CP violation and precision measurements at LHCb

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PSI 2013

3rd Workshop on the **P**hysics of Fundamental **S**ymmetries and **I**nteractions at low energies and the precision frontier

12 September 2013


LHCb
813 members
16 countries
59 institutes
(July 1, 2012)
Countries member of the LHCb Collaboration

Introduction

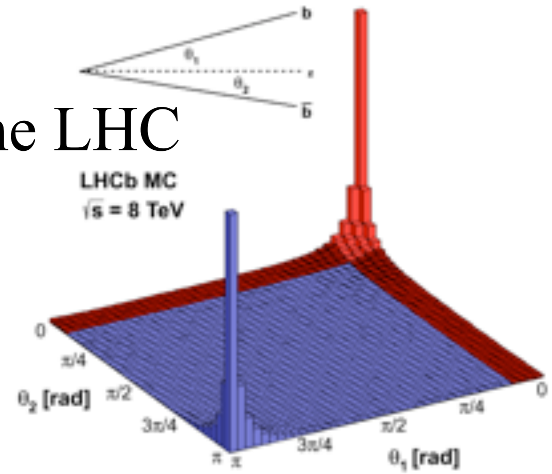
- LHCb physics goals:
  - precision tests of the Standard Model and search for New Physics
- Phenomena under study
  - *CP* violation in *B* and *D* decays
  - rare decays

  Indirect searches for New Physics

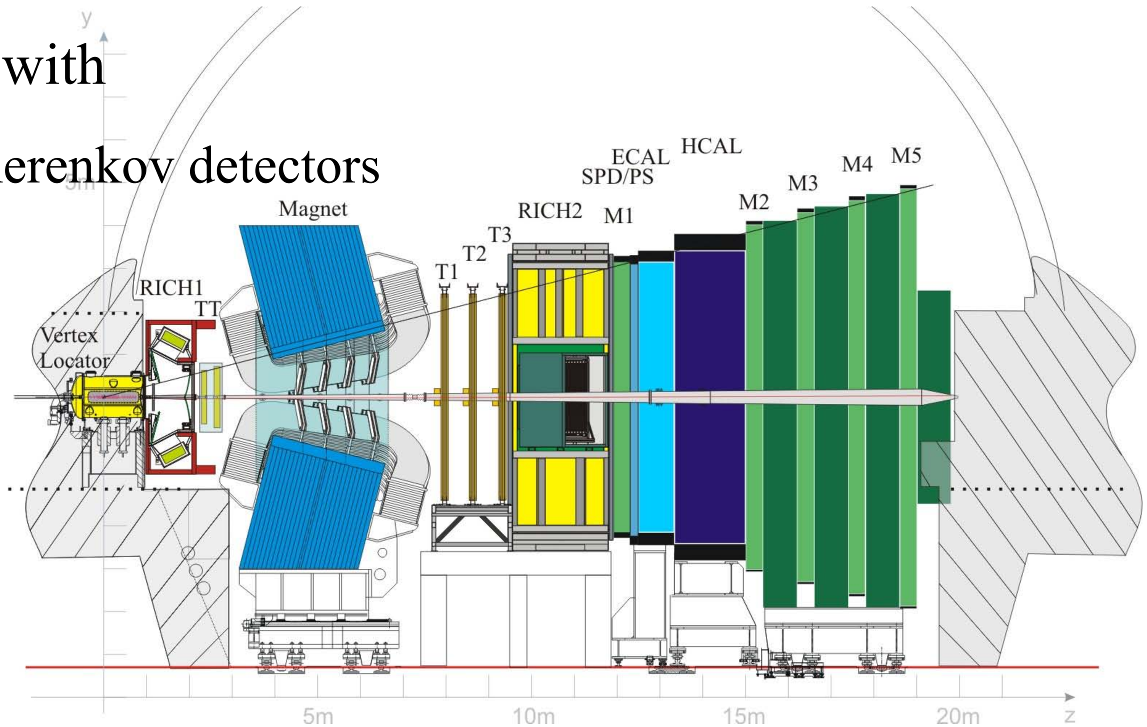
  - direct searches for New Physics in the forward region
- Finding New Physics (NP) at low energy
  - heavy NP particles can alter amplitude of loop processes
- New Physics can either:
  - be discovered in precision measurements and then confirmed with direct searches (e.g. @ ATLAS and CMS)
  - or NP particles are first observed at the energy frontier, and their properties then studied in precision measurements at 'low' energy

The LHCb detector

- LHCb is a single-arm forward spectrometer at the LHC
  - rapidity range: $1.9 < \eta < 4.9$
- Fully instrumented in the forward region
  - excellent vertex resolution (+boost)
    $\rightarrow$ 40–50fs lifetime resolution
  - tracking stations before and after 4Tm dipole magnet
  - particle identification with
    - two ring-imaging Cherenkov detectors
    - calorimetry
    - muon detectors

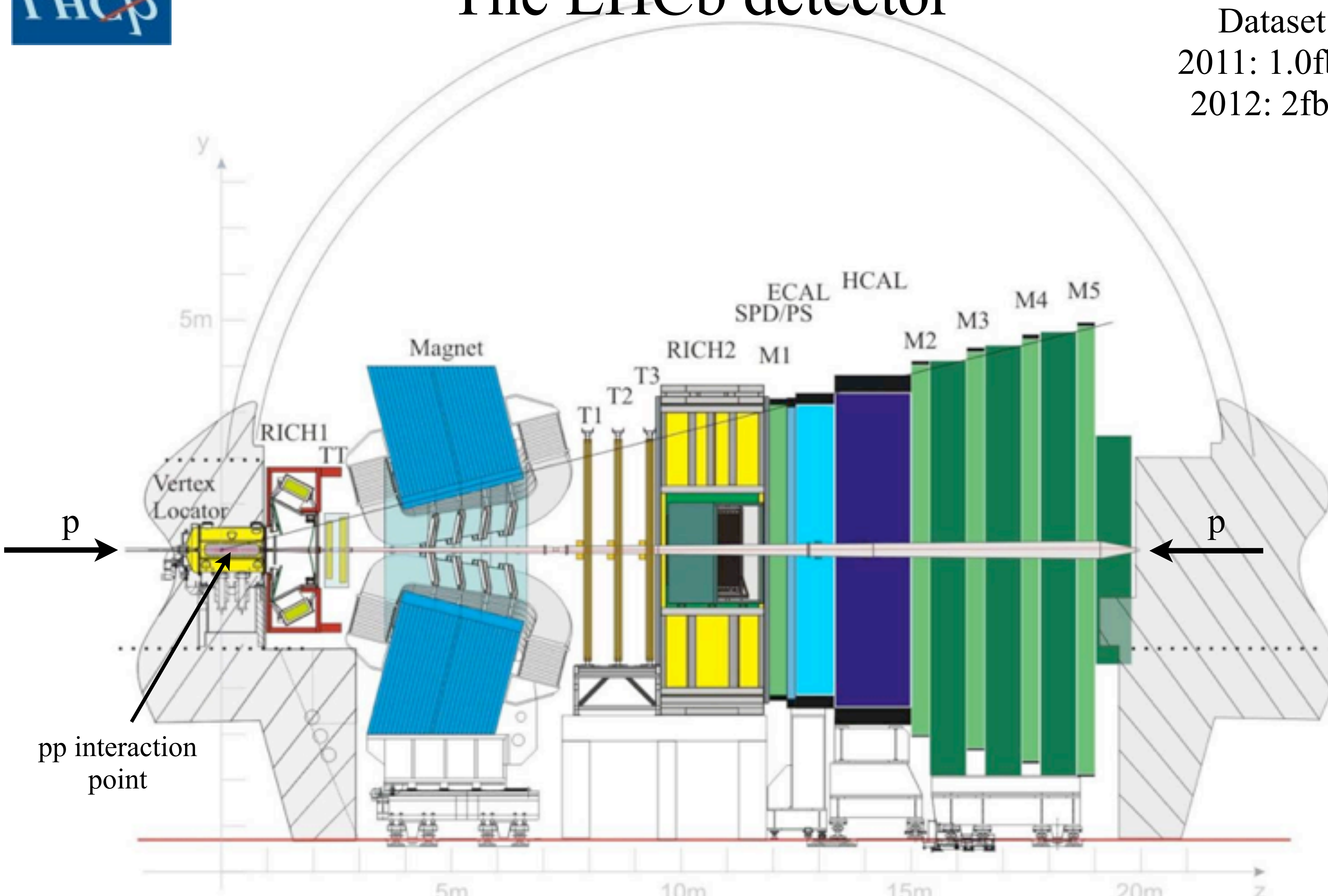


$\sim 10^{11}$ *b* hadrons / fb^{-1}
in LHCb



The LHCb detector

Dataset
2011: 1.0fb^{-1}
2012: 2fb^{-1}



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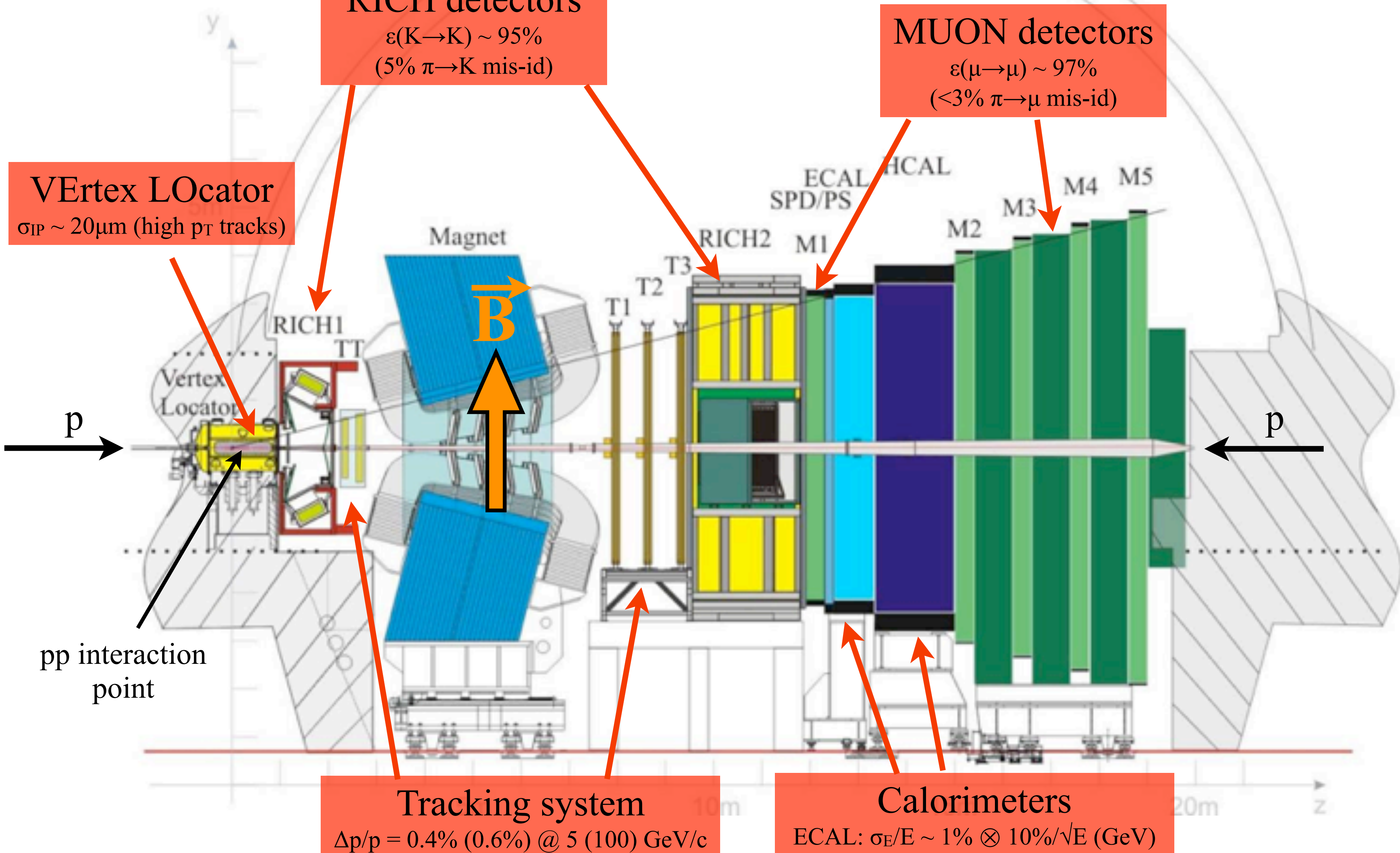
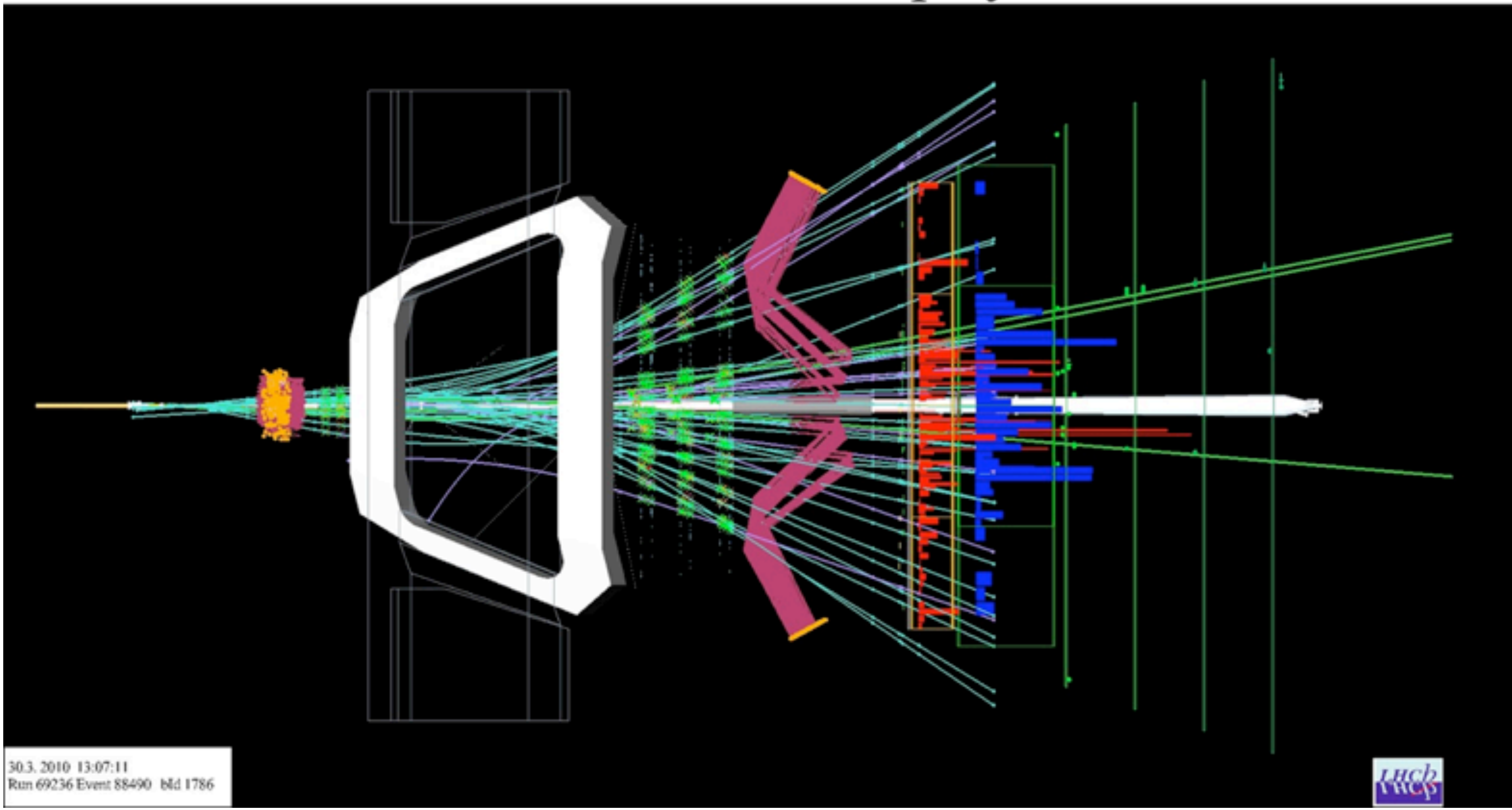


LHCb Event Display



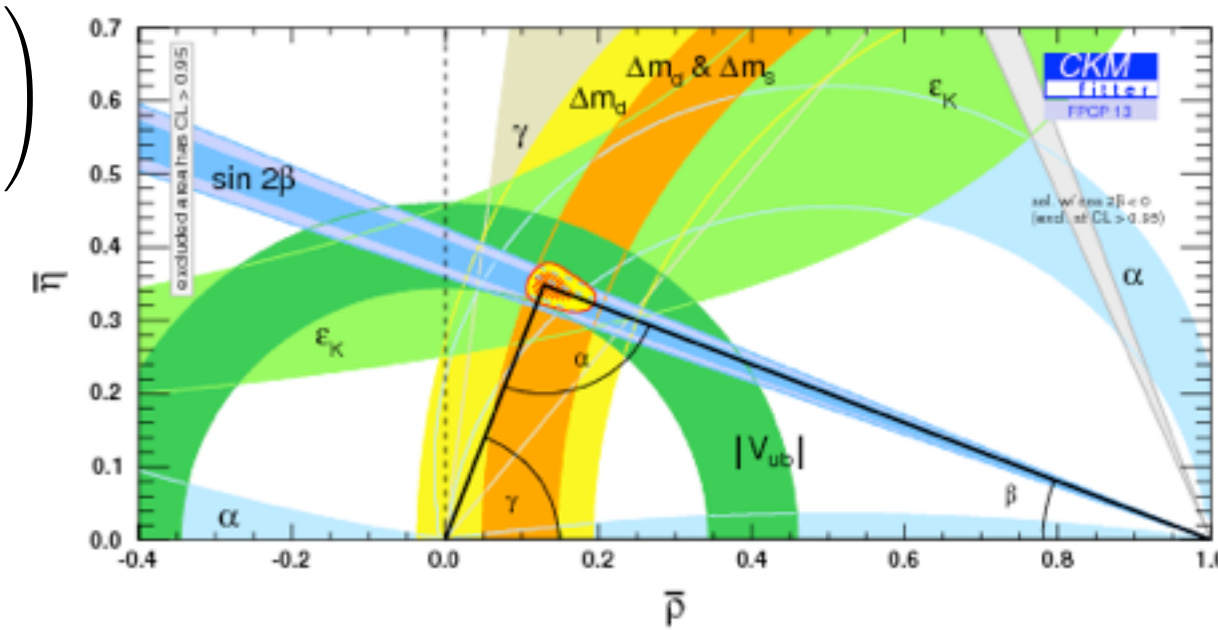
CKM matrix and the Unitarity Triangle

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

$$\mathcal{R}e(V_{\text{CKM}}) \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\mathcal{I}m(V_{\text{CKM}}) \approx \begin{pmatrix} 0 & 0 & \lambda^3 \\ \lambda^5 & 0 & 0 \\ \lambda^3 & \lambda^4 & 0 \end{pmatrix}$$

- Processes involving the b quark are sensitive to the CKM complex phase ⇒ CP violation
- Unitarity constraints ⇒ unitarity triangles
- "The" Unitarity Triangle from product of 1st and 3rd columns
  - 3 sides of comparable size ⇒ 3 large angles



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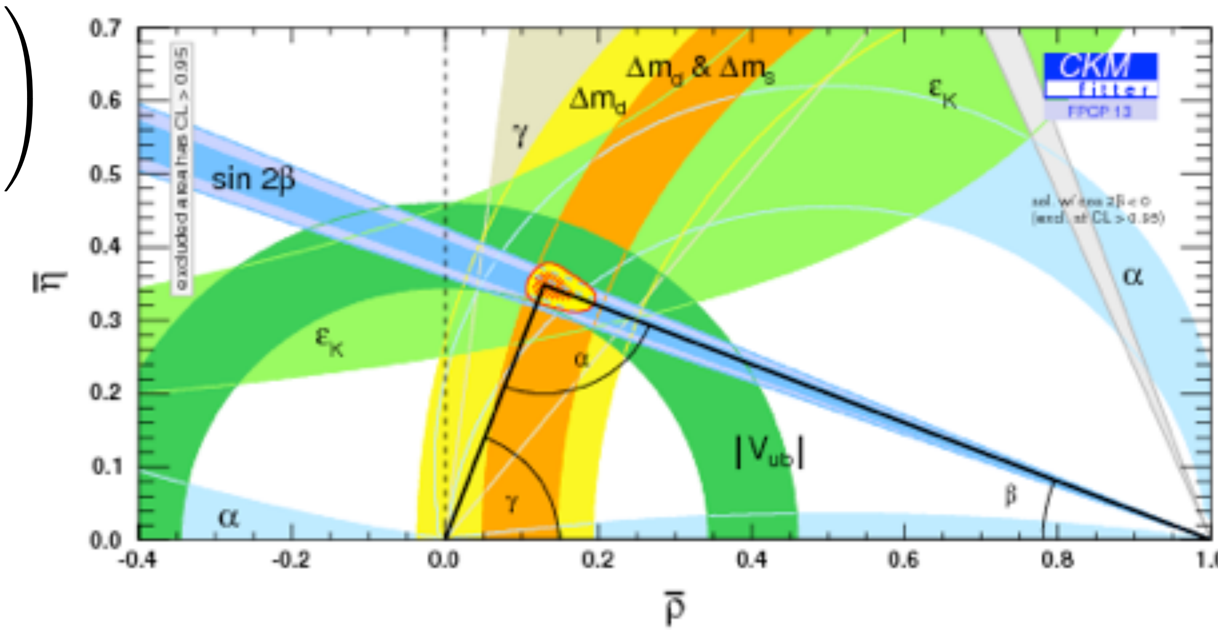

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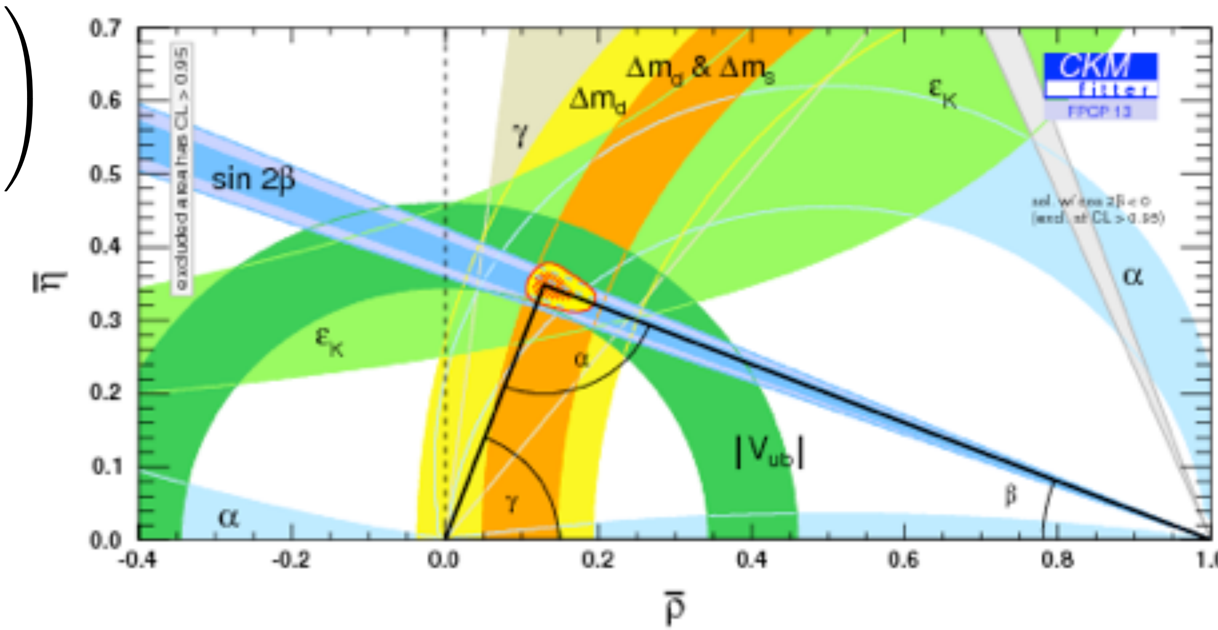
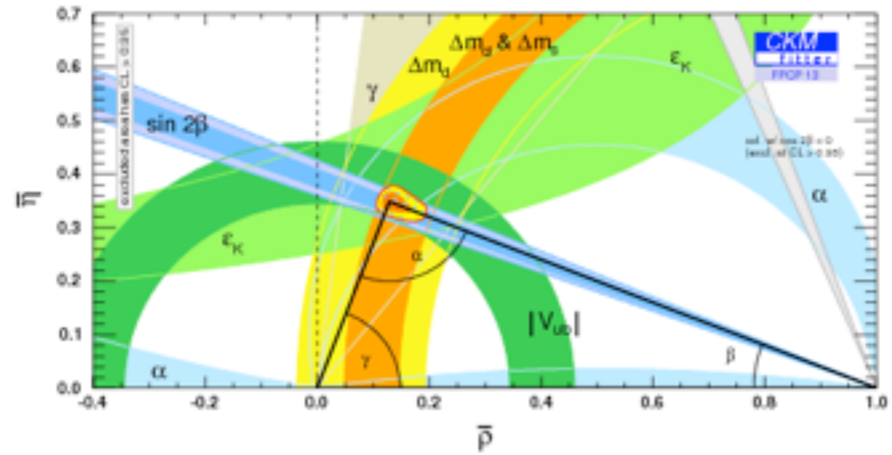
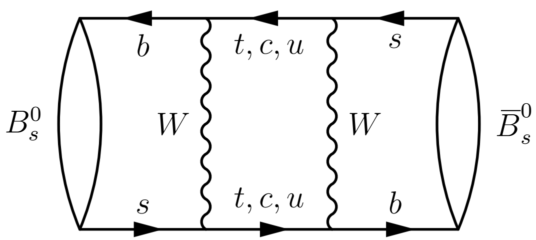


CP violation measurements in B decays

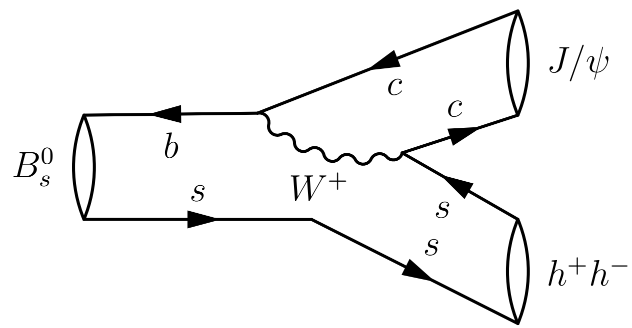
- Unitarity Triangle (*B^0* decays)
  - β is already well measured
  - γ from hadronic *B* decays
- In B_s system, probe the phase of CKM element V_{ts}



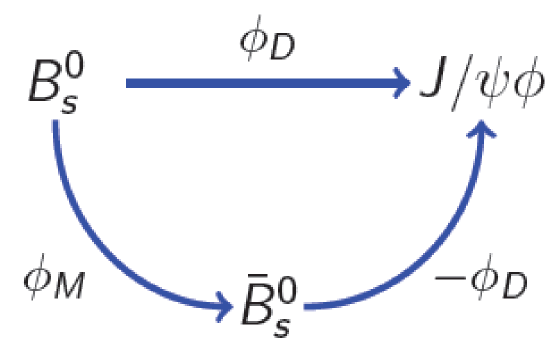
  - measure interference between decay and mixing



$\varphi_M = -2\arg(V_{ts}V_{tb}^*) \simeq -2\beta_s$



$\varphi_D = -2\arg(V_{cs}V_{cb}^*) \simeq 0$

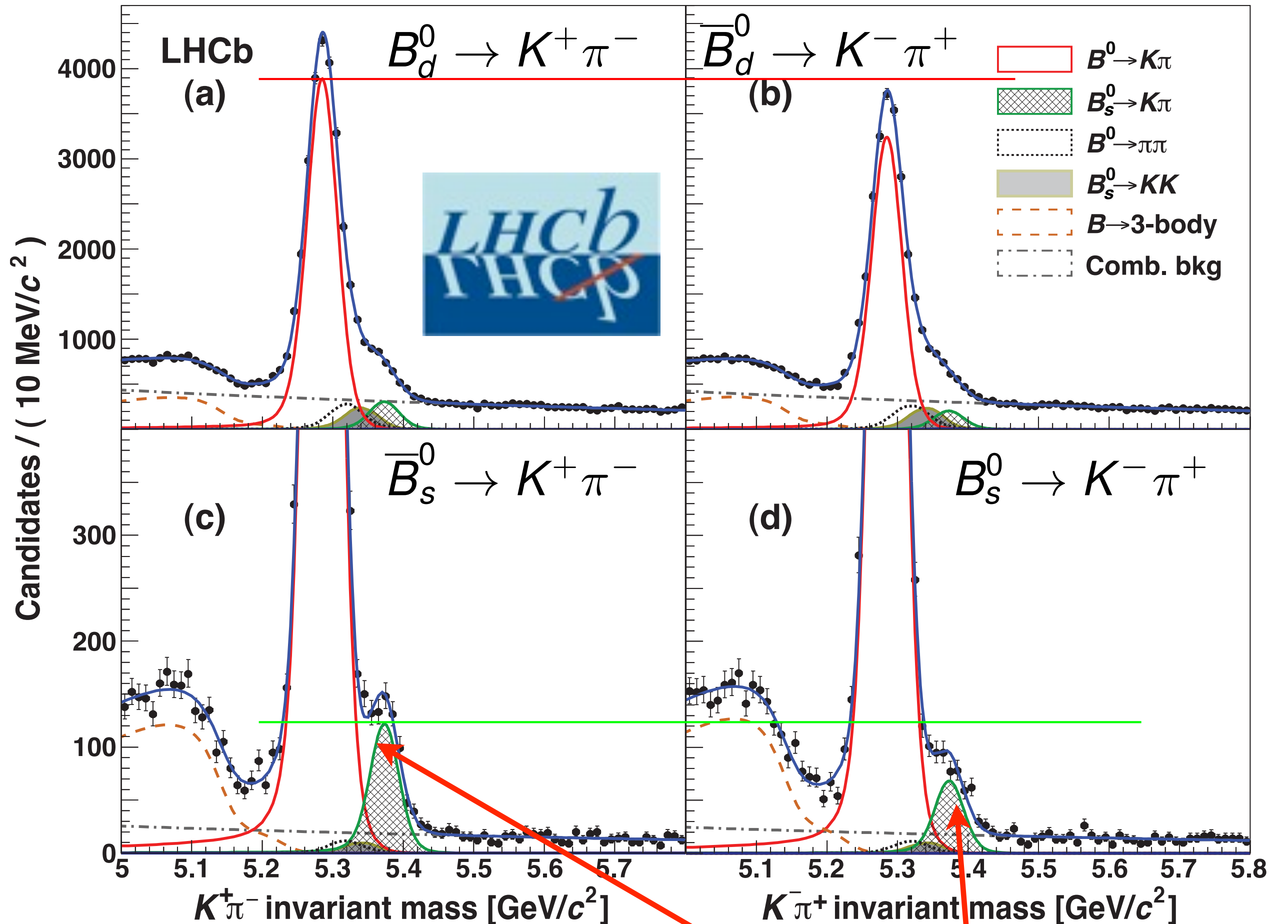


  - in SM, $\sin 2\beta_s = 0.0367 \pm 0.0014$ [CKM fitter]
  - NP contribution can enter the loop and modify this parameter

Direct CP violation in $B_{(s)}{}^0 \rightarrow K^{\pm}\pi^{\mp}$

- Measured direct CP asymmetry in $B_{(s)}{}^0 \rightarrow K^+\pi^-$
  - based on 1fb^{-1} collected in 2011 at 7TeV
- Kinematic and particle identification (PID) variables used for selection, optimizing sensitivity to CP violation

PRL 110 (2013) 221601

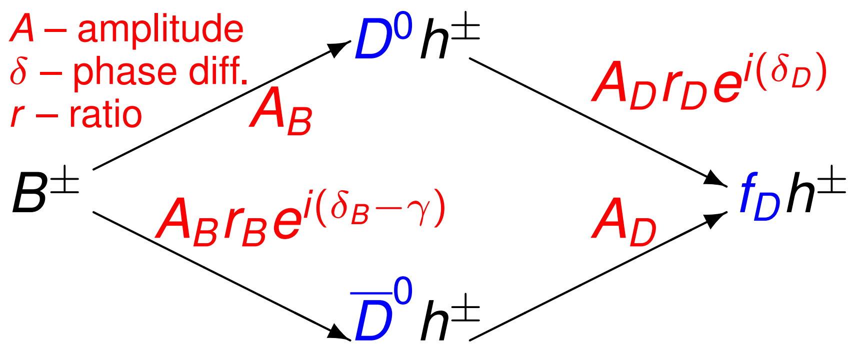


	LHCb	HFAG (2013)
$A_{CP}(B^0 \rightarrow K^+\pi^-)$	$-0.080 \pm 0.007_{stat} \pm 0.003_{syst}$	-0.082 ± 0.006
$A_{CP}(B_s \rightarrow \pi^+K^-)$	**$0.27 \pm 0.04 \pm 0.01$**	0.26 ± 0.04

First observation (6.5σ) of CP violation in B_s decays

Measuring angle γ

- Angle γ (phase of V_{ub}) from interference between b→c and b→u transitions
- Use $B^{\pm}\to D^0h^{\pm}$ and $B^{\pm}\to \overline{D}^0h^{\pm}$ decays



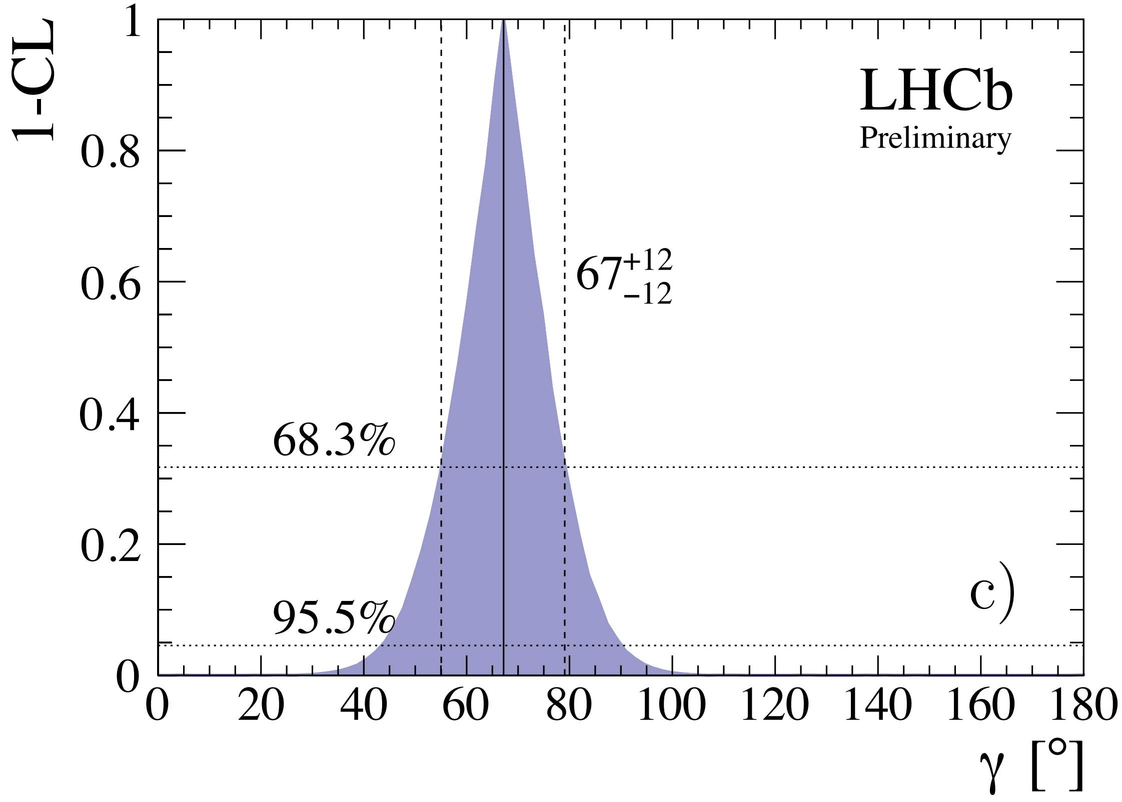
  - measure decay rates for identifiable initial and final states

- Determine γ with three methods
  - GLW: $f_D=K^+K^-$, $\pi^+\pi^-$ (CP eigenstates) PLB 253 (1991) 483; 265 (1991) 172
  - ADS: $f_D=K^{\pm}\pi^{\mp}$, $K^{\pm}\pi^{\mp}\pi^+\pi^-$ (Cabibbo favoured – doubly Cabibbo suppressed) PRL 78 (1997) 3257
  - GGSZ: Dalitz analysis with K_S^0 in the final state PRD 68 (2003) 054018

Angle γ measured at LHCb

- Combination of GGSZ ($3fb^{-1}$) and ADS/GLW ($1fb^{-1}$)

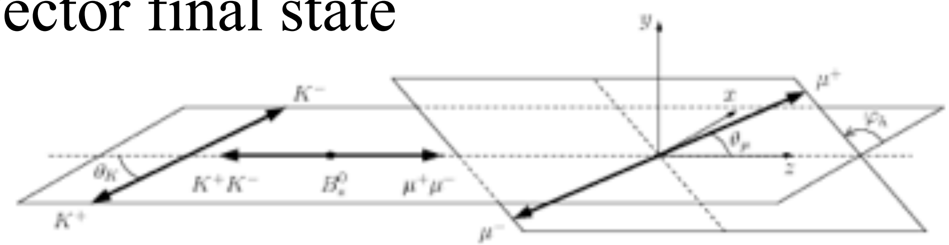
LHCb-CONF-2013-006



- γ **= 67º±12º** at 68% C.L., modulo 180º [PRELIMINARY]
- In agreement with CKM-unitarity fit $\gamma = (69.7^{+1.3}_{-2.8})^{o}$

Time-dependent CP in $B_s \to J/\psi\phi$

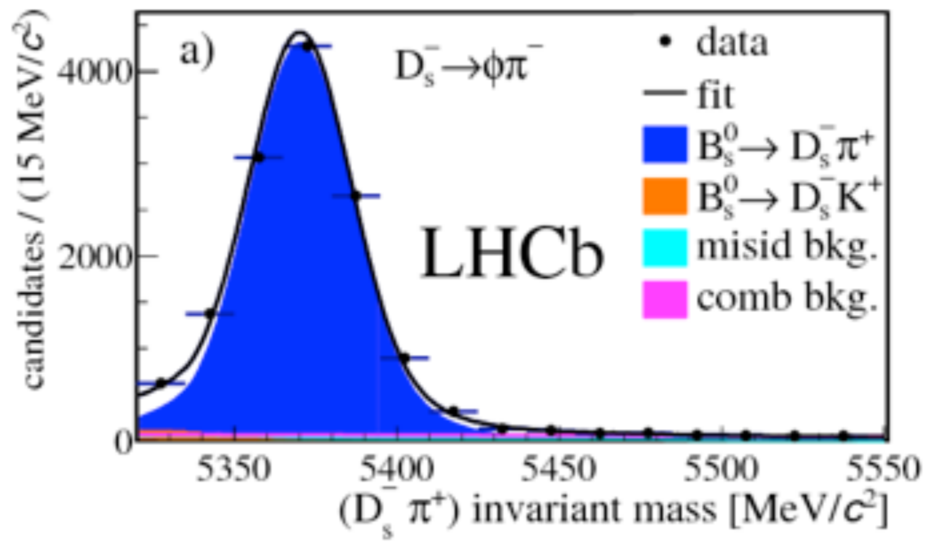
- Dataset: $1\mathrm{fb}^{-1}$
- Ingredients for measuring ϕ_s in $B_s \to J/\psi\phi$
  1. Excellent decay time resolution to resolve fast oscillations
     - measurement of Δm_s ($2\pi/\Delta m_s = 355$fs)
  2. flavor tagging to determine B flavor at time of production
     - use same- and opposite-side tagging algorithms
  3. angular analysis of Vector-Vector final state
     - disentangle CP even and odd amplitudes

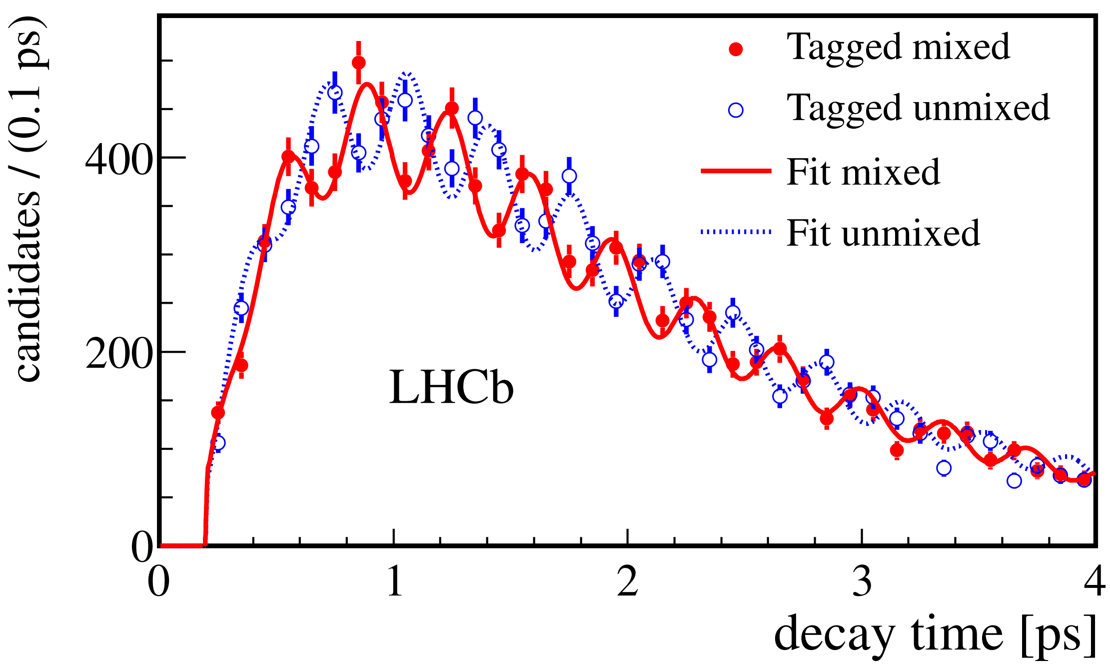


  4. apply maximum-likelihood fit to time-dependent angular analysis $\Rightarrow$ measure ϕ_s

Measurement of B_s oscillations

- Determine Δm_s from $B_s \to D_s^- \pi^+$
- 1 fb^{-1} dataset
  $\Rightarrow$ 34'000 signal candidates
- Tagged time-dependent fit to extract Δm_s





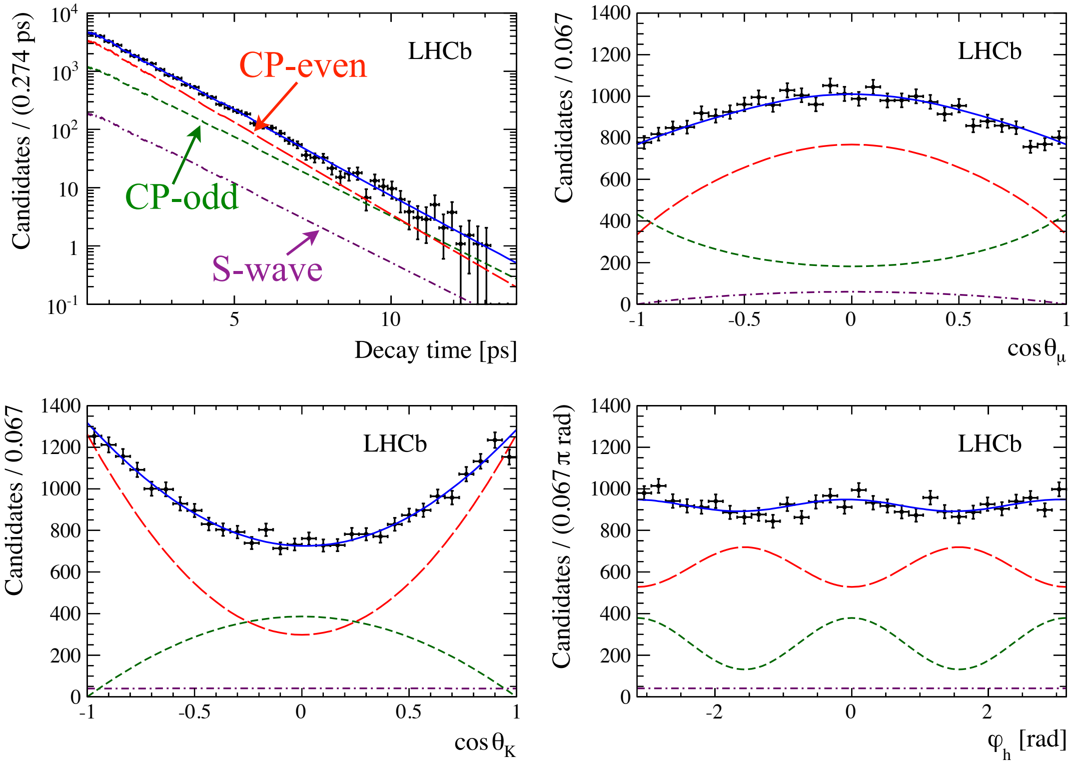
- Proper time resolution = 44 fs
- Demonstrates the excellent vertex resolution at LHCb

New J. Phys. 15 (2013) 053021

$$\Delta m_s = 17.768 \pm 0.023_{stat} \pm 0.006_{syst}\ ps^{-1}$$

ϕ_s from $B_s \to J/\psi\phi$

PRD 87 (2013) 112010



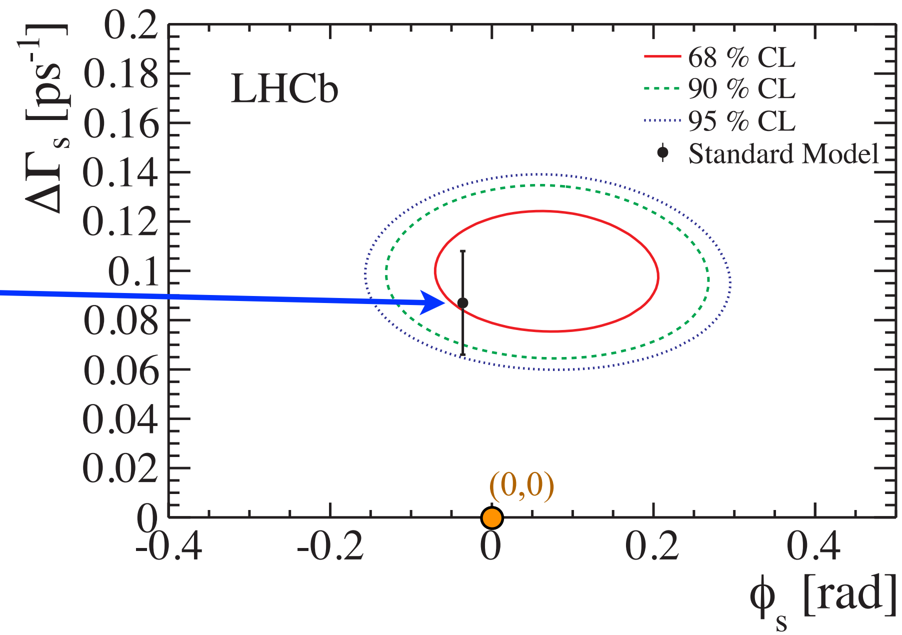
$\phi_s = 0.07 \pm 0.09_{stat} \pm 0.01_{syst}$ **rad**

$\Delta\Gamma_s = 0.100 \pm 0.016_{stat} \pm 0.003_{syst}$ **ps^{-1}**

and from combined analysis with $B_s \to J/\psi\pi^+\pi^-$

$\phi_s = 0.01 \pm 0.07_{stat} \pm 0.01_{syst}$ **rad**

Excellent agreement with standard model!



Many other time-dependent CP measurements at LHCb (e.g $B_s \to \phi\phi$, $\psi(2S)\phi$)

Flavour-specific asymmetry

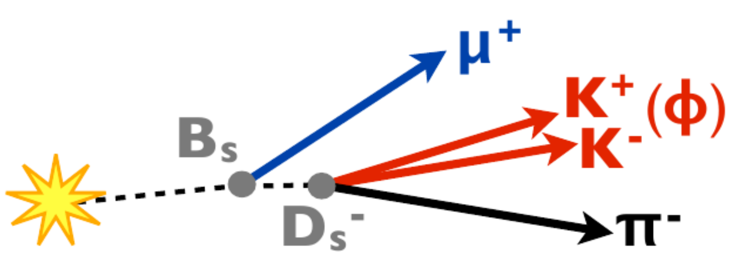
$$a_{sl}^{s} = \frac{\Gamma(\overline{B}{}_s^0(t) \to f) - \Gamma(B_s^0(t) \to \overline{f})}{\Gamma(\overline{B}{}_s^0(t) \to f) + \Gamma(B_s^0(t) \to \overline{f})}$$

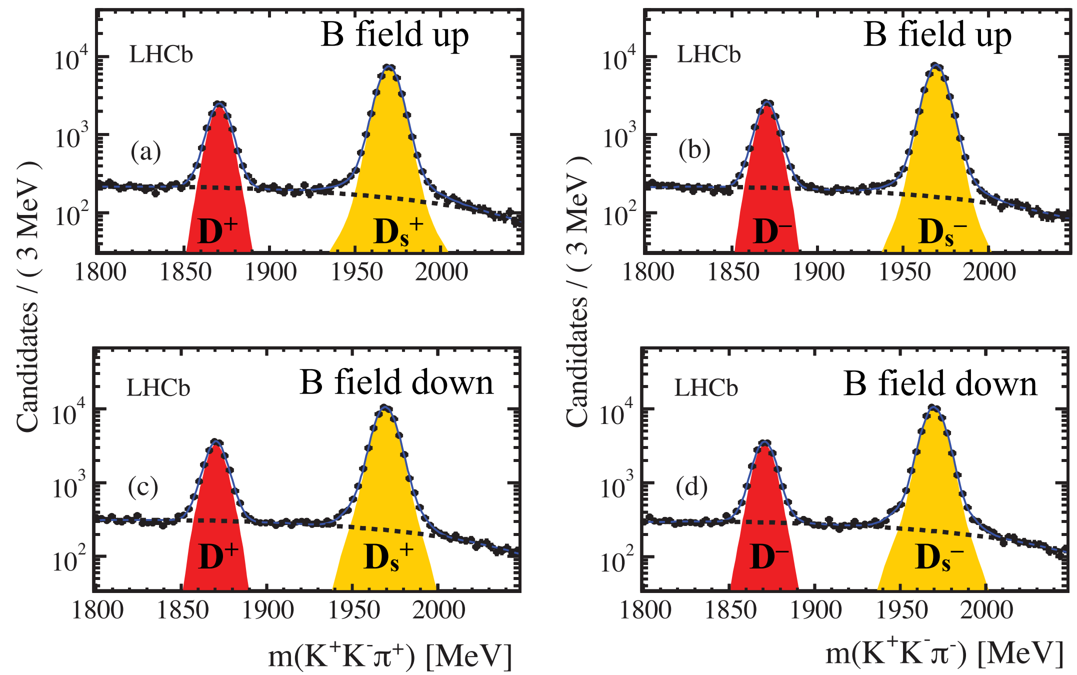
LHCb-PAPER-2013-033

- Probes CP violation in $B^0_s - \overline{B}{}^0_s$ mixing
- Predicted very small in SM: $a_{sl} = (1.9 \pm 0.3) \times 10^{-5}$ [Lenz, arXiv:1205.1444]

  => sensitive to NP entering $B^0_s - \overline{B}{}^0_s$ mixing

- LHCb uses $B^0_s \to D_s^- \mu^+ X$ semi-leptonic decay
  - production asymmetry (<few%) is diluted by rapid $B^0_s - \overline{B}{}^0_s$ oscillations

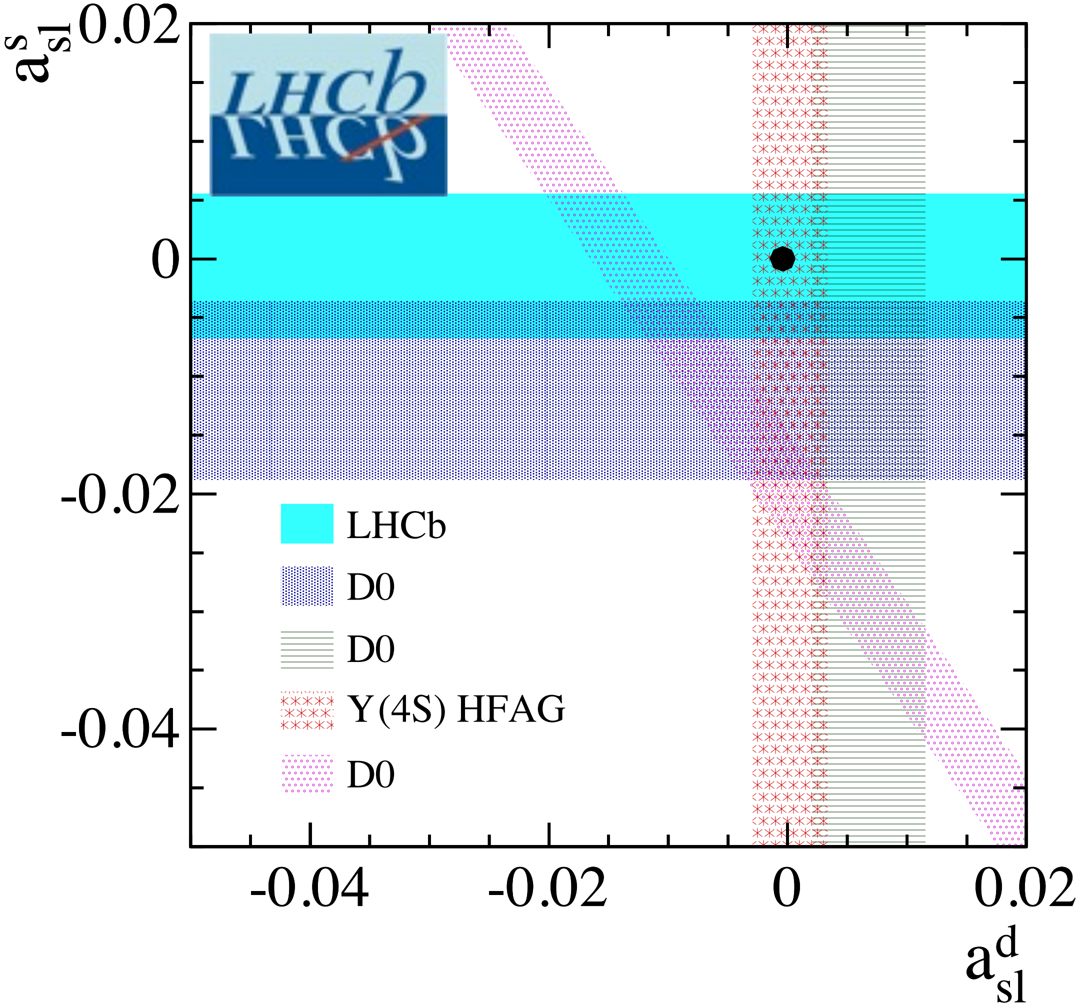




Flavour-specific asymmetry: results

$$\boldsymbol{a_{sl} = (-0.06 \pm 0.50_{stat} \pm 0.36_{syst})\%}$$

LHCb-PAPER-2013-033



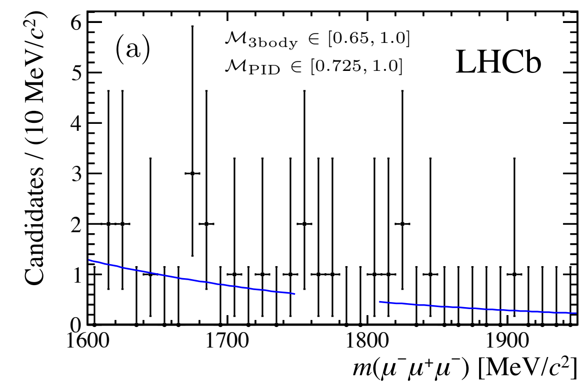
- Most precise measurement to date
- **In excellent agreement with SM**
- No confirmation of D0 same-sign dilepton anomaly

Searches for Lepton Flavor Violation (LFV)

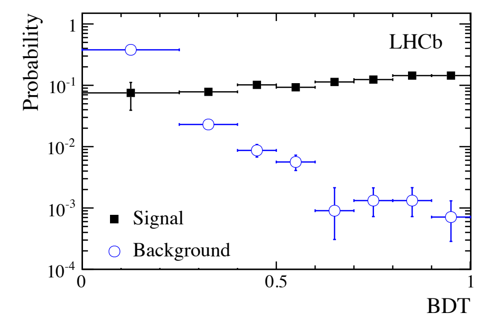
- Search for $\tau^- \to \mu^- \mu^+ \mu^-$ (1fb^{-1} at 7 TeV)

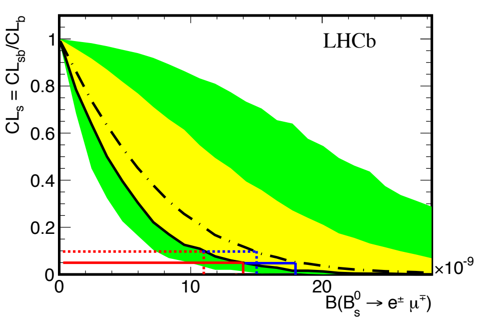
LHCb-PAPER-2013-014

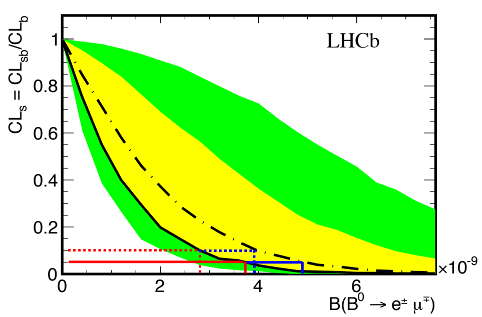
  - large $\tau^\pm$ production rate at the LHC (mostly from $D_s^\pm \to \tau^\pm \nu$)
  - exploit the excellent LHCb muon ID capabilities
  - normalize with respect to $D_s^\pm \to \phi\pi^\pm$
  - **BF($\tau^- \to \mu^- \mu^+ \mu^-$) < 8.3×10^{-8} @90% C.L.**
    (Belle: BF < 2.1×10^{-8})



- Search for $B_{(s)}^0 \to e^\pm \mu^\mp$ (1fb^{-1} at 7 TeV)
  - sensitive to SUSY, lepto-quarks (LQ), singlet Dirac neutrinos...
  - normalize with respect to $B^0 \to K^\pm \pi^\mp$
  - track and vertex quality cuts + BDT decision







LHCb-PAPER-2013-030

BF($B_s^0 \to e^\pm \mu^\mp$) < 1.1×10^{-8} @ 90% C.L.
BF($B^0 \to e^\pm \mu^\mp$) < 2.8×10^{-9} @ 90% C.L.

($\Rightarrow M_{LQ} > 101$ & 135 TeV/c^2!)

Summary and future prospects

- **Very successful first LHC run at LHCb ⇒ 3fb^{-1}**
- Obtained many new or best *B* (and *D*) physics measurements
  - CP violation
  - rare decays

  ⇒ Continue to probe fundamental symmetries and conservation laws
- **Results in agreement with SM, putting strong constraints on New Physics models**
- Detector maintenance and improvements during the current LHC shutdown
- Expect to collect ~5fb^{-1} @13TeV in 2015-2017
  ⇒ ~8 fb^{-1} total
- 2018: detector upgrade to allow 40MHz readout and operation at 5 times higher luminosity
  ⇒ physics output rate to increase by factor 10–20!