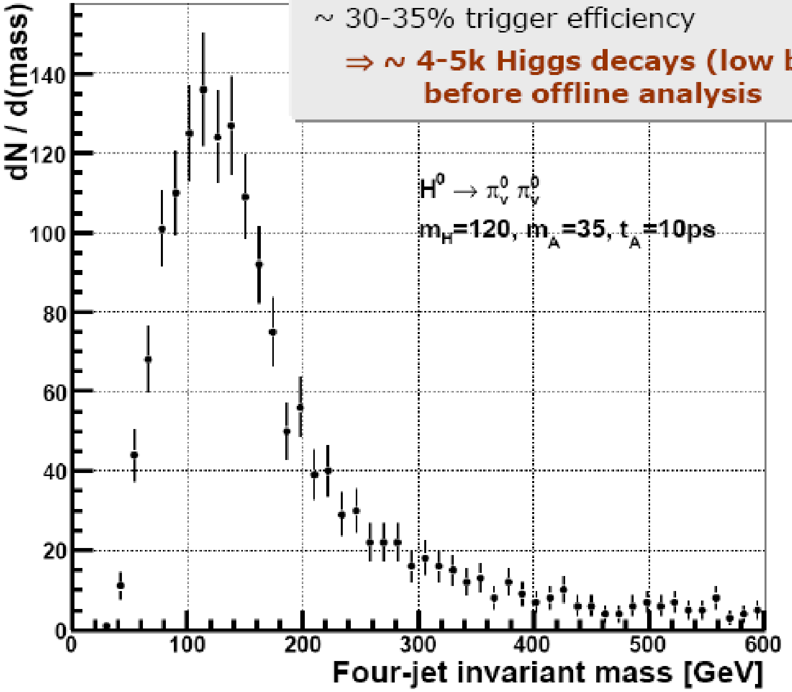
- Recall tension between predicted SM Higgs mass using Electroweak data & direct LEP limit
- Limit is based on SM decays, would be void if there were other modes
- Hidden Valley provides new scalars π^o_v, allowing $H^o \rightarrow \pi^o_v\, \pi^o_v \rightarrow b\bar{b}$, with long lifetimes possible.





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}

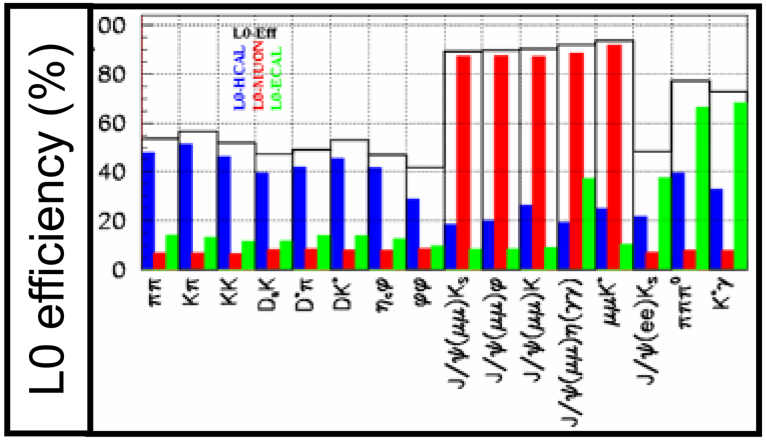
The LHCb Upgrade

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



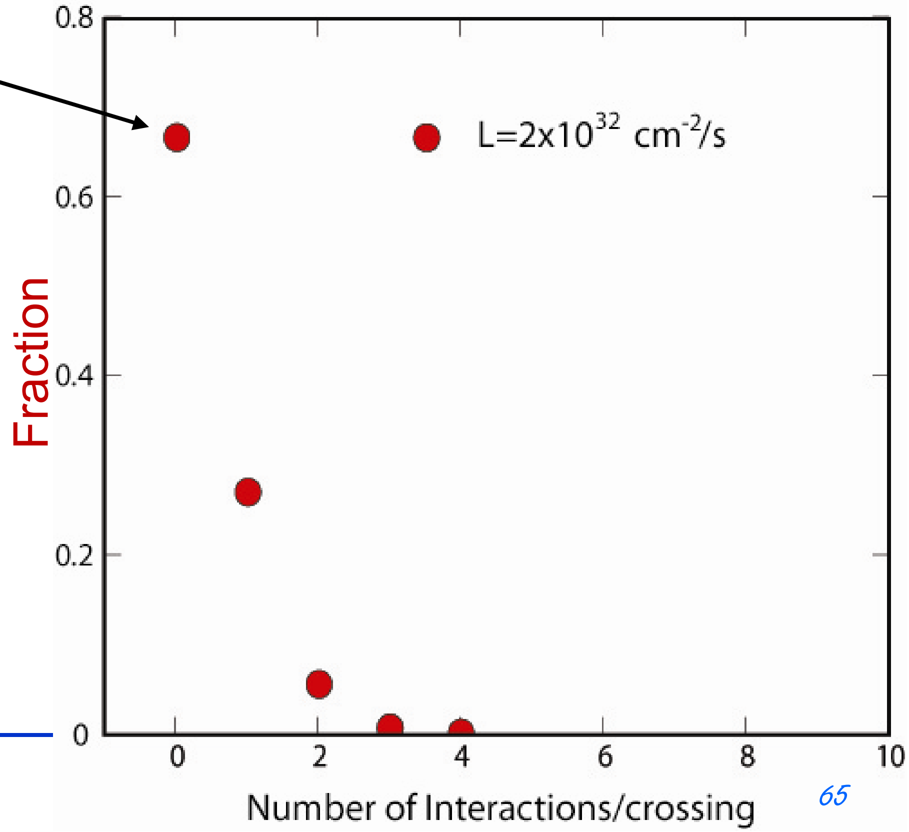
- L0 typically is 50% efficient on fully hadronic final states
- HLT1 is 60% on D_SK^-
- HLT2 is 85% on D_SK^-
- Product is 25%, room for improvement

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…

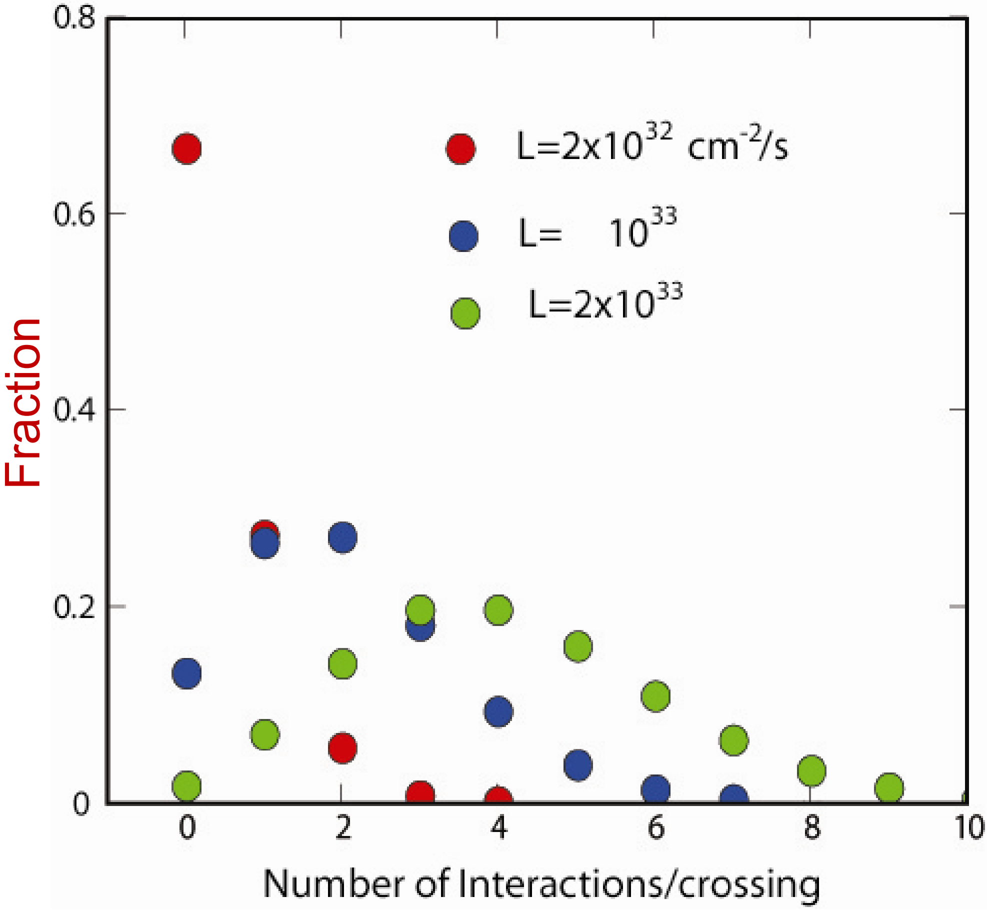
Current Running Conditions

- Luminosity $2\text{x}10^{32}$ 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 $2x10^{33}$ increases to ~4.6
- Trigger change: will readout entire detector each crossing & use software to select up to 20 kHz of events



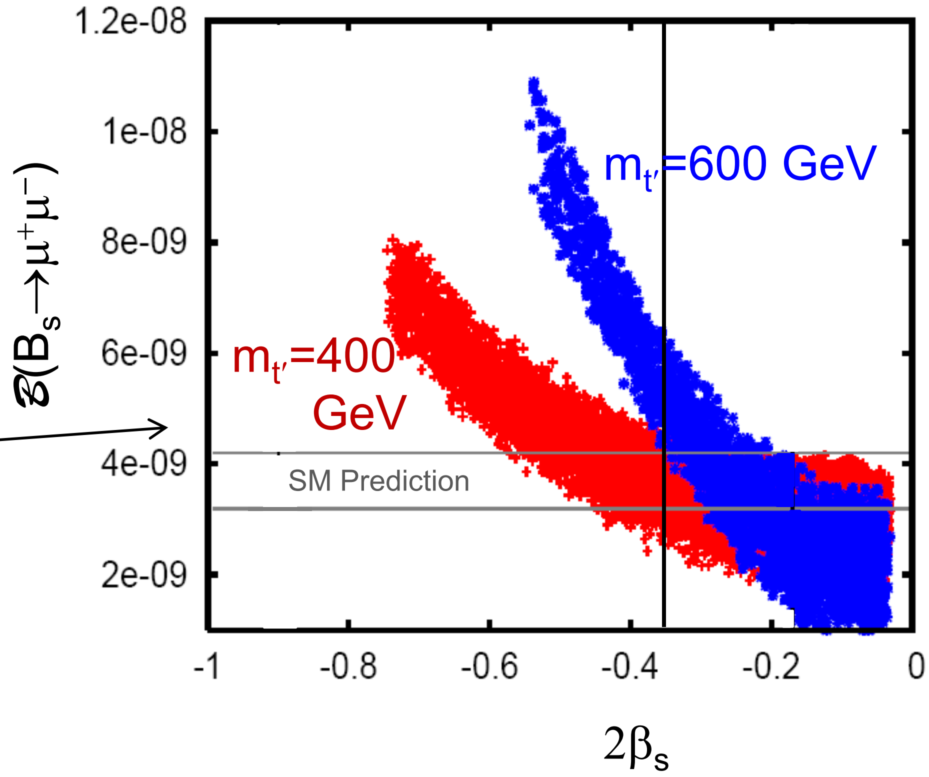
One Ex: LHCb Sensitivities for $2\beta_s$

	$0.3\ fb^{-1}$	**$2.0\ fb^{-1}$**	**$10\ fb^{-1}$**	**$100\ fb^{-1}$**
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^o
CPV($B_s \to D_s K$) (γ)	1-2^o
$\mathcal{B}(B_s \to \mu^+\mu^-)$	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	2x10^{-5}
Charm mixing y'	2.8x10^{-4}
Charm CP y_{CP}	1.5x10^{-4}

The Future

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

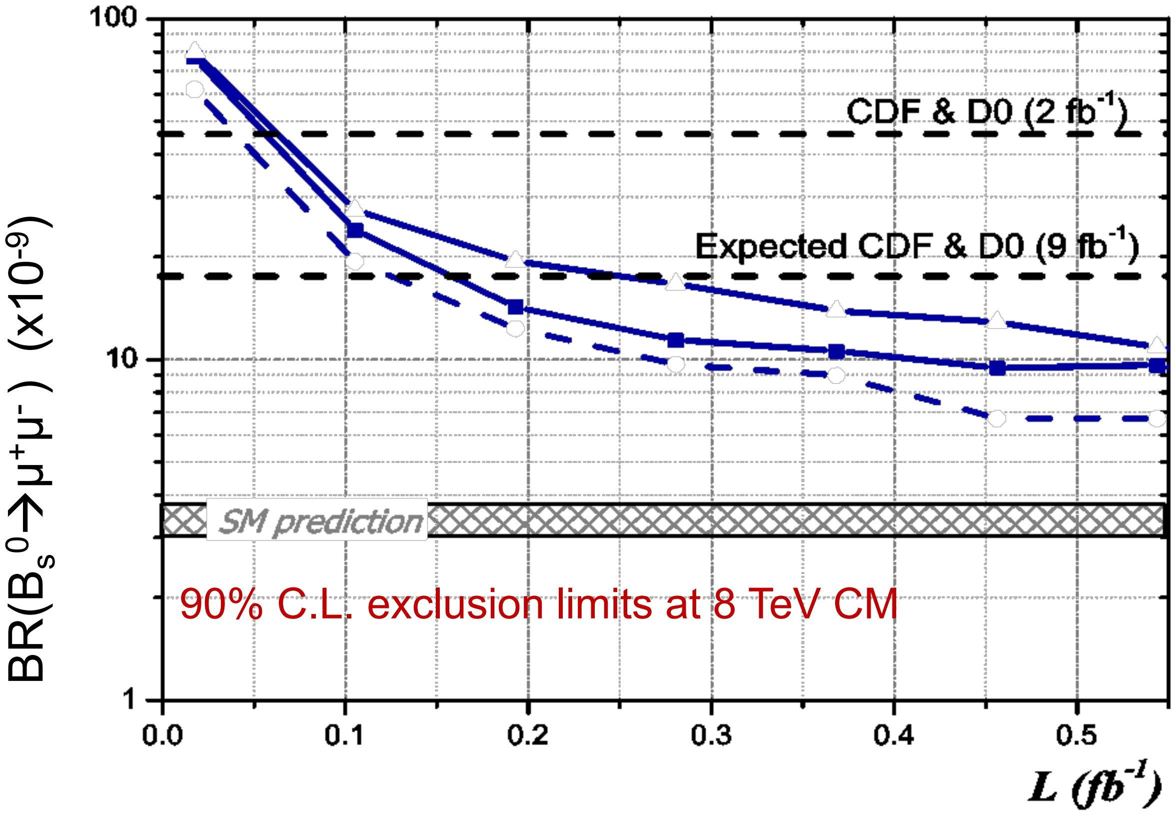
ATLAS CMS high p_T physics	BSM	Only SM	BSM
LHCb flavour physics	Only SM	BSM	BSM
Particle Physics	☺	☺	☺

- 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

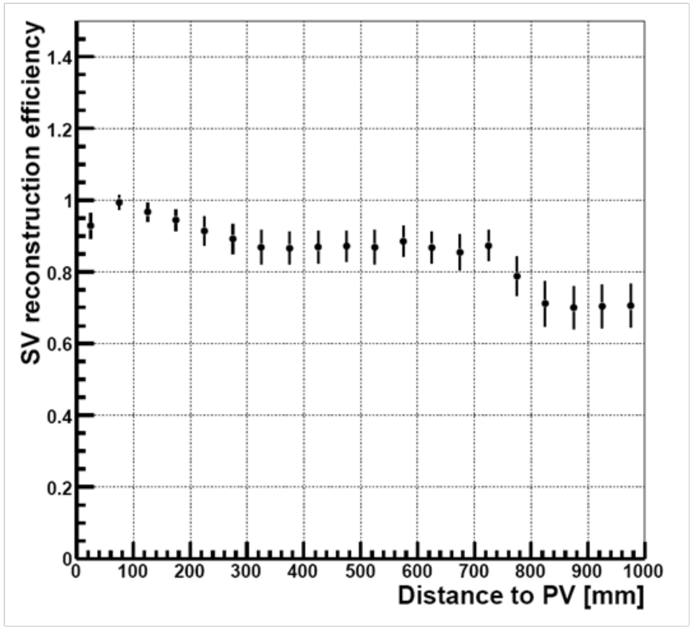
Device	User	date	Intended Use	Actual use
Optical Telescope	Galileo	1608	Navigation	Moons of Jupiter
Compound Microscope	Hooke	1650	Magnification	Bacteria, Cells…
Optical Telescope	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, 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 ⟨0.4 ms⟩ 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



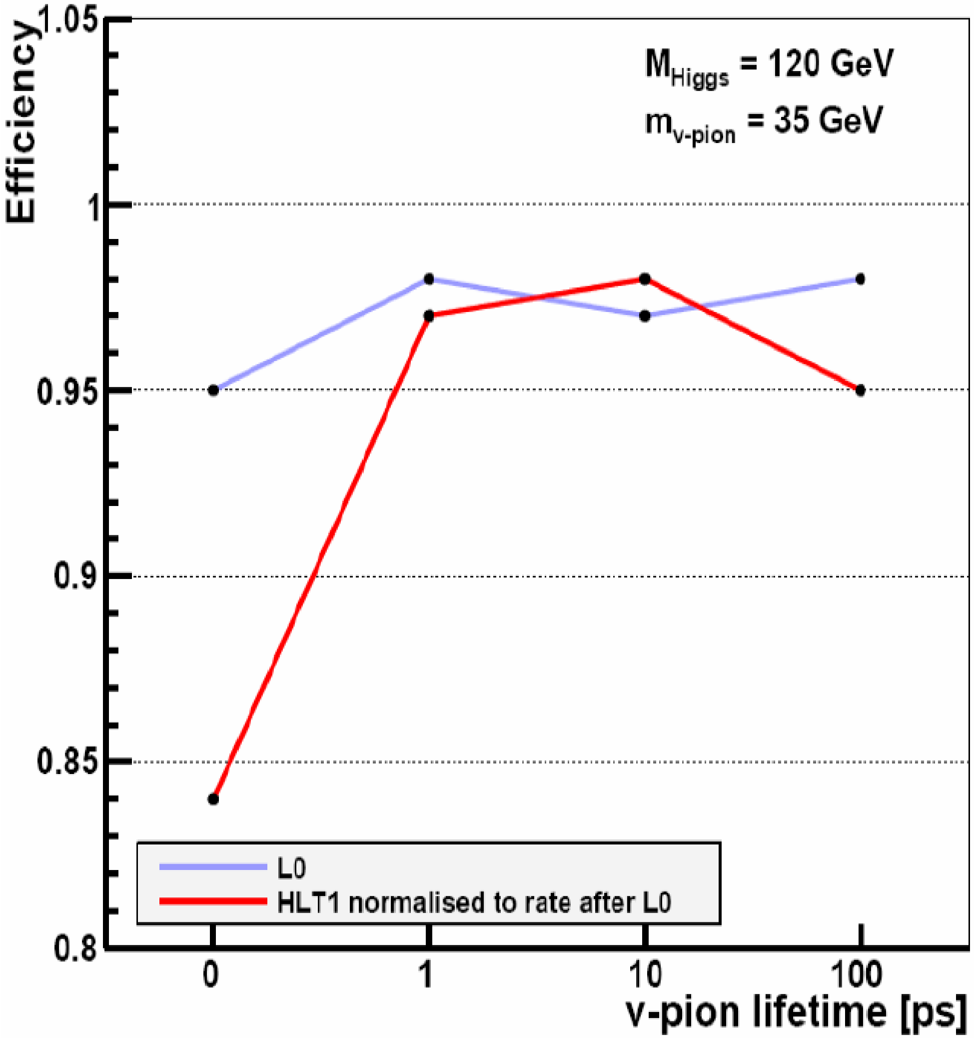
- ATLAS/CMS are designing triggers to see these decays if they occur in their calorimeters or muon system, sensitive to much longer lifetimes. See S. Giagu “Search for long-lived particles in ATLAS and CMS,“ arXiv:0810.1453v1 [hep-ex].

Higgs Studies

- Many different kinds of exotic decays possible, but we have studied only two so far
- We know H^o production cross-section as function of H^o mass, e.g. $gg \rightarrow H^o$ 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

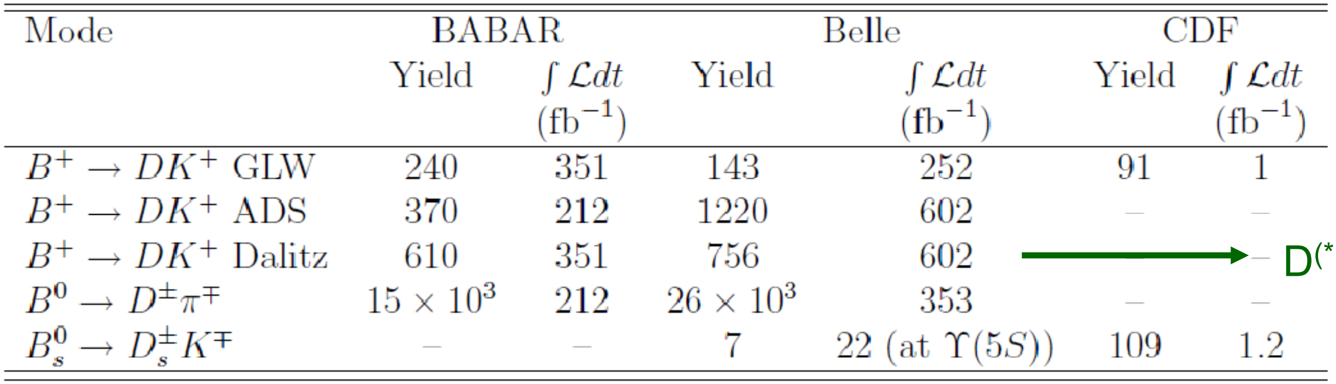
- More software cuts. Also high efficiency

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 Yield	BABAR $\int \mathcal{L}dt$ (fb^{-1})	Belle Yield	Belle $\int \mathcal{L}dt$ (fb^{-1})	CDF Yield	CDF $\int \mathcal{L}dt$ (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

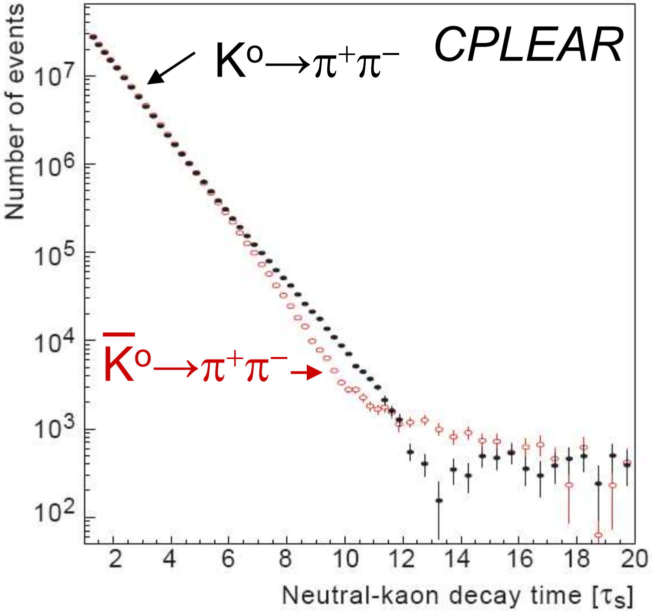
LHCb expectations with 100 pb^{-1}
(but including no HLT, and
assuming 14 TeV xsec)

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

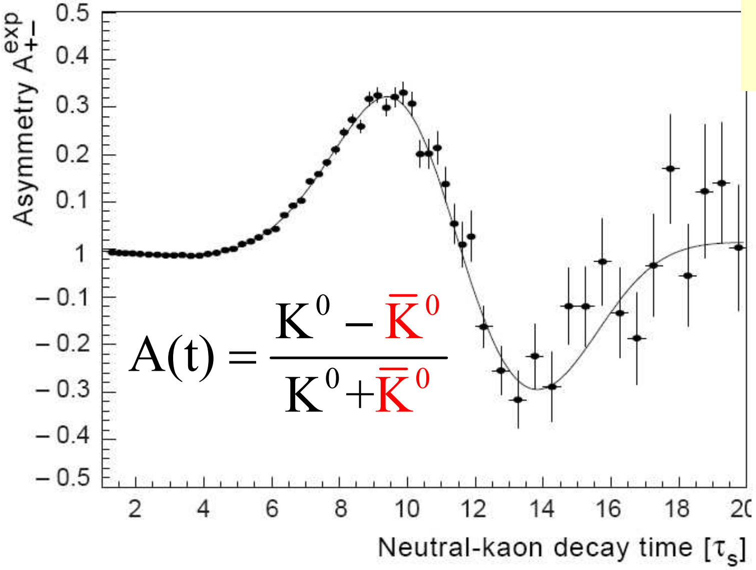
The Enigma of Baryogenesis

- 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

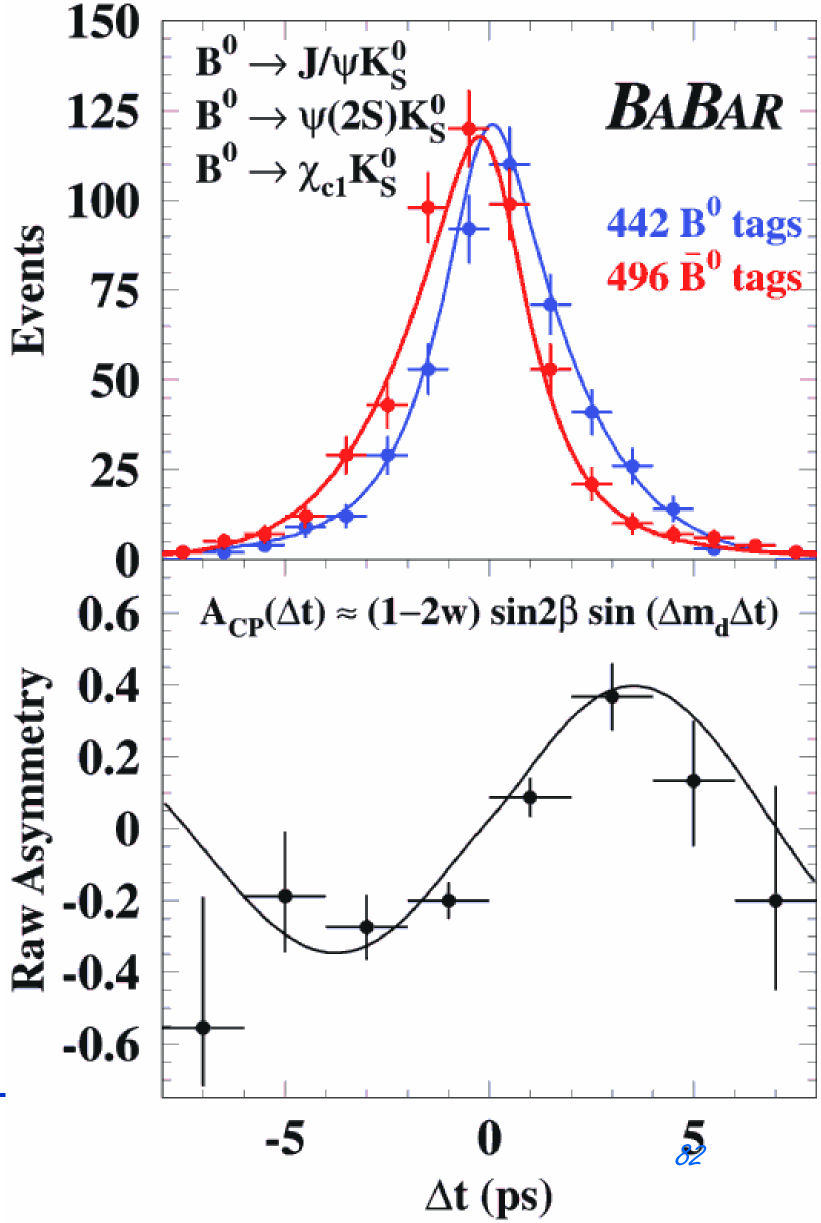
Physical Evidence for CP Violation



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



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



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!
  - $(n_B - n_{\bar{B}})/n_\gamma = \sim 6\times10^{-10}$, while SM can provide only $\sim10^{-20}$
- Therefore, there **must** be new physics

Hierarchy Problem

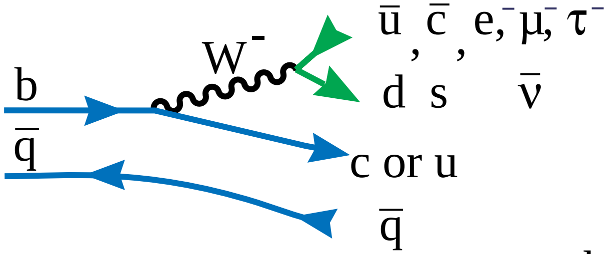
- We don't understand how we get from the Planck scale of Energy ~10^{19} GeV to the Electroweak Scale ~100 GeV without "fine tuning" quantum corrections

General Justification for Flavor Physics

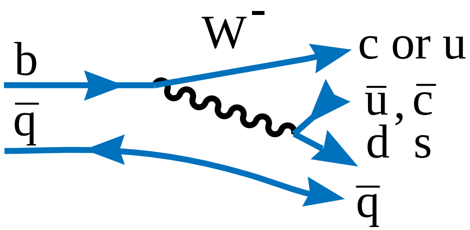
- Expect New Physics will be seen at LHC
  - Standard Model is violated by the Baryon Asymmetry of Universe & by Dark Matter
  - Hierarchy problem (why $M_{Higgs} << M_{Planck}$)
- However, it will be difficult to characterize this physics
- How the new particles interfere virtually in the decays of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

B Decay Diagrams

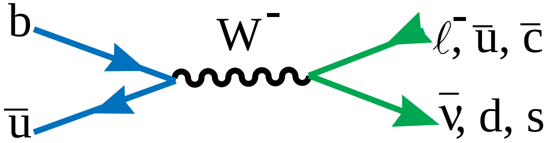
- a) is largest "tree" level diagram
- e) & f) contain "loops," other intermediate particles could contribute



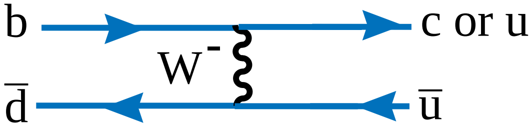
a) simple spectator



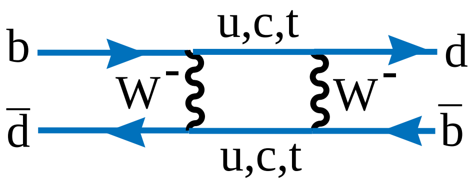
b) hadronic: color suppressed



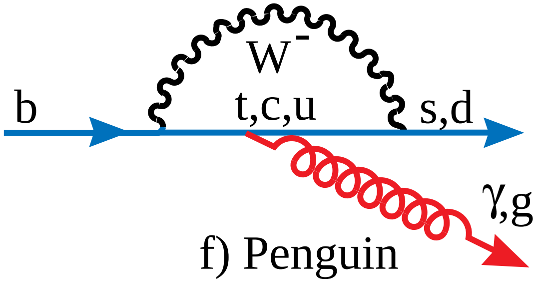
c) annihilation



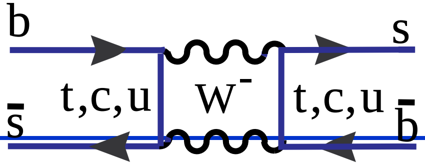
d) W exchange

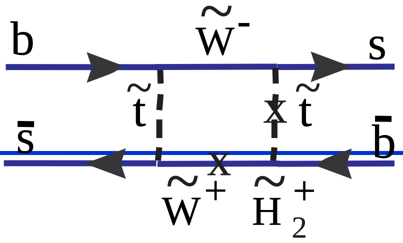


e) box: mixing



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

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

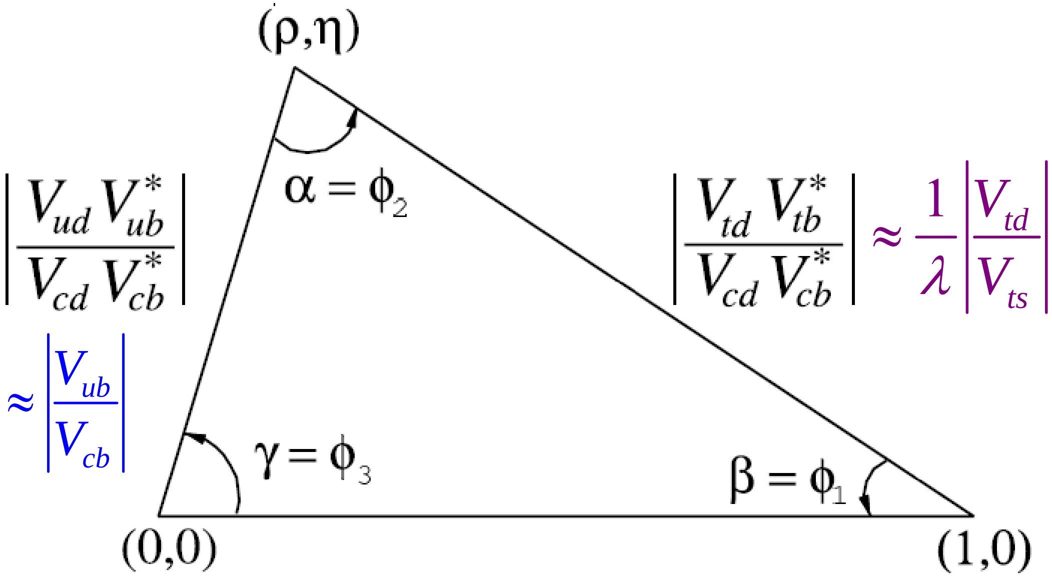
The CKM Matrix

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

- 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



$$\left|\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right| \approx \left|\frac{V_{ub}}{V_{cb}}\right|$$

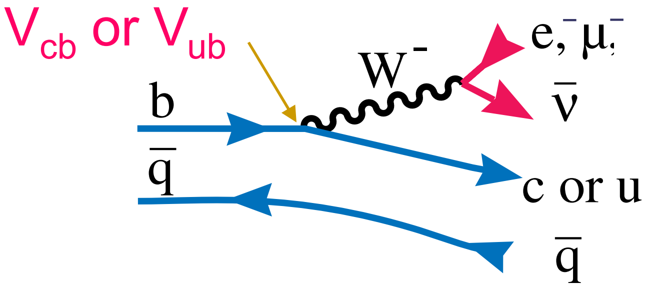
$$\left|\frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}}\right| \approx \frac{1}{\lambda}\left|\frac{V_{td}}{V_{ts}}\right|$$

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

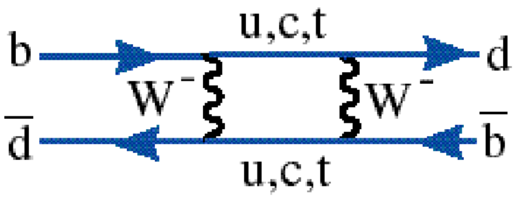
Existing Constraints on ρ & η



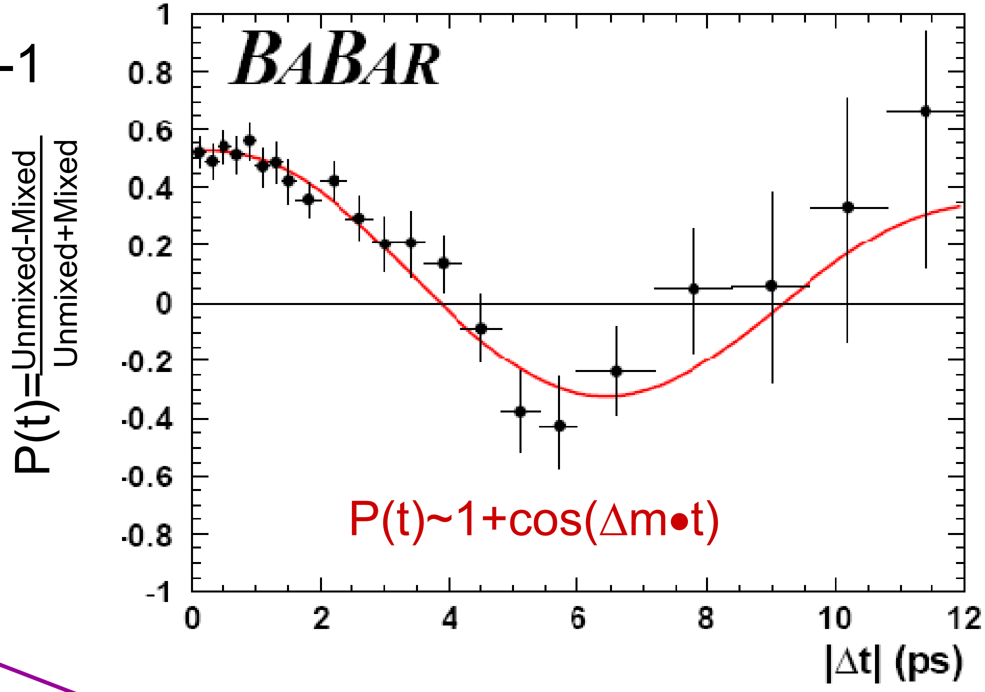
- Consider $V_{ub}/V_{cb} = \lambda(\rho + i\eta)$, we measure the ratio of rates $b \rightarrow u\ell\nu / b \rightarrow c\ell\nu \propto$ $|V_{ub}/V_{cb}|^2 = \lambda^2(\rho^2 + \eta^2)$, a circle
  - Unfortunately, there are theoretical errors due to the fact that the b quark is paired with a light 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 B° Mixing

- B° mixing measured by ARGUS in 1987



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



What we are interested in

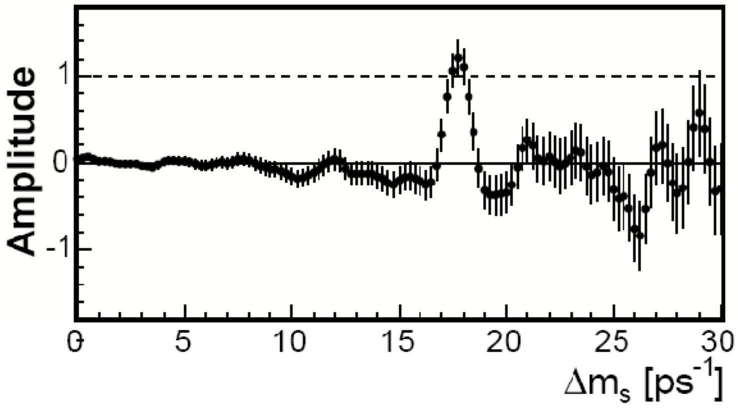
- $$x_d \equiv \frac{\Delta m}{\Gamma} = \frac{G_F^2}{6\pi^2} B_{B_d} f_B^2 m_B \tau_B |V_{tb}^* V_{td}|^2 m_t^2 F\left(\frac{m_t^2}{M_W^2}\right) \eta_{QCD}$$

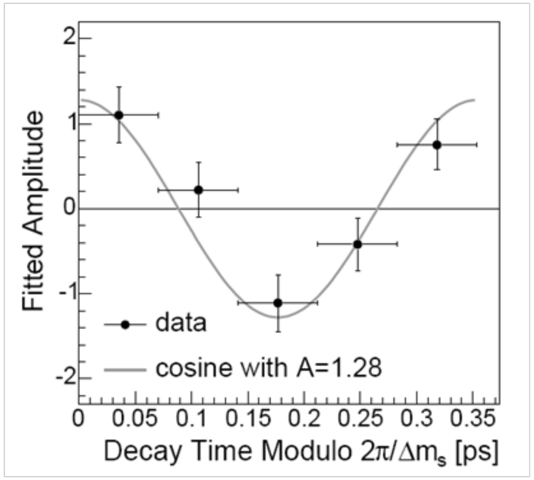
Theoretically determined parameters

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





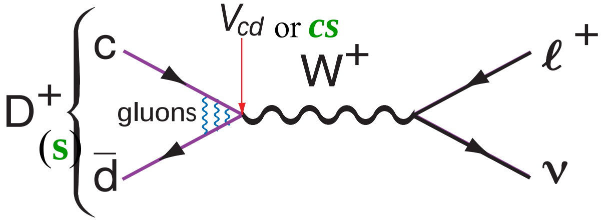
$$\Delta m_s = 17.31^{+0.33}_{-0.18} \pm 0.07\ \mathrm{ps}^{-1}$$

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

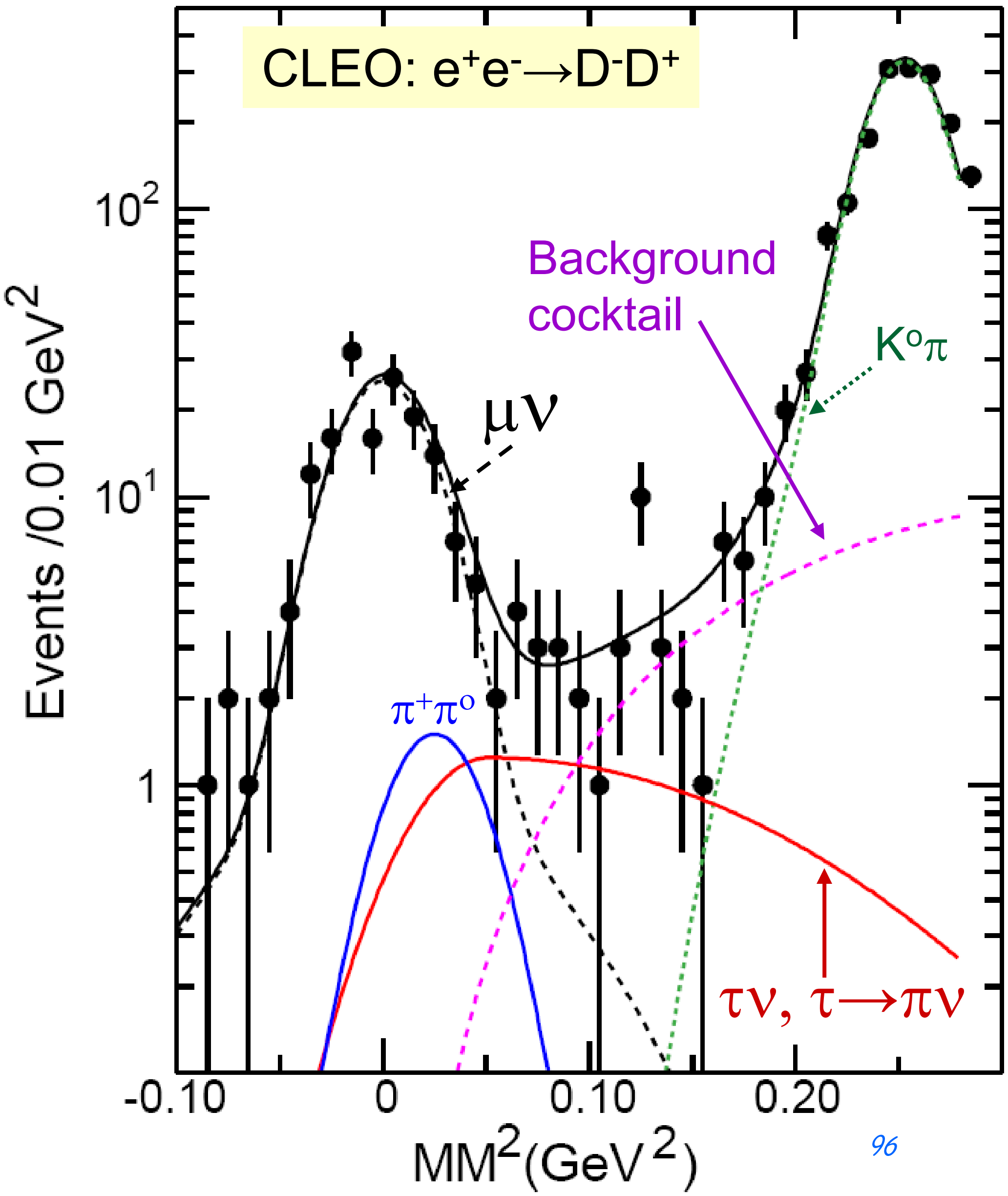
a circle in the ρ–η plane centered at (1,0)

Lattice QCD & Determination of f_B

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



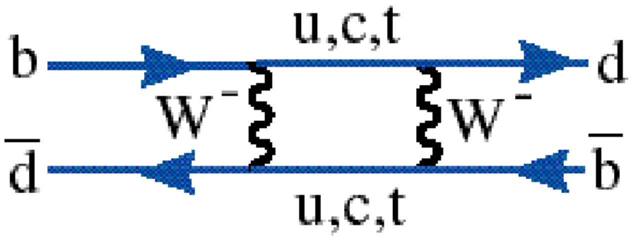
- f_{D^+} CLEO results
  f_{D^+}=(205.8±8.5±2.5) MeV
- Calculation of Follana et al
  208±4 MeV
- Excellent agreement!



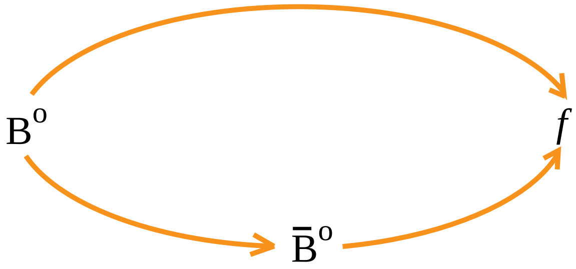
Problem with f_{Ds}?

- 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 $B^o \to f$ and $\overline{B}^o \to \bar{f}$, with $f = \bar{f}$

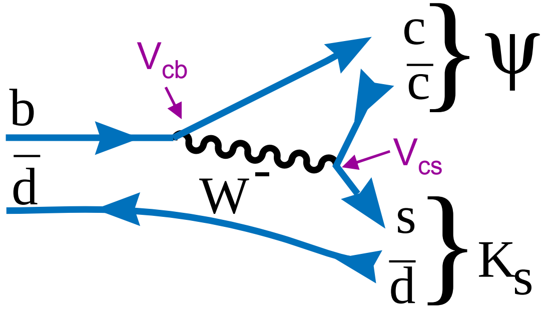


- The mixing amplitude for B_d generates an asymmetry ~$\sin(2\beta)$, where
  $\sin(2\beta) = -2(1-\rho)\eta / [(1-\rho)^2 + \eta^2]$
  - Asymmetry means

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

~~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

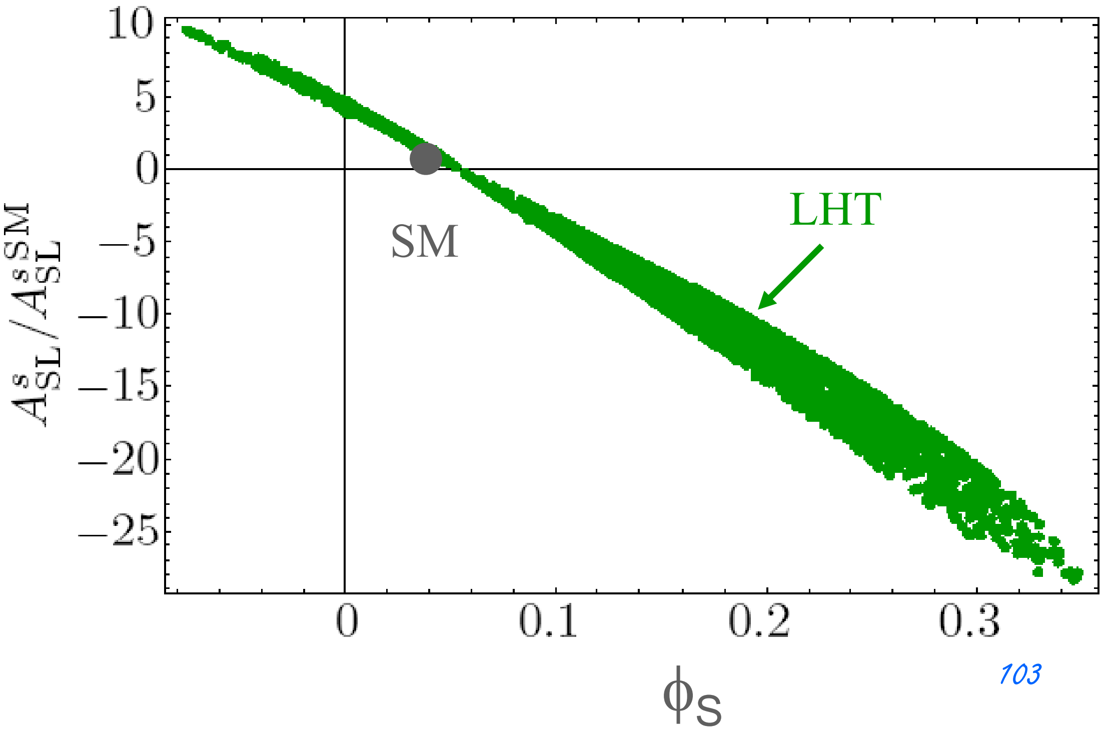
- Recently Completed
  - CLEO
  - BABAR
  - BELLE
- Ongoing
  - CDF (B$_S$)
  - D0 (B$_S$)
- New
  - LHCb (B$_S$)
  - BELLE Upgrade
- Proposed
  - Super B (at Frascati) & higher lumi Belle Upgrade
  - LHCb Upgrade (B$_S$)

Little Higgs Model with T Parity

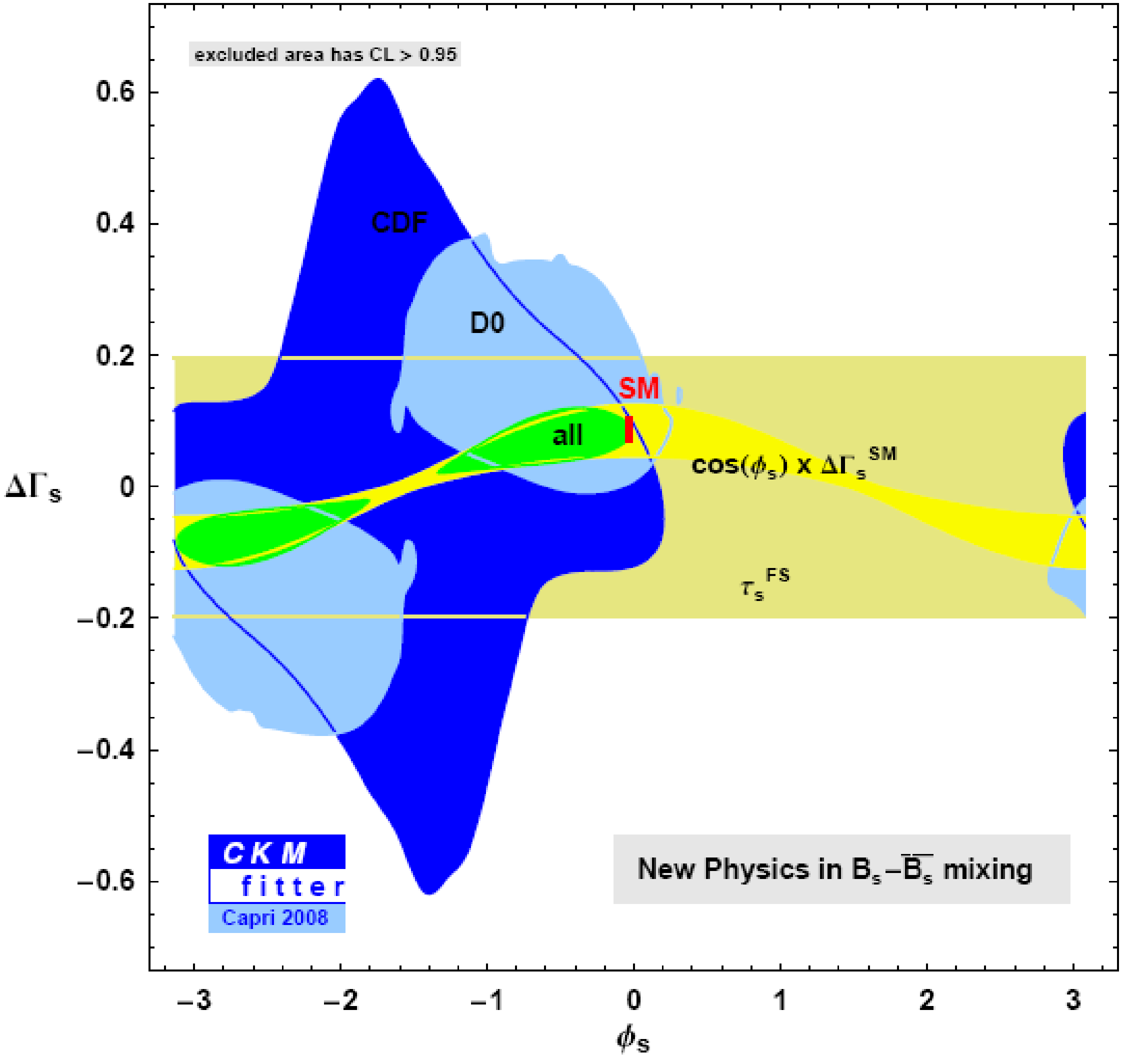
- There exist regions of parameter space consistent with measurement where large ϕ_S is predicted & ΔM_S is found somewhat smaller than in the SM.
- In particular, significant enhancement of ϕ_S & the semileptonic asymmetry $A_{SL}^{(S)}$ relative to the SM are found

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

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



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 $$a_f(t) = \frac{\Gamma\left(B^o(t) \rightarrow f\right) - \Gamma\left(\bar{B}^o(t) \rightarrow f\right)}{\Gamma\left(B^o(t) \rightarrow f\right) + \Gamma\left(\bar{B}^o(t) \rightarrow f\right)}$$
- 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

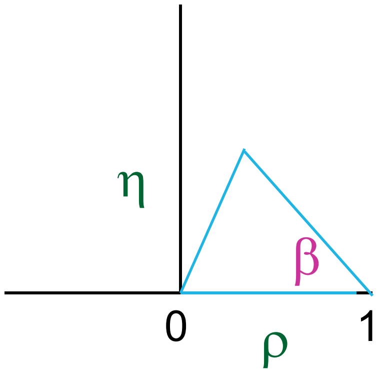
$$a_f(t) = -\frac{x}{1+x^2}\,\mathrm{Im}\,\lambda = -0.48\,\mathrm{Im}\,\lambda$$

good luck, maximum is –0.5

CP violation using CP eigenstates II

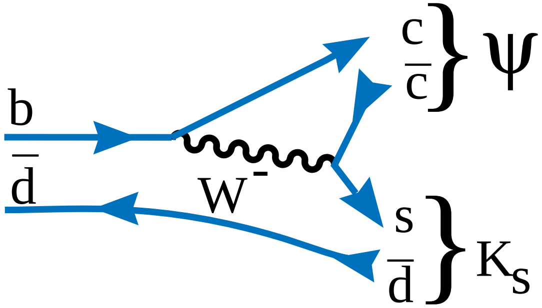
- For B_d, $$\frac{q}{p}=\frac{\left(V_{tb}^{*}V_{td}\right)^{2}}{\left|V_{tb}^{*}V_{td}\right|^{2}}=\frac{\left(1-\rho-i\eta\right)^{2}}{\left(1-\rho+i\eta\right)\left(1-\rho-i\eta\right)}=e^{-2i\beta}$$

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

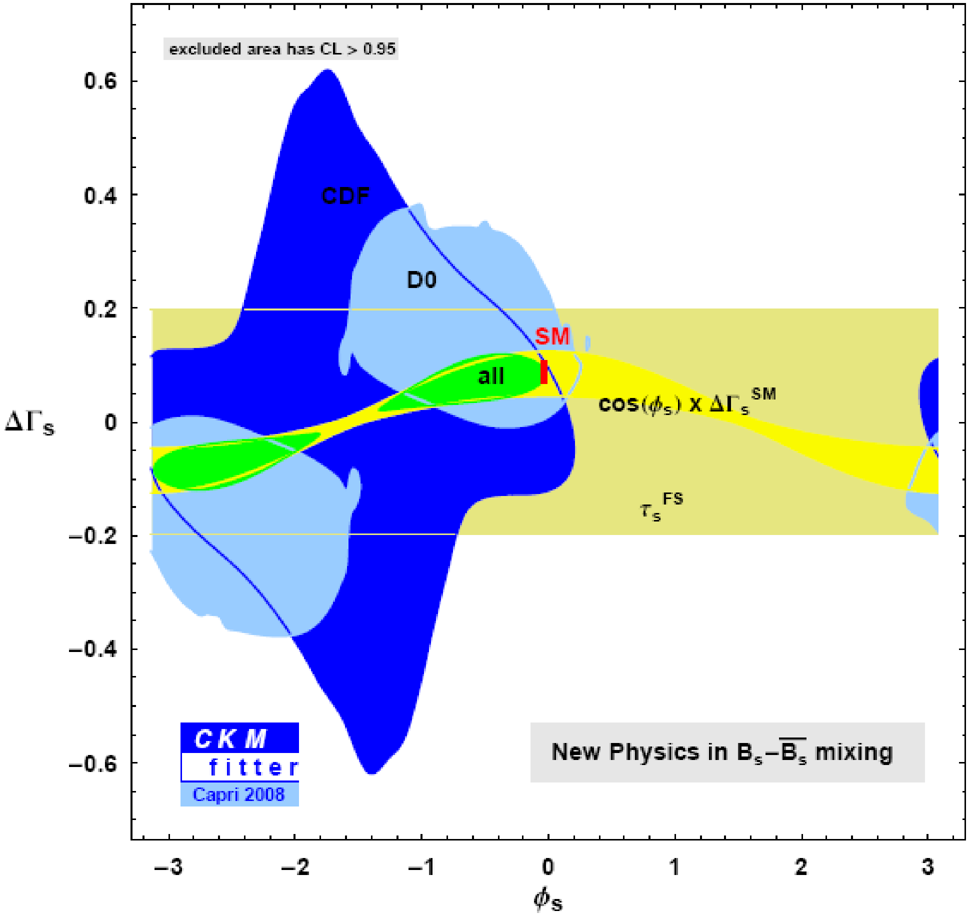


- Now need to add $\bar{A}/A$
  - for $J/\psi\ K_s$:

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



CDF & D0 May See Something

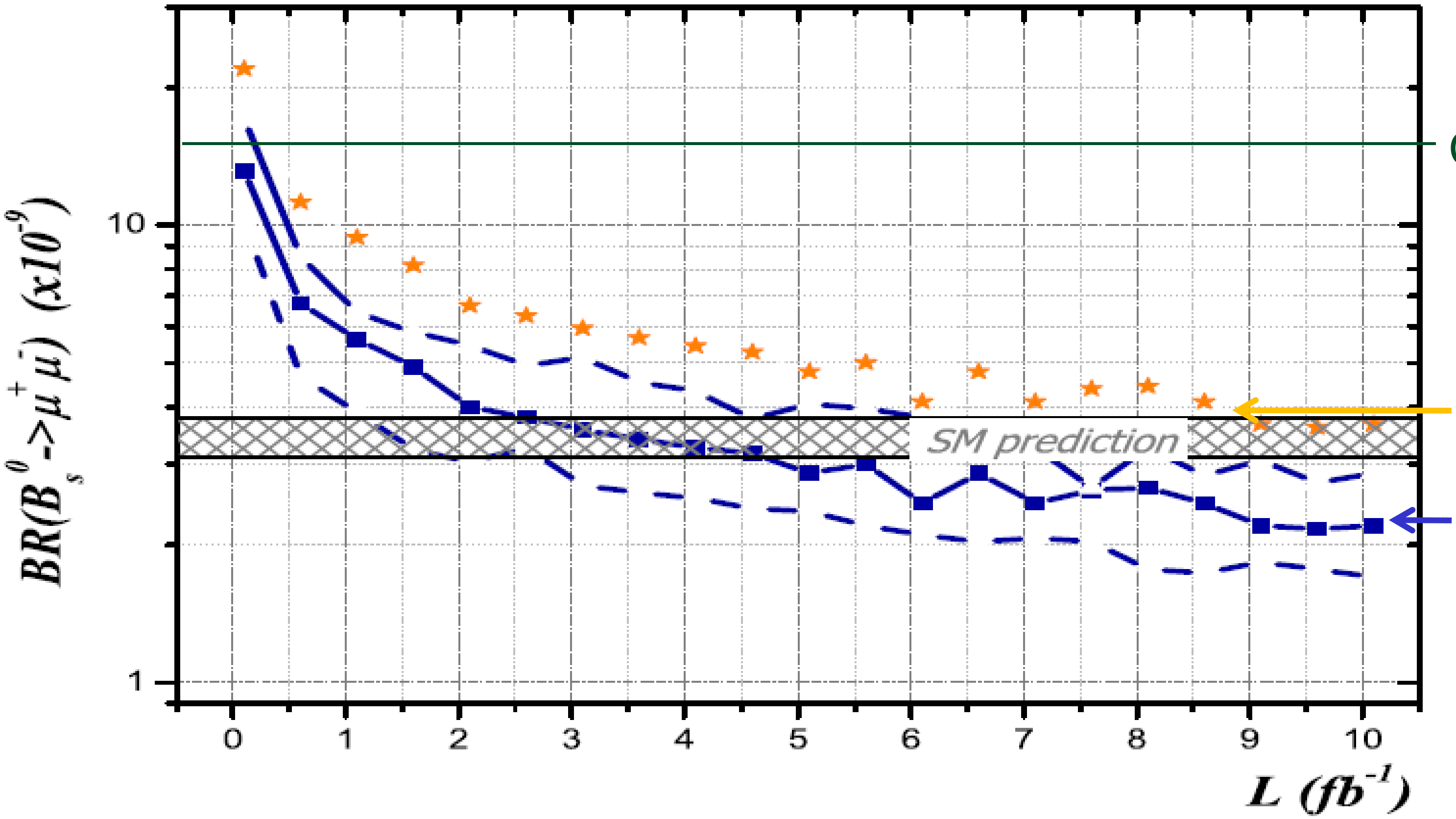


using all $(\phi_s, \Delta\Gamma_s)$ inputs, $\phi_s = -2\beta_s$ is excluded at 2.4σ, while the 2D hypothesis $\phi_s = -2\beta_s$, $\Delta\Gamma_s = \Delta\Gamma_s^{SM}$ is excluded at only 1.9σ (wrt to 1.4σ from FC treatment by CDF)

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



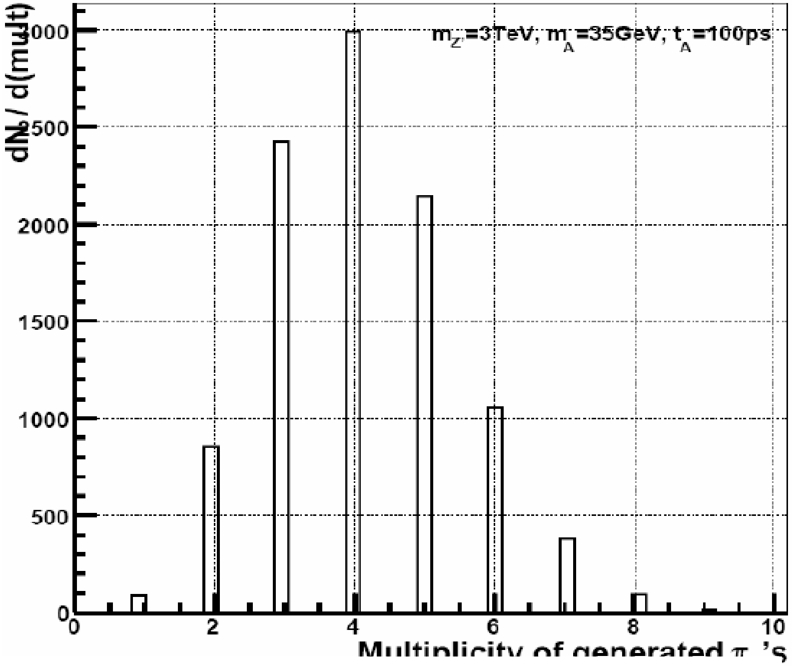
Current CDF Limit

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

Direct Hidden Valley Production



- Here we excite a virtual Z′, or other heavy object, that decays in multiple pv
- L0 & HLT1 efficiencies are large
- Higher Level

$M_{Z'}$=3 TeV m_v=35 GeV τ_v=100ps

# of vertices	0	1	2	3	4	5	> 5
HLT2 efficiency [%]	0	8	28	36	57	68	71

- Overall efficiency reasonably high, but we don’t know production cross-section

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	$\mu\to e\gamma$ $\tau\to\mu\gamma$