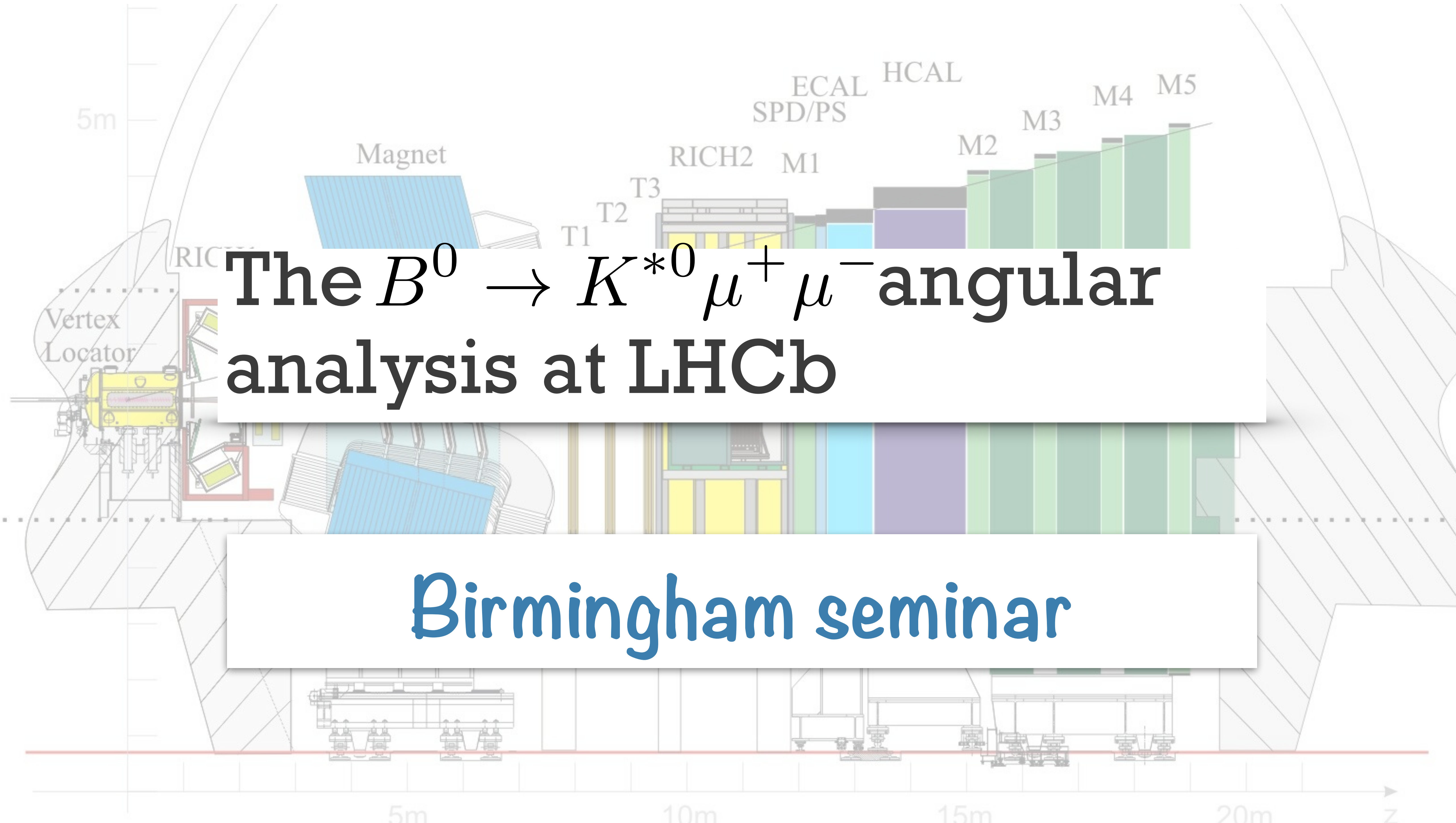


The $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis at LHCb

Birmingham seminar

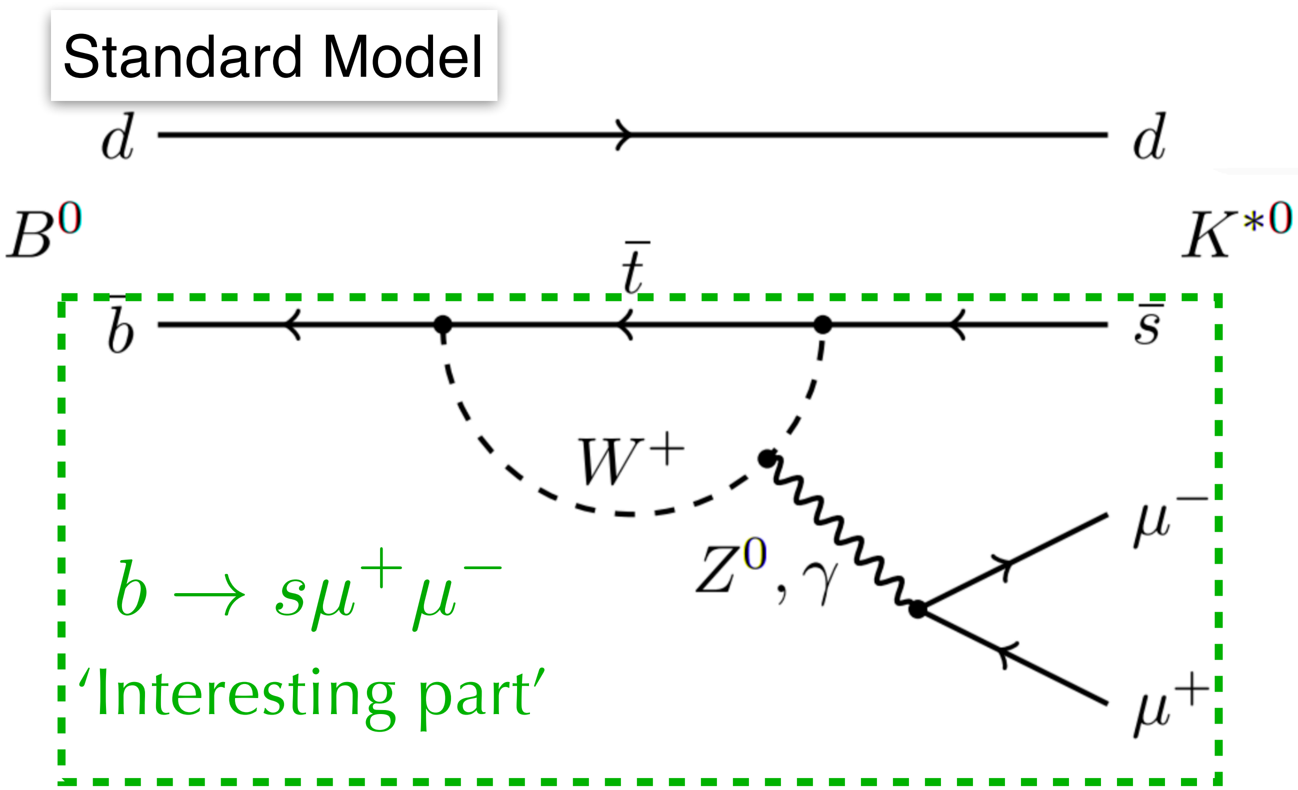
Eluned Smith

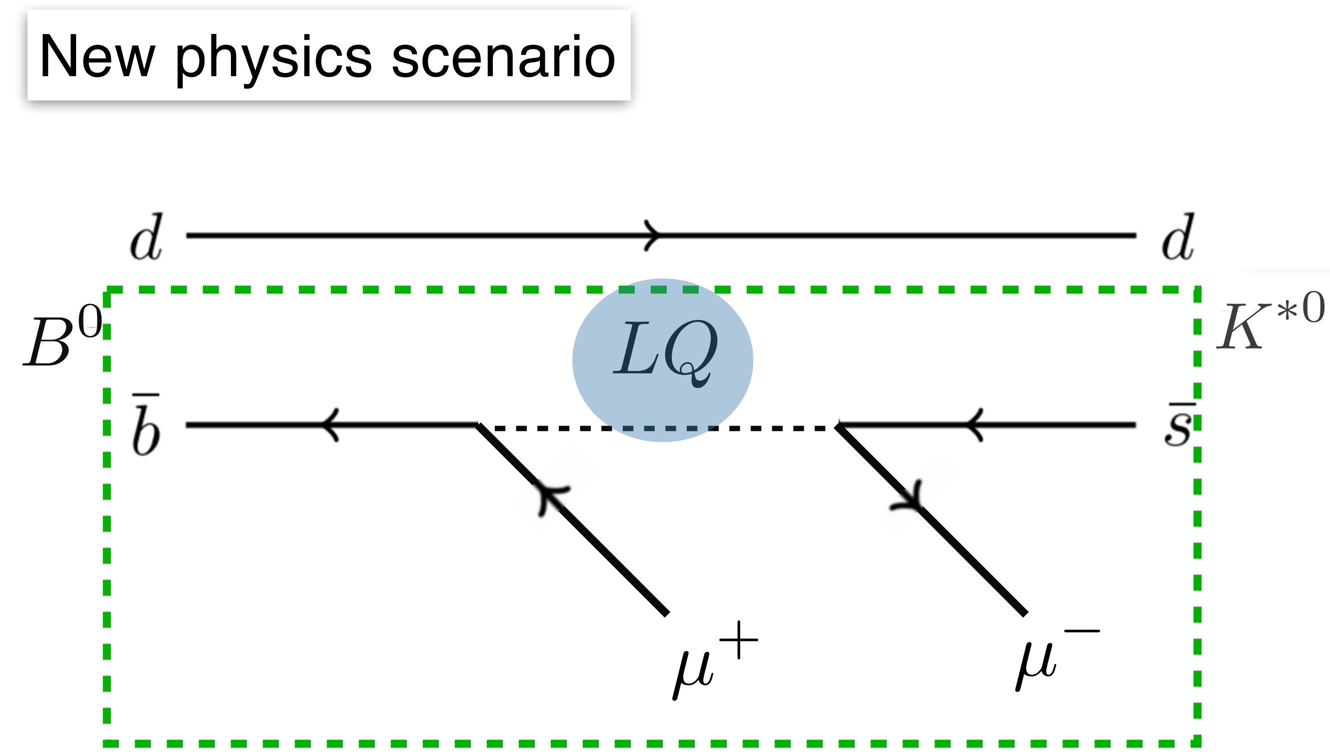
25/11/2020

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

LHCb

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



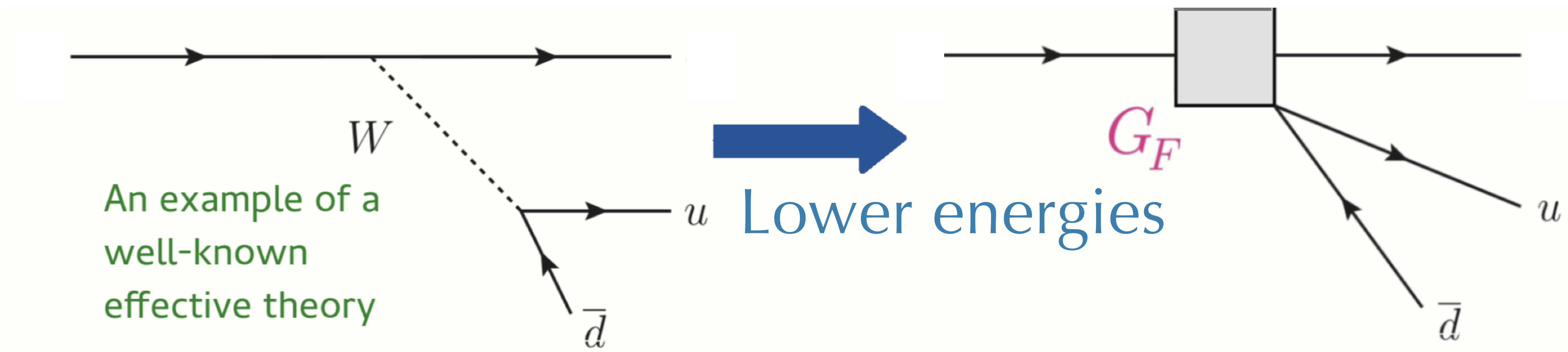


- A $b \to s\mu^+\mu^-$ transition requires a **flavour-changing neutral current** ⇨ forbidden at tree-level in the Standard Model (SM)
- **As suppressed in the SM** more sensitive to **New Physics (NP)**
- As NP particles appear virtually can probe heavier NP scales than those accessible via direct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

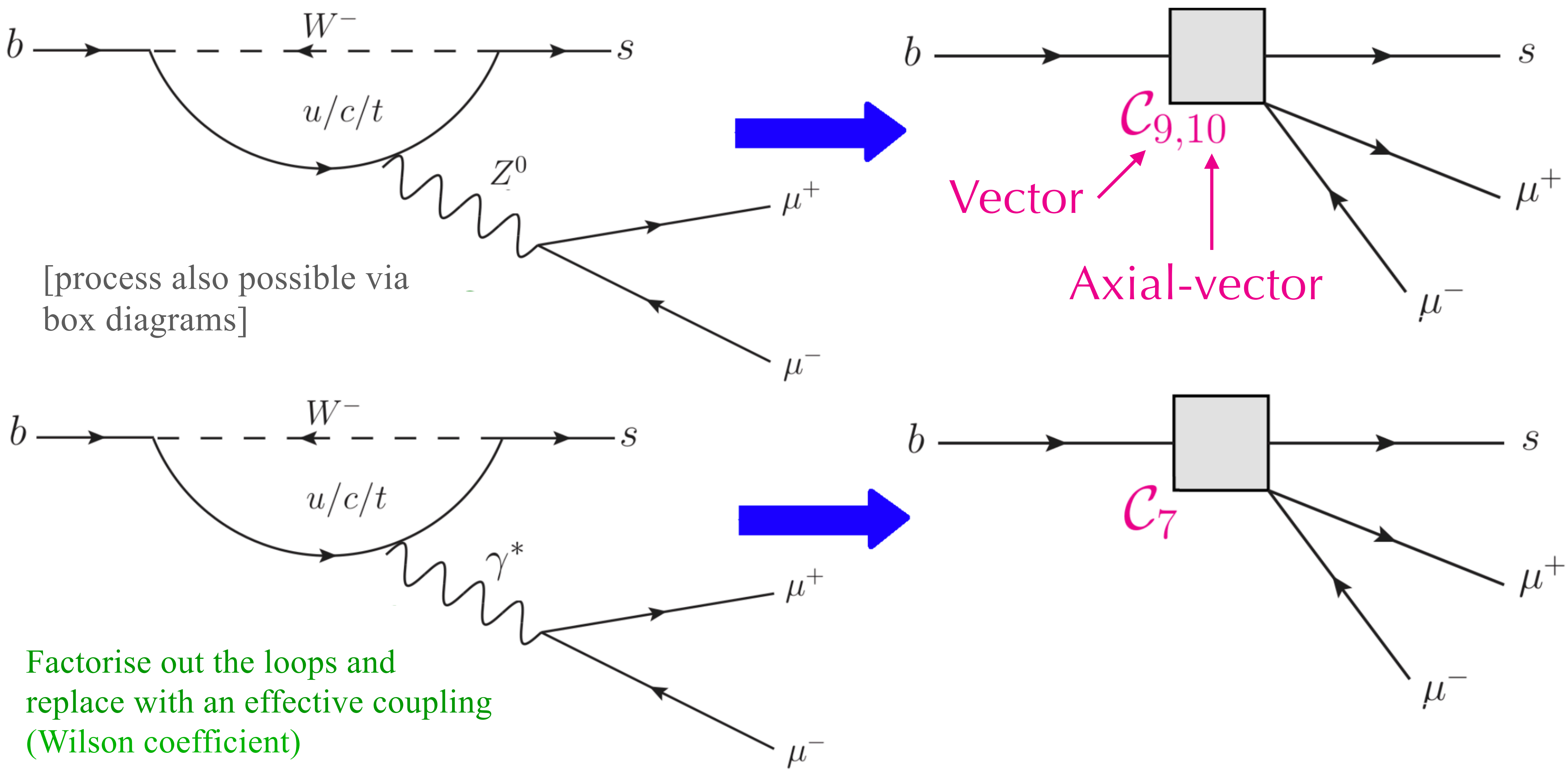
$b \to s\mu^+\mu^-$ transitions in effective theory

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



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

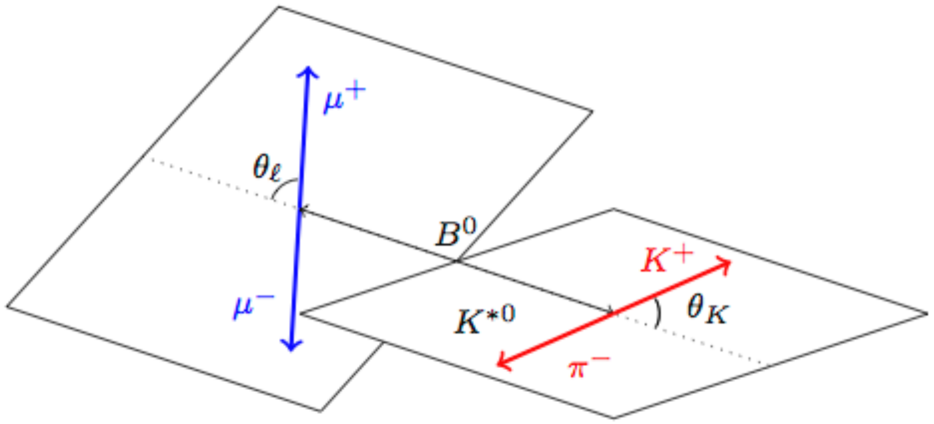
$b \to s\mu^+\mu^-$ transitions in effective theory

- 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.

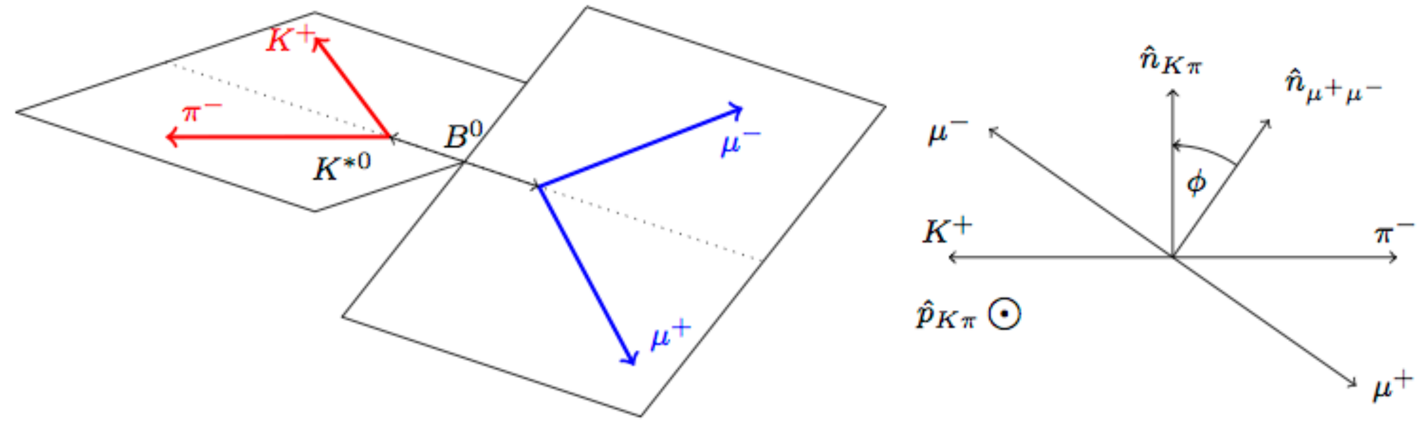
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

This is what we want to access….

Local operators describe non-perturbative QCD, large theory uncertainties



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

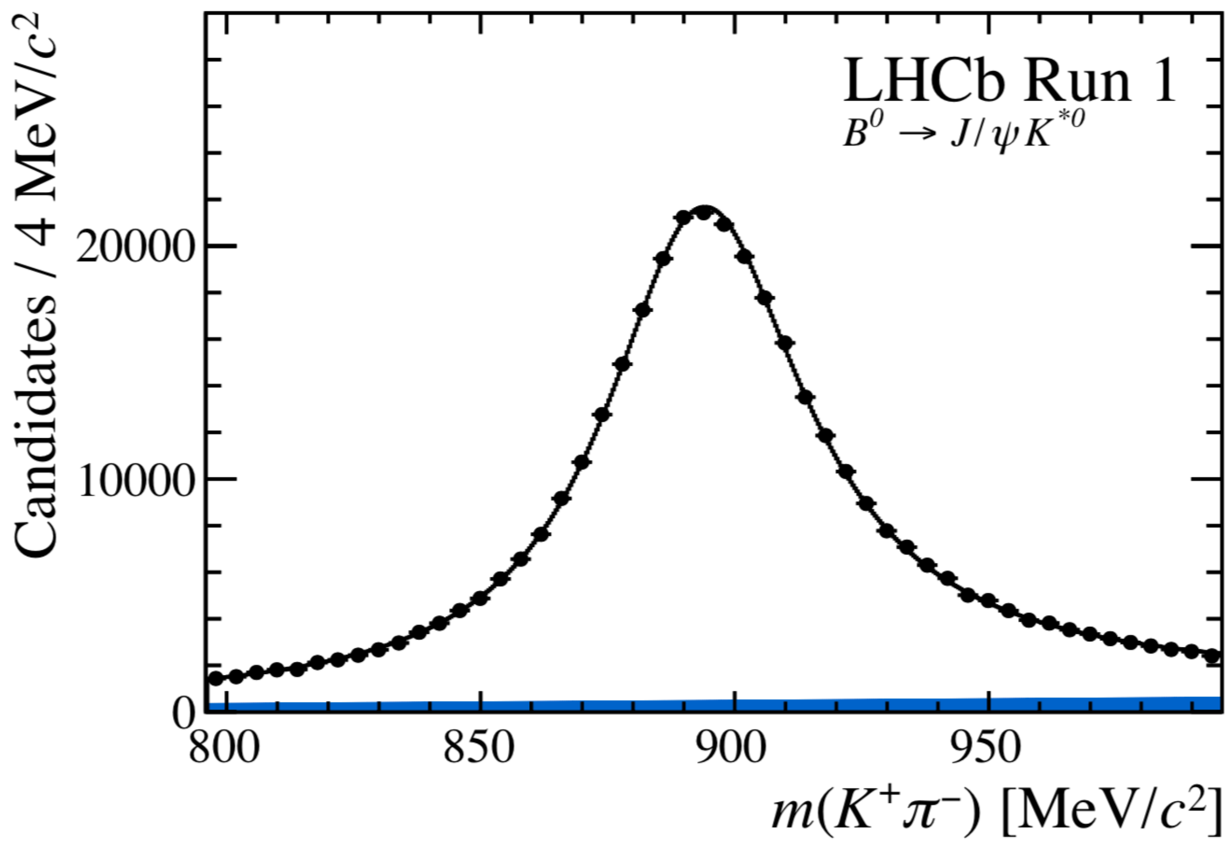


(b) ϕ definition for the B^0 decay

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'

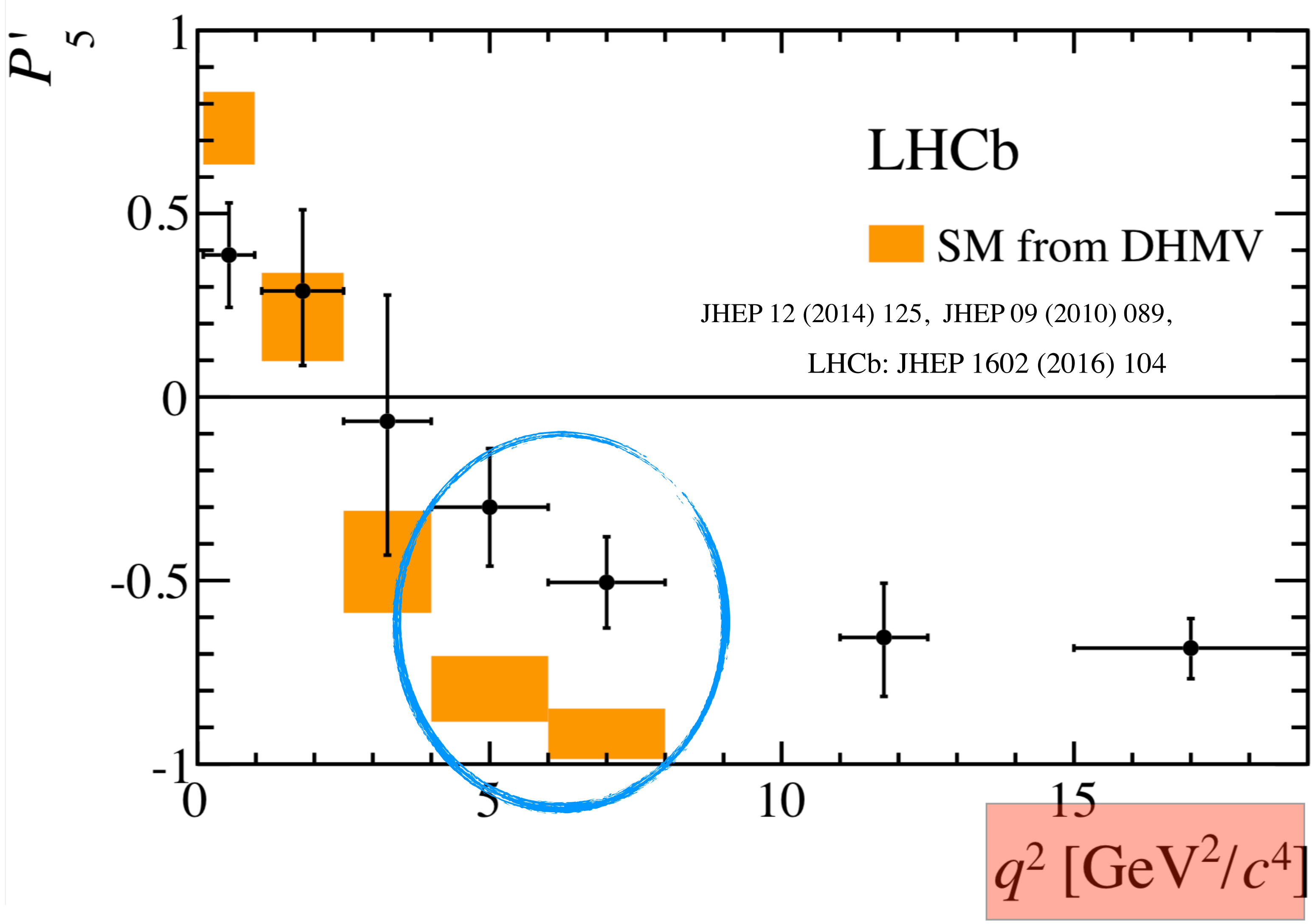
Run1 LHCb data only: 2016 publication

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

Local tension: 2.8σ

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

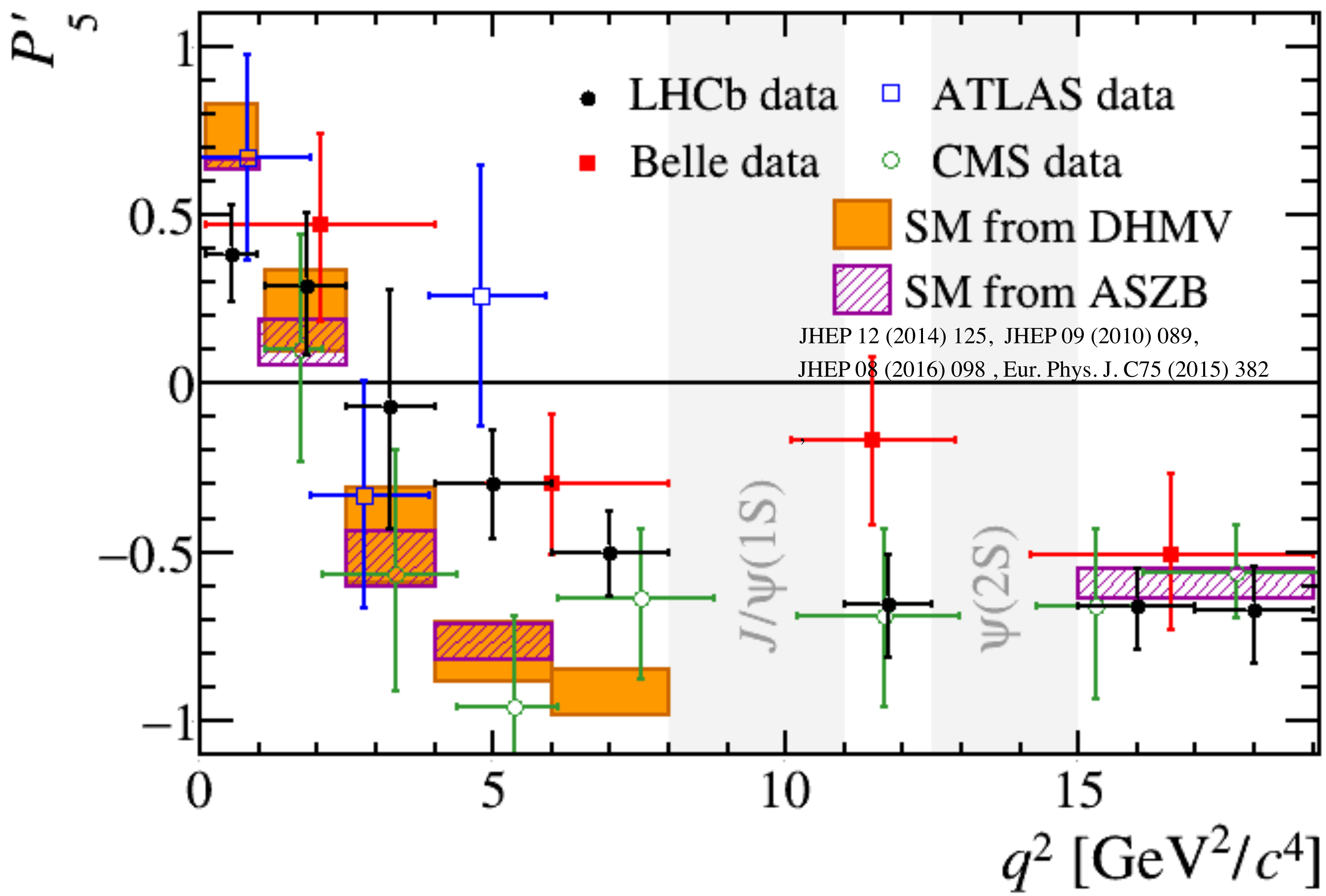
Local tension: 3.0σ



Dimuon mass squared

Distinctive local tension in P'_5

Angular analysis also performed by other collaborations



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

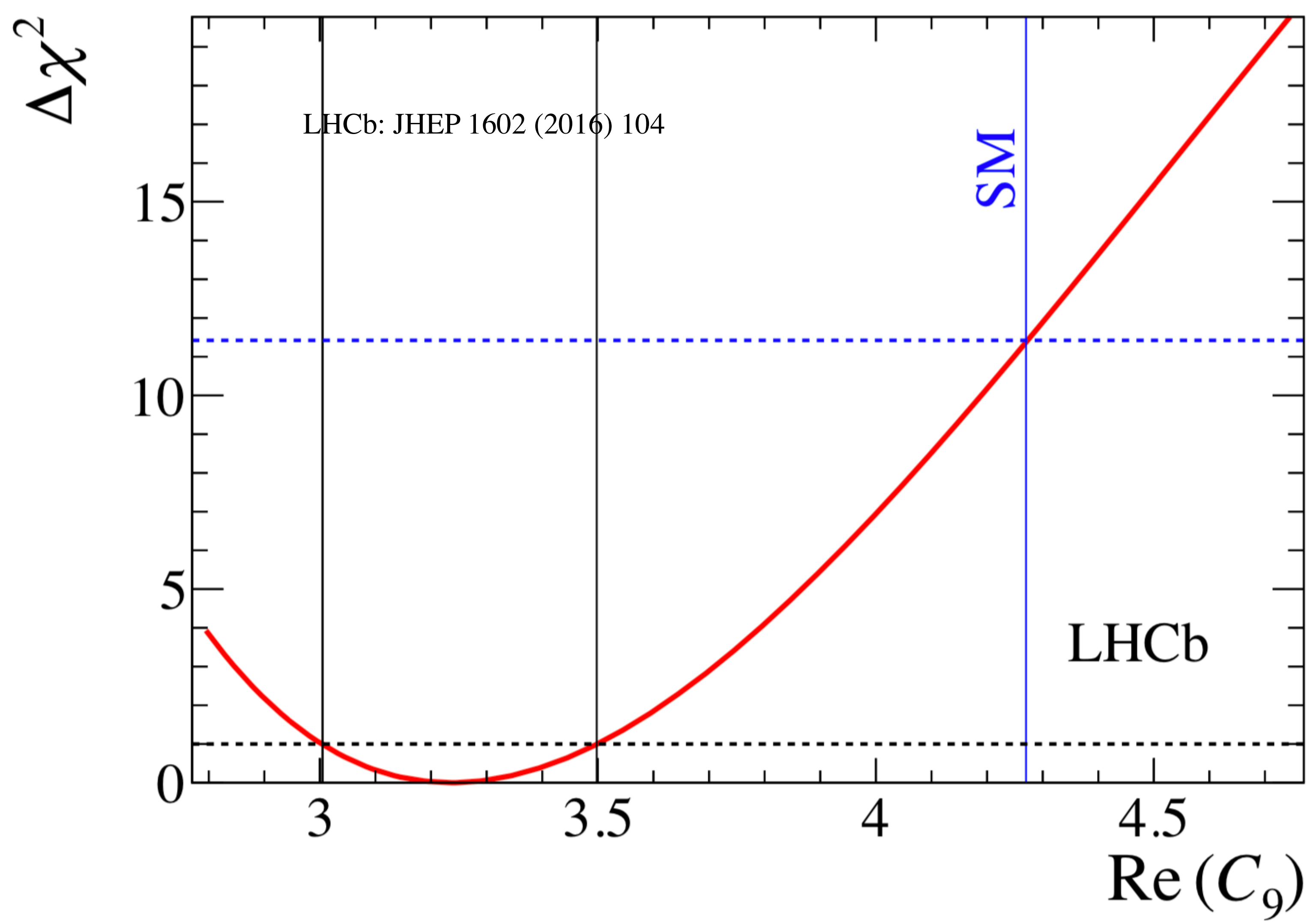
Run1 LHCb data only

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

Overall tension seen with the SM

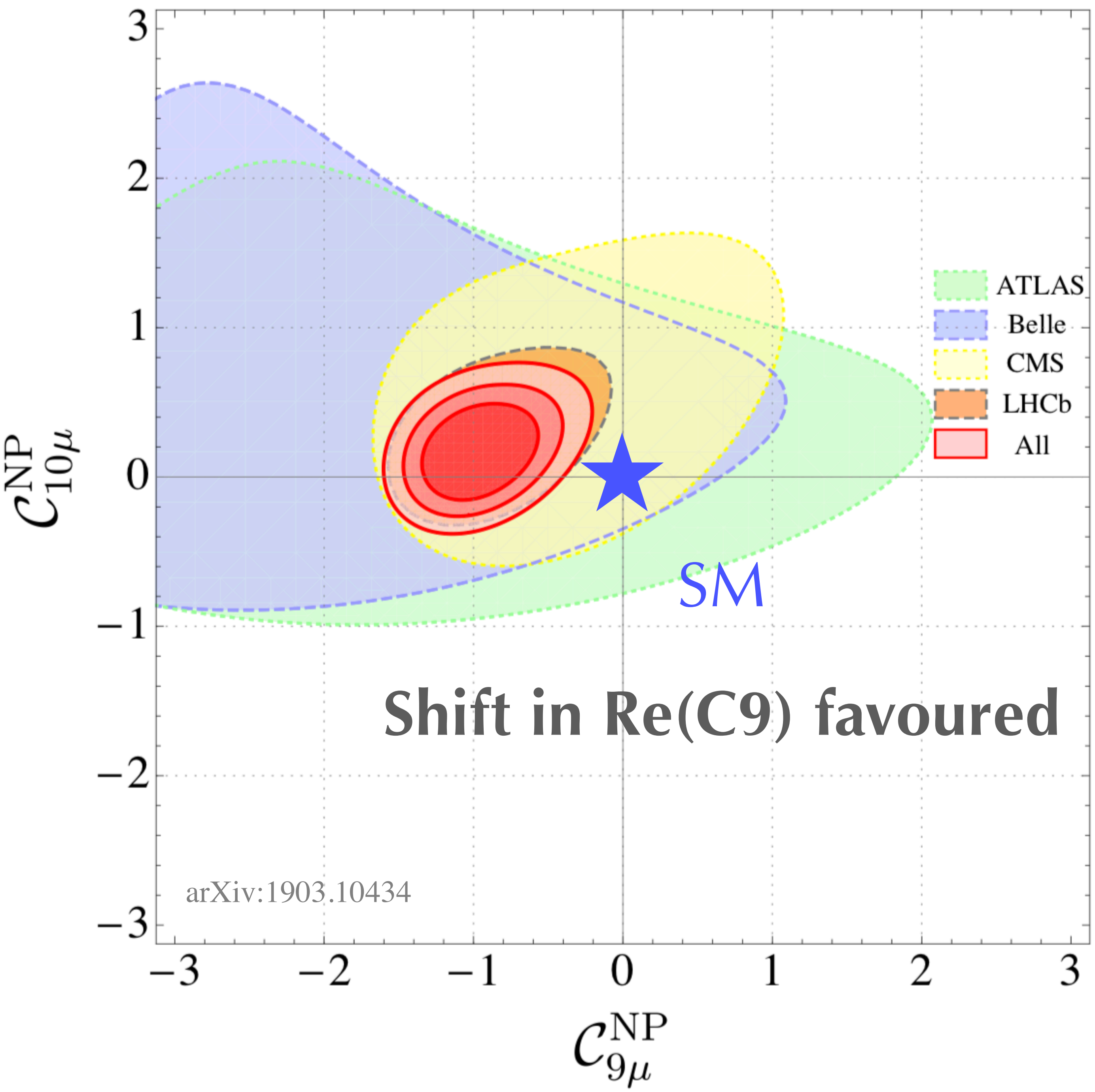
The value of the Wilson Coefficient $Re(C_9)$ obtained from the Run 1 result was 3.4σ (p-value:~0.0008) from the SM prediction when assuming the observations could be explained with a shift in $Re(C_9)$ alone.

3.4σ



Run1 LHCb data only

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



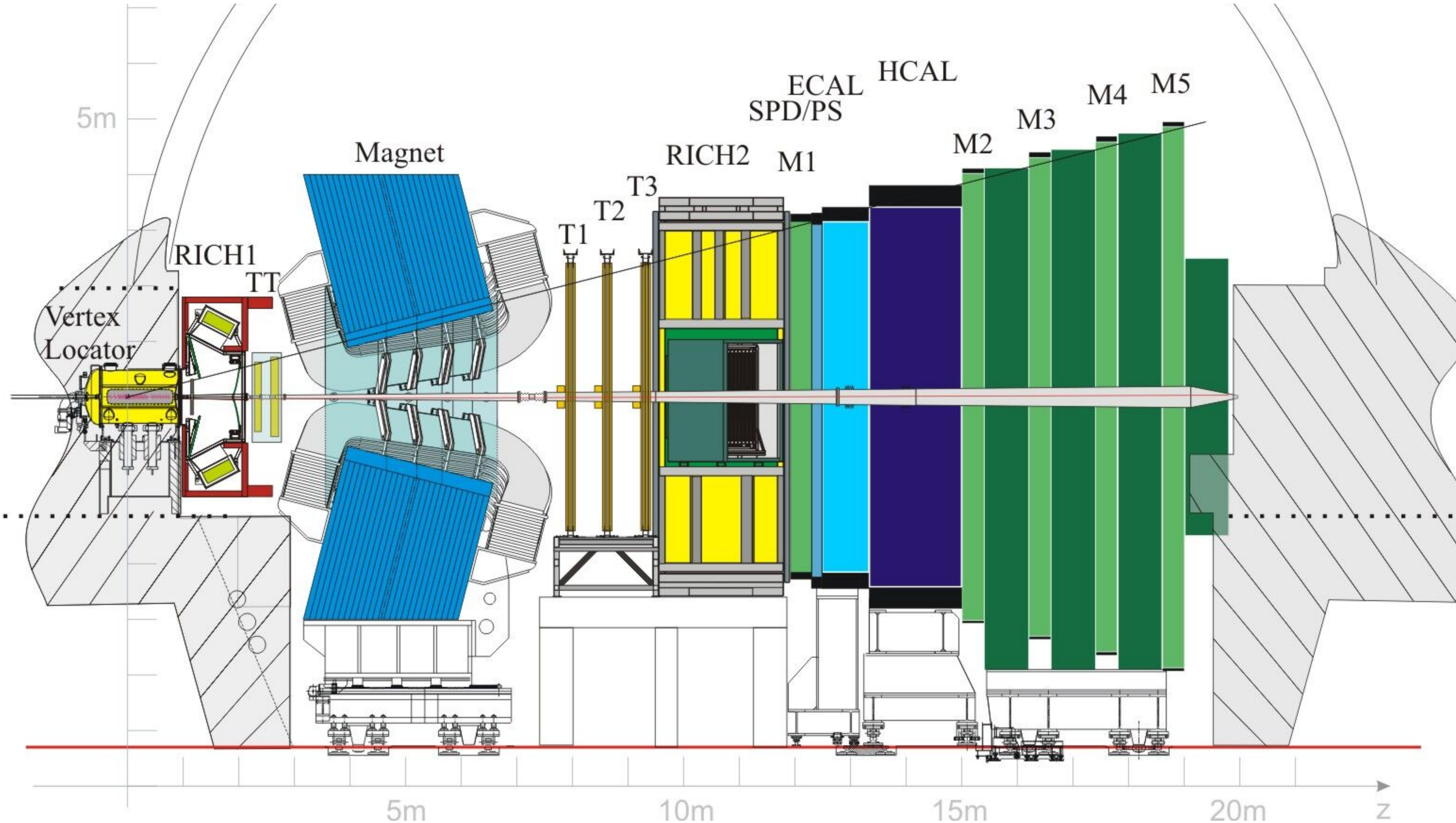
- Global fits performed to a **complete set of** $b \to sll$ **measurements** (rates, angular distributions)
- Fits yield up to 3-5 σ deviations in Wilson coefficients[*]
- Many global fits out there!

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

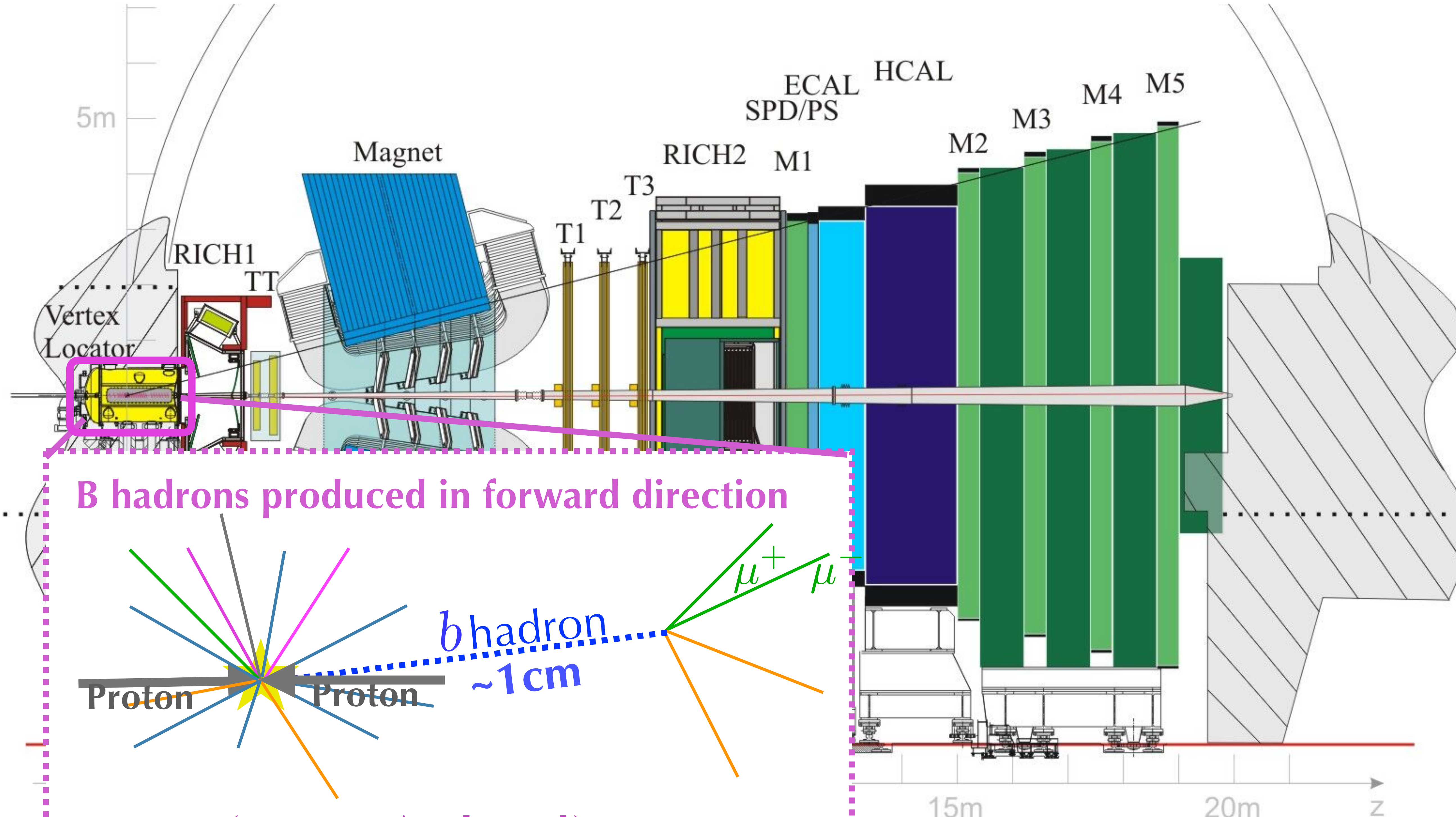
The LHCb detector

The LHCb experiment



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

The LHCb experiment

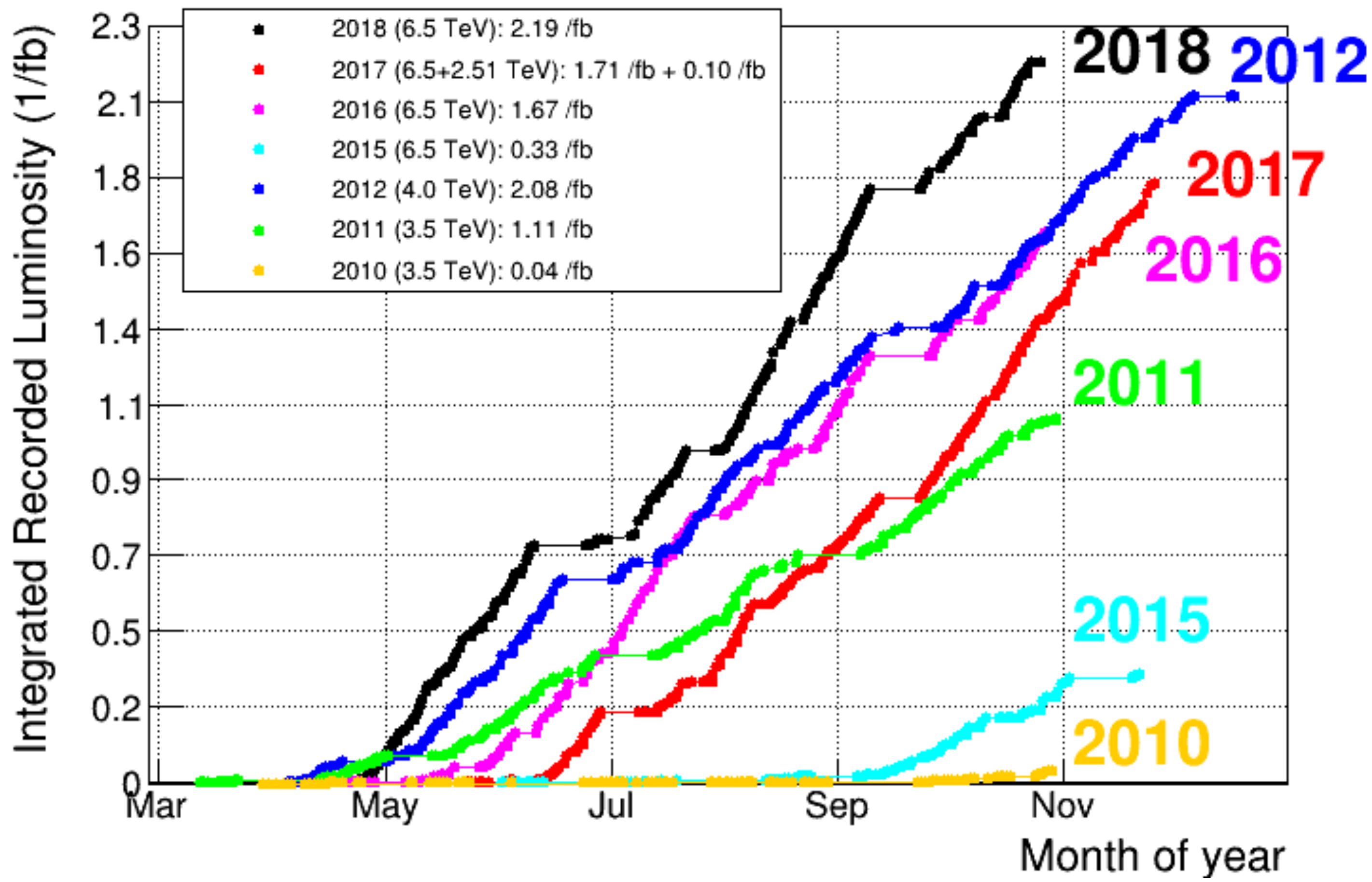


$$\sigma_{IP} = (15 + 29/p_T[\mathrm{GeV}])\mu\mathrm{m}$$

The data set

Data-taking during Run 1 + 2

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

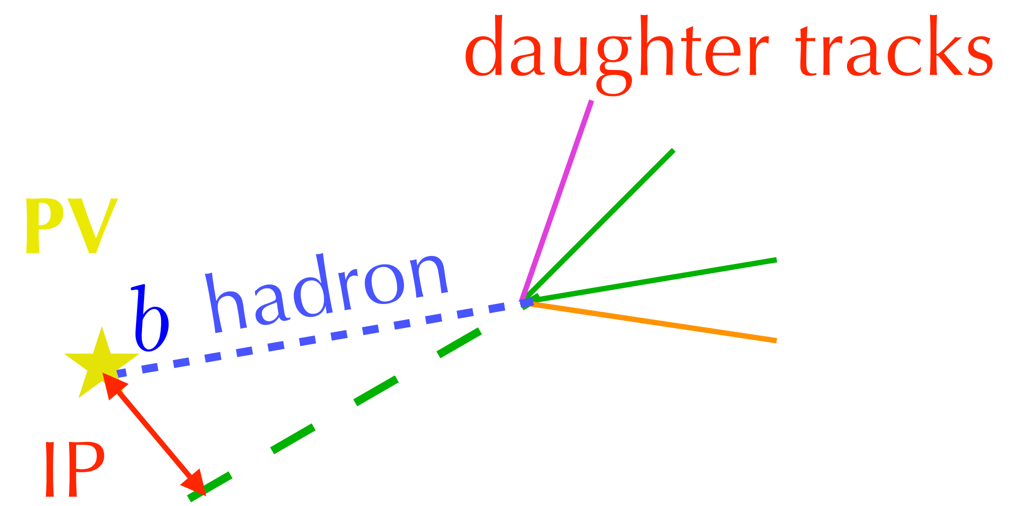


2011, 2012 and 2016 data collected from proton-proton collisions with centre of mass energies of $\sqrt{s}$ = 7,8 and 13 TeV respectively

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



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

- 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*

Examples of peaking backgrounds

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

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

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

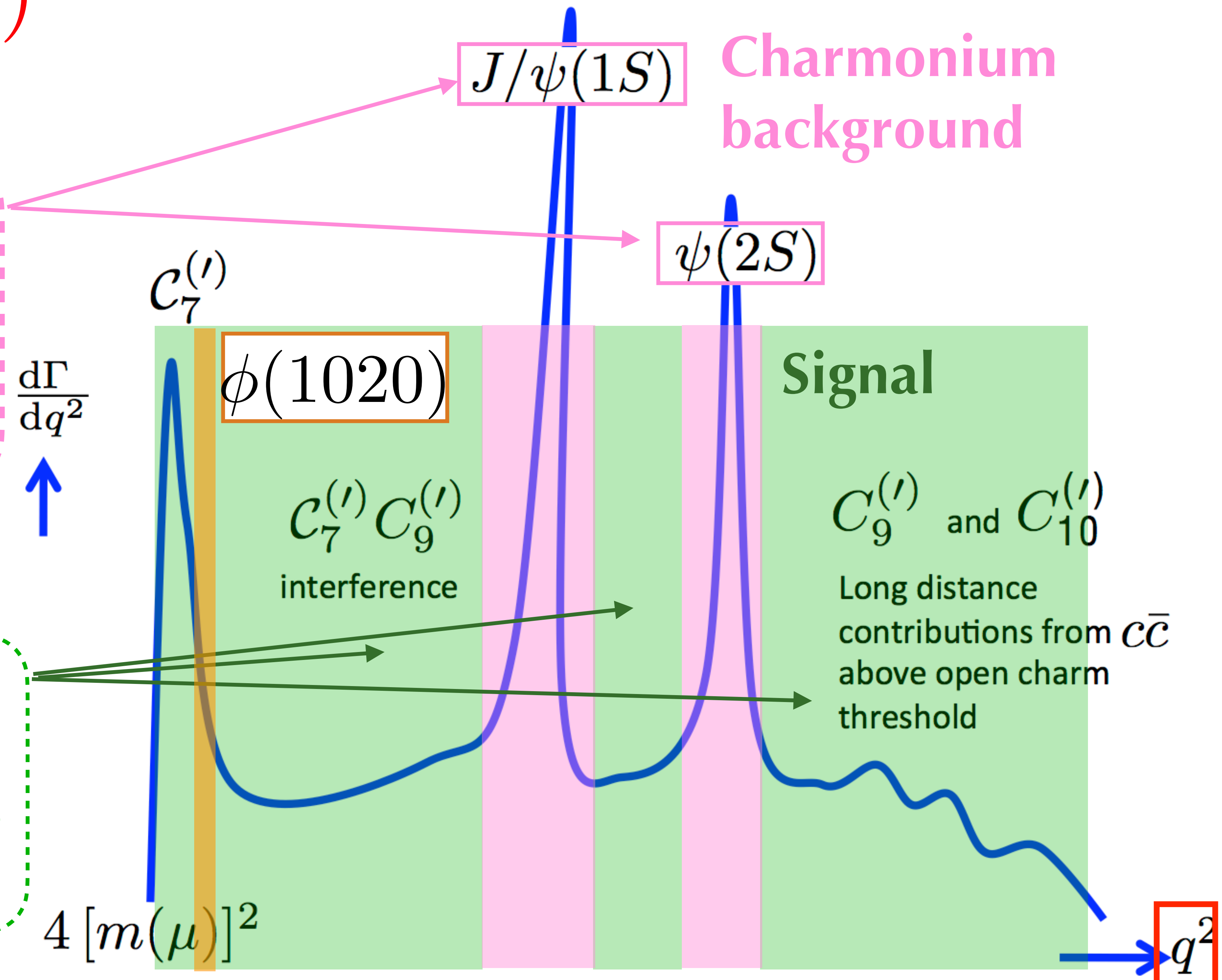
$\to$ = Misidentification

The regions we probe in q^2

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

$b \to s[c\bar{c} \to \mu\mu]$ decays
same final state as signal
Veto

$b \to s\mu\mu$ decays: signal
Look at signal in these q^2 regions



Binning in q^2

Narrow 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	$[15.0, 19.0]$

Wide bins

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

Control channel

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

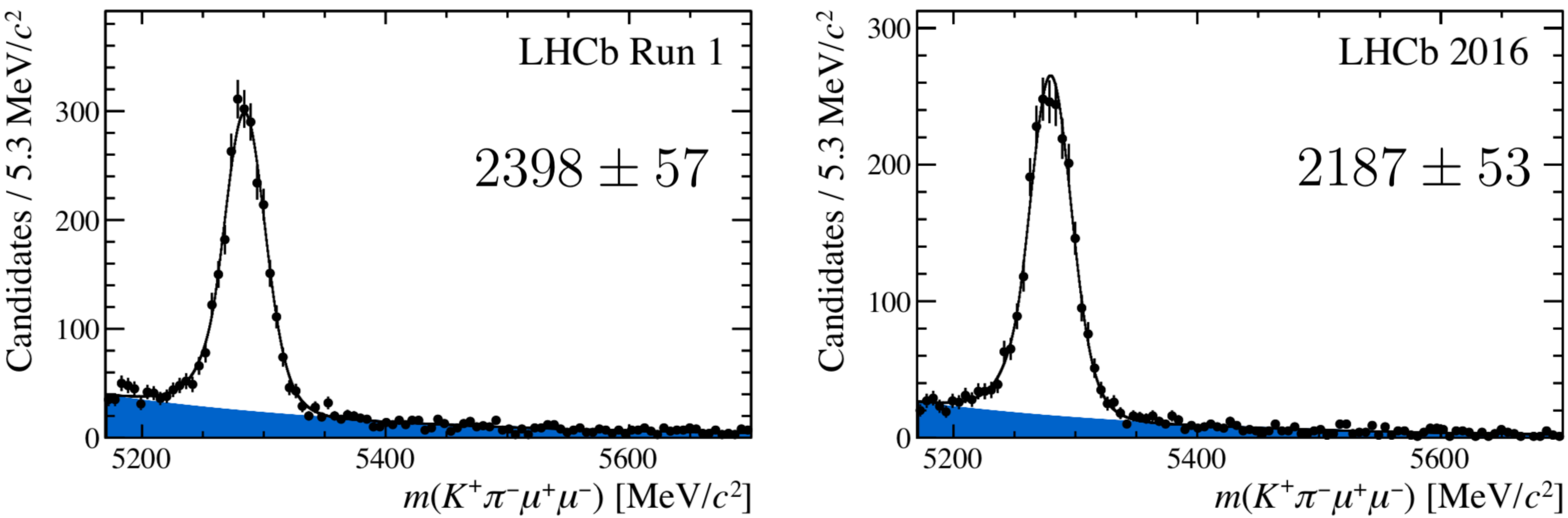
$B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-)$

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

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

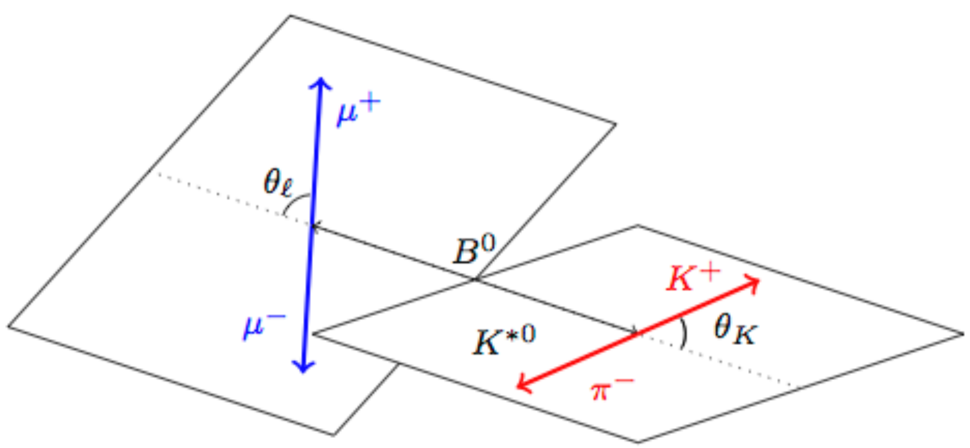
Remaining background is combinatorial only

Angular description of the decay

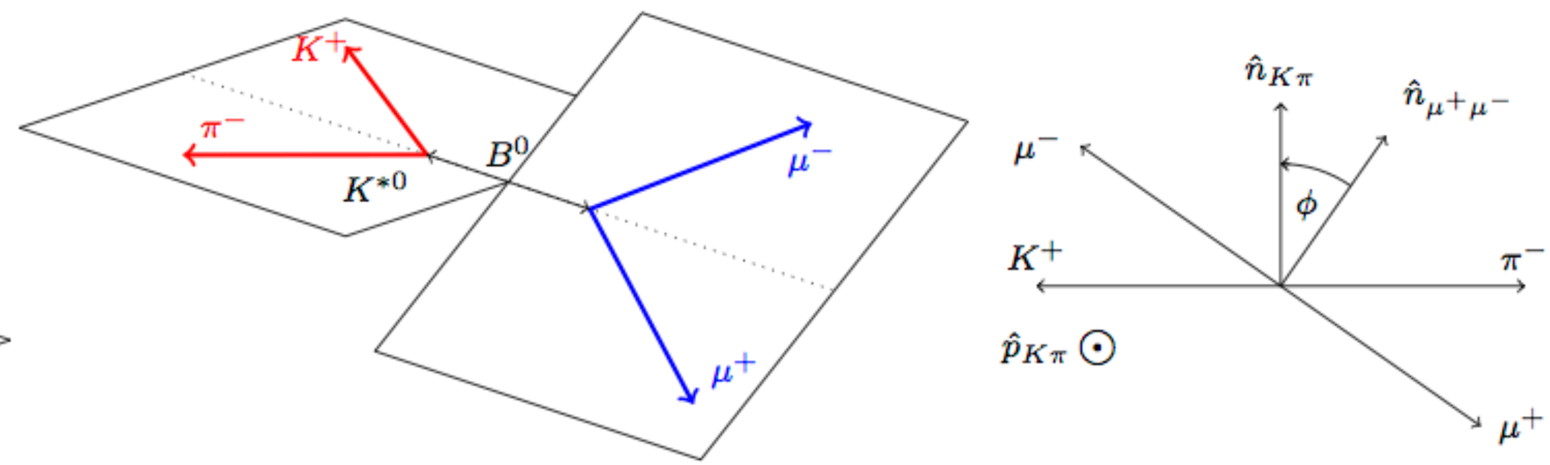
$B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$ angular description

- Decay rate fully described by:

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



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



(b) ϕ definition for the B^0 decay

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

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	$\frac{3}{4}\left[\|\mathcal{A}_\parallel^{\rm L}\|^2 + \|\mathcal{A}_\perp^{\rm L}\|^2 + \|\mathcal{A}_\parallel^{\rm R}\|^2 + \|\mathcal{A}_\perp^{\rm R}\|^2\right]$	$\sin^2\theta_K$
1c	$\|\mathcal{A}_0^{\rm L}\|^2 + \|\mathcal{A}_0^{\rm R}\|^2$	$\cos^2\theta_K$
2s	$\frac{1}{4}\left[\|\mathcal{A}_\parallel^{\rm L}\|^2 + \|\mathcal{A}_\perp^{\rm L}\|^2 + \|\mathcal{A}_\parallel^{\rm R}\|^2 + \|\mathcal{A}_\perp^{\rm R}\|^2\right]$	$\sin^2\theta_K \cos 2\theta_l$
2c	$-\|\mathcal{A}_0^{\rm L}\|^2 - \|\mathcal{A}_0^{\rm R}\|^2$	$\cos^2\theta_K \cos 2\theta_l$
3	$\frac{1}{2}\left[\|\mathcal{A}_\perp^{\rm L}\|^2 - \|\mathcal{A}_\parallel^{\rm L}\|^2 + \|\mathcal{A}_\perp^{\rm R}\|^2 - \|\mathcal{A}_\parallel^{\rm R}\|^2\right]$	$\sin^2\theta_K \sin^2\theta_l \cos 2\phi$
	…	…

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

Where the physics lies:

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

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

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

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

JHEP 0901:019,2009

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 → $S_i(q^2_{min}, q^2_{max})$

CP-averaged

S_i basis

8 CP-averaged observables are extracted from the fit

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The full fit model

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

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

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

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

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

- Perform maximum likelihood fit

nuisance parameters

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

angular coefficients

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

The full fit model

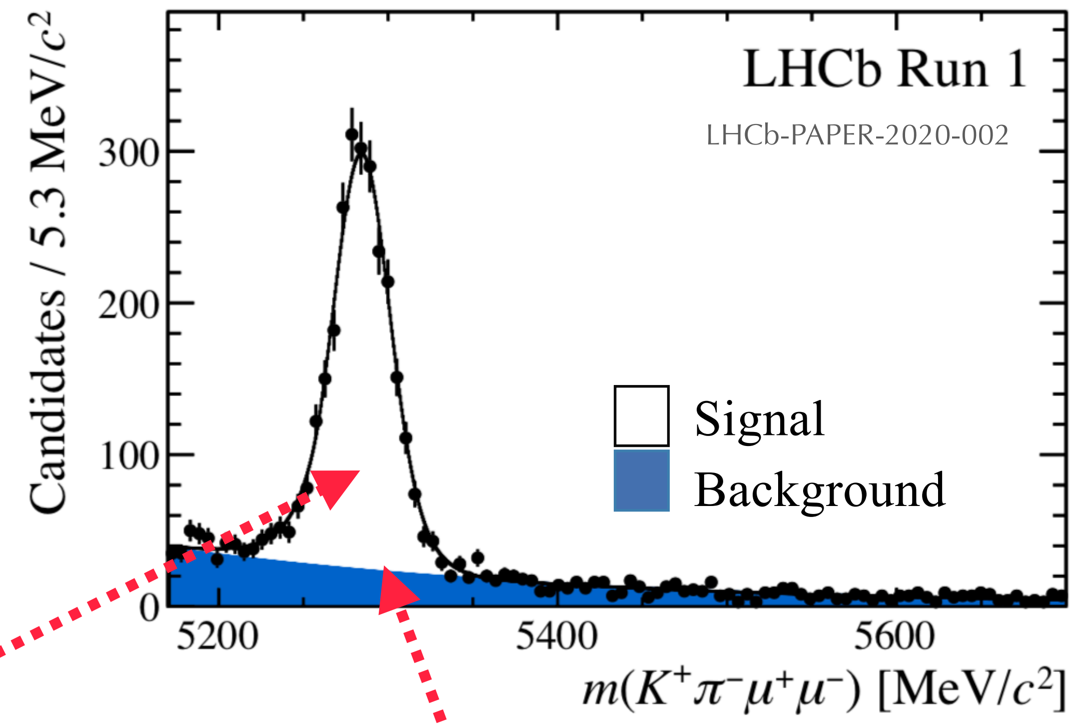
Signal

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

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

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

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

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

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

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

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

2016

shared

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

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

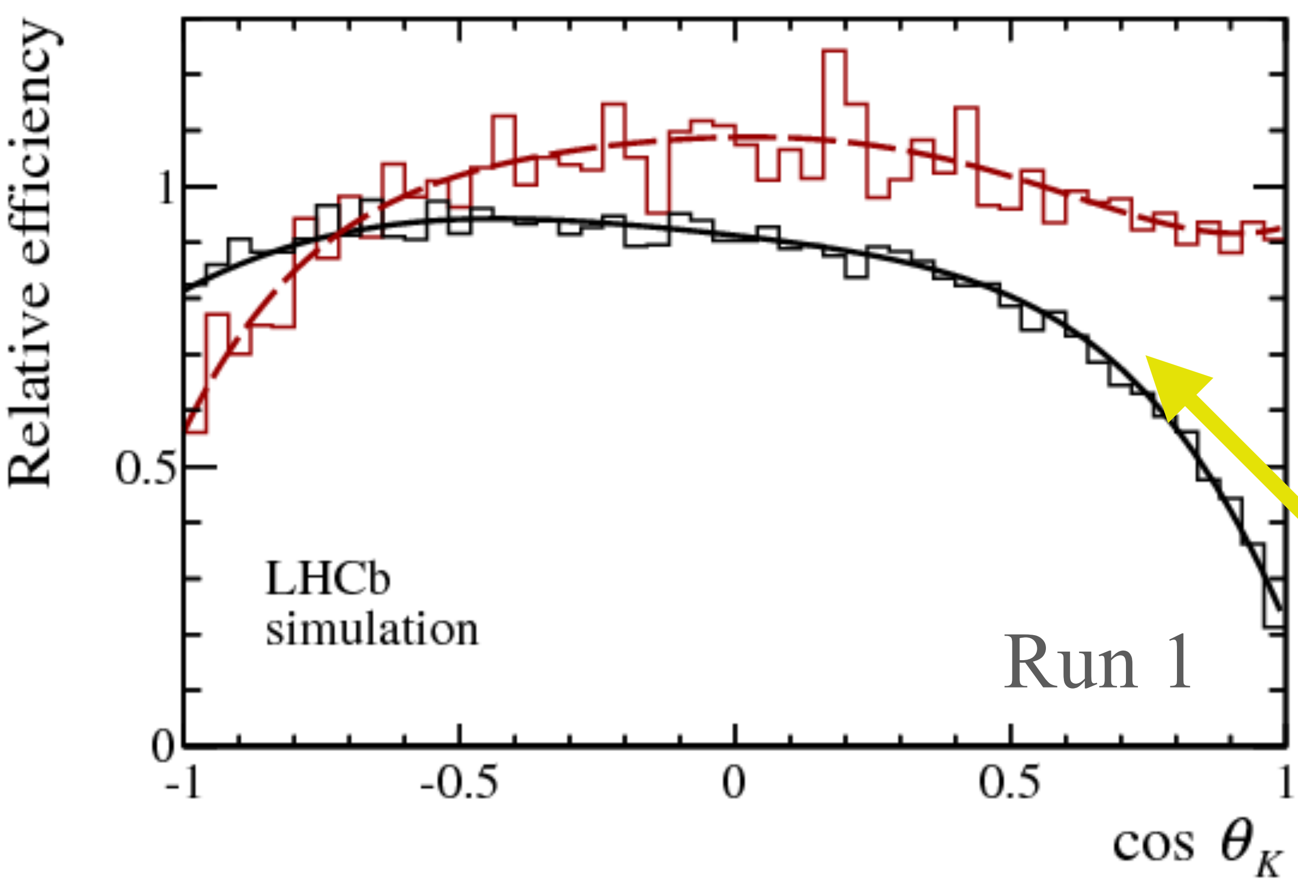
Not shared

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**



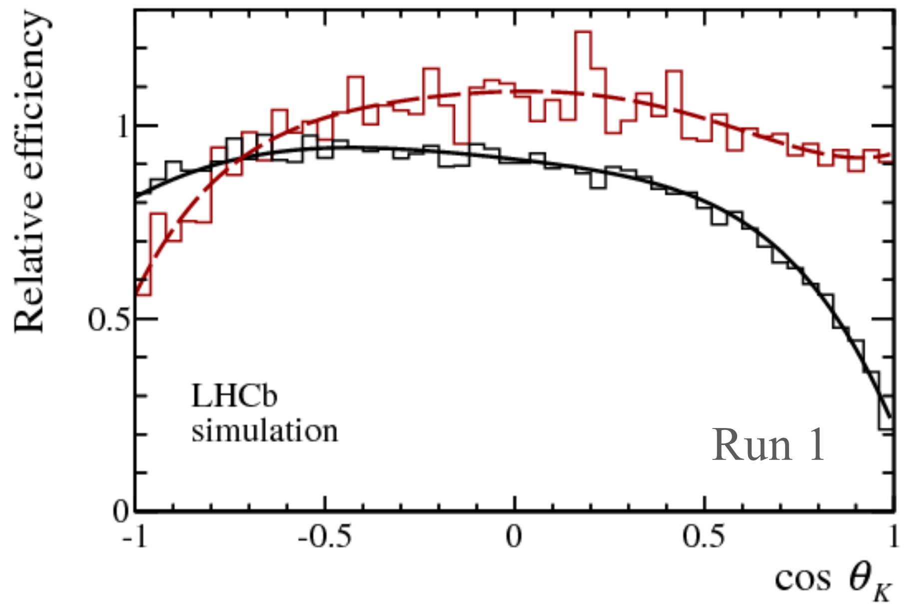
$0.1 < q^2 < 0.98\,\mathrm{GeV}^2/c^4$

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

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 Ω, 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.

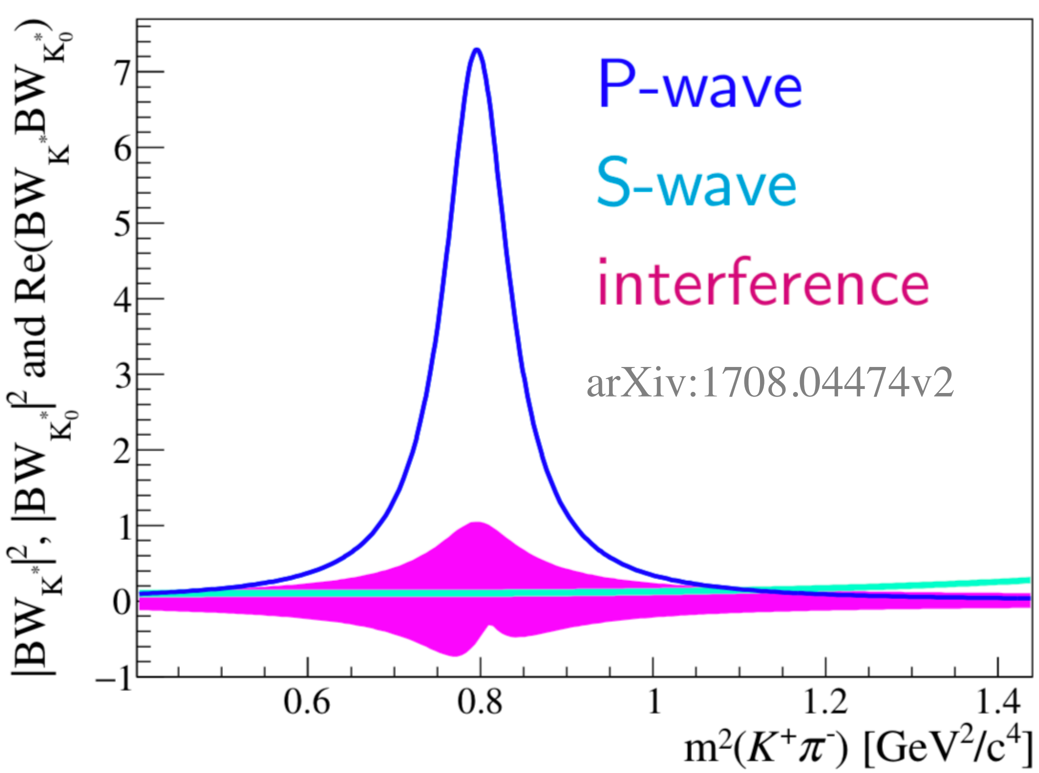
The S-wave component

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

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

$$+\frac{3}{16\pi}\big[F_S\sin^2\theta_l + S_{S1}\sin^2\theta_l\cos\theta_K$$
$$+ S_{S2}\sin 2\theta_l\sin\theta_K\cos\phi$$
$$+ S_{S3}\sin\theta_l\sin\theta_K\cos\phi$$
$$+ S_{S4}\sin\theta_l\sin\theta_K\sin\phi$$
$$+ S_{S5}\sin 2\theta_l\sin\theta_K\sin\phi\big].$$



Systematic uncertainties

Systematic uncertainties

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

Source	$F_{\rm L}$	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

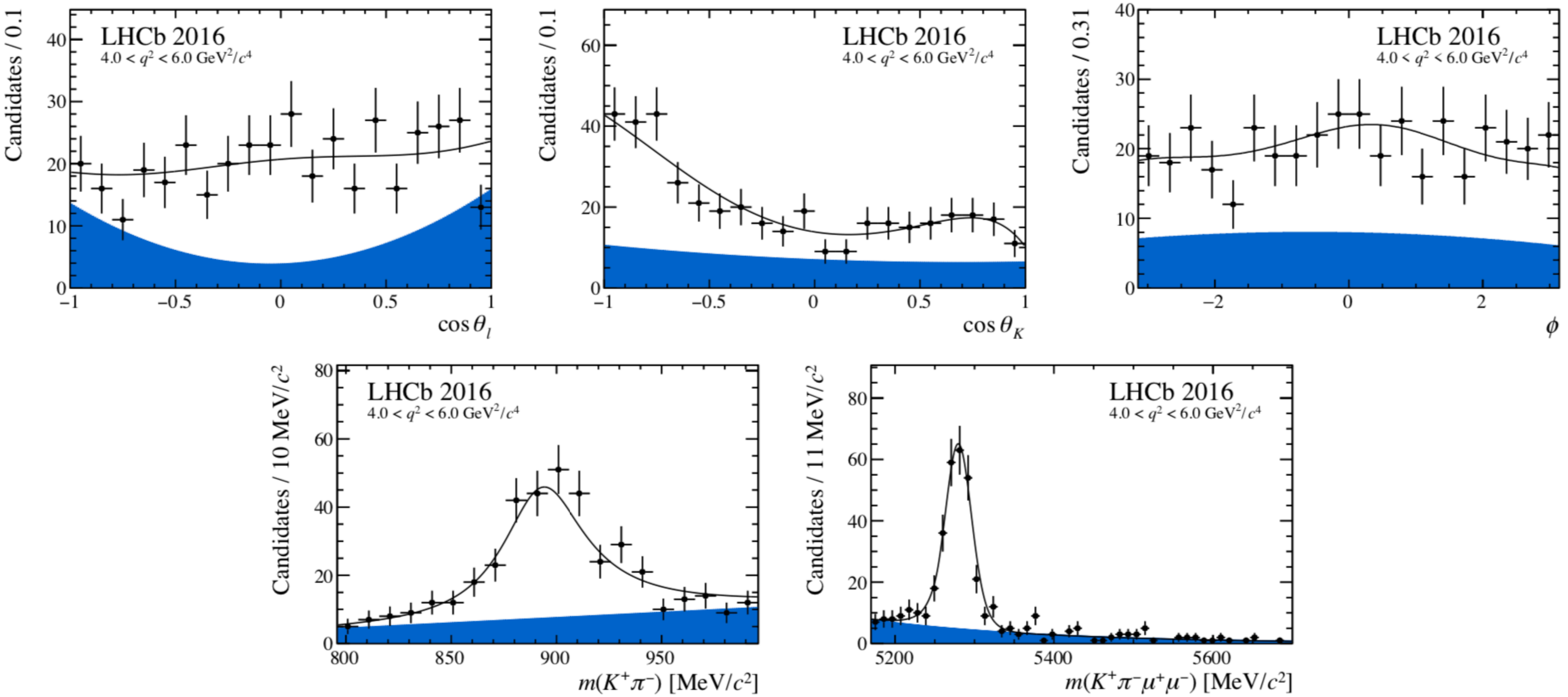
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l \, \mathrm{d}\cos\theta_K \, \mathrm{d}\phi}\bigg|_{\mathrm{S+P}} = (1-F_S) \frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l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

If this term is biased towards smaller values

Magnitude of P-wave biased towards larger values

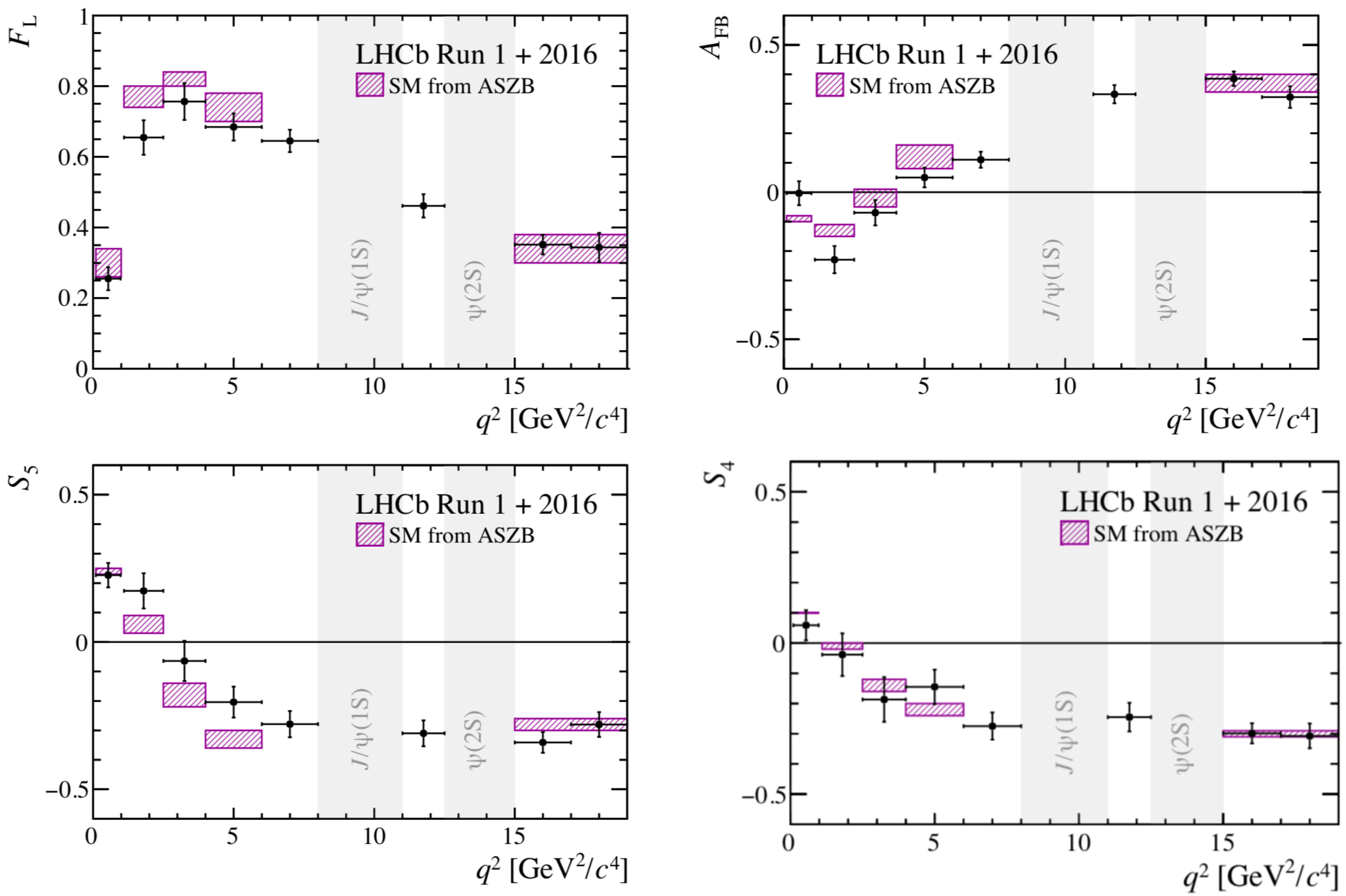
Results

Fit projections 2016 example



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

CP-averaged angular observables



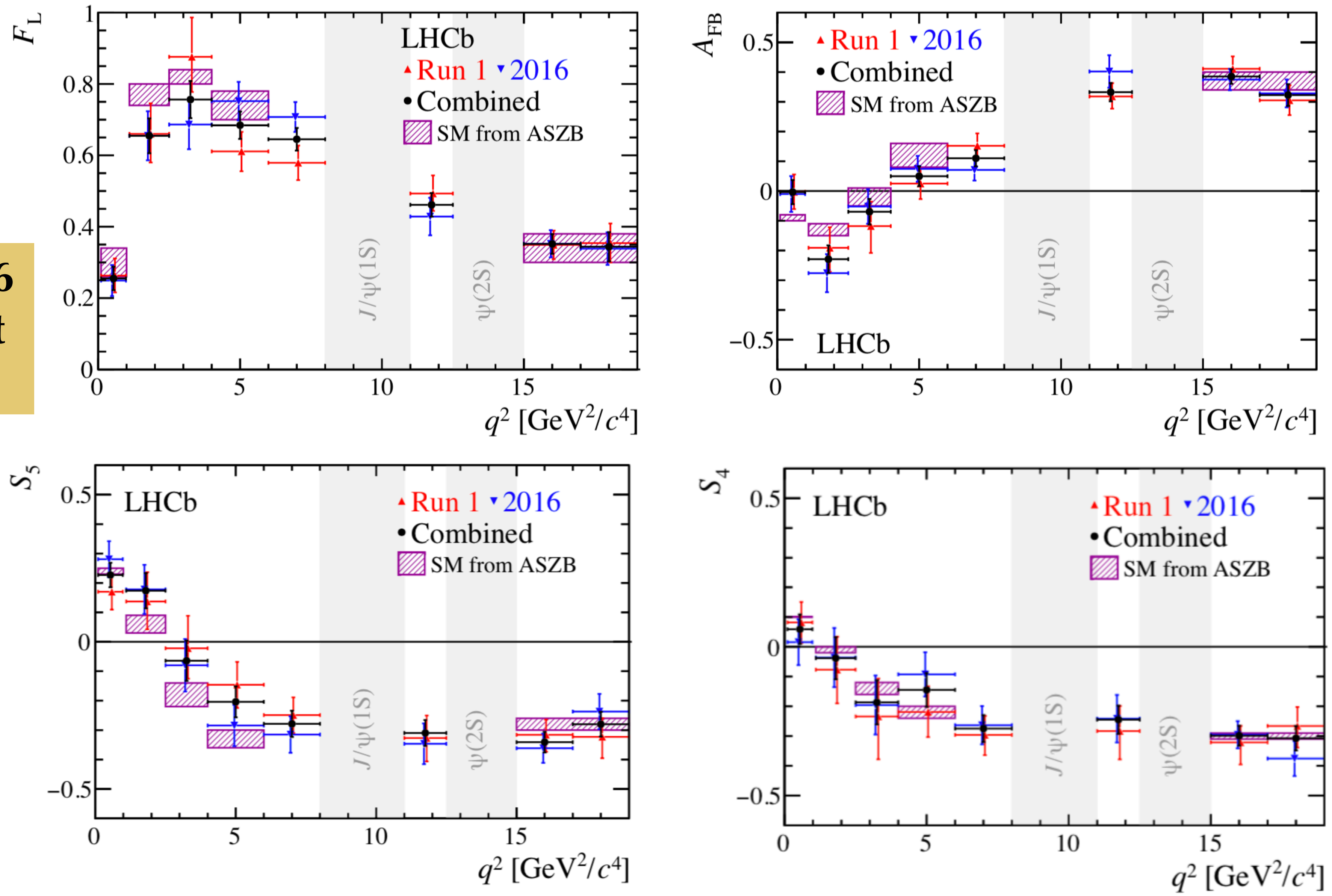
Theory predictions from JHEP 08 (2016) 098 , Eur. Phys. J. C75 (2015) 382

,

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

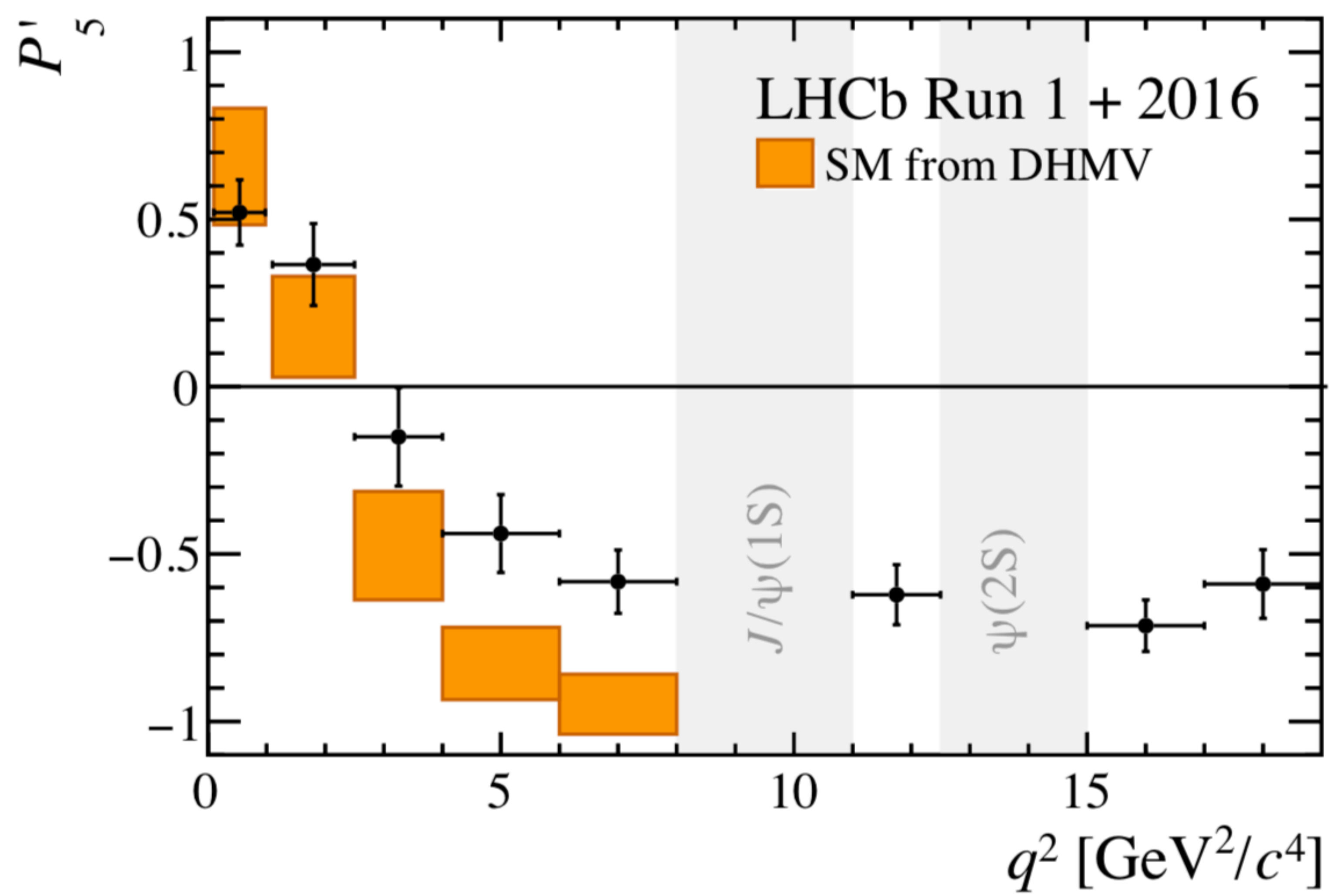
Theory predictions from JHEP 12 (2014) 125, JHEP 09 (2010) 089,

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

Run1+2016: 2.5σ

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

Run1+2016: 2.9σ



Local tension in P_5'

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

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

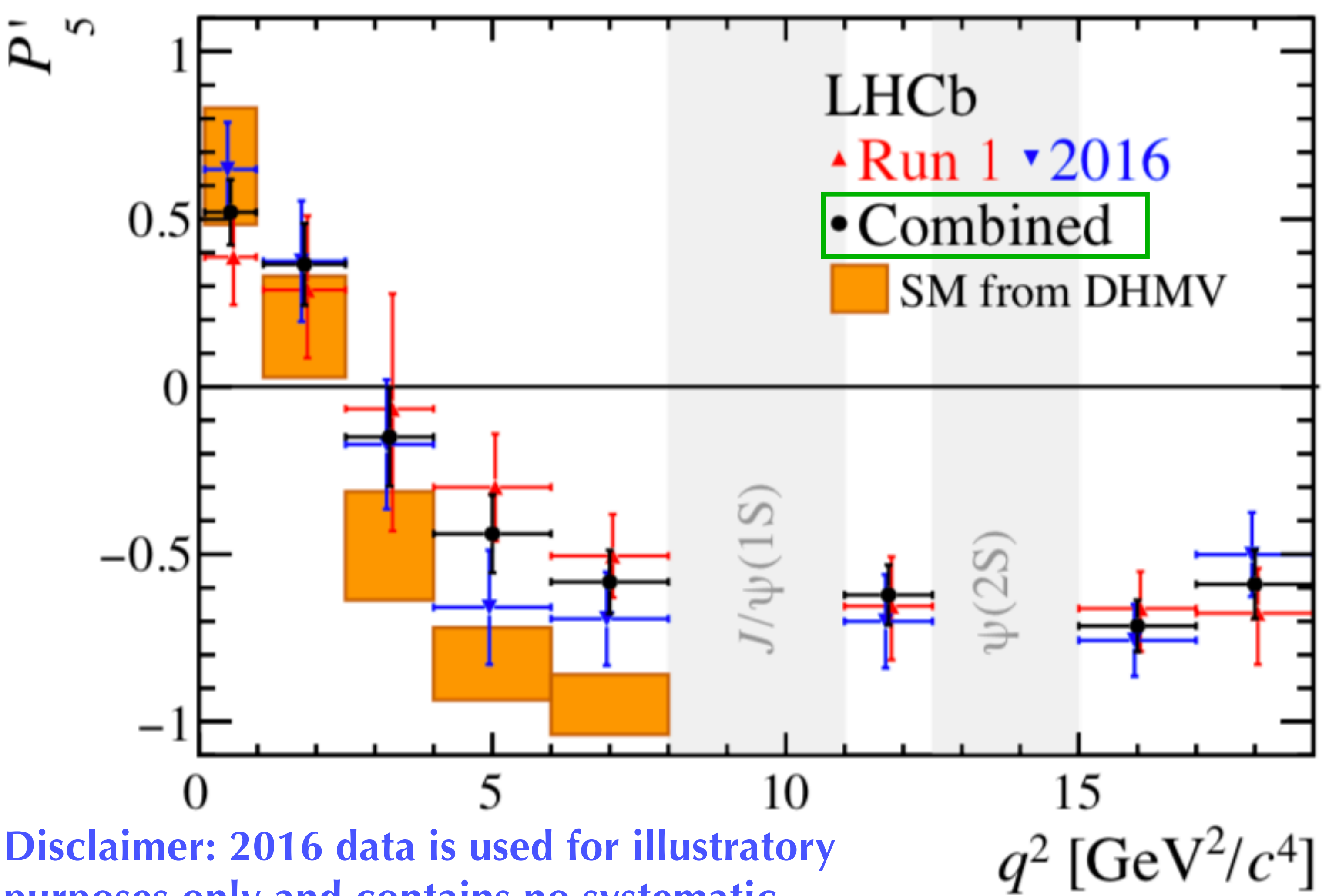
Run1+2016: 2.5σ

Run1 only: 2.8σ

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

Run1+2016: 2.9σ

Run1 only: 3.0σ



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)**

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

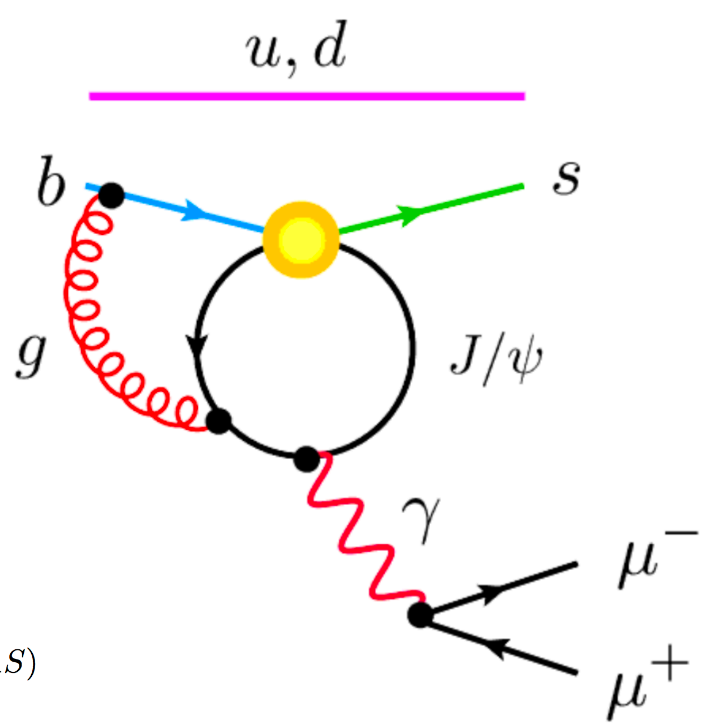
$$\mathcal{A}_\parallel^{L(R)} = -\mathcal{N}\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\prime\rm eff}) \mp (\mathcal{C}_{10}^{\rm eff} - \mathcal{C}_{10}^{\prime\rm eff})\right]\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\prime\rm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

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

JHEP 0901:019,2009

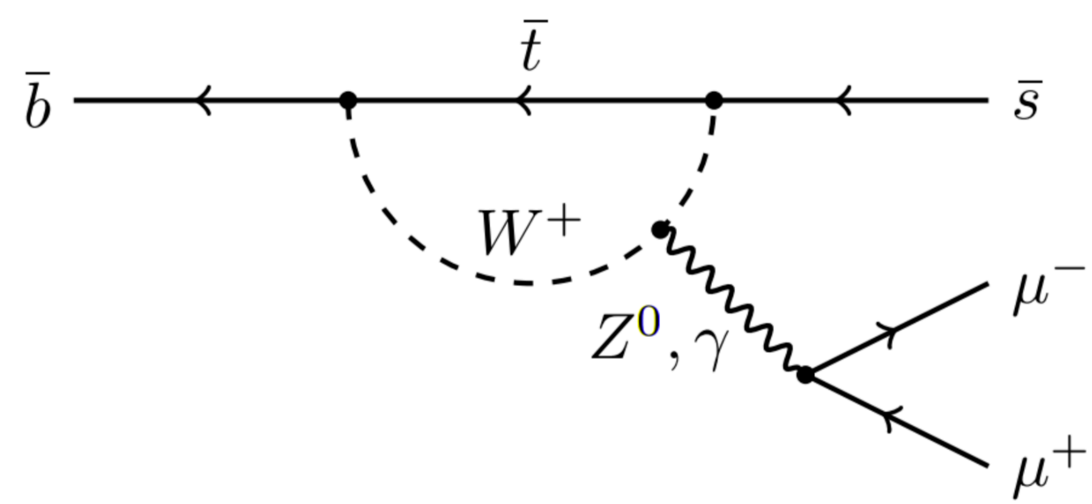
Key nuisance parameter: [2] sub-leading corrections

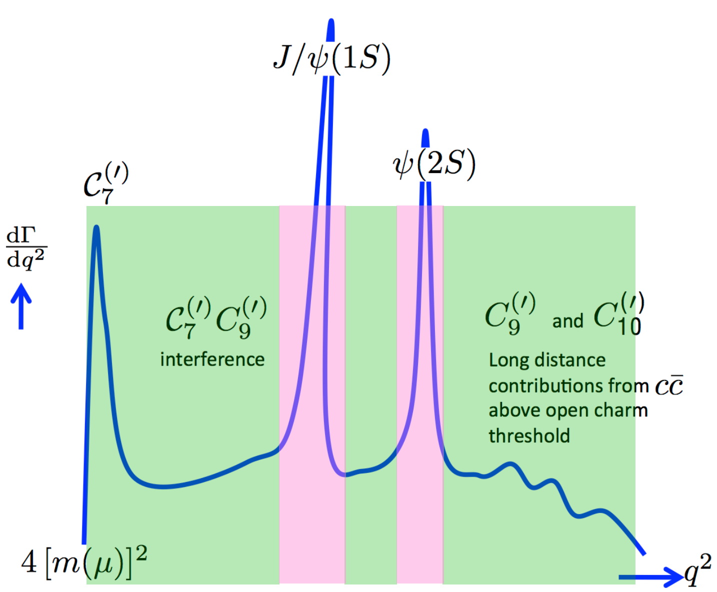
Charmonium loops



+

Signal mode





=

Long-distance effects that could affect signal mode even when outside the vetoed J/ψ 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

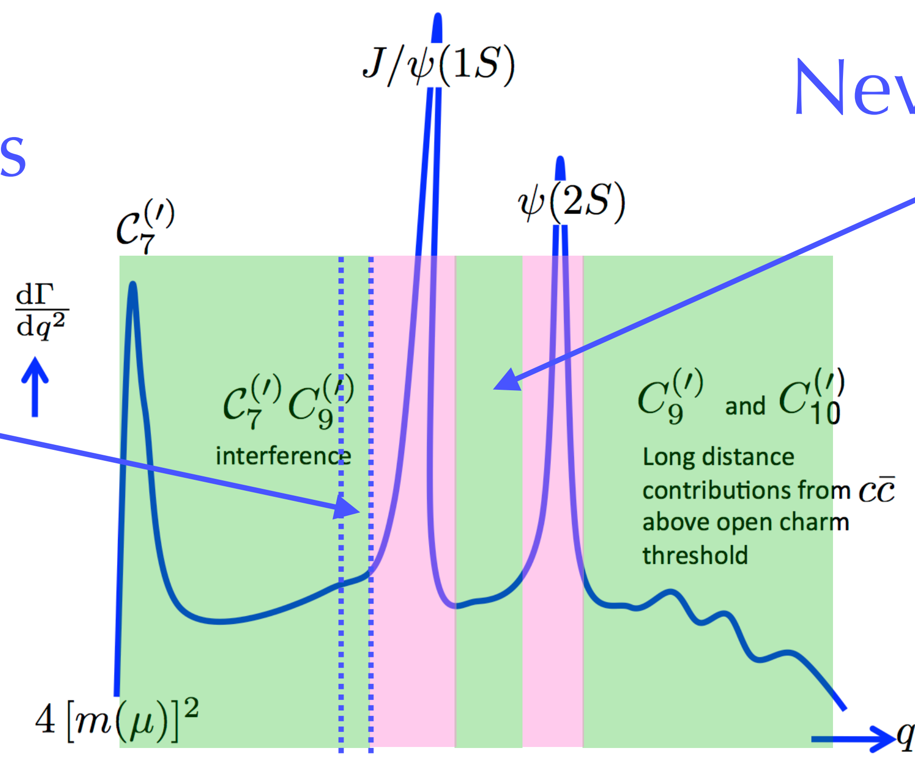
[1] arXiv:1810.08132.
[2] arXiv:1006.5013

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/ψ 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

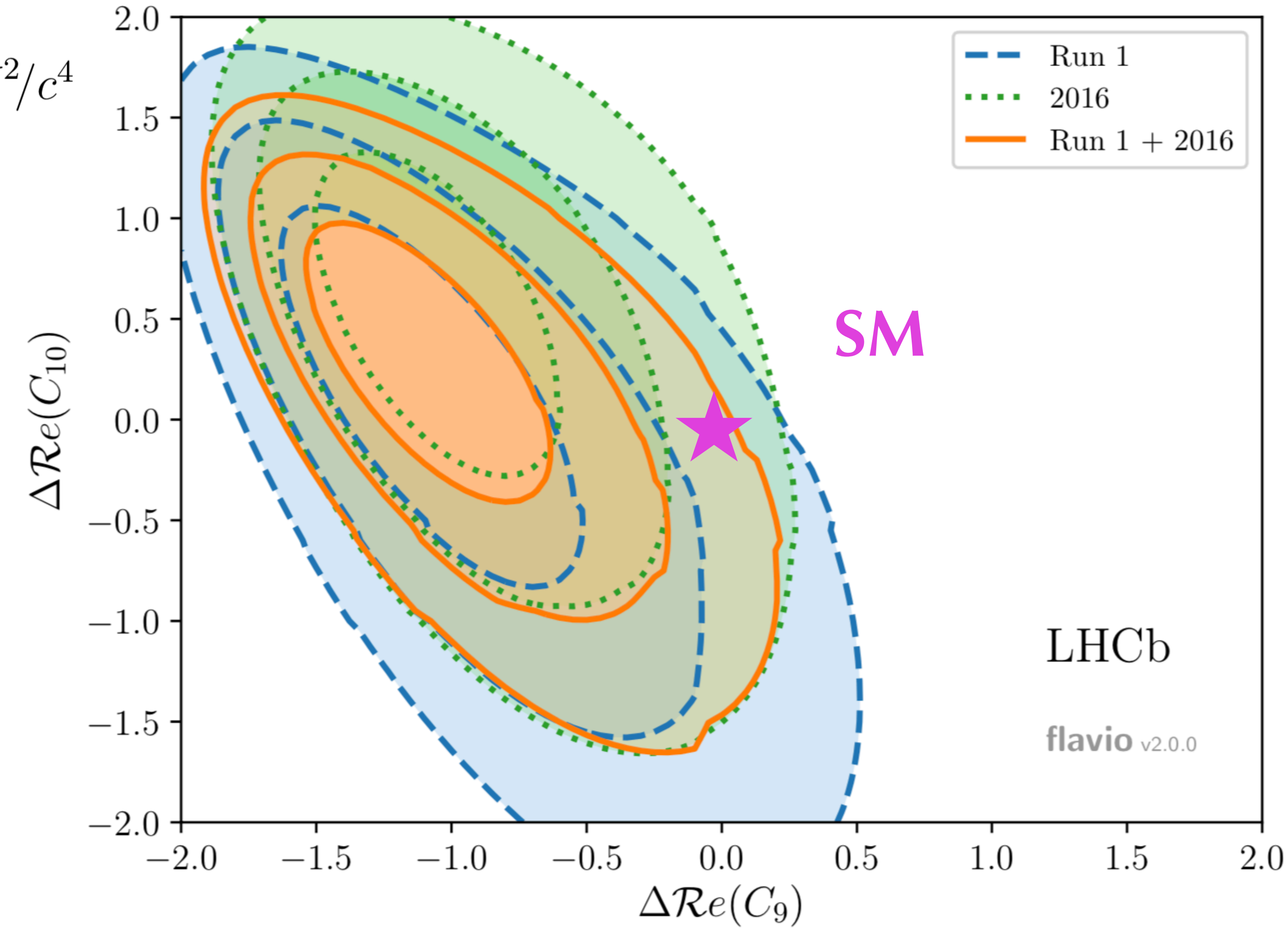
Varying $Re(C_9)$ and $Re(C_{10})$

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

Run 1 and 2016 in good agreement

Case 1

Including
$6.0 < q^2 < 8.0\,\text{GeV}^2/c^4$
bin



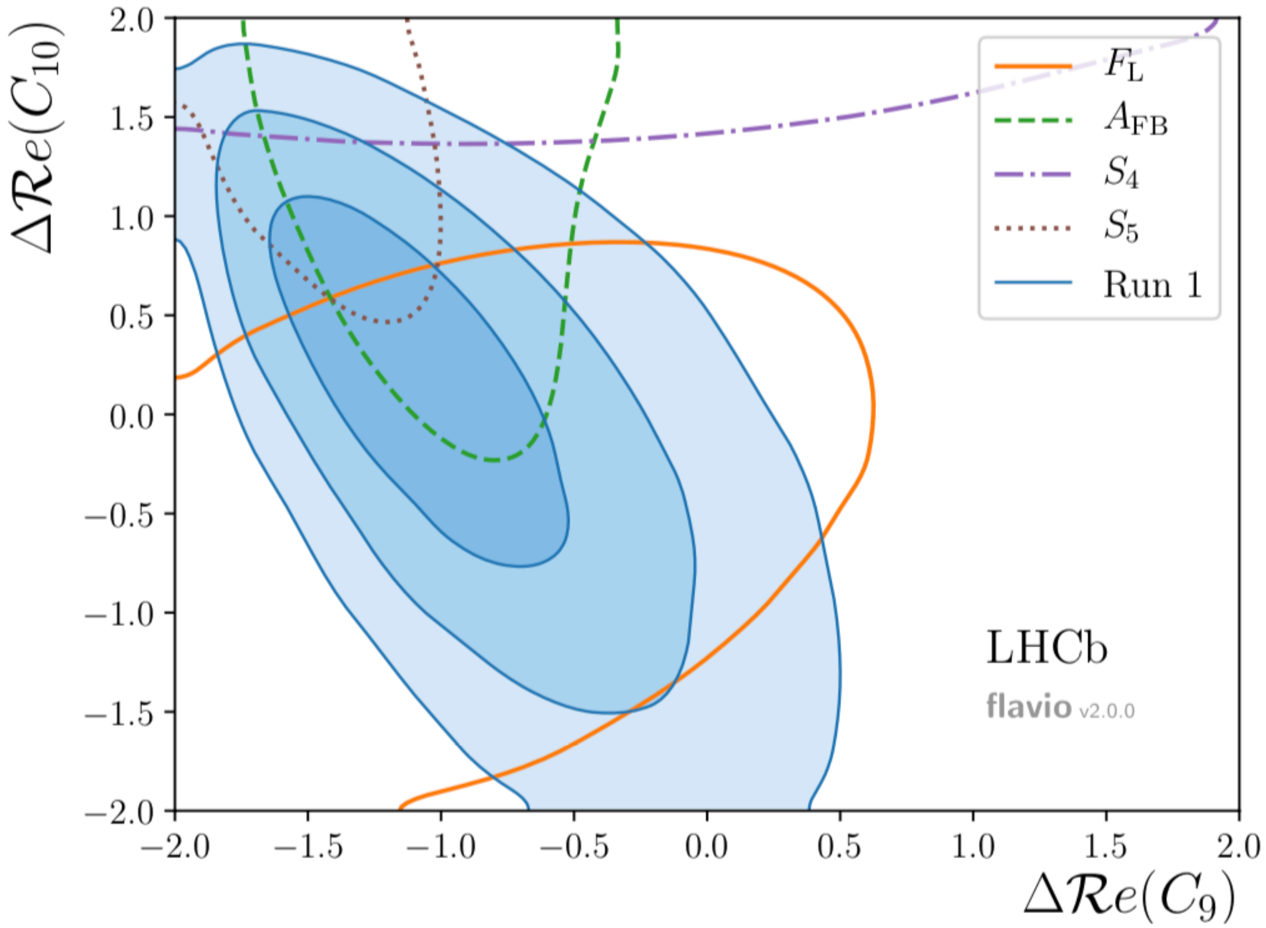
Disclaimer: 2016-only data is for illustratory purposes and contains no systematic uncertainties or bias and coverage corrections

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

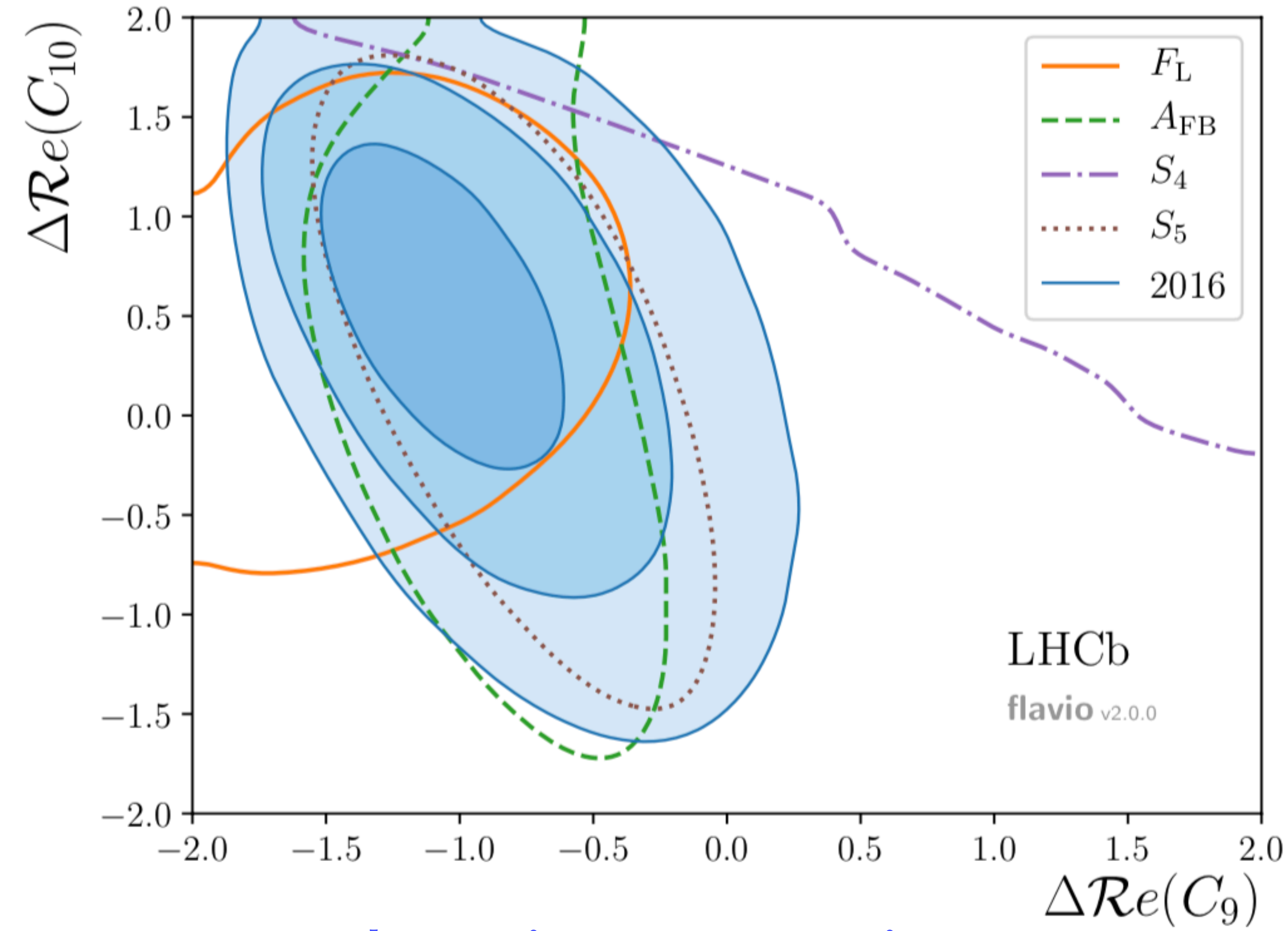
Case 1
Including
$6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$
bin

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

Run 1



2016



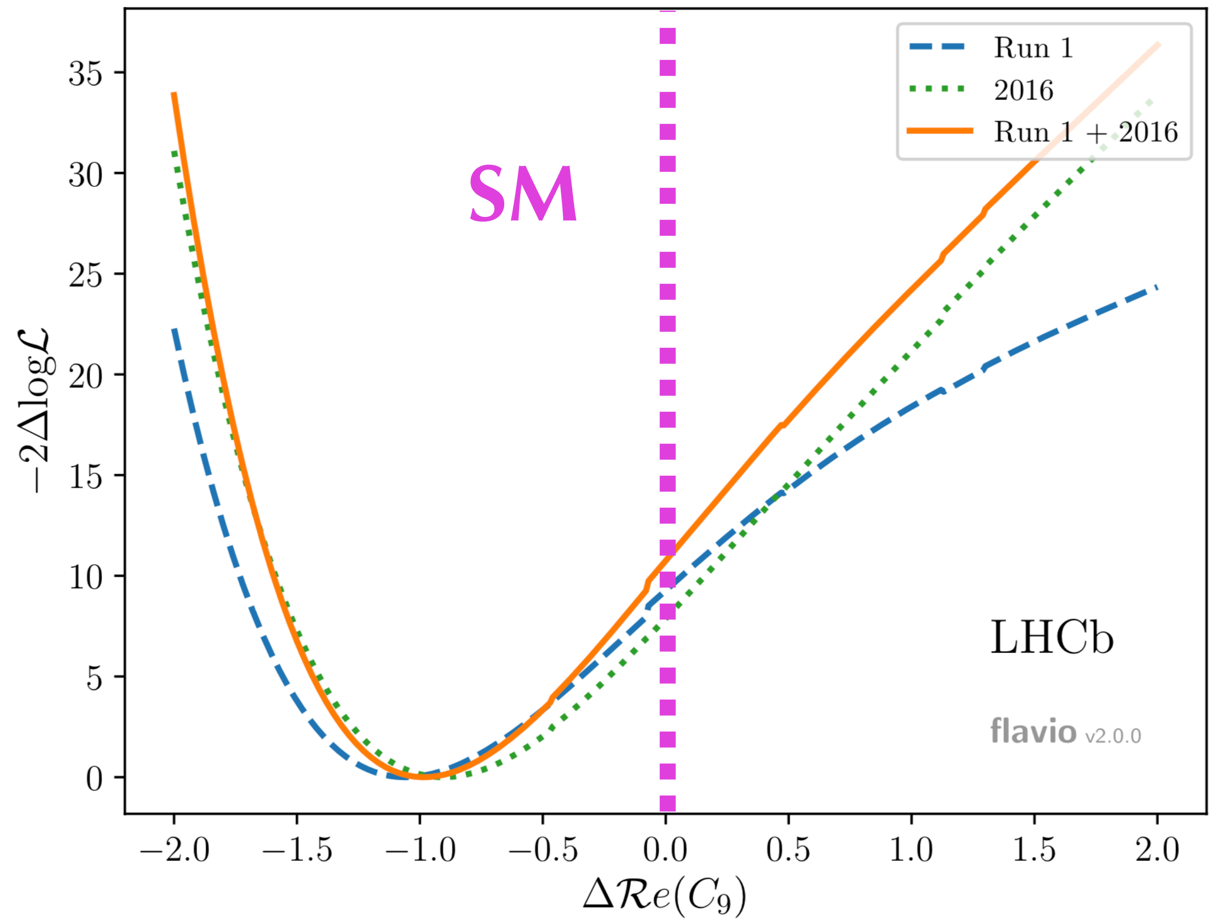
Disclaimer: 2016-only data is for illustratory purposes and contains no systematic uncertainties or bias and coverage corrections

Varying $Re(C_9)$ only

Varying $Re(C_9)$ only

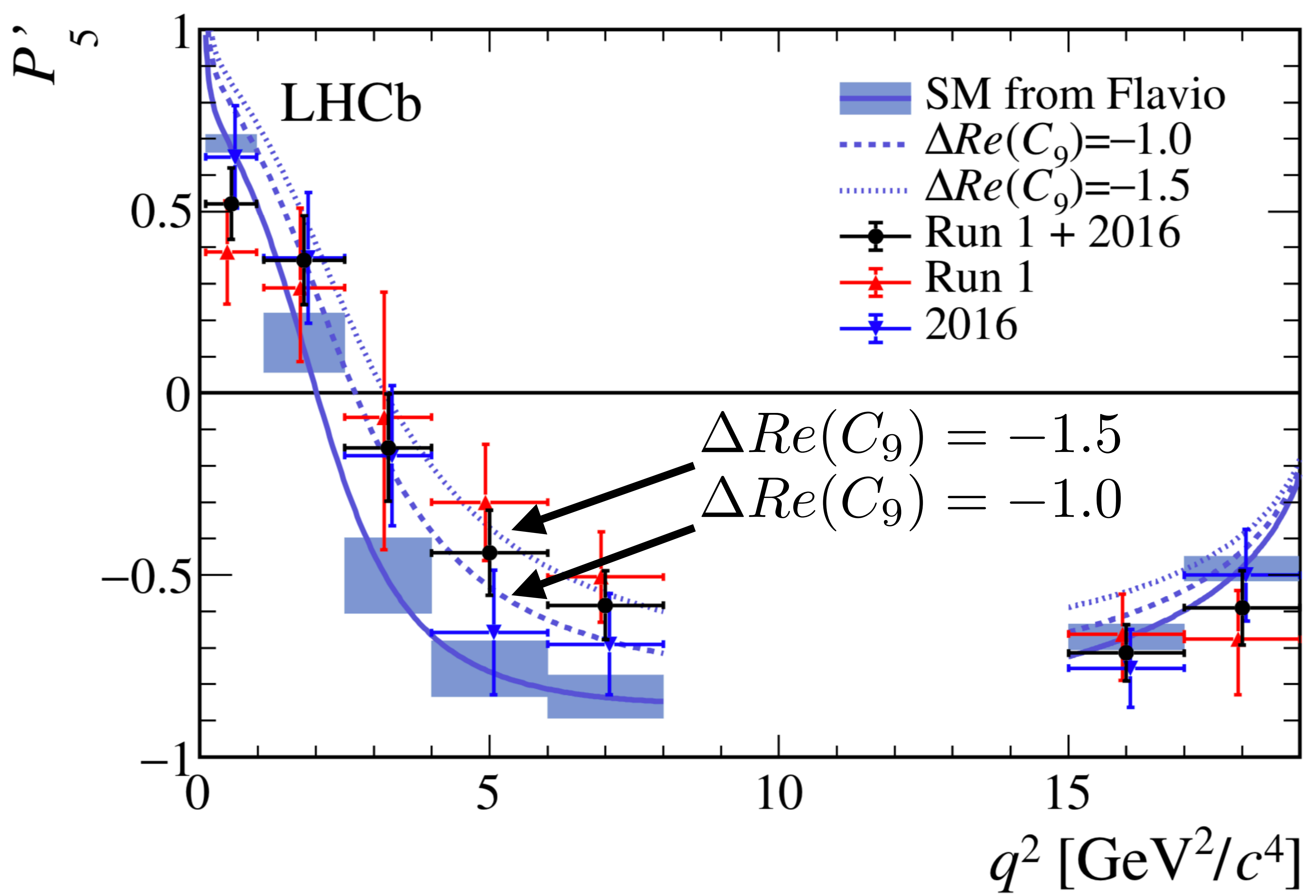
- When varying only $Re(C_9)$ significances are as follows
- Including $6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$
  - Run 1: $3.0\,\sigma$ (previous nuisances $3.4\,\sigma$)
  - Run 1 + 2016: $3.3\,\sigma$
- Excluding $6.0 < q^2 < 8.0\,\mathrm{GeV}^2/c^4$
  - Run 1: $2.4\,\sigma$
  - Run 1 + 2016: $2.7\,\sigma$

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 $\Delta Re(C_9) = -1, -1.5$



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

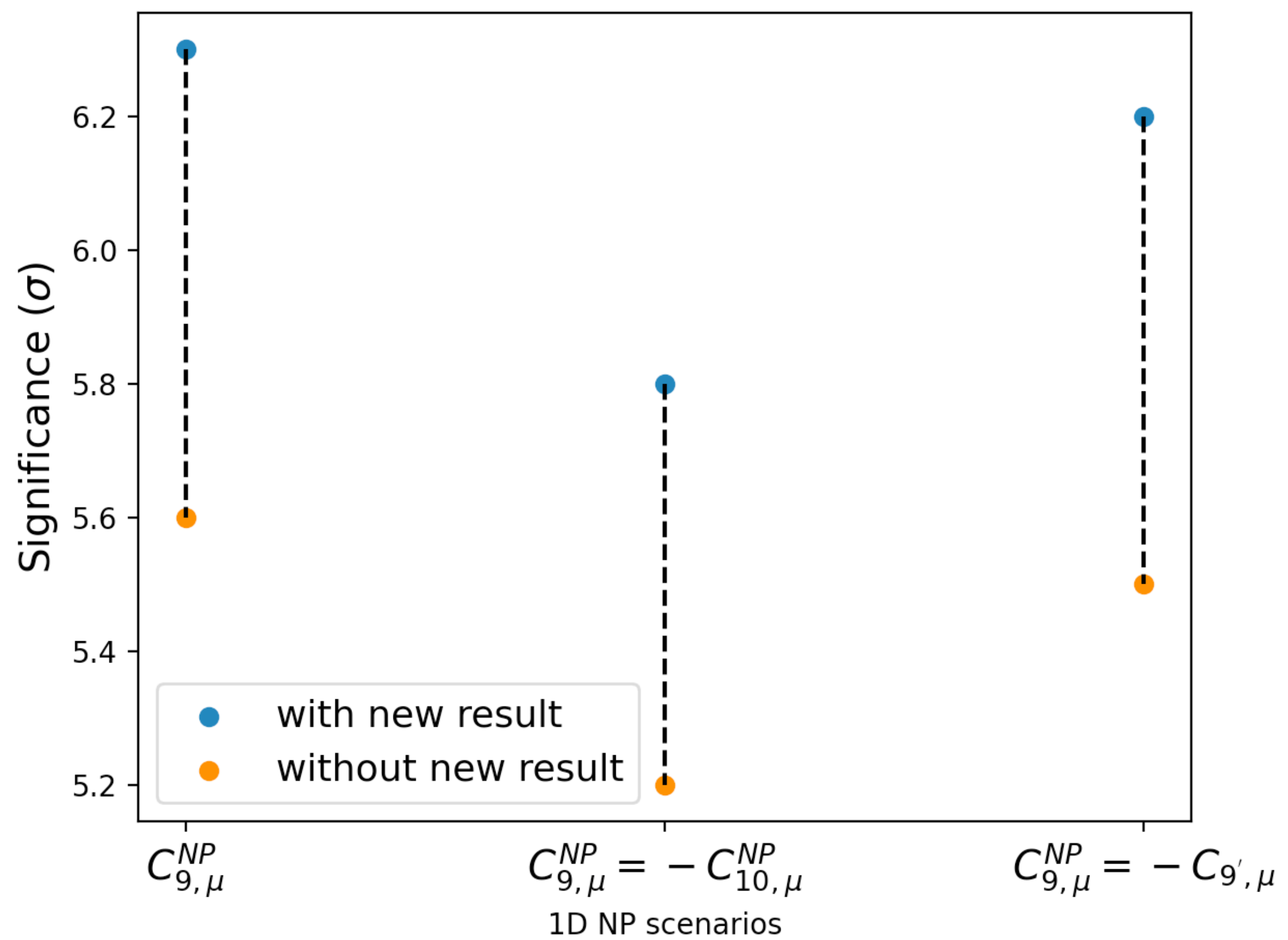
1D Hyp.	All: Best fit	$1\,\sigma/2\,\sigma$	Pull_{SM}	p-value
$\mathcal{C}_{9\mu}^{\text{NP}}$	-0.98	$[-1.15,-0.81]$ $[-1.31,-0.64]$	5.6	65.4 %
$\mathcal{C}_{9\mu}^{\text{NP}}=-\mathcal{C}_{10\mu}^{\text{NP}}$	-0.46	$[-0.56,-0.37]$ $[-0.66,-0.28]$	5.2	55.6 %
$\mathcal{C}_{9\mu}^{\text{NP}}=-\mathcal{C}_{9'\mu}$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

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

With result

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

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

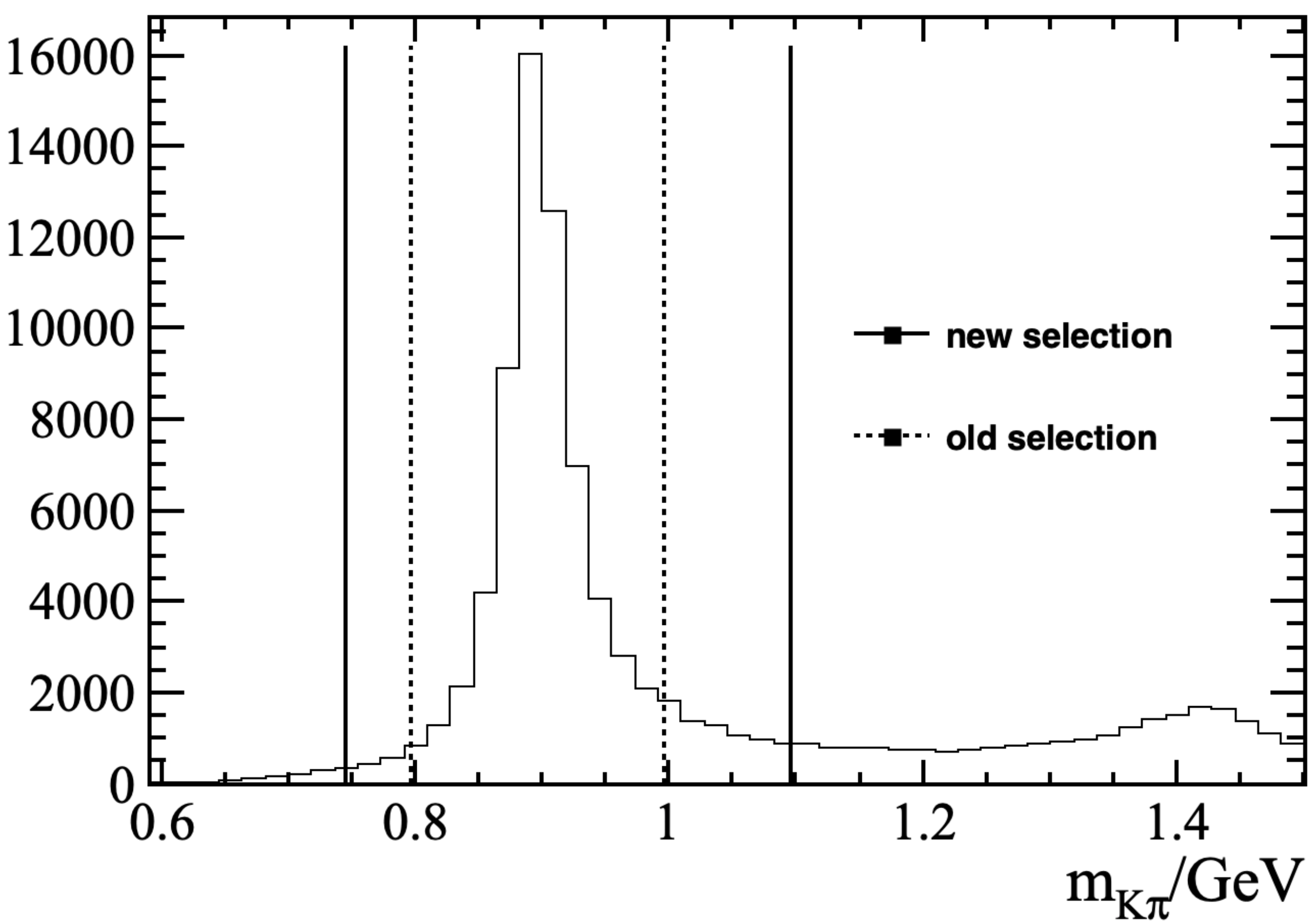


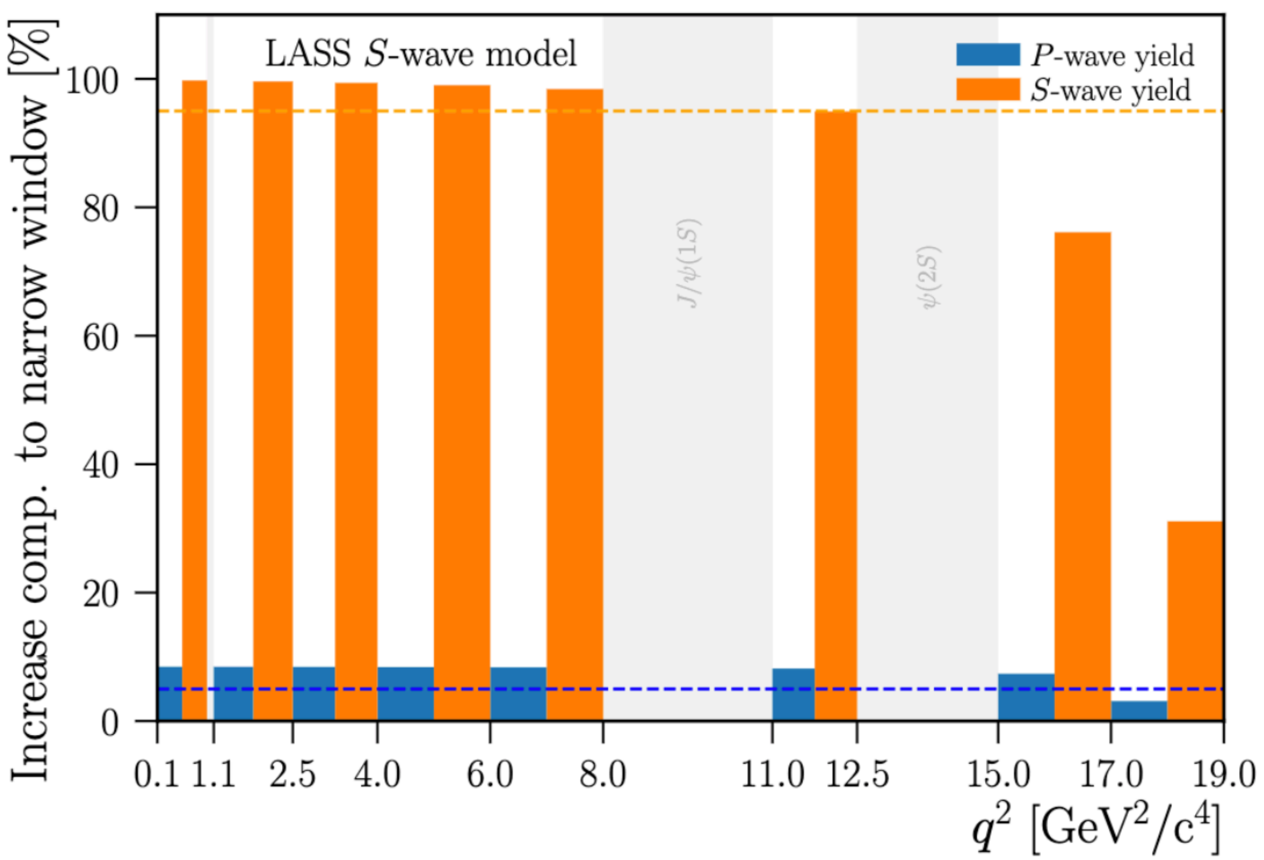
Towards publishing the full Run 2 dataset

- 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*

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

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

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

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

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

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)

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

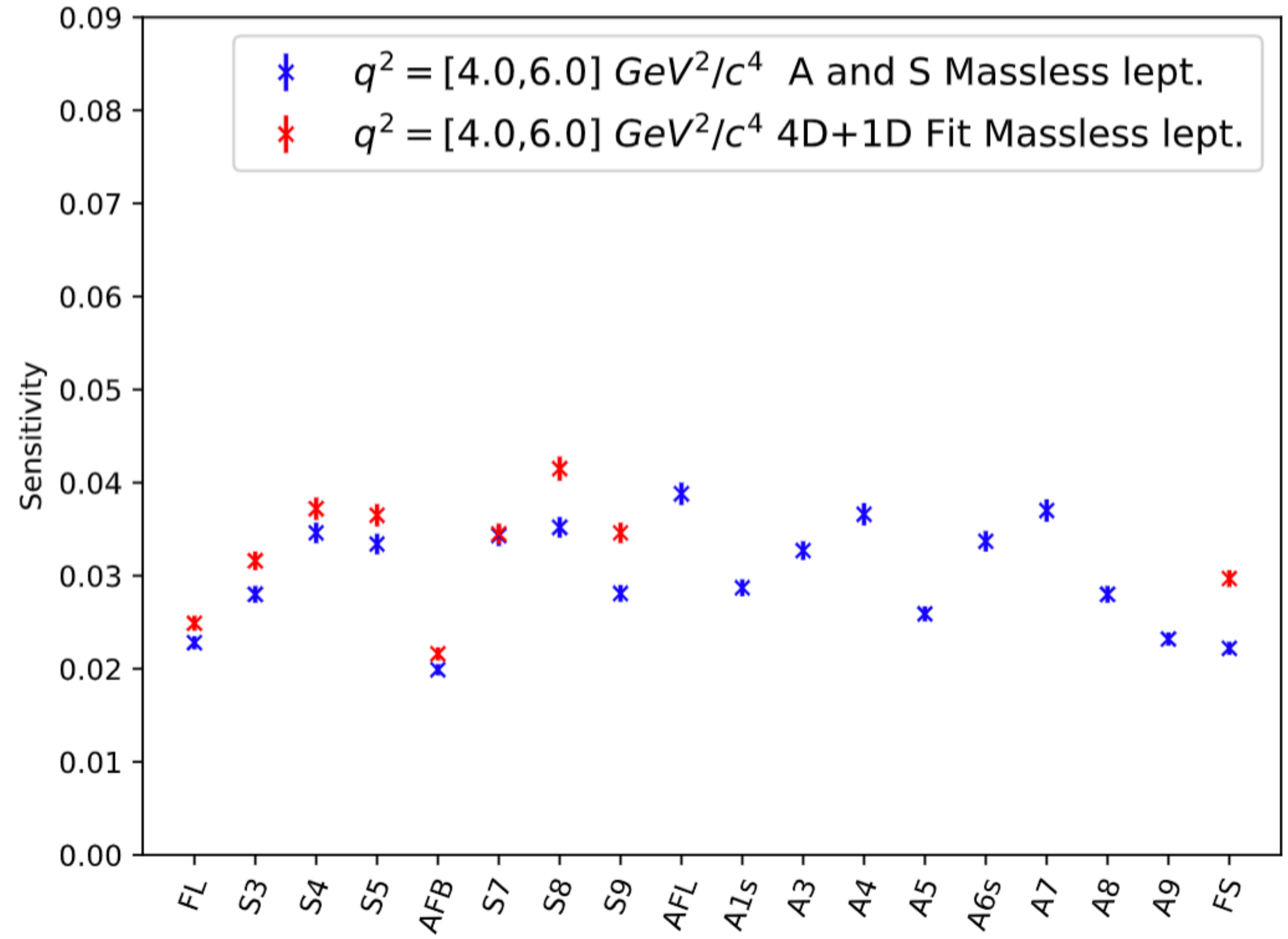
where $\alpha_i \in \mathrm{Im}, \mathrm{Re}$, dependent on observable

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)**

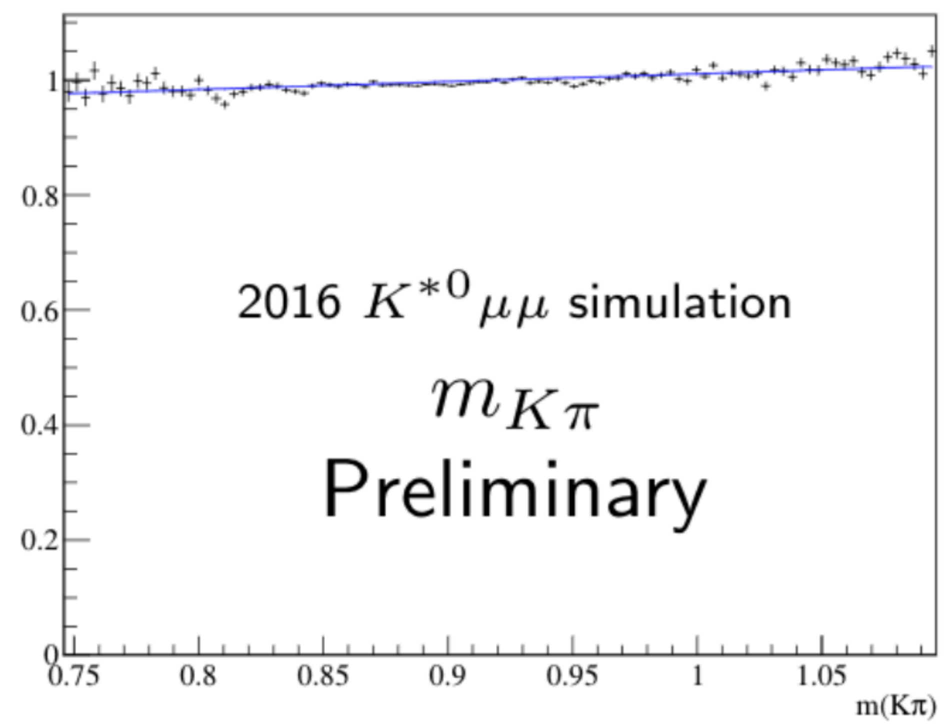
Other improvements

- 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

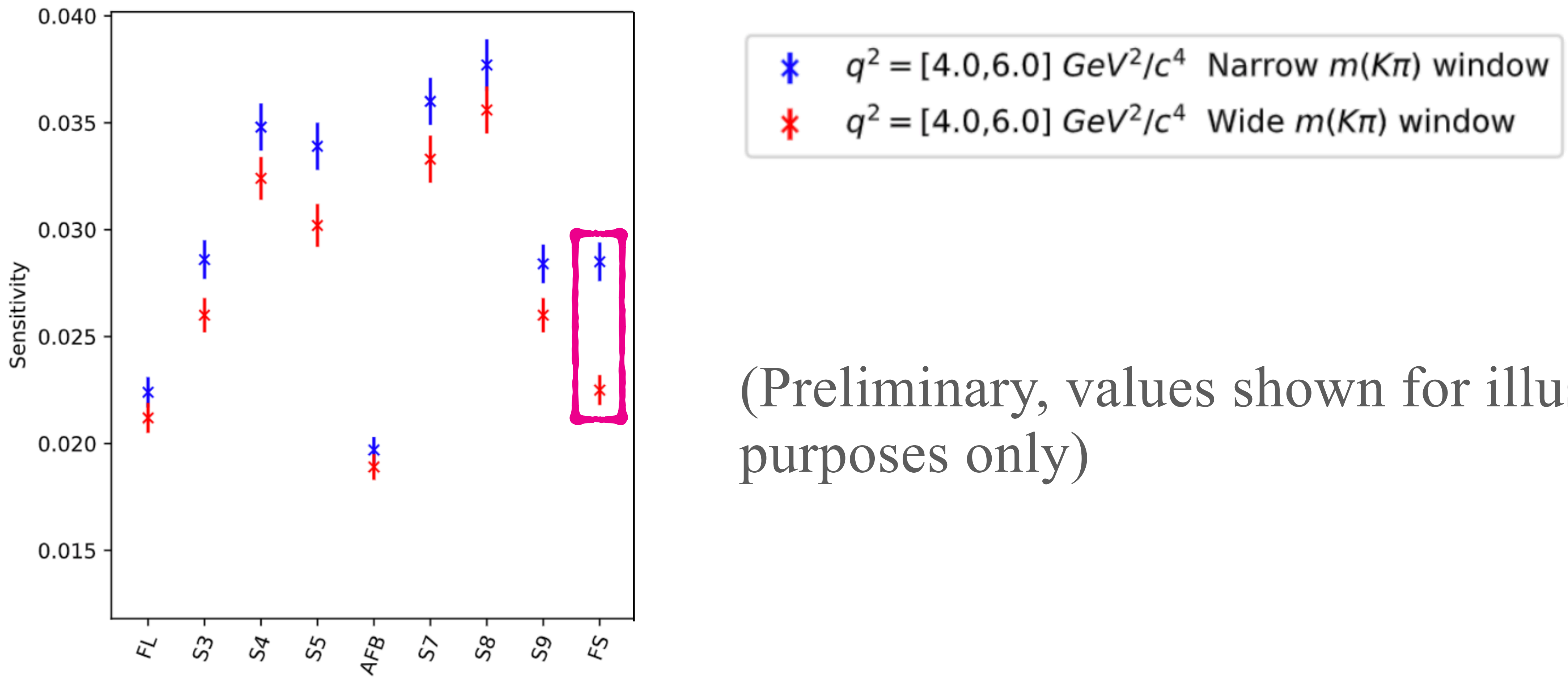
Conclusions

- Angular analyses provide access to theoretically clean observables
- Ongoing tensions seen in $B^0 \to K^{*0}\mu^+\mu^-$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

Back up slides

Improving selection

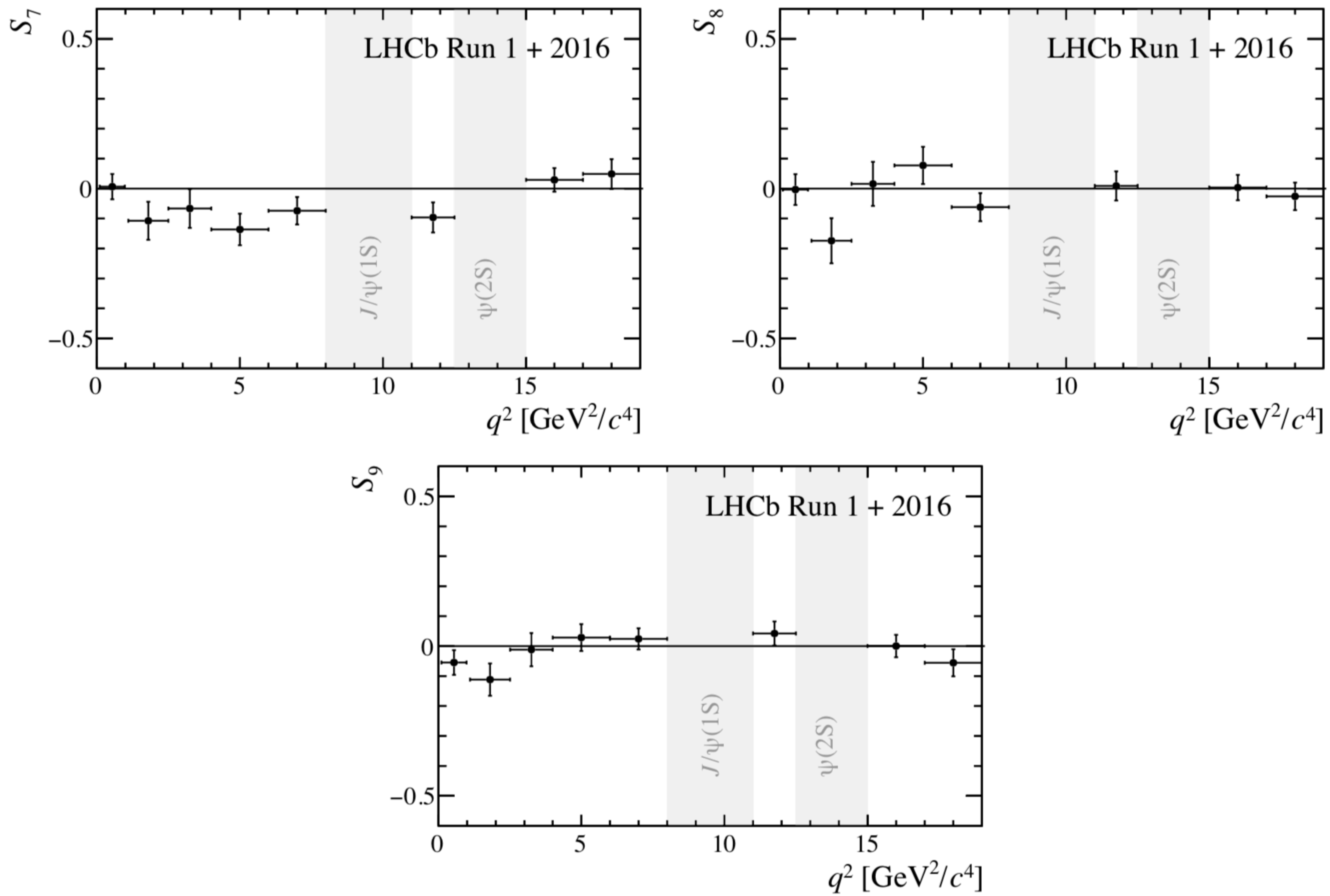
- Comparison of sensitivity (i.e. width of value distributions) from fit with narrow (red) and wide (blue) $m_{K\pi}$ window



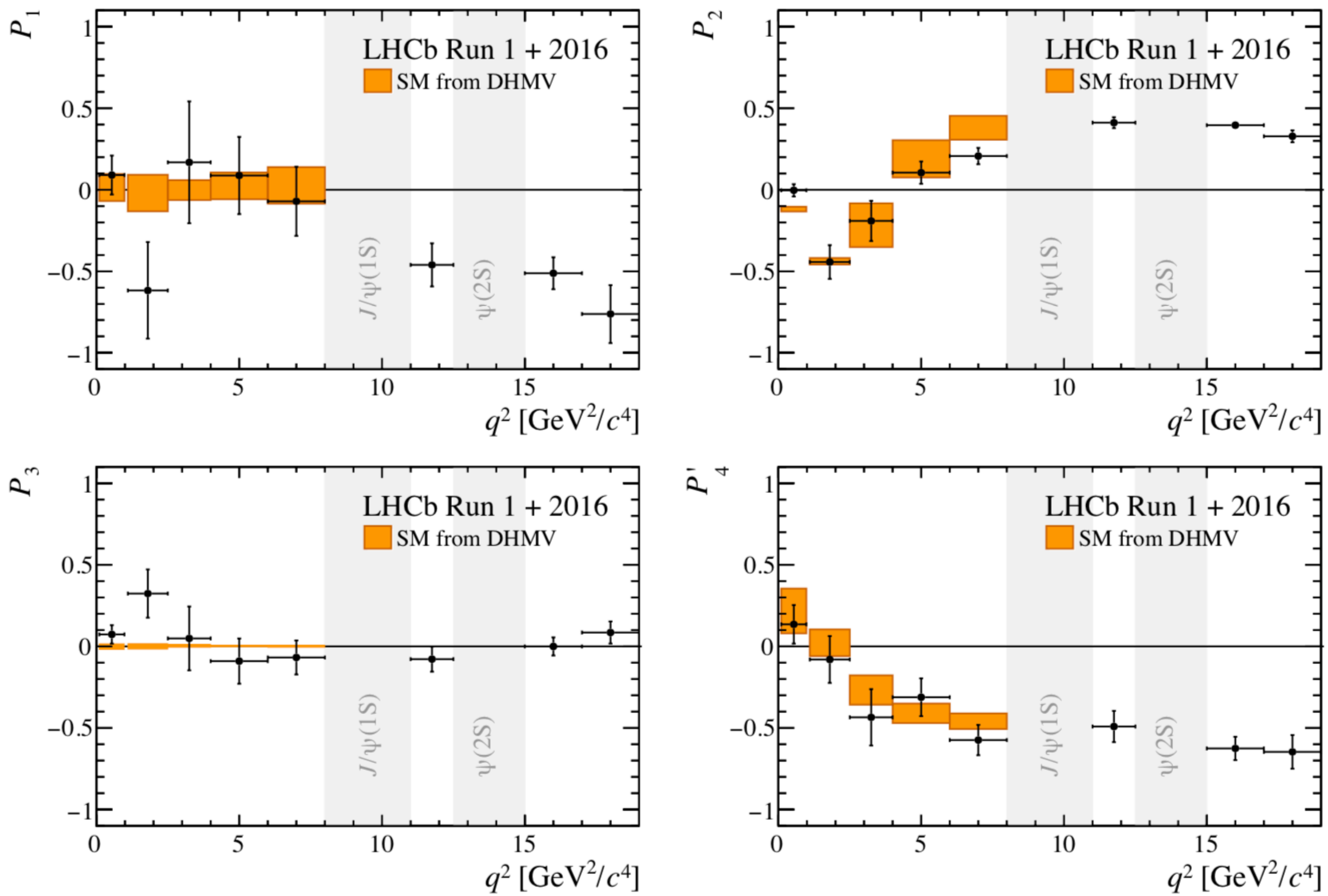
(Preliminary, values shown for illustrative purposes only)

- Sensitivity to F_S much improved

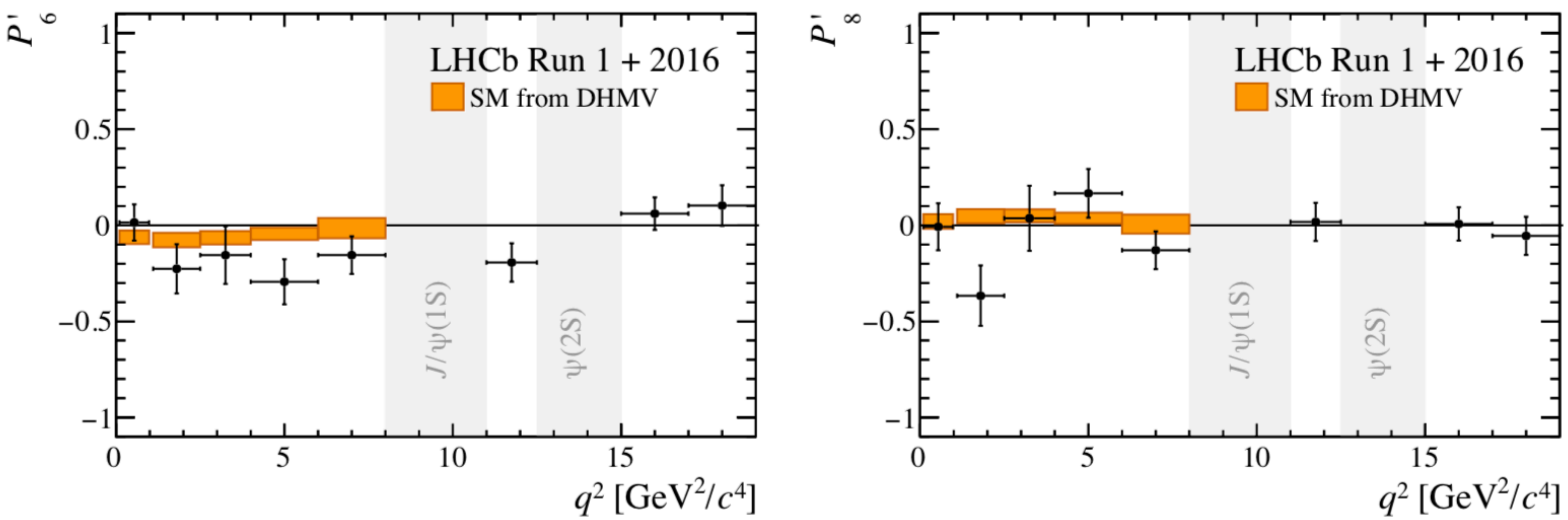
CP-averaged observables



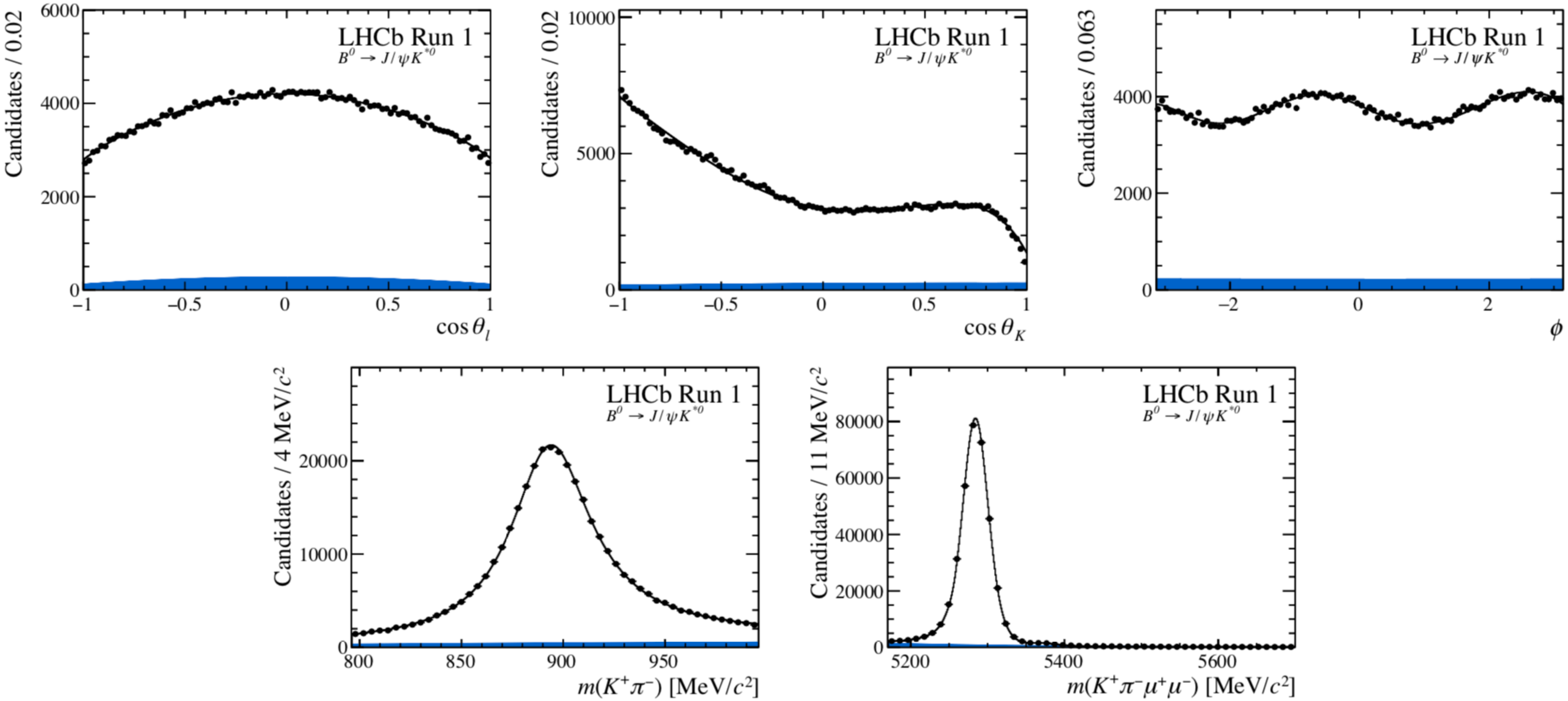
CP-averaged observables



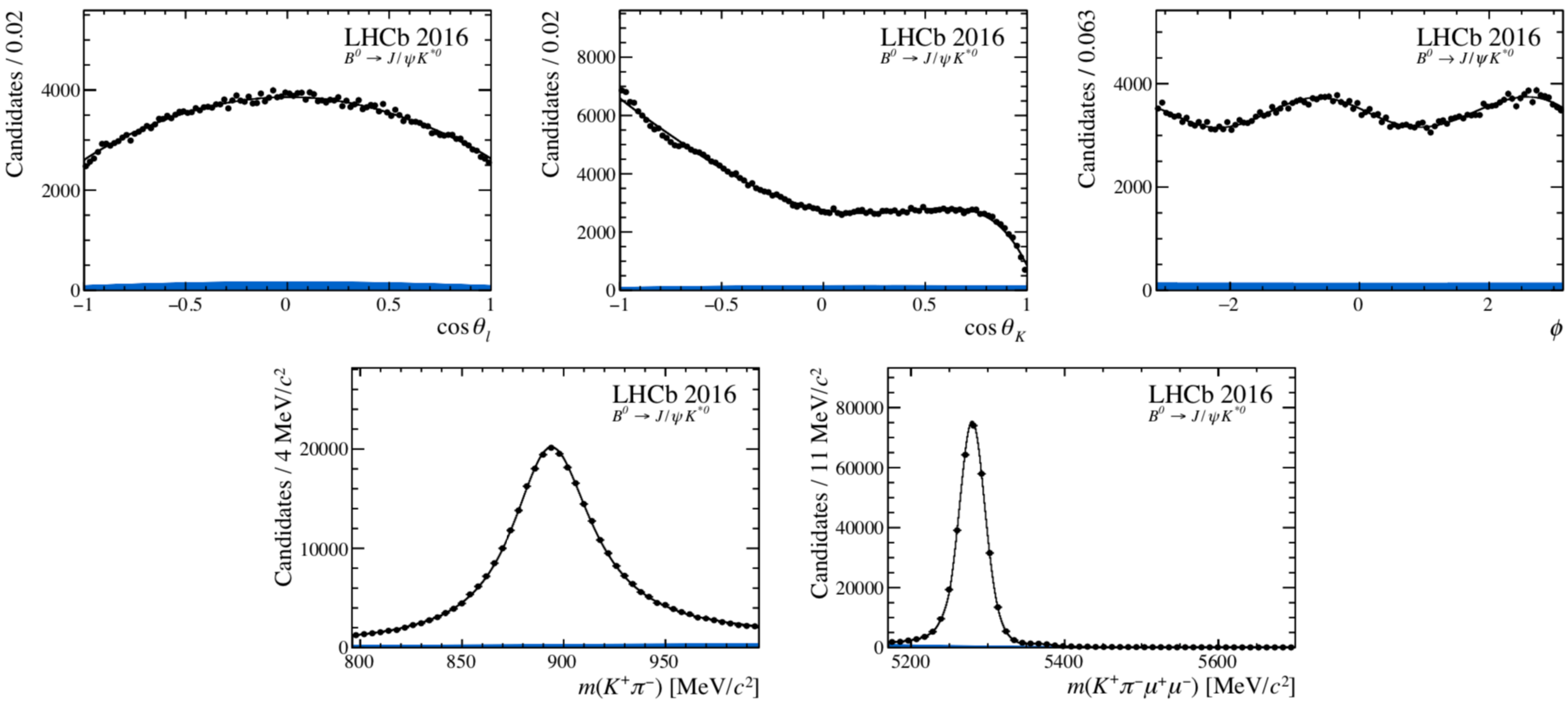
CP-averaged observables



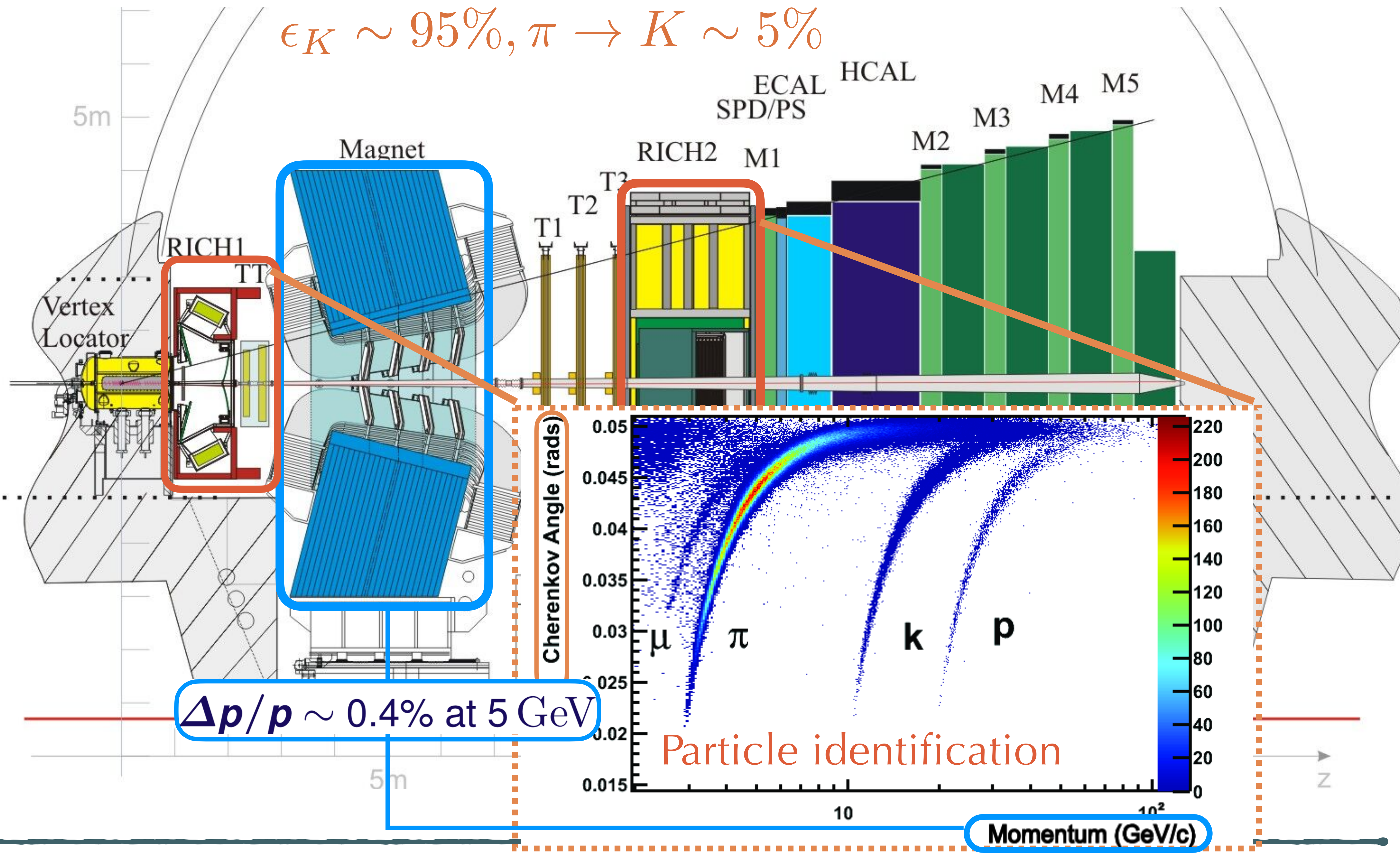
Control channel projections



Control channel projections

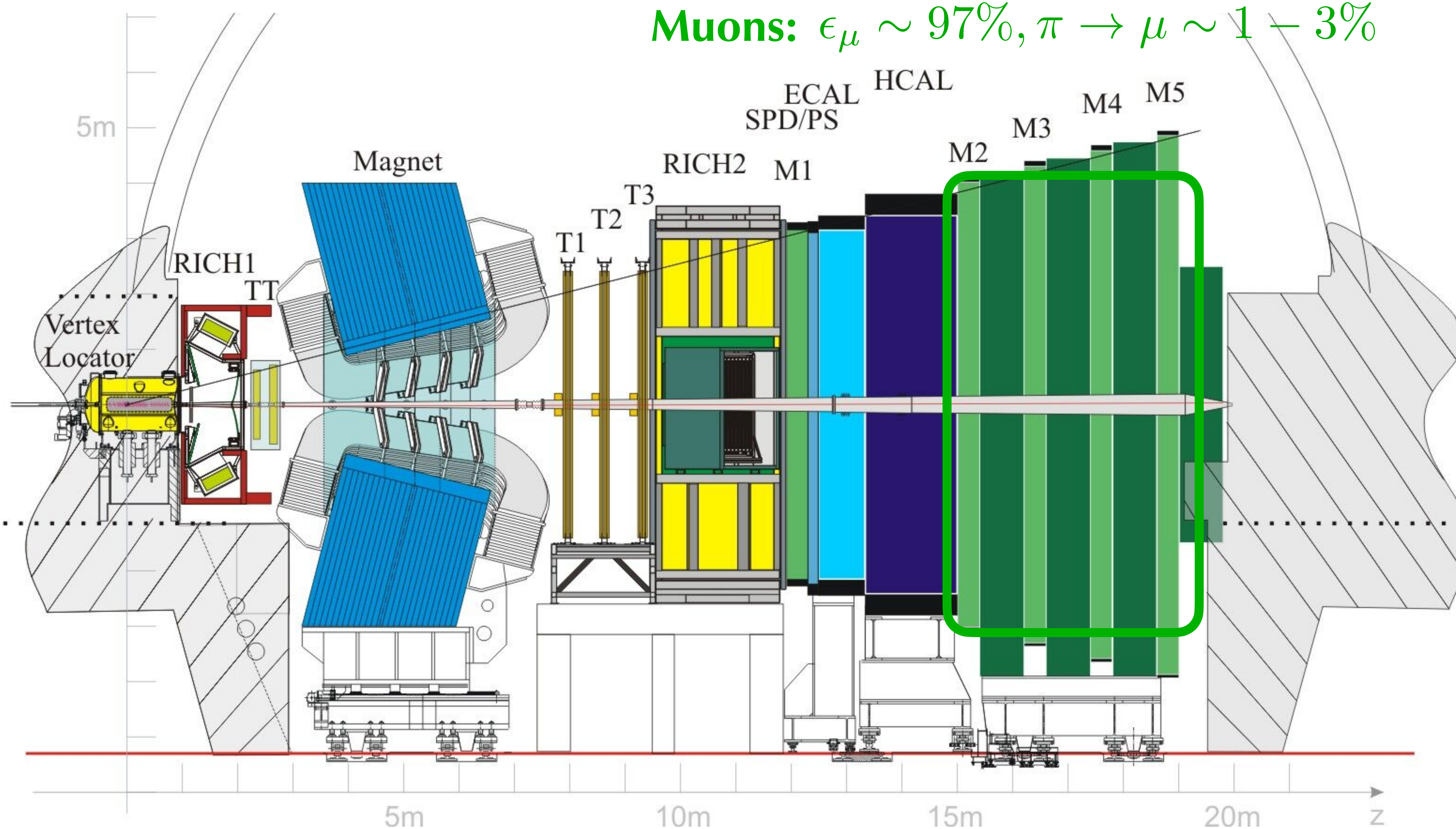


The LHCb experiment



The LHCb experiment

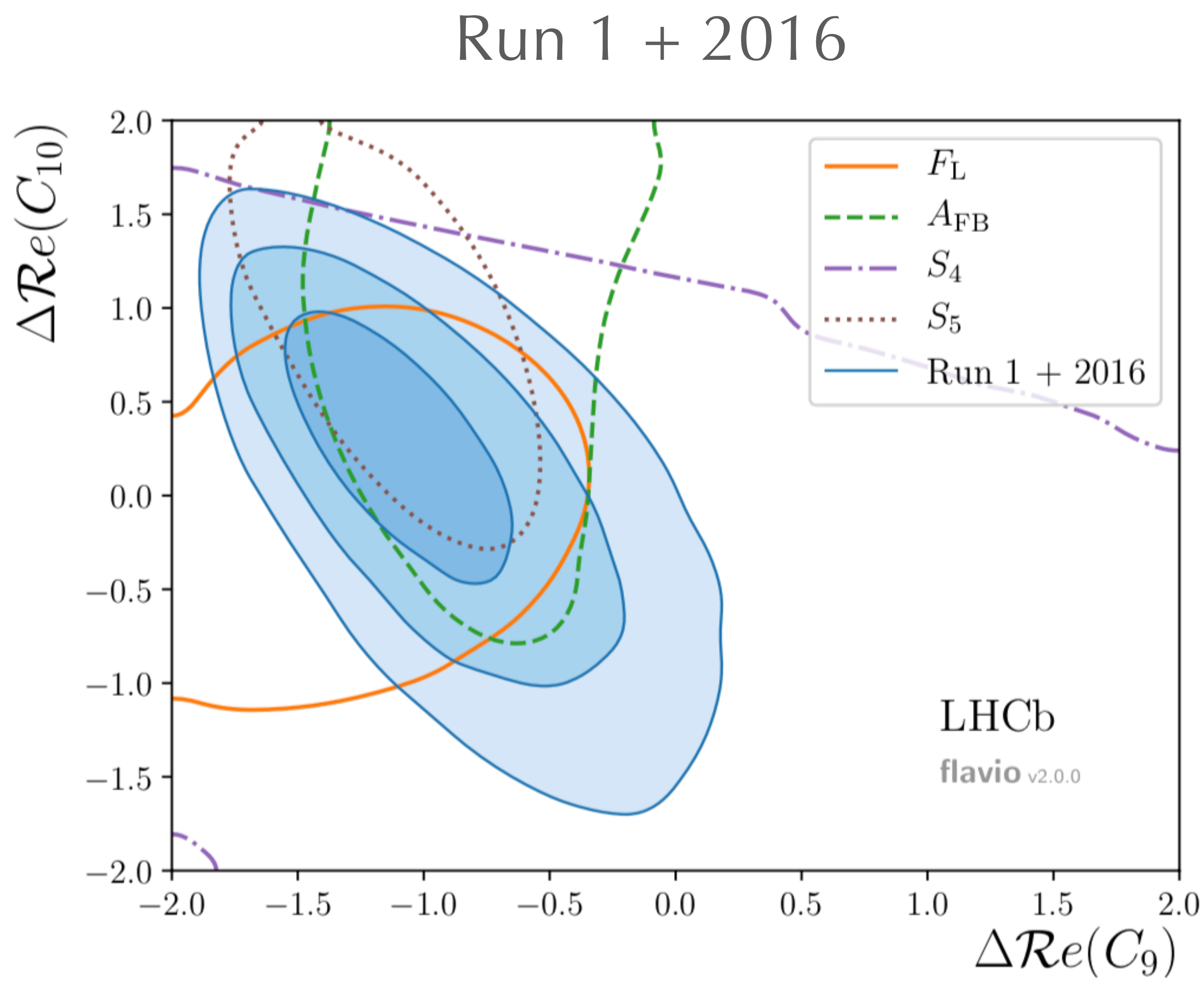
Muons: $\epsilon_\mu \sim 97\%, \pi \to \mu \sim 1-3\%$



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

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

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



What will be discussed today

- The results of the angular analysis updated with 2016 data (Phys. Rev. Lett. **125**, 011802)
  - Introduction to simultaneous fitting
  - Selection
  - Results on data
  - Interpretation
- Brief overview of current analysis going forward, changes to selection and PDF

Fit behaviour

Fit behaviour

- Reduced statistics (~4500) for many parameters (~40) - is maximum likelihood estimator well behaved?
- Use data as input, most biases under 10%, a few ~15%

$1.0 < q^2 < 2.5$

	sensitivity	pull mean	pull width
F_L	0.056 ± 0.002	0.055 ± 0.045	1.013 ± 0.032
S_3	0.056 ± 0.002	-0.035 ± 0.044	0.979 ± 0.031
S_4	0.081 ± 0.003	-0.034 ± 0.048	1.068 ± 0.034
S_5	0.074 ± 0.002	-0.005 ± 0.048	1.062 ± 0.034
A_{FB}	0.051 ± 0.002	-0.097 ± 0.047	1.059 ± 0.034
S_7	0.065 ± 0.002	0.024 ± 0.043	0.952 ± 0.030
S_8	0.077 ± 0.002	0.037 ± 0.046	1.018 ± 0.032
S_9	0.061 ± 0.002	-0.001 ± 0.047	1.057 ± 0.033

SM values for generation

$1.0 < q^2 < 2.5$

	sensitivity	pull mean	pull width
F_L	0.052 ± 0.001	0.075 ± 0.022	0.965 ± 0.015
S_3	0.062 ± 0.001	0.003 ± 0.024	1.087 ± 0.017
S_4	0.078 ± 0.001	0.146 ± 0.024	1.065 ± 0.017
S_5	0.067 ± 0.001	-0.094 ± 0.023	1.014 ± 0.016
A_{FB}	0.052 ± 0.001	-0.110 ± 0.024	1.067 ± 0.017
S_7	0.072 ± 0.001	-0.051 ± 0.024	1.059 ± 0.017
S_8	0.082 ± 0.001	-0.014 ± 0.024	1.078 ± 0.017
S_9	0.063 ± 0.001	-0.066 ± 0.025	1.098 ± 0.017

Date for generation

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

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

angular coefficients angular functions

$$\begin{aligned}\sum_i I_i(q^2) f_i(\Omega) &= I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*} + (I_2^s \sin^2\theta_{K^*} + I_2^c \cos^2\theta_{K^*})\cos 2\theta_l \\ &+ I_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi \\ &+ I_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi \\ &+ (I_6^s \sin^2\theta_{K^*} + I_6^c \cos^2\theta_{K^*})\cos\theta_l + I_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi \\ &+ I_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi\,.\end{aligned}$$