technische universität dortmund

Bundesministerium für Bildung und Forschung

LHCb

LHC flavour physics results

Julian Wishahi on behalf of the LHCb collaboration

Stress-testing the Standard Model at the LHC, KITP, University of California, Santa Barbara technische universität dortmund

Bundesministerium für Bildung und Forschung

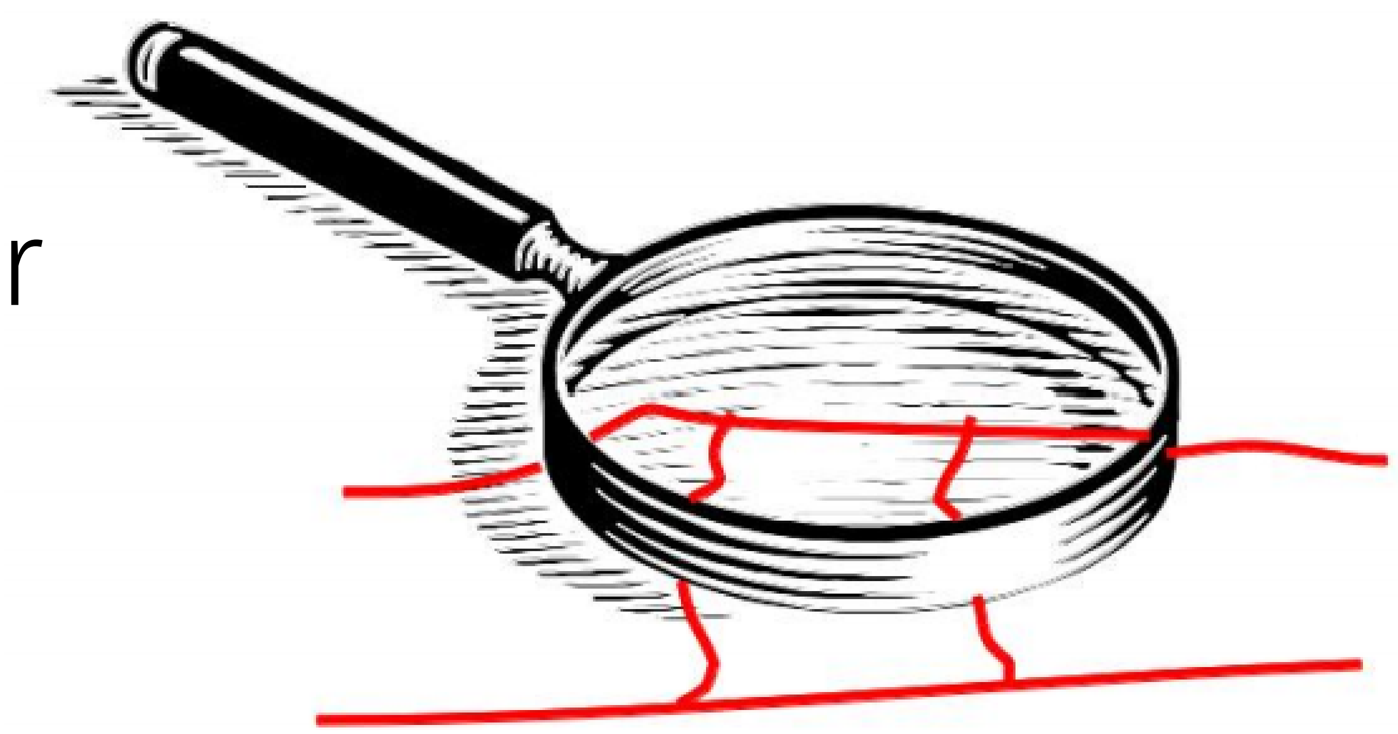
LHC flavour physics results (with a bias towards LHCb Run I results)

Julian Wishahi on behalf of the LHCb collaboration

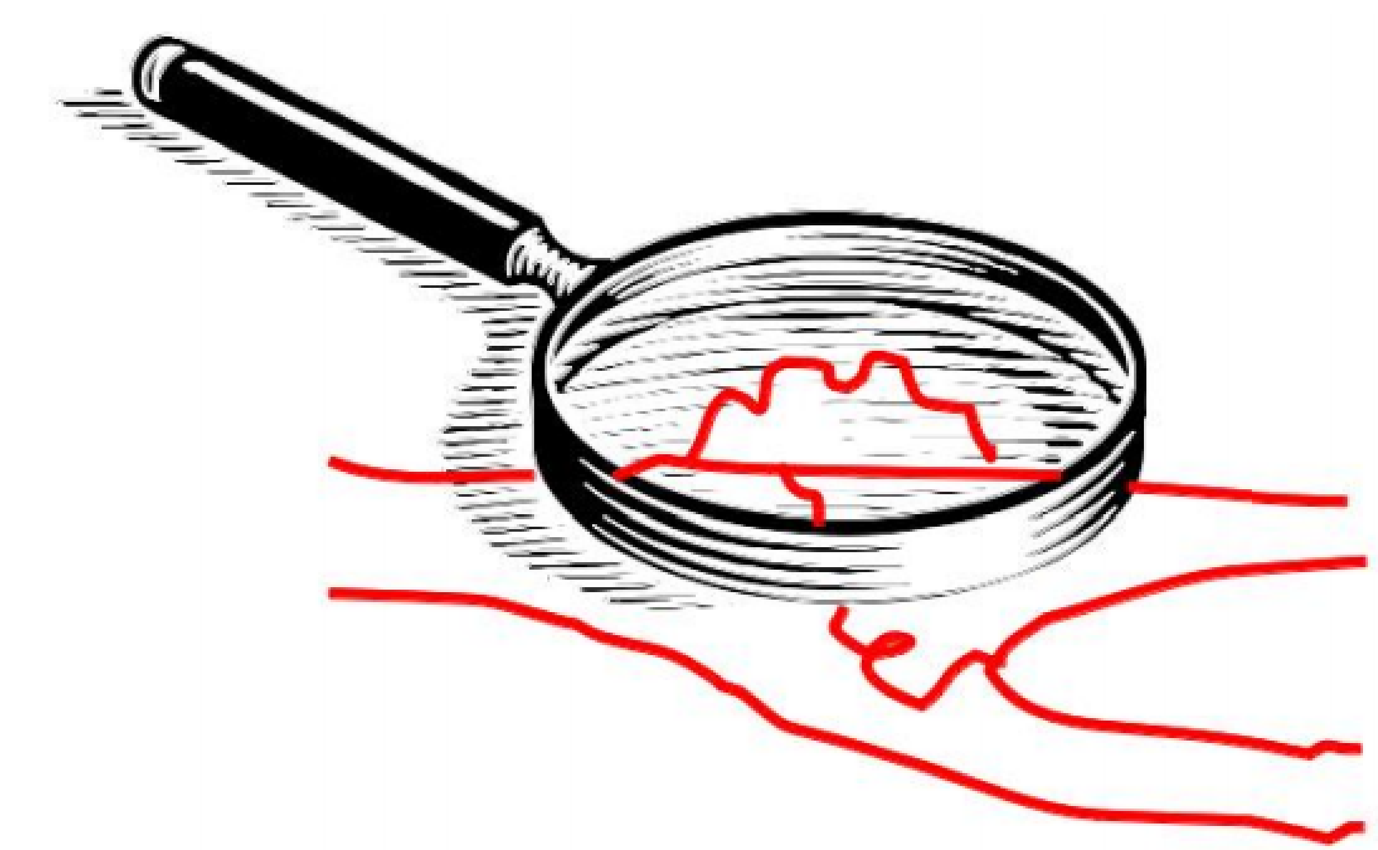
Stress-testing the Standard Model at the LHC, KITP, University of California, Santa Barbara

Flavour Physics

- Standard Model
  - 6 quark and 6 lepton flavours
  - most of the 18 (28) free parameters are related to flavour



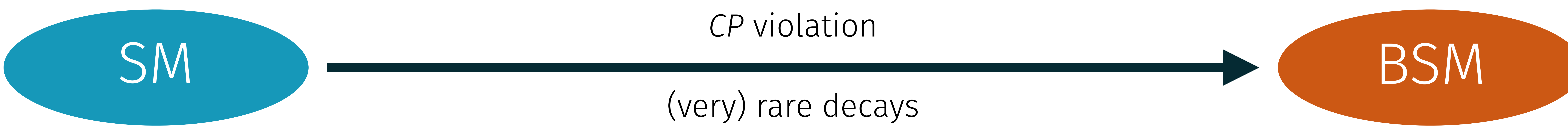
- probe for BSM: indirect searches
  - examine flavour processes involving loop processes
  - virtual contributions with new particles/couplings
  - sensitive to energy scales beyond the collider energy



- in this talk: b-quark system: $B^{\pm}$, B^{0}, B_s, Λ_b

Stress-testing the SM with flavour physics

- What to do?
  - get precise theoretical predictions
  - get precise experimental measurements
  - search for discrepancies!



Flavour Physics – Outline

- *CP* violation and CKM unitarity
  - CKM matrix elements $|V_{ub}|$ and $|V_{ts}/V_{td}|$
  - *CP* violation in B^0 and B_s mixing
  - mixing-induced *CP* violation and CKM angles
  - *CP* violation in *D* mesons
- rare decays
- tests of lepton flavour universality
- top quark
- neutrinos

CKM Unitarity

CKM triangles, *CP* violation & meson mixing

CKM matrix – basics

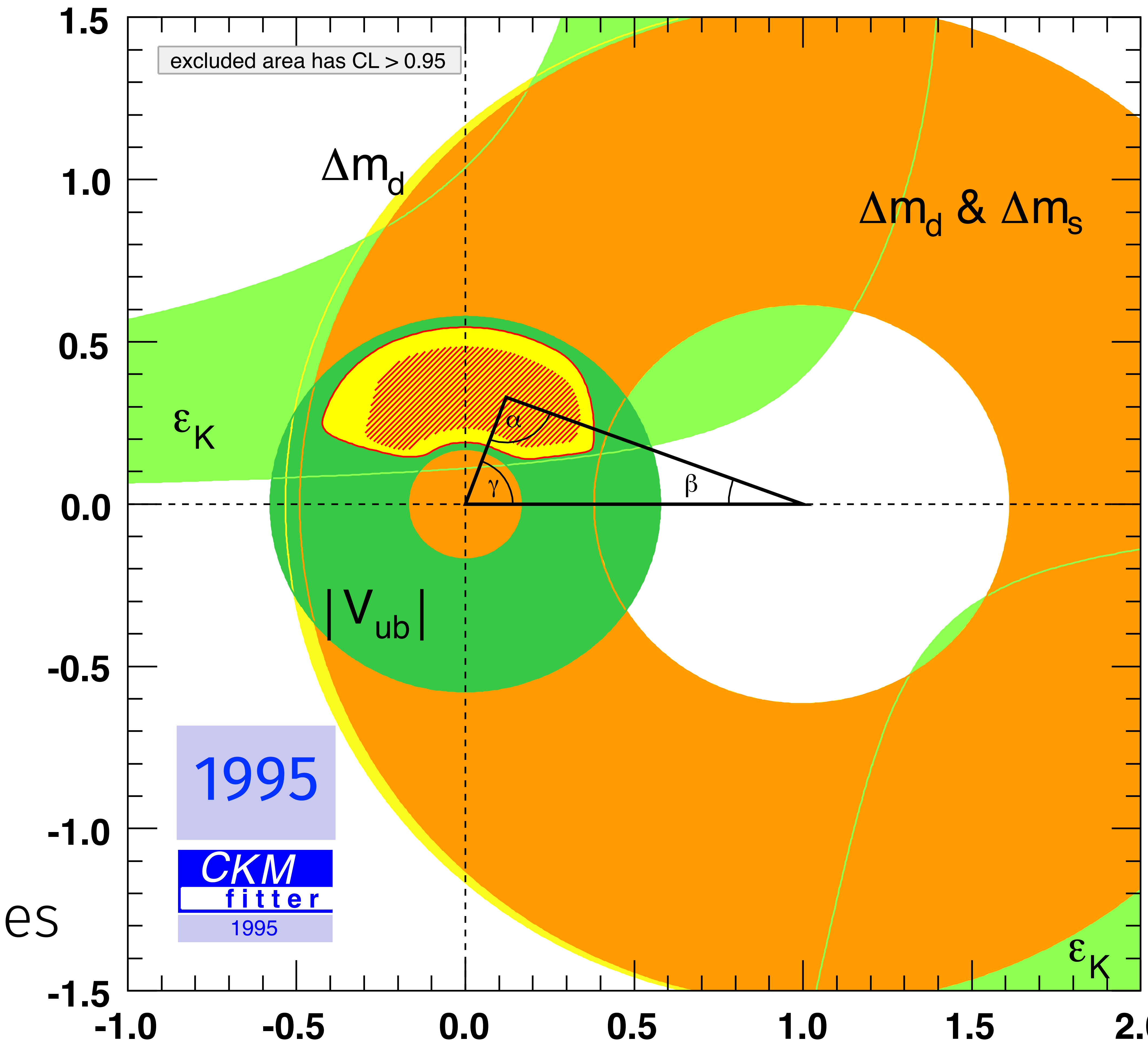
- unitary quark mixing matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{ub} \end{pmatrix}$$

  - 3 Euler angles
  - 1 phase = **the** source of *CP* violation in the SM

- unitarity ➔ stringent tests of the SM
  - BSM particles/couplings can enter loop processes
  ➔ measurement ≠ SM prediction

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

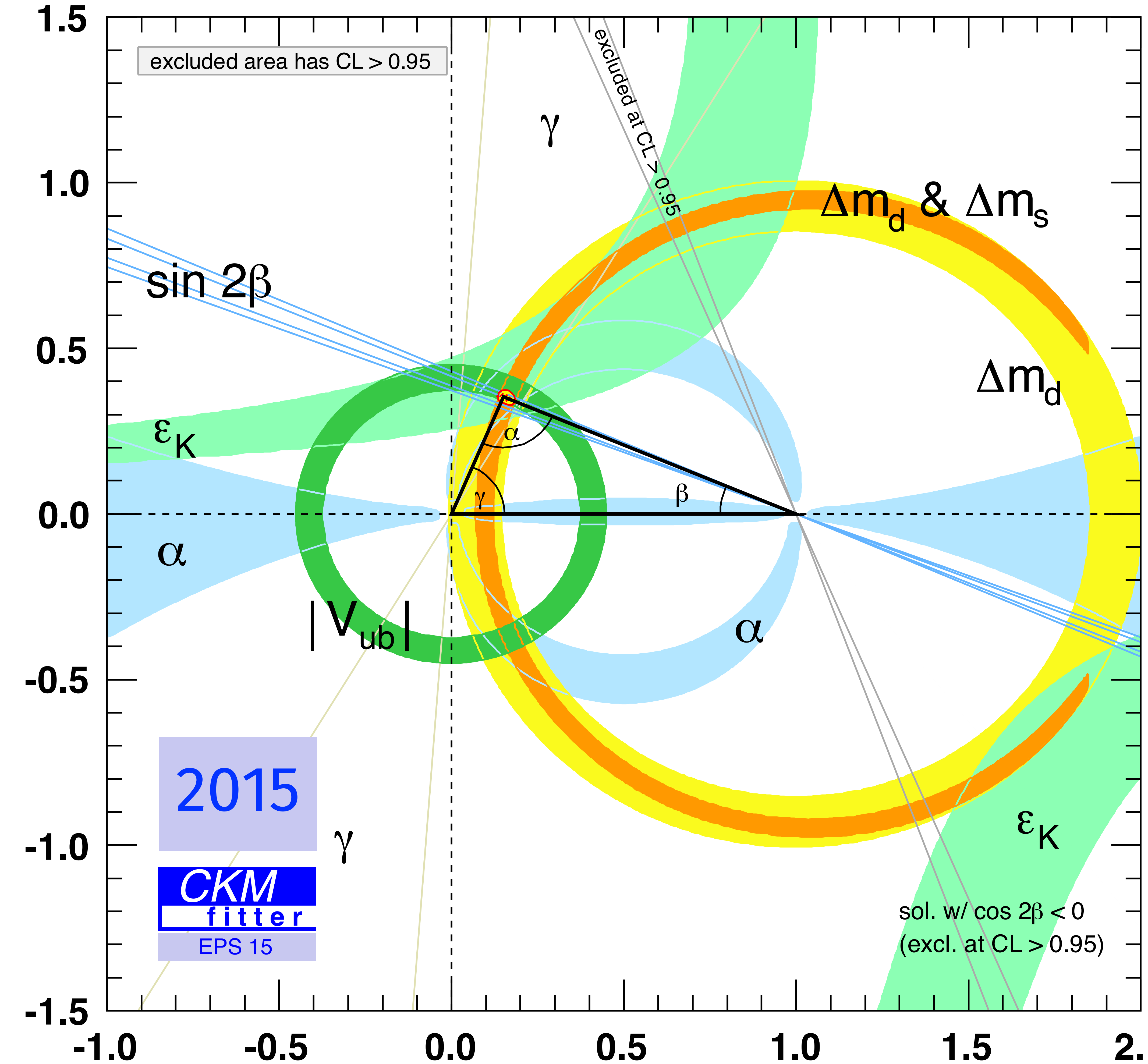


CKMfitter, EPJ. C41, 1-131 (2005)

CKM matrix – status

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

- current picture is consistent
- still interesting?
  - experimental uncertainties
    > theoretical uncertainties
  - require precision measurements!

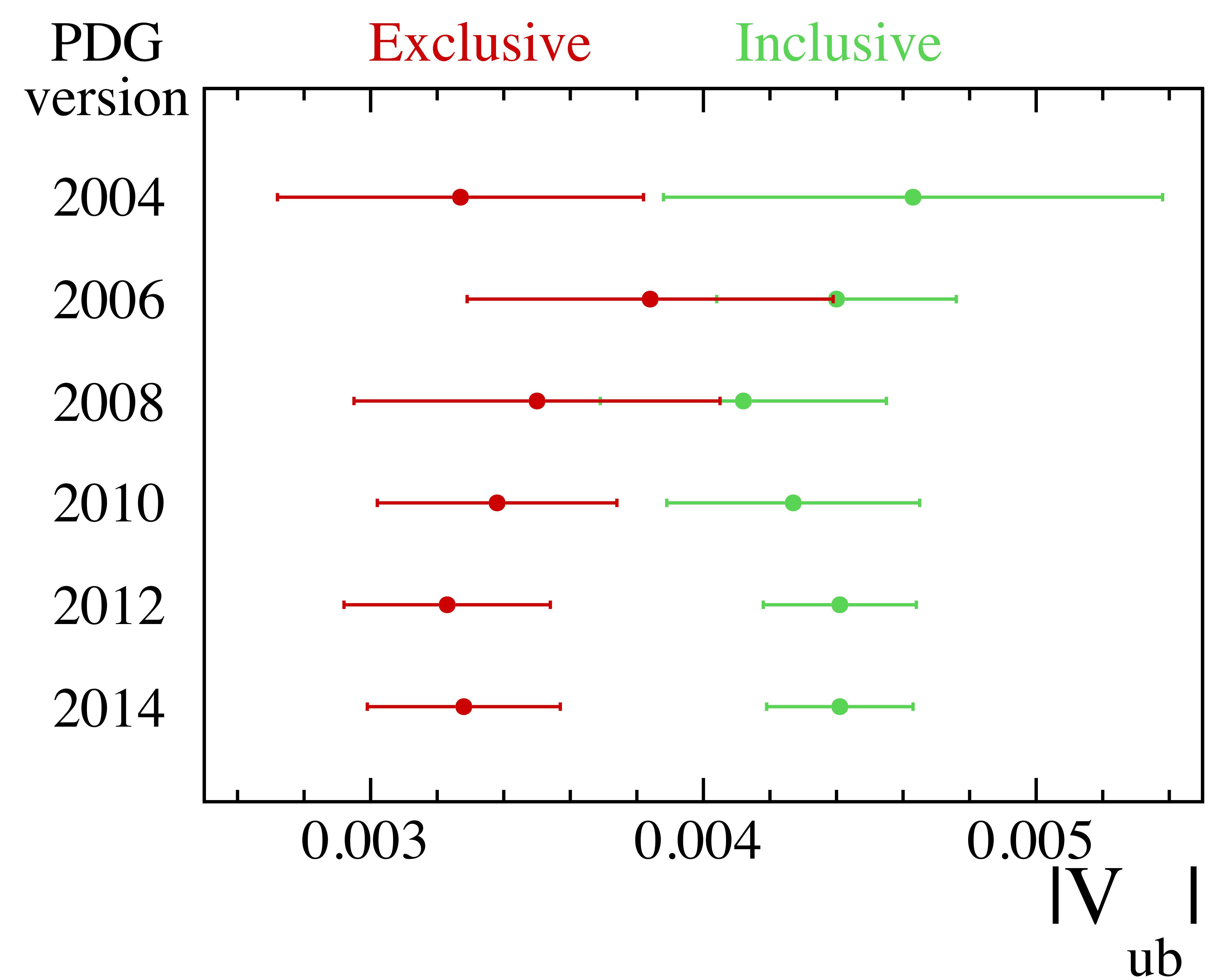


CKMfitter, EPJ. C41, 1-131 (2005)

CKM triangle sides

Measurements of $|V_{ub}|$ and $|V_{cb}|$

- long standing issue
  - inclusive determinations
    - $|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$ (incl. $b \to c l \nu_l$)
    - $|V_{ub}| = (4.49 \pm 0.23) \times 10^{-3}$ (incl. $b \to u l \nu_l$)
    - theo. input: extrapolate to full phase-space
  - exclusive determinations
    - $|V_{cb}| = (39.2 \pm 0.7) \times 10^{-3}$ (from $B \to D^{(*)} l \nu_l$)
    - $|V_{ub}| = (3.72 \pm 0.19) \times 10^{-3}$ (from $B \to \pi l \nu_l$)
    - theo. input: form factors



PDG review

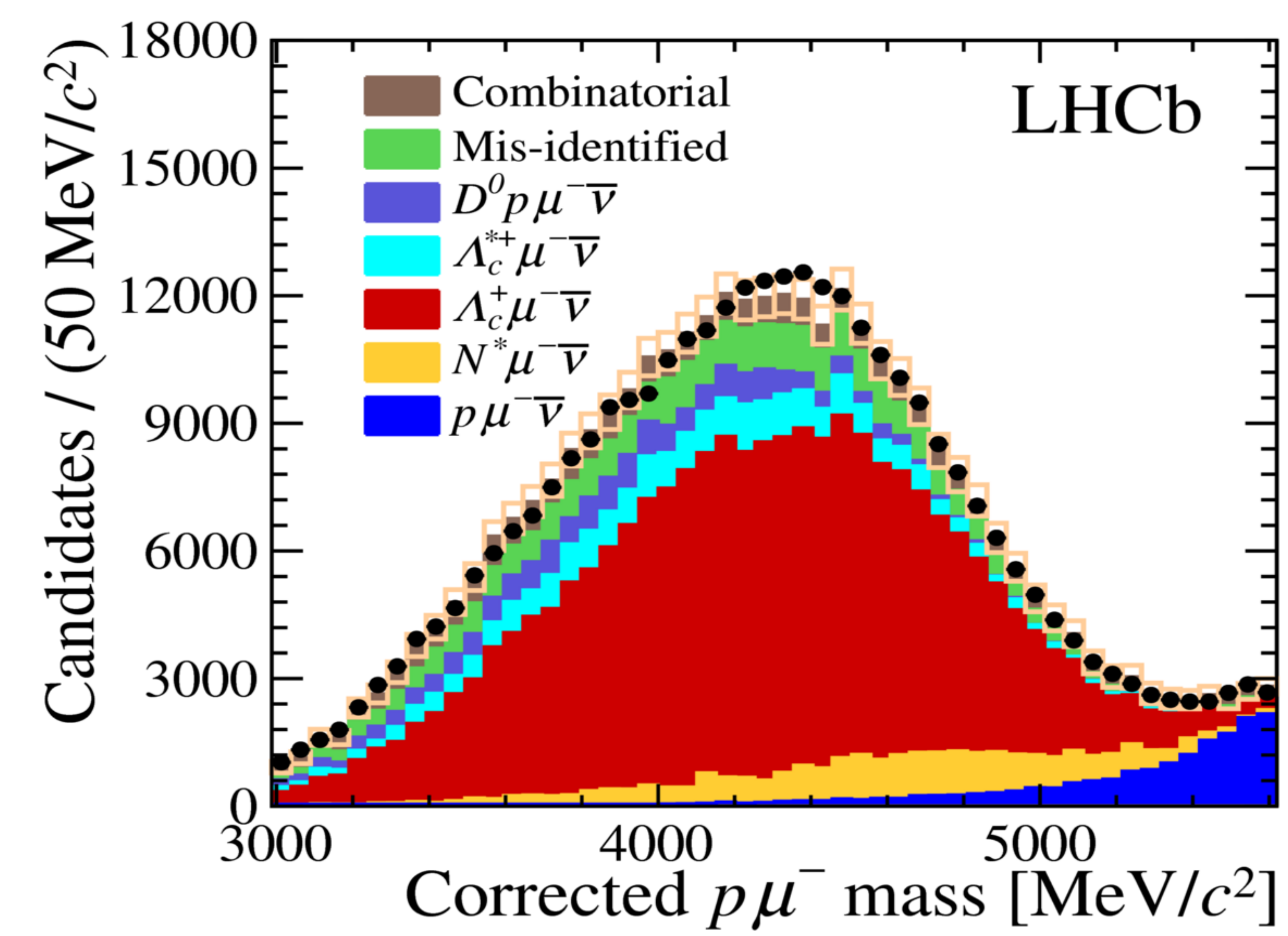
$|V_{ub}/V_{cb}|$ with $\Lambda_b \to p\mu^-\nu_\mu$ / $\Lambda_b \to \Lambda_c\mu^-\nu_\mu$

- LHCb: use *b* baryons instead of mesons
  - here: branching ratio $\Lambda_b \to p\mu^-\nu_\mu$ / $\Lambda_b \to \Lambda_c\mu^-\nu_\mu$
  - can deduct CKM element ratios from

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu^-\bar{\nu}_\mu)} = \frac{|V_{ub}|^2}{|V_{cb}|^2}\frac{G(\Lambda_b \to p\mu^-\bar{\nu}_\mu)}{G(\Lambda_b \to \Lambda_c\mu^-\bar{\nu}_\mu)}$$

theory input: Phys. Rev. D 92, 034503 (2015)

  - exploit displaced vertex to reconstruct corrected mass

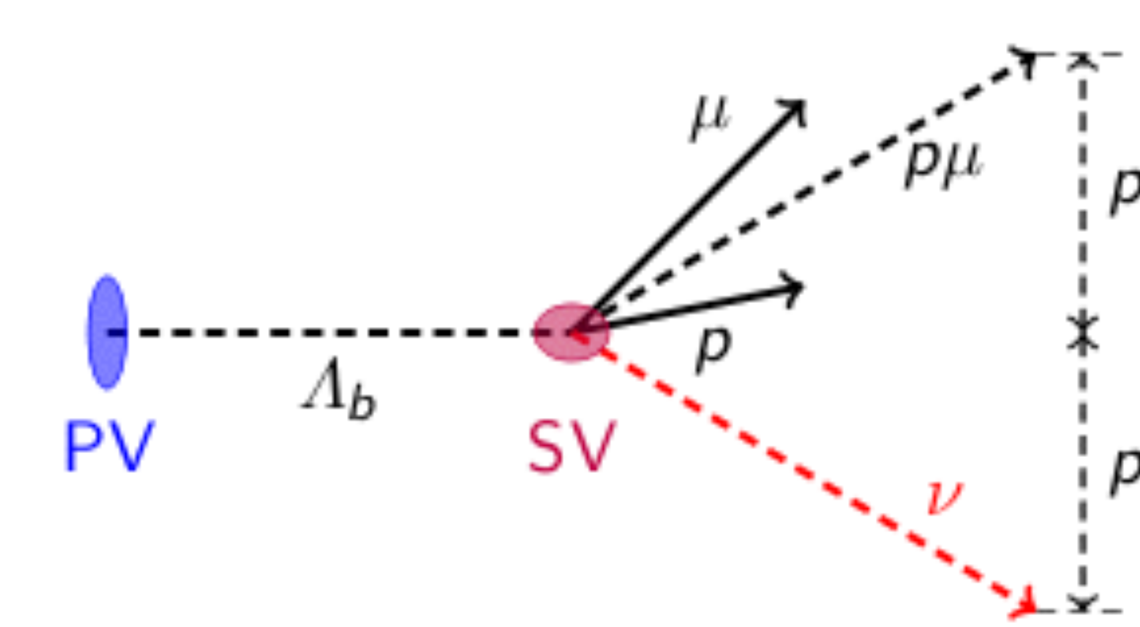


Nature Physics 10 (2015) 1038

$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$

- measured branching ratio for $q^2(\mu\nu) > 15(7)\ \mathrm{GeV}^2/c^4$

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu^-\bar{\nu}_\mu)} = (1.00 \pm 0.04\,(\mathrm{stat}) \pm 0.08\,(\mathrm{stat})) \times 10^{-2}$$

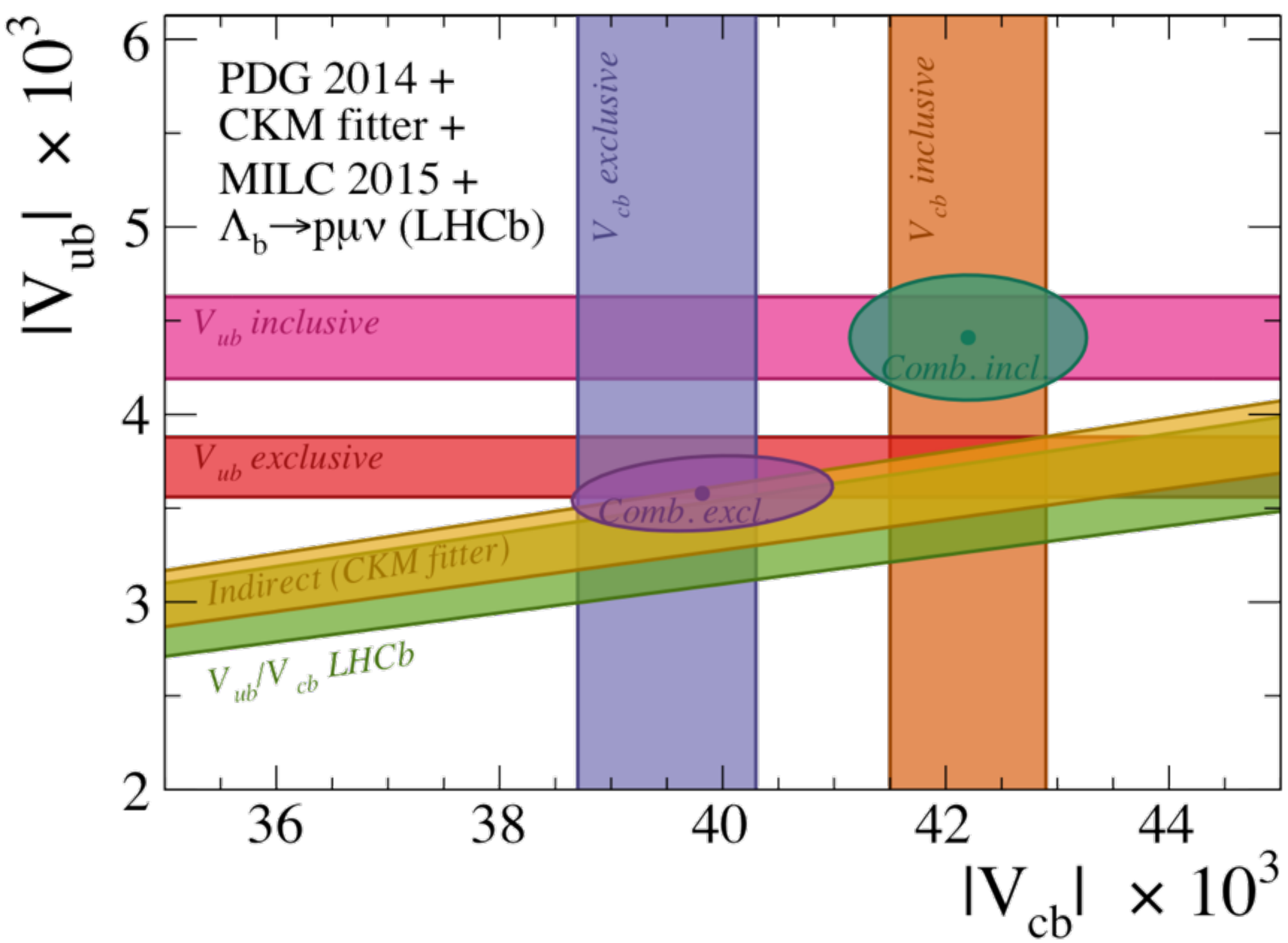


$|V_{ub}/V_{cb}|$ with $\Lambda_b \to p\mu^- \bar{\nu}_\mu$ / $\Lambda_b \to \Lambda_c \mu^- \bar{\nu}_\mu$

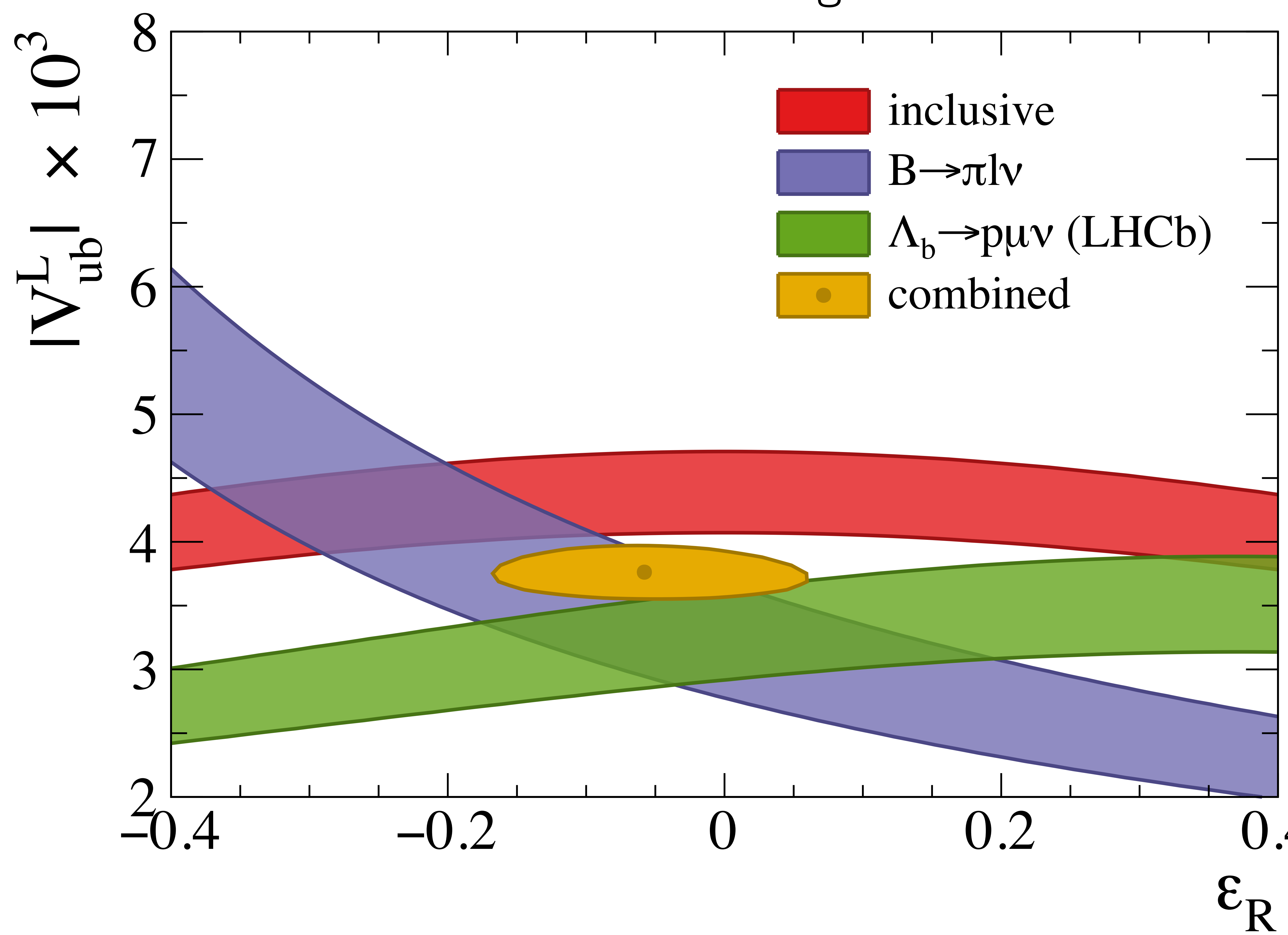
- resulting CKM-matrix ratio

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004\,(\text{exp}) \pm 0.004\,(\text{lat})$$

confirms discrepancy between incl. and excl. meas.



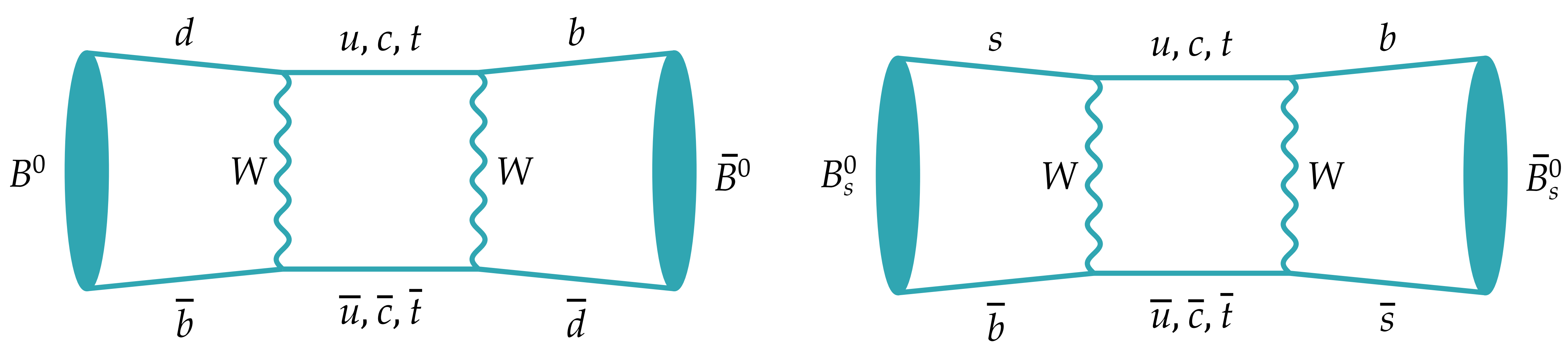
disfavours NP models with right-handed currents



Nature Physics 10 (2015) 1038

$|V_{td}/V_{ts}|$ from $\Delta m_d/\Delta m_s$

- mixing of B^0 and B_s mesons

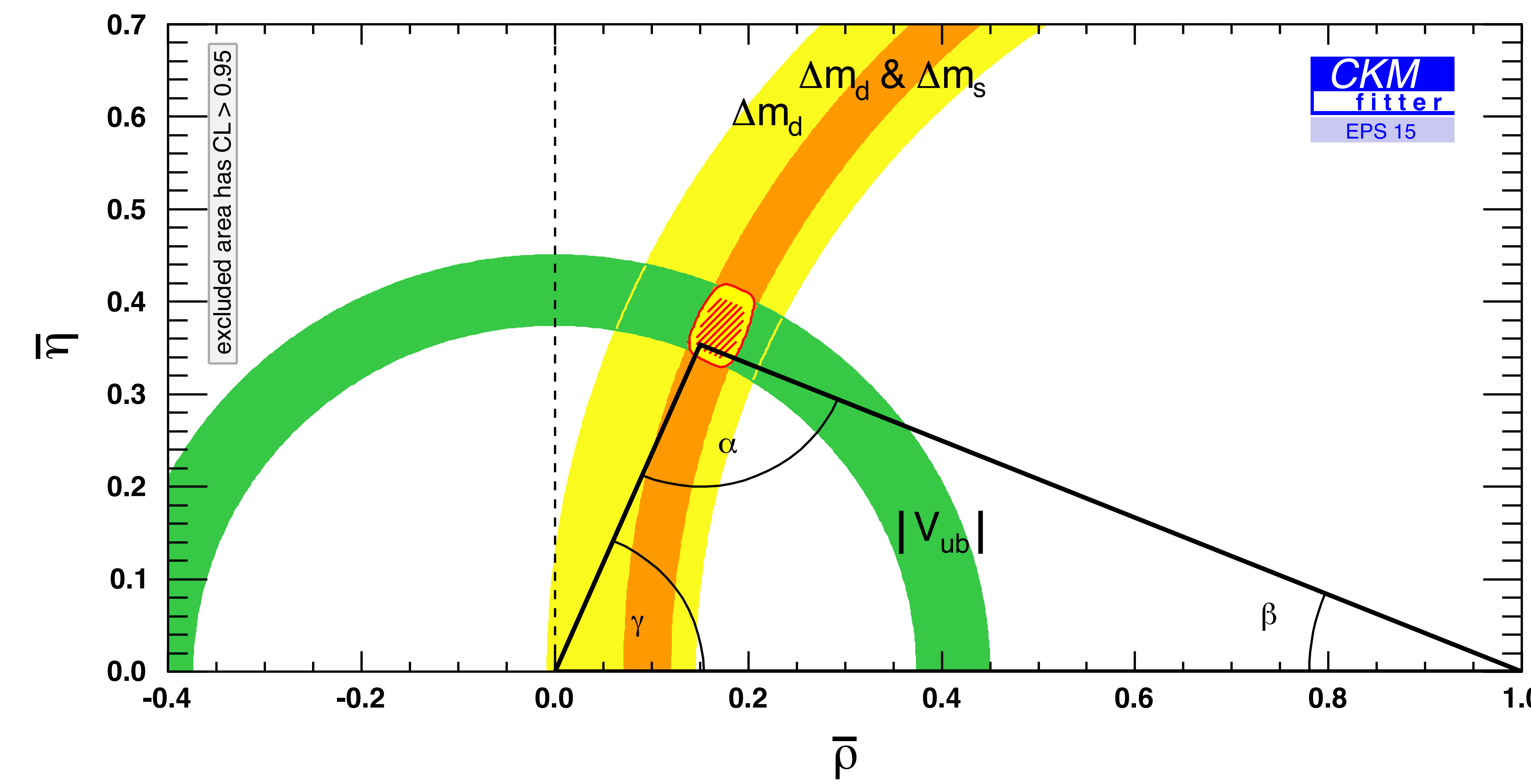


  - angular frequencies = "mixing frequencies"
  - $\Delta m_d/\Delta m_s \sim |V_{td}/V_{ts}|$

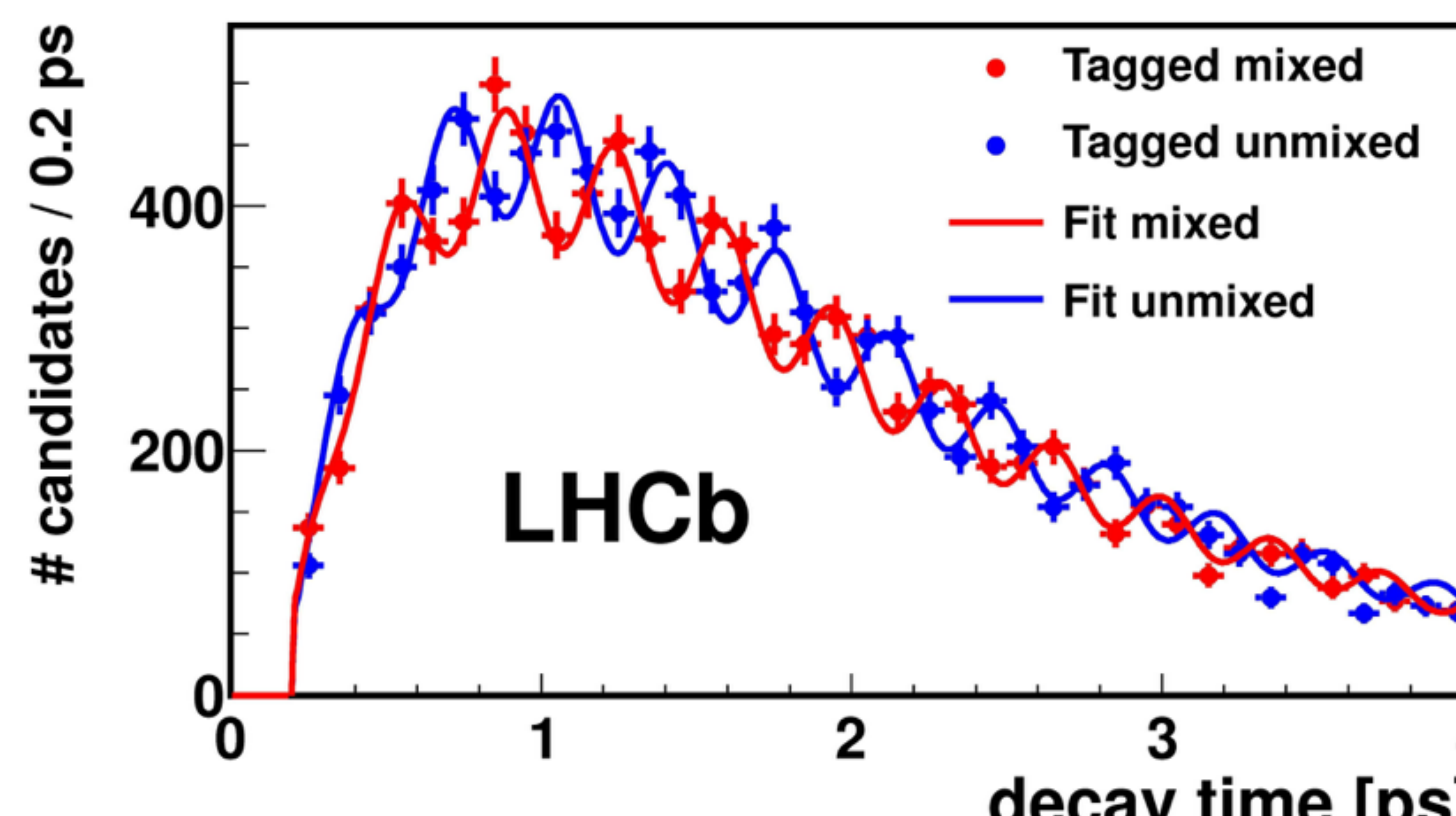
- mixing frequencies constrain UT side V_{td}
  - Δm_s precisely known

    $$\Delta m_s = 17.768 \pm 0.023\,(\text{stat}) \pm 0.006\,(\text{syst})\,\text{ps}^{-1}$$

  - limitations from
    - lattice calculations
    - oscillation frequency Δm_d of B^0 meson



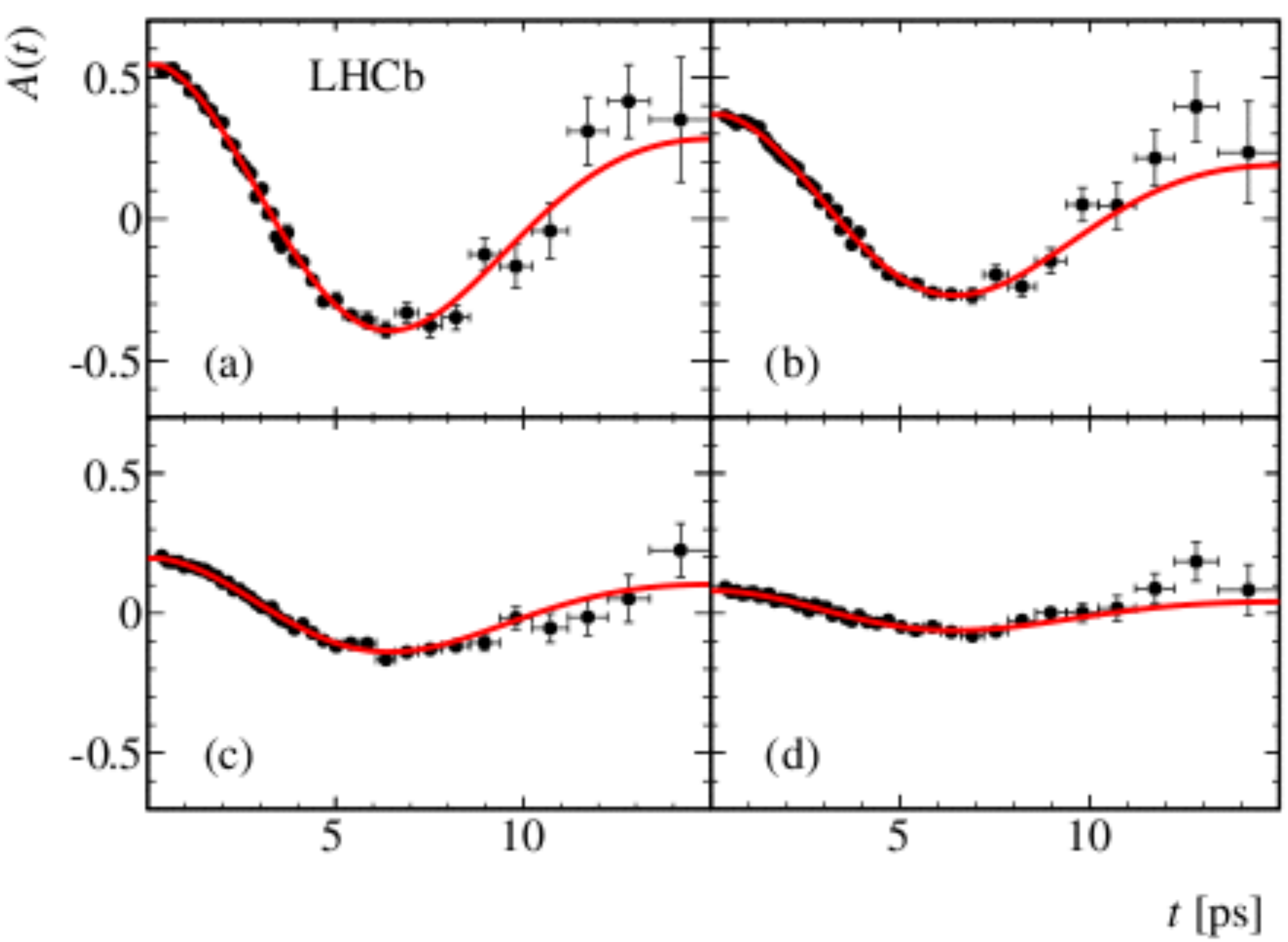
CKMfitter, EPJ. C41, 1-131 (2005)



NJP 15 (2013) 053021

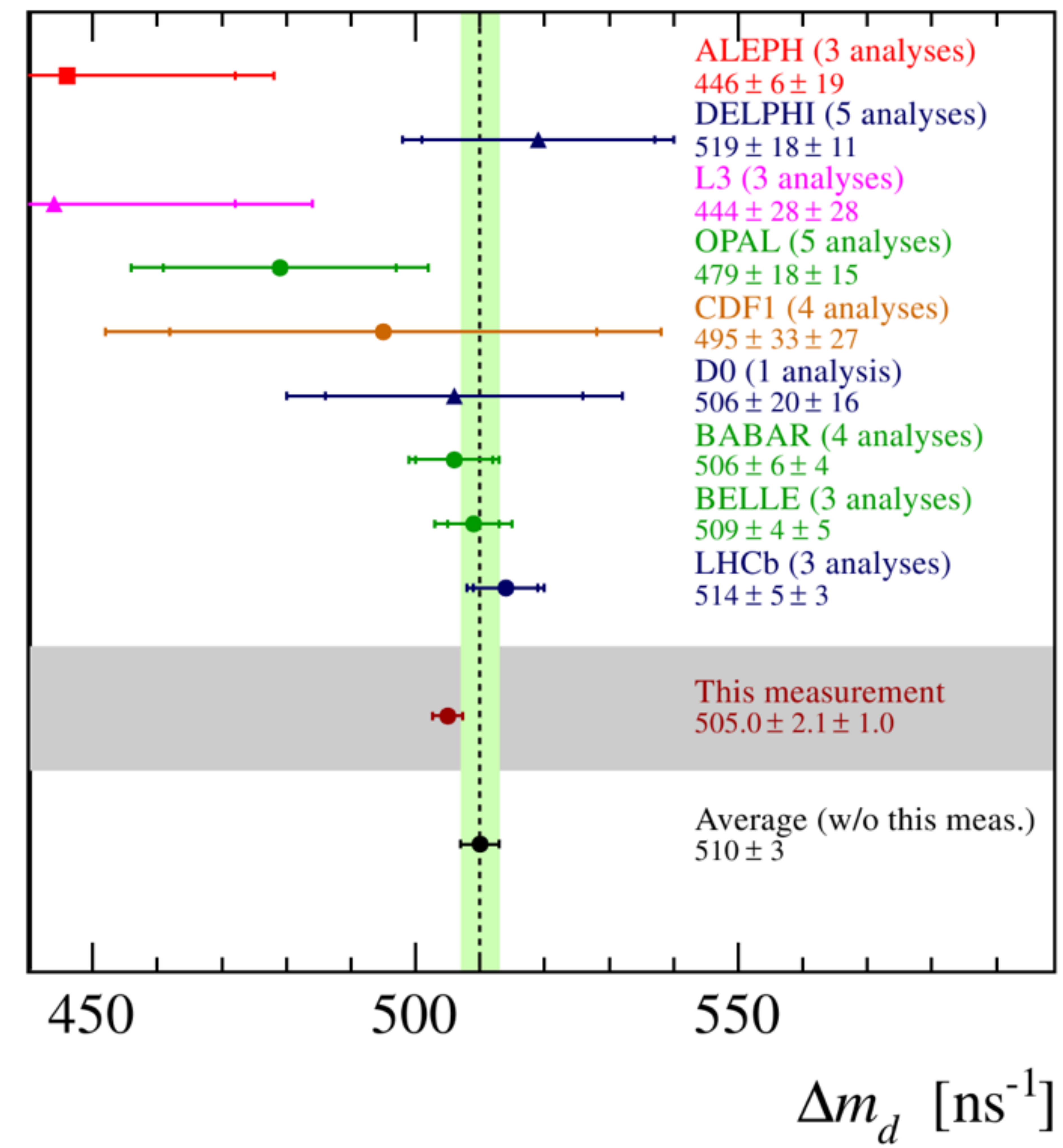
$|V_{td}/V_{ts}|$ from $\Delta m_d/\Delta m_s$

- LHCb measurement of Δm_d
  - use $B^0 \to D^{(*)-}\mu^+\nu_\mu$ decays
  - corrections for reconstructed mass



- result

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



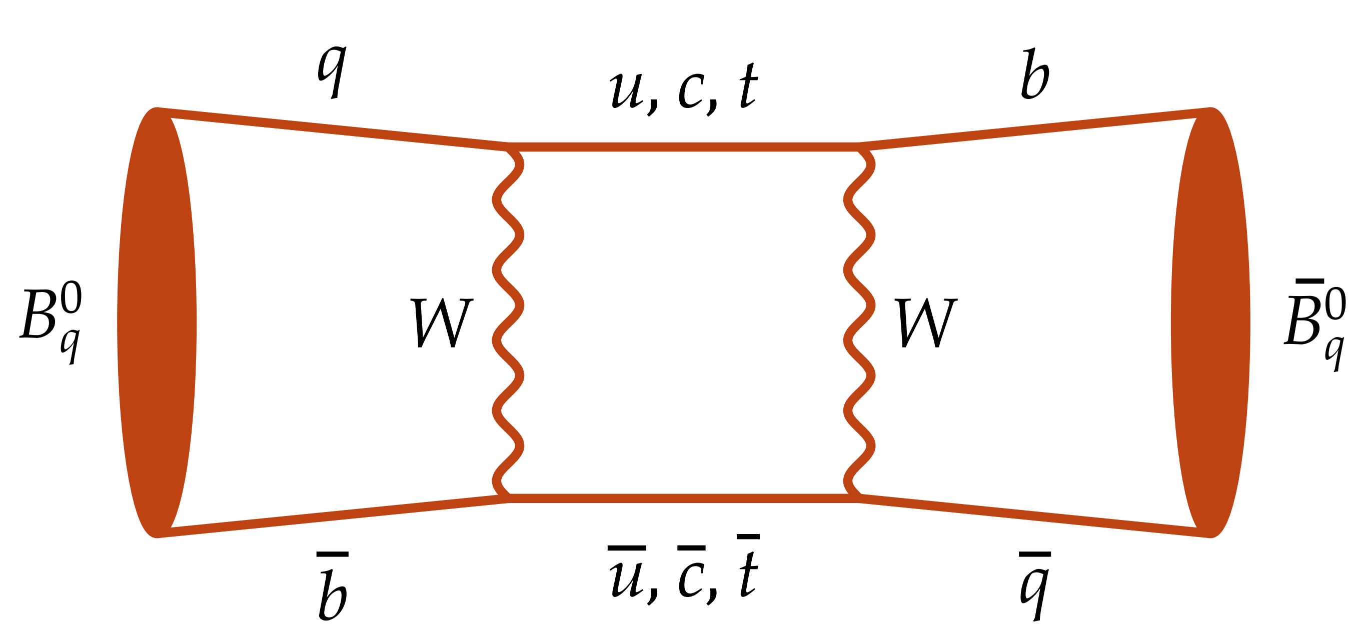
arXiv:1604.03475

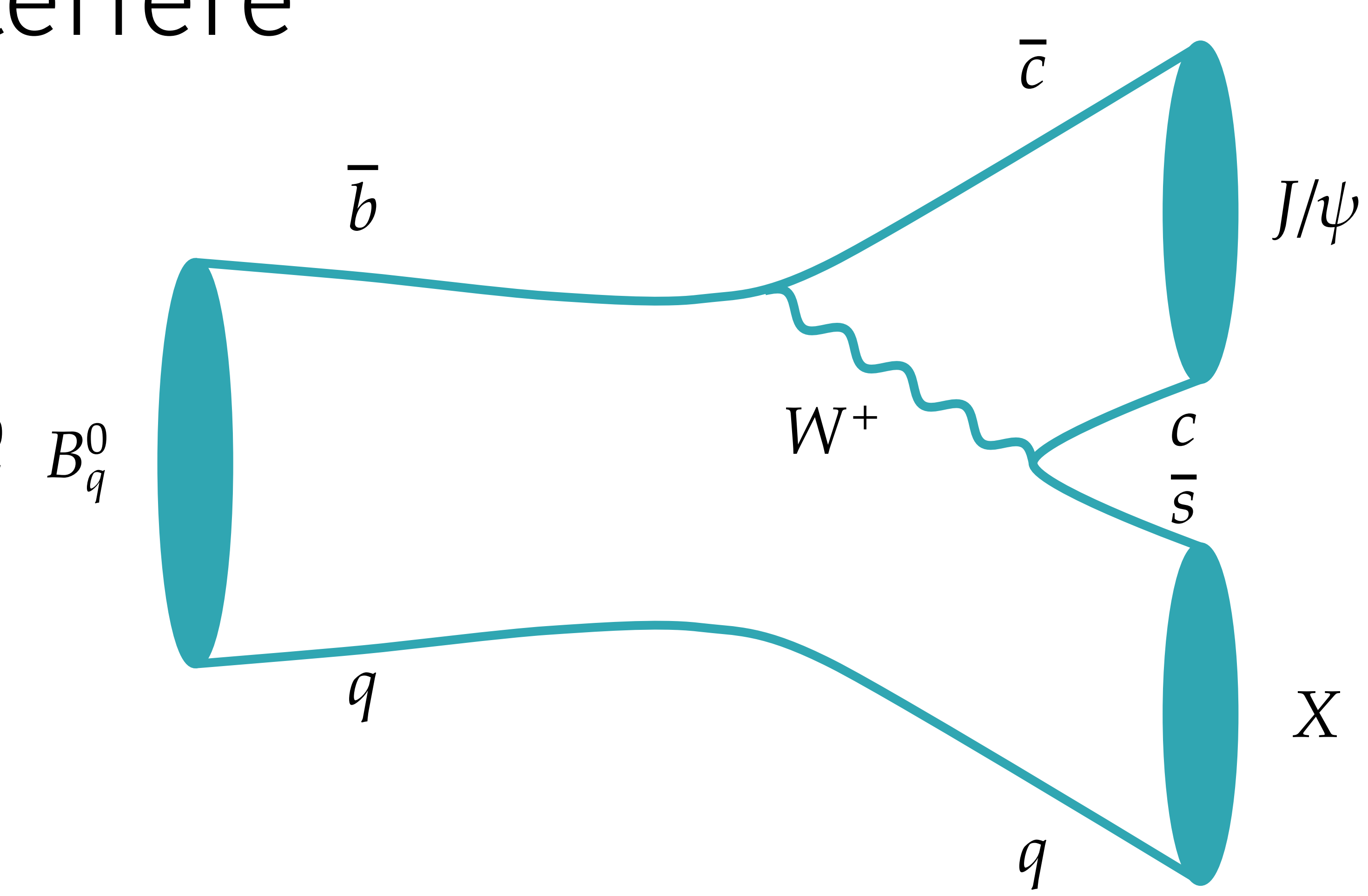
CP Violation

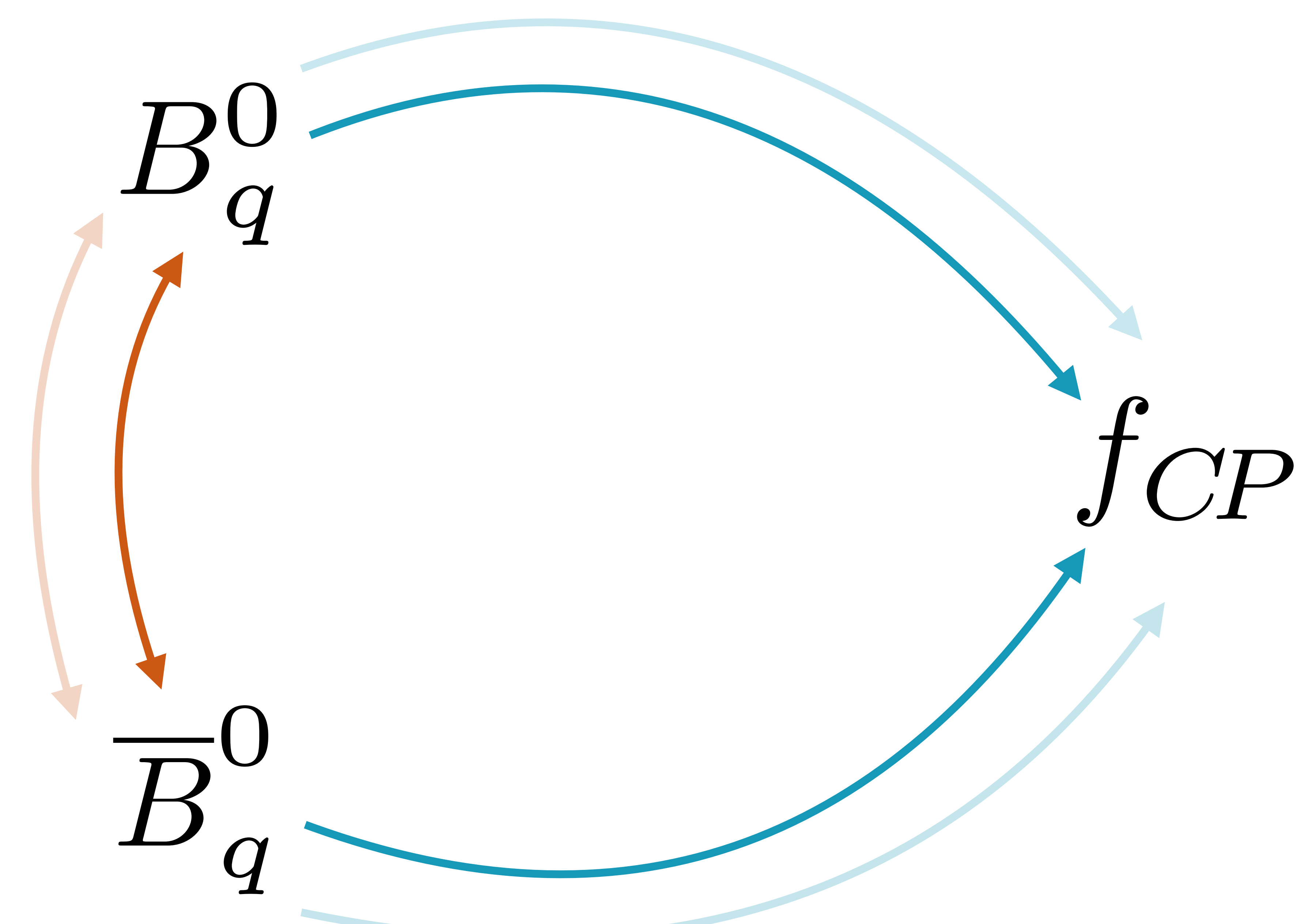
CP violation in neutral *B* mesons

- measure: ~~absolute phases~~, phase differences
  - interference of contributions with different phases

- neutral *B* mesons: B^0 and B_s oscillate
  - different paths can interfere



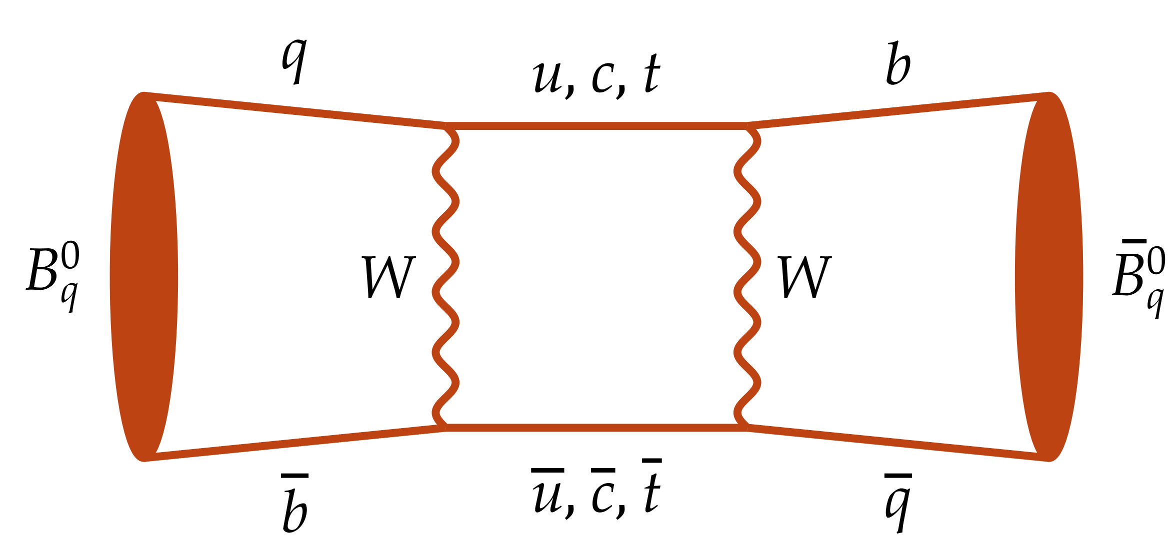


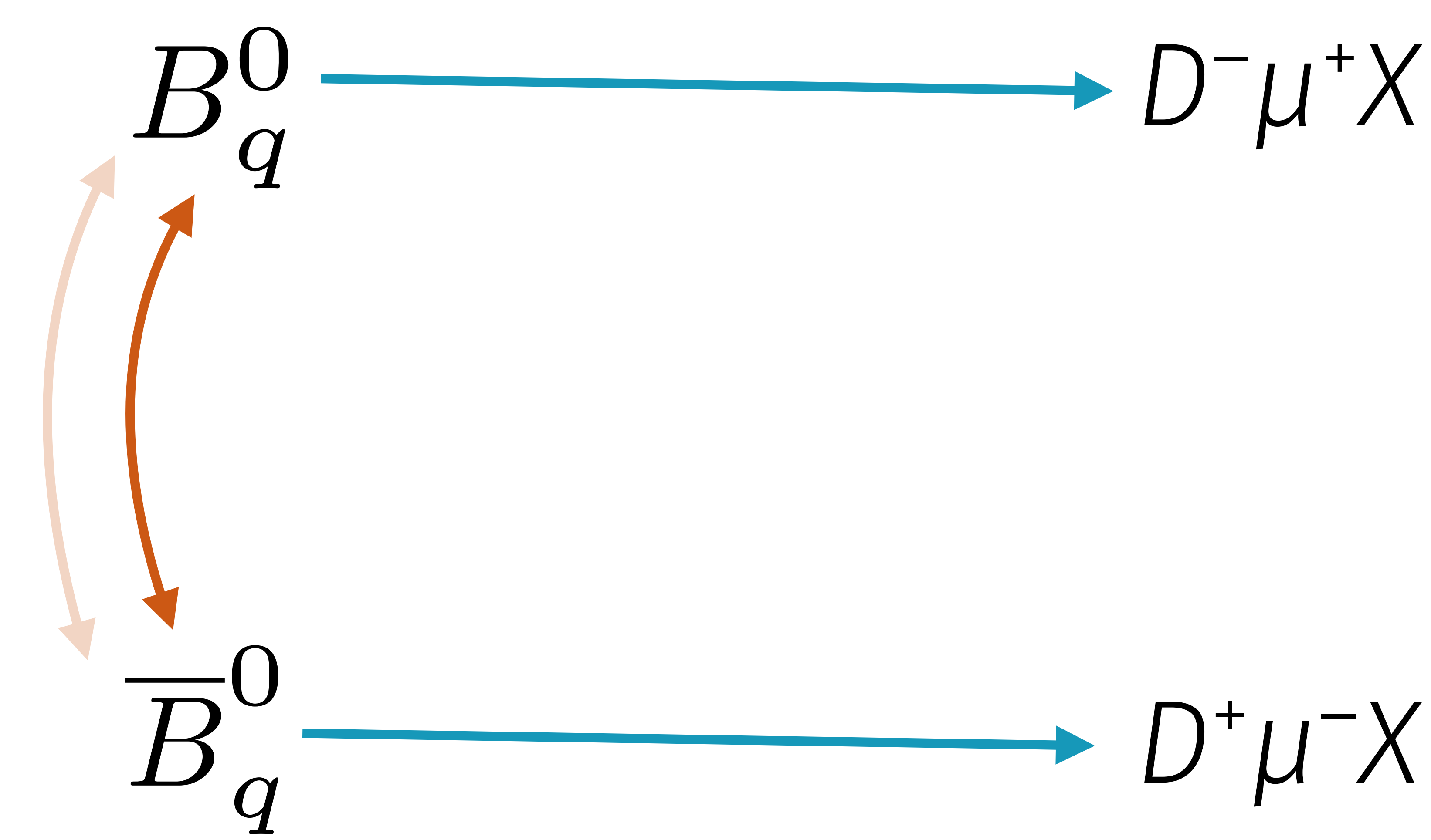


CP violation in mixing

- CPV in mixing related to semi-leptonic asymmetry a_{sl}

$$A = \frac{P(\overline{B} \to B) - P(B \to \overline{B})}{P(\overline{B} \to B) + P(B \to \overline{B})} \approx \frac{a_{\mathrm{sl}}}{2}$$





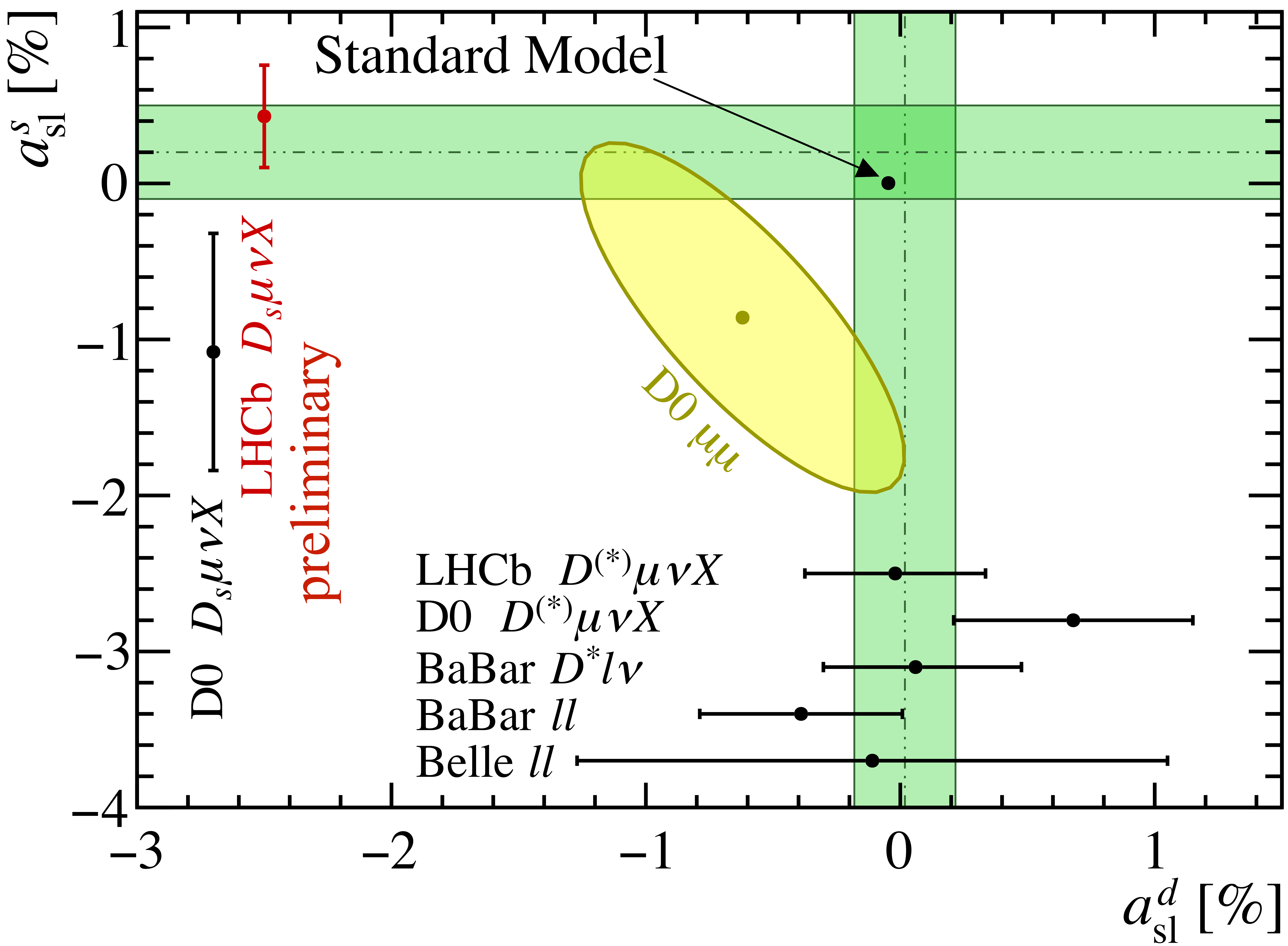
- measure raw asymmetry

$$A(t) = \frac{N(f,t) - N(\bar{f},t)}{N(f,t) + N(\bar{f},t)} = A_{\mathrm{D}} + \frac{a_{\mathrm{sl}}}{2} + \left(A_{\mathrm{P}} - \frac{a_{\mathrm{sl}}}{2}\right)\cos(\Delta m t)$$

PRL 115, 041601 (2015)

LHCb-PAPER-2016-013, in preparation

CP violation in mixing a.k.a. a_{sl}

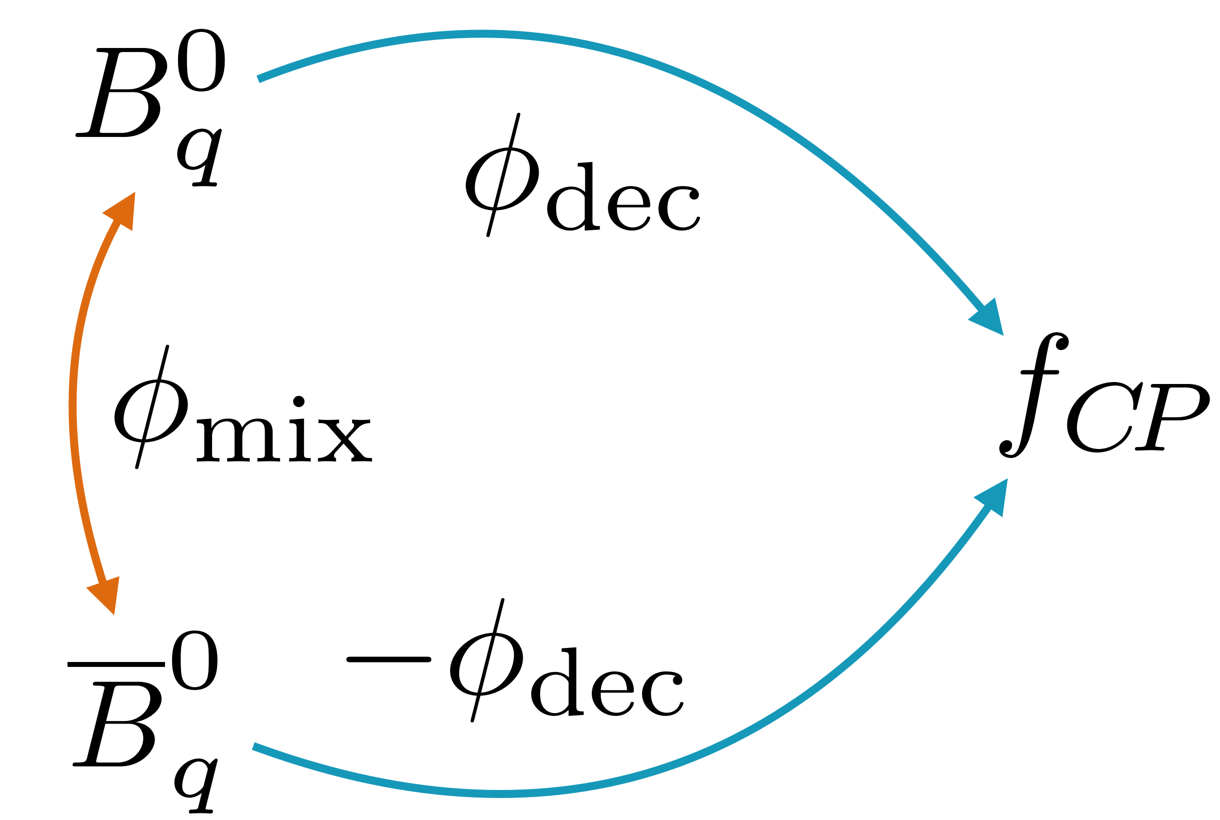


PRL 115, 041601 (2015)

LHCb-PAPER-2016-013, in preparation

CP violation: interference of mixing and decay

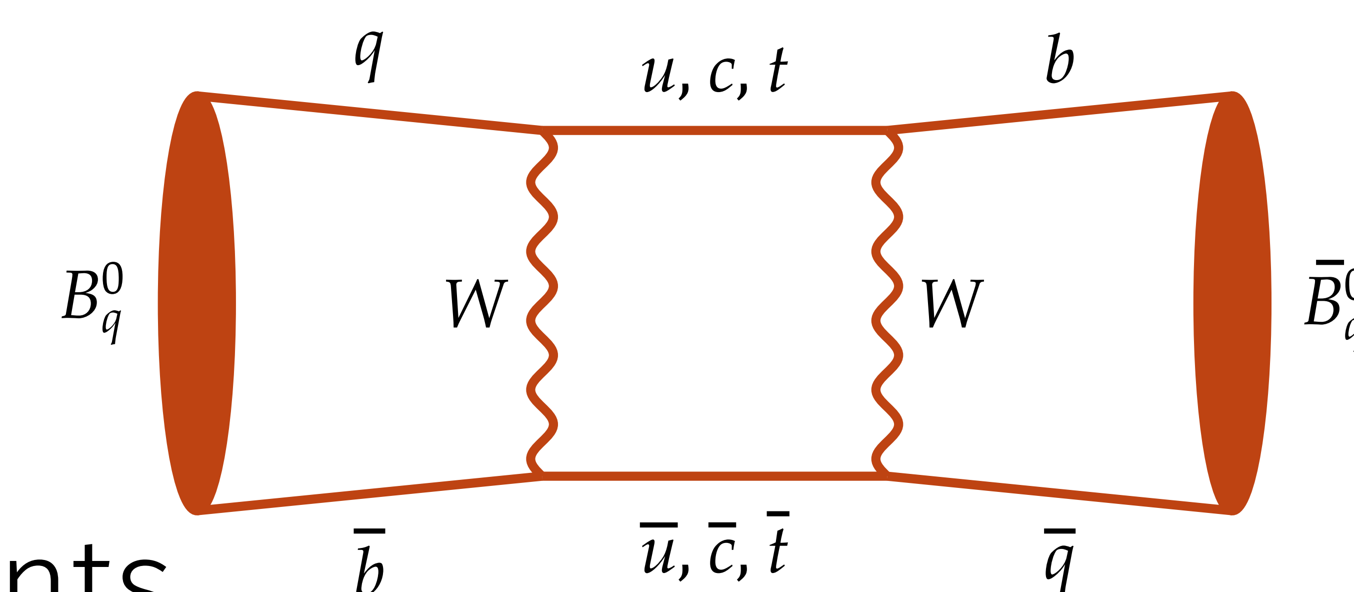
- simplest case: single dominant decay amplitude
  - ➡ phase difference $\phi_q = \phi_{mix} - 2\,\phi_{dec}$

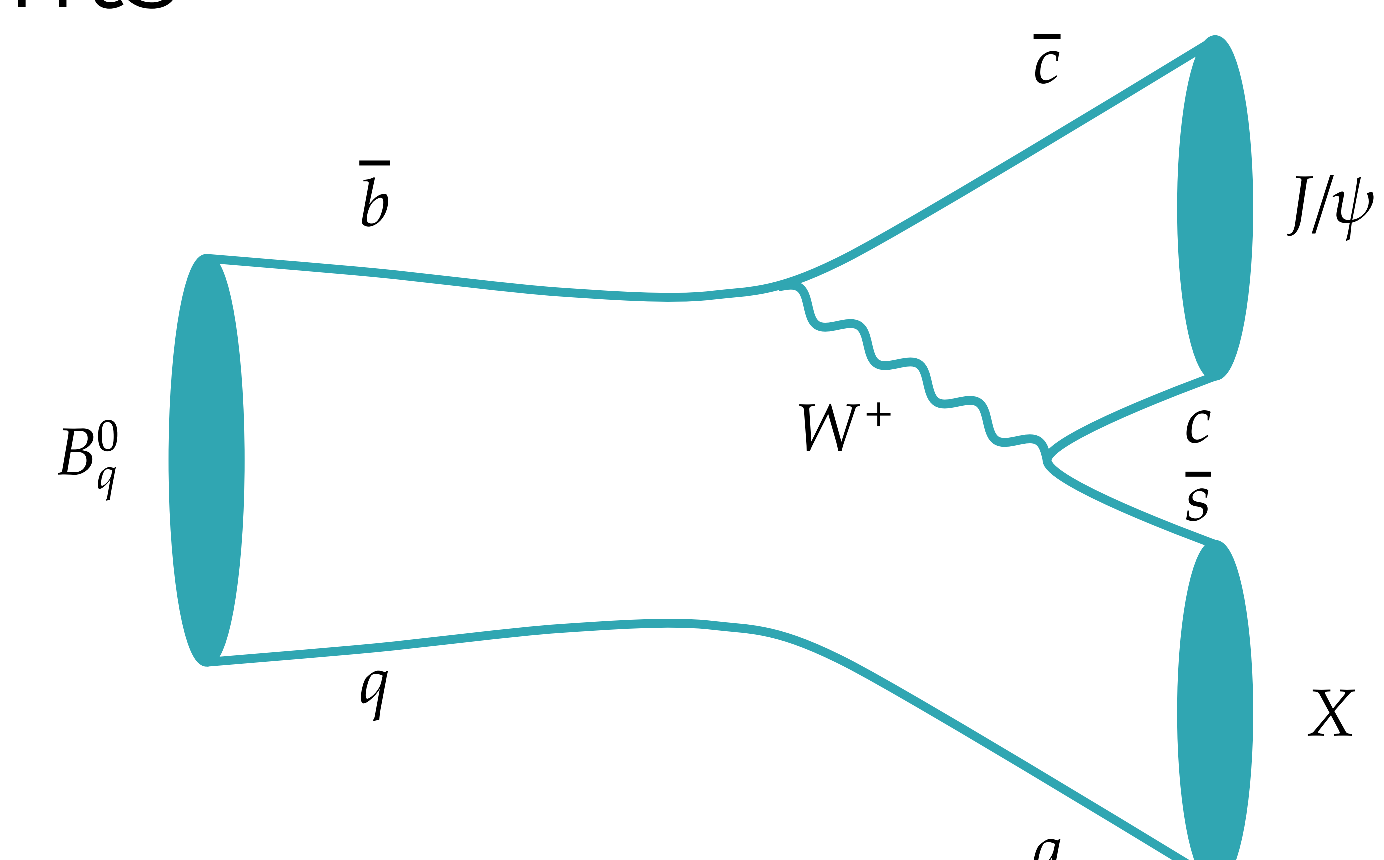


- phases are related to CKM angles
  - “golden” modes (dominant $b \to ccs$ tree decays)
    - $B^0 \to J/\psi\, K_S$ $(\phi_d = 2\beta)$
    - $B_s \to J/\psi\, h^+h^-$ $(\phi_s = -2\beta_s)$
  - other measurements + CKM unitarity ➔ precise constraints
    - $\sin\phi_d = 0{,}771\,^{+0{,}017}_{-0{,}041}$
    - $\sin\phi_s = -0{,}0365\,^{+0{,}0013}_{-0{,}0012}$

J. Charles et al.
arXiv:1501.05013

  - excellent probe for BSM contributions



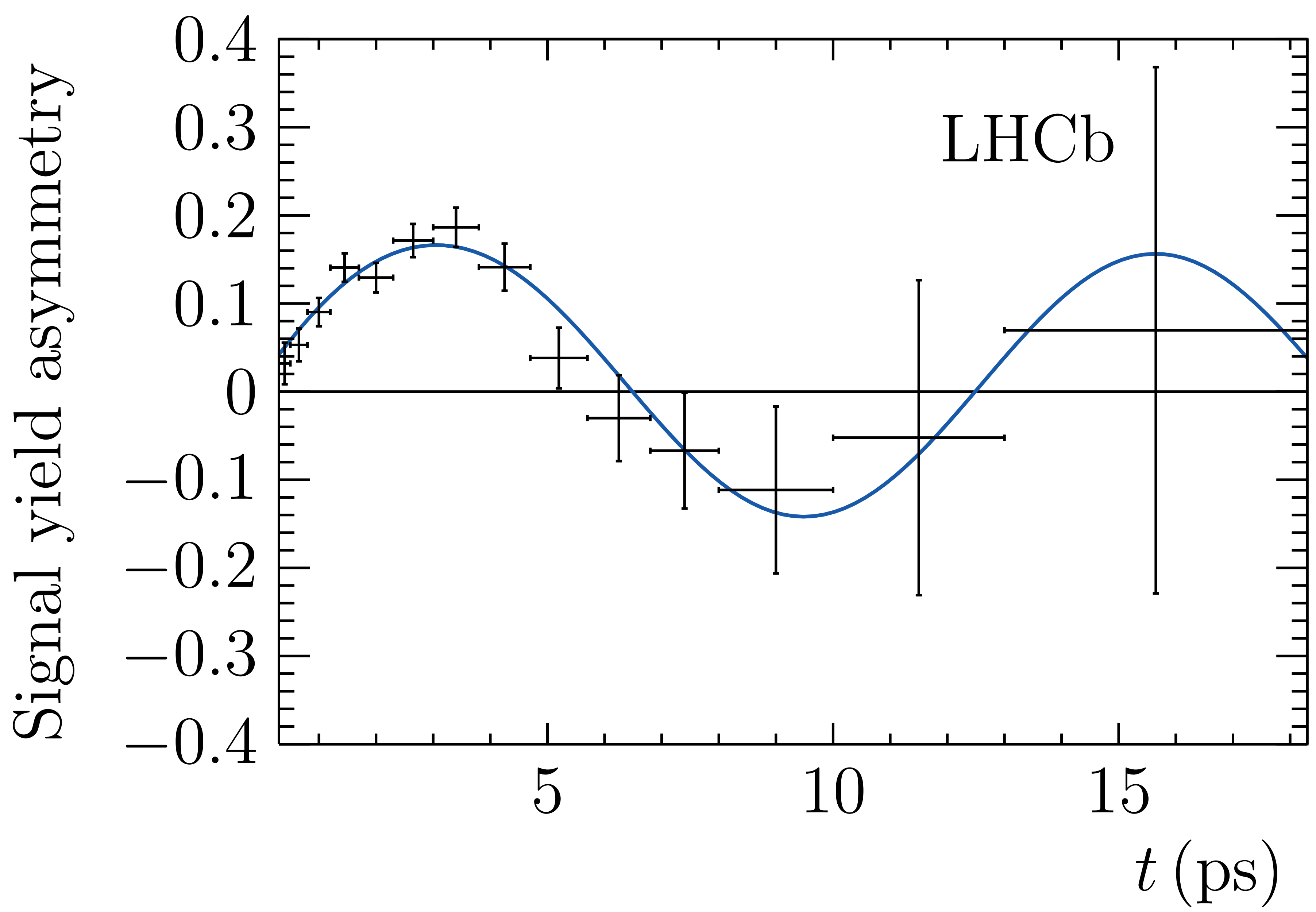


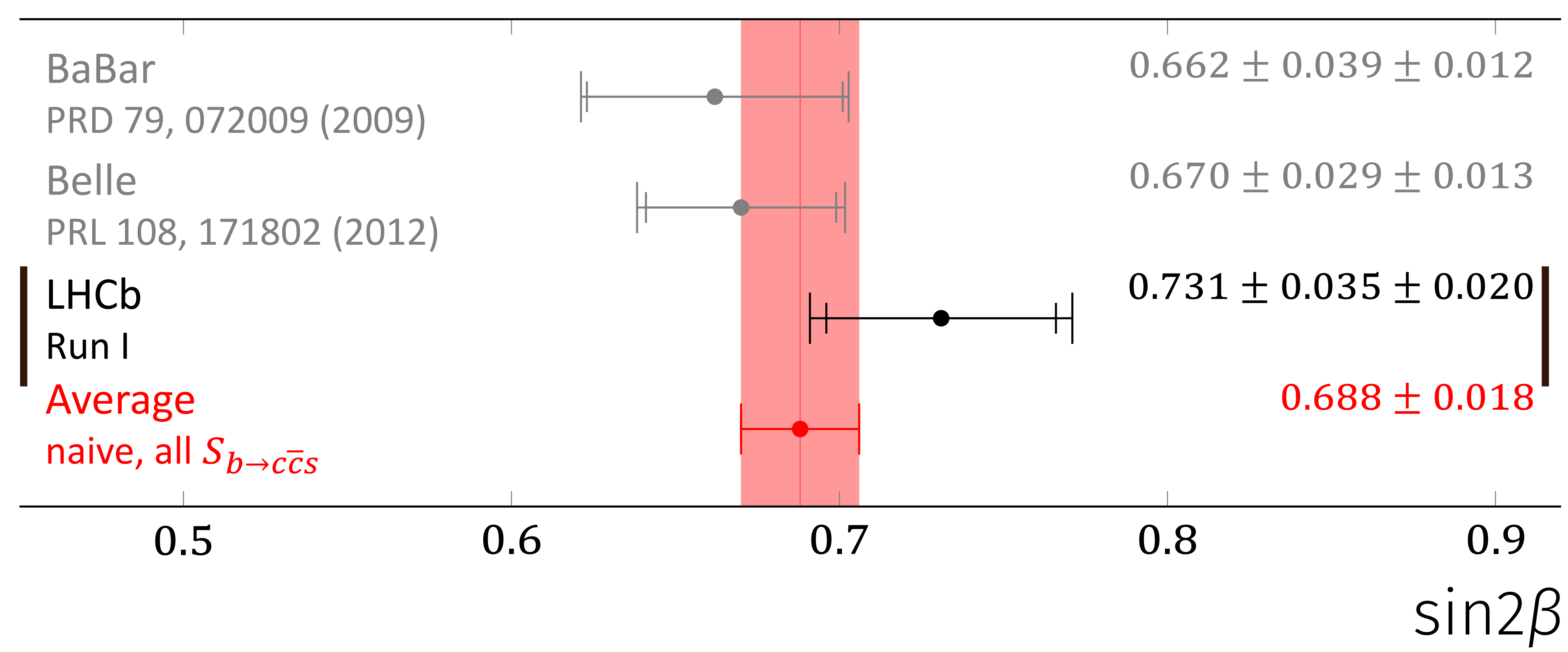
$\sin 2\beta$ from $B^0 \to J/\psi\, K_S$

- decay time dependent asymmetry

$$\mathcal{A}(t) = \frac{\Gamma(\overline{B}(t) \to f) - \Gamma(B(t) \to f)}{\Gamma(\overline{B}(t) \to f) + \Gamma(B(t) \to f)} \sim \sin 2\beta \sin \Delta m\, t$$

- LHCb measurement reaches precision of *B* factories



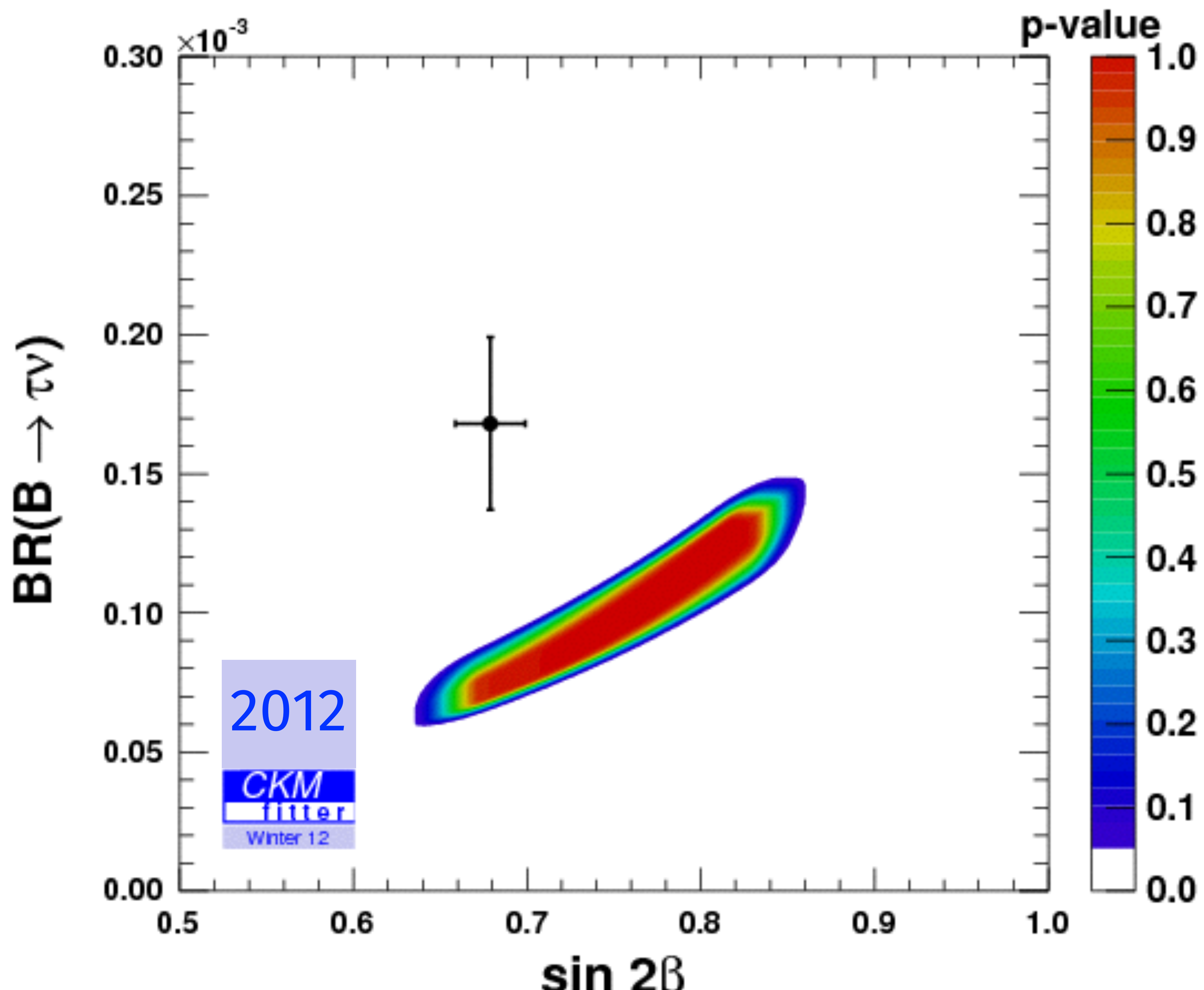


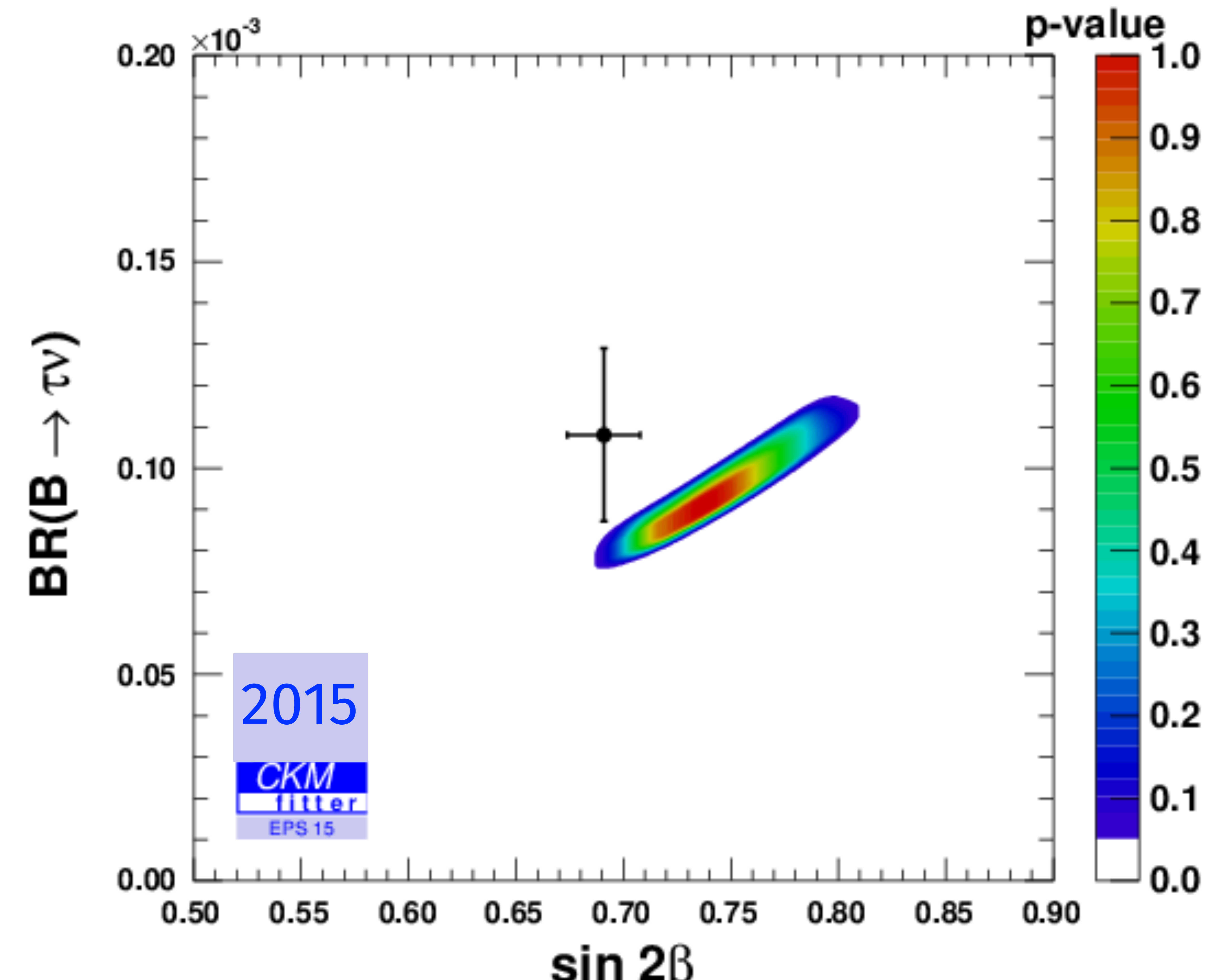
prospects: world best with Run II!

PRL 115, 031601 (2015)

$\sin 2\beta$ vs. $B(B^+ \to \tau^+ \nu_\tau)$

- discrepancies between indirect fit and direct measurement get smaller

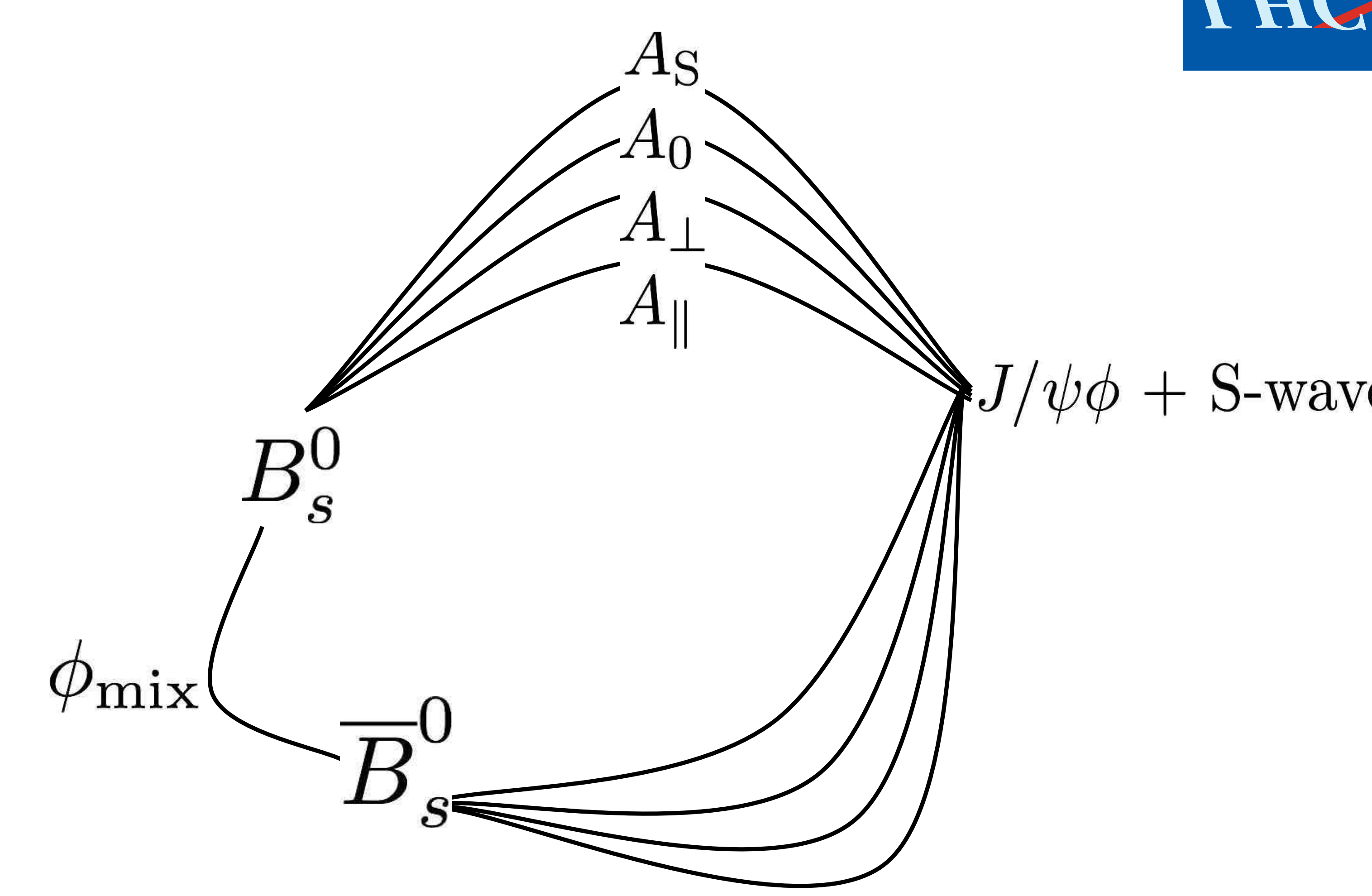




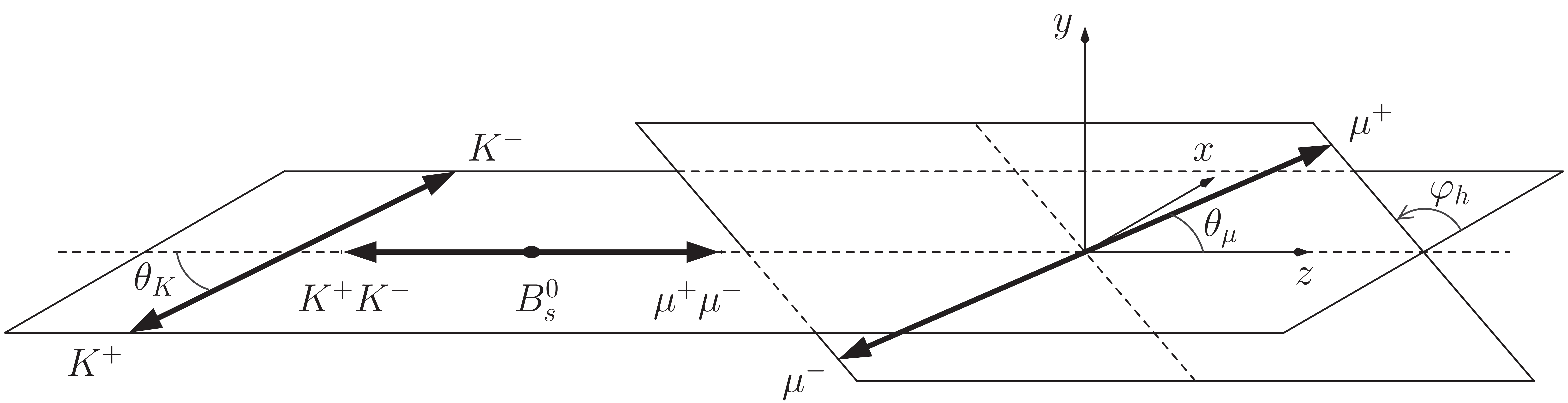
CKMfitter, EPJ. C41, 1-131 (2005)

ϕ_s from $B_s \to J/\psi\ h^+h^-$

- analysis of ≈96000 $B_s \to J/\psi\ K^+K^-$ decays
  - decay-time dependent and flavour tagged
  - angular analysis in 6 bins of K^+K^- mass
  - describe three *P*- and one *S*-wave contribution
  - distinguish *CP*-even and -odd *P*-wave contributions



PRL 114, 041801 (2015)



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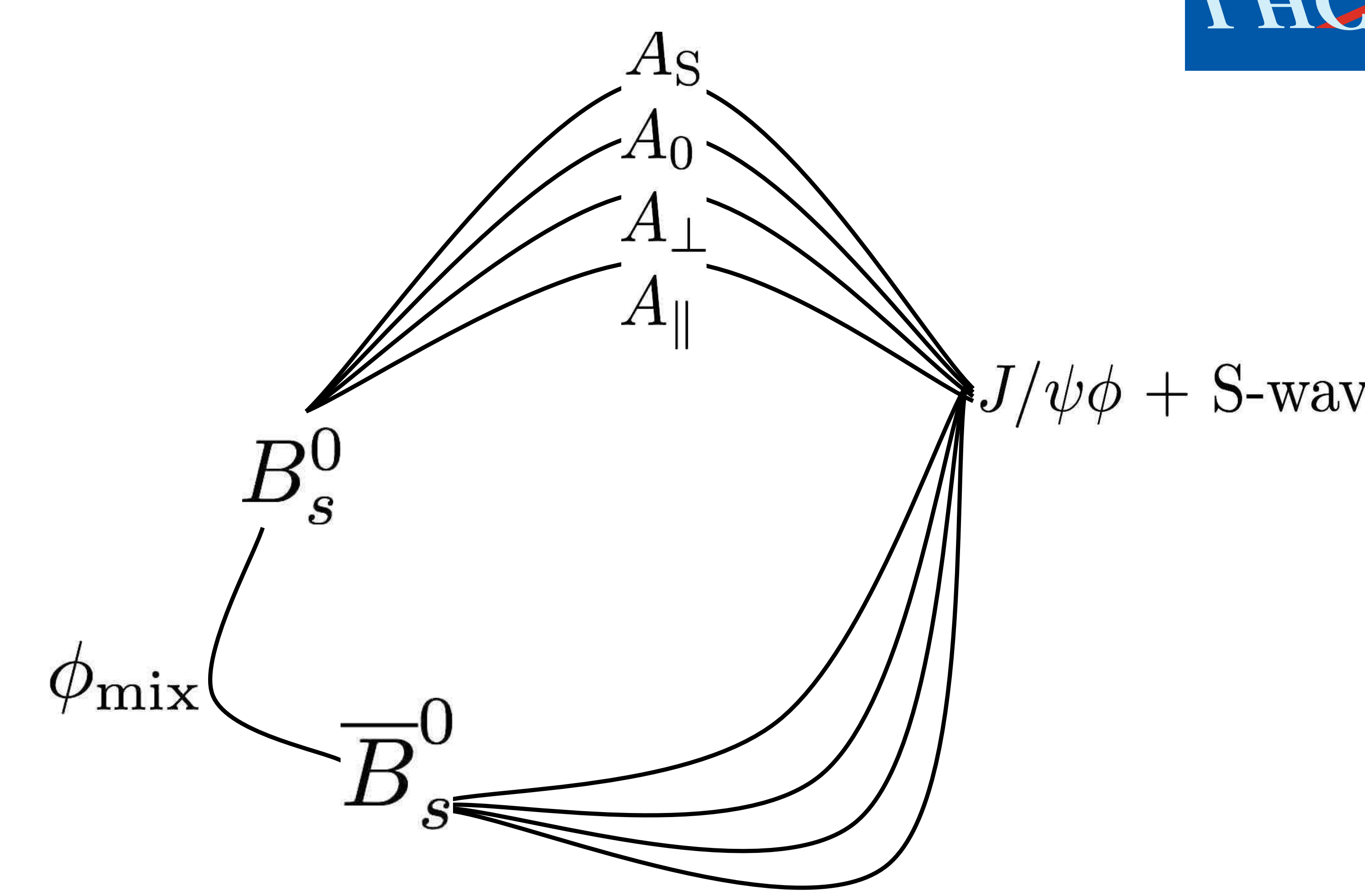
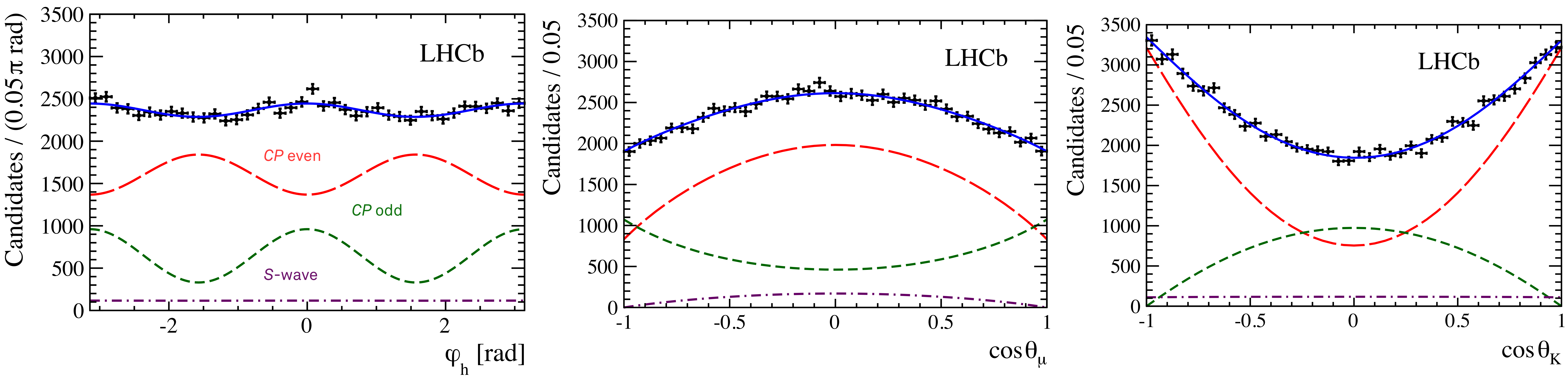


PRL 114, 041801 (2015)



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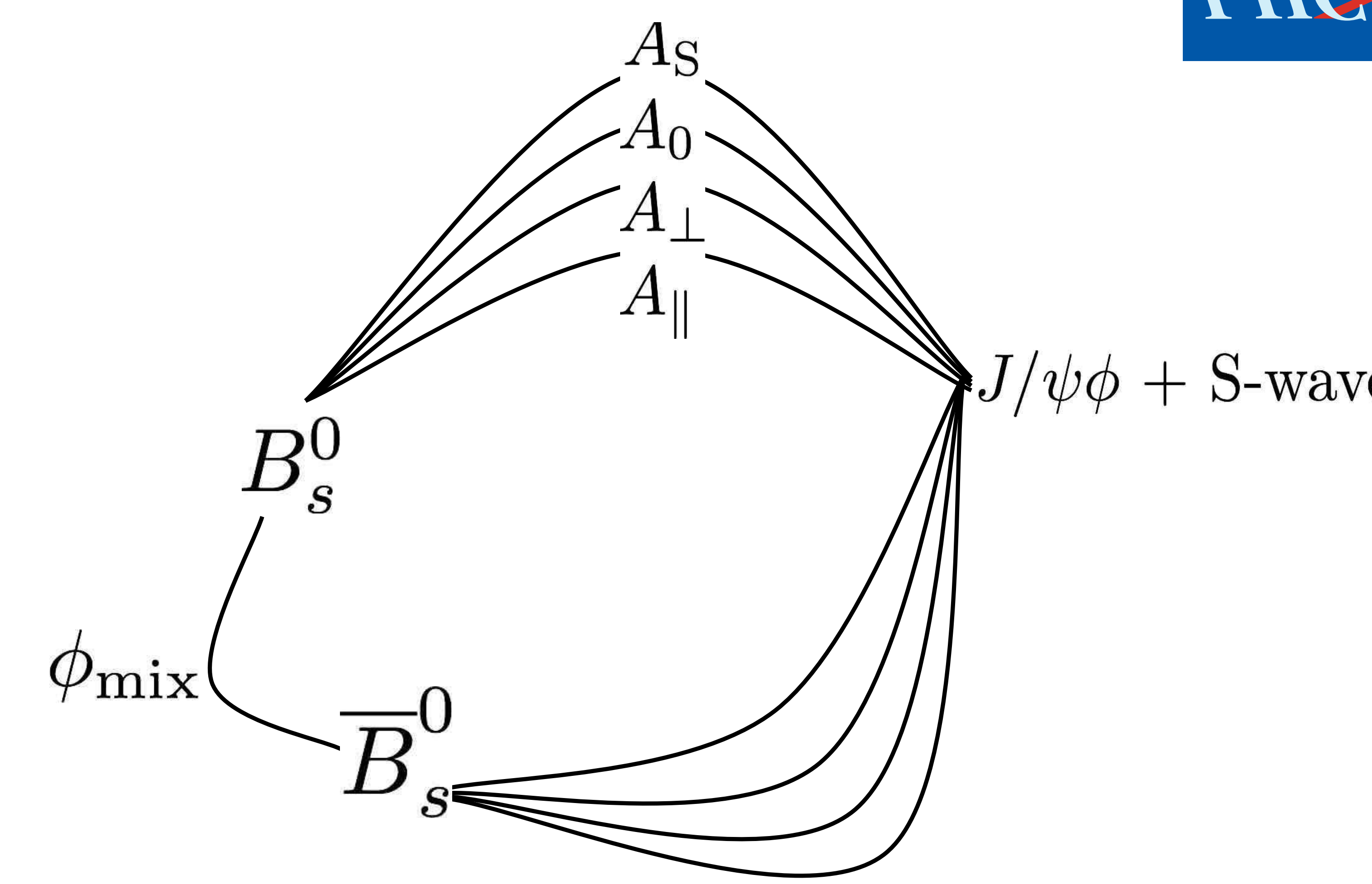
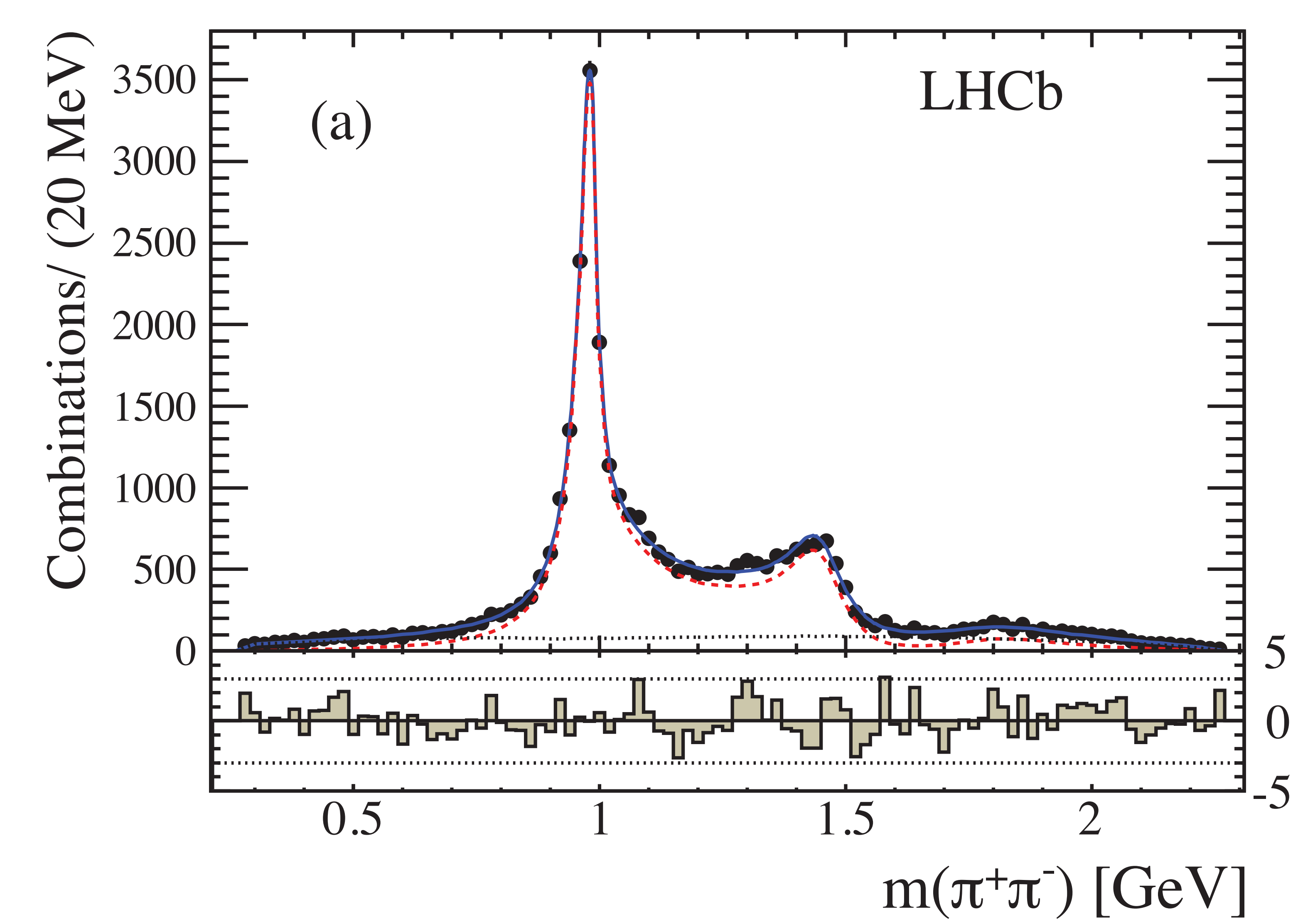


PRL 114, 041801 (2015)

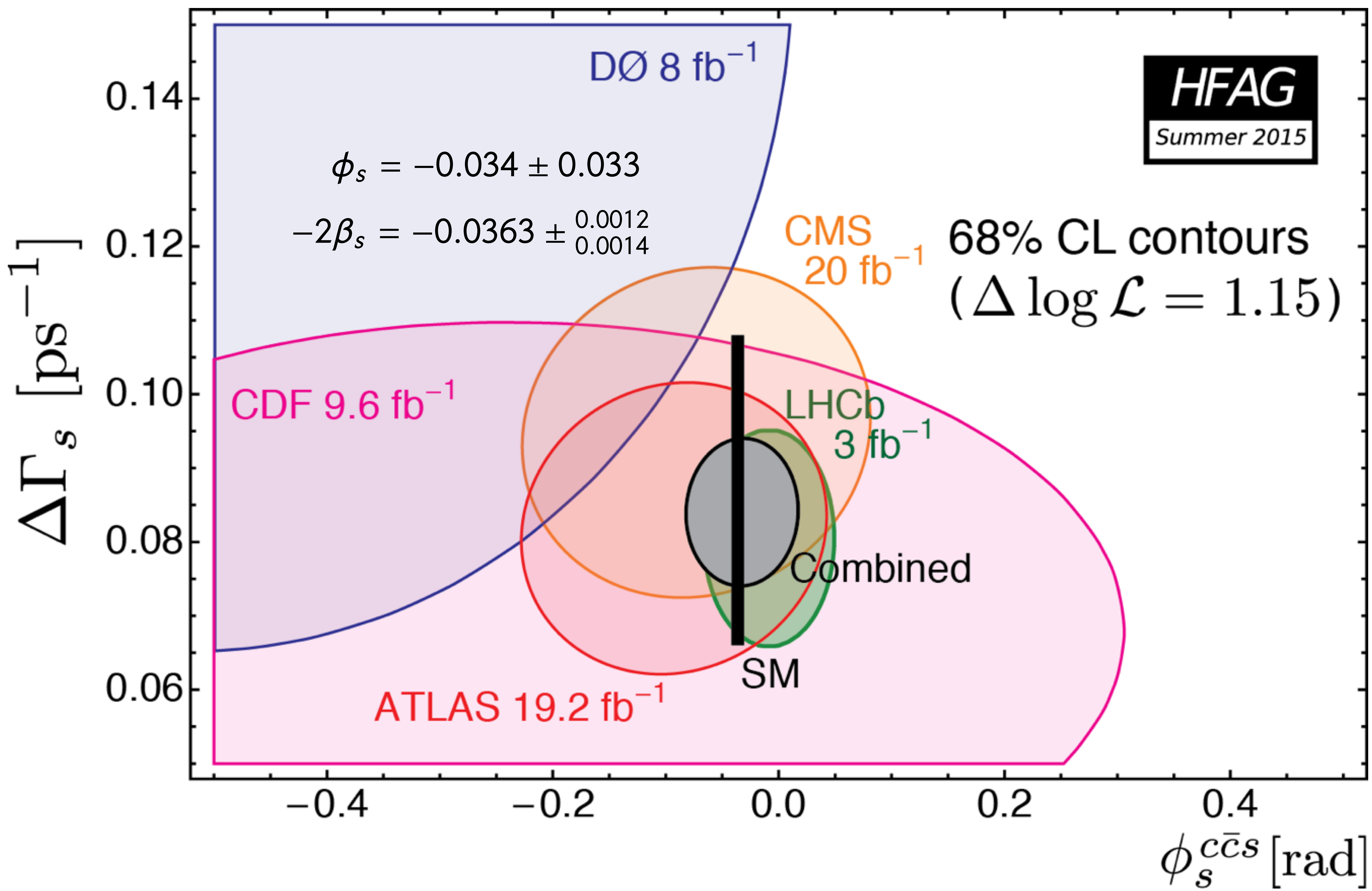
- combine result with $B_s \rightarrow J/\psi\ \pi^+\pi^-$

$$\phi_s = -0.010 \pm 0.039$$



PLB 736 (2014)

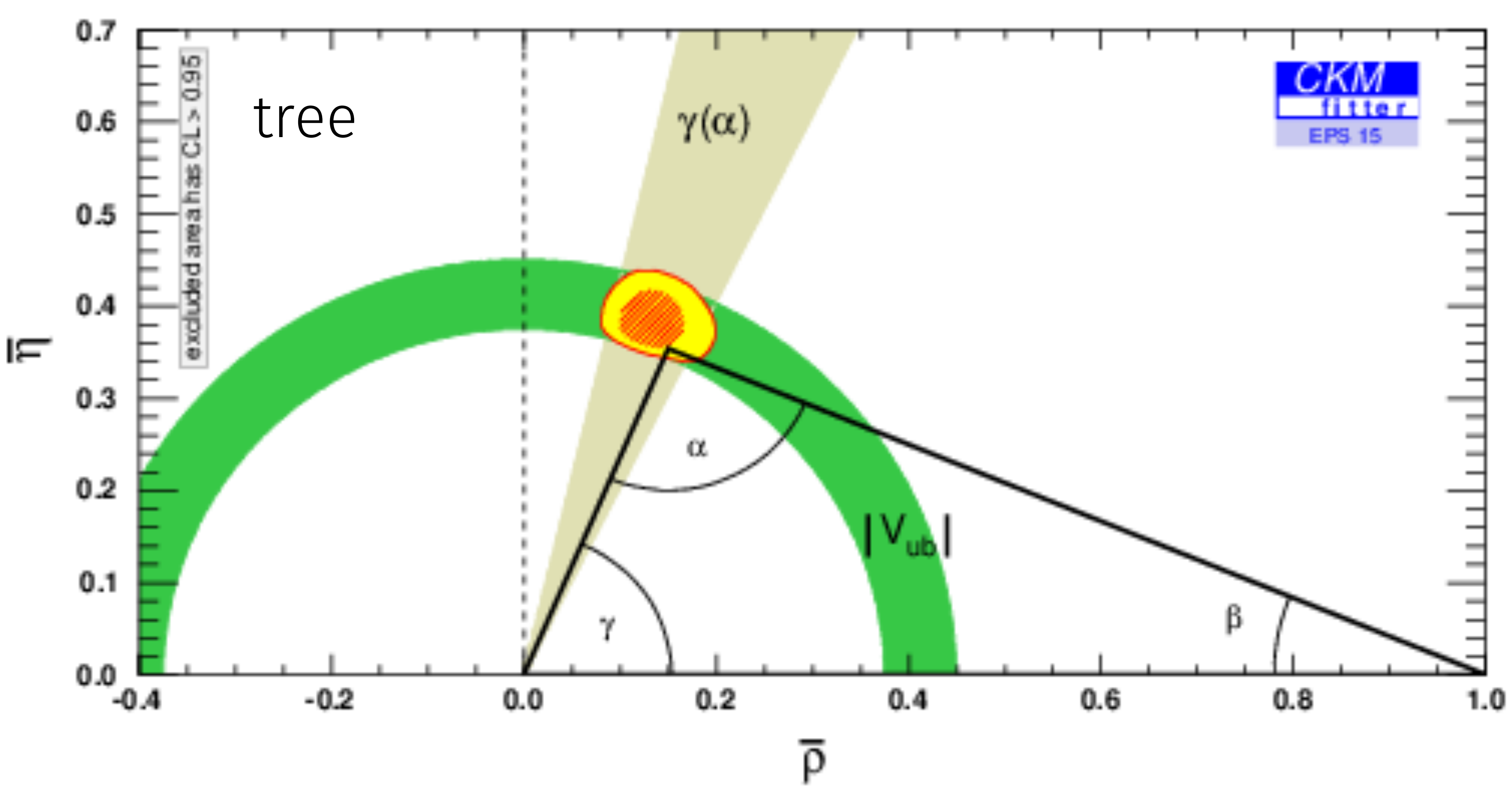
ϕ_s from LHC & Tevatron

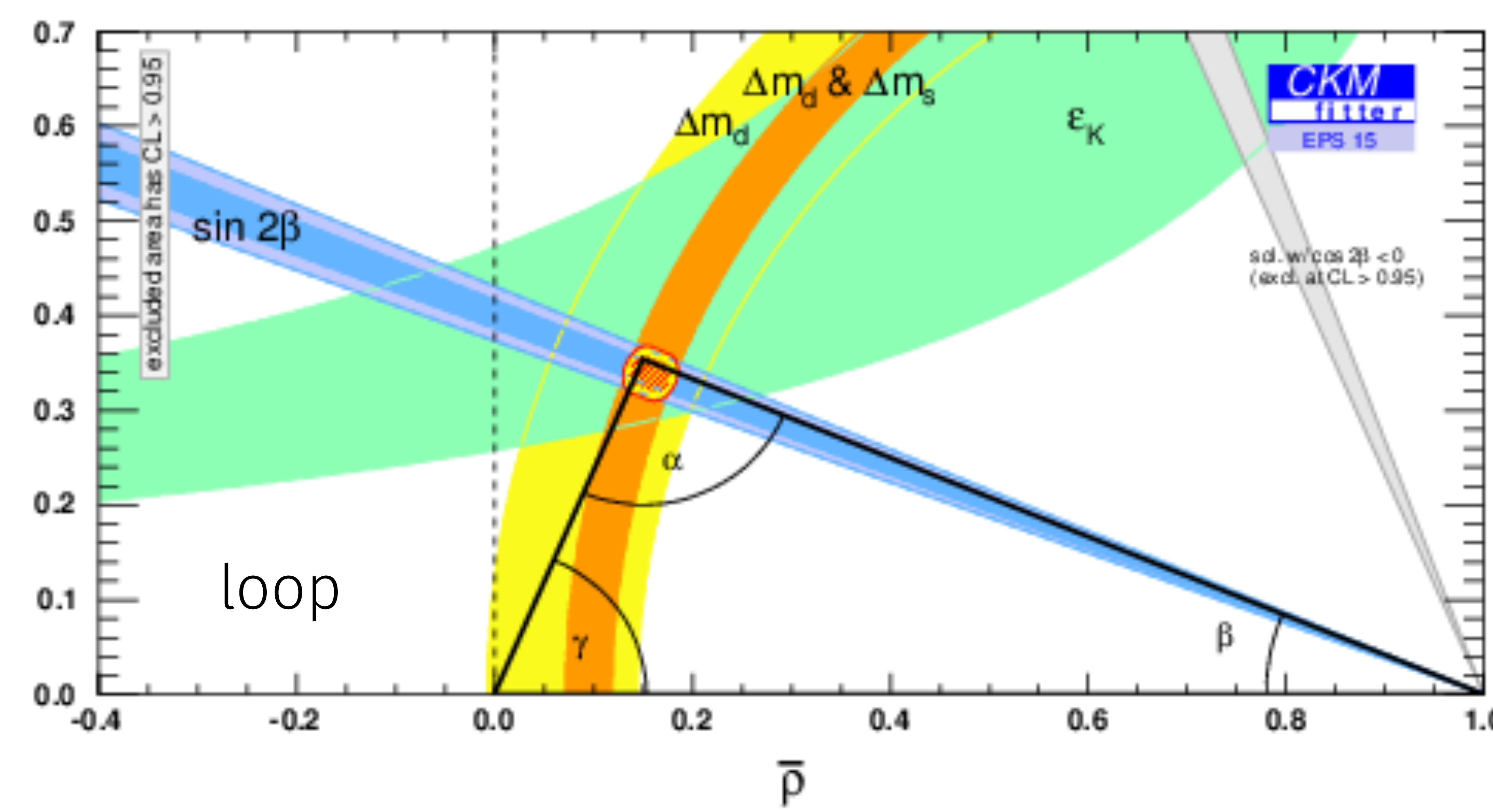


PRL 114, 041801 (2015)
PLB 736 (2014)
CERN-PH-2015-166
PLB 757 (2016) 97
PRL 109, 171802 (2012)
PRD 85, 032006 (2012)

CKM angle γ

- least well constrained CKM angle
- unique role
  - only *CP* violating parameter that can be determined from tree diagrams
  - nearly insensitive to NP
  - theoretically clean, $\delta\gamma/\gamma < O(10^{-7})$
- goal: compare tree measurements with loop predictions

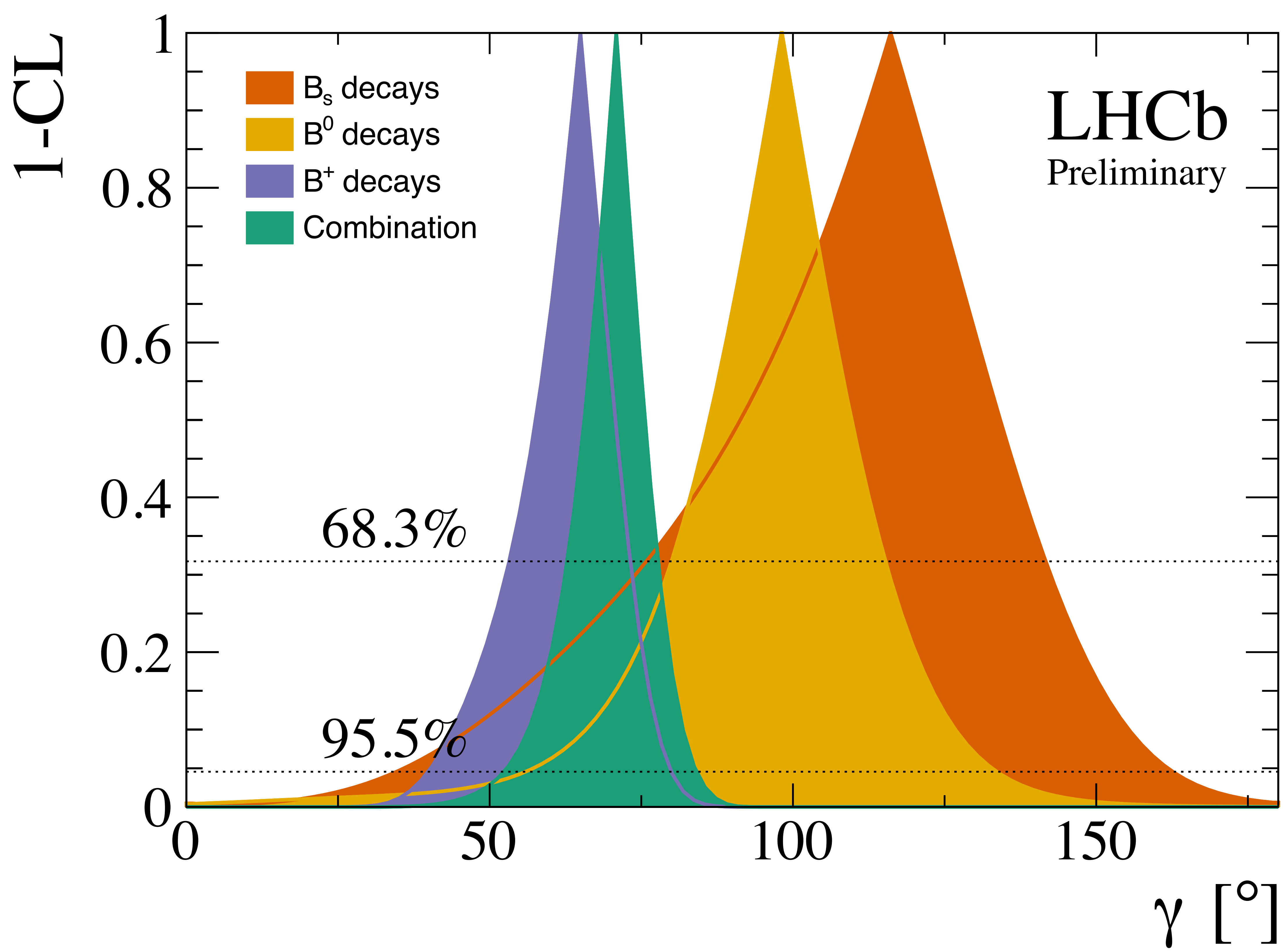


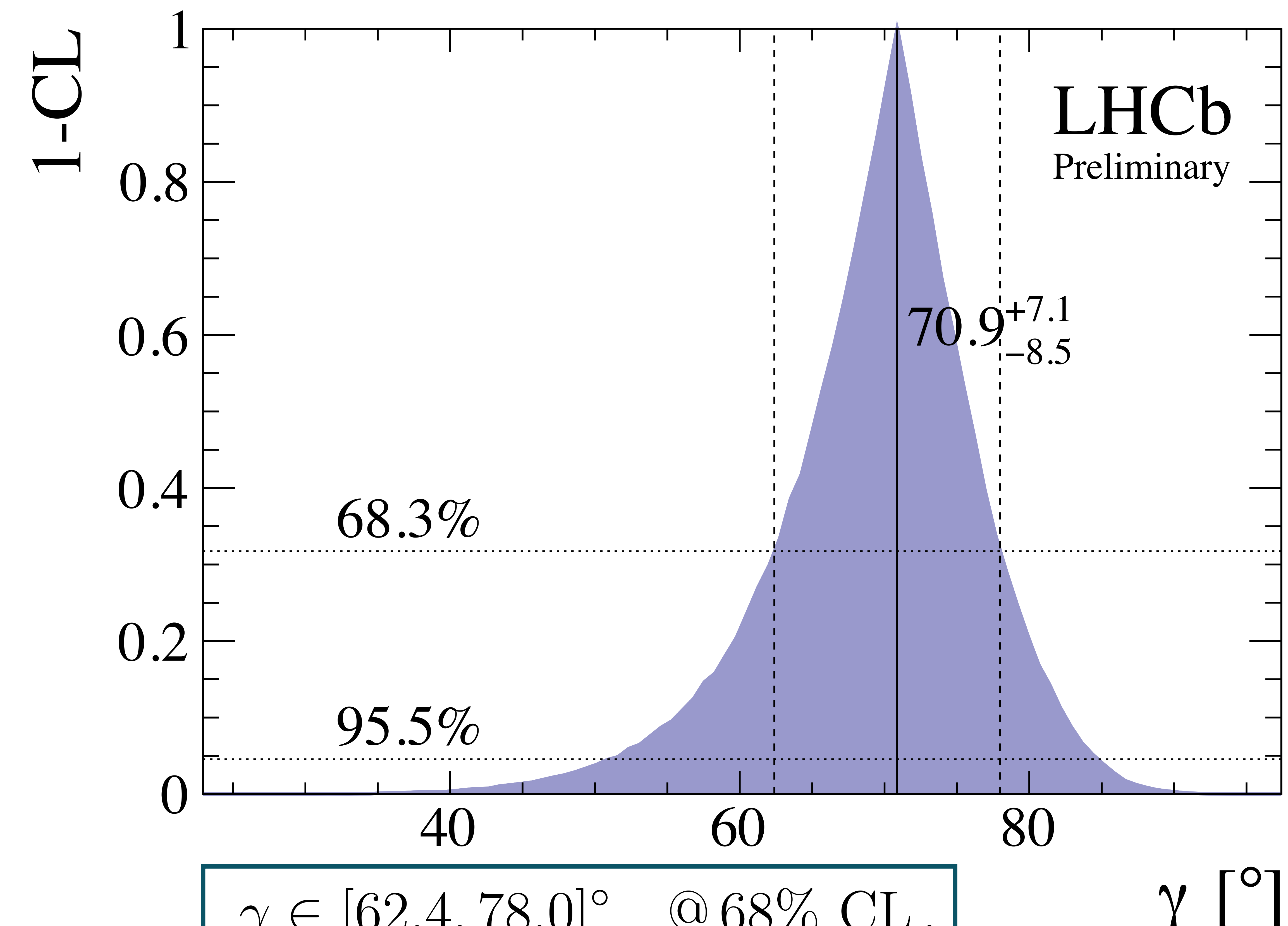


CKMfitter, EPJ. C41, 1-131 (2005)

LHCb γ combination

- various observables in $B \to DK$ decays sensitive to γ
- single measurements not very constraining ⇒ combine them



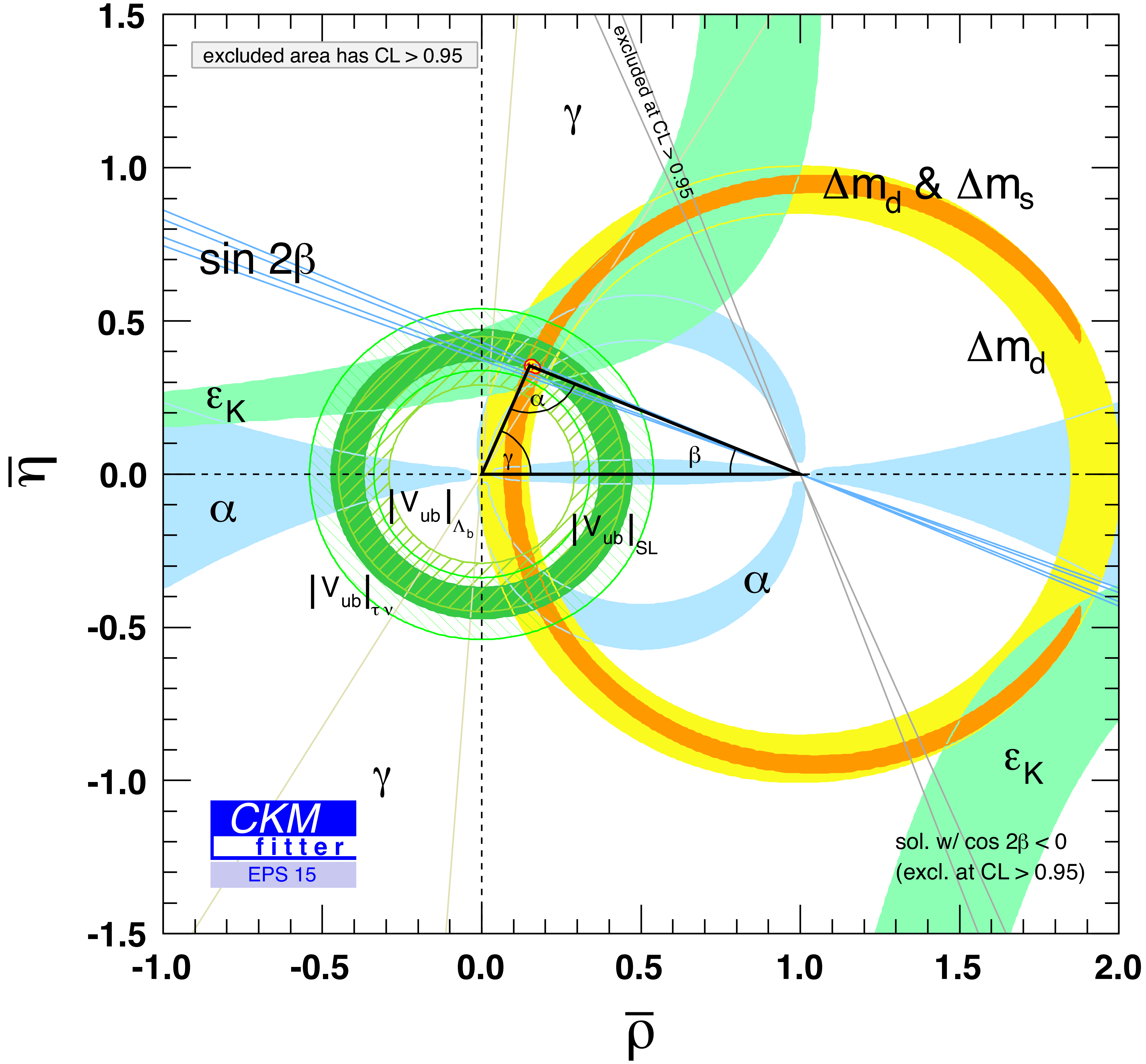


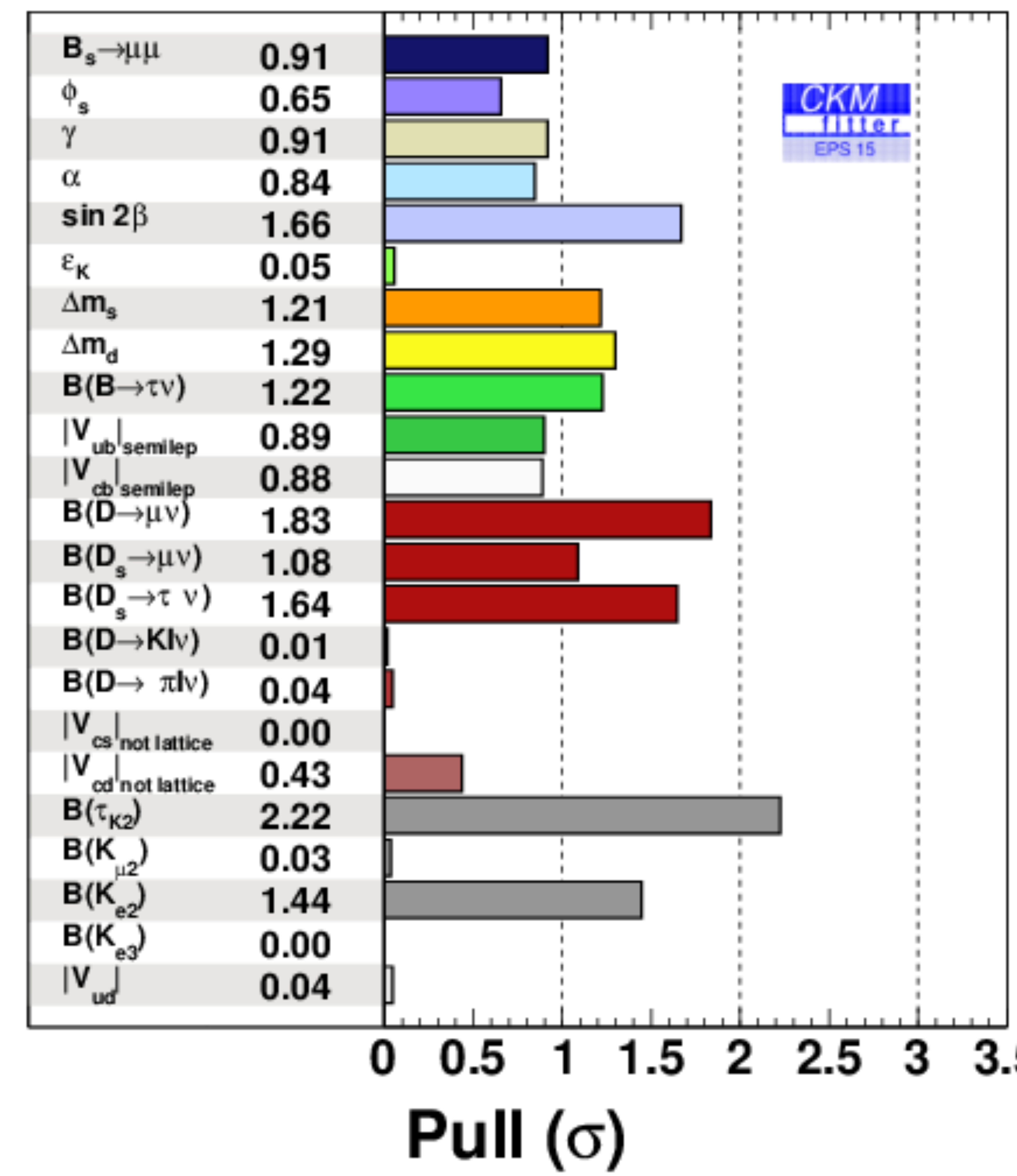
$$\gamma \in [62.4, 78.0]^\circ \quad @\,68\%\ \mathrm{CL}\,,$$
$$\gamma \in [51.0, 85.0]^\circ \quad @\,95\%\ \mathrm{CL}\,.$$

LHCb-CONF-2016-001

Global CKM fit

- so far: consistent





	Pull (σ)
$B_s \to \mu\mu$	0.91
ϕ_s	0.65
γ	0.91
α	0.84
sin 2β	1.66
ε_K	0.05
Δm_s	1.21
Δm_d	1.29
$B(B\to\tau\nu)$	1.22
$\lvert V_{ub}\rvert_{semilep}$	0.89
$\lvert V_{cb}\rvert_{semilep}$	0.88
$B(D\to\mu\nu)$	1.83
$B(D_s\to\mu\nu)$	1.08
$B(D_s\to\tau\nu)$	1.64
$B(D\to Kl\nu)$	0.01
$B(D\to\pi l\nu)$	0.04
$\lvert V_{cs}\rvert_{not\ lattice}$	0.00
$\lvert V_{cd}\rvert_{not\ lattice}$	0.43
$B(\tau_{K2})$	2.22
$B(K_{\mu2})$	0.03
$B(K_{e2})$	1.44
$B(K_{e3})$	0.00
$\lvert V_{ud}\rvert$	0.04

CKMfitter, EPJ. C41, 1-131 (2005)

Rare decays

and very rare decays

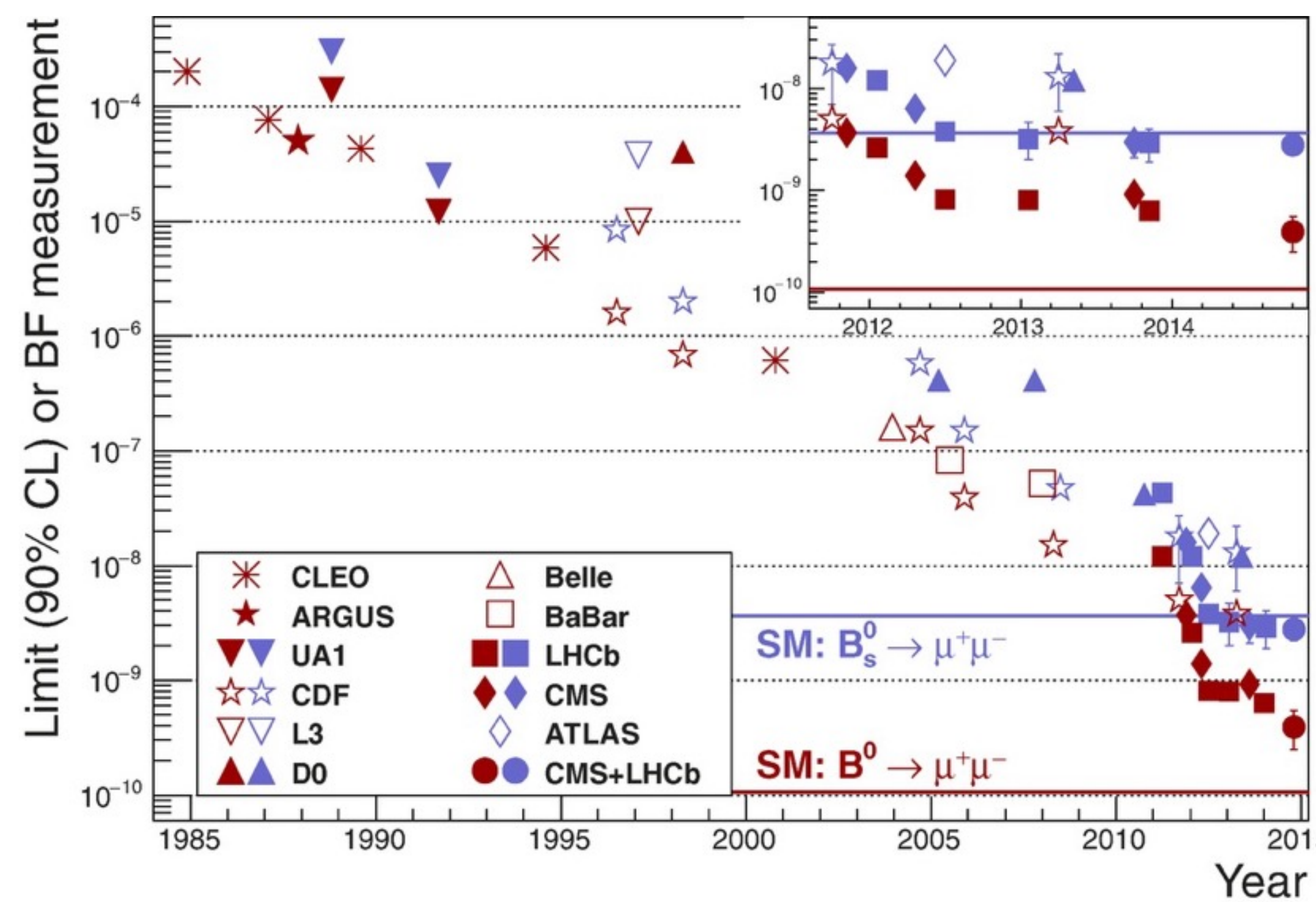
The rare decays $B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

- heavily suppressed in the SM
  - FCNC → loop processes
  - helicity suppression
  - highly sensitive to BSM
  - theoretically clean

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

  - clean experimental signature

- searches in the past 30 years

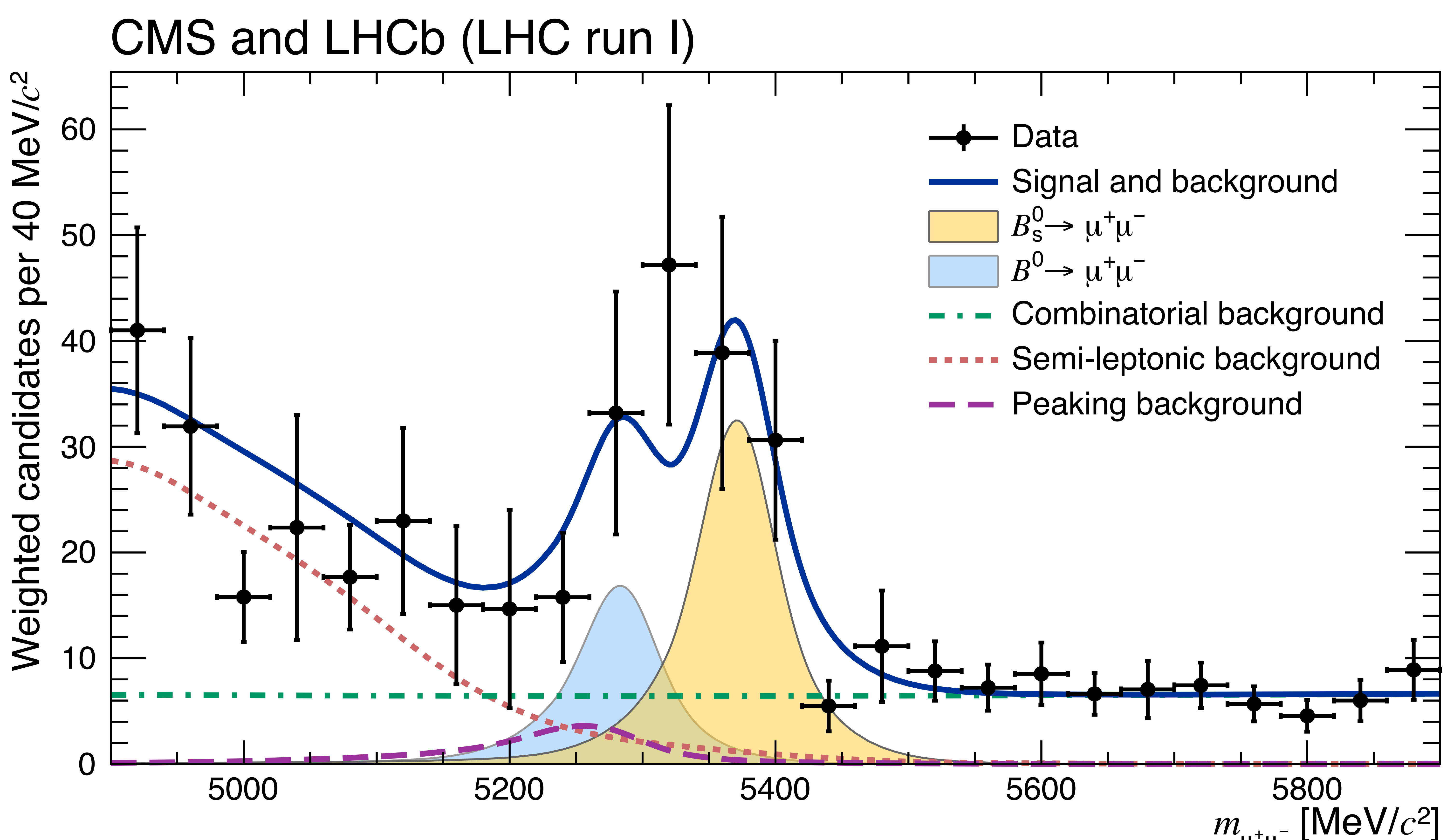


PRL 112, 101801 (2014)

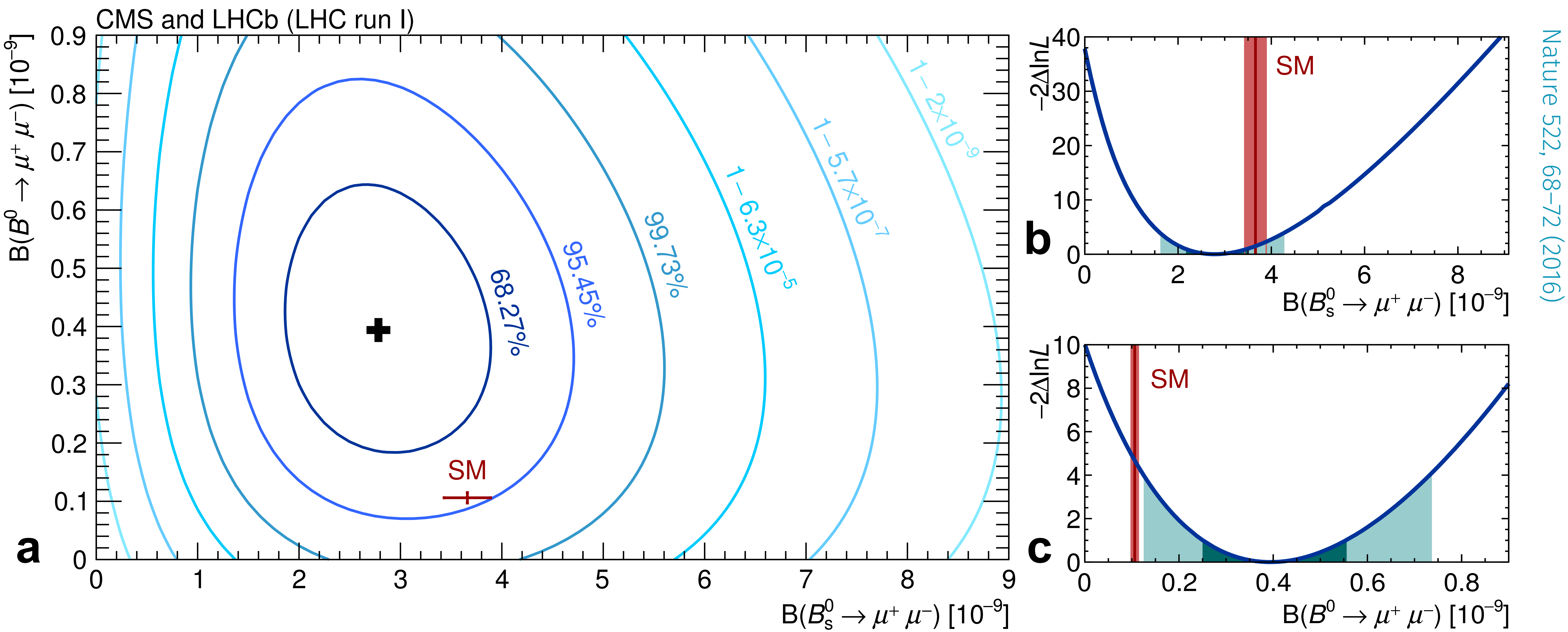
The rare decays $B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

- combined CMS & LHCb
  - first observation of $B_s \to \mu^+\mu^-$ (6.2σ)
    $$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8 \pm ^{0.7}_{0.6}) \times 10^{-9}$$
  - first evidence for $B^0 \to \mu^+\mu^-$ (3.0σ)
    $$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9 \pm ^{1.6}_{1.4}) \times 10^{-10}$$

Nature 522, 68–72 (2016)



The rare decays $B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

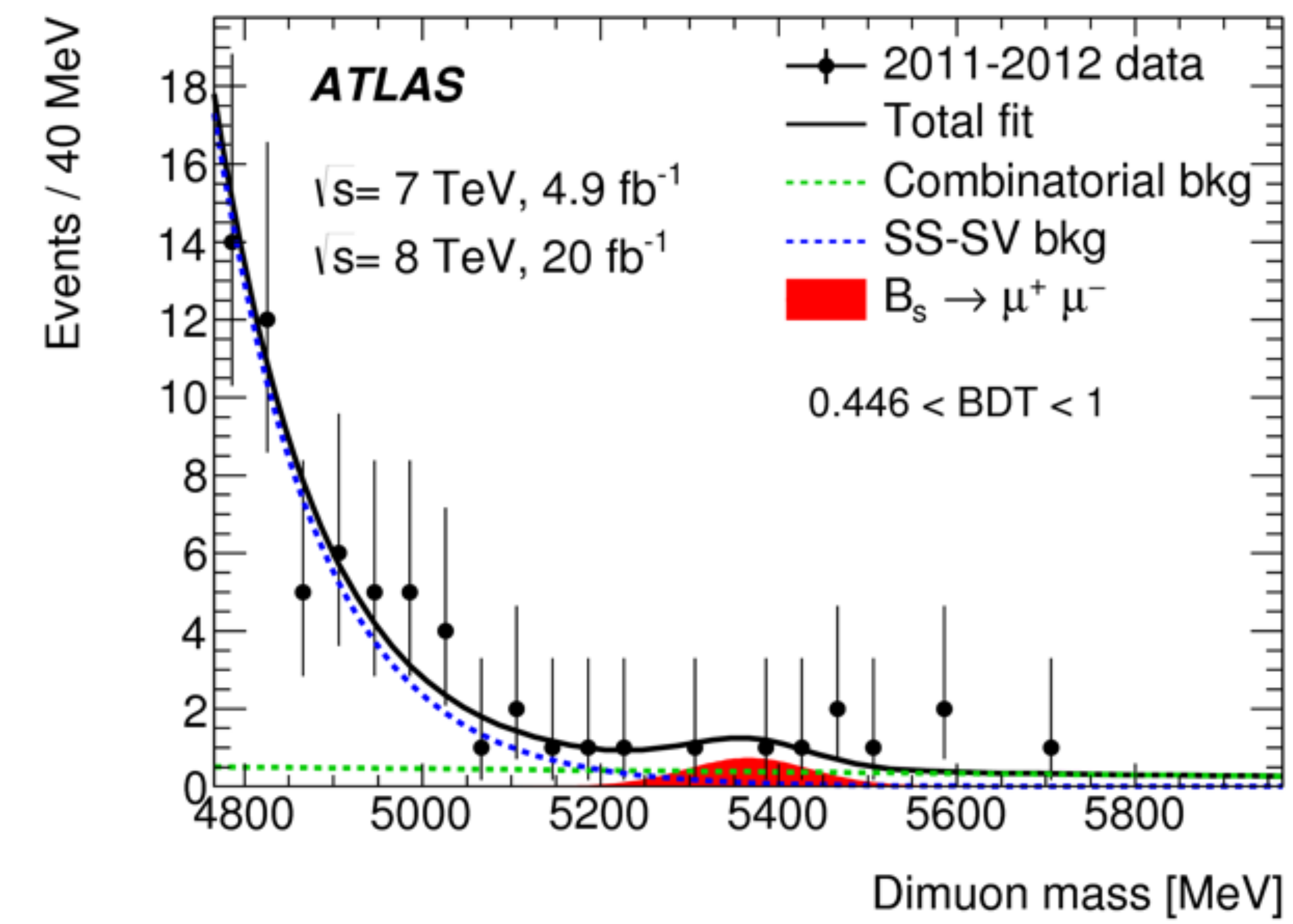


The rare decays $B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

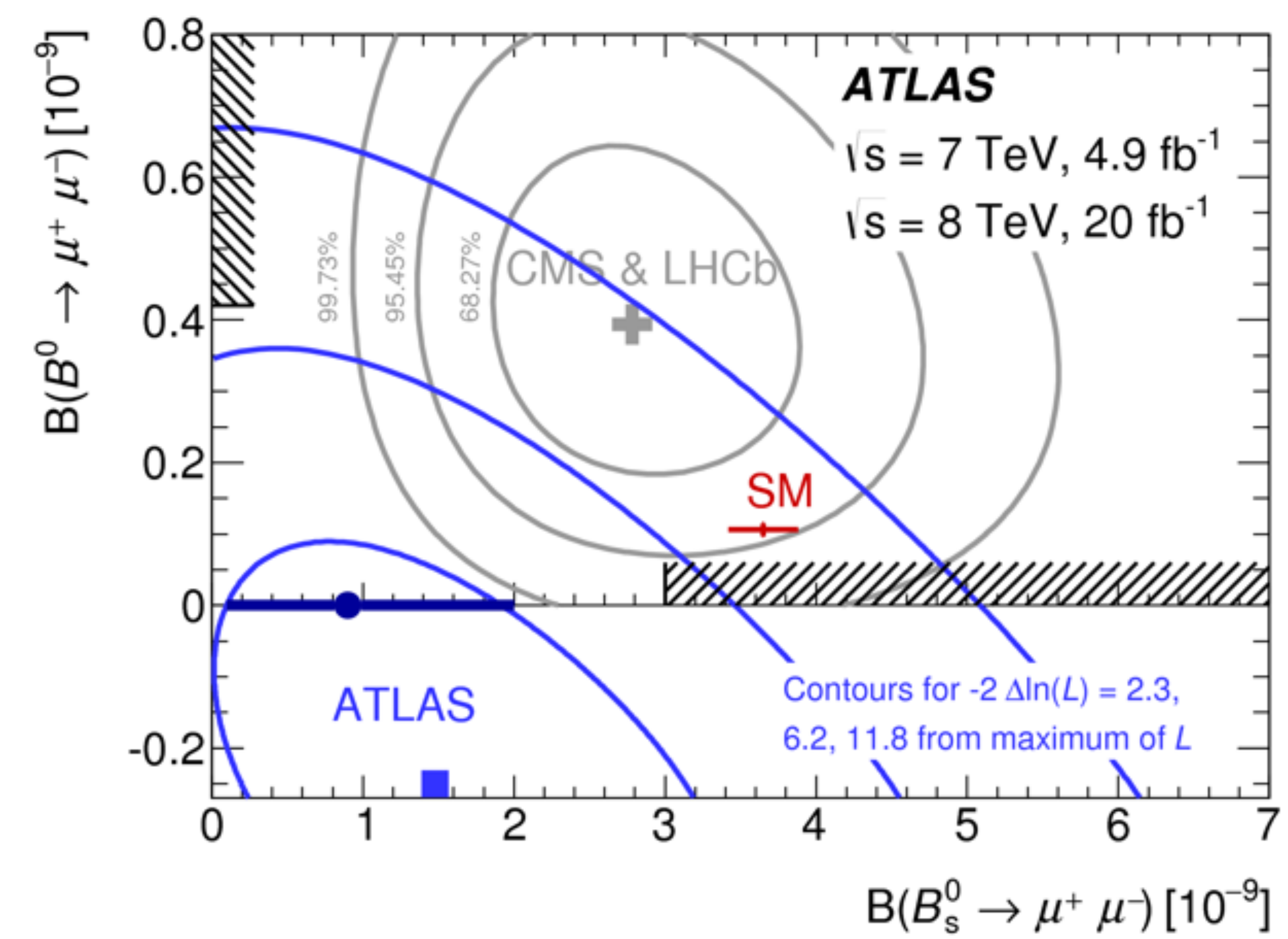
- preliminary result from ATLAS with Run I

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (0.9 \pm {}^{1.1}_{0.8}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \quad \text{at 95\% CL}$$



- ATLAS results
  - compatible w. SM at 2σ level
  - $B_s \to \mu^+\mu^-$ compatible w. CMS+LHCb result



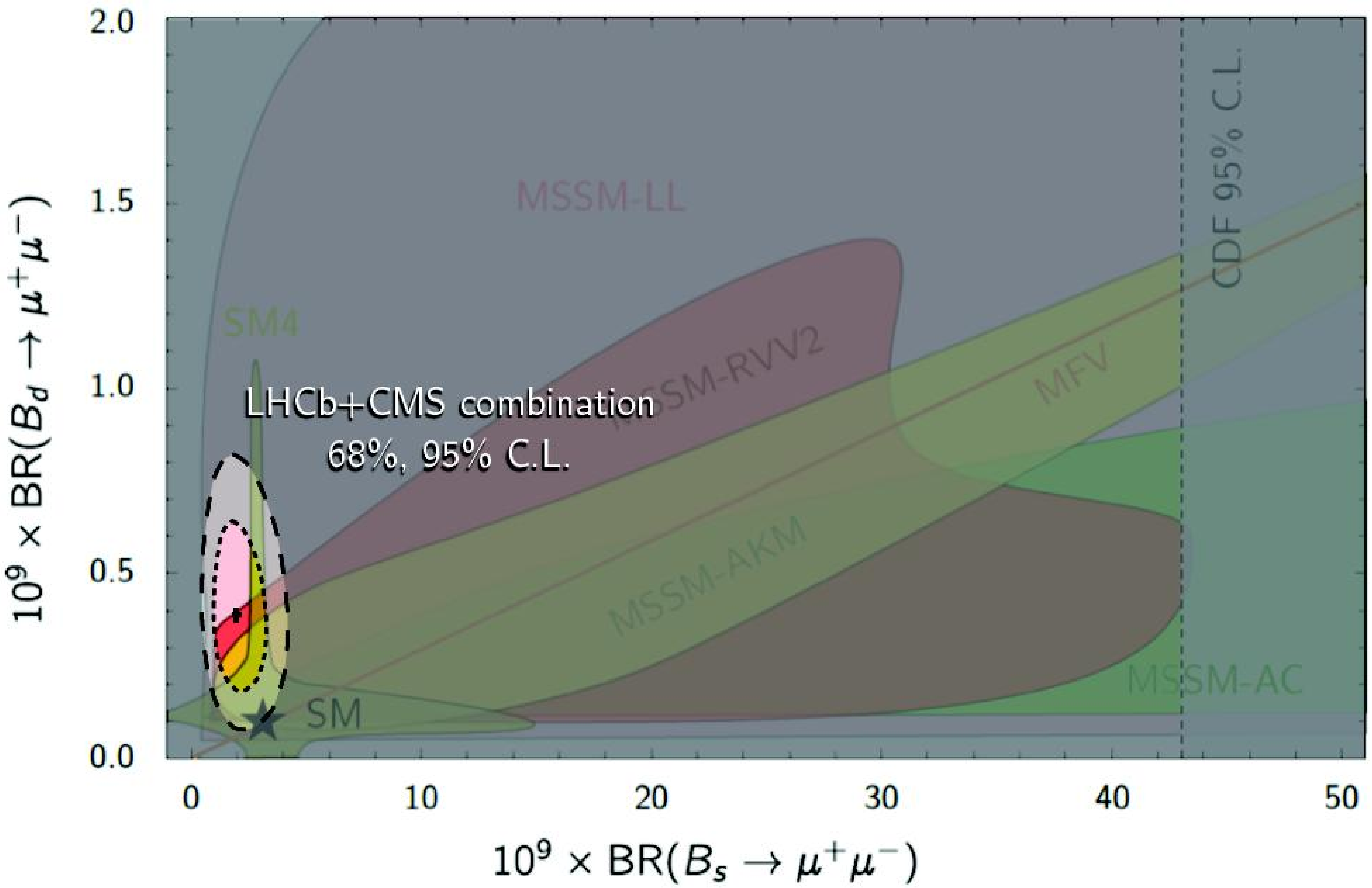
- not as sensitive as each CMS and LHCb, yet

CERN-EP-2016-064, submitted to Eur. Phys. J. C

The rare decays $B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

- strong constraints on various BSM models (in particular MSSM)

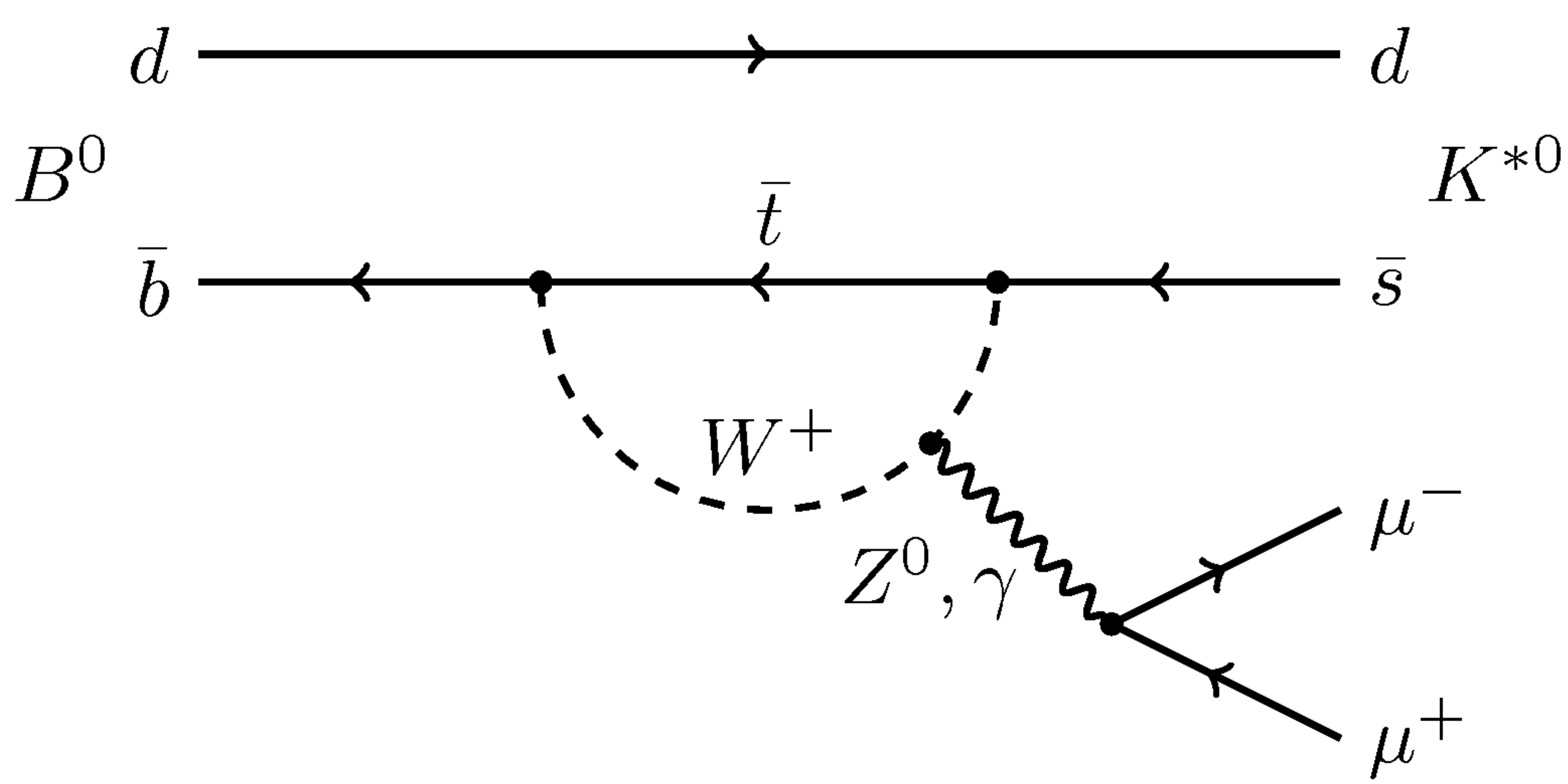
Modified from [D. Straub, Nuovo Cim. C035N1 (2012) 249]

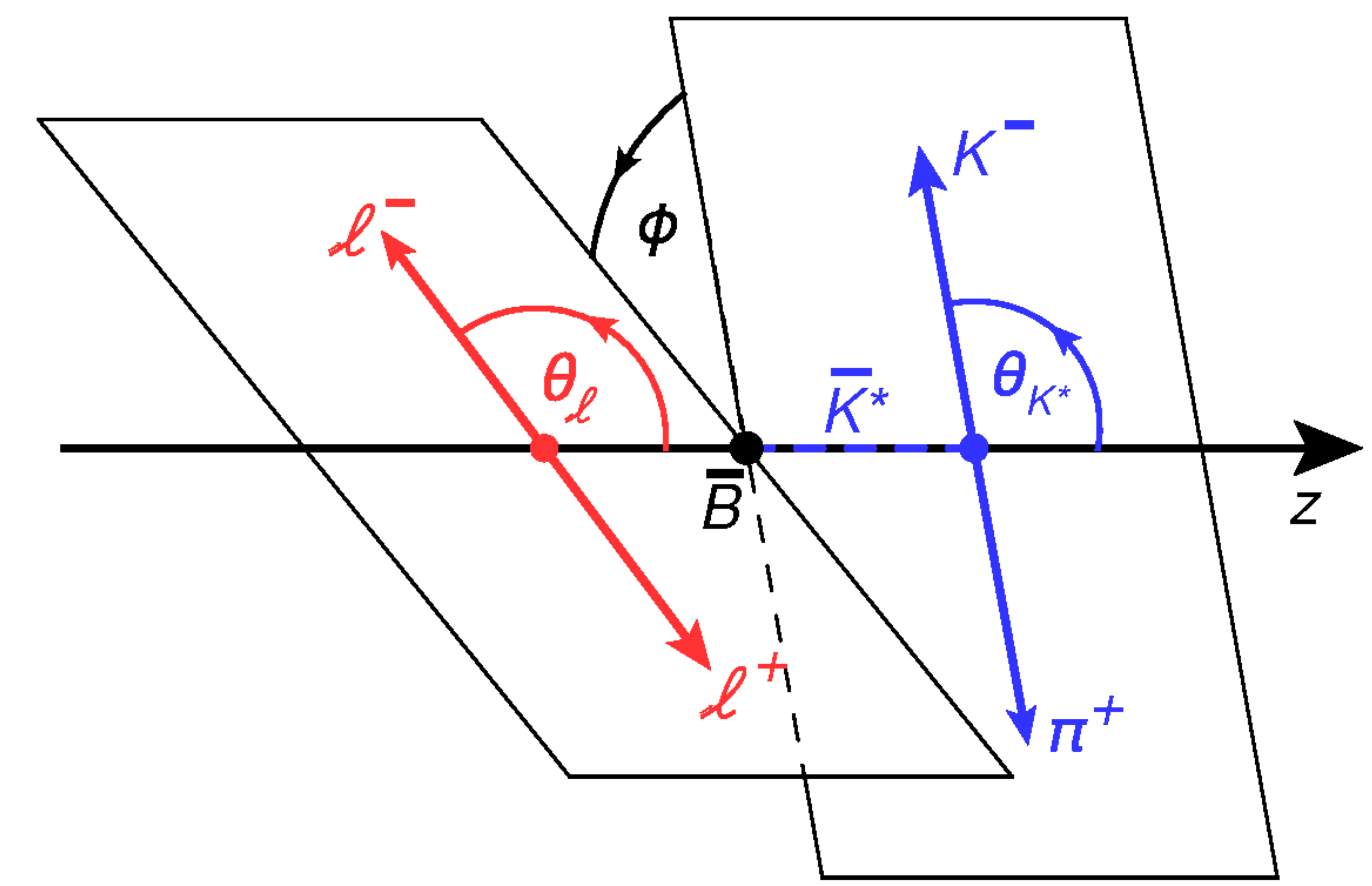


- SM4: Standard Model with a sequential fourth generation
- Left-handed currents only (MSSM-LL)
- Ross, Velasco-Sevilla and Vives (MSSM-RVV2)
- Antusch, King and Malinsky (MSSM-AKM)
- RSc: Randall-Sundrum model with custodial protection
- Agashe and Carone (MSSM-AC)

Full angular analysis of $B^0 \to K^* \mu^+ \mu^-$

- $B^0 \to K^* \mu^+ \mu^-$ is another ideal testbed for NP searches
  - $b \to sll$ FCNCs only via loops in SM





  - NP sensitivity in decay rates, angular distributions, asymmetries
  - experimentally clean signature
  - many observables with clean theoretical predictions

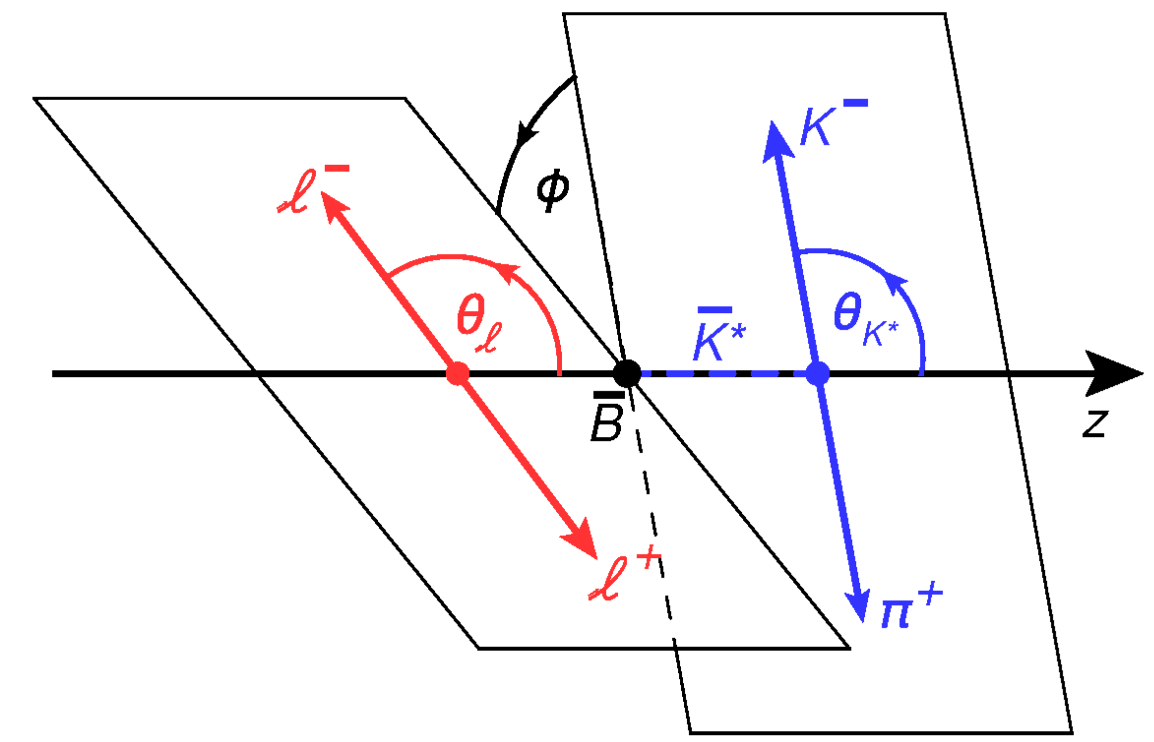
Full angular analysis of $B^0 \to K^* \mu^+ \mu^-$

- full angular description in q^2

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Big|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l - F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi + \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

fraction of longitudinal polarisation of the K*

forward-backward asymmetry of the dilepton system

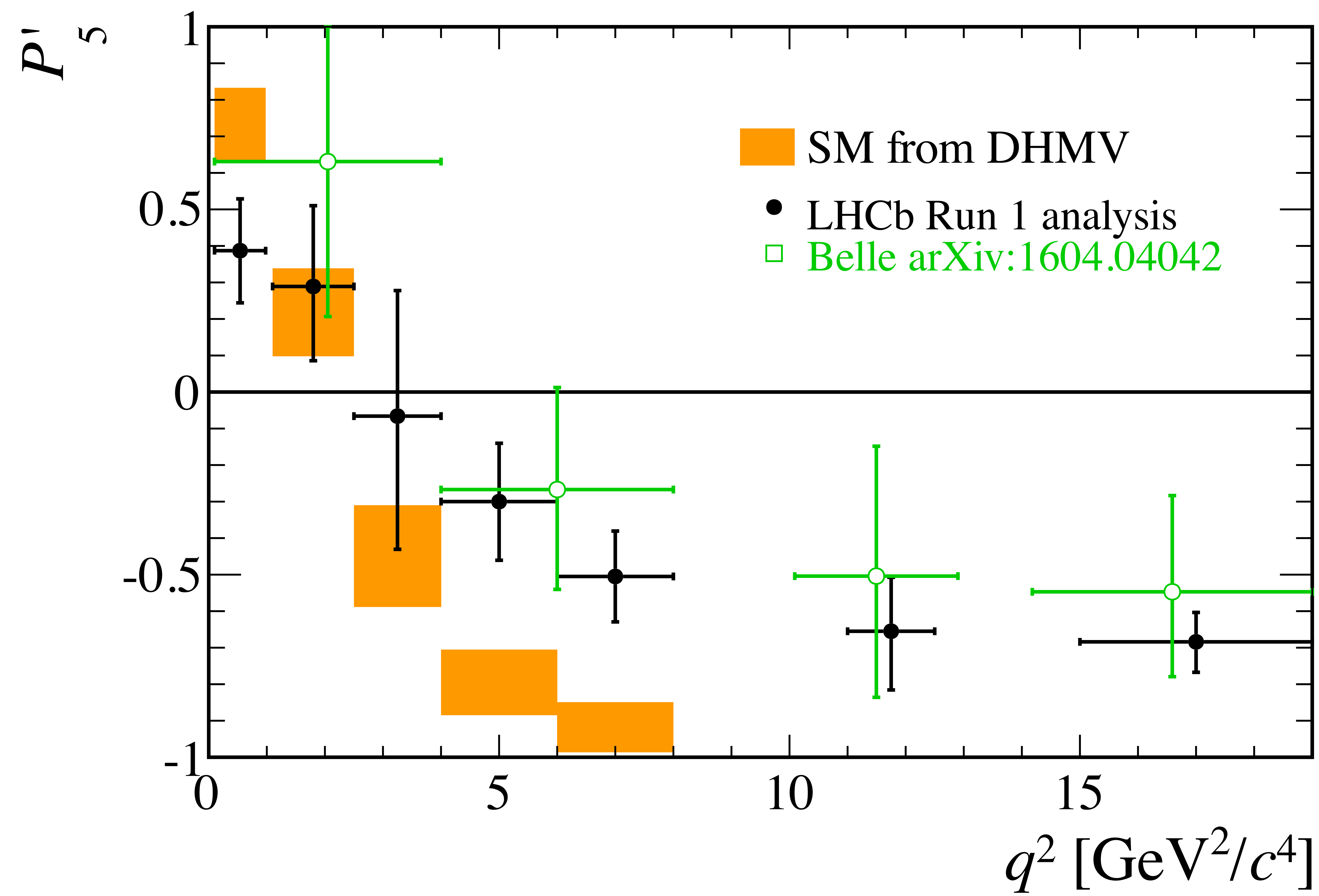


- observables depend on $B \to K$ form factors
- additionally: use observable basis in which form factors cancel at leading order
- example: $P_5' = \frac{S_5}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}$

Full angular analysis of $B^0 \to K^* \mu^+ \mu^-$

JHEP 02 (2016) 104

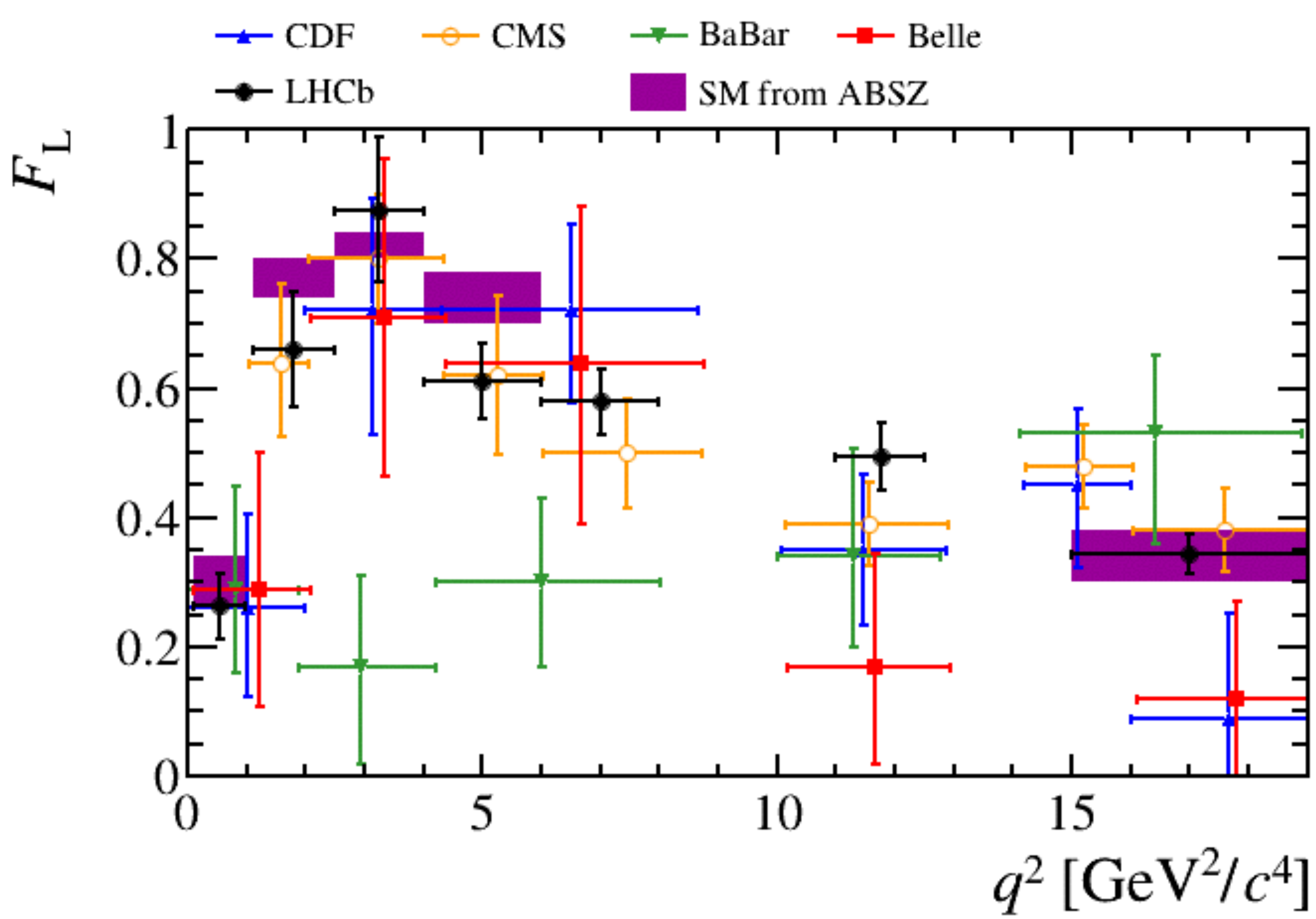
- in general: observables compatible with the SM expectations
  - except for P_5' observable
  - local 2.8 and 3σ deviations
  - Belle confirms LHCb

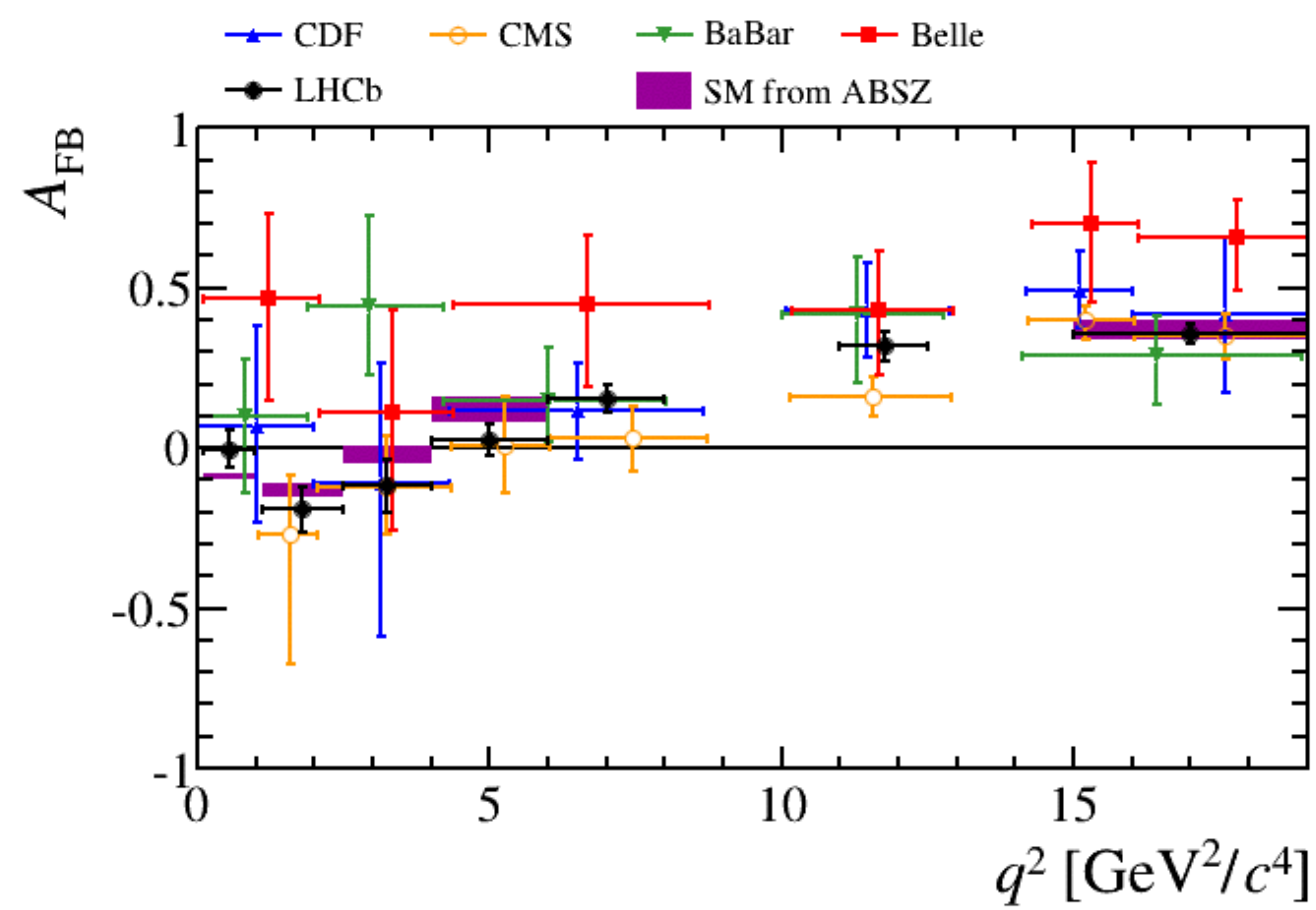


- theory work ongoing
  - NP or hadronic effects?

Full angular analysis of $B^0 \to K^* \mu^+ \mu^-$

- by now, many measurements from various experiments

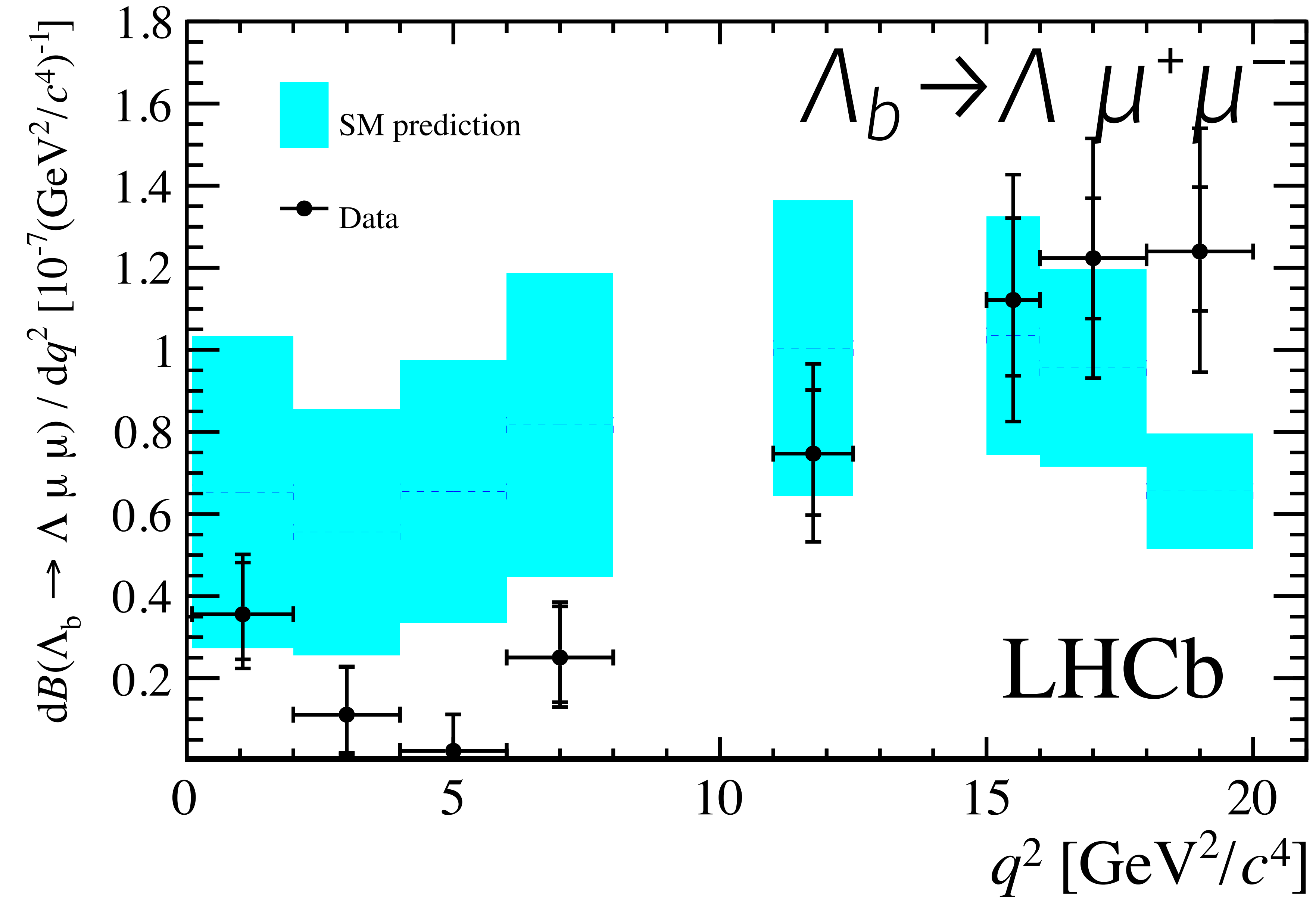




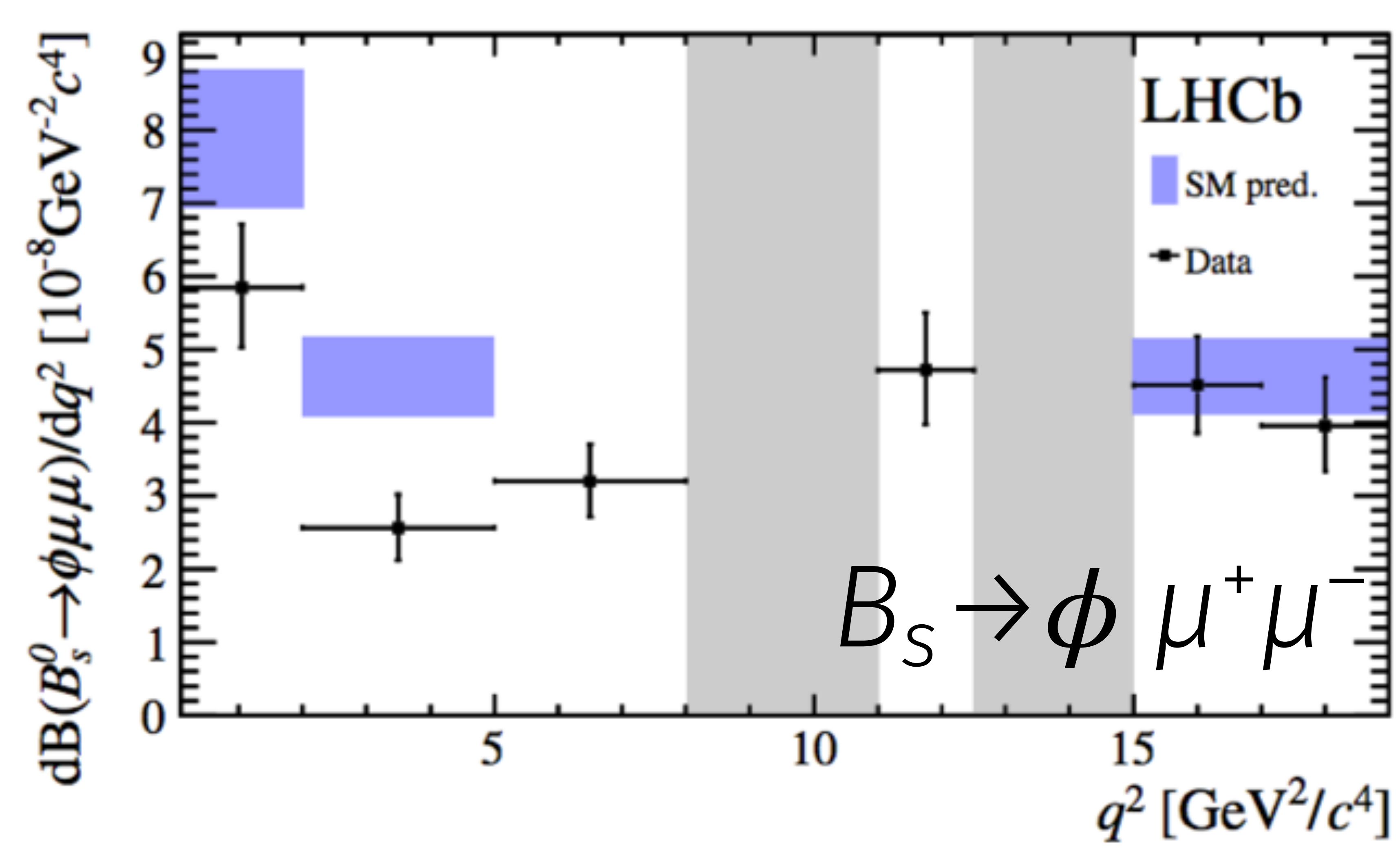
$B \to X\, \mu^+\mu^-$ differential branching fractions

- other $b \to s$ branching ratios in bins of q^2
  - $\Lambda_b \to \Lambda\, \mu^+\mu^-$
    - additional observables due to baryonic system
    - statistics too low for angular analysis
  - $B_s \to \phi\, \mu^+\mu^-$
    - BR for $1 < q^2 < 6\ \mathrm{GeV}^2/c^4$ deviates from SM by ≈3.3σ
    - angular observables consistent with SM

- consistent picture between channels
  - branching ratios overestimated in low q^2
  - angular distributions consistent with SM



JHEP 06 (2014) 133



JHEP 09 (2015) 179 JHEP 06 (2015) 115

Lepton Flavour Universality

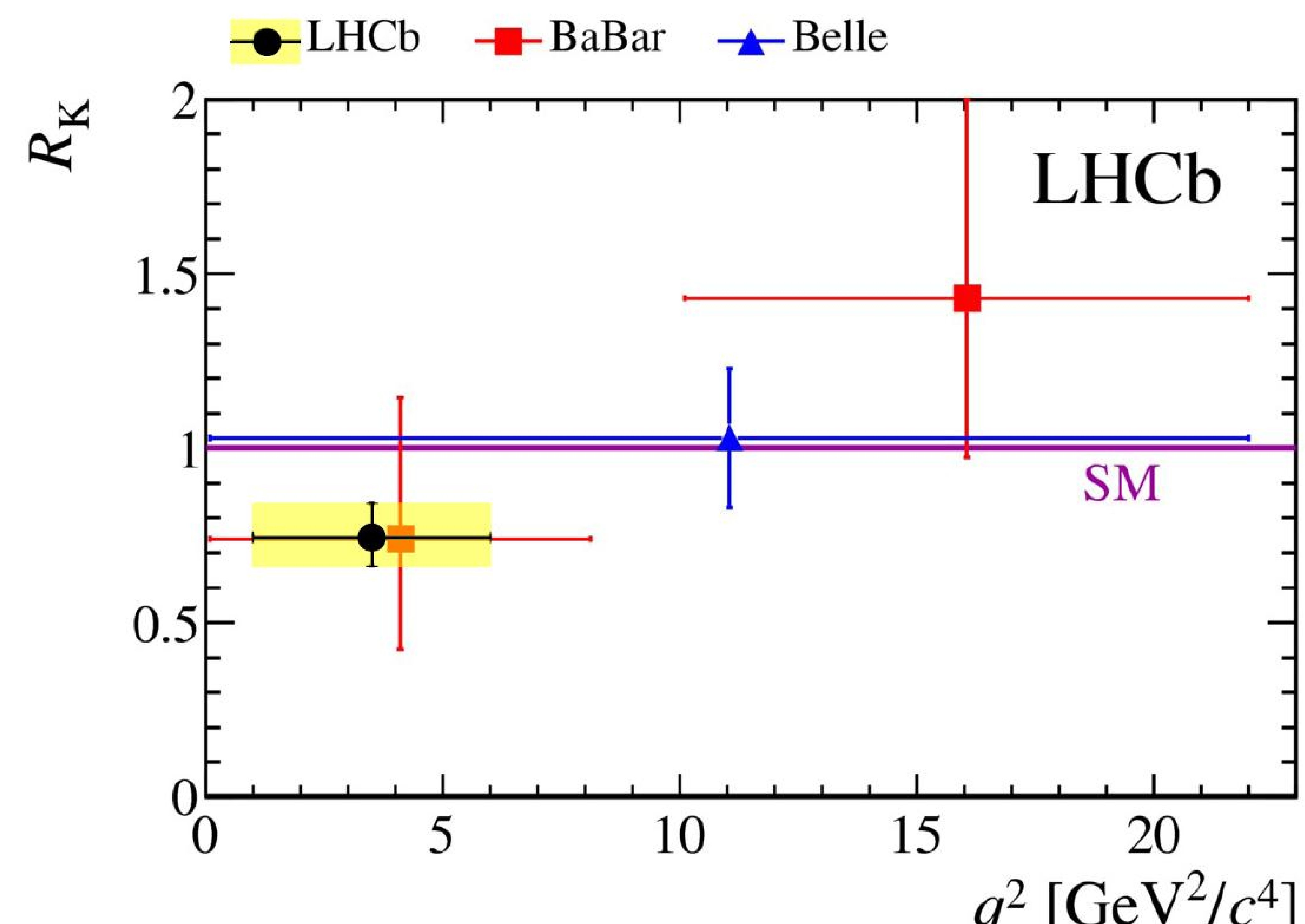
Lepton universality in $B^{\pm} \to K^{\pm} l^{+} l^{-}$

- SM expectation by Bobeth et al.

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 1.0003 \pm 0.0001$$

JHEP 0712 040 (2007)

- LHCb sees deficit for $1 < q^2 < 6\ \mathrm{GeV}^2/c^4$
  - $R_K = 0.745 \pm^{0.090}_{0.074} \pm 0.036$
  - (small) tension of $\approx 2.6\sigma$ with SM
- more statistics needed
- look at other modes!
  - e.g. $B^0 \to D^{(*)-} l^+ \nu_l$



PRL 113, 151601 (2014)

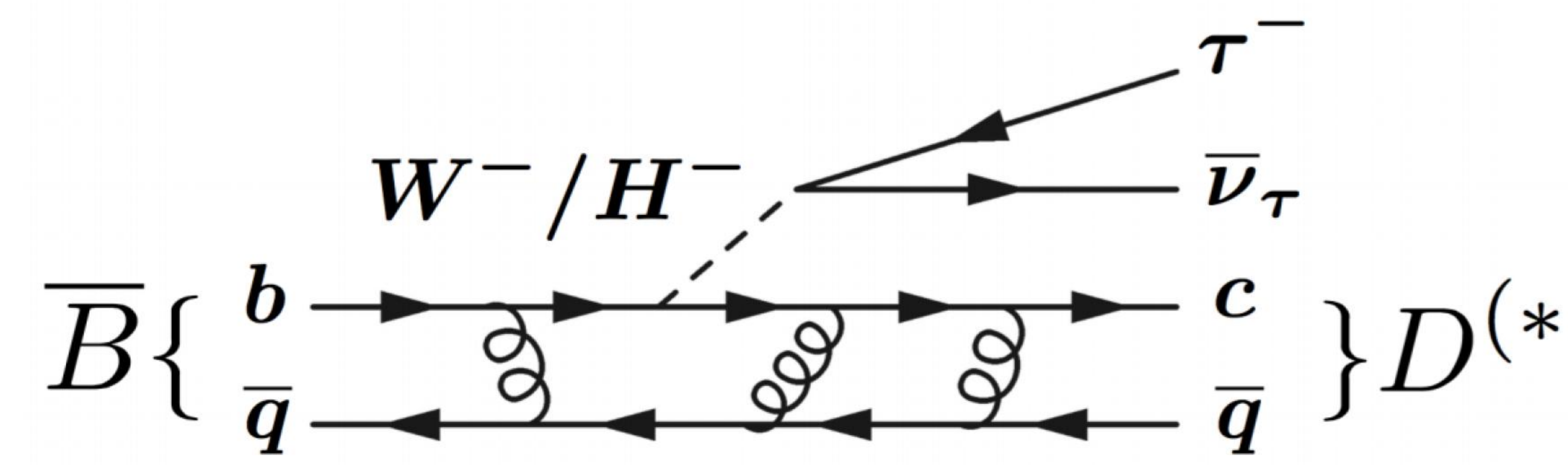
Lepton universality in $B^0 \to D^{(*)-} l^+ \nu_l$

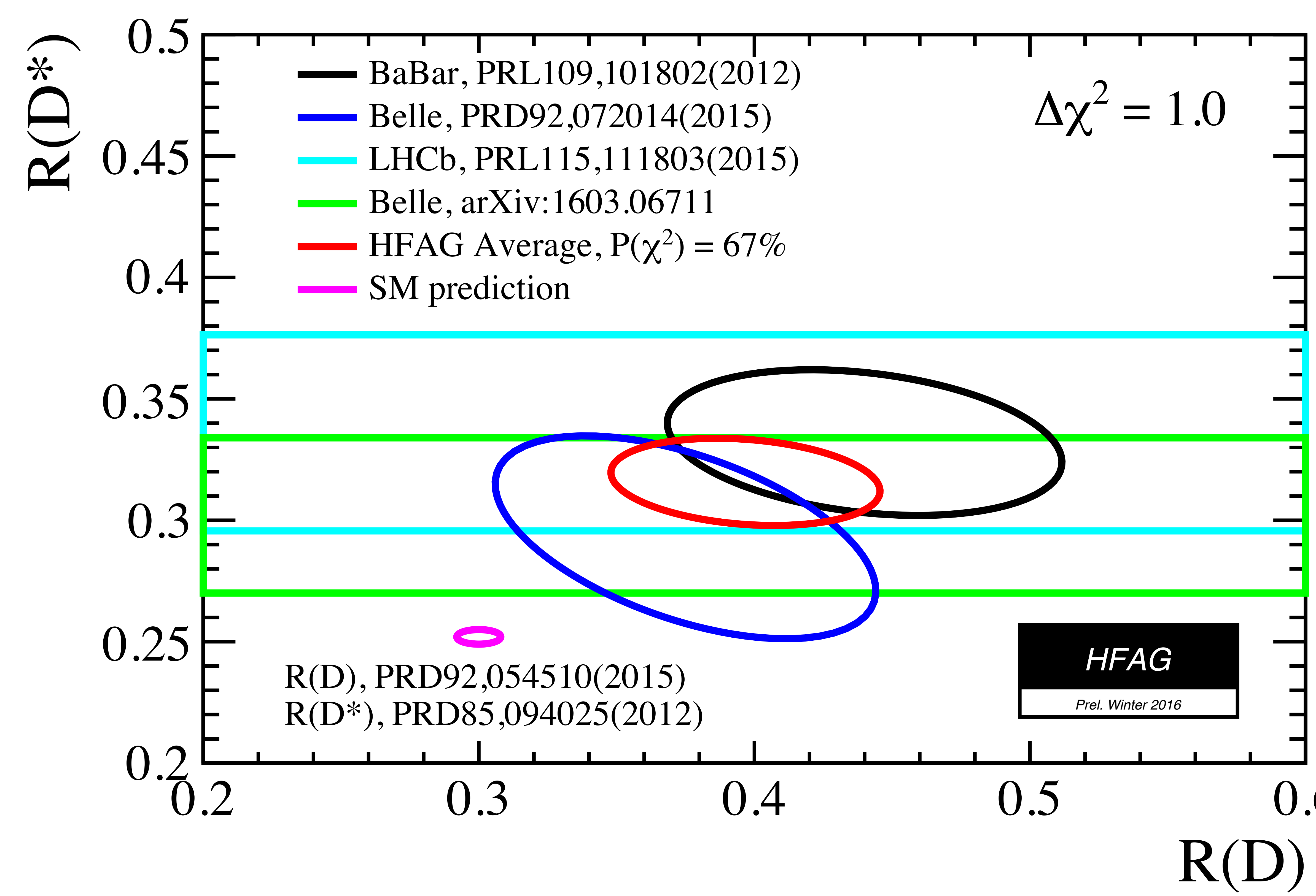
- sensitive to BSM at tree level
- theory predictions

$$R_D = \frac{\mathcal{B}(B^0 \to D^- \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^- l^+ \nu_l)} = 0.300 \pm 0.008$$

$$R_{D^*} = \frac{\mathcal{B}(B^0 \to D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^{*-} l^+ \nu_l)} = 0.252 \pm 0.003$$

- experimental results
  - combination of LHCb, Belle, BaBar
  - (R_D, R_{D^*}) tension with SM $\approx 4.0\sigma$
  - $R_D \approx 1.9\sigma$, $R_{D^*} \approx 3.3\sigma$





Conclusion & Outlook

Conclusion & Outlook

- flavour physics is a perfect testbed for the SM
  - a multitude of observables linked to a small number of SM parameters
  - cross-check and cross-validate the measurements

- LHC experiments have added many new aspects to the picture
  - no “smoking gun”, but several discrepancies
  - LFV w. R_K and R_{D^*} (incl. BaBar + Belle)
  - P_5' in $B^0 \to K^{*0}\mu^+\mu^-$
  - BF$(B^0 \to \mu^+\mu^-)$
  - $|V_{ub}|$ inclusive vs. exclusive

Conclusion & Outlook

- but: LHCb alone has published >300 papers
  - some discrepancies expected
  - overall picture (still) looks pretty consistent

- LHC Run II ongoing
  - LHCb will collect 5 fb^{-1} at 13 TeV until 2018
    - bb cross-section increases by a factor of 2 w.r.t. 7/8 TeV
    - corresponds to ≈4x statistics of Run I
  - CMS and ATLAS contribute with many flavour physics results

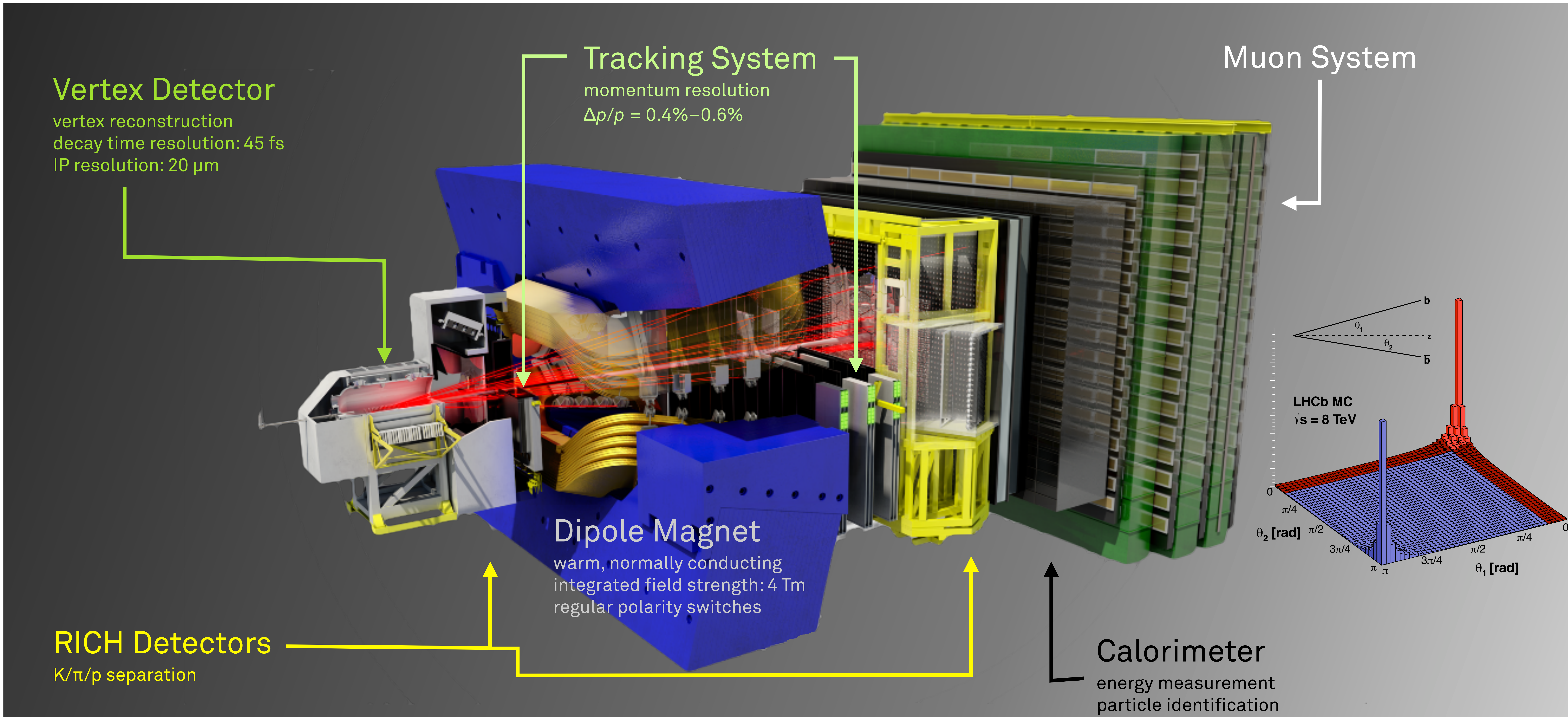
LHCb Prospects

Eur. Phys. J. C73 (2013) 2373

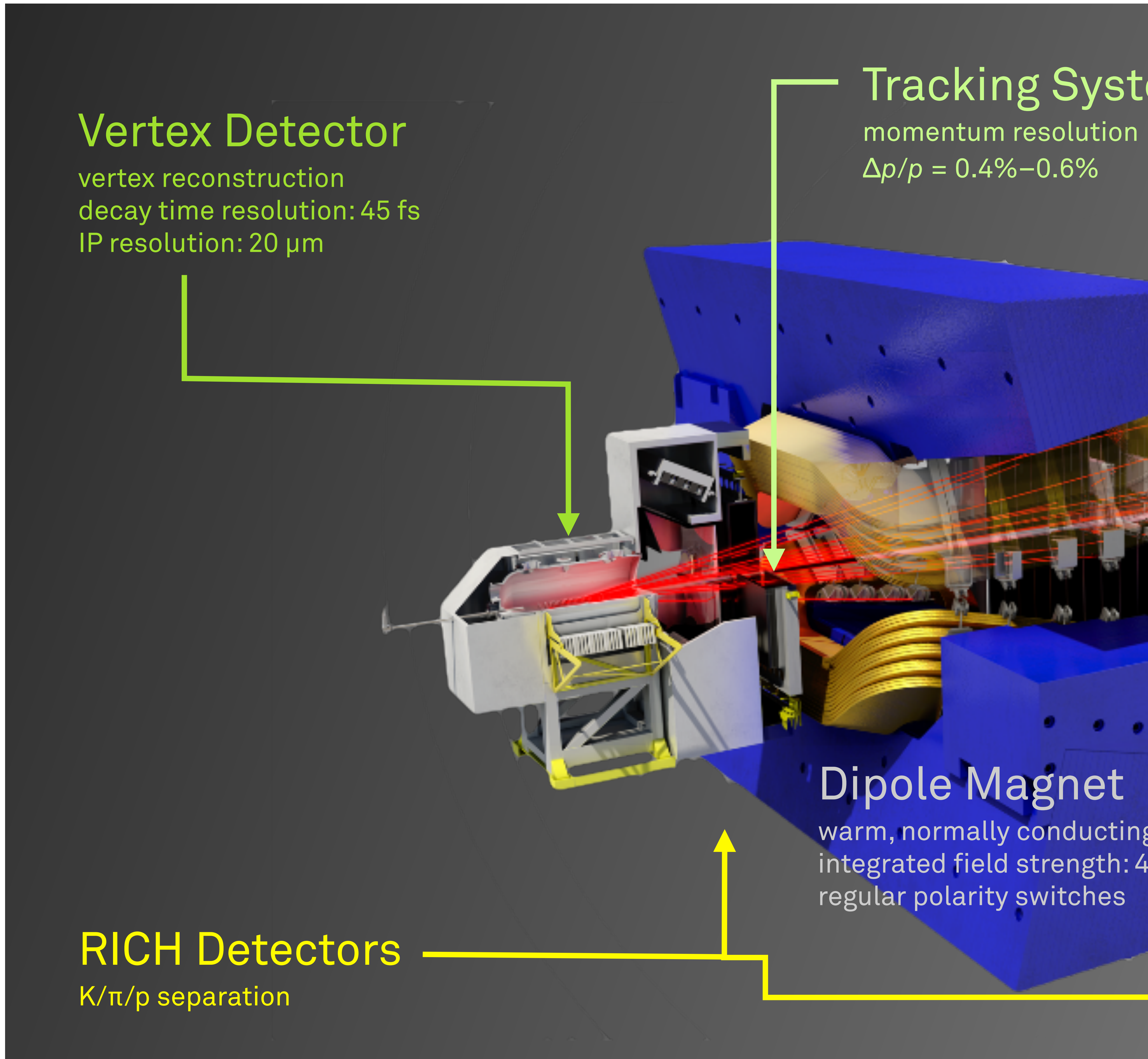
Type	Observable	Current precision	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.10 [139]	0.025	0.008	$\sim$0.003
	$2\beta_s(B_s^0 \to J/\psi f_0(980))$	0.17 [219]	0.045	0.014	$\sim$0.01
	$a_{\rm sl}^s$	6.4×10^{-3} [44]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\overline{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [44]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	$<$0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08 [68]	0.025	0.008	0.02
	$s_0 A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [68]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.25 [77]	0.08	0.025	$\sim$0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [86]	8 %	2.5 %	$\sim$10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim$100 %	$\sim$35 %	$\sim$5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	$\sim$10–12° [252, 266]	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.8° [44]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [44]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

Backup

The LHCb detector



The LHCb detector



- precision measurements in b/c-hadrons
- Run I (2011+2012)
  - dataset of 3 fb^{-1} at 7/8 TeV
  - $\approx 2 \cdot 10^{11}$ bb pairs in LHCb
  - > 300 publications
- Run II (since 2015)
  - dataset of 0.32 fb^{-1} bei 13 TeV