CPV measurements at LHCb

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on behalf of the LHCb Collaboration

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<u>Outline</u>

- Direct *CP* asymmetry in B^0 and $B_s \to K\pi$
- ϕ_s measurements in $B_s \to J/\psi\ \phi$ and $J/\psi\ f_0(980)$
- *CPV* in D^0 decays

Introduction

- Measurements of CP-violation in B and D sectors are a good way to search for New Physics.
  - Complementary to direct search in ATLAS and CMS
- LHCb was built to precisely measure CP violating and rare b & c decays:
  - Good proper time resolution for time dependent analyses with fast mixing frequencies
  - Good particle ID for flavour tagging and discrimination between final states
  - High statistics

A_{CP} in $B^0 \to K^+\pi^-$ and $B_s \to K^-\pi^+$

The direct *CP* asymmetry $A_{CP}(B \to K\pi) = \dfrac{\Gamma(\overline{B}) - \Gamma(B)}{\Gamma(\overline{B}) - \Gamma(B)}$

The raw yield asymmetry is corrected for Detection and Production effects

$$A_{CP} = A_{\mathrm{RAW}} - A_{\Delta}$$

$$A_{\Delta} = A_{\mathrm{D}} + \kappa A_{\mathrm{P}}$$

κ : reduction of production asymmetry due to neutral *B*-meson mixing, & lifetime acceptance $\kappa(B^0) \approx 0.3$, $\kappa(B_s) \approx -0.03$

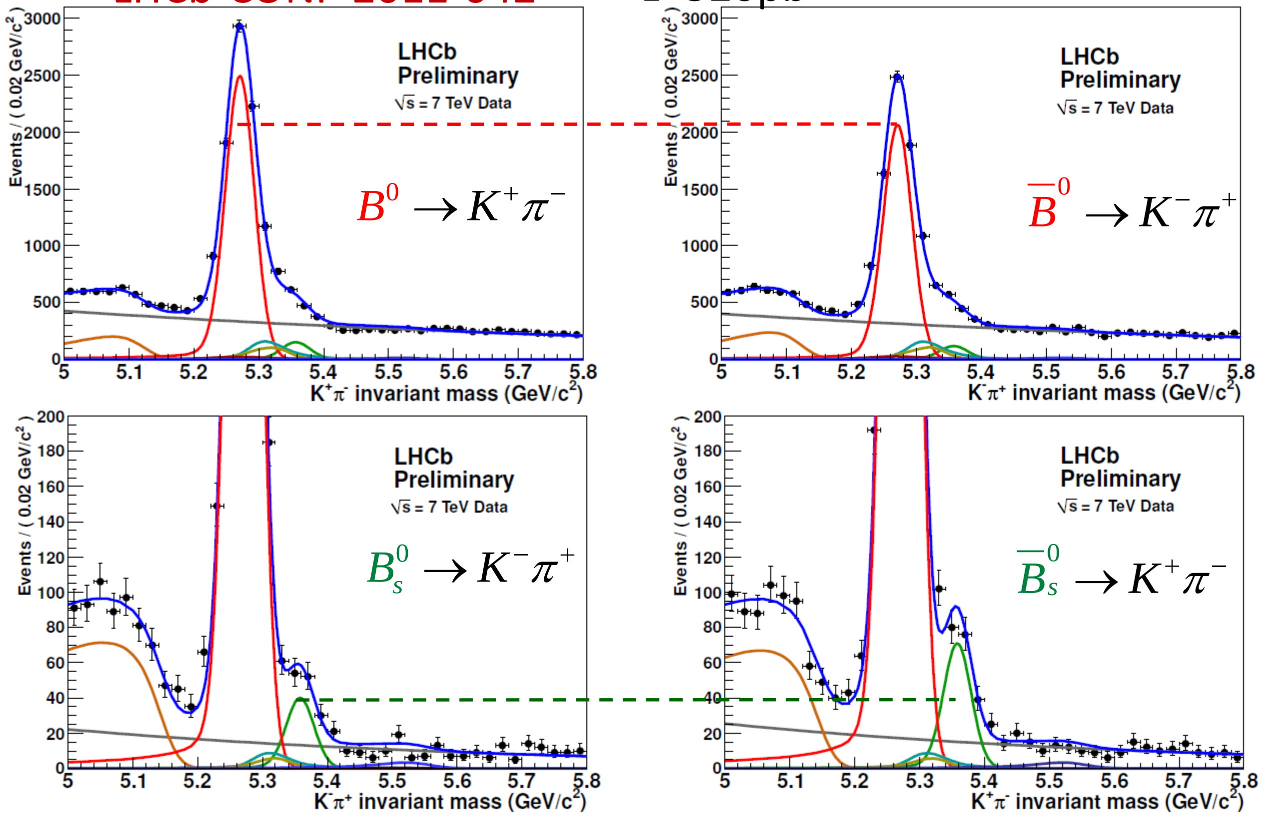
- $A_{\mathrm{D}}(K\pi)$ is measured in control channels $D^* \to D^0(\to K\pi)\pi^+$, $D^* \to D^0(\to KK)\pi^+$, using well measured world average (WA) of $A_{\mathrm{CP}}(D^0 \to KK)$ and negligible $A_{\mathrm{CP}}(D^0 \to K\pi)$.
- A_{P} is determined using $B^0 \to J/\psi K^*(\to K\pi)$.

$$A_{\Delta}(B^0 \to K^+\pi^-) = (-0.7 \pm 0.6)\%$$

$$A_{\Delta}(B_s^0 \to K^-\pi^+) = (1.0 \pm 0.2)\%$$

A_{CP} in $B^0 \to K^+\pi^-$ and $B_s \to K^-\pi^+$

LHCb-CONF-2011-042 L=320pb^{-1}



Selection optimized for $A_{CP}(B^0 \to K\pi)$

Selection optimized for $A_{CP}(B_s \to K\pi)$

$$\boxed{A_{CP}(B^0 \to K\pi) = (-8.8 \pm 1.1 \pm 0.8)\%}$$

WA: $(-9.8^{+1.2}_{-1.1})\%$

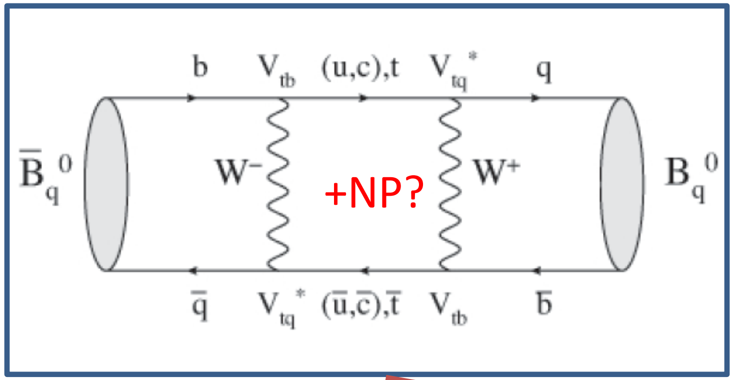
$$\boxed{A_{CP}(B_s^0 \to K\pi) = (27 \pm 8 \pm 2)\%}$$

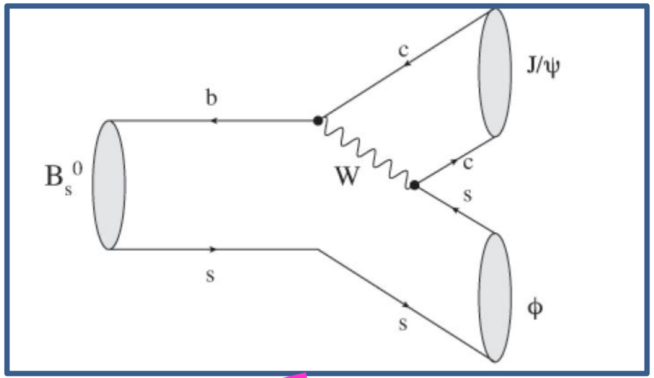
First evidence of *CPV* in $B_s \to K^-\pi^+$

Consistent with CDF value: (39 ± 15 ± 8)%

CPV in B$_s$ mixing

- Interference of decays with and without mixing in B_s allows to measure the *CPV* phase ϕ_s
- It's sensitive to New Physics in B_s mixing



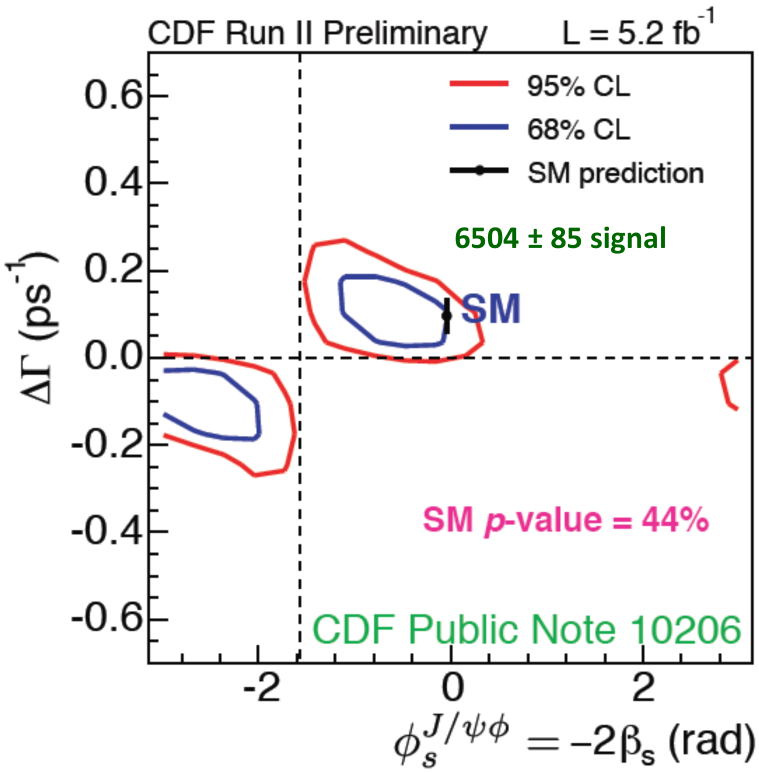


$$\phi_s^{SM} \simeq -2\beta_s \equiv \arg[(V_{tb}V_{ts}^*)^2 / (V_{cb}V_{cs}^*)^2]$$

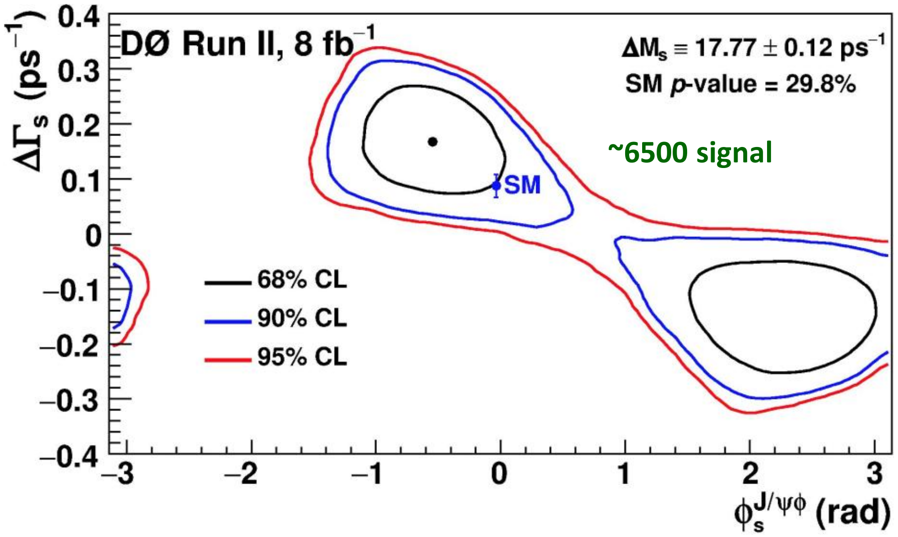
SM prediction (CKM fitter)

$-2\beta_s = -0.036 \pm 0.002$ rad

Measurements from Tevatron

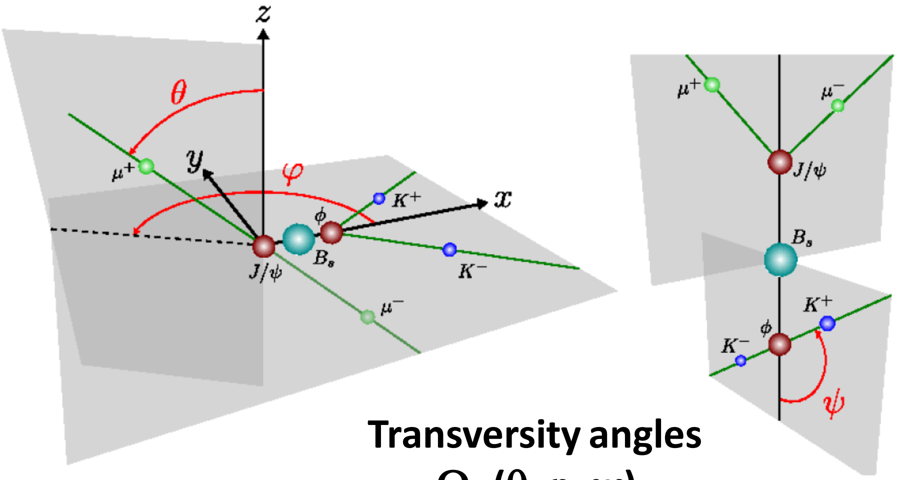


arXiv:1109.3166



$B_s \to J/\psi\phi$

- $B_s \to J/\psi\phi$ is $P \to VV$
  - L=1: $A_\perp$ (CP odd)
  - L=0, 2: A_0, $A_\parallel$ (CP even)
- Additional S-wave KK
  - A_S (CP odd)
- Separated by angular analysis in transversity basis



Transversity angles
Ω=(θ, φ, ψ)

- Signal PDF: flavour tagged, time and angular dependent

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

acceptance

flavour tagging
q: tag decision,
D = 1–2ω, ω: mistag rate

time resolution,
measured ≈50 fs using
prompt J/ψ + KK

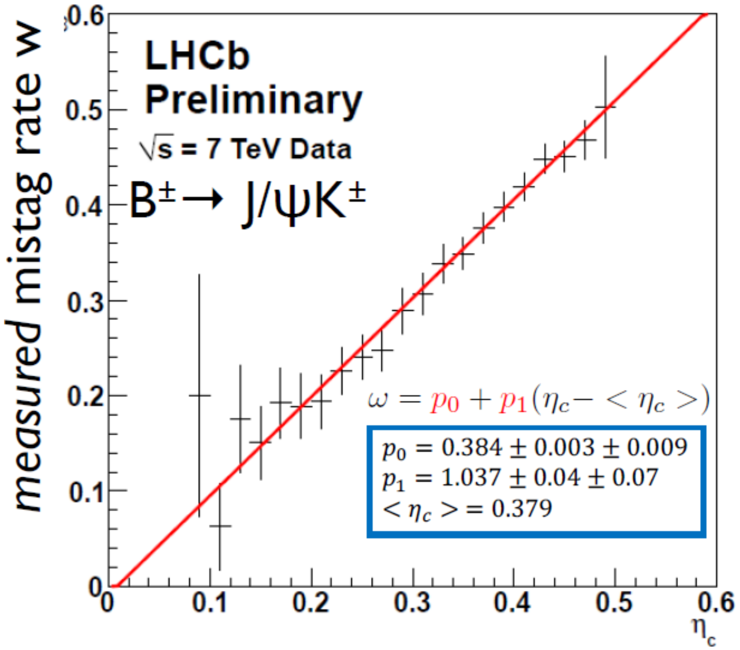
Physics parameters $\vec{\lambda} = (\Gamma_s, \Delta\Gamma_s, \Delta m_s, \phi_s, |A_0|^2, |A_\perp|^2, \delta_\parallel, \delta_\perp, |A_S|^2, \delta_S)$

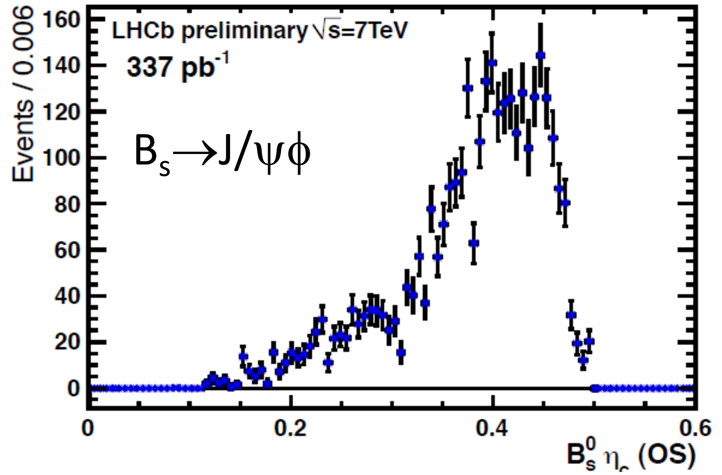
Δm_s=17.63 ± 0.11 ± 0.03 ps^{-1} with 2010 data LHCb-CONF-2011-005

New: 17.725±0.041±0.026 ps^{-1} with 2011 data

Flavor tagging

- By now we only use opposite side (OS) tagging
- Combine 4 observables into an estimated mistag probability η_c:
  - High-pt muons
  - High-pt electrons
  - High-pt kaons
  - Opposite side vertex charge
- Calibrate on $B^{\pm} \to J/\psi\ K^{\pm}$ data
- Tagging power $\varepsilon D^2 = (2.08 \pm 0.41)\%$





Fit Projections

8276 ± 94 signal @~337pb^{-1}

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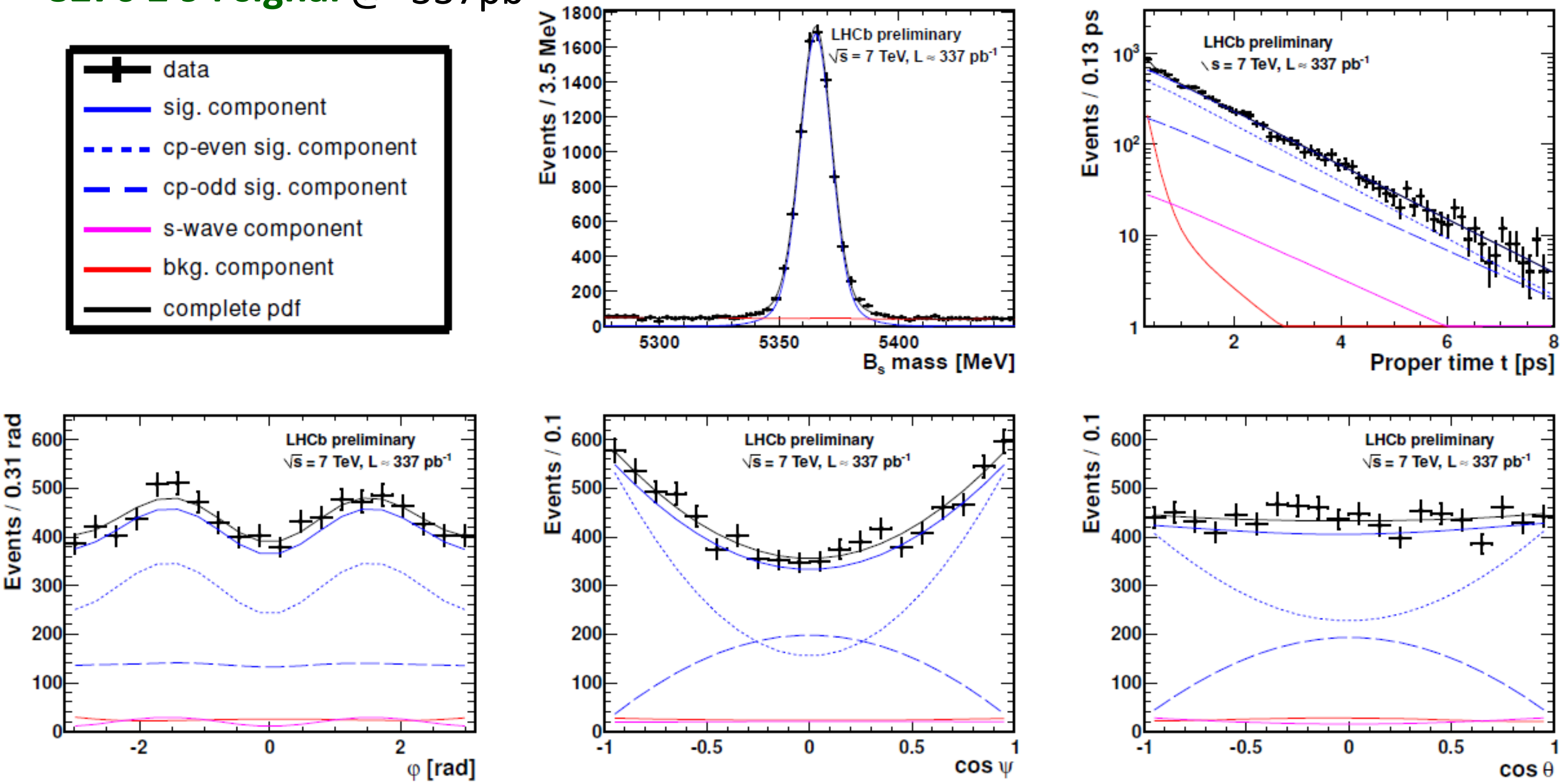

Goodness of Fit: p-value 44% using point-to-point dissimilarity test [arXiv:1006.3019]

ϕ_s from $B_s \to J/\psi\phi$

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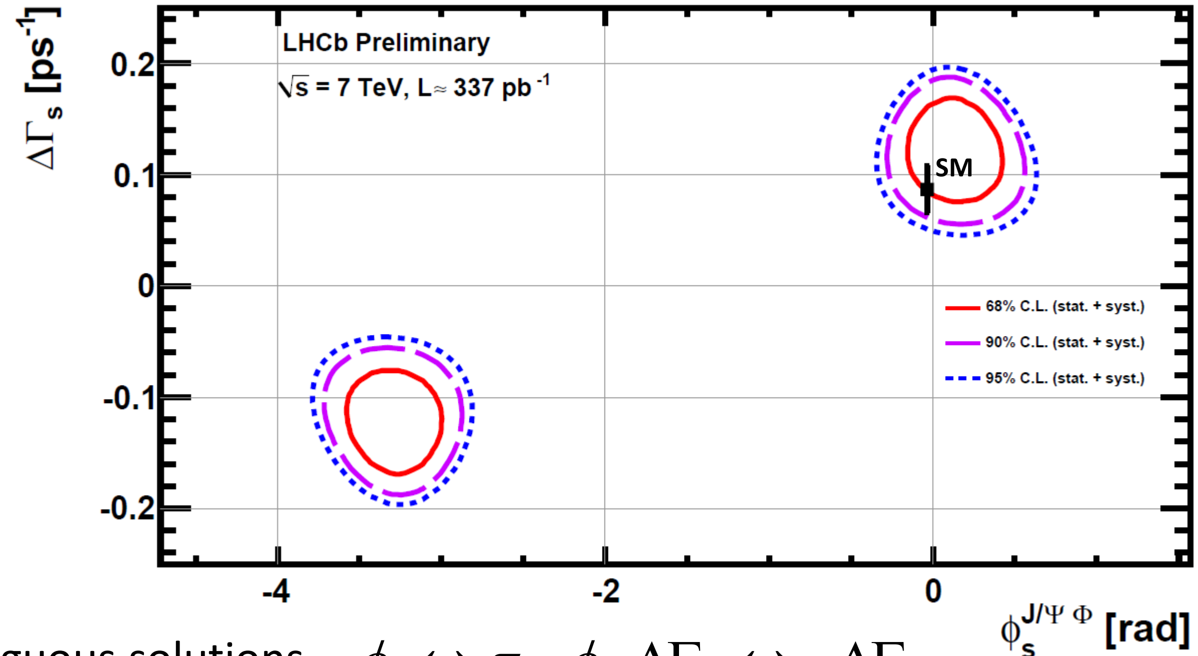


Two ambiguous solutions $\phi_s \leftrightarrow \pi - \phi_s, \Delta\Gamma_s \leftrightarrow -\Delta\Gamma_s$

Most precise measurement of ϕ_s

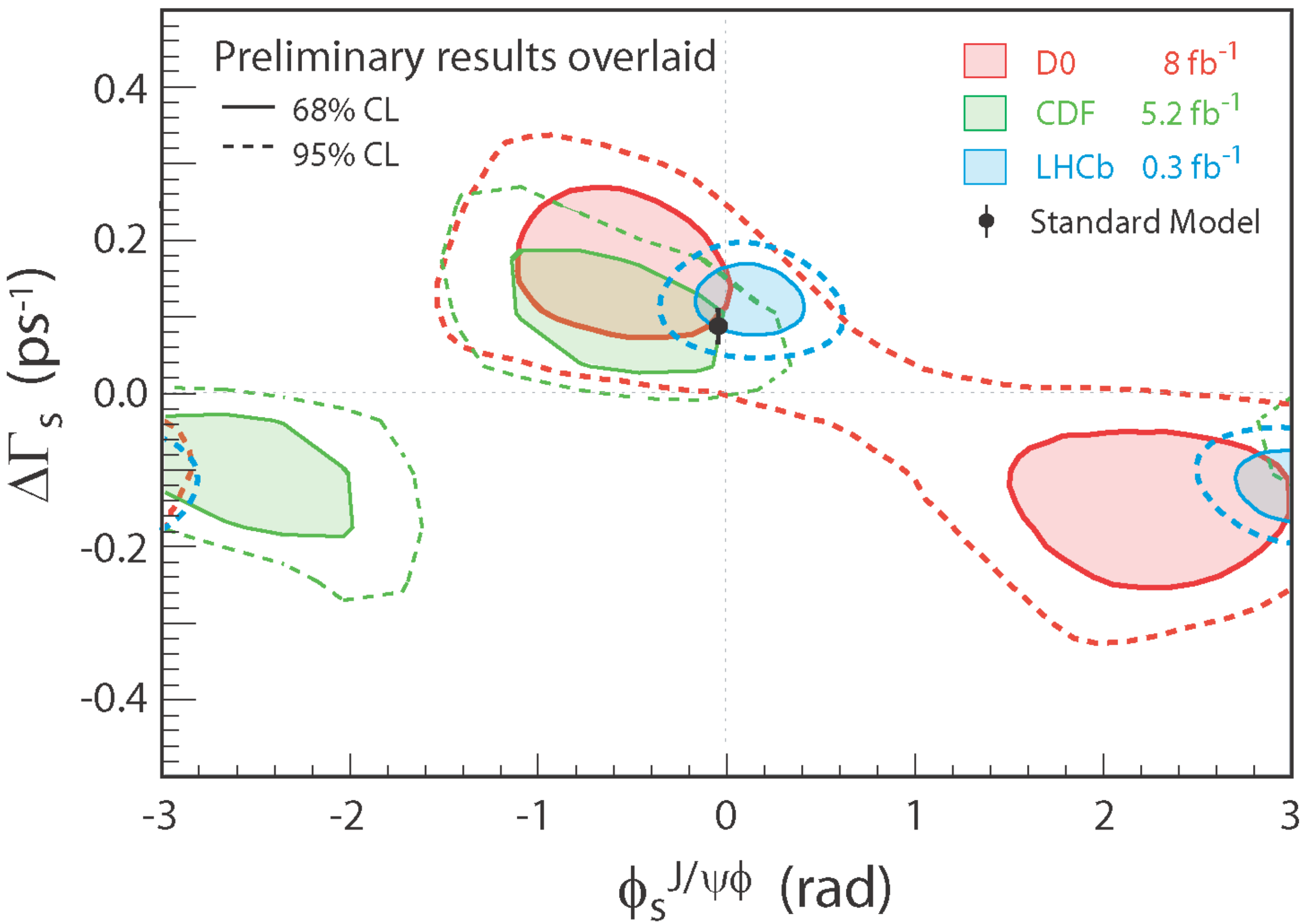
$$\phi_s^{J/\psi\phi} = 0.13 \pm 0.18(\text{stat}) \pm 0.07(\text{sys})\ \text{rad}$$

4σ evidence for $\Delta\Gamma_s \neq 0$

$$\Gamma_s = 0.656 \pm 0.009(\text{stat}) \pm 0.008(\text{sys})\ \text{ps}^{-1}$$

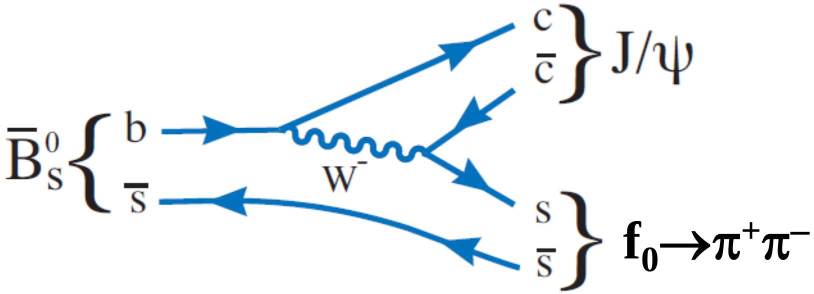
$$\Delta\Gamma_s = 0.123 \pm 0.029(\text{stat}) \pm 0.011(\text{sys})\ \text{ps}^{-1}$$

Overlay of all data

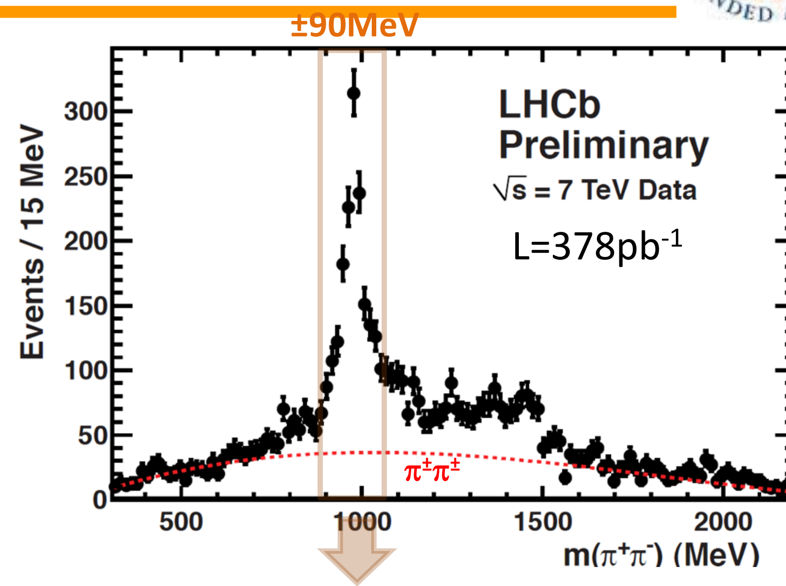


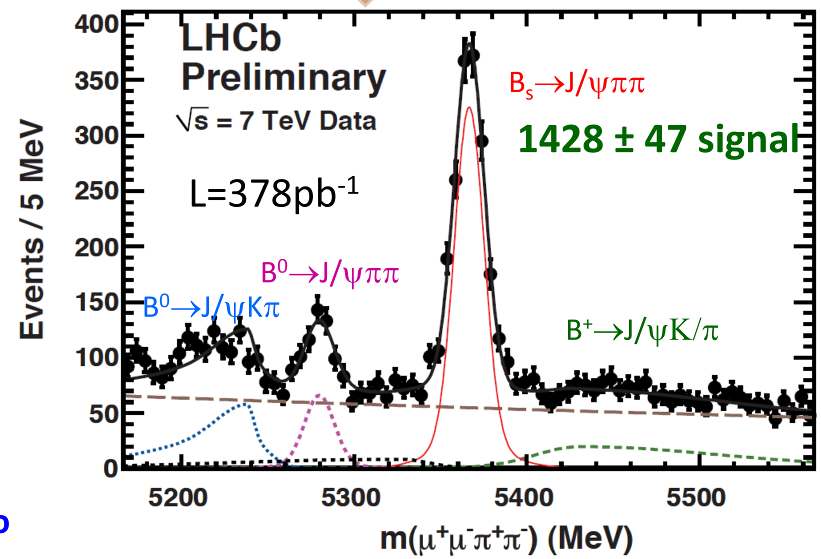
http://lhcb-public.web.cern.ch/lhcb-public/

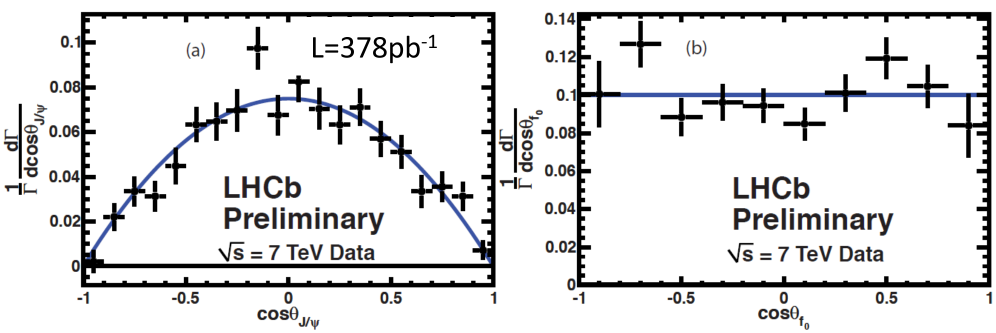
$B_s \to J/\psi f_0$



- **Feb. 1, 2011 – LHCb: "1st observation of $B_s \to J/\psi\ f_0(980)$ decays" using 37pb^{-1}** [PLB, 698, 115(2011)]
- **Here present the first use of this channel to measure ϕ_s**







Angular distributions show the events in $f_0(980)$ signal region consistent with pure S-wave => pure CP-odd eigenstate => no angular analysis needed.

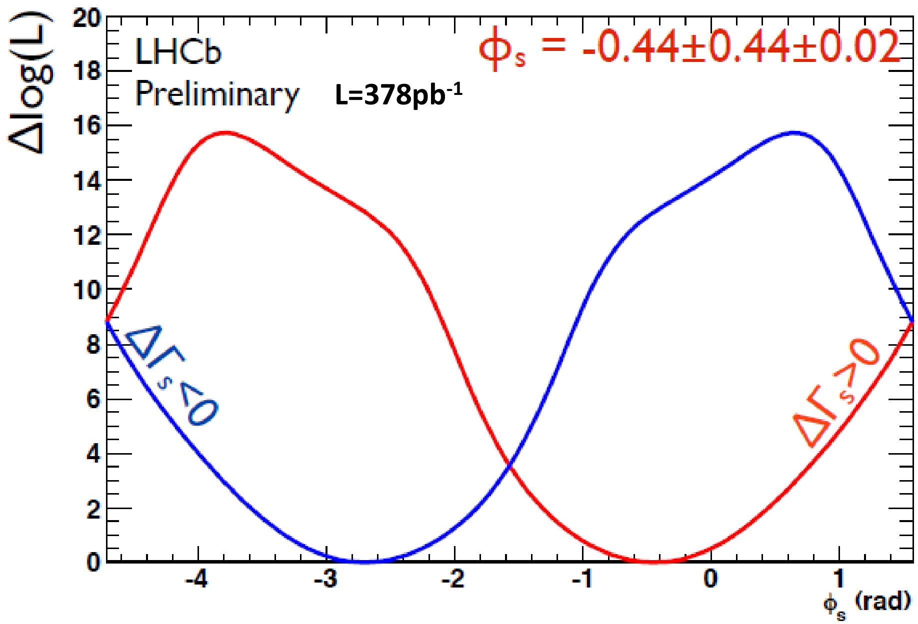
ϕ_s from $B_s \rightarrow J/\psi f_0$

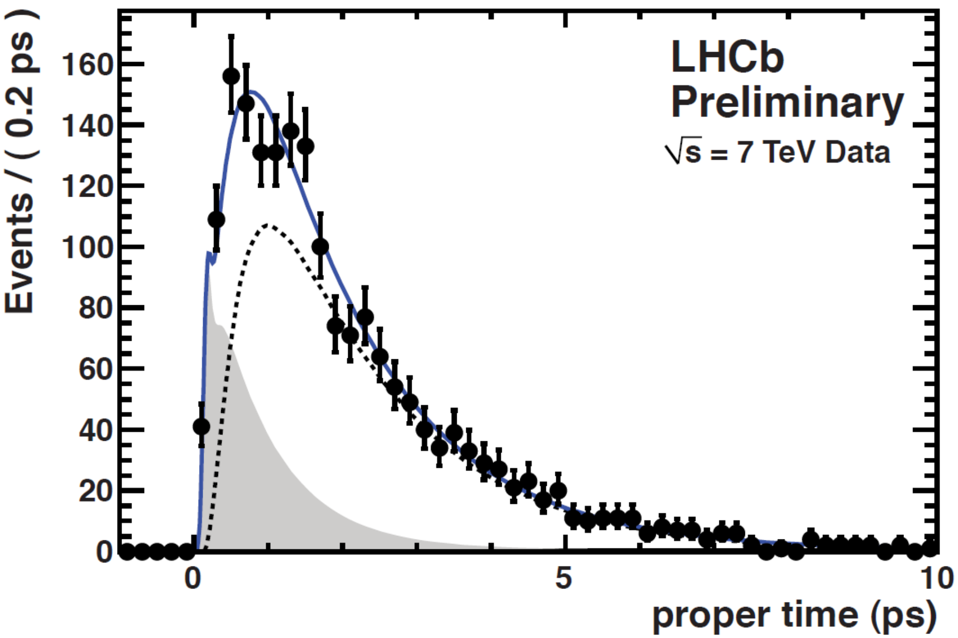
The time evolution of initial B_s ($\overline{B}_s$) to CP-odd eigenstate

$$\propto e^{-\Gamma_s t}\left\{\cosh\frac{\Delta\Gamma_s t}{2}+\cos\phi_s \sinh\frac{\Delta\Gamma_s t}{2}\mp\sin\phi_s\sin(\Delta m_s t)\right\}$$

– for B_s
+ for $\overline{B}_s$

$\Delta\Gamma_s$ and Γ_s constrained to LHCb's measurements in $J/\psi\phi$





$$\phi_s^{J/\psi f_0} = -0.44 \pm 0.44(\text{stat}) \pm 0.02(\text{sys})\ \text{rad}$$

LHCb-CONF-2011-051

SM p-value = 36%

Combination of ϕ_s

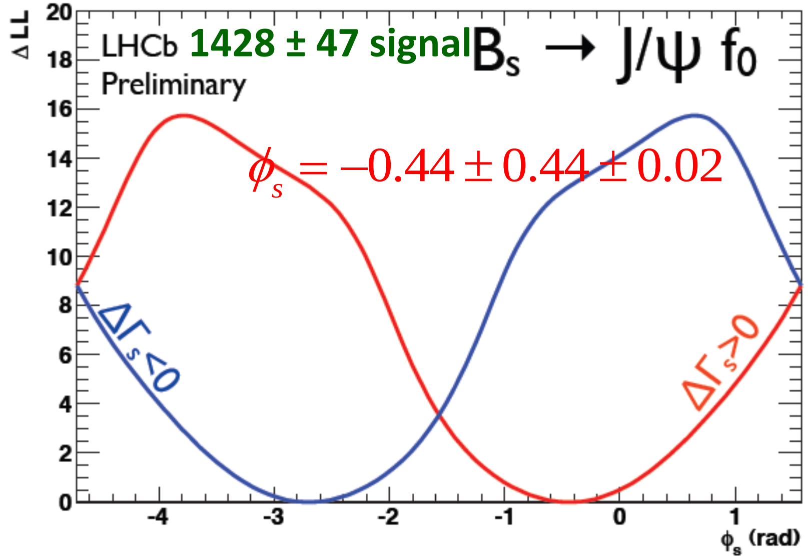
- Simultaneously fit $B_s \rightarrow J/\psi\phi$ and $J/\psi f_0$

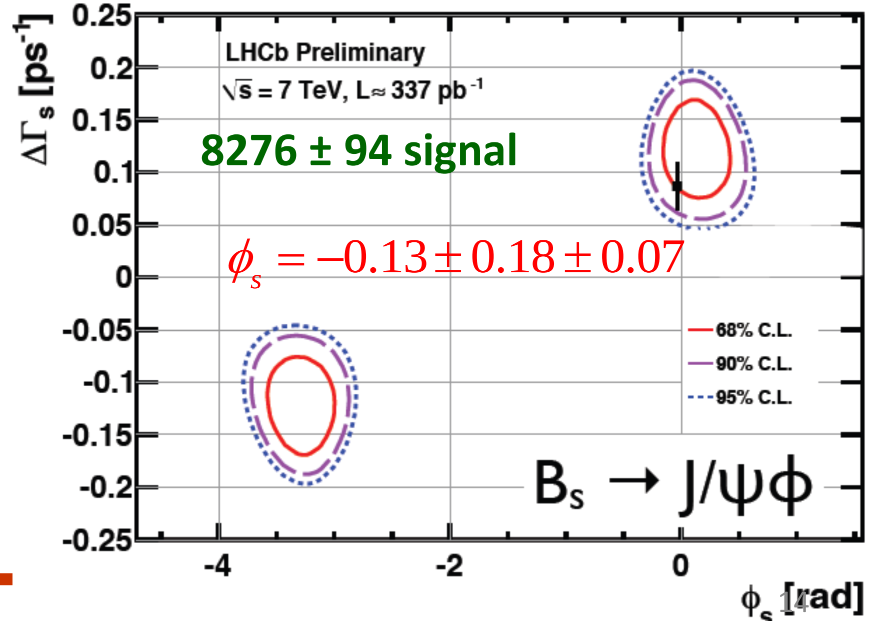
LHCb Preliminary LHCb-CONF-2011-056

$$\phi_s^{combined} = 0.03 \pm 0.16(\text{stat}) \pm 0.07(\text{sys})\ \text{rad}$$

SM

$$\phi_s = -0.036 \pm 0.002\ \text{rad}$$





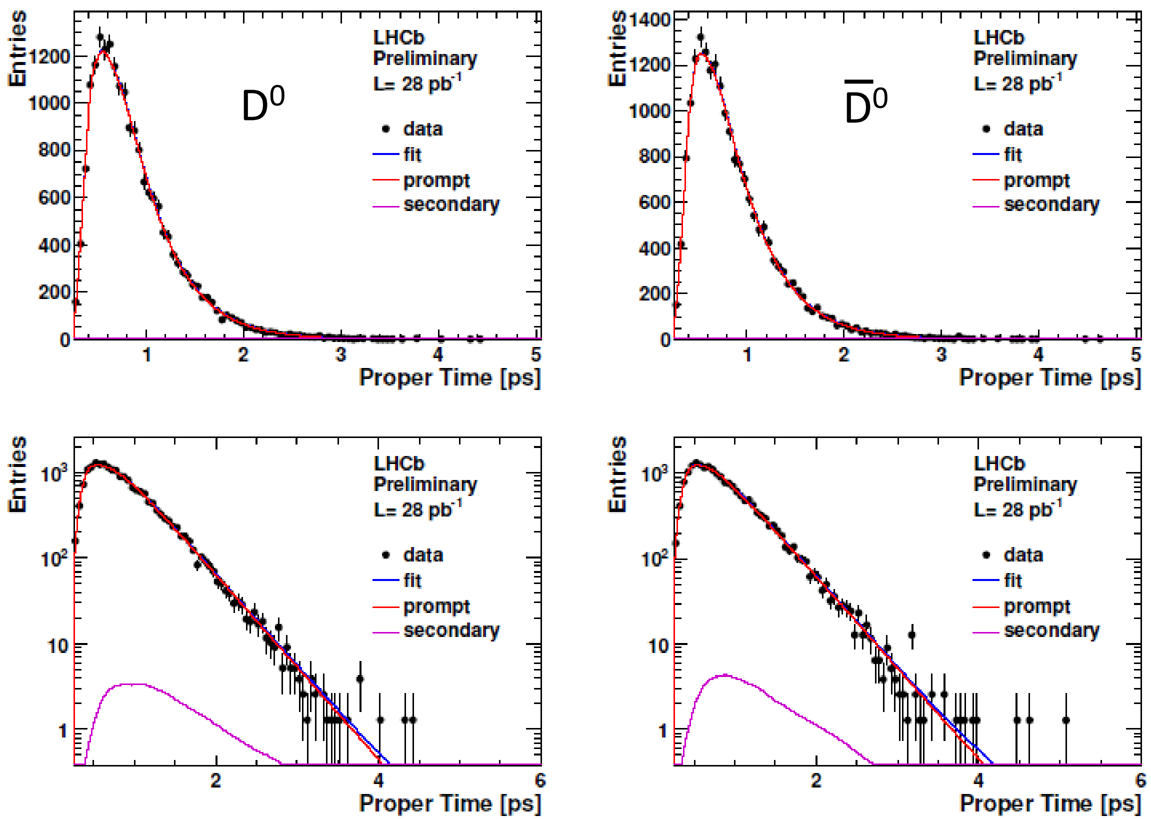
A_Γ in $D^0 \to KK$

- SM predicts CPV in charm is $\mathcal{O}(10^{-3})$
- Measurement with higher rate would clearly signal new physics

$$A_\Gamma \equiv \frac{\tau(\overline{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^+K^-) + \tau(D^0 \to K^+K^-)} = -a_{\mathrm{CP}}^{\mathrm{ind}}$$

2010 data, 28 pb^{-1}

D* tagged



LHCb-CONF-2011-046

$$A_\Gamma = (-0.59 \pm 0.59 \pm 0.21)\%$$

c.f. WA $(0.12 \pm 0.25)\%$

ΔA_{CP} in charm

Time-integrated *CP* Asymmetry:

$$A_{CP}(f) \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)} \approx a_{CP}^{\mathrm{dir}}(f) + \frac{\langle t \rangle}{\tau} a_{CP}^{\mathrm{ind}}$$

$$\boxed{\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \Delta a_{CP}^{\mathrm{dir}} + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{\mathrm{ind}}}$$

<t> is average proper time in selected sample, In this study, $\Delta\langle t\rangle/\tau \approx 0.1$

The raw yield asymmetry of D* is sum of asymmetries from physical *CP*, Detection and Production

=0

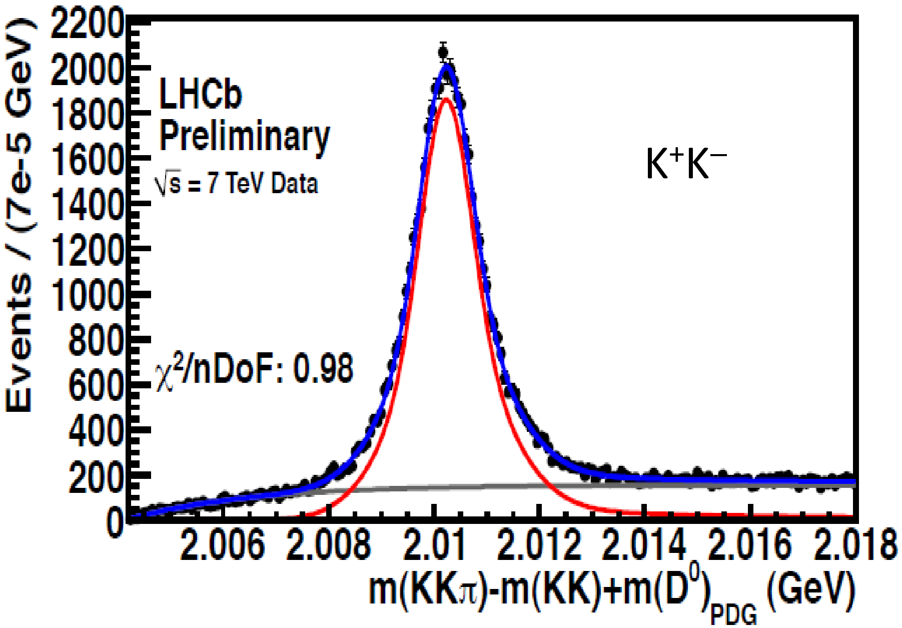
$$A_{RAW}(K^+K^-)^* = A_{CP}(K^+K^-) + \cancel{A_{\mathrm{D}}(K^+K^-)} + A_{\mathrm{D}}(\pi_s) + A_{\mathrm{P}}(D^*)$$

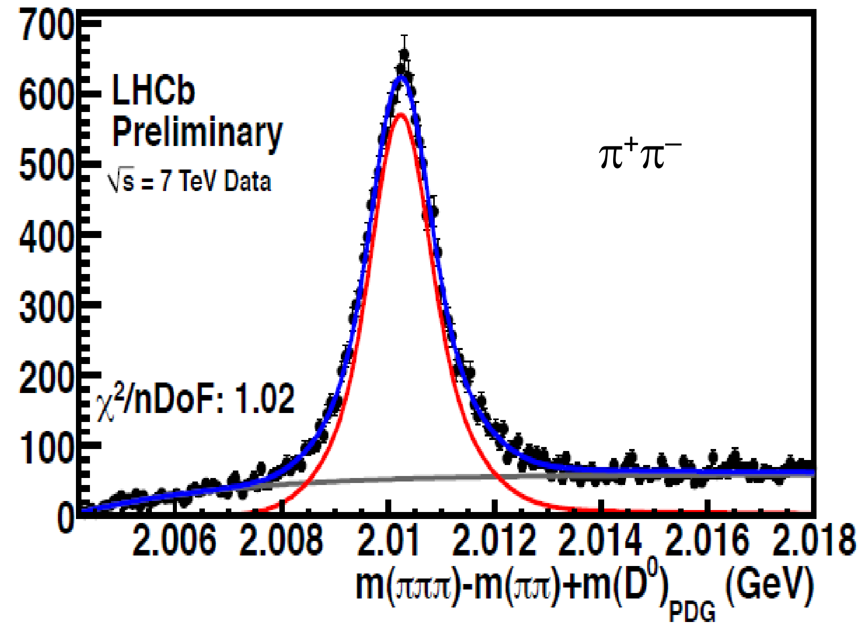
$$A_{RAW}(\pi^+\pi^-)^* = A_{CP}(\pi^+\pi^-) + \cancel{A_{\mathrm{D}}(\pi^+\pi^-)} + A_{\mathrm{D}}(\pi_s) + A_{\mathrm{P}}(D^*)$$

$$\boxed{\Delta A_{CP} = A_{RAW}(K^+K^-)^* - A_{RAW}(\pi^+\pi^-)^*}$$

ΔA_{CP} Result

2010 data, 37 pb^{-1}





The difference of raw yield asymmetries is calculated in 12 bins of D^* (p_T, η). Consistent numbers are seen. A weighted average is quoted.

$$\boxed{\Delta A_{CP}=(-0.28 \pm 0.70 \pm 0.25)\%}$$

LHCb-CONF-2011-023

LHCb is updating the result with 25 times more statistics

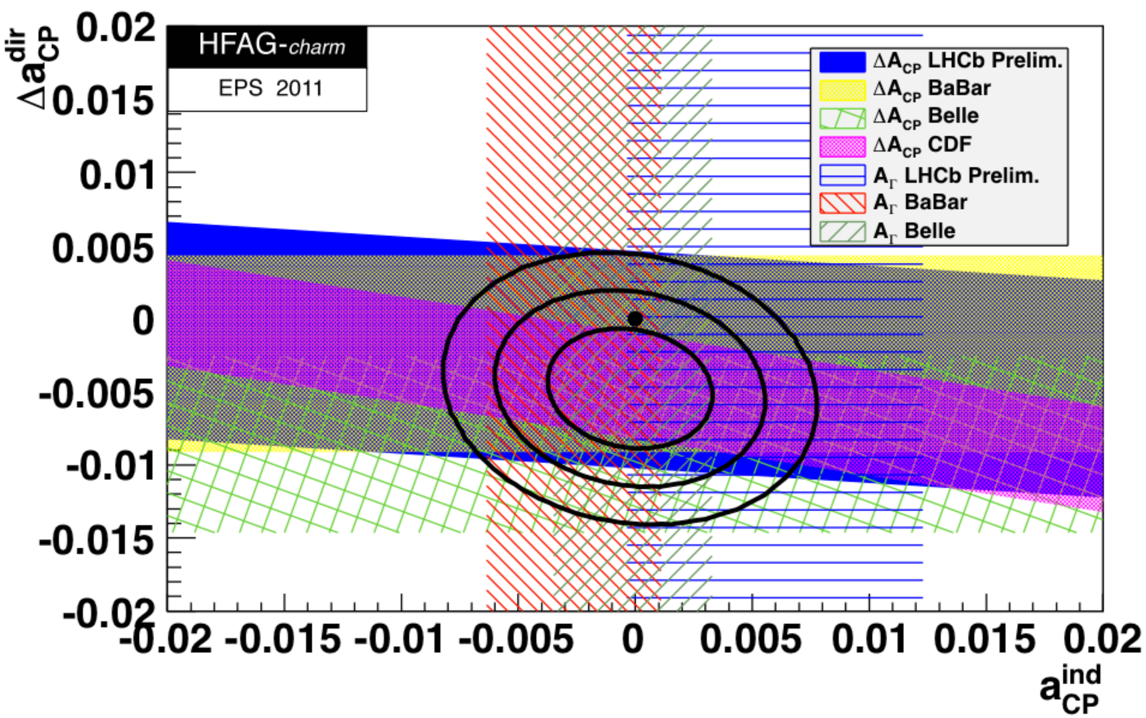
Conclusions

- LHCb has made several world-best measurements of CPV in beauty.
- The measurements in charm used only 2010 data, we will significantly improve the results with 2011 data.
- No sign of New Physics yet, but will have large increases in data: 1 fb^{-1} already collected in 2011, doubled in 2012 and then another factor of two after shutdown.

Backup

D^0 CPV in mixing and direct

$$A_\Gamma = -a_{CP}^{ind}; \qquad \Delta A_{CP} = \Delta a_{CP}^{dir} + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{ind}$$



$a_{CP}^{ind} = (-0.023 \pm 0.232)\%$

$\Delta a_{CP}^{dir} = (-0.477 \pm 0.270)\%$

Data are consistent with no CPV at 20% CL.

$$\frac{\mathrm{d}^4\Gamma(B_s^0 \to J/\psi\phi)}{\mathrm{d}t\ \mathrm{d}\cos\theta\ \mathrm{d}\varphi\ \mathrm{d}\cos\psi} \equiv \frac{\mathrm{d}^4\Gamma}{\mathrm{d}t\ \mathrm{d}\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega)$$

k	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0\rvert^2(t)$	$2\cos^2\psi\,(1-\sin^2\theta\cos^2\phi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\psi\,(1-\sin^2\theta\sin^2\phi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im(A_\parallel(t)\,A_\perp(t))$	$-\sin^2\psi\sin 2\theta\sin\phi$
5	$\Re(A_0(t)\,A_\parallel(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin^2\theta\sin 2\phi$
6	$\Im(A_0(t)\,A_\perp(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin 2\theta\cos\phi$
7	$\lvert A_s(t)\rvert^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
8	$\Re(A_s^*(t)A_\parallel(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$
9	$\Im(A_s^*(t)A_\perp(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$
10	$\Re(A_s^*(t)A_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

$$
\begin{aligned}
|A_0|^2(t) &= |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], && (4)\\
|A_\|(t)|^2 &= |A_\||^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], && (5)\\
|A_\perp(t)|^2 &= |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)\right], && (6)\\
\Im(A_\|(t)\, A_\perp(t)) &= |A_\||\,|A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_\|) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \cos(\delta_\perp - \delta\_\|) \cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_\|) \cos(\Delta m t)\right], && (7)\\
\Re(A_0(t)\, A_\|(t)) &= |A_0|\,|A_\|| e^{-\Gamma_s t} \cos(\delta_\| - \delta_0)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. + \sin\phi_s \sin(\Delta m t)\right], && (8)\\
\Im(A_0(t)\, A_\perp(t)) &= |A_0|\,|A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_0) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \cos(\delta_\perp - \delta_0) \cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_0) \cos(\Delta m t)\right], && (9)\\
|A_s(t)|^2 &= |A_s|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t\right], && (10)\\
\Re(A_s^*(t) A_\|(t)) &= |A_s|\,|A_\|| e^{-\Gamma_s t}\left[-\sin(\delta_\| - \delta_s) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\| - \delta_s)\ \cos\phi_s \sin(\Delta m t)\right. \\
&\quad \left. + \cos(\delta_\| - \delta_s) \cos(\Delta m t)\right], && (11)\\
\Im(A_s^*(t) A_\perp(t)) &= |A_s|\,|A_\perp| e^{-\Gamma_s t} \sin(\delta_\perp - \delta_s)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \sin\phi_s \sin(\Delta m t)\right], && (12)\\
\Re(A_s^*(t) A_0(t)) &= |A_s|\,|A_0| e^{-\Gamma_s t}\left[-\sin(\delta_0 - \delta_s) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \sin(\delta_0 - \delta_s) \cos\phi_s \sin(\Delta m t) + \cos(\delta_0 - \delta_s) \cos(\Delta m t)\right]. && (13)
\end{aligned}
$$

Source	$\phi_s^{J/\psi\,\phi}$[rad]	$\Delta\Gamma_s$ [ps^{-1}]
Description of background	0.06	0.004
Angular acceptances	0.004	0.008
z and momentum scale	–	0.002
Production asymmetry ($\pm$ 10%)	$<$ 0.01	$<$ 0.001
CPV in mixing & decay ($\pm$ 5%)	$<$ 0.03	$<$ 0.006
Quadratic sum	0.07	0.011

Table 4: Breakdown of the systematic uncertainties evaluated for $\phi_s^{J/\psi\,\phi}$and $\Delta\Gamma_s$

Systematic Errors for A_{CP}

Systematic uncertainty	$A_{CP}(B^0 \to K\pi)$	$A_{CP}(B_s^0 \to \pi K)$
PID calibration	0.0012	0.001
Final state radiation	0.0026	0.010
Signal model	0.0004	0.005
Combinatorial background model	0.0001	0.009
3-body background model	0.0009	0.007
Cross-feed background model (shift)	0.0009	0.005
Cross-feed background model (smearing)	0.0006	0.006
Instrumental and production asymmetries	0.0078	0.005
Total	0.0084	0.018

Summary of absolute systematic uncertainties for ΔA_{CP}

Effect	Uncertainty
Modeling of lineshapes	0.06%
D^0 mass window	0.20%
Multiple candidates	0.13%
Binning in (p_{T}, η)	0.01%
Total	0.25%

Table 1: Summary of systematic uncertainties.

Effect	A_Γ (10^{-3})
VELO length scale	negligible
Turning point bias	negligible
Turning point scaling	± 0.1
Combinatorial background	± 1.3
Proper time resolution	± 0.1
Minimum proper-time cut	± 0.1
Maximum proper-time cut	± 0.2
Secondary charm background	± 1.6
Total	± 2.1