53rd International Winter Meeting on Nuclear Physics
Bormio, 26-30 January 2015

CP violation in B and D systems at LHCb

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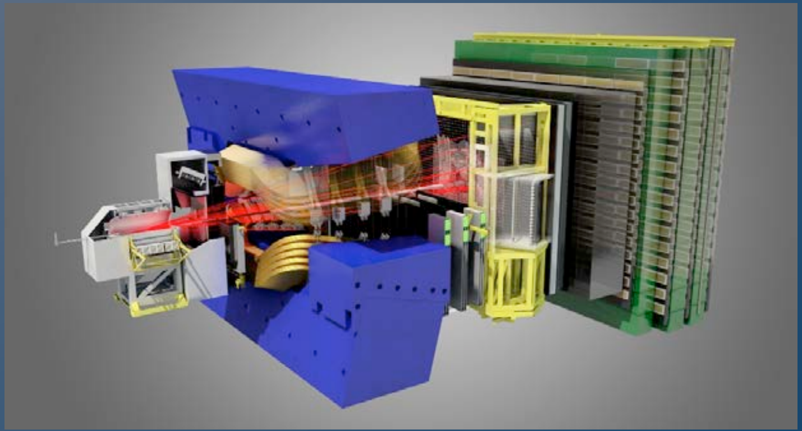
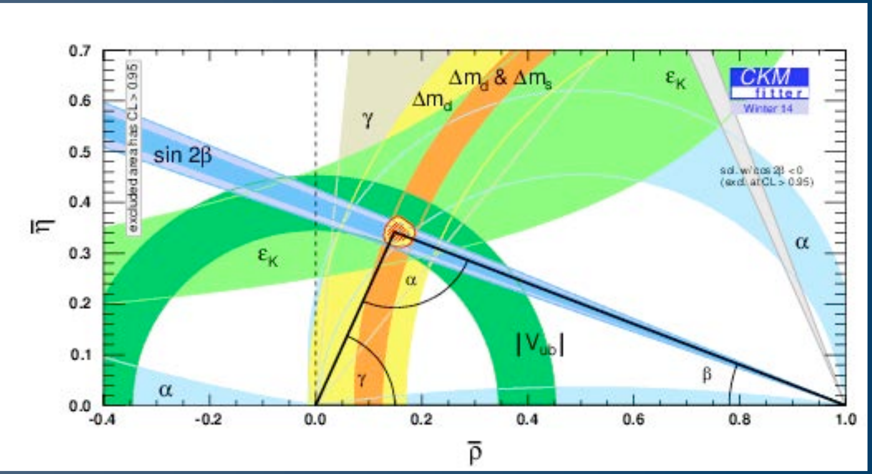
on behalf of the LHCb Collaboration



CP violation

- Violation of CP is required by matter-antimatter asymmetry of the Universe. Discovered in quark sector 50 years ago.

- SM predictions for CPV effects proven extremely successful
  - Quark sector well described by the CKM mechanism



- But SM is not complete
  → search for signs of New Physics
  - Indirect searches probe virtual effects of new particles.

- Aim of LHCb at LHC pp Collider: search for NP with precise measurements of CP violation and searches of rare decays of beauty and charmed hadrons. (→see also M.Kenzie talk this morning)

Outline

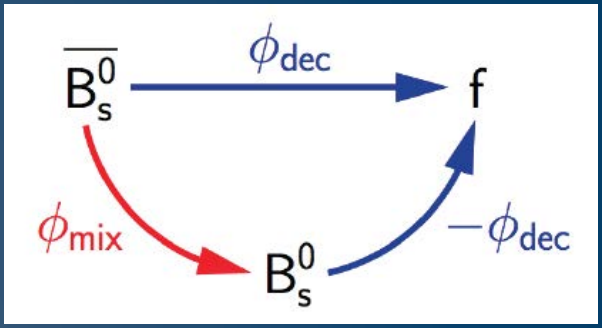
Highlights of LHCb results on CP violation in

- B^0_s mixing and decay
  - $B^0_s \to J/\psi\, K^+K^-$, $B^0_s \to D^-_s D^+_s$
- Gluonic penguins
  - $B^0_s \to \phi\phi$
- B^0 mixing
  - a_{fs} from $B^0 \to D^{(*)-} \mu^+ \nu$

- D^0 mixing and search for CPV in $D^0 \to K\pi$
- Direct CPV in $D^0 \to KK$, $D^0 \to \pi\pi$
- Indirect CPV in $D^0 \to KK$, $D^0 \to \pi\pi$ new

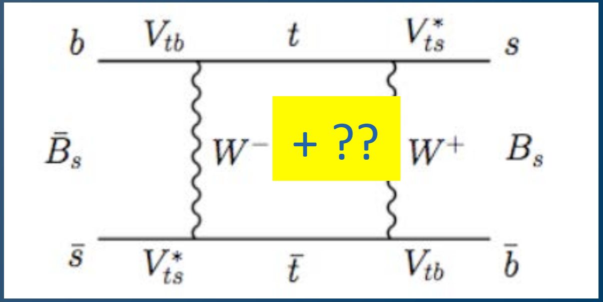
CPV in B^0_s mixing and decay

- A weak phase ϕ_s is arising from interference between B^0_s decays w and w/o mixing to a final state CP eigenstate.



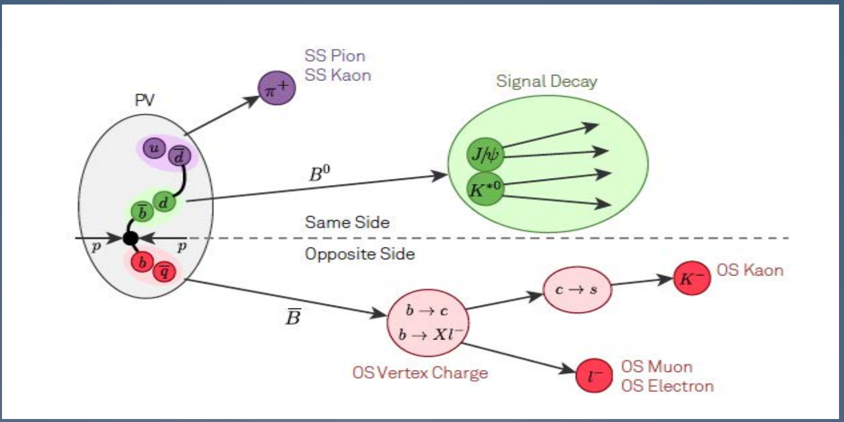
- In SM precise prediction for $b \to c\bar{c}s$ transitions, eg. $B^0_s \to J/\psi\ \phi$, neglecting penguins contributions
  - $\phi_s^{SM} = \phi_{mix} - 2\ \phi_{dec} = -2 \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$
    $= (-0.0363 \pm 0.013)$ rad

- New Physics might add large phases
  $\phi_s^{measured} = \phi_s^{SM} + \phi_s^{NP}$



- A precise measurement of ϕ_s is a sensitive test of NP presence in the B^0_s sector.

Flavour Tagging and Time Resolution



- Many possibilities for determination of B flavour at production
- Effective tagging power

$\varepsilon^{tag}(1\text{-}2\omega)^2$=(3.73 ±0.15)% $B^0_s \to J/\psi K^+K^-$

(5.33 ±0.25)% $B^0_s \to D_s^+ D_s^-$

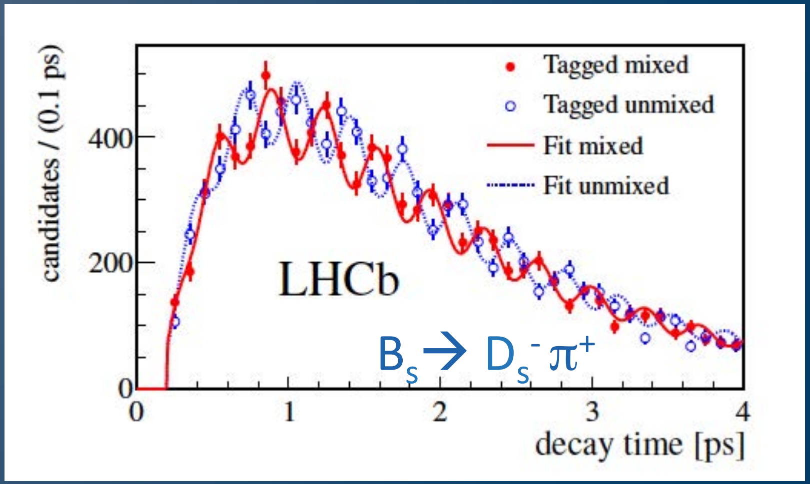
ε^{tag} = tagging efficiency

ω = mistag probability

- Fast $B^0_s \overline{B}^0_s$ oscillation frequency (period $2\pi/\Delta m_s$~ 355 fs) require very good time resolution for time dependent measurements
- Time resolution

$\sigma(t)$ ~ 45 fs $B^0_s \to J/\psi K^+K^-, \pi^+\pi^-$

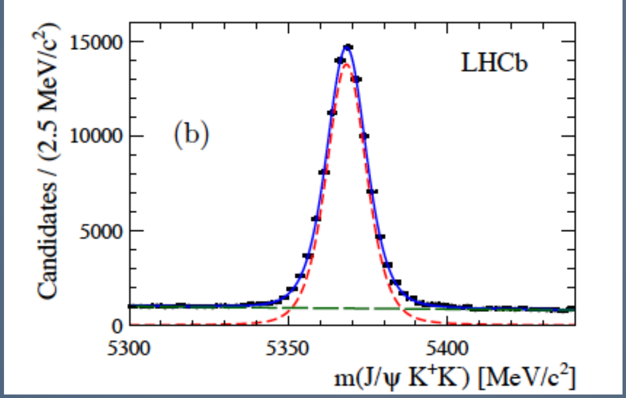
  - determined event-by-event from the vertex fit and calibrated on data

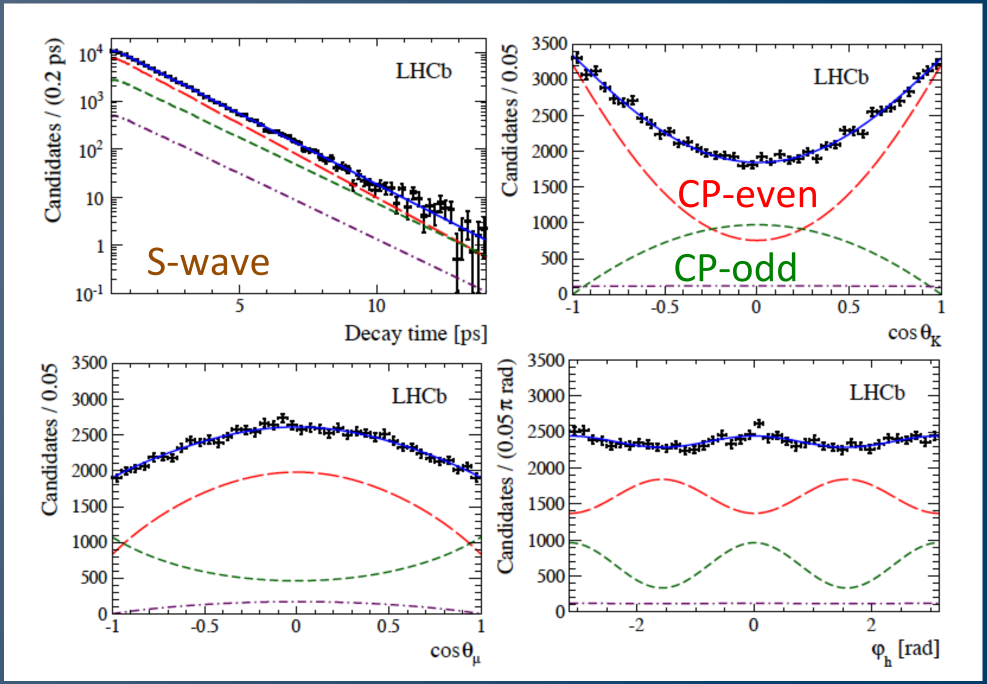


Eur. Phys. J. C (2013) 73:2655

ϕ_s from $B^0_s \rightarrow J/\psi K^+K^-$

- P→VV decay with CP-even and CP-odd components (P-wave, S-wave)
  - Fit to invariant mass, decay time and angular distributions of flavour tagged events.
  - 3 fb^{-1} data set: 95 690 ± 350 signal events





ϕ_s = -0.058 ±0.049±0.006 rad

Γ_s = 0.6603 ±0.0027±0.0015 ps^{-1}

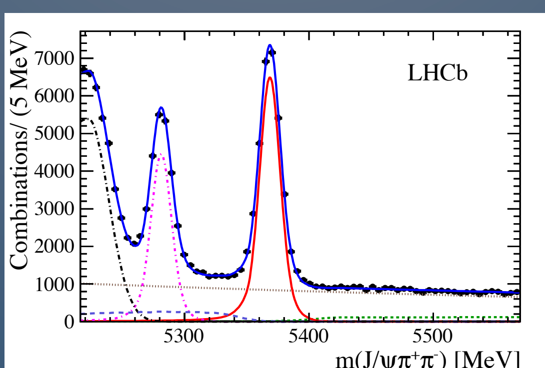
$\Delta\Gamma_s$= 0.0805 ±0.0091±0.0032 ps^{-1}

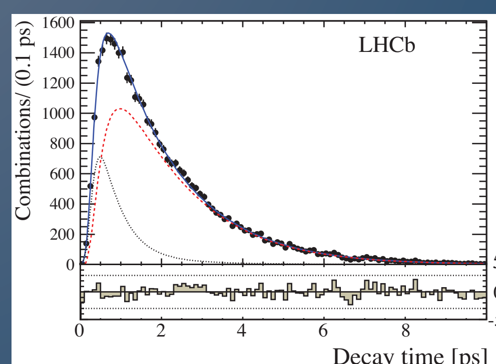
arXiv:1411.3104 Sub. to PRL

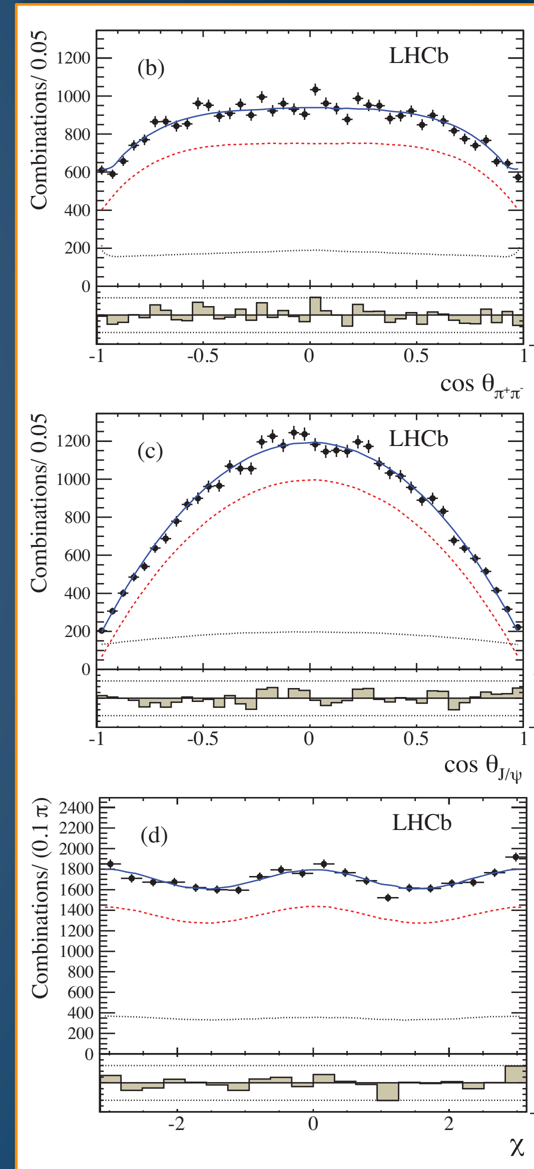
ϕ_s from $B^0_s \rightarrow J/\psi\, \pi^+\pi^-$

PLB 736(2014)186

- From amplitude analysis (PRD89 (2014) 092006) $B^0_s \rightarrow J/\psi\pi^+\pi^-$ is CP-odd > 97.7% at 95% CL.
- ϕ_s measured from likelihood fit to mass, time and angular distributions of tagged events with no CP assumption.
  - 27100 $B^0_s \rightarrow J/\psi\, \pi^+\pi^-$ signal events, 3fb^{-1}
- $\phi_s = 0.075 \pm 0.067 \pm 0.008$ rad
  - Consistent with $B^0_s \rightarrow J/\psi\, K^+K^-$ and SM prediction







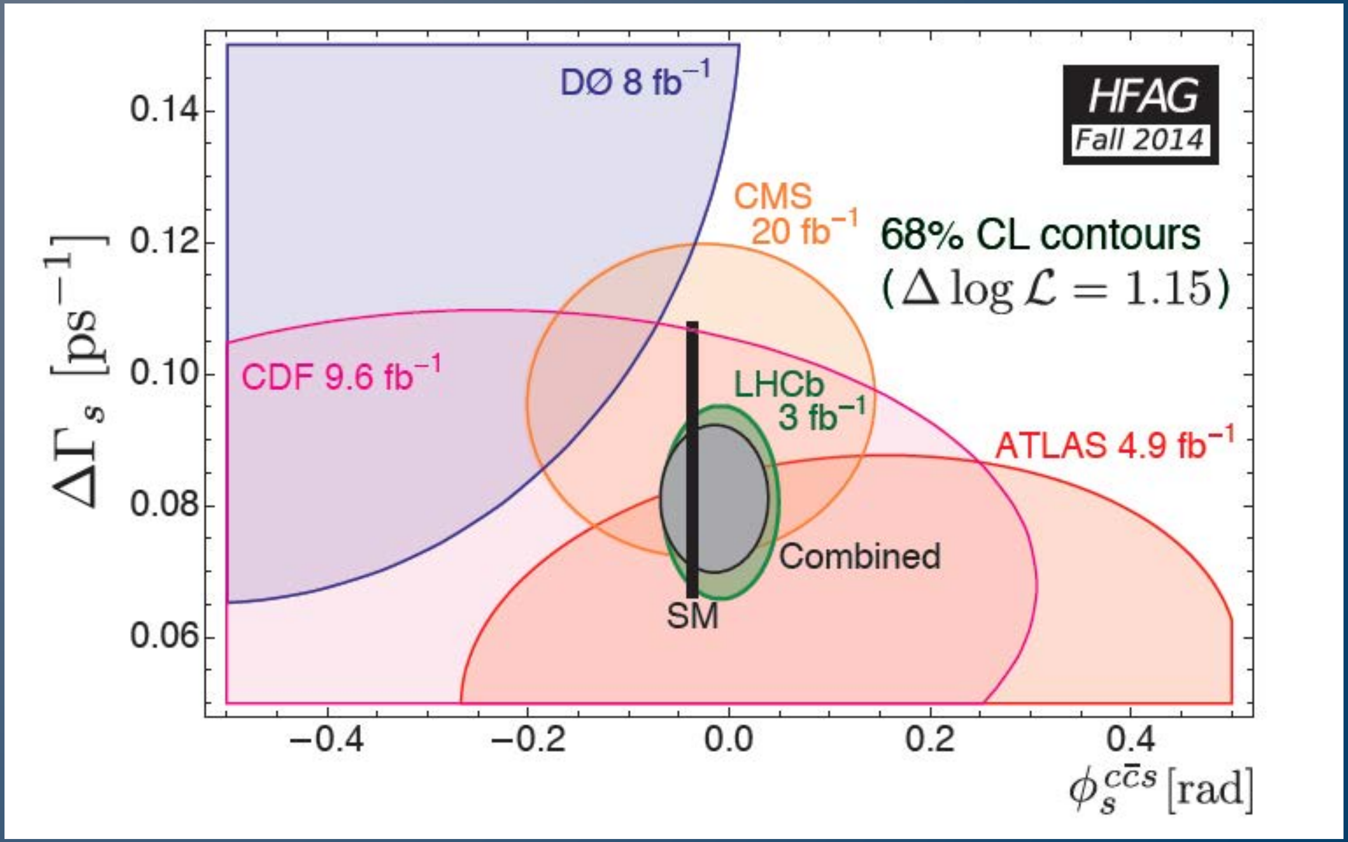
Mixing-induced CPV in B_s^0

- Combination $B^0_s \rightarrow J/\psi K^+K^-$ & $B^0_s \rightarrow J/\psi \pi^+\pi^-$ ($3fb^{-1}$)

ϕ_s = - (0.010 ± 0.039) rad

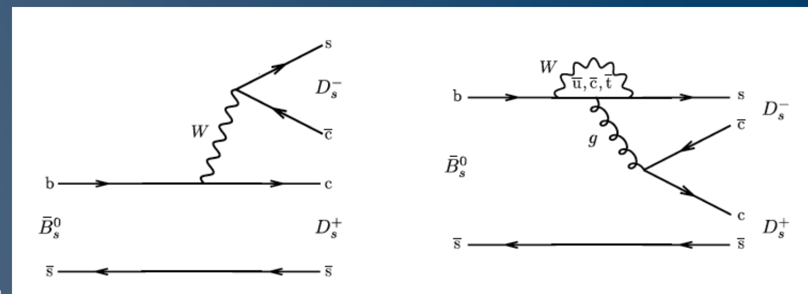
Dominating the wold average ($\phi_s^{\text{HFAG WA}}$ = - 0.015 ± 0.035 rad)

In agreement with SM predictions, but still room for NP



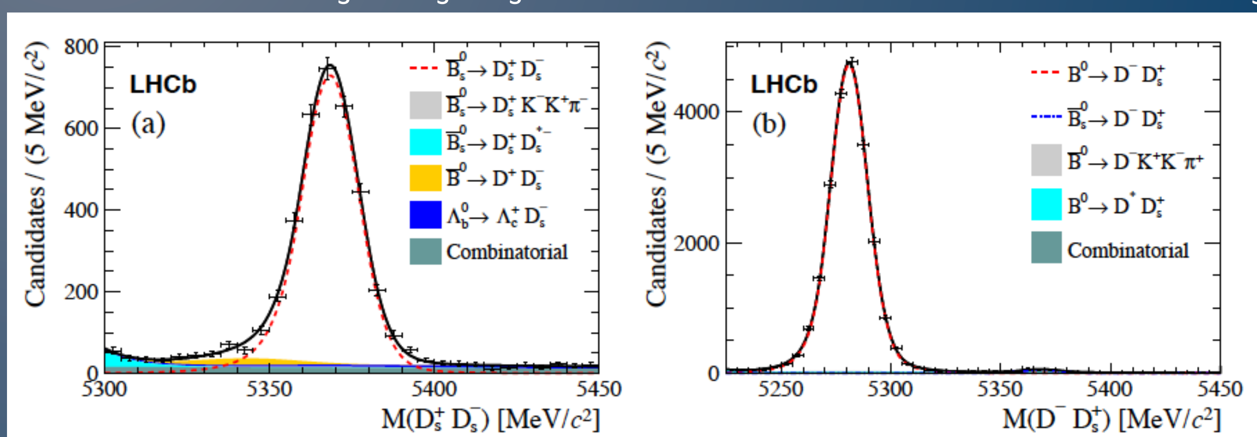
ϕ_s from $B^0_s \rightarrow D^-_s D^+_s$

- First measurement of ϕ_s in an open charm decay of B^0_s
  - Measurements of ϕ_s in mode with different penguin amplitudes
- CP-even final state, no angular analysis needed but low decay rate.



- Reconstruct signal and control channel in 3 D_s^+ mesons final states

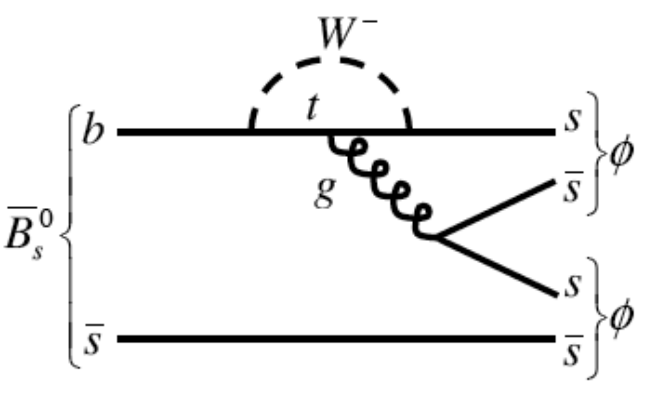
3345 ± 62 $B^0_s \rightarrow D_s^- D_s^+$ 21320 ± 148 $B^0 \rightarrow D^- D_s$



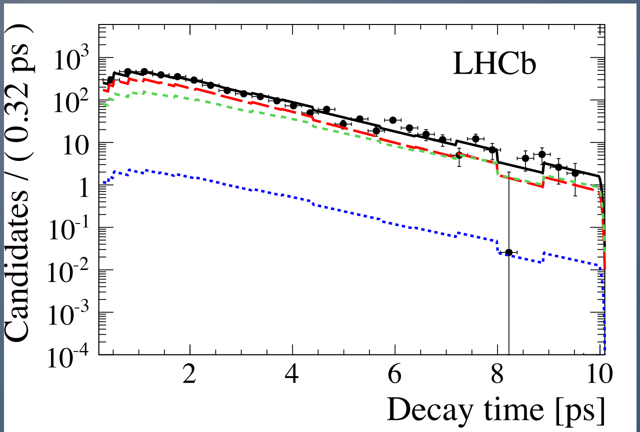
- $\phi_s = 0.02 \pm 0.17 \pm 0.02$ rad

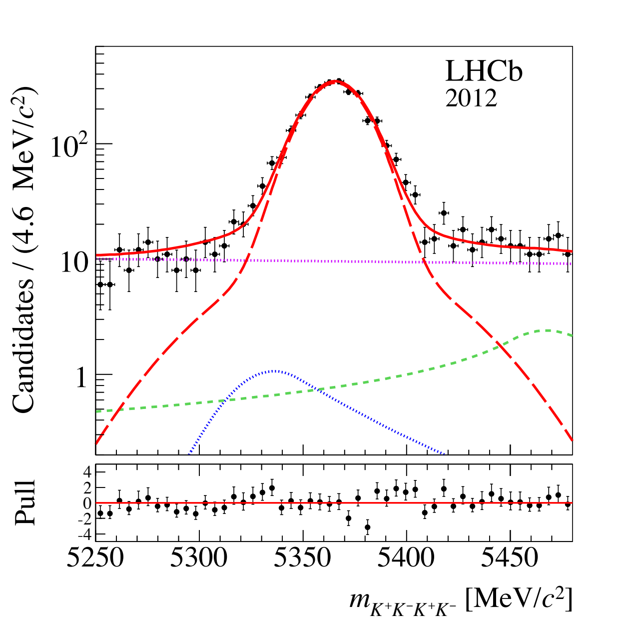
Phys.Rev.Lett. 113 (2014)11801

$B^0_s \to \phi\phi$, $\phi \to K^+K^-$



- b→ss̄s gluonic penguin induced decay.
  - SM prediction for CP violating phase ~0
  - Sensitive to NP
- Time-dependent angular analysis of tagged events.
  - 4000 $B^0_s \to \phi\phi$ signal candidates in 3fb^{-1}
  - Effective decay time resolution 44 fs





$\phi_s = -0.17 \pm 0.15 \pm 0.03$ rad

In agreement with SM prediction

Phys. Rev. D 90 (2014) 052011

CPV in B^0 and B_s^0 mixing

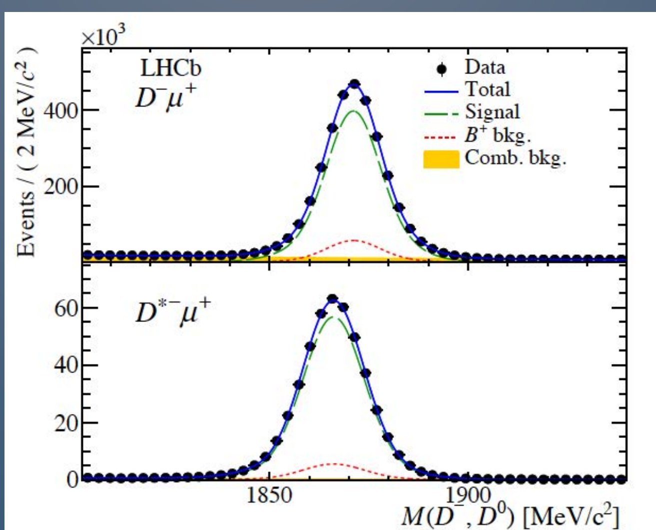
- Violation of CP symmetry in $B^0\overline{B}^0$ mixing can be proved by measuring the semileptonic asymmetry

$$a_{sl} = \frac{\Gamma(\overline{B}^0 \to D^- \ell^+ \nu X) - \Gamma(B^0 \to D^+ \ell^- \overline{\nu} X)}{\Gamma(\overline{B}^0 \to D^- \ell^+ \nu X) + \Gamma(B^0 \to D^+ \ell^- \overline{\nu} X)}$$

- In the SM a_{sl} is predicted to be very small
  arXiv:1102.4274
  → A good probe for NP contributions.

$$a_{sl}^d(SM) = (-4.1 \pm 0.6) \times 10^{-4}$$

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



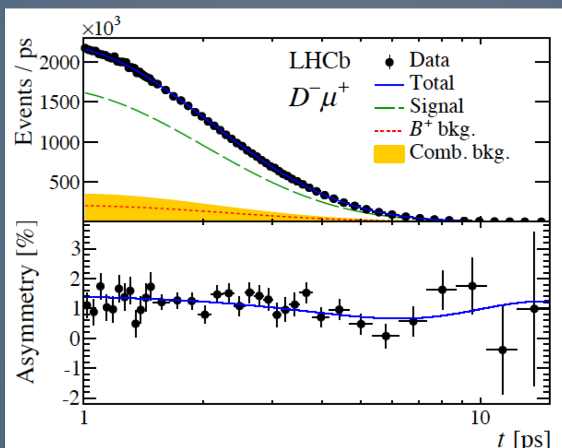
- LHCb had measured a_{sl} in the B^0_s system with 1 fb^{-1} of data
  (Phys Lett.B 728 (2014) 607)

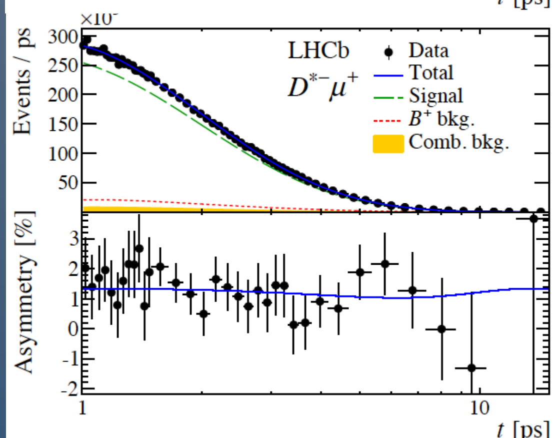
$$a_{sl}^s = (-0.06 \pm 0.50 \pm 0.36)\%$$

- New: a_{sl} in the B^0_d system in 3 fb^{-1} of data 2.1 x10^6 $B^0 \to D^{(*)-}\mu^+\nu$ decays

Semileptonic CP asymmetries a_{sl}

- Fit to mass and decay time distributions of $D^-\mu^+$ and $D^+\mu^-$ events.
- Correct for fake asymmetries
  - Detection asymmetry measured on control channels
  - $B^0\,\overline{B}{}^0$ production asymmetries measured in the same fit

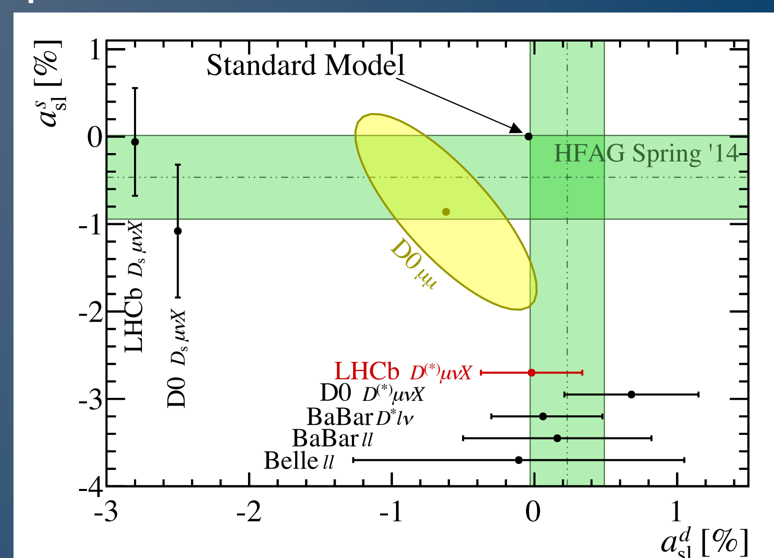




$$a_{sl}^d = (-0.02 \pm 0.19 \pm 0.30)\%$$

arXiv:1409.8586, Sub. to PRL

- Compatible with SM

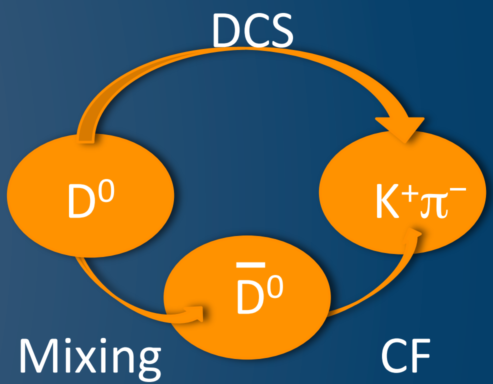


Mixing and CPV with $D^0 \rightarrow K\pi$

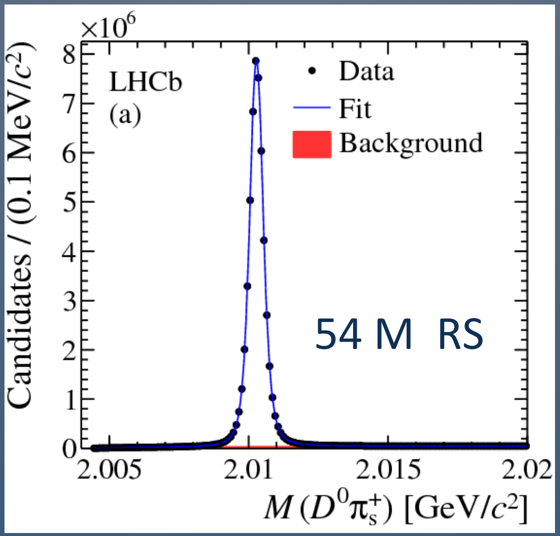
- Small CPV expected in SM ($\sim 10^{-3}$) good probe for NP in "up" quark sector.
- Measure time dependent decay rate of Right Sign and Wrong Sign

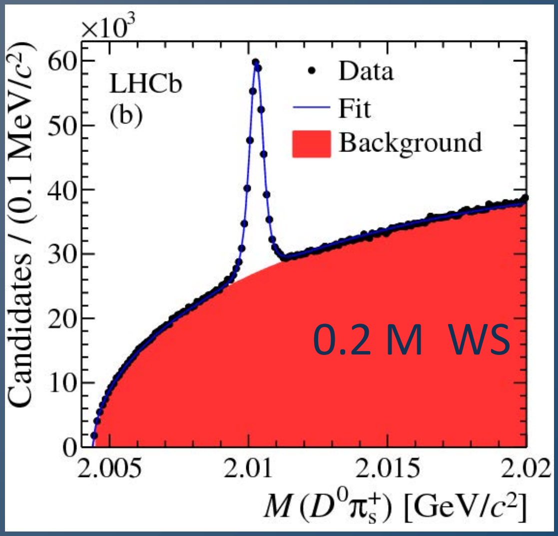
  RS = $D^0 \rightarrow K^-\pi^+$ CF decays

  WS = $D^0 \rightarrow K^+\pi^-$ DCS or oscillations



- D^0 flavour tagged by slow π^+ in $D^{*+} \rightarrow D^0\pi^+$





Time-dependent rate of $D^0 \rightarrow K\pi$

- Time-dependent ratio of WS to RS decay rates

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

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \quad |p|^2 + |q|^2 = 1 \qquad x \equiv \frac{\Delta m}{\Gamma} \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma} \qquad \begin{aligned} x' &= x\cos\delta + y\sin\delta \\ y' &= y\cos\delta - x\sin\delta \end{aligned}$$

R_D = ratio suppressed/favoured decay rates δ = strong phase difference

- Two sets of parameters for initially produced $D^0, \overline{D}^0$ are used for CPV studies
  - Direct CPV: $R_D^+ \neq R_D^-$
  - CPV in mixing or interference: $(x'^+, y'^+) \neq (x'^-, y'^-)$

CPV in WS $D^0 \rightarrow K\pi$

- Mixing parameters:

  $R_D = (0.3568 \pm 0.066) \times 10^{-3}$

  $x'^2 = (5.5 \pm 4.9) \times 10^{-5}$

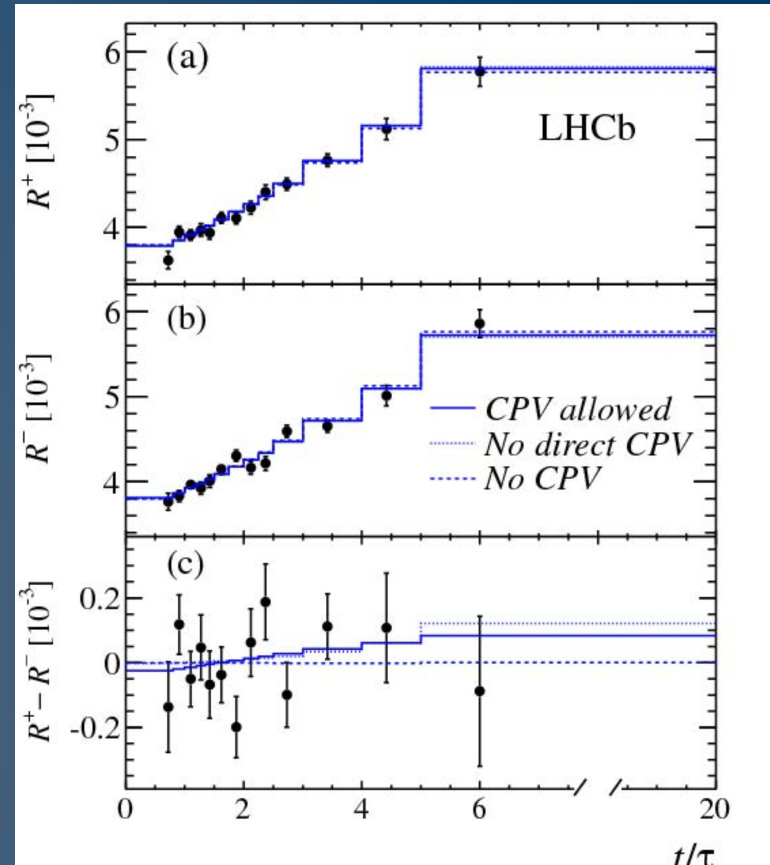
  $y' = (4.8 \pm 1.0) \times 10^{-3}$

  world best determination

- No evidence for CP violation

  $(R_D^+ - R_D^-)/(R_D^+ + R_D^-) = (-0.7 \pm 1.9)\%$

  $0.75 < |q/p| < 1.2$ at 68% CL



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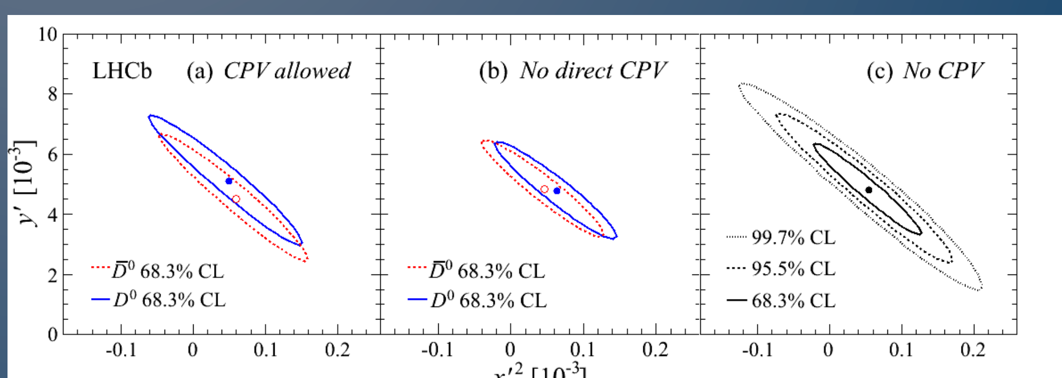
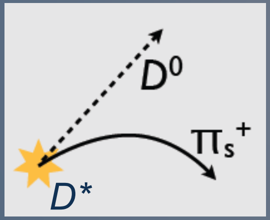


Direct CPV in $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$

- Time-integrated CP asymmetries measured in two channels

$$\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)$$

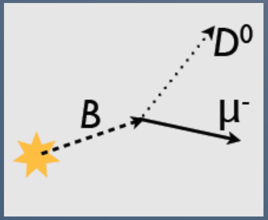
  - robust observable against detector systematics and production asymmetries



- D* tagged, $1 fb^{-1}$

ΔA_{CP}=(−0.34 ± 0.15 ± 0.10) %

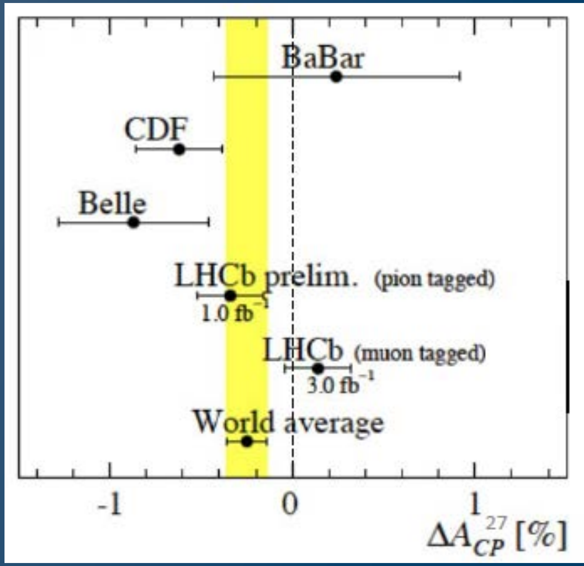
preliminary LHCb-CONF-2013-003



- $B \to D^0 \mu\nu$ tagged, $3 fb^{-1}$

ΔA_{CP}= (+0.14 ± 0.16 ±0.08) %

JHEP 07(2014) 041



- Consistent with no direct CPV

Indirect CPV in $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$

- Time-dependent CP asymmetry of D^0 decays to CP-even eigenstates *f*

$$A_{CP}(t) = \frac{\Gamma(D^0 \to f,t) - \Gamma(\overline{D}^0 \to f,t)}{\Gamma(D^0 \to f,t) + \Gamma(\overline{D}^0 \to f,t)} \approx A_{CP}^{dir} - A_\Gamma \frac{t}{\tau}$$

where A_Γ is given by the asymmetry of the effective lifetimes

$$A_\Gamma \equiv \frac{\hat{\tau}(\overline{D}^0) - \hat{\tau}(D^0)}{\hat{\tau}(\overline{D}^0) + \hat{\tau}(D^0)}$$

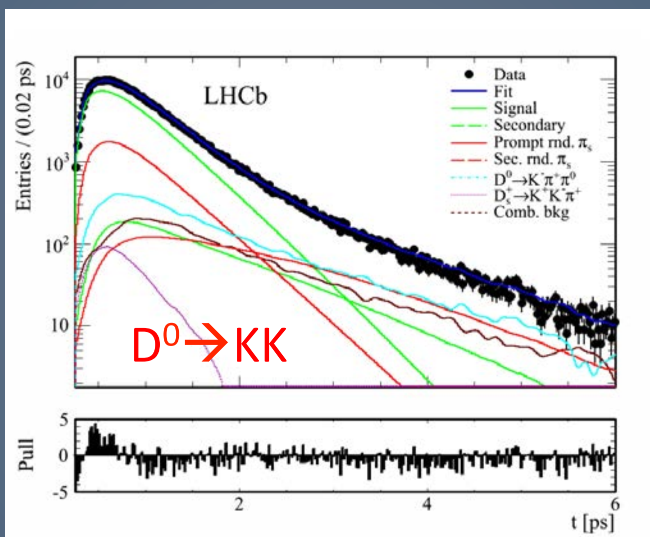
- In terms of x,y mixing parameters

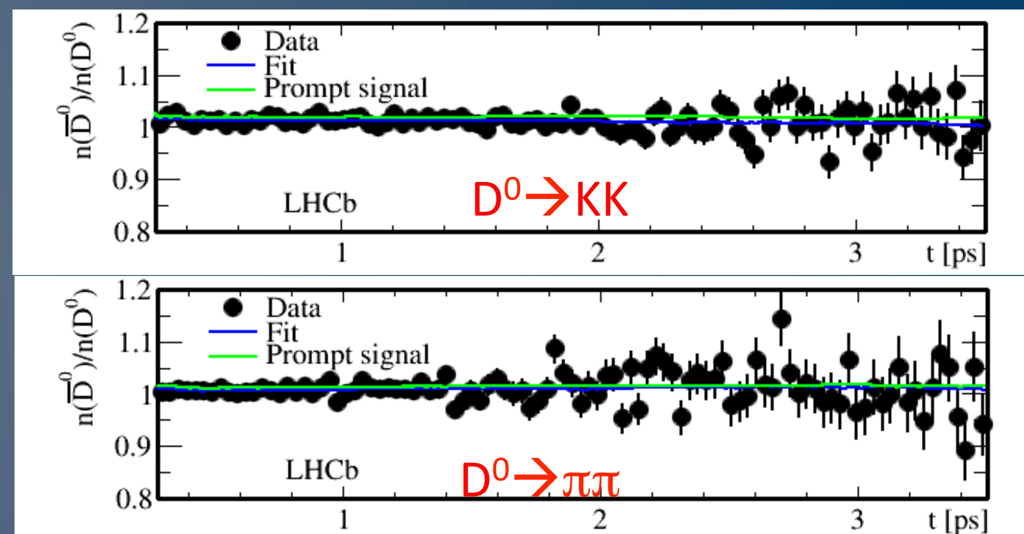
$$A_\Gamma \approx \left(\frac{1}{2} A_{CP}^{mix} - A_{CP}^{dir}\right) y \cos\phi - x \sin\phi$$

- In SM the phase ϕ is independent on final state and is zero if CP is conserved.

Effective lifetimes in $D^0 \rightarrow KK,\pi\pi$; D* tag

- 3M $D^0 \rightarrow KK$ and 1M $D^0 \rightarrow \pi\pi$ signal candidates tagged by $D^{*+} \rightarrow D^0\pi^+$
- Maximum likelihood fits to D^0 and Δm mass and D^0 time distributions





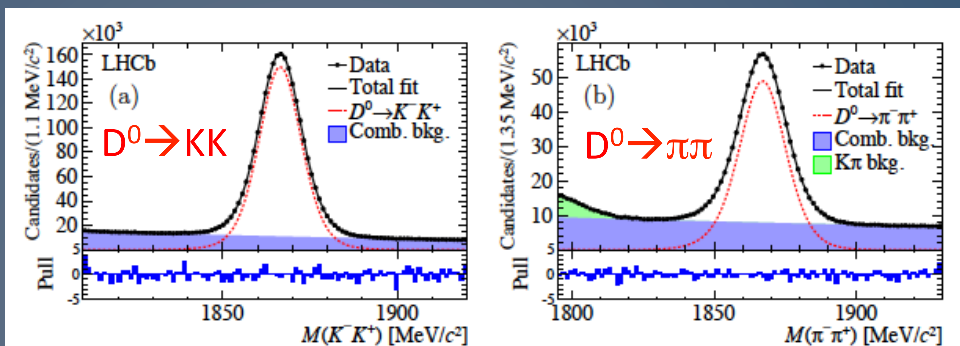
$$A_\Gamma(KK) = (-0.035 \pm 0.062 \pm 0.012)\%$$
$$A_\Gamma(\pi\pi) = (0.033 \pm 0.106 \pm 0.014)\%$$

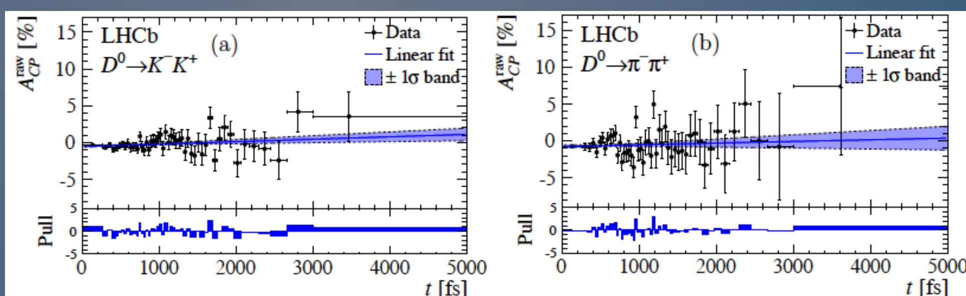
$1 fb^{-1}$
PRL 112 (2014) 041801

- No evidence of indirect CPV and no significant difference between the two final states.

Effective lifetimes in $D^0 \to KK, \pi\pi$; μ tag

- D^0 tagged by semileptonic decays $B \to D^0 \mu \nu$ with 3 fb^{-1} data
  - D^0 lifetime obtained from $D^0 \mu$ to $D^0 \to hh$ vertices

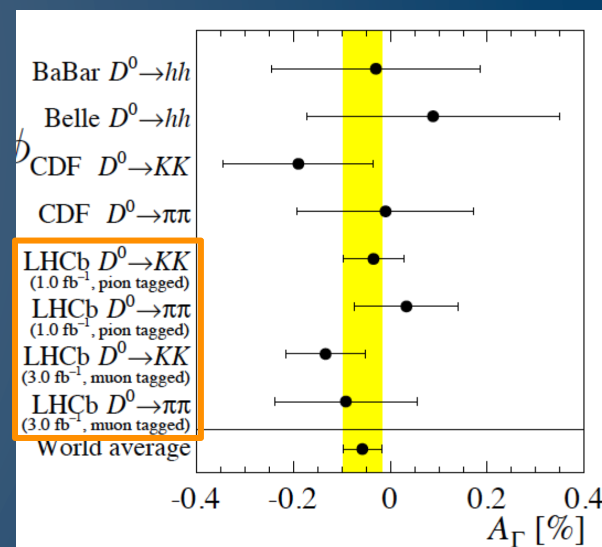




$$A_\Gamma(KK) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\%$$

$$A_\Gamma(\pi\pi) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\%$$

arXiv:1501.1637 Sub. to JHEP



- Consistent with no indirect CPV in $D^0 \to KK$, $D^0 \to \pi\pi$

Conclusion

- The excellent performance of LHCb in Run I have provided a large variety of tests of CP violation in the B and D systems.

- Examples are the world best measurement of
  - B^0_s mixing phase ϕ_s from $B^0_s \to J/\psi K^+K^-$, $\pi^+\pi^-$ decays
  - D^0 mixing parameters
  - Search for indirect CPV in $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$ decays

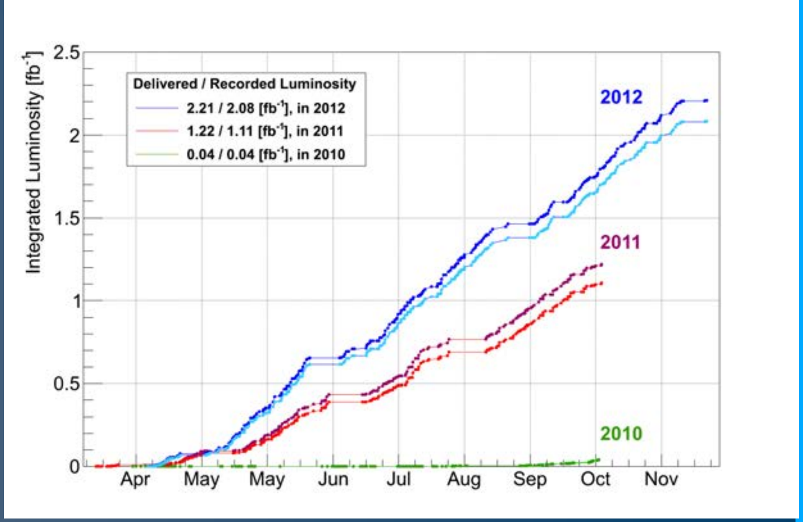
- All results show good agreement with the SM predictions.
  - No evidence of CP violation in charm sector.

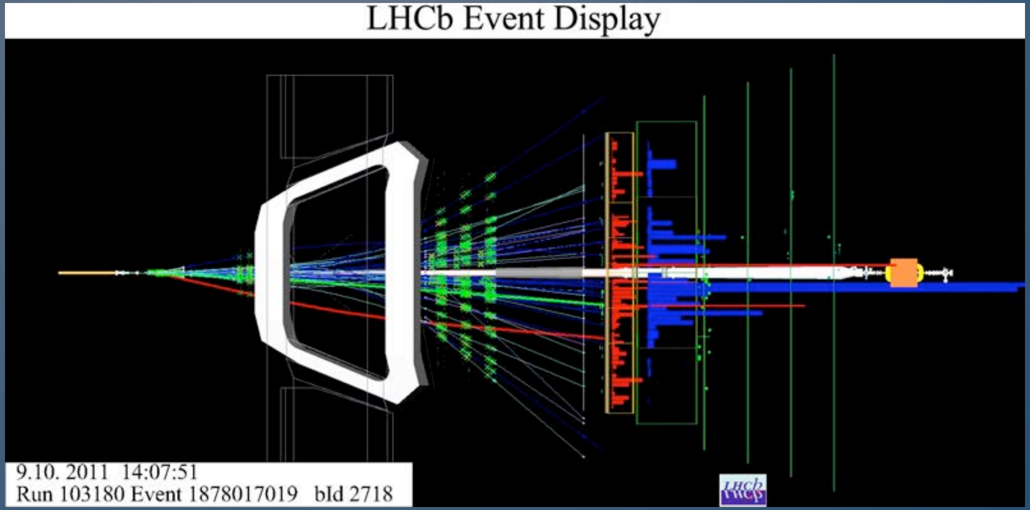
- Many new results to come with next data taking periods.

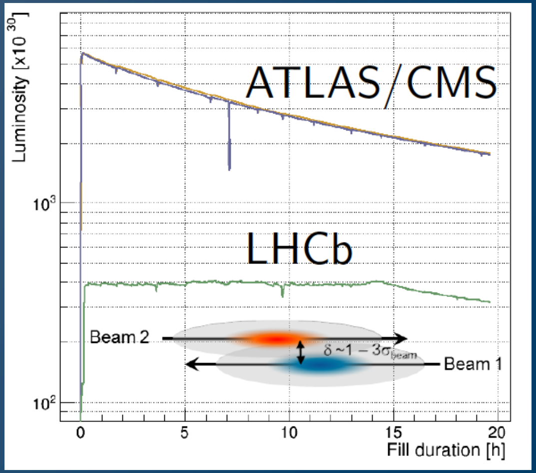
backup

LHCb data taking

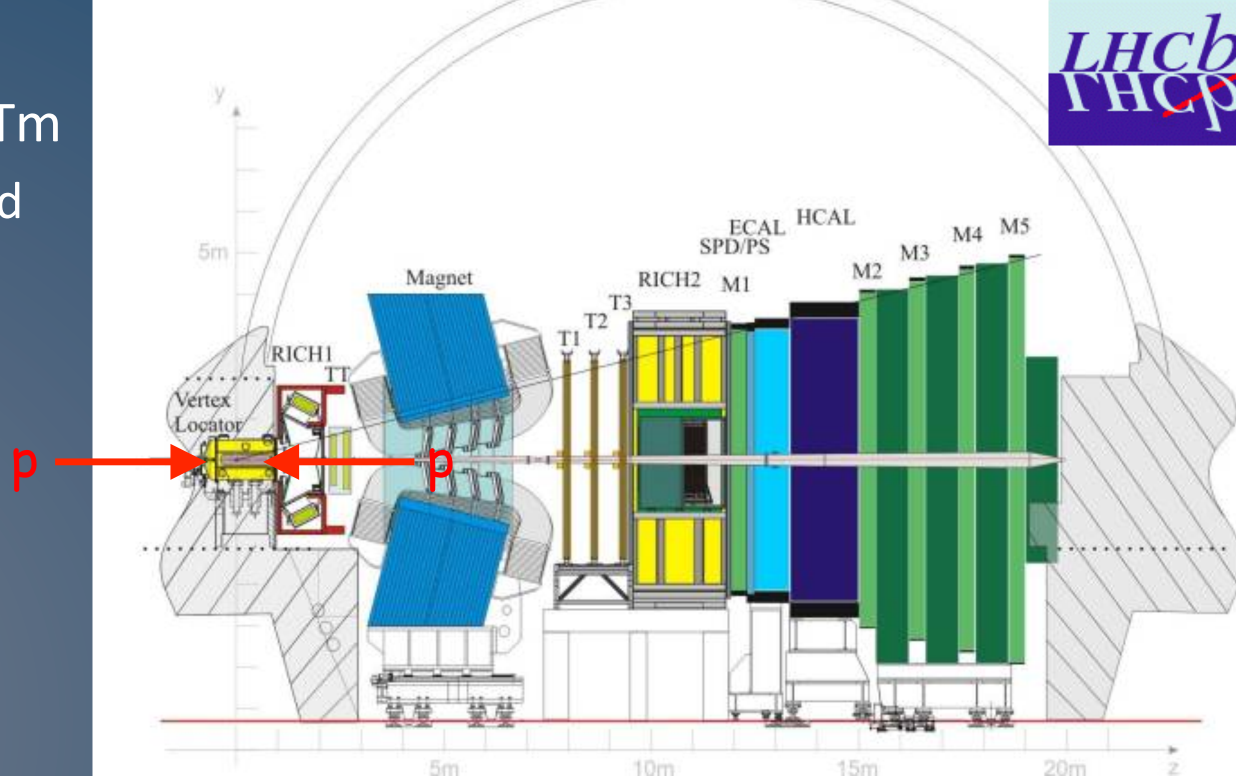
- Instantaneous luminosity limited to ~4×10^{32} s^{-1} cm^{-2} → Clean events
- Integrated luminosity in LHC Run 1
  - 2011 pp √s=7 TeV L = 1 fb^{-1}
  - 2012 pp √s=8 TeV L = 2 fb^{-1}





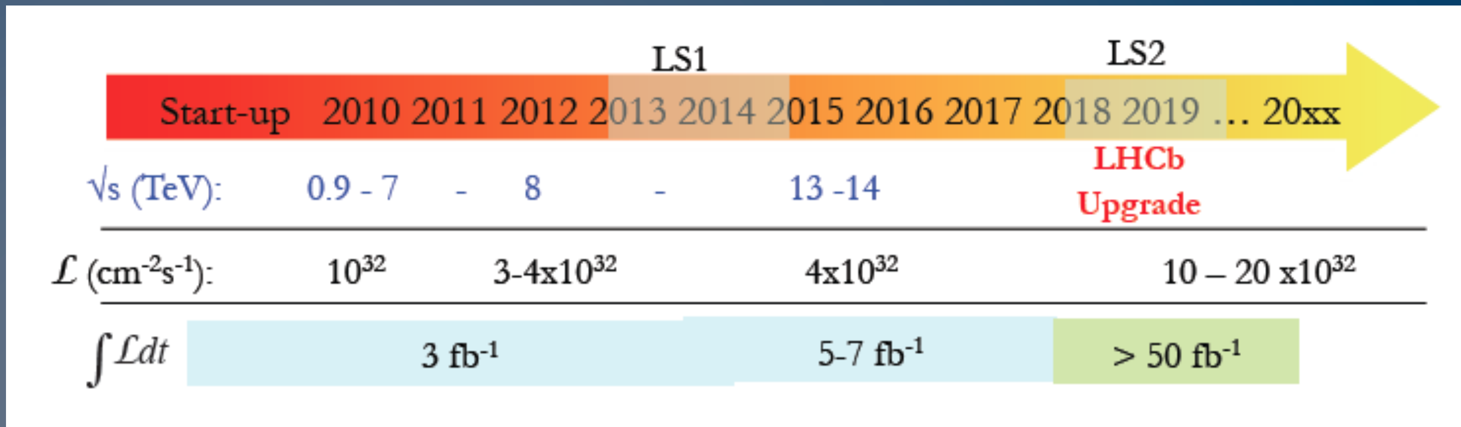


- Warm dipole magnet 4Tm
  - polarity can be reversed
- Excellent position and momentum resolution
  - ~20 μm for high p_T tracks
  - $\delta p/p = (0.4 - 0.6)$ %



- Excellent Particle Identification
  - ε(K ID) ~ 95% with 5% π mis-ID
  - ε(μ ID) ~ 97% with (1 - 3)% π mis-ID
- Versatile two stage trigger   40 MHz→ (3 - 4.5) kHz
  - ε(trigger) ~ 90% di-muon final states
  - ε(trigger) ~ 30% multi-body hadronic final states

Prospects: the LHCb upgrade



Observable	LHC run I	LHCb 2018	LHCb upgrade	Theory
ϕ_s ($B_s^0 \to J/\psi\,\phi$) (rad)	0.050	0.025	0.009	~ 0.003
ϕ_s ($B_s^0 \to J/\psi\, f_0(980)$) (rad)	0.068	0.035	0.012	~ 0.01
β ($B^0 \to J/\psi\, K_S^0$)	1.7°	0.8°	0.31°	negligible
ϕ_s^{eff} ($B_s^0 \to \phi\,\phi$) (rad)	0.15	0.10	**0.023**	0.02
ϕ_s^{eff} ($B_s^0 \to K^{*0}\,\overline{K}^{*0}$) (rad)	0.19	0.13	**0.029**	< 0.02
$2\beta^{eff}$ ($B^0 \to \phi\, K_S^0$) (rad)	0.30	0.20	**0.04**	0.02
γ ($B_s^0 \to D_s^{\pm} K^{\mp}$)	17°	11°	2.4°	negligible

"Impact of the LHCb upgrade detector design choices on physics and trigger performance"
LHCb-PUB-2014-040, to be published

ϕ_s from $B^0_s \rightarrow J/\psi\, K^+K^-$

$$\frac{d^4\Gamma(B^0_s \to J/\psi\phi)}{dt\, d\cos\theta_\mu\, d\varphi_h\, d\cos\theta_K} = f(\phi_s, \Delta\Gamma_s, \Gamma_s, \Delta m_s, M(B^0_s), |A_\perp|, |A_\parallel|, |A_S|, \delta_\perp, \delta_\parallel, \ldots)$$

Parameter	Value
Γ_s [ps^{-1}]	$0.6603 \pm 0.0027 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0805 \pm 0.0091 \pm 0.0032$
$\lvert A_\perp\rvert^2$	$0.2504 \pm 0.0049 \pm 0.0036$
$\lvert A_0\rvert^2$	$0.5241 \pm 0.0034 \pm 0.0067$
$\delta_\parallel$ [rad]	$3.26\ ^{+0.10}_{-0.17}\ ^{+0.06}_{-0.07}$
$\delta_\perp$ [rad]	$3.08\ ^{+0.14}_{-0.15} \pm 0.06$
ϕ_s [rad]	$-0.058 \pm 0.049 \pm 0.006$
$\lvert\lambda\rvert$	$0.964 \pm 0.019 \pm 0.007$
Δm_s [ps^{-1}]	$17.711\ ^{+0.055}_{-0.057} \pm 0.011$

Table 3: Statistical and systematic uncertainties for the polarisation-independent result.

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_\perp\rvert^2$	$\lvert A_0\rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\lvert\lambda\rvert$	Δm_s [ps^{-1}]
Total stat. uncertainty	0.0027	0.0091	0.0049	0.0034	$^{+0.10}_{-0.17}$	$^{+0.14}_{-0.15}$	0.049	0.019	$^{+0.055}_{-0.057}$
Mass factorisation	–	0.0007	0.0031	0.0064	0.05	0.05	0.002	0.001	0.004
Signal weights (stat.)	0.0001	0.0001	–	0.0001	–	–	–	–	–
b-hadron background	0.0001	0.0004	0.0004	0.0002	0.02	0.02	0.002	0.003	0.001
B_c^+ feed-down	0.0005	–	–	–	–	–	–	–	–
Angular resolution bias	–	–	0.0006	0.0001	$^{+0.02}_{-0.03}$	0.01	–	–	–
Ang. efficiency (reweighting)	0.0001	–	0.0011	0.0020	0.01	–	0.001	0.005	0.002
Ang. efficiency (stat.)	0.0001	0.0002	0.0011	0.0004	0.02	0.01	0.004	0.002	0.001
Decay-time resolution	–	–	–	–	–	0.01	0.002	0.001	0.005
Trigger efficiency (stat.)	0.0011	0.0009	–	–	–	–	–	–	–
Track reconstruction (simul.)	0.0007	0.0029	0.0005	0.0006	$^{+0.01}_{-0.02}$	0.002	0.001	0.001	0.006
Track reconstruction (stat.)	0.0005	0.0002	–	–	–	–	–	–	0.001
Length and momentum scales	0.0002	–	–	–	–	–	–	–	0.005
S-P coupling factors	–	–	–	–	0.01	0.01	–	0.001	0.002
Fit bias	–	–	0.0005	–	–	0.01	–	0.001	–
Quadratic sum of syst.	0.0015	0.0032	0.0036	0.0067	$^{+0.06}_{-0.07}$	0.06	0.006	0.007	0.011

ϕ_s from $B^0_s \rightarrow J/\psi K^+K^-$

Parameter	Value
$\lvert\lambda^0\rvert$	$1.012 \pm 0.058 \pm 0.013$
$\lvert\lambda^{\parallel}/\lambda^0\rvert$	$1.02 \pm 0.12 \pm 0.05$
$\lvert\lambda^{\perp}/\lambda^0\rvert$	$0.97 \pm 0.16 \pm 0.01$
$\lvert\lambda^{S}/\lambda^0\rvert$	$0.86 \pm 0.12 \pm 0.04$
ϕ_s^0 [rad]	$-0.045 \pm 0.053 \pm 0.007$
$\phi_s^{\parallel} - \phi_s^0$ [rad]	$-0.018 \pm 0.043 \pm 0.009$
$\phi_s^{\perp} - \phi_s^0$ [rad]	$-0.014 \pm 0.035 \pm 0.006$
$\phi_s^{S} - \phi_s^0$ [rad]	$0.015 \pm 0.061 \pm 0.021$

Table 4: Statistical and systematic uncertainties for the polarisation-dependent result.

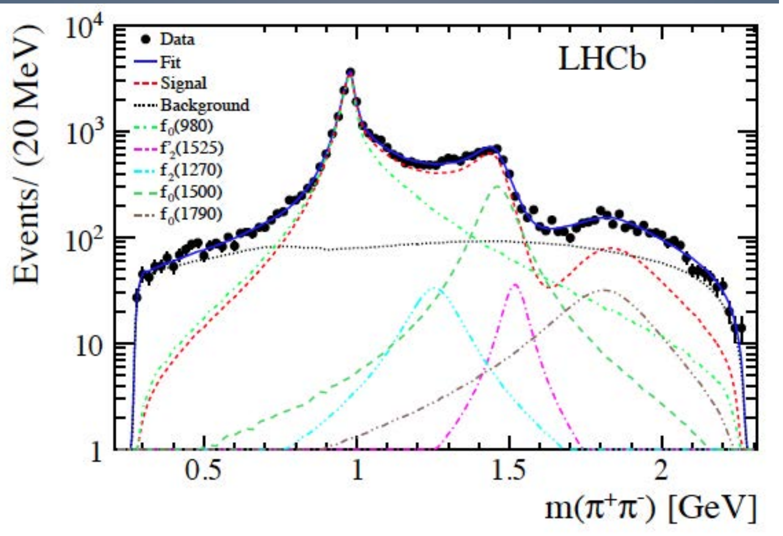
Source	$\lvert\lambda^0\rvert$	$\lvert\lambda^{\parallel}/\lambda^0\rvert$	$\lvert\lambda^{\perp}/\lambda^0\rvert$	$\lvert\lambda^{S}/\lambda^0\rvert$	ϕ_s^0 [rad]	$\phi_s^{\parallel} - \phi_s^0$ [rad]	$\phi_s^{\perp} - \phi_s^0$ [rad]	$\phi_s^{S} - \phi_s^0$ [rad]
Total stat. uncertainty	0.058	0.12	0.16	0.12	0.053	0.043	0.035	0.061
Mass factorisation	0.010	0.04	0.01	0.03	0.003	0.005	0.003	0.016
b-hadron background	0.002	0.01	–	0.01	0.003	0.001	0.001	0.009
Ang. efficiency (reweighting)	–	–	–	0.02	0.001	0.002	0.001	0.007
Ang. efficiency (stat.)	0.004	0.02	0.01	0.01	0.004	0.007	0.005	0.004
Decay-time resolution	0.006	0.01	–	0.01	0.003	0.002	0.001	0.002
S-P coupling factors	–	–	–	–	–	–	–	0.006
Quadratic sum of syst.	0.013	0.05	0.01	0.04	0.007	0.009	0.006	0.021

$B^0_s \rightarrow J/\psi\ \pi^+\pi^-$ amplitude analysis

- An amplitude analysis allows a precise study of CP content
  - Decay described by five interfering states:

    $f_0(980)$ dominant, $f_2(1270)$, $f_0(1500)$, $f'_2(1525)$, $f_0(1790)$
  - CP-odd > 97.7% at 95% CL

(PRD89 (2014)092006)

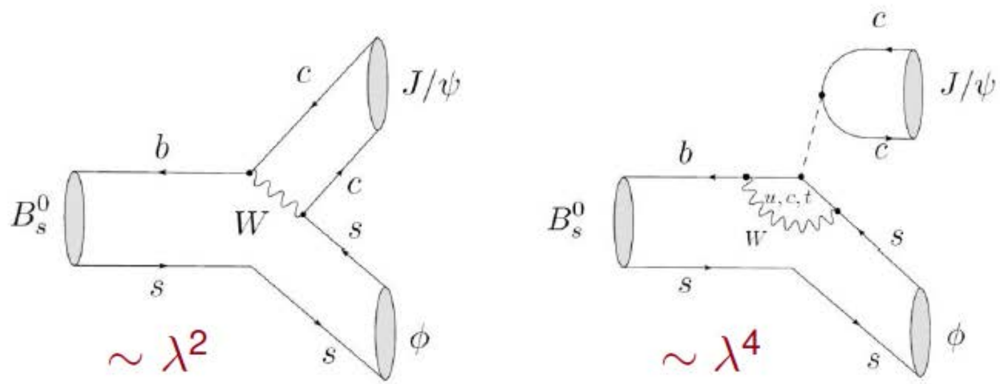


Fit fractions (%) of contributing components for both solutions.

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

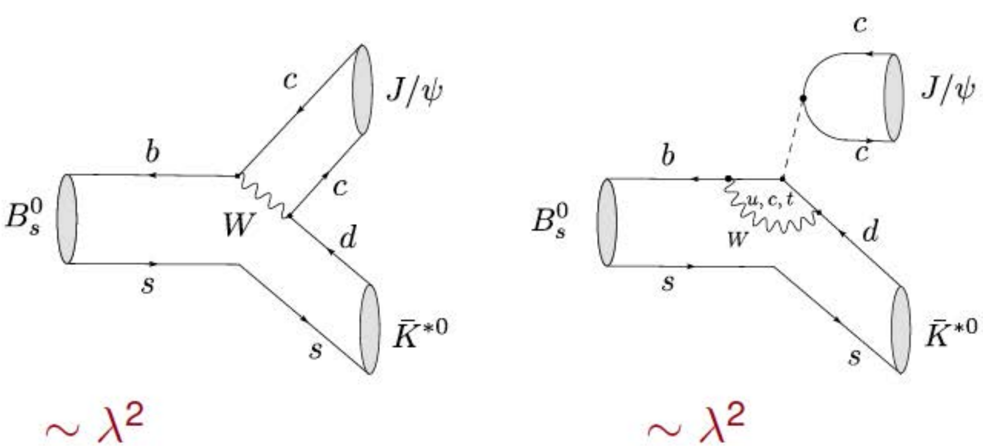
Penguin pollution to ϕ_s

- The main uncertainty to the SM prediction of ϕ_s is due to unknown penguin contributions $\phi_s^{SM} = -2\,\beta_s + \Delta\phi_s^{\,peng}$
- $B^0_s \rightarrow J/\psi\ K^{*0}$ bar decays can be used to estimate the contribution of penguin diagram to ϕ_s



$b \rightarrow c\bar{c}s$

penguins suppressed by λ^2 relative to tree

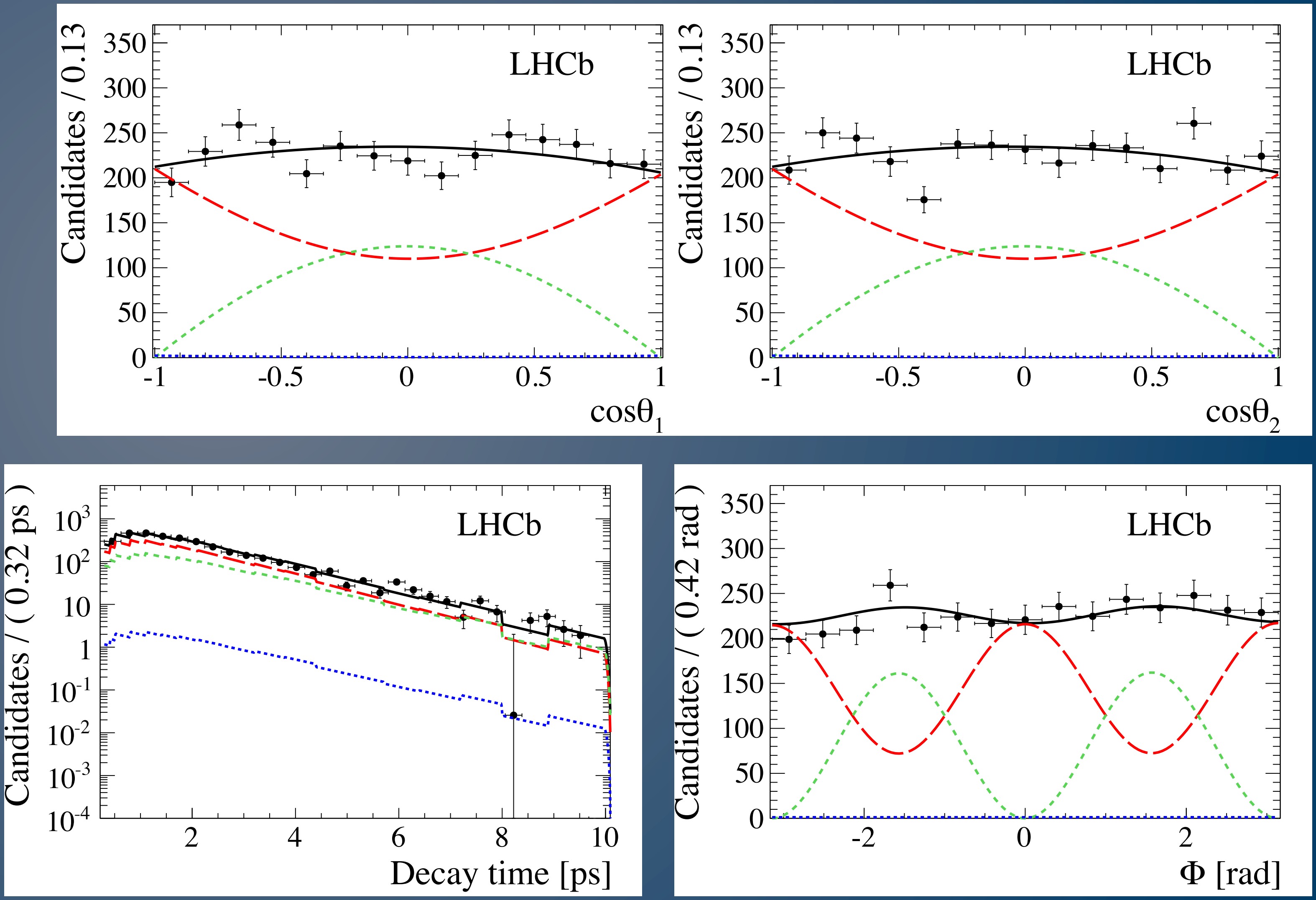


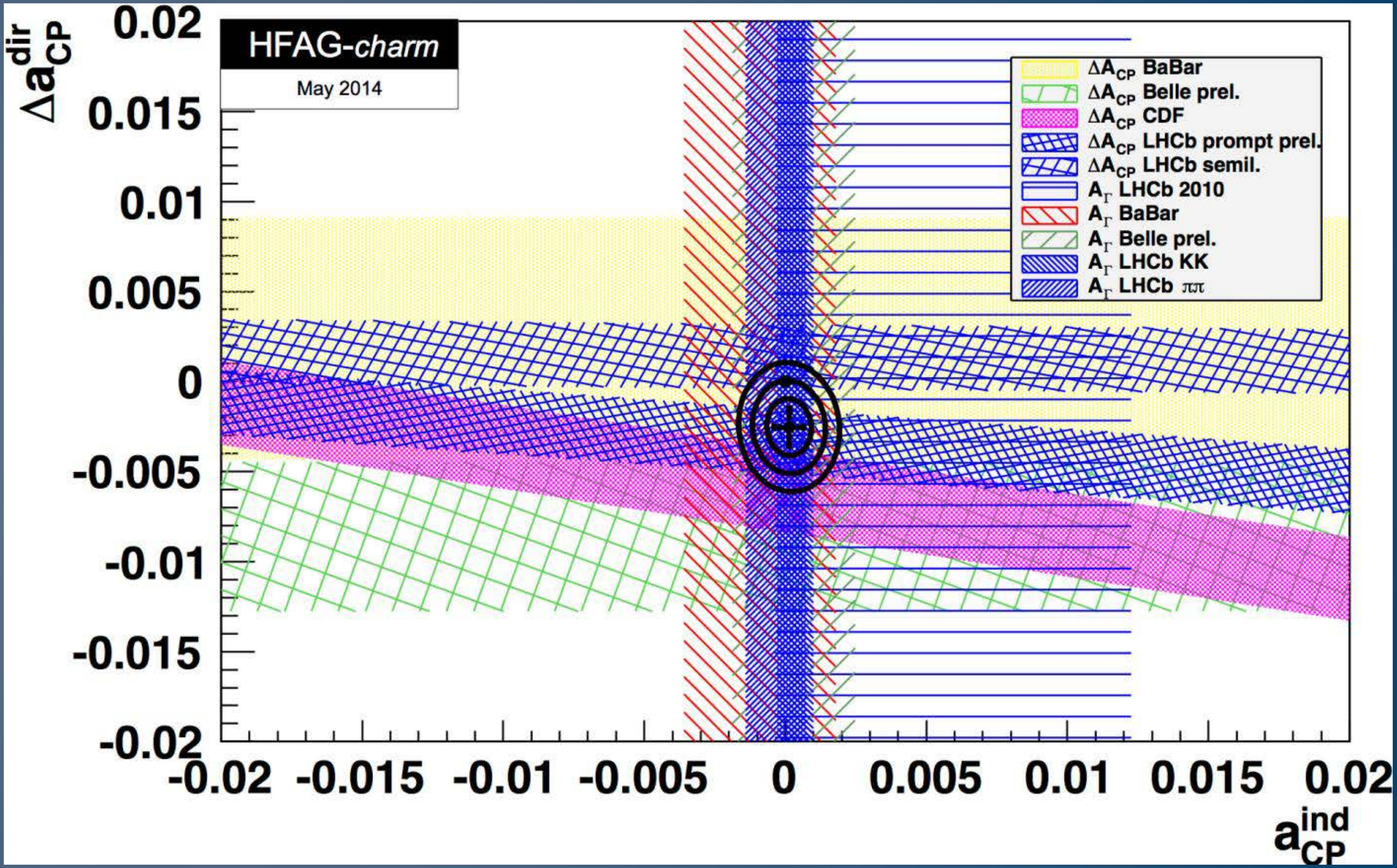
$b \rightarrow c\bar{c}d$

penguins are not suppressed relative to tree

$B^0_s \rightarrow \phi\phi$

$$\phi_s = -0.17 \pm 0.15\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})\ \mathrm{rad},$$
$$|\lambda| = 1.04 \pm 0.07\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst}).$$




HFAG-charm
May 2014
Δa_{CP}^{dir}
a_{CP}^{ind}
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
ΔA_{CP} BaBar
ΔA_{CP} Belle prel.
ΔA_{CP} CDF
ΔA_{CP} LHCb prompt prel.
ΔA_{CP} LHCb semil.
A_{Γ} LHCb 2010
A_{Γ} BaBar
A_{Γ} Belle prel.
A_{Γ} LHCb KK
A_{Γ} LHCb $\pi\pi$