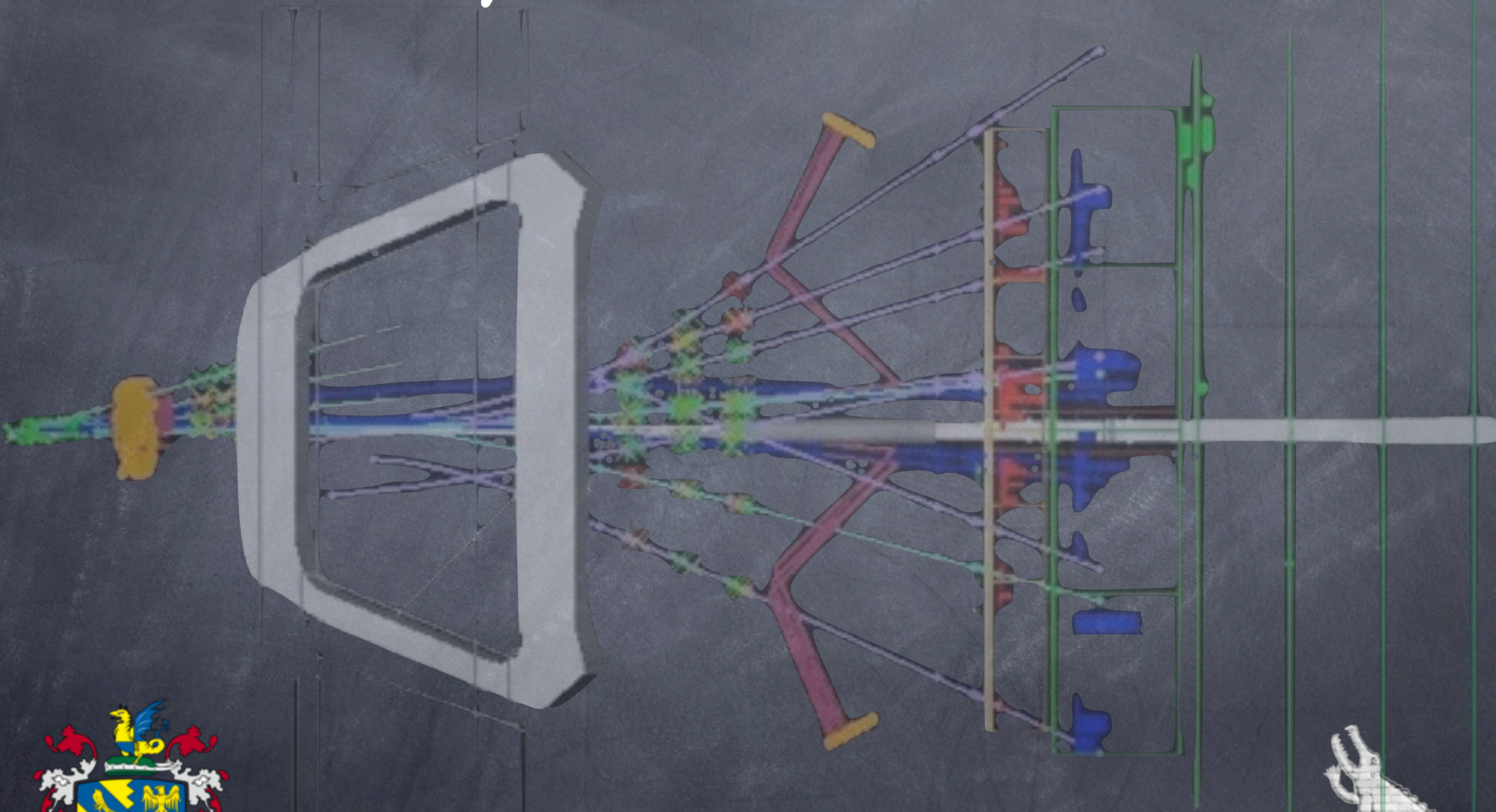
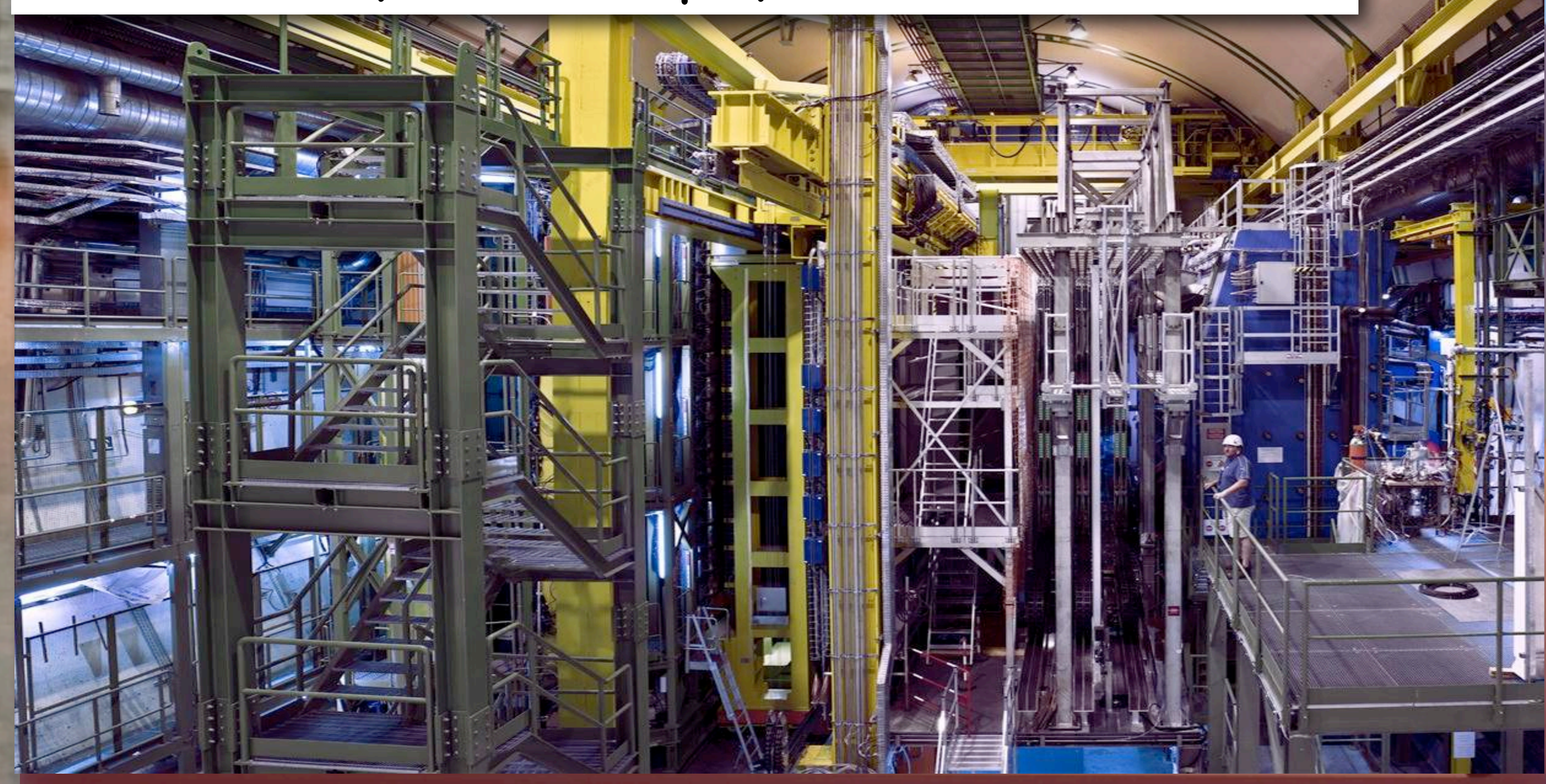
Early Data at LHCb



Ulrich Kerzel (University of Cambridge)
On behalf of the LHCb Collaboration

LHC at CERN

4 Experiments (ALICE, ATLAS, CMS, LHCb)
LHCb: Heavy flavour physics



LHC Operations

... from an experiment's point of view...

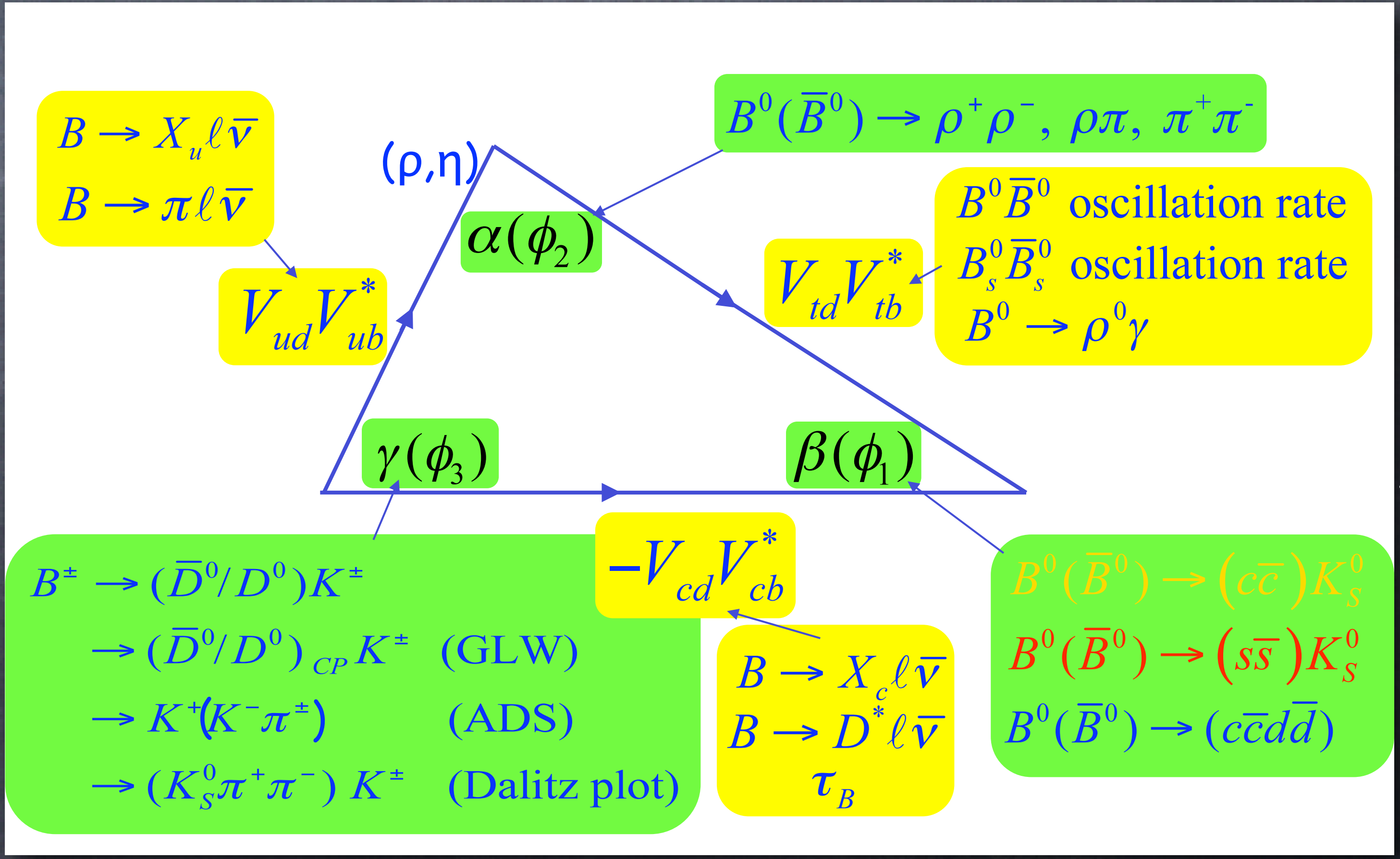
- Before November 2009: Detector commissioning
  - Cosmic radiation
    (n.b. LHCb not ideally suited for this...)
  - SPS / LHC beams shot on beam blocker at transfer lines
- Nov. / Dec. 2009
  - Commissioning with beam
  - Collisions at $\sqrt{s}$ = 900GeV, few collisions at higher energy
- Feb. 2010: LHC restart
- March 2010: Collisions at $\sqrt{s}$ = 7 TeV
  - Projected integrated luminosity:
    - 2010: ~ 200 pb^{-1}
    - 2011: ~ 1 fb^{-1}
- Shutdown to consolidate LHC for $\sqrt{s}$ = 10 - 14 TeV in 2011

Flavour Physics

- Standard Model very successful - but cannot be "Ultimate Theory"
  - Search for New Physics
- Flavour physics is the key to understanding New Physics
  - Directly observe new particles
    - ➥ Measure properties, coupling, etc.
  - Indirectly establish New Physics
    - ➥ Sensitive to small effects if the new particles are too heavy

Weak Eigenstates are non-trivial superposition of flavour Eigenstates
→ CKM matrix
➥ Popular representation: Wolfenstein
→ triangle in complex (ρ,η) plane

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



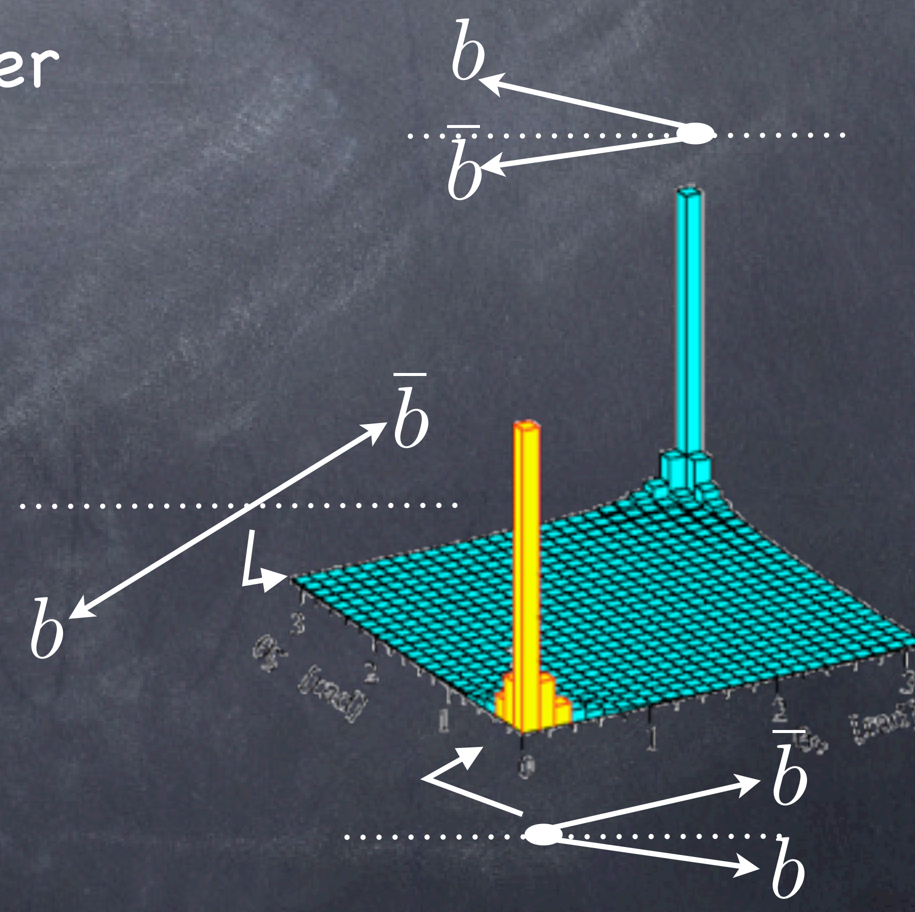
C. Matteuzzi, Moriond 2009

Flavour Physics at the LHC(b)

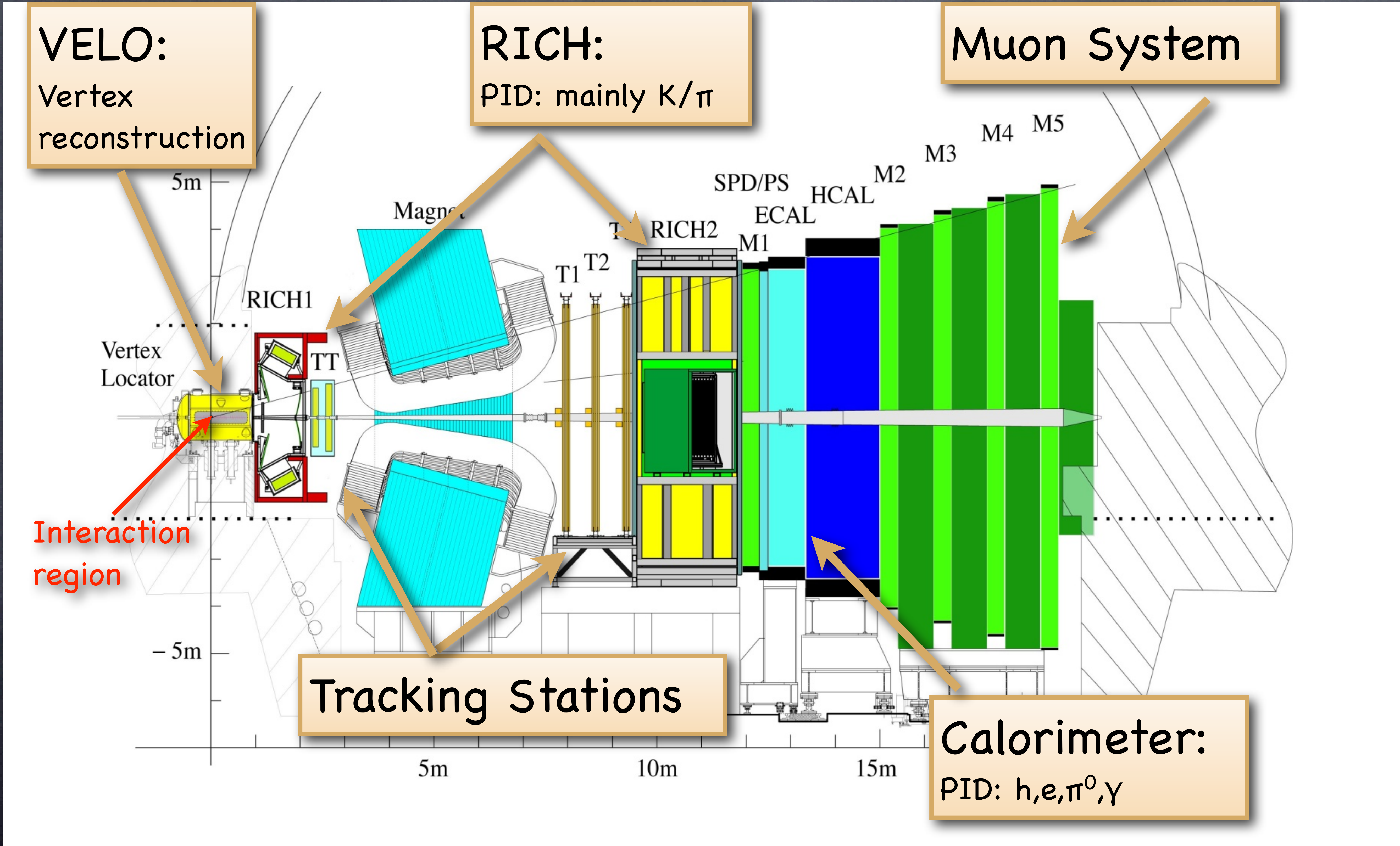
- The "good news":
  - Large b cross-section
  - All B hadrons (B^0, B_s, B_c, Λ_b) being produced
  - High luminosity (LHCb: limit to 2 10^{32} $s^{-2}cm^{-1}$ to reduce pile-up)

- The "challenges":
  - Huge inelastic background
  - High track multiplicity (>50 tracks/event)
    ➥ Need highly efficient and <u>selective</u> trigger

- b quark production mainly forward
  - Optimise LHCb detector design
    ➥ single arm spectrometer



The LHCb Experiment

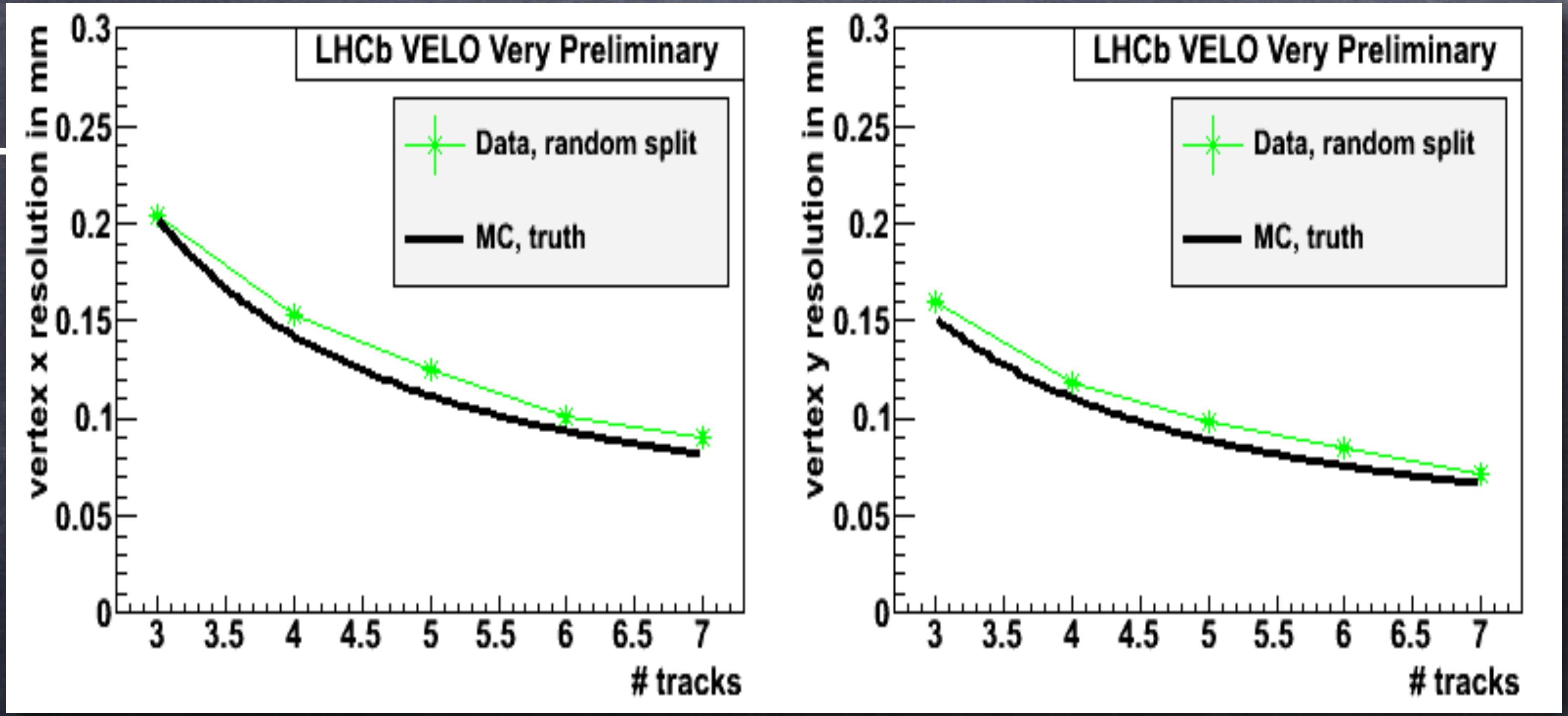


Vertex Detector (VELO)

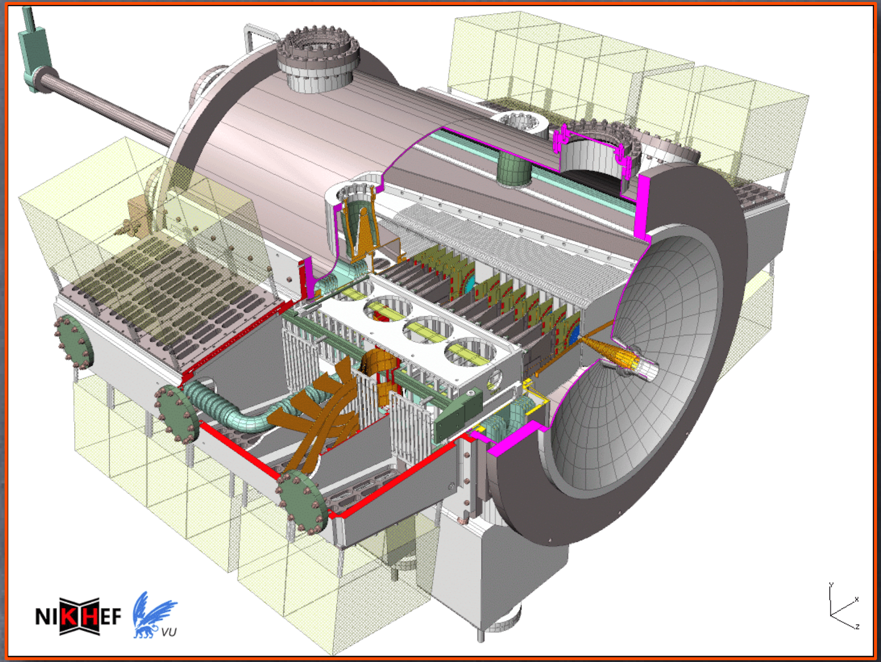
- 2 retractable detector halves inside vacuum
  - ~ 8mm from beam fully closed,
  - ~30mm retracted during beam injection
- 21 stations of Si wafers with R and ϕ readout

vertex resolution vs #tracks

VELO 15mm open



Excellent agreement between data and predictions from simulation!



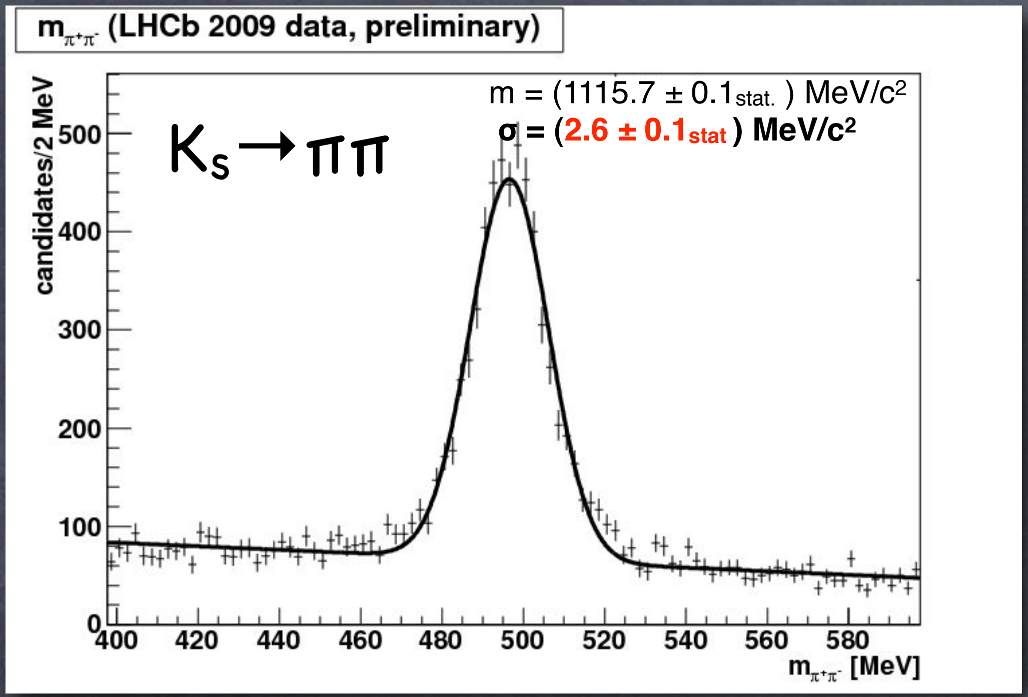
pp beam

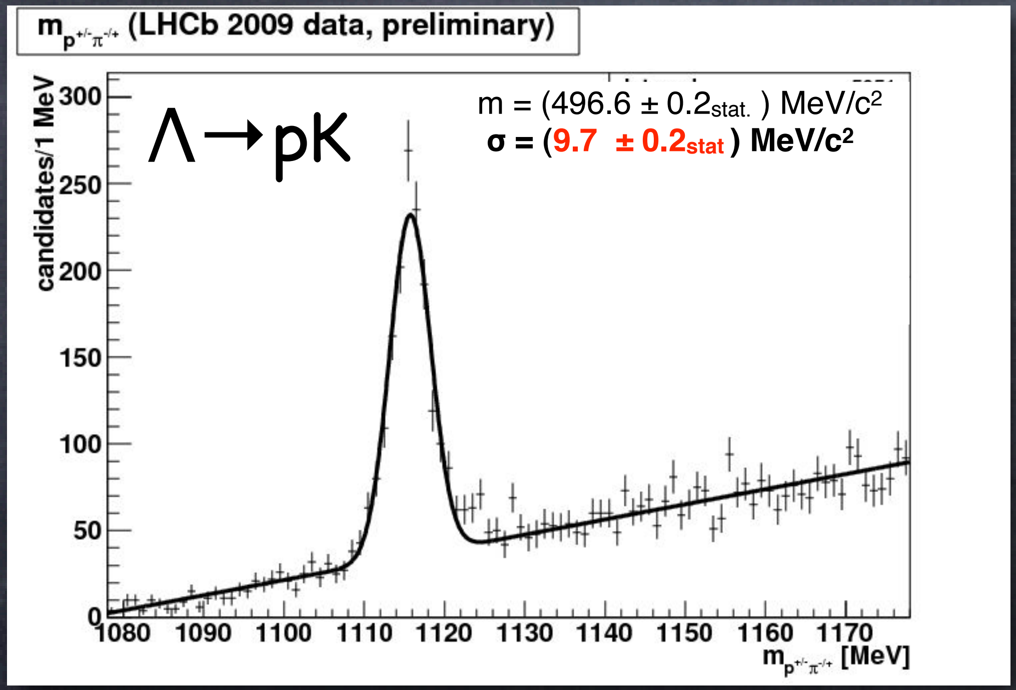
LHCb during 2009 data-taking

- Very successful start with colliding beam in 2009
- Recorded ~260k pp collisions (beam-gas subtracted, all detectors on)
- All sub-detectors operational and included in (most) data-recording
  - ➥ VELO very close to nominal(!) beam pos.: detailed closing strategy
    - ➥ detector halves moved in substantially during collision (but not fully closed)
- Tracking:
  - VELO: 99.3% of channels operational
  - Trigger Tracker (TT): 99.5% of channels operational
  - Inner Tracker (IT): 99.5% of channels operational
  - Outer Tracker (OT): 99.3% of channels operational
- Particle ID (RICH): >99 % of channels operational
- Calorimeter: 99.8% of channels operational
- Muon: >99 % of channels operational

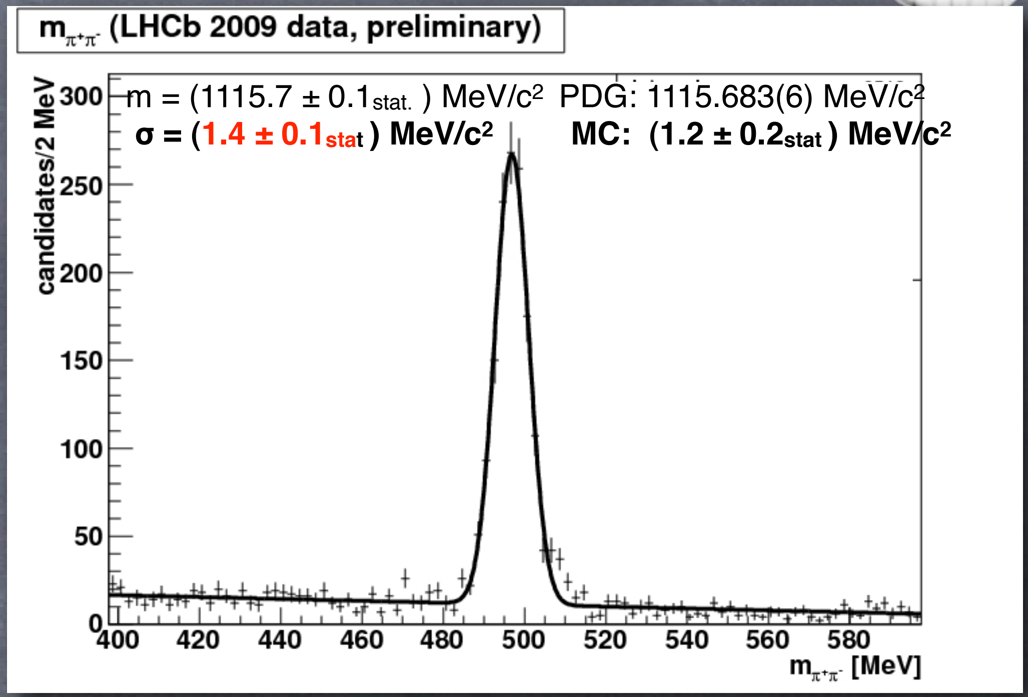
- Excellent performance of all systems!

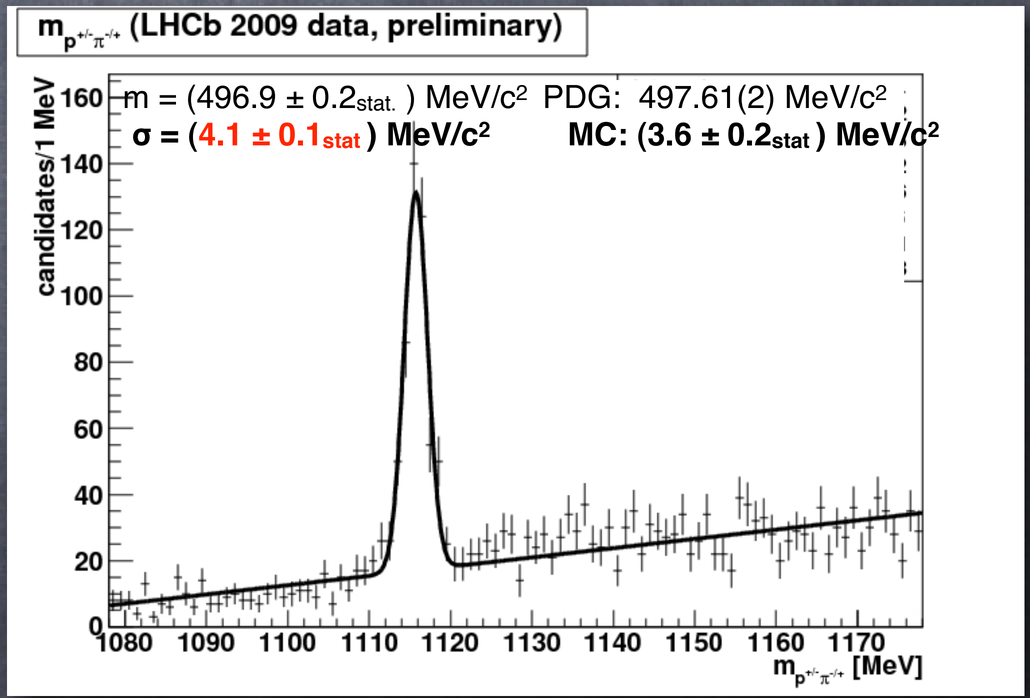
2009 Data: K_s and Λ





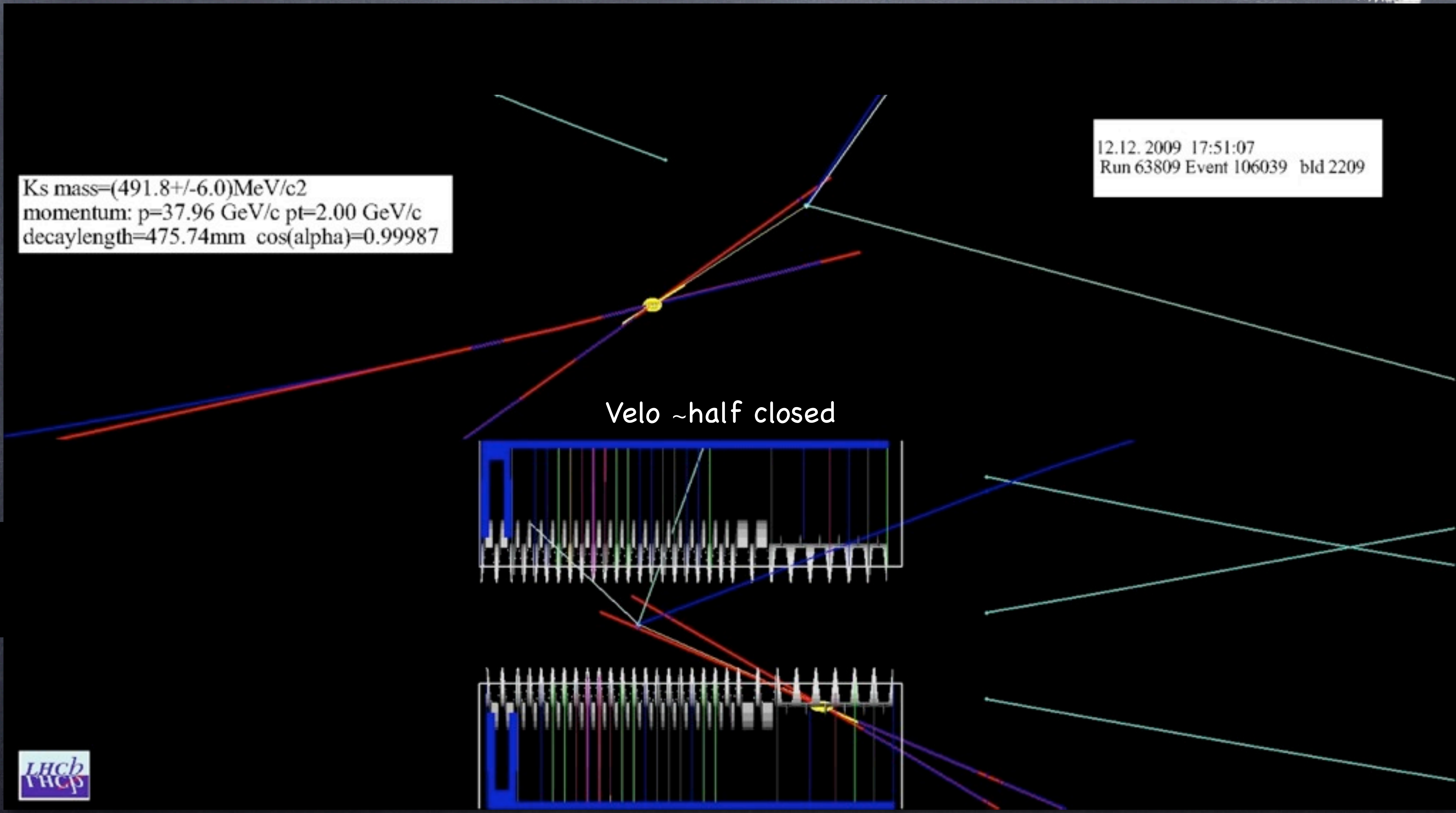
include
VELO



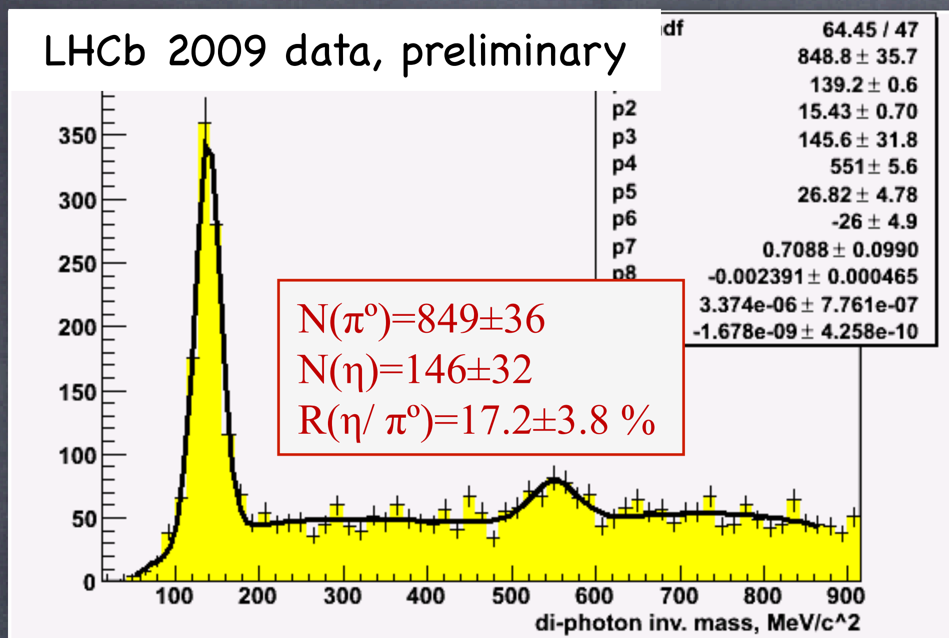


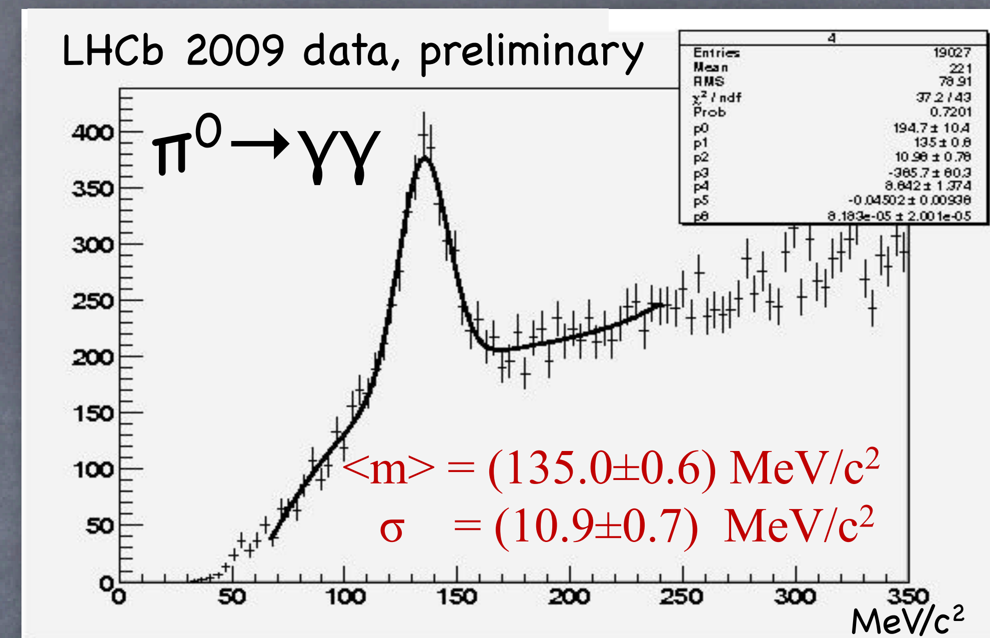
Big improvement in resolution including the (half-closed) VELO

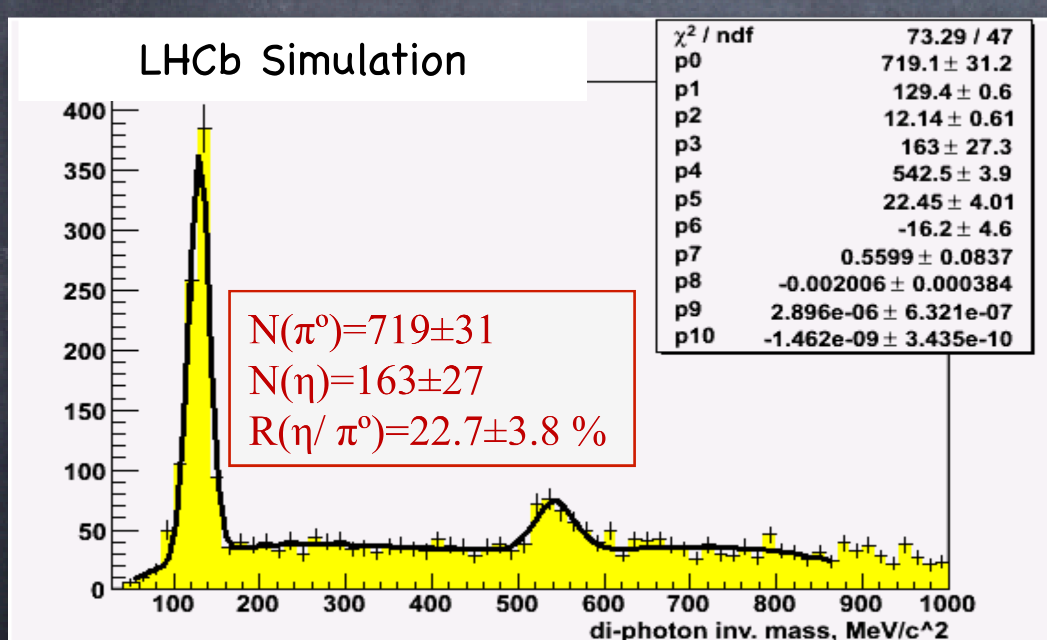
2009 Data: $K_s \rightarrow \pi\pi$ Candidate

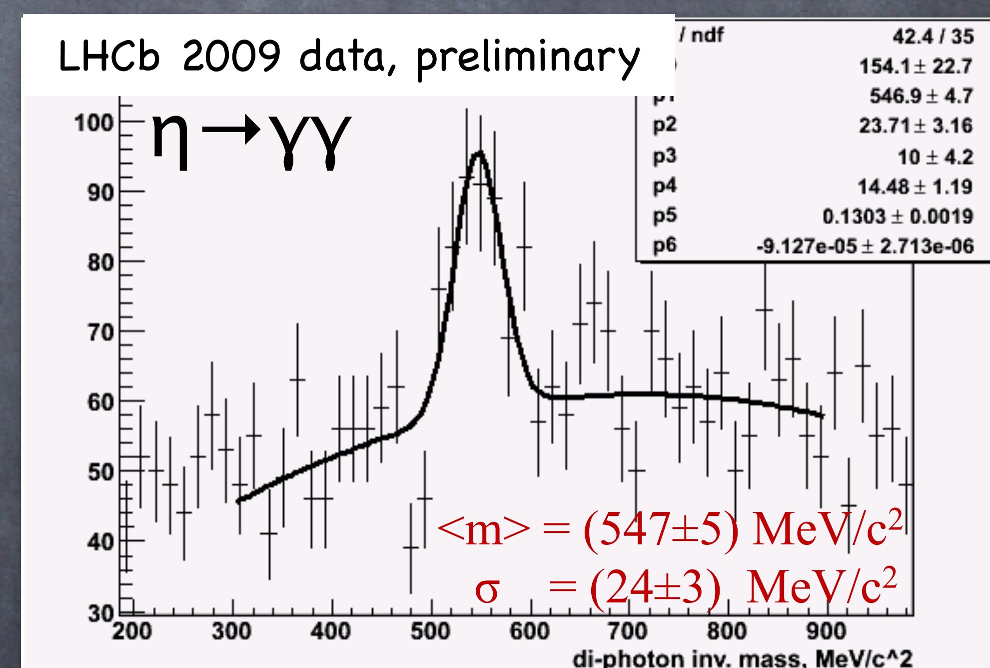


2009 Data: Calorimeter







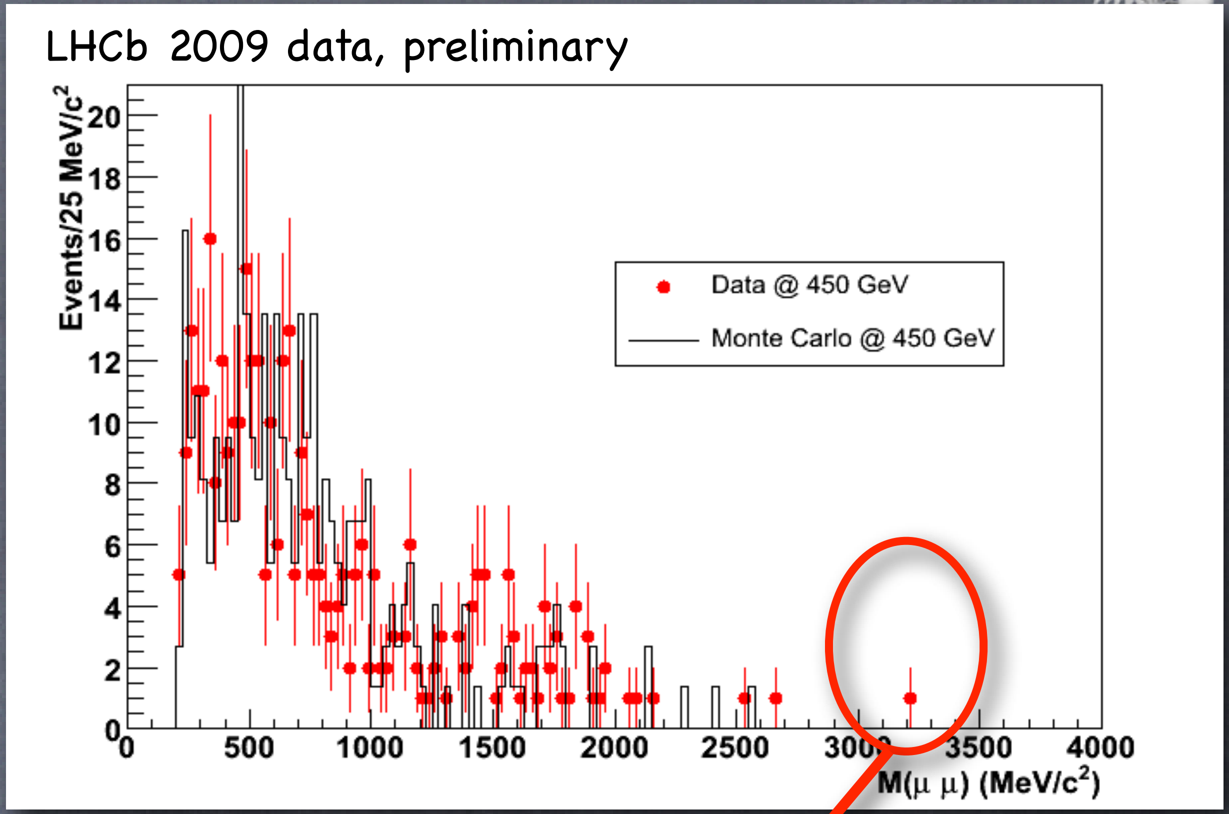


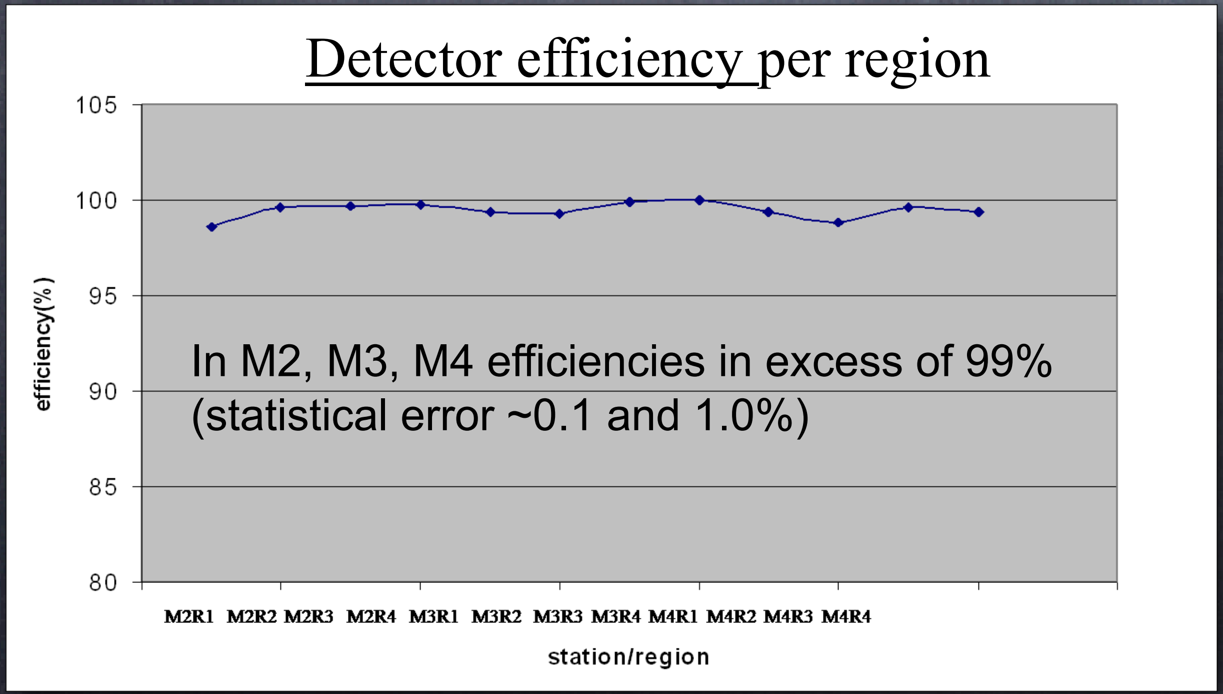
Impressive agreement between data and simulation

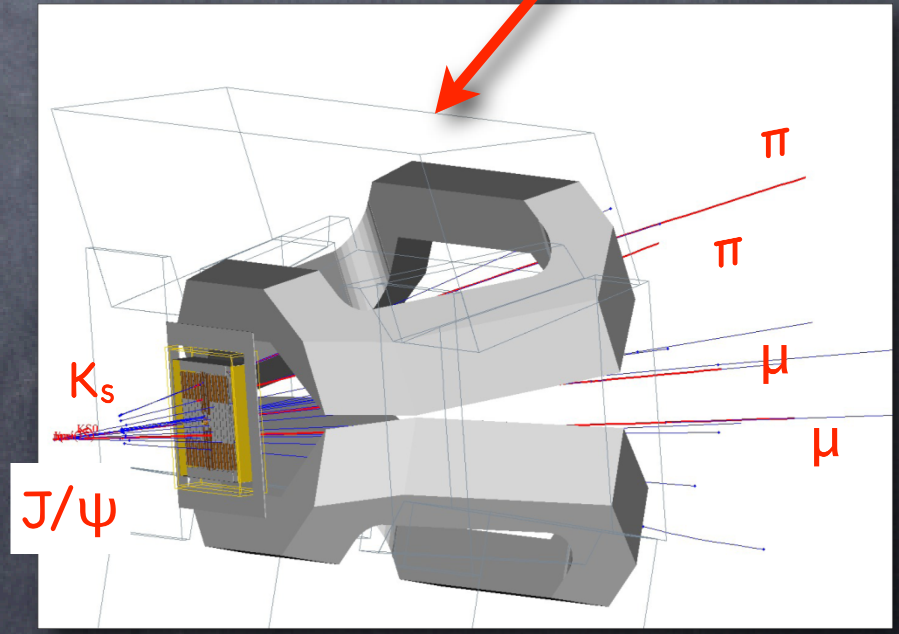
Very clear γγ signal
Excellent resolution

2009 Data: Muon

- Excellent performance of muon system
- Efficiencies measured >99%
- Di-muon spectrum agrees well with expectations from simulation
  - ➡ even one J/ψ candidate passing 3 different selection criteria

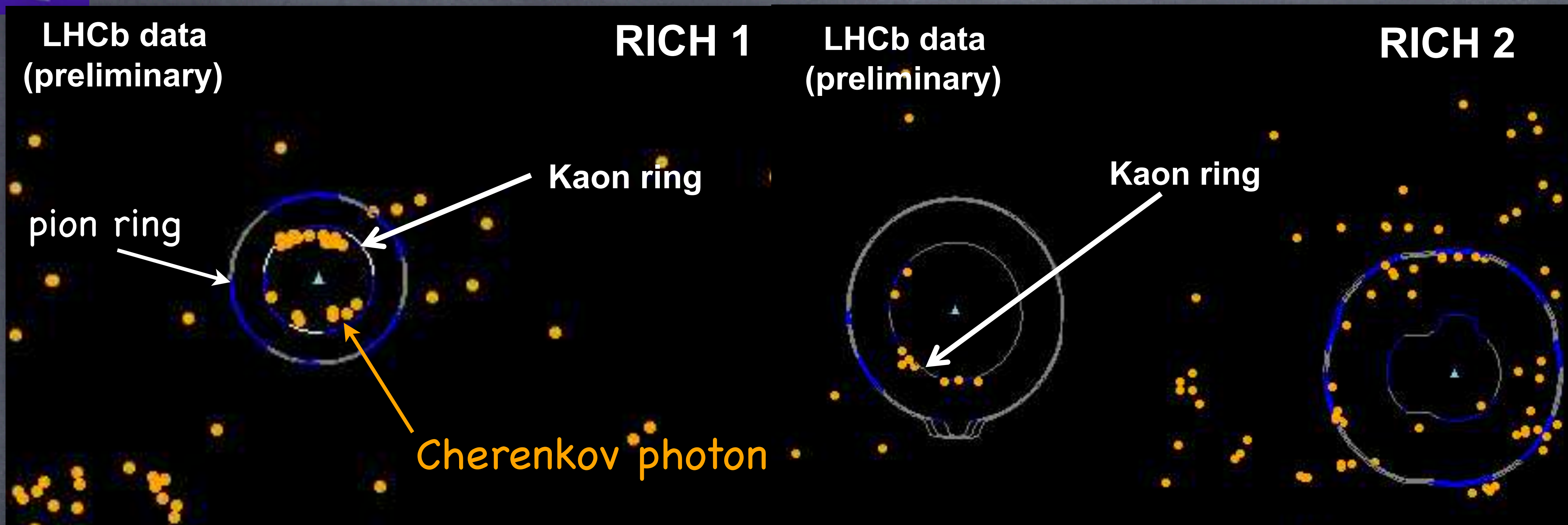


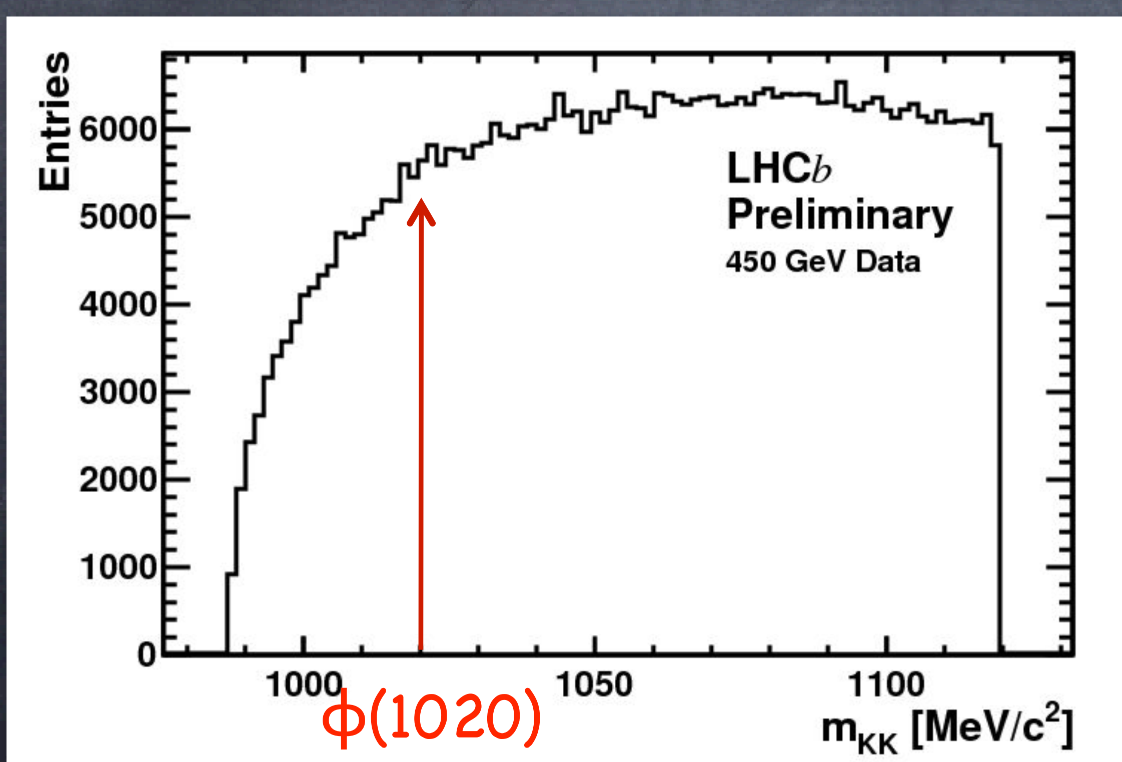




Event passes B→J/ψ K_s selection - two pions decaying in flight ?

2009 Data: $\phi \to KK$ With Particle ID





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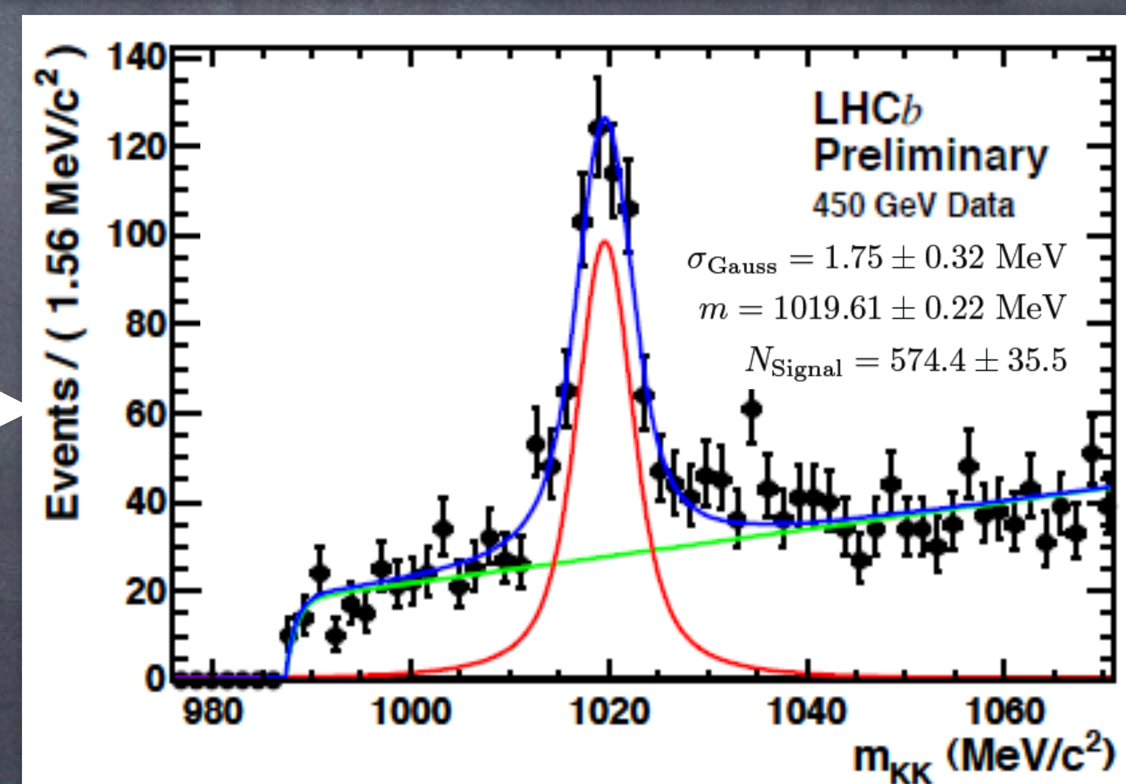
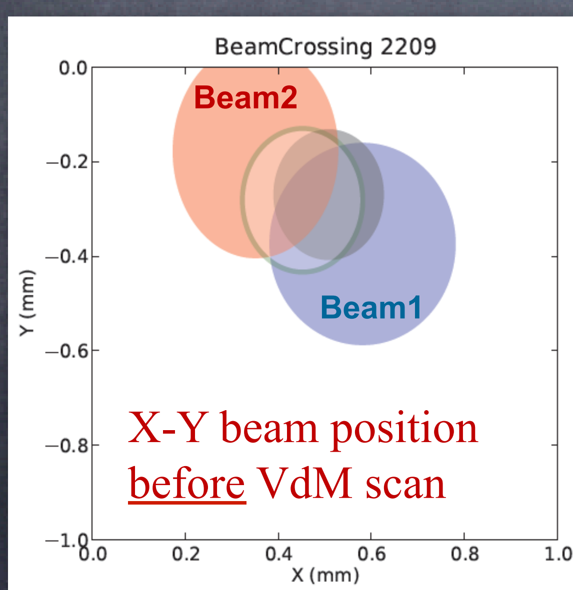
PID

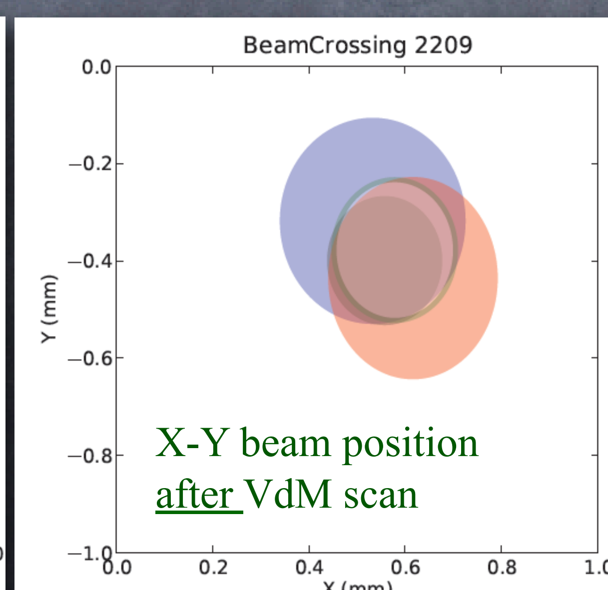


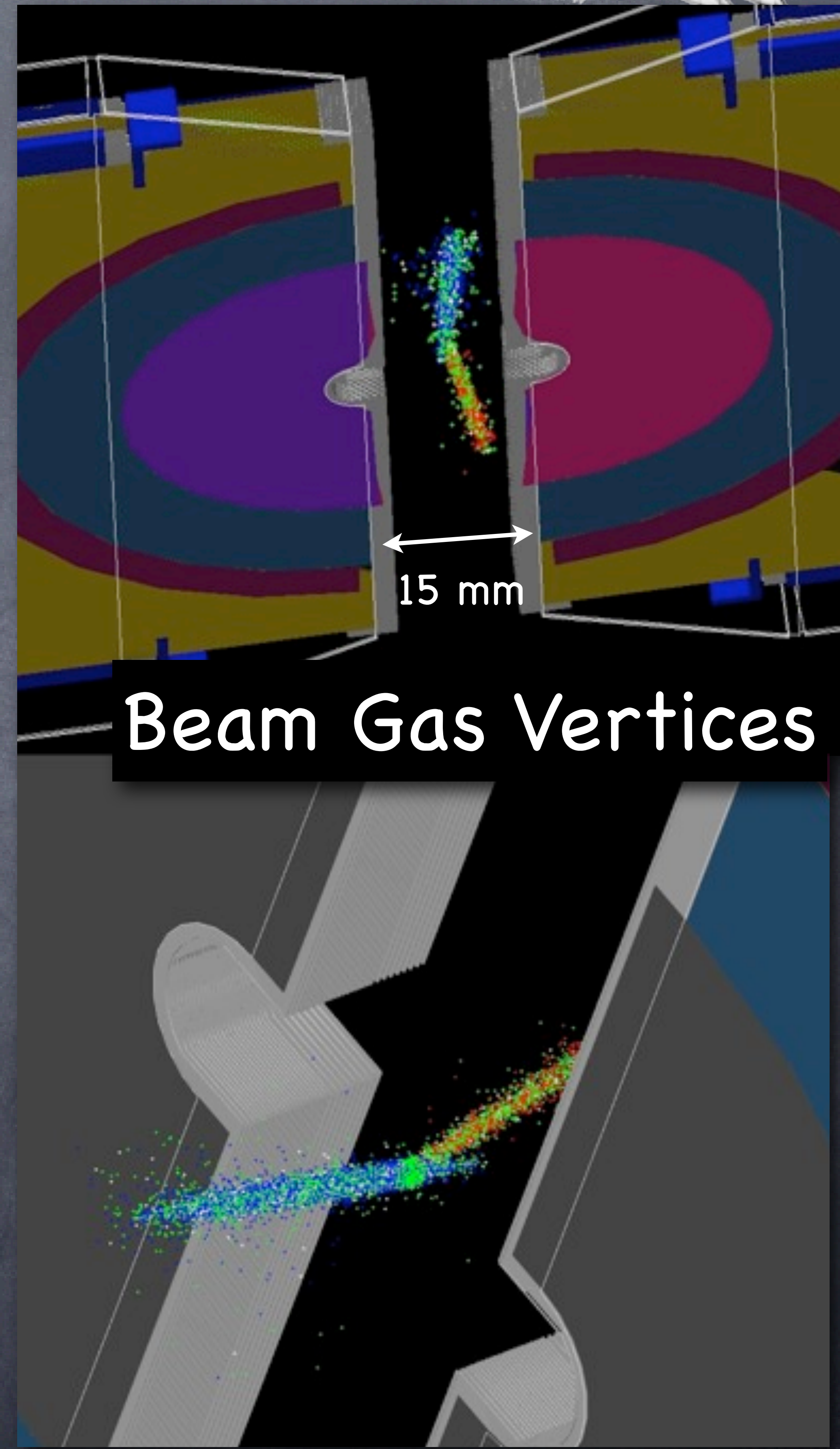
Luminosity Measurement

$$\mathcal{L} = n_1 n_2 f \frac{1}{A_{eff}}$$

- n: protons/bunch, f: collision freq.
- A_{eff} effective area calculated from beam size and position
- Van der Meer scan:
  - Measure and adjust beam parameters using beam - gas



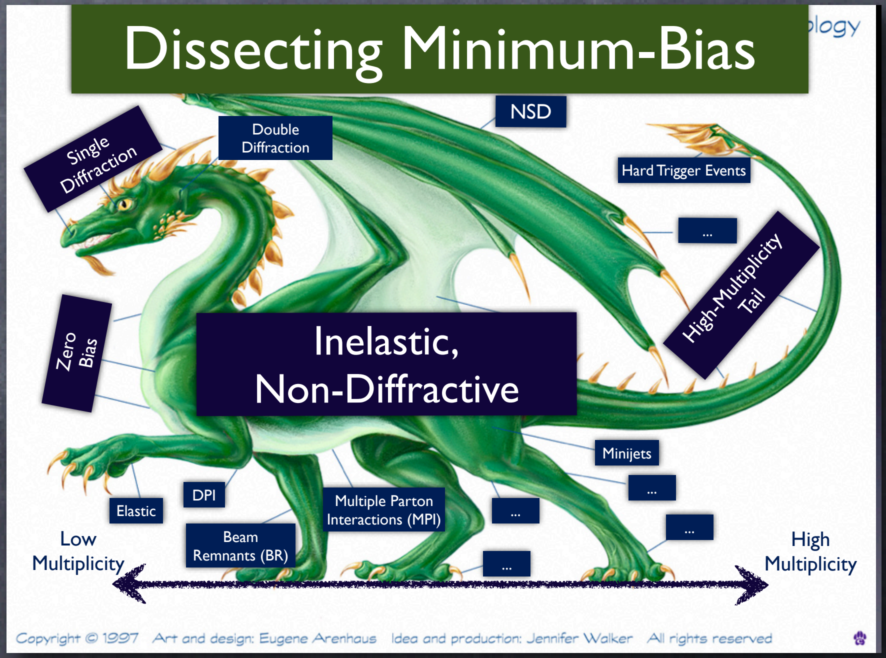




- Accuracy:
  - 2009: < 20% (stat. limited)
  - 2010: aim for < %5

2009 Data: Physics Results

- Pilot run at 900 GeV offers unique opportunities to settle long-standing issues
  - E.g. rel. cross-section measured by UA5 / E735 inconsistent
  - LHCb: unique rapidity range: $2 < \eta < 5$
  - ➥ crucial input to Event Simulation
- LHCb physics topics:
  - Charged track multiplicities
  - K_s / Λ cross-section as function of pt, η
  - Ratio strange baryon / strange meson
  - Ratio Λ vs $\bar{\Lambda}$
  - Jet structure
  - ...



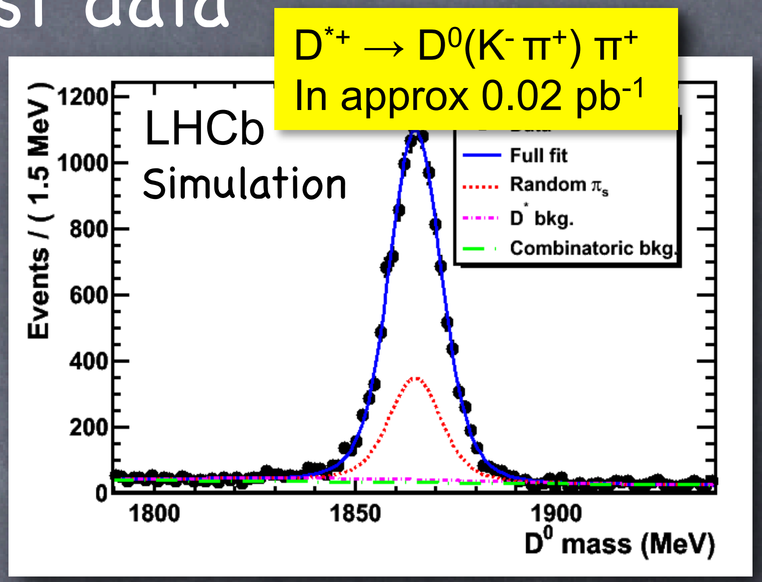
P. Skands

LHCb Physics Programme

- LHCb focuses on precision measurements
  - CP violation: e.g. mixing, CKM angle γ
  - Rare decays: e.g. $B \rightarrow \mu\mu$, $B \rightarrow K^{*}\mu\mu$
  - Flavour: e.g. spectroscopy, EW physics, soft QCD
- Highlight few key analyses:
  - Charm physics
  - B_s mixing phase ϕ_s
  - $B_s \rightarrow \mu\mu$
- Detailed "road-map": arXiv 0912.4179

Charm

- Charm physics offers unique potential to discover New Physics
  - Expect large Charm signal sample with first data
    - σ(c) factor ~7 larger than σ(b)
    - ~4 10^6 $D^{*+} \to D^0(K^+K^-)\pi^+$ in 100 pb^{-1} (compare BaBar: 0.26M PRD80:071103,2009)

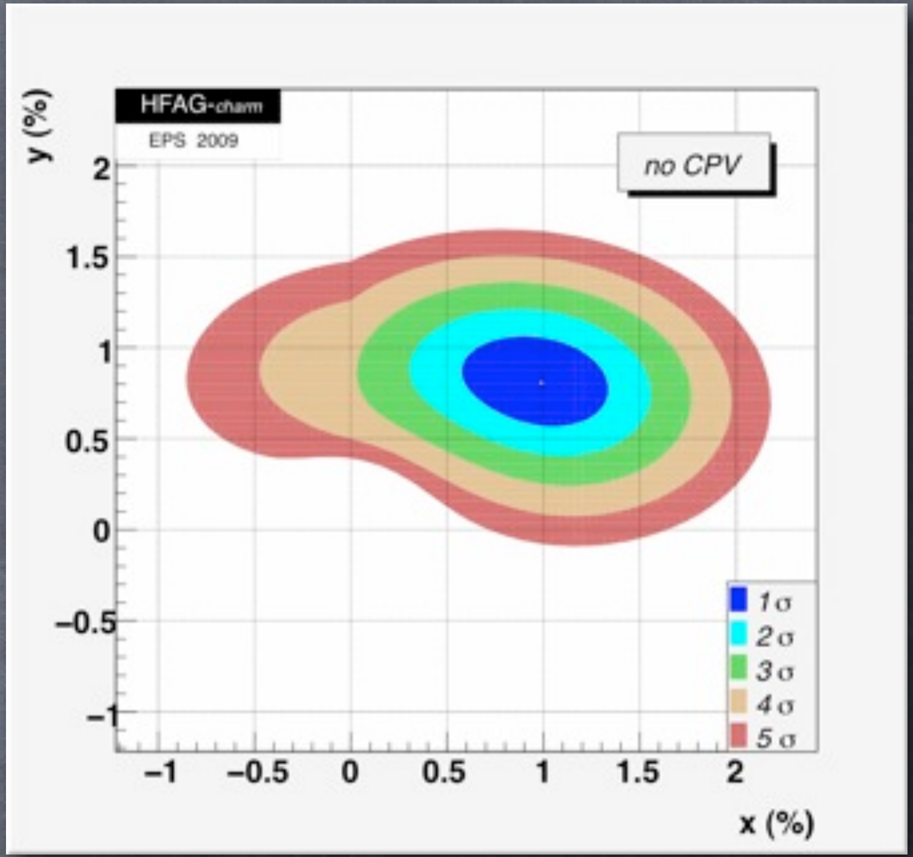


  - Optimised trigger ($\mathcal{L} < 10^{31} s^{-2} cm^{-1}$)
    - lower p_t, impact param. threshold
    - improve prompt charm yield by factor 4 w/o loss in B physics
  - Extensive Charm physics programme
    - Rare decays
      - E.g. $D^0 \to \mu\mu$, $D^+ \to h^+ll$
    - CP violation: Currently not observed
      - E.g. $D^0 \to K^+K^-$, $\pi^+\pi^-$
    - Mixing (next slide)

Charm Mixing

- First evidence for D mixing in 2007
  - Average shows significant evidence
  - No single 5σ measurement yet
  - >20 established models of NP
- Low mixing rate, >> D lifetime
- Parameters small (HFAG, EPS09)
  - x(no CPV) = 0.811 ± 0.334 %
  - y(no CPV) = 0.309± 0.281 %
  - y_{CP} = 1.107 ± 0.217 %
- Many measurements in preparation e.g. y_{CP} via CP eigenstates

$$y_{CP} = \frac{\tau(D^0 \to K^+\pi^-)}{\tau(D^0 \to K^+K^-, \pi^+\pi^-)} - 1$$

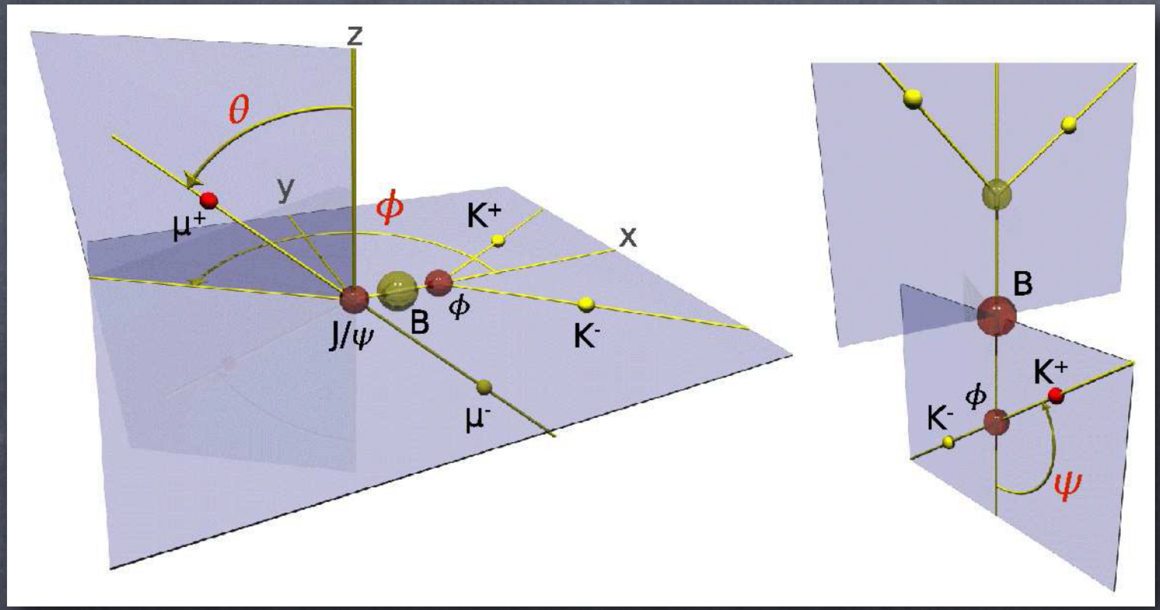


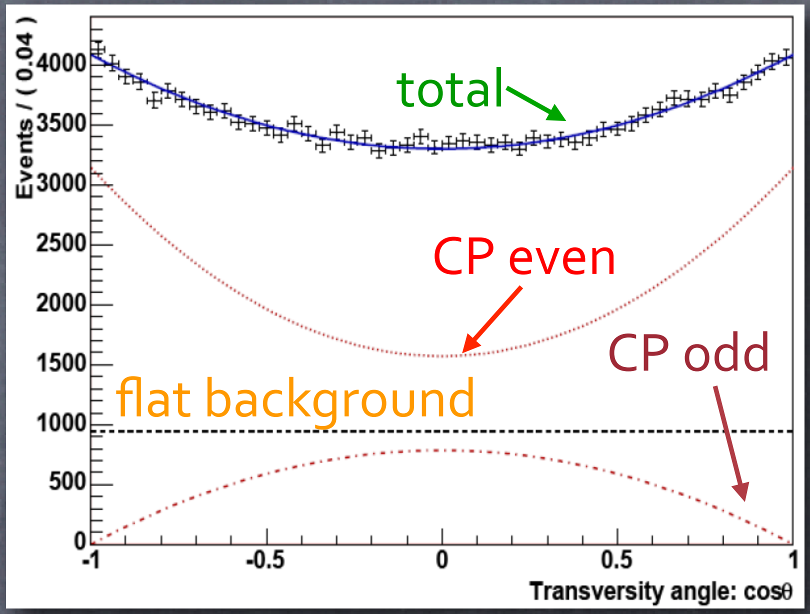
$$x = \frac{m_2 - m_1}{\Gamma}$$

$$y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

$B_s \rightarrow J/\psi\phi$

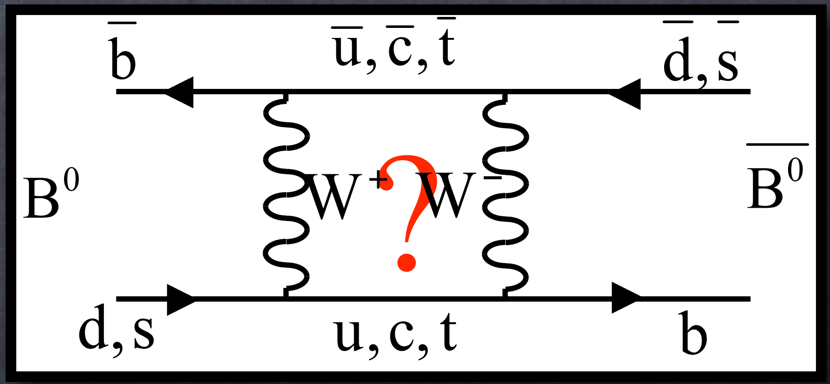
- New Physics in Bs mixing: Phase ϕ_s
  - Counterpart to phase in $B^0 \rightarrow J/\psi K$
  - Disentangle 2 even and 1 odd CP eigenstates





- Standard Model prediction:
  $\phi_s = -2\beta_s = -\arg(V_{ts}^2) = -0.036 \pm 0.002$

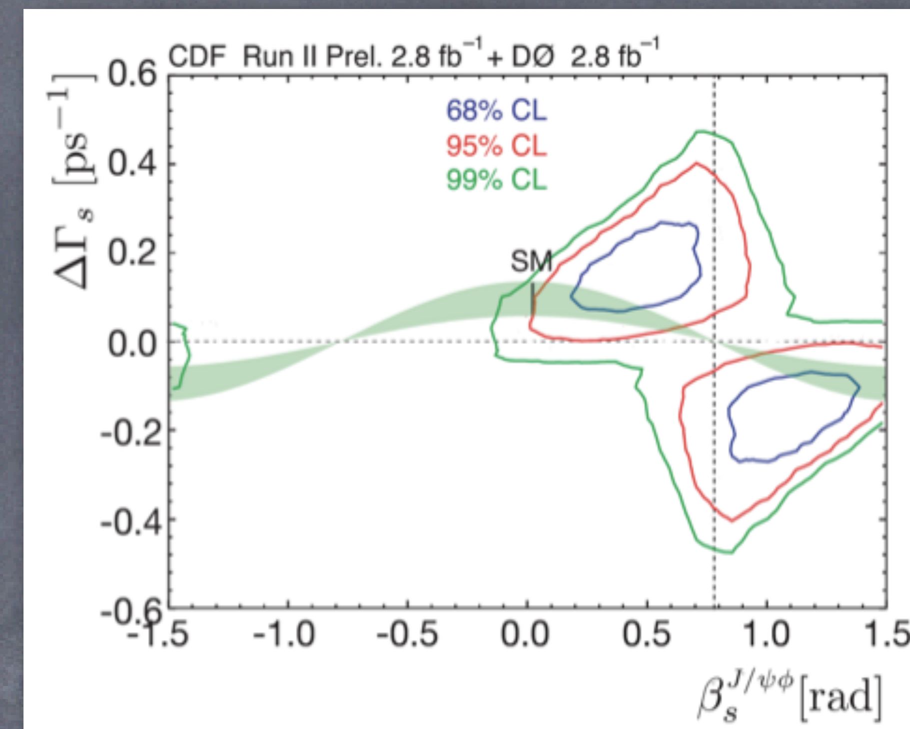
- Large contributions from NP ?



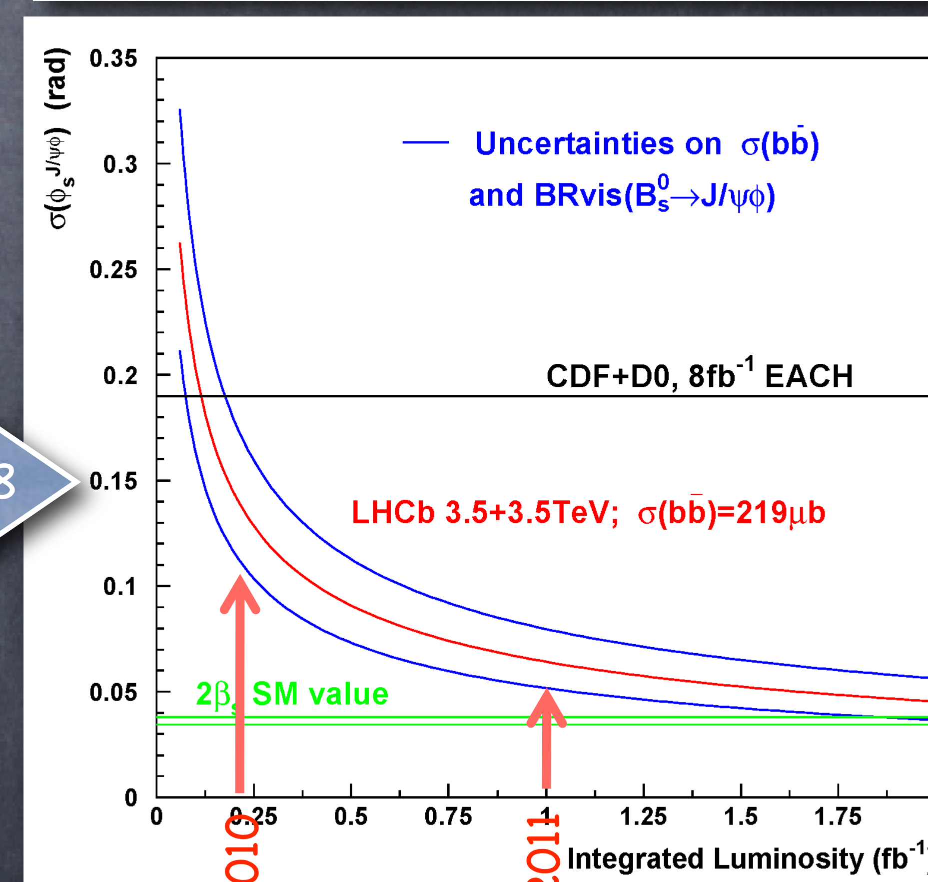
$B_s \to J/\psi\phi$

- Combined CDF/D0 result
  - ➥ 2 σ tension

- LHCb has the potential to discover New Physics with 2010/11 data
- Need:
  - Particle ID
    - ➥ $\phi \to KK$
  - Flavour tagging
    - ➥ PID crucial ingredient
  - Excellent proper-time resolution
    - ➥ Excellent resolution of V^0 decays including VELO

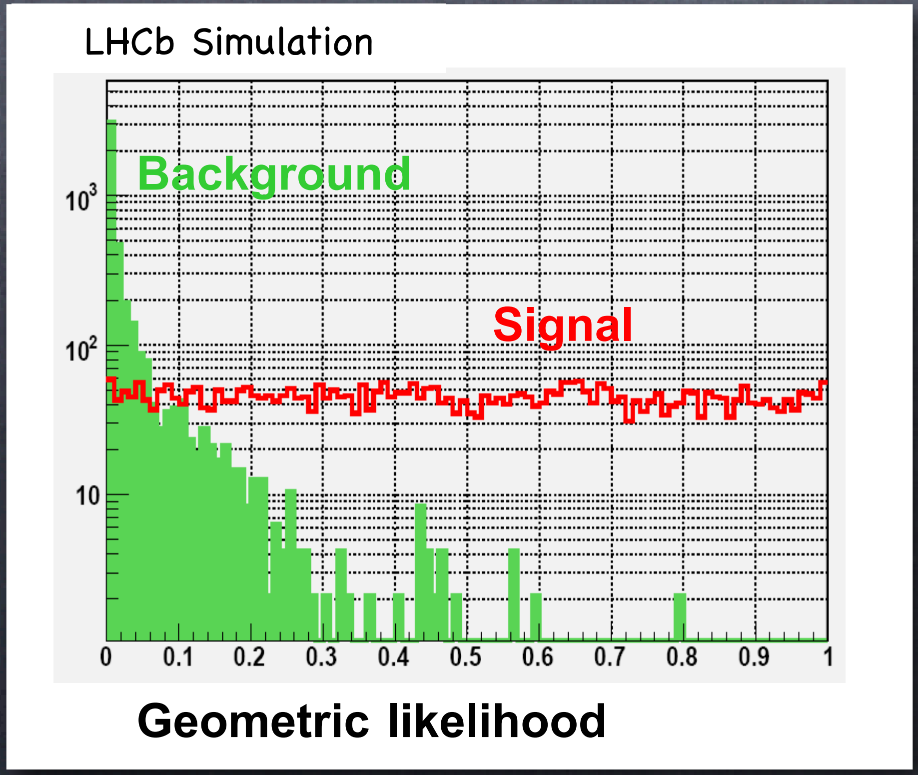


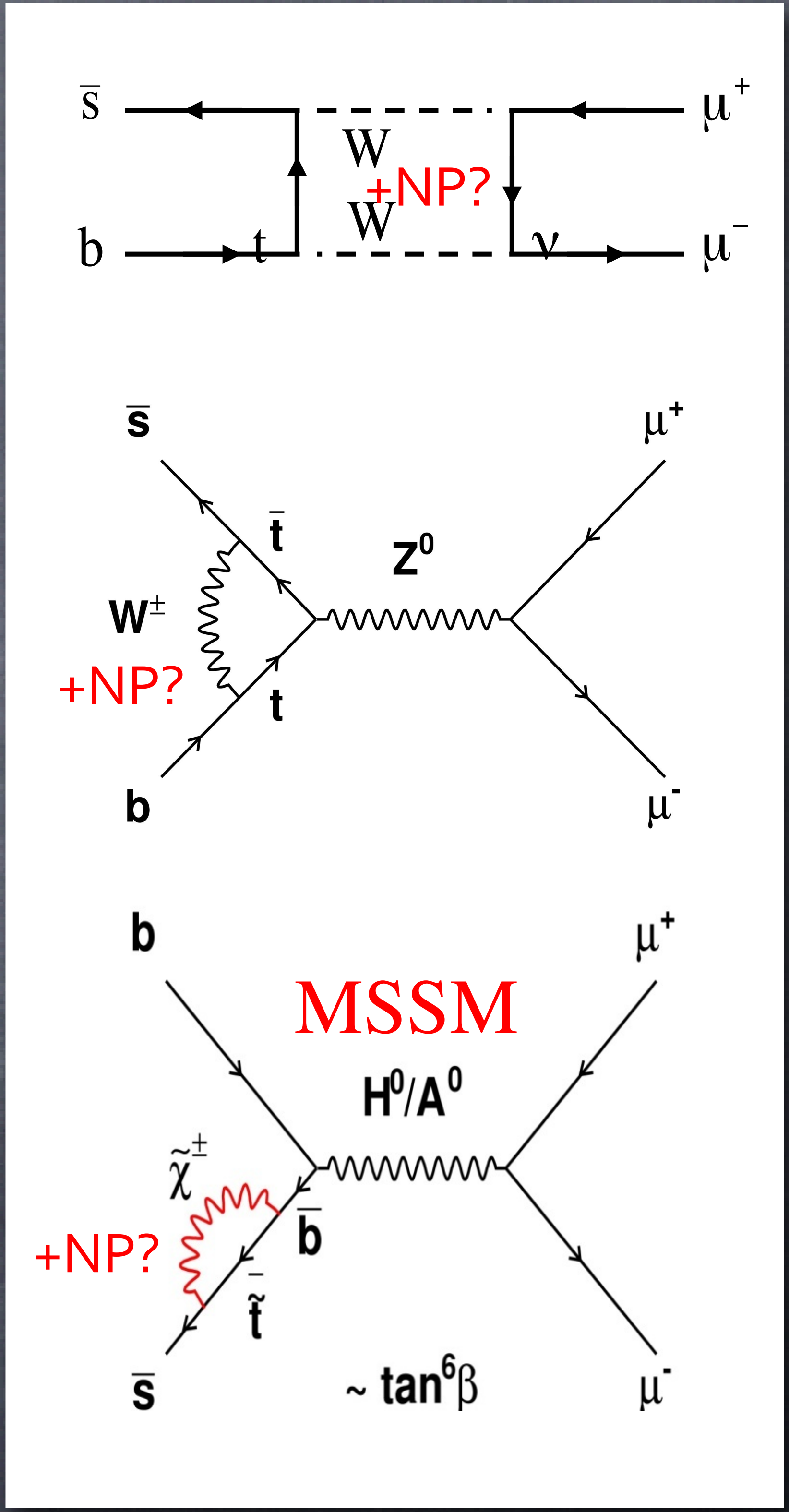
5σ if $2\beta_s$ = 0.8



$B_s \to \mu\mu$

- Extremely rare in Standard Model
  - $Br(B_s \to \mu\mu) = (3.35 \pm 0.32)\ 10^{-9}$
    (e.g. hep-ex/0604057)
- Br may be greatly enhanced by New Physics, SuSy
- Main experimental challenge:
  - ➥ background suppression
  - ➥ geometric likelihood
  - Handles: vertex separation, mass resolution, pointing constraint

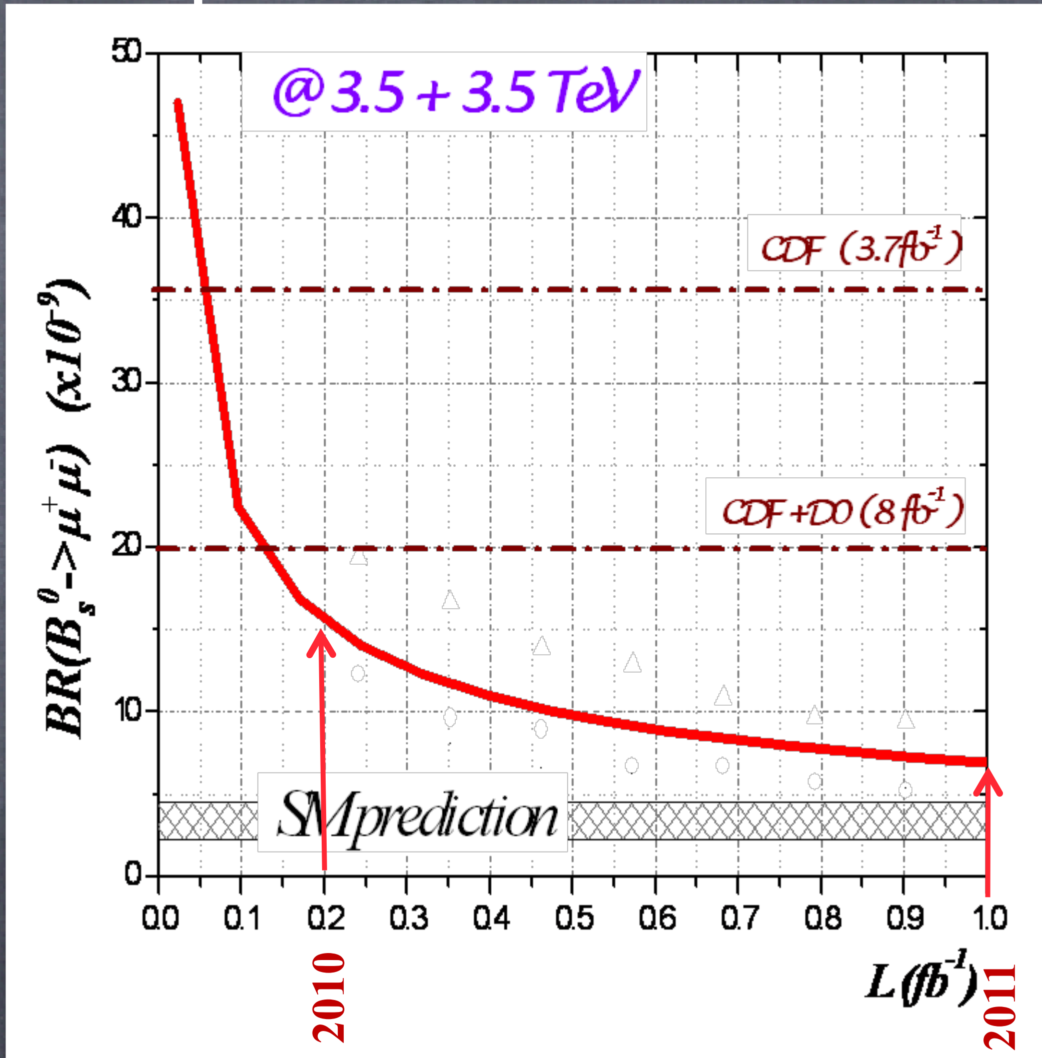




$B_s \to \mu\mu$

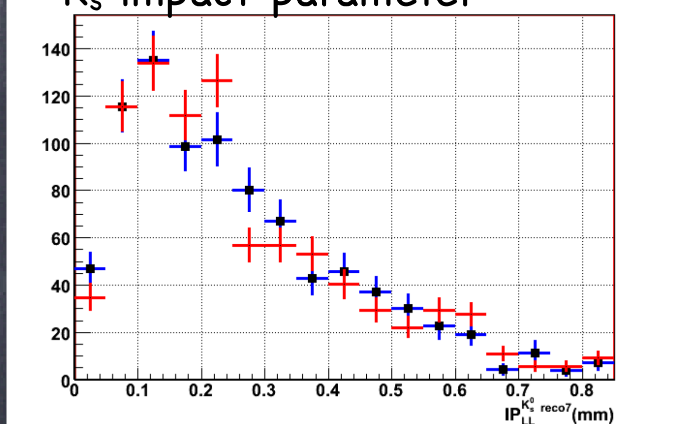
- Exploit $K_s \to \pi\pi$ in 2009 data
  - Tune event simulation
  - "Exercise" analysis with real data

Prospect for 2010/11 data

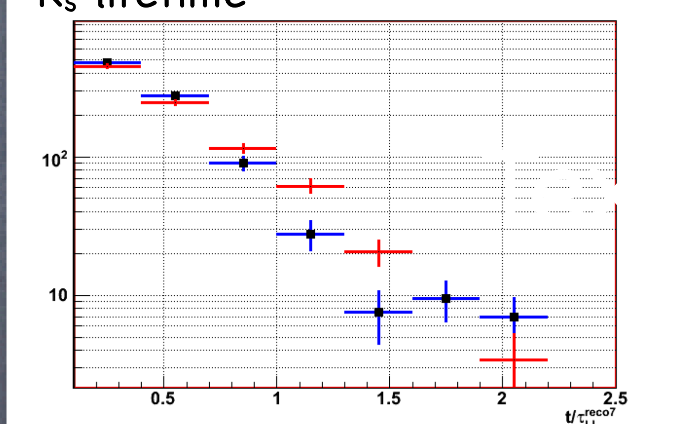


inputs to geom. likelihood:

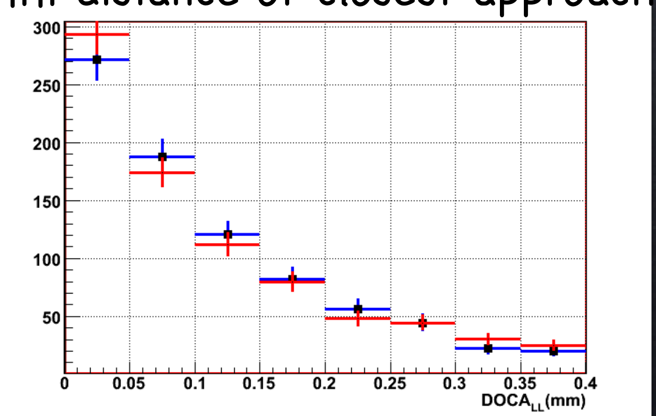
K_s impact parameter



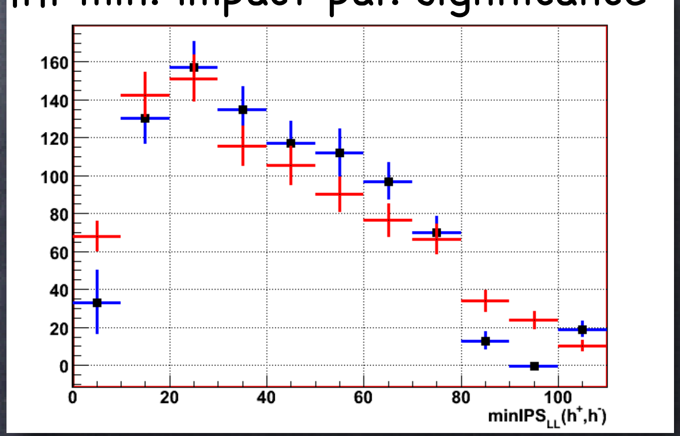
K_s lifetime



$\pi\pi$ distance of closest approach



$\pi\pi$ min. impact par. significance

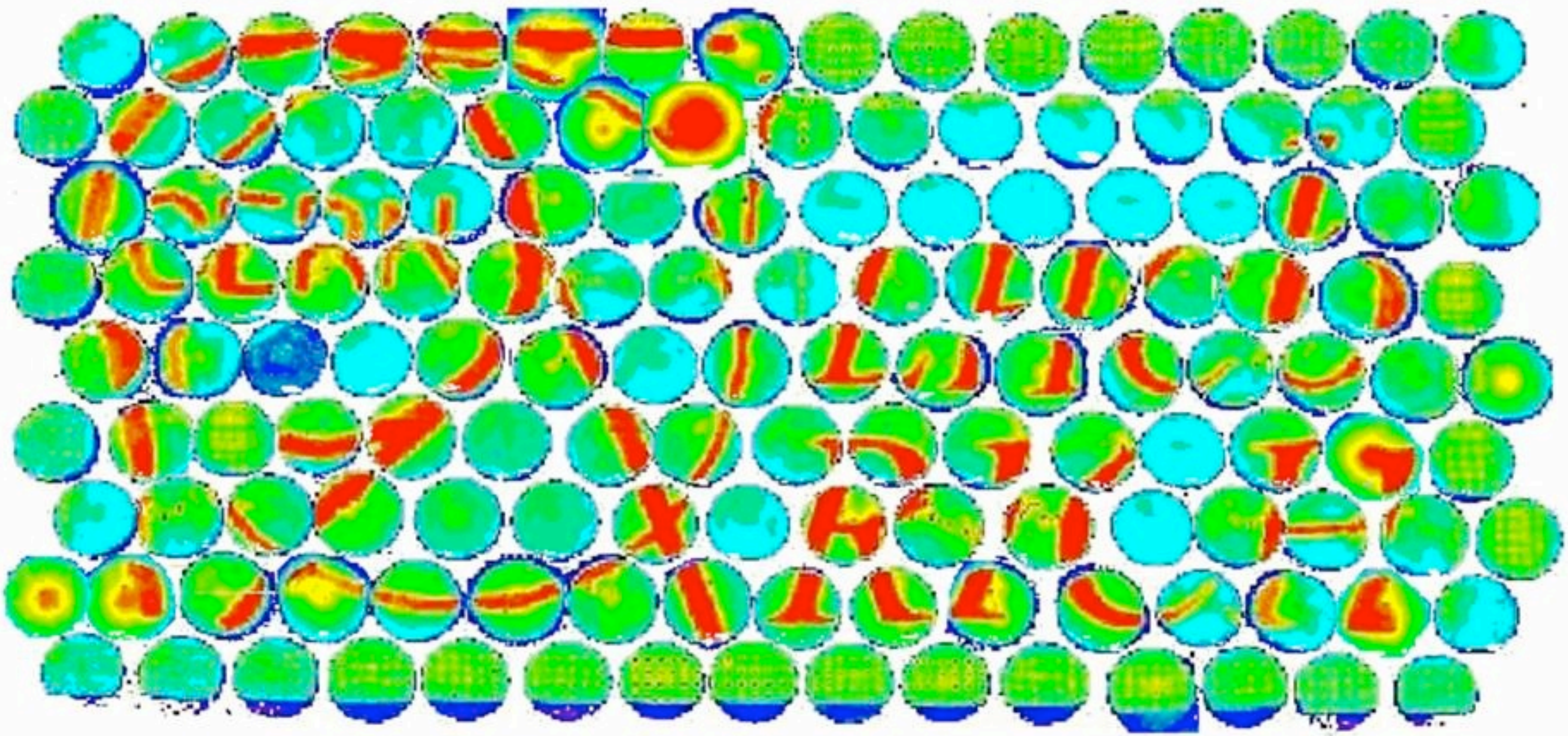


good agreement between
2009 data
LHCb simulation (Pythia 6.4 + Geant)

Summary

- LHCb focuses on discovery of New Physics using precision measurements in the Heavy Flavour sector
  - CP violation, rare decays, flavour physics, spectroscopy, charm, radiative decays, QCD, ...
- Very successful start in 2009
  - All sub-detectors ready and in excellent shape
  - Now calibrate and commission the detector
    - First "standard candles" seen - where they should be
- Significant amount of data expected from 2010/11 run
  - LHCb immediately competitive with BaBar/Belle and CDF/D0
- LHCb ready for the data-taking in 2010!

BACKUP



Single photon accumulated image taken shining from a projector (the same used for the magn. distortion) on the C-side of RICH2. The light level over the whole surface is ~100 phel per event.

Trigger for 2010

Few fills at injection energy

- 450 GeV, 2-4 bunches $5\cdot10^{10}$ p colliding, β * =10 => rate ~(few) 100 Hz

Ramp in energy

- 3.5 TeV, 2 bunches $1\cdot10^{10}$ p colliding, β*=10 => rate ~100 Hz

mbias triggers based on Level 0 objects: muon p_T, hadron p_T, Pile-Up System

Squeeze of β*

- 3.5 TeV, 2 bunches $1\cdot10^{10}$ p colliding, β* = 2 => rate ~500 Hz

Increased bunch charge

- 3.5 TeV, 2 bunches $5\cdot10^{10}$ p colliding, β*=2 => rate ~10 kHz

L0 and HLT optimized for prompt Charm and Beauty + (mbias & random triggers) downscaled

Prompt charm efficiency increased by more than a factor 4 w.r.t. design settings without loss in b-physics

Increasing number of bunches

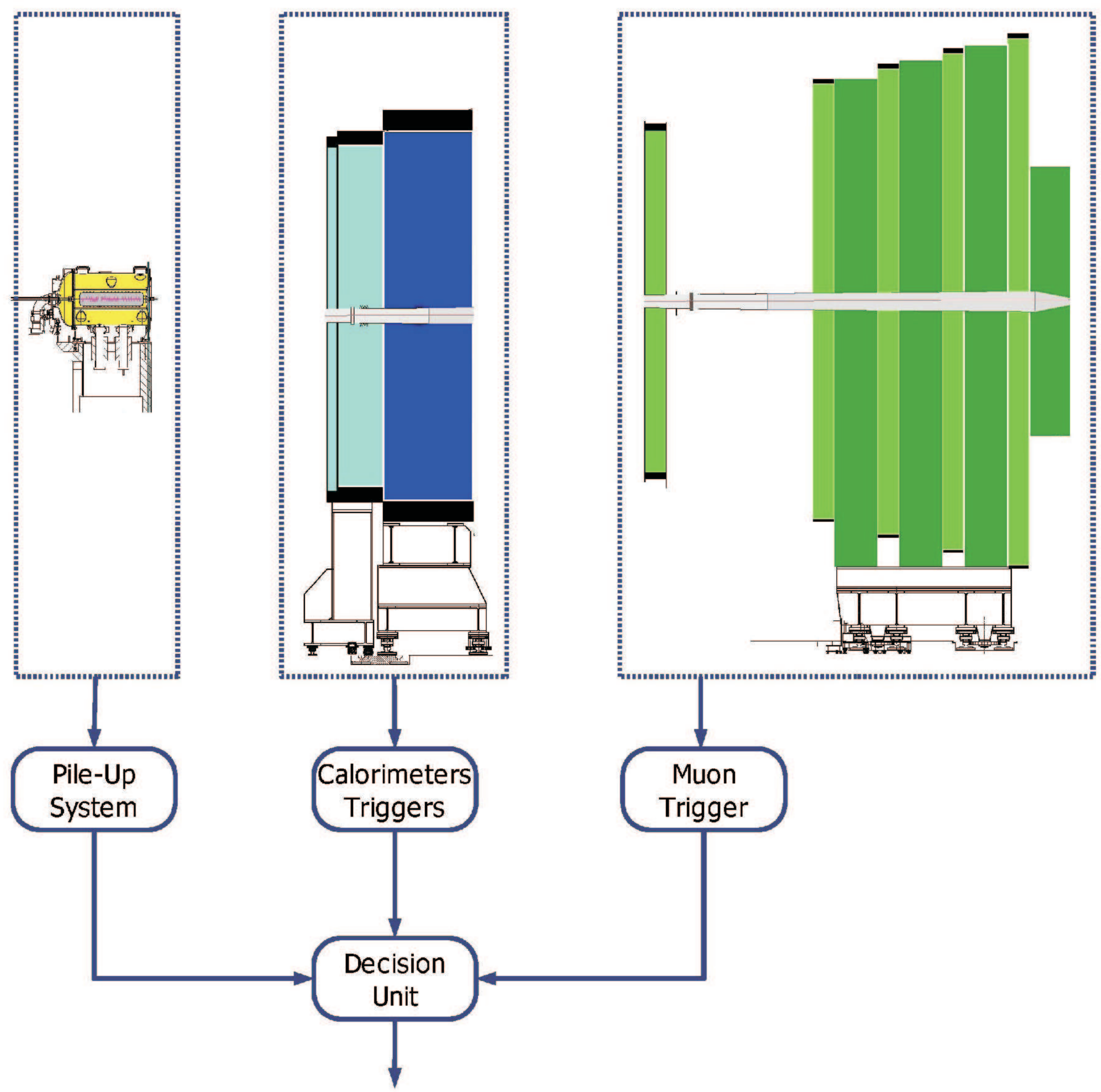
- 3.5 TeV, 19 bunches $5\cdot10^{10}$ p colliding, β*=2 => rate ~100 kHz

Optimized for Beauty Physics

Evolution of luminosity in first few months

- When moving to crossing angle and 50 ns bunch spacing we expect L~1-2$\cdot10^{32}$ $cm^{-2}s^{-1}$ with ~200 pb^{-1} in 2010 and ~1 fb^{-1} in 2011 (~1/2 of a nominal year for LHCb)

L0 Trigger



- Identify single particle *b*-hadron decay products,
  - Final state particles (π, K, e, γ, μ) with significant p_t,
  - Threshold p_t values of a few GeV,
  - Sets of thresholds optimized for physics goals.
- 40 MHz input $\rightarrow$ 1 MHz output

Trigger

- Two stage: 40MHz bunch crossing → 2kHz output
- L0 hardware trigger
  - Subset of detector information
  - 1 MHz output rate
- High Level Trigger - software
  - All detector information available
  - Multiple layers with increasing complexity
  - 2 kHz output rate (to disk)

New Physics in Charm Mixing

Summary: New Physics in mixing

Category	Model	Approximate Constraint
Extra fermions	Fourth Generation (Fig. 2)	$\|V_{ub'}V_{cb'}\| \cdot m_{b'} < 0.5$ (GeV)
	$Q = -1/3$ Singlet Quark (Fig. 4)	$s_2 \cdot m_S < 0.27$ (GeV)
	$Q = +2/3$ Singlet Quark (Fig. 6)	$\|\lambda_{uc}\| < 2.4 \cdot 10^{-4}$
	Little Higgs	Tree: See entry for $Q = -1/3$ Singlet Quark
		Box: Region of parameter space can reach observed x_D
Extra gauge bosons	Generic Z' (Fig. 7)	$M_{Z'}/C > 2.2 \cdot 10^3$ TeV
	Family Symmetries (Fig. 8)	$m_1/f > 1.2 \cdot 10^3$ TeV (with $m_1/m_2 = 0.5$)
	Left-Right Symmetric (Fig. 9)	No constraint
	Alternate Left-Right Symmetric (Fig. 10)	$M_R > 1.2$ TeV ($m_{D_1} = 0.5$ TeV)
		$(\Delta m/m_{D_1})/M_R > 0.4$ TeV^{-1}
Extra scalars	Vector Leptoquark Bosons (Fig. 11)	$M_{VLQ} > 55(\lambda_{PP}/0.1)$ TeV
	Flavor Conserving Two-Higgs-Doublet (Fig. 13)	No constraint
	Flavor Changing Neutral Higgs (Fig. 15)	$m_H/C > 2.4 \cdot 10^3$ TeV
	FC Neutral Higgs (Cheng-Sher ansatz) (Fig. 16)	$m_H/\|\Delta_{uc}\| > 600$ GeV
	Scalar Leptoquark Bosons	See entry for RPV SUSY
Exra dimensions	Higgsless (Fig. 17)	$M > 100$ TeV
	Universal Extra Dimensions	No constraint
	Split Fermion (Fig. 19)	$M/\|\Delta y\| > (6 \cdot 10^2$ GeV)
	Warped Geometries (Fig. 21)	$M_1 > 3.5$ TeV
SUSY	Minimal Supersymmetric Standard (Fig. 23)	$\|(\delta^u_{12})_{LR,RL}\| < 3.5 \cdot 10^{-2}$ for $\tilde{m} \sim 1$ TeV
		$\|(\delta^u_{12})_{LL,RR}\| < .25$ for $\tilde{m} \sim 1$ TeV
	Supersymmetric Alignment	$\tilde{m} > 2$ TeV
	Supersymmetry with RPV (Fig. 27)	$\lambda'_{12k}\lambda'_{11k}/m_{\tilde{d}_{R,k}} < 1.8 \cdot 10^{-3}/100$ GeV
	Split Supersymmetry	No constraint

- ✓ Considered 21 well-established models
- ✓ Only 4 models yielded no useful constraints
- ✓ Consult paper for explicit constraints on your favorite model!

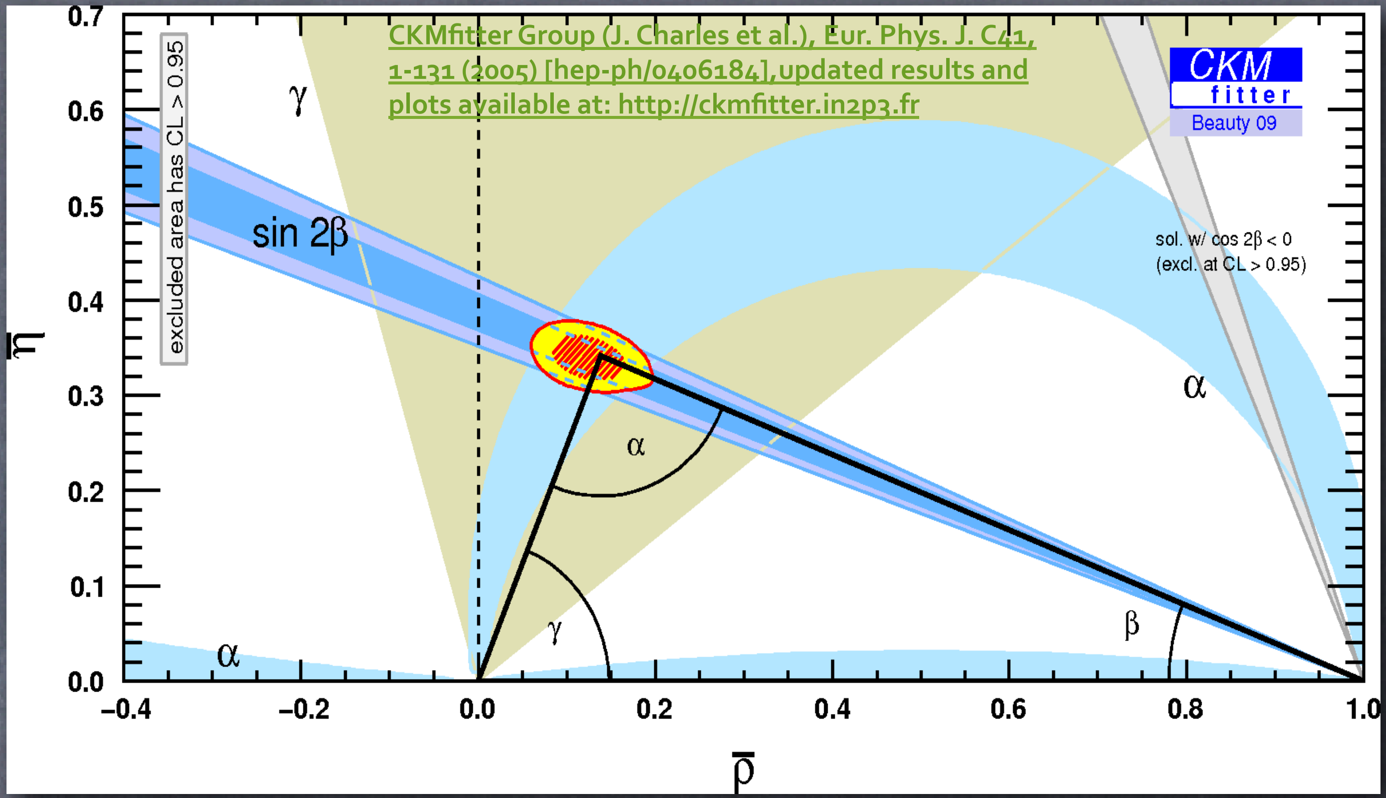
E.Golowich, J. Hewett, S. Pakvasa and A.A.P. Phys. Rev. D76:095009, 2007

Gedalia, Grossman, Nir, Perez arXiv:0906.1879 [hep-ph]

Bigi, Blanke, Buras, Recksiegel, JHEP 0907:097, 2009

CKM Angle γ

- Least known parameter in CKM picture
  - CKMFitter
    - $\alpha = (21.2 \pm 0.9)^\circ$
    - $\beta = (89 \pm 4)\ ^\circ$
    - $\gamma = (70\ ^{+22}{}_{-25})\ ^\circ$
  - UTFit
    - $\gamma = (75 \pm 15)\ ^\circ$



- Several complementary approaches
  - Interference of tree diagrams (time independent)
  - Time-dependent analysis of $B_s \to D_s^- K^+$
  - γ from loop diagrams

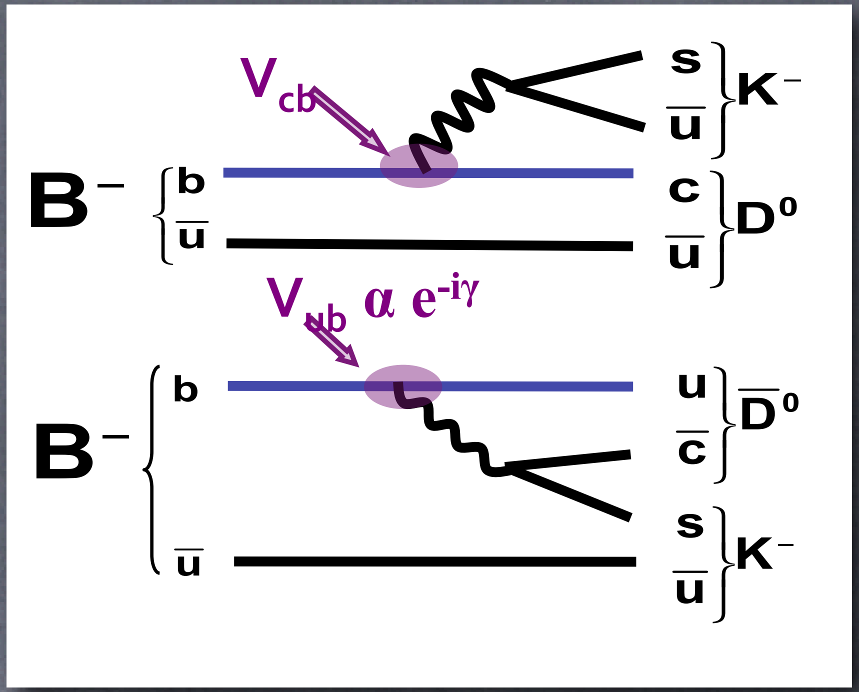
B →DK: γ From Trees

- Analysis methods
  - GLW: $D \to K^+K^-$, $\pi^+\pi^-$

    Phys. Lett. B 253, 483 (1991), Phys. Lett B 265, 171 (1991)
  - ADS: $D \to K^+\pi^-$

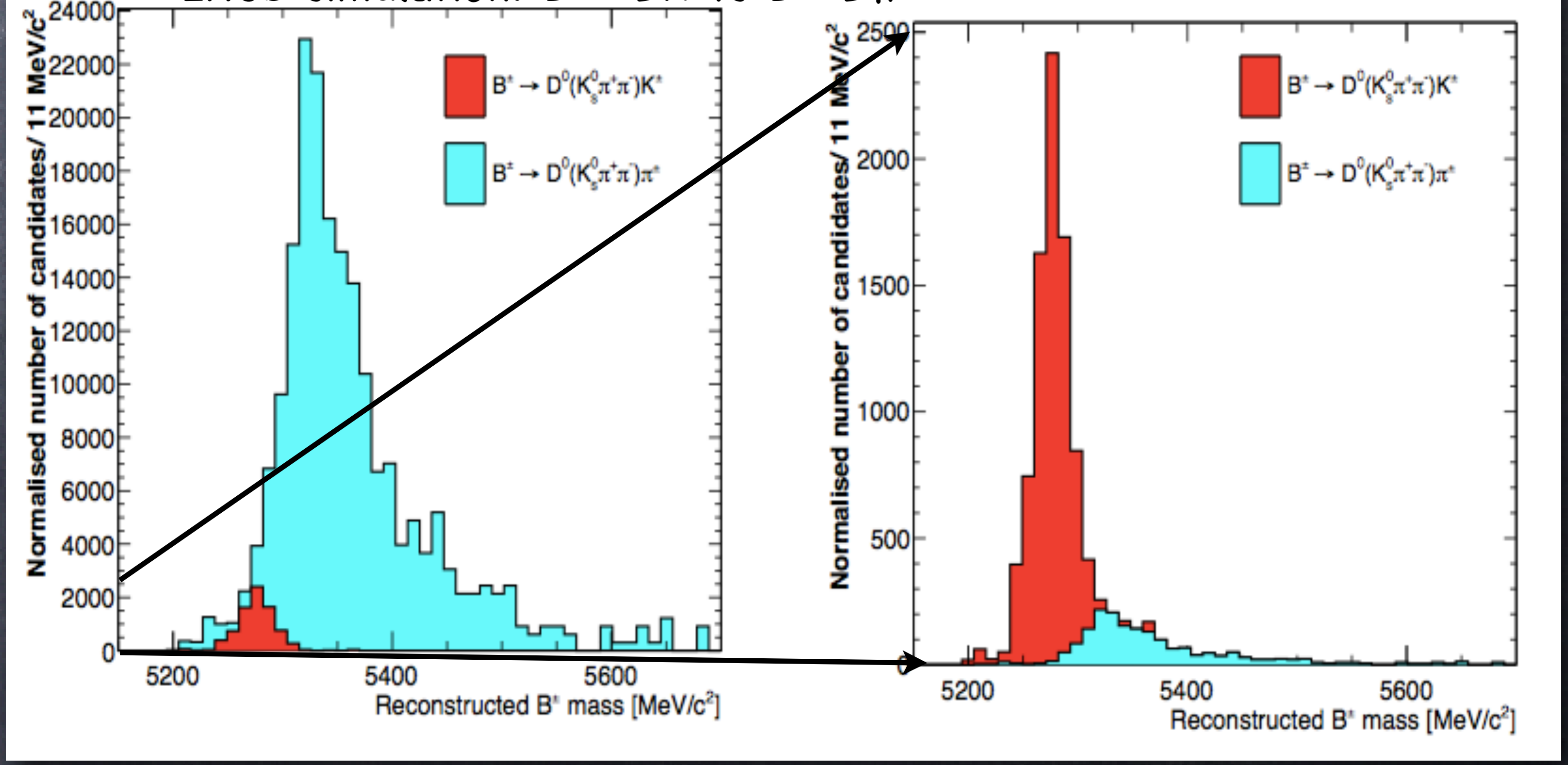
    Phys. Rev. Lett. 78, 3257(1997), Phys. Rev. D63, 036005 (2001)

    ➥ 6 measured rates, 5 unknowns
  - $B^\pm \to D^0(K_s\pi^+\pi^-)K^\pm$: full Dalitz analysis



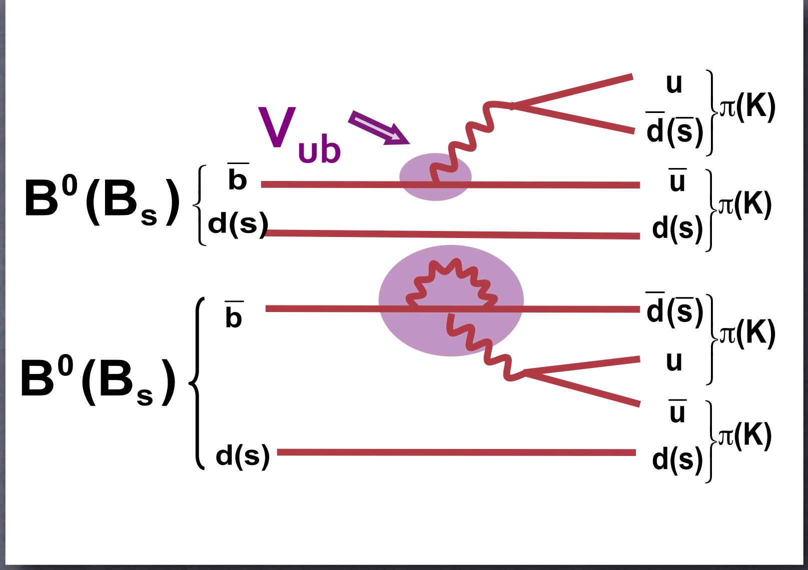
- Sensitivity (nominal year)
  - σ(γ) ~ 4°- 5° (tree)
  - σ(γ) ~ 9°- 13° (Dalitz)
- Particle ID crucial
  - KaonID ε > 95% [2-100 GeV/c]
  - π/K misID < 4%

LHCb simulation: B→ DK vs B→Dπ

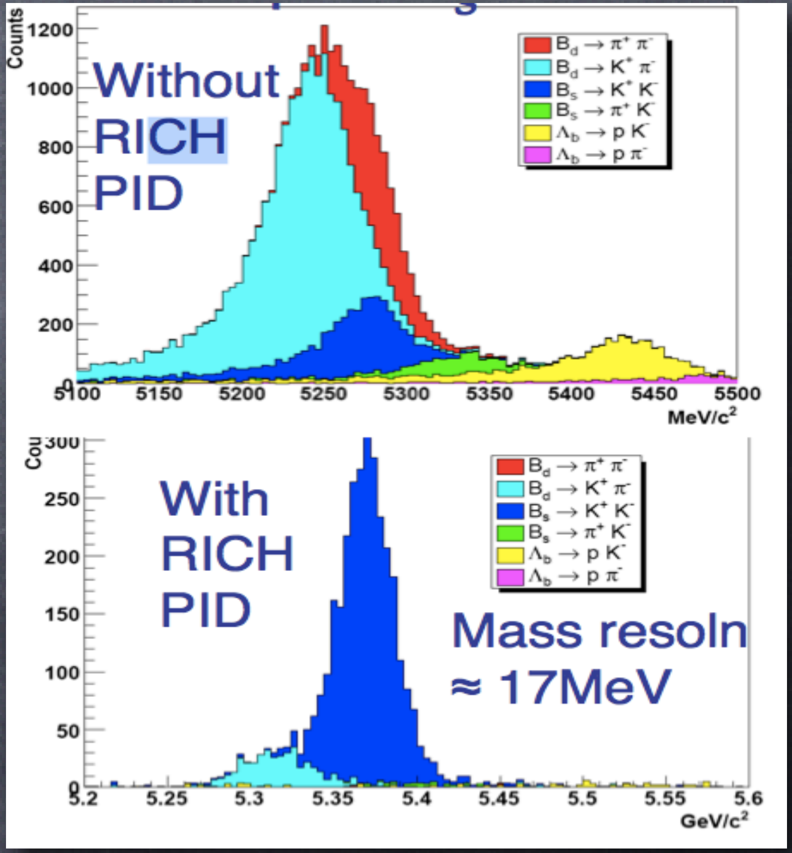


Charmless B Meson Decays

- Sensitive to γ (from interference)
  - Mixing
  - Tree / Penguin diagrams
  - Sensitivity: σ(γ) ~ 10°
  - Fit time dependent CP asymmetries
- Lifetime measurements sensitive to New Physics
  - Extract information about ΔΓ,…



- Large B→hh sample in 2010/11 data-set
  - Expect ~36k B_s→KK / nominal year
  - Ideal for "first physics"
    - Early BR and asymmetry measurements with > 500 pb^{-1}
    - First measurement of A_{CP} in B_s→KK



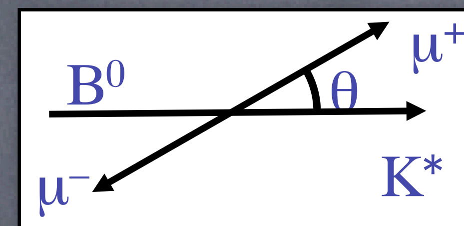
Particle ID crucial

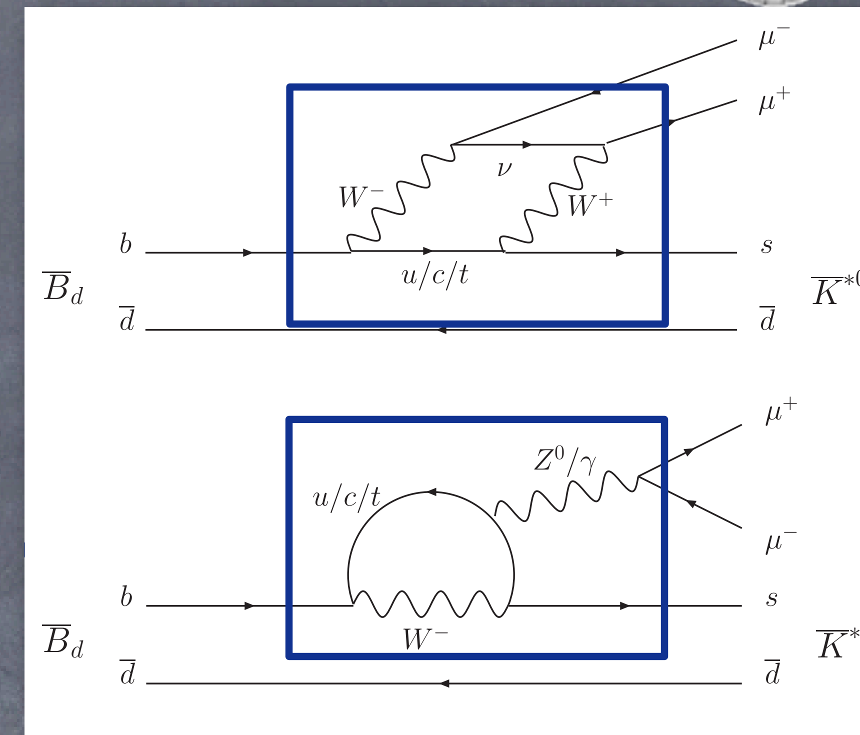
B → K*μμ

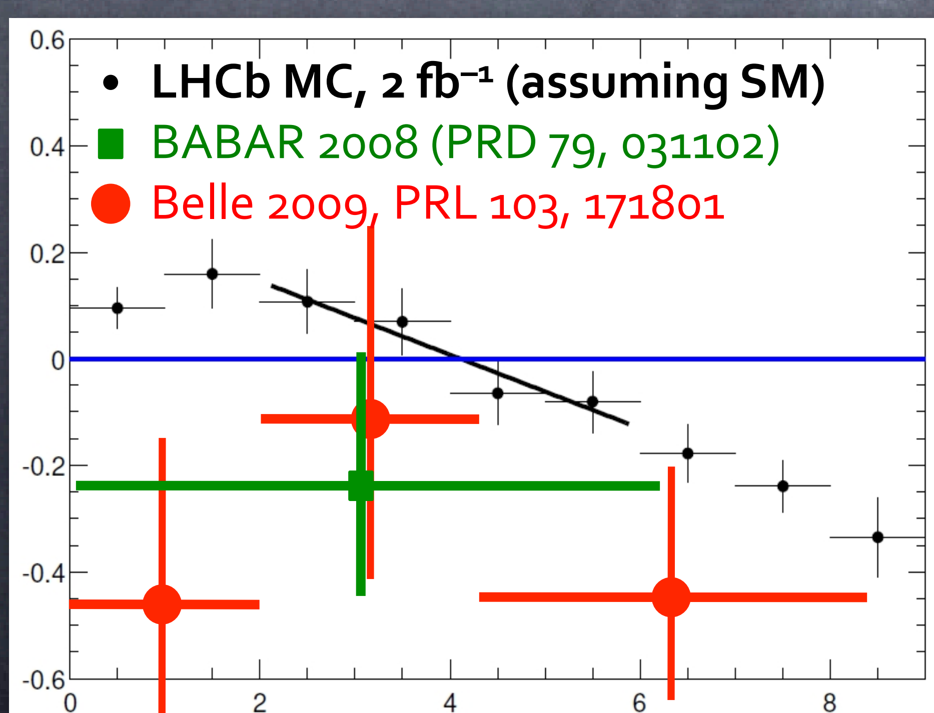
- Suppressed loop decay
- $A_{FB}(s)$ in μμ rest-frame probe of NP in b→s loop
  - Both neutral and charged NP
    - replace W±, Z/γ, u/c/t
  - $A_{FB}(s)$ distribution:
    - Zero crossing and shape

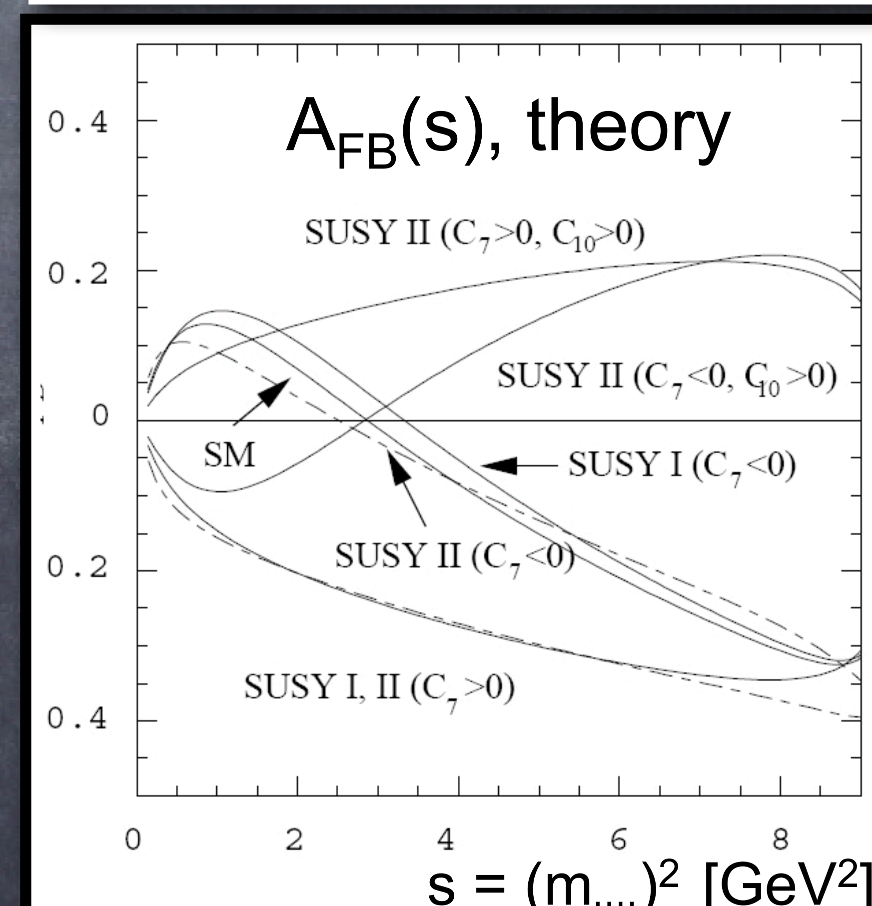
➥ Determine ratio of Wilson coefficients C_7/C_9

- Expected statistics:
  - 0.1 fb^{-1} ~ 300 events
  - ➥ competitive with BaBar, Belle, CDF in 2010!





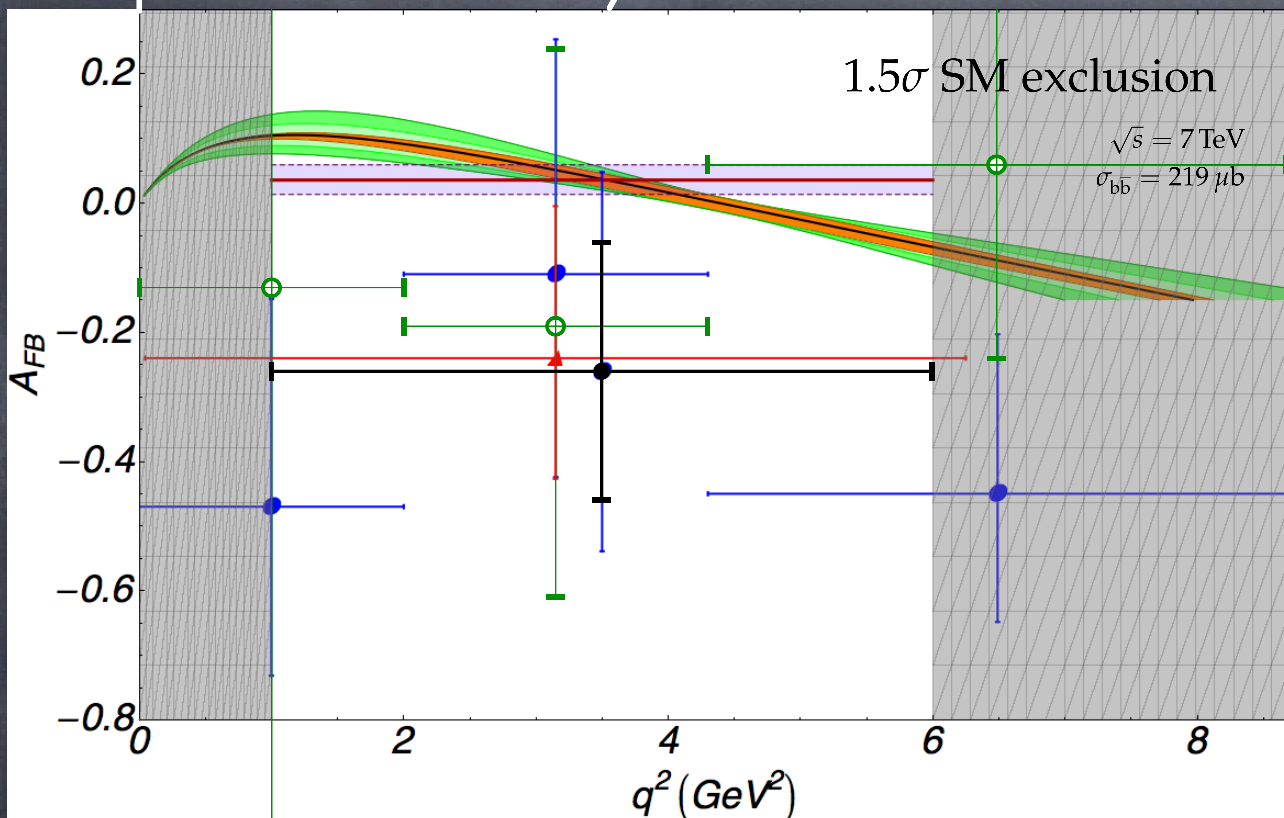




2 fb^{-1} = one nominal year at $\sqrt{s}$ = 14TeV

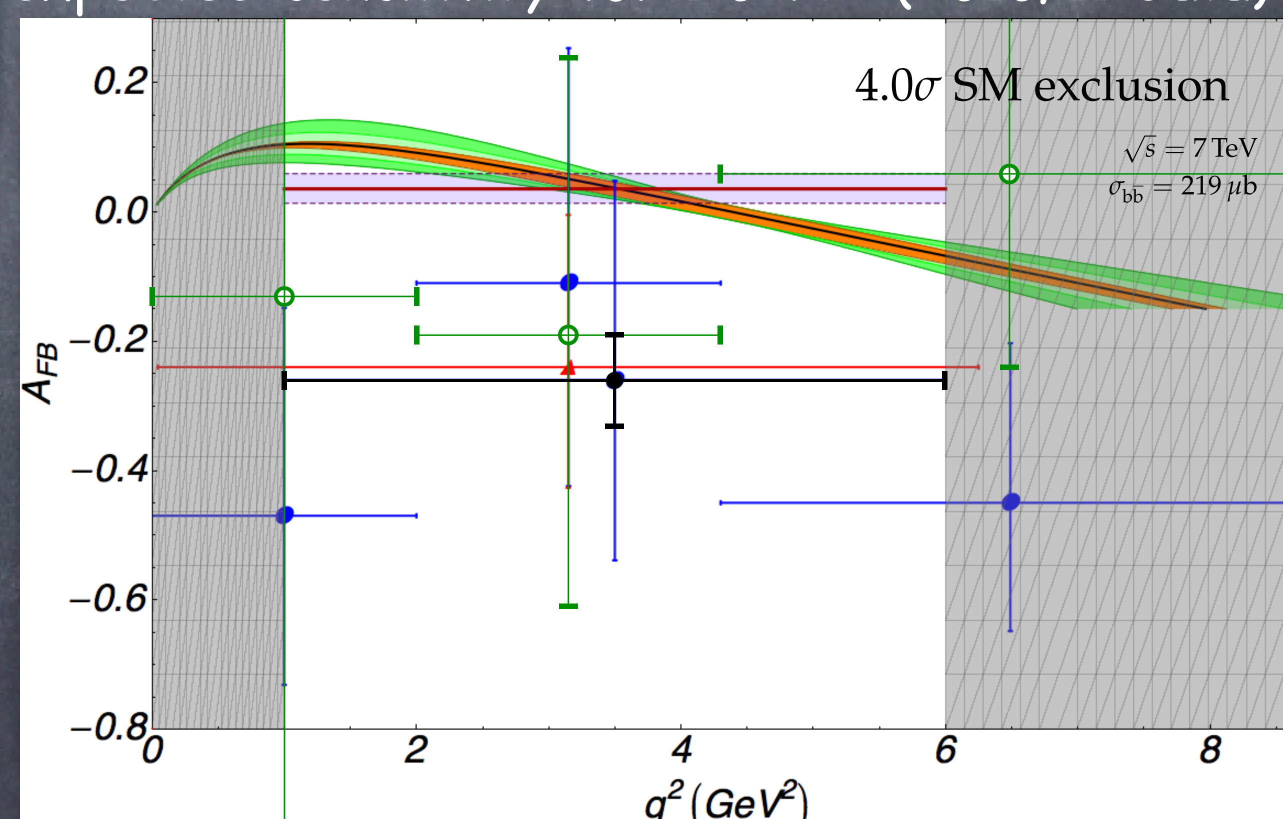
B → K*μμ

expected sensitivity for 0.1 fb^{-1}

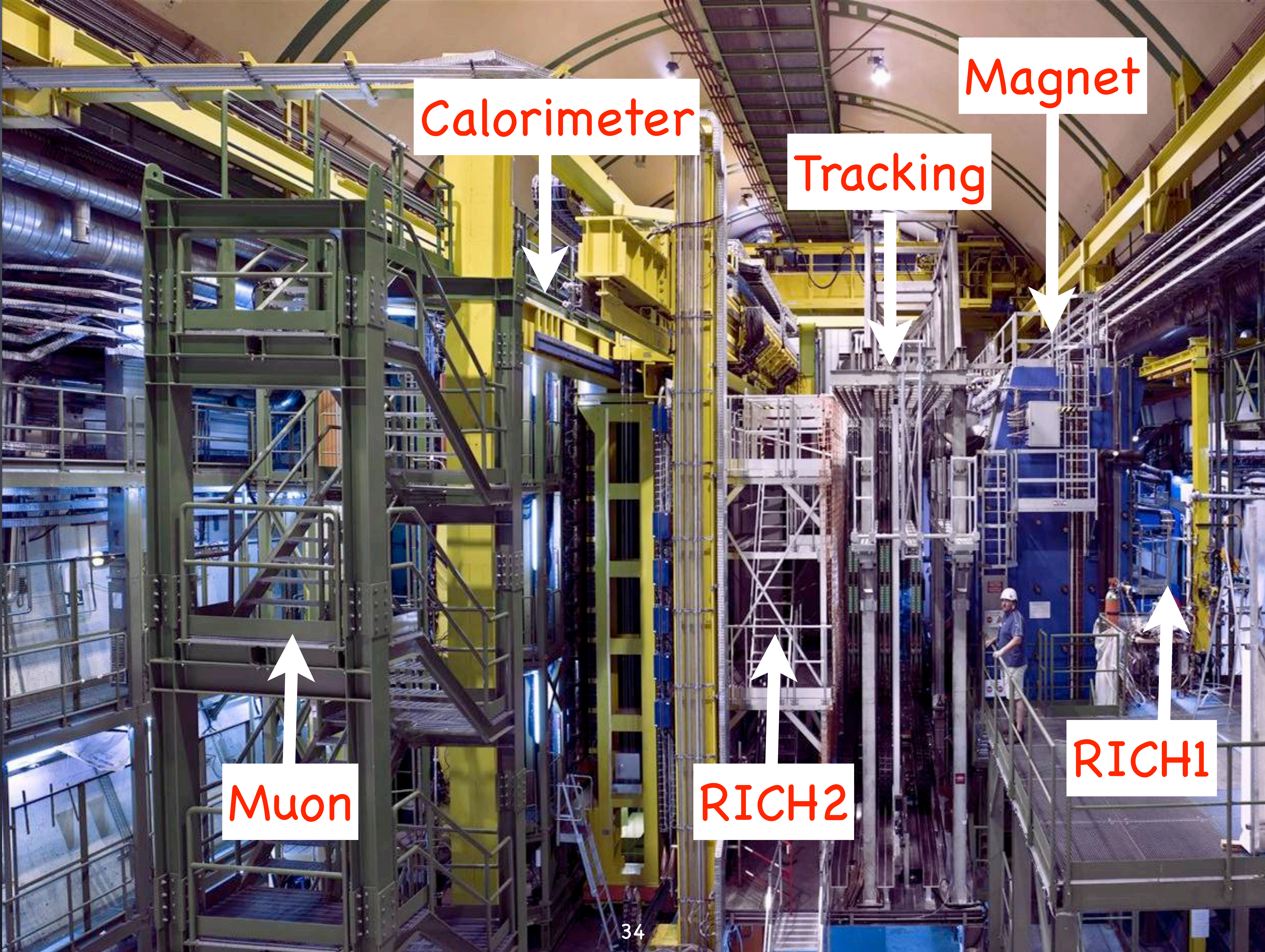


assuming √s = 7 TeV
LHCb very quickly competative
with the other experiments!

expected sensitivity for 1.0 fb^{-1} (2010/11 data)

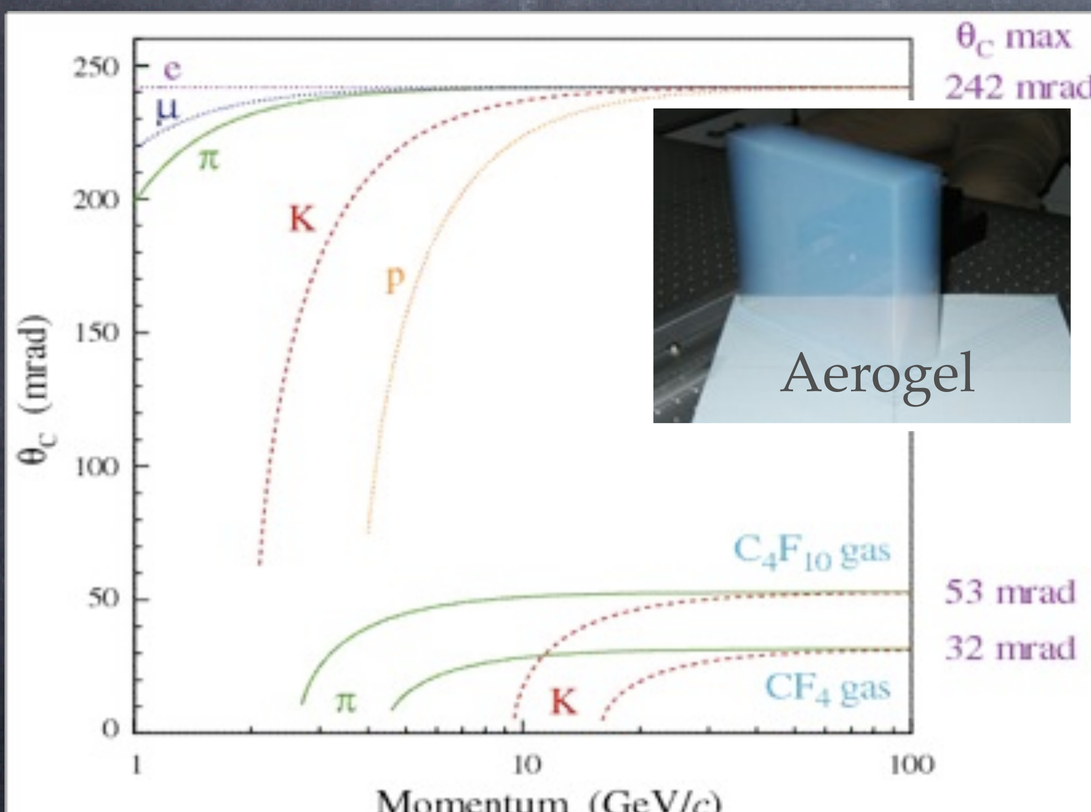


black: LHCb
red: BaBar
blue: Belle
green: CDF

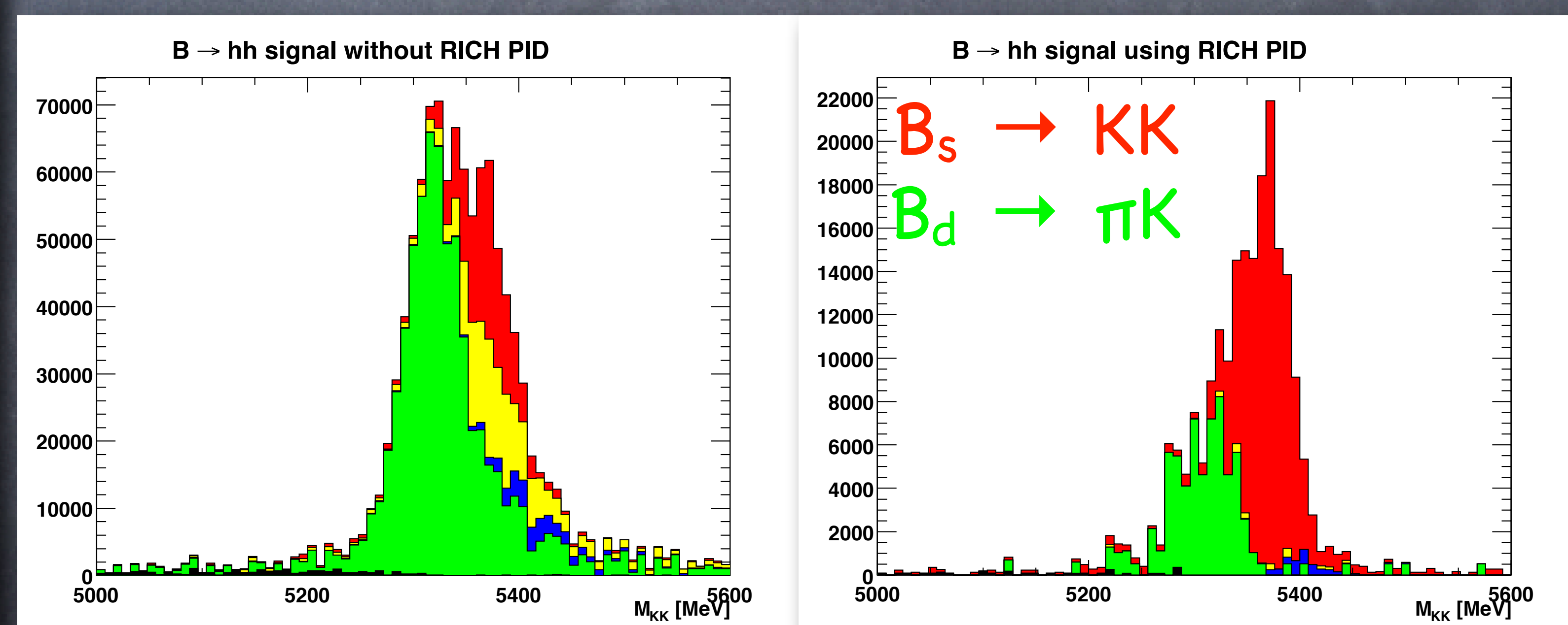

Calorimeter
Magnet
Tracking
Muon
RICH2
RICH1

Particle ID

- Excellent PID required for ambitious physics programme:
  - μ, e, γ : muon chambers and calorimeter
  - π / p / K : Ring Imaging Cherenkov Detectors + Tracker
    - Cherenkov angle ($\cos\theta_c = 1/\beta n$) and momentum → PID
    - Tune radiator materials to cover wide momentum range

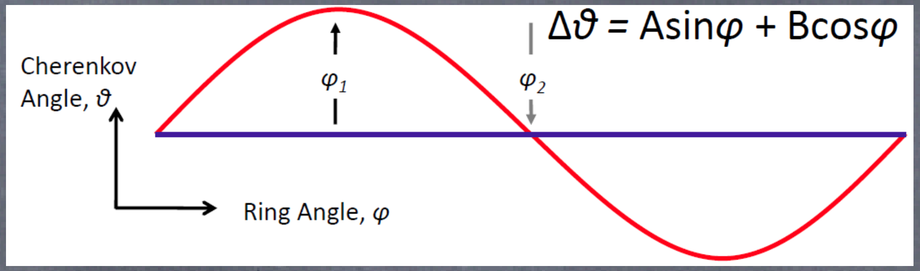


- Silica Aerogel (2-10 GeV/c)
- C_4F_{10} (10-60 GeV/c)
- CF_4 (16-100 GeV/c)

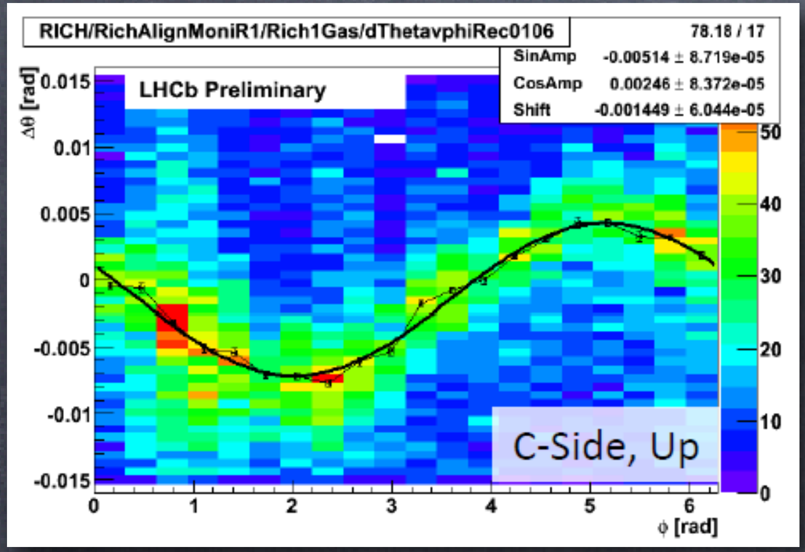


e. g. charmless two-body B decays

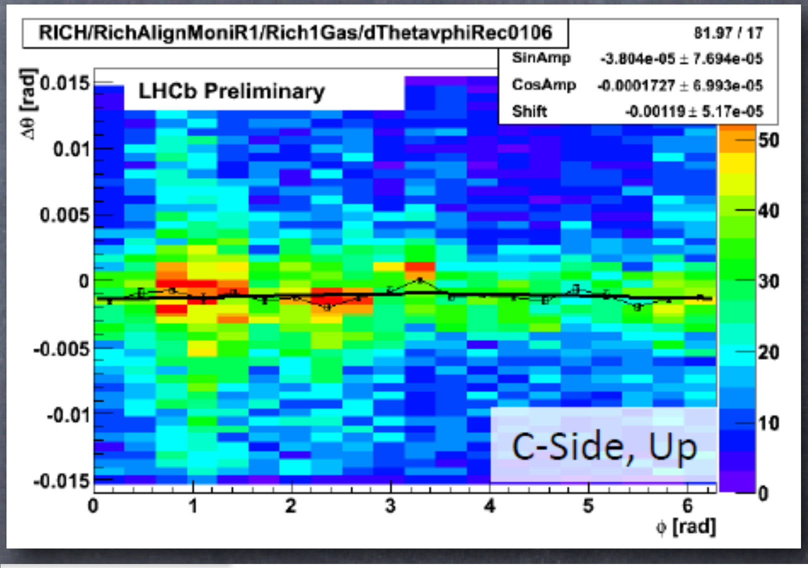
2009 Data: RICH alignment

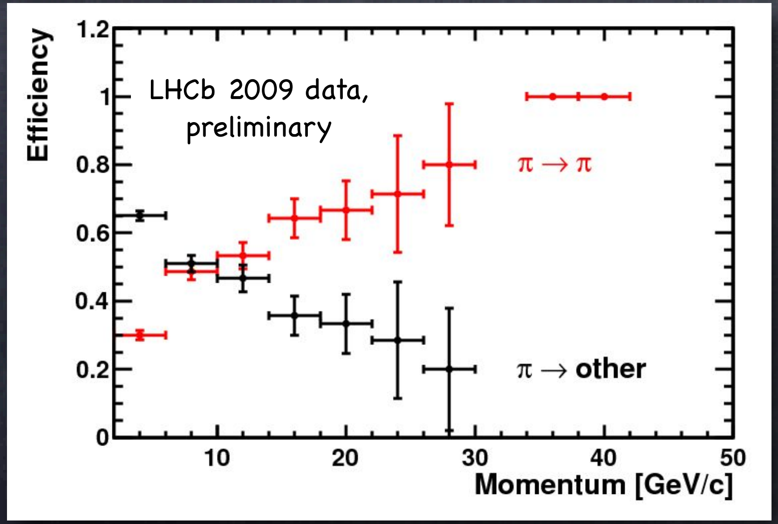


Misalignment of Cherenkov ring centres vs tracks results in sinusoidal variation of Cherenkov ϕ around the ring

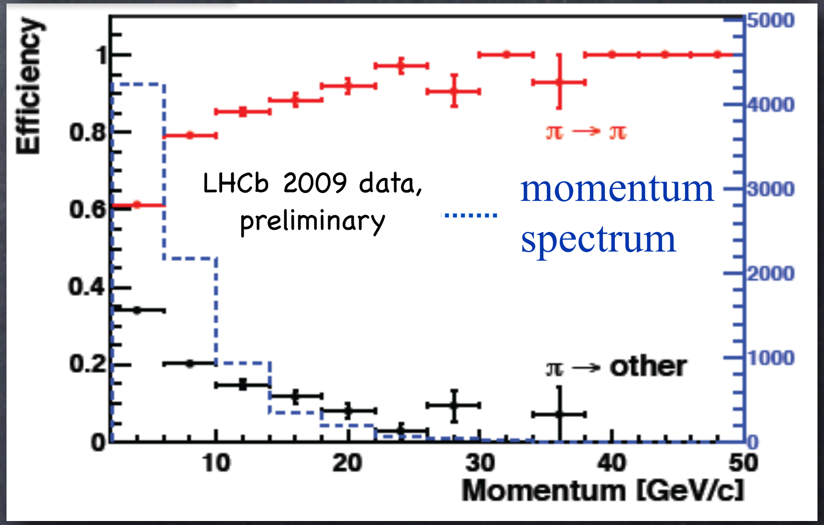


alignment correction





alignment correction



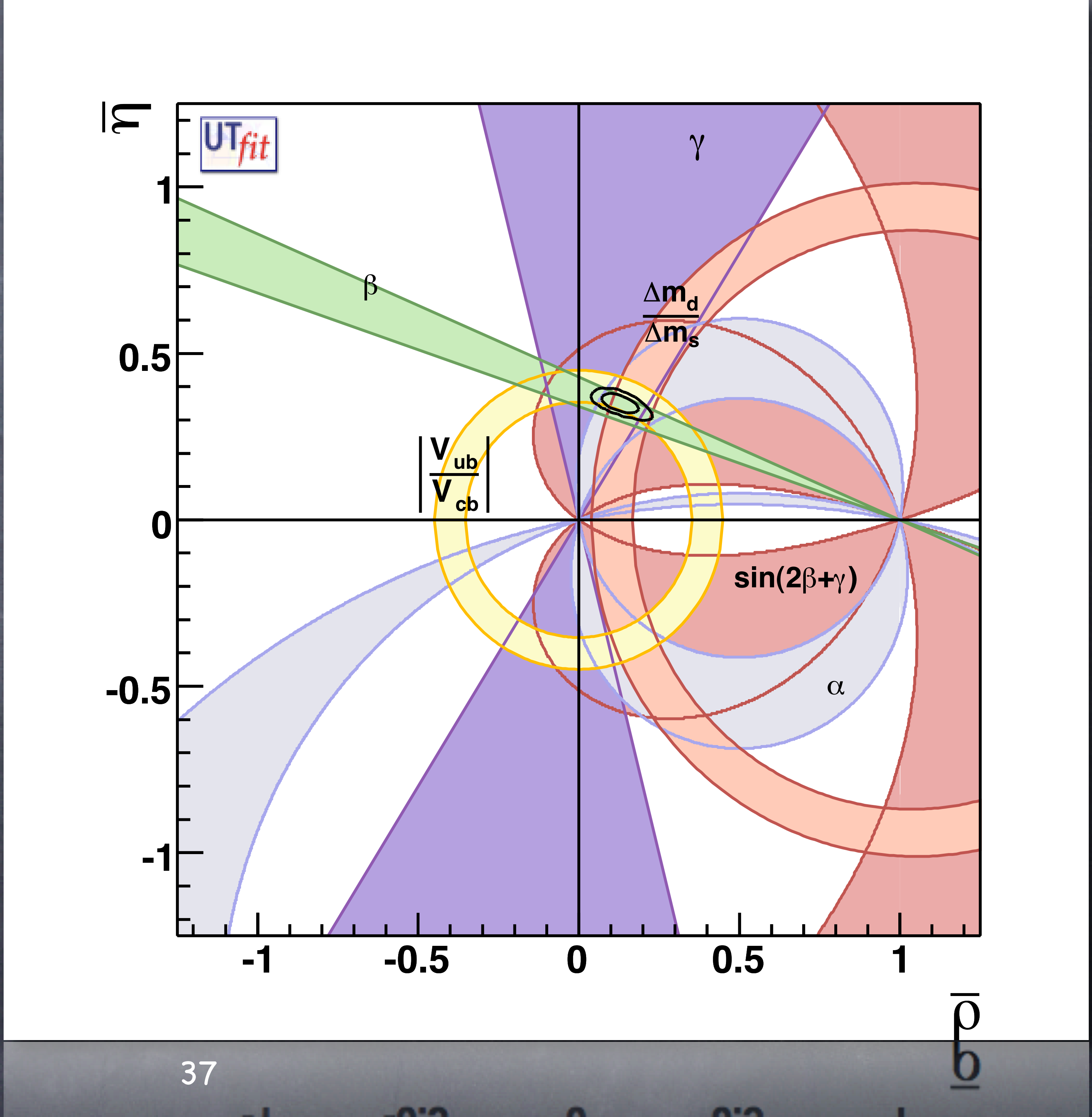
work in progress

Flavour Physics

- Current averages / summary from the UTFit collaboration

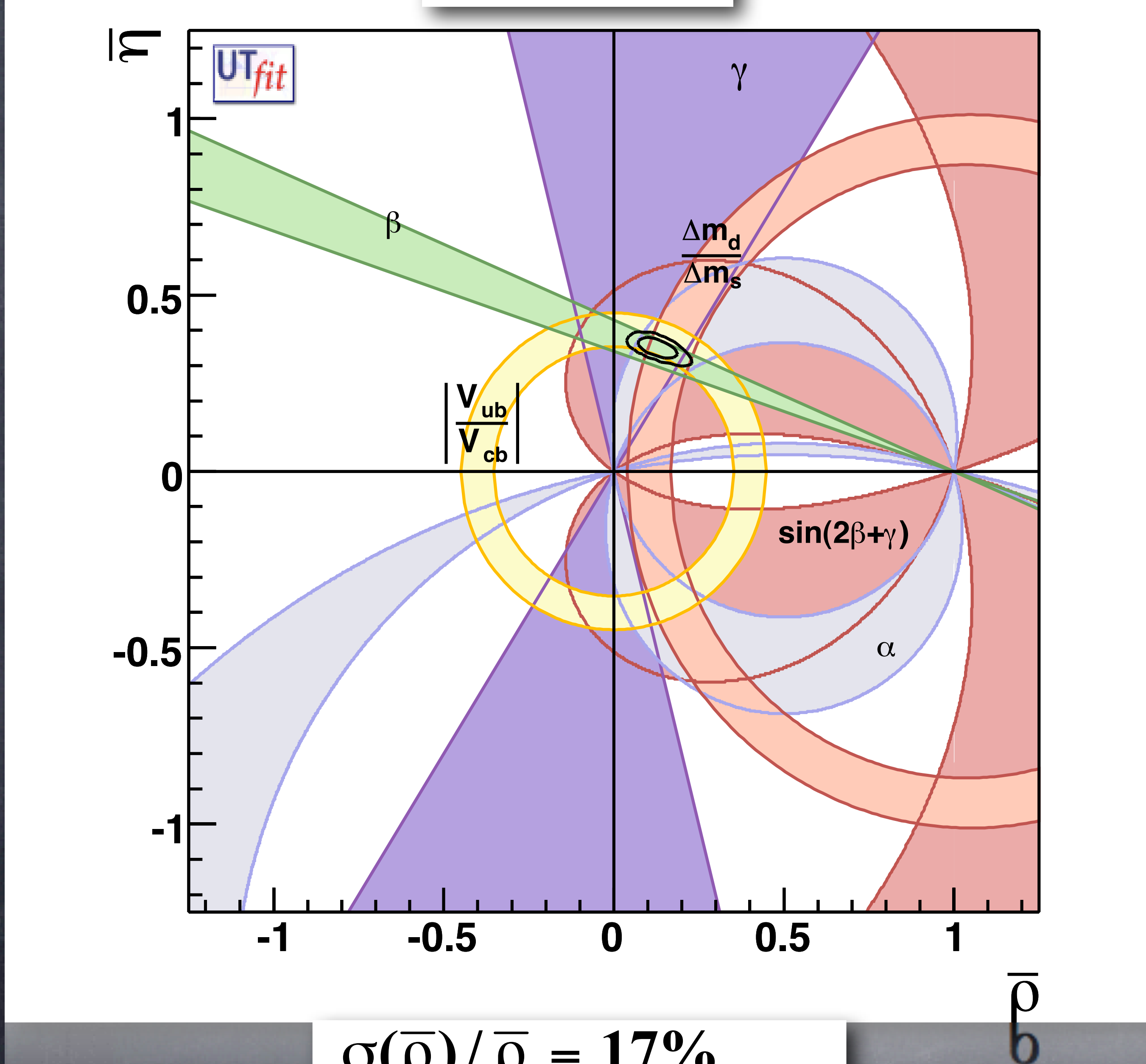
ρ = 0.1454 ± 0.022
η = 0.342 ± 0.014
α = 92.0 ± 3.2 °
β = 22.0 ± 0.8 °
γ = 65.6 ± 3.3 °
....

(many more ... worth a summary talk on its own...)



5+ years later ?

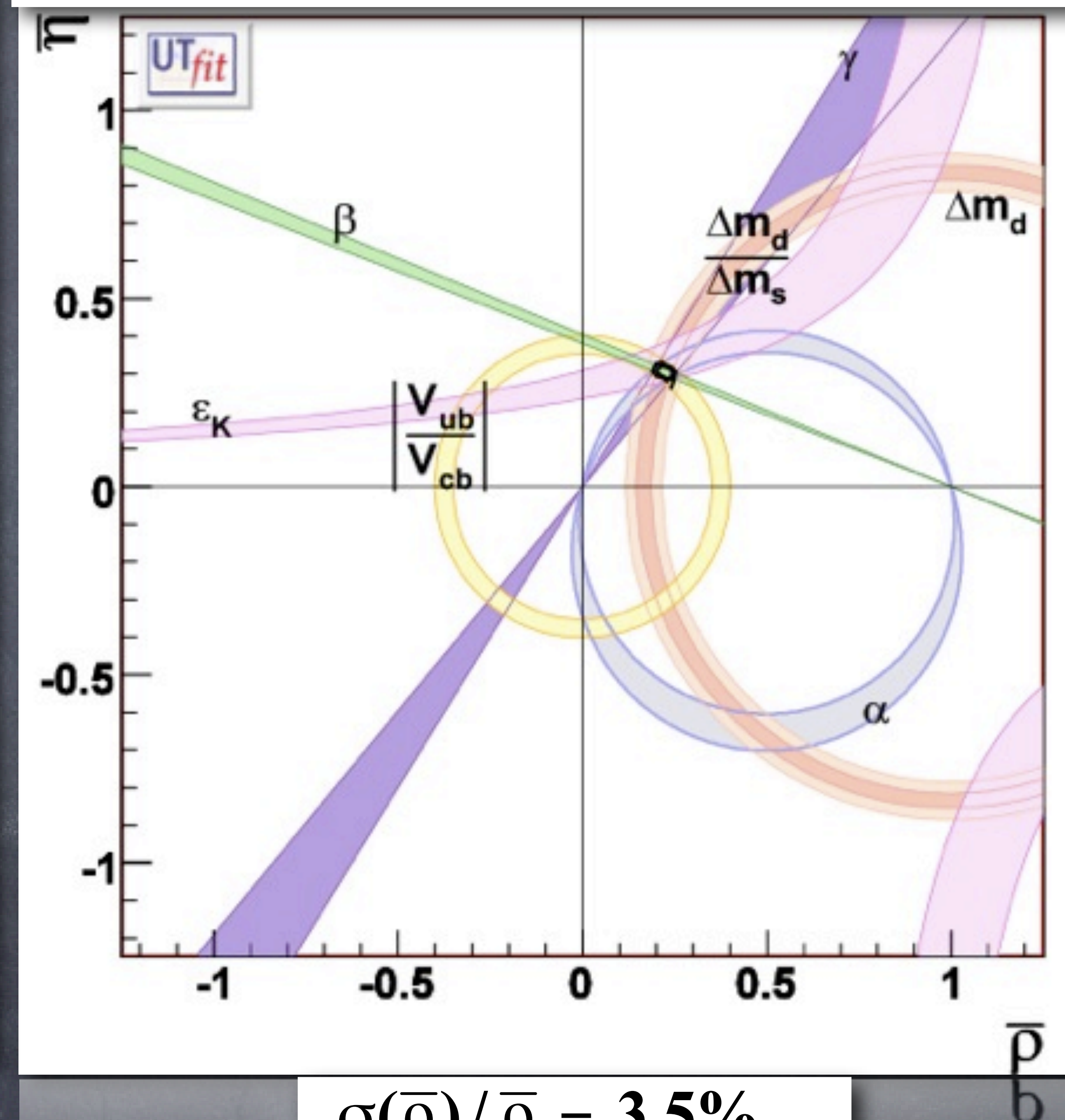
Now ...



$\sigma(\bar{\rho})/\bar{\rho}$ = **17%**

$\sigma(\bar{\eta})/\bar{\eta}$ = **4.7%**

LHCb projection (10 fb^{-1})



$\sigma(\bar{\rho})/\bar{\rho}$ = **3.5%**

$\sigma(\bar{\eta})/\bar{\eta}$ = **1.7%**

LHCb physics

- Dedicated B physics experiment
- Covering all aspects of Charm and Bottom physics
  - Cross-section, rare decays, lifetimes, spectroscopy, ...
- Higher cross-section than FNAL, better detector, trigger

➥ more B (D) per fb^{-1}

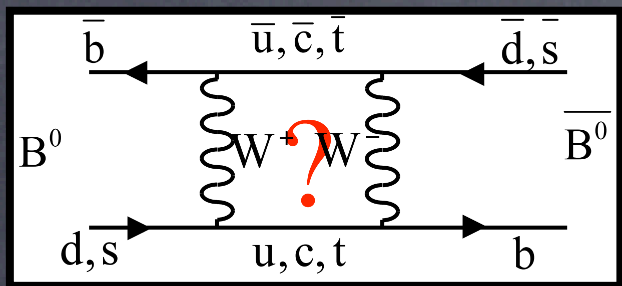
Channel	1 fb^{-1} at LHCb = ... fb^{-1} at Tevatron	
$D^0 \rightarrow K\pi$	20	50M / 2fb^{-1} at LHCb 0.5M / 0.35fb^{-1} at CDF
$B \rightarrow hh$	30	200k / 2fb^{-1} at LHCb 6.5k / 1fb^{-1} at CDF
$B^+ \rightarrow J/\psi K^+$	60	1.7M / 2fb^{-1} at LHCb 3.4k / 0.25fb^{-1} at CDF
$B_s \rightarrow D_s \pi$	10	120k / 2fb^{-1} at LHCb 5.6k / 1fb^{-1} at CDF

$B_s \to hh$ Yields

Mode	Yield	B/s
$B^0 \to \pi\pi$	36k	0.5
$B_s \to KK$	36k	0.15
$B^0 \to K\pi$	140k	<0.06
$B_s \to \pi K$	10k	1.9

untagged, per nominal year

LHCb - Key Analyses

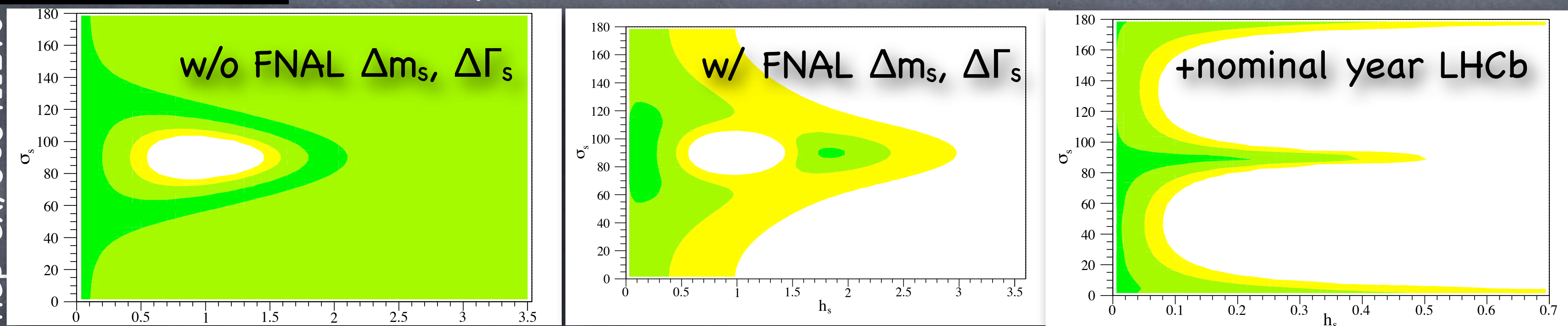


Bs mixing phase ϕ_s very small in SM

➥ potentially large contributions from NP

Analyses: $B_s \rightarrow J/\psi\phi$, $J/\psi\eta$, D_sD_s || $c\tau(B) \rightarrow \Delta\Gamma$ ...

hep-ex/0604112v3



CKM angle γ

Tree Level:

$B_s \rightarrow D_sK$

$B_d \rightarrow D^{(*)}\pi$

$B^{\pm}$, $B_d \rightarrow D^{(*)}K^{(*)}$, with D^0 decaying to:

2 bodies: πK, KK, $\pi\pi$

3 bodies: KS $\pi\pi$, KS KK, KS $K\pi$

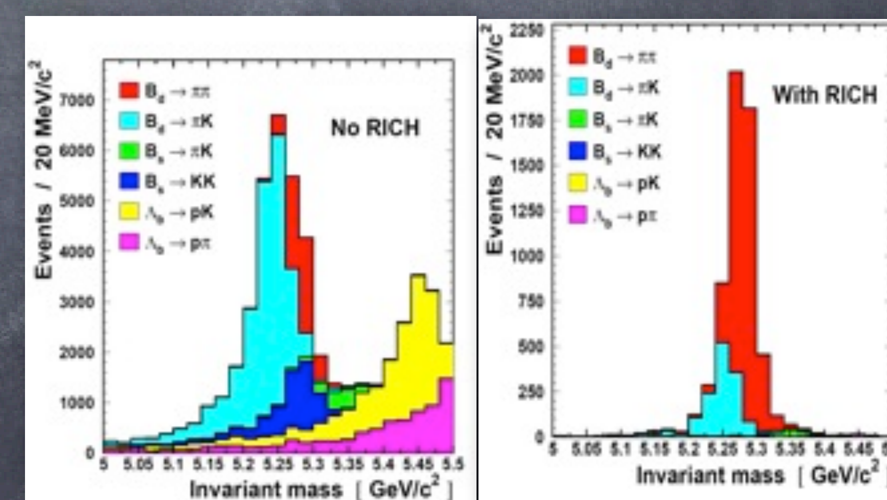
4 bodies: $K\pi\pi\pi$, $KK\pi\pi$

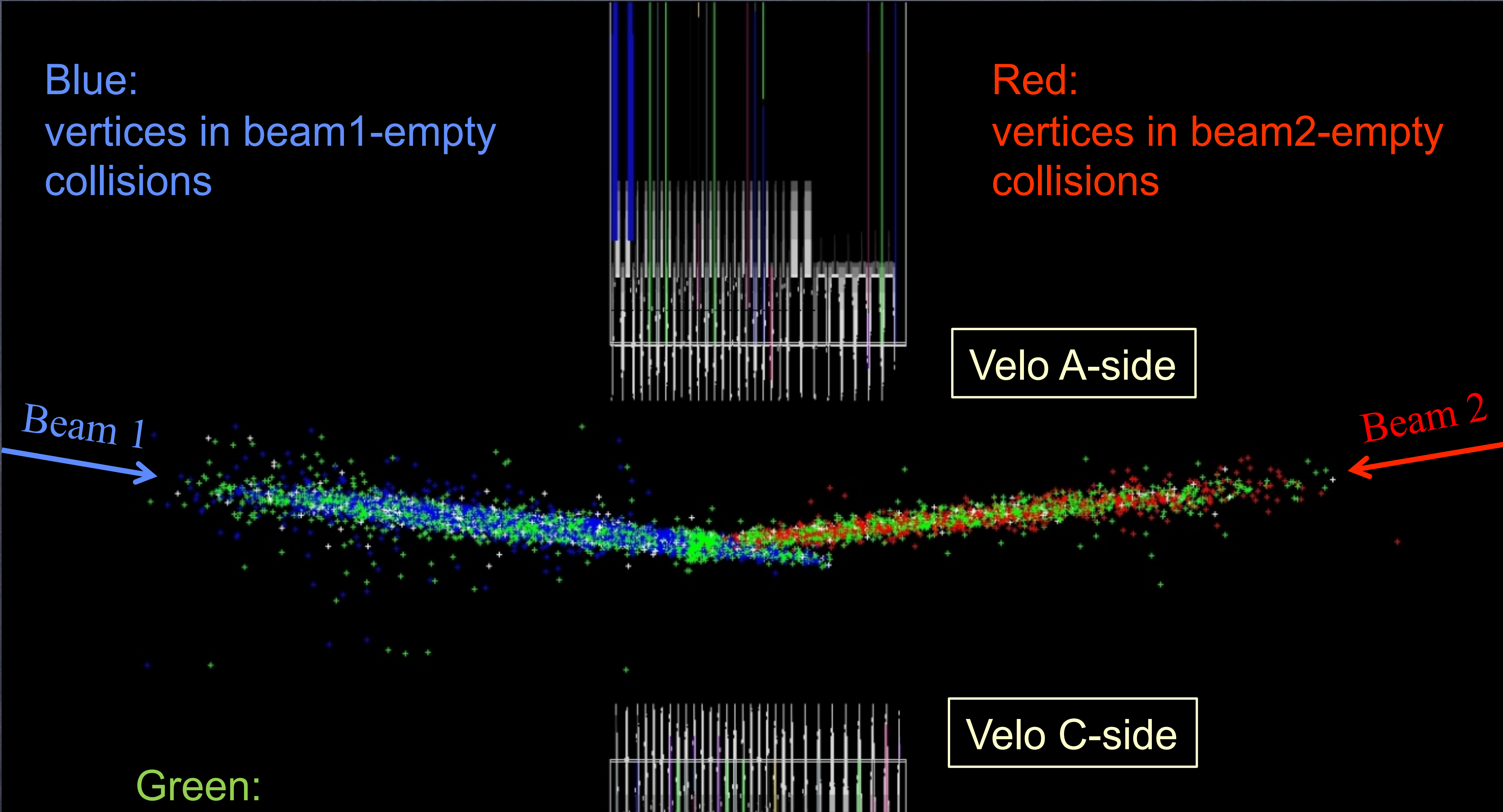
Penguin Level:

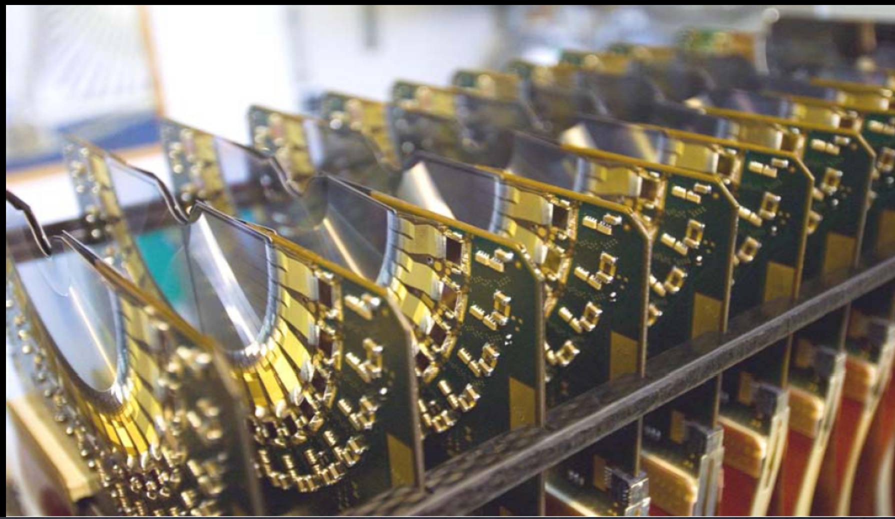
$B_s \rightarrow KK$, $B_d \rightarrow \pi\pi$

➥ PID paramount

U spin approach




Blue:
vertices in beam1-empty collisions
Red:
vertices in beam2-empty collisions
Velo A-side
Beam 1
Beam 2
Velo C-side
Green:
vertices in beam-beam collisions including beam-gas interactions
x
z



First Collisions in 2009