CP Violation in the B system at LHCb

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Outline

Highlights of LHCb results on CP violation (CPV) in the B system

Direct CPV

$$\Gamma\left(B \to f\right) \neq \Gamma\left(\overline{B} \to \overline{f}\right)$$

CPV in mixing

$$\Gamma\left(B \to \overline{B}\right) \neq \Gamma\left(\overline{B} \to B\right)$$

CPV in mixing-decay

$$\Gamma\left(B \to f_{CP}\right) \neq \Gamma\left(\overline{B} \to f_{CP}\right)$$

Direct CPV:

$B^0 \to \phi K^{*0}$

$B_{(s)} \to K\pi$

$B^\pm \to h'^\pm h^+ h^-$ $(h' = K, \pi)$

$B^\pm \to \phi K^\pm$

$B_s^0 \to K^+ K^-$

$B^0 \to \pi^+ \pi^-$

CPV in mixing:

$B_s^0 \to D_s^\pm(\phi\pi^\pm) X \mu^\pm \nu$

$B_s^0 \to K^+ K^-$

$B^0 \to \pi^+ \pi^-$

CPV in mixing-decay:

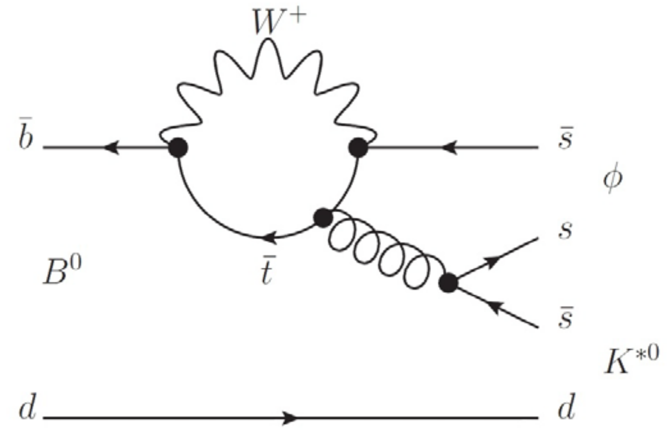
$B_s^0 \to J/\psi\phi$

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

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

Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^*$

$b \to s\bar{s}s$ FCNC process. Gluonic penguin in the SM.
Sensitive to NP contribution in the loop

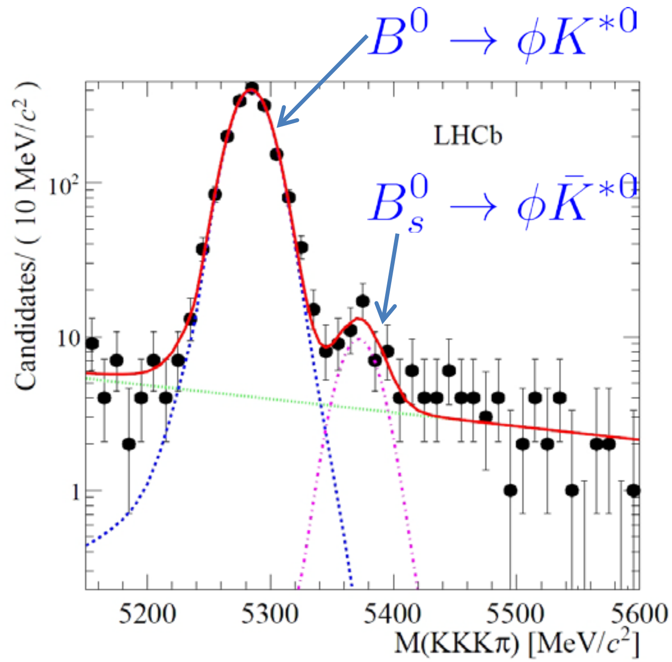


1 fb^{-1} of 2011 data at 7 TeV.

1655 ± 42 signal events

arXiv:1403.2888v1

P → VV decay: angular analysis to study the helicity structure



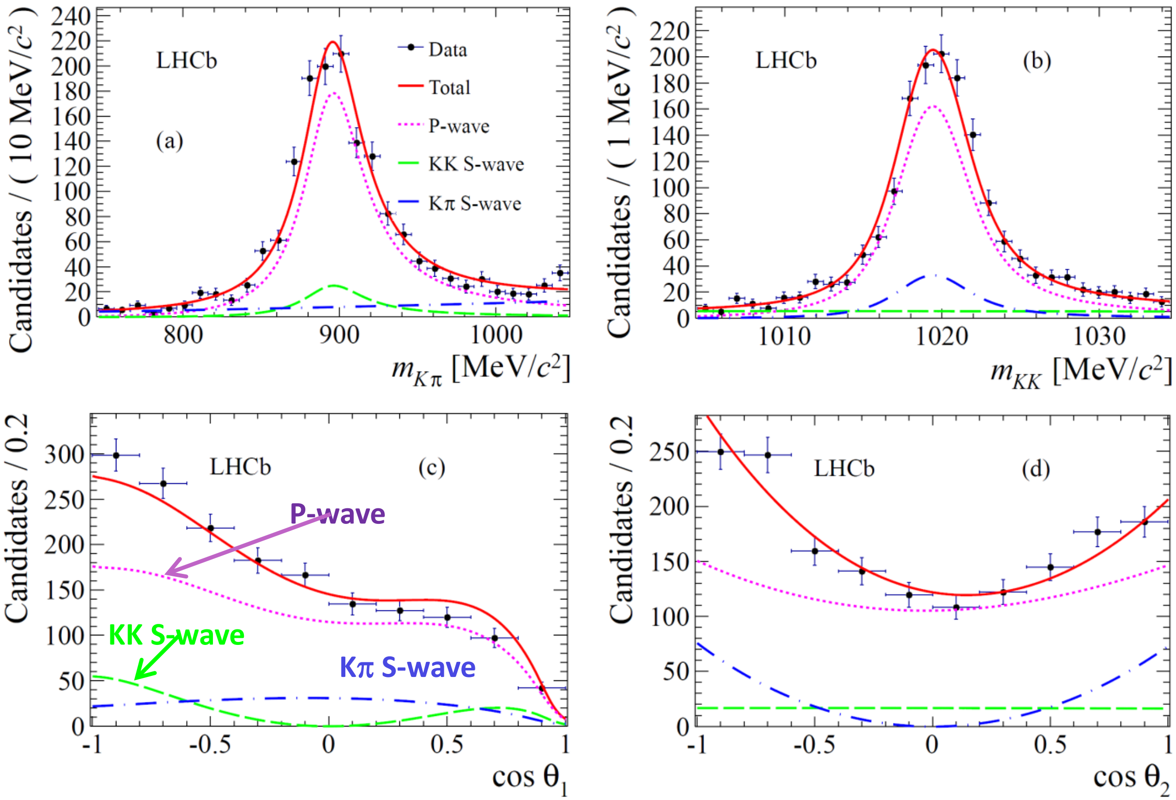
Three P-wave contributions:
$f_L, f_{||}$ and $f_\perp$ with $f_{||} = 1 - f_L - f_\perp$

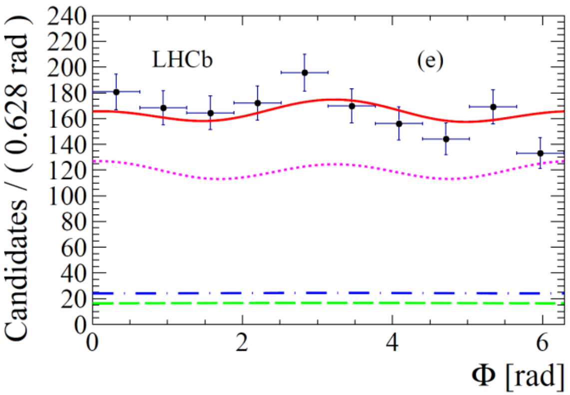
Naive theory predicts [Chen, Keum, PRD 66 (2002) 054013]
a dominant f_L (~ 0.8), but observed $f_L \sim 0.5$

Two S-wave contributions:
$B^0 \to \phi K^+ \pi^-$ and $B^0 \to K^*(892)^0 K^+ K^-$

$B^0 \to \phi K^*$ polarization amplitudes

arXiv:1403.2888v1

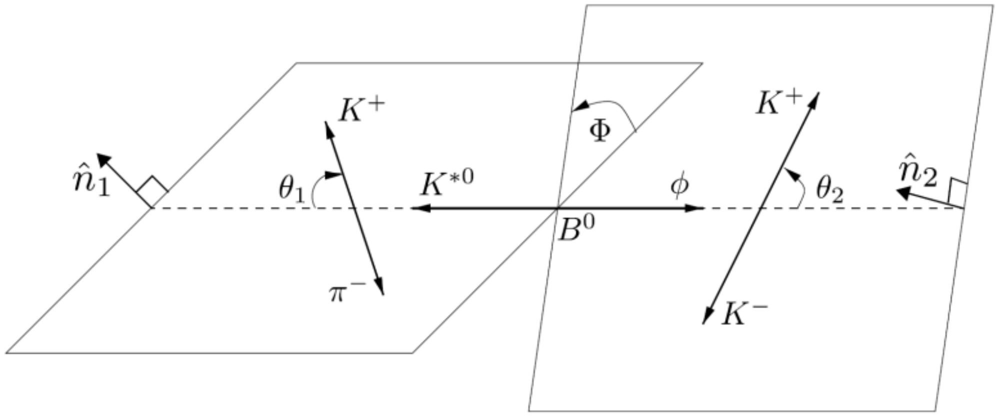




$$f_{\mathrm{L}} = 0.497 \pm 0.019 \pm 0.015$$
$$f_{\perp} = 0.221 \pm 0.016 \pm 0.013$$
$$f_{\mathrm{S}}(K\pi) = 0.143 \pm 0.013 \pm 0.012$$
$$f_{\mathrm{S}}(KK) = 0.122 \pm 0.013 \pm 0.008$$

Non-dominant f_L in agreement with BaBar [PRD 78(2008)092008] and Belle [PRD 88(2013)072004]

Significant S-wave contribution.



Direct CP asymmetry in $B^0 \to \phi K^*$

Flavor-specific decay: $B^0 \to \phi K^{*0}, \quad \bar{B}^0 \to \phi \bar{K}^{*0}$ $\quad K^{*0} \to K^+\pi^-, \quad \bar{K}^{*0} \to K^-\pi^+$

Measure the "raw" asymmetry from time-integrated rates:

$$A = \frac{N(\bar{B}^0 \to \phi \bar{K}^*(892)^0) - N(B^0 \to \phi K^*(892)^0)}{N(\bar{B}^0 \to \phi \bar{K}^*(892)^0) + N(B^0 \to \phi K^*(892)^0)}$$

Use the control channel $B^0 \to J/\psi K^{*0}$ to cancel instrumental and production asymmetries through the following difference:

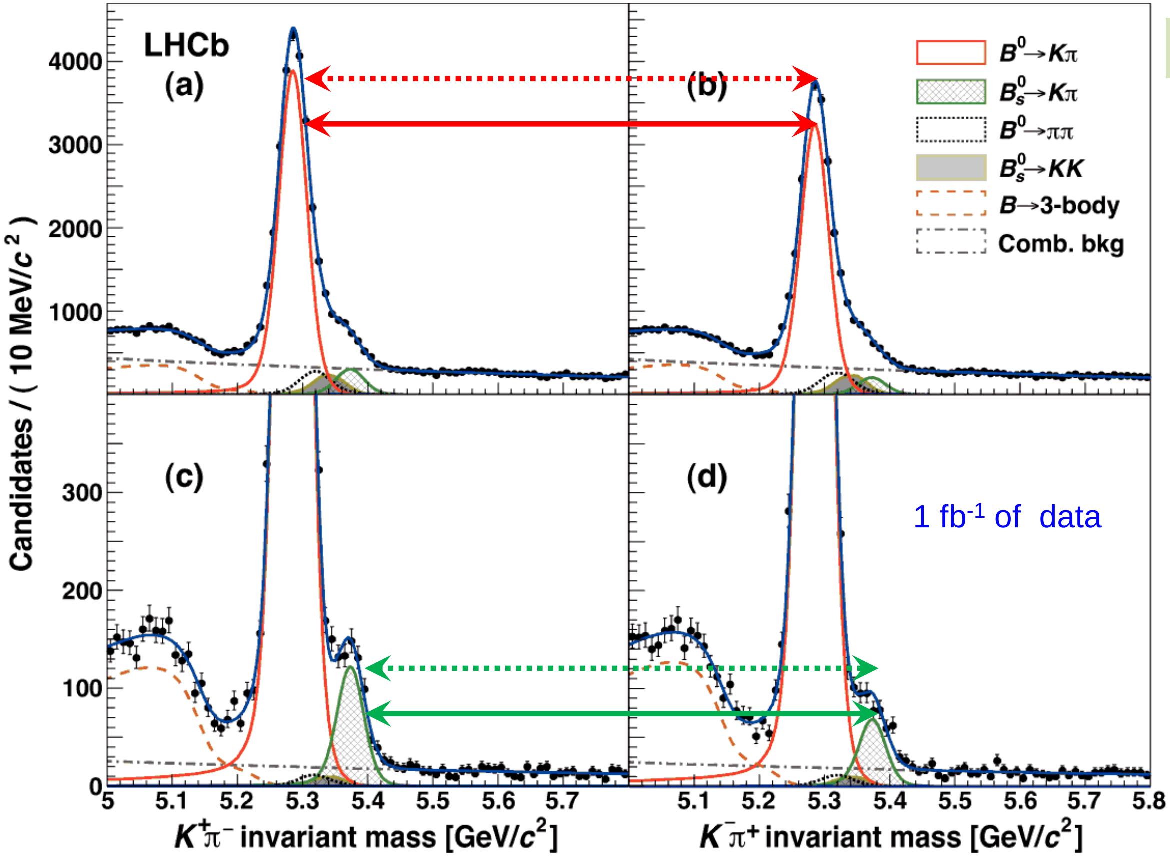
$$\Delta A_{CP} = A_{CP}(\phi K^{*0}) - \overbrace{A_{CP}(J/\psi K^{*0})}^{\approx 0} \approx A_{CP}(\phi K^{*0})$$

$$A_{CP}(\phi K^{*0}) = (+1.5 \pm 3.2 \pm 0.5)\%$$

arXiv:1403.2888v1

Result consistent with zero asymmetry, in agreement with BaBar and Belle results, but with smaller (factor 2) uncertainties.

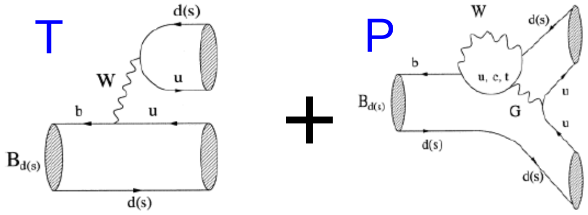
Direct CPV in B → Kπ decays



PRL 110, 221601, (2013)

1 fb^{-1} of data

$$B_s^0 \to K^-\pi^+$$
$$B^0 \to K^+\pi^-$$



First observation of CPV in B_s decays (6.5 σ)

$$A_{CP} = \frac{\Gamma(B\to f) - \Gamma(\bar{B}\to \bar{f})}{\Gamma(B\to f) + \Gamma(\bar{B}\to \bar{f})}$$

$$A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007 \pm 0.003$$
$$A_{CP}(B_s^0 \to K^-\pi^+) = -0.27 \pm 0.04 \pm 0.01$$

Test of SM expectation, using U-spin, Lipkin PLB 621 (2005) 126

$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + \frac{BF(B_s^0 \to K^-\pi^+)}{BF(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0$$

Using LHCb measurement of branching ratios (JHEP 10 (2012) 037) ➡

$$\Delta = -0.02 \pm 0.05 \pm 0.04$$

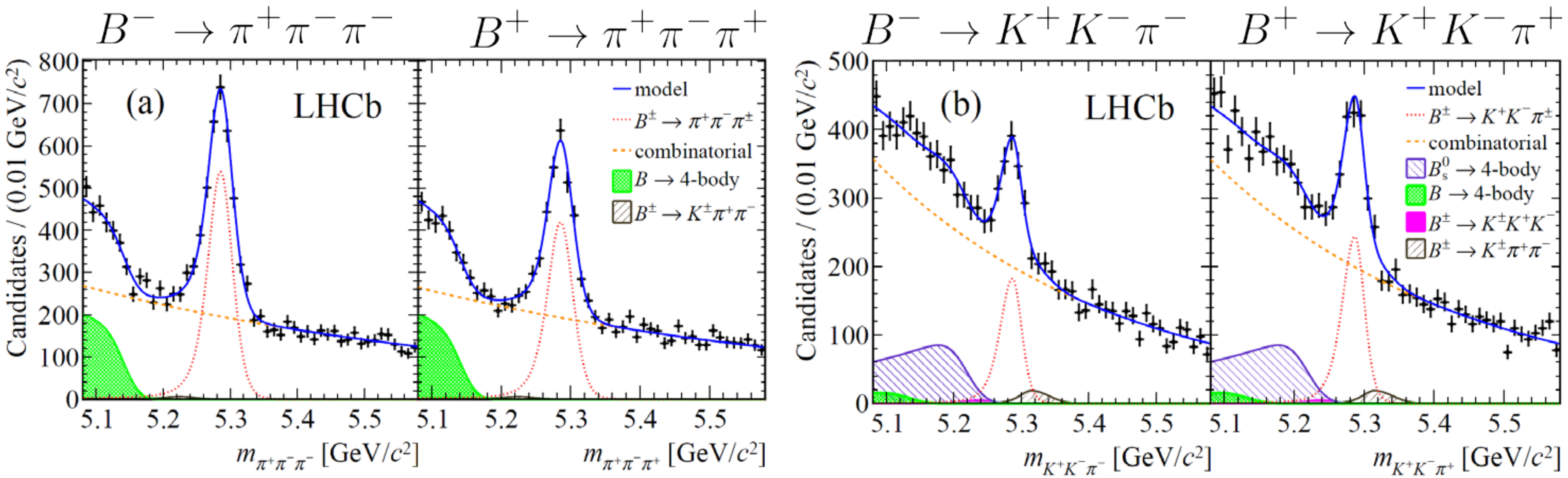
SM agreement

Direct CPV in 3-body charmless B decays

CP asymmetries measured in $B^{\pm} \to h'^{\pm} h^{+} h^{-}$ decays, with h' = K, π

1 fb^{-1} of data

[PRL 112, 011801 (2014)]



$$A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = 0.032 \pm 0.008 \pm 0.004 \pm 0.007$$
$$A_{CP}(B^\pm \to K^\pm K^+K^-) = -0.043 \pm 0.009 \pm 0.003 \pm 0.007$$

[PRL 111, 101801 (2013)]

$$A_{CP}(B^\pm \to K^+K^-\pi^\pm) = -0.141 \pm 0.040 \pm 0.018 \pm 0.007$$
$$A_{CP}(B^\pm \to \pi^+\pi^-\pi^\pm) = 0.117 \pm 0.021 \pm 0.009 \pm 0.007$$

[PRL 112, 011801 (2014)]

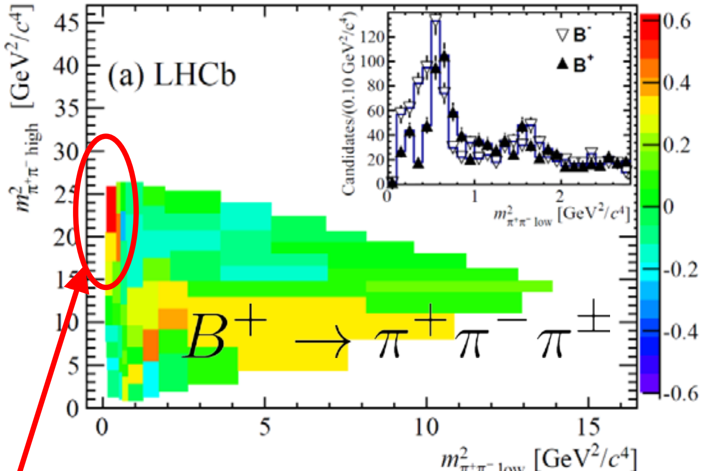
$$A_{CP}(B^\pm \to J/\psi K^\pm) = (0.1 \pm 0.7)\%$$

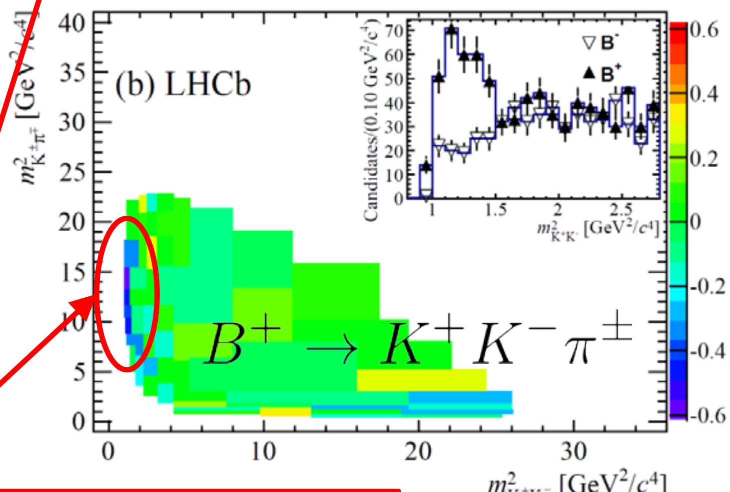
First evidence of inclusive CP asymmetries in B → 3h, (3σ – 5σ)

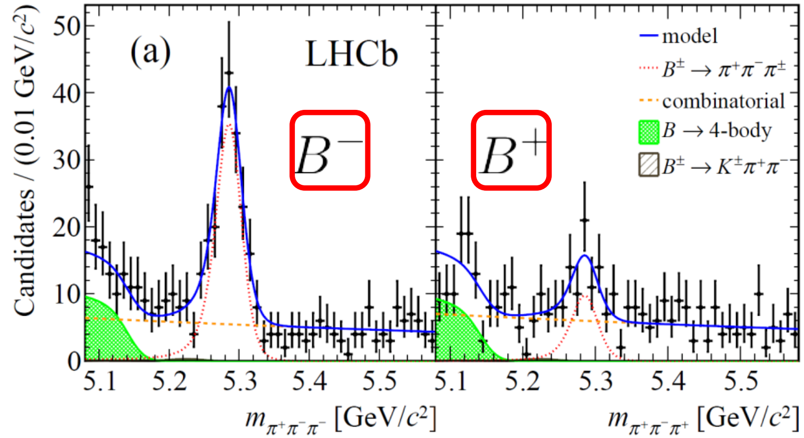
Phase-space dep. CPV in $B^+ \to h^+h^-h^+$ (h=K,π)

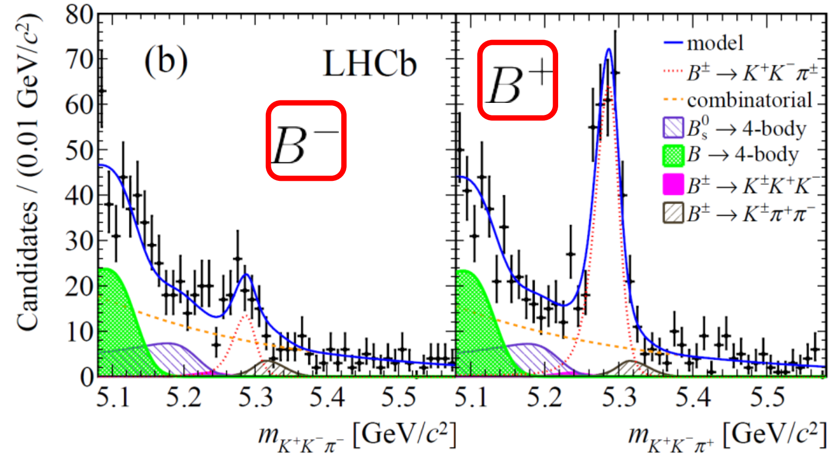
Large CP asymmetries observed in regions of phase space outside resonances

1 fb^{-1} of data









PRL 112, 011801, (2014)

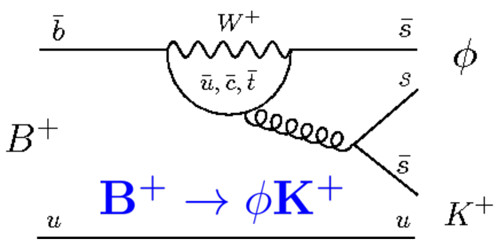
$$m^2_{\pi^+\pi^-\mathrm{high}} > 15\ \mathrm{GeV}^2/c^4$$
$$m^2_{\pi^+\pi^-\mathrm{low}} < 0.4\ \mathrm{GeV}^2/c^4$$
$$m^2_{K^+K^-} < 1.5\ \mathrm{GeV}^2/c^4$$

$$A^{\mathrm{reg}}_{CP}(B^\pm \to K^+K^-\pi^\pm) = -0.648 \pm 0.070 \pm 0.013 \pm 0.007$$
$$A^{\mathrm{reg}}_{CP}(B^\pm \to \pi^+\pi^-\pi^\pm) = 0.584 \pm 0.082 \pm 0.027 \pm 0.007$$

CP-violating charge asymmetries in $B^{\pm} \to \phi K^{\pm}$

$\mathbf{B^+ \to \phi K^+}$ is a $\mathbf{b \to s s \bar{s}}$ FCNC penguin process

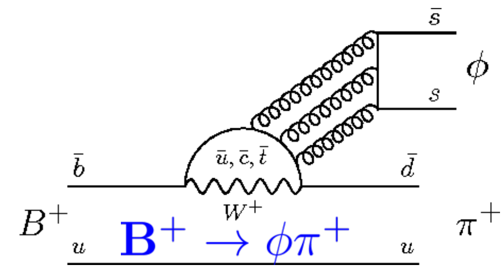
CP-violating charge asymmetry very small in the SM (1-2%).



$$A_{CP}(B^{\pm} \to \phi K^{\pm}) = \frac{\mathcal{B}(B^- \to \phi K^-) - \mathcal{B}(B^+ \to \phi K^+)}{\mathcal{B}(B^- \to \phi K^-) + \mathcal{B}(B^+ \to \phi K^+)}$$

$\mathbf{B^+ \to \phi \pi^+}$: FCNC $\mathbf{b \to d s \bar{s}}$ process, CKM and OZI suppressed.

SM prediction: $\mathcal{B}(B^{\pm} \to \phi \pi^{\pm}) \sim (5 - 10) \times 10^{-9}$



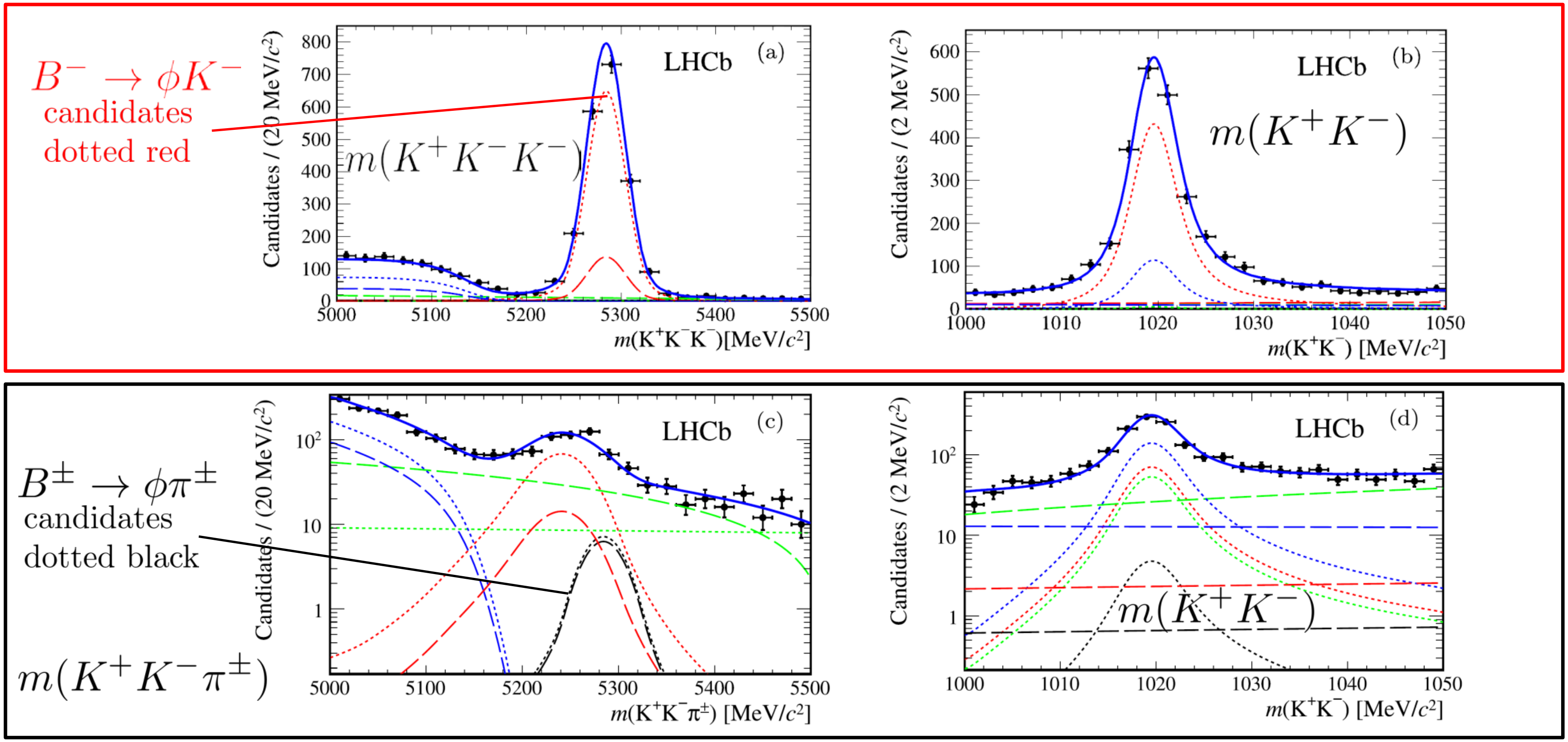
LHCb analysis of 1fb^{-1} of data to measure the two observables: [PLB 728 (2014) 85–94]

$$\Delta A_{CP} = A_{CP}(B^{\pm} \to \phi K^{\pm}) - A_{CP}(B^{\pm} \to J/\psi K^{\pm})$$

$$\frac{\mathcal{B}(B^{\pm} \to \phi \pi^{\pm})}{\mathcal{B}(B^{\pm} \to \phi K^{\pm})}$$

to finally determine $A_{CP}(B^{\pm} \to \phi K^{\pm})$ and $\mathcal{B}(B^{\pm} \to \phi \pi^{\pm})$

CPV-violating charge asymmetries in $B^{\pm} \to \phi K^{\pm}$



[PLB 728 (2014) 85–94]

$$A_{CP}(B^{\pm} \to \phi K^{\pm}) = 0.022 \pm 0.021 \pm 0.009$$

A factor of 2 more precise than the current world average (0.10 ± 0.04), and consistent both with the SM prediction and no CPV.

$$\mathcal{B}(B^{\pm} \to \phi\pi^{\pm}) = (5.8^{+6.1}_{-5.8} \pm 2.5) \times 10^{-8}, \quad \left[< 1.5(1.8) \times 10^{-7} \text{ at } 90\%(95\%) \text{ CL.} \right]$$

Time-dependet CPV in $B_s^0 \to K^+K^-$ and $B^0 \to \pi^+\pi^-$

$$\mathcal{A}(t) = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) - A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

C_f → direct CP violation

$A_f^{\Delta\Gamma}$, S_f → mixing-induced CP violation

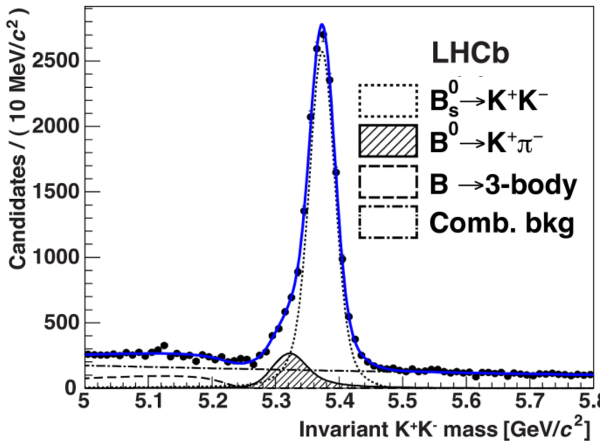
JHEP 10 (2013) 183

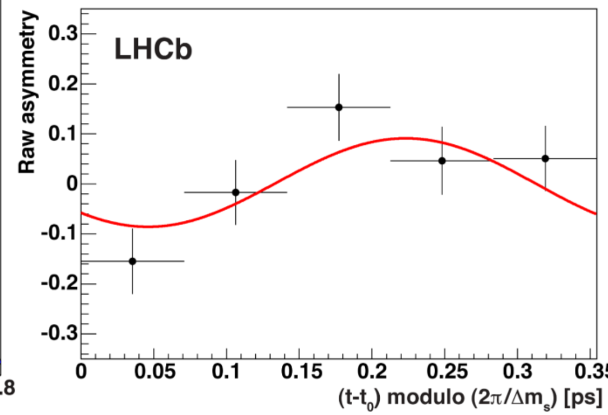
1 fb^{-1} of data

$B_s^0 \to K^+K^-$

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

First measurements.
2.7 σ from (0,0)



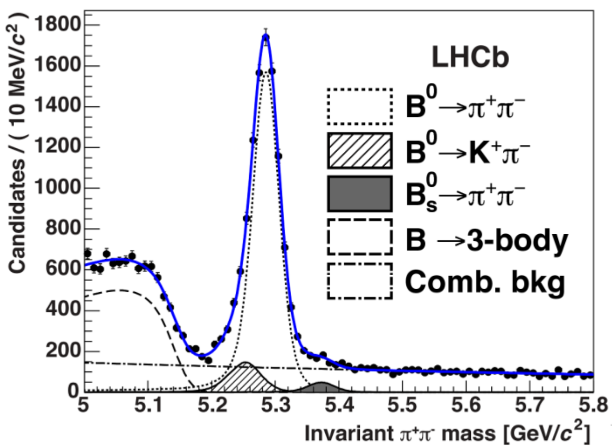


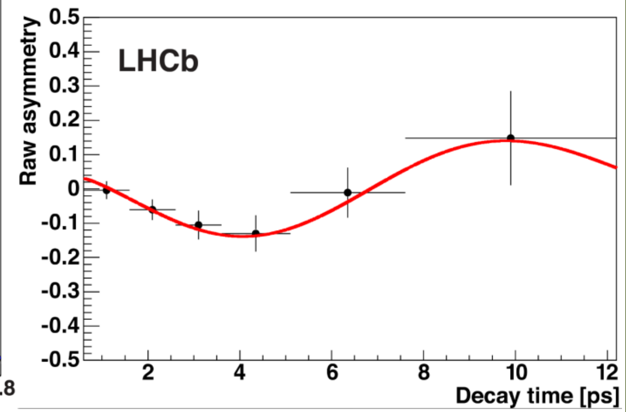
$B^0 \to \pi^+\pi^-$

$$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02$$
$$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02$$

Results compatible with previous Babar and Belle measurements

5.6 σ from (0,0)





CP-violating asymmetry a^s_{sl} in B^0_s decays

CP-violating semileptonic asymmetry a^s_{sl} measured in $B^0_s \to D^\pm_s(\phi\pi^\pm)X\mu^\pm\nu$ decays

$$a_{sl} = \frac{\Gamma(\bar{B}(t)\to f) - \Gamma(B(t)\to \bar{f})}{\Gamma(\bar{B}(t)\to f) + \Gamma(B(t)\to \bar{f})} \approx \frac{\Delta\Gamma}{\Delta M}\tan\phi_{12} \qquad \phi_{12} = \arg(-M_{12}/\Gamma_{12})$$

Measures CPV in mixing. f is a flavour-specific final state

ϕ_{12} very small in the SM: $a^s_{sl} = (1.9 \pm 0.3)\times 10^{-5}$ $a^d_{sl} = (-4.1 \pm 0.6)\times 10^{-4}$ Lenz, Nierste (2012)

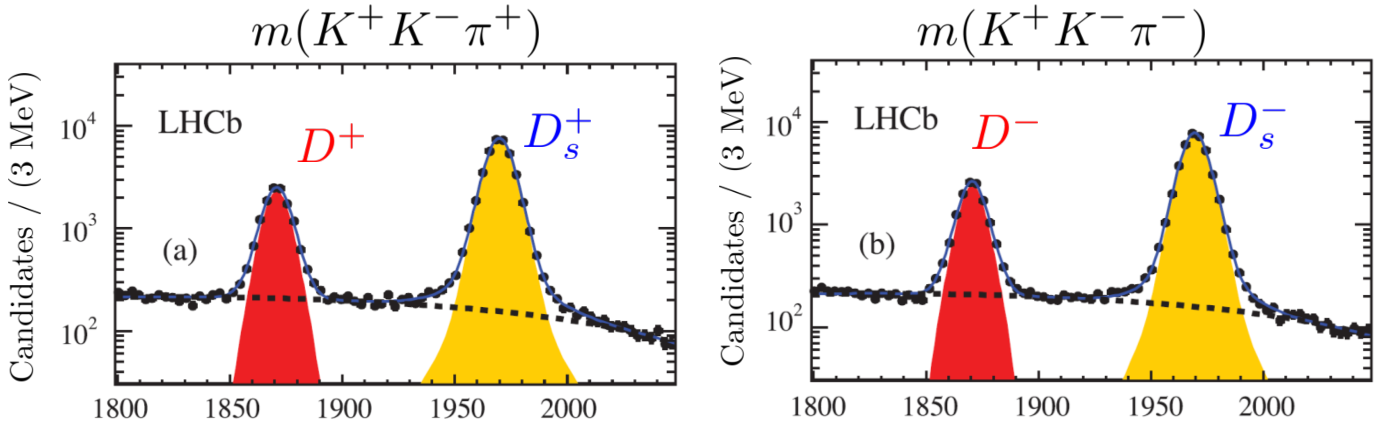
Measure time-integrated asymmetry with 1fb^{-1} of data. Use mostly data driven corrections.

$$A_{\rm meas} \equiv \frac{\Gamma[D_s^-\mu^+] - \Gamma[D_s^+\mu^-]}{\Gamma[D_s^-\mu^+] + \Gamma[D_s^+\mu^-]} \approx \frac{a^s_{sl}}{2}$$

$$\frac{a^s_{sl}}{2} = A_{\rm raw} - A_{\rm det} - A_{\rm bkg}$$

CP-violating asymmetry a^s_{sl} in B^0_s decays

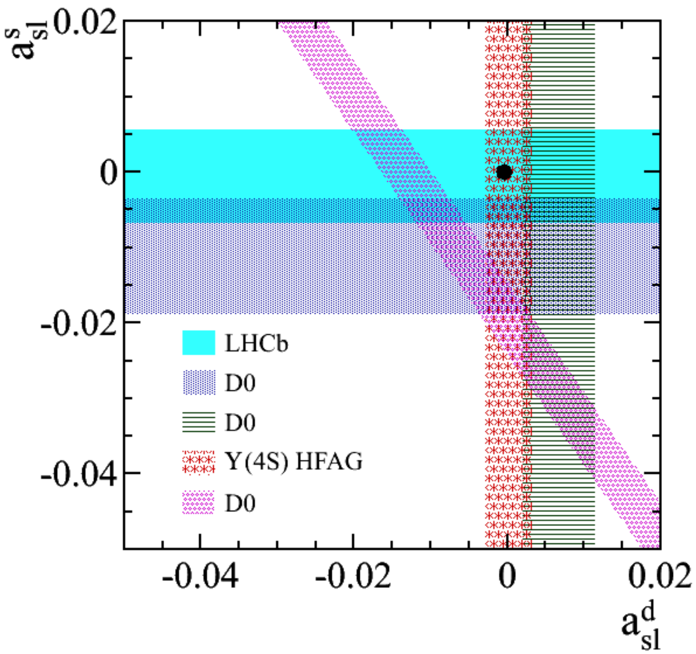
Data analyzed with different magnet polarities separately.



$D_s^+ \to \phi\pi^+$

$D_s^- \to \phi\pi^-$

Magnet "up"



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

PLB 728 (2014) 607-615

Consistent with the most precise measurement made up to now and with the SM prediction

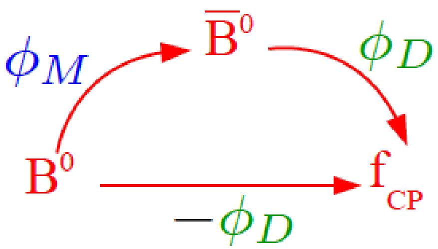
$a^s_{sl} = (-1.12 \pm 0.74 \pm 0.17)\%$ D0 , [PRL 110 (2013) 011801]

CPV through the interference between mixing and decay

The inteference between two “decay paths” of a B_s meson to a CP eigenstate

Gives rise to a (final state dependent) weak phase $\phi_s = \phi_M - 2\phi_D$

$$A_{CP}(t) = \frac{\Gamma(B_s^0 \to f) - \Gamma(\bar{B}_s^0 \to f)}{\Gamma(B_s^0 \to f) + \Gamma(\bar{B}_s^0 \to f)}$$
$$= -\eta_f \sin(\phi_s)\sin(\Delta m_s t)$$



$\phi_D \approx 0$ in the SM

NP might add larges phases to the SM prediction: $\phi_s = \phi_s^{SM} + \phi_s^{NP}$

For $b \to c\bar{c}s\ (B_s^0 \to J/\psi\phi)$ indirect determination in the SM via global fits gives (neglecting penguin contributions):

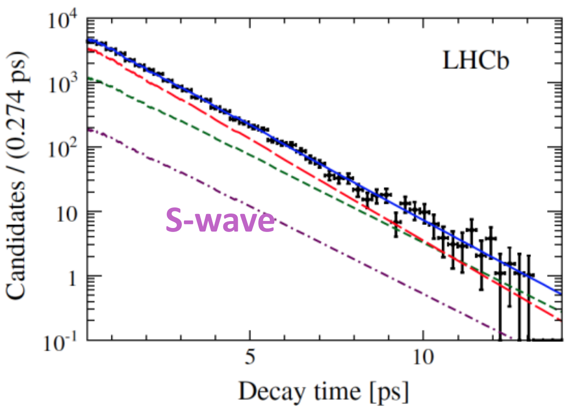
$$\phi_s^{SM} = -2\arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = 0.0364 \pm 0.0016\ \mathrm{rad}$$

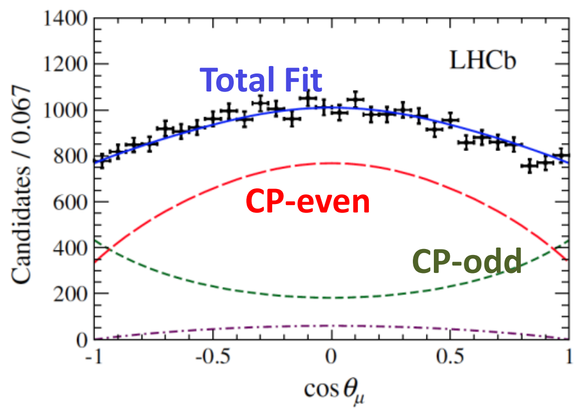
CKMfitter, PRD 84 (2011) 033005

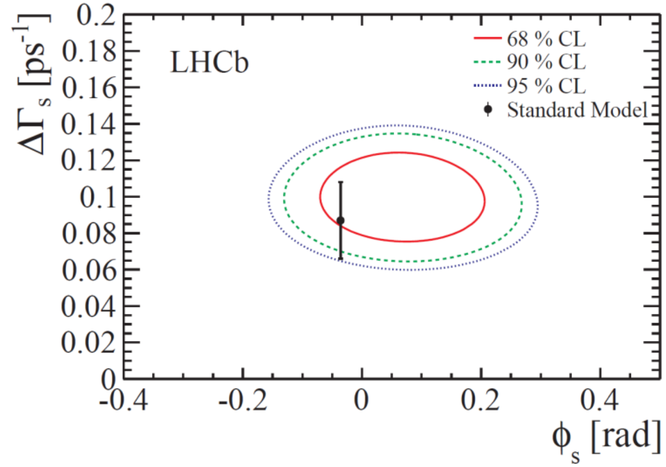
A precise determination of ϕ_s is as a sensitive test of NP in the B_s sector.

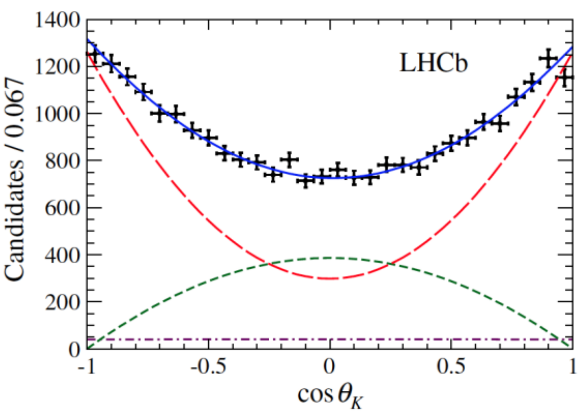
ϕ_s from $B_s^0 \to J/\psi K^+ K^-$

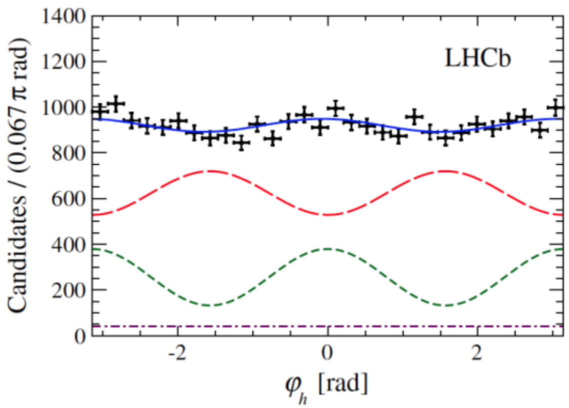
- P → VV decay with CP-even and CP-odd components.
- Fit invariant mass, decay time and angular distributions of flavour-tagged events.
- $1fb^{-1}$ of data at √s=7 TeV. (27617 ± 115 events)











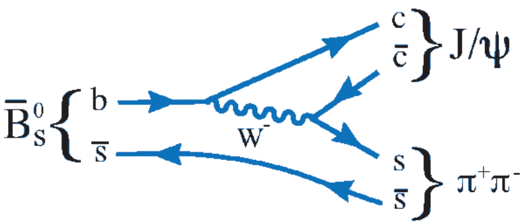
$$\begin{aligned}\phi_s &= 0.07 \pm 0.09 \pm 0.01 \text{ rad}\\ \Gamma_s &= 0.663 \pm 0.005 \pm 0.006 \text{ ps}^{-1}\\ \Delta\Gamma_s &= 0.100 \pm 0.016 \pm 0.003 \text{ ps}^{-1}\end{aligned}$$

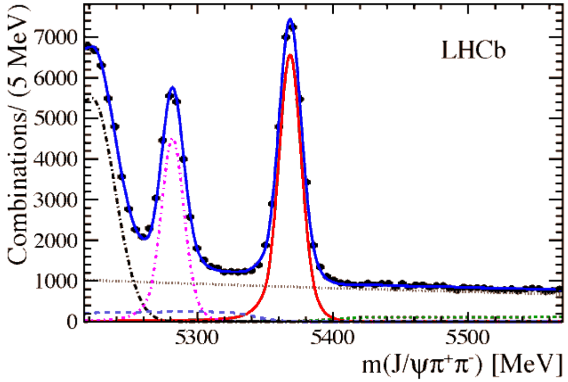
[PRD 87, 112010 (2013)]

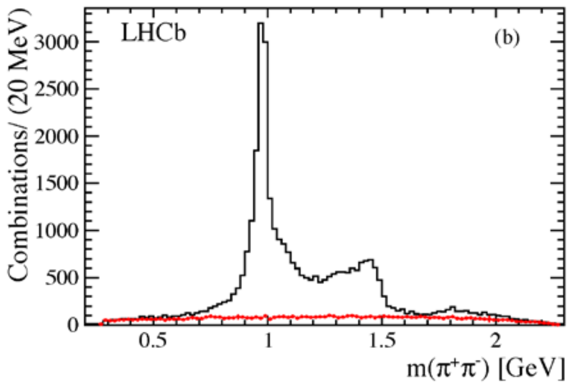
Single most precise measurements

(Definition of helicity angles as for the $B^0 \to \phi K^*$ decay in slide 4)

CP components in $B_s^0 \to J/\psi\pi^+\pi^-$ decays







CP-odd component in the final state > 97.7% at 95% CL ➔ no ang. analysis required.

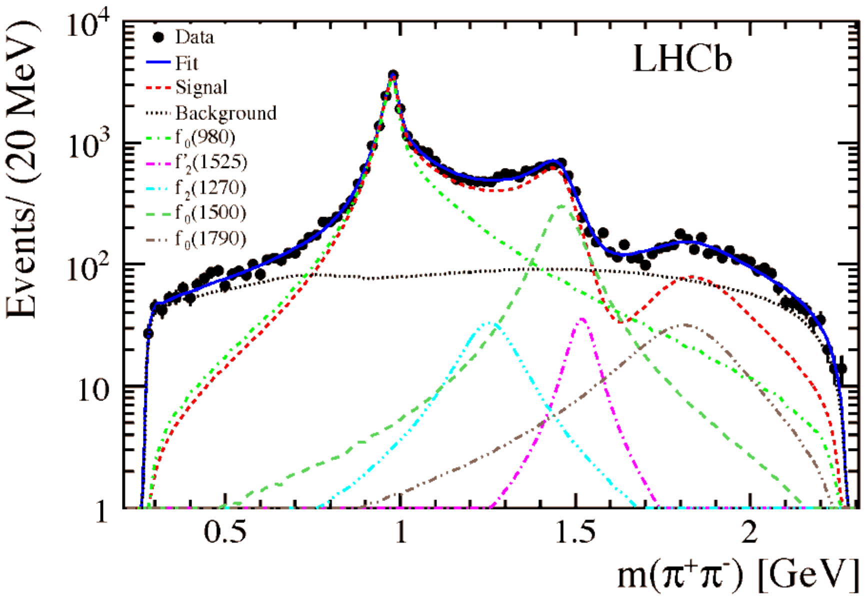
From the analysis of 1 fb^{-1} data [PLB 713 (2012) 378]: $\phi_s = -0.14^{+0.17}_{-0.16} \pm 0.01 \ \ \text{rad}$

- New amplitude analysis with 3 fb^{-1} (full LHCb data) to study resonant and CP components.

(arXive:1402.6248)

- Five interfering $\pi^+\pi^-$ states required to describe the decay: $f_0(980)$, $f_0(1500)$, $f_0(1790)$, $f_2(1270)$, $f_2(1525)$.

- CP-odd component > 97.7% confirmed.

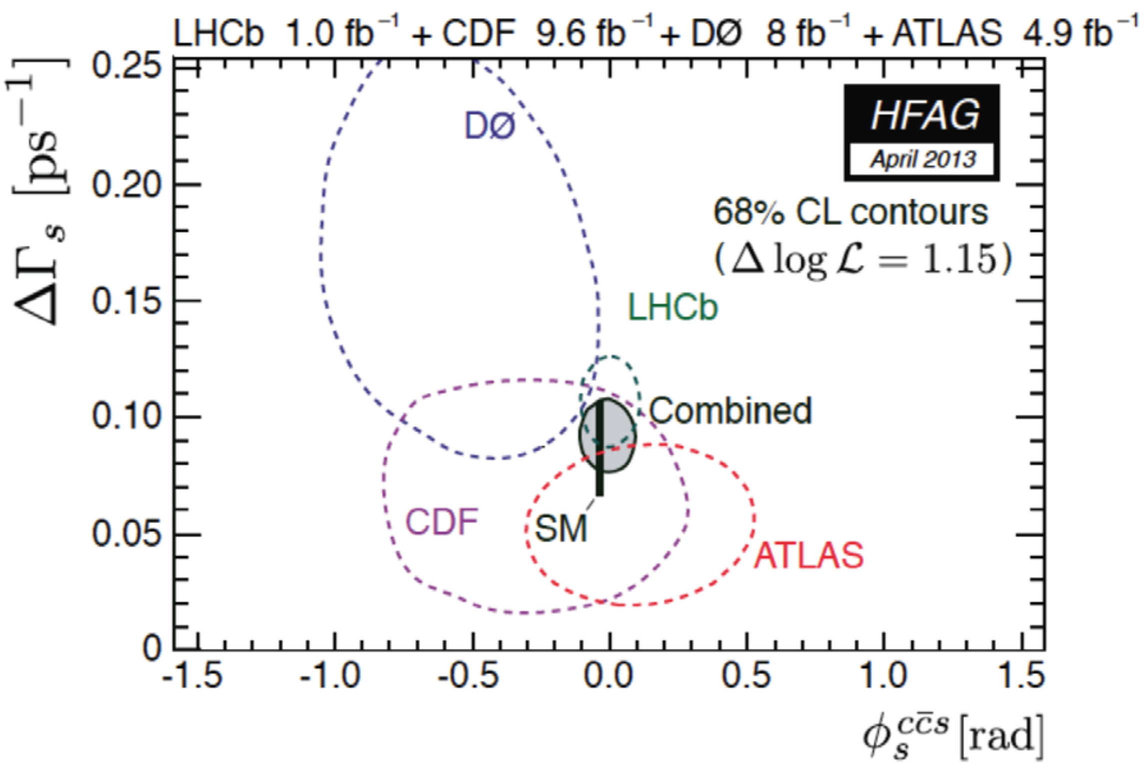


Combined measurement of ϕ_s

Combined fit to $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$ (1 fb^{-1}).

[PRD 87, 112010 (2013)]

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



- In agreement with the SM: ϕ_s = -0.0364 ± 0.0016 rad.
- Limits NP contributions to Bs mixing to less than 30% at 3σ (A. Lentz arXiv:1203.0238v2).
- Update with 3 fb^{-1} coming soon.

Conclusions

- All results (still) in good agreement with the SM. Many more not shown here.
- Most of the measurements based only on 1/3 of the data available.
- Results with 3 fb^{-1} luminosity gradually coming.
- Eagerly waiting for LHC run 2.

Thanks for your attention

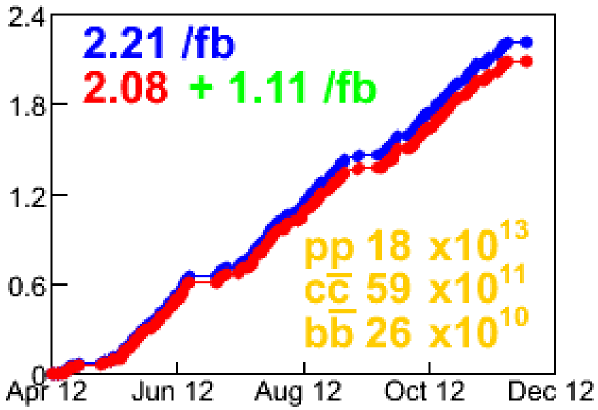
BACKUP

The LHCb detector

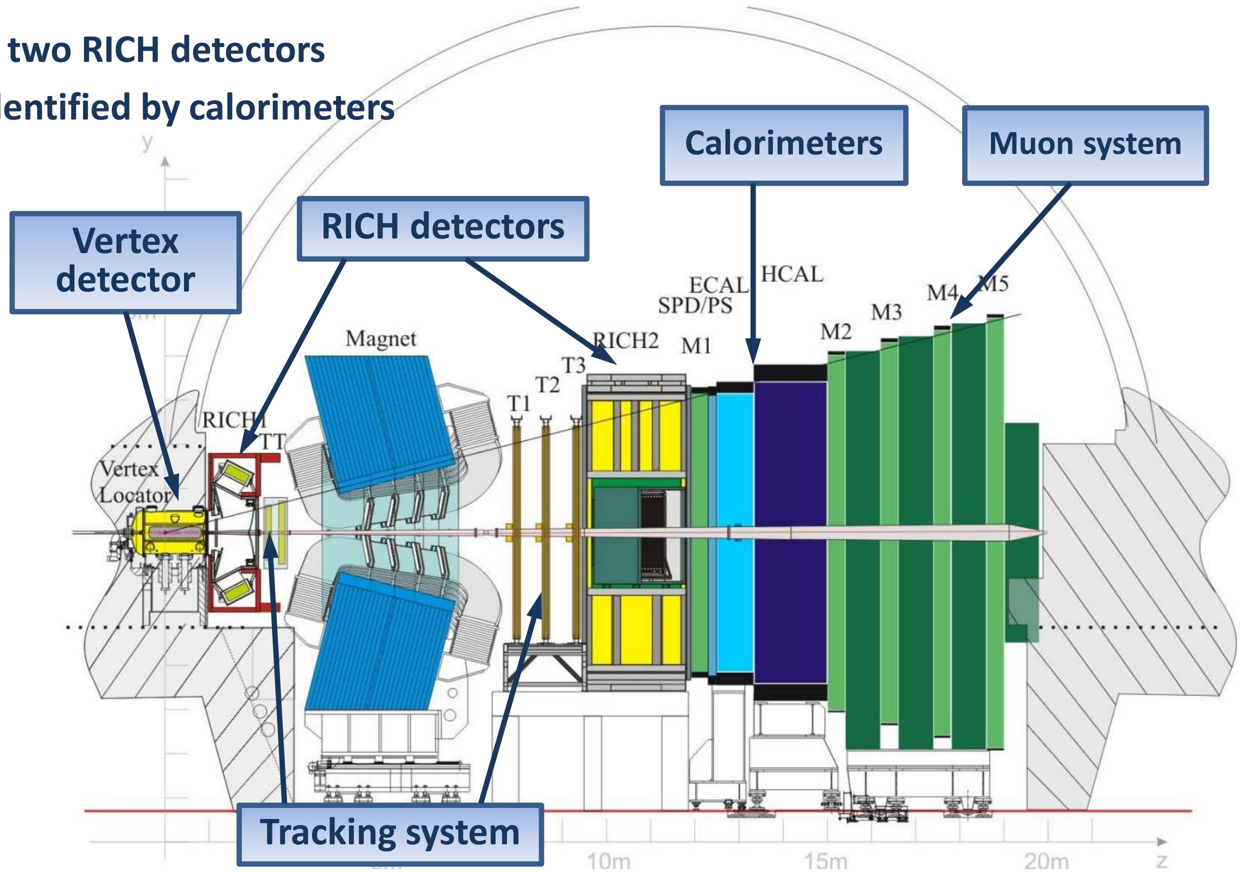
- Single arm forward spectrometer (2<η<5, 4% of solid angle).
- Trigger reduces rate from 40MHz to 5kHz.
- 3 fb-1 of data collected in 2011-2012.
- High-precision tracking system (Dp/p ~0.5%)
  - Vertex detector
  - Silicon-strip detector
- Charged hadrons identified using two RICH detectors
- Photon, electrons and hadrons identified by calorimeters

PV Impact Parameter (IP) resolution ~20 μm for high p_T tracks

Collected luminosity



- 1.11 fb^{-1} at $\sqrt{s}$=7TeV (2011)
- 2.08 fb^{-1} at $\sqrt{s}$=8TeV (2012)



$\bar{B}^0_s \to D^-_s D^+_s$ and $\bar{B}^0_s \to D^- D^+_s$ effective lifetimes

First measurement of the $\bar{B}^0_s$ effective lifetime in $\bar{B}^0_s \to D^-_s D^+_s$ decays with 3 fb^{-1}

CP-even

arXiv:1312.1217v1

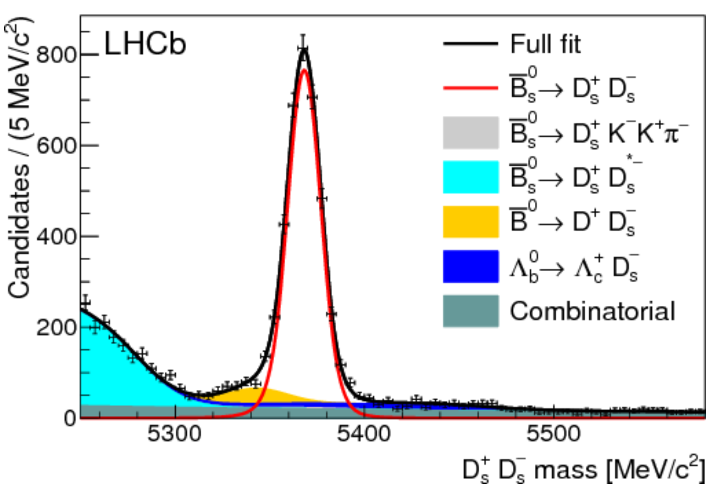
Untagged decay rate probes ϕ_s, Γ_L and Γ_H

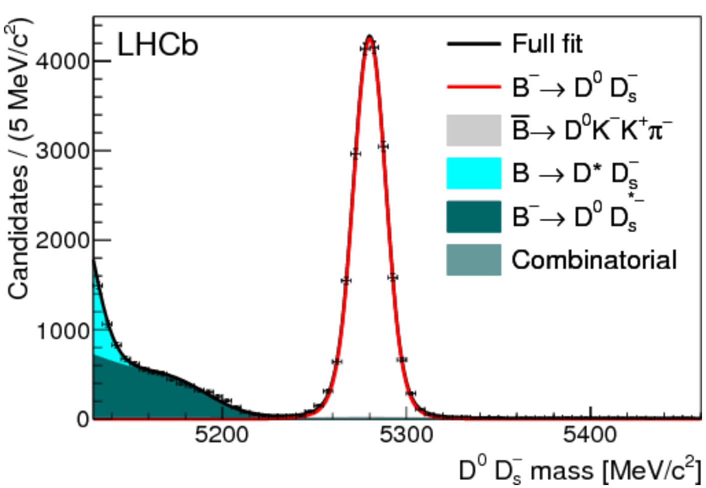
$$\Gamma_{\bar{B}^0_s \to D^-_s D^+_s}(t) + \Gamma_{B^0_s \to D^+_s D^-_s}(t) \propto (1+\cos\phi_s)e^{-\Gamma_L t} + (1-\cos\phi_s)e^{-\Gamma_H t} \propto e^{-t/\tau^{\mathrm{eff}}_{\bar{B}^0_s \to D^-_s D^+_s}}$$

Assuming negligible direct CPV ($\phi_s \approx 0.01$): $\tau^{\mathrm{eff}}_{\bar{B}^0_s \to D^-_s D^+_s} \approx \Gamma_L^{-1}$

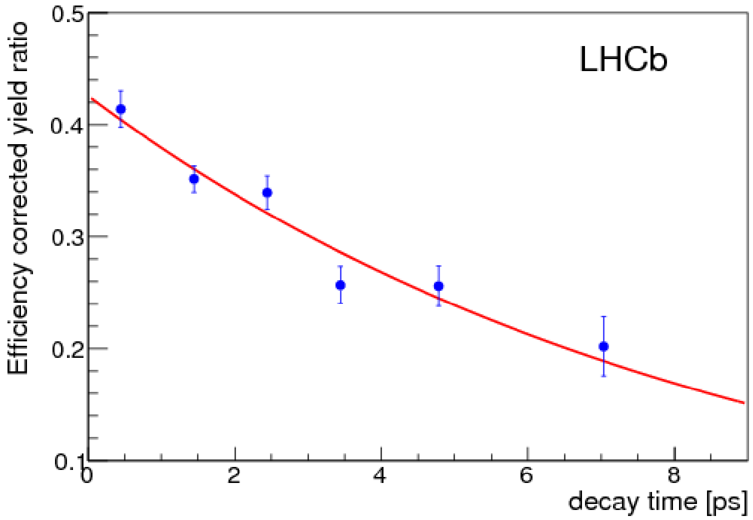
Normalize to the $B^- \to D^0 D^-_s$ decay, which has a $\tau_{B^-} = 1.641 \pm 0.008$ ps

$$\frac{\Gamma_{\bar{B}^0_s \to D^-_s D^+_s}(t) + \Gamma_{B^0_s \to D^+_s D^-_s}(t)}{\Gamma_{B^- \to D^0 D^-_s}(t) + \Gamma_{B^+ \to \bar{D}^0 D^+_s}(t)} \sim e^{-\alpha_{su} t} \qquad \alpha_{su} = \frac{1}{\tau^{\mathrm{eff}}_{\bar{B}^0_s \to D^-_s D^+_s}} - \frac{1}{\tau_{B^-}}$$





$\bar{B}^0_s \to D^-_s D^+_s$ and $\bar{B}^0_s \to D^- D^+_s$ effective lifetimes

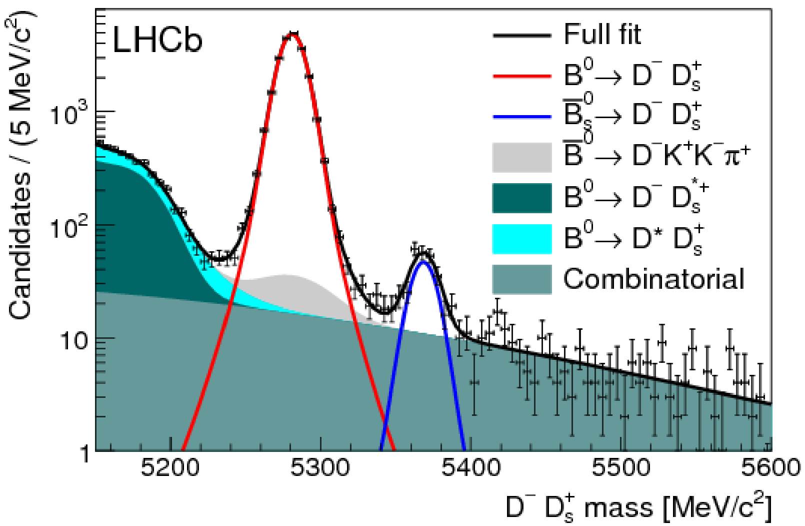


$$\tau^{\text{eff}}_{\bar{B}^0_s \to D^-_s D^+_s} = 1.379 \pm 0.026 \pm 0.017 \ \text{ps}$$

$$\Gamma_{\text{L}} = 0.725 \pm 0.014 \pm 0.009 \ \text{ps}^{-1}$$

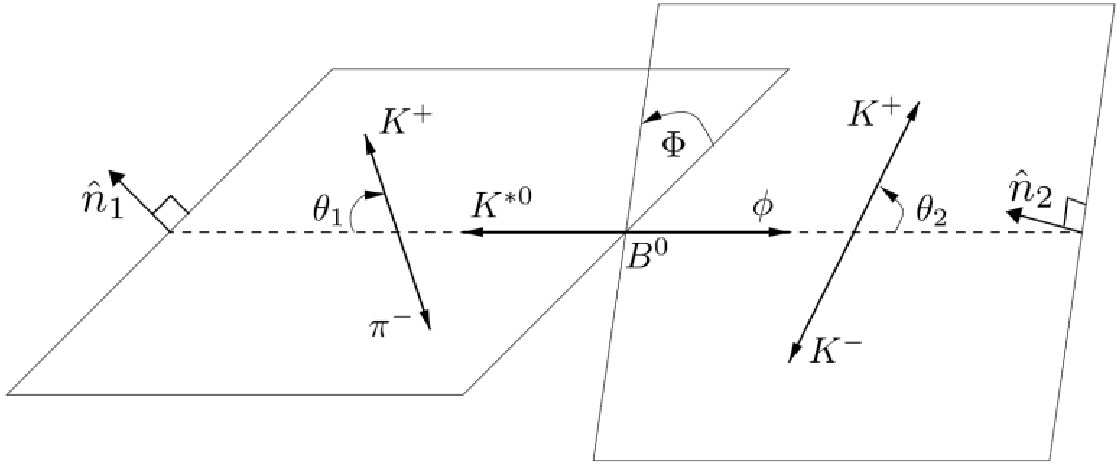
Most precise measurement of Γ_L

arXiv:1312.1217v1

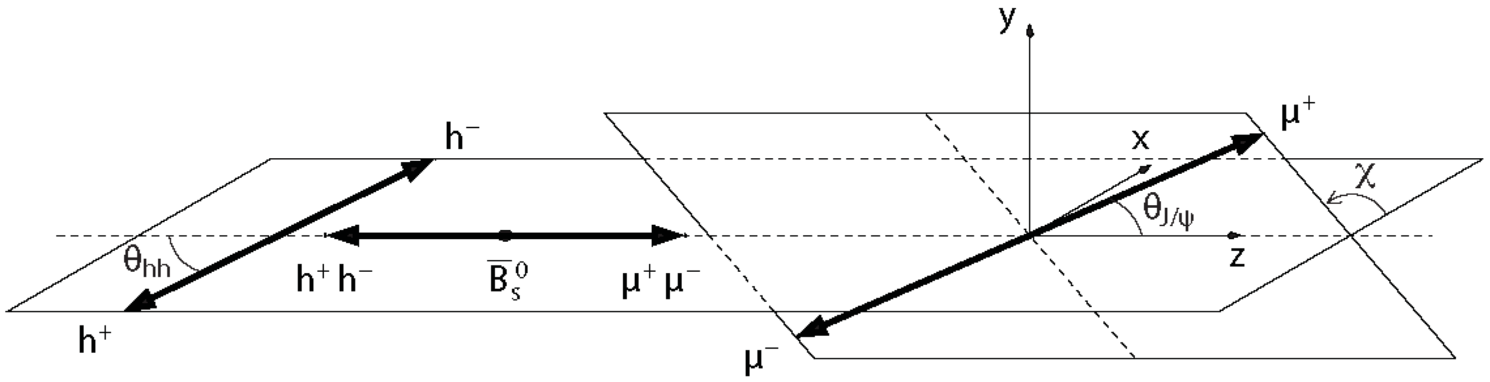


Measure also the $\bar{B}^0_s \to D^- D^+_s$ effective lifetime using $\bar{B}^0 \to D^- D^+_s$ for normalization

$$\tau^{\text{eff}}_{\bar{B}^0_s \to D^- D^+_s} = 1.52 \pm 0.15 \pm 0.01 \ \text{ps}$$



K^+
Φ
K^+
$\hat{n}_1$
θ_1
K^{*0}
ϕ
θ_2
$\hat{n}_2$
B^0
π^-
K^-



y
μ^+
h^-
x
χ
$\theta_{J/\psi}$
θ_{hh}
$h^+ h^-$
$\overline{B}_s^0$
$\mu^+ \mu^-$
z
h^+
μ^-