

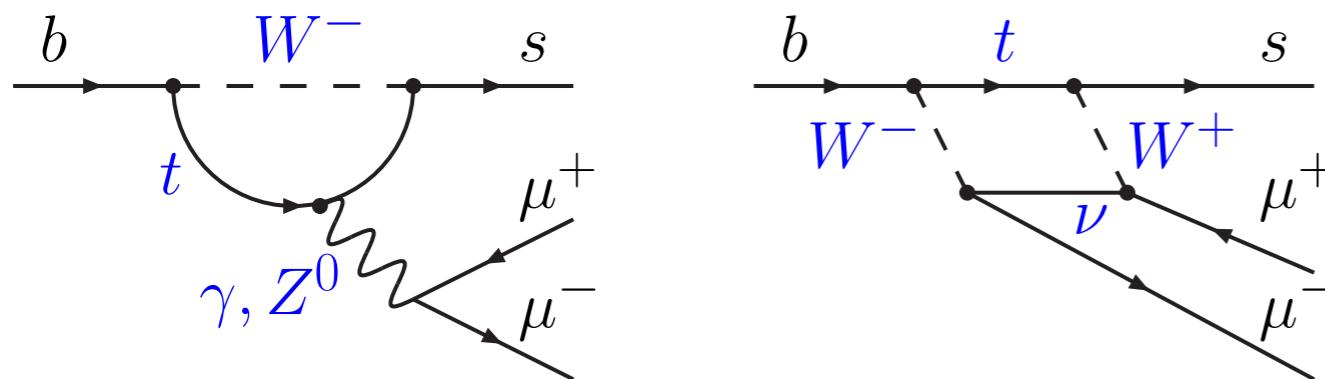
LHC results on FCNC beauty decays

T. Blake for the LHCb collaboration
(with results from ATLAS and CMS)

EPS Conference on High Energy Physics 2017

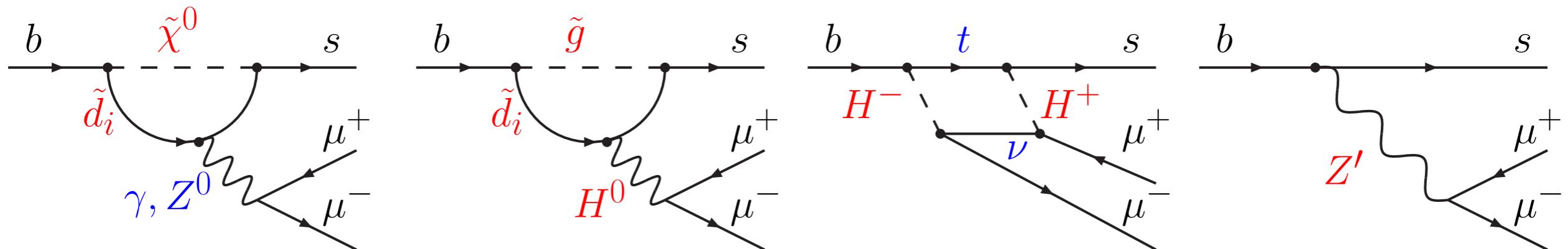
Rare FCNC decays

- 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 also contribute:



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

Outline

- Motivation
- Leptonic decays
 - $B_{(s,d)} \rightarrow \mu^+ \mu^-$ and $B_{(s,d)} \rightarrow \tau^+ \tau^-$
- Semileptonic $b \rightarrow s \ell^+ \ell^-$ -decays
 - Decay rates
 - Angular observables
 - Lepton flavour universality tests

Aim to give a quick overview of the experimental situation.

More detail in the talks by:

**Albert Puig (LHCb),
Carla Marin Benito (LHCb)
Stefano Lacaprara (CMS),
Umberto De Sanctis (ATLAS)**

More information can be found at

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults>

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH>

http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_RD.html

Effective theory

- Can write a Hamiltonian for an effective theory of $b \rightarrow s$ processes:

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

$$\Delta \mathcal{H}_{\text{eff}} = \frac{\kappa_{\text{NP}}}{\Lambda_{\text{NP}}^2} \mathcal{O}_{\text{NP}}$$

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

Wilson coefficient
(integrating out scales above μ)

Local 4 fermion operators with
different Lorentz structures

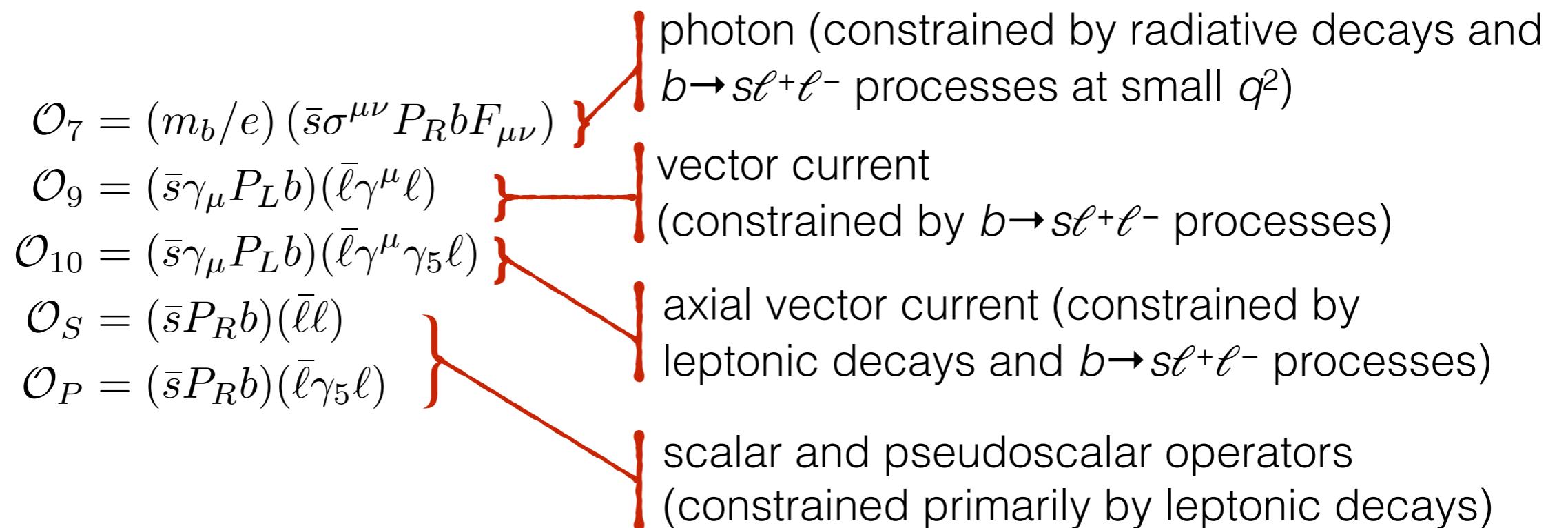
c.f. Fermi theory of weak interaction where at low energies:

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

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.



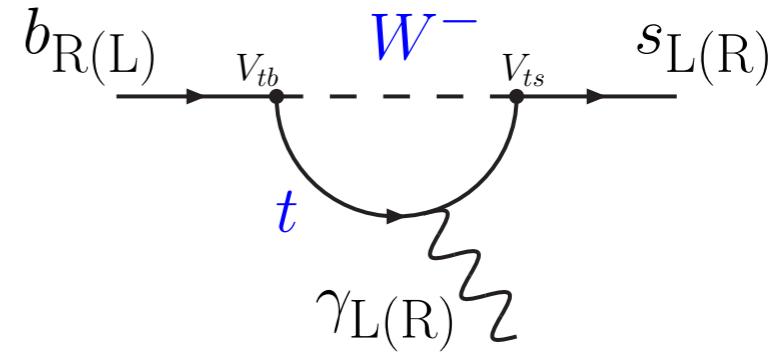
e.g.

$B_s^0 \rightarrow \mu^+ \mu^-$	constrains $C_{10} - C'_{10}$, $C_S - C'_S$, $C_P - C'_P$
$B^+ \rightarrow K^+ \mu^+ \mu^-$	constrains $C_9 + C'_9$, $C_{10} + C'_{10}$
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$	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.

Properties of $\Delta F = 1$ processes

- In the SM, photons from $b \rightarrow s\gamma$ 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 $b \rightarrow d$ processes is suppressed by $|V_{td}/V_{ts}|^2$ compared to $b \rightarrow s$ processes.
- In the SM, the rate $\Gamma[B \rightarrow M\mu^+\mu^-] \approx \Gamma[B \rightarrow Me^+e^-]$ 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 violating FCNC processes are unobservable in the SM at any conceivable experiment due to the small size of the neutrino mass.

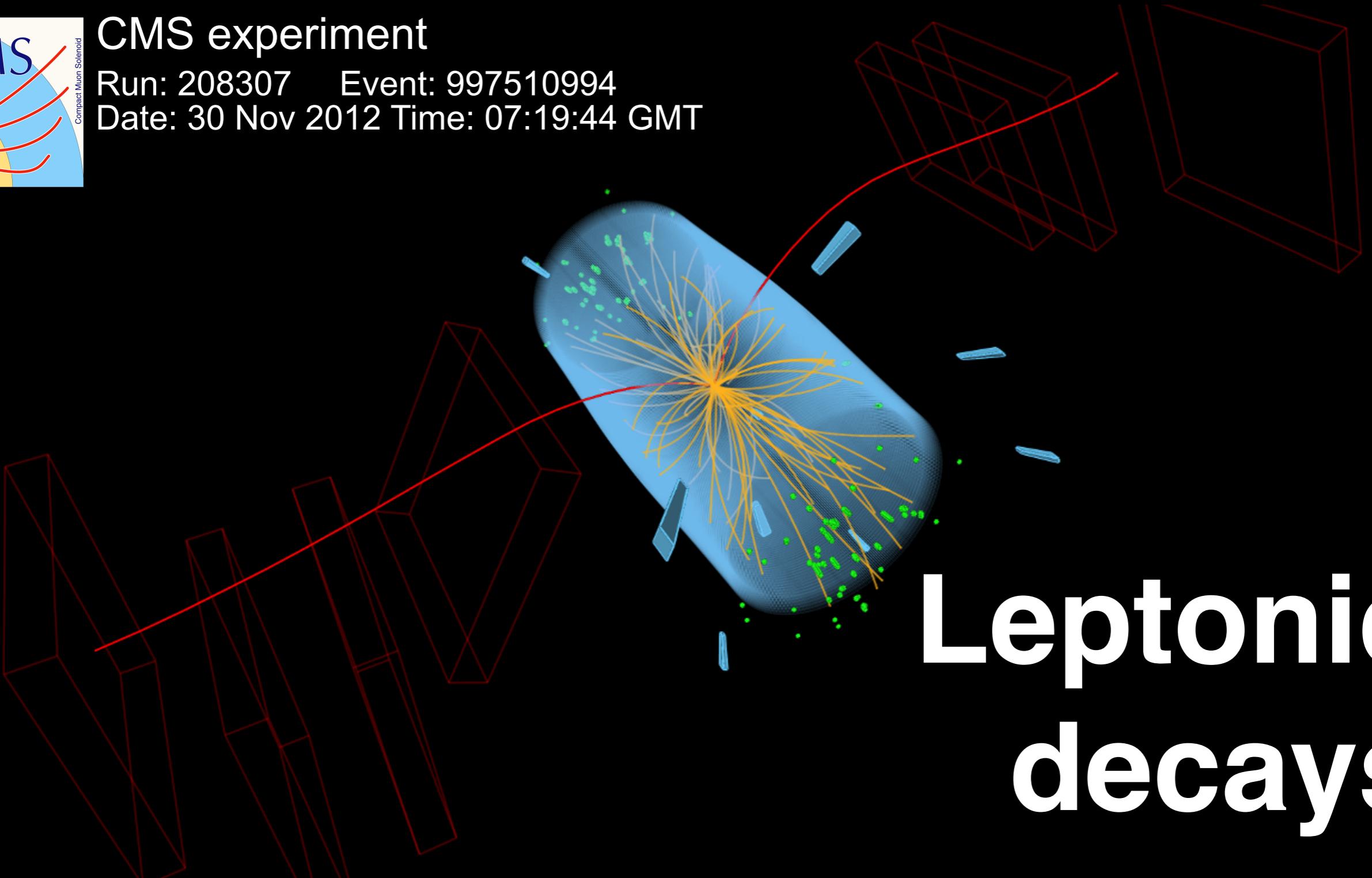




CMS experiment

Run: 208307 Event: 997510994

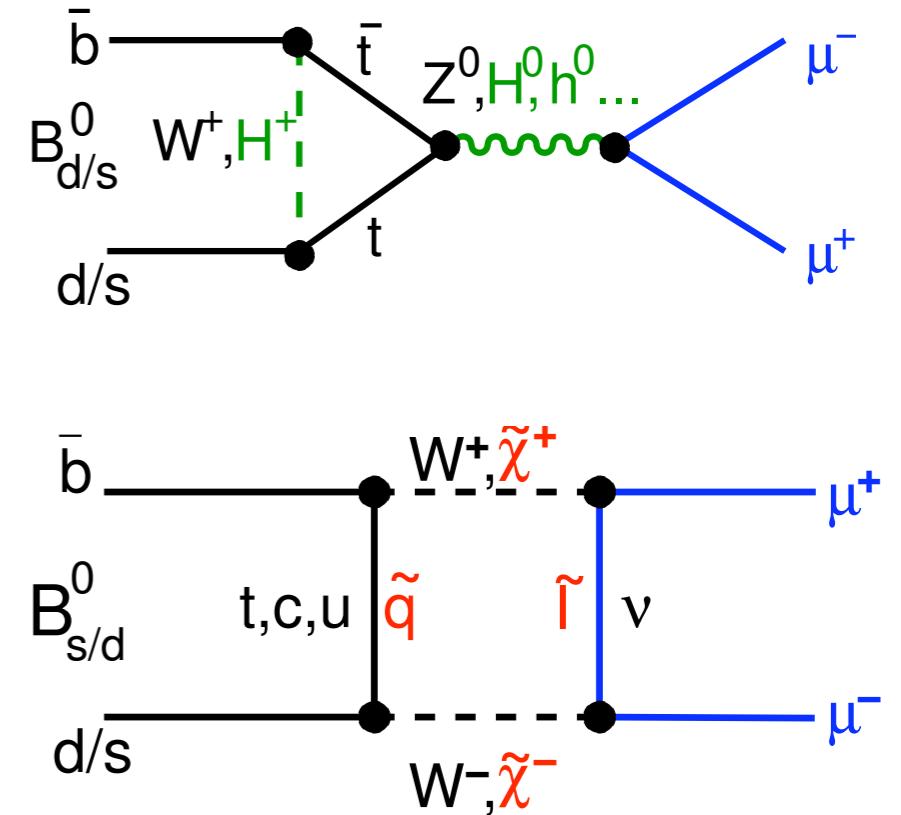
Date: 30 Nov 2012 Time: 07:19:44 GMT



Leptonic
decays

Rare leptonic decays

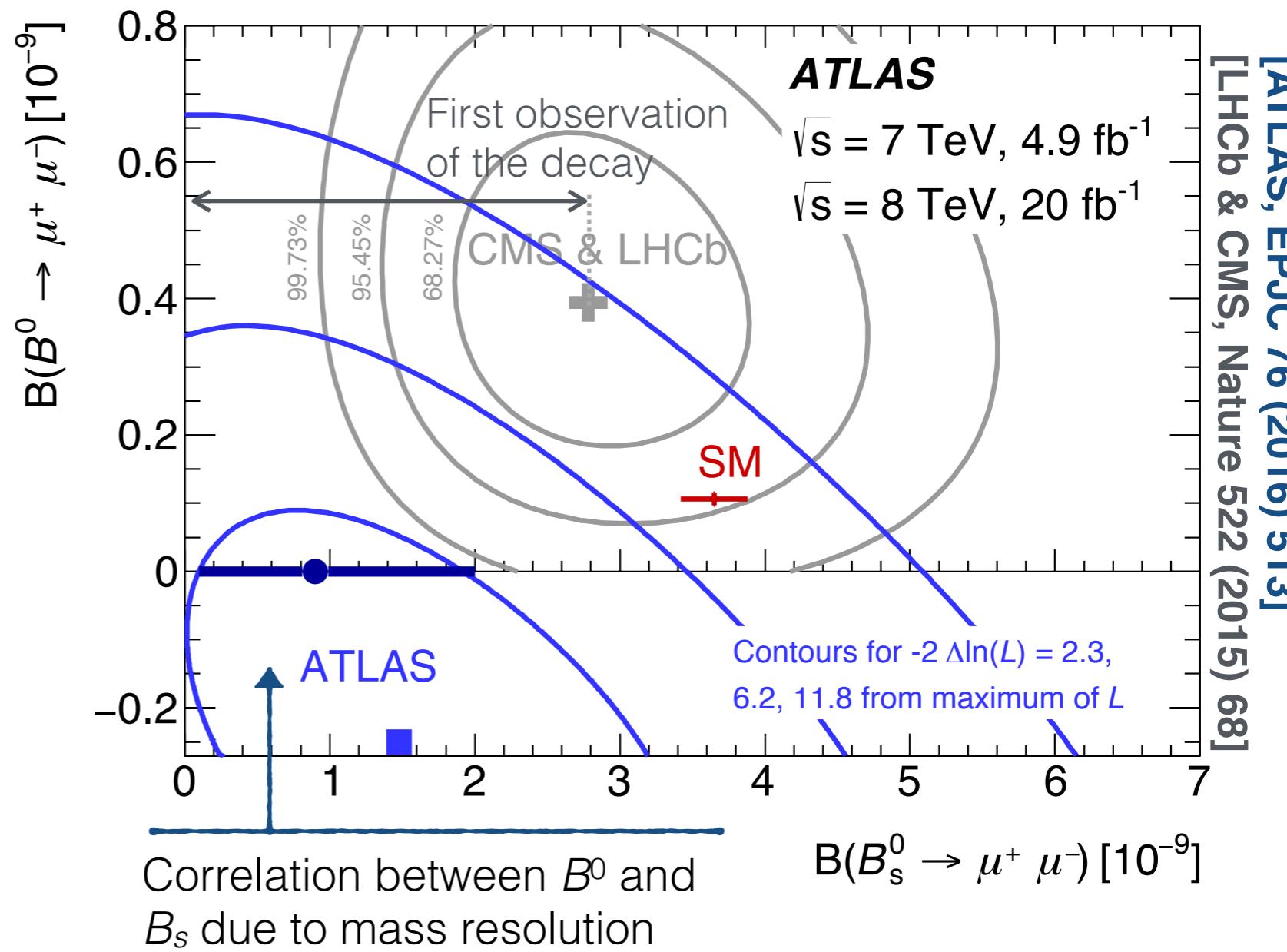
- $B_{(s,d)} \rightarrow \mu^+ \mu^-$ are golden modes to study at the LHC.
 - CKM suppressed, loop suppressed and helicity suppressed.
 - Powerful probe of models with new enhanced (pseudo)scalar interactions, e.g. SUSY at high $\tan\beta$.



$$\frac{\mathcal{B}(B_q \rightarrow \ell^+ \ell^-)_{\text{NP}}}{\mathcal{B}(B_q \rightarrow \ell^+ \ell^-)_{\text{SM}}} = \frac{1}{|C_{10}^{\text{SM}}|^2} \left\{ \left(1 - 4 \frac{m_\ell^2}{m_{B_q}} \right) \left| \frac{m_{B_q}}{2m_\ell} (C_S - C'_S) \right|^2 + \left| \frac{m_{B_q}}{2m_\ell} (C_P - C'_P) + (C_{10} - C'_{10}) \right|^2 \right\}$$

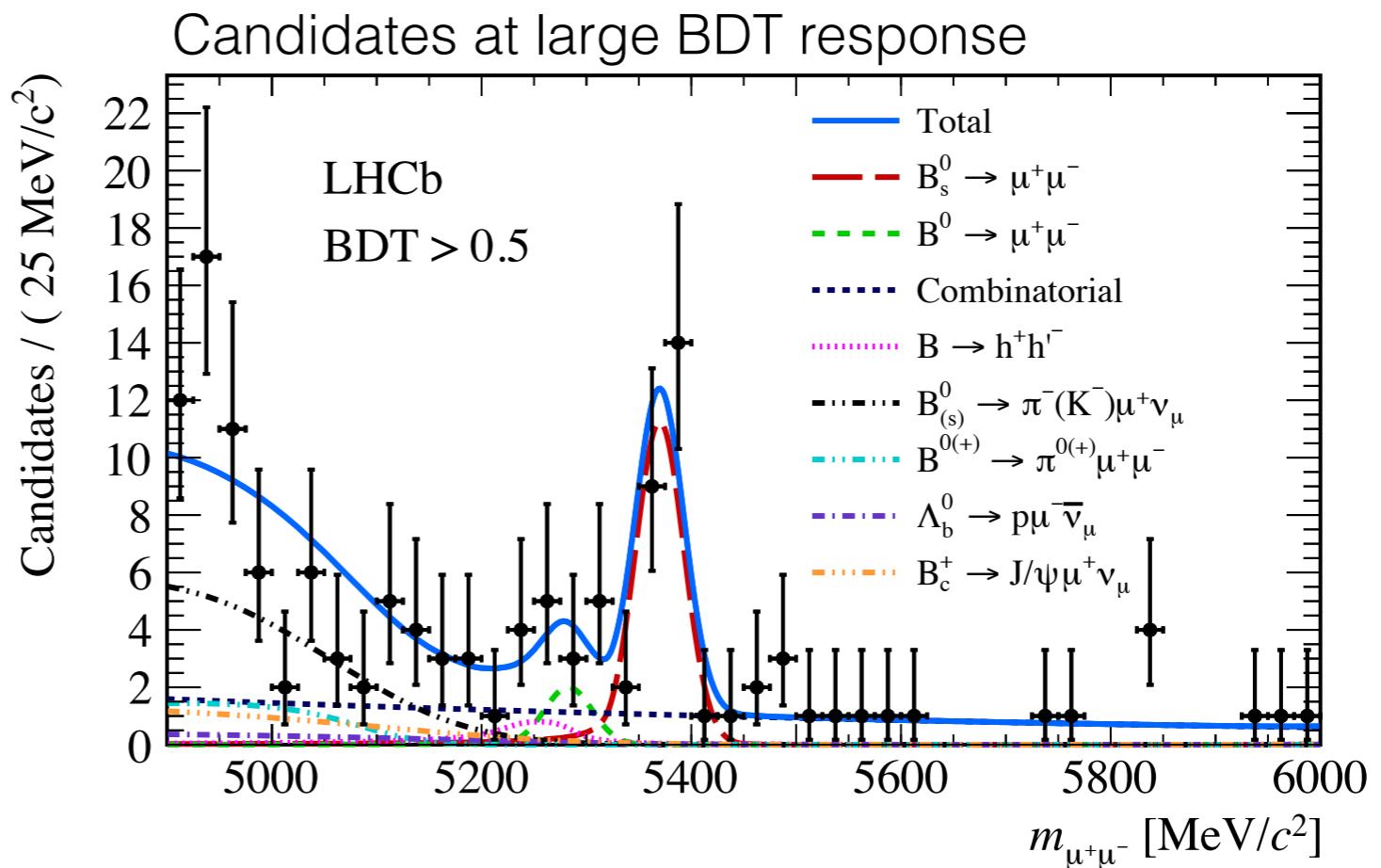
$B_s \rightarrow \mu^+ \mu^-$ fits

- Perform simultaneous fits to the bins of multivariate response to determine the B^0 and B_s branching fractions, e.g. for ATLAS
- Signal normalised to $B^+ \rightarrow J/\Psi K^+$ (plus $B \rightarrow K\pi$, $B_s \rightarrow J/\Psi \phi$ in LHCb), with input on the b -meson production fractions.



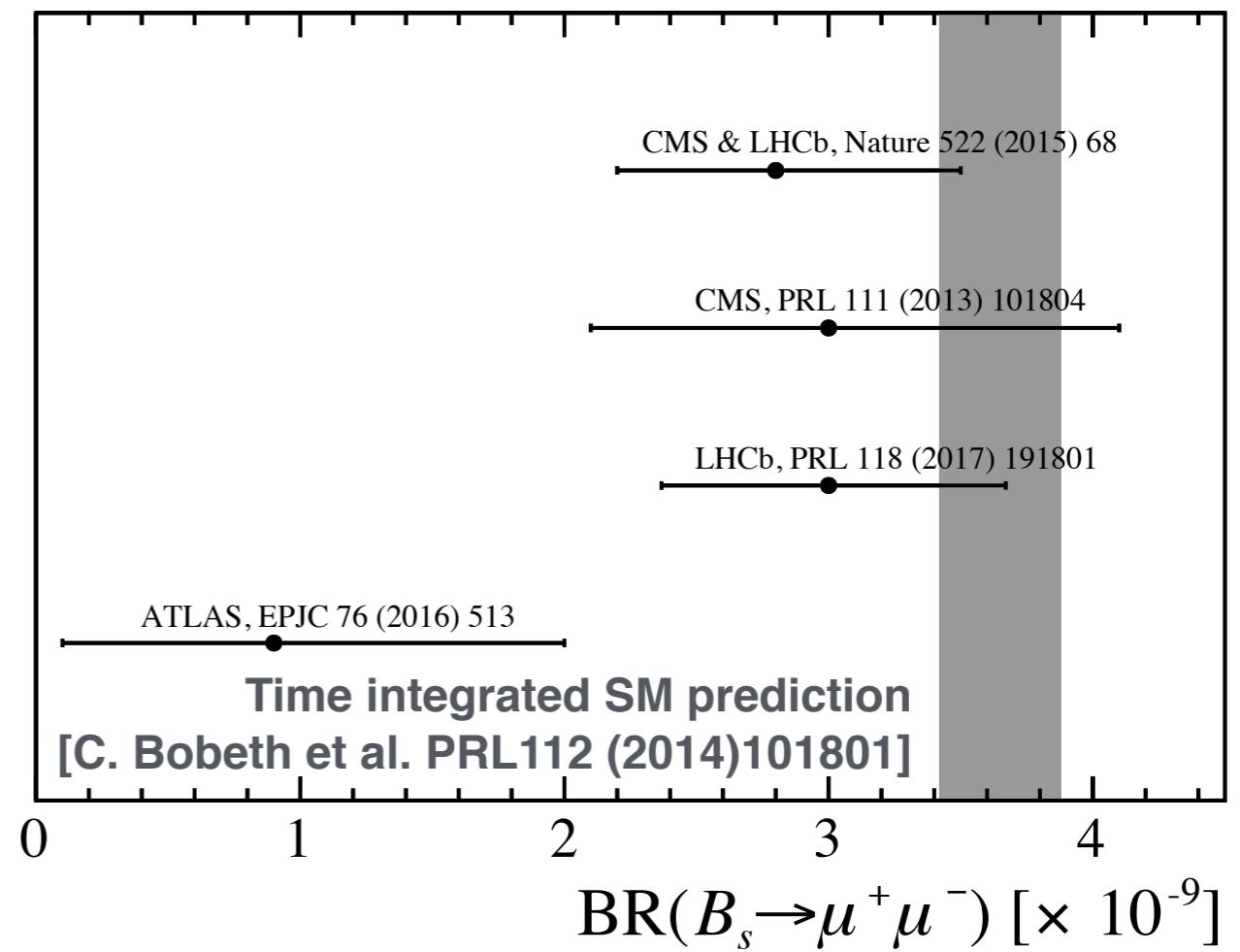
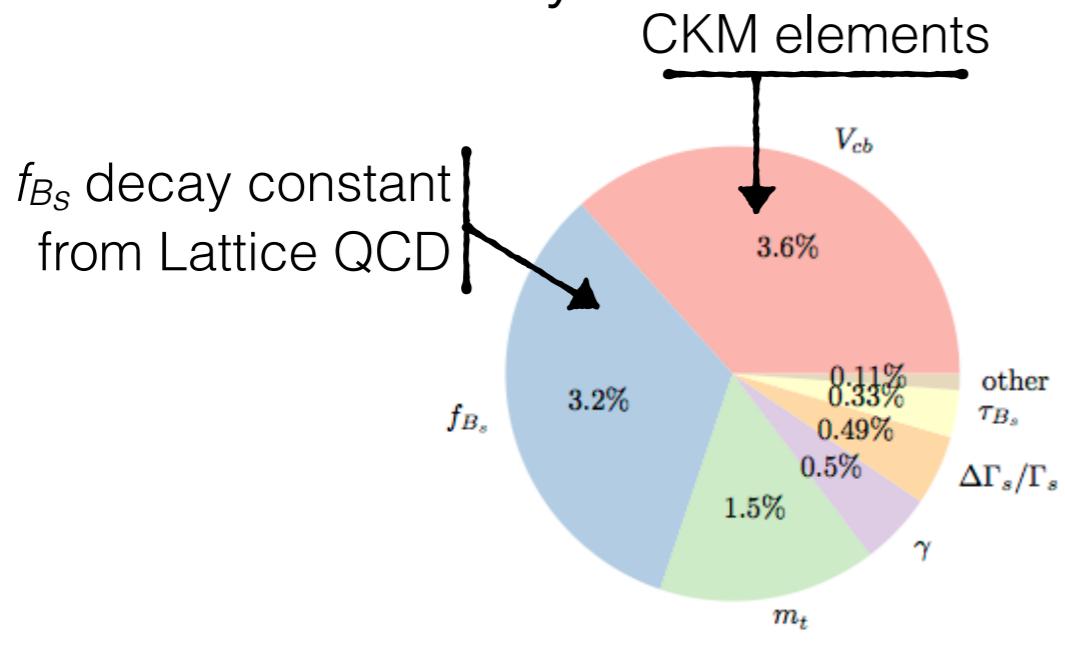
$B_s \rightarrow \mu^+ \mu^-$

- Recent LHCb analysis using run 1 and 2 data ($3\text{fb}^{-1} + 1.4\text{fb}^{-1}$) provided the first single experiment observation of $B_s \rightarrow \mu^+ \mu^-$ at more than 7σ .
[LHCb, PRL 118 (2017) 191801]



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[LHCb, PRL 118 (2017) 191801]
- Measurements are all consistent with the SM expectation.
 - Can exclude large scalar contributions.
- Branching fraction predicted precisely in the SM with a $\sim 6\%$ uncertainty.

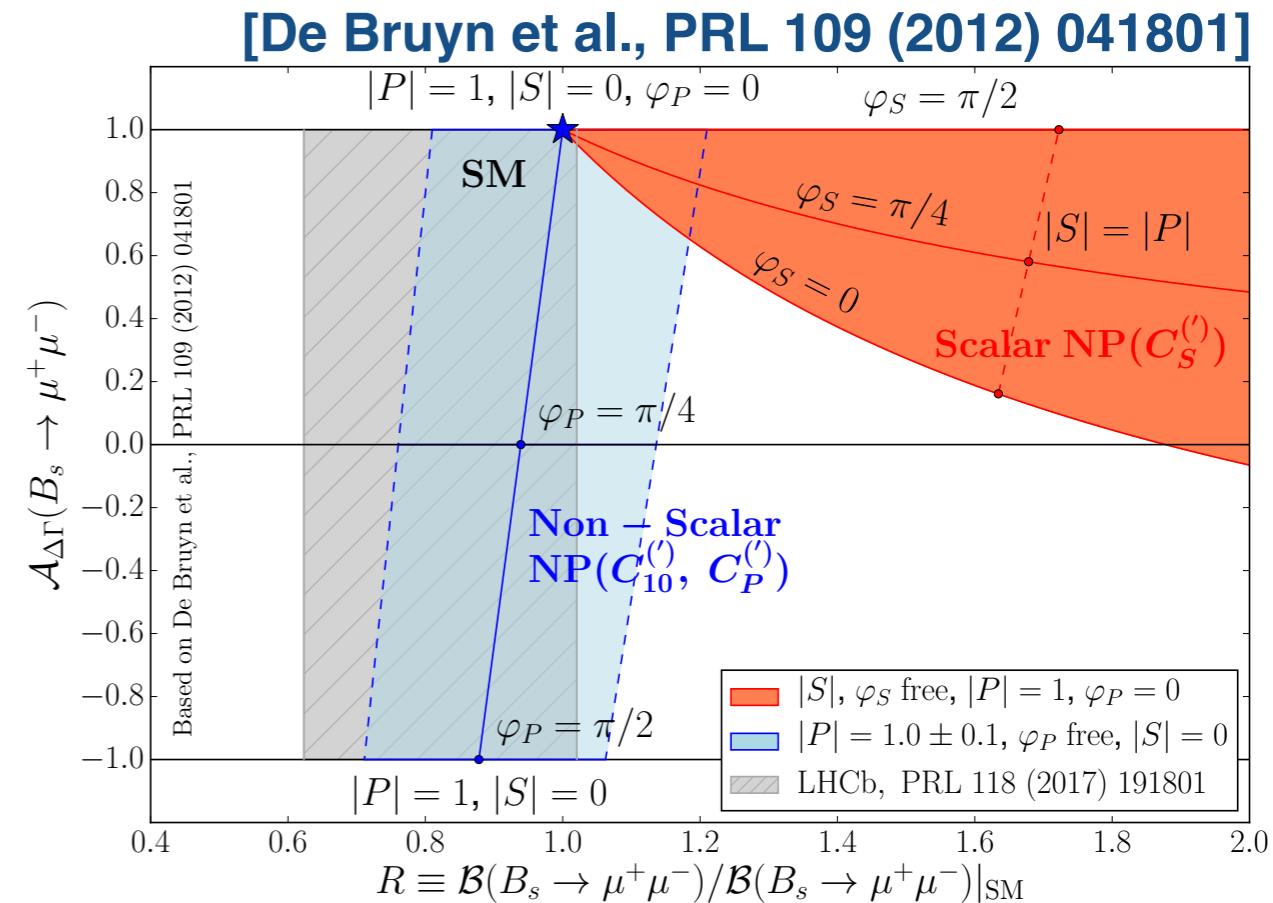


Effective lifetime

- The untagged time dependent decay rate is

$$\Gamma[B_s(t) \rightarrow \mu^+ \mu^-] + \Gamma[\bar{B}_s(t) \rightarrow \mu^+ \mu^-] \propto e^{-t/\tau_{B_s}} \left\{ \cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + A_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) \right\}$$

- $A_{\Delta\Gamma}$ provides additional separation between scalar and pesudoscalar contributions.
- In the SM $A_{\Delta\Gamma} = 1$ such that the system evolves with the lifetime of the heavy B_s mass eigenstate.



$B_s \rightarrow \mu^+ \mu^-$ effective lifetime

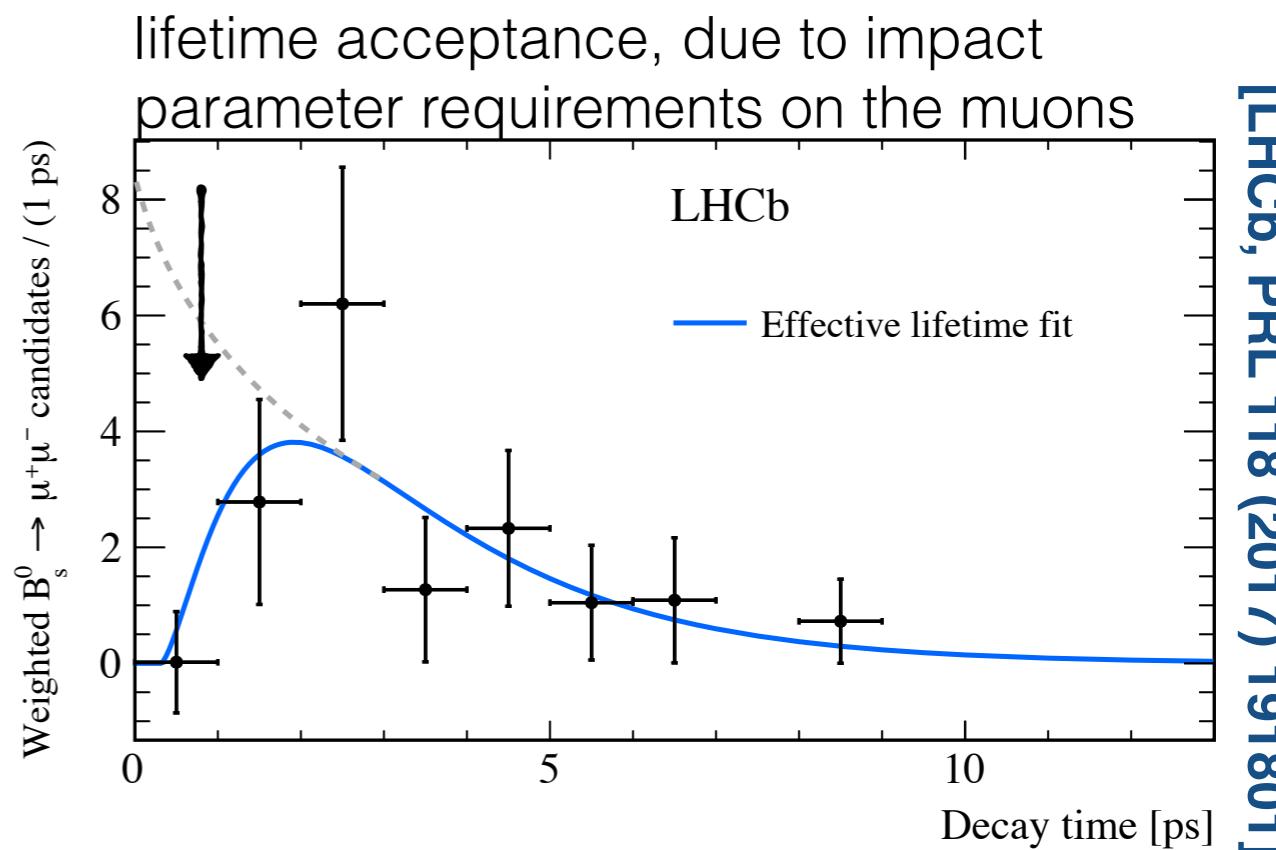
- The $A_{\Delta\Gamma}$ parameter modifies the effective lifetime of the decay:

$$\tau_{\text{eff}} = \frac{\tau_{B_s}}{1 - y_s^2} \left(\frac{1 + 2A_{\Delta\Gamma} y_s + y_s^2}{1 + A_{\Delta\Gamma} y_s} \right) \quad \text{where} \quad y_s = \tau_{B_s} \frac{\Delta\Gamma}{2}$$

- LHCb have performed a first measurement of τ_{eff} , giving

$$\tau[B_s^0 \rightarrow \mu^+ \mu^-] = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

NB Not yet sensitive to $A_{\Delta\Gamma}$ (the stat. uncertainty is larger than the change in the lifetime from $\Delta\Gamma_s$). This will become more interesting during runs 3 and 4.

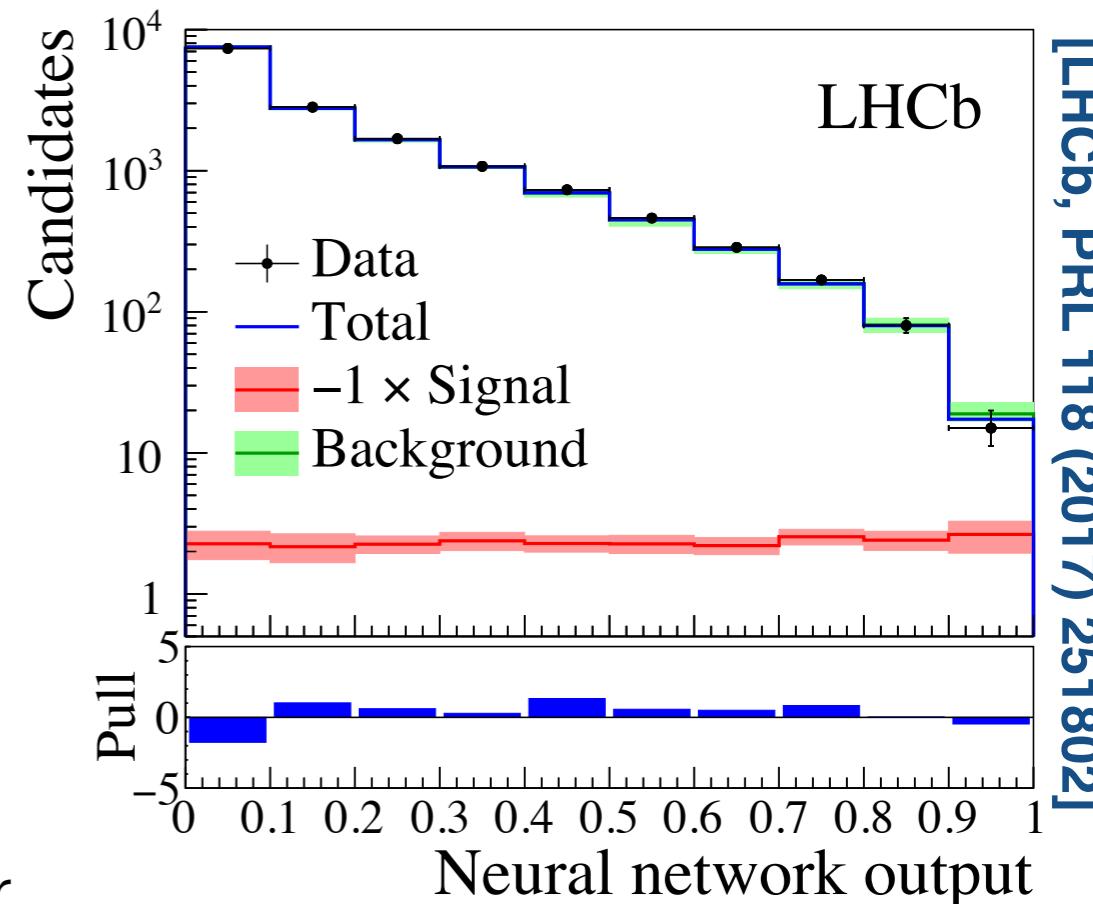


$B_{(s,d)} \rightarrow \tau^+ \tau^-$

- LHCb performs a search for $B_{(s,d)} \rightarrow \tau^+ \tau^-$ decays using $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$.
 - Exploit the $\tau^- \rightarrow a_1(1260)^- \nu_\tau$ and $a_1(1260)^- \rightarrow \rho(770)^0 \pi^-$ decays to select signal/control regions of dipion mass.
- Fit Neural network response to discriminate signal from background.
 - Dita mass is not a good discriminator due to missing neutrino energy.
- LHCb sets limits on:

$$\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-) < 6.8 \times 10^{-3} \text{ (95\% CL)}$$

$$\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) < 2.1 \times 10^{-3} \text{ (95\% CL)}$$

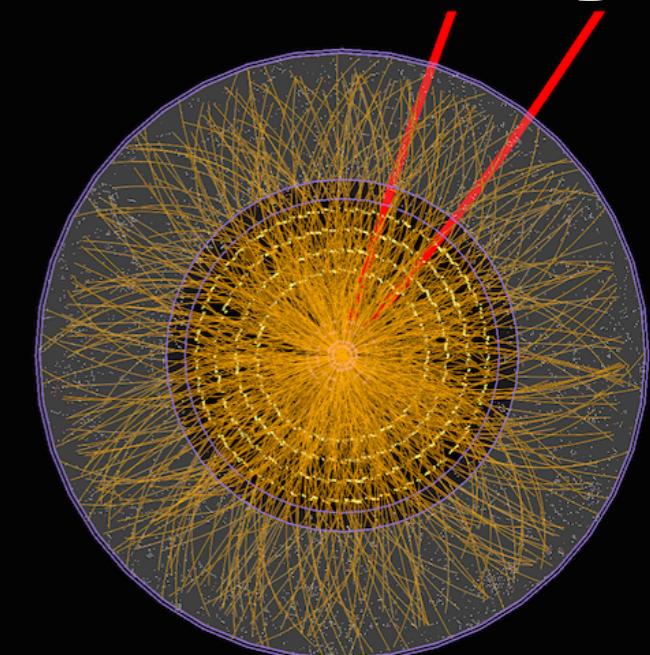


**First limit on $B_s \rightarrow \tau^+ \tau^-$ and
worlds best limit on $B^0 \rightarrow \tau^+ \tau^-$**



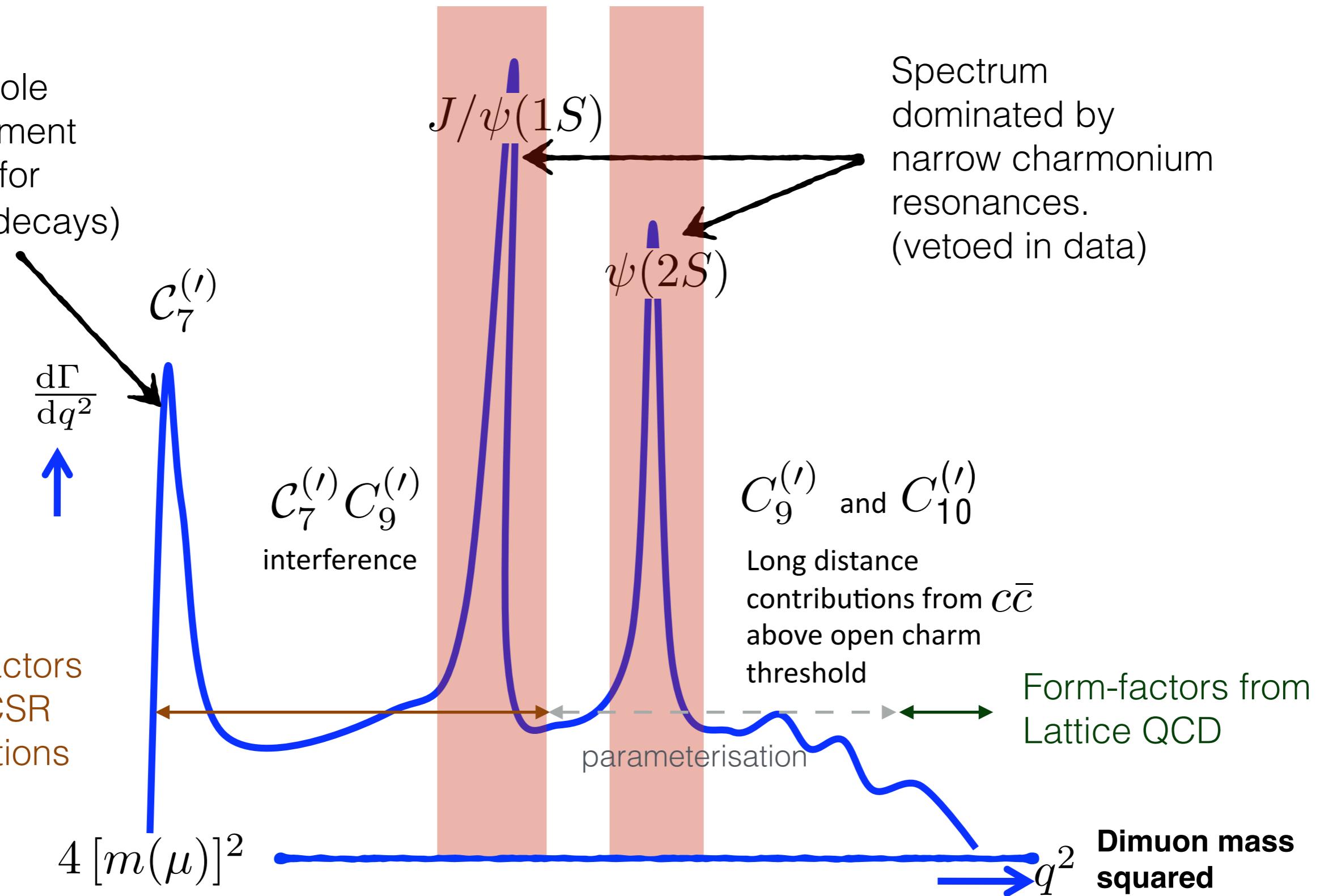
Semileptonic decays

Run: 267639
Event: 9576943
2015-06-14 08:51:30 CEST



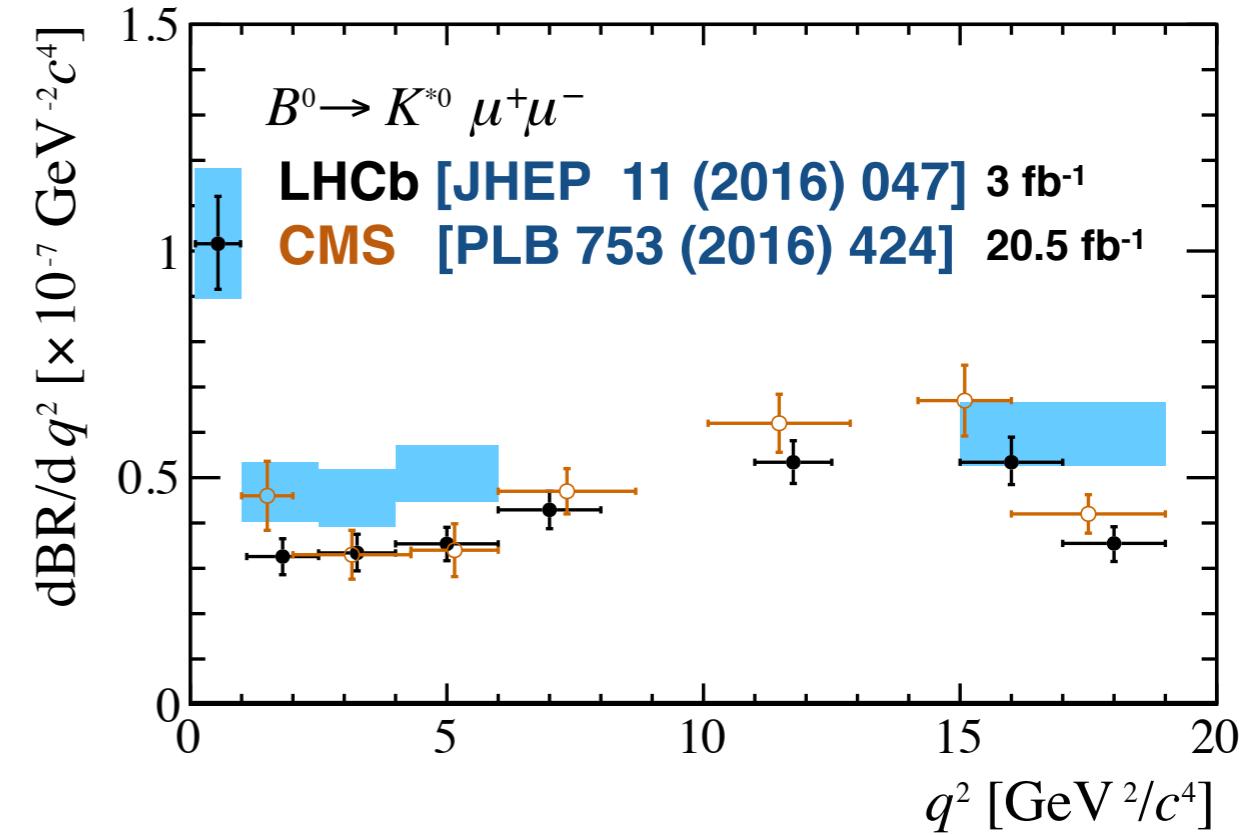
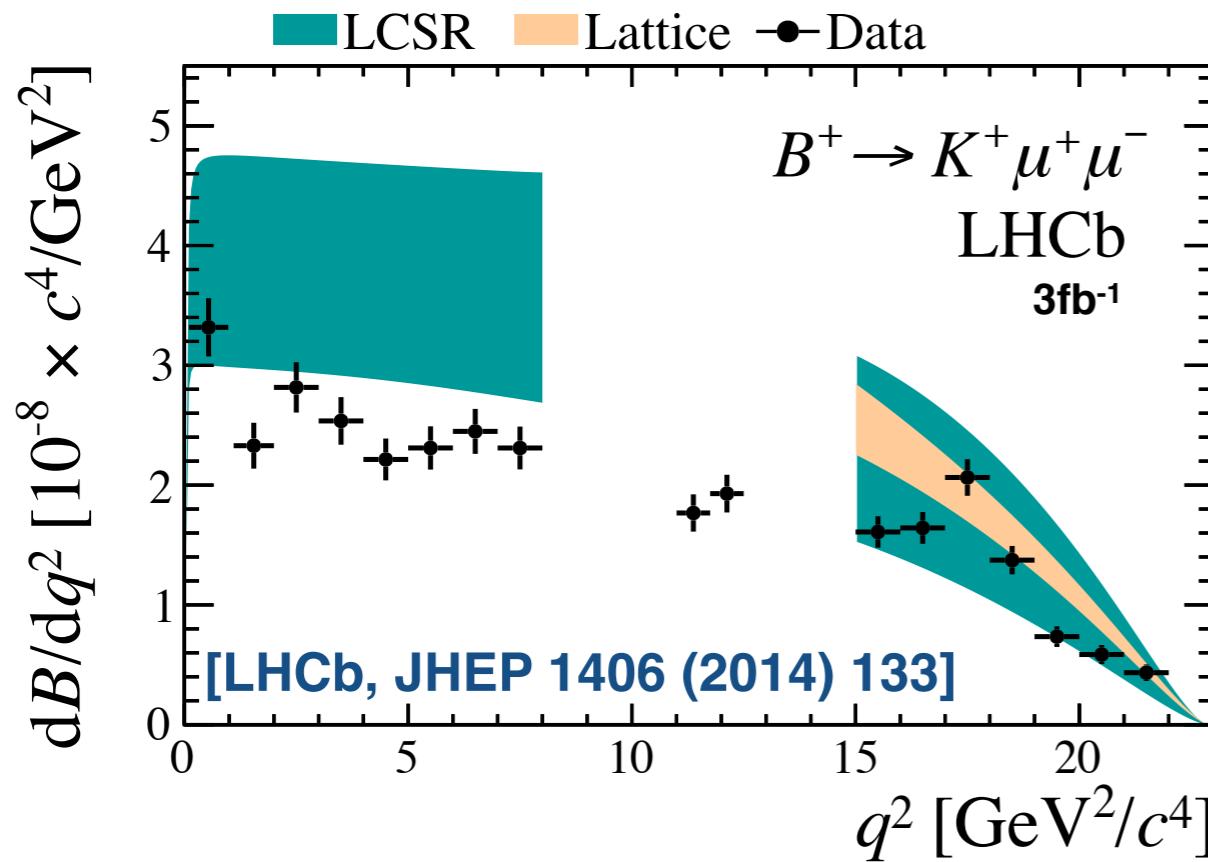
Expected $d\Gamma/dq^2$ spectrum

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



Branching fraction measurements

- We already have precise measurements of branching fractions in the run1 datasets with at least comparable precision to SM expectations:

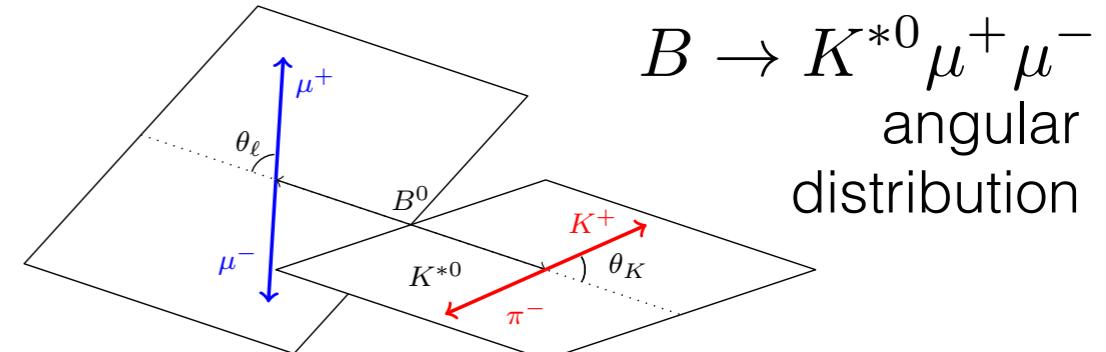


- SM predictions have large theoretical uncertainties from hadronic form factors (3 for $B \rightarrow K$ and 7 for $B \rightarrow K^*$ decays). For details see
[Bobeth et al JHEP 01 (2012) 107] **[Bouchard et al. PRL111 (2013) 162002]**
[Altmannshofer & Straub, EPJC (2015) 75 382]. Expect improvements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

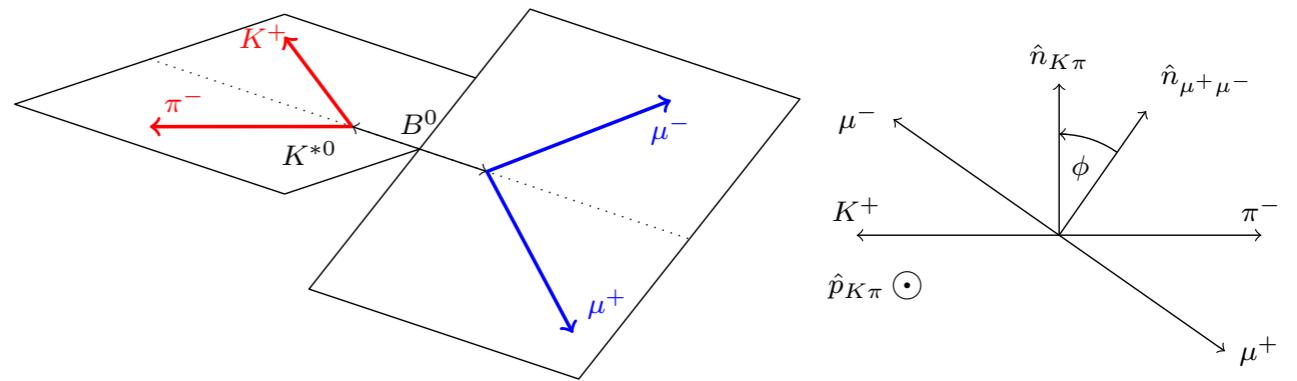
Angular observables

- Multibody final-states:
 - Angular distribution provides many observables that are sensitive to BSM physics.
 - Constraints are orthogonal to branching fraction measurements, both in their impact in global fits and in terms of experimental uncertainties.

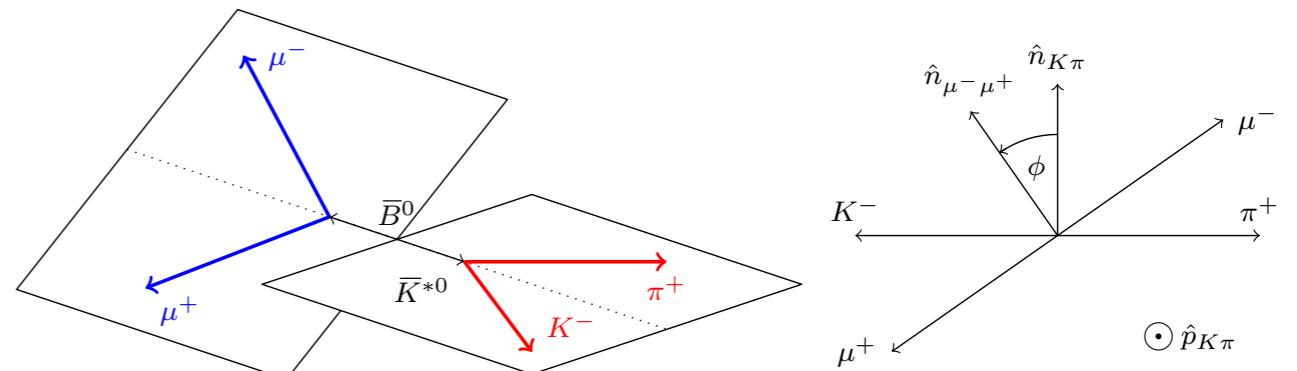
eg $B \rightarrow K^{*0} \ell^+ \ell^-$ system described by three angles and the dimuon invariant mass squared, q^2 .



(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 \bar{B}^0 decay

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

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

Complex angular distribution:

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

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

$- F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi$

$+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi$

$+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi$

$+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]$

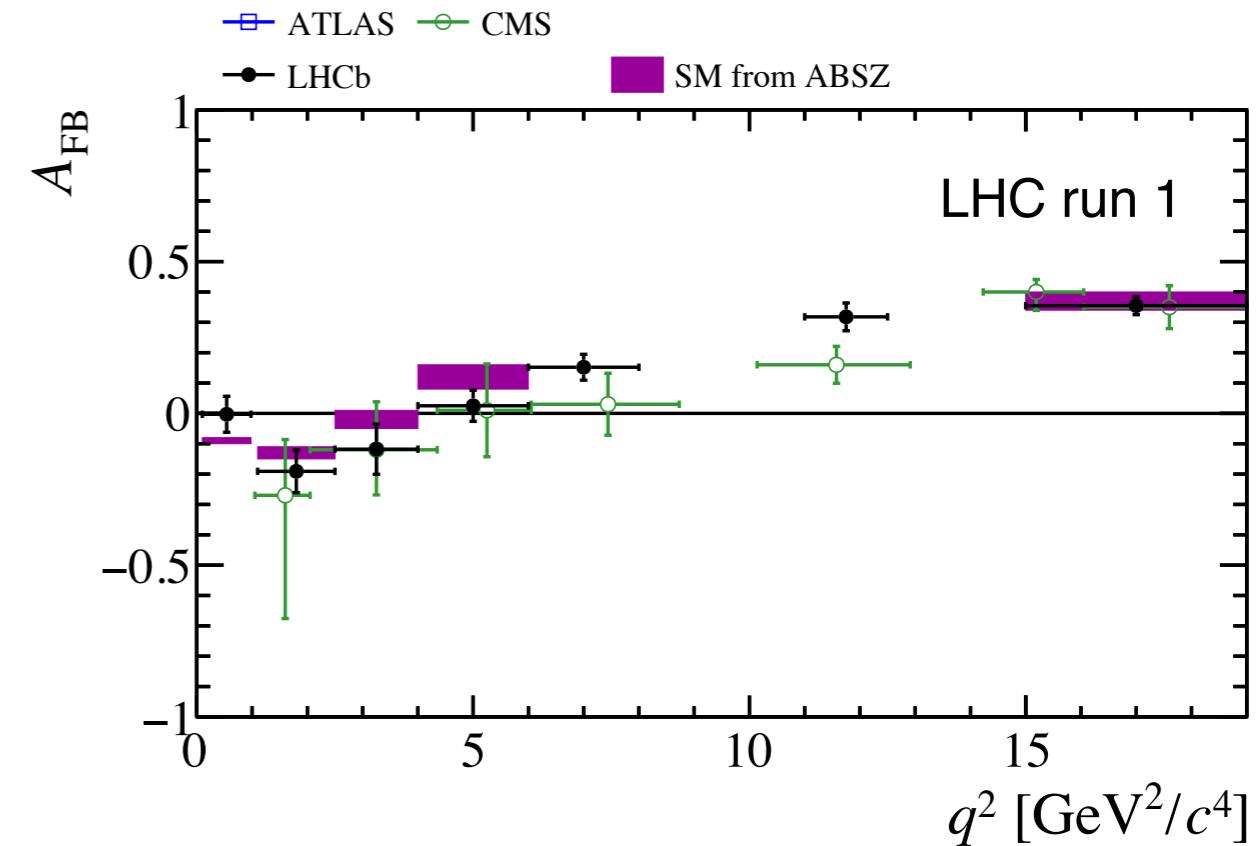
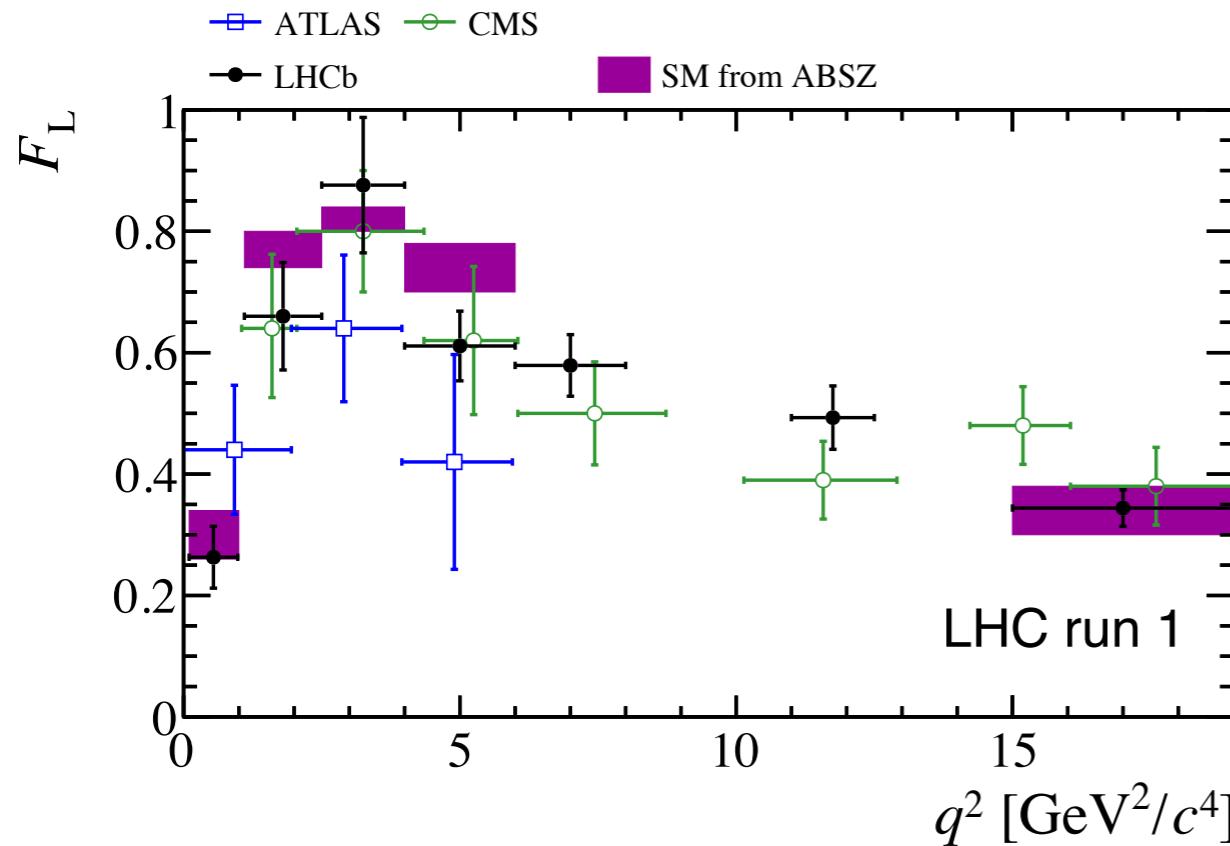
↑ fraction of longitudinal polarisation of the K^*

→ 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).

Experiments can reduce the complexity by folding the angular distribution, see
[LHCb, PRL 111 (2013) 191801]

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

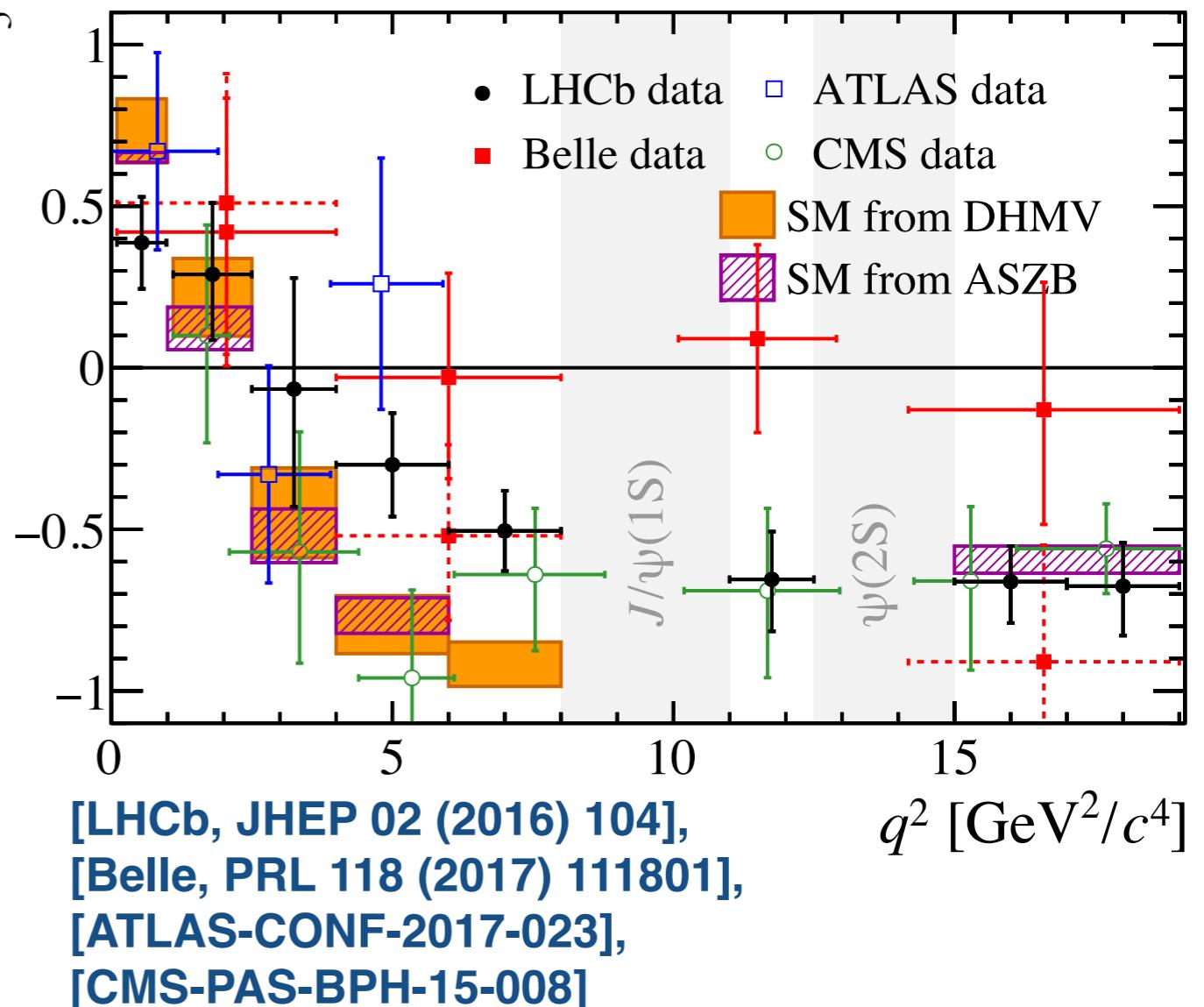


- Overlaying results for F_L and A_{FB} from LHCb [[JHEP 02 \(2016\) 104](#)] , CMS [[PLB 753 \(2016\) 424](#)] and ATLAS [[ATLAS-CONF-2017-023](#)].
- SM predictions based on
[\[Altmannshofer & Straub, EPJC 75 \(2015\) 382\]](#)
[\[LCSR form-factors from Bharucha, Straub & Zwicky, JHEP 08 \(2016\) 98\]](#)
[\[Lattice form-factors from Horgan, Liu, Meinel & Wingate arXiv:1501.00367\]](#) } Joint fit performed

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 these soft form-factors at leading order, e.g.

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

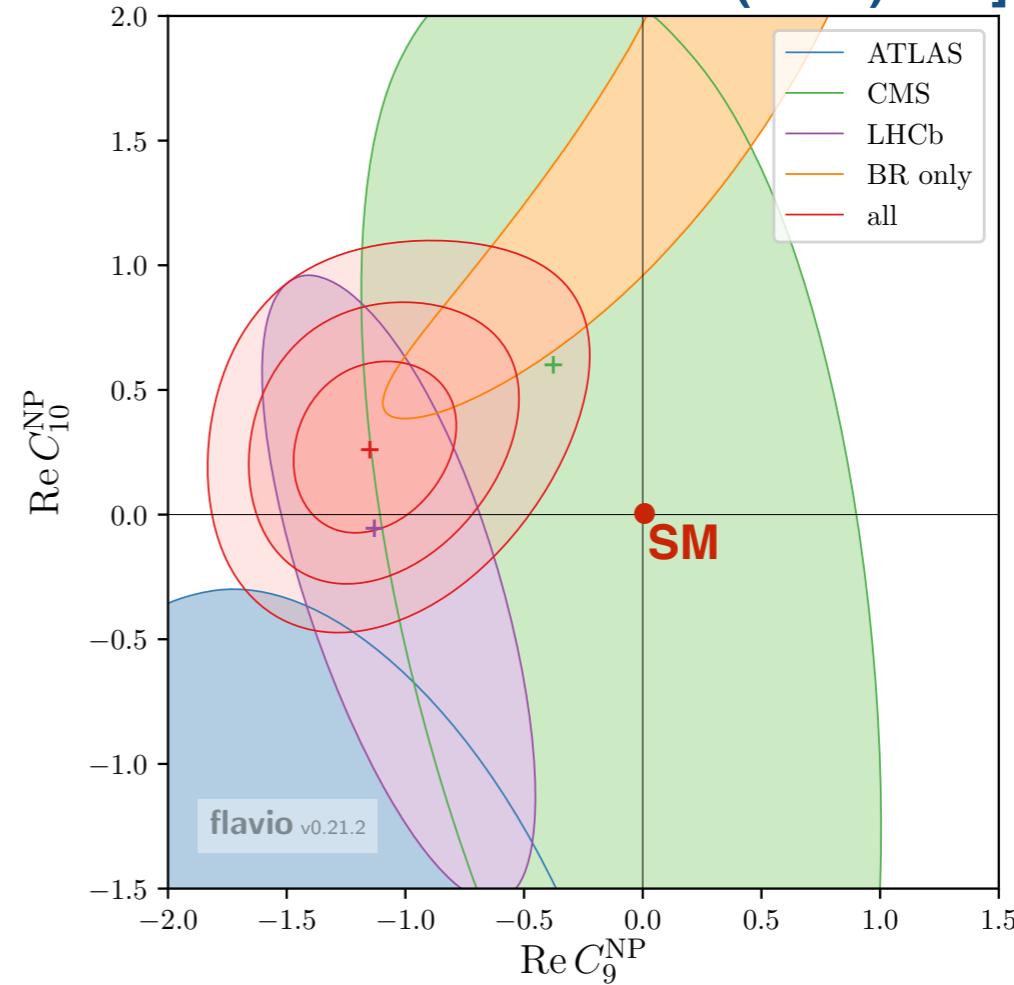
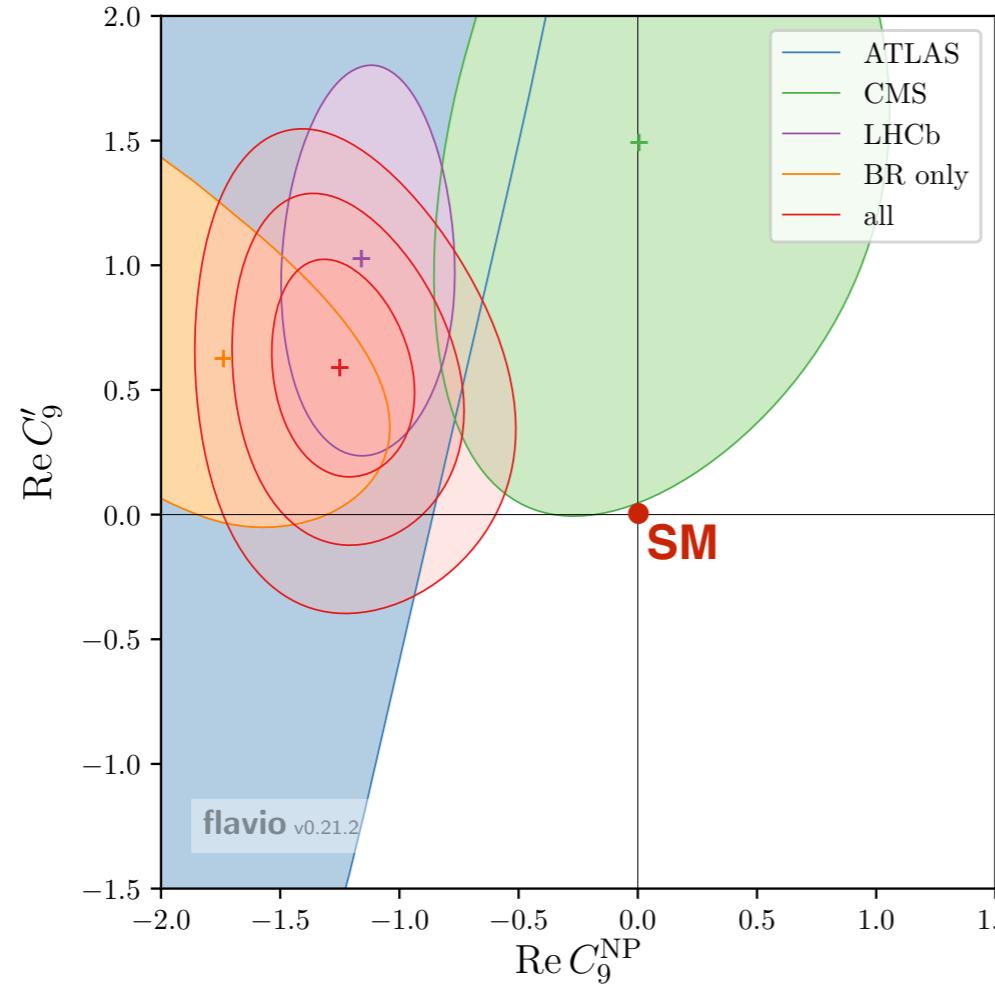


- P'_5 is one of a set of so-called form-factor free observables that can be measured [Descotes-Genon et al. JHEP 1204 (2012) 104].

Global fits

- Several attempts to interpret our results through global fits to $b \rightarrow s$ data.

[W. Altmannshofer et al. EPJC 77 (2017) 377]

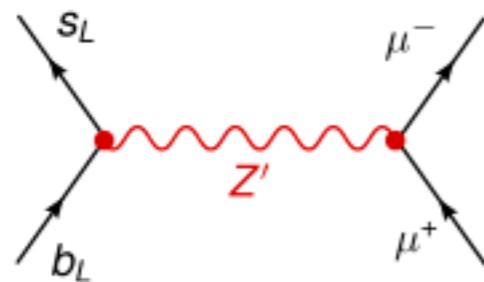


- General pattern of consistency between experiments/measurements.

Data favours a modified vector coupling ($C_9^{\text{NP}} \neq 0$) at 4-5 σ .

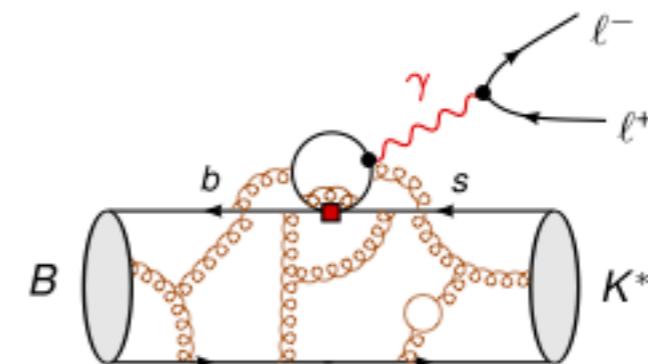
Interpretation of global fits

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

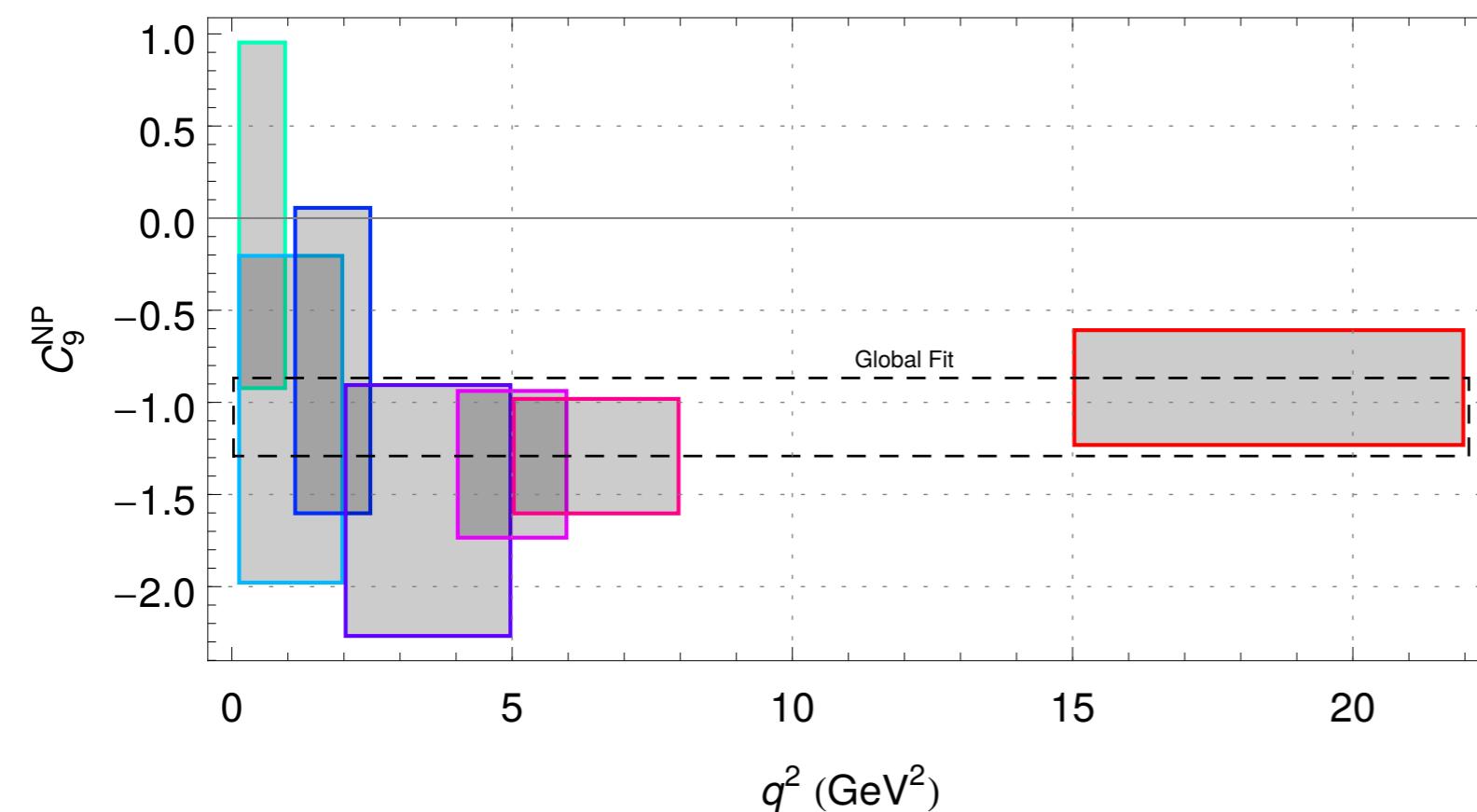


Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon?

More work needed from experiment/theory to disentangle the two

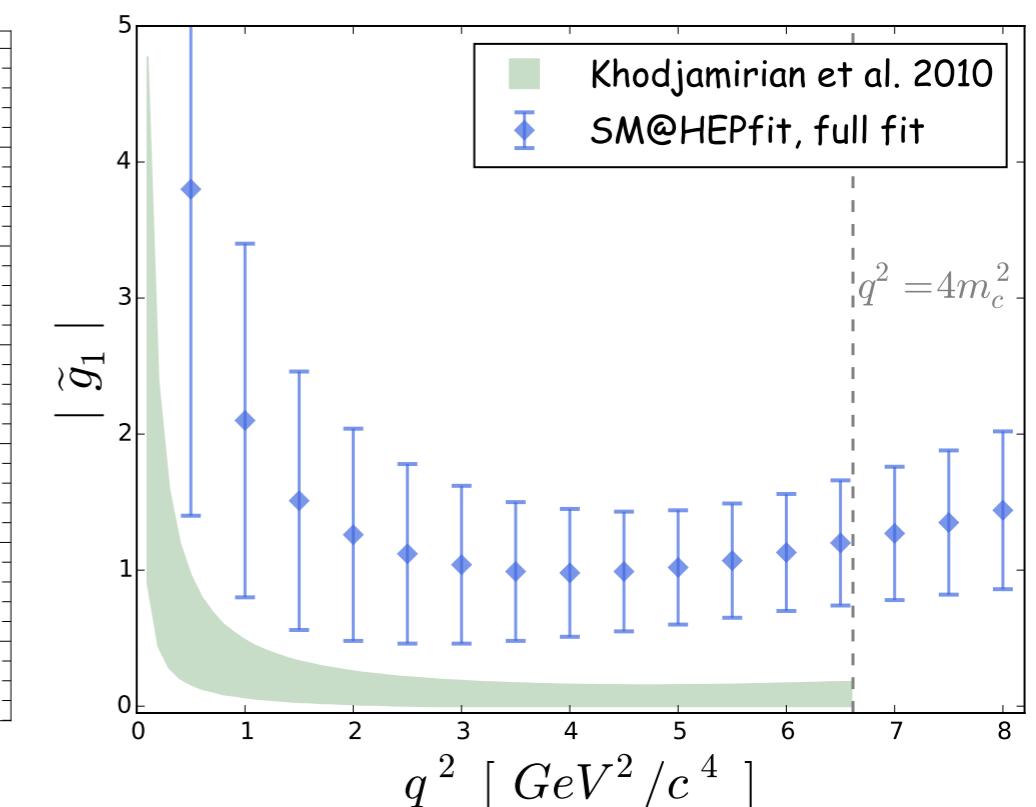
What can we learn from the data?

- 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 $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays with $C_9 = C_9^{\text{SM}}$.

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

Lepton universality tests

- In the SM, ratios

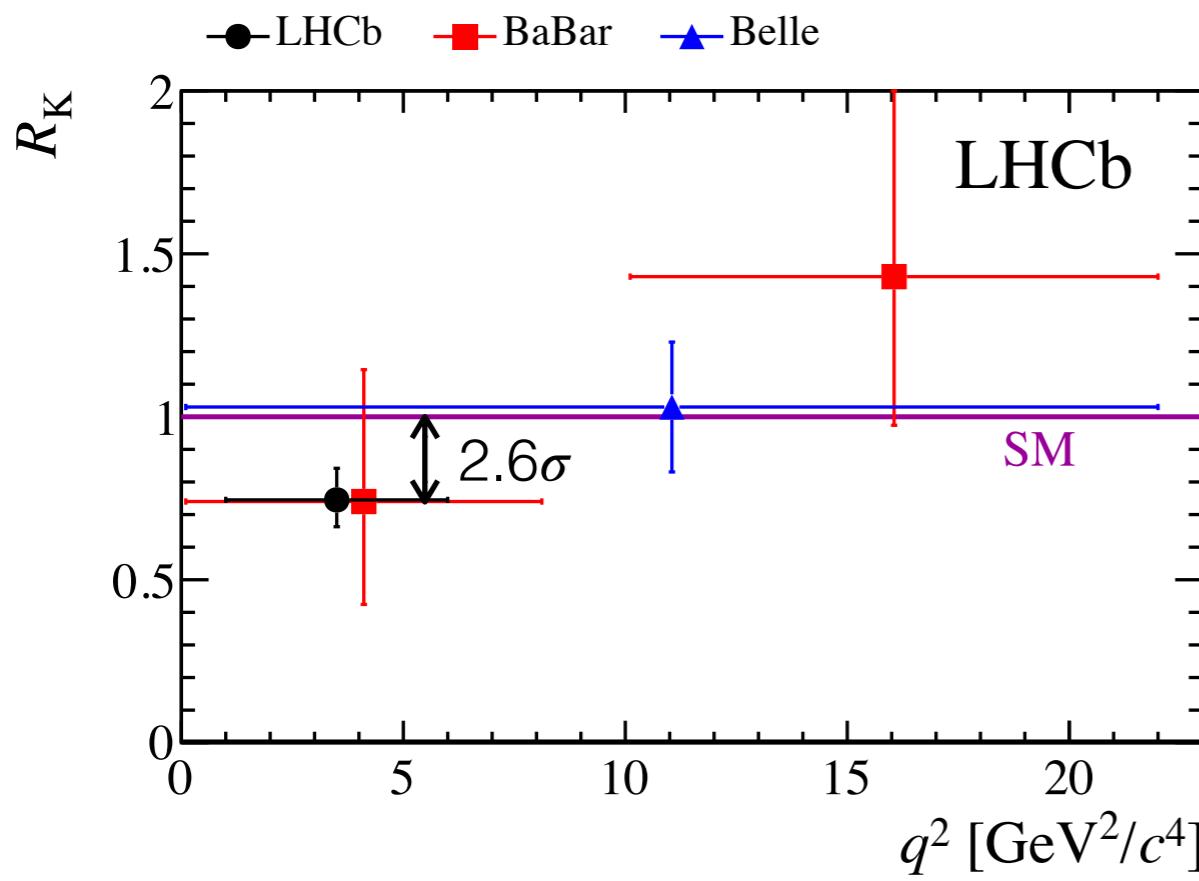
$$R_K = \frac{\int d\Gamma[B^+ \rightarrow K^+ \mu^+ \mu^-]/dq^2 \cdot dq^2}{\int d\Gamma[B^+ \rightarrow K^+ e^+ e^-]/dq^2 \cdot dq^2}$$

only differ from unity by phase space — the dominant SM processes couple equally to the different lepton flavours.

- Theoretically clean since hadronic uncertainties cancel in the ratio.
- Experimentally challenging due to differences in muon/electron reconstruction (in particular Bremsstrahlung from the electrons).
 - Take double ratios with $B \rightarrow J/\psi X$ decays to cancel possible sources of systematic uncertainty.
 - Correct for migration of events in q^2 due to FSR/Bremsstrahlung using MC (with PHOTOS).

Lepton universality tests

- We have interesting hints of non-universal lepton couplings in LHCb run 1 dataset:

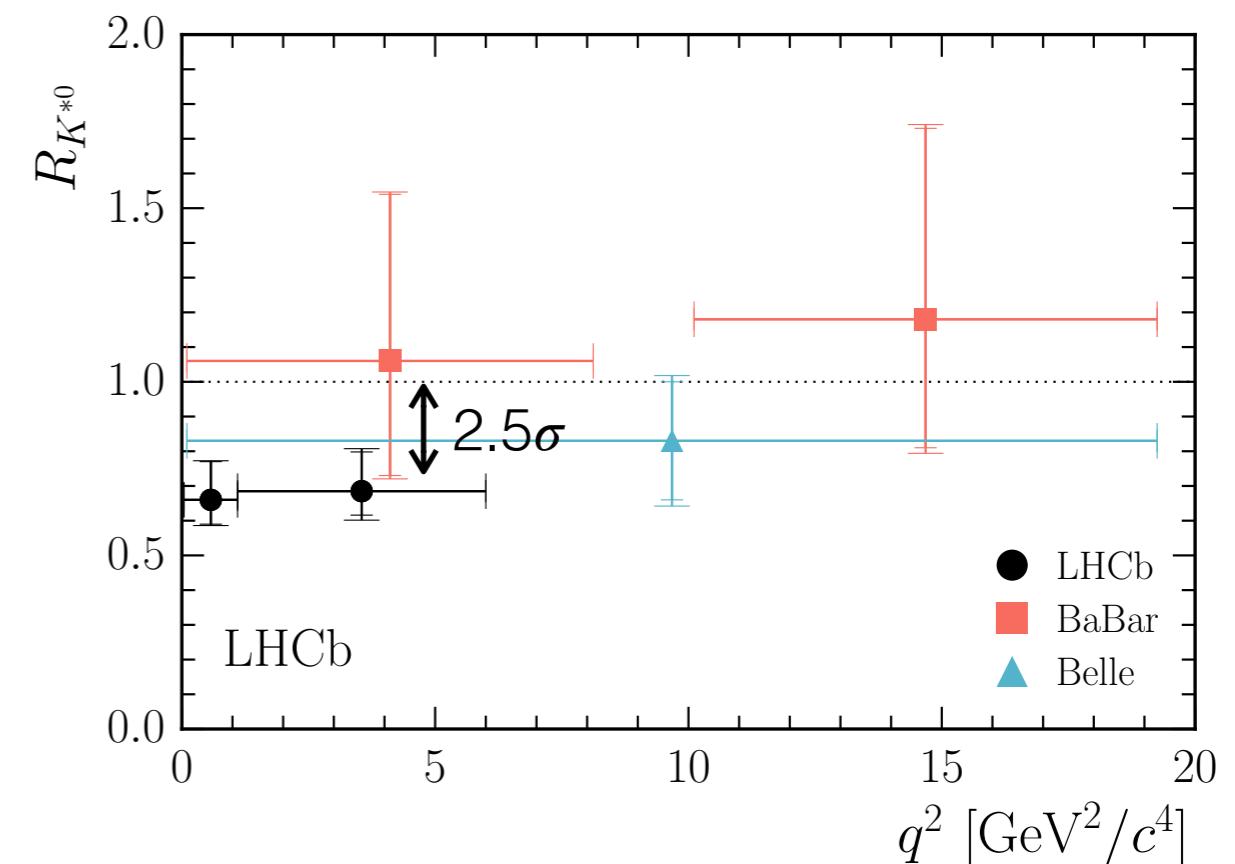


[LHCb , PRL 113 (2014) 151601]

[LHCb, LHCb-PAPER-2017-013]

[BaBar, PRD 86 (2012) 032012]

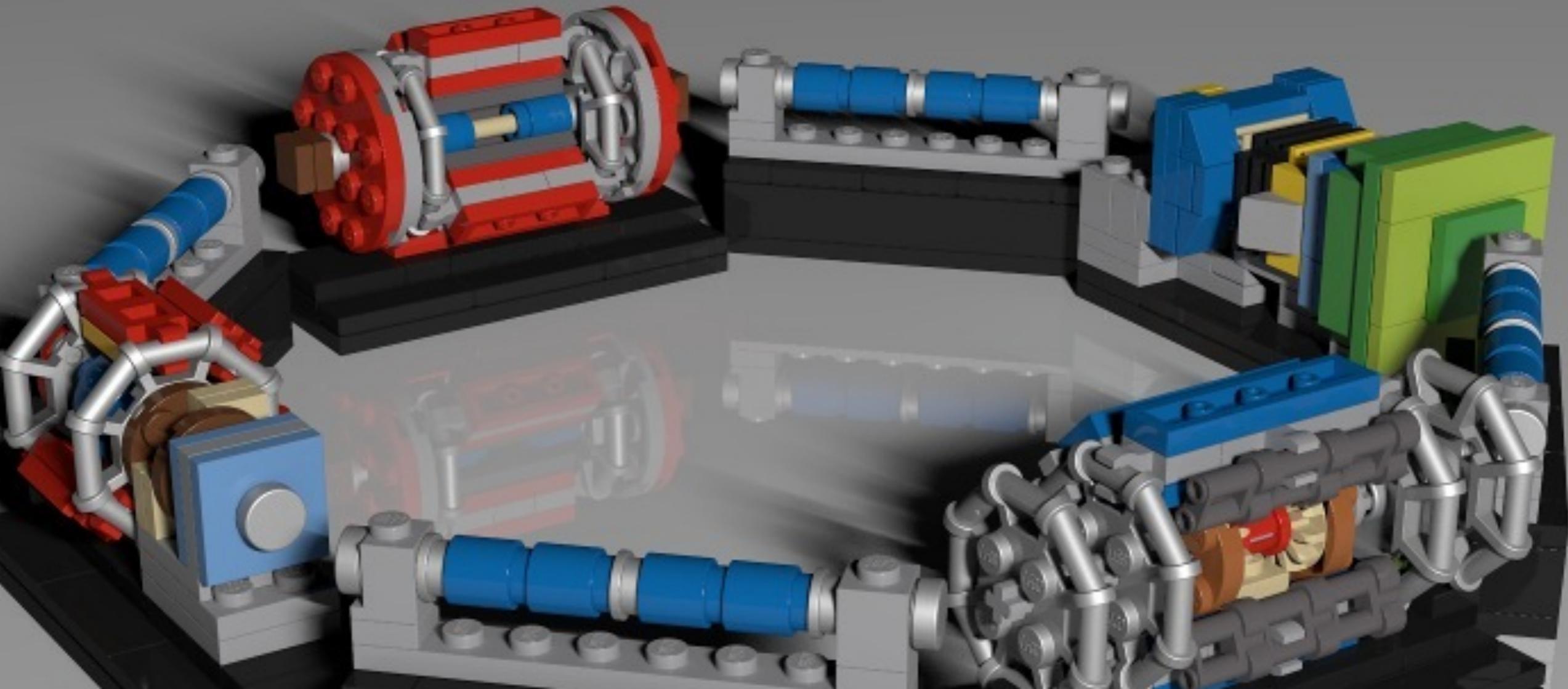
[Belle, PRL 103 (2009) 171801]



NB $R_K \approx 0.8$ is a prediction of one class of model explaining the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular observables, see $L_\mu - L_\tau$ models
W. Altmannshofer et al. [PRD 89 (2014) 095033]

Summary

- FCNC processes provide powerful constraints on extensions of the SM.
- Several interesting tensions are seen in data on $b \rightarrow s\ell^+\ell^-$ processes.
- Expect huge progress in the next five years with new data from LHC run 2 & Belle II.

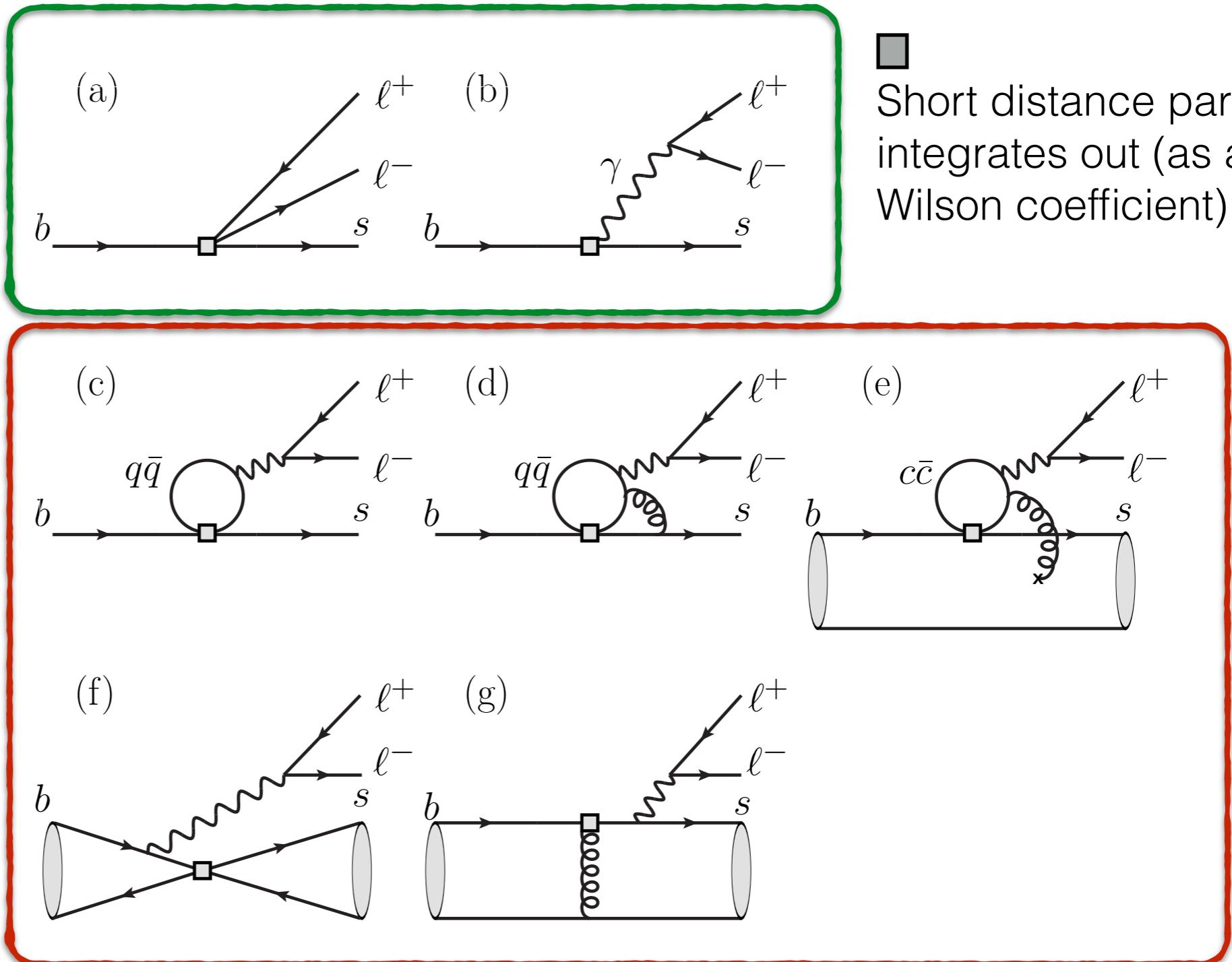


What can we measure?

- Leptonic decay rates, $\Gamma \sim |\text{axialvector}|^2$
 - Large helicity suppression for e^+e^- and $\mu^+\mu^-$ final-states, which can be lifted in BSM extensions with new (pseudo)scalar operators.
- Semileptonic decay rates, $\Gamma \sim |\text{vector}|^2 + |\text{axialvector}|^2$
 - Expect large hadronic uncertainties from form-factors.
 - Expect $\Gamma[B \rightarrow M\mu^+\mu^-] \approx \Gamma[B \rightarrow Me^+e^-]$ due to the universal coupling of the gauge bosons (except the Higgs).
- Angular observables in semileptonic decays:
 - Can be used to separate vector- and axialvector-currents and left- and right-handed contributions.
 - Can (partially) cancel hadronic uncertainties.
- Flavour structure of SM implies that the rate of $b \rightarrow d$ processes is suppressed by $|V_{td}/V_{ts}|^2$ compared to $b \rightarrow s$ processes.

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]

Theoretical Framework

- In leptonic decays the matrix element for the decay can be factorised into a leptonic current and B meson decay constant:

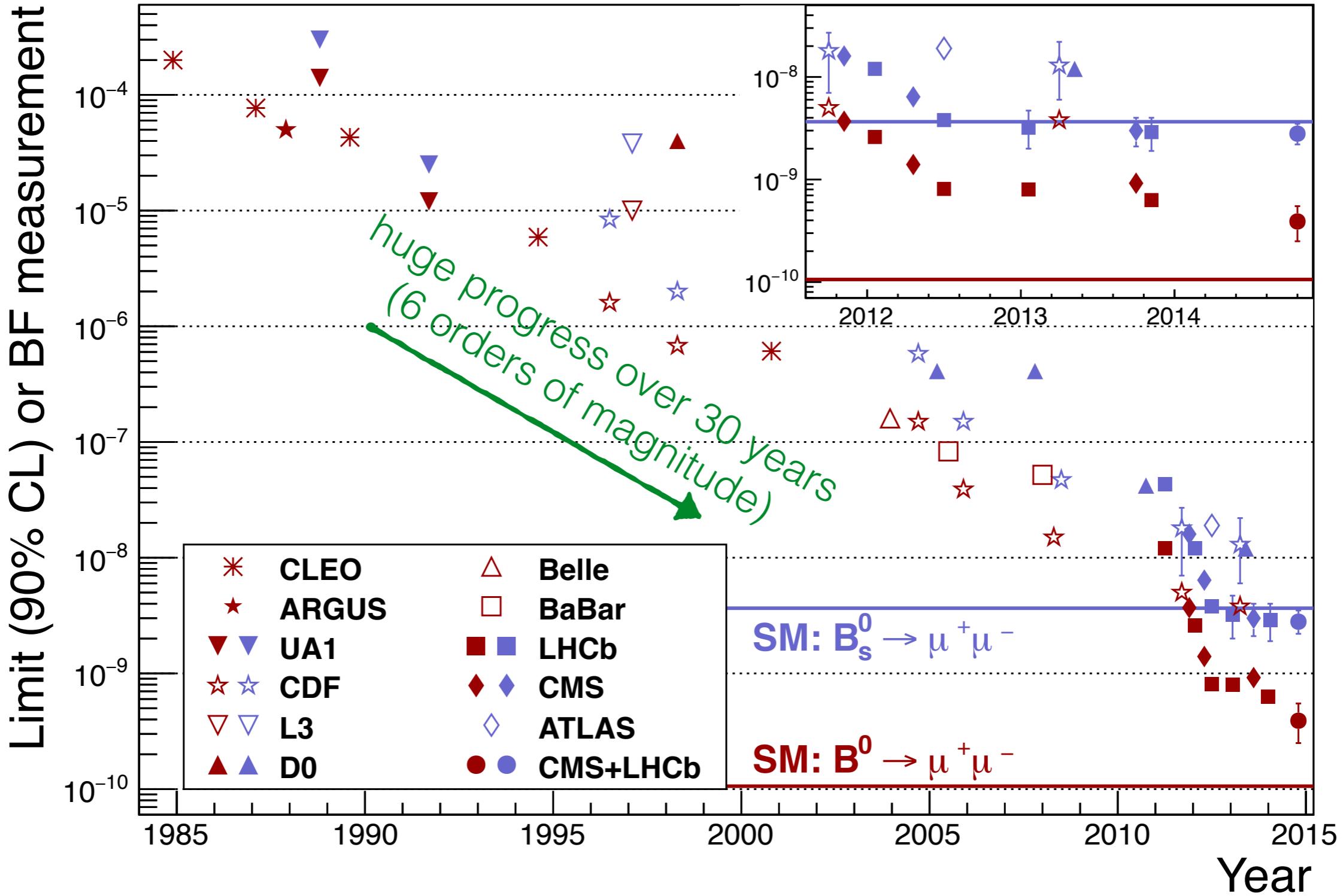
$$\begin{aligned}\langle \ell^+ \ell^- | j_\ell j_q | B_q \rangle &= \langle \ell^+ \ell^- | j_\ell | 0 \rangle \langle 0 | j_q | B_q \rangle \\ &\approx \langle \ell^+ \ell^- | j_\ell | 0 \rangle \cdot f_{B_q}\end{aligned}$$

- In semileptonic decays, the matrix element can be factorised into a leptonic current times a form-factor:

$$\begin{aligned}\langle \ell^+ \ell^- M | j_\ell j_q | B \rangle &= \langle \ell^+ \ell^- | j_\ell | 0 \rangle \langle M | j_q | B_q \rangle \\ &\approx \langle \ell^+ \ell^- | j_\ell | 0 \rangle \cdot F(q^2) + \mathcal{O}(\Lambda_{\text{QCD}}/m_B)\end{aligned}$$

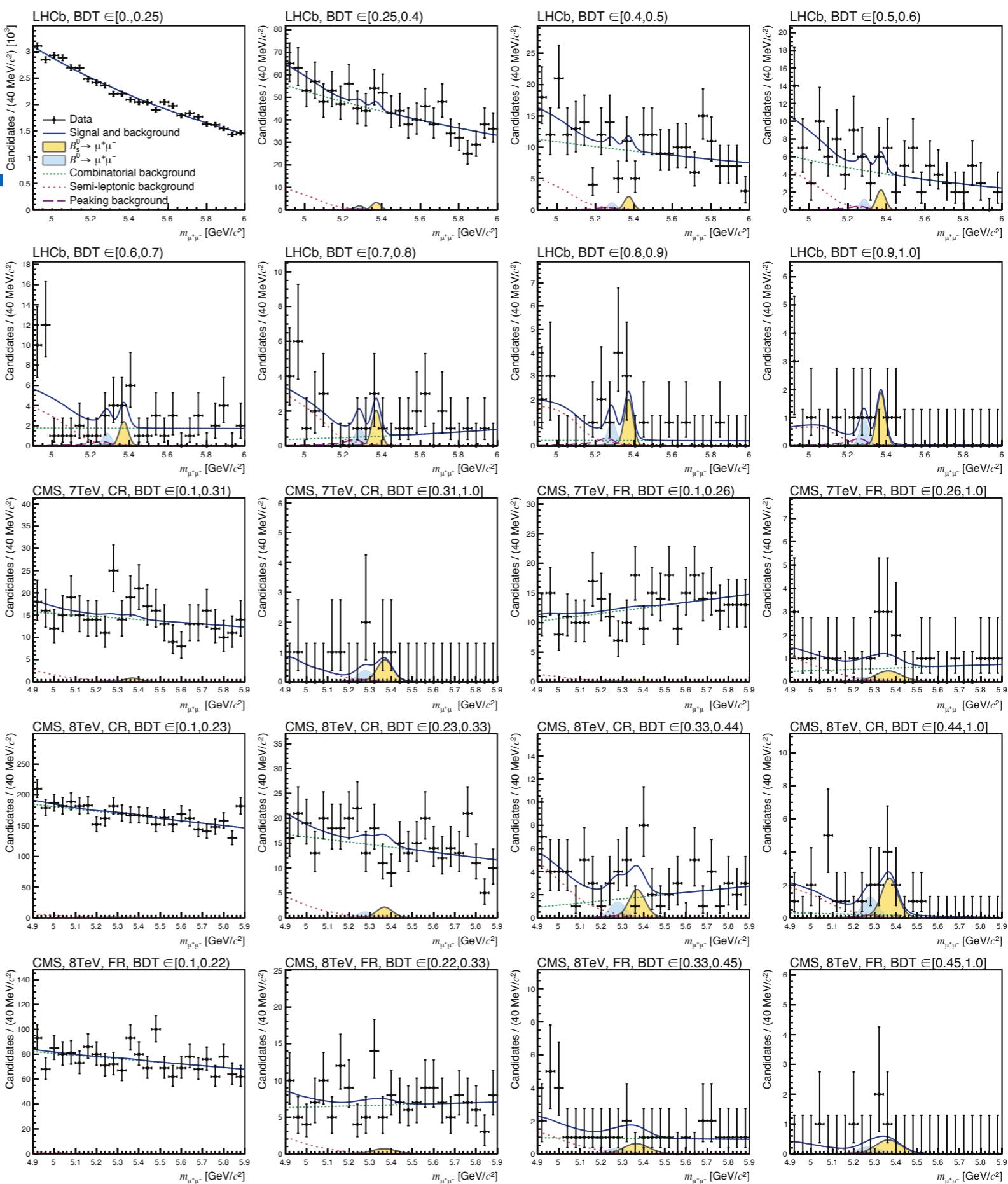
however this factorisation is not exact (due to hadronic contributions).

End of a long road



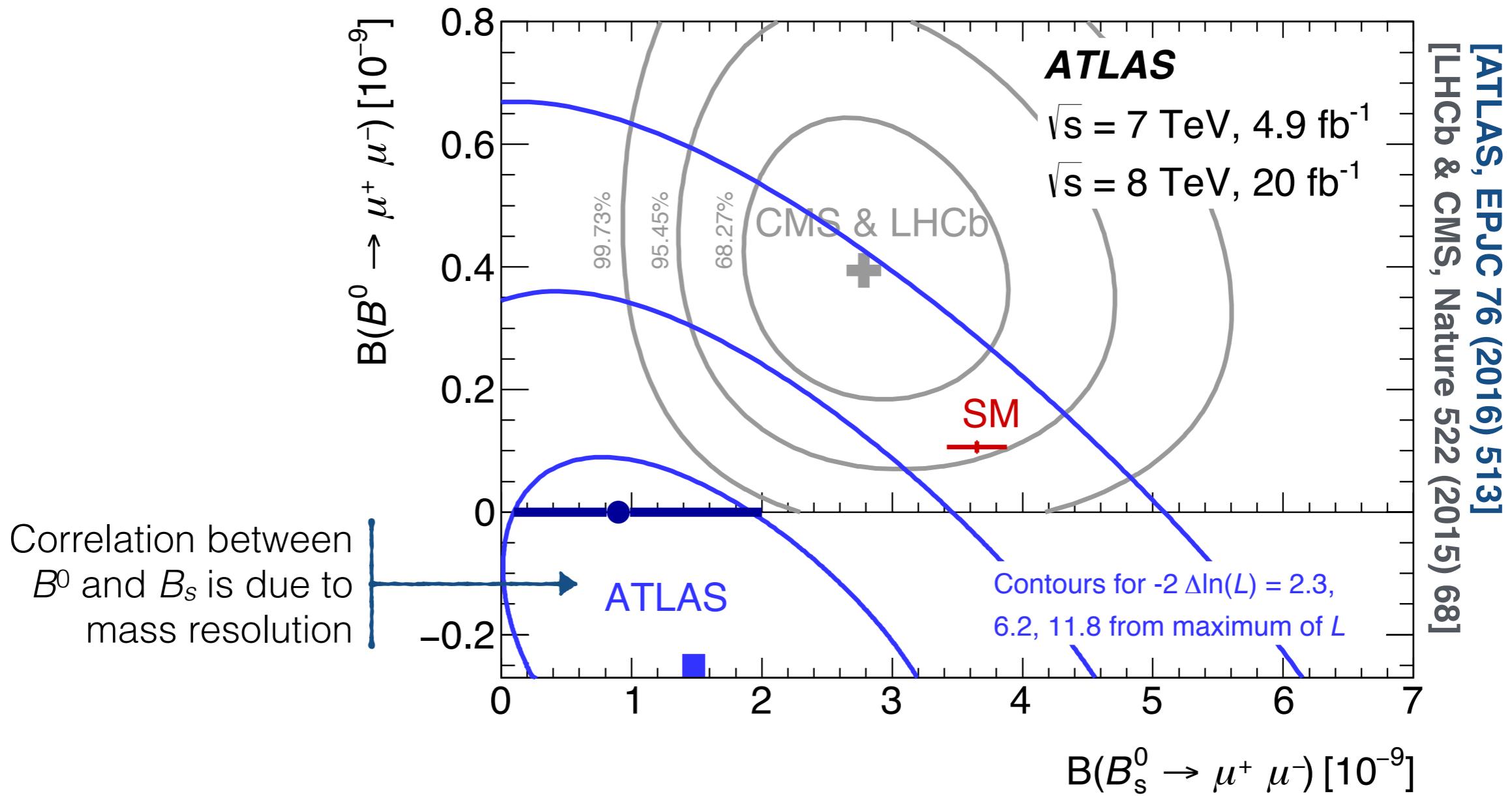
$B_{(s,d)} \rightarrow \mu^+ \mu^-$ analyses

- Analyses are performed in bins of multivariate response.
- Signal normalised to $B^+ \rightarrow J/\psi K^+$ (plus $B \rightarrow K\pi$, $B_s \rightarrow J/\psi \phi$ in LHCb), with input on the b -meson production fractions.
- Important backgrounds from two-body hadronic and semileptonic decays with $K \rightarrow \mu$ or $\pi \rightarrow \mu$ misid.



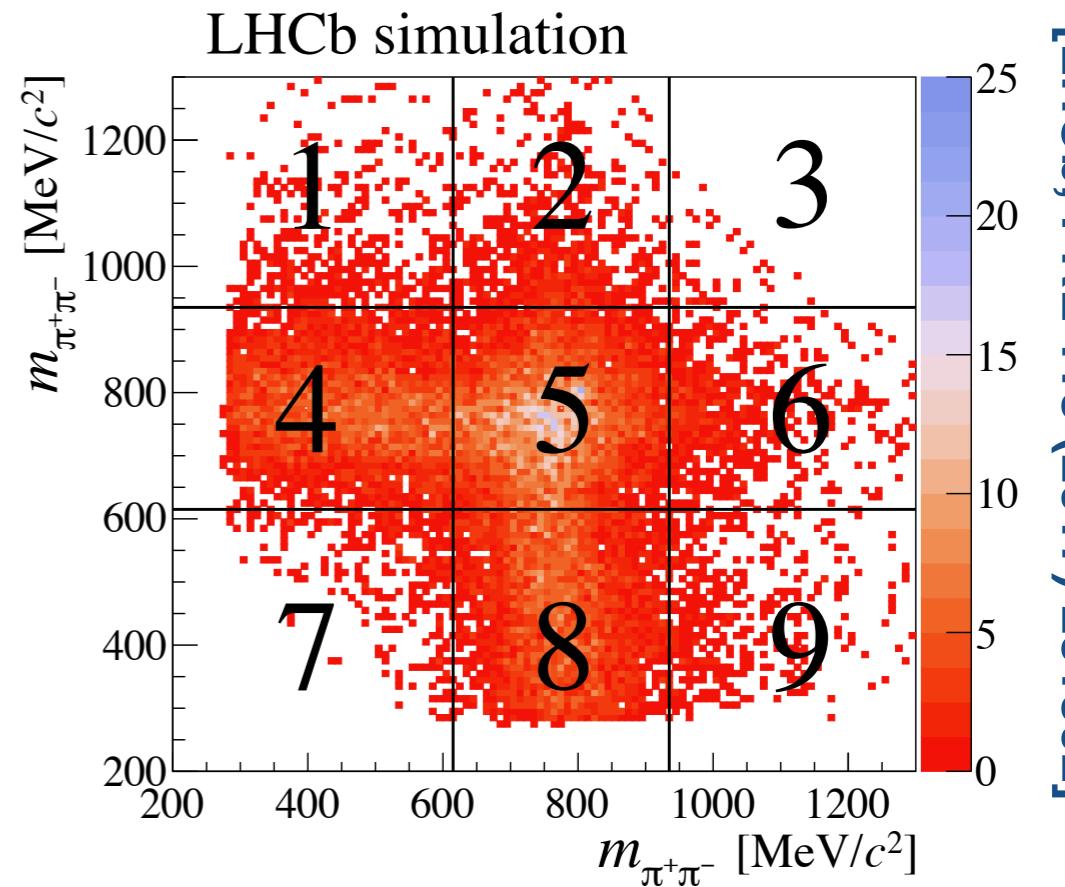
$B_s \rightarrow \mu^+ \mu^-$ fits

- Perform simultaneous fits to the bins of multivariate response to determine the B^0 and B_s branching fractions, e.g. for ATLAS



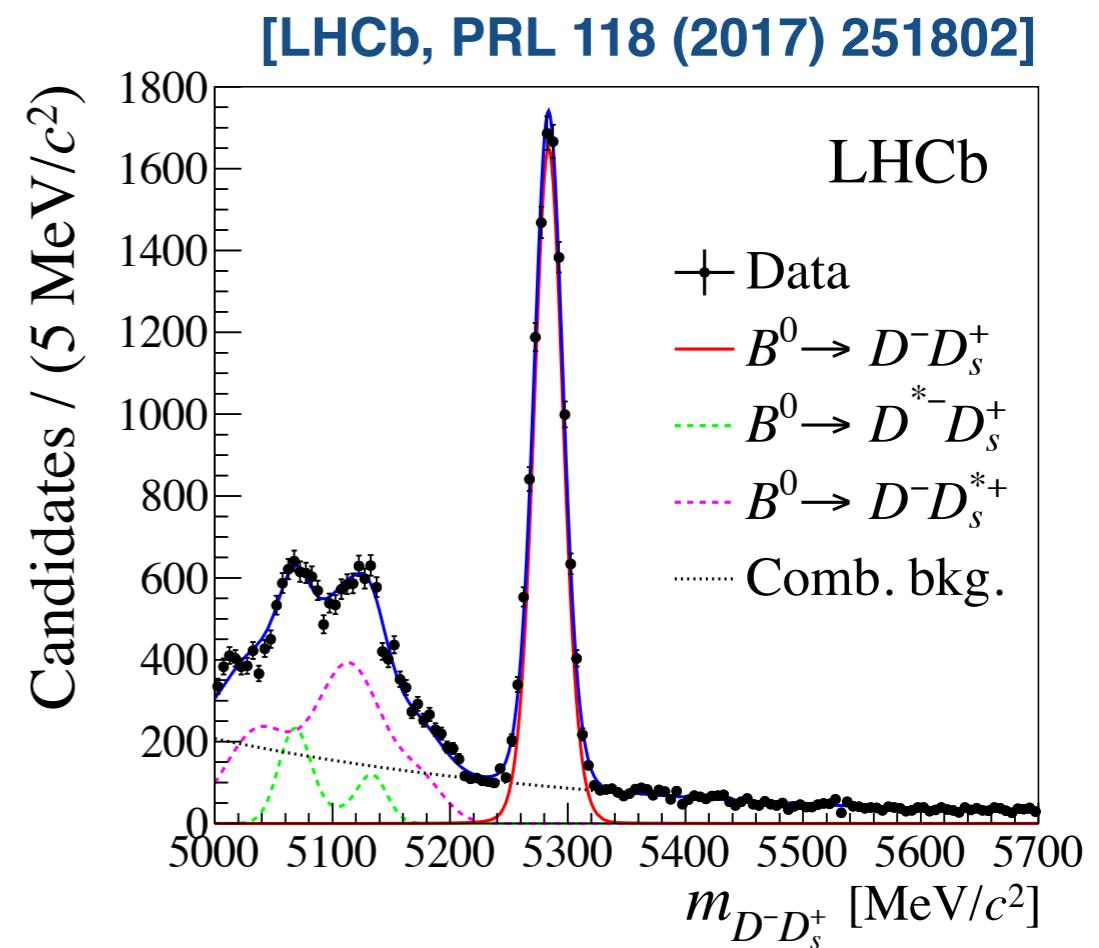
$B_{(s,d)} \rightarrow \tau^+ \tau^-$

- LHCb performs a search for $B_{(s,d)} \rightarrow \tau^+ \tau^-$ decays using $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$.
 - Exploit the $\tau^- \rightarrow a_1(1260)^- \nu_\tau$ and $a_1(1260)^- \rightarrow \rho(770)^0 \pi^-$ decays to select signal/control regions of dipion mass.



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

- Normalised the observed yield to $B^0 \rightarrow D^- [\rightarrow K^+ \pi^- \pi^-] D_s^+ [\rightarrow K^+ K^- \pi^+]$ which has a similar topology but no missing energy.

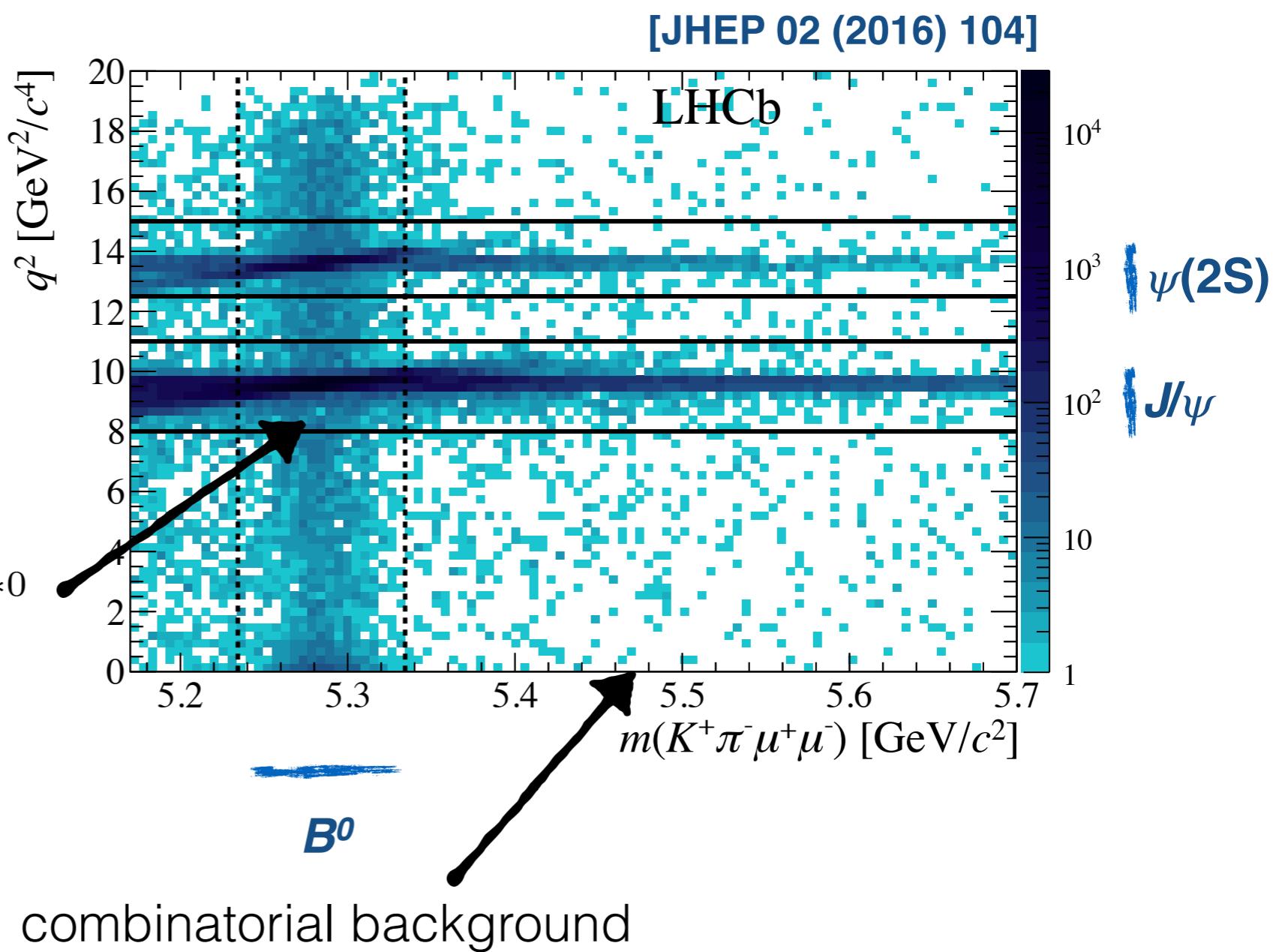


$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ reconstructed candidates

Can select a clean sample of signal events using multivariate classifier.

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

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



Systematic uncertainty on branching fraction measurements

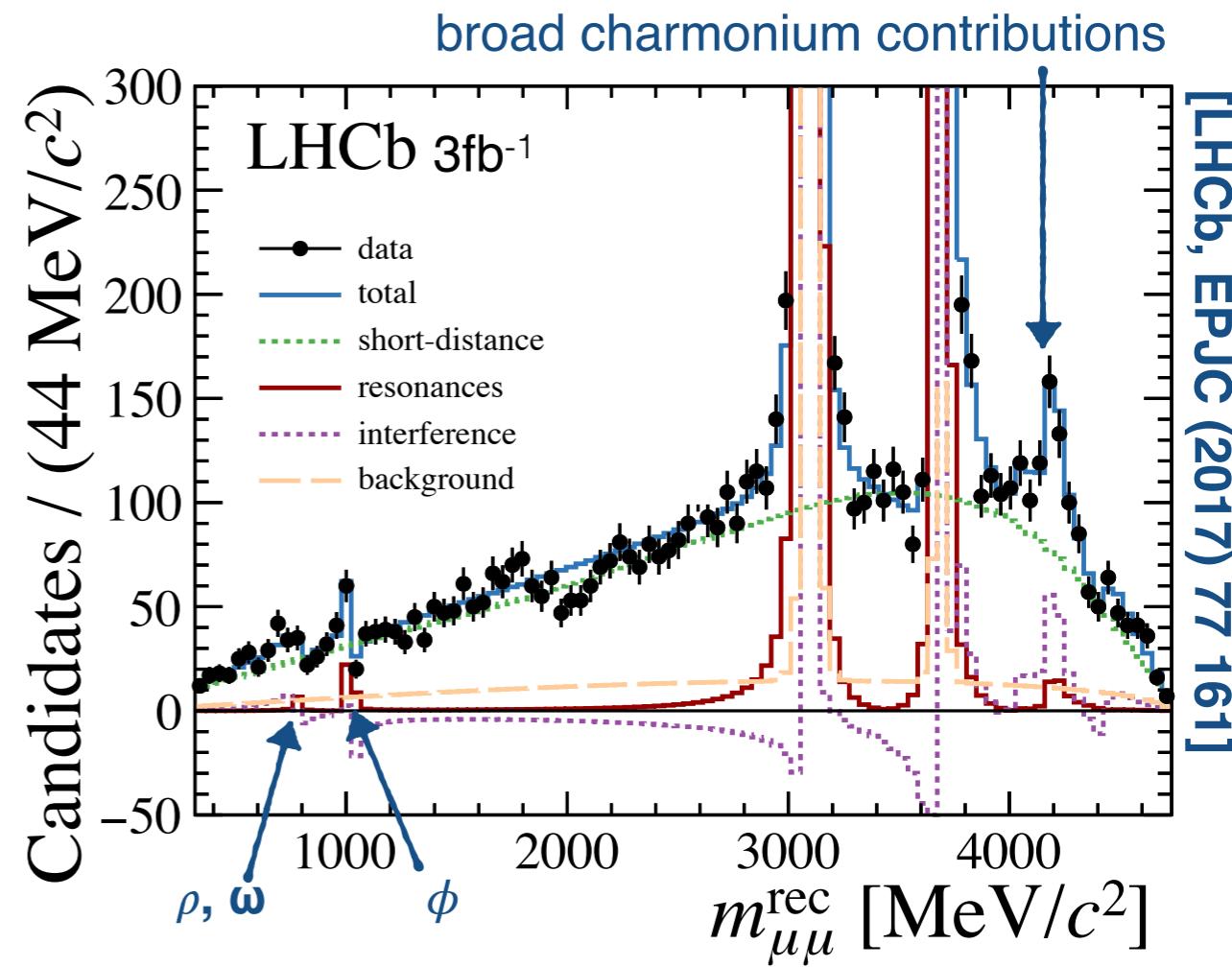
- Normalise measurements to $B \rightarrow J/\psi X$ control channel.
 - Cancels luminosity/cross-section/efficiency scale uncertainties.
- Use $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ at LHCb as an example of what systematic uncertainties are important:

[LHCb, JHEP 12 (2016) 065]			
	Source	$F_S _{644}^{1200}$	$d\mathcal{B}/dq^2 \times 10^{-7} (c^4/\text{GeV}^2)$
Need to separate $K^*(892)^0$ from other $K\pi$ contributions	Data-simulation differences	0.008–0.013	0.004–0.021
	Efficiency model	0.001–0.010	0.001–0.012
	S-wave $m_{K\pi}$ model	0.001–0.017	0.001–0.015
	$B^0 \rightarrow K^*(892)^0$ form factors	–	0.003–0.017
$\mathcal{B}(B^0 \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) K^{*0})$		–	0.025–0.079

Uncertainty on $\mathcal{B}(B \rightarrow J/\psi X)$ normalisation modes is already a limiting factor. Encourage Belle II to update these measurements!

Resonant contributions

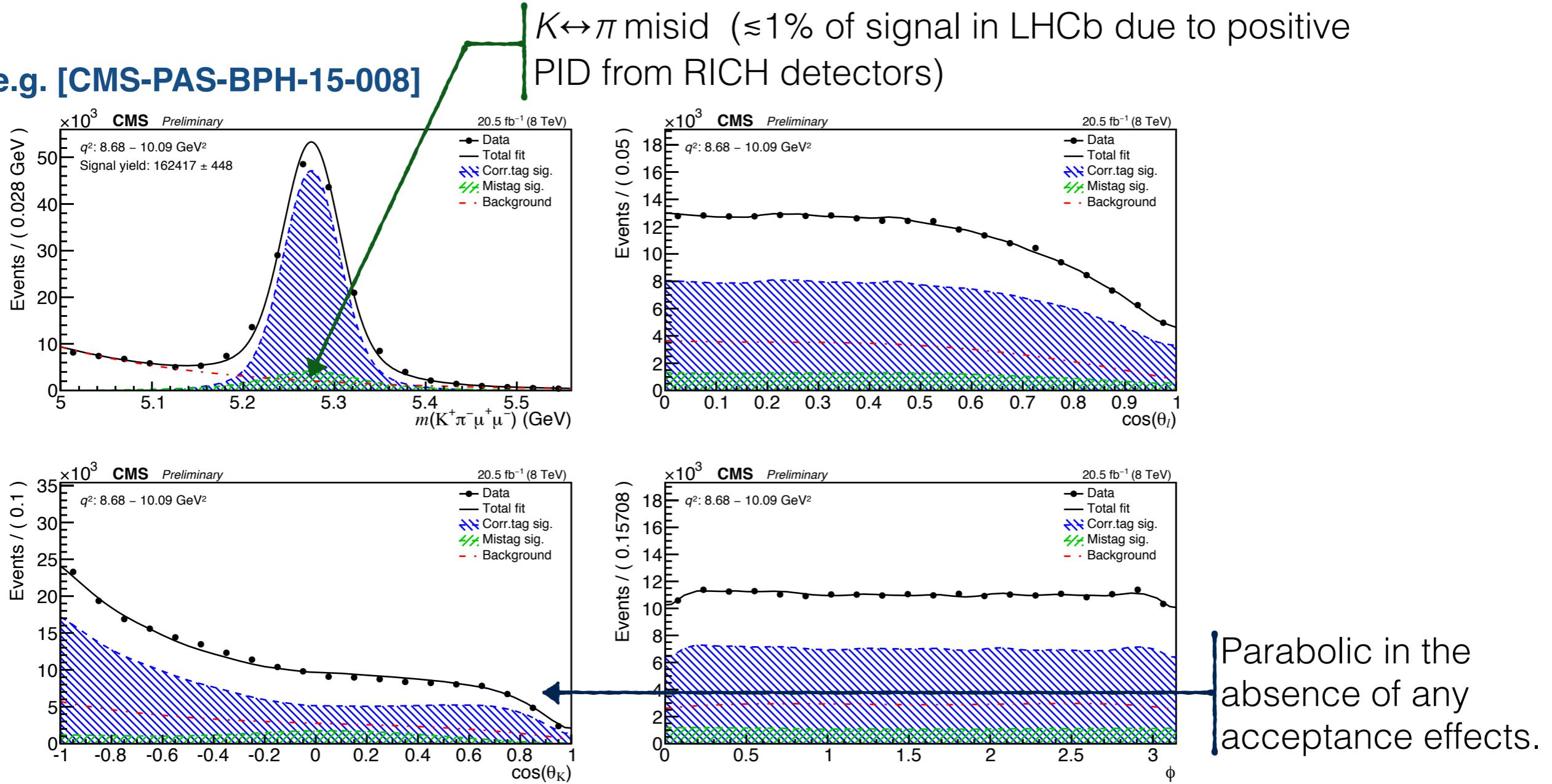
- With the large LHC datasets can also explore the shape of the $d\Gamma/dq^2$ spectrum in detail.
- See evidence for broad charmonium states and light quark contributions.
- Can determine relative magnitude/phases of the different contributions.
- Data could be used to exclude models proposing new GeV-scale particles as an explanation for R_K/R_{K^*} . **[F. Sala & D. Straub, arXiv:1704.06188]**



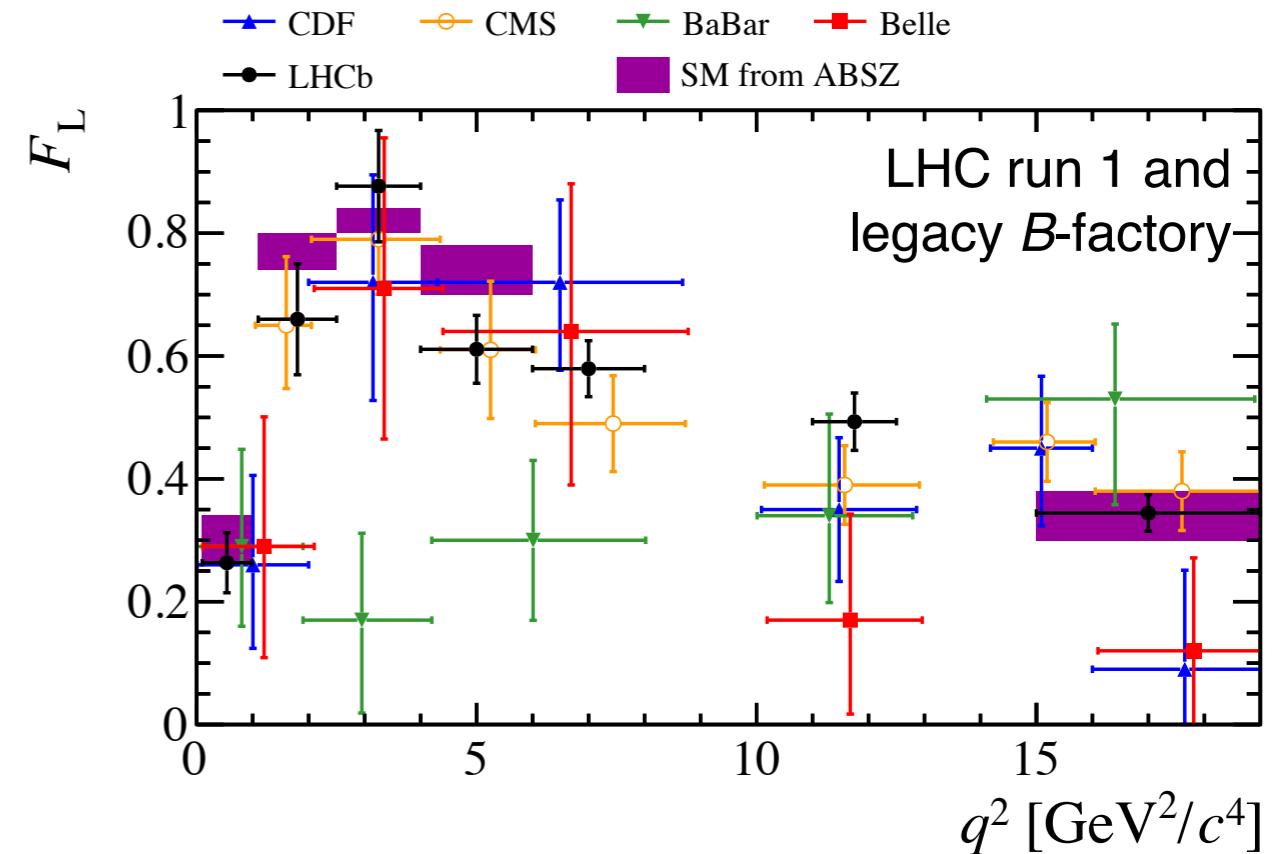
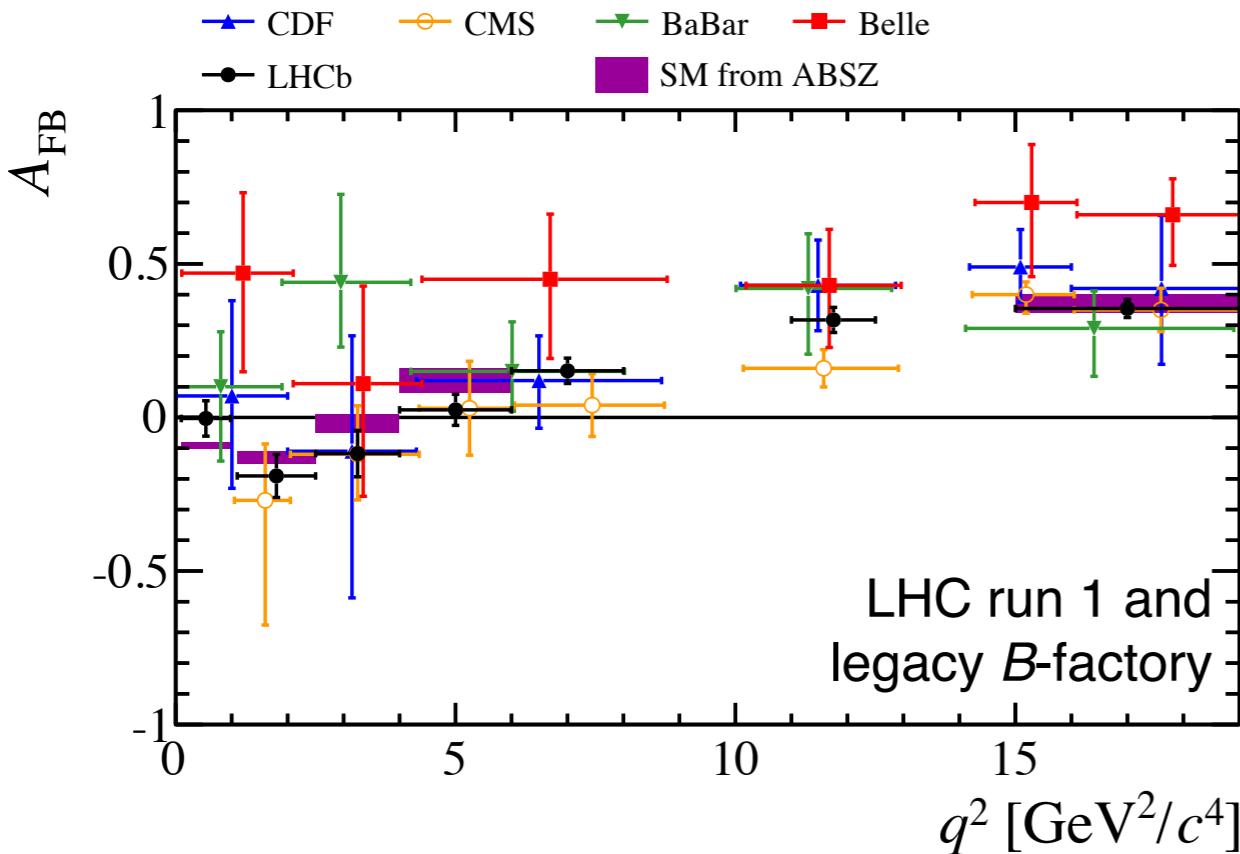
Angular acceptance

- Detector acceptance modelled using MC but can use $B \rightarrow J/\Psi K^{\star 0}$ candidates in data to understand the modelling.

e.g. [CMS-PAS-BPH-15-008]



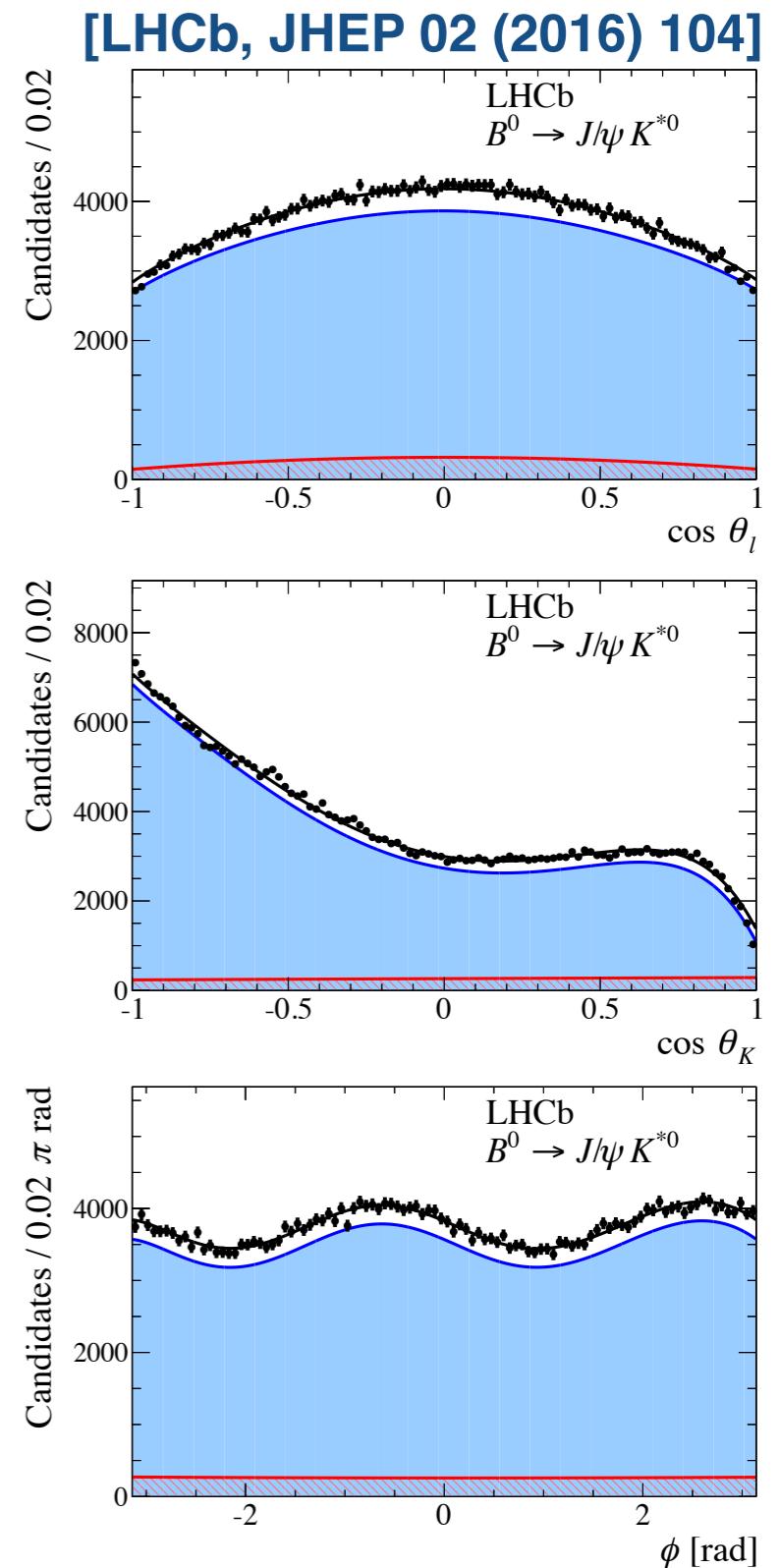
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular observables



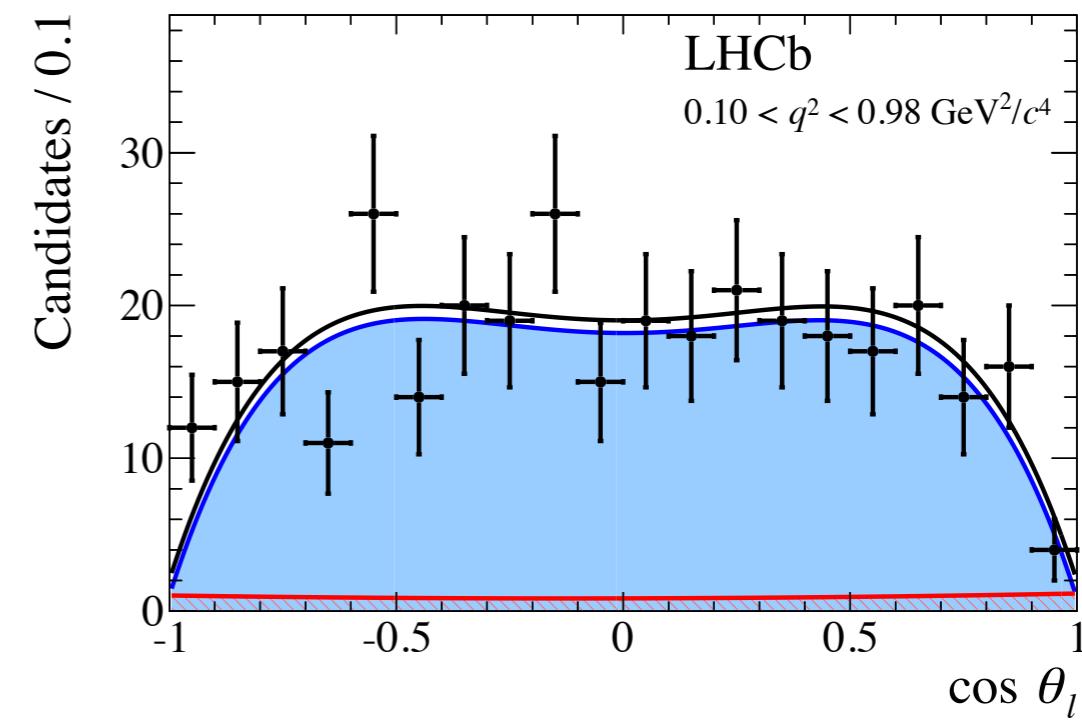
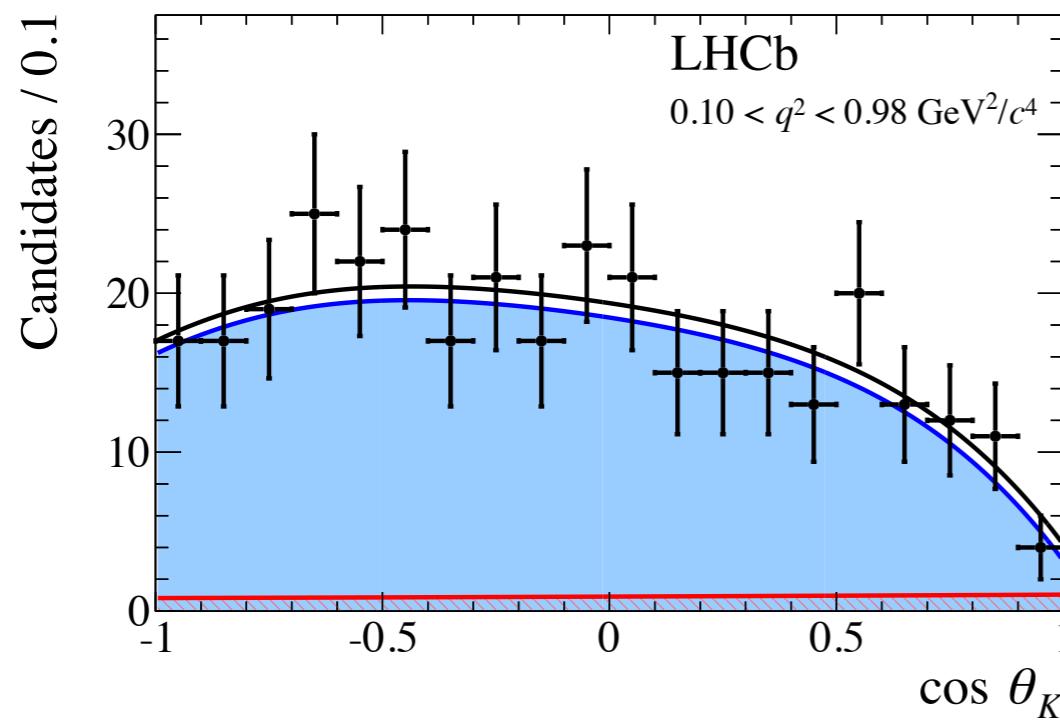
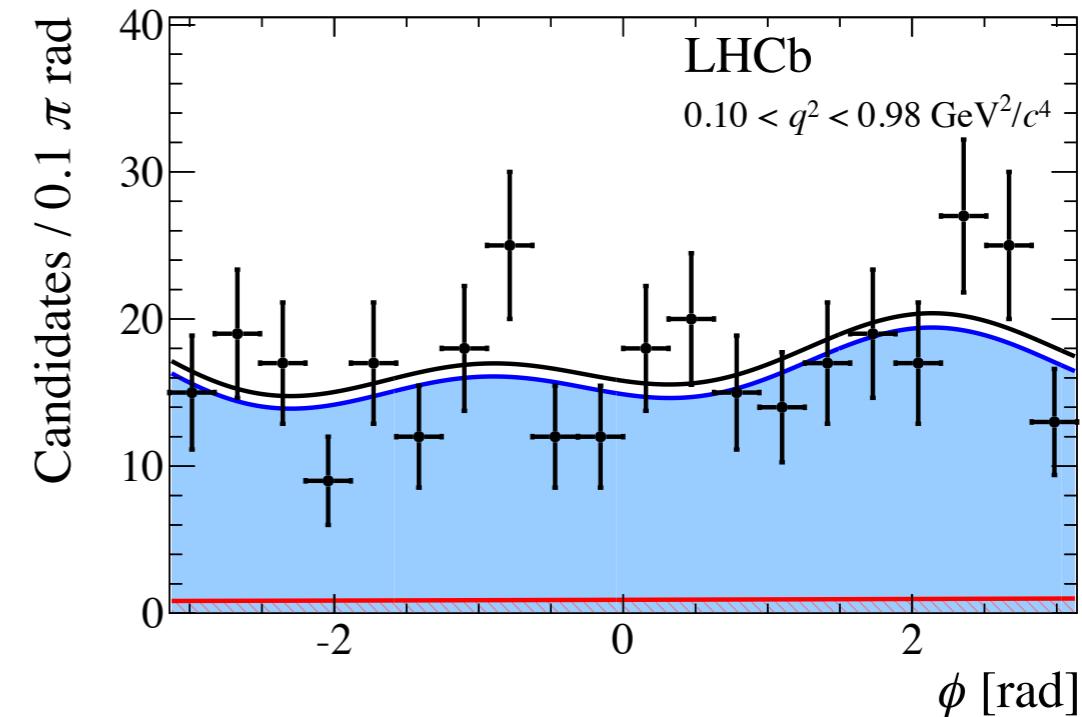
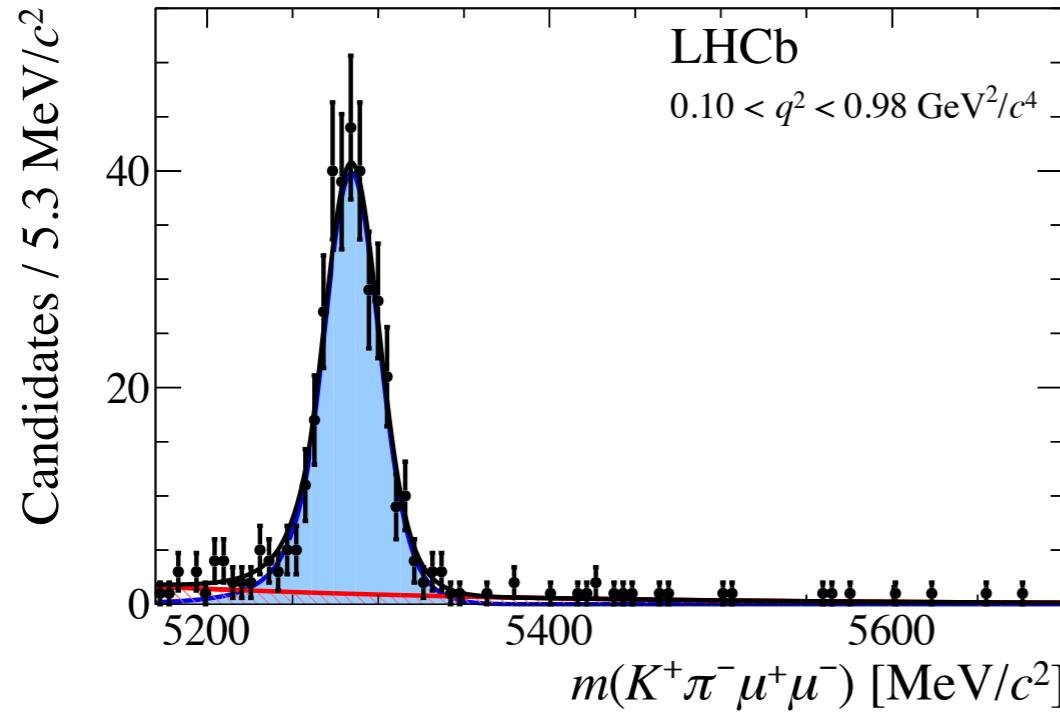
- Overlaying results for F_L and A_{FB} from LHCb [[JHEP 02 \(2016\) 104](#)] , CMS [[PLB 753 \(2016\) 424](#)] and BaBar [[PRD 93 \(2016\) 052015](#)] + measurements from CDF [[PRL 108 \(2012\) 081807](#)] and Belle [[PRL 103 \(2009\) 171801](#)].
- SM predictions based on
[\[Altmannshofer & Straub, 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

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

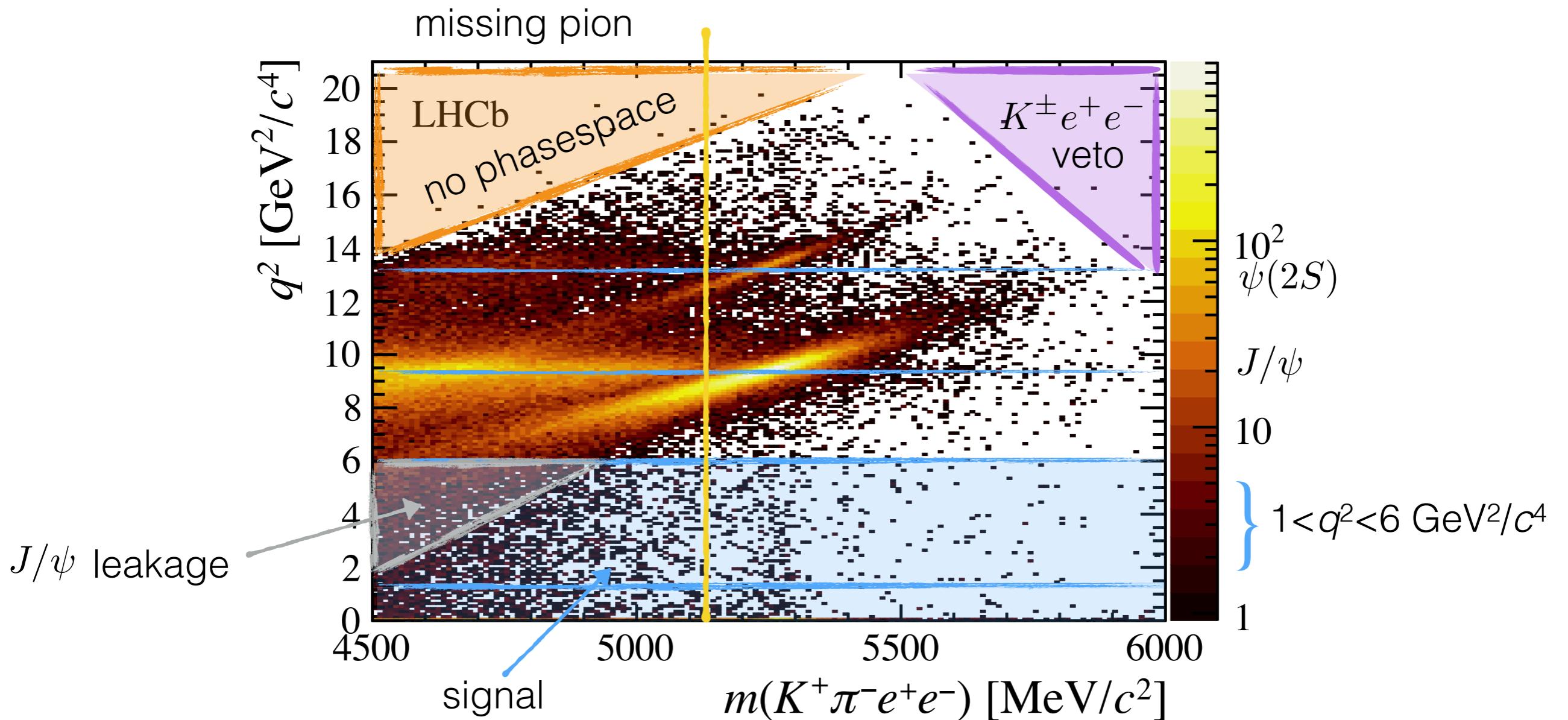


$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ example fit



R_{K^*} backgrounds

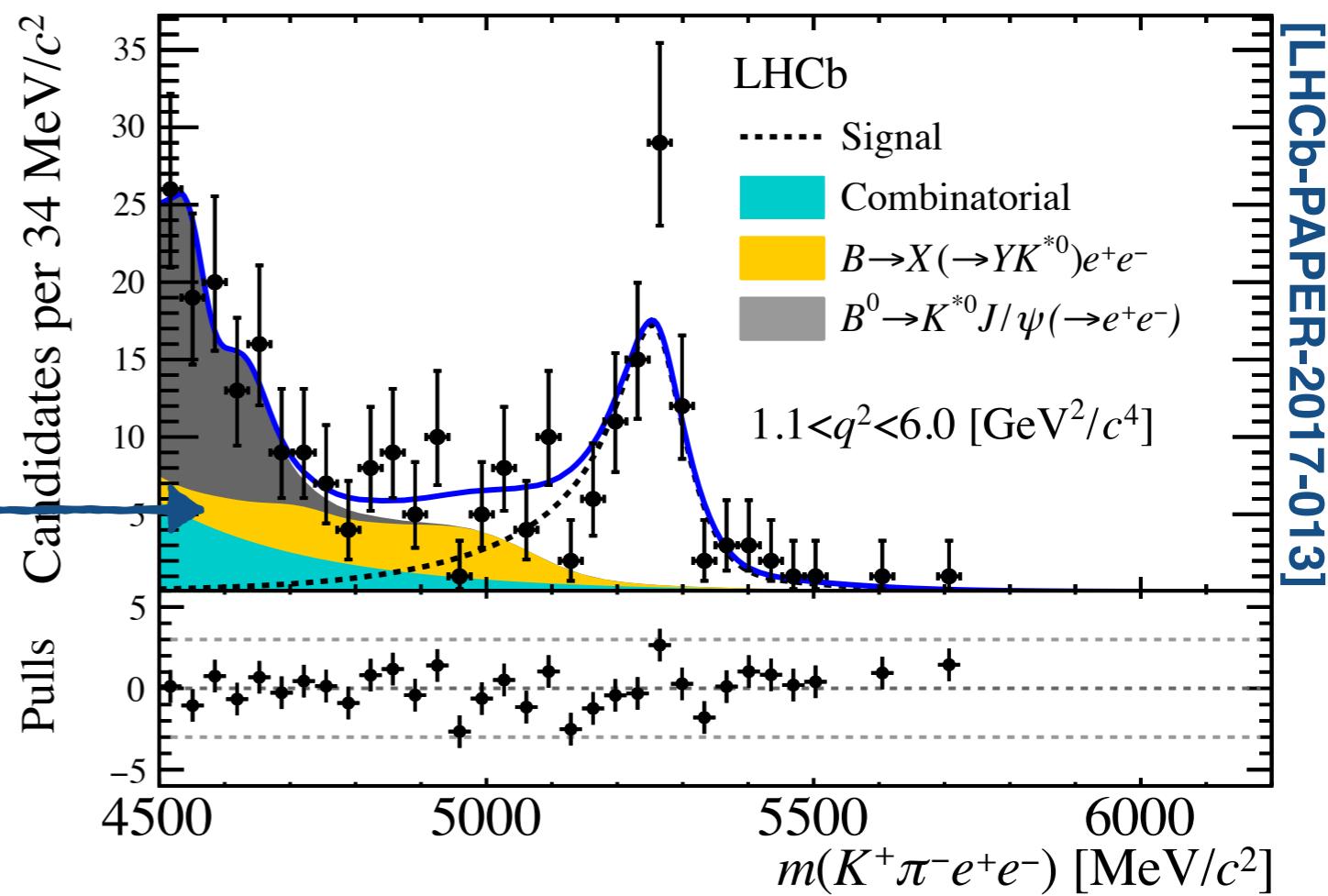
- It is much more difficult to separate dielectron final-state from physics backgrounds.



R_{K^*} mass fit

- Example fit for the L0Electron trigger category:

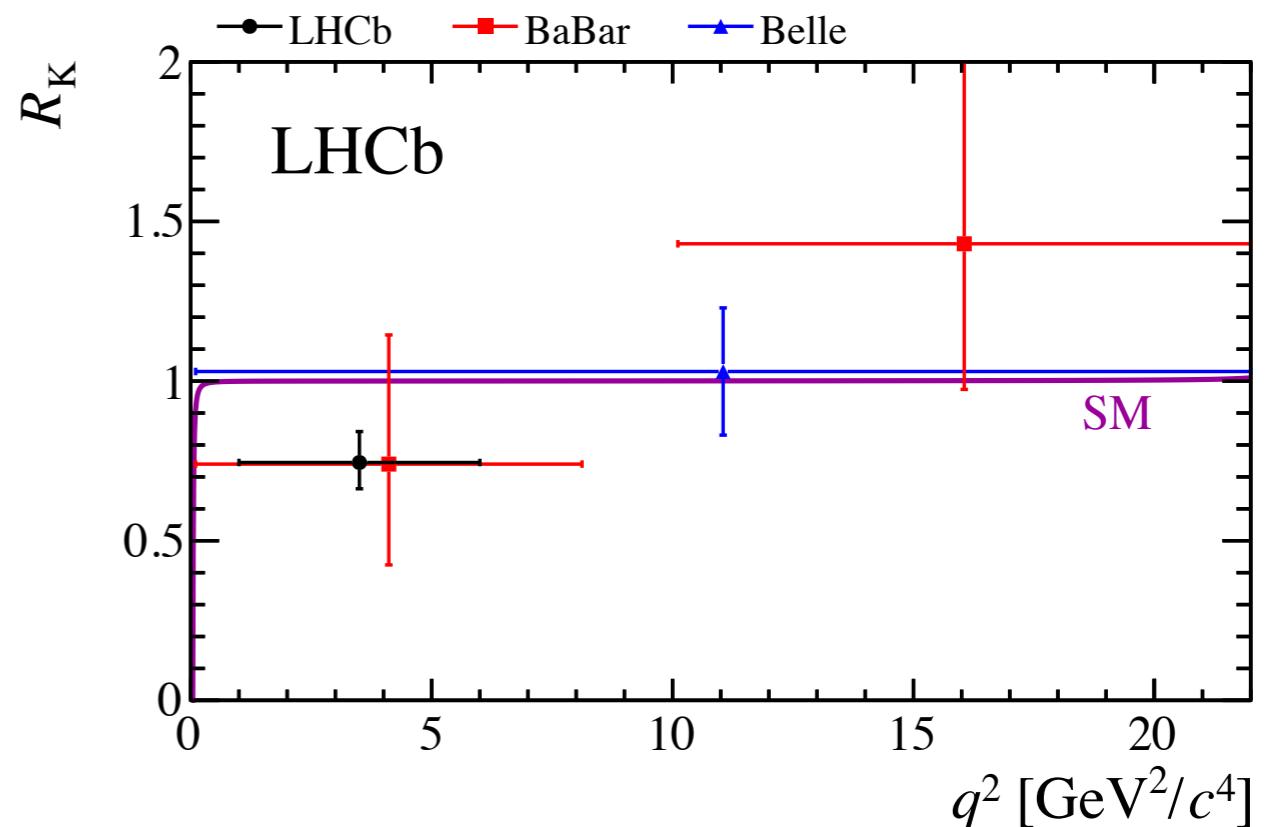
Partially reconstructed background is poorly known and comprises the largest source of systematic uncertainty



R_K result

- In the Run 1 dataset, LHCb determines:

$$R_K = 0.745^{+0.090 +0.036}_{-0.074 -0.036}$$
in the range $1 < q^2 < 6 \text{ GeV}^2$, which is consistent with the SM at 2.6σ .
- Take double ratio with $B^+ \rightarrow J/\Psi K^+$ 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 $R_K \approx 0.8$ is a prediction of one class of model explaining the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular observables, see L_μ - L_τ models
W. Altmannshofer et al. [PRD 89 (2014) 095033]

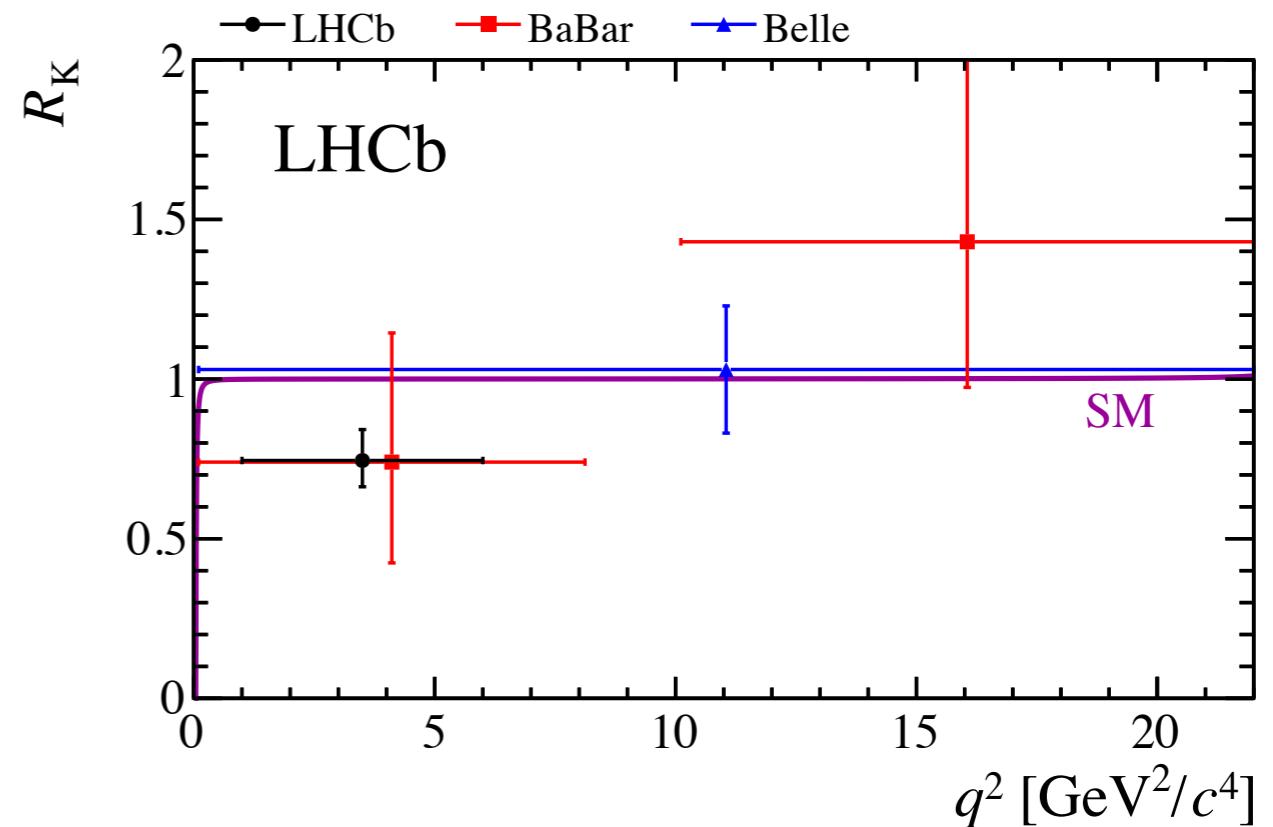
R_K result

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

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

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]

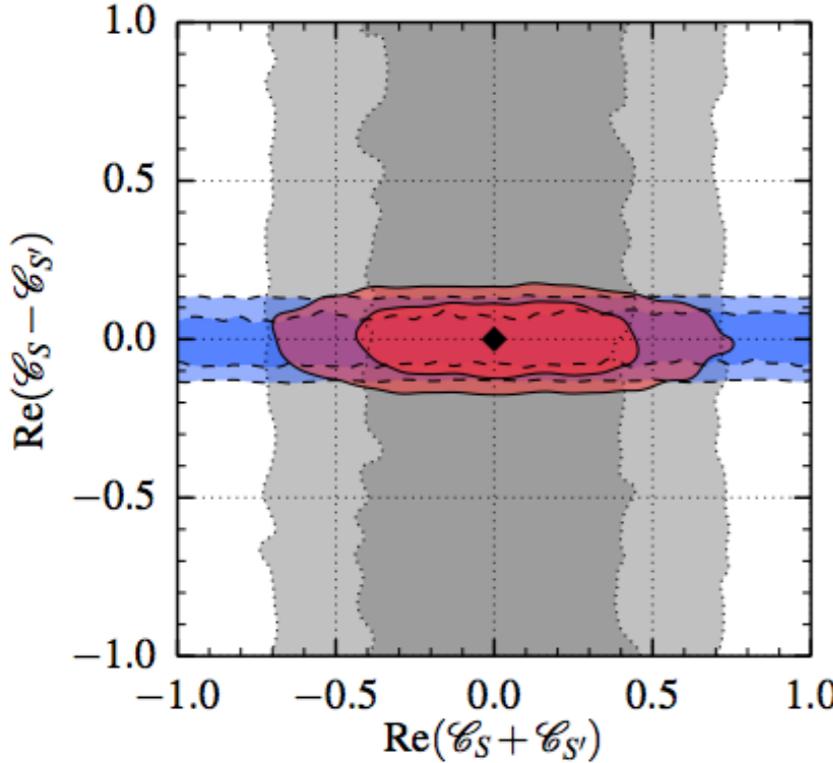
BaBar [PRD 86 (2012) 032012]

Belle [PRL 103 (2009) 171801]

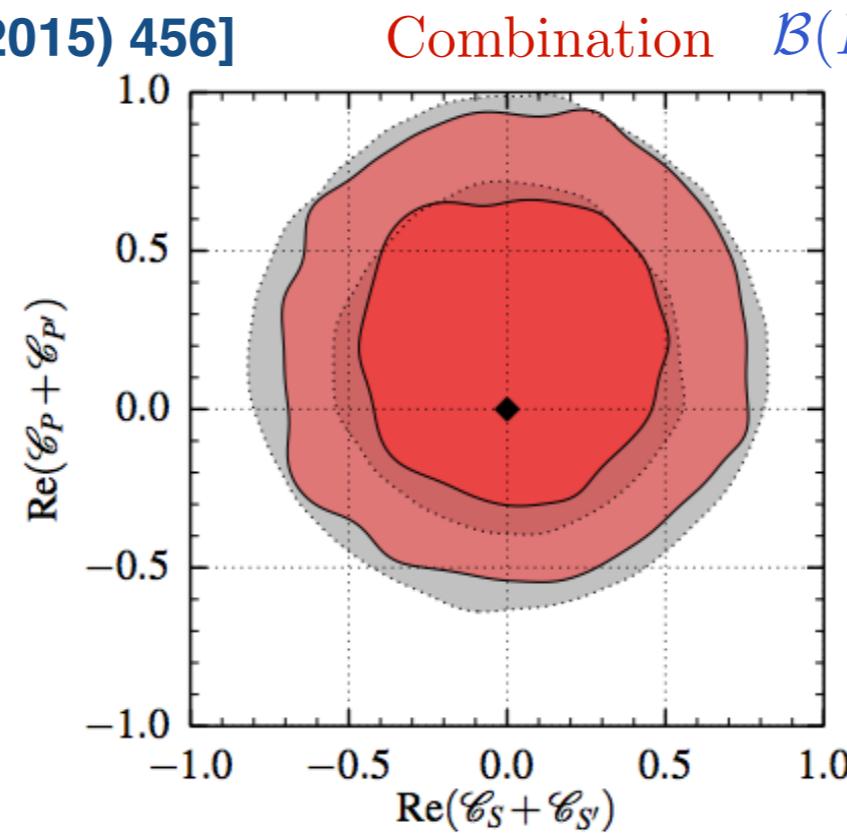
$B^+ \rightarrow K^+ \ell^+ \ell^-$

- Angular distribution of $B^+ \rightarrow K^+ \ell^+ \ell^-$ is a null test of SM, but can be sensitive to new scalar/pseudoscalar/tensor contributions, e.g.

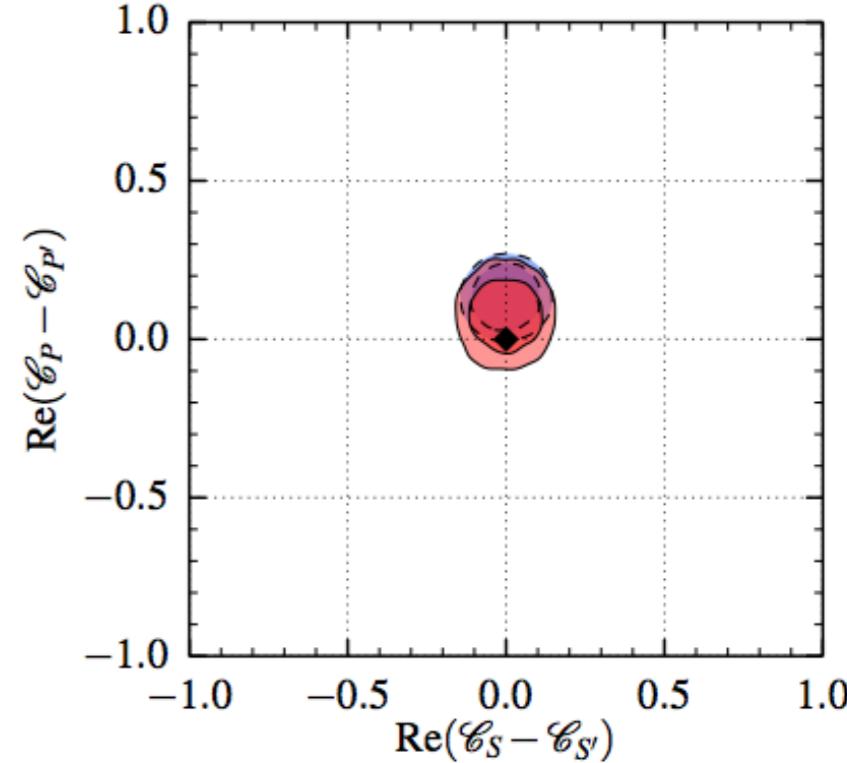
[F. Beaujean et al. EPJC 75 (2015) 456]



Combination

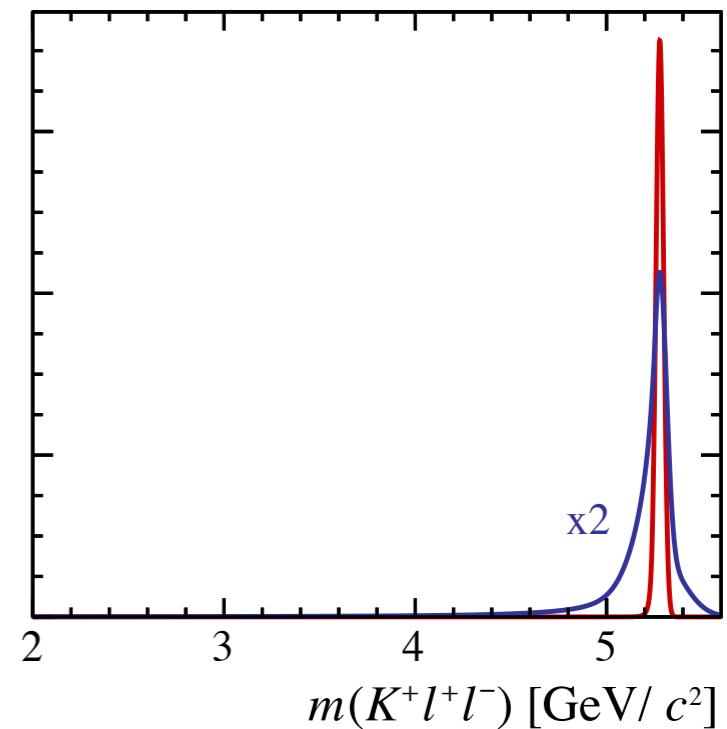
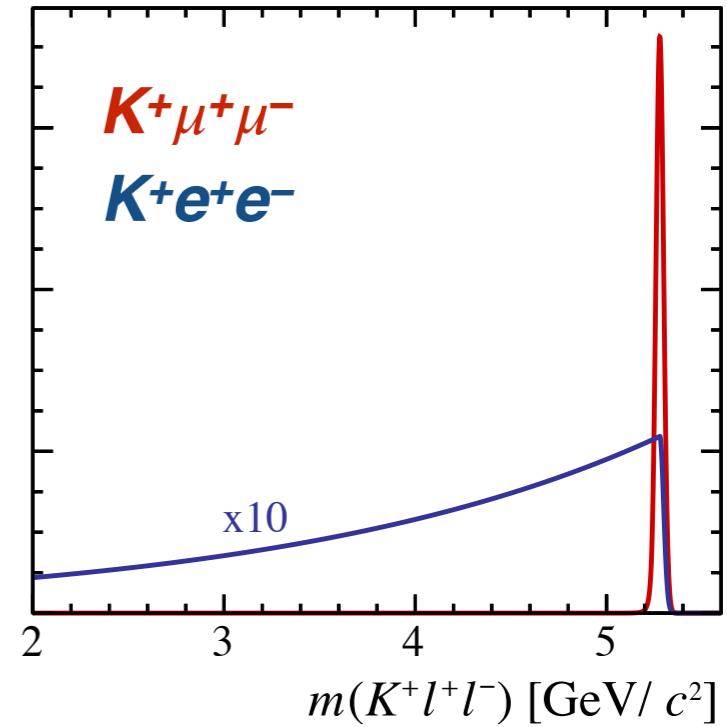


$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ $F_H[B^+ \rightarrow K^+ \mu^+ \mu^-]$



Bremsstrahlung recovery

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



Applying brem. recovery
↓