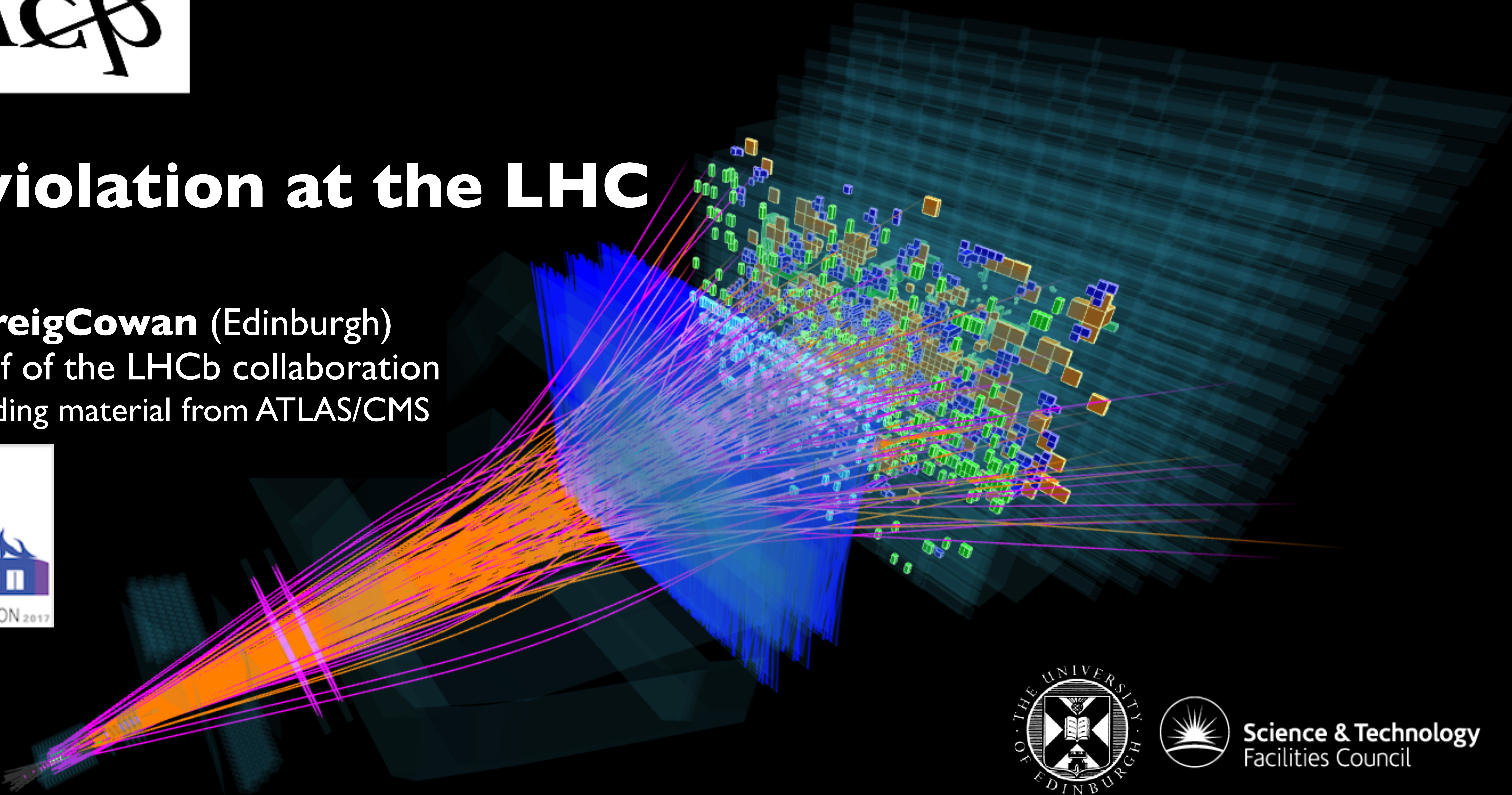
CP violation at the LHC

@GreigCowan (Edinburgh)
on behalf of the LHCb collaboration
and including material from ATLAS/CMS



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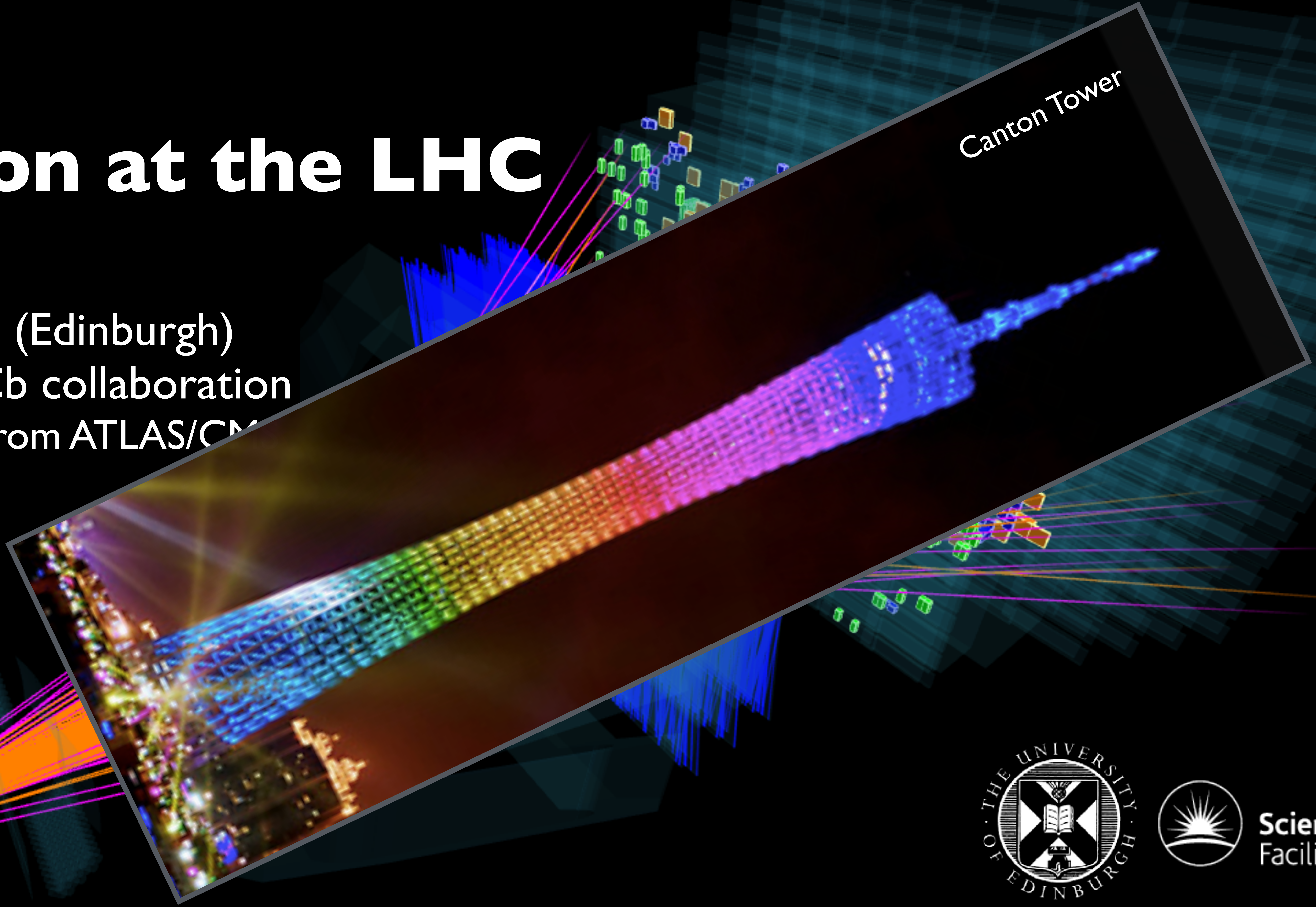

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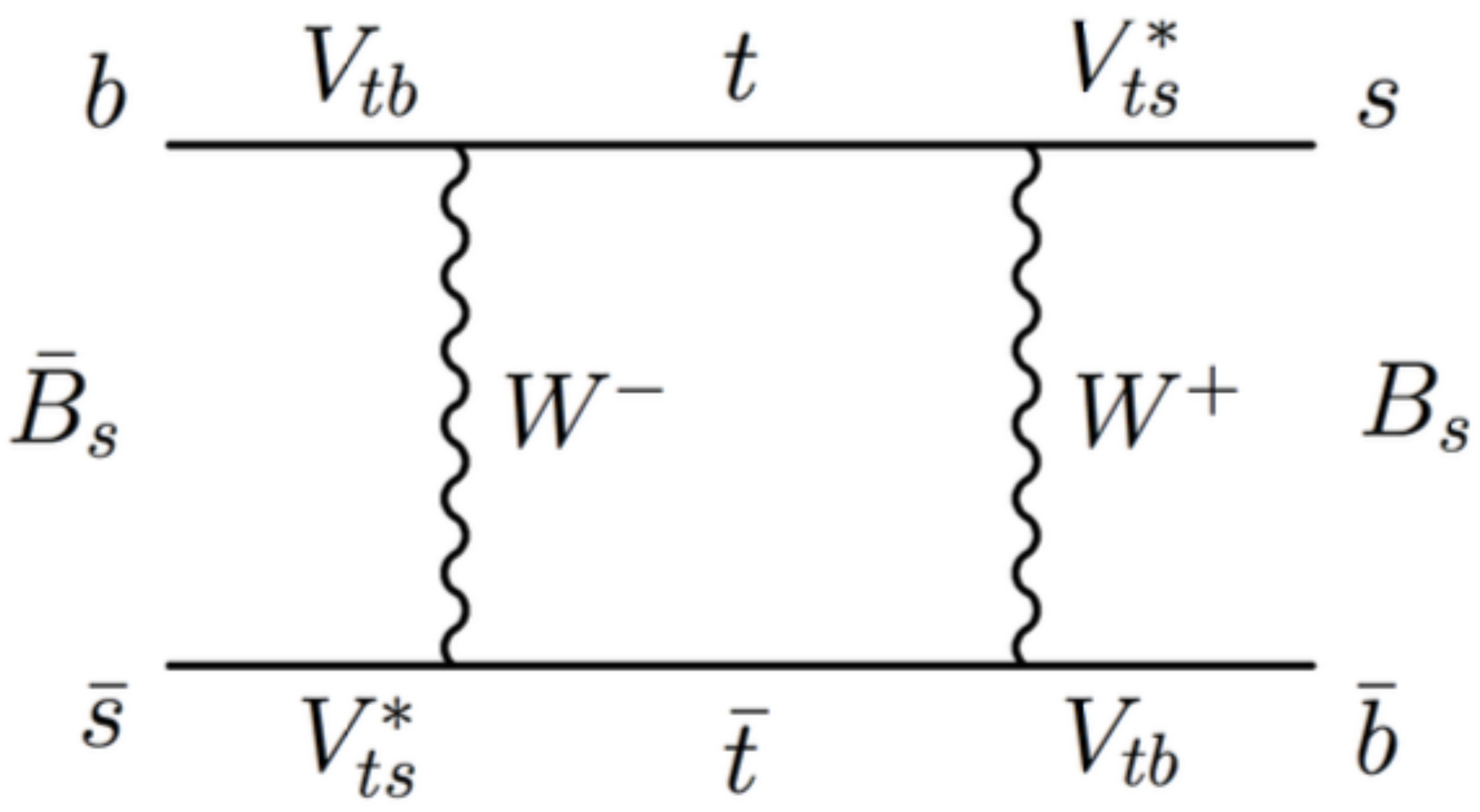
Why CP violation?

CP violation is necessary condition for baryon asymmetry of the Universe
[A. D. Sakharov, JETP Lett. 5, 24-27 (1967)].

CPV is present in the Standard Model but too small by 10^{10} to explain asymmetry.

Heavy-quark hadrons provide excellent place to search for new sources of CPV and probing high energy scales.

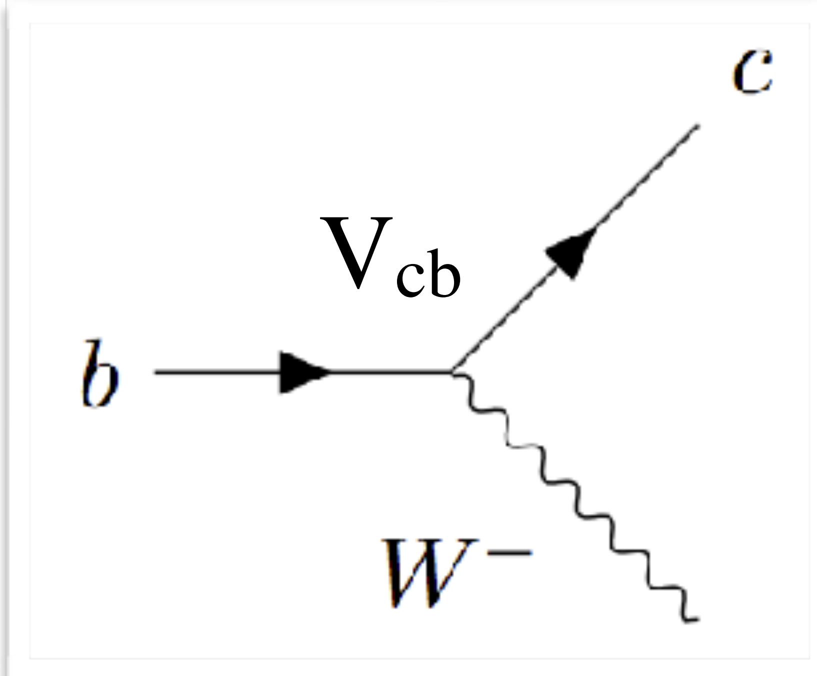


Historical precedent, e.g., B^0 meson mixing led to first indications about top quark mass [PLB 192 (1987) 245]
[PLB 186 (1987) 247]

2017 is 40th anniversary of the b-quark discovery
[FNAL-E-0288, PRL 39 (1977) 252]

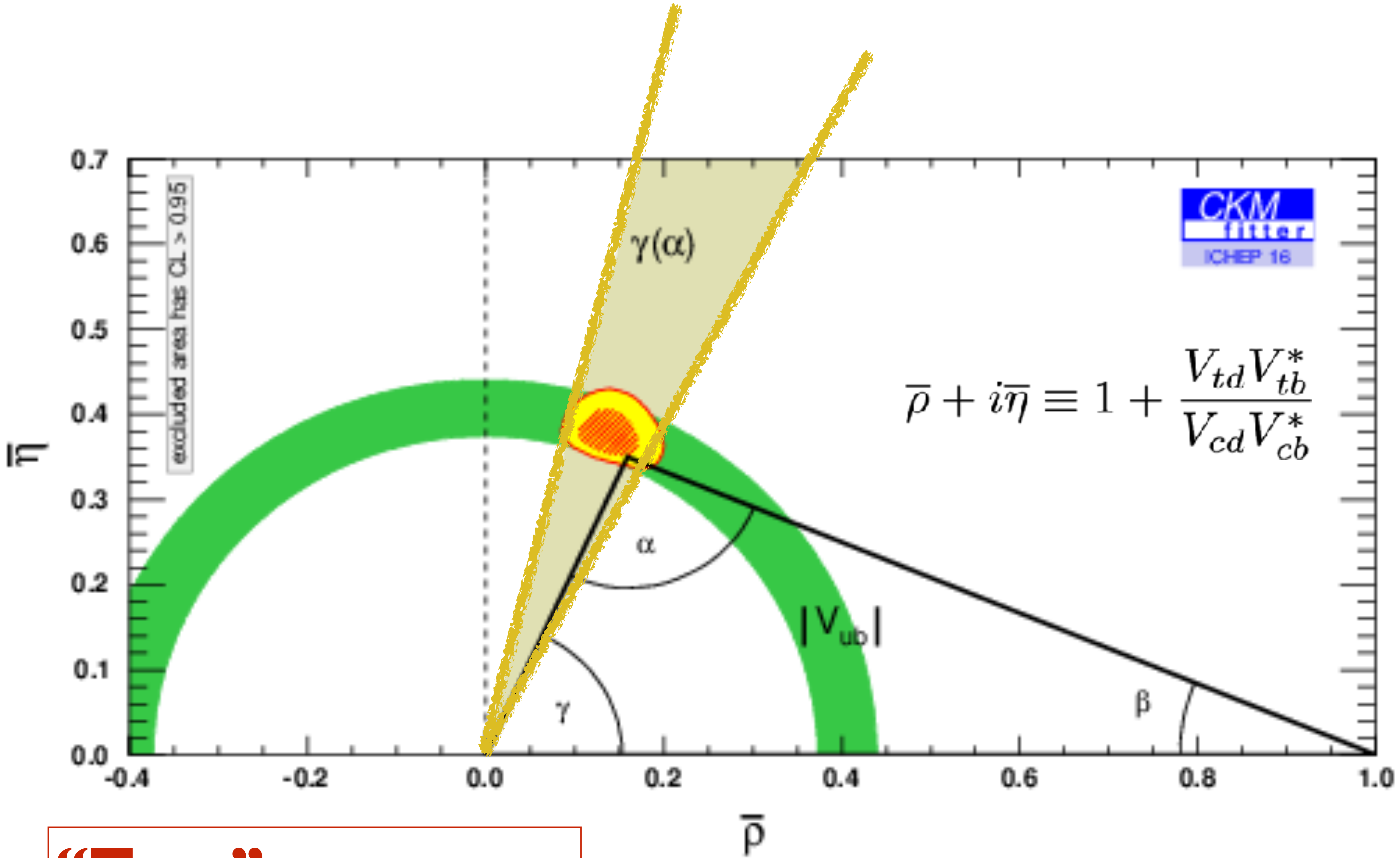
The CKM mechanism

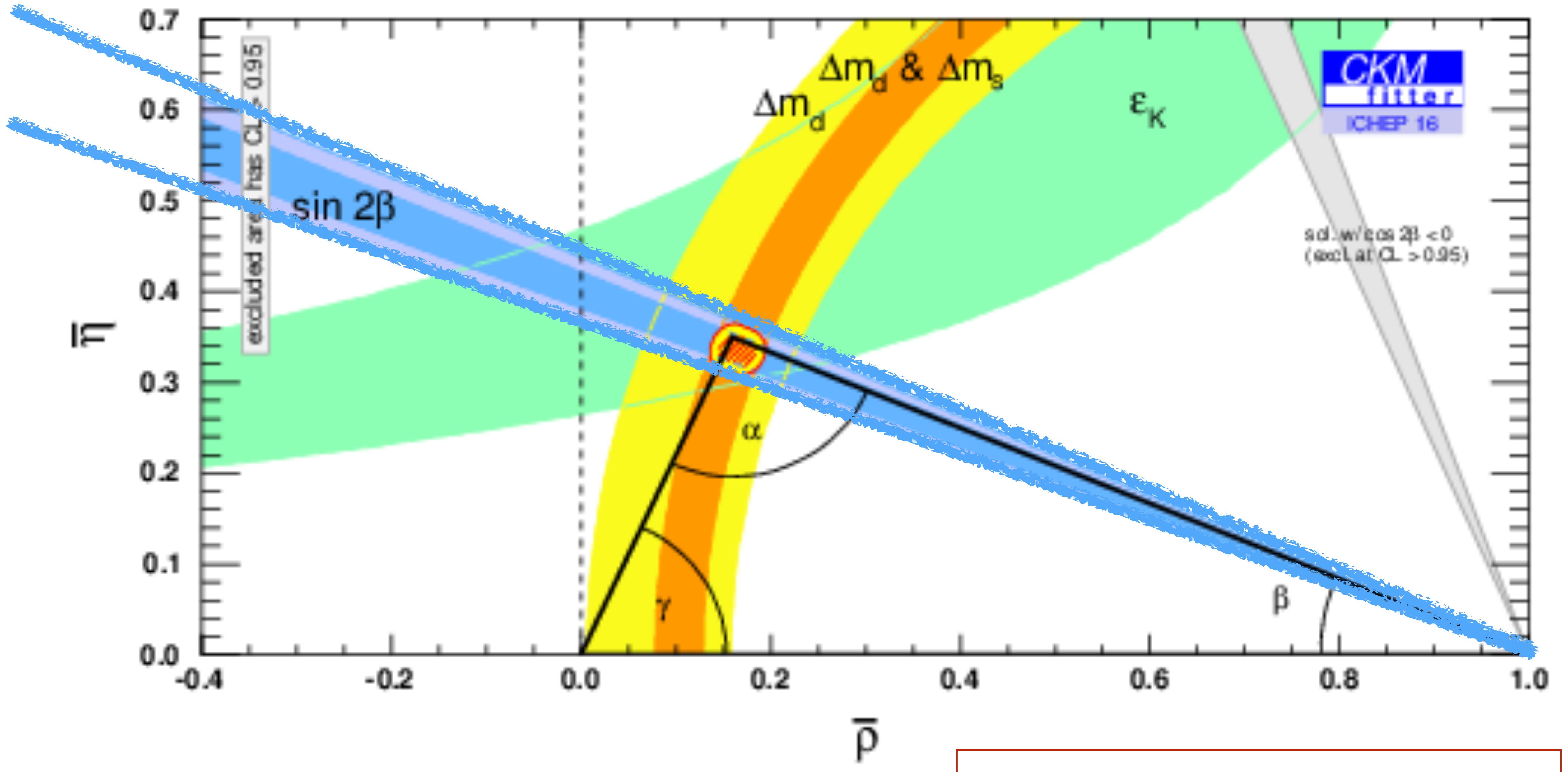
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



Wolfenstein parameterisation

$\lambda \sim 0.22$





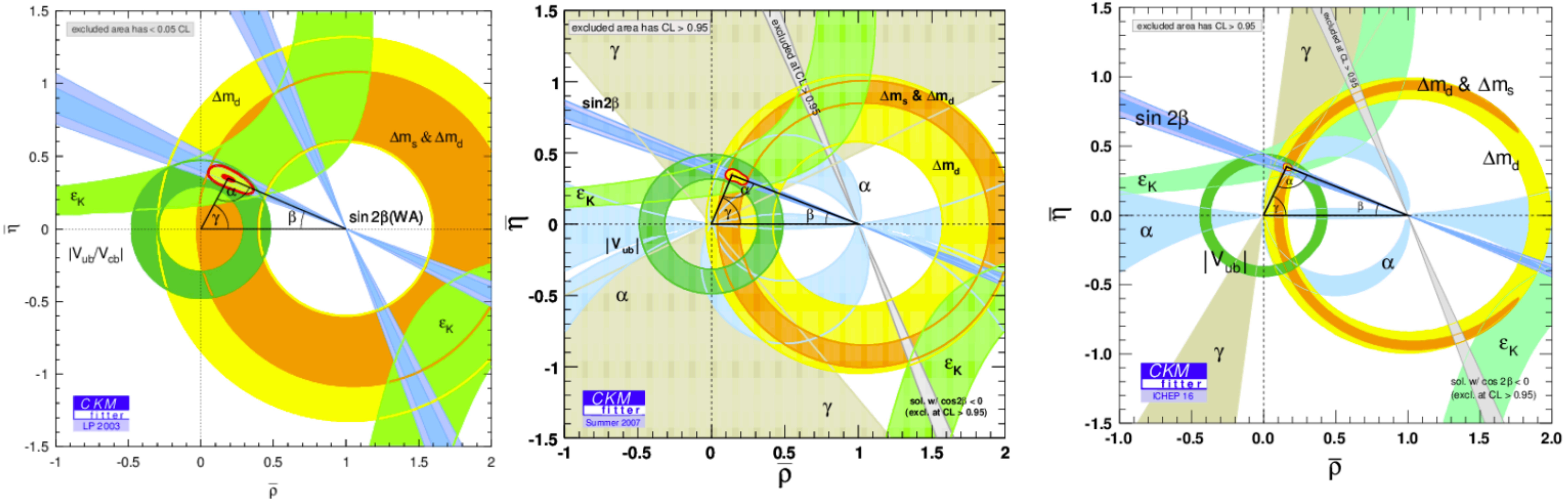
$$\bar\rho + i\bar\eta \equiv 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}$$

"Tree" processes

"Loop" processes

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

The CKM mechanism



Huge programme of experimental, theoretical and Lattice QCD calculations

e.g., [Fermilab-MILC, PRD 93 (2016) 113016]

SM working well, but still room for 10-20% NP contributions → More precision needed!

Three types of CP violation

CP violation in mixing

$|q/p| \neq 1$

$$|P^0 \to \overline{P}^0|^2 \neq |\overline{P}^0 \to P^0|^2$$

CPV in interference of mixing + decay

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

$$|P^0 \to \overline{P}^0 \to \overline{f}|^2 \neq |\overline{P}^0 \to P^0 \to f|^2$$

CP violation in decay

$|\overline{A}_{f_{CP}}/A_{f_{CP}}| \neq 1$

$$|P \to f|^2 \neq |\overline{P} \to \overline{f}|^2$$

Charged mesons + baryons only sensitive to CPV in decay

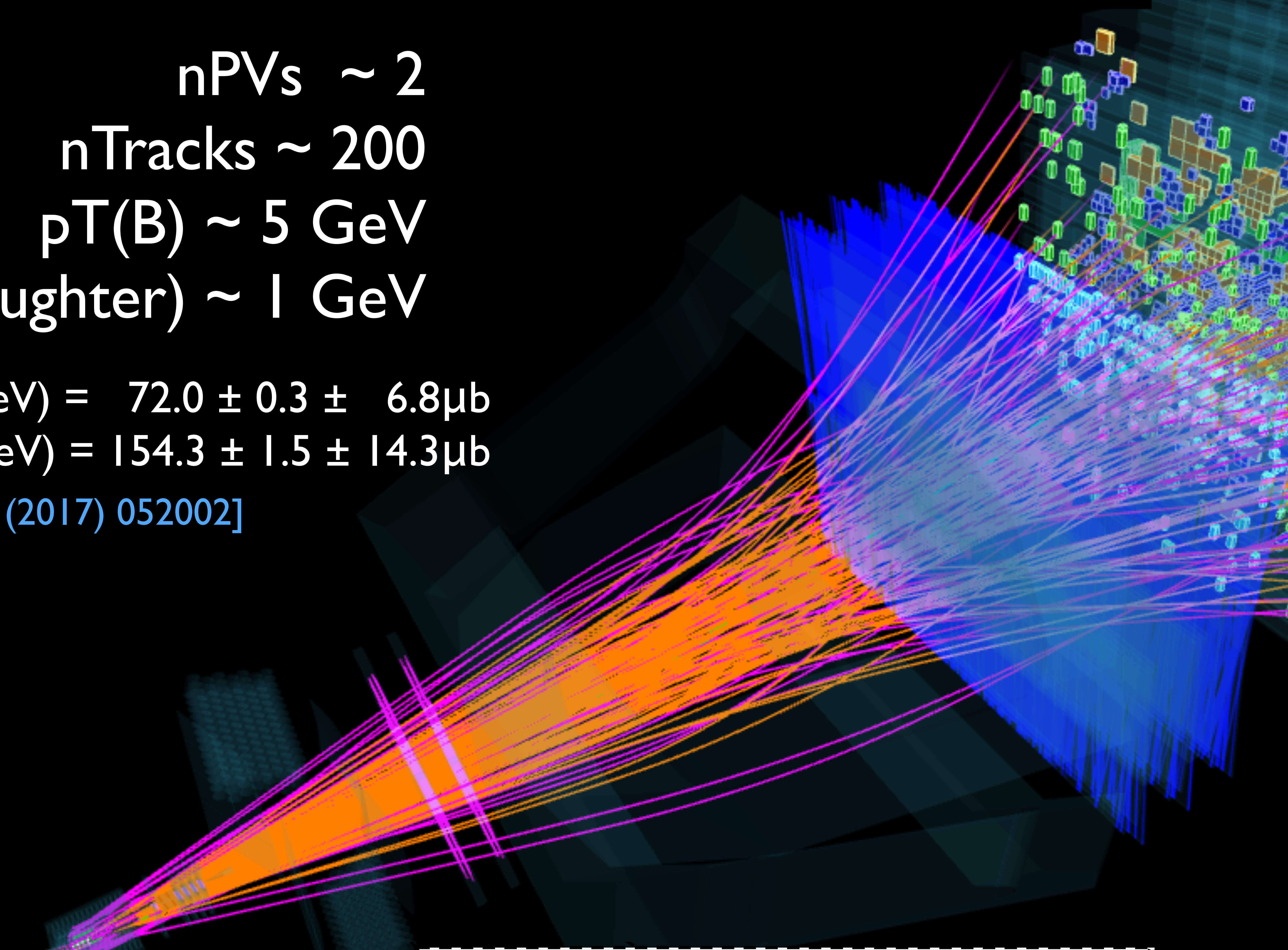
Beauty

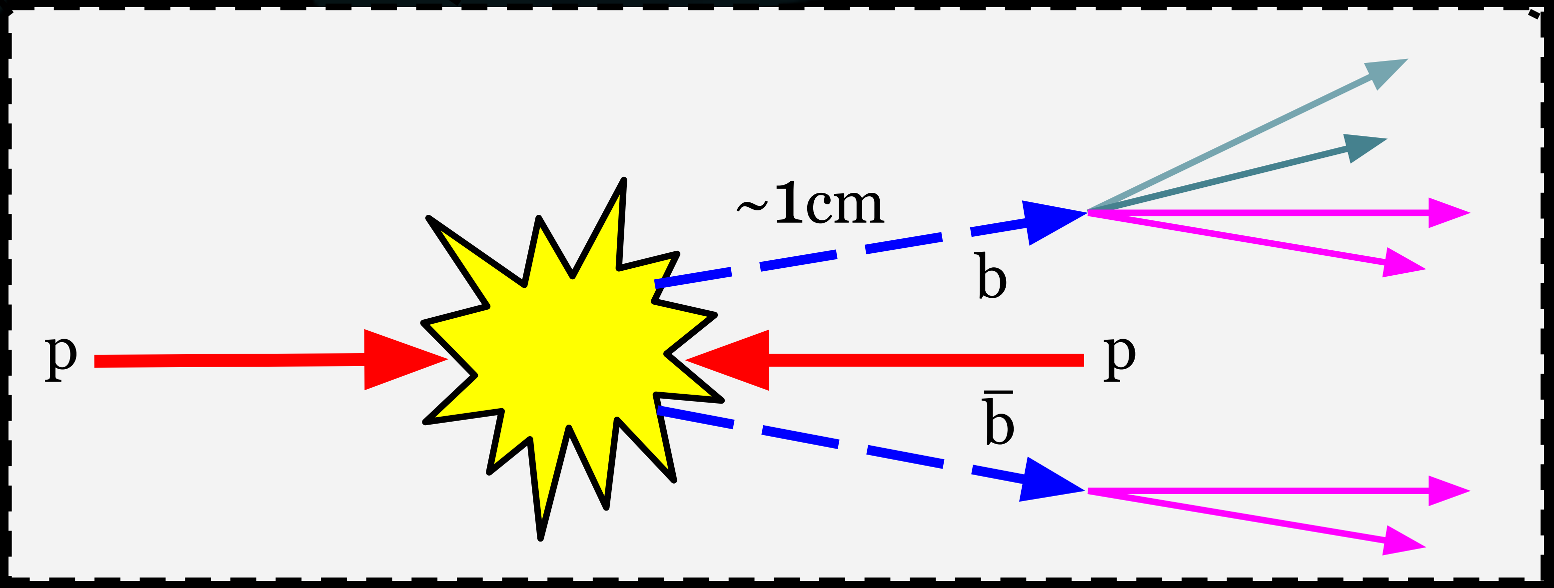
Results shown are Run 1 only or combination of Run 1 + 2

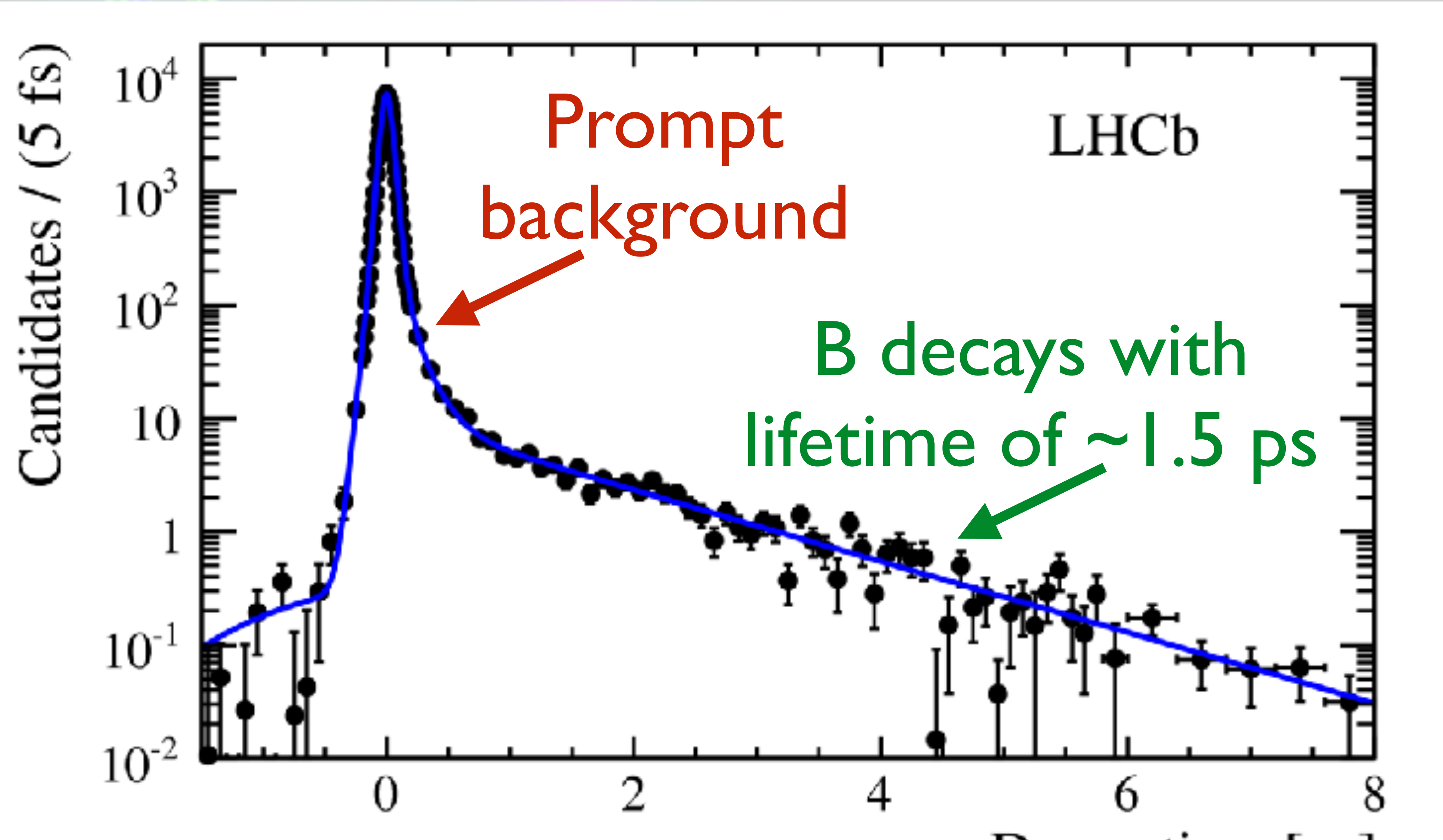
Flavour physics at the LHC

nPVs ~ 2
nTracks ~ 200
pT(B) ~ 5 GeV
pT(daughter) ~ 1 GeV

σ_{bb}(7 TeV) = 72.0 ± 0.3 ± 6.8μb
σ_{bb}(13 TeV) = 154.3 ± 1.5 ± 14.3μb
[PRL 118 (2017) 052002]

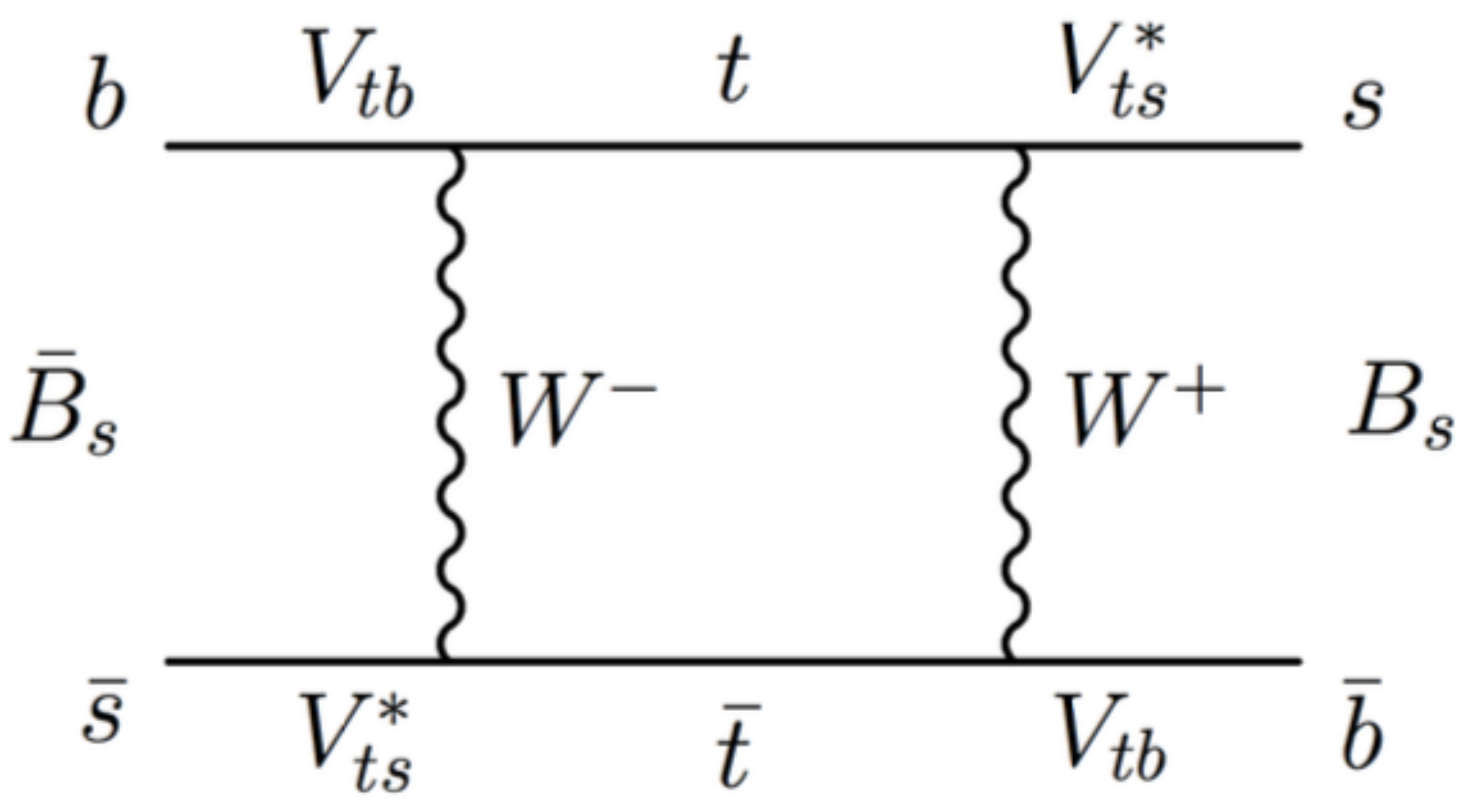


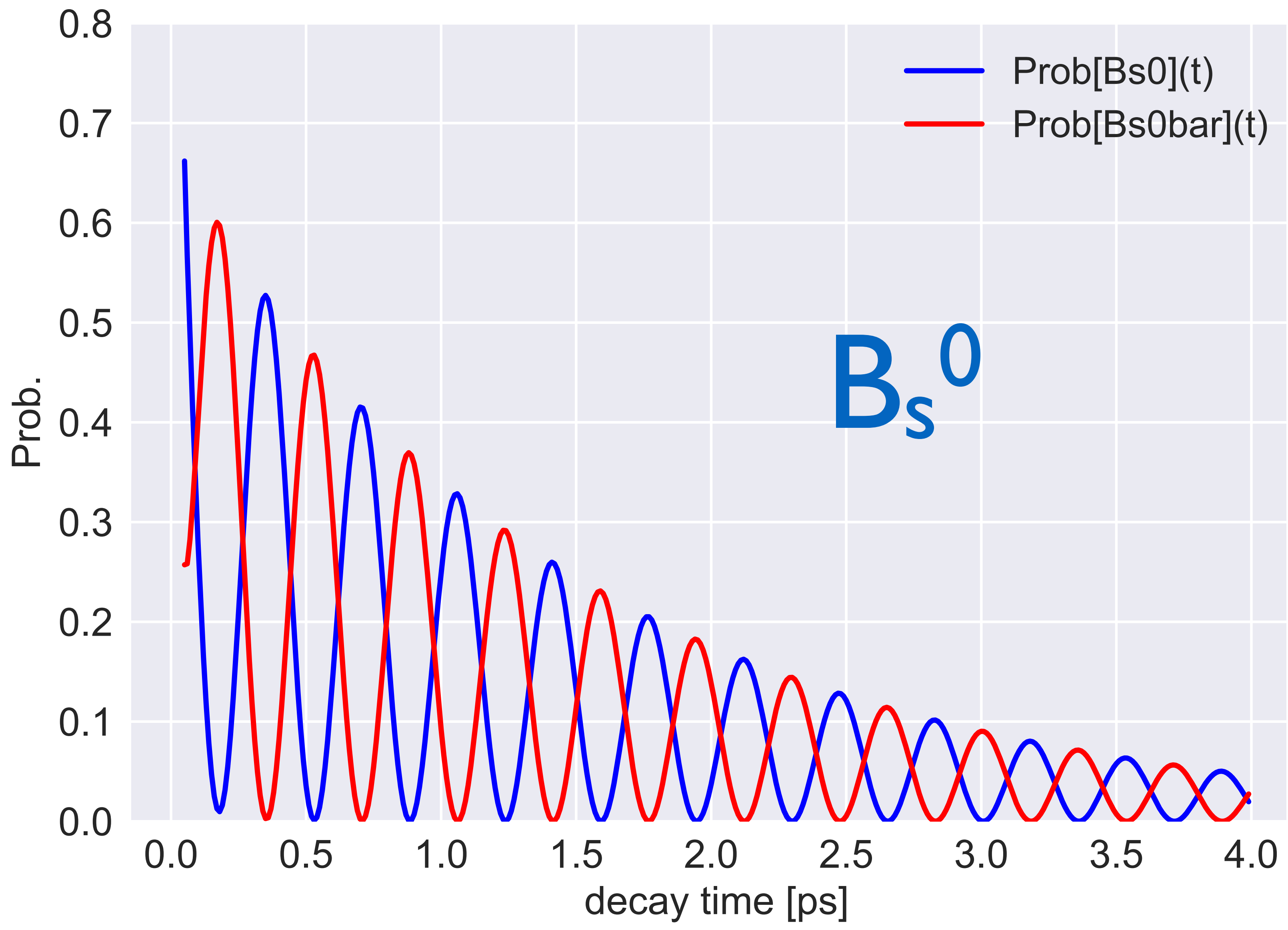


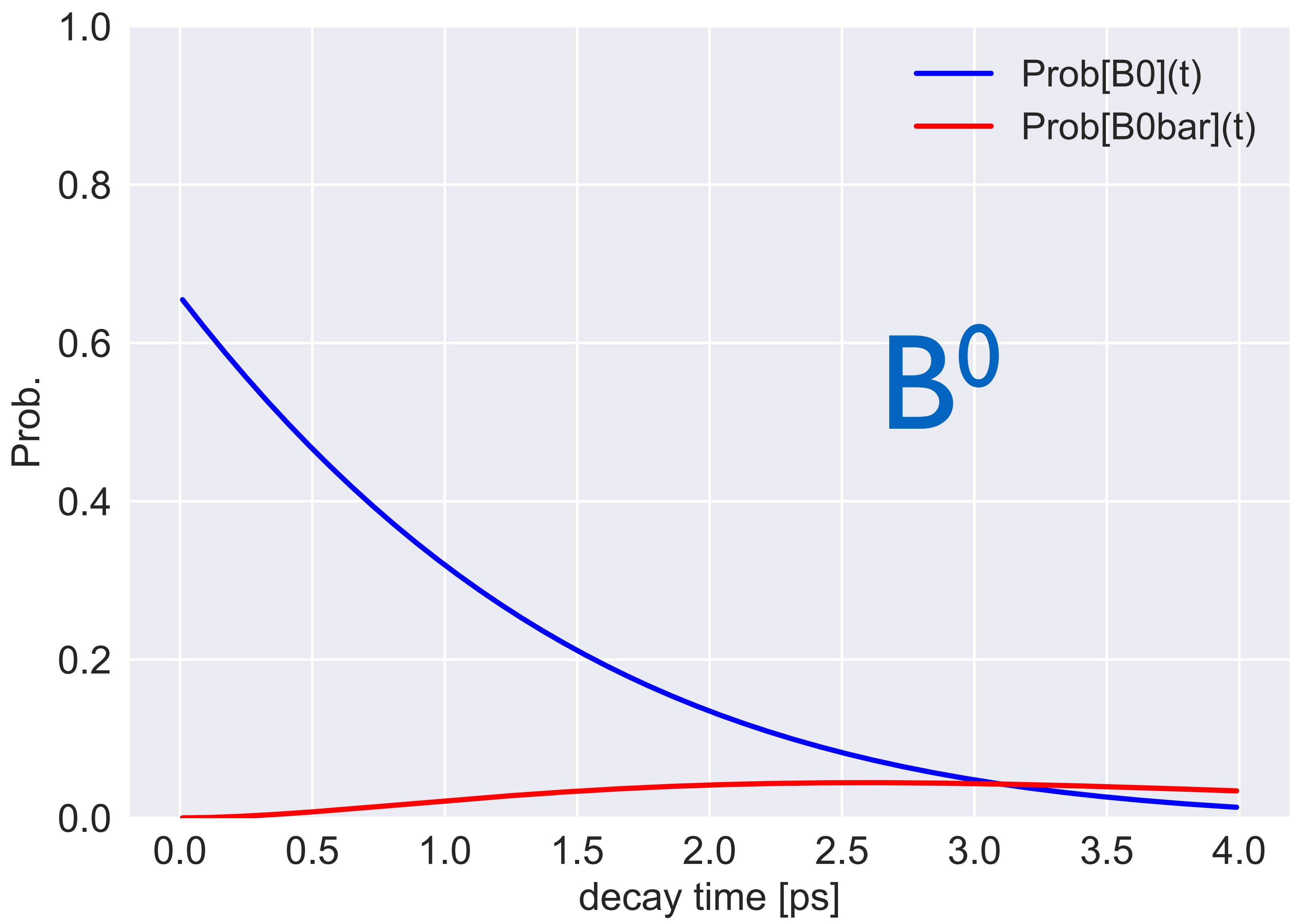


[PRD 87 (2013) 112010]

Neutral meson oscillations







$$|B^0_{\mathrm{L,H}}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle$$

$$\mathrm{Prob}(B^0 \to \overline{B}^0) = \frac{\Gamma e^{-\Gamma t}}{2}[\cosh(\Delta\Gamma/2t) - \cos(\Delta m t)]|q/p|^2$$

+ similar equations for other mixing probabilities

New physics particles could enter the loop.

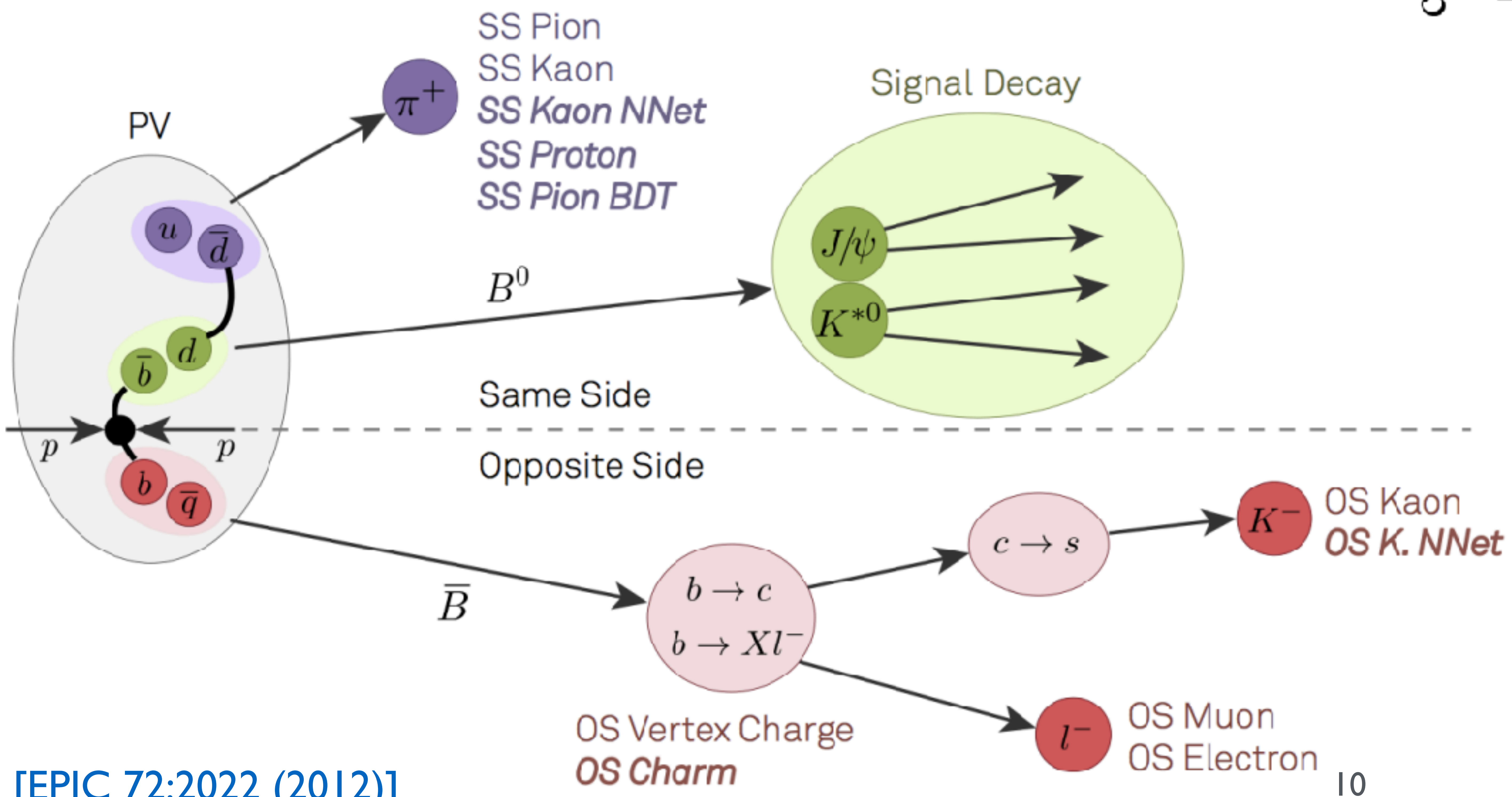
Same description for **charm system**, but mixing frequency much **smaller** due to no top quarks in the loop

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

Measuring B meson oscillations (+ CPV)

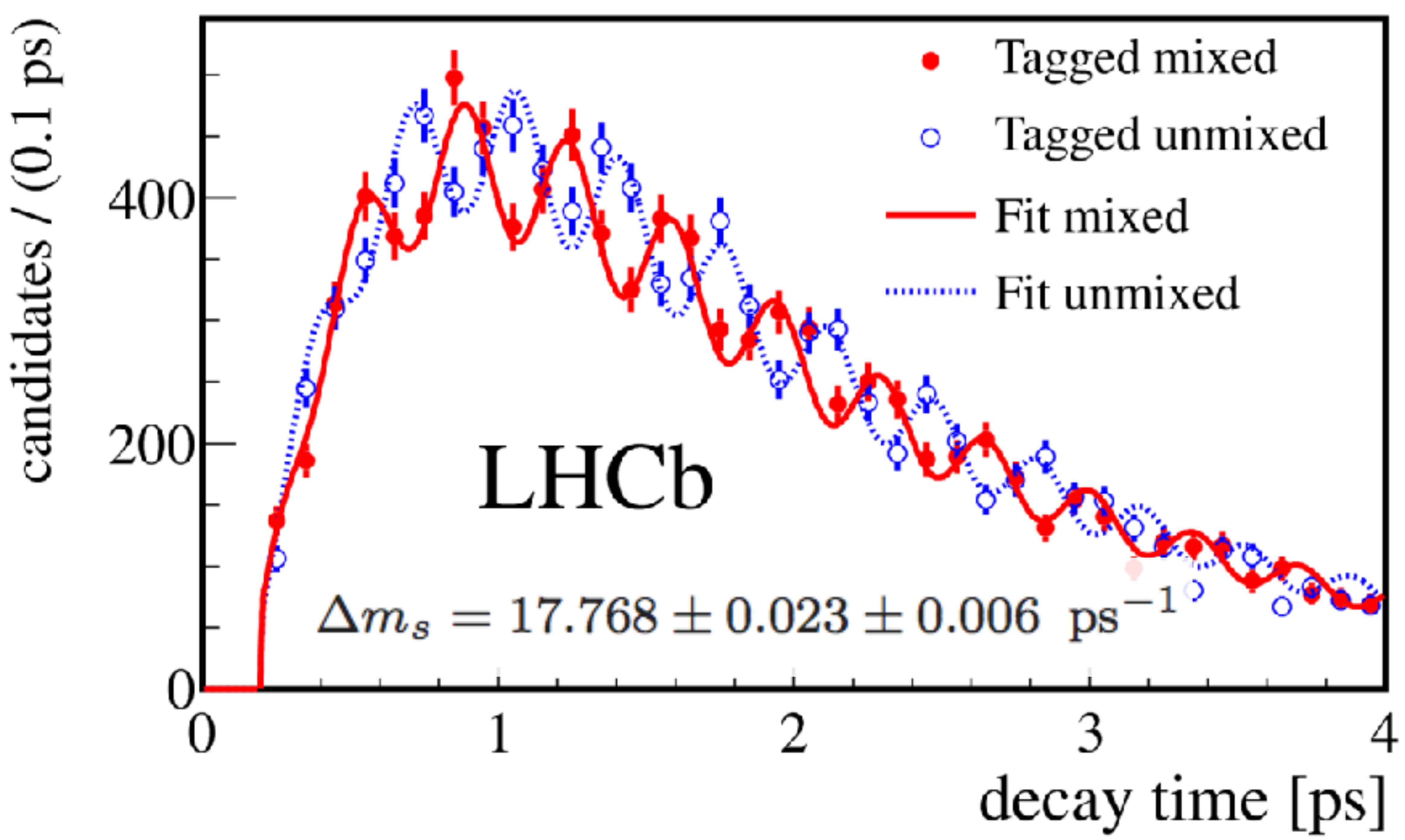
Typical analysis requirements:

- Excellent decay-time resolution (~45 fs)
- Modelling decay-time efficiency
- Production + detection asymmetries
- Tagging of meson flavour @ production



[EPJC 72:2022 (2012)]

$B_s^0 \to D_s^- \pi^+$ [NJP 15 (2013) 053021]

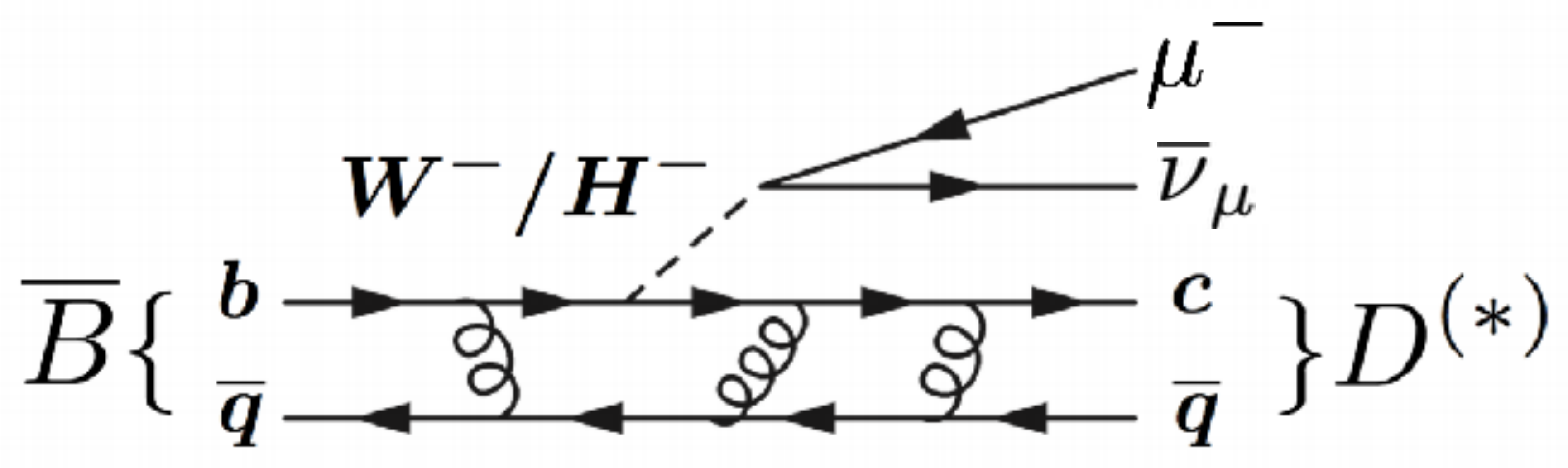


Typical tagging power

~ 4% LHCb (J/ψ modes)
~ 8% LHCb (open-charm modes)
~1.5% ATLAS/CMS
~ 30% B-factories

CPV in neutral B meson mixing

$$A_{sl} = \frac{\Gamma(\overline{B}^0 \to B^0 \to f) - \Gamma(B^0 \to \overline{B}^0 \to \overline{f})}{\Gamma(\overline{B}^0 \to B^0 \to f) + \Gamma(B^0 \to \overline{B}^0 \to \overline{f})} \approx \frac{\Delta\Gamma}{\Delta m} \tan\phi_M$$



[Artuso et al. arXiv:1511.09466] - tiny in SM

$$A^d_{\rm SL} = (-4.1 \pm 0.6) \times 10^{-4}$$
$$A^s_{\rm SL} = (+2.22 \pm 0.27) \times 10^{-5}$$

Semileptonic decays are tree-dominated so there should be no CPV in decay

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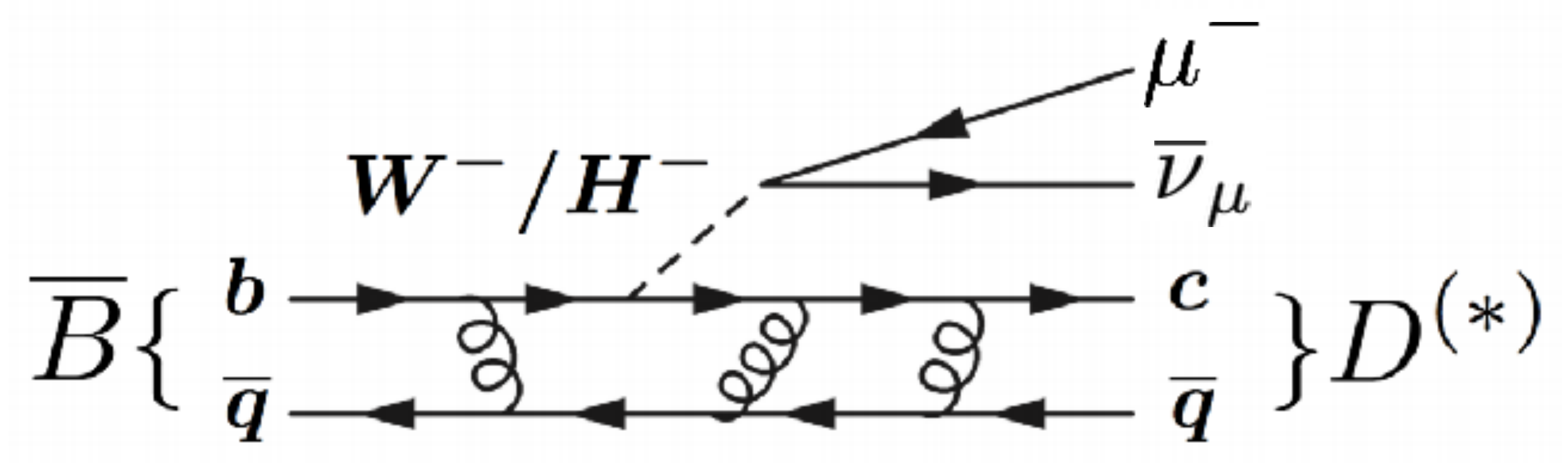

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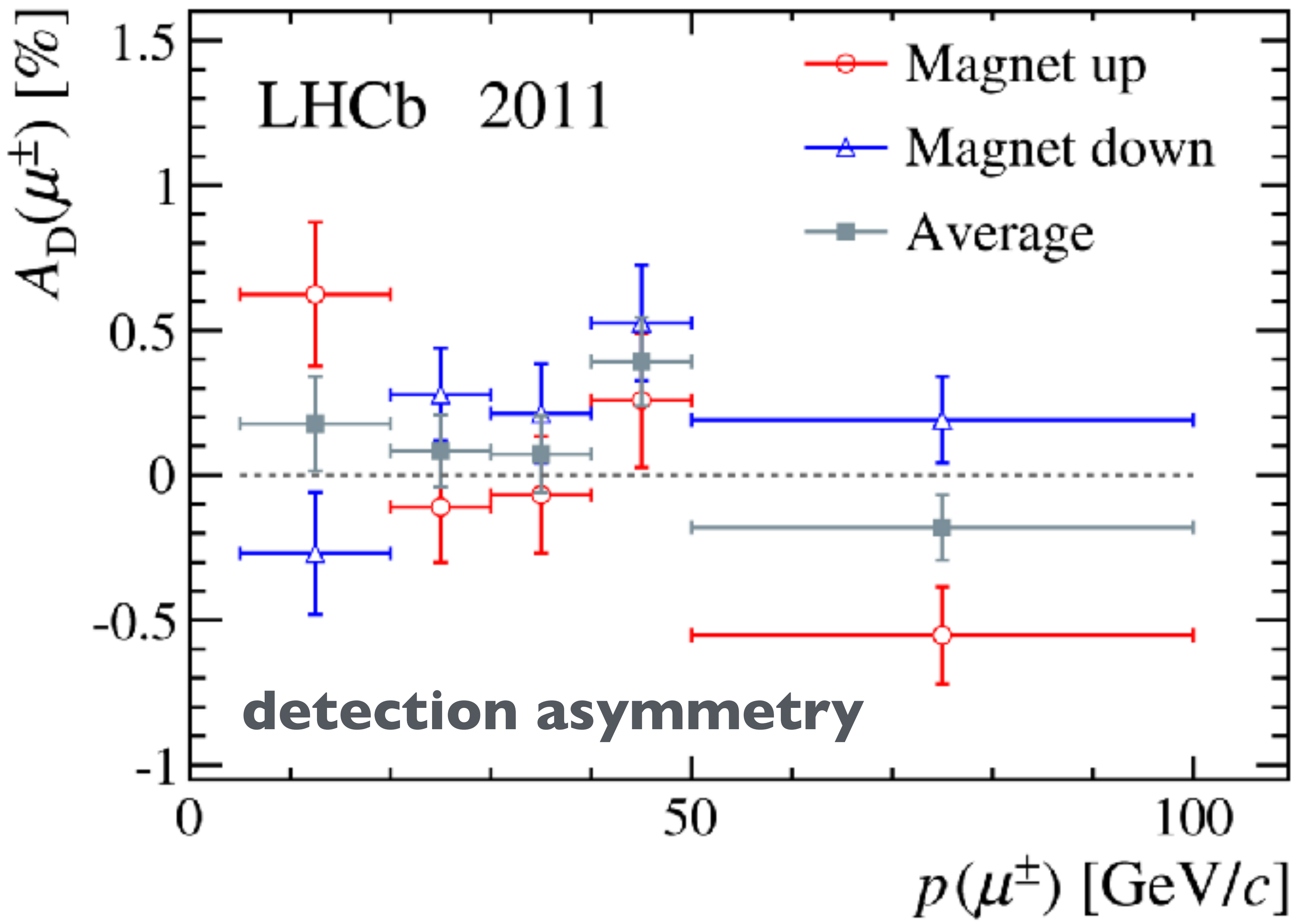
Semileptonic decays are tree-dominated so there should be no CPV in decay

$$A_{meas}(t) = \frac{N(D^-\mu^+\nu, t) - N(D^+\mu^-\nu, t)}{N(D^-\mu^+\nu, t) + N(D^+\mu^-\nu, t)}$$
$$\approx A_D + \frac{A_{sl}}{2} + \left(A_P - \frac{A_{sl}}{2}\right)\cos(\Delta m t)$$

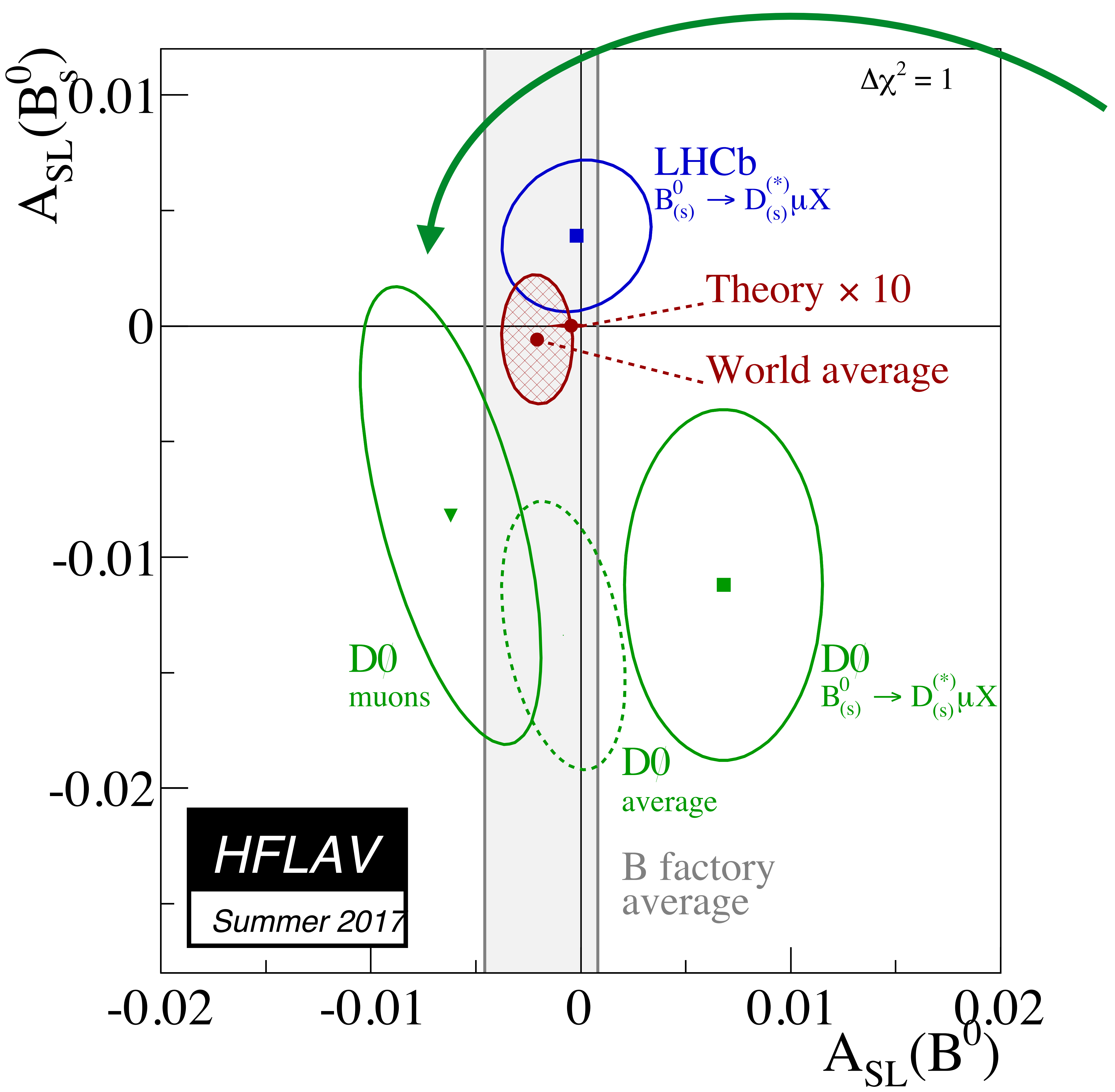
Integral of this term ~ 0 for B_s^0 mesons so can make decay-time-integrated measurement



[PRL 114, 041601 (2015)]
[PRL 117, 061803 (2016)]

CPV in neutral B meson mixing

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

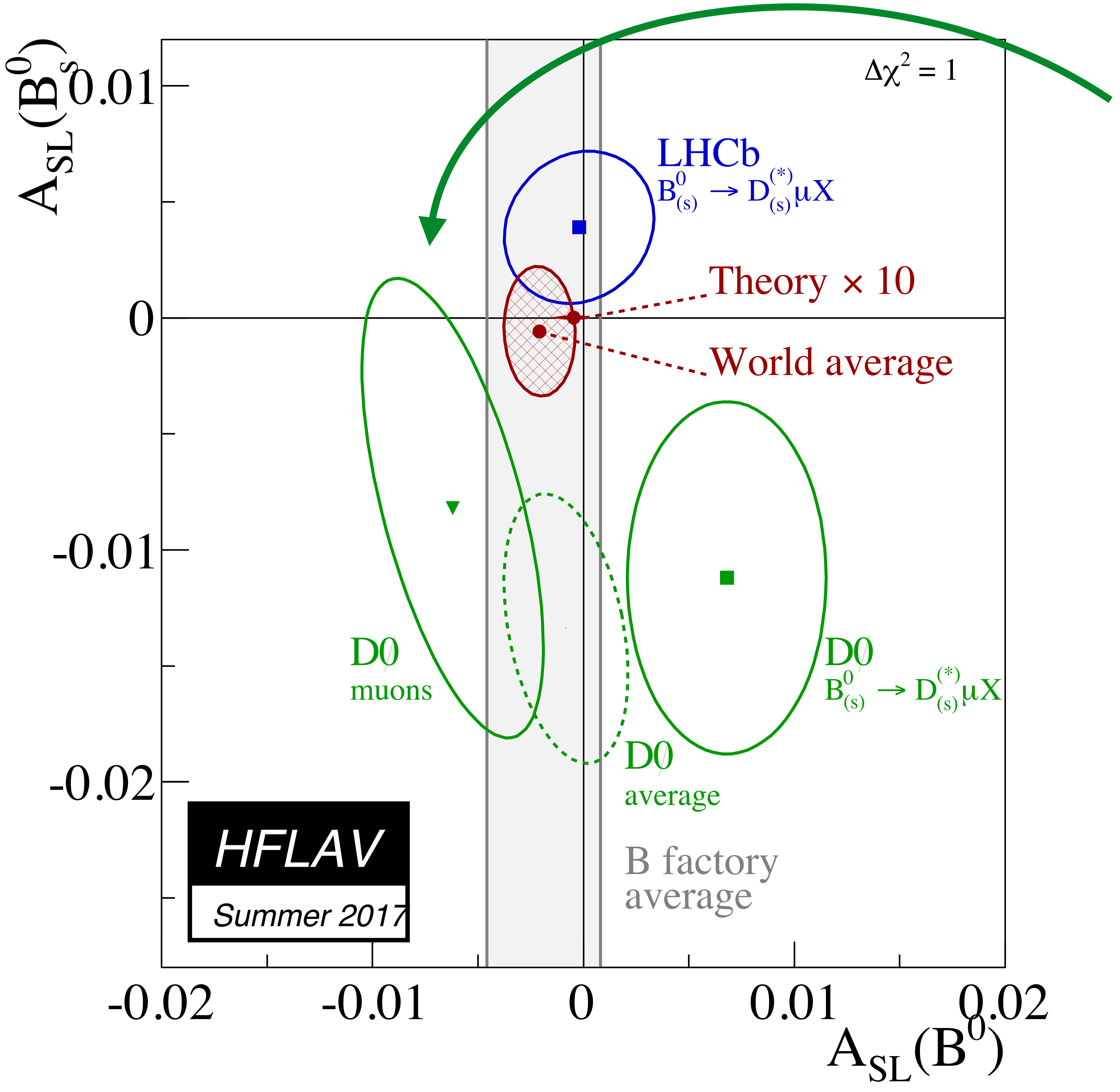


D0 dimuon asymmetry is ~3σ from SM

$$A_{CP} = C_d A^d_{SL} + C_s A^s_{SL} .$$

$A_{SL}(B^0) = (-0.21 \pm 0.17)\%$
$A_{SL}(B_s) = (-0.06 \pm 0.28)\%$

CPV in neutral B meson mixing



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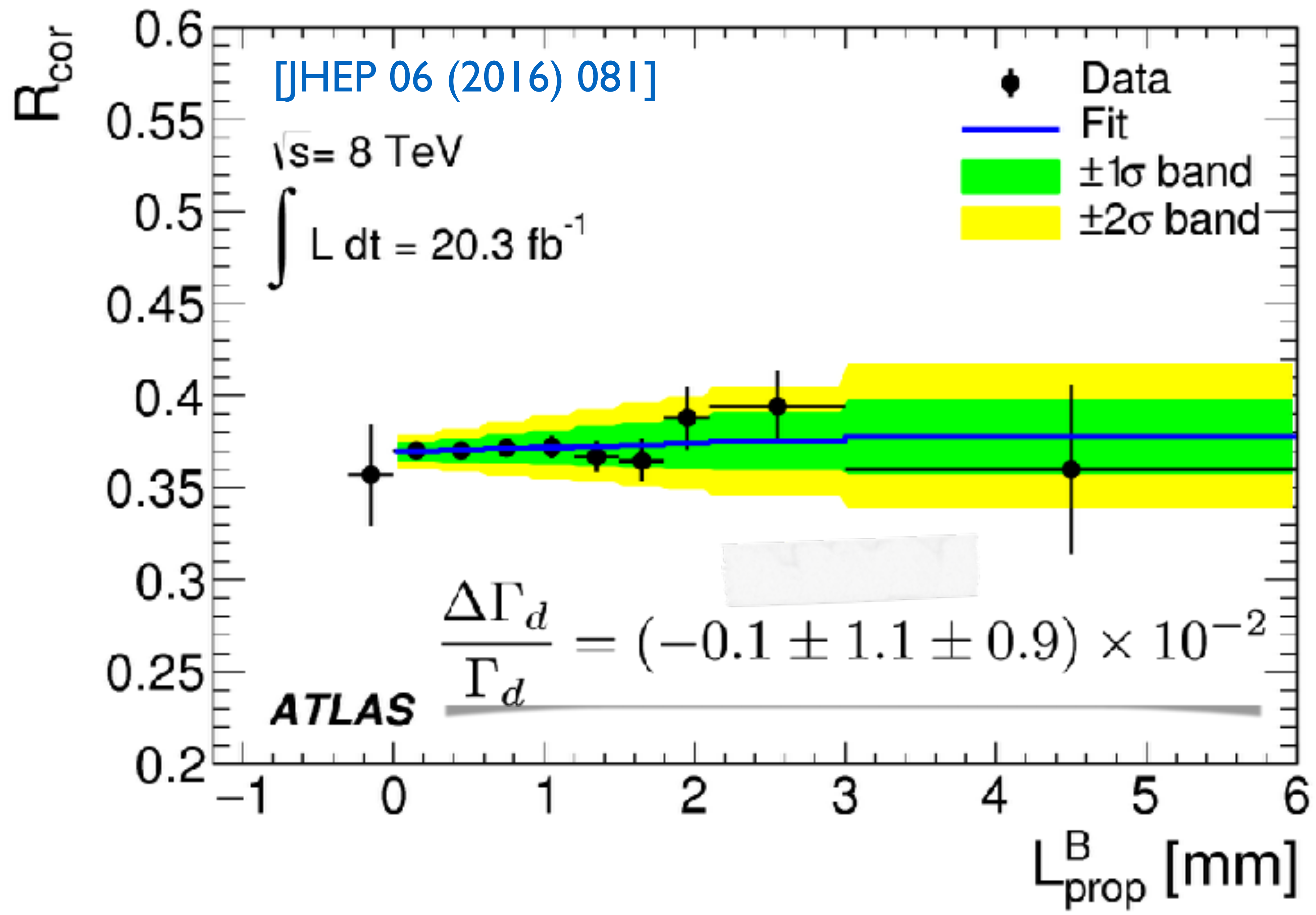
[Borissov, Hoeneisen PRD 87 (2013) 074020]
[D0, PRD 89 (2014) 012002]

D0 dimuon asymmetry is ~3σ from SM

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



[ATLAS, JHEP 02 (2017) 071]

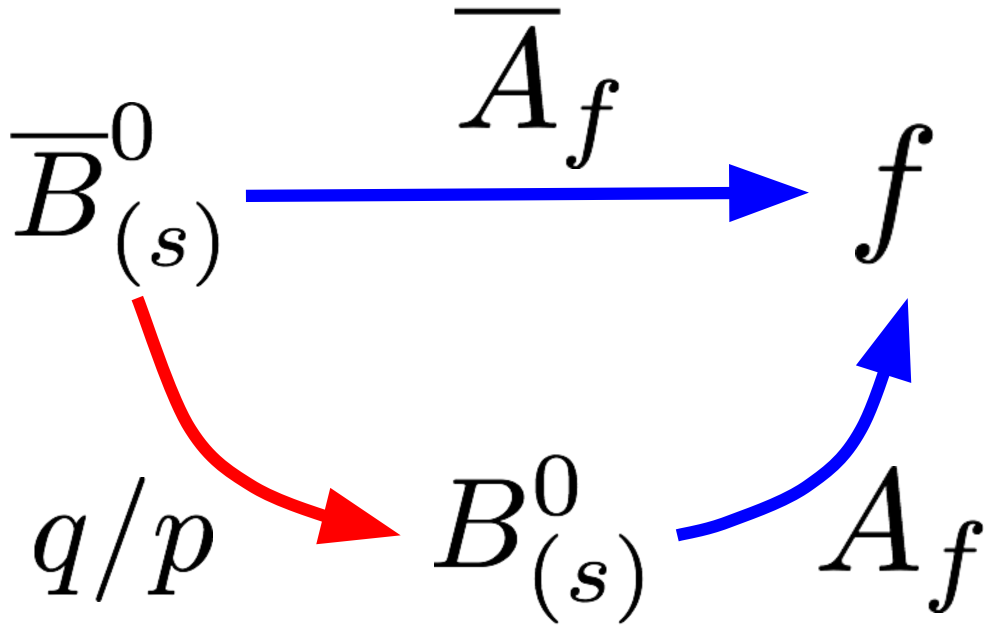
Most precise measurement of $\Delta\Gamma_d$ from comparing decay time distributions of $B^0 \to J/\psi K^*$ + $B^0 \to J/\psi K_S$

[also LHCb with fraction of Run 1 data sample, JHEP 04 (2014) 114]

CP violation in mixing + decay

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

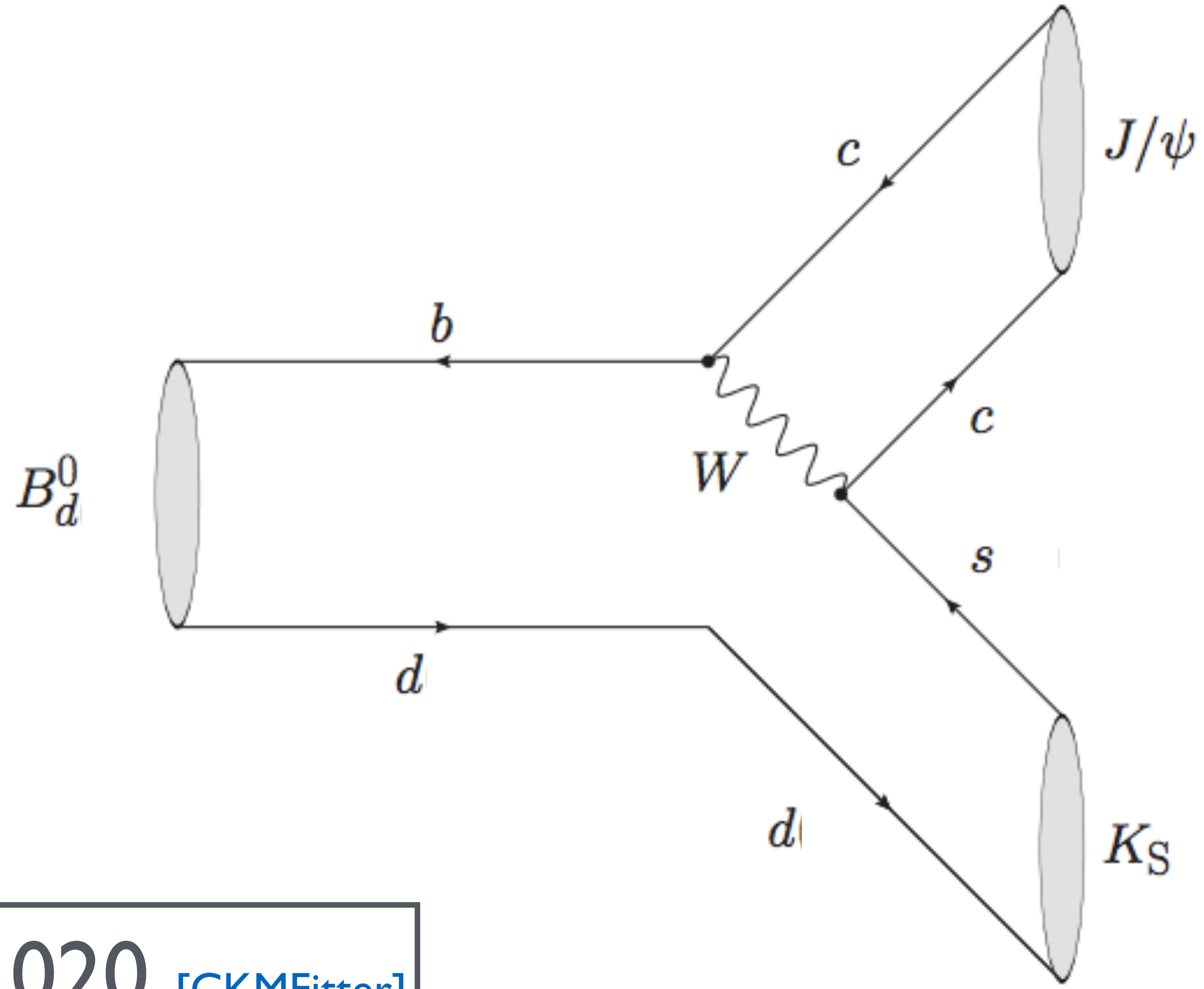
Ignore denominator for B^0 decays since $\Delta\Gamma \sim 0$



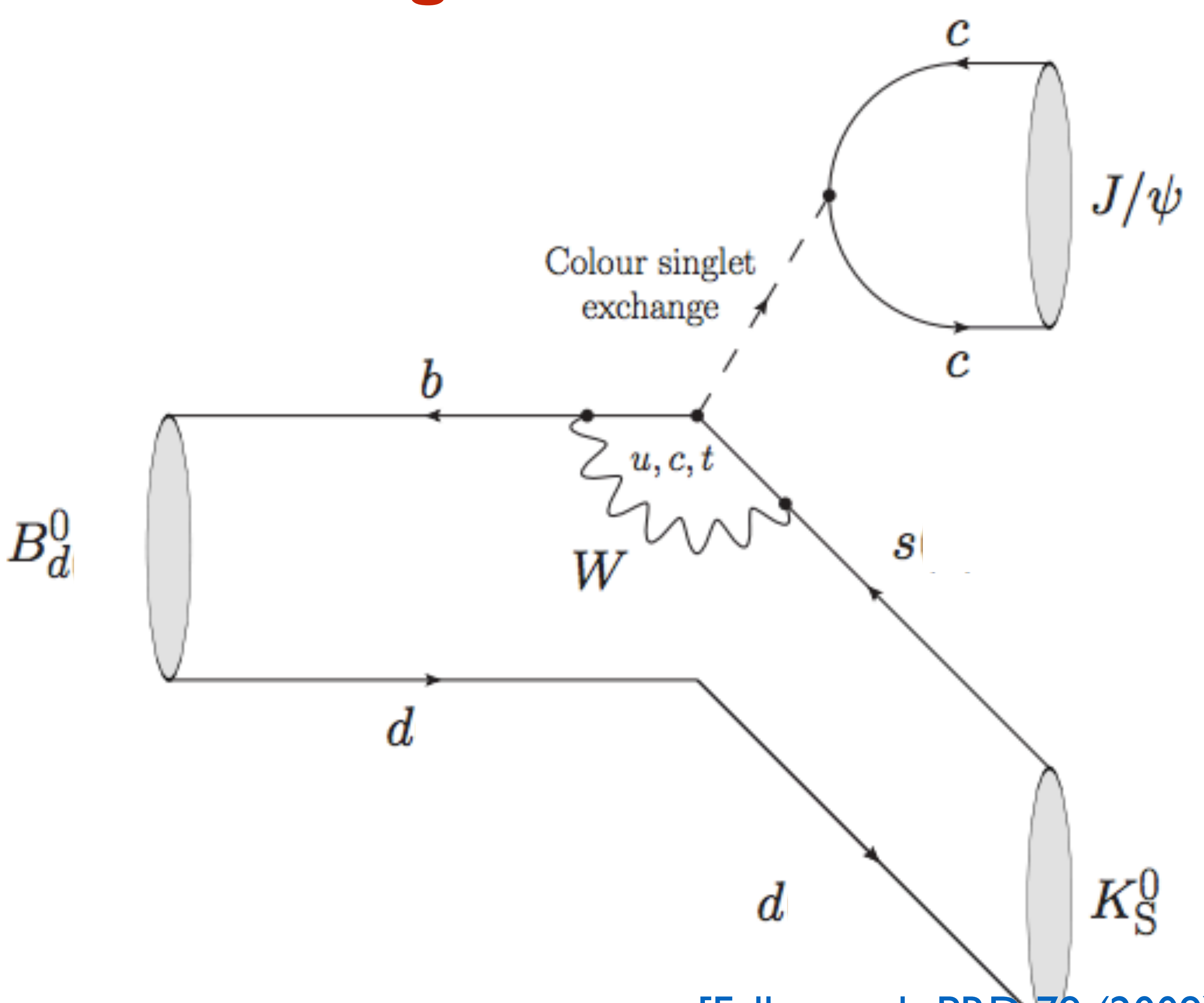
$$\beta \equiv arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$\sin 2\beta^{SM} = +0.711 \pm 0.020$ [CKMFitter]

Dominated by b → ccs tree diagram



Penguin should be small



[Faller et al., PRD 79 (2009) 014030]
[Jung, PRD 86 (2012) 053008]
[De Bruyn, Fleischer, JHEP 03 (2015) 145]
[Frings et al., PRL 115 (2015) 061802]

CP violation in mixing + decay

$$S_{J/\psi K^0_S} \approx \sin 2\beta$$

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

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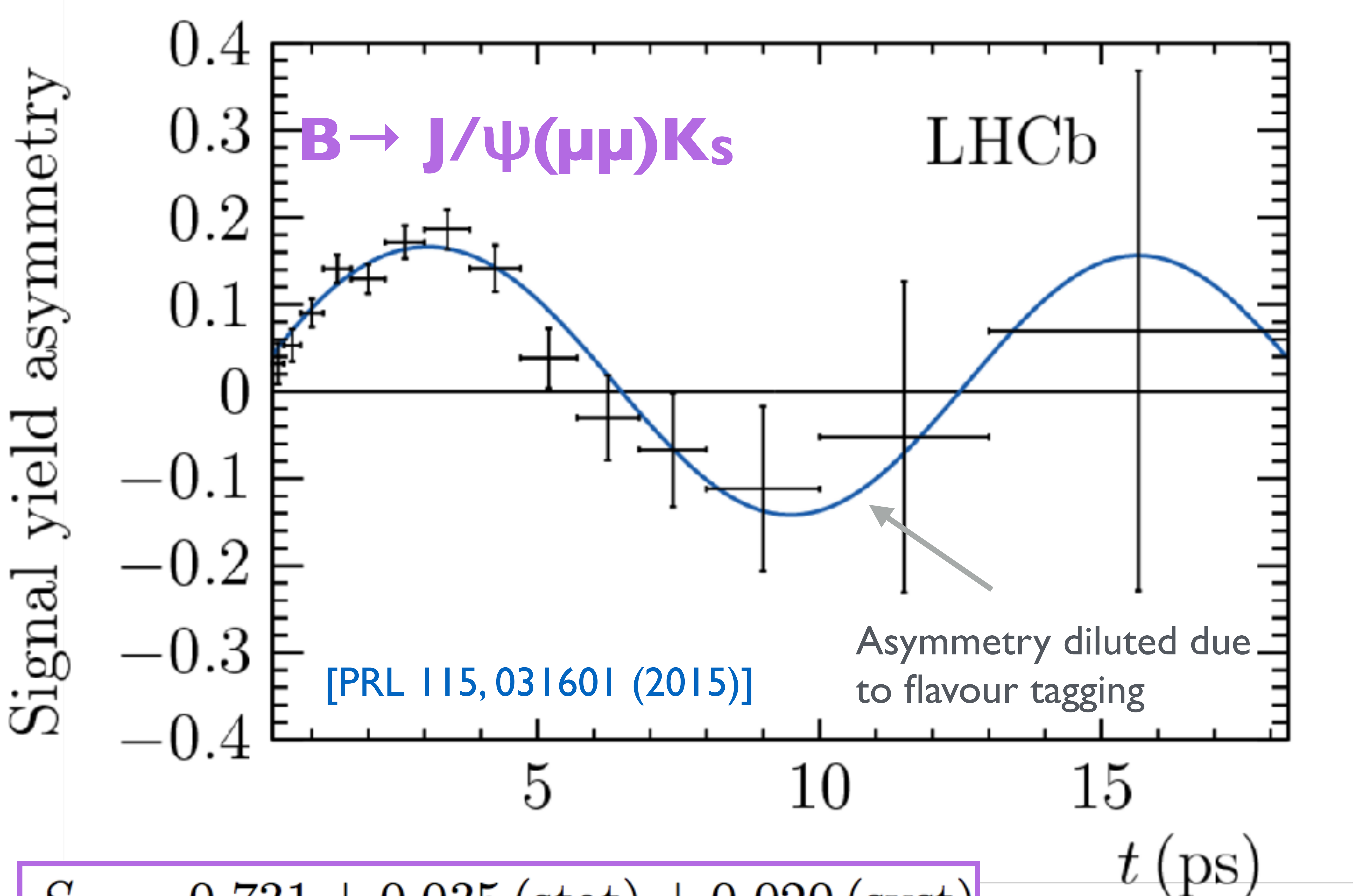
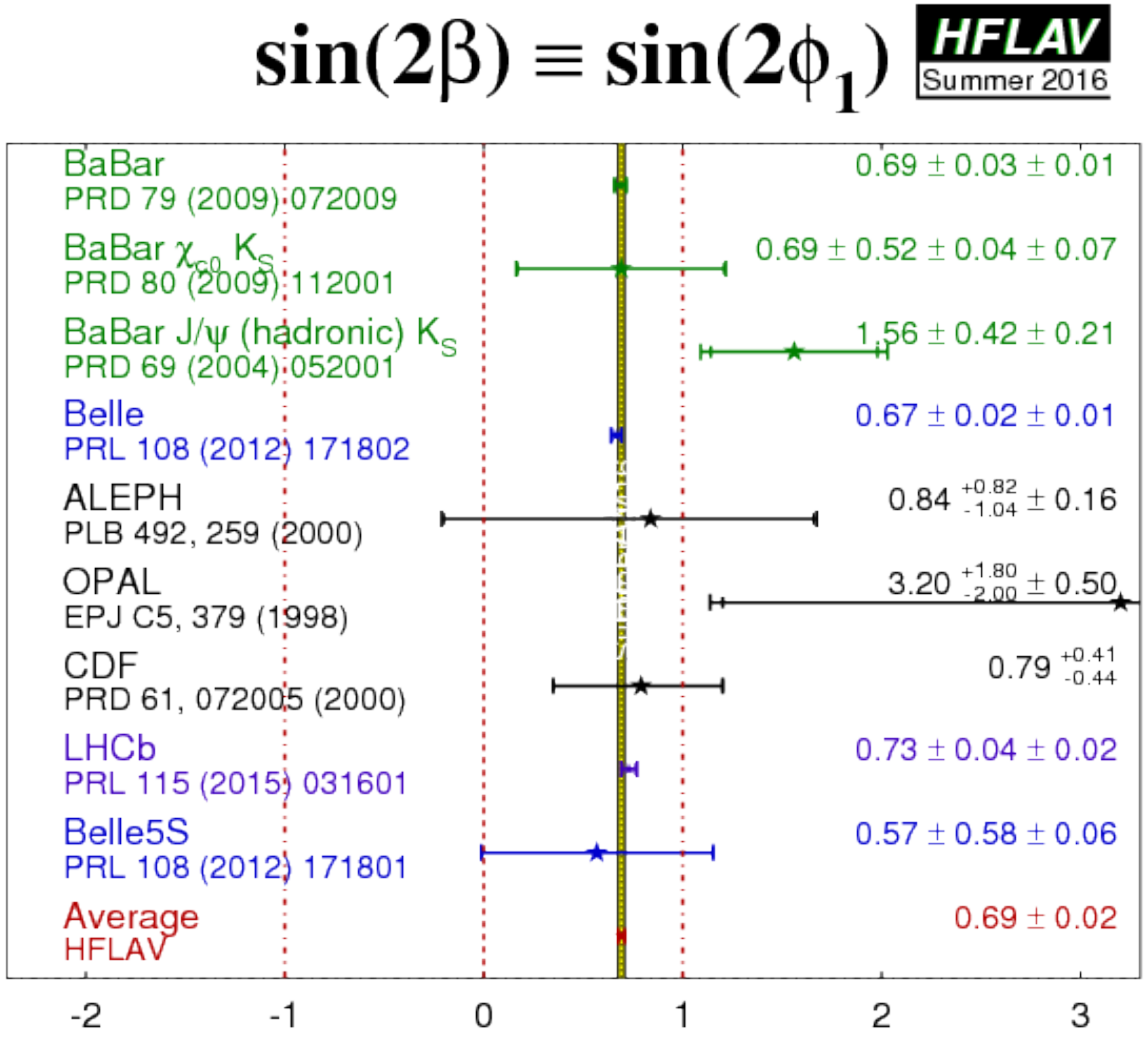


$$S = 0.731 \pm 0.035\,(\text{stat}) \pm 0.020\,(\text{syst})$$
$$C = -0.038 \pm 0.032\,(\text{stat}) \pm 0.005\,(\text{syst})$$

Dominated by background tagging asymmetry



LHCb measurement reduces tension between world average and indirect determination from global fit [CKMFitter, UTFit]

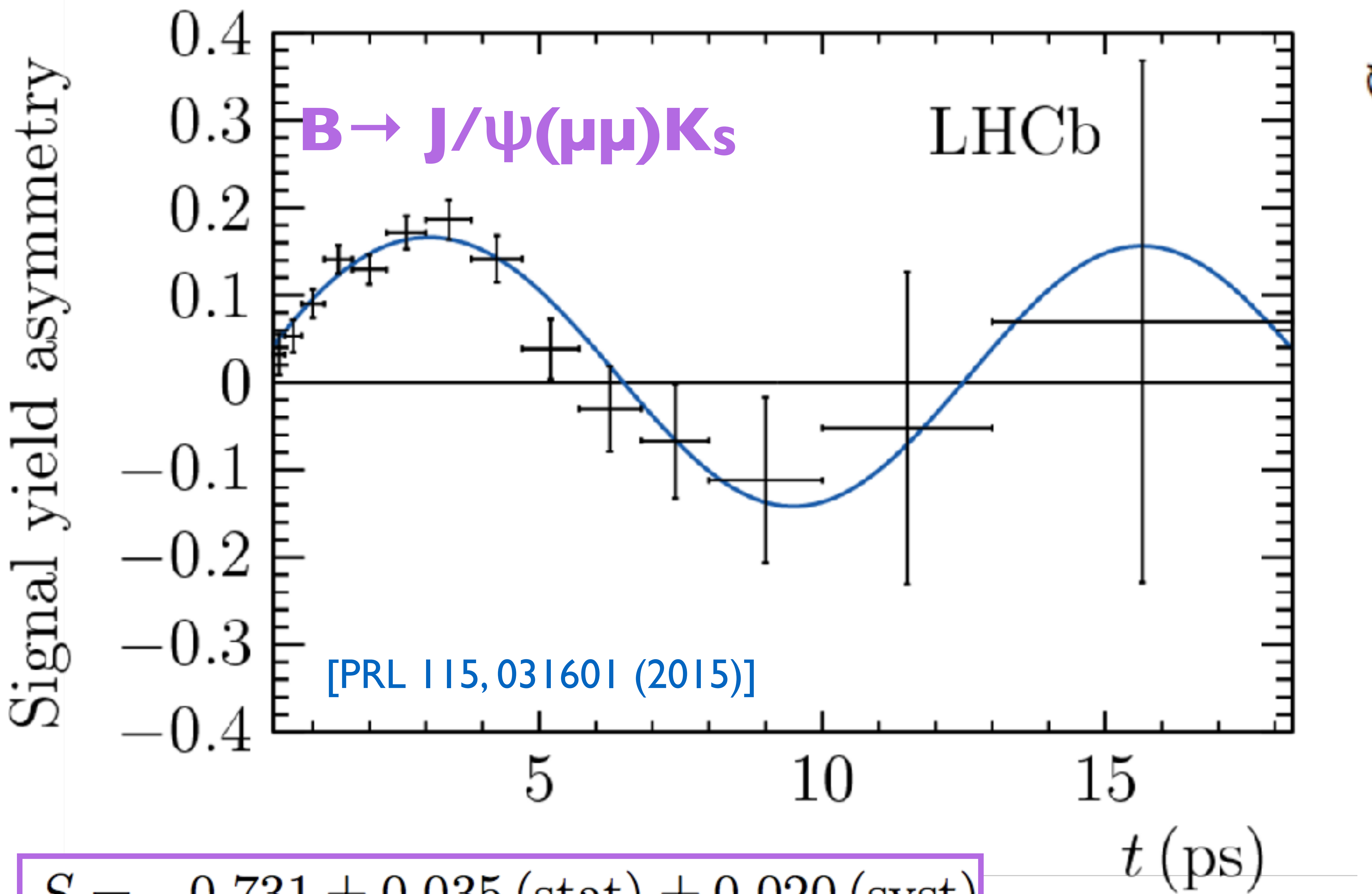
CP violation in mixing + decay NEW!

$$S_{J/\psi\, K^0_S} \approx \sin 2\beta$$

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

Ignore denominator for B^0 decays since $\Delta\Gamma \sim 0$

[LHCb-PAPER-2017-029]



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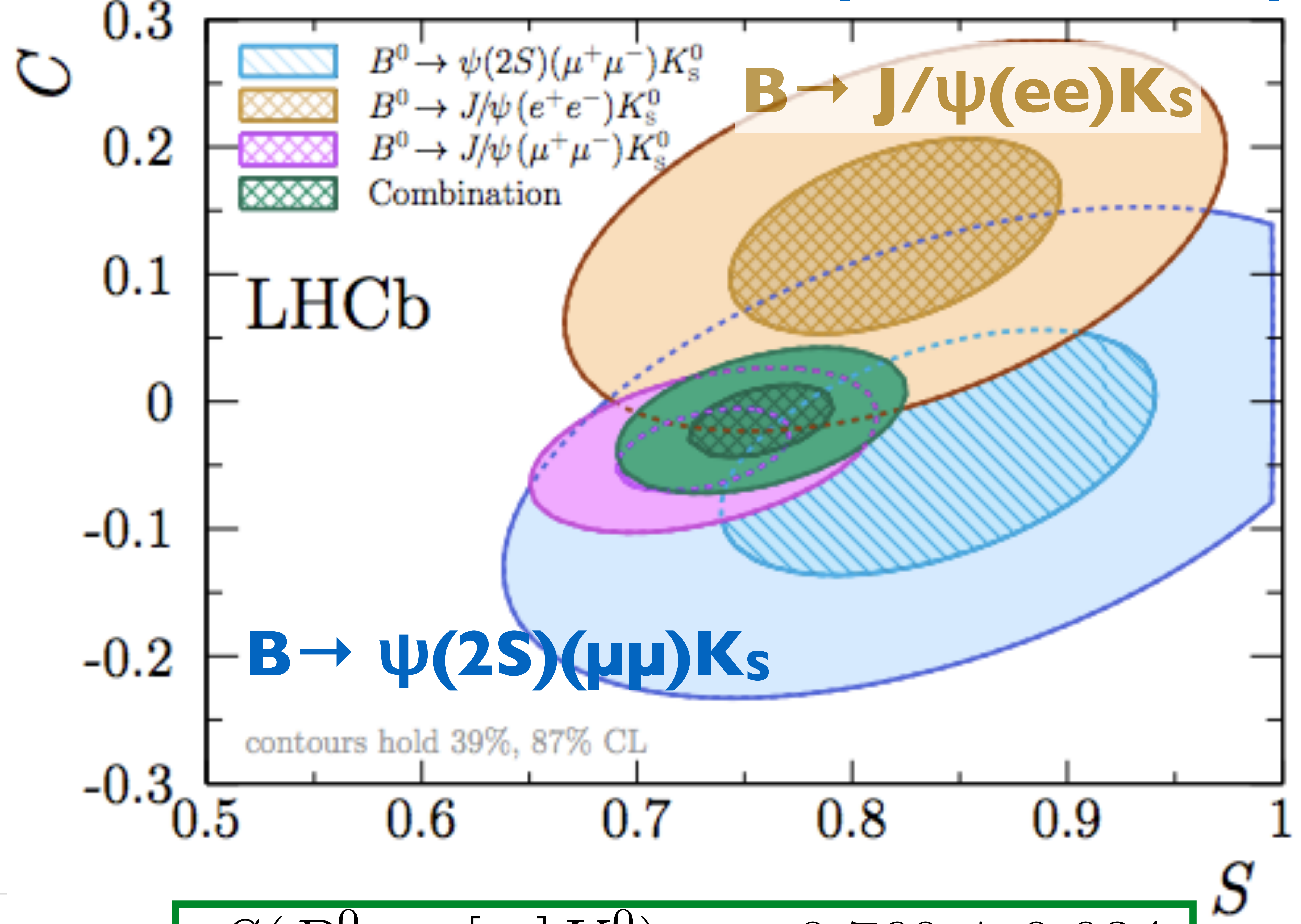


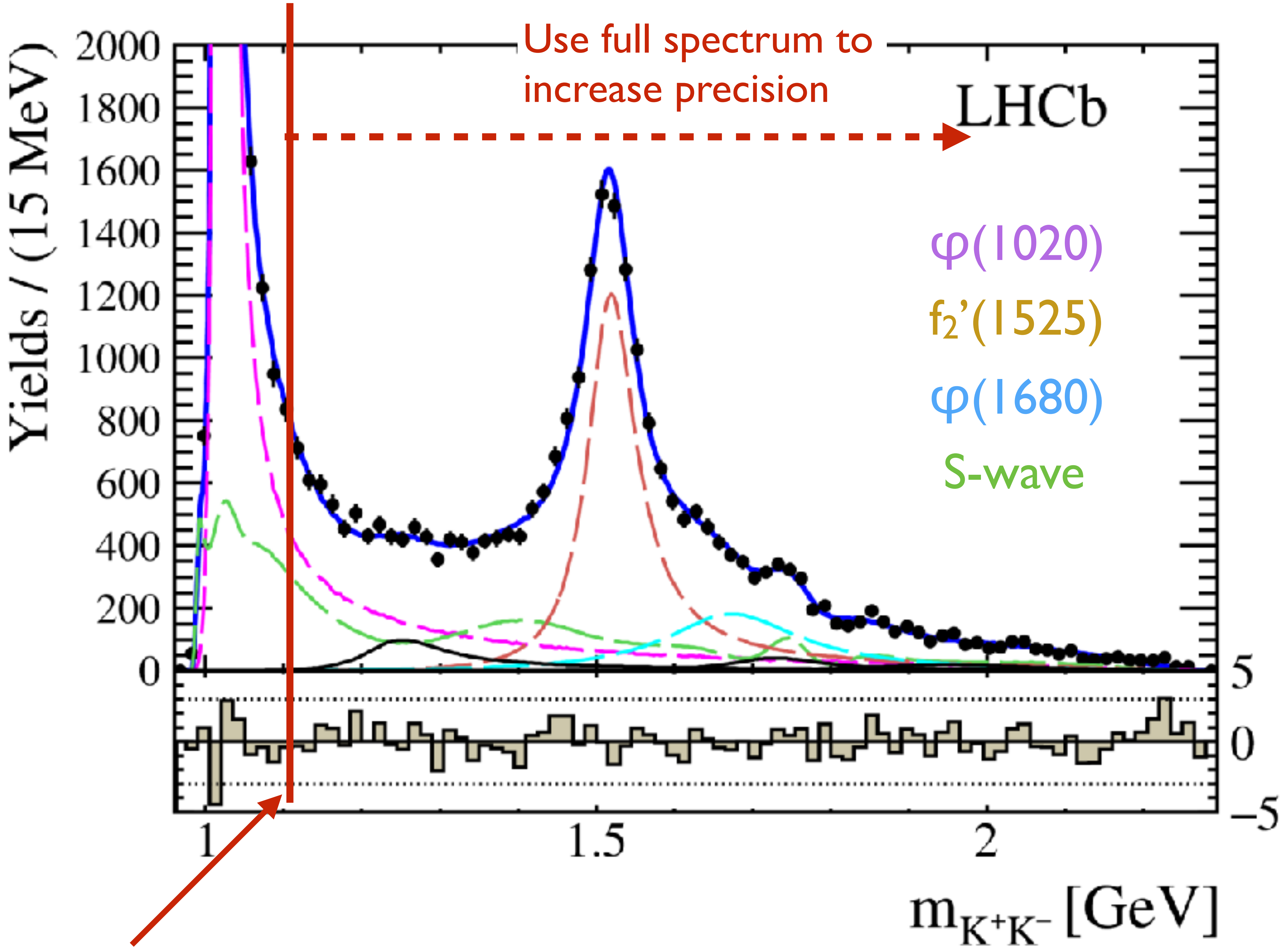
$$S(B^0\to[c\bar{c}]K^0_S) = 0.760 \pm 0.034$$
$$C(B^0\to[c\bar{c}]K^0_S) = -0.017 \pm 0.029$$

CP violation in mixing + decay: B^0_s

[arXiv:1704.08217]

$B_s \rightarrow J/\psi\varphi$ is the **golden mode** for measuring ϕ_s.

Fully exploit LHCb Run 1 data by analysing $B^0_s \rightarrow J/\psi KK$, with $m(KK) > 1.05$ GeV



Previous studies all focussed on φ(1020) mass region where φ meson dominates over a small KK S-wave

Flavour tagged, decay-time dependent amplitude fit to understand the different CP-odd/even resonant components of the spectrum

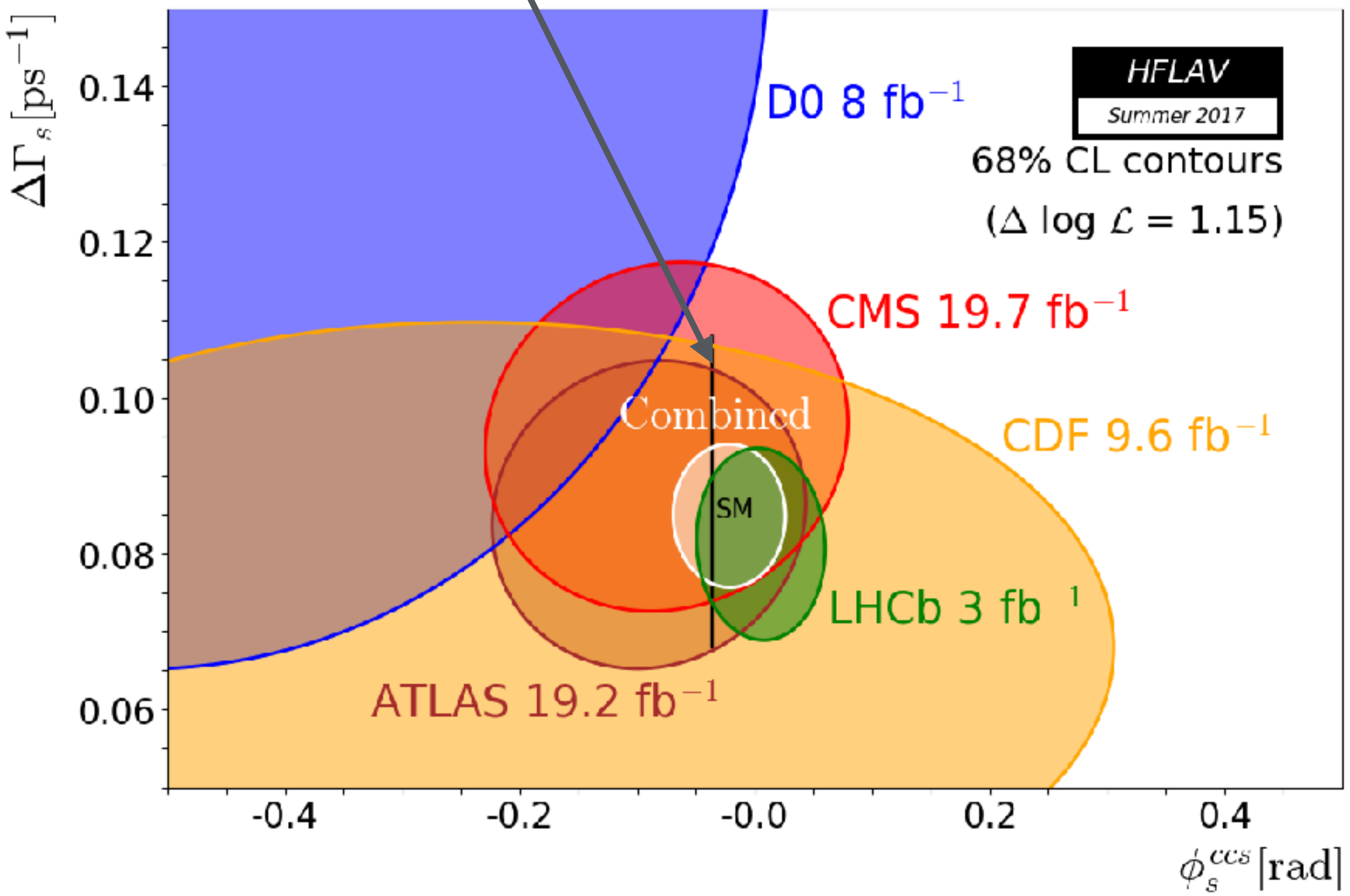
Parameter	Value
Γ_s [ps^{-1}]	$0.650 \pm 0.006 \pm 0.004$
$\Delta\Gamma_s$ [ps^{-1}]	$0.066 \pm 0.018 \pm 0.010$
ϕ_s [mrad]	$119 \pm 107 \pm 34$
$\lvert\lambda\rvert$	$0.994 \pm 0.018 \pm 0.006$

New LHCb average from
$B^0_s \rightarrow J/\psi\varphi$, $J/\psi KK$ (mKK > 1.05 GeV) and $J/\psi\pi\pi$

$\phi_s = 1 \pm 37$ mrad

ϕ_s-$\Delta\Gamma_s$ global combination

ϕ_s^{SM} = -36.5 ± 1.3 mrad [CKMFitter]



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]

ϕ_s = −21 ± 31 mrad
$\Delta\Gamma_s$ = +0.090 ± 0.005 ps^{-1}

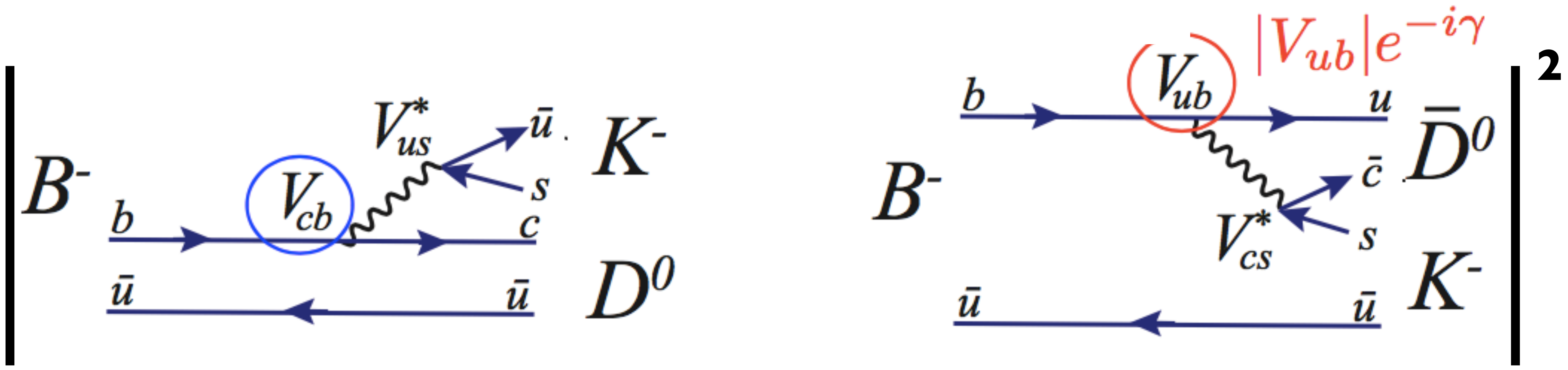
Precision improved by > x10 since Tevatron results

New physics is not large, so we need **increased precision**

Important to control size of the penguin diagram contributions → e.g., [LHCb, PLB 742 (2015) 38]

CKM angle γ

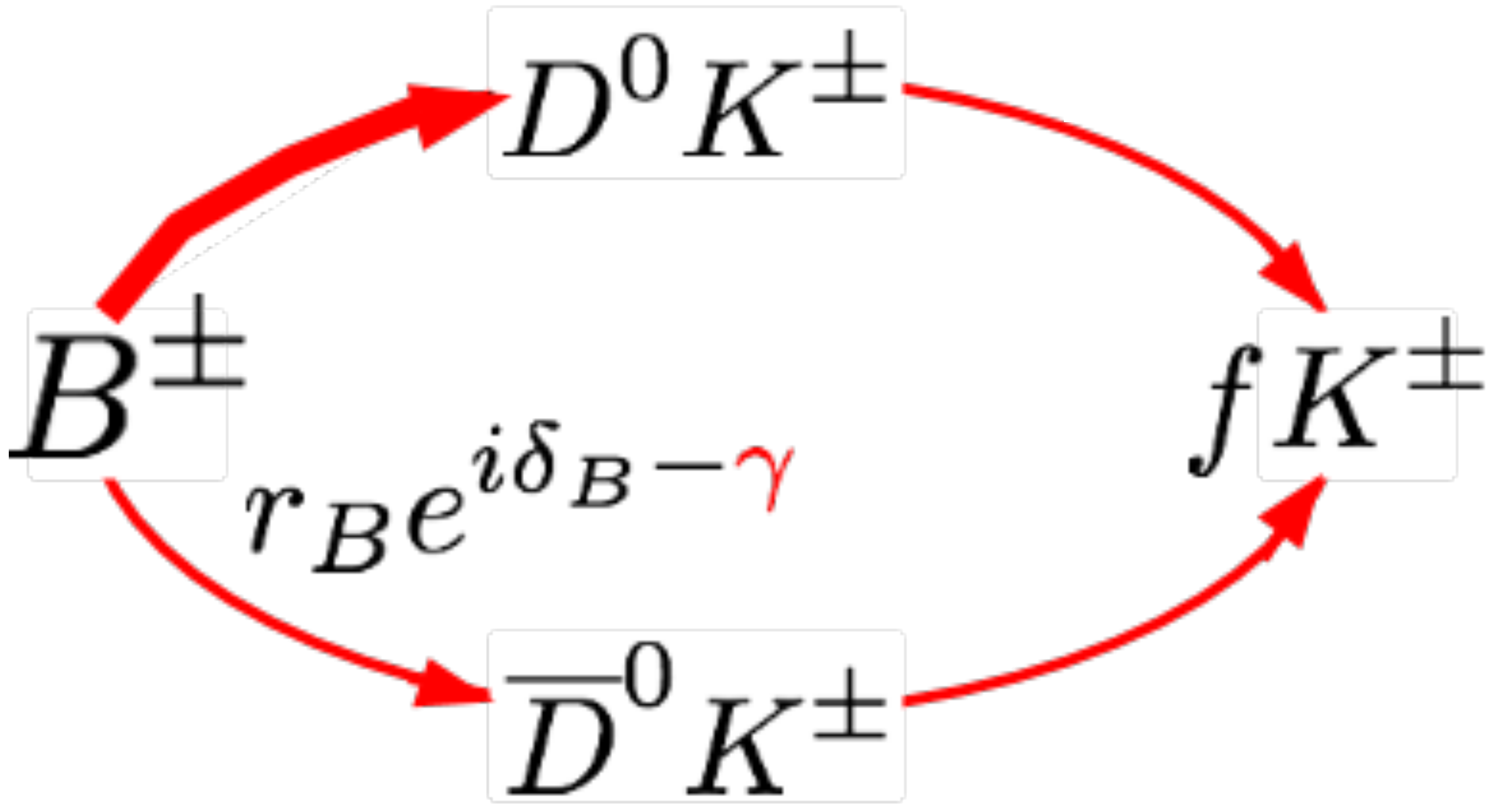
Only CP-violating parameter that can be measured from tree-level decays



$|\delta\gamma| \leq O(10^{-7})$ [Brod, Zupan JHEP 1401 (2014) 051]

Exploit interference between amplitudes, e.g.

$$\gamma = arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



GLW (f = K^+K^-, $\pi^+\pi^-$) [PLB 253 (1991) 483, PLB 265 (1991) 172]

ADS (f = $K\pi$) [PRL 78 (1997) 3257]

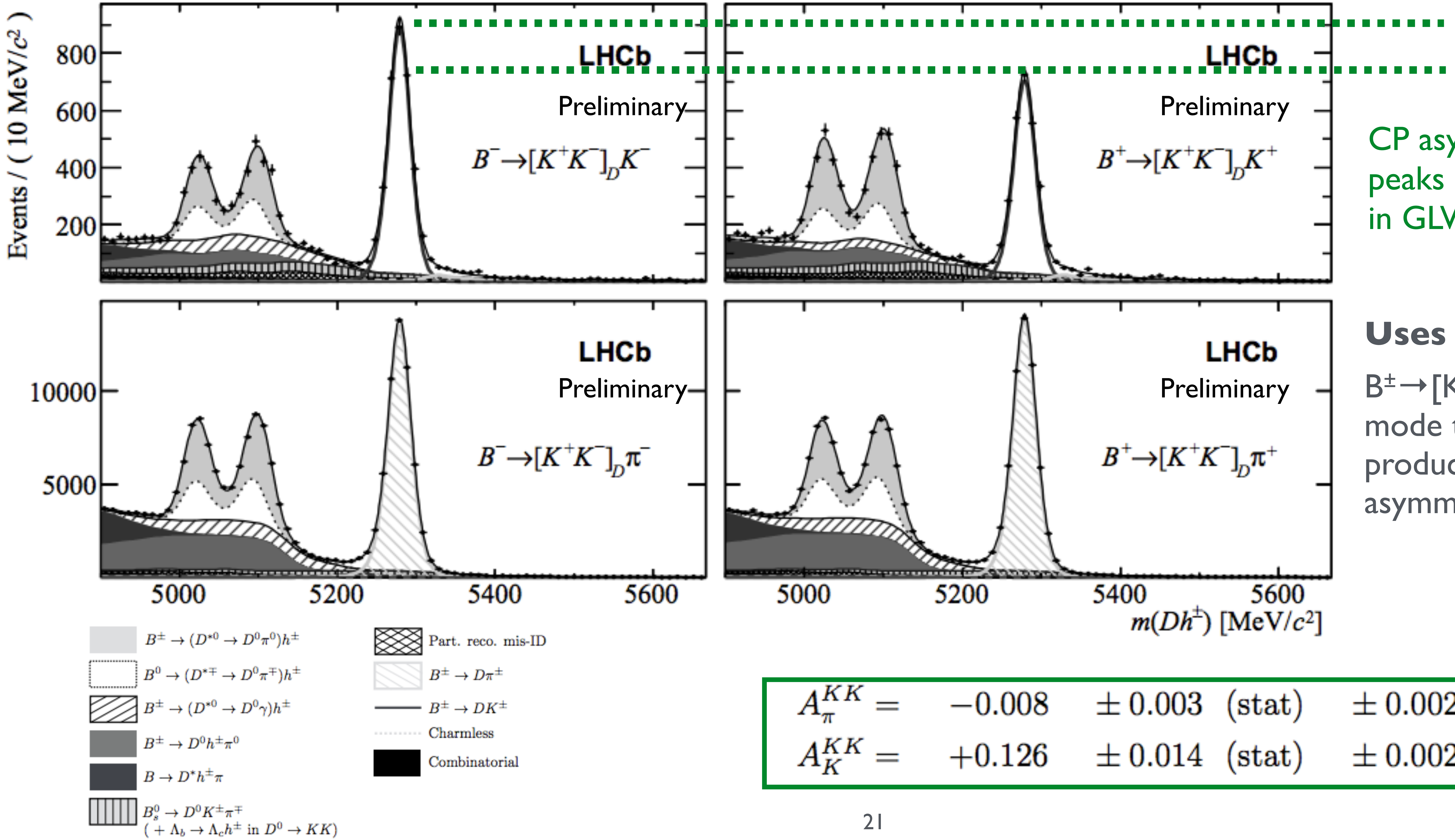
GGSZ (f = $K_S\pi^+\pi^-$) [PRD 68 (2003) 054018]

$$A_{CP+} \propto r_B \sin\delta_B \sin\gamma$$

Need non-zero strong and weak phase to observe A_{CP}

CP observables in B± → D(*)0K± and B± → D(*)0π±

[LHCb-PAPER-2017-021]



CP asymmetry in B → D^0K peaks related to γ, r^{DK}, δ^{DK} in GLW method

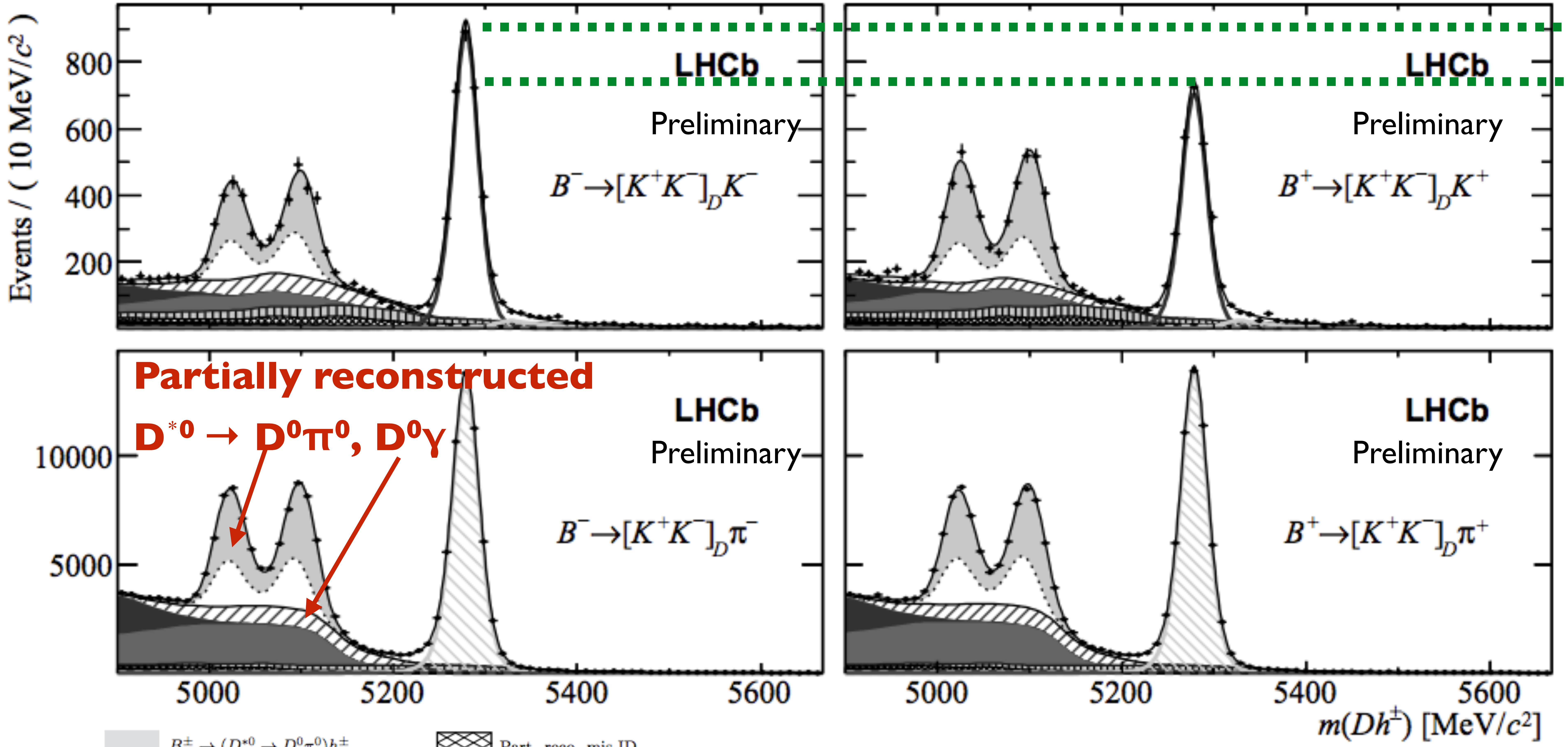
Uses 5 fb^{-1} (run 1+2)

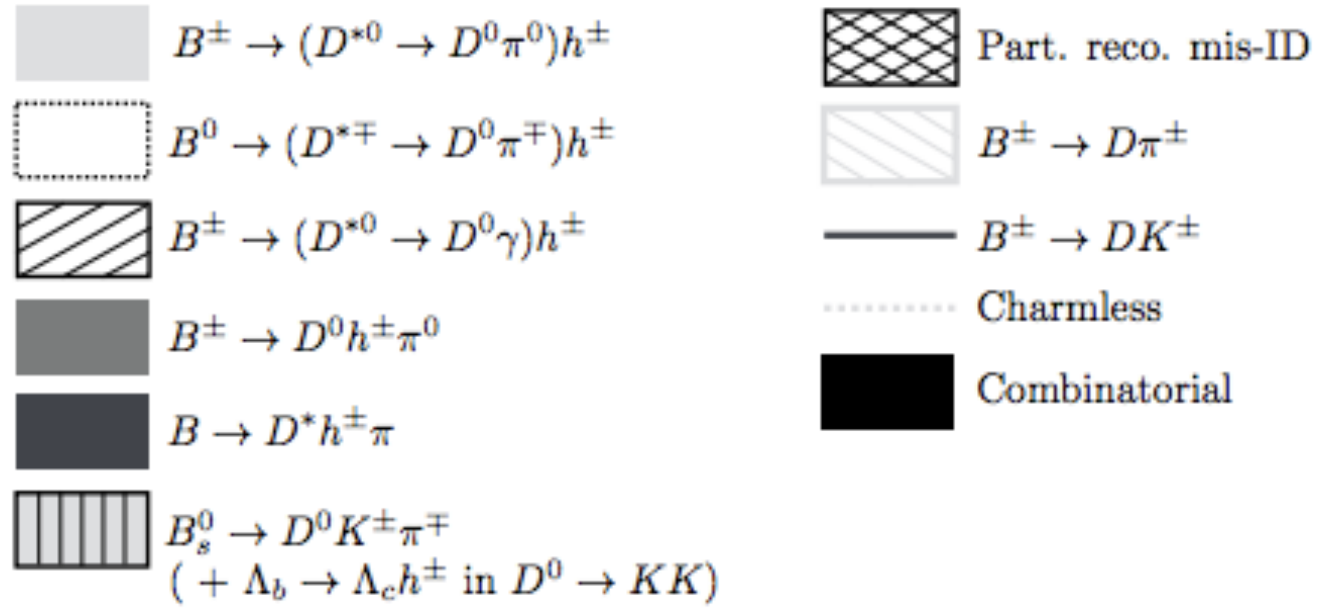
$B^\pm \to [K^\pm pi^\mp]_D \pi^\pm$ control mode to understand small production and detection asymmetries

$$A_\pi^{KK} = -0.008 \pm 0.003 \text{ (stat)} \pm 0.002 \text{ (syst)}$$
$$A_K^{KK} = +0.126 \pm 0.014 \text{ (stat)} \pm 0.002 \text{ (syst)}$$

CP observables in $B^\pm \to D^{(*)0}K^\pm$ and $B^\pm \to D^{(*)0}\pi^\pm$

[LHCb-PAPER-2017-021]





CP asymmetry in $B \to D^0K$ peaks related to γ, r^{DK}, δ^{DK} in GLW method

Uses 5 fb^{-1} (run 1+2)

$B\to[K\pi]_D\pi$ control mode to understand small production and detection asymmetries

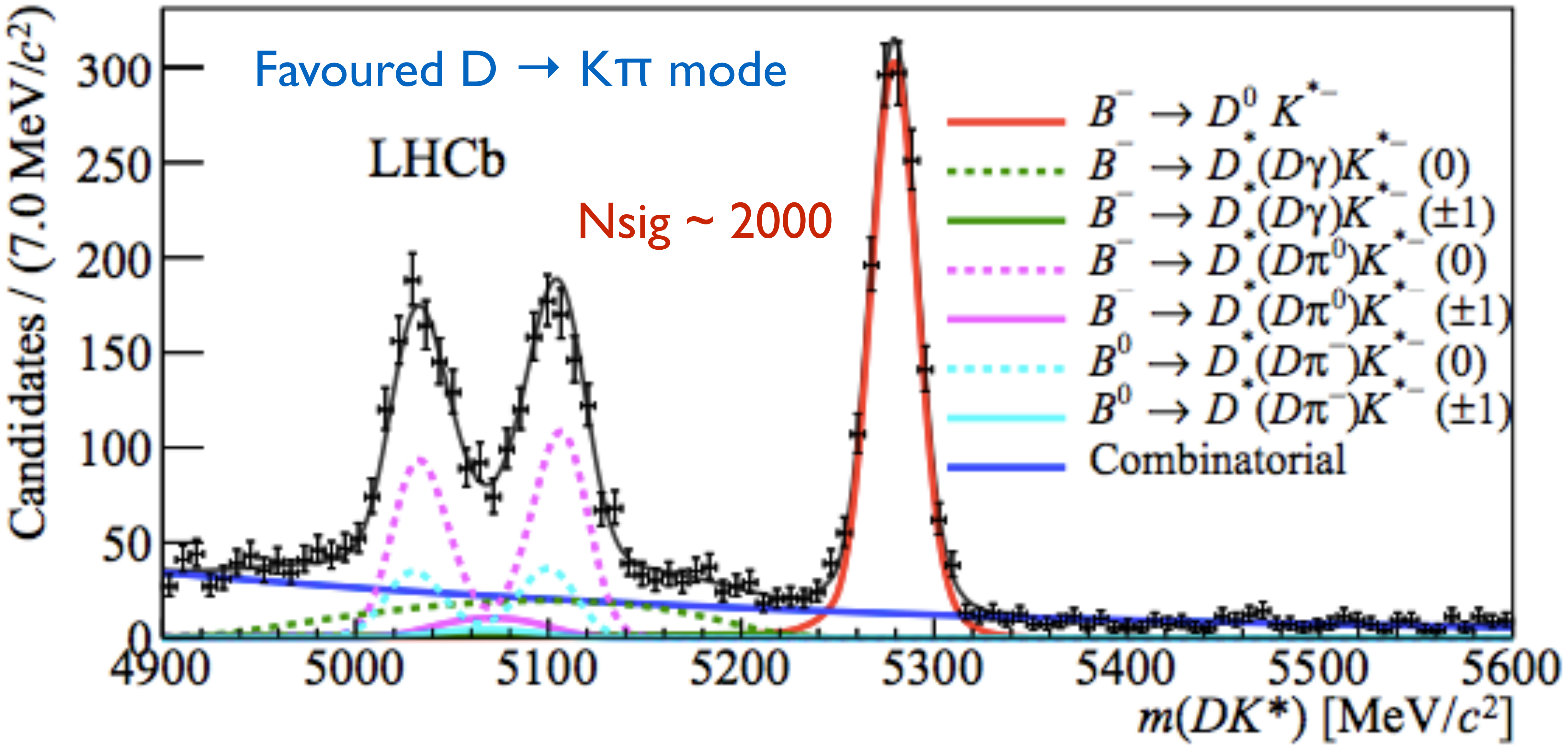
First time that novel part-reco approach used

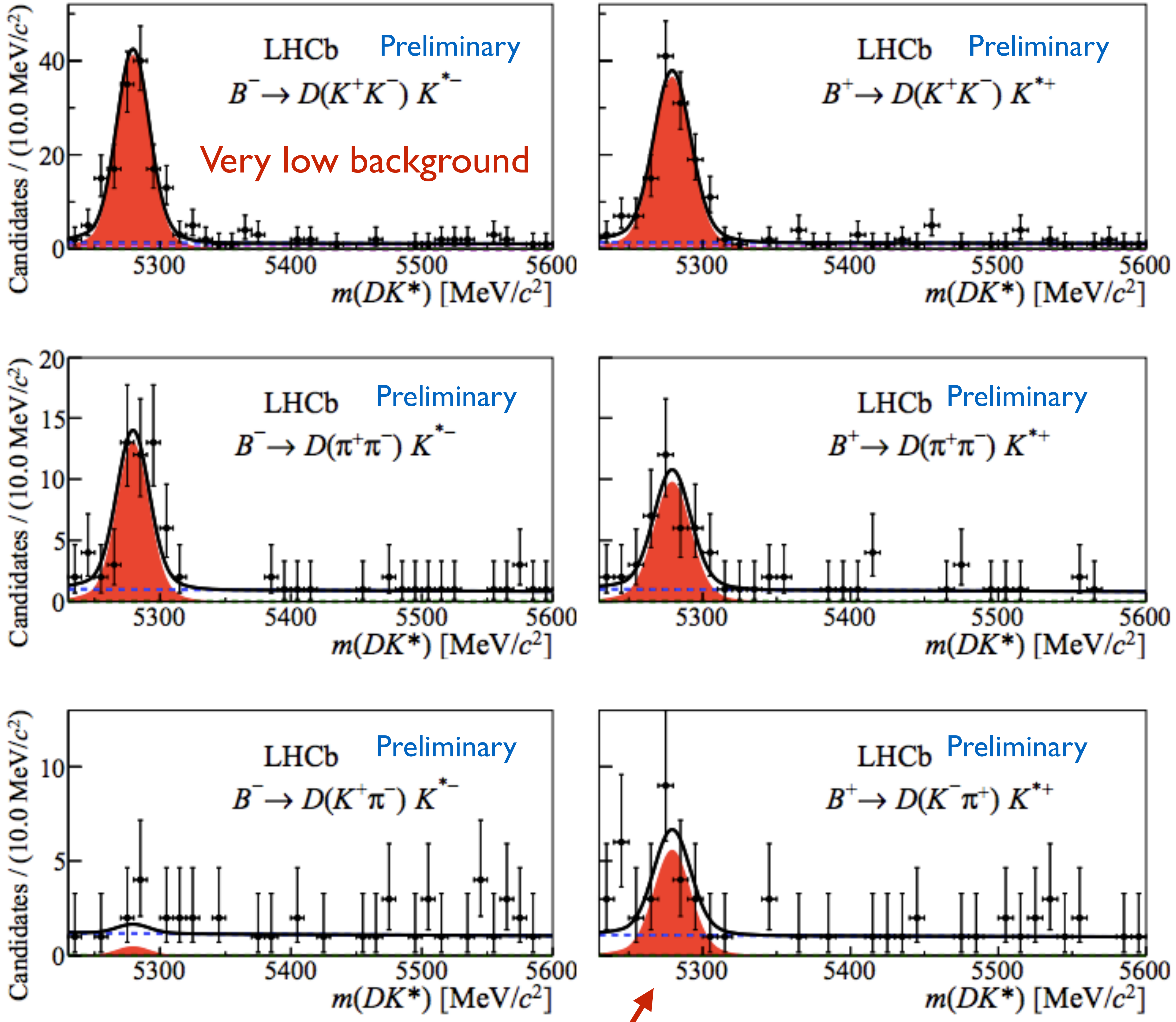
$$A_K^{CP,\pi^0} = -0.151 \pm 0.033\ \text{(stat)} \pm 0.011\ \text{(syst)}$$
$$A_K^{CP,\gamma} = +0.276 \pm 0.094\ \text{(stat)} \pm 0.047\ \text{(syst)}$$

4.3σ CPV
2.4σ CPV

CP observables in $B^{\pm} \to DK^{*\pm}$ NEW!!

[LHCb-PAPER-2017-030]





4.2σ evidence of suppressed ADS mode

Results consistent with and more precise than BaBar [PRD 80 (2009) 092001]

Uses 2- and 4-body D^0 decay modes (+ Run 2 data)

Rates and CP asymmetries provide constraints on $r^{DK^*}_B$, $\delta^{DK^*}_B$ and γ

$$R^{+}_{K\pi} = 0.020 \pm 0.006\,(\text{stat}) \pm 0.001\,(\text{syst})$$

γ combination

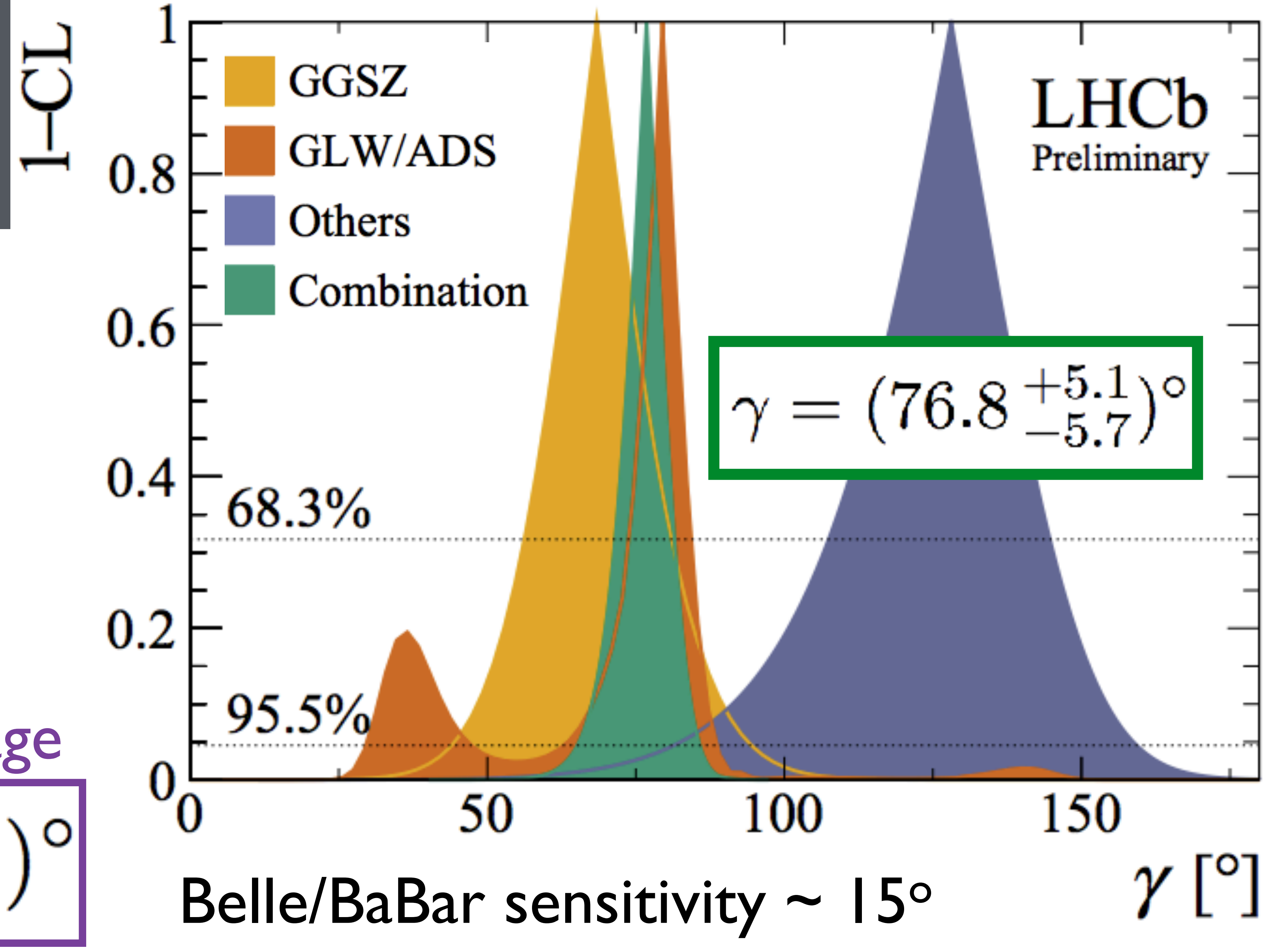
Use several B → DK measurements (85 observables, 37 parameters)

B decay	D decay	Method	Ref.	Status since last combination [JHEP 12 (2016) 087]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[16]	Updated to Run 1 + 2 fb^{-1} Run 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[17]	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[17]	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[18]	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[19]	As before
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[20]	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[16]	New
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[21]	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[22]	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[23]	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[24]	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[25]	As before
$B^0_s \to D^{\mp}_s K^{\pm}$	$D^+_s \to h^+h^-\pi^+$	TD	[26]	Updated to 3 fb^{-1} Run 1

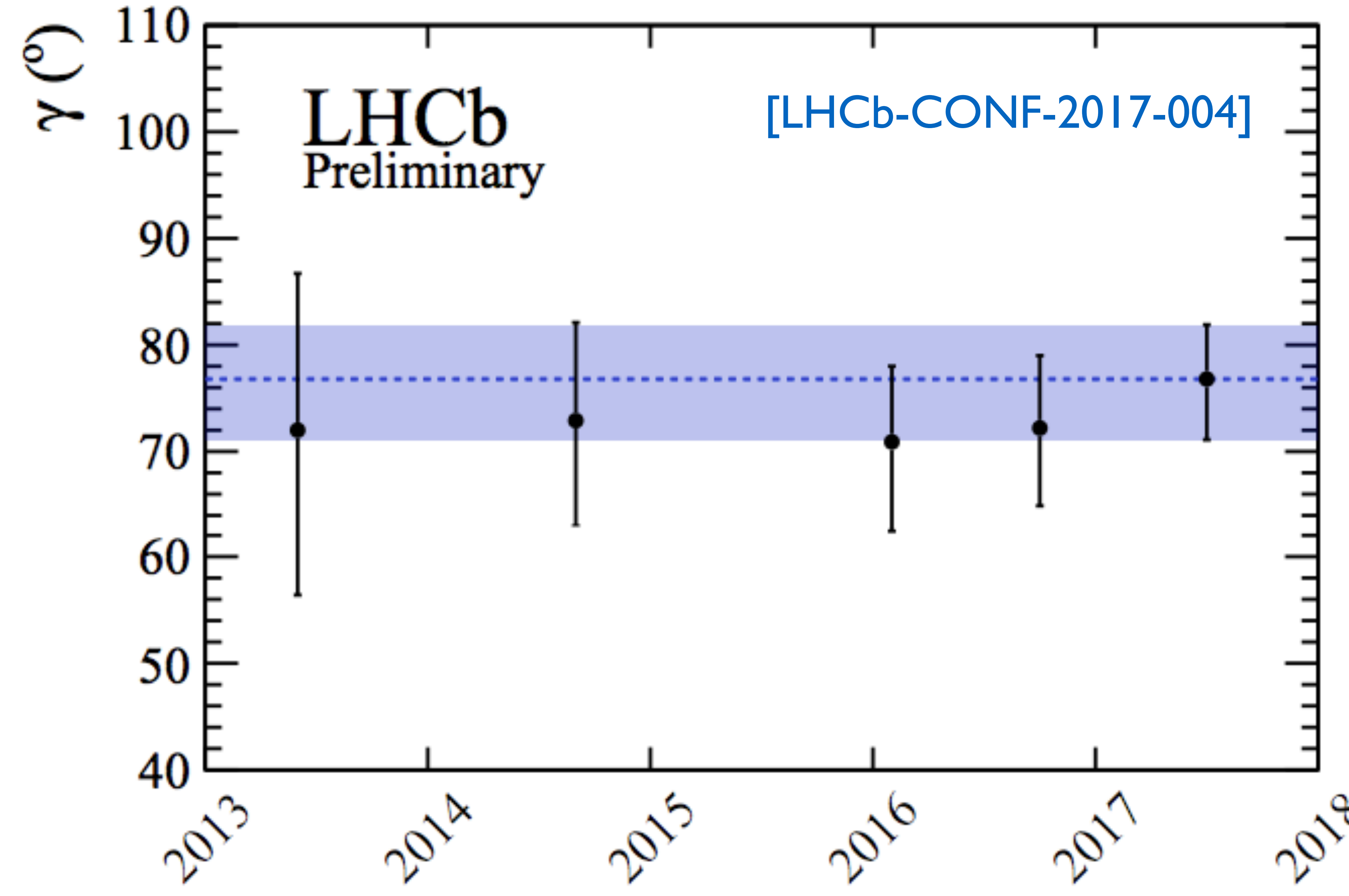
backup

HFLAV average

$$\gamma = (76.2^{+4.7}_{-5.0})^\circ$$



Belle/BaBar sensitivity ~ 15°



Many more Run-2 updates and channels expected soon

Expect O(1°) precision after LHCb upgrade

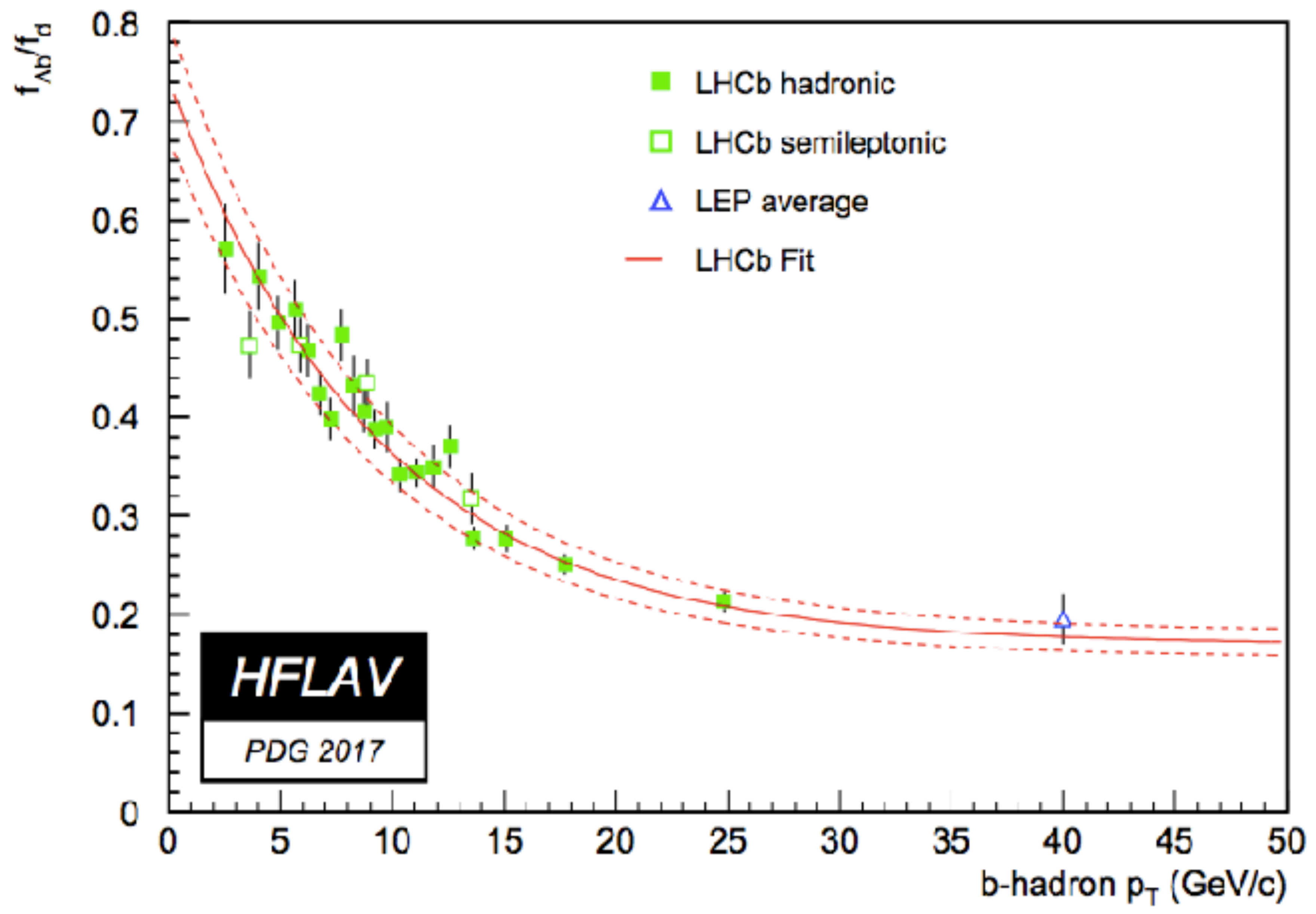
[see also next talk on Belle-II]

CP-violation in b baryon decays

No observation of CPV in b baryon decays
→ potential for non-zero effects in SM.

~~Two-body~~ [CDF, PRL 113 (2014) 242001]

~~Three-body~~ [LHCb, JHEP 04 (2014) 087, JHEP 05 (2016) 081]



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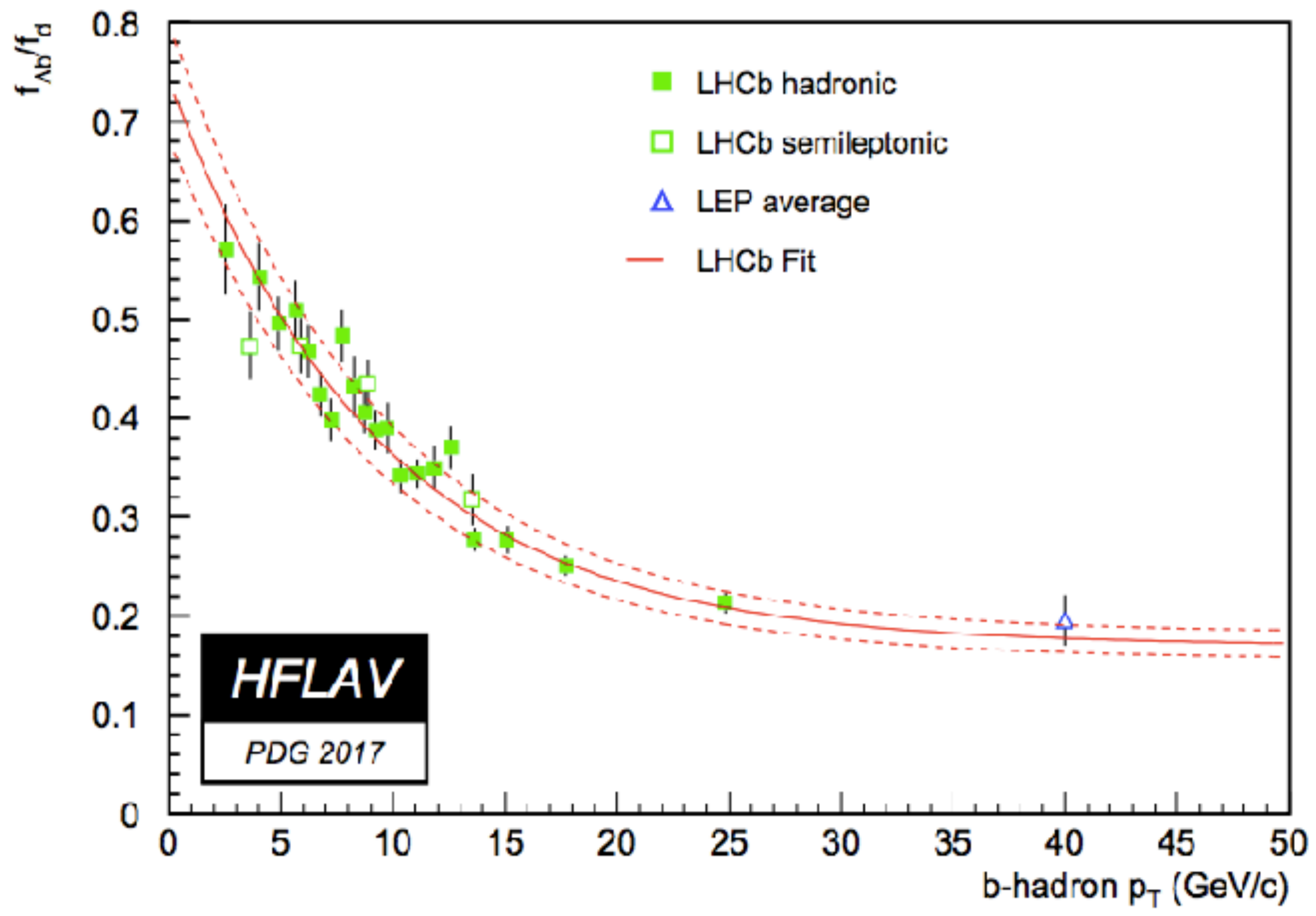
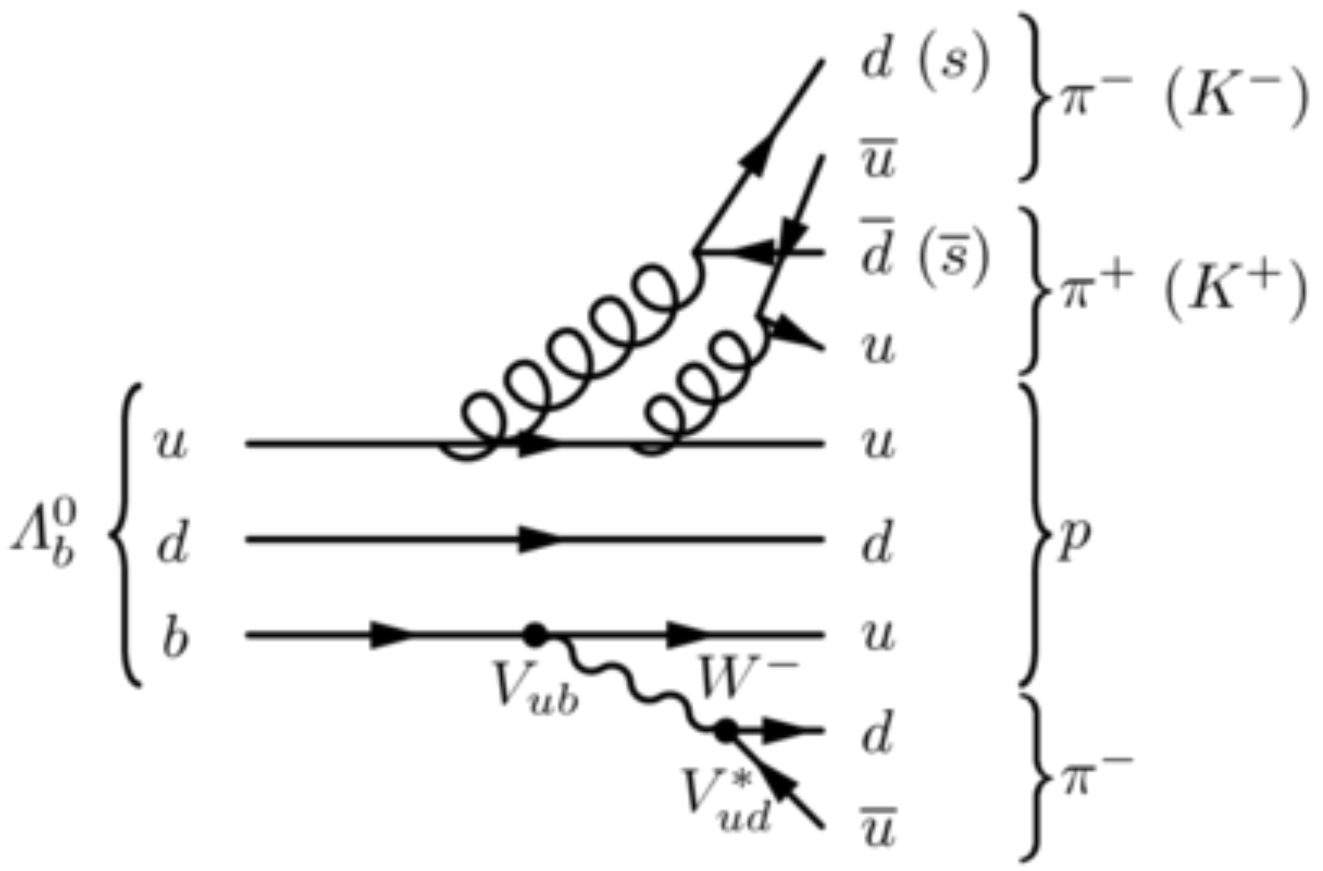
Four-body [LHCb Nature Physics 13 391 (2017)] $\Lambda_b^0 \to ph^-h^+h^-$



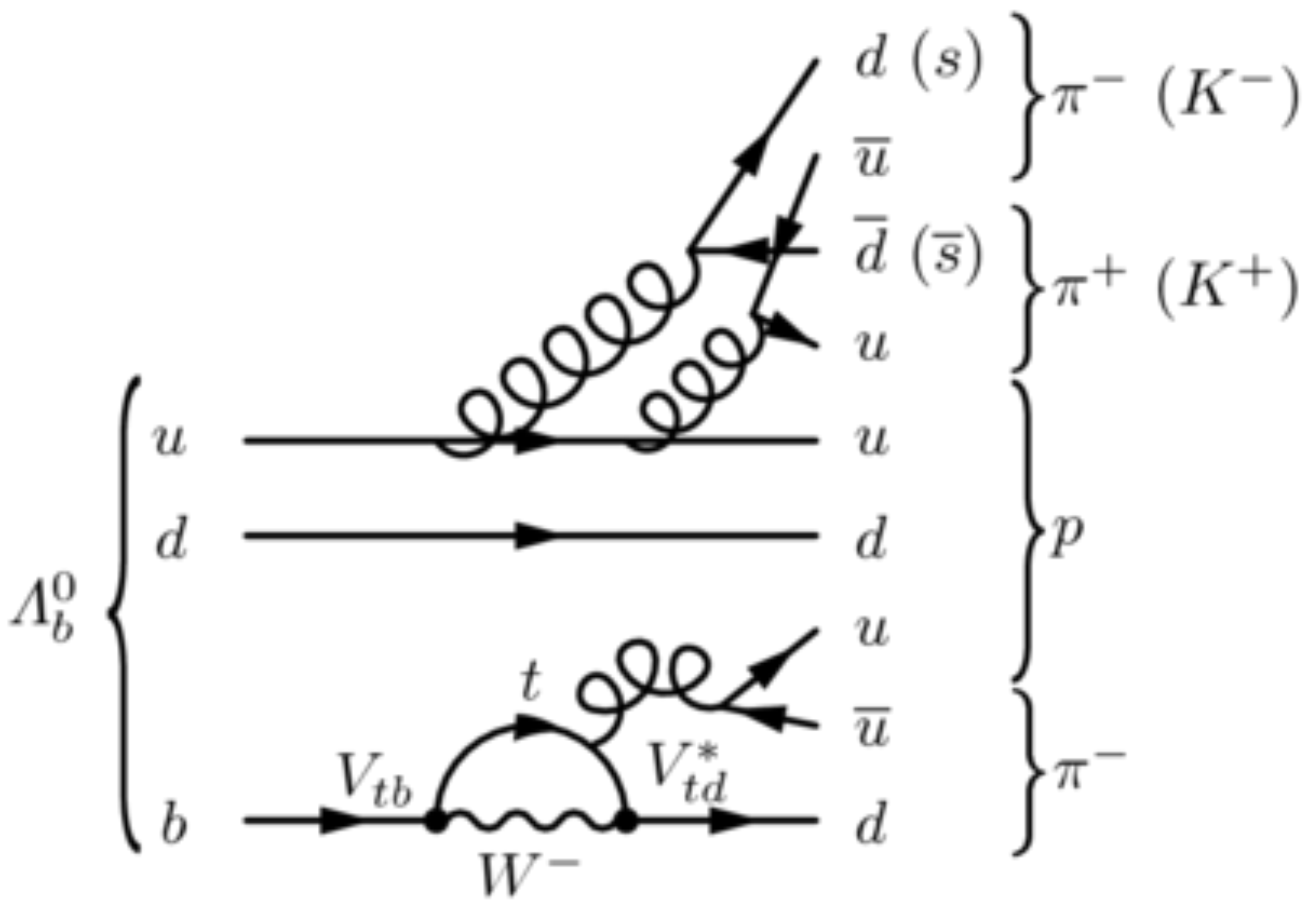
Transitions governed by ***b*** **→** ***udu*** tree and ***b*** **→** ***duu*** penguin amplitudes of similar magnitude.

Large relative weak phase α

[I.I. Bigi, arXiv:1608.06528]
[M. Gronau, J. Rosner, PLB 749 (2015) 104]
[W. Bensalem et al., PLB 538 (2002) 309]
[W. Bensalem et al., PRD 66 (2002) 094004]



$$V_{ub} \sim \lambda^3$$



$$\sum_{x=u,c,t} V_{bx}V_{xd} \sim \lambda^3$$

CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

$\bar{T}$ = motion reversal operator
(= P for spinless particles)

Use 4-body topology to build **triple products** (CP-odd observables)

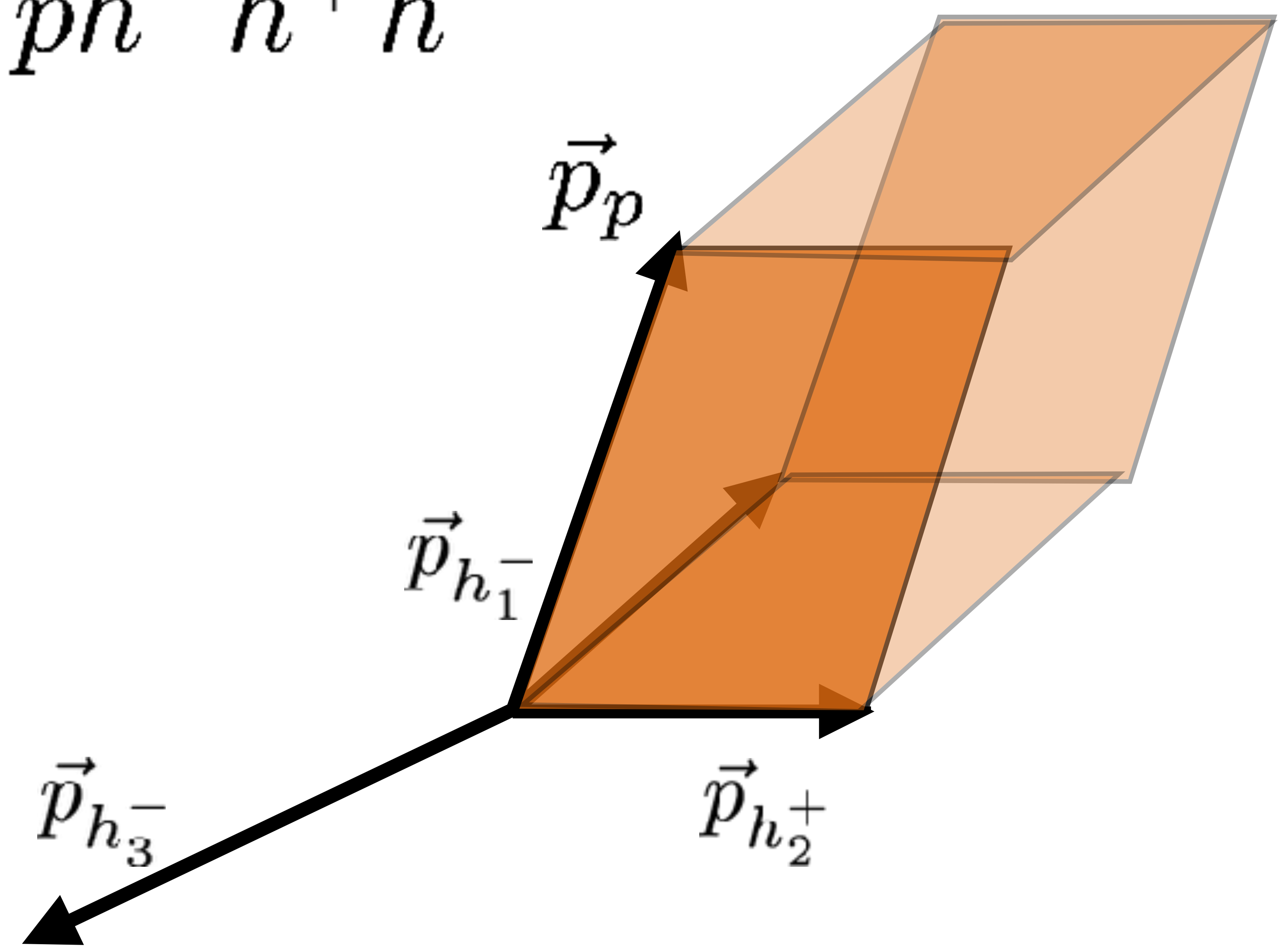
Insensitive to production and detection asymmetries that affect standard CP-asymmetries

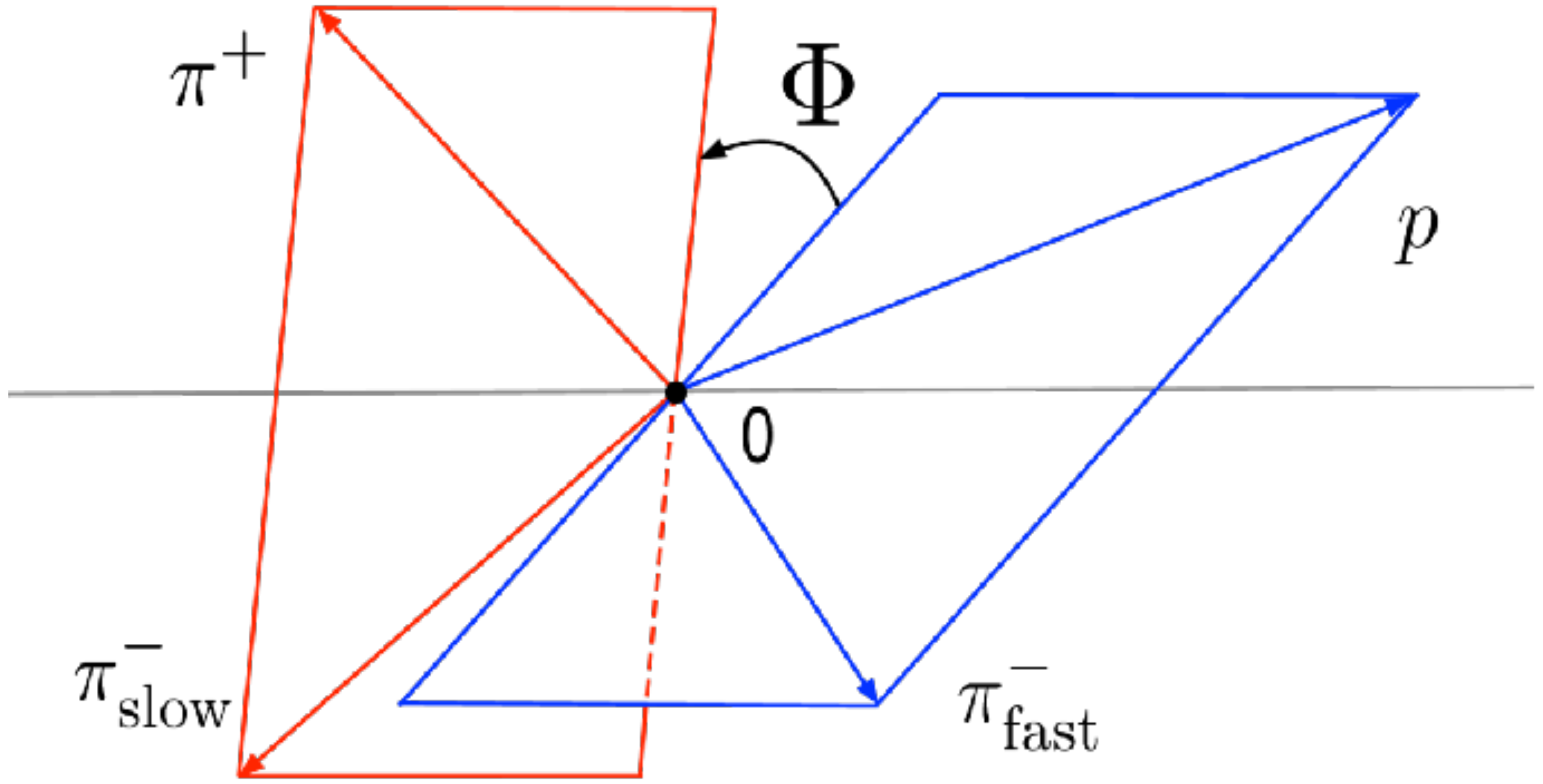
$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \propto \sin\Phi \text{ , for } \Lambda_b^0$$

P-odd
$\bar{T}$-odd

$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$

$\Lambda_b^0 \to p h^- h^+ h^-$





CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

$\hat{T}$ = motion reversal operator
(= P for spinless particles)

Use 4-body topology to build **triple products** (CP-odd observables)

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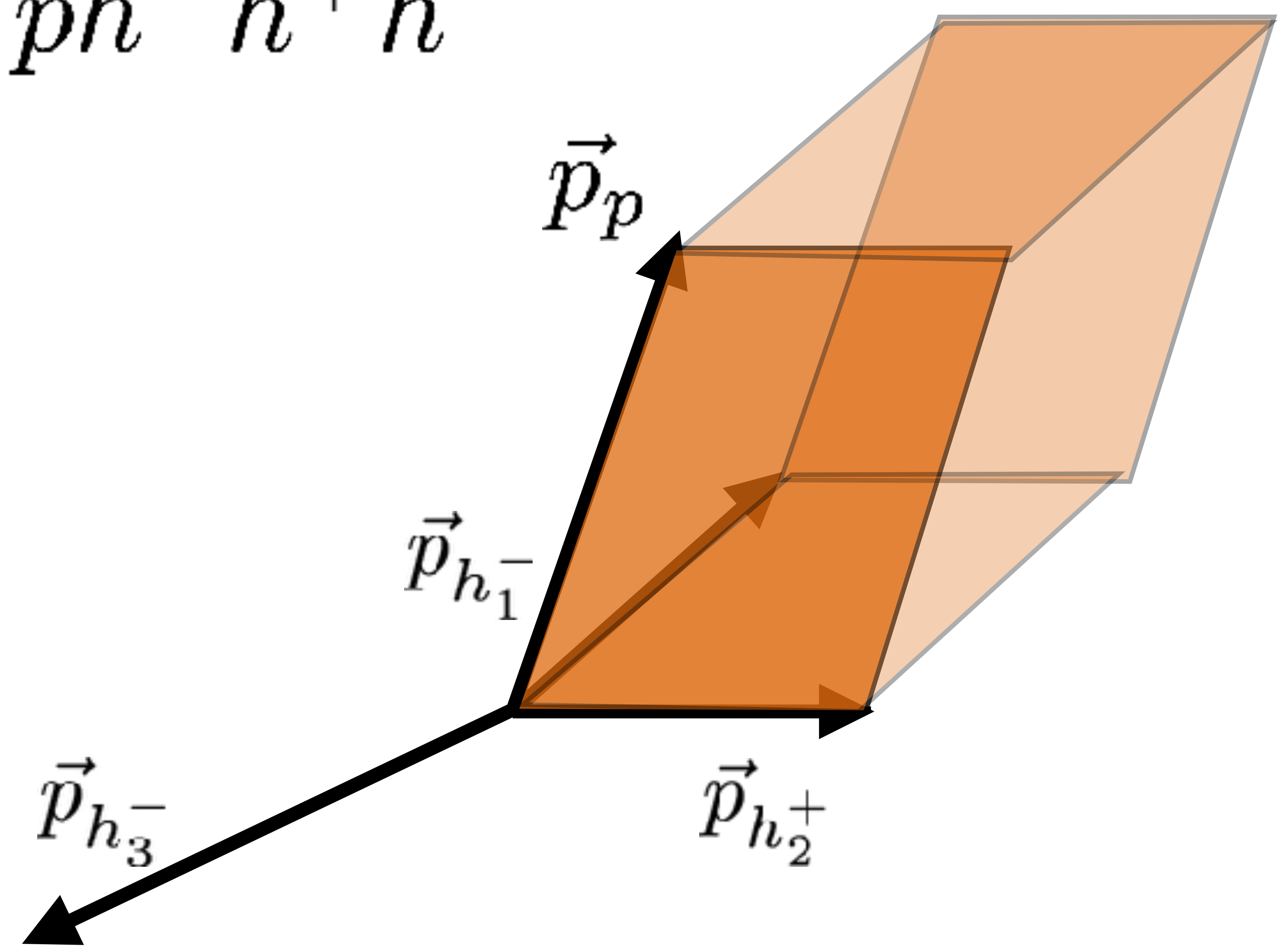
$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \propto \sin\Phi \text{ , for } \Lambda_b^0$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \propto \sin\overline{\Phi} \text{ , for } \overline{\Lambda}_b^0$$

P-odd
$\hat{T}$-odd

$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$
$$\overline{A}_{\hat{T}}(\overline{C}_{\hat{T}}) = \frac{\overline{N}(-\overline{C}_{\hat{T}} > 0) - \overline{N}(-\overline{C}_{\hat{T}} < 0)}{\overline{N}(-\overline{C}_{\hat{T}} > 0) + \overline{N}(-\overline{C}_{\hat{T}} < 0)}$$

$$\Lambda_b^0 \to p h^- h^+ h^-$$



$$a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}})$$

FSI cancel

$$A_{CP} \propto a_1^e a_2^e \sin(\delta_1^e - \delta_2^e) \sin(\phi_1^e - \phi_2^e)$$

$$a_{CP}^{\hat{T}\text{-odd}} \propto a_1^e a_1^o \cos(\delta_1^e - \delta_1^o) \sin(\phi_1^e - \phi_1^o)$$

Relative CP-even "strong" phase

Relative CP-odd "weak" phase

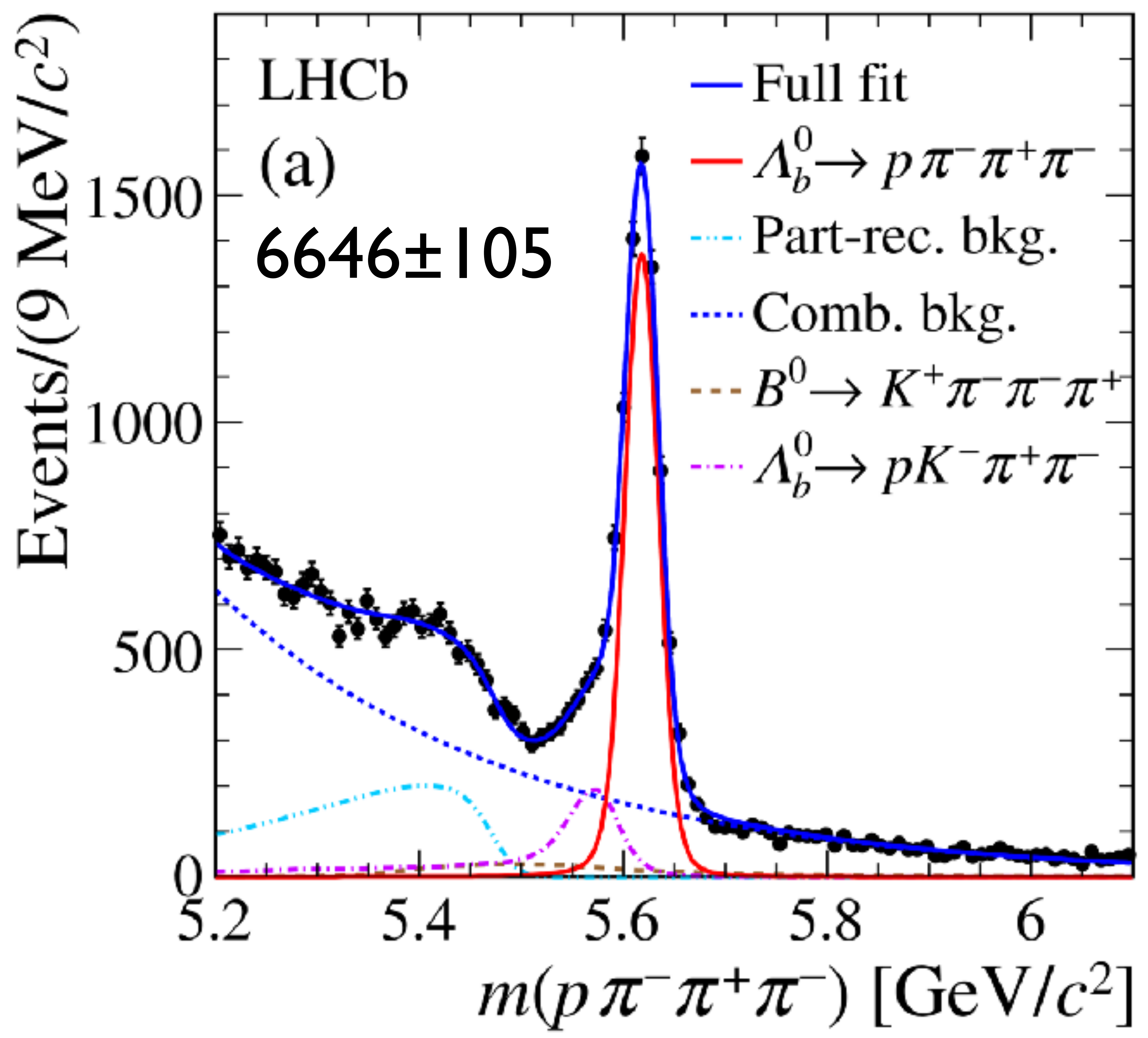
[G. Durieux, Y. Grossman, PRD 92 (2015) 076013]

CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

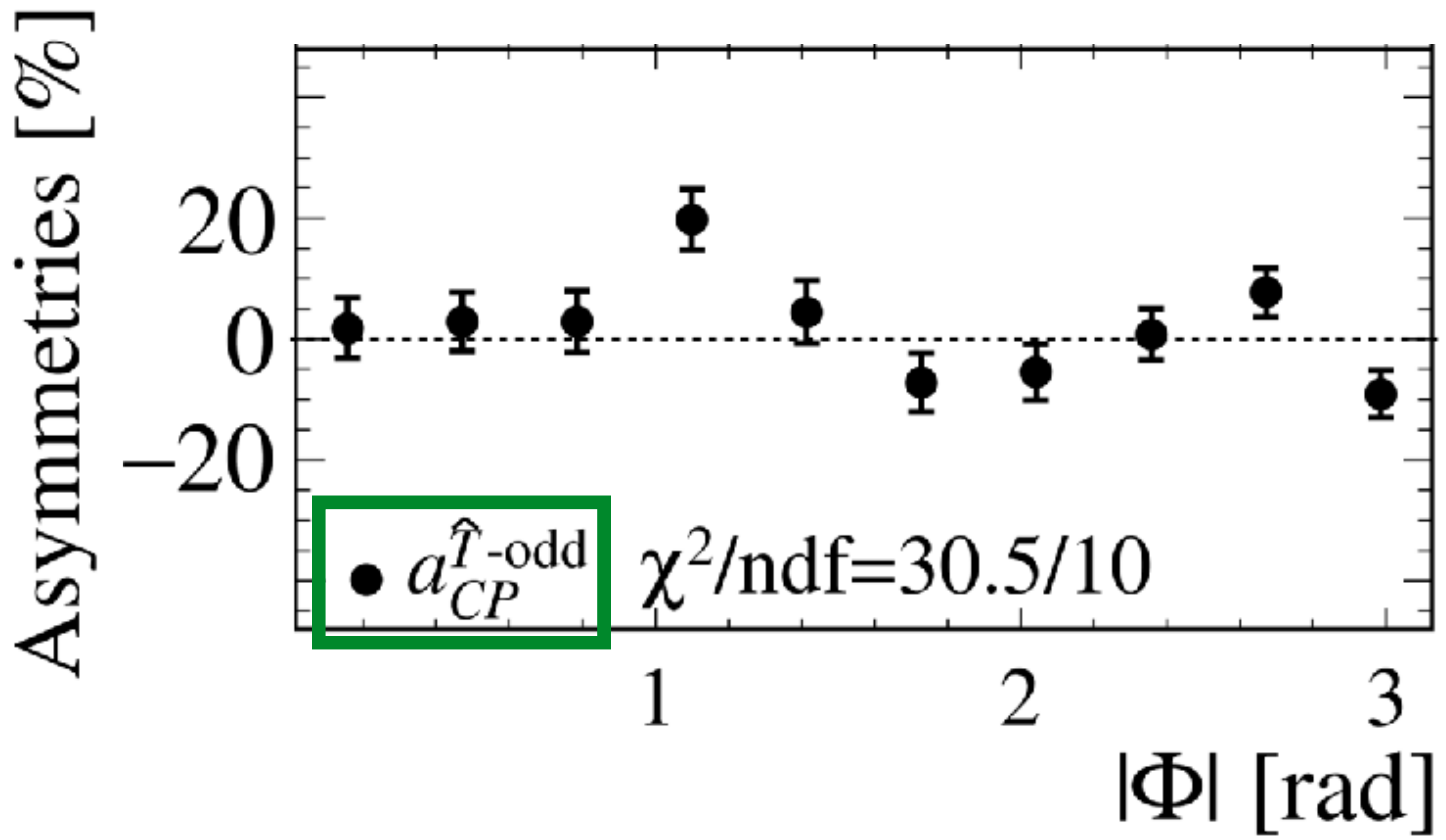
[Nature Physics 13 391 (2017)]

Global measurements consistent with CP symmetry

Search for localised CPV effects → enhanced sensitivity



$$a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}})$$



Similar methods used here but no CPV observed

[LHCb, JHEP 10 (2014) 005]
[LHCb, PLB 759 (2016) 282]
[LHCb, JHEP 06 (2017) 108]

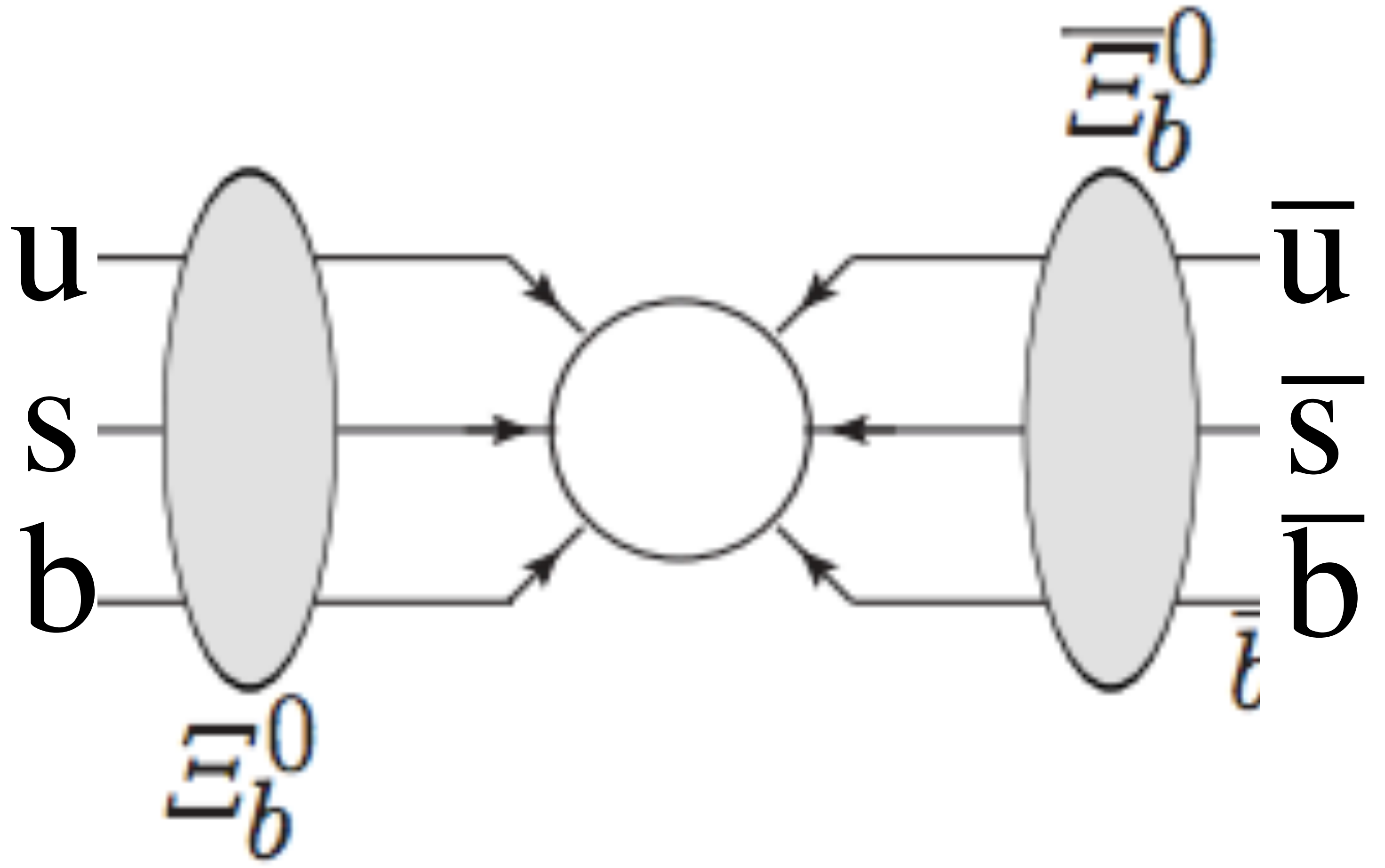
CP-symmetry p-value = 9.8×10^{-4}
→ $a_{CP}^{T\text{-odd}} \neq 0$ at 3.3σ

Baryon-number violation

BNV never been seen experimentally → strong constraints from proton lifetime.

BSM models with flavour-diagonal six fermion vertices allow BNV without violating constraints.
[PRD 85, 036005 (2012), PLB 721 82 (2013)]

Unambiguous experimental evidence:
baryon-antibaryon oscillations of hadrons that contain quarks of all three generations (usb).



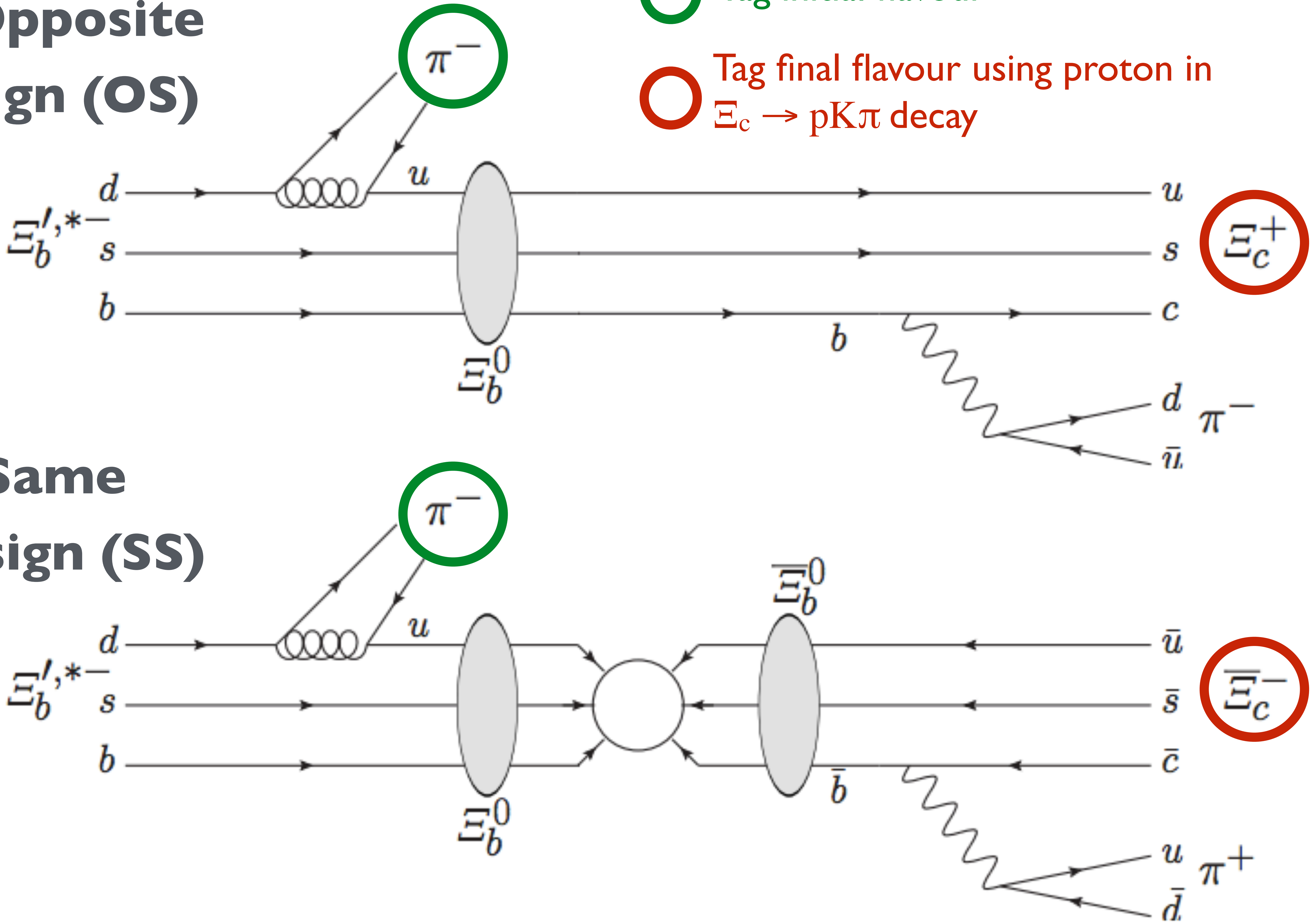
Baryon-number violation @ LHCb

Tag initial flavour

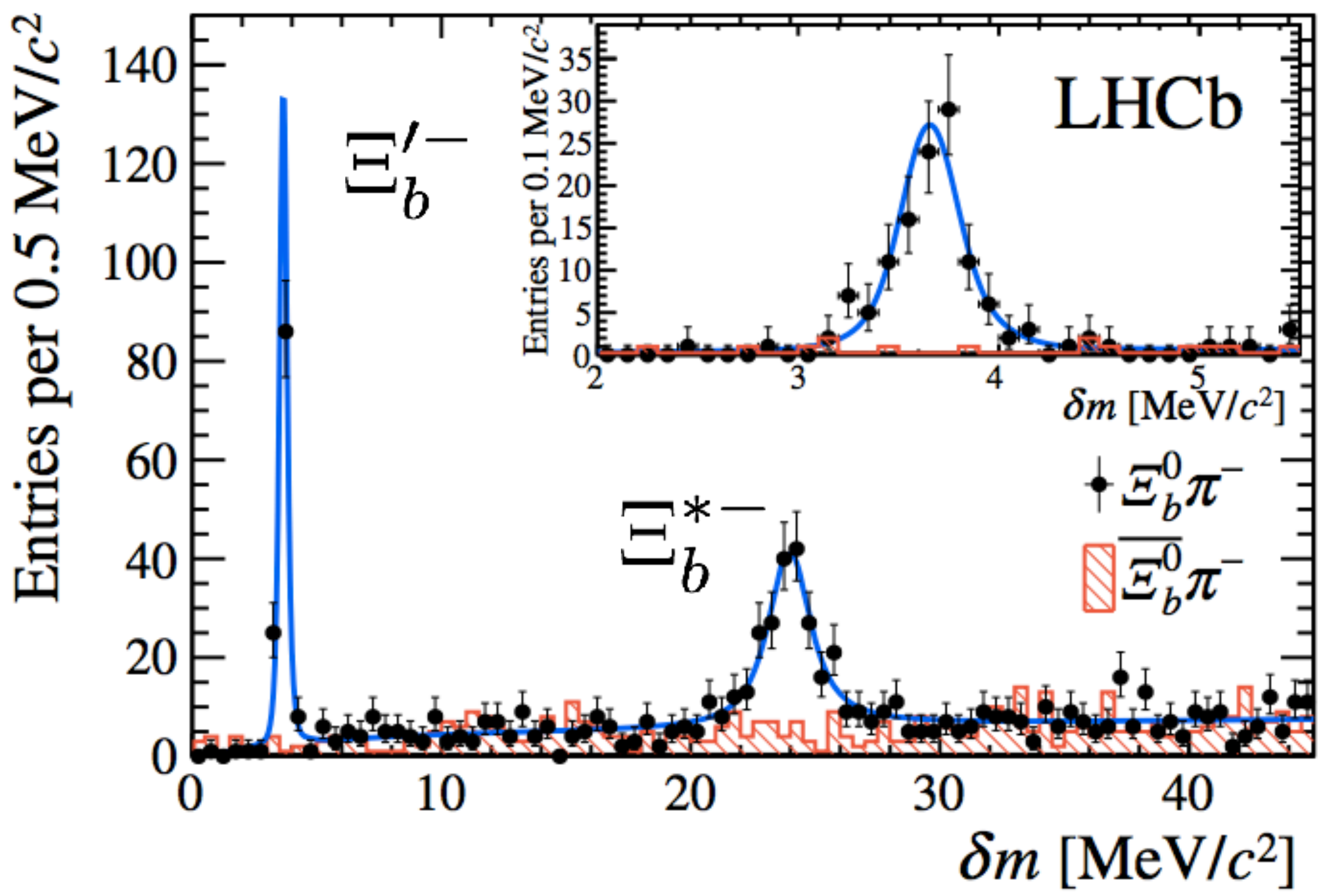
Tag final flavour using proton in $\Xi_c \to pK\pi$ decay

Opposite sign (OS)

Same sign (SS)



[Preliminary LHCb-PAPER-2017-023]



Similar method for measuring charm mixing

$$R(t) = \frac{\Gamma(\Xi_b^0 \to \bar{\Xi}_c^- \pi^+)}{\Gamma(\Xi_b^0 \to \Xi_c^+ \pi^-)} \approx \omega t^2$$

No evidence of BNV oscillations.

$\omega < 0.08\ \mathrm{ps}^{-1}$ @95% CL (using likelihood ratio test and CL_s method)

$\omega = 1/\tau^2_{mix}$ → mixing lifetime > 13 ps.

Charm

All results using Run 1 data only

Charm mixing and CPV

Charmed hadrons provide only way to probe CPV with up-type quarks

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

$$x \equiv \Delta m/\Gamma \qquad y \equiv \Delta\Gamma/(2\Gamma)$$

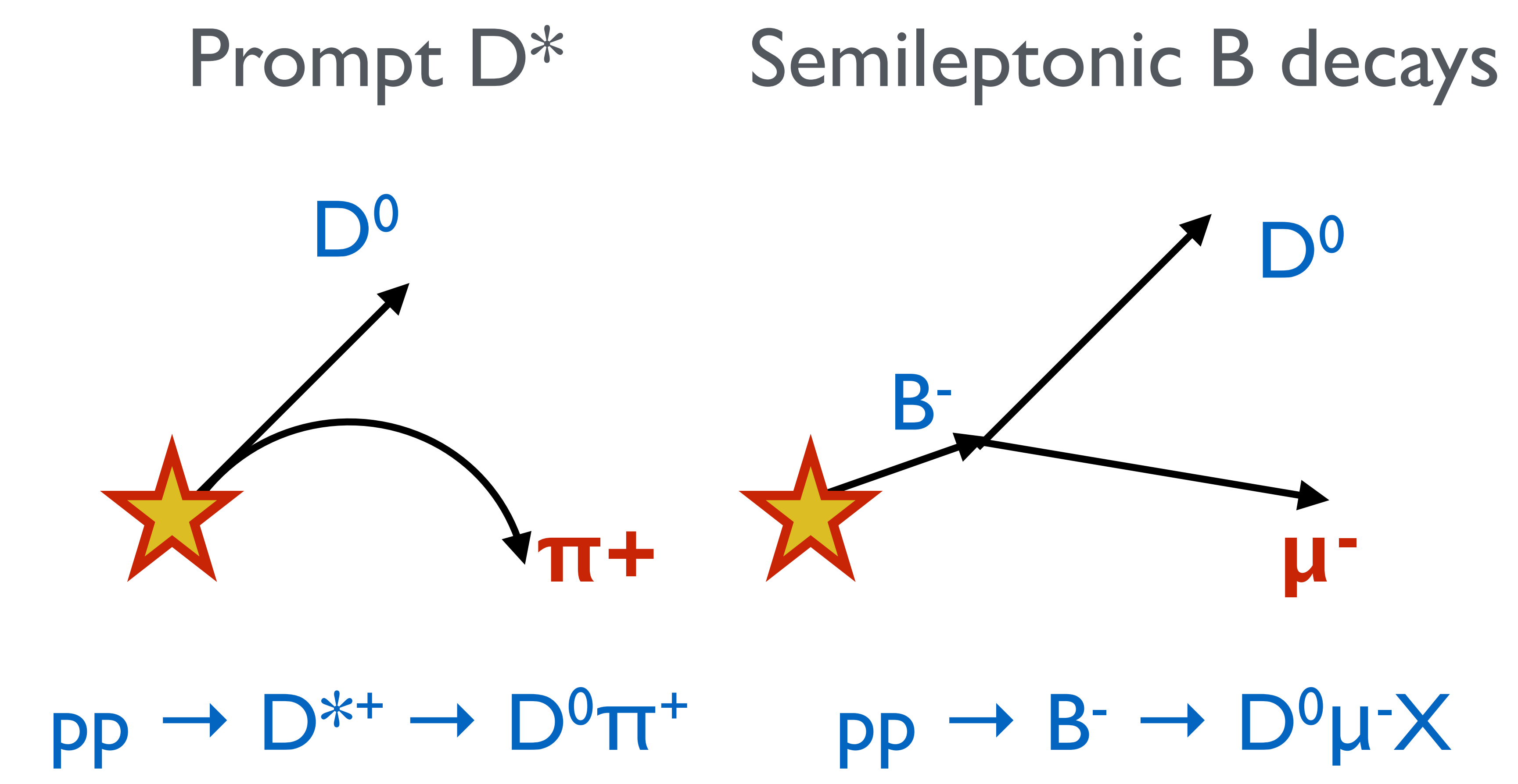
Mixing in charm sector dominated by long distance effects: $|x|, |y| < 10^{-2}$

Very small CPV expected: $< 10^{-3}$ [PRD 85 079901 (2012)]

So far **no evidence** for charm CP violation

Huge event yields at the LHC (millions of signal candidates in CF modes)

Flavour-tagging



Charm mixing and CPV in $D^0 \to K^+\pi^-$

Double-tag method ($B \to D^{*+}(\to D^0\pi^+)\mu^- X$) gives ~background-free sample and access to lower decay times than prompt sample (but with x40 fewer events)

Measure time-dependent ratio of Cabibbo-favoured and suppressed decay modes.

mixing

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

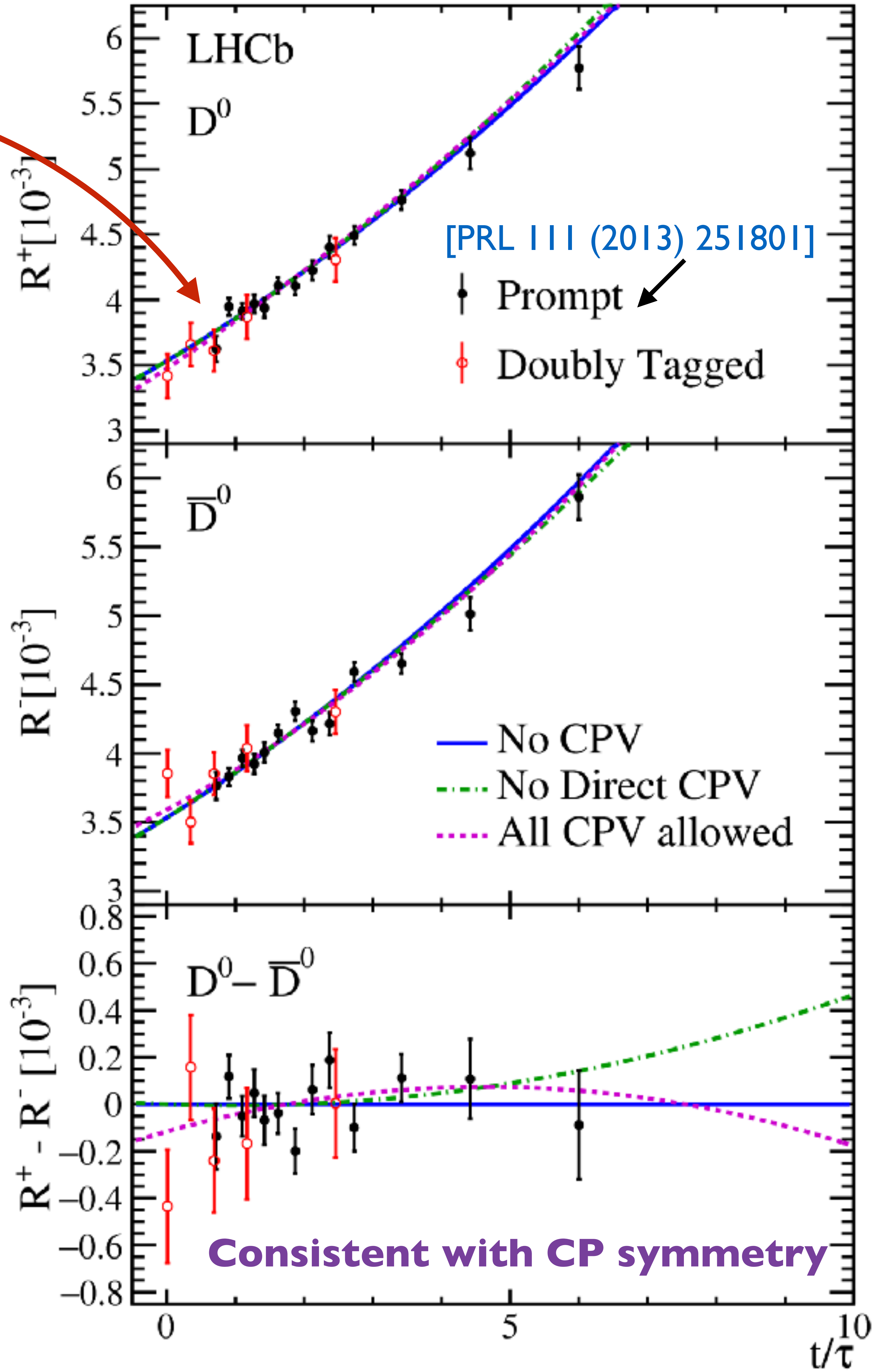
2nd order expansion in small x, y of mixing eqns

[PRD 95, 052004 (2017)]

Parameter	DT + Prompt	Prompt-only
	All CPV allowed	
$R_D^+[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095
$(x'^+)^2\,[10^{-4}]$	0.11 ± 0.65	0.49 ± 0.70
$y'^+[10^{-3}]$	5.97 ± 1.25	5.1 ± 1.4
$R_D^-[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090
$(x'^-)^2\,[10^{-4}]$	0.61 ± 0.61	0.60 ± 0.68
$y'^-[10^{-3}]$	4.50 ± 1.21	4.5 ± 1.4
χ^2/ndf	$95.0/108$	$85.9/98$

$R_D^+ \neq R_D^-$ ⇒ direct CPV

$x'^+ \neq x'^-$, $y'^+ \neq y'^-$ ⇒ CPV in mixing and interference



Direct CPV in charm

$$A_{\mathrm{raw}} \equiv \frac{N(D^0 \to K^-K^+) - N(\bar{D}^0 \to K^-K^+)}{N(D^0 \to K^-K^+) + N(\bar{D}^0 \to K^-K^+)}$$

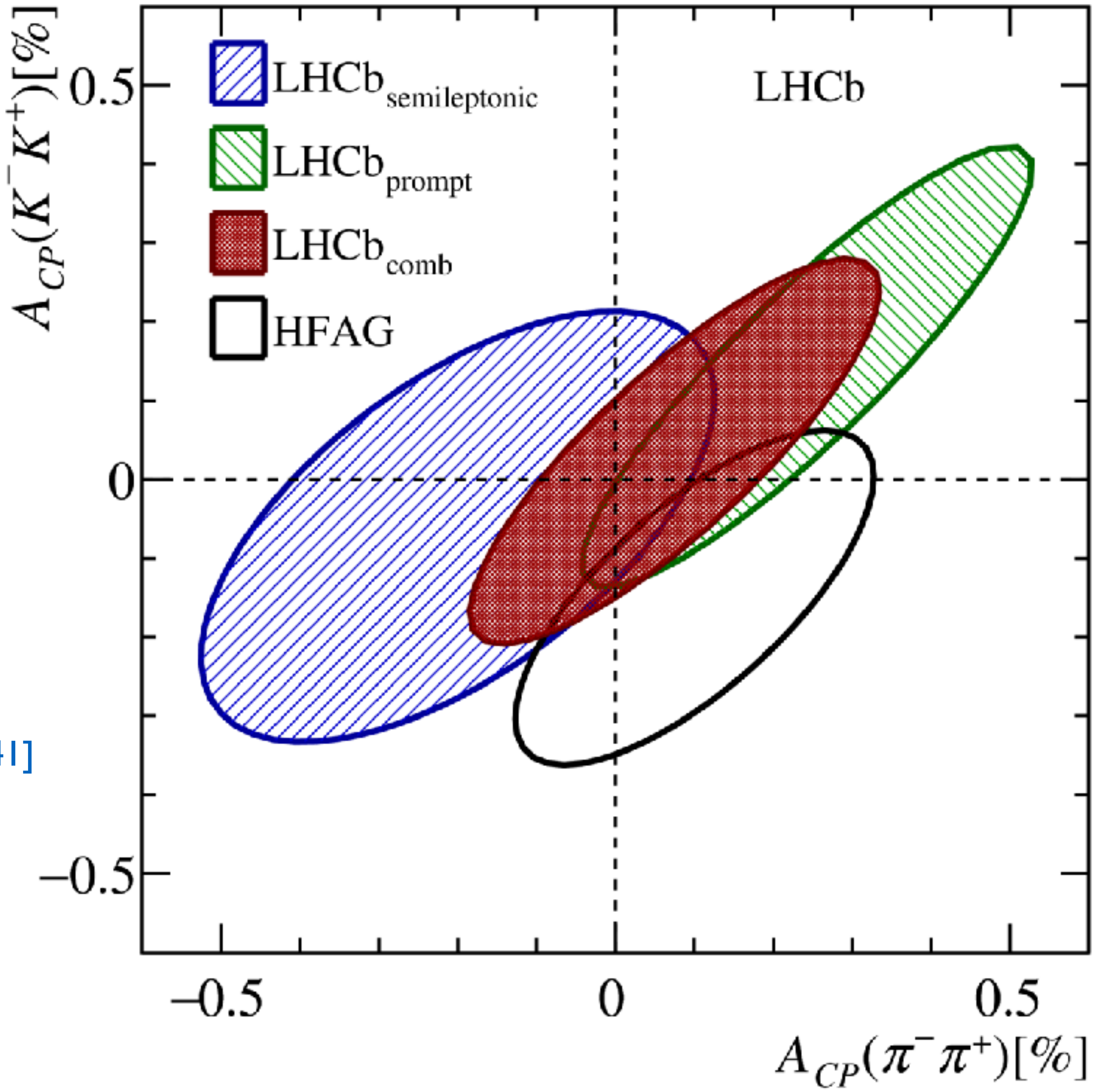
$$A_{CP}(D^0 \to K^-K^+) = A_{\mathrm{raw}}(D^0 \to K^-K^+) - \boxed{A_P(D^{*+}) - A_D(\pi_s^+)}$$

Prompt-tagged sample [PLB 767 (2017), 177]

Multiple control channels to assess production and detection asymmetries (dominate systematics).

Combine results from semileptonic-tagged sample. [JHEP 07 (2014) 041]

$$A_{CP}(K^-K^+) = (0.04 \pm 0.12\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}))\%$$
$$A_{CP}(\pi^-\pi^+) = (0.07 \pm 0.14\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst}))\%$$



O(‰) precision, but no signs of CPV

now looking in other modes

$D^{\pm}_{(s)} \to \eta'\pi^{\pm}$ [PLB 771 (2017) 21]

$D^0 \to \pi\pi\pi\pi$ [PLB 769 (2017) 345]

Indirect CPV in charm

Since time-integrated CP asymmetries in charm sector are small and mixing parameters are small:

$$A_{CP}(t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \simeq a^f_{\text{dir}} - A_\Gamma \frac{t}{\tau_D}$$

CPV in decay (~0)

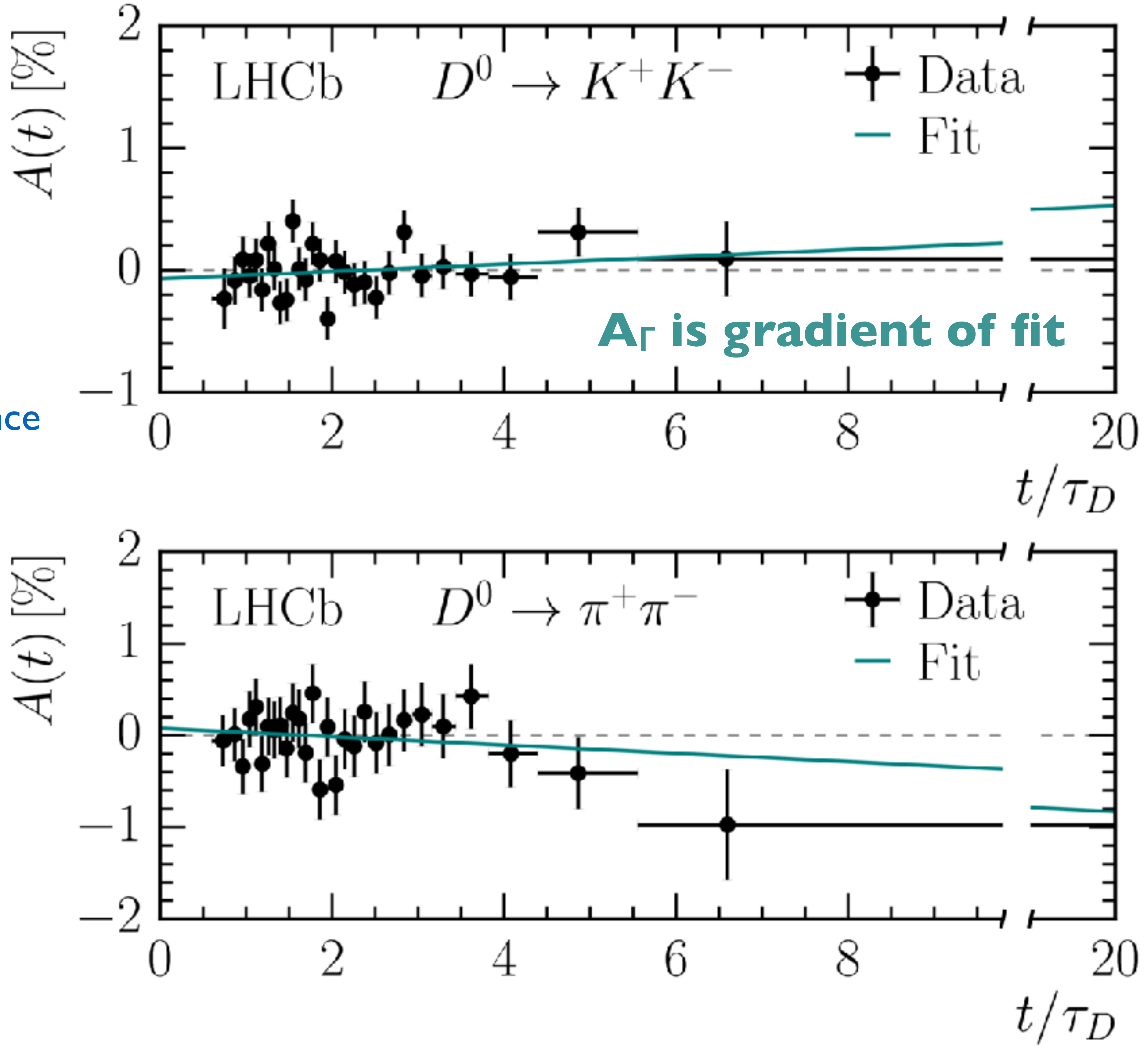
CPV in mixing/interference

Expect < 5 x 10^{-3}

$$A_\Gamma \equiv \frac{\hat{\Gamma}_{D^0 \to f} - \hat{\Gamma}_{\bar{D}^0 \to f}}{\hat{\Gamma}_{D^0 \to f} + \hat{\Gamma}_{\bar{D}^0 \to f}}$$

inverse of effective lifetime

[PRL 118 (2017) 261803]



Use prompt D* tags.

D → Kπ control channel for production/detection asymmetries

Consistent results with unbinned and binned methods

$$A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$$

Combine with independent semileptonic tagged sample:
[LHCb JHEP 04 (2015) 043]

$$A_\Gamma = (-0.29 \pm 0.28) \times 10^{-3}$$

Most **precise** measurement of CPV in charm system ever made!

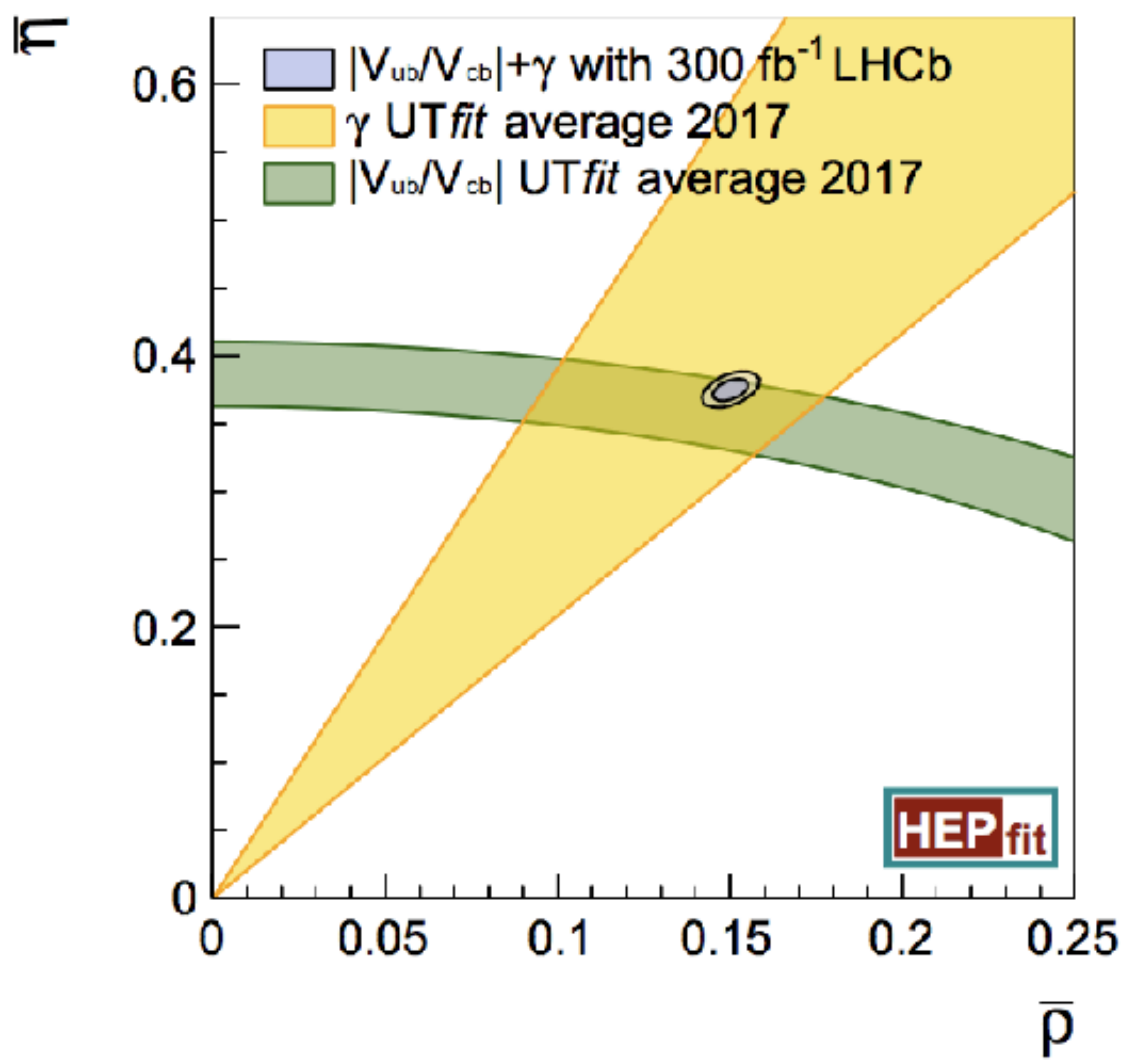
Looking to the future

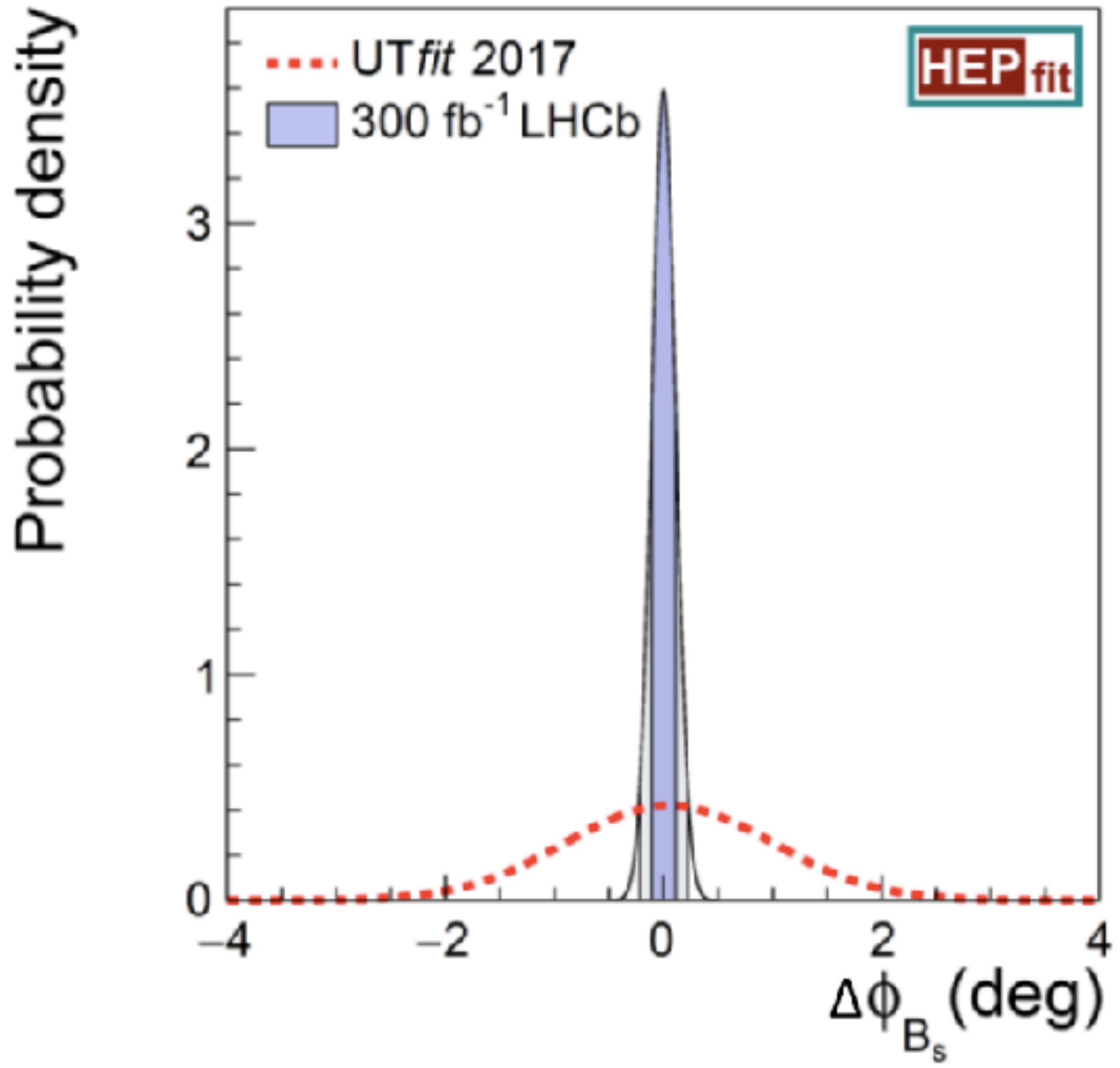
Most beauty and charm measurements are statistically limited.

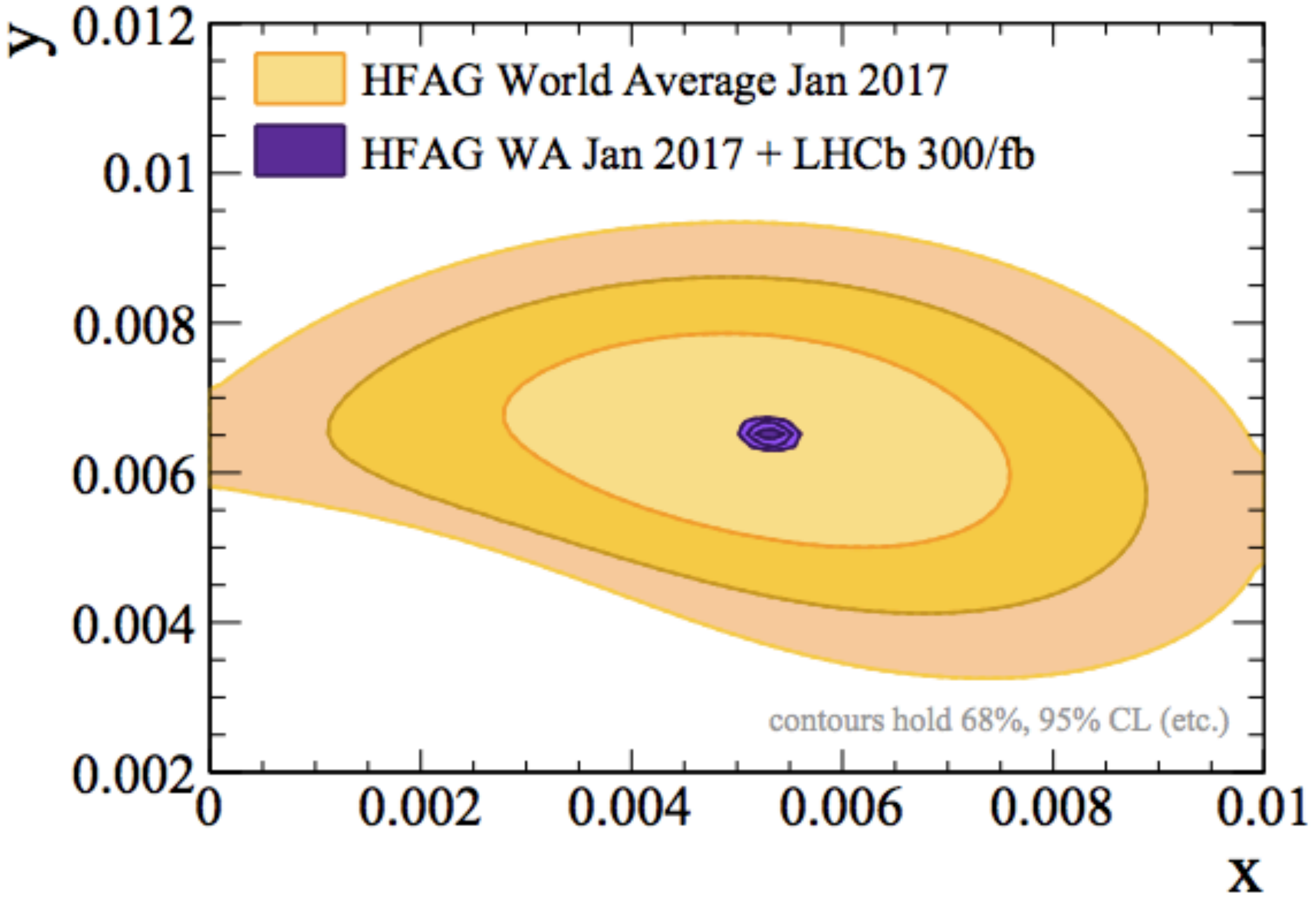
Strong case for **improved precision** of many charm and beauty observables to constrain/find new physics.

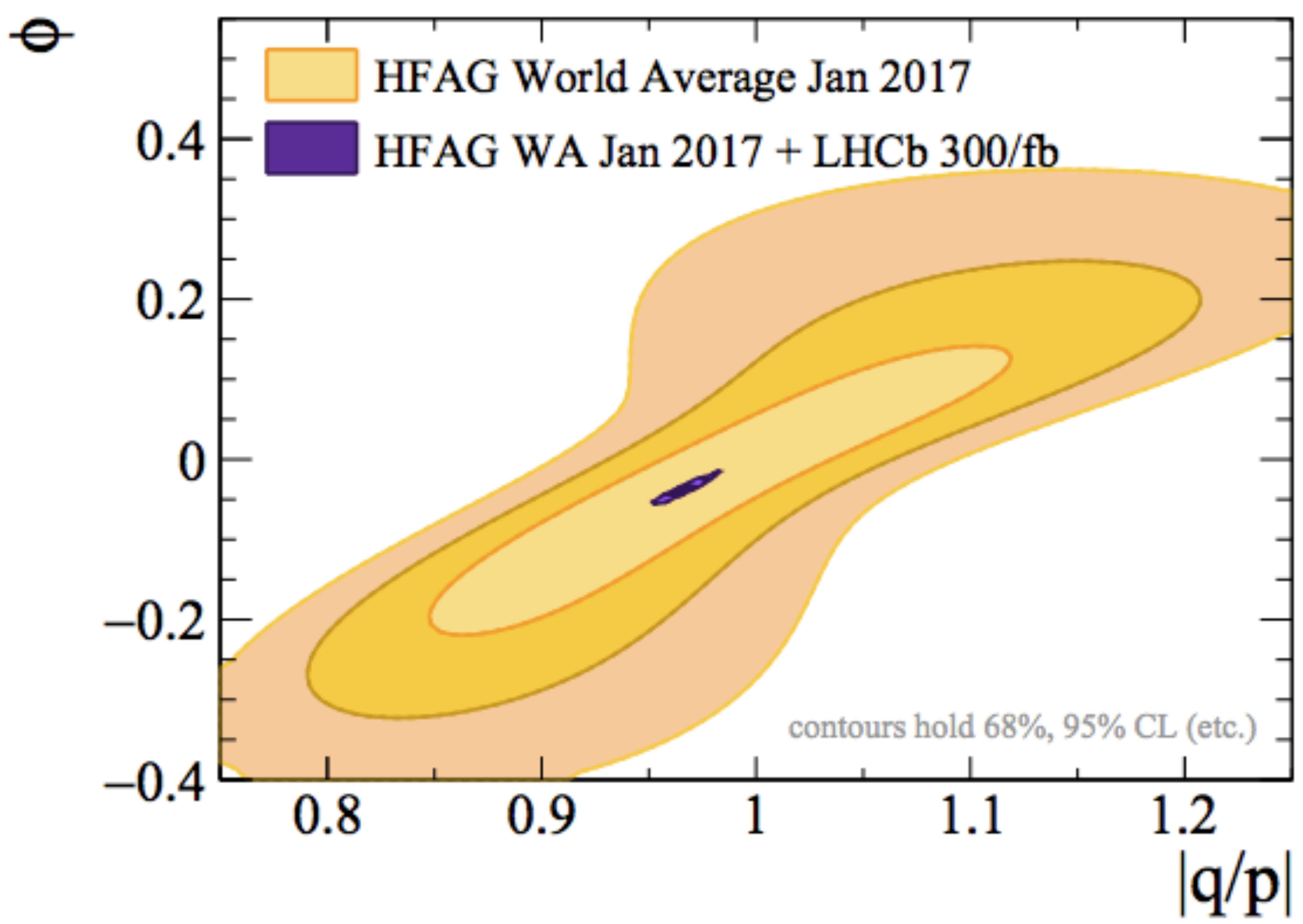
LHCb recently submitted EoI about future phase 1b + 2 upgrades for LHC runs 4 + 5.

[CERN-LHCC-2017-003]
[LHCb-PUB-2014-040]
[ATL-PHYS-PUB-2013-010]

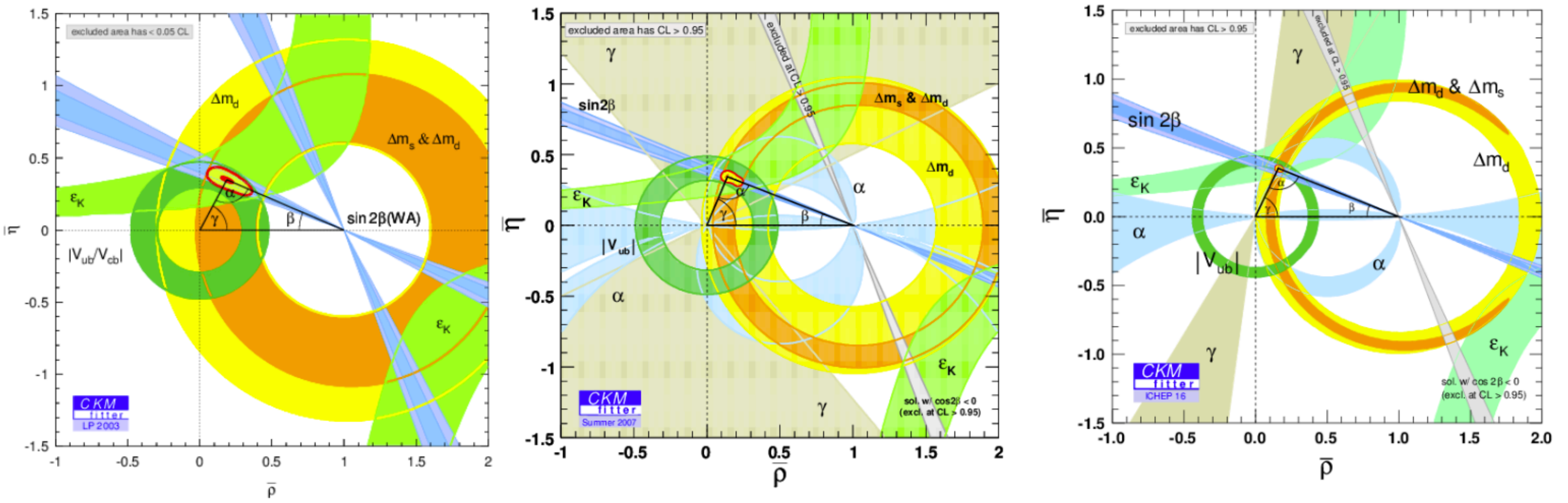








Summary



Huge progress in understanding CPV in the heavy-quark sector.

New explorations in b baryons

New precision measurements in b mesons

Approaching per-mille precision in charm sector - no CPV yet!

Looking forward to the 50th birthday of the b quark and Lepton-Photon 2027!

SM holding strong, but what will happen after the **precision measurements** from LHC Run 2/3/4…?

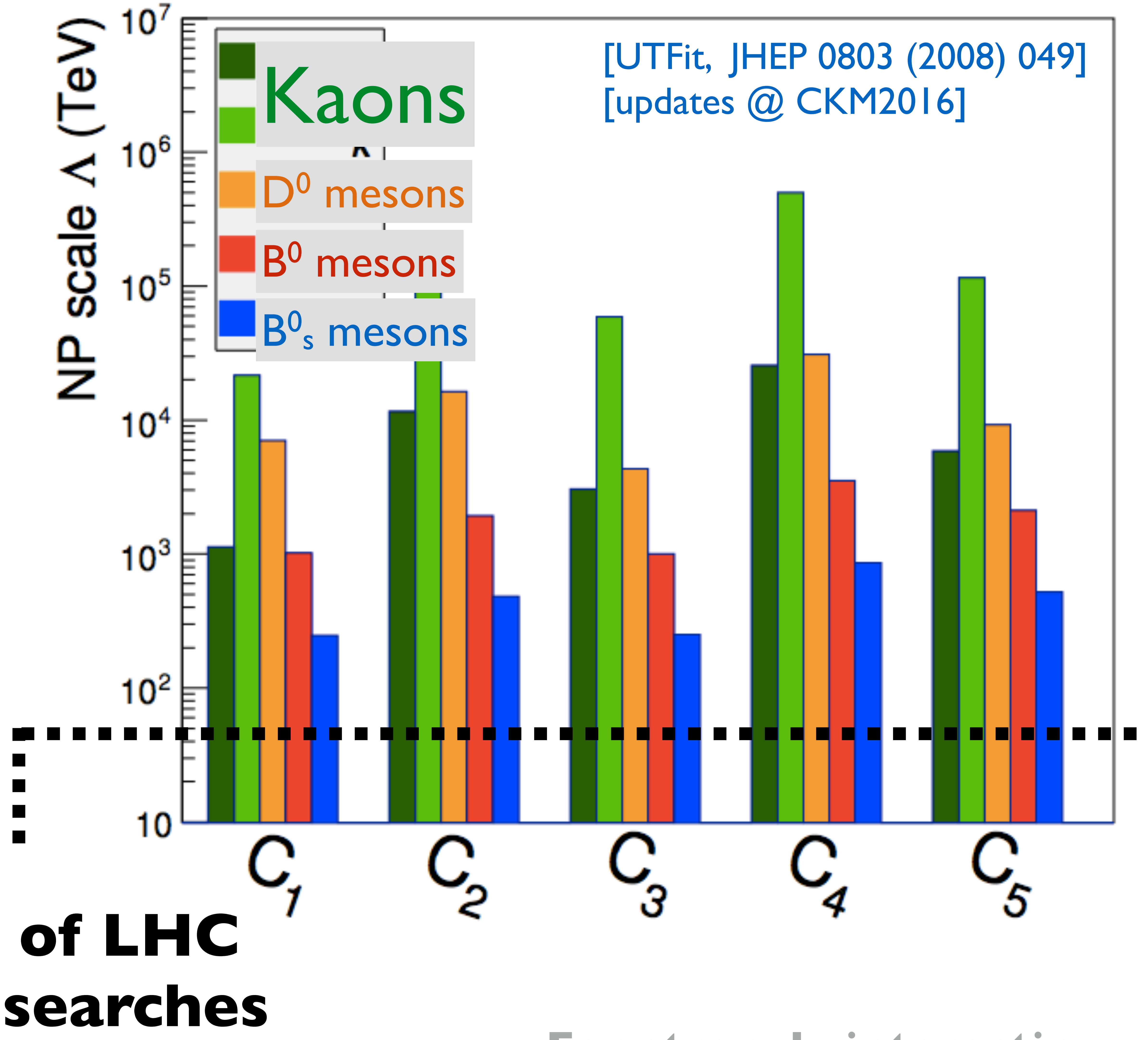
Backup

Why CP violation?

CP violation is necessary condition for baryon asymmetry of the Universe
[A. D. Sakharov, JETP Lett. 5, 24-27 (1967)].

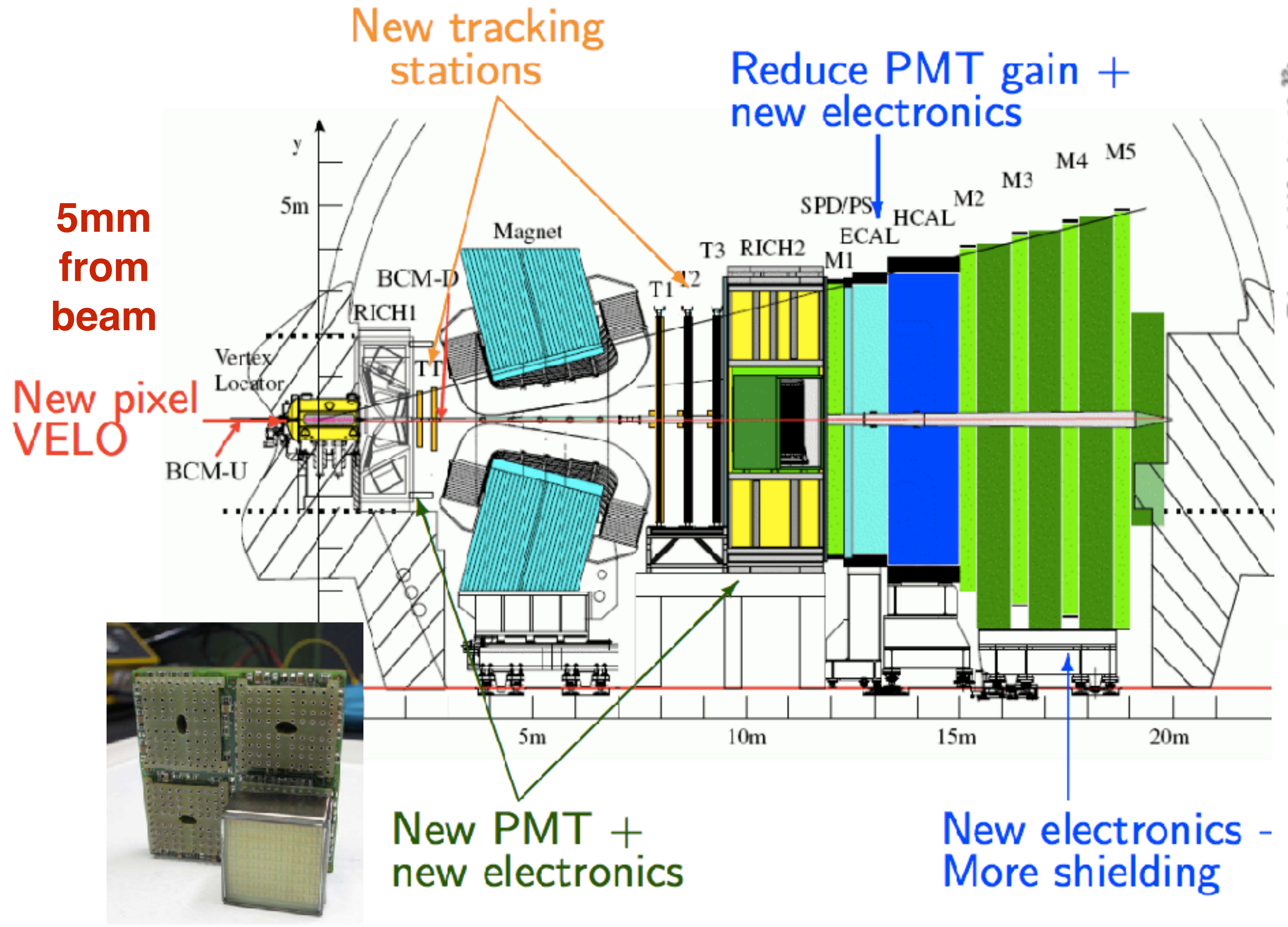
CPV is present in the Standard Model but too small by 10^{10} to explain asymmetry.

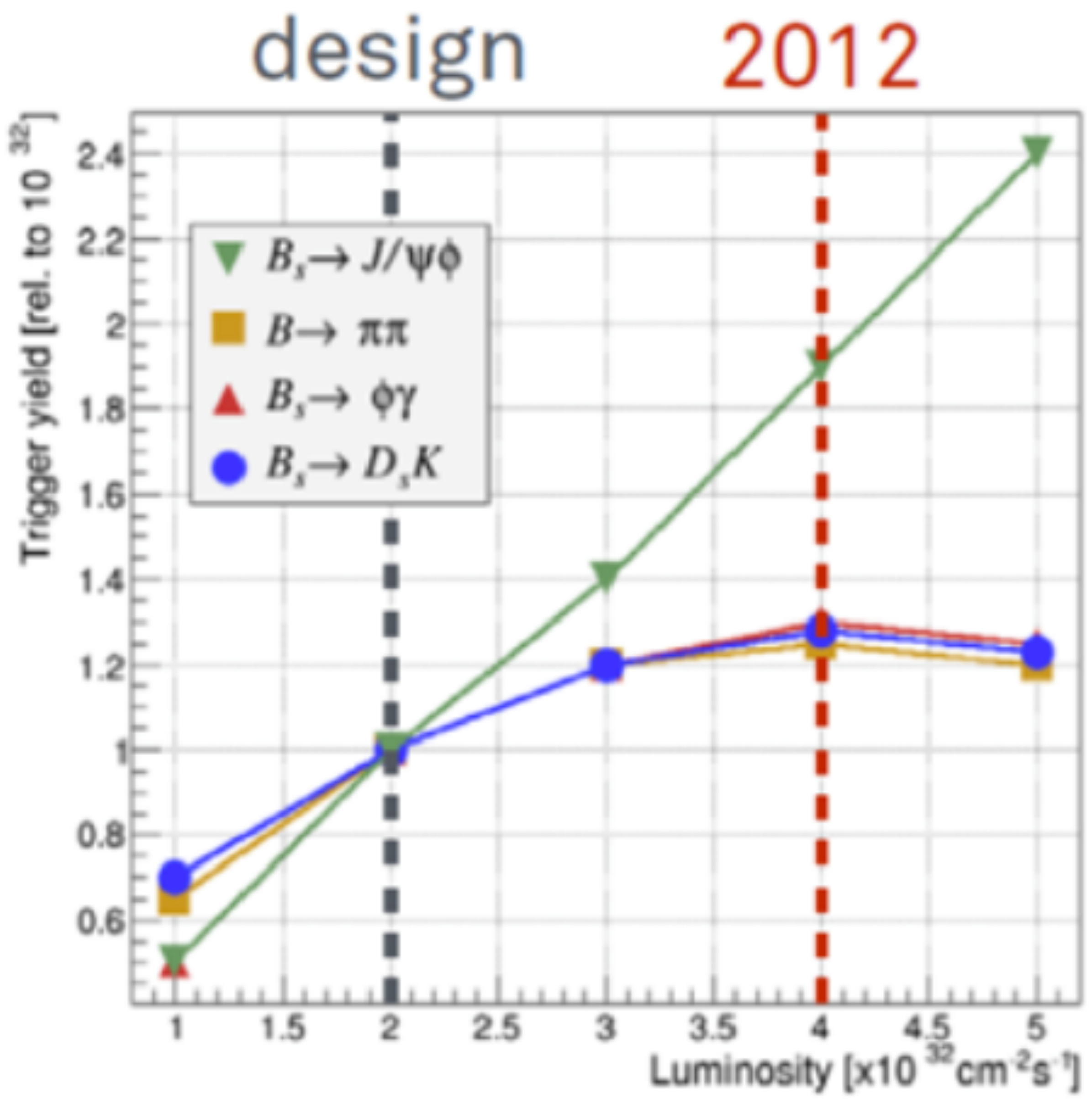
Heavy-quark hadrons provide excellent place to search for new sources of CPV and probing high energy scales.

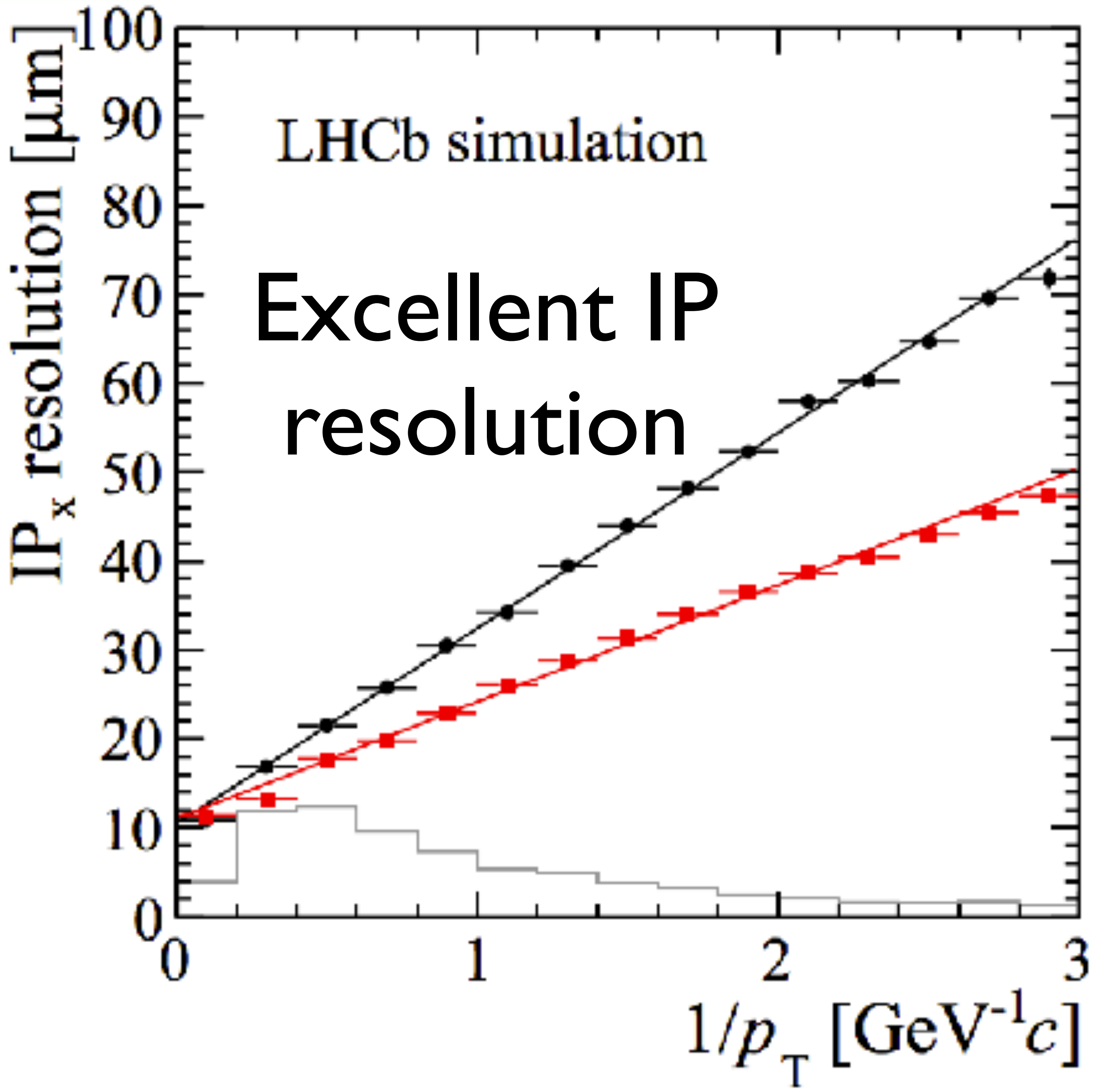


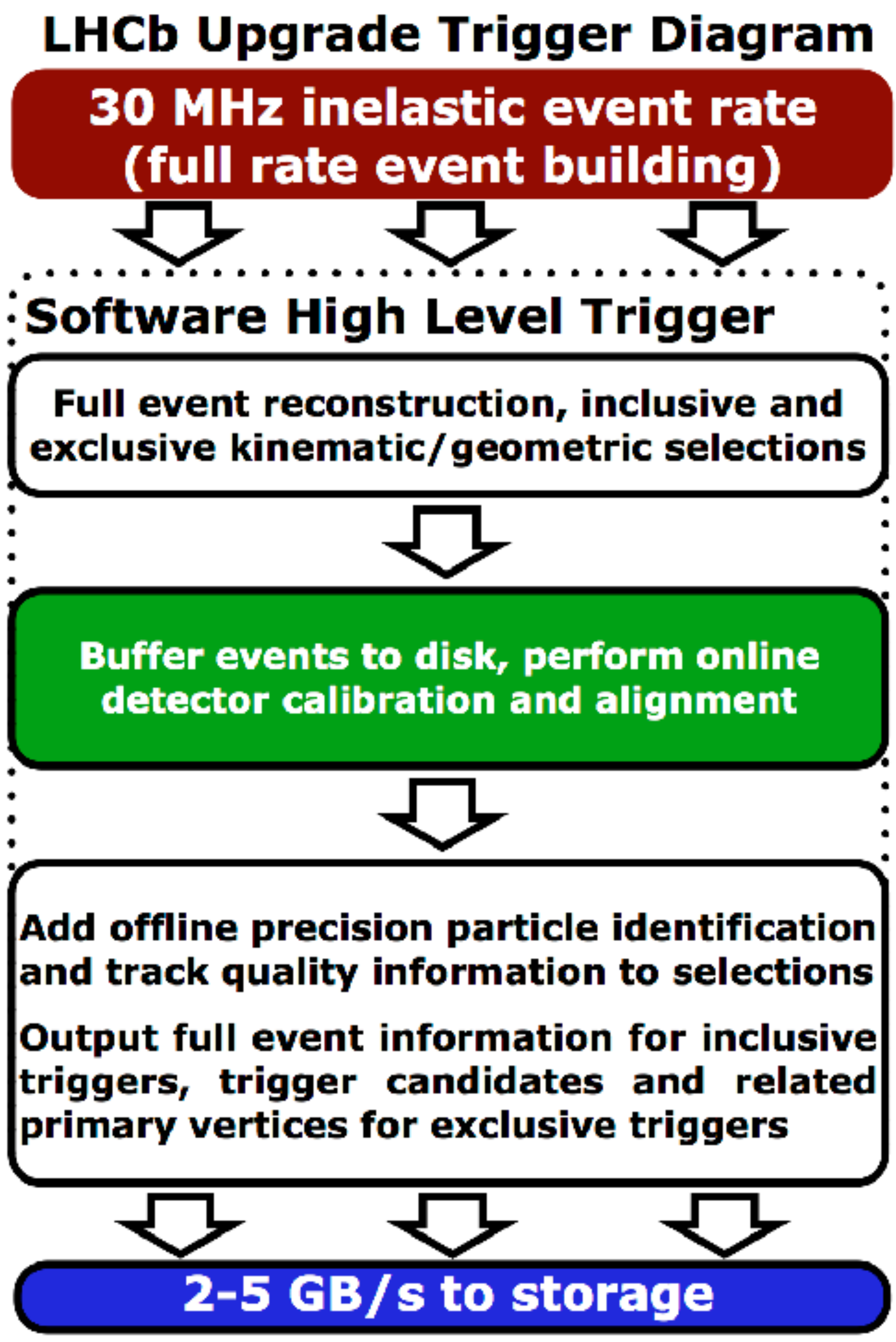
For strongly interacting and/or tree-level NP

LHCb upgrade (phase 1)







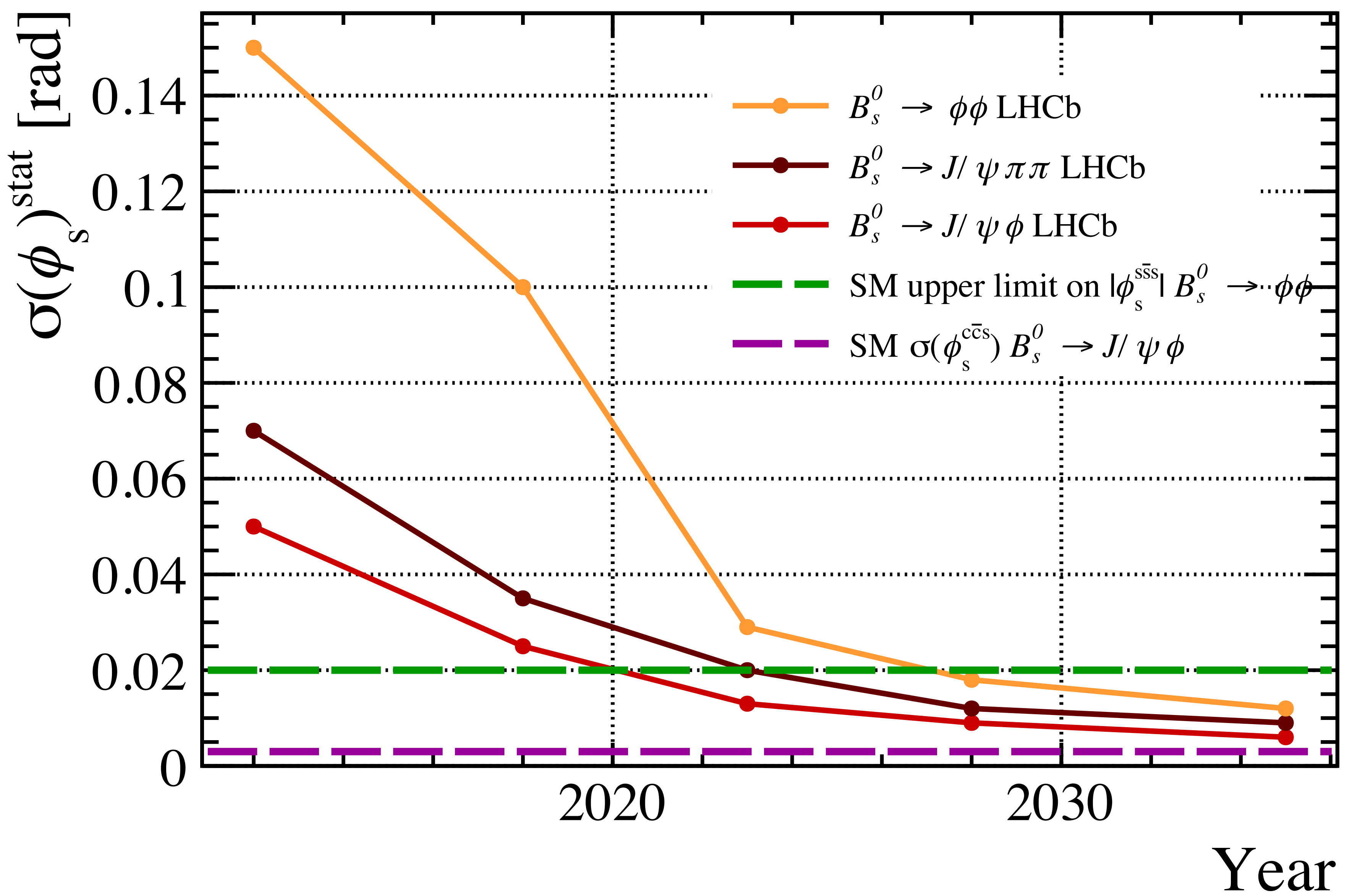


Many LHCb measurements will be statistically limited after Run 1+2.

Increase luminosity from ~4×10^{32} to ~2×10^{33}

LHCb upgrade (phase 1)

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–



[numbers from LHCb-PUB-2014-040]

2025: $\sigma_{\rm LHCb}(\gamma) \sim \sigma_{\rm Belle-II}(\gamma) < 1°$

$\sigma_{\rm syst} < 1°$

LHCb upgrade 50 fb^{-1}
+ Belle-II 50 ab^{-1}
[PRD 89, 033016 (2014)]

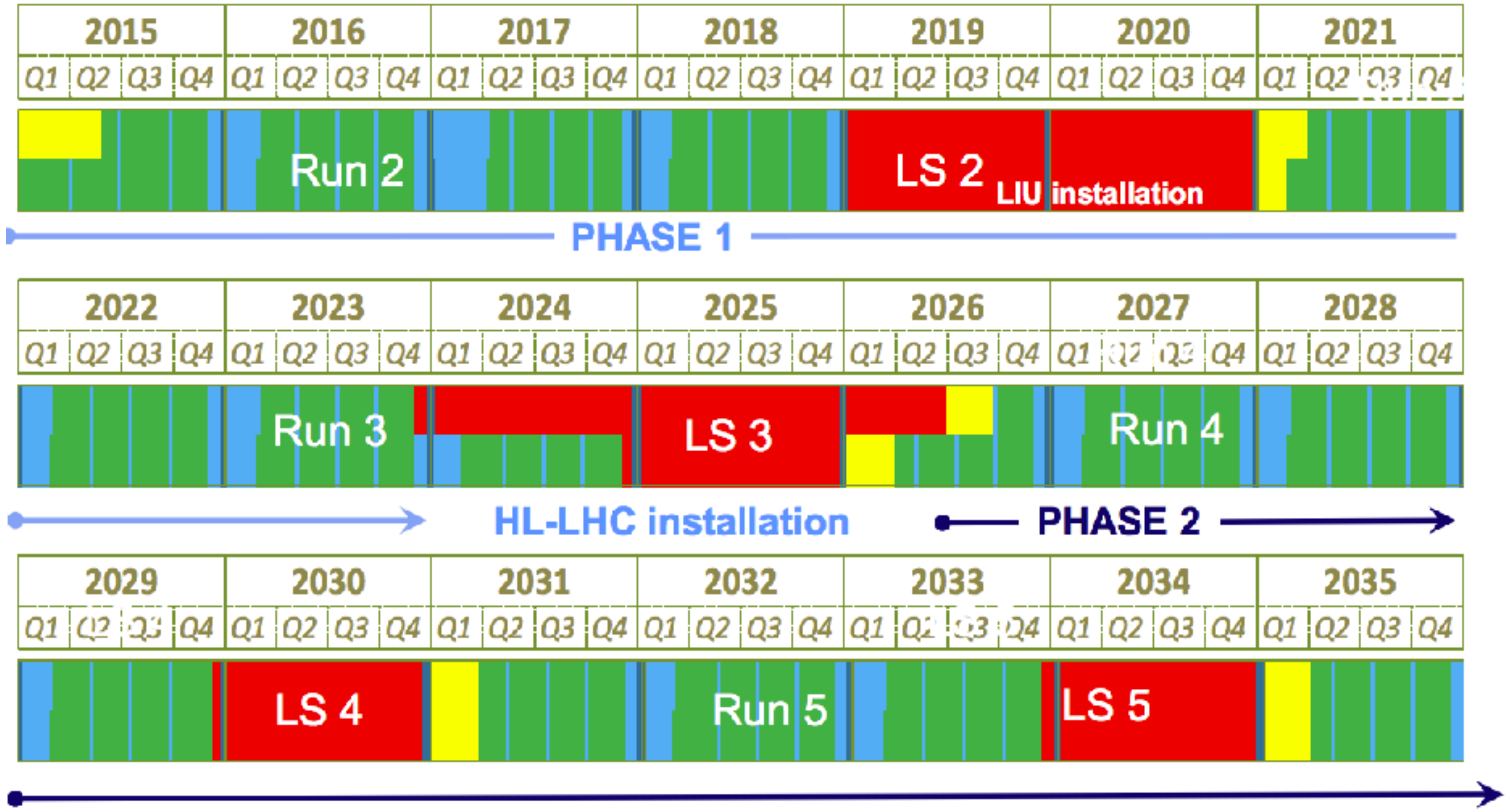
LHCb upgrade (phase 1b and 2)

LHCb-upgrade will be installed in LS2 and operate during Run-3.

Phase 1b upgrade in LS3, for operation in Run-4 (HL-LHC).

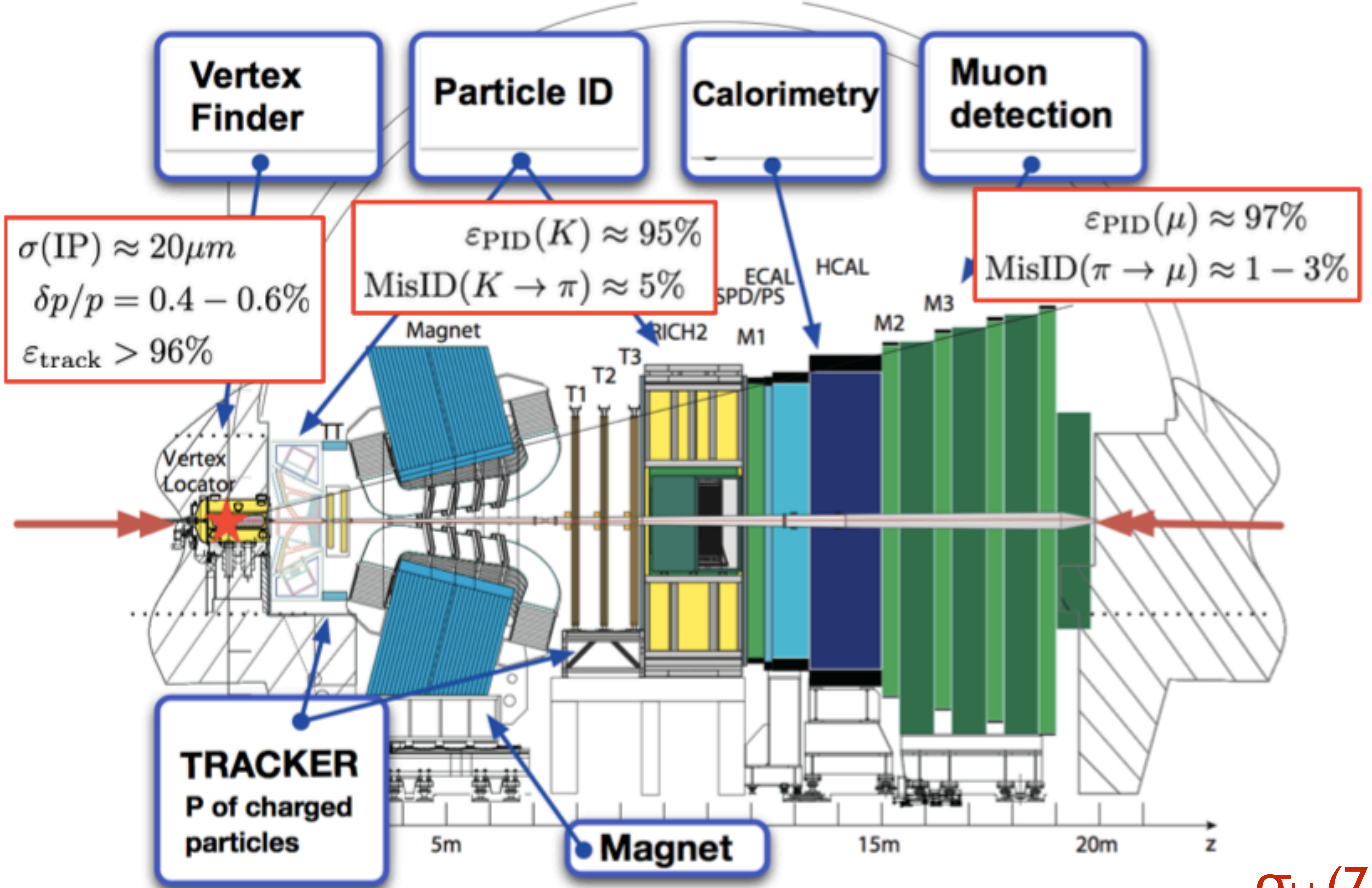
- Stations in the magnet (to improve reconstruction of multi-body final states).
- Improvements to PID via time-of-flight (TORCH project).

Increase luminosity to ~10^{34}.

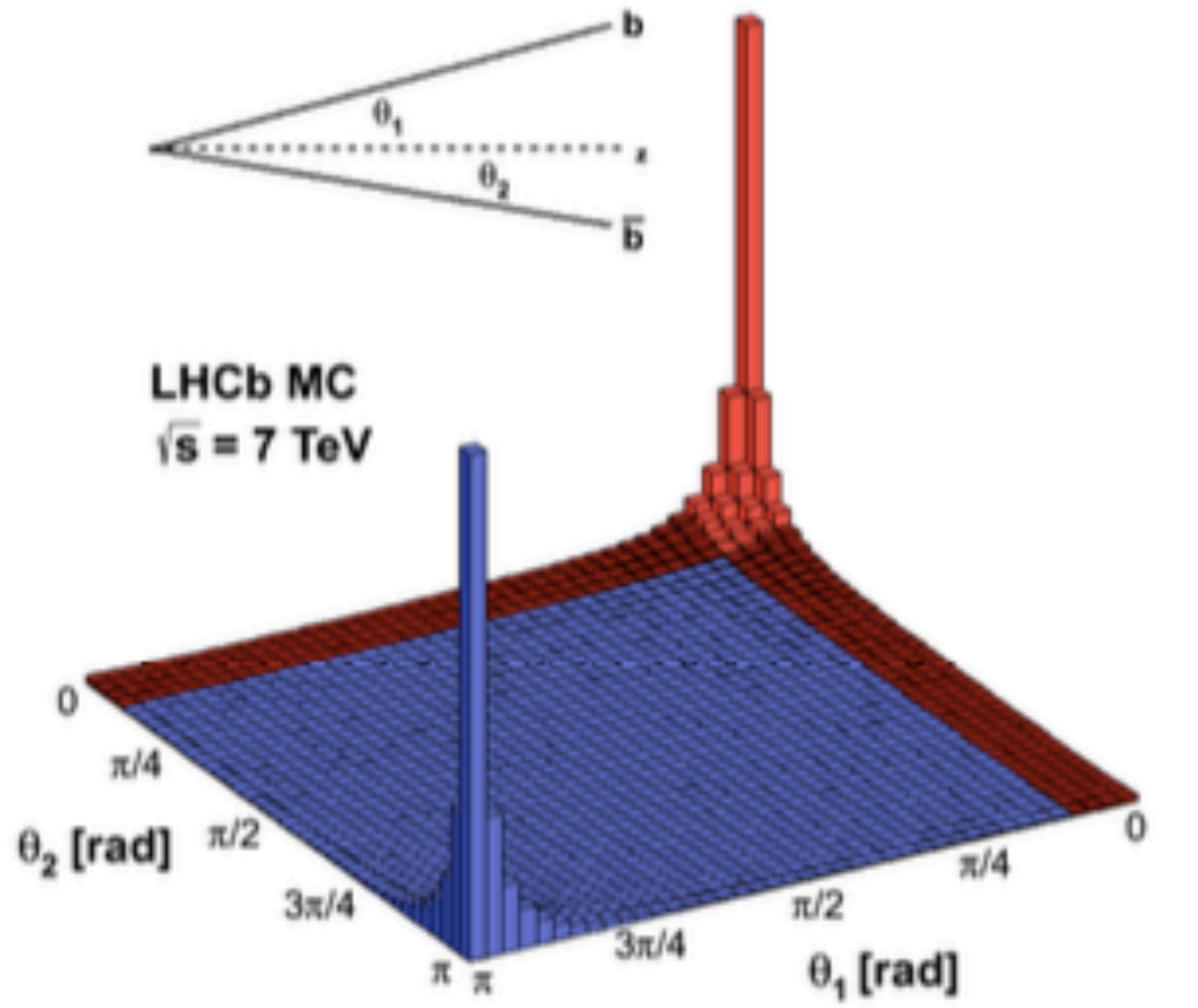


$\int \mathcal{L}\,dt$	LHC era			HL-LHC era	
	2010-12 (Run-1)	2015-18 (Run-2)	2021-23 (Run-3)	2026-29 (Run-4)	2031++ (Run-5)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	$\rightarrow$	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

The LHCb detector



- Covers 4% of solid angle, but accepts 40% of heavy quark production cross section.

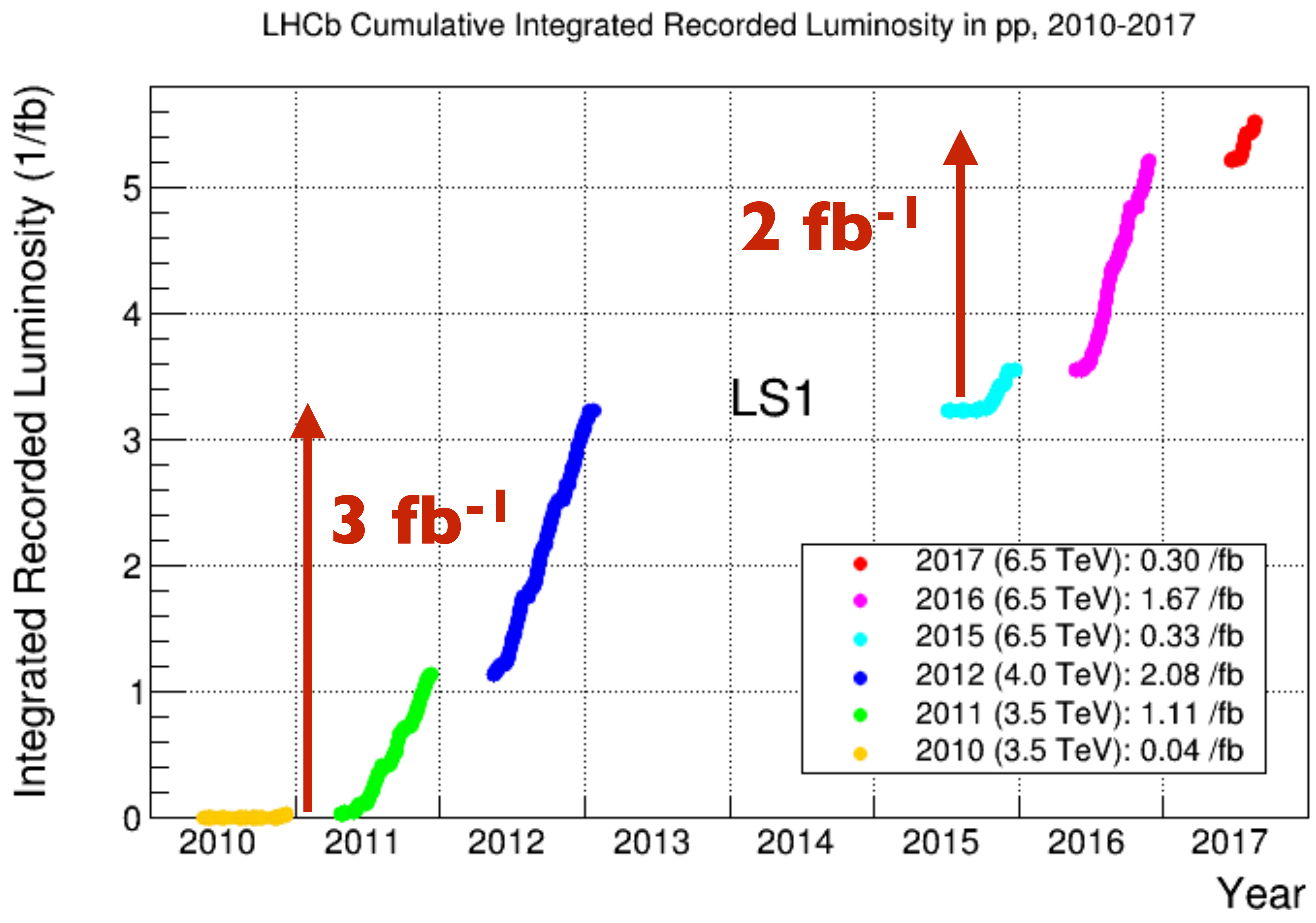


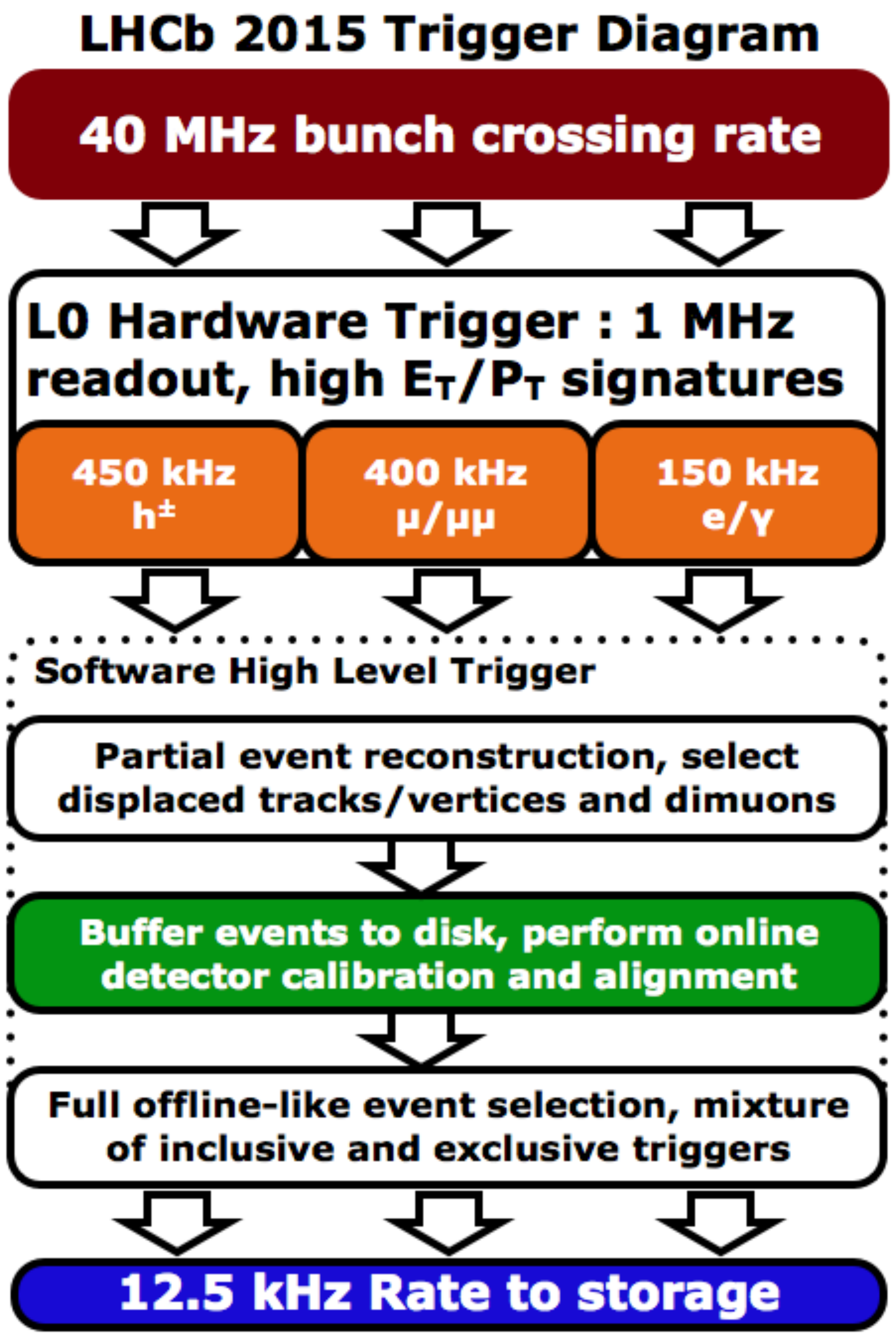
[PRL 118, 052002 (2017)]

$\sigma_{bb}(7\,\mathrm{TeV}) = 72.0 \pm 0.3 \pm 6.8\mu b$

$\sigma_{bb}(13\,\mathrm{TeV}) = 154.3 \pm 1.5 \pm 14.3\mu b$

LHCb run 1 and 2

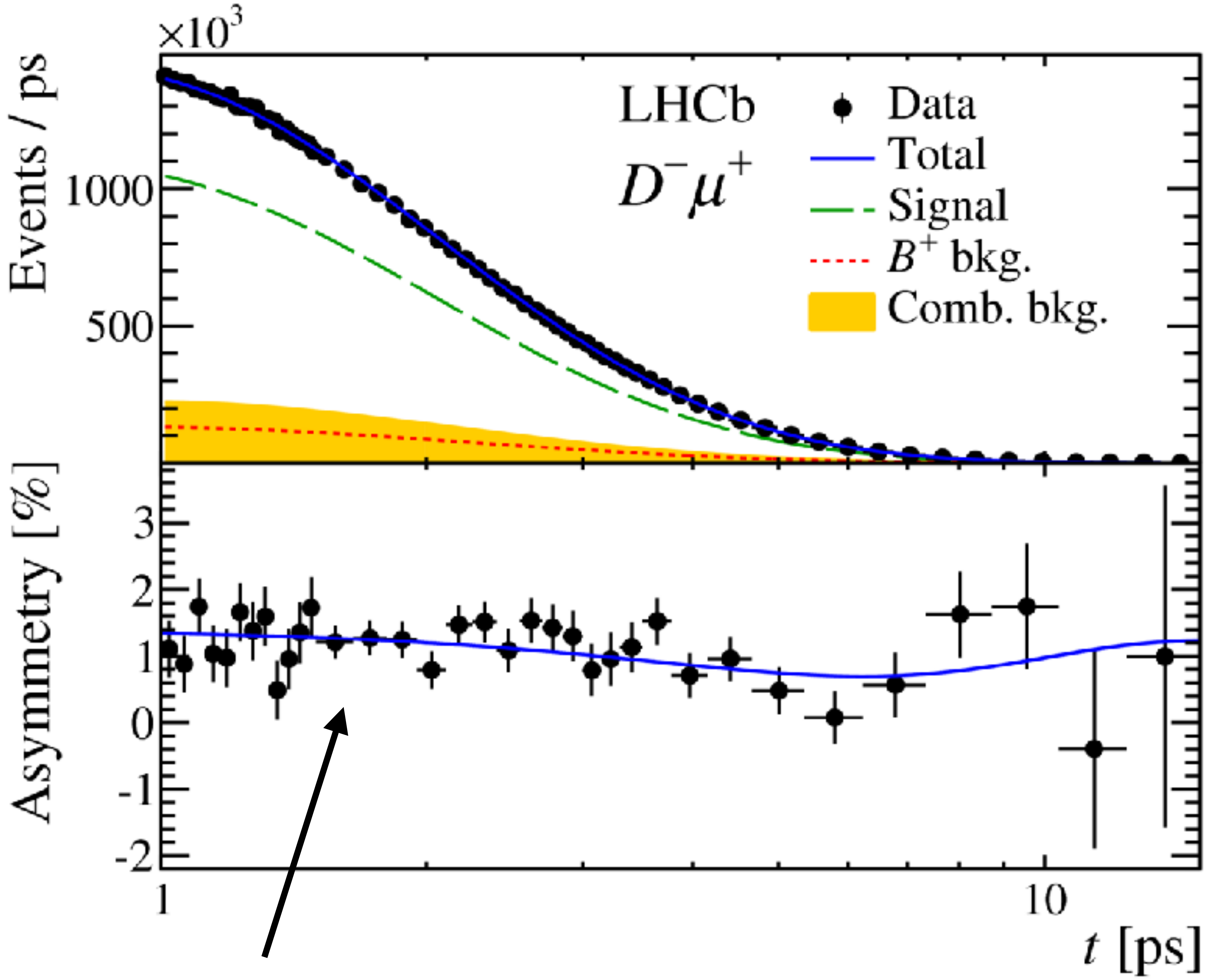




CPV in neutral B meson mixing

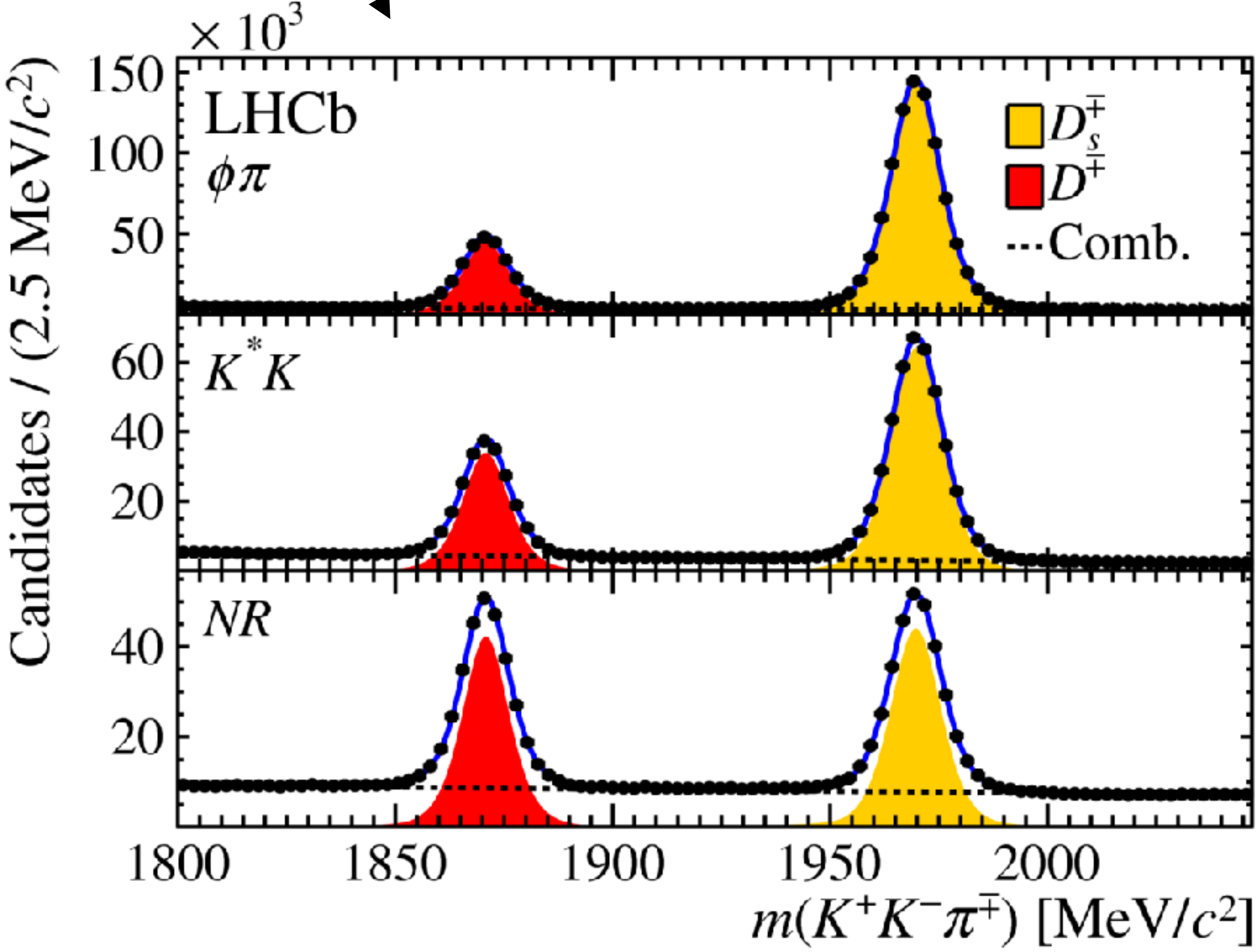
$$B^0 \to D^{(*)-}\mu^+\nu X \text{ and } B_s^0 \to D_s^-\mu^+\nu X$$

[PRL 114, 041601 (2015)]



Visible asymmetry only from detector effects

[PRL 117, 061803 (2016)]



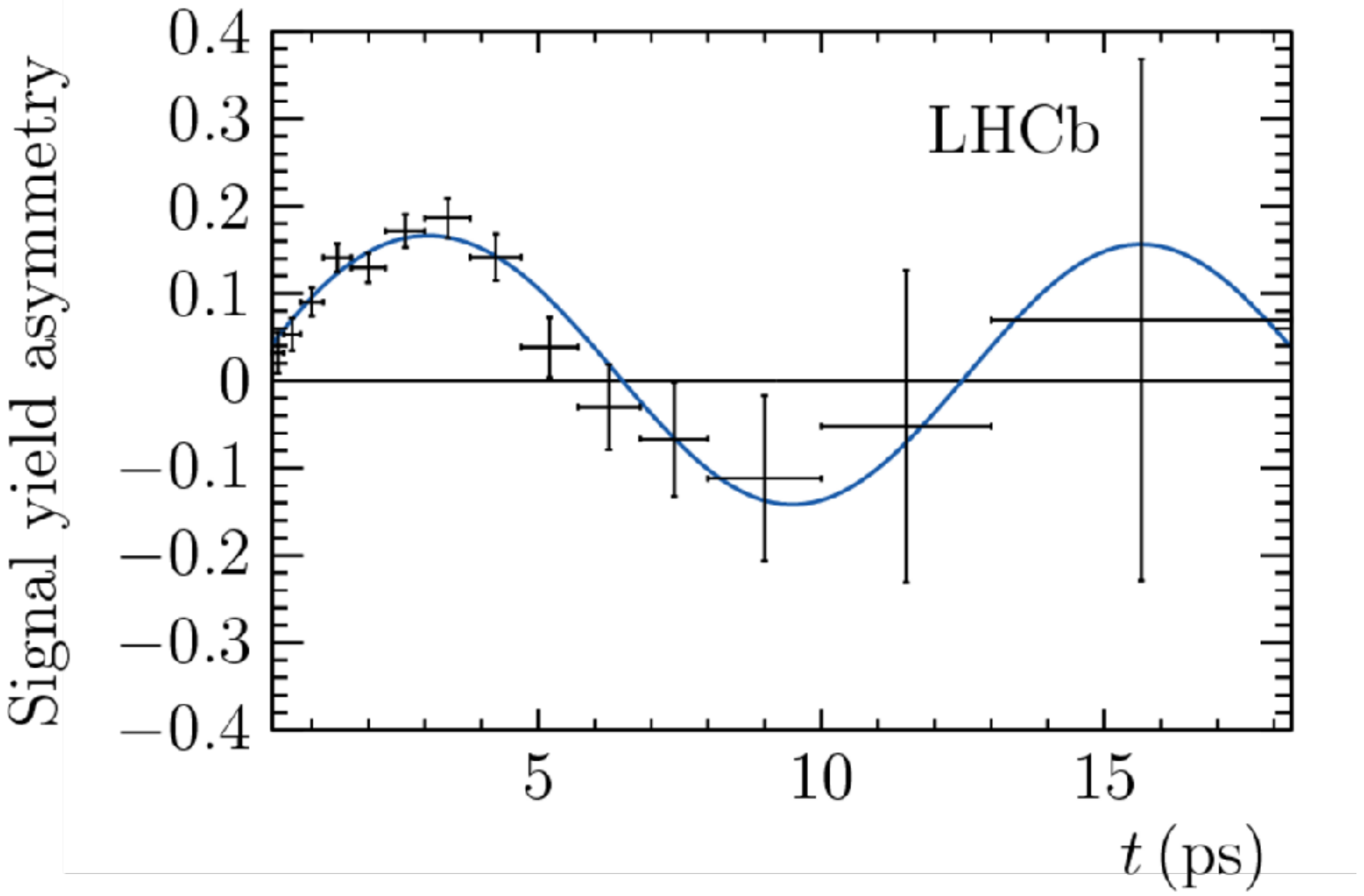
CP violation in mixing+decay

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

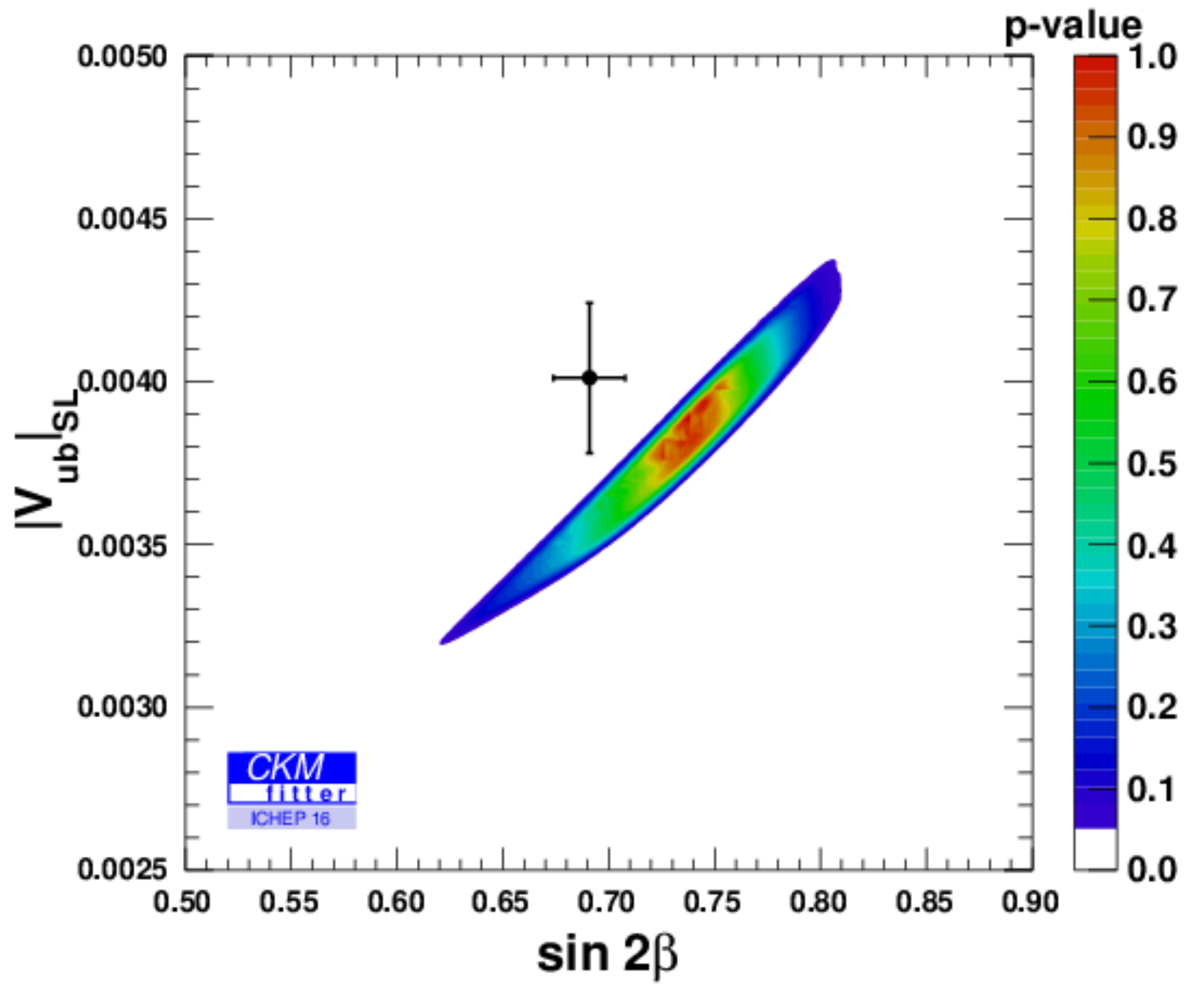
$$B^0 \to J/\psi K^0_S$$

$$S_{J/\psi\, K^0_S} \approx \sin 2\beta$$

[PRL 115, 031601 (2015)]



Similar precision to the B-factories, but LHCb measurement pulled world average up towards indirect determination from global fit

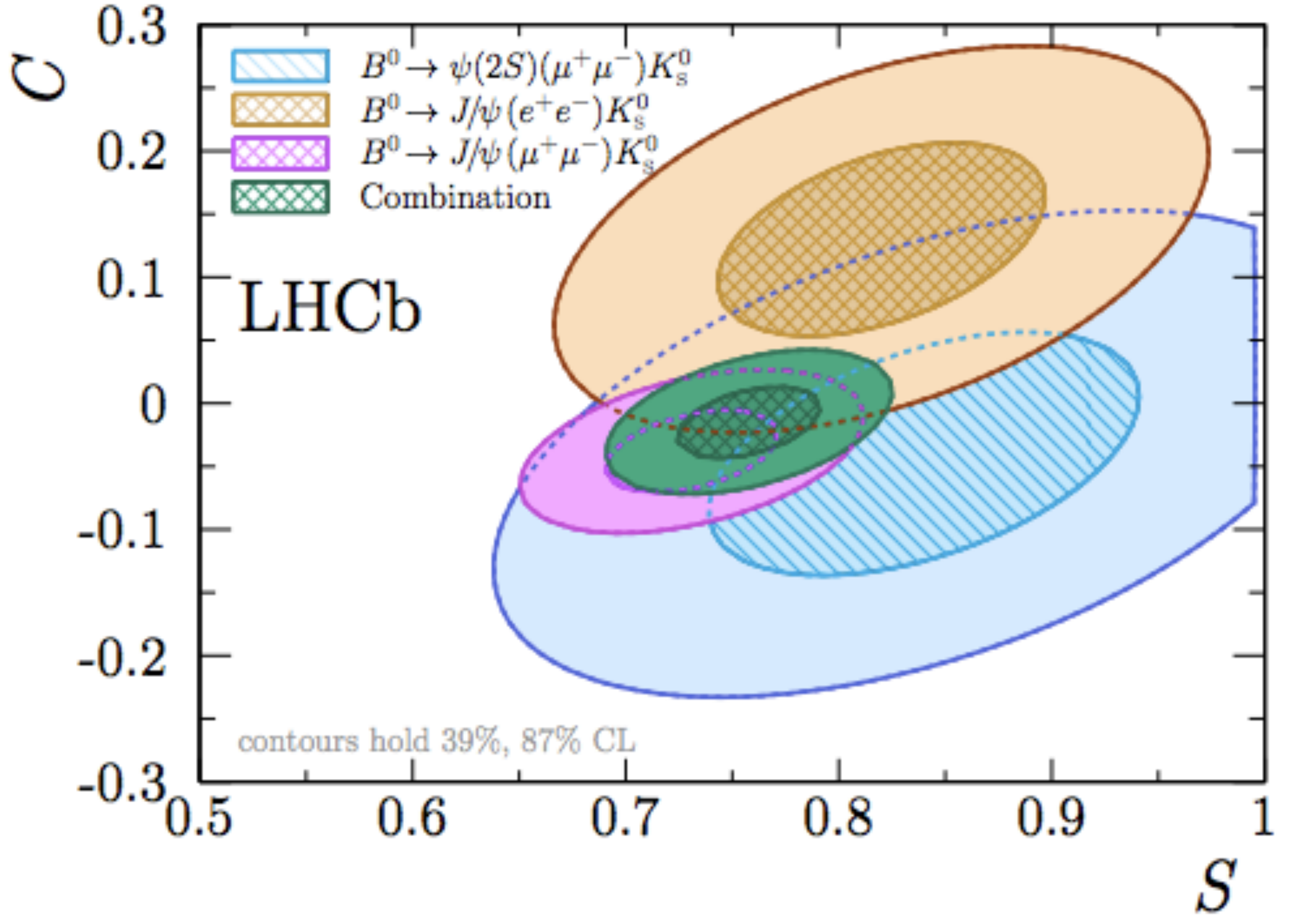


S = +0.731 ± 0.035 (stat) ± 0.020 (syst)
C = −0.038 ± 0.032 (stat) ± 0.005 (syst)

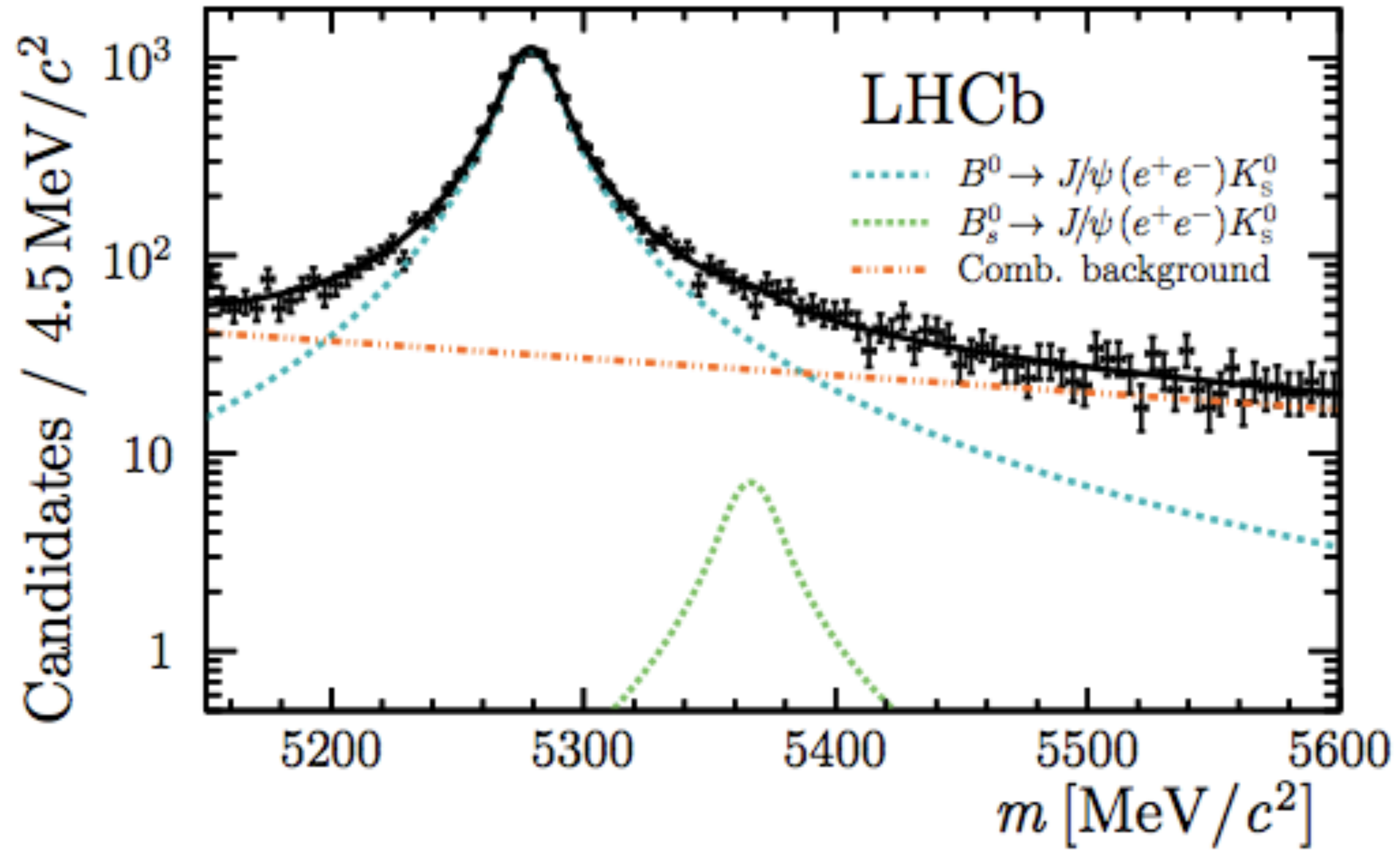
CP violation in mixing + decay **NEW!**

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

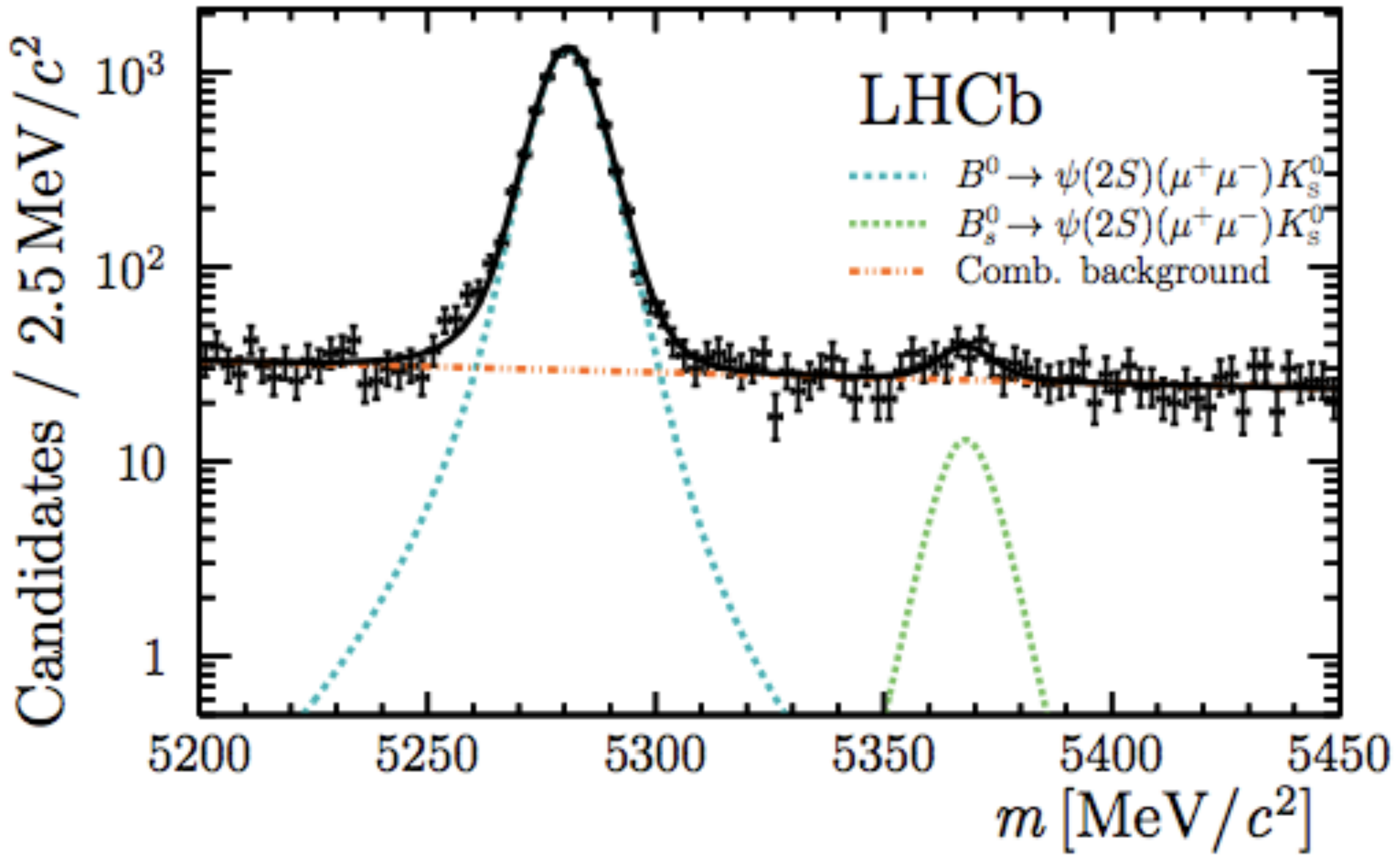
[LHCb-PAPER-2017-029]

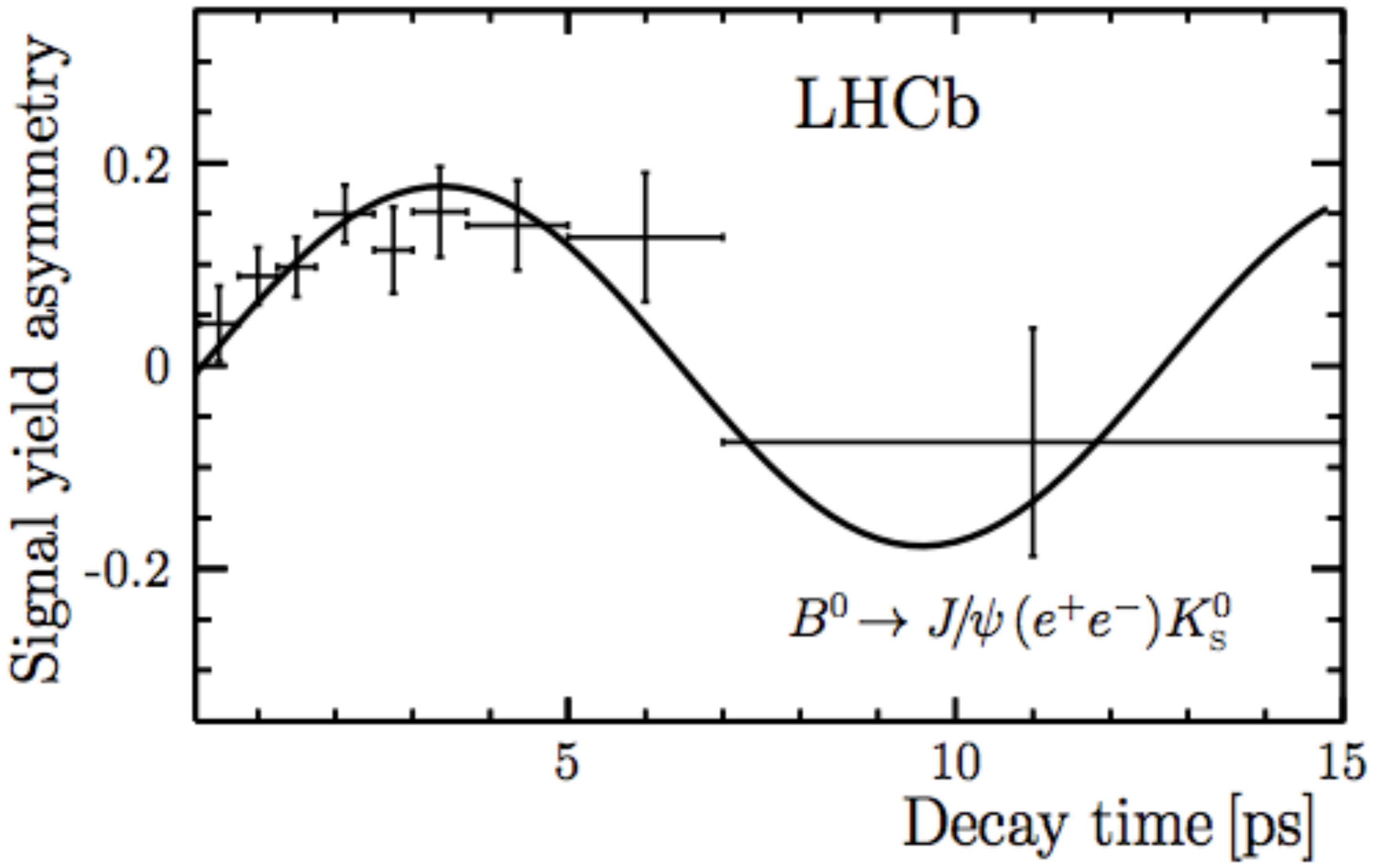


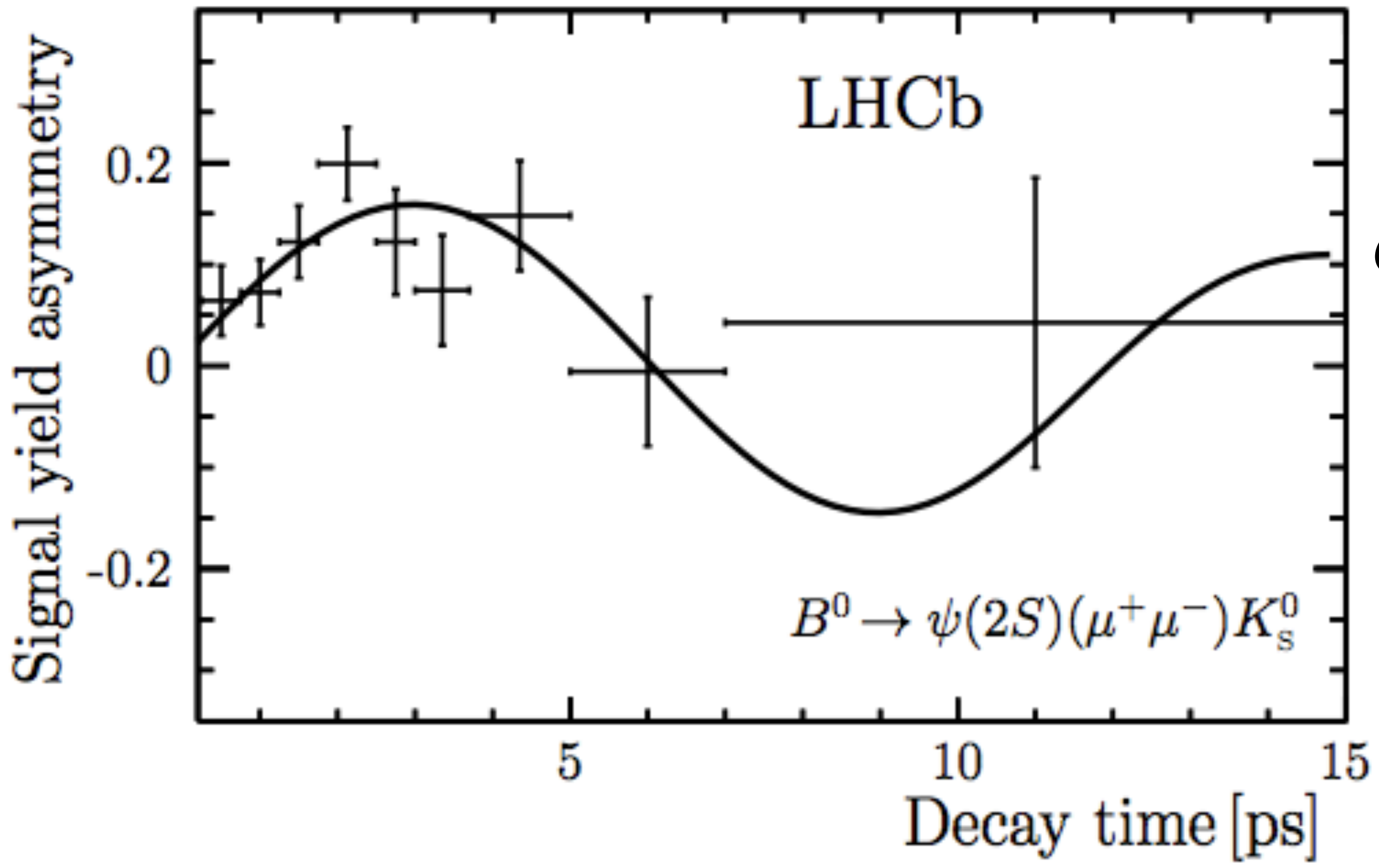
$B\to J/\psi(ee)K_S$



$B\to \psi(2S)(\mu\mu)K_S$



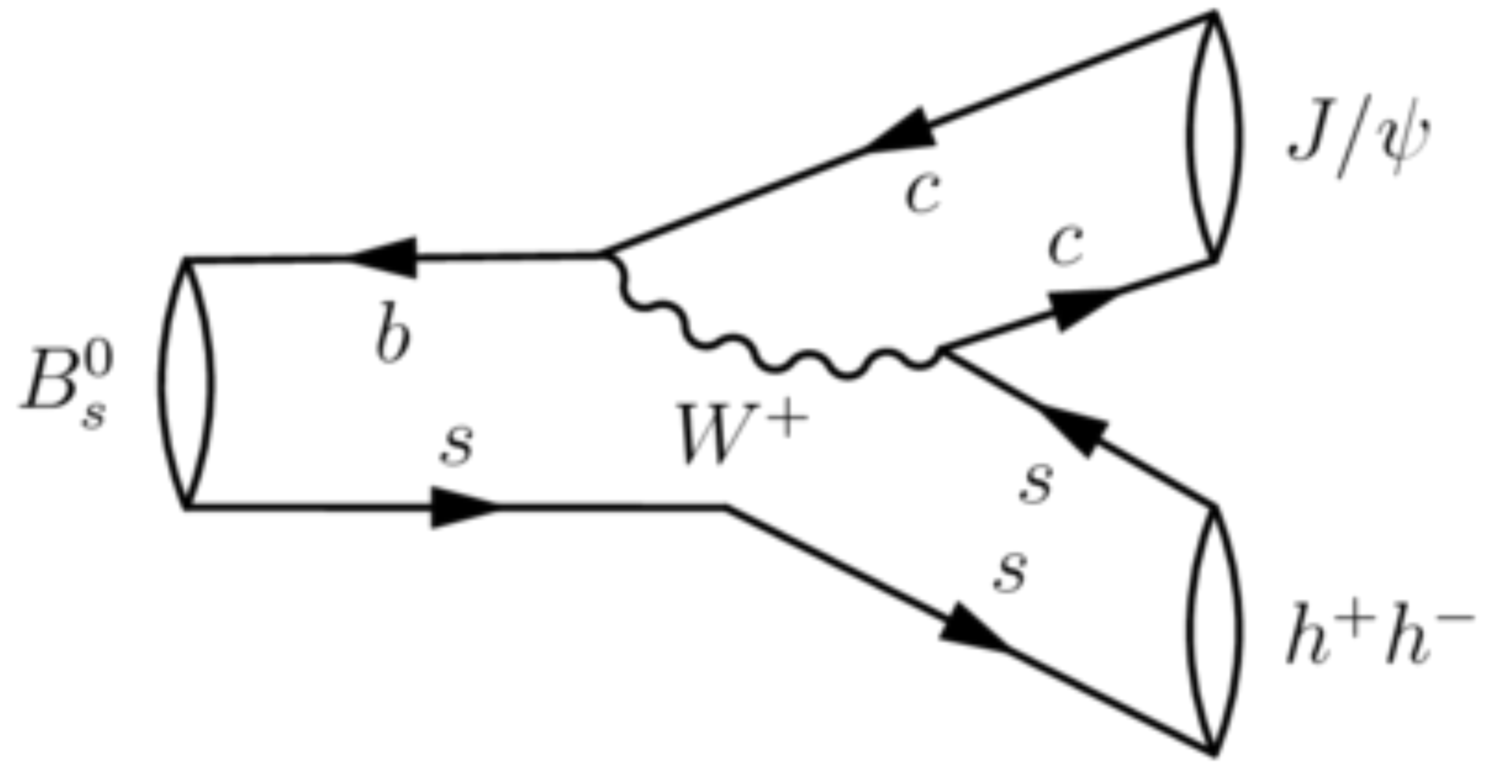




$$C(B^0\to J/\psi(e^+e^-)K^0_S) = 0.12\,^{+0.07}_{-0.07}\,(\text{stat}) \pm 0.02\,(\text{syst})$$
$$S(B^0\to J/\psi(e^+e^-)K^0_S) = 0.83\,^{+0.07}_{-0.08}\,(\text{stat}) \pm 0.01\,(\text{syst})$$
$$C(B^0\to \psi(2S)(\mu^+\mu^-)K^0_S) = -0.05\,^{+0.10}_{-0.10}\,(\text{stat}) \pm 0.01\,(\text{syst})$$
$$S(B^0\to \psi(2S)(\mu^+\mu^-)K^0_S) = 0.84\,^{+0.10}_{-0.10}\,(\text{stat}) \pm 0.01\,(\text{syst})$$

$$C(B^0\to J/\psi\, K^0_S) = -0.014 \pm 0.030\,,$$
$$S(B^0\to J/\psi\, K^0_S) = 0.75 \pm 0.04\,,$$

CP violation in mixing + decay: B^0_s



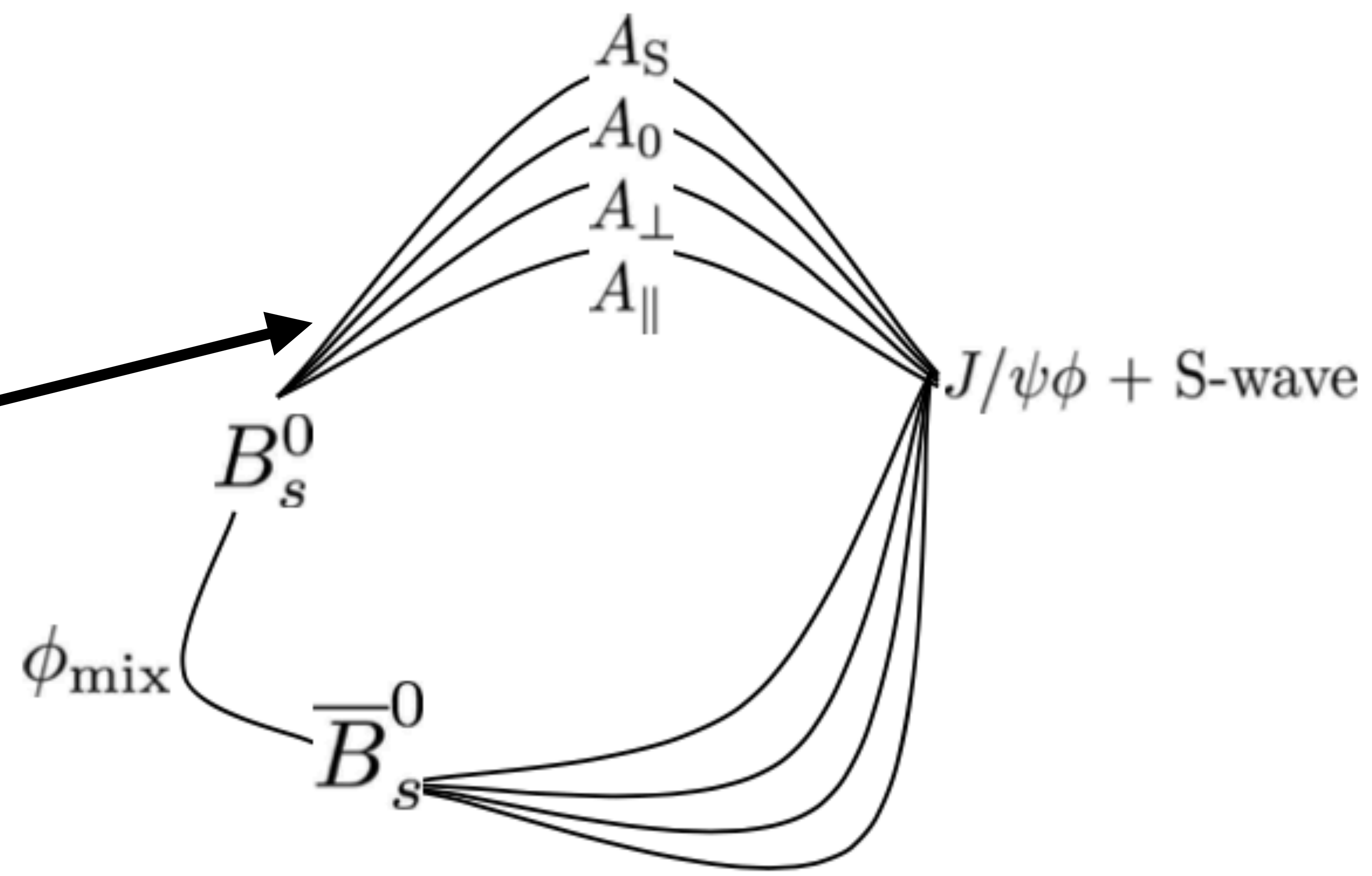
$$\phi_s \stackrel{\text{SM}}{=} -2\arg\left(-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right) \equiv -2\beta_s$$

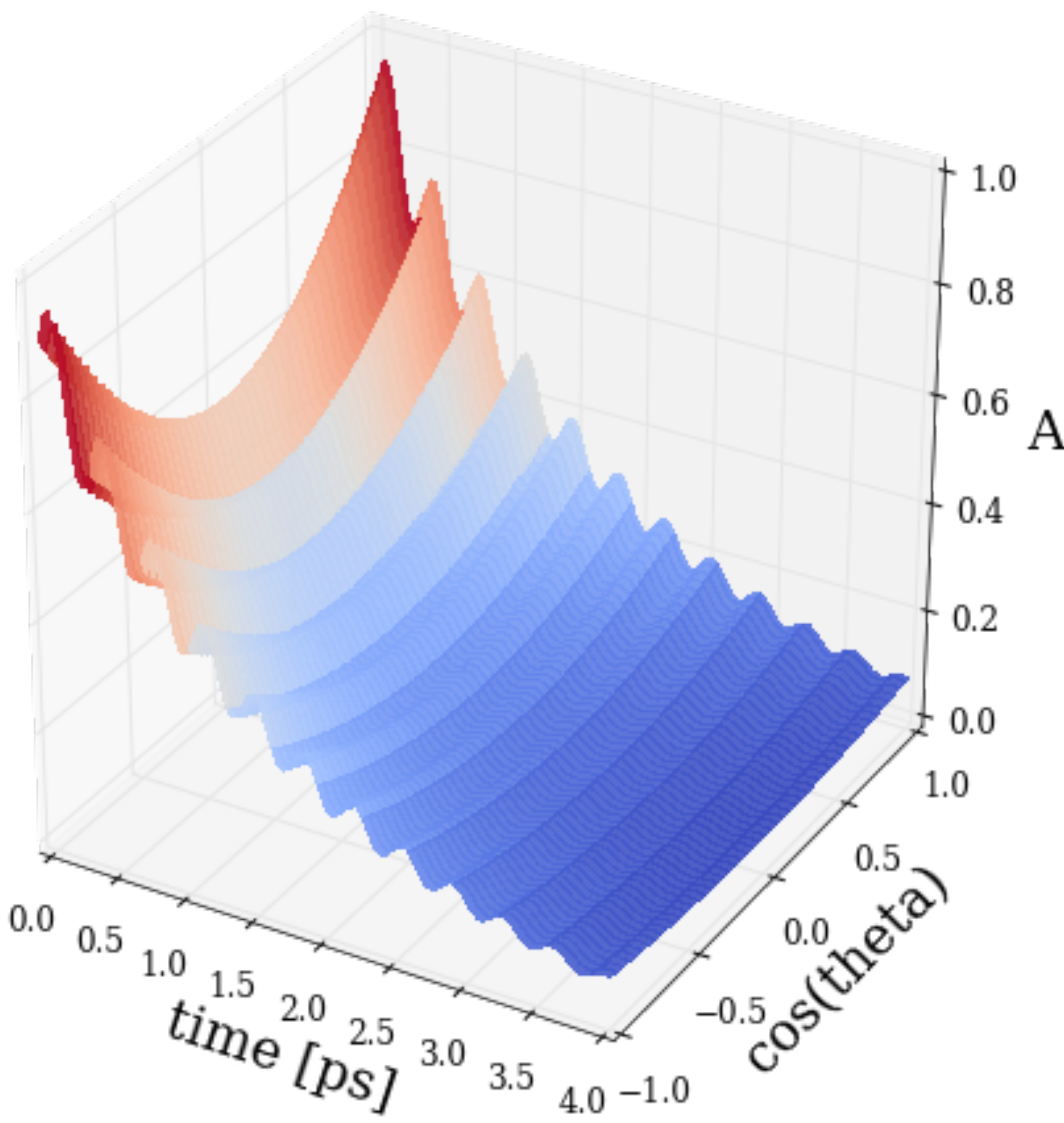
ϕ_s^{SM} = -36.5 ± 1.3 mrad [CKMFitter]

$B_s \to J/\psi\varphi$ is the **golden mode** for measuring ϕ_s.

2 vector particles in final state so require angular analysis to separate CP-odd, CP-even components.

Extensively studied by D0, CDF, ATLAS, CMS and LHCb.

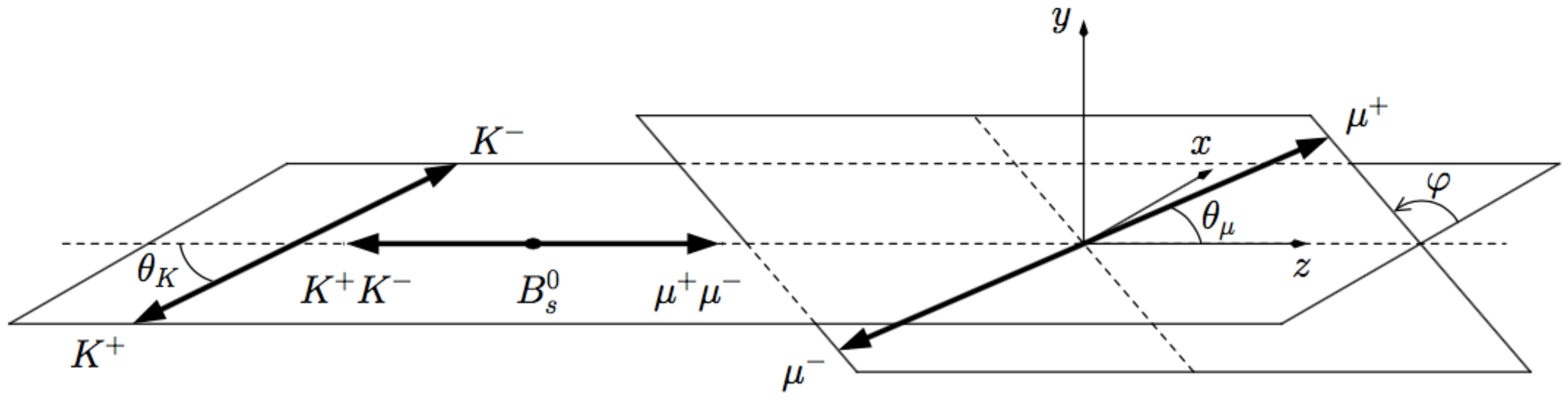


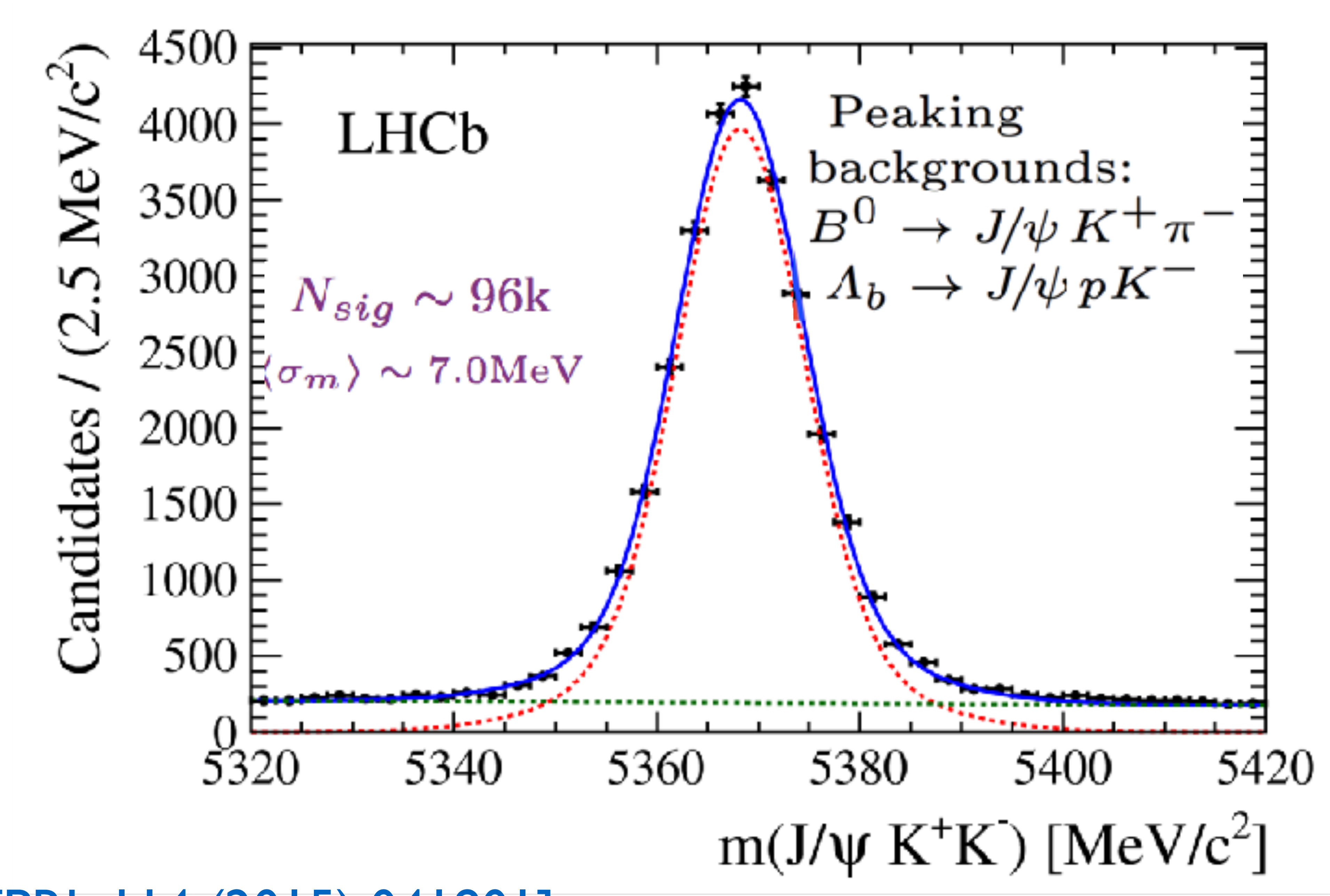


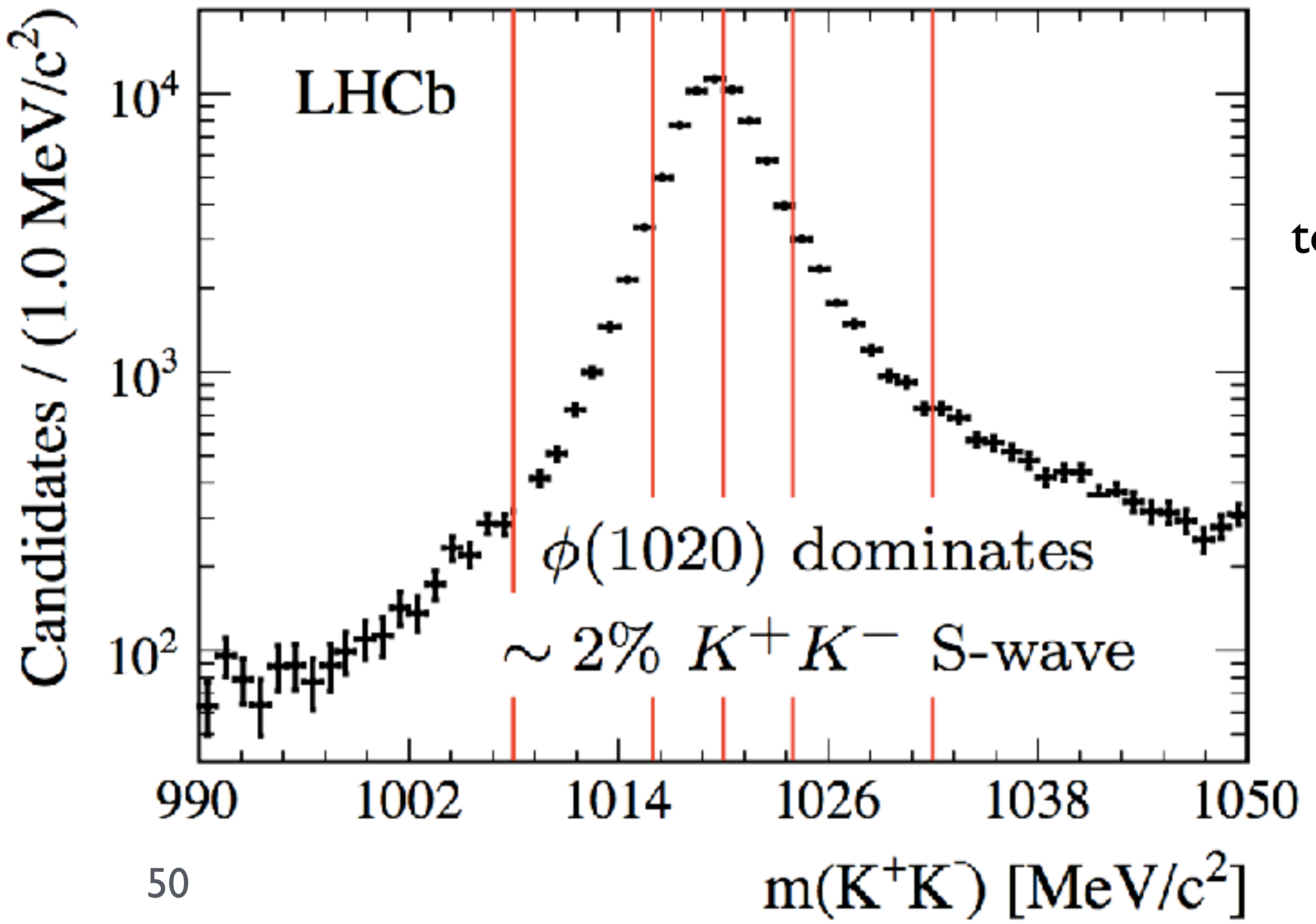
$$\text{CP}|\,\text{J}/\psi\phi\rangle_\ell \quad = \quad (-1)^\ell|\,\text{J}/\psi\phi\rangle_\ell$$

B^0_s CPV in mixing + decay: ϕ_s

- $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$
- Time-dependent tagged analyses ($\sigma_t \sim 45\,\text{fs}, \varepsilon\mathcal{D}^2 \sim 4\%$).
- $B^0_s \to J/\psi\,\phi$ is $P \to VV$ decay so use angular information to disentangle CP-odd and CP-even components.
- Measure $\phi_s, \Delta m_s, \Gamma_s, \Delta\Gamma_s, |\lambda_f| \ldots$
  [this makes $B^0_s \to J/\psi\,\phi$ special]



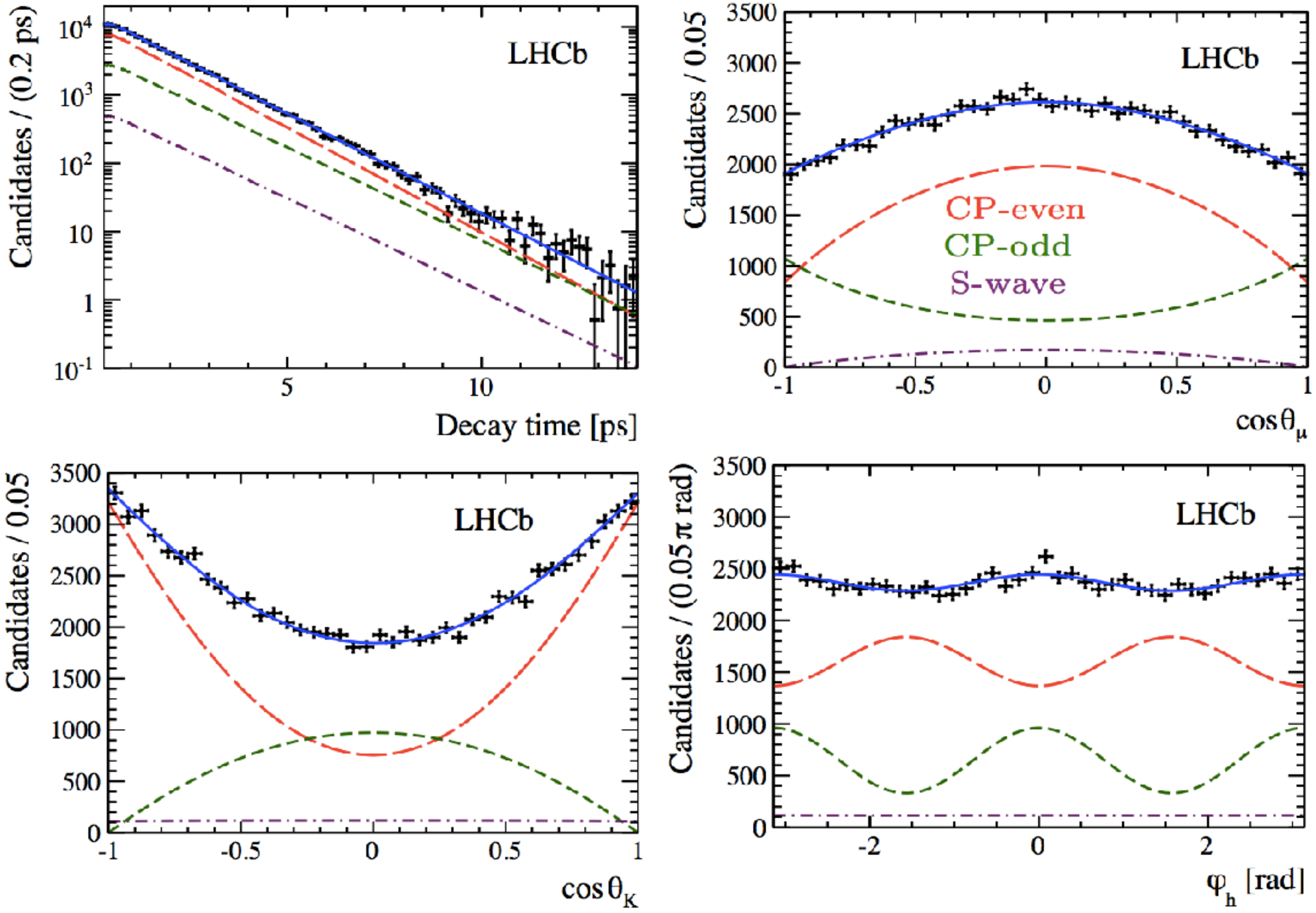




Make flavour tagged decay-time dependent angular fit in 6 bins of mKK to account for KK S-wave

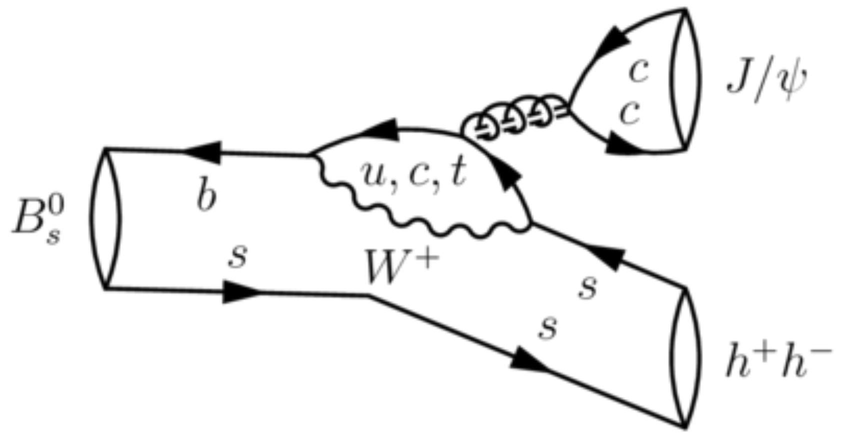
[PRL 114 (2015) 041801]

B^0_s CPV in mixing + decay: ϕ_s



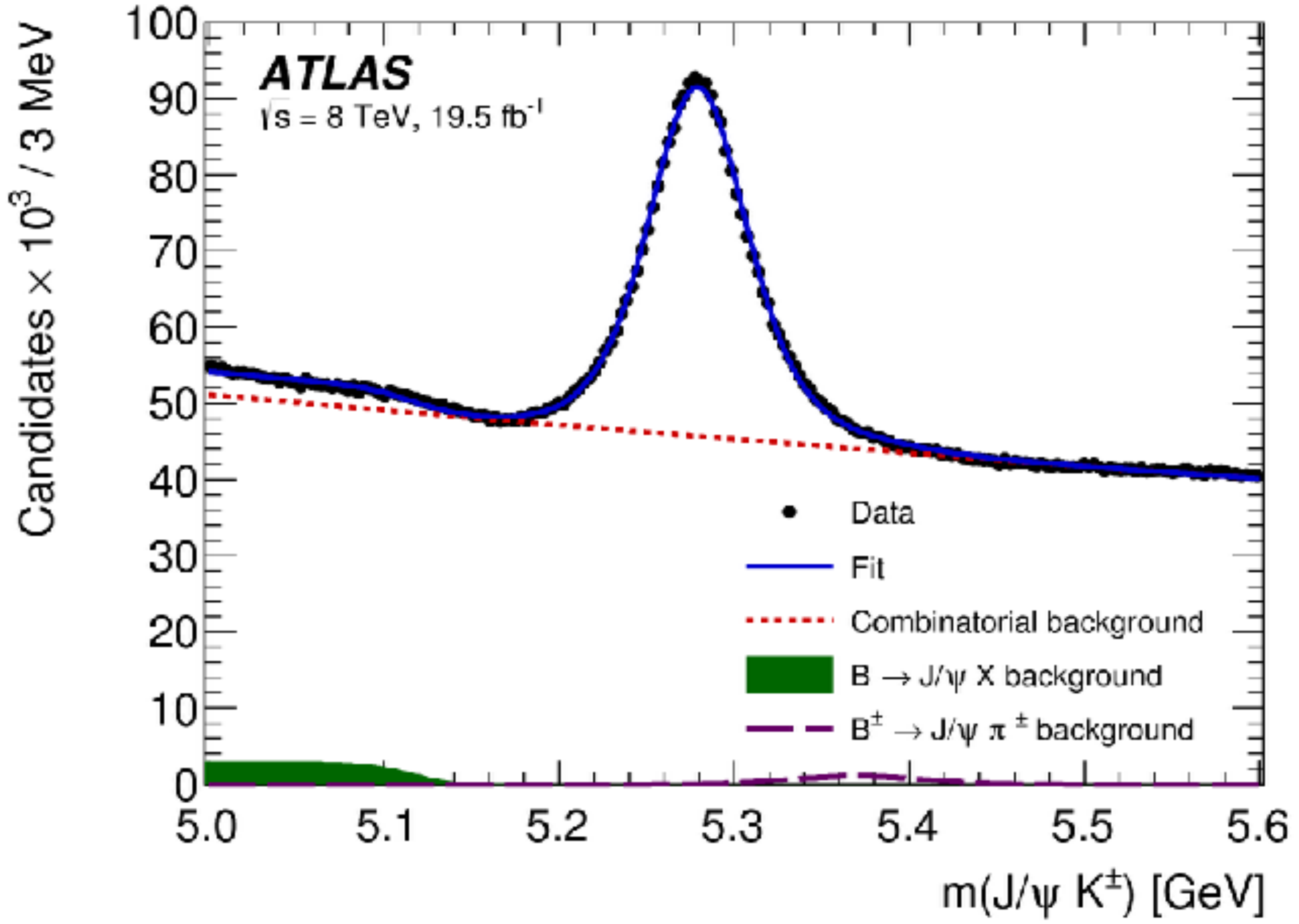
ϕ_s	$-0.058 \pm 0.049 \pm 0.006$ rad
$\lvert\lambda\rvert$	$0.964 \pm 0.019 \pm 0.007$
Γ_s	$0.6603 \pm 0.0027 \pm 0.0015\ \mathrm{ps}^{-1}$
$\Delta\Gamma_s$	$0.0805 \pm 0.0091 \pm 0.0032\ \mathrm{ps}^{-1}$
Δm_s	$17.711\ ^{+0.055}_{-0.057} \pm 0.011\ \mathrm{ps}^{-1}$

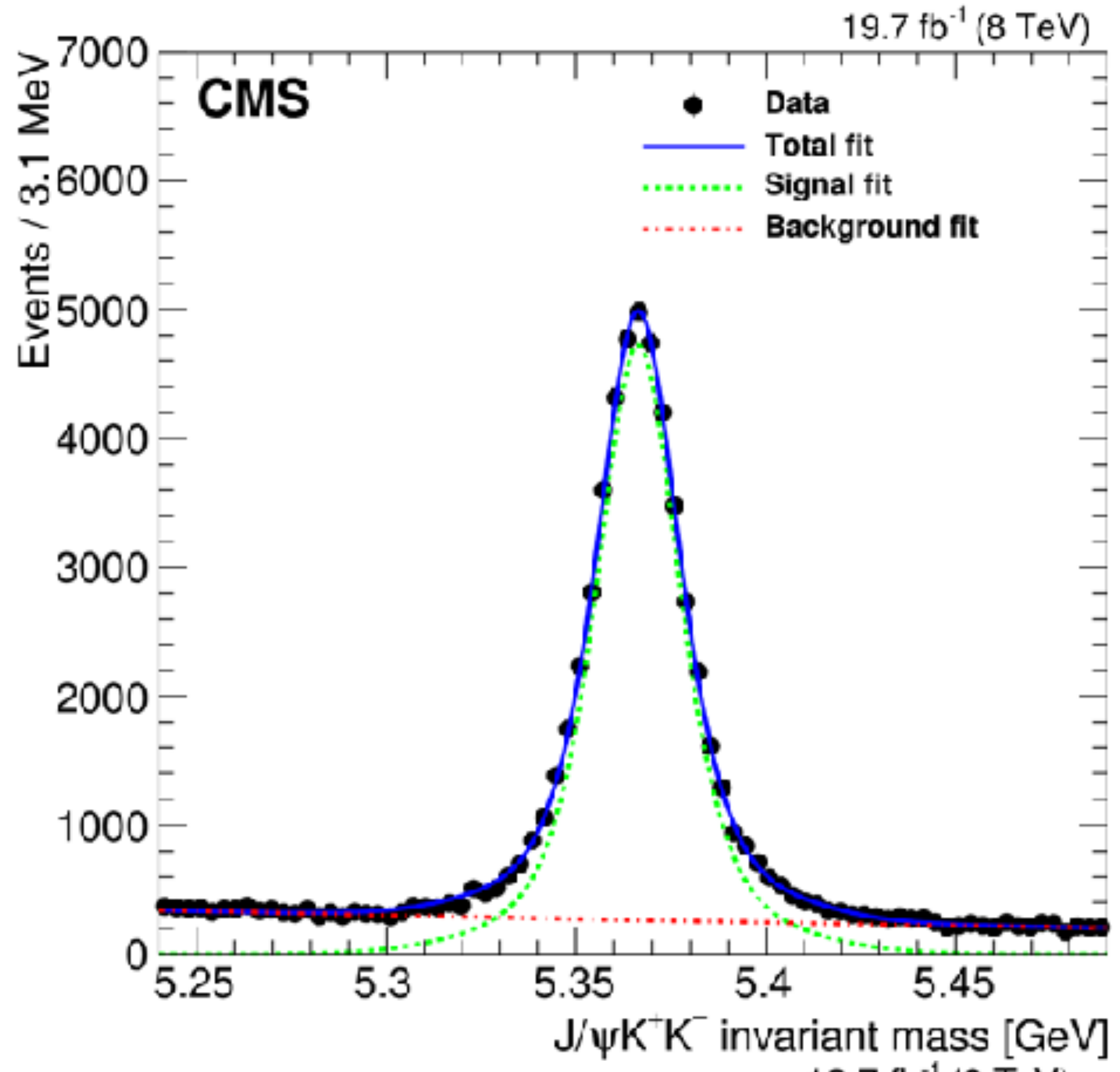
- Everything consistent with the SM
- Dominant sysmtematics from decay-time and angular efficiencies
- No sign of polarisation dependent ϕs
  - Penguin pollution likely to be small



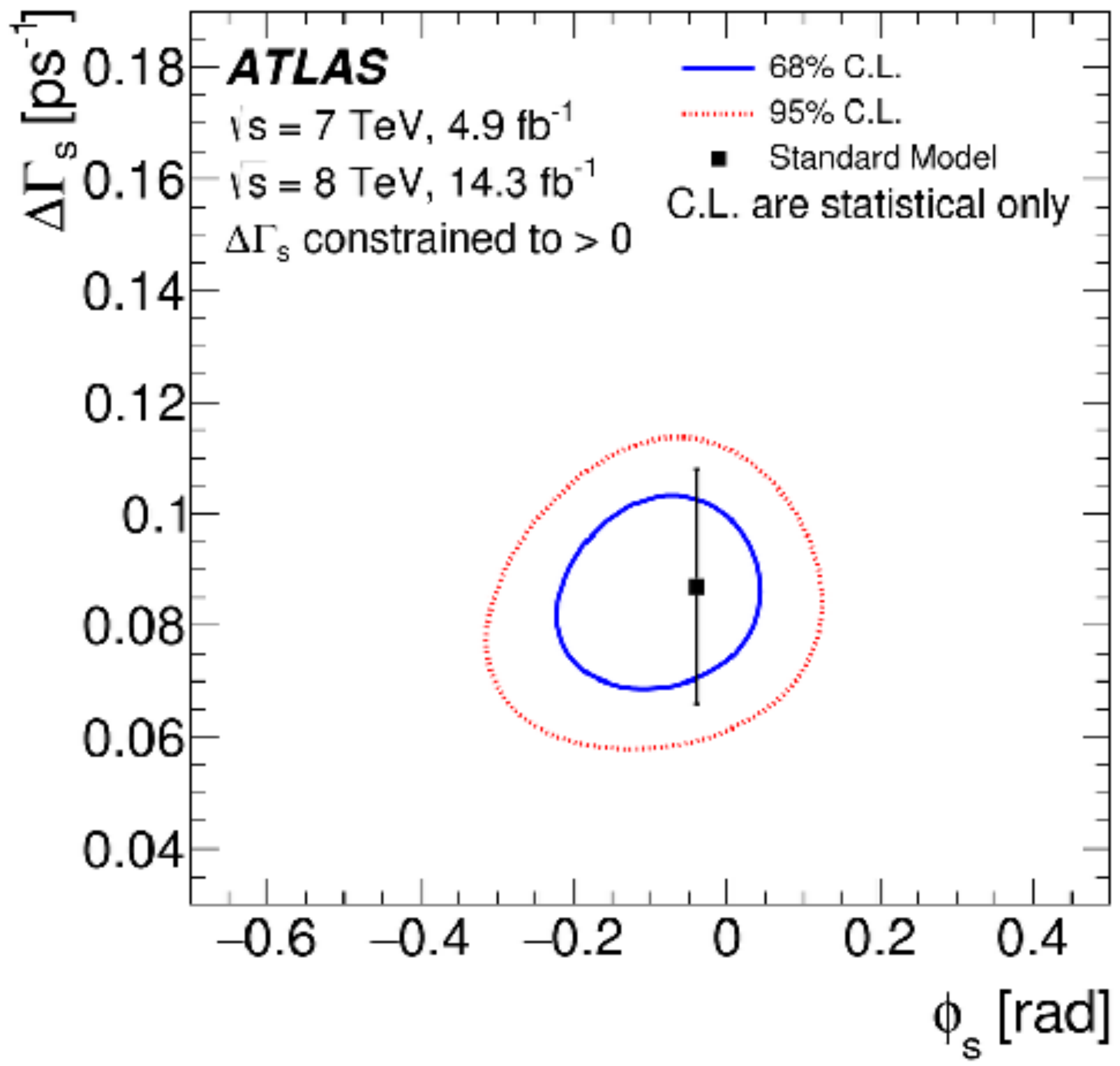
[PRL 114 (2015) 041801]

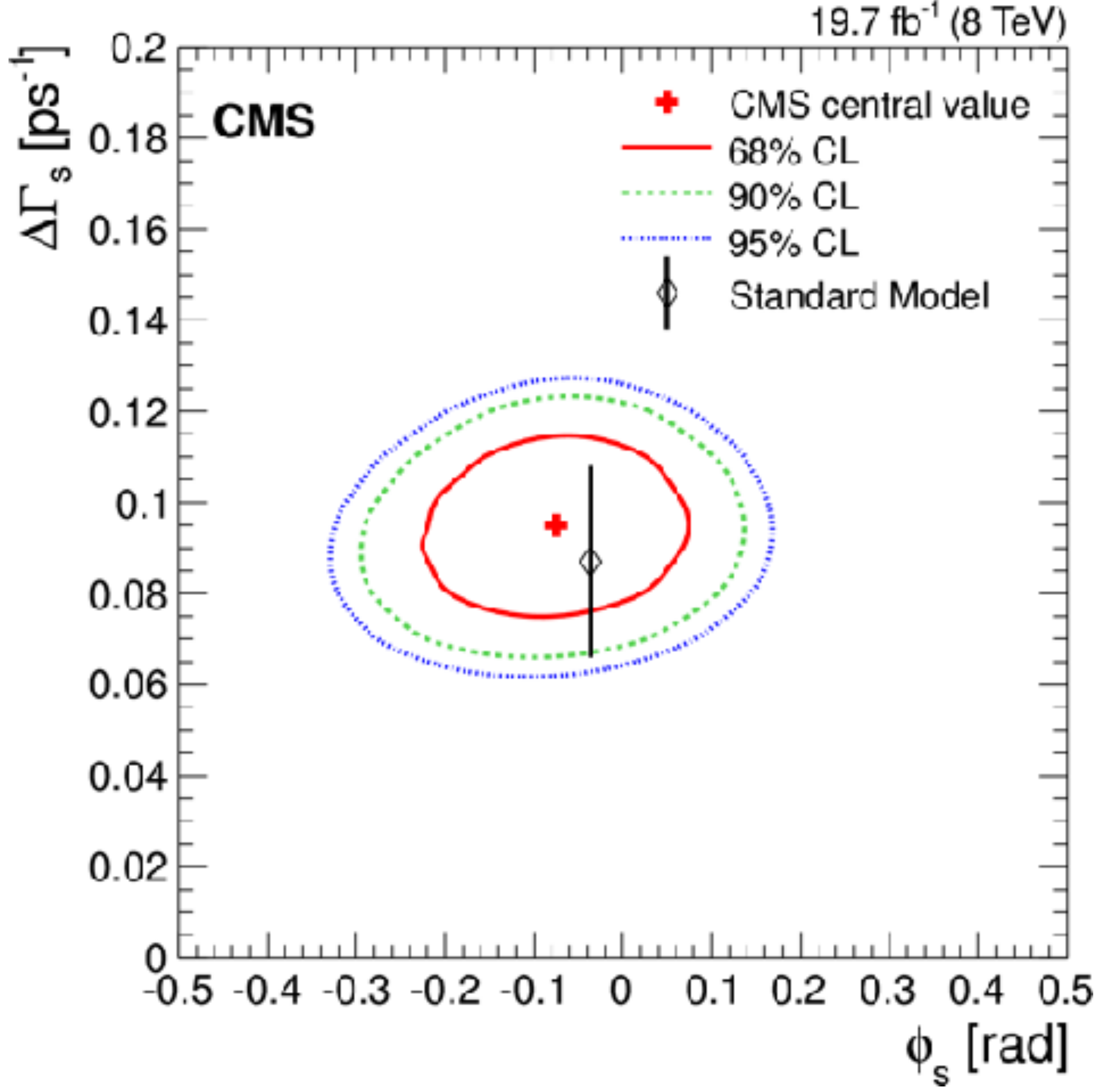
ATLAS and CMS ϕ_s





[ATLAS JHEP 1608 (2016) 147]
[CMS PLB 757 (2016) 97]

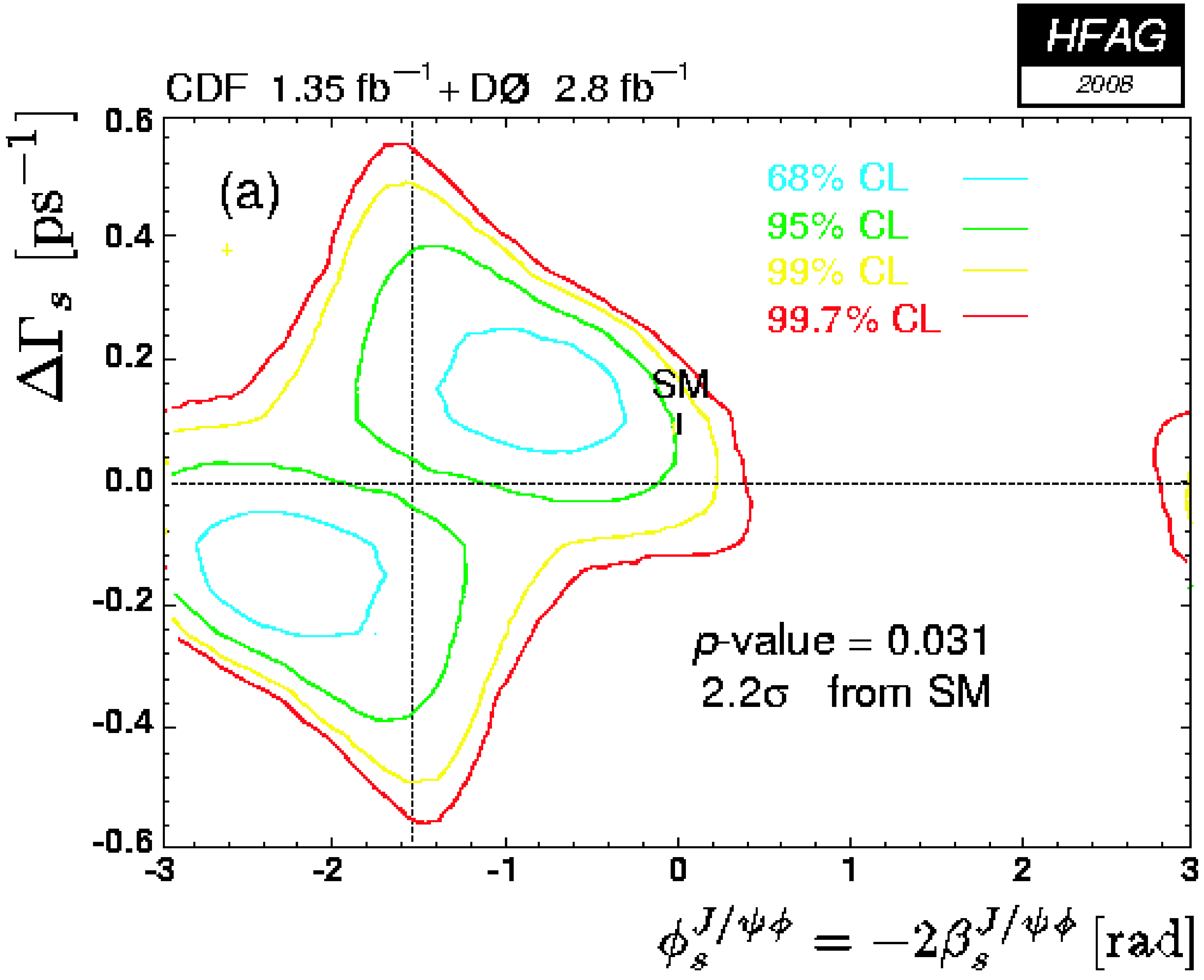




CP violation in mixing + decay: B^0_s

[ATLAS JHEP 1608 (2016) 147]
[CMS PLB 757 (2016) 97]

φ_s-$\Delta\Gamma_s$ global combination (cira 2008)



$$\sigma(\phi_s) \sim \pm 0.400 \text{ rad}$$
$$\sigma(\Delta\Gamma_s) \sim \pm 0.060 \text{ ps}^{-1}$$

CP violation in charmless B decays

Decay-time dependent CPV observables are sensitive to CKM phases (γ, $\phi_{s,d}$) [Fleischer, PLB 459 (1999) 306] [Ciuchini et al., JHEP 10 (2012) 029] [LHCb, PLB 741 (2015) 1]

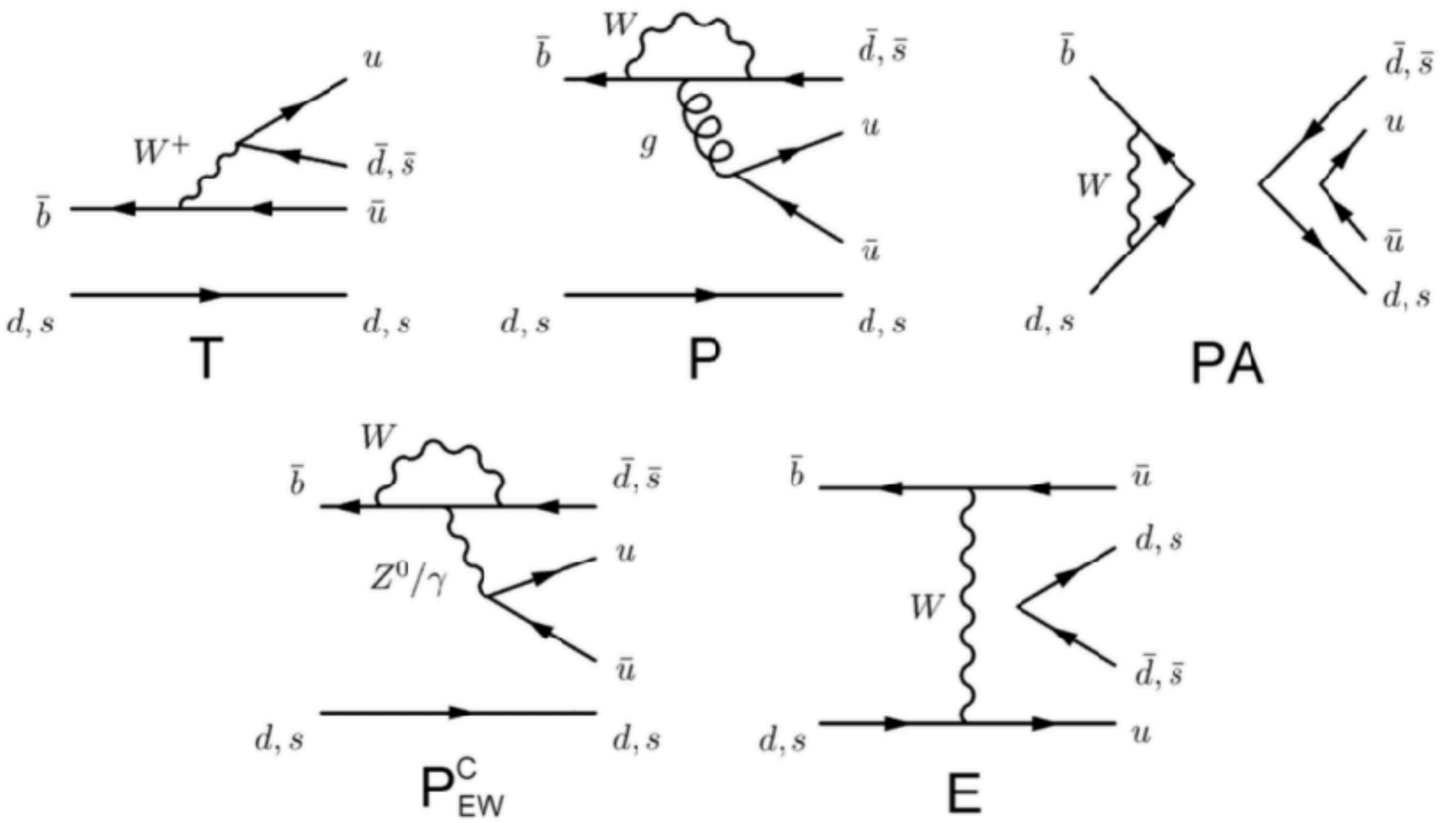
Loop diagrams ⇒ **hadronic uncertainties**

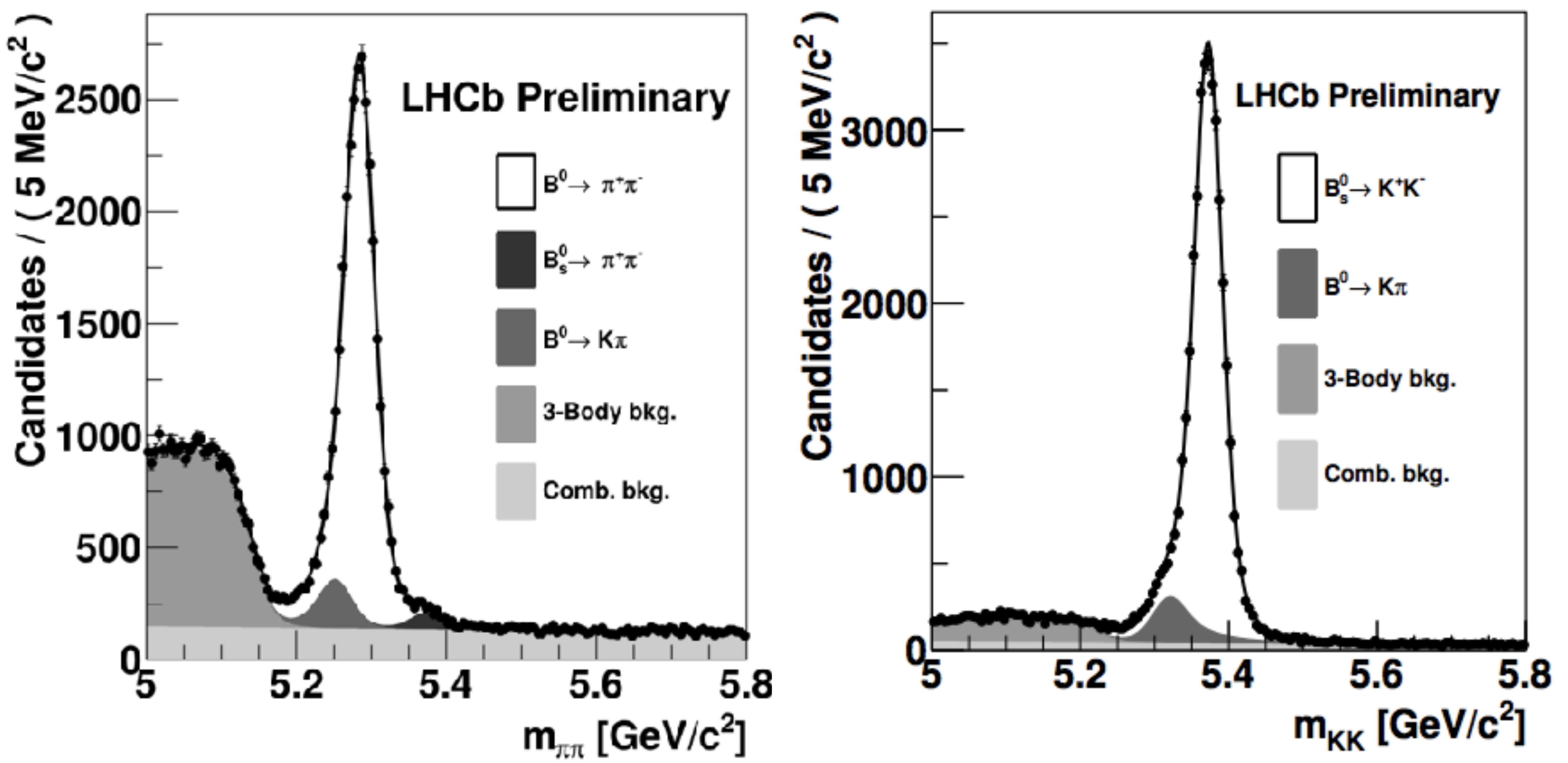
Loop diagrams ⇒ **CPV observables sensitive to New Physics**

Compare results with the CKM phases determined from decays dominated by tree-level topologies

$B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$

[LHCb-CONF-2016-018]





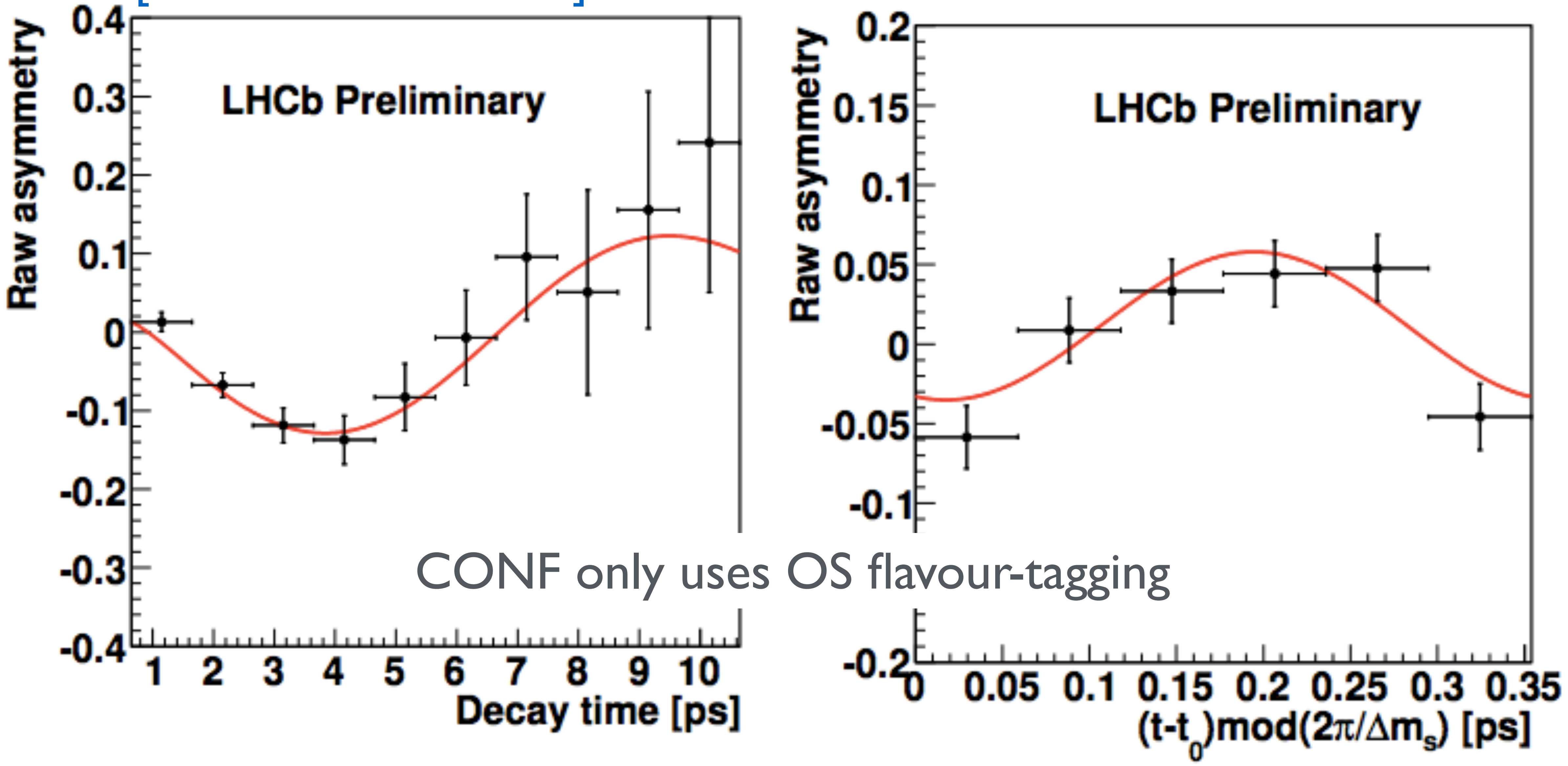
CP violation in charmless B decays

$B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ has been used to constrain CKM angle γ and ϕ_s assuming U-spin/isospin symmetry
[LHCb PLB 741 (2015) 1]

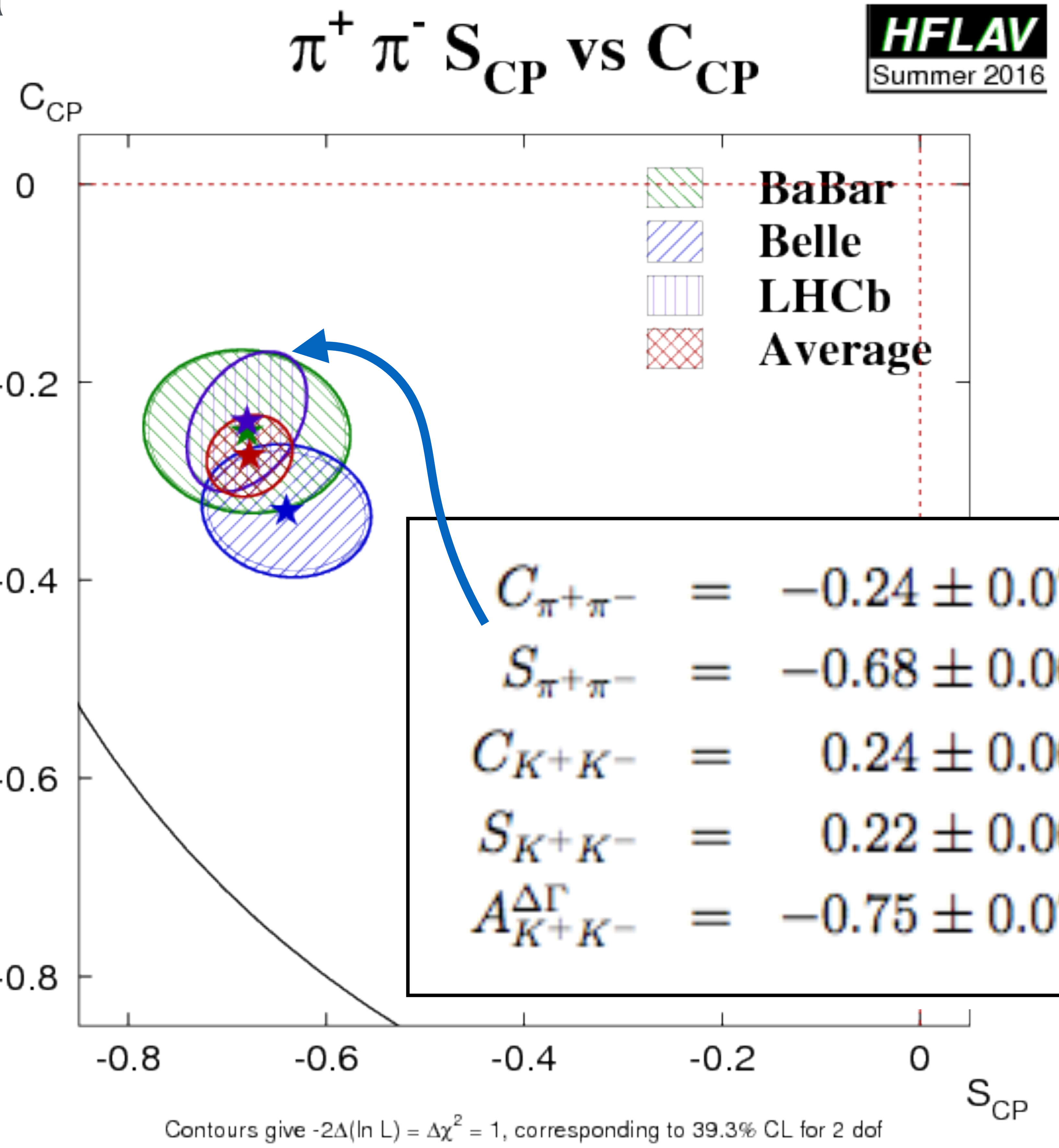
$$A_{CP}(t) \equiv \frac{\Gamma_{\overline{B}^0\to f} - \Gamma_{B^0\to f}}{\Gamma_{\overline{B}^0\to f} + \Gamma_{B^0\to f}} = \frac{S_f \sin(\Delta m\, t) - C_f \cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma\, t/2)}$$

Production asymmetries determined directly from $B \to K\pi$ control sample

[LHCb-CONF-2016-018]



CONF only uses OS flavour-tagging



$$\begin{aligned} C_{\pi^+\pi^-} &= -0.24 \pm 0.07 \pm 0.01, \\ S_{\pi^+\pi^-} &= -0.68 \pm 0.06 \pm 0.01, \\ C_{K^+K^-} &= 0.24 \pm 0.06 \pm 0.02, \\ S_{K^+K^-} &= 0.22 \pm 0.06 \pm 0.02, \\ A^{\Delta\Gamma}_{K^+K^-} &= -0.75 \pm 0.07 \pm 0.11, \end{aligned}$$

} unique

$B_s^0 \to K^+K^-$ shows >4σ evidence for CPV

Expect publication soon using SSK flavour-tagging

Also, ϕ_s consistent with zero in $B_s \to \phi\phi$ decays [PRD 90 (2014) 052011]

ϕ_s from charmless B decays

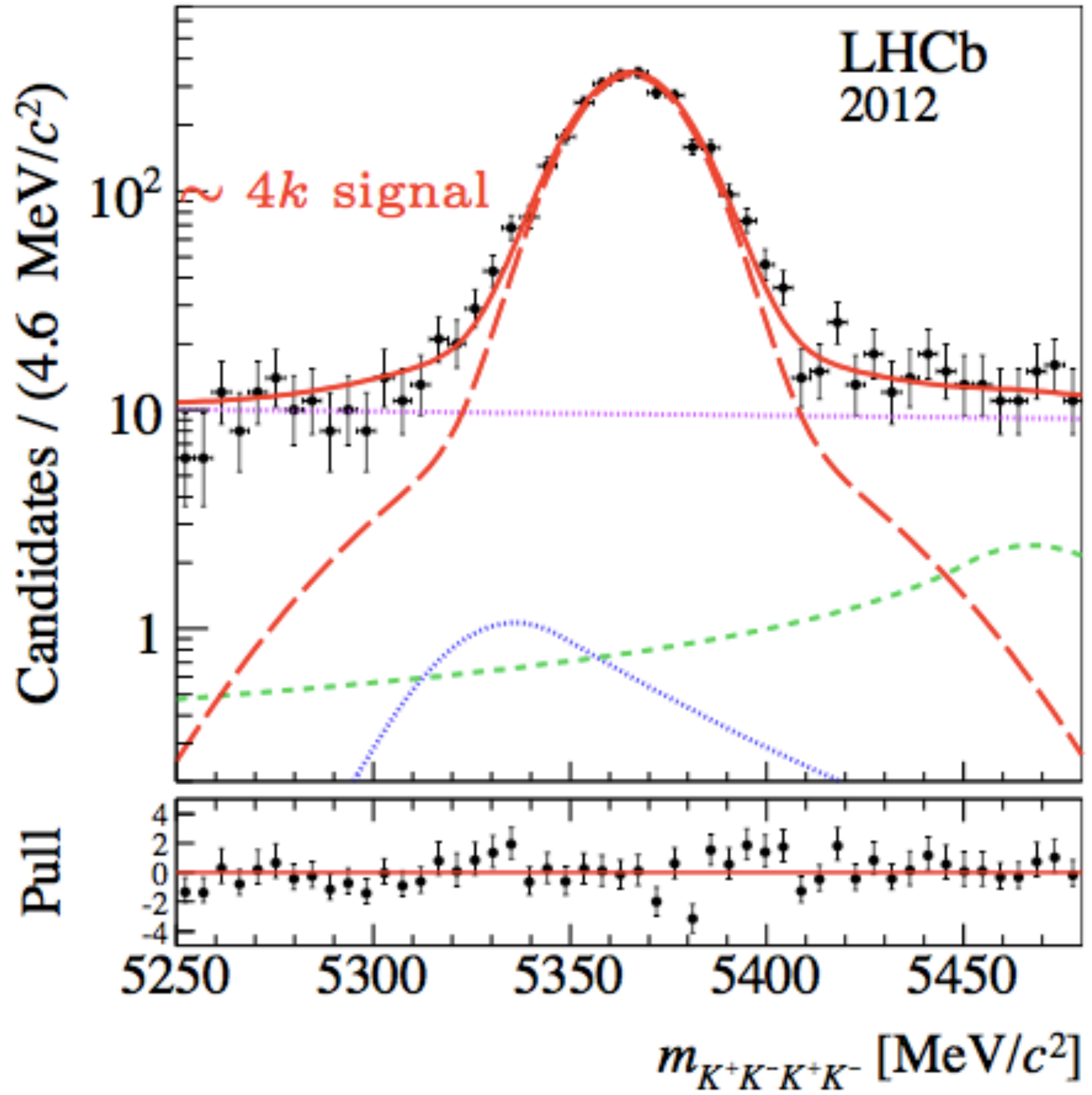
- $B_s^0 \to \phi\phi$: $b \to s$ penguin decays sensitive to NP in the loops.
- $\phi \to KK$: 5 different polarisation amplitudes $\Rightarrow$ angular analysis.
- Decay time resolution: ~ 43 fs.
- Tagging power: $\varepsilon(1-2\omega)^2 = 3.04 \pm 0.24\%$
- Angular efficiency from MC.

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

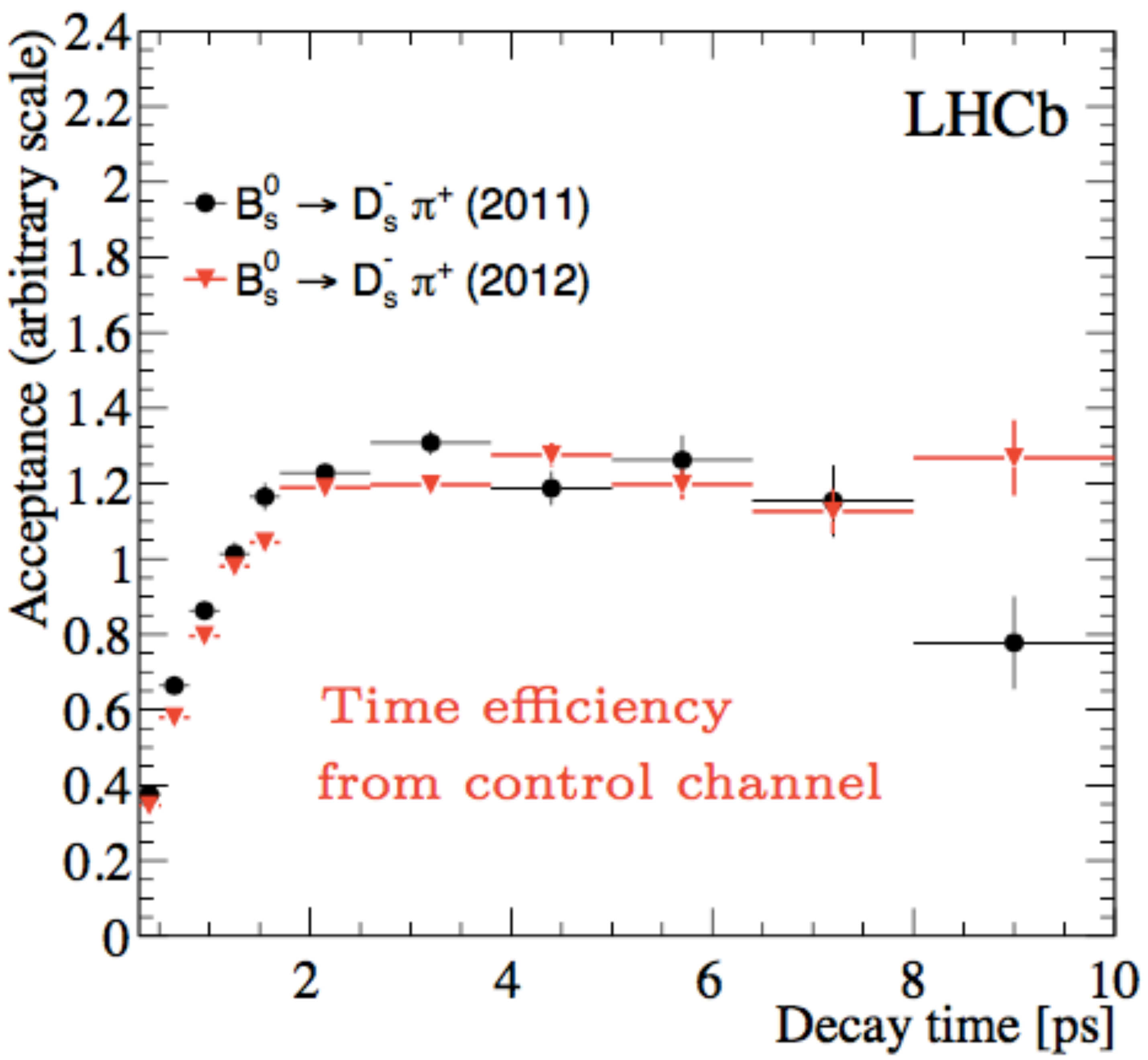
[Bartsch et al. arXiv:0810.0249]

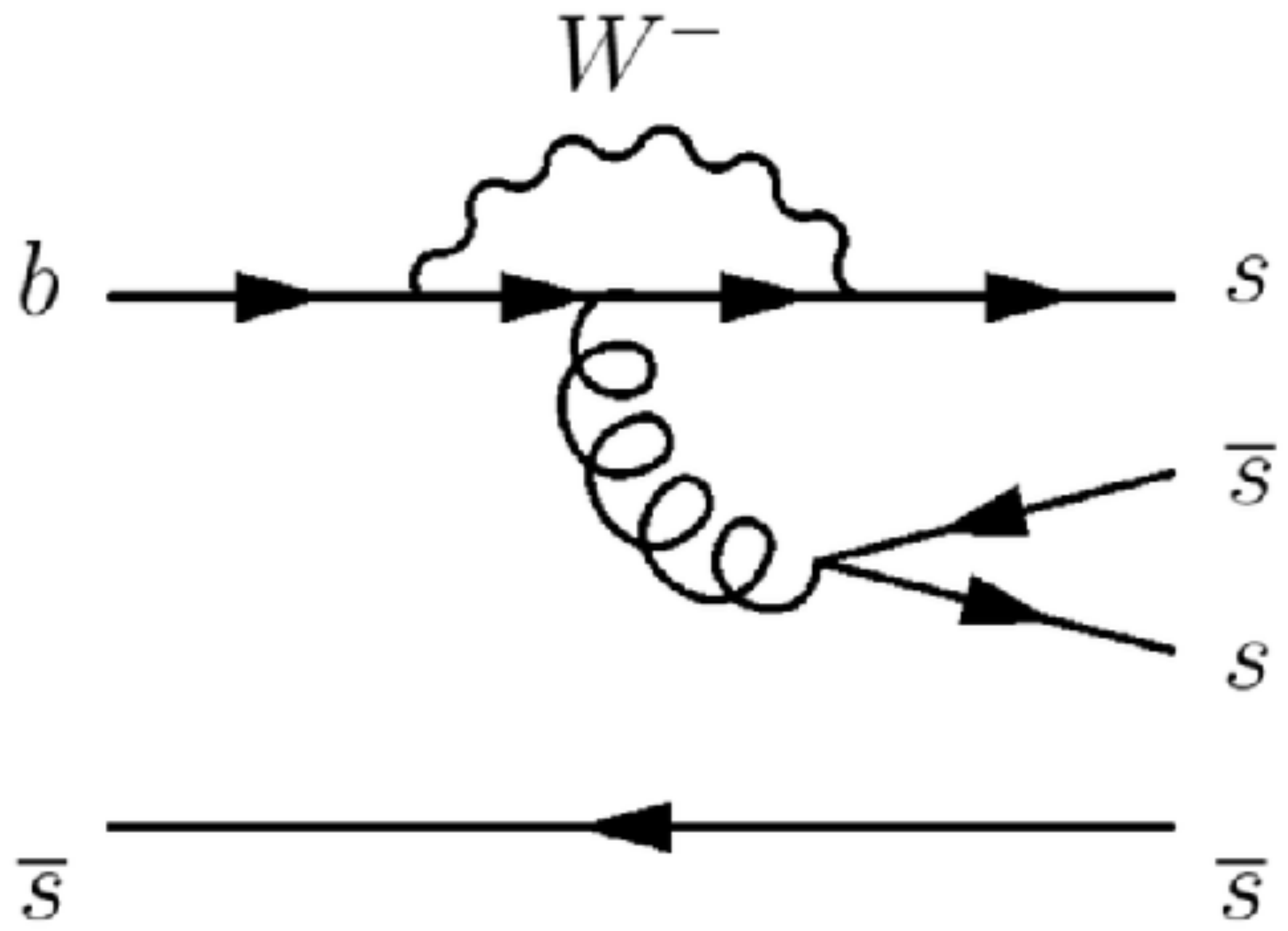
[Beneke et al. NPB 774 (2007) 64-101]

[Cheng et al. PRD 80 (2009) 114026]



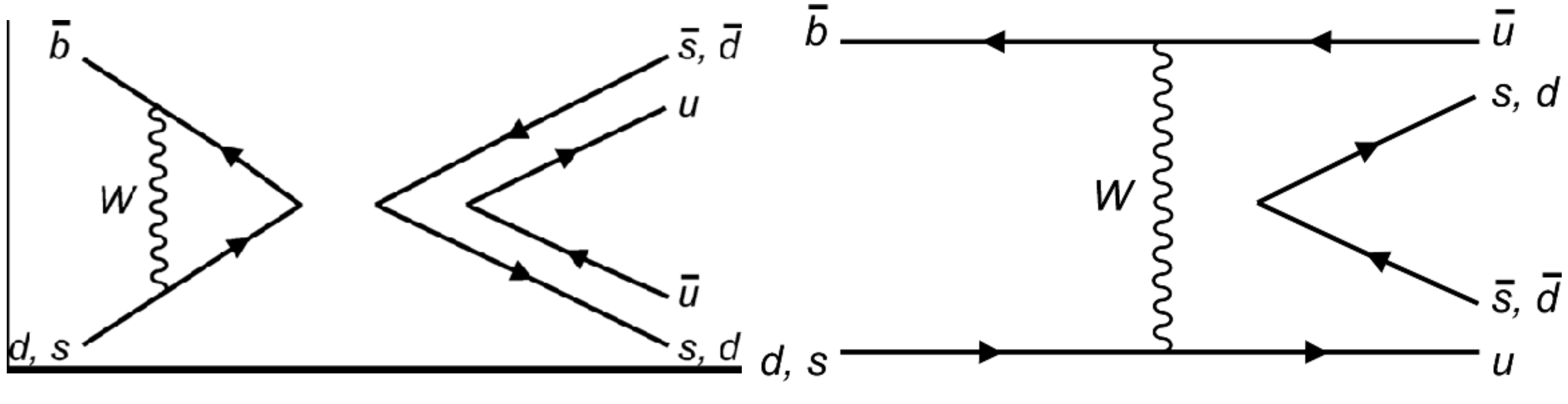
[PRD 90 (2014) 052011]

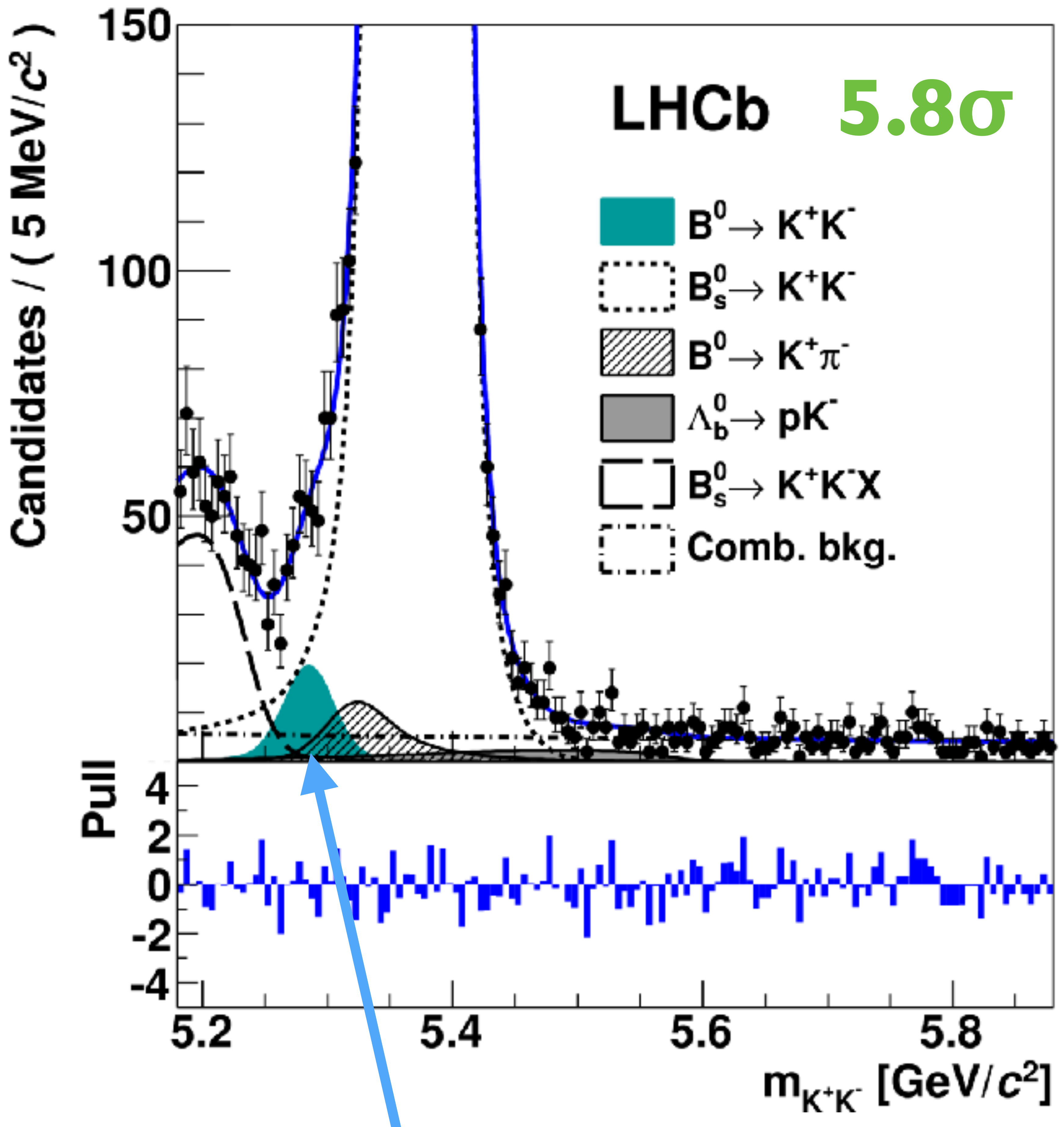




$\phi_s^{s\bar{s}s}$ [rad]	$-0.17 \pm 0.15 \pm 0.03$
$\lvert\lambda\rvert$	$1.04 \pm 0.07 \pm 0.03$

Rare charmless B meson decays





Particular class of decays that can proceed only through so-called annihilation diagrams

B0→K+K- decay observed for the first time after many years of searches.

This is the rarest B meson decay to a fully hadronic final state

$$\mathcal{B}(B^0 \to K^+K^-) = (7.80 \pm 1.27 \pm 0.81 \pm 0.21) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \pi^+\pi^-) = (6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.40) \times 10^{-7}$$

The signal!

Requires excellent RICH PID

[arXiv:1610.08288]

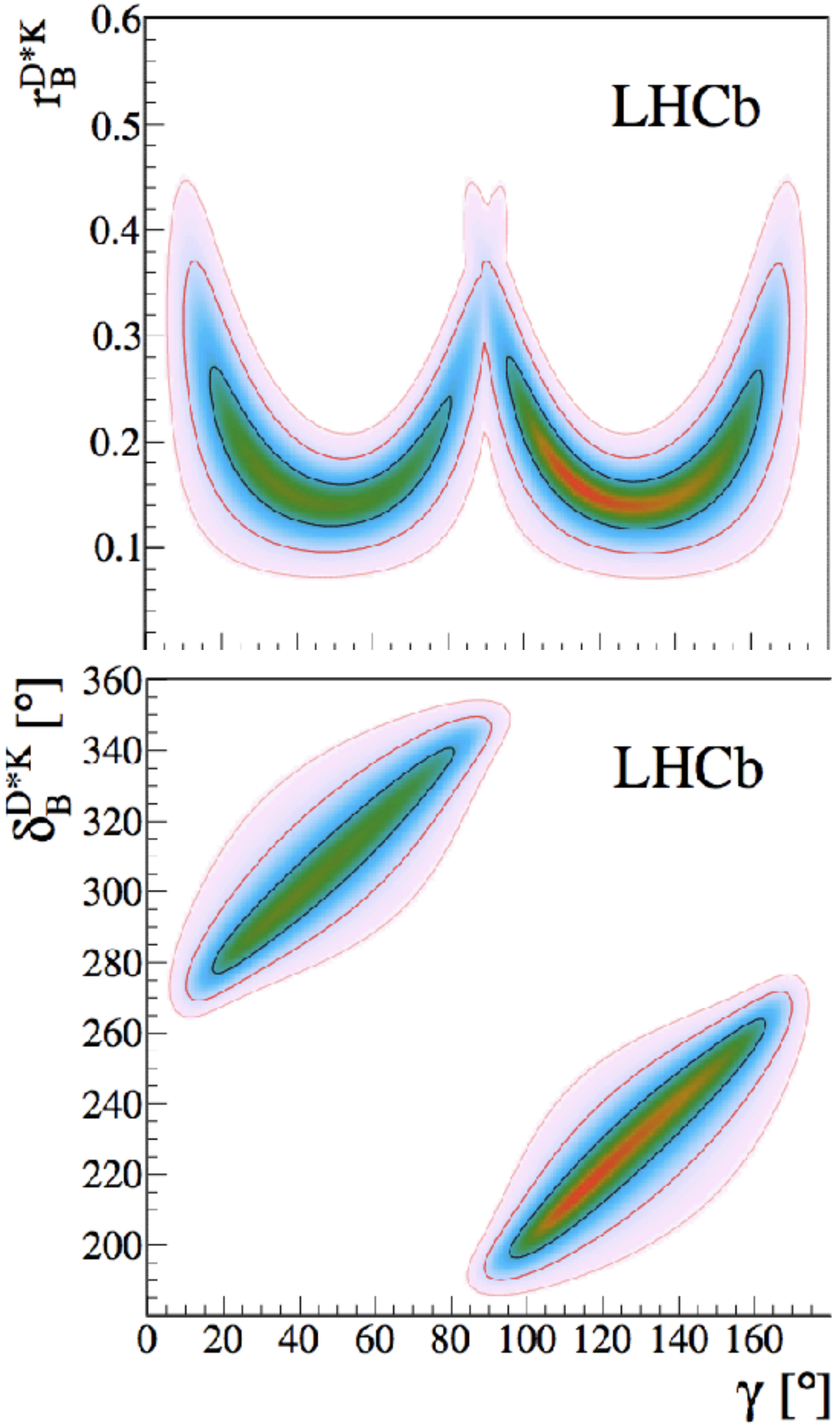
CP observables in $B^{\pm} \to D^{(*)0}K^{\pm}$ and $B^{\pm} \to D^{(*)0}\pi^{\pm}$

6 partially reconstructed GLW CP observables used to constrain r^{D*K}_B , δ^{D*K}_B and γ

r^{D*K}_B , δ^{D*K}_B match HFLAV GGSZ averages [arXiv:1612.07233]

γ within 1σ of current LHCb combination [JHEP 12 (2016) 087]

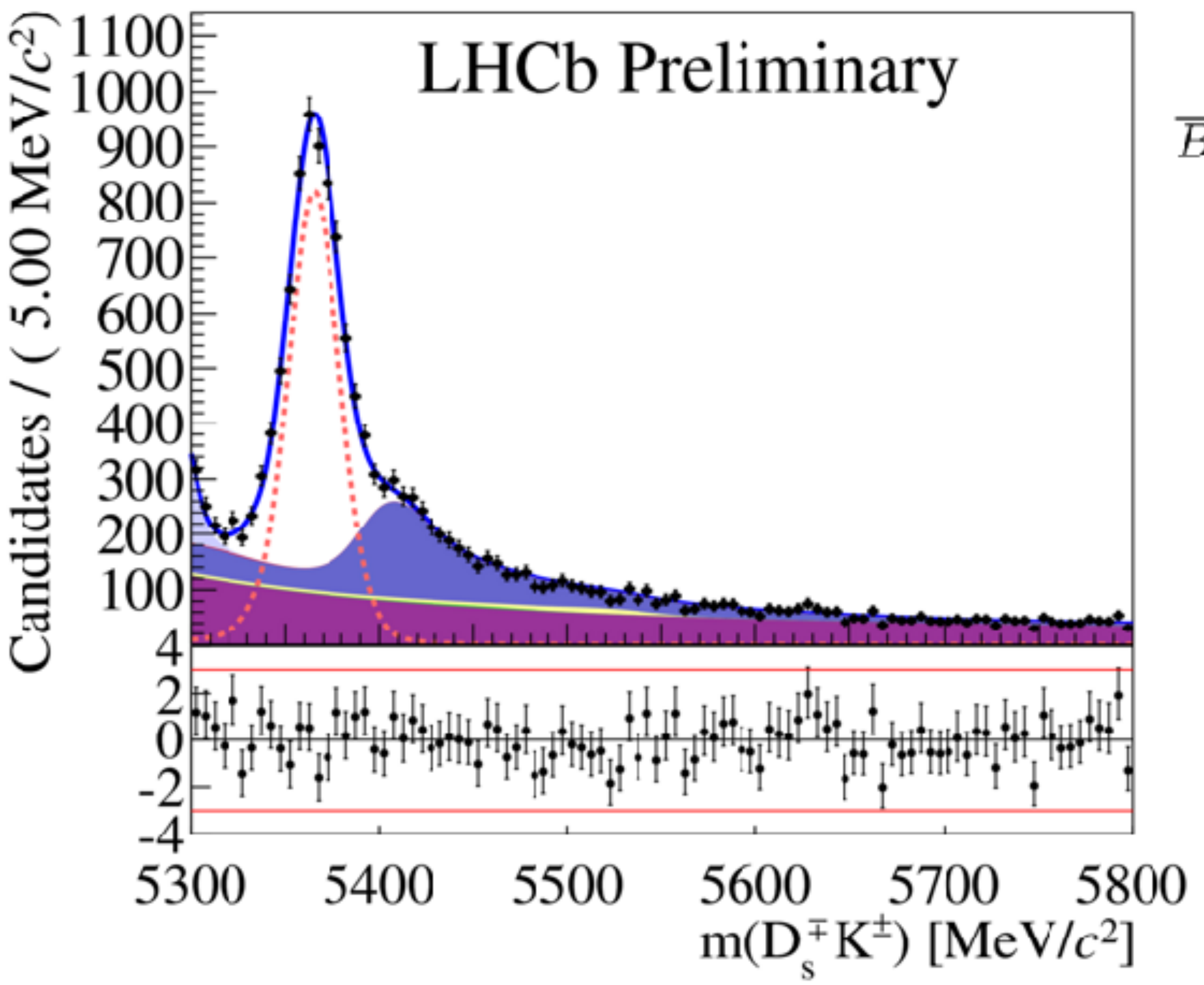
Future: improve precision by adding ADS modes

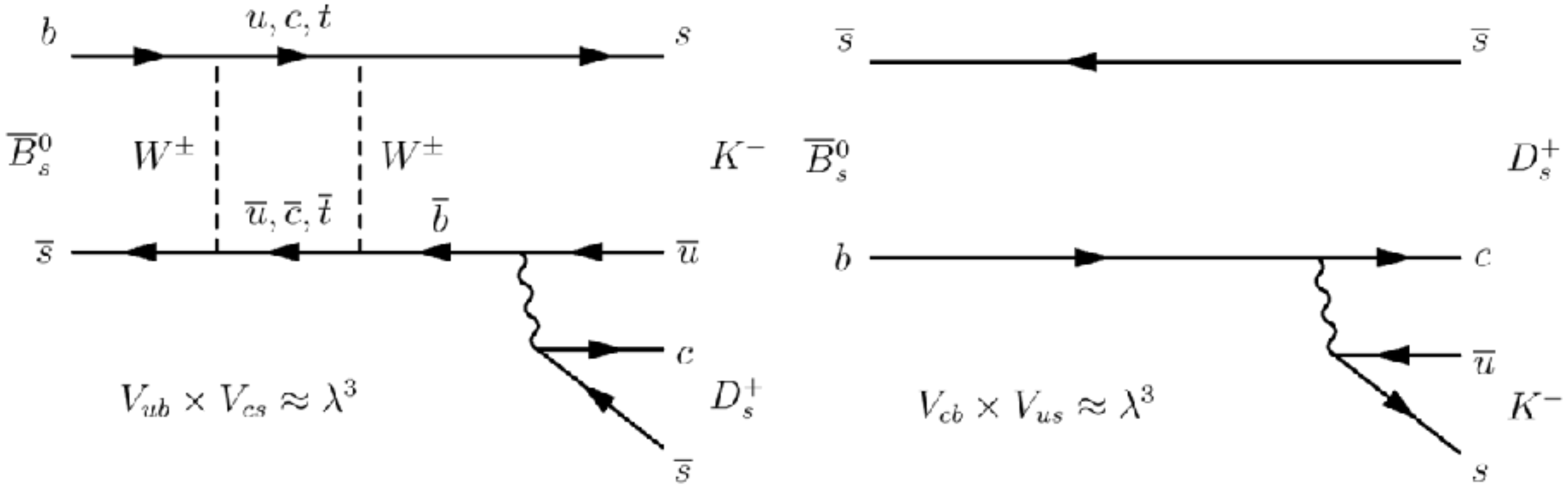


[LHCb-PAPER-2017-021]

CP asymmetry in $B^0_s \to D^{\mp}_s K^{\pm}$ decays

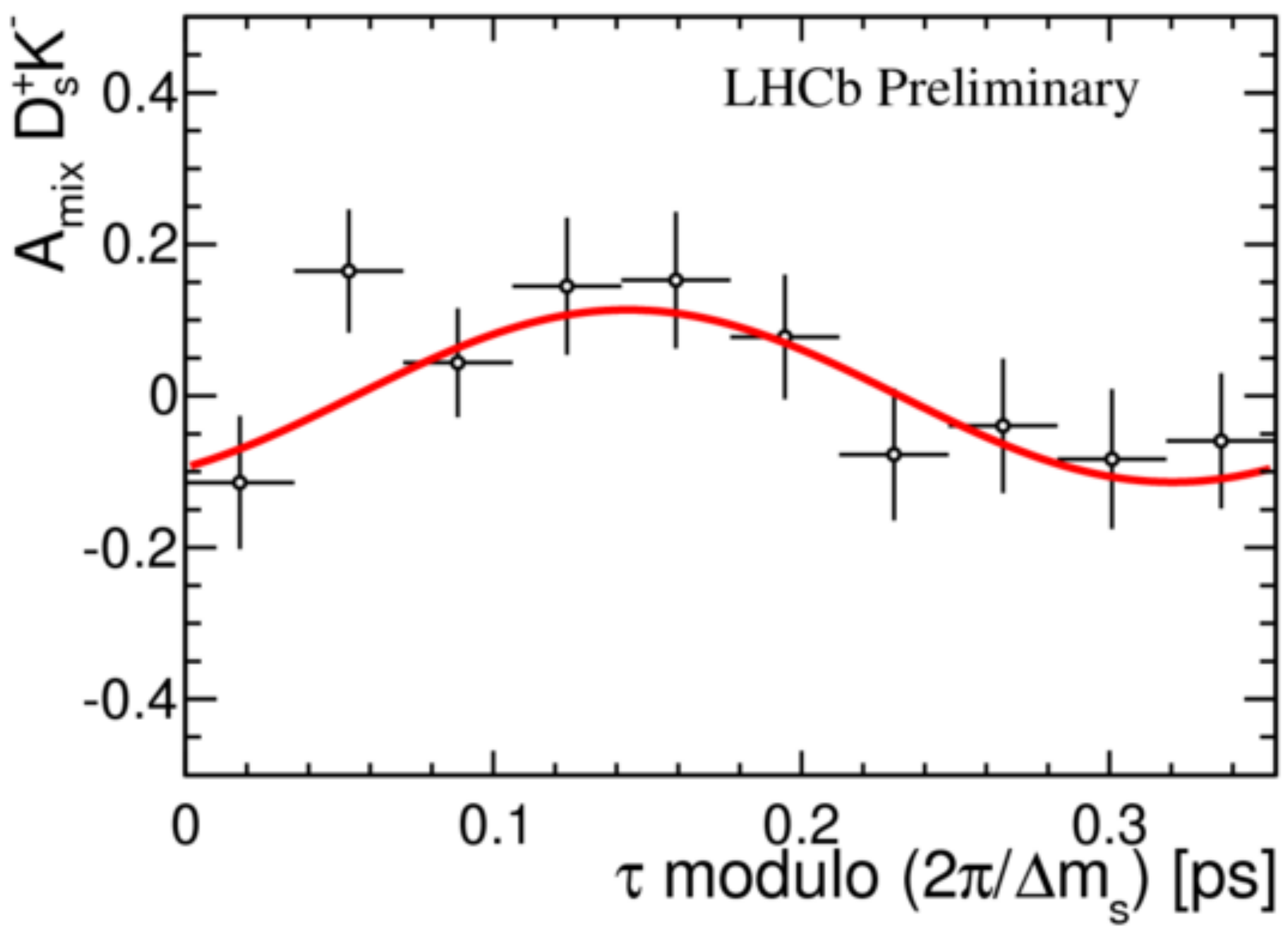
[LHCB-CONF-2016-015]



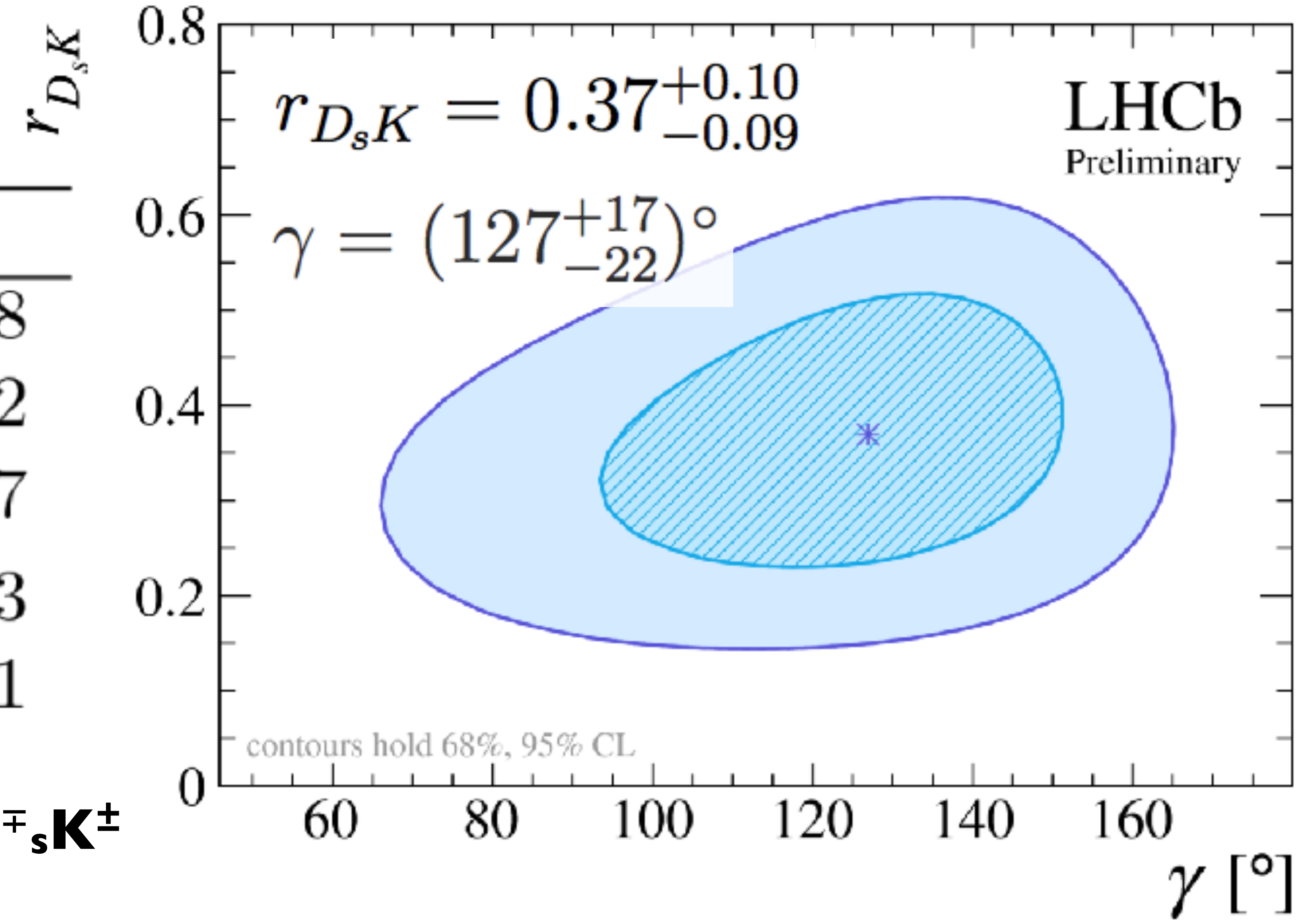


Both decay amplitudes are O(λ^3)
→ LARGE INTERFERENCE

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



Parameter	Value
C_f	$0.735 \pm 0.142 \pm 0.048$
$A_f^{\Delta\Gamma}$	$0.395 \pm 0.277 \pm 0.122$
$A_{\overline{f}}^{\Delta\Gamma}$	$0.314 \pm 0.274 \pm 0.107$
S_f	$-0.518 \pm 0.202 \pm 0.073$
$S_{\overline{f}}$	$-0.496 \pm 0.197 \pm 0.071$



3.6σ evidence for CP violation in $B^0_s \to D^{\mp}_s K^{\pm}$

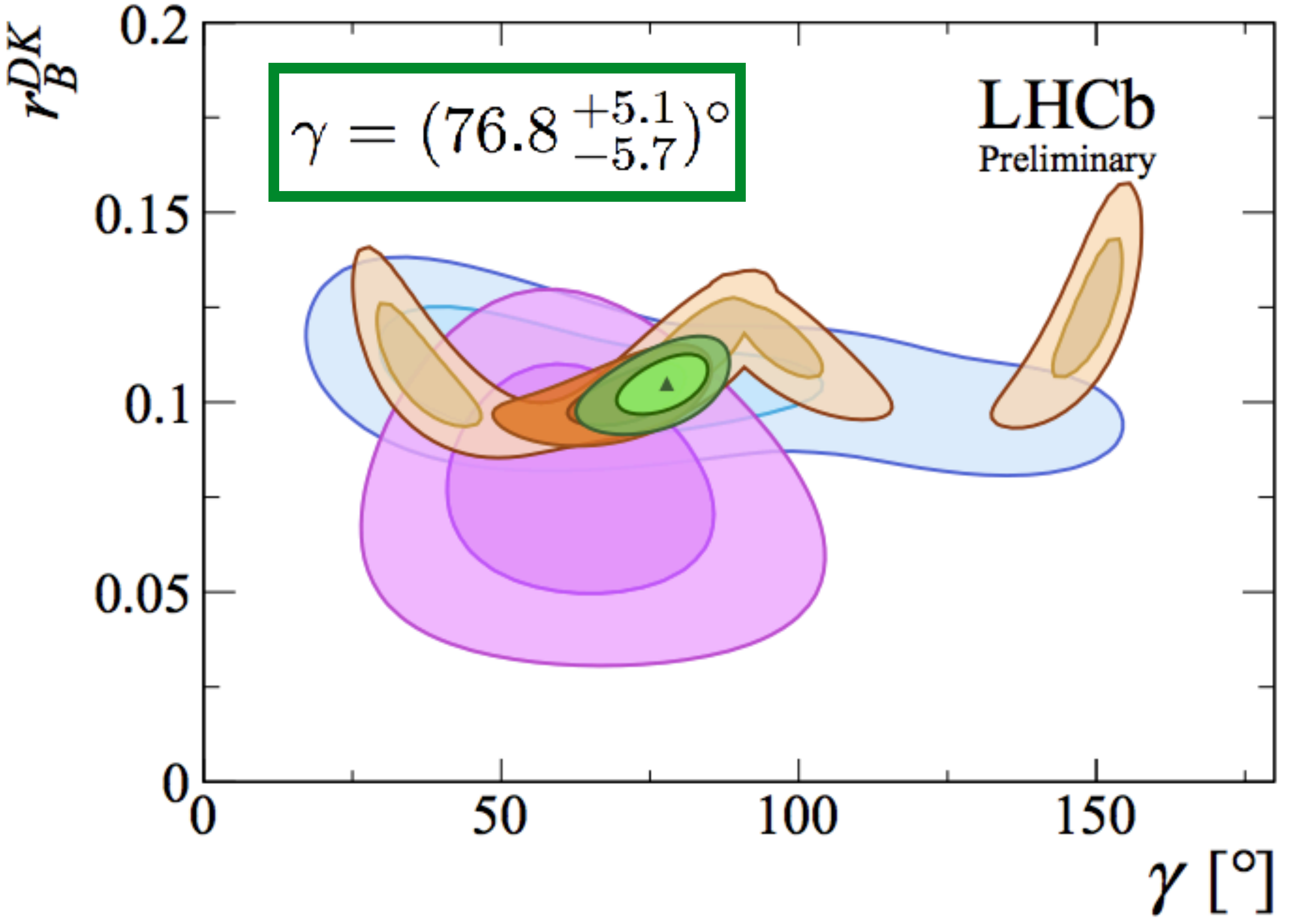
γ combination

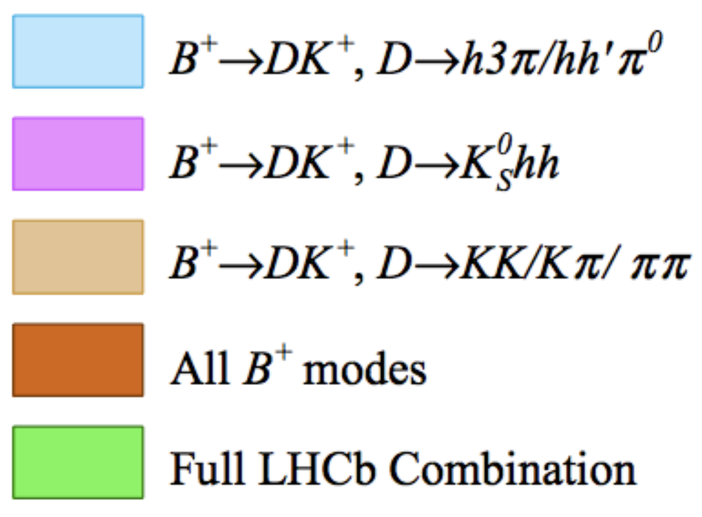
Use several B → DK measurements (85 observables, 37 parameters)

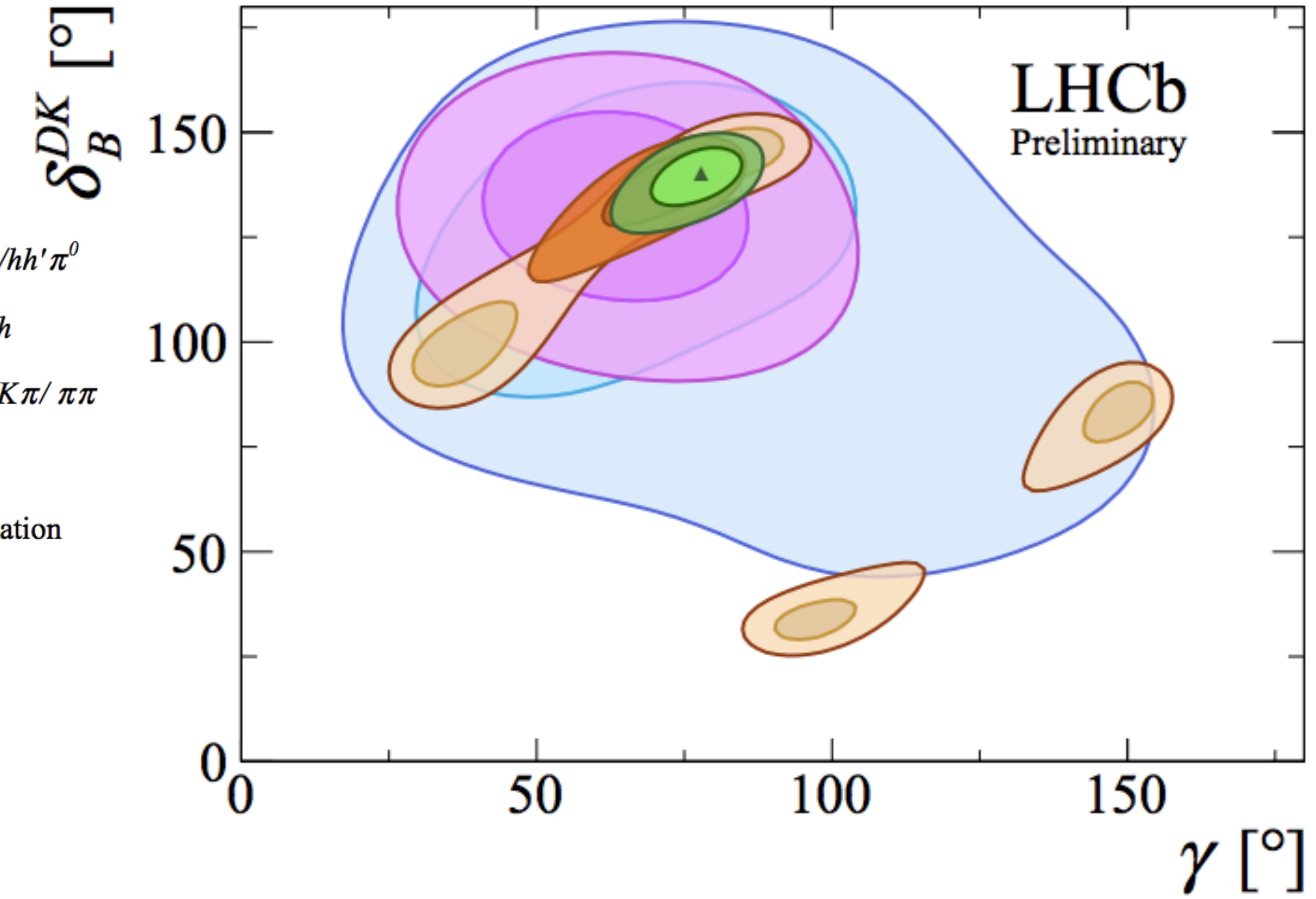
Most precise measurement of γ [LHCb-CONF-2017-004]

B decay	D decay	Method	Ref.	Status since last combination [JHEP 12 (2016) 087]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[16]	Updated to Run 1 + $2\,\text{fb}^{-1}$ Run 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[17]	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[17]	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[18]	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[19]	As before
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[20]	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[16]	New
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[21]	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[22]	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[23]	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[24]	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[25]	As before
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	TD	[26]	Updated to $3\,\text{fb}^{-1}$ Run 1

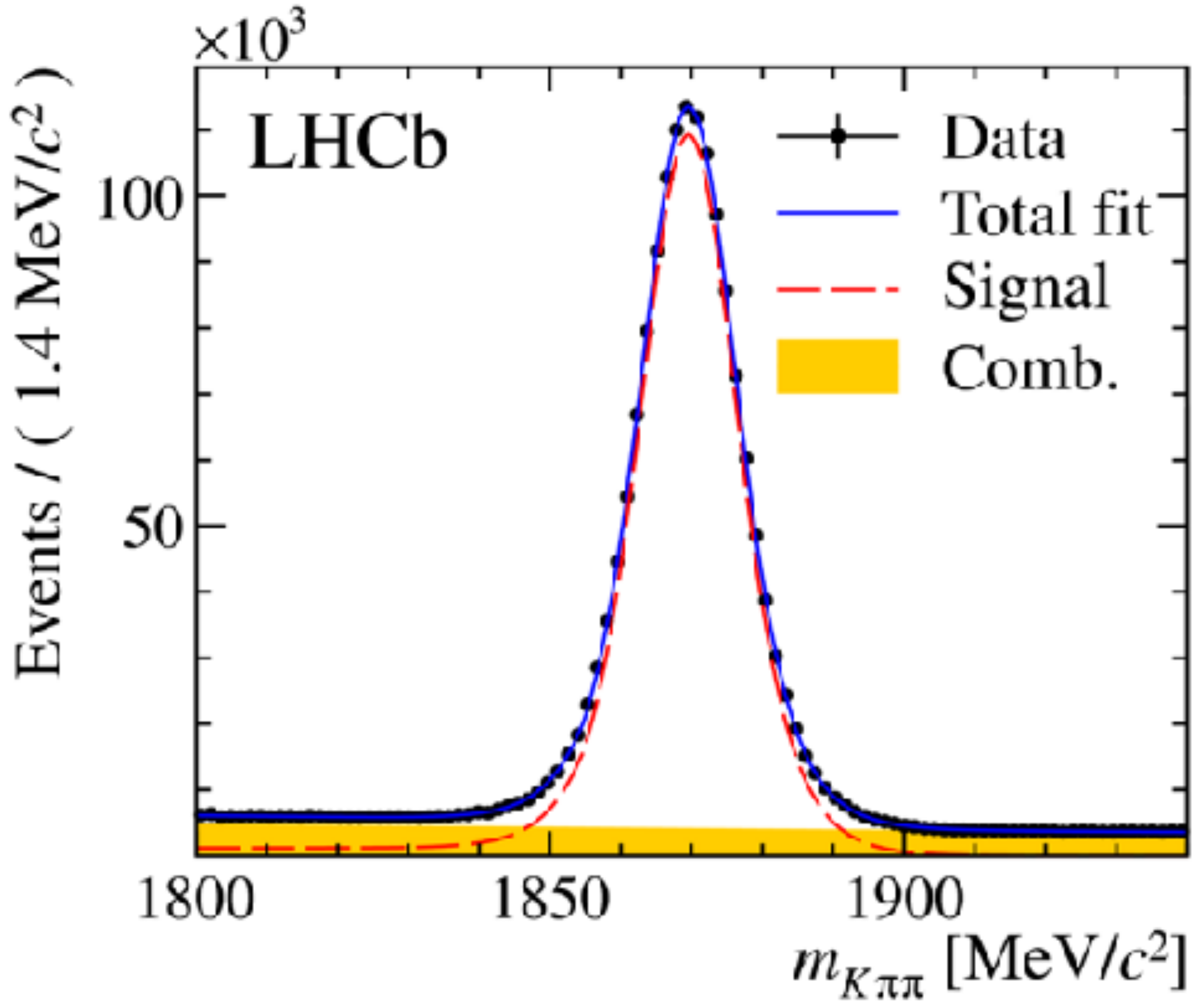
Belle/BaBar sensitivity ~ 15°

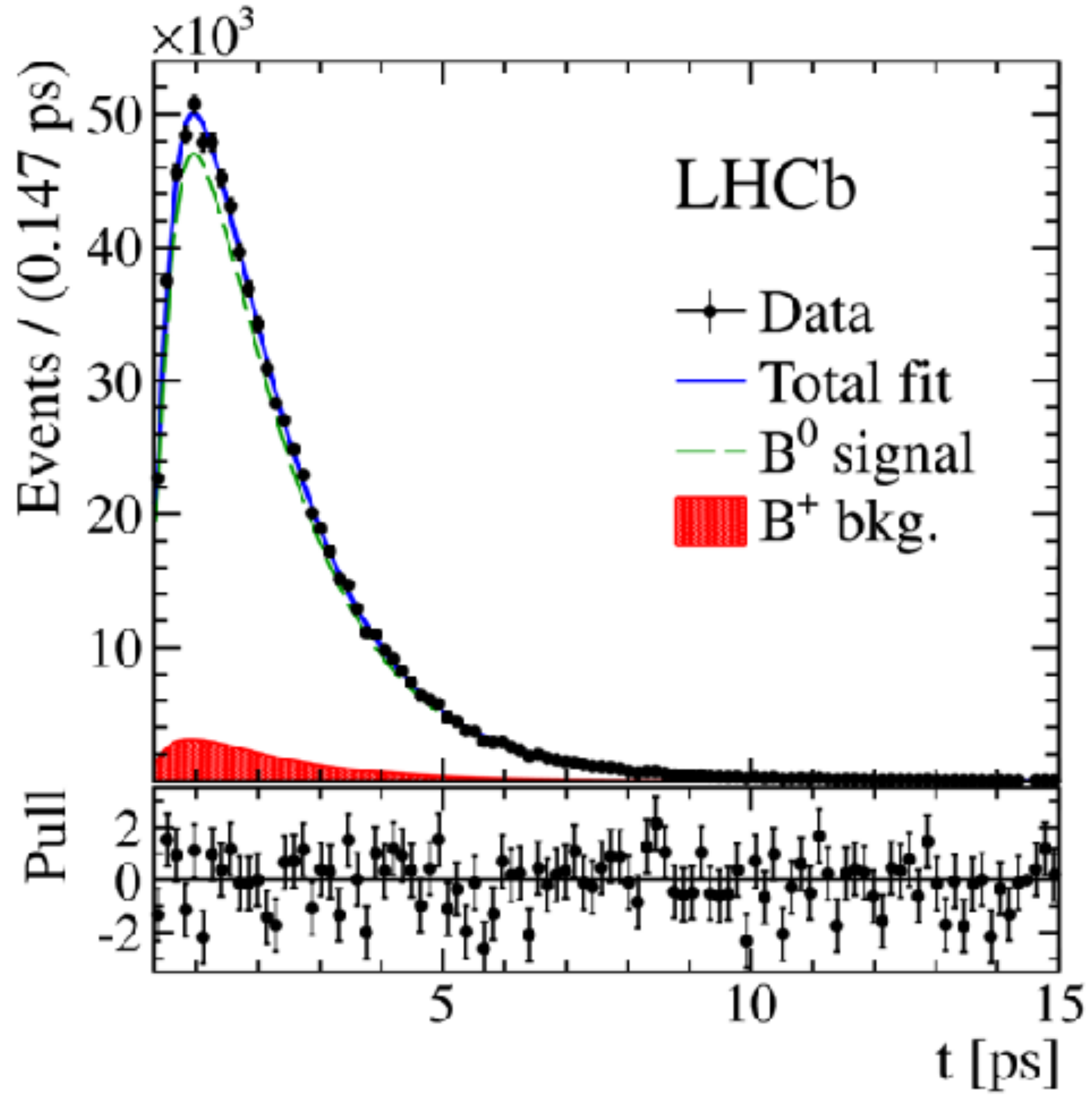


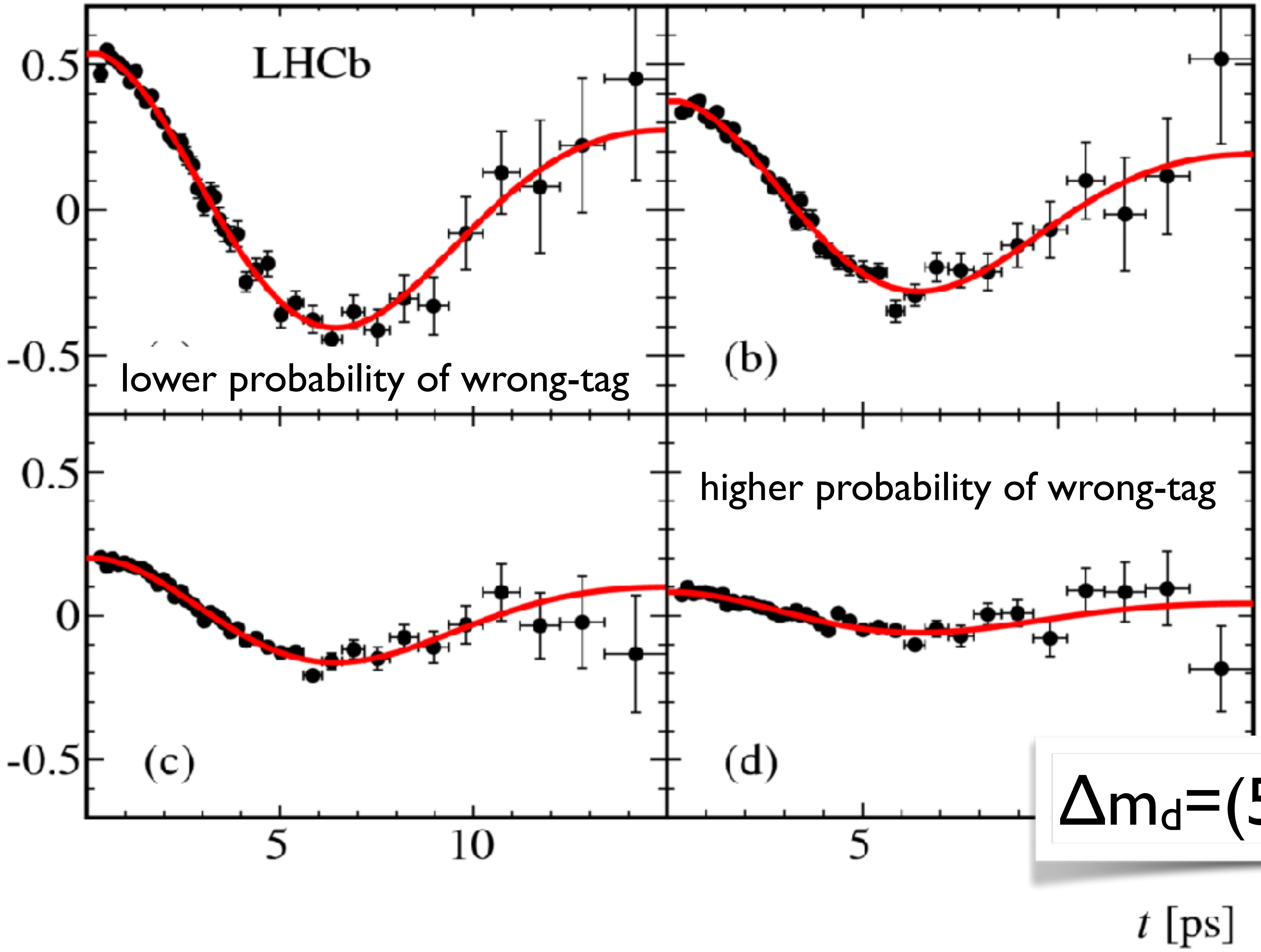




Measuring the B^0 meson oscillation frequency







[EPJC 76 (2016) 412]

$B^0 \rightarrow D^- \mu^+ \nu_\mu X$

$\Delta m_d = (505.0 \pm 2.1 \pm 1.0)\,\text{ns}^{-1}$

Huge sample of semi-leptonic decays.

Main systematic from B^+ backgrounds.

Constraining penguin pollution

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

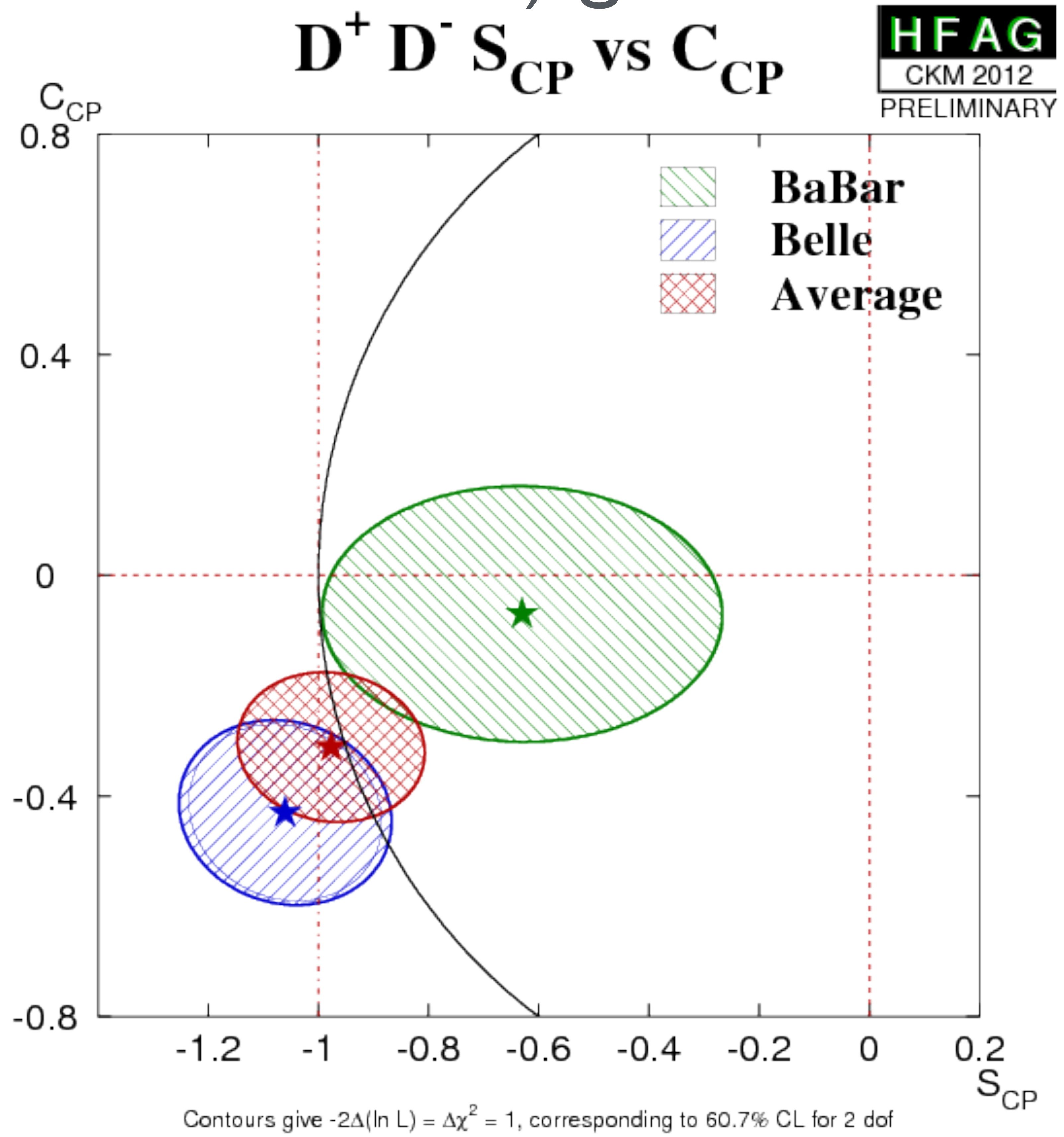
Ignore denominator for B^0 decays since $\Delta\Gamma \sim 0$

Decay-time dependent CPV in $B^0 \to D^+D^-$ decays ($b \to ccd$ transitions) give complimentary information to sin2β.

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

phase shift due to penguin

Belle result outside of physics region ($S^2 + C^2 < 1$) → large penguin contribution?



Contours give $-2\Delta(\ln L) = \Delta\chi^2 = 1$, corresponding to 60.7% CL for 2 dof

Constraining penguin pollution

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

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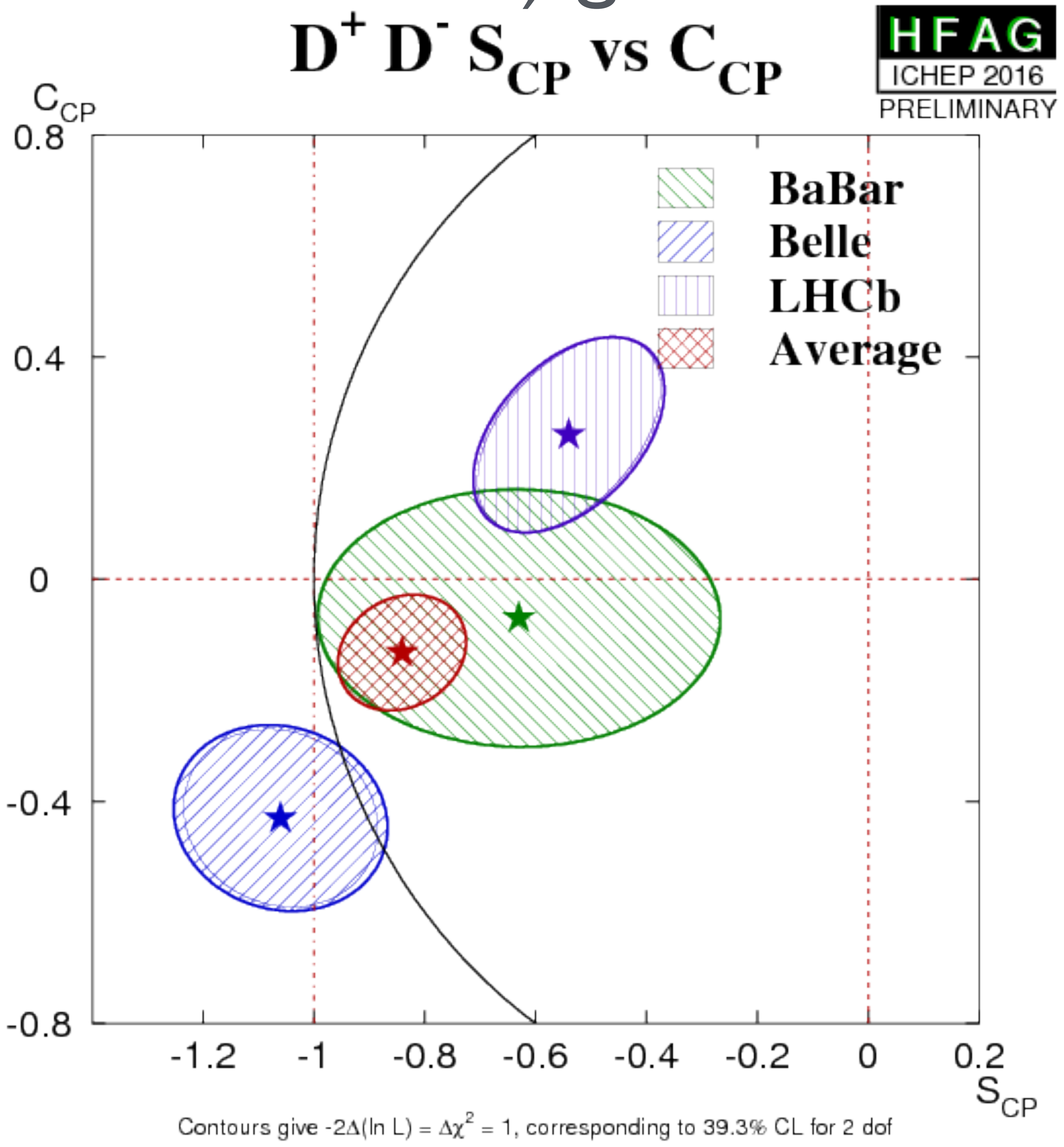
phase shift due to penguin

Belle result outside of physics region ($S^2 + C^2 < 1$)
→ large penguin contribution?

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

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

consistent with no penguin pollution



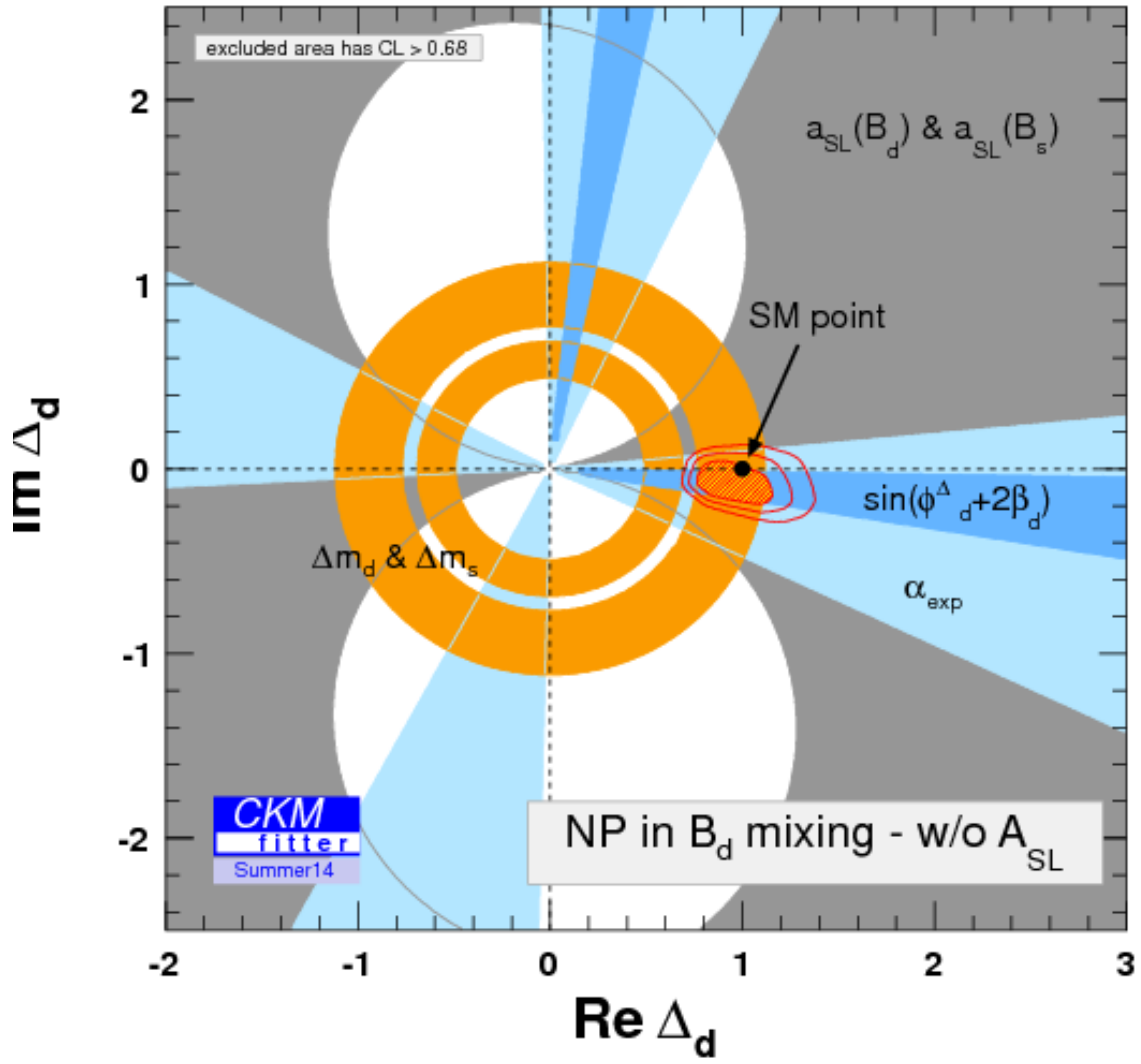
[LHCb, PRL 117 (2016) 261801]

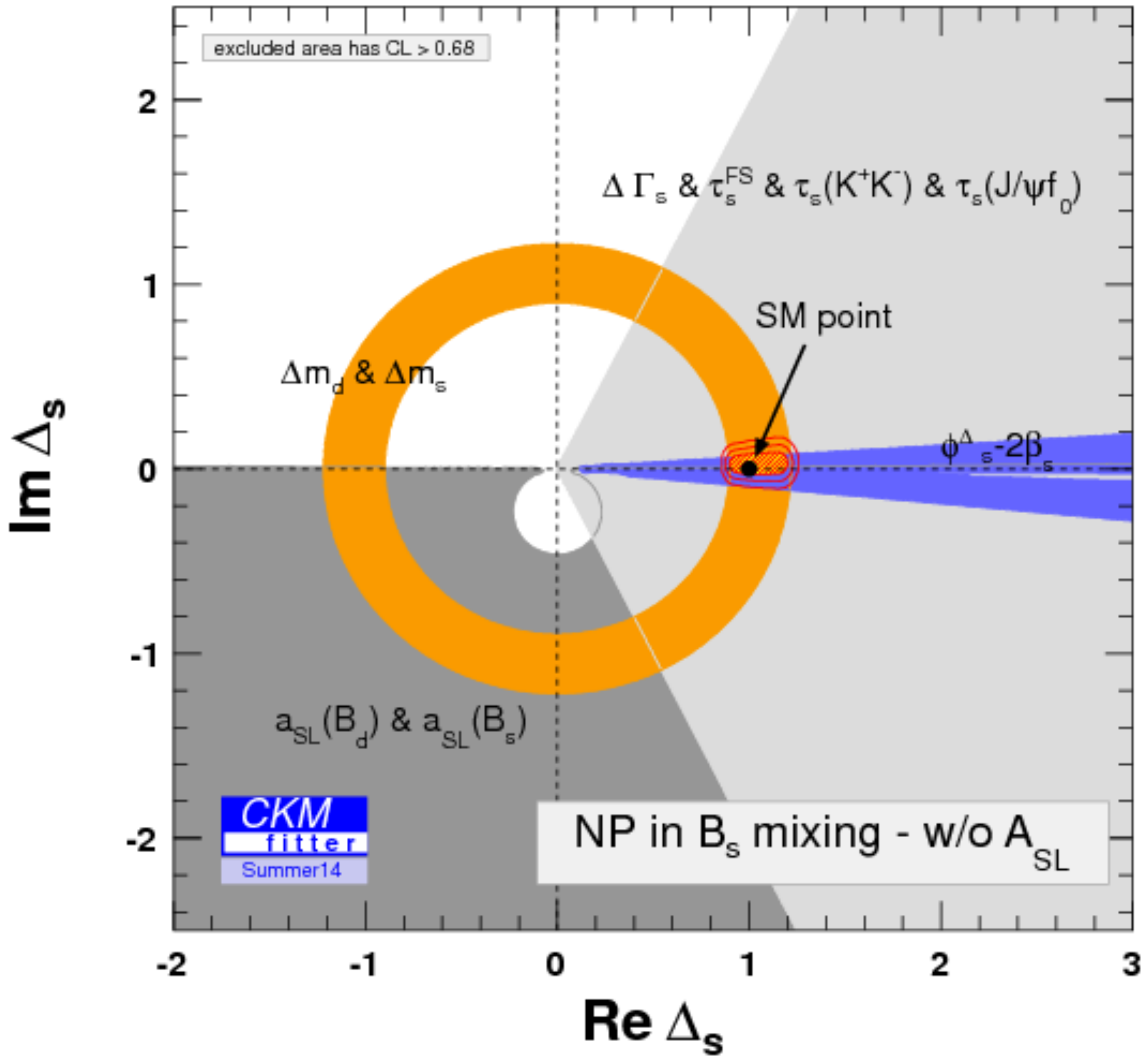
Impact on new physics

$$M_{12}^{NP,s} = M_{12}^{SM,s}\Delta_s$$

$$\Delta_s = |\Delta_s| e^{i\phi_s^\Delta}$$

$$\Delta_s^{SM} = 1$$





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

Two complementary CP-odd observables

$\bar{T}$ = motion reversal operator
(= P for spinless particles)

Relative CP-even "strong" phase ↓ — Relative CP-odd "weak" phase ↓

$$\mathcal{A}_{CP} \propto a_1^e a_2^e \sin(\delta_1^e - \delta_2^e) \sin(\phi_1^e - \phi_2^e)$$

Depends on interference of $\bar{T}$-even amplitudes

$$a_{CP}^{\hat{T}\text{-odd}} \propto a_1^e a_1^o \cos(\delta_1^e - \delta_1^o) \sin(\phi_1^e - \phi_1^o)$$

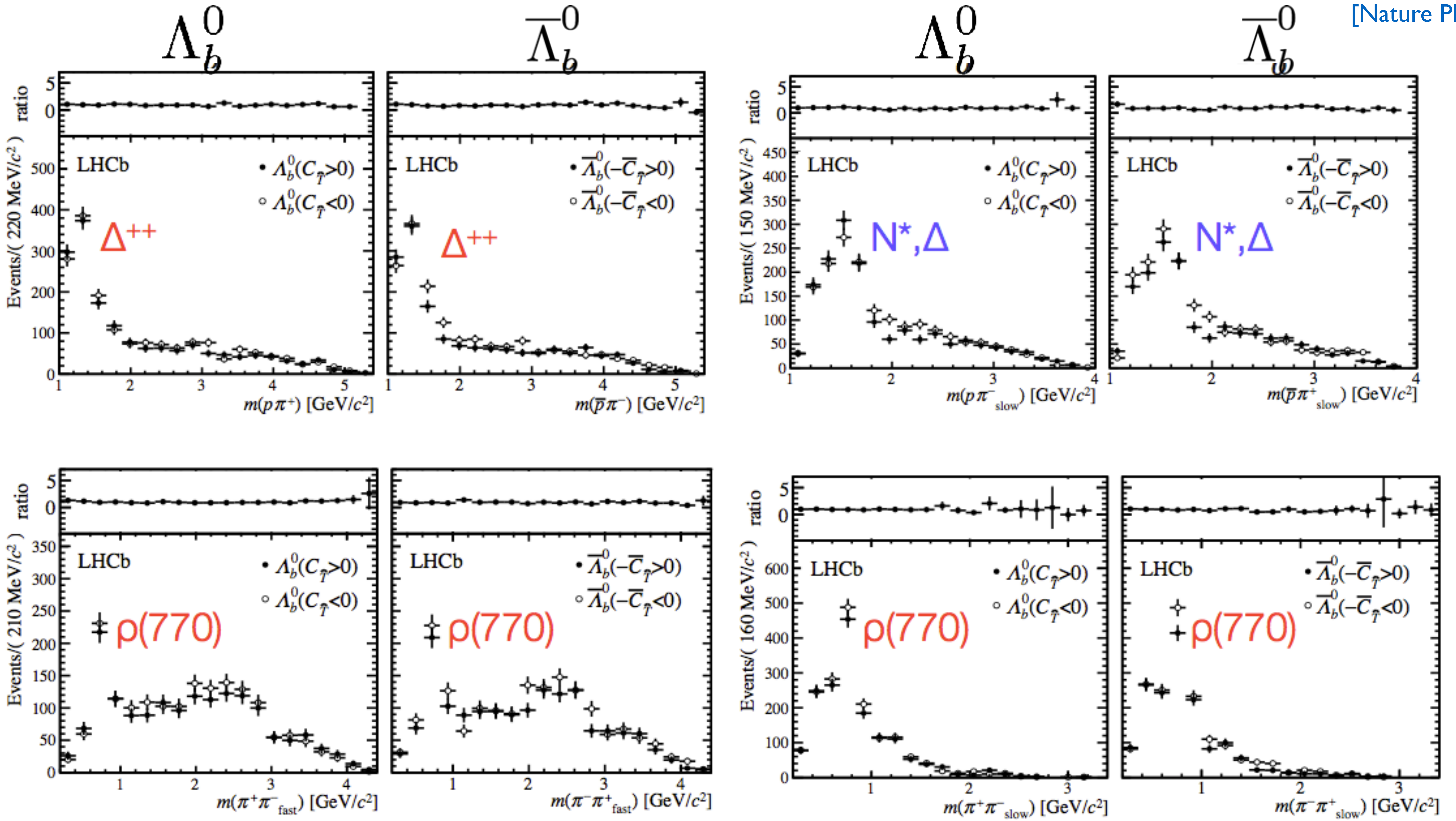
Depends on interference of $\bar{T}$-odd and $\bar{T}$-even amplitudes

Even if strong phase difference is zero then still have sensitivity CPV

[G. Durieux, Y. Grossman, PRD 92 (2015) 076013]

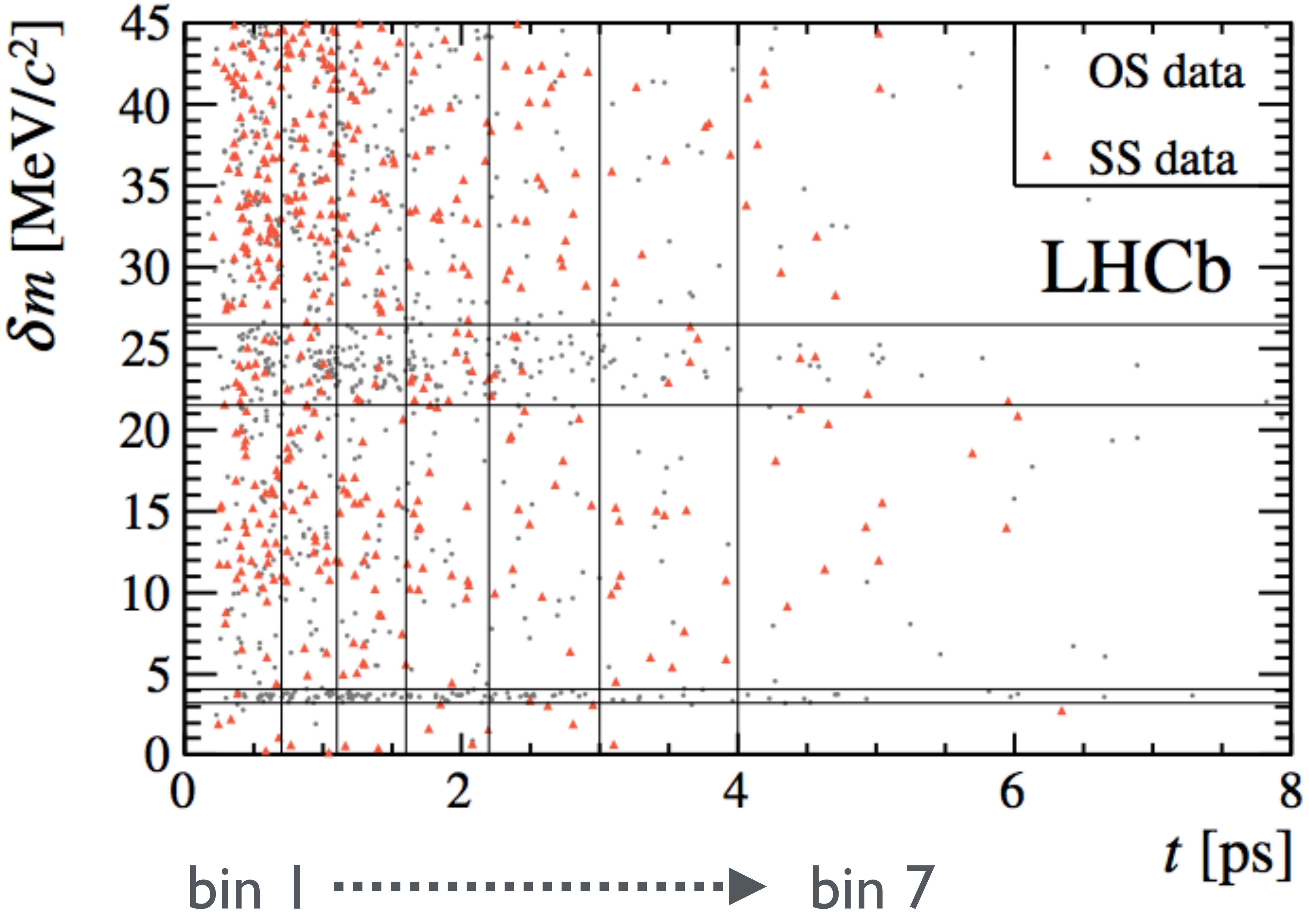
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ phase space distributions

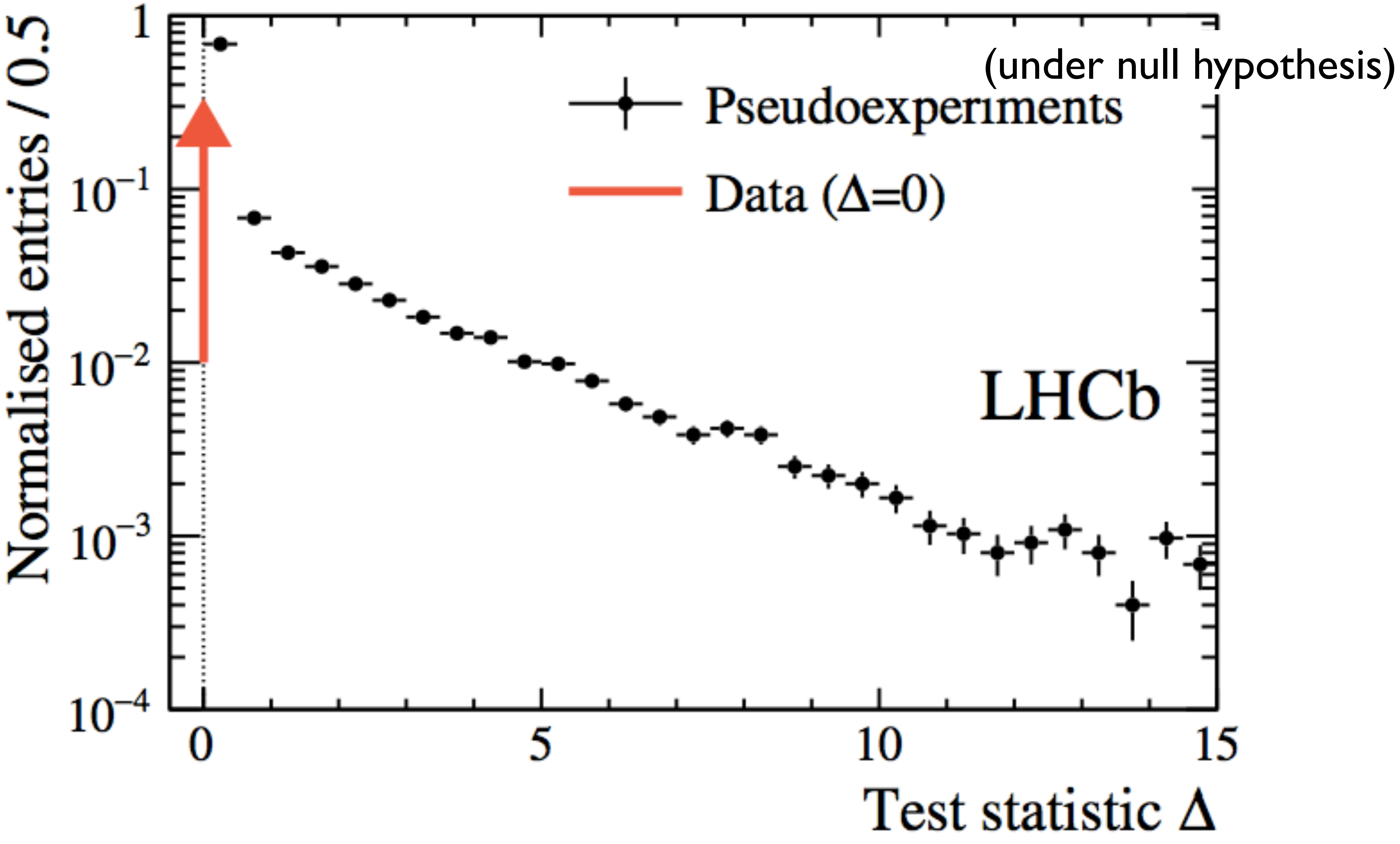
[Nature Physics 13 391 (2017)]



Background subtracted using sPlot. CP asymmetry not localised to any resonance.

Search for baryon-number violation @ LHCb





No evidence of BNV oscillations.

ω < 0.08 ps^{-1} @95% CL (using CL$_s$ method with pseudoexperiments).

$\omega = 1/\tau^2_{mix}$ → mixing lifetime > 13 ps.

[LHCb-PAPER-2017-023]

Strong CP violation?

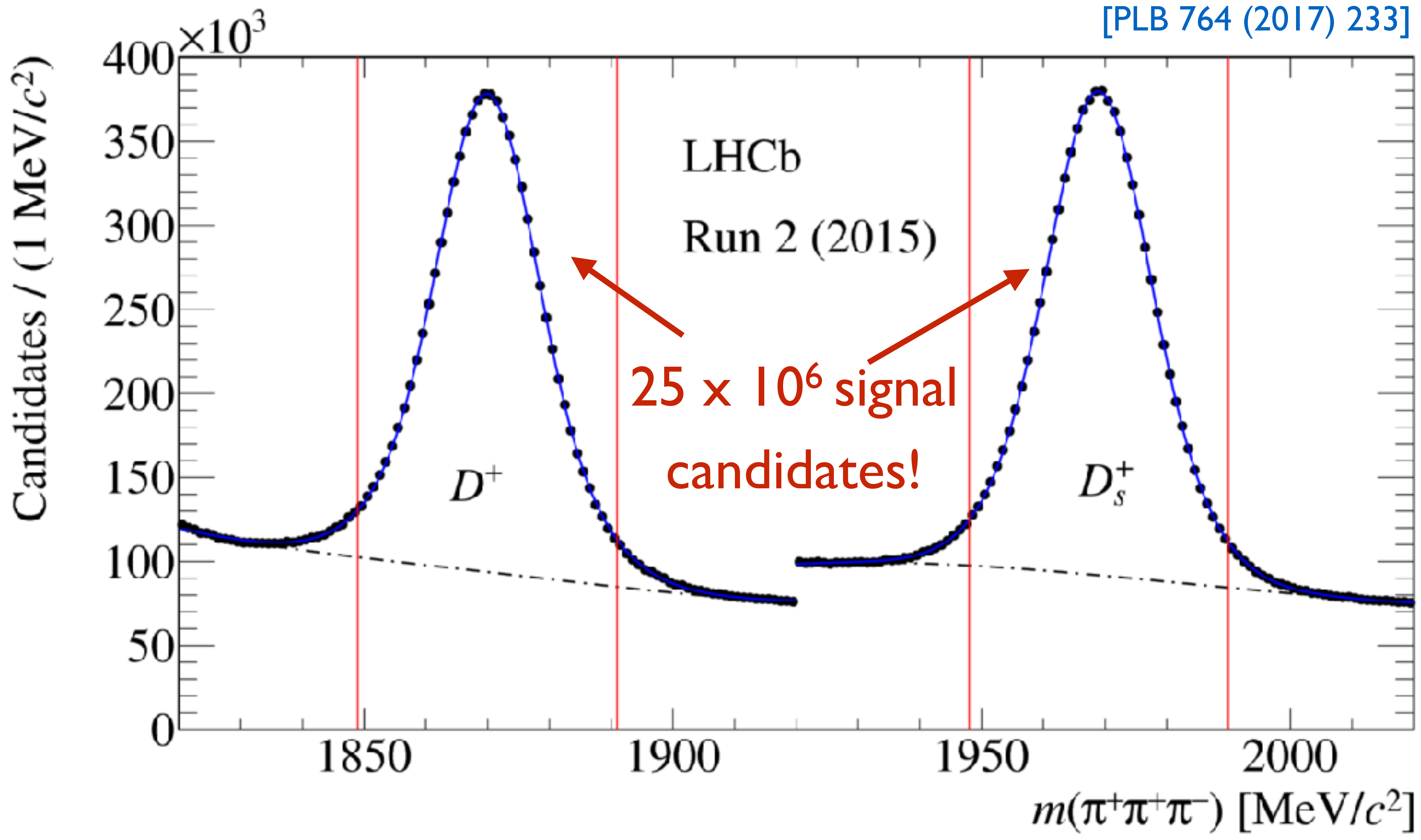
QCD Lagrangian could contain θ term that would give rise to CP violation in strong interactions.

nEDM measurements → $\theta < 10^{-10}$
[Phys. Atom. Nucl. 70 (2007) 349]

Search for CPV $\eta^{(\prime)} \to \pi^+\pi^-$ decays in dipion mass spectrum of $D^+_{(s)} \to \pi^+\pi^+\pi^-$ decays.

No signal so place upper limit.

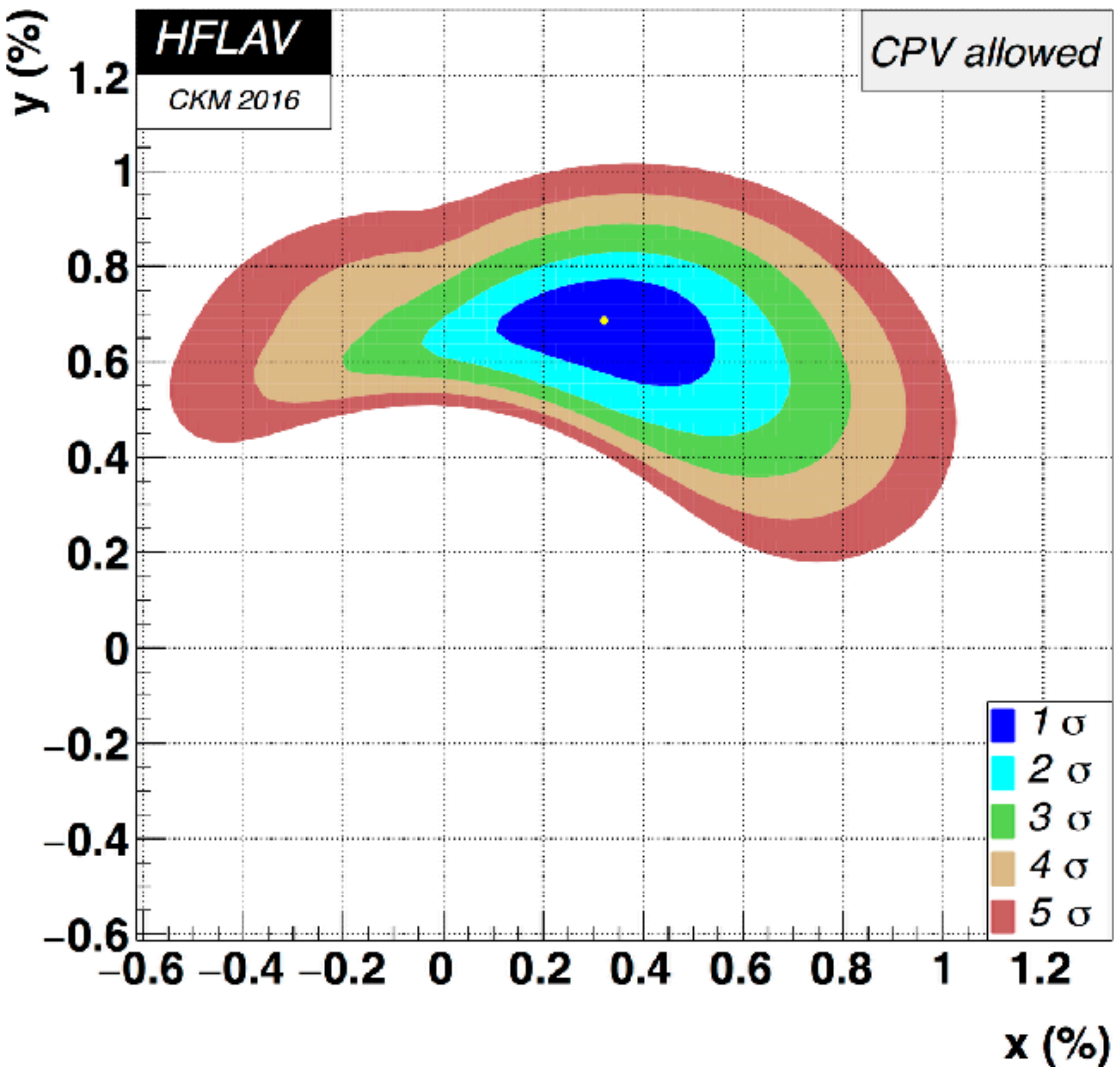
[PLB 764 (2017) 233]



$$\mathcal{B}\left(\eta \to \pi^+\pi^-\right) < 1.6 \times 10^{-5}$$

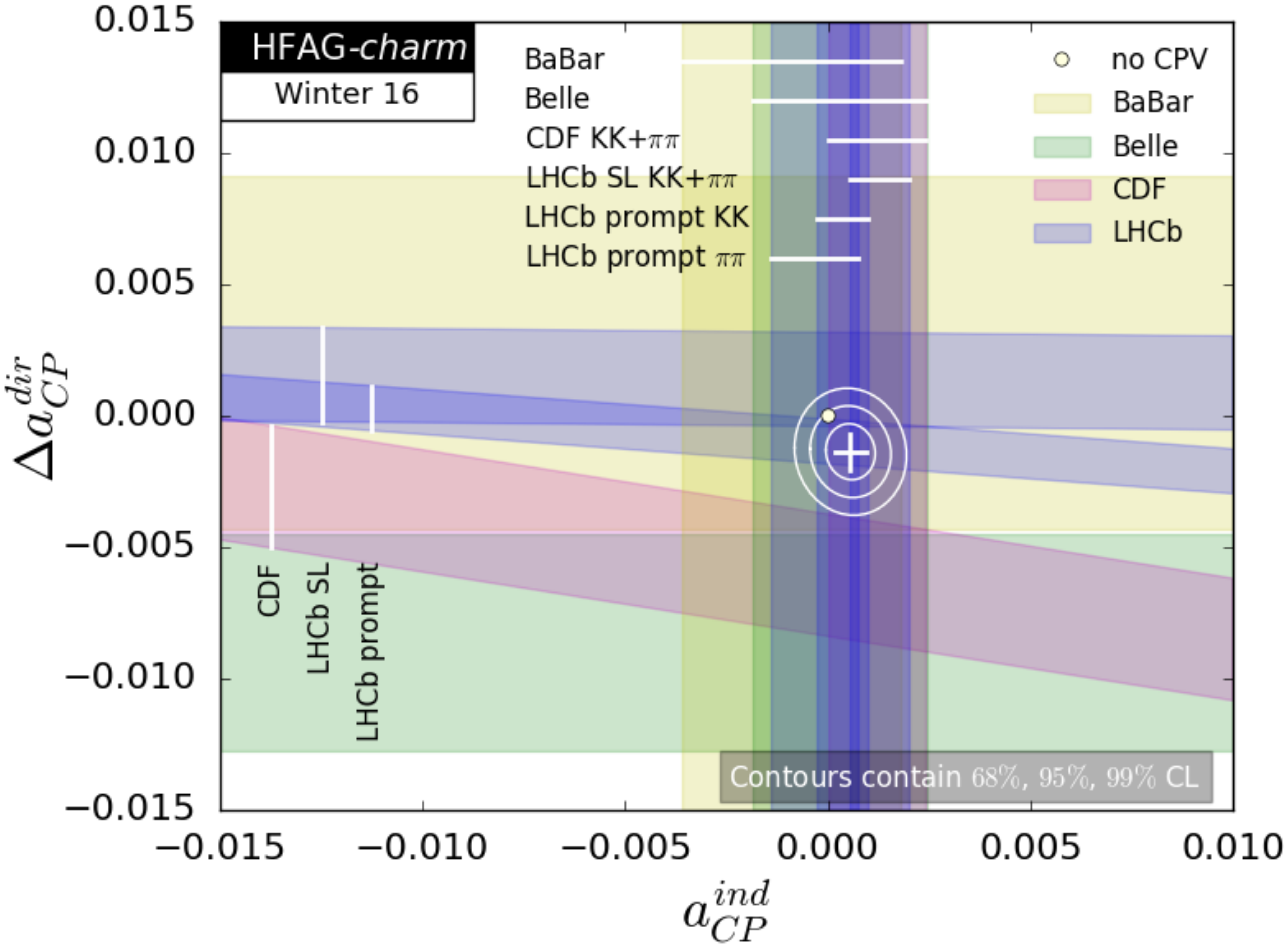
$$\mathcal{B}\left(\eta' \to \pi^+\pi^-\right) < 1.8 \times 10^{-5}$$

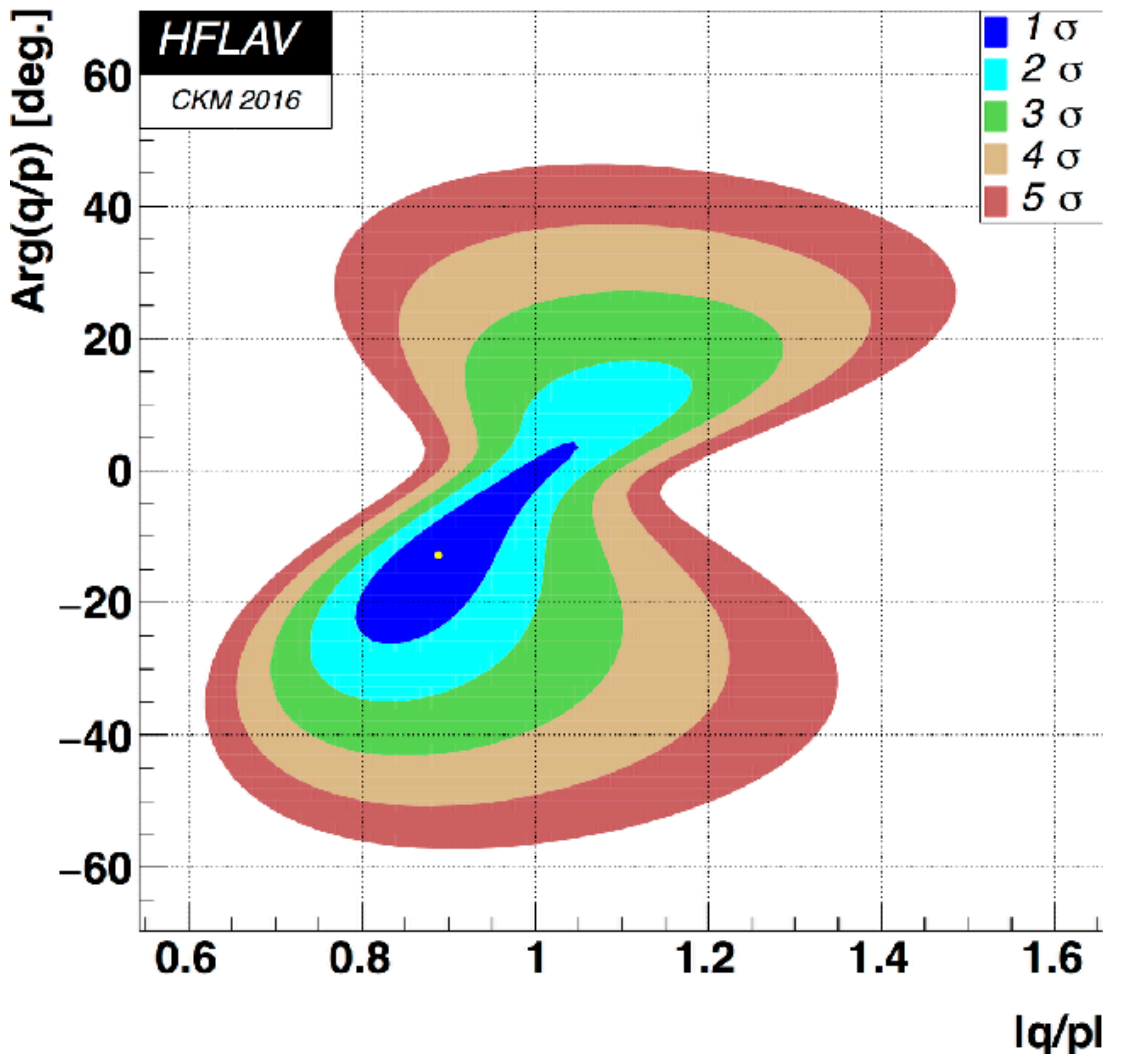
Charm mixing global fit



Parameter	No CPV	No direct CPV in DCS decays	CPV-allowed
x (%)	$0.46^{+0.14}_{-0.15}$	$0.41^{+0.14}_{-0.15}$	0.32 ± 0.14
y (%)	0.62 ± 0.08	0.61 ± 0.07	$0.69^{+0.06}_{-0.07}$
$\delta_{K\pi}$ (°)	$8.0^{+9.7}_{-11.2}$	$4.8^{+10.4}_{-12.3}$	$15.2^{+7.6}_{-10.0}$
R_D (%)	$0.348^{+0.004}_{-0.003}$	$0.347^{+0.004}_{-0.003}$	$0.349^{+0.004}_{-0.003}$
A_D (%)	–	–	-0.88 ± 0.99
$\|q/p\|$	–	0.999 ± 0.014	$0.89^{+0.08}_{-0.07}$
ϕ (°)	–	$0.05^{+0.54}_{-0.53}$	$-12.9^{+9.9}_{-8.7}$
$\delta_{K\pi\pi}$ (°)	$20.4^{+23.3}_{-23.8}$	$22.6^{+24.1}_{-24.4}$	$31.7^{+23.5}_{-24.2}$
A_π(%)	–	0.02 ± 0.13	0.01 ± 0.14
A_K(%)	–	-0.11 ± 0.13	-0.11 ± 0.13

Charm: direct and indirect CPV





$a_{CP}^{ind} = (+0.056 \pm 0.040)\%$

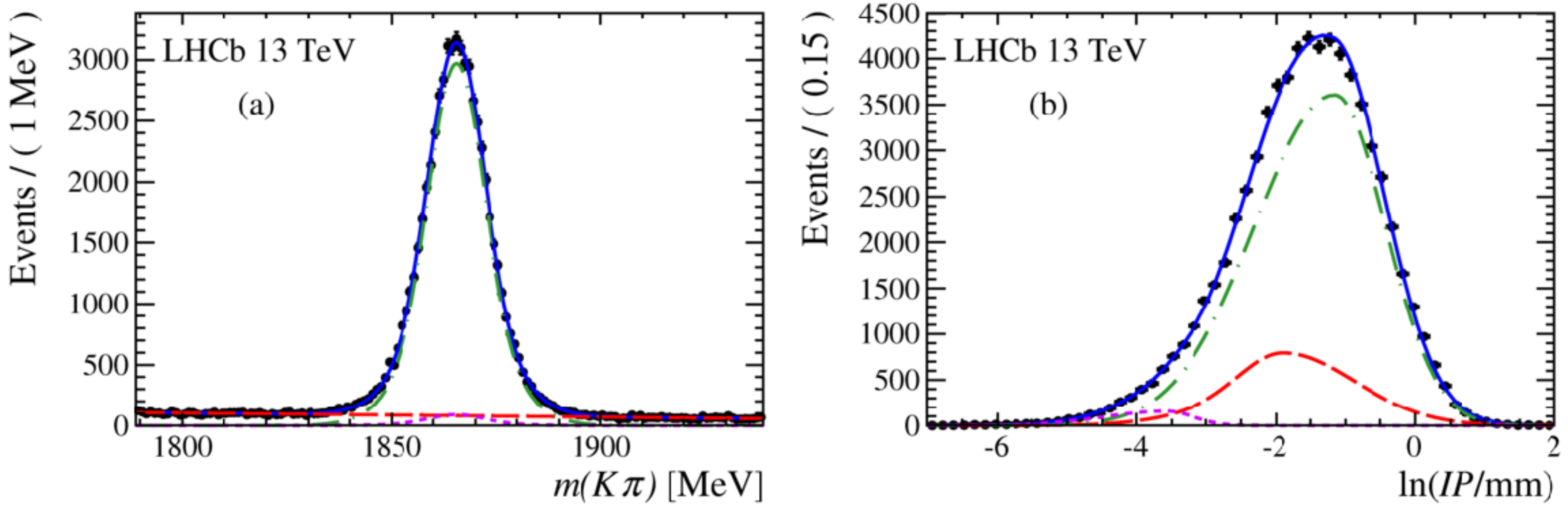
$\Delta a_{CP}^{dir} = (-0.137 \pm 0.070)\%$

b-quark cross-section

b-quark production cross-section in pp→bbX.

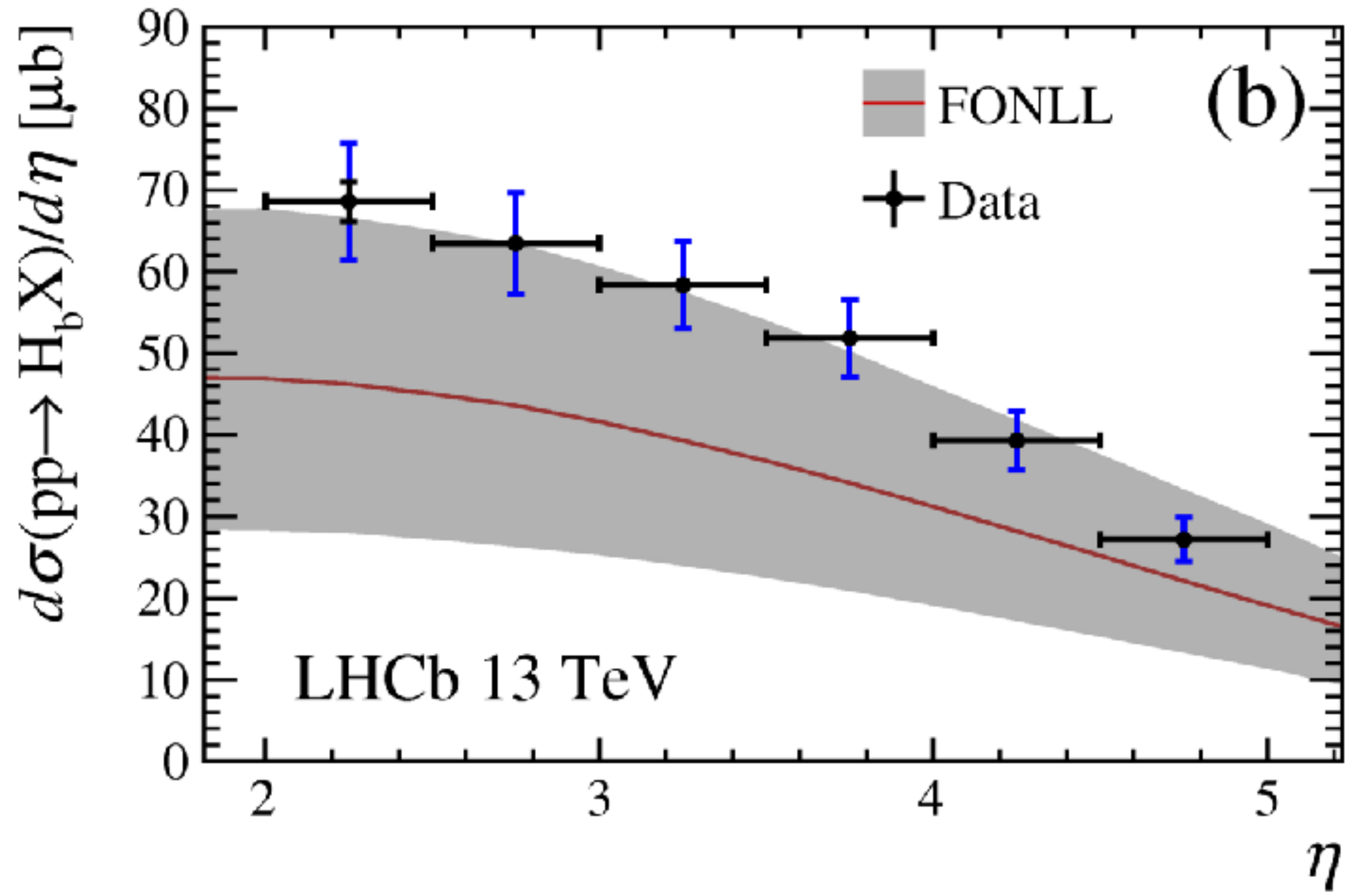
Use semileptonic decays.

Use open-charm mass and IP distribution to separate **D-from-B** and **prompt** components.



Dominated by luminosity measurement

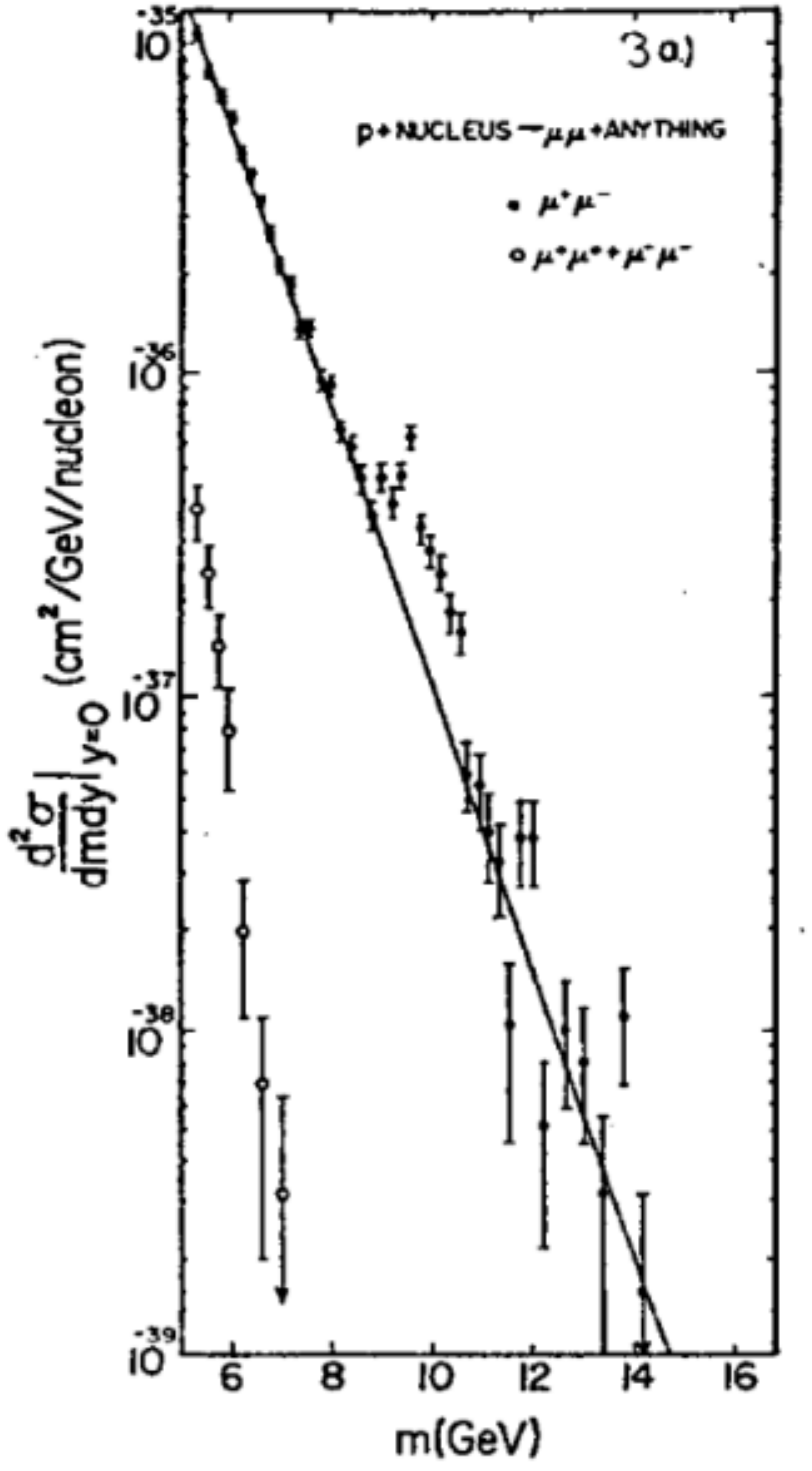
$\sigma(\ 7\text{ TeV}) = \ \ 72.0 \pm 0.3 \pm \ \ 6.8\mu b$
$\sigma(13\text{ TeV}) = 154.3 \pm 1.5 \pm 14.3\mu b$



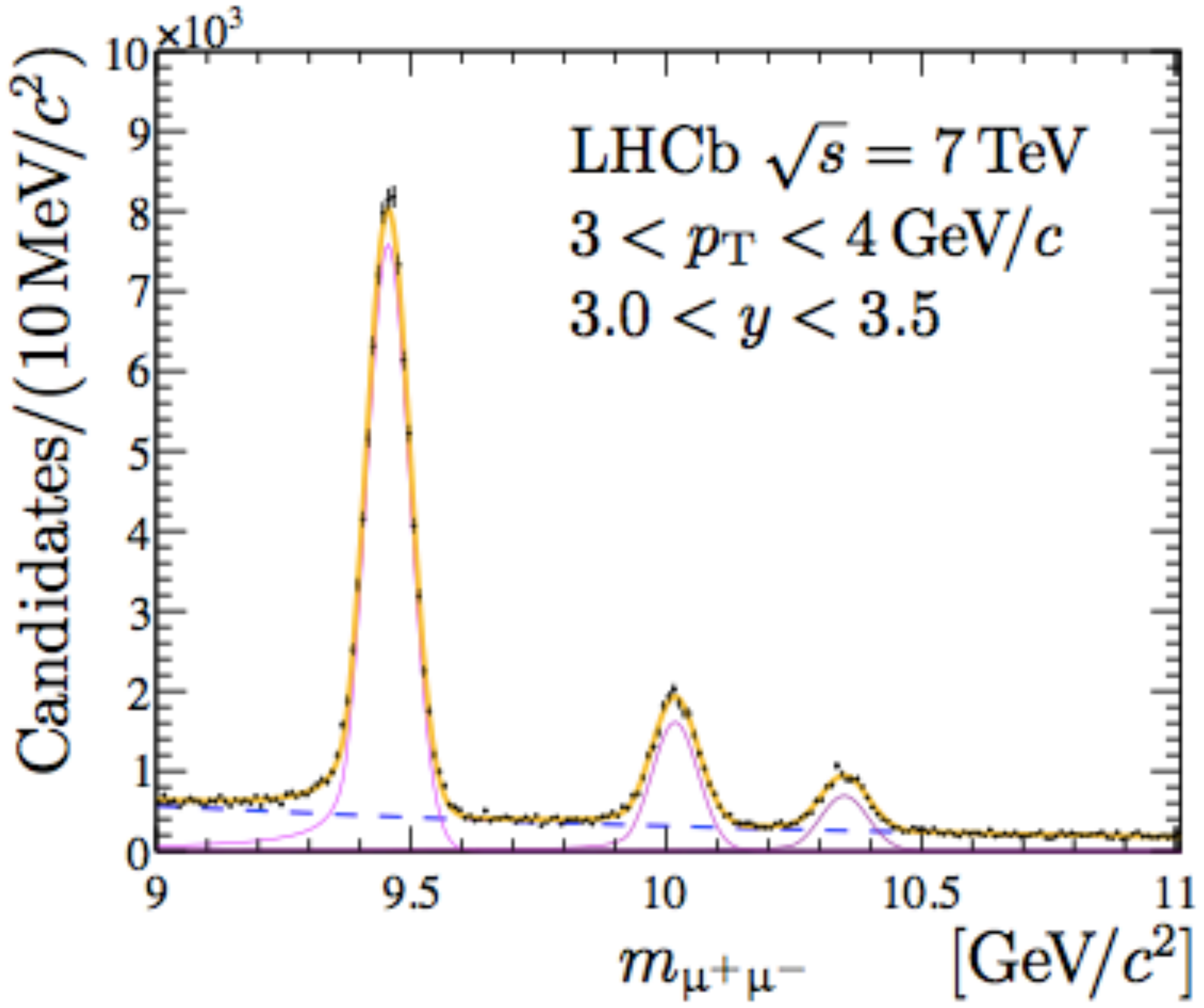
[PRL 118, 052002 (2017)]

The b-quark: then and now

[FNAL-E-0288, PRL 39 (1977) 252]



[LHCb, JHEP 1511 (2015) 103]



Excellent mass resolution
from LHCb's tracking system