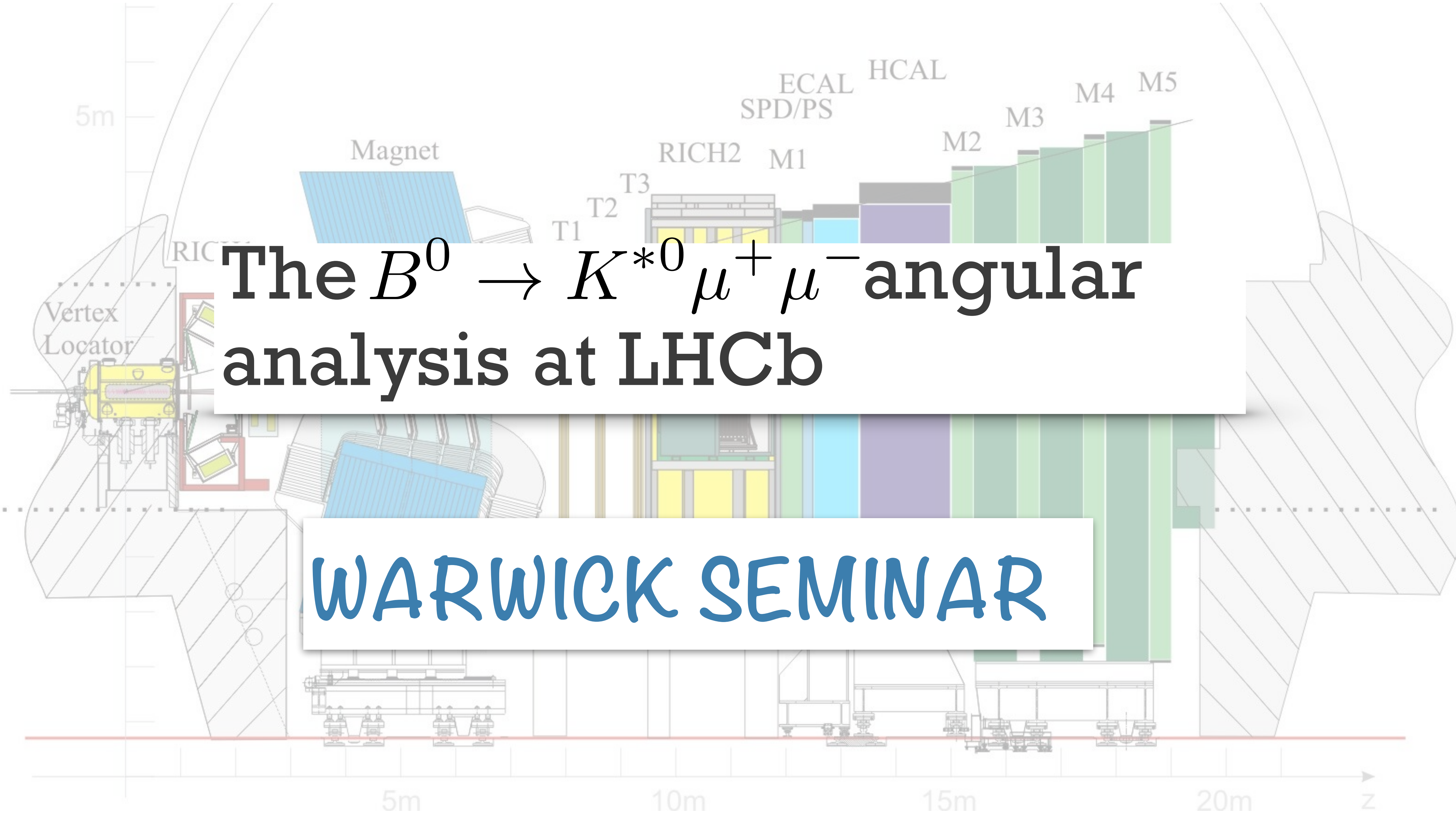
# The $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis at LHCb



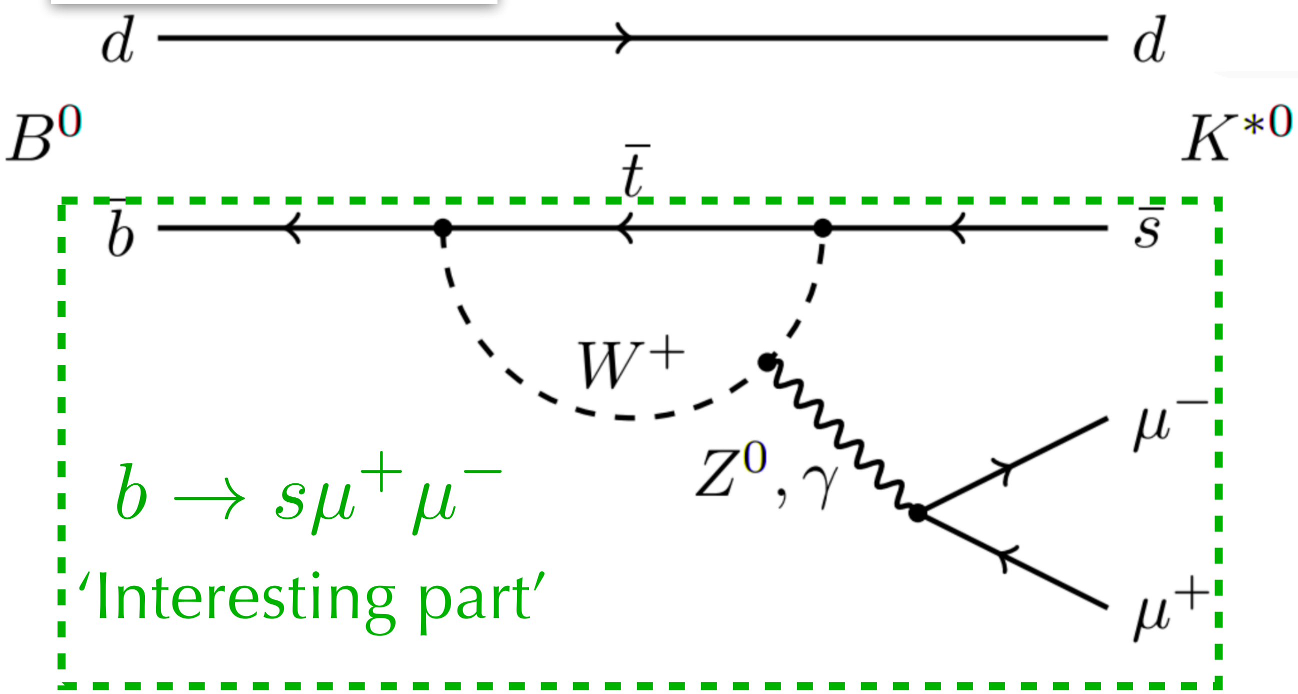
## WARWICK SEMINAR

Eluned Smith

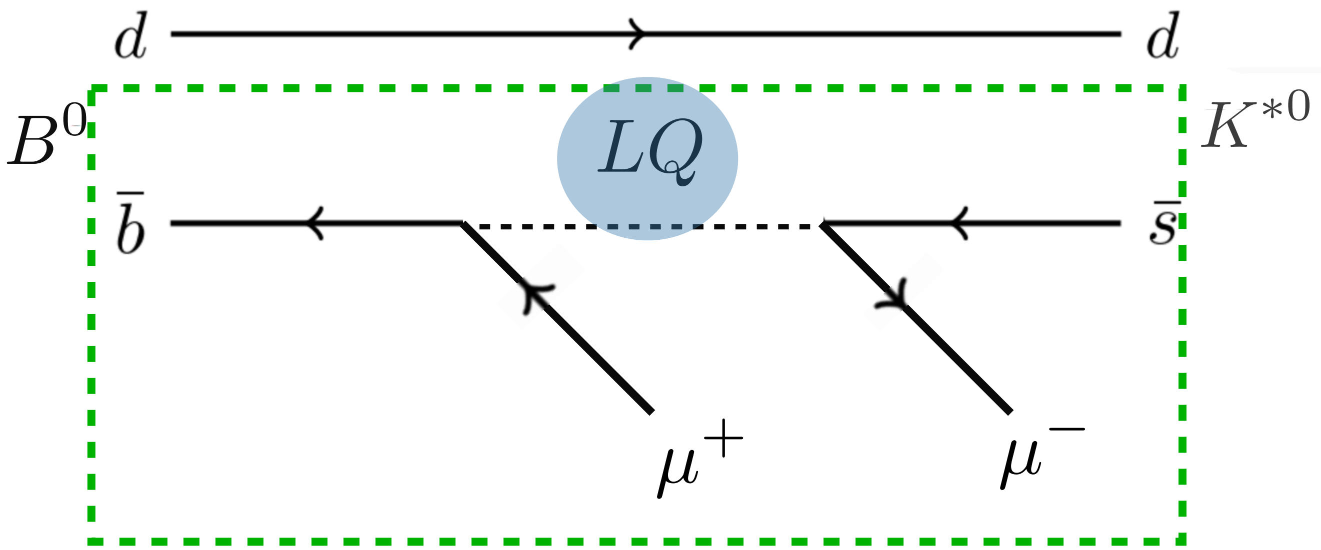
*22/10/2020*

# Why $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$?

Standard Model



New physics scenario

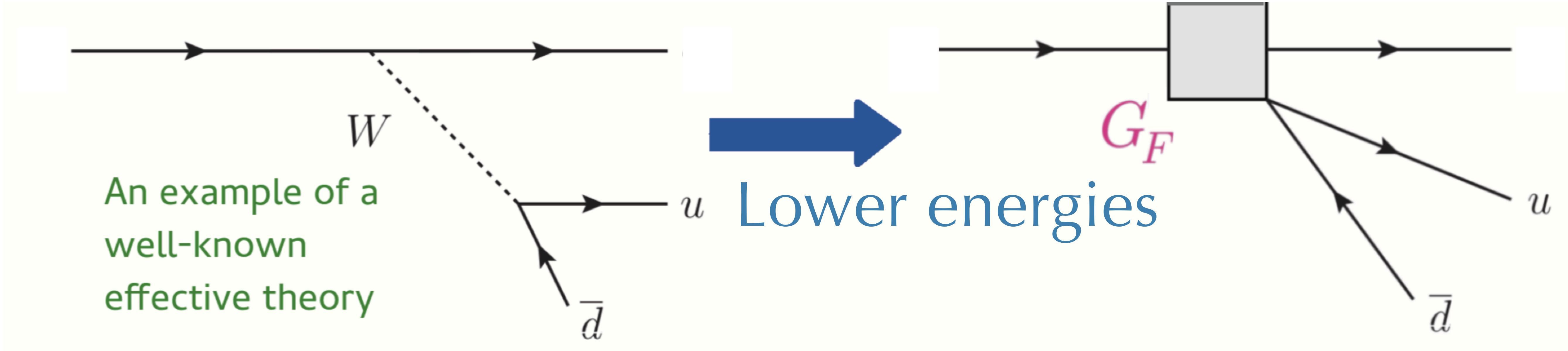


- A $b \to s\mu^+\mu^-$ transition requires a **flavour-changing neutral current** ⇨ forbidden at tree-level in the Standard Model (SM)
- **As suppressed in the SM** more sensitive to New Physics (NP)
- As NP particles appear virtually can probe heavier NP scales than those accessible via direct searches

# $b \to s\mu^+\mu^-$ transitions in effective theory

- $b \to s\mu^+\mu^-$ transitions can be described using an **effective field theory** approach
- Effective field theories: only calculate the relevant phenomena for a given energy scale

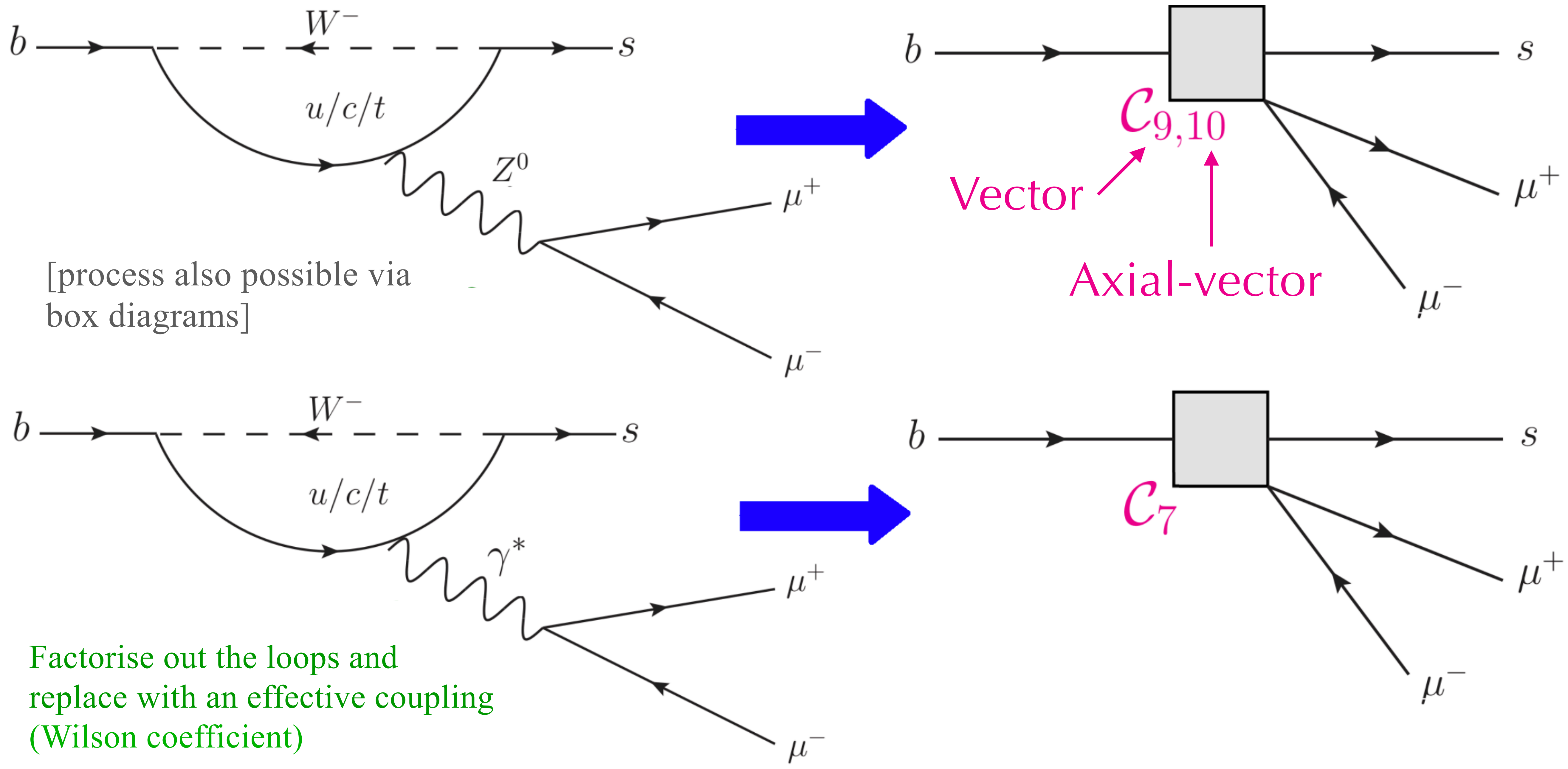
**Example: Fermi's constant**



An example of a well-known effective theory

Lower energies

# $b \to s\mu^+\mu^-$ transitions in effective theory



[process also possible via box diagrams]

Factorise out the loops and replace with an effective coupling (Wilson coefficient)

- ➤ As the Wilson Coefficients $[C_i]$ describes the loops, they are sensitive to New Physics

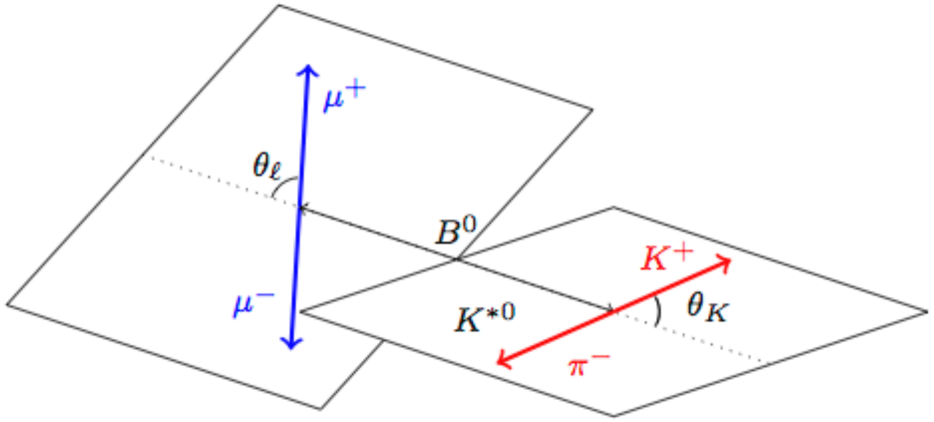
# $b \to s\mu^+\mu^-$ transitions in effective theory

- Can write Hamiltonian as combination of these **Wilson coefficients**, $C_i$ [short distance] and **operators**, $\mathcal{O}_i$, [long distance, low energy]
- As the operators $\mathcal{O}_i$ describe low-energy QCD (described using ***form factors***) they have large theory uncertainties.

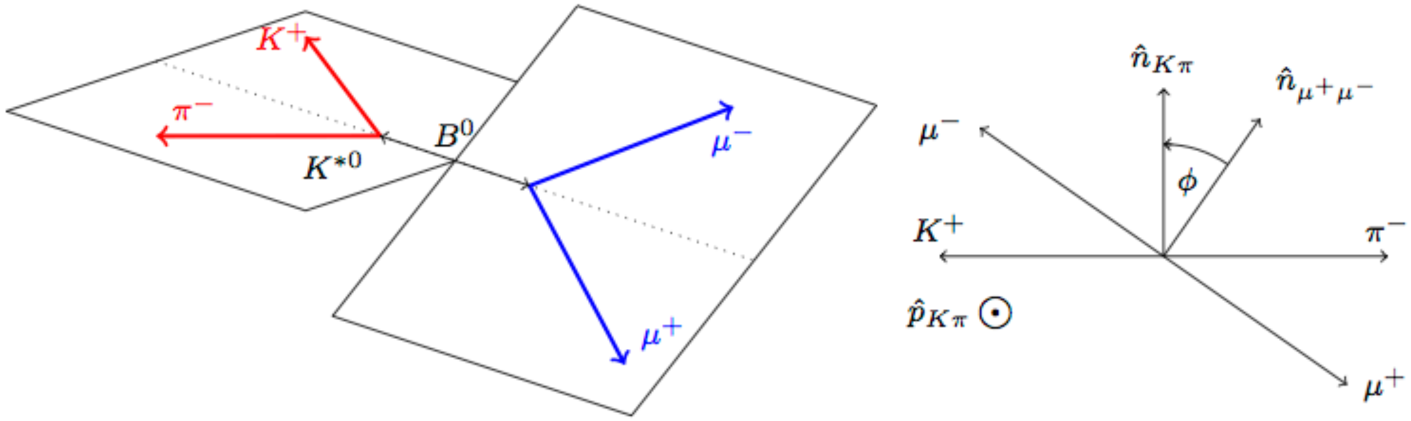
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

**This is what we want to access….**

Local operators describe non-perturbative QCD, large theory uncertainties



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

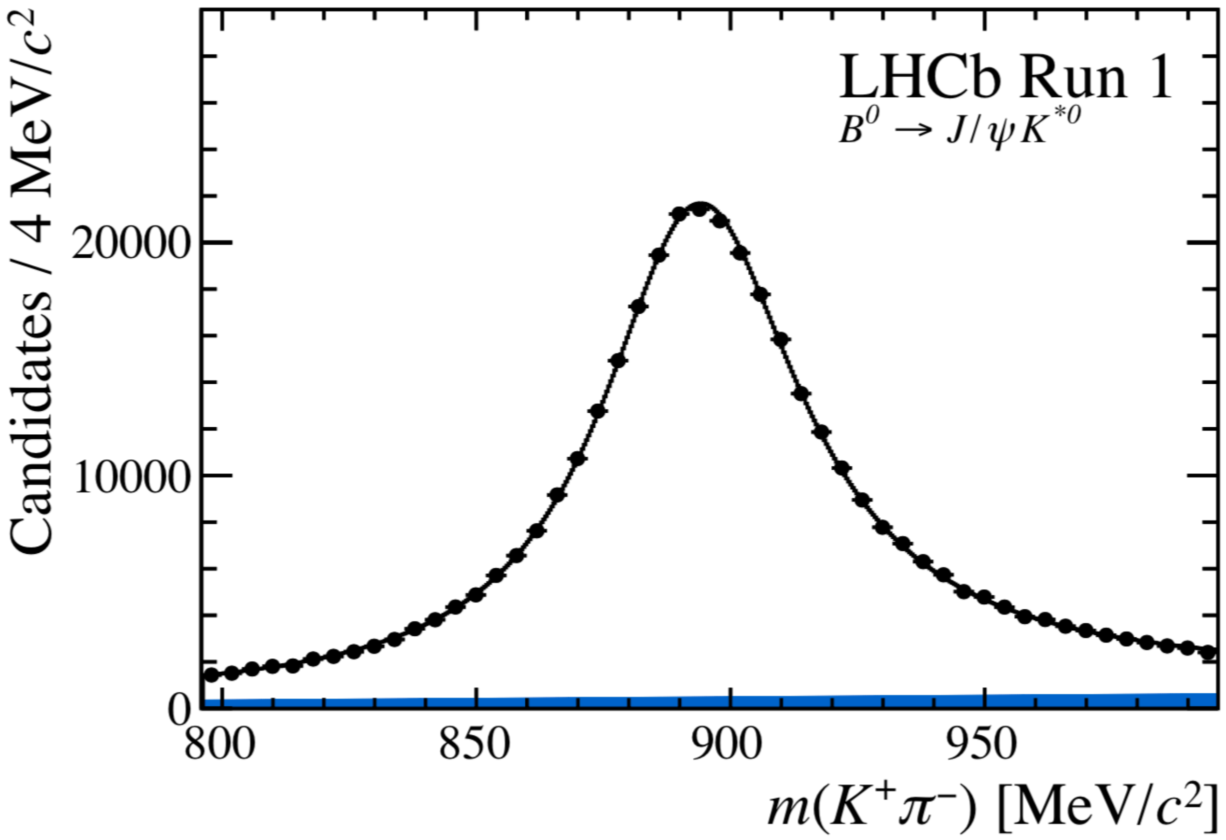


(b) $\phi$ definition for the $B^0$ decay

# Why angular analysis?

- **Angular analysis:** measure the **rate of a decay process** as a **function of the angles** of the final decay products
- Compared to measuring the decay rate alone (i.e. the branching fractions), angular analysis can give access to a large range of observables with **reduced theory uncertainties**
- **Can help deduce nature of new physics models**

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



- The $K^{*0}$ meson is a **vector with spin 1**: 3 polarisations
- This allows for a **rich angular structure**
- The $K^{*0}$ is reconstructed easily at LHCb via $K^{*0} \to K^+\pi^-$

# A brief history of $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis at LHCb

- Partial Run 1 data, *Phys. Rev. Lett.* 108 (2012) 181806
- Full Run 1 data (2011+2012) , JHEP 1602 (2016) 104
- Run 1 + partial Run 2 data (2016), Phys. Rev. Lett. **125**, (2020) 011802
- Full Run 2 … aiming for next year

# Distinctive local tension in $P_5'$

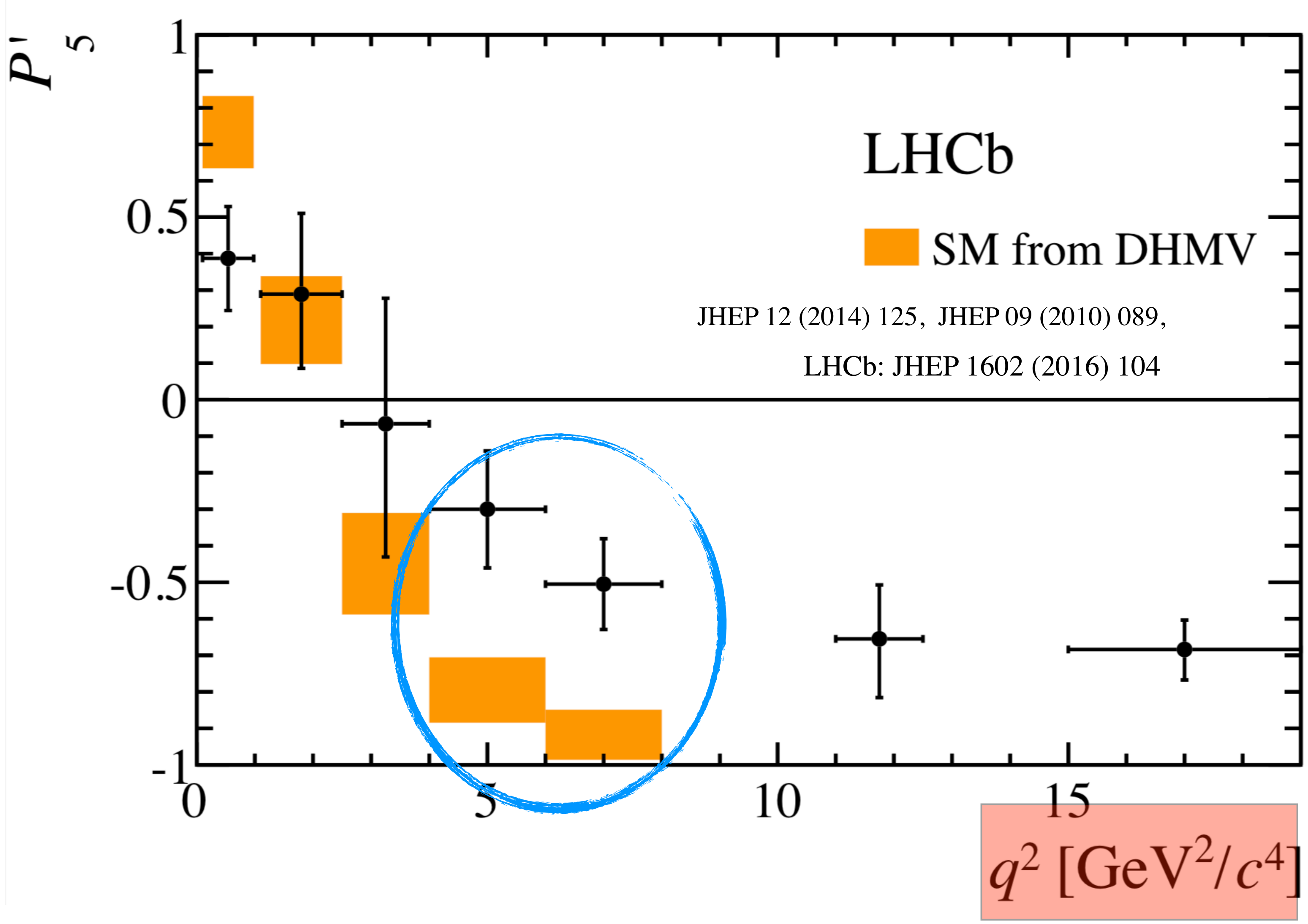
## Run1 LHCb data only: 2016 publication

$$4.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$$

Local tension: $2.8\sigma$

$$6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$$

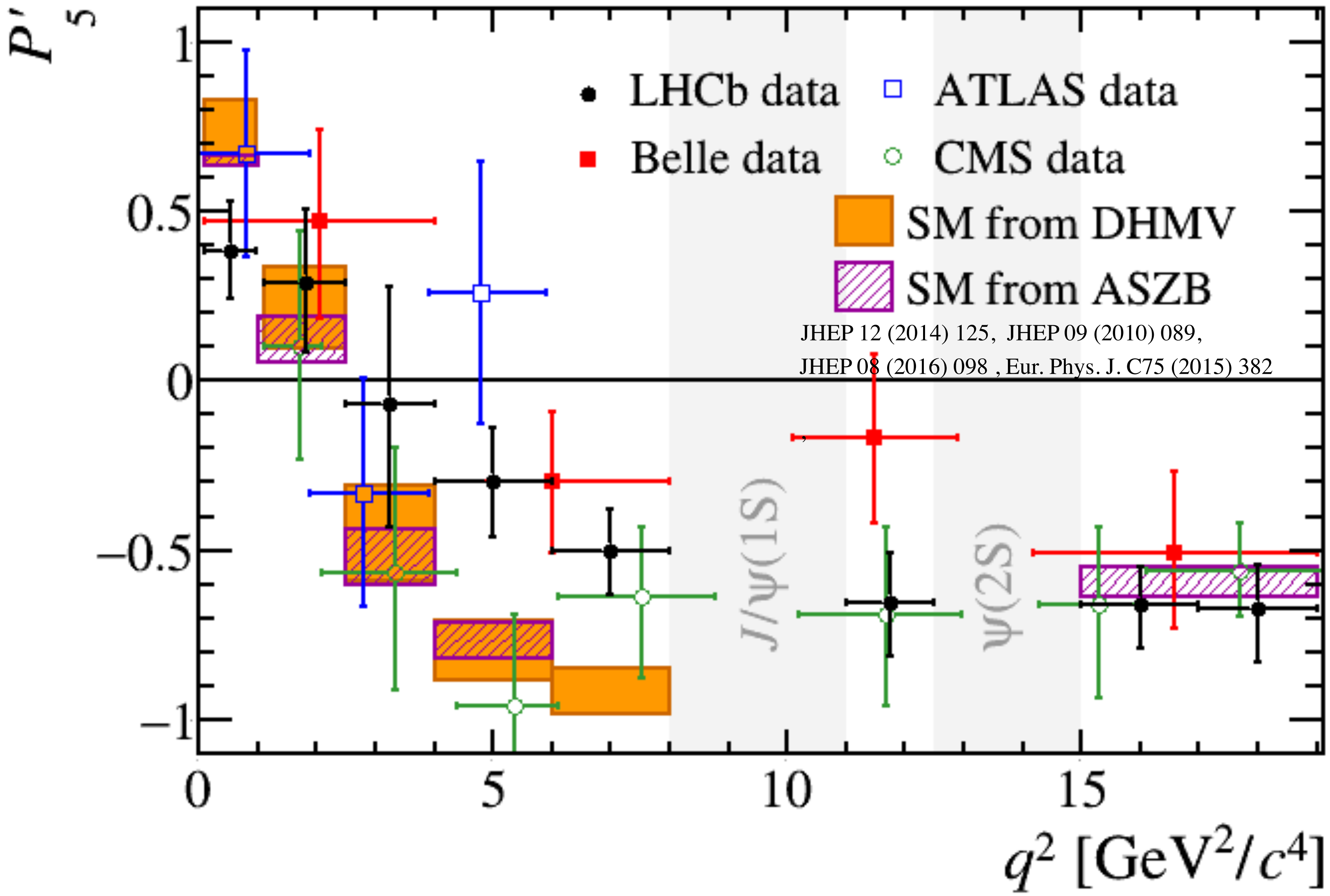
Local tension: $3.0\sigma$



Dimuon mass squared

# Distinctive local tension in $P_5'$

## Angular analysis also performed by other collaborations



JHEP 12 (2014) 125, JHEP 09 (2010) 089,
JHEP 08 (2016) 098 , Eur. Phys. J. C75 (2015) 382

**Belle:** PRL 118 (2017), **CMS:**PLB 781 (2018) 517541

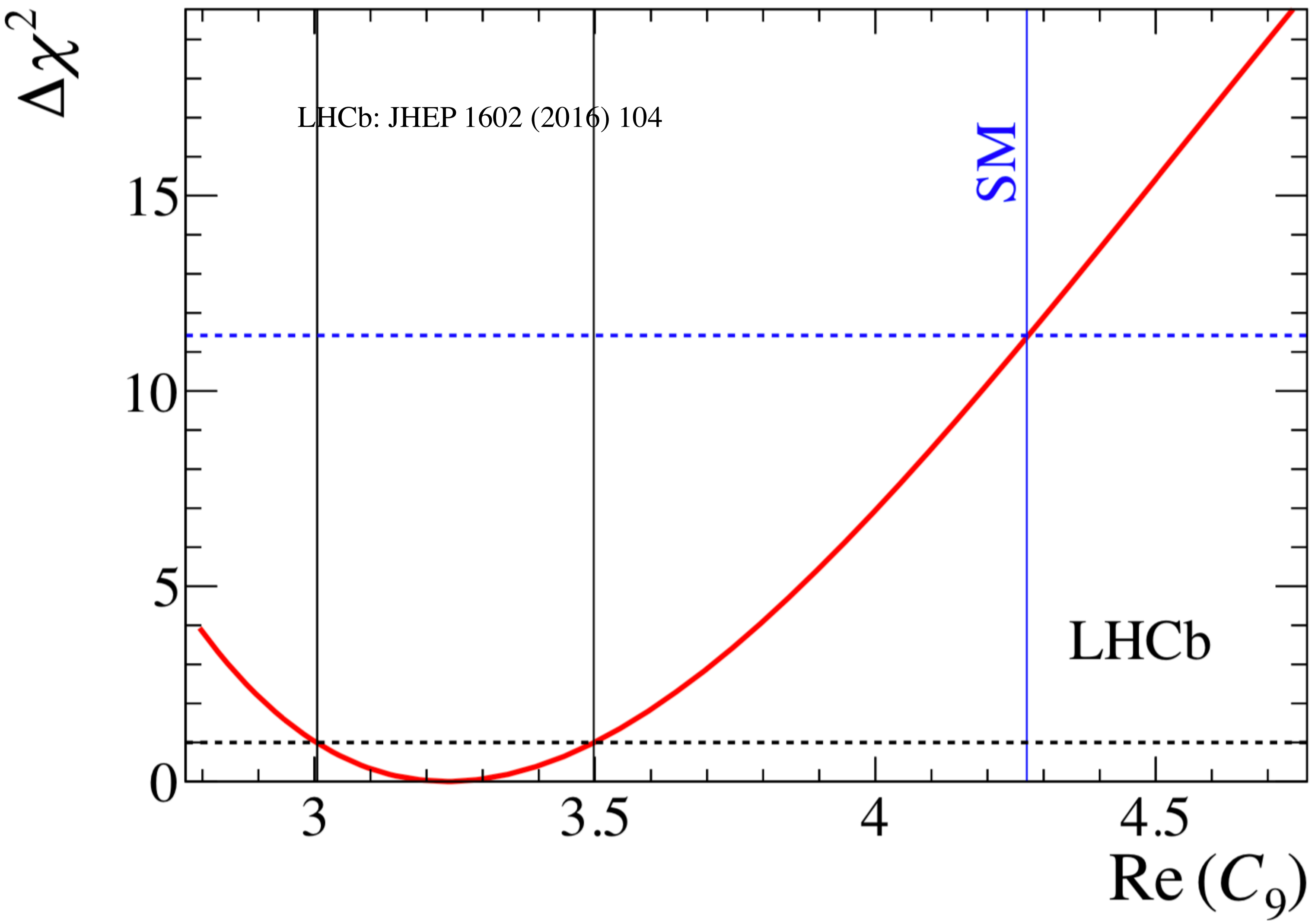
**LHCb:** JHEP 02 (2016) 104, **ATLAS:** JHEP 10 (2018) 047

Run1 LHCb data only

# Overall tension seen with the SM

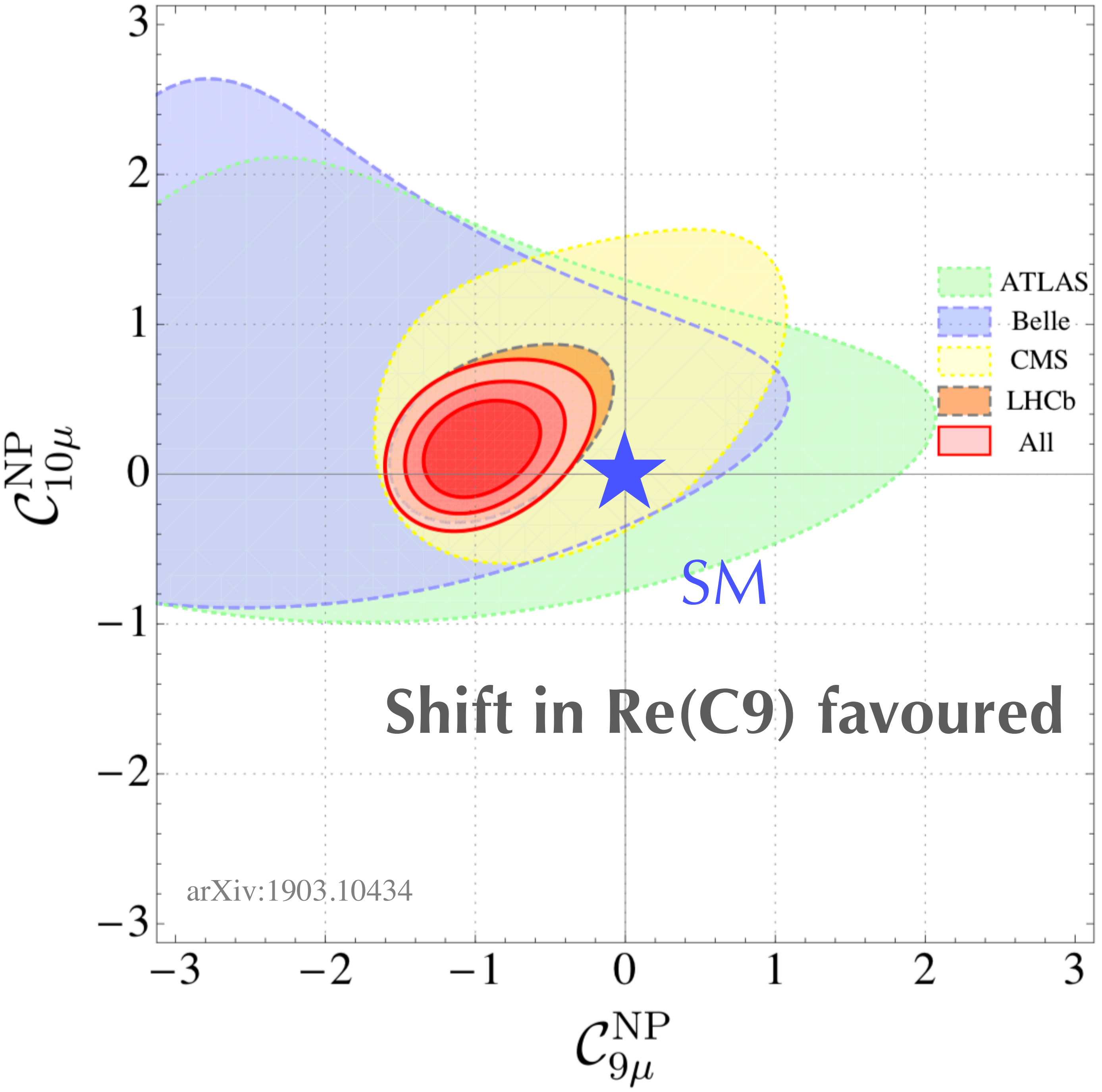
The value of the Wilson Coefficient $Re(C_9)$ obtained from the Run 1 result was $3.4\sigma$ (p-value:~0.0008) from the SM prediction when assuming the observations could be explained with a shift in $Re(C_9)$ alone.

$\boxed{3.4\,\sigma}$



Run1 LHCb data only

# Shift in $Re(C_9)$ seen in global fits



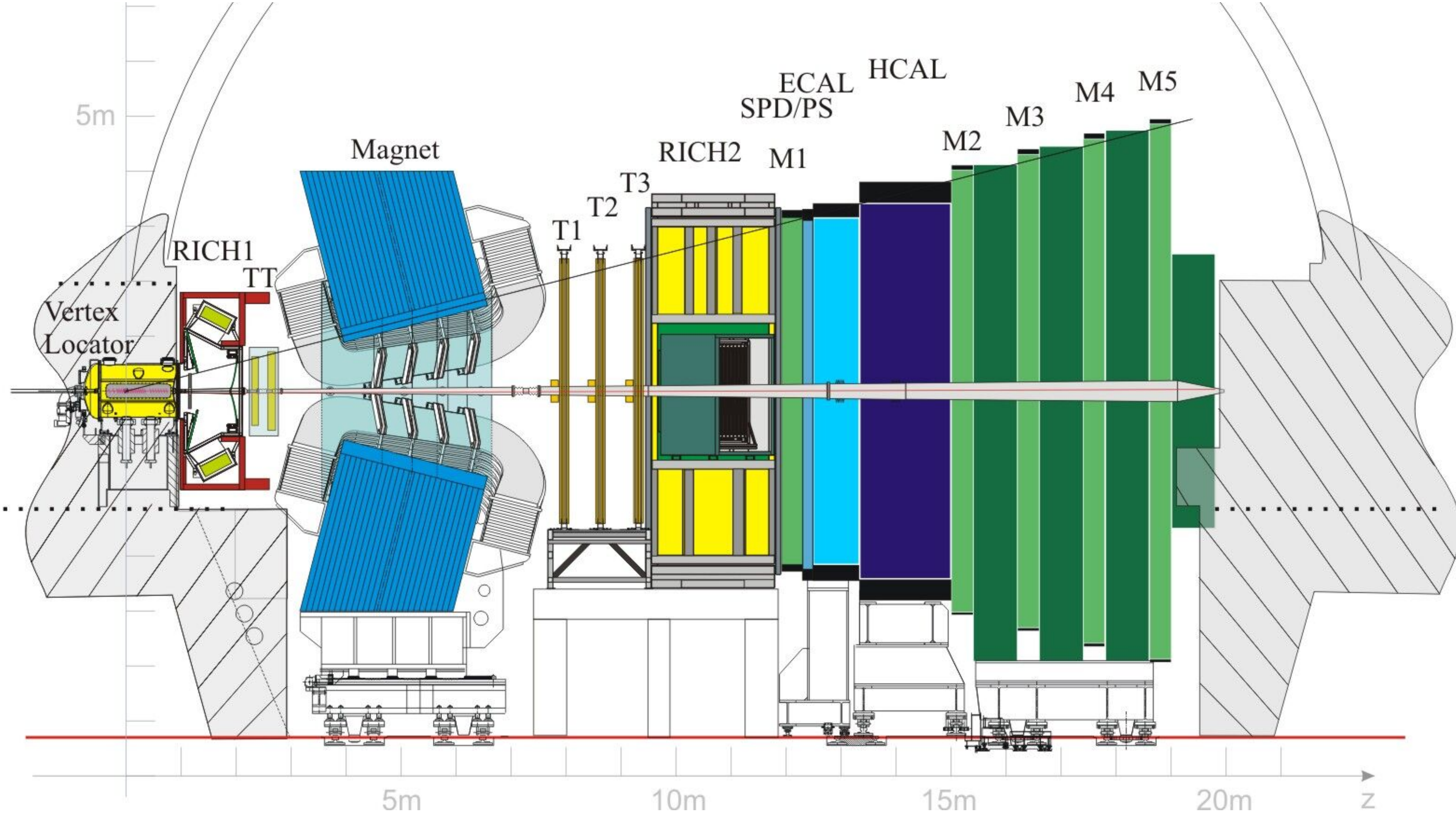
- Global fits performed to a **complete set of** $b \to sll$ **measurements** (rates, angular distributions)
- Fits yield up to 3-5 $\sigma$ deviations in Wilson coefficients[*]
- Many global fits out there!

Non-exhaustive list of global fit examples: Eur. Phys. J. C79 (2019) 714, Phys. Rev. D100 (2019) 015045 Eur. Phys. J. C79 (2019) ,Eur. Phys. J. C79 (2019) 840, JHEP 06 (2019) 089

[*] dependent on assumptions used in global fit

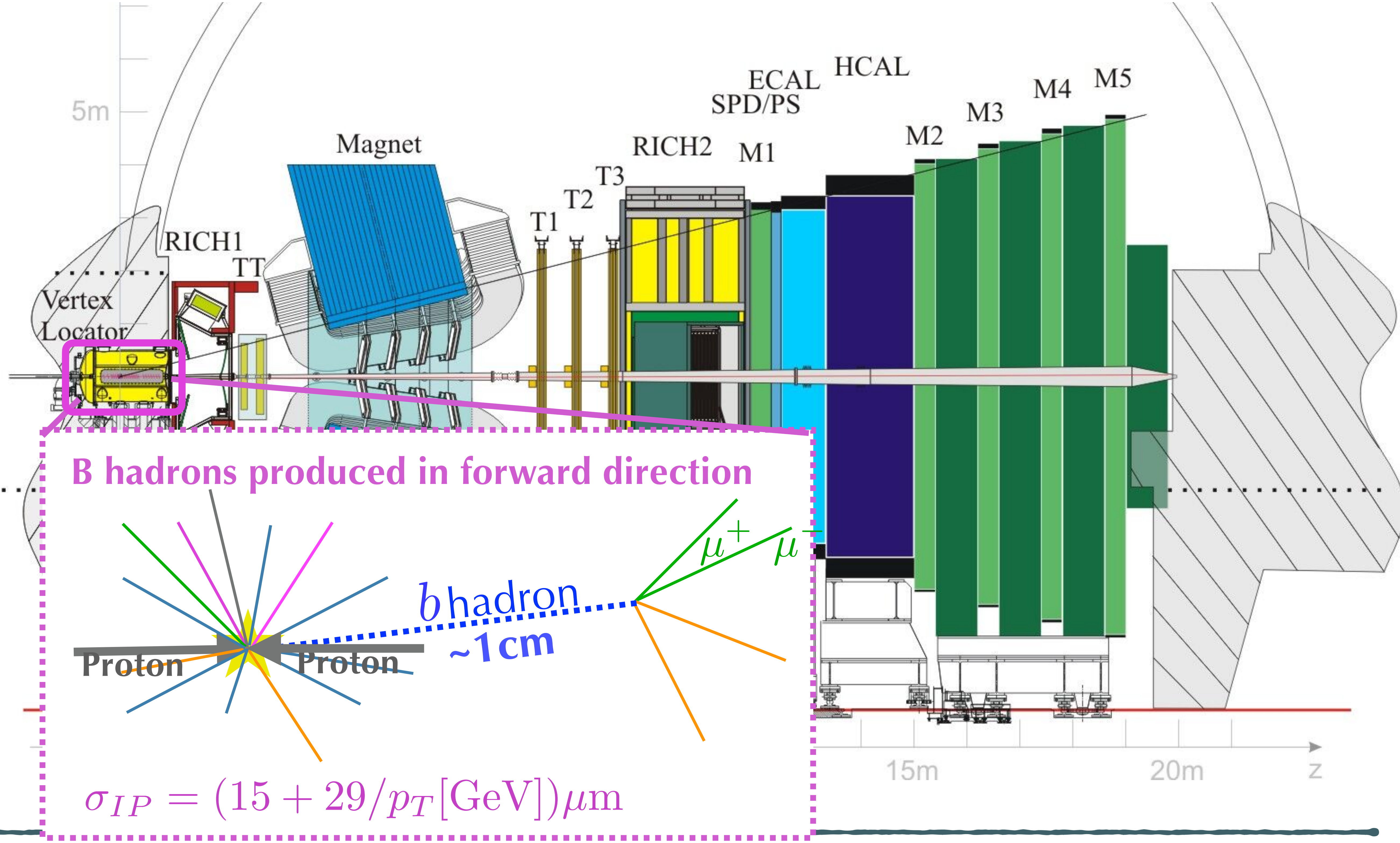
# The LHCb detector

# The LHCb experiment



*Int. J. Mod. Phys. A* 30 (2015) 1530022

# The LHCb experiment

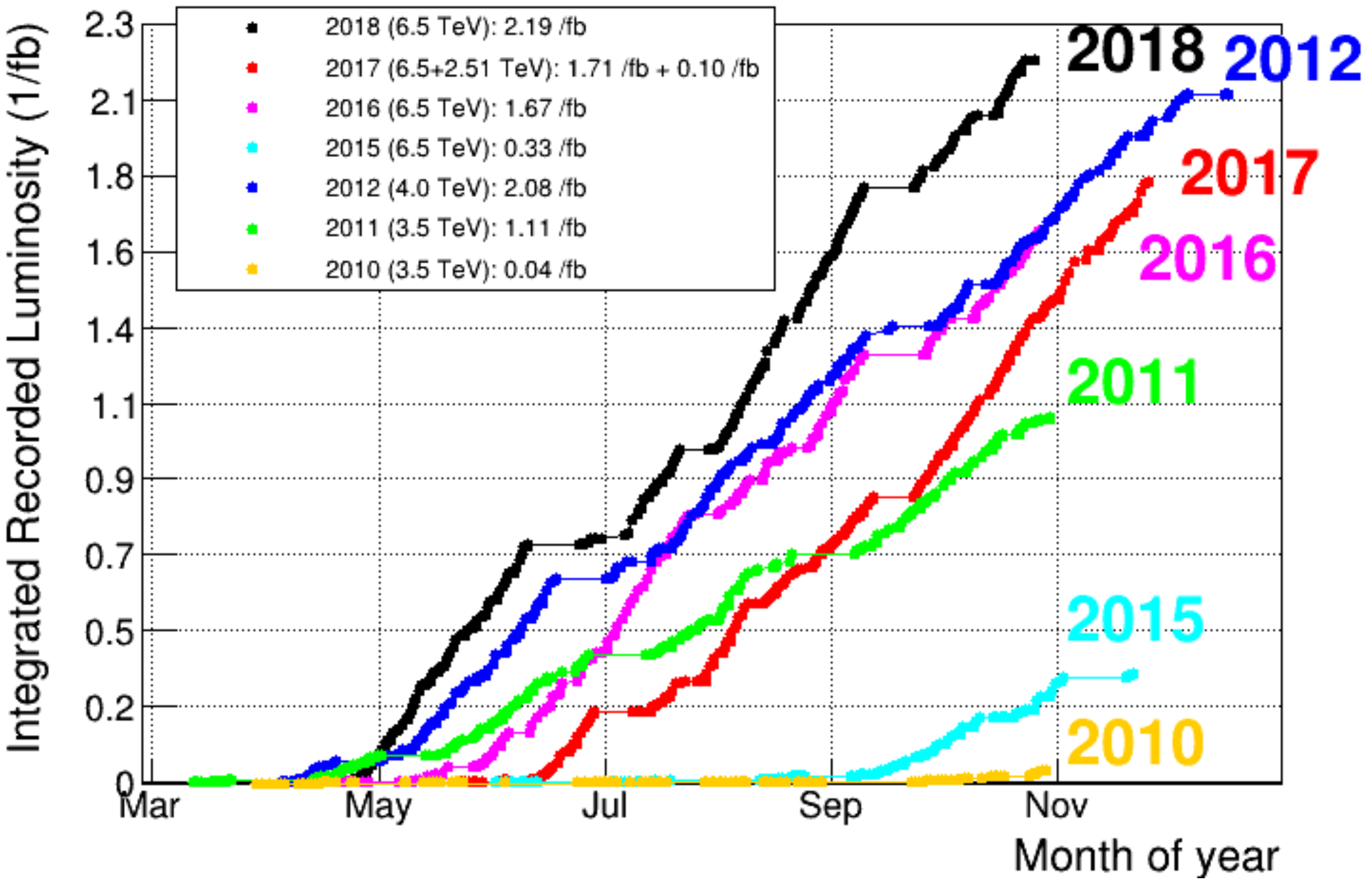


$$\sigma_{IP} = (15 + 29/p_T[\mathrm{GeV}])\mu\mathrm{m}$$

# The data set

# Data-taking during Run 1 + 2

**2011, 2012 (Run 1) and 2016 used for most recent update**



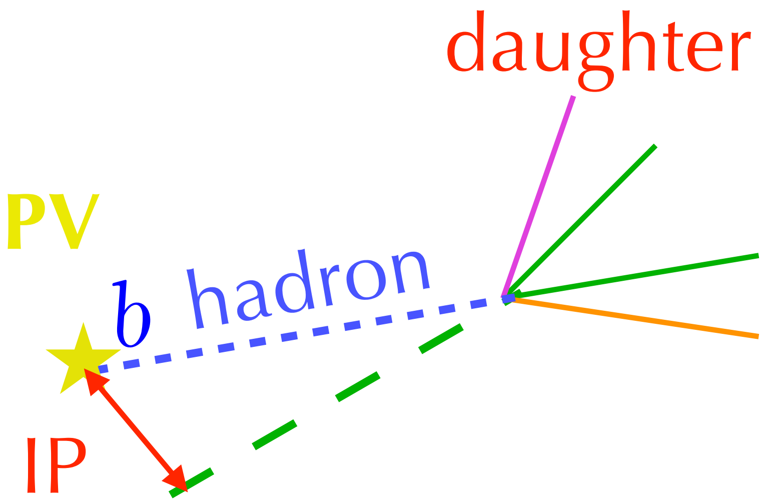
2011, 2012 and 2016 data collected from proton-proton collisions with centre of mass energies of $\sqrt{s}$ = 7,8 and 13 TeV respectively

Increase in $\sqrt{s}$ : **adding 2016 data roughly doubles statistics** (4.7 fb$^{-1}$)

# Selection of candidates

$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ candidates

- Selection: require significant impact parameter (IP) for daughters, and small IP for B meson + quality vertex
- Particle IDentification is used to suppress "peaking backgrounds"
- Machine learning **multivariate techniques** employed to suppress *combinatorial background*



Impact Parameter: small for candidates coming directly from from PV, large for candidates which aren't

**Examples of peaking backgrounds**

$$\overline{\Lambda}_b^0 \to \overline{p} {\color{red}\to \pi^-} K^+\mu^+\mu^-$$

$$\overline{B}^0 \to \overline{K}^{*0}[\to (K^- {\color{red}\to \pi^-})(\pi^+ {\color{red}\to K^+})]\mu^+\mu^-$$

$$B_s^0 \to \phi(1020)[\to K^+({\color{red}\to \pi^+})K^-]\mu^+\mu^-$$

${\color{red}\to}$ = Misidentification

# The regions we probe in $q^2$

$$q^2 = m^2(\mu^+\mu^-)$$

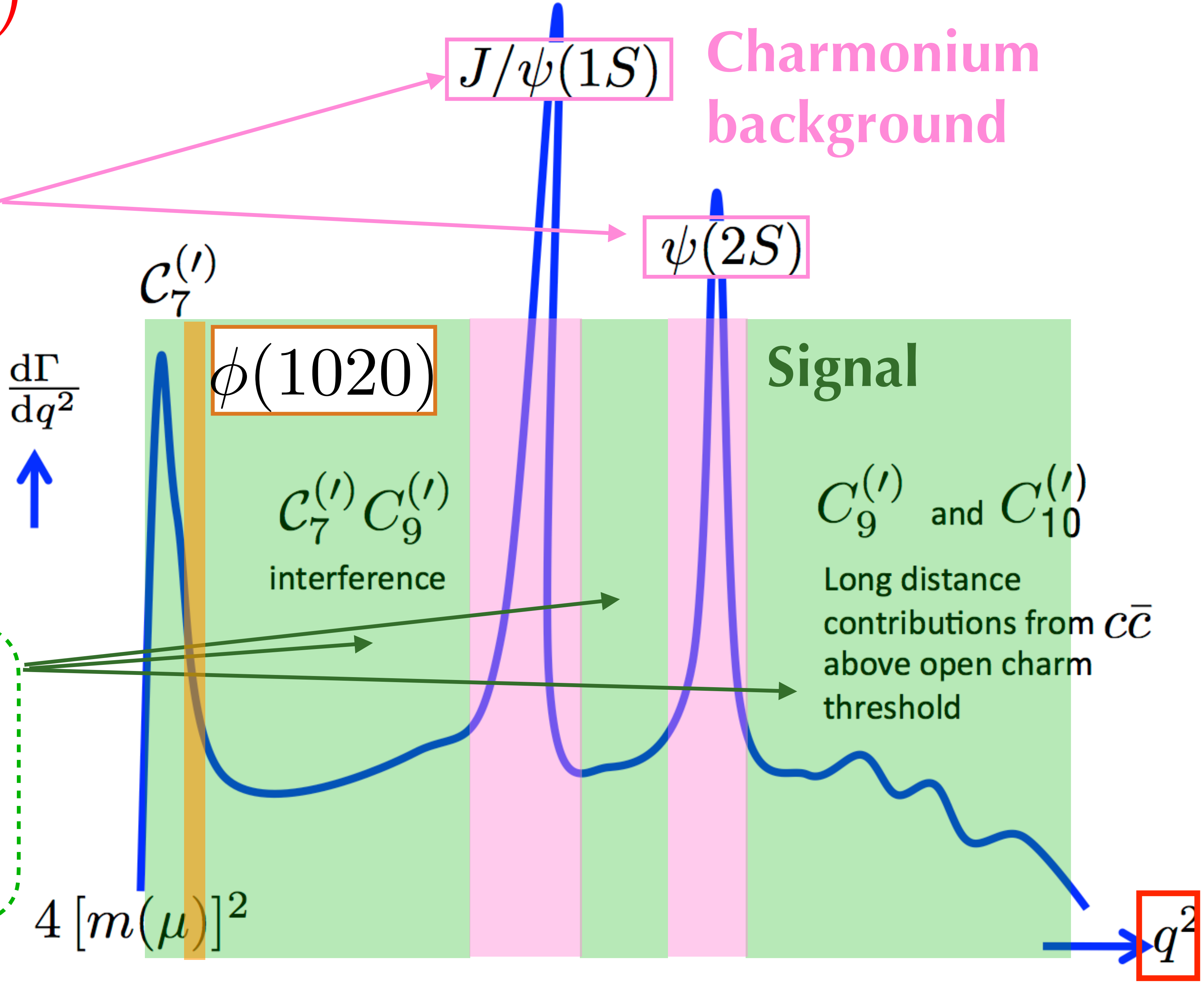
$b \rightarrow s[c\bar{c} \rightarrow \mu\mu]$ decays

same final state as signal

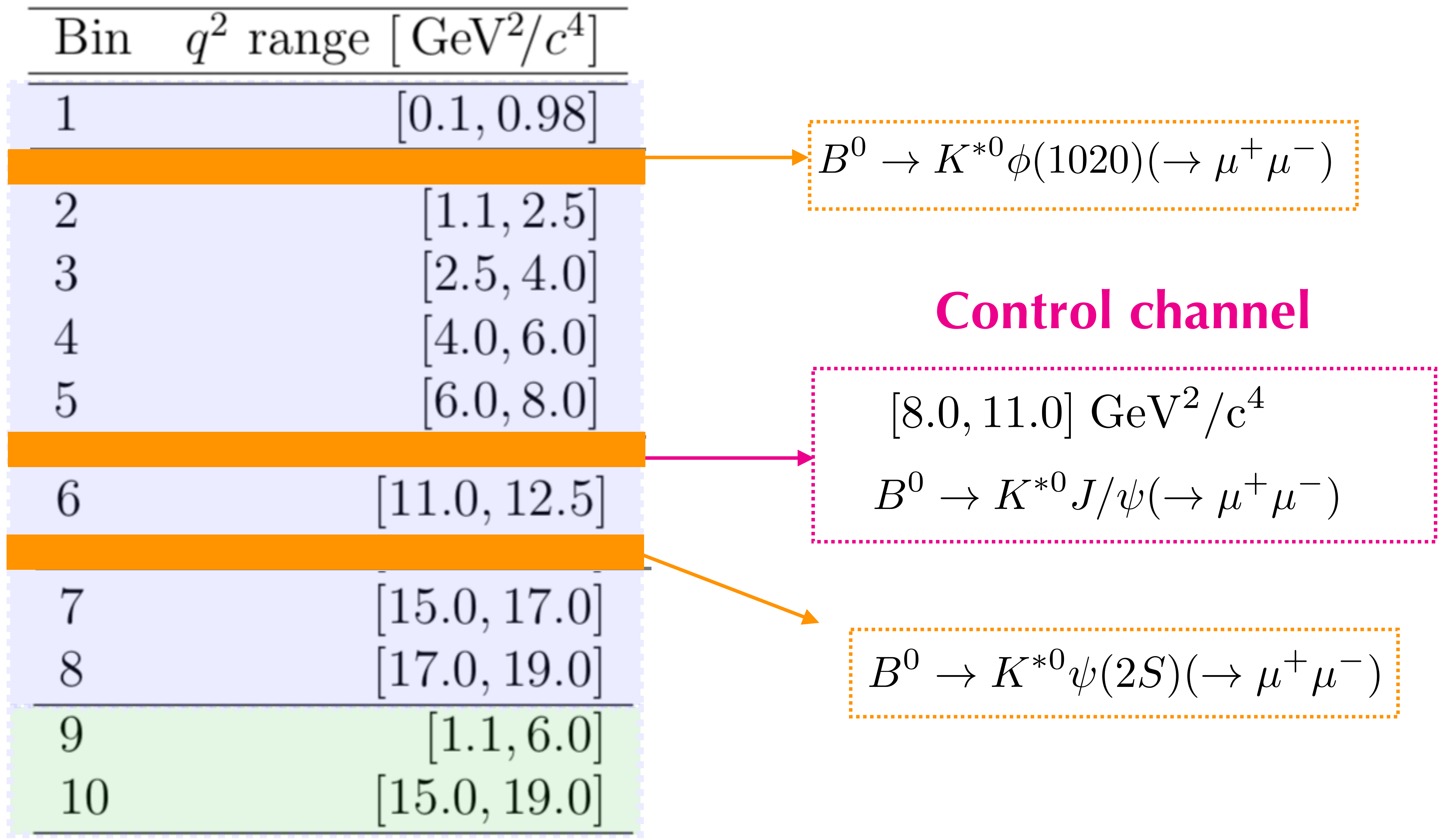
**Veto**

$b \rightarrow s\mu\mu$ decays: signal

**Look at signal in these $q^2$ regions**



# Binning in $q^2$



**Narrow bins**

**Wide bins**

| Bin | $q^2$ range $[\mathrm{GeV}^2/c^4]$ |
|---|---|
| 1 | $[0.1, 0.98]$ |
| 2 | $[1.1, 2.5]$ |
| 3 | $[2.5, 4.0]$ |
| 4 | $[4.0, 6.0]$ |
| 5 | $[6.0, 8.0]$ |
| 6 | $[11.0, 12.5]$ |
| 7 | $[15.0, 17.0]$ |
| 8 | $[17.0, 19.0]$ |
| 9 | $[1.1, 6.0]$ |
| 10 | $[15.0, 19.0]$ |

$B^0 \to K^{*0}\phi(1020)(\to \mu^+\mu^-)$

**Control channel**

$[8.0, 11.0]\ \mathrm{GeV}^2/\mathrm{c}^4$

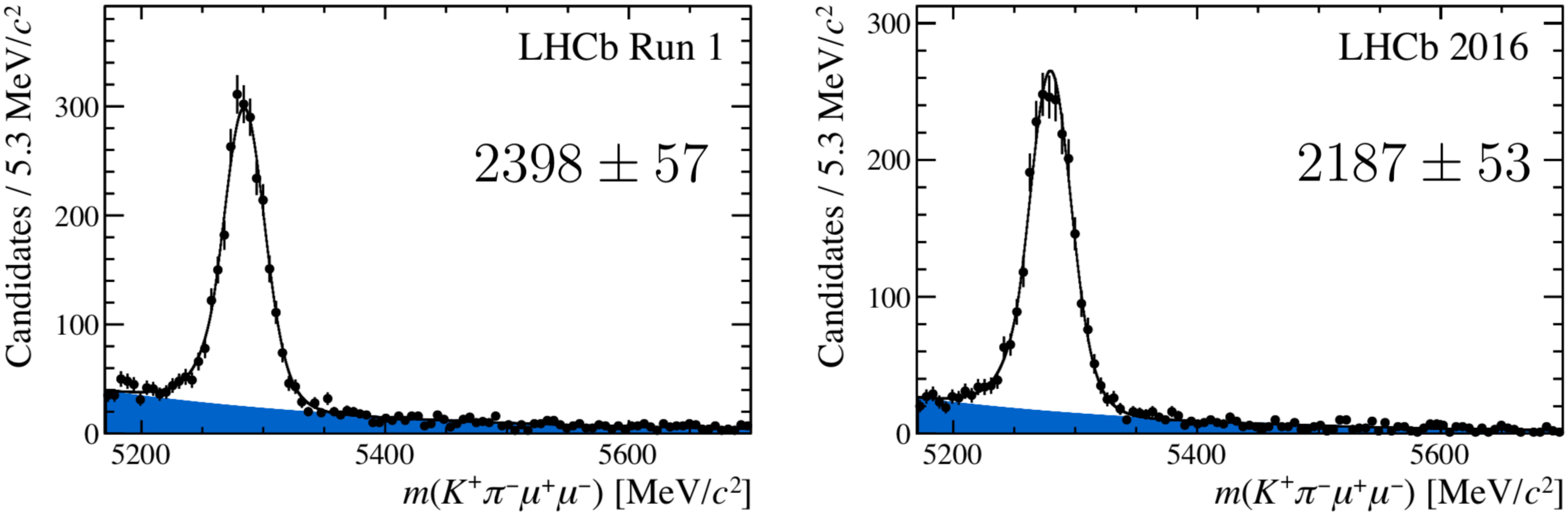
$B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-)$

$B^0 \to K^{*0}\psi(2S)(\to \mu^+\mu^-)$

**Analysis is performed blind, control channel is used to validate the fit**

# Signal yields

- Adding the 2016 data we roughly double the number of signal candidates



Yields excluding all the charmonium and light resonance regions

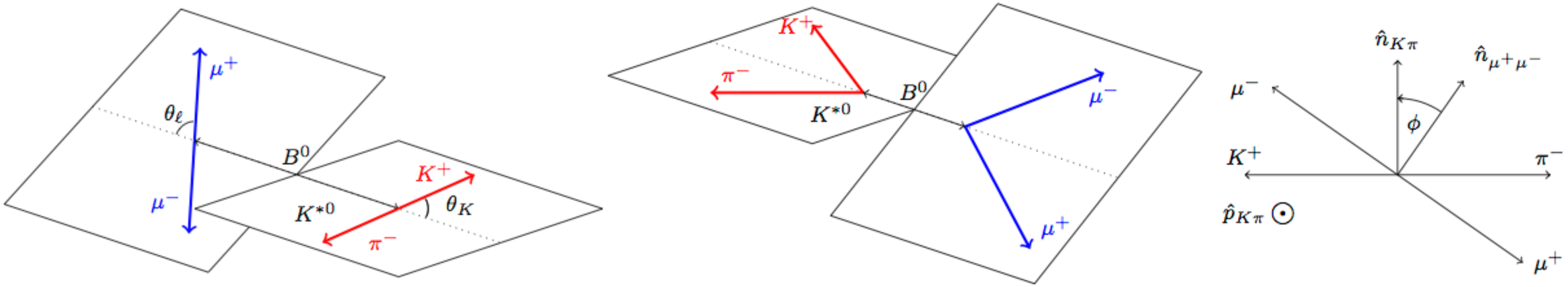
Remaining background is combinatorial only

# Angular description of the decay

# $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$ angular description

- Decay rate fully described by:

$$\vec{\Omega} = (\cos\theta_l, \cos\theta_k, \phi), q^2 = m^2(\mu^+\mu^-)$$



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

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

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

angular coefficients angular functions

# $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$ angular description

## What are angular coefficients?

➤ Angular coefficients are combinations of the different $K^{*0}$ amplitudes

| i | $I_i(q^2)$ | $f_i(\vec{\Omega})$ |
|---|---|---|
| 1s | $\frac{3}{4}\left[\lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm L}\rvert^2 + \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2\right]$ | $\sin^2\theta_K$ |
| 1c | $\lvert\mathcal{A}_0^{\rm L}\rvert^2 + \lvert\mathcal{A}_0^{\rm R}\rvert^2$ | $\cos^2\theta_K$ |
| 2s | $\frac{1}{4}\left[\lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm L}\rvert^2 + \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2\right]$ | $\sin^2\theta_K\cos 2\theta_l$ |
| 2c | $-\lvert\mathcal{A}_0^{\rm L}\rvert^2 - \lvert\mathcal{A}_0^{\rm R}\rvert^2$ | $\cos^2\theta_K\cos 2\theta_l$ |
| 3 | $\frac{1}{2}\left[\lvert\mathcal{A}_\perp^{\rm L}\rvert^2 - \lvert\mathcal{A}_\parallel^{\rm L}\rvert^2 + \lvert\mathcal{A}_\perp^{\rm R}\rvert^2 - \lvert\mathcal{A}_\parallel^{\rm R}\rvert^2\right]$ | $\sin^2\theta_K\sin^2\theta_l\cos 2\phi$ |
|  | • • • | • • • |

# $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$ angular description

***Where the physics lies:***

- The $K^{*0}$ **amplitudes** are in turn dependent on **Wilson coefficients** and **form factors (non-perturbative QCD)**

$$\mathcal{A}_\perp^{\rm L(R)} = \mathcal{N}\sqrt{2\lambda}\left\{\left[(\mathcal{C}_9^{\rm eff}+\mathcal{C}_9'^{\rm eff}) \mp (\mathcal{C}_{10}^{\rm eff}+\mathcal{C}_{10}'^{\rm eff})\right]\frac{V(q^2)}{m_B+m_{K^*}} + \frac{2m_b}{q^2}(\mathcal{C}_7^{\rm eff}+\mathcal{C}_7'^{\rm eff})T_1(q^2)\right\}$$

$$\begin{aligned}\mathcal{A}_\parallel^{\rm L(R)} &= -\mathcal{N}\sqrt{2}(m_B^2-m_{K^*}^2)\left\{\left[(\mathcal{C}_9^{\rm eff}-\mathcal{C}_9'^{\rm eff}) \mp (\mathcal{C}_{10}^{\rm eff}-\mathcal{C}_{10}'^{\rm eff})\right]\frac{A_1(q^2)}{m_B-m_{K^*}}\right.\\ &\left.+\frac{2m_b}{q^2}(\mathcal{C}_7^{\rm eff}-\mathcal{C}_7'^{\rm eff})T_2(q^2)\right\}\end{aligned}$$

$$\begin{aligned}\mathcal{A}_0^{\rm L(R)} &= -\frac{\mathcal{N}}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathcal{C}_9^{\rm eff}-\mathcal{C}_9'^{\rm eff}) \mp (\mathcal{C}_{10}^{\rm eff}-\mathcal{C}_{10}'^{\rm eff})\right]\right.\\ &\times\left[(m_B^2-m_{K^*}^2-q^2)(m_B+m_{K^*})A_1(q^2)-\lambda\frac{A_2(q^2)}{m_B+m_{K^*}}\right]\\ &\left.+2m_b(\mathcal{C}_7^{\rm eff}-\mathcal{C}_7'^{\rm eff})\left[(m_B^2+3m_{K^*}-q^2)T_2(q^2)-\frac{\lambda}{m_B^2-m_{K^*}^2}T_3(q^2)\right]\right\}\end{aligned}$$

JHEP 0901:019,2009

# The angular fit

# The angular PDF: $S_i$ basis

Perform measurement in bins of $q^2 = m^2(\mu\mu)$

- Integrate over $q^2$ & combine $B^0, \overline{B}^0$ decays → $\boxed{S_i}(q^2_{min}, q^2_{max})$

***CP-averaged***

$S_i$ **basis**

***8 CP-averaged observables are extracted from the fit***

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K \\ + \boxed{F_{\mathrm{L}}}\cos^2\theta_K + \tfrac{1}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K\cos 2\theta_l \\ - \boxed{F_{\mathrm{L}}}\cos^2\theta_K\cos 2\theta_l + \boxed{S_3}\sin^2\theta_K\sin^2\theta_l\cos 2\phi \\ + \boxed{S_4}\sin 2\theta_K\sin 2\theta_l\cos\phi + \boxed{S_5}\sin 2\theta_K\sin\theta_l\cos\phi \\ + \tfrac{4}{3}\boxed{A_{\mathrm{FB}}}\sin^2\theta_K\cos\theta_l + \boxed{S_7}\sin 2\theta_K\sin\theta_l\sin\phi \\ + \boxed{S_8}\sin 2\theta_K\sin 2\theta_l\sin\phi + \boxed{S_9}\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]. \tag{29}$$

$F_L$ :fraction of longitudinal polarisation of the $K^{*0}$

$A_{FB}$ :forward-backward asymmetry of dimuon system

# The angular PDF: $P_i^{(\prime)}$ basis

Perform measurement in bins of $q^2 = m^2(\mu\mu)$

$P_i^{(\prime)}$ **basis**

***Reparameterise the fit to obtain optimised observables:***

*form factor uncertainties cancel at first order*

JHEP 12 (2014) 125, JHEP 09 (2010) 089

***7 CP-averaged observables are extracted from the fit (+$F_L$)***

Extracted by reparametrising the fit PDF in this basis

$$\frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$$

$$P_1 = \frac{2\,S_3}{(1-F_{\rm L})} = \boxed{A_{\rm T}^{(2)}}$$

$$P_2 = \frac{2}{3}\frac{A_{\rm FB}}{(1-F_{\rm L})}\,,$$

$$P_3 = \frac{-S_9}{(1-F_{\rm L})}\,,$$

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,,$$

$$P'_6 = \frac{S_7}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,.$$

# The angular PDF: $P_i^{(\prime)}$ basis

Perform measurement in bins of $q^2 = m^2(\mu\mu)$

$P_i^{(\prime)}$ **basis**

***Reparameterise the fit to obtain optimised observables:***

*form factor uncertainties cancel at first order*

**JHEP 12 (2014) 125, JHEP 09 (2010) 089**

In summary: the fit is performed in 2 bases, $S_i$ & $P_i^{(\prime)}$

$$\frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$$

Extracted by reparametrising the fit PDF in this basis

$$P_1 = \frac{2\,S_3}{(1-F_\mathrm{L})} = \boxed{A_\mathrm{T}^{(2)}}$$

$$P_2 = \frac{2}{3}\frac{A_\mathrm{FB}}{(1-F_\mathrm{L})}\,,$$

$$P_3 = \frac{-S_9}{(1-F_\mathrm{L})}\,,$$

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}\,,$$

$$P'_6 = \frac{S_7}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}\,.$$

# The full fit model

- Use **mass shape** to determine **fraction of signal** and background contributions

$$\mathcal{P}_{\text{tot}} = f_{\text{sig}}\mathcal{P}_{\text{sig}}(\vec{\Omega}, m) + (1 - f_{\text{sig}})\mathcal{P}_{\text{bkg}}(\vec{\Omega}, m)$$

- **Assume mass and angular components independent:**

$$\mathcal{P}_{\text{sig}}(\vec{\Omega}, m) = \mathcal{P}_{\text{sig}}(\vec{\Omega}) \times \mathcal{P}_{\text{sig}}(m)$$

$$\mathcal{P}_{\text{bkg}}(\vec{\Omega}, m) = \mathcal{P}_{\text{bkg}}(\vec{\Omega}) \times \mathcal{P}_{\text{bkg}}(m)$$

- Perform maximum likelihood fit

nuisance parameters

$$-\sum_{\text{events},e} \log\mathcal{P}_{tot}(\vec{\Omega}_e, m_e | S_i, \vec{\lambda}')$$

angular coefficients

$$\vec{\Omega} = (\cos\theta_l, \cos\theta_k, \phi)$$

# The full fit model

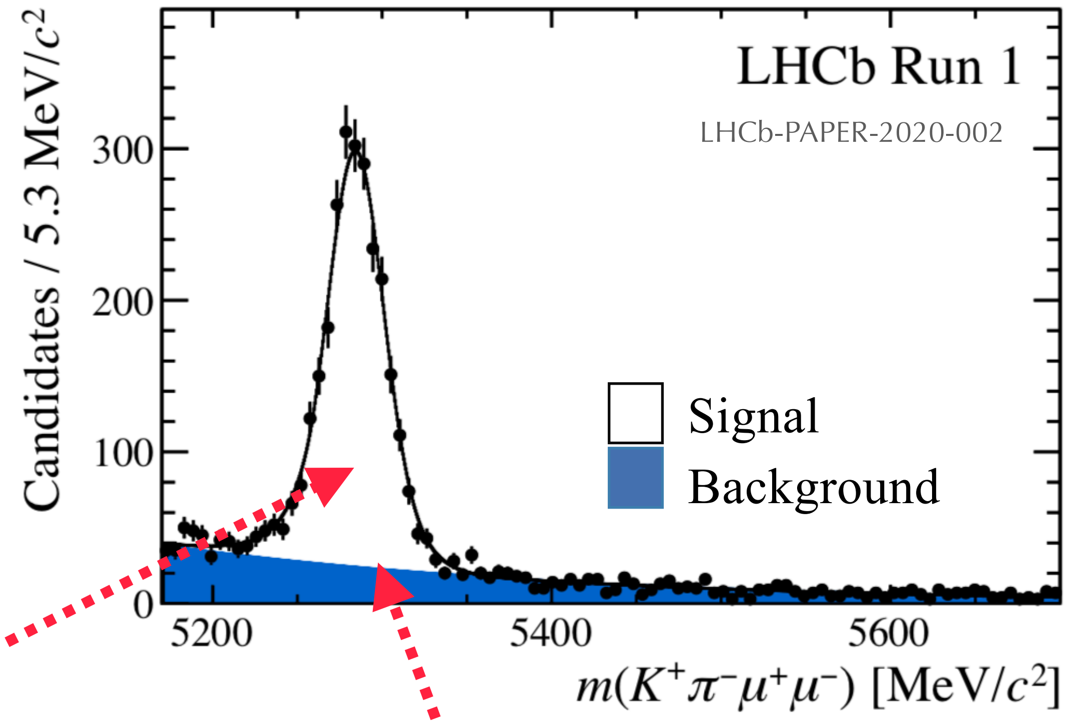
**Signal**

$B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$

$$\mathcal{P}_{\rm sig}(\vec{\Omega}, m) = \mathcal{P}_{\rm sig}(\vec{\Omega}) \times \mathcal{P}_{\rm sig}(m)$$

angular PDF: $\sum_I \boxed{S_i}_{q^2_{\rm bin}} \boxed{f_i(\Omega)}$

Gauss with radiative tail



**Background**

Combinatorial

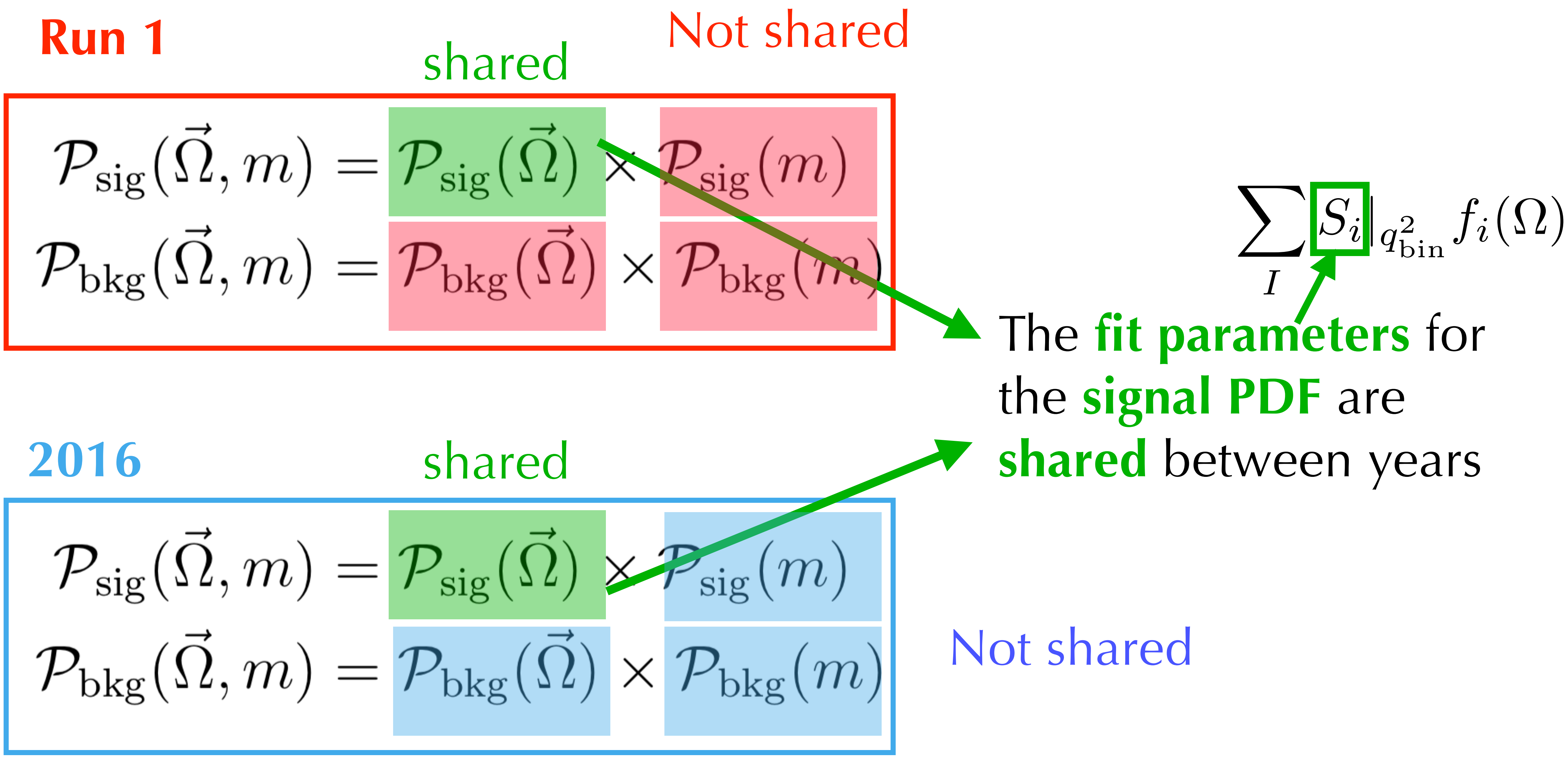
(random tracks which are incorrectly vertexed)

$$\mathcal{P}_{\rm bkg}(\vec{\Omega}, m) = \mathcal{P}_{\rm bkg}(\vec{\Omega}) \times \mathcal{P}_{\rm bkg}(m)$$

Polynomials (assume factorisation in angles)

Exponential

# The full fit model: simultaneous fitting



**Run 1**

shared

Not shared

$$\mathcal{P}_{\rm sig}(\vec{\Omega}, m) = \mathcal{P}_{\rm sig}(\vec{\Omega}) \times \mathcal{P}_{\rm sig}(m)$$

$$\mathcal{P}_{\rm bkg}(\vec{\Omega}, m) = \mathcal{P}_{\rm bkg}(\vec{\Omega}) \times \mathcal{P}_{\rm bkg}(m)$$

$$\sum_I \boxed{S_i}|_{q^2_{\rm bin}} f_i(\Omega)$$

The **fit parameters** for the **signal PDF** are **shared** between years

**2016**

shared

$$\mathcal{P}_{\rm sig}(\vec{\Omega}, m) = \mathcal{P}_{\rm sig}(\vec{\Omega}) \times \mathcal{P}_{\rm sig}(m)$$

$$\mathcal{P}_{\rm bkg}(\vec{\Omega}, m) = \mathcal{P}_{\rm bkg}(\vec{\Omega}) \times \mathcal{P}_{\rm bkg}(m)$$

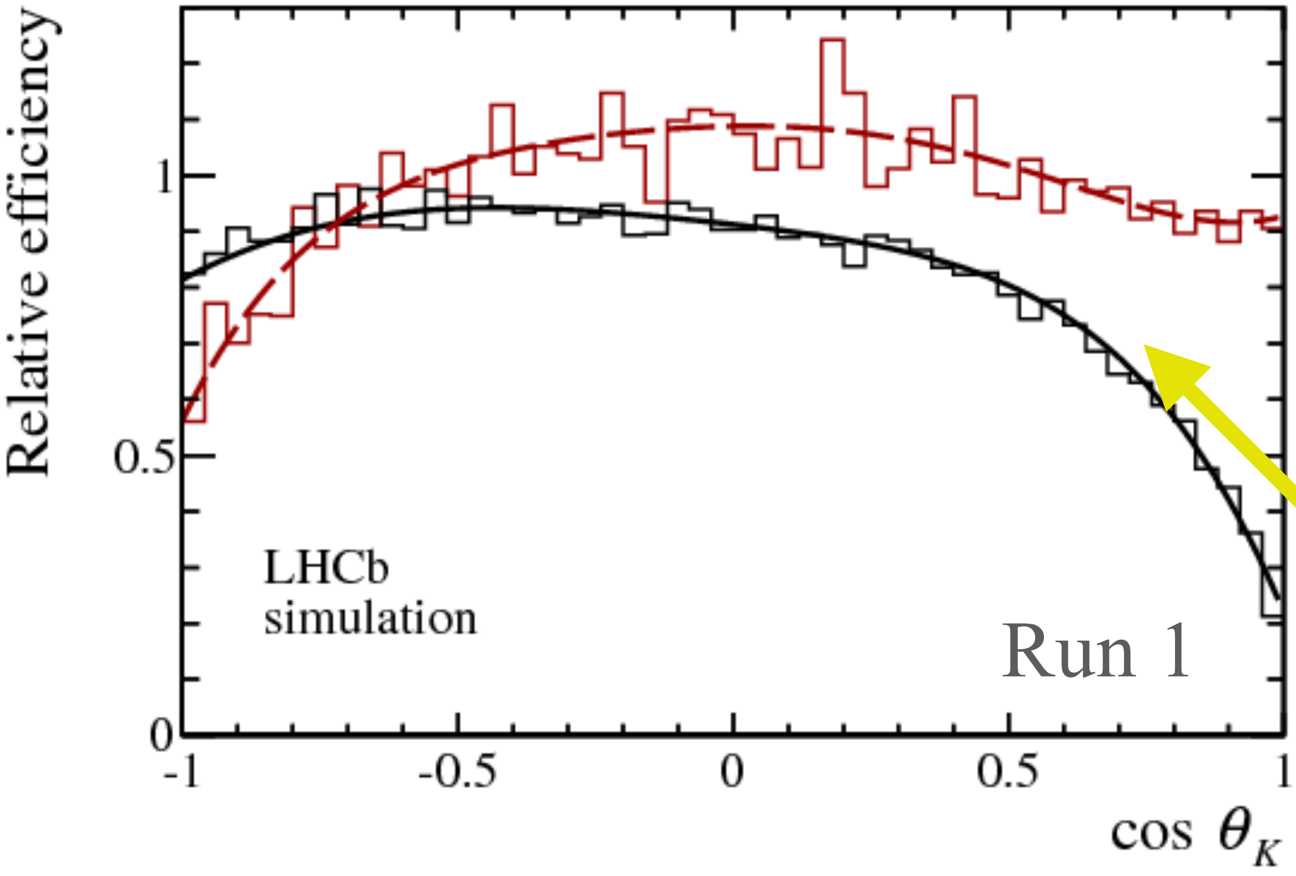
Not shared

Differences in reconstruction between years: **the mass and angular background components are not shared** between Run 1 and 2016

# The angular acceptance

# Modelling the efficiency

- Angular and $q^2$ distributions will be sculpted by the efficiencies of the selection and reconstruction.
- Parameterise this using an **acceptance function**
- **Use different acceptance for Run 1 and 2016**



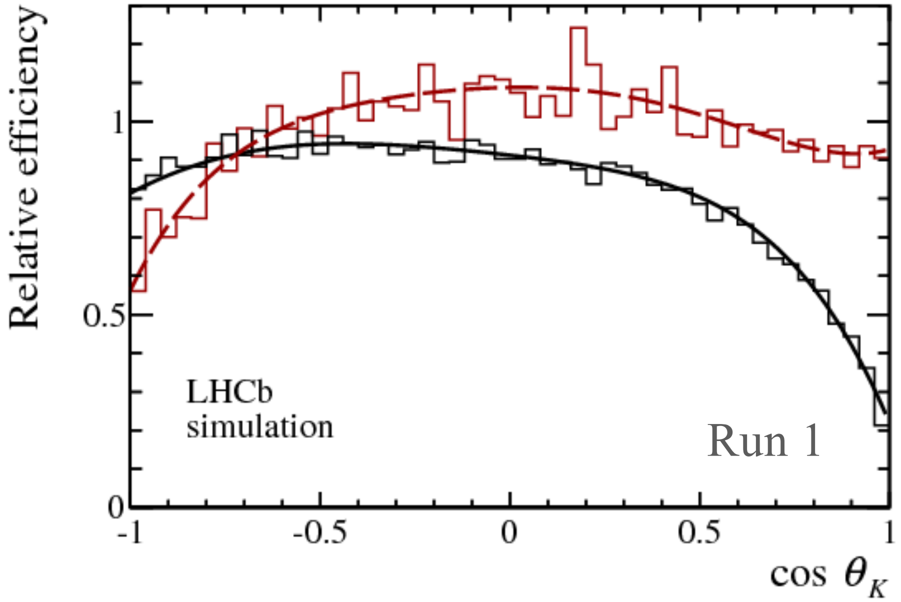
$0.1 < q^2 < 0.98\,\mathrm{GeV}^2/c^4$

$18.0 < q^2 < 19.0\,\mathrm{GeV}^2/c^4$

The efficiency across the angles and $q^2$ is not flat

# Modelling the efficiency

- 3 angles + $q^2$ = a 4-D efficiency parameterisation
- Efficiency is parametrised in $\Omega, q^2$ using Legendre polynomials



$$\varepsilon(\cos\theta_\ell, \cos\theta_K, \phi, q^2) = \sum_{k,l,m,n} c_{k,l,m,n} P(\cos\theta_\ell, k) P(\cos\theta_K, l) P(\phi, m) P(q^2, n)$$

- The coefficients $c_{k,l,m,n}$ are calculated via the method of moments using large statistic simulation samples

$$c_{k,l,m,n} = \frac{1}{N'} \sum_{i=1}^{N} w_i \left[ \left(\frac{2k+1}{2}\right) \left(\frac{2l+1}{2}\right) \left(\frac{2m+1}{2}\right) \left(\frac{2n+1}{2}\right) \times P(\cos\theta_\ell, k) P(\cos\theta_K, l) P(\phi, m) P(q^2, n) \right]$$

$$\int_{-1}^{+1} P(x,m) P(x,m') \mathrm{d}x = \frac{2}{2m+1} \delta_{mm'}$$

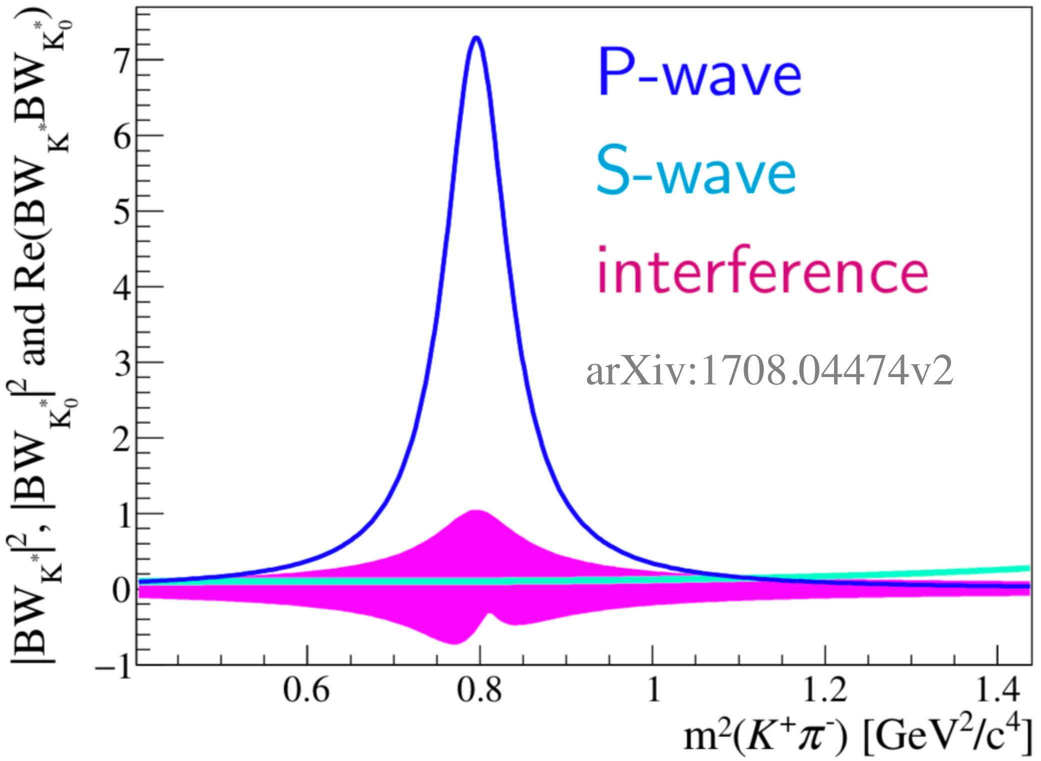
Correction to sim.

# The S-wave component

# S-wave contribution

- Background contribution from spin 0 $K\pi$ resonances
- Must therefore include additional angular terms
- Use the $m_{K^+\pi^-}$ distribution to further constrain S-wave

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi}\bigg|_{\mathrm{S+P}} = (1-F_S)\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi}\bigg|_{\mathrm{P}}$$
$$+\frac{3}{16\pi}\Big[F_S\sin^2\theta_l + S_{S1}\sin^2\theta_l\cos\theta_K$$
$$+ S_{S2}\sin 2\theta_l\sin\theta_K\cos\phi$$
$$+ S_{S3}\sin\theta_l\sin\theta_K\cos\phi$$
$$+ S_{S4}\sin\theta_l\sin\theta_K\sin\phi$$
$$+ S_{S5}\sin 2\theta_l\sin\theta_K\sin\phi\Big].$$

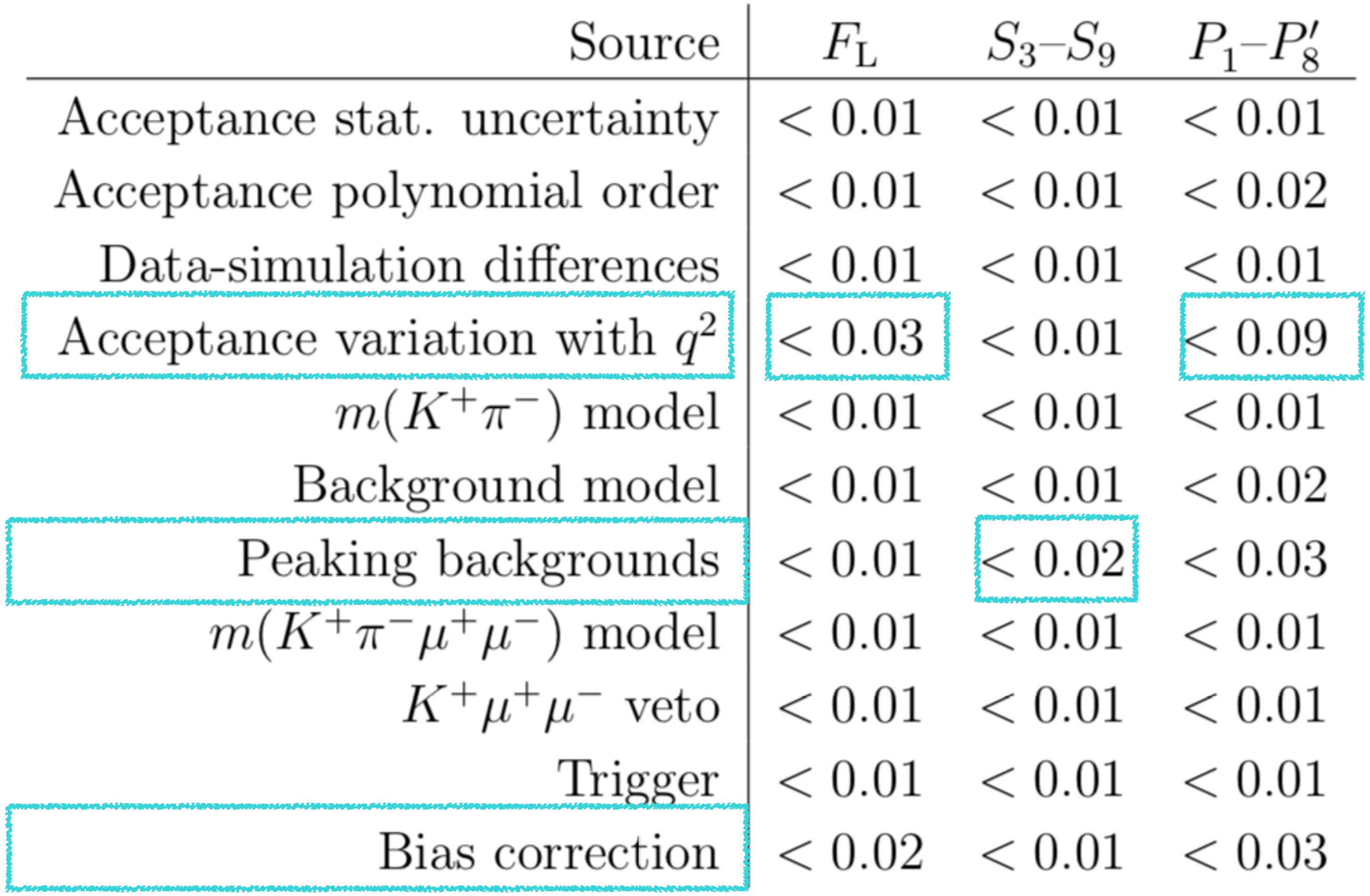


arXiv:1708.04474v2

# Systematic uncertainties

# Systematic uncertainties

Summary table showing the largest value for the systematic indicated across all the $q^2$ bins



| Source | $F_L$ | $S_3$–$S_9$ | $P_1$–$P_8'$ |
|---|---|---|---|
| Acceptance stat. uncertainty | $< 0.01$ | $< 0.01$ | $< 0.01$ |
| Acceptance polynomial order | $< 0.01$ | $< 0.01$ | $< 0.02$ |
| Data-simulation differences | $< 0.01$ | $< 0.01$ | $< 0.01$ |
| Acceptance variation with $q^2$ | $< 0.03$ | $< 0.01$ | $< 0.09$ |
| $m(K^+\pi^-)$ model | $< 0.01$ | $< 0.01$ | $< 0.01$ |
| Background model | $< 0.01$ | $< 0.01$ | $< 0.02$ |
| Peaking backgrounds | $< 0.01$ | $< 0.02$ | $< 0.03$ |
| $m(K^+\pi^-\mu^+\mu^-)$ model | $< 0.01$ | $< 0.01$ | $< 0.01$ |
| $K^+\mu^+\mu^-$ veto | $< 0.01$ | $< 0.01$ | $< 0.01$ |
| Trigger | $< 0.01$ | $< 0.01$ | $< 0.01$ |
| Bias correction | $< 0.02$ | $< 0.01$ | $< 0.03$ |

**Dominant systematics in each observable category**

**Systematic uncertainties small compared to stat. error**

# Systematic uncertainties

### Peaking background

Events are drawn from angular distributions of peaking backgrounds neglected in the fit.

Events are then injected into pseudoexperiments

$$\overline{\Lambda}_b^0 \to \overline{p} \to \pi^- K^+ \mu^+ \mu^-$$

$$\overline{B}^0 \to \overline{K}^{*0}[\to (K^- \to \pi^-)(\pi^+ \to K^+)]\mu^+\mu^-$$

$$B_s^0 \to \phi(1020)[\to K^+(\to \pi^+)K^-]\mu^+\mu^-$$

### Bias corrections

Small biases induced by boundary effects e.g. requirement that $F_S>0$

**If $F_S$ is small, it is biased towards higher values, which in turn biases the P-wave**

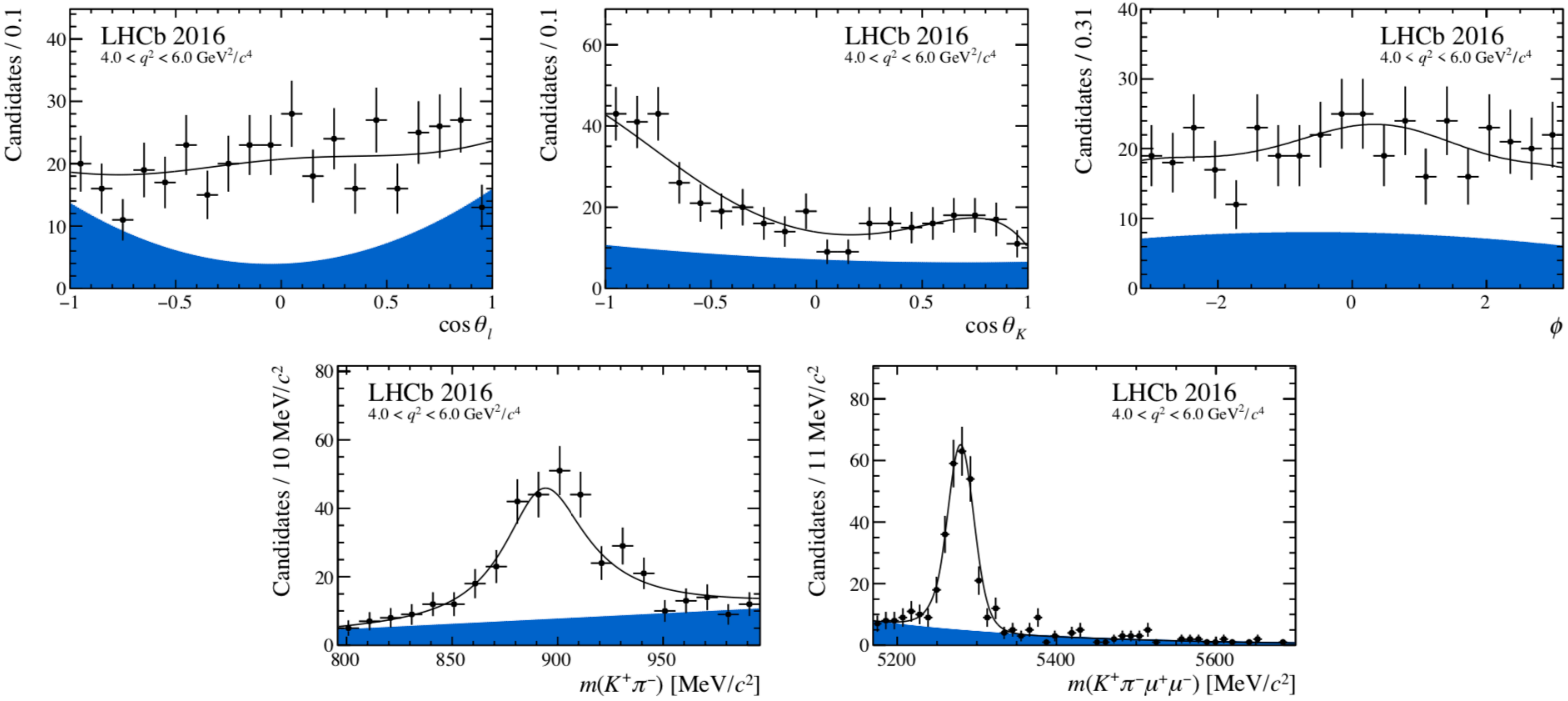
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi}\Bigg|_{\mathrm{S+P}} = (1-F_S)\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi}\Bigg|_{\mathrm{P}}$$

**If this term is biased towards smaller values**

**Magnitude of P-wave biased towards larger values**

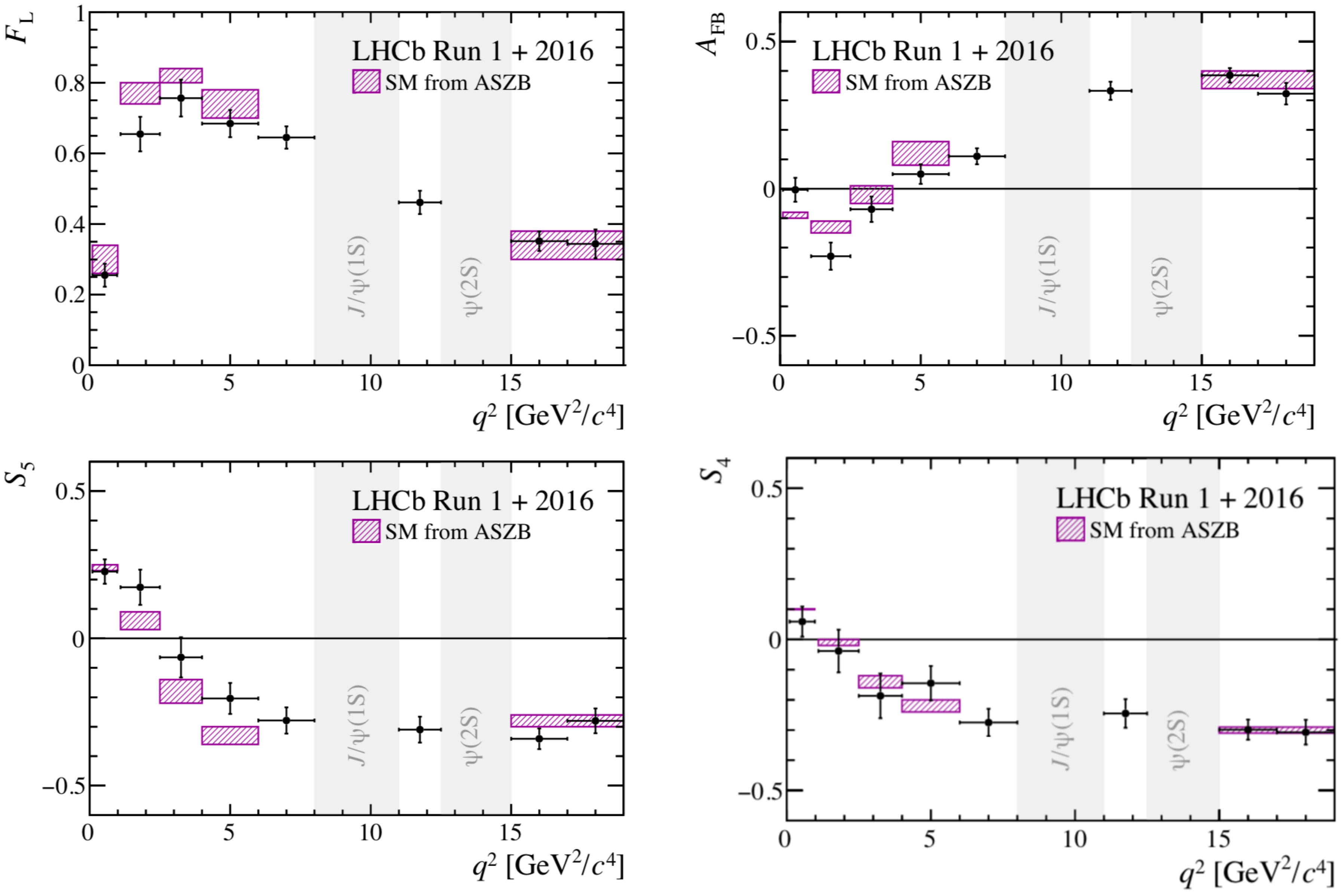
# Results

# Fit projections 2016 example



Fit projections for the bin $4.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$ for 2016 data

# CP-averaged angular observables



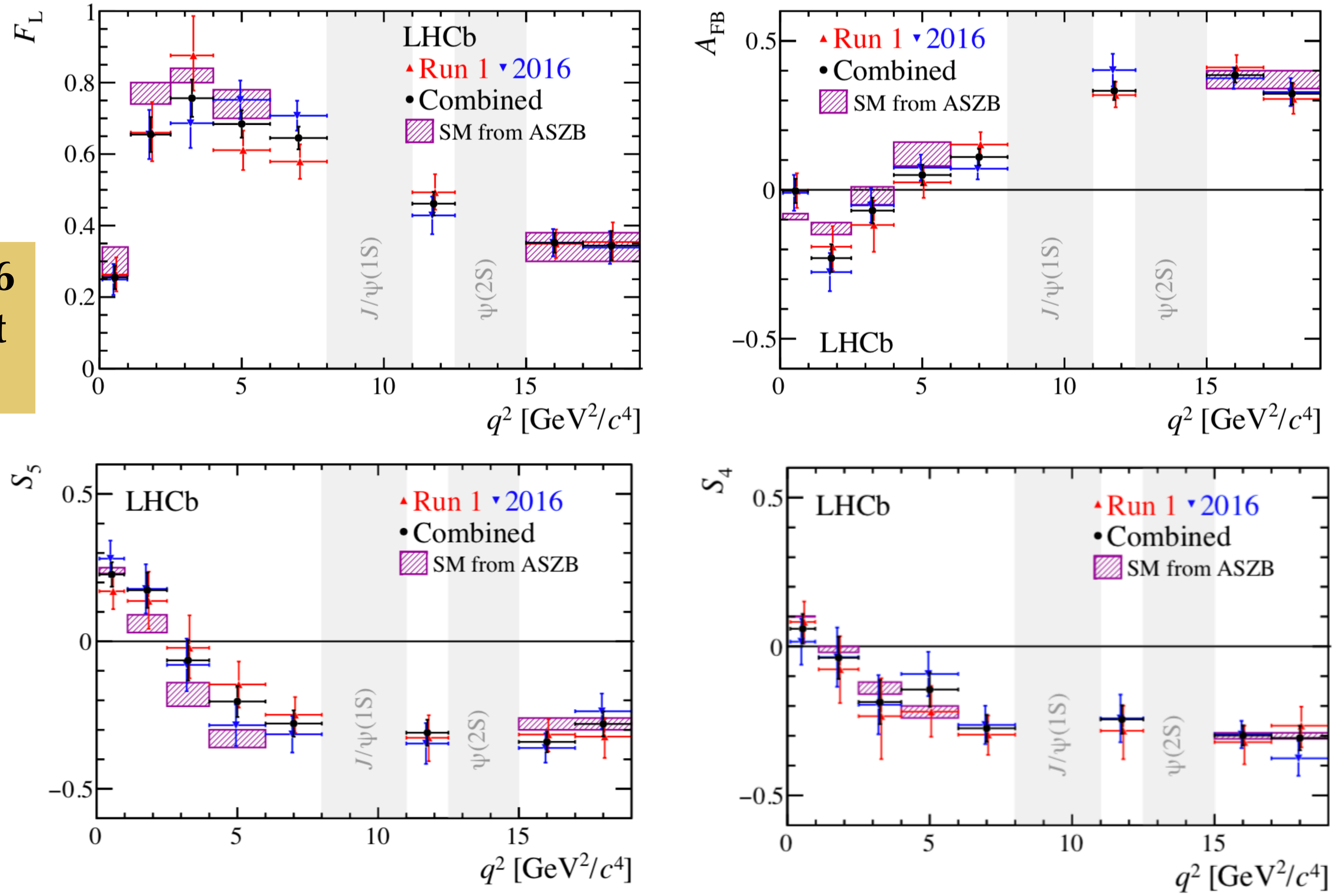
Theory predictions from JHEP 08 (2016) 098 , Eur. Phys. J. C75 (2015) 382

,

4 of the 8 CP-averaged observables for the Run 1 + 2016 combined fit in the $S_i$ basis, shown across narrow bins in $q^2$

# CP-averaged angular observables

**Run 1 and 2016 are in excellent agreement**



**Disclaimer: 2016-only data is for illustratory purposes and contains no systematic uncertainties or bias and coverage corrections**

4 of the 8 CP-averaged observables for the Run 1, 2016 & combined fit in the $S_i$ basis, shown across narrow bins in $q^2$

# Local tension in $P_5'$

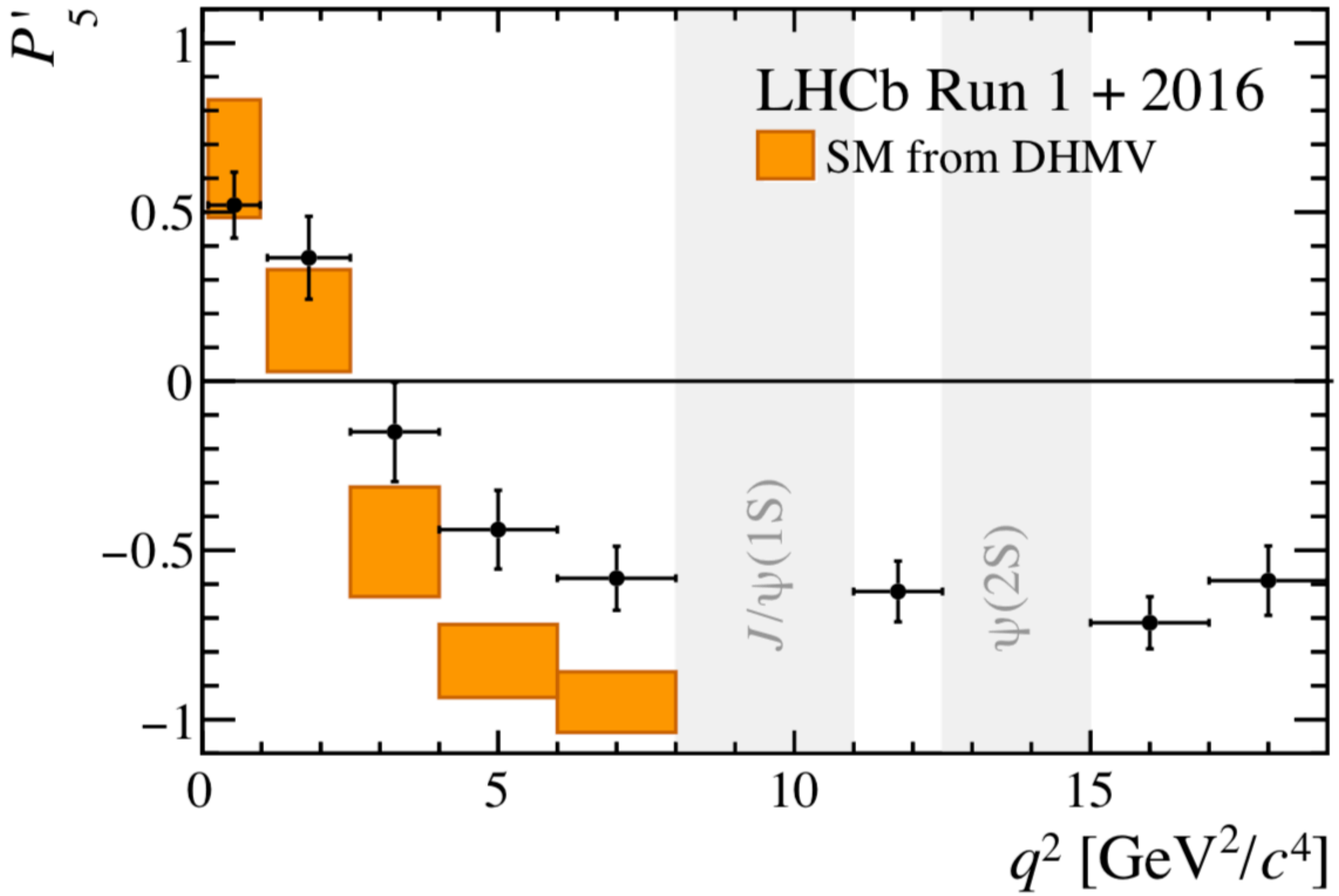
Theory predictions from JHEP 12 (2014) 125, JHEP 09 (2010) 089,

$4.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$

Run1+2016: $2.5\sigma$

$6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$

Run1+2016: $2.9\sigma$



# Local tension in $P_5'$

Theory predictions from JHEP 12 (2014) 125, JHEP 09 (2010) 089,

$$4.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$$

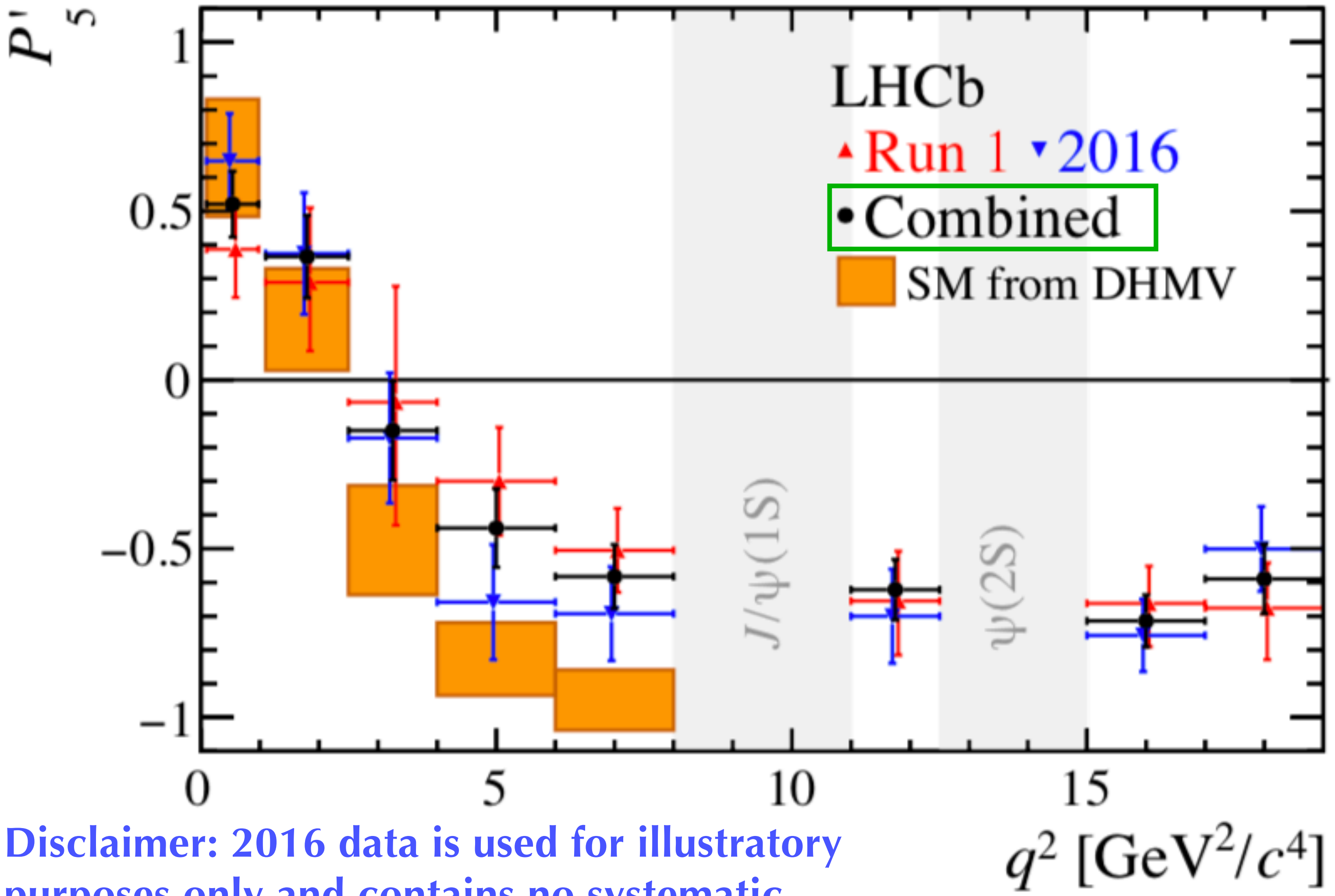
Run1+2016: 2.5$\sigma$

Run1 only: 2.8$\sigma$

$$6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$$

Run1+2016: 2.9$\sigma$

Run1 only: 3.0$\sigma$



**Disclaimer: 2016 data is used for illustratory purposes only and contains no systematic uncertainties or bias and coverage corrections**

Reduced local tension in $P_5'$, what about overall significance?

# Overall significance

# REMINDER: Wilson coefficients and theory uncertainties

In order to obtain a global significance, we fit to all the observables in the $S_i$ basis, to extract values of $C_{9,10}$

In order to do these, we need a parameterisation of the theory uncertainties (or so-called **SM nuisance parameters**)

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

# Key nuisance parameter: [1] Form factors

***Where the physics lies:***

- The $K^{*0}$ **amplitudes** are in turn dependent on **Wilson coefficients** and **form factors (non-perturbative QCD)**

$$\mathcal{A}_\perp^{\mathrm{L(R)}} = \mathcal{N}\sqrt{2\lambda}\left\{\left[(\mathcal{C}_9^{\mathrm{eff}} + \mathcal{C}_9^{\prime\mathrm{eff}}) \mp (\mathcal{C}_{10}^{\mathrm{eff}} + \mathcal{C}_{10}^{\prime\mathrm{eff}})\right]\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathcal{C}_7^{\mathrm{eff}} + \mathcal{C}_7^{\prime\mathrm{eff}})T_1(q^2)\right\}$$

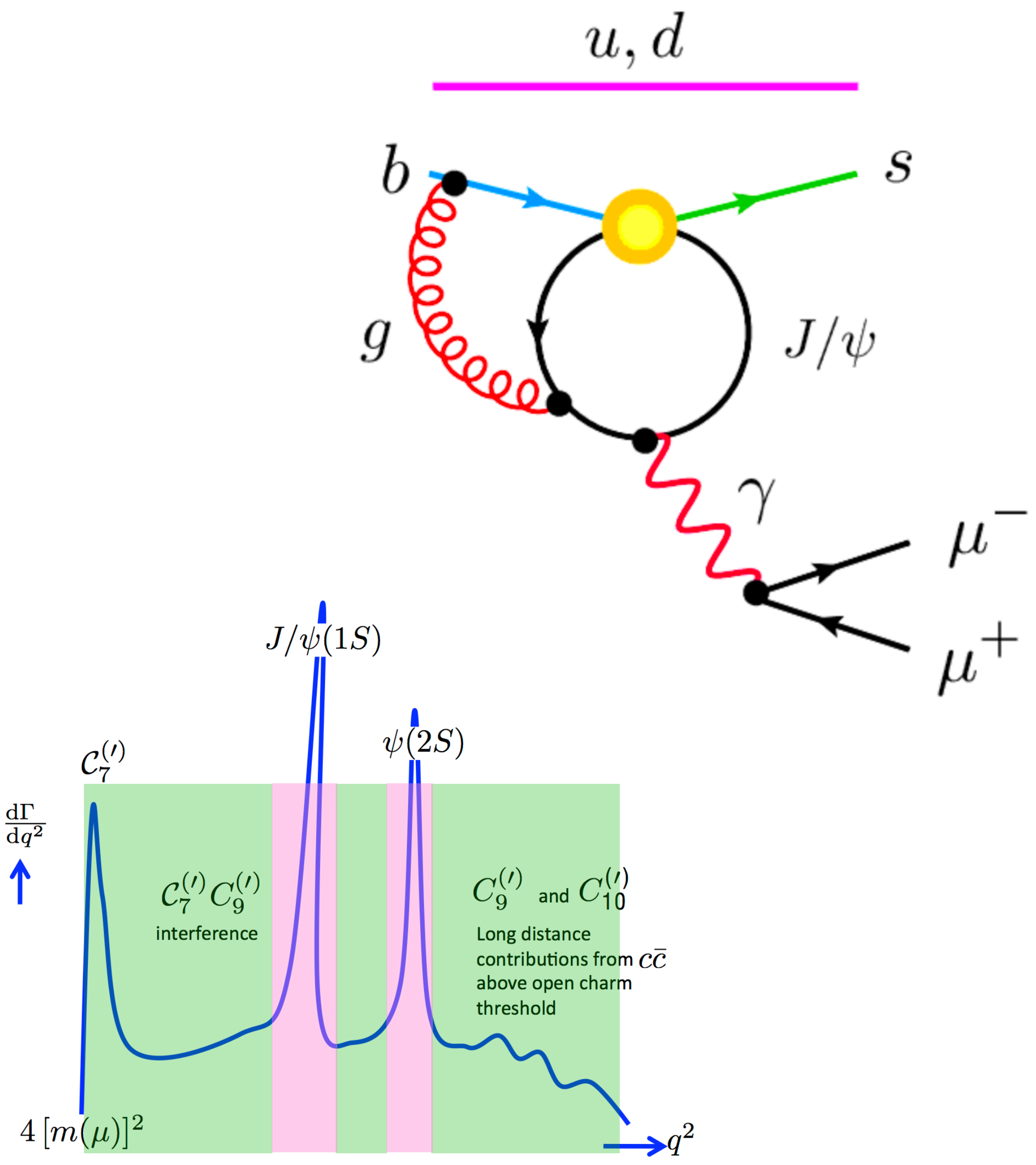
$$\mathcal{A}_\parallel^{\mathrm{L(R)}} = -\mathcal{N}\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(\mathcal{C}_9^{\mathrm{eff}} - \mathcal{C}_9^{\prime\mathrm{eff}}) \mp (\mathcal{C}_{10}^{\mathrm{eff}} - \mathcal{C}_{10}^{\prime\mathrm{eff}})\right]\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(\mathcal{C}_7^{\mathrm{eff}} - \mathcal{C}_7^{\prime\mathrm{eff}})T_2(q^2)\right\}$$

$$\mathcal{A}_0^{\mathrm{L(R)}} = -\frac{\mathcal{N}}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathcal{C}_9^{\mathrm{eff}} - \mathcal{C}_9^{\prime\mathrm{eff}}) \mp (\mathcal{C}_{10}^{\mathrm{eff}} - \mathcal{C}_{10}^{\prime\mathrm{eff}})\right] \times \left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})A_1(q^2) - \lambda\frac{A_2(q^2)}{m_B + m_{K^*}}\right] + 2m_b(\mathcal{C}_7^{\mathrm{eff}} - \mathcal{C}_7^{\prime\mathrm{eff}})\left[(m_B^2 + 3m_{K^*} - q^2)T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2}T_3(q^2)\right]\right\}$$

JHEP 0901:019,2009

# Key nuisance parameter: [2] sub-leading corrections

Charmonium loops



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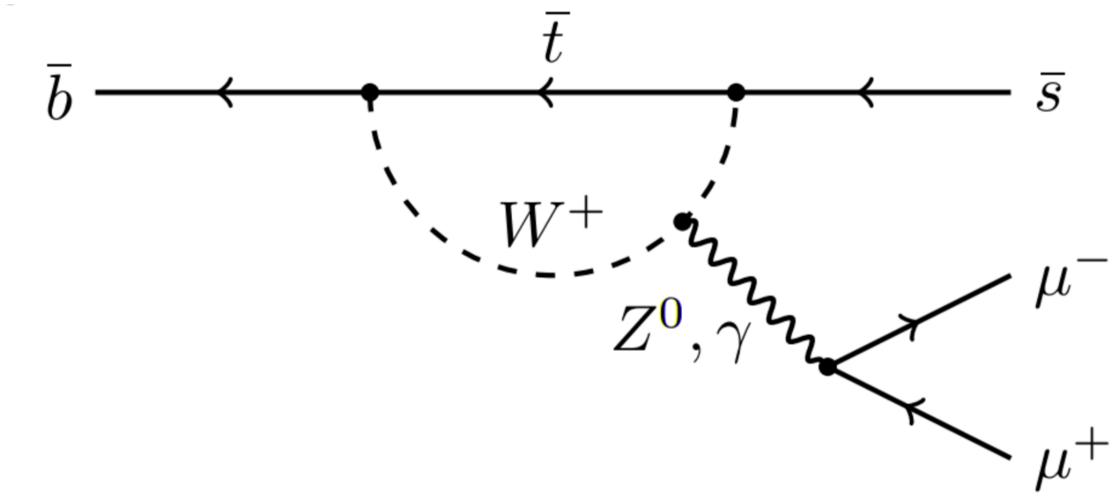
Signal mode



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Long-distance effects that could affect signal mode even when outside the vetoed $J/\psi$ region

# Nuisance parameters: Now and then

- Theory uncertainties associated with form factors have decreased since previous publication
- Parameterisation of sub-leading corrections is now more conservative, [and the parameterisation of sub-leading corrections is more sophisticated]

Currently implementing the following in the **Flavio** software package[1]

- The **current LHCb analysis uses** form factors and subleading corrections from JHEP (2016) 08 2016:98 and Eur. Phys. J. C75 (2015), no. 8

Previously implemented the following in the **EOS** software package[2]

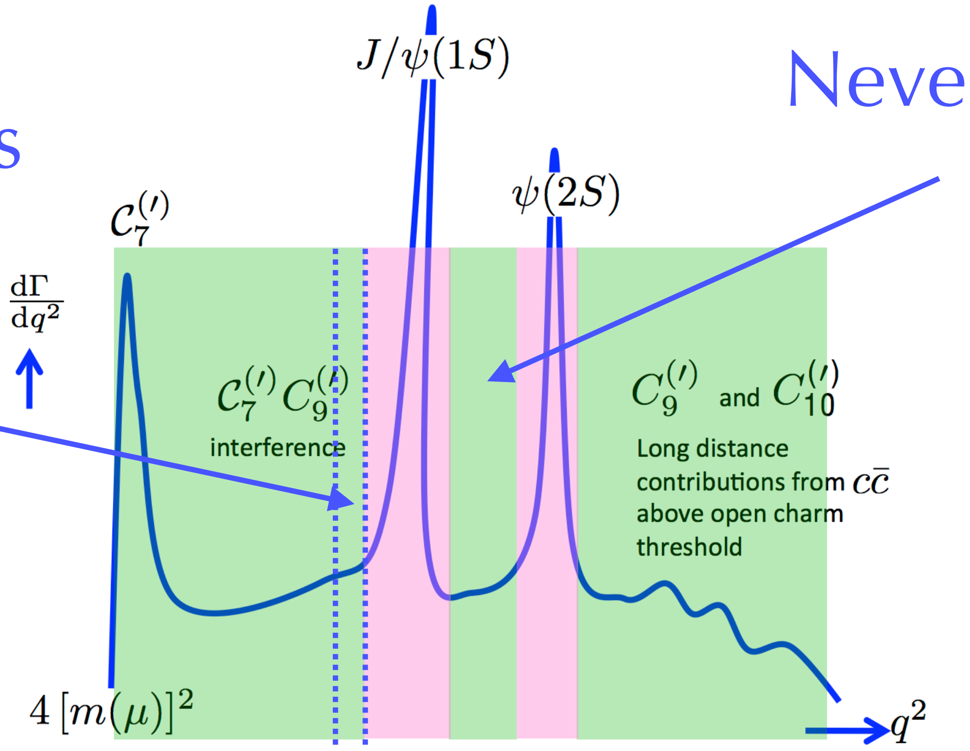
- The **previous LHCb analysis used** form factors and subleading corrections from: Eur. Phys. J. C 74 (2014) 2897

[1] arXiv:1810.08132.
[2] arXiv:1006.5013

# What do we include in the global fit?

- Nominal fit: Use same $q^2$ range as last analysis = all narrow $q^2$ bins below $8.0\,\mathrm{GeV}^2/c^4$ and the wide bin $15.0 < q^2 < 19.0\,\mathrm{GeV}^2/c^4$ **[case 1]**
- Repeat fit removing $6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$ (near to $J/\psi$ region, sub-leading corrections problematic) **[case 2]**

Don't include this region in case 2



Never include this region

**All global fits use CP-averaged observables in the $S_i$ basis**

# Varying $Re(C_9)$ and $Re(C_{10})$

# Varying $Re(C_9)$ and $Re(C_{10})$

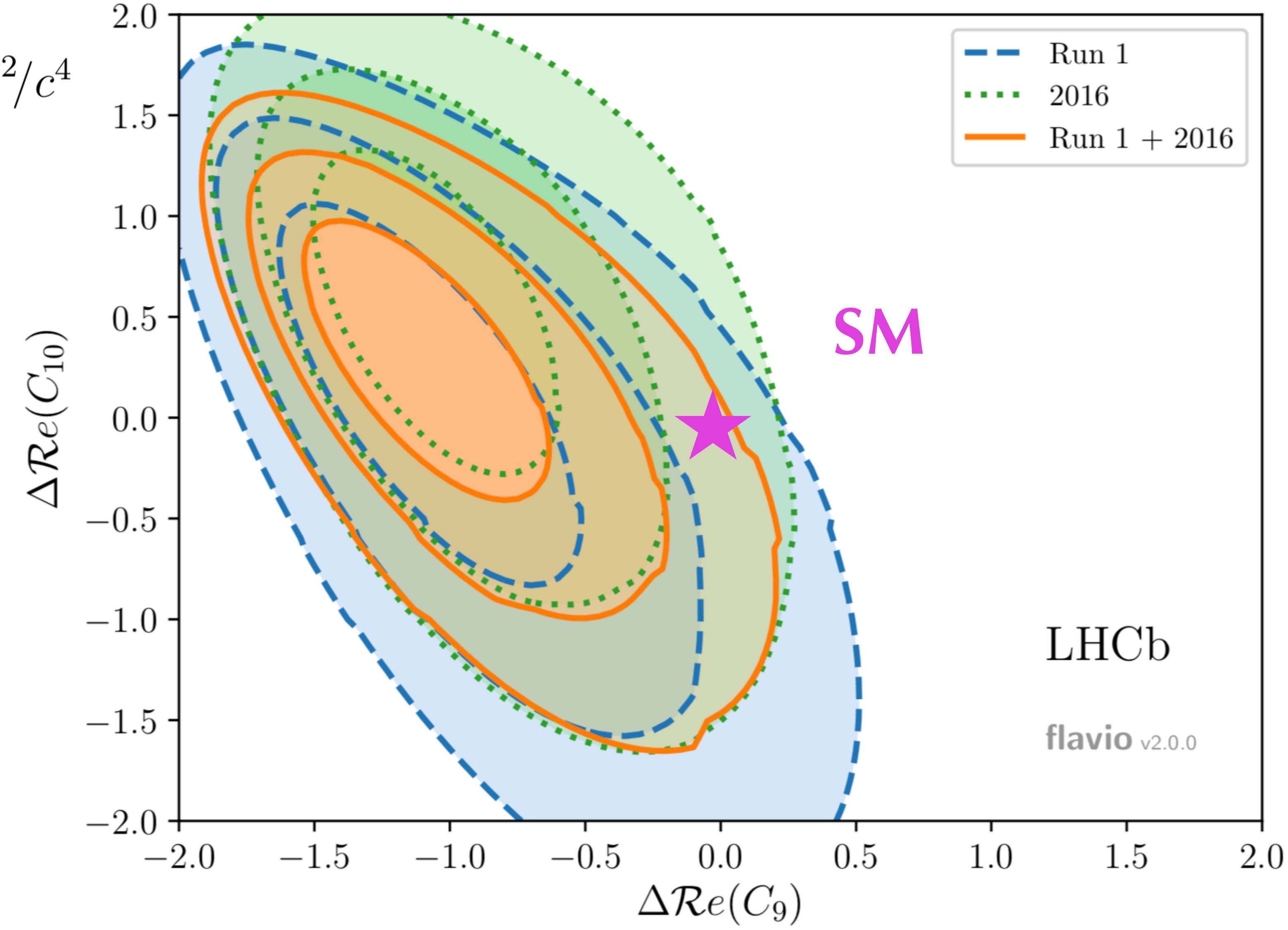
Run 1 and 2016 in good agreement

***Case 1***

Including

$6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$

bin



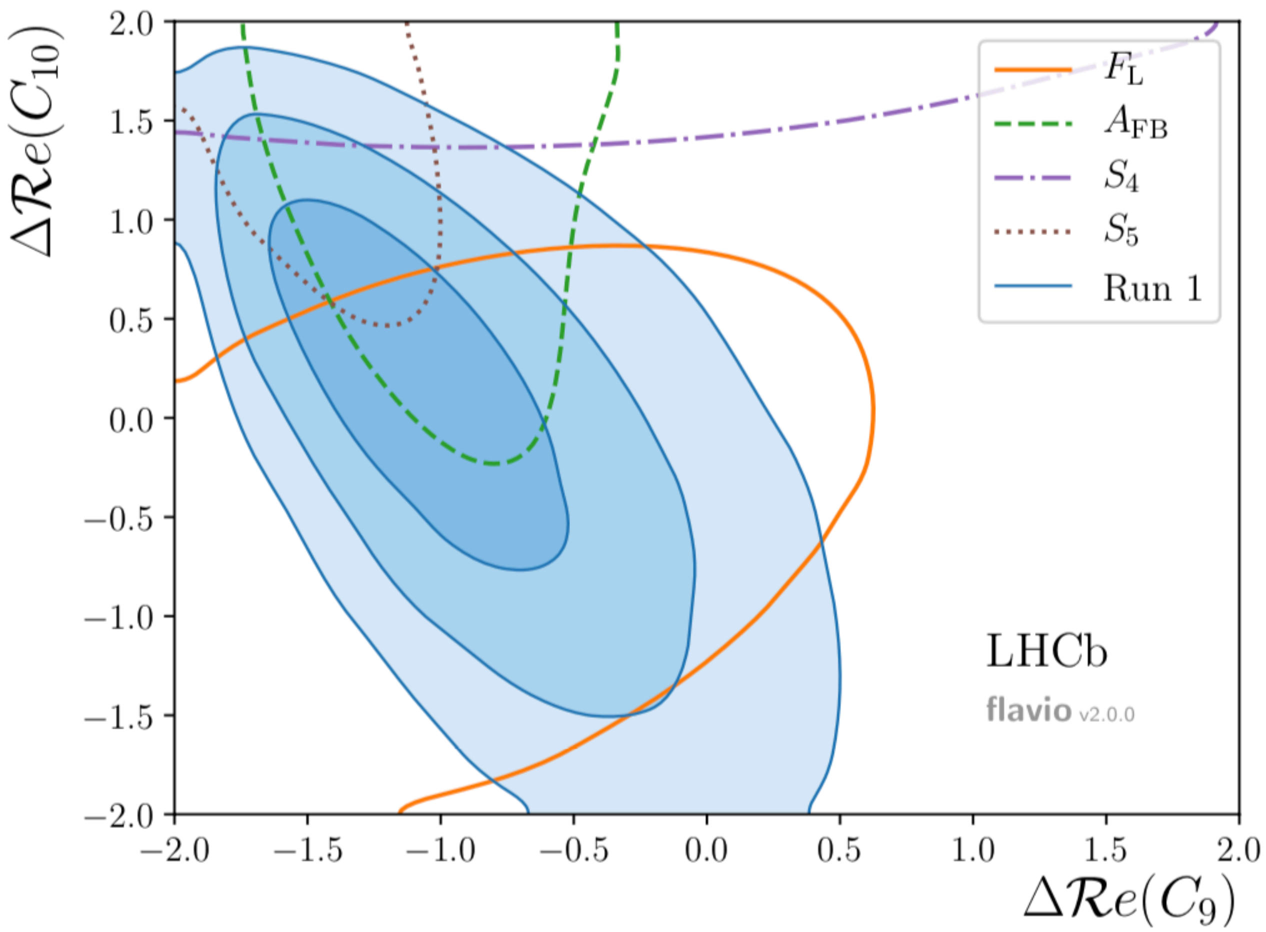
**Disclaimer: 2016-only data is for illustratory purposes and contains no systematic uncertainties or bias and coverage corrections**

# Varying $Re(C_9)$ and $Re(C_{10})$

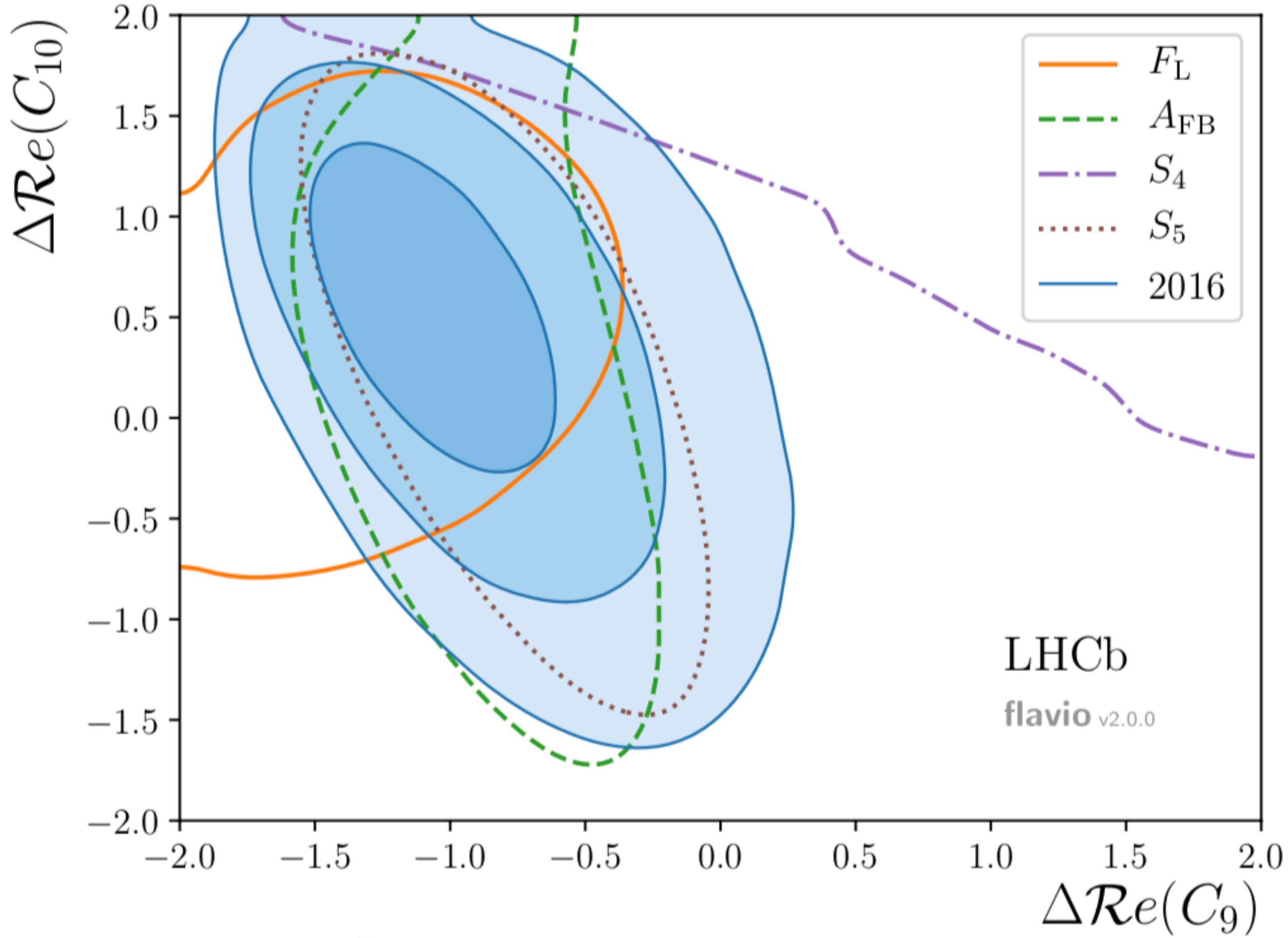
**Case 1**
Including
$6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$
bin

Best fit point for $Re(C_9)$ and $Re(C_{10})$ for different angular observables for Run 1 and 2016 separately

Run 1



2016



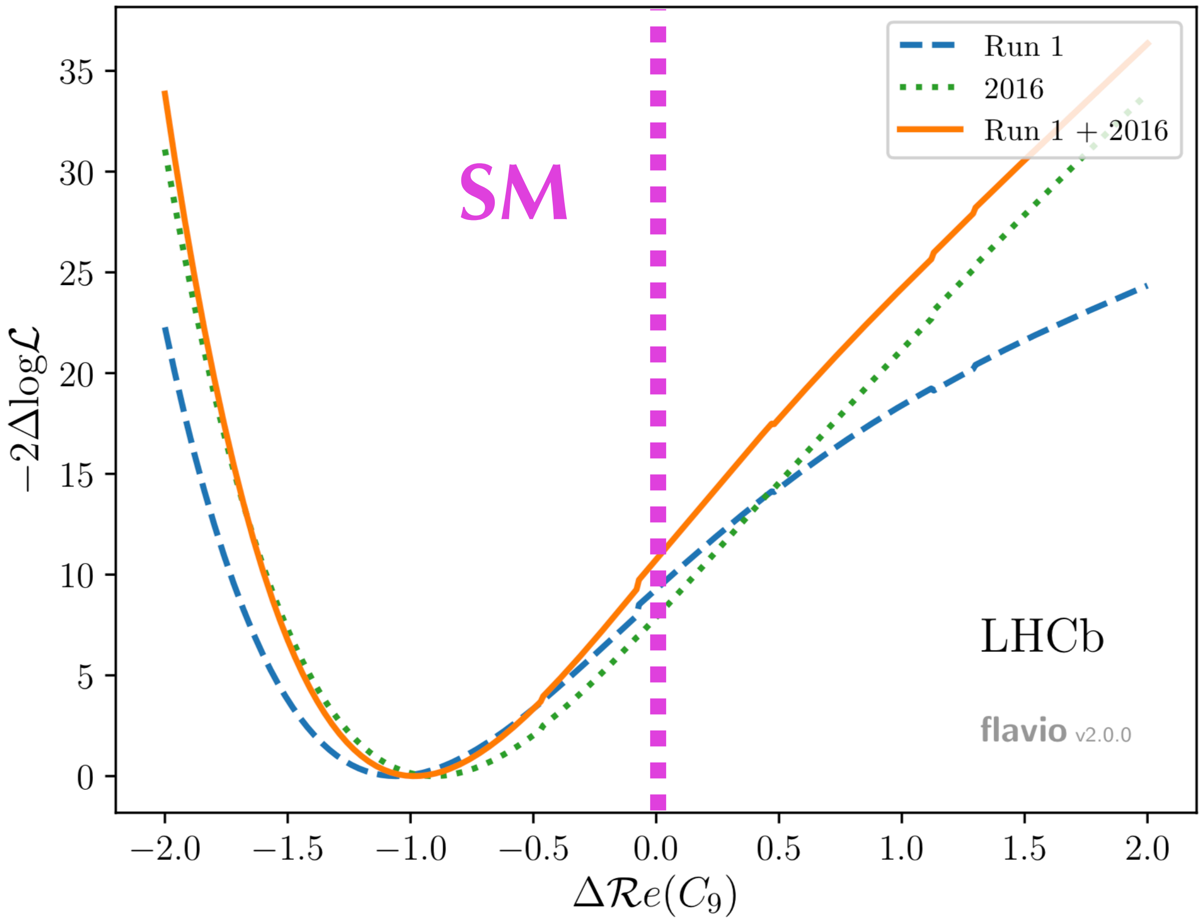
**Disclaimer: 2016-only data is for illustratory purposes and contains no systematic uncertainties or bias and coverage corrections**

# Varying $Re(C_9)$ only

# Varying $Re(C_9)$ only

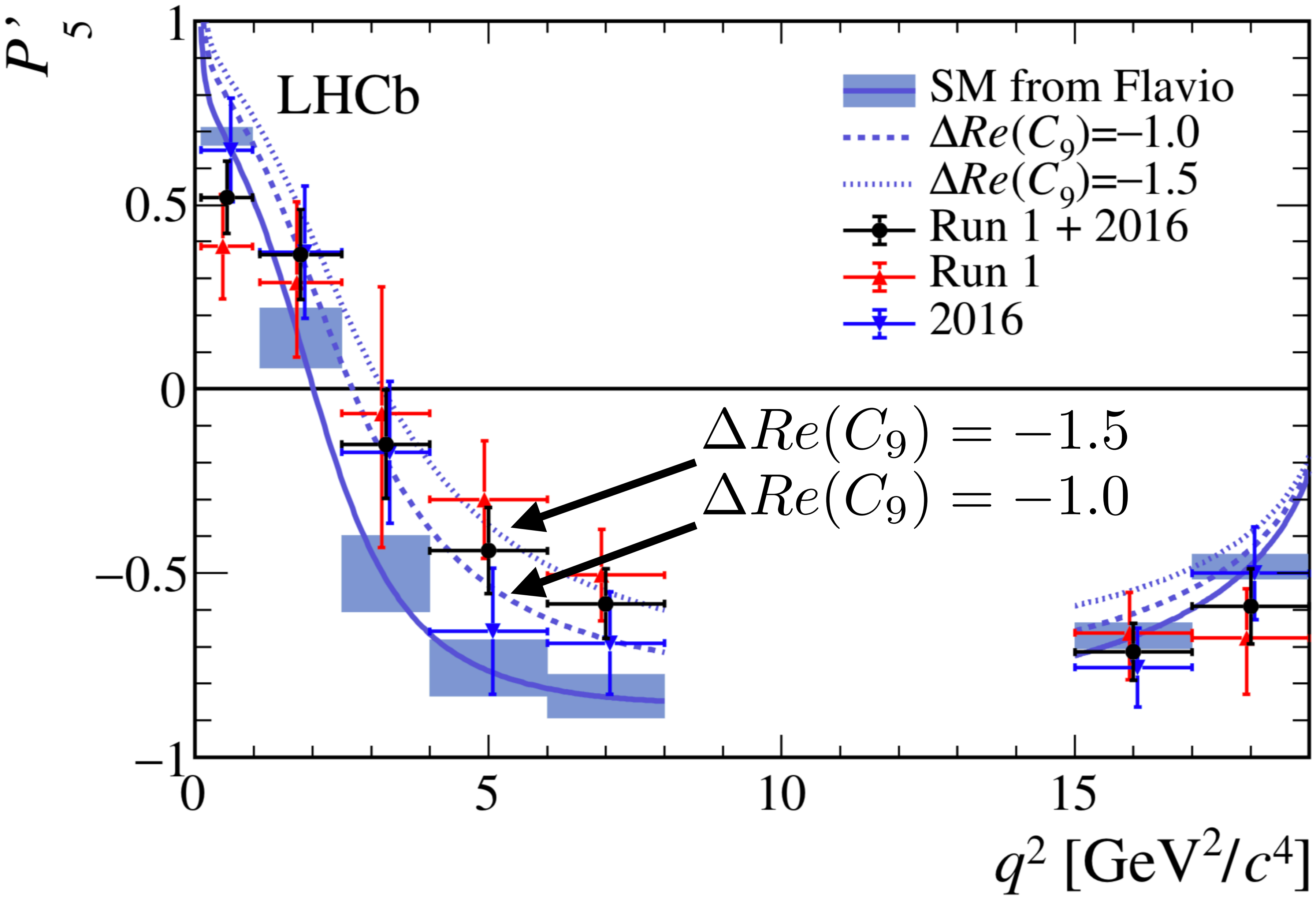
- When varying only $Re(C_9)$ significances are as follows
- Including $6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$
  - Run 1: $3.0\,\sigma$ (previous nuisances 3.4 $\sigma$ )
  - Run 1 + 2016: $3.3\,\sigma$
- Excluding $6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$
  - Run 1: $2.4\,\sigma$
  - Run 1 + 2016: $2.7\,\sigma$

Run 1 and 2016 in good agreement



**Disclaimer: 2016-only data is for illustratory purposes and contains no systematic uncertainties or bias and coverage corrections**

# $P_5'$ when $\Delta Re(C_9) = -1, -1.5$



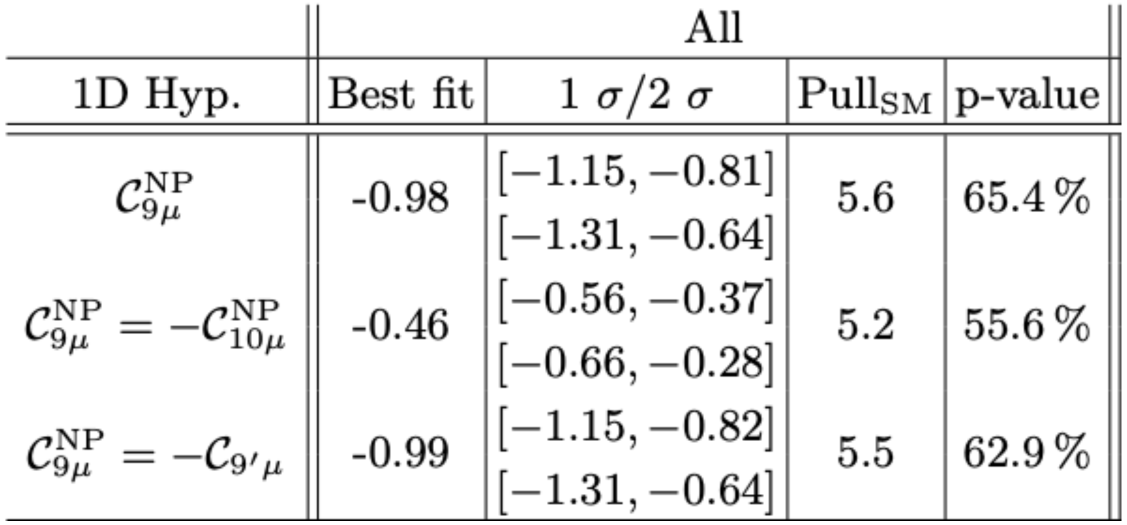
$\Delta Re(C_9) = -1.5$

$\Delta Re(C_9) = -1.0$

**Disclaimer: 2016-only data is for illustratory purposes and contains no systematic uncertainties or bias and coverage corrections**

# Effect of result on global fits

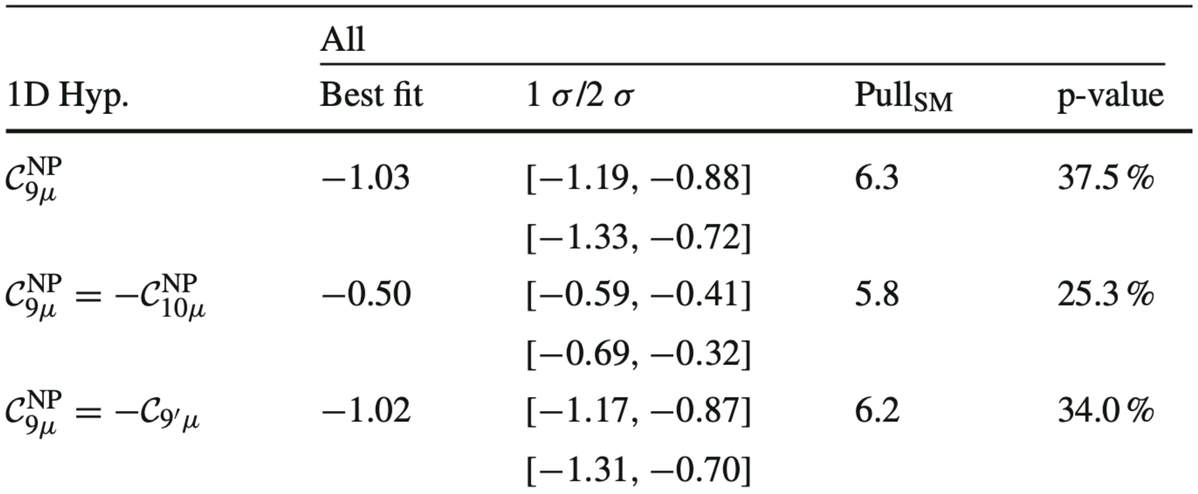
## Without result



| | All | | | |
|---|---|---|---|---|
| 1D Hyp. | Best fit | $1\ \sigma/2\ \sigma$ | $\mathrm{Pull}_{\mathrm{SM}}$ | p-value |
| $\mathcal{C}_{9\mu}^{\mathrm{NP}}$ | -0.98 | $[-1.15,-0.81]$<br>$[-1.31,-0.64]$ | 5.6 | 65.4 % |
| $\mathcal{C}_{9\mu}^{\mathrm{NP}}=-\mathcal{C}_{10\mu}^{\mathrm{NP}}$ | -0.46 | $[-0.56,-0.37]$<br>$[-0.66,-0.28]$ | 5.2 | 55.6 % |
| $\mathcal{C}_{9\mu}^{\mathrm{NP}}=-\mathcal{C}_{9'\mu}$ | -0.99 | $[-1.15,-0.82]$<br>$[-1.31,-0.64]$ | 5.5 | 62.9 % |

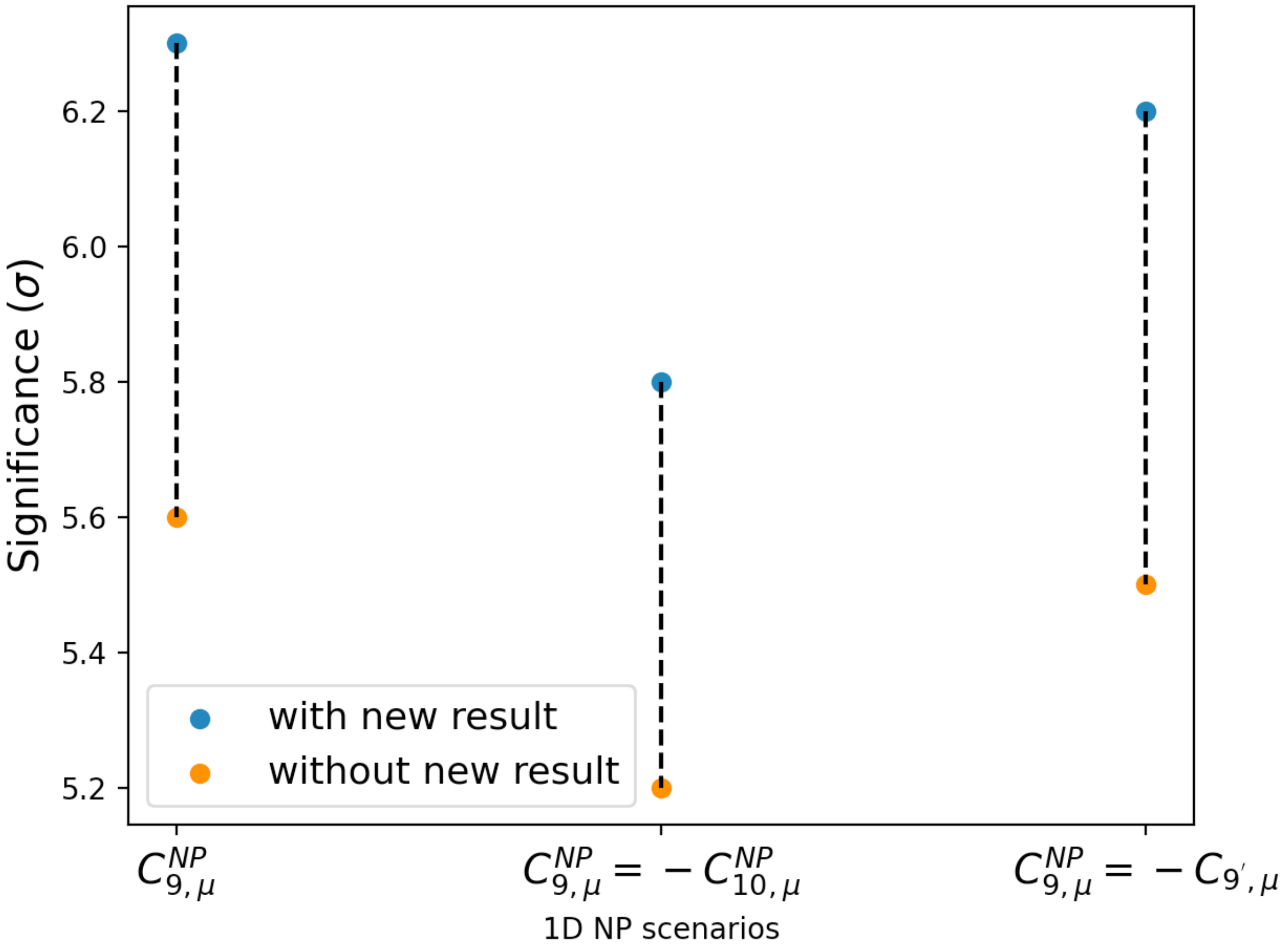
- Eur. Phys. J. **C79**, 714 (2019)

## With result



| | All | | | |
|---|---|---|---|---|
| 1D Hyp. | Best fit | $1\ \sigma/2\ \sigma$ | $\mathrm{Pull}_{\mathrm{SM}}$ | p-value |
| $\mathcal{C}_{9\mu}^{\mathrm{NP}}$ | $-1.03$ | $[-1.19,-0.88]$<br>$[-1.33,-0.72]$ | 6.3 | 37.5 % |
| $\mathcal{C}_{9\mu}^{\mathrm{NP}}=-\mathcal{C}_{10\mu}^{\mathrm{NP}}$ | $-0.50$ | $[-0.59,-0.41]$<br>$[-0.69,-0.32]$ | 5.8 | 25.3 % |
| $\mathcal{C}_{9\mu}^{\mathrm{NP}}=-\mathcal{C}_{9'\mu}$ | $-1.02$ | $[-1.17,-0.87]$<br>$[-1.31,-0.70]$ | 6.2 | 34.0 % |

- Addendum to Eur. Phys. J. **C79**, 714 (2019)

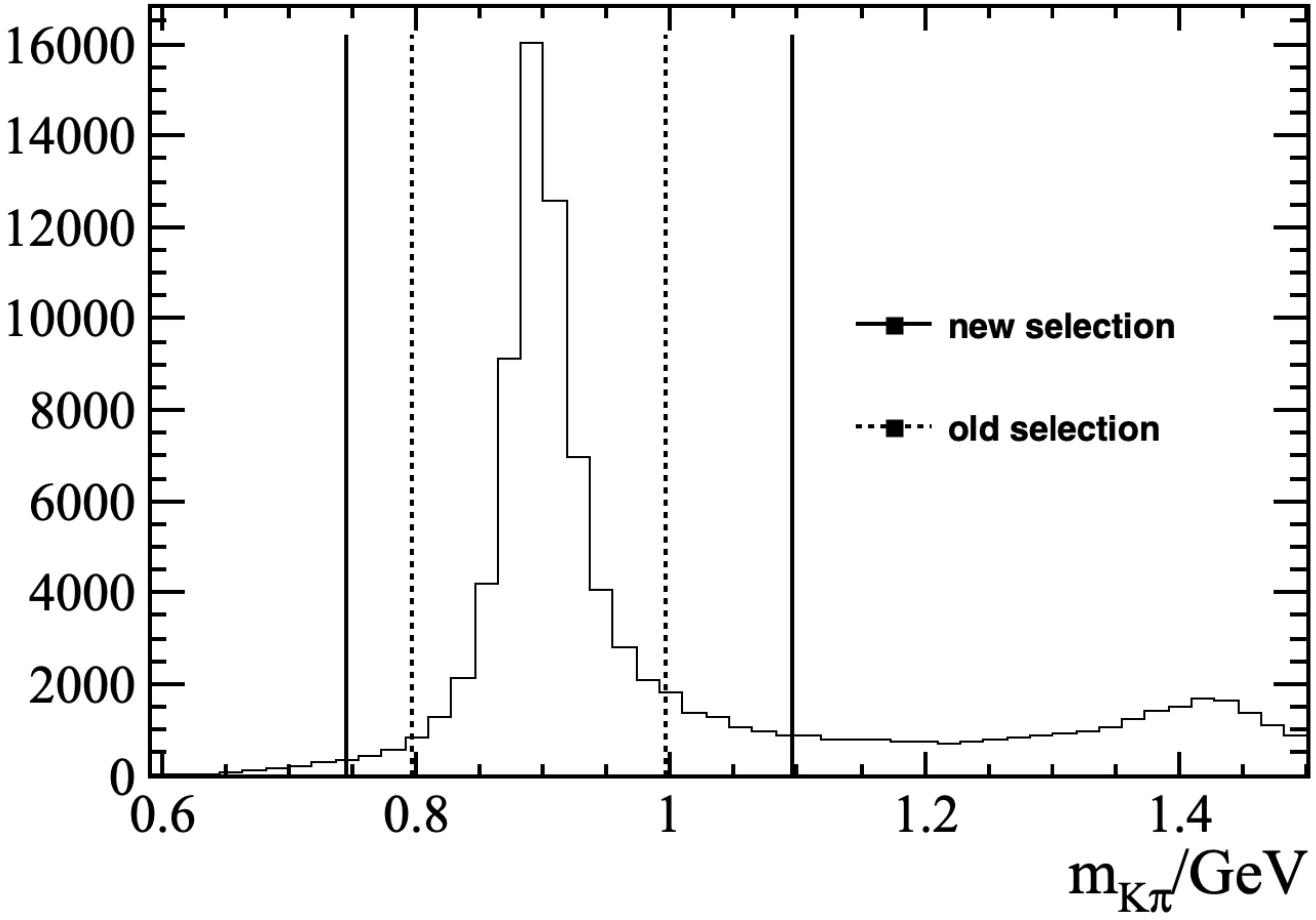


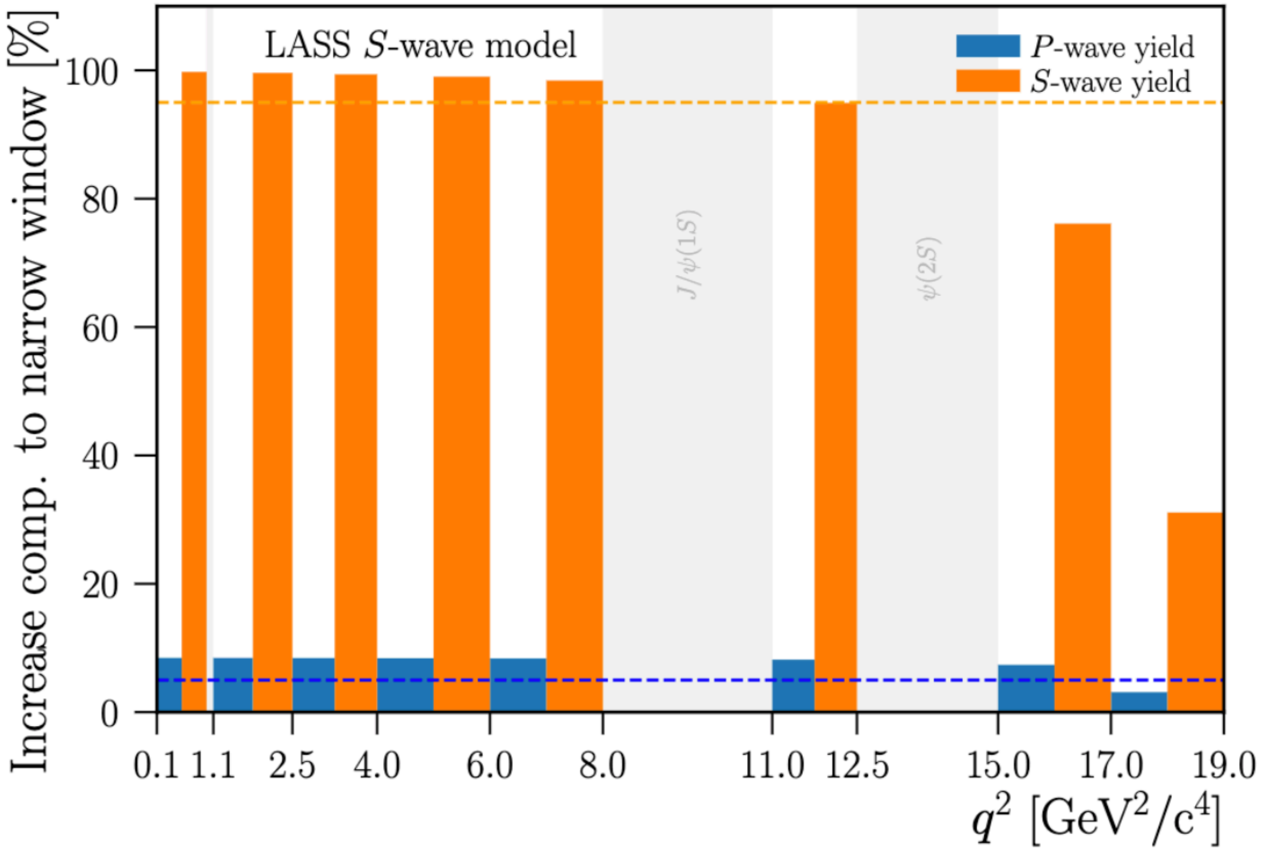
# Towards publishing the full Run 2 dataset

- Add 2017 and 2018 data
- Excepted to more than double signal yields compared to Run 1+ 2016 analysis

# Improving selection

- ➤ Improved selection: peaking backgrounds more suppressed for similar/better signal efficiency => widen $m_{K\pi}$ window!





- ➤ Gain in yield (right) most significant in S-wave

# Improving PDF: Fitting for asymmetries

- The last analysis fitted only for CP-averaged angular observables
- Include CP-average and CP-asymmetric observables in PDF *simultaneously*

$$\left.\frac{\mathrm{d}^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\right|_{\mathrm{P}} = \frac{9}{32\pi}\sum_i \boxed{I_i(q^2)}\, f_i(\vec{\Omega})$$

$$S_i = (I_i + \bar{I}_i)\Big/\left.\frac{\mathrm{d}(\Gamma + \bar{\Gamma})}{\mathrm{d}q^2}\right|_{\mathrm{P}}$$

$$A_i = (I_i - \bar{I}_i)\Big/\left.\frac{\mathrm{d}(\Gamma + \bar{\Gamma})}{\mathrm{d}q^2}\right|_{\mathrm{P}}$$

$$\boxed{I_i(q^2) = \left.\frac{\mathrm{d}(\Gamma + \bar{\Gamma})}{\mathrm{d}q^2}\right|_{\mathrm{P}} \times \tfrac{1}{2}(S_i + A_i)}$$

$$\bar{I}_i(q^2) = \left.\frac{\mathrm{d}(\Gamma + \bar{\Gamma})}{\mathrm{d}q^2}\right|_{\mathrm{P}} \times \tfrac{1}{2}(S_i - A_i)$$

# Improving PDF: [4D + 1D] to 5D

- The decay rate is dependent on $m_{K\pi}$ as well as $q^2$ and $\vec{\Omega}$
- Include $m_{K\pi}$ dependence into PDF directly
- For P-wave observables (and $F_S$), $m_{K\pi}$ line-shape and $K^*$ amplitudes (i.e. angular observables) factorise
- Interference terms less trivial (split into *Re*, *Im* parts)

$$\begin{aligned}\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\bigg|_{\mathrm{P+S}}\frac{\mathrm{d}^5\overleftrightarrow{\Gamma}}{\mathrm{d}q^2\,\mathrm{d}m_{K\pi}\,\mathrm{d}\vec{\Omega}} =& (1-F_{\mathrm{S}})\frac{9}{32\pi}\sum_{i\,\in\,\text{P-wave}}\tfrac{1}{2}(S_i\pm A_i)f_i(\vec{\Omega})|\mathcal{BW}_{\mathrm{P}}(m_{K\pi})|^2\\ &+\frac{3}{16\pi}\sum_{i\,\in\,10,12}\tfrac{1}{2}(S_i\pm A_i)f_i(\vec{\Omega})|\mathcal{BW}_{\mathrm{S}}(m_{K\pi})|^2\\ &+\frac{3}{16\pi}\sum_{i\,\in\,\text{interference}}\tfrac{1}{2}(S_i^{\alpha_i}\pm A_i^{\alpha_i})f_i(\vec{\Omega})\mathrm{Re}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]\\ &+\frac{3}{16\pi}\sum_{i\,\in\,\text{interference}}\tfrac{1}{2}(S_i^{\alpha_i}\pm A_i^{\alpha_i})f_i(\vec{\Omega})\mathrm{Im}[\mathcal{BW}_{\mathrm{S}}(m_{K\pi})\mathcal{BW}^*_{\mathrm{P}}(m_{K\pi})]\end{aligned}$$

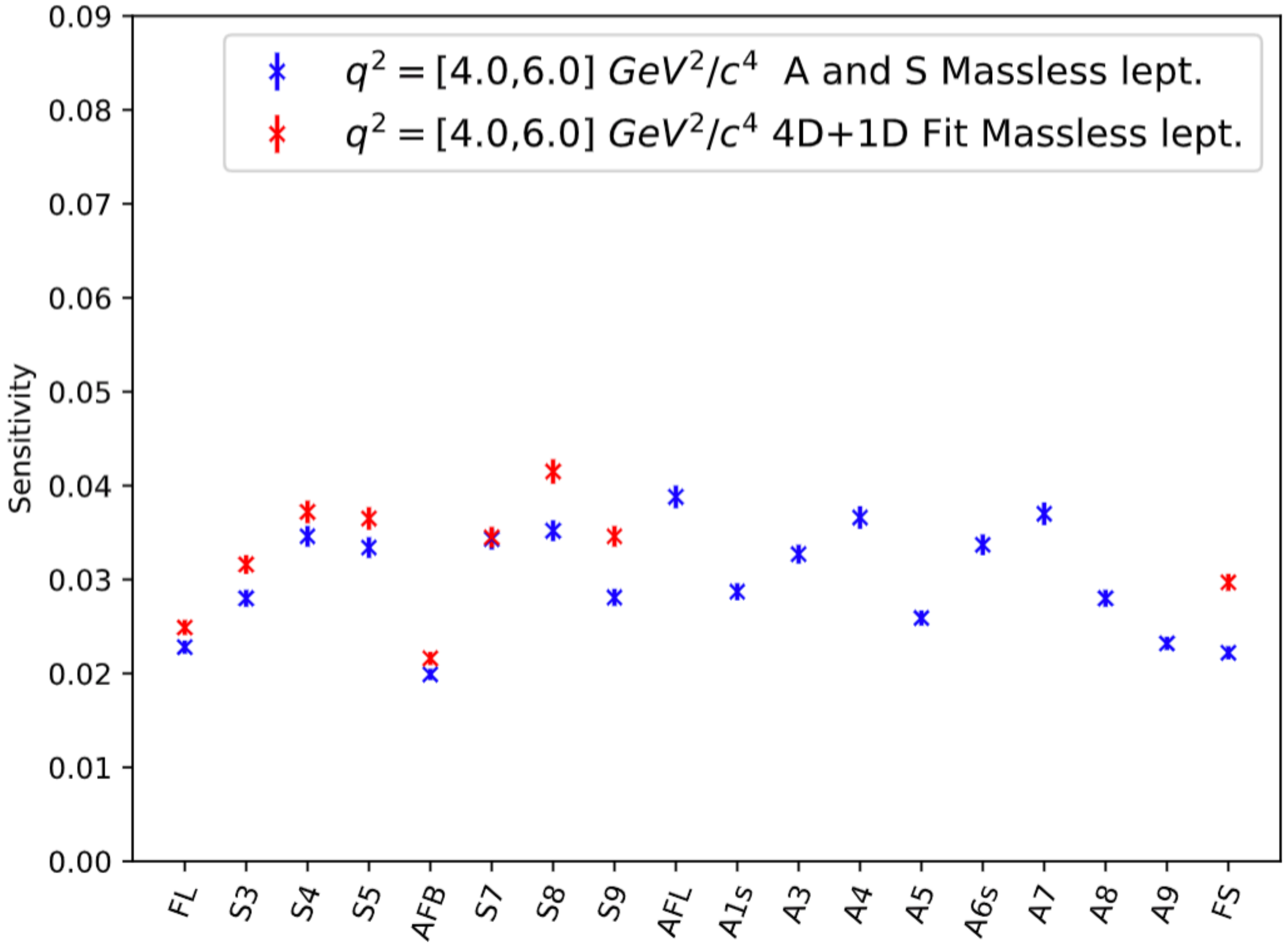
where $\alpha_i \in \mathrm{Im}, \mathrm{Re}$, dependent on observable

# Comparison to old PDF

- ➤ Compare sensitivity when changing **just the PDF** (i.e. same selection/yields used to evaluate both PDFs)

4D + 1D & just CP-averaged observables

5D & both CP-averaged and CP-asymmetric observables



☑ **Improved sensitivity (+ added bonus of obtaining correlations between CP-average/asymmetric observables)**

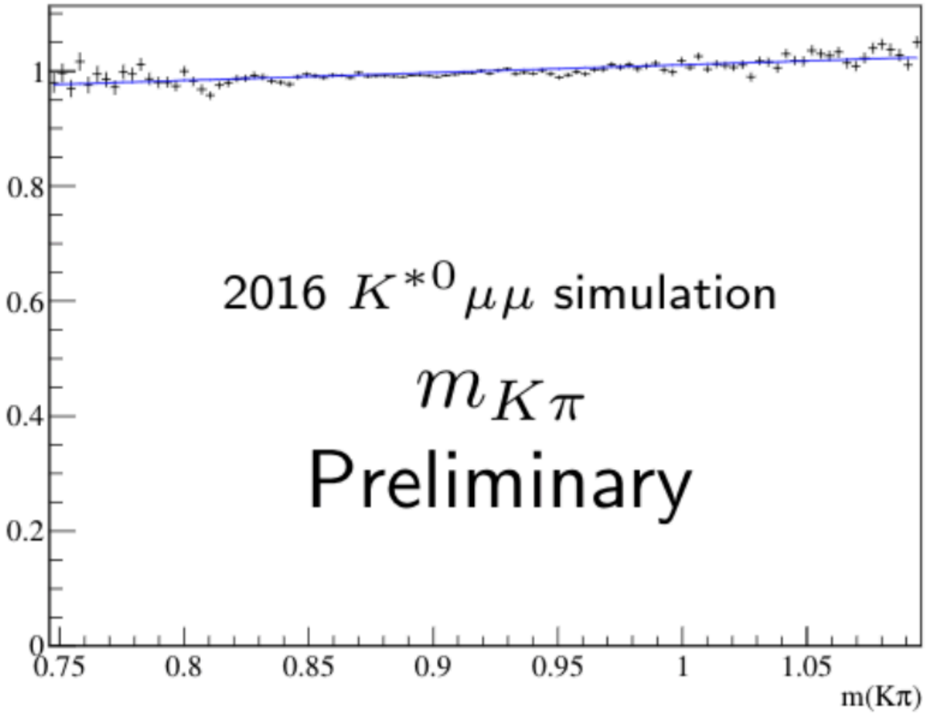
# Other improvements

- Perform angular acceptance now in 5D to include $m_{K\pi}$

$$\epsilon = \sum_{k,l,m,n,o} c_{klmno} P(cos(\theta_l), k) P(cos(\theta_K), l) P(\phi, m) P(q^2, n) P(m(K\pi), o)$$

1D projection of 5D acceptance onto $m_{K\pi}$

Not flat, but well within systematic assigned to last analysis



- Allow for massive leptons in the first $q^2$ bin

# Conclusions

- Angular analyses provide access to theoretically clean observables
- Ongoing tensions seen in $B^0 \rightarrow K^{*0}\mu^+\mu^-$observables
- These tensions are confirmed with 2016 data
- The exact significance of the discrepancy depends on the nuisance parameters chosen and $q^2$ bins fitted
- Update with full Run 2 is underway
- We are pulling out all the stops to make sure this updated "legacy" analysis makes the best possible use of the available data