Selected physics highlights from LHCb

Neville Harnew

University of Oxford

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Outline

- The LHCb detector and running conditions
- Selected physics highlights

Focus on current measurements from LHCb: based on 1 fb^{-1} (2011) and 3 fb^{-1} (2011&12) *pp* collision data at 7 & 8 TeV CM energy.

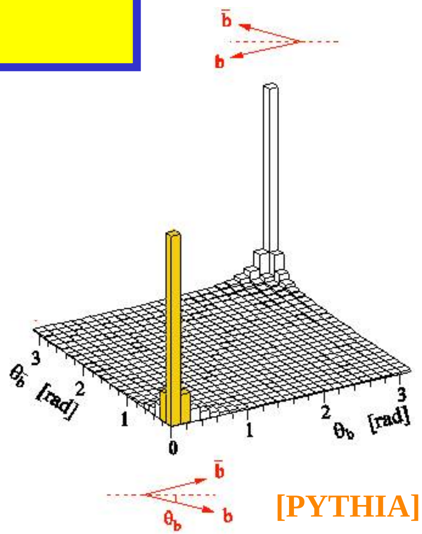
  - Parameters of the CKM matrix
  - Rare B decays
  - Studies of CPV in the B_s system
  - Mixing and CP violation in charm
  - Other highlights.
- Summary and Outlook


The Large Hadron Collider

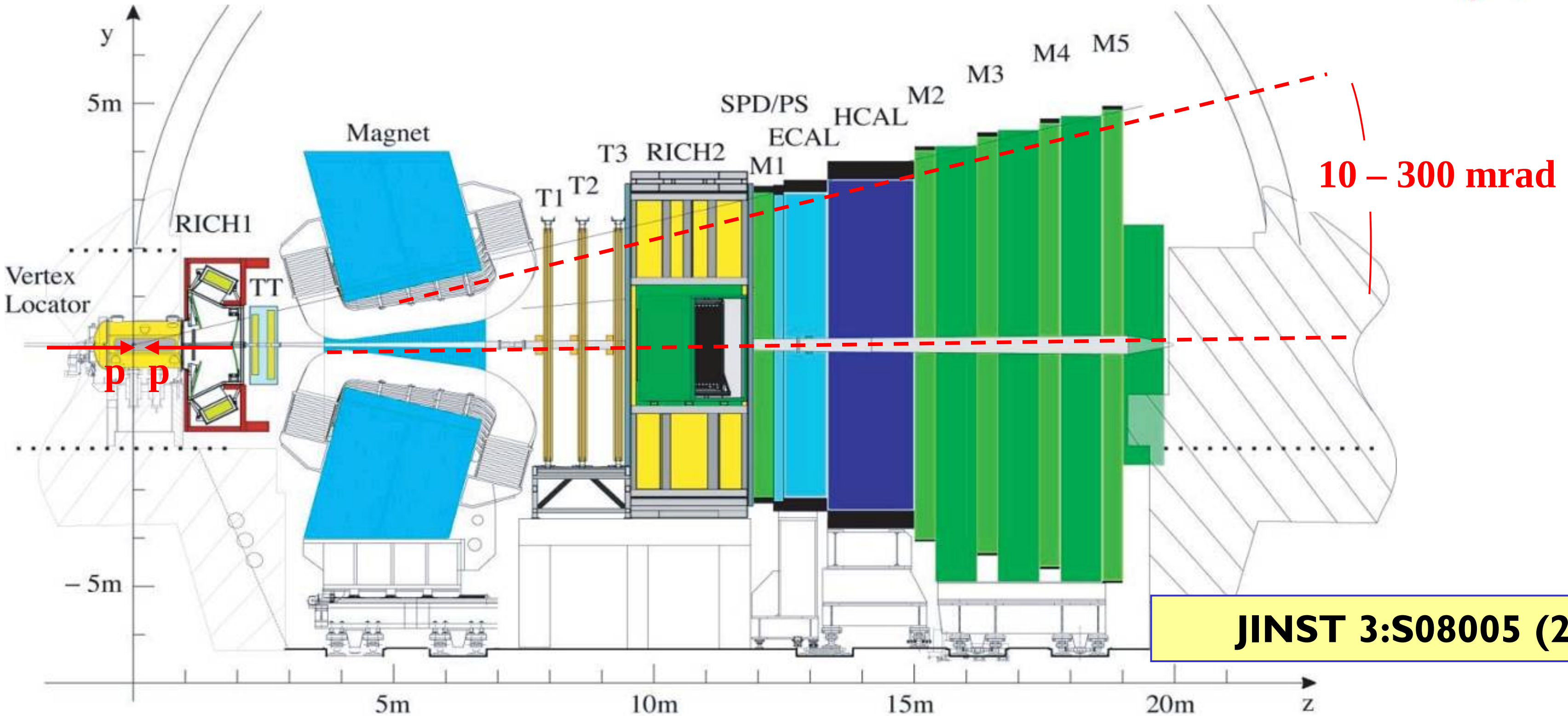
LHCb- forward spectrometer

- Forward-peaked production → LHCb is a forward spectrometer (operating in LHC collider mode)
- $b\bar{b}$ cross-section = 284 ± 53 μb at $\sqrt{s}$ = 7 TeV [PLB 694 209]

→ ~ 100,000 $b\bar{b}$ pairs produced/second (10^4 × B factories)

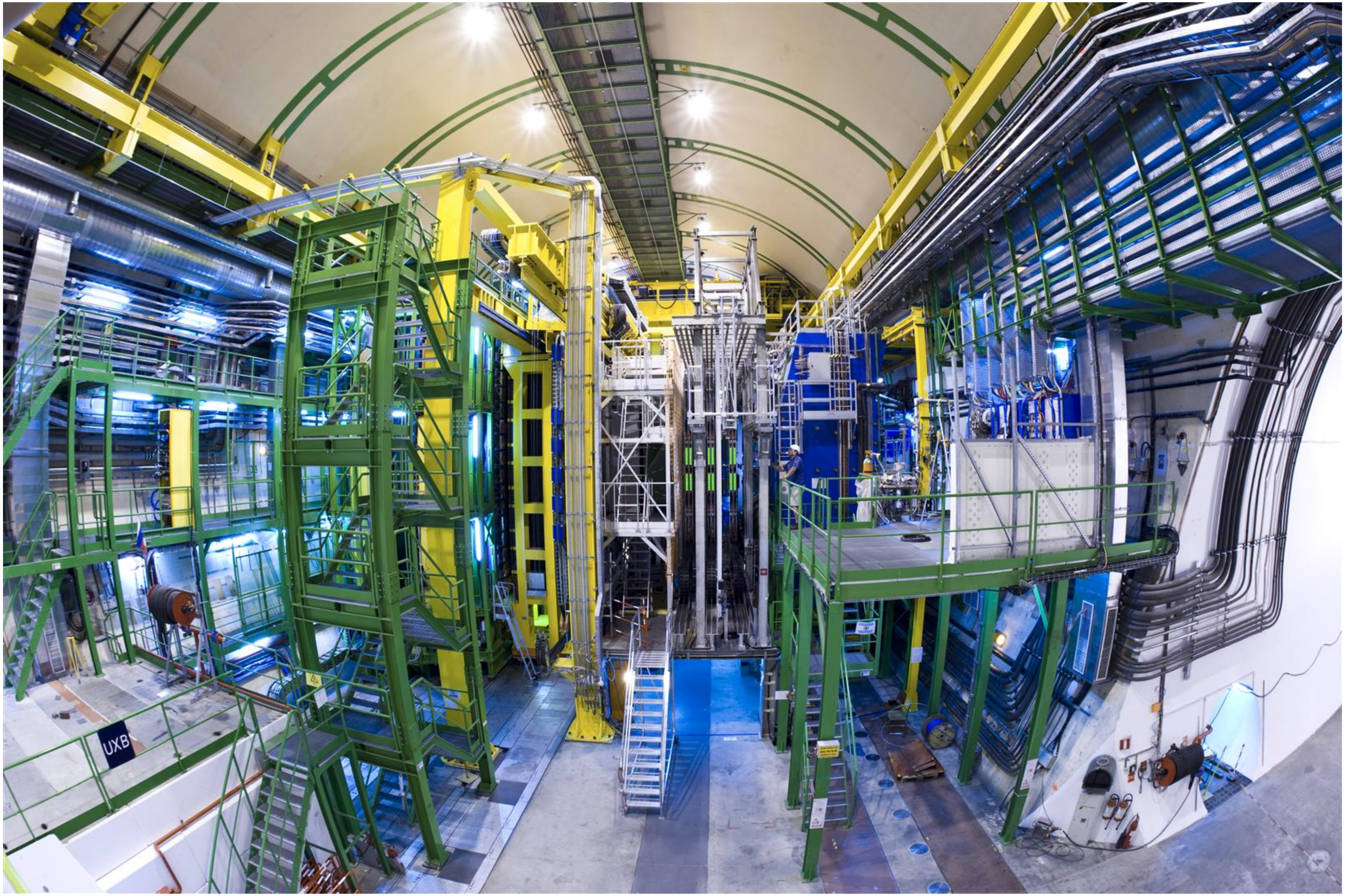


[PYTHIA]



JINST 3:S08005 (2008)

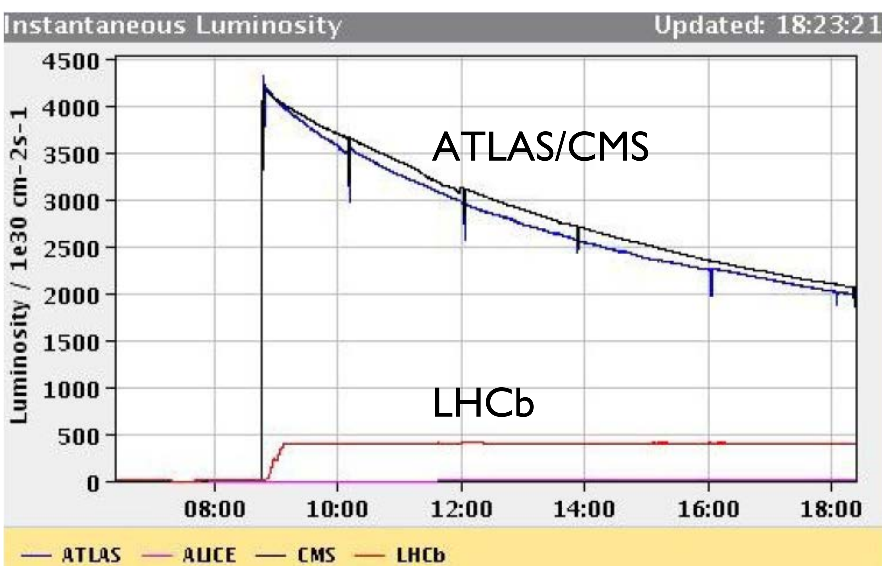
A fish-eye view

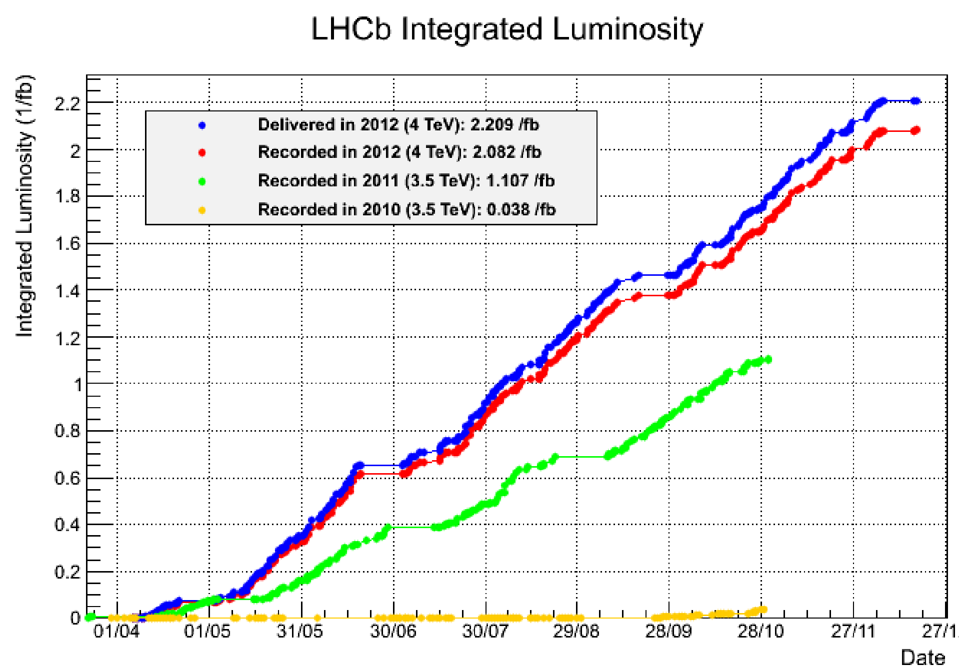


LHCb data taking

- Nominal luminosity = 2×10^{32} cm^{-2} s^{-1} : however, LHCb has learned to run at >2 times this.
- Continuous (automatic) adjustment of offset of colliding beams allows luminosity to be *levelled*
  - 37 pb^{-1} collected in 2010
  - 1 fb^{-1} in 2011
  - >2 fb^{-1} recorded in 2012

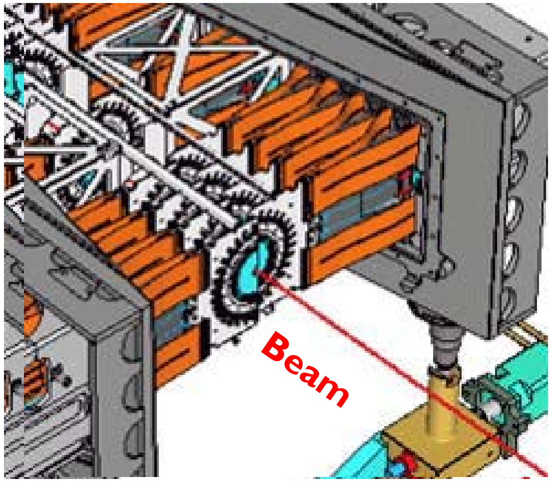
2013/14 : long shutdown

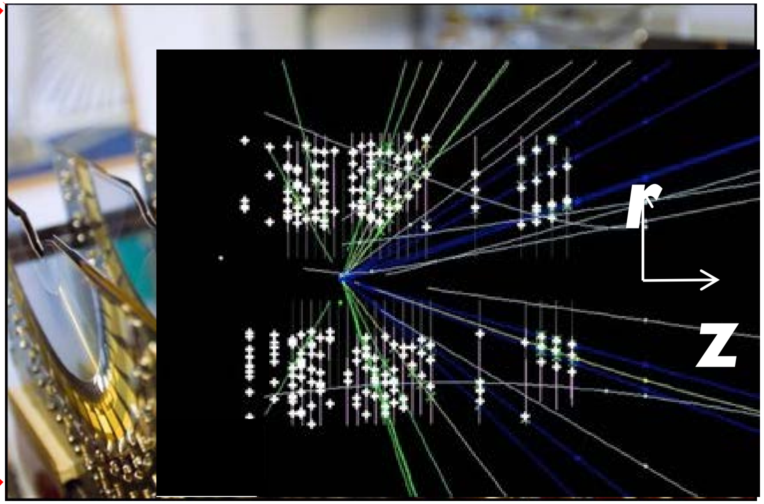




Detector performance – VELO

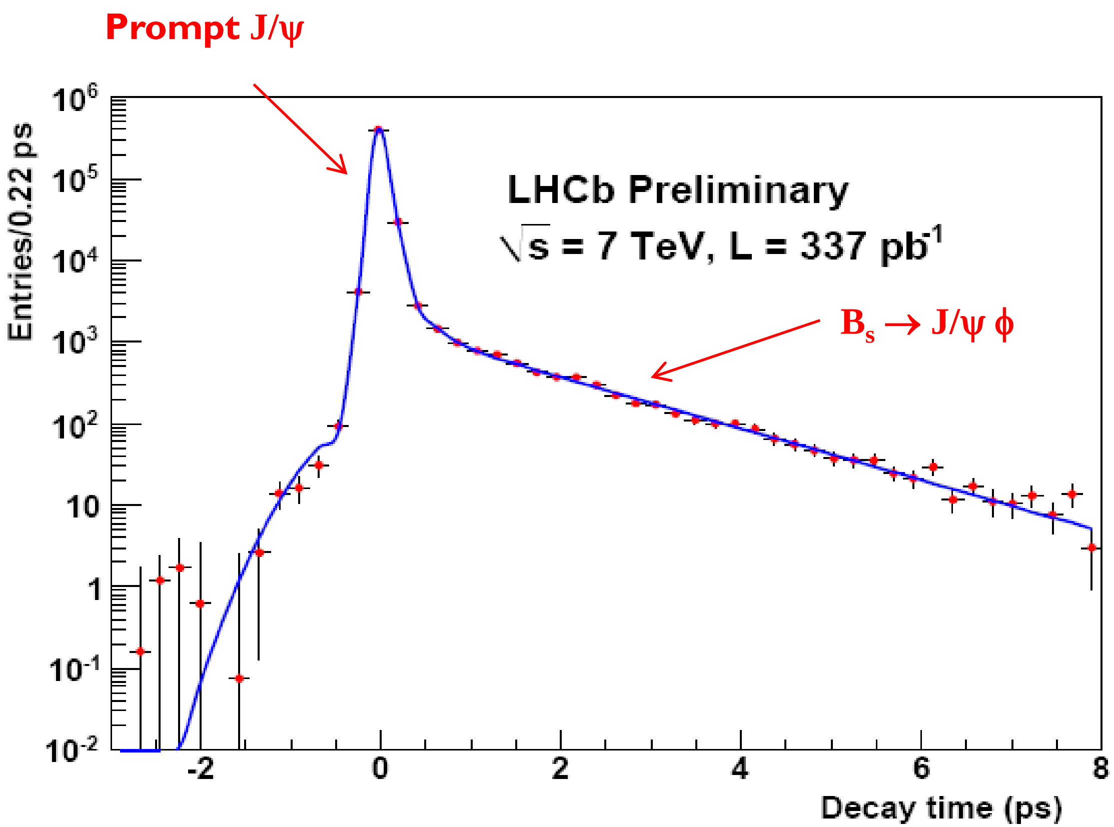
- Vertex Locator (VELO):
  21 modules of back-to-back silicon sensor disks, R-ϕ strip geometry
- Silicon is only 8 mm from beams. Must be retracted for safety during beam injection
- 300 μm-thick silicon
  2048 strips/sensor, 40 μm inner pitch





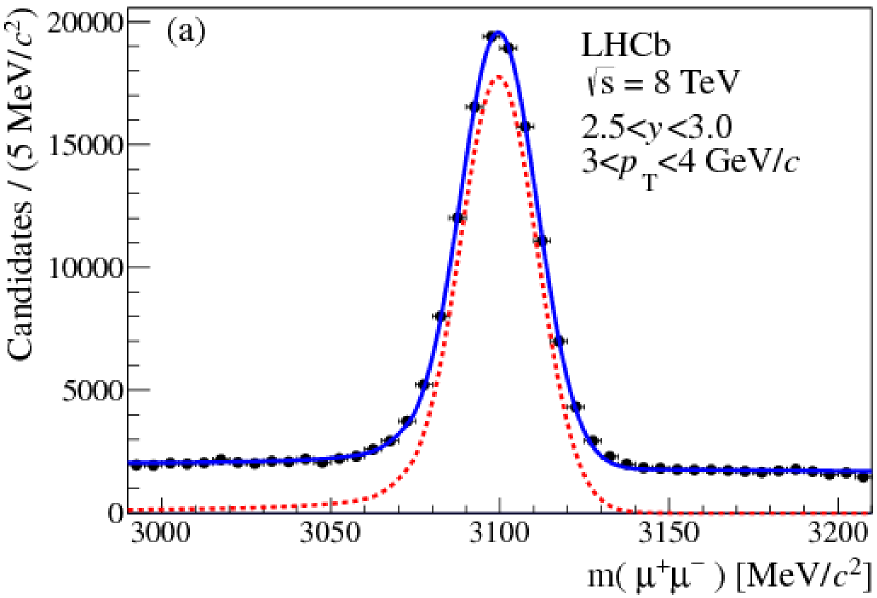
Vertex reconstruction performance

- Impact parameter resolution = 12 μm for high p_T tracks from VELO detector.
- Proper-time resolution: σ_t = 45 fs for eg. $B_s \to J/\psi\phi$



LHCb-CONF-2011-49

Tracking performance



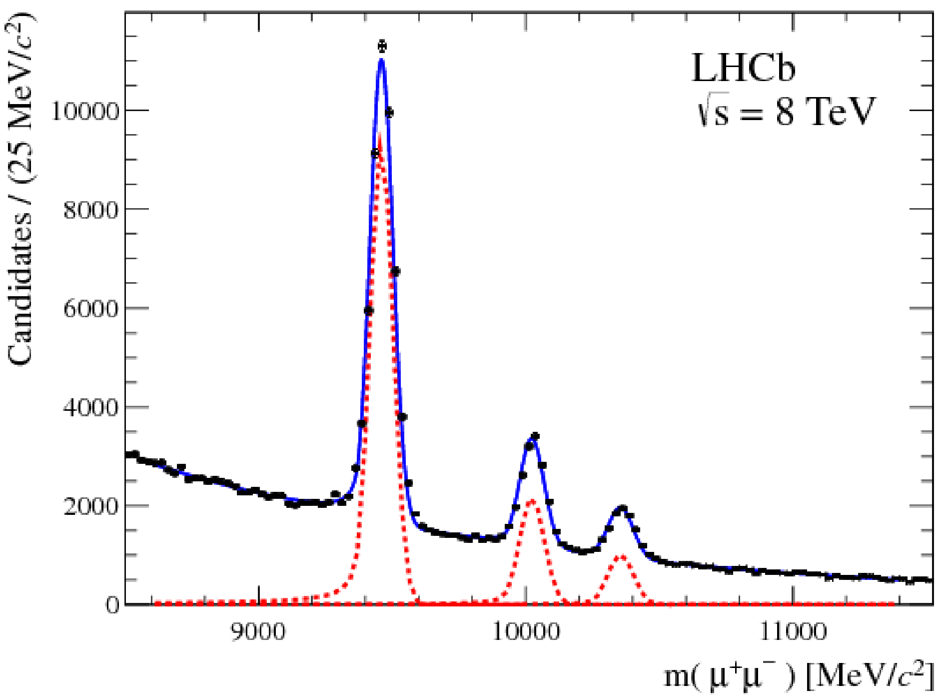
JHEP06 (2013) 064

- Integrated field strength 4 Tm from dipole magnet
- Planes of straw tubes

$\sigma(m_{J/\psi})$=13 MeV/c^2

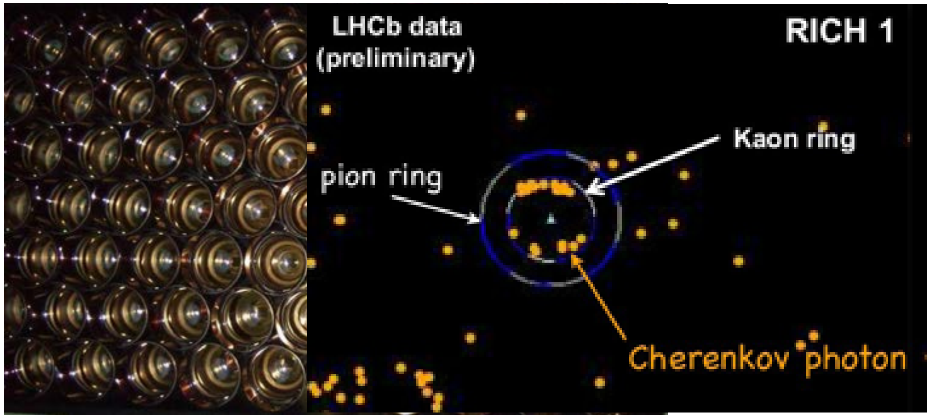
$\sigma(m_{Y(1S)})$=43 MeV/c^2

JHEP06 (2013) 064



Particle identification

- Charged particles identified with two Ring-Imaging Cherenkov detectors covering $2 < p < 100$ GeV/c
- Cherenkov angle resolution 0.66 mrad per photon achieved (in RICH 2)



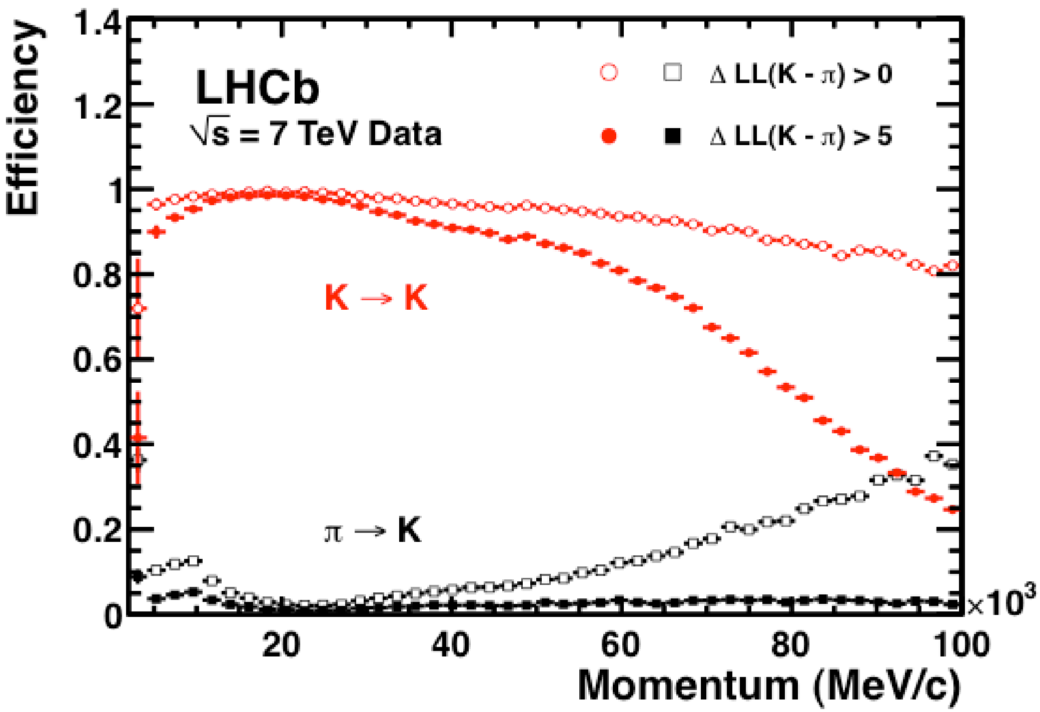
PID performance

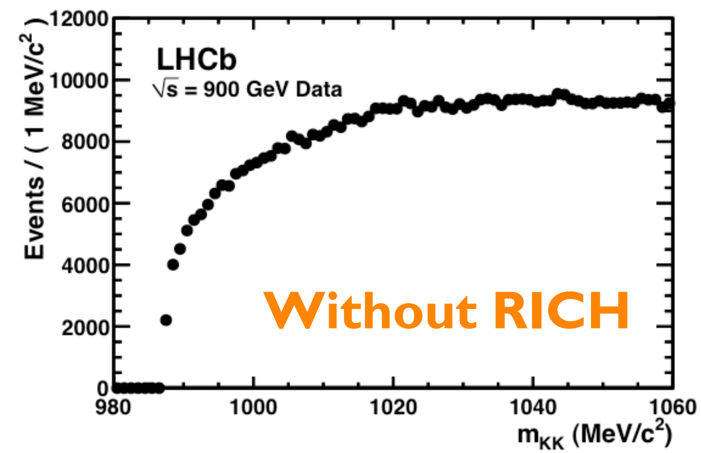
arXiv:1211.6759

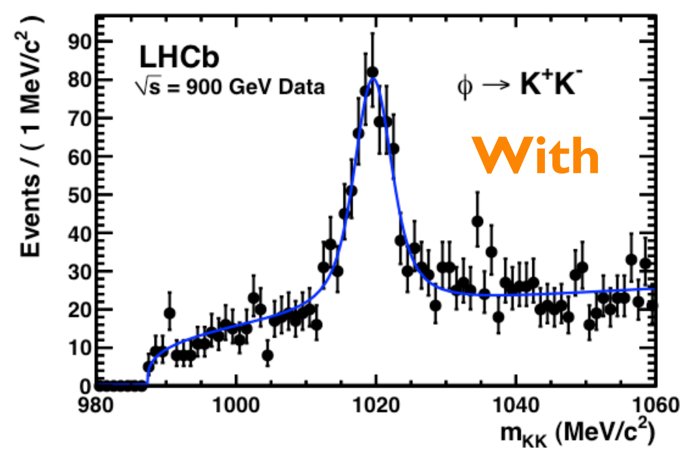
- Kaon identification efficiency > 90% for pion misidentification < 5% over a large momentum range ($2 < p < 100$ GeV/c)

- Allows strong suppression of combinatorial background *eg* for $\phi \to K^+K^-$

Calibration data







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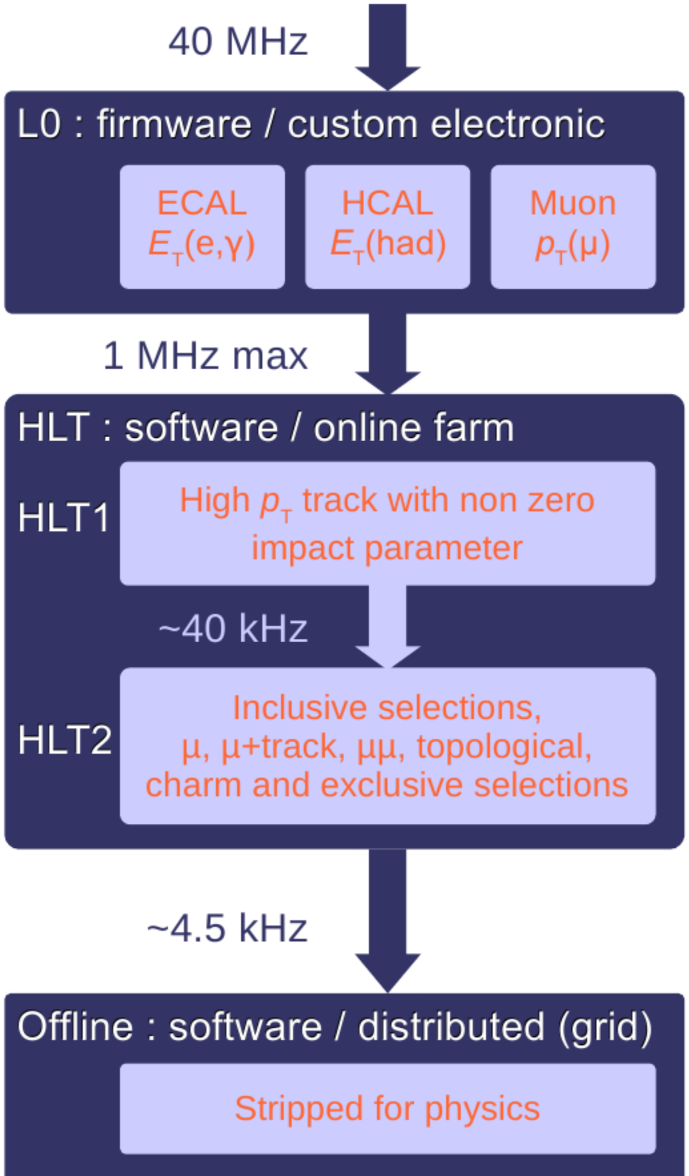
The LHCb trigger performance

arXiv:1211.3055



Hardware level (L0):

- 4 μs latency @ 40MHz
  - high-p_T μ, e, γ, hadron candidates, typically

$p_T(\mu)>1.4$; $E_T(e/\gamma)>2.7$; $E_T(\text{hadron})>3.6$ [GeV]

Software level (HLT):

- ~30000 tasks in parallel on ~1500 nodes

Combined efficiency (L0+HLT):

- ~90 % for di-muon channels
- ~30 % for multi-body hadronic final states

Offline processing:

- ~10^{10} events, 700 TB recorded per year
- ~800 "stripping" selections to reduce to samples with 0(10^7) events for analyses

Selected physics highlights

- Parameters of the CKM matrix
- Studies of CPV in the B_s system
- CP violation in charm
- Rare B decays

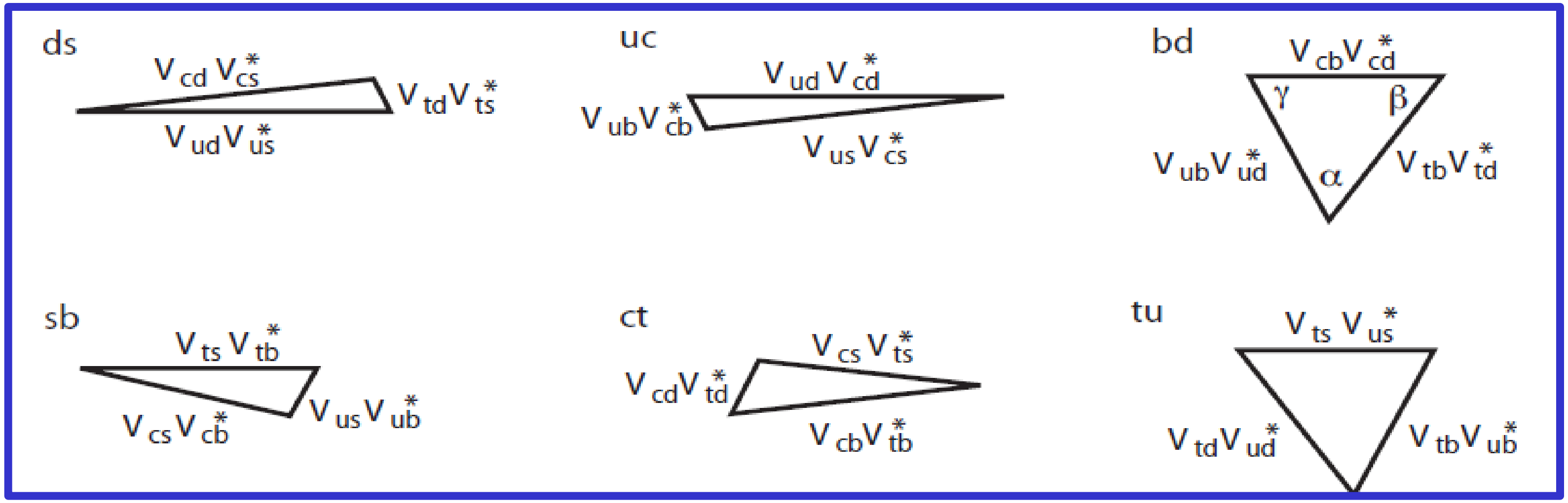
Quark mixing and CKM matrix

- In the SM charge −1/3 quarks (d, s, b) are mixed
- Mixing described by CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- 6 unitarity conditions of CKM matrix, 2 of which give triangles which do not have a side much shorter than the other two:

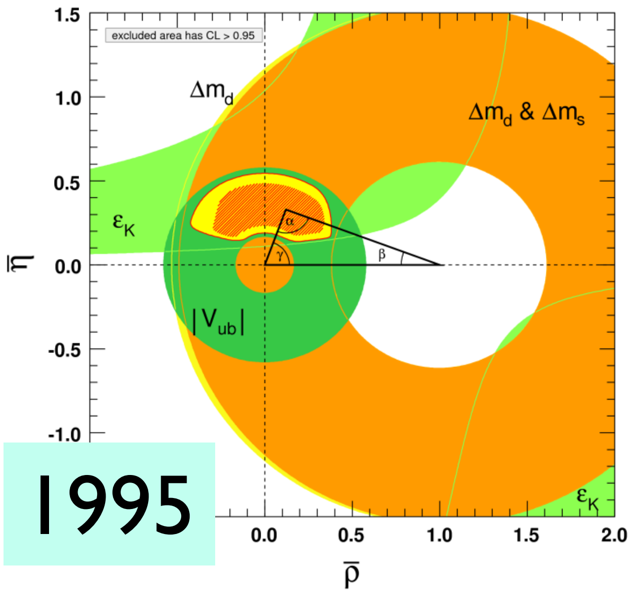
$(V^*_{ub}V_{ud}+V^*_{cb}V_{cd}+V^*_{tb}V_{td}) = 0$ $(V^*_{ud}V_{td}+V^*_{us}V_{ts}+V^*_{ub}V_{tb}) = 0$

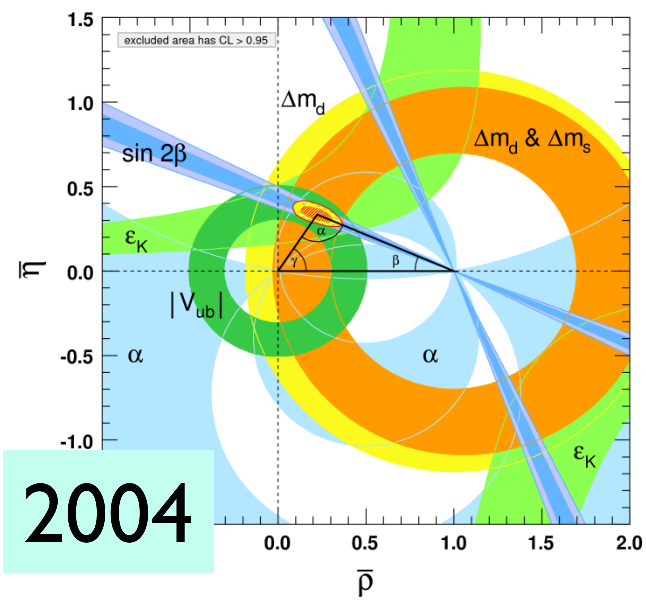


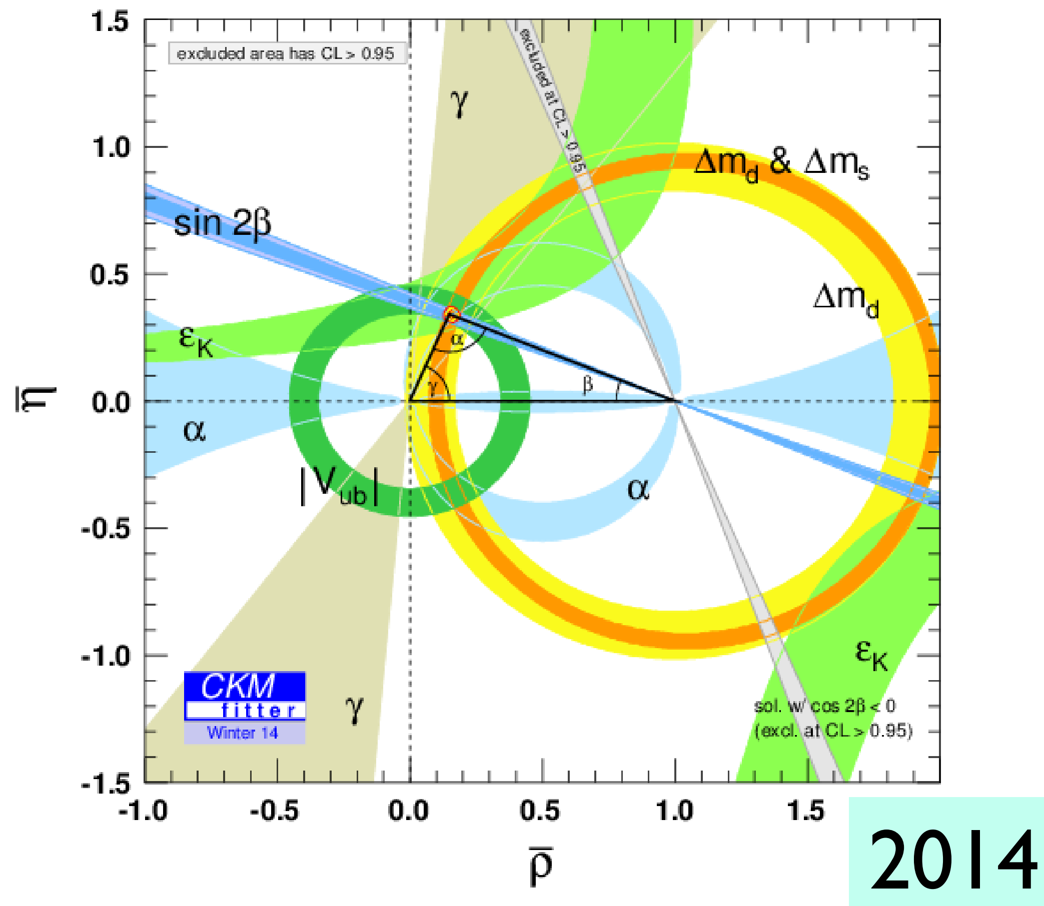
Unitarity triangle : CKM fitter

- The CKM describes all the flavour-changing processes in the SM
- Amazing progress in the last 20 years; the SM remains intact, but still a whole lot still to learn

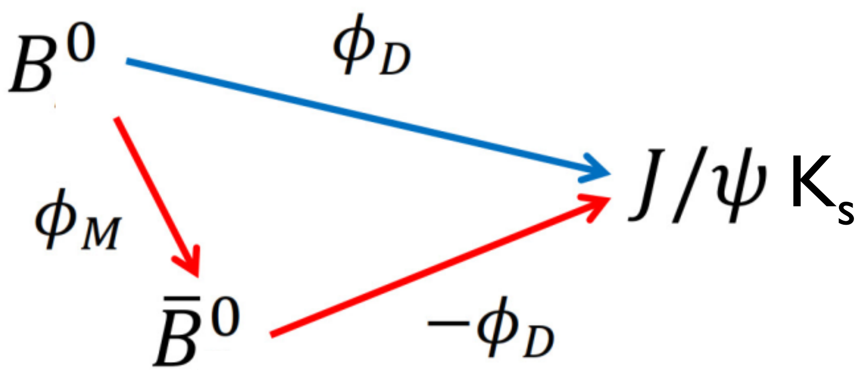
http://ckmfitter.in2p3.fr

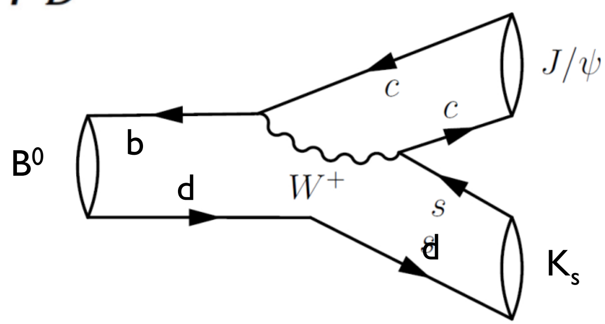


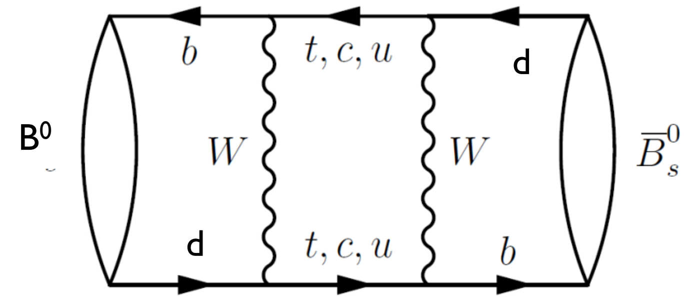




Measurement of angle β







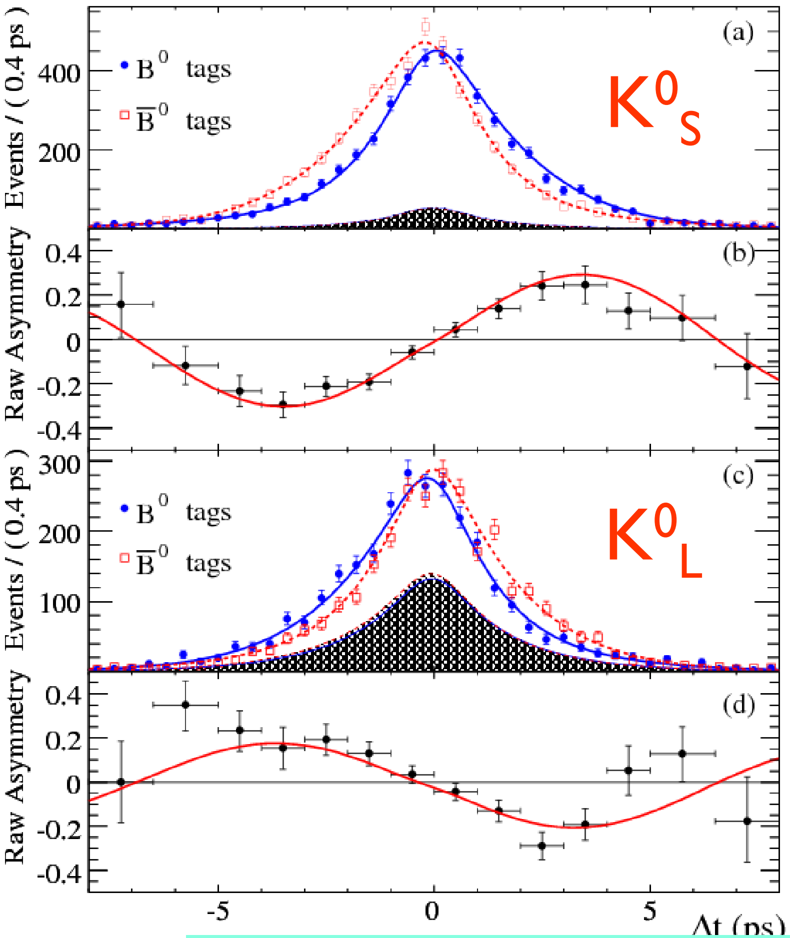
- *Interference* between B^0 decay to J/ψK^0_S directly and via B^0 $\overline{\text{B}^0}$ oscillation gives rise to a CP violating phase

  $\phi = \phi_{\text{Mixing}} - 2\,\phi_{\text{Decay}} = 2\beta$

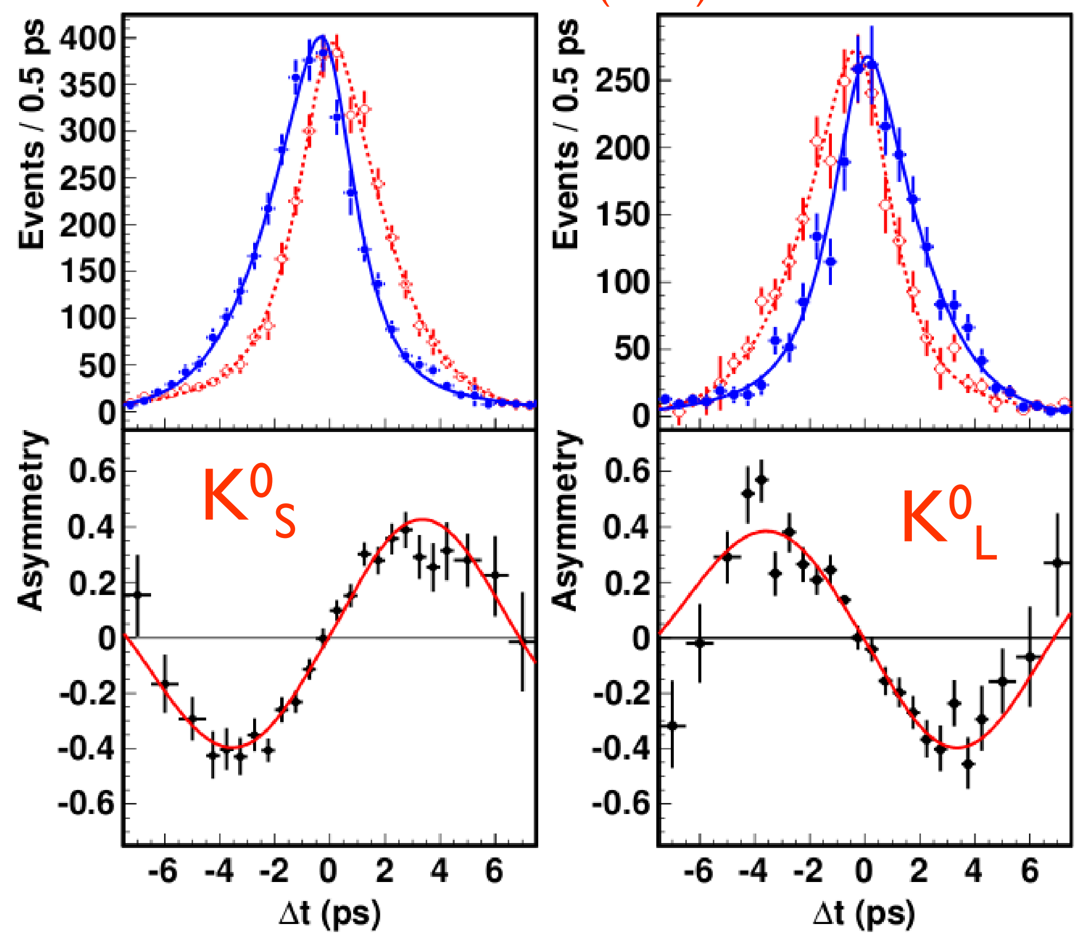
Spectacular results from e^+e^- B factories on CP violation

Large CP violation effects : $\sin(2\beta)$ from $B^0 \rightarrow J/\psi K^0_{S/L}$

Babar PRD 79 (2009) 072009



Belle PRL 108 (2012) 171802



World average (Winter 2014) : $\sin(2\beta) = 0.679 \pm 0.020$

and LHCb comes into the game …

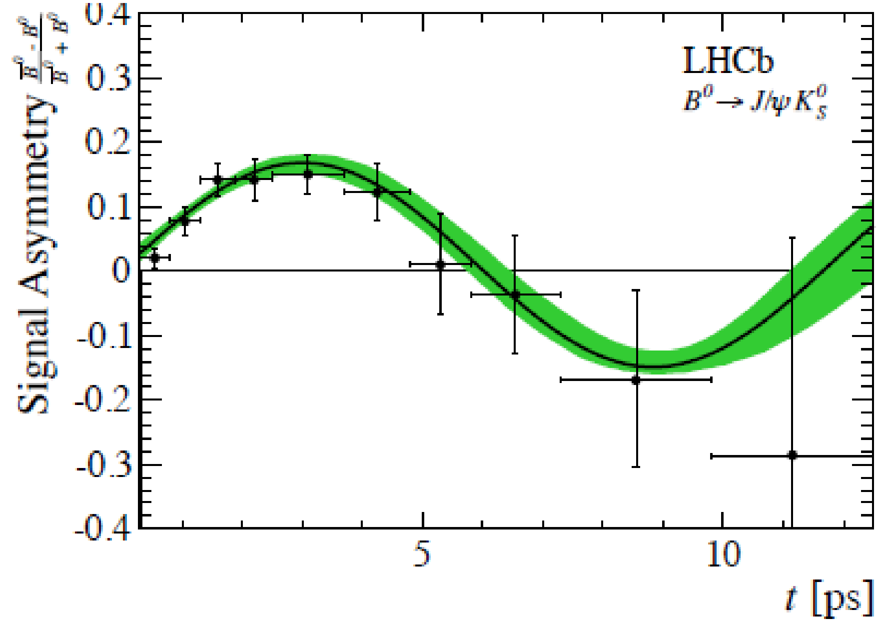
sin(2β) from $B^0 \to J/\psi K^0_S$

$$\mathcal{A}_{J/\psi K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)}$$
$$= S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t).$$

$S_{J/\psi Ks}$ = 0.73 ± 0.07 (stat) ± 0.04 (syst)

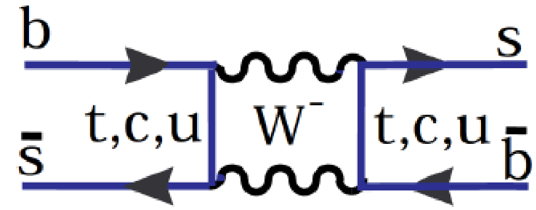
$C_{J/\psi Ks}$ = 0.030 ± $^{0.089}_{0.091}$ at) ± 0.012 (syst)

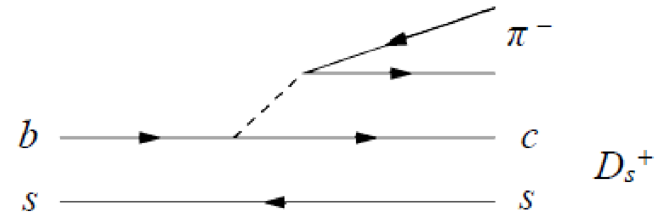
Phys.Lett B721 (2013) 24-31



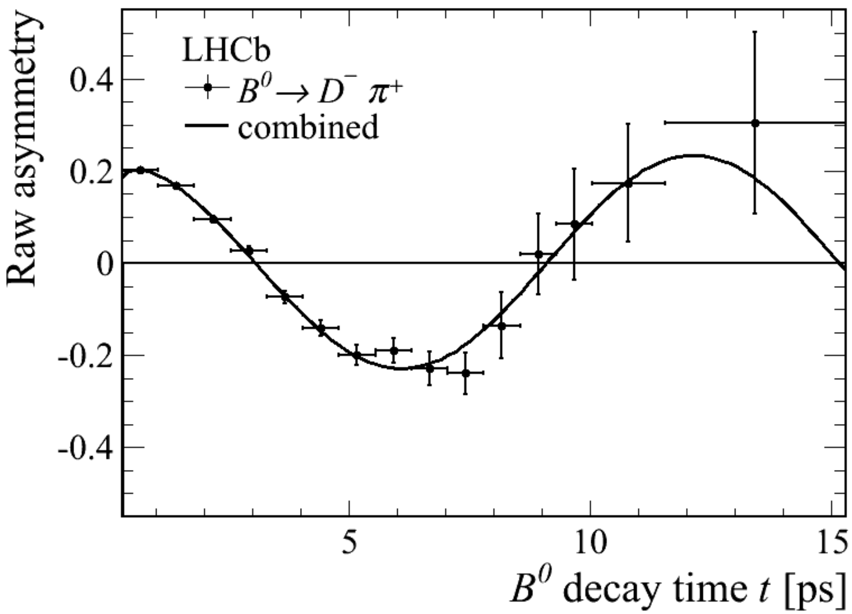
World average (Winter 2014) : sin(2β) = 0.679 ± 0.020

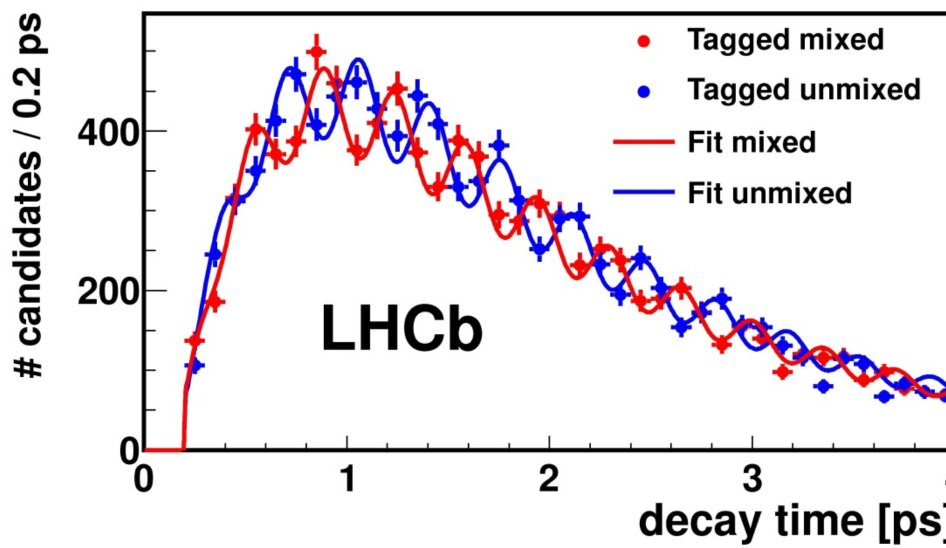
… and $B_{(s)}$ mixing





$$\frac{N(B^0 \rightarrow B^0) - N(B^0 \rightarrow \overline{B^0})}{N(B^0 \rightarrow B^0) + N(B^0 \rightarrow \overline{B^0})}$$





$\Delta m_d = 0.5156 \pm 0.0051 \pm 0.0033\ ps^{-1}$

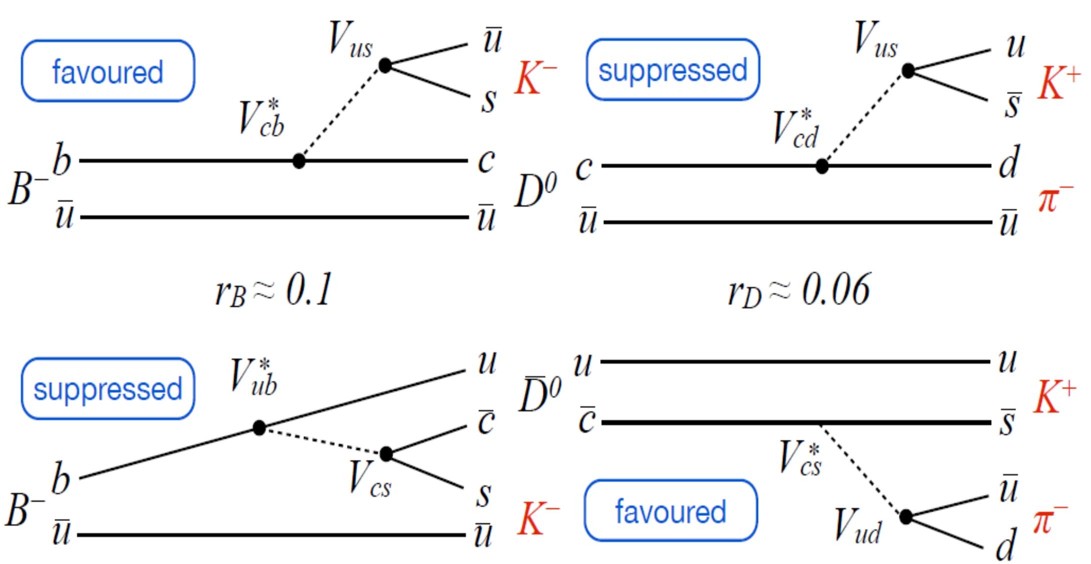
$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ ps^{-1}$

Phys.Lett B721 (2013) 24-31

J. Phys. 15 (2013) 053021

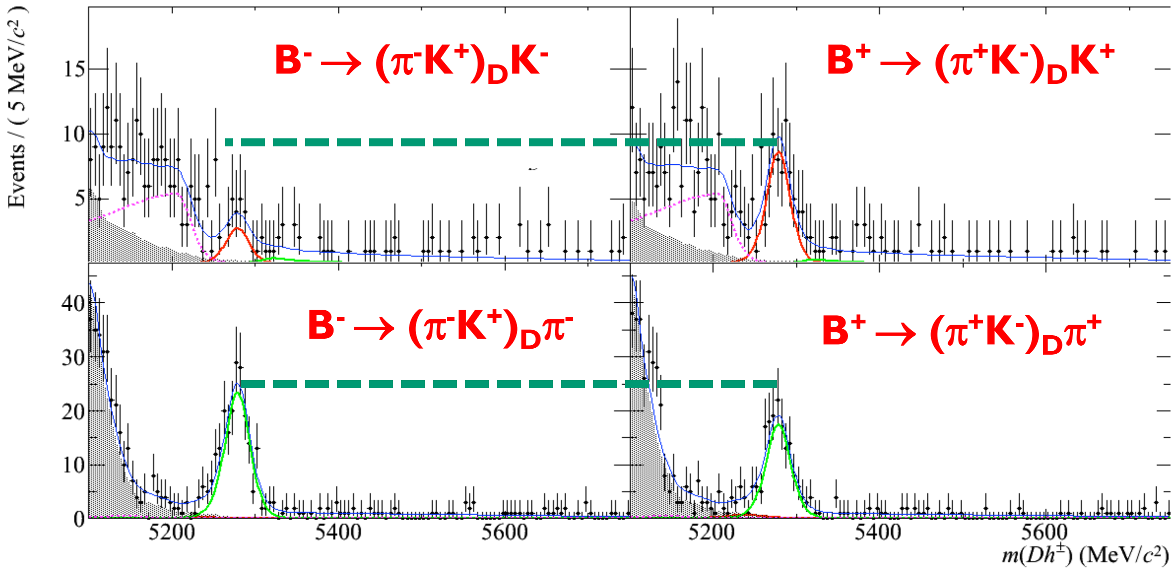
A measurement of γ from $B^{\pm} \rightarrow DK^{\pm}$ and $D\pi^{\pm}$

- Four methods, comprising 14 $B^{\pm}$ decays included in a combined fit
  - $B^{\mp}\rightarrow DK^{\mp}$, $D\rightarrow K_S^0\pi^{\pm}\pi^{\mp}$ and $D\rightarrow K_S^0K^{\pm}K^{\mp}$ — "GGSZ" — Phys Lett B718 (2012) 43
  - $B^{\mp}\rightarrow Dh^{\mp}$, $D\rightarrow \pi^{\mp}K^{\pm}\pi^{\mp}\pi^{\pm}$ and $D\rightarrow K^{\mp}\pi^{\pm}\pi^{\mp}\pi^{\pm}$ — "K3π" : — LHCb-CONF-2012-030
  - $B^{\mp}\rightarrow Dh^{\mp}$, $D\rightarrow \pi^{\mp}K^{\pm}$ and $D\rightarrow K^{\mp}\pi^{\pm}$ — "ADS" — Phys Lett B712 (2012) 203
  - $B^{\mp}\rightarrow Dh^{\mp}$, $D\rightarrow K^{\pm}K^{\mp}$, $D\rightarrow \pi^{\pm}\pi^{\mp}$ — "GLW" — Phys Lett B712 (2012) 203



- Two paths to the same final state via D^0 and $\overline{D}^0$ => interference sensitive to gamma

$B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ ADS & GLW modes



Phys. Lett. B 712 (2012) 203-212

A_{ADS} = (-52±15±2)%

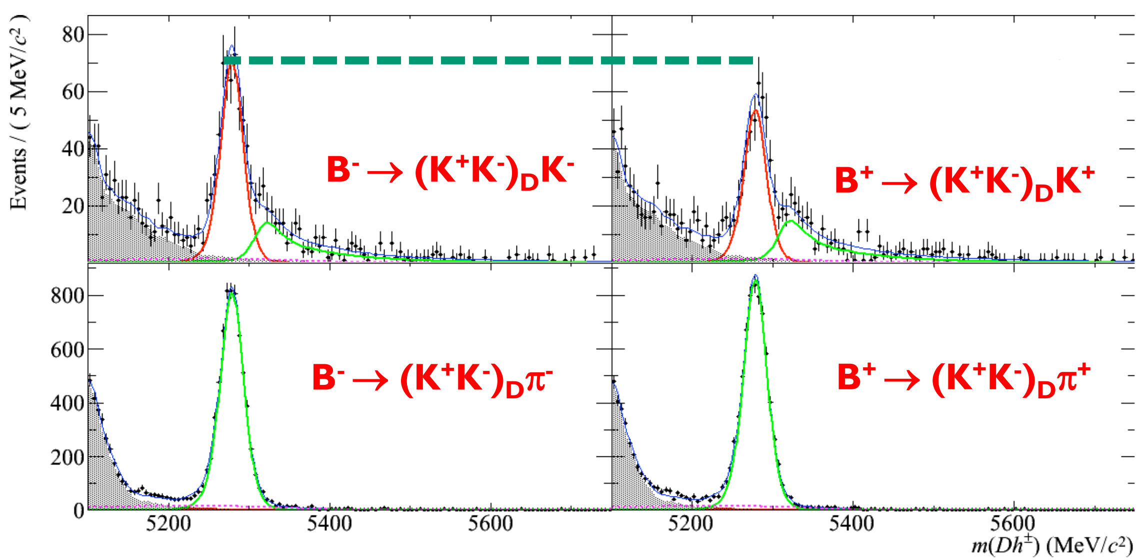
ADS modes

$A_{ADS(\pi)}$ = (14.3±6.2±1.1)%

1 fb^{-1}, 7 TeV data

A_{CP+} = (14.5±3.2±1.0)%

GLW modes



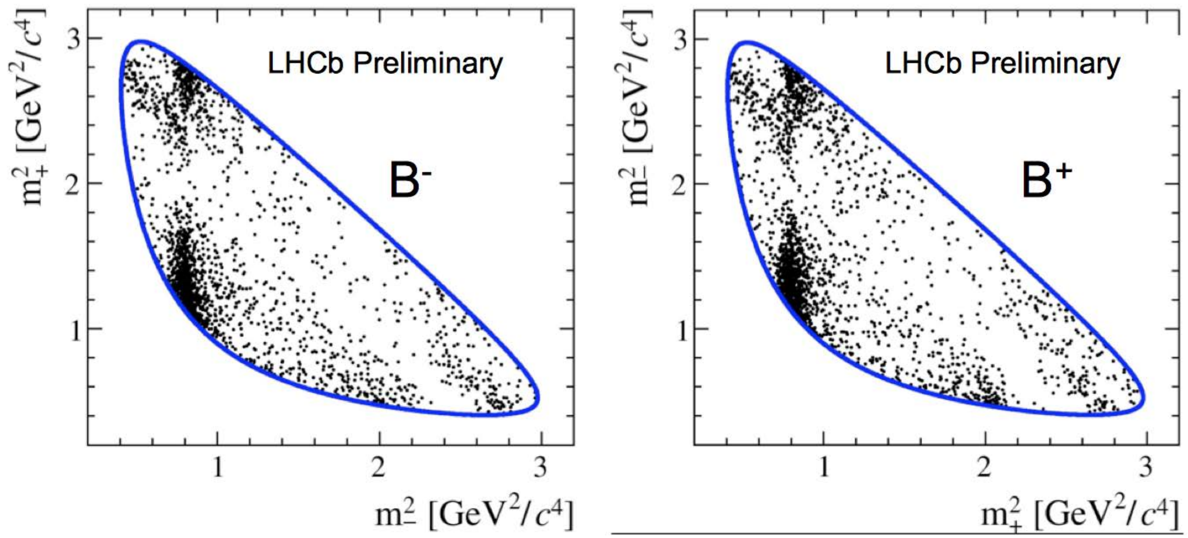
$B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ GGSZ & $K(3\pi)$ modes

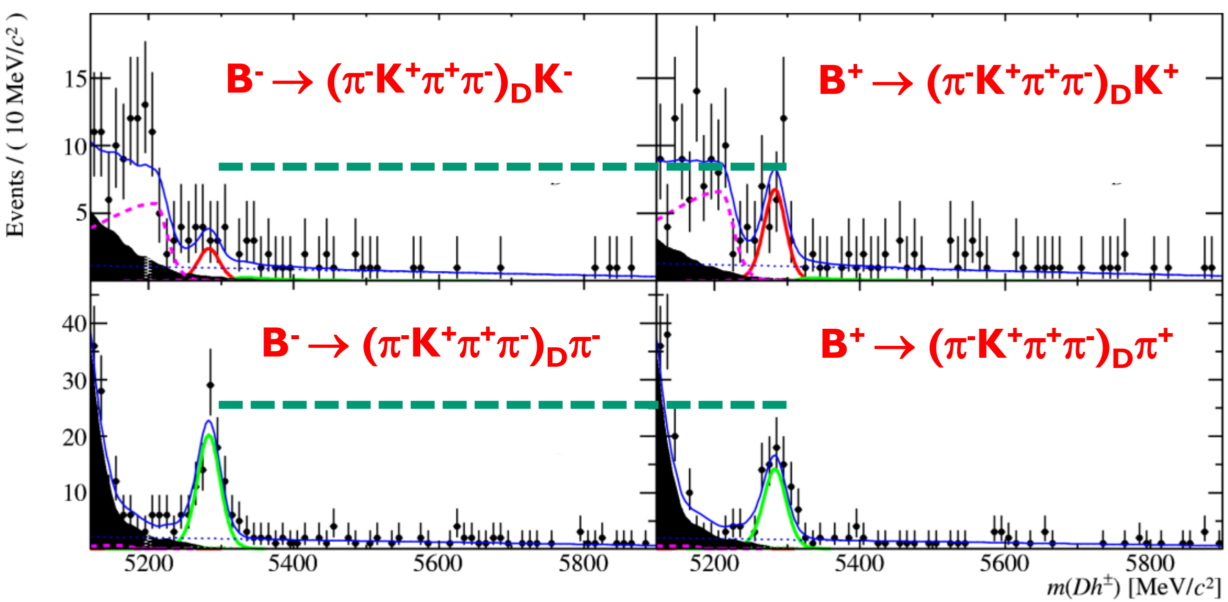
arXiv:1408.2748

GGSZ mode

$(K_S\pi\pi)_D$

3 fb^{-1}





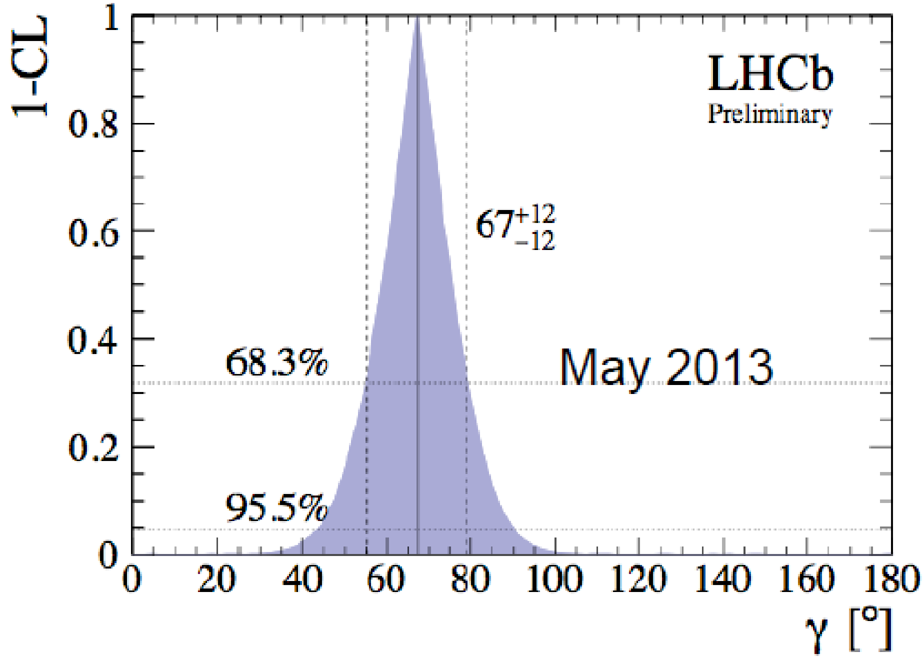
$K(3\pi)$ modes

1 fb^{-1}

LHCb-CONF-2012-030

$B^\pm \to DK^\pm$ γ measurement

LHCb-CONF-2013-006



LHCb combined

GLS ($D^0 \to \pi^+ \pi^-, K^+ K^-$) $1 fb^{-1}$

ADS ($D^0 \to K^+ \pi^-, K^+ \pi^- \pi^+ \pi^-$) $1 fb^{-1}$

GGSZ($D^0 \to K_S \pi^+ \pi^-, K_S K^+ K^-$) $3 fb^{-1}$

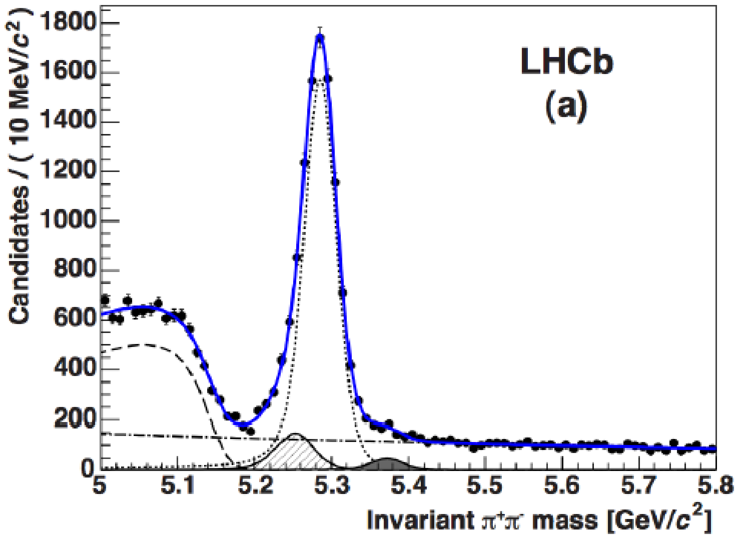
$$\gamma = (67 \pm 12)^\circ$$

Compare: $Belle : (69^{+17}_{-16})^\circ$

$BaBar : (68^{+15}_{-14})^\circ$

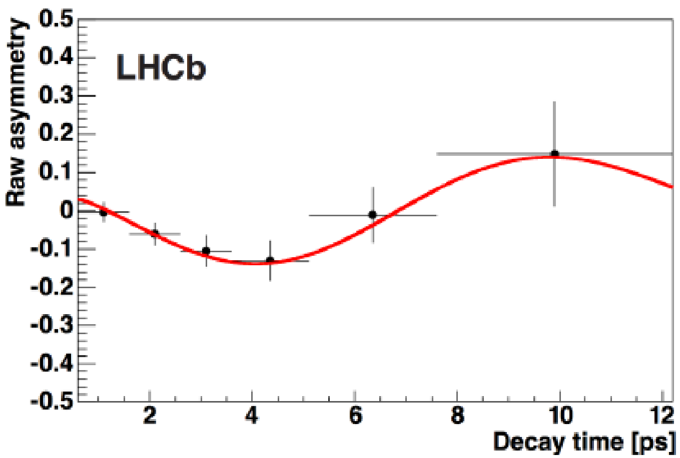
- Indirect γ value from global CKM fit: 66.5° +1.3° -2.5°

CP violation in $B\to\pi^+\pi^-$ & $B_s\to K^+K^-$ (angle α/γ)



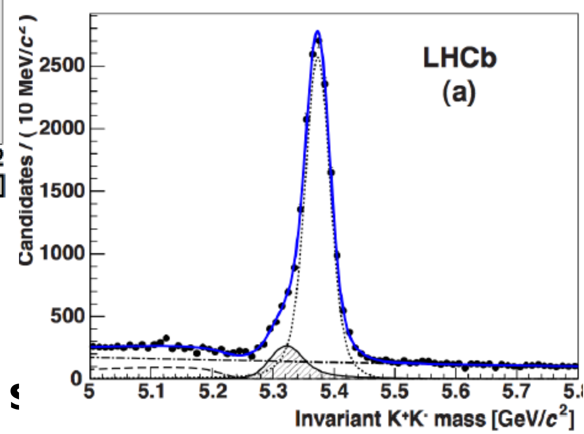
- 1 fb^{-1} : ~9000k $B^0\to\pi^+\pi^-$ events
- First time-dependent CP asymmetry plot of $B^0\to\pi^+\pi^-$ at a hadron collider

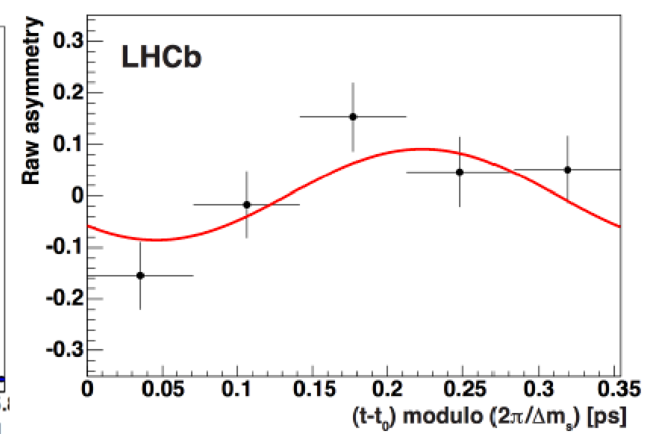
$$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02 \quad \text{Cos term (direct)}$$
$$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02 \quad \text{Sine term (indirect)}$$



- Also first ever time-dependent asymmetry seen in $B_s\to K^+K^-$

$$C_{KK} = 0.14 \pm 0.11 \pm 0.03$$
$$S_{KK} = 0.30 \pm 0.12 \pm 0.04$$





JHEP 10 (2013) 183

Selected physics highlights

- Parameters of the CKM matrix
- Rare B decays
- Studies of CPV in the B_s system
- CP violation in charm

Rare decay $B^0_{(s)} \rightarrow \mu^+\mu^-$

- Decays strongly suppressed in SM

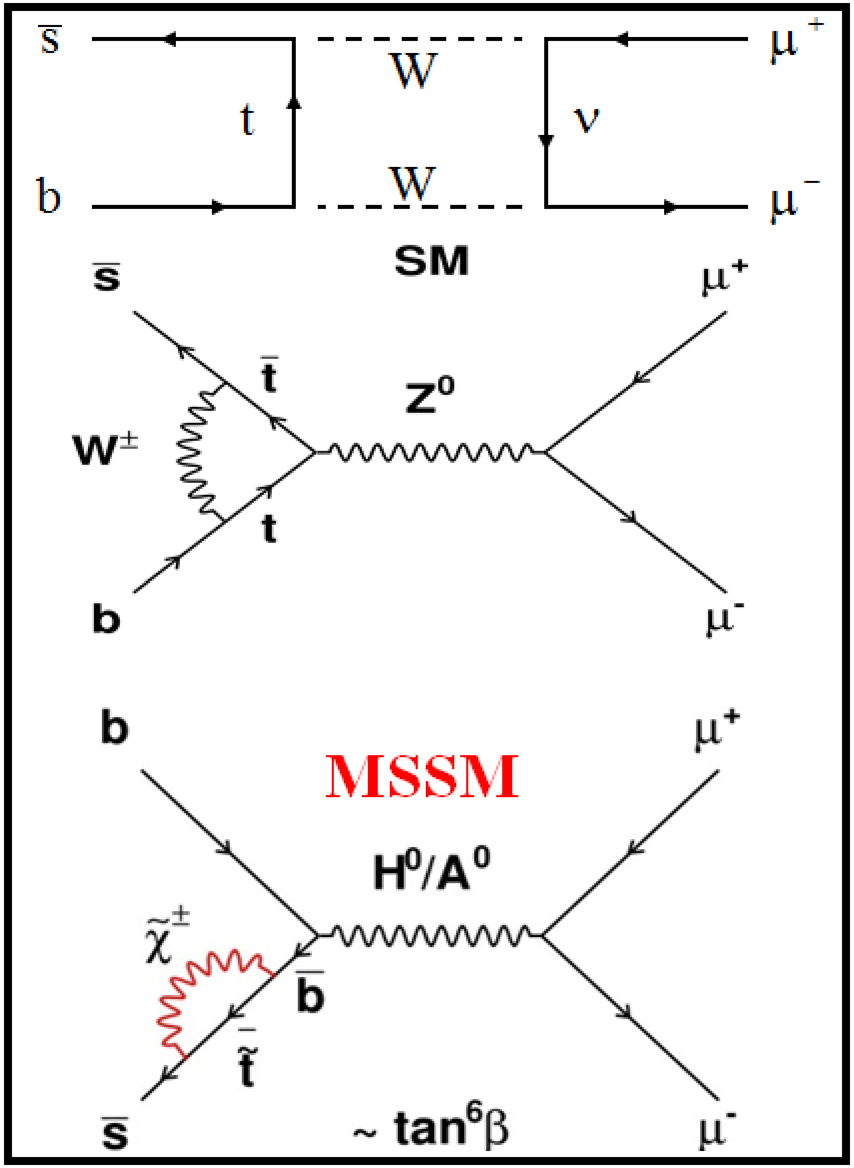
- Predicted BRs

  $B^0_s \rightarrow \mu^+\mu^- = (3.56 \pm 0.30) \times 10^{-9}$

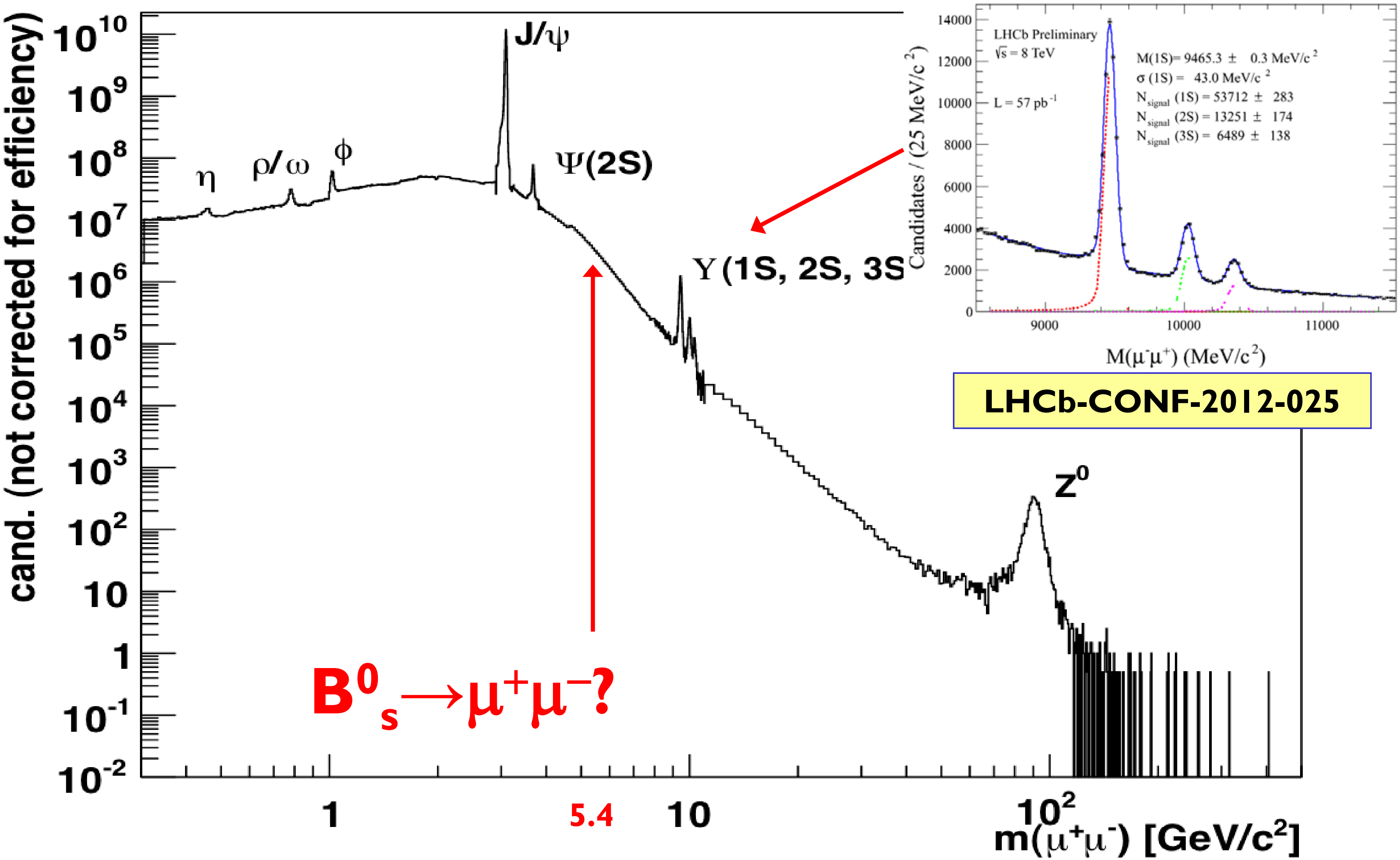
  $B^0 \rightarrow \mu^+\mu^- = (1.07 \pm 0.10) \times 10^{-10}$

  arXiv:1208:0934 & PRL 109 041801 (2012)

- Very sensitive to new physics - e.g. MSSM
- But it's a bit like looking for a needle in a haystack



LHCb μ+μ– mass spectrum

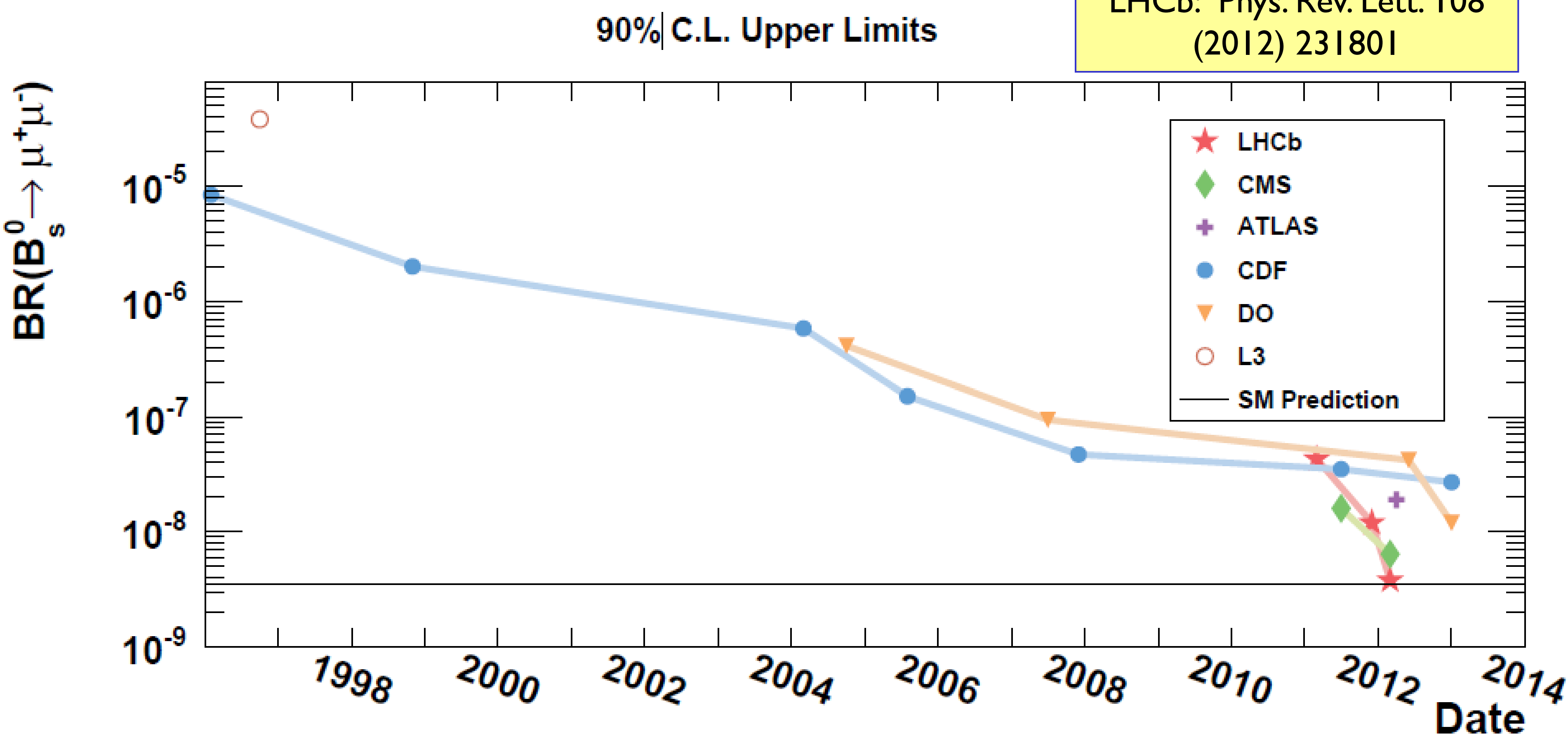


LHCb-CONF-2012-025

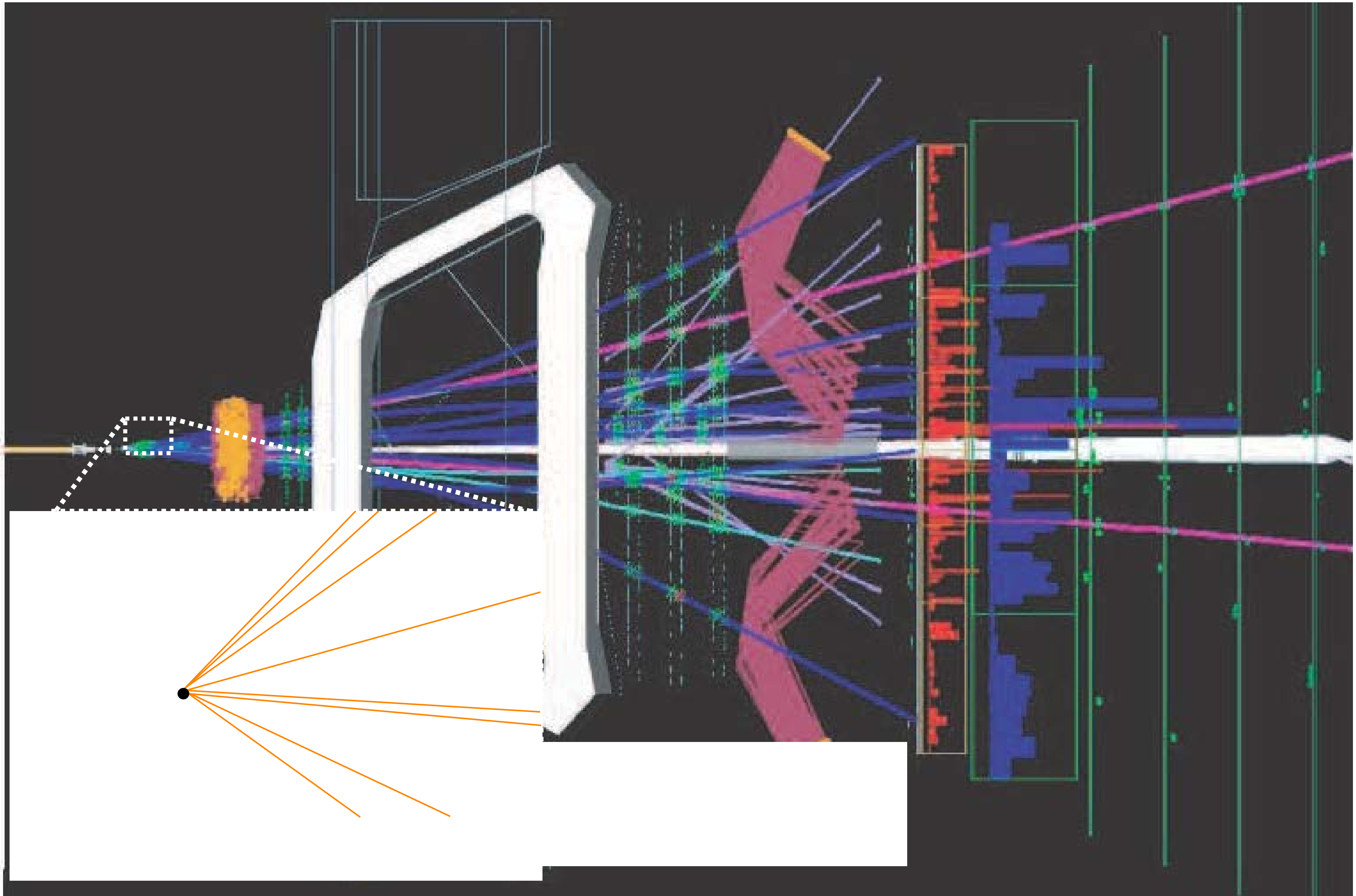
History

- $B^0_{(s)} \to \mu^+\mu^-$ sensitivity to NP has motivated searches since 1984 !
- $BR(B^0_s \to \mu^+\mu^-)$ has now reached SM prediction

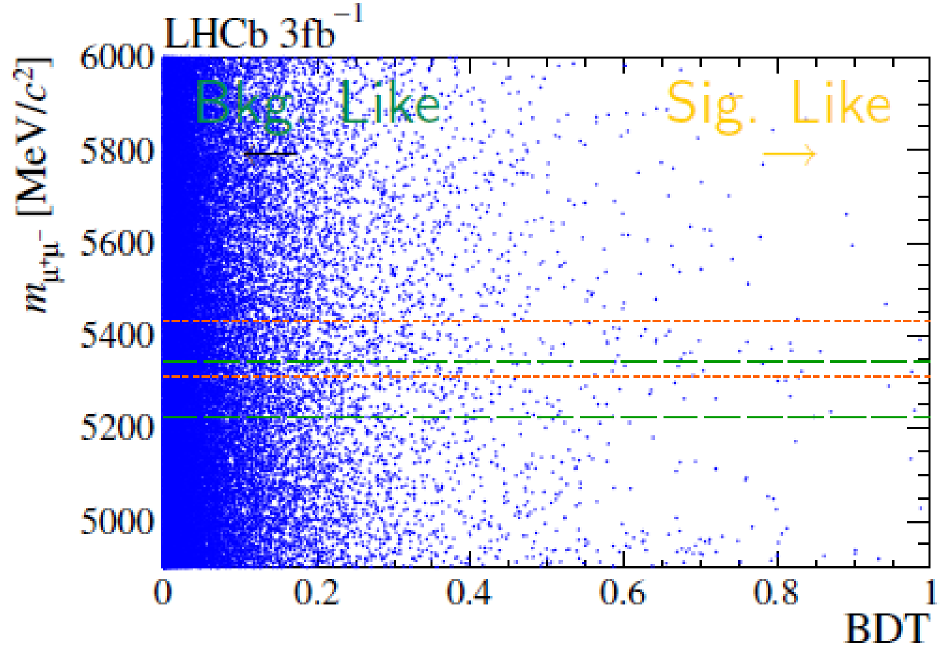
LHCb: Phys. Rev. Lett. 108 (2012) 231801



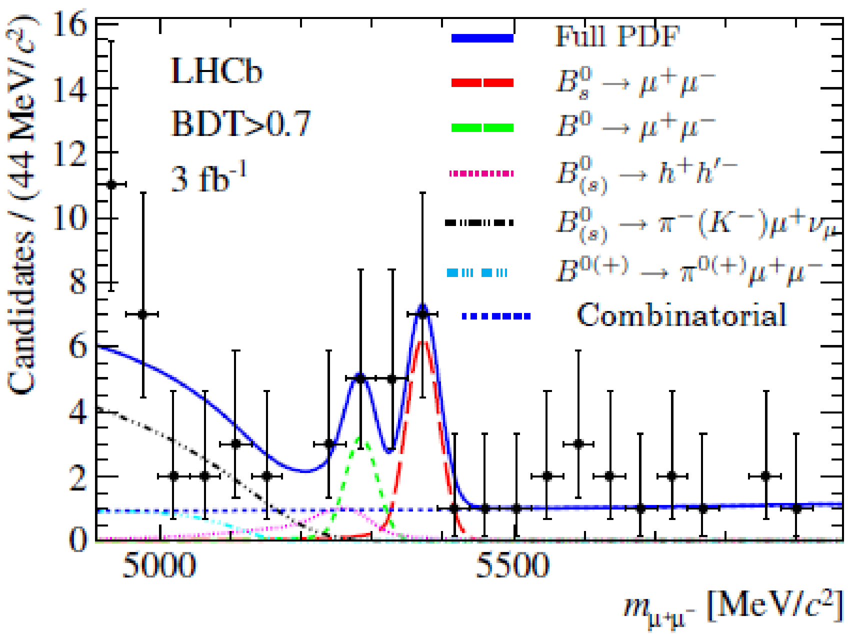
LHCb $B_s \to \mu^+\mu^-$ candidate



- Results based on 2011/12 data: 3 fb blinded analysis
- Selection based on multivariate estimator (BDT) combining vertex and topological information
- Cut on BDT>0.5
- The known B masses and widths are fixed in the fit



PRL 111 (2013) 101805



$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}st\ ^{+0.3}_{-0.1}sy) \times 10^{-9}$$

Significance : 4.0 (*Expected* 5.0)

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}st\ ^{+0.6}_{-0.4}sy) \times 10^{-10}$$

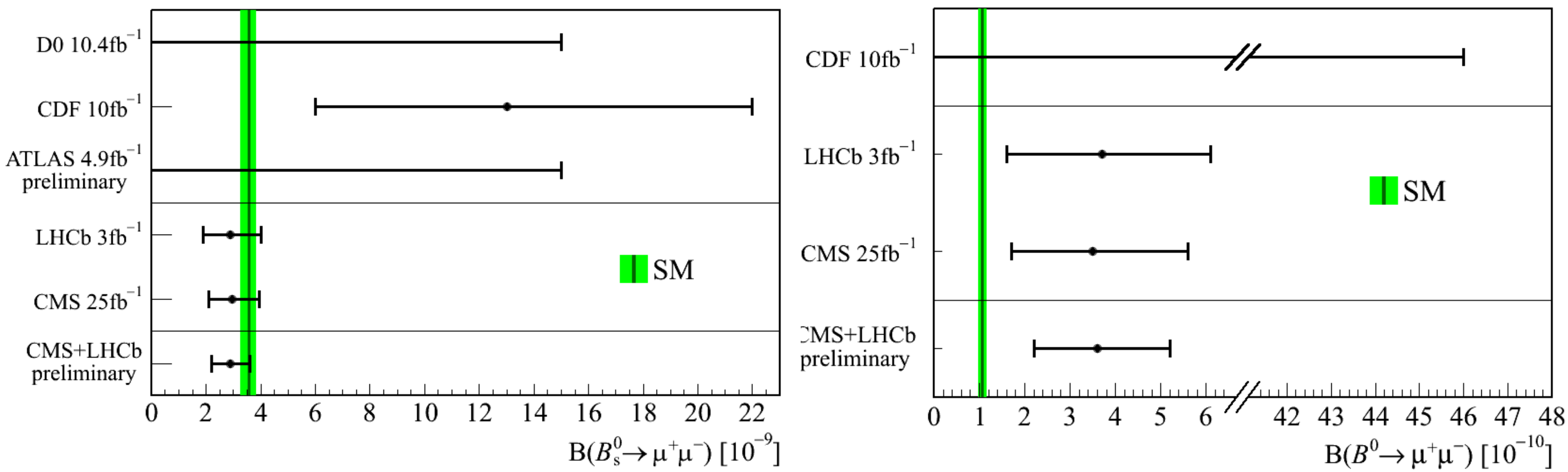
Significance : 2.0

Upper Limit

No compelling $B^0 \to \mu^+\mu^-$ signal hint

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ at 95%C.L.

Combining with CMS results



- Preliminary combination of CMS+LHCb yields

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

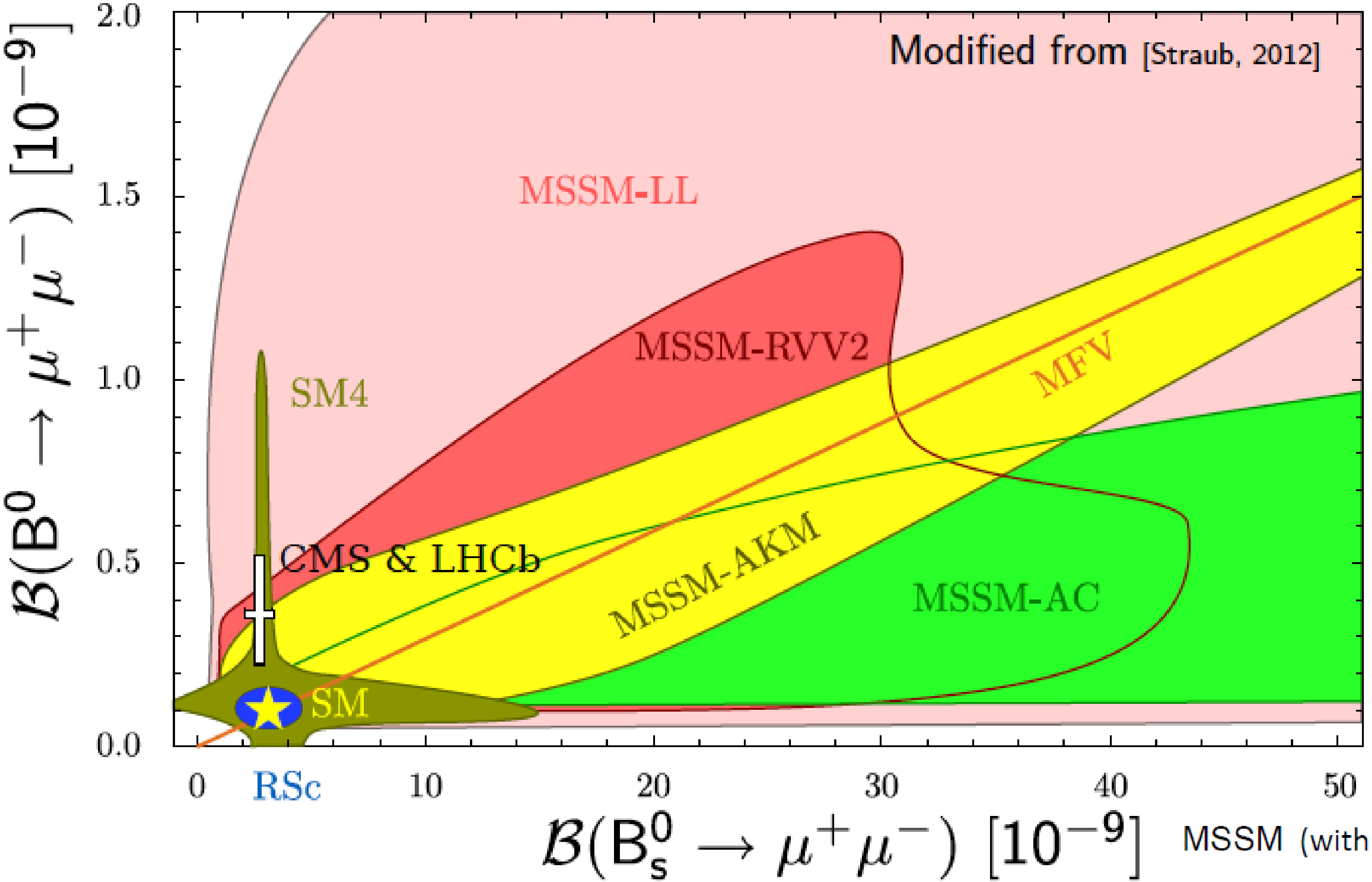
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.6 \, ^{+1.6}_{-1.4}) \times 10^{-10}$$

Observation at more than 5 σ

PRL 112 (2014) 101801

F.N.Mahmoudi, arXiv:1310.2556

Constraints on new physics models

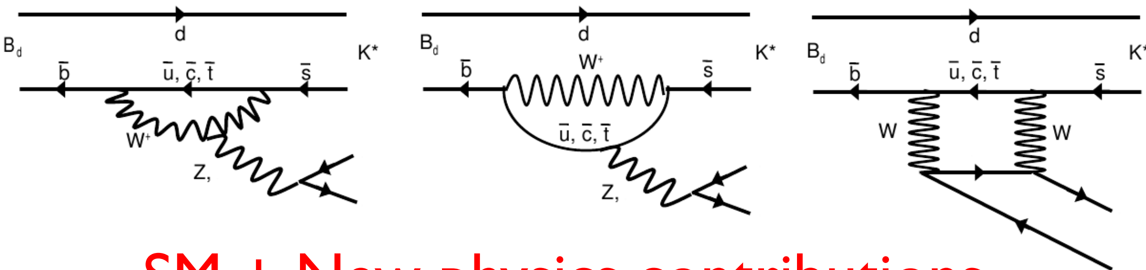


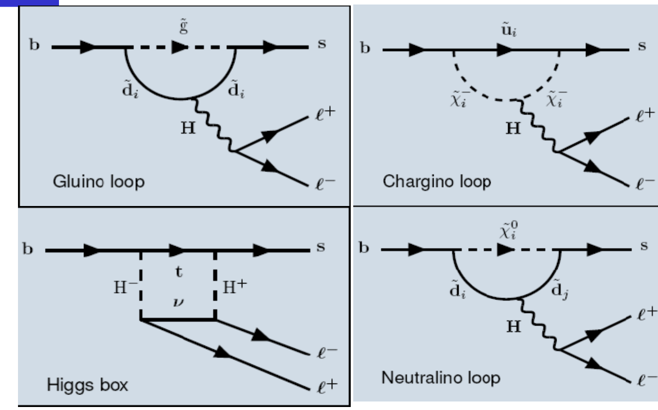
MSSM (with R-Parity conservation)

$$B(B_s \to \mu^+\mu^-) \;\alpha\; \frac{\tan^6\beta}{m_A^4}$$

Straub Moriond 2012
(http://phys.davidstraub.de/files/dstraub-moriond12.pdf)

FCNC decay $B^0 \to K^{*0}\mu^+\mu^-$





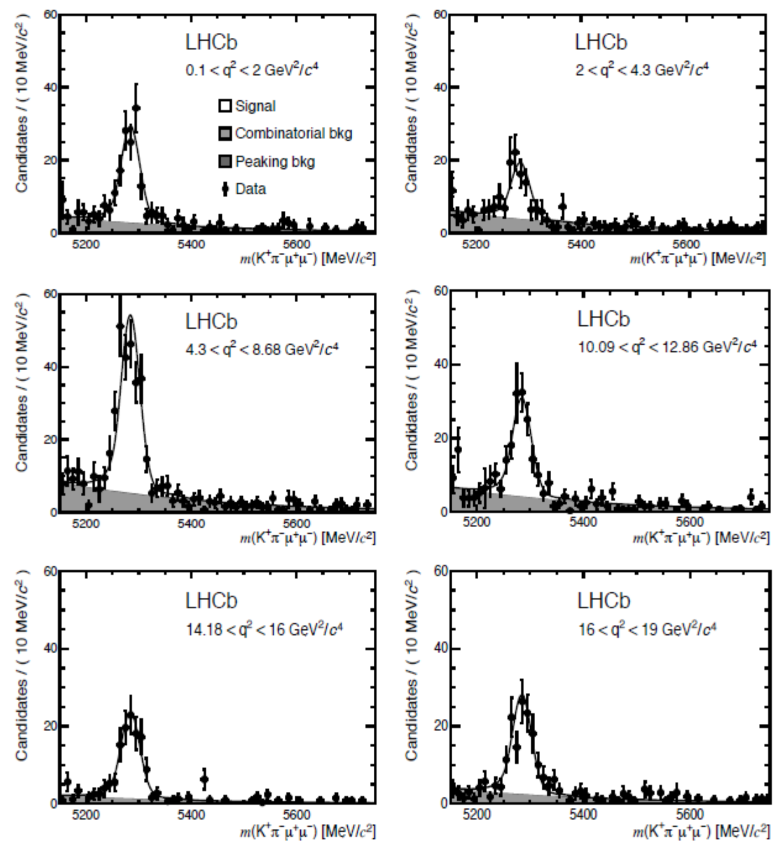
SM + New physics contributions

- LHCb has largest sample in world, as clean as the B Factories!
- LHCb BR = $(1.22^{+0.38}_{-0.32}) \times 10^{-6}$ agrees to within ~30% of SM

arXiv:1210.4492

- Analysis presented here based on 883 ± 34 events ($1\,fb^{-1}$ at 7 TeV)

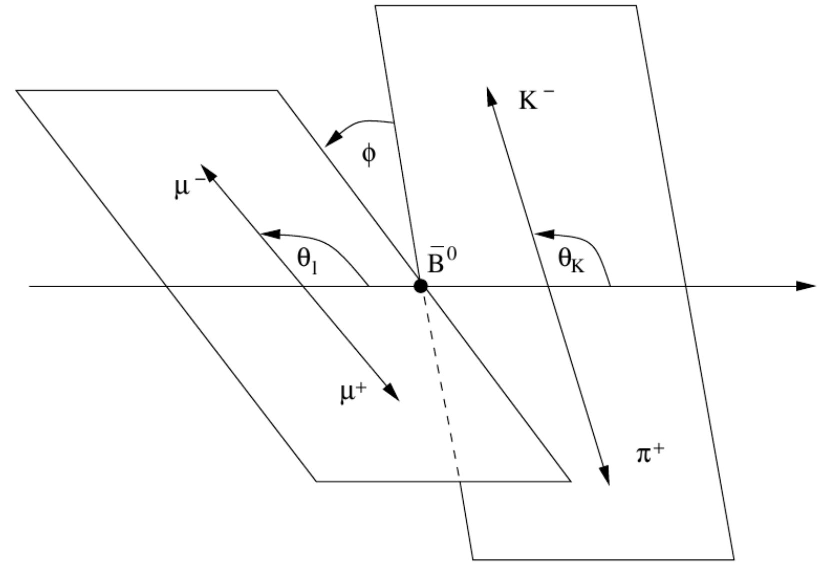
JHEP 08 (2013) 131

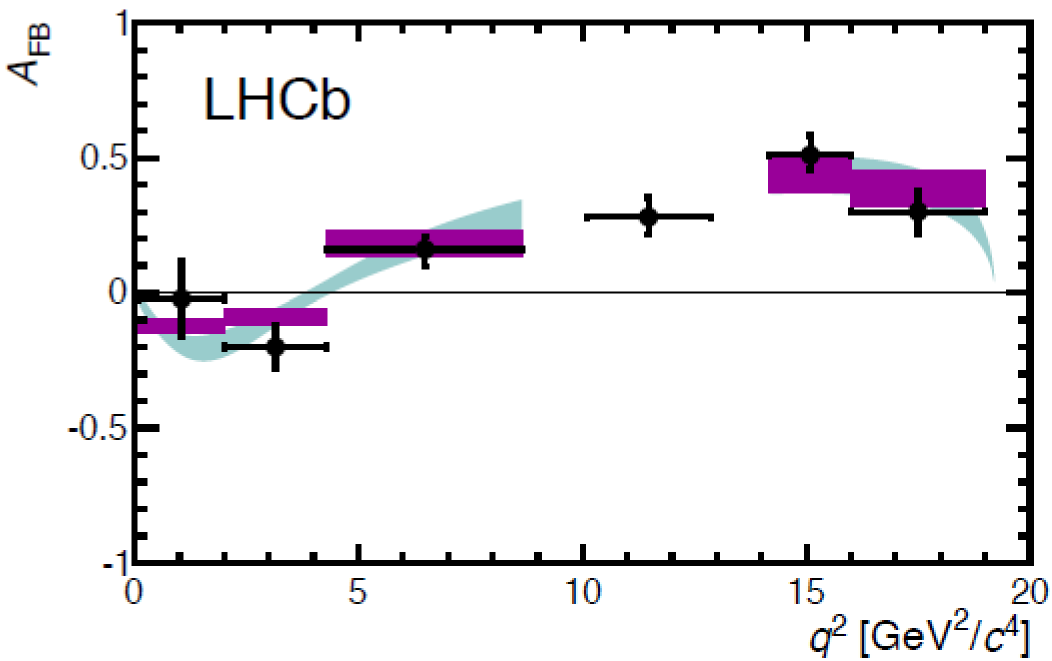


$B^0 \to K^*\mu^+\mu^-$ continued

JHEP 08 (2013) 131

- But forward-backward asymmetry $A_{FB}(q^2)$ in the $\mu\mu$ rest-frame is a sensitive NP probe ($q^2 = m_{\mu\mu}{}^2$)
- First measurement of zero crossing point: $q^2 = 4.9 \pm 0.9$ GeV^2
- A_{FB} measured by LHCb consistent with Standard Model





$B^0 \to K^*\mu^+\mu^-$ continued

JHEP 08 (2013) 131

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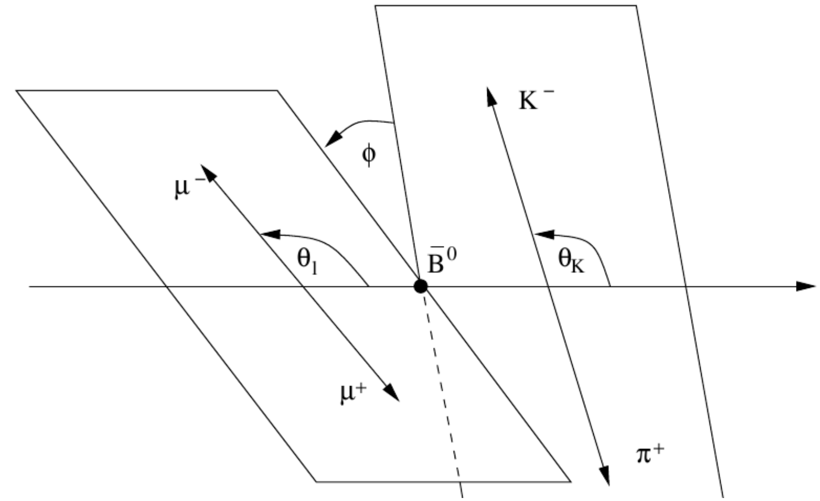
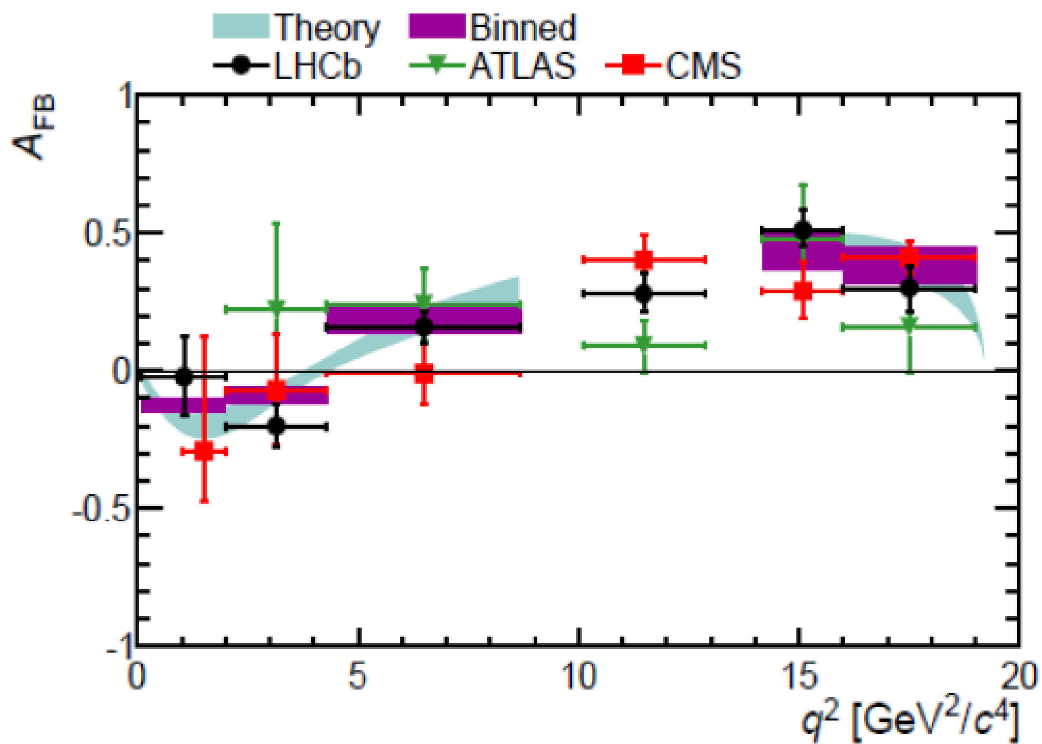
- First measurement of zero crossing point: $q^2 = 4.9 \pm 0.9\ \mathrm{GeV}^2$
- A_{FB} measured by LHCb consistent with Standard Model
- ATLAS & CMS now enter the game





New observables in $B^0 \to K^*\mu^+\mu^-$

- Goal: express differential decay rate in terms of parameters that are less sensitive to the hadronic matrix element uncertainty ⇔ prevent NP from hiding under strong interaction effects.
- Same 1 fb^{-1} 7 TeV dataset

PRL 111 (2013) 191801

- Angular differential distribution given by:

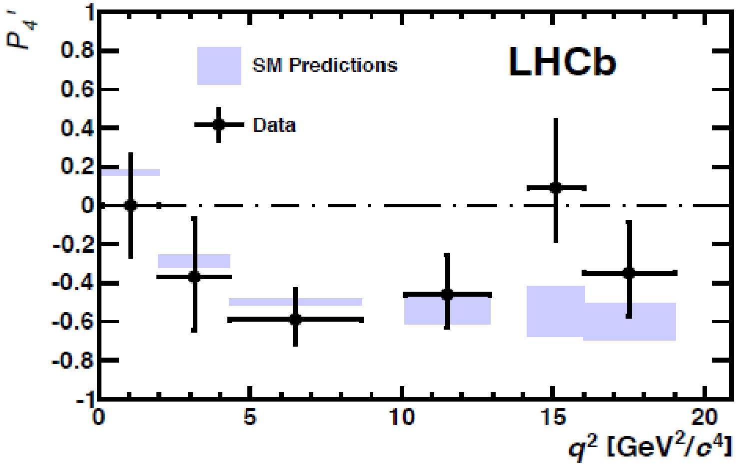
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_L)}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_L)A_{Re}^T\sin^2\theta_K\cos\theta_\ell + \sqrt{F_L(1-F_L)}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_L(1-F_L)}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

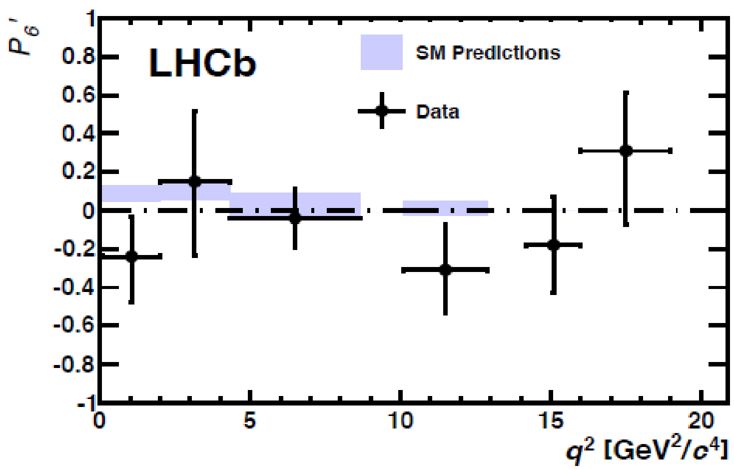
New observables in $B^0 \to K^* \mu^+ \mu^-$ cont'

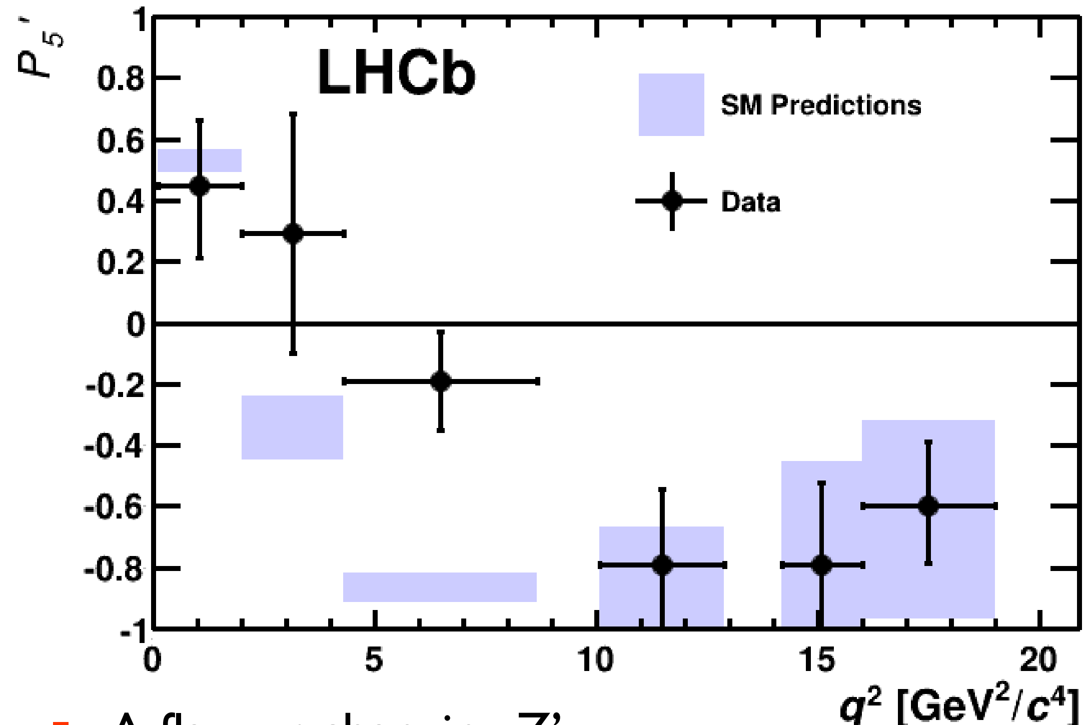
- Local discrepancy of 3.7σ in 3rd bin of P_5'

PRL 111 (2013) 191801

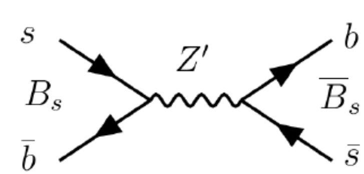
(SM prediction J.Mathias et al, JHEP 05 (2013) 137)







- A flavour changing Z' boson, QCD effects, or just statistical fluctuation?
- More data required



Lepton universality test using $B^+ \to K^+ \ell^+ \ell^-$

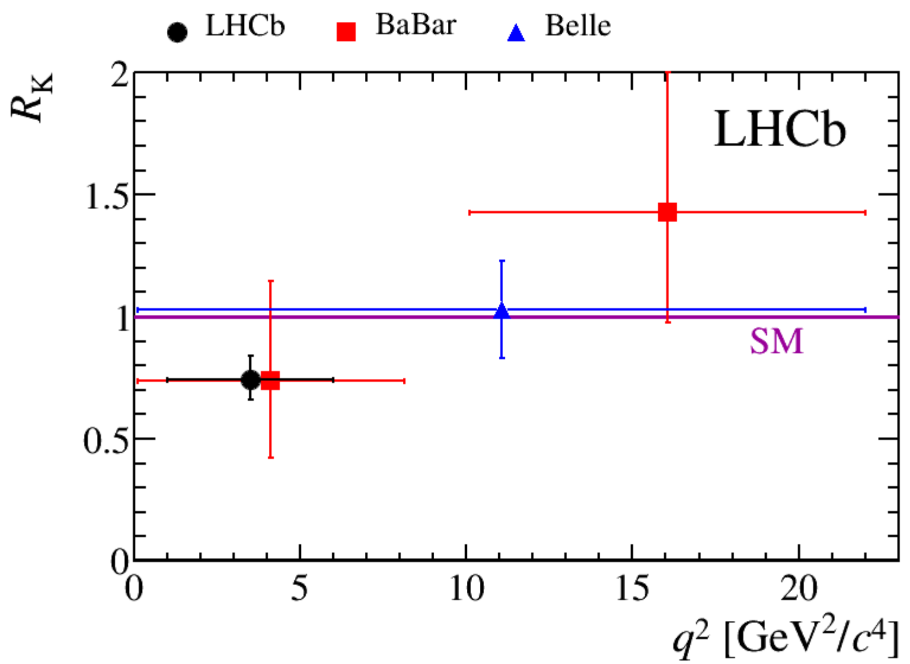
- Define R_K as: $R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 1 \pm \mathcal{O}(10^{-3})$ in SM

- To cancel systematics, form double ratios with

  $B^+ \to K^+ J/\psi(\to \ell^+ \ell^-)$ assuming lepton universality for

  $J/\psi \to \ell^+ \ell^-)$

- Reconstruction of $B^+ \to K^+ e^+ e^-$ is experimentally challenging due to bremsstrahlung emission
- The result for R_K differs from SM at 2.6 sigma level. This is using the 3 fb^{-1} of data .
- This is the most precise measurement of RK to date.

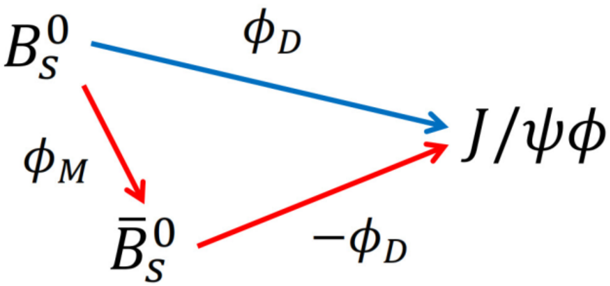


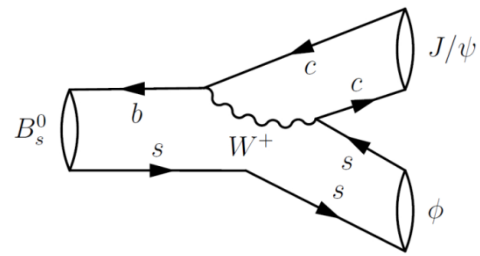
$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

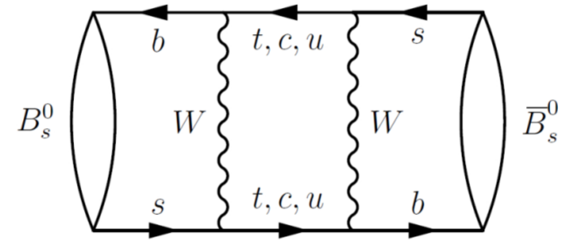
Selected physics highlights

- Parameters of the CKM matrix
- Rare B decays
- Studies of CPV in the B_s system
- CP violation in charm

B_s weak mixing phase ϕ_s in $B_s \to J/\psi\, \phi$







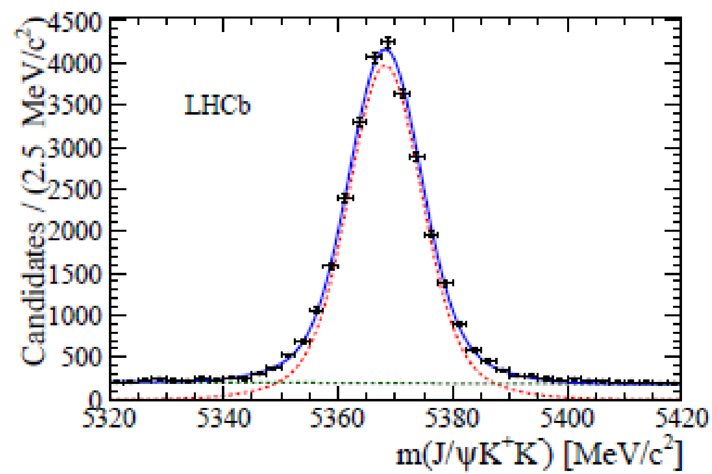
- Golden mode for this study is $B_s \to J/\psi\, \phi$
- Analogue of 2β (phase of B^0 mixing) but in the B_s system
- *Interference* between B^0 decay to $J/\psi K^0_S$ directly and via B^0 - $\bar{B}^0$ oscillation gives rise to a CP violating phase

$$\phi = \phi_{Mixing} - 2\,\phi_{Decay} = -2\phi_s$$

- ϕ_s is expected to be very small in the SM and precisely predicted:

  $\phi_s = -0.036 \pm 0.002$

  (see eg Charles et al PRD84 (2011) 033005)

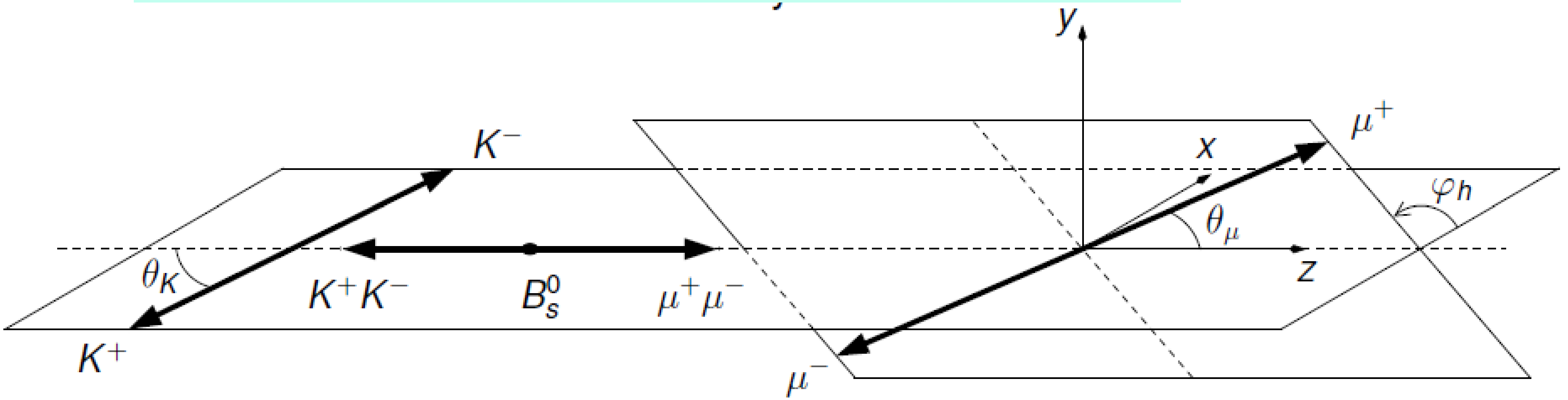


1fb^{-1}, 7 TeV PRD 87 112010 (2013)

$B_s \to J/\psi\ \phi$ angular analysis

- ϕ is a vector meson (spin 1)
- Vector-vector final state: mixture of CP-odd and CP-even components

Need to perform $B_s \to J/\Psi\ \phi$ angular analysis



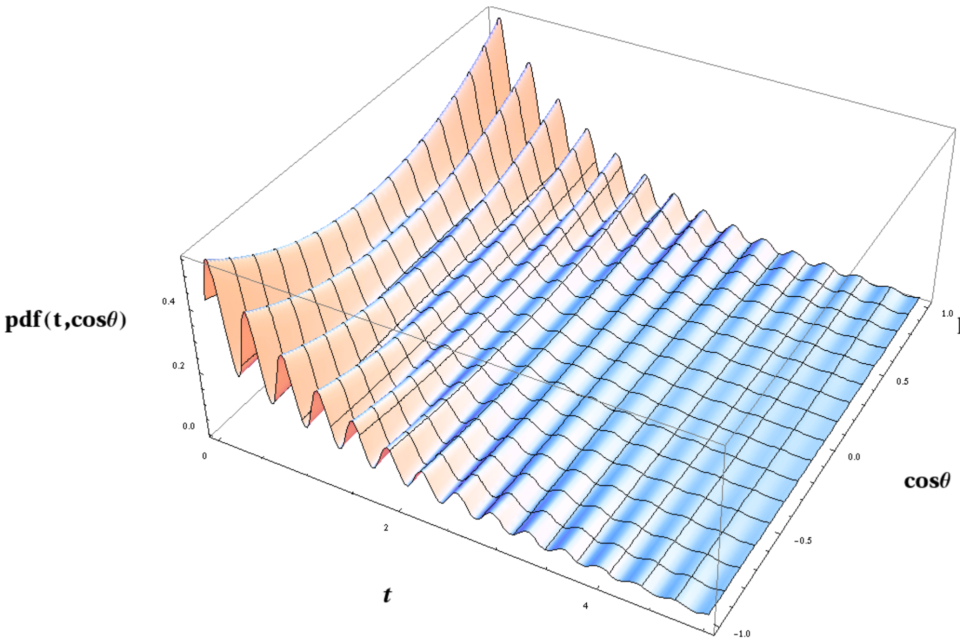
LHCb: 1fb^{-1}, 7 TeV, 27617 candidates

Use opposite side tag: Power = 2.10 ± 0.08 ± 0.24%

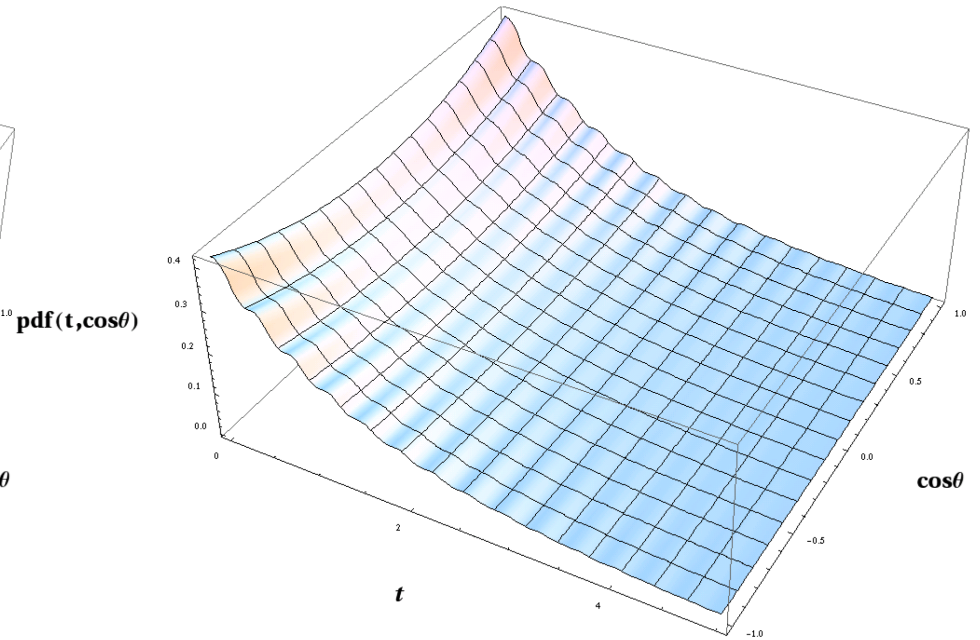
- First measurements from the Tevatron indicated large values for ϕ_s discrepancy with SM reaching ~3σ

“Visualizing” the effect of ϕ_s in $B_s \rightarrow J/\psi\, \phi$

- Amplitude of asymmetry $\propto \sin \phi_s$
- Frequency is the same as in $B_s \rightarrow D_s \pi$ decays

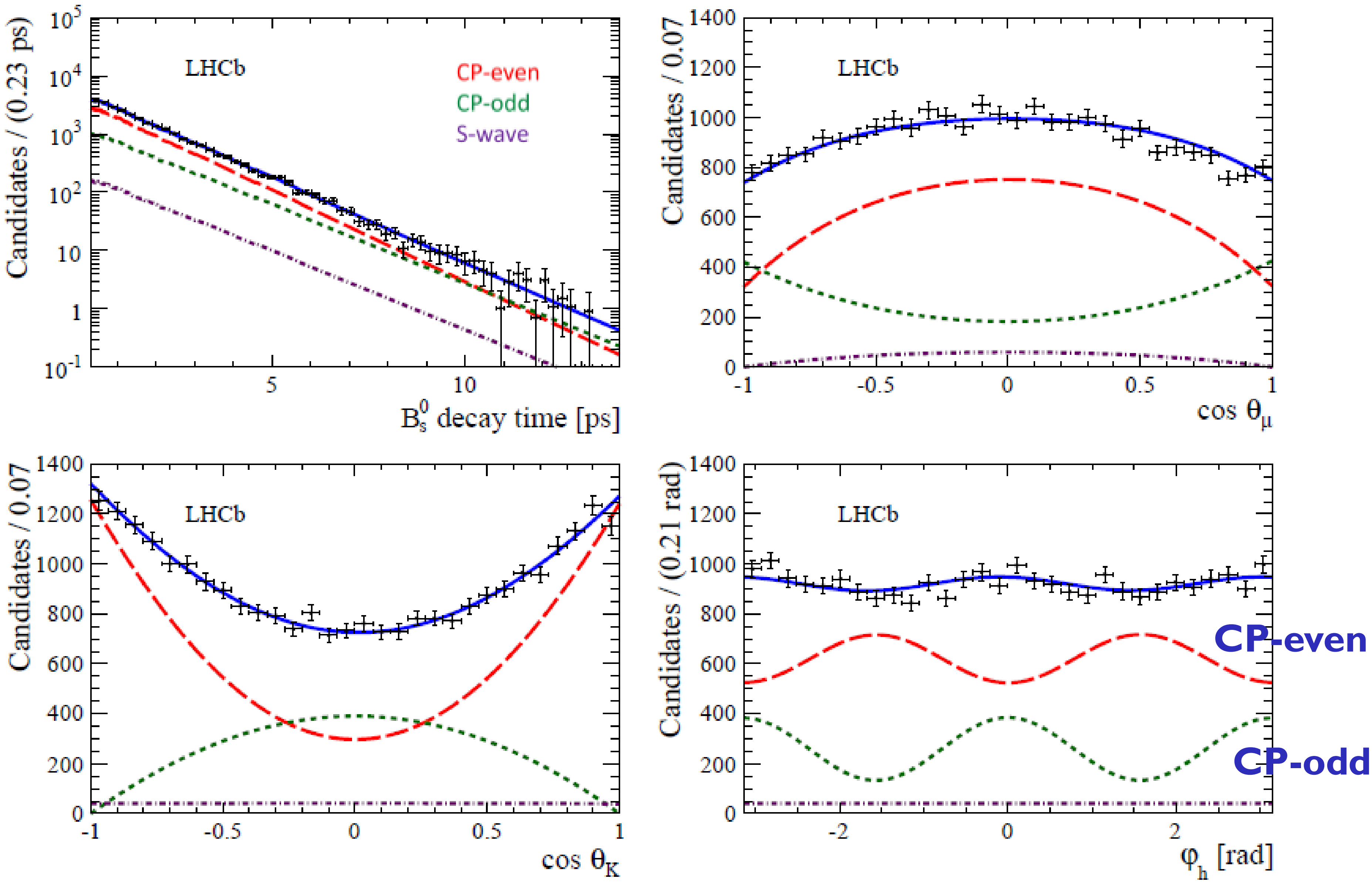


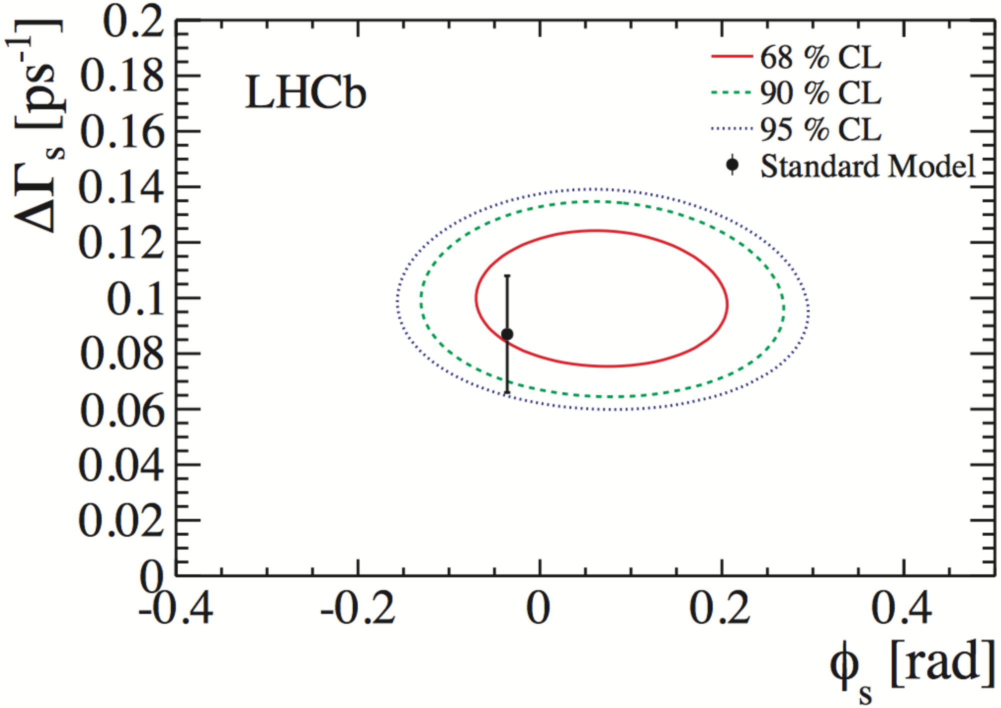
$\phi_s = 0.4$



$\phi_s = 0.04$ (SM)

$B_s \to J/\psi\ \phi$: fit projections





Results correlated with $\Delta\Gamma_s$ = width diff. of the B_s mass eigenstates → plot as contours in (ϕ_s *vs* $\Delta\Gamma_s$) plane

Also add in $B_s \to J/\psi\, \pi\pi$

World's most significant direct measurement of ϕ_s & Γ_s , $\Delta\Gamma_s$

$$\phi_s = 0.01 \pm 0.07\ \text{(stat)} \pm 0.01\ \text{(syst) rad},$$
$$\Gamma_s = 0.661 \pm 0.004\ \text{(stat)} \pm 0.006\ \text{(syst)}\ \text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.106 \pm 0.011\ \text{(stat)} \pm 0.007\ \text{(syst)}\ \text{ps}^{-1}$$

Still much room for new physics in ϕ_s, will continue to improve precision

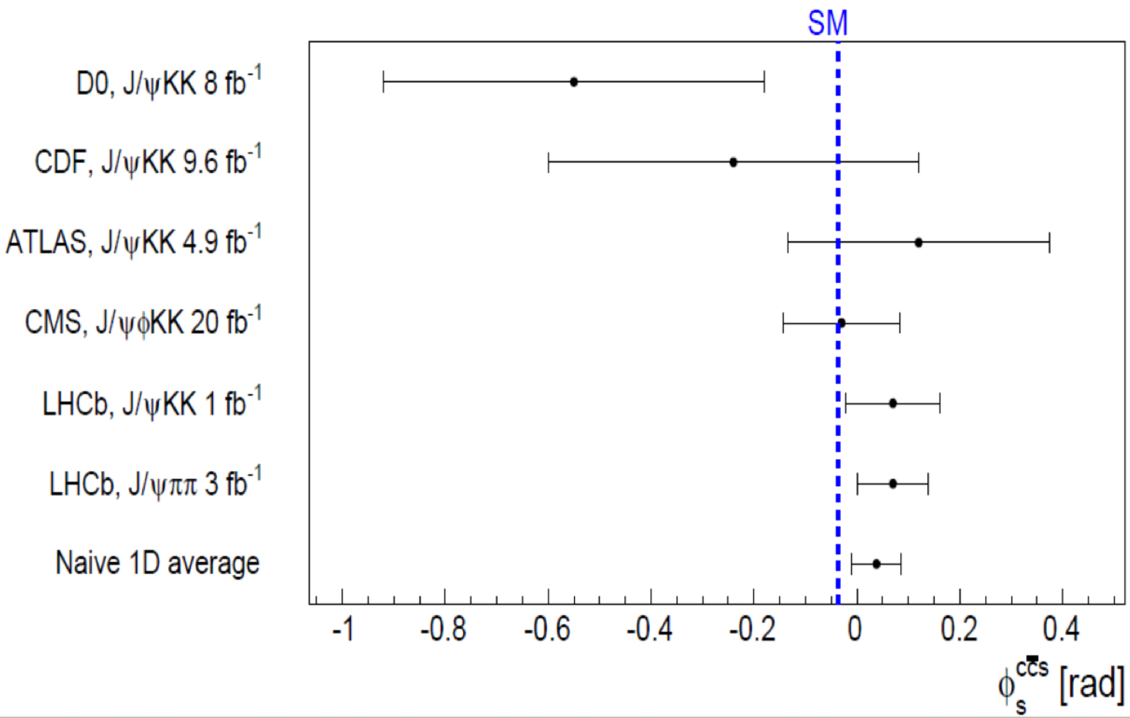
- ATLAS and CMS also measure ϕ_s

ATLAS

$\phi_s = +120 \pm 250 \pm 50$ mrad
5fb^{-1} result.

CMS

$\phi_s = -30 \pm 110 \pm 30$ mrad
20fb^{-1} result.



A naive 1D combination of ϕ_s shows data not incompatible with the SM

$\phi_s = +38 \pm 48$ mrad
naive world average
$\phi_s^{SM} = -36 \pm 2$ mrad

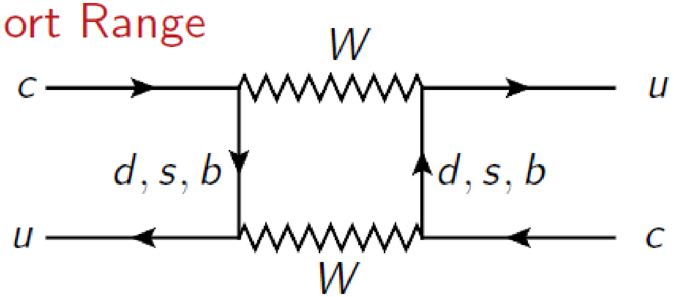
New 3 fb^{-1} LHCb results coming soon

Selected physics highlights

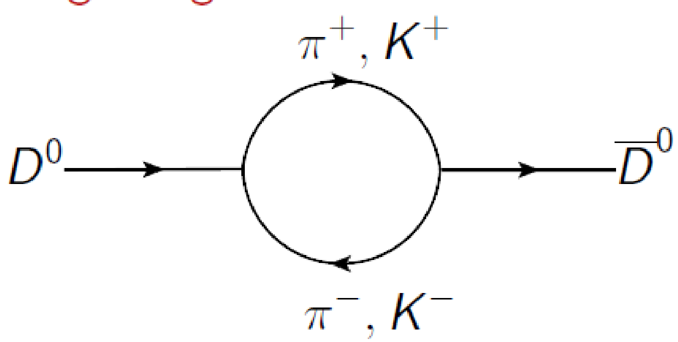
- Parameters of the CKM matrix
- Rare B decays
- Studies of CPV in the B_s system
- CP violation in charm

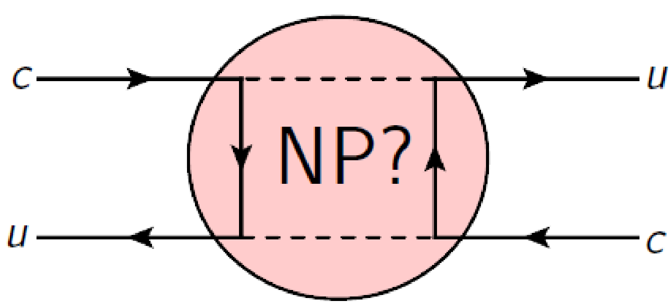
Mixing (and CP-violation) in charm decays

Short Range



Long Range





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15 November 2011 Last updated at 12:18 GMT

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LHC reveals hints of 'new physics' in particle decays

By Jason Palmer
Science and technology reporter, BBC News

Large Hadron Collider researchers have shown off what may be the facility's first "new physics" outside our current understanding of the Universe.

Particles called D-mesons seem to decay slightly differently from their antiparticles, LHCb physicist Matthew Charles **told the HCP 2011 meeting** on Monday.

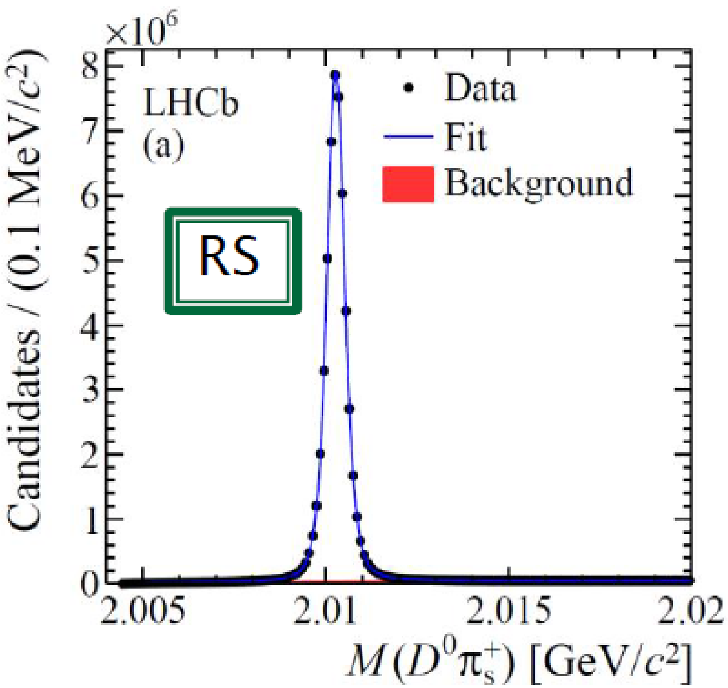
The result may help explain why we see so much more matter than antimatter.

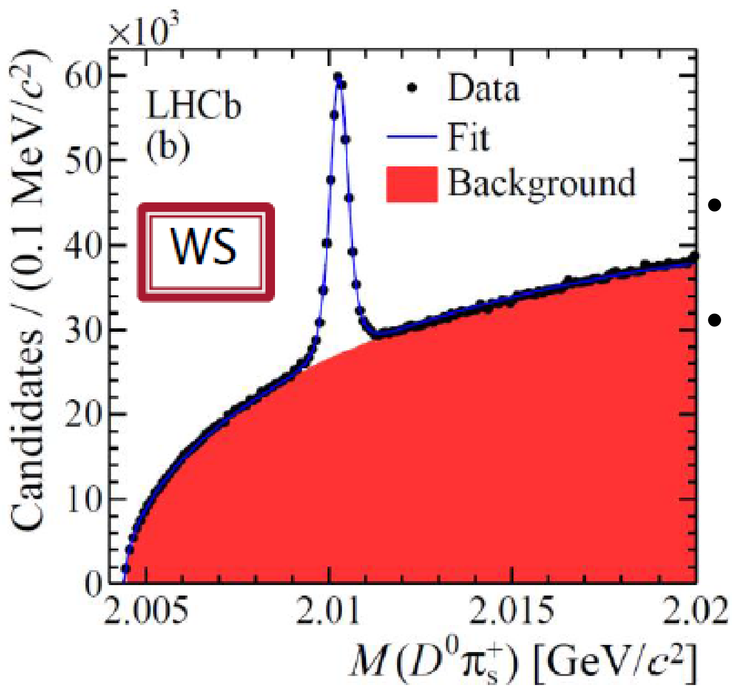
Charm mixing measurement

- Charm mixing has been confirmed by BaBar, Belle & CDF, but LHCb now shows clear observation in a single experiment.
- LHCb measures the time-dependent ratio of D^0 decays to Wrong Sign to Right Sign (will have contribution from mixing)

$$R(t) = \frac{N(D^0 \to K^+\pi^-)}{N(D^0 \to K^-\pi^+)}$$

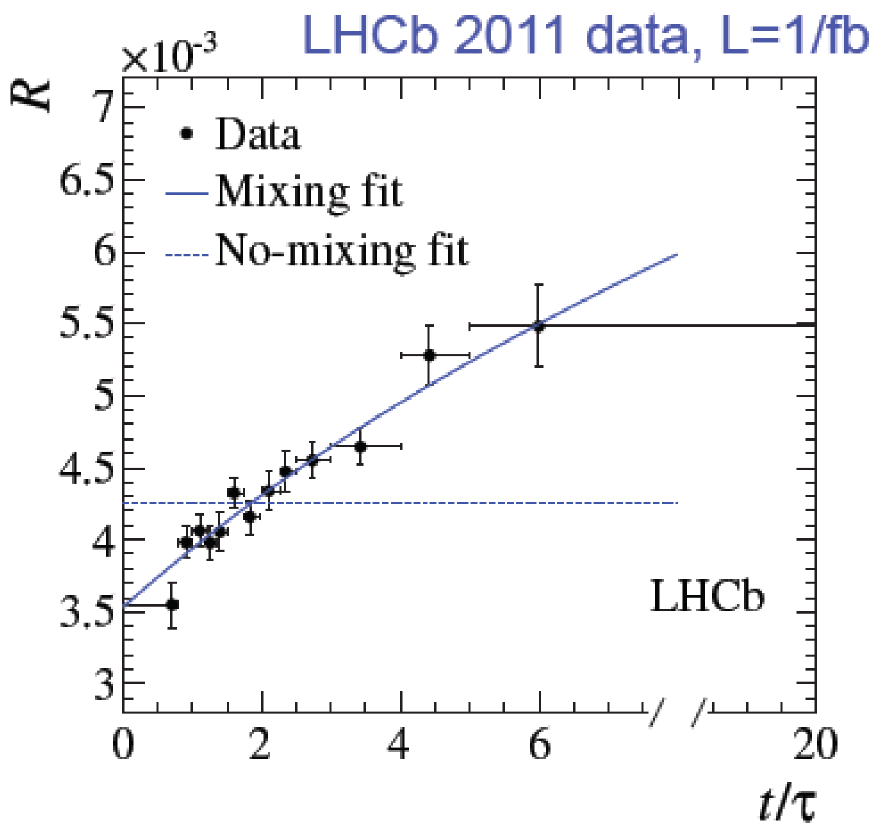
- Use the sign of the slow pion from $D^{*+} \to D^o \pi^+_s$ and $D^{*-} \to \bar{D}^o \pi^-_s$ to tag the initial D^0 flavour.





- Analysis now uses 3 fb^{-1} of data
- Huge samples of D candidates: 230k WS and 54M RS

Charm mixing measurement (2011 data)



The no mixing hypothesis is excluded at the 9.1σ level in a single experiment

PRL 110, 101802 (2013)

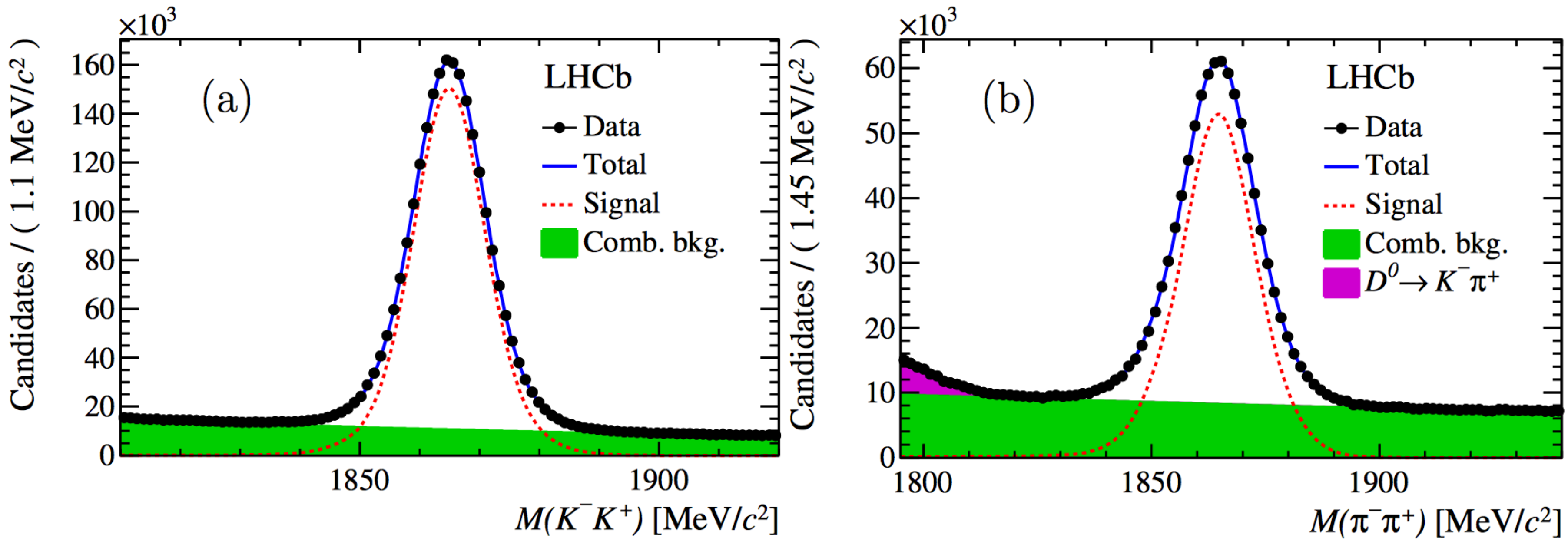
CP violation in charm

Phys. Rev. Lett. 108 (2012) 111602

Measure $D^0/\overline{D^0}$ decay asymmetries – charge of π from D* decay determines production state of the D^0, also include events with muon tag on opposite side.

$$A_K = \frac{N(D^0 \to K^+K^-) - N(\overline{D^0} \to K^+K^-)}{N(D^0 \to K^+K^-) + N(\overline{D^0} \to K^+K^-)} \qquad A_\pi = \frac{N(D^0 \to \pi^+\pi^-) - N(\overline{D^0} \to \pi^+\pi^-)}{N(D^0 \to \pi^+\pi^-) + N(\overline{D^0} \to \pi^+\pi^-)}$$

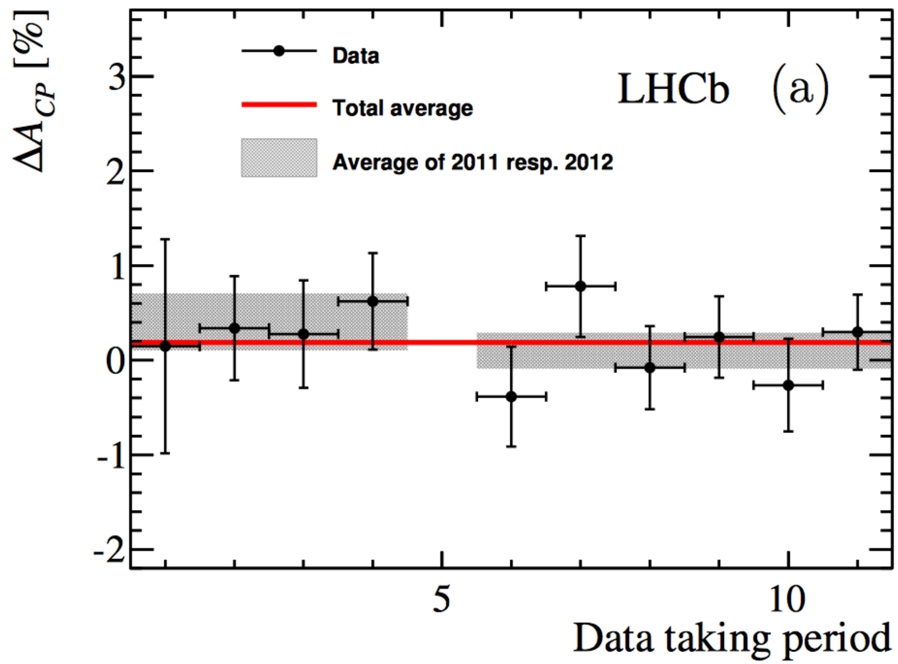
In the Standard Model these asymmetries should be close to zero



The quantity $\Delta A_{CP} = A_K - A_\pi$ is measured (since systematics largely cancel)

CP violation in charm

- From $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$



$$\Delta A_{CP} = (+0.14 \pm 0.16\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst}))\%$$

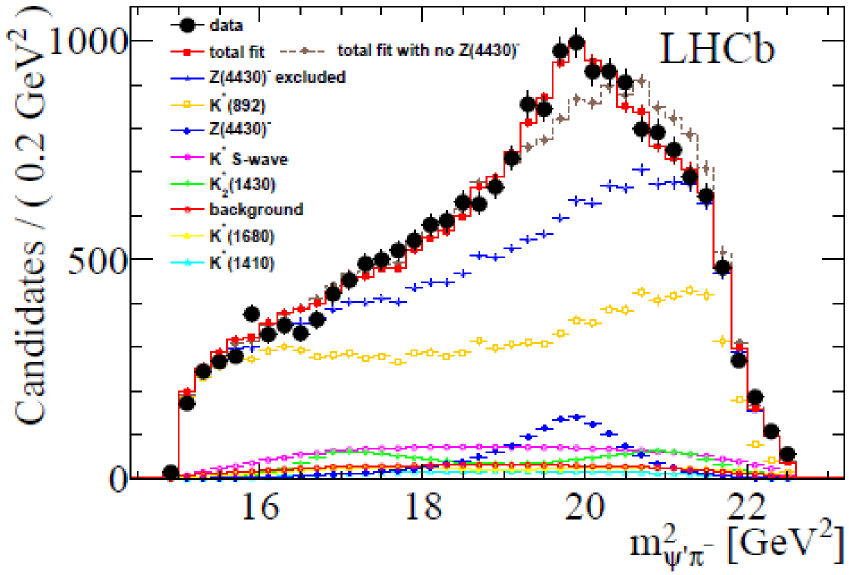
Combination consistent with zero CP violation

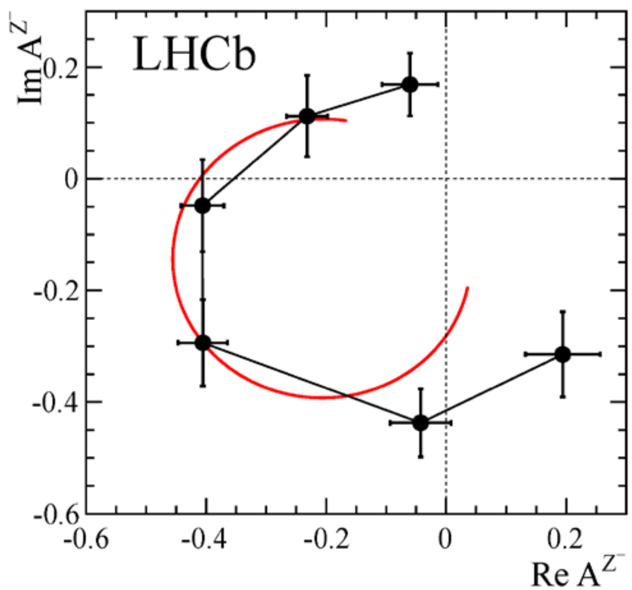
And finally … the Z(4430) tetraquark

- First observed by Belle (but not seen by Babar)
- LHCb: use very clean sample of 25,200 $B^0 \to \psi' K^+ \pi^-$, ($\psi' \to \mu^+\mu^-$) decays observed in 3 fb^{-1} of data (7 and 8 TeV).
- $Z(4430)^-$ peak seen in $\psi' \pi^-$ mass with significance of the signal 13.9σ
- Spin-parity $J^P = 1^+$ at 9.7σ
- Being charged, it cannot be a cc(bar) state. The minimal quark content of the Z(4430) is cc(bar)du(bar). It is therefore a two-quark plus two-antiquark state

$$m = 4475 \pm 7 \,^{+15}_{-25} \text{ MeV}/c^2$$
$$\Gamma = 172 \pm 13 \,^{+37}_{-34} \text{ MeV}/c^2$$

Phys. Rev. Lett. 112, 222002 (2014)





Summary and Outlook

- The LHCb experiment is performing spectacularly well
- So far all is in good agreement with the Standard Model
  $\longrightarrow$ New physics is becoming constrained in the flavour sector
  $\longrightarrow$ Hints of new physics await more data.
- Up to 2017 we expect 7-8 fb^{-1} of data in total, and much of this at ~double the current heavy-flavour production cross-section (since $\sqrt{s}$: 8$\rightarrow$14 TeV)
- Still much room for new physics, higher precision required …
  $\longrightarrow$ LHCb Upgrade (see talk tomorrow).

Spare slides from here on

LHCb 2012 data-taking in numbers

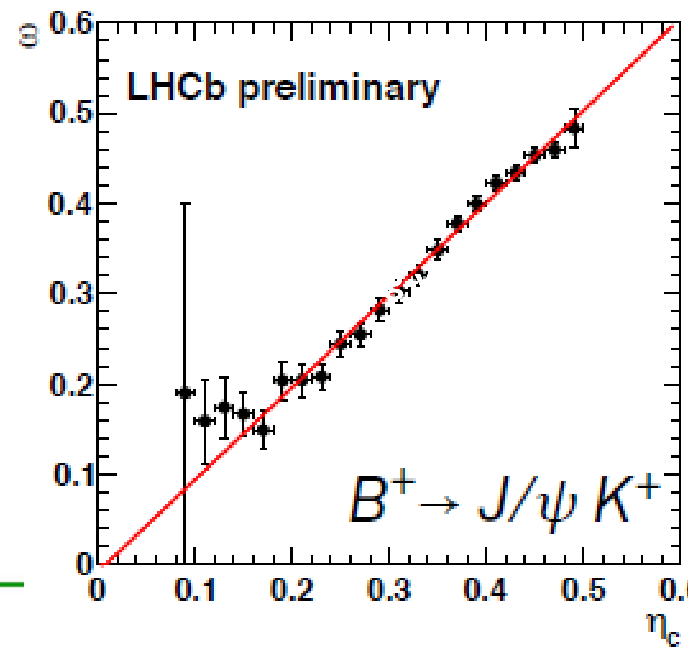
Quantity	Unit	TDR	2011	2012	2012/TDR
Peak Luminosity	$\mu b^{-1}/s$	280	400	400	142%
Average Luminosity	$\mu b^{-1}/s$	200	265	390	195%
Seconds of running t	$10^7 s$	1	0.46	0.63	63%
Integrated lumi $\int Ldt$	fb^{-1}	2.0	1.2	2.1	105%
Bunches		2600	1300	1300	50%
CM energy	TeV	14	7	8	57%
Inelastic cross sec σ_{inel}	mb	80	64	67	84%
bb(bar) cross sec $\sigma_{bb(bar)}$	μb	500	284	~330	58%
pp interactions/BeamX		0.55	1.15	1.65	272%
Average min bias rate	MHz	16	17	22	131%
bb(bar) yield: $\sigma_{bb(bar)}\int Ldt$	10^{12}	1	0.35	0.63	63%
HLT rate λ_{HLT}	kHz	2	2.45	4.1	205%
Stored events λ_{HLT} t	10^9	20	11	26	130%

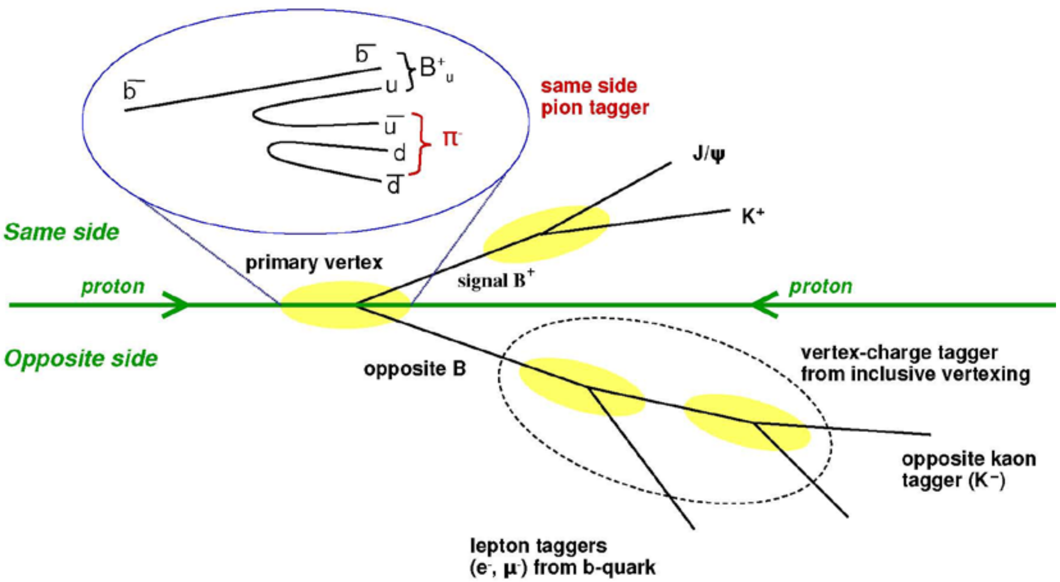
Flavour tagging

- Tagging of production flavour (B or $\overline{B}$) important for mixing and CP analyses. Performance calibrated using control channels such as $B^+ \to J/\psi K^+$
- Current opposite side tagging power:

$$\varepsilon\,(1-w)^2 = (2.10 \pm 0.08 \pm 0.24)\%$$

European Physical Journal C 72 (2012) 1-16

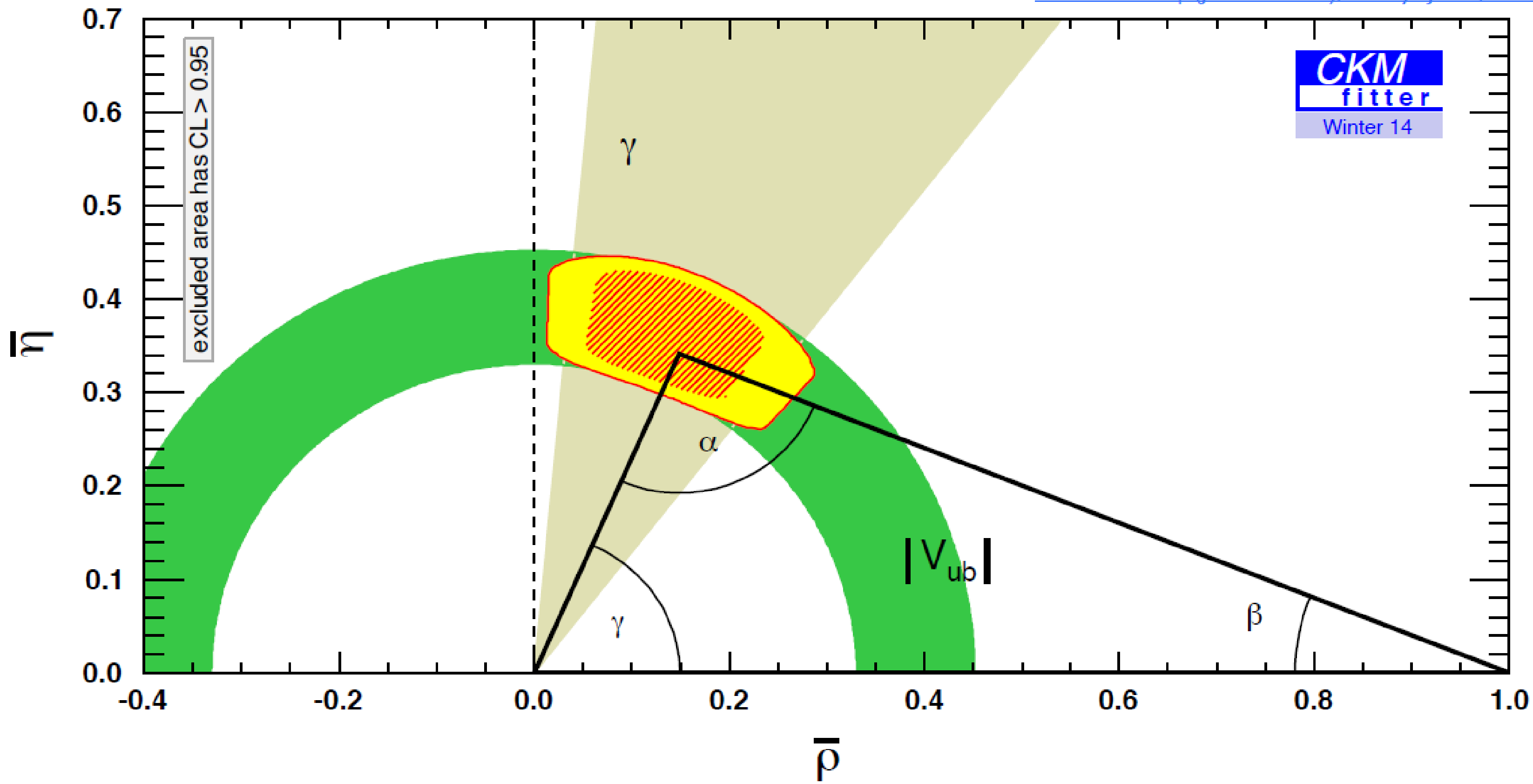




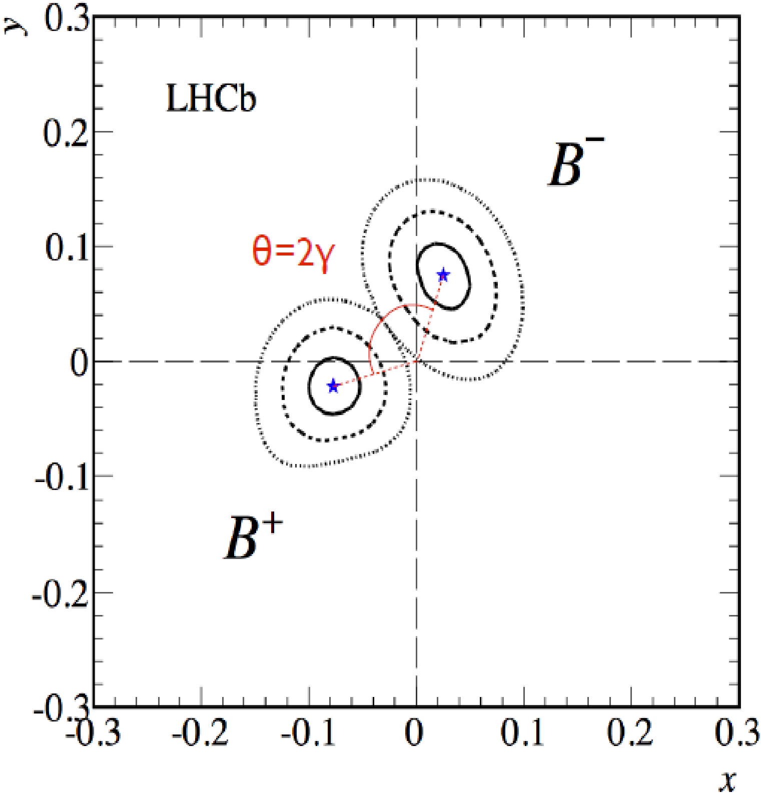
Constraints from tree level quantities

- γ is the only angle directly accessible in tree decays
- "Standard Model" measurement possible
- Direct measurements (all results combined): 70.0 +7.7 -9.9 degrees
- Indirect precision from global CKM fit: 66.5 +1.3 -2.5 degrees

CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005)



3 fb^{-1} γ analysis of the self-conjugate final states



$$N_i^{\pm} = h\left(K_{\pm i} + r_B^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}\left[x_{\pm} c_i \pm y_{\pm} s_i\right]\right)$$

- $N_i^{\pm}$: D from $B^{\pm}$ events in bin *i* of Dalitz plot
- K: Fraction of events in bin for pure D^0 sample with the efficiency profile of signal
- $x_{\pm} = r_B \cos(\delta_B \pm \gamma)$
- $y_{\pm} = r_B \sin(\delta_B \pm \gamma)$

$$\gamma = (62\,^{+15}_{-14})^{\circ}$$

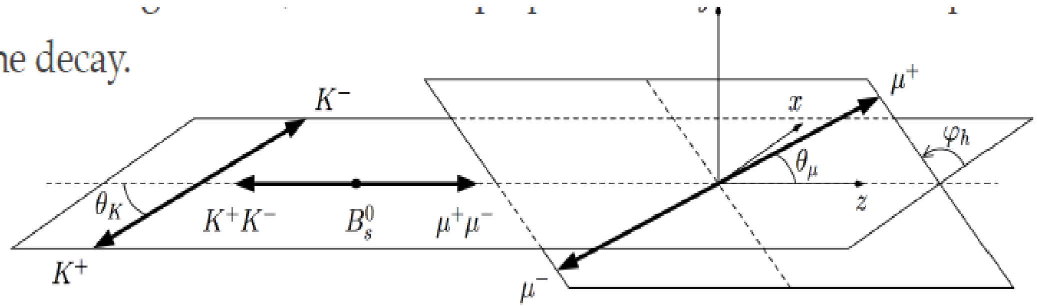
Result is as precise as either B-factory final result

Soon to be combined with new ADS/GLW analyses to form a world-leading sub-10° measurement

LHCb upgrade (2020-2027) will reduce experimental error to ~1°

Parameterization for phi_s fit

Three angles characterise the decay.



- Non-negligible $Bs \to J/\psi KK$ is selected in with $Bs \to J/\psi\phi$ and is included. This swells the list of terms to 10

$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega) \qquad h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right],$$

k	$f_k(\theta_\mu, \theta_K, \varphi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\lvert A_0\rvert^2$	1	D	C	$-S$
2	$\sin^2\theta_K\left(1-\sin^2\theta_\mu \cos^2\varphi_h\right)$	$\lvert A_\parallel\rvert^2$	1	D	C	$-S$
3	$\sin^2\theta_K\left(1-\sin^2\theta_\mu \sin^2\varphi_h\right)$	$\lvert A_\perp\rvert^2$	1	$-D$	C	S
4	$\sin^2\theta_K \sin^2\theta_\mu \sin 2\varphi_h$	$\lvert A_\parallel A_\perp\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \cos\varphi_h$	$\lvert A_0 A_\parallel\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \sin\varphi_h$	$\lvert A_0 A_\perp\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\lvert A_S\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \cos\varphi_h$	$\lvert A_S A_\parallel\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \sin\varphi_h$	$\lvert A_S A_\perp\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K \sin^2\theta_\mu$	$\lvert A_S A_0\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

$$S \equiv -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}, \qquad D \equiv -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2}$$

$$C \equiv \frac{1-|\lambda|^2}{1+|\lambda|^2} \qquad \lambda_i \equiv \frac{q}{p}\frac{\bar{A}_i}{A_i}$$

$$\lambda_i = \eta_i \lambda \qquad \begin{array}{l} \eta_i = +1 \text{ for } i \in \{0, \parallel\} \\ \eta_i = -1 \text{ for } i \in \{\perp, S\} \end{array}$$

The sign of $\Delta\Gamma_s$

PRL 108 (2012) 241801

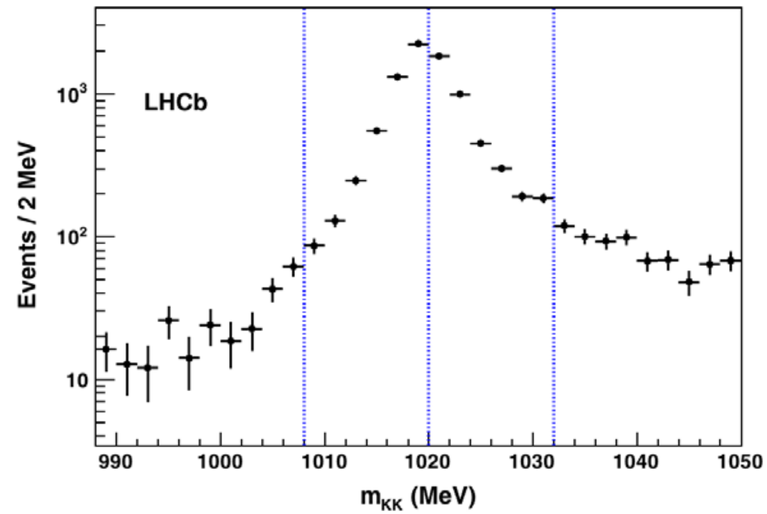
- To resolve ambiguity
  $(\phi_s, \Delta\Gamma_s, \delta_{||}, \delta_{\perp}) \leftrightarrow (\pi-\phi_s, -\Delta\Gamma_s, 2\pi-\delta_{||}, -\delta_{\perp})$
  study strong phase difference $\delta_{s\perp} = \delta_s - \delta_{\perp}$
  between K^+K^- P-wave and S-wave amplitudes
  as a function of $m(K^+K^-)$ around the $\phi(1020)$

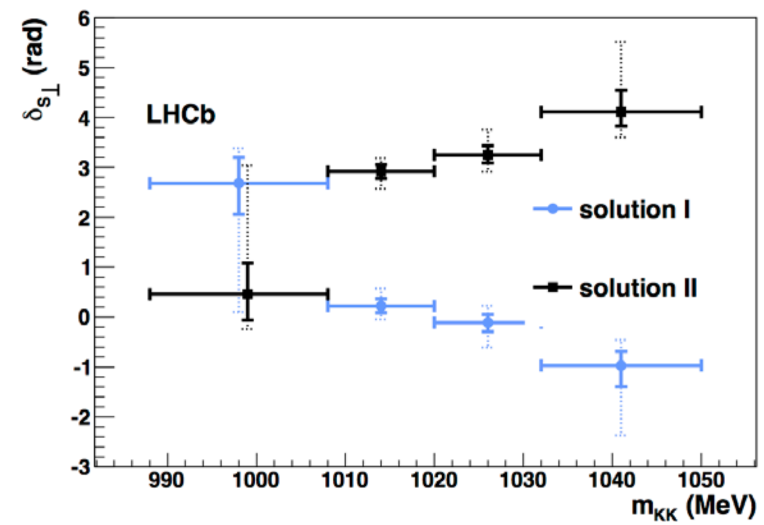
- P-wave: $\phi(1020)$, going through resonance
  $\rightarrow$ expect rapid positive phase shift

  - S-wave: non-resonant and tail from $f_0(980)$
    $\rightarrow$ expect no fast variation of phase

- Analysis based on 0.37 fb^{-1}

  - Determine $\delta_{s\perp}$ in four K^+K^- mass bins





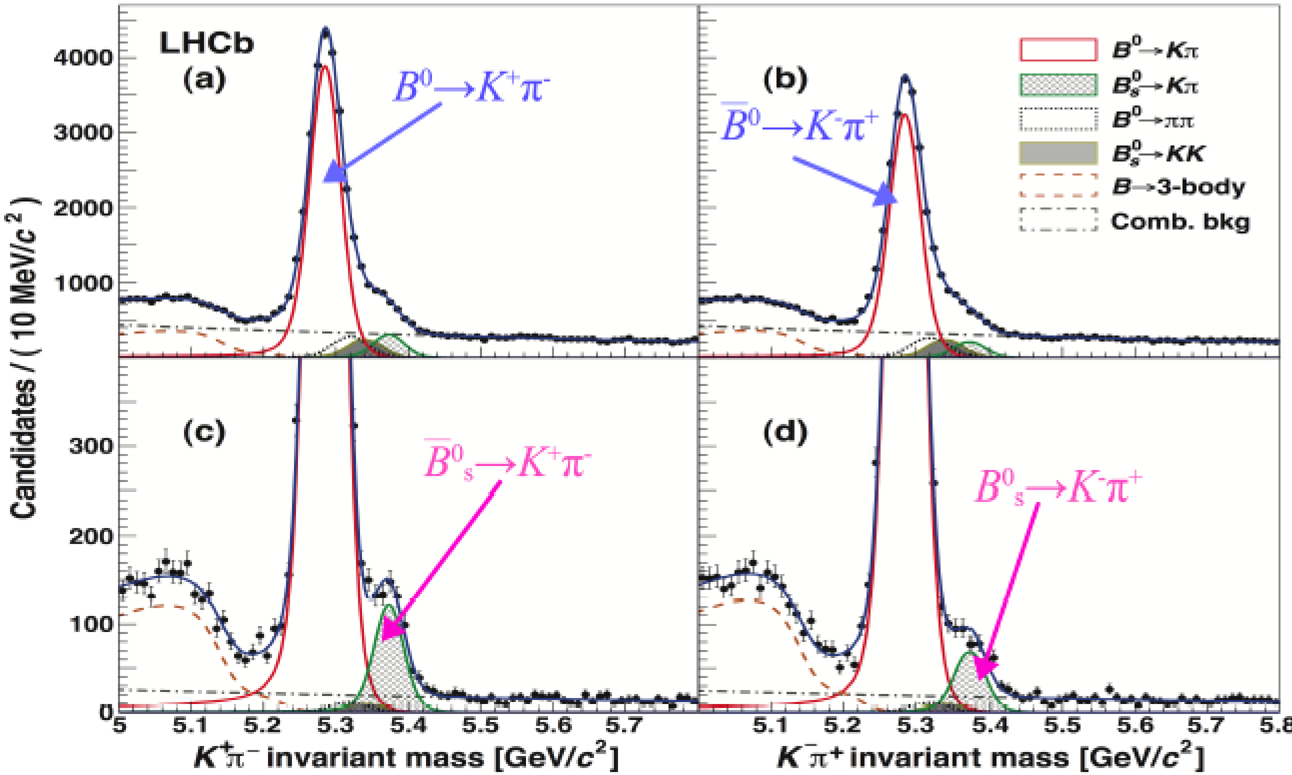
Solution corresponding to $\Delta\Gamma_s > 0$
preferred with 4.7σ significance

CP violation in $B \to K\pi$ and $B_s \to K\pi$

$$A_{CP}(B^0 \to K\pi) = \frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$

$$A_{CP}(B_s^0 \to \pi K) = \frac{\Gamma(\bar{B}_s^0 \to \pi^- K^+) - \Gamma(B_s^0 \to \pi^+ K^-)}{\Gamma(\bar{B}_s^0 \to \pi^- K^+) + \Gamma(B_s^0 \to \pi^+ K^-)}$$

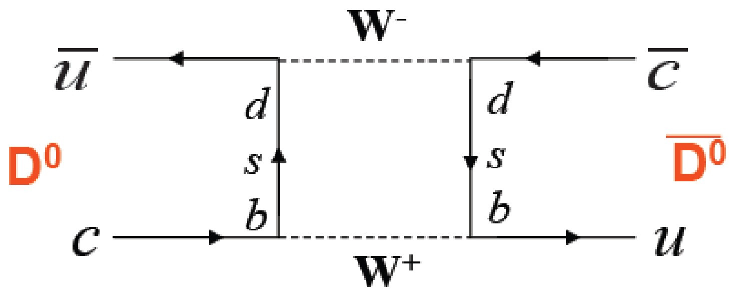
- Using 1/fb (2011) @ $\sqrt{s}$ = 7 TeV.

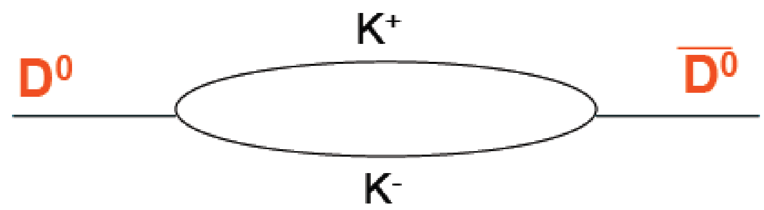


- $\mathcal{A}_{CP}(B^0)$ = -0.080 ± 0.007 ± 0.003 (most precise measurement, 10.5σ)
- $\mathcal{A}_{CP}(B^0_s)$ = -0.27 ± 0.04 ± 0.01 (first observation of CPV in B^0_s decays, 6.5σ)

PRL 110, 221601 (2013)

Charm mixing formulism





mass difference *x*:

$$x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma}$$

decay width difference *y*:

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

In the limit of small mixing |x|,|y| << 1 and assuming negligible CPV:

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D} y' t + \frac{x'^2 + y'^2}{4} t^2$$

the ratio of DCS to CF decay rates

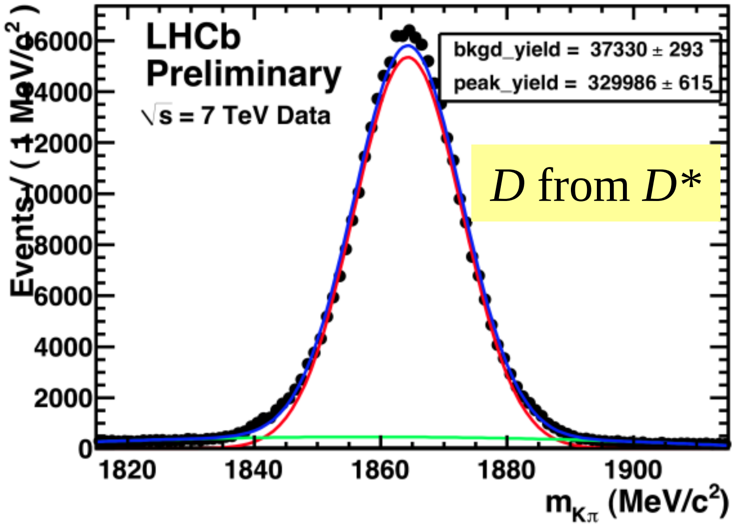
the interference of the DCS and mixed decays

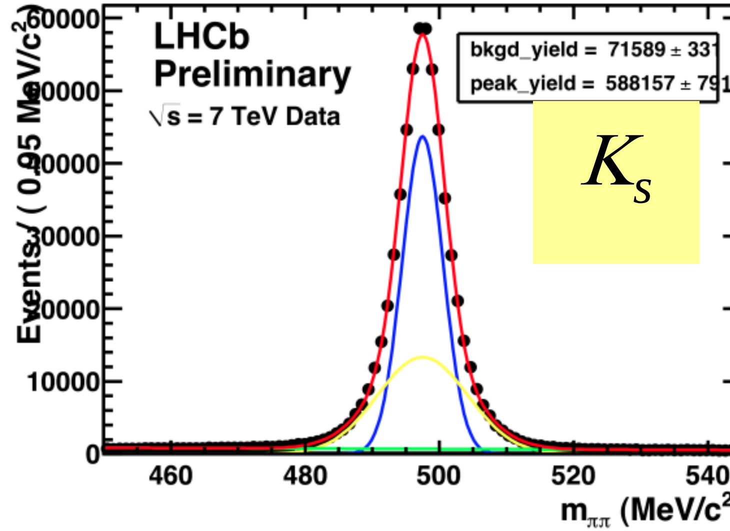
mixing parameters

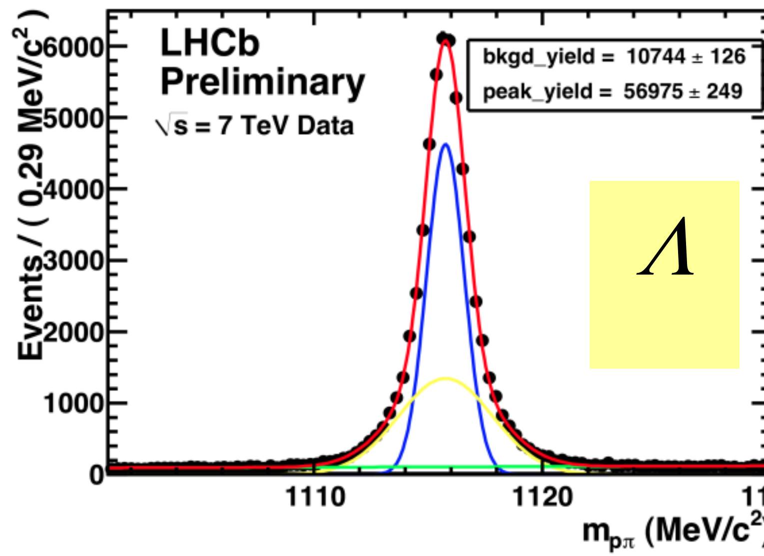
$$x' = x\cos\delta + y\sin\delta \qquad y' = y\cos\delta - x\sin\delta$$

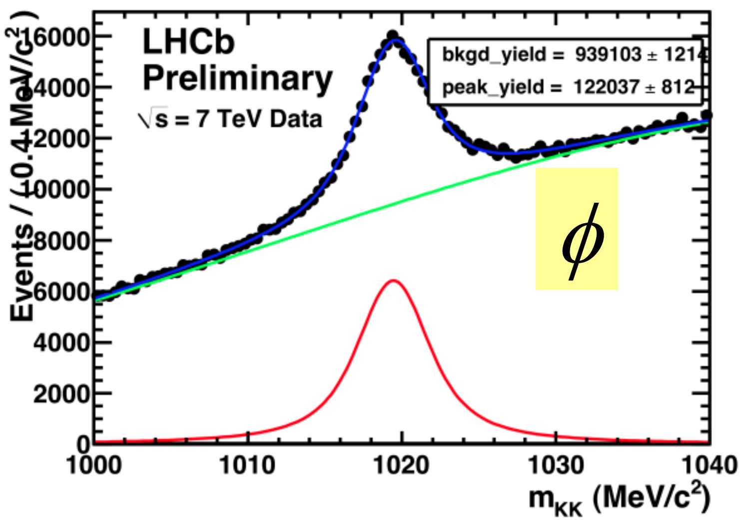
δ is a strong phase difference between DCS and CF amplitudes

PID calibration samples







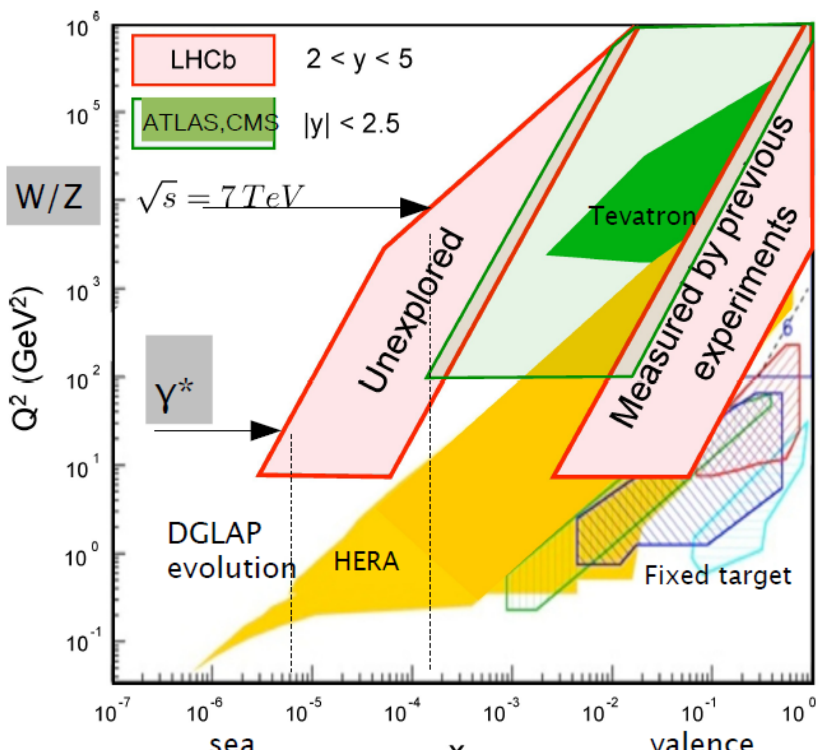


- Impressive calibration purity → samples allow F
calibrations in efficiency and purity to be evalua
with data

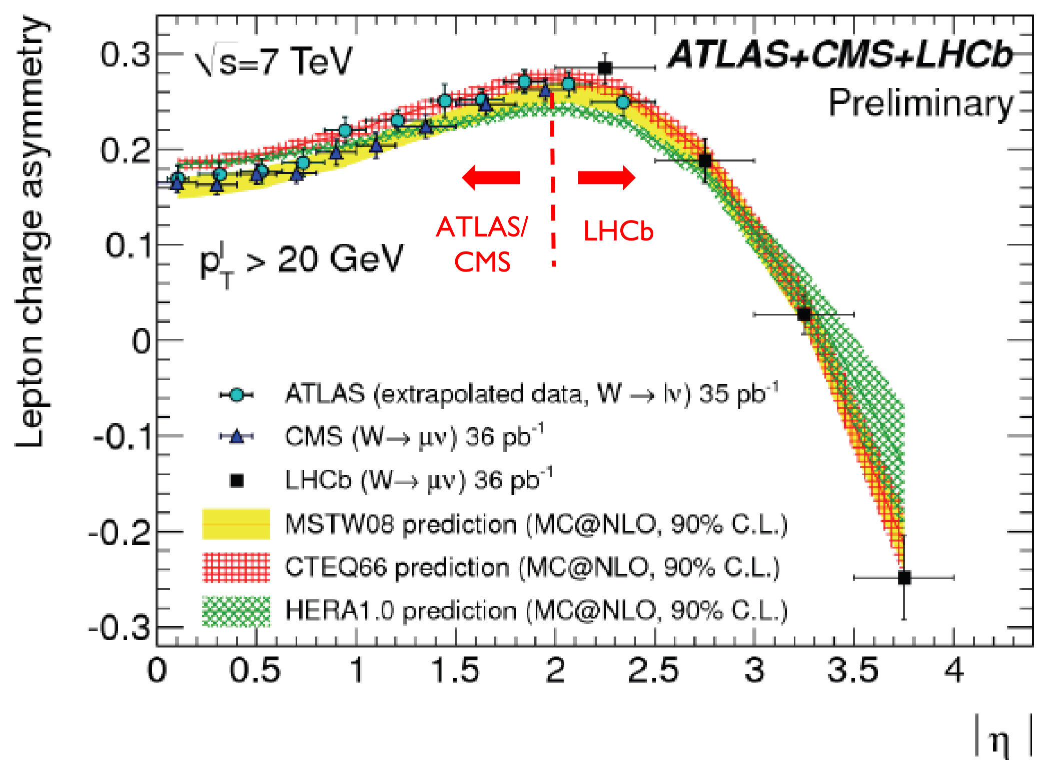
W/Z production

LHCb's unique forward and low p_T acceptance equips it to perform EW / QCD measurements which are highly complementary to those of mid-rapididty GPDs

Unique kinematical acceptance



Studies of W/Z production [JHEP 6 (2012) 58] alongside ATLAS/CMS gives complete picture

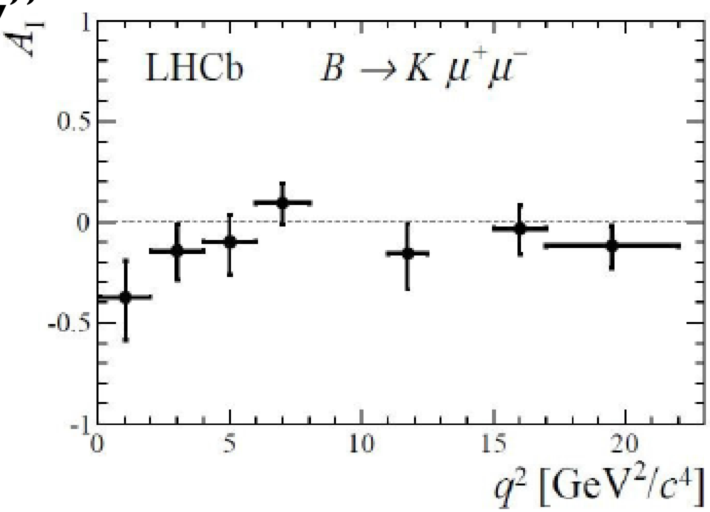


Isospin asymmetry in $B^0 \to K^{0(*)}\mu^+\mu^-$

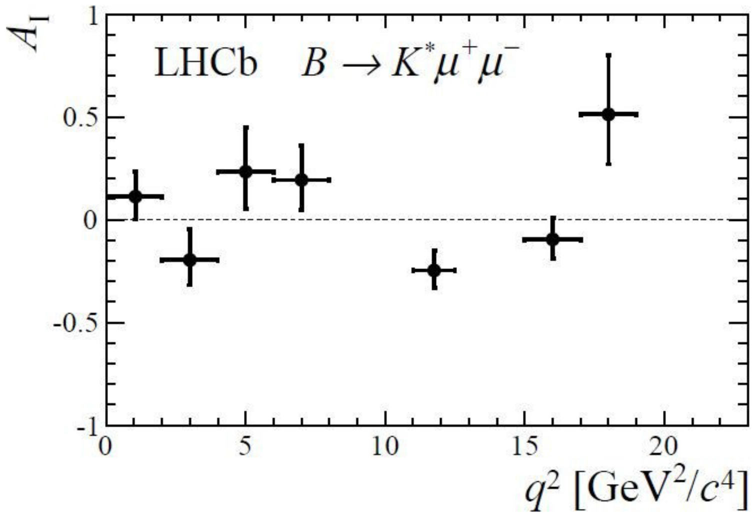
arXiv:1403.8044

- LHCb measure "isospin asymmetry"

$$\frac{\Gamma(B^0\to K^0\mu^+\mu^-)-\Gamma(B^+\to K^+\mu^+\mu^-)}{\Gamma(B^0\to K^0\mu^+\mu^-)+\Gamma(B^+\to K^+\mu^+\mu^-)}$$



- Expected to be ~zero in SM
- Significant had emerged (4.6σ from zero) in early K^0 data not in K^*). JHEP 7 (2012) 133
- With full 3 fb^{-1} data set the isospin asymmetry is compatible with zero at the 1.5σ level



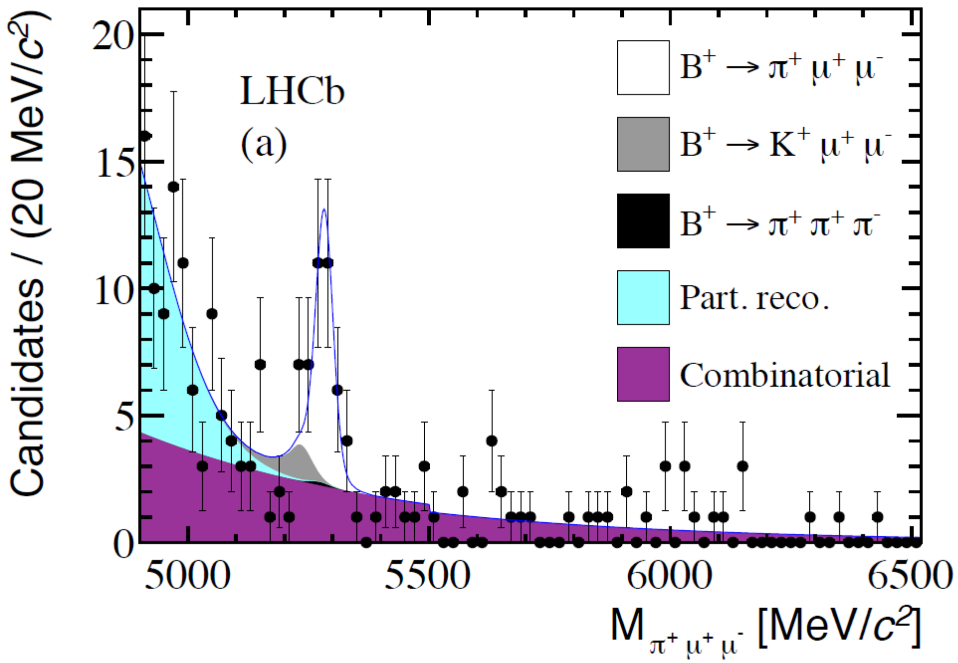
$B^+ \rightarrow \pi^+\mu^+\mu^-$ rare penguin decay

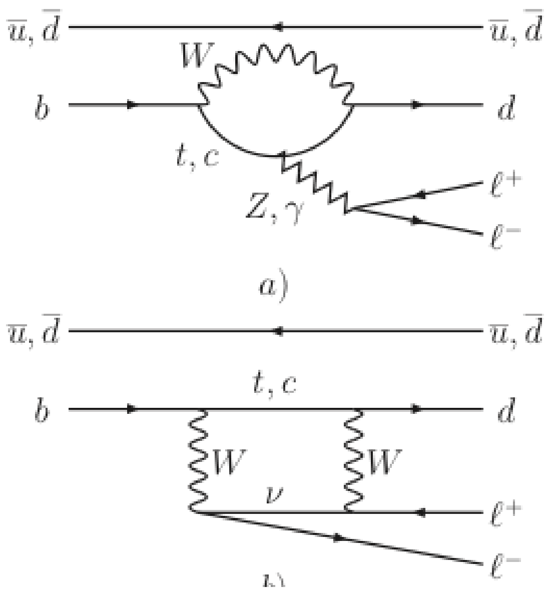
- $B^+ \rightarrow \pi^+\mu^+\mu^-$

  First observation – (rarest B decay ever observed that has >5σ significance)

JHEP 12 (2012) 125

25±6 events
5.2 σ significance





- SM prediction: $(2.0 \pm 0.2)\times10^{-8}$

PRD77 (2008) 014017

- BR measured

  $(2.4\pm0.6\pm0.2)\ 10^{-8}$

CP-violating asymmetry a^s_{sl} in B_s decays

- CPV in mixing $P(B \to \bar{B}) \neq P(\bar{B} \to B)$
- First step to resolving the issue of the D0 di-muon asymmetry anomaly.

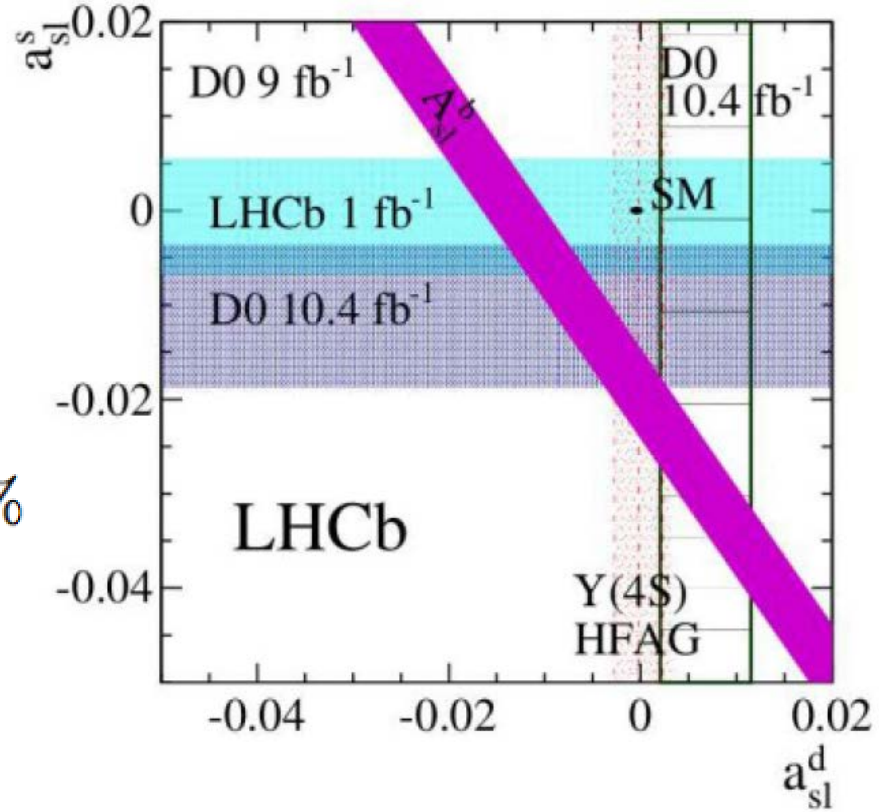
Phys. Rev. D 84, 052007 (2011), Phys. Rev. D 86, 072009 (2012)

- LHCb 1 fb^{-1} result for a^s_{sl}

$$a^s_{sl} \equiv \frac{\Gamma(B^0_s \to D^-_s \mu^+) - \Gamma(\overline{B}^0_s \to D^+_s \mu^-)}{\Gamma(B^0_s \to D^-_s \mu^+) + \Gamma(\overline{B}^0_s \to D^+_s \mu^-)}$$

$$a^s_{sl}[\text{LHCb}] = (-0.06 \pm 0.50 \pm 0.36)\%$$

arxiv: 1308.1048



- D0 result not confirmed nor ruled out.

Standard Model predictions

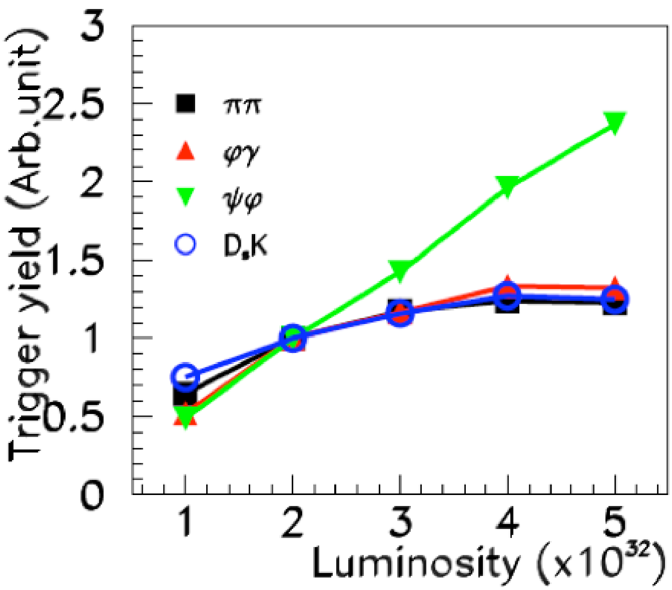
$$a^s_{sl} = (1.9 \pm 0.3) \times 10^{-5}$$

$$a^d_{sl} = (-4.1 \pm 0.6) \times 10^{-4}$$

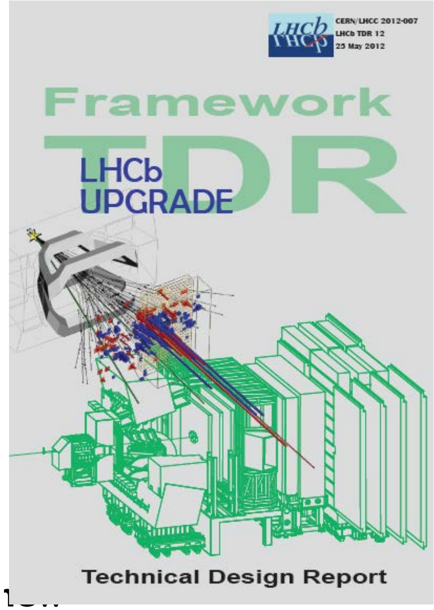
A.Lenz arXiv:1205.1444

Outlook: LHCb Upgrade

- Main limitation that prevents exploiting higher luminosity is the Level-0 (hardware) trigger
- To keep output rate < 1 MHz requires raising thresholds → hadronic yields reach plateau
- Proposed upgrade is to *remove* hardware trigger: read out detector at 40 MHz (bunch crossing rate). Trigger fully in software in CPU farm. Requires replacing all front-end electronics
- Will allow to increase luminosity by factor ~ 10 to 1–2 × 10^{33} cm^{-2} s^{-1}
- TDRs being approved by CERN : Physics case enthusiastically endorsed, detector R&D underway



Upgrade of LHCb detector planned for 2019 to take at least 10× more data: 50 fb^{-1}



Upgrade sensitivities 50 fb^{-1}

LHCb-PUB-2012-009

Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s$ $(B_s^0 \to J/\psi\ \phi)$	0.10 [24]	0.025	0.008	~ 0.003
	$2\beta_s$ $(B_s^0 \to J/\psi\ f_0(980))$	0.17 [26]	0.045	0.014	~ 0.01
	$A_{\rm fs}(B_s^0)$	6.4×10^{-3} [41]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [41]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [42]	0.025	0.008	0.02
	$s_0\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [42]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [9]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [43]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [4]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ $(B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [28, 29]	4°	0.9°	negligible
	γ $(B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	β $(B^0 \to J/\psi\ K_S^0)$	0.8° [41]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [41]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [8]	0.65×10^{-3}	0.12×10^{-3}	–

LHC(b) Long Term Plan

$\int L\,dt$

2009 — ✧ LHC startup, $\sqrt{s}$ = 900 GeV

2010–2012 (50ns) — √ $\sqrt{s}$=7/8TeV; L_{LHCb}= 3-4x10^{32} cm^{-2}s^{-1}
→ ~1.5fb^{-1}/year

~20-25 fb^{-1}

3/fb

2013–2014 (LS1) — Go LHCb first infrastructure for Upgrade

2015–2017 (25ns) — $\sqrt{s}$=13/14TeV; L_{LHCb}= 4x10^{32} cm^{-2}s^{-1}
√s → 1.5-2fb^{-1}/year

5-7/fb

~75-100 fb

F. Bordry ... re - PM2012, La Biodola

2018 (LS2) — Inj LHCb Upgrade Installation

2019–2021 (25ns) — √ $\sqrt{s}$=14TeV; L_{LHCb}= 1-2x10^{33} cm^{-2}s^{-1}
→ >5fb^{-1}/year

50/fb

~350

2022 (LS3) — HL-LHC Phase-2 upgrade, IR, crab cavities?

2023 ... 2030? (?ns) — √ $\sqrt{s}$=14TeV; L_{LHCb}= ~2x10^{33} cm^{-2}s^{-1}

...000 fb^{-1}