Anomalies in flavour physics

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Flavour anomalies

- A number of different flavour anomalies have appeared in recent years:

[~4σ] Enhanced $B\to D^{(*)}\tau\nu$ decay rate (c.f. $B\to D^{(*)}\mu\nu$).

[~3.5σ] Muon g-2.

[~3σ] Like-sign dimuon asymmetry from D0.

[~3σ] Branching fraction of $B_s\to\phi\mu^+\mu^-$.

[~3σ] Inclusive and exclusive determinations of V_{ub}.

[~3σ] Angular distribution of $B^0\to K^*\mu^+\mu^-$ decays.

[~2.5σ] Larger experimental value of ϵ'/ϵ

[~2.5σ] Lepton universality in $B^+\to K^+\ell^+\ell^-$.

[~2σ] Determination of V_{td}/V_{ts} from mixing c.f. CKM unitarity

Flavour anomalies

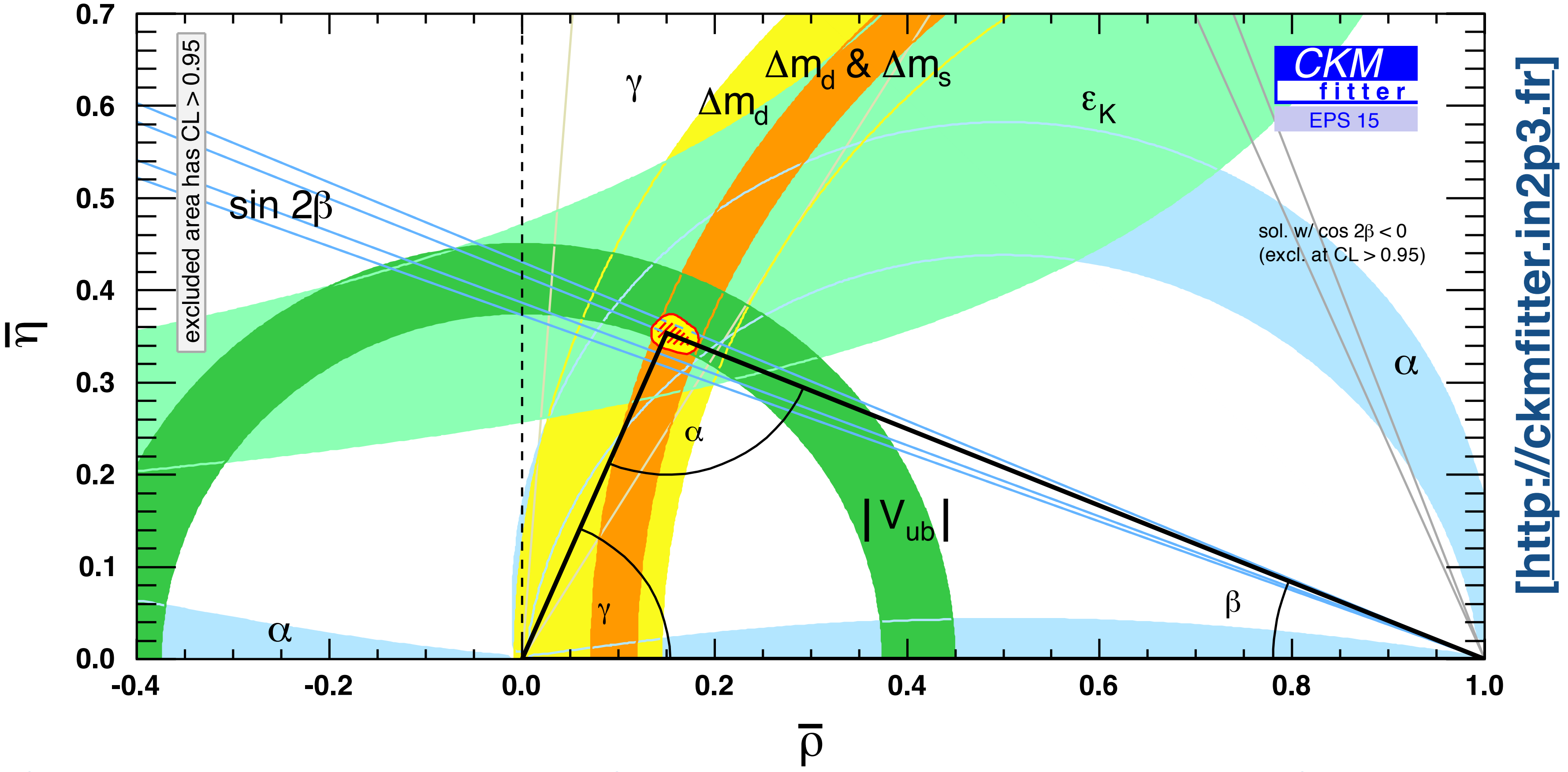
- Aim to discuss some of these tensions with a focus on:

[~4σ]	Enhanced $B \to D^{(*)} \tau \nu$ decay rate (c.f. $B \to D^{(*)} \mu \nu$).
[~3.5σ]	Muon g-2.
[~3σ]	Like-sign dimuon asymmetry from D0.
[~3σ]	Branching fraction of $B_s \to \phi \mu^+ \mu^-$.
[~3σ]	Inclusive and exclusive determinations of V_{ub}.
[~3σ]	Angular distribution of $B^0 \to K^* \mu^+ \mu^-$ decays.
[~2.5σ]	Larger experimental value of ϵ'/ϵ.
[~2.5σ]	Lepton universality in $B^+ \to K^+ \ell^+ \ell^-$.
[~2σ]	Determination of V_{td}/V_{ts} from mixing c.f. CKM unitarity.

- For each anomaly we can ask: Are the SM predictions correct? Could we be seeing evidence of BSM particles?

Quark flavour in the SM

- Flavour violation is associated to the charged current interaction.
- Parameterised by the CKM matrix with a single complex phase (the only source of *CP* violation in SM).
- Unitarity conditions imply e.g. $V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$



Data are consistent with a triangle in the complex plane.
⇒ Precision test of the flavour structure of the SM!

BSM constraints?

- Flavour observables place strong bounds on scale of NP.

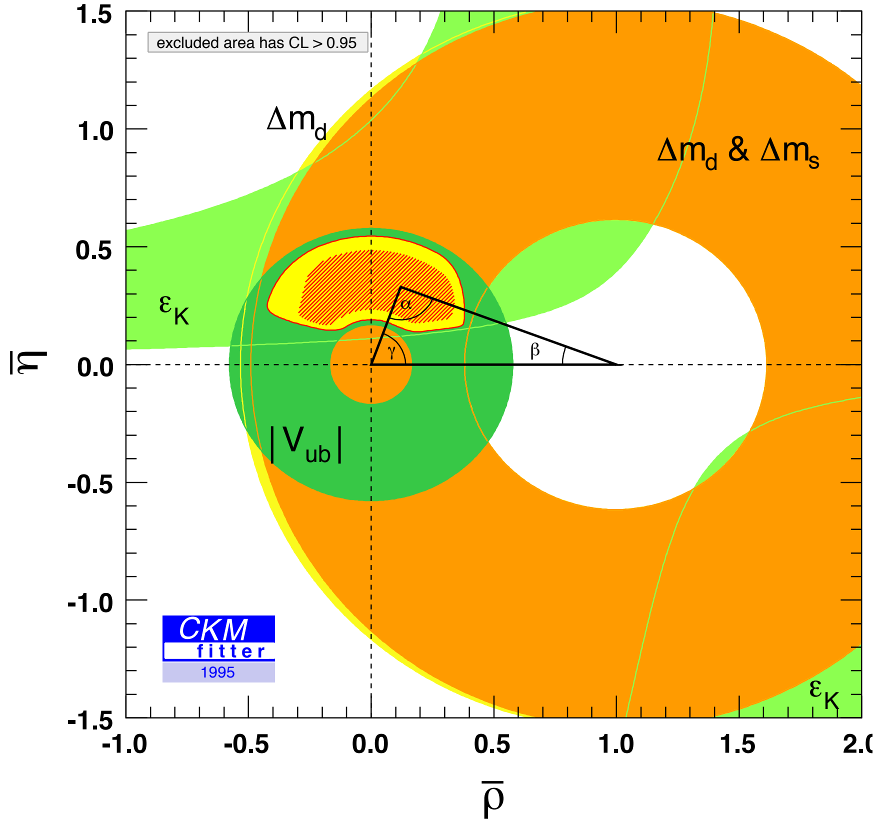
e.g. Bounds on EFT with dimension-six operators and effective coupling $c_{\rm NP}/\Lambda_{\rm NP}^2$.

Operator	Λ in TeV $(c_{\rm NP} = 1)$		Bounds on $c_{\rm NP}$ $(\Lambda = 1$ TeV$)$		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p \rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\ S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

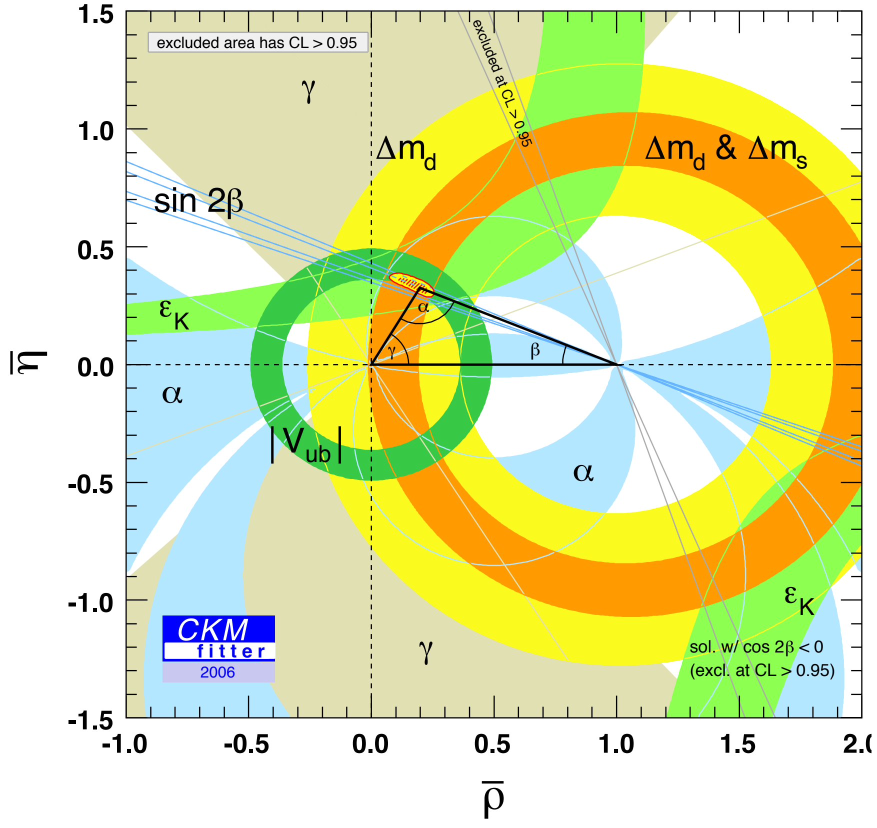
from G. Isidori, Y. Nir and G. Perez, Ann. Rev. Nucl. Part. Sci. 60:355 (2010) [updated in 2015]

“The” Unitarity triangle

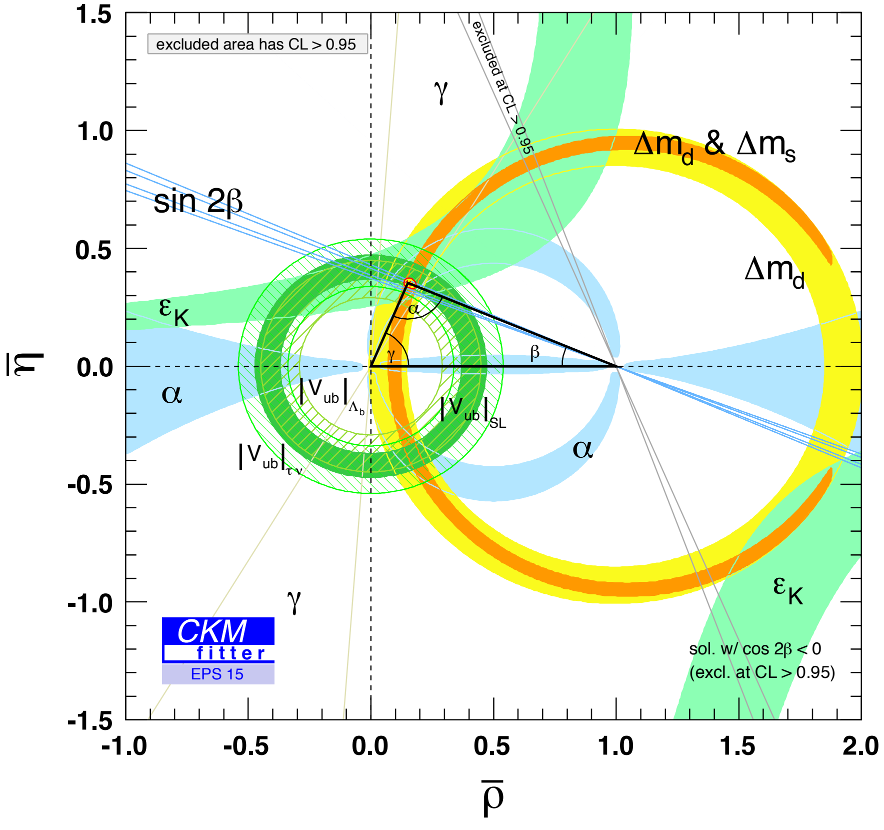
1995



2006



2015



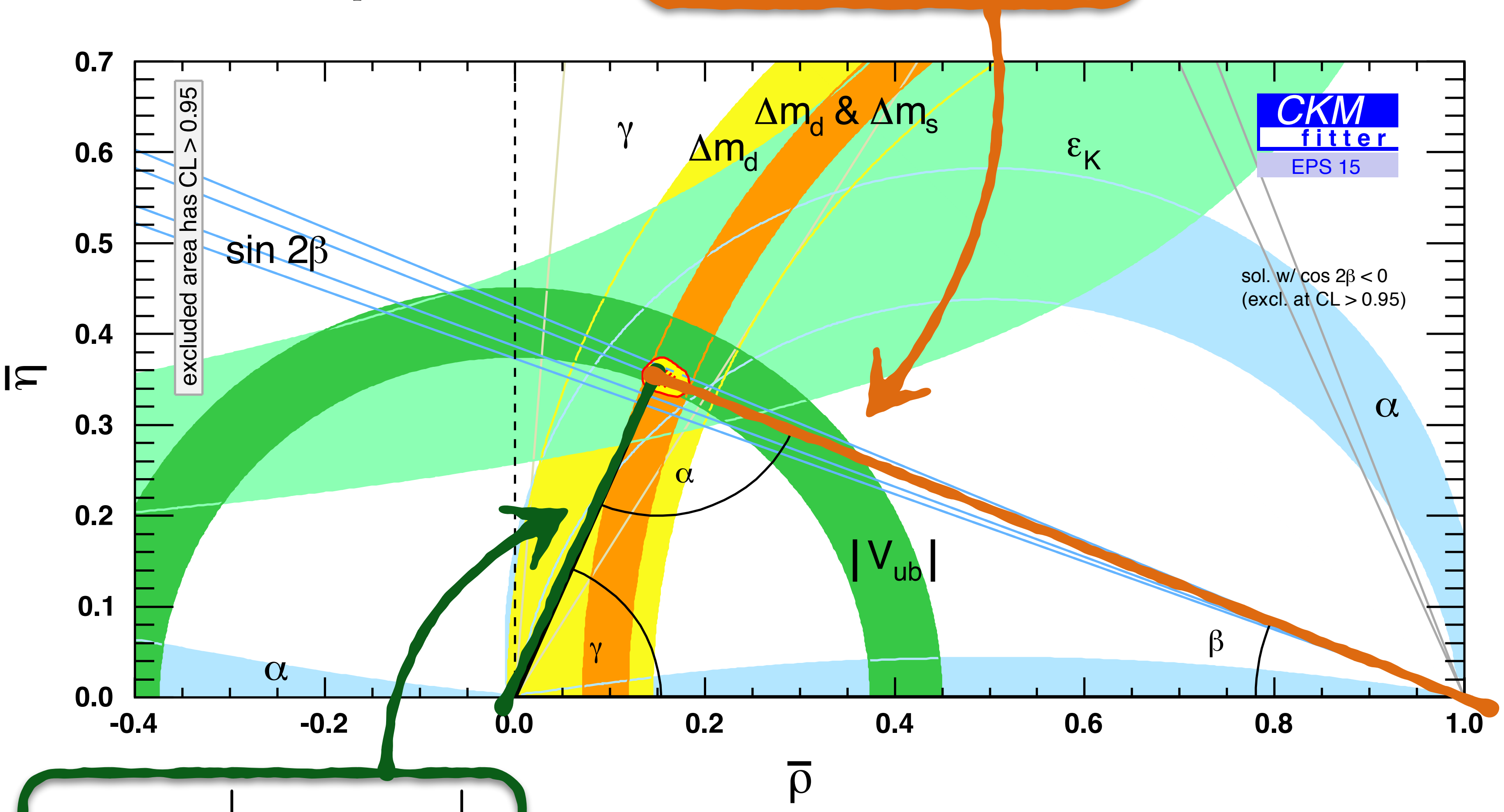
- Huge progress in flavour physics in the past 20 years from both experiment and theory:

  ➡ Most recent constraints exploit the final datasets from the *B*-factory & TeVatron experiments, the data from run 1 of the LHC and theoretical progress from Lattice QCD, effective theories, QCD sum rules etc.

Sides of the triangle

Determined using $B-\overline{B}$ oscillation frequencies Δm_d and Δm_s with input from lattice (f_{B_q} and $\hat{B}_{B_q}$).

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



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

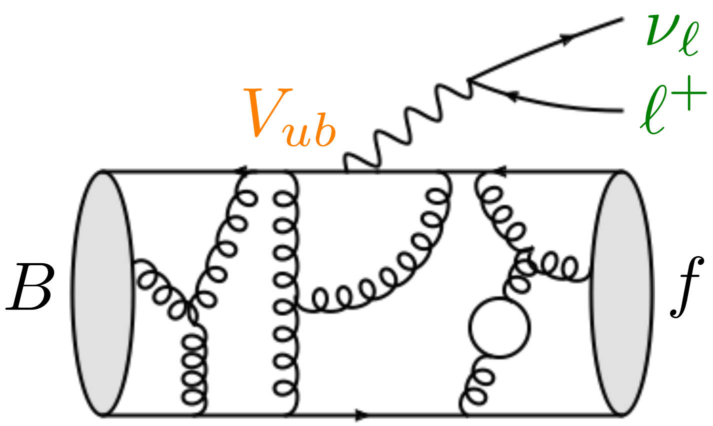
Determined from *b*→*u* semileptonic *b*-hadron decays

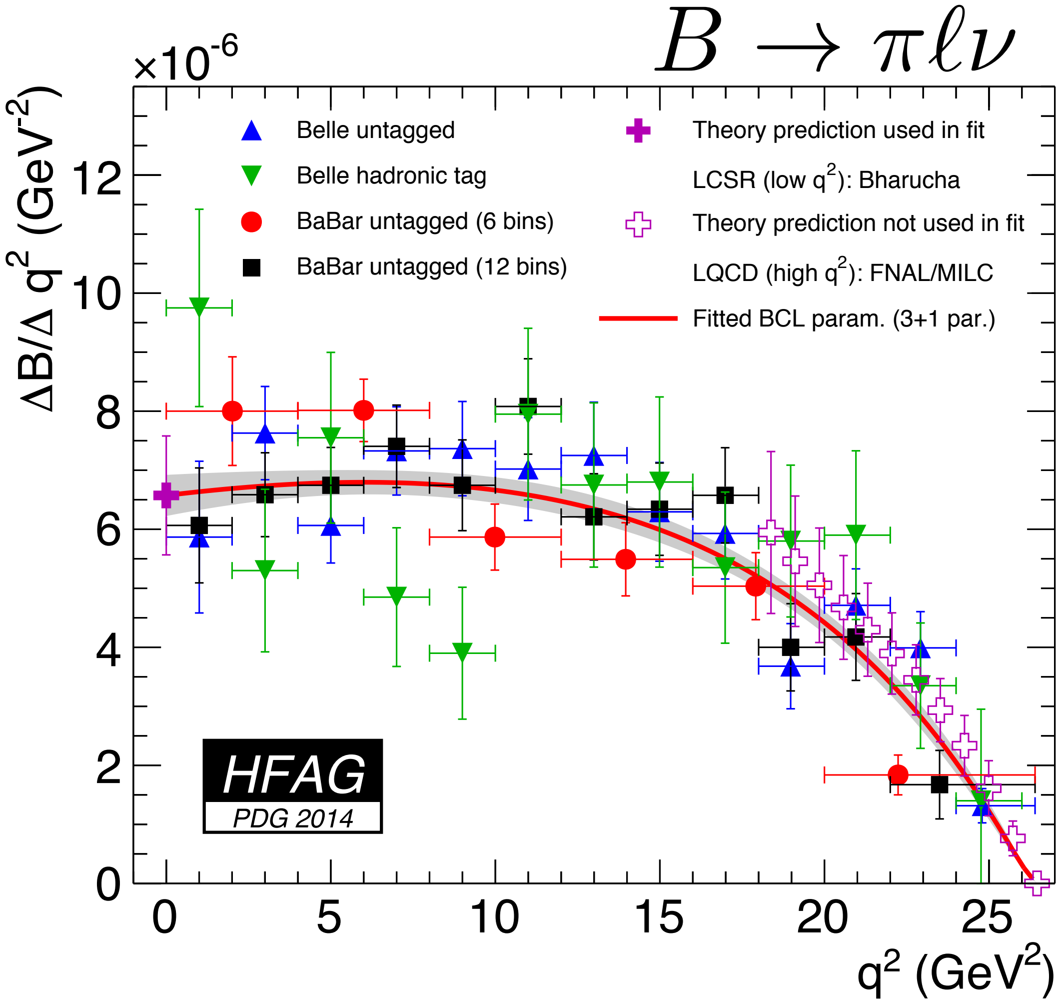
Exclusive V_{ub}

- Can determine V_{ub} by fitting the differential decay rate of exclusive semileptonic processes from BaBar and Belle, e.g. for $B \to \pi\ell\nu$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} = |V_{ub}|^2 \frac{G_F^2}{192\pi^3 m_B^3} \lambda(m_B, m_\pi, q^2)^{3/2} |f_+(q^2)|^2$$

- Hadronic form-factors needed as an external input.
    - ➡ Taken from Lattice QCD/LCSR calculations.





[http://www.slac.stanford.edu/xorg/hfag]

$$\langle \pi(p)|\bar{u}\gamma_\mu b|B(k)\rangle = (k+p)_\mu f_+(q^2) + (k-p)_\mu f_-(q^2)$$

V_{ub} from Λ_b decays

- Can also determine $|V_{ub}/V_{cb}|$ using Λ_b baryon decays at LHCb by measuring

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

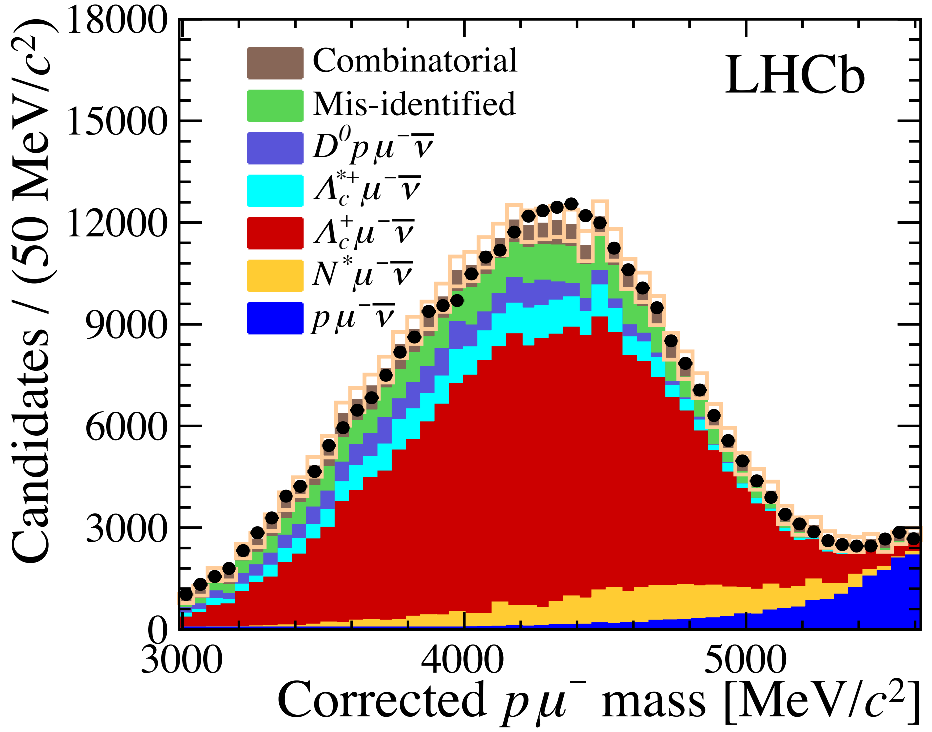
- Use secondary vertex to define corrected mass

$$\sqrt{m_{p\mu}^2 + p_\perp^2} + p_\perp$$

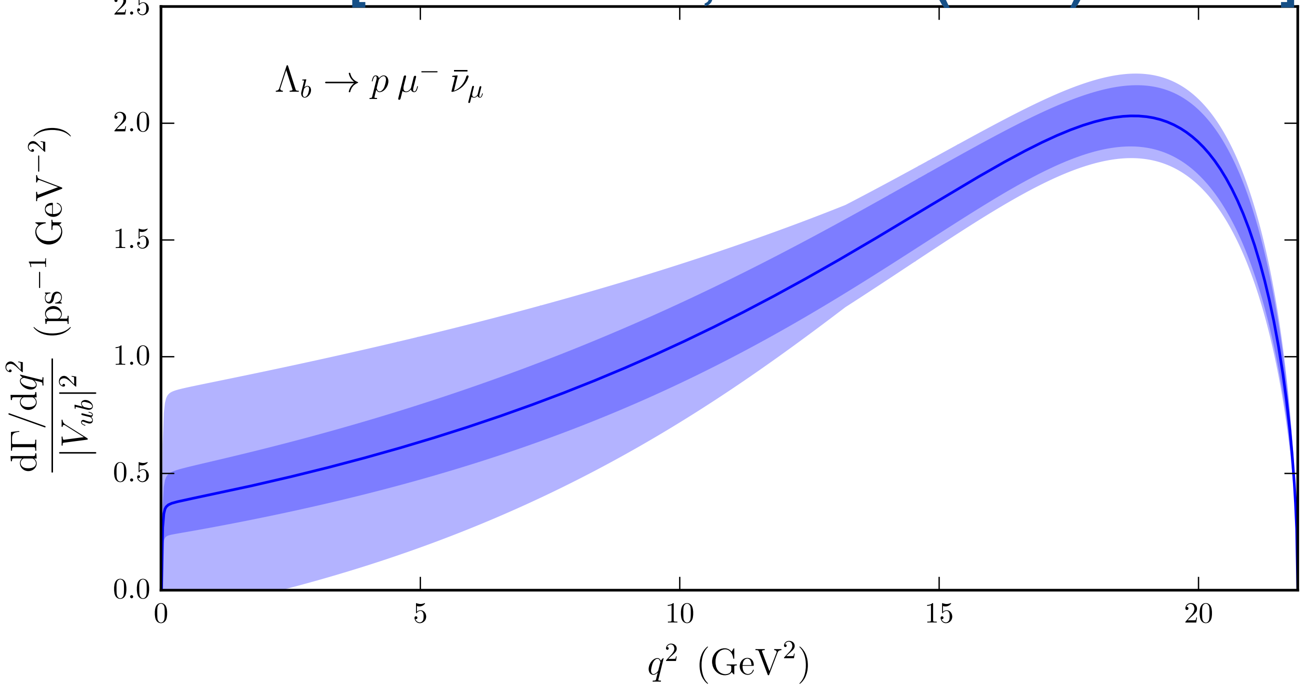
where $p_\perp$ is the missing transverse momentum.

- Use form-factors from Lattice QCD at high q^2 to determine $|V_{ub}/V_{cb}|$

[LHCb, Nature Physics (2015) 3415]



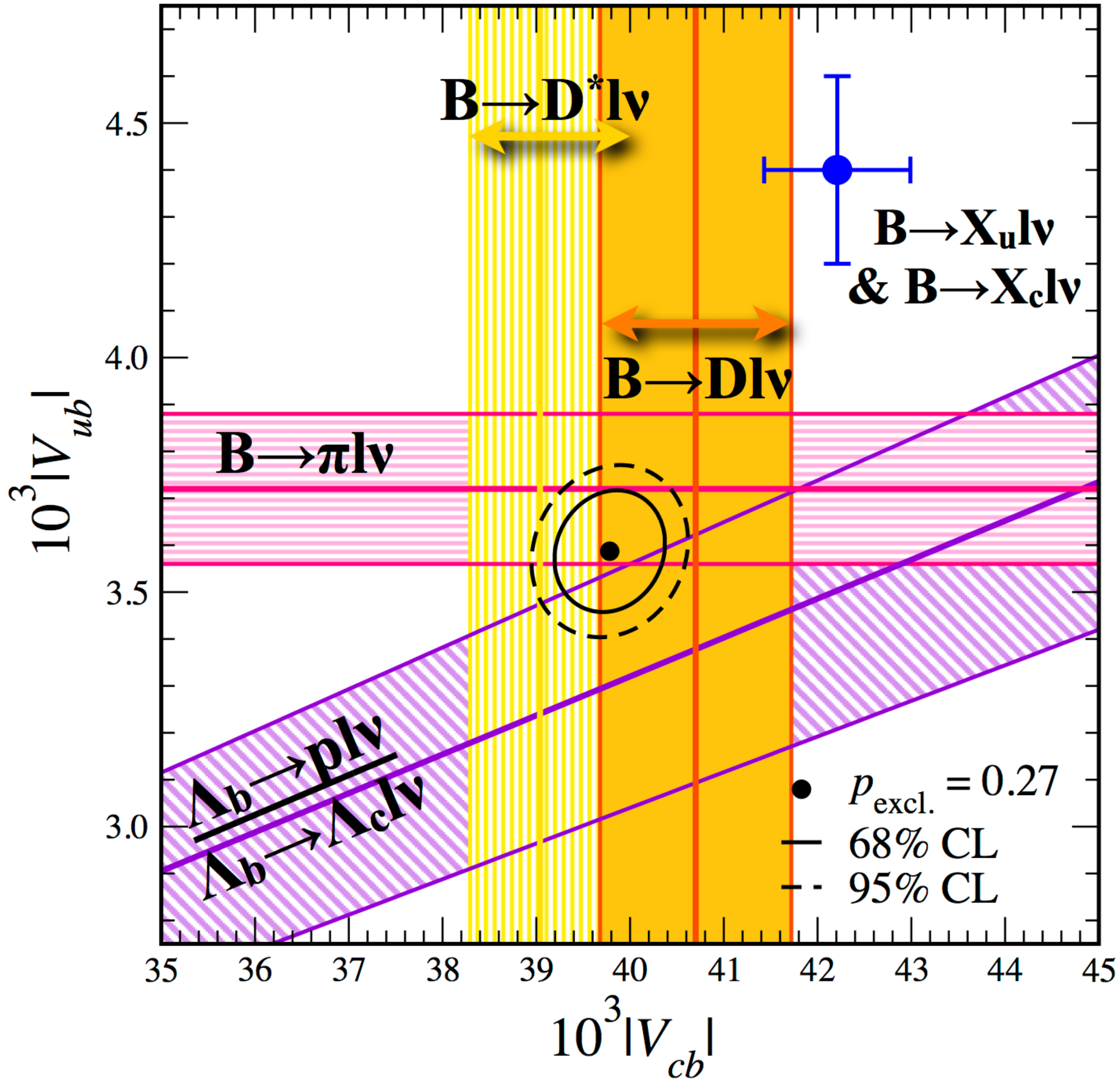
[Detmold et al, PRD 92 (2015) 034503]



Inclusive vs exclusive V_{ub}

- Can also determine V_{ub} using inclusive $B \to X_u \ell \nu$ decays and Heavy Quark Effective Theory.

➡ **See large tension between the inclusive and exclusive rates (>3σ).**



From talk by Ruth Van der Water at FPCP 16.

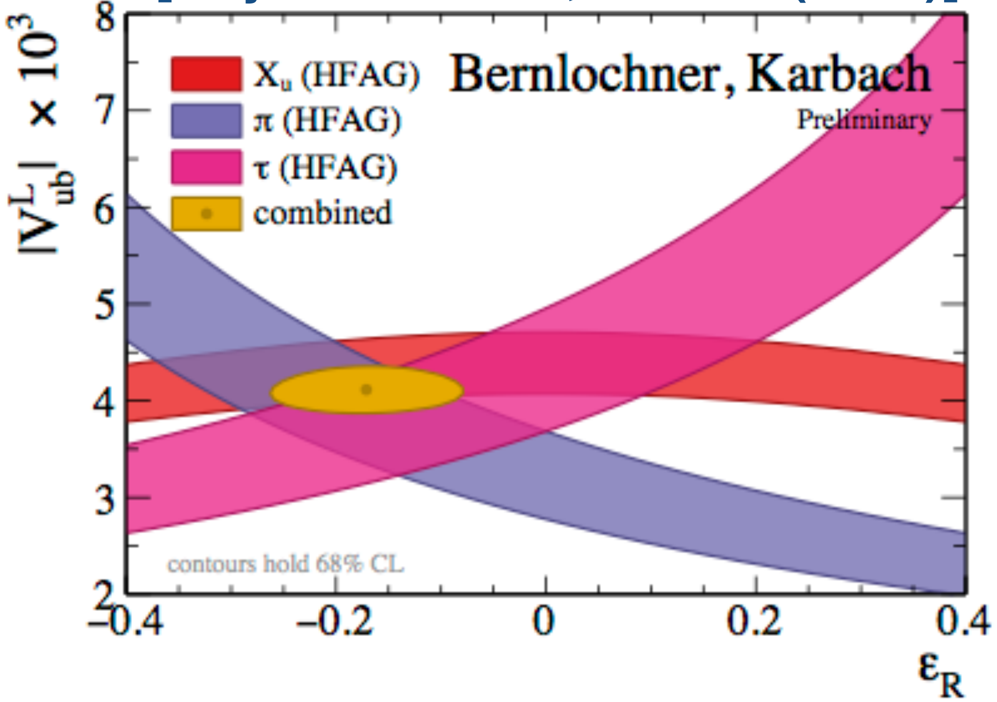
V_{ub} interpretation

- Can attempt to explain the V_{ub} tension by introducing a RH current with small parameter ε_R

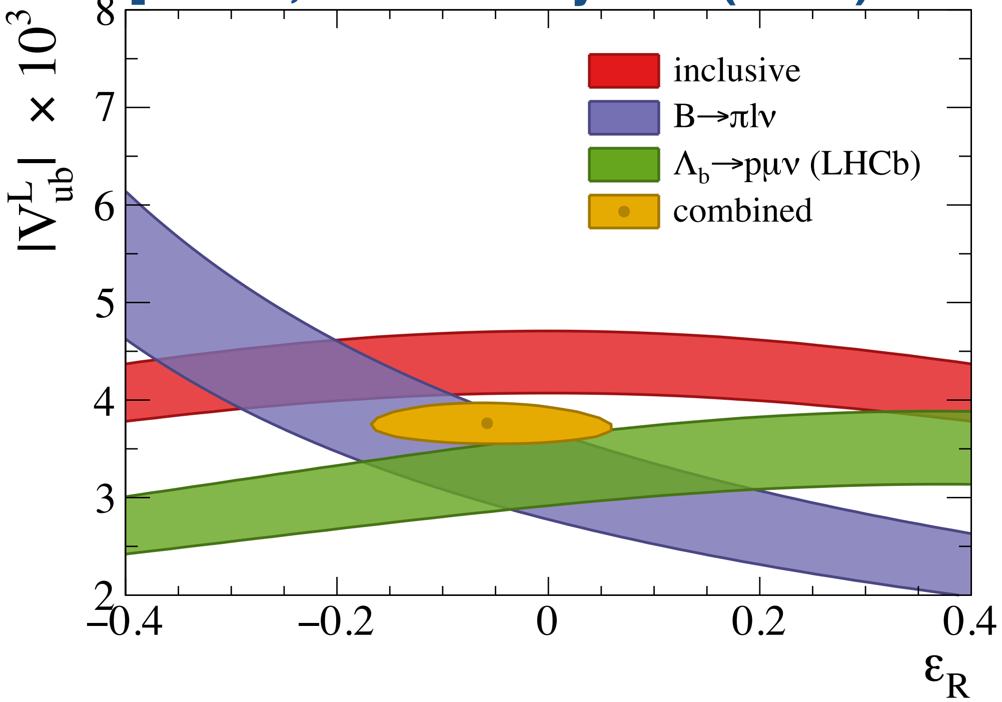
$$\mathcal{L}_{\rm eff} \propto V^{\rm L}_{ub}(\overline{u}\gamma_\mu P_{\rm L} b + \varepsilon_{\rm R}\overline{u}\gamma_\mu P_{\rm R} b)(\bar{\nu}\gamma^\mu P_{\rm L}\ell) + {\rm h.c}$$

- Unfortunately it's difficult to reconcile all the measurements of V_{ub} in this model.
- Could there an experimental issue or failure with the theoretical framework (Lattice, LCSR or HQET)?

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



[LHCb, Nature Physics (2015) 3415]



Semitauonic decays

- Ratio $R(D^{(*)}) = \dfrac{\Gamma[B \to D^{(*)}\tau\nu]}{\Gamma[B \to D^{(*)}\ell\nu]}$

  is theoretically clean in the SM:

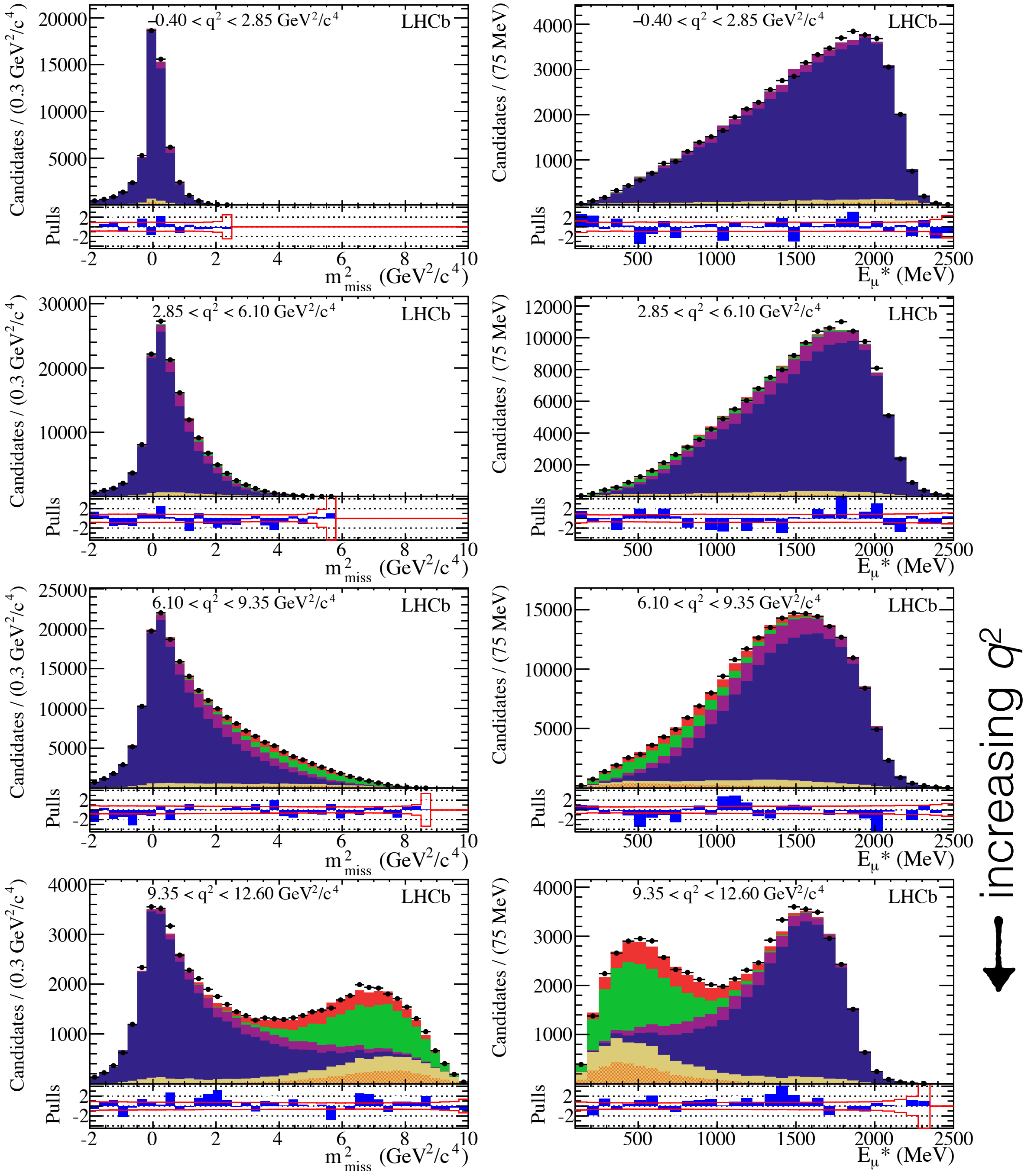
  - ➡ Coupling to leptons is universal in the SM due to accidental symmetries (the universality is only broken by the Higgs).
  - ➡ Except Hadronic uncertainties & $|V_{cb}|$ to cancel in the ratio.

  and can be enhanced in extensions of the SM (*e.g.* in models with charged Higgs).

Semitauonic decays

- Experimental challenge is to separate signal from backgrounds.
  - ➡ Use missing mass, lepton energy, q^2 and multivariate discriminants.
- *B*-factory experiments can also exploit leptonic/hadronic tag of the other *B* in the event.

[LHCb, PRL 115 (2015) 111803]

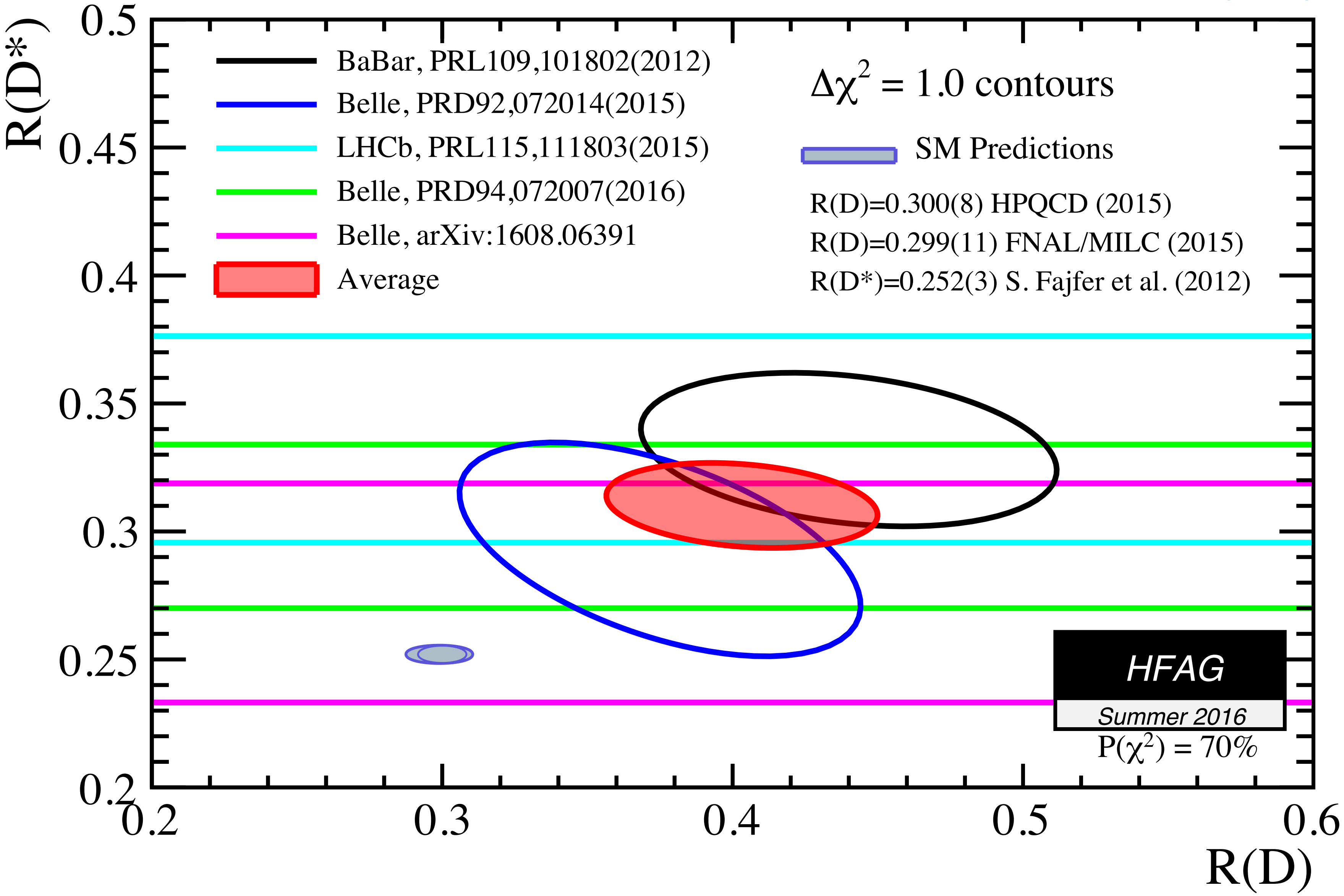


increasing q^2

$B \to D^* \tau \nu$, $B \to D^* H_c(\to \mu \nu X') X$, $B \to D^{**} \mu \nu$, $B \to D^* \mu \nu$, combinatorial, misidentified

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

[http://www.slac.stanford.edu/xorg/hfag]



- Combination is **3.9**σ from the SM expectation:

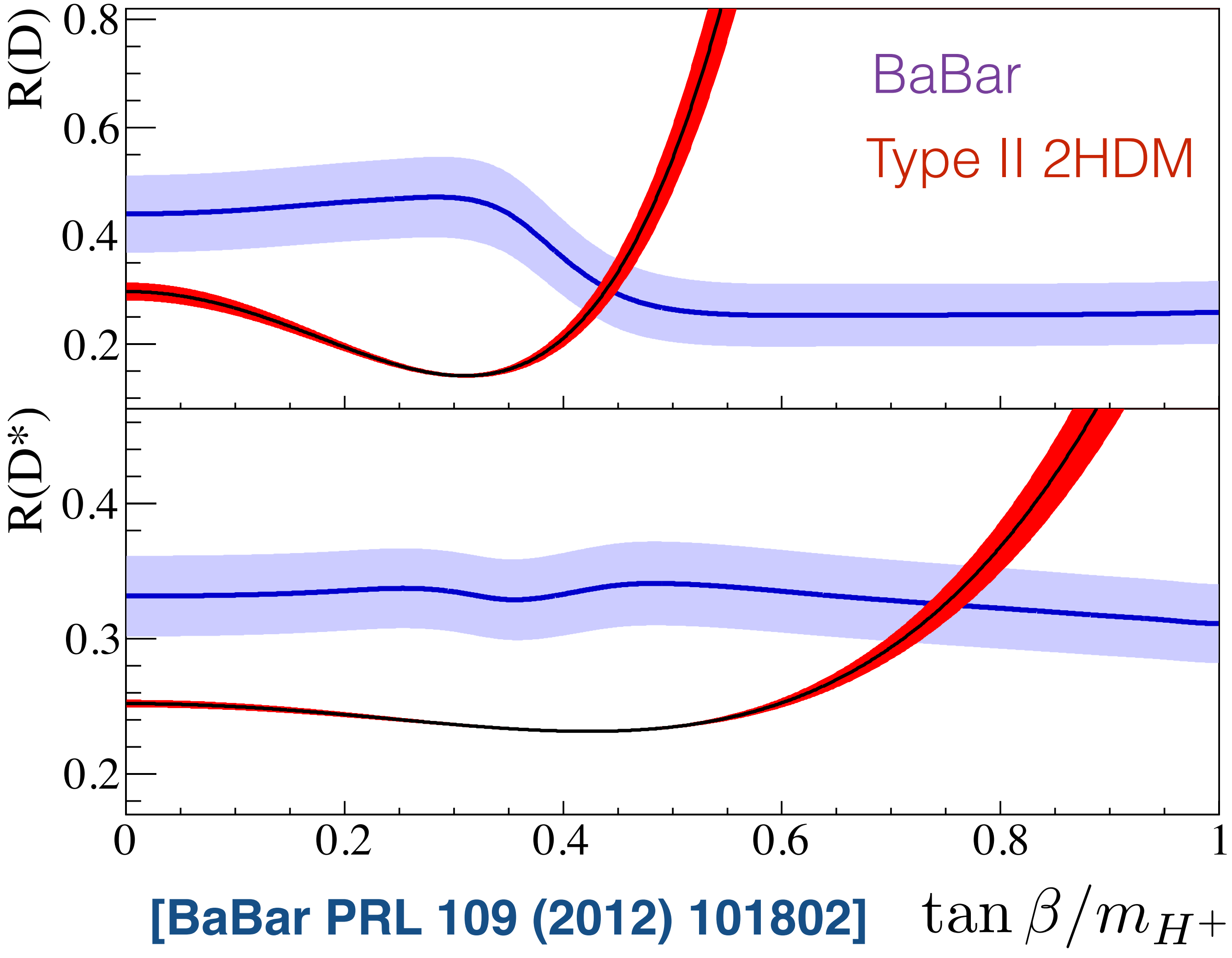
$$R(D) = 0.297 \pm 0.017 \quad , \quad R(D^*) = 0.252 \pm 0.003$$

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

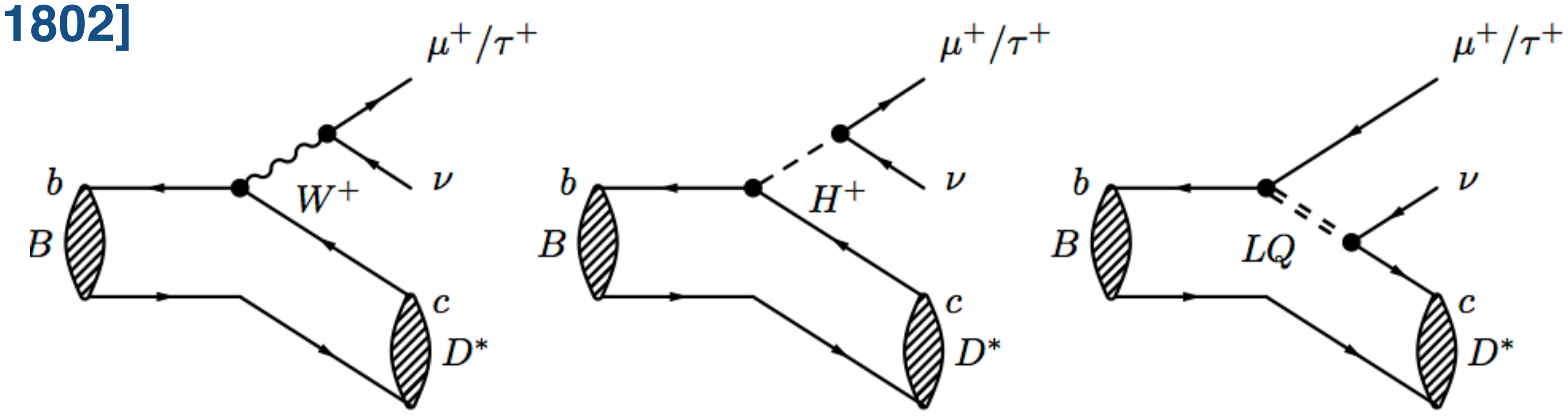
R(*D*) and *R*(*D**) interpretation

- Can expect enhancement of *R*(*D*) and *R*(*D**) in models with charged scalars (e.g. 2HDM). However generically expect larger enhancement of *R*(*D*) than *R*(*D**).
  See e.g.
  [Fajfer et al. PRL 109 (2012) 161801]

- Can also get enhancements in models with leptoquarks.
  See e.g.
  [Bauer et al. PRL 116 (2016) 141802]

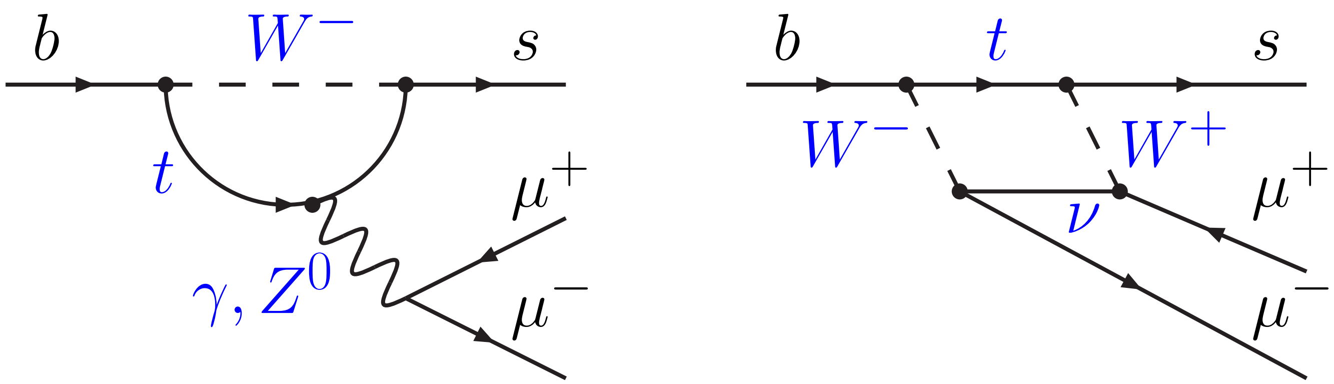


[BaBar PRL 109 (2012) 101802]



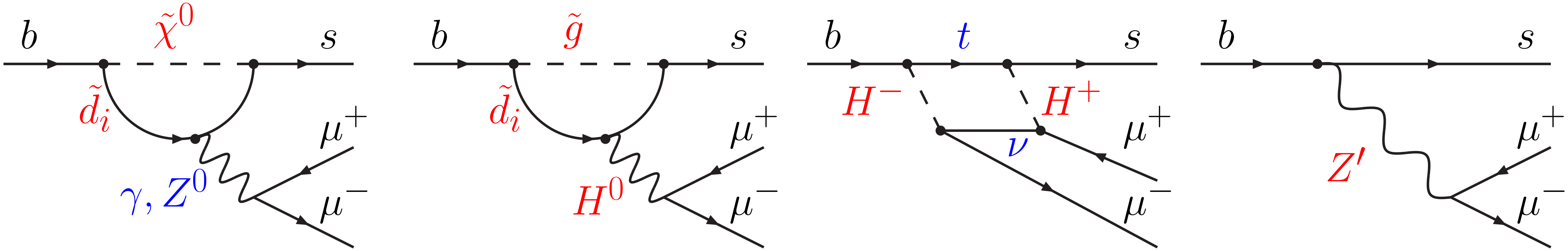
Rare FCNC decays

- Flavour changing neutral current transitions only occur at loop order (and beyond) in the SM.



SM diagrams involve the charged current interaction.

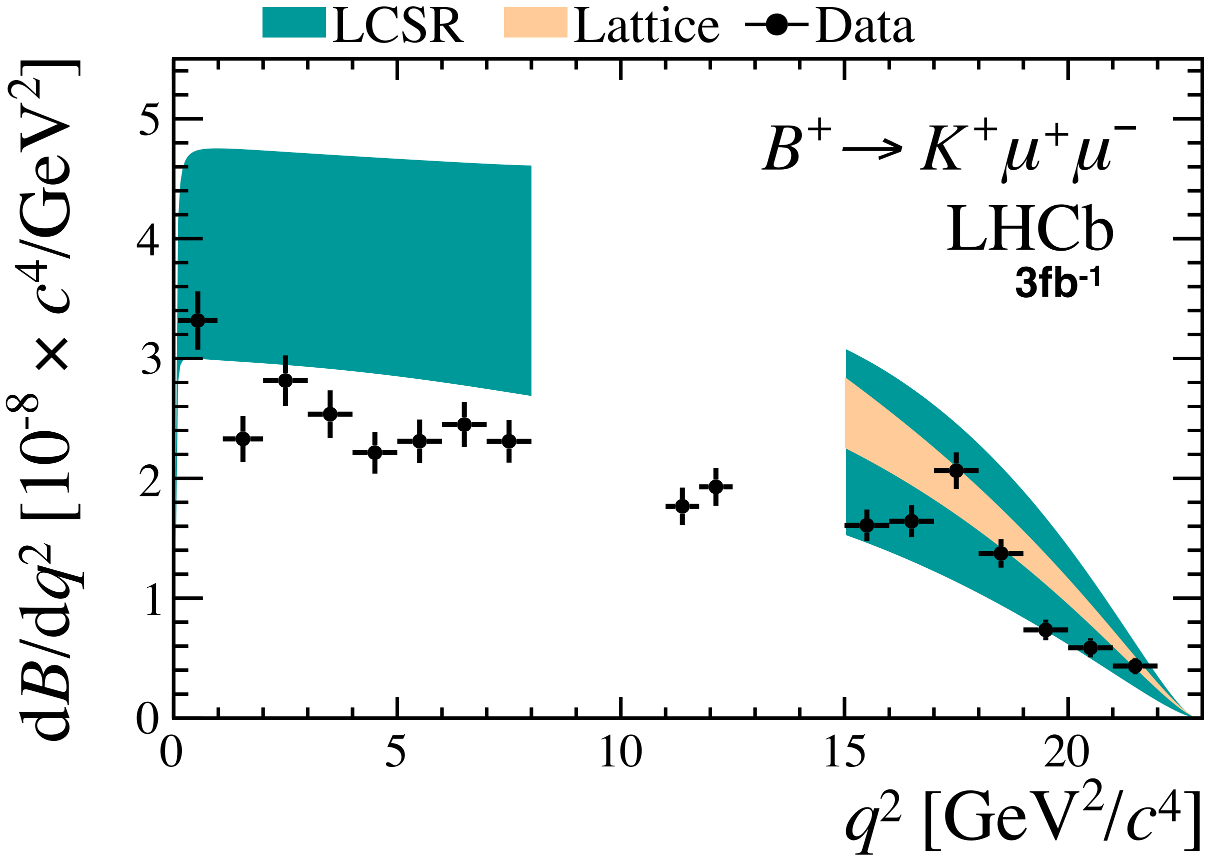
- New particles can contribute at loop or tree level:



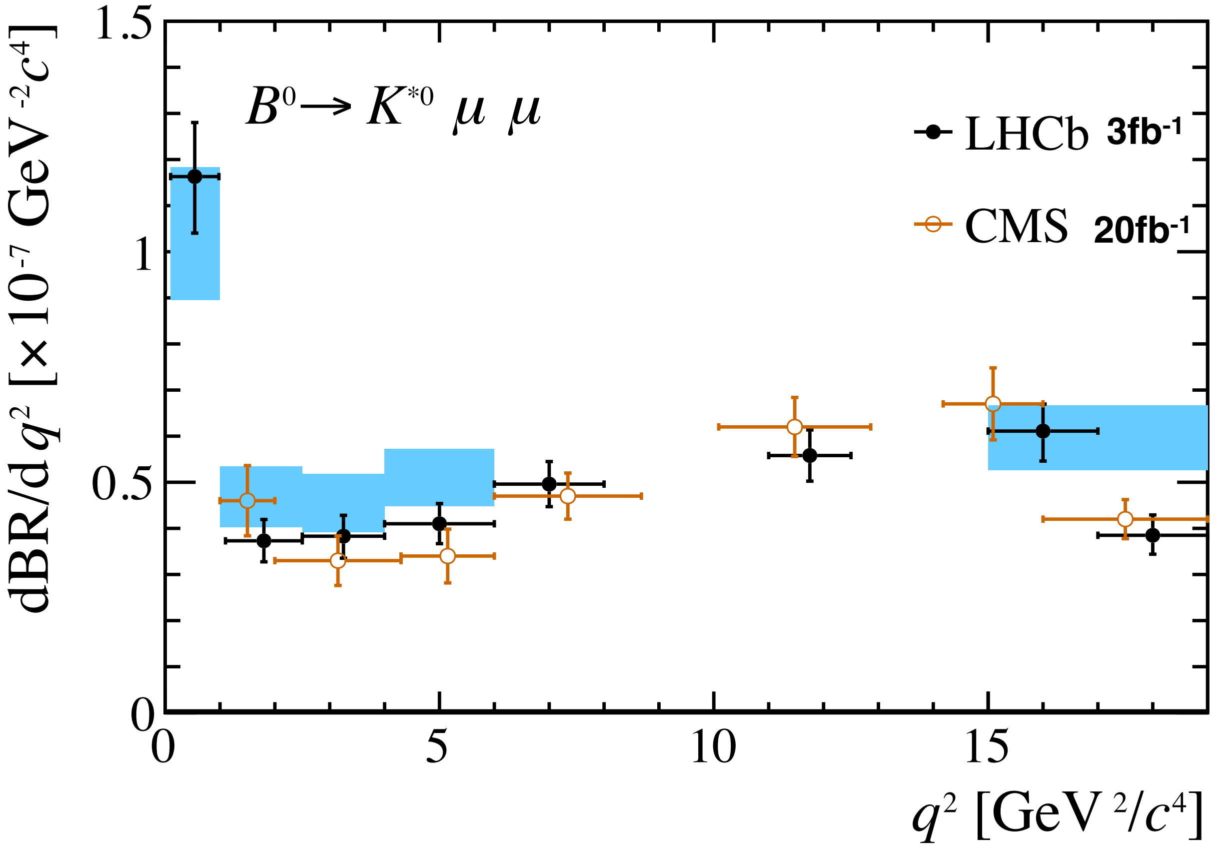
- Enhancing/suppressing decay rates, introducing new sources of *CP* violation or modifying the angular distribution of the final-state particles.

Exclusive $b\to s\mu^+\mu^-$ decay rates

[LHCb, JHEP 1406 (2014) 133]



[LHCb, arXiv:1606.04731]
[CMS, PLB 753 (2016) 424]

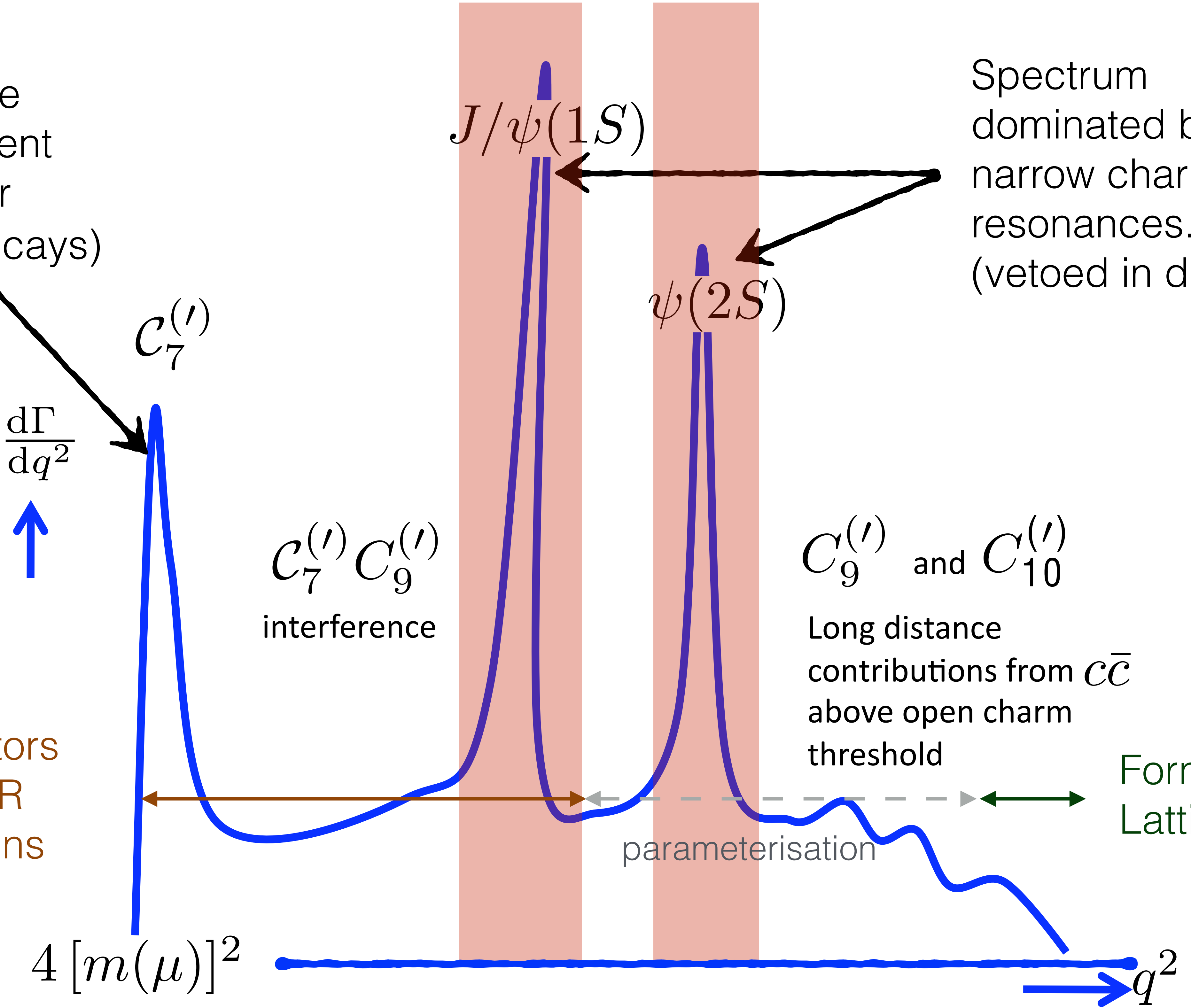


- Large samples of exclusive decays available at the LHC:

  e.g. Select 2400 (1400) $B\to K^*\mu^+\mu^-$ candidates in the LHCb (CMS) dataset.

- SM predictions have large theoretical uncertainties from hadronic form factors (3 for $B\to K$ and 7 for $B\to K^*$ decays). For details see **[Bobeth et al JHEP 01 (2012) 107] [Bouchard et al. PRL111 (2013) 162002] [Altmannshofer & Straub, EPJC (2015) 75 382]**

Dilepton mass spectrum



Photon pole enhancement (no pole for $B \to P\ell\ell$ decays)

Spectrum dominated by narrow charmonium resonances. (vetoed in data)

$\mathcal{C}_7^{(\prime)} C_9^{(\prime)}$ interference

$C_9^{(\prime)}$ and $C_{10}^{(\prime)}$

Long distance contributions from $c\bar{c}$ above open charm threshold

Form-factors from LCSR calculations

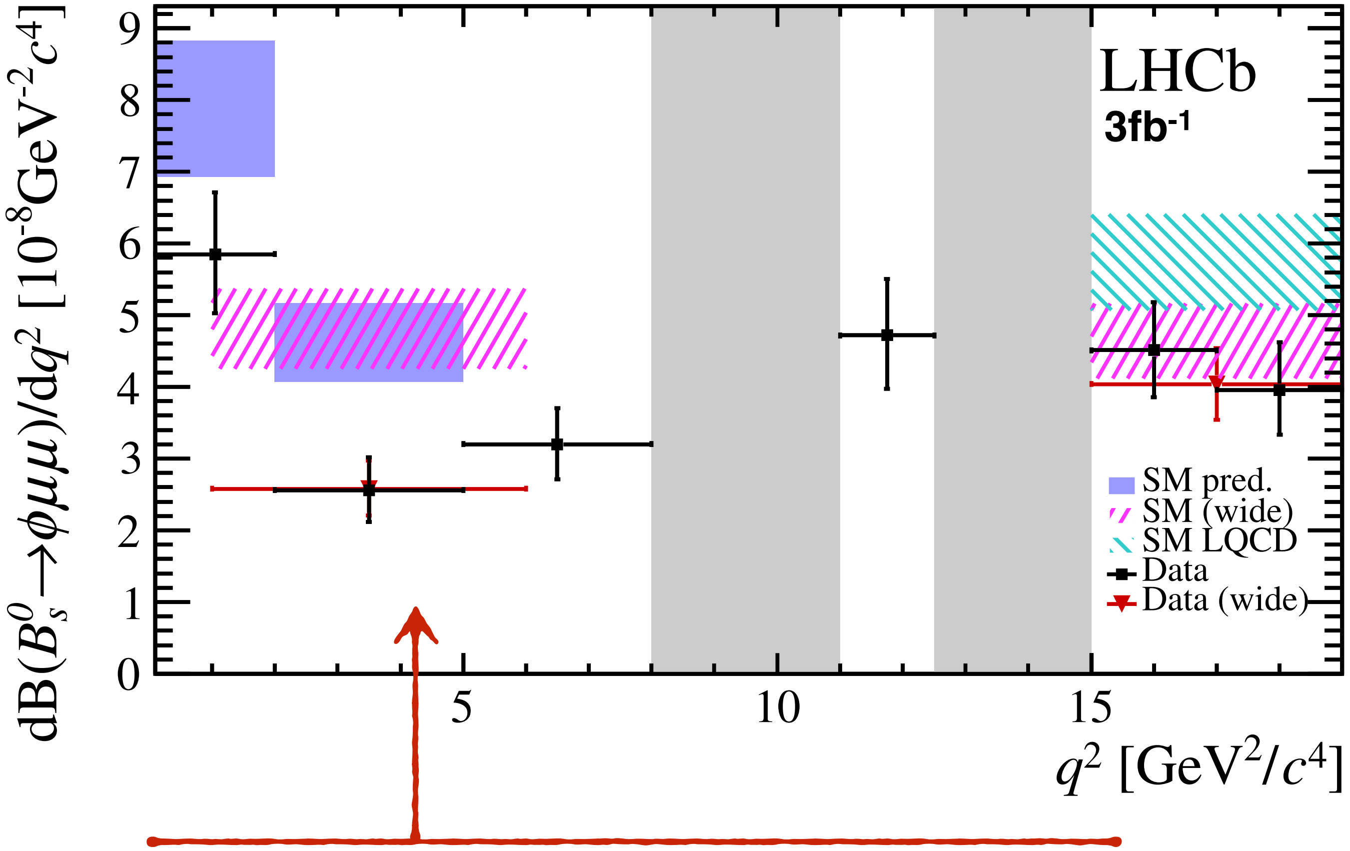
Form-factors from Lattice QCD

Dimuon mass squared

$B_s \rightarrow \phi\mu^+\mu^-$ decay rate

- Equivalent process for the B_s system is $B_s \rightarrow \phi\mu^+\mu^-$.
  - ➡ Branching fraction below SM predictions at low q^2 (similar trend seen in other $b \rightarrow s\mu^+\mu^-$ processes).

[LHCb, JHEP 09 (2015) 179]



In a wide bin from 1 < q^2 < 6 GeV$^2/c^4$, the data is >3σ from the SM prediction

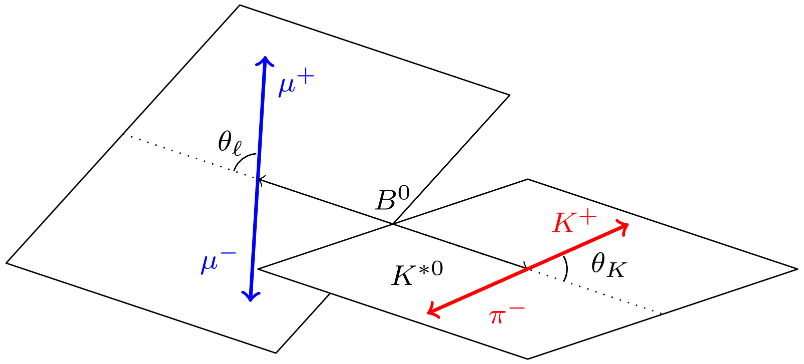
- SM predictions based on
  [Altmannshofer & Straub, EPJC (2015) 75 382]
  [LCSR form-factors from Bharucha et al. arXiv:1503.05534]
  [Lattice prediction from Horgan et al. PRD 89 (2014) 094501]

$B^0 \to K^{*0}\mu^+\mu^-$ angular distribution

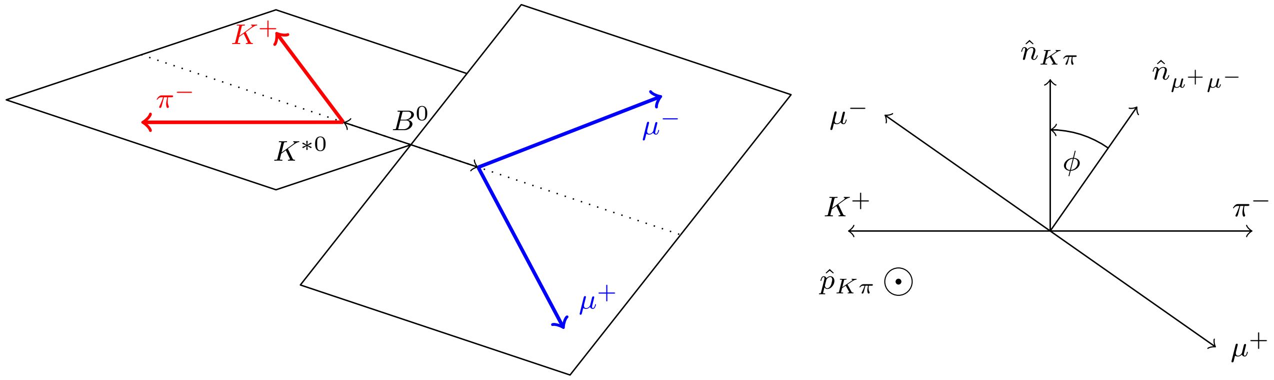
- Four-body final state.
    - ➡ Angular distribution provides many observables that are sensitive to BSM physics.

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

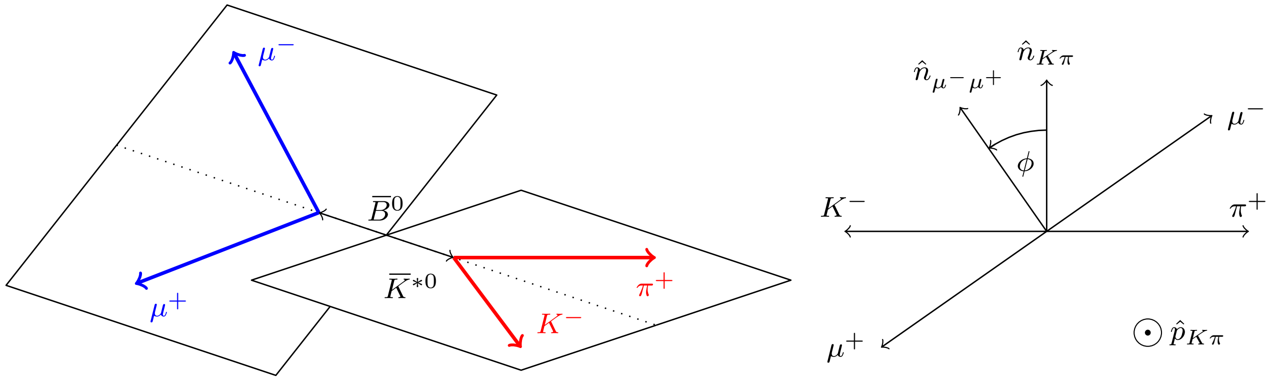
- System described by three angles and the dimuon invariant mass squared, q^2.



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay



(c) ϕ definition for the $\overline{B}^0$ decay

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular distribution

- Complex angular distribution:

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

fraction of longitudinal polarisation of the K*

forward-backward asymmetry of the dilepton system

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

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular analysis

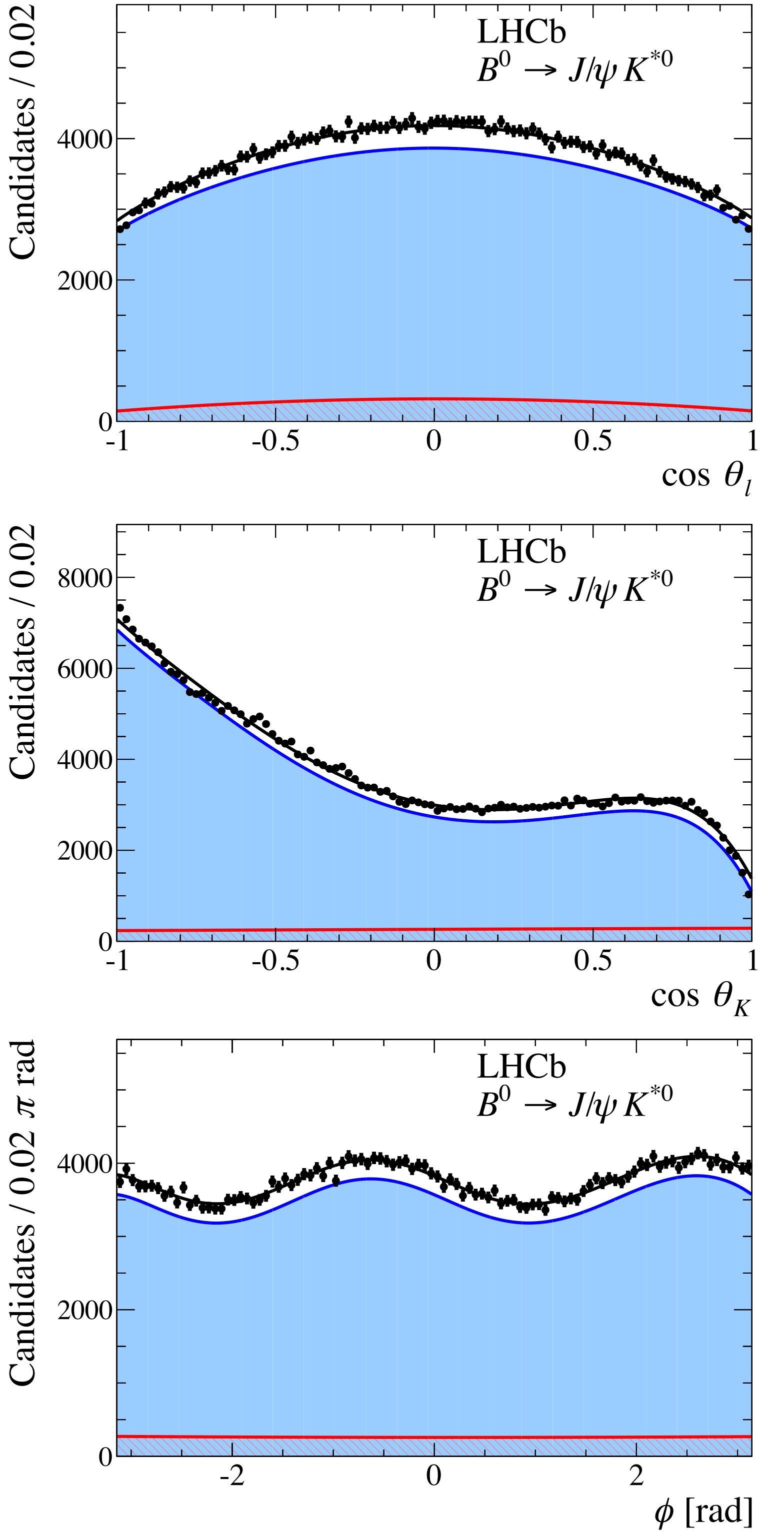
- Typically integrate over all but one angle or perform angular folding to reduce the number of observables.

- **LHCb has performed the first full angular analysis of the decay.**
  - **Access the full set of angular observables and their correlations.**

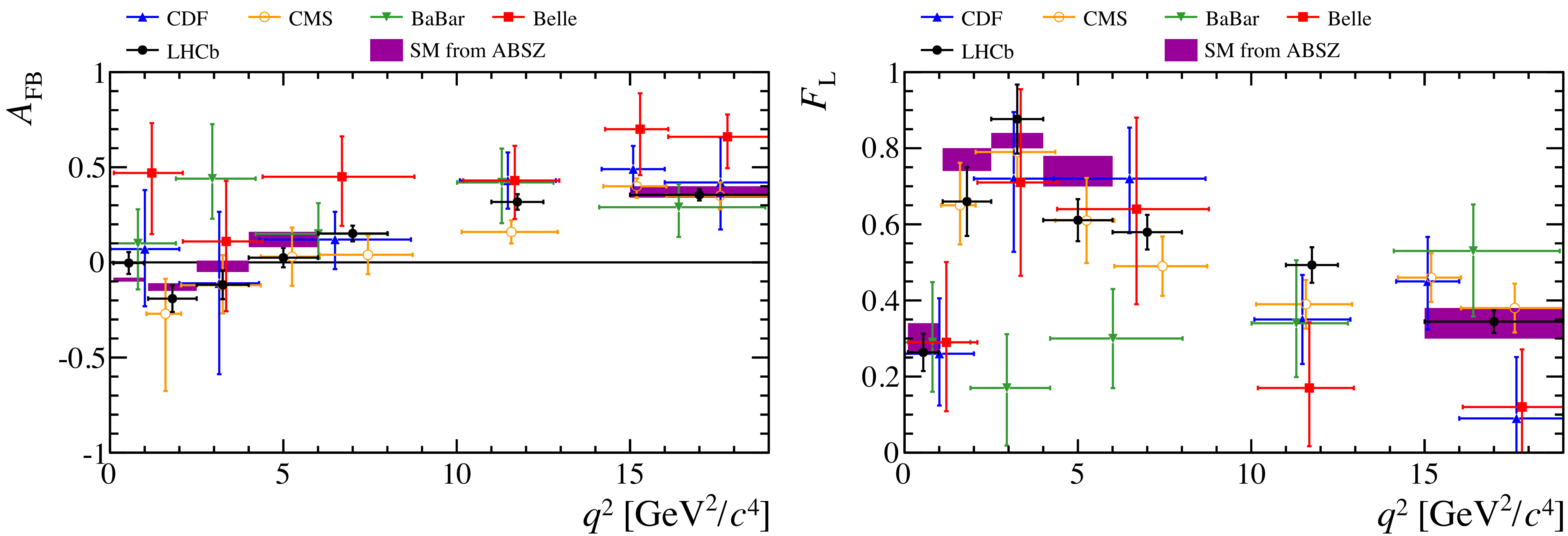
- Experiments need good control of detector efficiencies and to understand background from decays where the $K\pi$ is in an S-wave configuration.

- Use $B^0 \rightarrow J/\psi K^{*0}$ as a control channel to understand the acceptance of the detector.

[LHCb, JHEP 02 (2016) 104]



$B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular observables



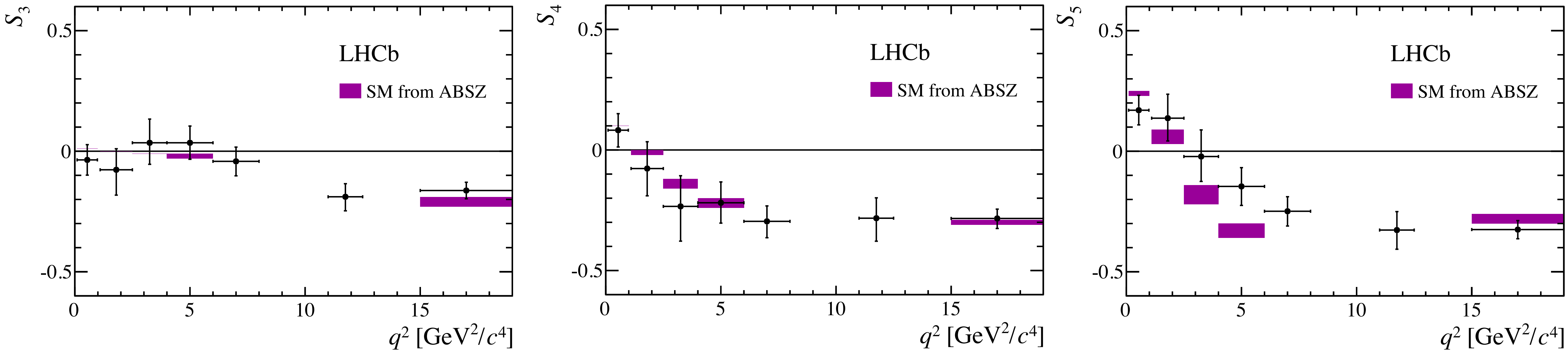
- New results for F_L and A_{FB} last year from LHCb **[JHEP 02 (2016) 104]** , CMS **[PLB 753 (2016) 424]** and BaBar **[PRD 93 (2016) 052015]** + measurements from CDF **[PRL 108 (2012) 081807]** and Belle **[PRL 103 (2009) 171801].**

- SM predictions based on
  [Altmannshofer & Straub, EPJC 75 (2015) 382]
  [LCSR form-factors from Bharucha, Straub & Zwicky, arXiv:1503.05534]
  [Lattice form-factors from Horgan, Liu, Meinel & Wingate arXiv:1501.00367] } Joint fit performed

Results

- LHCb has performed the first full angular analysis of the decay:
  - ➡ Extract the full set of *CP*-averaged angular terms and their correlations and determine a full set of *CP*-asymmetries.

[LHCb, JHEP 02 (2016) 104]



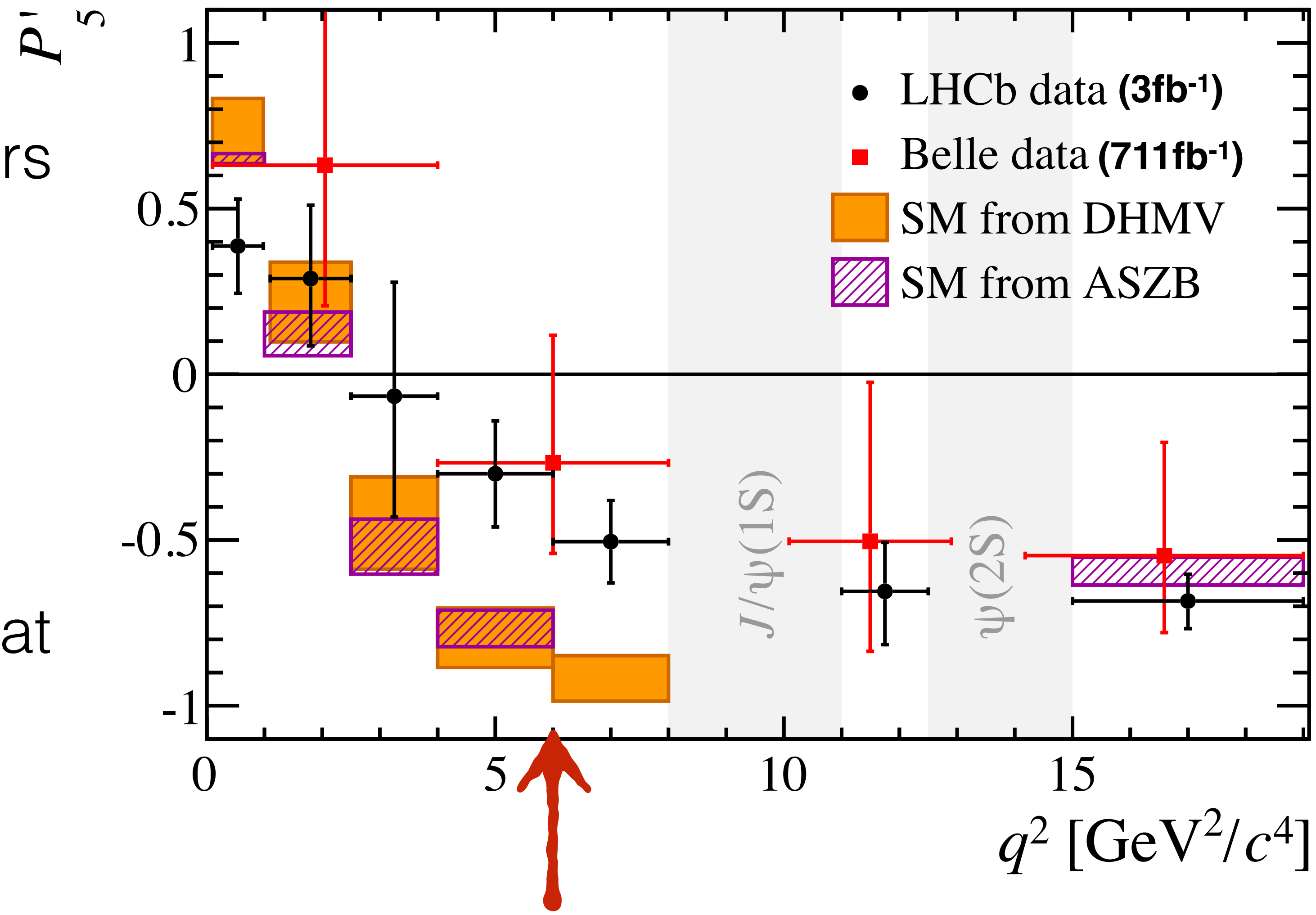
NB: These observables cancel when integrating over the ϕ-angle

Statistical coverage of the observables corrected using Feldman-Cousins (treating the nuisance parameters with the plug-in method).

Form-factor “free” observables

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

$$P_5' = S_5/\sqrt{F_{\rm L}(1 - F_{\rm L})}$$



Local tension with SM predictions.

[LHCb, JHEP 02 (2016) 104] [Belle, arXiv:1604.04042]

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

Effective theory

- Can write a Hamiltonian for an effective theory of *b*→*s* processes:

Wilson coefficient
(integrating out scales above *μ*)

Local 4 fermion operators with
different Lorentz structures

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i \boxed{C_i(\mu)}\boxed{\mathcal{O}_i(\mu)},$$

$$\Delta\mathcal{H}_{\rm eff} = \frac{\kappa_{\rm NP}}{\underline{\Lambda^2_{\rm NP}}}\boxed{\mathcal{O}_{\rm NP}}$$

NP scale

NP can modify
SM contribution
or introduce
new operators

- $\kappa_{\rm NP}$ can have all/some/none of the suppression of the SM, e.g MFV inherits SM CKM suppression.

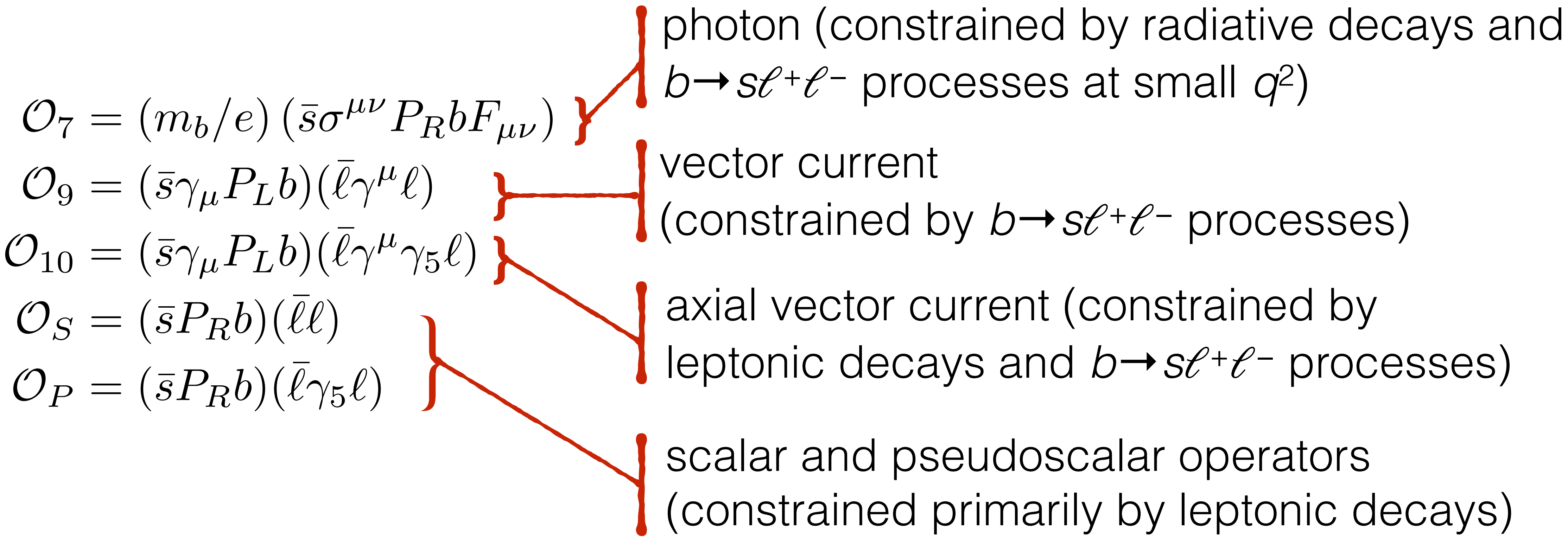
c.f. Fermi theory of
weak interaction where
at low energies:

$$\lim_{q^2\to 0}\left(\frac{g^2}{m_W^2 - q^2}\right) = \frac{g^2}{m_W^2}$$

i.e. the full theory can
be replaced by a 4-
fermion operator and a
coupling constant, G_F.

Operators

- Different processes are sensitive to different 4-fermion operators.
  - ➡ Can exploit this to over-constrain the system.



$$\mathcal{O}_7 = (m_b/e)\,(\bar{s}\sigma^{\mu\nu}P_R bF_{\mu\nu})$$
$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$
$$\mathcal{O}_S = (\bar{s}P_R b)(\bar{\ell}\ell)$$
$$\mathcal{O}_P = (\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell)$$

photon (constrained by radiative decays and $b \rightarrow s\ell^+\ell^-$ processes at small q^2)

vector current (constrained by $b \rightarrow s\ell^+\ell^-$ processes)

axial vector current (constrained by leptonic decays and $b \rightarrow s\ell^+\ell^-$ processes)

scalar and pseudoscalar operators (constrained primarily by leptonic decays)

e.g.

$B_s^0 \to \mu^+\mu^-$ constrains $C_{10} - C'_{10},\ C_S - C'_S,\ C_P - C'_P$

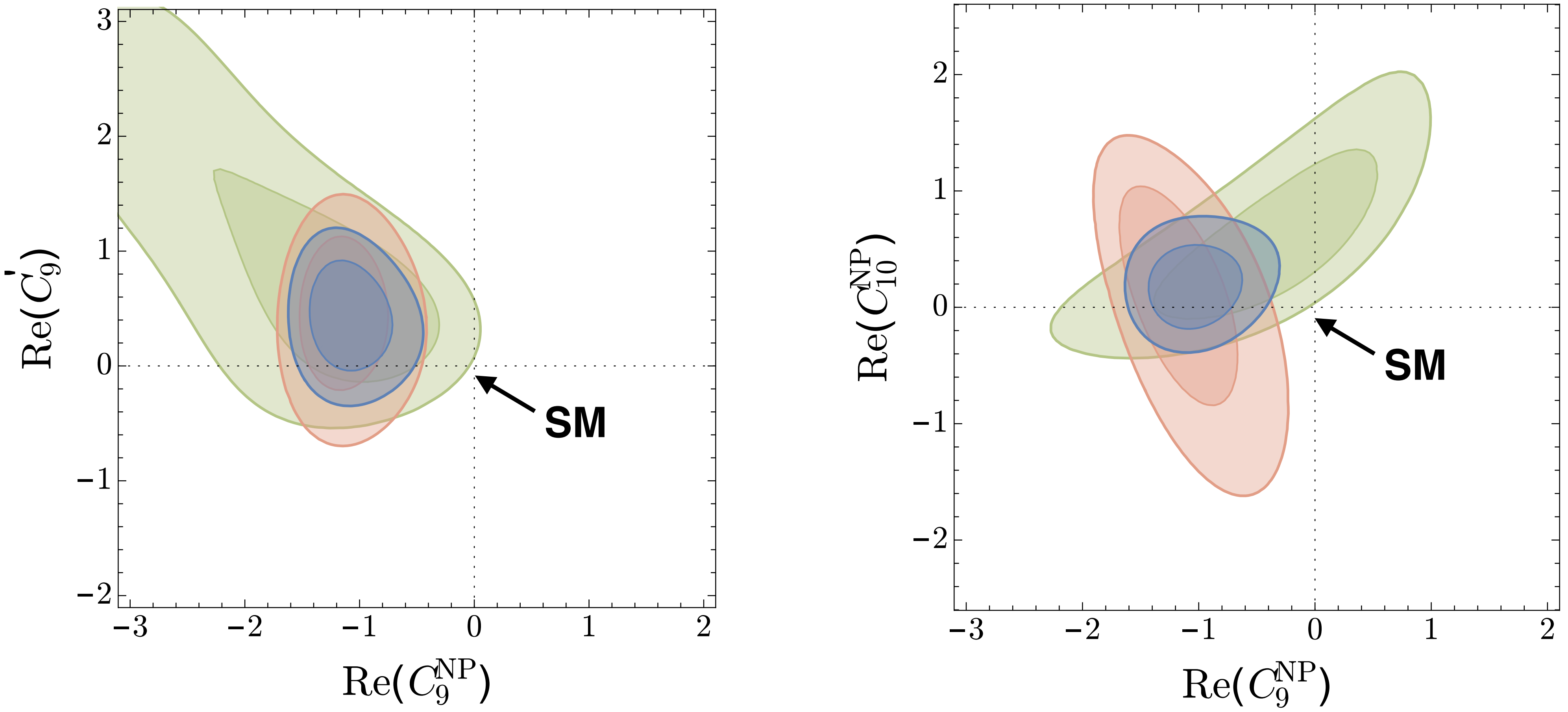
$B^+ \to K^+\mu^+\mu^-$ constrains $C_9 + C'_9,\ C_{10} + C'_{10}$

$B^0 \to K^{*0}\mu^+\mu^-$ constrains $C_7 \pm C'_7,\ C_9 \pm C'_9,\ C_{10} \pm C'_{10}$

The primes denote right-handed counterparts of the operators whose contribution is small in the SM.

Global fits

- Several attempts to interpret our results by performing global fits to $b \rightarrow s$ data (e.g. **[JHEP 06 (2016) 092], [Nucl. Phys. B 909 (2016) 737]**).



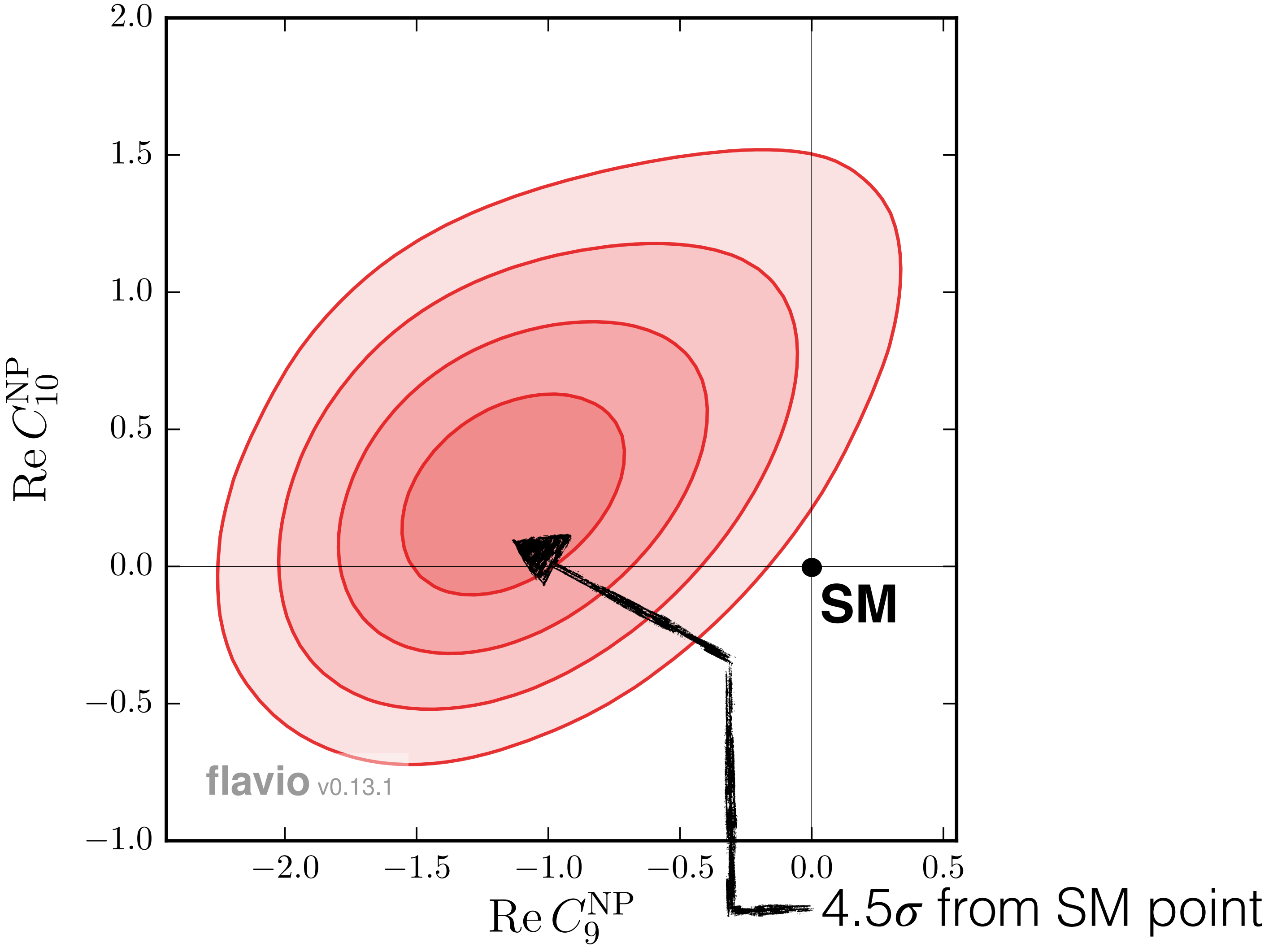
Altmannshofer & Straub [EPJC 75 (2015) 382]

branching fractions, angular observables and combination

➡ **Consistent picture, data favours modified vector coupling ($C_9^{\mathrm{NP}} \neq 0$) at about 4σ.**

Global fits

- A more recent example
  [from talk by D. Straub at the LHCb Implications Workshop 2016].

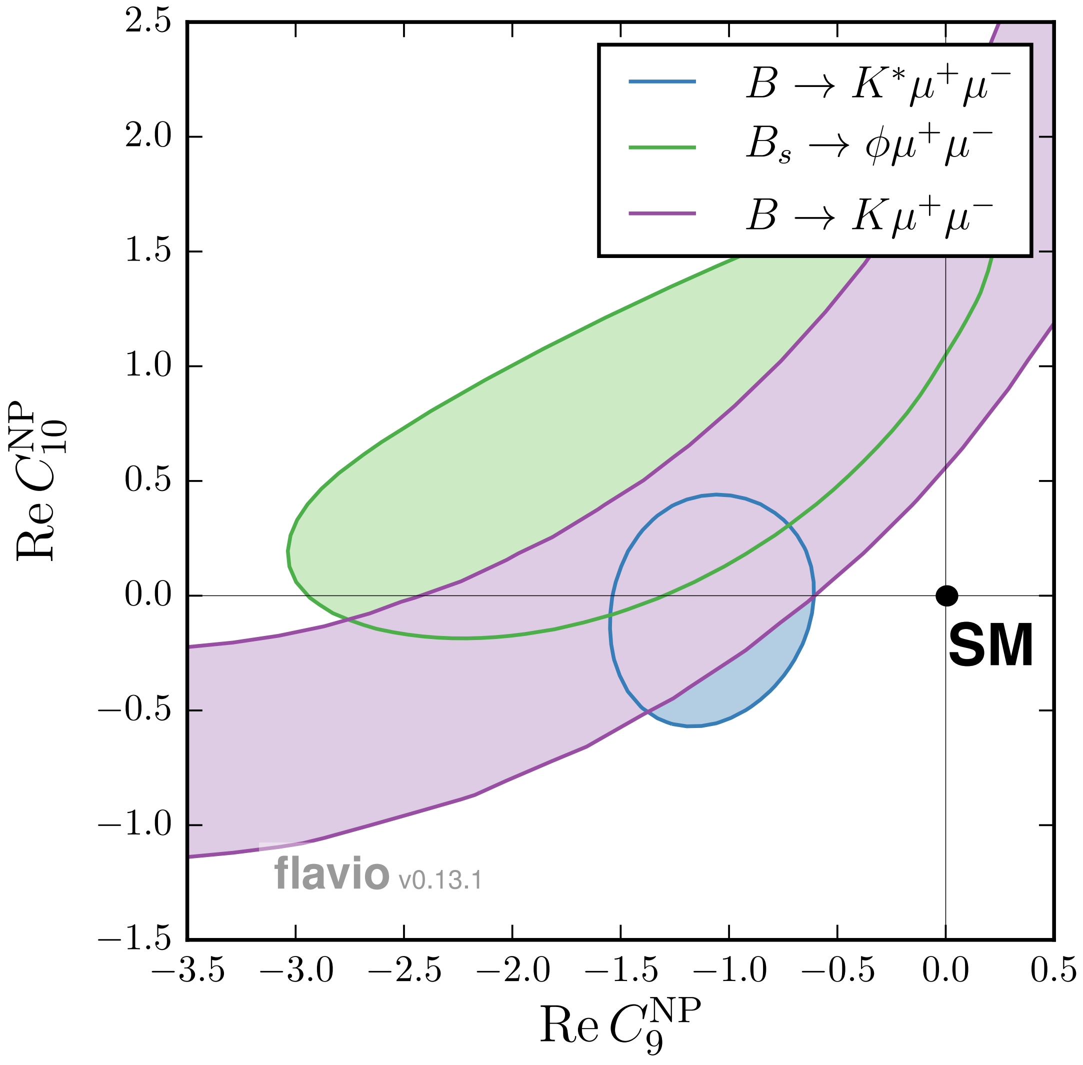


4.5σ from SM point

Reproducible using **[Flavio]**

Global fits

- A more recent example
  [from talk by D. Straub at the LHCb Implications Workshop 2016].

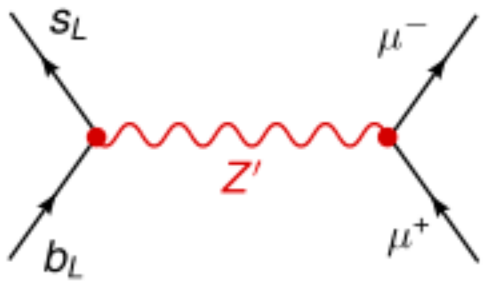


- Looking at individual contributions:
  - ➡ 2.7σ pull from angular observables in $B^0 \to K^{*0}\mu^+\mu^-$ (*i.e.* P_5' anomaly).
  - ➡ 3.4σ pull from $B_s \to \phi\mu^+\mu^-$ branching fraction.
  - ➡ 2.6σ pull from $B^+ \to K^+\mu^+\mu^-$ branching fraction (see later).

Reproducible using **[Flavio]**

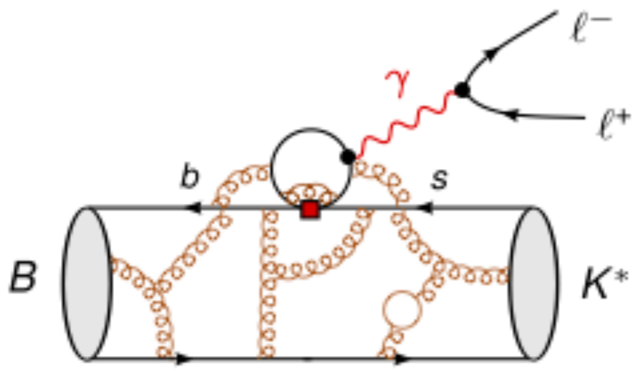
Interpretation of global fits

Optimist's view point



Vector-like contribution could come from e.g. new tree level contribution from a Z' with a mass of a few TeV.

Pessimist's view point

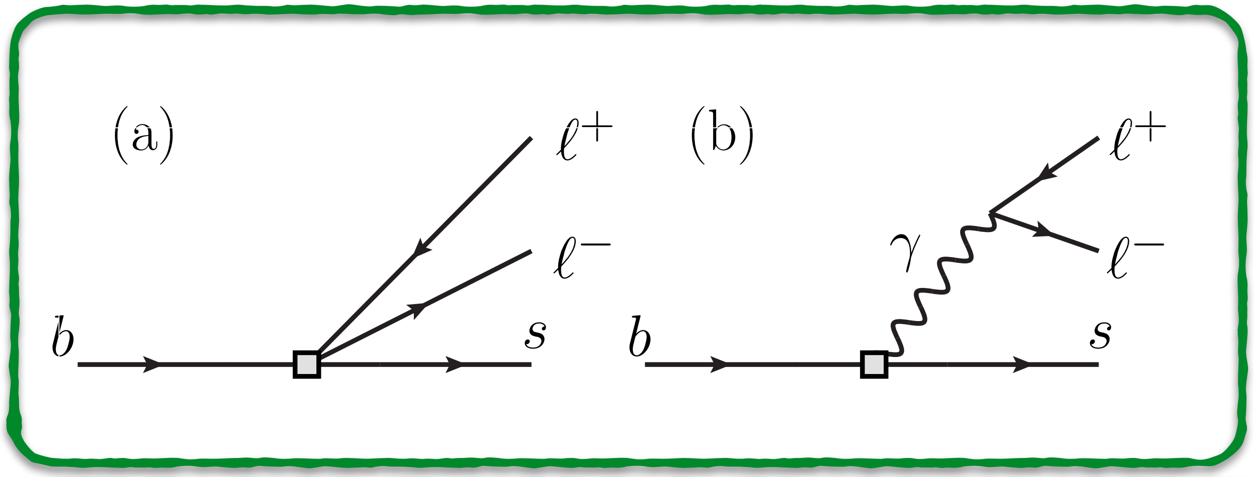


Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon?

More work needed from experiment/theory to disentangle the two

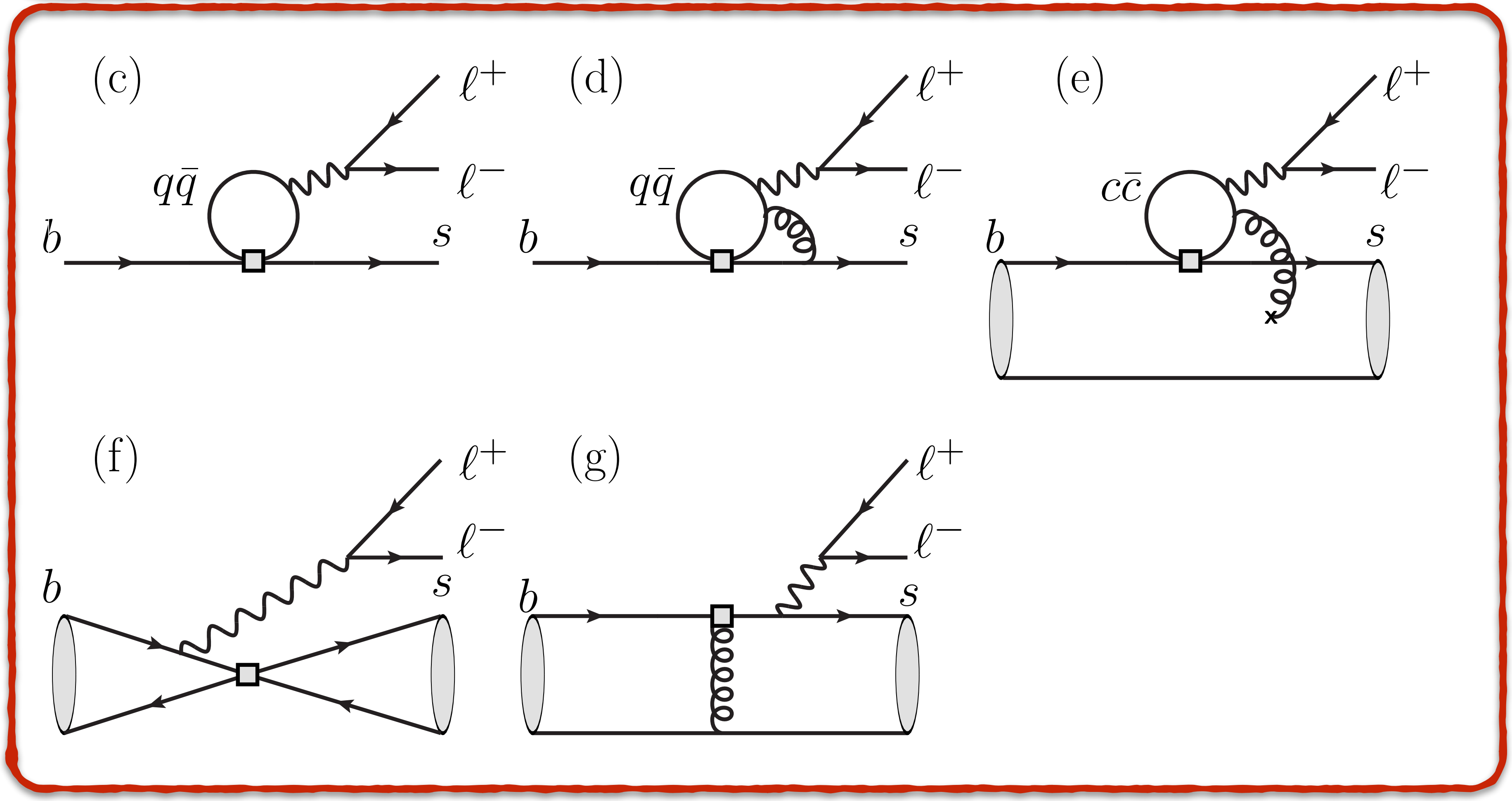
SM contributions

- Interested in new short distance contributions.
- We also get long-distance hadronic contributions.
- Need estimate of non-local hadronic matrix elements **[Khodjamirian et al. JHEP 09 (2010) 089]**



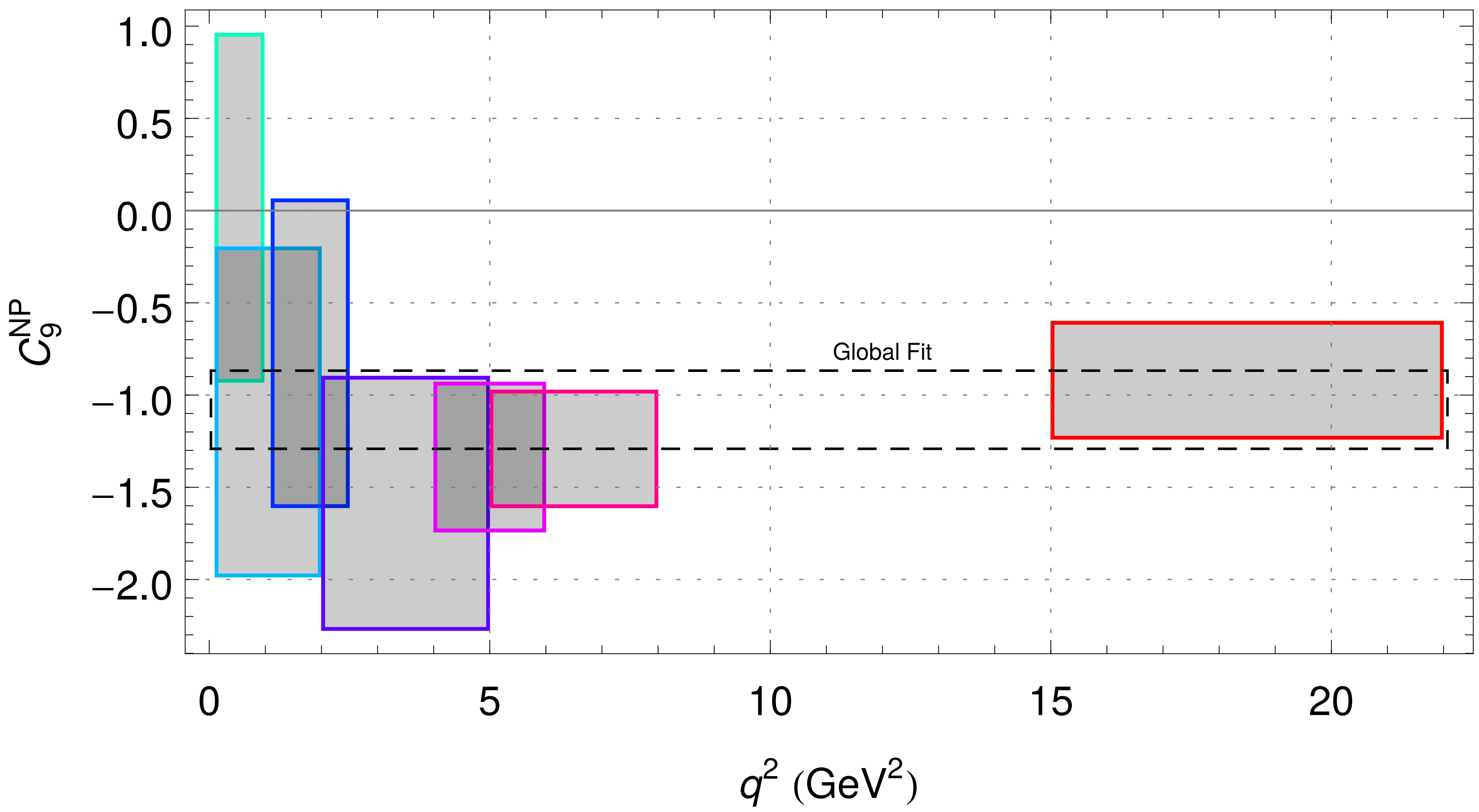
■

Short distance part integrates out (as a Wilson coefficient)



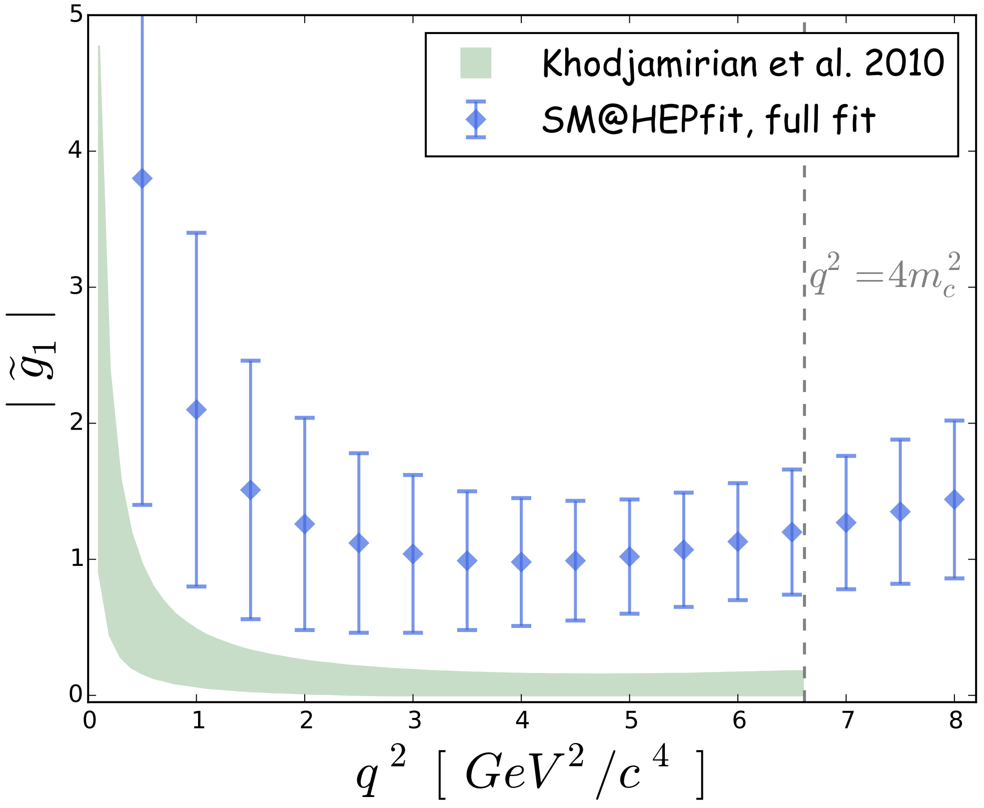
What can we learn from the data?

- If we are underestimating $c\bar{c}$ contributions then naively expect to see the shift in C_9 get larger closer to the narrow charmonium resonances.



[Decotes-Genon et al JHEP 06 (2016) 092]

Fitting separately for C_9 in different q^2 regions.



[M. Ciuchini et al, JHEP 06 (2016) 116]

Parameterised fit for charm contributions in $B^0 \to K^{*0}\mu^+\mu^-$ decays with C_9 = C_9^{SM}.

➡ **No clear evidence for a rise in the data (but more data is needed).**

Lepton universality

- In the SM, ratios

$$R_{\mathrm{K}} = \frac{\int \mathrm{d}\Gamma[B^{+} \to K^{+}\mu^{+}\mu^{-}]/\mathrm{d}q^{2} \cdot \mathrm{d}q^{2}}{\int \mathrm{d}\Gamma[B^{+} \to K^{+}e^{+}e^{-}]/\mathrm{d}q^{2} \cdot \mathrm{d}q^{2}}$$

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

- Theoretically clean since hadronic uncertainties cancel in the ratio (same hadronic matrix element + QED couples only to lepton charge).

- Experimentally challenging due to differences in muon/electron reconstruction (in particular Bremsstrahlung from the electrons).

R_K result

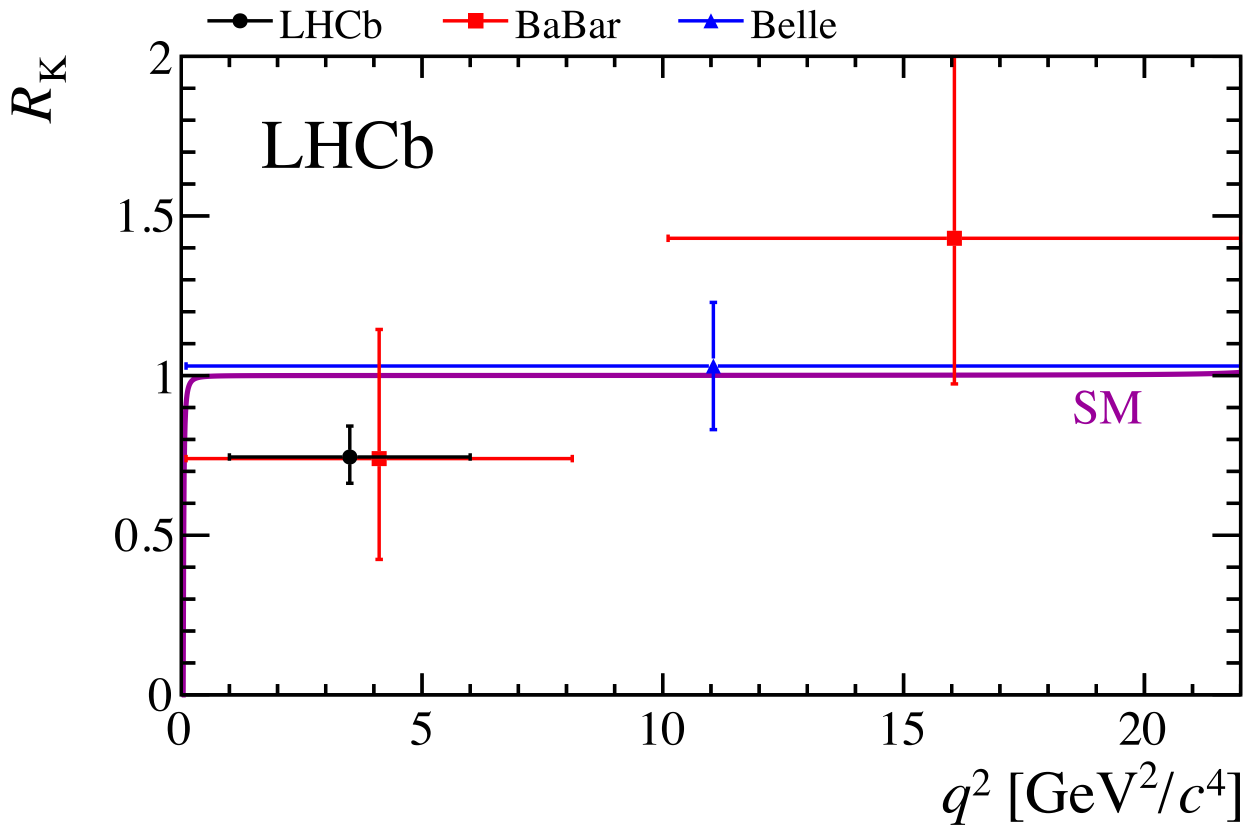
- In the Run 1 dataset, LHCb determines:

$$R_{\rm K} = 0.745\,^{+0.090}_{-0.074}\,^{+0.036}_{-0.036}$$

in the range $1 < q^2 < 6$ GeV^2, which is consistent with the SM at 2.6σ.

- Take double ratio with $B^+ \to J/\psi K^+$ to cancel possible sources of systematic uncertainty.

- Correct for migration of events in q^2 due to Bremsstrahlung using MC (with PHOTOS).



LHCb [PRL113 (2014) 151601]
BaBar [PRD 86 (2012) 032012]
Belle [PRL 103 (2009) 171801]

NB $R_K \simeq 0.8$ is a prediction of one class of model explaining the $B^0 \to K^{*0}\mu^+\mu^-$ angular observables, see L_μ - L_τ models

W. Altmannshofer et al. [PRD 89 (2014) 095033]

R_K result

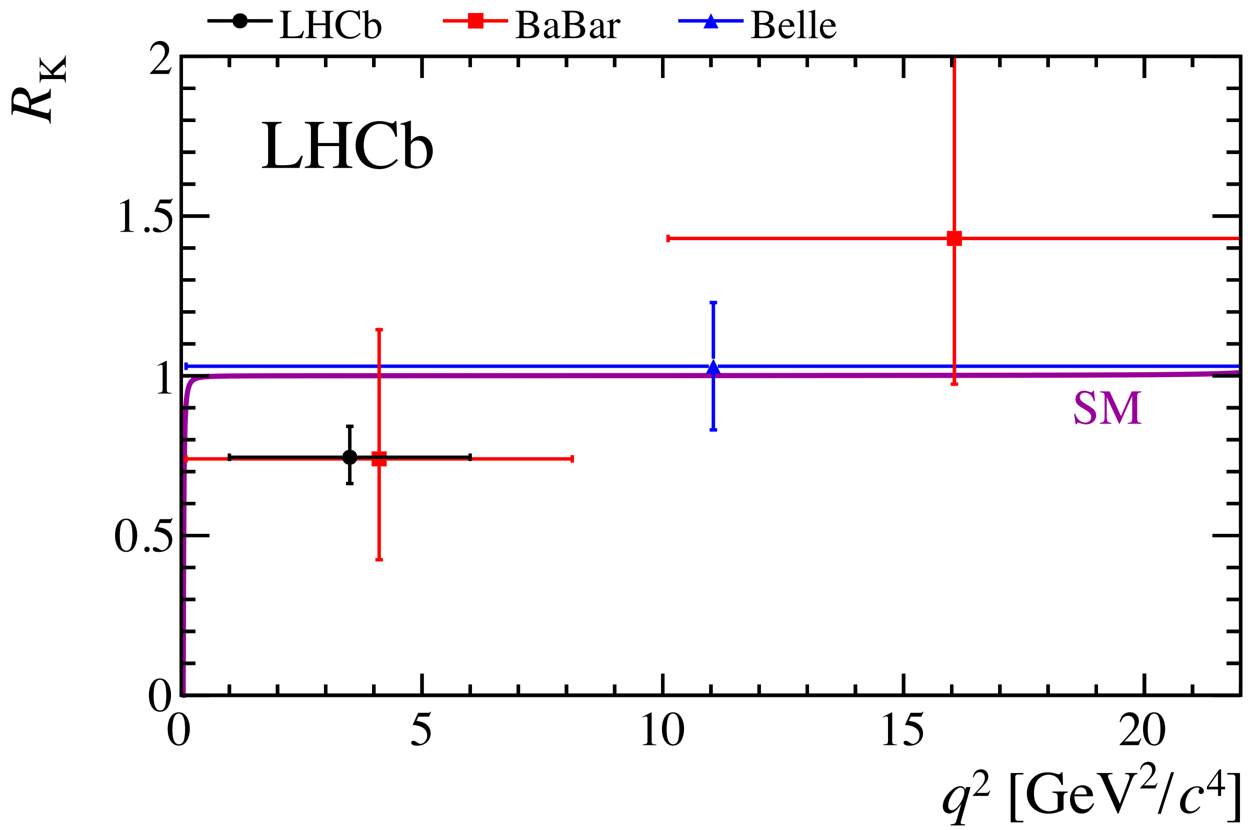
- QED corrections to R_K = 1 are known to be small and are well modelled by PHOTOS. They enter as

$$\frac{\alpha_{\rm EM}}{\pi}\log\left(\frac{m_\mu^2}{m_e^2}\right)$$

see **[Isidori et al. EPJC 76 (2016)]**

- Can also consider decays to other hadronic systems as the prediction is (almost) independent of mass/spin of hadronic final state.

- Await results from LHCb run II dataset/first data from Belle II.

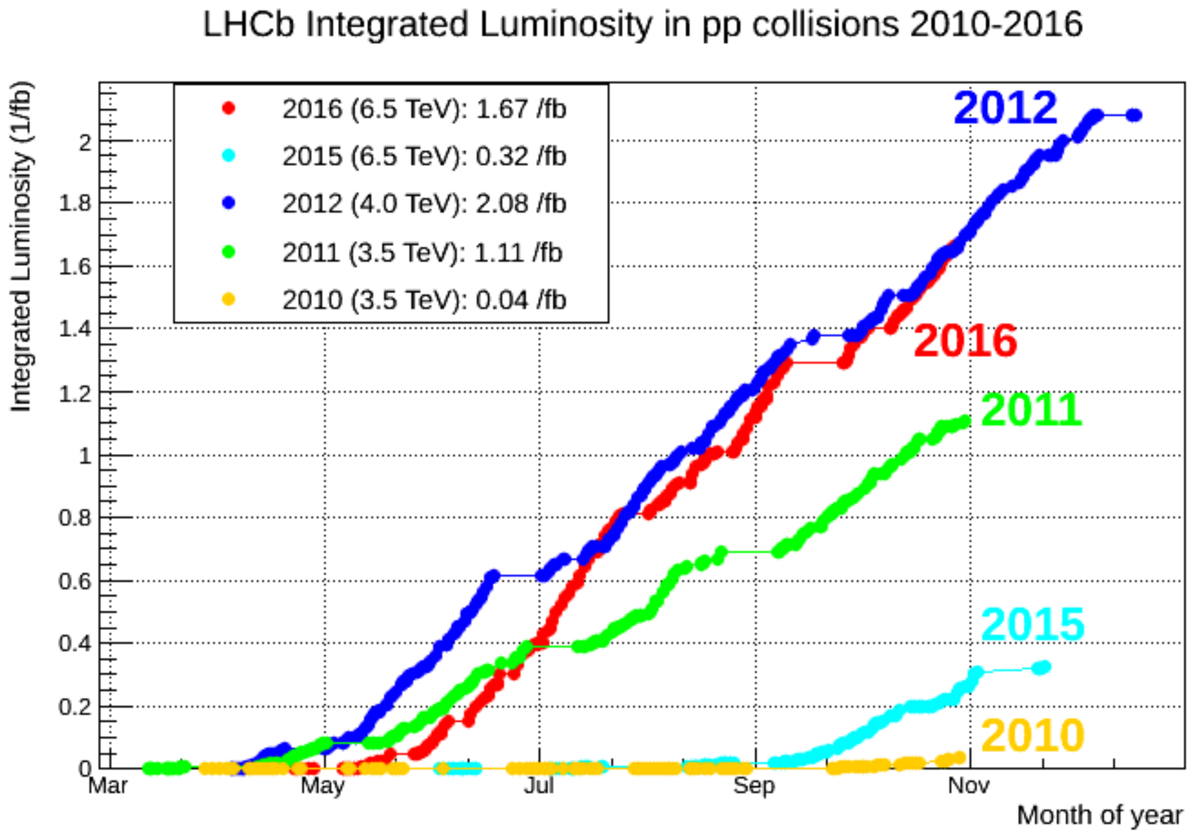


LHCb [PRL113 (2014) 151601]
BaBar [PRD 86 (2012) 032012]
Belle [PRL 103 (2009) 171801]

Looking to the future

- The LHCb results in this talk are based on 3 fb^{-1} of integrated luminosity collected during run 1 of the LHC. We have already collected 2 fb^{-1} of integrated luminosity (at $\sqrt{s}$ of 13TeV) in run 2.

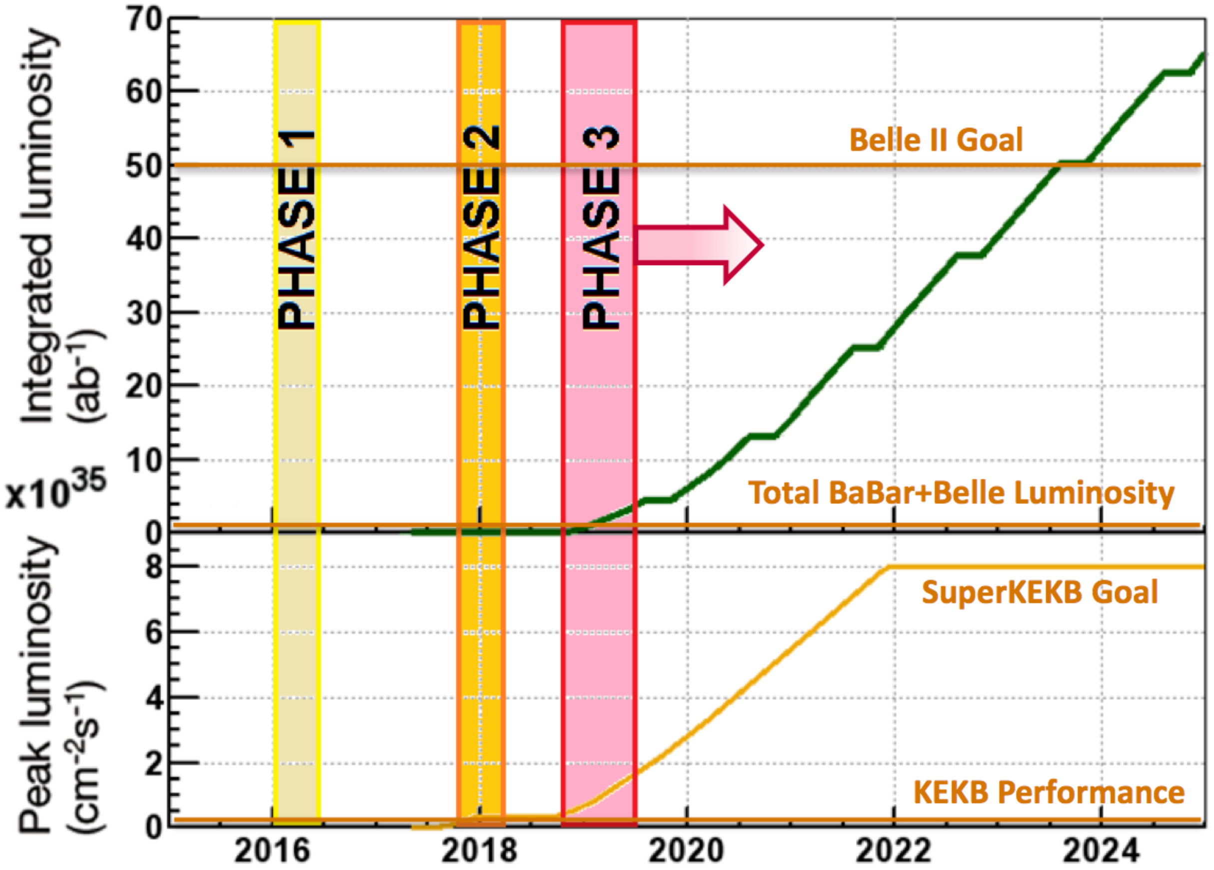
- LHCb upgrade planned for LS3, with the goal of reading out the full detector at 40 MHz into a fully software trigger.
  - ➡ Aims to collect a dataset corresponding to 50 fb^{-1}.



- Discussion has also started about a longer term (high luminosity) upgrade of the LHCb experiment.

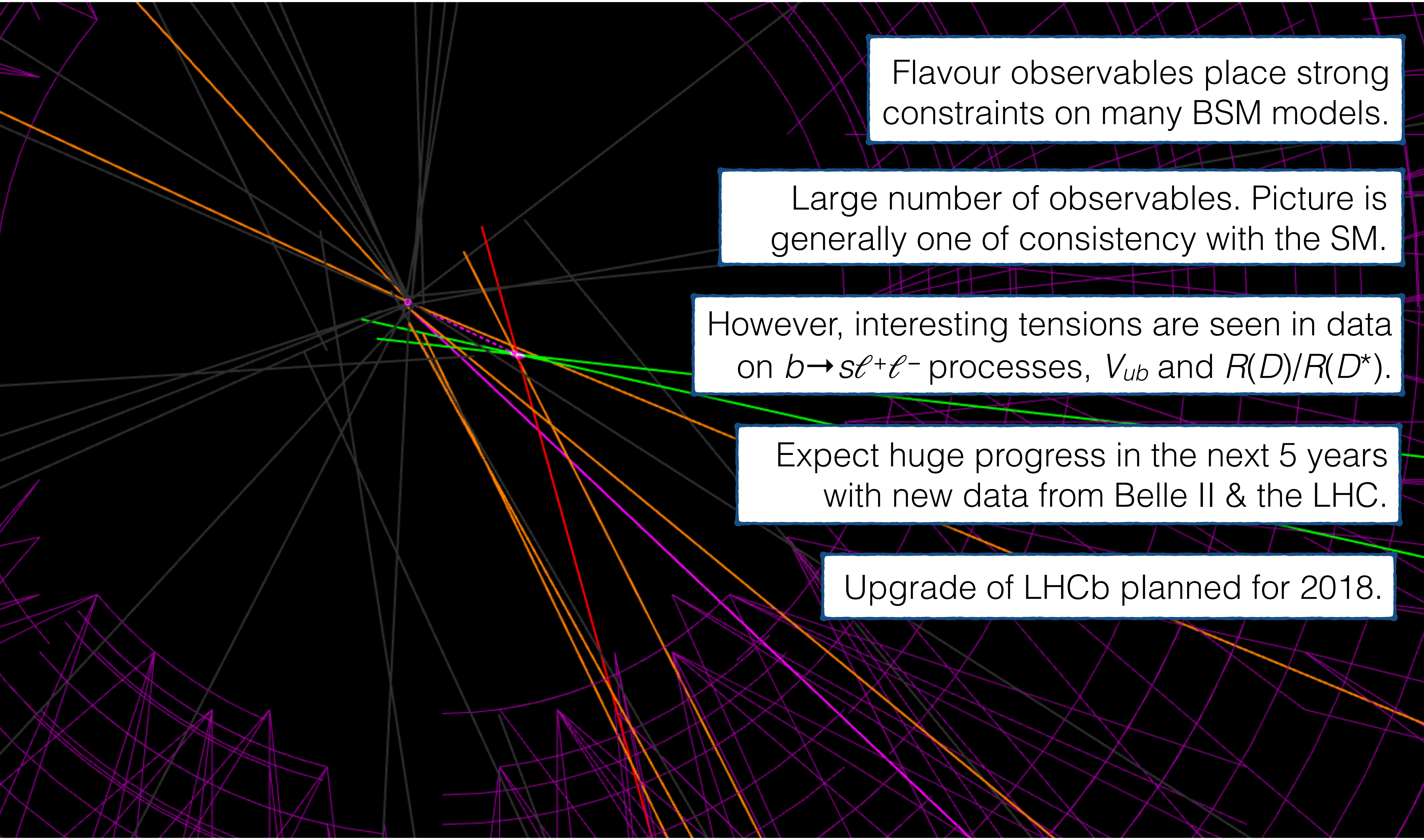
Looking to the future

- Belle II will start physics data taking in 2019.
- Aiming to collect a dataset corresponding to 50 ab^{-1} of integrated luminosity (50x the total BaBar and Belle dataset).
    - ➡ Expect to reach a precision of 2-3% on *R*(*D**).
- First commissioning run of the SuperKEKB accelerator has already been successfully completed.



1. Accelerator commissioning
2. First collisions with a partial detector
3. Physics data taking

Summary



Flavour observables place strong constraints on many BSM models.

Large number of observables. Picture is generally one of consistency with the SM.

However, interesting tensions are seen in data on $b \to s \ell^+ \ell^-$ processes, V_{ub} and $R(D)/R(D^*)$.

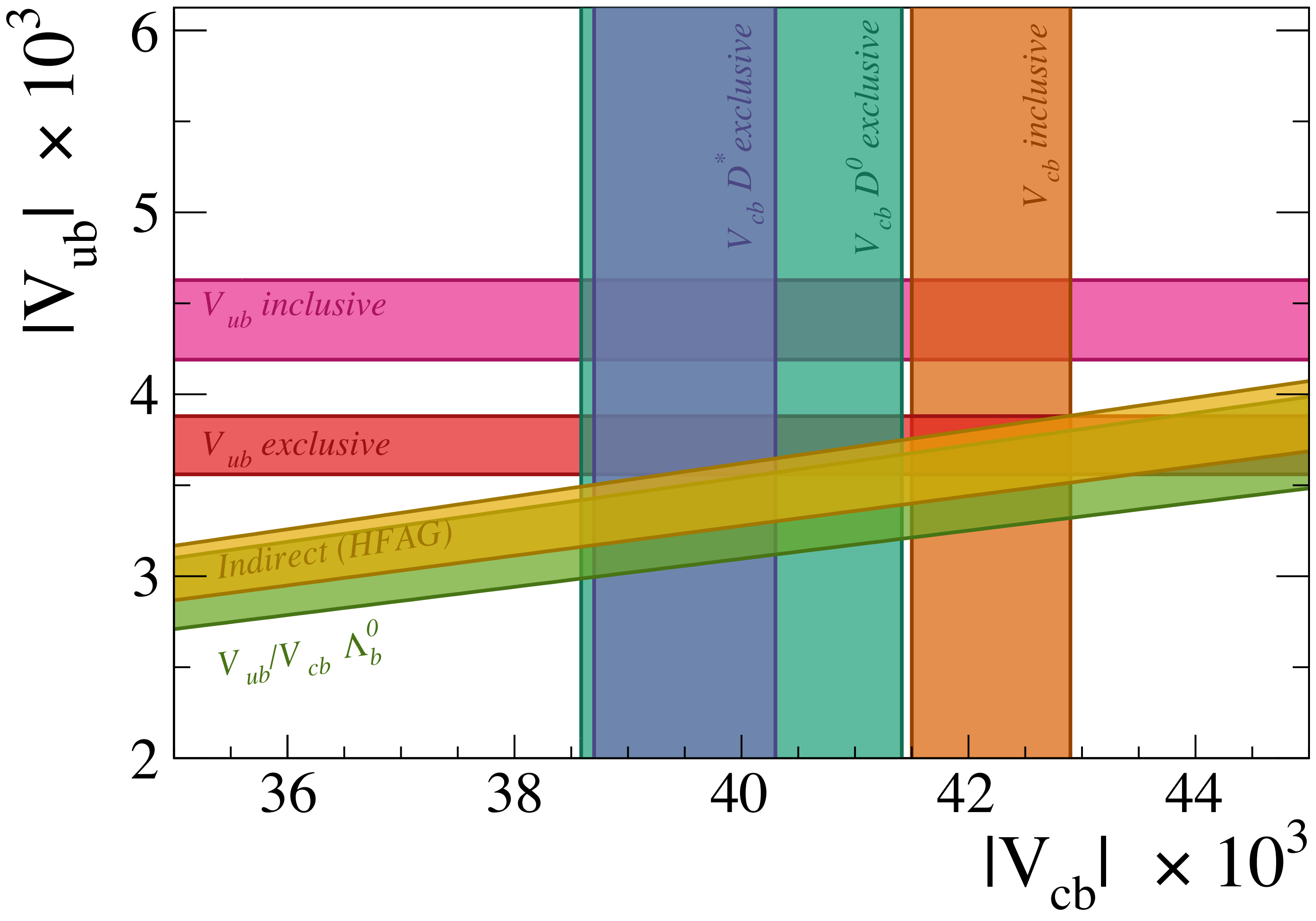
Expect huge progress in the next 5 years with new data from Belle II & the LHC.

Upgrade of LHCb planned for 2018.

Inclusive vs exclusive V_{ub}

- Can also determine V_{ub} using inclusive $B \to X_u \ell \nu$ decays and Heavy Quark Effective Theory.

➡ **See large tension between the inclusive and exclusive rates (>3σ).**



Semitauonic decays

- Ratio

$$R(D^{(*)}) = \frac{\Gamma[B \to D^{(*)}\tau\nu]}{\Gamma[B \to D^{(*)}\ell\nu]}$$

is theoretically clean

➡ Hadronic uncertainties & $|V_{cb}|$ cancel in ratio.

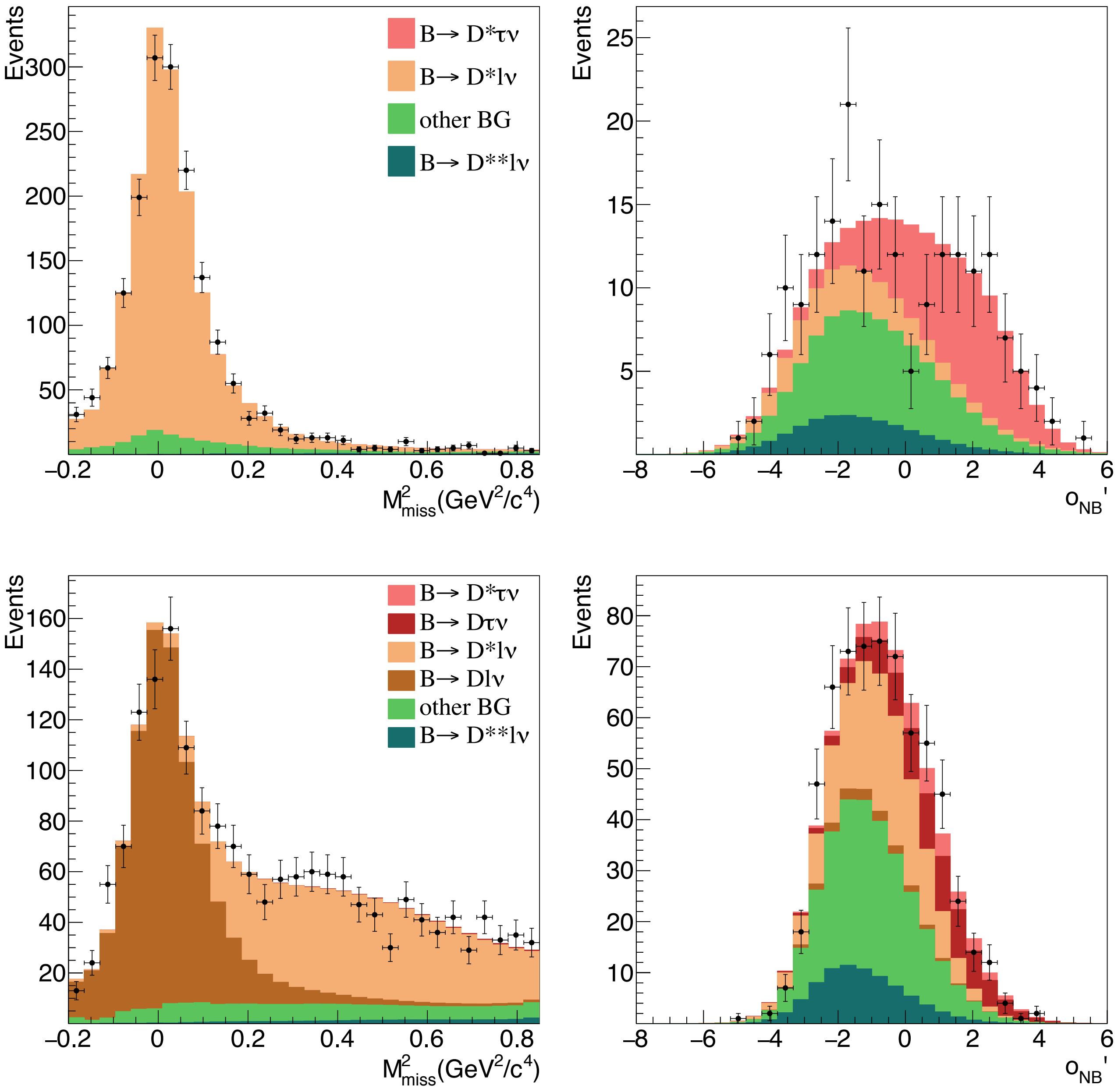
and can be enhanced in extensions of the SM (e.g. with charged Higgs).

- Experimental challenge is to separate signal from backgrounds.

➡ Use missing mass, lepton energy, q^2 and multivariate discriminants.

- *B*-factory experiments can also exploit leptonic/hadronic tag of the other *B* in the event.

[Belle, PRD 92 (2015) 072014]



$R(D^*)$ consistency

- Can also calculate inclusive rate using OPE:

$$\mathcal{B}(B\rightarrow X_c\tau\nu) = (2.42 \pm 0.06)\%$$

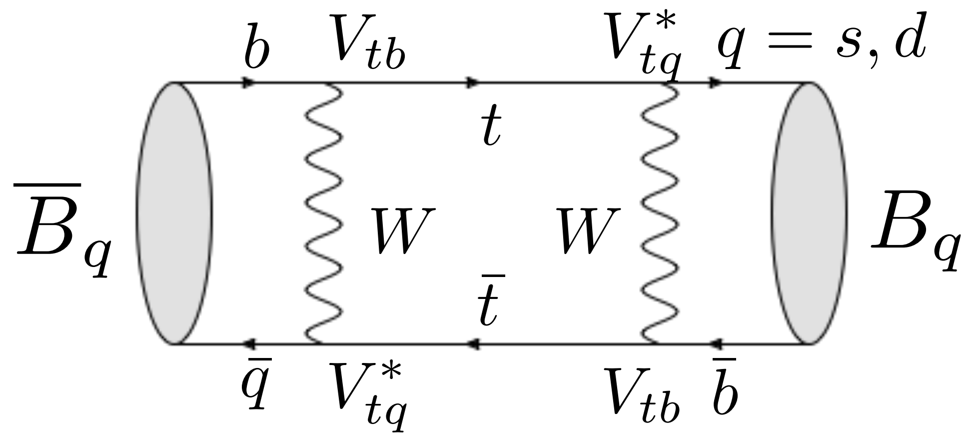
[Ligeti and Tackmann, PRD 90 (2014) 034021]

and cross-check against the inclusive measurement from LEP

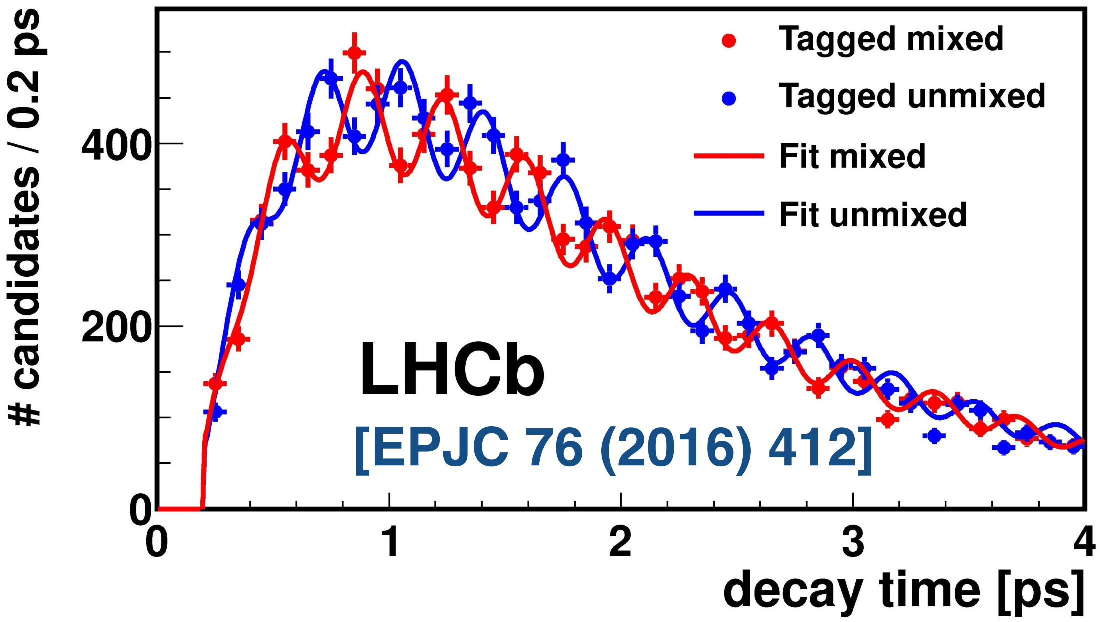
$$\mathcal{B}(B\rightarrow X_c\tau\nu) = (2.41 \pm 0.23)\%$$

➡ **In inclusive rate there is excellent agreement between experiment and theory.**

Neutral meson mixing



- Mass eigenstates are not the same as the weak eigenstates.
- Oscillation frequency controlled by the mass difference between the heavy and light mass eigenstates.
- Ratio of oscillation frequencies can be computed precisely in Lattice CQD (computing $\langle \overline{B}^0 | B^0 \rangle$ and $\langle \overline{B}{}^0_s | B^0_s \rangle$)

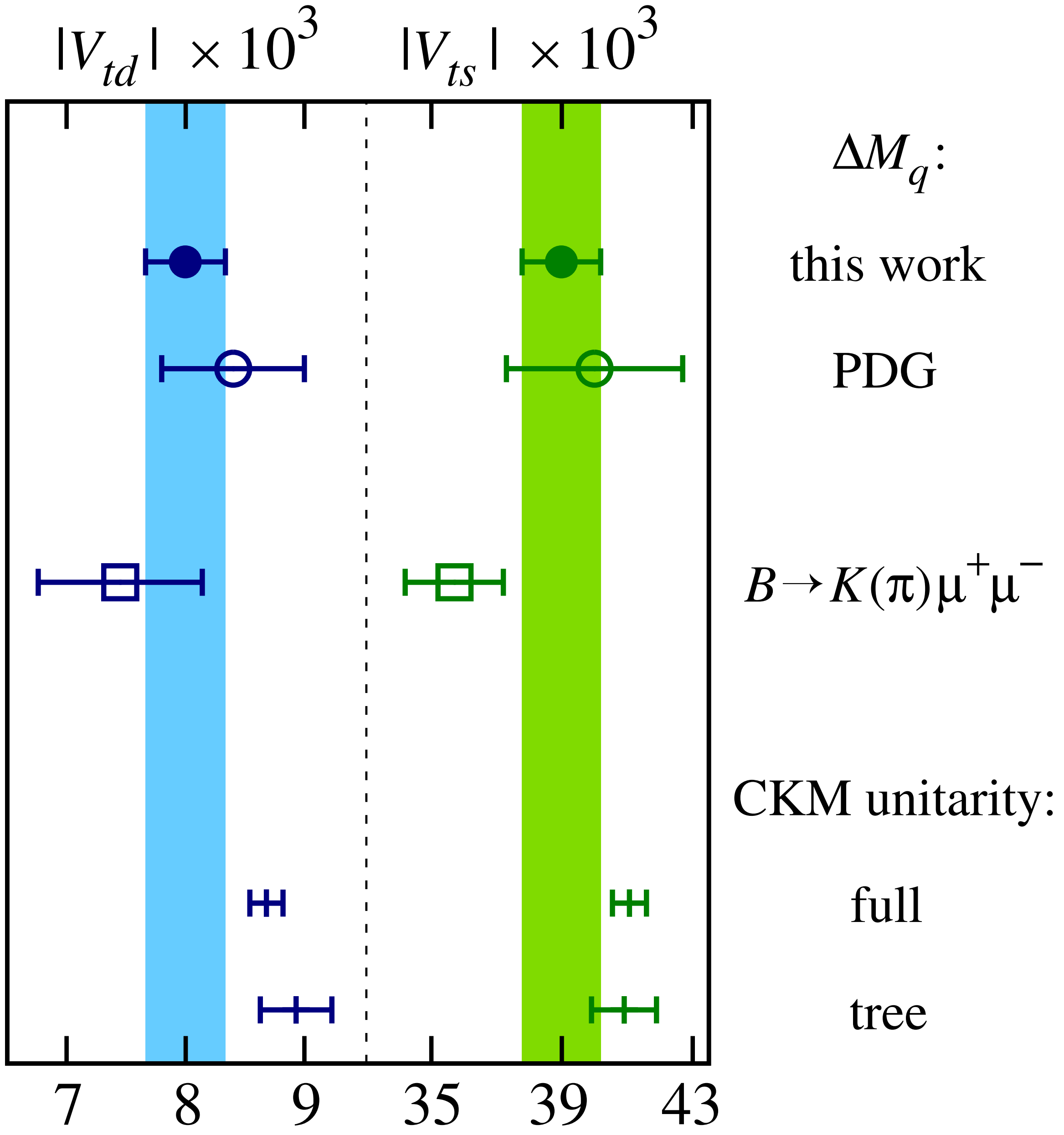


$$\frac{\Delta m_d}{\Delta m_s} = \left(\frac{f_{B^0} \sqrt{\hat{B}_{B^0}}}{f_{B^0_s} \sqrt{\hat{B}_{B^0_s}}} \right)^2 \frac{m_{B^0}}{m_{B^0_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

Use experimental inputs for Δm_d/Δm_s + masses and decay constants + bag-parameters from lattice.

Neutral meson mixing

- See 2σ tension between V_{td}/V_{ts} determination from $\Delta m_d / \Delta m_s$ and expectation from CKM unitarity.



[Fermilab-MILC PRD 93 (2016) 113016]

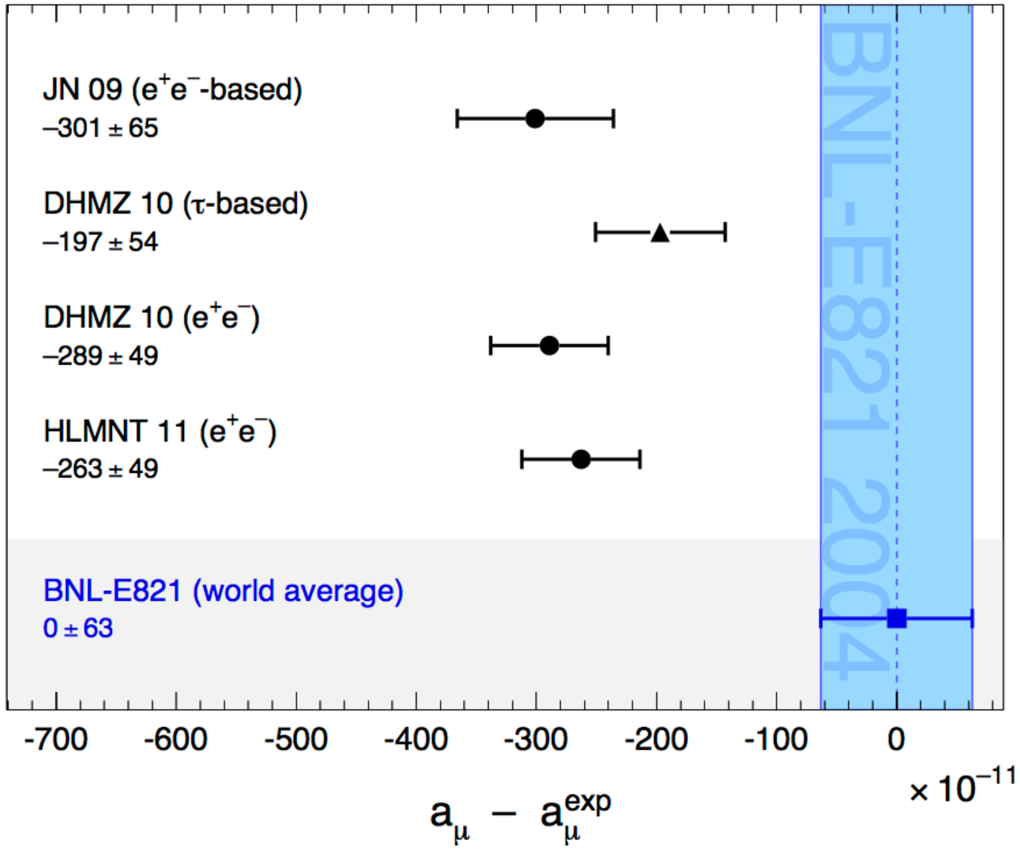
Muon g-2

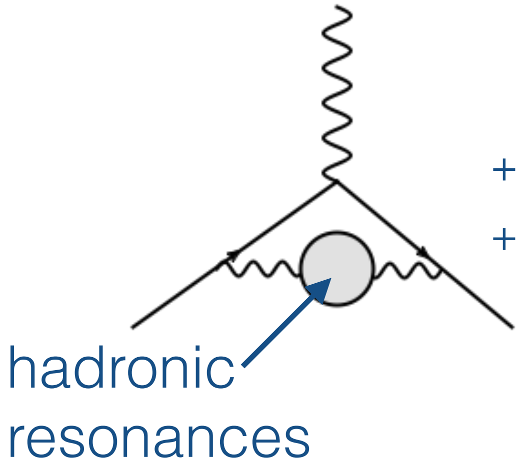
http://pdg.lbl.gov/2015/reviews/rpp2015-rev-g-2-muon-anom-mag-moment.pdf

- **Long-standing tension in muon g-2 at level of 3.6σ.**

$$\Delta a_\mu = (288 \pm 63(\mathrm{Exp.}) \pm 49(\mathrm{SM})) \times 10^{-11}$$

- New muon g-2 experiment will start soon at Fermilab.
- SM prediction limited by hadronic uncertainties.
  - ➡ Hadronic contributions determined from e^+e^- data or τ-decays.
  - ➡ Prospect for improvement using lattice in the near future.

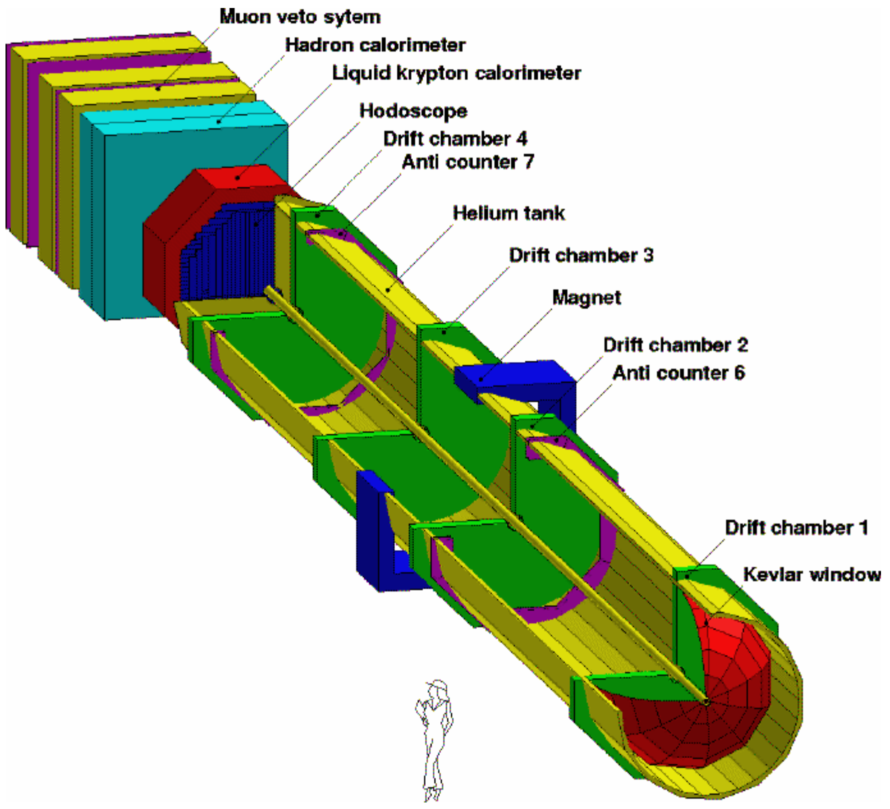




+ QED at 5-loop,
+ EWK at 3-loop.

CP violation in the kaon system

- Direct *CP* violation observed in the kaon system by the NA48 experiment at CERN & KTeV at Fermilab.



- Experimental result for **ϵ'/ϵ**:

$$\mathrm{Re}(\epsilon'/\epsilon) = (16.5 \pm 2.3) \times 10^{-4}$$

where $$\mathrm{Re}(\epsilon'/\epsilon) \approx \frac{1}{6}\left(1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right)$$

Probes direct *CP* violation Probes indirect *CP* violation

$$\eta_{00} = \frac{\mathcal{A}(K_\mathrm{L} \to \pi^0\pi^0)}{\mathcal{A}(K_\mathrm{S} \to \pi^0\pi^0)} \quad \eta_{+-} = \frac{\mathcal{A}(K_\mathrm{L} \to \pi^+\pi^-)}{\mathcal{A}(K_\mathrm{S} \to \pi^+\pi^-)}$$

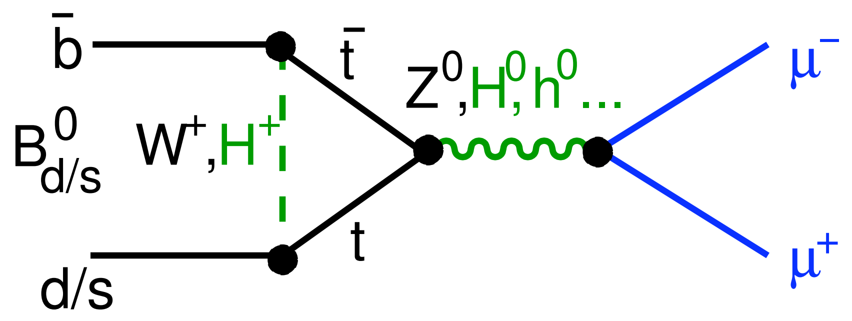
- Recent lattice inputs give

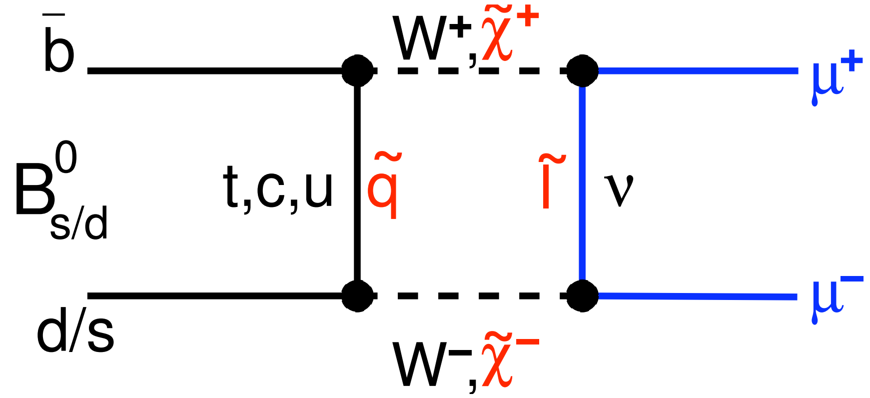
$$\mathrm{Re}(\epsilon'/\epsilon) = (1.9 \pm 4.5) \times 10^{-4}$$ **[Buras et al, JHEP 11 (2015) 202]**

➡ **Compatibility at the level of 2.6σ.**

Rare leptonic decays

- $B_s \to \boldsymbol{\mu}^+\boldsymbol{\mu}^-$ is a golden mode to study FCNCs at the LHC.
  - ➡ CKM suppressed, loop suppressed and helicty suppressed.
  - ➡ Powerful probe of models with new or enhanced scalar/pseudoscalar interactions, e.g. SUSY at high tan$\boldsymbol{\beta}$.





Rare leptonic decays

- $B_s \to \boldsymbol{\mu}^+\boldsymbol{\mu}^-$ is a golden mode to study FCNCs at the LHC.
  - ➡ Predicted precisely in the SM (6% uncertainty on branching fraction). **[Bobeth et al. PRL 112 (2014) 101801]**
  - ➡ Depends on single decay constant: $\langle 0|\bar{s}\gamma^\mu\gamma_5 b|B\rangle = i f_B p^\mu$

$$\mathrm{BR}(B_q \to \ell^+\ell^-)_{\mathrm{SM}} = \tau_{B_q} \frac{G_F^2 \alpha_{\mathrm{em}}^2}{16\pi^2} f_{B_q}^2 m_\ell^2 m_{B_q} \sqrt{1 - \frac{4m_\ell^2}{m_{B_q}^2}} |V_{tb}V_{tq}^*|^2 |C_{10}^{\mathrm{SM}}|^2$$

4% uncertainty

4% uncertainty

BR($B_{(s,d)} \to \mu^+\mu^-$)

- Combined measurement by LHCb and CMS gives

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

  ➡ B_s decay observed at 6.2σ, evidence for B^0 decay at 3.0σ.

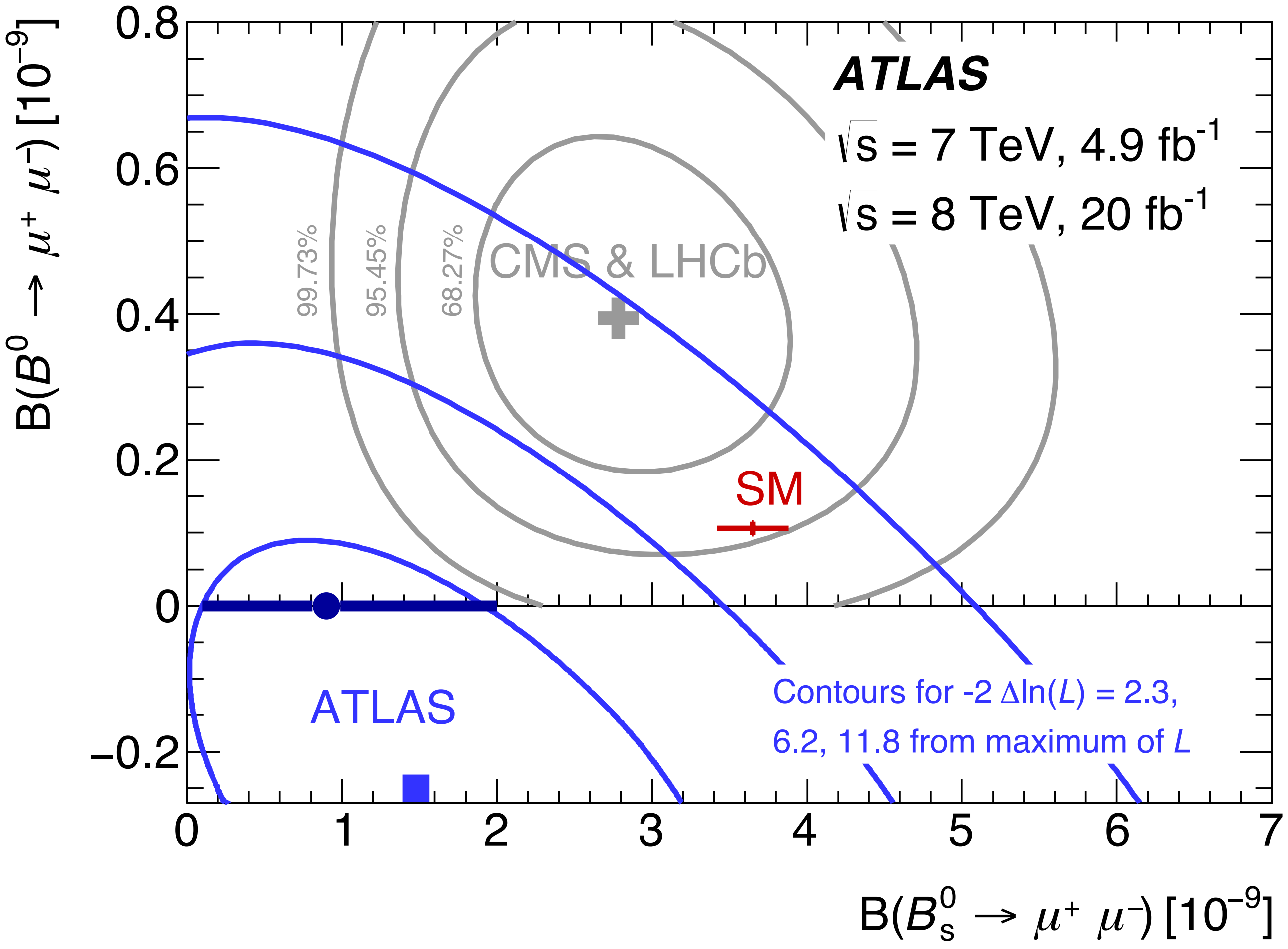
  ➡ Compatible with SM predictions at 1.2σ (Bs) and 2.2σ (B^0).

  [CMS & LHCb, Nature, 522 (2015) 68]

- ATLAS sets an upper limit of:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 3.0 \times 10^{-9}$$

  [ATLAS collaboration, arXiv:1604.04263]

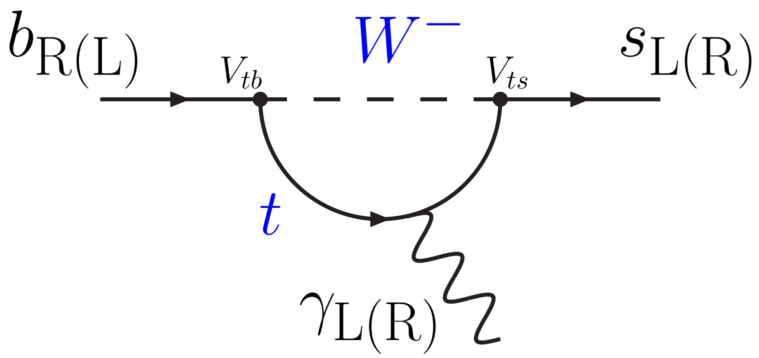


SM predictions from [Bobeth et al. PRL 112 (2014) 101801]

Properties of ΔF = 1 processes

Can also look at other properties of the decays:

- In the SM, photons from *b*→*sγ* decays are predominantly left-handed ($C_7/C'_7 \sim m_b/m_s$) due to the charged-current interaction.

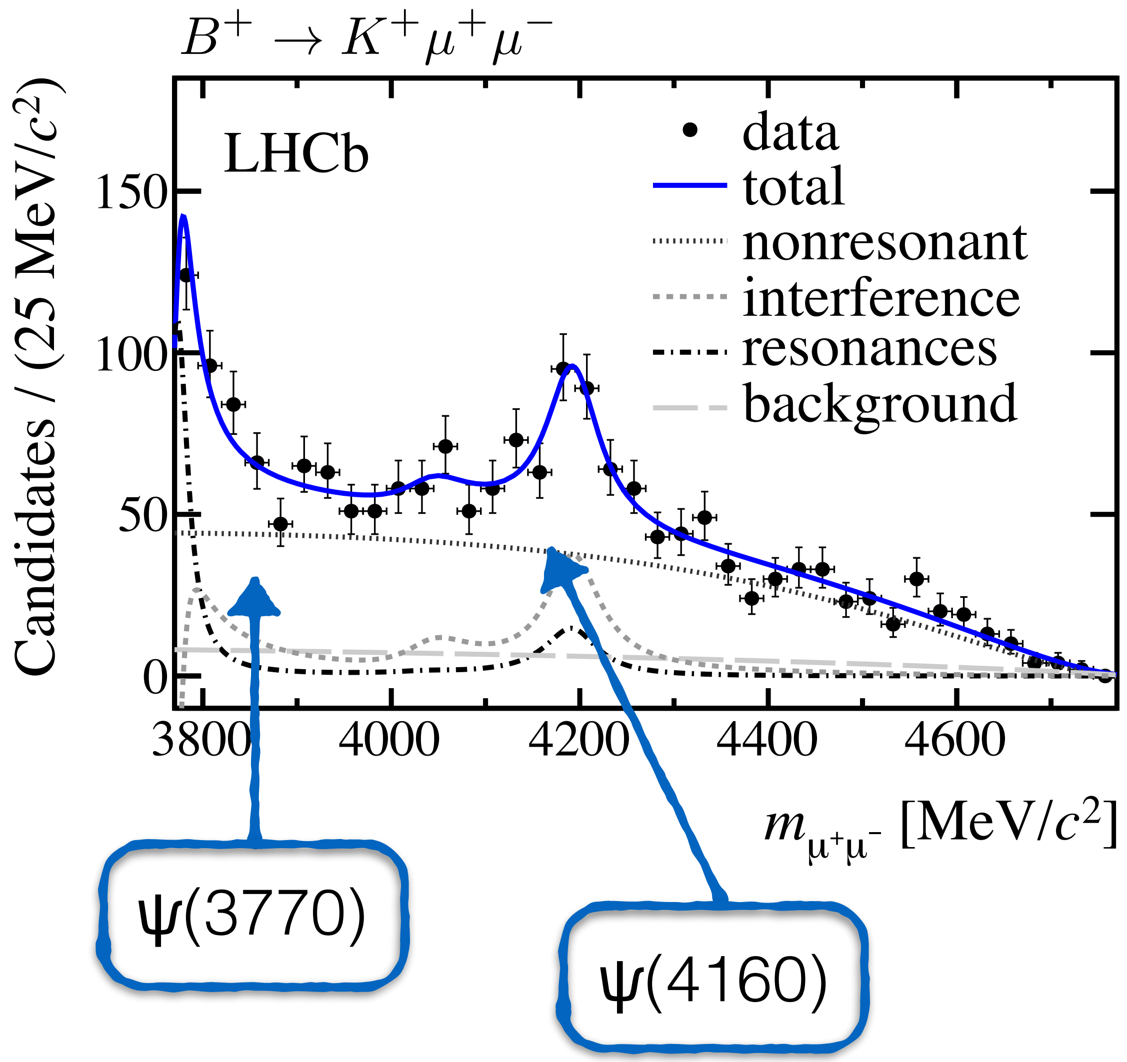


- Flavour structure of SM implies that the rate of *b*→*d* processes is suppressed by $|V_{td}/V_{ts}|^2$ compared to *b*→*s* processes.
- In the SM, the rate $\Gamma[B \to M\mu^+\mu^-] \approx \Gamma[B \to Me^+e^-]$ due to the universal coupling of the gauge bosons (except the Higgs) to the different lepton flavours. Any differences in the rate are due to phase-space.
- Lepton flavour violation is unobservable in the SM at any conceivable experiment due to the small size of the neutrino mass.

Resonance structure

- See large resonant contributions from $c\bar{c}$ states at large dimuon masses.
- We can fit this with a Breit-Wigner ansatz (but only after assuming some q^2 parameterisation for the non-resonant part) to extract magnitudes and relative phases.

i.e. use a shape



ψ(3770)

ψ(4160)

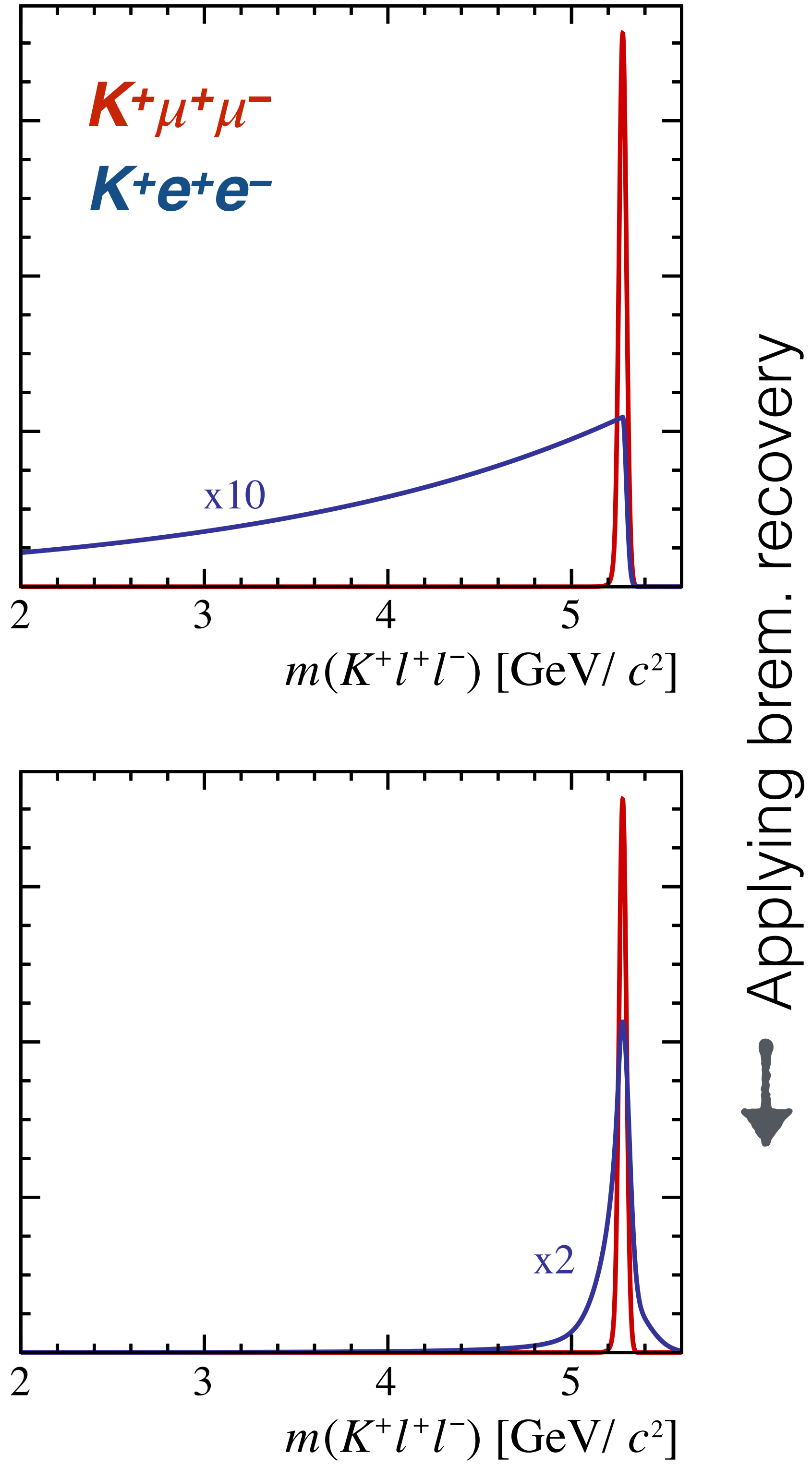
[LHCb, PRL 111 (2013) 112003]

$$\text{phsp} \times (|\mathcal{A}_{\rm V}(m_{\mu\mu}) + \sum_i e^{i\phi_i}\mathcal{A}_i(m_{\mu\mu}, \mu_i, \Gamma_i)|^2 + |\mathcal{A}_A|^2) f_+^2(m_{\mu\mu})$$

for narrow states this needs to be convoluted by our experimental resolution

Bremsstrahlung recovery

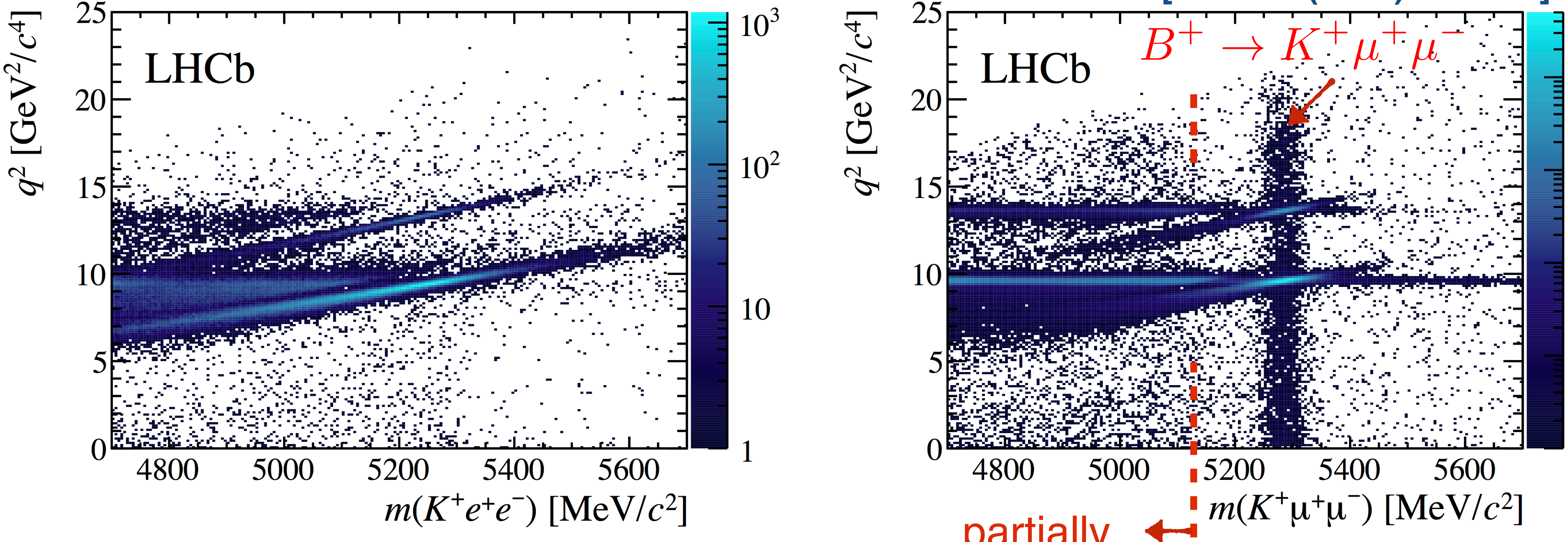
- Two big experimental differences between electrons/muons:
    - ➡ Bremsstrahlung/FSR from the electrons.
    - ➡ Typically require higher trigger thresholds for electrons than muons ($E_T > 3$ GeV c.f. $p_T > 1.76$ GeV/c in 2012) and have a lower tracking efficiency.
- Bremsstrahlung causes migration of events in q^2 and in reconstructed B mass.
    - ➡ Recover clusters with $E_T > 75$ MeV/c^2 to correct for Bremsstrahlung.



$B^+ \rightarrow K^+\ell^+\ell^-$ candidates

- Even after Bremsstrahlung recovery there are significant differences between dielectron and dimuon final states:

LHCb [PRL113 (2014) 151601]



$B^+ \rightarrow K^+\mu^+\mu^-$

partially reconstructed decays

$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

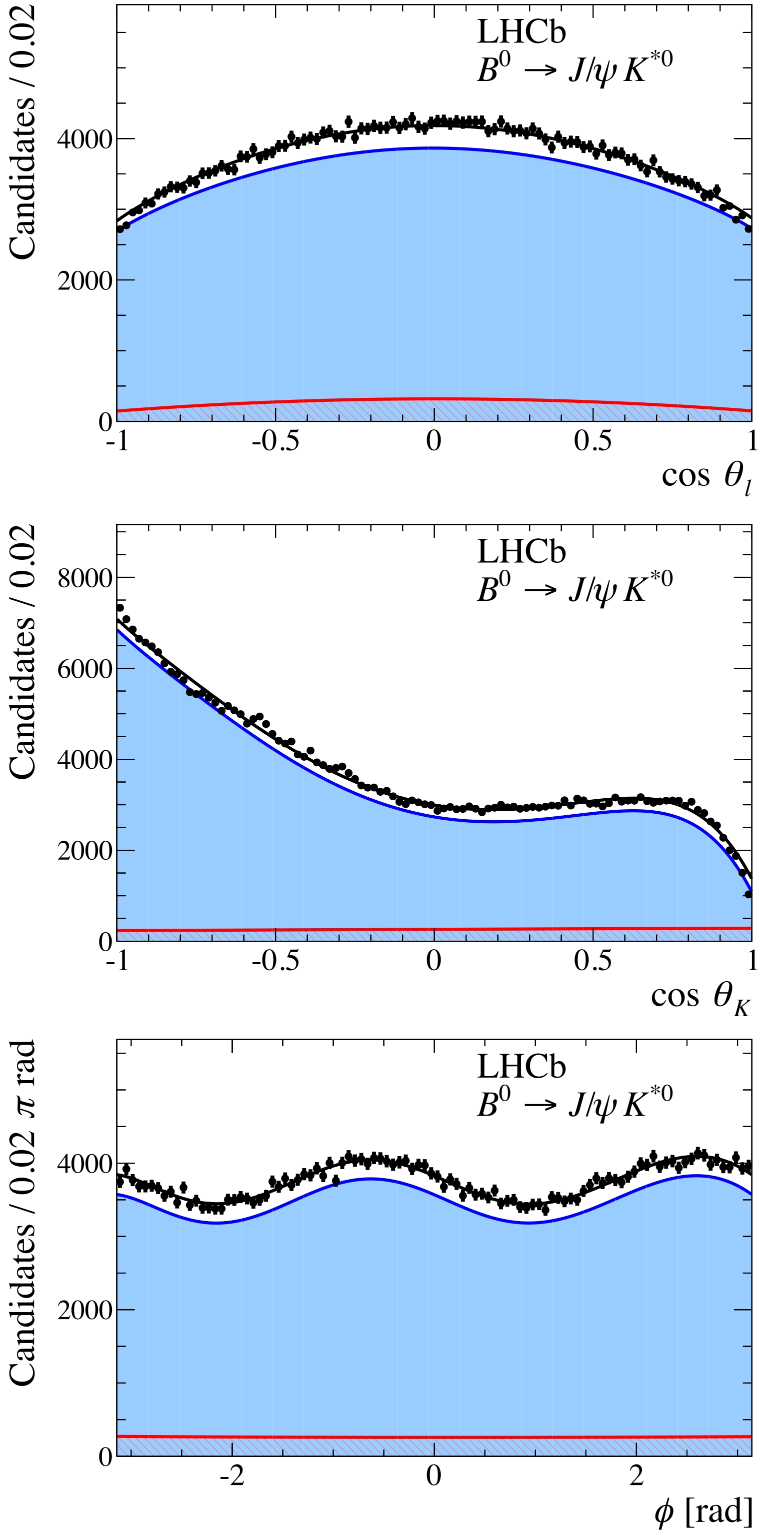
- LHCb has performed the first full angular analysis of the decay.
- Perform an unbinned maximum likelihood fit to the $K\pi\mu^+\mu^-$ mass and the three decay angles in bins of q^2.
    - ➡ Simultaneously fit the $K\pi$ mass to constrain contributions where the $K\pi$ is in an S-wave configuration.
- Model efficiency in four-dimensions:

$$\varepsilon(\cos\theta_l, \cos\theta_K, \phi, q^2) = \sum_{ijmn} c_{ijmn} L_i(\cos\theta_l) \times L_j(\cos\theta_K) L_m(\phi) L_n(q^2)$$

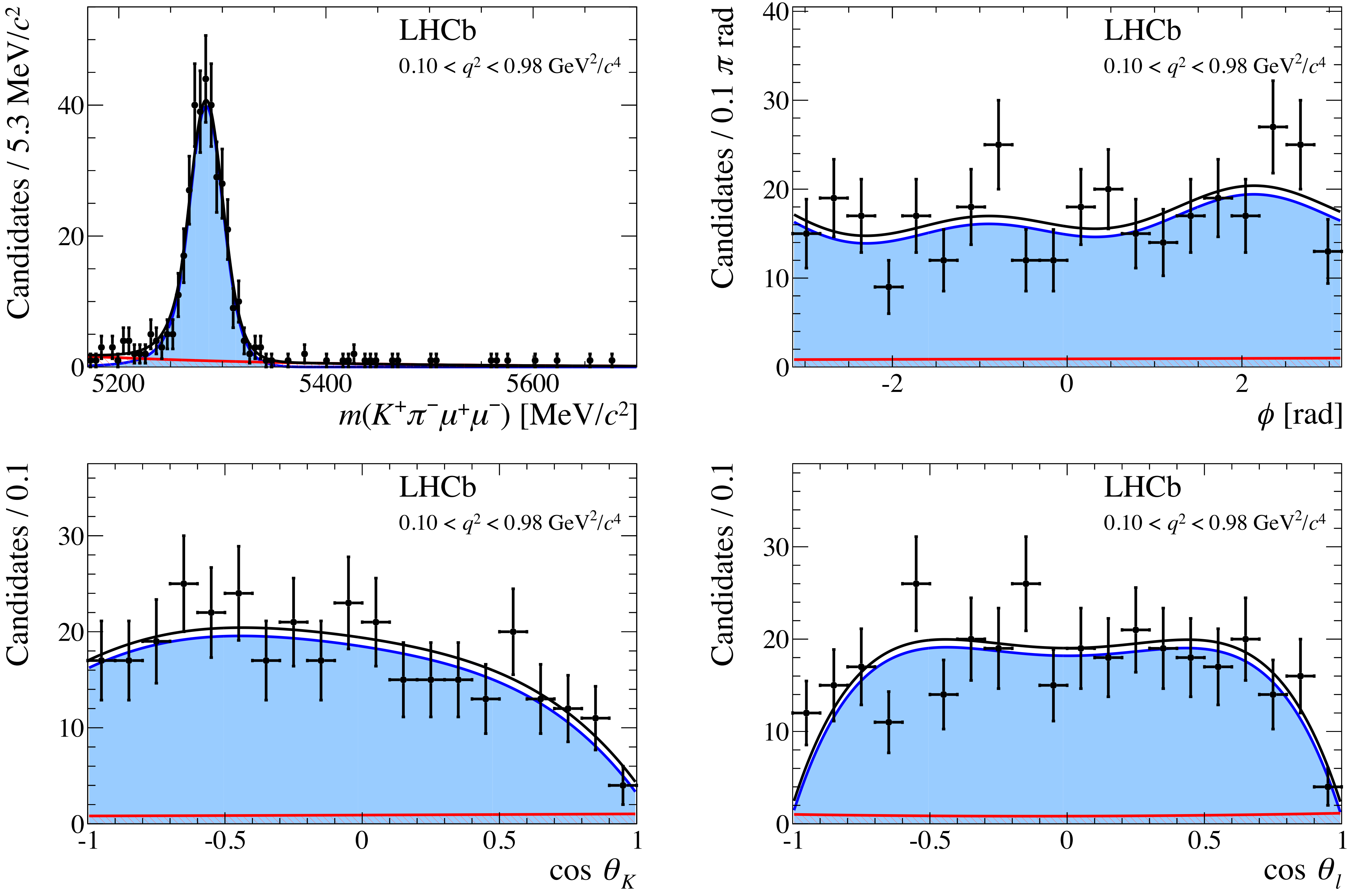
Legendre polynomial of degree *i*.

- Use $B^0 \to J/\psi K^{*0}$ as a control channel to understand the acceptance of the detector.

[LHCb, JHEP 02 (2016) 104]

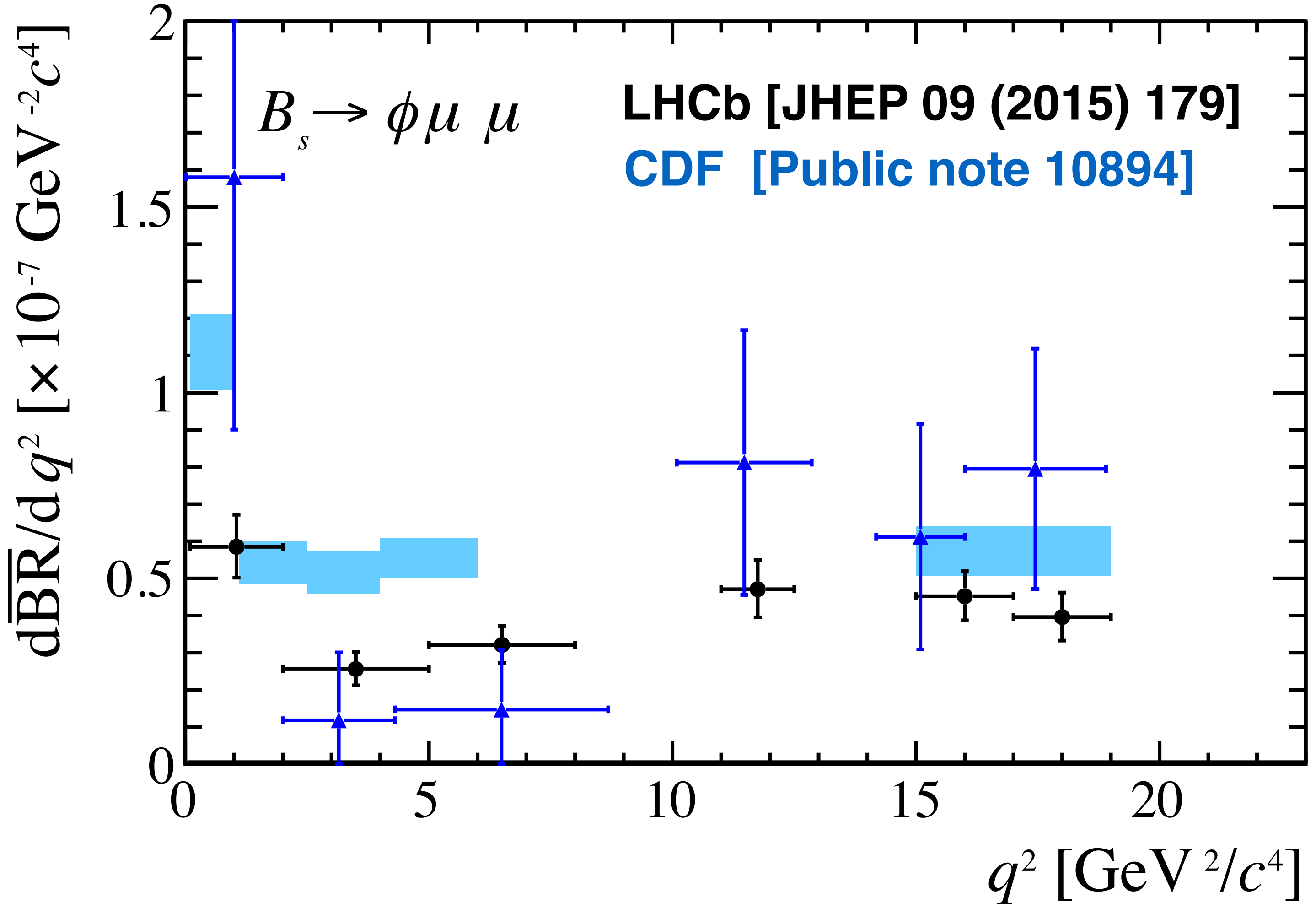


$B^0 \to K^{*0}\mu^+\mu^-$ example fit



$B_{(s,d)} \to \phi \mu^+ \mu^-$ decay rate

- 7 form-factors.
- Enhancement at low q^2 from virtual photon.
- Large tension between the SM prediction and the data at low q^2 (~3σ).



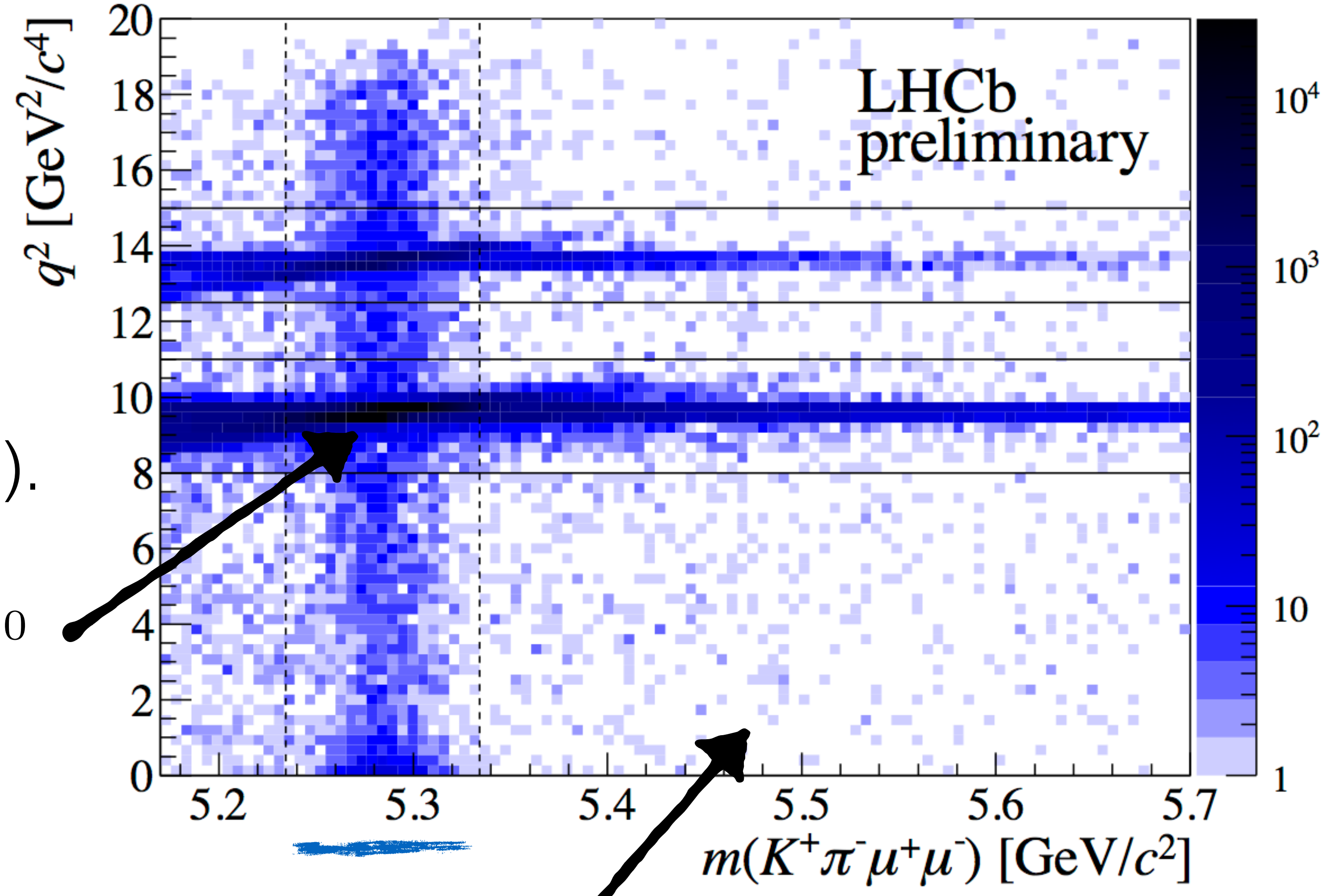
SM predictions based on
[Altmannshofer & Straub, arXiv:1411.3161]
[LCSR form-factors from Bharucha, Straub & Zwicky, arXiv:1503.05534]

Reconstructed candidates

Select clean sample of signal events using multivariate classifier.

2398 ± 57 candidates in $0.1 < q^2 < 19$ GeV^2 after removing the J/ψ and $\psi(2S)$.

[LHCb-CONF-2015-002]



ψ(2S)

J/ψ

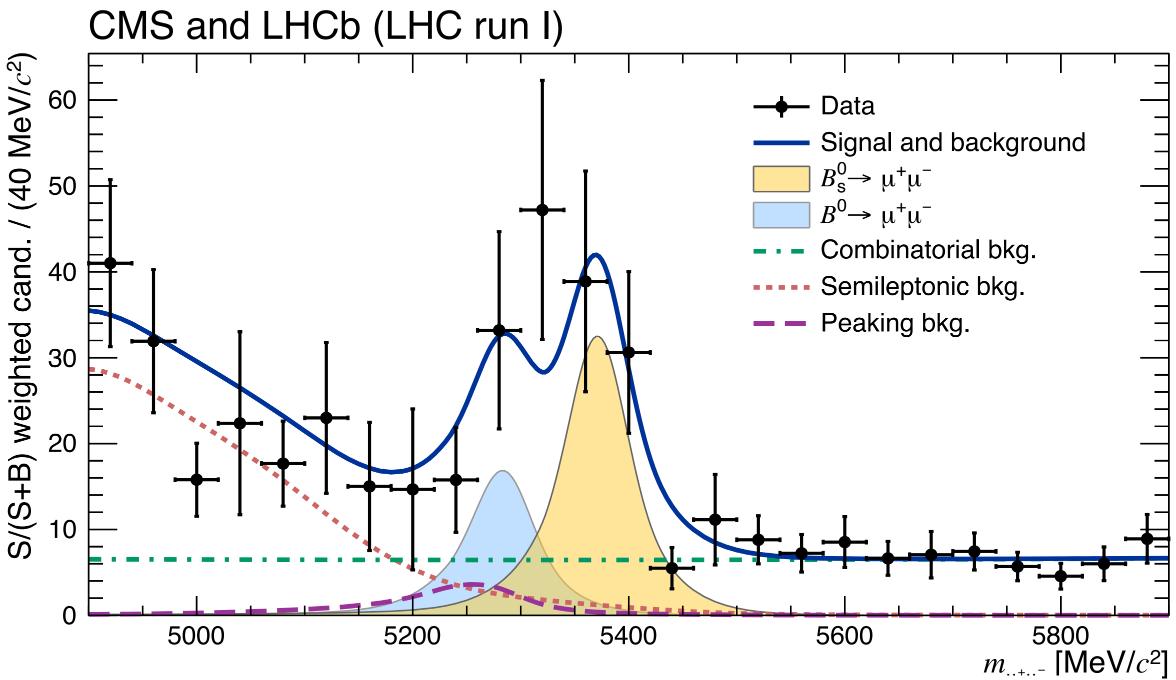
$B^0 \rightarrow J/\psi K^{*0}$

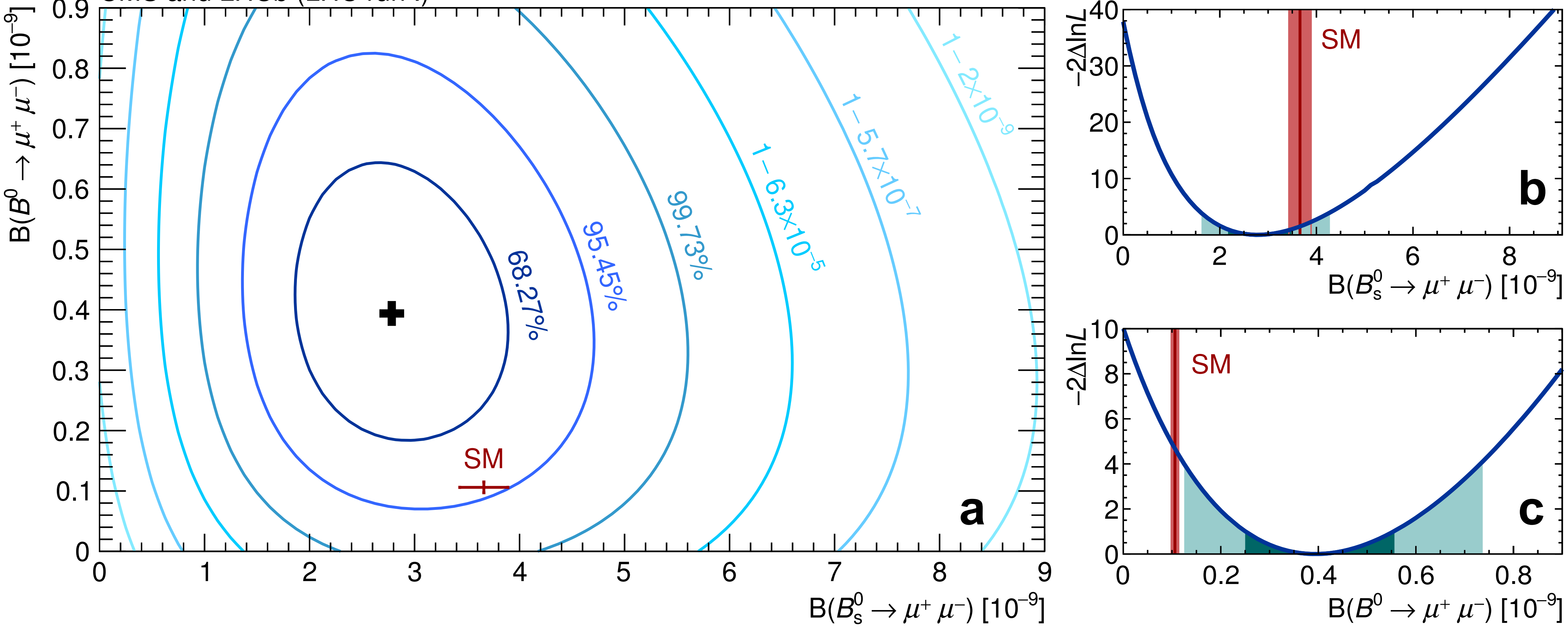
B^0

combinatorial background

$B_s \to \mu^+\mu^-$ combination

- Combining results from CMS and LHCb experiments from LHC run 1.
    - ➡ Observe B_s signal and evidence for B^0.





LHCb + CMS, Nature 522 (2015) 68, [arXiv:1411.4413]

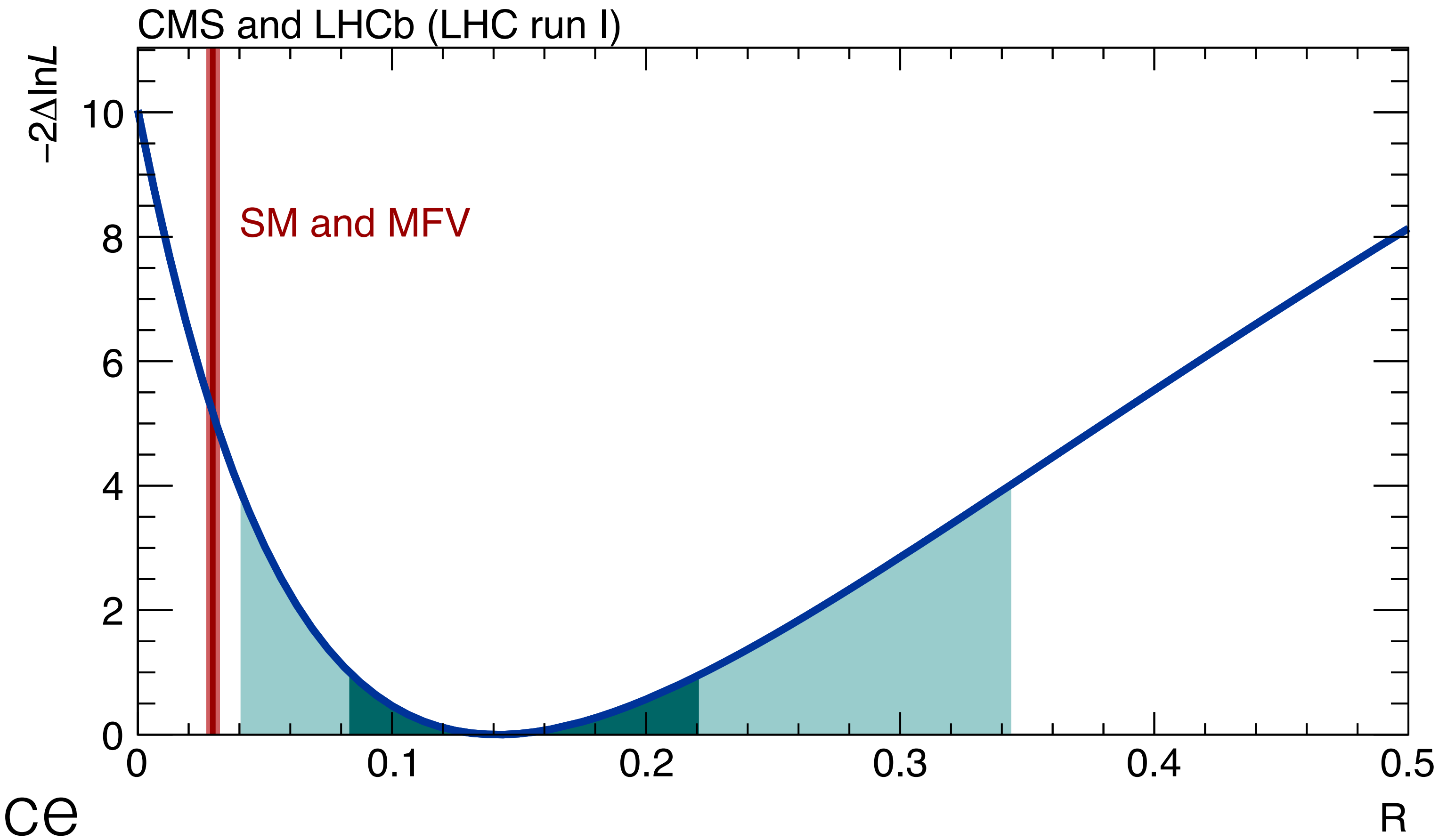
Testing MFV

- Ratio of the rates of the two decays is a test of MFV which predicts:

$$\mathcal{R}(B^0/B^0_s) \propto \frac{|V_{td}|^2}{|V_{ts}|^2}\frac{f^2_{B^0}}{f^2_{B^0_s}}$$

~1/25

from Lattice



LHCb + CMS, Nature 522 (2015) 68, [arXiv:1411.4413]

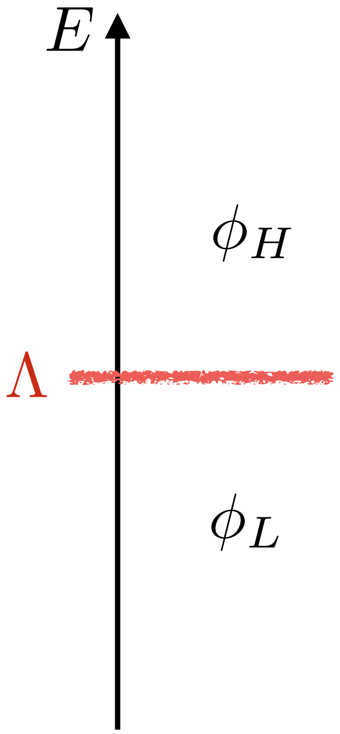
Data are consistent with SM/MFV

Effective theories

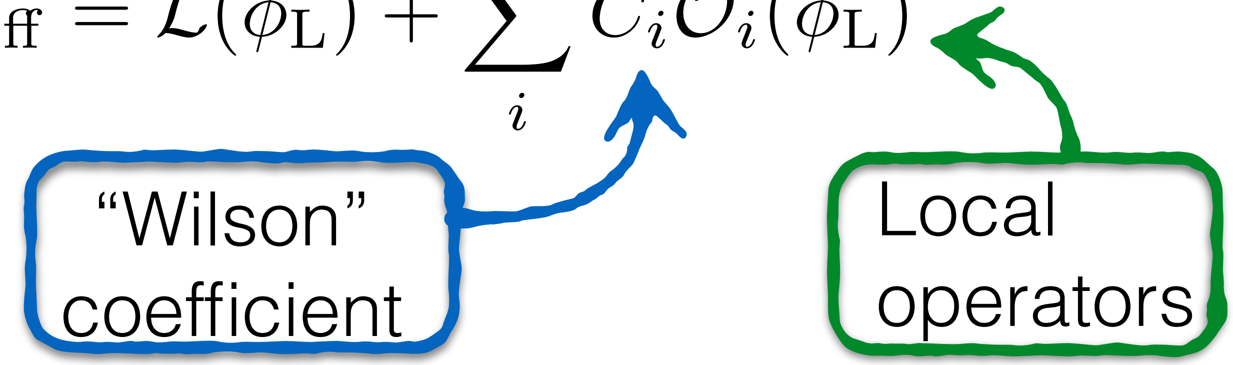
- In *b*-hadron decays there is a clear separation of scale.

$$m_W \gg m_b > \Lambda_{\rm QCD}$$

- We want to study the physics of the mixing/decay at or below a scale Λ, in a theory in which contributions from particles at a scale below and above Λ are present. Replace the full theory with an effective theory valid at Λ,

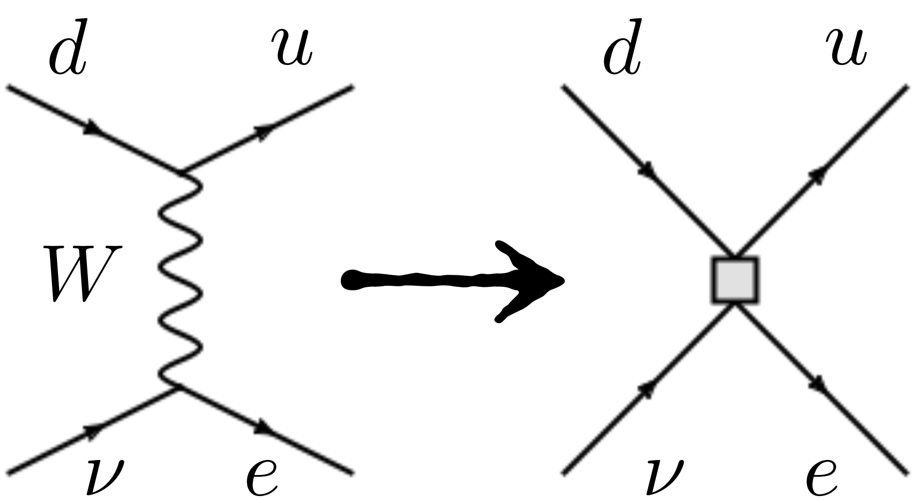


$$\mathcal{L}(\phi_{\rm L}, \phi_{\rm H}) \to \mathcal{L}(\phi_{\rm L}) + \mathcal{L}_{\rm eff} = \mathcal{L}(\phi_{\rm L}) + \sum_i C_i \mathcal{O}_i(\phi_{\rm L})$$



Example: Fermi theory

- In the Fermi model of the weak interaction, the full electroweak Lagrangian (which was unknown at the time) is replaced by the low-energy theory (QED) plus a single operator with an effective coupling constant.



$$\mathcal{L}_{\rm EW} \rightarrow \mathcal{L}_{\rm QED} + \frac{G_{\rm F}}{\sqrt{2}} (\overline{u}d)(e\bar{\nu})$$

At low energies:

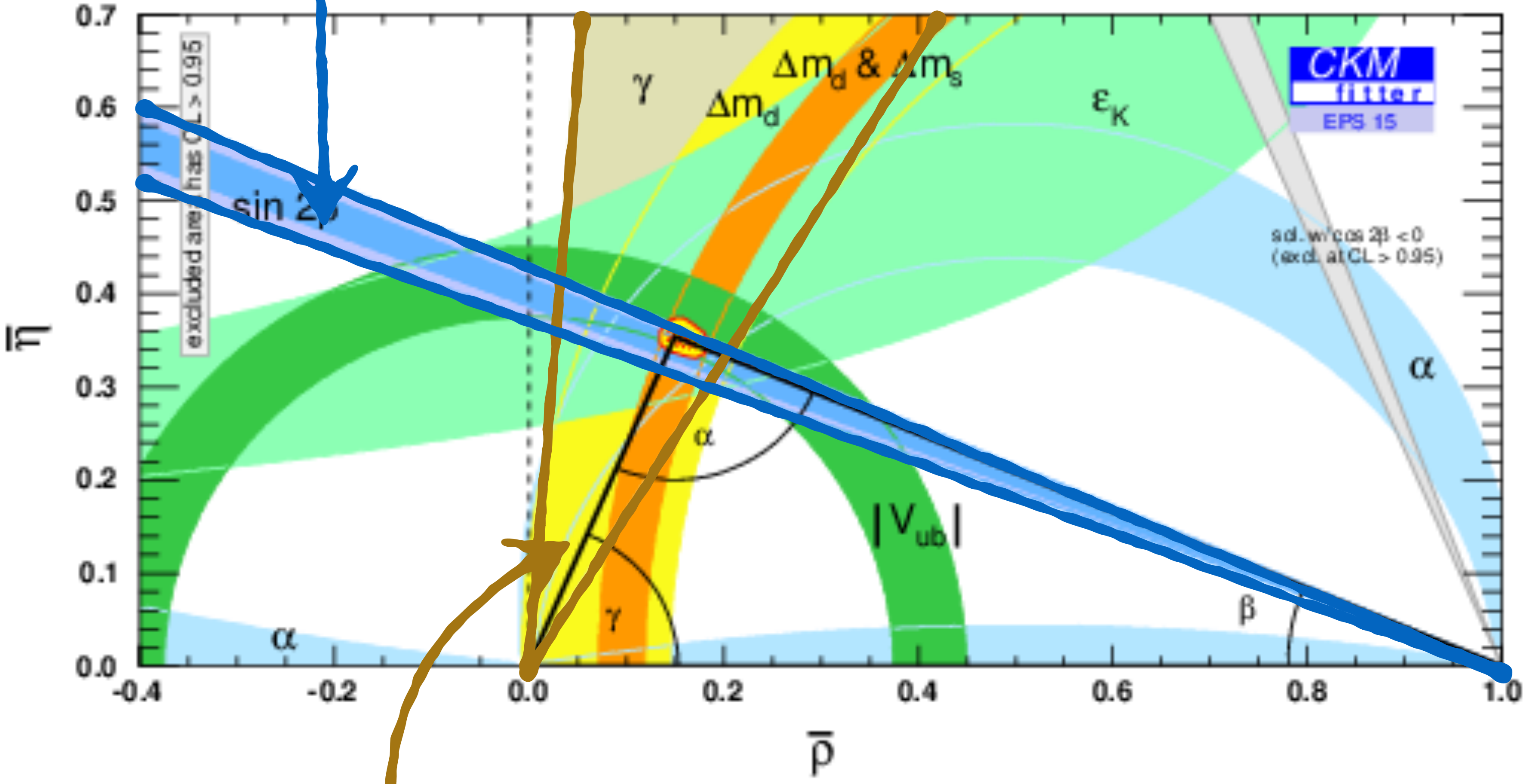
$$\lim_{q^2\to 0}\left(\frac{g^2}{m_W^2 - q^2}\right) = \frac{g^2}{m_W^2}$$

i.e. the full theory can be replaced by a 4-fermion operator and a coupling constant, $G_{\rm F}$.

Angles of the triangle

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

From time dependent *CP* violation in *B* system.



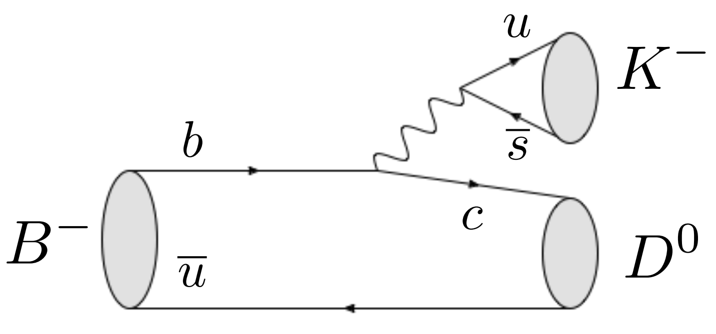
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)$$

From interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$

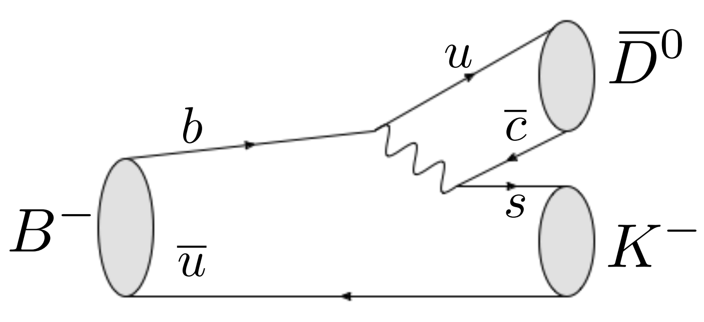
Angle γ

- From interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transitions.
- Need the D^0 and $\bar{D}^0$ to decay to a common final state.

eg Atwood, Dunietz and Soni method using $D^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^+\pi^-$.

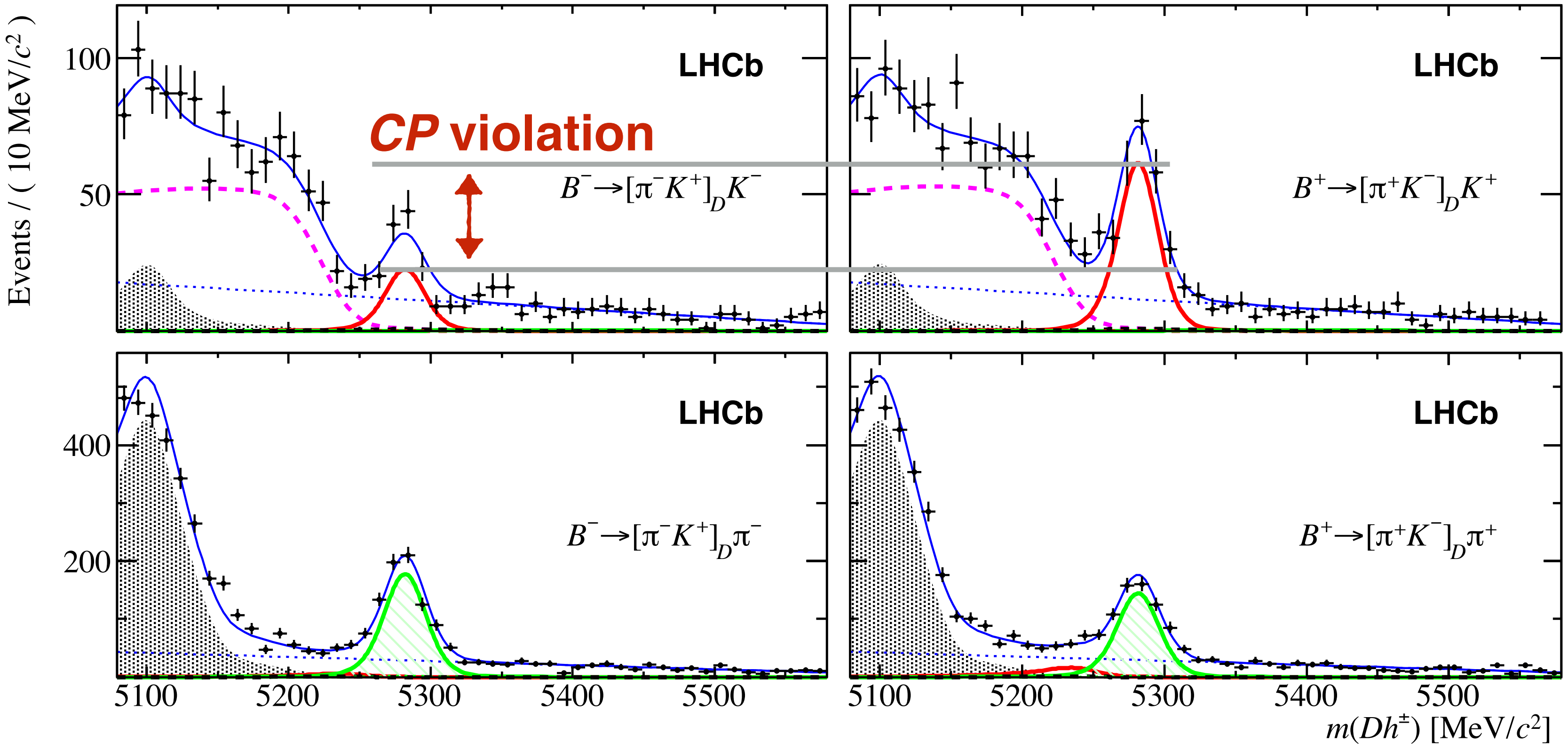


$V_{cb}V_{us}^*$



$V_{ub}V_{cs}^*$

[LHCb collaboration, PLB 760 (2016) 117]



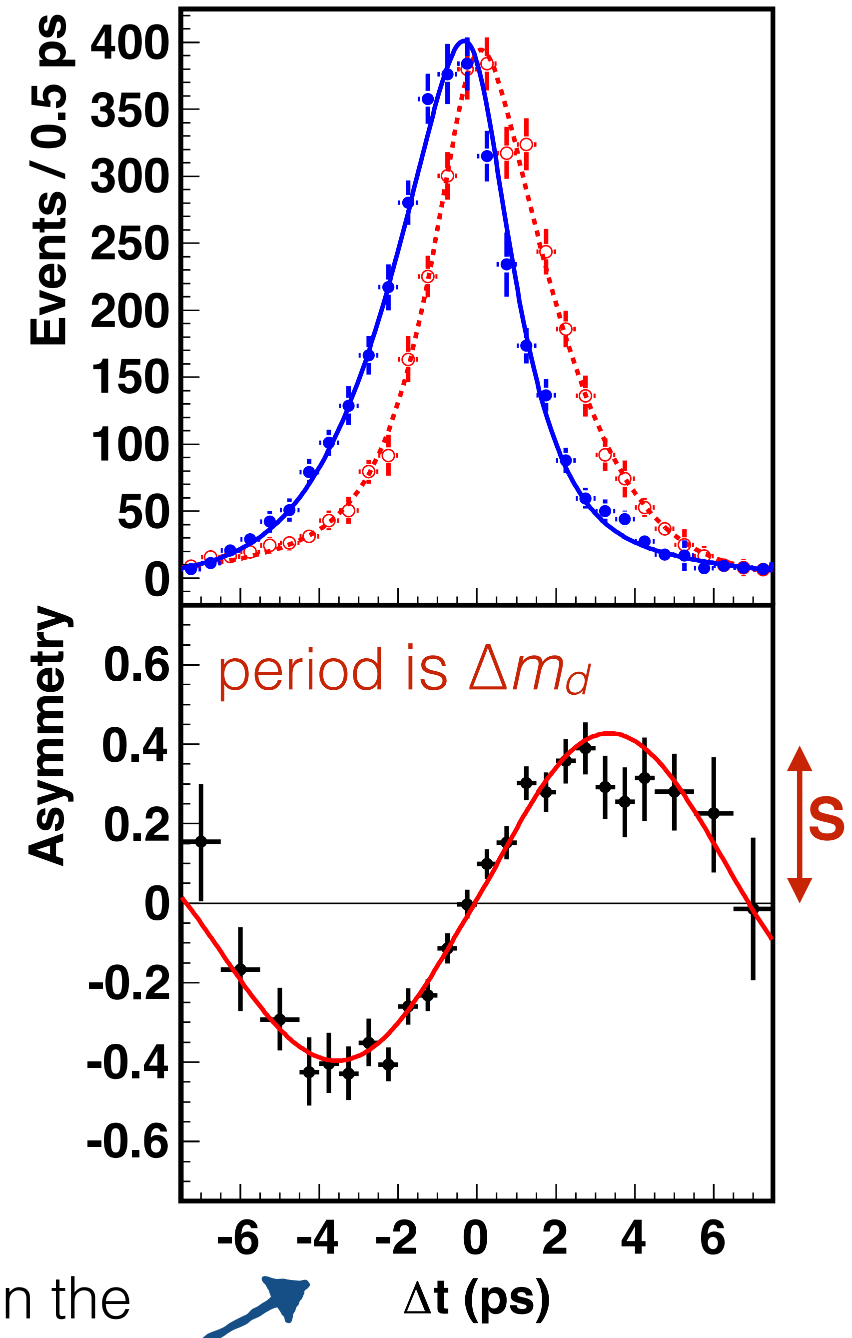
CP violation

Angle $\boldsymbol{\beta}$

- In B^0 mixing, phase is

$$\frac{q}{p} = \frac{V_{tb}^* V_{td} V_{tb}^* V_{td}}{|V_{tb}^* V_{td} V_{tb}^* V_{td}|} = e^{-2i\beta}$$

- Can be determined from the time-dependent *CP* asymmetry in $b \to c\bar{c}s$ and $\bar{b} \to c\bar{c}\bar{s}$ decays to a common final-state (e.g. $J/\psi K_{\rm S}$).



Belle PRL 108 171802 (2012) [arXiv:1201.4643]

Difference in time between the signal *B* decay and the decay of the other *B* in the event.