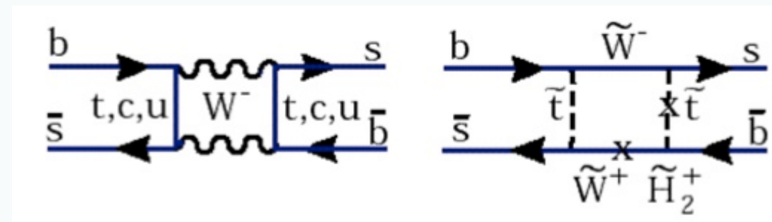
Measurements of CP violation in B_s^0 oscillations @ LHCb

B. Souza de Paula on behalf of LHCb Collaboration

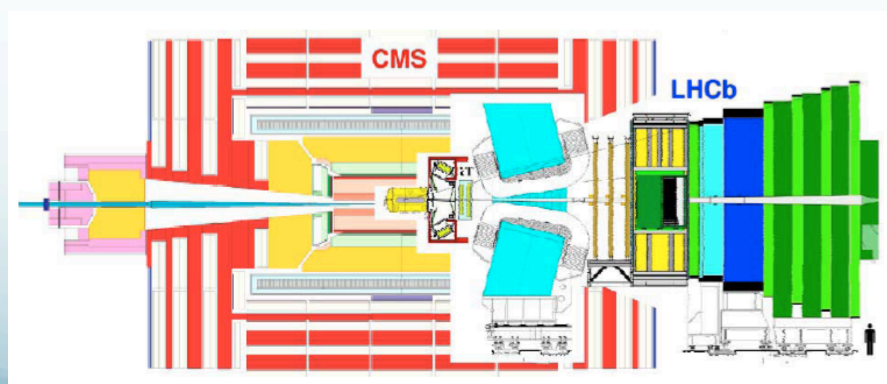
FPCP 2013– 21/5/2013 – Búzios-RJ

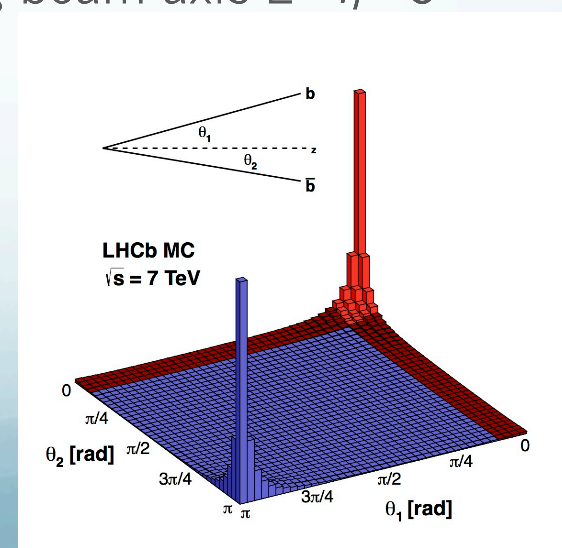
LHCb experiment

- 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

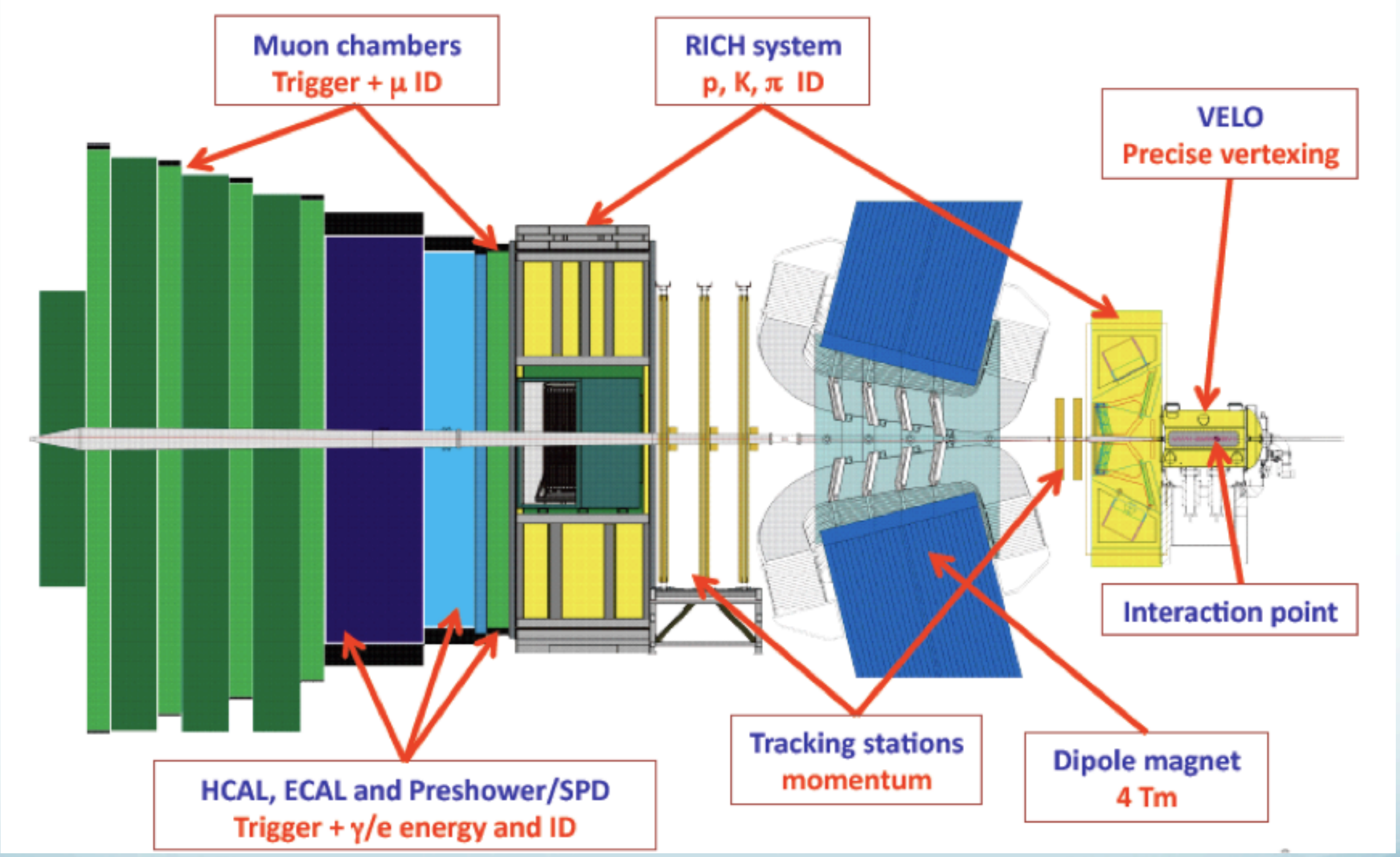


  - Forward spectrometer as $b\bar{b}$ are boosted along beam axis $2 < \eta < 5$





LHCb experiment

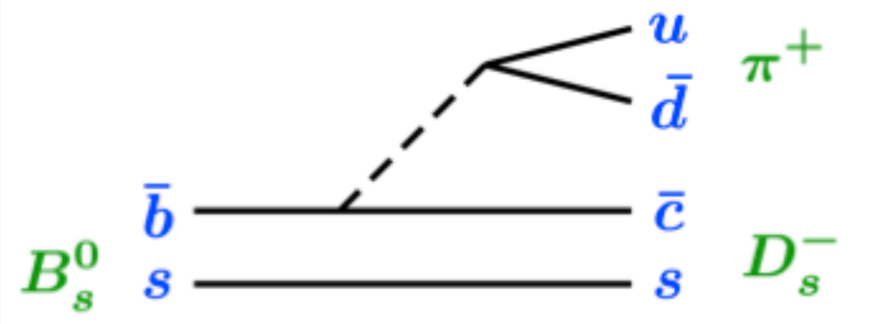


Results to be presented

- Oscillation frequency Δm_s from $B_s^0 \rightarrow D_s^- \pi^+$
- Mixing CP asymmetry a_{sl}^s
- Indirect CP violation phase Φ_s
  - From $B_s^0 \rightarrow J/\psi K^+ K^-$
  - From $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$
  - From $B_s^0 \rightarrow \phi\phi$
- All results presented with 1.0fb^{-1} recorded in 2011

B_s^0 oscillations

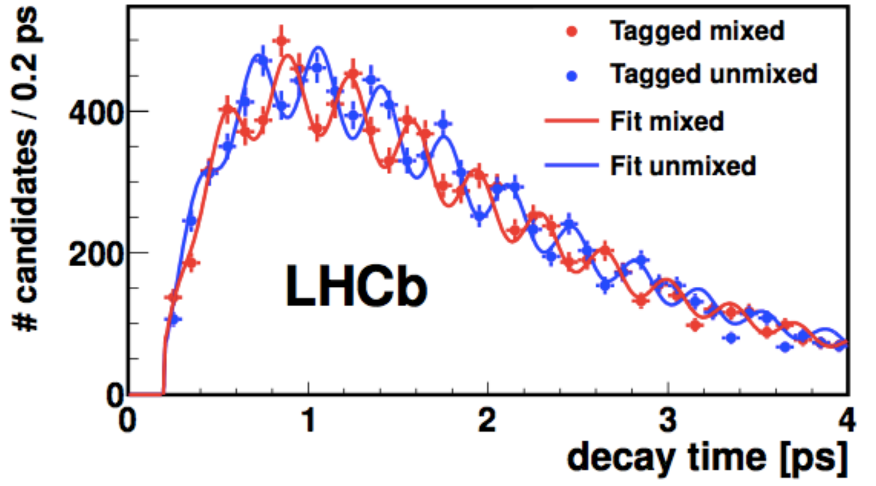
- B_s oscillates much faster than B^0 ➔need precise measurement of Δm_s for CPV measurements
- Better channel is $B_s^0 \to D_s^- \pi^+$
- Using 5 different D_s modes (adds up to ~34 k events in 1.0 fb^{-1})

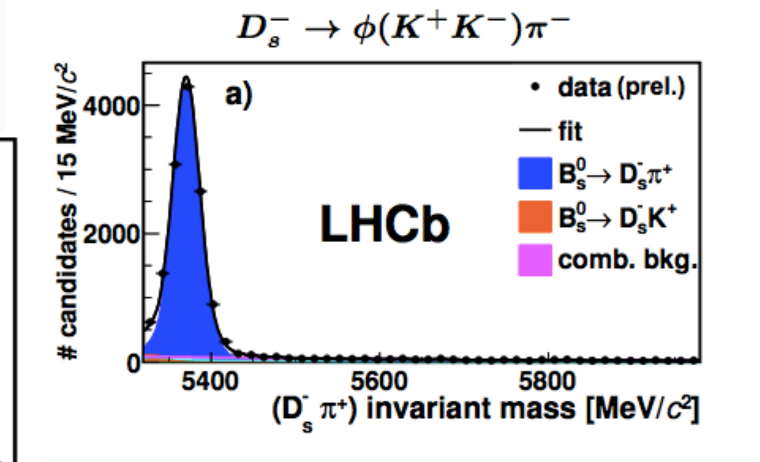


$$D_s^- \to \phi(K^+K^-)\pi^-$$
$$D_s^- \to K^{*0}(K^+\pi^-)K^-$$
$$D_s^- \to K^+K^-\pi^-$$
$$D_s^- \to K^-\pi^+\pi^-$$
$$D_s^- \to \pi^-\pi^+\pi^-$$

Δm_s measurement

- With ~34k events in 1.0fb^{-1}





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

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

- World's most precise measurement

arXiv:1304.4741, NJP **15** 053021

~~CP~~ in mixing

- With a flavour specific decay we can measure the time integrated CP asymmetry in $B_s^0 - \bar{B}_s^0$ mixing

$$a_{sl}^s = \frac{\Gamma\left(B_s^0 \to D_s^- \mu^+\right) - \Gamma\left(\bar{B}_s^0 \to D_s^+ \mu^-\right)}{\Gamma\left(B_s^0 \to D_s^- \mu^+\right) + \Gamma\left(\bar{B}_s^0 \to D_s^+ \mu^-\right)} \approx 1 - \left|\frac{q}{p}\right|^2$$

- The mass eigenstates are

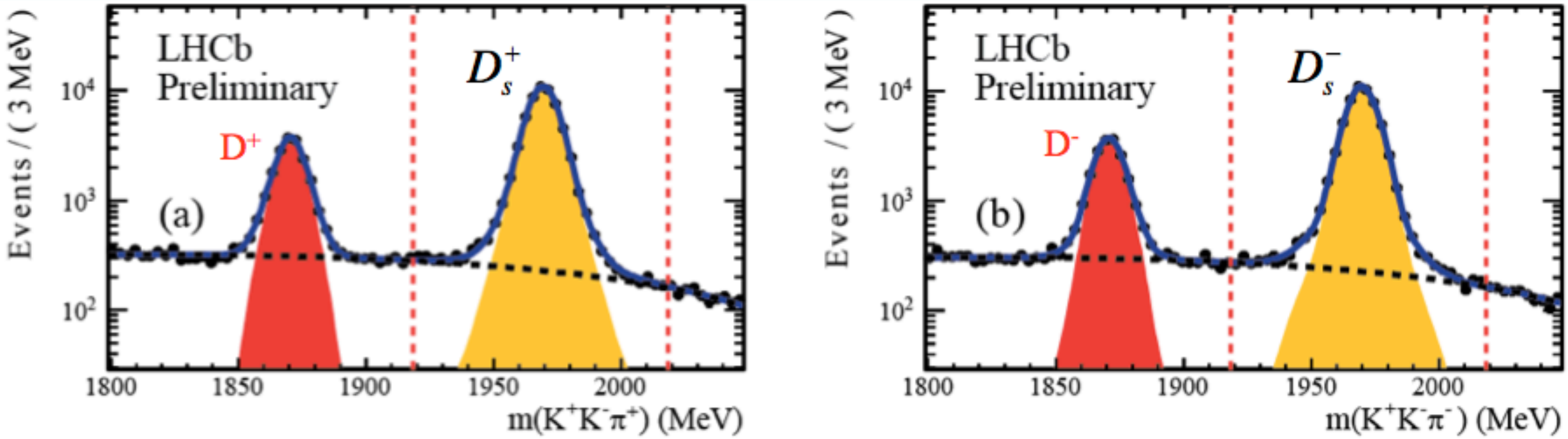
$$|B_{sL}\rangle = p\left|B_s^0\right\rangle + q\left|\bar{B}_s^0\right\rangle$$
$$|B_{sH}\rangle = p\left|B_s^0\right\rangle - q\left|\bar{B}_s^0\right\rangle$$

- Standard Model prediction $a_{sl}^s = (1.9 \pm 0.3) \times 10^{-5}$

A.Lenz arXiv1205:1444

$\not{CP}$ in mixing

- Signal yields extracted from mass fit to 1.0fb^{-1} of data
- PDF takes into account D^+ and combinatorial backgrounds



About 40k signal events for each charge

LHCb-CONF-2012-022, Preliminary

$\not{C}\not{P}$ in mixing

- Main systematics due to efficiency ratio extraction $\left[\frac{\epsilon(D_s^- \mu^+)}{\epsilon(D_s^+ \mu^-)}\right]$ taken from calibration samples
  - Will go down with more statistics)
- LHCb obtains

$$a_{sl}^{s} = (-0.24 \pm 0.54 \pm 0.33)\%$$

- Most precise measurement of the asymmetry

LHCb-CONF-2012-022, Preliminary

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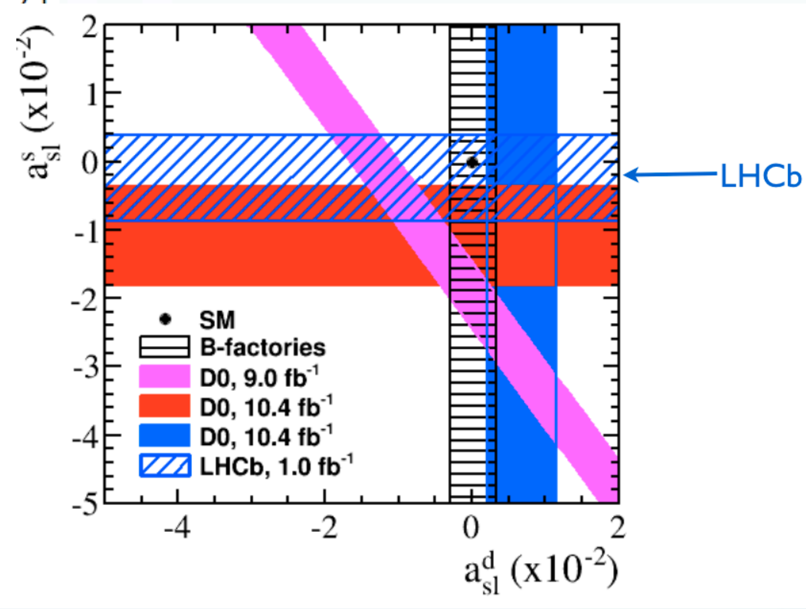
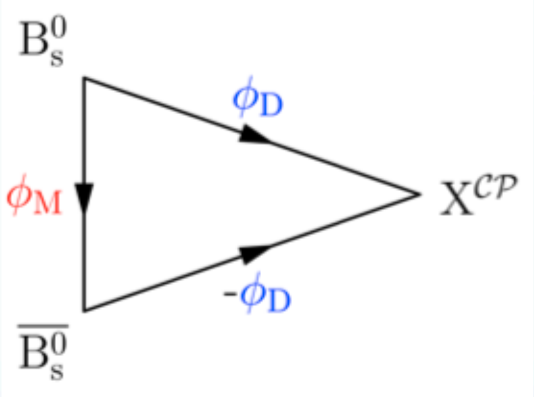


LHCb-CONF-2012-022, Preliminary

Indirect ~~CP~~

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

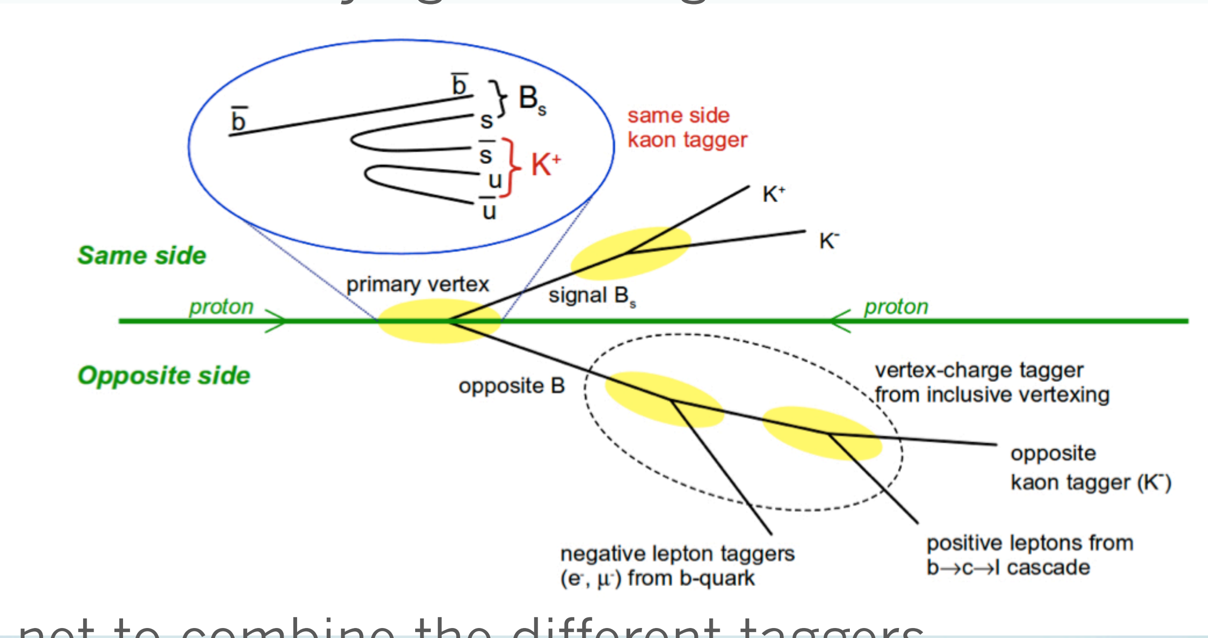


$$\Phi_f = \Phi_M - 2\,\Phi_D$$

- A time dependent analysis is sensitive to Φ_f
- Need to measure oscillation and the flavour of the B_s^0 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

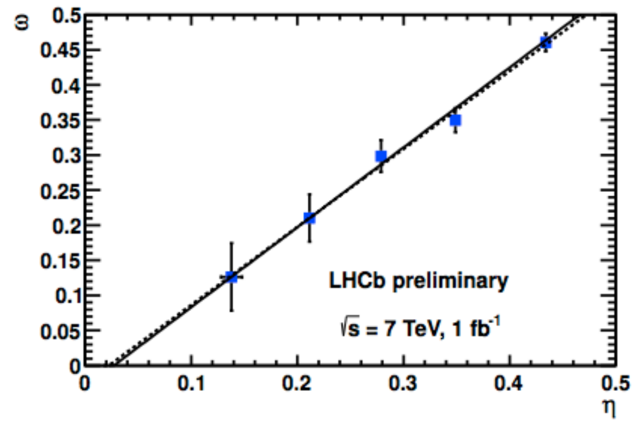
Tagging system

- Calibrate tagging using flavour specific decays as $B^+ \rightarrow J/\psi K^+$ for opposite side and $B_s^0 \rightarrow D_s^- \pi^+$ for same side tagger

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

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

LHCb-CONF-2012-033



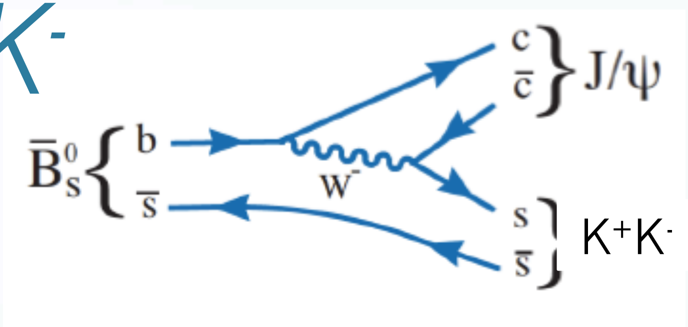
$B_s \rightarrow D_s^- \pi^+$

- Dilution depends on final state and we have a per event ω

- Combined tagging power ε_{eff}=(3.13±0.23)% for $B_s^0 \rightarrow J/\psi K^+ K^-$

Use of SST new wrt previous analysis (ε_{eff}(OST)=2.29%)

$B_s^0 \rightarrow J/\psi K^+ K^-$

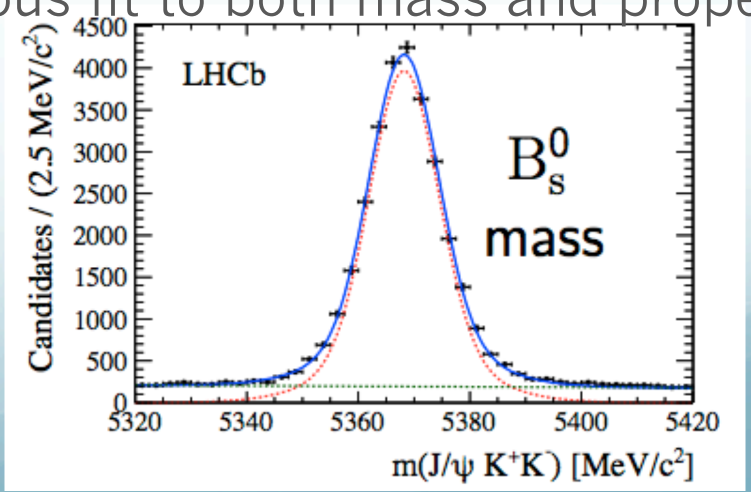


- Golden mode for Φ_s (Analogue in B_s^0 sector to $B^0 \rightarrow J/\psi K_S$)
- Small & well predicted in SM $\phi_s^{c\bar{c}s} = -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = (-0.036 \pm 0.002)$

CKM fitter, arXiv:1106.4041

- New Physics could add large terms to Φ_s
- Dominated by $\Phi \rightarrow K^+K^-$
- We perform a MLL simultaneous fit to both mass and proper-time

Analysis with 1.0 fb^{-1} yields about 28k signal events



arXiv:1304.2600, submitted to PRD

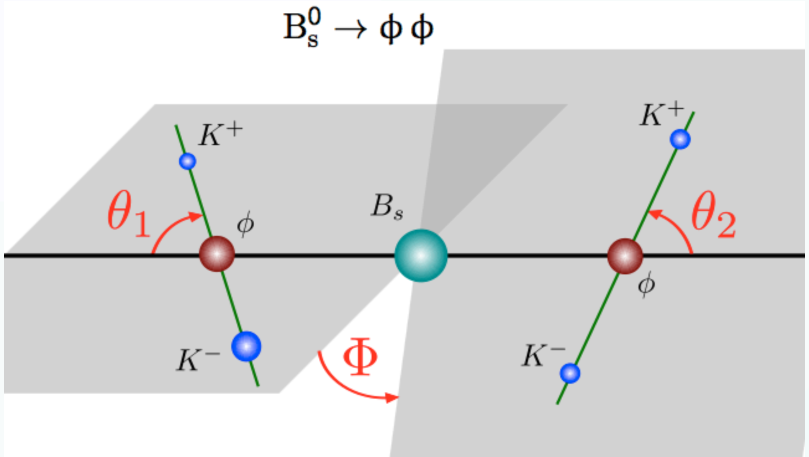
$B_s^0 \rightarrow J/\psi K^+K^-$

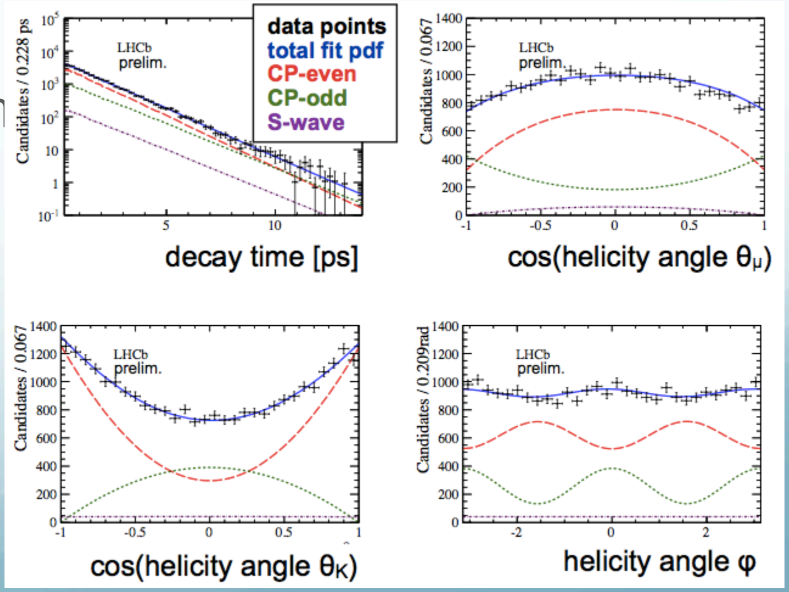
- VV final state: is not a CP eigenstate and needs to separate CP odd and even components with angular analysis (s-wave ~ 1%)

- Well described using helicity basis (same as $B_s^0 \rightarrow \phi\phi$)

- Observables of the fit: mass, proper-time, angles, tagging decision

- Time resolution obtained from prompt J/ψ (with effective width of σ_t=45fs)





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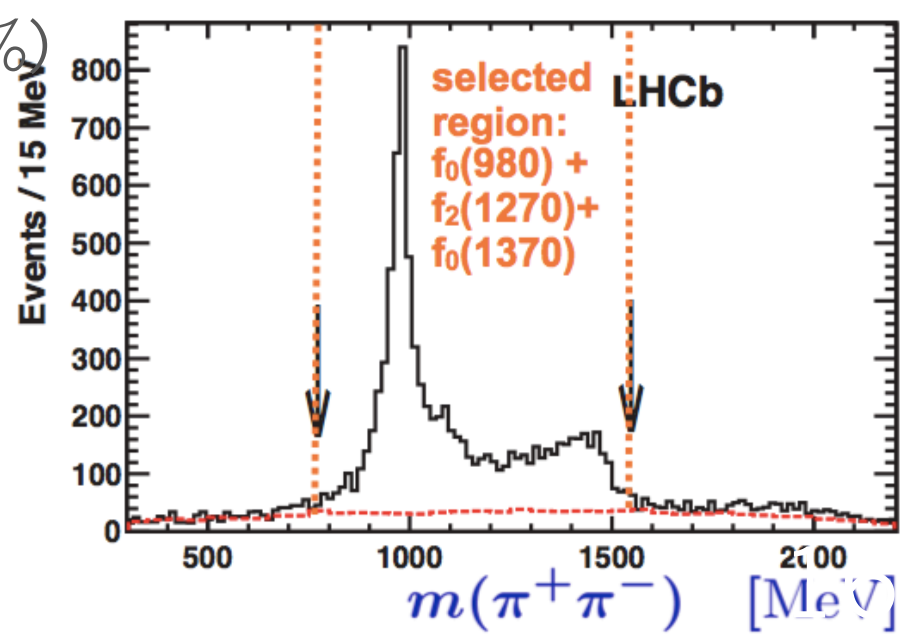
$B_s^0 \rightarrow J/\psi\pi^+\pi^-$

- There is a vector-pseudo scalar final state with the same diagram as $B_s^0 \rightarrow J/\psi K^+K^-$
- $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ (dominated by $f_0(980)$)
- No angular analysis needed
- CP-odd eigenstate (>97.7%)
- ~1/3 of $B_s \rightarrow J/\psi K^+K^-$ yield
- First observed by LHCb in 2011

PRD 86(2012) 052006



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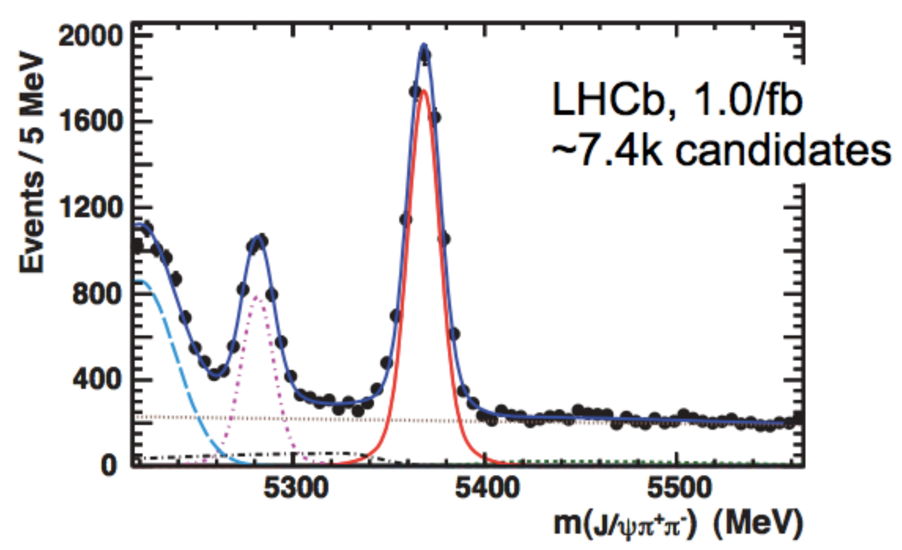
PLB 713(2012) 378

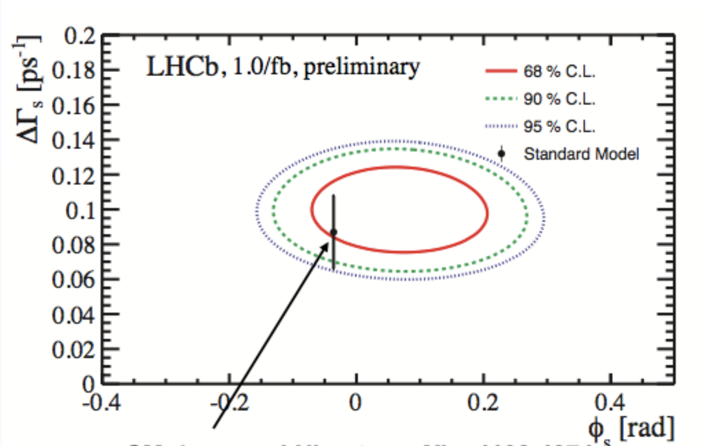


ϕ_s fit results

- Results MLL fit for $B_s^0 \to J/\psi K^+K^-$

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

- Main systematics due to acceptance of the angles



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

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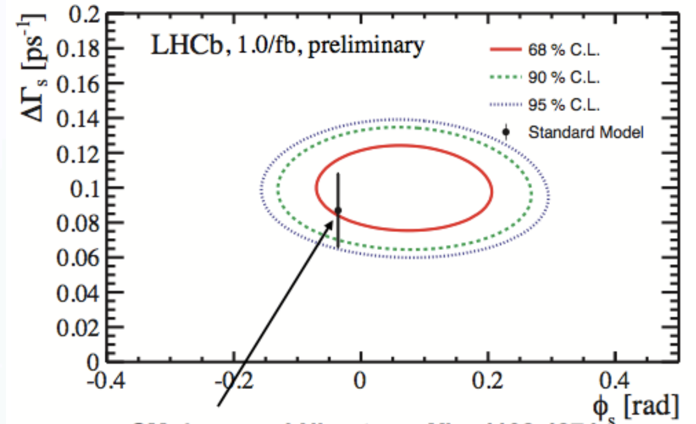


SM: Lenz and Nierste, arXiv: 1102.4274, CKM fitter, arXiv:1106.4041

- Enough data to also measure Δm_s

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

- Good agreement with $B_s^0 \to D_s^- \pi^+$

arXiv:1304.2600, submitted to PRD

Φ_s fit results

- Results for $B_s^0 \to J/\psi\pi^+\pi^-$

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

- Combining the results from $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$

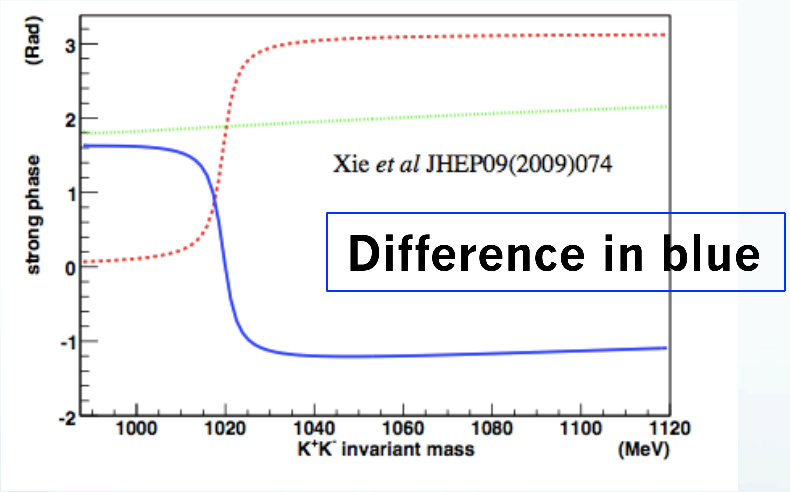
$$\begin{aligned}
\phi_s &= 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad},\\
\Gamma_s &= 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1},\\
\Delta\Gamma_s &= 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst) ps}^{-1}.
\end{aligned}$$

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

PLB 713 (2012) + arXiv:1304.2600

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



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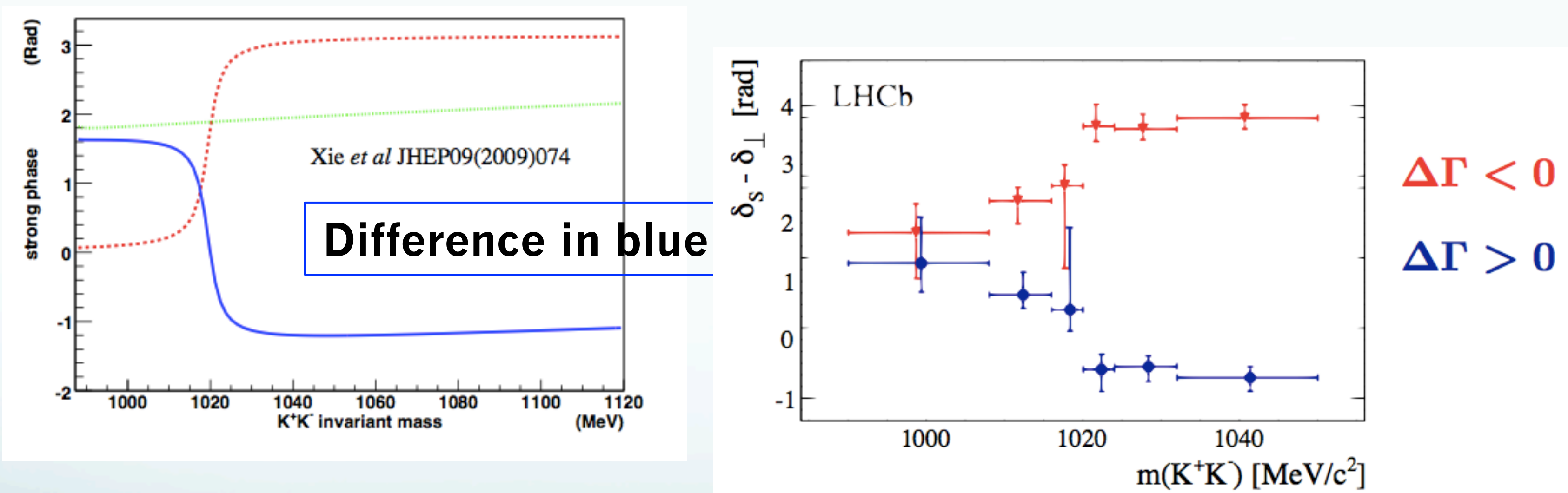
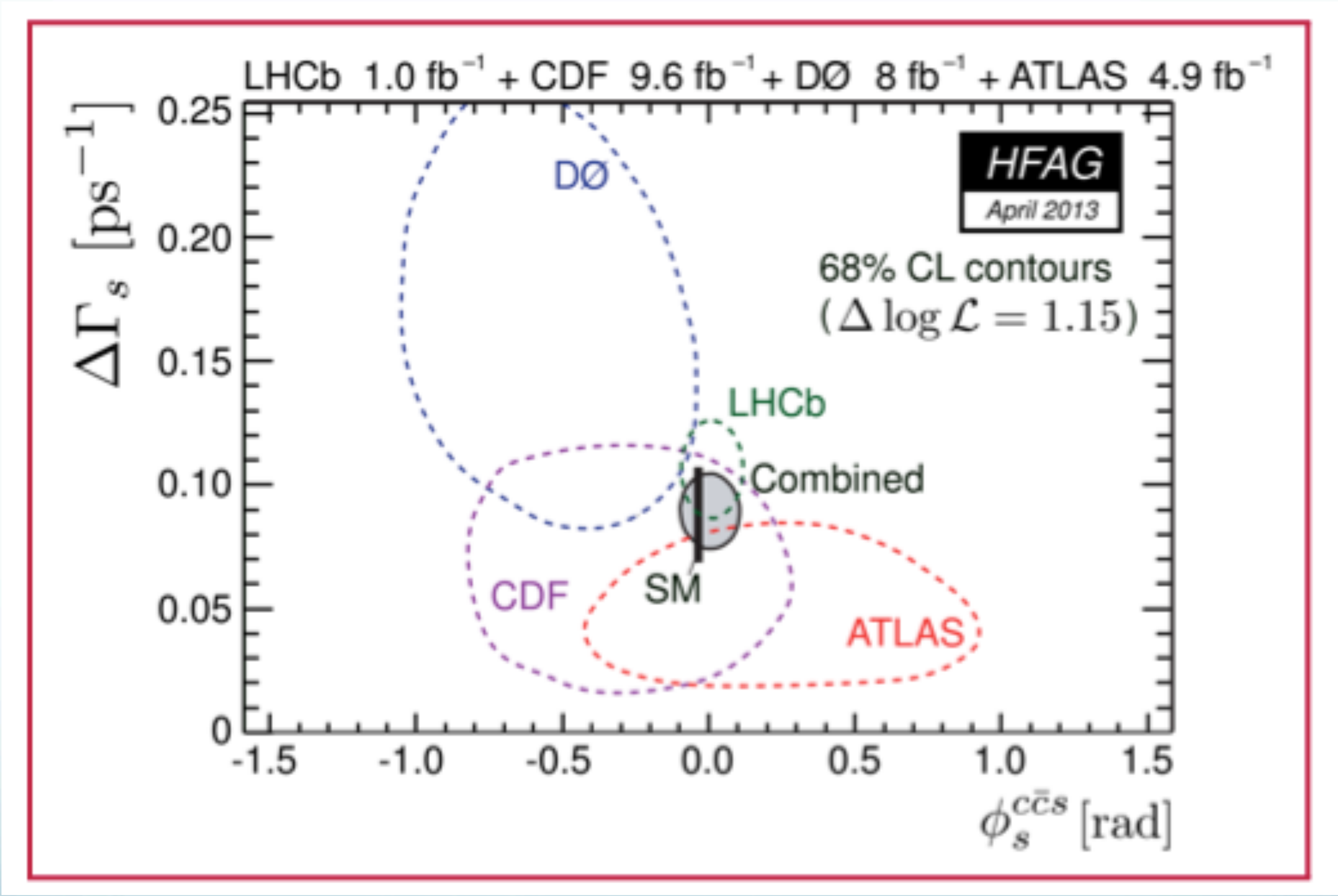


- Only $\Delta\Gamma_s > 0$ fits the expected pattern

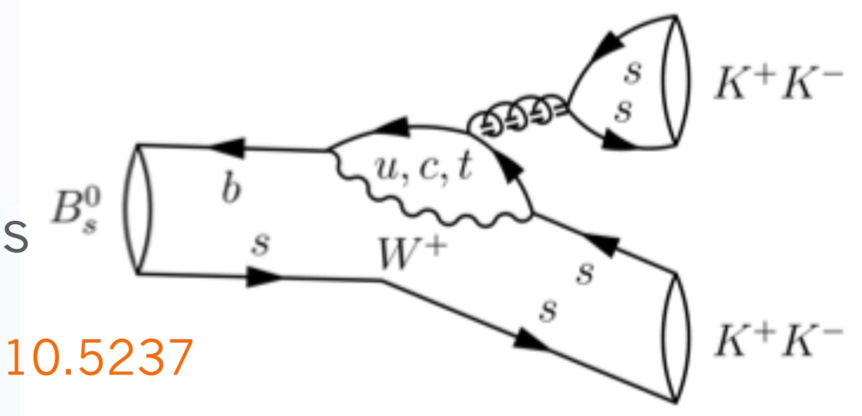
$\phi_s^{c\bar{c}s}$ summary



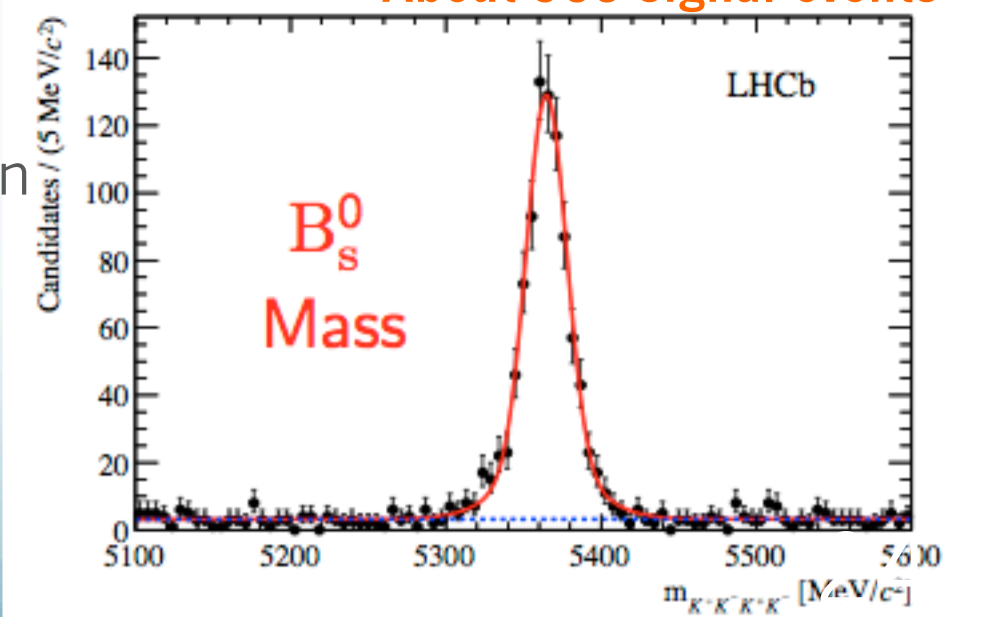
Without latest ATLAS result

$B_s^0 \to \phi\phi$

- Decay via $b \to s\bar{s}s$ transition
- Only through penguin diagrams
- In SM $\phi_s = (0.0 \pm 0.2)$ arXiv:09010.5237
- Analysis performed also with 1.0 fb^{-1}
- Similar tagging power and proper-time resolution to $J/\psi K^+K^-$
- Also VV final state



About 900 signal events

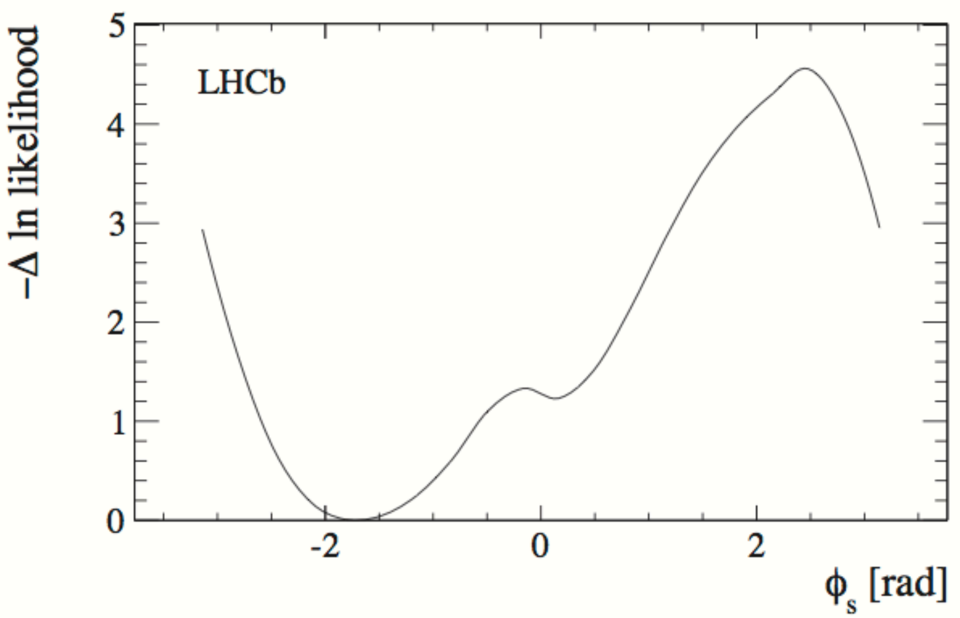


arXiv:1303.7125, accepted by PRL

$B_s^0 \to \phi\phi$

- Fit results for ϕ_s
- Including systematics

$$\phi_s = [-2.46, -0.76]$$



arXiv:1303.7125, accepted by PRL

- p-value of Standard Model hypothesis is 16%
- First measurement of CP violating phase in $B_s^0 \to \phi\phi$

Conclusion

- LHCb produced very interesting results of CP violation in B_s oscillations
  - Δm_s (mandatory ingredient)

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

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

    arXiv:1304.4741, NJP **15** 053021

  - Precise measument of mixing asymmetry a_{sl}^s

    $$a_{sl}^s = \left(-0.24 \pm 0.54 \pm 0.33\right)\%$$

    LHCb-CONF-2012-022, Preliminary

Conclusion

- Most precise measurement of CP violation phase in $B_s^0 \to J/\psi K^+K^-, \pi^+\pi^-$:

PLB 713 (2012) + arXiv:1304.2600

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

- First measurement of CP violation phase in $B_s^0 \to \phi\phi$:

$$\phi_s = [-2.46, -0.76]$$

arXiv:1303.7125, submitted to PRL

Prospects

- All results presented are in agreement with Standard Model
- All results are still limited by statistics
  - Update those results with 2012 data (2 fb^{-1})
  - 2015-2017: more data
  - LHCb Upgrade **see R. Le Gac's talk on friday**

Backup

LHCb performance

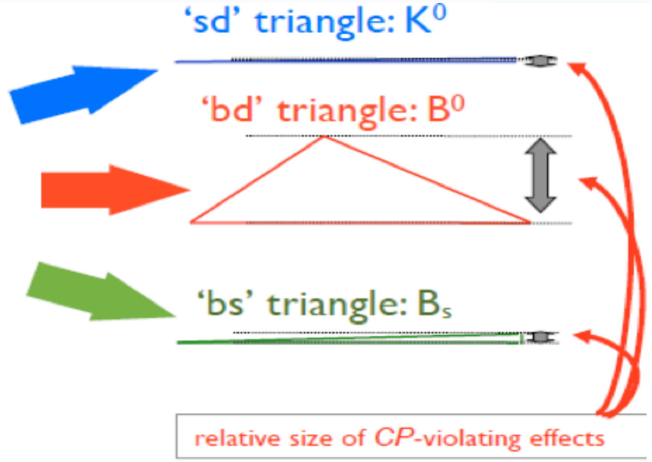
- VELO silicon planes gets closer (8 mm) to beam in collision mode ➔ IP resolution of ~12 μm and proper time of ~40fs
- 2 RICH detectors give better particle identification (p/K/π) separation 2-100GeV/c
- Tracking system gives a resolution of σp/p ~0.5% (2-100GeV/c)
- In 2011: 1.0 fb^{-1} recorded: ~3.10^{11}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

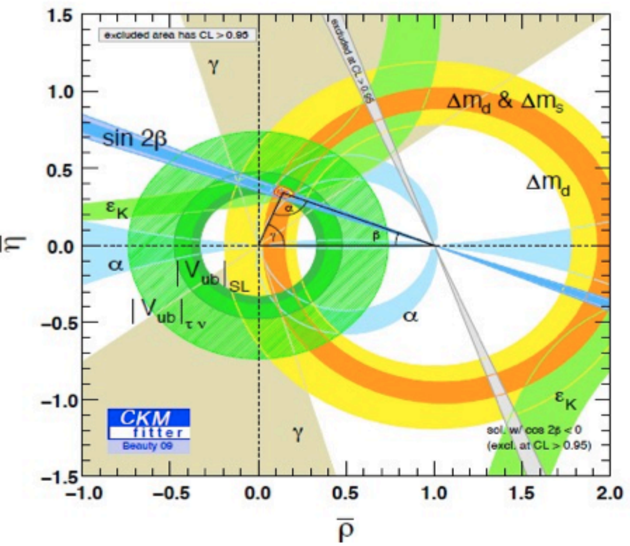
CKM triangles

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

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

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





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

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

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

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a_{sl} systematics

Source	δa_{sl} (%)
Signal model in D_s mass fit	0.12
Background from other b hadrons	0.10
Kinematic difference between π and μ	0.12
Kaon asymmetries	0.04
Varying run conditions between field-up and field-down	0.02
Muon corrections	0.10
Muon related software trigger biases	0.10
Statistical uncertainty on efficiency ratios	0.20
Total	**0.33**

Tagging calibration

- For each event an estimated probability of the tagging 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 $\omega = p_0 + p_1 \cdot (\eta - \bar{\eta})$

- $B^+ \to J/\psi K^+$ used for calibration, and the kinematically similar $B^0 \to J/\psi K^*$ is used as crosscheck

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

  Study correction function between actual mistag and calibrated mistag

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

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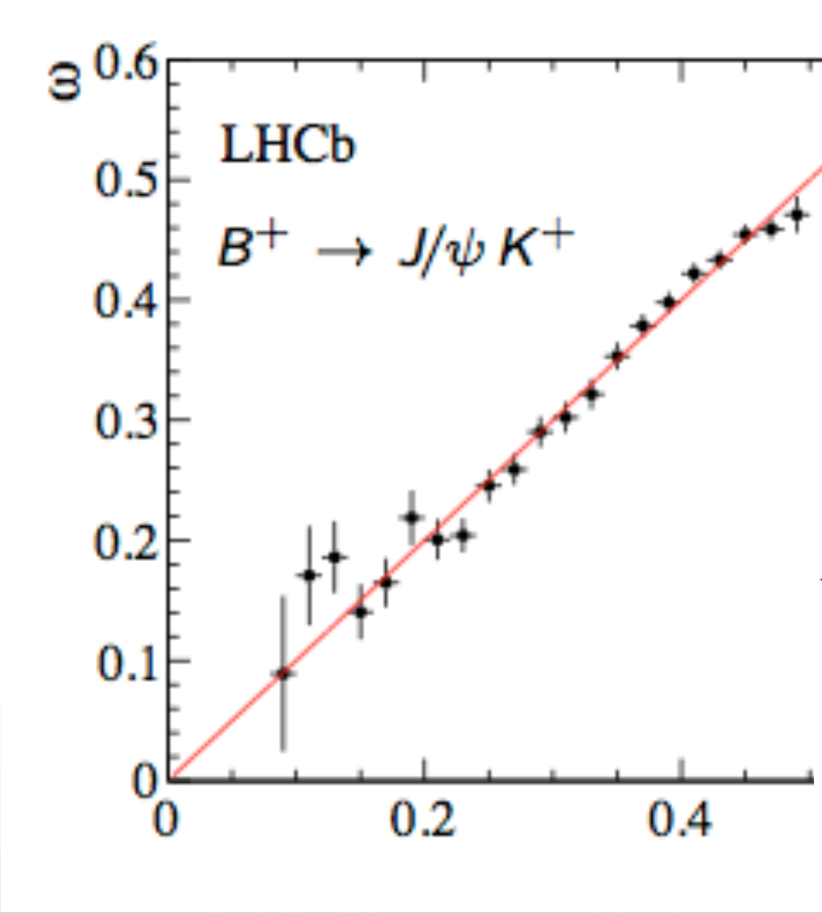
OST calibration



$B_s^0 \to D_s^- \pi^+$

algorithm	$\epsilon(1-2\omega)^2$ [%]
SSK	1.5 ± 0.4
OS	2.29 ± 0.06
OS + SSK	3.8 ± 0.7

Φ_s from $b \rightarrow c\bar{c}s$

- In SM

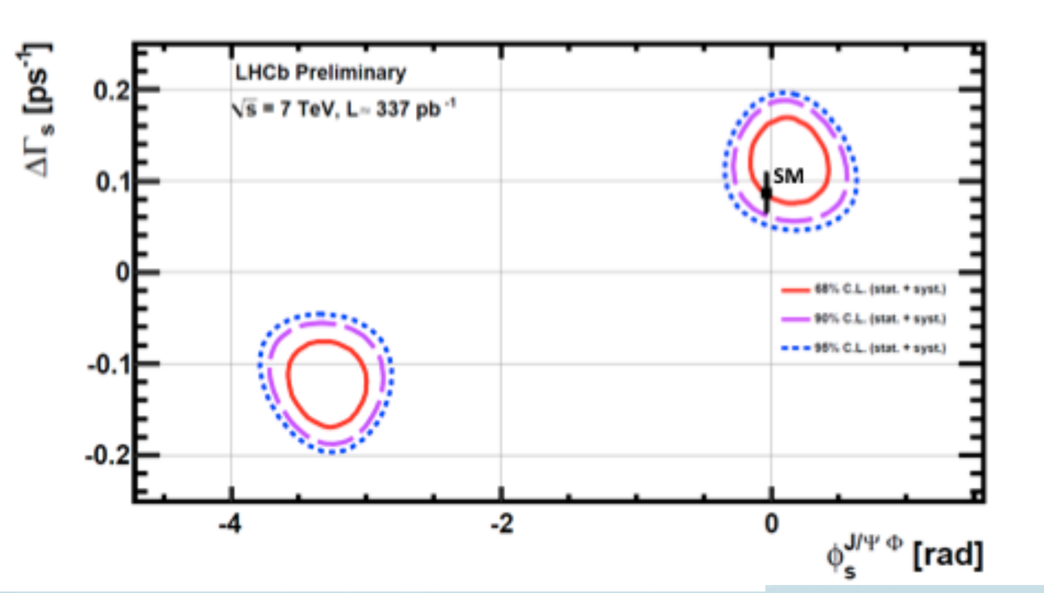
$$\phi_s = -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = (-0.036 \pm 0.002)rad$$

- 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 and proper-time resolution

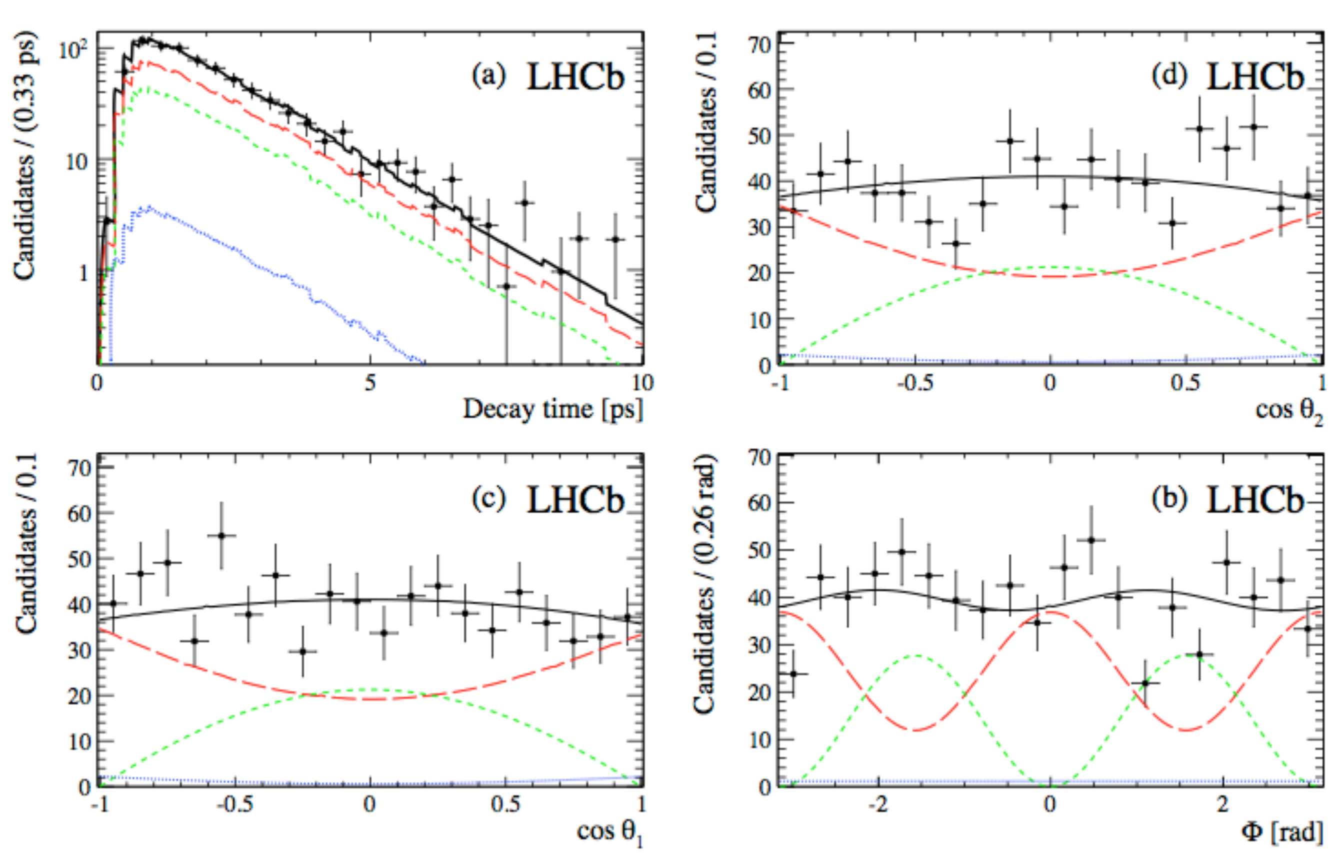
$$S(\vec{\lambda}, t, \vec{\Omega}) = \epsilon(t, \vec{\Omega}) \times \left(\frac{1+qD}{2} s(\vec{\lambda}, t, \vec{\Omega}) + \frac{1-qD}{2} \bar{s}(\vec{\lambda}, t, \vec{\Omega}) \right) \otimes R_t$$



$B_s \to J/\psi\ \Phi$ systematics

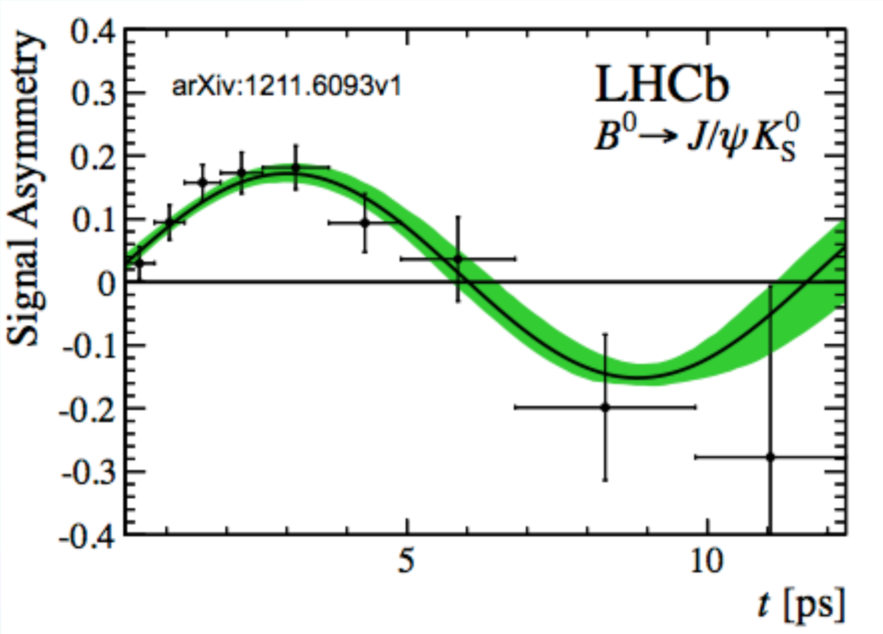
Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\|A_\perp\|^2$	$\|A_0\|^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\|\lambda\|$
Stat. uncertainty	0.0048	0.016	0.0086	0.0061	$^{+0.13}_{-0.21}$	0.22	0.091	0.031
Background subtraction	0.0041	0.002	-	0.0031	0.03	0.02	0.003	0.003
$B^0 \to J/\psi K^{*0}$ background	-	0.001	0.0030	0.0001	0.01	0.02	0.004	0.005
Ang. acc. reweighting	0.0007	-	0.0052	0.0091	0.07	0.05	0.003	0.020
Ang. acc. statistical	0.0002	-	0.0020	0.0010	0.03	0.04	0.007	0.006
Lower decay time acc. model	0.0023	0.002	-	-	-	-	-	-
Upper decay time acc. model	0.0040	-	-	-	-	-	-	-
z + p scale	0.0009	-	-	-	-	-	-	-
Fit bias	-	-	0.0010	-	-	-	-	-
Quadratic sum of syst.	0.0063	0.003	0.0064	0.0097	0.08	0.07	0.009	0.022
Total uncertainties	0.0079	0.016	0.0107	0.0114	$^{+0.15}_{-0.23}$	0.23	0.091	0.038

$B_s \rightarrow \Phi\,\Phi$ projections



Points: Data
Black: Total
Red: $\mathcal{CP}$-Even
Green: $\mathcal{CP}$-Odd
Blue: S-wave

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



$$S_{J/\psi K_S^0} = 0.73 \pm 0.07_{stat} \pm 0.04_{syst}$$

$$C_{J/\psi K_S^0} = 0.03 \pm 0.09_{stat} \pm 0.01_{syst}$$

arXiv:1211.6093v1, accepted by PLB

- First measurement of S in hadronic environment
- C compatible with SM and S with WA $\sin 2\beta = 0.679 \pm 0.020$
- Systematics will also go down with more statistics