LHCb实验上的 ϕ_s 测量

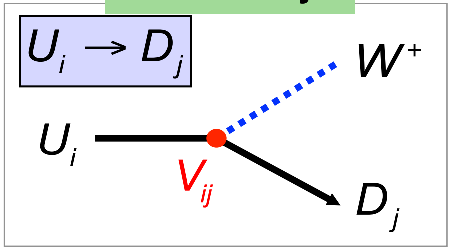
张黎明（清华大学）

2019.12.14

Source of CPV in SM

- *CPV* could happen when

Quark decays



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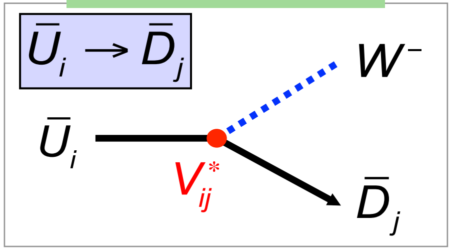
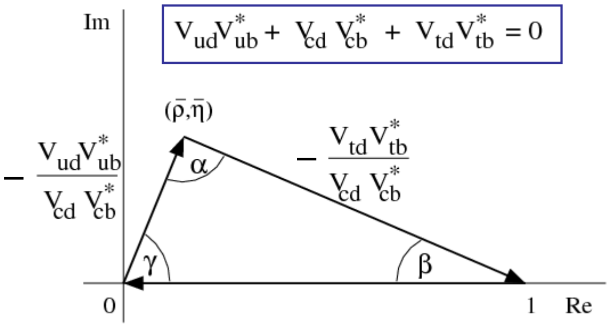
Anti-quark decays





- Wolfenstein parametrization (1983)

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} |V_{ud}| & |V_{us}| & e^{-i\gamma}|V_{ub}| \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ e^{-i\beta}|V_{td}| & -e^{-i\beta_s}|V_{ts}| & |V_{tb}| \end{pmatrix} + O\left(\lambda^5\right)$$

$\lambda \approx 0.23$

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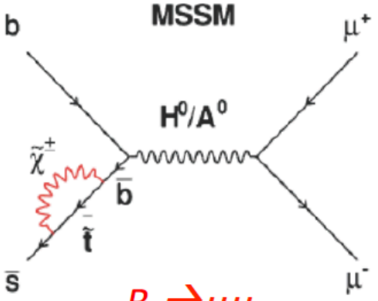
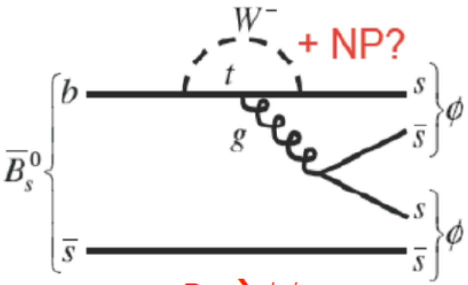
Precision measurements of CPV and rare decays: why important?

- Instead of searching for NP particles directly produced, look for their indirect effects to low energy processes (e.g. *b*-hadron decays)

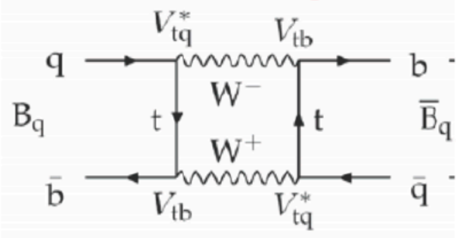


$B_s \to \mu\mu$



$B_s \to \phi\phi$

B-$\bar{B}$ mixing



+ NP?

- In presence of sizeable SM contributions, NP effects might be hidden => need precision measurements
- NP may be more visible in these SM suppressed processes

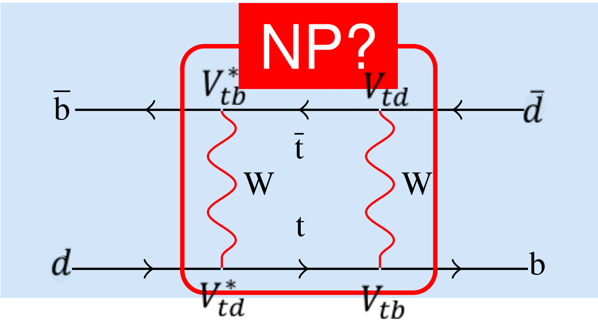
$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

- Studying CPV processes => two fundamental tasks can be accomplished
  - Identify new symmetries (and their breaking) beyond the SM
  - Probe mass scales not accessible directly at nowadays colliders

Neutral B mixing

Weak states mix via box diagram： flavour oscillation

$$|B_q\rangle = |\bar{b}q\rangle$$



$$|\bar{B}_q\rangle = |b\bar{q}\rangle$$

$$q = d, s$$

Mass eigenstates

$\Delta m_q = m_{\rm H} - m_{\rm L}, \Delta\Gamma_q = \Gamma_{\rm H} - \Gamma_{\rm L}$

$$|B_L^q\rangle = p|B_q\rangle + q|\bar{B}_q\rangle$$

$$|B_H^q\rangle = p|B_q\rangle - q|\bar{B}_q\rangle$$

CPV observables

- Interference between direct decay and decay via mixing →
- Mixing-induced CPV: $\phi_s, \phi_d = 2\beta$

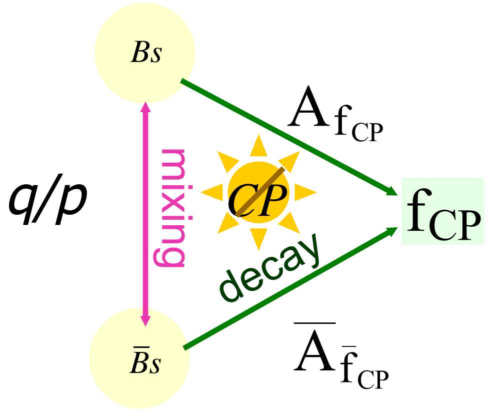
ϕ_q and Δm_q are very sensitive to NP in mixing

$$\begin{tikzcd}
\bar{B}^0_s \arrow[rr, "\phi_{\rm dec}"] \arrow[dr, "\phi_{\rm mix}"'] & & f \\
& B^0_s \arrow[ur, "-\phi_{\rm dec}"'] &
\end{tikzcd}$$

ϕ_s: a crucial goal of LHCb

10% of b-hadrons in pp collisions are B_s^0 mesons!

Measuring B_s^0 CPV is LHC(b) territory.



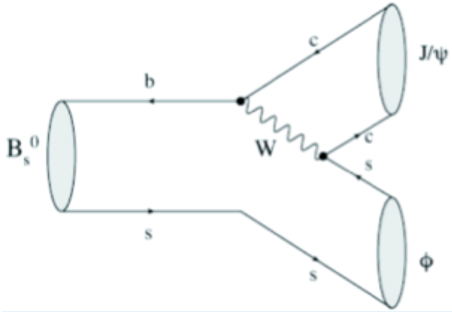
For $b \to c\bar{c}s$ decay such as $B_s^0 \to J/\psi h^+h^- \; (h = K, \pi)$

$$\boxed{\phi_s = -\arg(\eta_f \lambda); \;\; \lambda = \frac{q}{p}\frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}}$$

ϕ_s is precisely predicted in SM

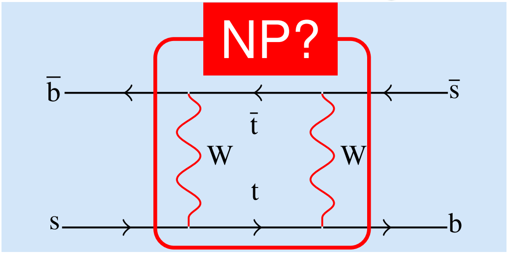
$\phi_s^{SM} = -2\beta_s = -37 \pm 1 \text{ mrad} = (2.11 \pm 0.06)^\circ$

(up to small correction for penguins)



ϕ_s is very sensitive to NP in mixing

$$\phi_s = \phi_s^{SM} + \Delta\phi^{NP}$$



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Analysis strategy of $B_s^0 \to J/\psi\phi$

- Theoretical time-dependent CP asymmetry

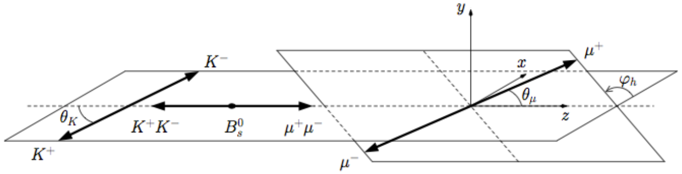
$$A_{\mathrm{CP}} \equiv \frac{\Gamma\left(\overline{B}_s^0 \to f\right) - \Gamma\left(B_s^0 \to f\right)}{\Gamma\left(\overline{B}_s^0 \to f\right) + \Gamma\left(B_s^0 \to f\right)} = \eta_f \sin\phi_s \sin(\Delta m_s t)$$

- From flavour tagged time-dependent angular analysis

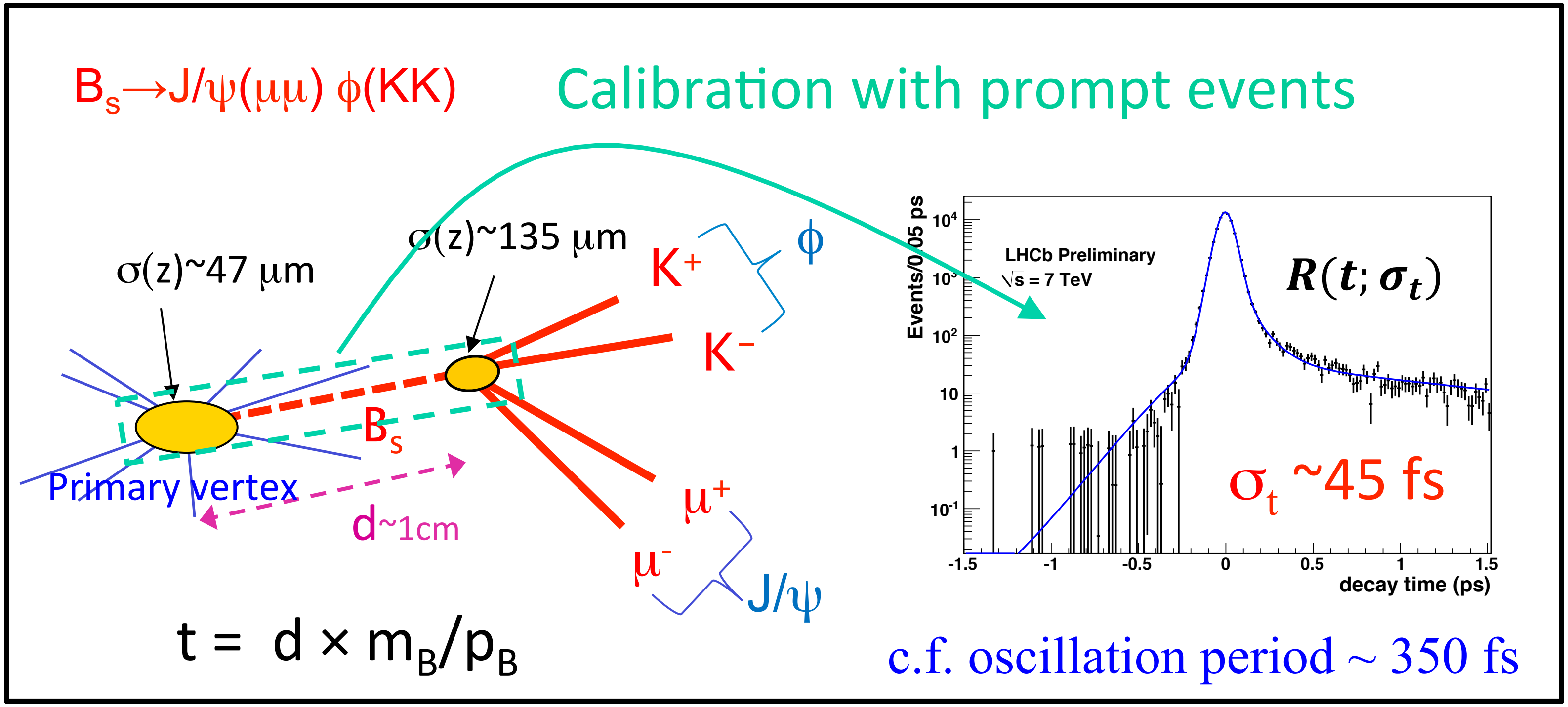
$$A_{\mathrm{CP}} \approx (1-2w)e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2}\eta_f \sin\phi_s \sin(\Delta m_s t)$$

Requirements

- Good performance to tag initial flavour of B_s^0
- Good time resolution to resolve fast B_s^0 oscillation and determine Δm_s
- Angular analysis to separate CP eigenstates



Decay time resolution



$B_s \to J/\psi(\mu\mu)\ \phi(KK)$

Calibration with prompt events

σ_t ~45 fs

$t = d \times m_B/p_B$

c.f. oscillation period ~ 350 fs

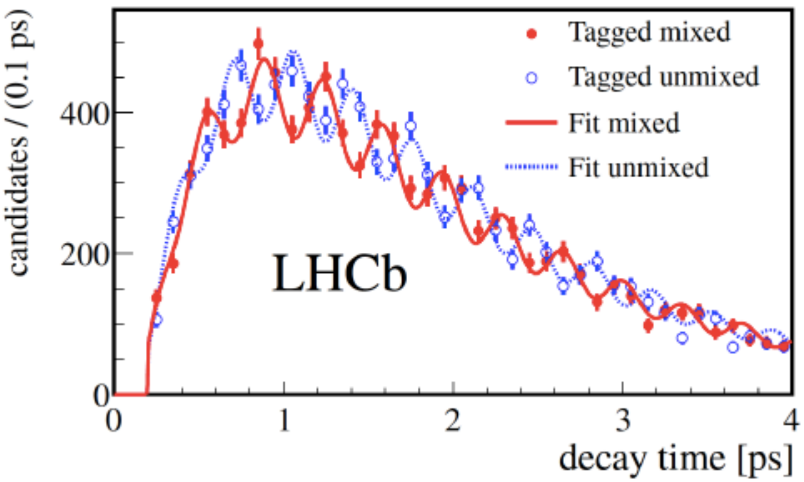
Impact of decay time resolution， $\Delta m_s \approx 17.7\ \text{ps}^{-1}$

- If σ_t = 45 fs, dilution factor $\exp(-\Delta m_s^2 \sigma_t^2/2) \approx$ 0.73 (improved 5-10% in run3)
- If σ_t = 90 fs, dilution factor $\exp(-\Delta m_s^2 \sigma_t^2/2) \approx$ 0.28

$\Delta m_{s/d}$ measurements

$B_s^0 \to D_s^- \pi^+$ (1 fb^{-1})

LHCb, New J.Phys. 15 (2015) 053201

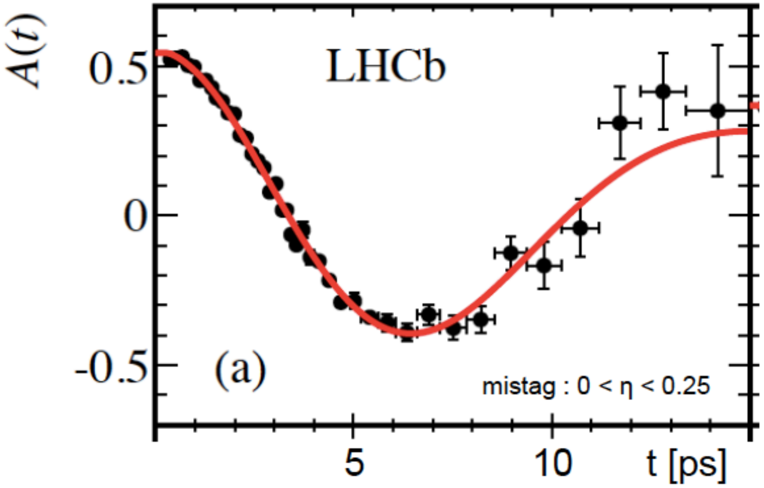


$$\Delta m_s = (17.768 \pm 0.023 \pm 0.006)\ \mathrm{ps}^{-1}$$

SM: Δm_s = 16.3 ± 1.1 ps^{-1}

$B^0 \to D^{(*)-}\mu^+\nu$ (3 fb^{-1})

LHCb, EPJC 76 (2016) 412



$$\Delta m_d = (0.5050 \pm 0.0021 \pm 0.0010)\ \mathrm{ps}^{-1}$$

SM: $\Delta m_d = 0.566^{+0.035}_{-0.043}$ ps^{-1}

SM predictions suffer large uncertainties in Lattice QCD calculation of hadronic parameters (theory inputs?)

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Tagging the initial flavour

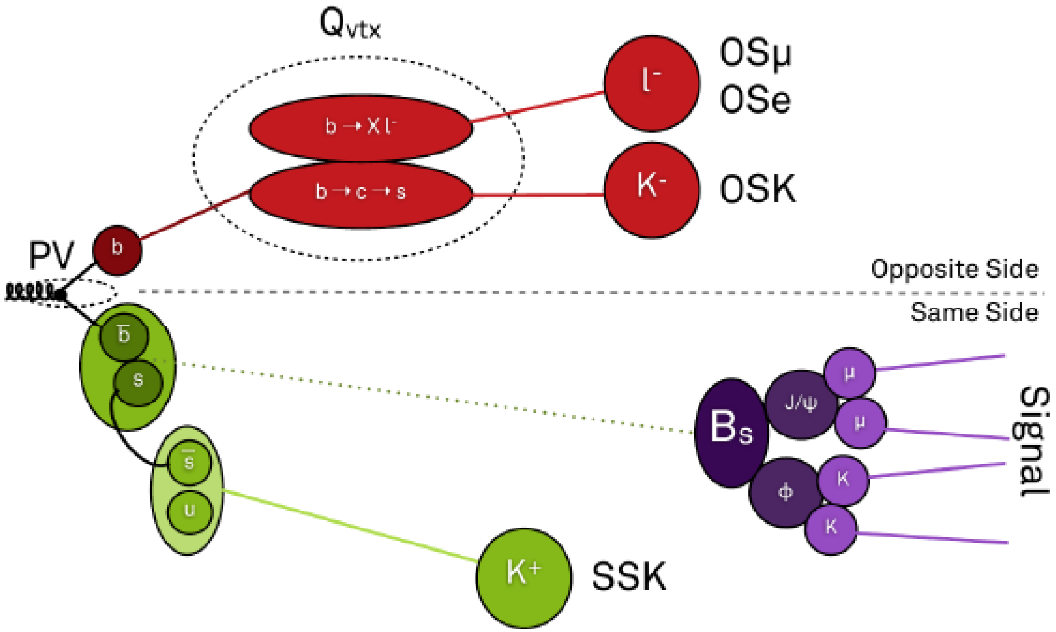
Opposite side (OS): using charges of decay products of the other B hadron

LHCb, EPJC 72 (2012) 2022

Same side (SS): using charges of particles produced in association with the signal B

LHCb, JINST 11 (2016) P05010

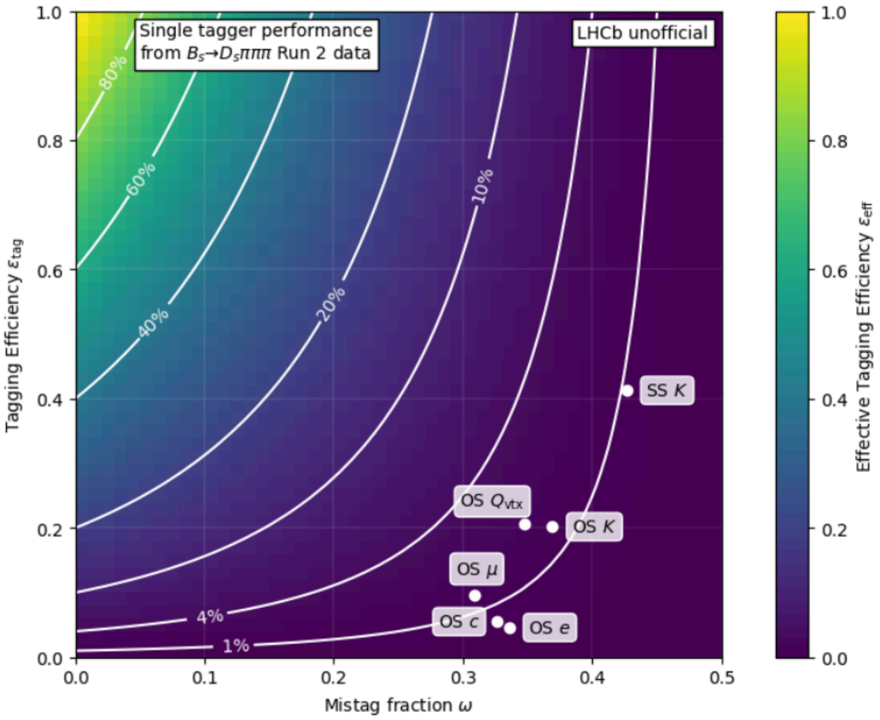
category	Effective εD^2 （%）
only OS tagged	0.88 ± 0.04
only SS tagged	1.38 ± 0.30
OS&SS tagged	2.47 ± 0.15
Total	4.73 ± 0.34

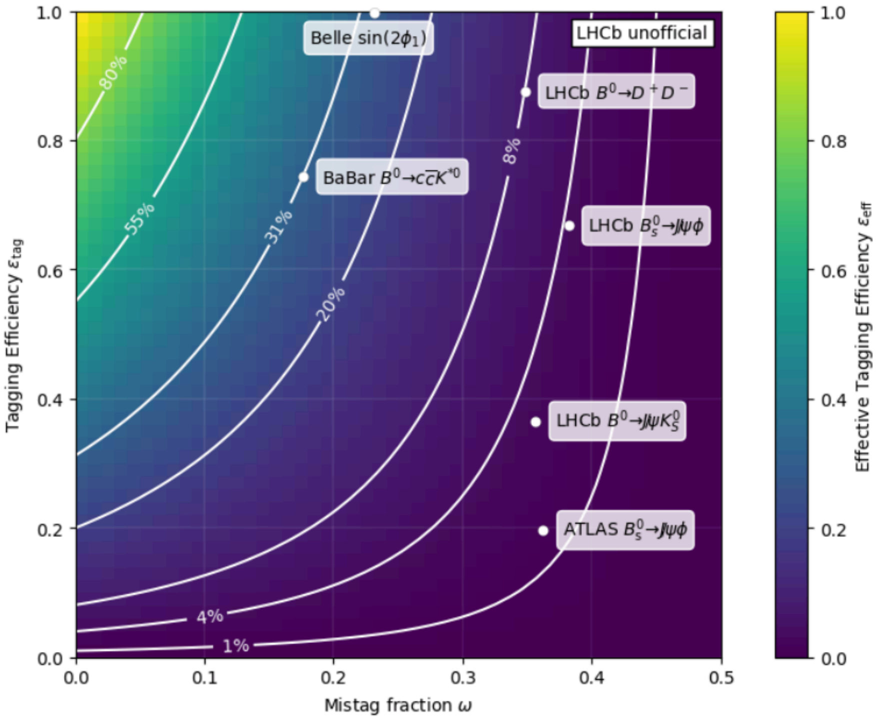


Tagging performance

Kevin Heinicke

gitlab.cern.ch/kheinick/ft-contour-plot





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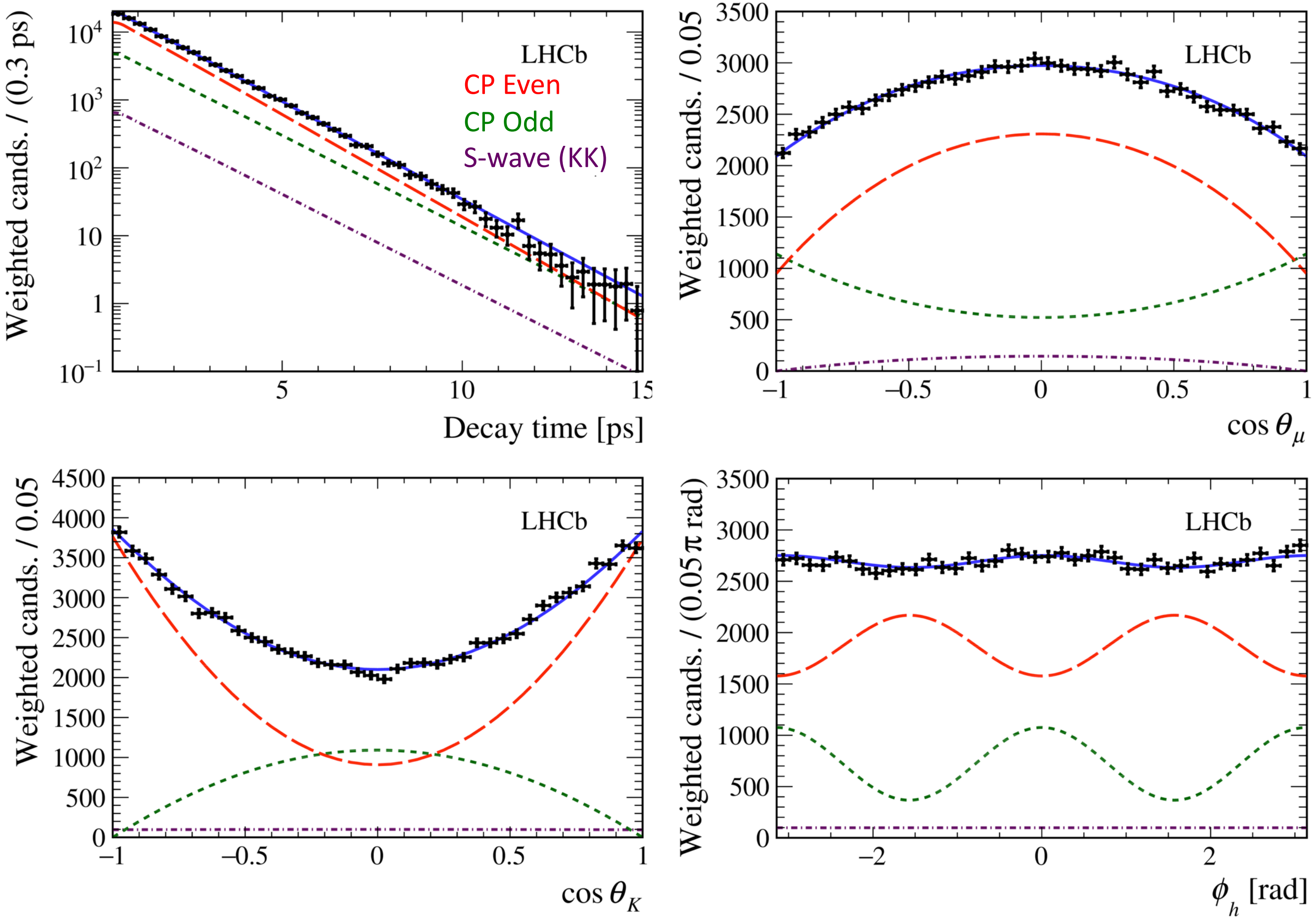
Time-dependent angular analysis of $B_s^0 \to J/\psi\phi$

[EPJC 79 (2019) 706]



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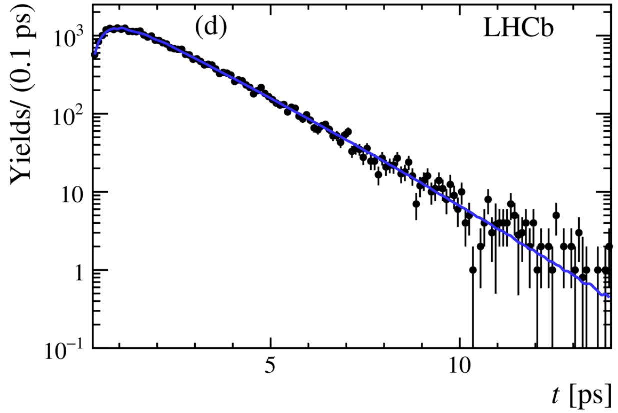
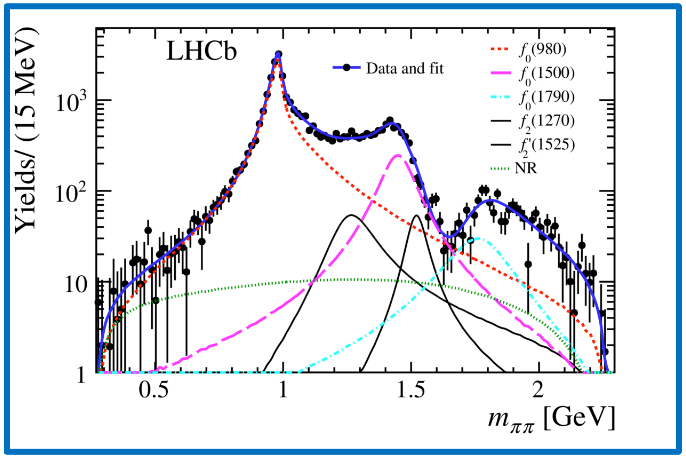
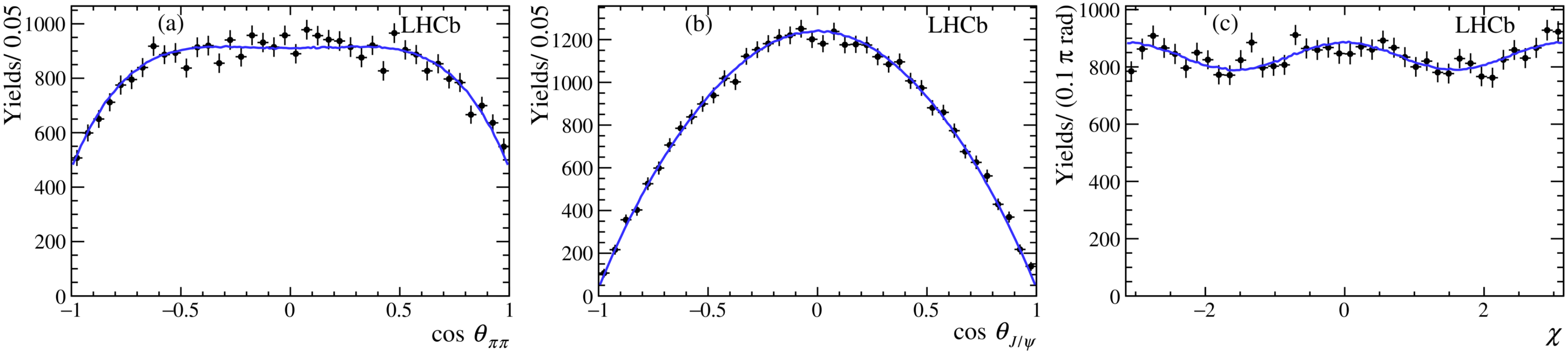
Time-dependent amplitude analysis of $B_s^0 \to J/\psi\pi^+\pi^-$

- Simultaneous fit $m_{\pi\pi}$ to separate $\pi\pi$ resonances **[LZ,SS, PLB 719 (2013) 383]**
- Better sensitivity per # of signal
  - Final state is almost pure CP-odd (>97%)







Recent results

5 fb^{-1}

$B_s^0 \to J/\psi K^+K^-$ [EPJC 79 (2019) 706]

$$\phi_s = -0.080 \pm 0.032 \text{ rad}$$
$$|\lambda| = 0.993 \pm 0.013$$
$$\Gamma_s = 0.6570 \pm 0.0023 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0784 \pm 0.0062 \text{ ps}^{-1}$$

$B_s^0 \to J/\psi \pi^+\pi^-$ [PLB 797(2019) 134789]

$$\phi_s = 0.002 \pm 0.044 \pm 0.012 \text{ rad}$$
$$|\lambda| = 0.949 \pm 0.036 \pm 0.019$$
$$\Gamma_H - \Gamma_{B^0} = -0.050 \pm 0.004 \pm 0.004 \text{ ps}^{-1}$$

Combination of all LHCb (Run I+II) results

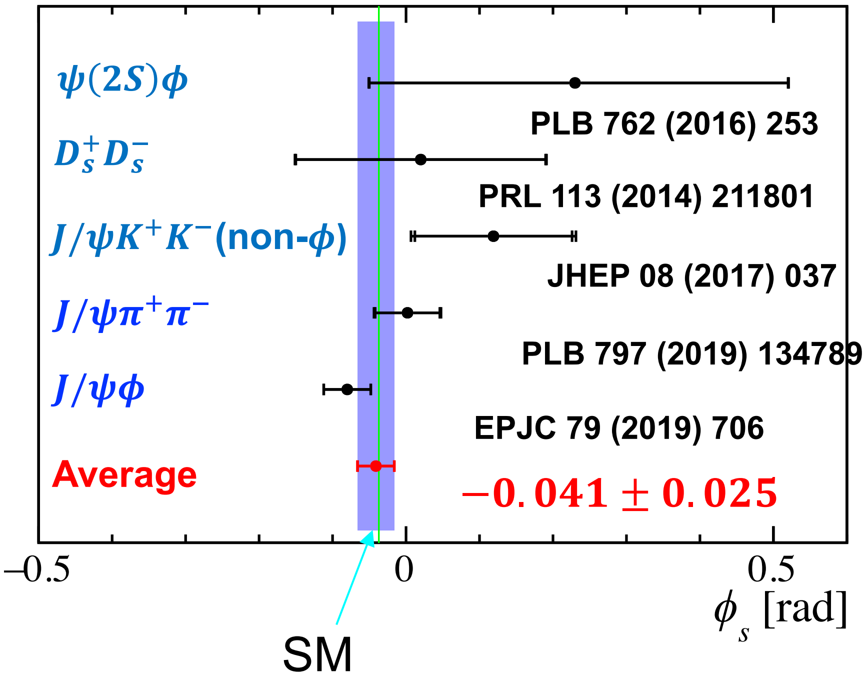
Statistics dominated

[EPJC 79 (2019) 706]

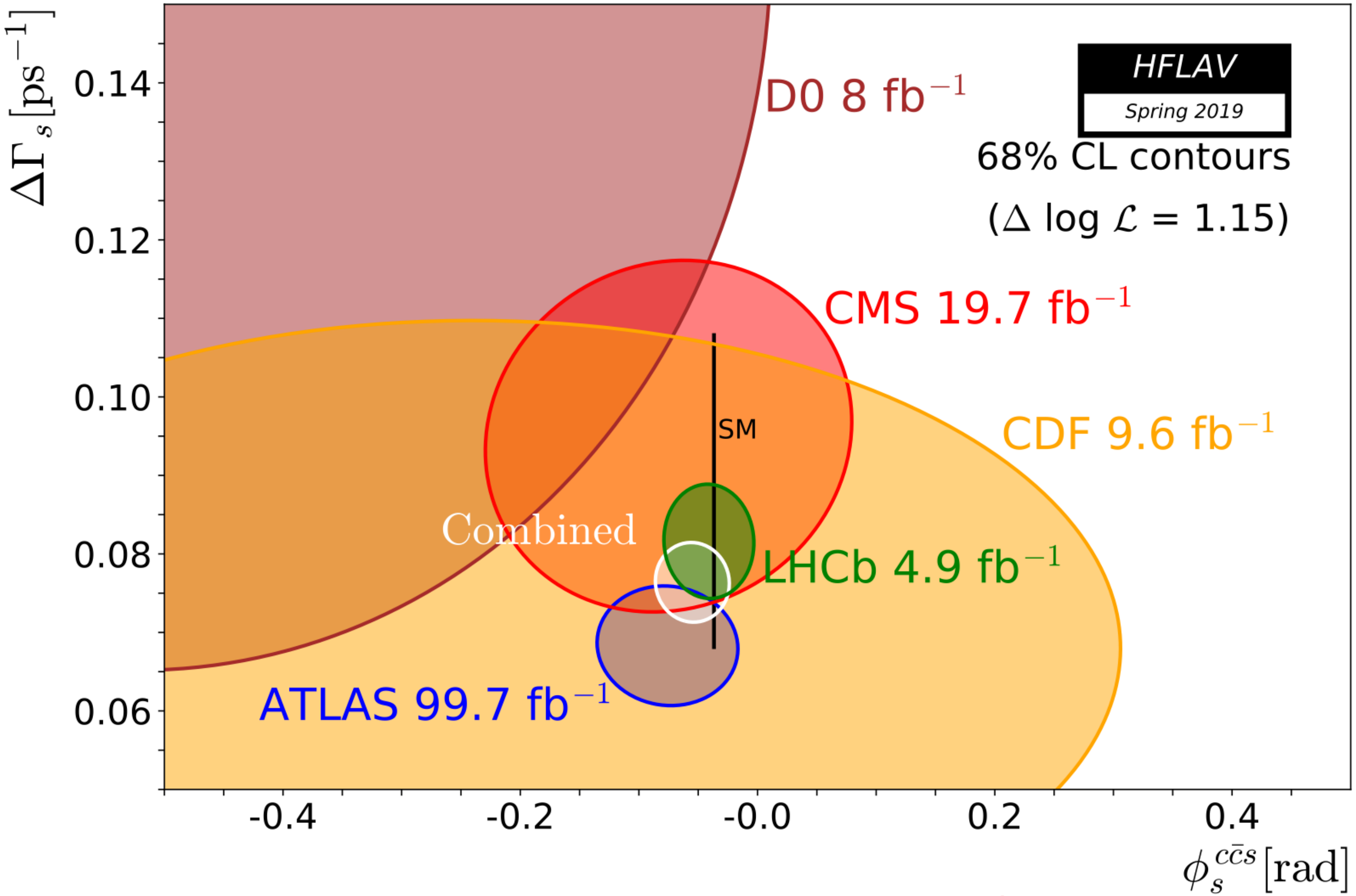
$$\boldsymbol{\phi_s = -0.041 \pm 0.025} \textbf{ rad}$$
$$|\lambda| = 0.993 \pm 0.010$$
$$\Gamma_s = -0.6562 \pm 0.0021 \text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.0816 \pm 0.0048 \text{ps}^{-1}$$

3 fb^{-1}

5 fb^{-1}



World Average



WA: $\boldsymbol{\phi_s = -0.055 \pm 0.021}$ rad

$\phi_s^{SM} = -2\beta_s$ = -37 ± 1 mrad = $(2.11 \pm 0.06)^\circ$

(up to small correction for penguins)

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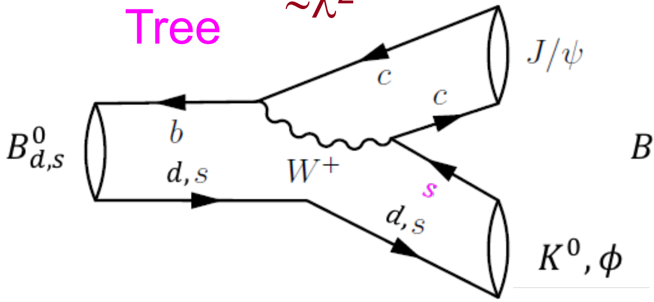
Penguin pollution

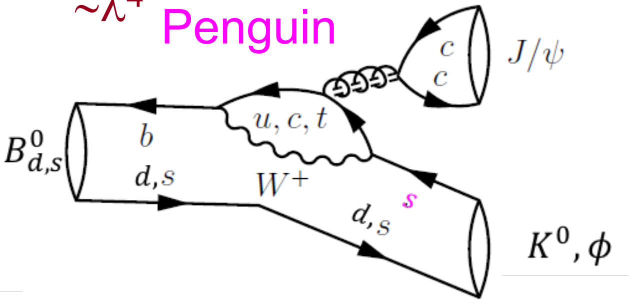
- Small pollution to SM predictions of ϕ_d and ϕ_s must be taken under control

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

~λ² Tree



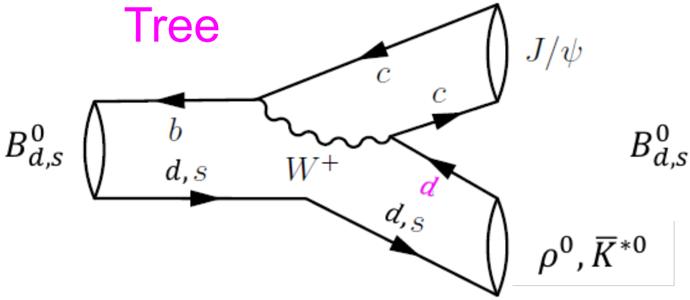
~λ⁴ Penguin



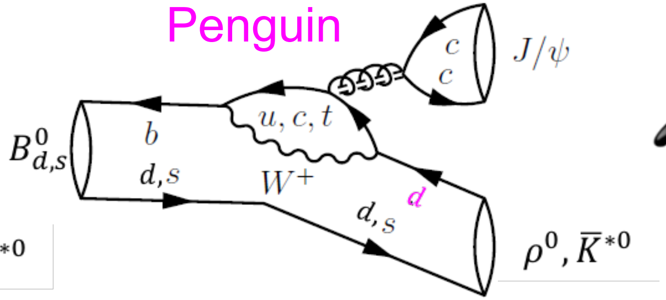
- Use penguin enhanced processes

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

~λ³ Tree



~λ³ Penguin



Penguin pollution in ϕ_s

Polarization dependent
$i \in \{0, \perp, \parallel\}$

- Penguin parameters definition:

$$A(B_s^0 \to (J/\psi\,\phi)_i) = \left(1 - \frac{\lambda^2}{2}\right) \mathcal{A}_i \left[1 + \epsilon a_i e^{i\theta_i} e^{i\gamma}\right]$$

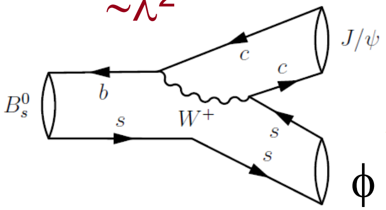
a_i: size of “Penguin / tree” ratio, θ_i: strong phase

“Penguin / tree” ratio is suppressed due to:

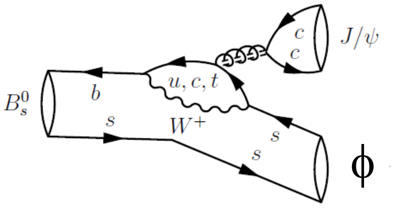
$\epsilon = \lambda^2/(1-\lambda^2)$=0.0536, $\lambda = |V_{us}| = 0.22$

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

$\sim\lambda^2$



$\sim\lambda^4$



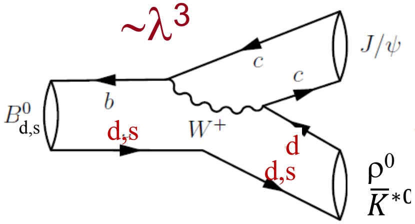
$$\sqrt{2}A(B^0 \to (J/\psi\,\rho^0)_i) = A(B_s^0 \to (J/\psi\,\overline{K}^{*0})_i) = -\lambda \mathcal{A}_i' \left[1 - a_i' e^{i\theta_i'} e^{i\gamma}\right]$$

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

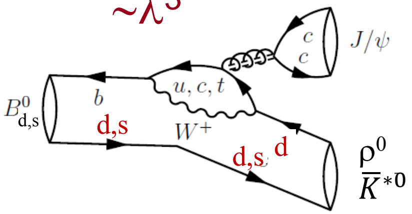
“Penguin / tree” ratio isn’t suppressed anymore

Ideal to study penguin contribution

$\sim\lambda^3$



$\sim\lambda^3$



Assuming perfect SU(3) flavor symmetry: $a_i' = a_i$, $\theta_i' = \theta_i$

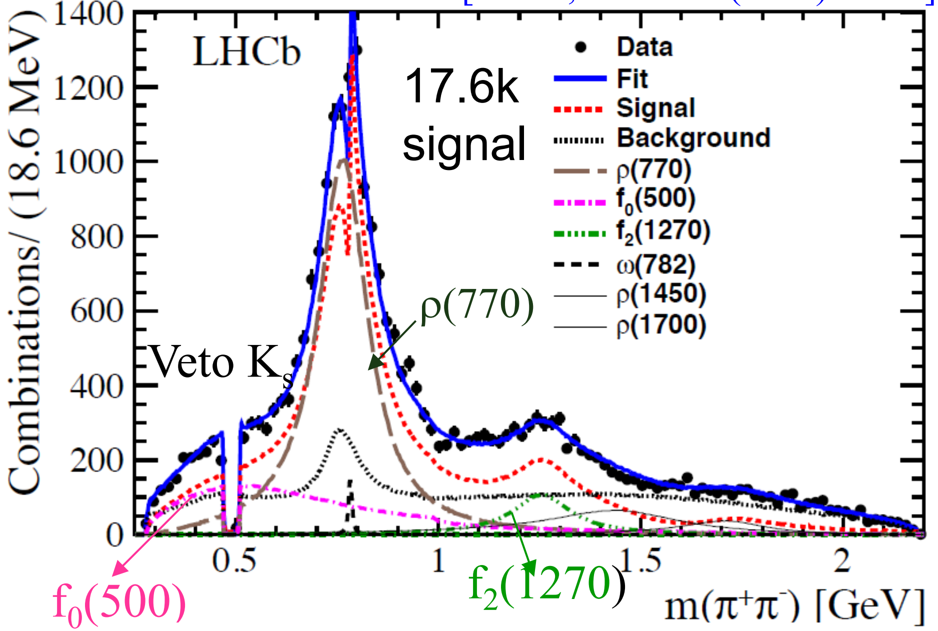
SU(3) breaking for a′ =a & θ ′ = θ need to considered

$B_d \to J/\psi\rho^0$

[LHCb, PLB 742 (2015) 38-49]

- P2VV decay to control penguin in ϕ_s
- Time-dependent amplitude fit to $B_d \to J/\psi\pi^+\pi^-$

$$2\beta^{J/\psi\rho} - 2\beta^{J/\psi K^0_S} = \left(-0.9 \pm 9.7^{+2.8}_{-6.3}\right)^\circ.$$



17.6k signal

ρ(770)

Veto K_s

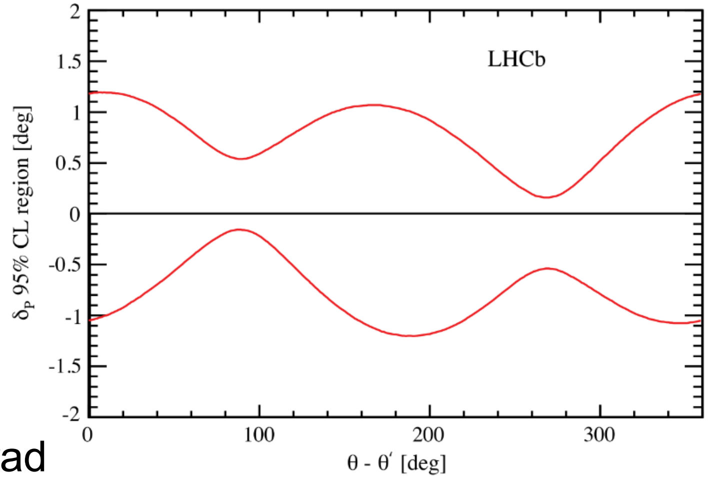
f_0(500)

f_2(1270)

- Penguin pollution in ϕ_s is small

[−18, +18] mrad @68.3% CL

for maximum breaking in phase and 0.5<a/a'<1.5

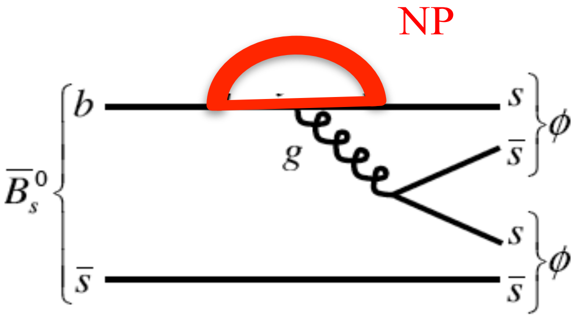


Smaller than ϕ_s experimental uncertainty ±21 mrad

CPV in loop decays

b→s penguin decay. Weak phase |ϕ|<0.02 in SM.
Can be affected by NP in decay and/or mixing.

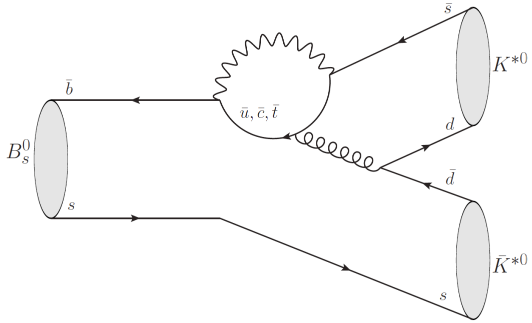
$B_s\to\phi\phi$



ϕ = -0.073 ± 0.115 ± 0.027 rad 5fb^{-1}

LHCb, arXiv:1907.10003

$B_s\to\overline{K}^{*0}K^{*0}$



ϕ = -0.10 ± 0.13 ± 0.14 rad 3.0fb^{-1}

LHCb, JHEP 03 (2018) 140

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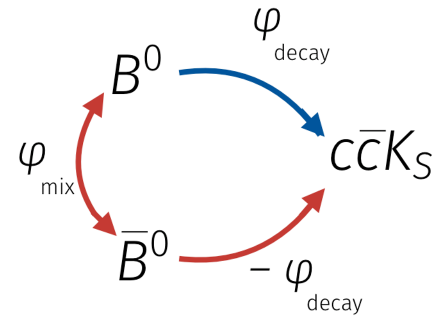
sin2β from $B^0 \to [c\bar{c}]K_S^0$

- Time dependent CP asymmetry

$$A_{[c\bar{c}]K_S^0}(t) = \frac{\bar{\Gamma}_{[c\bar{c}]K_S^0}(t) - \Gamma_{[c\bar{c}]K_S^0}(t)}{\bar{\Gamma}_{[c\bar{c}]K_S^0}(t) - \Gamma_{[c\bar{c}]K_S^0}(t)}$$
$$= \boldsymbol{S} \cdot \sin(\Delta m_d t) - \boldsymbol{C} \cdot \cos(\Delta m_d t)$$

$$\boldsymbol{S} = \frac{2Im(\lambda)}{1+|\lambda|^2} = \sqrt{1-C^2}\sin(2\beta) \approx \sin(2\beta)$$
$$\boldsymbol{C} = \frac{1-|\lambda|^2}{1+|\lambda|^2} \approx 0$$



$\varphi_{CP} = \varphi_{\text{mix}} - 2\varphi_{\text{decay}} \sim 2\beta$

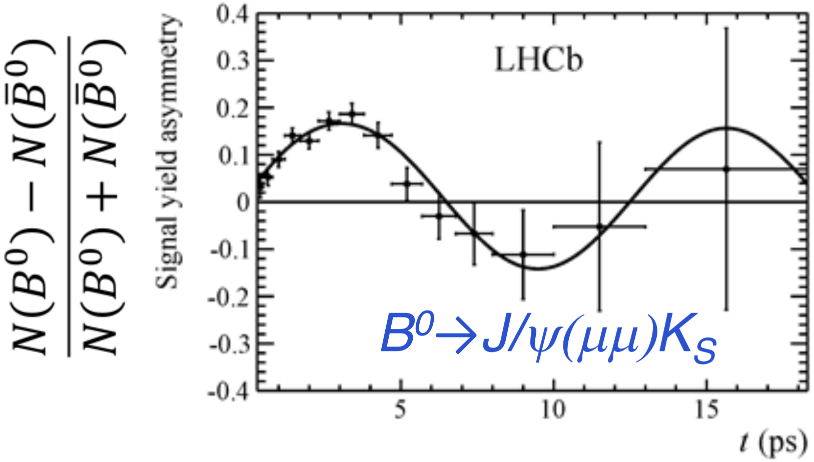
- Long term puzzle: ~2σ tension between indirect fit in SM and B-factory measurements
  - $\sin(2\beta)^{\text{SM}} = 0.738^{+0.027}_{-0.030}$ [CKMfitter’18]
  - $\sin(2\beta)^{\text{B-factory}} = 0.679 \pm 0.020$ [HFLAV’17]

$\sin 2\beta$ from $B^0 \to [c\bar{c}]K_s^0$

- LHCb precision approaches that of B factories [Run-I results]

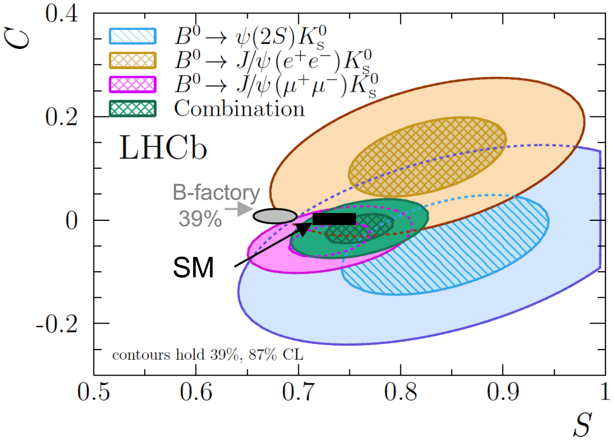
$c\bar{c}$	Tagged yields	Mass resolution	εD^2	Ref.
$J/\psi \to \mu^+\mu^-$	41,560	7 MeV	3.02%	PRL 115 (2015) 031601
$J/\psi \to e^+e^-$	10,630	29 MeV	**5.93%**	JHEP 11 (2017) 170
$\psi(2S) \to \mu^+\mu^-$	7,970	7 MeV	3.42%	

Precision will be further improved with Run-2 data



Measurements	$\sin 2\beta$
Indirect fit	$0.738^{+0.027}_{-0.030}$
B-factories	$\mathbf{0.679 \pm 0.020}$
LHCb	0.760 ± 0.034
World average	0.699 ± 0.017

2σ tension



Semi-leptonic asymmetries

Semi-leptonic asymmetry $a_{\rm sl}^{q}$ quantifies *CPV* in mixing.

$a_{\rm sl}^{q}$ is precisely predicted to be tiny in SM: ~*O*(10^{-4}), can be enhanced by NP

$$a_{\rm sl} = \frac{N(\bar{B}\to B \to f) - N(B\to\bar{B} \to \bar{f})}{N(\bar{B}\to B \to f) + N(B\to\bar{B} \to \bar{f})}$$

$$\begin{tikzcd} B^0_{\rm q} \arrow[rr] & & f \\ \overline{B^0_{\rm q}} \arrow[rr, "/" marking] \arrow[dr, bend right] & & f \\ & B^0_{\rm q} \arrow[ur, bend right] & \end{tikzcd}$$

(1) Measure time-integrated raw asymmetry

$$A_{\rm raw} = \frac{N(D_s^-\mu^+) - N(D_s^+\mu^-)}{N(D_s^-\mu^+) + N(D_s^+\mu^-)}$$

(2) Correct for detection asymmetry and background effect

$$a_{\rm sl}^{s} = \frac{2}{1-f_{\rm bkg}}(A_{\rm raw} - A_{\rm det} - f_{\rm bkg}A_{\rm bkg})$$

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For B_d, also correct for production asymmetry

LHCb results of a_{sl}^{q}

$B_s \to D_s^- \mu^+ \bar{\nu}$: $a_{\mathrm{sl}}^{s} = (0.39 \pm 0.26 \pm 0.20)\ \%$

LHCb, PRL 117 (2016) 061803

$B_d \to D^{(*)-} \mu^+ \bar{\nu}$: $a_{\mathrm{sl}}^{d} = (-0.02 \pm 0.19 \pm 0.30)\ \%$

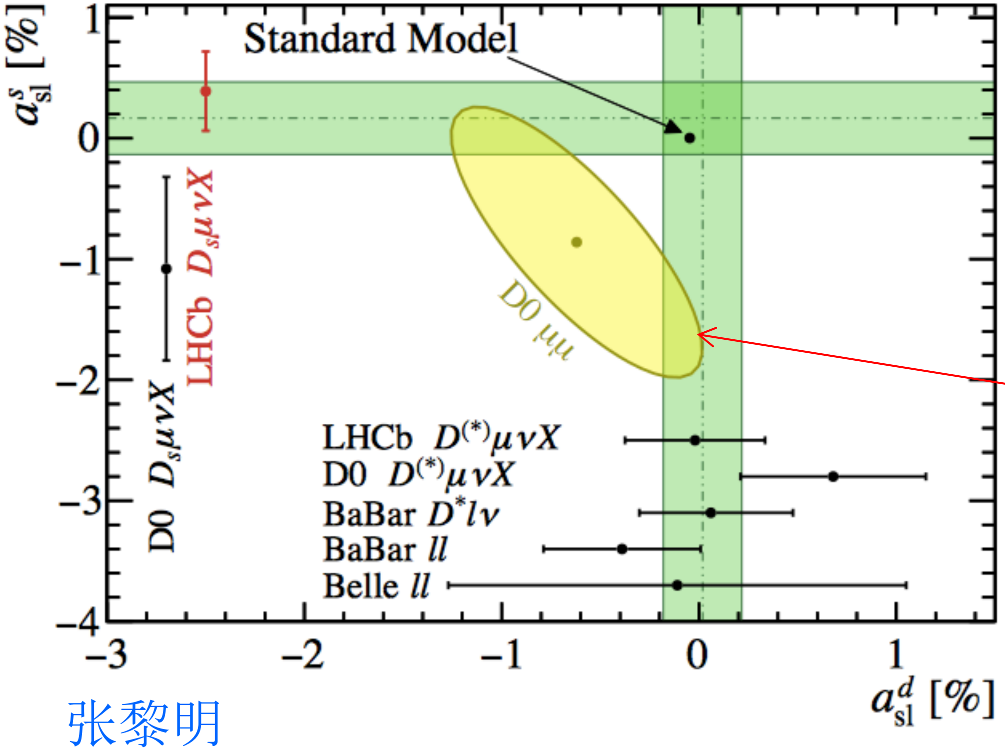
LHCb, PRL 114 (2014) 041601

SM predictions

A.Lenz
arXiv:1205.1444

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

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



Consistent with SM prediction & CP conservation

In tension with D0 dimuon asymmetry

$$A_{\mathrm{sl}}^{b} = c_1\, a_{\mathrm{sl}}^{d} + c_2\, a_{\mathrm{sl}}^{s} = (0.957 \pm 0.251 \pm 0.146)\%$$

D0, PRL 105 (2010) 081801

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Tagging performance in run-3

- **Degradation of tagging because pipe-up introduce PV misassociation?**
- **Improved tagging would benefit all time-dependent analyses**

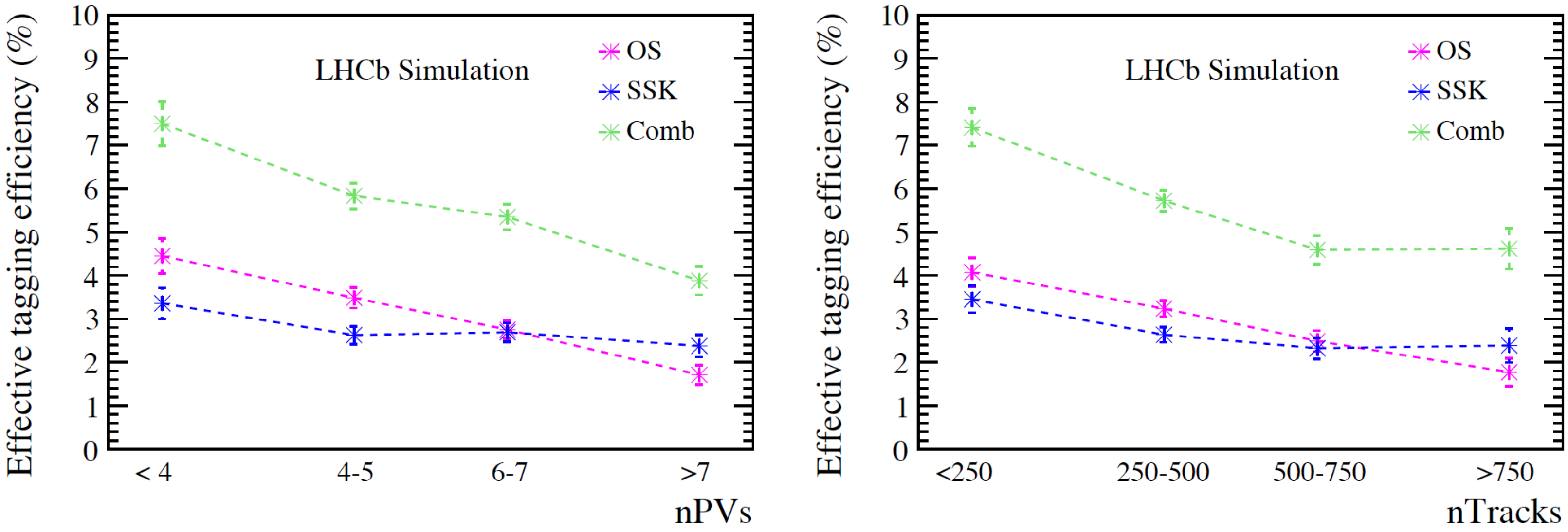
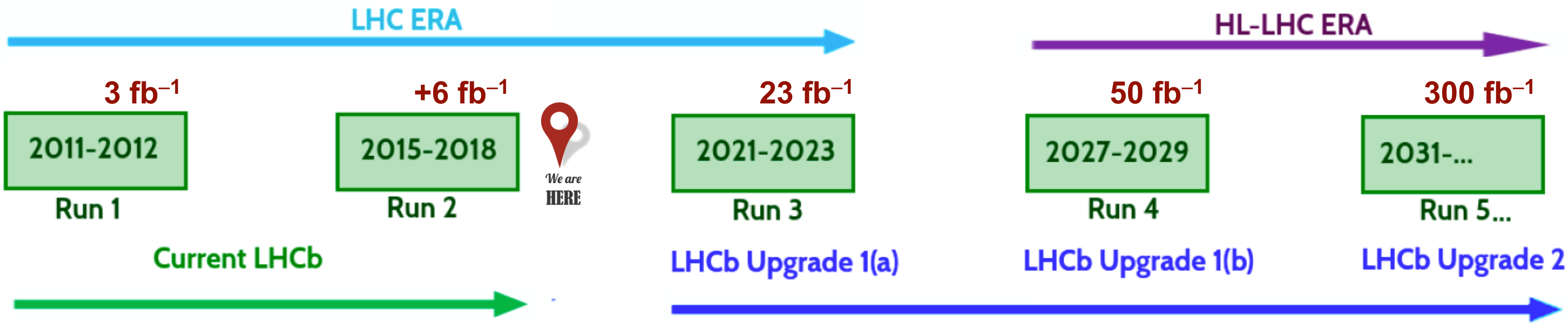


Figure 3.2: Effective tagging efficiency of OS and SS kaon taggers, and their combination, (left) in bins of pile-up vertices and (right) in bins of track multiplicity. These results are obtained from Upgrade I simulation of $B_s^0 \to D_s^- \pi^+$ decays. The OS performances correspond to those obtained from combination of the individual OS taggers.

Prospects



LHC ERA

HL-LHC ERA

3 fb^{-1} 2011-2012 Run 1

+6 fb^{-1} 2015-2018 Run 2

We are HERE

23 fb^{-1} 2021-2023 Run 3

50 fb^{-1} 2027-2029 Run 4

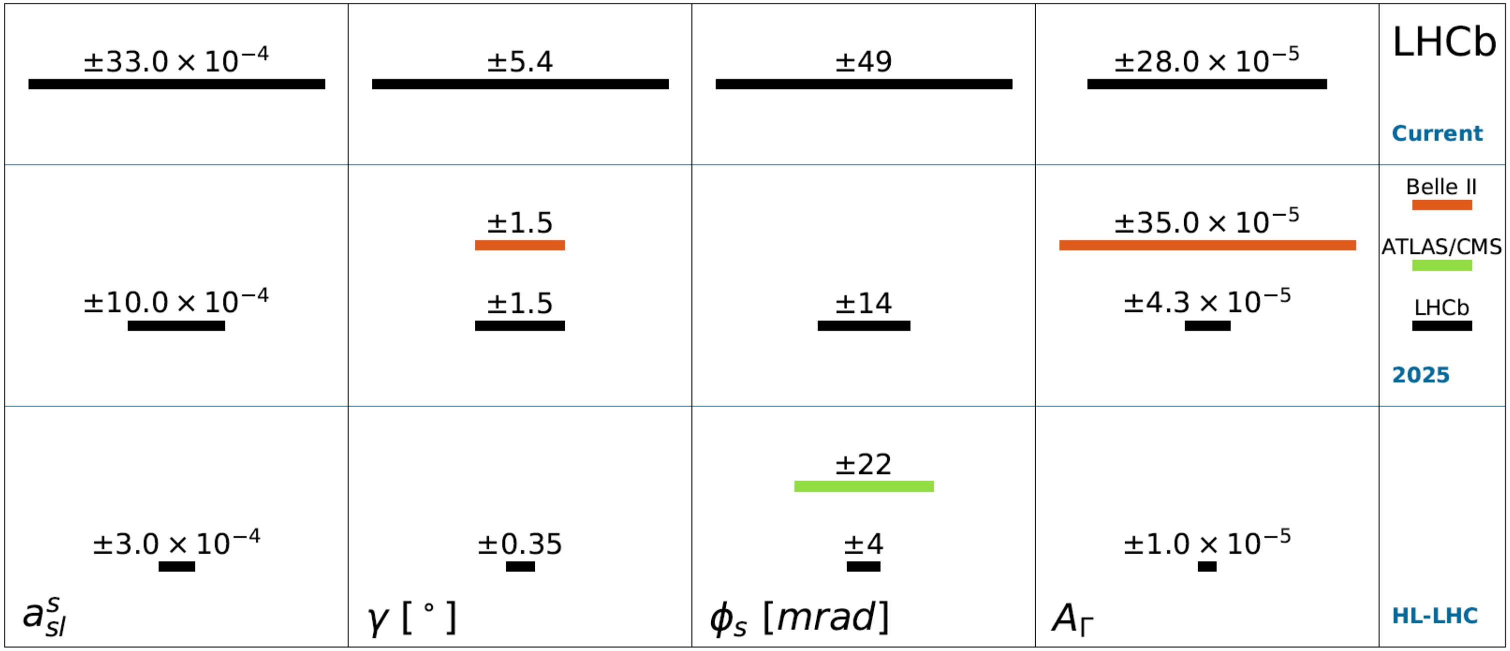
300 fb^{-1} 2031-... Run 5...

Current LHCb

LHCb Upgrade 1(a)

LHCb Upgrade 1(b)

LHCb Upgrade 2



(3fb^{-1})

(23fb^{-1})

(300fb^{-1})

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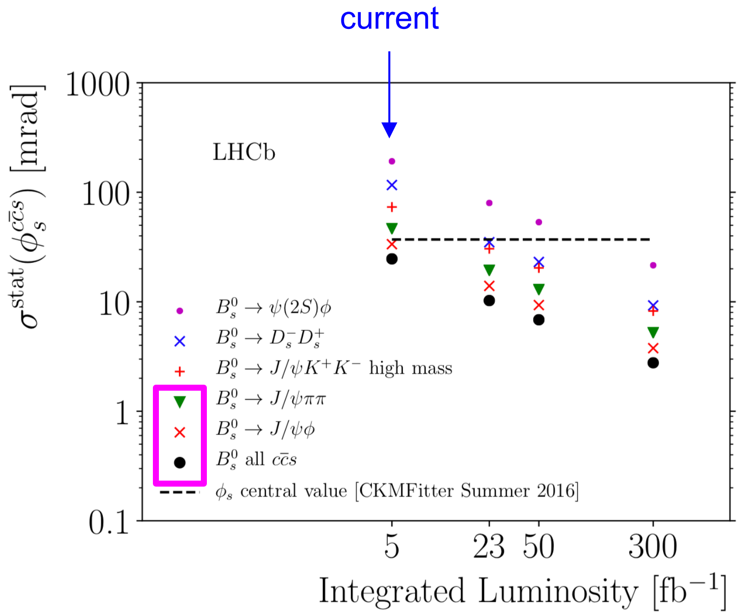
arXiv:1808.08865

Prospects



- ϕ_s would be statistically limited
- Expect to have with 300/fb
  - $\sigma^{\rm stat} \sim$ 4mrad ($B_s^0 \to J/\psi\phi$)
  - $\sigma^{\rm stat} \sim$ 3mrad (total)

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Table 3.1: Statistical sensitivity on $\phi_s^{s\bar{s}s}$ and $\phi_s^{d\bar{d}s}$.

Decay mode	σ(stat.) [rad]			
	3 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B_s^0 \to \phi\phi$	0.154	0.039	0.026	0.011
$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ (inclusive)	0.129	0.033	0.022	0.009
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	–	0.127	0.086	0.035

Summary and Plan

- Upgrade of LHCb will enable a wide range of flavour observables determined with unprecedented precision
  - Expect to **7x** more data (**14x** more hadronic events) by 2029
  - Could have another factor of **6** increase from Upgrade II

LHCb Chinese group plan on ϕ_s

- **Should put 1-2 students on improving Tagging**
- **ϕ_s from $b \to c\bar{c}s$**
  - Should concentrate on channels that give most precise measurements (h^+h^-)
  - Update the penguin control
- **ϕ_s from $b \to sq\bar{q}$ ($q = s$ or d) loops**
  - should continue on $B_s^0 \to \phi\phi$
  - Explore more possible modes (need theory inputs)?

谢谢

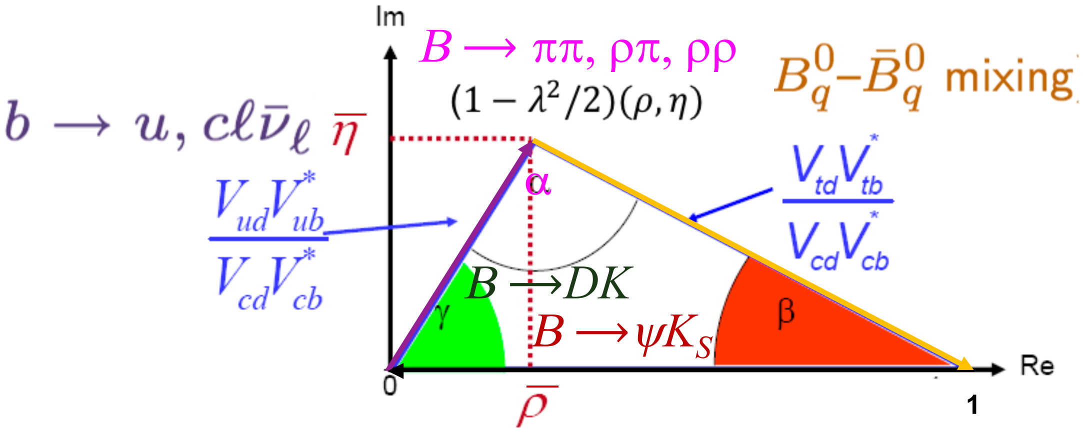
Backup

The Unitarity triangle

$$\mathbf{V}_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & e^{-i\gamma}|\boldsymbol{V}_{\boldsymbol{ub}}| \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ e^{-i\beta}|\boldsymbol{V}_{\boldsymbol{td}}| & -|V_{ts}| & |V_{tb}| \end{pmatrix}$$

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

- ***Sides** are measured with decay rates*
- ***Angles** are measured with CP asymmetries*



$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right] \qquad \alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \qquad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

UT defined by two parameters only → Can be overconstrained

Inconsistent measurements could indicate new physics

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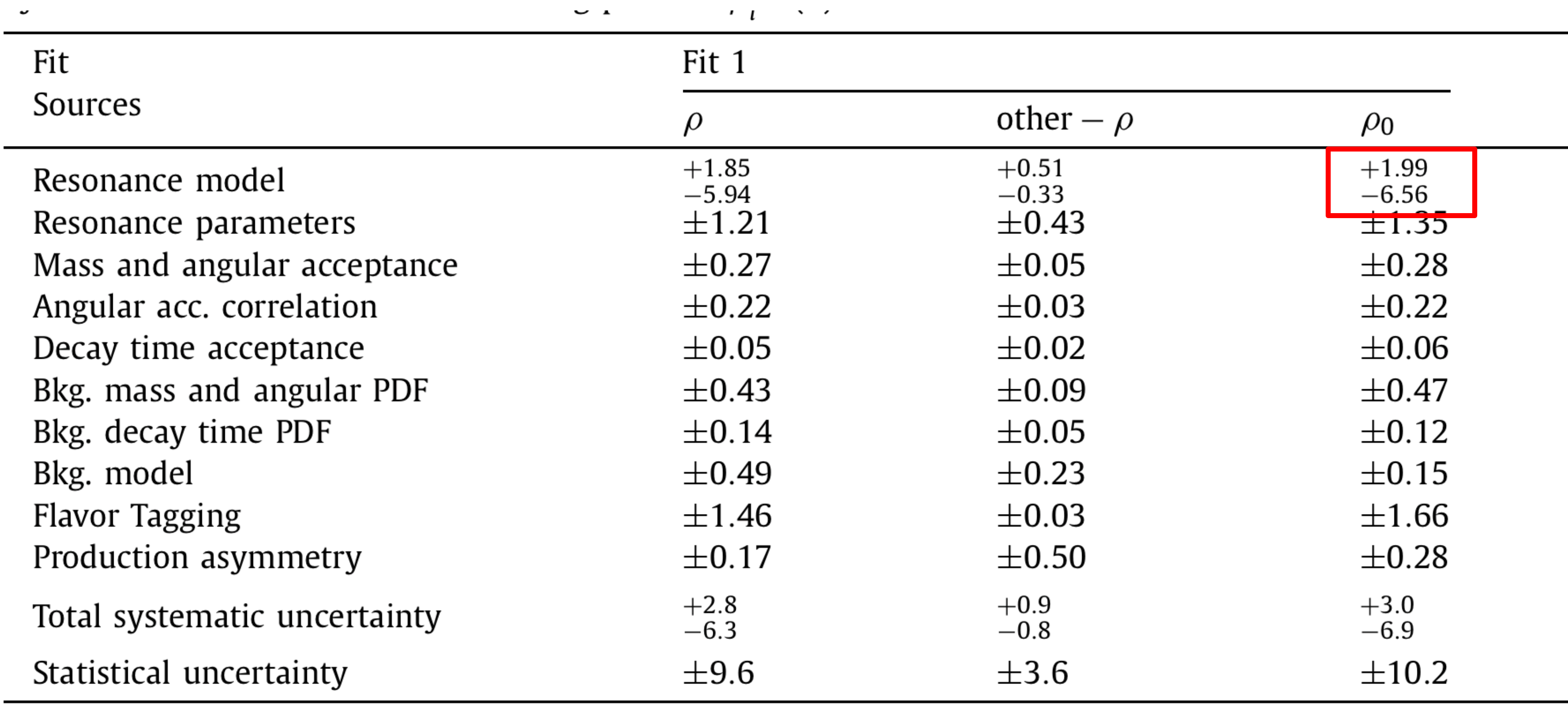
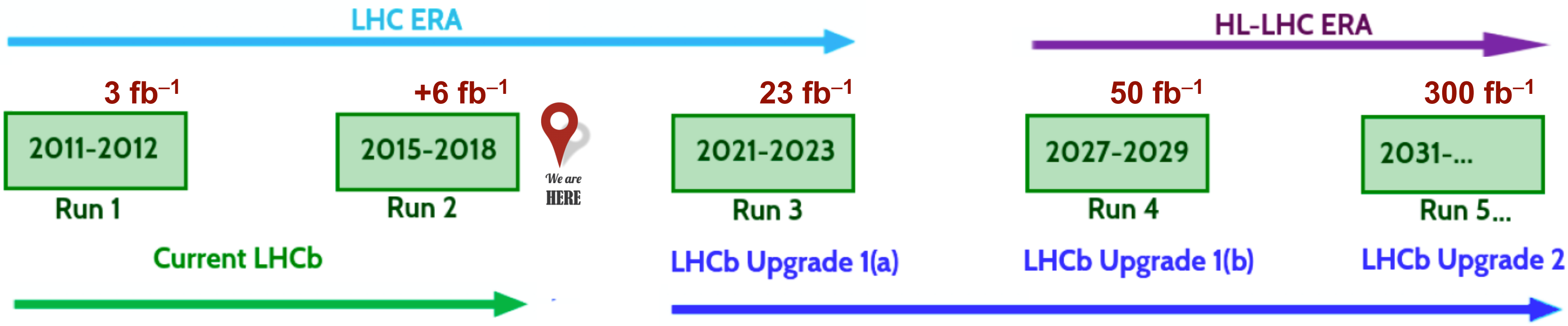
Systematics on $2\beta^{J/\psi\rho}$



Fit Sources	Fit 1		
	ρ	other $-\ \rho$	ρ_0
Resonance model	$^{+1.85}_{-5.94}$	$^{+0.51}_{-0.33}$	$^{+1.99}_{-6.56}$
Resonance parameters	±1.21	±0.43	±1.35
Mass and angular acceptance	±0.27	±0.05	±0.28
Angular acc. correlation	±0.22	±0.03	±0.22
Decay time acceptance	±0.05	±0.02	±0.06
Bkg. mass and angular PDF	±0.43	±0.09	±0.47
Bkg. decay time PDF	±0.14	±0.05	±0.12
Bkg. model	±0.49	±0.23	±0.15
Flavor Tagging	±1.46	±0.03	±1.66
Production asymmetry	±0.17	±0.50	±0.28
Total systematic uncertainty	$^{+2.8}_{-6.3}$	$^{+0.9}_{-0.8}$	$^{+3.0}_{-6.9}$
Statistical uncertainty	±9.6	±3.6	±10.2

Prospects



Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
CKM tests				
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [44]	14 mrad	–	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad
$a_{\rm sl}^s$	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%

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