Selected physics highlights from LHCb

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Outline

- The LHCb detector and running conditions
- Selected physics highlights:

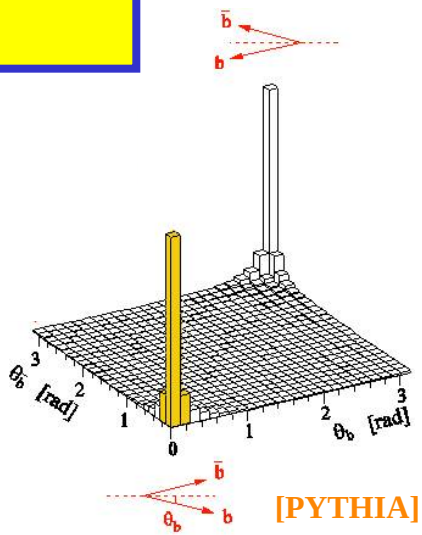
  Measurements based on 1 fb^{-1} (2011) and 2 fb^{-1} (2012) *pp* collision data at 7 & 8 TeV CM energy.

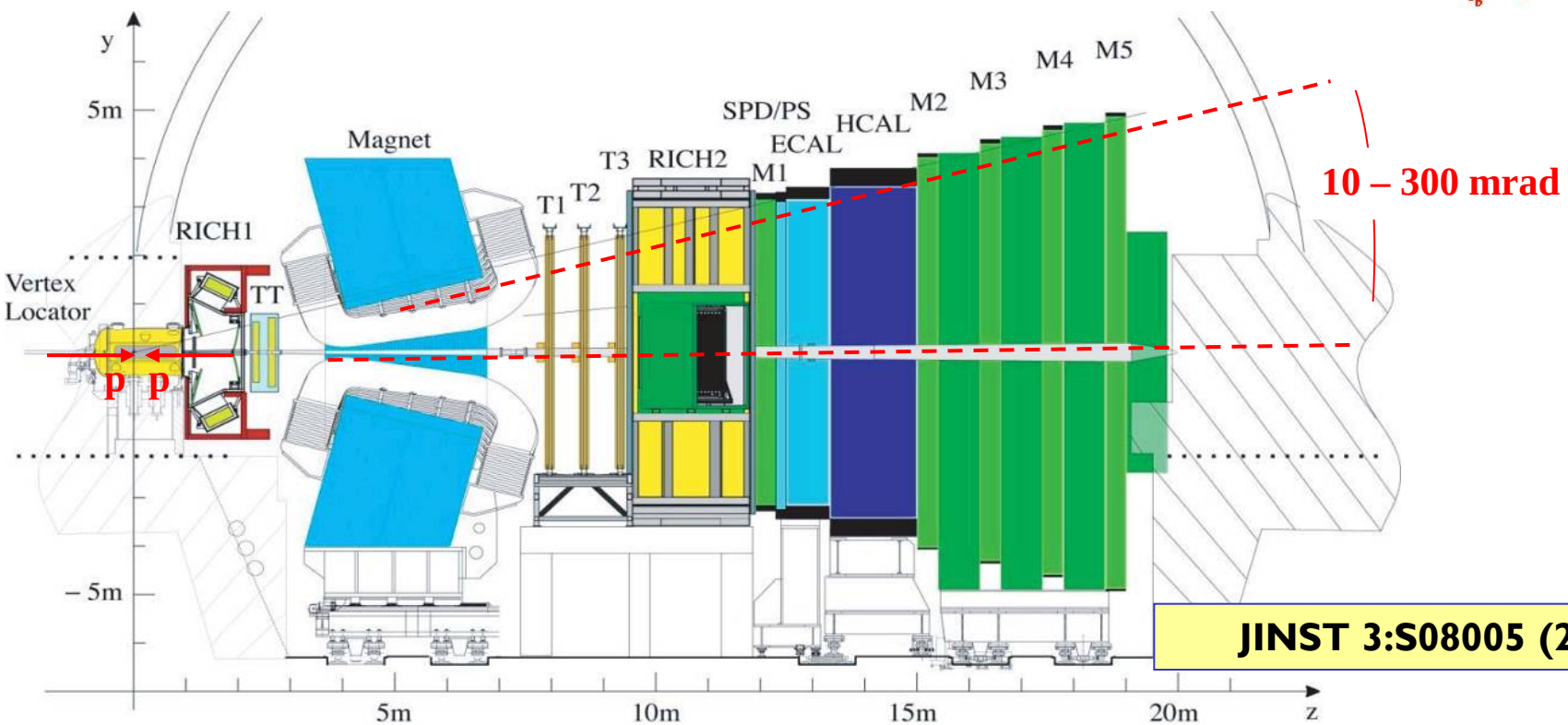
  - Parameters of the CKM matrix
  - Studies of CP violation in the B_s system
  - Mixing & CP violation in charm
  - Rare B decays (See also Fatima Soomro talk in parallel session)
  - New resonances
- Summary and Outlook

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)



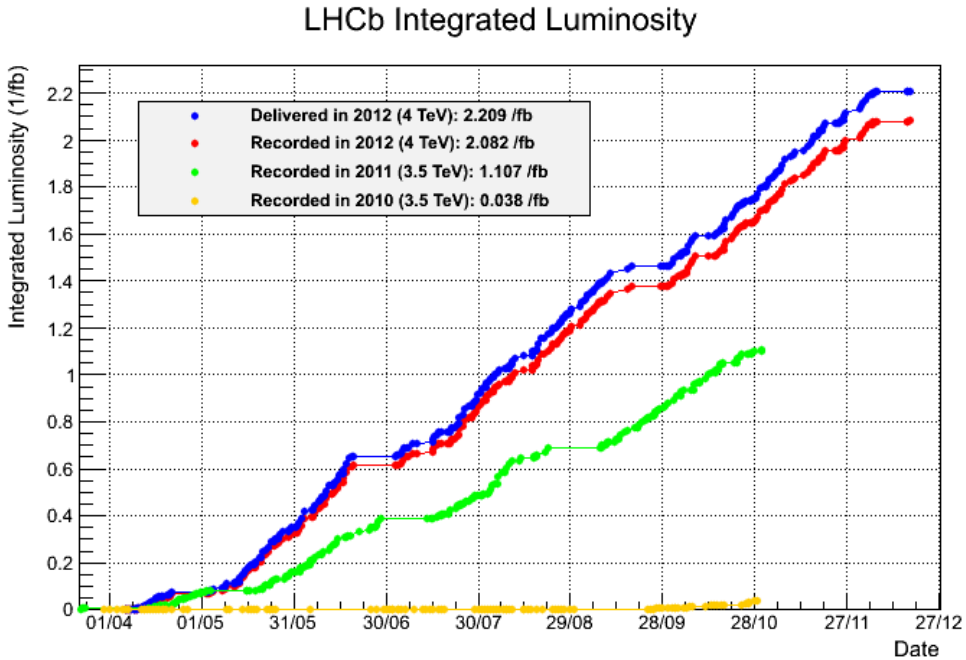


JINST 3:S08005 (2008)

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 : currently in long shutdown



Selected physics highlights

- Parameters of the CKM matrix

- Studies of CP violation in the B_s system

- Mixing & CP violation in charm

- Rare B decays

- New observed resonances

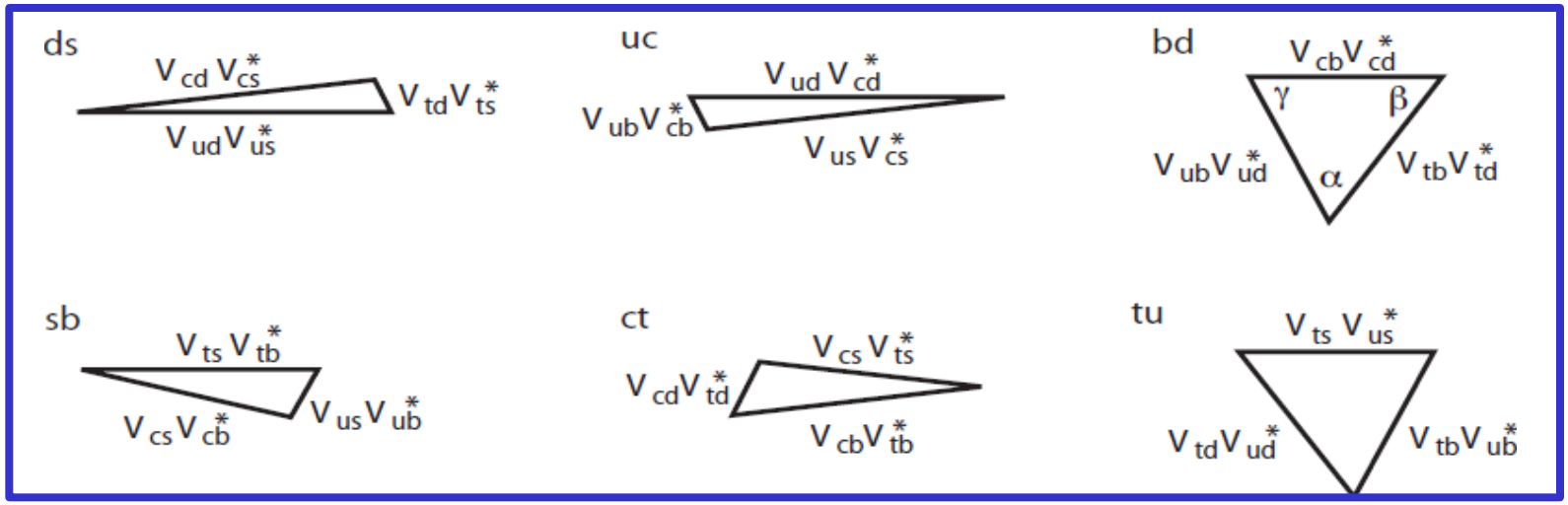
Quark mixing and CKM matrix

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

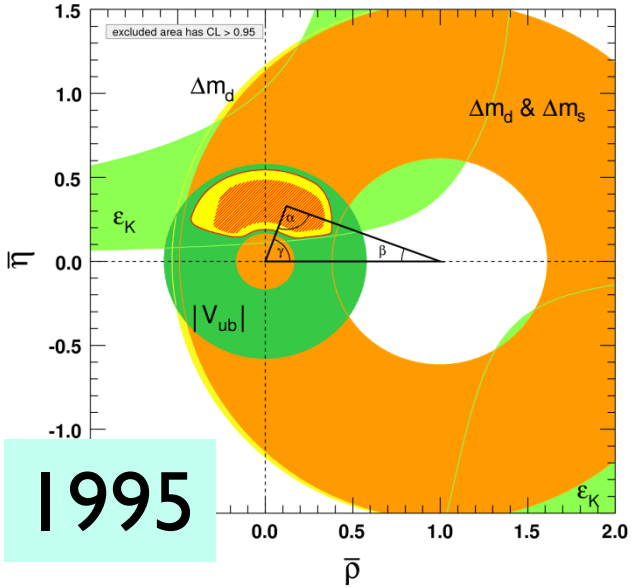
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

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

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



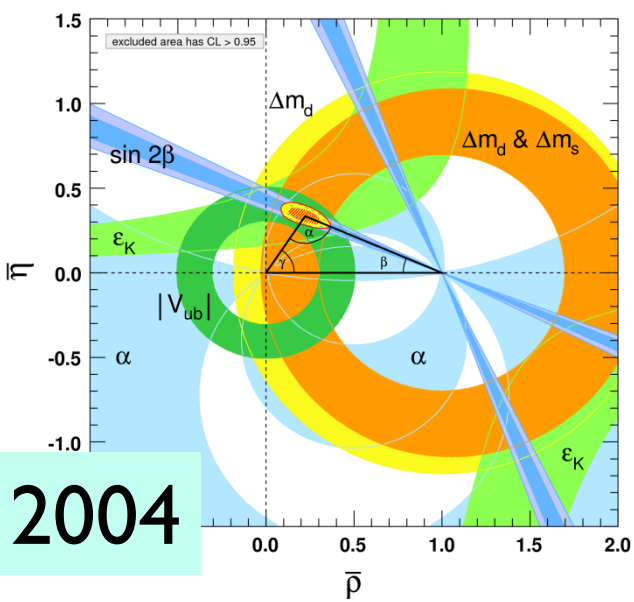
Unitarity triangle : CKM fitter



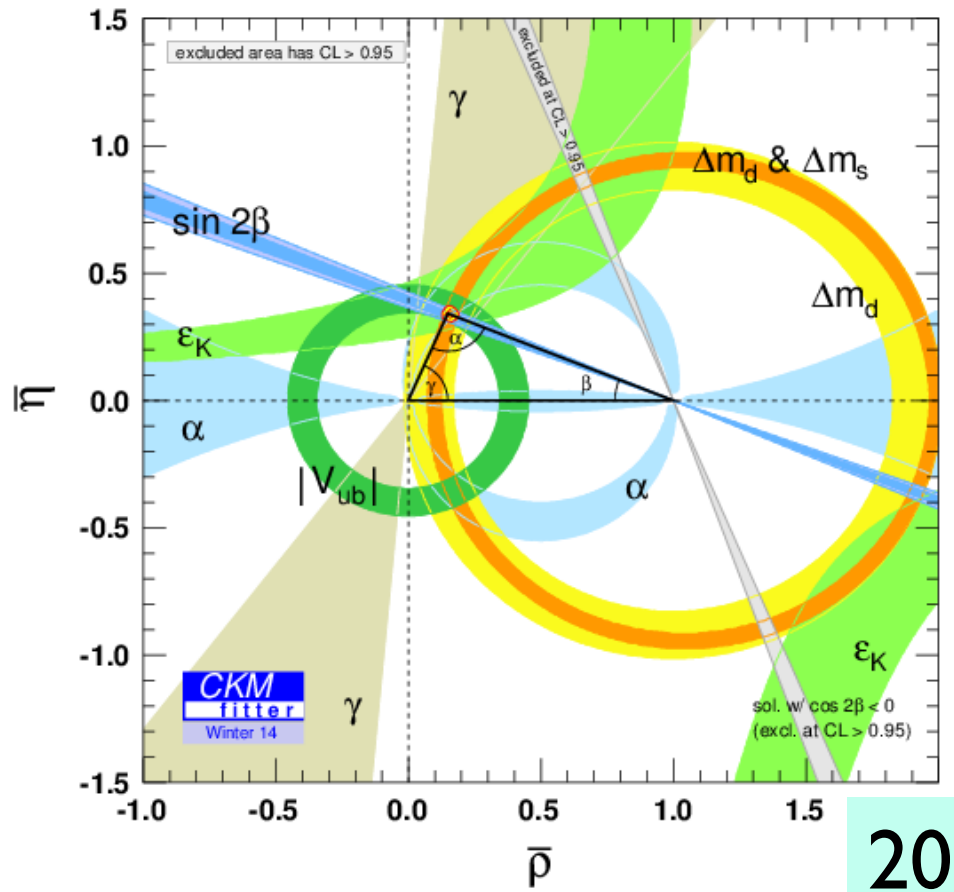
1995

- 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



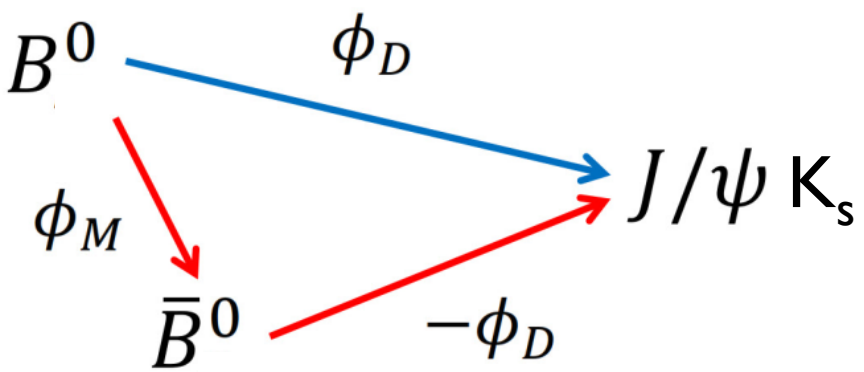
2004

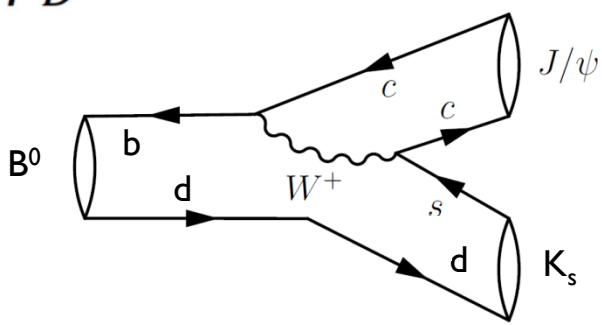


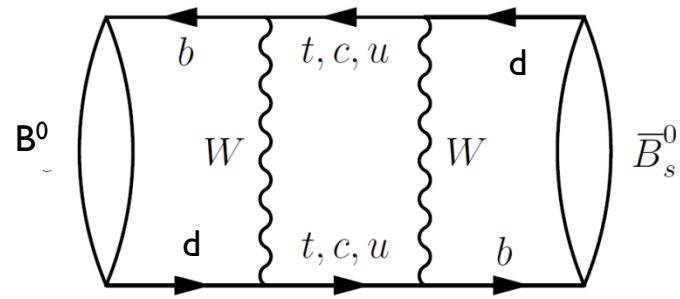
2014

.ondc

Measurement of angle β







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

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

LHCb sin(2β) measurement

sin(2β) from $B^0 \to J/\psi K^0_S$

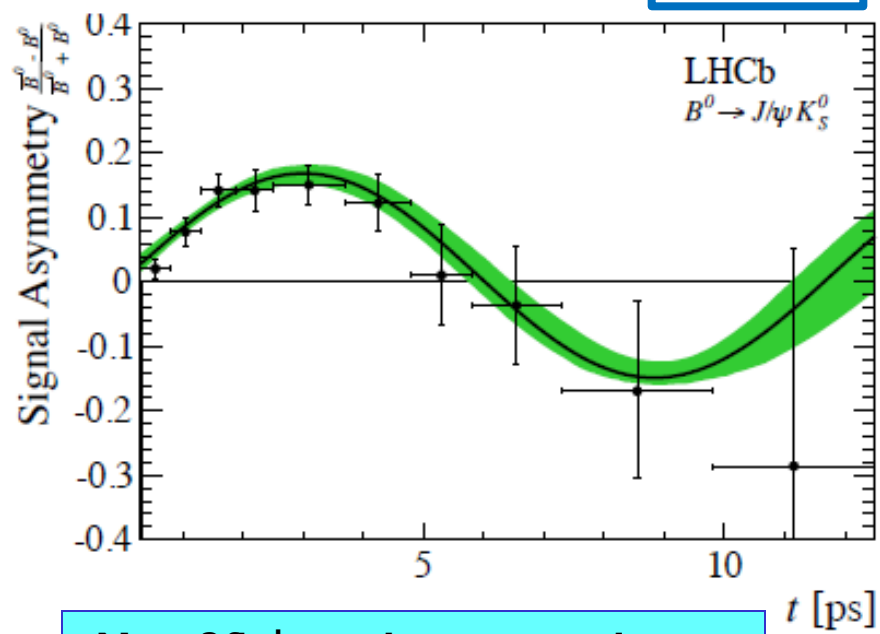
$$\mathcal{A}_{J/\psi K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)}$$
$$= S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t).$$

1 fb^{-1}

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

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

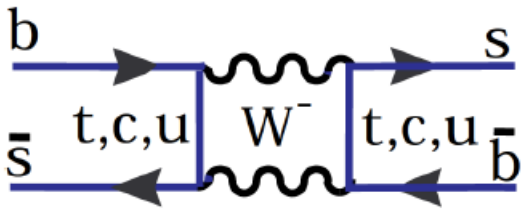
Phys.Lett B721 (2013) 24-31



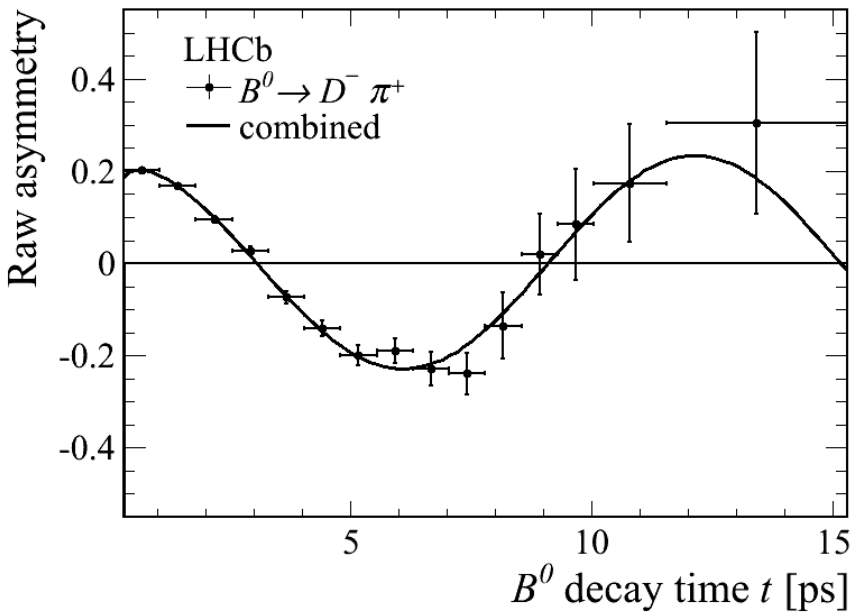
World average (Winter 2014) :
sin(2β) = 0.679 ± 0.020

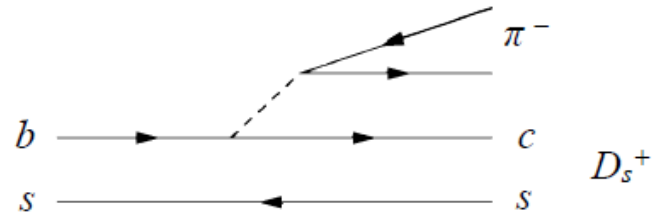
New 3fb^{-1} results expected soon with much improved precision

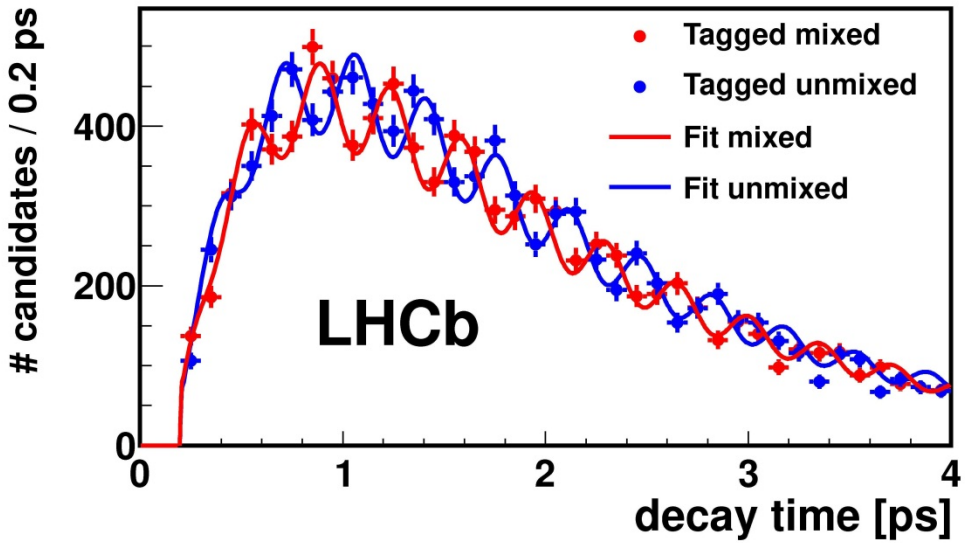
… and $B_{(s)}$ mixing



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







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

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

Phys.Lett B721 (2013) 24-31

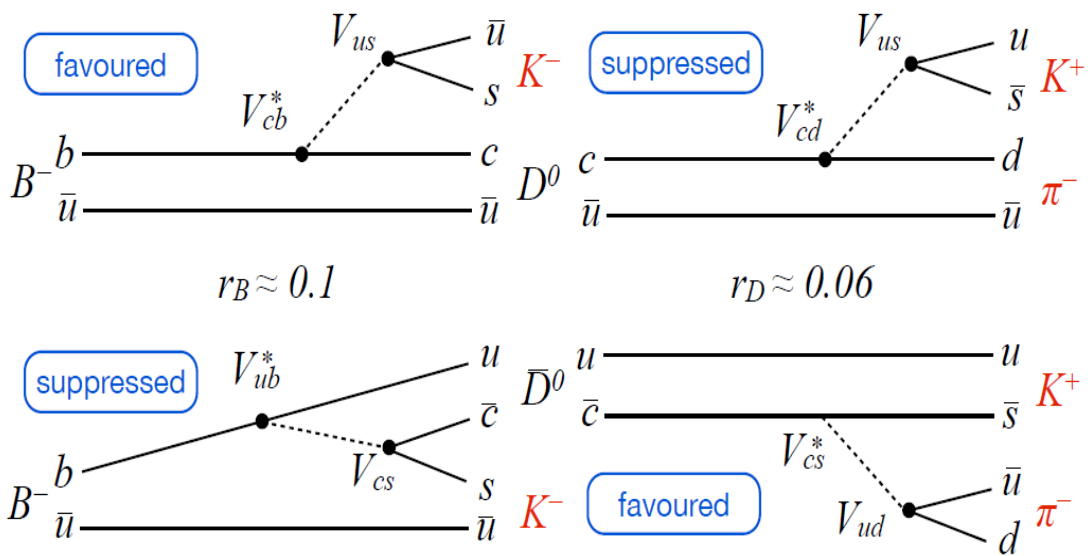
J. Phys. 15 (2013) 053021

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

- Four methods, comprising 14 $B^{\pm}$ decays included in a combined fit

- $B^{\pm} \to DK^{\pm}$, $D \to K_S^0 \pi^{\pm} \pi^{\mp}$ and $D \to K_S^0 K^{\pm} K^{\mp}$
- $B^{\pm} \to Dh^{\pm}$, $D \to \pi^{\pm} K^{\mp} \pi^{\pm} \pi^{\mp}$ and $D \to K^{\pm} \pi^{\mp} \pi^{\pm} \pi^{\mp}$
- $B^{\pm} \to Dh^{\pm}$, $D \to \pi^{\pm} K^{\mp}$ and $D \to K^{\pm} \pi^{\mp}$
- $B^{\pm} \to Dh^{\pm}$, $D \to K^{\pm} K^{\mp}$ and $D \to \pi^{\pm} \pi^{\mp}$

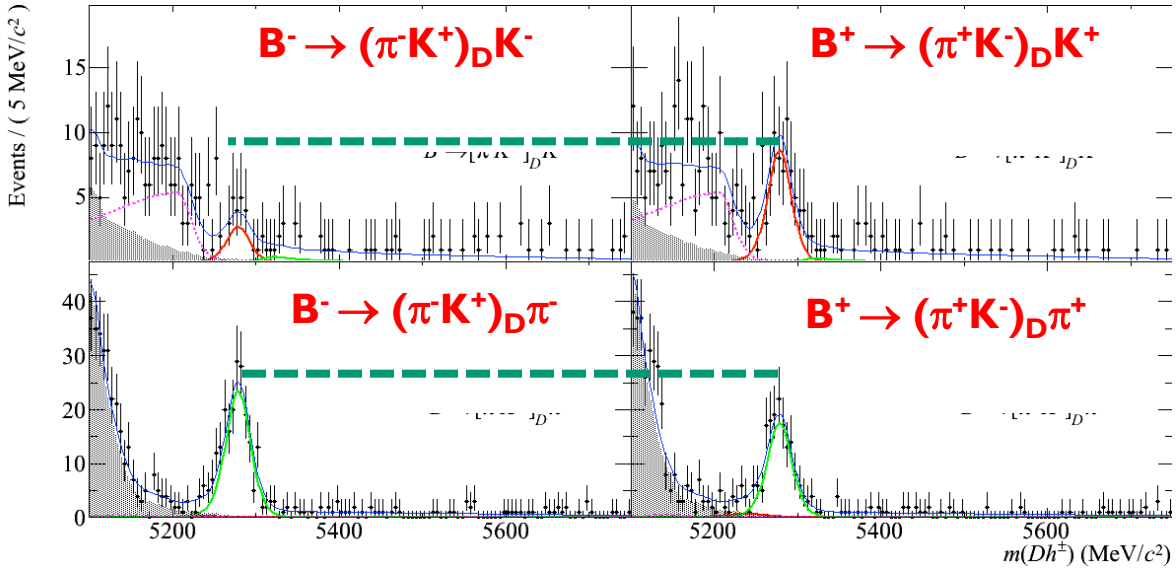
"GGSZ"	JHEP 10 (2014) 097
"K3π" :	PLB 712 (2012) 203
"ADS"	Phys Lett B712 (2012) 203
"GLW"	Phys Lett B712 (2012) 203



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

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

Phys Lett B712 (2012) 203



ADS modes

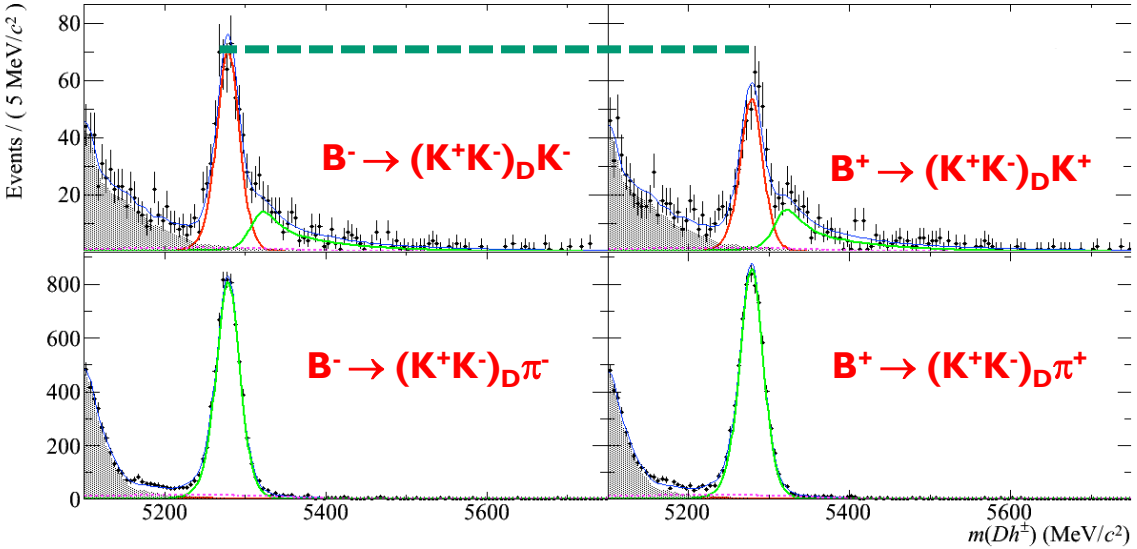
$A_{ADS}(K) = (-52 \pm 15 \pm 2)\%$

$A_{ADS}(\pi) = (14.3 \pm 6.2 \pm 1.1)\%$

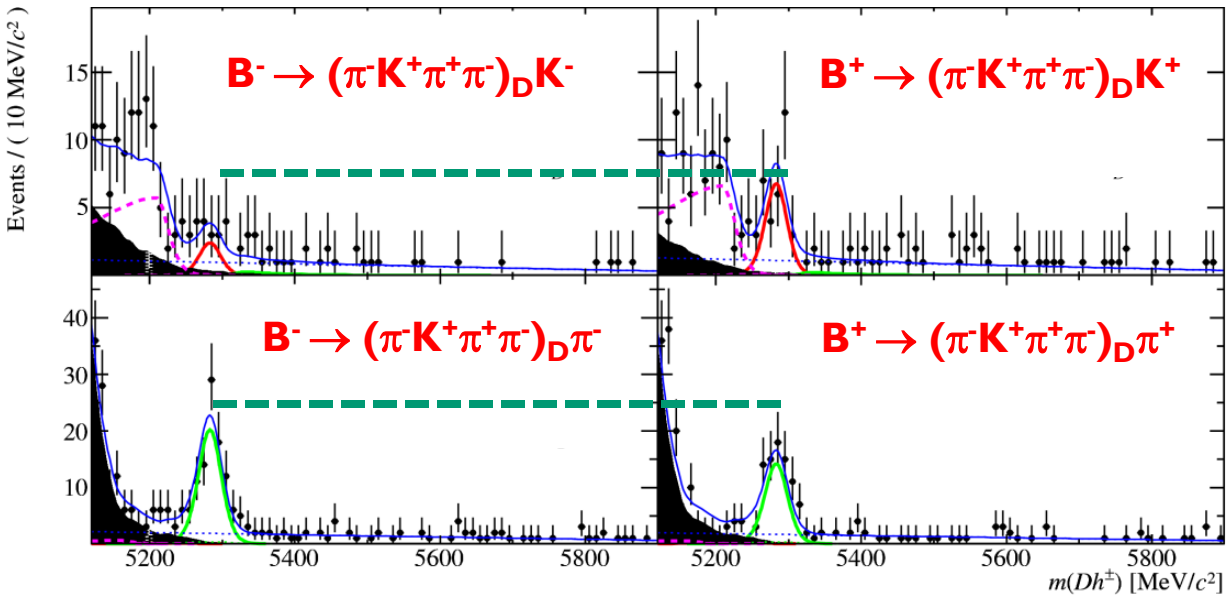
1 fb^{-1}, 7 TeV data

GLW modes

$A_{GLW} = (14.5 \pm 3.2 \pm 1.0)\%$



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



K(3π) modes

1 fb^{-1}

PLB 712 (2012) 203

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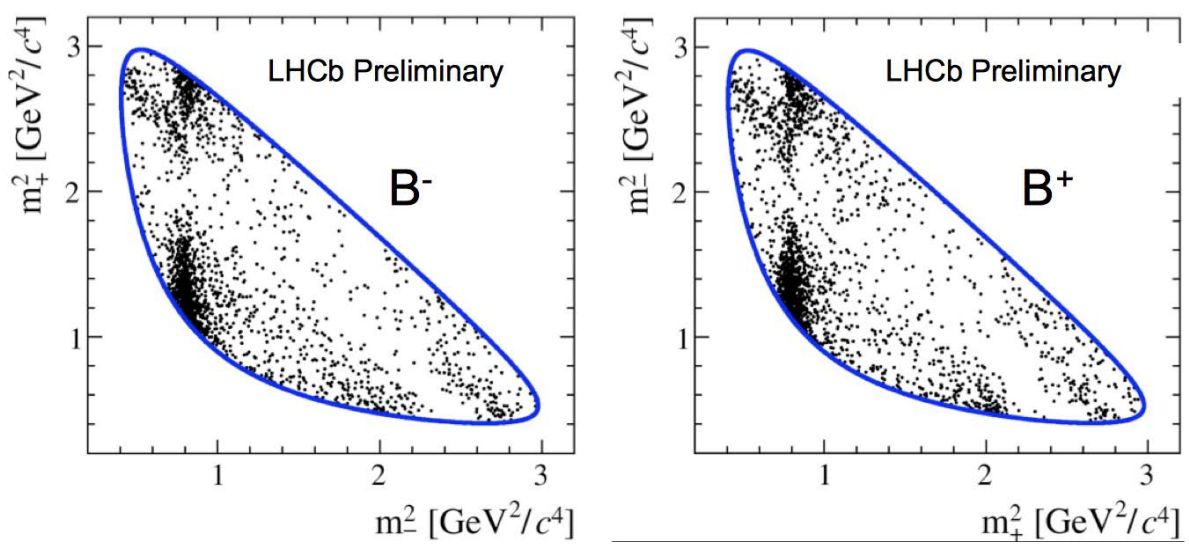
GGSZ mode

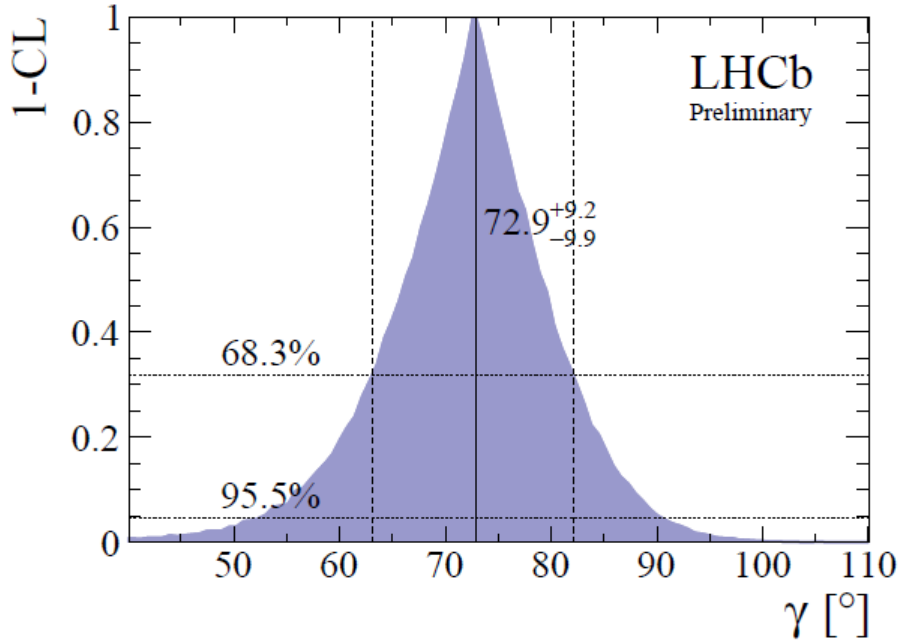
$(K_S\pi^+\pi^-)_D$

3 fb^{-1}



$B^{\pm} \to DK^{\pm}$ γ measurement

LHCb-CONF-2014-004



LHCb combined

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

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

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

Combined: $\gamma = (72.9^{+9.2}_{-9.9})^{\circ}$

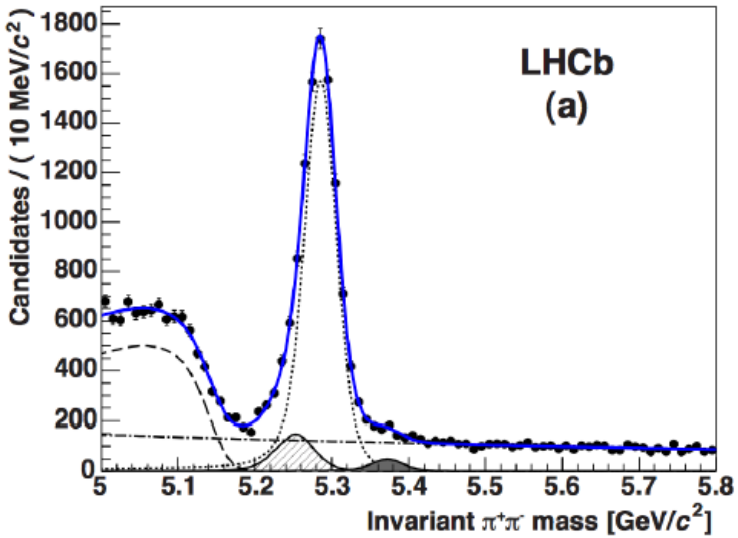
- Compare :

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

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

- Indirect γ value from global CKM fit: $\gamma = (66.5^{+1.3}_{-2.5})^{\circ}$

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

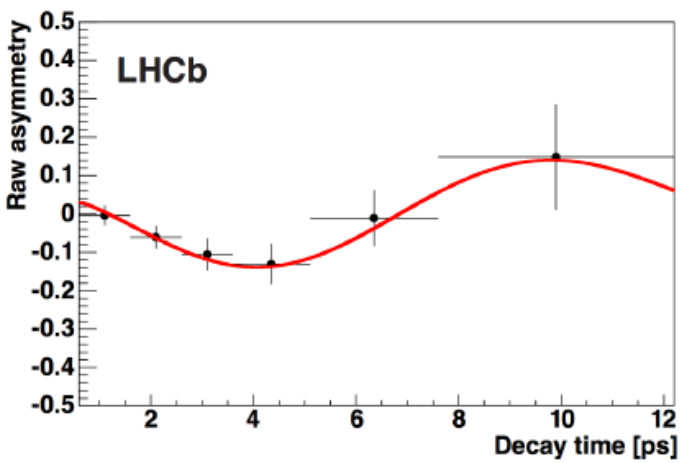


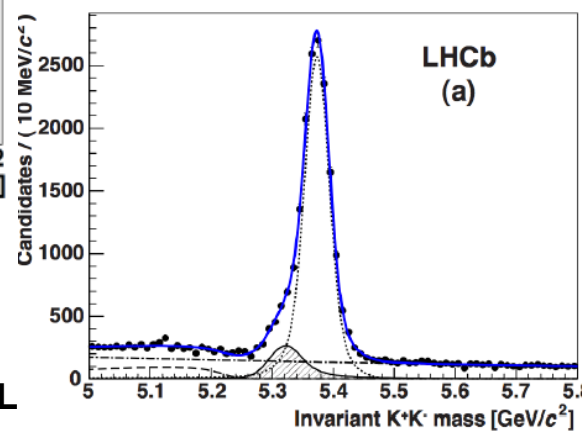
- 1 fb^{-1} : ~9000 $B^0 \to \pi^+\pi^-$ events
- First time-dependent CP asymmetry plot of $B^0 \to \pi^+\pi^-$ at a hadron collider

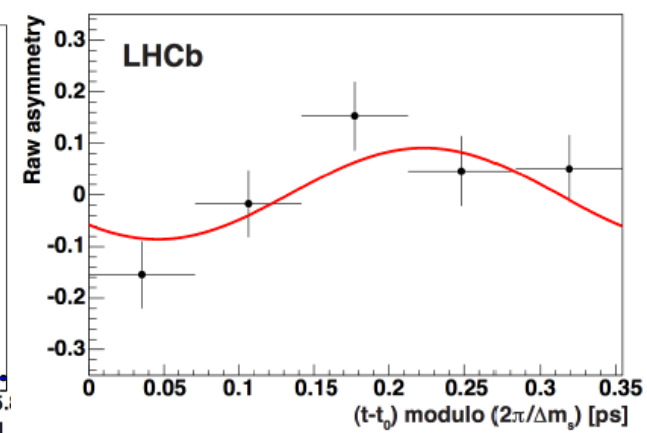
$$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02 \quad \text{cos term (direct)}$$
$$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02 \quad \text{sine term (indirect)}$$

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

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





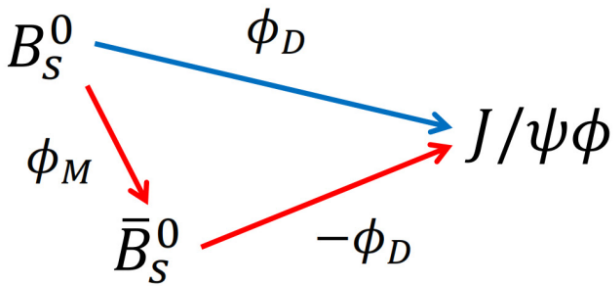


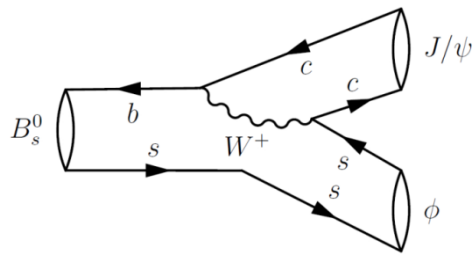
JHEP 10 (2013) 183

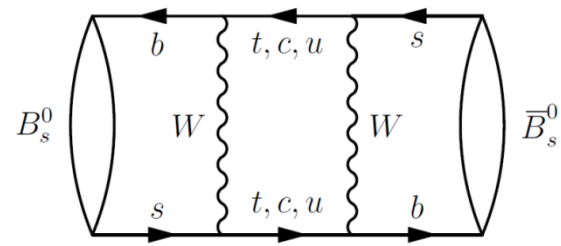
Selected physics highlights

- Parameters of the CKM matrix
- Studies of CP violation in the B_s system
- Mixing & CP violation in charm
- Rare B decays
- New observed resonances

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







- Golden mode for this study is $B_s \to J/\psi\ \phi$

3 fb^{-1} arXiv:1411.3104

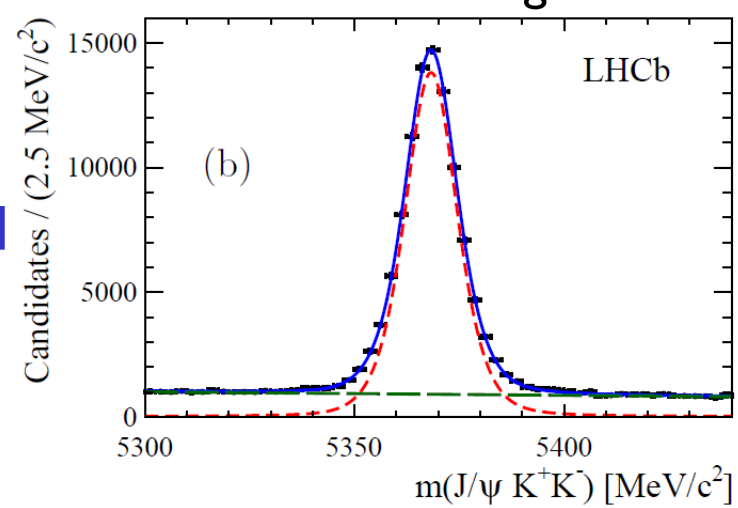
- Analogue of 2β (phase of B^0 mixing) but in the B_s system
- *Interference* between B^0 decay to $J/\psi\phi$ directly and via B^0 - $\bar{B}^0$ oscillation gives rise to a CP violating phase

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

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

  $\phi_s = -0.036 \pm 0.002$

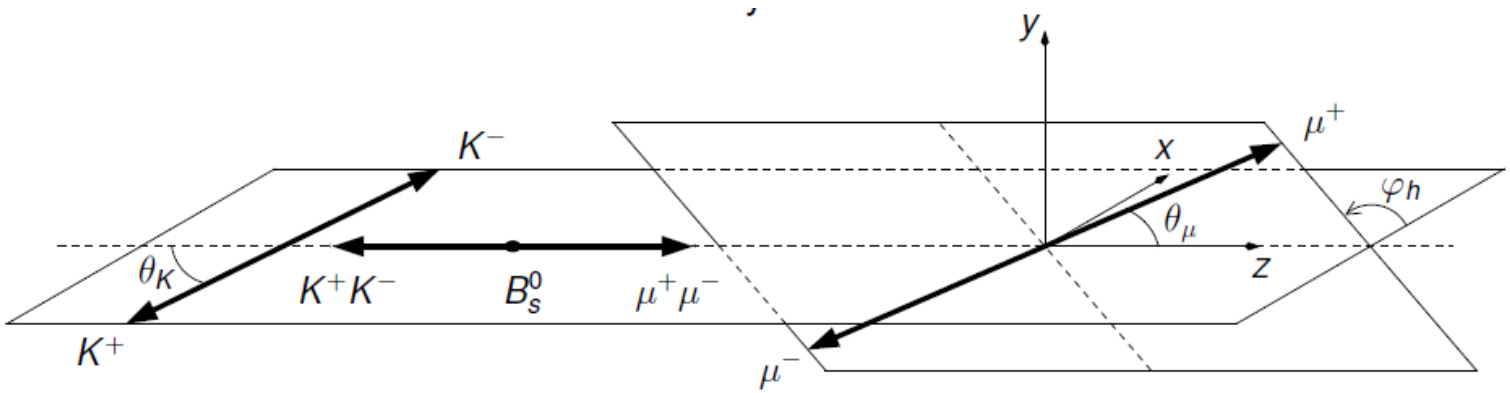
  (see eg Charles et al PRD84 (2011) 033005)



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



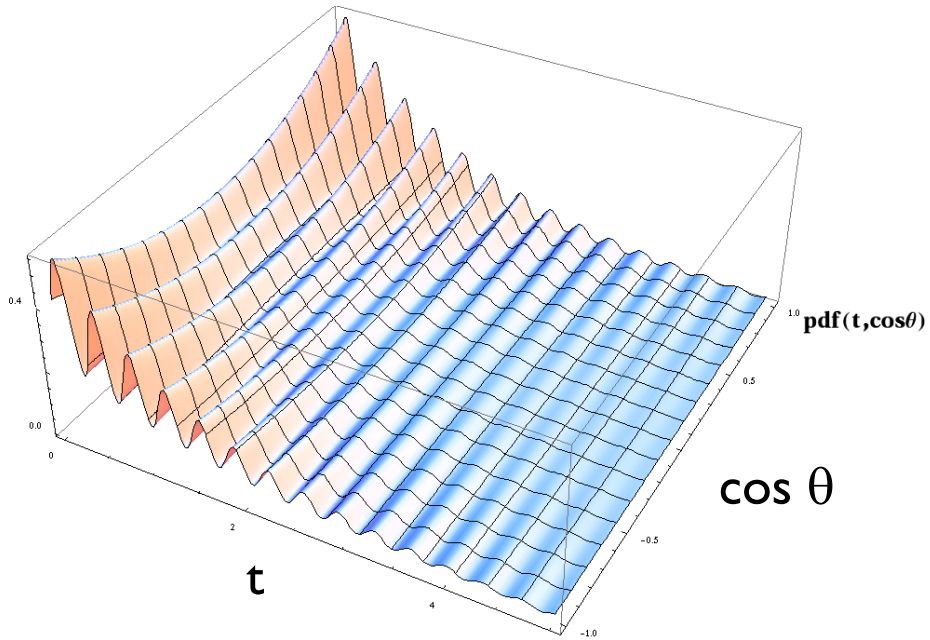
- LHCb 7 & 8TeV, $3fb^{-1}$: 95,690 ± 350 candidates
- Tagging: Opposite side tagging power 2.55% (+15% w.r.t. 2011)

  Same Side Kaon Tagger 1.25% (+40% w.r.t. 2011)

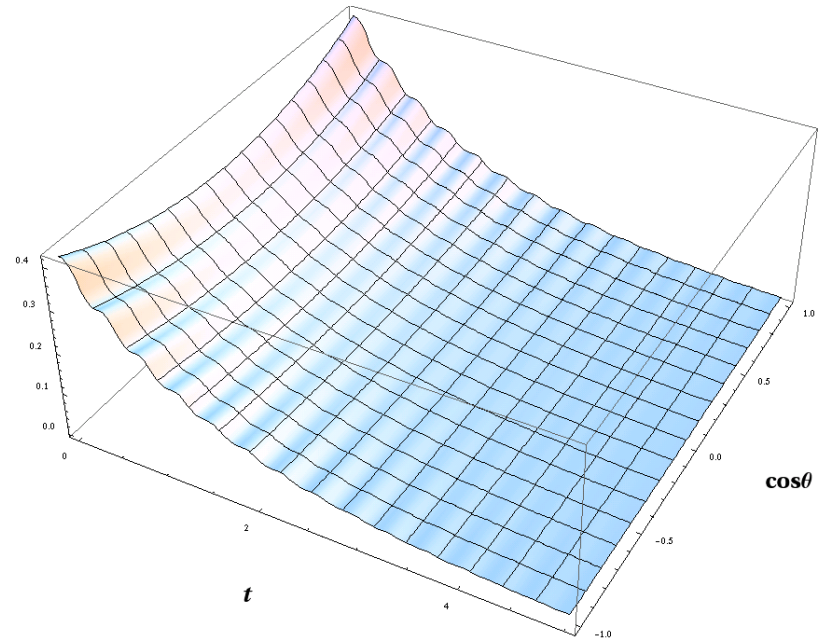
"Visualizing" the effect of ϕ_s in $B_s \to J/\psi\ \phi$

- Amplitude of asymmetry $\propto \sin \phi_s$
- Frequency is the same as in B_s mixing

Ampl.

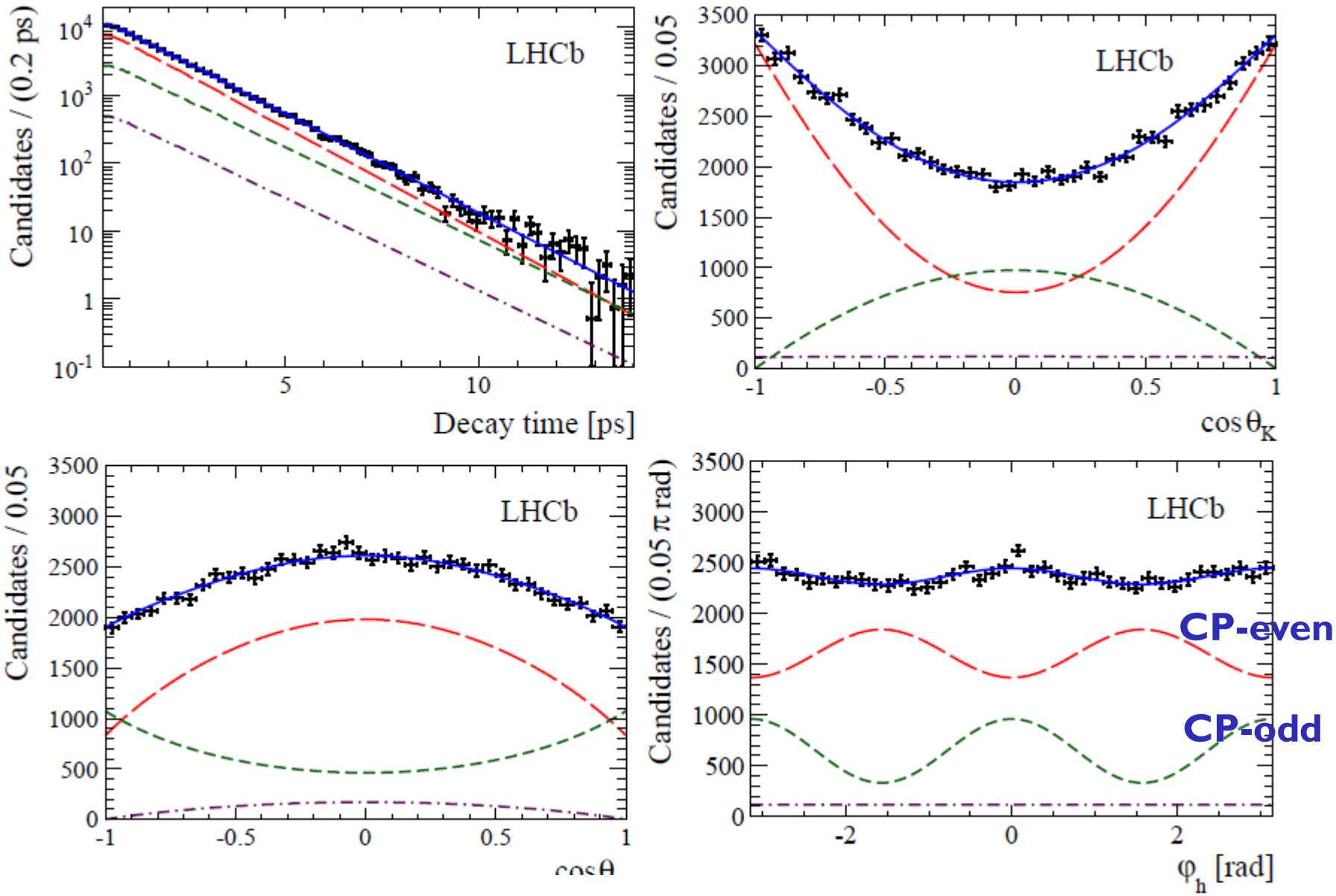


$\phi_s = 0.4$



$\phi_s = 0.04$ (SM)

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



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

- $\Gamma_S = 0.6603 \pm 0.0027 \pm 0.0015$ ps^{-1}
- $\Delta\Gamma_S = 0.0805 \pm 0.0091 \pm 0.0033$ ps^{-1}

  CP-violating phase:
- $\phi_S = -0.058 \pm 0.049 \pm 0.006$ rad

3 fb^{-1} arXiv:1411.3104

World's most significant direct measurement of ϕ_S & $\Delta\Gamma_S$, $\Delta\Gamma_S$

- Also add in $B_s \rightarrow J/\psi\ \pi\pi$

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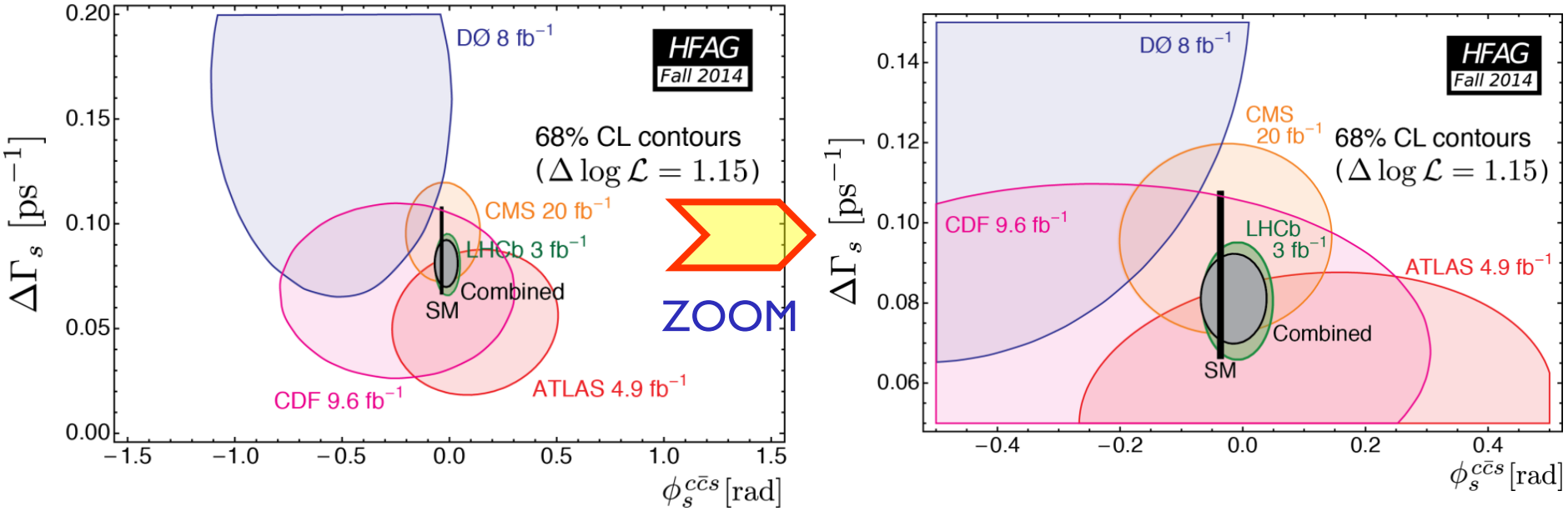
$\phi_S = -0.010 \pm 0.039$ rad



A combination of ϕ_S shows data not incompatible with the SM

Still much room for new physics in ϕ_S, will continue improved precision

Selected physics highlights

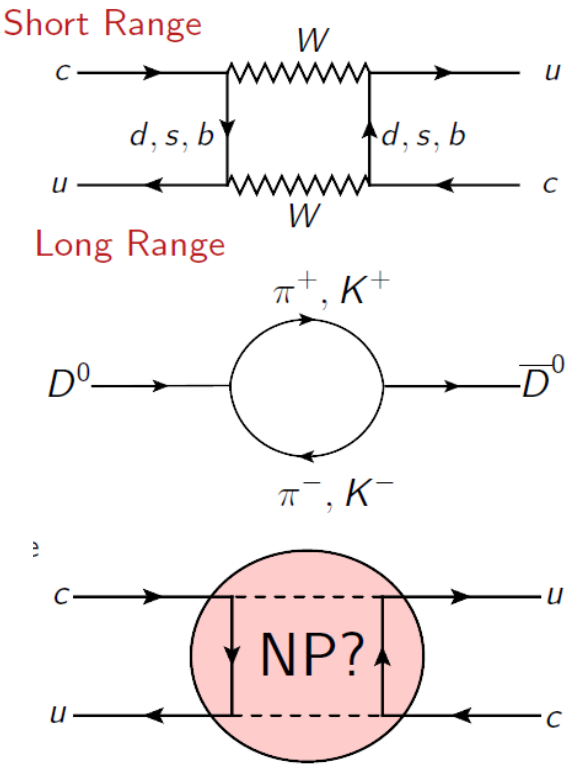
- Parameters of the CKM matrix
- Studies of CP violation in the B_s system
- Mixing & CP violation in charm
- Rare B decays
- New observed resonances

Mixing in charm decays

- Charm mixing was confirmed by BaBar, Belle & CDF, but LHCb 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)

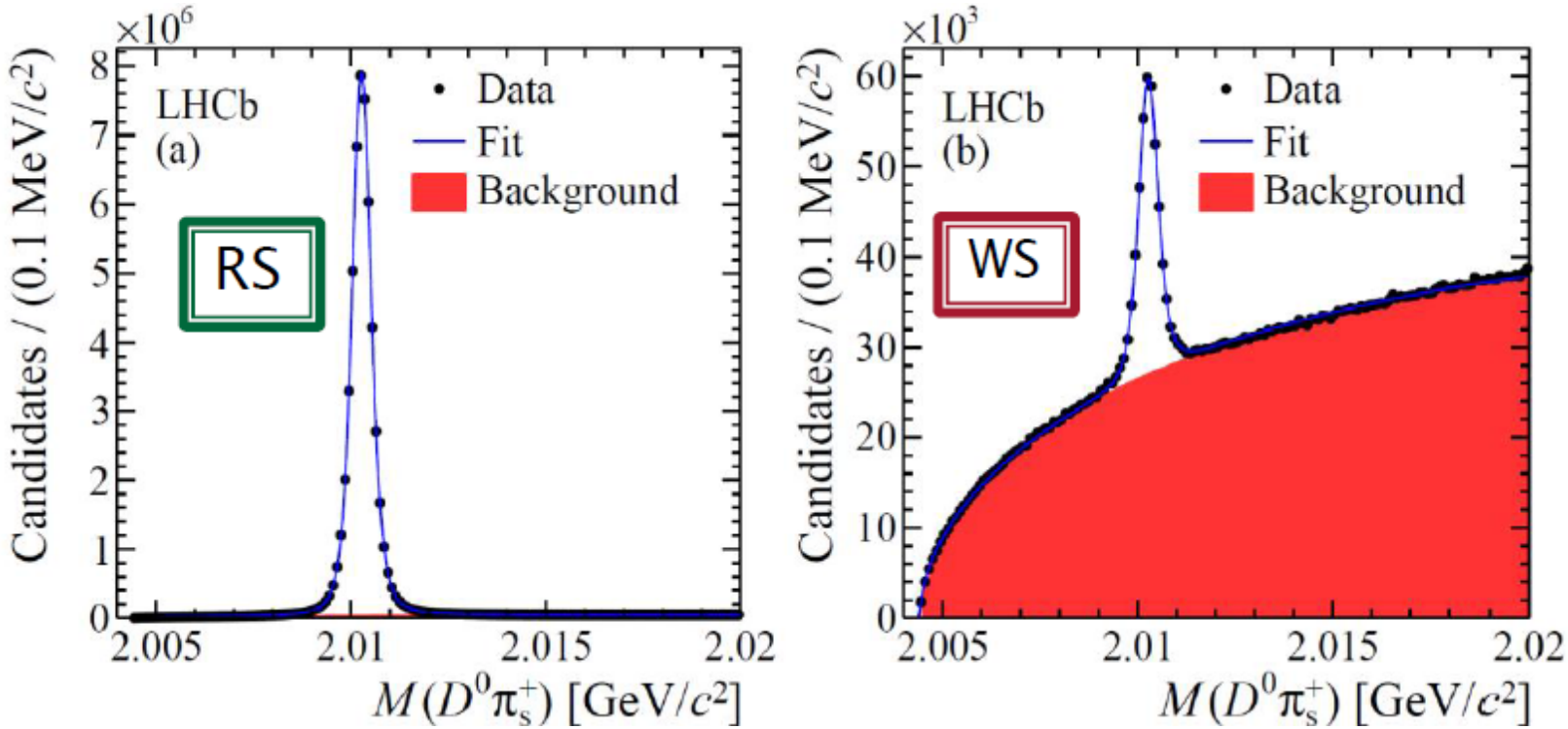
$$R(t) = \frac{N(D^0 \to K^+\pi^-)}{N(D^0 \to K^-\pi^+)}$$

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



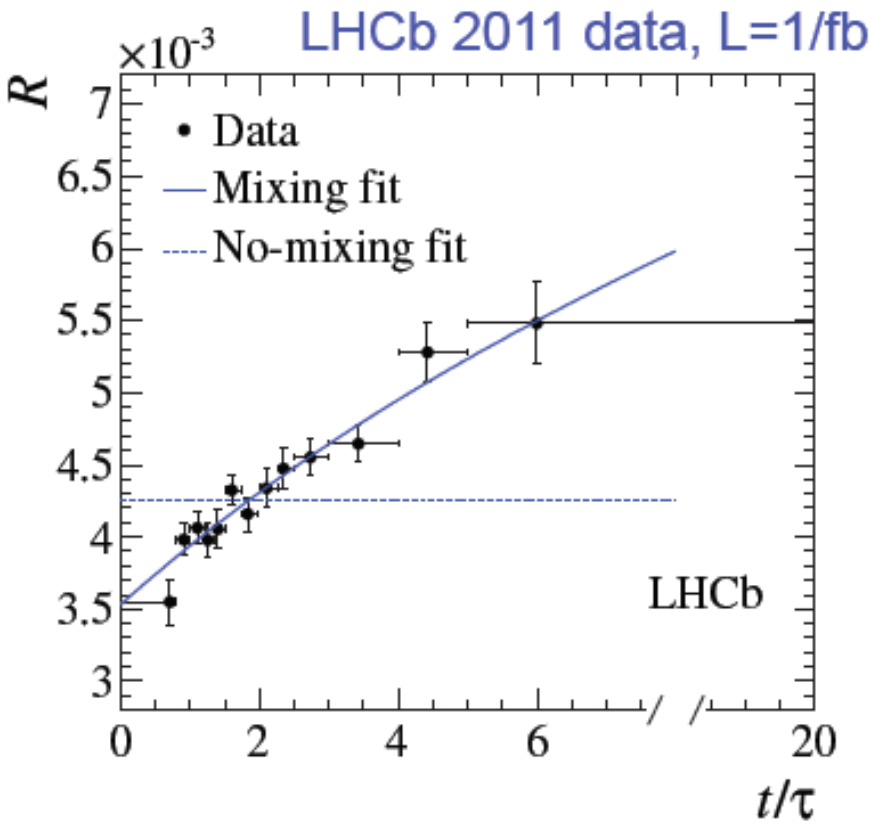
Charm mixing measurement

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



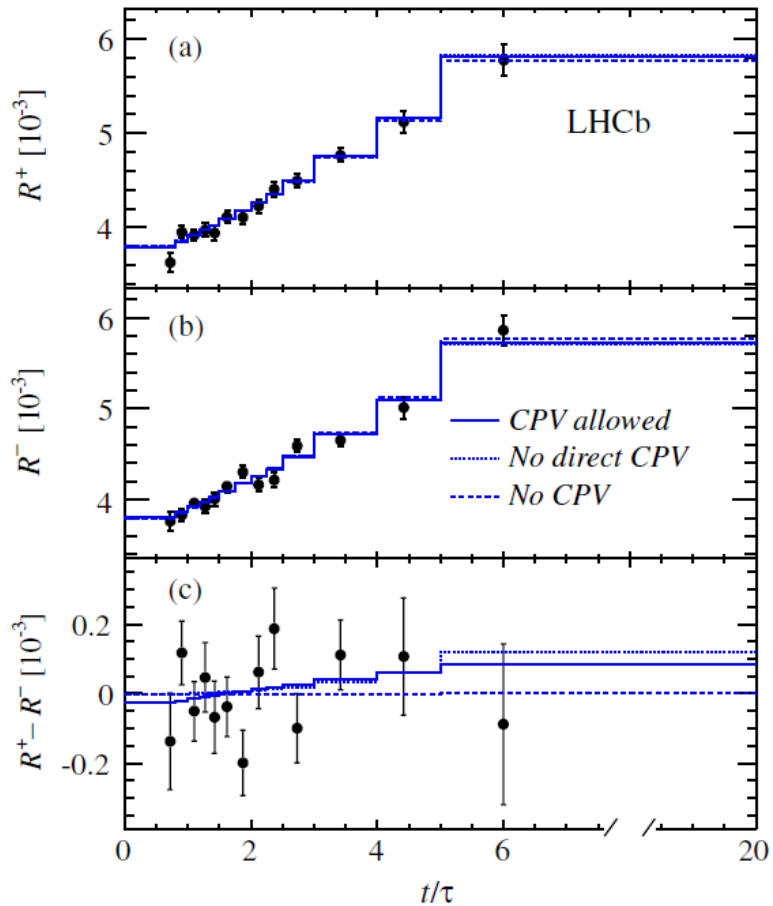
- New analysis uses 3 fb^{-1} of data (results coming soon)
- Huge samples of D candidates: 230k WS and 54M RS

Charm mixing (and CP-violation)



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

PRL 110, 101802 (2013)



CP violation in charm

New J.Phys. 15 (2013) 053021

Selected physics highlights

- Parameters of the CKM matrix
- Studies of CP violation in the B_s system
- Mixing & CP violation in charm
- Rare B decays : See also Fatima Soomro talk in parallel session
- New observed resonances

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

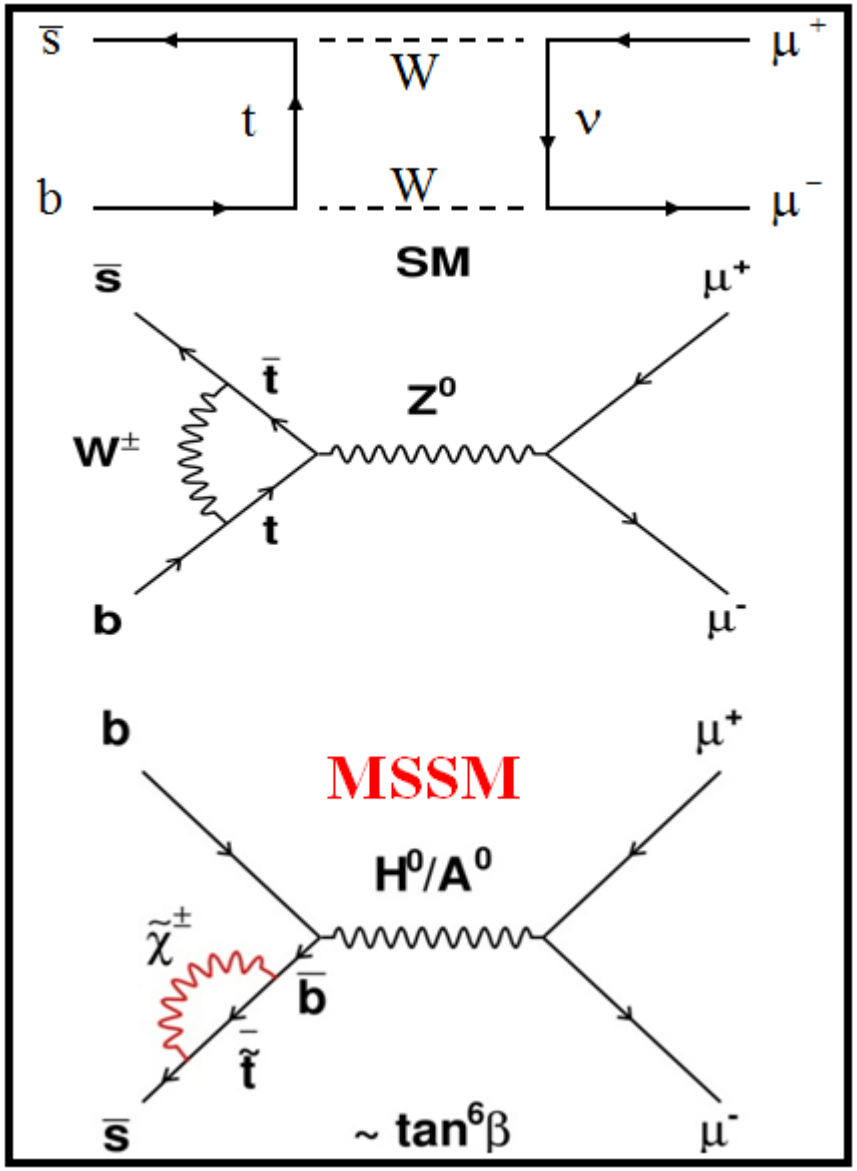
- Decays strongly suppressed in SM
- Predicted BRs

  $B^0_s \rightarrow \mu^+\mu^- = (3.65 \pm 0.23) \times 10^{-9}$

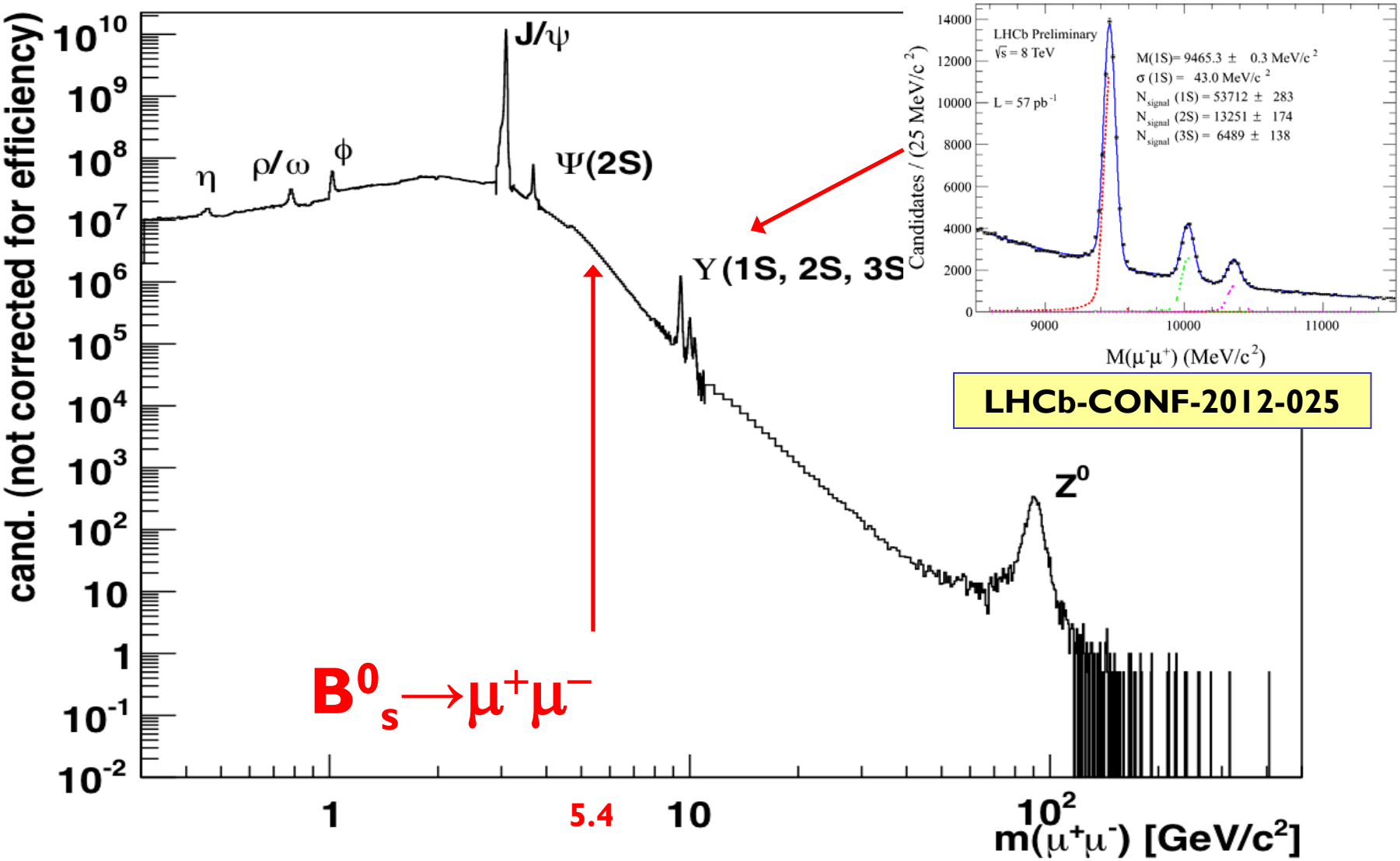
  $B^0 \rightarrow \mu^+\mu^- = (1.06 \pm 0.09) \times 10^{-10}$

  Bobeth et al. PRL 112 101801 (2014)

- Very sensitive to new physics - e.g. MSSM



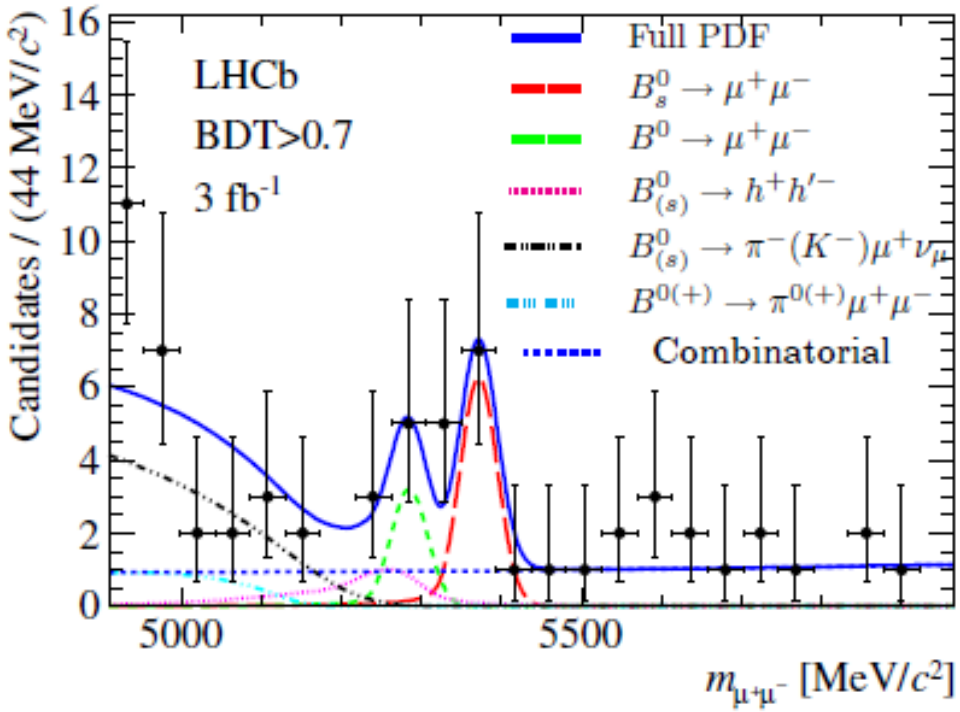
A needle in a haystack ….



LHCb-CONF-2012-025

PRL 111 (2013) 101805

- Results based on 2011/12 data: 3 fb^{-1} blinded analysis



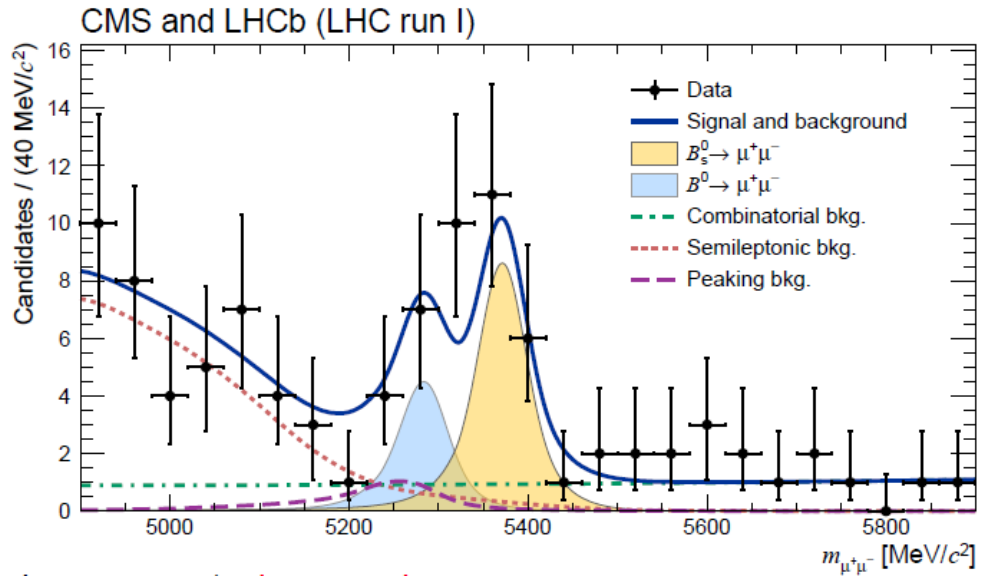
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}st\ ^{+0.3}_{-0.1}sy) \times 10^{-9}$$

$$\textit{Significance} : 4.0\ (\textit{Expected}\ 5.0)$$

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

$$\textit{Significance} : 2.0$$

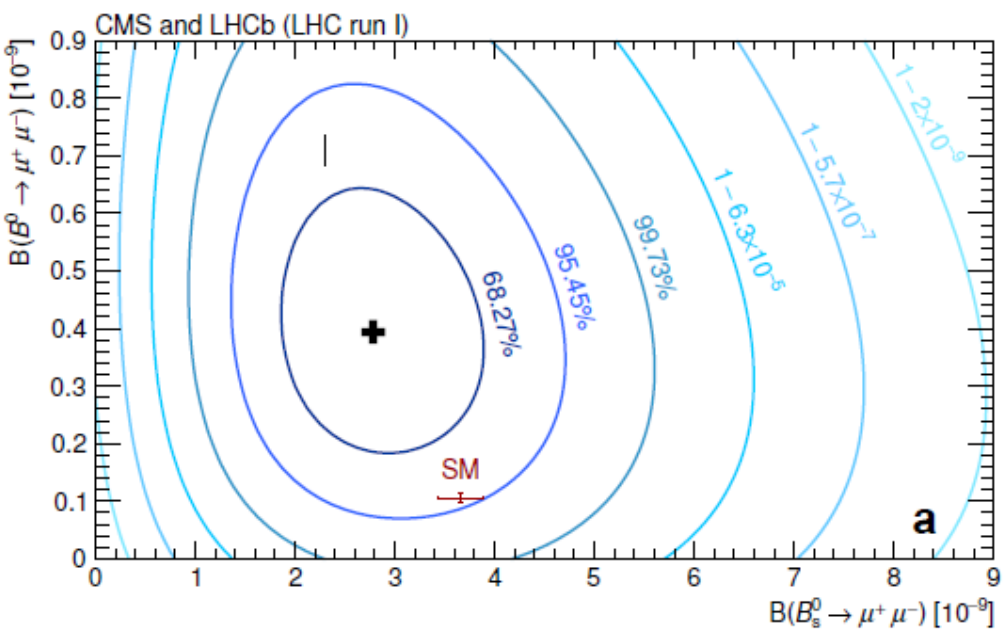
Combining with CMS results



arXiv:1411.4413

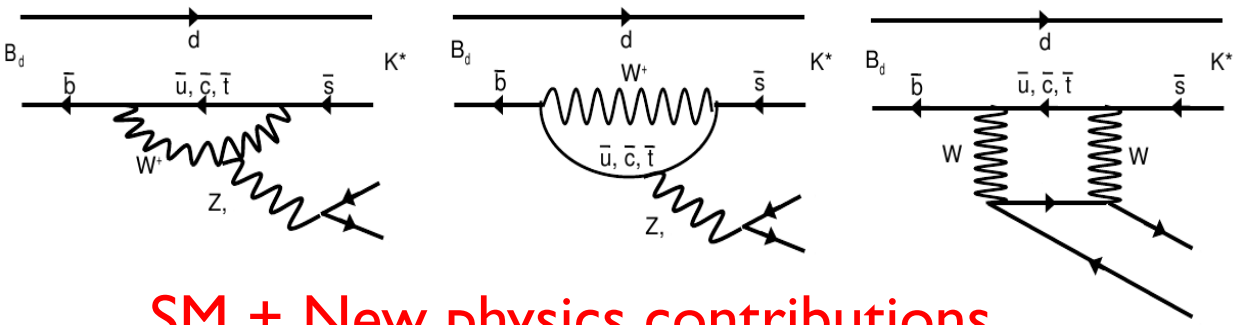
$$BR(B_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

$$BR(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

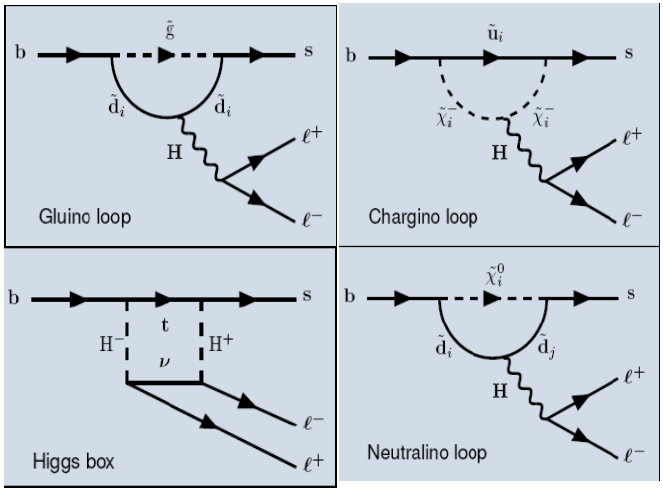


B^0 compatible at 2.2σ with SM, B_s at 1.2σ

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



SM + New physics contributions



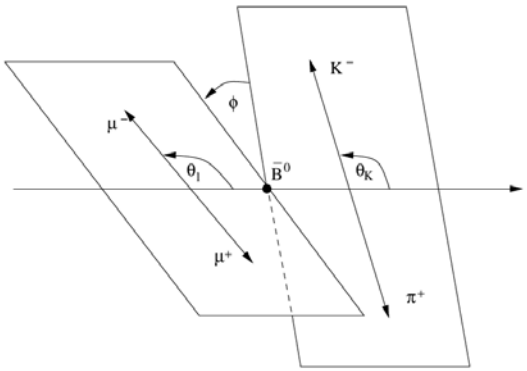
- LHCb has largest sample in world, as clean as the B Factories!
- Analysis presented here based on 883 ± 34 events (1fb^{-1} at 7 TeV)

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:

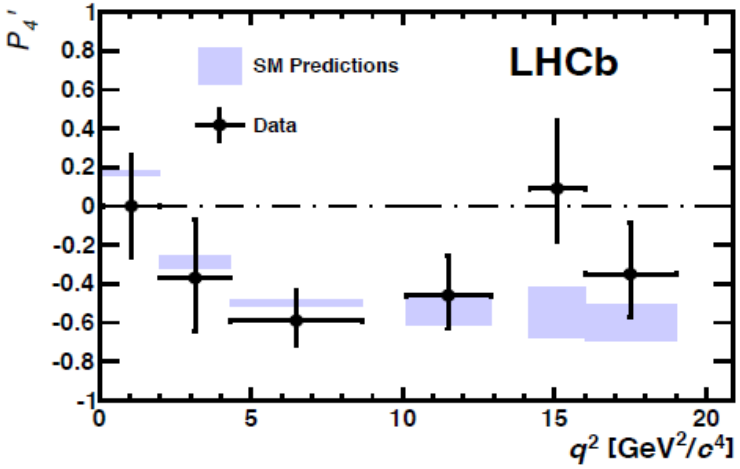


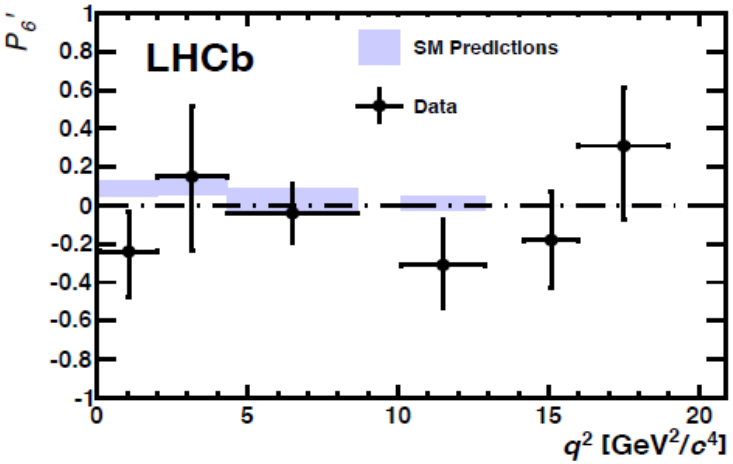
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos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

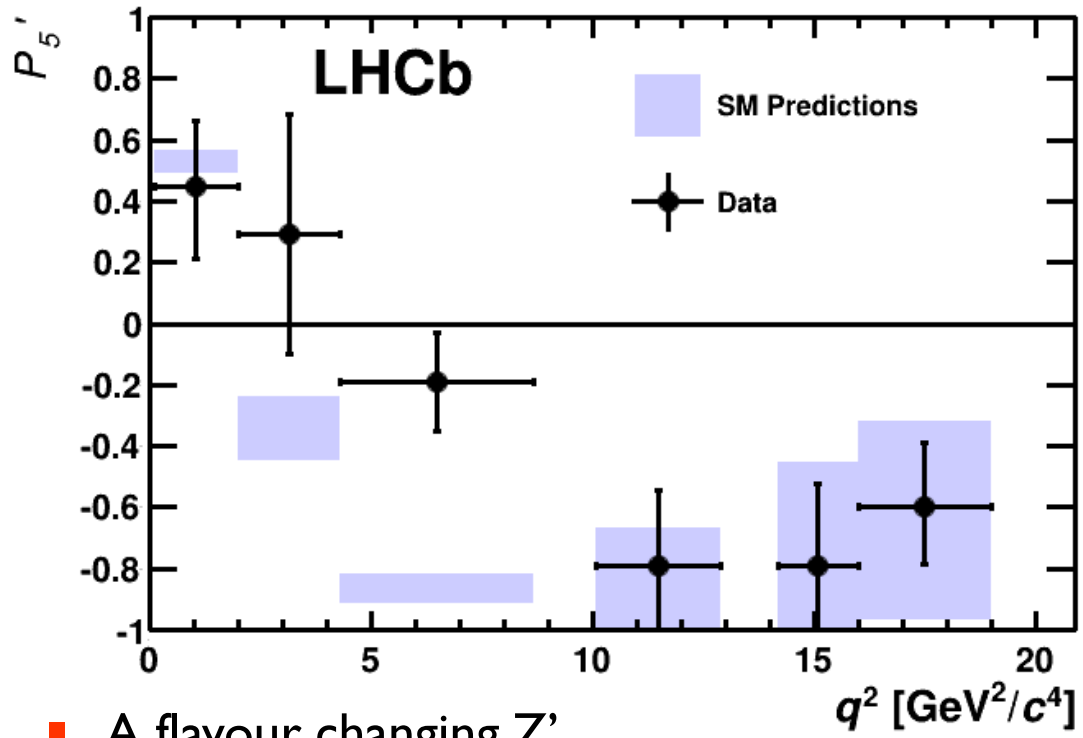
New observables in $B^0 \to K^*\mu^+\mu^-$ cont'

- Local discrepancy of 3.7σ in 3rd bin of P_5'
  (SM prediction J. Mathias et al, JHEP 05 (2013) 137)

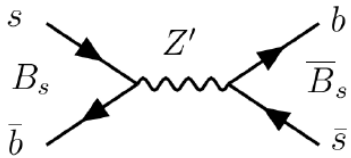
PRL 111 (2013) 191801







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



Lepton universality test in $B^+ \to K^+ l^+ l^-$

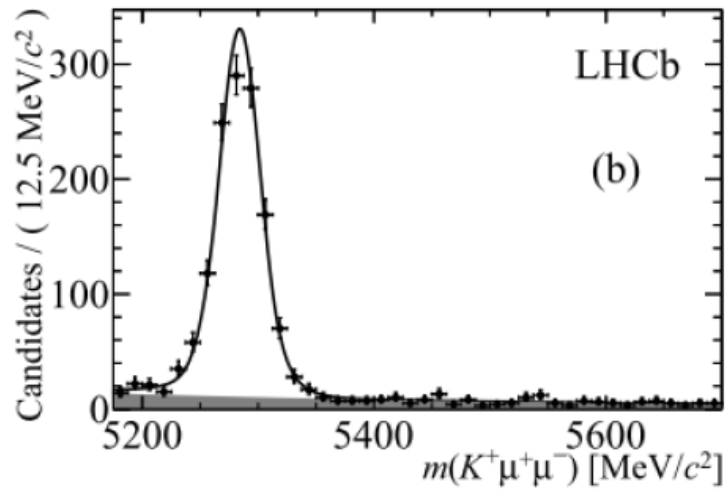
- Due to lepton universality, the $B^+ \to K^+ \mu^+ \mu^-$ and $B^+ \to K^+ e^+ e^-$ decays should have same BF to within a factor 10^{-3}
- The ratio

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$

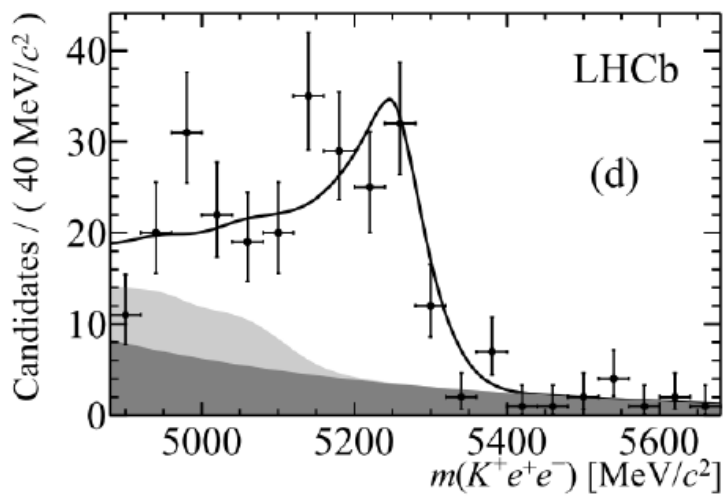
is sensitive to lepton flavour violating NP

- The electron mode is a challenge for LHCb

LHCb : arXiv:1406.6482



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

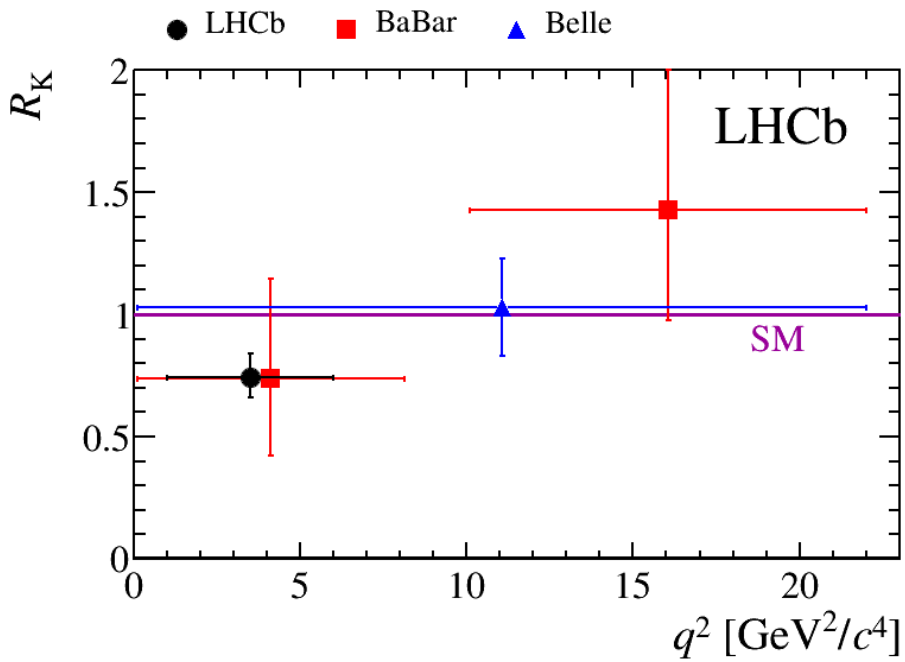


$B^+ \to K^+ e^+ e^-$

Lepton universality test in $B^+ \to K^+ l^+ l^-$

- 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 $B^+ \to K^+ J/\psi(\to l^+ l^-)$ (assuming lepton universality for $J/\psi \to l^+ l^-$)
- 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 R_K to date.



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

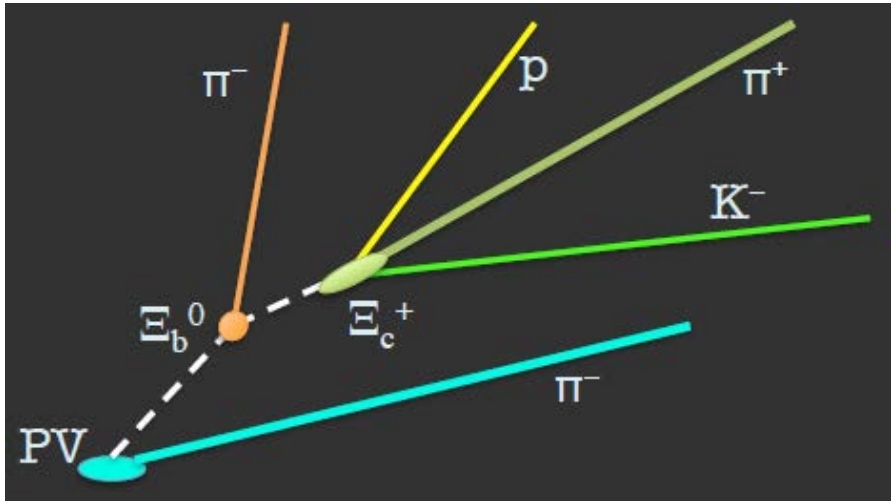
Selected physics highlights

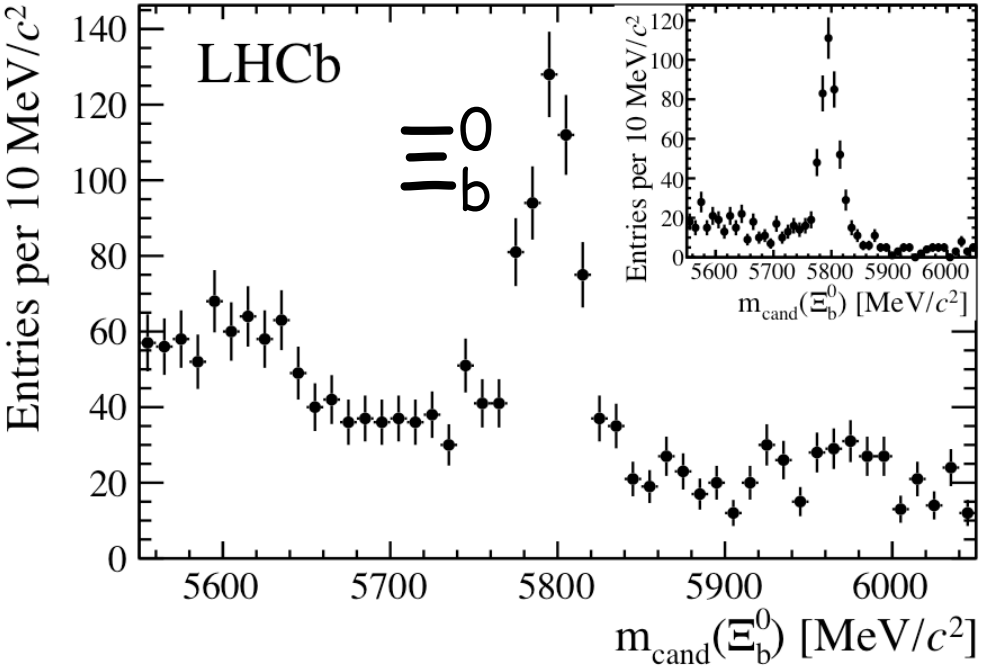
- Parameters of the CKM matrix
- Studies of CP violation in the B_s system
- Mixing & CP violation in charm
- Rare B decays
- New observed resonances

Two new baryons recently observed

- Spectrum of known b-baryons still sparsely populated.
- For the Ξ_b (bsd, bsu) states only the ground states, Ξ_b^- & Ξ_b^0, and one resonance, Ξ_b^0 (5945), observed.
- cf. the Ξ_c pattern, there must be
  - $\Xi_b'^-$ $J^P = 1/2^+$, spin(sd) = 1
  - Ξ_b^{*-} $J^P = 3/2^+$, spin(sd) = 1
- Study the ($\Xi_b^0 \pi^-$) mass spectrum, with $\Xi_b^0 \to \Xi_c^+ (\to p K^- \pi^+) \pi^-$.
- Require good tracks and vertices; PID on kaon and proton; exploit the long Ξ_b^0 lifetime
- Require soft π_s^- and Ξ_b^0 from PV.

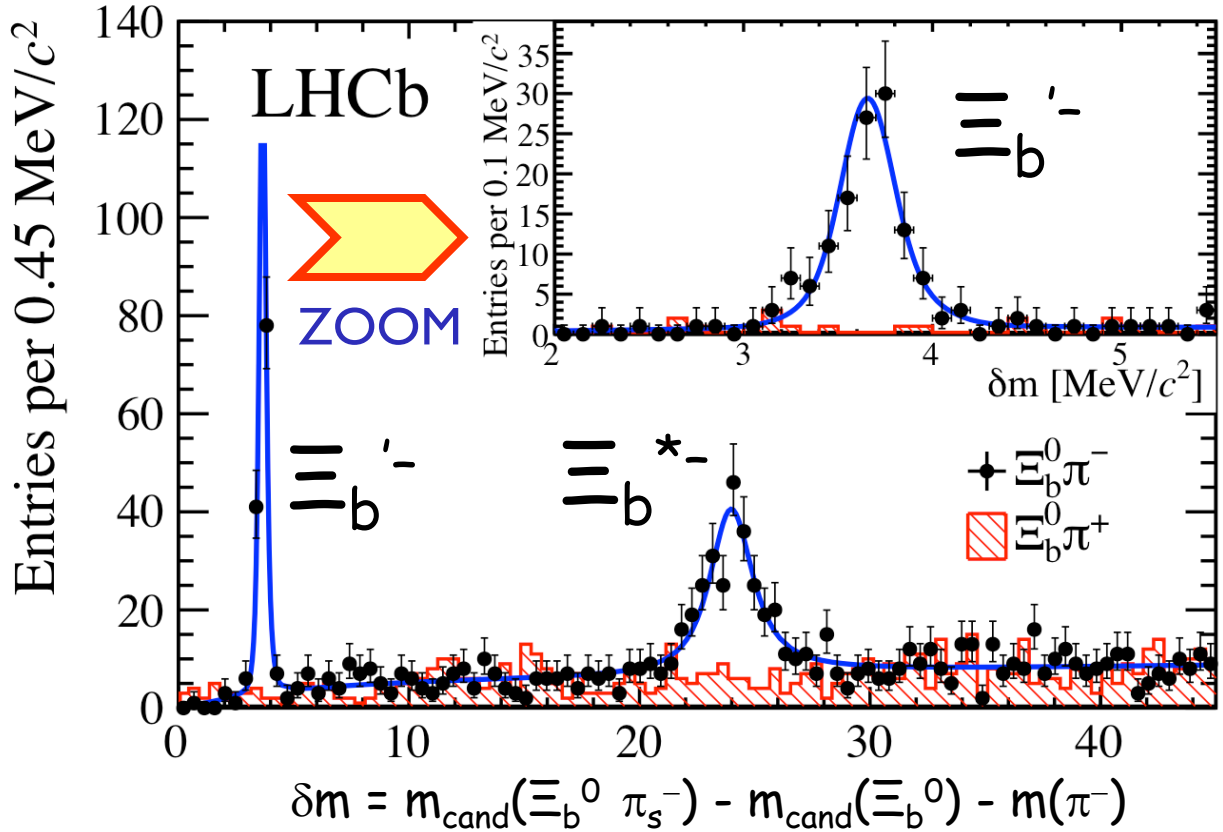
LHCb-PAPER-2014-061





Two new baryons cont'

LHCb-PAPER-2014-061



$m(\Xi_b'^-) = 5935.02 \pm 0.02 \pm 0.01 \pm 0.50$ MeV

$\Gamma(\Xi_b'^-) < 0.08$ MeV at 95% CL

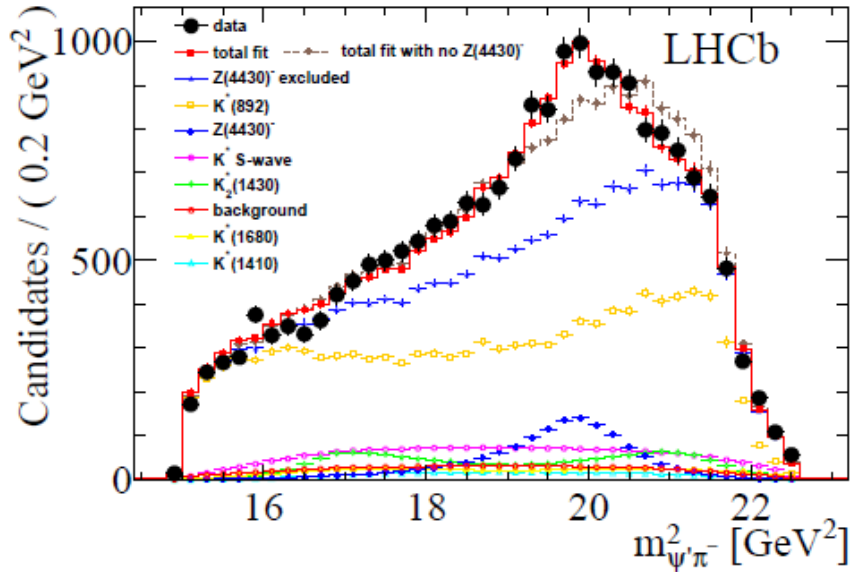
$m(\Xi_b^{*-}) = 5955.33 \pm 0.12 \pm 0.06 \pm 0.50$ MeV

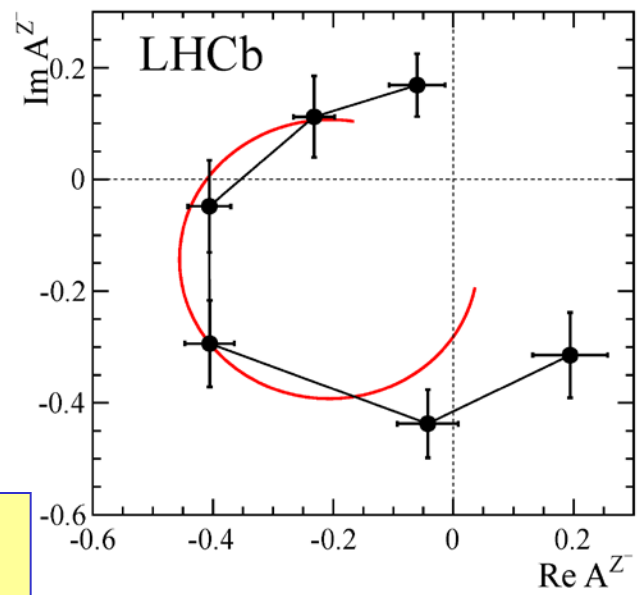
$\Gamma(\Xi_b^{*-}) = 1.65 \pm 0.31 \pm 0.10$ MeV

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

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





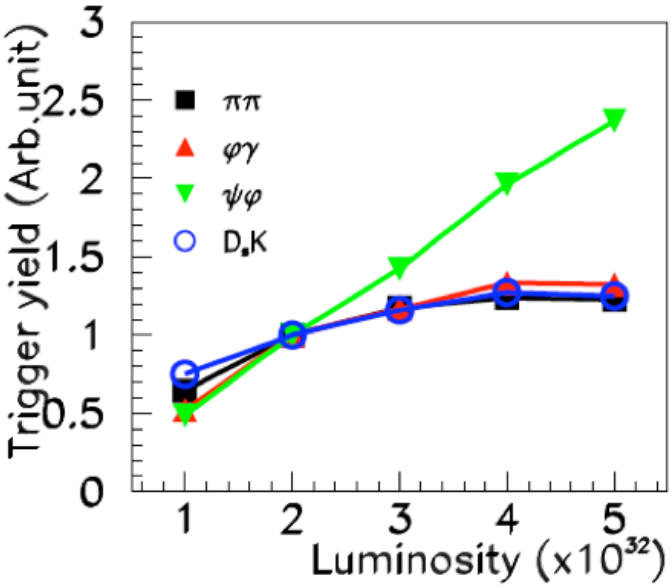
Phys. Rev. Lett. 112, 222002 (2014)

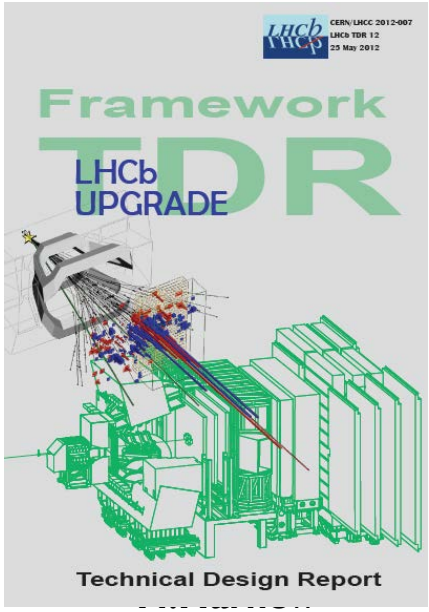
Summary and Outlook

- The LHCb experiment is performing spectacularly well
- So far all is in good agreement with the Standard Model
  → New physics is becoming constrained in the flavour sector
  → Possible hints of new physics await more data.
- Up to 2017 in Run 2 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→14 TeV)
- Still much room for new physics, higher precision required …
  → LHCb upgrade.

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}
- All TDRs approved by CERN : Physics case enthusiastically endorsed, detector R&D and design well underway





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

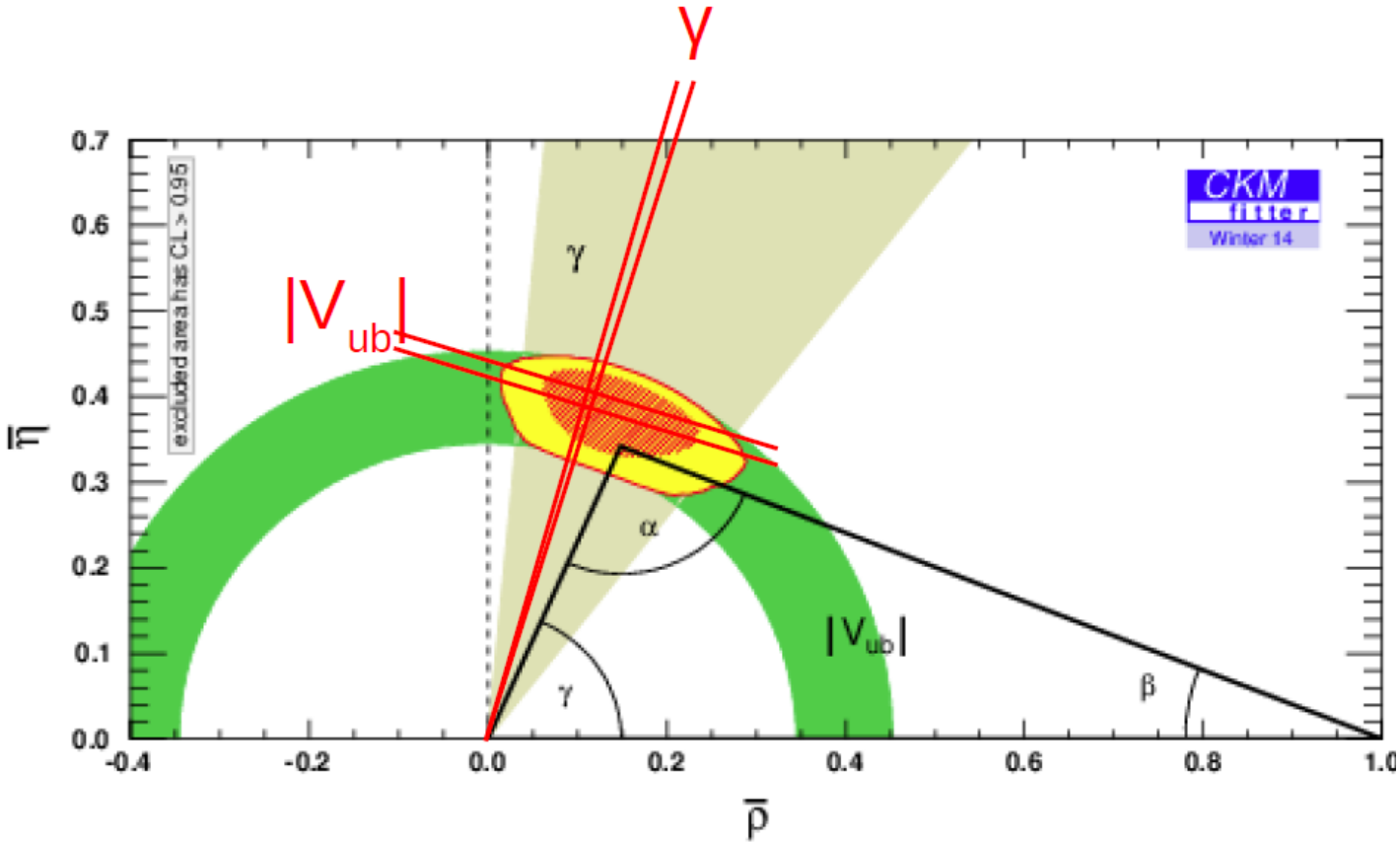
Upgrade sensitivities 50 fb^{-1}

Eur. Phys. J C (2013) 73:2373

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	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
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [41]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [41]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [42]	0.025	0.008	0.02
	$s_0\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [42]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	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	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [28, 29]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\, K_S^0)$	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}	–

In 2025 with the LHCb upgrade …

- $(|V_{ub}|/|V_{cb}|)$ and the angle γ will be precision measurements in the future



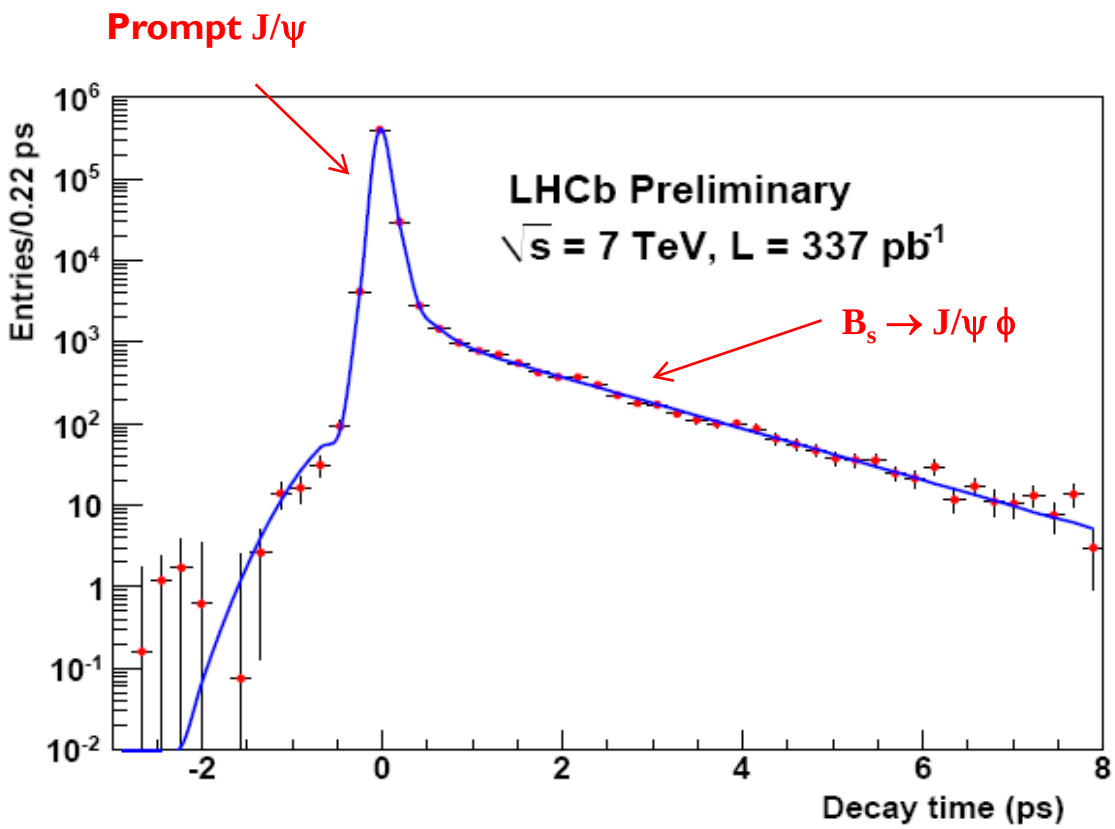
Spare slides from here on

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%

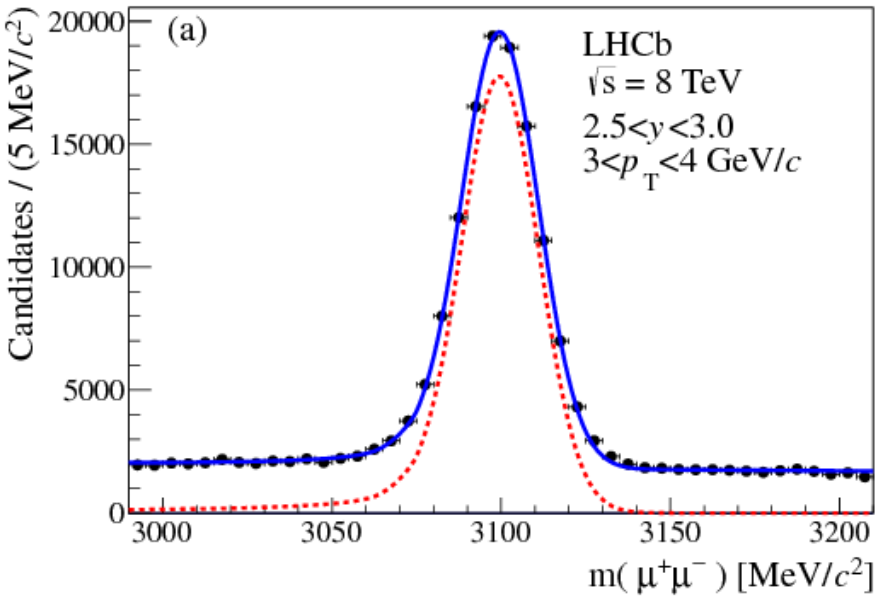
Vertex reconstruction performance

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



LHCb-CONF-2011-49

Tracking performance



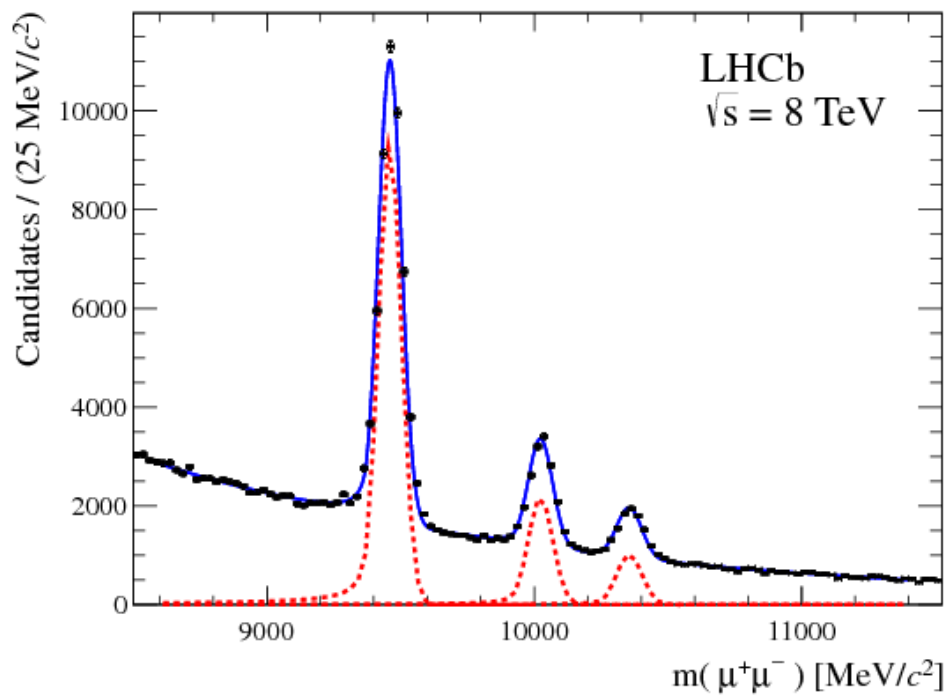
JHEP06 (2013) 064

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

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

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

JHEP06 (2013) 064

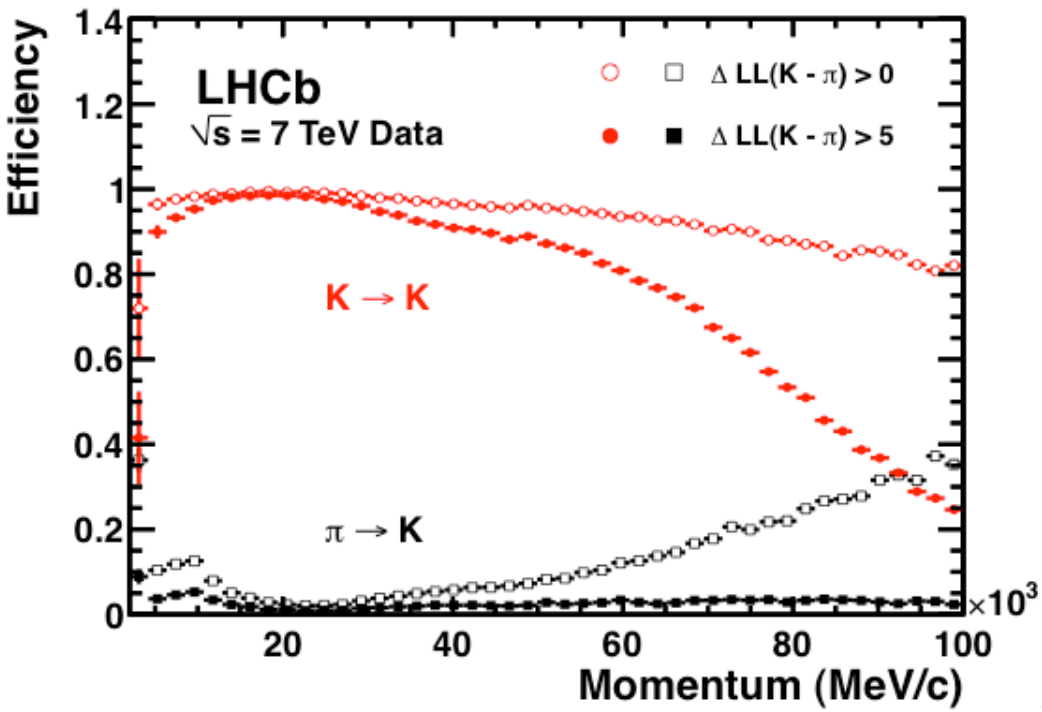


PID performance

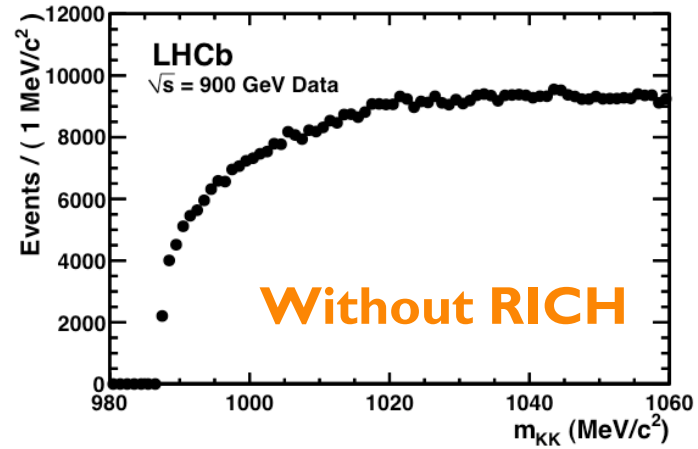
arXiv:1211.6759

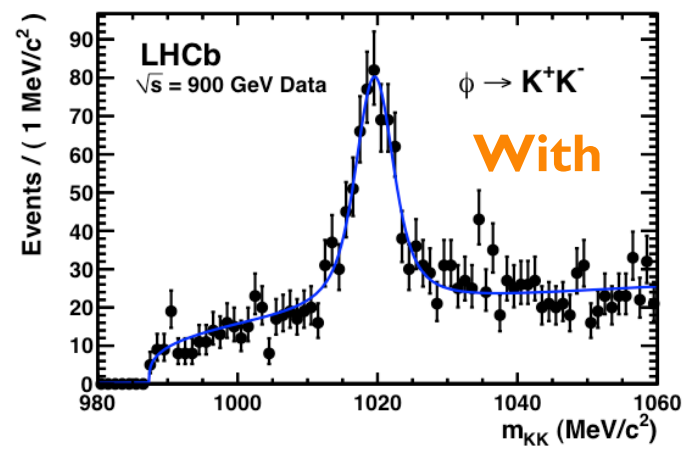
- Kaon identification efficiency > 90% for pion misidentification < 5% over a large momentum range ($2 < p < 100$ GeV/c)

Calibration data



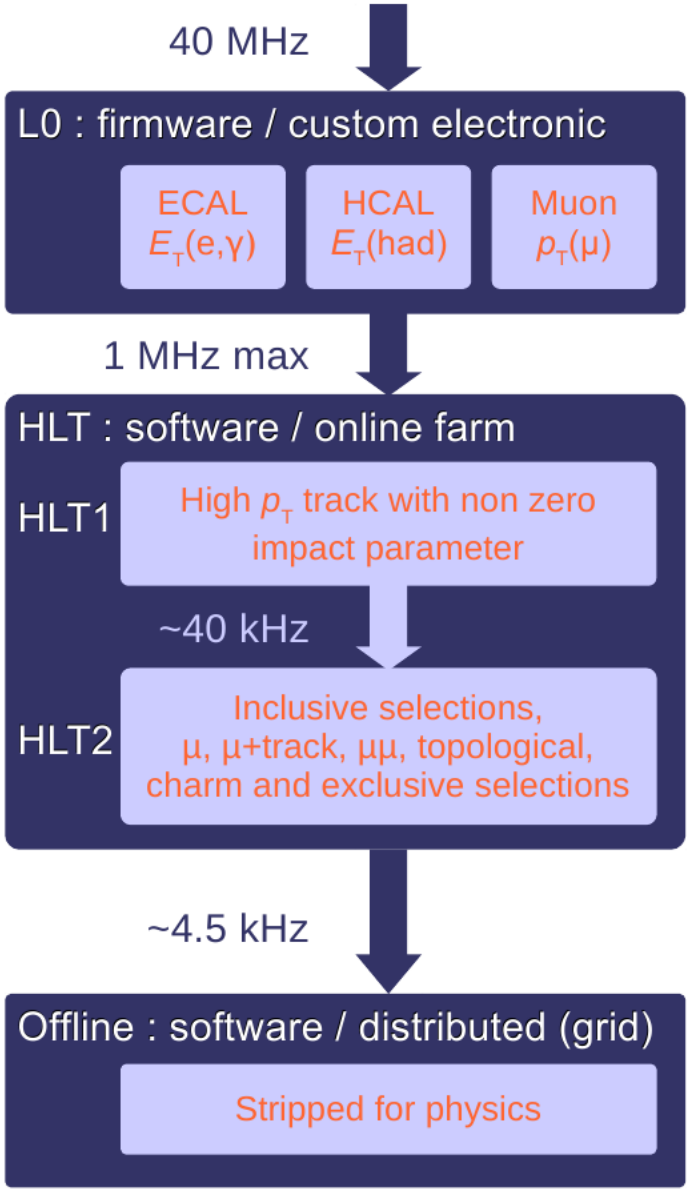
- Allows strong suppression of combinatorial background *eg* for $\phi \to K^+K^-$





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

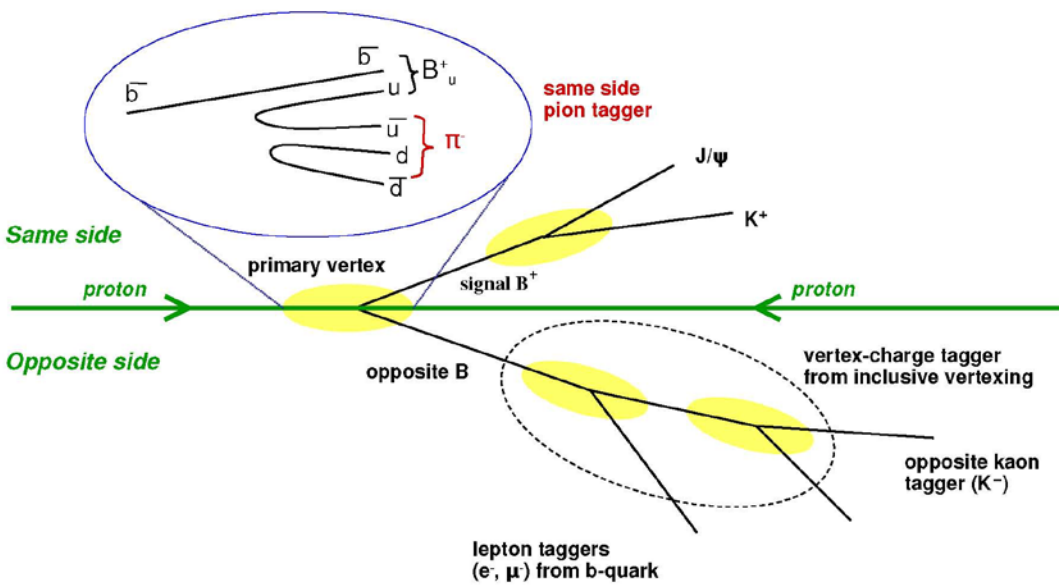
Offline processing:

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

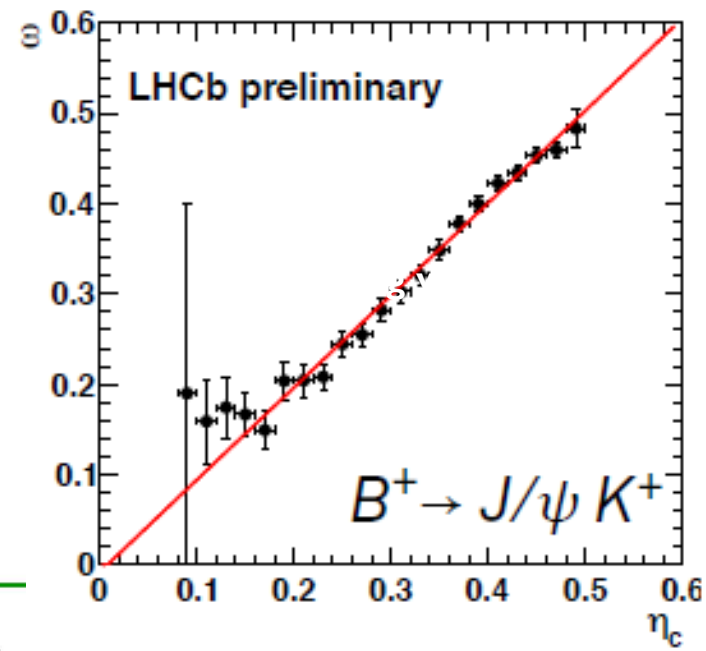
Flavour tagging

- Tagging of production flavour (B or $\bar{B}$) important for mixing and CP analyses. Performance calibrated using control channels such as $B^+ \to J/\psi\, K^+$
- Opposite side tagging power (2011):

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



European Physical Journal C 72 (2012) 1-16



The sign of $\Delta\Gamma_s$

PRL 108 (2012) 241801

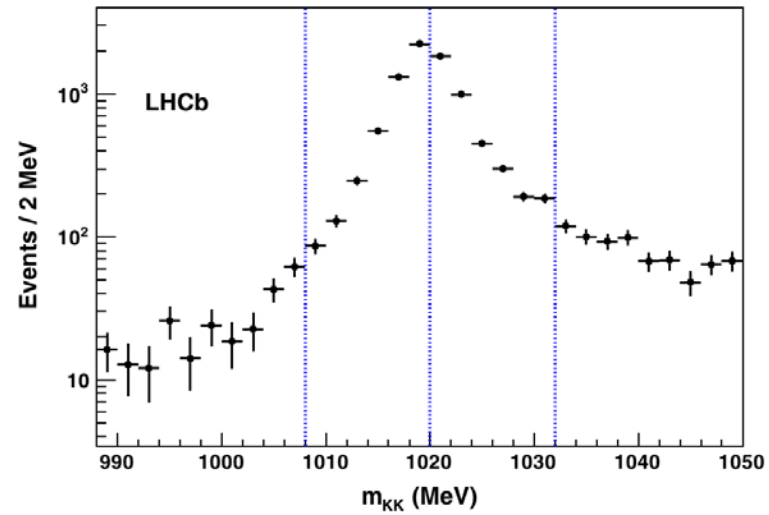
- To resolve ambiguity
  $(\phi_s, \Delta\Gamma_s, \delta_{||}, \delta_\perp) \leftrightarrow (\pi-\phi_s, -\Delta\Gamma_s, 2\pi-\delta_{||}, -\delta_\perp)$
  study strong phase difference $\delta_{s\perp} = \delta_s - \delta_\perp$
  between K^+K^- P-wave and S-wave amplitudes
  as a function of $m(K^+K^-)$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

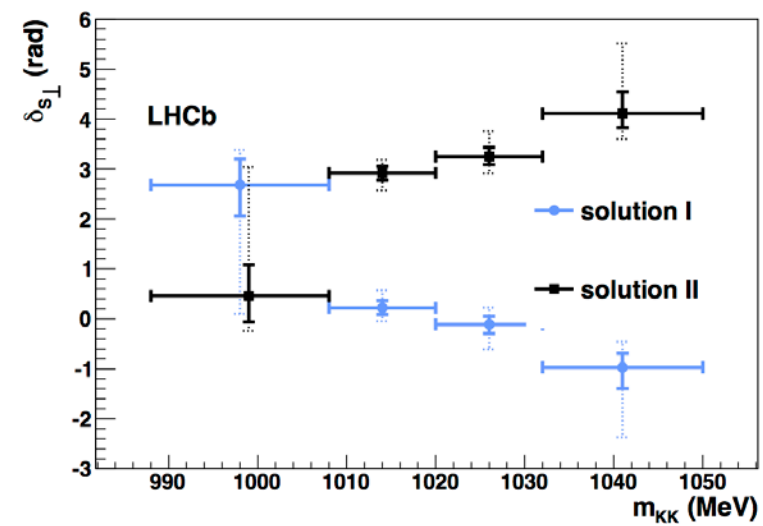
- P-wave: $\phi(1020)$, going through resonance
  $\rightarrow$ expect rapid positive phase shift

  - 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





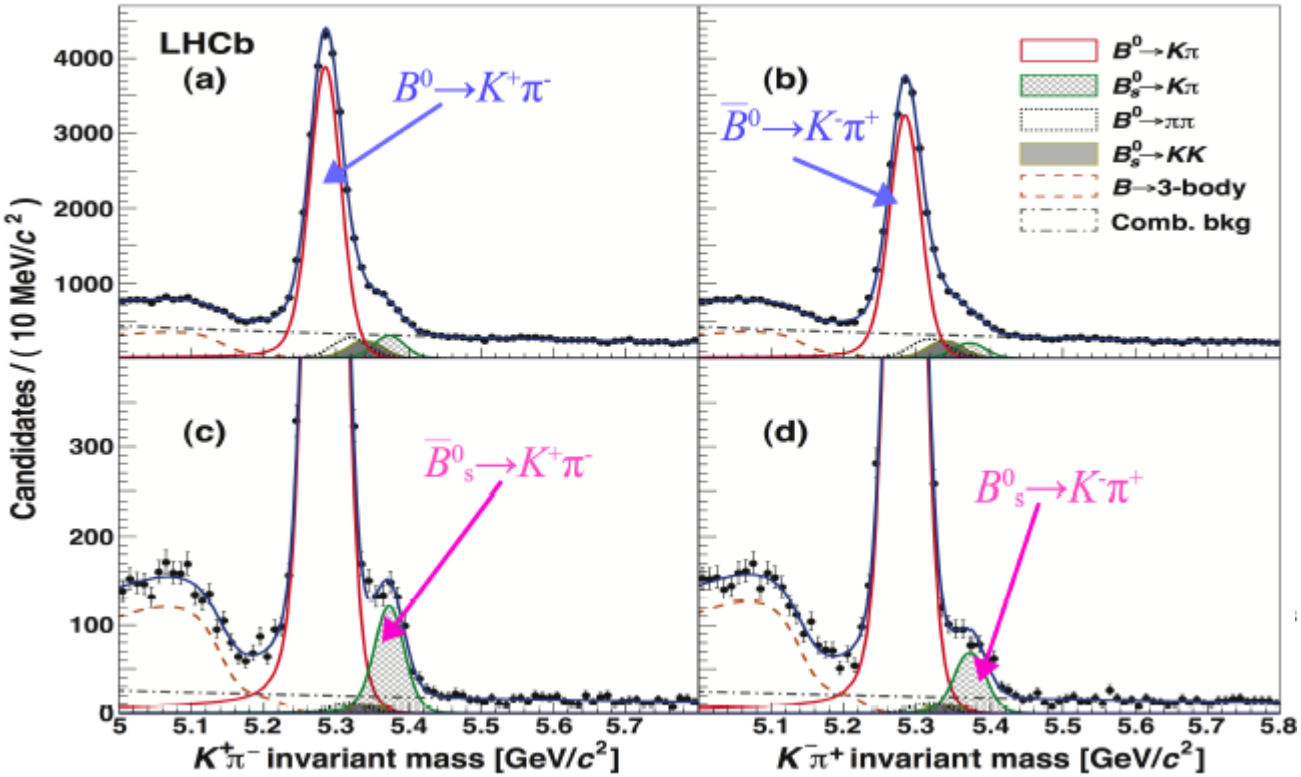
Solution corresponding to $\Delta\Gamma_s > 0$
preferred with 4.7σ significance

CP violation in B→Kπ and B_s→Kπ

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

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

- Using 1/fb (2011) @ √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)

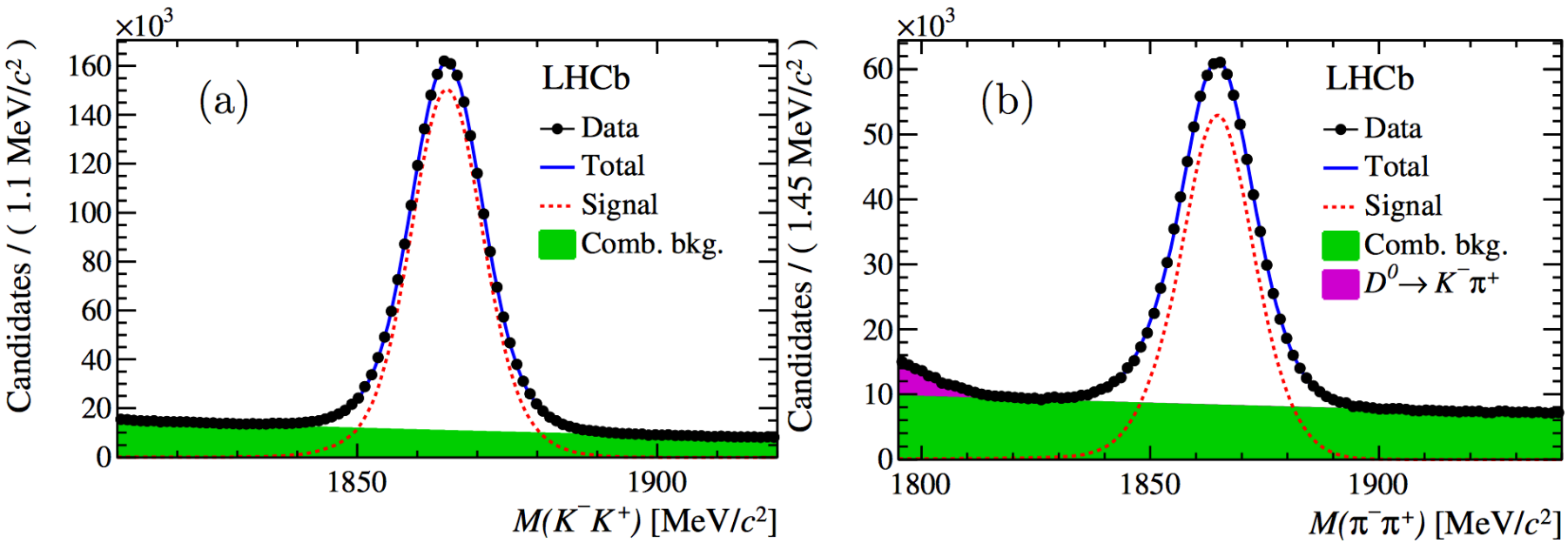
CP violation in charm

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.

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

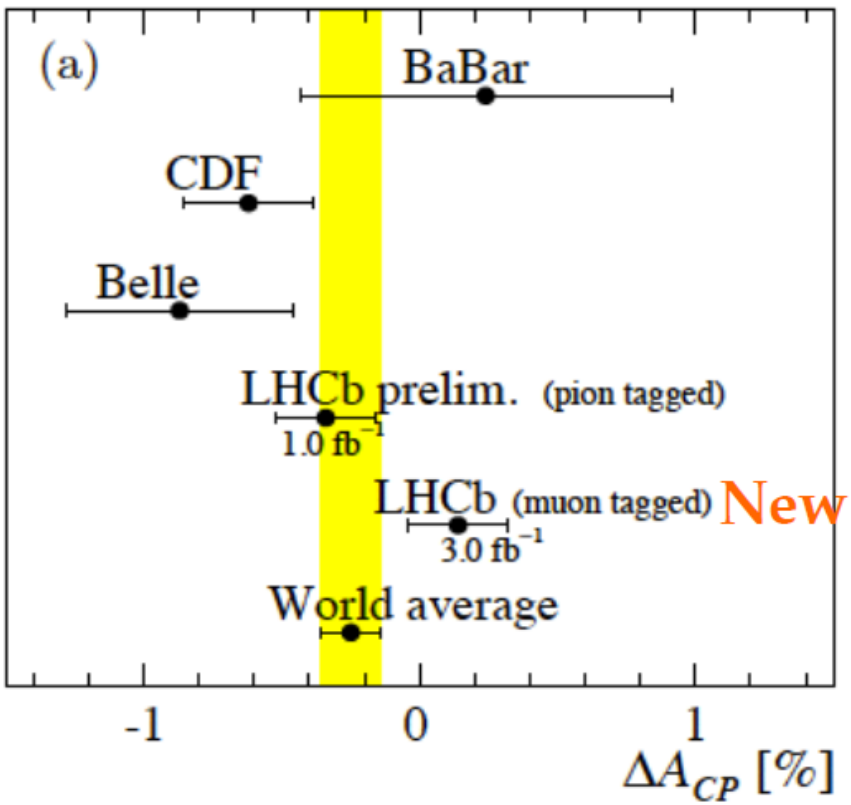
In the Standard Model these asymmetries should be very close to zero



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

CP violation in charm

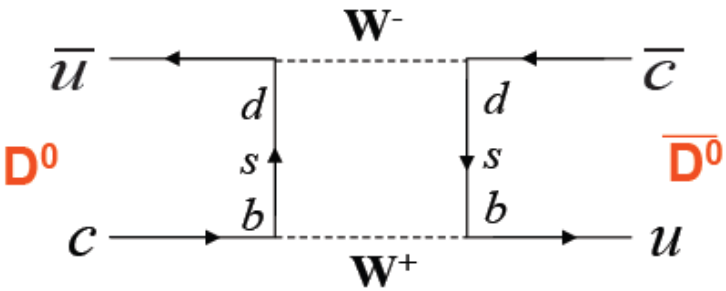
- $\Delta A_{CP} = A_K - A_\pi$

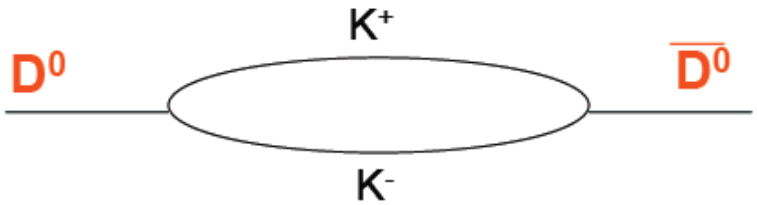


$$\Delta A_{CP} = (+0.14 \pm 0.16\,(\text{stat}) \pm 0.08\,(\text{syst}))\%$$

Combination consistent with zero CP violation

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

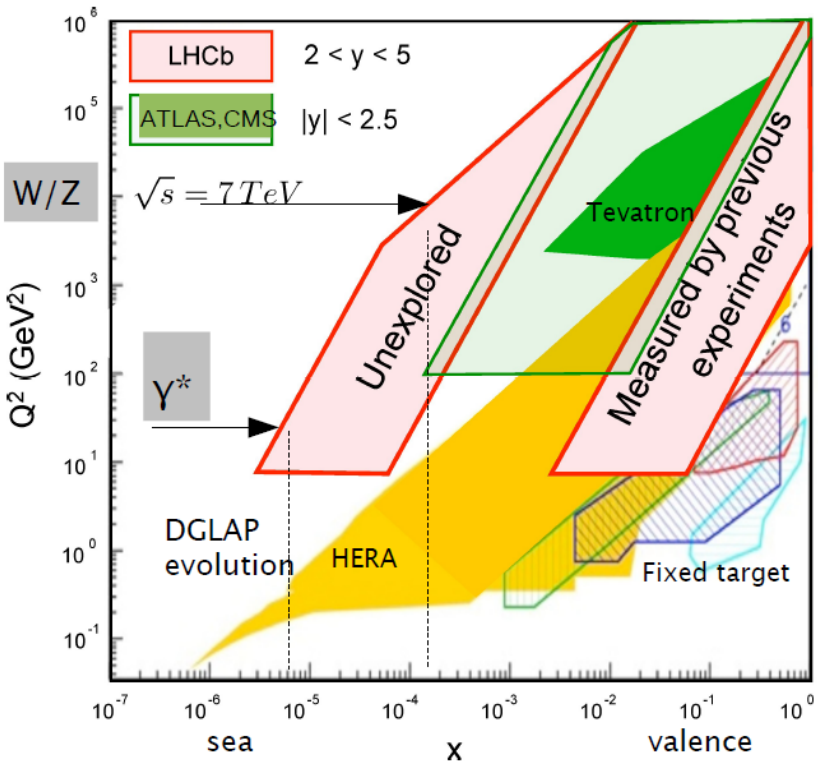
$$x' = x \cos\delta + y \sin\delta \qquad y' = y \cos\delta - x \sin\delta$$

δ is a strong phase difference between DCS and CF amplitudes

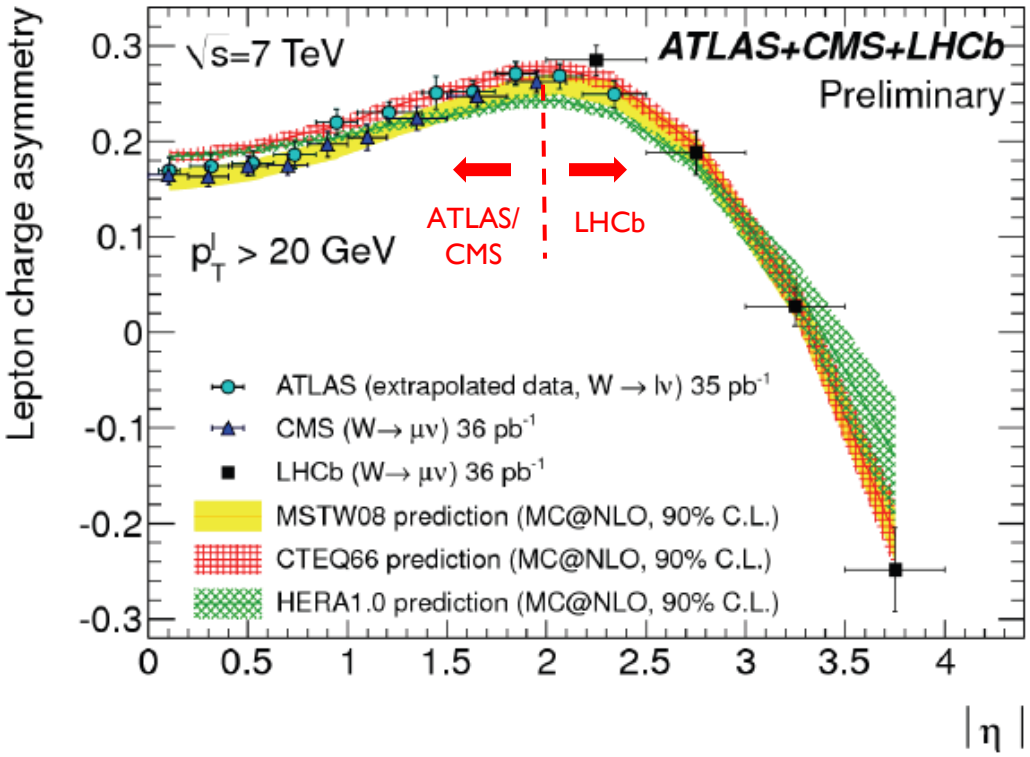
W/Z production

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

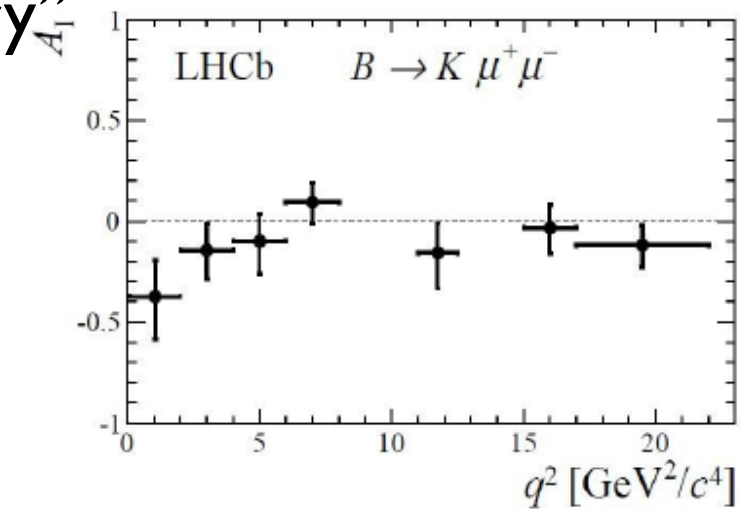
- LHCb measure "isospin asymmetry"

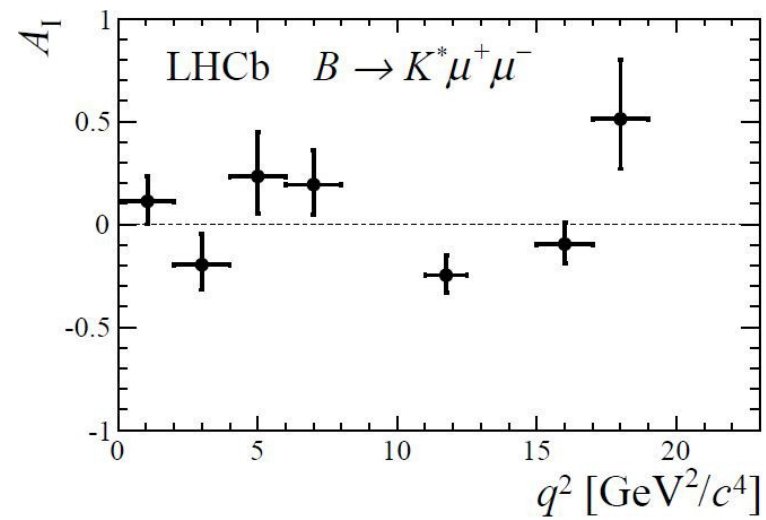
$$\frac{\Gamma(B^0\to K^0\mu^+\mu^-)-\Gamma(B^+\to K^+\mu^+\mu^-)}{\Gamma(B^0\to K^0\mu^+\mu^-)+\Gamma(B^+\to K^+\mu^+\mu^-)}$$

- Expected to be ~zero in SM
- Significant had emerged (4.6σ from zero) in early K^0 data not in K^*).

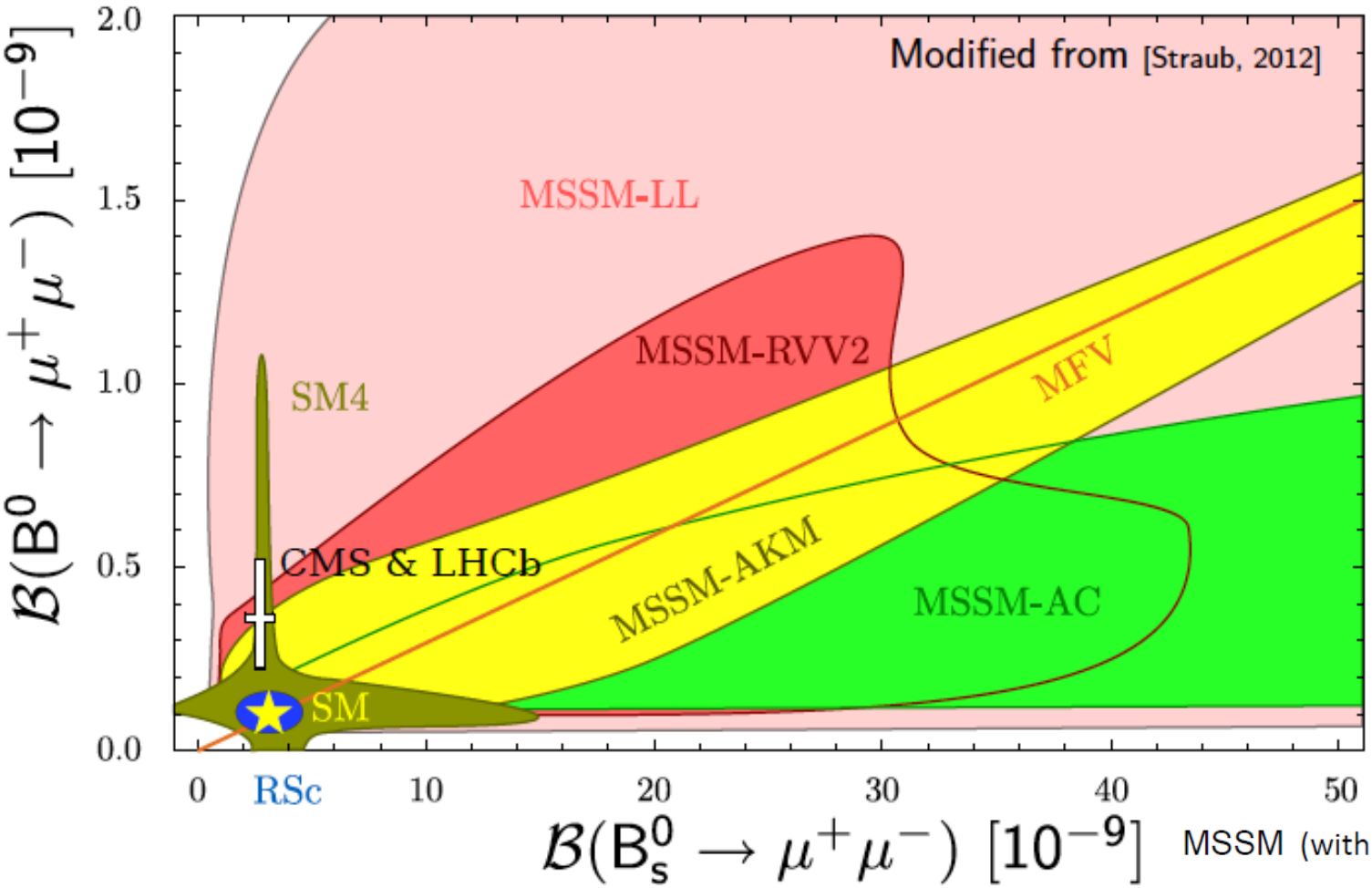
JHEP 7 (2012) 133

- With full 3 fb^{-1} data set the isospin asymmetry is compatible with zero at the 1.5σ level





Constraints on new physics models



MSSM (with R-Parity conservation)

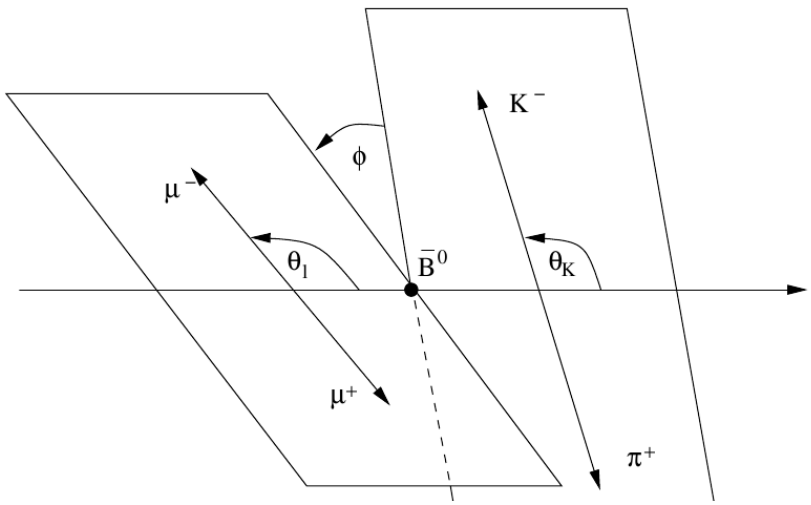
$$B(B_s \to \mu^+\mu^-)\ \alpha\ \frac{\tan^6\beta}{m_A^4}$$

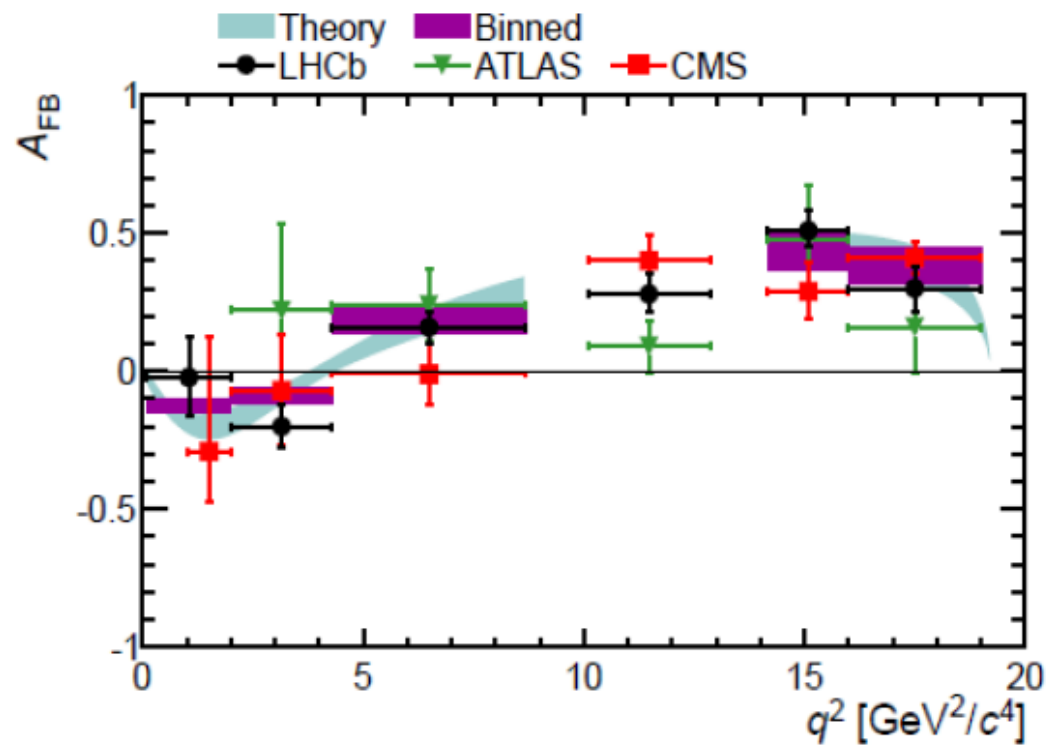
Straub Moriond 2012
(http://phys.davidstraub.de/files/dstraub-moriond12.pdf)

$B^0 \to K^*\mu^+\mu^-$ F-B asymmetry

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 (and now ATLAS & CMS) consistent with Standard Model





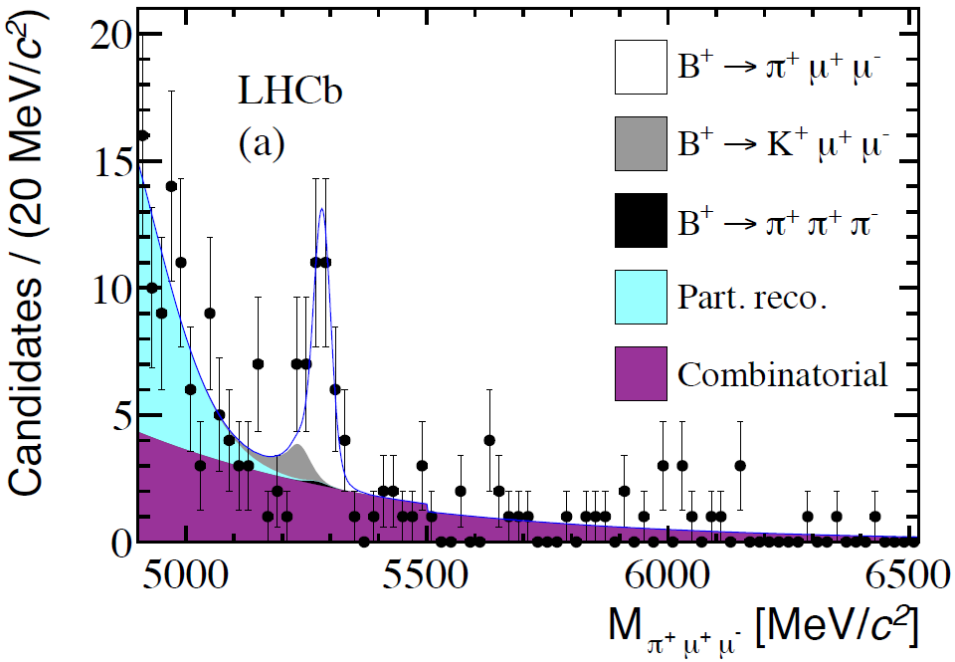
$B^+ \to \pi^+\mu^+\mu^-$ rare penguin decay

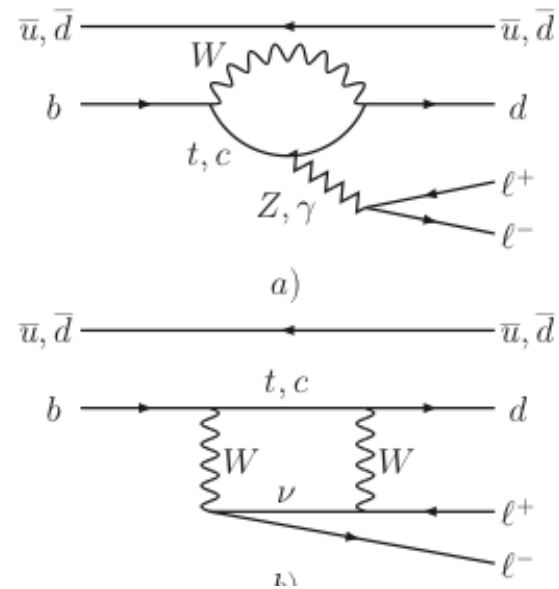
- $B^+ \to \pi^+\mu^+\mu^-$

  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)

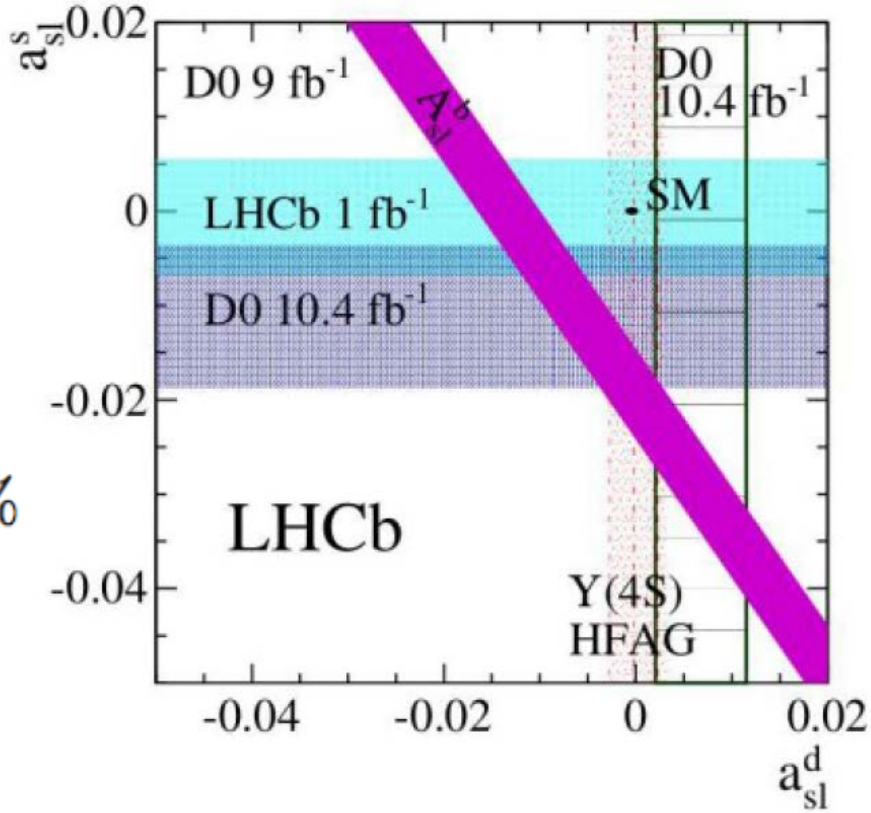
- LHCb 1 fb^{-1} result for a^s_{sl}

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

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

arxiv: 1308.1048

- D0 result not confirmed nor ruled out.



Standard Model predictions

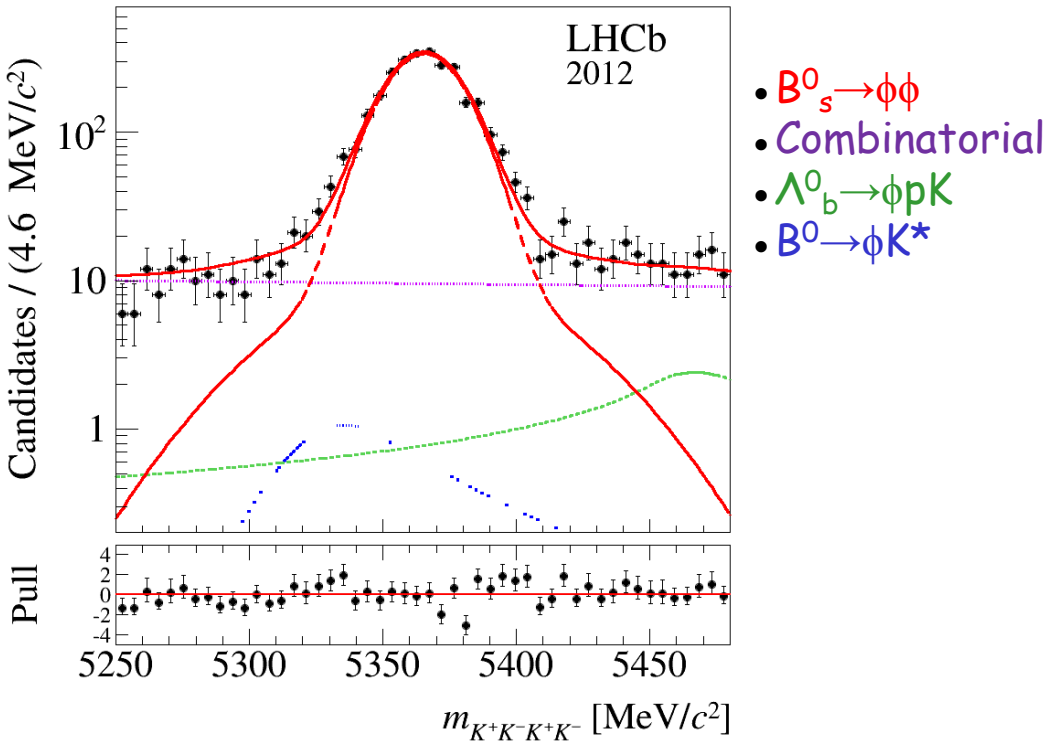
$$a^s_{sl} = (1.9 \pm 0.3) \times 10^{-5}$$
$$a^d_{sl} = (-4.1 \pm 0.6) \times 10^{-4}$$

A.Lenz
arXiv:1205.1444

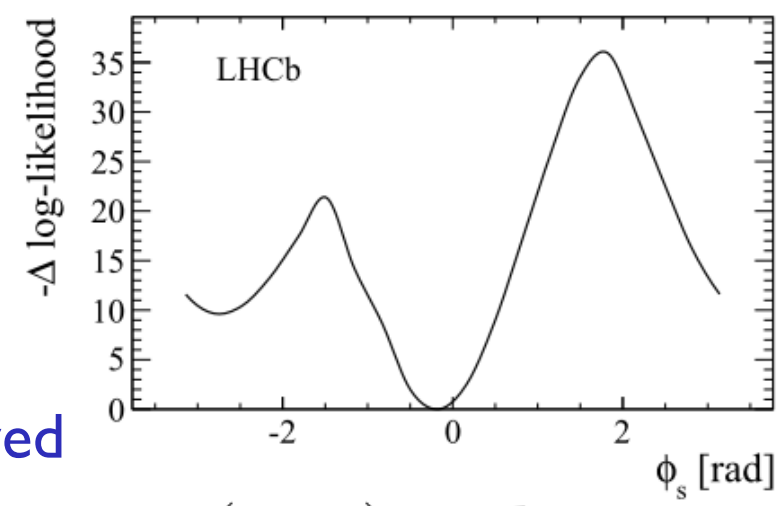
$B^0_s \to \varphi\varphi$

arXiv:1407.2222

- Current status of LHCb's $B^0_s \to \phi\phi$ measurement



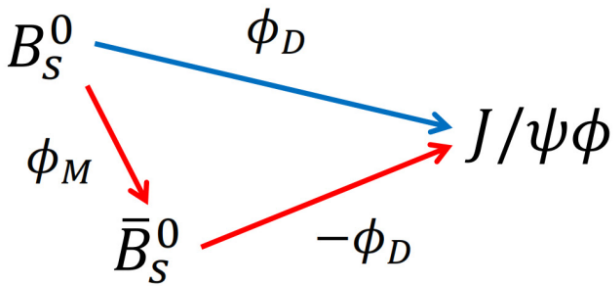
- N_{events} ~ 4000 of $B^0_s \to \phi(K^+K^-)\phi(K^+K^-)$
- A vector-vector decay; a mixture of CP even and CP odd distributions

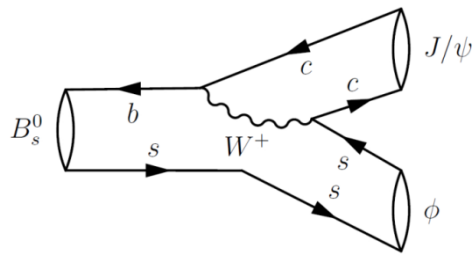


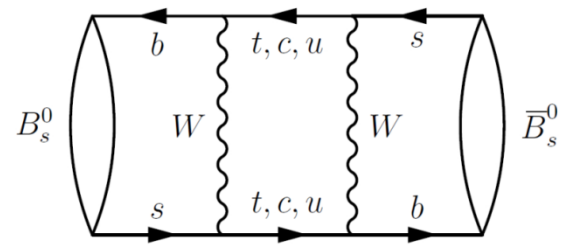
- No significant CP violation observed

$$\phi_s = -0.17 \pm 0.15\,(\text{stat}) \pm 0.03\,(\text{syst})\ \text{rad}$$

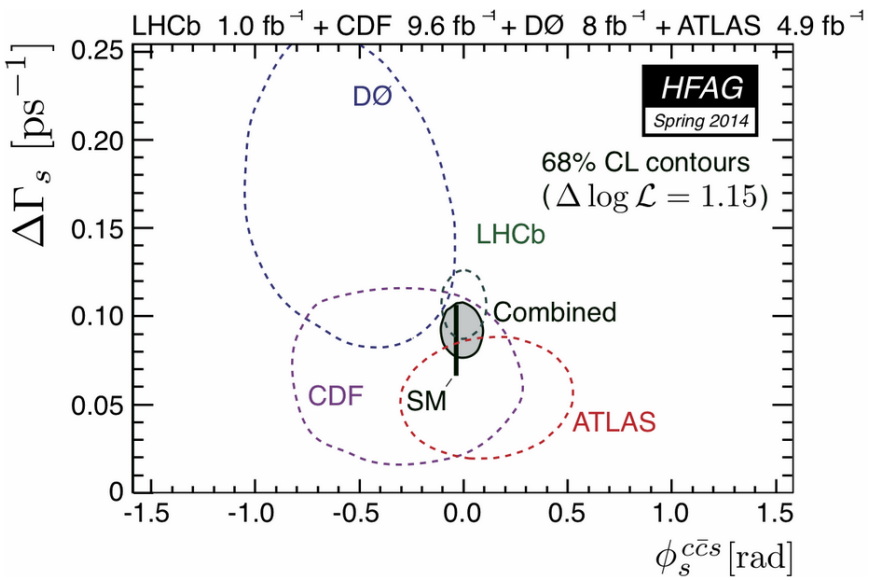
B_s weak mixing phase ϕ_s in $B_s \to J/\psi\ \phi$

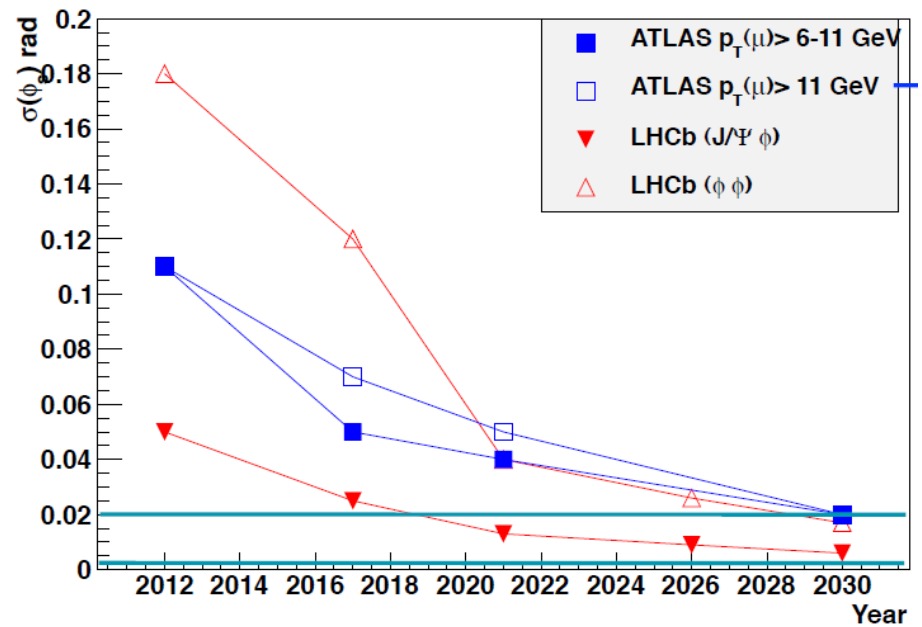






- Measurements by ATLAS, CMS and LHCb:
  LHCb (50 fb^{-1}): $\delta\varphi_s \approx \pm\ 0.009$ (SM -0.036 ±0.003) (current meas. ± 0.07)





Complementarity with Belle-II

LHCb

ATLAS & CMS

- Rare decays: $B_{d,s} \to \mu\mu$
- B_s system
- b-baryons
- Spectroscopy
- CKM phases (β, γ)
- Gluonic penguins
- EW penguins
- Charm physics
- Semileptonics: Mixing, A_{SL}
- Semileptonics: V_{xb}
- $B \to \tau\nu$, $D\tau\mu$,
- $B \to K^*\nu\nu$
- τ-physics

Some only LHCb, some only Belle II

On-going

Belle II

Why upgrade: current LHCb limitations

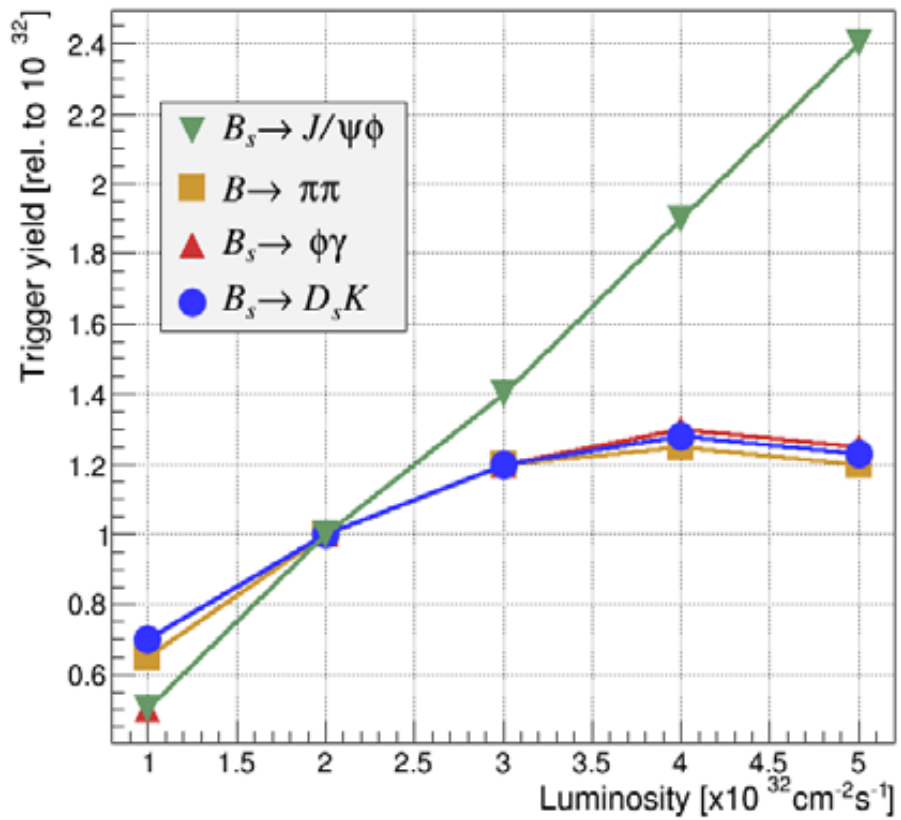
- No evidence for New Physics in LHC Run1
  - Need more (x10 or more) data, aiming at experimental sensitivities comparable to theoretical uncertainties

- Need to increase levelled luminosity from 0.4×10^{33} up to $2\times10^{33}cm^{-2}s^{-1}$ (pile-up ~8)

- However the current 1 MHz level-0 trigger output is a severe limitation!

- If we increase the luminosity
  - Need harder cuts on P_t due to the 1 MHz bandwidth limit
  - The trigger yield of hadronic events saturates
  - there's no real gain in statistics

Need a radical change in the trigger strategy to get to $5pb^{-1}$ per year



The timeline …