$$b \to s\ell^+\ell^-$$

Angular analyses and studies with muons at LHCb

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Beauty 2019

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Rare Decays of b hadrons: $b \to s\ell^+\ell^-$

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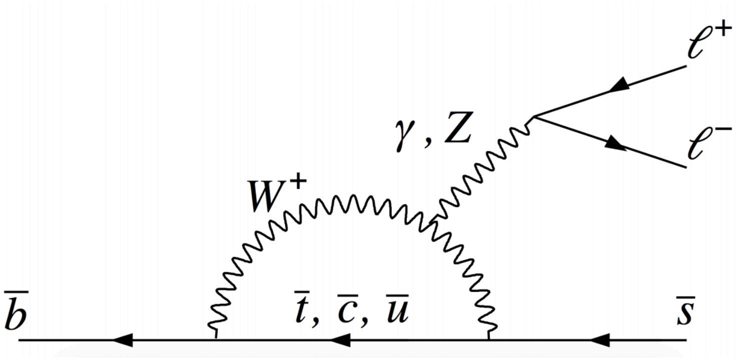
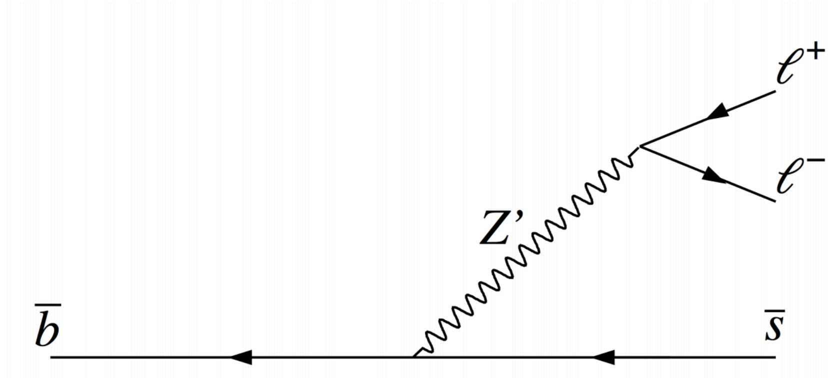
- Proceed via a flavour-changing neutral current transition
- Forbidden at tree level in the SM
- Can only occur at lowest order via electroweak penguin and box diagrams
- New Physics could already appear at tree level
- Sensitive to new particles at higher energy scales than direct searches



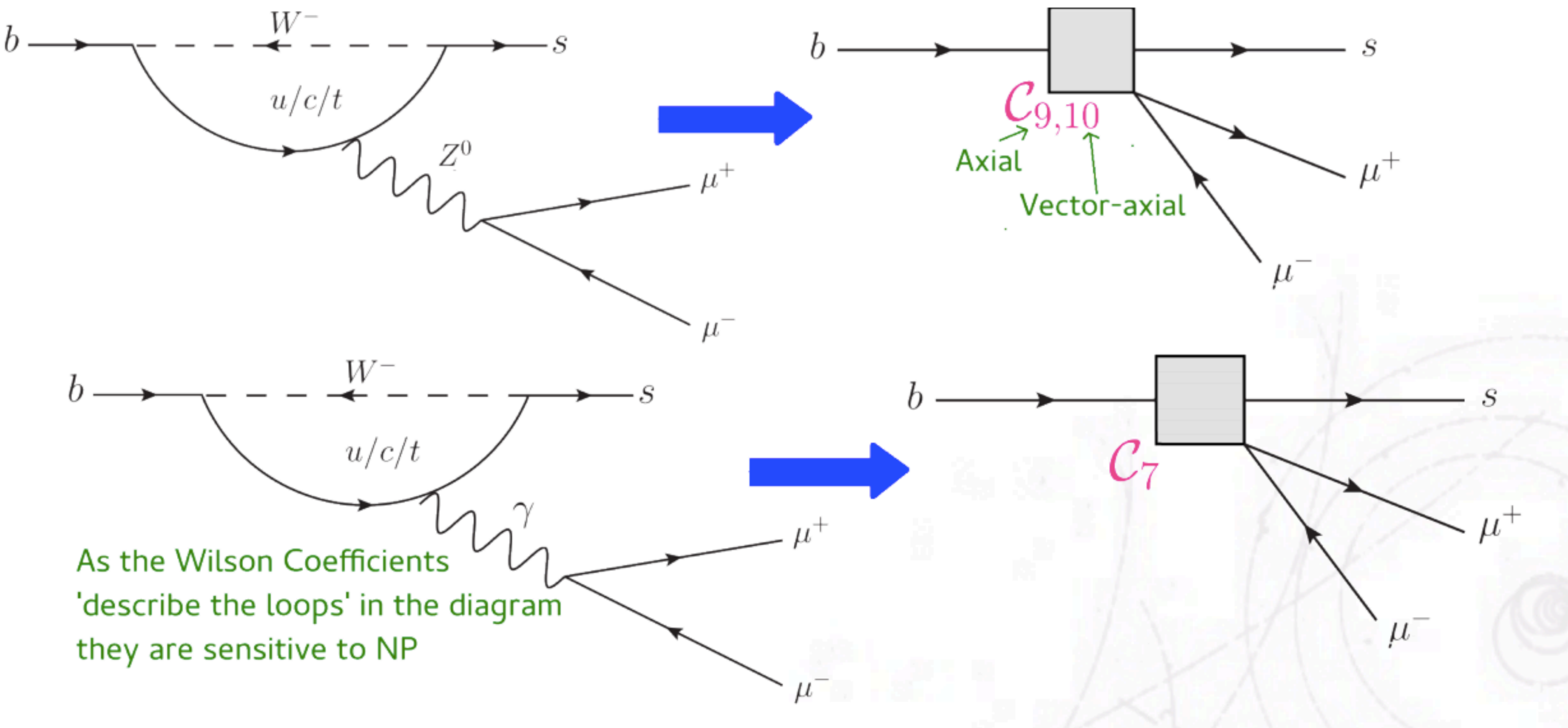
SM loop level diagram



New Physics tree level diagram

Effective theories for SM predictions

- The heavy physics contributions in $b \to s\ell^+\ell^-$ can be integrated out to give effective couplings, parameterised by Wilson coefficients (C_i)
- $b \to s\ell^+\ell^-$ transitions are most sensitive to C_7, C_9 and C_{10}



As the Wilson Coefficients 'describe the loops' in the diagram they are sensitive to NP

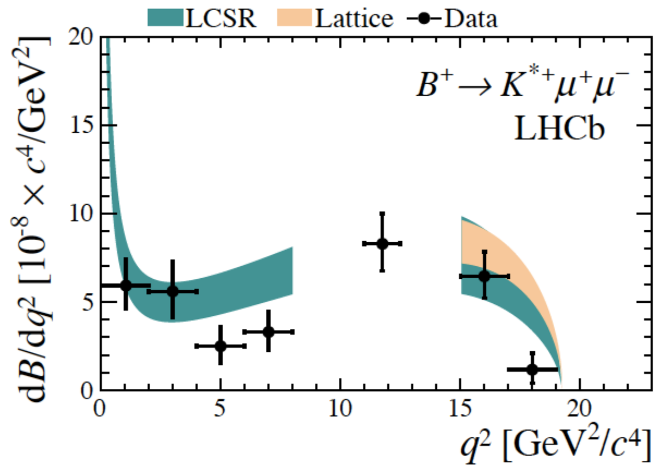
Experimental status of $b \to s\ell^+\ell^-$

Three different types of measurements:

1.) Branching fractions: suffer from form factor and hadronic uncertainties

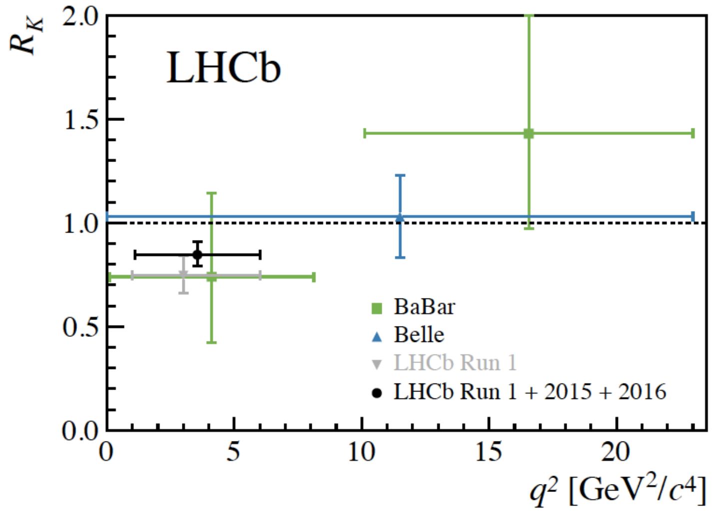
2.) Angular analysis: some observable's form factors cancel to first order however, vigorous debate about theory control of hadronic uncertainties

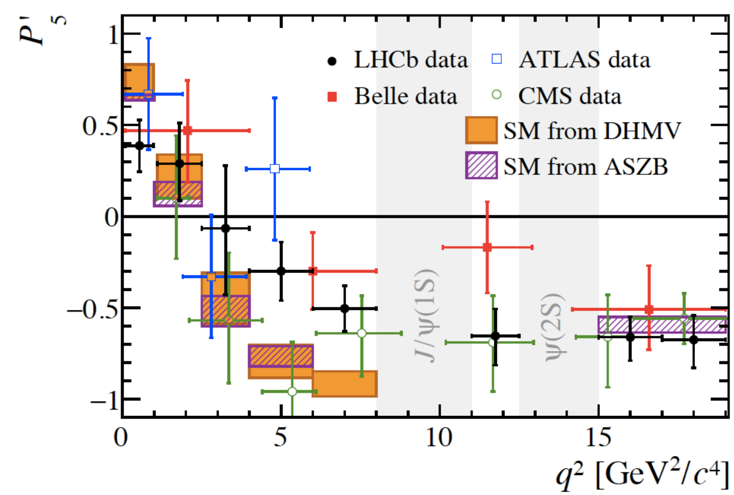
3.) Branching fraction ratios: theoretically pristine, all hadronic effects cancel (see Christoph Langenbruch's talk)



JHEP 06 (2014) 133

LHCb: Phys. Rev. Lett. 122, 191801 (2019)
Belle: PRL103(2009)171801
BaBar: PRD86(2012)032012



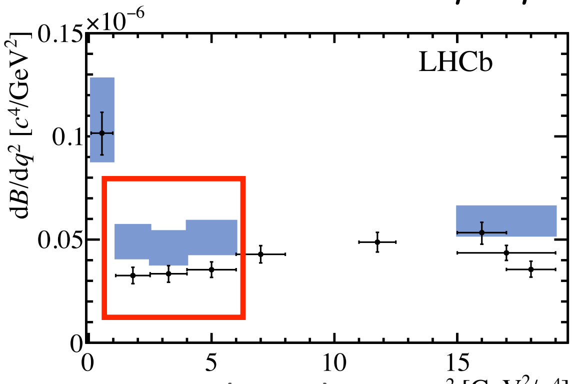


LHCb: JHEP 02 (2016) 104 Atlas-Conf-2017-023
Belle: PRL 118 2017 CMS: PLB 781 (2018) 517541

Branching fractions: $b \to s\ell^+\ell^-$

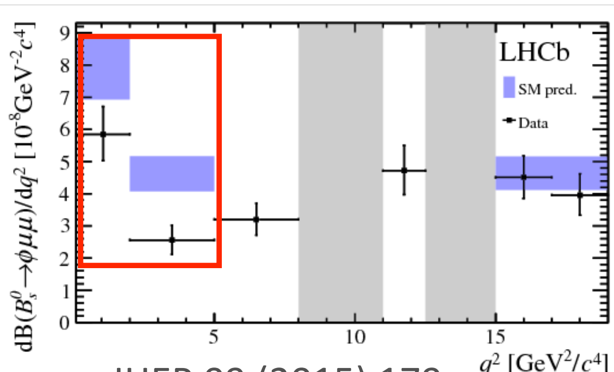
LHCb measurements tend to lie below the SM predictions for low q^2

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



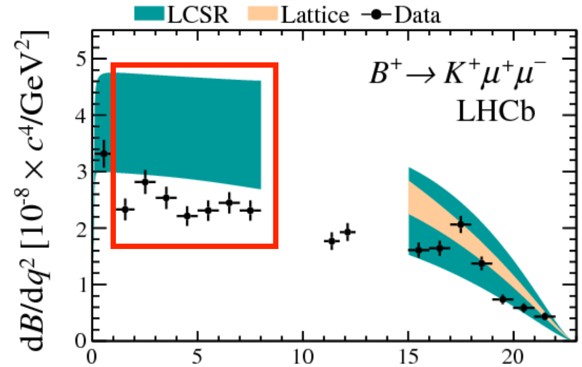
JHEP 11 (2016) 047

LHCb $B_s^0 \to \phi\mu^+\mu^-$



JHEP 09 (2015) 179

LHCb $B^+ \to K^+\mu^+\mu^-$



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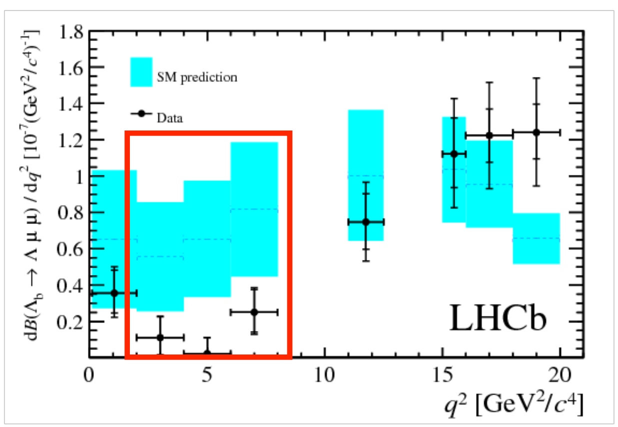
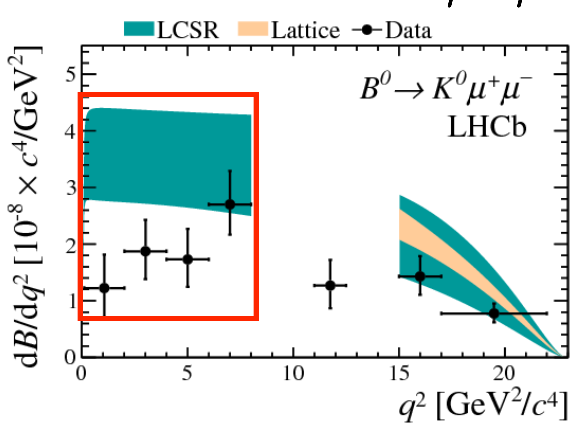
LHCb $\Lambda_b^0 \to \Lambda\mu^+\mu^-$



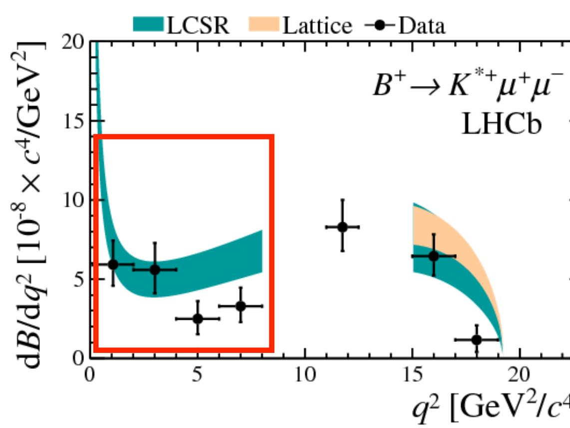
JHEP 06 (2015) 115

LHCb $B^0 \to K^0\mu^+\mu^-$



JHEP 06 (2014) 133

LHCb $B^+ \to K^{*+}\mu^+\mu^-$



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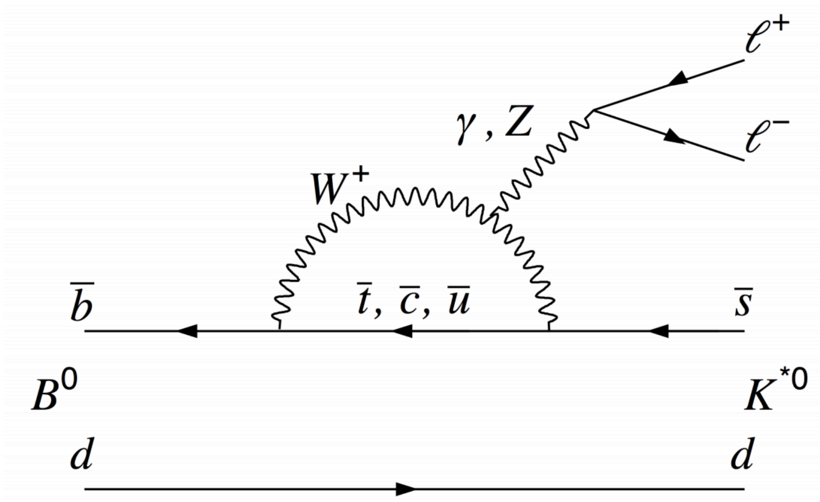
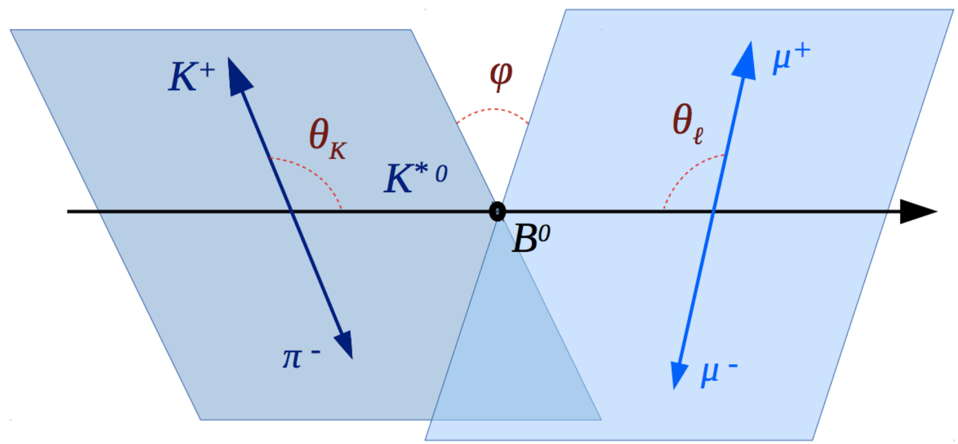
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

- Angular distribution is a function of q^2, the invariant mass squared of the dimuon system and $\vec{\Omega} = (\cos(\theta_l), \cos(\theta_K), \phi)$





$$\frac{\mathrm{d}^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega})$$

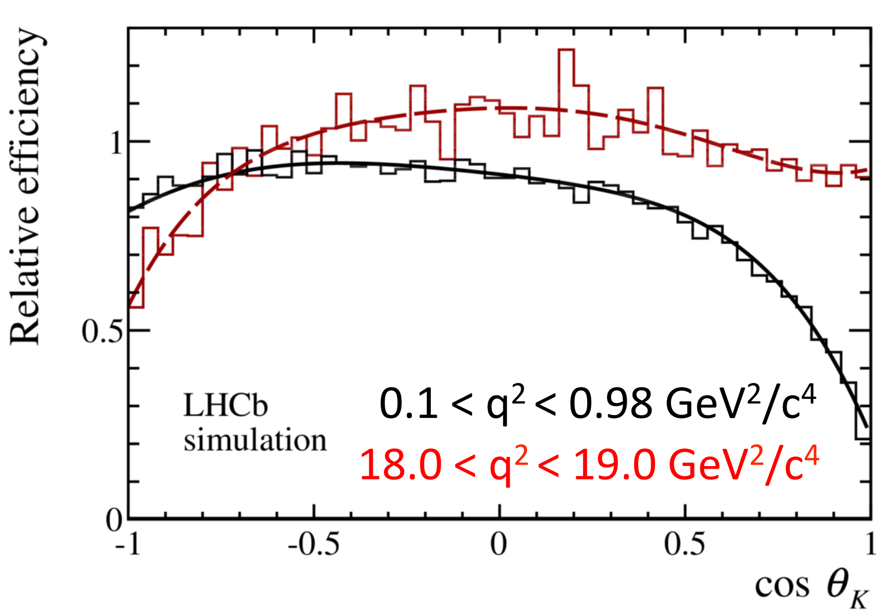
- In order to extract the angular observables a fit to the three angles, $m_{K\pi\mu\mu}$ and $m_{K\pi}$ is performed in bins of q^2

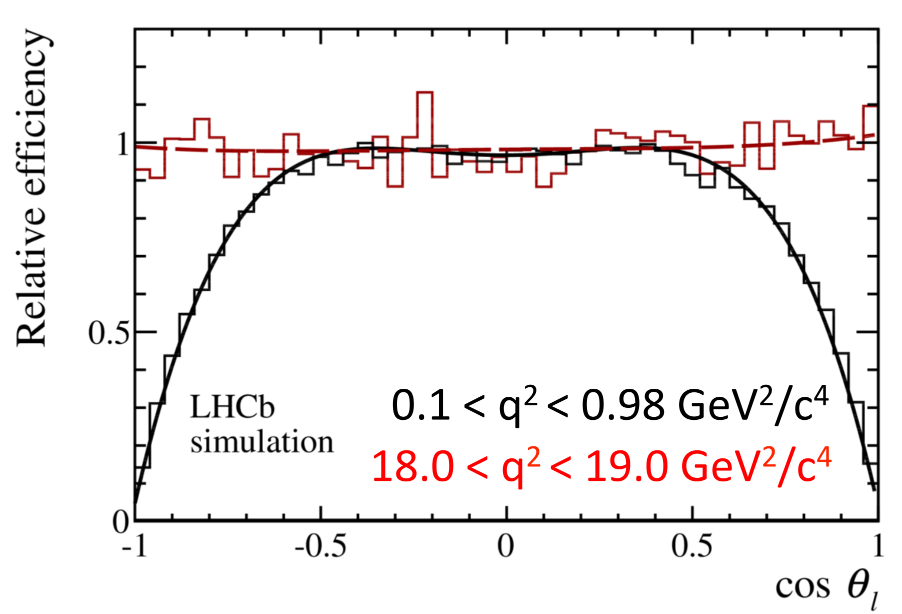
$B^0 \to K^{*0}\mu^+\mu^-$: Acceptance

- Acceptance effects: Angular distribution is distorted due to detector effects, reconstruction and selection

$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2 d\vec{\Omega}}(\text{observed}) = \boxed{\varepsilon}\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2 d\vec{\Omega}}(\text{physical})$$

- Use simulation to model efficiency properly:
  1.) Simulation needs to model data correctly
  2.) Parameterise efficiency to implement in fit





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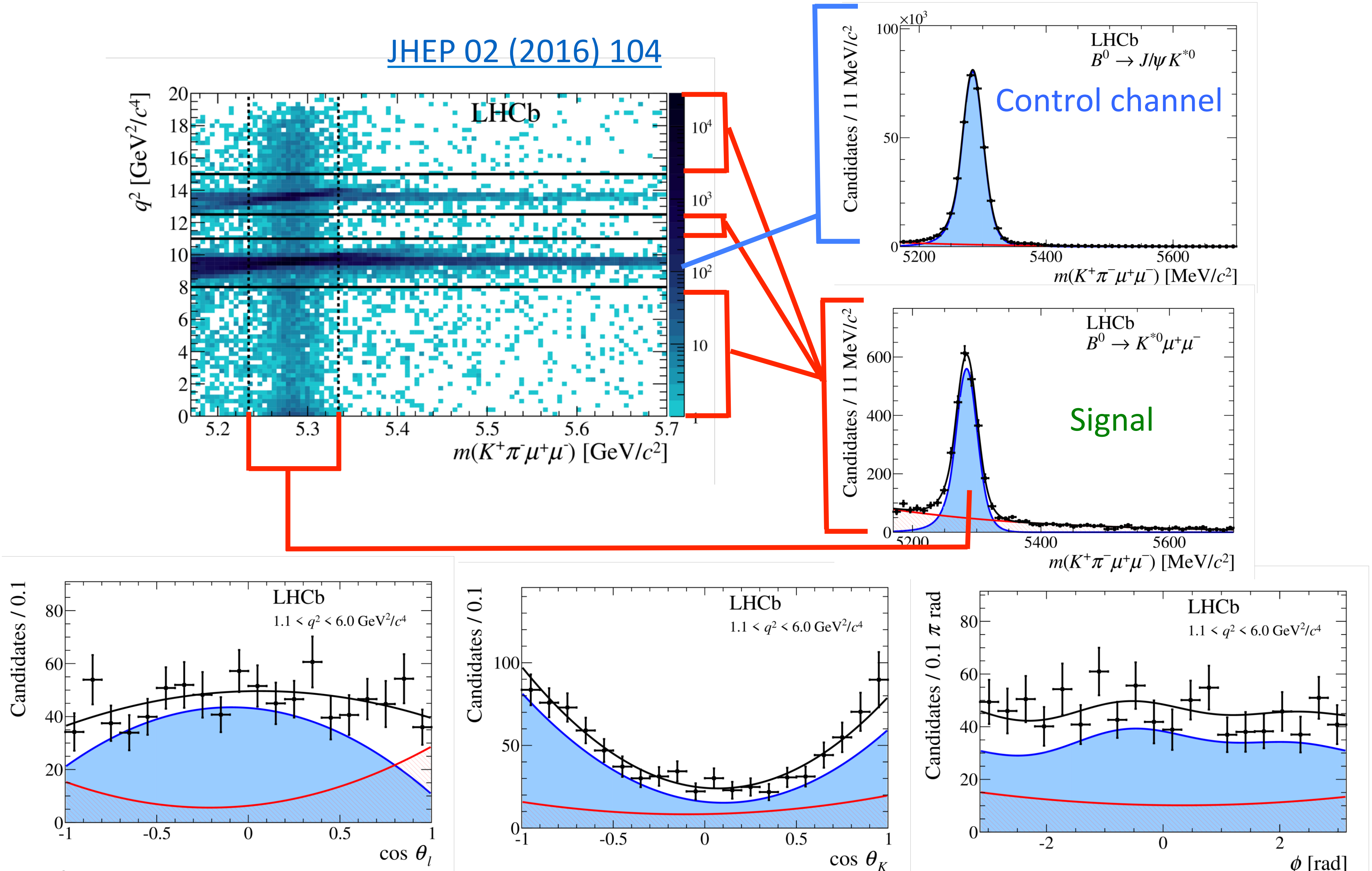
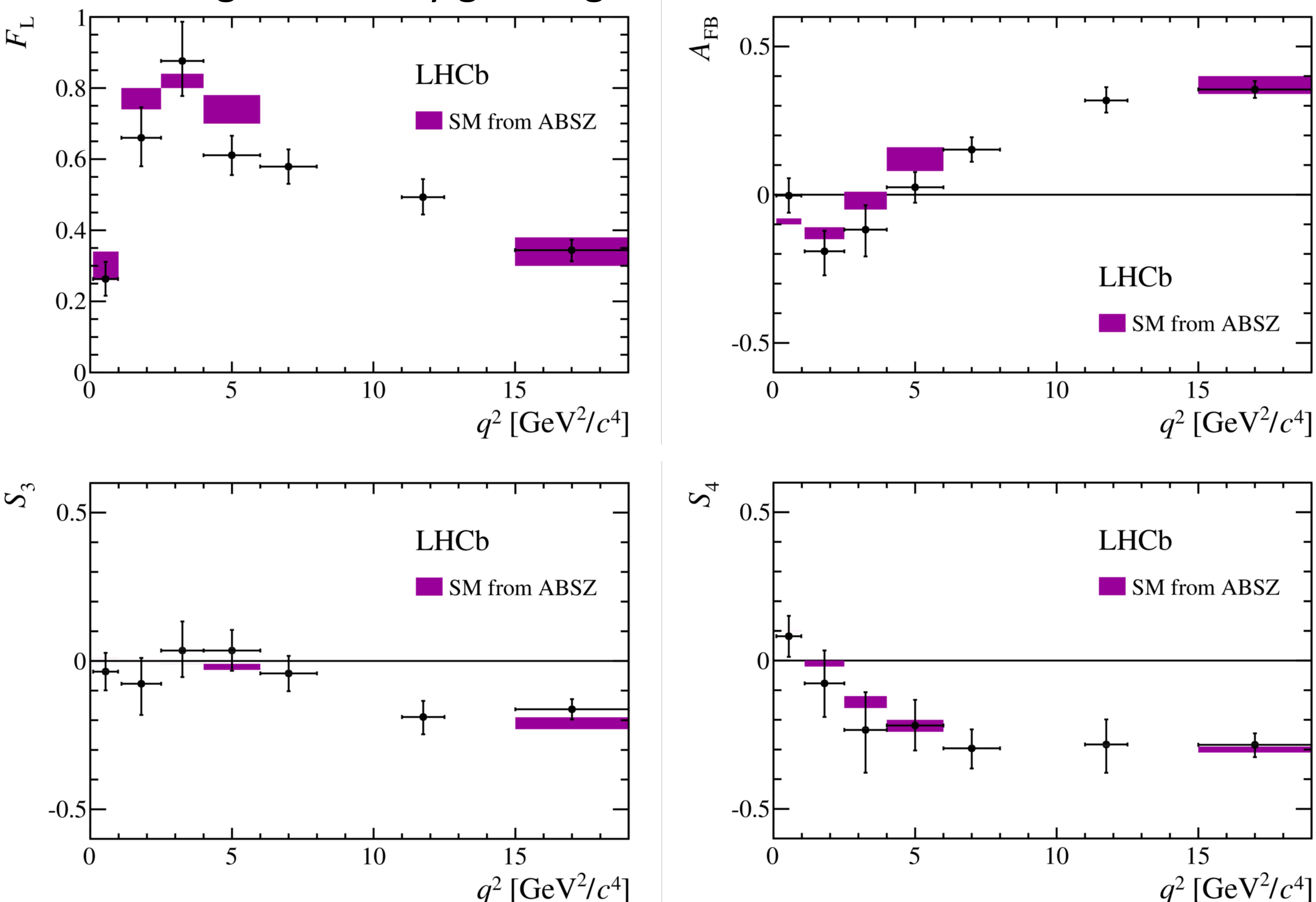
$B^0 \to K^{*0}\mu^+\mu^-$: Results



$B^0 \to K^{*0}\mu^+\mu^-$: Results

In general very good agreement with the Standard Model



$B^0 \to K^{*0}\mu^+\mu^-$: Results

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LHCb: JHEP 02 (2016) 104 Atlas-Conf-2017-023
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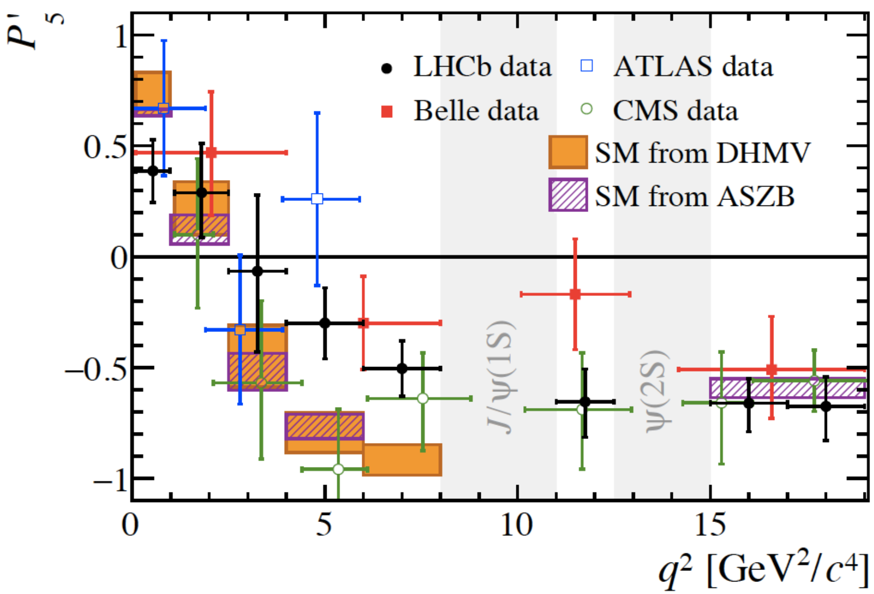
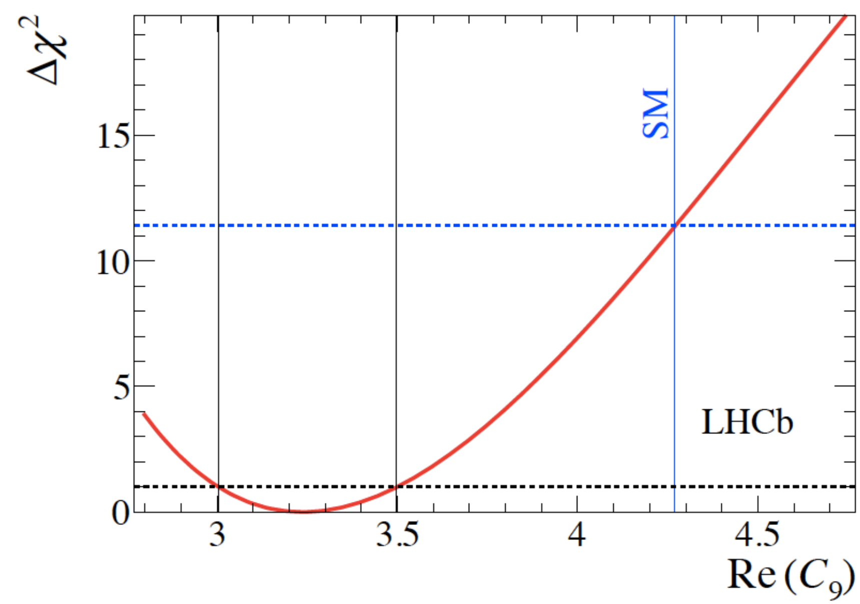


Optimised observable: form factor uncertainties cancel to first order



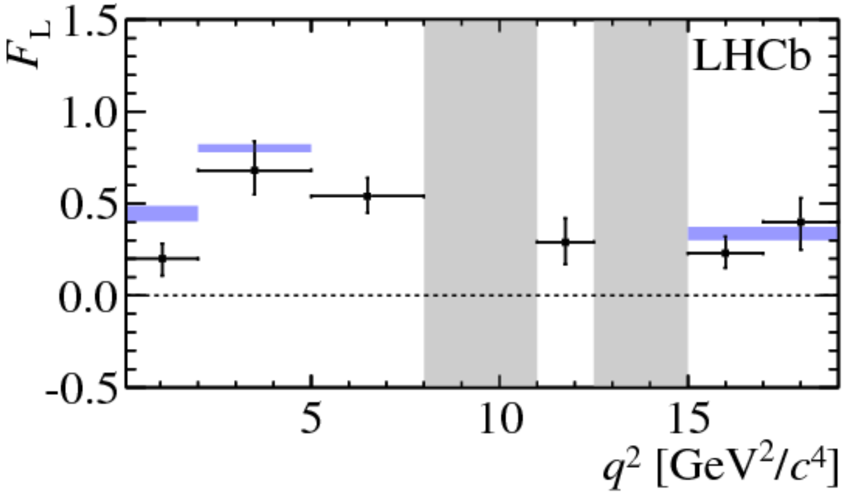
The best fit point is found to be 3.23, while the SM prediction is at 4.27

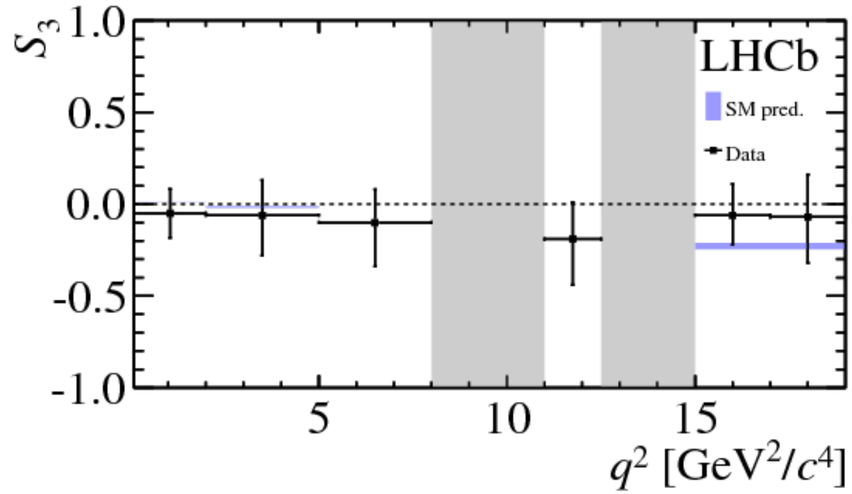
LHCb result:

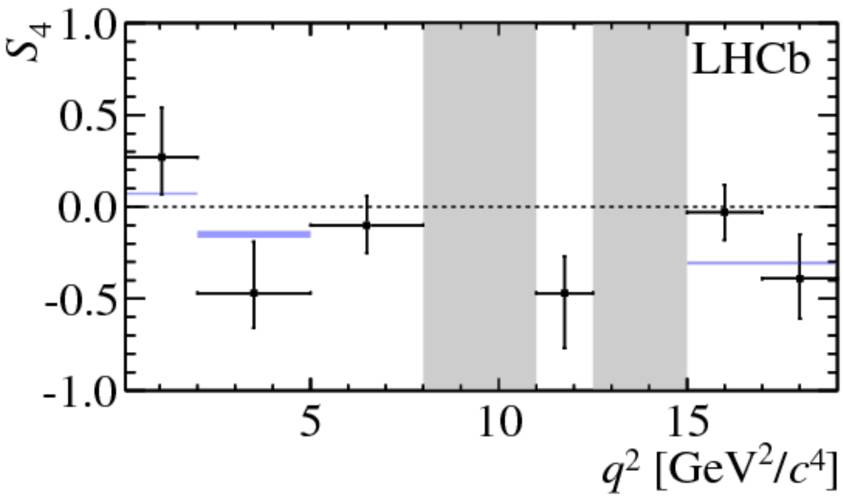
- Local tensions of 2.8σ and 3.0σ observed in the 4th and 5th bin of P'_5 respectively
- Performing a global fit to all the angular observables results in a value of Re(C_9) of 3.23, which is 3.4σ from the Standard Model

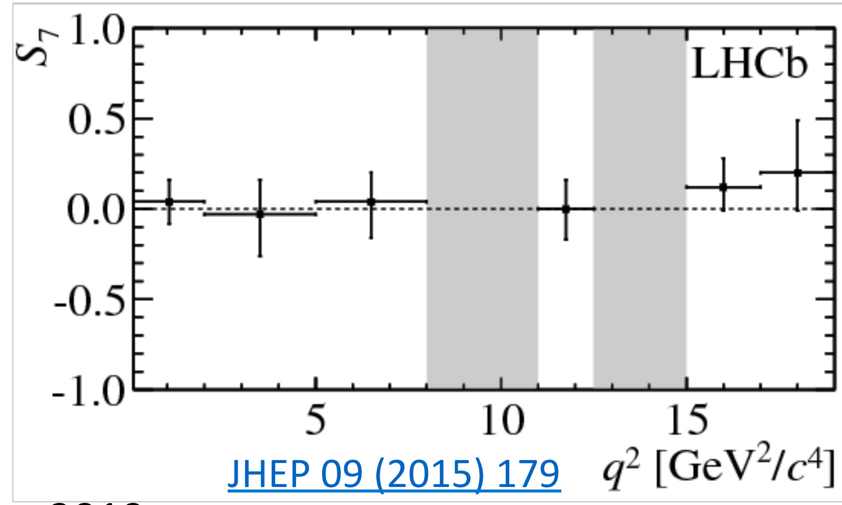
$B_s^0 \to \phi(\to K^+K^-)\mu^+\mu^-$

- Equivalent process of $B^0 \to K^{*0}\mu^+\mu^-$ for B_s^0 mesons
- Not as powerful a channel because the process is not self tagging
- Angular observables are consistent with the Standard Model









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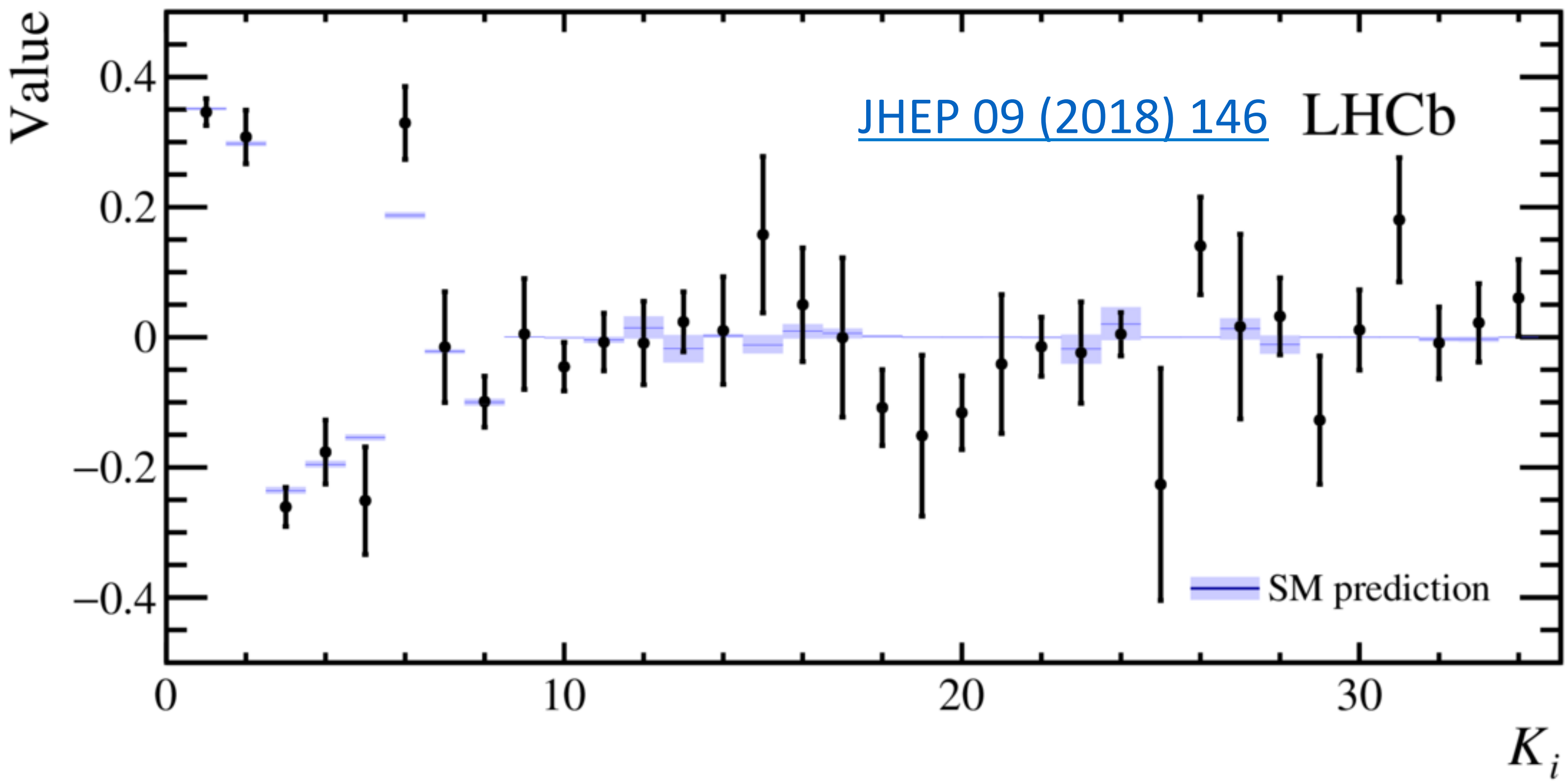
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$

- $b \to s\ell^+\ell^-$ transition in the baryon sector
- First full angular analysis performed by LHCb in August last year using 2011-2016 data corresponding to 5 fb^{-1} of data
- Angular observables were determined using a method of moment analysis in the range $15 < q^2 < 20$ GeV^2/c^4
- Results were found to be consistent with the Standard Model predictions



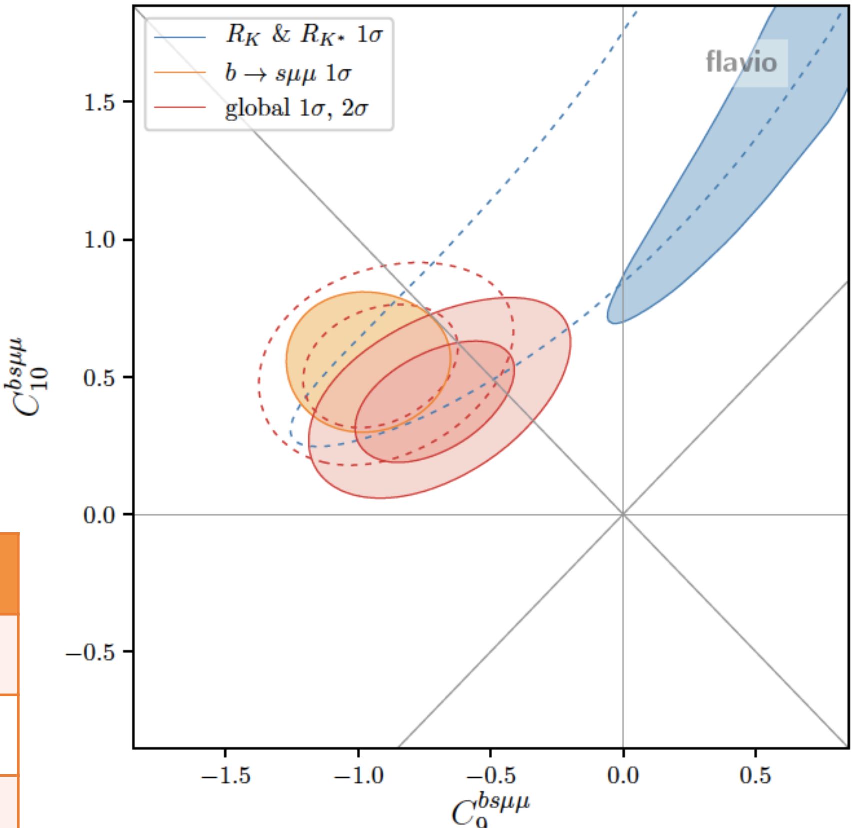
Theoretical interpretation of $b \to s\ell^+\ell^-$

$$H_{eff} \propto \sum_i \left(C_i^{SM} + C_i^{NP}\right) \cdot O_i$$

- Wilson coefficients (C_i) are extracted from global fits to data
- Any deviations from SM calculations would point to New Physics effects

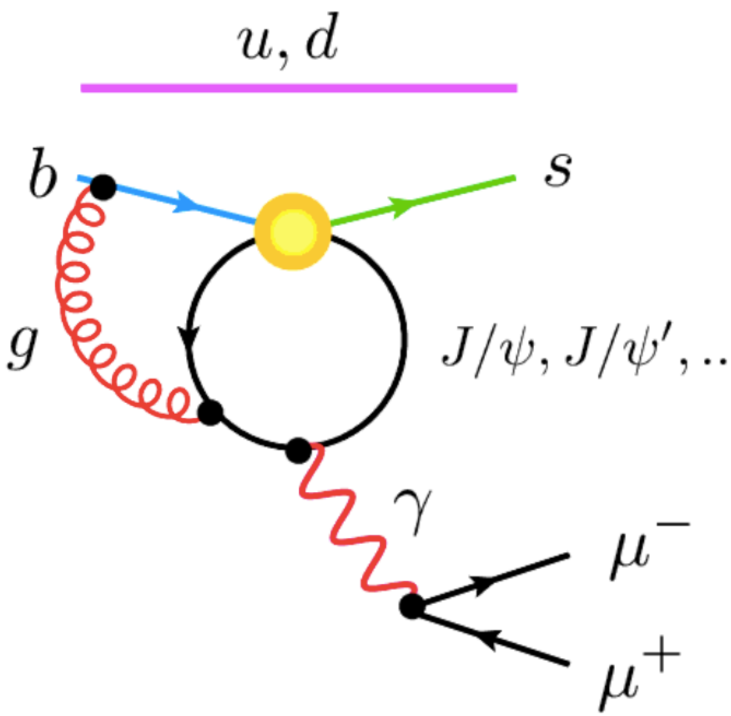
- C_9: vector coupling
- C_{10}: axial vector coupling
- Plot shows one of the recent global fits to data
- $b \to s\ell^+\ell^-$ experimental results can be interpreted in a coherent way

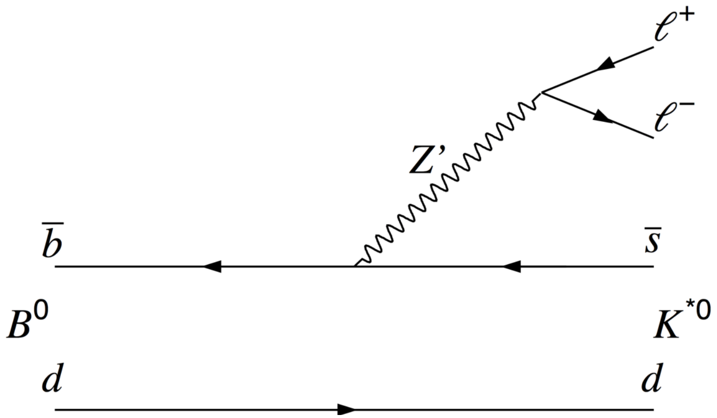
Coeff. varied	Best fit	Pull from SM
$C_9^{NP} = - C_{10}^{NP}$	-0.53	6.6 σ
C_9^{NP}	-0.97	5.9 σ
C_{10}^{NP}	+0.75	5.7 σ

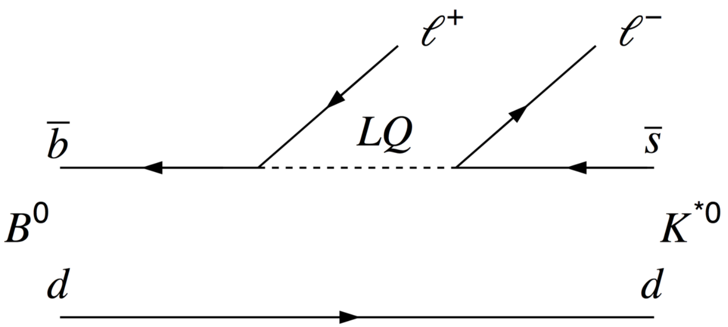


https://arxiv.org/abs/1903.10434v2
Aebischer et al.

Hadronic uncertainties in angular observables of $b \to s\ell^+\ell^-$ decays



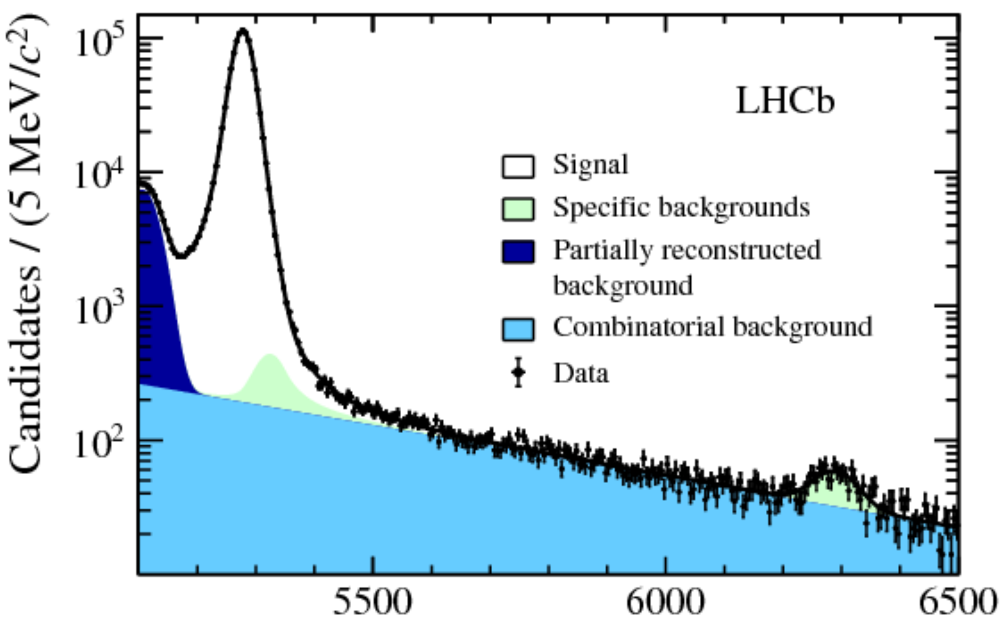




Long distance SM effects or Short distance NP effects?

Data driven measurements of short and long distance interference

- Usually the charmonium resonances J/ψ and $\psi(2S)$ are removed from data
- However, the resonances could still contribute by interfering with the penguin decay
- If this happened destructively, it could explain the muon deficiency in the branching fraction measurements, as well as the P_5' anomaly
- Can study interference by including the resonances



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Unbinned q^2 fit for

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

Resonances are modelled by Breit-Wigners with individual phases and widths

Results of unbinned q² fit to $B^+ \to K^+\mu^+\mu^-$

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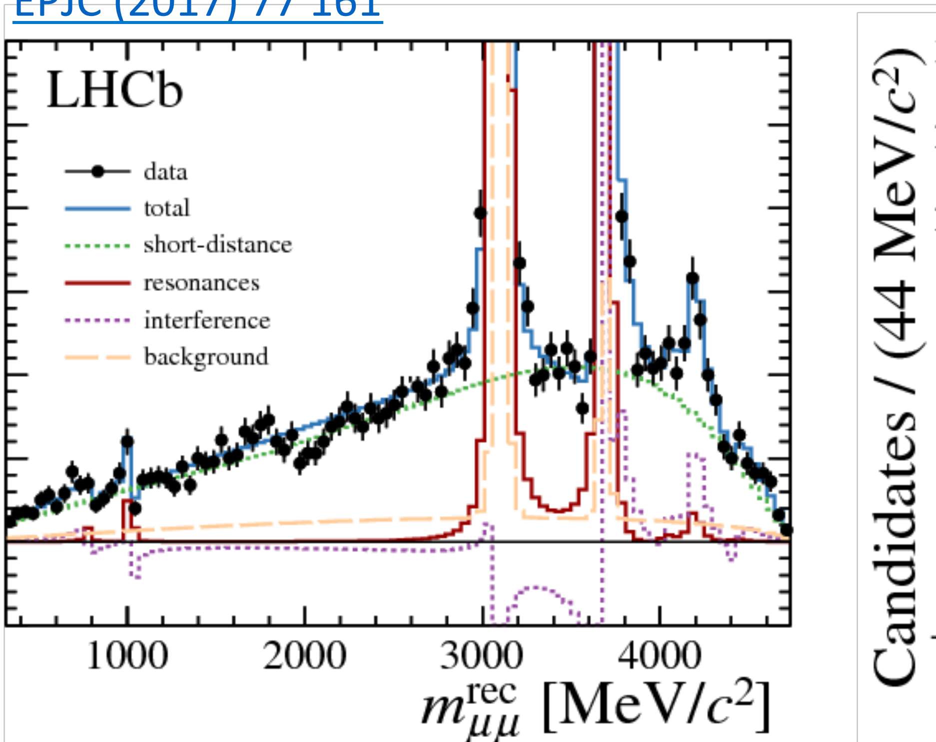

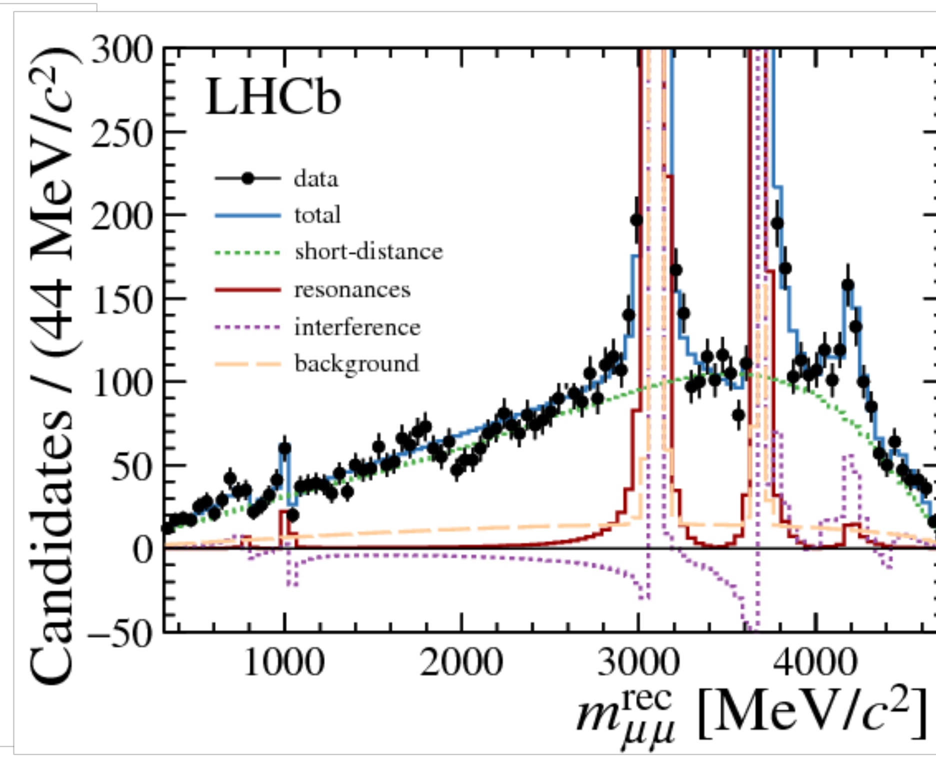

- Model fits data very well
- Four-fold ambiguity due to unknown sign of the J/ψ and $\psi(2S)$ phases
- The phases that are measured suggest a small contribution to the short-distance component in the dimuon mass regions far from J/ψ and $\psi(2S)$ masses, given the assumptions in the model

Conclusion and Outlook

- $b \to s\ell^+\ell^-$ decays hint at discrepancies with predictions of the SM
- Observations can be interpreted in a coherent way in New Physics models by introducing a new (axial-)vector particle
- It is extremely important to update experimental results such as the Angular Analysis of $B^0 \to K^{*0}\mu^+\mu^-$ in order to establish clarity
- Stay tuned for new results!

Backup

LHCb Data on tape and upgrades I & II

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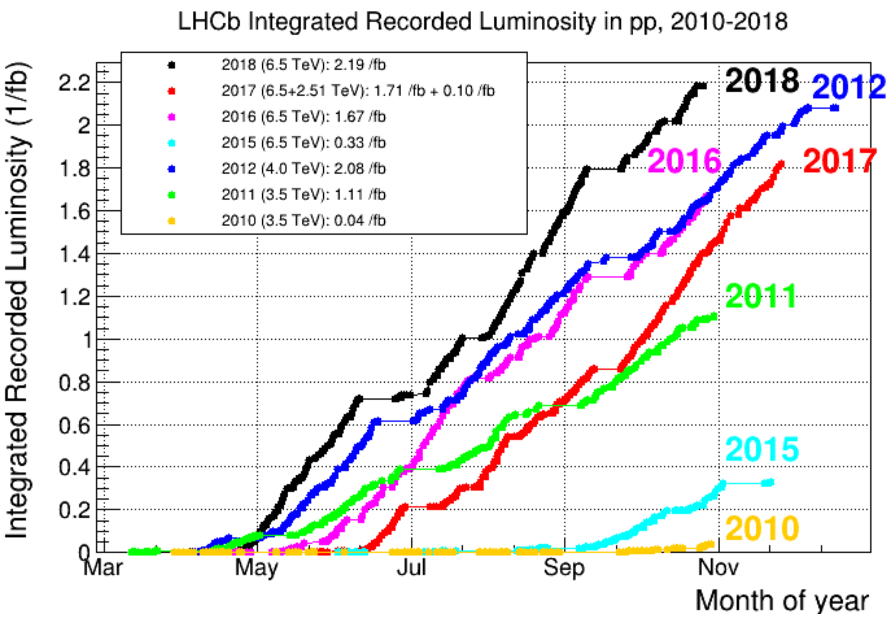
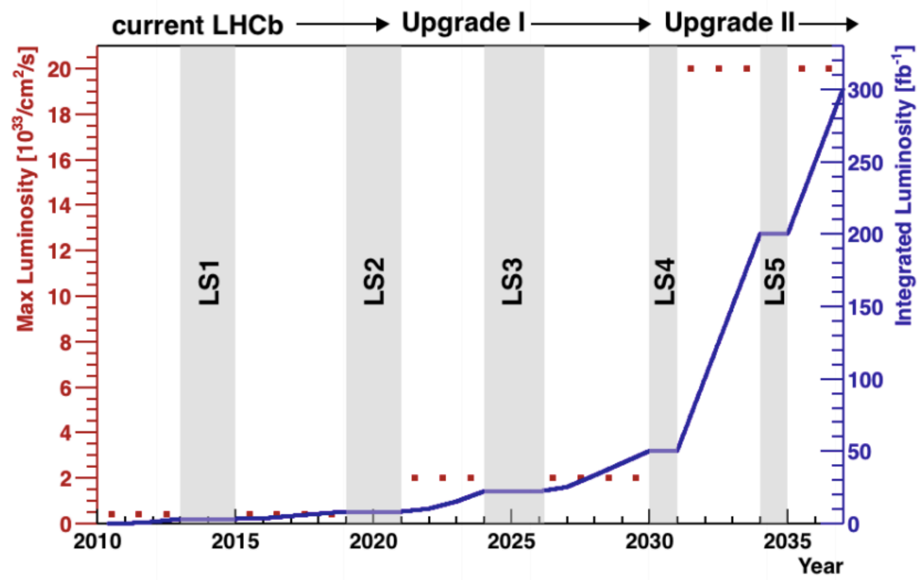




2018-2021	Run 3 (2021-2023)	2023-2025	Run 4 (2025-2028)	2028-2030	Run 5 (2030-2035+)
Shutdown	~23fb^{-1}	Shutdown	~50fb^{-1}	Shutdown	~300fb^{-1}
LHCb upgrade PhaseI				LHCb upgrade PhaseII	

https://arxiv.org/pdf/1808.08865v4.pdf

LHCb Data on tape and upgrades I & II

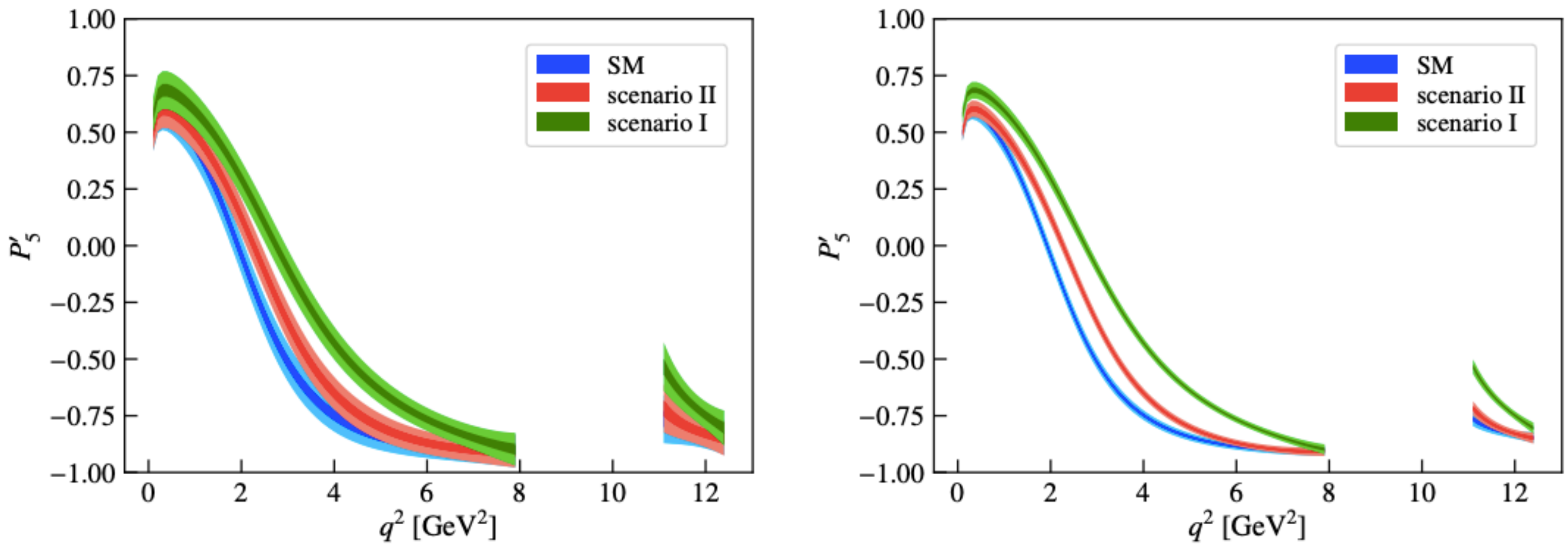


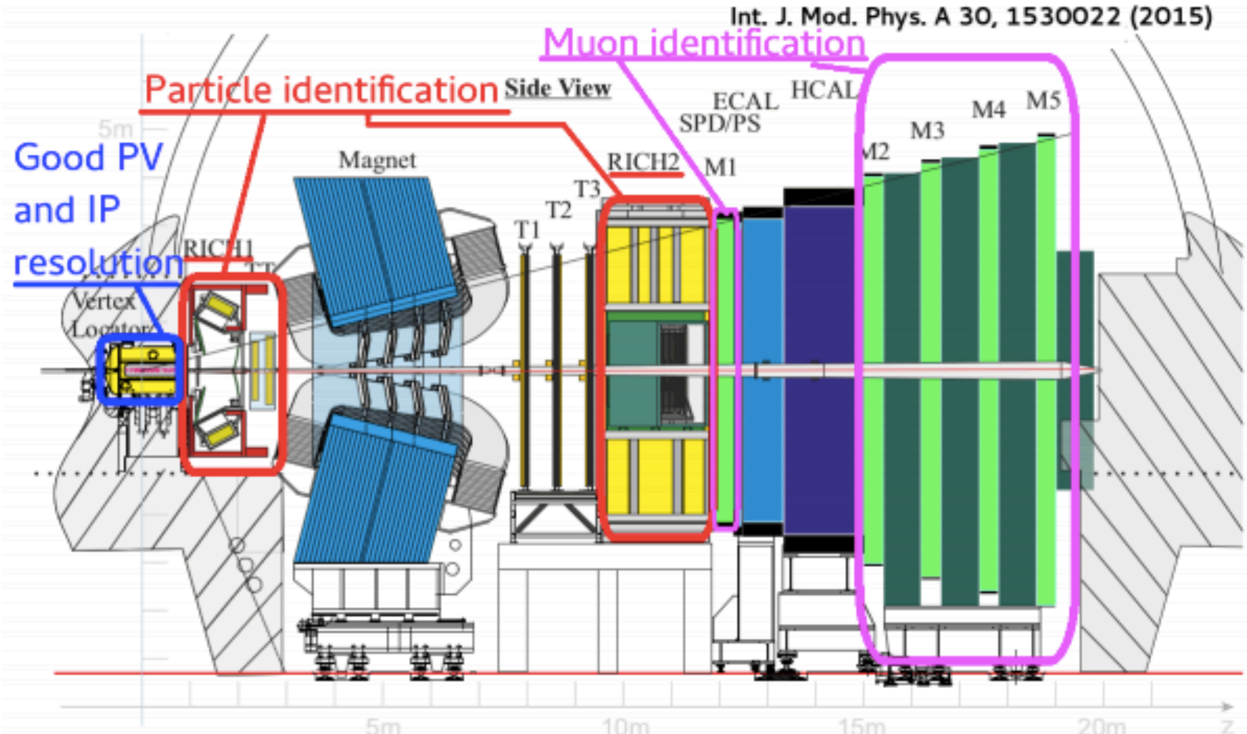
Figure 7.3: Experimental sensitivity to the P_5' angular observable in the SM, Scenarios I and II for (left) the Runs 1–3 and (right) the Upgrade II data sets. The sensitivity is computed assuming that the charm-loop contribution is determined from the data.

scenario	$C_9^{\rm NP}$	$C_{10}^{\rm NP}$	C_9'	C_{10}'
I	−1.4	0	0	0
II	−0.7	0.7	0	0
III	0	0	0.3	0.3
IV	0	0	0.3	−0.3

https://arxiv.org/pdf/1808.08865v4.pdf

LHCb Detector

The LHCb detector is a single arm spectrometer which covers the forward region at LHC.



$\Delta p/p \sim 0.4\%$ at $5\,\mathrm{GeV}$, $\sigma_{IP} = 20\ \mu\mathrm{m}$ for high p_T tracks.

π/K separation: $\epsilon_K \sim 90\%$, 5% $\pi \to K$ mis-id.

π/μ separation: $\epsilon_\mu \sim 97\%$, 1-3% $\pi \to K$ mis-id.

Angular distribution of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

Described by five angles and dimuon invariant mass squared (q^2).

[Adapted from Phys. Rev. D97 (2018) 072010]