



# Status of quark flavour physics

T. Blake on behalf of the LHCb collaboration,  
including results from ATLAS, CMS, BaBar and Belle

SUSY 2015

# Outline

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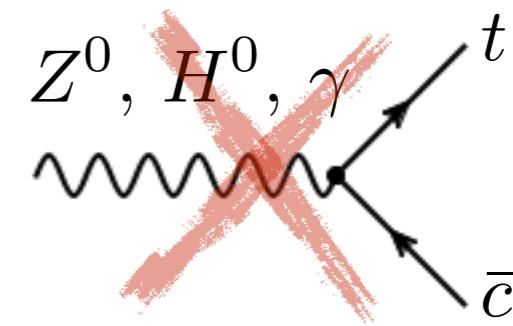
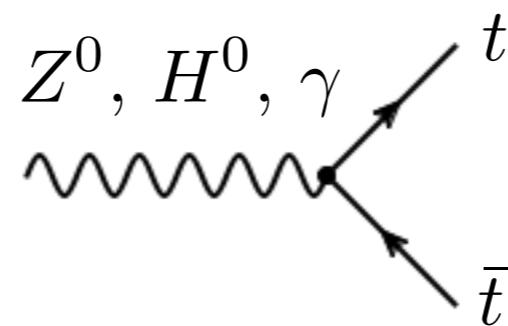
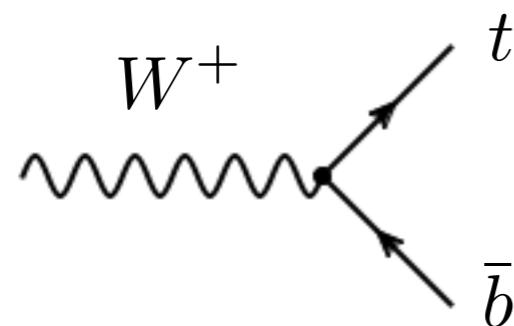
- CP violation and the Unitary triangle
  - ▶ The angle  $\gamma$ ,  $V_{ub}$ , and  $\phi_s$ .
- Rare decays
  - ▶  $B_s \rightarrow \mu^+ \mu^-$  and  $B \rightarrow K^* \mu^+ \mu^-$ .
- Lepton universality
  - ▶  $R_K$ ,  $R(D)$  and  $R(D^*)$ .

# Flavour in the SM

- Particle physics can be described to excellent precision by a very simple theory:

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{Gauge}}(A_a, \psi_i) + \mathcal{L}_{\text{Higgs}}(\phi, A_a, \psi_i)$$

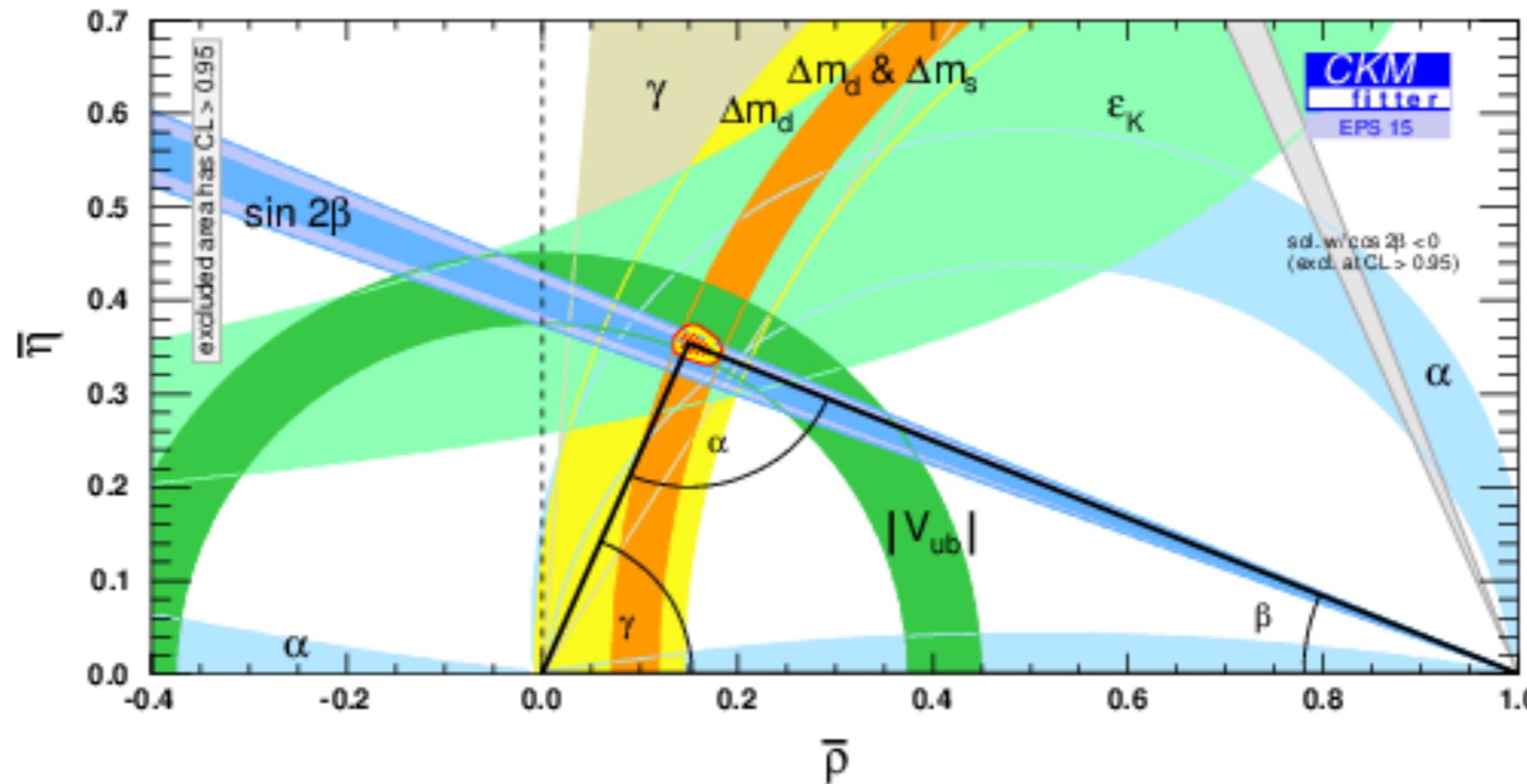
- $\mathcal{L}_{\text{Higgs}}$  is responsible for flavour in the SM. Without the Higgs, the three fermion families would be identical replicas.
- Yukawa matrices are the only source of flavour violation,



- Quark flavour-violating interactions governed by the CKM.
- No tree level FCNCs in the SM.

# The Unitary triangle

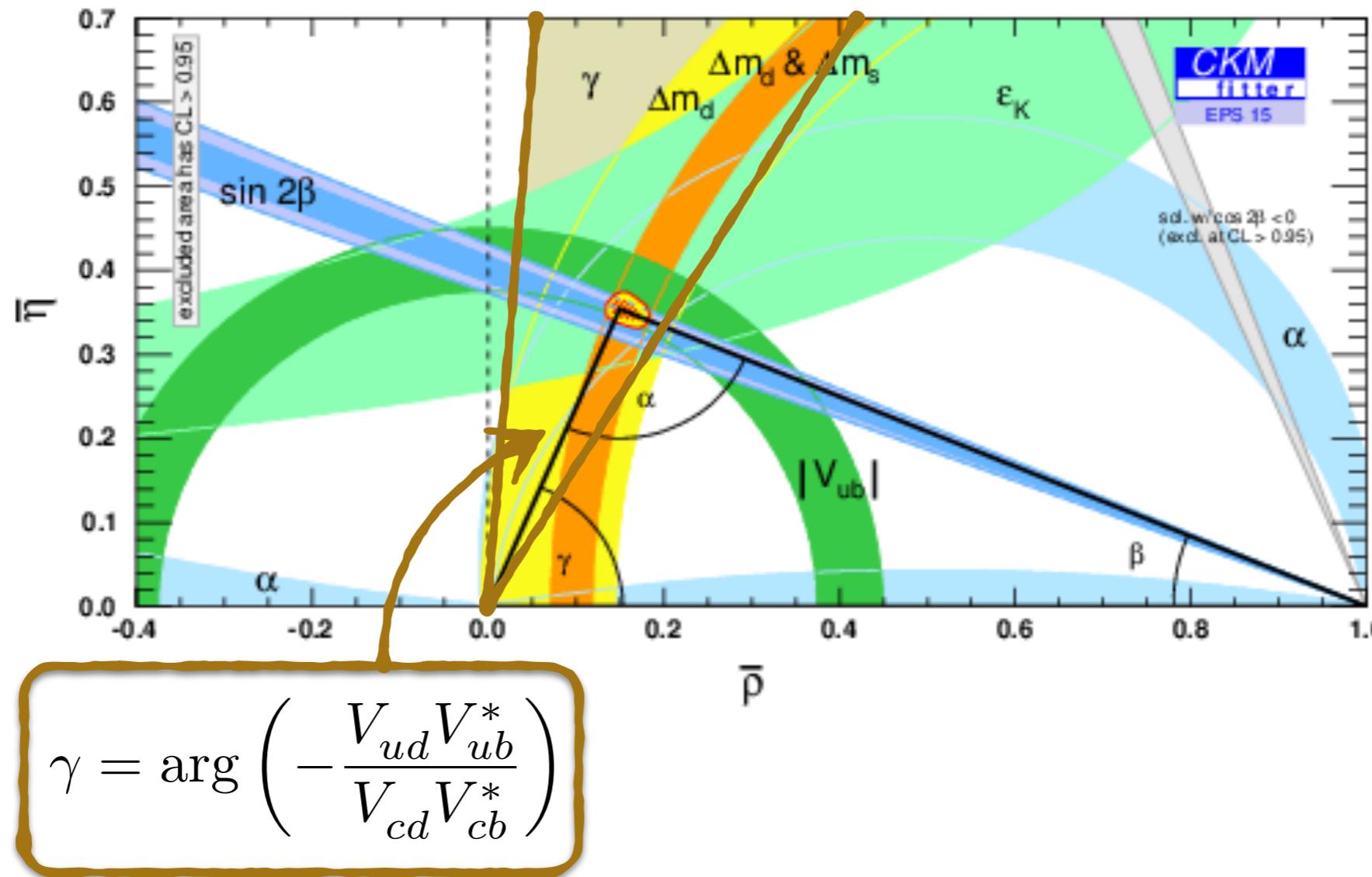
- CKM matrix is the only source of CP violation in SM.
- Unitary condition  $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$  can be expressed as a triangle in the complex plane.



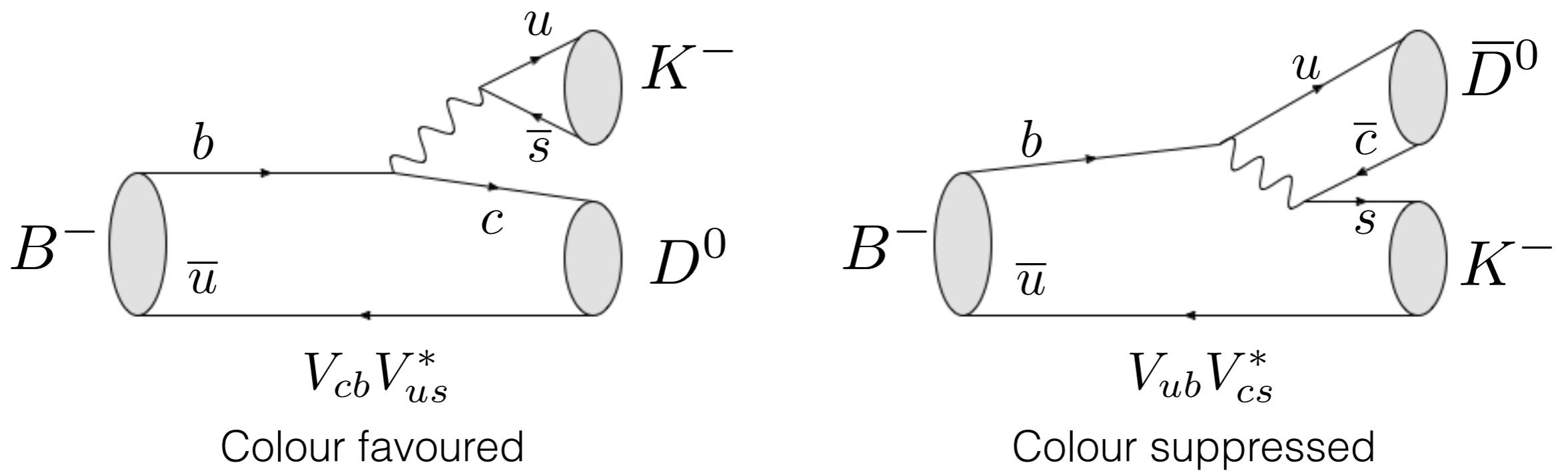
SM picture: data are consistent with a triangle in the complex plane.

# Angle $\gamma$

- $\gamma$  is the least well known of the angles of the unitary triangle.
  - The only angle that can be determined from tree level processes.



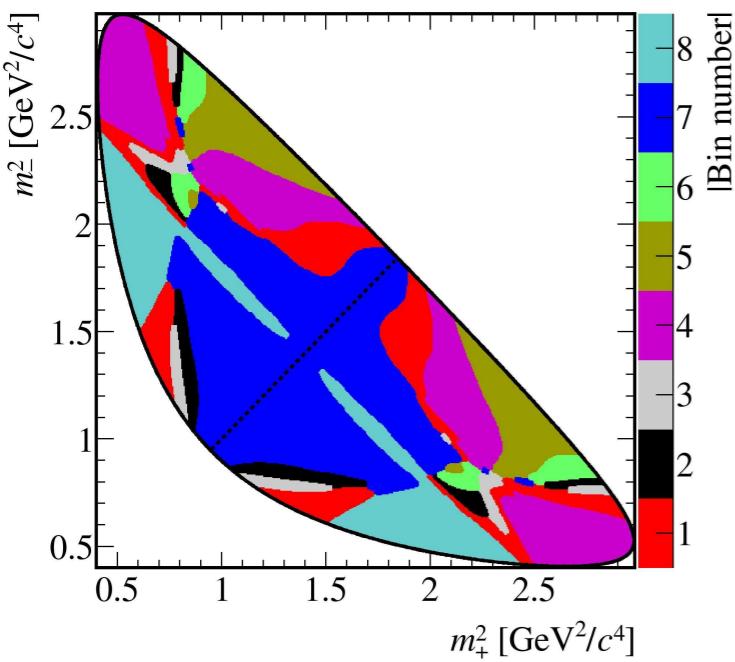
# Measuring $\gamma$



- Relative weak phase between the diagrams is  $\gamma$ . To determine  $\gamma$ , need decays to a common final state.
  - ADS using  $\bar{D}^0 \rightarrow K^+ \pi^-$ ,  $D^0 \rightarrow K^+ \pi^-$   
**[Atwood, Dunietz and Soni, Phys. Rev. Lett. 78, 3257 (1997)]**
  - GLW using  $D^0 \rightarrow h^+ h^-$   
**[Gronau, London, Wyler Phys.Lett. B265 (1991) 172; Phys.Lett. B253 (1991) 483]**
  - GGSZ using  $D^0 \rightarrow K_S^0 h^+ h^-$   
**[Giri, Grossman, Soffer and Zupan Phys.Rev. D68 (2003) 054018]**

# GGSZ method

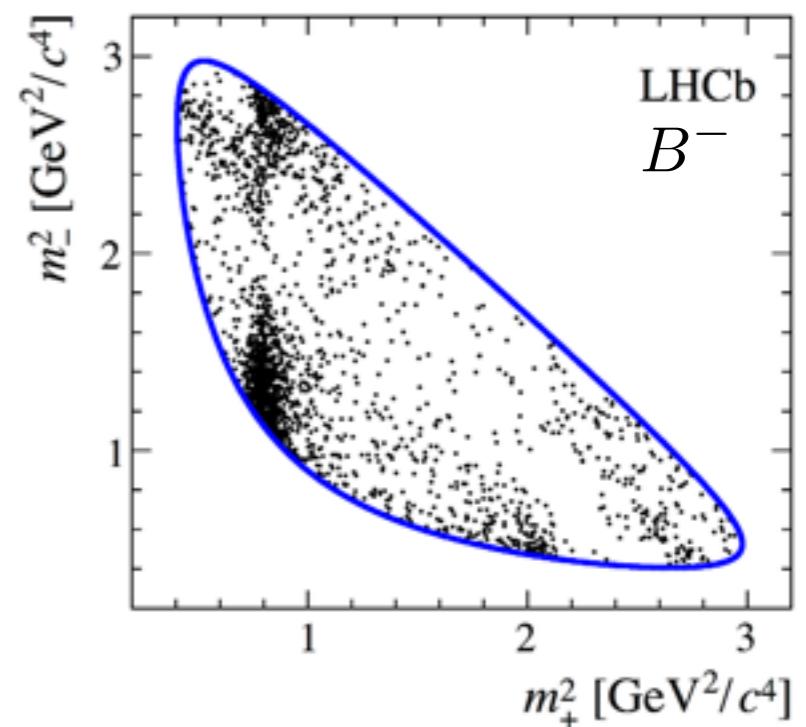
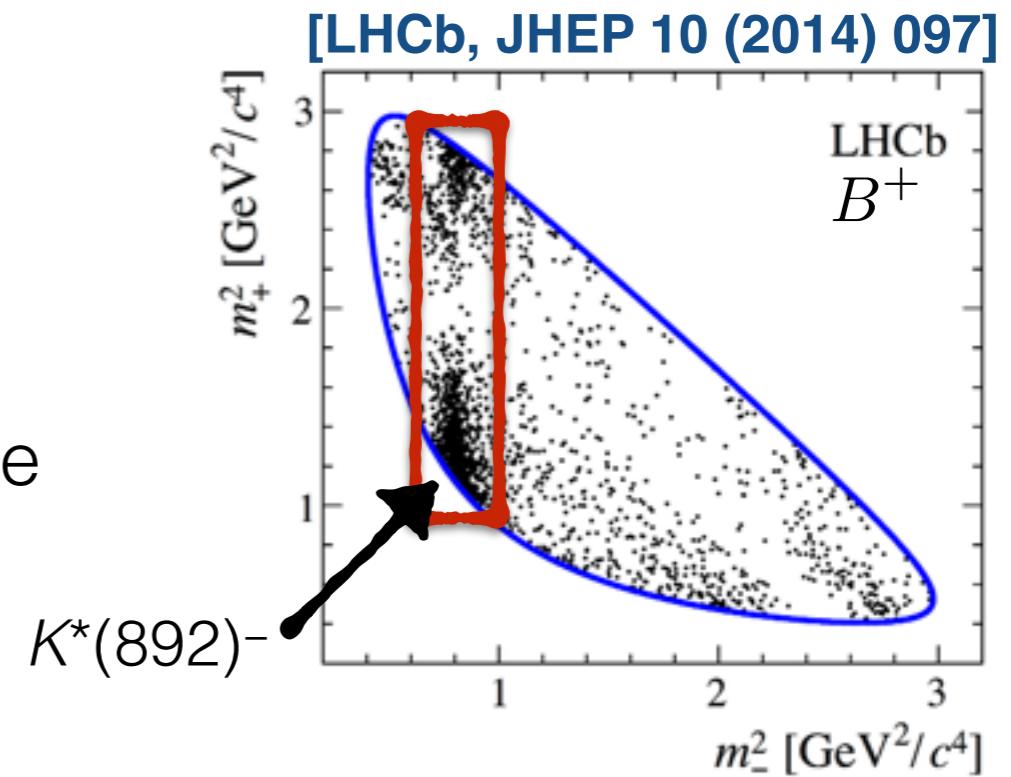
- Determine  $\gamma$  using  $D^0 \rightarrow K_S^0 h^+ h^-$
- Resonant structure provides phase information that can be used to remove ambiguities in determination of  $\gamma$ .



Bins of equal strong phase from CLEO-c

[Phys. Rev. D82 (2010) 112006]

To extract  $\gamma$ , we can either use CLEO-c data on strong phases across the Dalitz plot or perform an amplitude analysis.

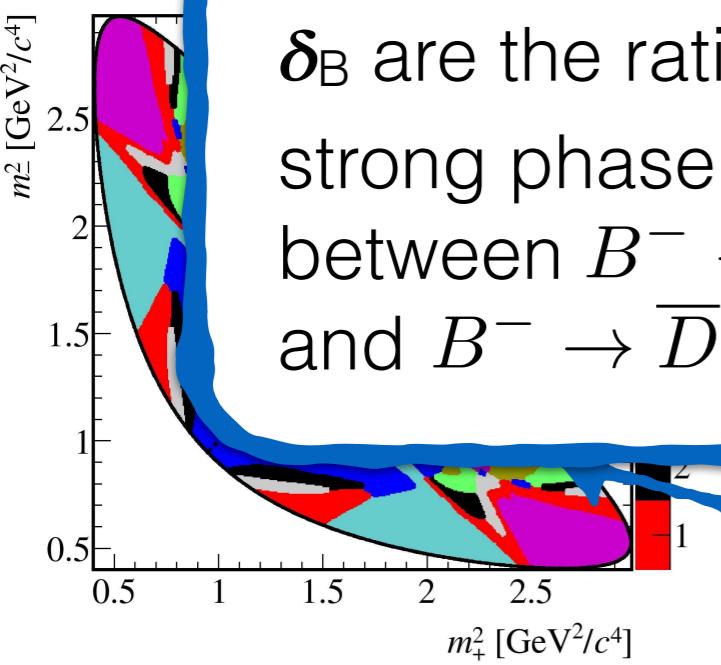


# GGSZ method

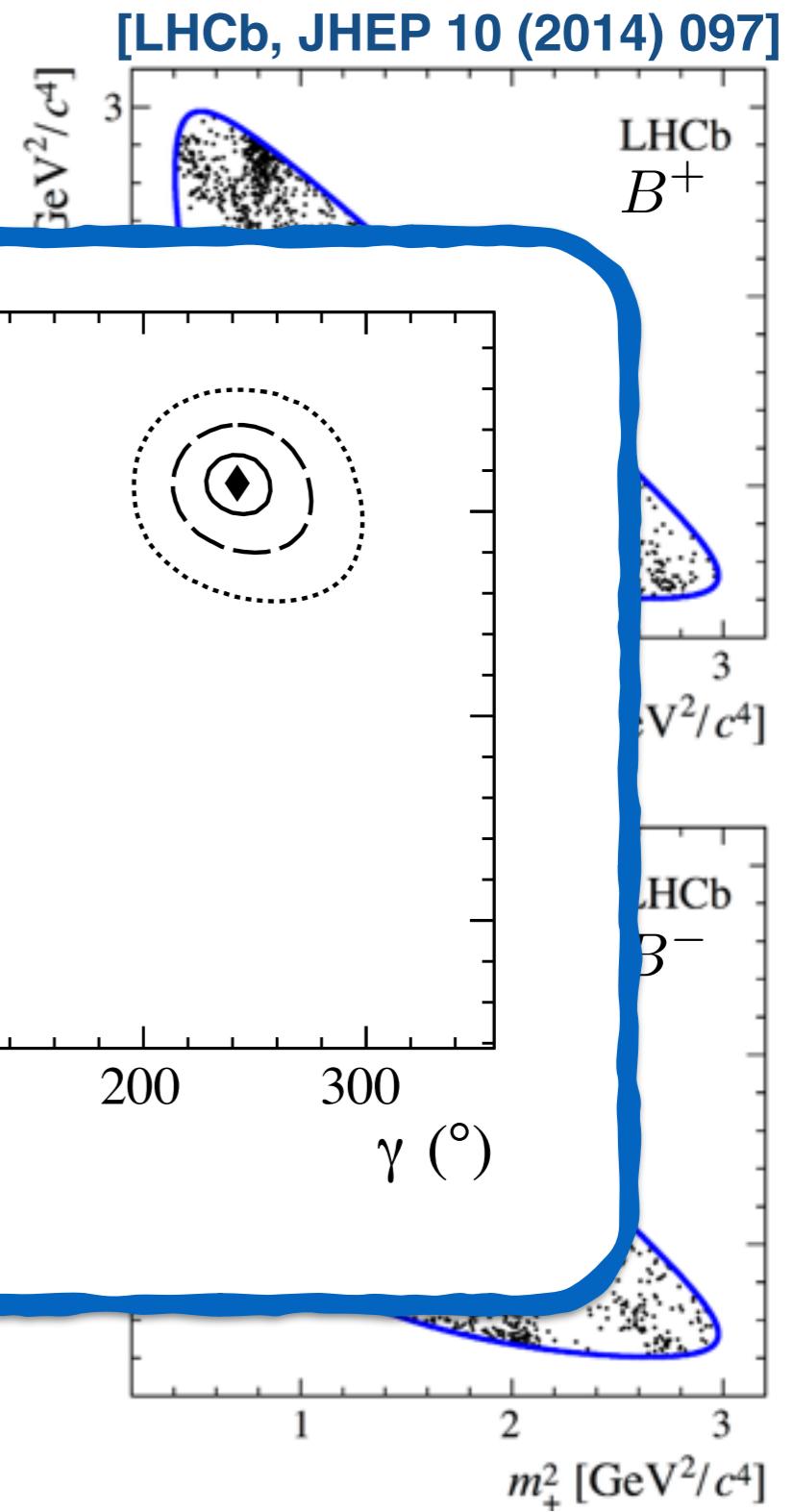
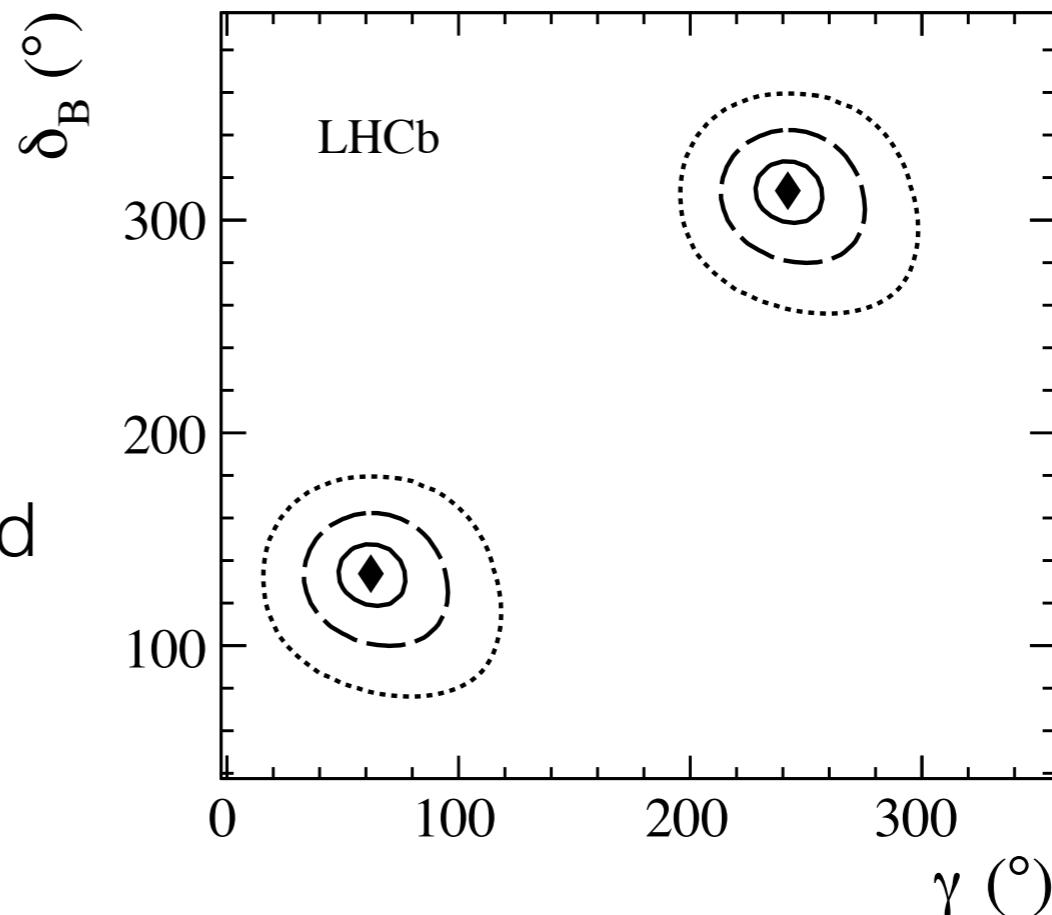
- Can access  $\gamma$  from interference

Extract

- $$x_{\pm} = r_B \cos(\delta_B \pm \gamma)$$
$$y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$
which can be used to determine  $\gamma$ , where  $r_B$  and  $\delta_B$  are the ratio of and strong phase difference between  $B^- \rightarrow D^0 K^-$  and  $B^- \rightarrow \bar{D}^0 K^-$ .



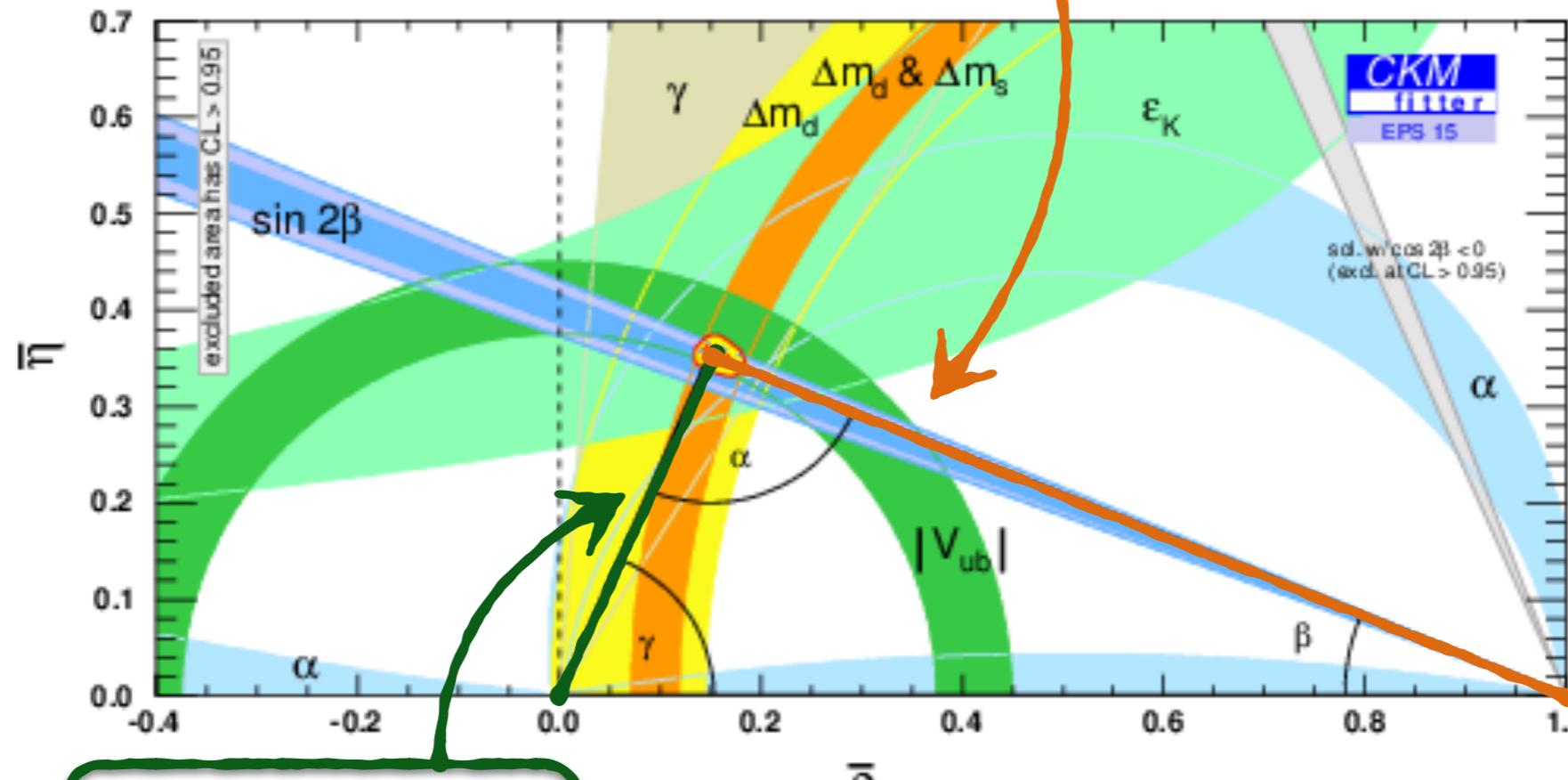
Bins of equal strong phase.



# Sides of the triangle

Determined from B mixing  
oscillation frequency  $\Delta m_d$

$$R_u = \left| \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} \right|$$



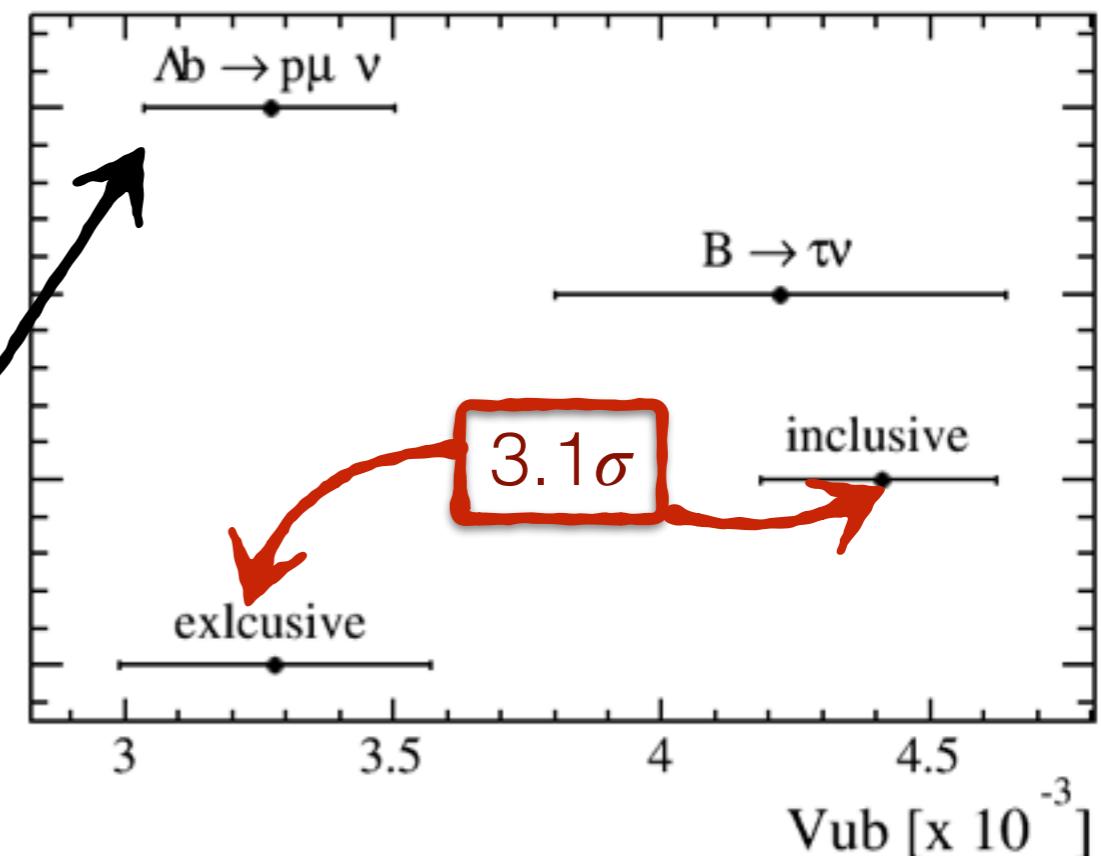
$$R_u = \left| \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right|$$

Determined from  $b \rightarrow u$  semileptonic  
 $b$ -hadron decays

# $V_{ub}$ “tension”

- Long-standing tension between  $V_{ub}$  measured by exclusive and inclusive measurement at the B-factories.

New “exclusive” result from LHCb at Moriond EW 2015 using  $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu$   
[LHCb, Nature Physics (2015) 3415]



There are also new inclusive  $B \rightarrow X_u e\nu$  results from BaBar  
[see talk by G. Eigen in the flavour parallel sessions]

# $\Lambda_b \rightarrow p\mu^-\bar{\nu}$

- Measure ratio of

$$\frac{\mathcal{B}(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+\mu^-\bar{\nu}_\mu)}$$

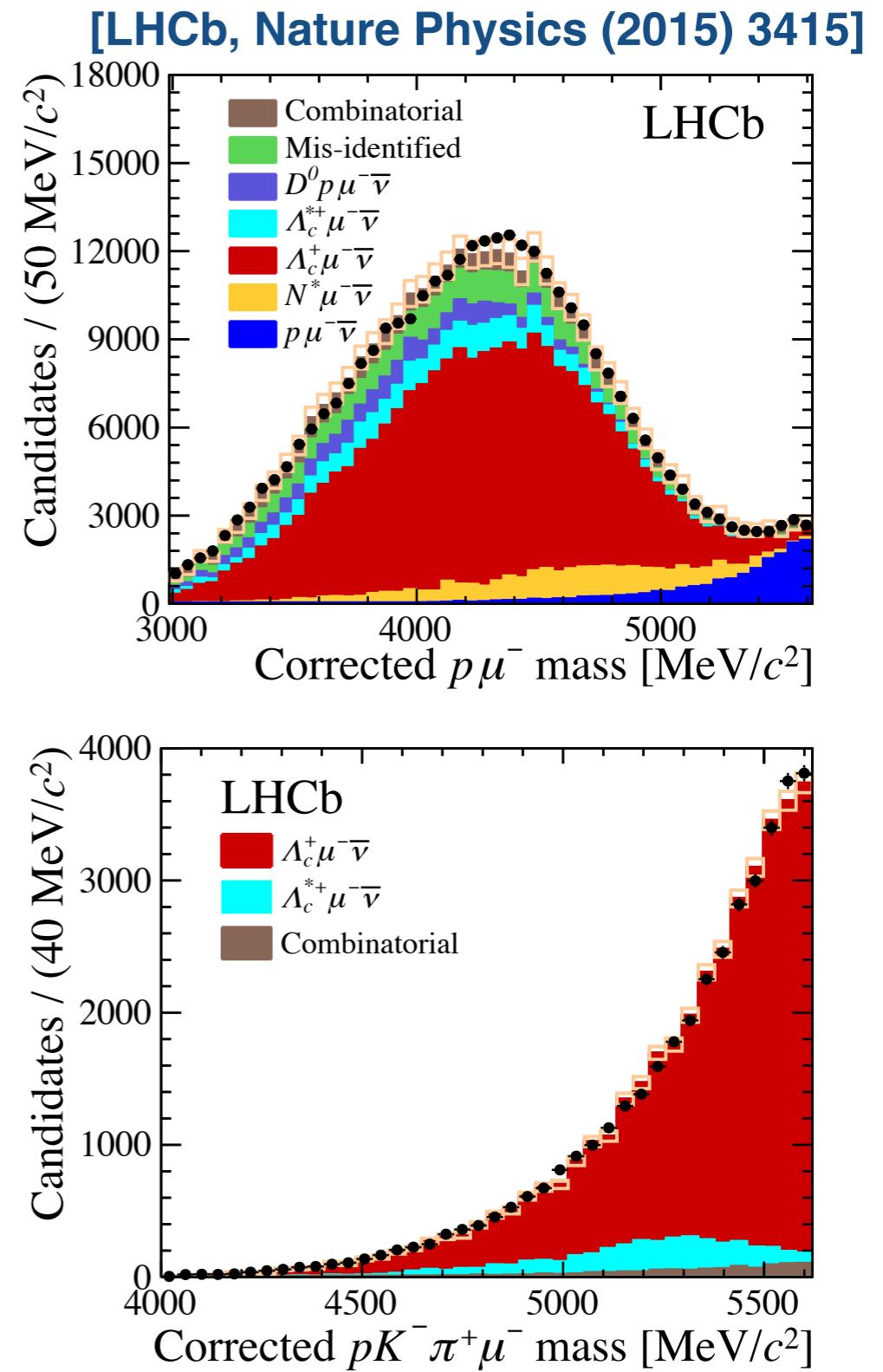
- Use secondary vertex to define corrected mass

$$\sqrt{m(p + \mu^-)^2 + p_\perp^2} + p_\perp$$

where  $p_\perp$  is the missing transverse momentum.

- Use form-factors from lattice QCD at high  $q^2$  to determine  $V_{ub}$ .

[RBC/UKQCD, Phys. Rev. D 92, 034503 (2015)]



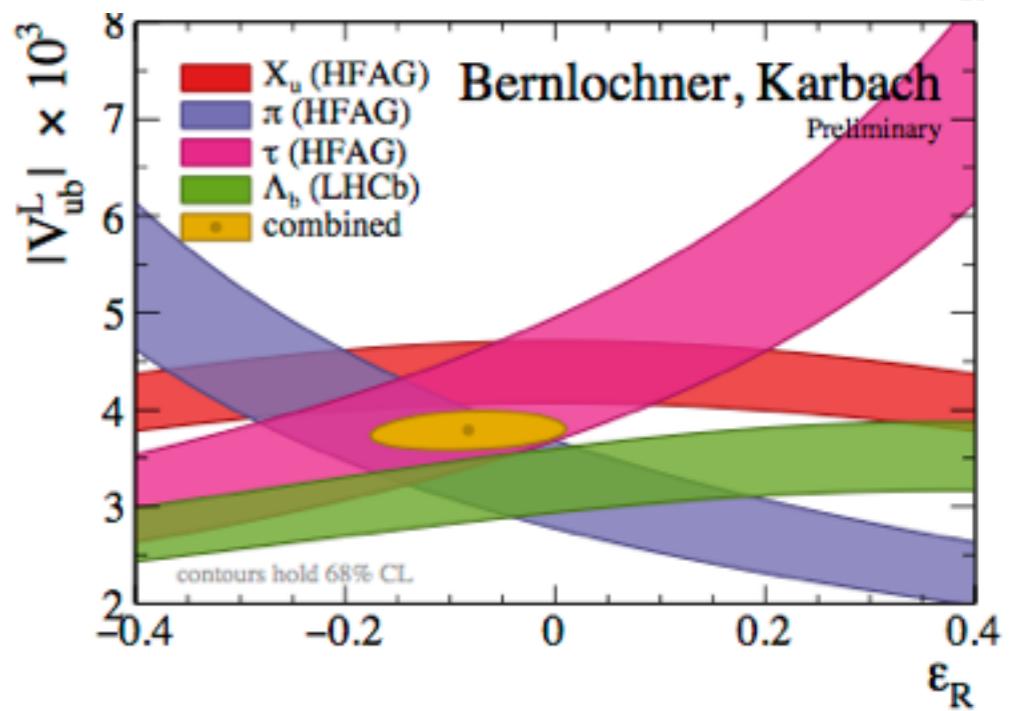
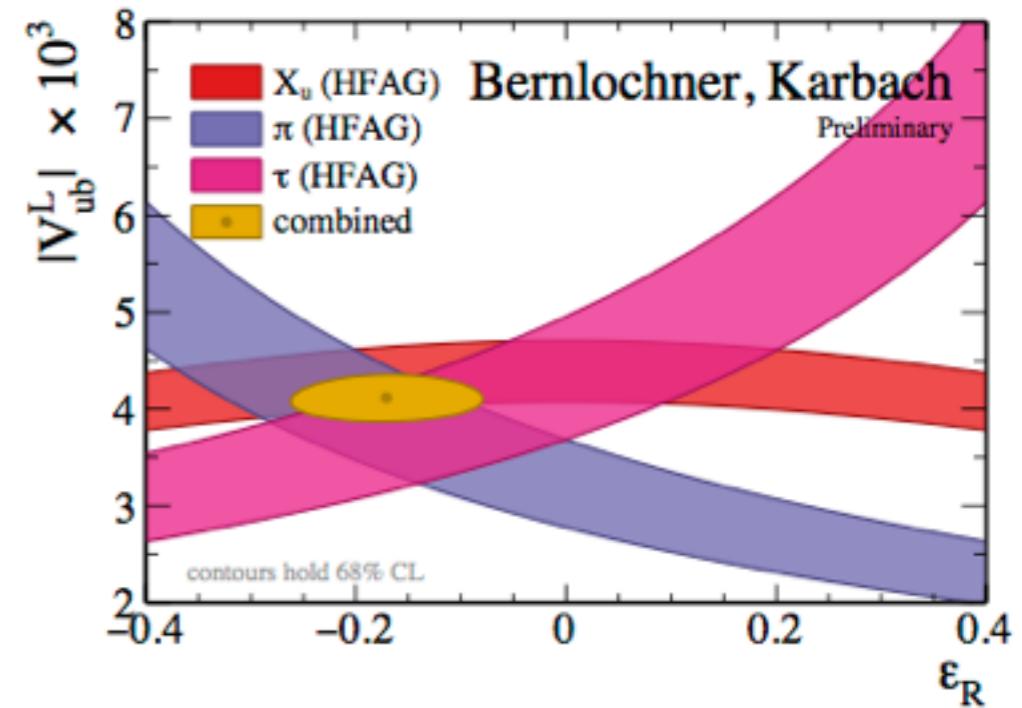
# $V_{ub}$ interpretation

- Can attempt to explain the  $V_{ub}$  tension by introducing a RH current

$$\mathcal{L}_{\text{eff}} \propto V_{ub}^L (\bar{u} \gamma_\mu P_L b + \varepsilon_R \bar{u} \gamma_\mu P_R b) (\bar{\nu} \gamma^\mu P_L \ell) + \text{h.c}$$

- Unfortunately it's difficult to reconcile with the new measurement of  $V_{ub}$  from  $\Lambda_b$  decays.
- Alternatively, is there a failure with the theoretical framework (Lattice QCD, LCSR or HQET)?

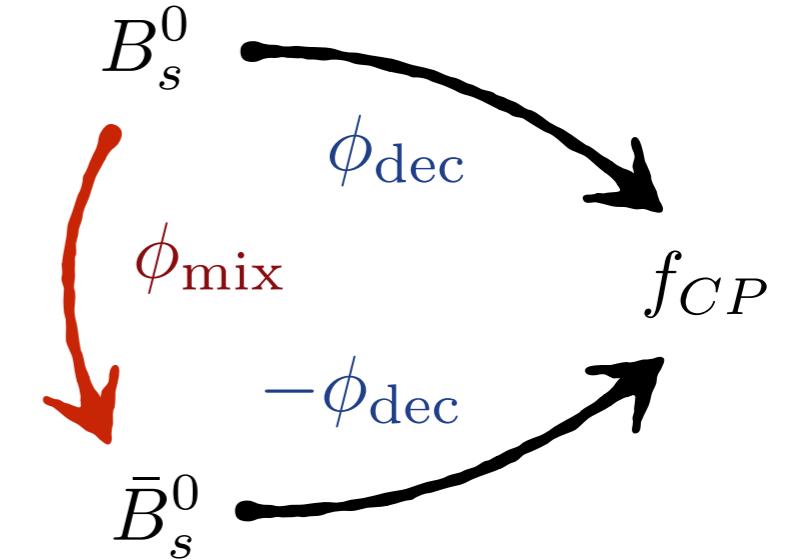
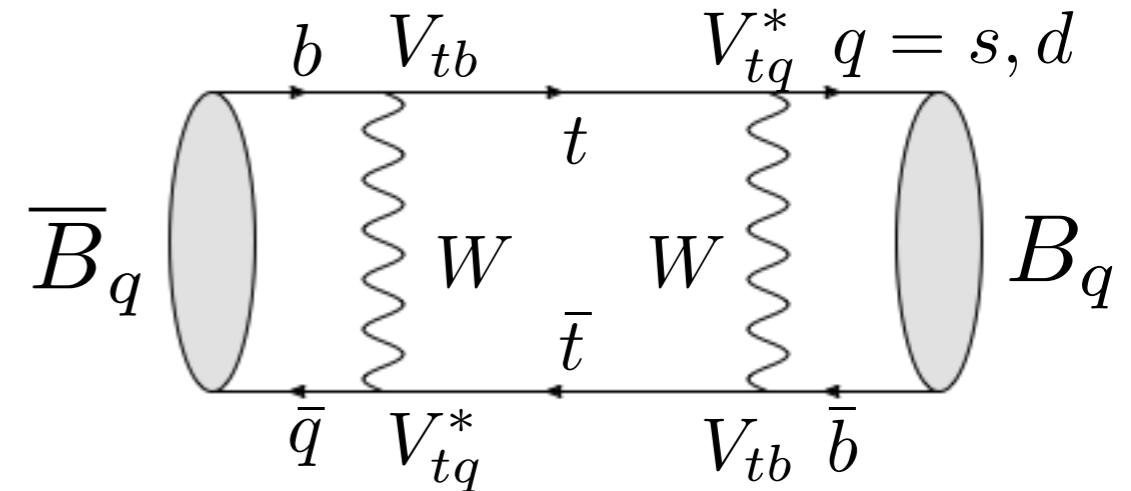
[Phys. Rev. D 90, 094003 (2014)]



# Mixing induced CP

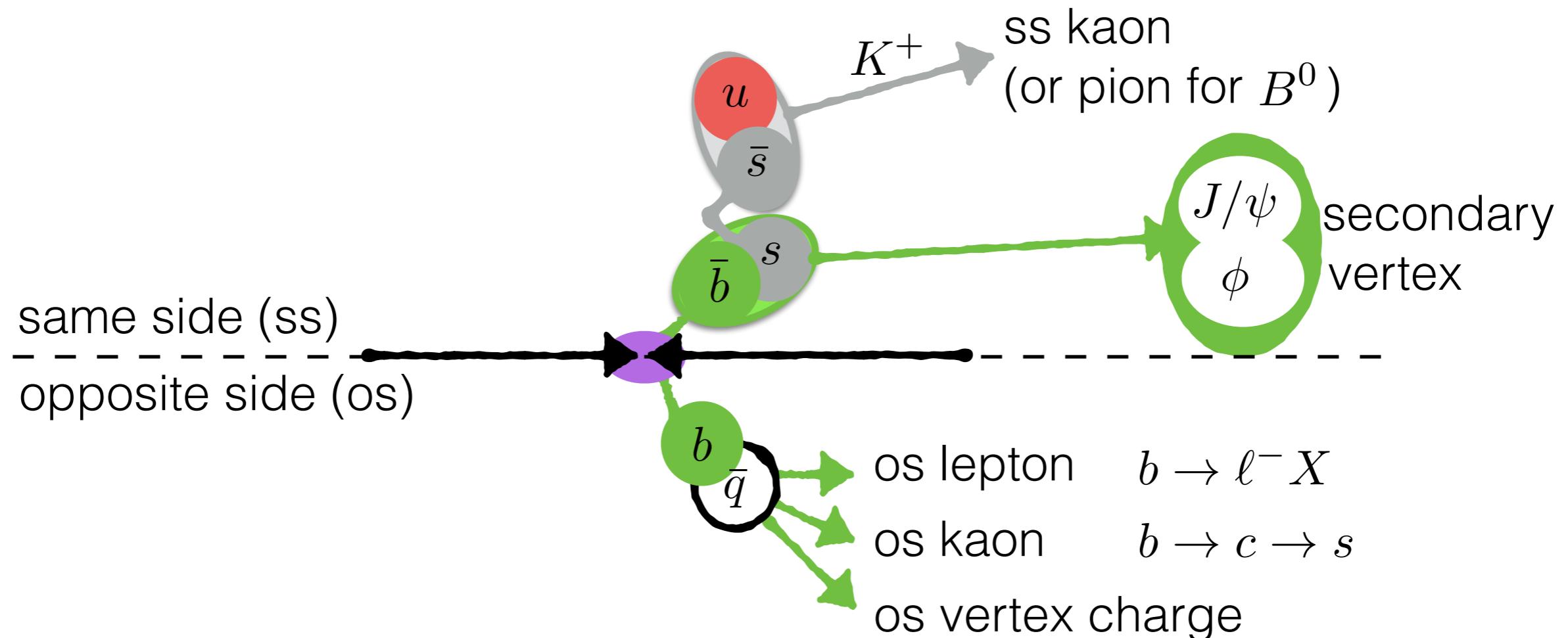
- Look at tree level  $b \rightarrow c\bar{c}s$  decays to a common final state.
  - Studied using  $B_s \rightarrow J/\psi \phi$  decays in the  $B_s$  system.
- Probes CP violation from interference between decays with and without mixing (and NP contributions to the box diagram).
- Relative phase is

$$\phi_s = \phi_{\text{mix}} - 2\phi_{\text{dec}}$$



# Flavour tagging

- Major challenge in these analyses is to tag the flavour of the  $B$  at production:

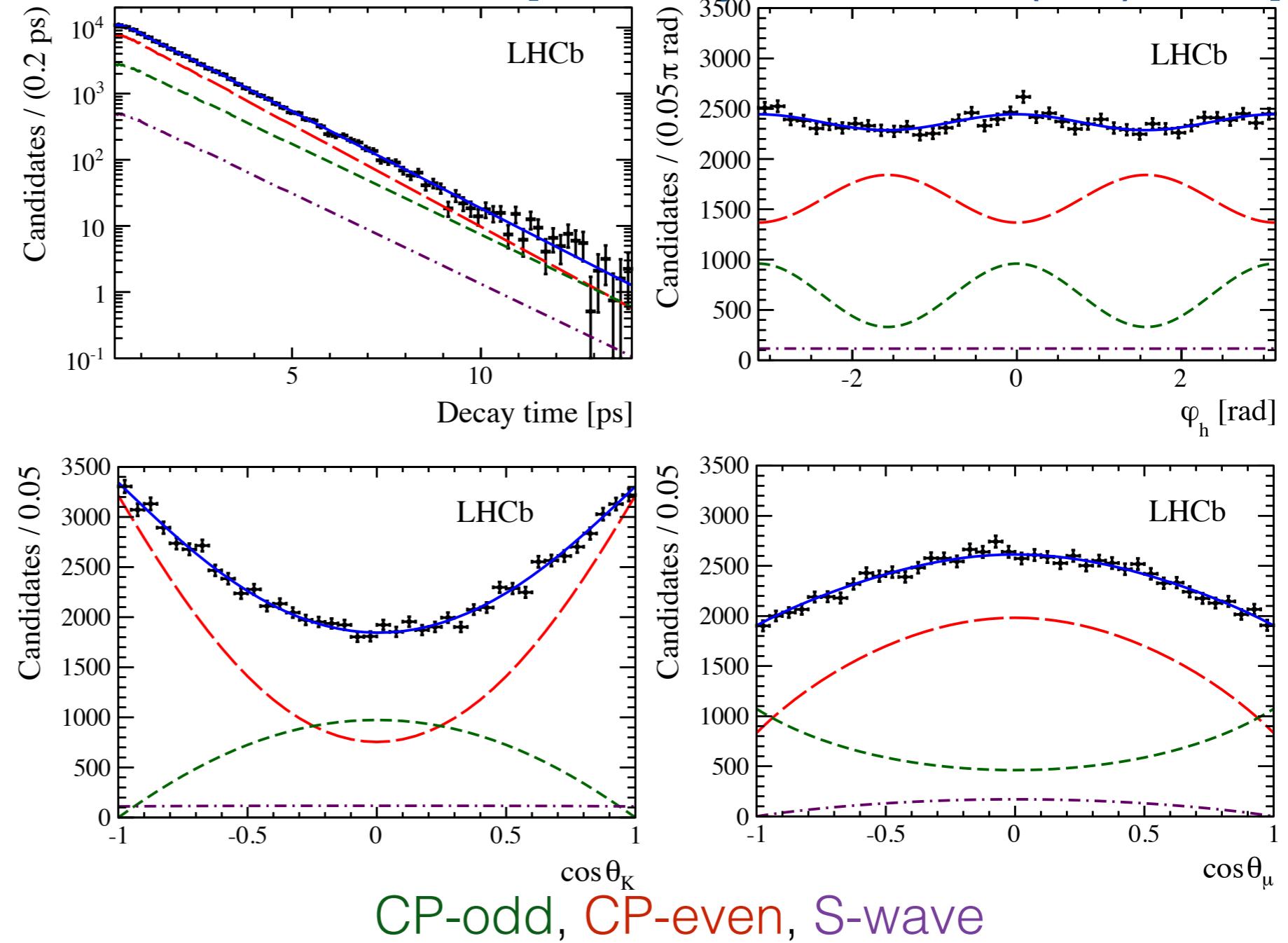


- ATLAS  $\epsilon D^2 = (1.49 \pm 0.02)\%$ ,  
CMS  $\epsilon D^2 = (1.31 \pm 0.03)\%$ ,  
LHCb  $\epsilon D^2 = (3.73 \pm 0.15)\%$ .

# $\Delta\Gamma_s$ and $\phi_s$

- $B_s \rightarrow J/\Psi \phi$  final state is a mixture of CP-odd and CP-even. Separate using a time-dependent angular analysis.

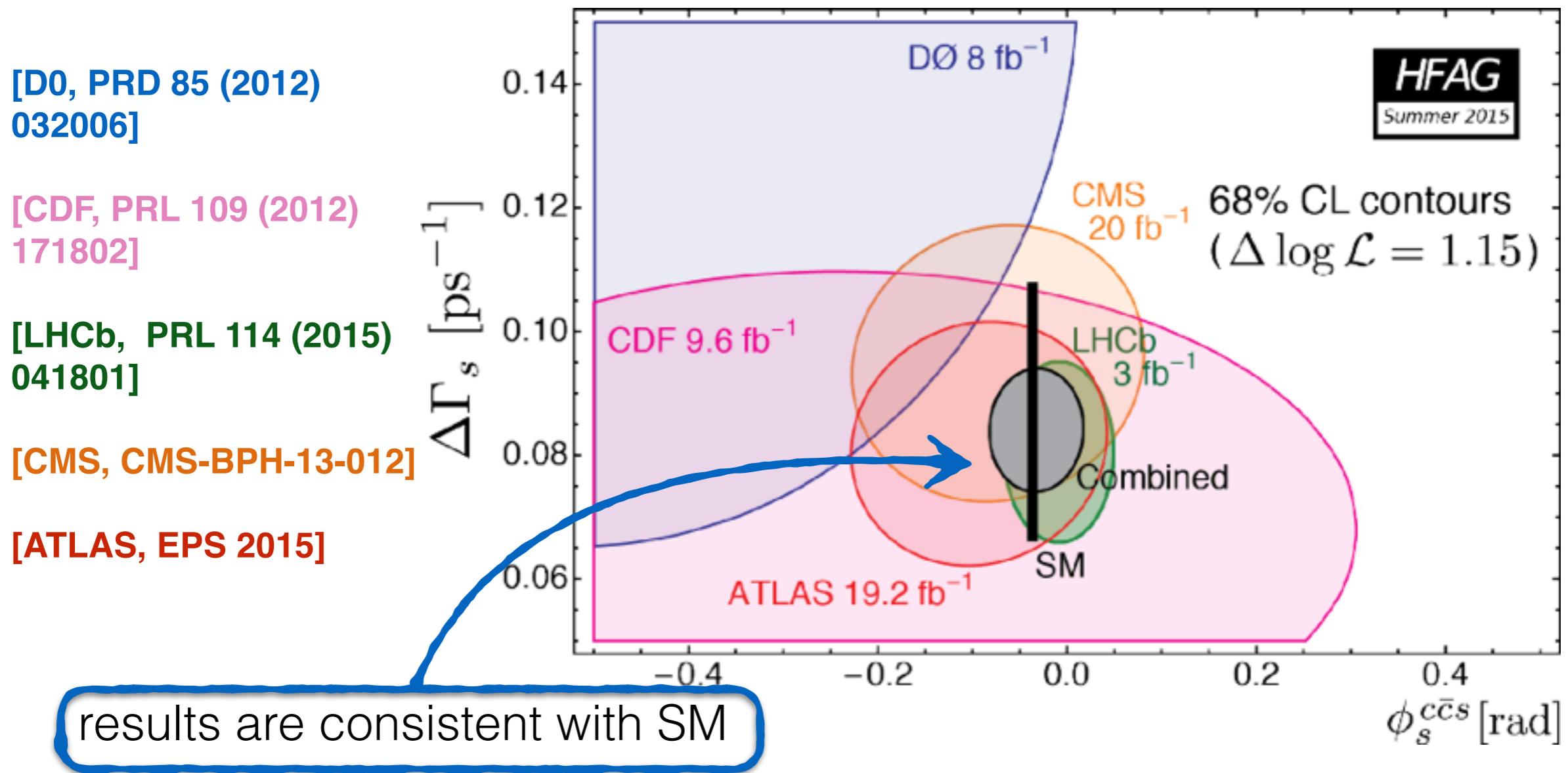
[LHCb, Phys. Rev. Lett. 114 (2015) 041801]



Also perform measurements with  $B_s \rightarrow J/\Psi \pi^+\pi^-$  and  $B_s \rightarrow D_s^+D_s^-$

# $\Delta\Gamma_s$ versus $\phi_s$

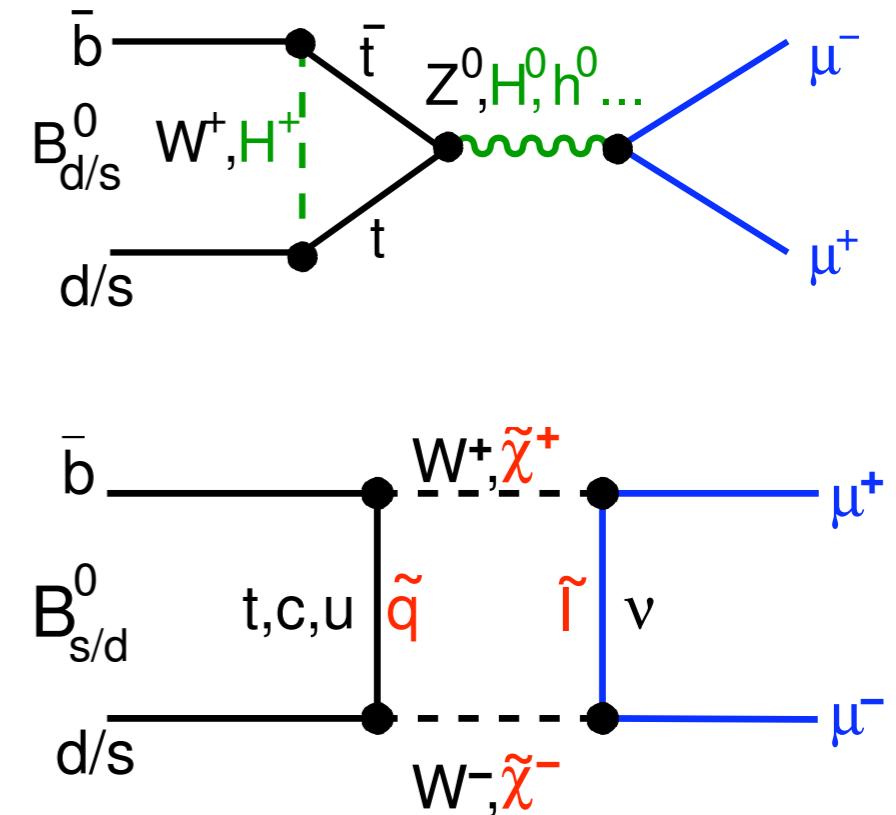
- Combining the measurements:



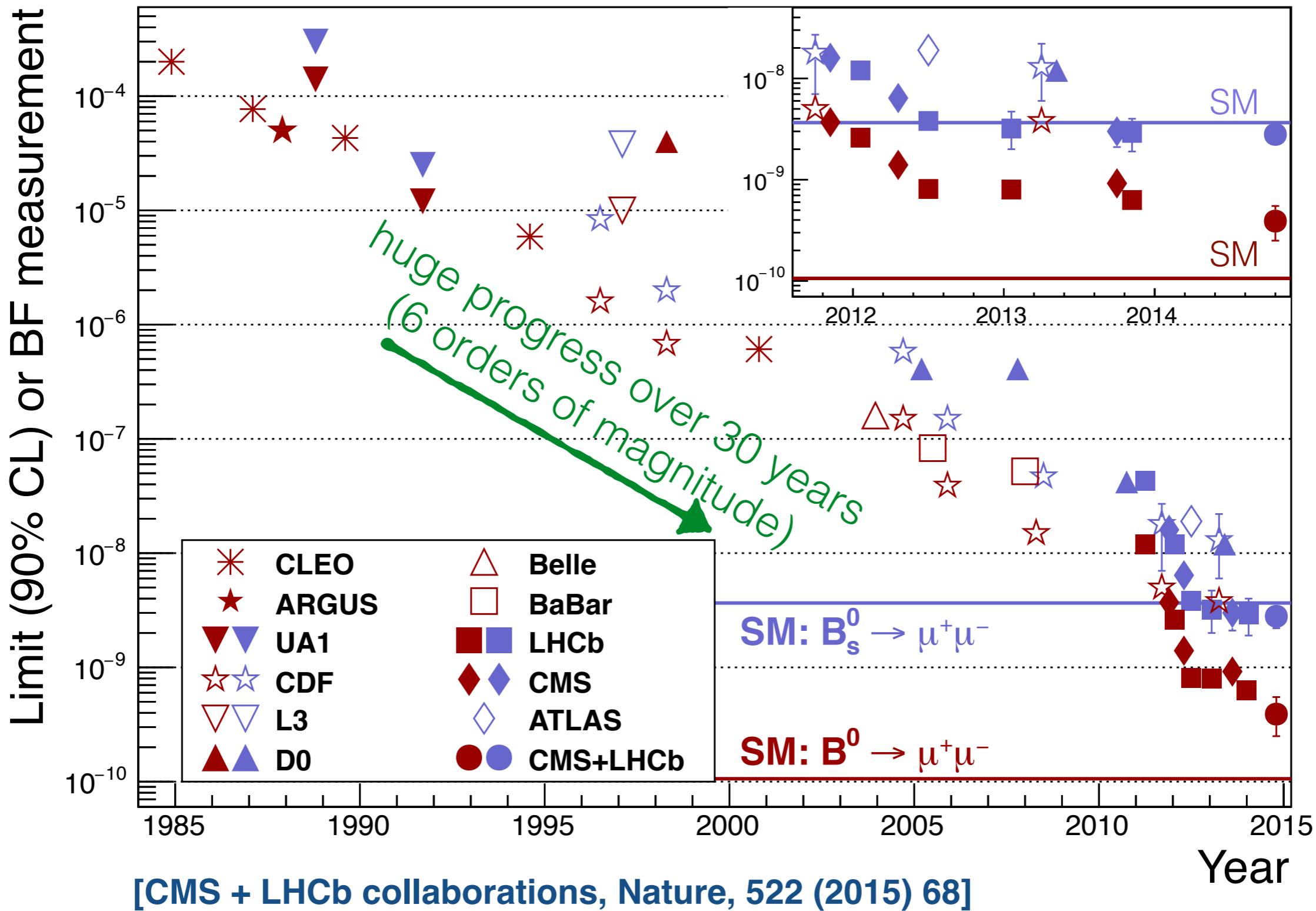
- Measurements are statistically limited (and major systematic uncertainties can be reduced with larger datasets)

# Leptonic decays

- $B_s \rightarrow \mu^+ \mu^-$  is a golden mode to study FCNCs at the LHC.
  - CKM suppressed, loop suppressed and helicity suppressed (pseudoscalar B meson producing two muons).
  - Predicted precisely in the SM (6% uncertainty on branching fraction).  
**[Bobeth et al. PRL 112 (2014) 101801]**
- Powerful probe of models with new or enhanced scalar/pseudoscalar interactions, e.g. SUSY at high  $\tan\beta$ .

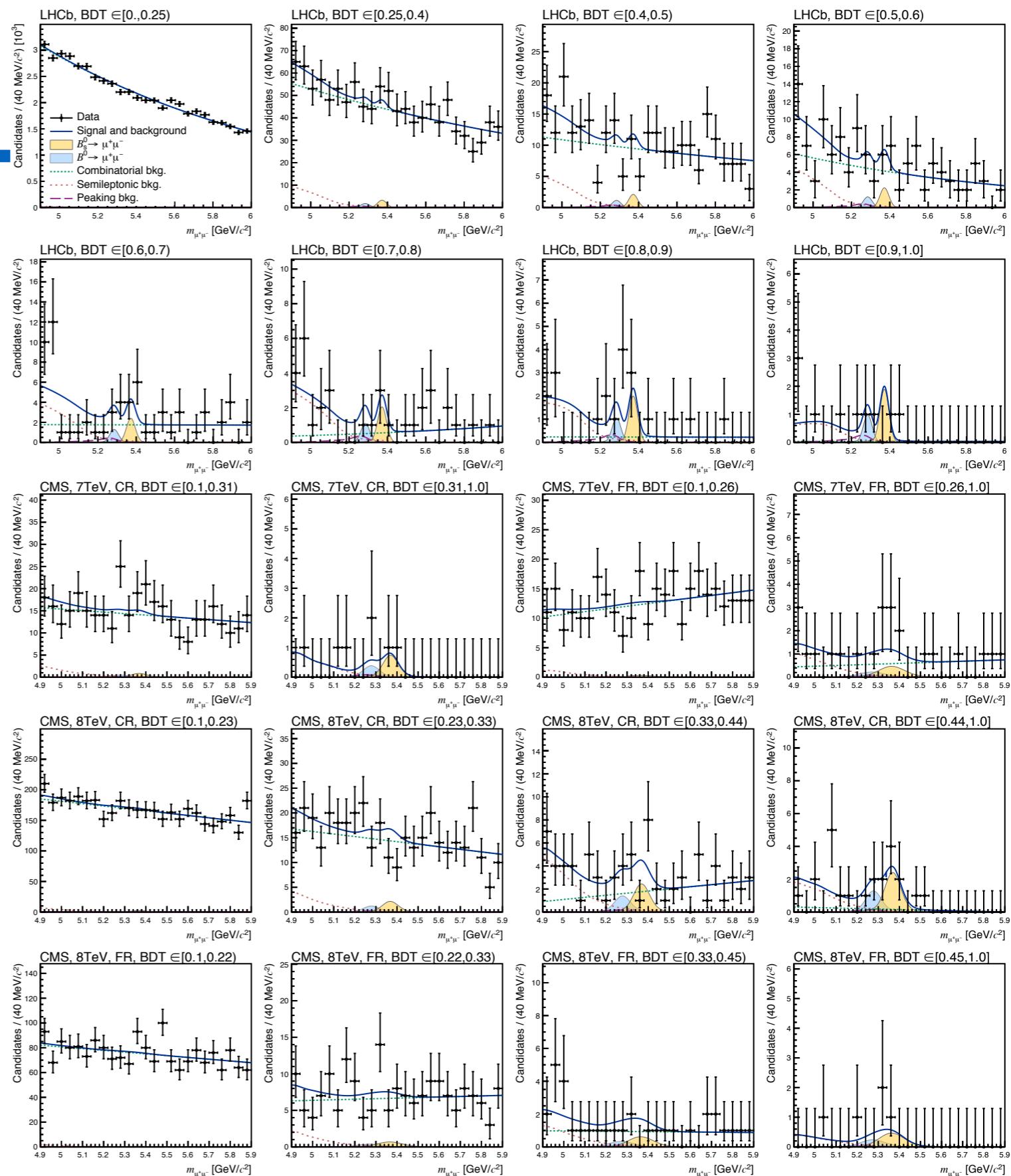


# $B_{(s,d)} \rightarrow \mu^+ \mu^-$ history



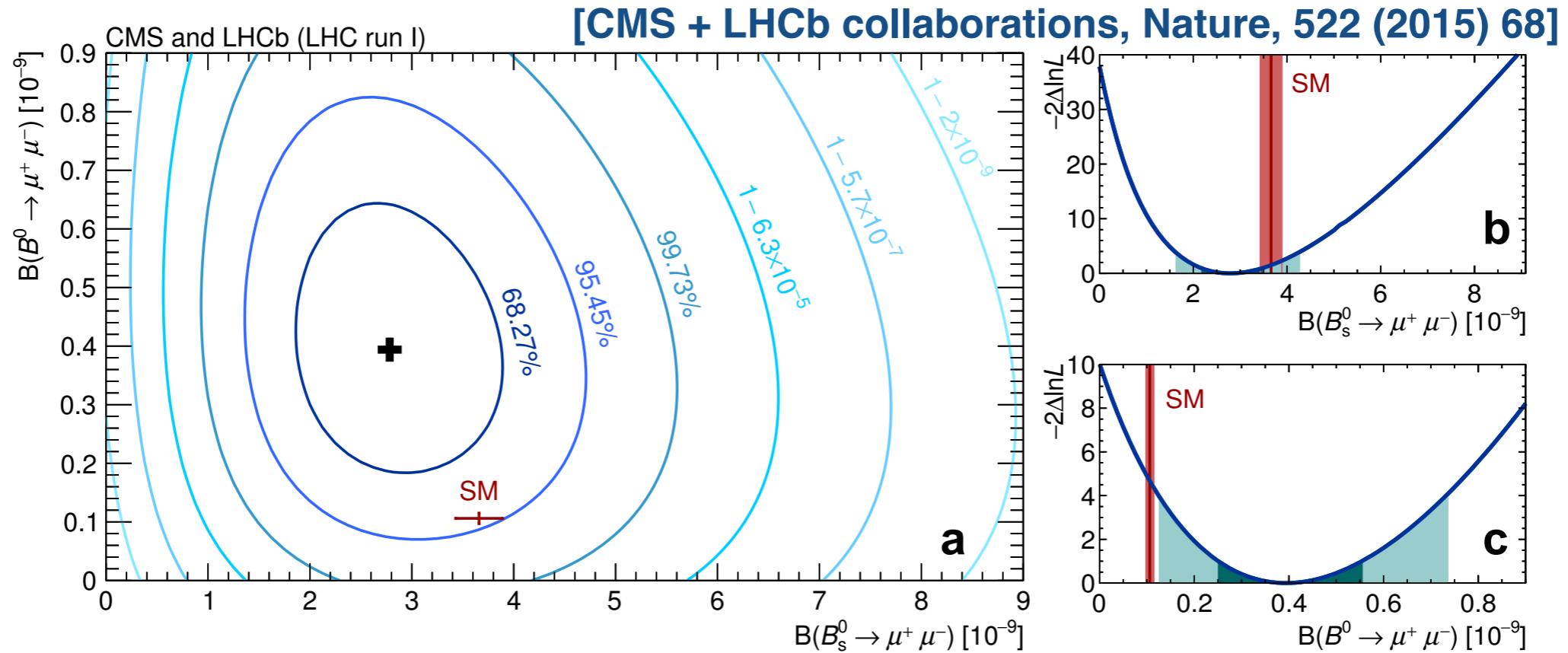
$$B(s,d) \rightarrow \mu^+ \mu^-$$

- CMS + LHCb have performed a simultaneous analysis of the datasets from the two experiments.
  - Binned in MVA response.
  - CMS data also split by barrel/end cap.
- Nuisance parameters (backgrounds,  $f_s/f_d$ ) shared between the experiments.



[CMS + LHCb collaborations, Nature, 522 (2015) 68]

# $B_{(s,d)} \rightarrow \mu^+ \mu^-$



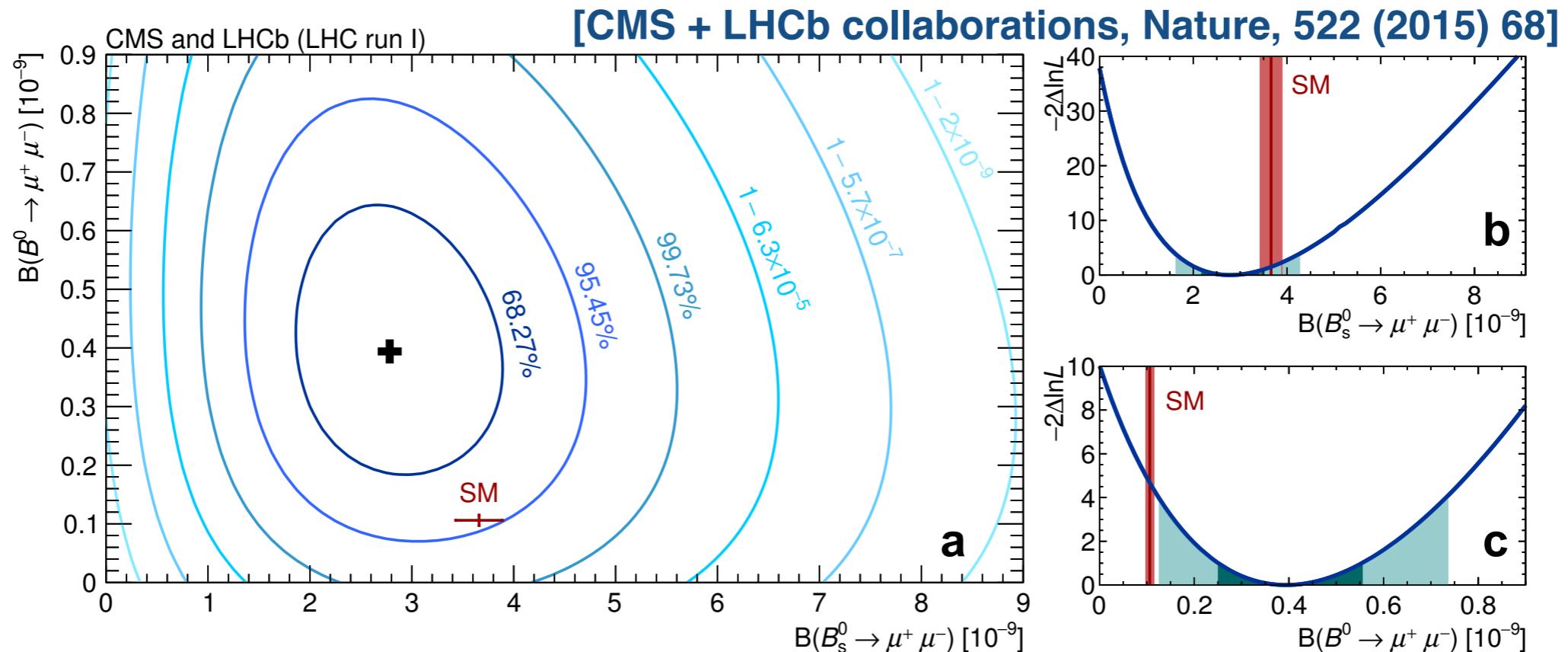
- Best fit results:

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

$$\mathcal{B}(B_d^0 \rightarrow \mu^+ \mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

→  $B_s$  decay observed at  $6.2\sigma$ , evidence for  $B^0$  decay at  $3.0\sigma$

# $B_{(s,d)} \rightarrow \mu^+ \mu^-$



- Compatible with SM at  $1.2\sigma$  ( $B_s$ ) and  $2.2\sigma$  ( $B^0$ ).

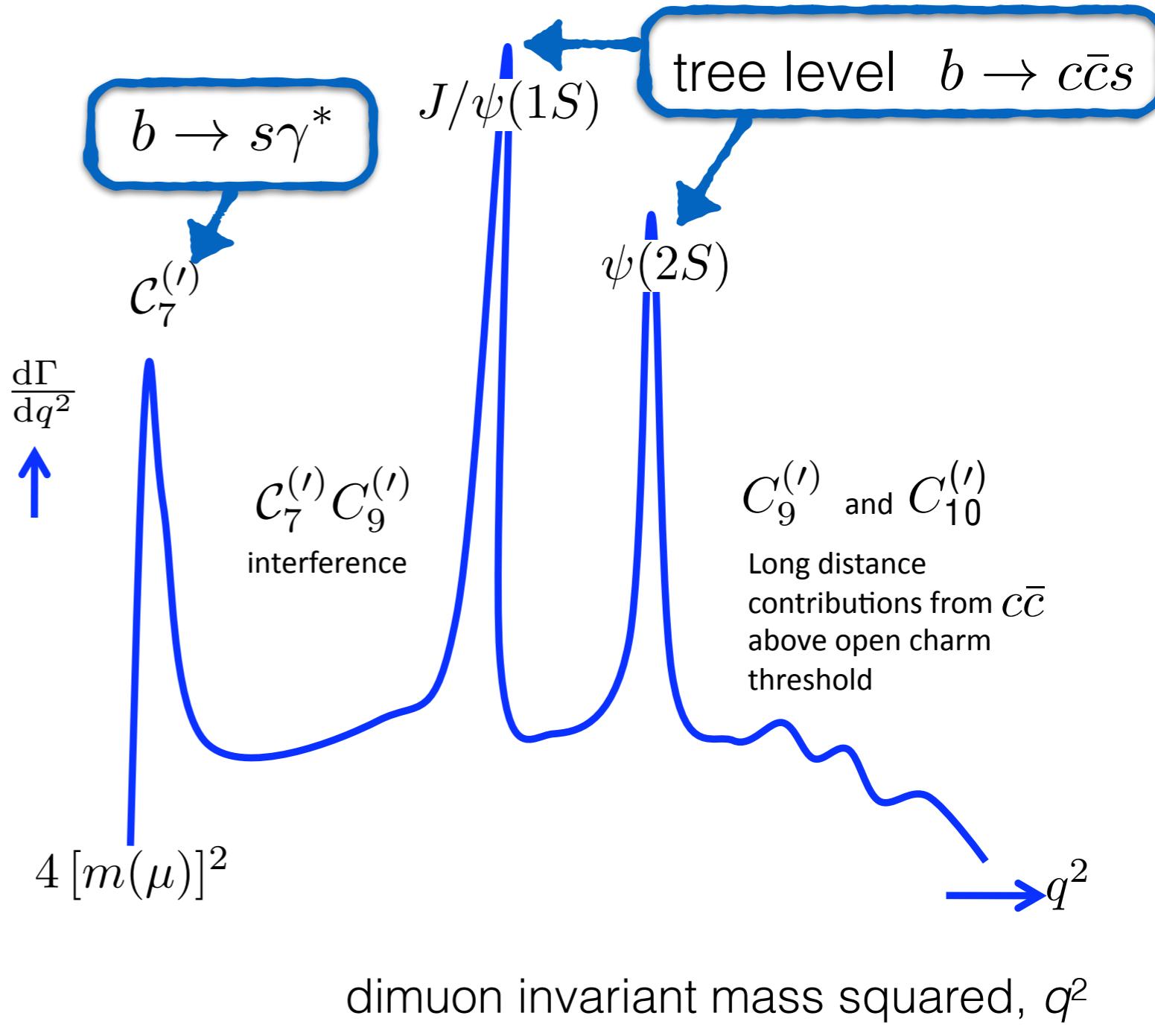
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.6 \pm 0.2) \times 10^{-9}$$

$$\mathcal{B}(B_d^0 \rightarrow \mu^+ \mu^-) = (1.0 \pm 0.1) \times 10^{-10}$$

[Bobeth et al. PRL 112 (2014) 101801]

# $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay

- Large number of observables: branching fractions, CP asymmetries and angular observables.
- Sensitive to new vector/ axial-vector currents and virtual photon polarisation (left-handed in SM).
- Reconstructed as a four track final state containing a kaon, pion and dimuon pair.



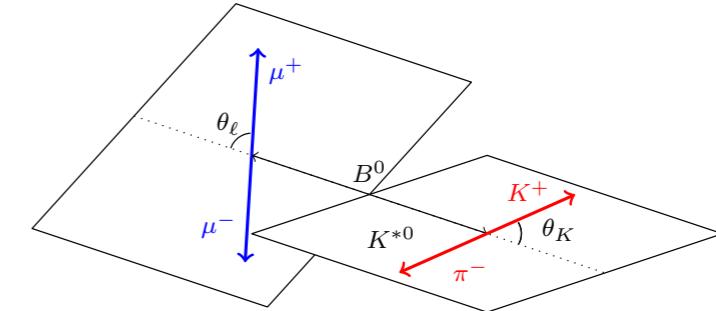
# Angular basis

- Four-body final state.

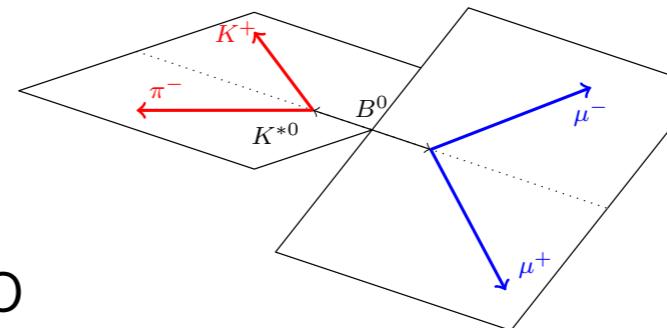
→ Angular distribution provides many observables that are sensitive to NP.

e.g. at low  $q^2$  the angle between the decay planes,  $\phi$ , is sensitive to the photon polarisation.

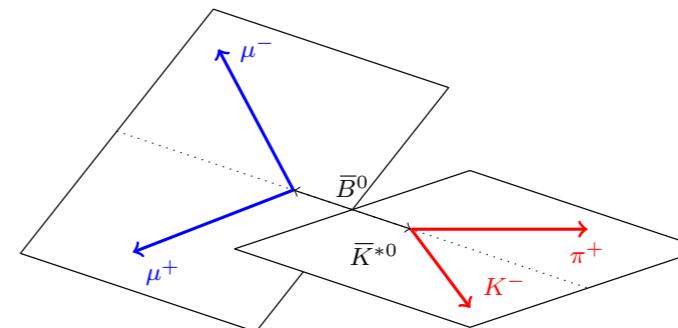
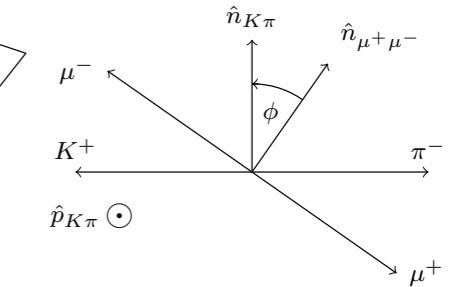
- System described by three angles and the dimuon invariant mass squared,  $q^2$ .
- Use Helicity basis for the angles.



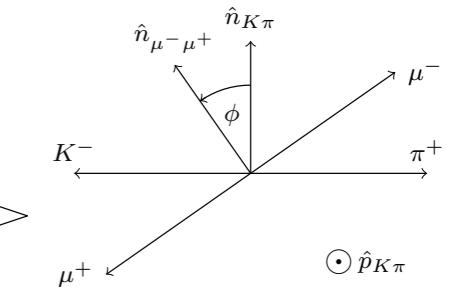
(a)  $\theta_K$  and  $\theta_\ell$  definitions for the  $B^0$  decay



(b)  $\phi$  definition for the  $B^0$  decay



(c)  $\phi$  definition for the  $\bar{B}^0$  decay



# Angular distribution

- Complex angular distribution:

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \left. \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} \right|_P = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \right.$$

**fraction of longitudinal polarisation of the  $K^*$**  

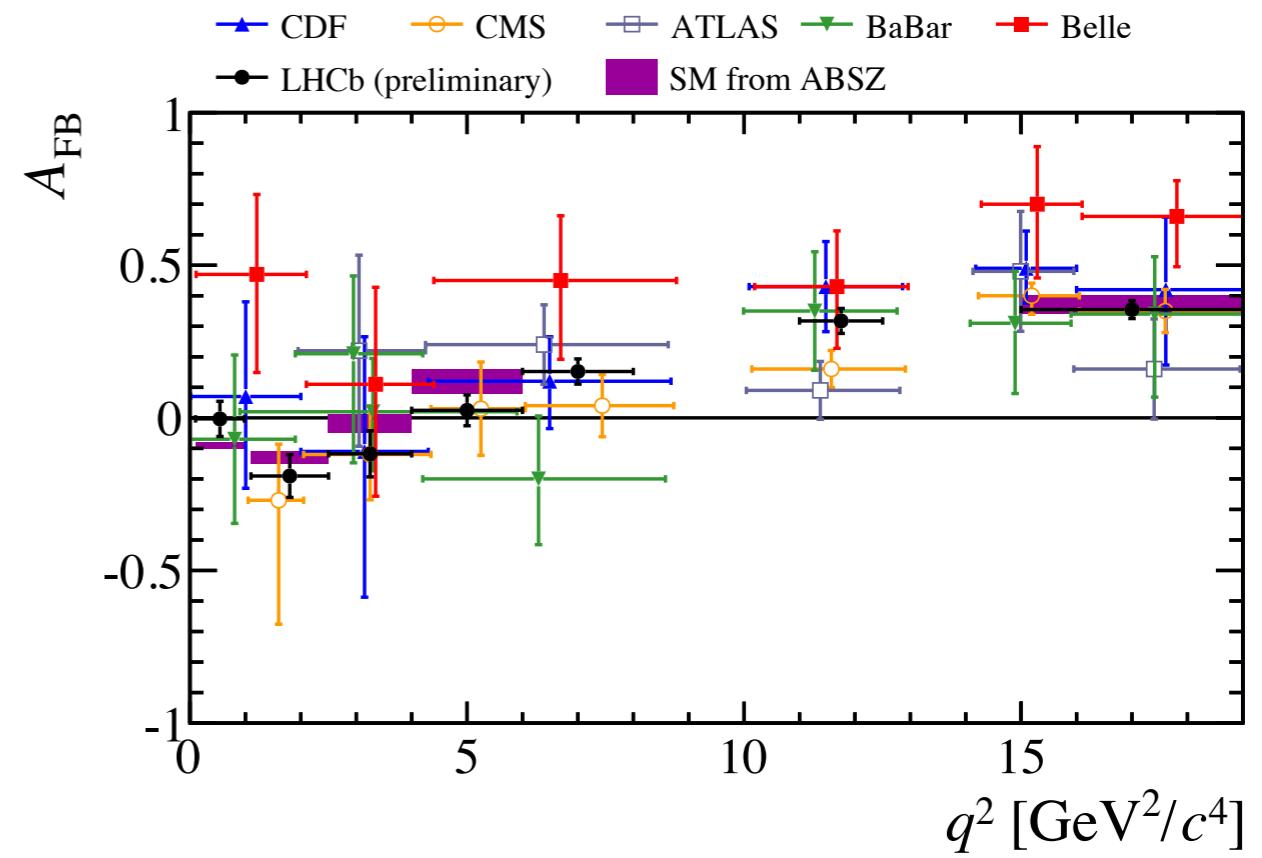
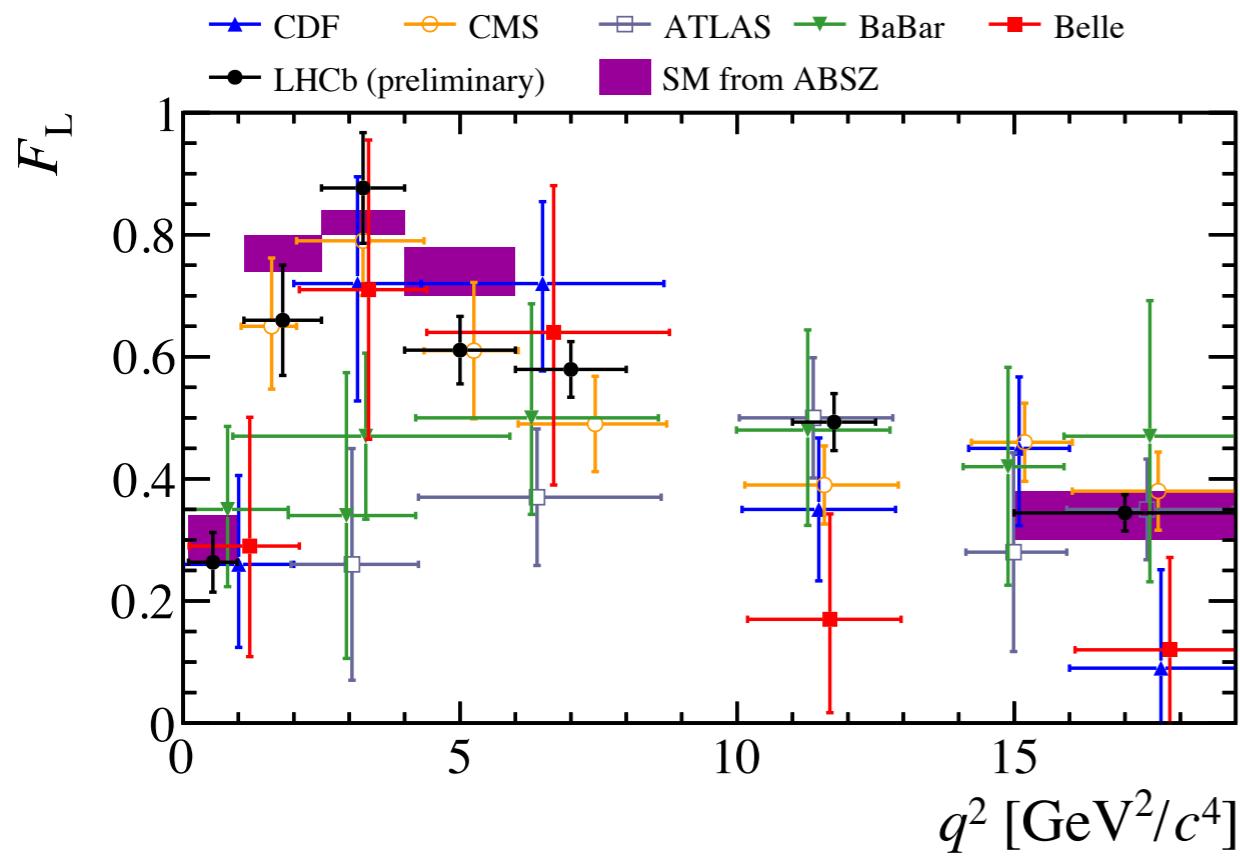
$$+ \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_l - F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi$$

**forward-backward asymmetry of the dilepton system** 

$$+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]$$

The observables depend on form-factors for the  $B \rightarrow K^*$  transition plus the underlying short distance physics (Wilson coefficients).

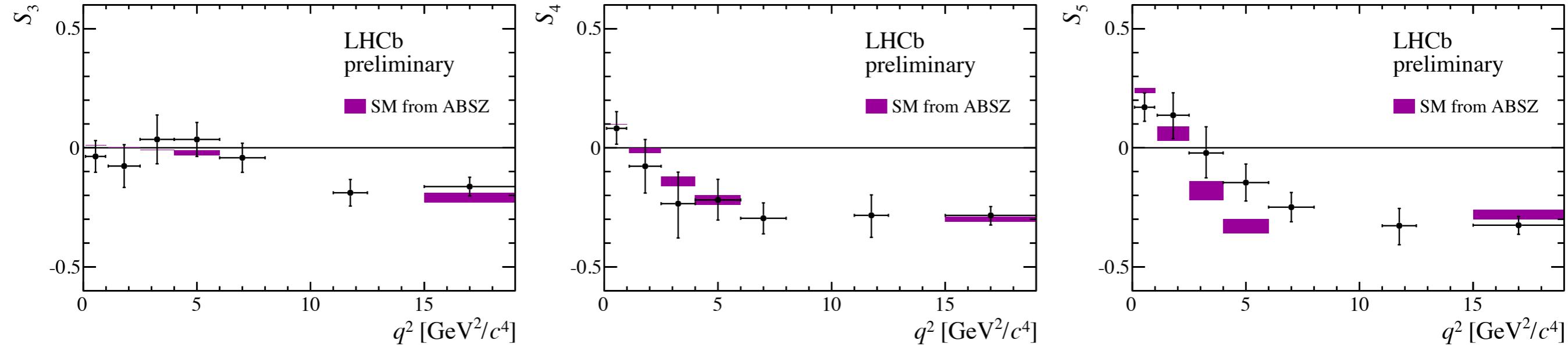
# Results



- New results shown for  $F_L$  and  $A_{FB}$  this year by LHCb [[LHCb-CONF-2015-002](#)] and CMS [[CMS-BPH-13-010](#)].
- SM predictions based on  
[\[Altmannshofer & Straub, arXiv:1411.3161\]](#)  
[\[LCSR form-factors from Bharucha, Straub & Zwicky, arXiv:1503.05534\]](#)  
[\[Lattice form-factors from Horgan, Liu, Meinel & Wingate arXiv:1501.00367\]](#)

# Results

[LHCb-CONF-2015-002]

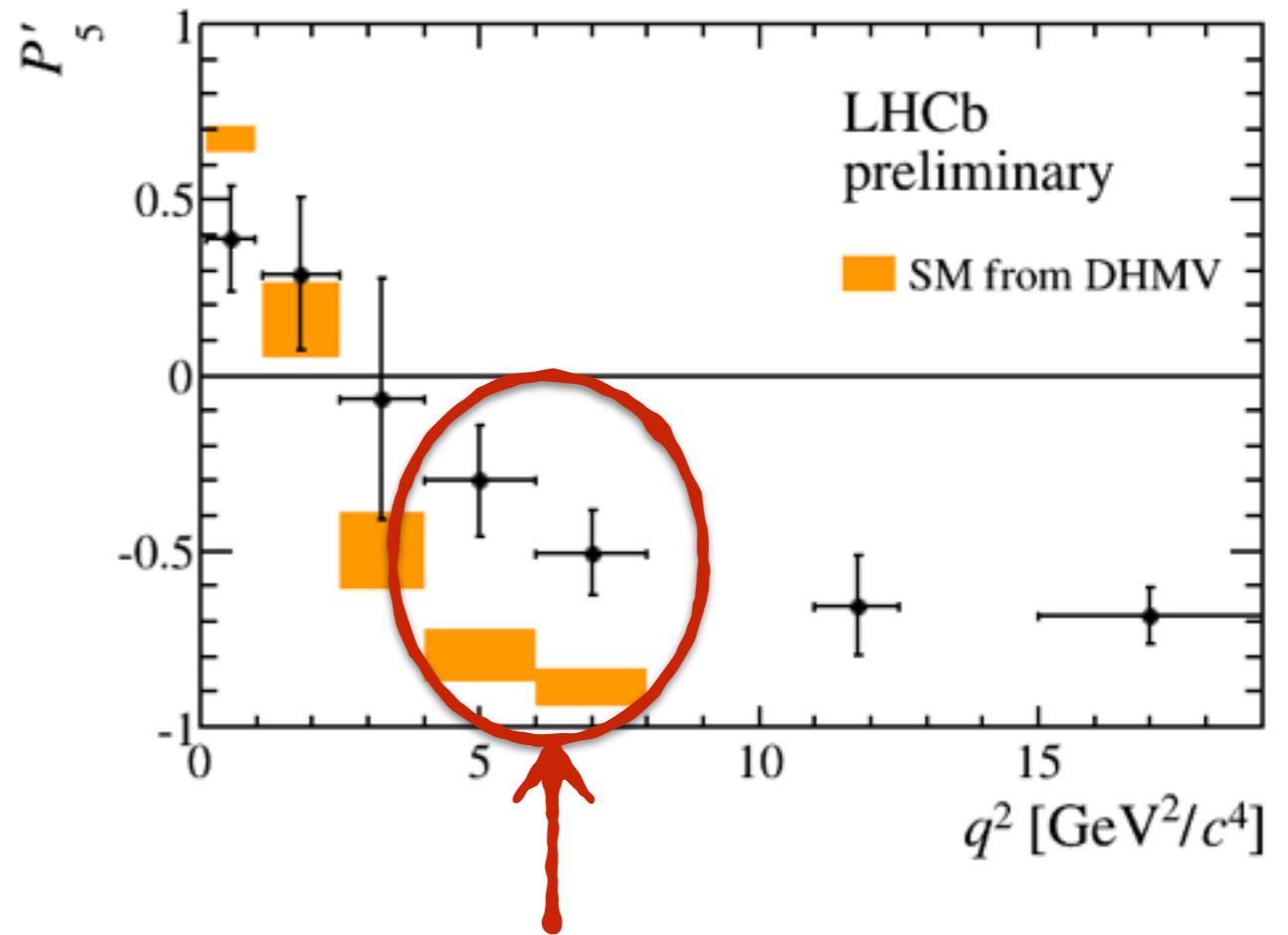


- LHCb has also measured the other CP-averaged angular terms (which are cancelled in the CMS analysis by integrating over  $\phi$ )

# Form-factor “free” observables

- In QCD factorisation/SCET there are only two form-factors
  - One is associated with  $A_0$  and the other  $A_{\parallel}$  and  $A_{\perp}$ .
- Can then construct ratios of observables which are independent of form-factors, e.g.

$$P'_5 = S_5 / \sqrt{F_L(1 - F_L)}$$

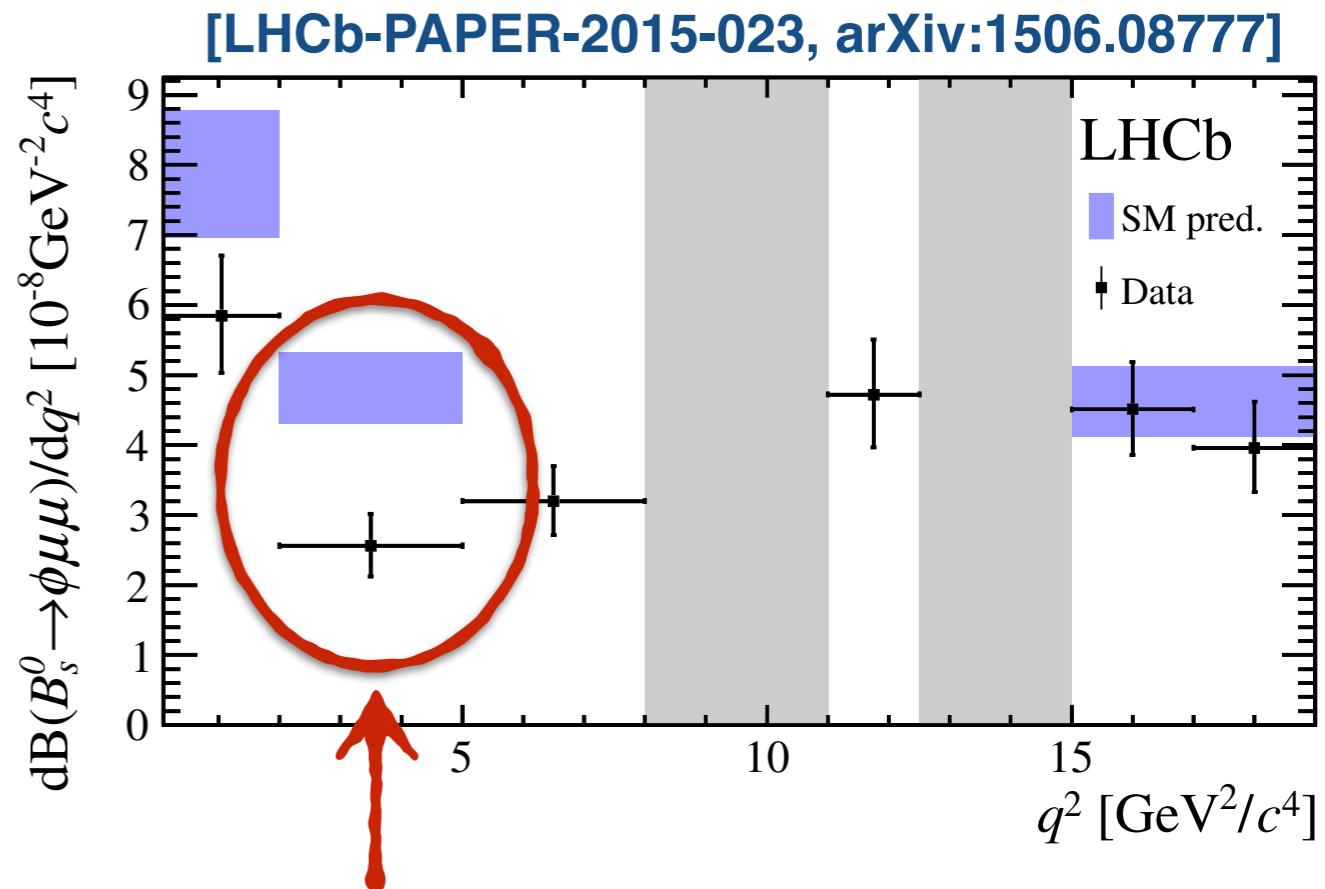


local tension with SM predictions  
( $2.9\sigma$  in each bin)

- $P'_5$  is one of a set of so-called form-factor free observables that can be measured [[S. Descotes-Genon et al. JHEP 1204 \(2012\) 104](#)].

# $B_s \rightarrow \phi \mu^+ \mu^-$

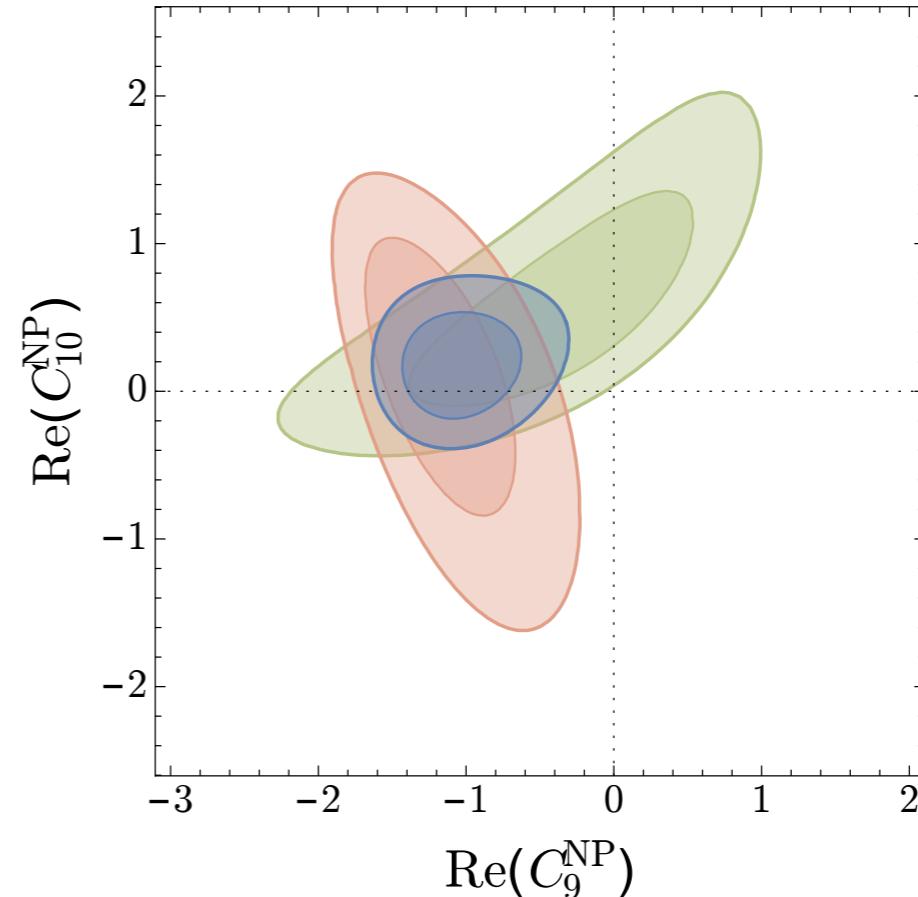
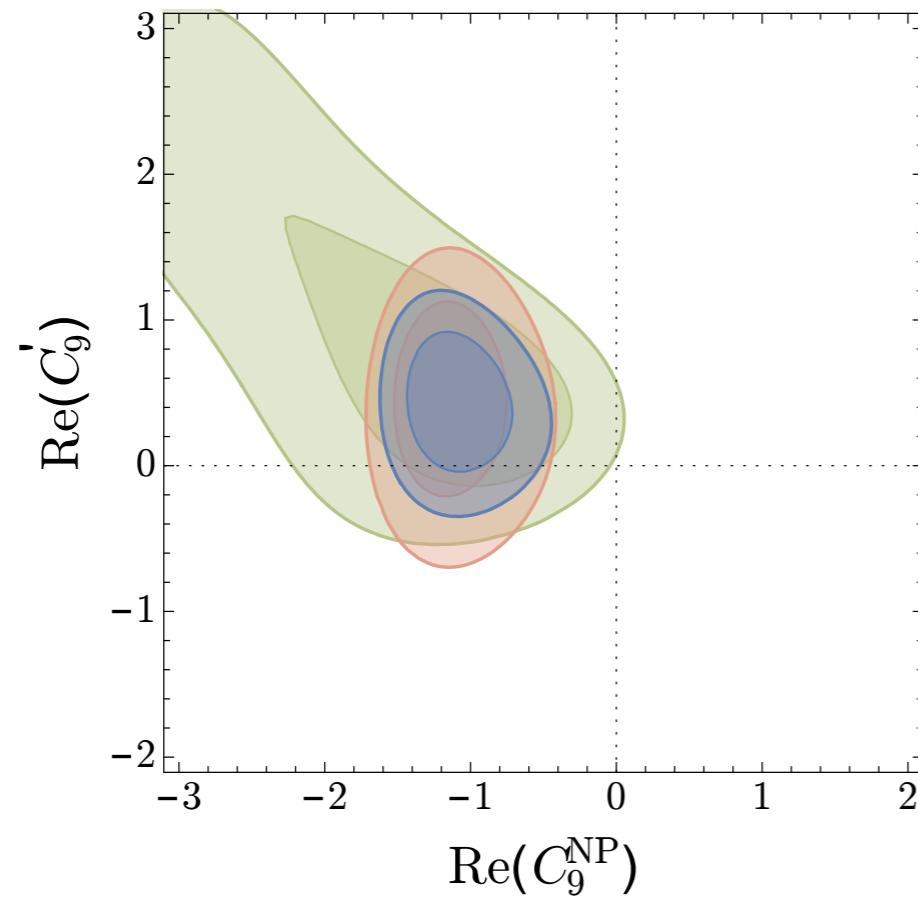
- Equivalent process for the  $B_s$  system is  $B_s \rightarrow \phi \mu^+ \mu^-$ .
  - Not a CP specific final state so cannot determine  $P_5$ .
- New results shown by LHCb at FPCP.



In a wide bin from  $1 < q^2 < 6 \text{ GeV}^2/\text{c}^4$ , there is a local  $3.3\sigma$  discrepancy between the data and the SM prediction

# Global fits

- First global fits to the new data were shown at Moriond EW by J. Matias and D. Straub, e.g. [\[arXiv:1503.06199\]](#)



branching fractions, angular observables and combination

- Consistent picture, data favours  $C_9^{\text{NP}} \neq 0$  (at  $3-4\sigma$ ).
  - Doesn't include latest result from CMS on  $B^0 \rightarrow K^{*0}\mu^+\mu^-$  and LHCb on  $B_s \rightarrow \phi\mu^+\mu^-$ .

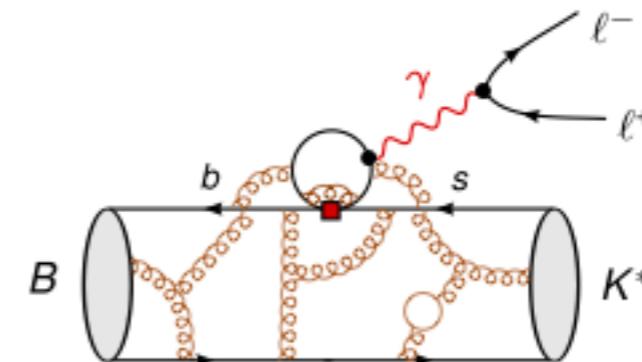
# Interpretation of global fits

Optimist's view point



Vector-like contribution could come from new tree level contribution from a  $Z'$  with a mass of a few TeV (the  $Z'$  will also contribute to mixing, a challenge for model builders)

Pessimist's view point



Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon.

More work needed from experiment/theory to disentangle the two

# Lepton universality

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- In the SM, ratios

$$R_K = \frac{\int d\Gamma[B^+ \rightarrow K^+ \mu^+ \mu^-]/dq^2 \cdot dq^2}{\int d\Gamma[B^+ \rightarrow K^+ e^+ e^-]/dq^2 \cdot dq^2}$$

and

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu_\ell)}$$

only differ from unity by phase space — the dominant SM processes couple equally to the different lepton flavours (with the exception of the Higgs).

- The ratios are theoretically clean since hadronic uncertainties cancel in the ratio. Experimentally more challenging due to differences in muon/electron/tau reconstruction.

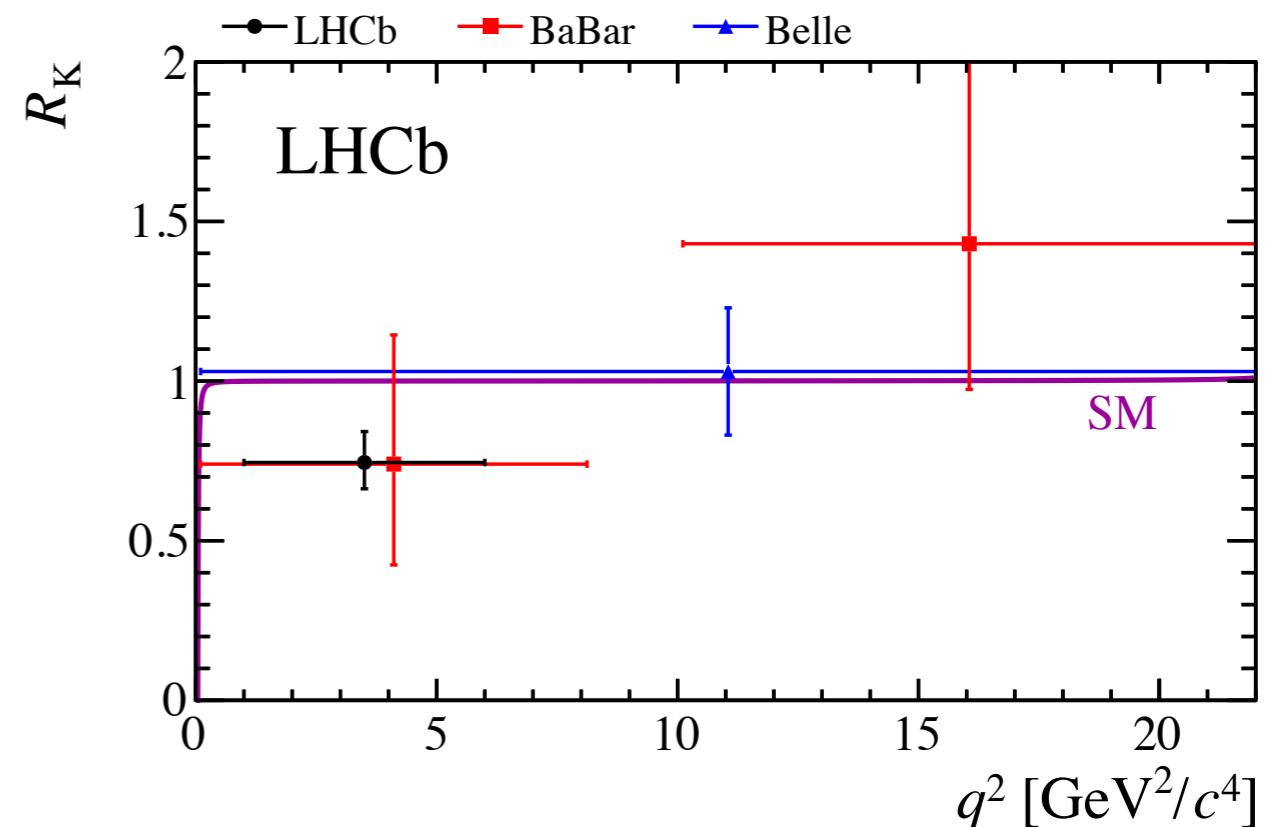
# $R_K$ result

- In the run 1 dataset, LHCb determines:

$$R_K = 0.745^{+0.090}_{-0.074} {}^{+0.036}_{-0.036}$$

in the range  $1 < q^2 < 6 \text{ GeV}^2$ , which is consistent with the SM at  $2.6\sigma$ .

- Take double ratio with  $B^+ \rightarrow J/\psi K^+$  to cancel possible sources of systematic uncertainty.
- Correct for migration of events in/out of the window due to Bremsstrahlung using MC (with PHOTOS).



**LHCb [PRL113 (2014) 151601 ]**

**BaBar [PRD 86 (2012) 032012]**

**Belle [PRL 103 (2009) 171801]**

$R_K < 1$  implies a deficit of muons w.r.t. electrons.

# $R(D)$ and $R(D^*)$

- BaBar observed a  $3.4\sigma$  excess over SM expectations in  
[Phys. Rev. D 88, 072012 (2013)]

$$R(D) = 0.440 \pm 0.058 \pm 0.042$$

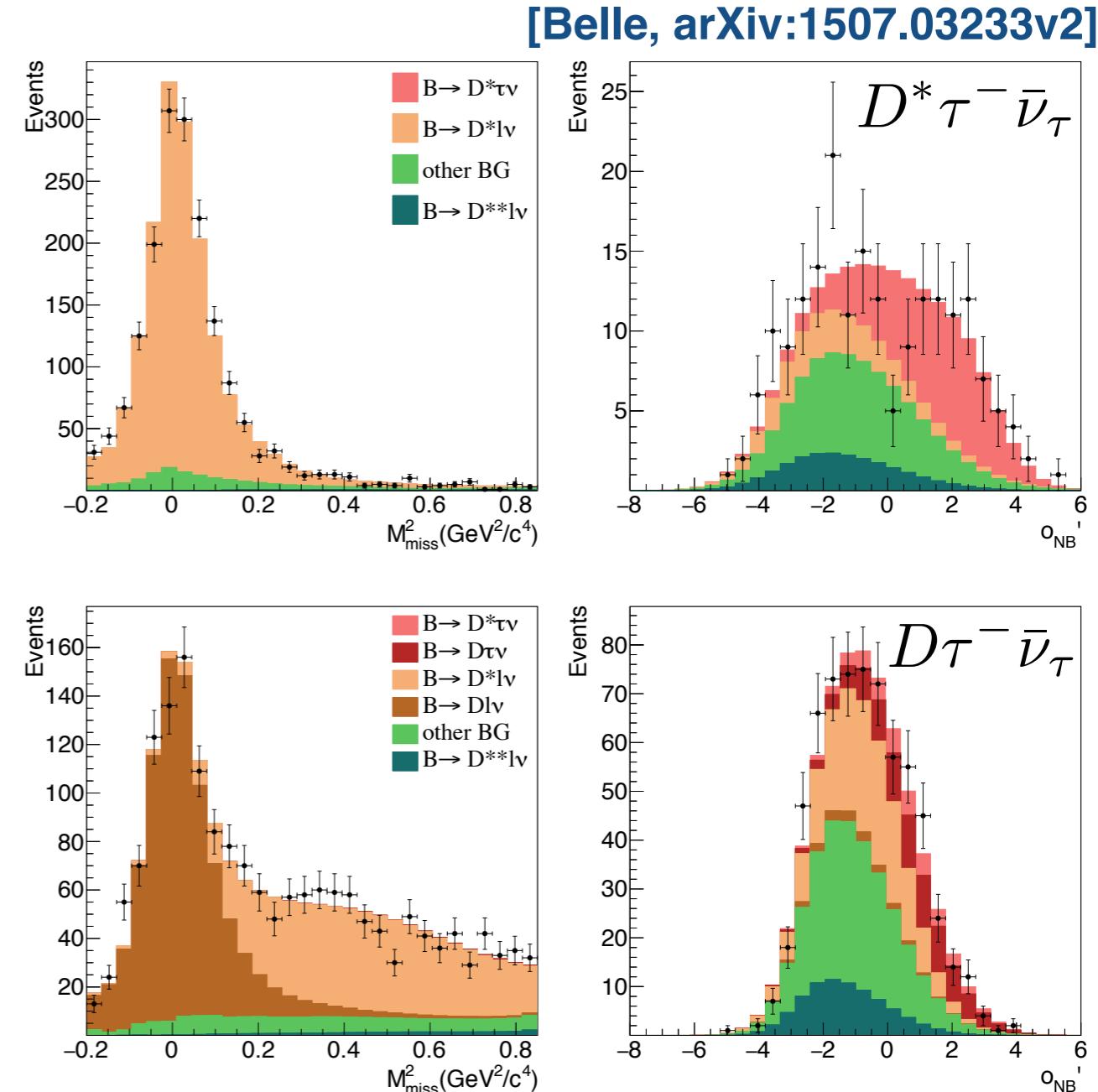
$$R(D^*) = 0.332 \pm 0.024 \pm 0.018$$

- New result from Belle shown at EPS 2015 [Belle, arXiv:1507.03233v2]

$$R(D) = 0.375 \pm 0.064 \pm 0.026$$

$$R(D^*) = 0.293 \pm 0.038 \pm 0.015$$

- At B-factories, can profit from the beam energy constraint.



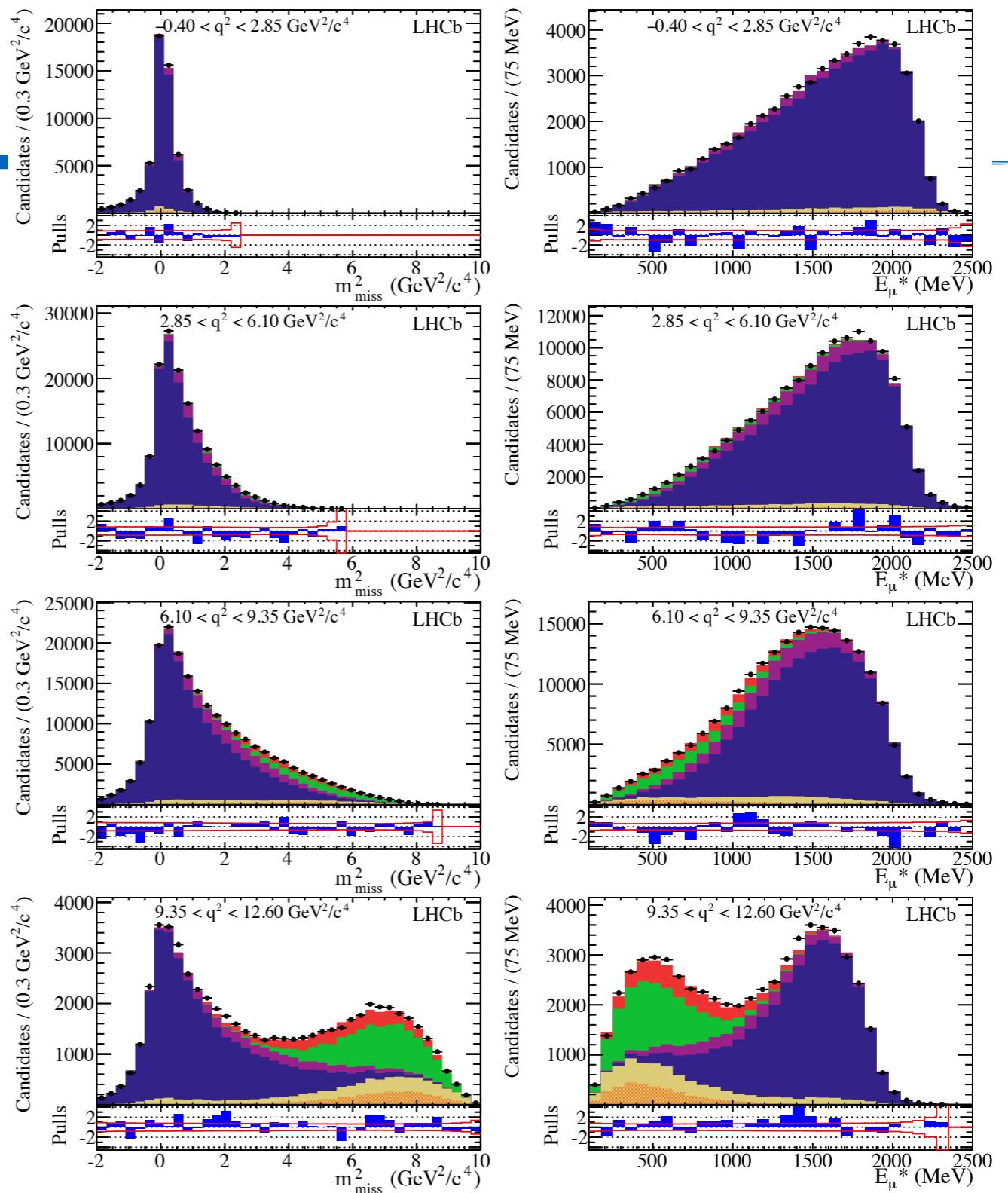
Belle fit the missing mass squared and the output of a NN trained to reject backgrounds with missing particles.

# $R(D^*)$

- Challenging at the LHC, no kinematic constraint and large backgrounds.
- Use decays to the same final state,

$$R(D^*) = \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- (\mu^- \bar{\nu}_\mu \nu_\tau) \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)}$$

- Separated using, missing mass,  $E_\mu$  and  $q^2 = (p_\mu + p_\nu)^2$ .
- Use MVA to reject backgrounds with missing charged particles.



$B \rightarrow D^* \tau \bar{\nu}$ ,  $B \rightarrow D^* H_c (\rightarrow \mu \bar{\nu} X)$ ,  $X$ ,  $B \rightarrow D^{**} \mu \bar{\nu}$ ,  
 $B \rightarrow D^* \mu \bar{\nu}$ , **combinatorial**, misidentified  $\mu^\pm$ ,

# $R(D)$ and $R(D^*)$

BaBar

$$R(D) = 0.440 \pm 0.058 \pm 0.042$$

$$R(D^*) = 0.332 \pm 0.024 \pm 0.018$$

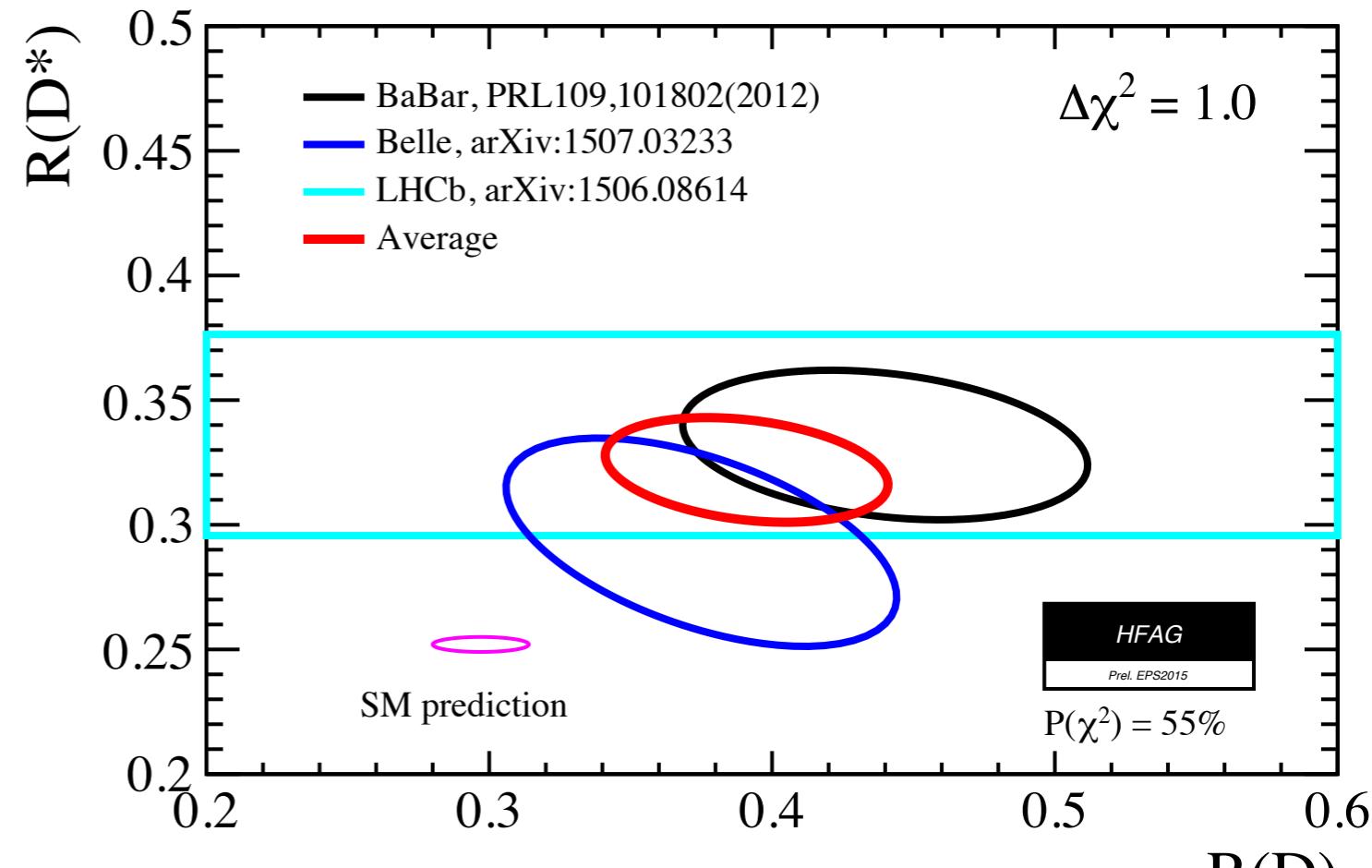
Belle

$$R(D) = 0.375 \pm 0.064 \pm 0.026$$

$$R(D^*) = 0.293 \pm 0.038 \pm 0.015$$

LHCb

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$



- Combination is  **$3.9\sigma$**  from the SM expectation:

$$R(D) = 0.297 \pm 0.017 \quad , \quad R(D^*) = 0.252 \pm 0.003$$

[Kamenik et al. Phys. Rev. D78 014003 (2008), S. Jajfer et al. Phys. Rev. D85 094025 (2012)]

# Summary

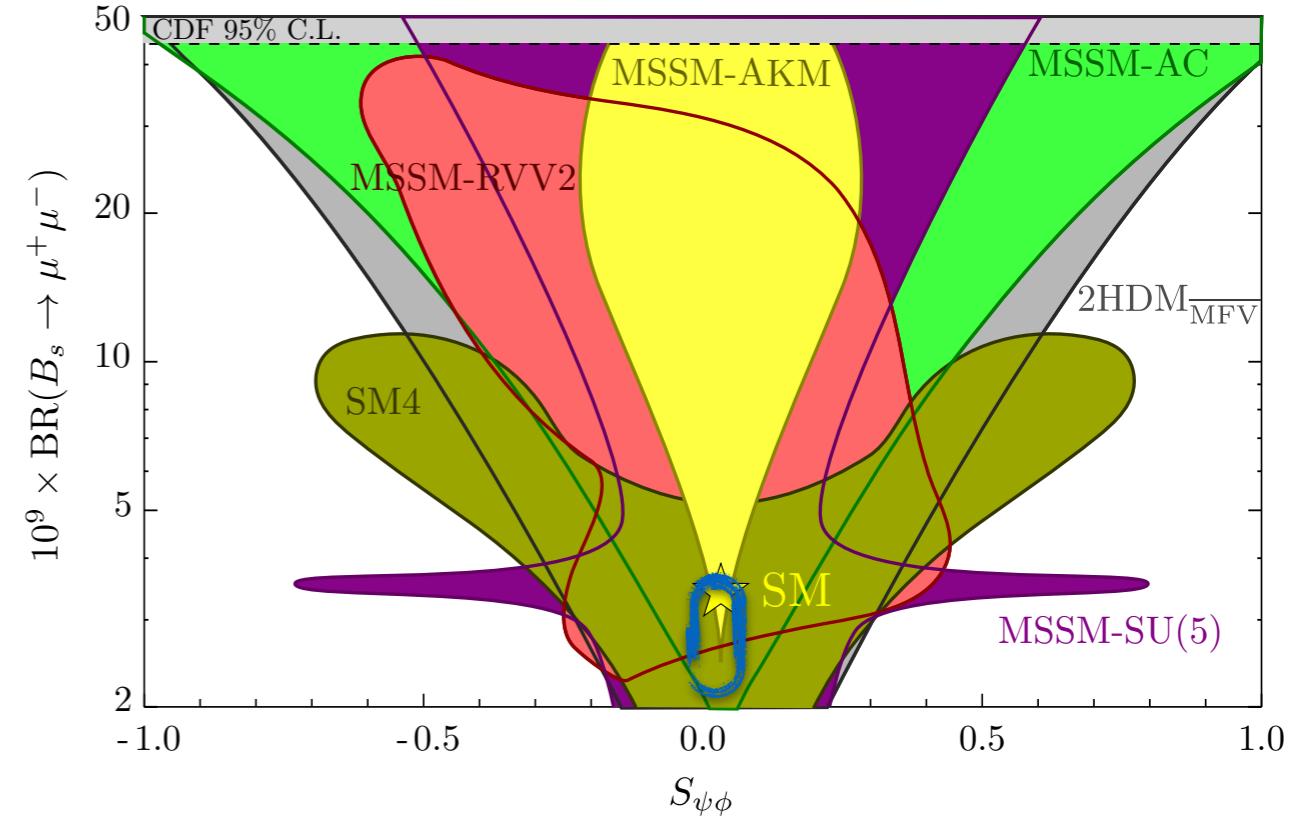
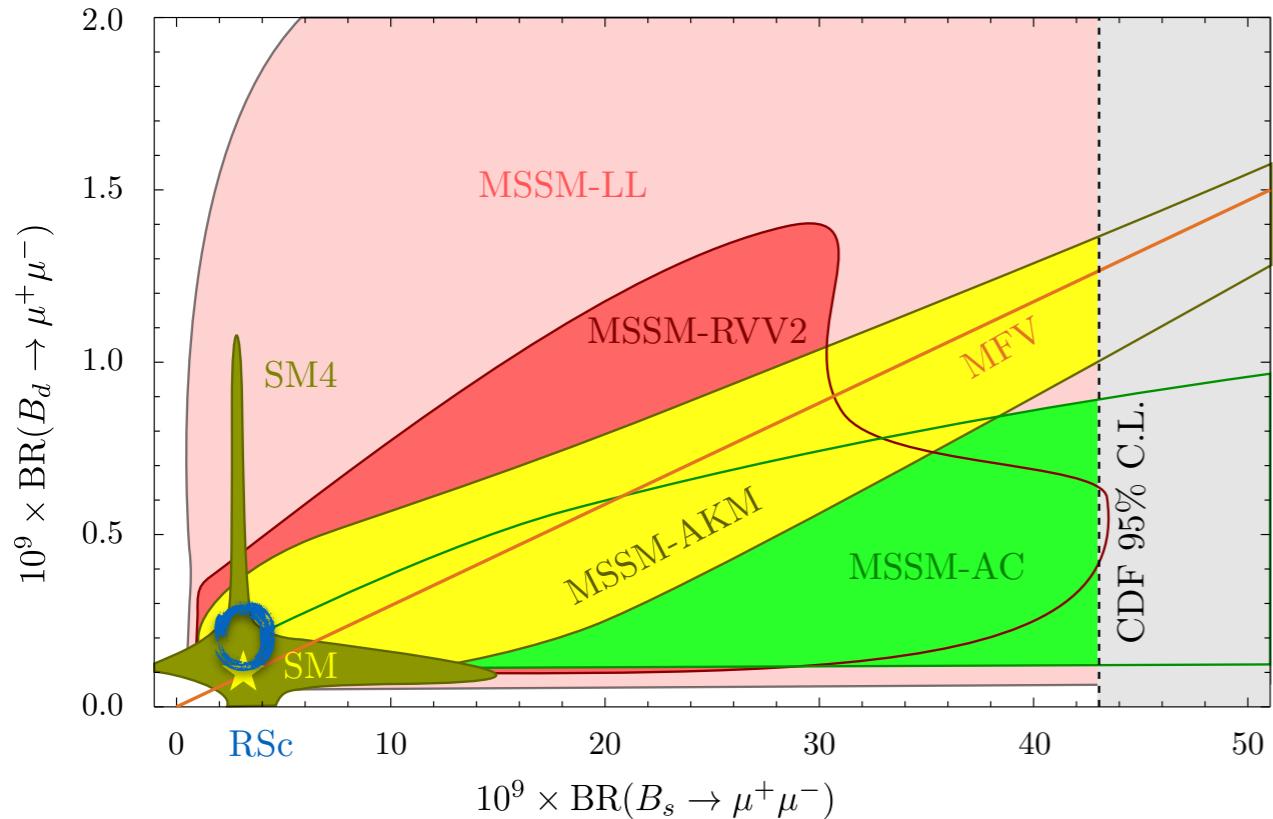
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- Flavour observables place strong constraints on many BSM models.
- Several interesting tensions seen in data from the B-factories and LHC;  $V_{ub}$ ,  $R(D)$  and  $R(D^*)$  and in  $b \rightarrow s\ell^+\ell^-$  processes.
- Exciting times ahead:
  - ➔ Run 2 of the LHC has started,
  - ➔ Data taking at KOTO ( $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$ ) and NA62 ( $K^+ \rightarrow \pi^+\nu\bar{\nu}$ ) is underway.
  - ➔ Expect first data taking at Belle 2 in 2018.

# Backup

# Flavour constraints

[Straub, arXiv:1107.0266]



**constraints prior to LHC, constraints at the end of Run 1**

- FCNC processes can be highly sensitive to the presence of new TeV-scale particles.  
e.g.  $B_s \rightarrow \mu^+ \mu^-$  branching fraction or CP violation in  $B_s$  mixing.