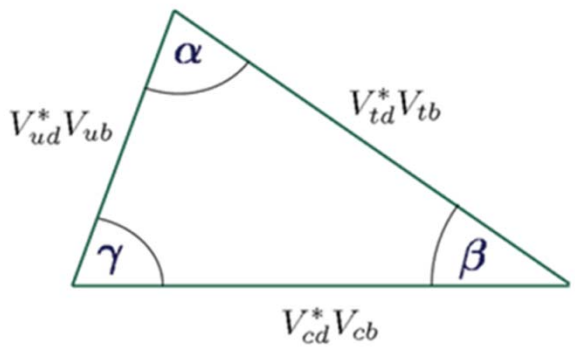
CPV in charm and b decays at LHCb

Brian Meadows
For the LHCb collaboration

1. *CP* violation (*CPV*) and neutral meson mixing
2. Measurement of $-2\beta_s$ from $B_s \rightarrow J/\psi\pi\pi$ (3 fb^{-1})
3. CKM γ modes
4. Polarization amplitudes and direct *CPV* in $B_s \rightarrow \phi K^*$
5. *CPV* in D^0 mixing and decays

3 CKM Unitarity Triangles



<u>B_d decays</u>

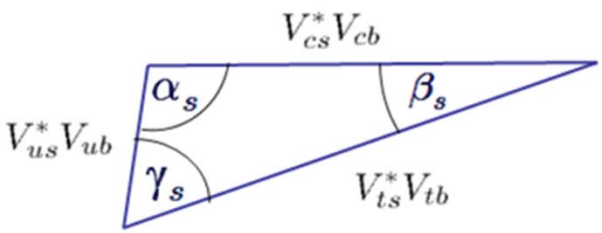
β = 22.01 ± 0.86^0 (UTFIT)

γ = 70 ± 15^0

Well studied by B factories

$\sigma(\beta) \sim 0.9^0$

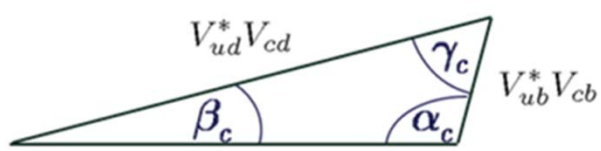
$\sigma(\gamma) \sim 15^0$



<u>B_s decays</u>

β_s = 1.073 ± 0.042^0 (UTFIT)

LHC precision approaching required range



<u>D decays</u>

$\beta_c \sim 0.035^0$ (UTFIT)

$\gamma_c = \gamma$

β_c very small but penguin phase(γ) ~70^0

M^0 Mixing

- Flavour oscillations in the neutral *"M"* system arise from the propagation of two mass eigen-states M_1 and M_2 that comprise the flavour states

$$|M_1> \;=\; p|M^0> + q|\bar{M}^0> \qquad |M_1(t)> \;=\; |M_1>\, e^{-i(\Gamma_1/2 + i m_1)t}$$
$$|M_2> \;=\; p|M^0> - q|\bar{M}^0> \qquad |M_2(t)> \;=\; |M_2>\, e^{-i(\Gamma_2/2 + i m_2)t}$$

Eigen-values are $m_{1,2} + i\Gamma_{1,2}/2$
with means: $M = (m_1 + m_2)/2$, $\Gamma = (\Gamma_1 + \Gamma_2)/2$

- It is usual to define four mixing parameters:

$$\Delta m = m_2 - m_1 \;;\quad \Delta\Gamma = \Gamma_2 - \Gamma_1 \;;\qquad \left|\frac{q}{p}\right| \;;\quad \phi_M = \mathrm{Arg}\left\{\frac{q}{p}\right\}$$

D0 decays: $x = \Delta m/\Gamma \;;\quad y = \Delta\Gamma/(2\Gamma)$

CPV signalled by $p \neq q$

- Decays M and $\overline{M}$ to state *"f"* are characterised by quantity λ_f

Define decay amplitudes:

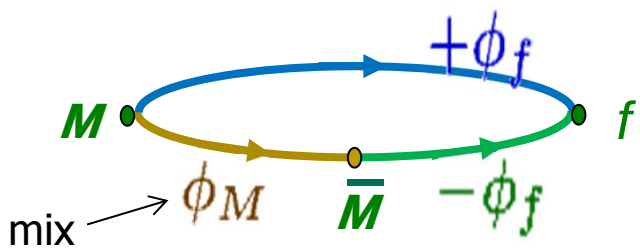
$$\mathcal{A}_f(D^0 \to f)$$
$$\overline{\mathcal{A}}_f(\overline{D}^0 \to f)$$

$$\lambda_f = \frac{q\bar{\mathcal{A}}_f}{p\mathcal{A}_f} \propto e^{i(\phi_M - 2\phi_f + \delta_f)}$$

Mixing — Weak decay — Strong decay

Mixing-induced CPV

- For decays where final state f is accessible to both M and $\bar{M}$ (e.g. f is CP eigenstate, hadronic, etc.) mixing brings M and $\bar{M}$ into interference



Relative weak phase is
$\phi = \mathrm{Arg}\lambda_f = \phi_M - 2\phi_f$

- t-dependence for M and $\bar{M}$ differ - induces oscillatory CP asymmetry

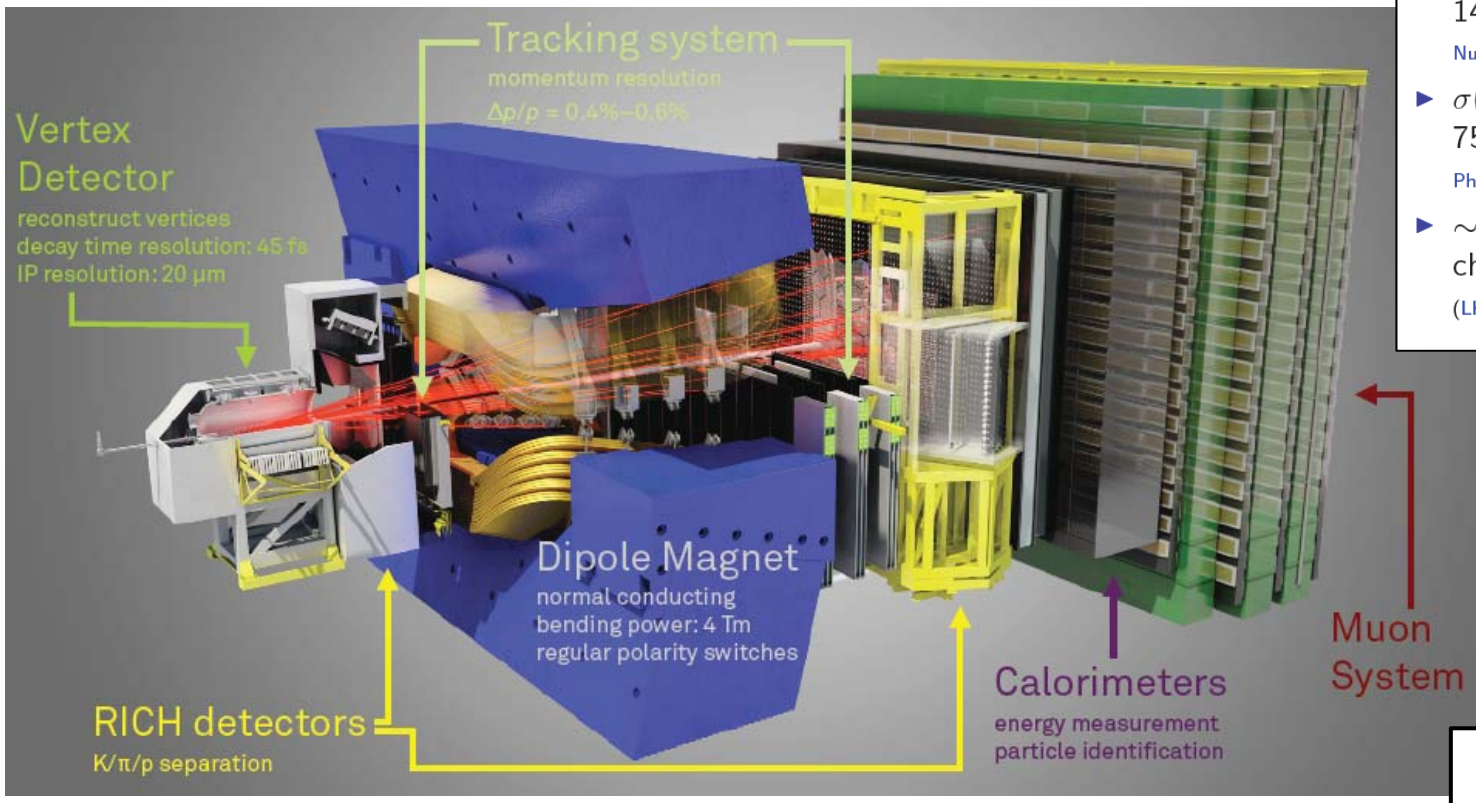
$$A^{CP}(t) = \frac{|\bar{\mathcal{A}}_f|^2 - |\mathcal{A}_f|^2}{|\bar{\mathcal{A}}_f|^2 + |\mathcal{A}_f|^2} = \eta_f \frac{-C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \mathcal{A}_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma}{2}t\right)}$$

- <u>This allows λ_f (and thus ϕ) to be measured</u>:

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \quad S_f = \frac{2\Im\lambda_f}{1 + |\lambda_f|^2}, \quad \mathcal{A}_f^{\Delta\Gamma} = \frac{2\Re\lambda_f}{1 + |\lambda_f|^2}$$

Direct CPV Mixing-induced CPV

The LHCb Detector



- $\sigma(c\bar{c})_{\text{LHCb, 7TeV}} = 1419 \pm 133 \mu b$
  Nucl.Phys.B 871(2013), 1
- $\sigma(b\bar{b})_{\text{LHCb, 7TeV}} = 75.3 \pm 14.1 \mu b$
  Phys. Lett. B 694 (2010), 209
- $\sim$ 350M reconstructed charm decays in 2011!
  (LHCb-TALK-2012-078)

$2 < \eta < 5$

Data so far (pp collisions):
2011 run: 1 fb^{-1} at 7 TeV
2012 run: 2 fb^{-1} at 8 TeV

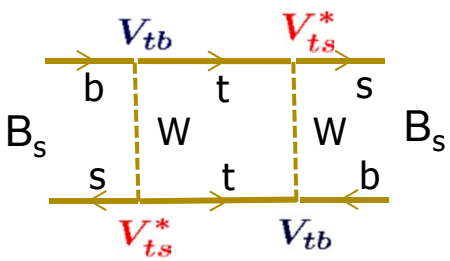
Still to come:
2015 run: ~3 fb^{-1} at 14 TeV (new triggers)
Post-upgrade: ~10x at 14 TeV

New Measurement of β_s

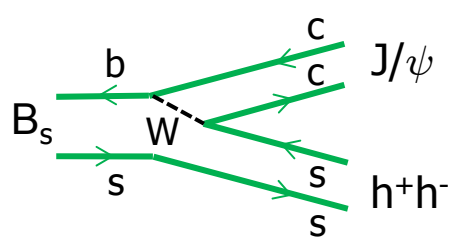
β_s from $B_s \to J/\psi\ \pi^+\pi^-$ decays

New result Arxiv: 1405.4140 (3 fb^{-1})

- In the SM, β_s = 18.2 $\pm$ 0.8 mrad is precisely predicted
  - Good test for NP
- For decay to $J/\psi\ \pi^+\pi^-$, final state is sum of *CP* (η) eigenstates
  - So strong phases in direct decay or decay through mixing cancel.
  - Mixing induces weak phase difference $\mathrm{Arg}(\lambda) = \phi_s = -2\beta_s$



$\phi_M = -2\beta_s$



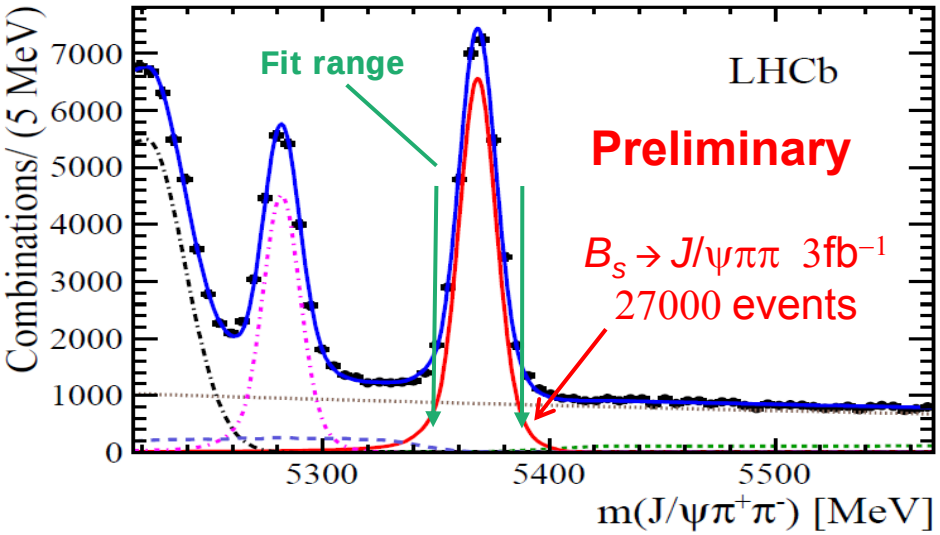
$\phi_D \approx 0$

+ Small penguin (same weak phase)

$\Rightarrow$ $\phi_s = -2\beta_s$

- *t*-dependence is fn. of *CP* structure in the $J/\psi\pi^+\pi^-$ Dalitz plot

Improved time-integrated isobar model fit

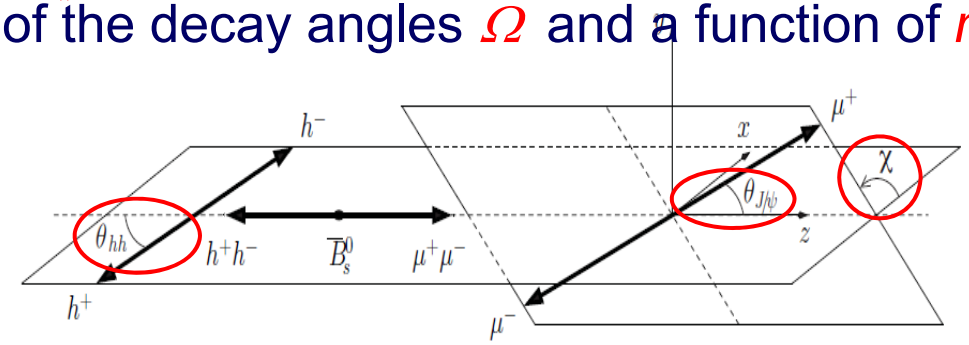


(3 fb^{-1})

arXiv:1402.6248v1

Phys. Rev. D. 89, 092006 (2014)

- Decays were fit to a sum of isobar model transversity amplitudes ($A_{\parallel}$, $A_{\perp}$, A_0, A_S), each a *CP* eigenstate with characteristic distribution of the decay angles Ω and a function of $m_{\pi\pi}$.



Helicity angles

$$\Omega \equiv (\theta_{hh}, \theta_{J/\psi}, \chi)$$

Improved time-integrated isobar model fit

Phys. Rev. D. 89, 092006 (2014) (3 fb^{-1})

Component	Solution I	Solution II
$f_0(980)$	$70.3 \pm 1.5^{+0.4}_{-5.1}$	$92.4 \pm 2.0^{+0.8}_{-16.0}$
$f_0(1500)$	$10.1 \pm 0.8^{+1.1}_{-0.3}$	$9.1 \pm 0.9 \pm 0.3$
$f_0(1790)$	$2.4 \pm 0.4^{+5.0}_{-0.2}$	$0.9 \pm 0.3^{+2.5}_{-0.1}$
$f_2(1270)_0$	$0.36 \pm 0.07 \pm 0.03$	$0.42 \pm 0.07 \pm 0.04$
$f_2(1270)_\parallel$	$0.52 \pm 0.15^{+0.05}_{-0.02}$	$0.42 \pm 0.13^{+0.11}_{-0.02}$
$f_2(1270)_\perp$	$0.63 \pm 0.34^{+0.16}_{-0.08}$	$0.60 \pm 0.36^{+0.12}_{-0.09}$
$f_2'(1525)_0$	$0.51 \pm 0.09^{+0.05}_{-0.04}$	$0.52 \pm 0.09^{+0.05}_{-0.04}$
$f_2'(1525)_\parallel$	$0.06^{+0.13}_{-0.04} \pm 0.01$	$0.11^{+0.16+0.03}_{-0.07-0.04}$
$f_2'(1525)_\perp$	$0.26 \pm 0.18^{+0.06}_{-0.04}$	$0.26 \pm 0.22^{+0.06}_{-0.05}$
NR	-	$5.9 \pm 1.4^{+0.7}_{-4.6}$
Sum	85.2	110.6
$-\ln\mathcal{L}$	-93738	-93739
χ^2/ndf	2005/1822	2008/1820

Sum of CP-even: 0.89% 0.86%

- Two models of the form: $B_s \rightarrow J/\psi$ + (resonance) were found to describe the data well
- For each model, two *CP*-even states were found to be present, though their fractions were very small.

t-Dependent fit - Signal PDF

New result Arxiv: 1405.4140 (3 fb^{-1})

B_s lineshape.
$M=J/\psi\pi\pi$ inv. mass.

Acceptance.

$\omega = B_s$ mis-tag rate.
$\overline{\omega} = \overline{B_s}$ mis-tag rate.

$$R(t, M, m_{\pi\pi}, \Omega, q) = G(M) \times \epsilon(t, \Omega) \times$$
$$[1 + q(1 - 2\omega)]\,\Gamma(t, m_{\pi\pi}, \Omega) + [1 - q(1 - 2\bar{\omega})]\,\overline{\Gamma}(t, m_{\pi\pi}, \Omega)$$

$q = +1 (B_s^0)$
$q = -1 (\overline{B}_s^0)$
$q = 0 (\text{untagged})$

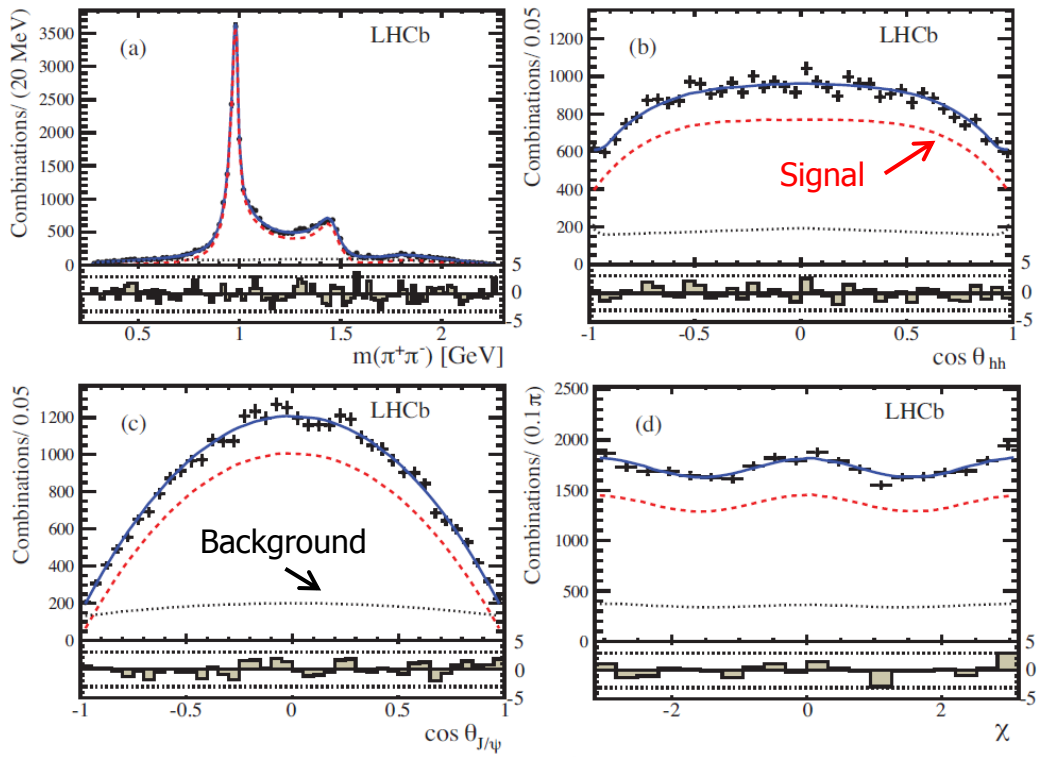
t-dependent decay rates of B_s ($\overline{B_s}$) decays
Contain λ and mixing/*CPV* parameters

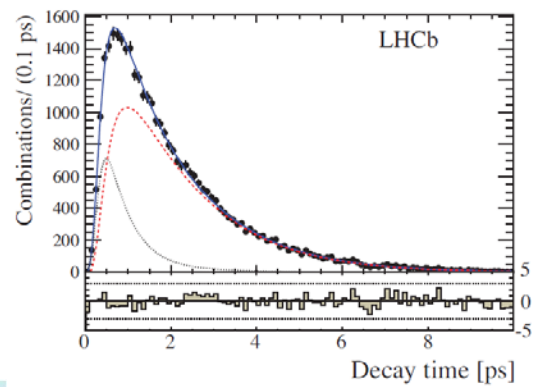
Event-by-event time resolution ($\langle\sigma_t\rangle$~40.3 fs) is folded in.
and backgrounds added.

LHCb Preliminary (3 fb^{-1})

- Assume no *CPV* in mixing.
- Constrain Δm_s to previous result 17.768 ± 0.024 ps^{-1}
- Isobar coeffs can vary

- Two fits performed:
  a) $|\lambda| = 1.0$ (no direct *CPV*)
  b) allow $|\lambda|$ to float





Main systematics:

	$-2\beta_s$	$\lvert\lambda\rvert$
Add ρ	± 5.8 mrad	± 0.010
Prod. Asymm.	± 6 mrad	± 0.008

Results (PRELIMINARY)

Preliminary result: (3 fb^{-1})

No direct CPV	Direct CPV allowed
$-2\beta_s = 75 \pm 68 \pm 8\text{mrad}$	$-2\beta_s = 70 \pm 68 \pm 8\text{mrad}$
$\lvert\lambda\rvert = 1(\text{fixed})$	$\lvert\lambda\rvert = 0.89 \pm 0.05 \pm 0.01$

Preliminary

This result supercedes the previous measurement:

$$-2\beta_s = -19^{+173+4}_{-174-4}\ \text{mrad}$$

LHCb (1 fb^{-1})

Phys.Rev. D87 (2013) 11, 112010

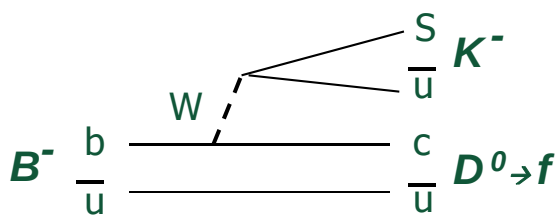
This result is consistent with the SM.

Measurements of γ

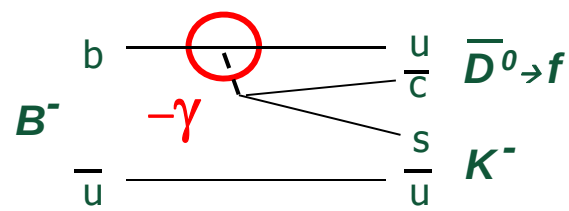
Measurements of γ

- Exploit interference between $B^- \to (D^0 \to f) K^-$ and $B^- \to (\bar{D}^0 \to f) K^-$ decays where flavour neutral f is accessible to both D^0 and $\bar{D}^0$.

Cabibbo Favoured



Colour and b → u suppressed



$$\frac{A_{B^\mp \to \bar{D}^0 K^\mp}}{A_{B^\mp \to D^0 K^\mp}} = r_B \, e^{i(\delta_B \mp \gamma)} \times r_D \, e^{i\delta_D}$$

Fit B data for (r_B , δ_B , γ)

Requires input from D^0 decay using external sources.
(Weak phase is neglected)

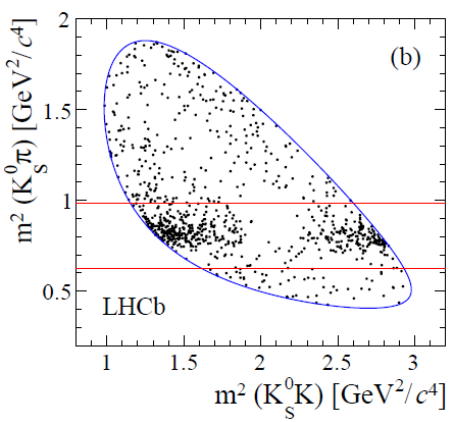
- No penguin diagram for these modes - theoretically clean !
- Many analyses also use $B^- \to (D^0 \to f)\pi^-$ decays for control purposes.

Measure γ from $B \to D(\to K_s K^{\pm}\pi^{\mp})h$

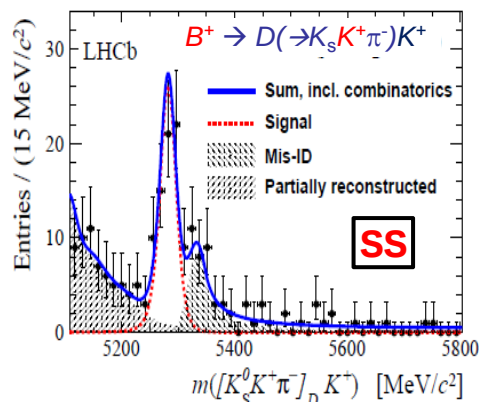
Phys.Lett. B733 (2014) 36-45 (3 fb^{-1})

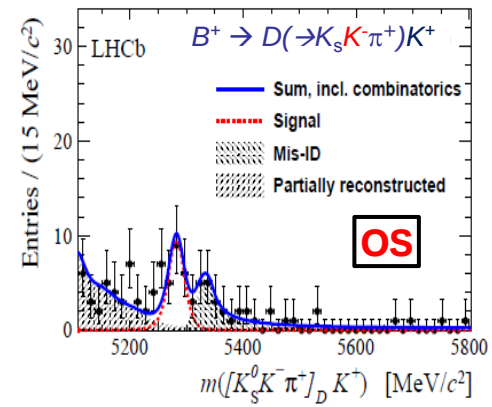
D^0 decay information comes from coherence factor κ and average strong phase δ_D from CLEO in 2 regions of Dalitz plot:

Phase space region	κ	δ_D
Whole Dalitz plot:	0.73 ± 0.08	$8.3 \pm 15.2°$
$K^*(890)$	1.00 ± 0.16	$26.5 \pm 15.8°$



- Divide B signals into 8 sub-samples:
  - a. B^+ and B^-
  - b. $B \to DK$ and $B \to D\pi$
  - c. "SS" and "OS" (Charge of K from D^0 is of same or opposite sign to the B)
- Form 3 ratios and 4 CP asymmetries



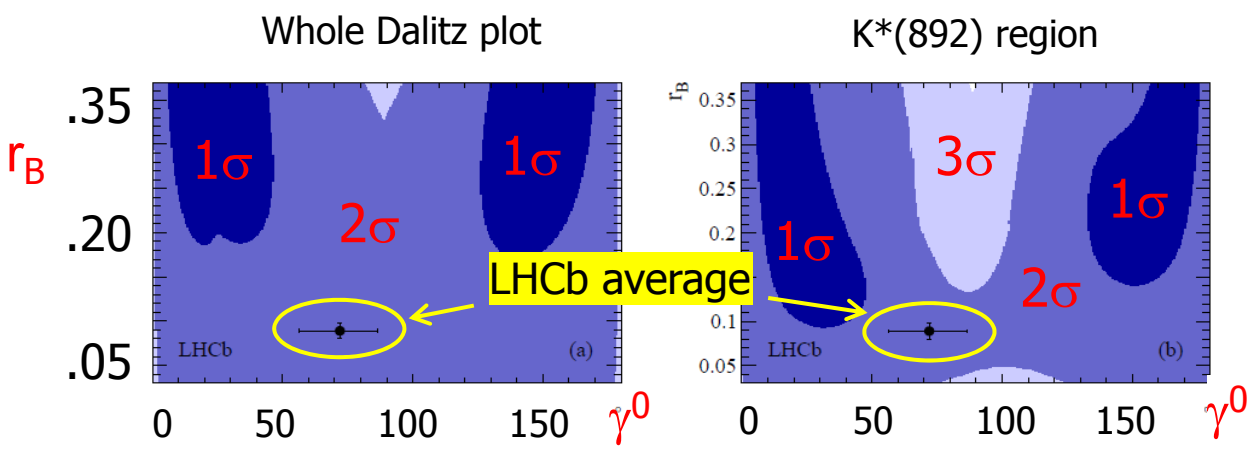


SS $\Gamma^{\pm}_{SS,DK} \propto 1 + r_B^2 r_D^2 + 2 r_B r_D \kappa \cos(\delta_B \pm \gamma - \delta_D)$

OS $\Gamma^{\pm}_{OS,DK} \propto r_B^2 + r_D^2 + 2 r_B r_D \kappa \cos(\delta_B \pm \gamma + \delta_D)$

Results

- Scan r_B vs. γ space computing χ^2 probability for the 7 observables to be described by (r_B, γ) values at each point. INCLUDE:
  - Statistical and systematic uncertainties and their correlations
  - Effects of mixing, but NOT *CP* violation in D^0 system.



68.3% confidence level:

LHCb: $\gamma = 72.0^{+14.7^\circ}_{-15.6}$

BABAR: $\gamma = 69.0^{+17^\circ}_{-16}$

Belle: $\gamma = 68.0^{+15^\circ}_{-14}$

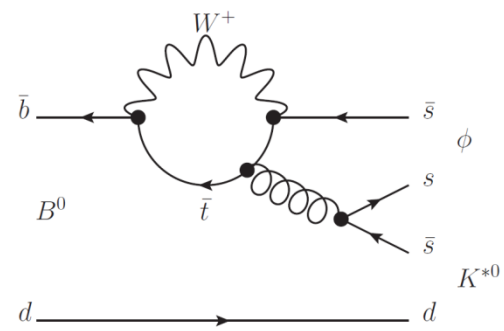
- Results are consistent with current LHCb average in both Dalitz plot ranges. Also consistent with zero.
- NOTE: The 2σ range is more restrictive for the K*(892) region

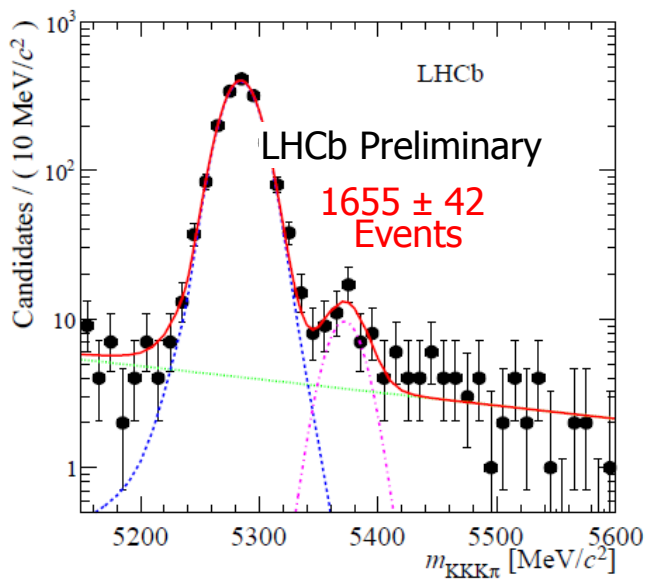
$B \to VV$ Decays

Polarization Amplitudes in $B^0 \to \phi K^*$

Recent result (1 fb^{-1}: arXiv:1403.2888

- Decays are dominated by a gluonic penguin
  - $BF = (9.8 \pm 0.6) \times 10^{-6}$
    (First observed by CLEO)
  - Open to influence from NP effects in the loop.
- Direct CPV should be very small.





- Angular analysis of $B \to V V$ decays is interesting:
  - At Tree level, longitudinal helicity component dominates (f_L~1). Verified in $B_d \to \rho\rho$ decays.
  - For penguin decay, equal transverse components are found (f_L~0.5)

Angular Analysis

Amplitudes included:

P-wave: $A_L, A_{\parallel}, A_{\perp}$ ($B \to K^{*0}\phi$)

S-wave: A_S^{KK} ($B \to K^{*0} K^+K^-$)

" : $A_S^{K\pi}$ ($B \to \phi K^+\pi^-$)

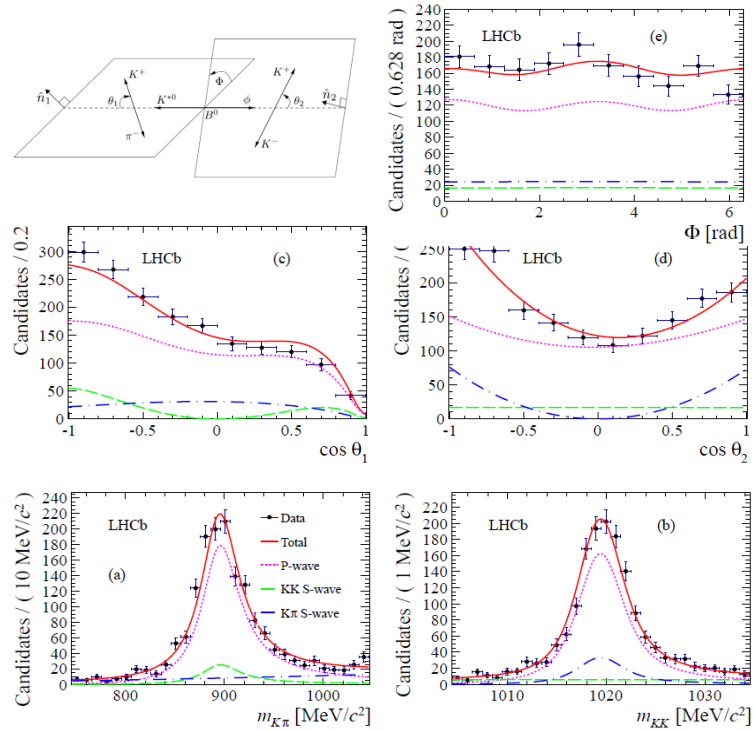
Inv. Mass shapes:

P-wave: Breit-Wigners

S-wave: Flatte $f_0(980)$
LASS-type $K\pi$

Results:

f_L	$0.497 \pm 0.019 \pm 0.015$
$f_\perp$	$0.221 \pm 0.016 \pm 0.013$
$f_S(K\pi)$	$0.143 \pm 0.013 \pm 0.012$
$f_S(KK)$	$0.122 \pm 0.013 \pm 0.008$



- Longitudinal polarization ~0.5, in agreement with BaBar and Belle (PRD 78(2008)092008, PRD 88(2013)072004)
- Significant S-wave contribution.

Direct *CPV* in $B^0 \to \phi K^*$

- The B^0 flavour is self-tagged by the charge of the K from K^*
- The raw asymmetry comes from fits to mass distributions

$$A^{\mathrm{RAW}} = \frac{N[\bar{B}^0 \to \phi K^*] - N[B^0 \to \phi K^*]}{N[\bar{B}^0 \to \phi K^*] + N[B^0 \to \phi K^*]}$$

- This is corrected for production asymmetry A_P by subtracting the observed asymmetry in $B^0 \to J/\psi K^*$ decays to obtain

$$A^{CP} = (+1.5 \pm 3.2(\mathrm{stat}) \pm 0.5(\mathrm{syst}))\%$$

$$(\ +1\ \pm\ 6(\mathrm{stat})\ \pm\ 3(\mathrm{syst}))\%$$ Babar [Phys.Rev.D 78, 092008(2008)]

$$(-0.7 \pm 4.8(\mathrm{stat})\ \pm 2.1(\mathrm{syst}))\%$$ Belle [Phys.Rev.D 88, 072004(2013)]

Asymmetries in $|A_L|^2$ and $|A_\perp|^2$ are also computed:

$$A_L^{CP} = -0.003 \pm 0.038 \pm 0.005$$

$$A_\perp^{CP} = +0.047 \pm 0.072 \pm 0.009$$

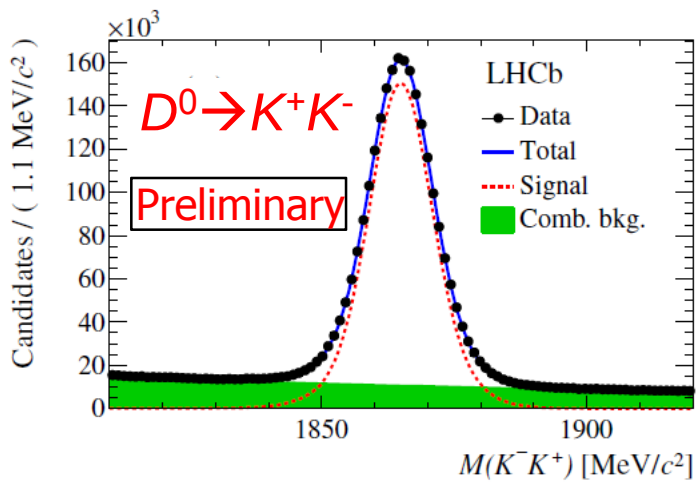
All *CP* asymmetries consistent with zero.

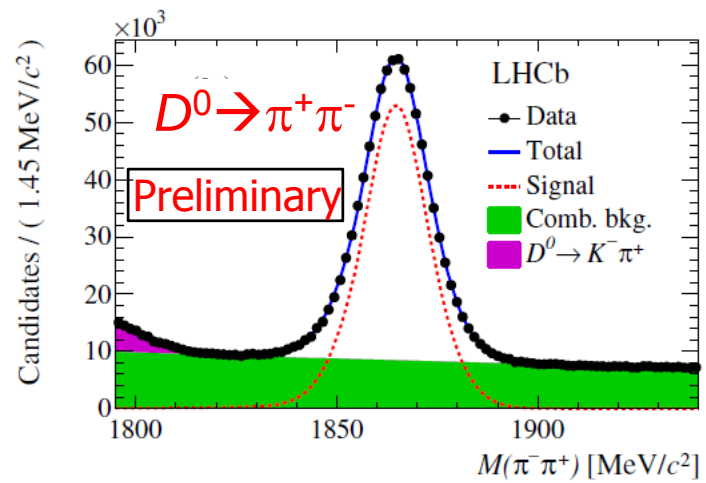
CP Violation in D decays

t-Integrated *CP* asymmetry in $D^0 \to h^+h^-$ decays

New result Arxiv:1405.2797v1 (3 fb^{-1})

- Evidence for *CPV* in the charm sector is yet absent, though the SM could accommodate asymmetries at the few per mille level.
  - This is experimentally within the reach of LHCb.
- Study triggers on $\bar{B} \to D^0\mu^-\nu X$ -- the μ charge labels the D^0 flavour.
  - Approx. signals: $D^0 \to K^+K^-$ (2M), $D^0 \to \pi^+\pi^-$ (0.7M),
  - Approx. control: $D^0 \to K^-\pi^+$ (9M), $D^+ \to K^-\pi^+\pi^+$. etc. (45M),





Experimental asymmetries

- The raw asymmetry is related to that due to *CP*:

$$A_{\rm raw} \equiv \frac{N(D\to f) - N(\overline{D}\to \overline{f})}{N(D\to f) + N(\overline{D}\to \overline{f})} = A_{CP} + A_D(\mu^-) + A_P(\overline{B})$$

We want μ detect. *B* Production

- A_D(m-) and $A_P(\overline{B})$ are ~same for both K^+K^- and $\pi^+\pi^-$ (modulo kinematic corrections) so:

$$\Delta A_{CP} = A_{\rm raw}(K^-K^+) - A_{\rm raw}(\pi^-\pi^+) = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

- Then to obtain $A_{CP}(K^-K^+)$
  - Measure raw asymmetries in CF modes - $D^0 \to K^-\pi^+$, $D^+ \to \overline{K}^0\pi^+$ & $D^+ \to K^-\pi^+\pi^+$ for which we expect that $A_{CP} = 0$.

Preliminary Results

- The 3 fb^{-1} sample has been used to select D^0 decays tagged by the charge of the μ from $\bar{B} \to D^0 \mu^- \nu_\mu X$ decays and to measure

$$\Delta A_{CP} = (+0.14 \pm 0.16\,(\text{stat}) \pm 0.08\,(\text{syst}))\%$$
$$A_{CP}(K^-K^+) = (-0.06 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

Preliminary

These are correlated with correlation coefficient 0.28.

- From this result, the asymmetry for $\pi\pi$ decays is extracted:

$$A_{CP}(\pi^-\pi^+) = (-0.20 \pm 0.19\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

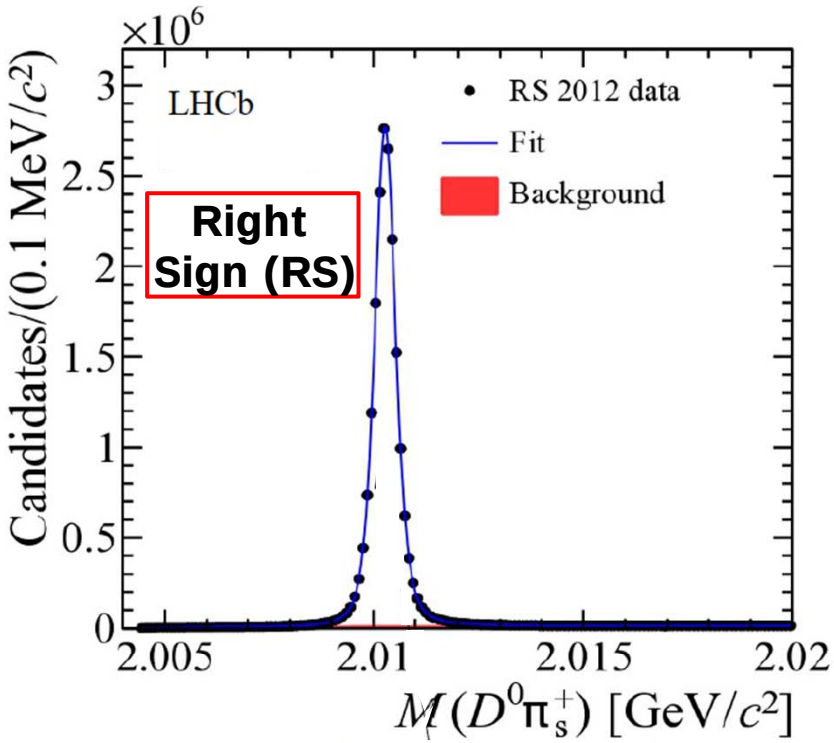
Preliminary

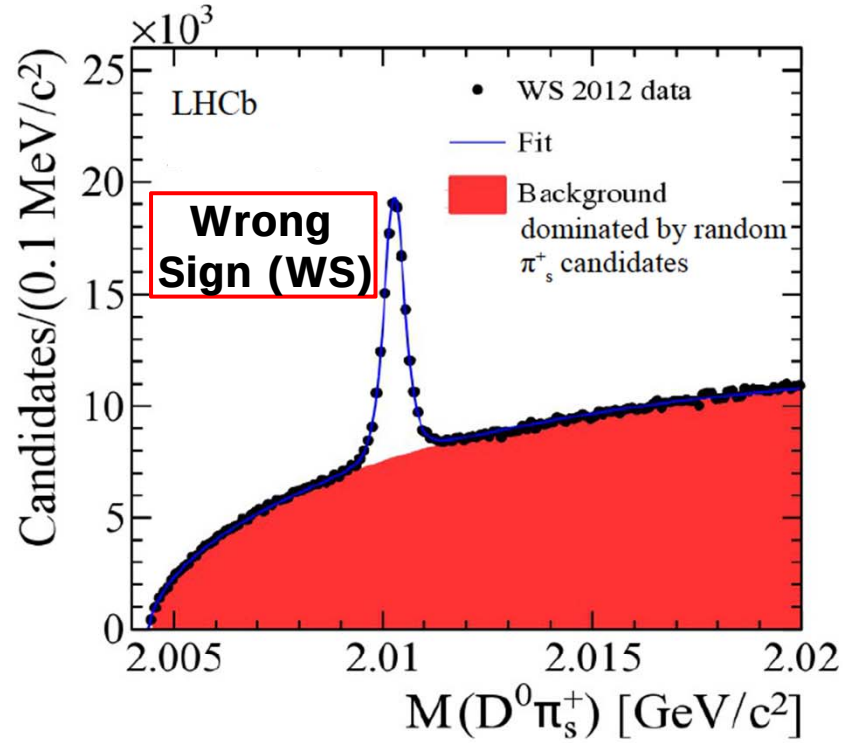
- These results supercede our earlier ones from semi-leptonic *B* decays. Most precise *CPV* limit in these decays from a single experiment.

Asymmetry levels in parts per mille should remain measurable.

CPV in mixing from *WS* $D^0 \rightarrow K^+\pi^-$ decays

Phys.Rev.Lett. 112 (2014) 091802 (3 fb^{-1})





"Prompt D^0" (not from B decay)
Tagged by $D^{*+} \rightarrow D^0\pi^+$

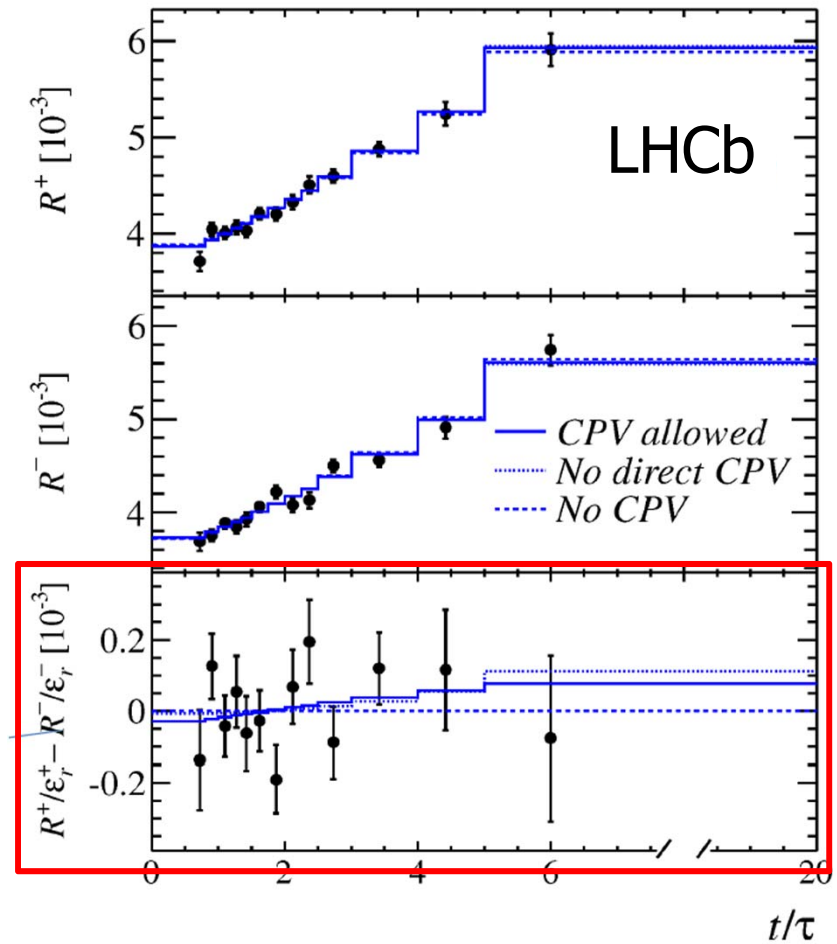
	RS (Events)	WS (Events)
LHCb	54,000,000	230,000
BaBar	1,141,500	4,030
Belle	1,073,993	4,024
CDF	7,604,000	32,700

CPV in mixing from *WS* $D^0 \rightarrow K^+\pi^-$ decays

$$R^{\pm}(t) \equiv \frac{WS(t)}{RS(t)} = R_D^{\pm} + \sqrt{R_D^{\pm}}y'^{\pm}\left(\frac{t}{\tau}\right) + \left(\frac{x'^{2\pm} + y'^{2\pm}}{4}\right)\left(\frac{t}{\tau}\right)^2$$

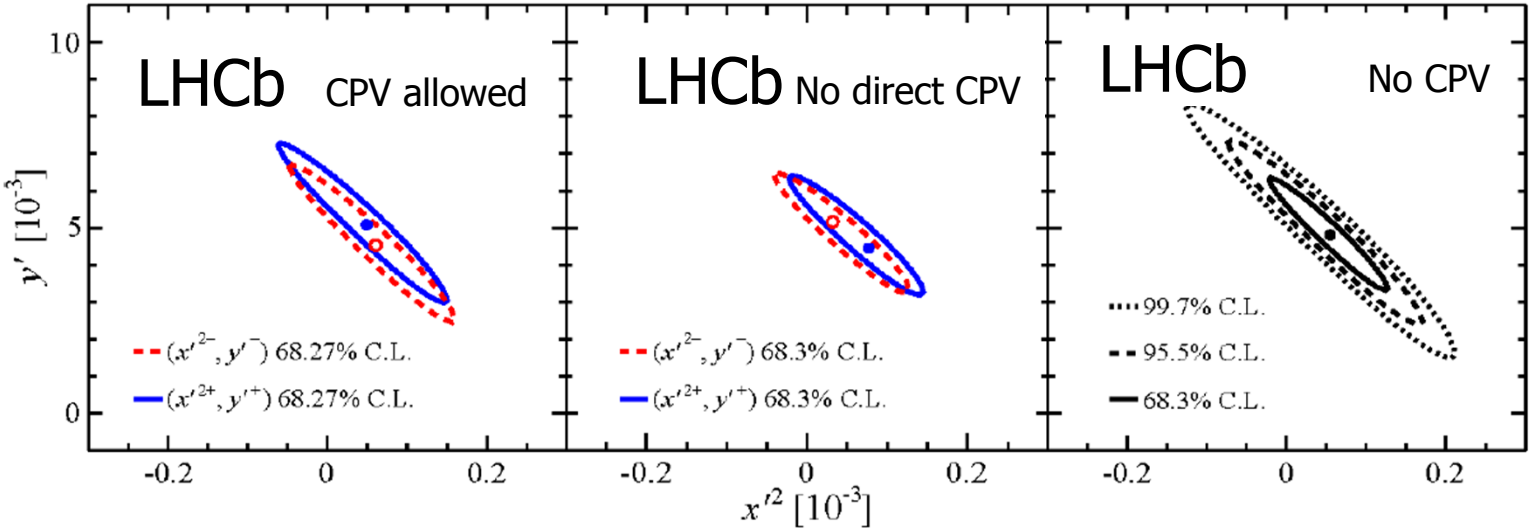
- Measure the WS/RS ratio in each of 13 decay time bins, separately for D^0 and $\bar{D}^0$.
- Fit the *WS*/*RS* ratio as a function of decay time under three hypotheses:
  - No CPV
  - No direct CPV $(R_D^+ = R_D^-)$
  - Full CPV allowed
- Account for relative reconstr. efficiency $\varepsilon_R = \varepsilon(K^-\pi^+)/\varepsilon(K^+\pi^-)$

$R^+/\varepsilon^+ - R^-/\varepsilon^- \sim 1-|q/p|^2$ is very small
Drives *HFAG - CPV* results.



Phys.Rev.Lett. 112 (2014) 091802 (3 fb^{-1})

$D^0 \rightarrow K\pi$ Mixing and CPV Results

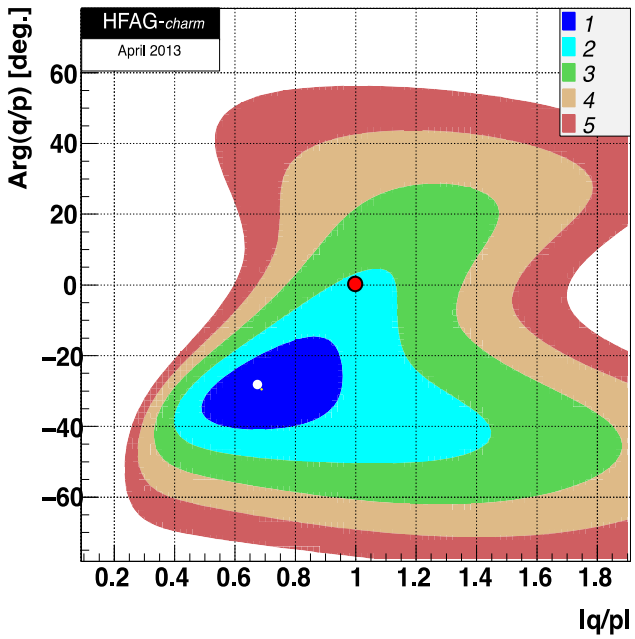


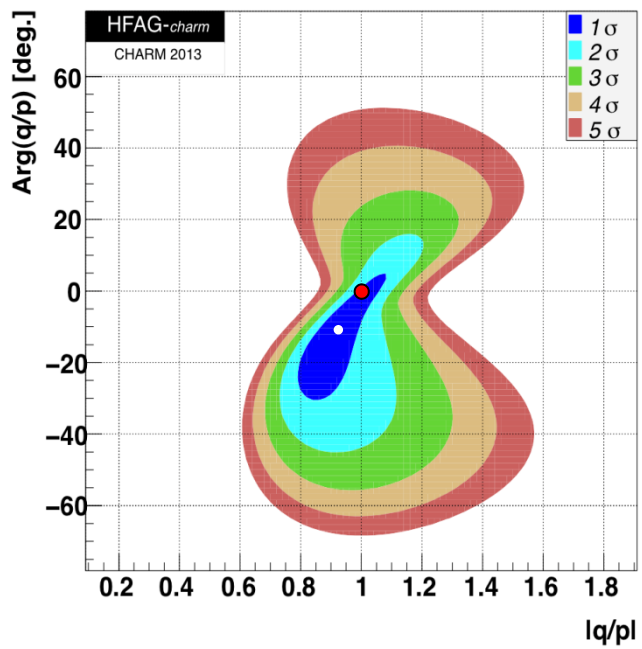
LHCb *preliminary* — *Uncertainties are statistical and systematic combined*

Direct and indirect CP violation			no direct CP violation			no CP violation		
R_D	$[10^{-3}]$	3.568 ± 0.066	R_D	$[10^{-3}]$	3.568 ± 0.066	R_D	$[10^{-3}]$	3.568 ± 0.066
A_D	$[10^{-2}]$	-0.7 ± 1.9	y'^{+}	$[10^{-3}]$	4.78 ± 1.07	y'	$[10^{-3}]$	4.81 ± 1.00
y'^{+}	$[10^{-3}]$	5.1 ± 1.4	x'^{2+}	$[10^{-5}]$	6.4 ± 5.5	x'^2	$[10^{-5}]$	5.5 ± 4.9
x'^{2+}	$[10^{-5}]$	4.9 ± 7.0	y'^{-}	$[10^{-3}]$	4.83 ± 1.07	χ^2/ndf		$86.41/101$
y'^{-}	$[10^{-3}]$	4.5 ± 1.4	x'^{2-}	$[10^{-5}]$	4.6 ± 5.5			
x'^{2-}	$[10^{-5}]$	6.0 ± 6.8	χ^2/ndf		$85.99/99$			
χ^2/ndf		$85.87/98$						

Results are consistent with no *CPV*

HFAG - April → September, 2013





Allow direct and indirect CPV

HFAG Charm 2013 ⇒

x	(0.39 ± 0.11)%
y	(0.67 ± 0.08)%
|q/p|	(91 ± 10)%
ϕ	(-10.9 ± 11.4)°

Also assume that $\tan\phi = \left(1 - \left|\frac{q}{p}\right|\right)\frac{x}{y}$ ⇒

|q/p|	(99.3 ± 1.3)%
ϕ	(+0.4 ± 0.7)°

Conclusions

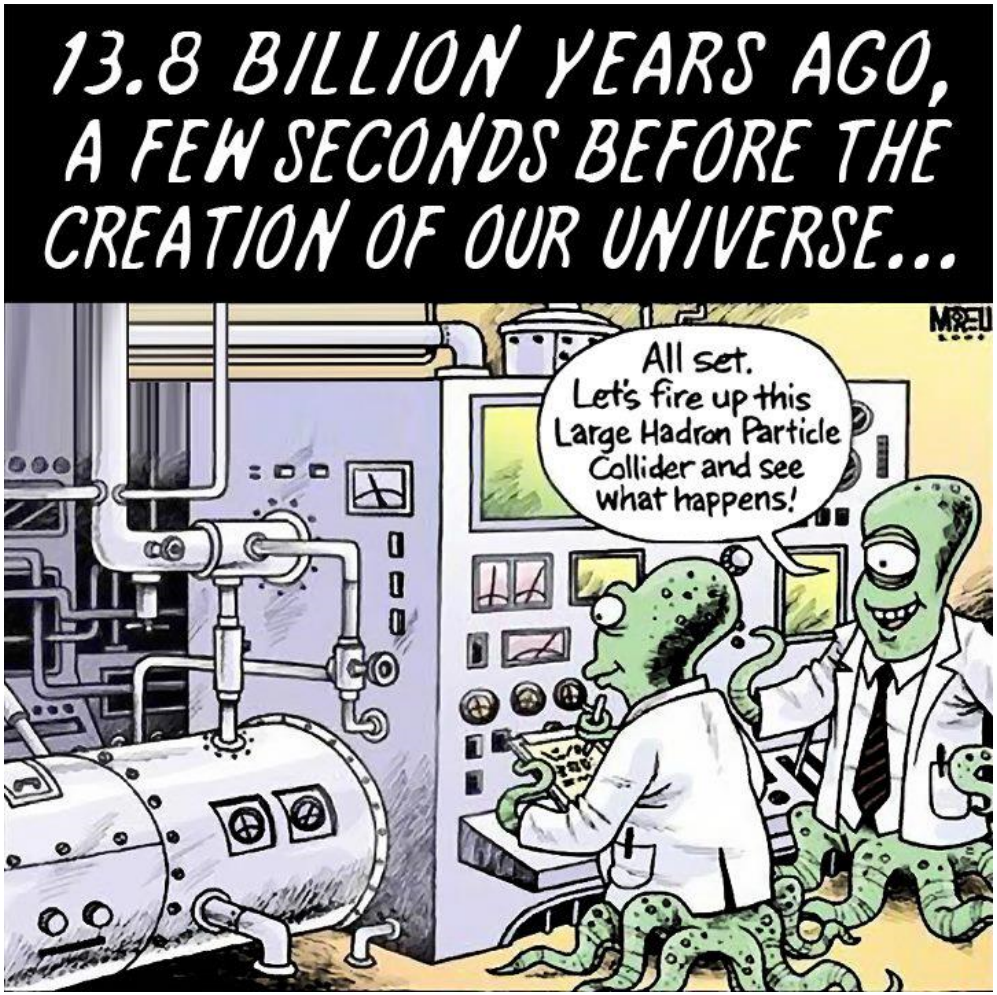
- In *B* decays, LHCb has covered many of the *CPV* studies made in the B factories – with competitive precision and large, clean samples. With data in hand, measurement of CKM γ will exceed the precision achieved in the B factories

- Since establishing *CPV* in B_s decays LHCb is pursuing a program to study the patterns in these decays and is well on track to measure β_s with precision ~0.5^0 before the upgrade.

- LHCb has provided much improved limits on CPV in *D* meson mixing. The precision required for finding CPV in *D* and D_s decays is unlikely to reach systematic uncertainty levels for some time.

Back-up Slides

It all began …



the ONION

"America's finest News source"

LHCb results from the 1 fb^{-1} sample

Two-body decays:

$f = K^+K^-, \pi^+\pi^-$ (GLW) and $K\pi$ (ADS)

PLB 712 (2012) 203

Multi-body decays:

$f = K\pi\pi\pi$ (ADS)

PLB 723 (2012) 44

- Similar to the two-body ADS modes BUT
- Use coherence factor (κ=0.33) and mean δ_D from CLEO
- NEW information used by LHCb.

PRD 80 (2009) 031105

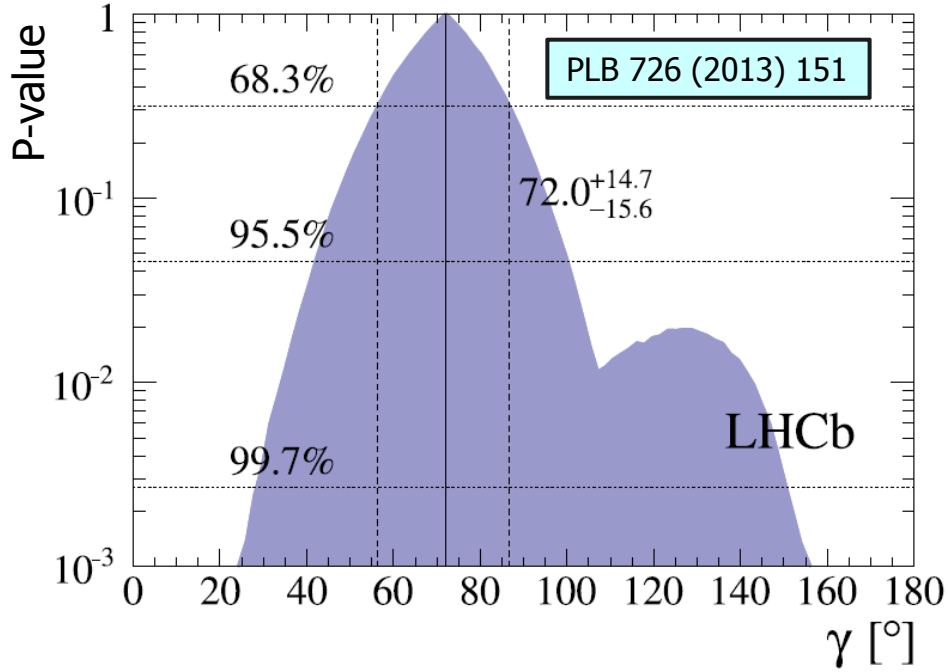
$f = K^0_s\pi\pi, K^0_sKK$ (GGSZ)

PLB 718 (2012) 43

- Fit K^0_shh Dalitz plots from B decays to a coherent sum of Dalitz plot models from D^*-tagged D^0 decays.
- Use bins (16 for $\pi\pi$ and 4 for KK) and strong phases δ_D from CLEO

LHCb 1 fb^{-1} Results

- Best (r_B,δ_B,γ) values are fit to these 1 fb^{-1} results, including systematic uncertainties).
- Frequentist confidence intervals are evaluated.



PLB 726 (2013) 151

68.3% confidence level:

LHCb: $\gamma = 72.0^{+14.7^\circ}_{-15.6}$

BABAR: $\gamma = 69.0^{+17^\circ}_{-16}$

Belle: $\gamma = 68.0^{+15^\circ}_{-14}$

Preliminary LHCb (3 fb^{-1}):

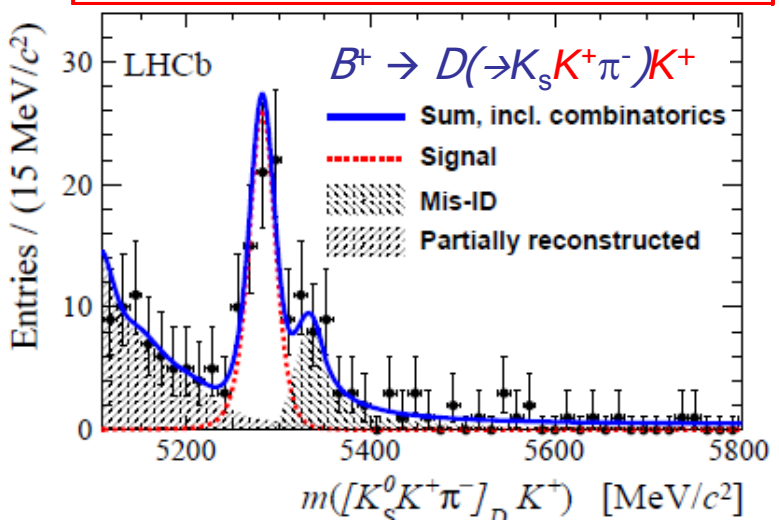
$\gamma = 67.2^{+11.9^\circ}_{-12.1}$

LHCb-CONF-2013-006

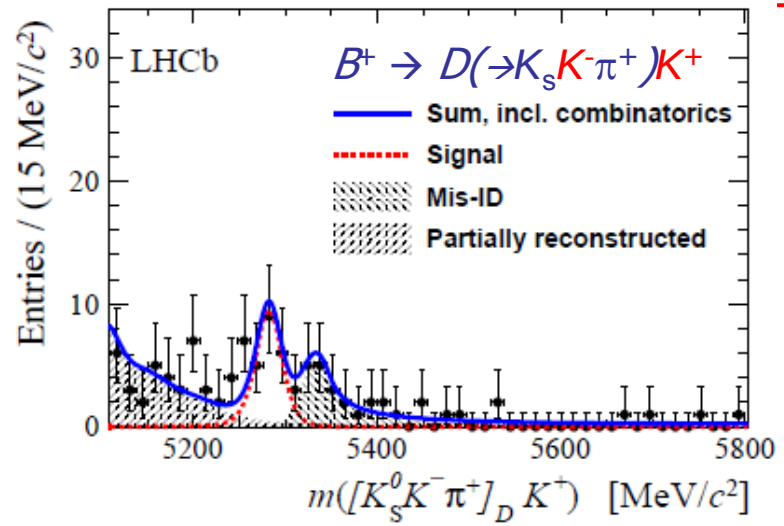
Need more channels at (3 fb^{-1}):

LHCb PRELIMINARY

SS (Same Sign) for *B* and *K* from *D*



OS (Opposite Sign) for *B* and *K* from *D*



- Fits to B mass plots (two shown here) provide eight decay rates:
  - SS or OS (Same or Opposite Sign charge for $B^\pm$ and $K^\pm$ from D decay)
  - Charge of $B^\pm$
  - $B^\pm \to D^0 K^\pm$ or $B^\pm \to D^0 \pi^\pm$
- These are efficiency corrected and combined into 7 observables (3 ratios and 4 CP asymmetries) that are related to the parameters (r_B, δ_B, γ).
- Major systematic uncertainty is $B \to DK$ / $B \to D\pi$ efficiency ratio.

Indirect *CPV* in $D^0 \rightarrow K^+K^-$ and $\pi^+\pi^-$

PRL112,041801 (2014) LHCb (1 fb^{-1})

- The asymmetry in effective lifetimes to *CP* eigen-states:

$$A_\Gamma = \frac{\hat{\tau}(\overline{D}^0) - \hat{\tau}(D^0)}{\hat{\tau}(\overline{D}^0) + \hat{\tau}(D^0)} \approx \eta_{CP}\left(\frac{A_m + A_d}{2} y\cos\phi - x\sin\phi\right)$$

where

Direct *CPV (v. small)*

CPV in mixing

$$A_d = \frac{|\mathcal{A}_f|^2 - ||\overline{\mathcal{A}}_f|^2}{|\mathcal{A}_f|^2 - ||\overline{\mathcal{A}}_f|^2} \;;\quad A_m = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2} \;;\quad \phi = \arg\frac{q}{p}$$

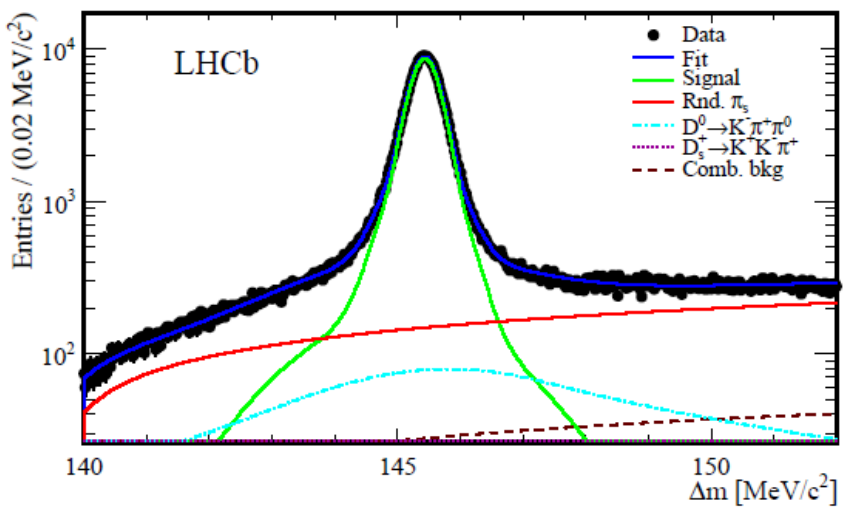
is sensitive mostly to *CP* in mixing parameters *q/p*

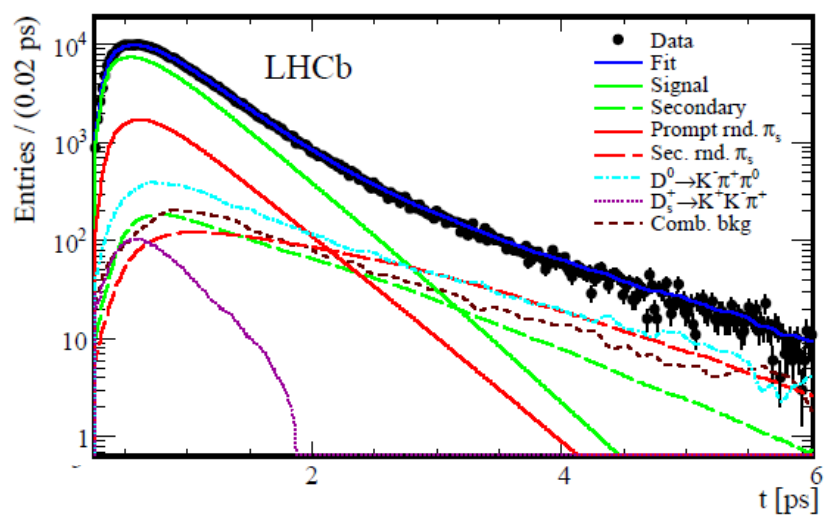
- Total of 3.11×10^6 *KK* and 1.03×10^6 $\pi\pi$ decays used from the 1 fb^{-1} data sample.

- Each decay mode split into 8 sub-samples
  - Magnet UP/DOWN
  - Two run periods with well-known calibrations and alignments
  - D^0 and $\overline{D}^0$ using slow pion $\pi_s^{\pm}$ from $D^* \rightarrow D^0\pi$

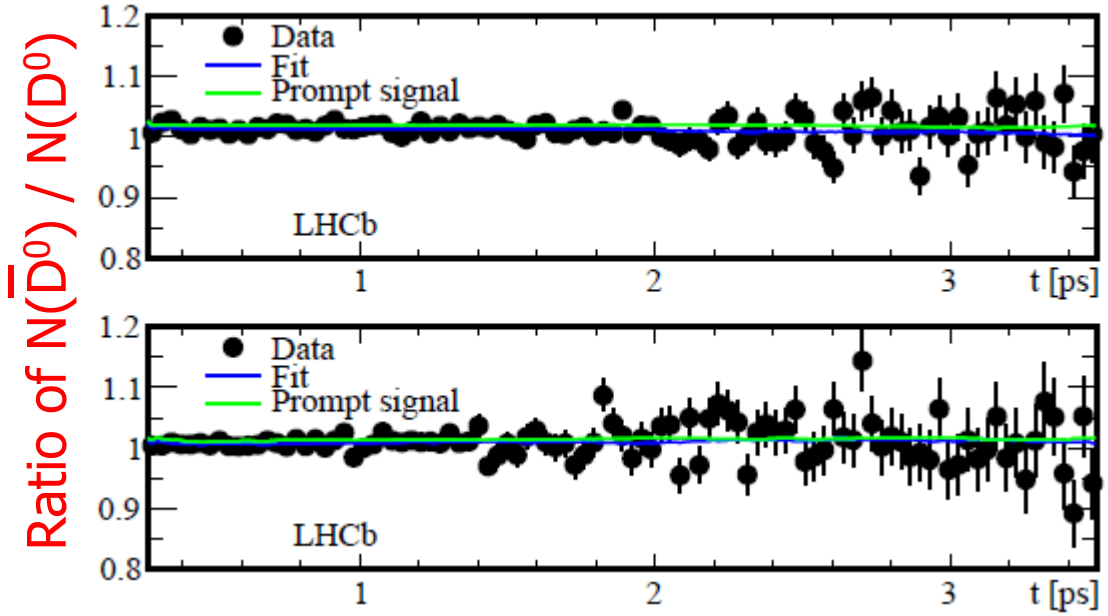
- Fits to each of the eight subsets were made in two steps:
  - Two-dim. fit to $M(KK$ or $\pi\pi)$ invariant mass vs. $\Delta M \equiv M(hh\pi^{\pm})-M(hh)$

    → Extracts signal yield
  - Two-dimensional fit to decay time vs. "point-back" criterion for D^* to be "prompt" i.e. to come from *primary vertex* rather than from a *b quark decay*.





Results



$D^0 \rightarrow K^+K^-$

t [ps] →

$D^0 \rightarrow \pi^+\pi^-$

$$A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$$
$$A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$$

- No evidence for indirect *CPV*, nor any dependence on *t*.

CPV in Mixing

Brian Meadows

arXiv:1308.1048v2

Flavour-specific *CP* asymmetry a_{sl}

- The asymmetry for decays to flavor-specific states (e.g. semi-leptonic) probes *CPV* in mixing:

$$a_{sl} = \frac{\Gamma_{\overline{B}^0 \to f}(t) - \Gamma_{B^0 \to f}(t)}{\Gamma_{\overline{B}^0 \to f}(t) + \Gamma_{B^0 \to f}(t)} \simeq \frac{\Delta\Gamma}{\Delta m} \tan \phi_M$$

Individual rates depend on time t but a_{sl} is not t-dependent

Here, ϕ_M is the *CP*-violating weak mixing phase and Δm, $\Delta\Gamma$ are differences in mass and width of the two *B* mass eigenstates.

- In the SM, $\phi_M \sim 0.2^0$ so a_{sl} is expected to be small:

Lenz & Nierst arXiv:1102.4274

$$B_s : a_{sl}^s = (+1.9 \pm 0.3) \times 10^{-5} \qquad B^0 : a_{sl}^d = (-4.1 \pm 0.6) \times 10^{-4}$$

- The D0 collaboration has reported, for a combination of neutral semi-leptonic *B* decays, an asymmetry of $A_{sl}^b = (-0.787 \pm 0.172 \pm 0.093)\%$ some way beyond these expectations. This has not been confirmed.

arXiv:1308.1048v2

"Flavour-specific" *CP* asymmetry a_{sl}

- Measure *raw* time-integrated asymmetry in reconstructed $B_s \to D_s^+ \mu^- \nu_\mu X$ and $\overline{B}_s \to D_s^- \mu^+ \overline{\nu}_\mu X$ decays:
  - Identify and reconstruct $D_s \to \phi\pi$ decay mode
  - Find good vertex for D_s with a μ.
- Make corrections for μ, K and π charge asymmetry
- For B_s decays, effect of production asymmetry a_P is a factor 2 :

Semi-Leptonic modes are "flavour-specific"

$$A_{\text{meas}} = \frac{\Gamma[D_s^- \mu^+] - \Gamma[D_s^+ \mu^-]}{\Gamma[D_s^- \mu^+] + \Gamma[D_s^+ \mu^-]} = \frac{a_{sl}^s}{2} + \left[a_P - \frac{a_{sl}^s}{2}\right] \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cos(\Delta m_s t)\, \epsilon(t) dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \epsilon(t) dt}$$

~a_P (~5%) **x** Rapid oscillations make integral term 0.2% **~ 10^{-4}**

N e g l e c t

- So $A_{\text{meas}} \sim a_{sl}^s/2$

Result for a_{sl}^s

ArXiv:1308.1048v2

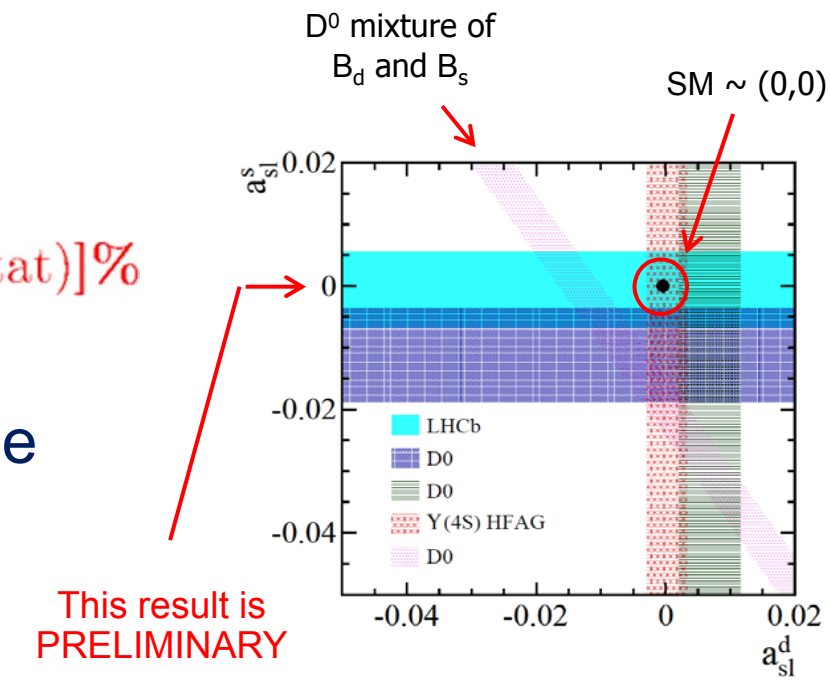
- Taking $a_{sl}^s = 2A_{raw}$ we obtain

$$a_{sl}^s = [-0.06 \pm 0.50(\text{stat}) \pm 0.36(\text{stat})]\%$$

- Systematic uncertainty lies in the limited sample for charge asymmetry calibration.

- We do not confirm the 3σ SM anomaly from D0

- This result is in accord with the SM.



Three types of *CPV*

1. In the mixing ("indirect *CPV*")

$$\frac{q}{p} = r_M e^{i\phi_M} \neq 1 \qquad (r_M \equiv \left|\frac{q}{p}\right|).$$

2. In interference between mixing and decay ("indirect *CPV*" – a.k.a. "mixing-induced *CPV*")

$$\lambda_f = \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \neq 1$$

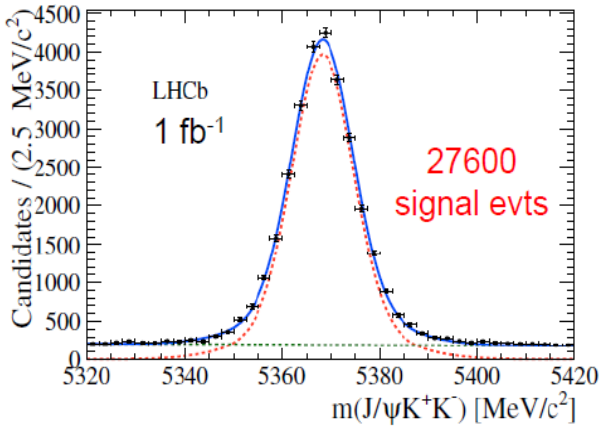
3. In the decay ("direct *CPV*")

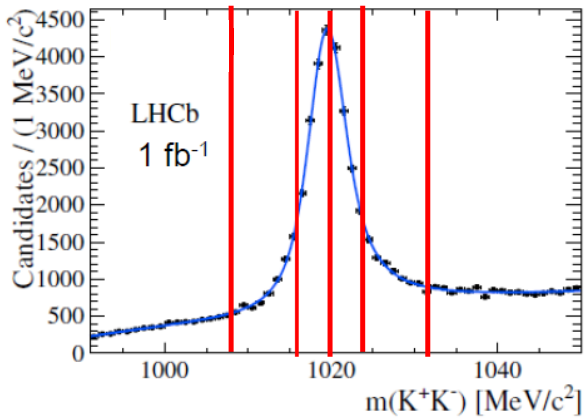
$$|\bar{\mathcal{A}}_f| \neq |\mathcal{A}_{\bar{f}}|$$

(requires two amplitudes with different weak AND different strong phases).

In the last two, *CP* asymmetry can depend on decay mode

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





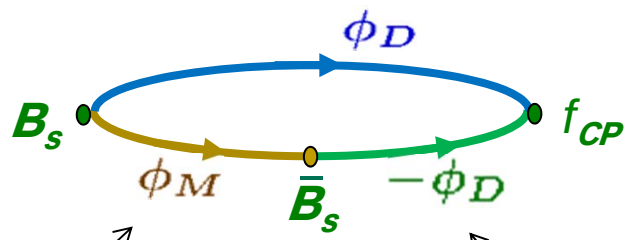
Very clean $B_s \rightarrow J/\psi K^+K^-$ signal is isolated

K^+K^- system consists of approx. linear S-wave background under P-wave ϕ

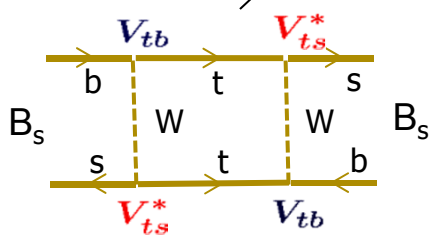
- Similar analysis but
  - The K^+K^- mass m_{KK} is taken in 6 slices within $\pm$30 MeV of the ϕ Each has different magnitude and phase.
  - A S-wave K^+K^- amplitude is included with $\|$, $\perp$ and 0 components in P-wave.

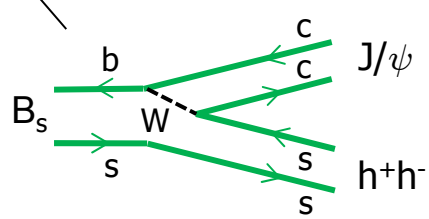
Measuring β_s in $B^0 \to J/\psi\, K^+K^-$ ($\pi^+\pi^-$) decays

- Interference between mixing and decay



Strong phases cancel
Weak phase changes sign
So relative phase is
$\phi_s = \phi_M - 2\phi_D$





+ Small penguin (same weak phase)

$\phi_M = 2\arg\{V_{ts}^* V_{tb}\} = -2\beta_s$ $\quad$ $\phi_D = 2\arg\{V_{bc}^* V_{cs}\} \approx 0$ $\quad \Rightarrow \quad$ $\phi_s = -2\beta_s$

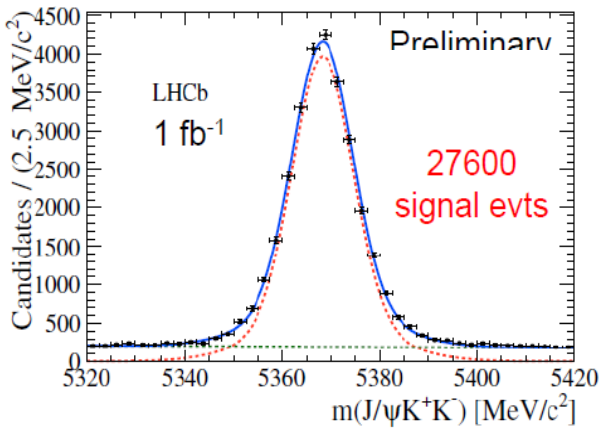
- The phase ϕ_s is determined from time-dependent *CP* asymmetry:

$$A_{CP}(t) = \frac{\Gamma(B_s^0 \to f_{CP}) - \bar{\Gamma}(\bar{B}_s^0 \to \bar{f}_{CP})}{\Gamma(B_s^0 \to f_{CP}) + \bar{\Gamma}(\bar{B}_s^0 \to \bar{f}_{CP})}$$

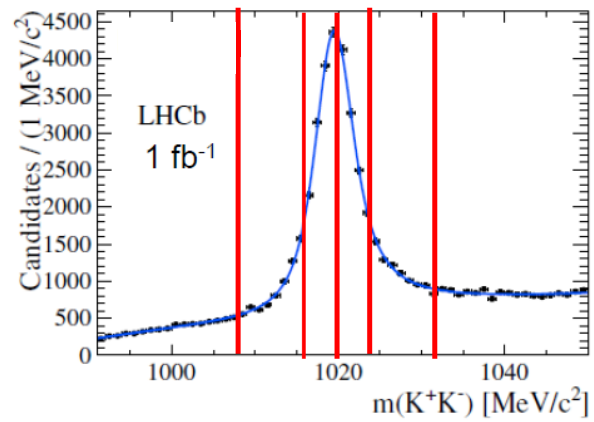
$$\approx -\eta_f \sin\phi_s \sin(\Delta m_s t)$$

- o Ignores penguin
- o Assumes $\Delta\Gamma_s = 0$
- o and no *CPV* in mixing

Standard model (CKM fitter): $\beta_s = -0.0182 \pm 0.0008$



Very clean $B_s \rightarrow J/\psi K^+K^-$ signal is isolated



K^+K^- system consists of approx. linear *S*-wave background under *P*-wave ϕ

- The K^+K^- mass m_{KK} is taken in 6 slices within ± 30 MeV of the ϕ
  Each has different *magnitude and phase* in each m_{KK} bin.
- Angular structure of decays described by 4 helicity amplitudes:

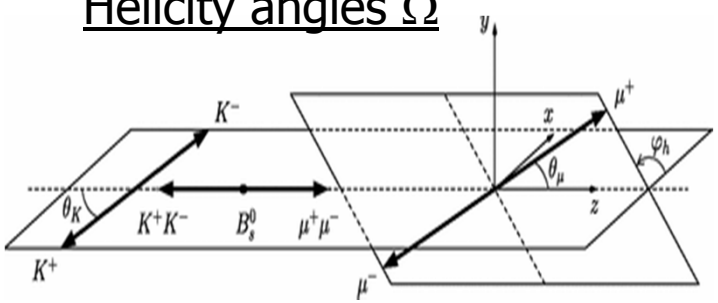
$$\left.\begin{array}{l} A_S e^{i\delta_S} \\ A_\perp e^{i\delta_\perp} \end{array}\right\} \eta_{CP} = -1 \qquad \text{and} \qquad \left.\begin{array}{l} A_\parallel e^{i\delta_\parallel} \\ A_0 e^{i\delta_0} \end{array}\right\} \eta_{CP} = +1$$

- To measure ϕ_s, an angular analysis to separate *CP* states is necessary.

Decay time and angular dependence

- The decay rate for each m_{KK} slice depends on 4 variables, (Ω, t)
- Angular terms of the same *CP* are grouped with the appropriate decay time distributions:

Helicity angles Ω



$$\frac{d^4\Gamma}{dt d\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega) \qquad [\Omega \equiv (\theta_k, \theta_\mu, \phi_k)]$$

with 10 pairings of the four K^+K^- helicity amplitudes and

$$h_k(t) = N_k e^{-\Gamma_s t} [a_k \cosh(\Delta\Gamma_s t/2) + b_k \sinh(\Delta\Gamma_s t/2) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)]$$

with coefficients a_k, .. d_k that are functions of $\lambda = \frac{q}{p}\frac{\bar{A}}{A}$.

Signal PDF

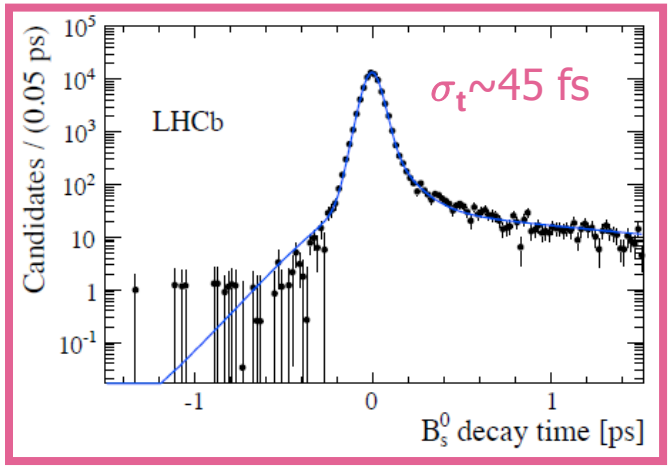
$\lambda = \frac{q}{p}\frac{\bar{A}}{A}$ Defines the a_k, …, d_k

$$S(\lambda, t, \Omega) = \epsilon(t,\Omega) \cdot \left[\left(\frac{1+qD}{2} \cdot P_B(\lambda, t, \Omega) + \frac{1-qD}{2} \cdot \overline{P_B}(\lambda, t, \Omega)\right) \otimes R_t\right]$$

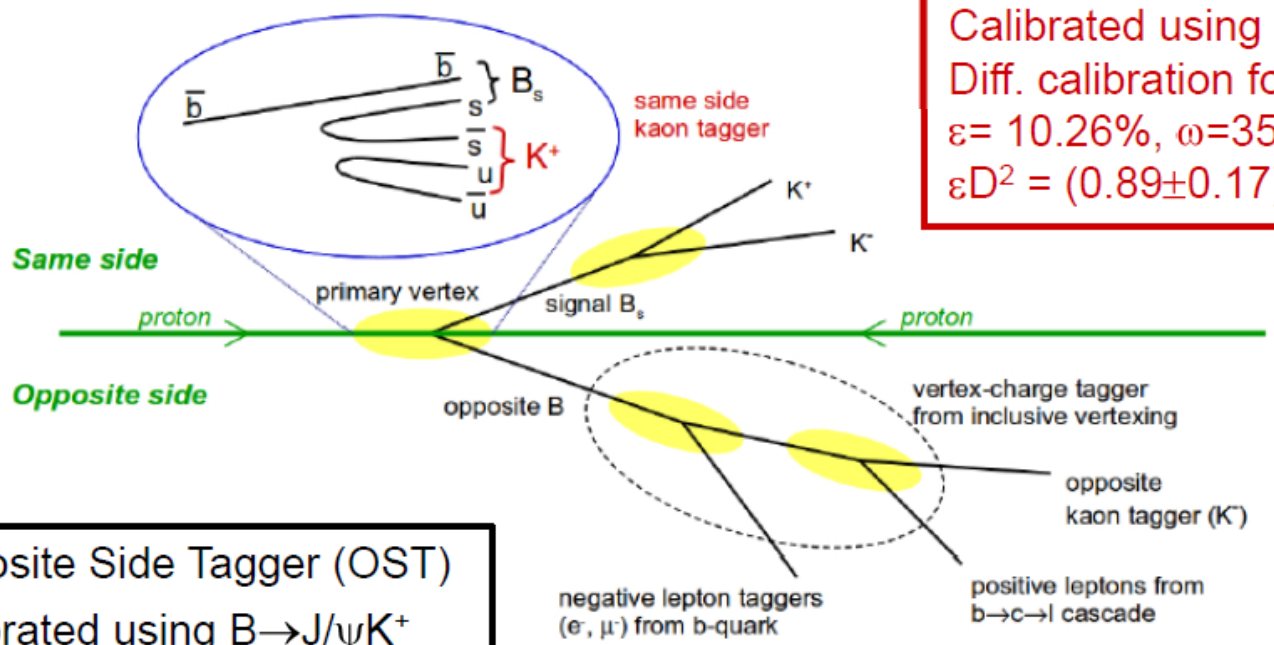
Efficiency:
T-dep. from data
Ω Using simulation

Tagging efficiency:

$q = \pm 1$ for $B_s^0(\bar{B}_s^0)$
D = dilution = $\epsilon(1-2\omega)$
ϵ = efficiency
ω = mistag Prob.



The B_s flavor is tagged at production



Same Side Kaon Tagger

Calibrated using $B_s \to D_s \pi$

Diff. calibration for B_s / $\bar{B}_s$

ε= 10.26%, ω=35.27%

εD^2 = (0.89±0.17)%

Opposite Side Tagger (OST)

Calibrated using $B \to J/\psi K^+$

Different calibration for $B/\bar{B}$

ε = 33.00%, ω=36.83%

εD^2 = (2.29 ± 0.06)%

Combined tagging performance

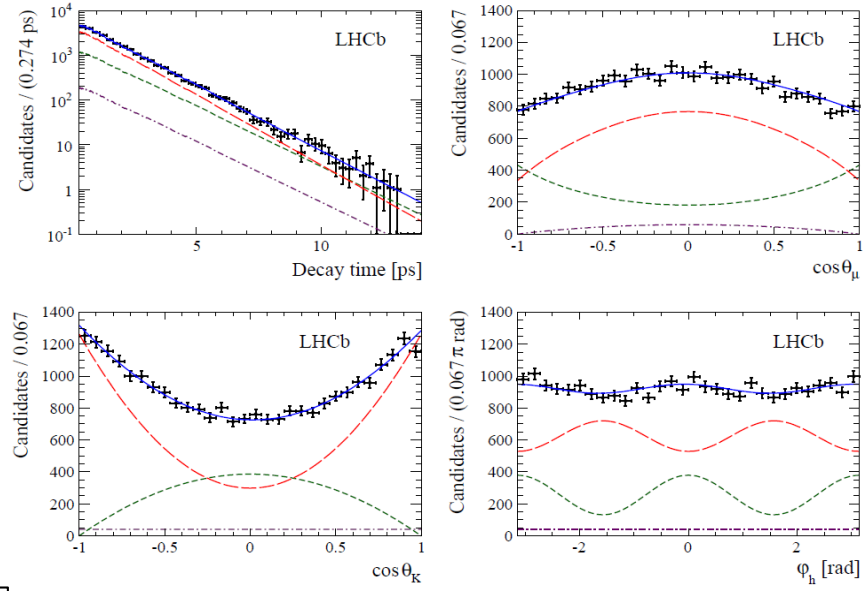
ε = 39.36%, ω=35.9%

εD^2 = (3.13±0.23)%

From U. Uwer

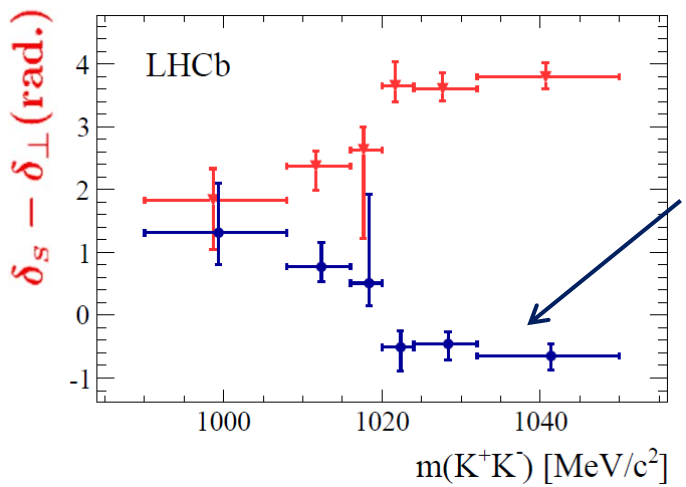
Results for $B_s \to J/\psi KK$ fit

- Projections of the 4 variables (Ω,t) in the fit:



- Sign ambiguity for $\Delta\Gamma_s$

Invariance: $(\phi_s, \Delta\Gamma_s, \delta_0, \delta_{\parallel}, \delta_{\perp}, \delta_s) \Leftrightarrow (\pi-\phi_s, -\Delta\Gamma_s, -\delta_0, -\delta_{\parallel}, \pi-\delta_{\perp}, -\delta_s)$



Correct solution $\Delta\Gamma_s > 0$

Use the 6 values for $\delta_s - \delta_\perp$ (one per K^-K^+ mass slice).

S-P wave behaviour governed by the ϕ meson.

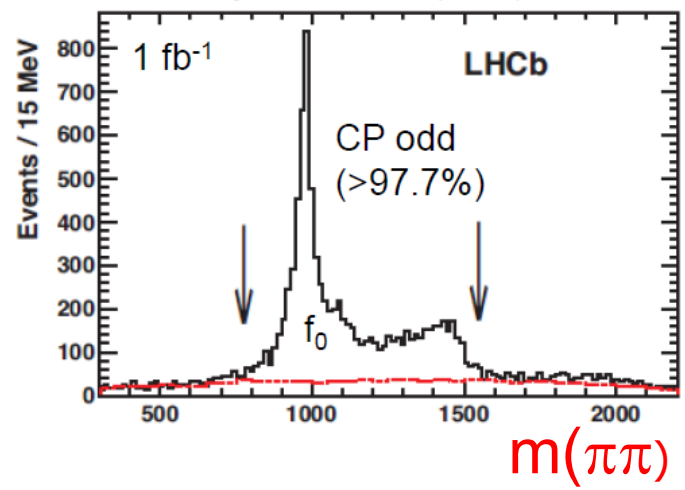
- Combined fit to $B_s \to J/\psi K^+K^-$ and $B_s \to J/\psi \pi^+\pi^-$

(The pion channel is simpler – 97% S-wave with η = -1)

Constrain Γ, $\Delta\Gamma$ to be same in both modes:

→ $\phi_s = -0.14^{+0.17}_{-0.16} \pm 0.01\,\mathrm{rad}$

Phys.Lett. B713 (2012) 378-386



$\Delta\Gamma_s$ not zero

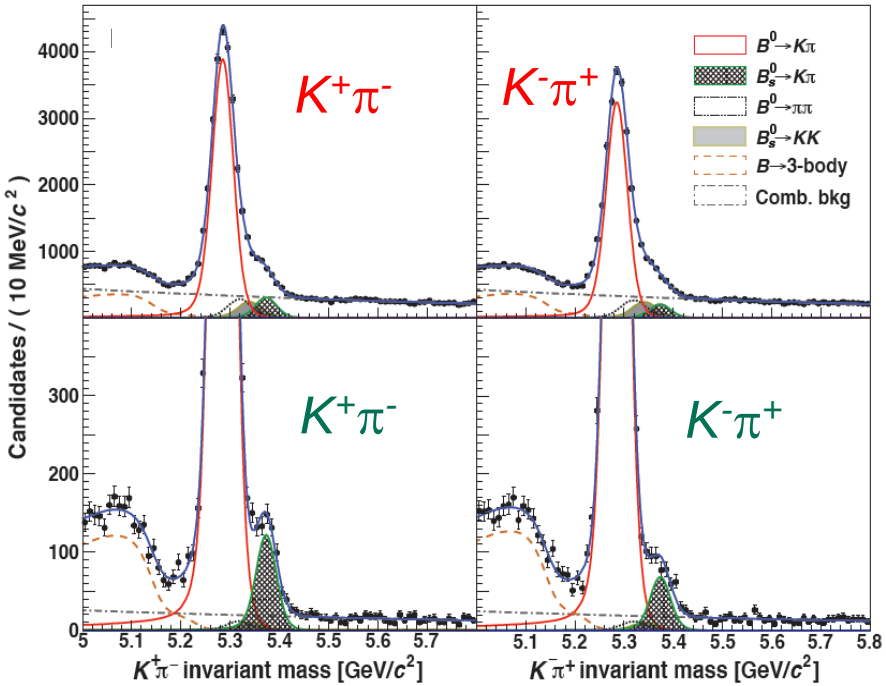
$$\begin{aligned}
\phi_s &= 0.01 \pm 0.07\ (\mathrm{stat}) \pm 0.01\ (\mathrm{syst})\ \mathrm{rad}, \\
\Gamma_s &= 0.661 \pm 0.004\ (\mathrm{stat}) \pm 0.006\ (\mathrm{syst})\ \mathrm{ps}^{-1} \\
\Delta\Gamma_s &= 0.106 \pm 0.011\ (\mathrm{stat}) \pm 0.007\ (\mathrm{syst})\ \mathrm{ps}^{-1}
\end{aligned}$$

- The interference effects can be enhanced by the choice and number of *D* decay modes *f*.
- Three methods used, differentiated by the (flavour-anonymous) D^0 decay modes:
  - GLW: *f* is *CP* eigen-state (KK, $\pi\pi$, $K_S\pi^0$, etc.) — $\delta_d = 0$
    PLB253, 483 (1991), PLB265, 172 (1991)
  - ADS: *f* is $K^{\pm}\pi^{\mp}$ (CF or DCS) and — δ_d from $\psi(3770)$ (CLEO or BES3)
    PRL78, 3257 (1997), PRD63, 036005 (2001)
  - GGSZ: *f* is multi-body, *CP* self conjugate state ($K_s h^+ h^-$, etc.) — $\delta_d = 0$ for some modes; Measures γ directly
    PRD68, 054018 (2003)

Direct *CPV* in $B^0_s \rightarrow K^+\pi^-$ and $B^0 \rightarrow K^+\pi^-$

PRL 110 (2013) 221601

Penguin and Tree can contribute, so direct CPV is possible.



Event selection optimized for B_d

Event selection optimized for B_s

http://cerncourier.com/cws/article/cern/53407

- The "raw" asymmetries A_{raw}, obtained from fits to invariant mass distributions:

$$A_{\rm raw} = \frac{N(K^+\pi^-] - N(K^-\pi^+)}{N(K^+\pi^-] + N(K^-\pi^+)}$$

➔

$$A_{\rm raw}^{B^0} = -0.091 \pm 0.006$$
$$A_{\rm raw}^{B_s^0} = -0.28 \pm 0.04$$

- Must be corrected for *D*etector and *P*roduction asymmetry:

$$A_{CP} = A_{\rm raw} \pm A_D(K\pi) - \kappa A_{\rm P}$$

B^0 ↘ ↗ B_s^0

Mixing dilution

Detector charge asymmetry

Production asymmetry

As required in all CPV asymmetry measurements at the LHCb

- Detector asymmetry A_D estimated from D^*/D decays involving $K^-\pi^+$

$$A_D(K\pi) = \frac{\overline{\epsilon}(K\pi) - \epsilon(K\pi)}{\overline{\epsilon}(K\pi) + \epsilon(K\pi)}$$

➔

$$A_D^{B^0} = (-1.22 \pm 0.21)\%$$
$$A_D^{B_s^0} = (-1.15 \pm 0.23)\%$$

- A production asymmetry A_P induces oscillations in A_{raw} with the B (B_s) mixing frequency & amplitude A_P

$$A_{\rm raw}(t) \approx A_{CP} + A_D + A_P \cos(\Delta m t)$$

- So productions measured to be

$$A_P = \frac{\overline{N}_P - N_P}{\overline{N}_P + N_P}$$

➔

$$A_P^{B^0} = (+0.1 \pm 1.0)\%$$
$$A_P^{B_s^0} = (4 \pm 8)\%$$

- Combining these corrections leads to the measured *CP* asymmetries:

$$A_{CP}(B_s) = \frac{\Gamma[\bar{B}_s^0 \to K^+\pi^-] - \Gamma[B_s^0 \to K^-\pi^+]}{\Gamma[\bar{B}_s^0 \to K^+\pi^-] + \Gamma[B_s^0 \to K^-\pi^+]} = 0.27 \pm 0.04 \pm 0.01$$

$$A_{CP}(B) = \frac{\Gamma[\bar{B}^0 \to K^-\pi^+] - \Gamma[B^0 \to K^+\pi^-]}{\Gamma[\bar{B}^0 \to K^-\pi^+] + \Gamma[B^0 \to K^+\pi^-]} = -0.080 \pm 0.007 \pm 0.003$$

More mixing-induced *CPV*

First Time-dependent *CPV* in $B_s \to K^+K^-$

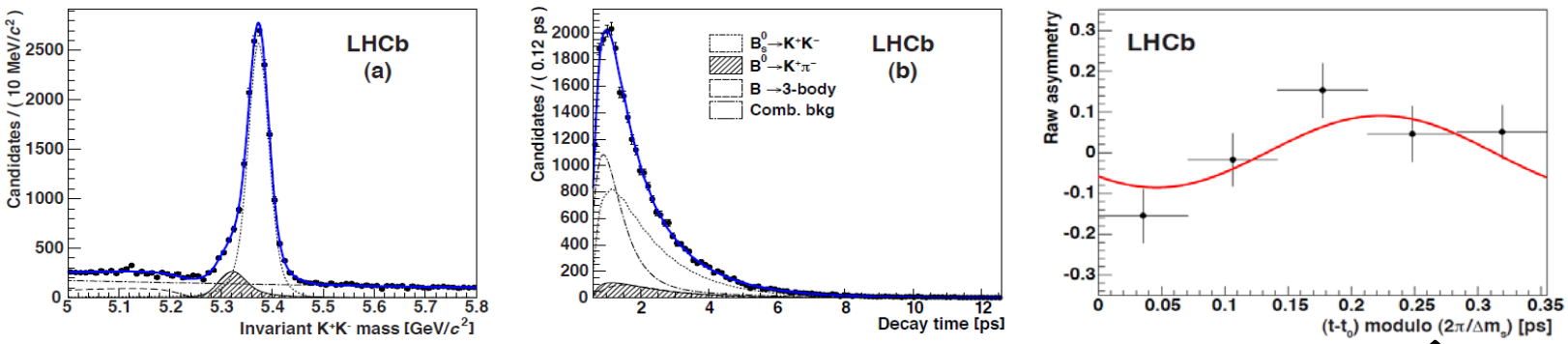
JHEP 10 (2013) 183 (1 fb^{-1} @ 7 TeV)

- The *time-dependent CP* asymmetry is

$$A^{CP}(t) = \frac{\Gamma_{\bar{B}_s^0 \to KK} - \Gamma_{\bar{B}_s^0 \to KK}}{\Gamma_{\bar{B}_s^0 \to KK} + \Gamma_{\bar{B}_s^0 \to KK}} = \frac{-C_{KK}\cos(\Delta m_s t) + S_{KK}\sin(\Delta m_s t)}{\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \mathcal{A}_{KK}^{\Delta\Gamma_s}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right)}$$

$$C_{KK} = \frac{1-|\lambda_{KK}|^2}{1+|\lambda_{KK}|^2}, \quad S_{KK} = \frac{2\Im\lambda_{KK}}{1+|\lambda_{KK}|^2}, \quad \mathcal{A}_{KK}^{\Delta\Gamma_s} = \frac{2\Re\lambda_{KK}}{1+|\lambda_{KK}|^2}$$

Direct CPV Mixing-induced CPV



$$\left.\begin{aligned} C_{KK} &= 0.14 \pm 0.11 \pm 0.03 \\ S_{KK} &= 0.30 \pm 0.12 \pm 0.04 \end{aligned}\right\} \text{ 2.7}\sigma \text{ from (0, 0)}$$

14,646 events

Time-dependent *CPV* in $B_d \to \pi^+\pi^-$

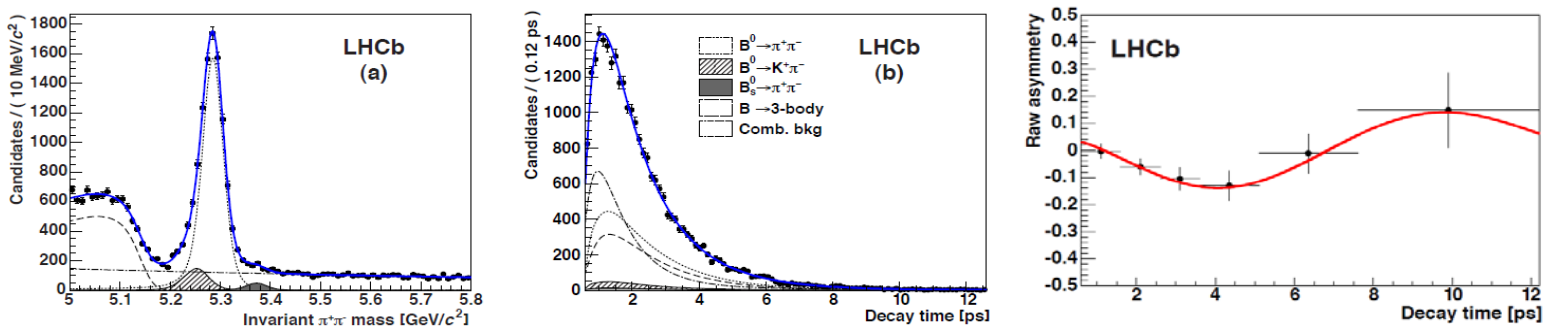
JHEP 10 (2013) 183 (1 fb^{-1} @ 7 TeV)

- The *time-dependent CP* asymmetry is

$$A^{CP}(t) = \frac{\Gamma_{\bar{B}^0_d \to \pi\pi} - \Gamma_{\bar{B}^0_d \to \pi\pi}}{\Gamma_{\bar{B}^0_d \to \pi\pi} + \Gamma_{\bar{B}^0_d \to \pi\pi}} = \frac{-C_{\pi\pi}\cos(\Delta m_d t) + S_{\pi\pi}\sin(\Delta m_d t)}{\cosh\left(\frac{\Delta\Gamma_d}{2}t\right) - \mathcal{A}_{\pi\pi}^{\Delta\Gamma_d}\sinh\left(\frac{\Delta\Gamma_d}{2}t\right)}$$

$$C_{KK} = \frac{1-|\lambda_{\pi\pi}|^2}{1+|\lambda_{\pi\pi}|^2}, \quad S_{KK} = \frac{2\Im\lambda_{\pi\pi}}{1+|\lambda_{\pi\pi}|^2}, \quad \mathcal{A}_{KK}^{\Delta\Gamma_s} = \frac{2\Re\lambda_{\pi\pi}}{1+|\lambda_{\pi\pi}|^2}$$

Direct CPV Mixing-induced CPV



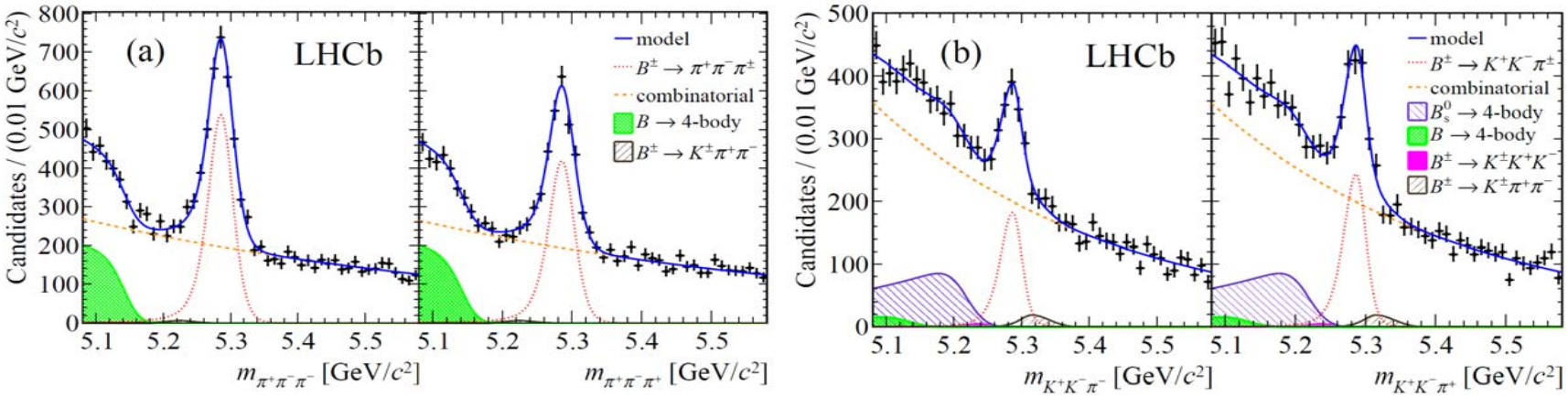
	$S_{\pi\pi}$	$C_{\pi\pi}$	CL
LHCb	$-0.71 \pm 0.13 \pm 0.02$	$-0.38 \pm 0.15 \pm 0.02$	5.6σ
Belle	$-0.64 \pm 0.08 \pm 0.03$	$-0.33 \pm 0.06 \pm 0.03$	
BABAR	$-0.68 \pm 0.10 \pm 0.03$	$-0.25 \pm 0.08 \pm 0.02$	

9,170 events

Other decays with direct CPV

Direct CPV in 3-body charmless B decays

[Data sample 1 fb^{-1}]



$B^- \to \pi^+\pi^-\pi^-$ $\quad B^+ \to \pi^+\pi^-\pi^+$ $\quad B^- \to K^+K^-\pi^-$ $\quad B^+ \to K^+K^-\pi^+$

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

[PRL 111, 101801 (2013)]

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

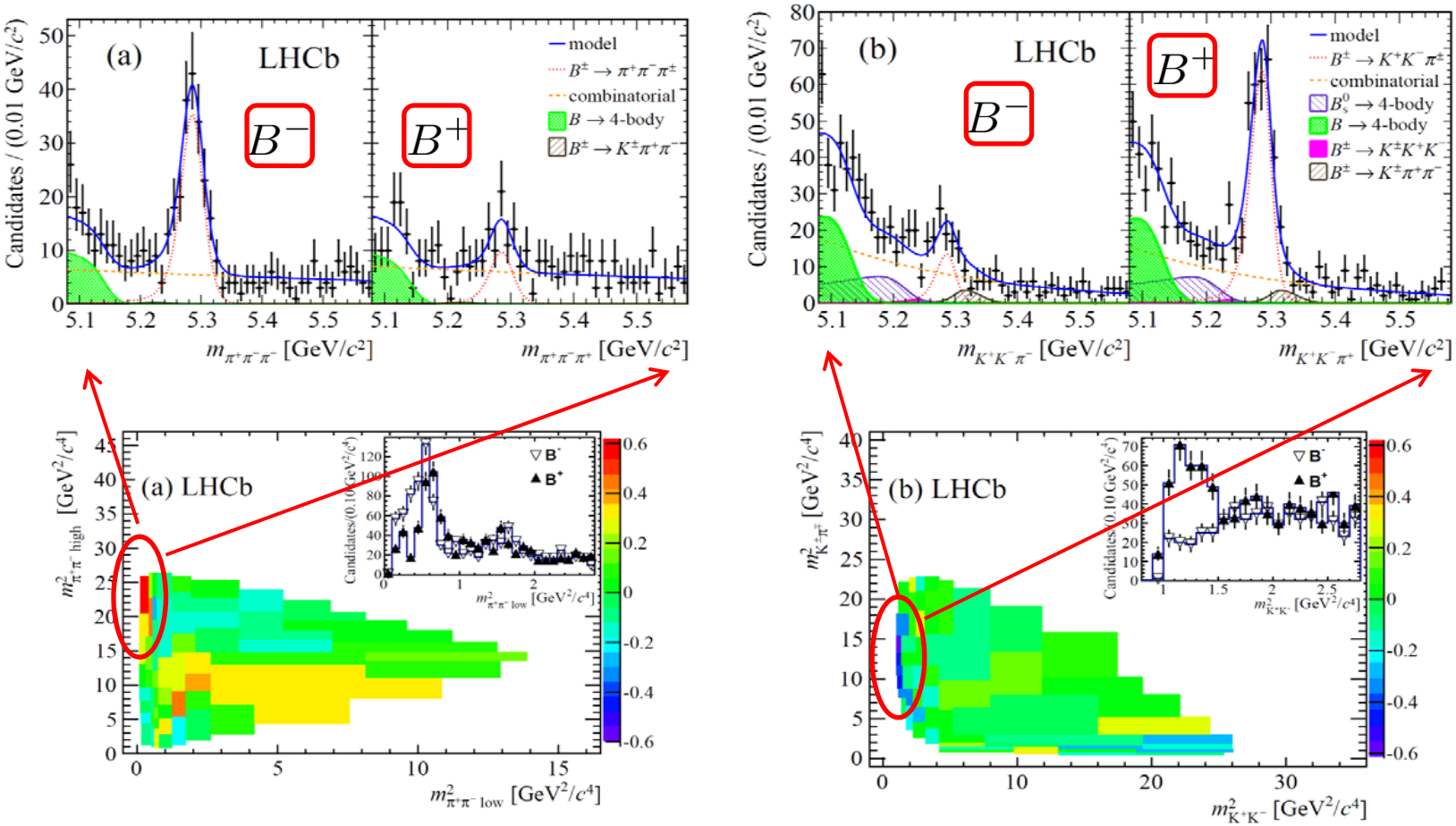
[PRL 112, 011801 (2014)]

$$A_{CP} = A_{raw} - A_{\pi^\pm} - A_P(B^\pm)$$
$$A_P(B^\pm) = A_{raw}(B \to J/\psi K) - A_{CP}(B \to J/\psi K) - A_{raw}(D^0 \to K^\pm h^\mp)$$

(0.1\pm 0.7)%

Evidence for inclusive *CP* asymmetries in $B \to 3h$.

CP violation is highly localized



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