LHCb CP violation

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The CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$
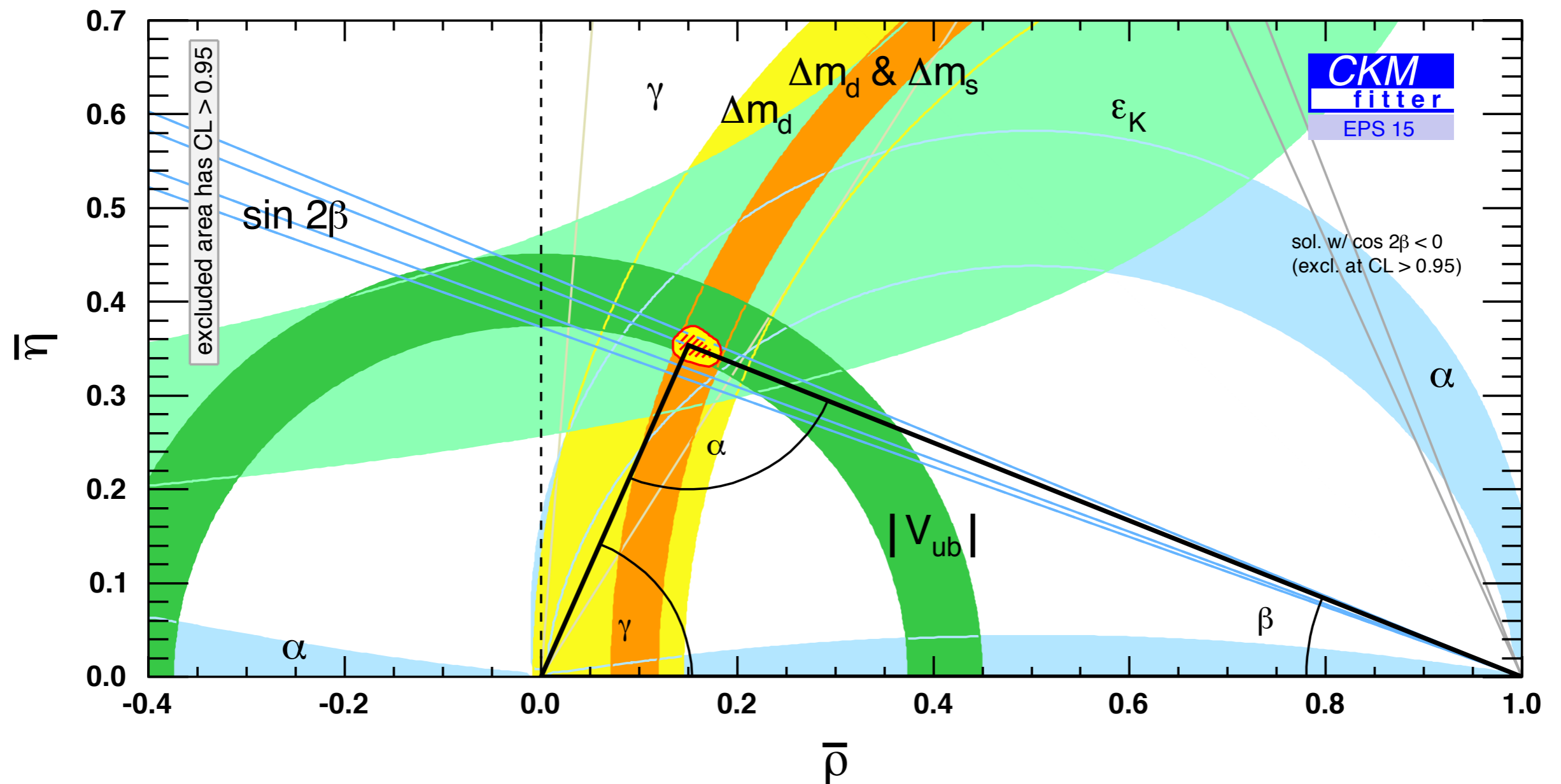
$$\begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$
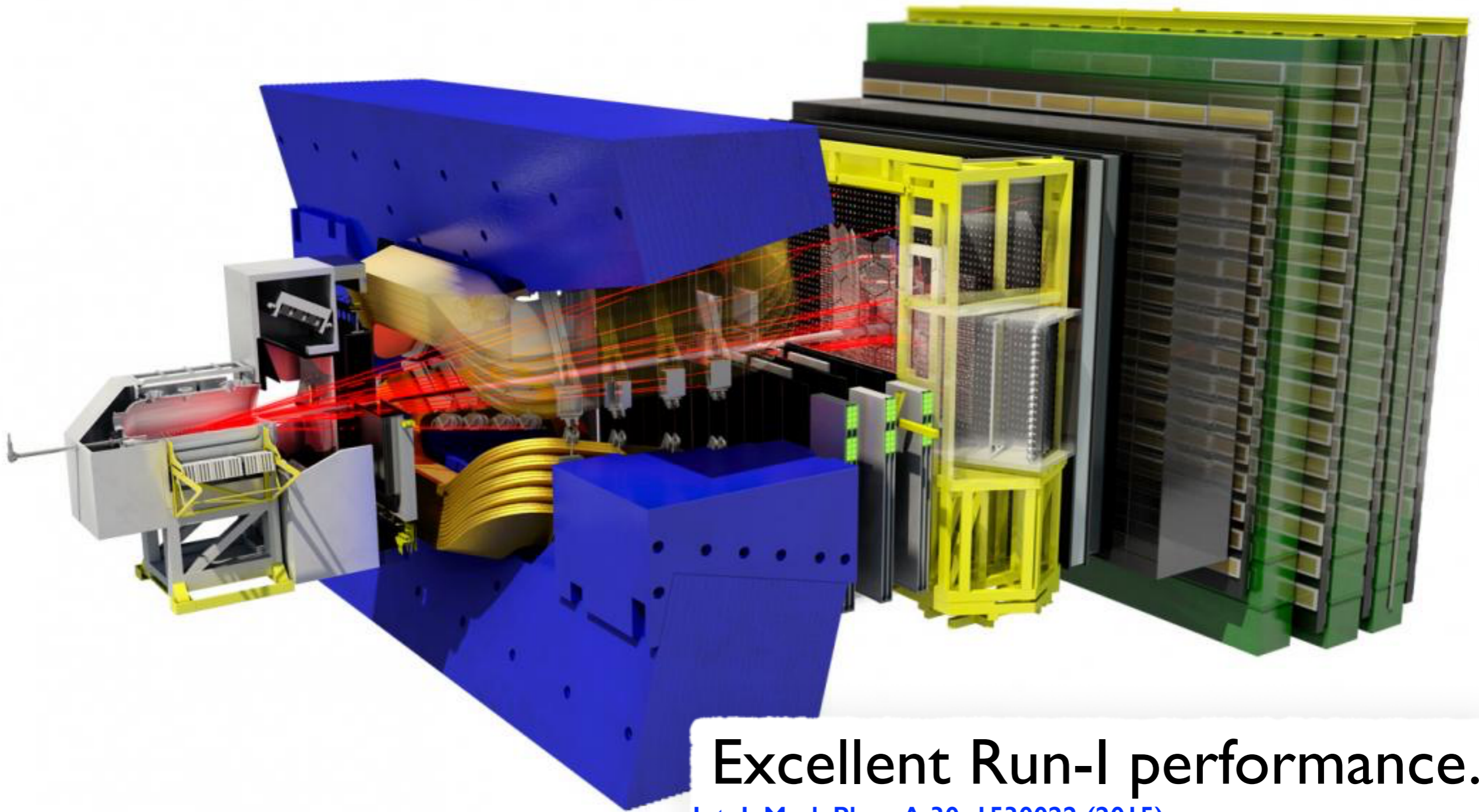
Only CP violating phase affecting quark sector?

Unitarity

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

# The LHCb detector

Excellent Run-I performance.

$3 \text{ fb}^{-1} \rightarrow O(10^{12})$ b hadrons!

Recent CPV results

sin2β with $B_d \rightarrow J/\Psi K_s$	3 fb^{-1}	**PRL 115, 031601** [LHCb-PAPER-2015-004]
ΔM_d with semileptonic B decays	3 fb^{-1}	**LHCb-CONF-2015-003** **preliminary**
Penguin study with $B_s \rightarrow J/\Psi K^*$	3 fb^{-1}	**arXiv:1509.00400** [LHCb-PAPER-2015-034]
γ with $B \rightarrow Dh\pi\pi$	3 fb^{-1}	**arXiv:1505.07044** [LHCb-PAPER-2015-020]
$|V_{ub}|/|V_{cb}|$ with $\Lambda_b \rightarrow p\mu\nu$	2 fb^{-1}	**Nature Phys 10 (2015) 1038** [LHCb-PAPER-2015-013]

Loop processes

sin2β with B_d → J/ψK_s

B_d^0

ϕ_{dec}
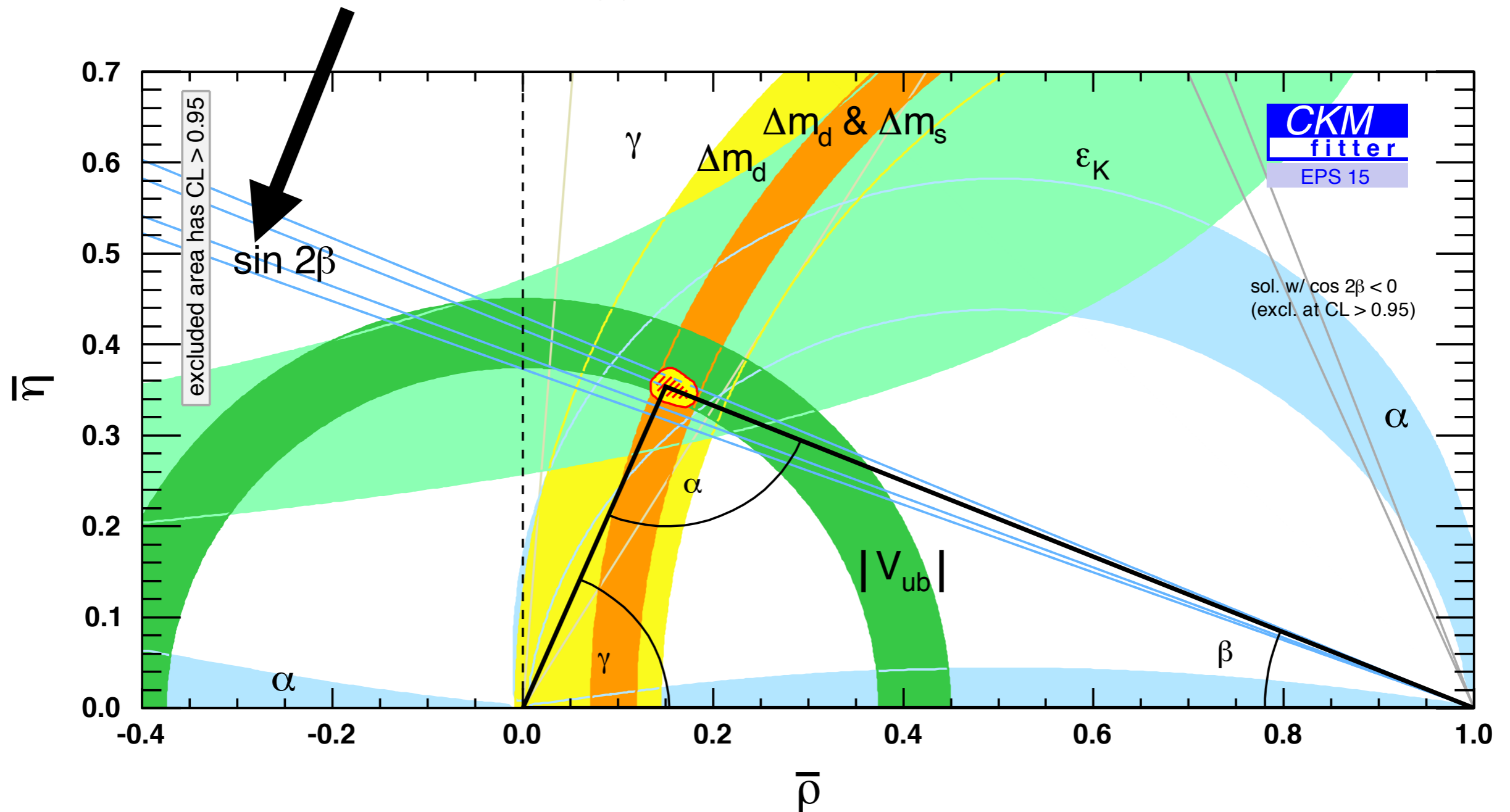
ϕ_{mix}

f

$\overline{B}_d^0$

$-\phi_{\mathrm{dec}}$
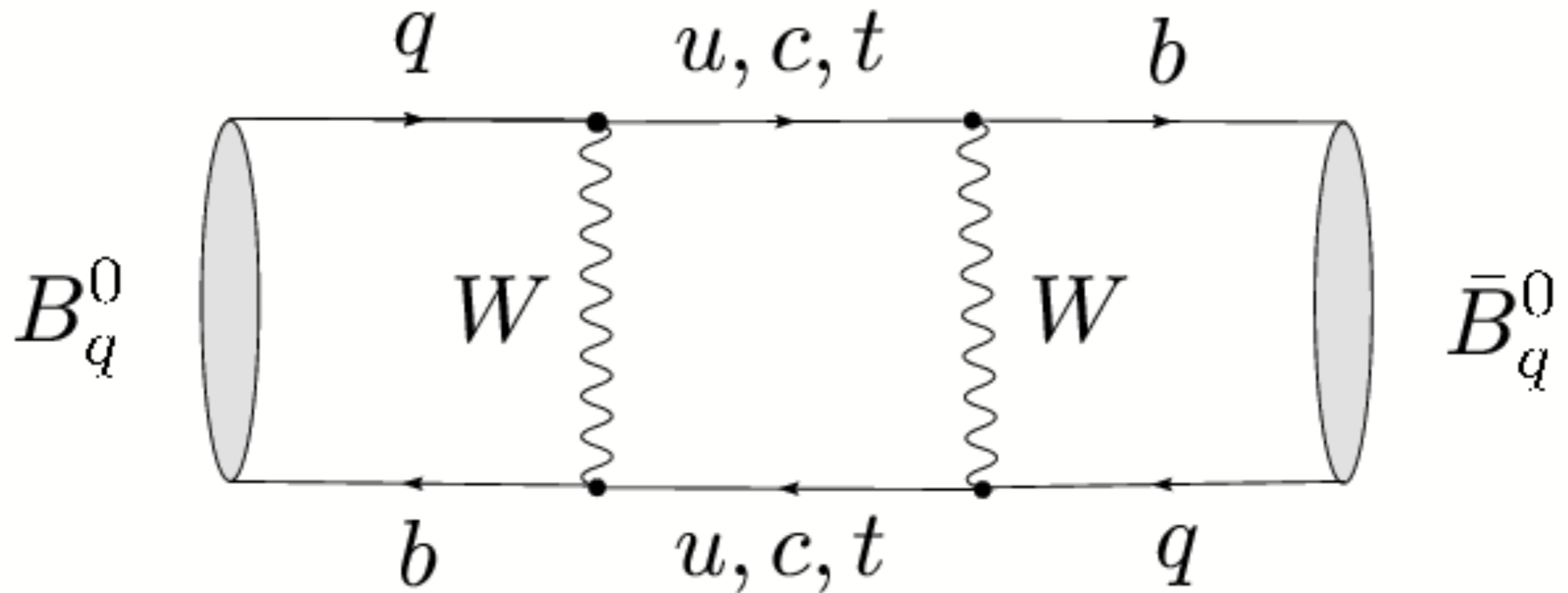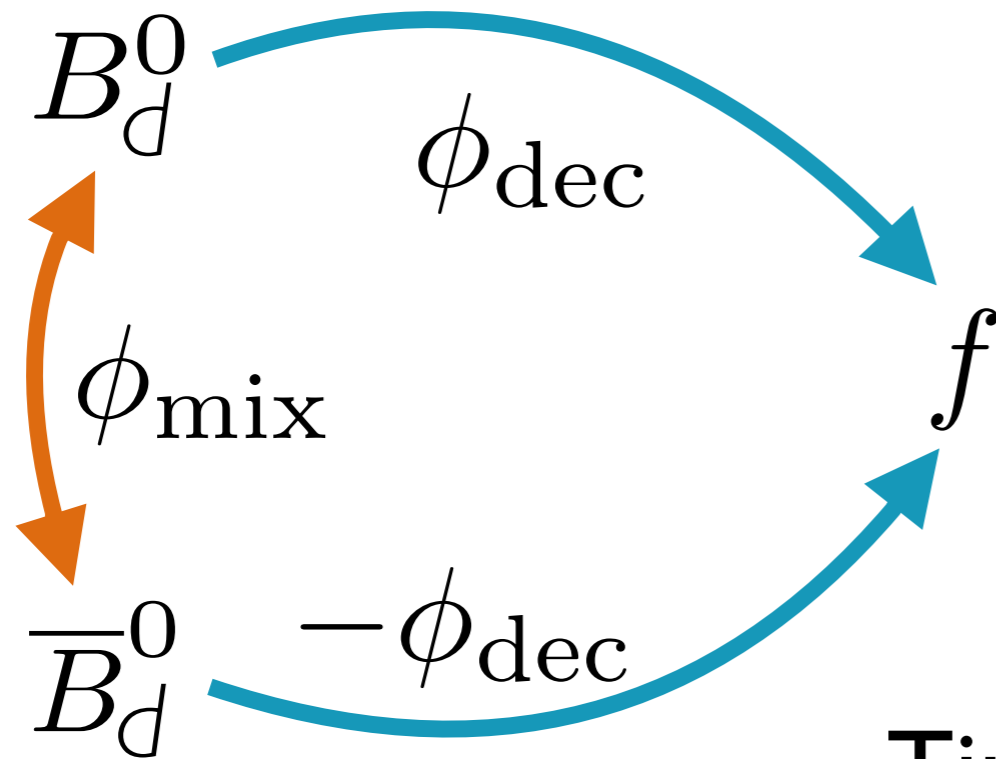
Time dependent CP asymmetry

$$\frac{\Gamma(\bar{B}_d^0(t) \to f) - \Gamma(B_d^0(t) \to f)}{\Gamma(\bar{B}_d^0(t) \to f) + \Gamma(B_d^0(t) \to f)} = \frac{S \sin(\Delta m_d t) - C \cos(\Delta m_d t)}{\cosh\left(\frac{\Delta \Gamma_d t}{2}\right) + A_{\Delta \Gamma} \sinh\left(\frac{\Delta \Gamma_d t}{2}\right)}$$
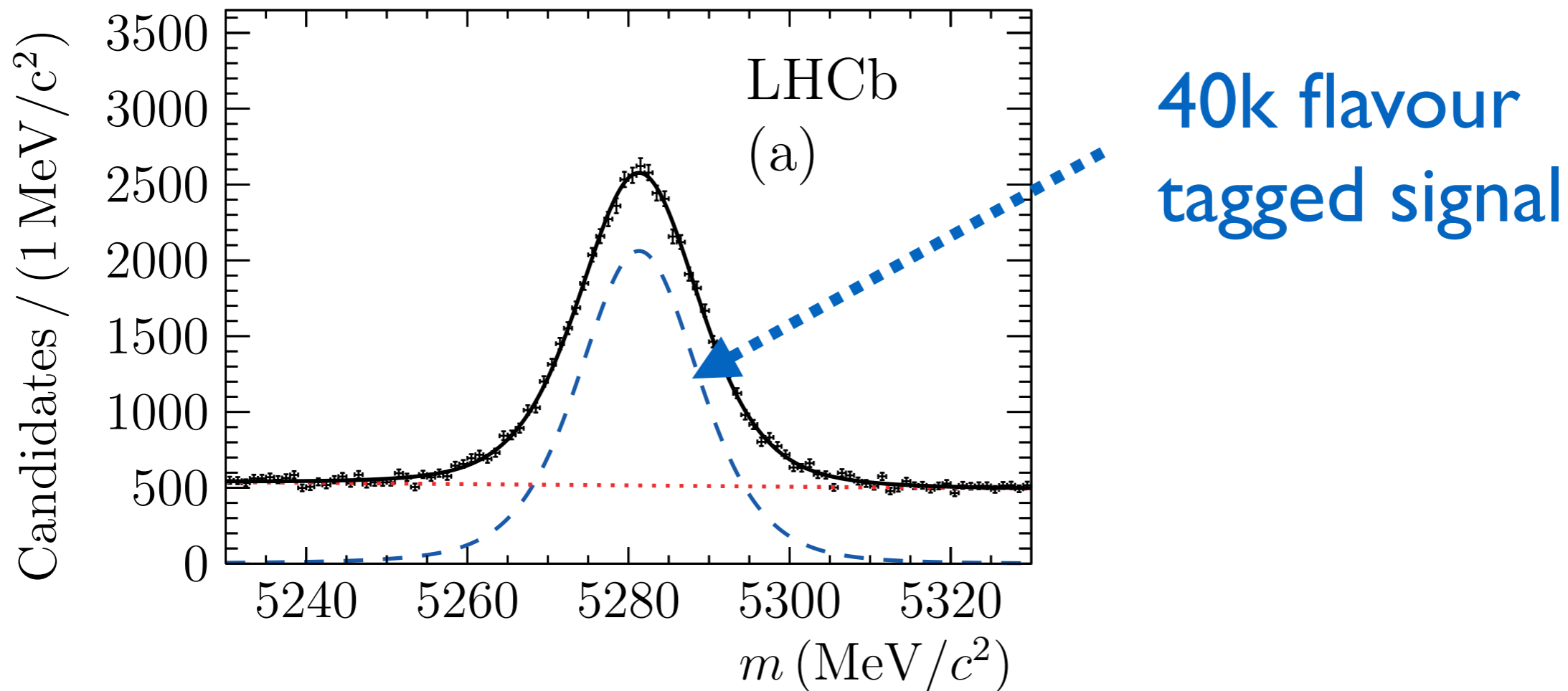
S=sin2β

sin2β with B$_d$ → J/ψK$_s$

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

sin2β with $B_d \to J/\psi K_s$

40k flavour tagged signal

Compared to previous analysis (**PLB 721 24 (2013)**), tagging efficiency, ϵD^2 increased from 2.4% to 3%, with addition of SSπ algorithm.
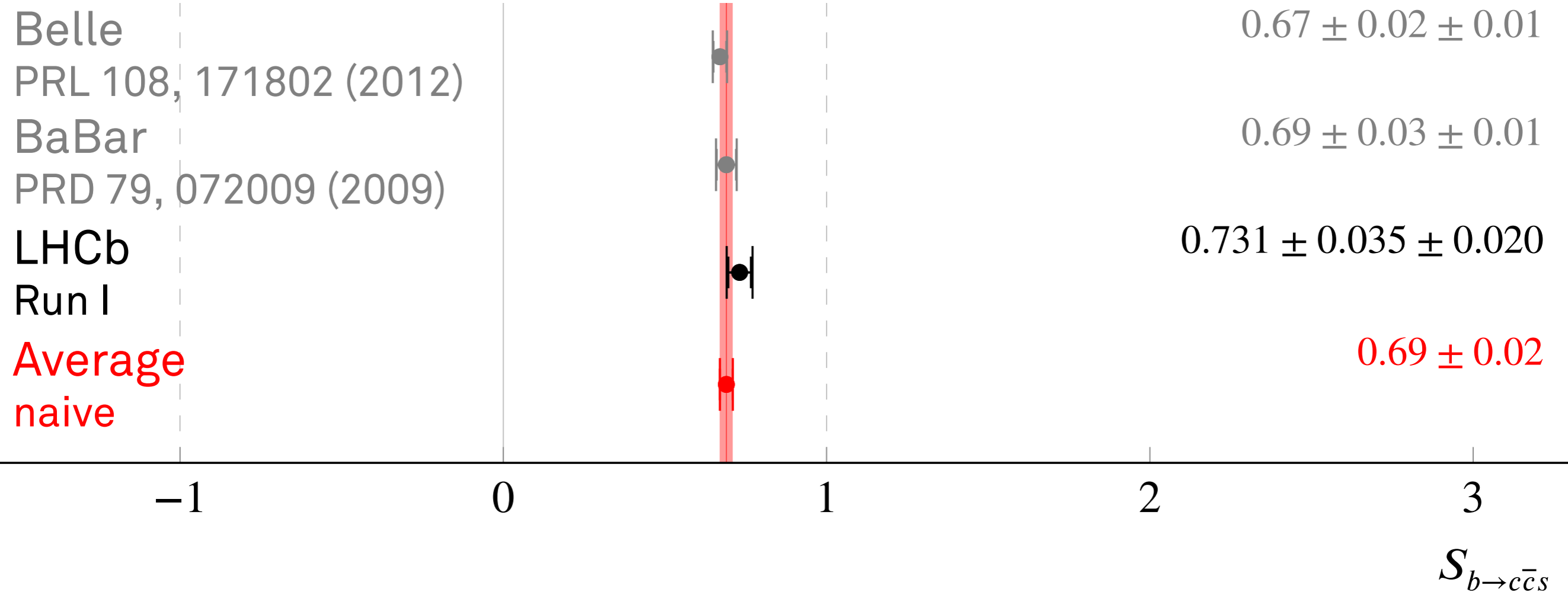
sin2β with B$_d$ →J/ψK$_s$
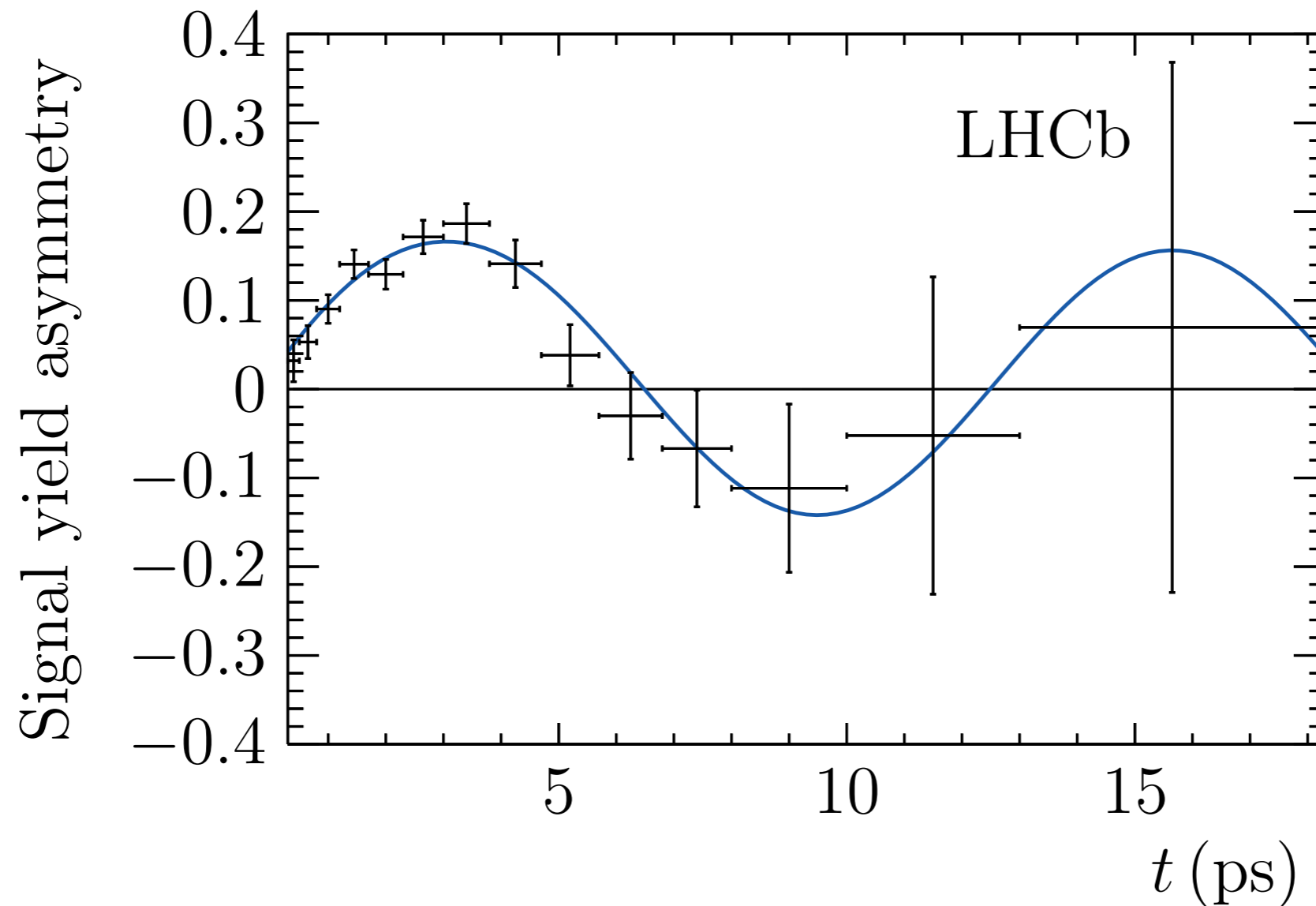
$$S = \quad 0.731 \pm 0.035 \pm 0.020$$

$$C = -0.038 \pm 0.032 \pm 0.005$$

The best three

Belle
PRL 108, 171802 (2012)

$0.67 \pm 0.02 \pm 0.01$

BaBar
PRD 79, 072009 (2009)

$0.69 \pm 0.03 \pm 0.01$

LHCb
Run I

$0.731 \pm 0.035 \pm 0.020$

Average
naive

0.69 ± 0.02

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

LHCb already competitive with the B-factories
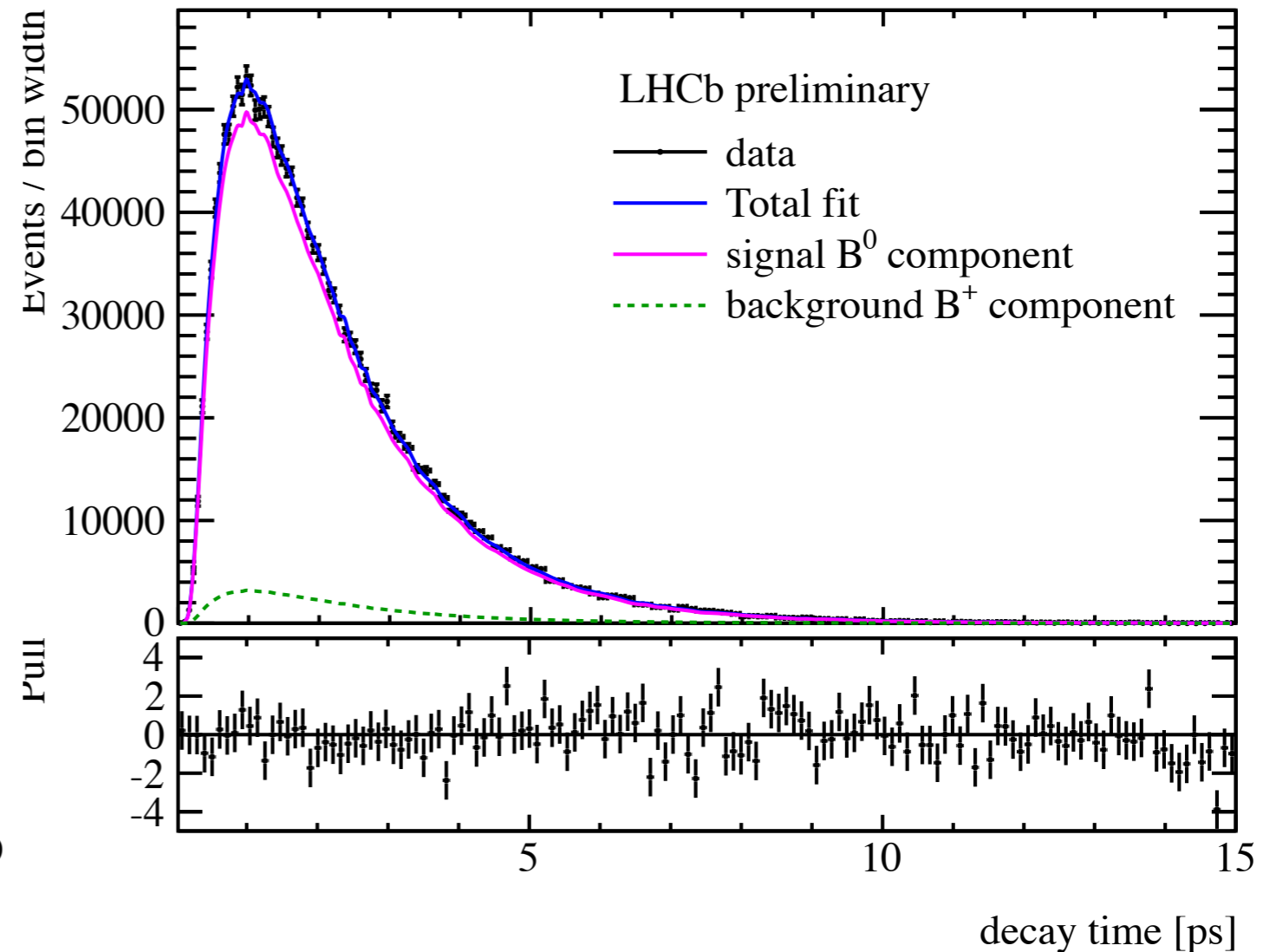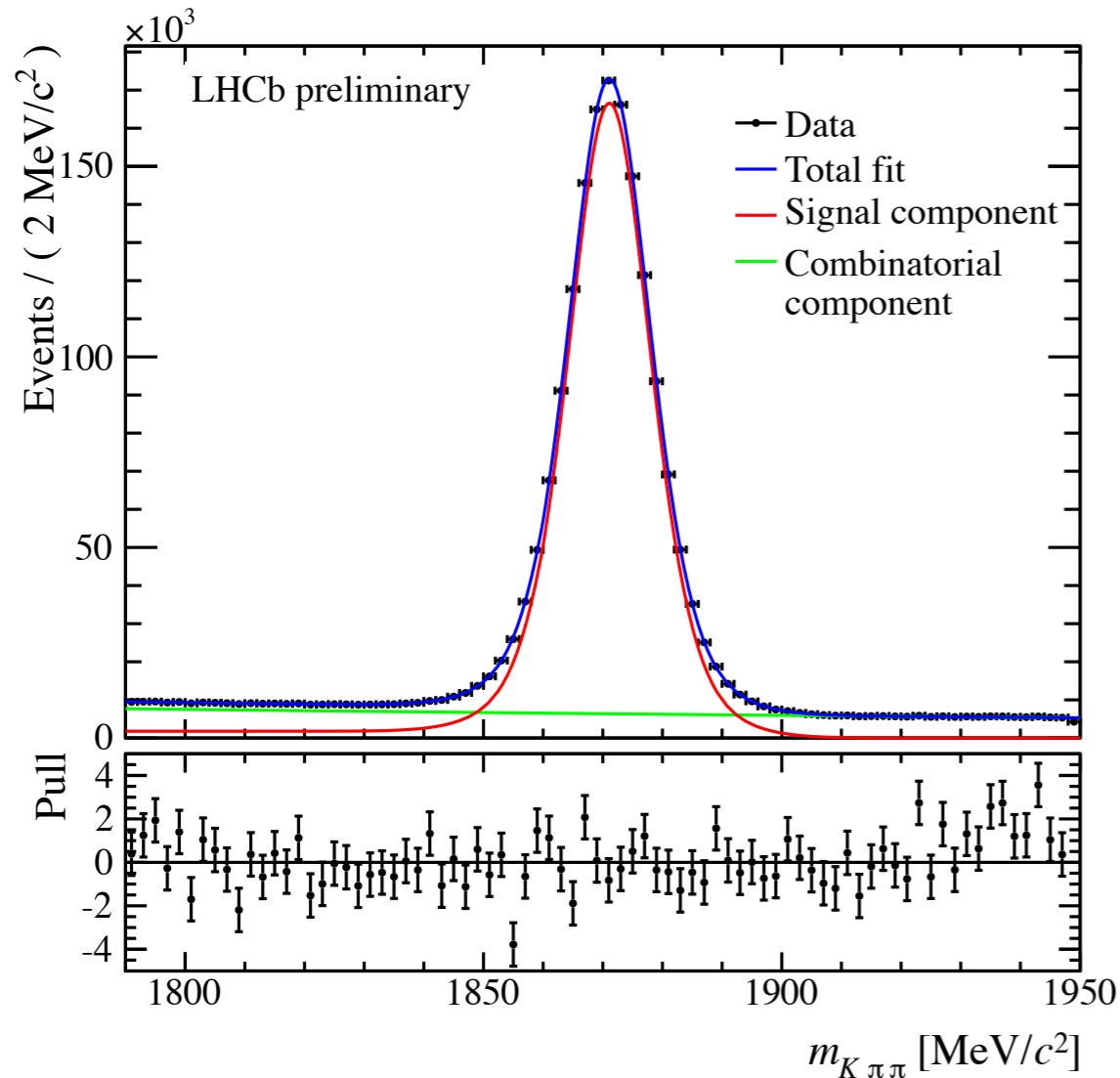
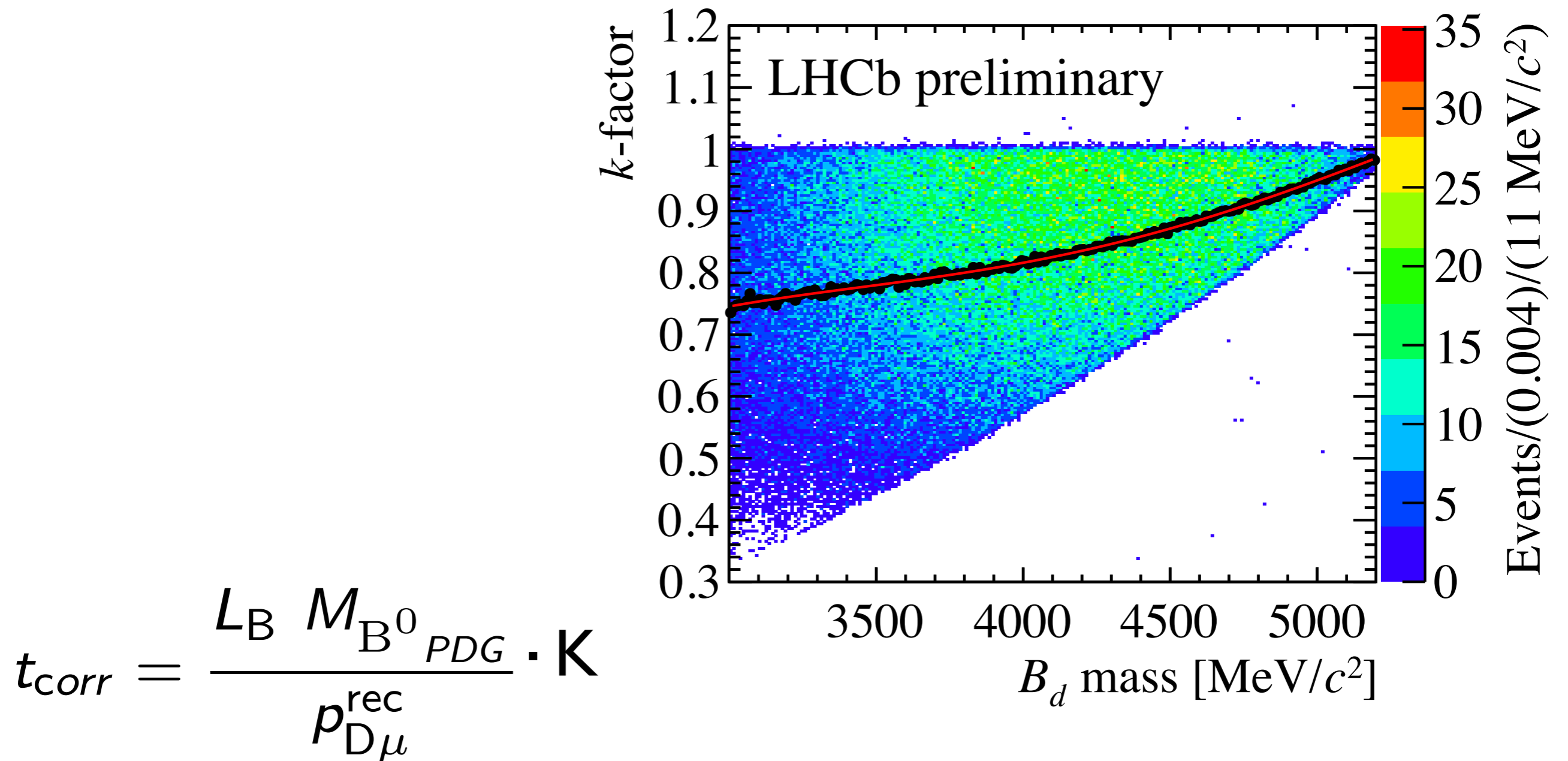# Δm_d with $B \to D^{(*)}\mu\nu$

Flavour tag as mixed or unmixed, and study the asymmetry

$$\frac{N^{\mathrm{unmix}}(t) - N^{\mathrm{mix}}(t)}{N^{\mathrm{unmix}}(t) + N^{\mathrm{mix}}(t)} = \cos(\Delta m_d t)$$

Dependence on $\Delta\Gamma_d$ is neglected in the above formula

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Δm_d with $B \rightarrow D^{(*)}\mu\nu$

Correct decay time for average momentum loss to neutrino, as estimated fro[m]

LHCb preliminar[y]

$$t_{corr} = \frac{L_B \; M_{B^0_{PDG}}}{p^{rec}_{D\mu}} \cdot \mathsf{K}$$
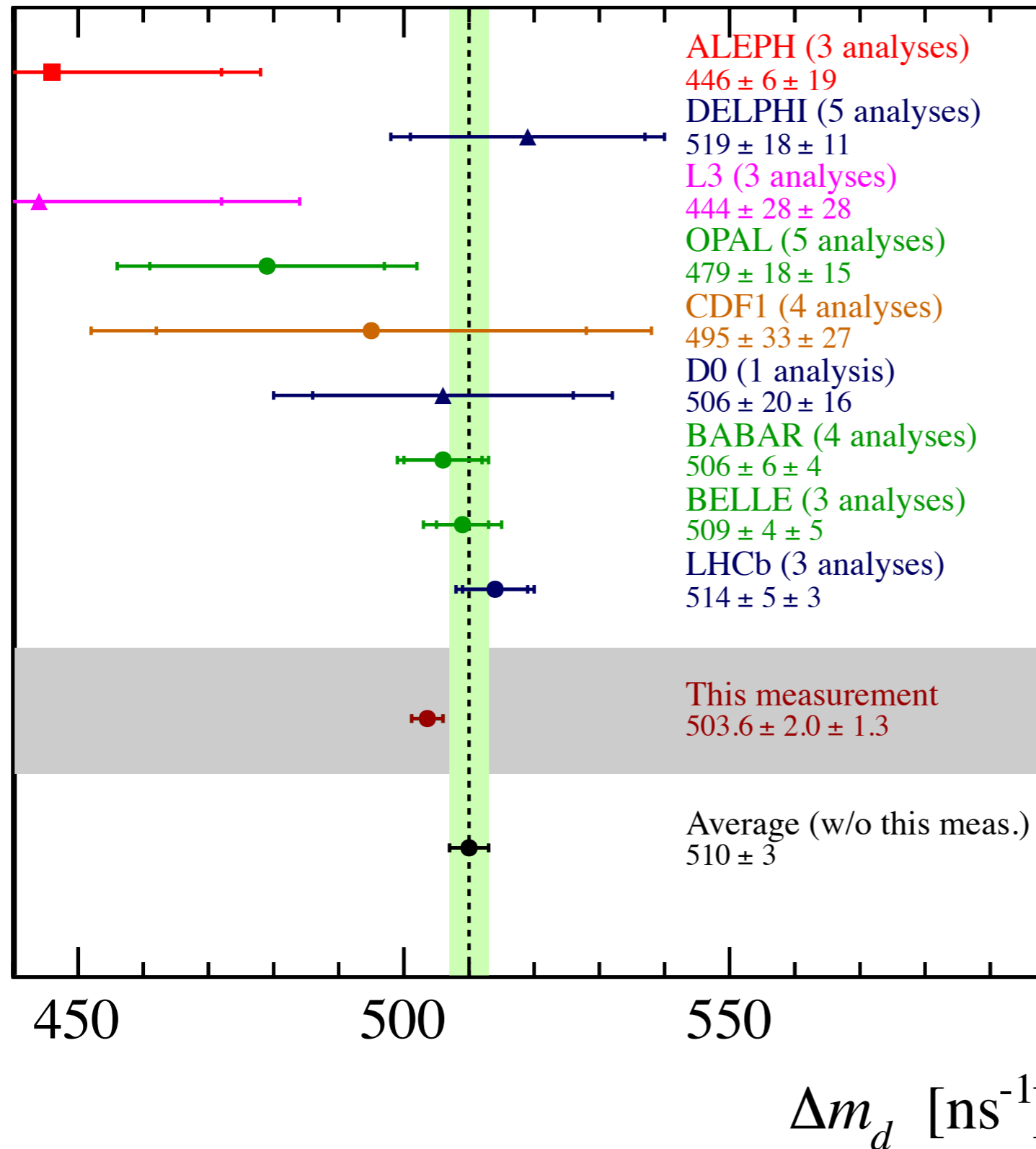
Δm_d with $B \rightarrow D^{(*)} \mu \nu$

Mixing asymmetries, in four bins of mistag probability

2012, D^+
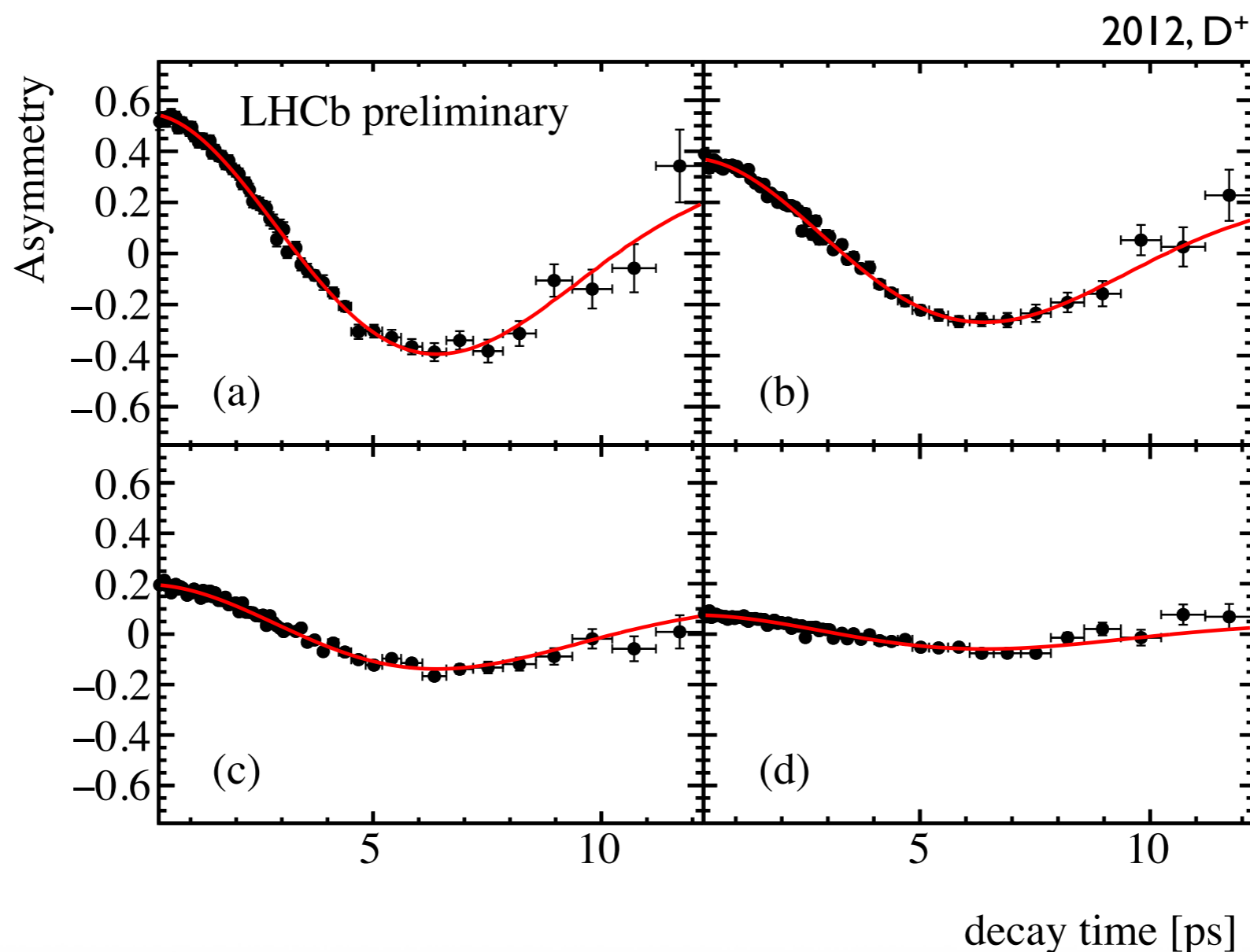
$$\Delta m_d = 503.6 \pm 2.0_{stat} \pm 1.3_{syst} \ ns^{-1}$$

Δm_d with B → D$^{(*)}$μν

ALEPH (3 analyses)
446 ± 6 ± 19
DELPHI (5 analyses)
519 ± 18 ± 11
L3 (3 analyses)
444 ± 28 ± 28
OPAL (5 analyses)
479 ± 18 ± 15
CDF1 (4 analyses)
495 ± 33 ± 27
D0 (1 analysis)
506 ± 20 ± 16
BABAR (4 analyses)
506 ± 6 ± 4
BELLE (3 analyses)
509 ± 4 ± 5
LHCb (3 analyses)
514 ± 5 ± 3

This measurement
503.6 ± 2.0 ± 1.3

Average (w/o this meas.)
510 ± 3

Most precise single measurement

Δm_d [ns^{-1}]

φ_s status
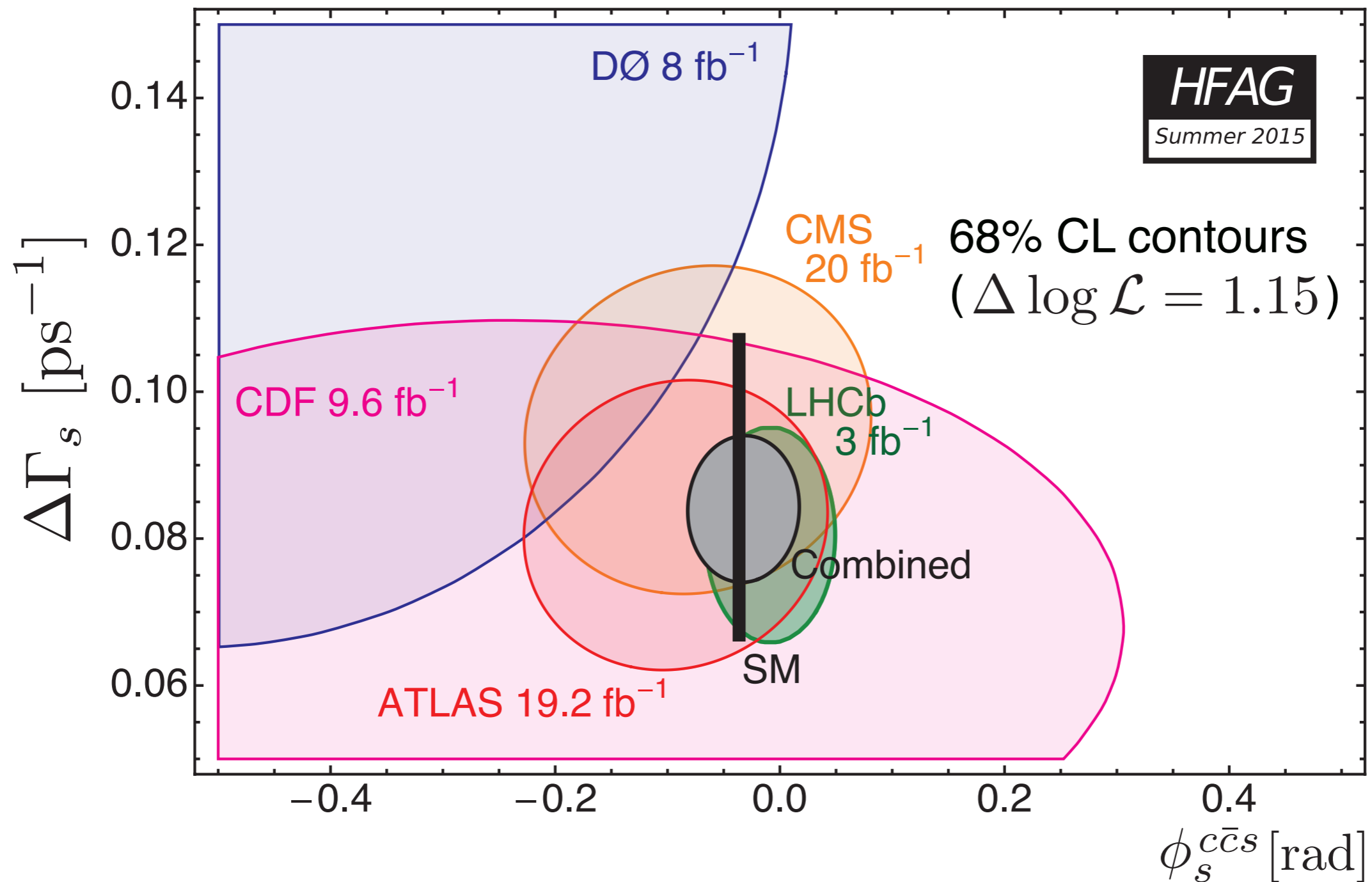
Combination of B_s → J/ΨKK, J/Ψππ, D_sD_s gives:

$$\phi_s = -0.034 \pm 0.033 \text{ rad}$$

Penguin pollution

$$\phi_{s,i} = -2\beta_s + \phi_s^{\text{BSM}} + \Delta\phi_{s,i}^{J/\psi\,\phi}(a_i', \theta_i')$$

V_{cs}

B_s^0 b W c J/ψ c s ϕ s

s

φ

Colour singlet exchange

B_s^0 b u, c, t W s ϕ s c J/ψ c

Colour singlet exchange

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Penguin pollution
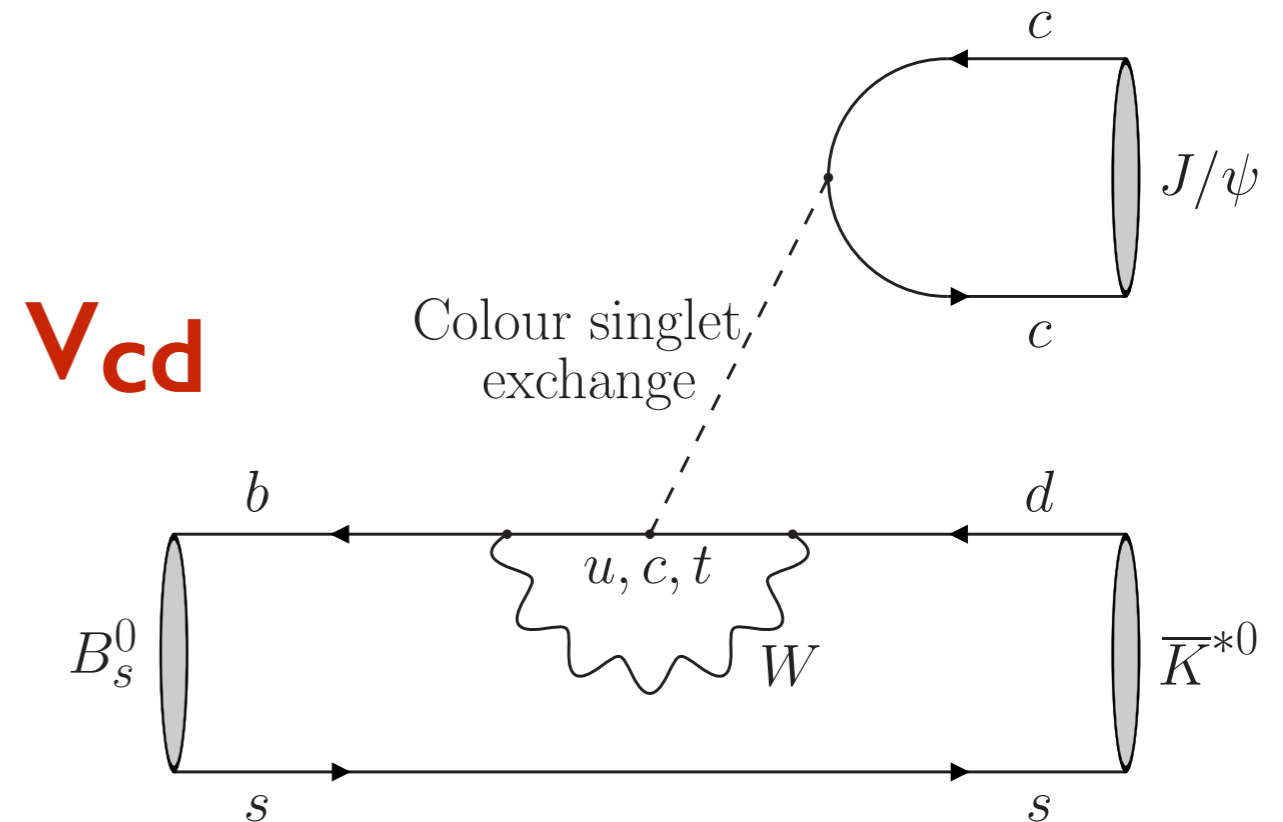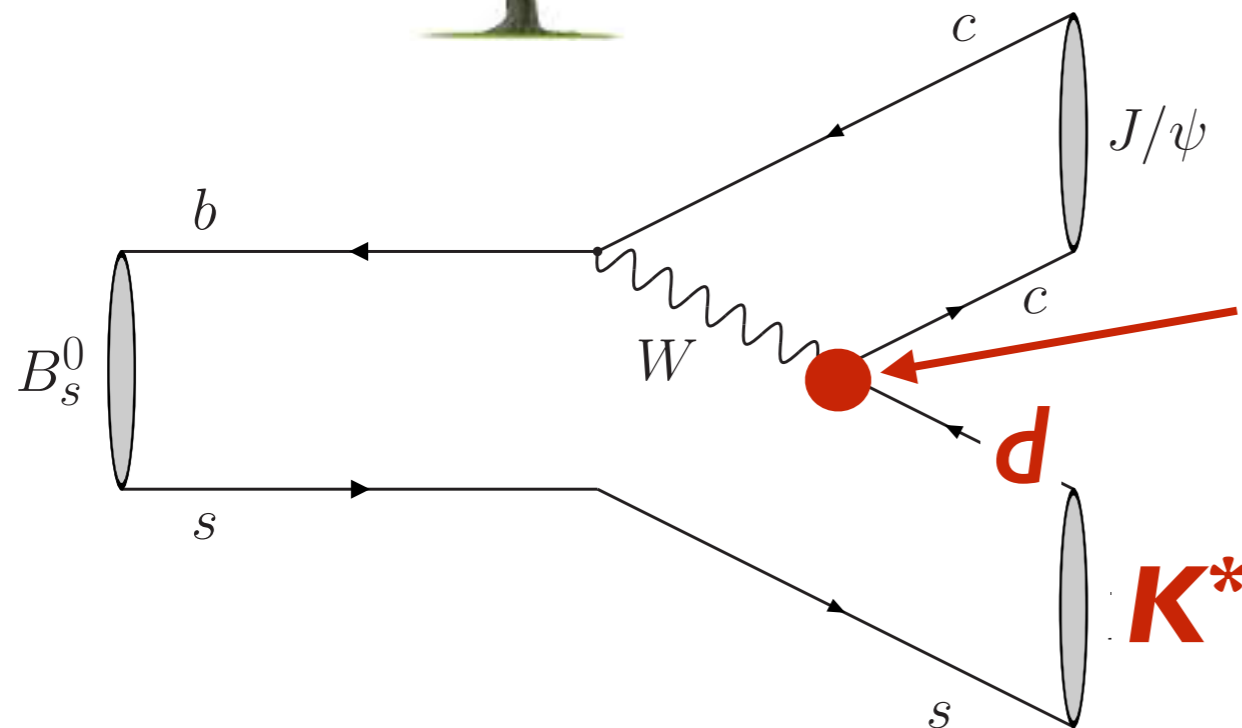

$$\phi_{s,i} = -2\beta_s + \phi_s^{\text{BSM}} + \Delta\phi_{s,i}^{J/\psi\,\phi}(a_i', \theta_i')$$

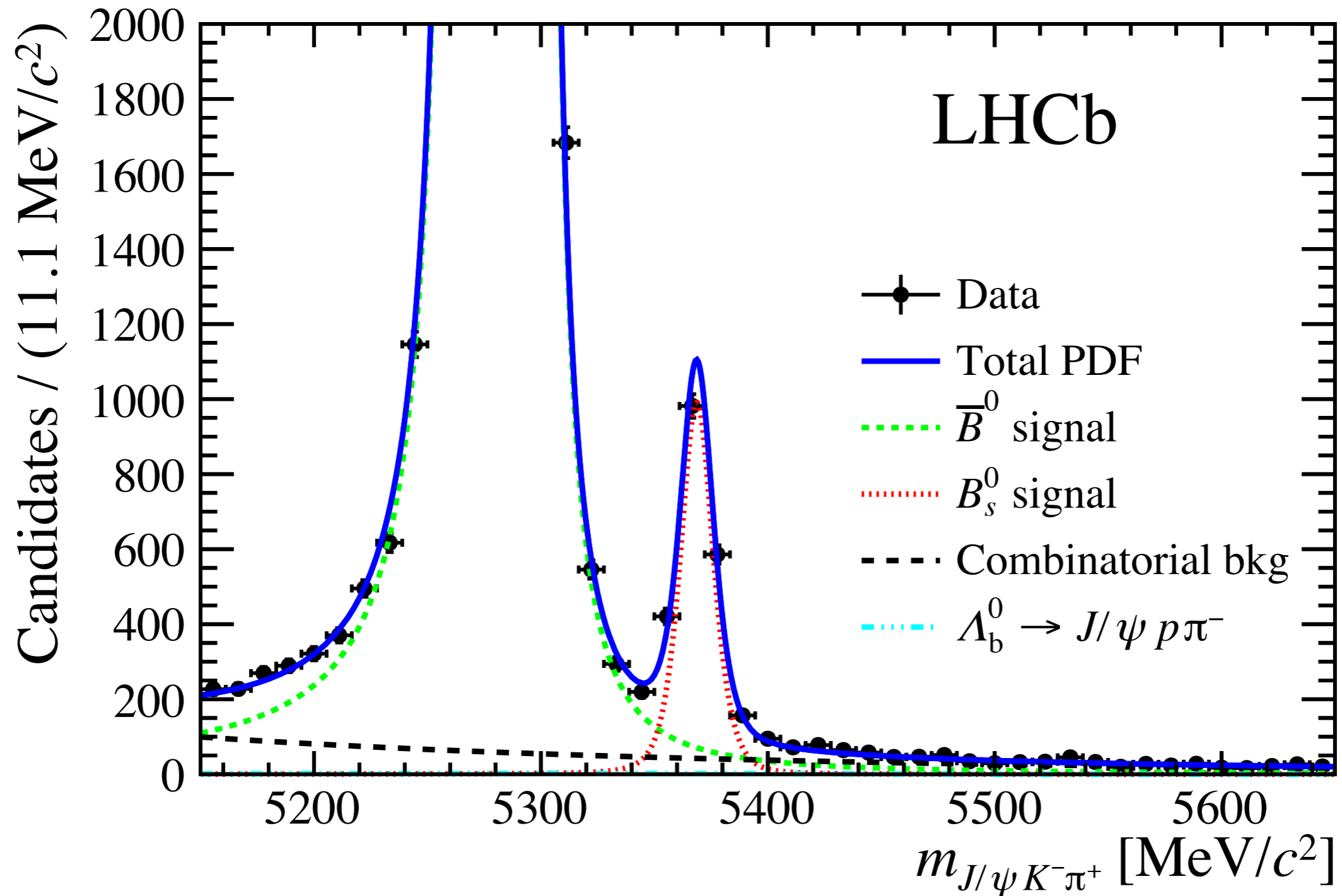Study decay in which the tree diagram is CKM suppressed

Penguin study, B$_s$ → J/ψK*

Penguin study, B$_s$ → J/ΨK*

- Measure the branching fraction,

$$\mathcal{B}(B_s^0 \to J/\psi \, \overline{K}^{*0}) = \left(4.17 \pm 0.18(\text{stat}) \pm 0.26(\text{syst}) \pm 0.24(f_d/f_s) \right) \times 10^{-5}$$

- Polarisation fractions,

$$f_0 = 0.497 \pm 0.025 \ (\text{stat}) \pm 0.025 \ (\text{syst})$$
$$f_\parallel = 0.179 \pm 0.027 \ (\text{stat}) \pm 0.013 \ (\text{syst})$$

- And CP asymmetries,

$$A_0^{CP}(B_s^0 \to J/\psi \, \overline{K}^{*0}) = -0.048 \pm 0.057 \ (\text{stat}) \pm 0.020 \ (\text{syst})$$
$$A_\parallel^{CP}(B_s^0 \to J/\psi \, \overline{K}^{*0}) = 0.171 \pm 0.152 \ (\text{stat}) \pm 0.028 \ (\text{syst})$$
$$A_\perp^{CP}(B_s^0 \to J/\psi \, \overline{K}^{*0}) = -0.049 \pm 0.096 \ (\text{stat}) \pm 0.025 \ (\text{syst})$$

Penguin study, B$_s$ → J/ψK*

Combination with LHCb study of SU(3) related B$_d$ → J/ψρ
(PLB 742 (2015) 38-49)

$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}\,(\mathrm{stat}) \quad {}^{+0.004}_{-0.009}\,(\mathrm{syst})\,\mathrm{rad}\,,$$

$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014}\,(\mathrm{stat}) \pm 0.008\,(\mathrm{syst})\,\mathrm{rad}\,,$$

$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014}\,(\mathrm{stat}) \pm 0.008\,(\mathrm{syst})\,\mathrm{rad}\,.$$
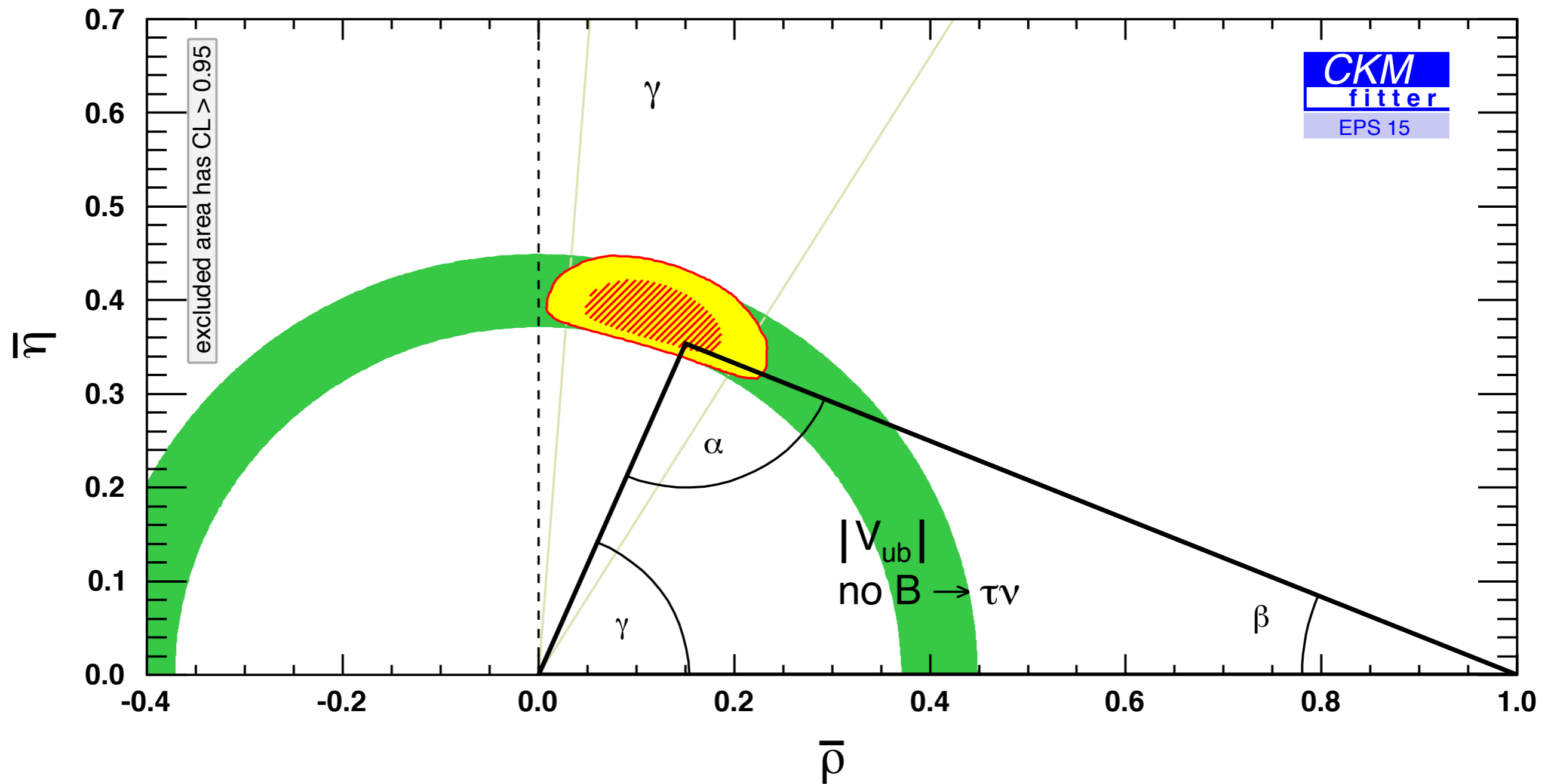
$$\phi_{s,i} = -2\beta_s + \phi_s^{\mathrm{BSM}} + \Delta\phi_{s,i}^{J/\psi\phi}(a_i', \theta_i')$$
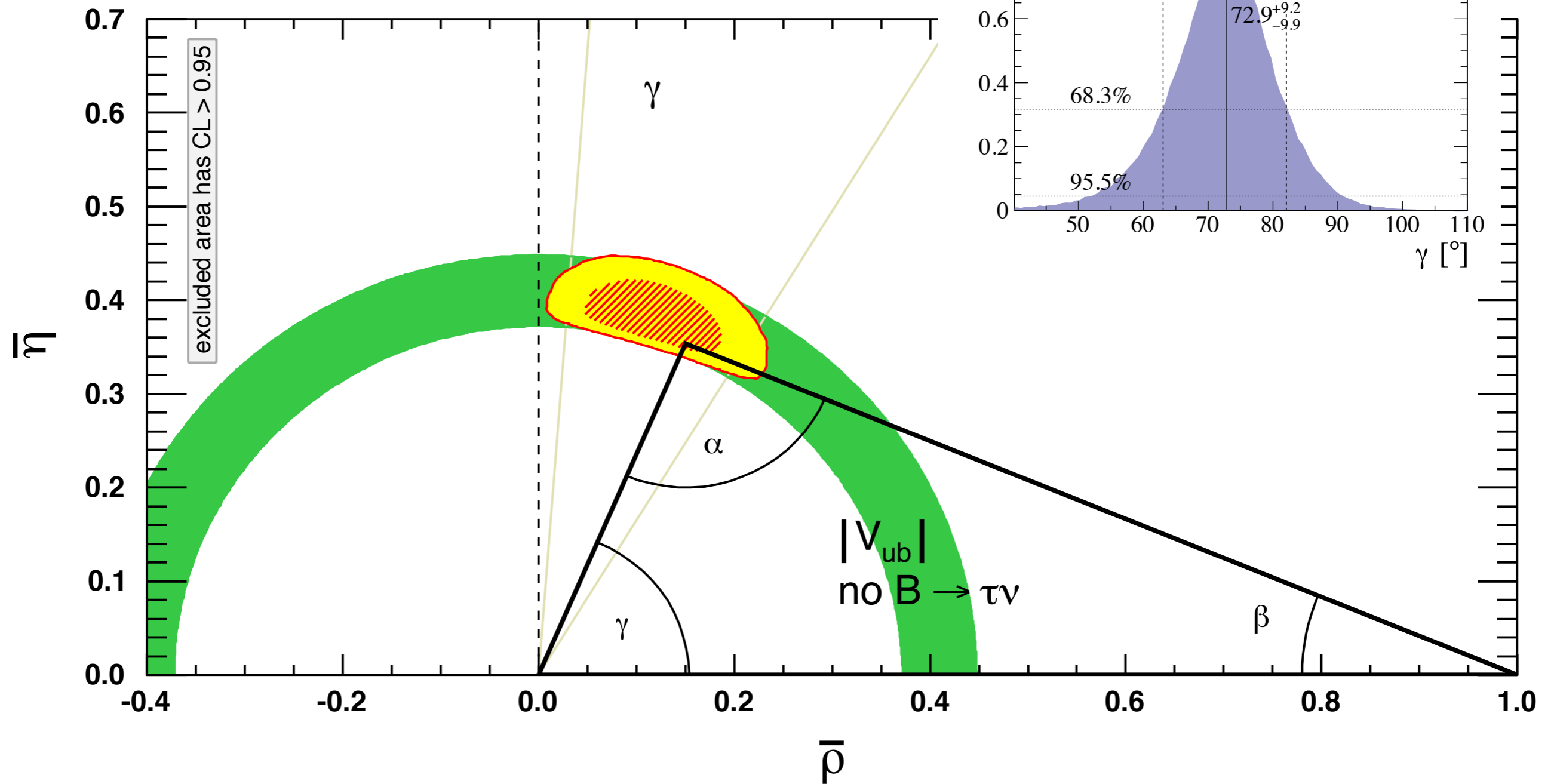
Penguin pollution to Φ$_s$ is small

Tree level constraints

$$\gamma \equiv \arg(-V_{ud}V_{ub}^*/V_{cb}V_{cd}^*)$$

Tree level constraints

$$\gamma \equiv \arg(-V_{ud}V_{ub}^*/V_{cb}V_{cd}^*)$$

$72.9^{+9.2}_{-9.9}$

$126.8^{+9.9}_{-11.5}$

$0.0914^{+0.0083}_{-0.0088}$

excluded area has CL > 0.95

no B → τν

Measuring γ

$$\gamma \equiv \arg(-V_{ud}V_{ub}^*/V_{cb}V_{cd}^*)$$

Interference between b→u and b→c decays
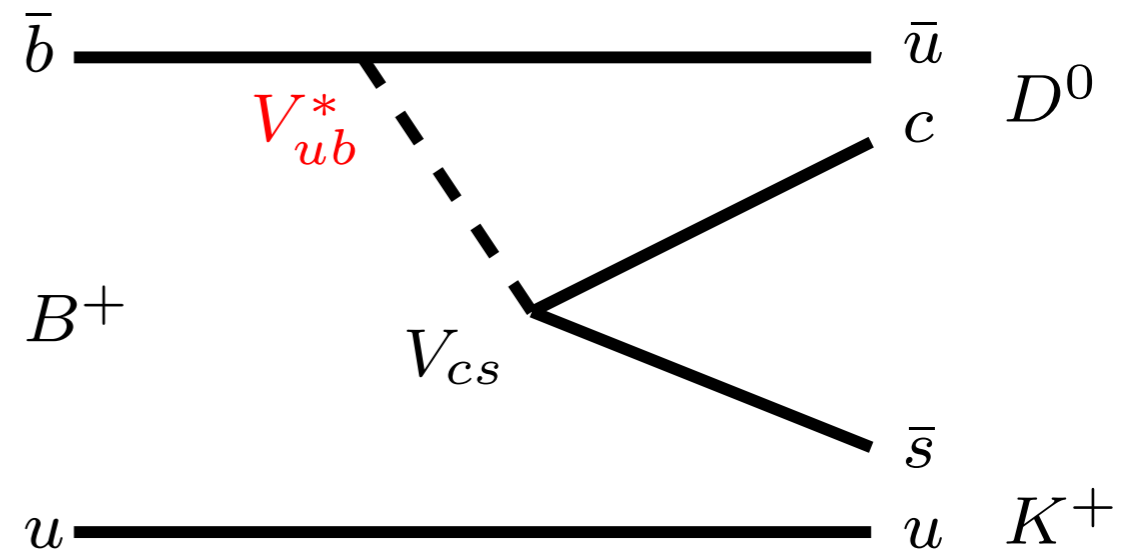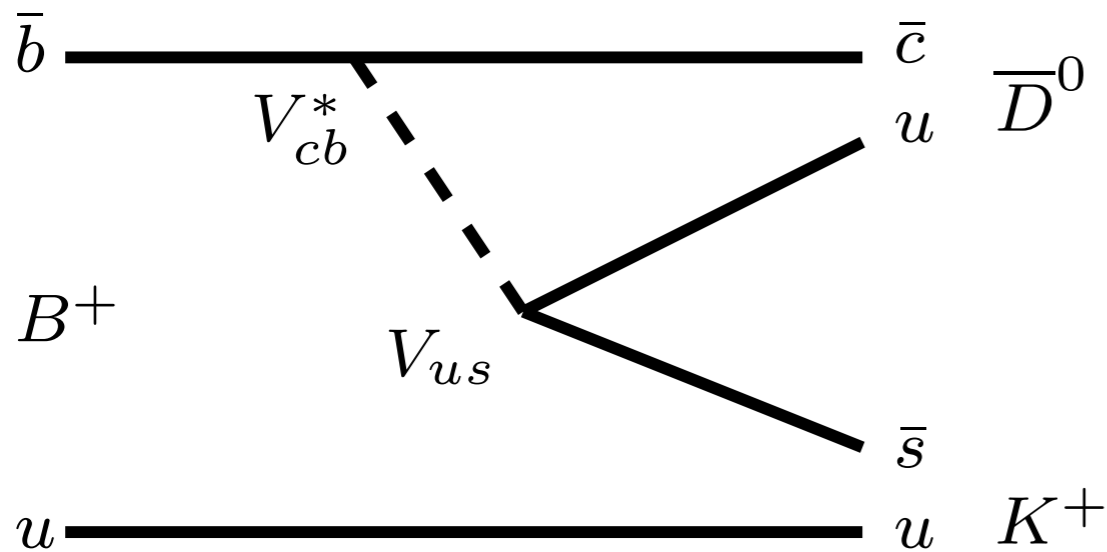
With other recoiling strange systems? (**Gronau, PLB557 (2003) 198**)

e.g., K⁺π⁻π⁺?

γ from $B^- \to D^0 h^- \pi^+ \pi^-$

Measure BRs and CP asymmetries in 16 different decay modes (8 x $D^0 K\pi\pi$, 8 x $D^0 \pi\pi\pi$)

Decay mode	B^- yield (N^f_{fit,X_d^-})	B^+ yield (N^f_{fit,X_d^+})
$B^\pm \to DX_d^\pm$, $D \to K^-\pi^+$	$36\,956 \pm 214$	$37\,843 \pm 219$
$B^\pm \to DX_d^\pm$, $D \to K^+\pi^-$	161 ± 20	162 ± 20
	(N^f_{fit,X_s^-})	(N^f_{fit,X_s^+})
$B^\pm \to DX_s^\pm$, $D \to K^-\pi^+$	1234 ± 37	1226 ± 37
$B^\pm \to DX_s^\pm$, $D \to K^+\pi^-$	13.0 ± 5.3	6.6 ± 4.0

ADS modes
Quasi flavour specific D decays into $K^\pm \pi^\mp$

($X_s = K^\pm \pi^+ \pi^-$, $X_d = \pi^\pm \pi^+ \pi^-$)

GLW modes
D decays into CP-eigenstates $K^+ K^-$ and $\pi^+\pi^-$.

Decay mode	B^- yield (N^f_{fit,X_d^-})	B^+ yield (N^f_{fit,X_d^+})
$B^\pm \to DX_d^\pm$, $D \to K^-\pi^+$	$45\,213 \pm 226$	$46\,488 \pm 230$
$B^\pm \to DX_d^\pm$, $D \to K^+K^-$	3899 ± 63	4084 ± 65
$B^\pm \to DX_d^\pm$, $D \to \pi^+\pi^-$	1669 ± 38	1739 ± 40
	(N^f_{fit,X_s^-})	(N^f_{fit,X_s^+})
$B^\pm \to DX_s^\pm$, $D \to K^-\pi^+$	1699 ± 47	1744 ± 47
$B^\pm \to DX_s^\pm$, $D \to K^+K^-$	155 ± 14	171 ± 14
$B^\pm \to DX_s^\pm$, $D \to \pi^+\pi^-$	59 ± 9	70 ± 9

γ from $B^- \to D^0 h^- \pi^+ \pi^-$

Evidence (3.6σ) for the ADS decay, $B^\pm \to [K^\mp \pi^\pm]_D K^\pm \pi^\mp \pi^\pm$

19.6 ± 6.6

γ from $B^- \rightarrow D^0 h^- \pi^+ \pi^-$

Legend:
- $B^- \rightarrow DK^- \pi^+ \pi^-$, $D \rightarrow h^+ h^-$, 3 fb^{-1}
- $B^- \rightarrow Dh^- \pi^+ \pi^-$, $D \rightarrow h^+ h^-$, 3 fb^{-1}

LHCb

74^{+20}_{-22}
74^{+20}_{-18}

68.3%

95.4%
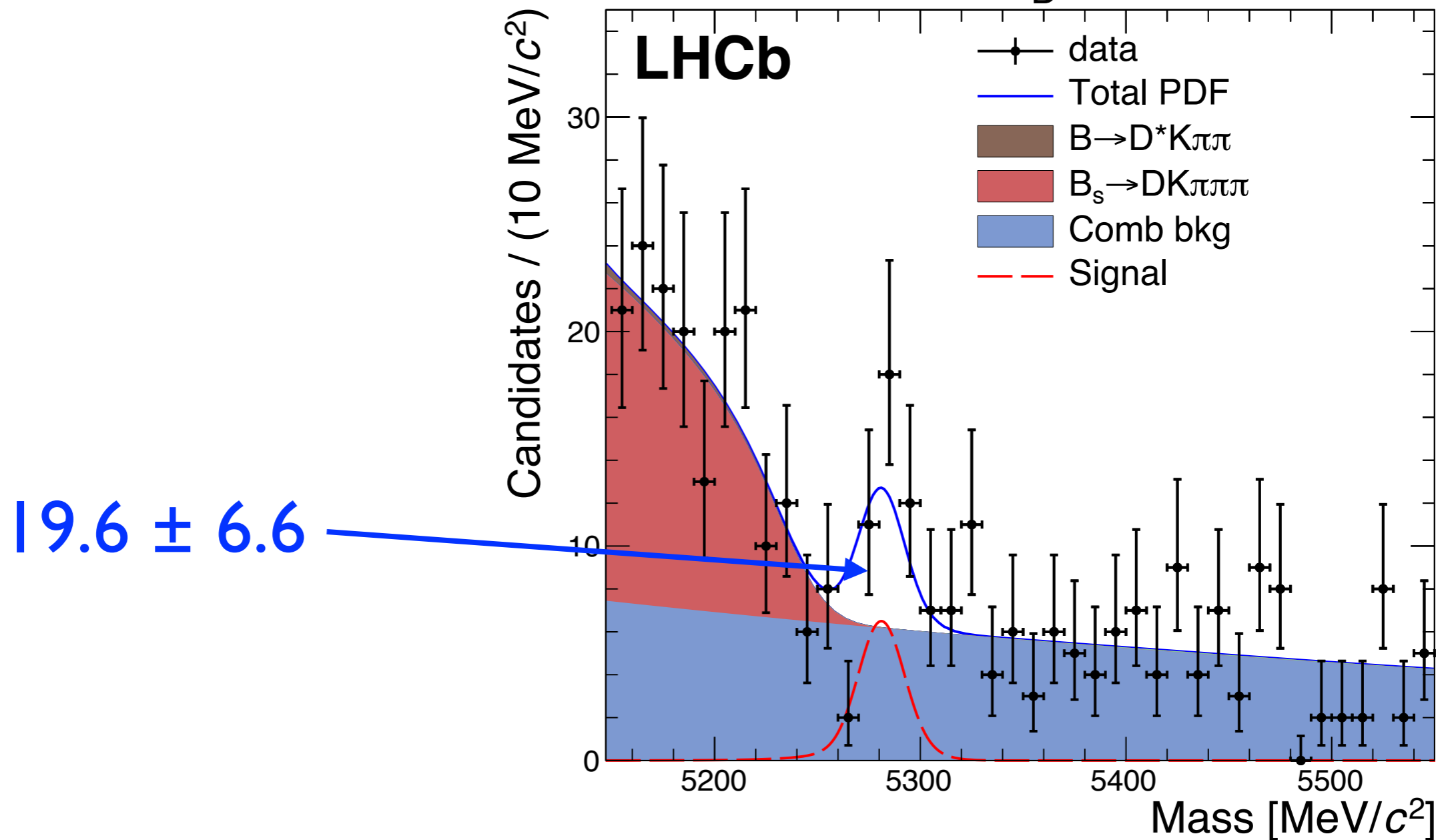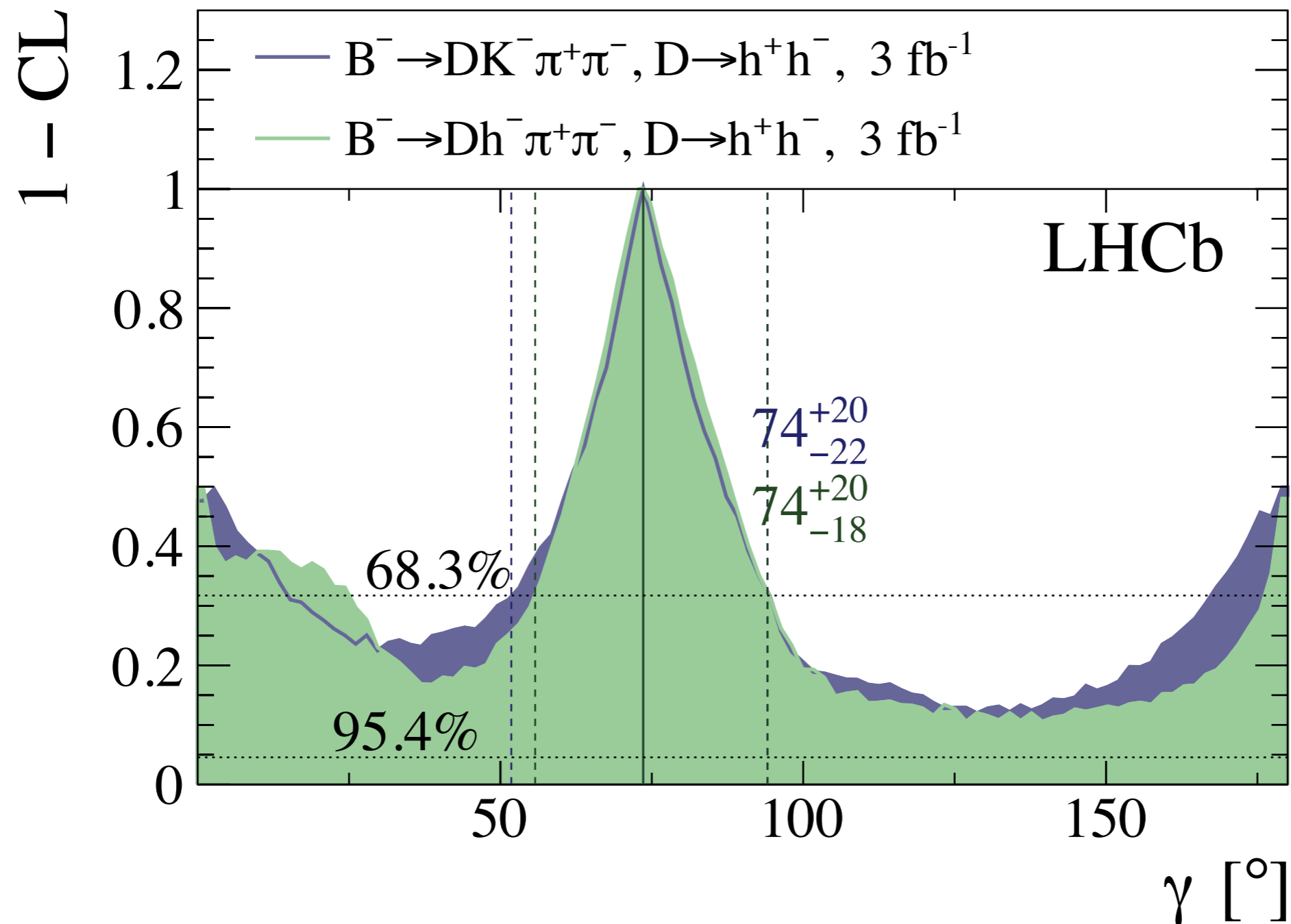
First γ measurement with these modes
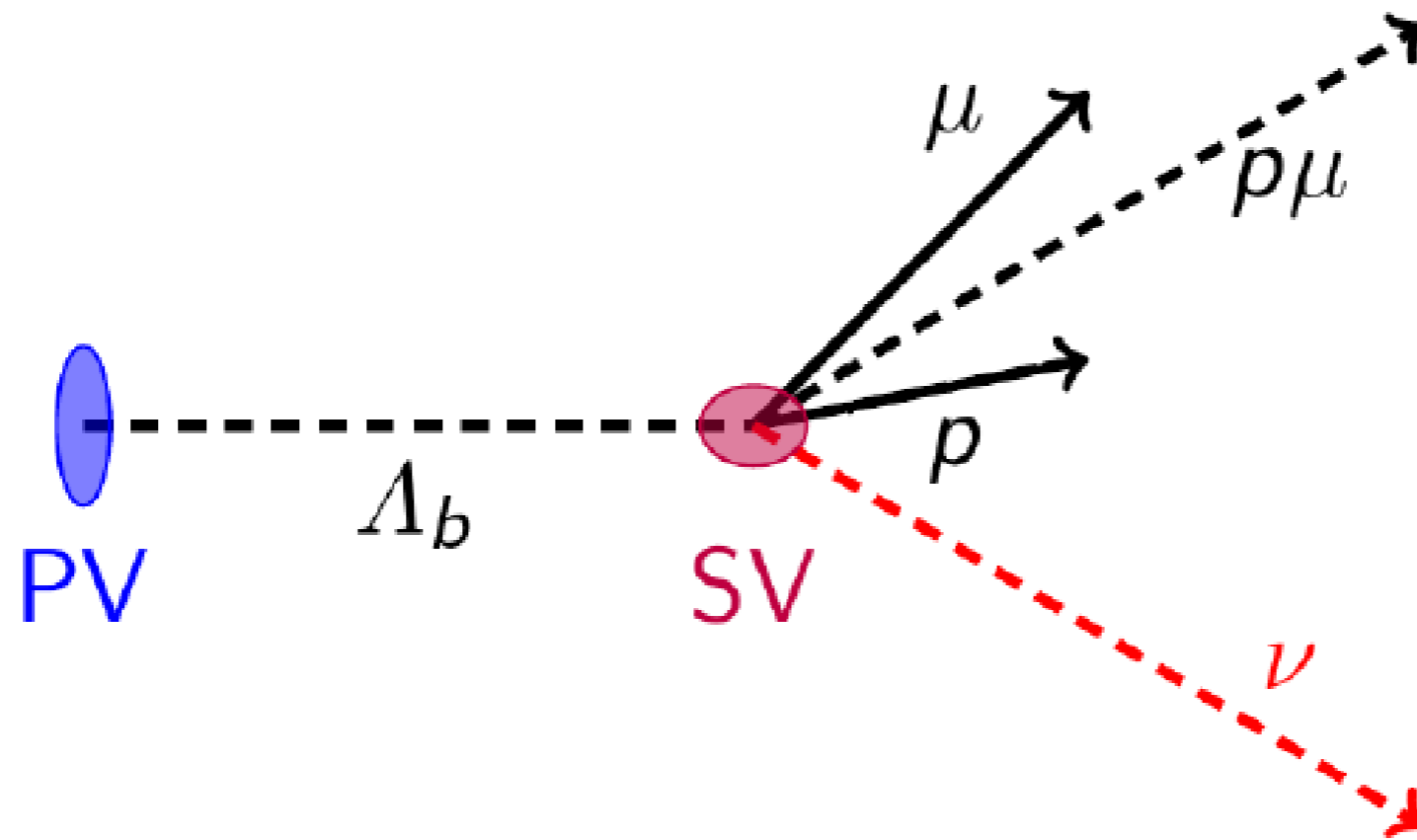
|V$_{ub}$| landscape

Long standing inclusive versus exclusive puzzle
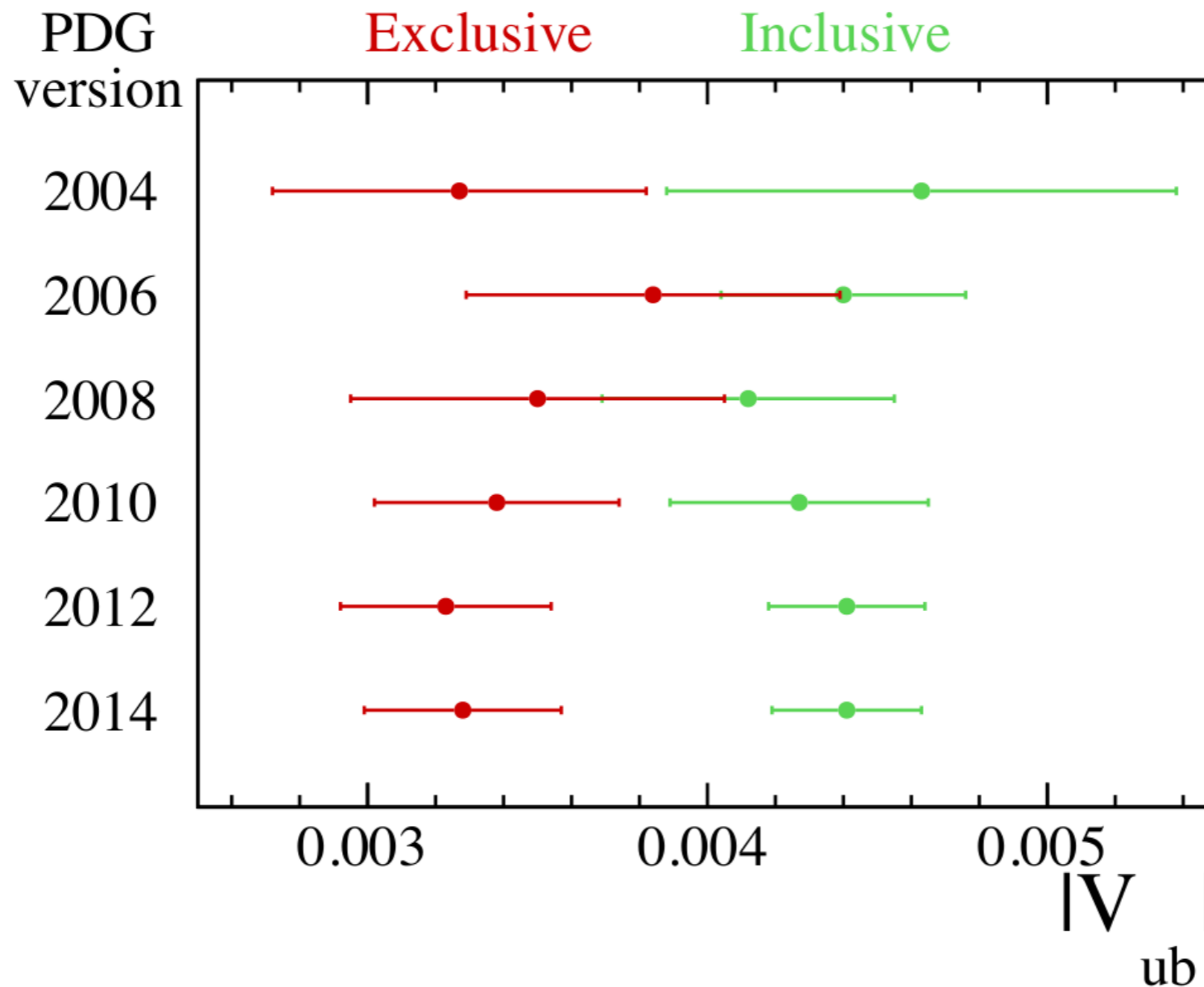
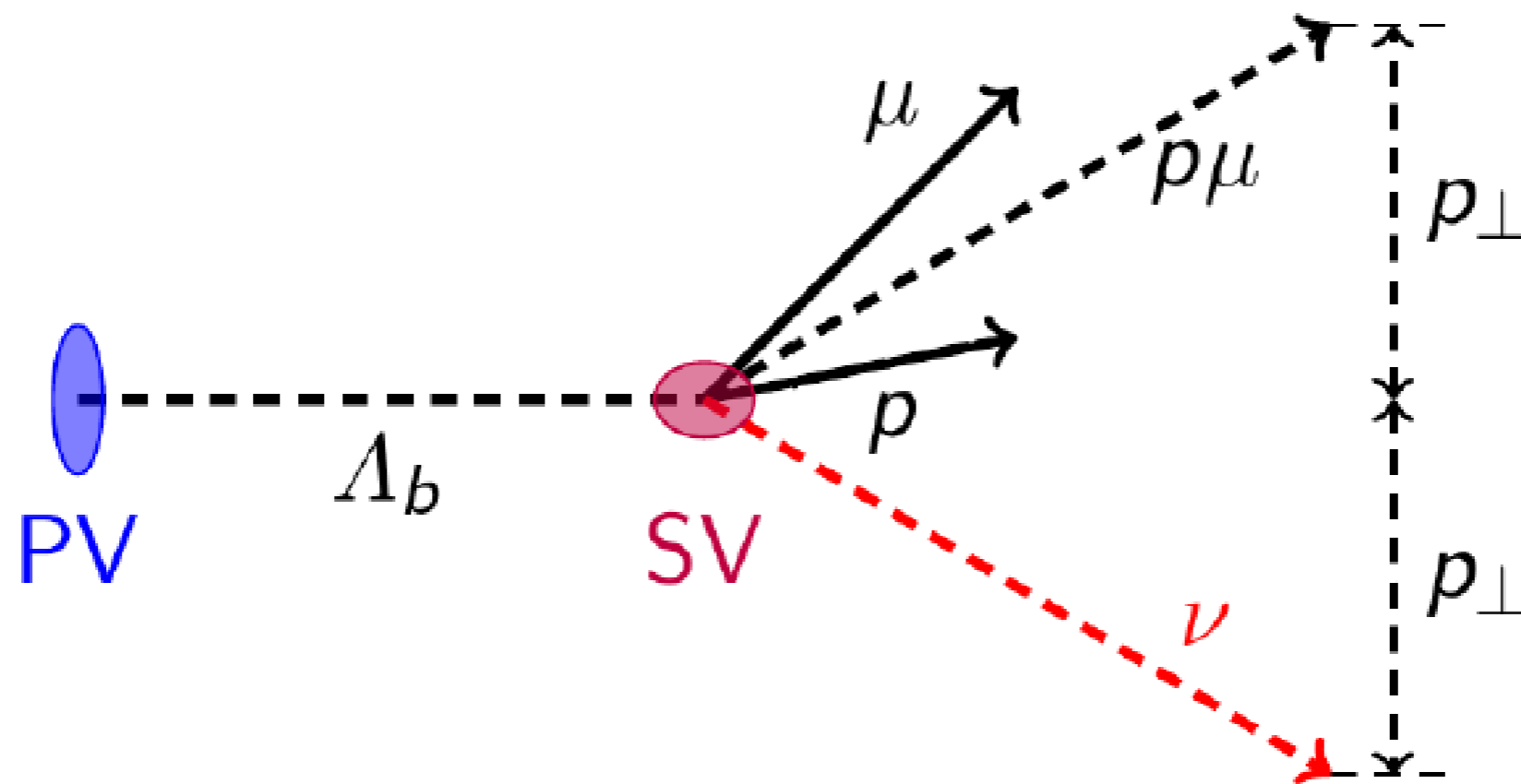Measurements with other b-hadron species needed

$|V_{ub}|$ with $\Lambda_b \rightarrow p\mu\nu$

LHCb is a b-baryon factory ($\Lambda_b/B_{u,d} \sim 50\%$)

$V_{ub}|$ with $\Lambda_b \rightarrow p\mu\nu$

6000

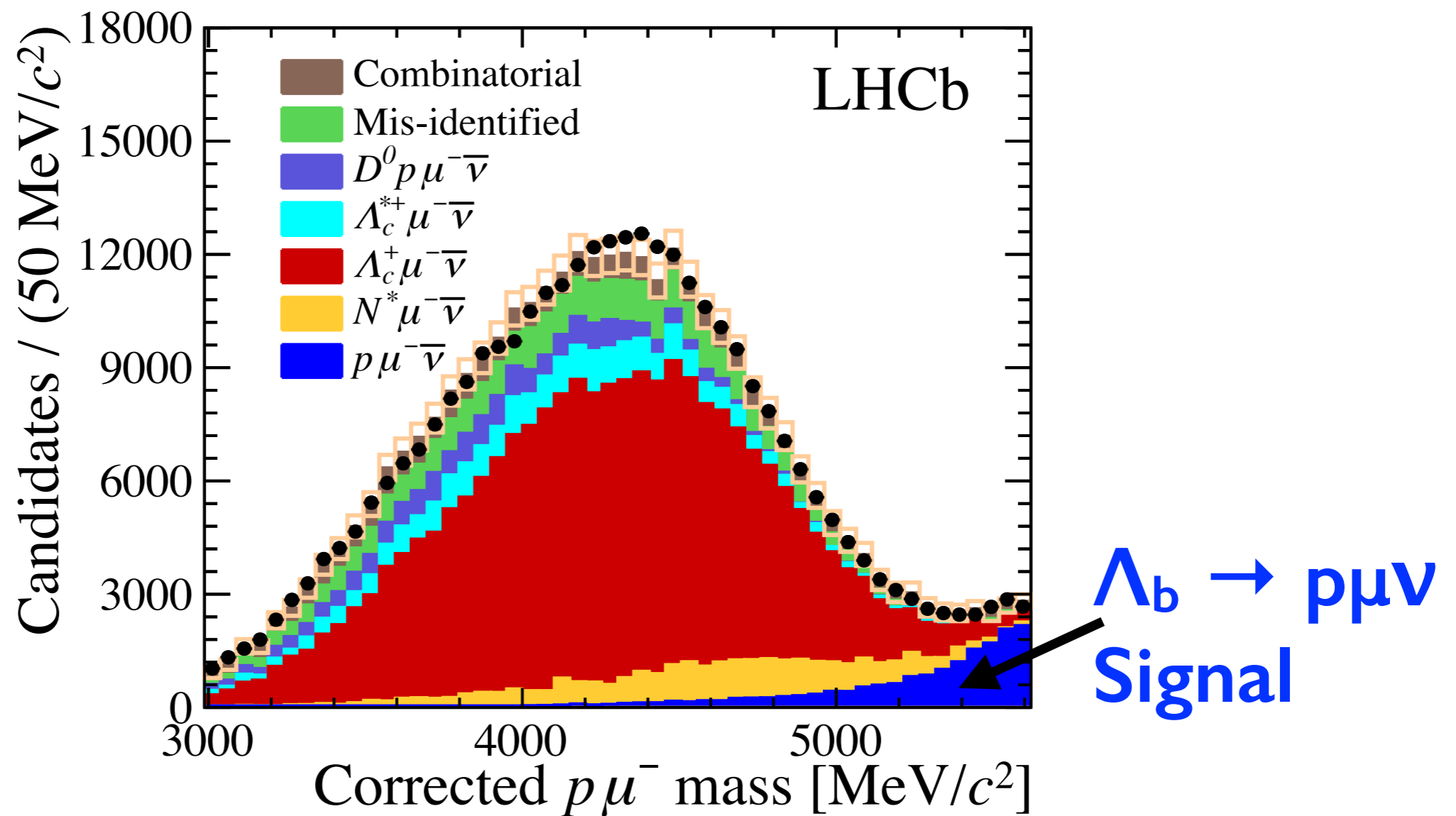LHCb is a b-baryon factory ($\Lambda_b/B_{u,d} \sim 50\%$)

The corrected mass

$$m_{\text{corr}} = \sqrt{m^2 + p_\perp^2} + p_\perp$$

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|V$_{ub}$| with Λ$_b$ → pμν

LHCb is a b-baryon factory (Λ$_b$/B$_{u,d}$ ~ 50%)

Λ$_b$ → pμν
Signal

$|V_{ub}|$ with $\Lambda_b \rightarrow p\mu\nu$

Measure the ratio of branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\mu\nu)_{q^2>15\ \mathrm{GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+\mu\nu)_{q^2>7\ \mathrm{GeV}/c^2}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$

$\Lambda_b \rightarrow p\mu\nu$ $\Lambda_b \rightarrow \Lambda_c\mu\nu$
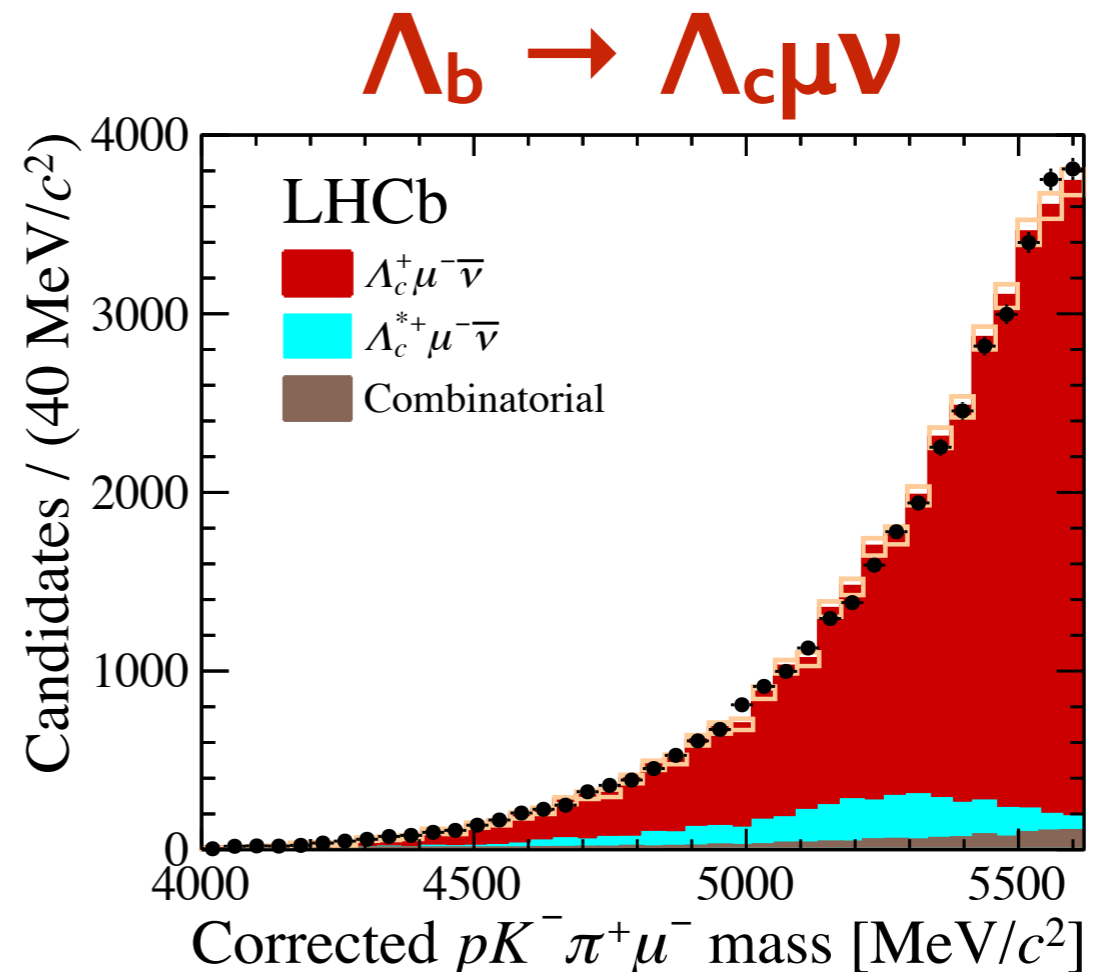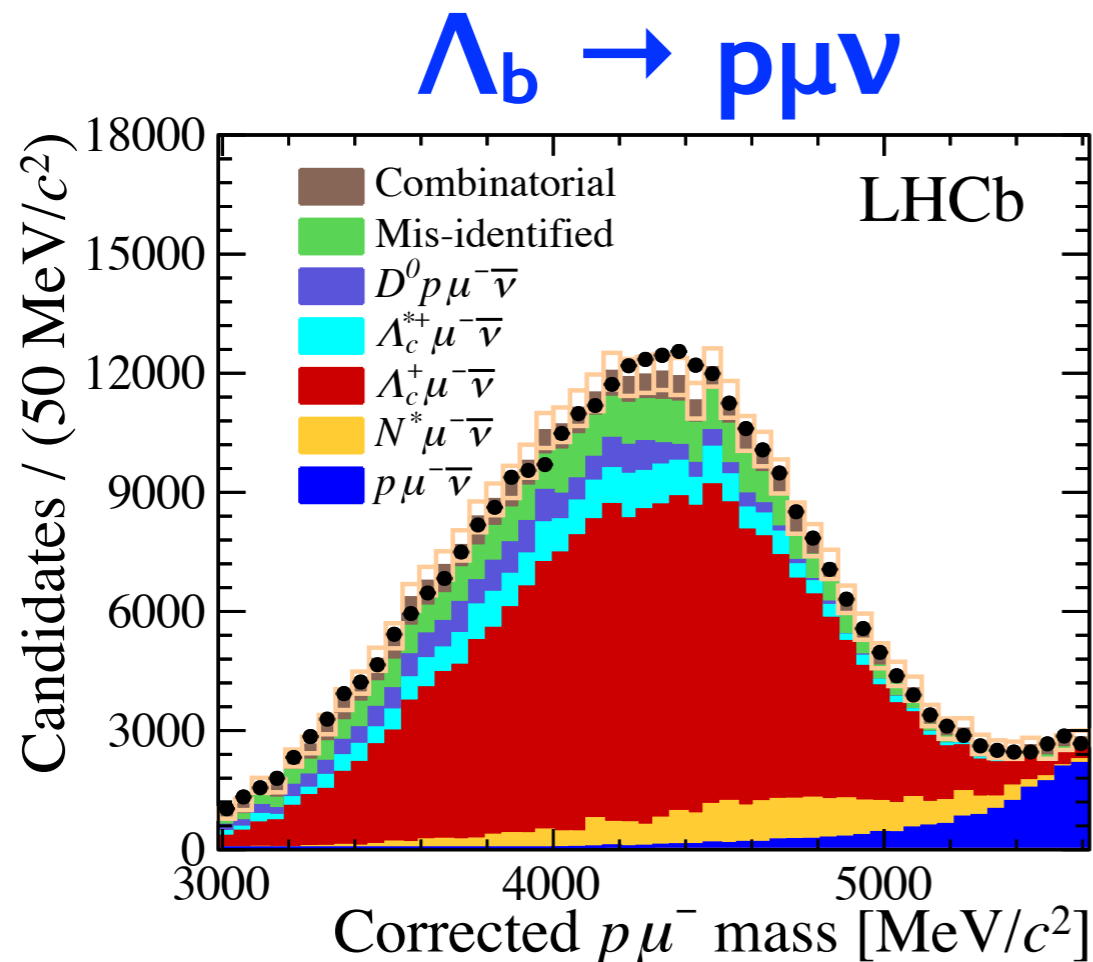
$|V_{ub}|$ with $\Lambda_b \rightarrow p\mu\nu$

Measure the ratio of branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\mu\nu)_{q^2 > 15\ \mathrm{GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu\nu)_{q^2 > 7\ \mathrm{GeV}/c^2}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} R_{\mathrm{FF}}$$

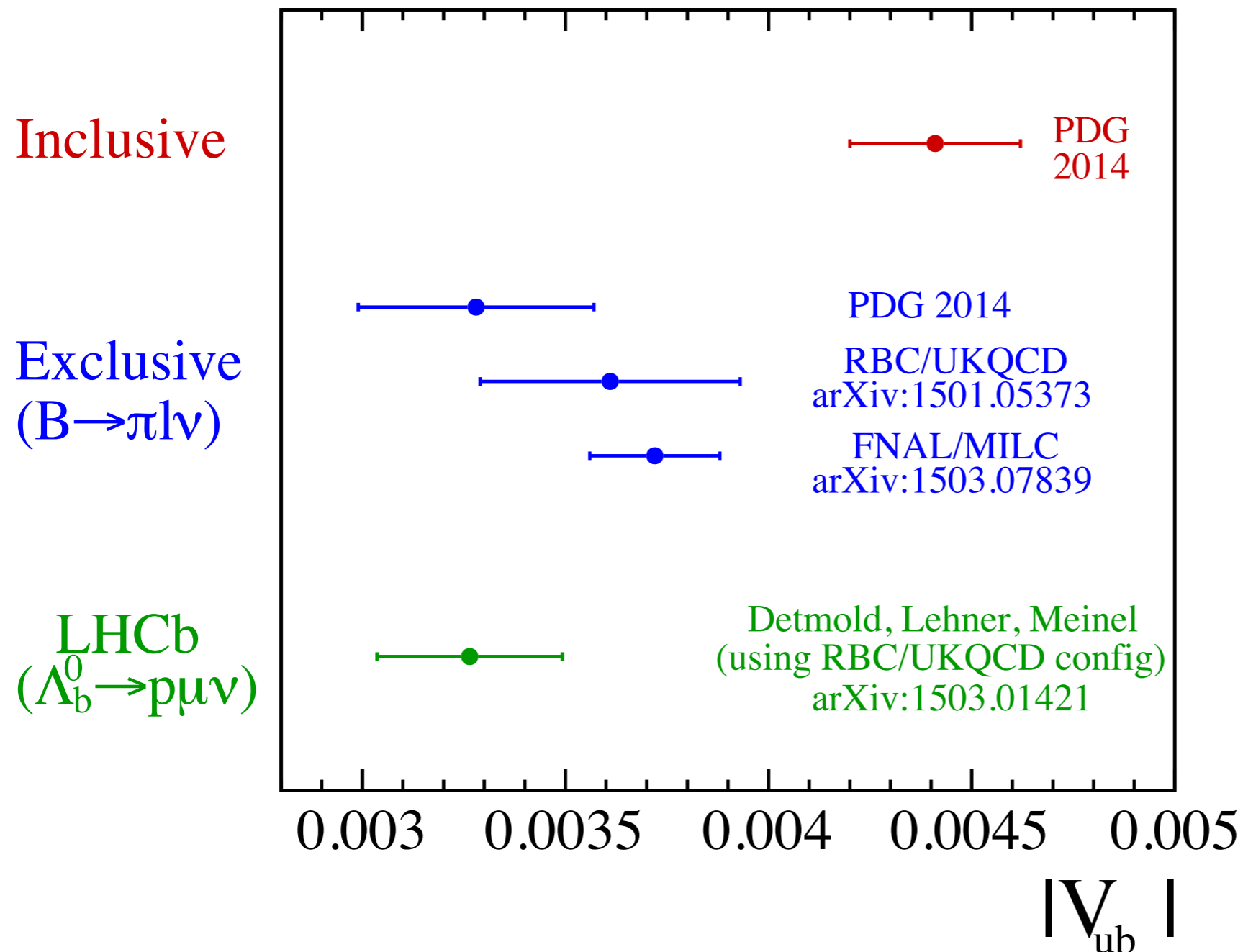Form Factors from LQCD

$$0.68 \pm 0.07$$

Detmold, Lehner, Meinel,
PRD 92, 034503 (2015)

Resulting in

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004_{\mathrm{exp}} \pm 0.004_{R_{FF}}$$

$|V_{ub}|$ with $\Lambda_b \rightarrow p\mu\nu$

Using exclusive $|V_{cb}|$ average:

Inclusive

PDG
2014

Exclusive
$(B \rightarrow \pi l \nu)$

PDG 2014

RBC/UKQCD
arXiv:1501.05373

FNAL/MILC
arXiv:1503.07839

LHCb
$(\Lambda_b^0 \rightarrow p\mu\nu)$

Detmold, Lehner, Meinel
(using RBC/UKQCD config)
arXiv:1503.01421

0.003   0.0035   0.004   0.0045   0.005
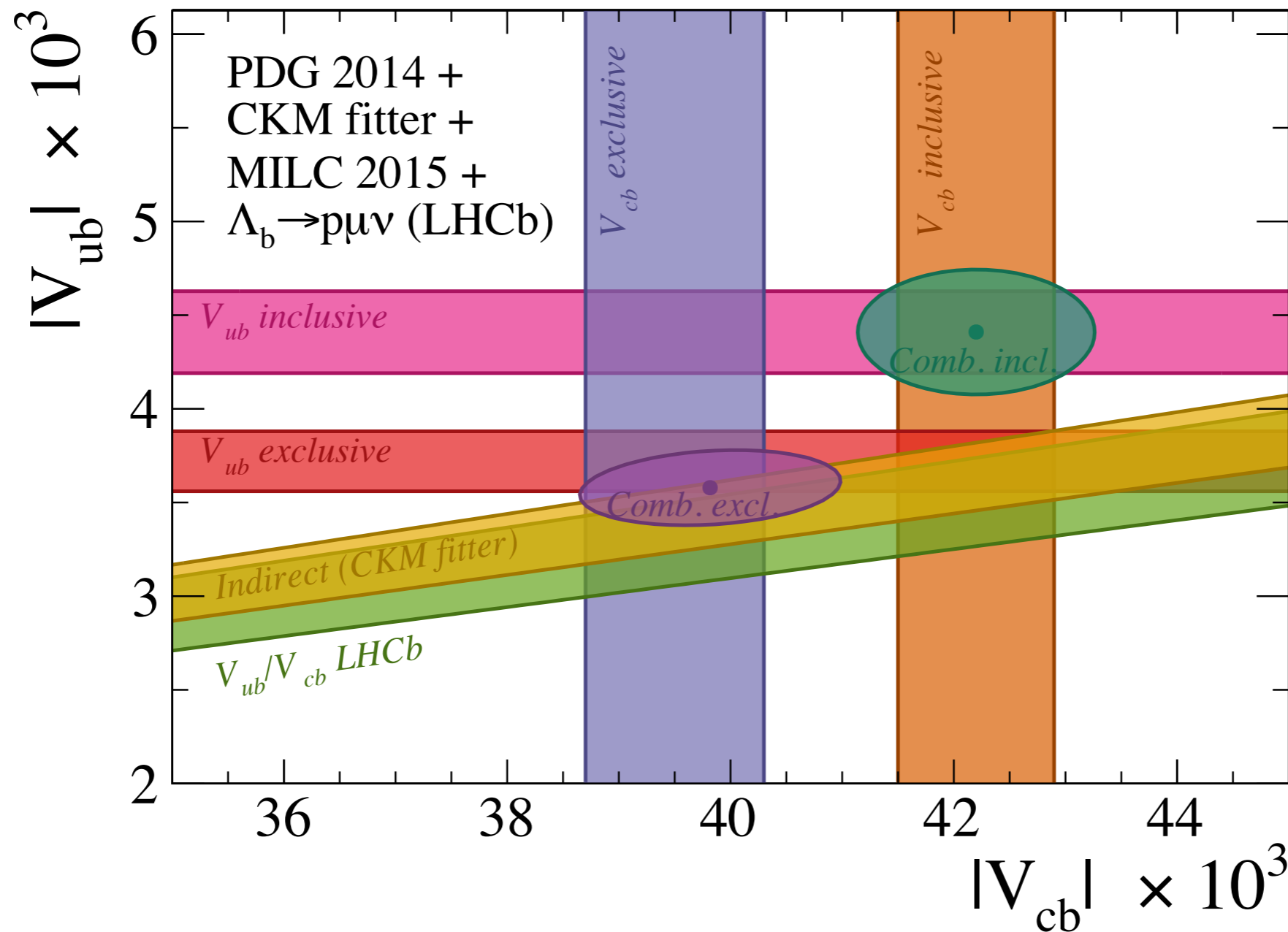
$|V_{ub}|$

The $|V_{ub}|$ puzzle lives on…

Conclusions

- Successful LHCb Run-I

- The data seem to be compatible with the CKM picture of CPV, but $|V_{ub}|$ puzzle remains.
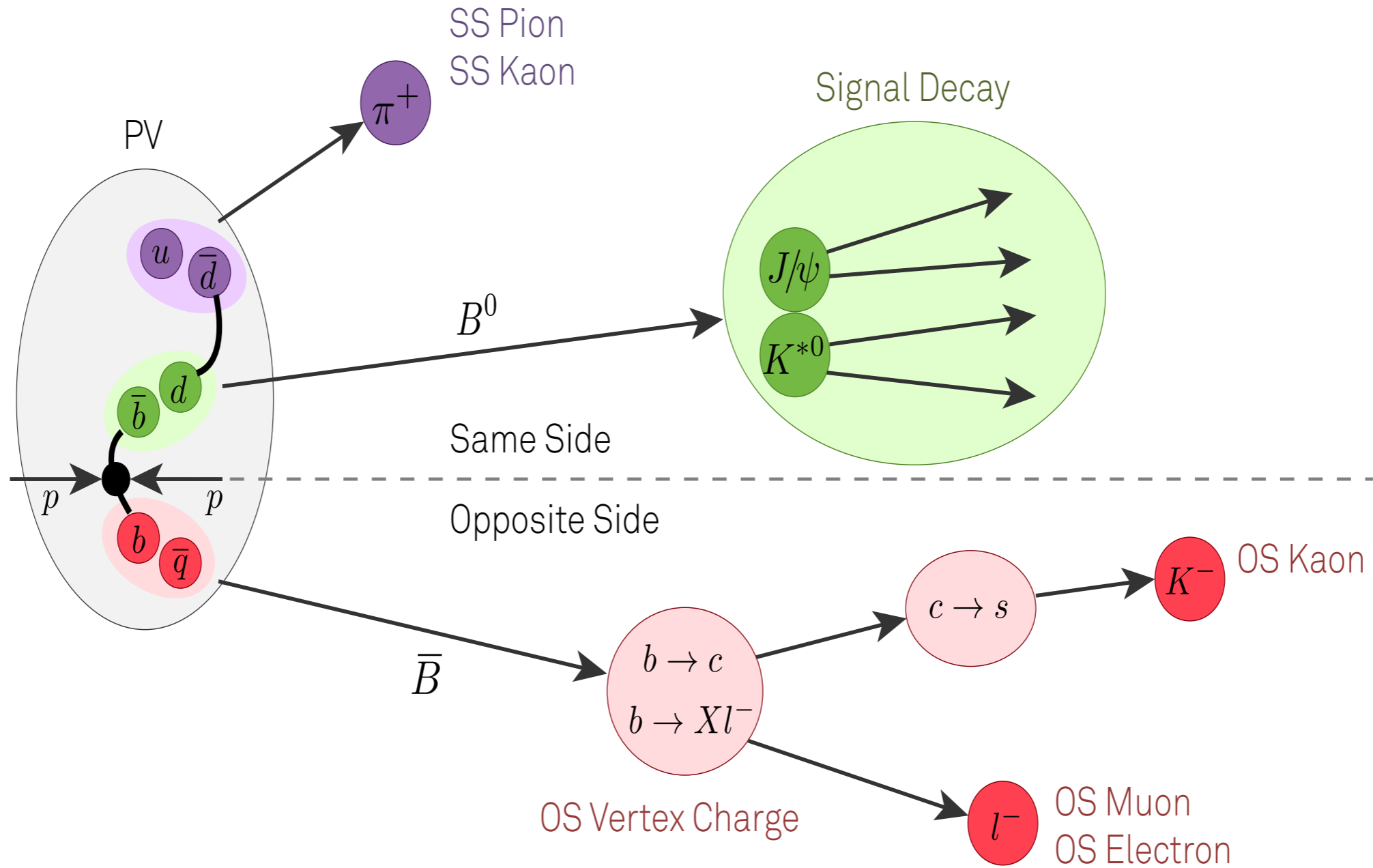
- Much more to come from LHCb in Run-II and beyond.

Backup slides

$|V_{ub}|$ with $\Lambda_b \rightarrow p\mu\nu$

What LHCb really measures though is $|V_{ub}|/|V_{cb}|$, while the B-factories measure $|V_{ub}|$ and $|V_{cb}|$ separately

Flavour tagging at LHCb

SS Pion
SS Kaon

π^+

PV

Signal Decay

u $\bar{d}$

J/ψ

B^0

K^{*0}

$\bar{b}$ d

Same Side

p p

Opposite Side

b $\bar{q}$

OS Kaon

K^-

$c \to s$

$\overline{B}$
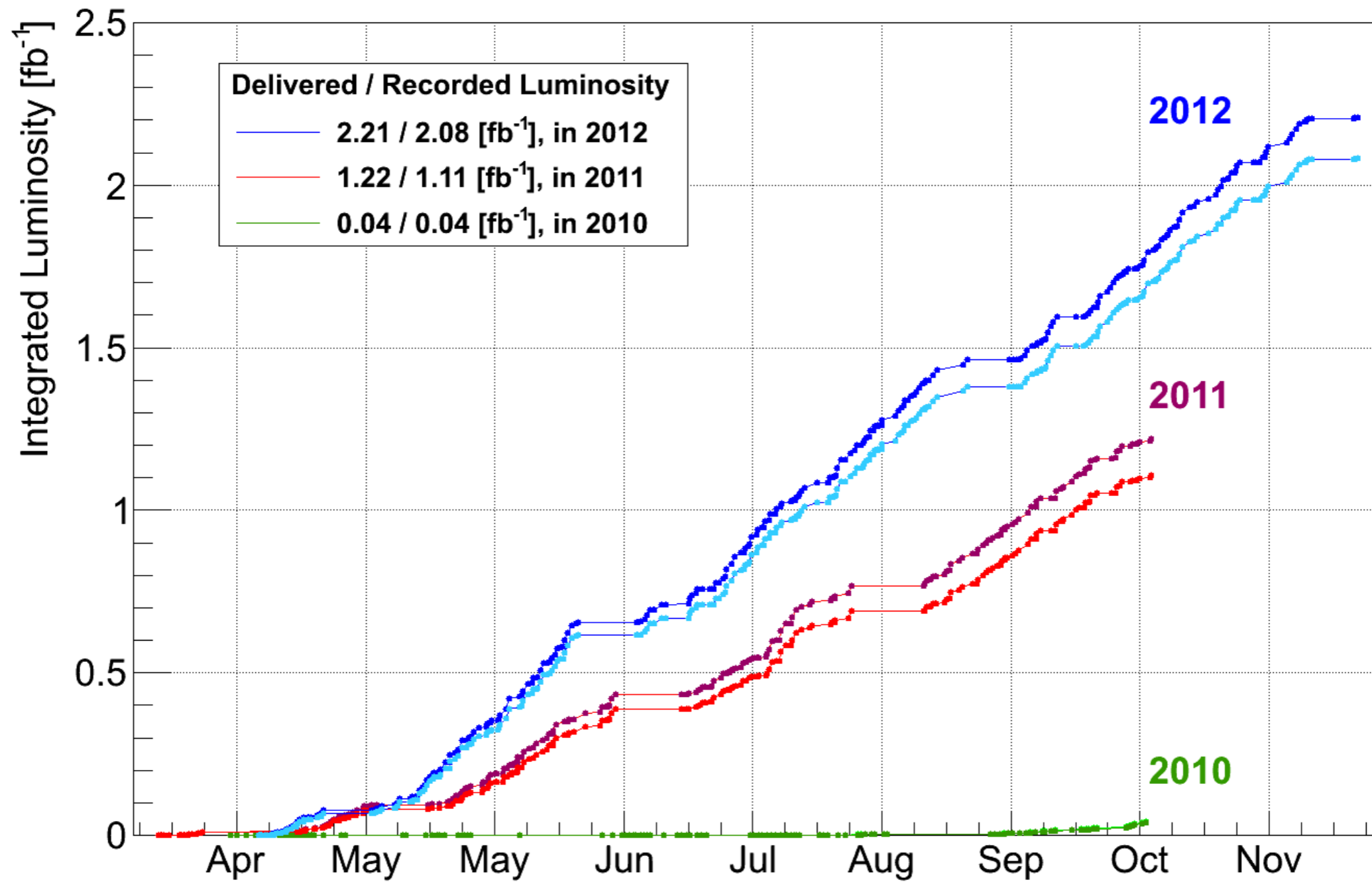
$b \to c$
$b \to Xl^-$

OS Vertex Charge

OS Muon
OS Electron

l^-

New OS charm tagger

[LHCb, submitted to J. Instr., arXiv:1507.07892]

Run-I

$|V_{ub}|$ with $\Lambda_b \rightarrow p\mu\nu$

LHCb simulation

- $p\mu\nu$ low σ_{mcorr}
- $p\mu\nu$ high σ_{mcorr}
- $\Lambda_c\mu\nu$ low σ_{mcorr}
- $\Lambda_c\mu\nu$ high σ_{mcorr}

Corrected mass [MeV/c^2]