CP violation in $B_{(s)}$ decays to final states including charmonia @ LHCb

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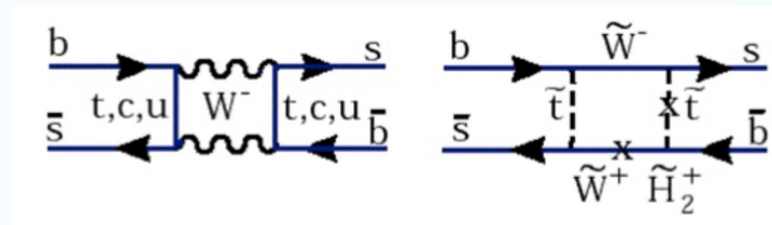
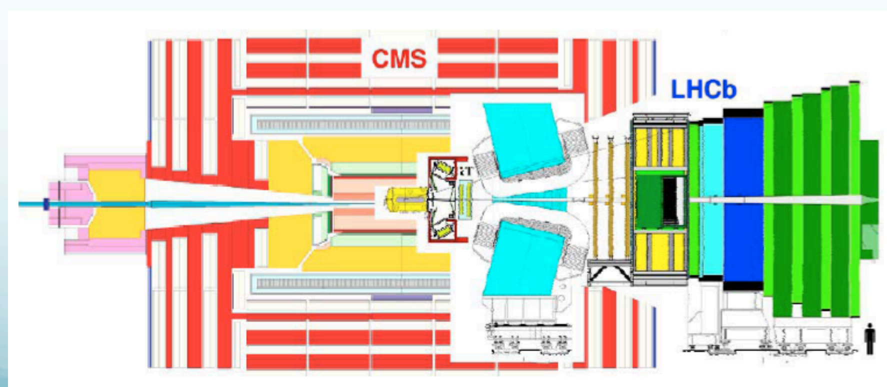
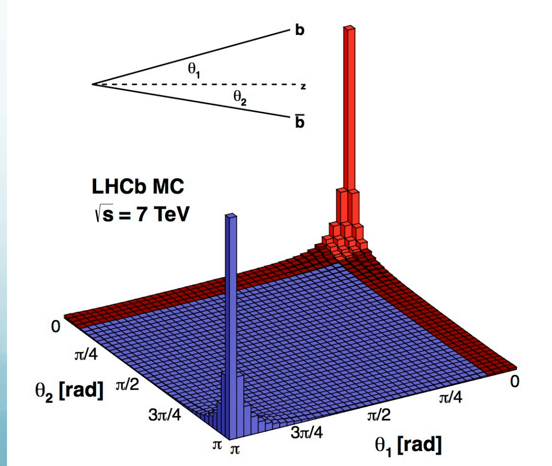
LHCb experiment

- Complementary to B Factories (look for B_s sector)
- Complementary to ATLAS and CMS
  - Dedicated to flavour physics in B (and D) sector(s)
  - LHCb searches for indirect effect of New Physics through loop diagrams sensitive to higher mass scales

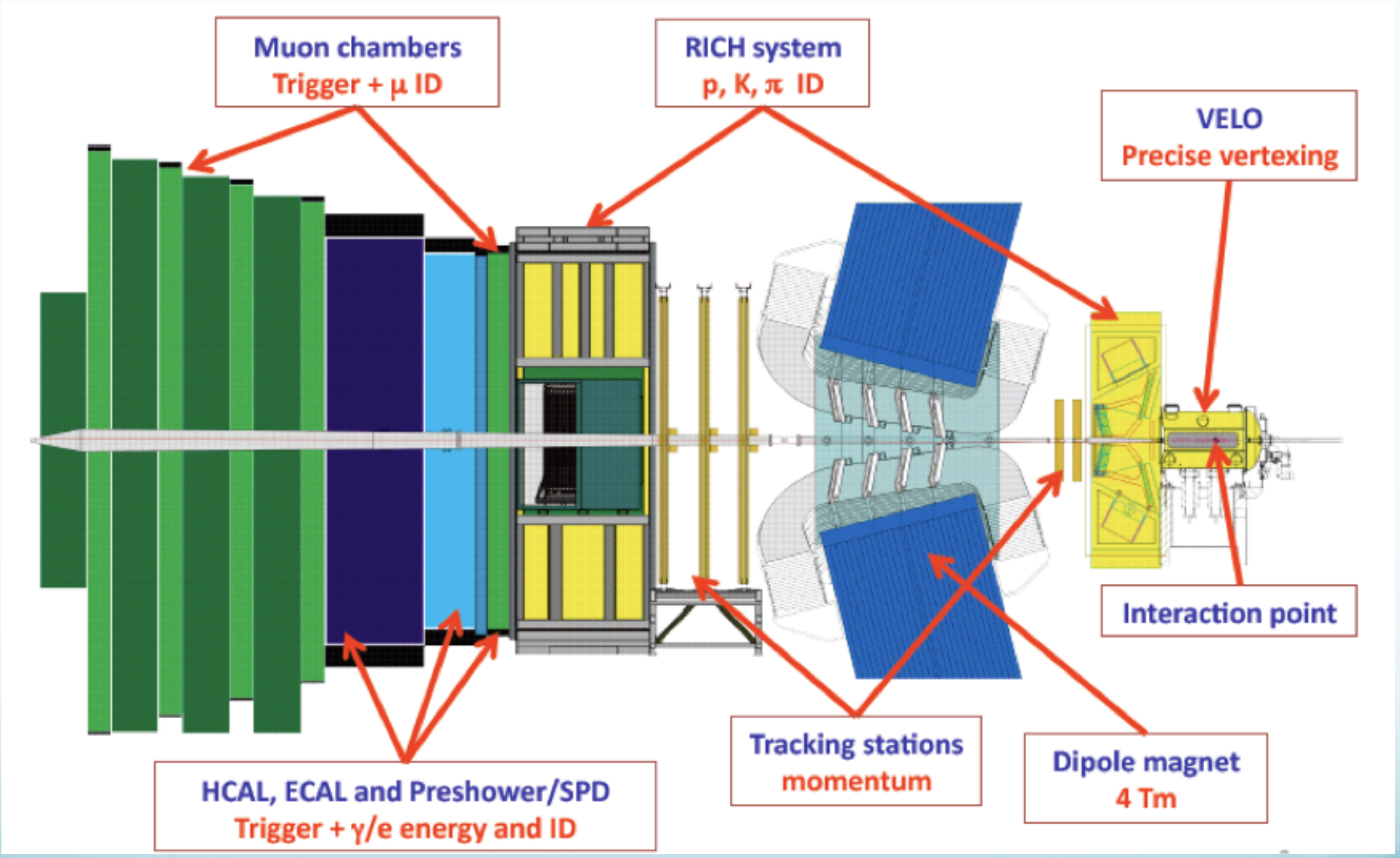


  - Forward spectrometer as $b\bar{b}$ are boosted along beam axis $2 < \eta < 5$





LHCb experiment

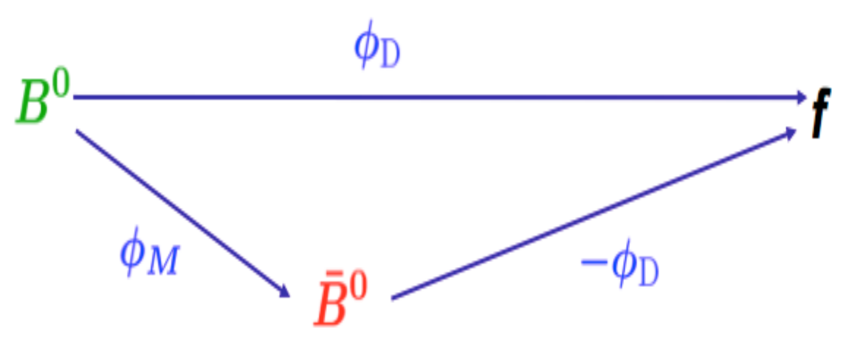


LHCb performance

- VELO silicon planes gets closer (8 mm) to beam in collision mode ➔ IP resolution of ~12 μm and proper time of ~40fs
- 2 RICH detectors give better particle identification (p/K/π) separation 2-100GeV/c
- Tracking system gives a resolution of σp/p ~0.5% (2-100GeV/c)
- In 2011: 1.0 fb^{-1} recorded: ~3.10^{11} $b\bar{b}$ pairs produced

Indirect CP

- When both B^0, B_s and $\overline{B^0}, \overline{B_s}$ have the same final state we can have CP asymmetry in the interference between decay and mixing

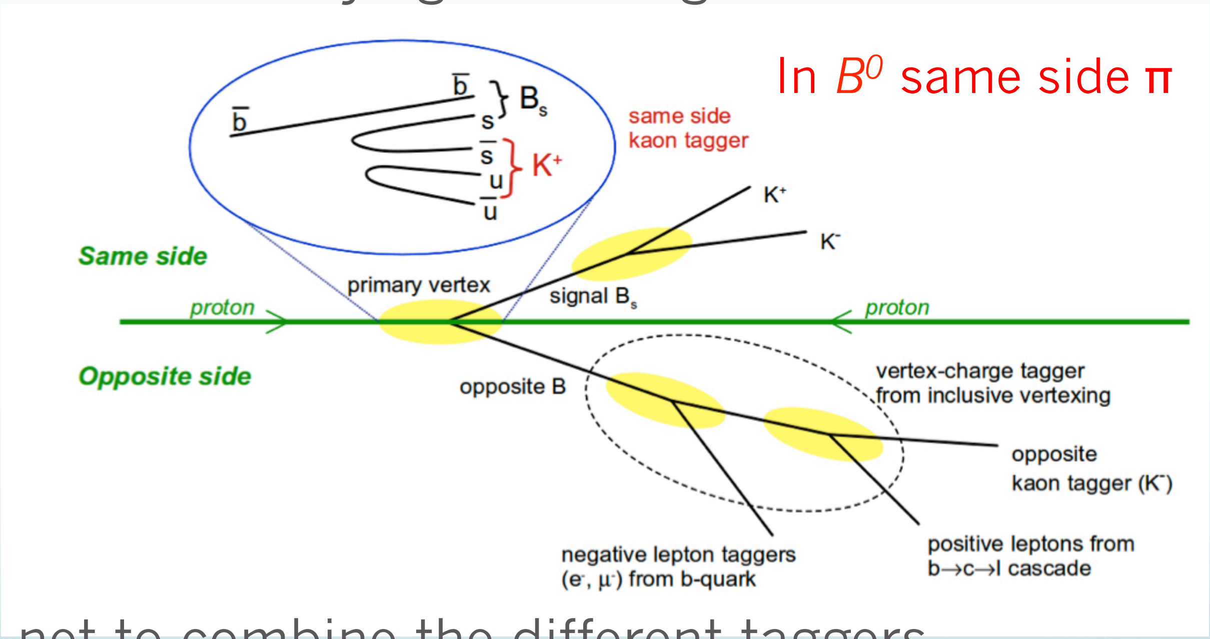


$$\Phi_f = \Phi_M - 2\,\Phi_D$$

- Same is true for B_s
- Have to measure the oscillation and the flavour of the B^0, B_s at t=0

Tagging system

- Flavour Tagging is the procedure to determine the flavour of the reconstructed B meson at production
- Looks for the underlying event to get an answer



- Neural net to combine the different taggers

Tagging system

- Calibrate tagging using flavour specific decays as $B^+ \rightarrow J/\psi K^+$

$$\varepsilon_{tag} = \frac{N_R + N_W}{N_R + N_W + N_U} \qquad \omega = \frac{N_W}{N_R + N_W}$$

$$\varepsilon_{eff} = \varepsilon_{tag}(1 - 2\omega)^2$$

- Dilution depends on final state and we have a per event ω
- Combined tagging power ε_{eff}=(3.4±0.3)% (for $B_s \rightarrow J/\psi\, \Phi$)

CPV in $B^0 \rightarrow J/\psi K_S$

- We measure the time-dependent asymmetry (assuming $\Delta\Gamma=0$)

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

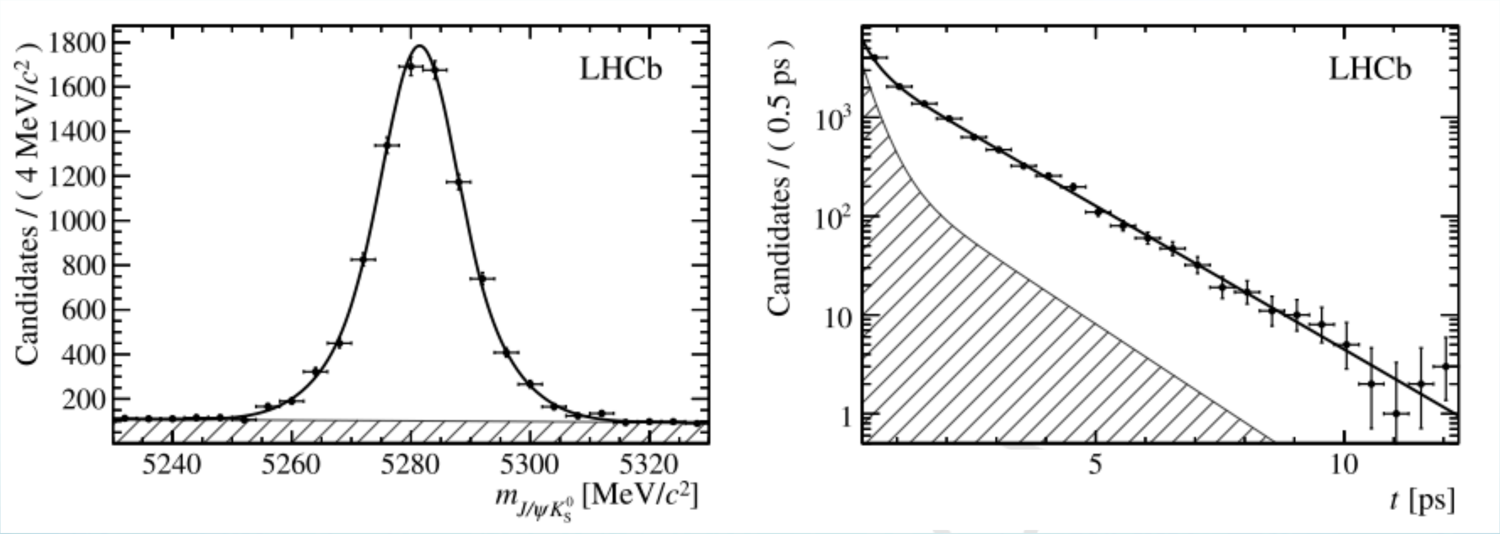
- In SM $C_{J/\psi KS}=0$ and $S_{J/\psi KS}=\sin 2\beta$ ($2\beta=\Phi_f$)
- One of the most precisely CP parameter measured

$\sin 2\beta = 0.679 \pm 0.020$ (CKM fitter)

- Good test for the analysis method (and Flavour tagging)

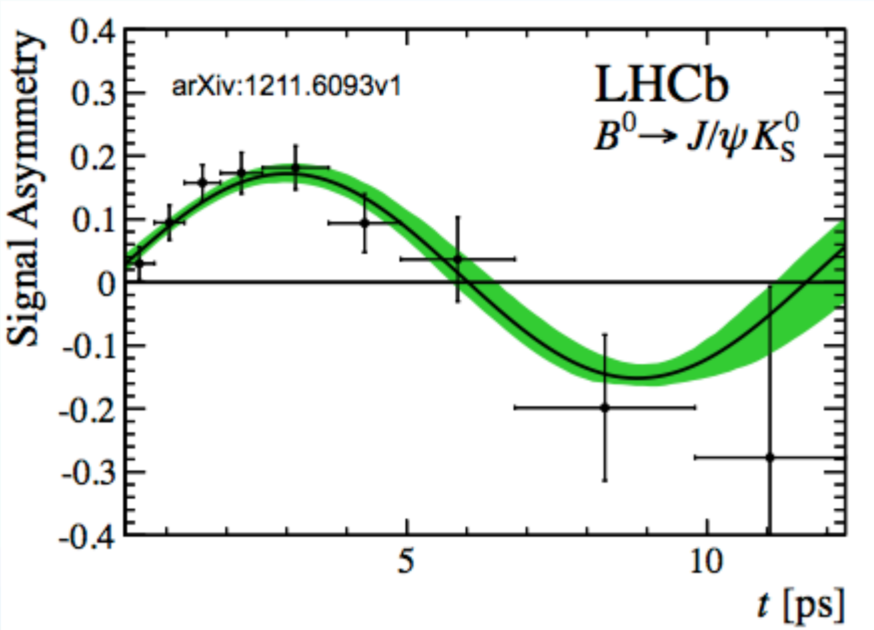
CPV in $B^0 \rightarrow J/\psi K_S$

- Analysis with ~8200 events in 1.0fb^{-1}
- Simultaneous MLL fit to mass and proper-time (more than 20 parameters)



arXiv:1211.6093v1, accepted by PLB

CPV in $B^0 \to J/\psi K_S$



$$S_{J/\psi K^0_S} = 0.73 \pm 0.07_{\text{stat}} \pm 0.04_{\text{syst}}$$
$$C_{J/\psi K^0_S} = 0.03 \pm 0.09_{\text{stat}} \pm 0.01_{\text{syst}}$$

arXiv:1211.6093v1, accepted by PLB

- First measurement of S in hadronic environment
- C compatible with SM and S with WA

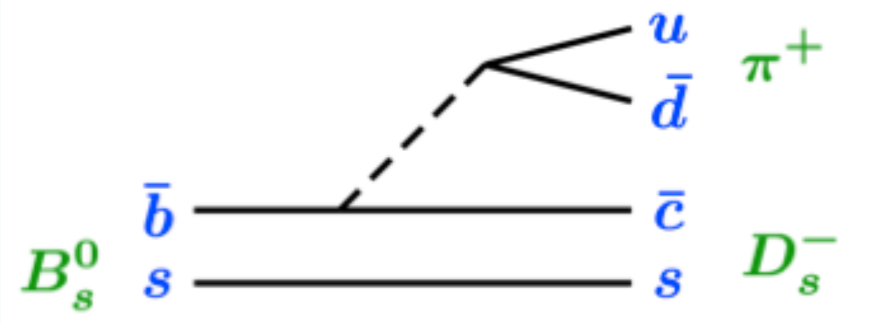
sin2β=0.679±0.020

- Systematics will also go down with more statistics

CPV in B_s system

- Can do a similar analysis in B_s system
- B_s oscillates much faster than B^0 ➔need precise measurement of Δms
- Better channel is B_s➔$D_s^-\pi^+$
- Using 5 different D_s modes

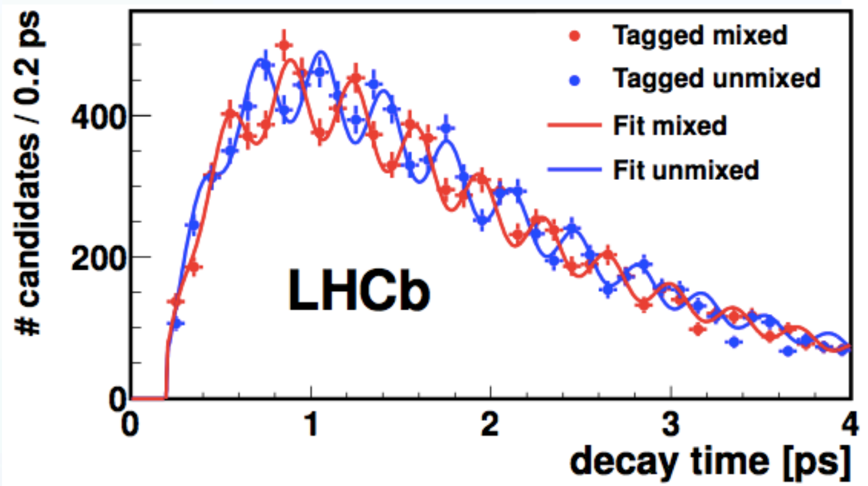
  (adds up to ~34 k events in 1.0 fb^{-1})

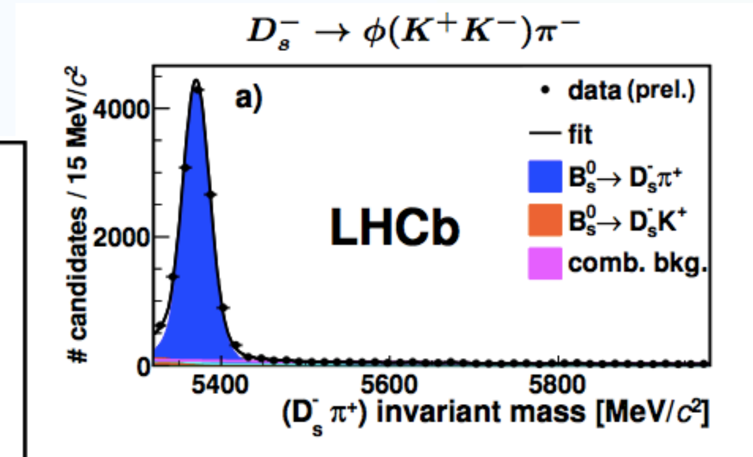


$$D_s^- \to \phi(K^+K^-)\pi^-$$
$$D_s^- \to K^{*0}(K^+\pi^-)K^-$$
$$D_s^- \to K^+K^-\pi^-$$
$$D_s^- \to K^-\pi^+\pi^-$$
$$D_s^- \to \pi^-\pi^+\pi^-$$

$\Delta\, m_s$ measurement

- With ~34k events in 1 fb^{-1}





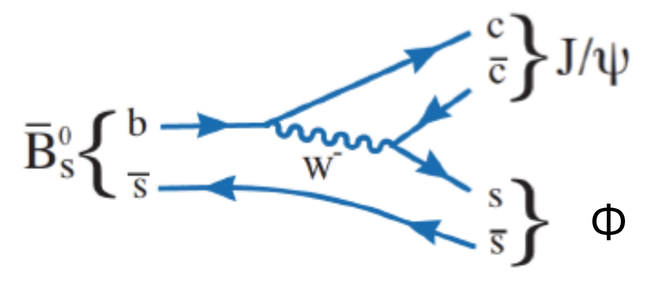
$$\Delta m_s = (17.728 \pm 0.023 \pm 0.006)\ \text{ps}^{-1}$$

Compatible with SM prediction
$\Delta\, m_s = (17.3 \pm 2.6)\text{ps}^{-1}$

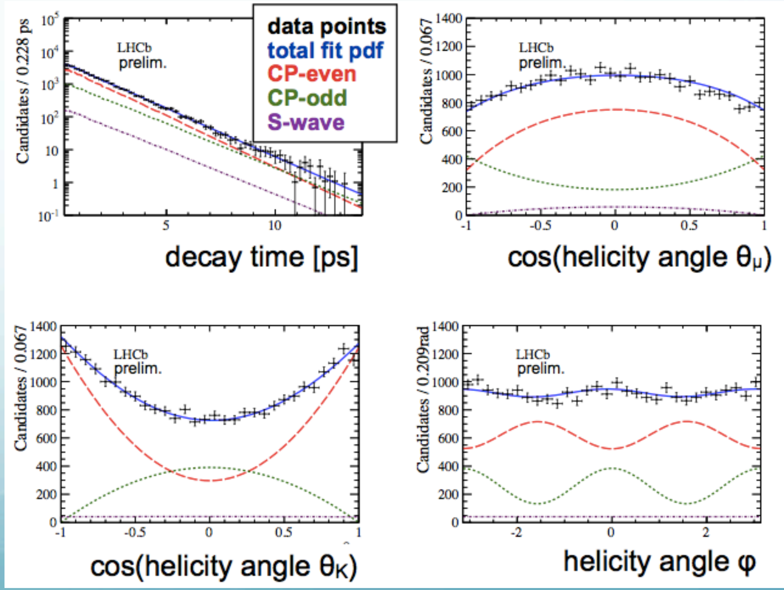
LHCB-PAPER-2013-006, preliminary

- World's most precise measurement

$B_s \rightarrow J/\psi\, \Phi$



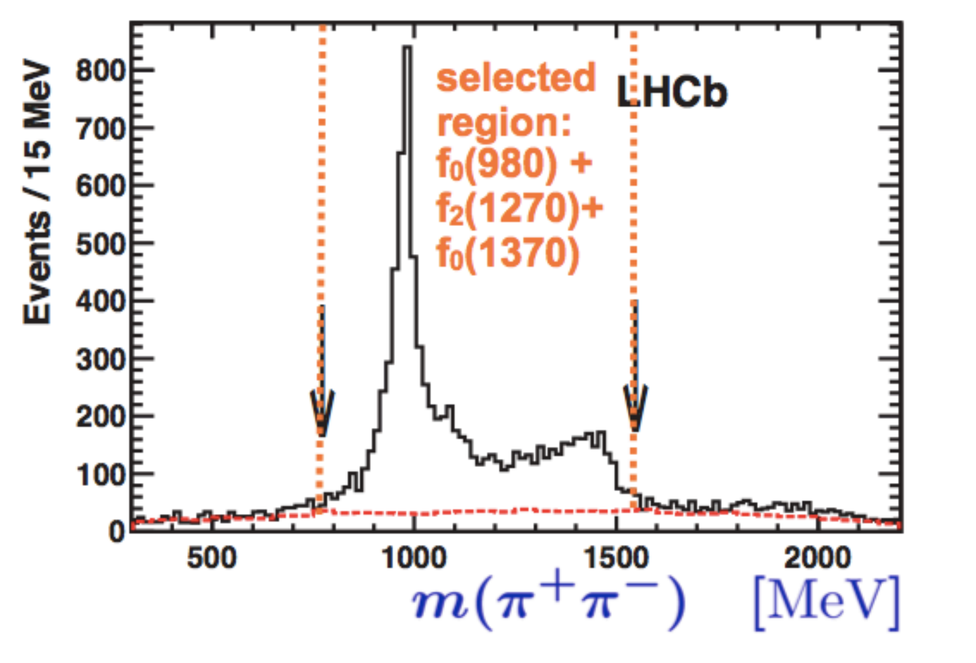
- Golden mode for Φ_s (Analogue in B_s sector to $B^0 \rightarrow J/\psi K_S$)
- Very small well predicted in SM Φ_s=(-0.036±0.002) rad (CKM fitter)
- New Physics could add large terms to Φ_s
- VV final state: is not a CP eigenstate and needs to separate CP odd and even components with angular analysis (s-wave ~ 1%)
- Described using transversity basis



$B_s \rightarrow J/\psi \pi^+\pi^-$

- There is a vector-pseudo scalar final state with the same diagram as $B_s \rightarrow J/\psi\, \Phi$
- $B_s \rightarrow J/\psi \pi^+\pi^-$ (dominated $f_0(980)$)
- No angular analysis needed
- Is CP eigenstate (CP-odd)
- ~1/3 of $B_s \rightarrow J/\psi\, \Phi$ yield
- First observed by LHCb in 2011

PRD 86(2012) 052006



$B_s \to J/\psi\pi^+\pi^-$

- There is a vector-pseudo scalar final state with the same diagram as $B_s \to J/\psi\,\Phi$
- $B_s \to J/\psi f_{0,2}(\pi^+\pi^-)$
- No angular analysis needed
- Is CP eigenstate (CP-odd)
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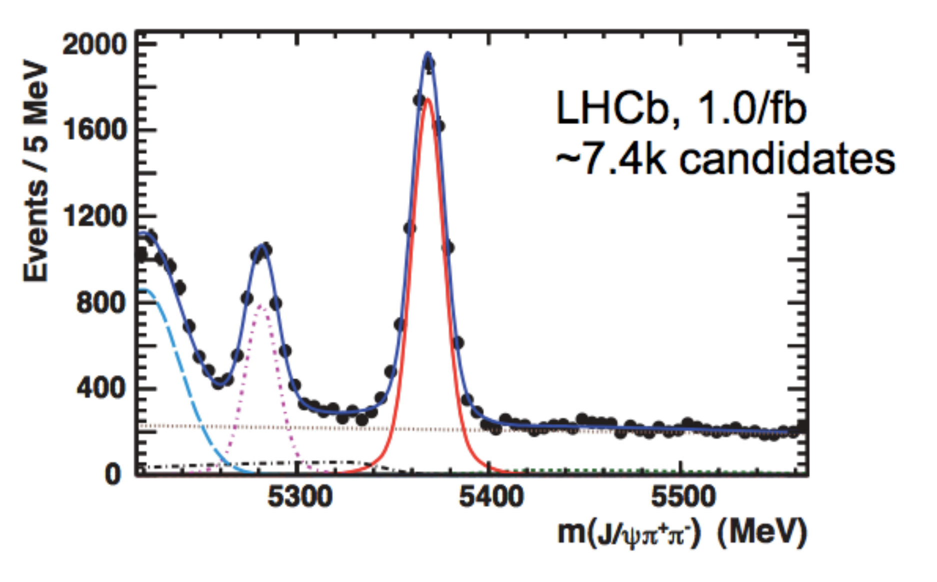
- First observed by LHCb in 2011

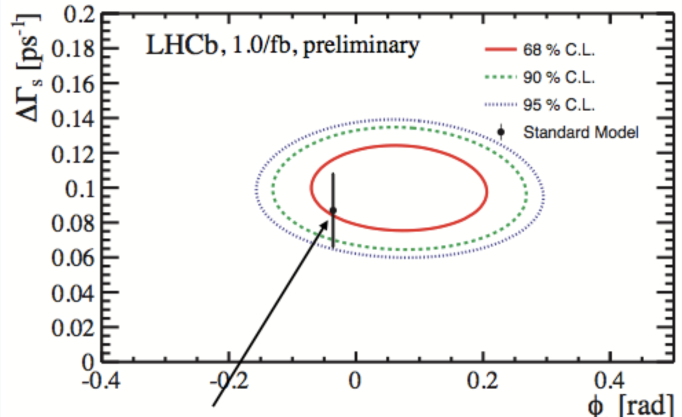
PLB 713(2012) 378



Φ_s fit results

- Results MLL fit for $B_s \rightarrow J/\psi\, \Phi$

ϕ_s	$= 0.07$	± 0.09 (stat)	± 0.01 (syst)	rad
Γ_s	$= 0.663$	± 0.005 (stat)	± 0.006 (syst)	ps^{-1}
$\Delta\Gamma_s$	$= 0.100$	± 0.016 (stat)	± 0.003 (syst)	ps^{-1}
$\lvert\lambda\rvert$	$= 0.94$	± 0.03 (stat)	± 0.02 (syst)	



SM: Lenz and Nierste, arXiv: 1102.4274, CKM fitter, arXiv:1106.4041

- Main systematics

  due to acceptance of the angles

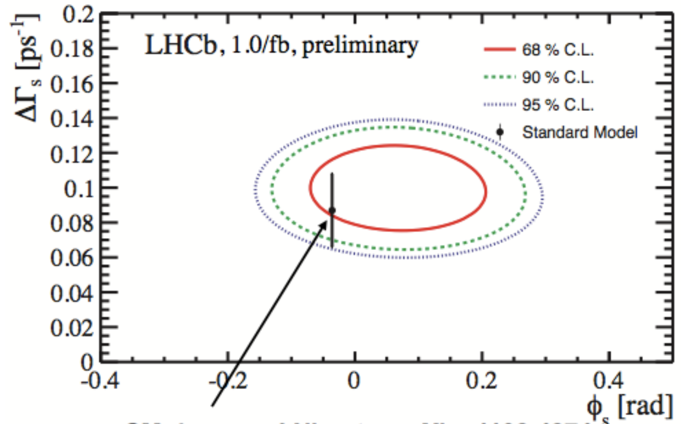
LHCB-PAPER-2013-002, preliminary

Φ_s fit results

LHCB-PAPER-2013-002, preliminary

- Results MLL fit for $B_s \rightarrow J/\psi\,\Phi$

$$\begin{aligned}
\phi_s &= 0.07 \pm 0.09\ (\mathrm{stat}) \pm 0.01\ (\mathrm{syst})\ \mathrm{rad} \\
\Gamma_s &= 0.663 \pm 0.005\ (\mathrm{stat}) \pm 0.006\ (\mathrm{syst})\ \mathrm{ps}^{-1} \\
\Delta\Gamma_s &= 0.100 \pm 0.016\ (\mathrm{stat}) \pm 0.003\ (\mathrm{syst})\ \mathrm{ps}^{-1} \\
|\lambda| &= 0.94 \pm 0.03\ (\mathrm{stat}) \pm 0.02\ (\mathrm{syst})
\end{aligned}$$



SM: Lenz and Nierste, arXiv: 1102.4274,
CKM fitter, arXiv:1106.4041

- Main systematics

  due to acceptance of the angles

- Enough data to also measure Δm_s

$$\Delta m_s = (17.70 \pm 0.10 \pm 0.01)\ \mathrm{ps}^{-1}$$

- Good agreement with $B_s \rightarrow D_s^- \pi^+$

Φ_s fit results

- Results for $B_s \rightarrow J/\psi\pi^+\pi^-$

$$\phi_s = -0.14^{+0.17}_{-0.16} \pm 0.01$$

- Combining the results from $B_s \rightarrow J/\psi\,\Phi$ and $B_s \rightarrow J/\psi\pi^+\pi^-$

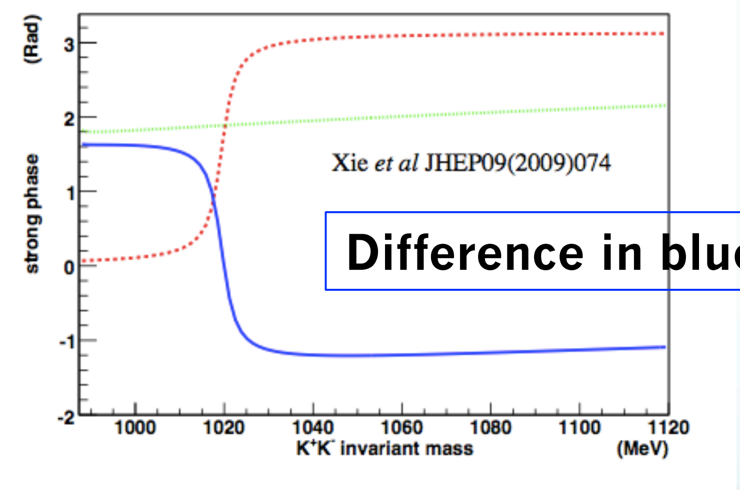
$$\begin{aligned}
\phi_s &= 0.01 \pm 0.07\ (\text{stat}) \pm 0.01\ (\text{syst})\ \text{rad},\\
\Gamma_s &= 0.661 \pm 0.004\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1},\\
\Delta\Gamma_s &= 0.106 \pm 0.011\ (\text{stat}) \pm 0.007\ (\text{syst})\ \text{ps}^{-1}.
\end{aligned}$$

- +ambigous solution $(\Phi_s, \Delta\Gamma_s) \rightarrow (\Pi - \Phi_s, -\Delta\Gamma_s)$

PLB 713 (2012) + LHCB-PAPER-2013-002, preliminary

Solution of ambiguity

- To solve ambiguity it is possible to measure the difference between S-wave and P-wave in bins of K^+K^- mass



Difference in blue

Solution of ambiguity

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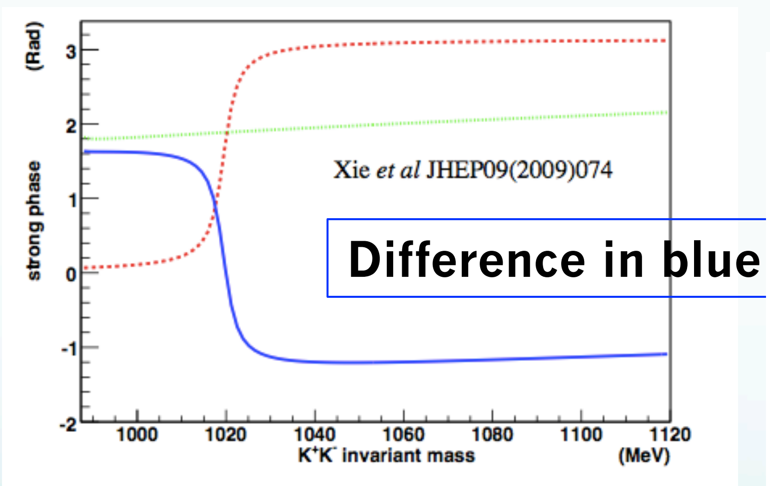
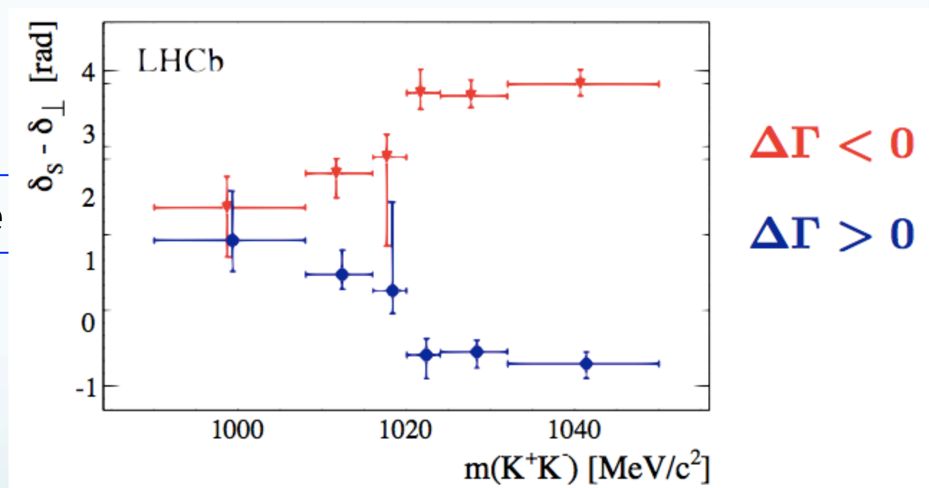




- Only $\Delta\Gamma_s > 0$ fits the expected pattern

Conclusion

- LHCb produced very interesting results of CP violation in B to charmonia decays
  - sin2β in $B^0 \to J/\Psi K_S$:

arXiv:1211.6093v1, acc. by PLB

$$S_{J/\psi K^0_S} = 0.73 \pm 0.07_{\text{stat}} \pm 0.04_{\text{syst}}$$
$$C_{J/\psi K^0_S} = 0.03 \pm 0.09_{\text{stat}} \pm 0.01_{\text{syst}}$$

  - B_s oscillation (mandatory ingredient)

    From $B_s \to D_s^- \pi^+$

LHCB-PAPER-2013-006, preliminary

$$\Delta m_s = (17.728 \pm 0.023 \pm 0.006)\,\text{ps}^{-1}$$

  - CP violation in $B_s \to J/\Psi\,\Phi, \pi^+\pi^-$:

LHCB-PAPER-2013-002, preliminary

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

Prospects

- All results presented are in good agreement with Standard Model
- All results are still limited by statistics
  - Update those results with 2012 data (2fb^{-1})
  - 2015-2017: 2x more data
  - With more data, we can measure penguin modes ($B_s \rightarrow J/\psi K_S$, $B_s \rightarrow D_S D_S$)

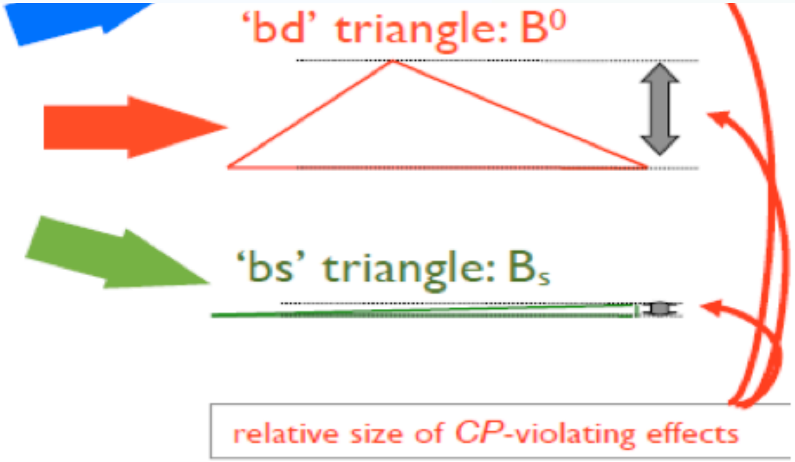
Backup

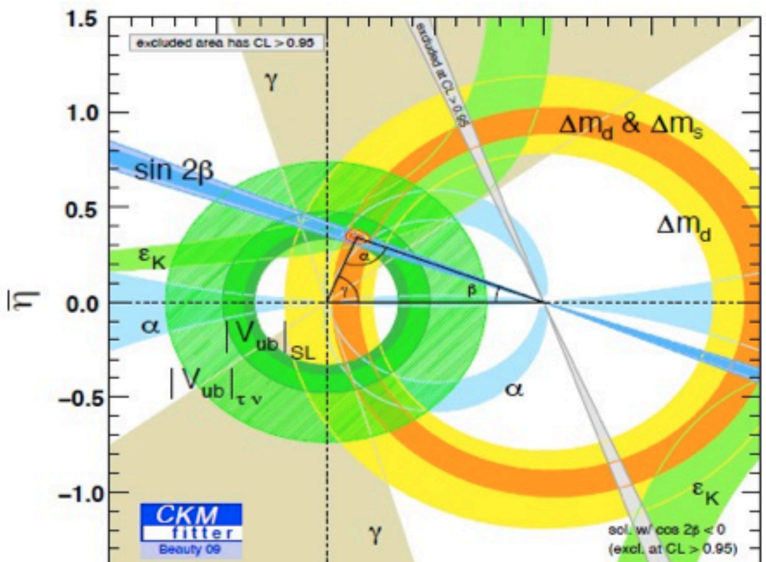
CKM triangles

$$V_{us}^*V_{ud} + V_{cs}^*V_{cd} + V_{ts}^*V_{td} = 0$$

$$V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0$$

$$V_{ub}^*V_{us} + V_{cb}^*V_{cs} + V_{tb}^*V_{ts} = 0$$





$$\alpha = \arg\left(-\frac{V_{tb}^*V_{td}}{V_{ub}^*V_{ud}}\right)$$

$$\gamma = \arg\left(-\frac{V_{ub}^*V_{ud}}{V_{cb}^*V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^*V_{cd}}{V_{tb}^*V_{td}}\right)$$

Tagging calibration

decision to be correct (η) is given by a neural net.

Calibration of η is needed to obtain an ω event per event

- Use per event mistag as observable $\omega = p_0 + p_1 \cdot (\eta - \bar{\eta})$
- $B^+ \rightarrow J/\psi K^+$ used for calibration, and the kinematically similar $B^0 \rightarrow J/\psi K^*$ is used as crosscheck

MC ω distribution/calibration totally compatible with $B^0 \rightarrow J/\psi K_s$

Study correction function between actual mistag and calibrated mistag

Expected	Obtained
$p_0 = \bar{\eta} = 0.35$	$p_0 = 0.333 \pm 0.025$
$p_1 = 1$	$p_1 = 0.71 \pm 0.36$

Φ_s

- In SM

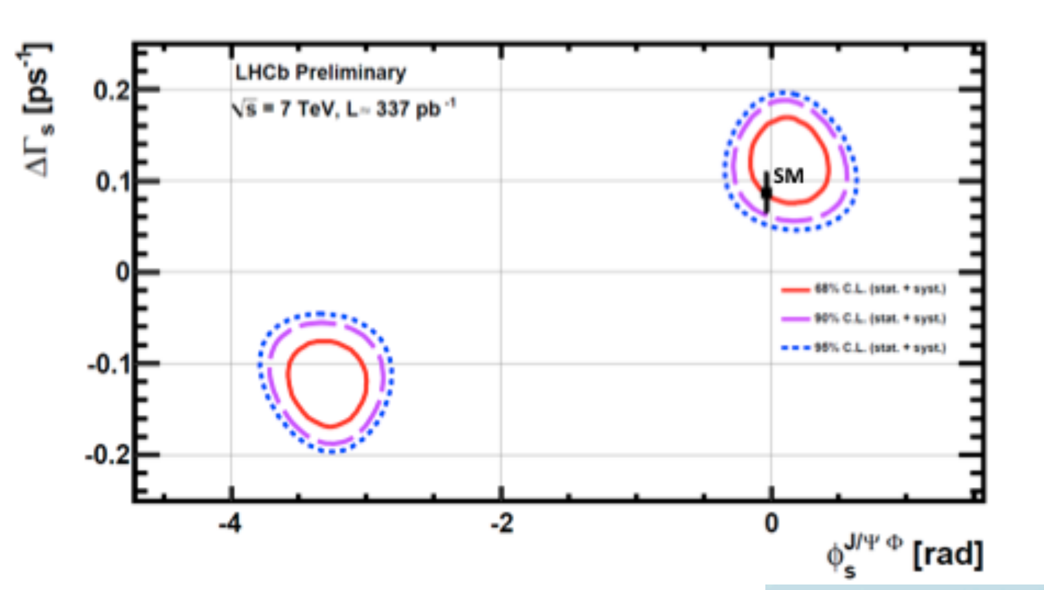
$$\phi_s = -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = (-0.036 \pm 0.002)rad$$

- We measure $\phi_s = \phi_s^{SM} + \phi^{NP}$
- Many NP terms can be added to Φ_s due to mixing: eg. SUSY, extra dimensions, 4th generation

$B_s \rightarrow J/\psi\ \Phi$ Fit

- Signal pdf depends on acceptance, flavour tagging andproper time resolution

$$S(\vec{\lambda}, t, \vec{\Omega}) = \epsilon(t, \vec{\Omega}) \times \left(\frac{1+qD}{2} s(\vec{\lambda}, t, \vec{\Omega}) + \frac{1-qD}{2} \bar{s}(\vec{\lambda}, t, \vec{\Omega}) \right) \otimes R_t$$



Angles definition