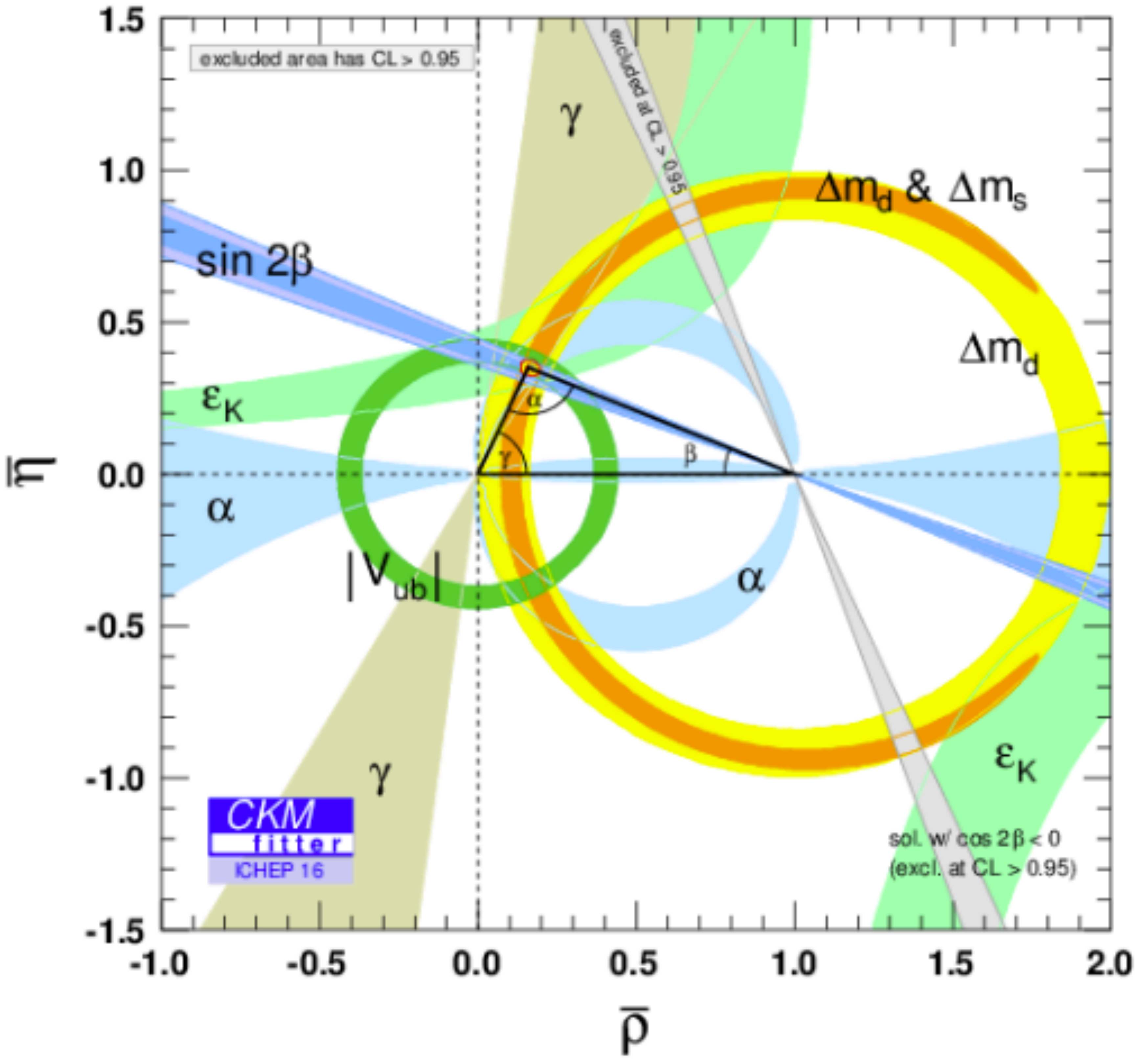
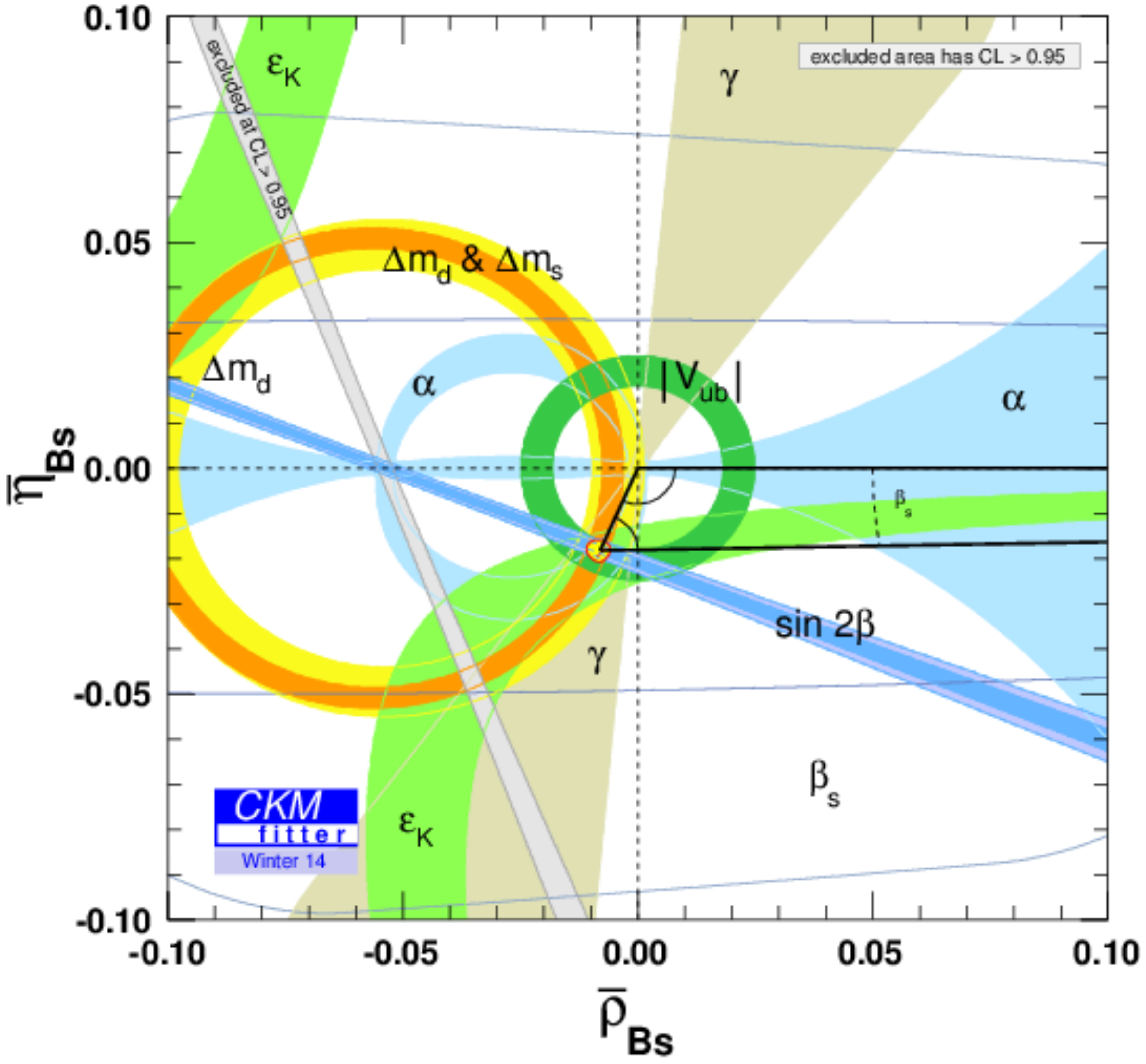
$$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$



$$\beta_s \equiv \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

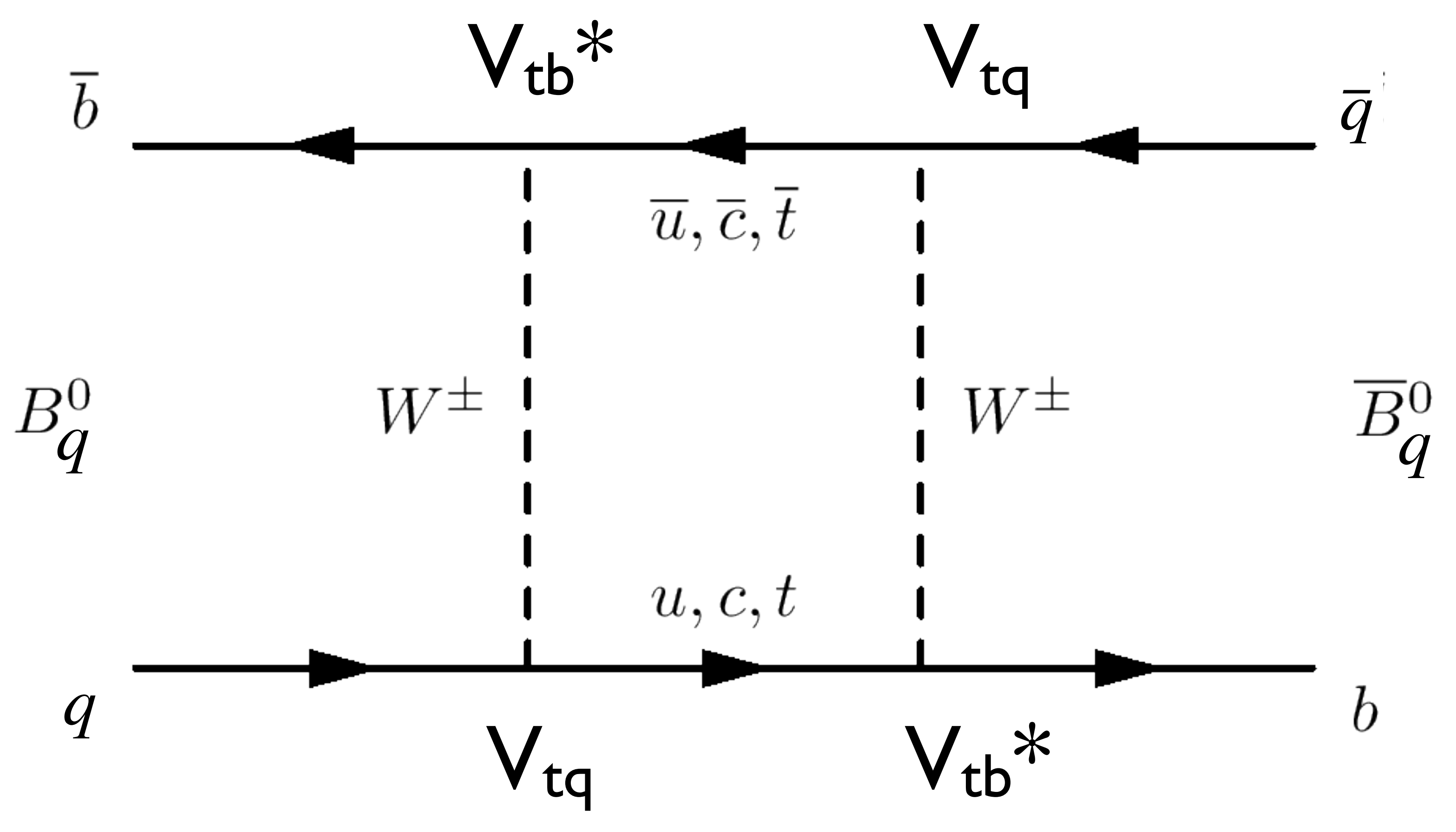


Measurements of β and β_s

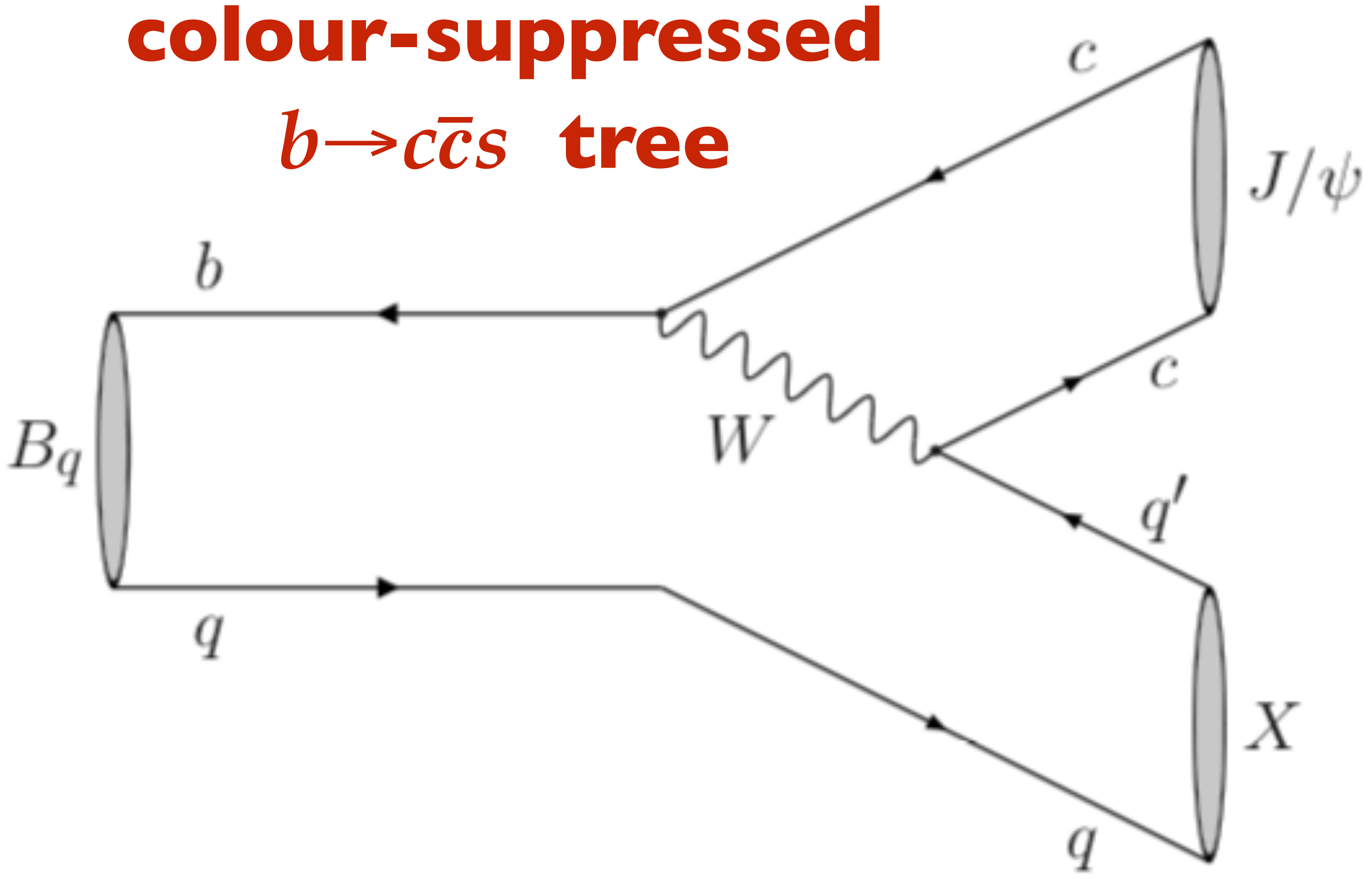
Beauty - Isola d'Elba - 7th May 2018

@GreigCowan (Edinburgh), on behalf of the LHCb collaboration

CPV in $B_{(s)}{}^0$ mixing and decay



colour-suppressed
$b \to c\bar{c}s$ tree



$$B^0_{\mathrm{H(L)}} = pB^0 \pm q\overline{B}^0 \qquad \lambda_{f_{CP}} = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

$$\arg(\lambda_{f_{CP}}) \neq 0$$

Measurable phases

$\phi_d = \ 2\beta$

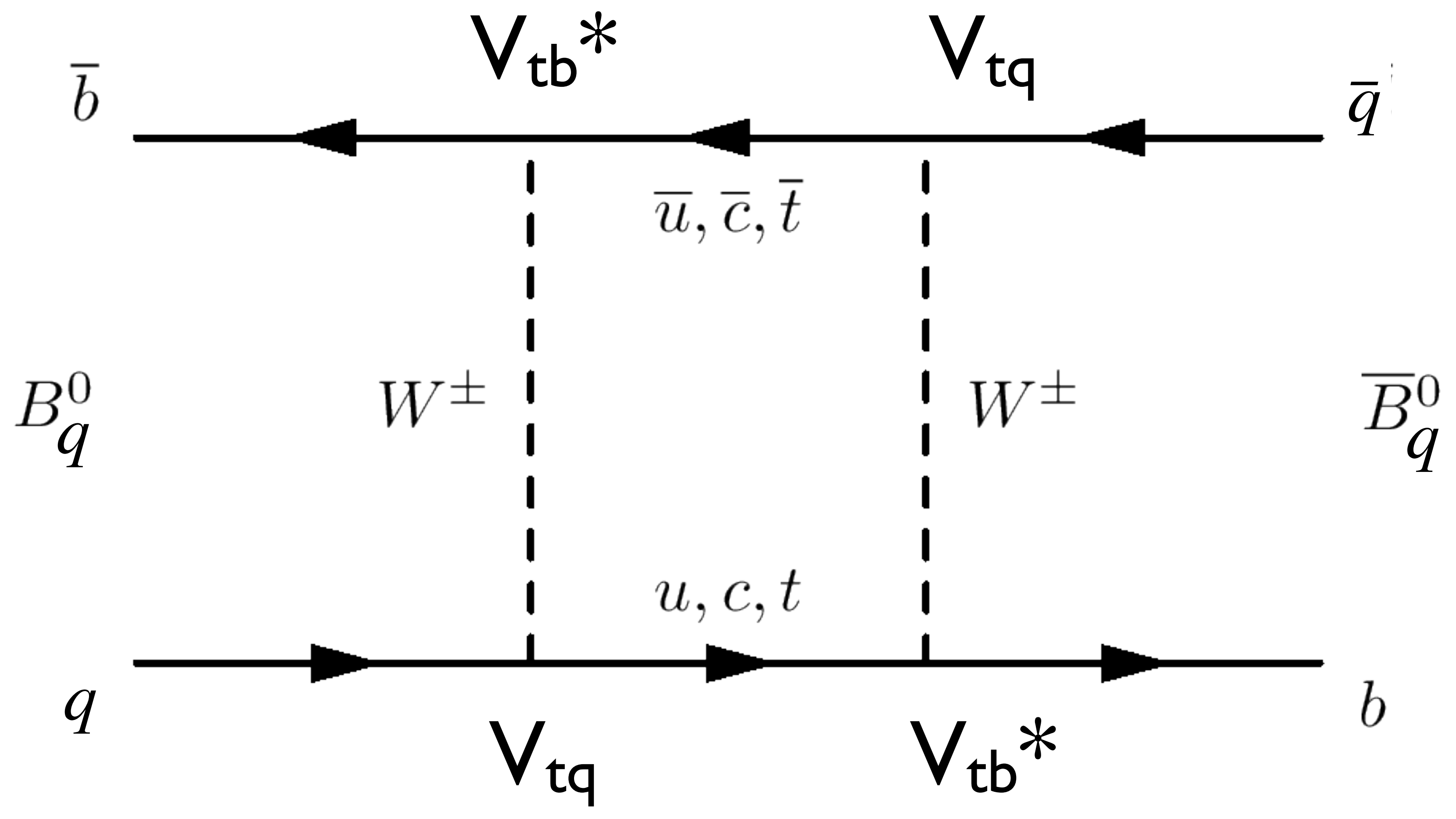
$\phi_s = -2\beta_s$

Precise predictions

$$2\beta^{\mathrm{SM}} = (47.48^{+2.26}_{-1.96})^\circ$$
$$2\beta_s^{\mathrm{SM}} = (2.122 \pm 0.037)^\circ$$

[CKMFitter]

CPV in $B_{(s)}{}^0$ mixing and decay



$$B^0_{\mathrm{H(L)}} = pB^0 \pm q\overline{B}^0 \qquad \lambda_{f_{CP}} = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

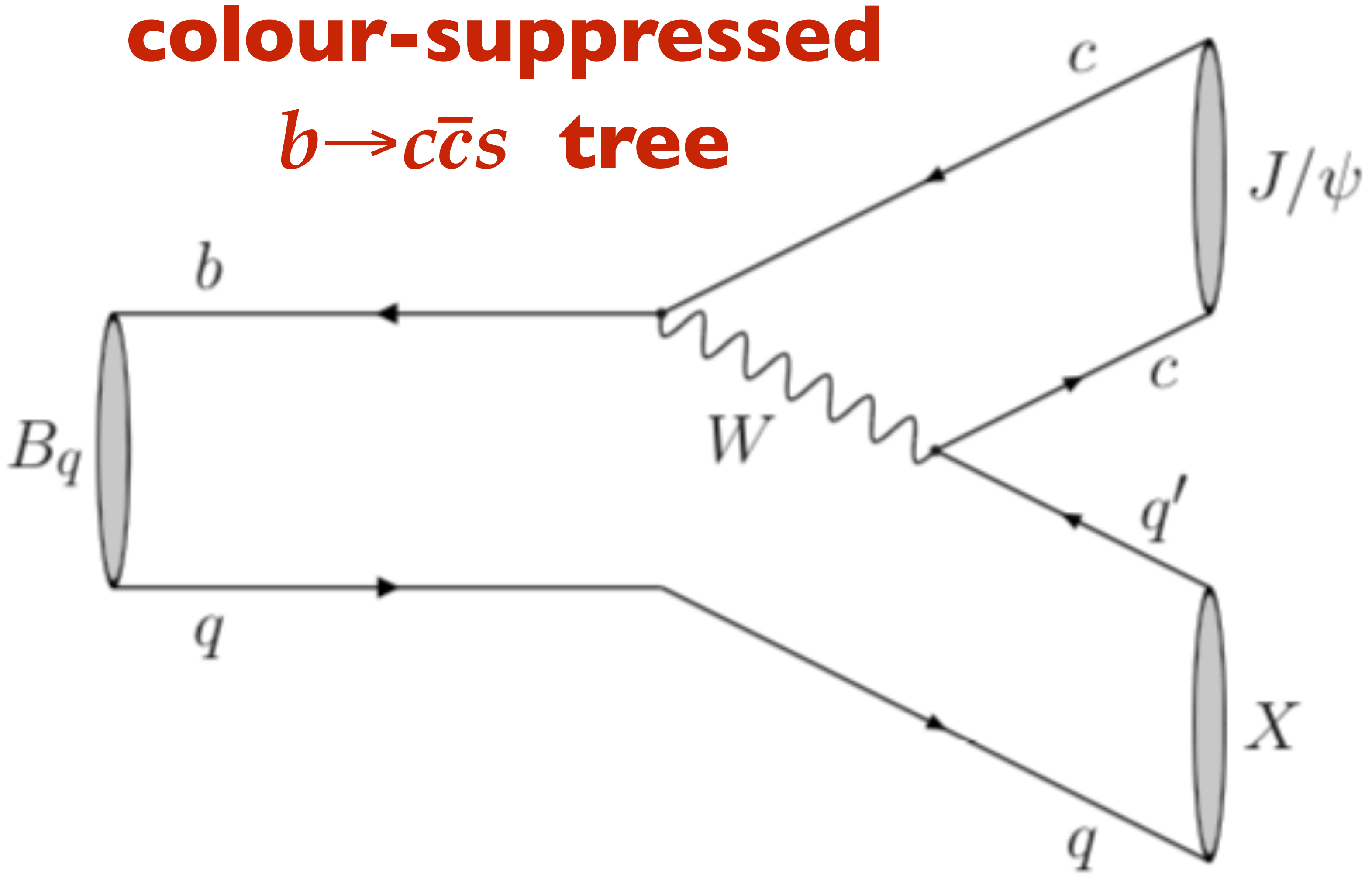
$$\arg(\lambda_{f_{CP}}) \neq 0$$

Measurable phases

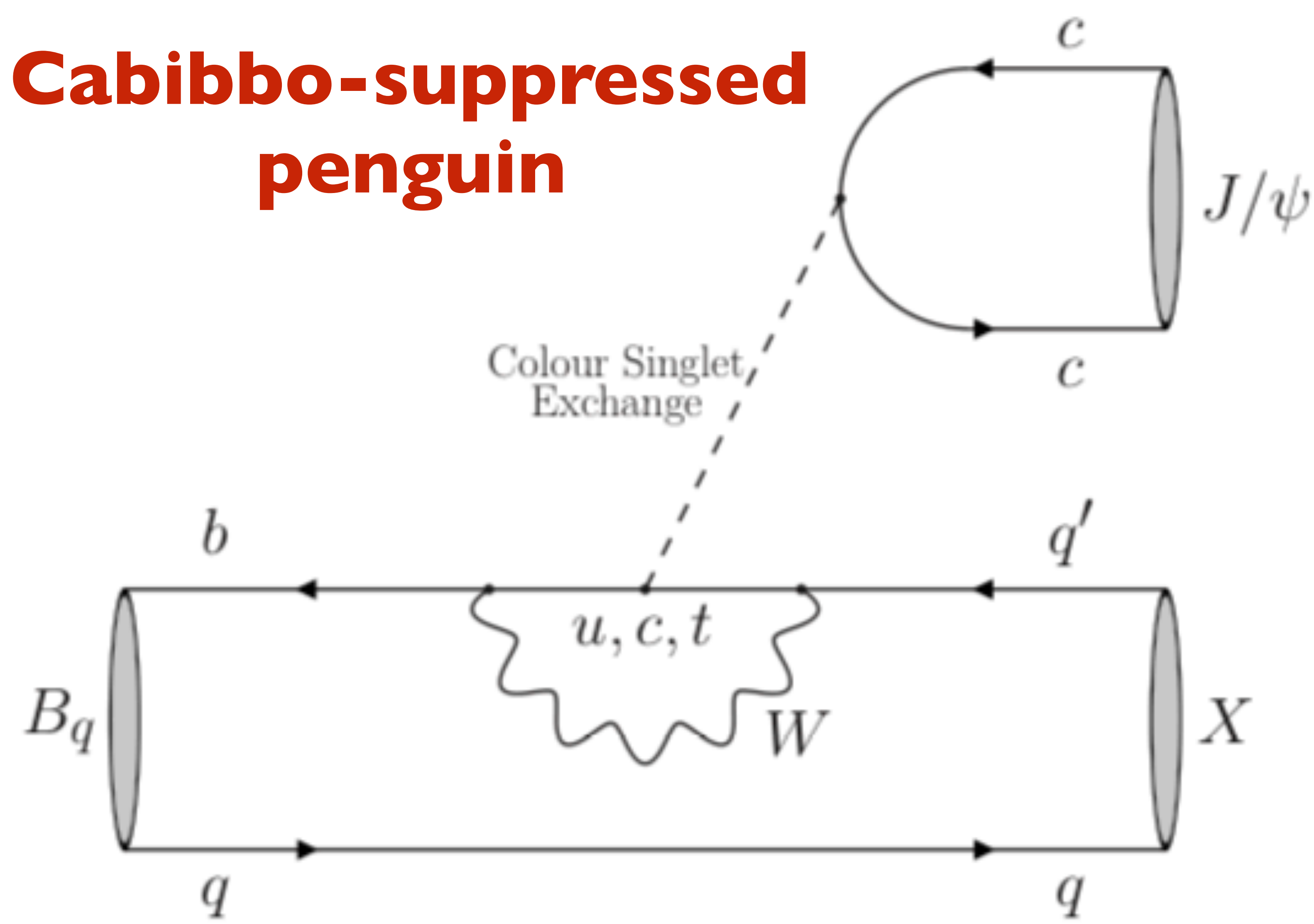
$$\phi_d = \quad 2\beta \;+ \Delta\phi^{pen} + \Delta\phi^{NP}$$

$$\phi_s = -2\beta_s + \Delta\phi_s{}^{pen} + \Delta\phi_s{}^{NP}$$

colour-suppressed
$b \to c\bar{c}s$ **tree**



Cabibbo-suppressed penguin



+ smaller weak exchange (E) and penguin annihilation (PA) diagrams

[Fleischer, PRD 60 (1999) 073008]
[Ciuchini et al., PRL 95 (2005) 221804]
[Faller et al., PRD 79 (2009) 014005]
[Faller et al., PRD 79 (2009) 014030]
[Jung, PRD 86 (2012) 053008]
[Jung, Schacht, PRD 91 (2015) 034027]
[De Bruyn, Fleischer, JHEP 03 (2015) 145]
[Ligeti, Robinson, PRL 115 (2015) 251801]
[Frings et al., PRL 115 (2015) 061802]
[...]

Precise predictions

$$2\beta^{\mathrm{SM}} = (47.48^{+2.26}_{-1.96})^\circ$$

$$2\beta_s^{\mathrm{SM}} = (2.122 \pm 0.037)^\circ$$

[CKMFitter]

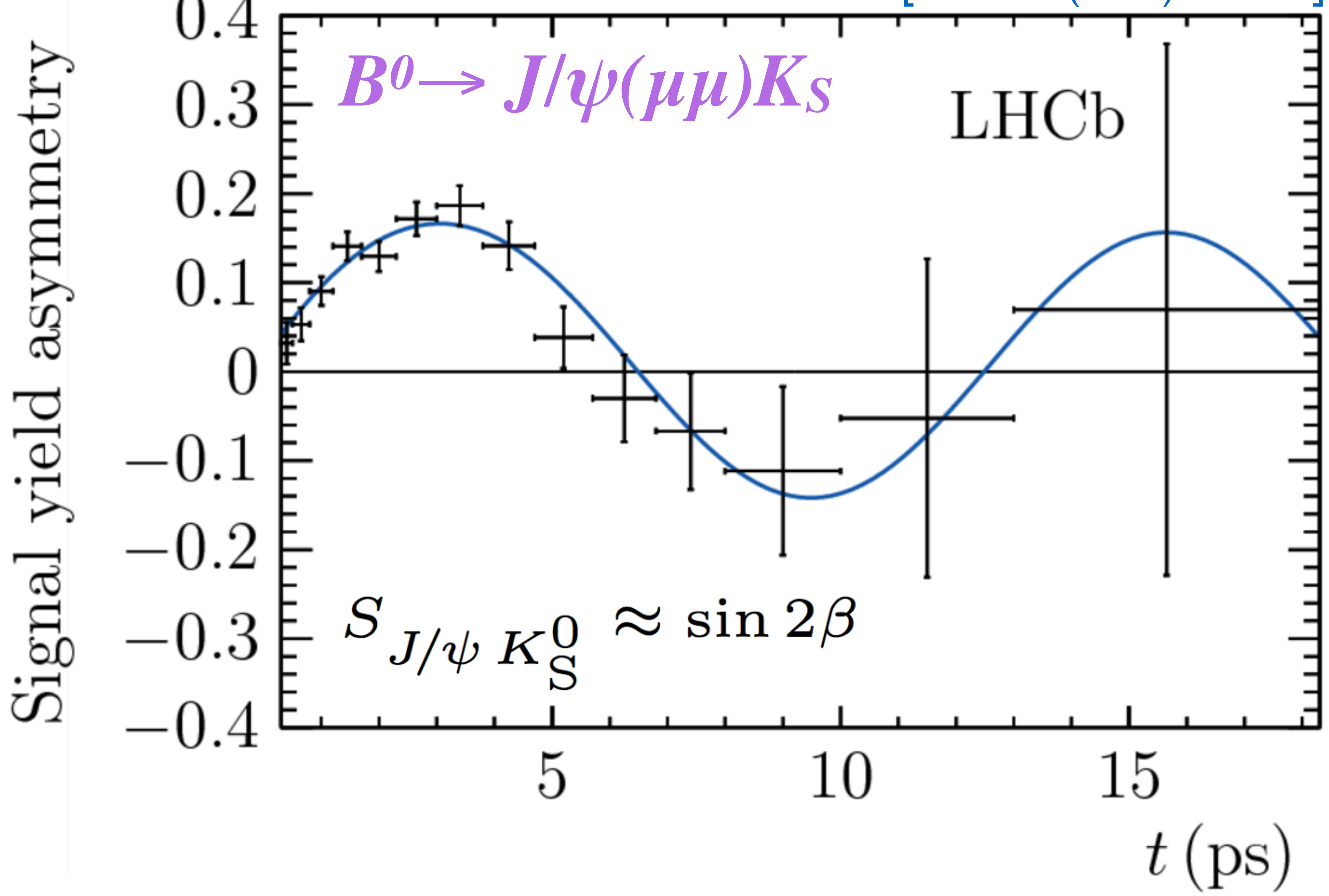
Measuring ϕ_q

Study time-dependent CP asymmetry

$$\frac{\Gamma_{\overline{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\overline{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{S_f \sin(\Delta m_{(s)} t) - C_f \cos(\Delta m_{(s)} t)}{\cosh(\frac{\Delta\Gamma_{(s)} t}{2}) + A_f^{\Delta\Gamma_{(s)}} \sinh(\frac{\Delta\Gamma_{(s)} t}{2})}$$

$$A_f^{\Delta\Gamma} \equiv -\frac{2\,\Re(\lambda_f)}{1+|\lambda_f|^2}, \quad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad S_f \equiv \frac{2\,\Im(\lambda_f)}{1+|\lambda_f|^2},$$

[PRL 115 (2015) 031601]



Mixing parameters

$\Delta m \equiv (m_H - m_L)$	Mixing frequency
$\Gamma \equiv (\Gamma_L + \Gamma_H)/2$	Average width
$\Delta\Gamma \equiv \Gamma_L - \Gamma_H$	Width difference

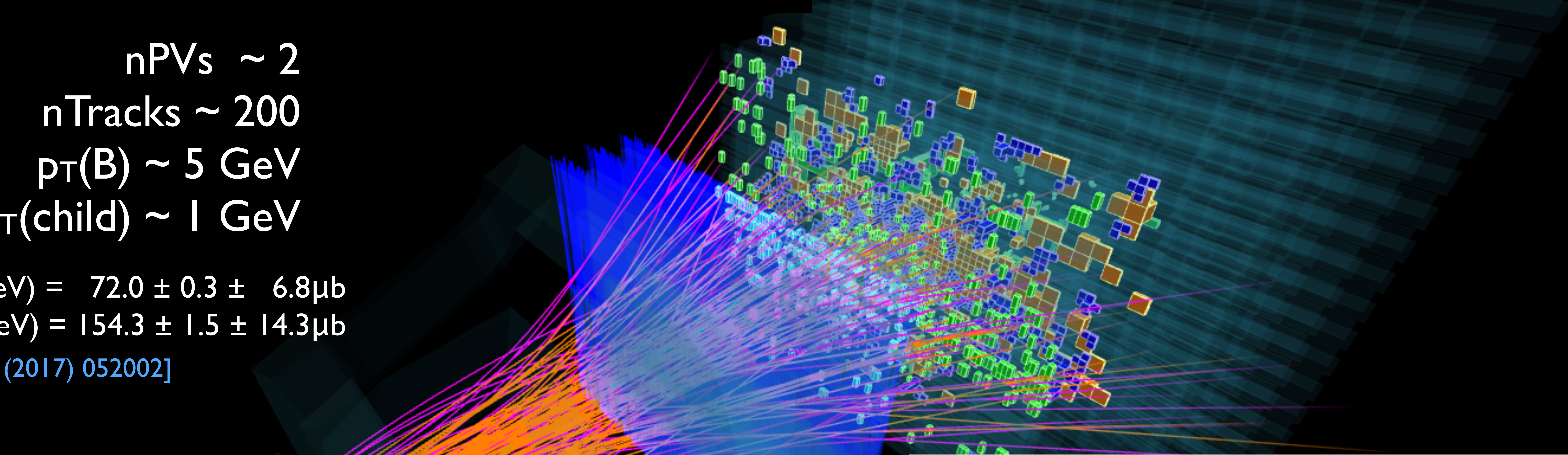
Experimental requirements:

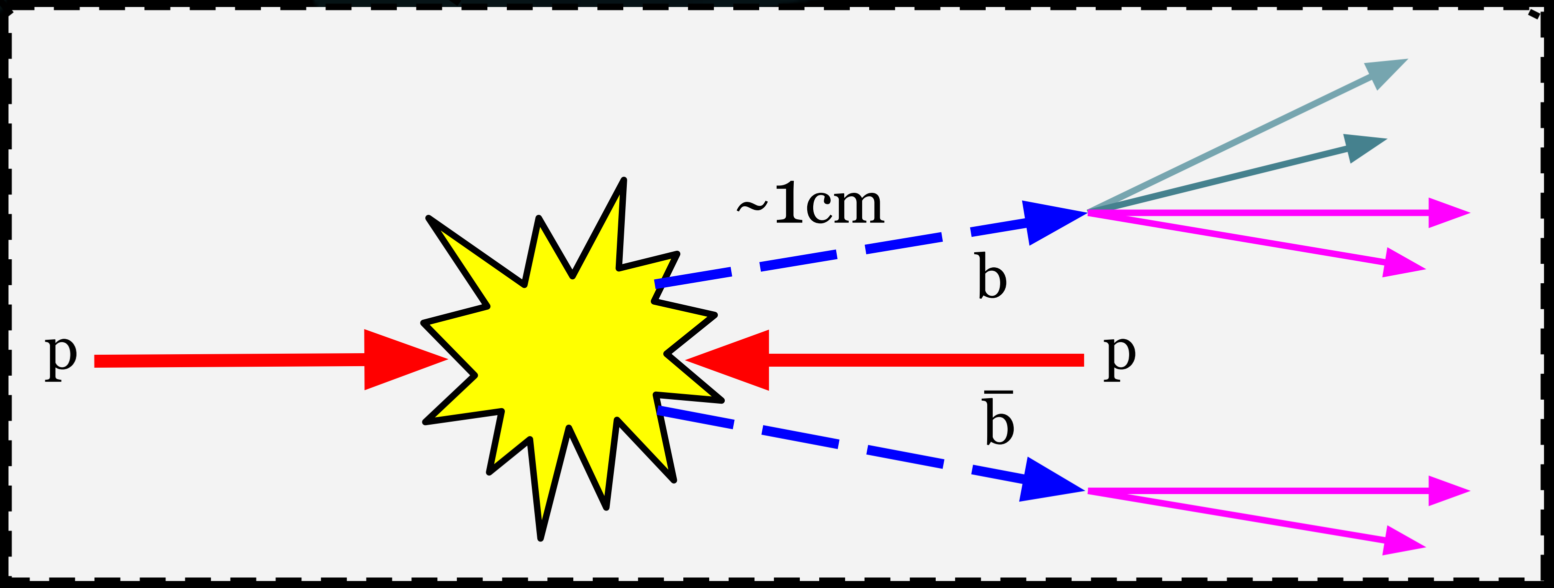
- Excellent decay-time resolution (~45 fs)
- Modelling decay-time efficiency (due to lifetime/IP cuts)
- Production + detection asymmetries (~1%)
- Tagging of meson flavour @ production

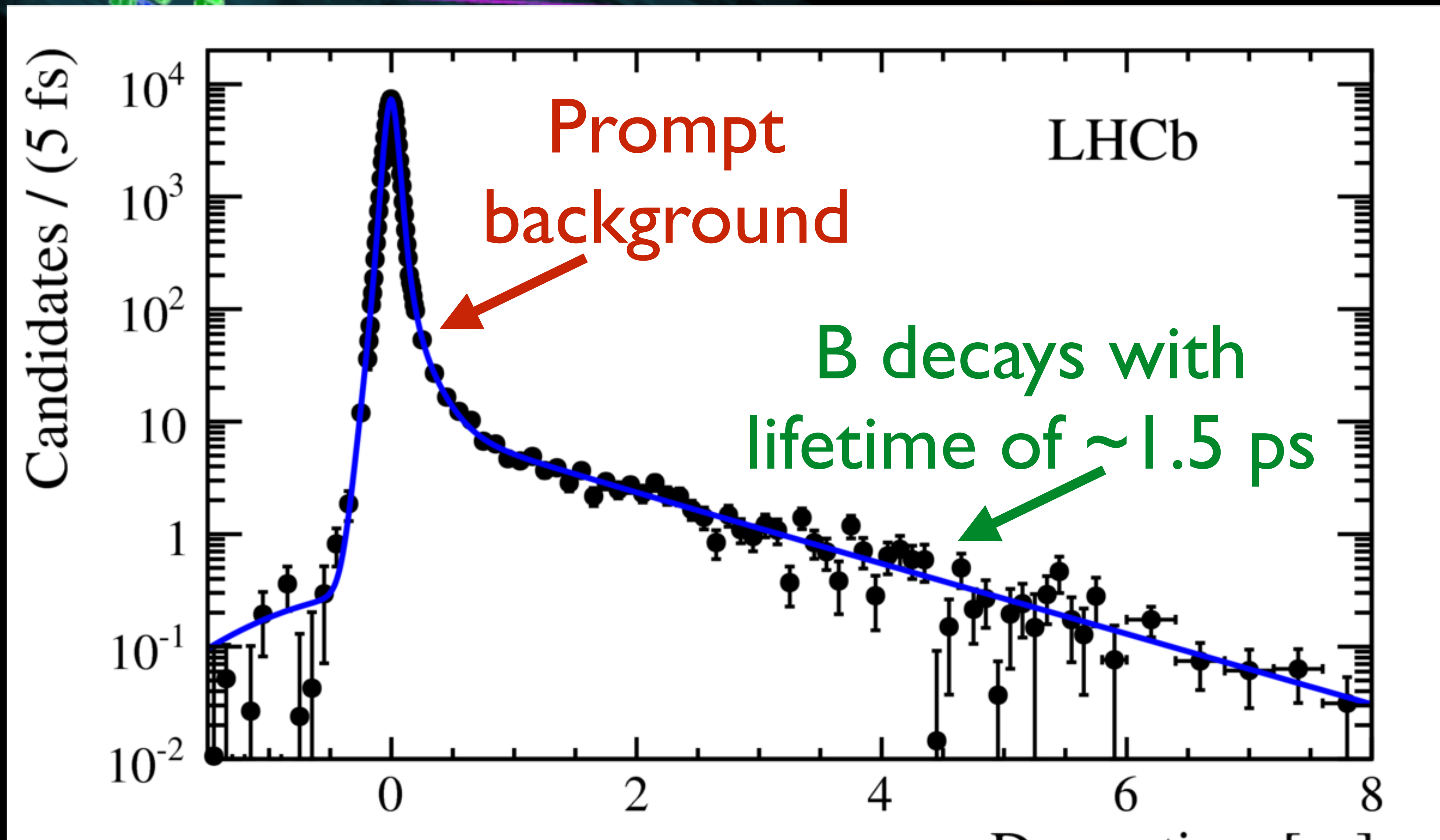
Flavour physics at the LHC

nPVs ~ 2
nTracks ~ 200
$p_T(B)$ ~ 5 GeV
$p_T(\text{child})$ ~ 1 GeV

$\sigma_{bb}(7\text{ TeV}) = 72.0 \pm 0.3 \pm 6.8\,\mu b$
$\sigma_{bb}(13\text{ TeV}) = 154.3 \pm 1.5 \pm 14.3\,\mu b$
[PRL 118 (2017) 052002]

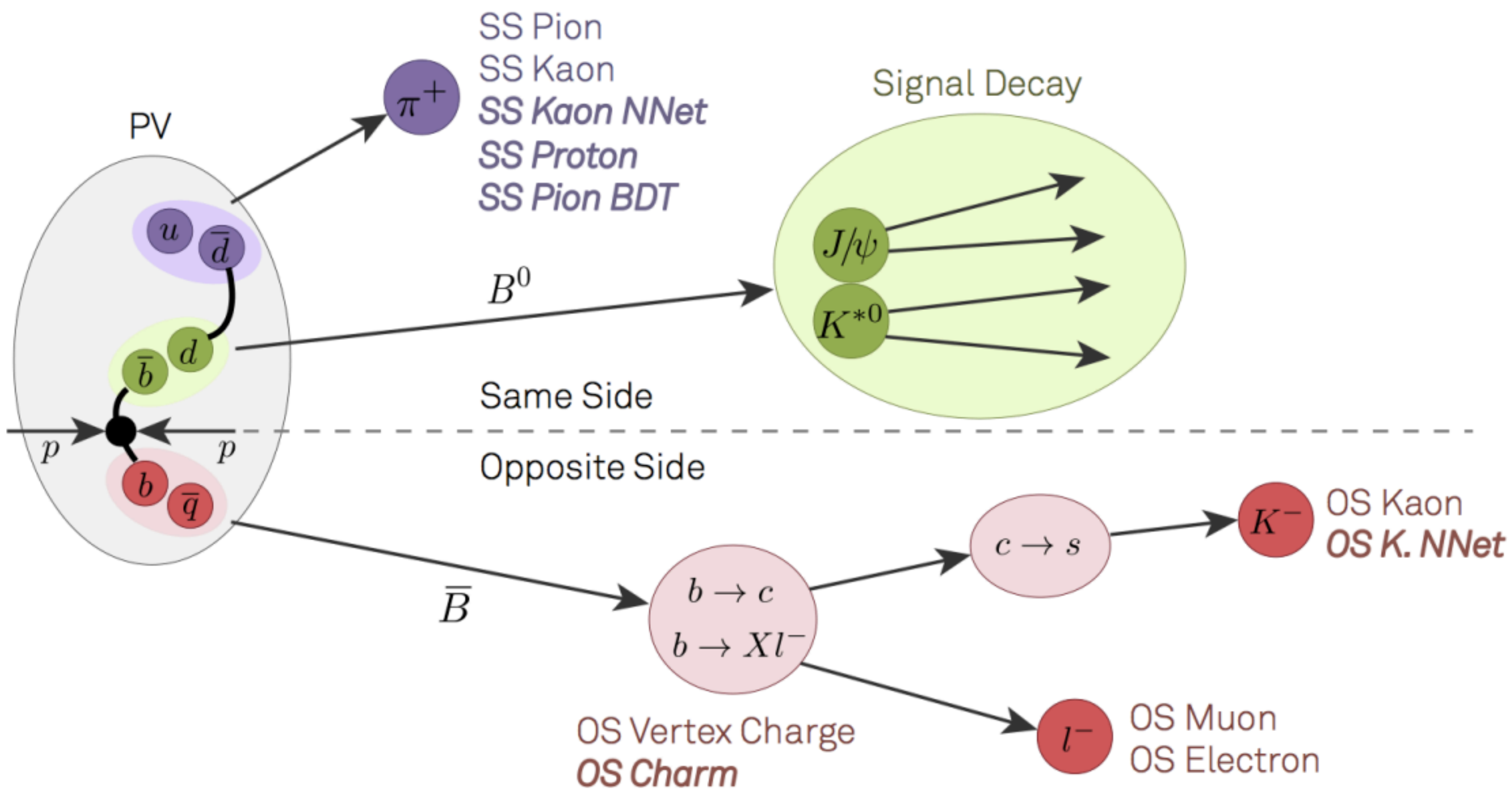


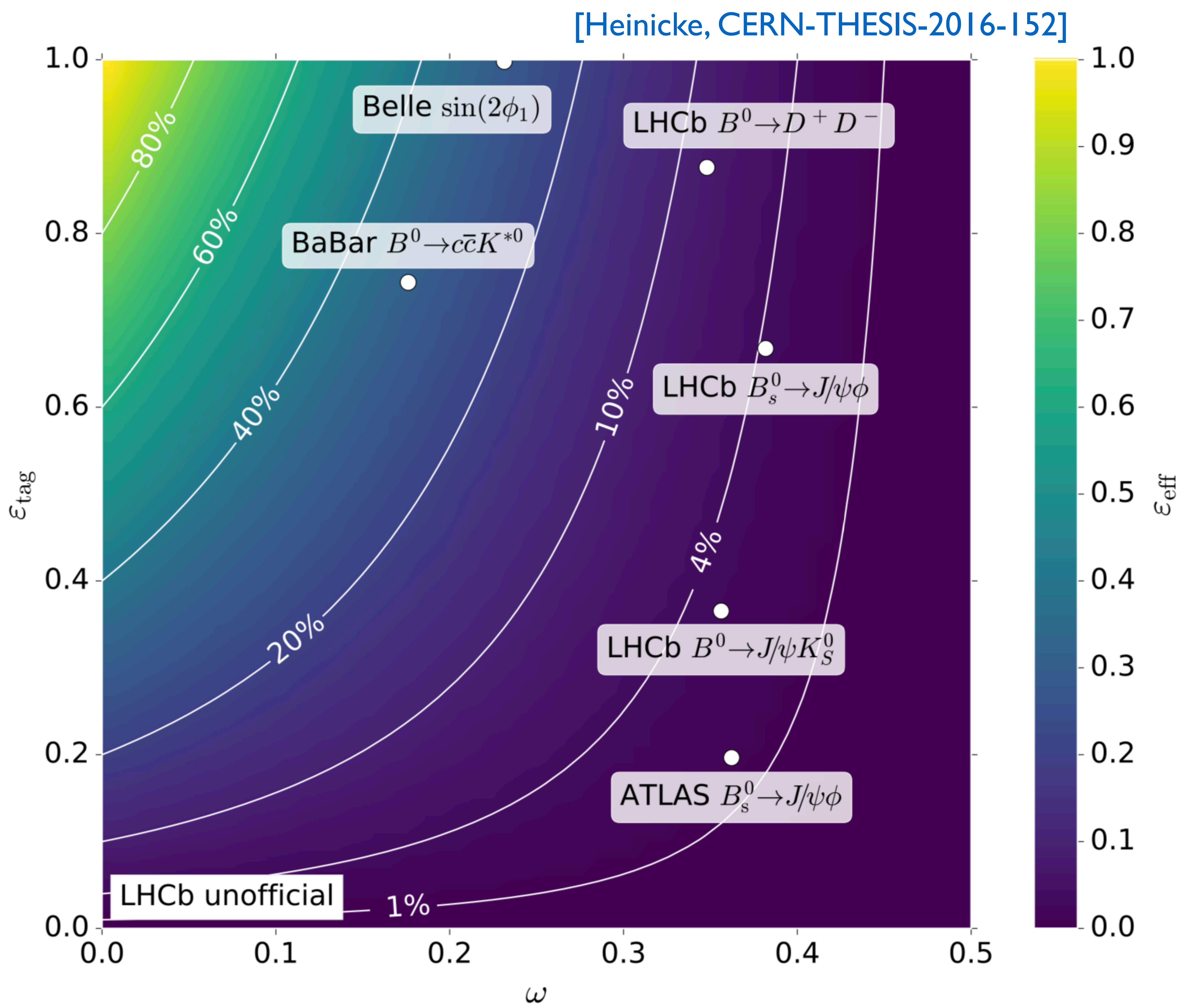




[PRD 87 (2013) 112010]

Flavour tagging





Use information in the event (e.g., charge of kaon associated with b-quark hadronisation) to tag flavour of B meson at production

Precision on A_{CP} scales with tagging power

Calibrate tagging algorithm response using modes with known flavour (e.g., $B^+ \to J/\psi K^+$, $B_s^0 \to D_s\pi\ldots$)

$$\epsilon_{\text{tag}} = \frac{N_{\text{tagged}}}{N_{\text{tagged}} + N_{\text{untagged}}} \qquad \omega = \frac{N_{\text{wrong}}}{N_{\text{right}} + N_{\text{wrong}}}$$

$$\epsilon_{\text{eff}} = \epsilon_{\text{tag}}\mathcal{D}^2 = \epsilon_{\text{tag}}\langle(1-2\omega)^2\rangle \qquad \sigma_{\text{stat}}(A_{CP}) \propto 1/\sqrt{\epsilon_{\text{eff}}N}$$

Measuring ϕ_d

$$\frac{\Gamma_{\overline{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\overline{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{S_f \sin(\Delta m_{(s)} t) - C_f \cos(\Delta m_{(s)} t)}{\cosh(\frac{\Delta\Gamma_{(s)} t}{2}) + A_f^{\Delta\Gamma_{(s)}} \sinh(\frac{\Delta\Gamma_{(s)} t}{2})}$$

Golden mode: $B^0 \to J/\psi K_S$

With Run 1, LHCb has a similar precision to Belle/BaBar

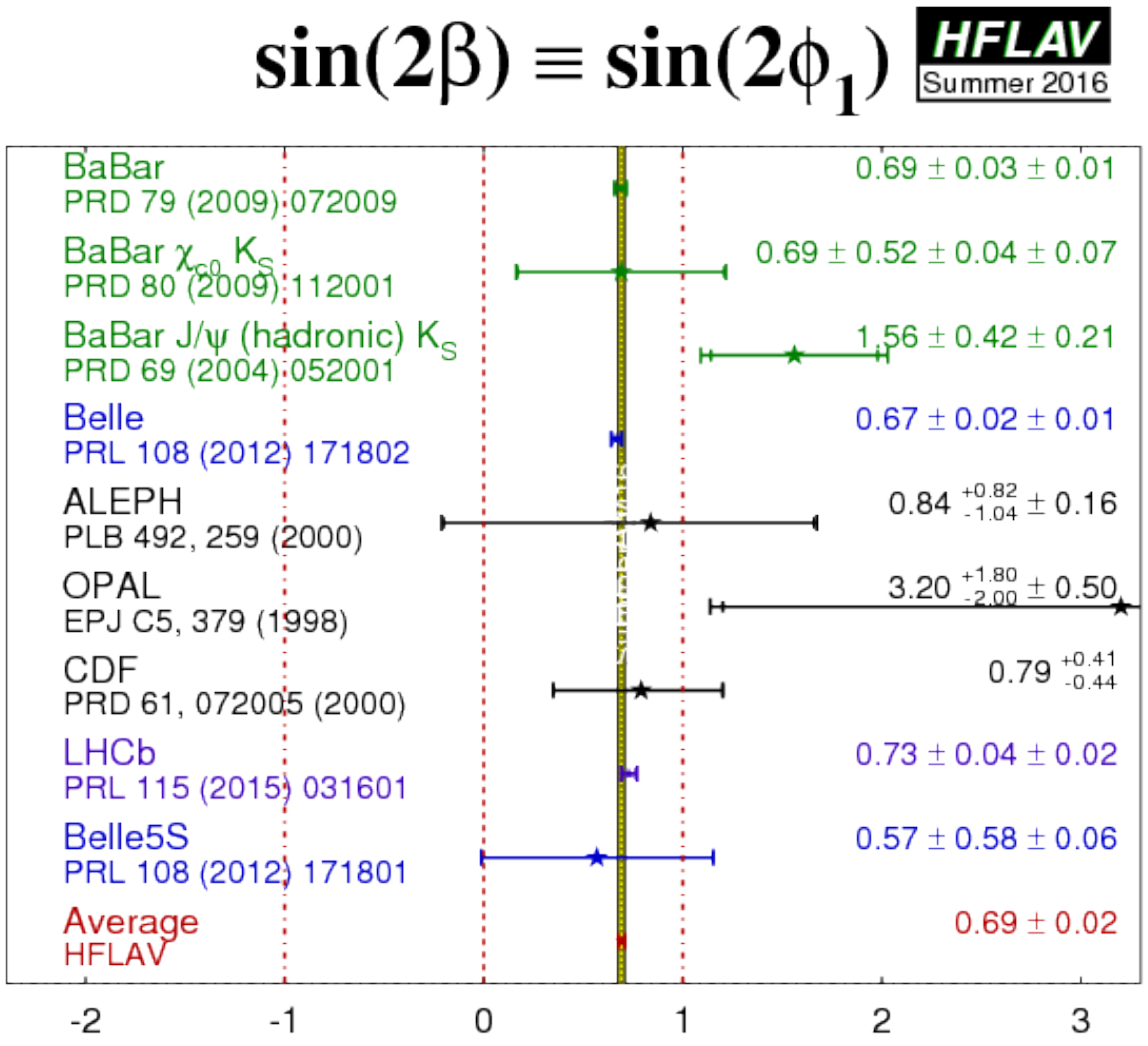
$$S_f = \sin 2\beta = 0.691 \pm 0.017$$ [HFLAV]

$$\sin 2\beta^{\rm SM} = 0.740^{+0.020}_{-0.025}$$ [CKMFitter]

Dominant systematics:

LHCb background tagging asymmetry → expect to scale with more data

Belle vertex reconstruction and time resolution



$\Delta\Gamma_d \neq 0$?

$s\times\Delta\Gamma_d/\Gamma_d = (-2 \quad \pm 10.\ ) \times 10^{-3}$ [HFLAV]

SM $\Delta\Gamma_d/\Gamma_d = (-3.97 \pm 0.90) \times 10^{-3}$ [Artuso et al]

Measuring ϕ_d

$$\frac{\Gamma_{\overline{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\overline{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{S_f \sin(\Delta m_{(s)} t) - C_f \cos(\Delta m_{(s)} t)}{\cosh(\frac{\Delta\Gamma_{(s)} t}{2}) + A_f^{\Delta\Gamma_{(s)}} \sinh(\frac{\Delta\Gamma_{(s)} t}{2})}$$

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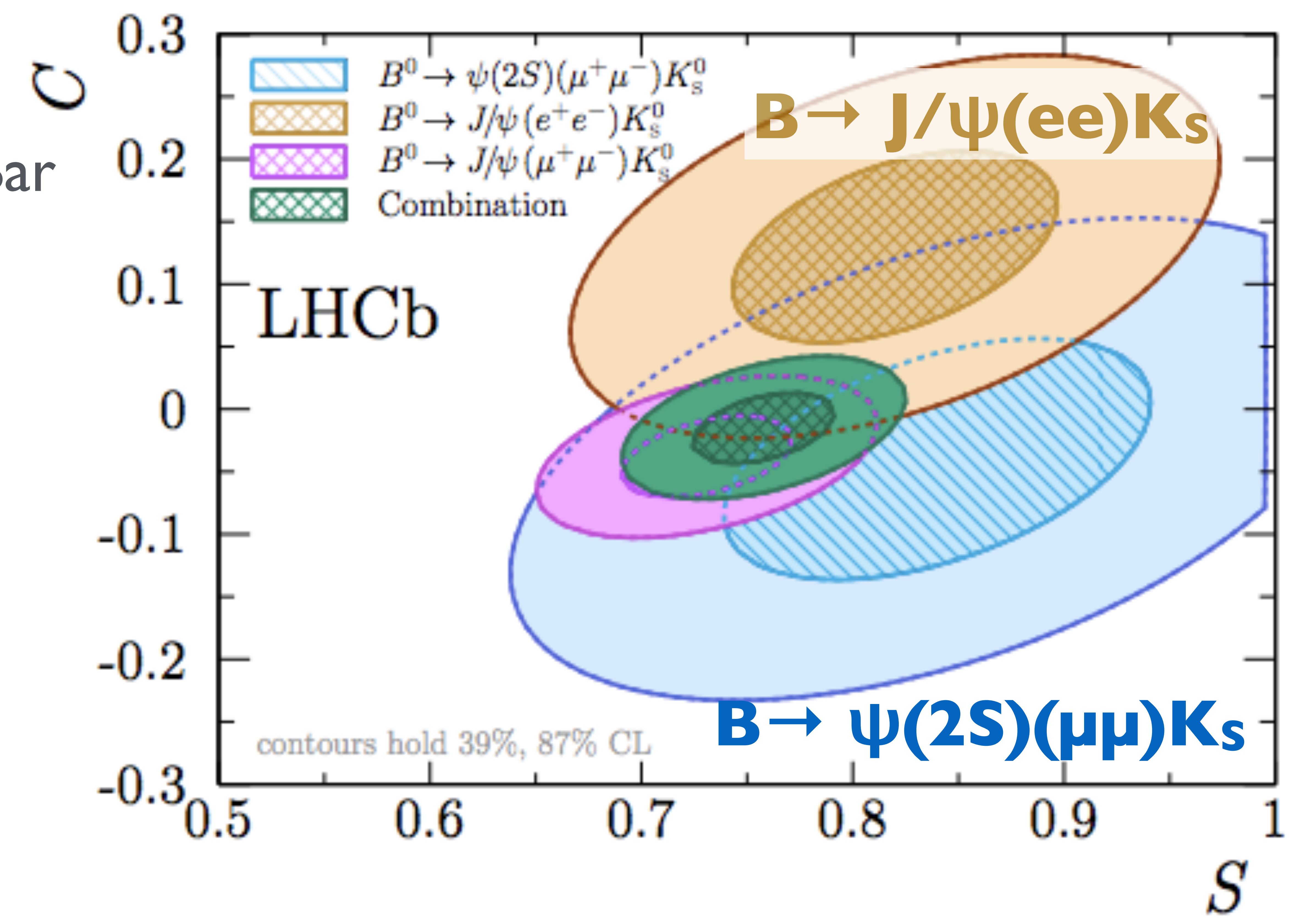
$$\sin 2\beta^{\mathrm{SM}} = 0.740^{+0.020}_{-0.025} \quad \text{[CKMFitter]}$$

Electron and other $[c\bar{c}]$ modes provide additional ~15% on the overall precision → improved electro reconstruction in LHCb upgrade-II would help

LHCb @ 300/fb → $\sigma(S)$ ~ 0.003



$$S(B^0 \to [c\bar{c}]K^0_S) = 0.760 \pm 0.034$$
$$C(B^0 \to [c\bar{c}]K^0_S) = -0.017 \pm 0.029$$

[JHEP 11 (2017) 170]

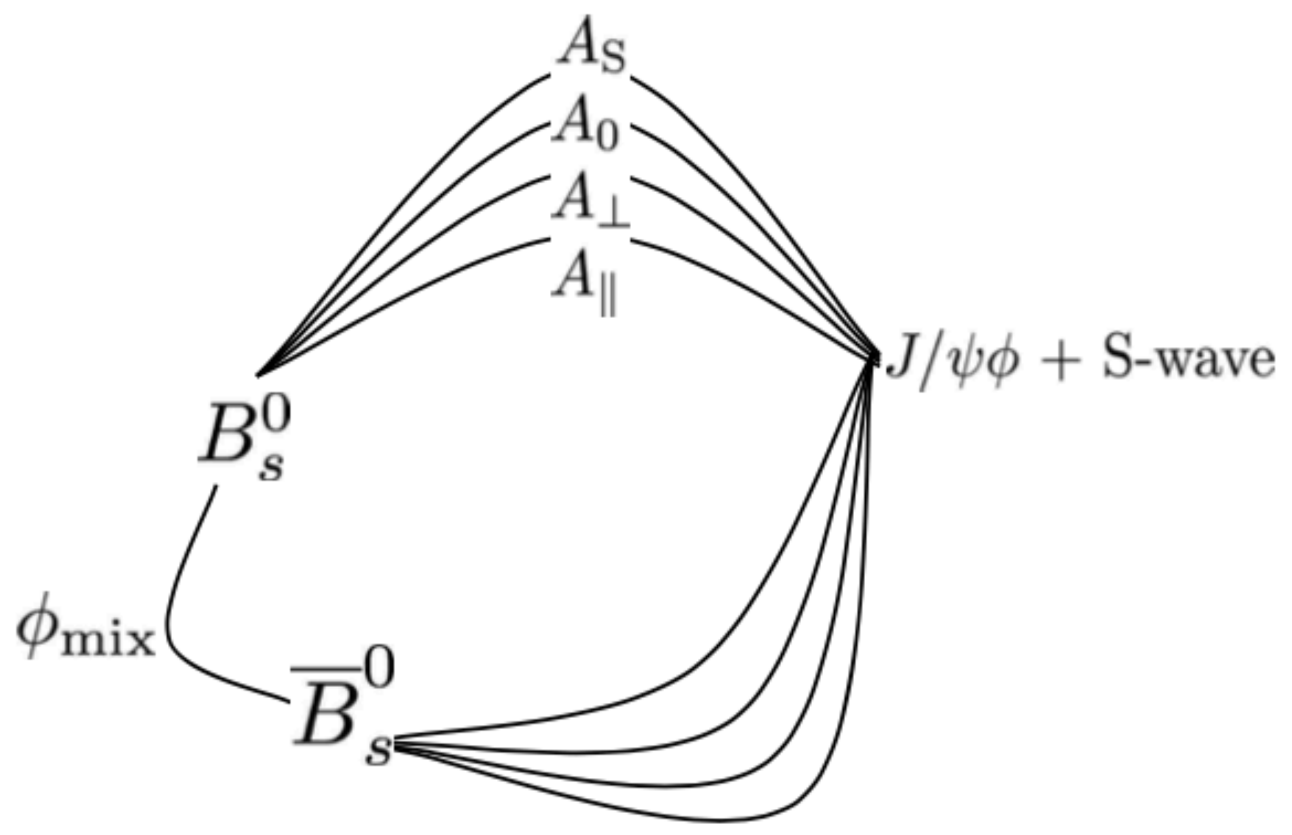
Measuring ϕ_s

$$\frac{\Gamma_{\overline{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\overline{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{S_f \sin(\Delta m_{(s)} t) - C_f \cos(\Delta m_{(s)} t)}{\cosh(\frac{\Delta\Gamma_{(s)} t}{2}) + A_f^{\Delta\Gamma_{(s)}} \sinh(\frac{\Delta\Gamma_{(s)} t}{2})}$$

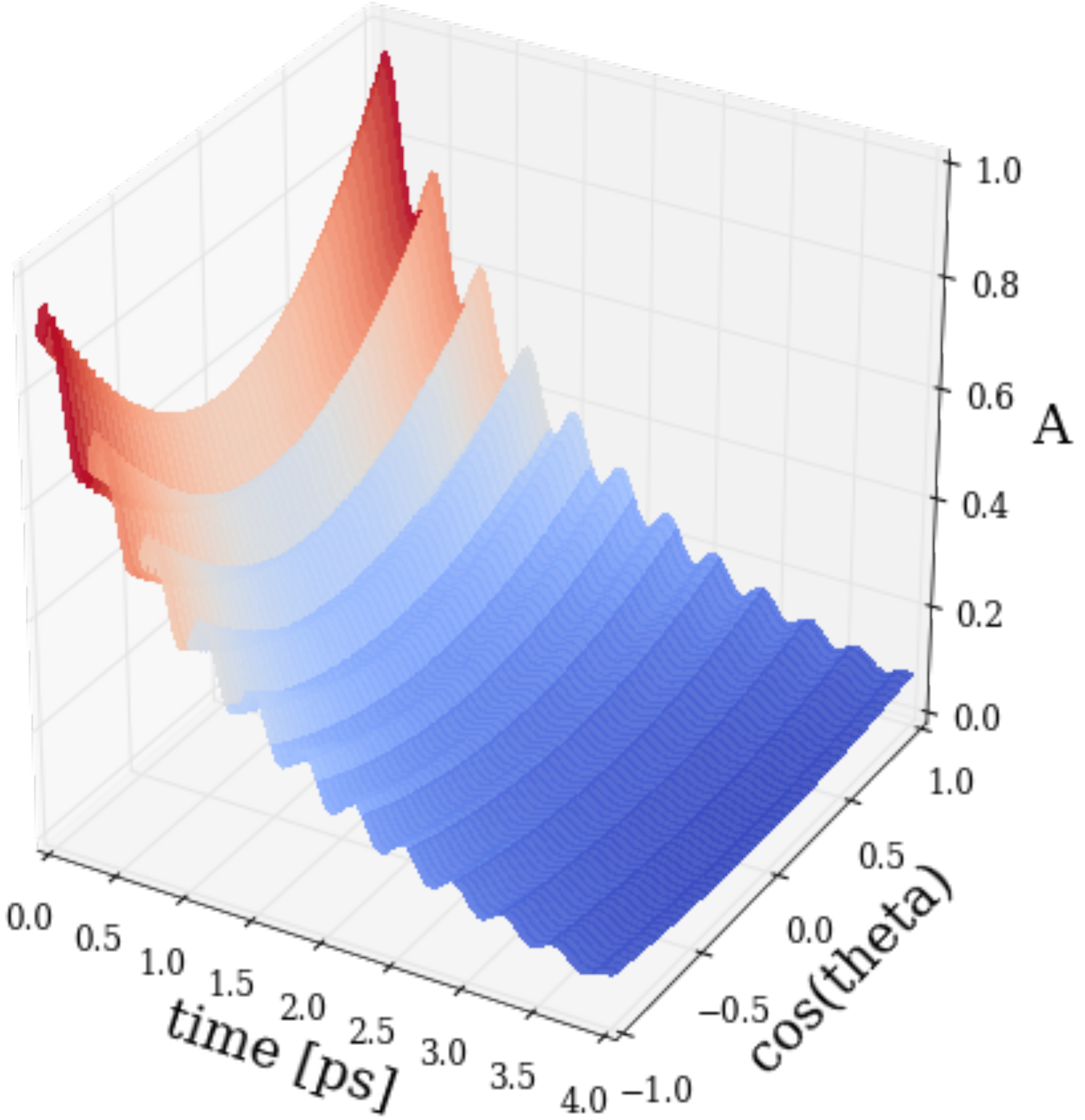
Golden mode: $B^0{}_s \to J/\psi\phi$, but need angular analysis to separate CP-odd/even components as we have two vectors in final state and small K^+K^- S-wave

Bonus feature: measure ϕ_s, $\Delta\Gamma_s$, Γ_s, Δm_s

New physics is not large → stat-limited so need **increased precision** and to control size of penguin contributions



$$\text{CP}|\,\text{J}/\psi\phi\rangle_\ell \quad = \quad (-1)^\ell|\,\text{J}/\psi\phi\rangle_\ell$$



Measuring ϕ_s

Golden mode: $B^0{}_s \to J/\psi\phi$, but need angular analysis to separate CP-odd/even components as we have two vectors in final state and small K^+K^- S-wave

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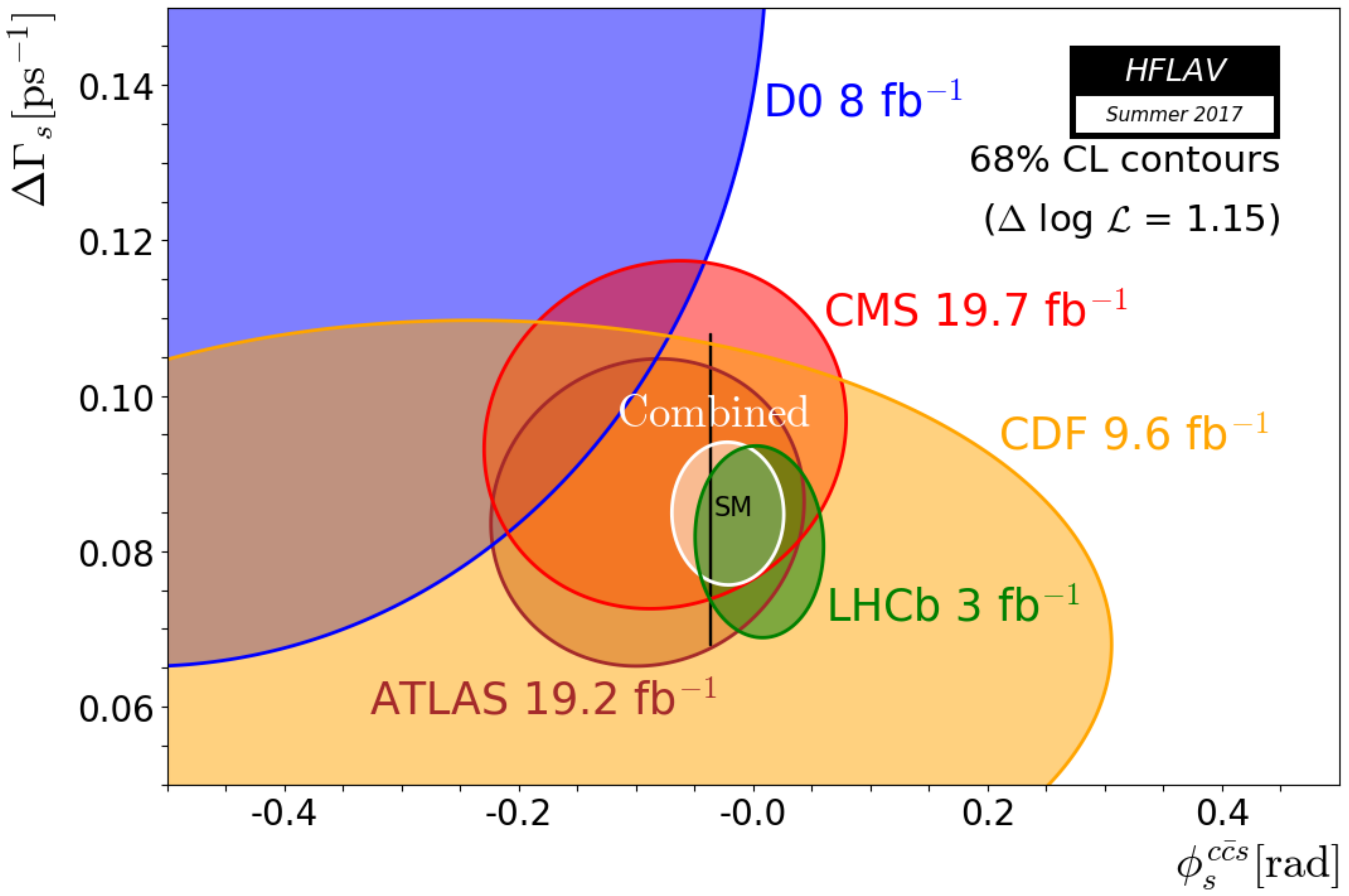
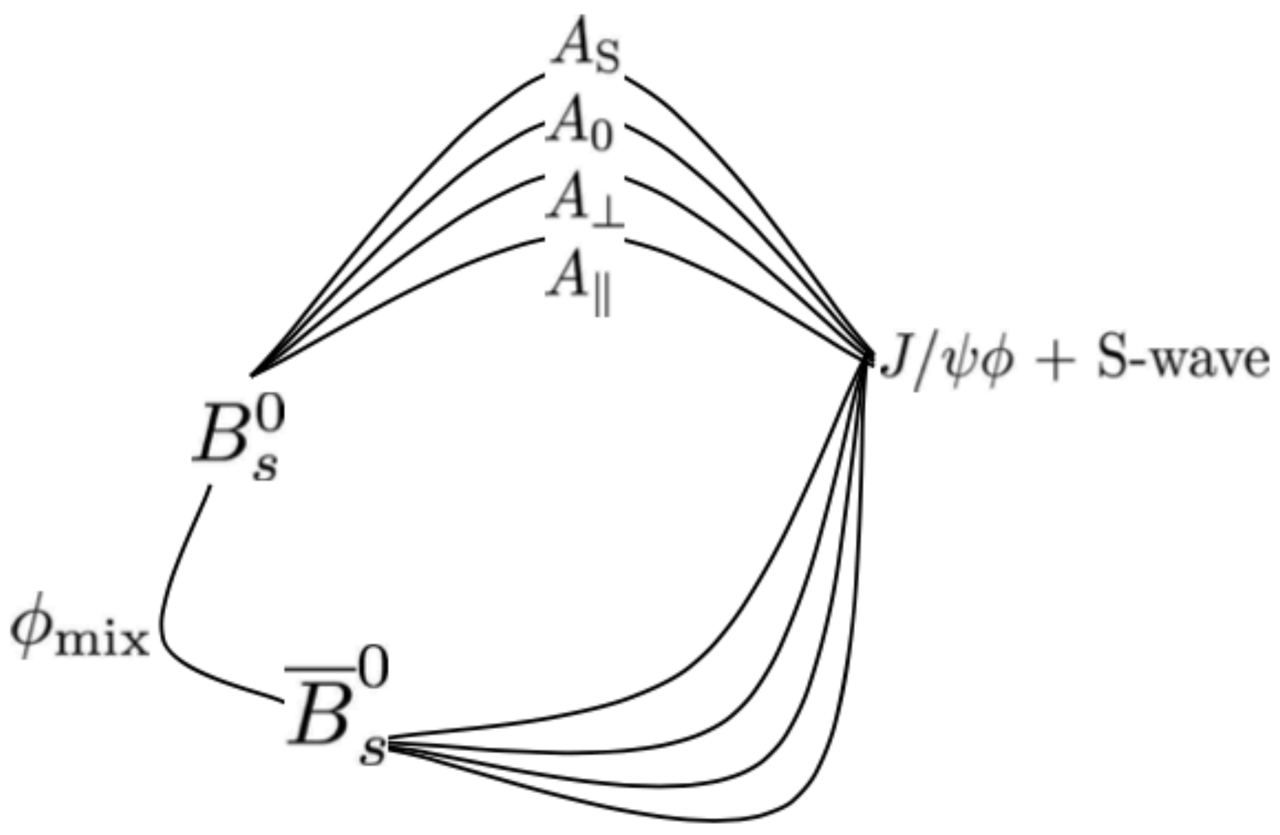




$$\mathrm{CP}|\,\mathrm{J}/\psi\phi\rangle_\ell \quad = \quad (-1)^\ell|\,\mathrm{J}/\psi\phi\rangle_\ell$$

[HFLAV]

$$\phi_s = -21 \pm 31\,\mathrm{mrad}$$
$$\Delta\Gamma_s = 0.090 \pm 0.005\,\mathrm{ps}^{-1}$$

[CKMFitter]

$$\phi_s^{\mathrm{SM}} = -37.6^{+0.7}_{-0.8}\,\mathrm{mrad}$$

LHCb:

- $J/\psi\phi$ [PRL114, 041801 (2015)]
- $J/\psi K^+K^-$ [arXiv:1704.08217 (2017)]
- $J/\psi\pi^+\pi^-$ [Phys. Lett. B736, (2014) 186]
- $\psi(2S)\phi$ [Phys. Lett. B762 (2016) 253-262]
- $D_s^+D_s^-$ [PRL113, 211801 (2014)]

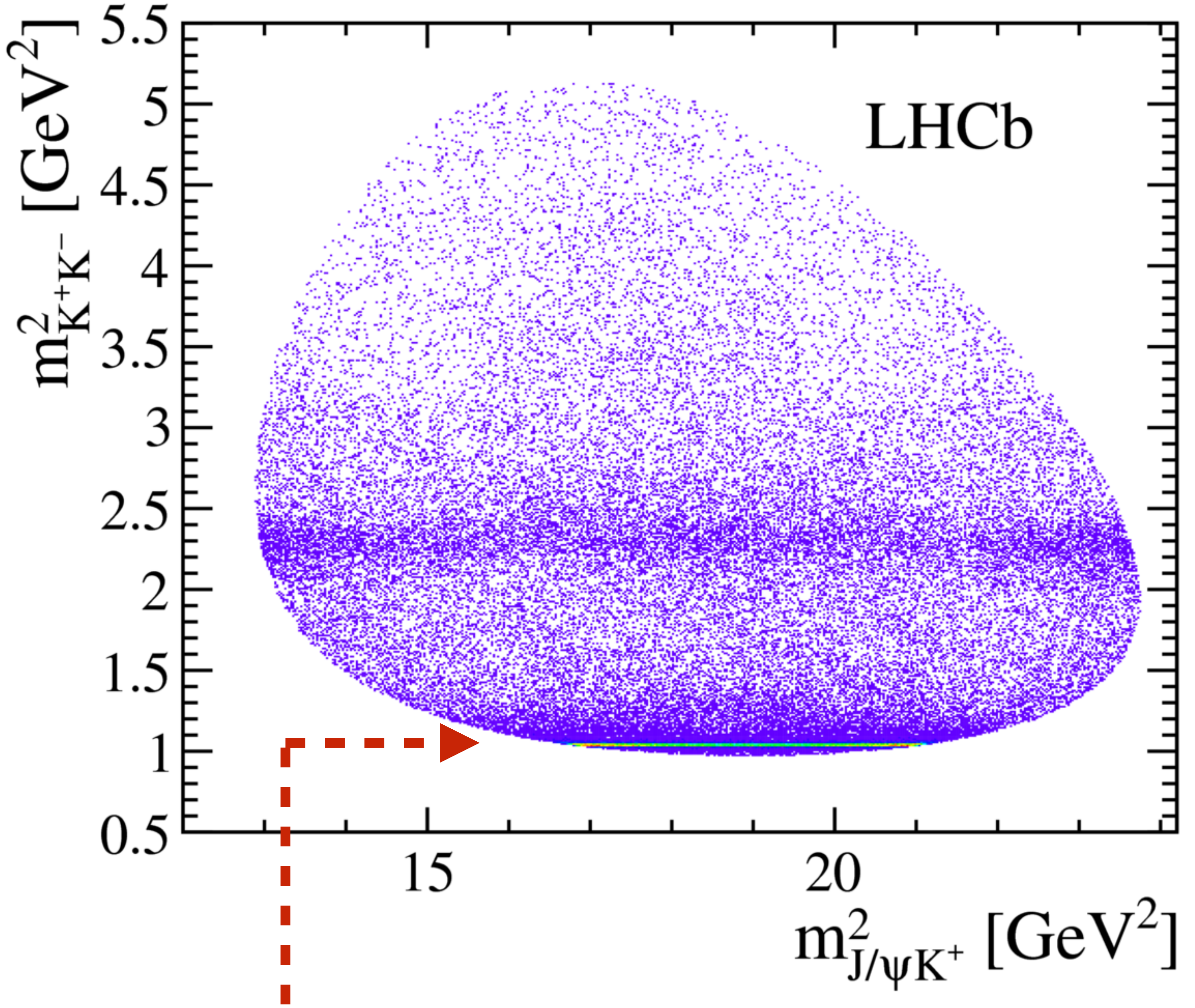
CMS:

- $J/\psi\phi$ [Phys. Lett. B 757 (2016) 97]

ATLAS:

- $J/\psi\phi$ [JHEP 08 (2016) 147]

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



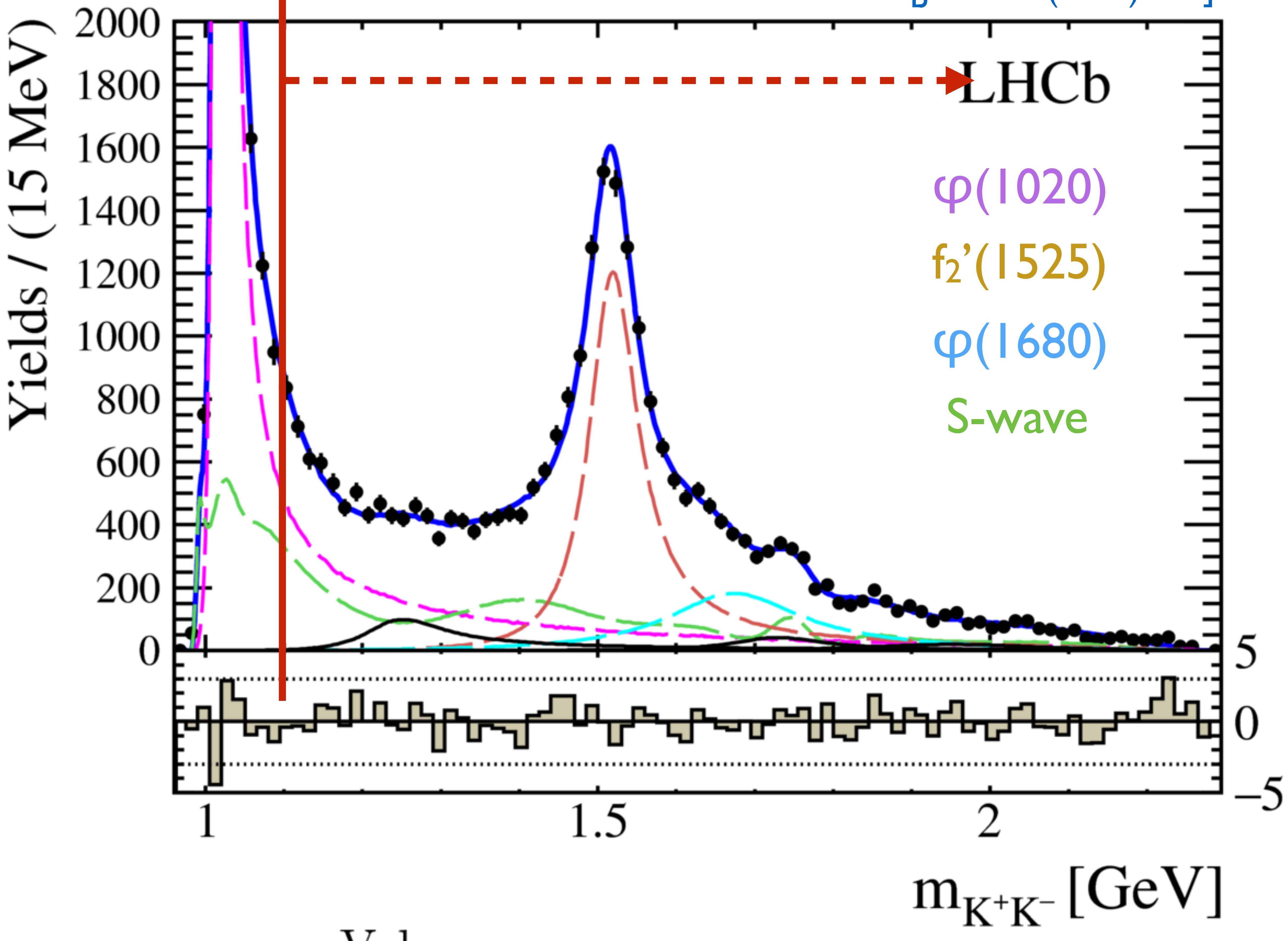
Previous studies focussed on low-mass region where $\phi(1020)$ dominates over a small KK S-wave

Use time-dependent amplitude analysis to increase sensitivity to ϕ_s using high $m(KK)$ region

[Stone, Zhang, PLB 719 (2013) 383]

Use full spectrum to increase precision

[JHEP 08 (2017) 037]



Parameter	Value
Γ_s [ps^{-1}]	$0.650 \pm 0.006 \pm 0.004$
$\Delta\Gamma_s$ [ps^{-1}]	$0.066 \pm 0.018 \pm 0.010$
ϕ_s [mrad]	$119 \pm 107 \pm 34$
$\lvert\lambda\rvert$	$0.994 \pm 0.018 \pm 0.006$

~2x larger uncertainty than the $B^0_s \to J/\psi\phi$ analysis

Systematics from **resonance line-shapes**

ϕ_s ultimate precision

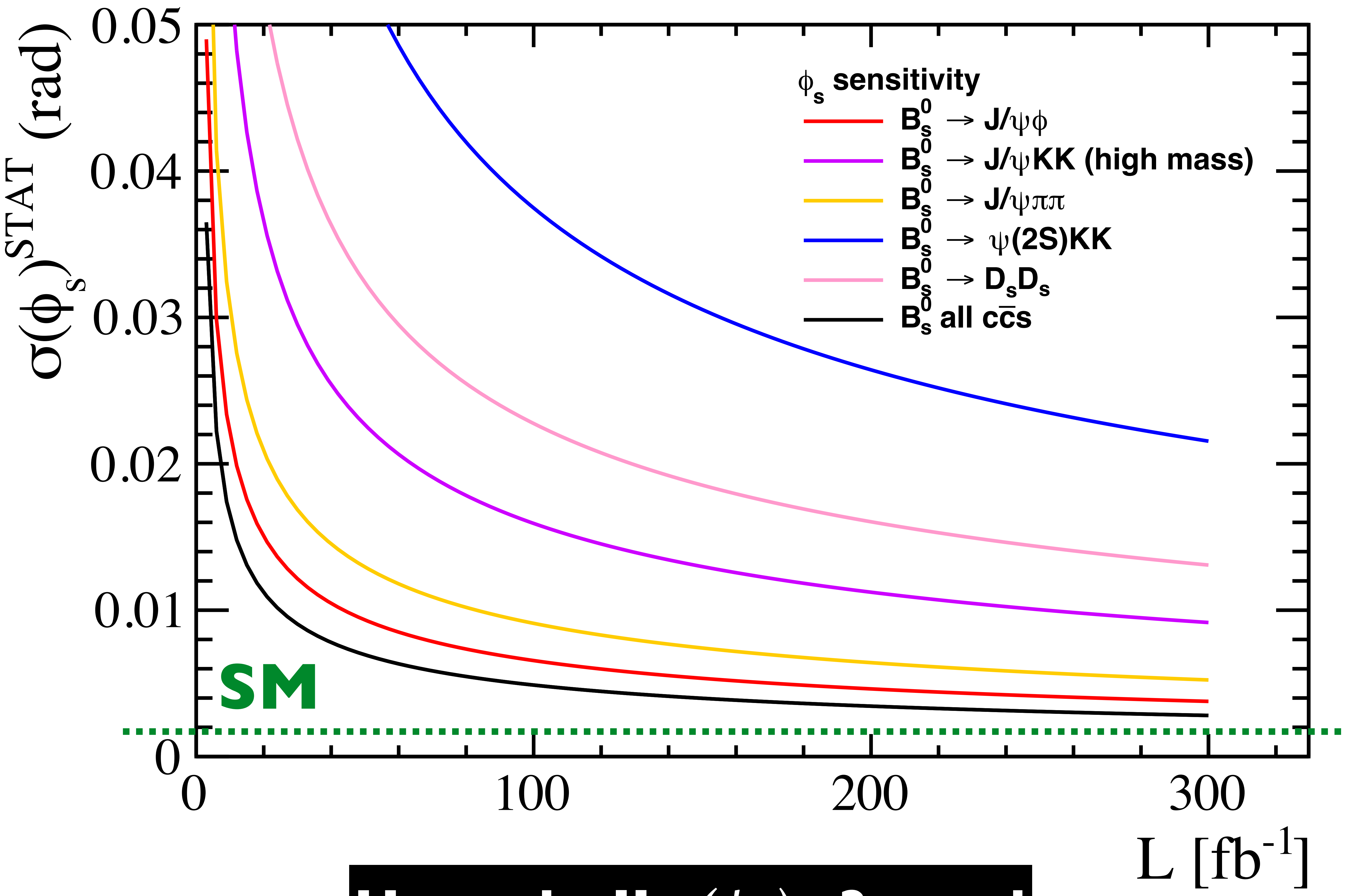
Scaling of current precision using current detector and expected running conditions

$B^0{}_s \to J/\psi KK$ and $B^0{}_s \to J/\psi\pi\pi$ will remain the dominant modes

Currently stat dominated, but must be able to control systematics (efficiencies and resolutions)

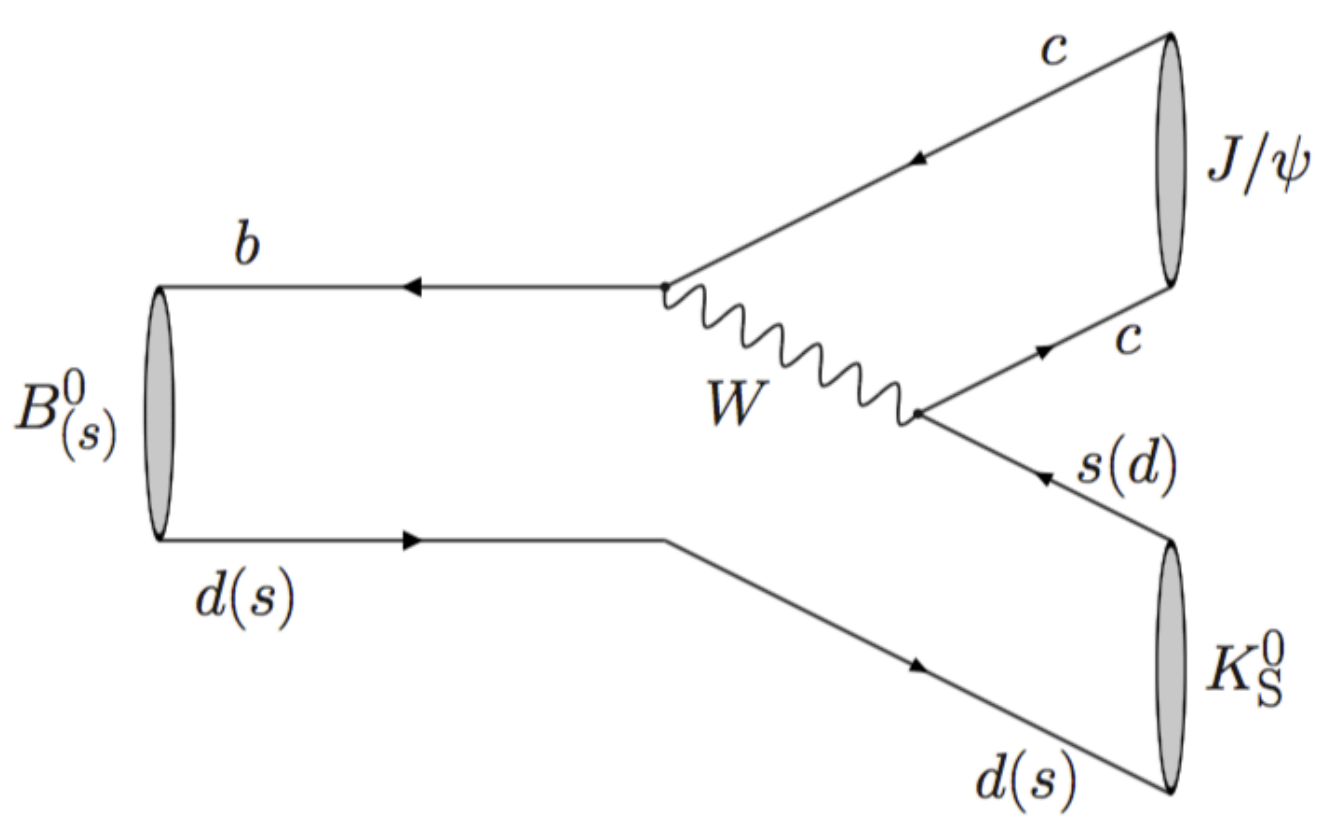
Hadronic trigger improvements in upgrade will help $B_s \to D_s D_s$ and if we can use timing to improve photon reconstruction in LHCb upgrade-II then $B_s{}^0 \to J/\psi\eta$ becomes interesting (no angular analysis needed for both channels)

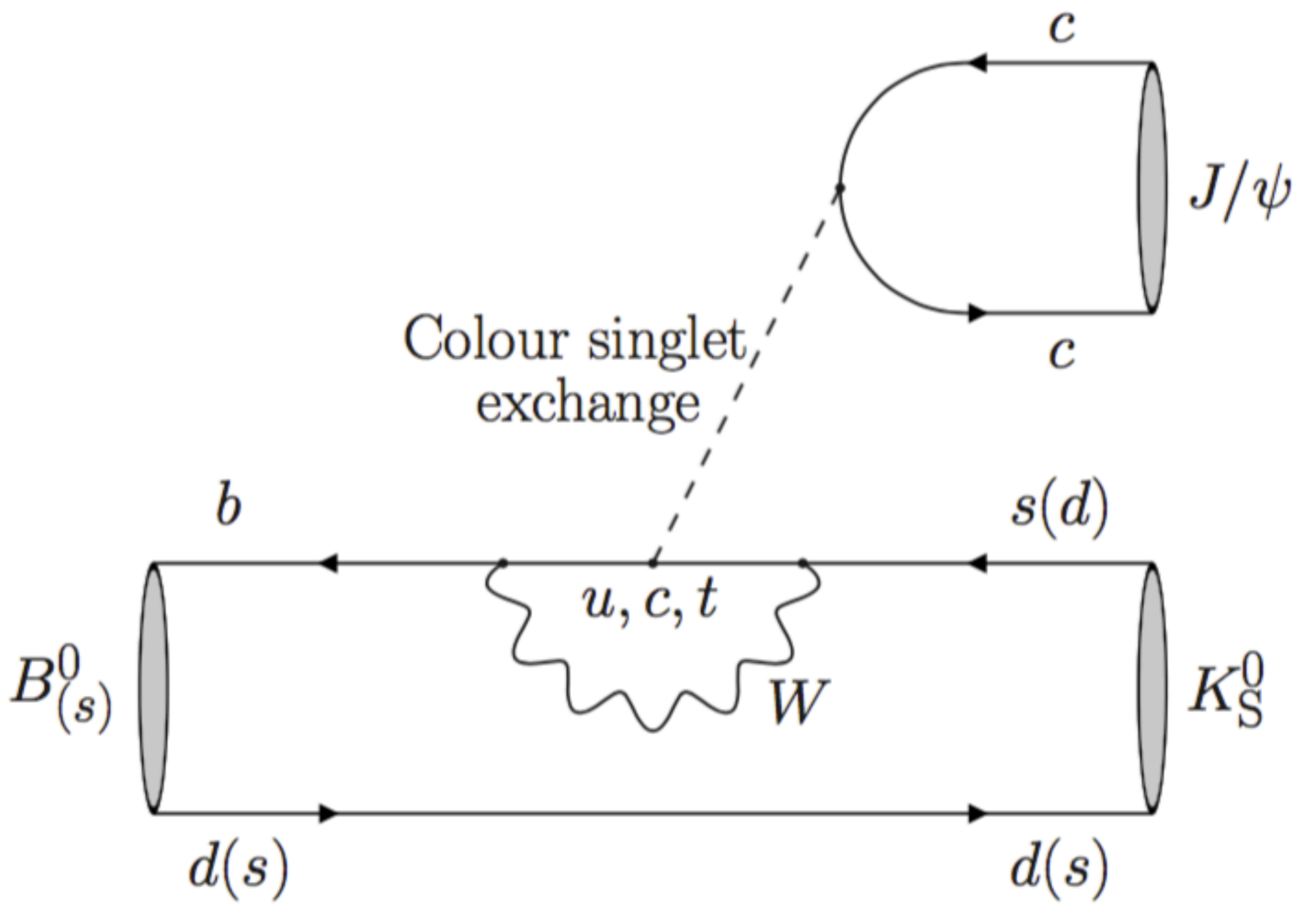
[PRL 113 (2014) 211801] [PLB 762C (2016) 484]



Upgrade-II $\sigma(\phi_s)$ ~3 mrad

Penguin pollution roadmap: ϕ_d





[De Bruyn, Fleischer, JHEP 03 (2015) 145]

$$\boxed{A\left(B_d^0 \to J/\psi K_S^0\right) = \left(1 - \frac{\lambda^2}{2}\right) \mathcal{A}' \left[1 + \epsilon a' e^{i\theta'} e^{i\gamma}\right]}$$

$$\boxed{A\left(B_s^0 \to J/\psi K_S^0\right) = -\lambda \mathcal{A} \left[1 - a e^{i\theta} e^{i\gamma}\right]}$$

suppression in the overall rate

no penguin suppression

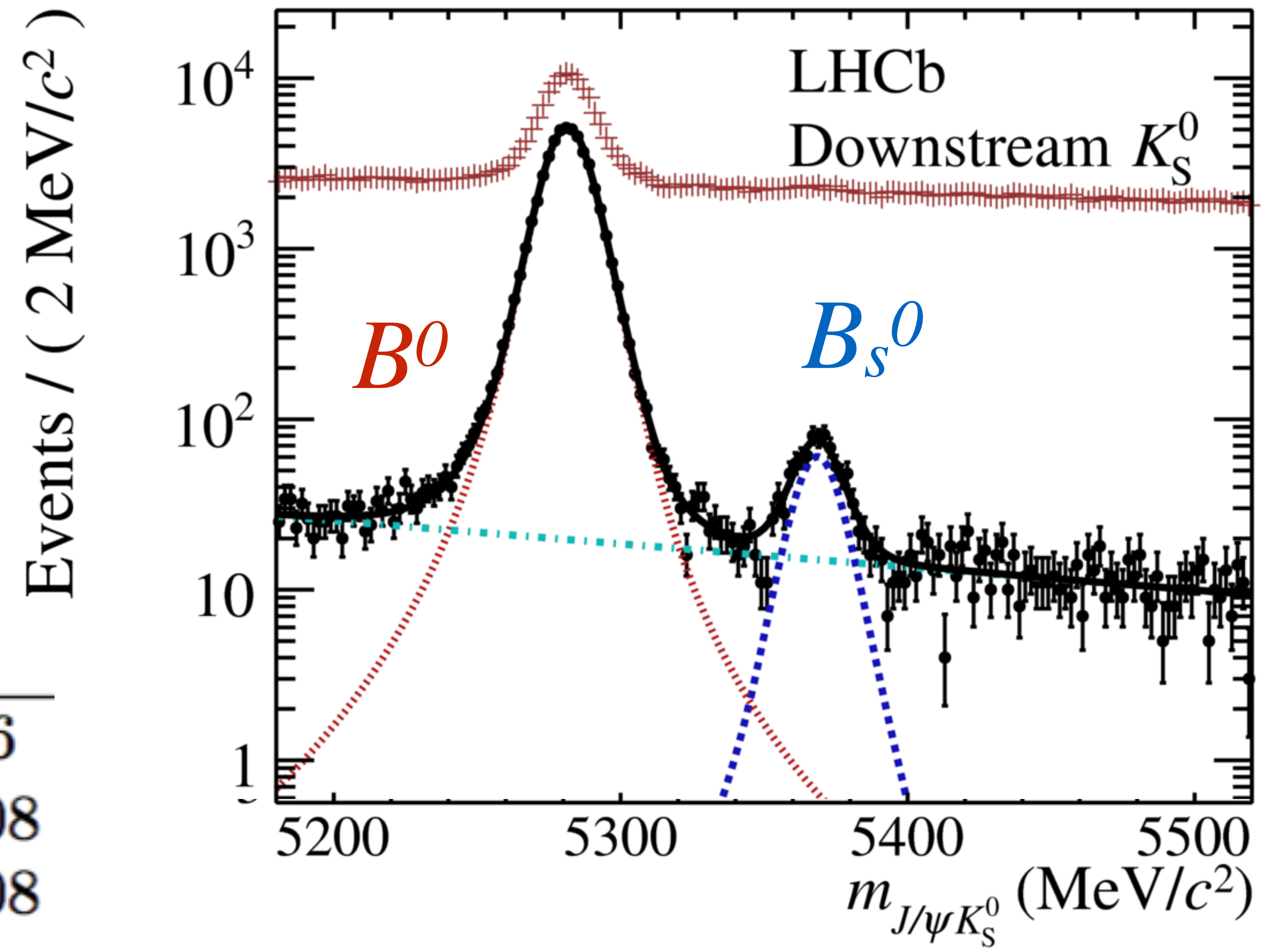
ε~5%

U-spin or SU(3) **flavour symmetry** (+ dynamically assumptions) to constrain size of penguin with $b \to c\bar{c}d$ or **compute** them with OPE, QCD- factorisation

$B_s^0 \to J/\psi K_S$ and $B^0 \to J/\psi K_S$ are U-spin partners → control penguins in ϕ_d, but limited precision with Run 1 data

Improved K_S reconstruction in LHCb upgrade will help

Param	Fitted value
$A_{\Delta\Gamma}$	$0.49^{+0.77}_{-0.65} \pm 0.06$
C_{dir}	$-0.28 \pm 0.41 \pm 0.08$
S_{mix}	$-0.08 \pm 0.40 \pm 0.08$

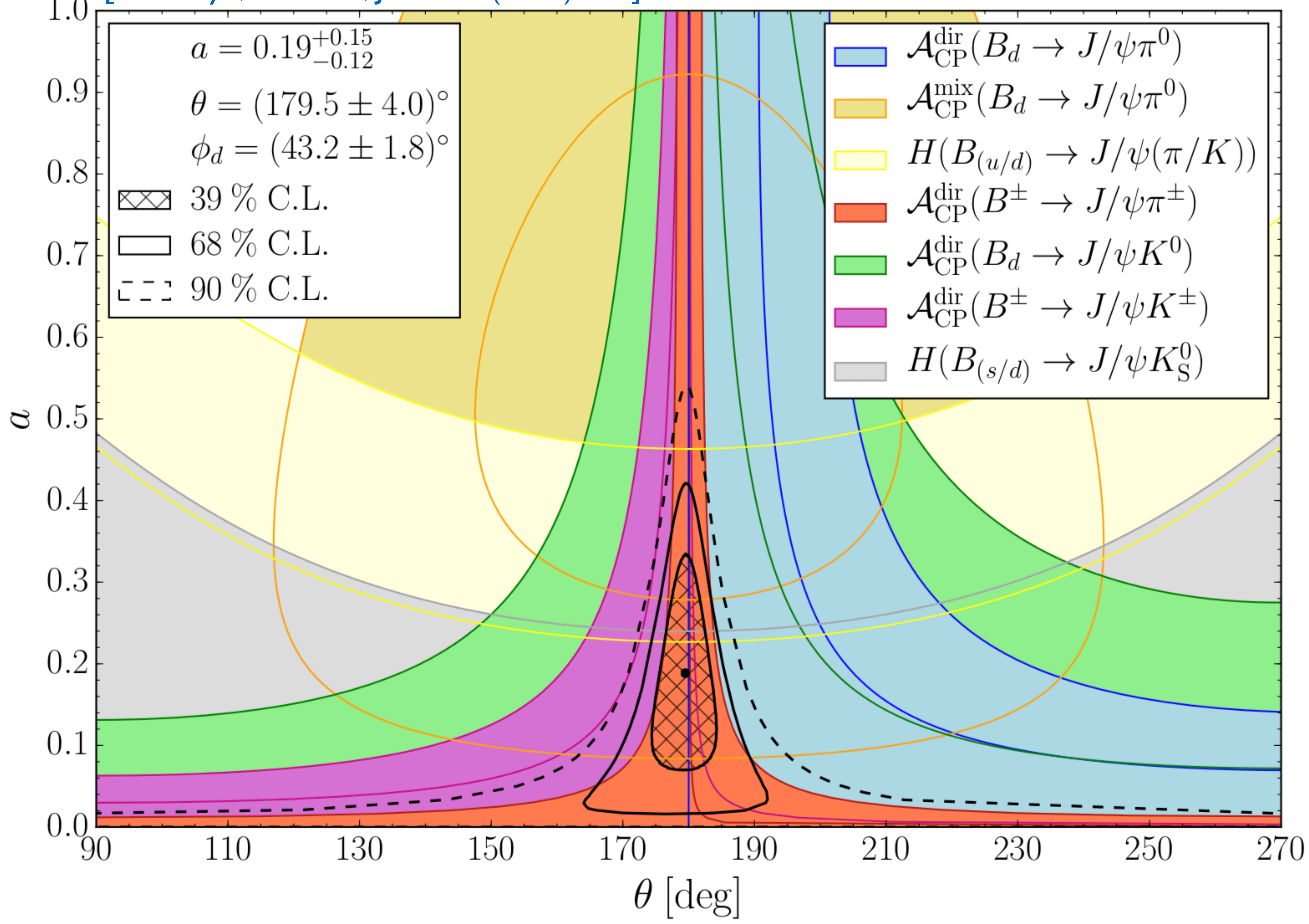


[JHEP 06 (2015) 131]

$$\boxed{\phi_d = 2\beta + \Delta\phi_d^{pen} + \Delta\phi_d^{NP}}$$

Penguin pollution roadmap: ϕ_d

[De Bruyn, Fleischer, JHEP 03 (2015) 145]



$$\Delta\phi_d^{\psi K^0_{\rm S}} = -\left(1.10^{+0.70}_{-0.85}\right)^\circ$$

Small penguin shift but experimental precision is $\sigma(\phi_d) \sim 1.6^\circ$ so must continue to improve

Limited precision from $B_s \to J/\psi K_S$ limited but can place constraints on penguin size from direct/mixing CP asymmetries (A_{CP}) and ratios of BRs (H) of $B \to J/\psi X$ decays, e.g.,

Mostly Kπ detector asymmetry

$$\mathcal{A}_{CP}(B^+ \to J/\psi K^+) = (0.09 \pm 0.27 \pm 0.07) \times 10^{-2}$$
$$\mathcal{A}^{CP}(B^+ \to J/\psi \pi^+) = (1.91 \pm 0.89 \pm 0.16) \times 10^{-2}$$

[LHCb PRD 95 (2017) 052005] [LHCb JHEP 03 (2017) 036]

E + PA amplitudes must be neglected in $B^0 \to J/\psi\pi^0$ as they have no counterpart in $B^0 \to J/\psi K_S$. These effects are should be tiny and can be probed through $B^0{}_{(s)} \to J/\psi\pi^0$ and $B^0 \to J/\psi\rho^0$ in the future

$$S(J/\psi\pi^0)\ \sigma = 0.027\ (\text{stat}) \pm 0.027\ (\text{syst})$$
$$A(J/\psi\pi^0)\ \sigma = 0.035\ (\text{stat}) \pm 0.017\ (\text{syst})$$

[Belle-II projections @ 50 ab-1 from A. Gaz, P. Urquijo, L Li Gioi]

Penguin pollution roadmap: ϕ_s

Relax assumption that $\lambda_f \equiv \eta_f (q/p)(\bar{A}_f/A_f)$ is same for all $(J/\psi K^+K^-)_f$ polarisations → measure $\lambda_f = |\lambda_f| \exp(-i\phi_s^f)$, but this shows **no sign of polarisation dependence**

[PRL 114 (2015) 041801]

SU(3)$_f$ **:** $B_s^0 \to J/\psi K^*$ and $B^0 \to J/\psi \rho^0$ are $b \to c\bar{c}d$ transitions (related by s-d spectator exchange). $B^0 \to J/\psi \rho^0$ contains E + PA diagrams that are not present in $B_s^0 \to J/\psi K^*$

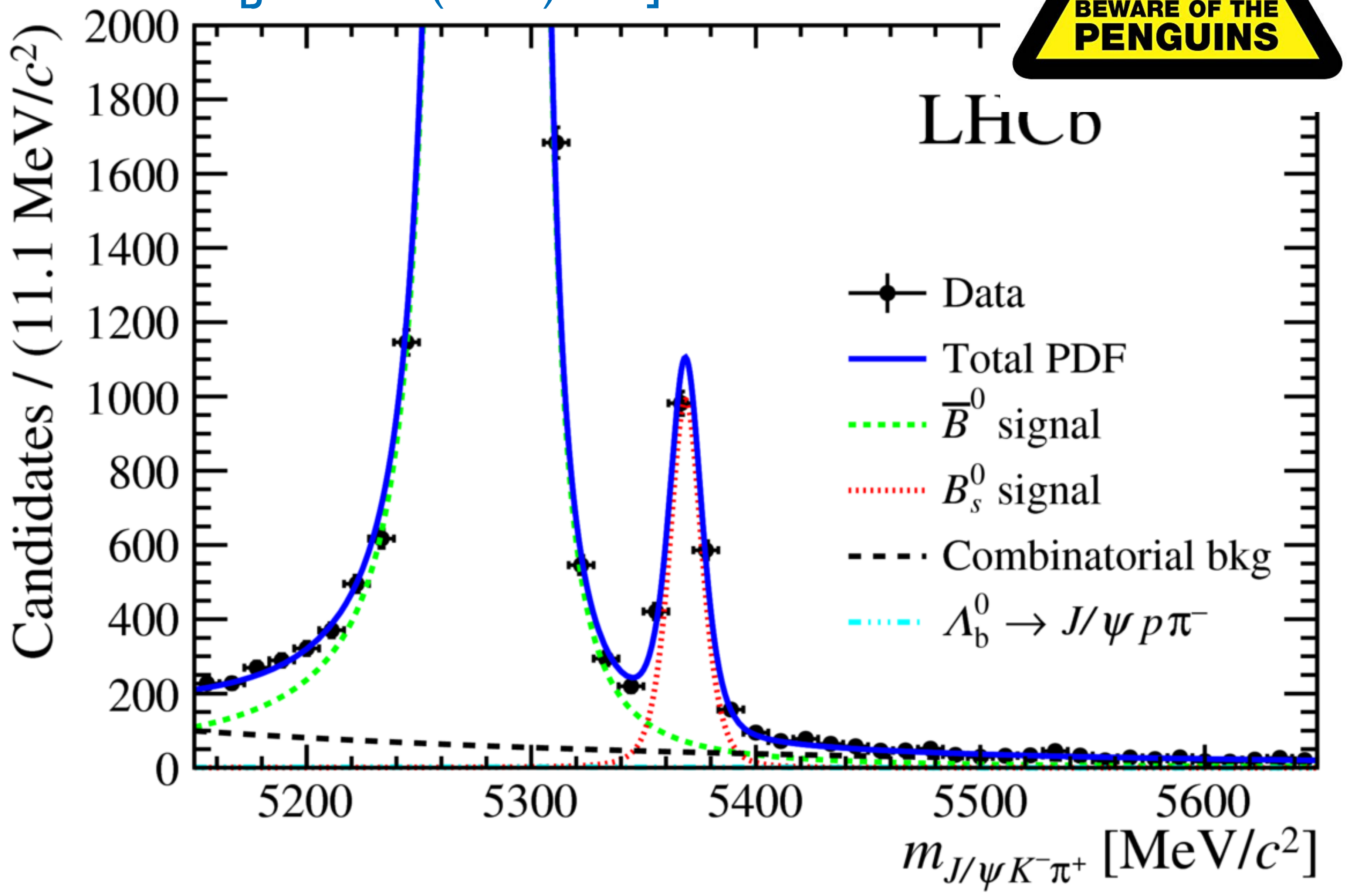
Measure penguin phase shift for each polarisation state, $f \in (0, \perp, \parallel, S)$

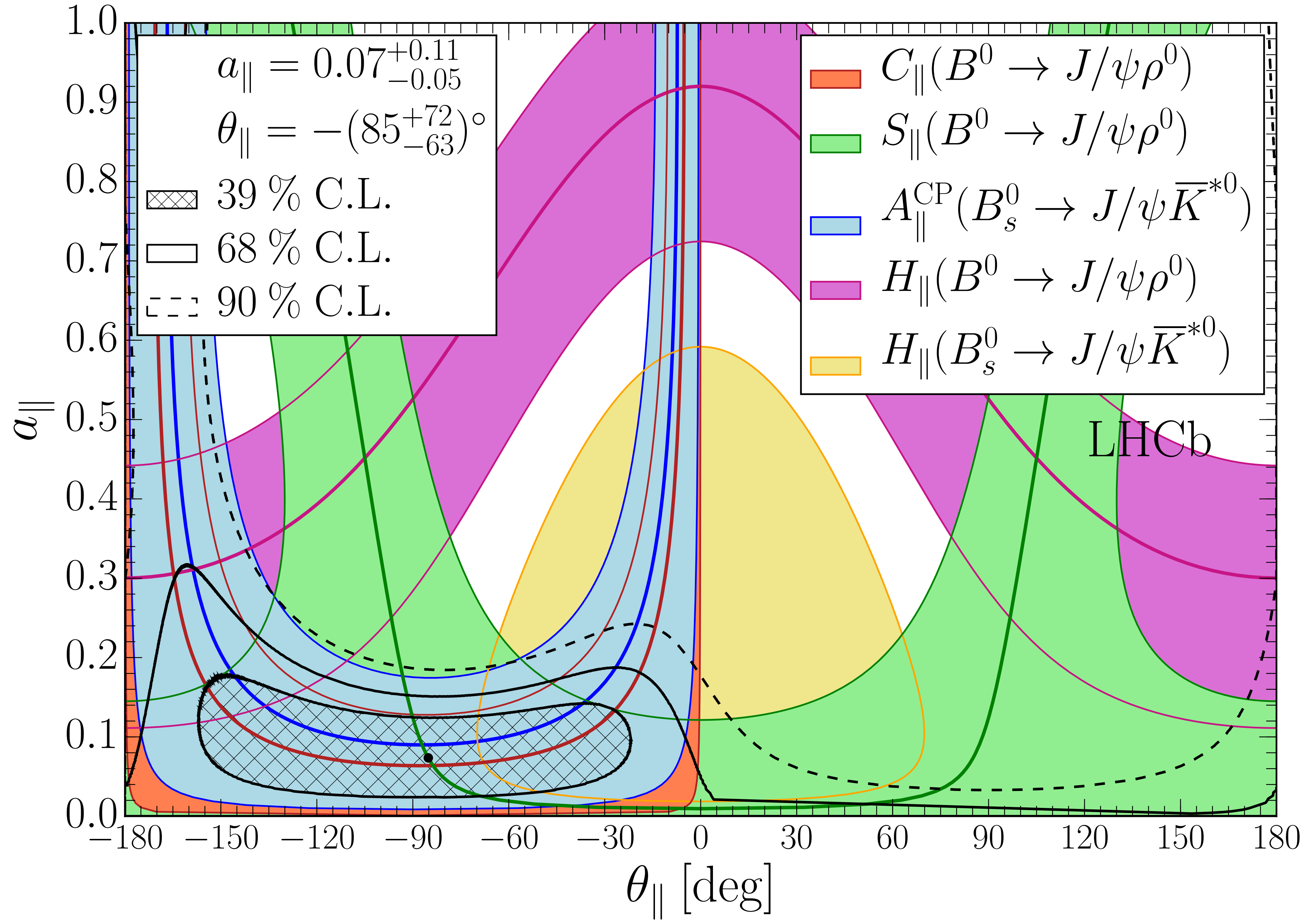
$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}\,(\text{stat})\ {}^{+0.004}_{-0.009}\,(\text{syst})\ \text{rad}$$
$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\ \text{rad}$$
$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\ \text{rad}$$

[JHEP 11 (2015) 082]

Small penguin shift (~0.06°) to be compared with current experimental precision is $\sigma(\phi_s)$ ~ 0.03 rad

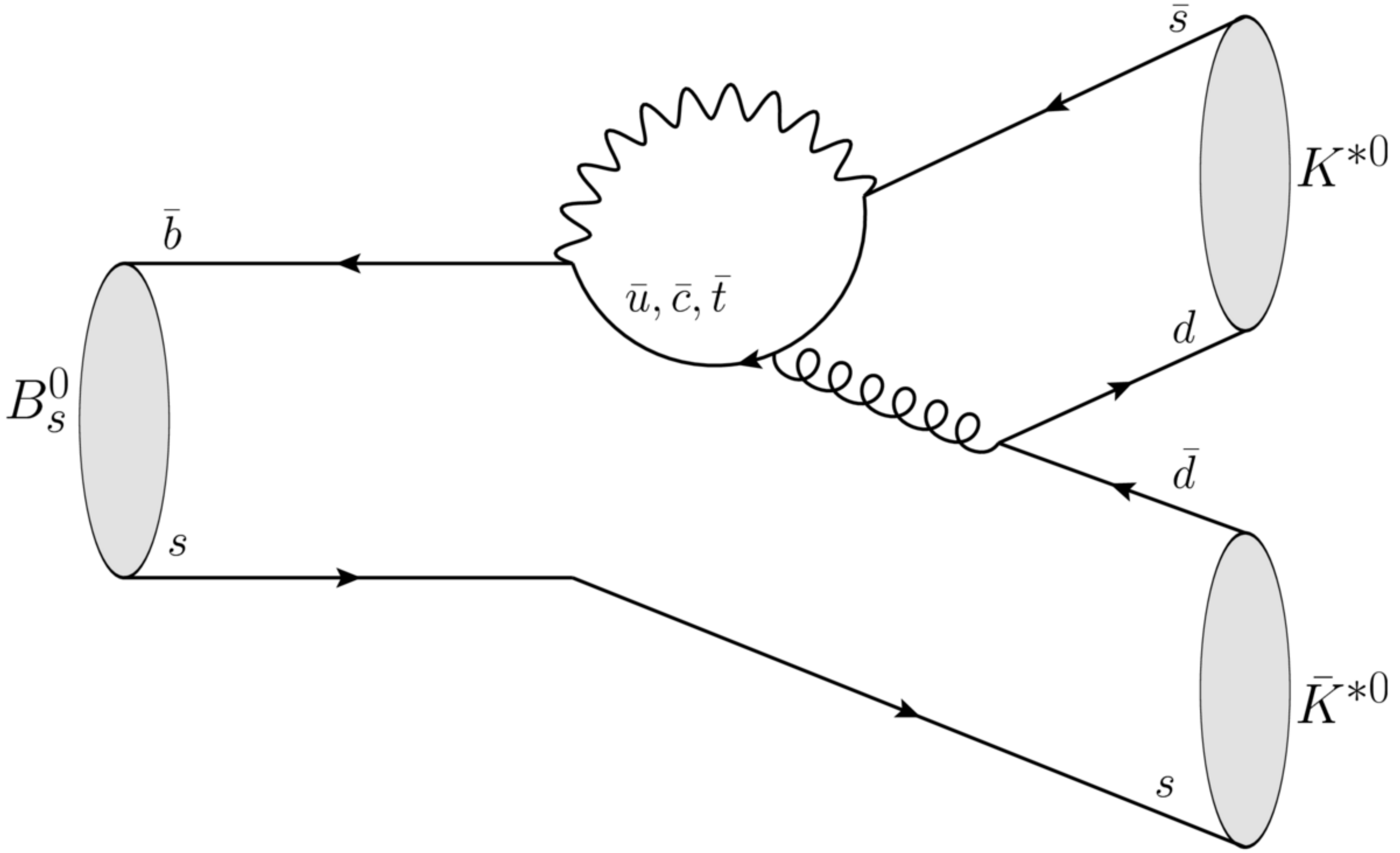
[JHEP 11 (2015) 082]

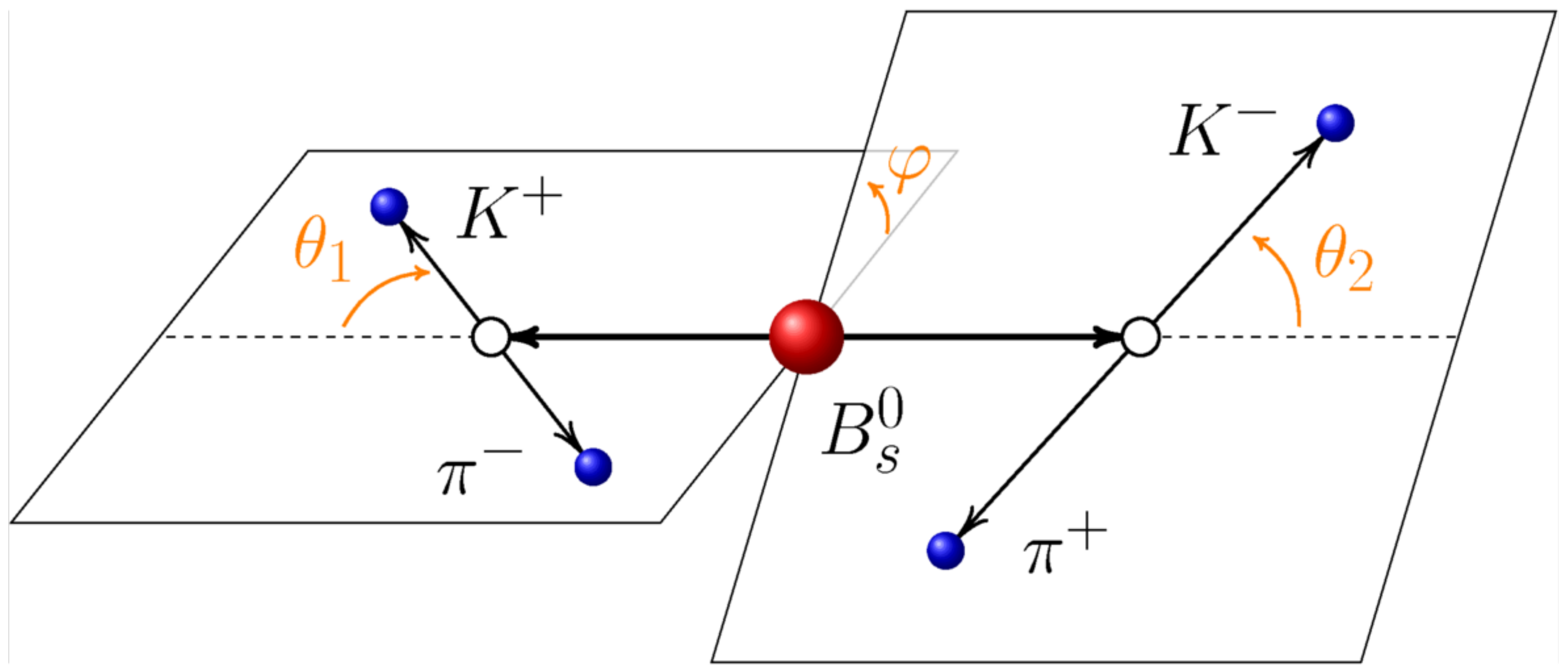




$\phi_s^{q\bar{q}}$ from loop-dominated B_s^0 decays

[JHEP 03 (2018) 140]
[LHCb-CONF-2018-001]





Measure CPV phase from mixing + decay in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$
and $B_s^0 \to \phi\phi \to (K^+K^-)(K^+K^-)$. Compare to $B^0_s \to J/\psi\phi$

$|\phi_s^{s\bar{s}}|^{SM} < 0.02$ rad

[Bartsch et al., arXiv:0810.0249]
[Beneke et al., NPB 774 (2007) 64]
[Cheng et al., PRD 80 (2009) 114026]

$\phi_s^{d\bar{d}}$ from $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$

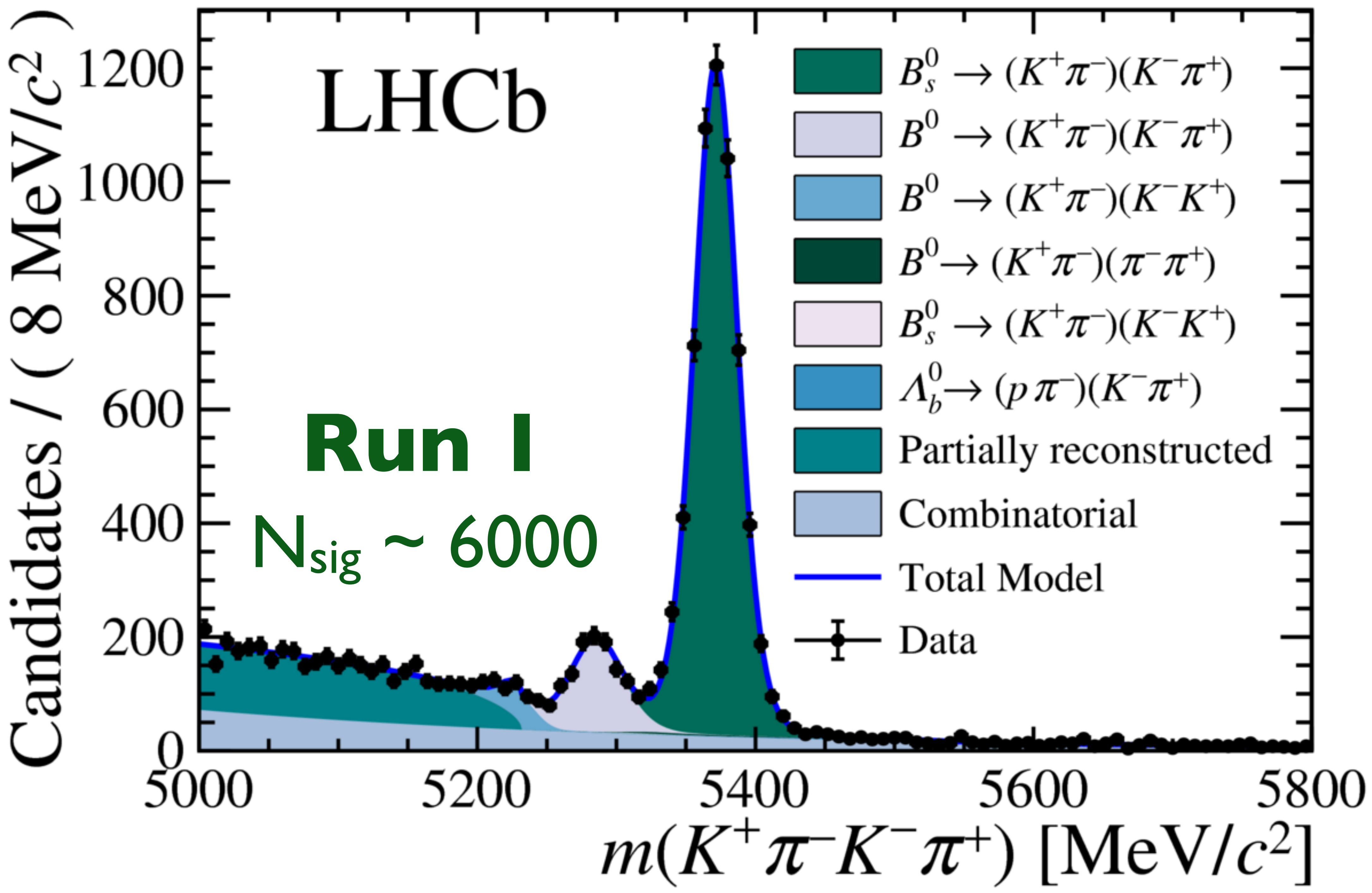
[JHEP 03 (2018) 140]

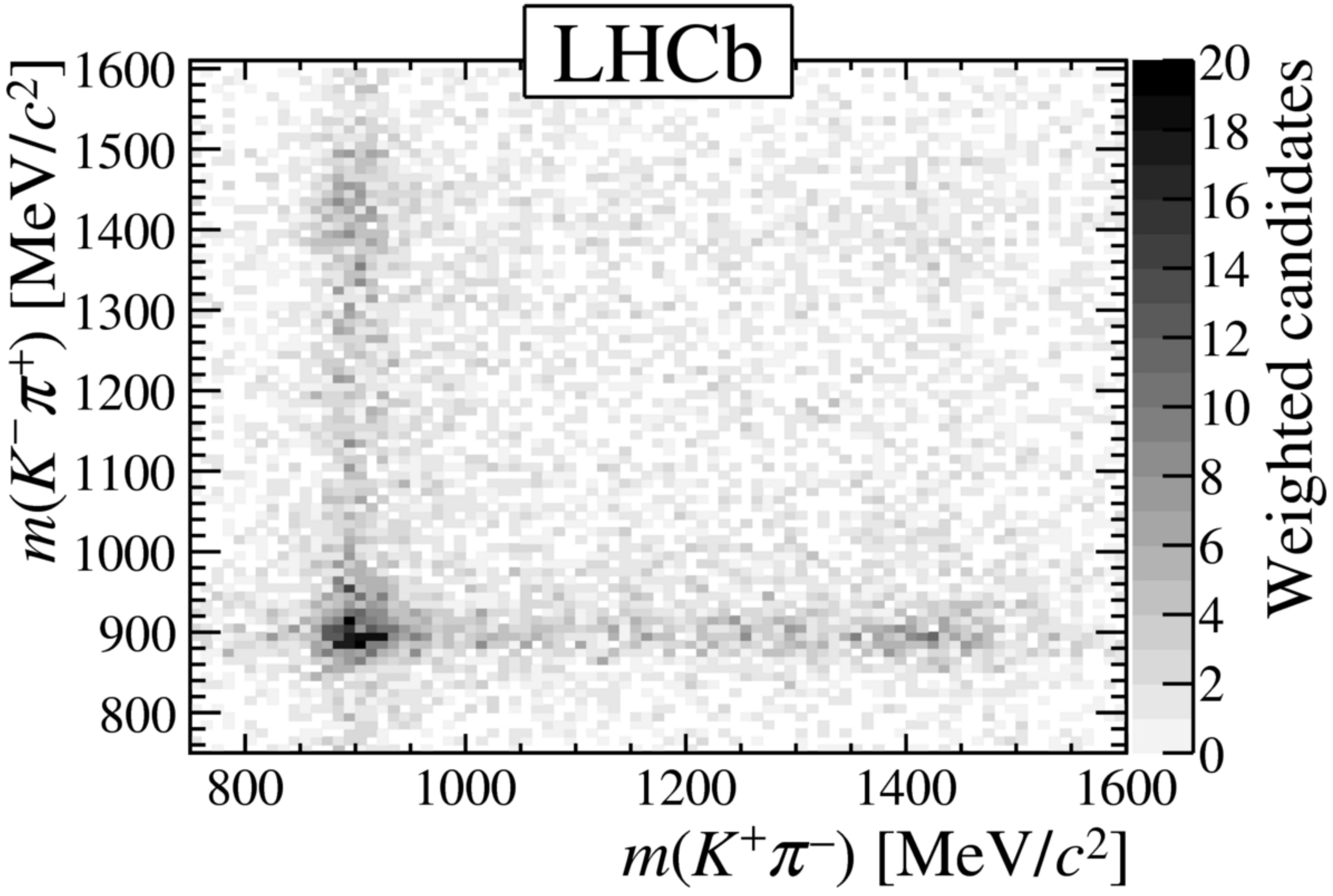
Flavour-tagged (ε_{tag}~5%), decay-time dependent amplitude analysis of the 4-body final state (6D to analyse)

Rich structure of interfering scalar/vector/tensor $K\pi$ resonances in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$, including $K_0^*(1430)^0$, $K^*(892)^0$, $K_2^*(1430)^0$

9 Q2B channels → 19 amplitudes

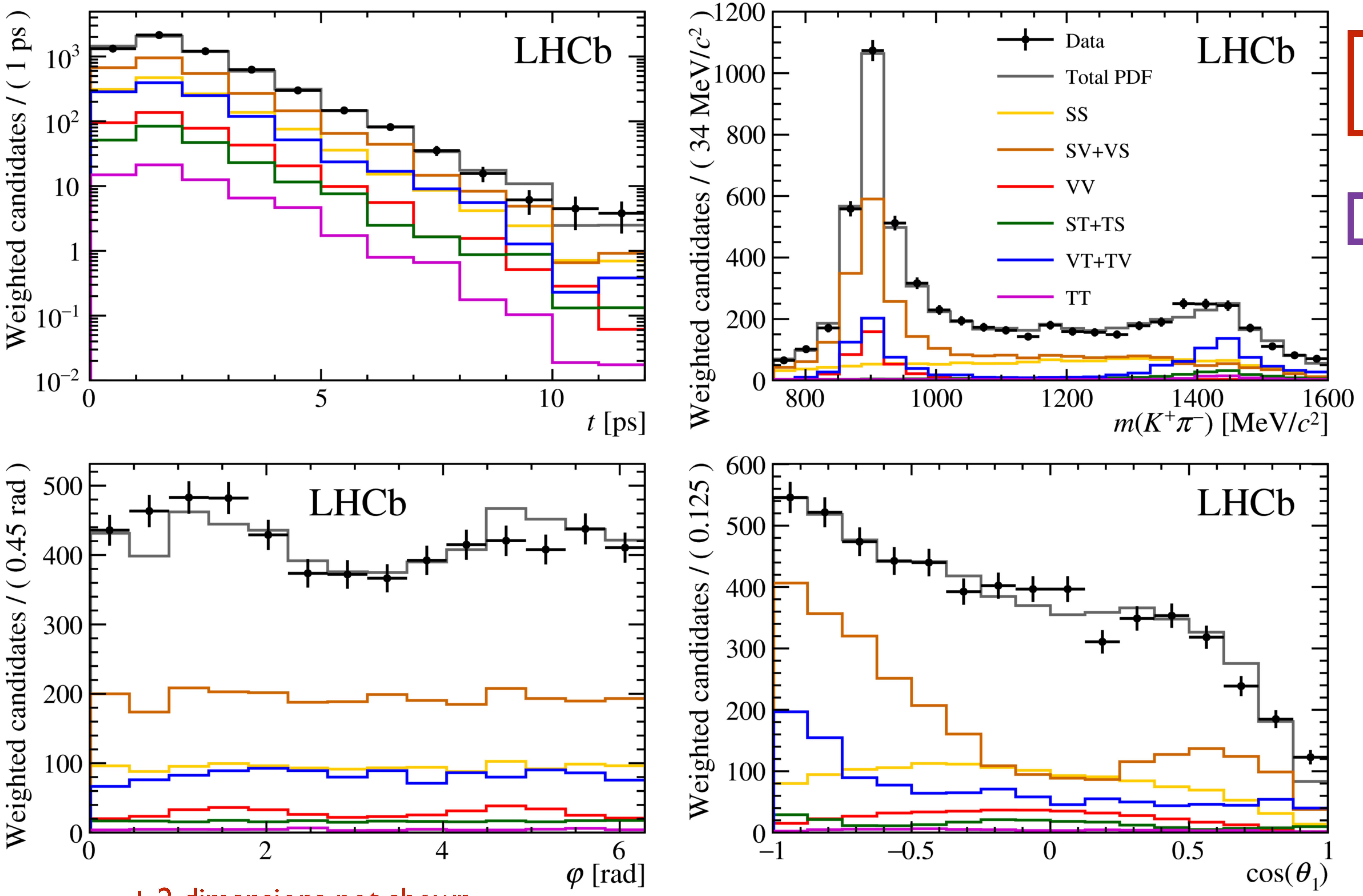
Excellent hadron-PID for bkg suppression





$\phi_s^{d\bar{d}}$ from $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$

[JHEP 03 (2018) 140]



+ 2 dimensions not shown

Parameter	Value
Common parameters	
$\phi_s^{d\bar{d}}$ [rad]	$-0.10 \pm 0.13 \pm 0.14$
$\lvert\lambda\rvert$	$1.035 \pm 0.034 \pm 0.089$
Vector/Vector (VV)	
f^{VV}	$0.067 \pm 0.004 \pm 0.024$
f_L^{VV}	$0.208 \pm 0.032 \pm 0.046$
$f_\parallel^{VV}$	$0.297 \pm 0.029 \pm 0.042$
$\delta_\parallel^{VV}$ [rad]	$2.40 \pm 0.11 \pm 0.33$
$\delta_\perp^{VV}$ [rad]	$2.62 \pm 0.26 \pm 0.64$
Scalar/Vector (SV and VS)	
f^{SV}	$0.329 \pm 0.015 \pm 0.071$
f^{VS}	$0.133 \pm 0.013 \pm 0.065$
δ^{SV} [rad]	$-1.31 \pm 0.10 \pm 0.35$
δ^{VS} [rad]	$1.86 \pm 0.11 \pm 0.41$
Scalar/Scalar (SS)	
f^{SS}	$0.225 \pm 0.010 \pm 0.069$
δ^{SS} [rad]	$1.07 \pm 0.10 \pm 0.40$
Scalar/Tensor (ST and TS)	
f^{ST}	$0.014 \pm 0.006 \pm 0.031$
f^{TS}	$0.025 \pm 0.007 \pm 0.033$
δ^{ST} [rad]	$-2.3 \pm 0.4 \pm 1.7$
δ^{TS} [rad]	$-0.10 \pm 0.26 \pm 0.82$

First CPV results

Small longitudinal VV fraction

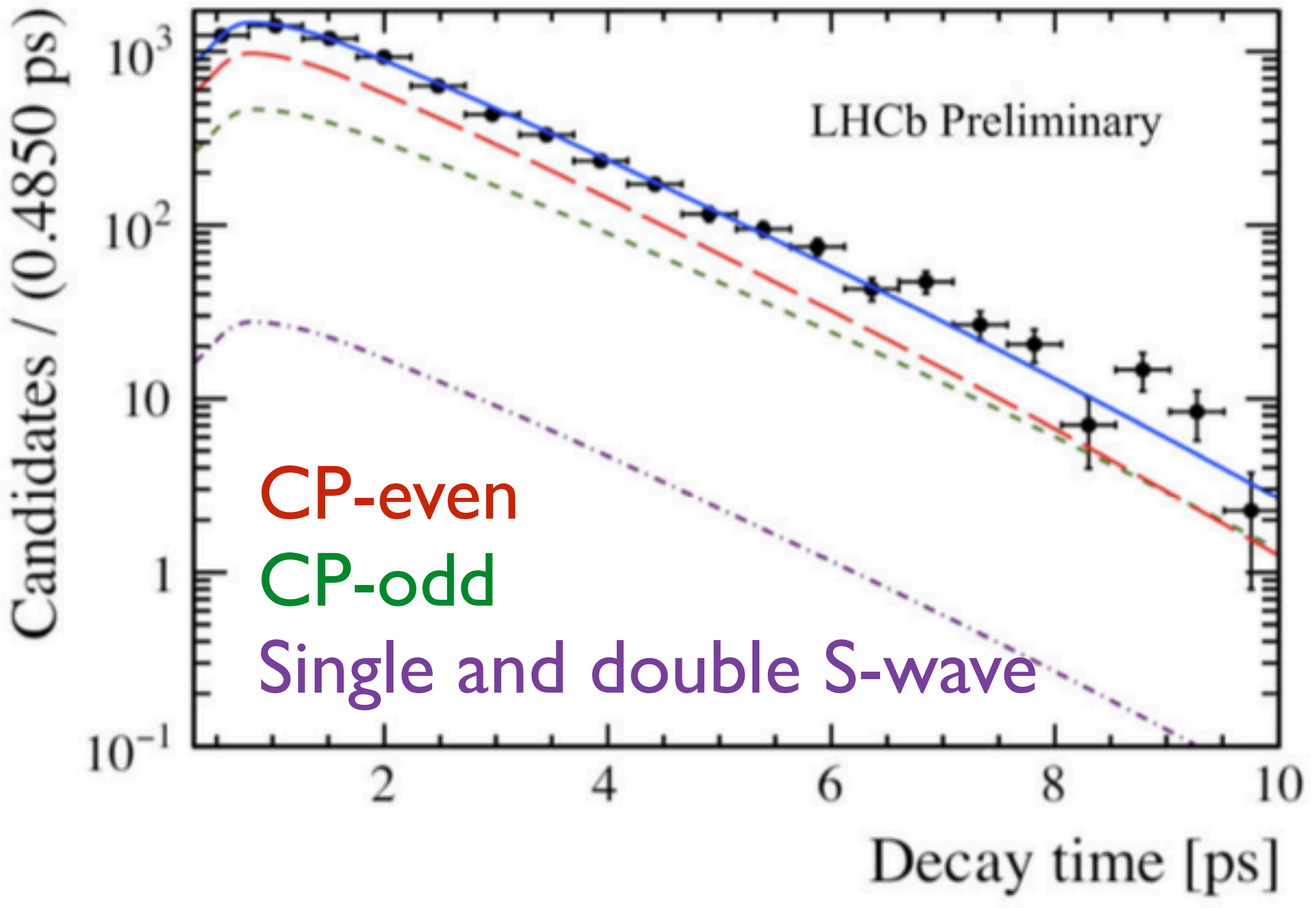
+ other results for fractions/phases of other Q2B amplitudes

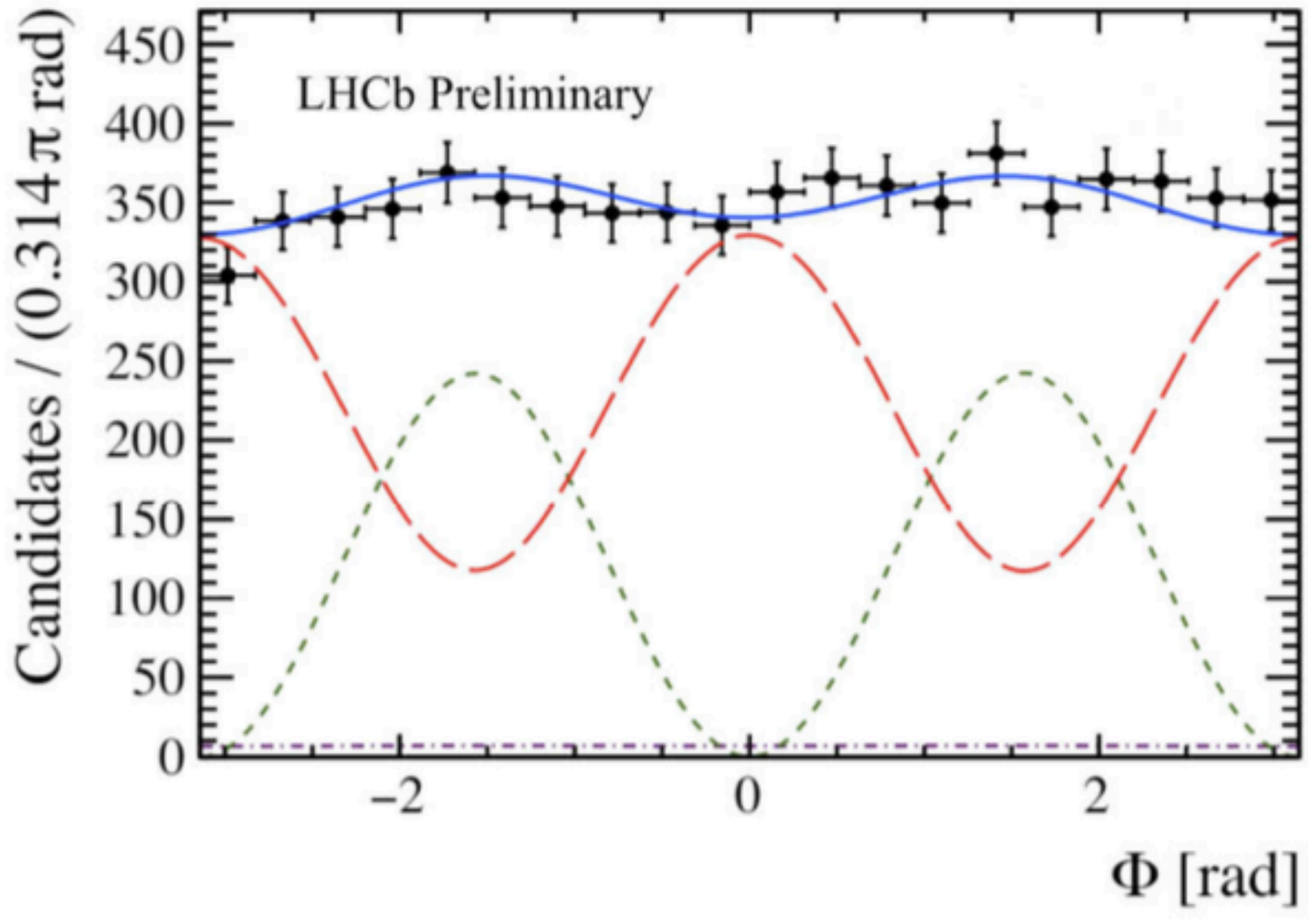
Systematic uncertainty dominated by modelling the angular efficiency from simulation

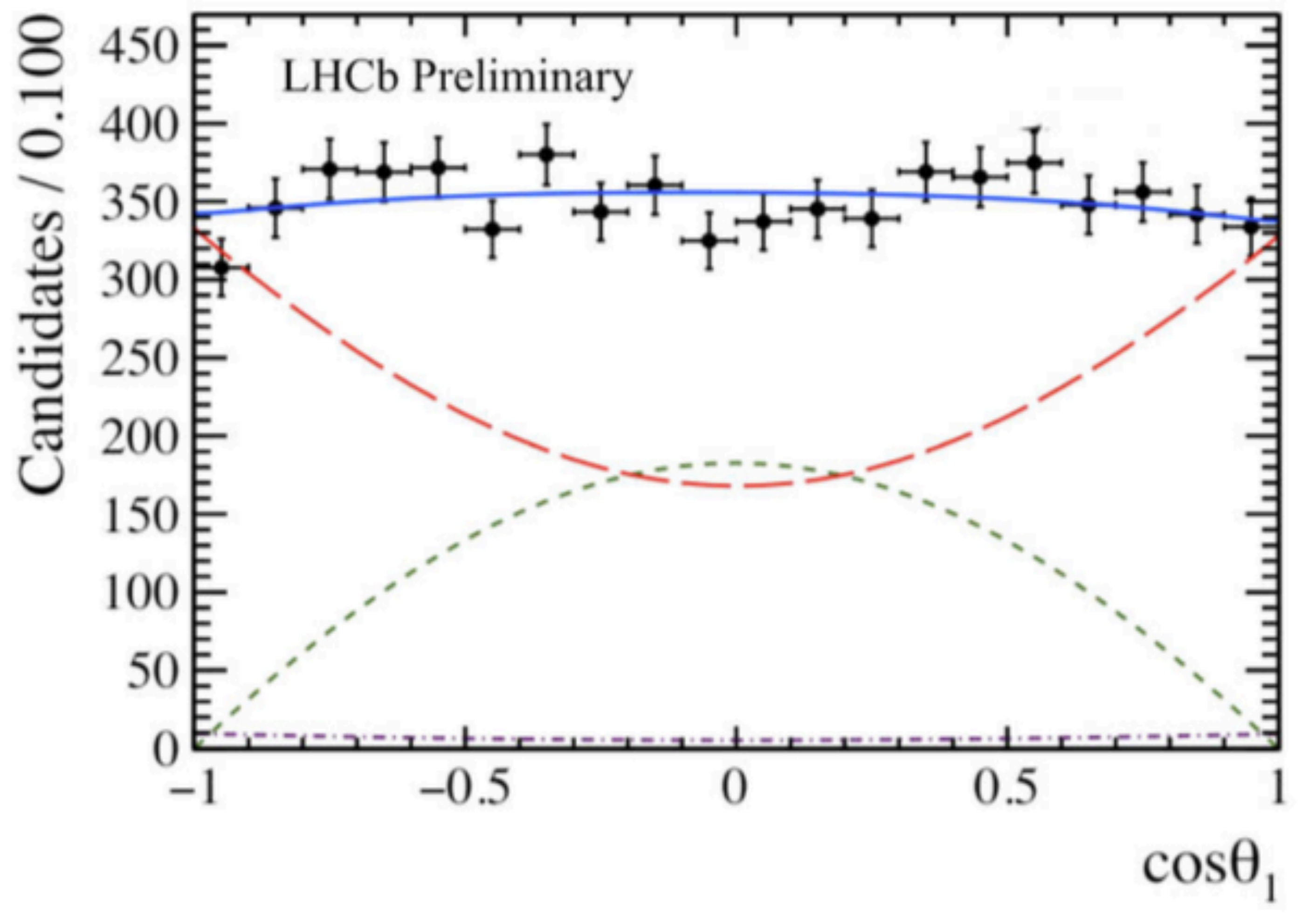
$\phi_s^{s\bar{s}}$ from $B_s^0 \to \phi\phi \to (K^+K^-)(K^+K^-)$

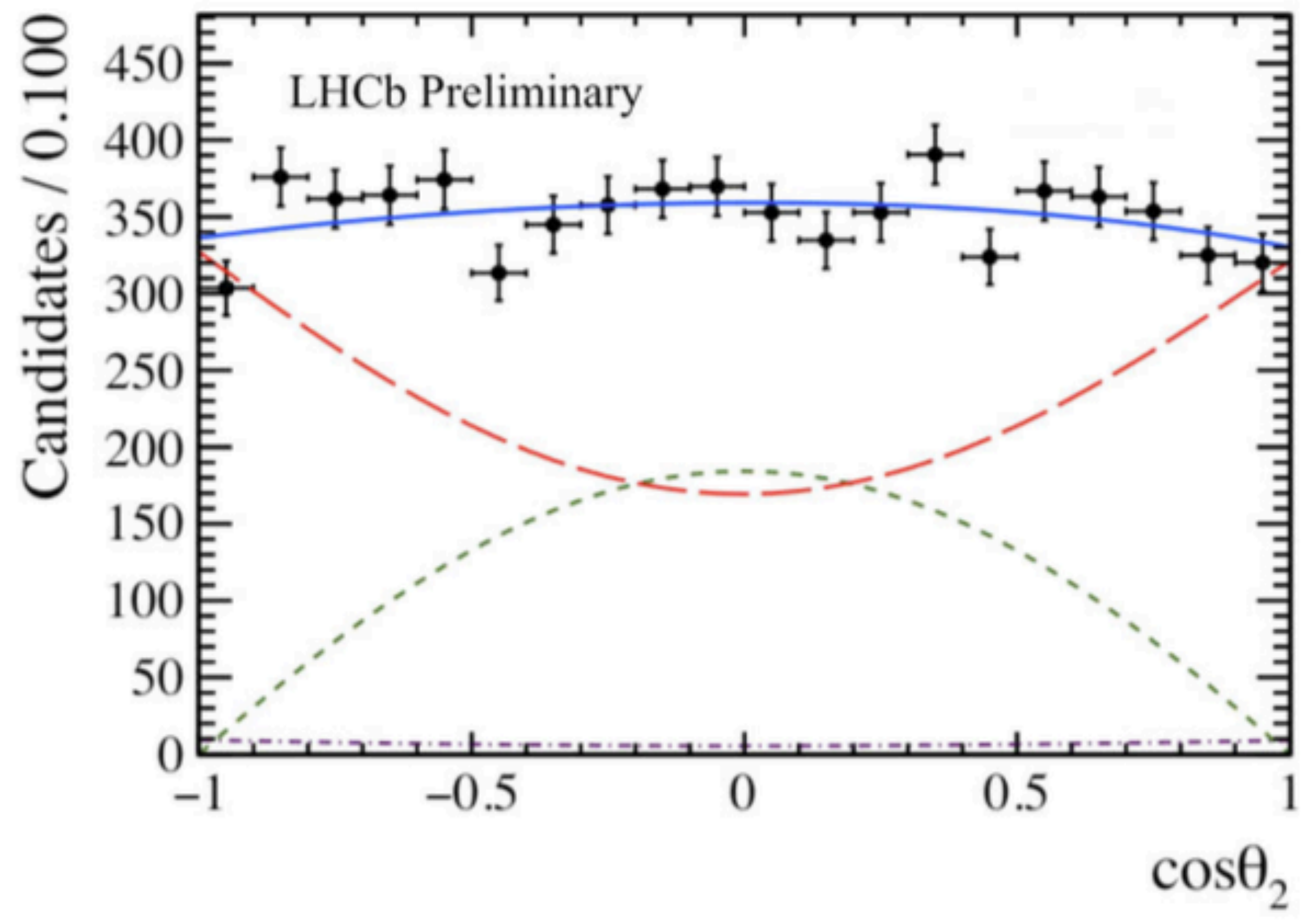
[LHCb-CONF-2018-001]

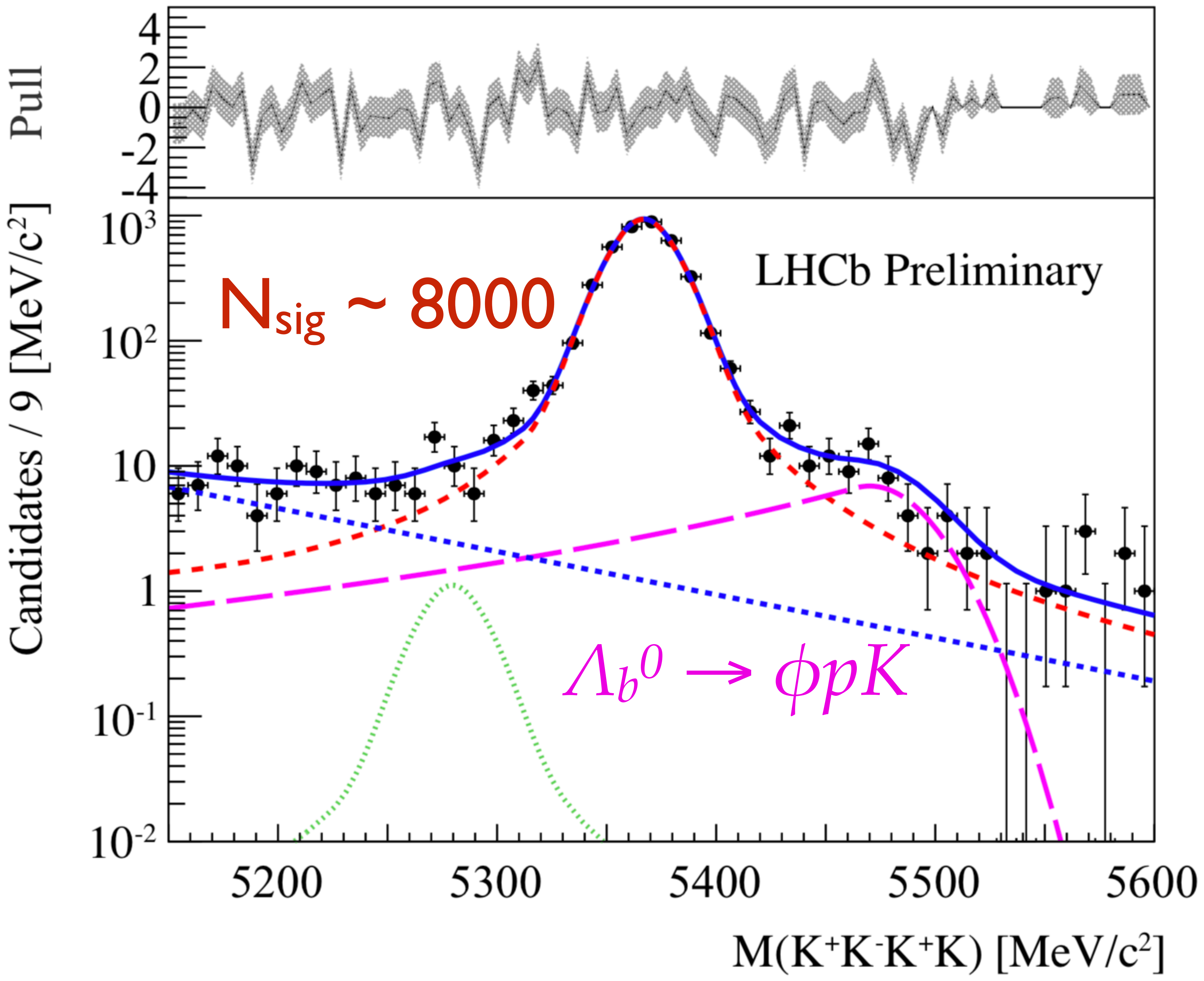
2011-2016 dataset











$$\phi_s^{s\bar{s}} = -0.07 \pm 0.13 \pm 0.03 \text{ rad}$$
$$|\lambda| = +1.02 \pm 0.05 \pm 0.03$$

Dominant uncertainty from knowledge mass shape and angular/time efficiency from simulation/control samples

TPAs
$$A_U = 0.000 \pm 0.012\,(\text{stat}) \pm 0.004\,(\text{syst})$$
$$A_V = -0.003 \pm 0.012\,(\text{stat}) \pm 0.004\,(\text{syst})$$

$b \to c\bar{u}d(s)$ and $b \to u\bar{c}d(s)$

Tagged, decay time dependent $B_{(s)}{}^0 \to D_{(s)}{}^{\mp}h^{\pm}$ are sensitive to $\gamma \pm 2\beta_{(s)}$ without penguin pollution. Taking $\beta_{(s)}$ from $b \to c\bar{c}s$ transitions we can measure γ. $r(D\pi) \sim 0.02$, $r(D_sK) \sim 0.4$

Data-driven time efficiency, tagging and resolution calibration. **Yields increase by ~4** after Run 2 (hadronic trigger eff and σ_{bb} 8 → 13 TeV)

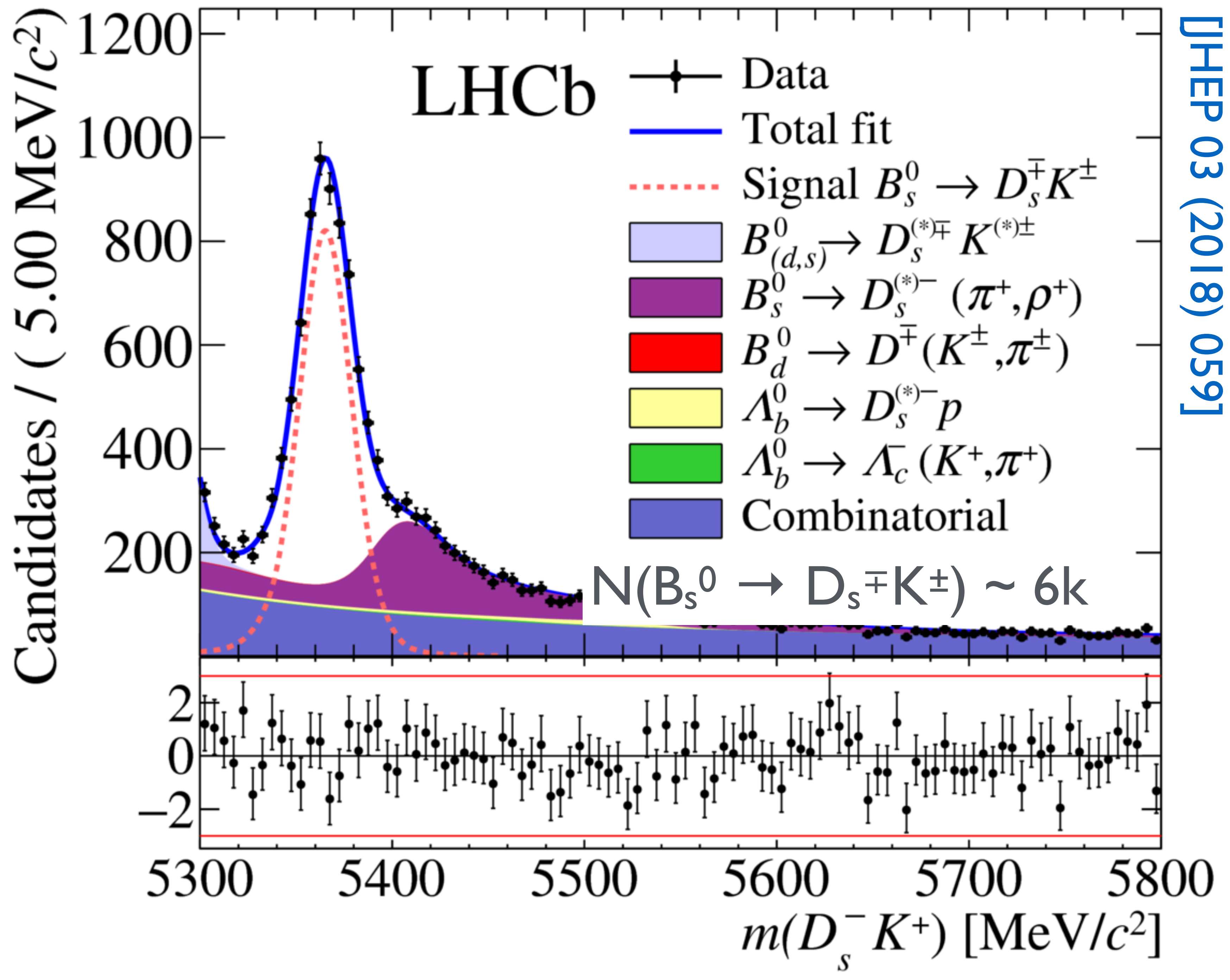
$B^0 \to D^{\mp}\pi^{\pm}$	S_f[%]	$S_{\bar{f}}$ [%]
Belle [11]	$6.8 \pm 2.9 \pm 1.2$	$3.1 \pm 3.0 \pm 1.2$
Babar [10]	$-2.3 \pm 4.8 \pm 1.4$	$4.3 \pm 4.8 \pm 1.4$
This analysis	$5.8 \pm 2.0 \pm 1.1$	$3.8 \pm 2.0 \pm 0.7$

[LHCb-PAPER-2018-009]

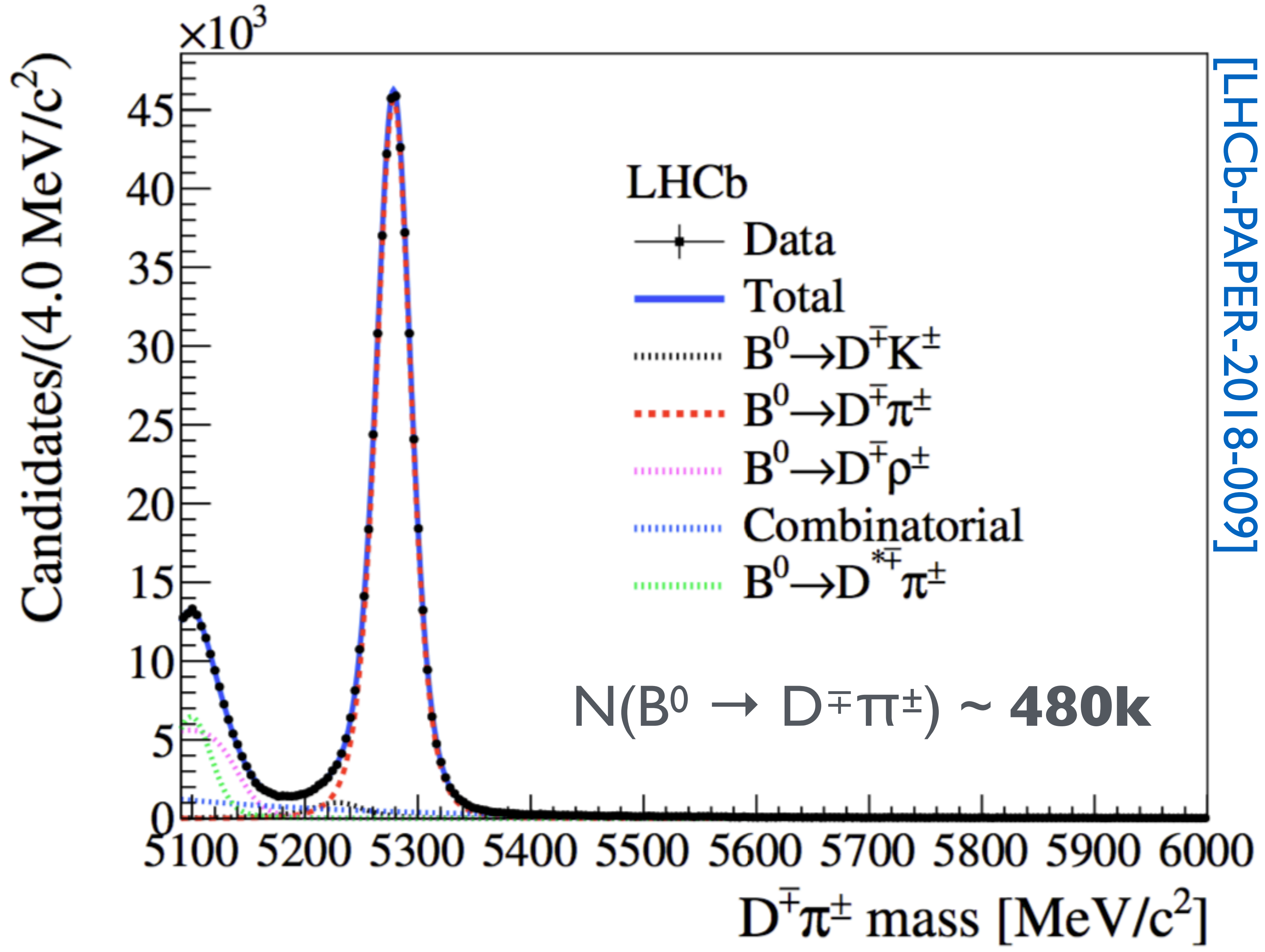
Ultimate precision:

@300/fb expect $\sigma(\gamma) \sim 1°$ → use γ as input and measure $\beta_{(s)}$

Need improved $\Delta m_{(s)}$, currently statistics limited → require better understanding of LHCb length/momentum scales (~0.03%), more simulation (LHCb k-factor correction), vertex resolution (Belle-II) and fit biases (LHCb+Belle-II)



[JHEP 03 (2018) 059]



[LHCb-PAPER-2018-009]

Joint analysis for γ? [Fleischer, NPB 659 (2003) 321]

Summary

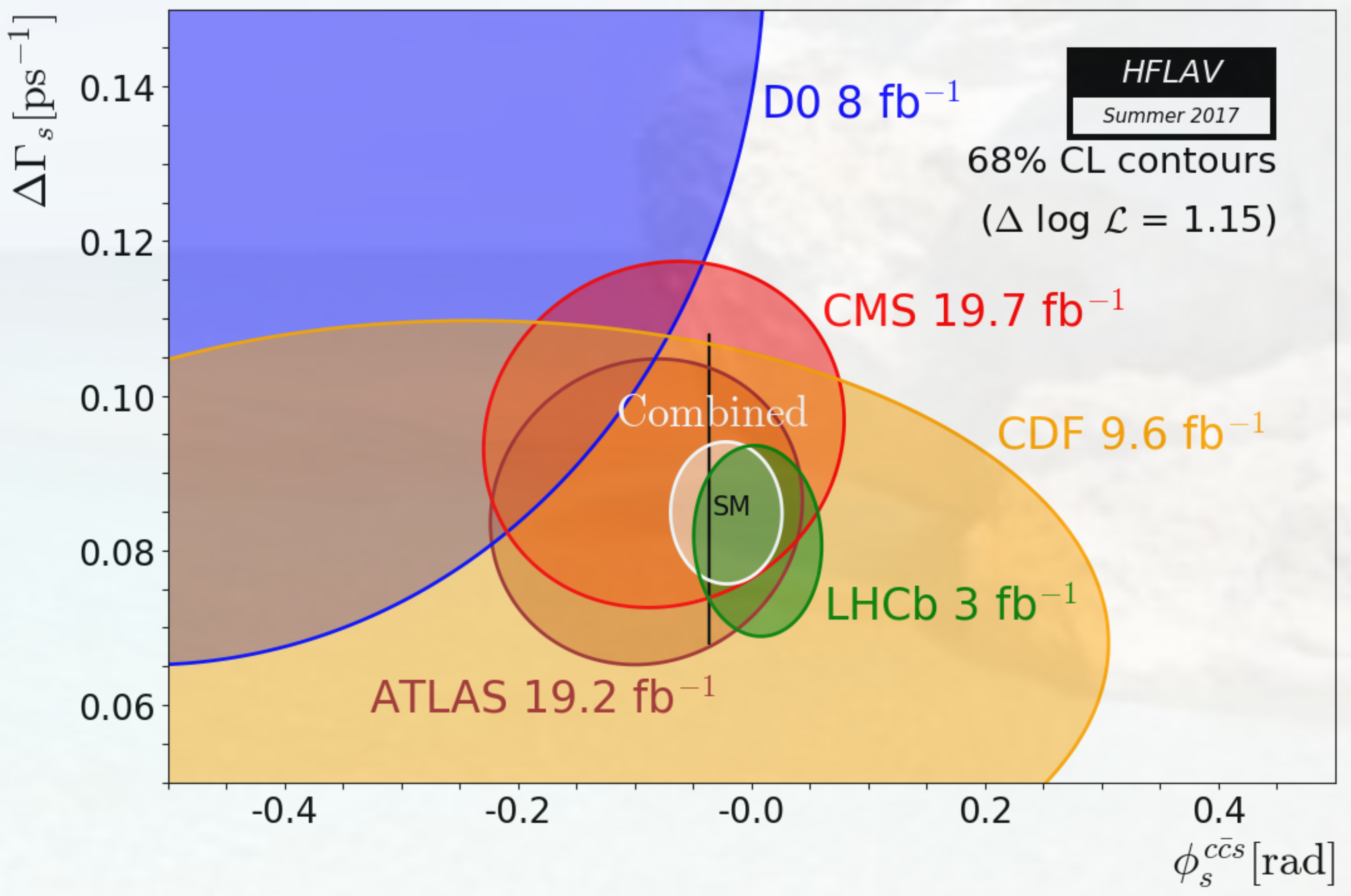
Most precise, **statistically dominated**, measurements of $\phi_{d,s}$ from $b \to c\bar{c}s$ transitions → look forward to Run-2 updates (and LHCb-upgrade)

- $B_s^0 \to J/\psi KK$, $B_s^0 \to J/\psi\pi\pi$, … *and* $B^0 \to J/\psi K_S$ + *higher* $[c\bar{c}]$ *modes*

Roadmap to control **penguin contributions** defined (U-spin, $SU(3)_f$)

LHCb measuring ϕ_s using penguin-dominated modes → promising precision

- $B_s^0 \to \phi\phi$ *and* $B_s^0 \to (K\pi)(K\pi)$



Future:

- need improved measurements of **B-mixing parameters/lifetimes**
- penguin-free $b \to c\bar{u}d$ transitions (e.g., $B_s^0 \to D^0 K_S$, $B^0 \to D^0\pi^+\pi^-$) will become interesting

[Also see talks from Keri, Matt, Tom and Marina in this session]

Penguin pollution roadmap: ϕ_s

$\phi(1020)$ is mixture of SU(3)$_f$ **octet** and **singlet** → how to handle this in SU(3) analysis of $B_s^0 \to J/\psi\phi$?

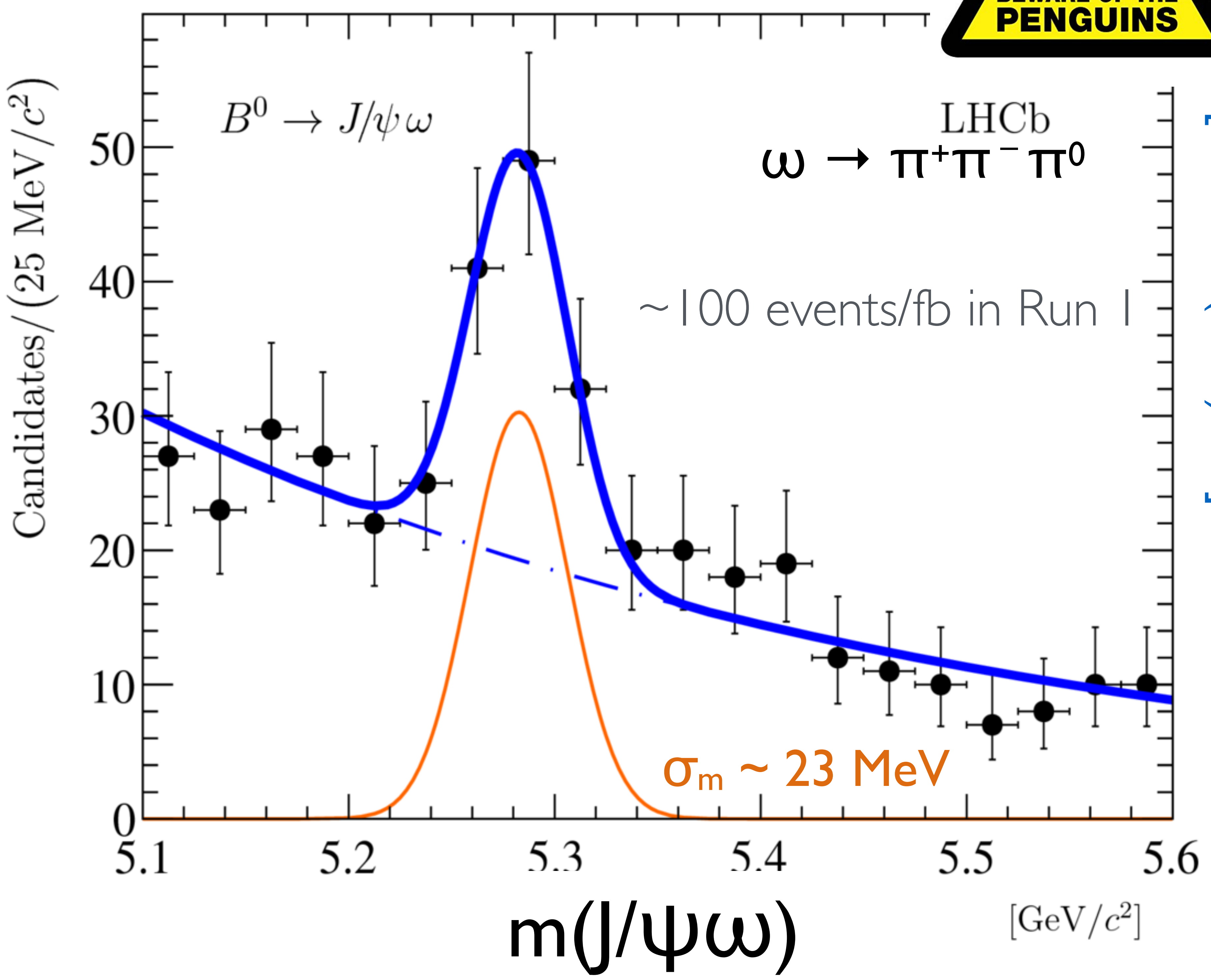
[Martin's talk]

Option: use $b \to c\bar{c}d$ modes such as $B_s^0 \to J/\psi K^*$ and $B^0 \to J/\psi\omega$

What about $B_s^0 \to J/\psi\omega$ with predicted BR ~ 6x10^{-6} ? → will require good mass resolution, which is ~3x worse than $B^0 \to J/\psi\pi\pi$

[Gronau, Rosner, PLB 672 (2009) 349]

With 300/fb, we could look at $\omega \to \mu\mu$, giving better resolution and low background



[NPB 867 (2013) 547]

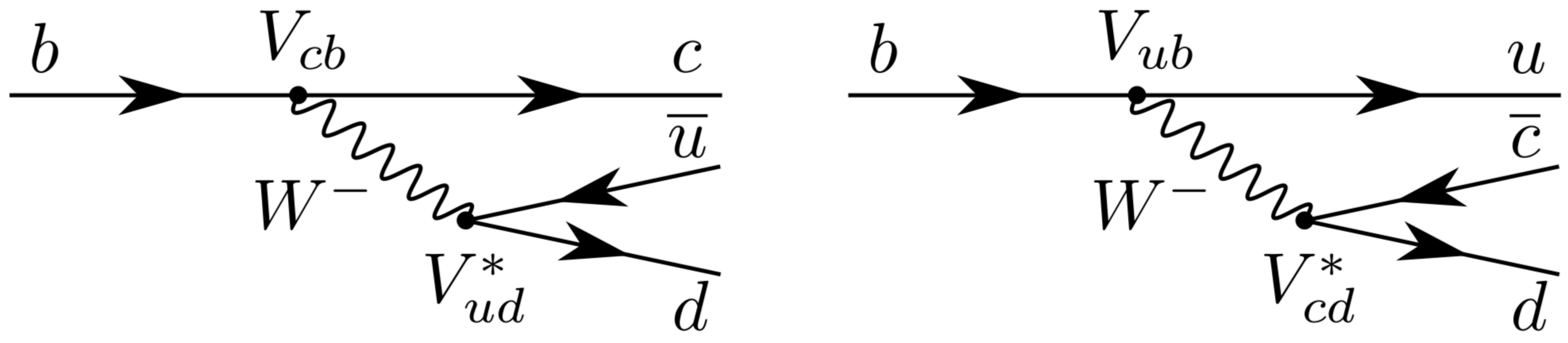
$$\mathcal{B}(\mathrm{B}^0 \to \mathrm{J}/\psi\,\omega) = (2.41 \pm 0.52\,(\mathrm{stat})\,^{+0.19}_{-0.35}\,(\mathrm{syst}) \pm 0.36\,(\mathcal{B}_{\mathrm{B}^0\to \mathrm{J}/\psi\,\rho^0})) \times 10^{-5}$$

Search for $B^0 \to J/\psi\phi$, with predicted BR ~2x10^{-7}, which proceeds only via E + PA diagrams, which can tell us about comparisons between $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi K^*$

$$\mathcal{B}(\overline{B}^0 \to J/\psi\,\phi) < 1.9 \times 10^{-7}$$

[LHCb, PRD 88 (2013) 072005]

Pengiun-free modes



Time evolution of e.g., $B^0 \to D^{(*)}h^0$ decays governed by β with **no penguin contribution** → provides SM reference

ϕ_d from $b \to c\bar{u}d$ transitions

$B^0 \to D_{CP}^{(*)} h^0$	sin2β = 0.66 ± 0.10 ± 0.06,	C = −0.02 ± 0.07 ± 0.03
$B^0 \to D^{(*)} h^0$, $D \to K_S \pi\pi$	sin2β = 0.80 ± 0.14 ± 0.06 ± 0.03;	cos2β = 0.91 ± 0.22 ± 0.09 ± 0.07

[Belle+BaBar, PRL 115 (2015) 121604]
[Belle+BaBar arXiv:1804.06152]

Dominant systematic from **vertex reconstruction, peaking backgrounds (and $D \to K_S\pi\pi$ Dalitz model)**

[Bondar et al., PLB 624 (2005) 1]

$B^0 \to D^{(*)} h^0$ is difficult at LHCb due to γ's in h^0 decay so target for upgrade-I, -II is time-dependent Dalitz analysis of $\boldsymbol{B^0 \to D^0\pi^+\pi^-}$ ***and*** $\boldsymbol{B^0_s \to D^0K^+K^-}$, which measures $cos2\beta$ and $sin2\beta$ when $D \to CP$ eigenstate [Latham, Gershon, JPG 36 (2009) 025006]

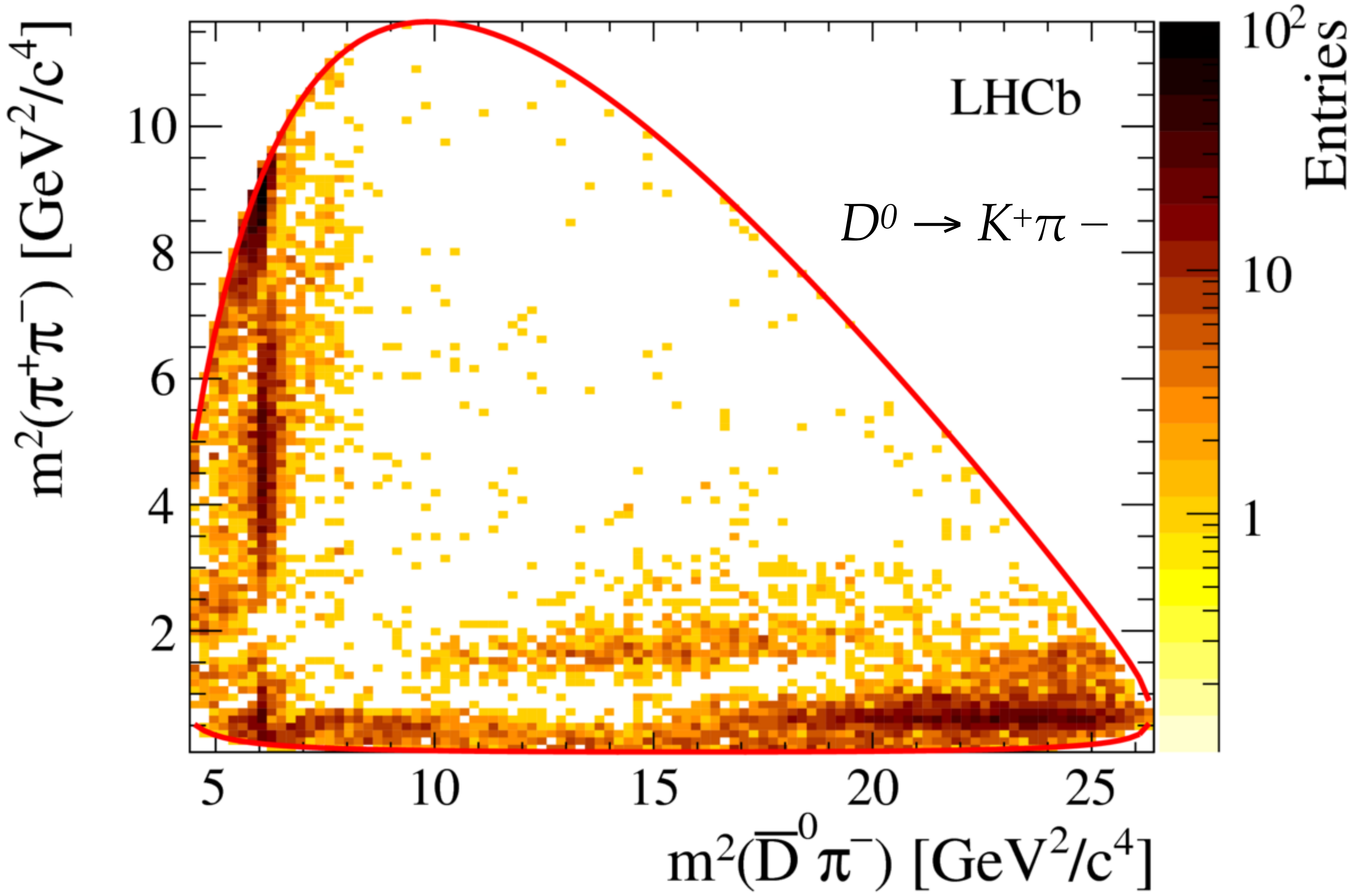
Ultimate precision @ 50 (300) fb^{-1}:

$\sigma(sin2\beta)$ ~ 0.018 (0.007) and $\sigma(cos2\beta)$ ~ 0.030 (0.017). Need to model $\pi\pi$ S-wave [LHCb upgrade-II physics document, in prep]

Model-independent $D \to K_S\pi\pi$ can give $\sigma(\beta) < 1°$

[Bondar et al., JHEP 03 (2018) 195]

[PRD 92 (2015) 032002]



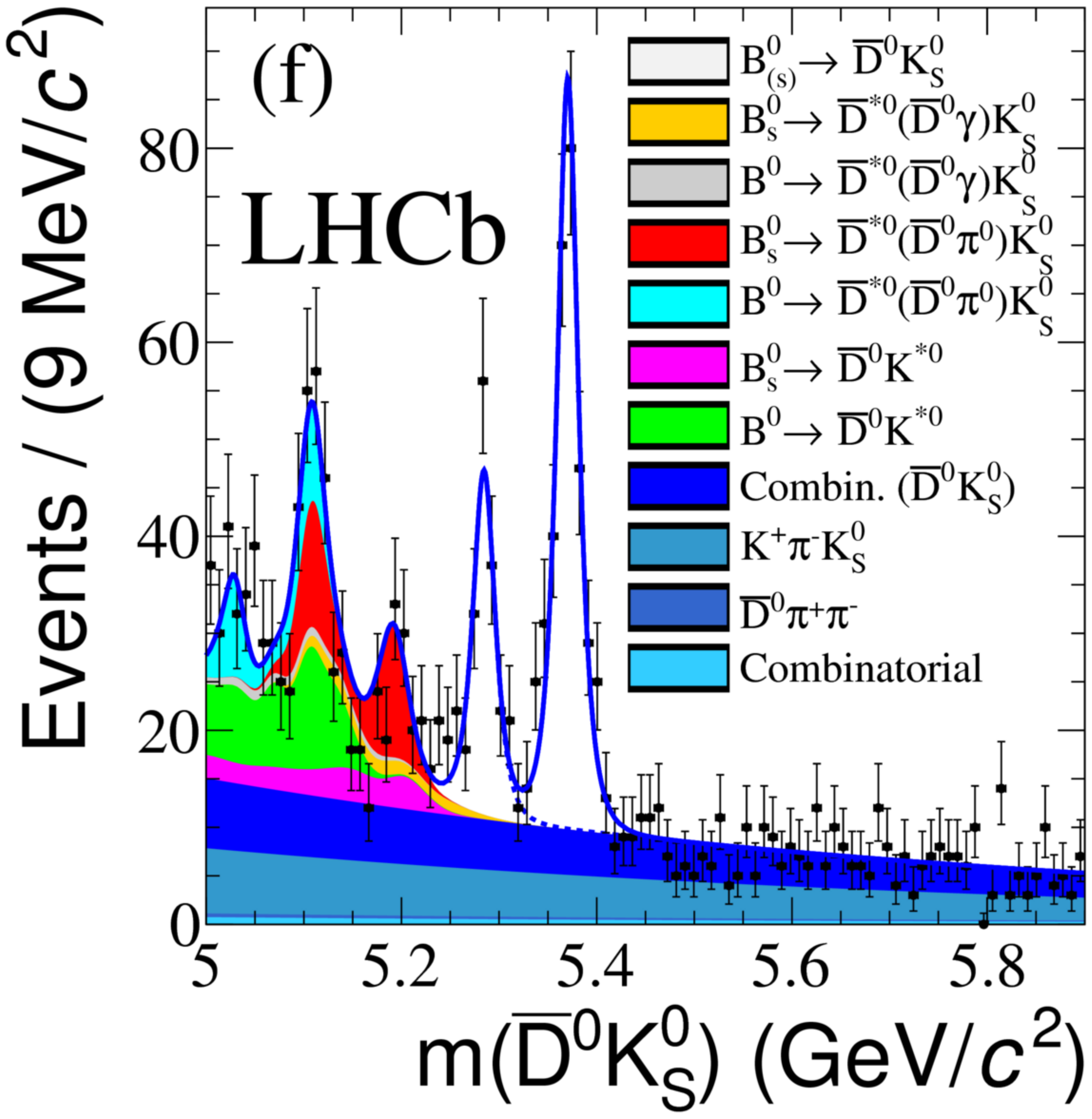
ϕ_s from $b \to c\bar{u}d$ transitions

[LHCb, PRL 116 (2016) 161802]

$B_s{}^0 \to D^0 K_S$: no possibility of penguin pollution ($r \sim 0.02$), but typically requires knowledge of γ, so expect some biases. Theoretically cleaner by x10 [Fleischer, NPB 659 (2003) 321] [Fleischer, PLB 562 (2003) 234]

$$\mathcal{B}(B_s^0 \to \bar{D}^0 \bar{K}^0) = [4.3 \pm 0.5(\text{stat}) \pm 0.3(\text{syst}) \pm 0.3(\text{frag}) \pm 0.6(\text{norm})] \times 10^{-4}$$
$$\mathcal{B}(B_s^0 \to \bar{D}^{*0} \bar{K}^0) = [2.8 \pm 1.0(\text{stat}) \pm 0.3(\text{syst}) \pm 0.2(\text{frag}) \pm 0.4(\text{norm})] \times 10^{-4}$$

fs/fd and BR($B^0 \to D^0 K_S$)



3.0/fb
~500 Bs → D0KS
~250 Bs → D0*KS

$D^0 \to K\pi$

Future:

- improved K_S reconstruction
- inclusion of more D decay modes, including multibody D decays, either model dependent or independent.

$b \to c\bar{u}d(s)$ and $b \to u\bar{c}d(s)$

$B_{(s)}{}^0 \to D_{(s)}{}^{\mp}h^{\pm}$ are sensitive to $\gamma \pm 2\beta_{(s)}$ without penguin pollution. Taking $\beta_{(s)}$ from $b \to c\bar{c}s$ transitions we can measure γ. $r(D\pi) \sim 0.02$, $r(D_sK) \sim 0.4$

Data-driven decay time efficiency, tagging and resolution calibration. **Yields increase by factor ~4** after Run 2 (hadronic trigger efficiency and σ_{bb} 8 → 13 TeV)

$B^0 \to D^{\mp}\pi^{\pm}$	S_f [%]	$S_{\bar{f}}$ [%]
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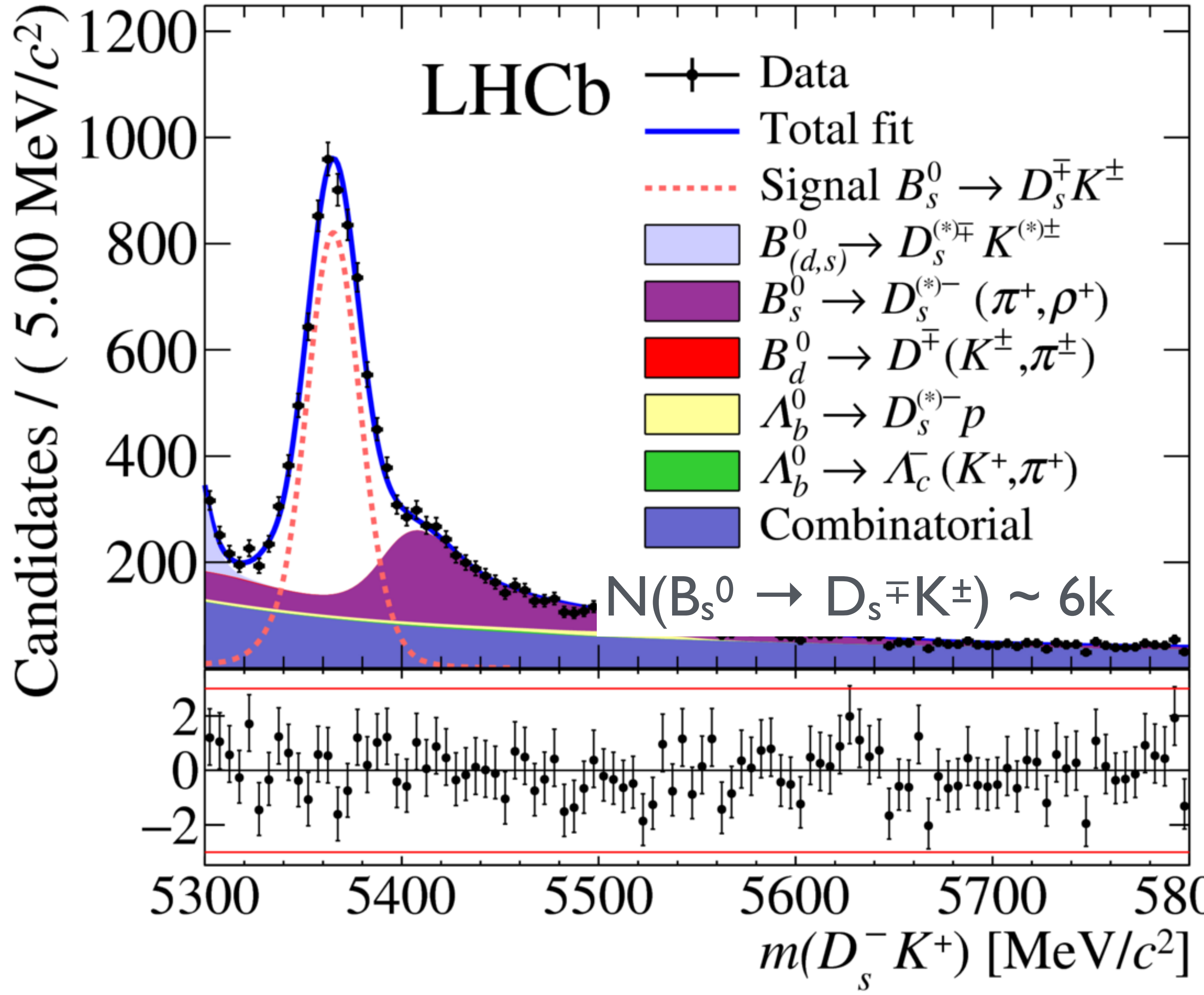
This analysis	$5.8 \pm 2.0 \pm 1.1$	$3.8 \pm 2.0 \pm 0.7$

[LHCb-PAPER-2018-009]

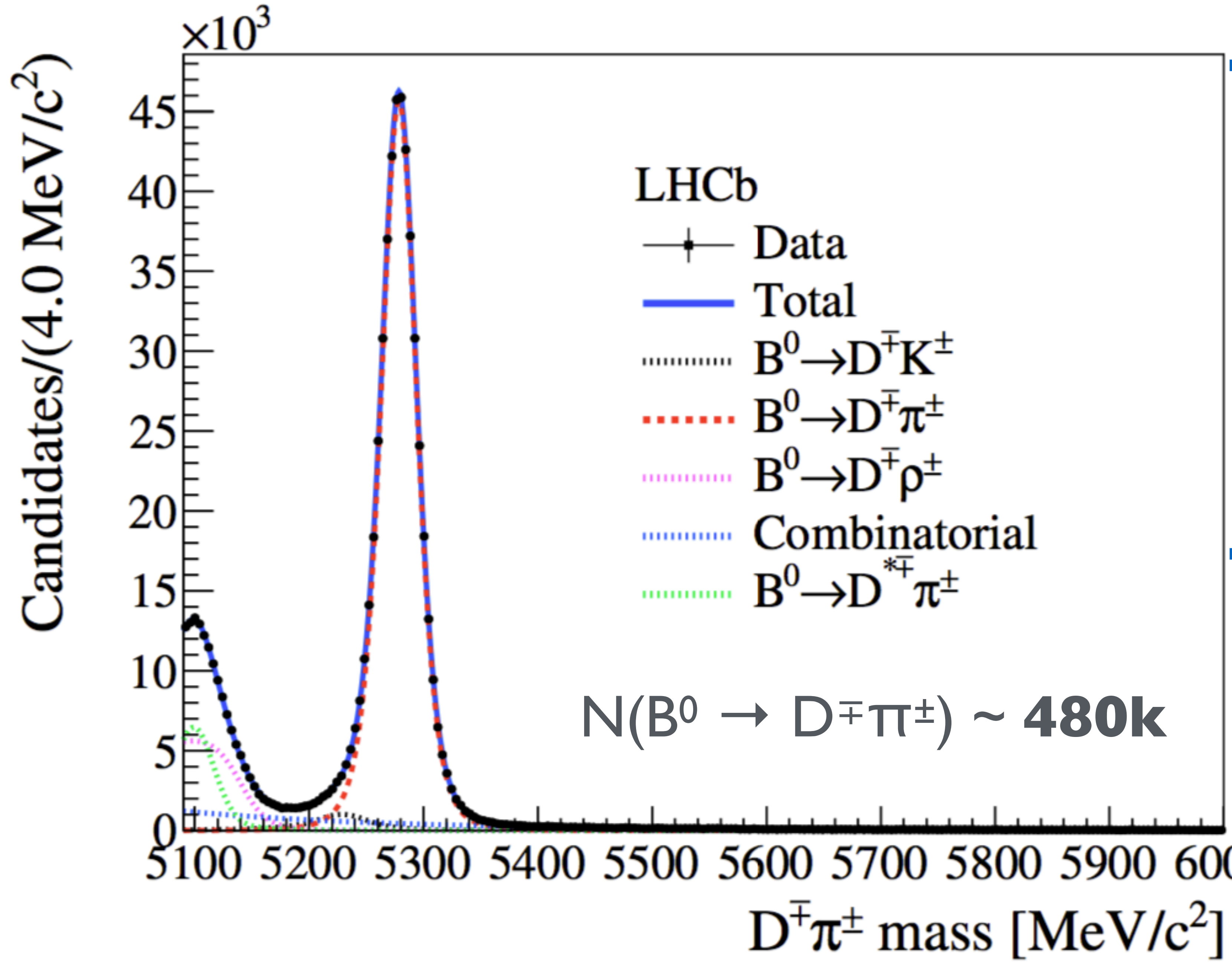
Ultimate precision:

@300/fb expect $\sigma(\gamma)$ ~0.4° → use γ as input and measure $\beta_{(s)}$

Need improved $\Delta m_{(s)}$, currently statistics limited → require better understanding of LHCb length/momentum scales (~0.03%), more simulation (LHCb k-factor correction), vertex resolution (Belle-II) and fit biases (LHCb+Belle-II)



[JHEP 03 (2018) 059]

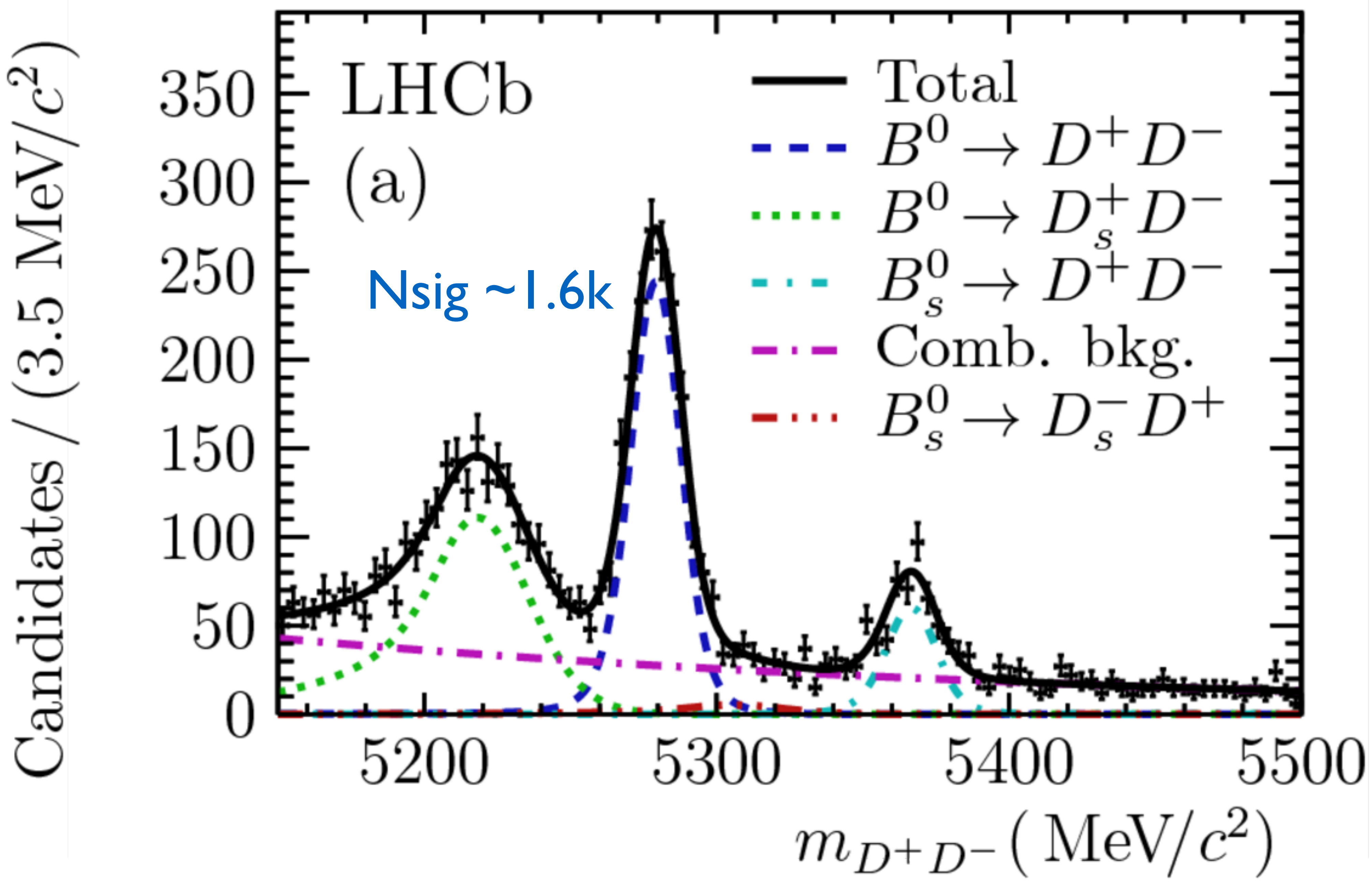


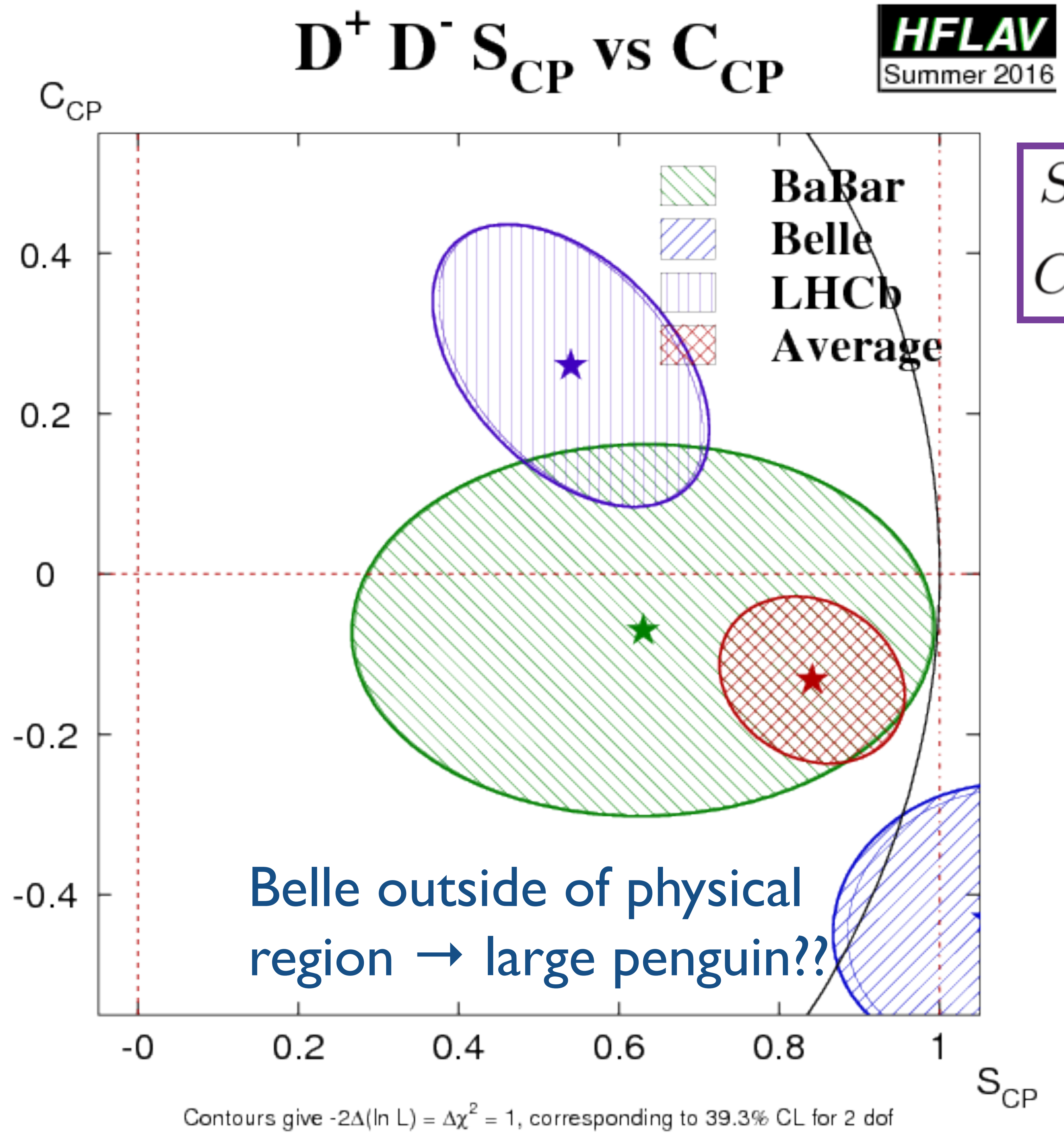
[LHCb-PAPER-2018-009]

Joint analysis for γ? [Fleischer, NPB 659 (2003) 321]

ϕ_d from $b \to c\bar{c}d$ transitions

[PRL 117 (2016) 261801]





$$S = -0.54\,^{+0.17}_{-0.16}\,(\text{stat}) \pm 0.05\,(\text{syst})$$
$$C = 0.26\,^{+0.18}_{-0.17}\,(\text{stat}) \pm 0.02\,(\text{syst})$$

$$\frac{S}{\sqrt{1-C^2}} = -\sin(2\beta + \Delta\phi)$$

phase shift due to penguin

$$\boxed{\Delta\phi = -0.16\,^{+0.19}_{-0.21}\,\text{rad}}$$

consistent with no penguin pollution

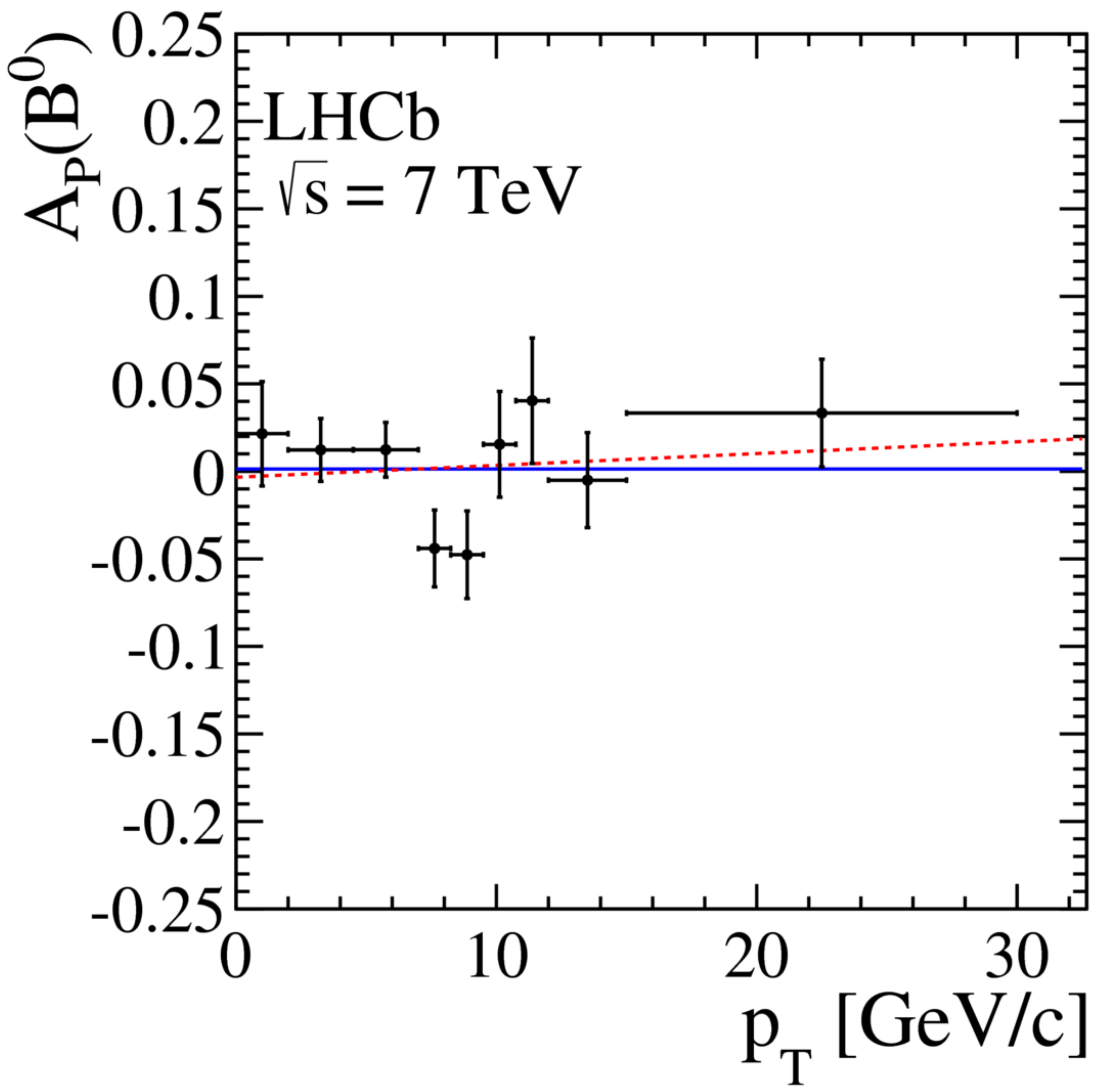
4σ evidence for CPV in $B^0 \to D^+D^-$

Use ϕ_d from $b \to c\bar{c}s$ as input to compute the penguin phase shift

SU(3) relation to Bs → DsDs, control penguins

[Belle, PRD 86 (2012) 071103]
[Fleischer, EPJC 51 (2007) 849]
[Jung, Schacht, PRD 91 (2015) 034027]
[Bel et al., JHEP 07 (2015) 108]

Production asymmetries



Source	Uncertainty [$\sqrt{s}$ = 7 TeV] $A_{\mathrm{P}}(B^+)$	$A_{\mathrm{P}}(B^0)$	$A_{\mathrm{P}}(B^0_s)$	$A_{\mathrm{P}}(\Lambda^0_b)$
Signal mass shape	0.0016	0.0005	0.0036	0.0024
Decay-time bias	0.0000	0.0000	0.0008	0.0004
Δm_d , Δm_s	0.0000	0.0001	0.0014	0.0007
Decay-time resolution	0.0000	0.0000	0.0026	0.0014
Final-state radiation	0.0000	0.0001	0.0000	0.0001
Decay-time reconstruction efficiency	0.0000	0.0001	0.0000	0.0001
Combinatorial background mass shape	0.0003	0.0000	0.0004	0.0003
Partially reconstructed background mass shape	0.0000	0.0000	0.0029	0.0015
$\Delta\Gamma_s$	0.0000	0.0000	0.0000	0.0000
$A_{\mathrm{D}}(K^+)$	0.0018	0.0000	0.0000	0.0013
$\lvert q/p\rvert_{B^0}$, $\lvert q/p\rvert_{B^0_s}$	0.0000	0.0009	0.0021	0.0013
Uncertainties from fragmentation fractions	0.0000	0.0000	0.0000	0.0058
Difference between ω_i or ω_i^{data}	0.0003	0.0003	0.0003	0.0003
Neglecting term with $A_{\mathrm{P}}(\Xi_b)$ in Eq. 3	0.0000	0.0000	0.0000	0.0071
Validity of $N_b = N_{\bar{b}}$ in each bin	0.0000	0.0000	0.0000	0.0032
$A_{CP}(B^+ \to J/\psi\, K^+)$	0.0028	0.0000	0.0000	0.0028
$A_{\mathrm{D}}(\overline{K}^0)$	0.0001	0.0000	0.0000	0.0002
Total systematic uncertainty	0.0037	0.0011	0.0059	0.0108

[PLB 774 (2017) 139-158]

$$
\begin{aligned}
A_{\mathrm{P}}(B^0)_{\sqrt{s}=7\,\mathrm{TeV}} &= 0.0044 \pm 0.0088\ (\mathrm{stat}) \pm 0.0011\ (\mathrm{syst})\\
A_{\mathrm{P}}(B^0)_{\sqrt{s}=8\,\mathrm{TeV}} &= -0.0140 \pm 0.0055\ (\mathrm{stat}) \pm 0.0010\ (\mathrm{syst})\\
A_{\mathrm{P}}(B^0_s)_{\sqrt{s}=7\,\mathrm{TeV}} &= -0.0065 \pm 0.0288\ (\mathrm{stat}) \pm 0.0059\ (\mathrm{syst})\\
A_{\mathrm{P}}(B^0_s)_{\sqrt{s}=8\,\mathrm{TeV}} &= 0.0198 \pm 0.0190\ (\mathrm{stat}) \pm 0.0059\ (\mathrm{syst})
\end{aligned}
$$

$\Delta\Gamma_d \neq 0$?

$$A_{CP}(t) \equiv \frac{\Gamma_{\overline{B}^0\to f} - \Gamma_{B^0\to f}}{\Gamma_{\overline{B}^0\to f} + \Gamma_{B^0\to f}} = \frac{S_f \sin(\Delta m\, t) - C_f \cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + A_{\Delta\Gamma} \sinh(\Delta\Gamma\, t/2)}$$

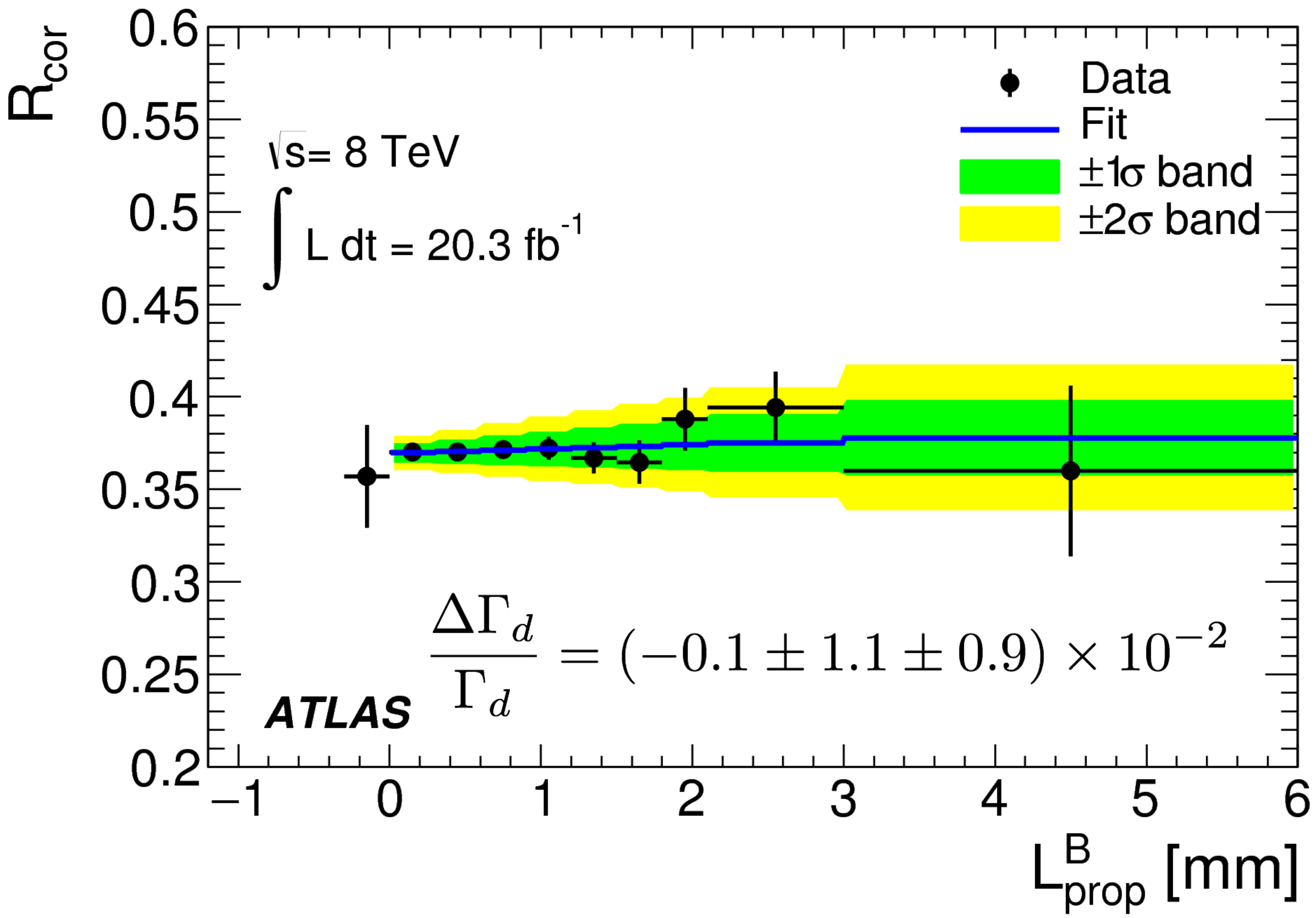
Measurements of $S_f = sin2\beta$ assume $\Delta\Gamma_d = 0$

Measure $\Delta\Gamma_d$ by comparing decay time distributions of $B^0 \to J/\psi K^* + B^0 \to J/\psi K_S$ [Gershon, JPG 38 (2011) 015007]

$\Delta\Gamma_d \neq 0$ could explain the D0 dimuon asymmetry

$$A_{CP} = C_d A^d_{SL} + C_s A^s_{SL} \boxed{+ C_{\Delta\Gamma_d} \frac{\Delta\Gamma_d}{\Gamma_d}}$$

[Borissov, Hoeneisen PRD 87 (2013) 074020] [D0, PRD 89 (2014) 012002]



$s\times\Delta\Gamma_d/\Gamma_d = (-2 \pm 10.) \times 10^{-3}$ [HFLAV]

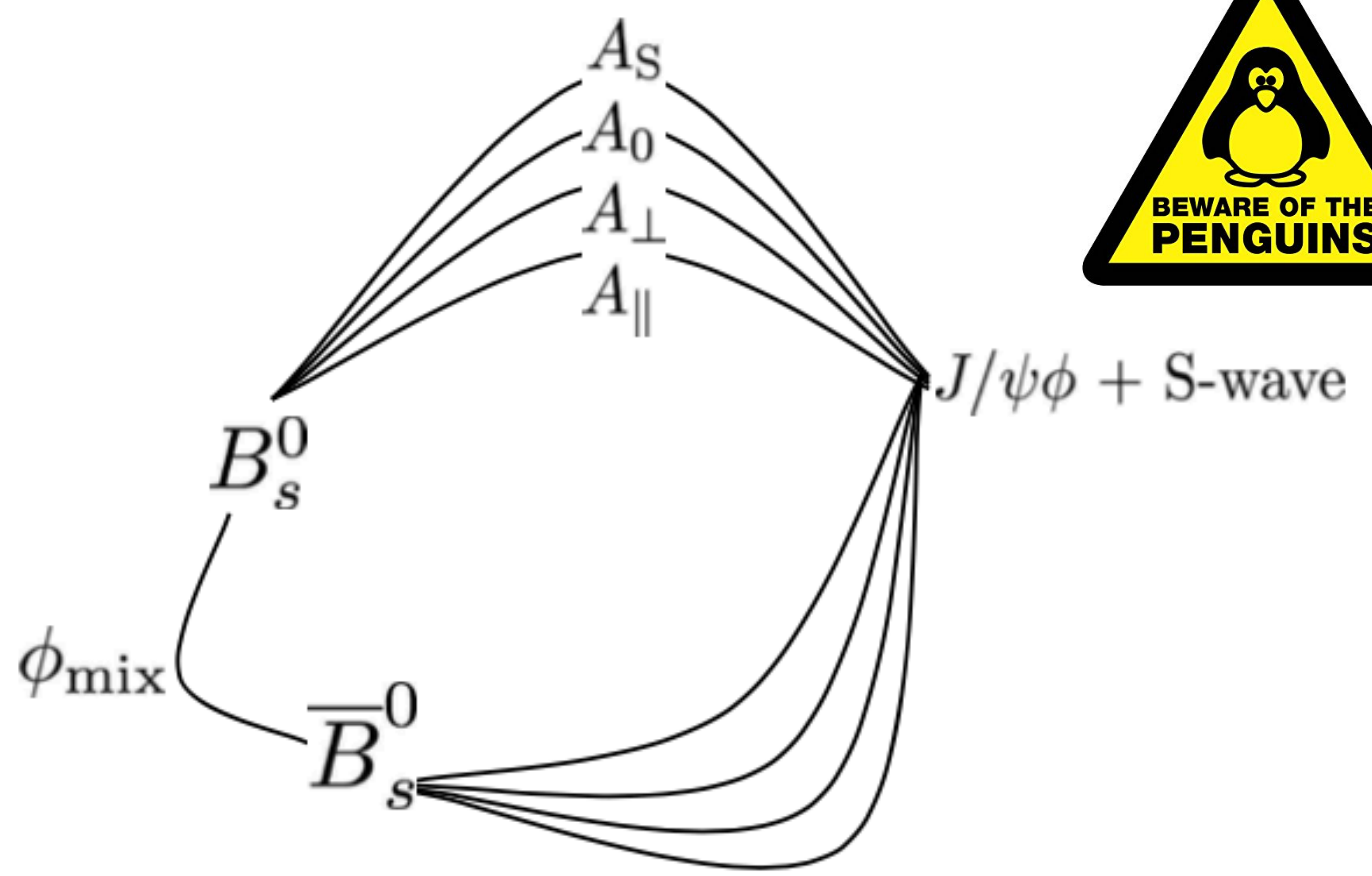
SM $\Delta\Gamma_d/\Gamma_d = (-3.97 \pm 0.90) \times 10^{-3}$ [Artuso et al]

[also LHCb with only 2011 data, JHEP 04 (2014) 114]

Polarisation-dependent ϕ_s

Penguin pollution and/or *CP* violation could be different for each polarisation state, $f \in (0, \perp, \parallel, S)$

[Bhattacharya et al., IJMP A28 (2013) 1350063]
[Liu et al., PRD 89 (2014) 094010]
[Fleischer, …]



Relax assumption that $\lambda^f \equiv \eta_f (q/p)(\bar{A}_f/A_f)$ is same for all $(J/\psi K^+K^-)_f$ polarisations → measure $\lambda^f = |\lambda^f| \, exp(-i\phi^f_s)$

$$\mathrm{CP}|\,\mathrm{J}/\psi\phi\rangle_\ell \quad = \quad (-1)^\ell|\,\mathrm{J}/\psi\phi\rangle_\ell$$

No sign of polarisation dependence → penguins are small

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

Ultimate precision: Need to monitor stat + syst correlations between these parameters and others (e.g., $\Delta\Gamma_s$, $|A_f|^2$) from $B_s^0 \to J/\psi K^+K^-$ angular fit

alternative parameterisation [van Leerdam, CERN-THESIS-2016]

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

[PRL 114, 041801 (2015)]

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\|A_\perp\|^2$	$\|A_0\|^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\|\lambda\|$	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

Next $B^0_s \to J/\psi\phi$ update will fix mass factorisation (new model). Backgrounds should scale

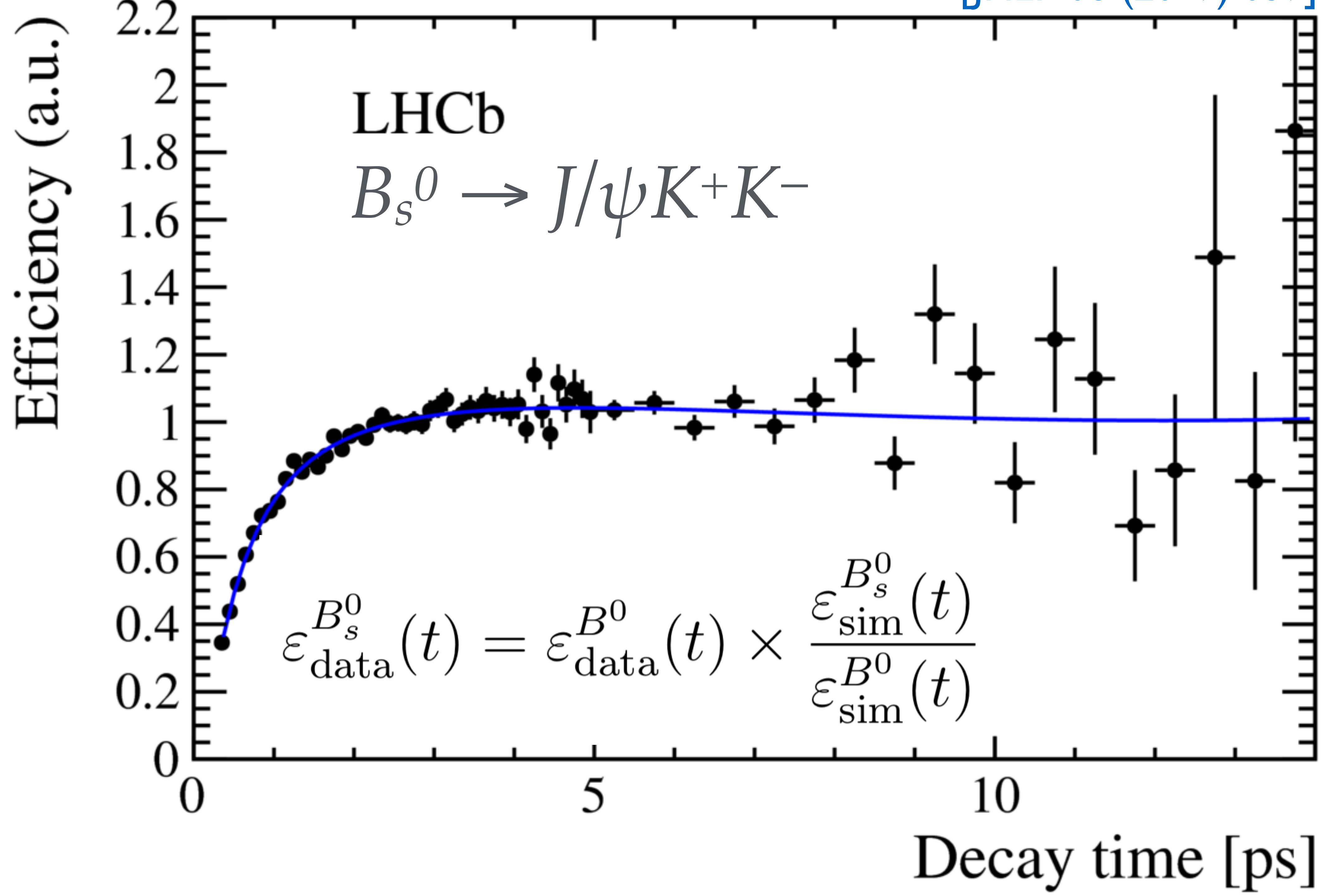
Angular efficiencies will continue to dominate → large MC and data control channels (e.g., $B^0 \to J/\psi K^*$)

Lifetime efficiency → next slide

Systematic uncertainties: lifetimes

Major systematic will continue to be understanding decay time efficiency ⇒ need large MC samples and data control channels

[JHEP 08 (2017) 037]



Need **improved measurement of** B^0 , B^+ **lifetimes,** which requires excellent control of absolute efficiency (LHCb) and vertex resolution (Belle-II)

$\tau(B^0)$ = 1.518 ± 0.004 ps [HFLAV]
$\tau(B^+)$ = 1.638 ± 0.004 ps

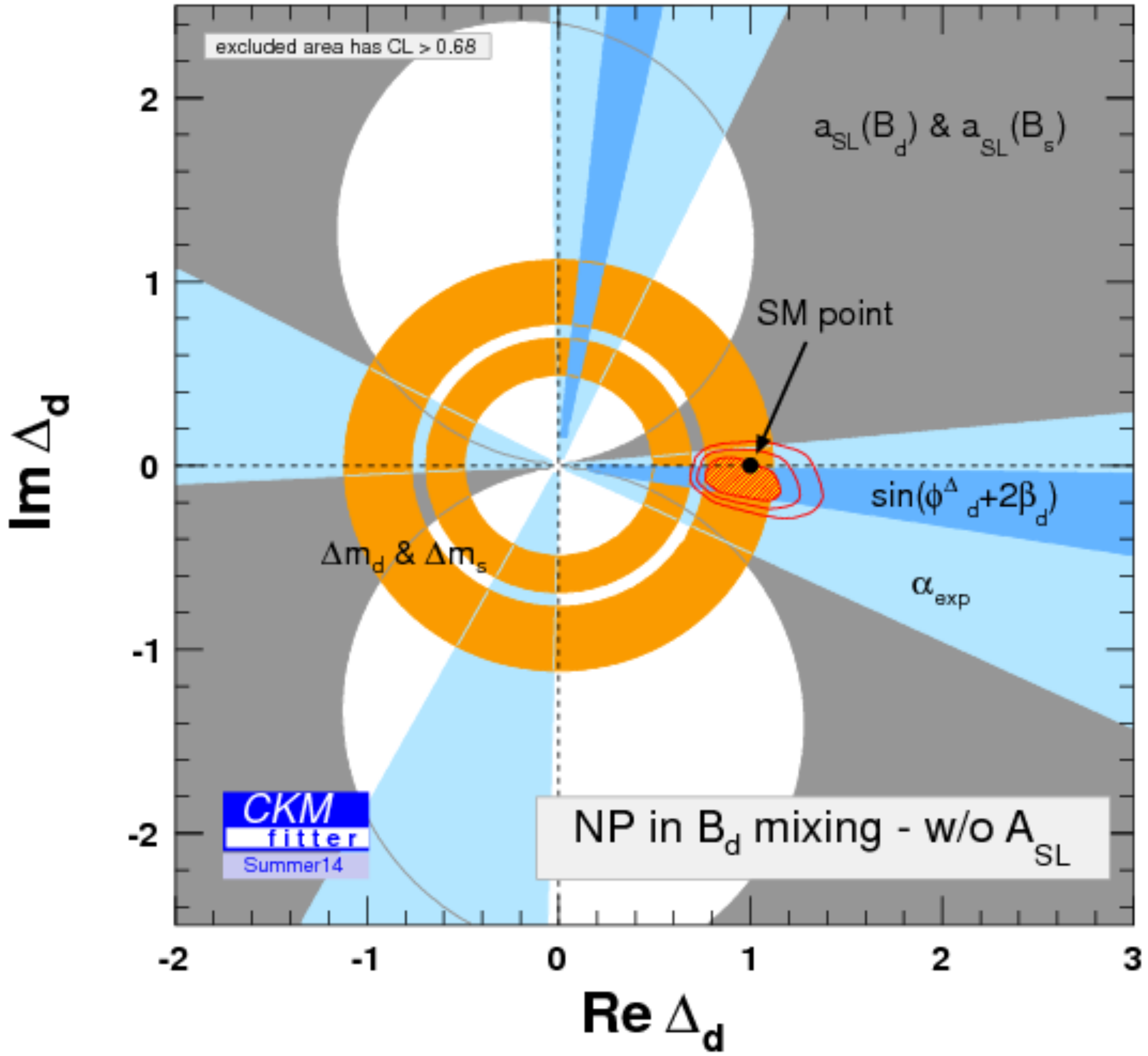
Absolute lifetime predictions suffer from uncertainties ~ m_b^5; lifetime ratios under better control [Lenz, arXiv:1405.3601]

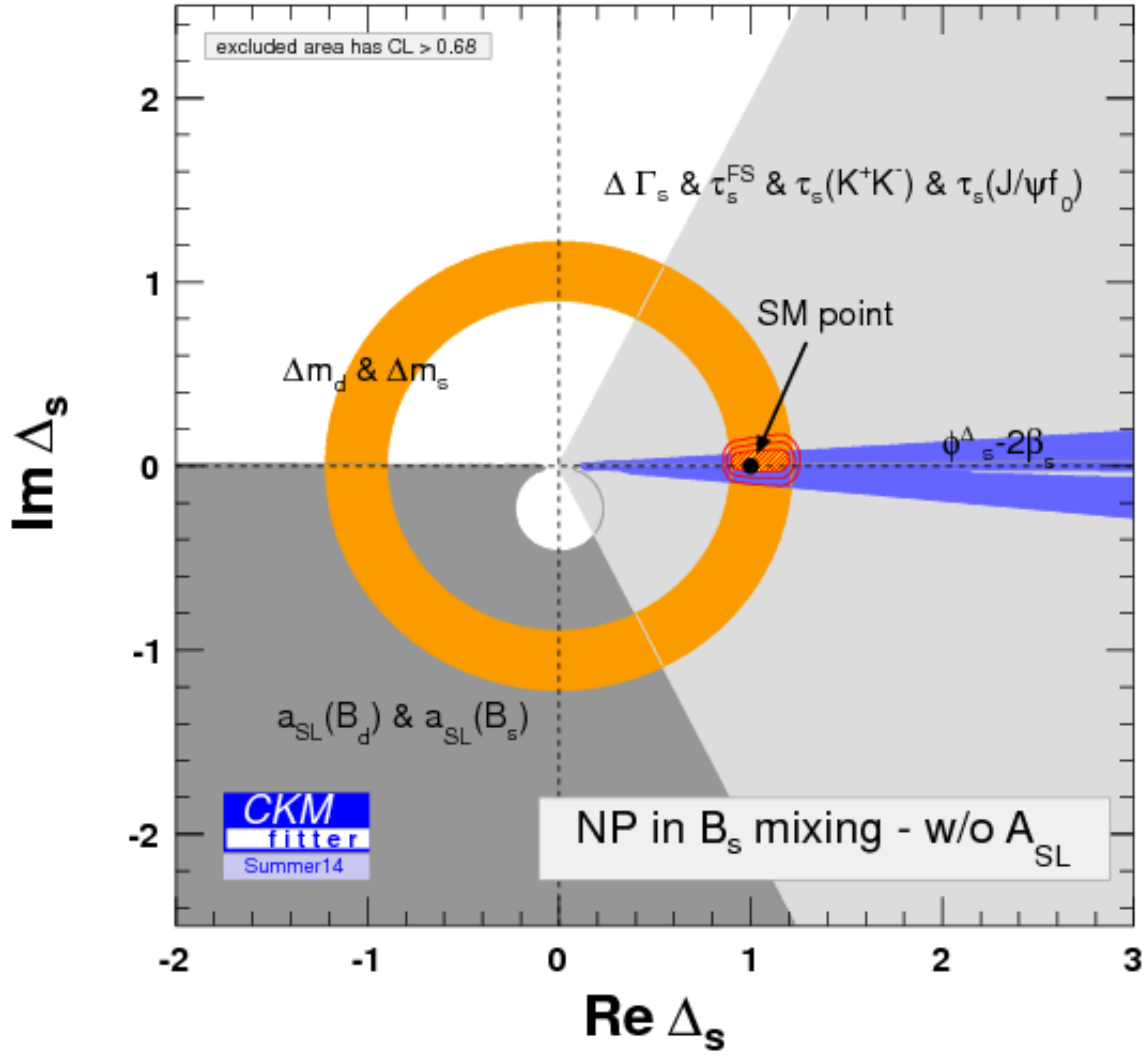
$\tau(B_s)/\tau(B^0)$ = 1.00050 ± 0.00108 − 0.0225δ [Jubb et al, arXiv:1603.07770]
$\tau(B_s)/\tau(B^0)$ = 0.990 ± 0.004 [HFLAV]

Next LHCb $B_s^0 \to J/\psi\phi$ update will measure $\sigma(\Gamma_s / \Gamma_d) \sim$ 0.005

Impact on new physics

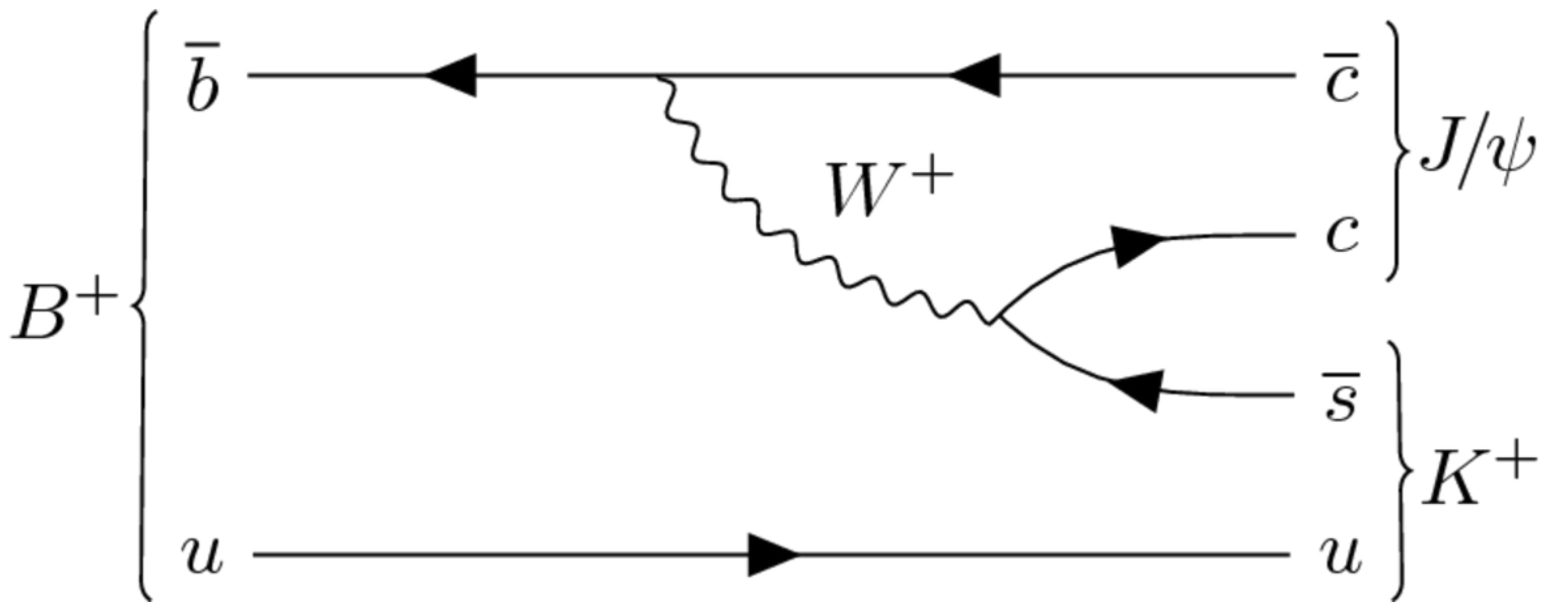
$$M_{12}^{NP,s} = M_{12}^{SM,s}\Delta_s$$
$$\Delta_s = |\Delta_s| e^{i\phi_s^\Delta}$$
$$\Delta_s^{SM} = 1$$

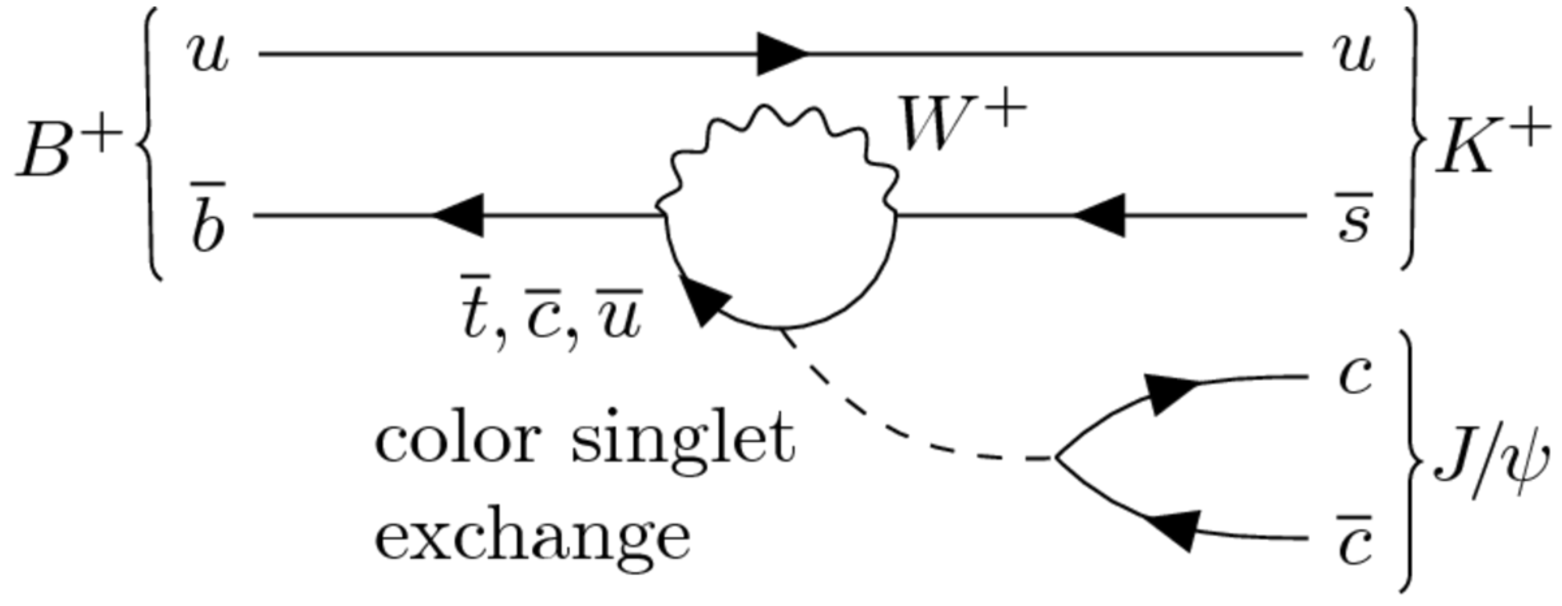




Even given the constraints that show consistency with the SM, NP still allowed at the 10% level

Penguin contributions





Penguin contribution could lead to non-zero CPV in decay for $b \to c\bar{c}s$ transitions. Currently C_f values in $B^0{}_{(s)}$ decays are consistent with zero at few %

Most precise constraint from $A_{CP}(B^+ \to J/\psi K^+)$ but possible suppression from small strong phase difference → more information required

$$\mathcal{A}_{CP}(B^+ \to J/\psi\, K^+) = (0.09 \pm 0.27 \pm 0.07) \times 10^{-2}$$

$$\mathcal{A}^{CP}(B^+ \to J/\psi\, \pi^+) = (1.91 \pm 0.89 \pm 0.16) \times 10^{-2}$$

[LHCb PRD 95 (2017) 052005]
[LHCb JHEP 03 (2017) 036]

Dominant syst from Kπ detector asymmetry determination

Same argument for $b \to c\bar{c}d$ transitions

$(B^+ \to J/\psi\pi^+, B^- \to D^- D^0)$

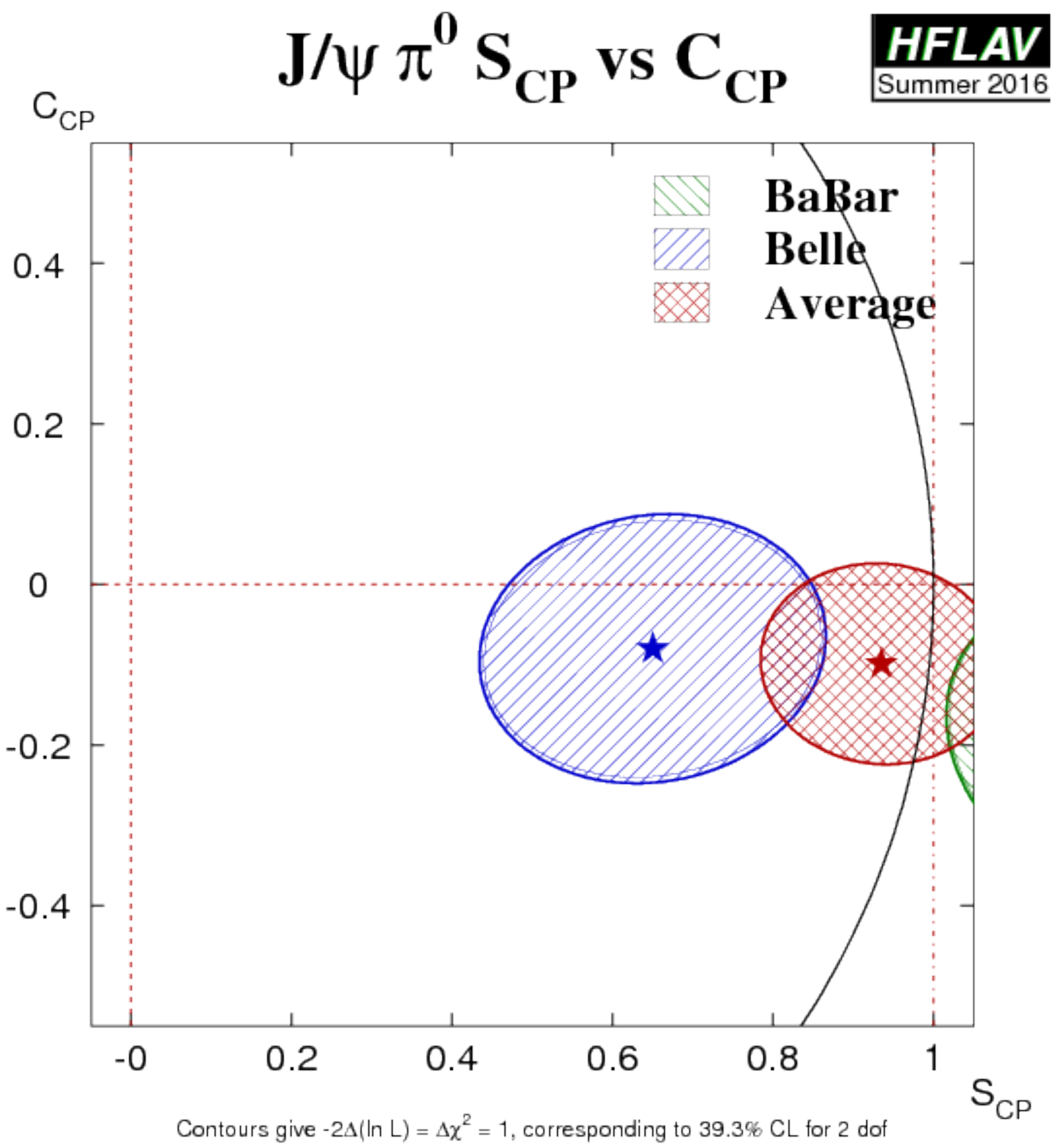
B-factories have precision of ~10% on D^- mode

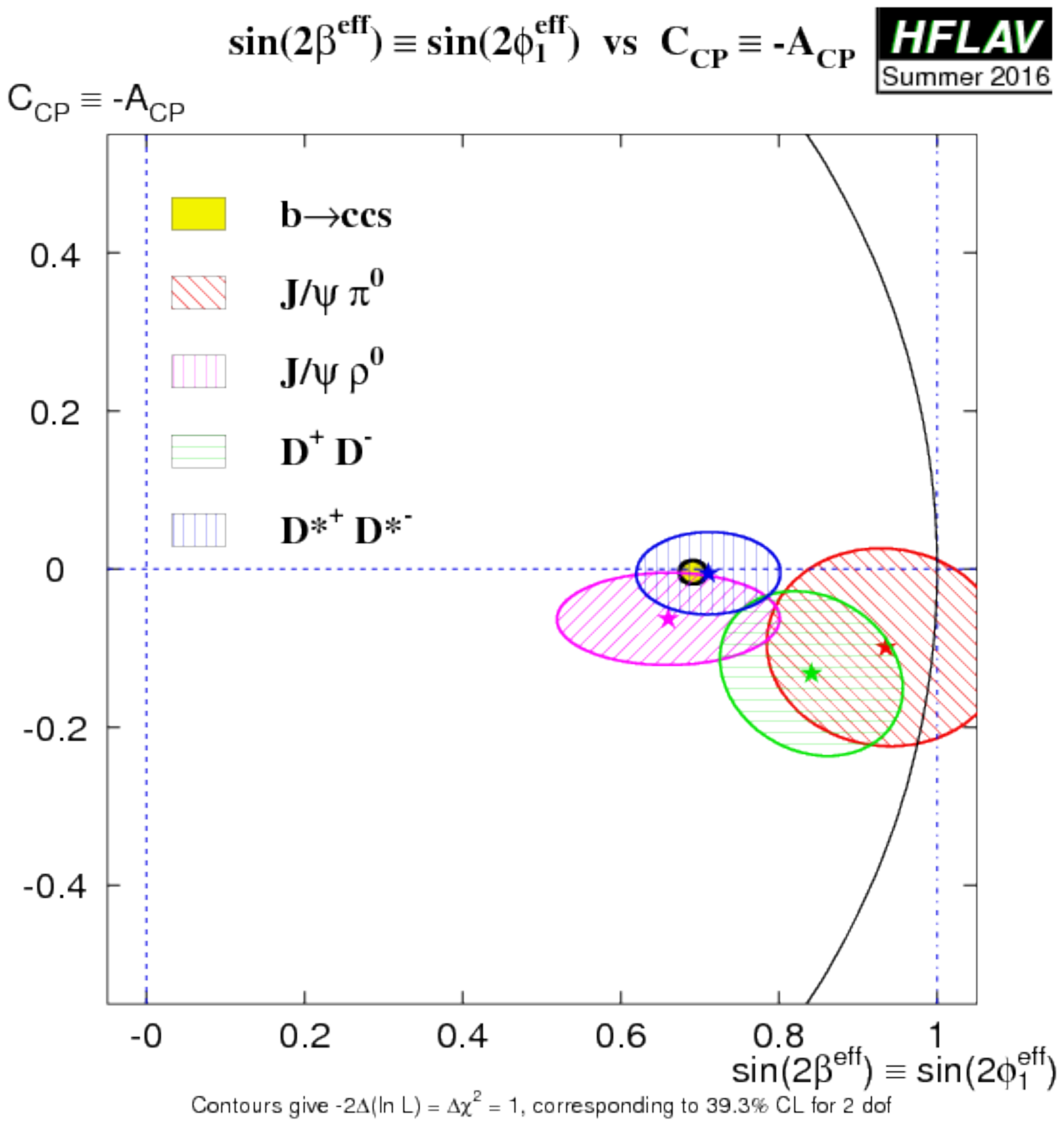
$$\mathcal{A}^{CP}(B^- \to D_s^- D^0) = (-0.4 \pm 0.5 \pm 0.5)\%$$

$$\mathcal{A}^{CP}(B^- \to D^- D^0) = (\ \ 2.3 \pm 2.7 \pm 0.4)\%$$

[LHCb arXiv:1803.10990]

$B^0 \to J/\psi\pi^0$ and DD





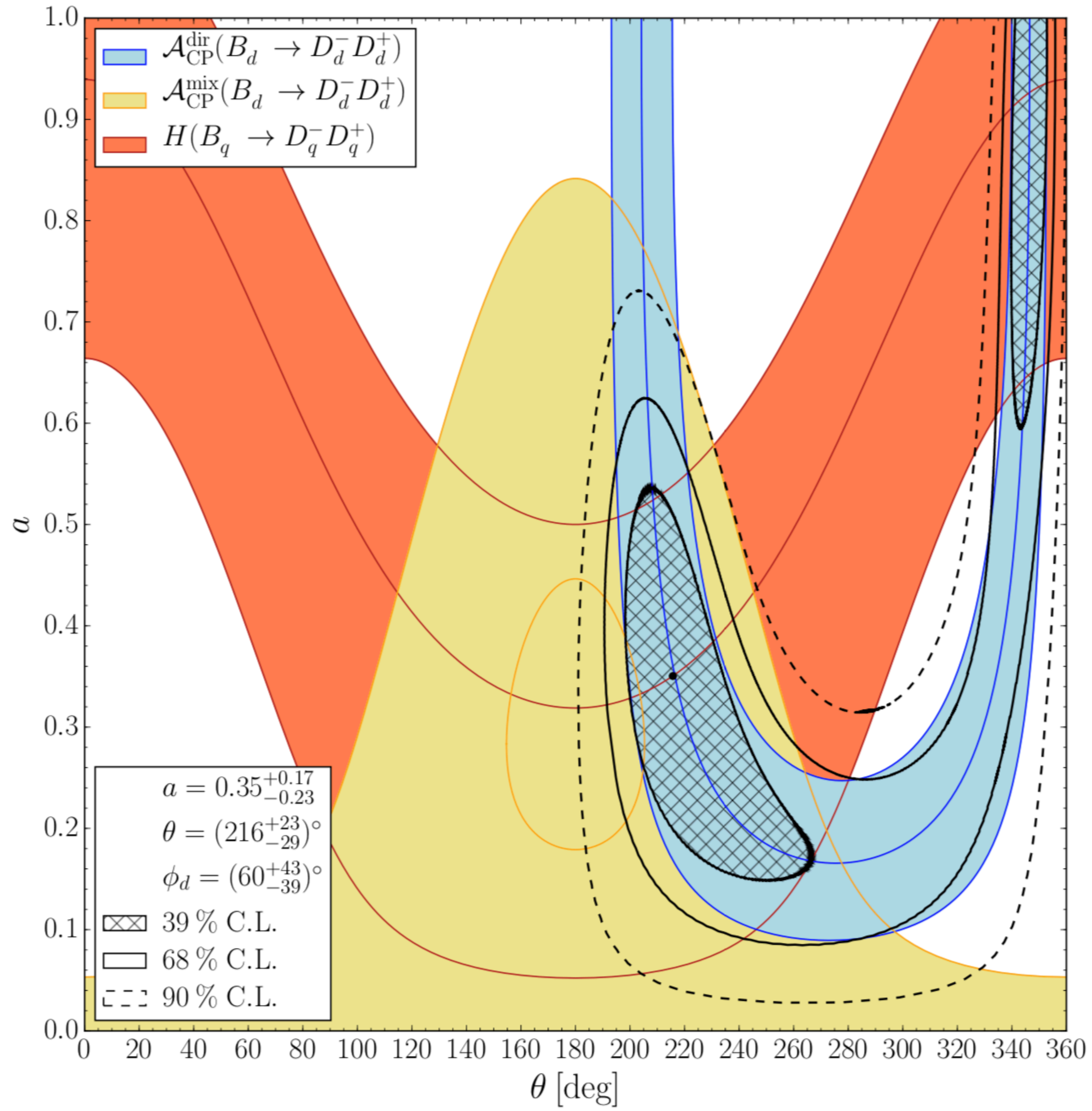
[Belle-II projections @ 50 ab⁻¹ from A. Gaz, P. Urquijo, L Li Gioi]

$\sigma(S) = 0.027$ (stat) $\pm$ 0.027 (syst)
$\sigma(A) = 0.035$ (stat) $\pm$ 0.017 (syst)

[Belle, PRD 86 (2012) 071103]

Penguin pollution roadmap: ϕ_s

[Bel et al., JHEP 07 (2015) 108]



Similar story for ϕ_s from $B_s \to D_s D_s$ decays

Use direct/mixing CP asymmetries and ratios of BRs of $B^0 \to D^+ D^-$ decays to constrain size of penguins

H observable is not theoretically clean due to possible sizeable E+PA contributions

penguin shift may be larger here…

Enhanced E + PA topologies, indications for significant penguin contributions → ultimately control penguins for ϕ_s in Bs → DsDs decays

Future: Bs0 → Ds*Ds* and B0 → D*D*, need TD angular analysis

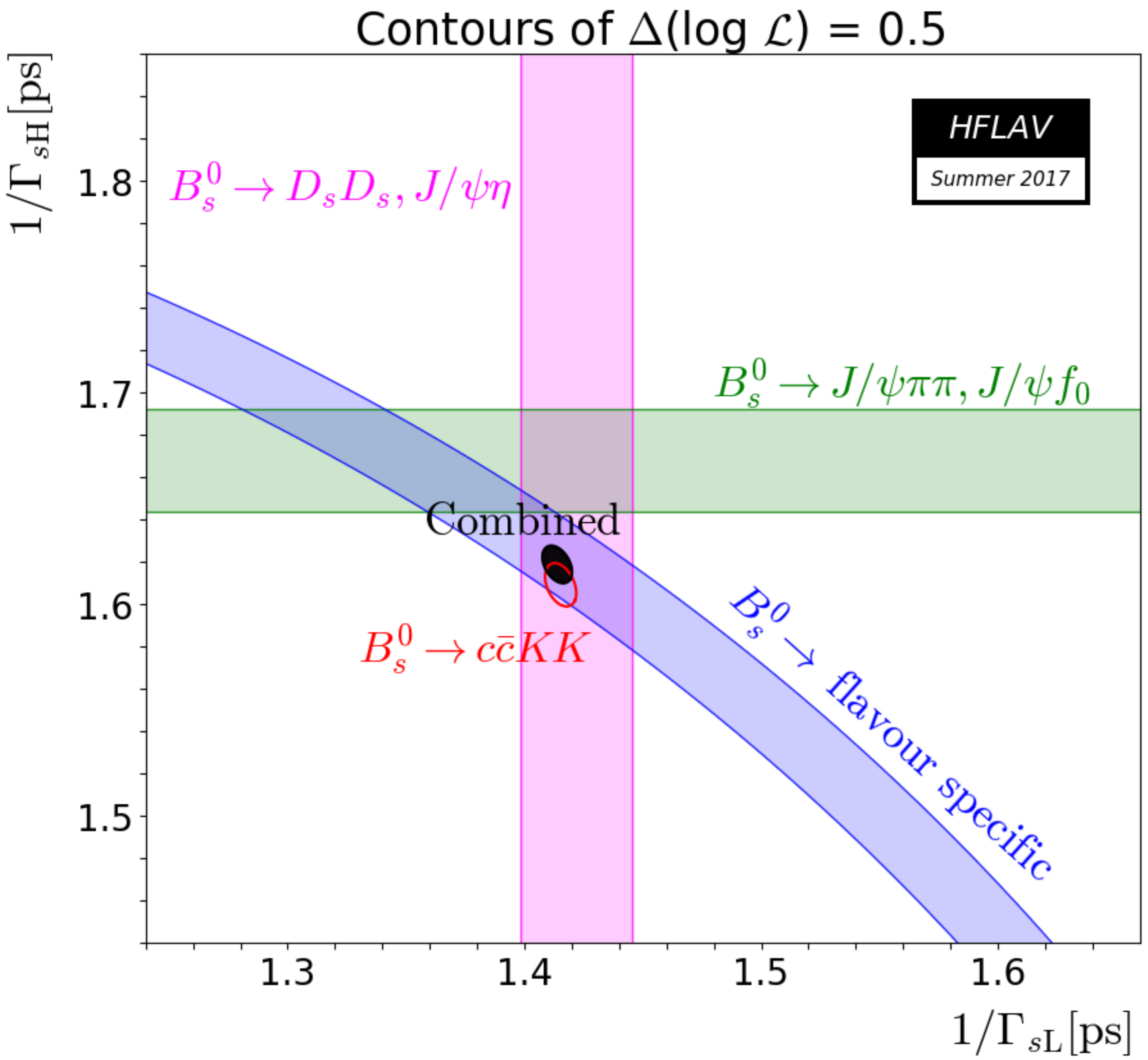
[Fleischer, PRD 55 (1997) 259]

B_s^0 effective lifetimes

Effective lifetimes of CP-even/odd final states constrain $\Gamma_{L,H}$ an
give information on ϕ_s (ignores sub-leading penguins…)

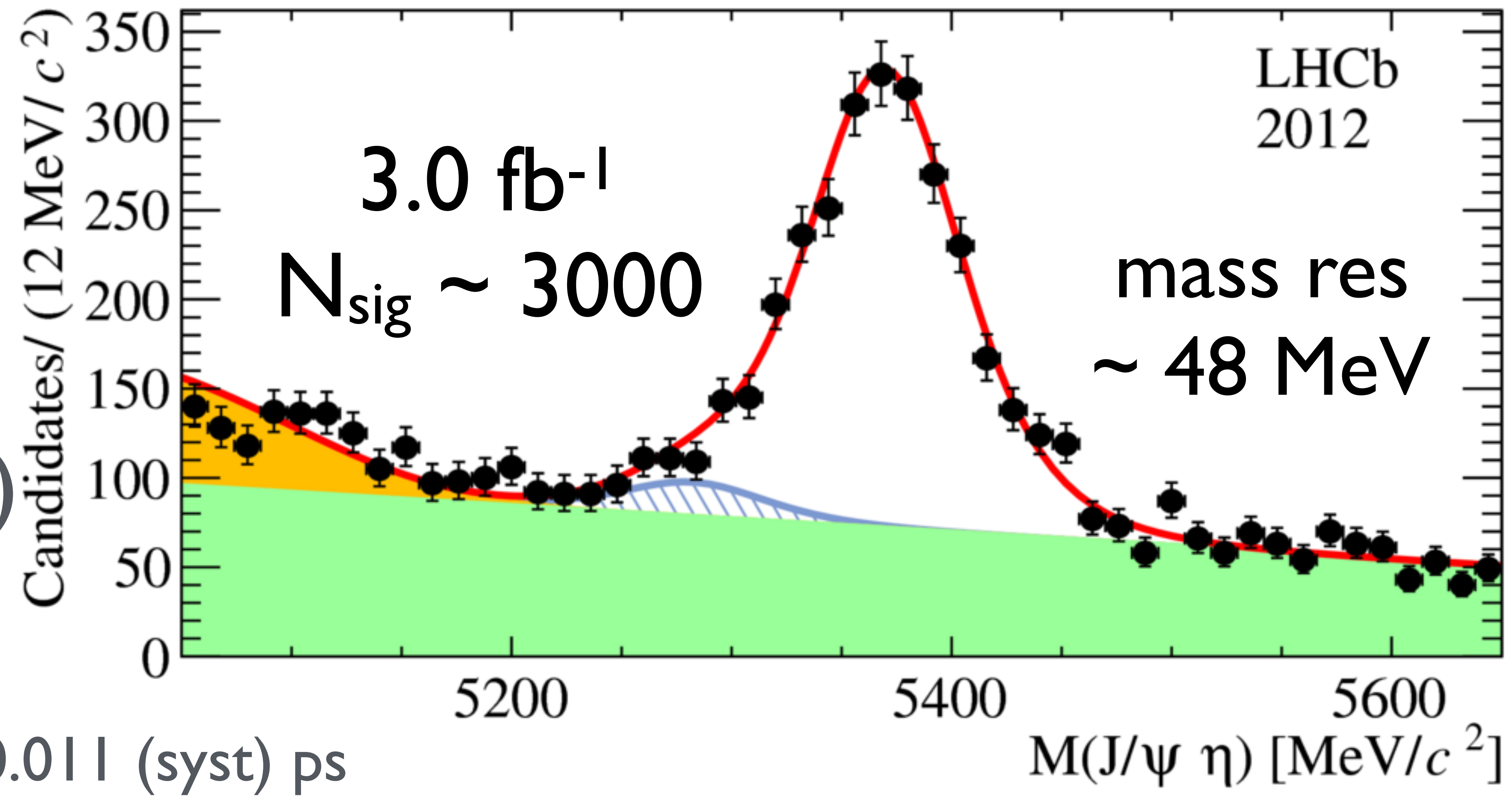
$$\tau_{\rm eff}\Gamma_s = 1 + A_f^{\Delta\Gamma_s} y_s + \left[2 - (A_f^{\Delta\Gamma_s})^2\right] y_s^2 + \ldots \qquad y_s = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

[Fleischer, Knegjens, EPJC (2011) 1789]



Tagged $B_s^0 \to J/\psi\phi$ will always dominate the precision for mixing and lifetime quantities, but useful to measure τ_{eff} as cross-check

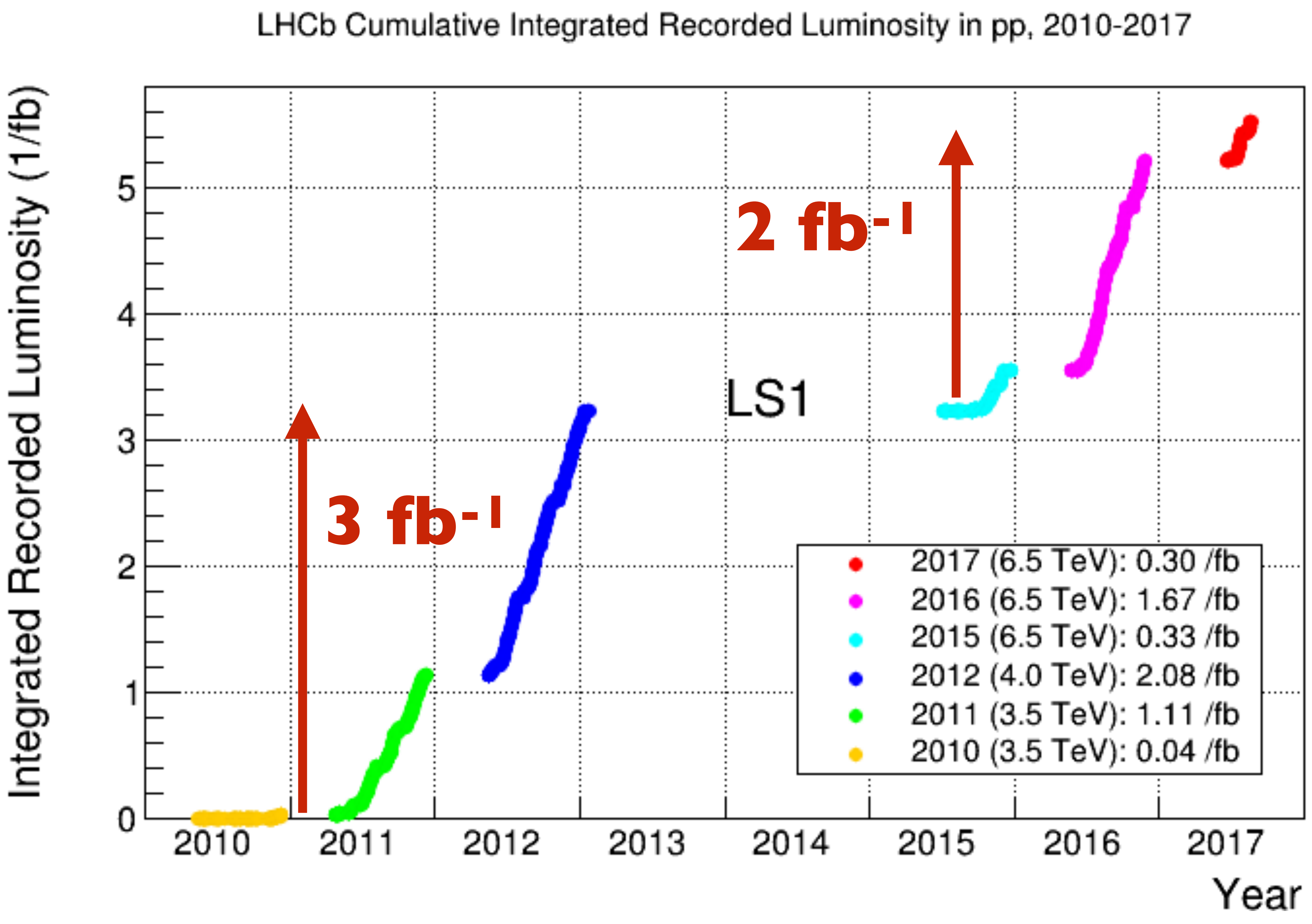
Run 2 and beyond: time-dependent flavour-tagged analyses become possible for some channels (e.g., with 300/fb, we could have 4% x 300k = ~12k tagged $B_s^0 \to J/\psi\eta$, $\eta \to \gamma\gamma$ candidates)

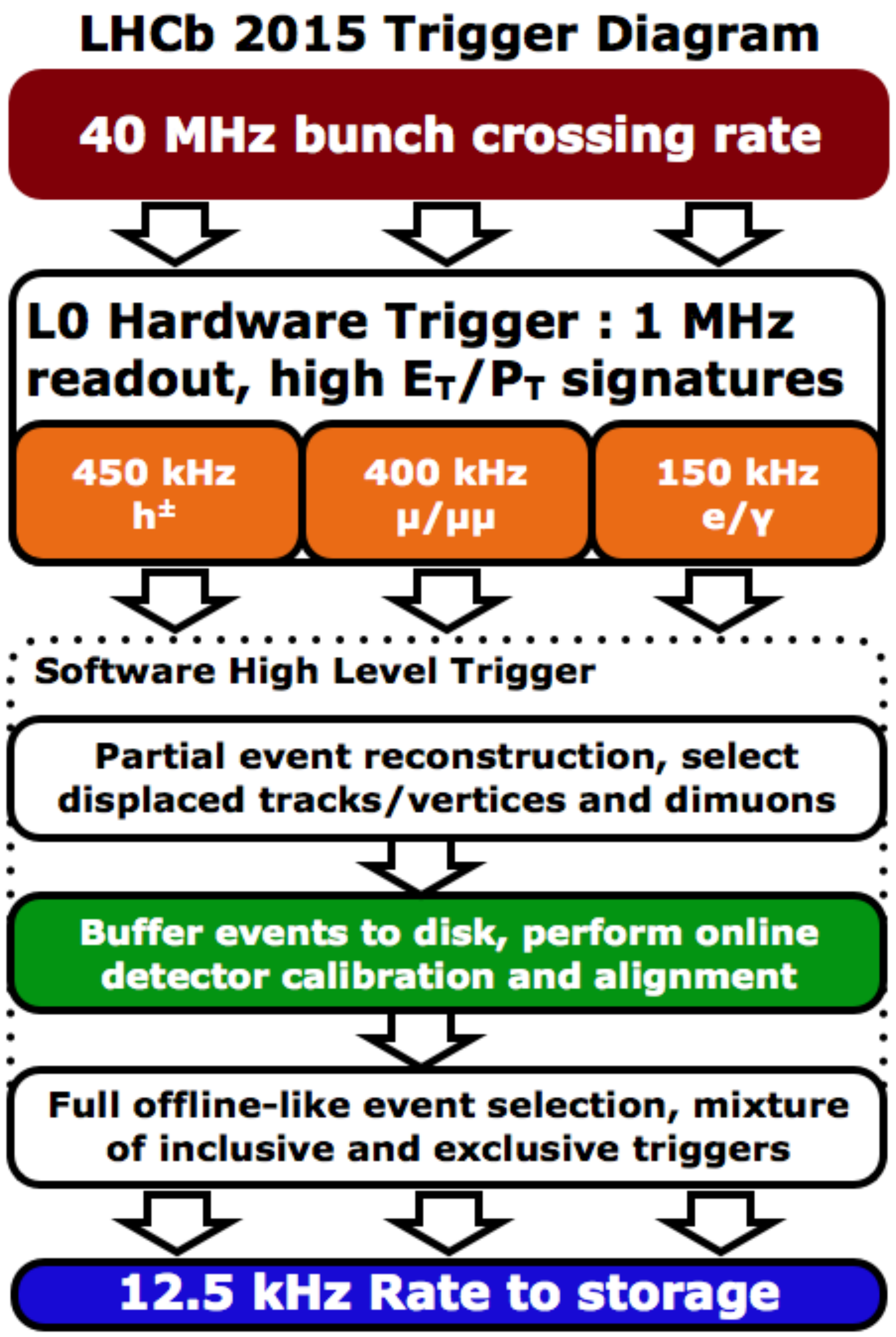


[PLB 762C (2016) 484]

$\tau_L(J/\psi\eta)$ = 1.479 ± 0.034 (stat) ± 0.011 (syst) ps

LHCb run 1 and 2





Flavour tagging

$$\epsilon_{\text{tag}} = \frac{N_{\text{tagged}}}{N_{\text{tagged}} + N_{\text{untagged}}} \qquad \omega = \frac{N_{\text{wrong}}}{N_{\text{right}} + N_{\text{wrong}}}$$

$$\epsilon_{\text{eff}} = \epsilon_{\text{tag}}\mathcal{D}^2 = \epsilon_{\text{tag}}\langle(1-2\omega)^2\rangle \qquad \sigma_{\text{stat}}(A_{CP}) \propto 1/\sqrt{\epsilon_{\text{eff}} N}$$

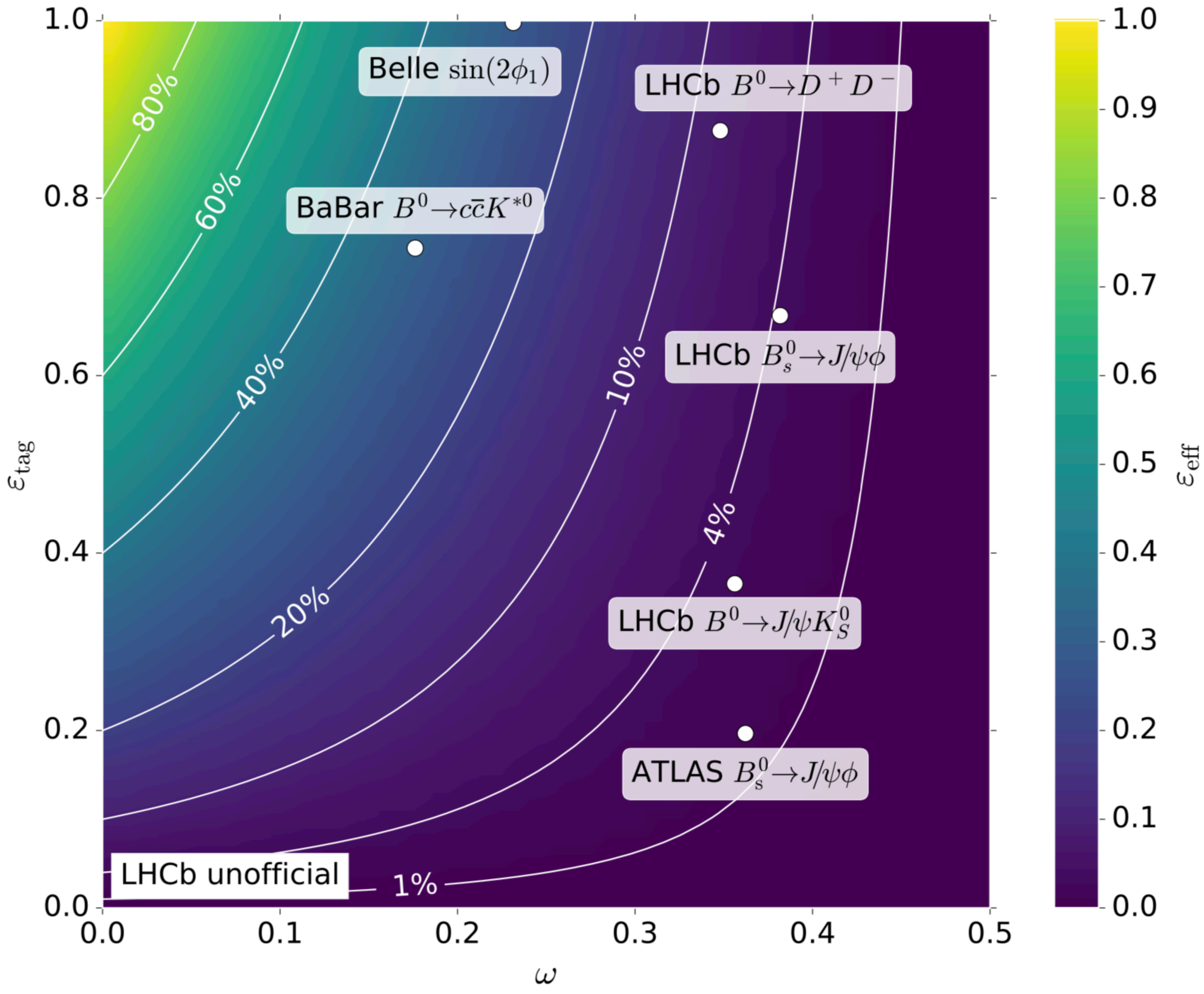
Upgrade challenge: increase in track multiplicity and pile-up (~6 for upgrade-I and ~55 for upgrade-II) that have negative effect on ω and ε(tag)

FT performance directly linked to the ability to associate PV $\Longleftrightarrow$ track. To improve/maintain tagging performance need:

Hardware: timing information (upgrade-II workshops)

Software: deep neural networks to learn correlations between all tracks and the signal B meson

Should be able to regain Run-2 performance in Run-3 by retuning algorithms and use of deep learning inclusive tagger



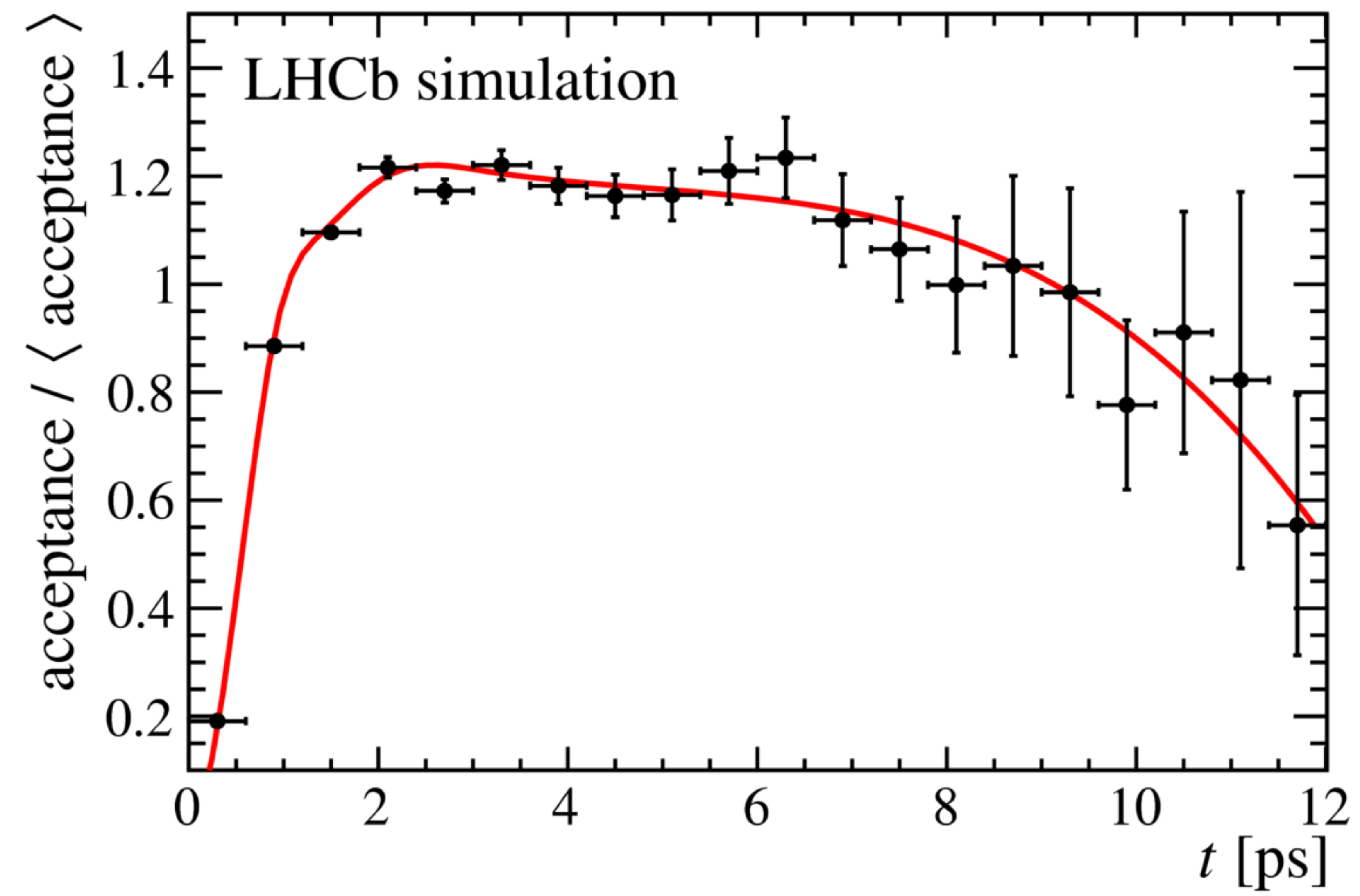
[Heinicke, CERN-THESIS-2016-152]

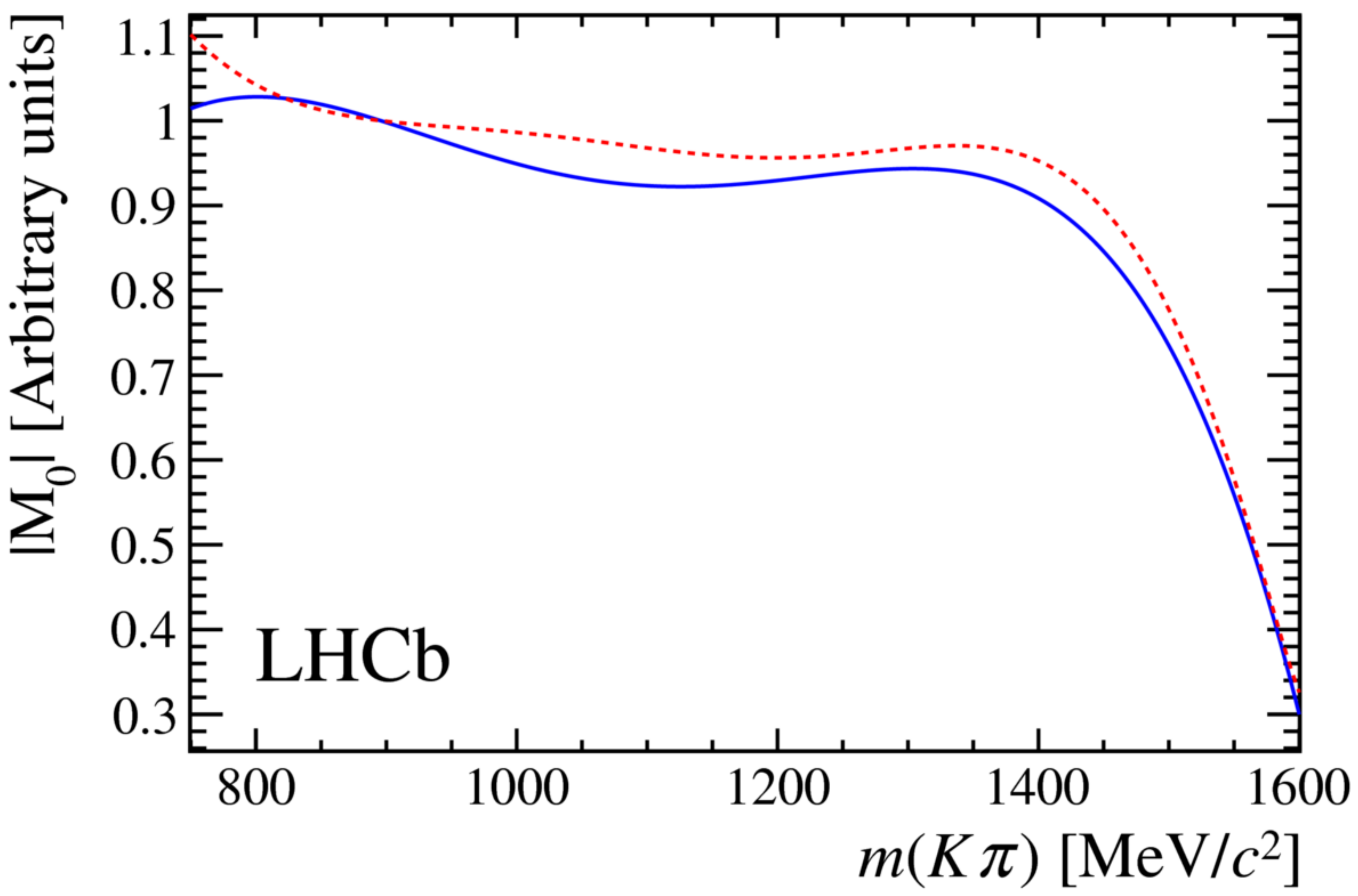
"In view of this situation it is safe to say that $SU(3)_F$-based estimates of the penguin pollution in $B_s^0 \to J/\psi\phi$ rest on **shaky ground**"

[Nierste CKM2016 arXiv:1704.04529]

$\phi_s^{d\bar{d}}$ from $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$

[JHEP 03 (2018) 140]





Parameter	Value
Common parameters	
$\phi_s^{d\bar{d}}$ [rad]	$-0.10 \pm 0.13 \pm 0.14$
$\lvert\lambda\rvert$	$1.035 \pm 0.034 \pm 0.089$
Vector/Vector (VV)	
f^{VV}	$0.067 \pm 0.004 \pm 0.024$
$f_{\rm L}^{VV}$	$0.208 \pm 0.032 \pm 0.046$
$f_{\parallel}^{VV}$	$0.297 \pm 0.029 \pm 0.042$
$\delta_{\parallel}^{VV}$ [rad]	$2.40 \pm 0.11 \pm 0.33$
$\delta_{\perp}^{VV}$ [rad]	$2.62 \pm 0.26 \pm 0.64$
Scalar/Vector (SV and VS)	
f^{SV}	$0.329 \pm 0.015 \pm 0.071$
f^{VS}	$0.133 \pm 0.013 \pm 0.065$
δ^{SV} [rad]	$-1.31 \pm 0.10 \pm 0.35$
δ^{VS} [rad]	$1.86 \pm 0.11 \pm 0.41$
Scalar/Scalar (SS)	
f^{SS}	$0.225 \pm 0.010 \pm 0.069$
δ^{SS} [rad]	$1.07 \pm 0.10 \pm 0.40$
Scalar/Tensor (ST and TS)	
f^{ST}	$0.014 \pm 0.006 \pm 0.031$
f^{TS}	$0.025 \pm 0.007 \pm 0.033$
δ^{ST} [rad]	$-2.3 \pm 0.4 \pm 1.7$
δ^{TS} [rad]	$-0.10 \pm 0.26 \pm 0.82$
Vector/Tensor (VT and TV)	
f^{VT}	$0.160 \pm 0.016 \pm 0.049$
$f_{\rm L}^{VT}$	$0.911 \pm 0.020 \pm 0.165$
$f_{\parallel}^{VT}$	$0.012 \pm 0.008 \pm 0.053$
f^{TV}	$0.036 \pm 0.014 \pm 0.048$
$f_{\rm L}^{TV}$	$0.62 \pm 0.16 \pm 0.25$
$f_{\parallel}^{TV}$	$0.24 \pm 0.10 \pm 0.14$
δ_0^{VT} [rad]	$-2.06 \pm 0.19 \pm 1.17$
$\delta_{\parallel}^{VT}$ [rad]	$-1.8 \pm 0.4 \pm 1.0$
$\delta_{\perp}^{VT}$ [rad]	$-3.2 \pm 0.3 \pm 1.2$
δ_0^{TV} [rad]	$1.91 \pm 0.30 \pm 0.80$
$\delta_{\parallel}^{TV}$ [rad]	$1.09 \pm 0.19 \pm 0.55$
$\delta_{\perp}^{TV}$ [rad]	$0.2 \pm 0.4 \pm 1.1$
Tensor/Tensor (TT)	
f^{TT}	$0.011 \pm 0.003 \pm 0.007$
$f_{\rm L}^{TT}$	$0.25 \pm 0.14 \pm 0.18$
$f_{\parallel_1}^{TT}$	$0.17 \pm 0.11 \pm 0.14$
$f_{\perp_1}^{TT}$	$0.30 \pm 0.18 \pm 0.21$
$f_{\parallel_2}^{TT}$	$0.015 \pm 0.033 \pm 0.107$
δ_0^{TT} [rad]	$1.3 \pm 0.5 \pm 1.8$
$\delta_{\parallel_1}^{TT}$ [rad]	$3.00 \pm 0.29 \pm 0.57$
$\delta_{\perp_1}^{TT}$ [rad]	$2.6 \pm 0.4 \pm 1.5$
$\delta_{\parallel_2}^{TT}$ [rad]	$2.3 \pm 0.8 \pm 1.7$
$\delta_{\perp_2}^{TT}$ [rad]	$0.7 \pm 0.6 \pm 1.3$

$\phi_s^{d\bar{d}}$ from $B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$

[JHEP 03 (2018) 140]

$K\pi$ S-wave and higher K^* resonances

Table 4: Summary of the systematic uncertainties on the two CP parameters, the CP-averaged fractions and the strong phase differences (in radians) for each of the components listed in Table 1.

Parameter	$\phi_s^{d\bar{d}}$ [rad]	$\lvert\lambda\rvert$	f^{VV}	f_L^{VV}	$f_\parallel^{VV}$	$\delta_\parallel^{VV}$	$\delta_\perp^{VV}$	f^{SV}	f^{VS}	δ^{SV}	δ^{VS}	f^{SS}	δ^{SS}
Yield and shape of mass model	0.012	0.001	0.001	0.004	0.004	0.011	0.020	0.002	0.003	0.023	0.023	0.004	0.012
Signal weights of mass model	0.012	0.007	0.002	0.006	0.005	0.024	0.112	0.004	0.005	0.049	0.022	0.005	0.047
Decay-time-dependent fit procedure	0.006	0.002	0.001	0.006	0.002	0.007	0.017	0.003	0.002	0.007	0.027	0.001	0.009
Decay-time-dependent fit parameterisation	0.049	0.013	0.021	0.025	0.026	0.187	0.202	0.042	0.029	0.159	0.234	0.064	0.227
Acceptance weights (simulated sample size)	0.106	0.078	0.004	0.031	0.029	0.236	0.564	0.037	0.039	0.250	0.290	0.015	0.256
Other acceptance and resolution effects	0.063	0.008	0.005	0.018	0.005	0.136	0.149	0.006	0.004	0.167	0.124	0.017	0.194
Production asymmetry	0.002	0.002	0.000	0.000	0.000	0.001	0.017	0.002	0.002	0.002	0.008	0.000	0.002
Total	0.141	0.089	0.024	0.046	0.042	0.333	0.641	0.071	0.065	0.346	0.405	0.069	0.399

Parameter	f^{ST}	f^{TS}	δ^{ST}	δ^{TS}	f^{VT}	f_L^{VT}	$f_\parallel^{VT}$	f^{TV}	f_L^{TV}	$f_\parallel^{TV}$	δ_0^{VT}	$\delta_\parallel^{VT}$	$\delta_\perp^{VT}$	δ_0^{TV}	$\delta_\parallel^{TV}$	$\delta_\perp^{TV}$
Yield and shape of mass model	0.002	0.004	0.111	0.023	0.001	0.003	0.001	0.001	0.043	0.025	0.023	0.055	0.110	0.053	0.018	0.065
Signal weights of mass model	0.004	0.006	0.151	0.105	0.002	0.003	0.001	0.001	0.043	0.029	0.025	0.131	0.126	0.080	0.073	0.150
Decay-time-dependent fit procedure	0.001	0.002	0.248	0.017	0.002	0.004	0.002	0.002	0.008	0.005	0.012	0.069	0.025	0.062	0.017	0.030
Decay-time-dependent fit parameterisation	0.006	0.017	0.736	0.247	0.011	0.053	0.019	0.008	0.080	0.048	0.286	0.308	0.260	0.260	0.228	0.405
Acceptance weights (simulated sample size)	0.014	0.015	1.463	0.719	0.026	0.145	0.054	0.027	0.199	0.102	1.117	1.080	0.888	0.712	0.417	0.947
Other acceptance and resolution effects	0.002	0.003	0.184	0.226	0.015	0.024	0.004	0.005	0.045	0.017	0.163	0.168	0.191	0.229	0.246	0.171
Production asymmetry	0.001	0.001	0.037	0.026	0.001	0.003	0.001	0.002	0.012	0.006	0.015	0.030	0.018	0.003	0.007	0.041
Total	0.031	0.033	1.688	0.817	0.049	0.165	0.063	0.048	0.252	0.143	1.171	1.159	0.970	0.802	0.546	1.076

Parameter	f^{TT}	f_L^{TT}	$f_{\parallel_1}^{TT}$	$f_{\perp_1}^{TT}$	$f_{\parallel_2}^{TT}$	δ_0^{TT}	$\delta_{\parallel_1}^{TT}$	$\delta_{\perp_1}^{TT}$	$\delta_{\parallel_2}^{TT}$	$\delta_{\perp_2}^{TT}$
Yield and shape of mass model	0.000	0.045	0.019	0.037	0.002	0.038	0.027	0.009	0.079	0.114
Signal weights of mass model	0.000	0.066	0.025	0.024	0.002	0.147	0.046	0.112	0.123	0.215
Decay-time-dependent fit procedure	0.001	0.022	0.022	0.014	0.004	0.127	0.036	0.068	0.058	0.040
Decay-time-dependent fit parameterisation	0.005	0.051	0.071	0.113	0.038	1.213	0.199	0.685	0.820	0.476
Acceptance weights (simulated sample size)	0.003	0.135	0.110	0.127	0.077	1.328	0.454	1.348	1.443	1.161
Other acceptance and resolution effects	0.002	0.031	0.028	0.056	0.024	0.226	0.275	0.156	0.343	0.301
Production asymmetry	0.000	0.002	0.001	0.008	0.003	0.005	0.002	0.062	0.015	0.043
Total	0.007	0.176	0.142	0.205	0.107	1.825	0.573	1.546	1.706	1.330

$\phi_s^{s\bar{s}}$ from $B_s^0 \to \phi\phi \to (K^+K^-)(K^+K^-)$

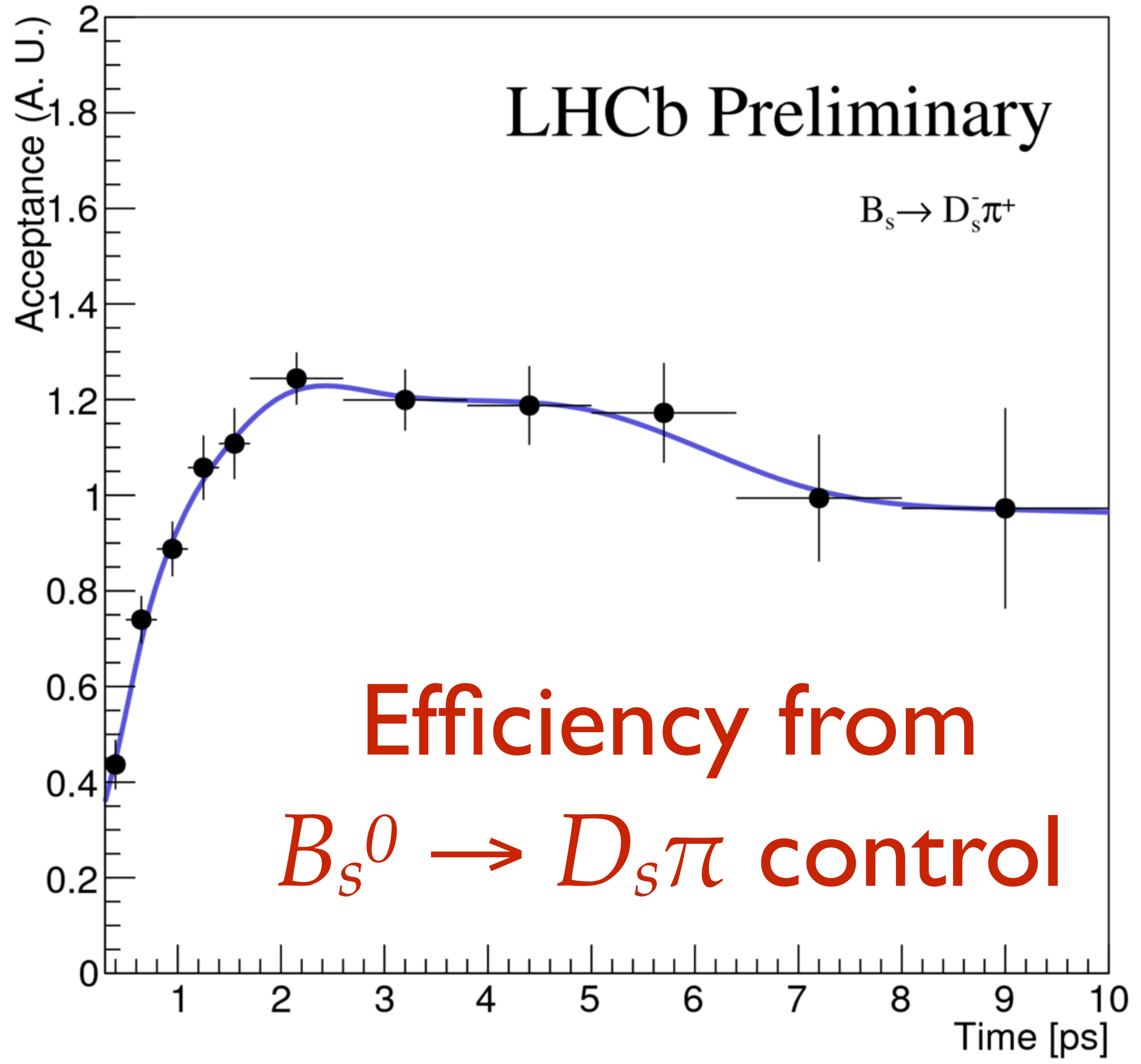
[LHCb-CONF-2018-001]

2011-2016 dataset

Parameter	Result
$\phi_s^{s\bar{s}s}$ (rad)	-0.07 ± 0.13
$\lvert\lambda\rvert$	1.02 ± 0.05
$\lvert A_\perp\rvert^2$	0.287 ± 0.008
$\lvert A_0\rvert^2$	0.382 ± 0.008
$\delta_\perp$ (rad)	2.81 ± 0.21
$\delta_\parallel$ (rad)	2.52 ± 0.05

	$\delta_\parallel$	$\lvert A_\perp\rvert^2$	$\delta_\perp$	$\lvert A_0\rvert^2$	$\lvert\lambda\rvert$	$\phi_s^{s\bar{s}s}$
$\delta_\parallel$	1.00	0.14	0.13	-0.03	0.02	0.01
$\lvert A_\perp\rvert^2$		1.00	0.01	-0.45	0.00	-0.03
$\delta_\perp$			1.00	0.00	-0.26	-0.15
$\lvert A_0\rvert^2$				1.00	-0.01	0.01
$\lvert\lambda\rvert$					1.00	-0.05
$\phi_s^{s\bar{s}s}$						1.00

Parameter	Mass model	AA	TA	TR	Fit bias	Total
$\lvert A_0\rvert^2$	0.0035	0.0098	0.0008	0.0001	0.0018	0.0106
$\lvert A_\perp\rvert^2$	0.0021	0.0046	0.0007	0.0002	0.0012	0.0052
$\delta_\parallel$ (rad)	0.0128	0.0653	0.0049	0.0031	0.0179	0.0692
$\delta_\perp$ (rad)	0.0640	0.0100	0.0085	0.0064	0.0701	0.0960
$\phi_s^{s\bar{s}s}$ (rad)	0.0119	0.0072	0.0077	0.0035	0.0126	0.0206
$\lvert\lambda\rvert$	0.0063	0.0217	0.0023	0.0053	0.0097	0.0253



Triple product asymmetries from $B_s^0 \to \phi\phi$

[LHCb-CONF-2018-001]

$$\sin\Phi = (\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1},$$
$$\sin 2\Phi = 2(\hat{n}_{V_1} \cdot \hat{n}_{V_2})(\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1}$$

$$A_U \equiv \frac{\Gamma(U>0)-\Gamma(U<0)}{\Gamma(U>0)+\Gamma(U<0)}$$

$$U \equiv \sin\Phi\cos\Phi \qquad V \equiv \sin(\pm\Phi)$$

$$A_V \equiv \frac{\Gamma(V>0)-\Gamma(V<0)}{\Gamma(V>0)+\Gamma(V<0)}$$