



Update of the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
angular analysis at LHCb

CERN SEMINAR

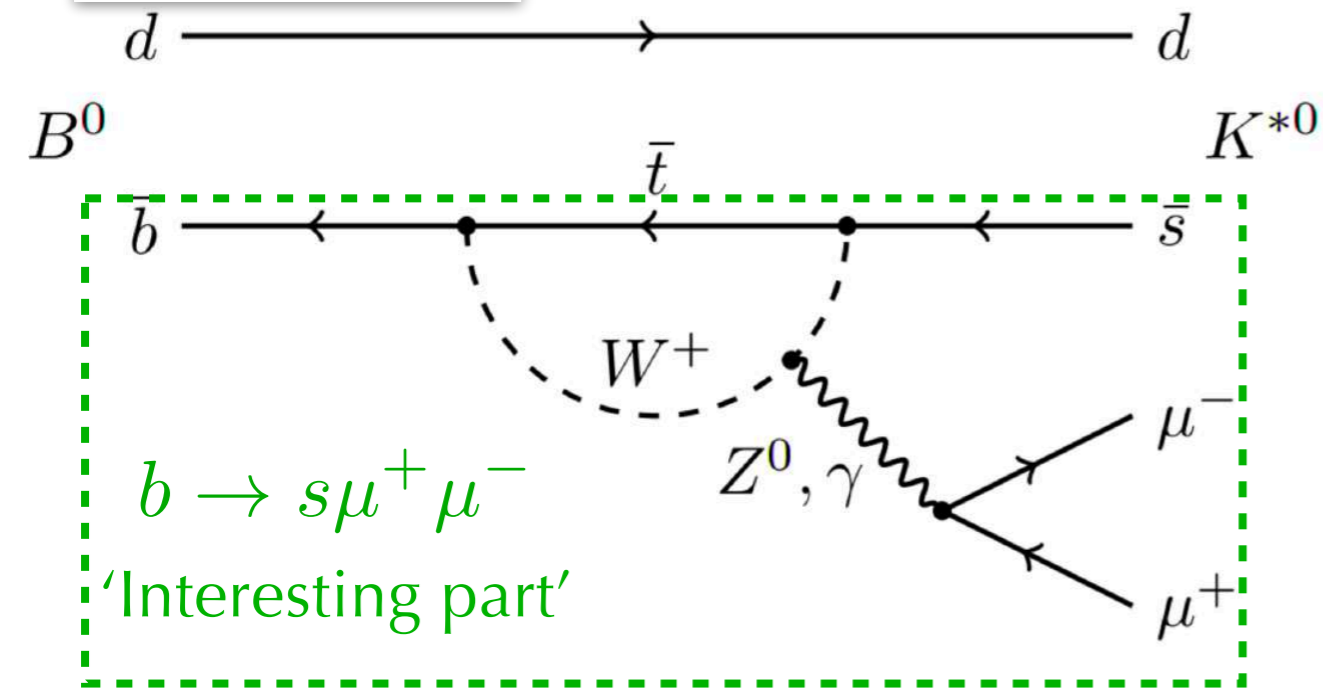
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on behalf of the LHCb collaboration

10/03/2020

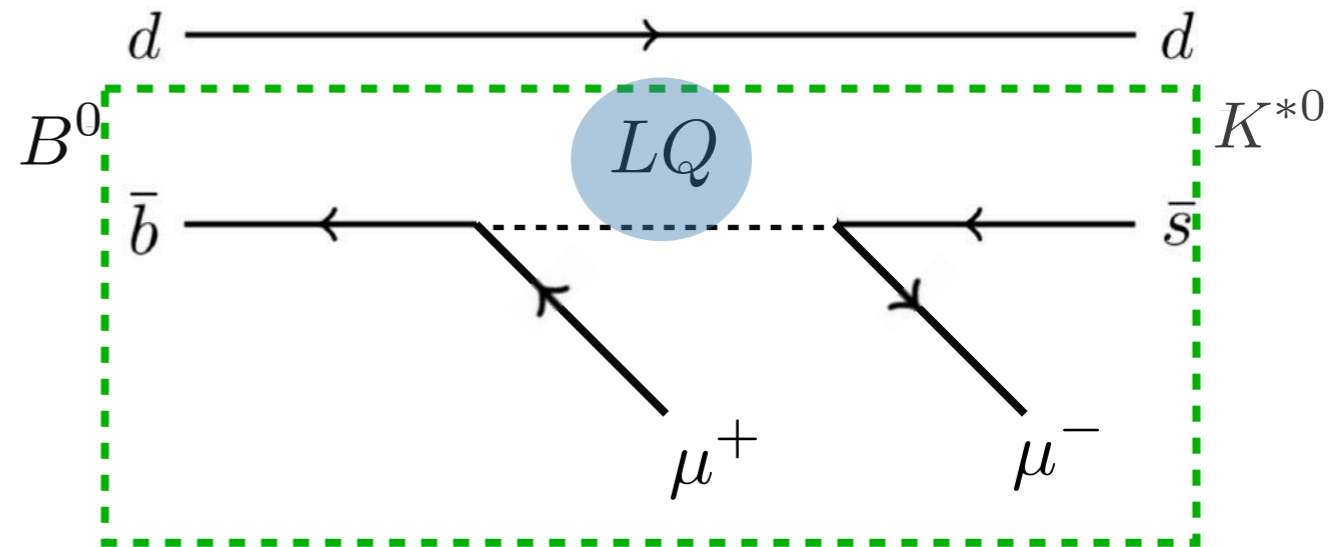


Why $B^0 \rightarrow K^{*0} [\rightarrow K^+ \pi^-] \mu^+ \mu^-$?

Standard Model



New physics scenario

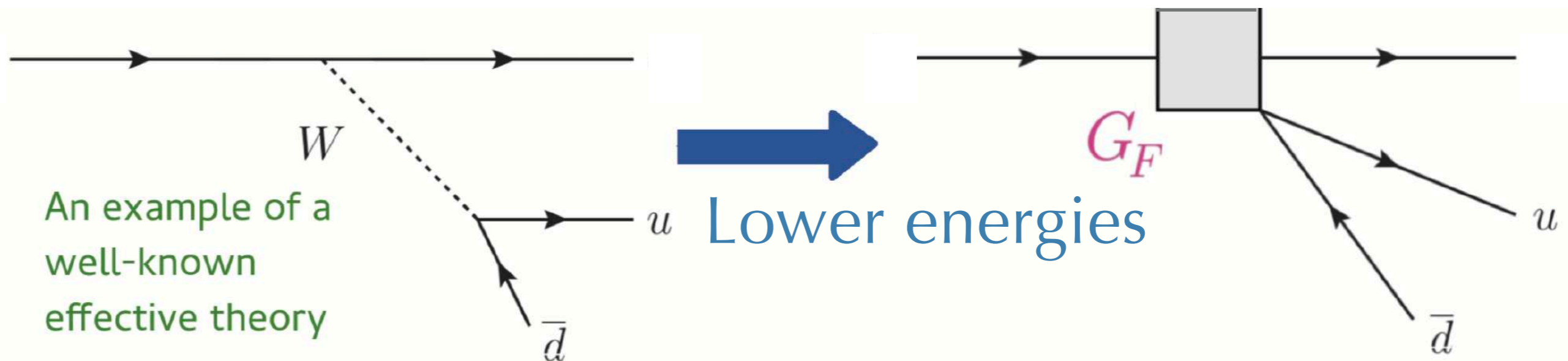


- A $b \rightarrow s \mu^+ \mu^-$ transition requires a **flavour-changing neutral current** \Rightarrow forbidden at tree-level in the Standard Model (SM)
- **As suppressed in the SM** more sensitive to **New Physics (NP)**
- As NP particles appear virtually can probe heavier NP scales than those accessible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

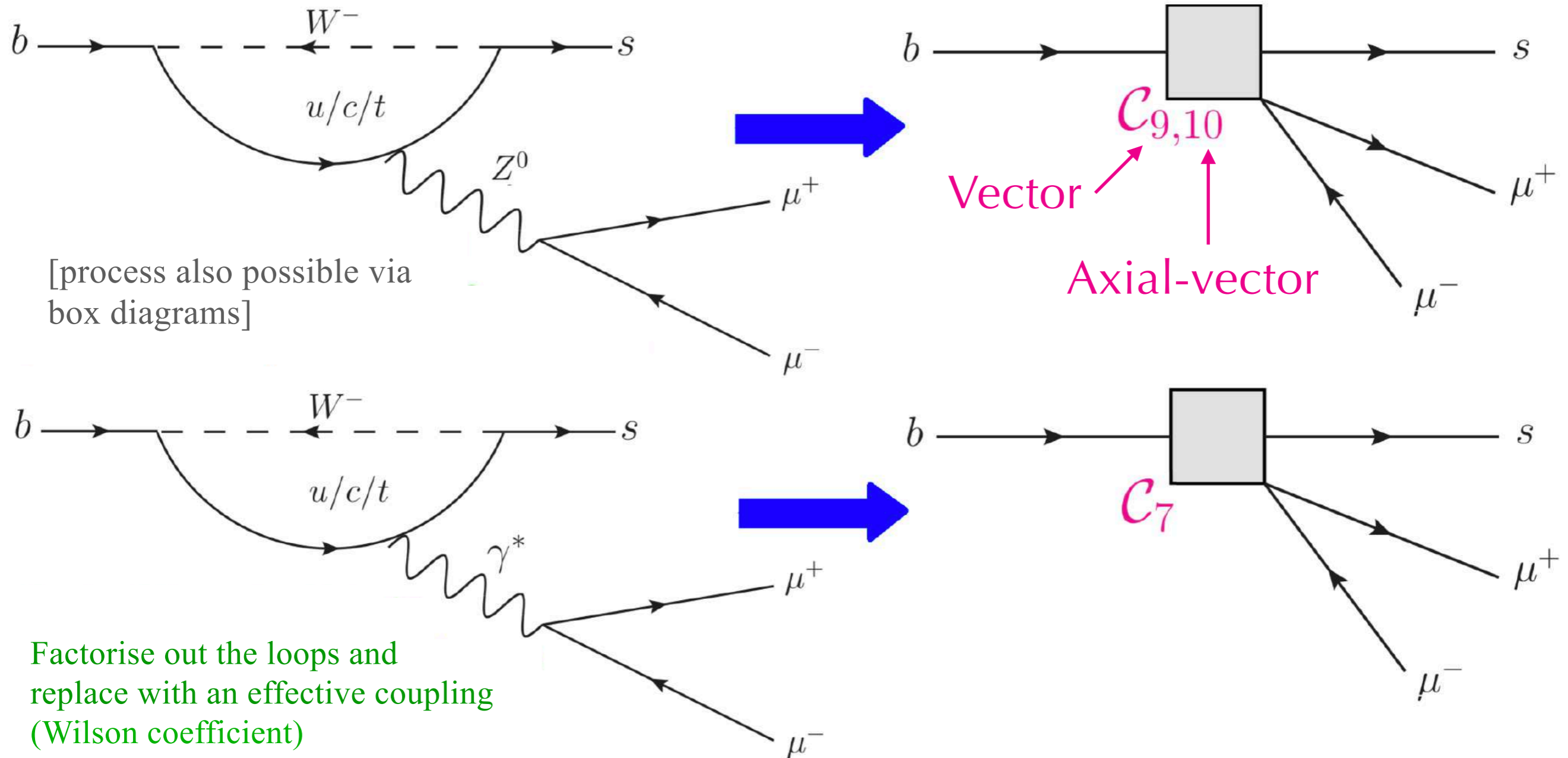
$b \rightarrow s \mu^+ \mu^-$ transitions in effective theory

- ▶ $b \rightarrow s \mu^+ \mu^-$ 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



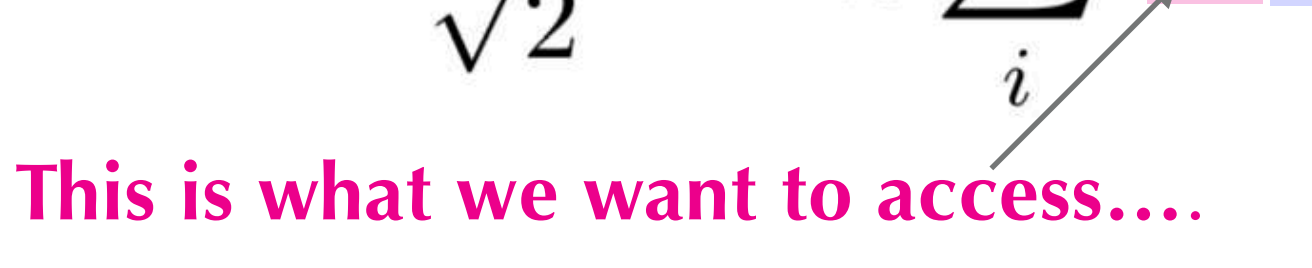
$b \rightarrow s \mu^+ \mu^-$ transitions in effective theory



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

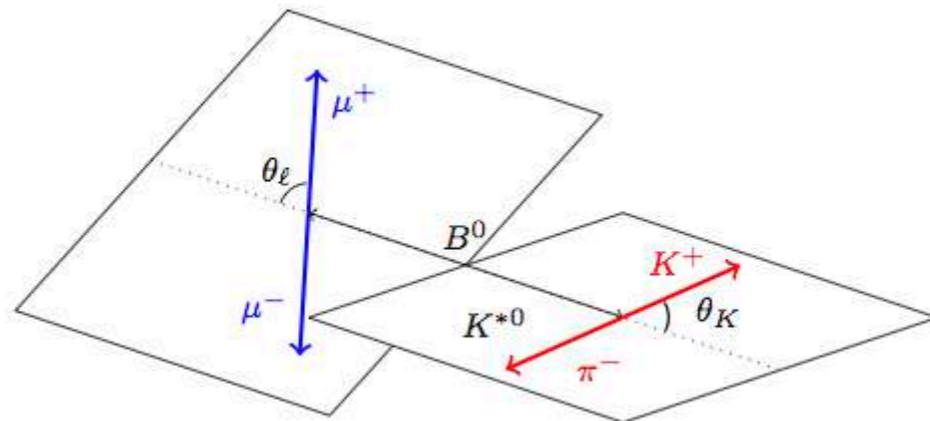
$b \rightarrow s \mu^+ \mu^-$ transitions in effective theory

- ▶ 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.

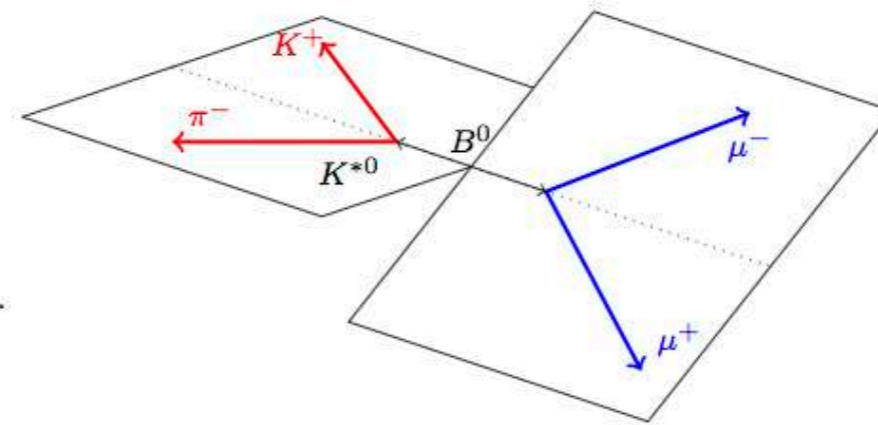
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C'_i \mathcal{O}'_i)$$


This is what we want to access....

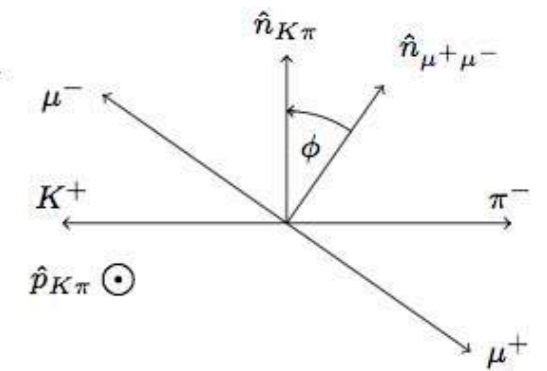
Local operators describe non-perturbative QCD,
large theory uncertainties



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



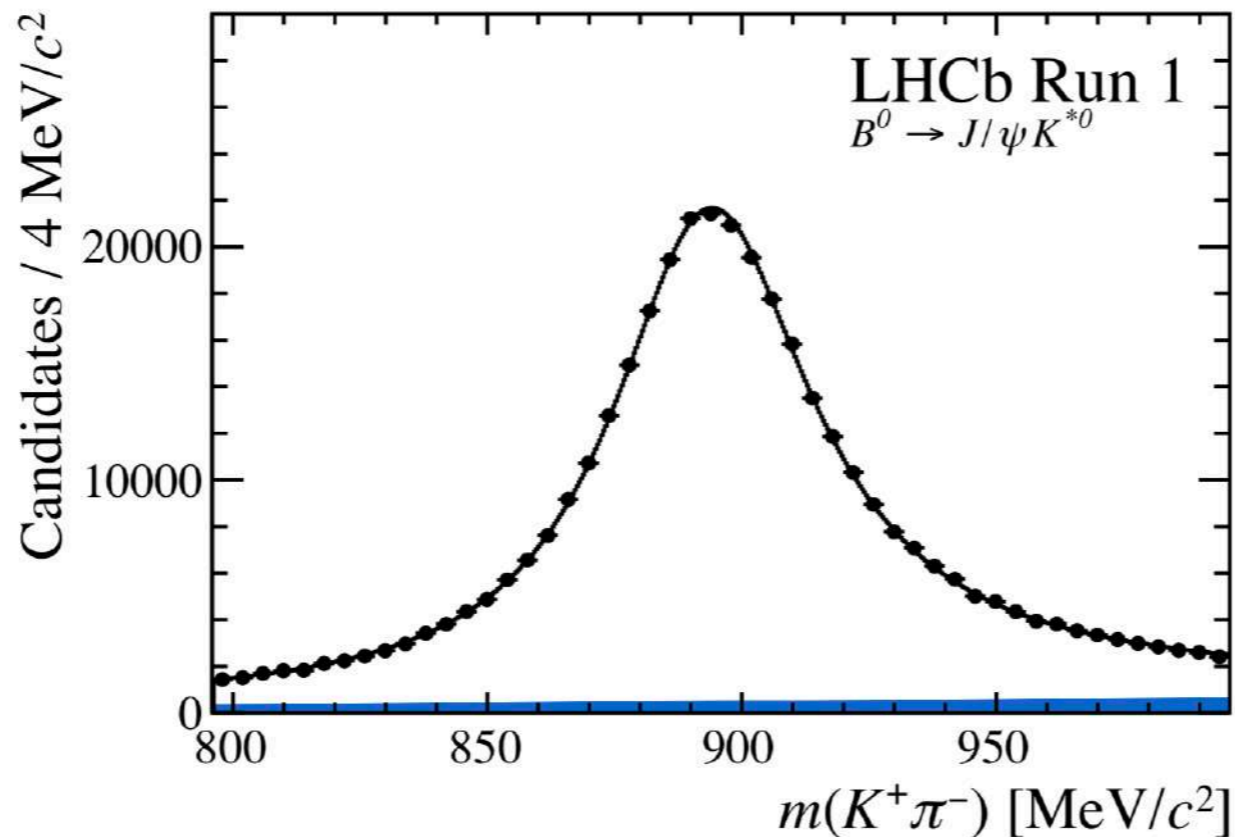
(b) ϕ definition for the B^0 decay



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



- 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 $K^{*0} \rightarrow K^+ \pi^-$

Previous LHCb measurement

(Run1 data only)

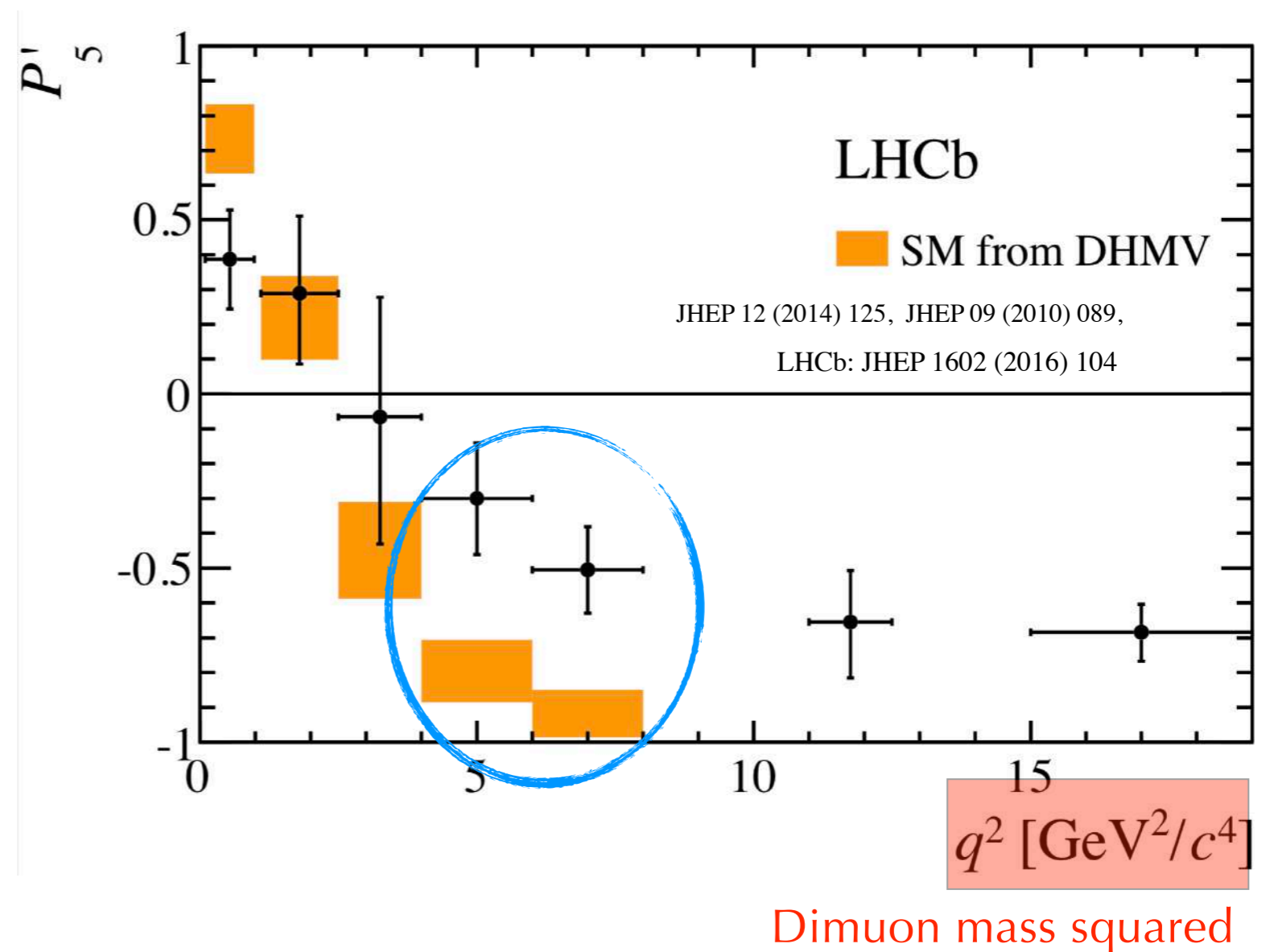
Distinctive local tension in P'_5

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

Local tension: 2.8σ

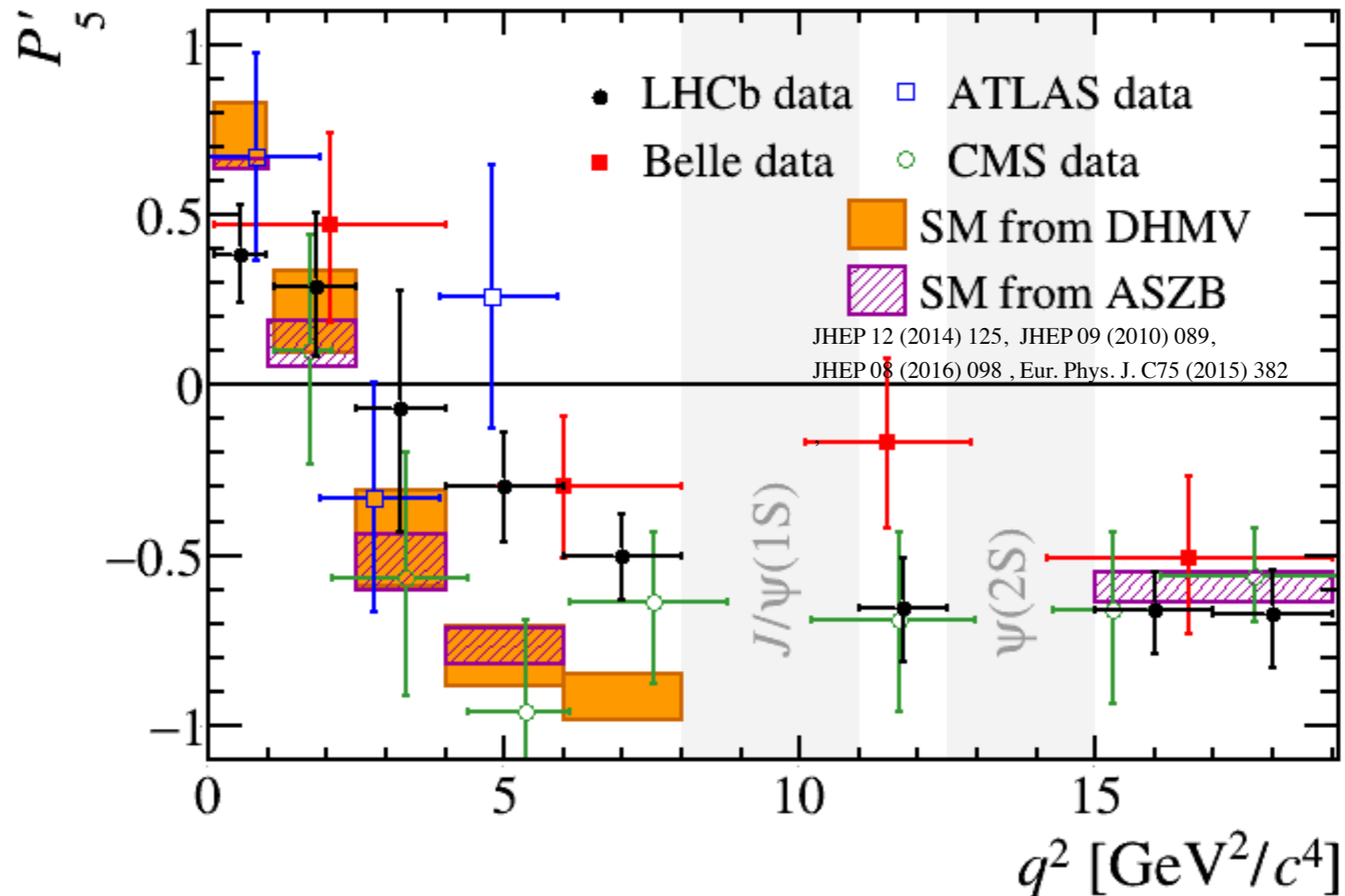
$$6.0 < q^2 < 8.0 \text{ GeV}^2/c^4$$

Local tension: 3.0σ



Distinctive local tension in P'_5

Angular analysis also performed by other collaborations



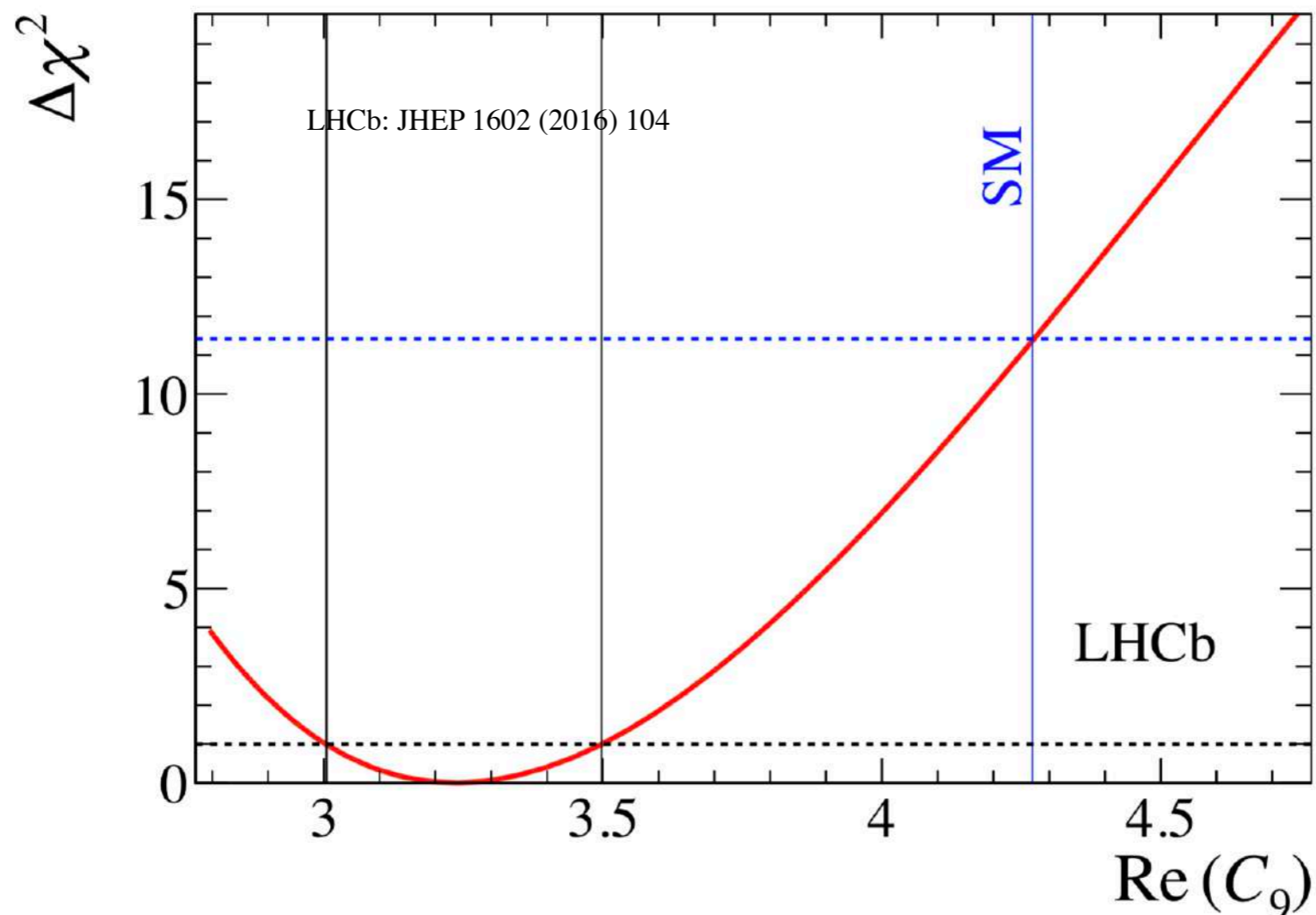
Belle: PRL 118 (2017), **CMS:**PLB 781 (2018) 517541

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

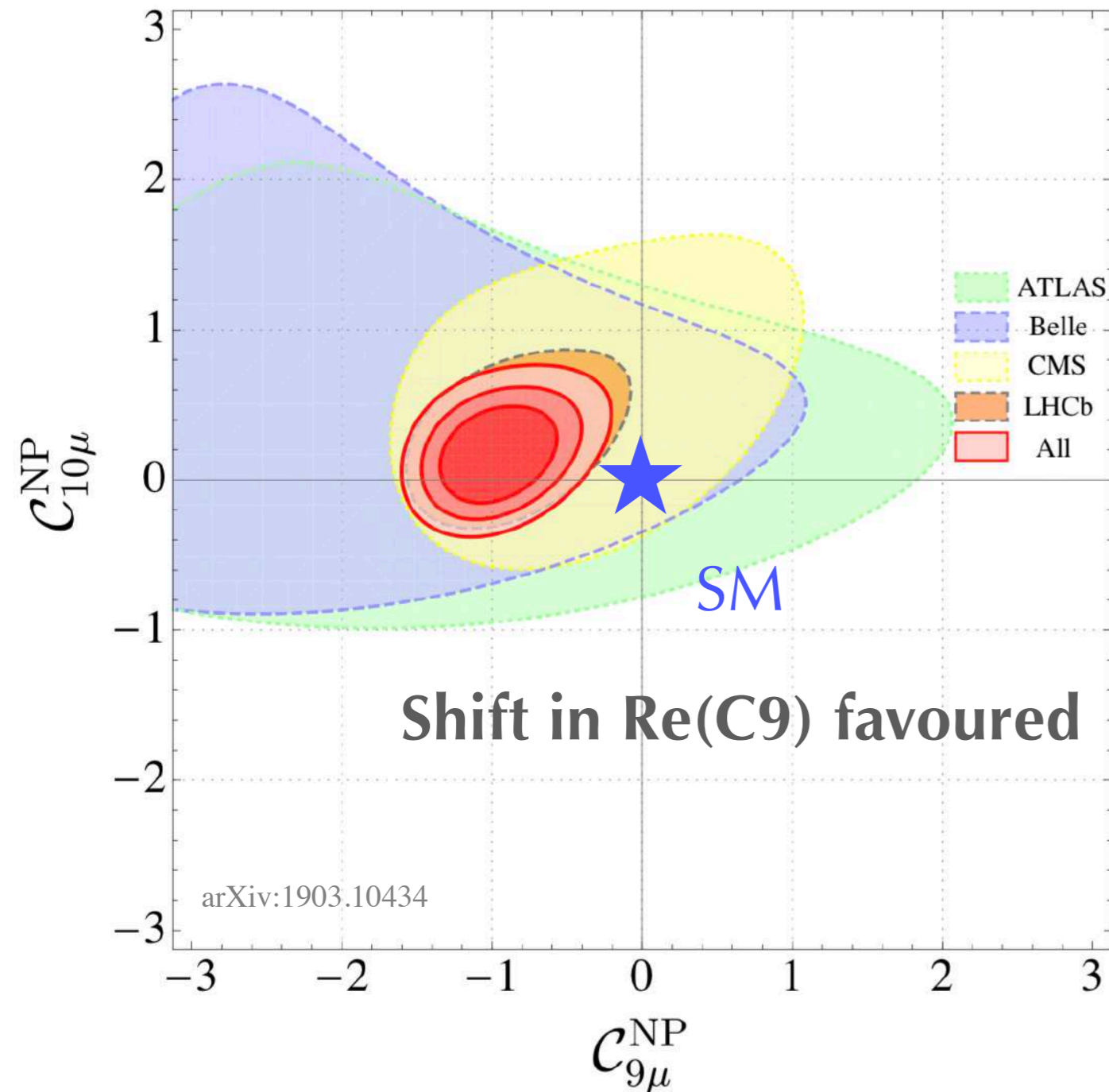
Overall tension seen with the SM

The value of the **Wilson Coefficient $Re(C_9)$** obtained from **the last LHCb 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



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



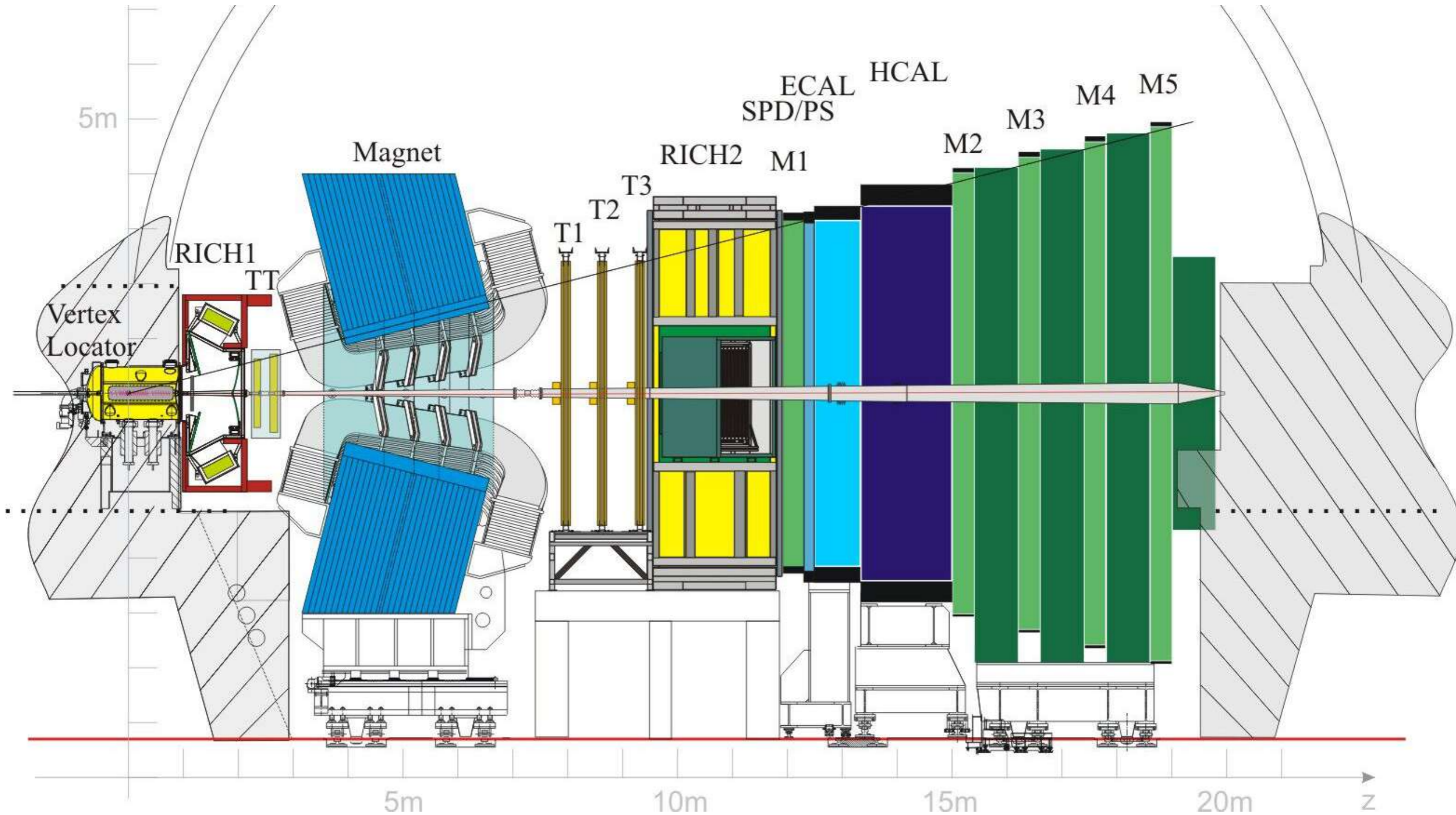
- ▶ Global fits performed to a **complete set of $b \rightarrow sll$ measurements** (rates, angular distributions)
- ▶ Fits yield up to 3-5 σ deviations in Wilson coefficients[*]
- ▶ Many global fits out there!

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

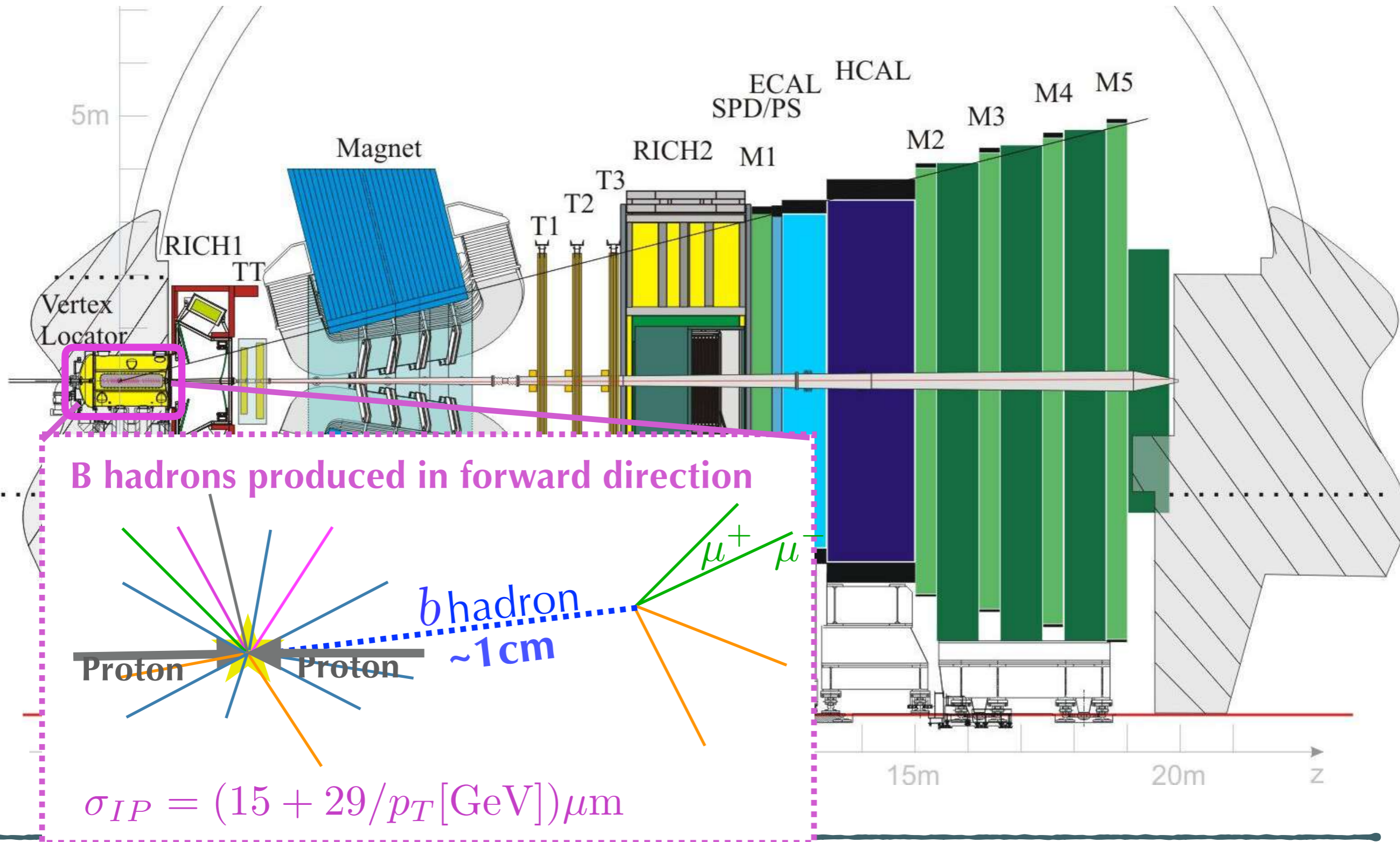
The LHCb detector

The LHCb experiment



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

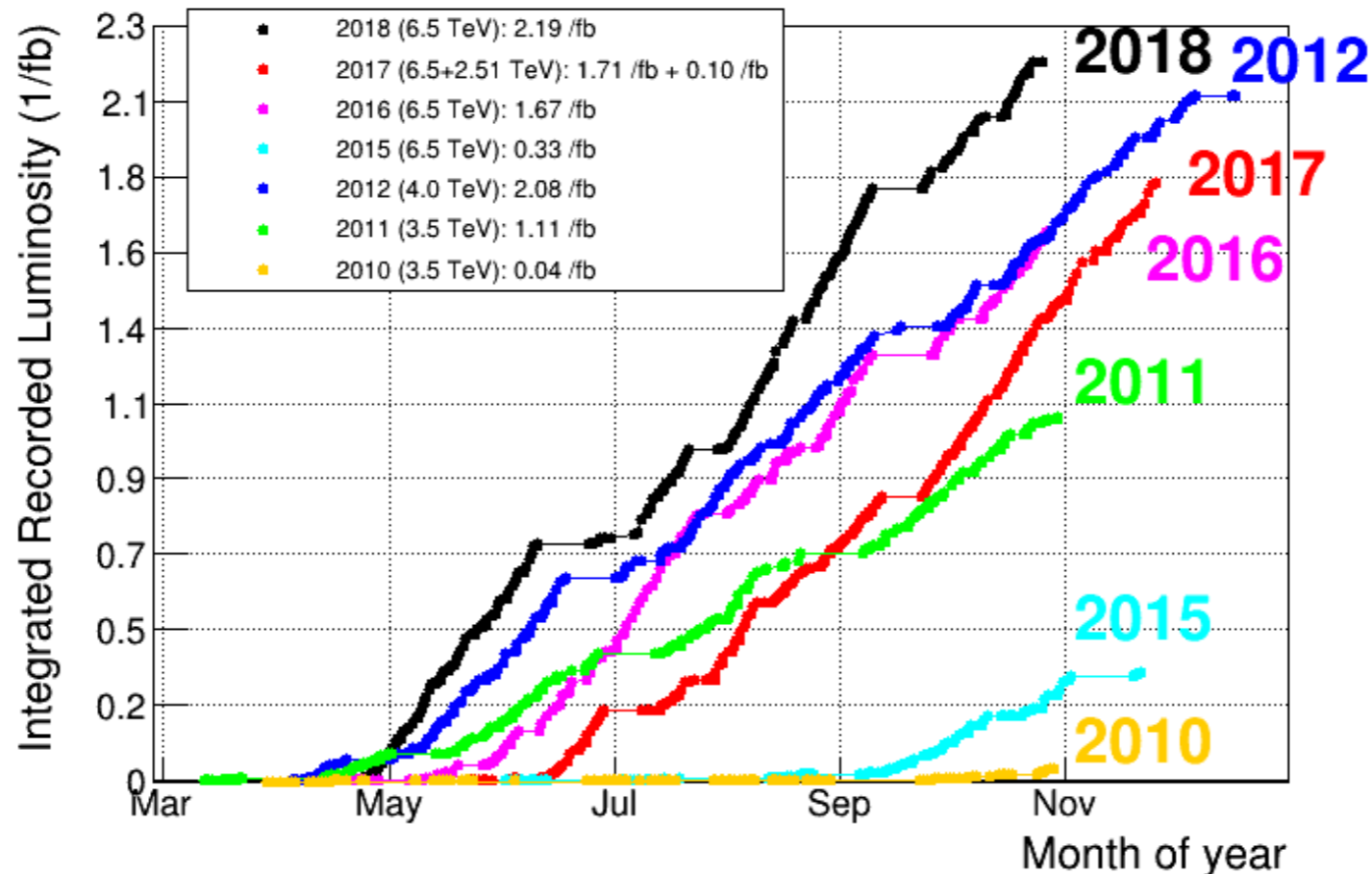
The LHCb experiment



The data set

Data-taking during Run 1 + 2

We use **2011**, **2012** (Run 1) and **2016** for this analysis



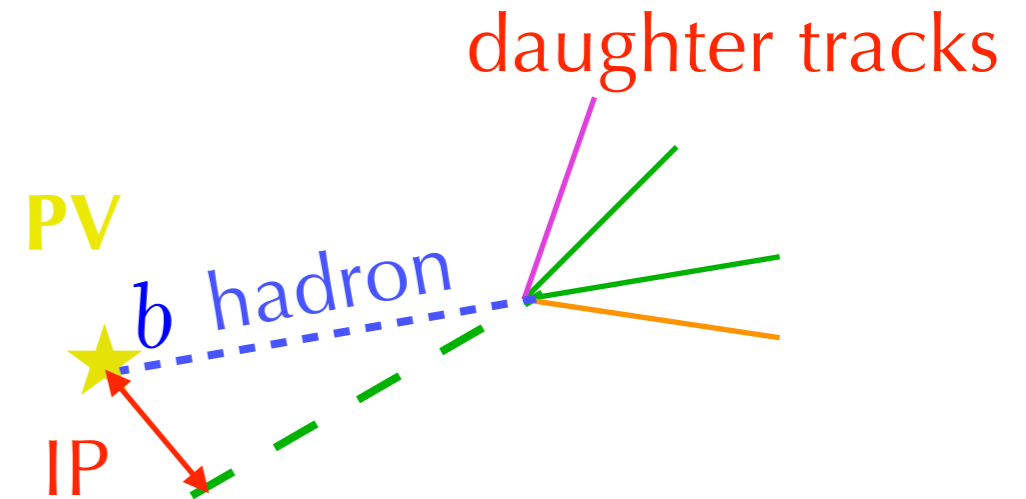
2011, 2012 and 2016 data collected from proton-proton collisions with centre of mass energies of $\sqrt{s} = 7, 8$ and 13 TeV respectively

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

Selection of candidates

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

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

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

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

\rightarrow = Misidentification

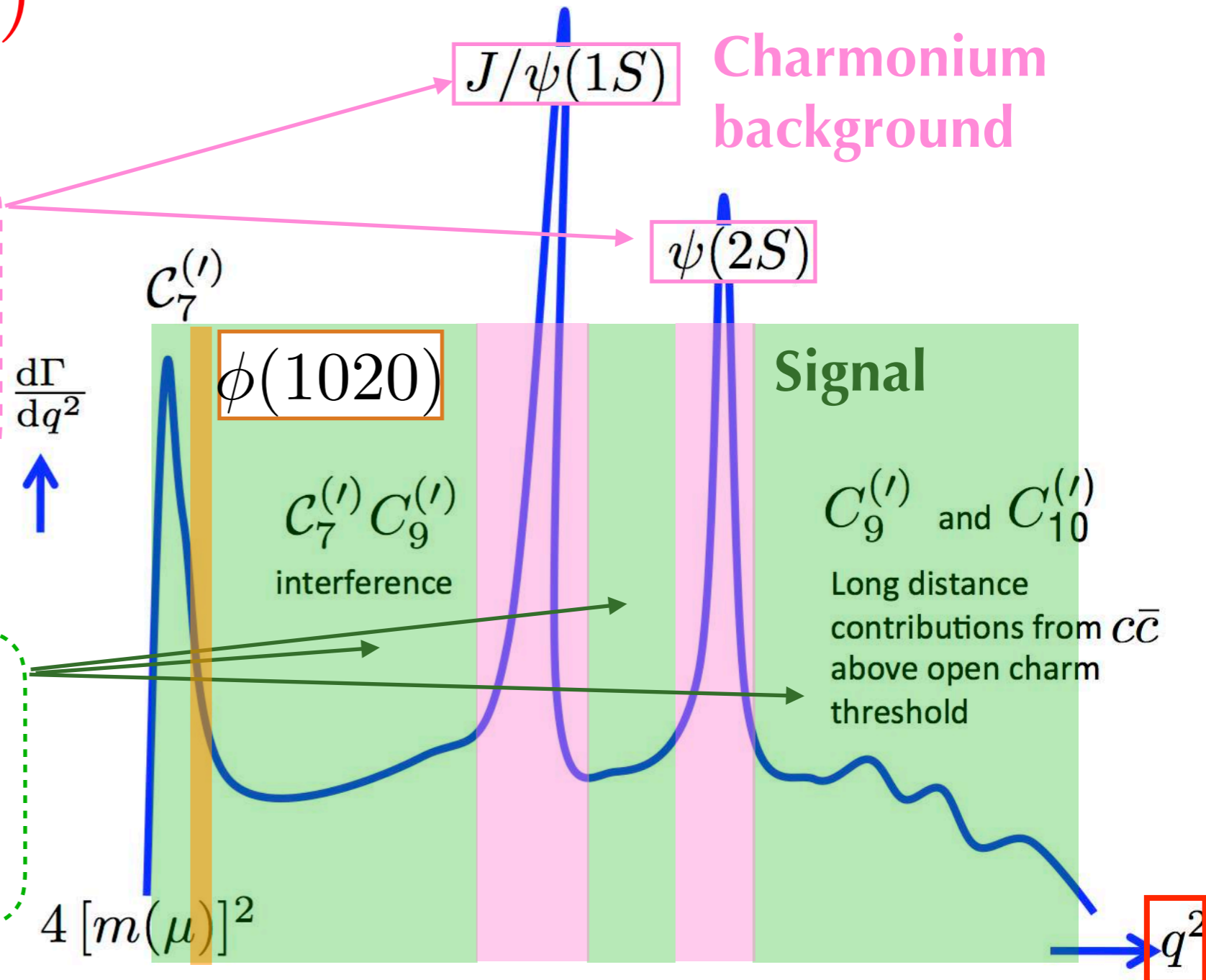
The regions we probe in q^2

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

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

Veto

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

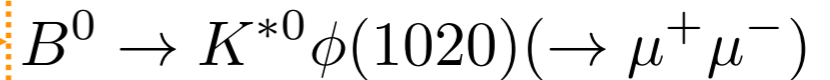


Binning in q^2

Bin	q^2 range [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]

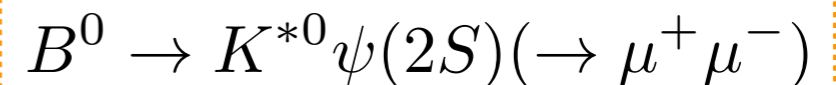
Narrow bins

Wide bins



Control channel

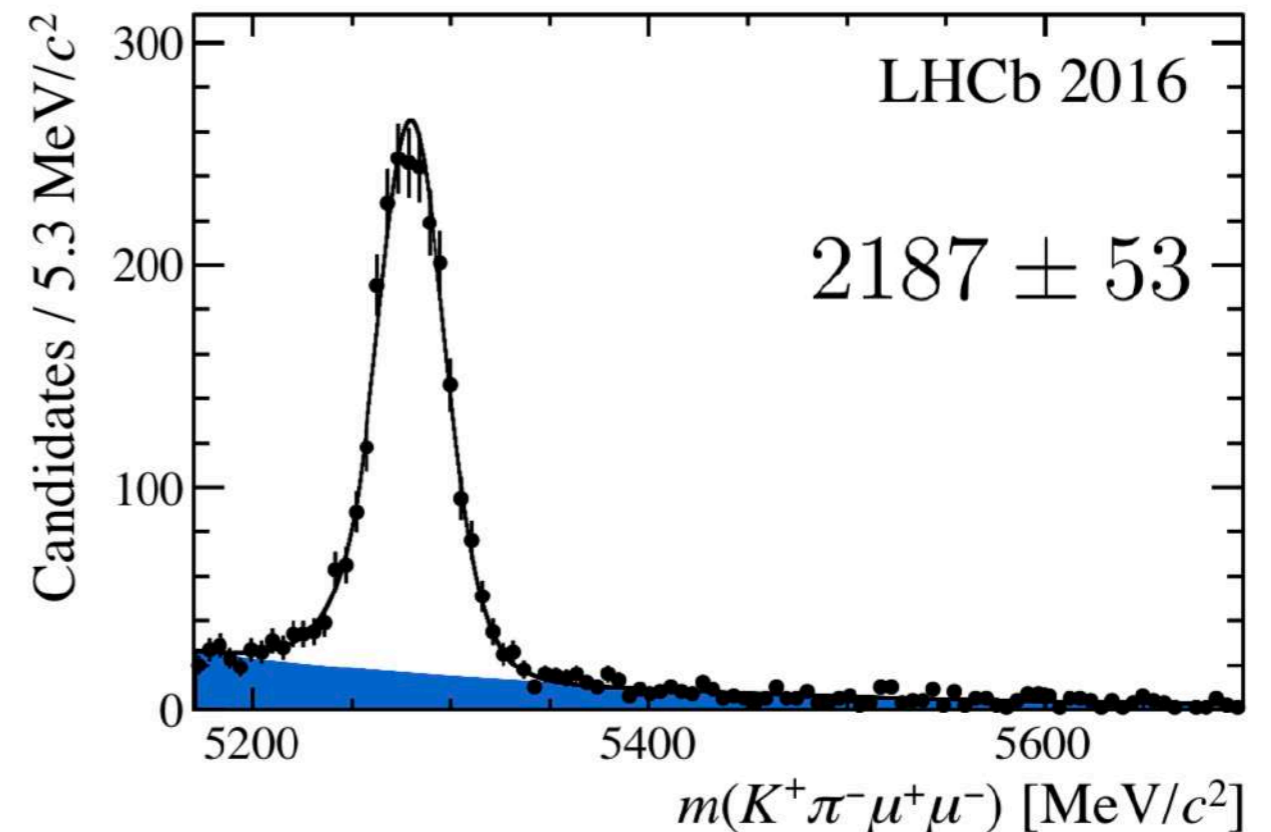
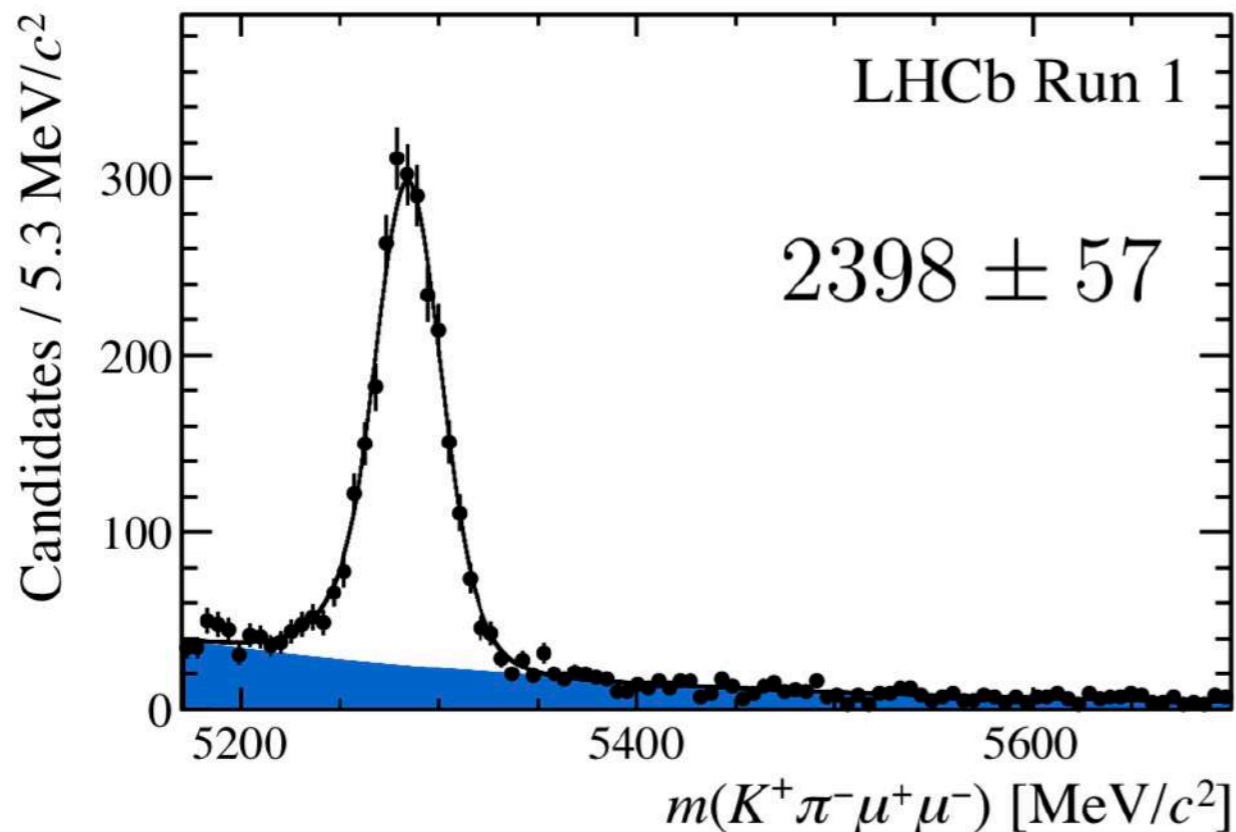
$$[8.0, 11.0] \text{ GeV}^2 / c^4$$



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

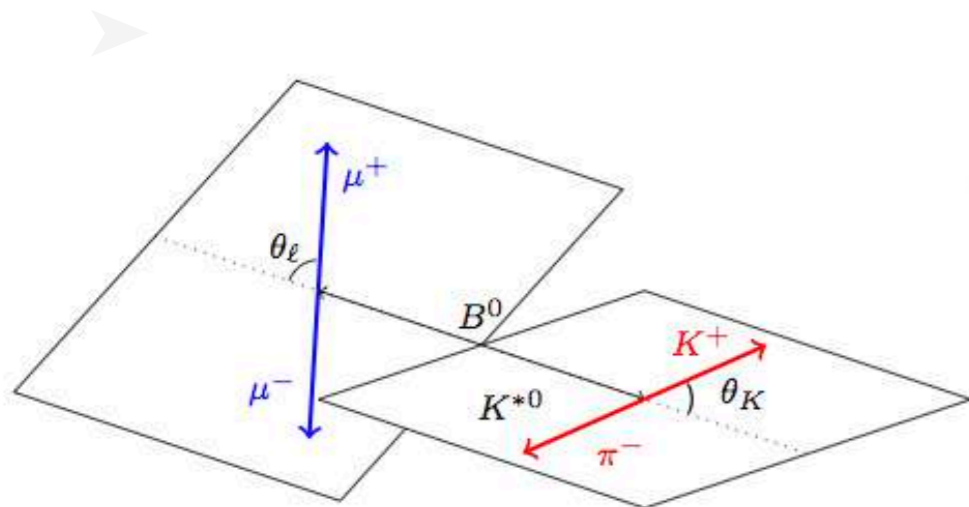
Remaining background is combinatorial only

Angular description of the decay

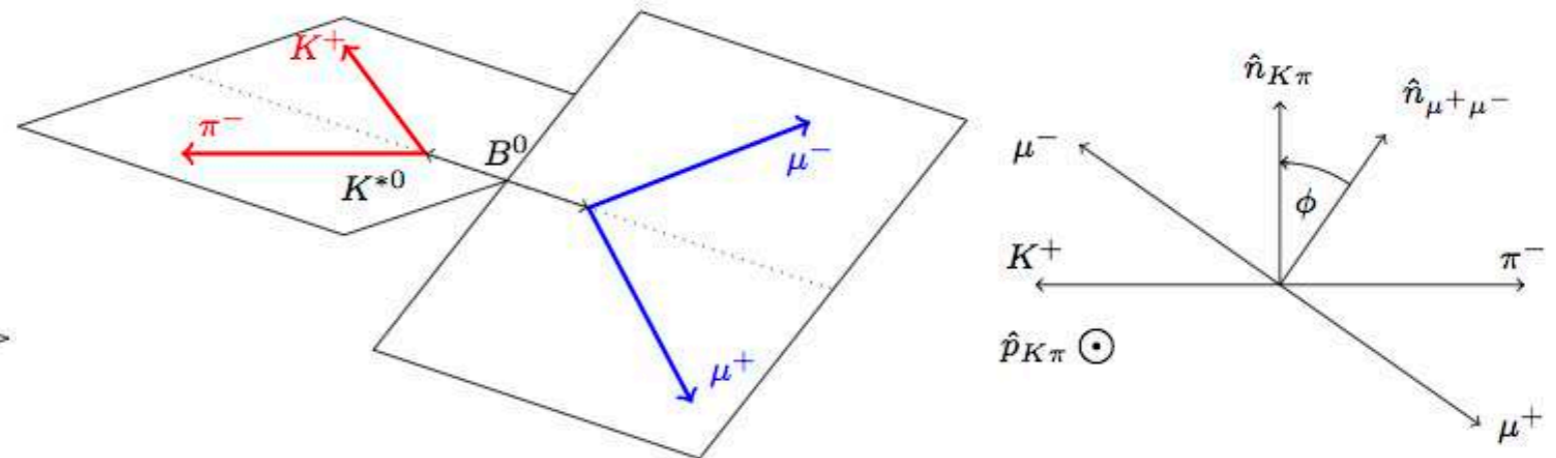
$B^0 \rightarrow K^{*0} [\rightarrow K^+ \pi^-] \mu^+ \mu^-$ angular description

- Decay rate fully described by:

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



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



(b) ϕ definition for the B^0 decay

$$\frac{d^4\Gamma[\bar{B}^0 \rightarrow \bar{K}^{*0} \mu^+ \mu^-]}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi} \sum_i \underbrace{I_i(q^2)}_{\text{angular coefficients}} \underbrace{f_i(\vec{\Omega})}_{\text{angular functions}}$$

angular coefficients angular functions

$B^0 \rightarrow K^{*0} [\rightarrow K^+ \pi^-] \mu^+ \mu^-$ 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	$\frac{3}{4} \left[\mathcal{A}_{\parallel}^L ^2 + \mathcal{A}_{\perp}^L ^2 + \mathcal{A}_{\parallel}^R ^2 + \mathcal{A}_{\perp}^R ^2 \right]$	$\sin^2 \theta_K$
1c	$ \mathcal{A}_0^L ^2 + \mathcal{A}_0^R ^2$	$\cos^2 \theta_K$
2s	$\frac{1}{4} \left[\mathcal{A}_{\parallel}^L ^2 + \mathcal{A}_{\perp}^L ^2 + \mathcal{A}_{\parallel}^R ^2 + \mathcal{A}_{\perp}^R ^2 \right]$	$\sin^2 \theta_K \cos 2\theta_l$
2c	$- \mathcal{A}_0^L ^2 - \mathcal{A}_0^R ^2$	$\cos^2 \theta_K \cos 2\theta_l$
3	$\frac{1}{2} \left[\mathcal{A}_{\perp}^L ^2 - \mathcal{A}_{\parallel}^L ^2 + \mathcal{A}_{\perp}^R ^2 - \mathcal{A}_{\parallel}^R ^2 \right]$	$\sin^2 \theta_K \sin^2 \theta_l \cos 2\phi$
	• • •	• • •

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

Where the physics lies:

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

$$\begin{aligned}
 \mathcal{A}_{\perp}^{\text{L(R)}} &= \mathcal{N} \sqrt{2\lambda} \left\{ \left[(C_9^{\text{eff}} + C_9^{\prime\text{eff}}) \mp (C_{10}^{\text{eff}} + C_{10}^{\prime\text{eff}}) \right] \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} (C_7^{\text{eff}} + C_7^{\prime\text{eff}}) T_1(q^2) \right\} \\
 \mathcal{A}_{\parallel}^{\text{L(R)}} &= -\mathcal{N} \sqrt{2} (m_B^2 - m_{K^*}^2) \left\{ \left[(C_9^{\text{eff}} - C_9^{\prime\text{eff}}) \mp (C_{10}^{\text{eff}} - C_{10}^{\prime\text{eff}}) \right] \frac{A_1(q^2)}{m_B - m_{K^*}} \right. \\
 &\quad \left. + \frac{2m_b}{q^2} (C_7^{\text{eff}} - C_7^{\prime\text{eff}}) T_2(q^2) \right\} \\
 \mathcal{A}_0^{\text{L(R)}} &= -\frac{\mathcal{N}}{2m_{K^*} \sqrt{q^2}} \left\{ \left[(C_9^{\text{eff}} - C_9^{\prime\text{eff}}) \mp (C_{10}^{\text{eff}} - C_{10}^{\prime\text{eff}}) \right] \right. \\
 &\quad \times \left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*}) A_1(q^2) - \lambda \frac{A_2(q^2)}{m_B + m_{K^*}} \right] \\
 &\quad \left. + 2m_b (C_7^{\text{eff}} - C_7^{\prime\text{eff}}) \left[(m_B^2 + 3m_{K^*}^2 - q^2) T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2} T_3(q^2) \right] \right\}
 \end{aligned}$$

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, \bar{B}^0 decays → $S_i(q_{min}^2, q_{max}^2)$
CP-averaged

S_i basis

8 CP-averaged observables are extracted from the fit

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d(\Gamma + \bar{\Gamma})}{d\cos\theta_l d\cos\theta_K d\phi} \Big|_P = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K \right. \quad (29)$$

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

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

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

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

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

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

$$\begin{aligned}
 P_1 &= \frac{2 S_3}{(1 - F_L)} = A_T^{(2)} \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2} \\
 P_2 &= \frac{2 A_{\text{FB}}}{3 (1 - F_L)}, & P'_{4,5,8} &= \frac{S_{4,5,8}}{\sqrt{F_L(1 - F_L)}}, \\
 P_3 &= \frac{-S_9}{(1 - F_L)}, & P'_6 &= \frac{S_7}{\sqrt{F_L(1 - F_L)}}.
 \end{aligned}$$

The angular PDF: $P_i^{(')}$ basis

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

$P_i^{(')}$ 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 & $P_i^{(')}$

Extracted by reparametrising the fit PDF in this basis

$$\begin{aligned}
 P_1 &= \frac{2 S_3}{(1 - F_L)} = \boxed{A_T^{(2)}} \\
 P_2 &= \frac{2 A_{\text{FB}}}{3 (1 - F_L)}, \\
 P_3 &= \frac{-S_9}{(1 - F_L)}, \\
 P'_{4,5,8} &= \frac{S_{4,5,8}}{\sqrt{F_L(1 - F_L)}}, \\
 P'_6 &= \frac{S_7}{\sqrt{F_L(1 - F_L)}}.
 \end{aligned}$$

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

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

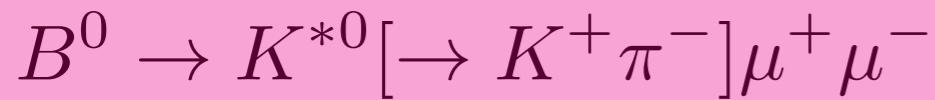
nuisance parameters

angular coefficients

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

The full fit model

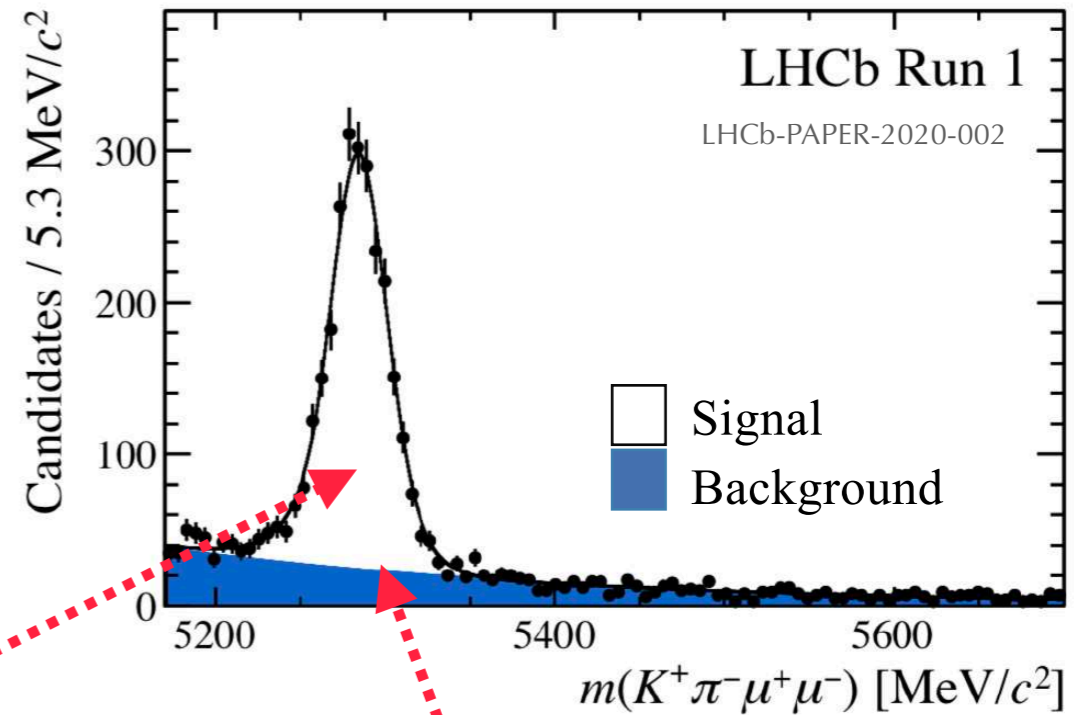
Signal



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

angular PDF: $\sum_I S_i q_{\text{bin}}^2 f_i(\Omega)$

Gauss with radiative tail



Background

Combinatorial
(random tracks
which are
incorrectly vertexed)

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

Polynomials (assume factorisation in angles)

Exponential

The full fit model: simultaneous fitting

Run 1

shared

Not shared

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

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

$$\sum_I S_i |_{q_{\text{bin}}^2} f_i(\Omega)$$

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

2016

shared

Not shared

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

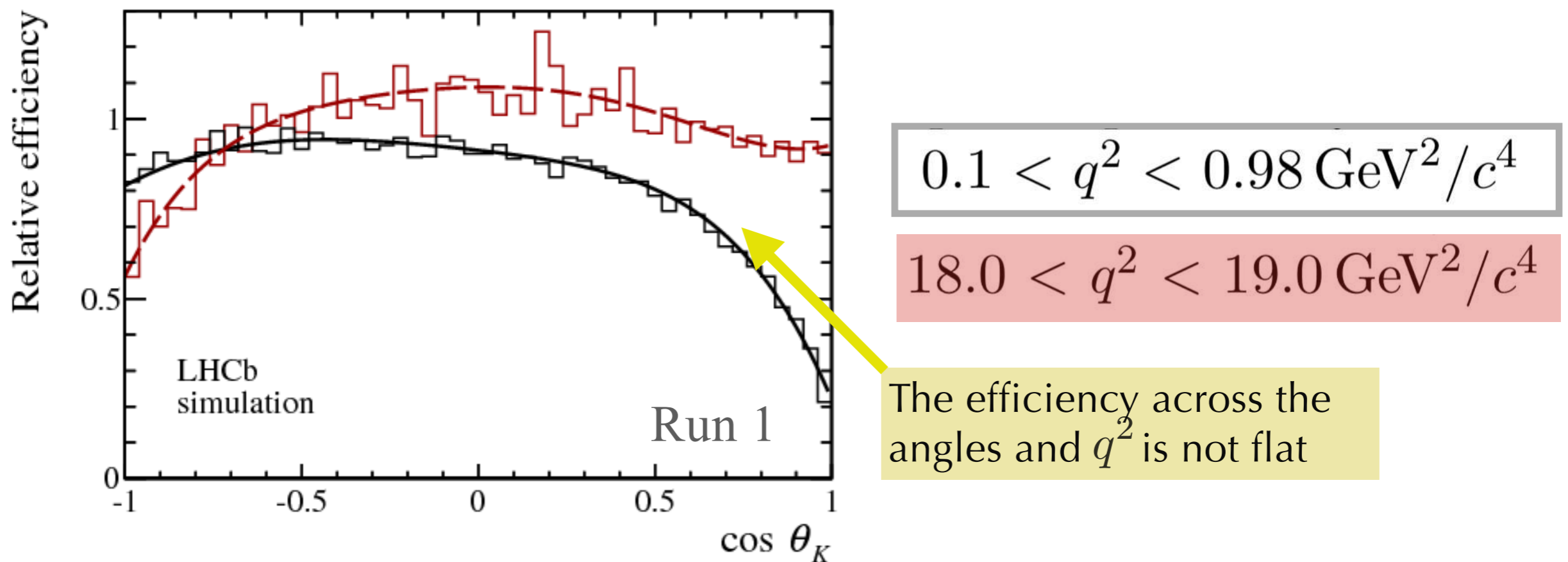
$$\mathcal{P}_{\text{bkg}}(\vec{\Omega}, m) = \mathcal{P}_{\text{bkg}}(\vec{\Omega}) \times \mathcal{P}_{\text{bkg}}(m)$$

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

The angular acceptance

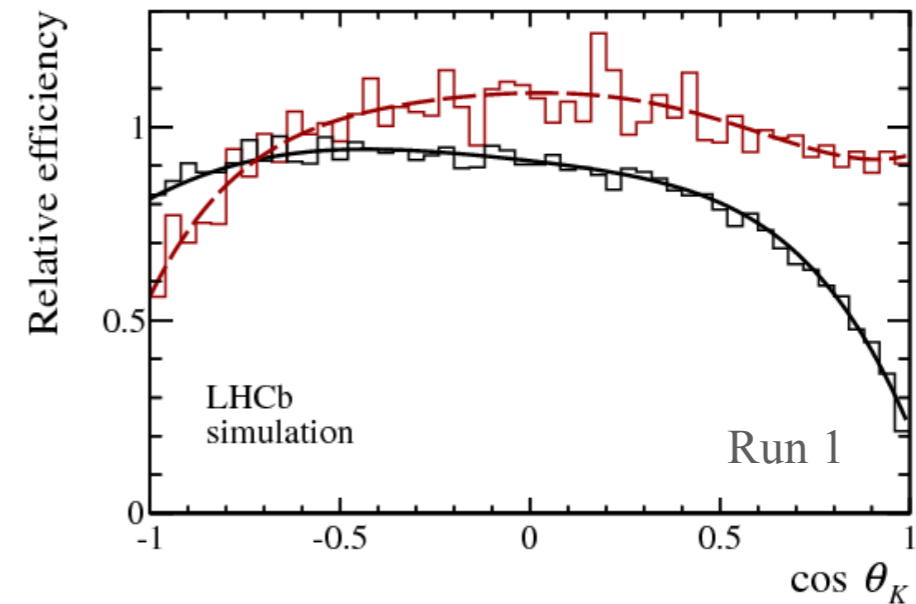
Modelling the efficiency

- 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**



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

$$c_{k,l,m,n} = \frac{1}{N'} \sum_{i=1}^N w_i \left[\left(\frac{2k+1}{2} \right) \left(\frac{2l+1}{2} \right) \left(\frac{2m+1}{2} \right) \left(\frac{2n+1}{2} \right) \right]$$

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

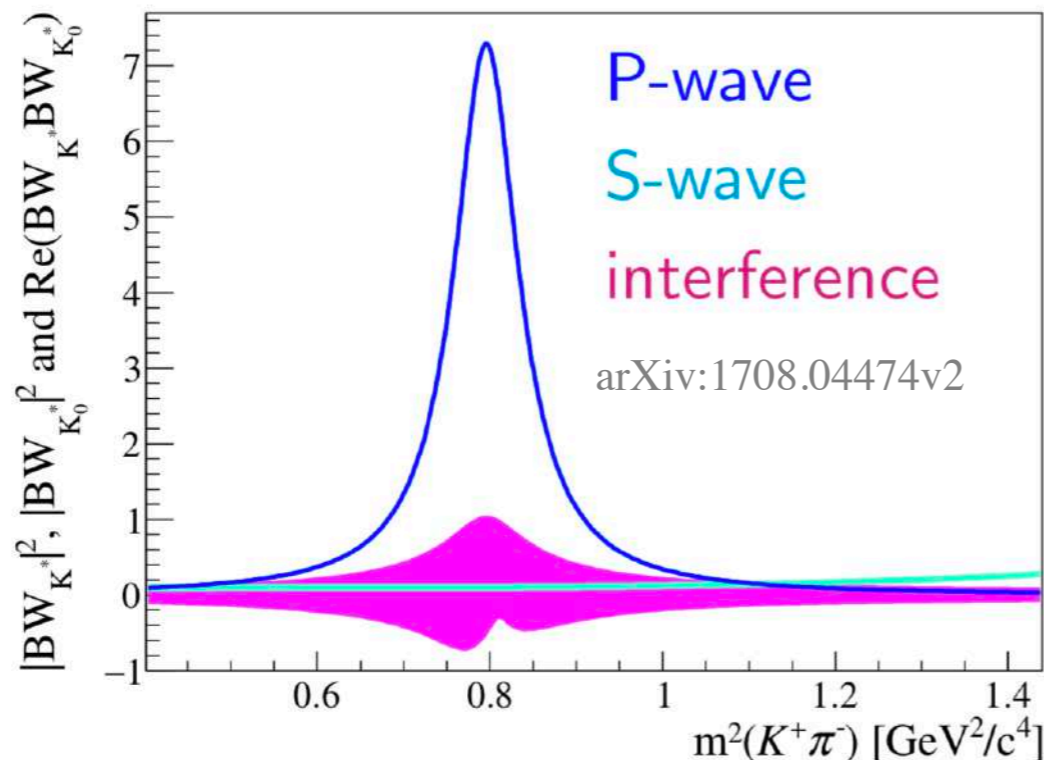
$$\text{Correction to sim.} \times P(\cos \theta_\ell, k) P(\cos \theta_K, l) P(\phi, m) P(q^2, n)$$

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

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d(\Gamma + \bar{\Gamma})}{d\cos\theta_l d\cos\theta_K d\phi} \Big|_{S+P} = (1 - F_S) \frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d(\Gamma + \bar{\Gamma})}{d\cos\theta_l d\cos\theta_K d\phi} \Big|_P$$



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

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

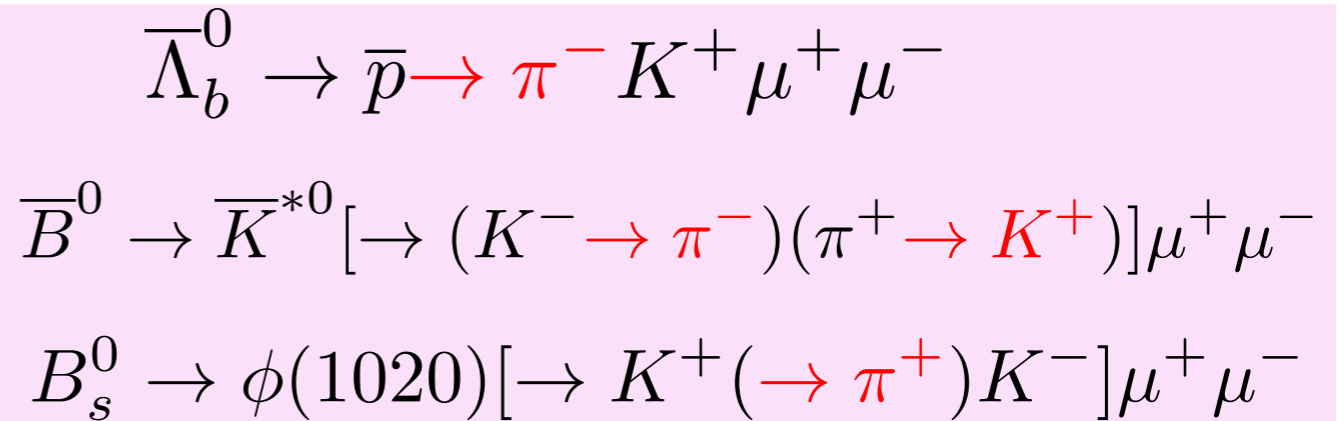
Systematic uncertainties small compared to stat. error

Systematic uncertainties

Peaking background

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

Events are then injected into pseudoexperiments



Bias corrections

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

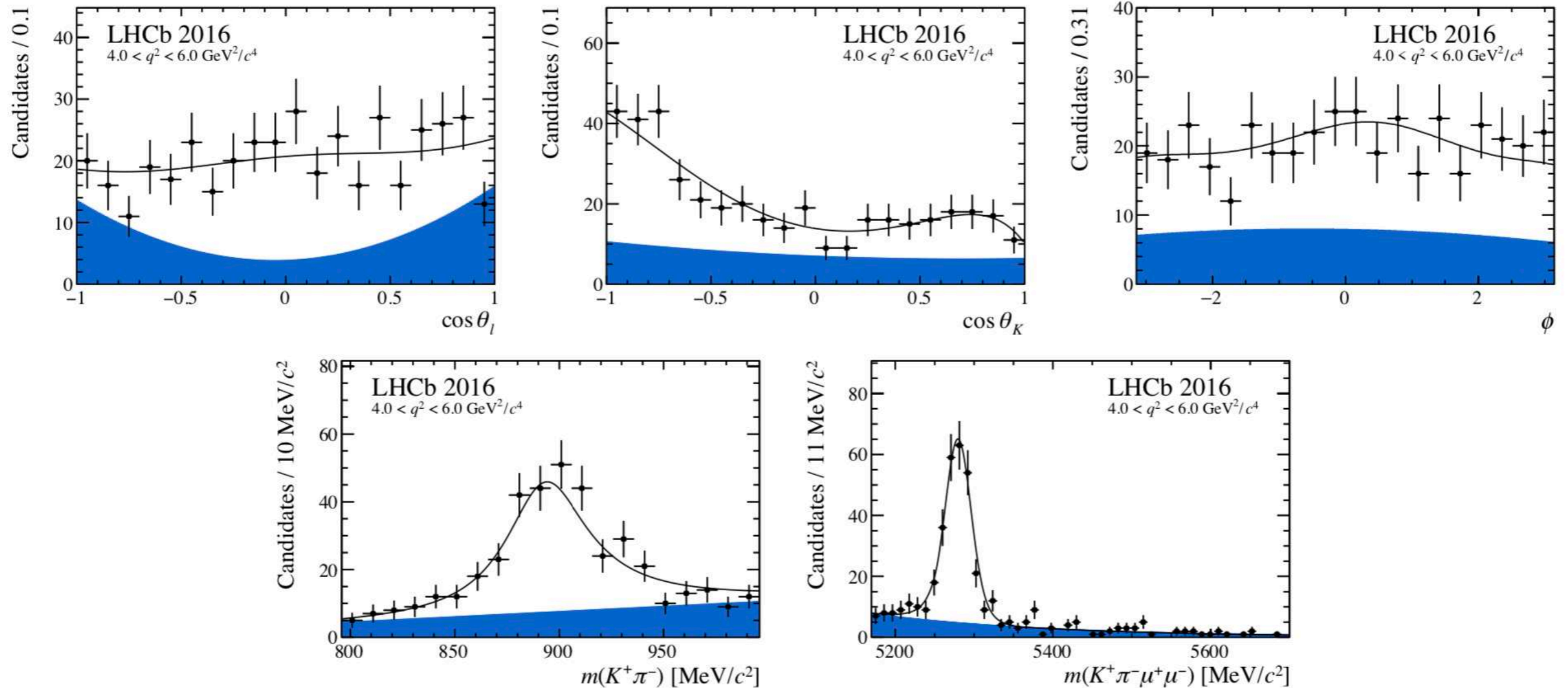
If F_S is small, it is biased towards higher values, which in turn biases the P-wave

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

If this term is biased towards smaller values Magnitude of P-wave biased towards larger values

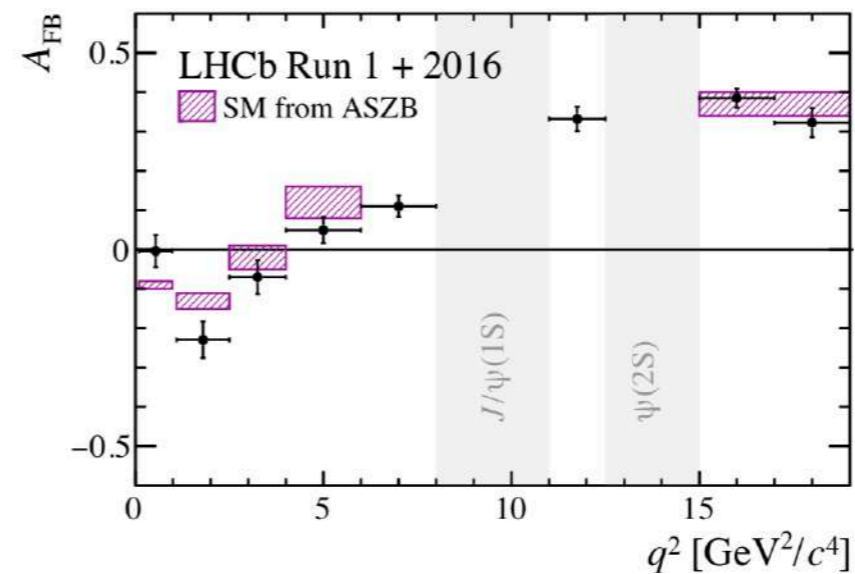
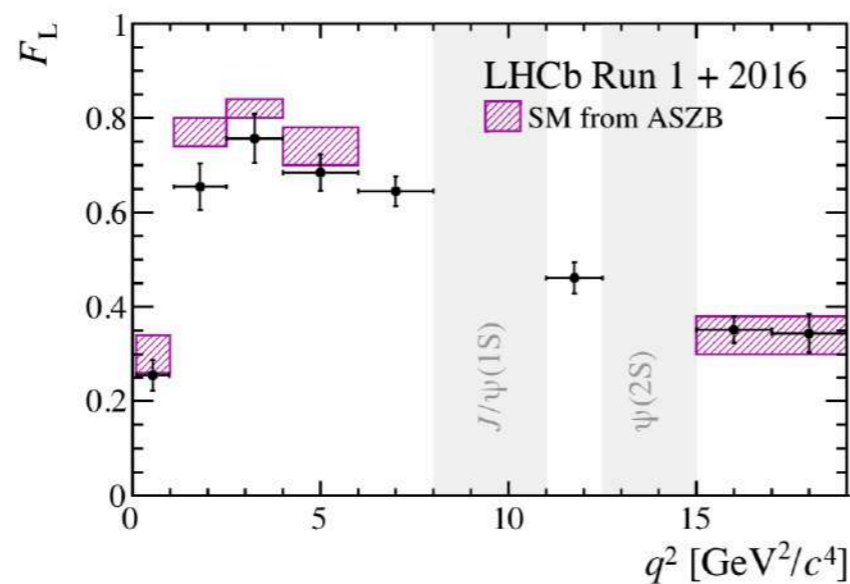
Results

Fit projections 2016 example

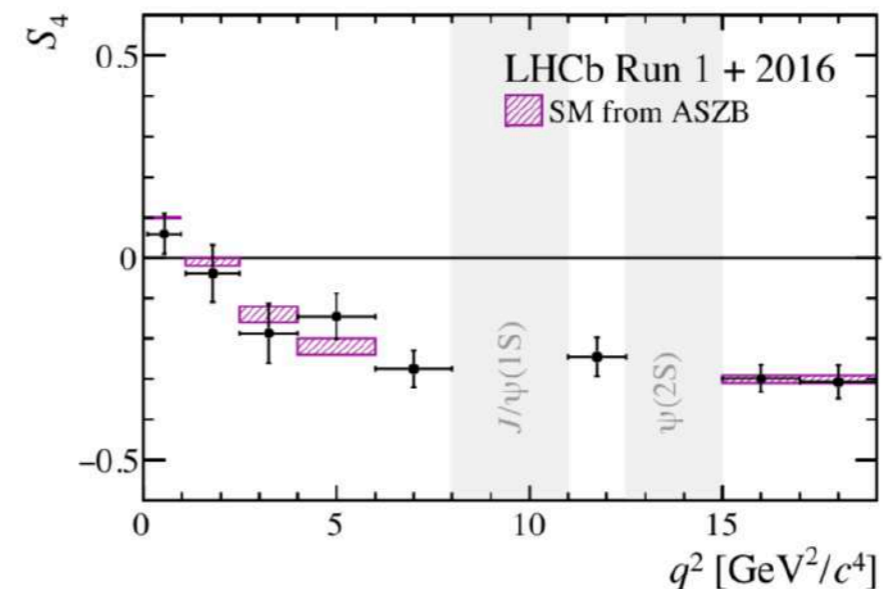
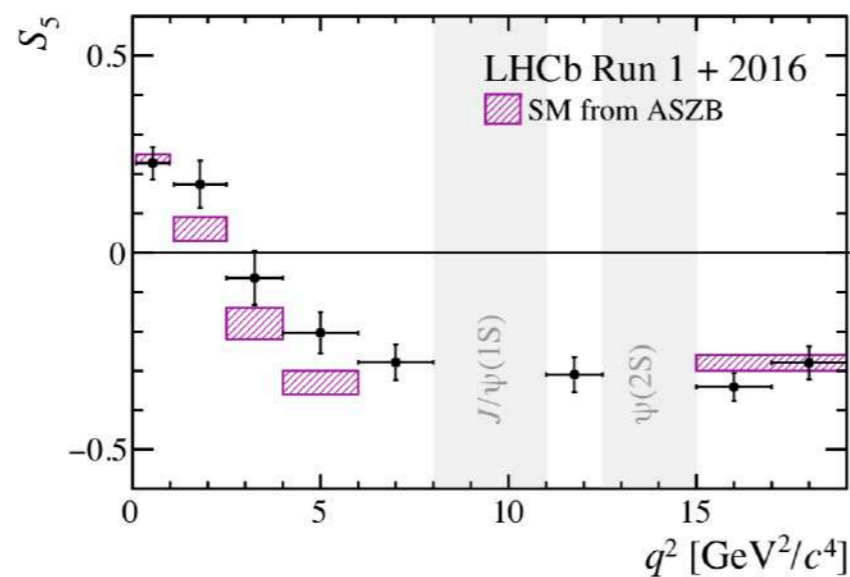


Fit projections for the bin $4.0 < q^2 < 6.0 \text{ GeV}^2/c^4$ for 2016 data

CP-averaged angular observables



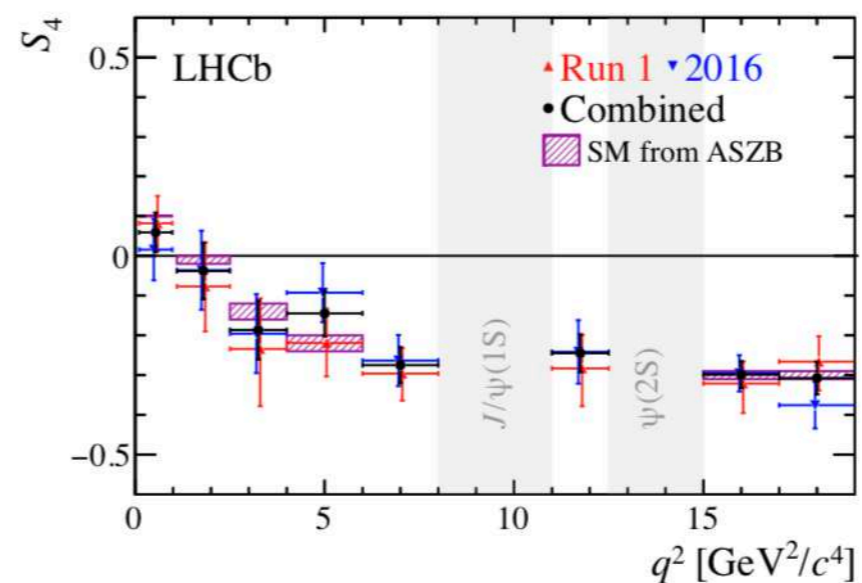
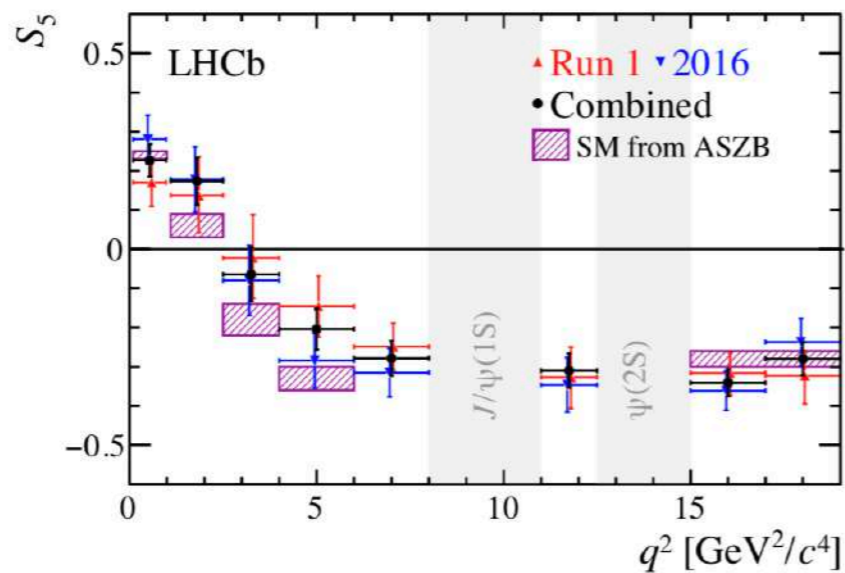
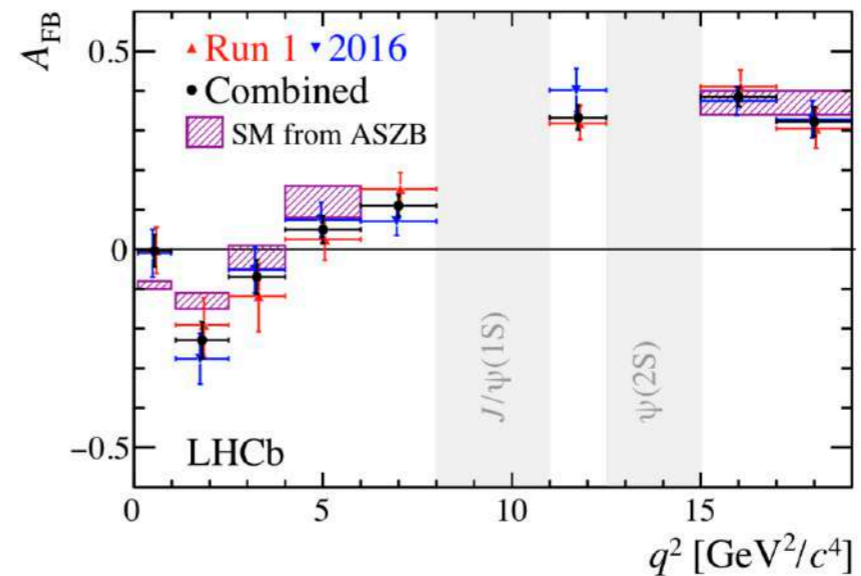
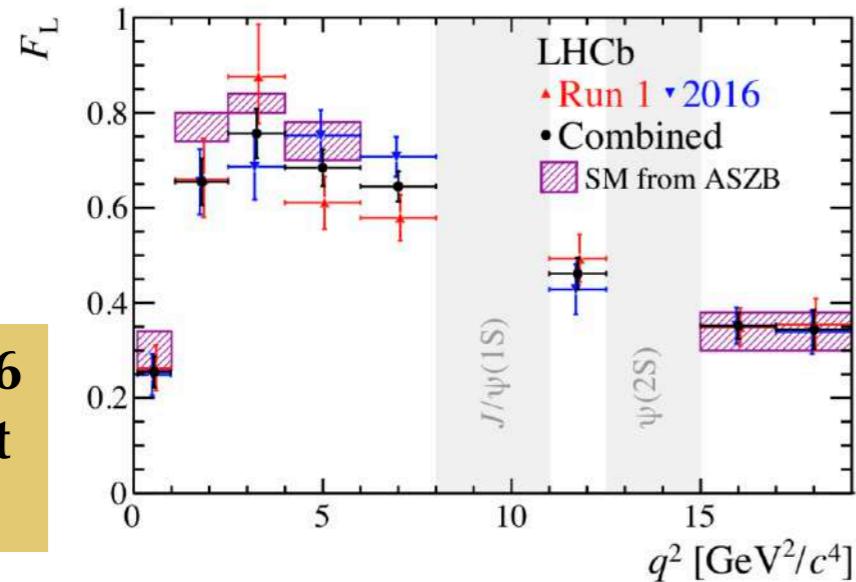
Theory predictions
from JHEP 08 (2016)
098, Eur. Phys. J. C75
(2015) 382



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 illustrative 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

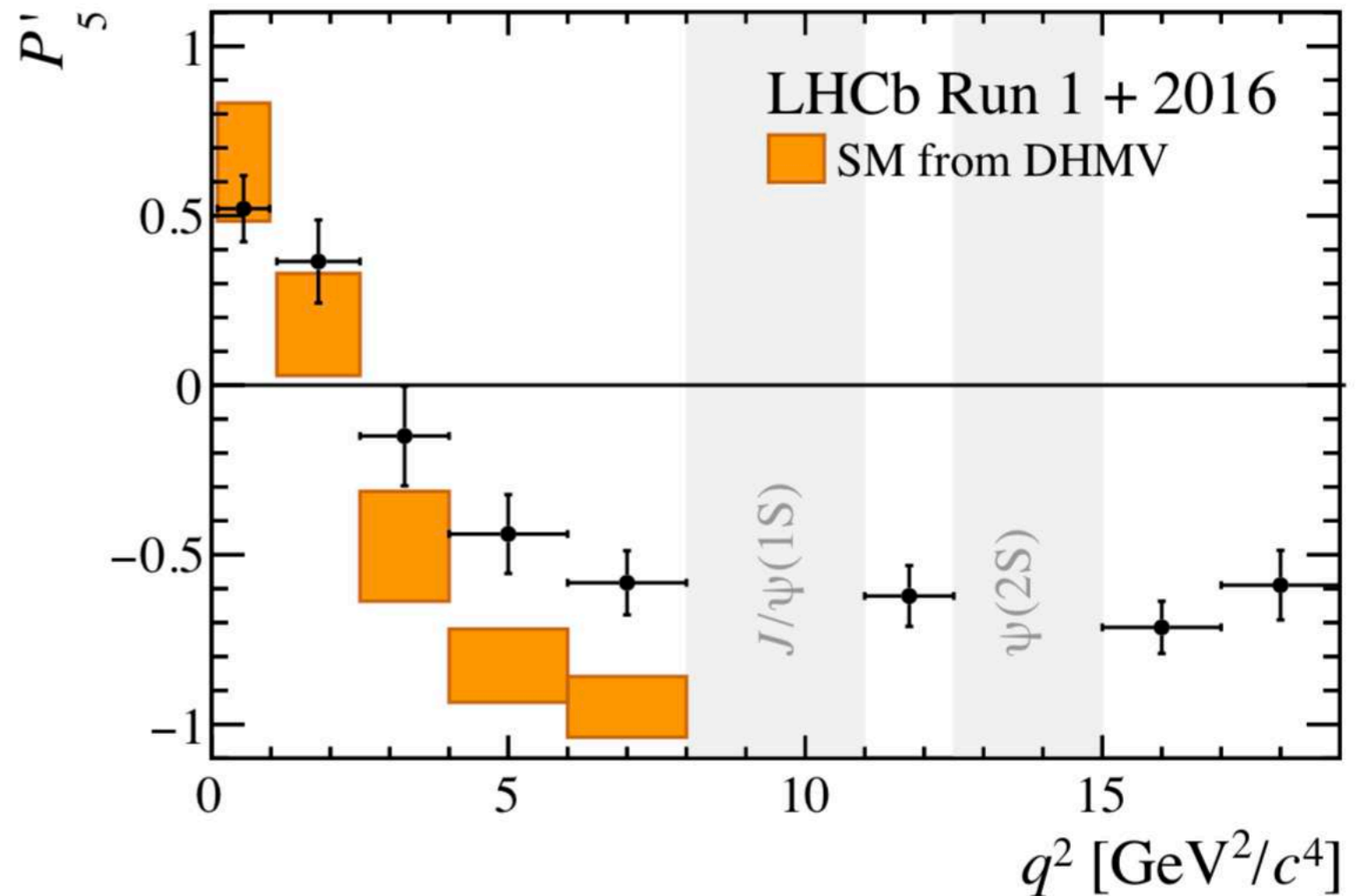
Theory predictions from JHEP 12 (2014) 125, JHEP 09 (2010) 089,

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

Run1+2016: 2.5σ

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

Run1+2016: 2.9σ



Local tension in P'_5

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

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

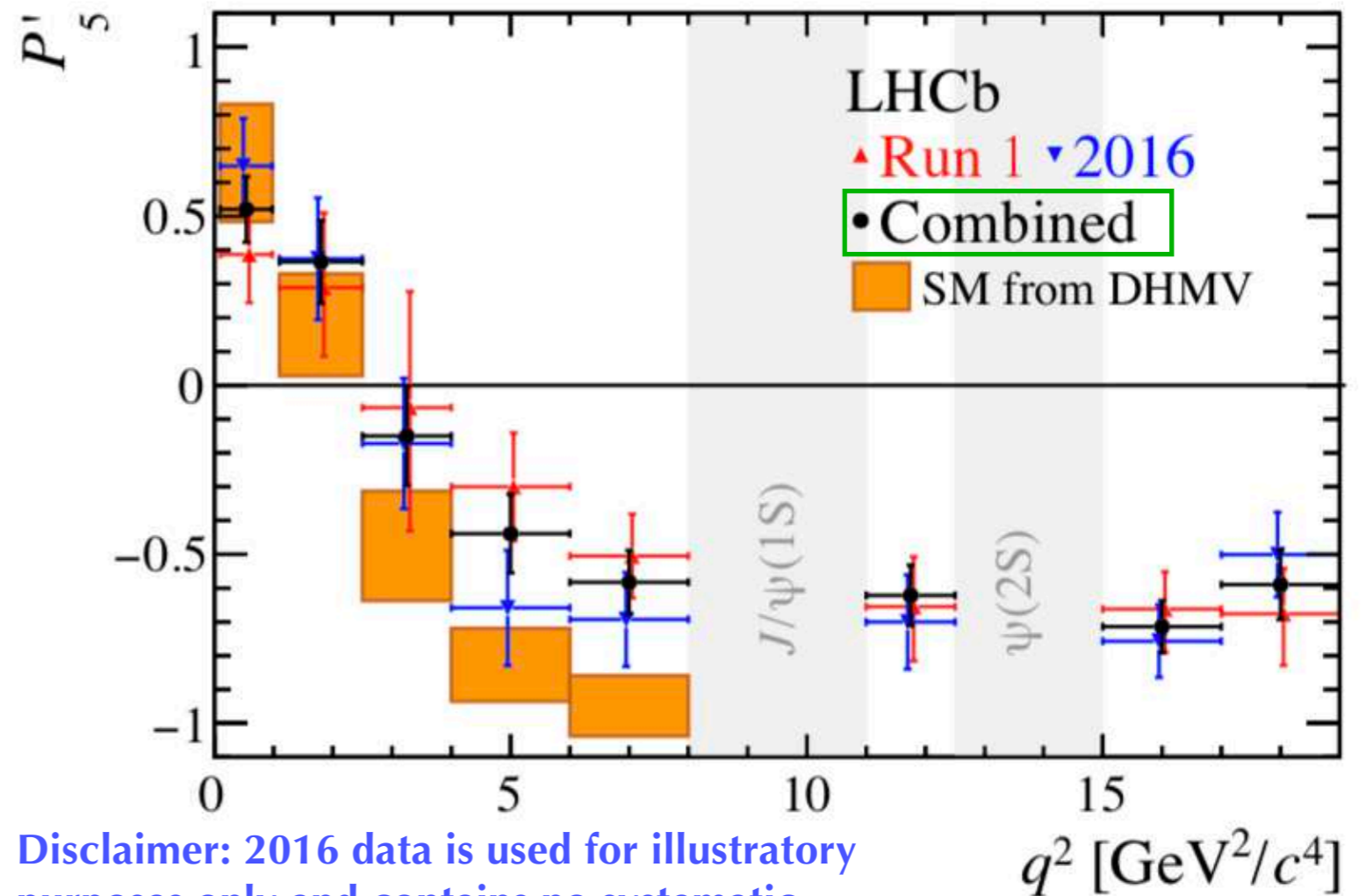
Run1+2016: 2.5σ

Run1 only: 2.8σ

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

Run1+2016: 2.9σ

Run1 only: 3.0σ



Disclaimer: 2016 data is used for illustrative 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:

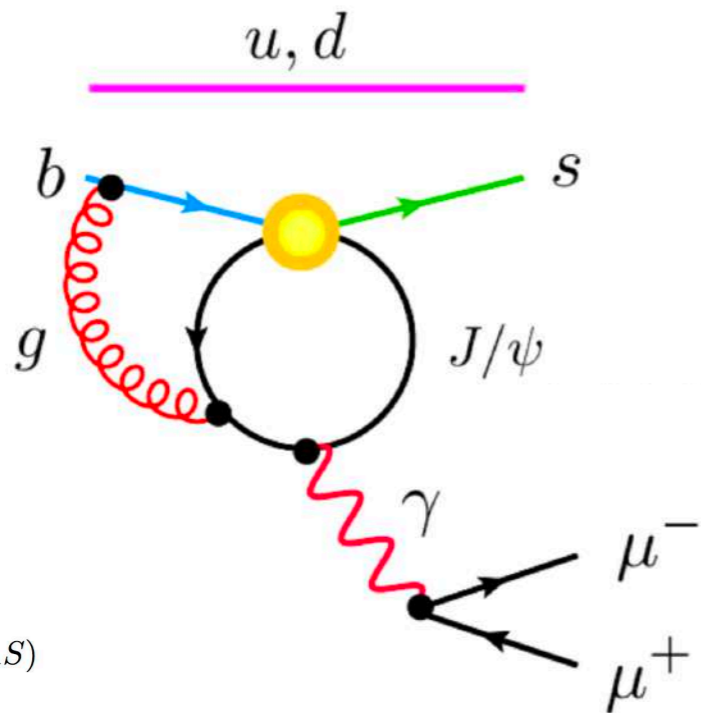
- The K^{*0} **amplitudes** are in turn dependent on **Wilson coefficients** and **form factors (non-perturbative QCD)**

$$\begin{aligned}
 \mathcal{A}_{\perp}^{L(R)} &= \mathcal{N}\sqrt{2\lambda} \left\{ \left[(C_9^{\text{eff}} + C_9'^{\text{eff}}) \mp (C_{10}^{\text{eff}} + C_{10}'^{\text{eff}}) \right] \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} (C_7^{\text{eff}} + C_7'^{\text{eff}}) T_1(q^2) \right\} \\
 \mathcal{A}_{\parallel}^{L(R)} &= -\mathcal{N}\sqrt{2}(m_B^2 - m_{K^*}^2) \left\{ \left[(C_9^{\text{eff}} - C_9'^{\text{eff}}) \mp (C_{10}^{\text{eff}} - C_{10}'^{\text{eff}}) \right] \frac{A_1(q^2)}{m_B - m_{K^*}} \right. \\
 &\quad \left. + \frac{2m_b}{q^2} (C_7^{\text{eff}} - C_7'^{\text{eff}}) T_2(q^2) \right\} \\
 \mathcal{A}_0^{L(R)} &= -\frac{\mathcal{N}}{2m_{K^*}\sqrt{q^2}} \left\{ \left[(C_9^{\text{eff}} - C_9'^{\text{eff}}) \mp (C_{10}^{\text{eff}} - C_{10}'^{\text{eff}}) \right] \right. \\
 &\quad \times \left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*}) A_1(q^2) - \lambda \frac{A_2(q^2)}{m_B + m_{K^*}} \right] \\
 &\quad \left. + 2m_b (C_7^{\text{eff}} - C_7'^{\text{eff}}) \left[(m_B^2 + 3m_{K^*}^2 - q^2) T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2} T_3(q^2) \right] \right\}
 \end{aligned}$$

JHEP 0901:019,2009

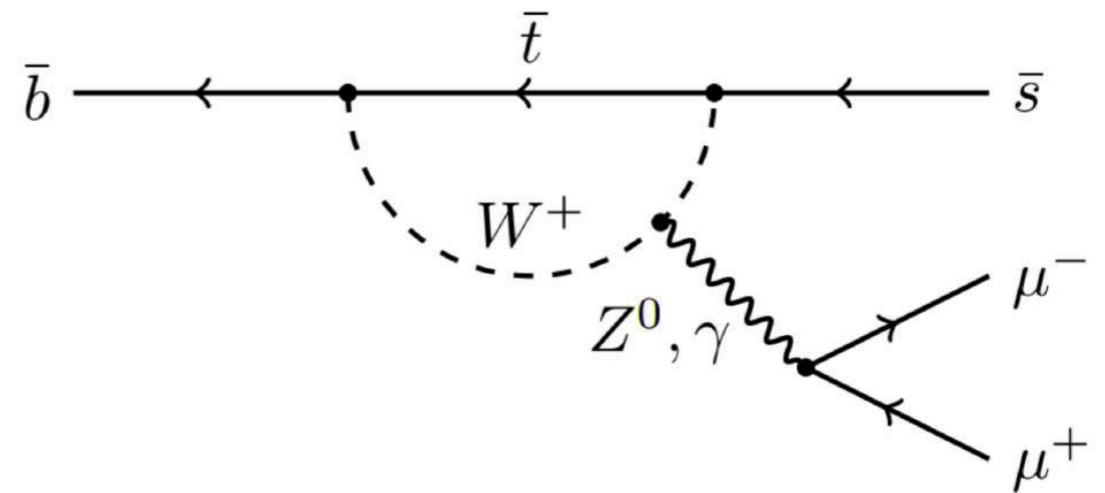
Key nuisance parameter: [2] sub-leading corrections

Charmonium loops



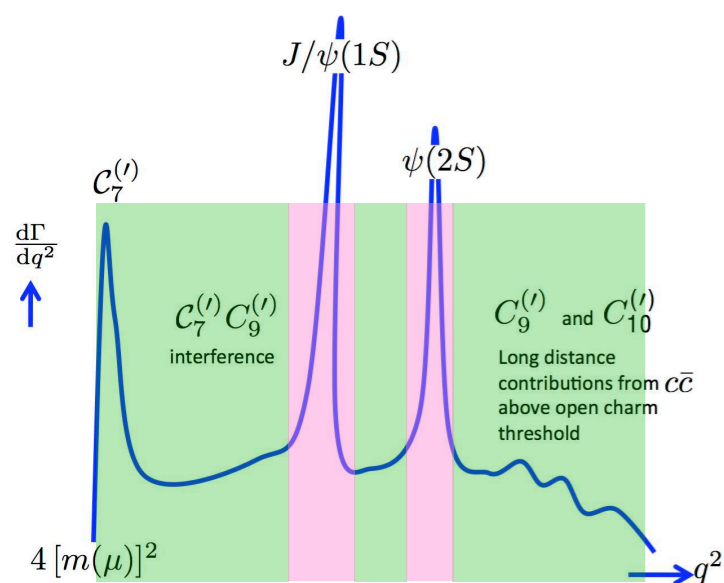
+

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](#)

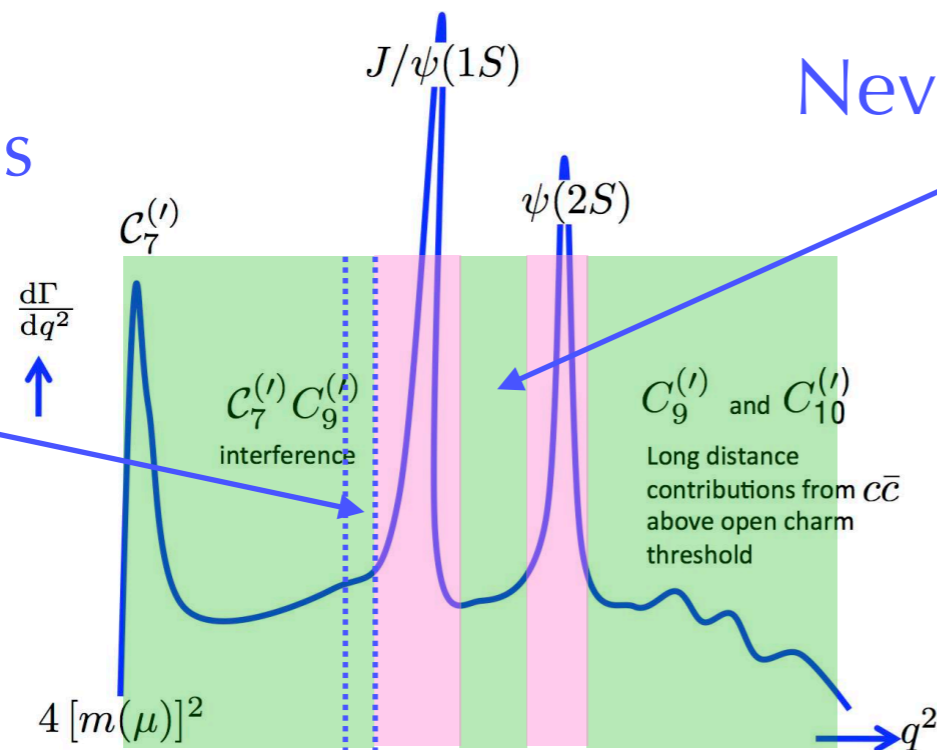
[1] arXiv:1810.08132.

[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 $8.0 \text{ GeV}^2/c^4$ and the wide bin $15.0 < q^2 < 19.0 \text{ GeV}^2/c^4$; **[case 1]**
- Repeat fit removing $6.0 < q^2 < 8.0 \text{ GeV}^2/c^4$ (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

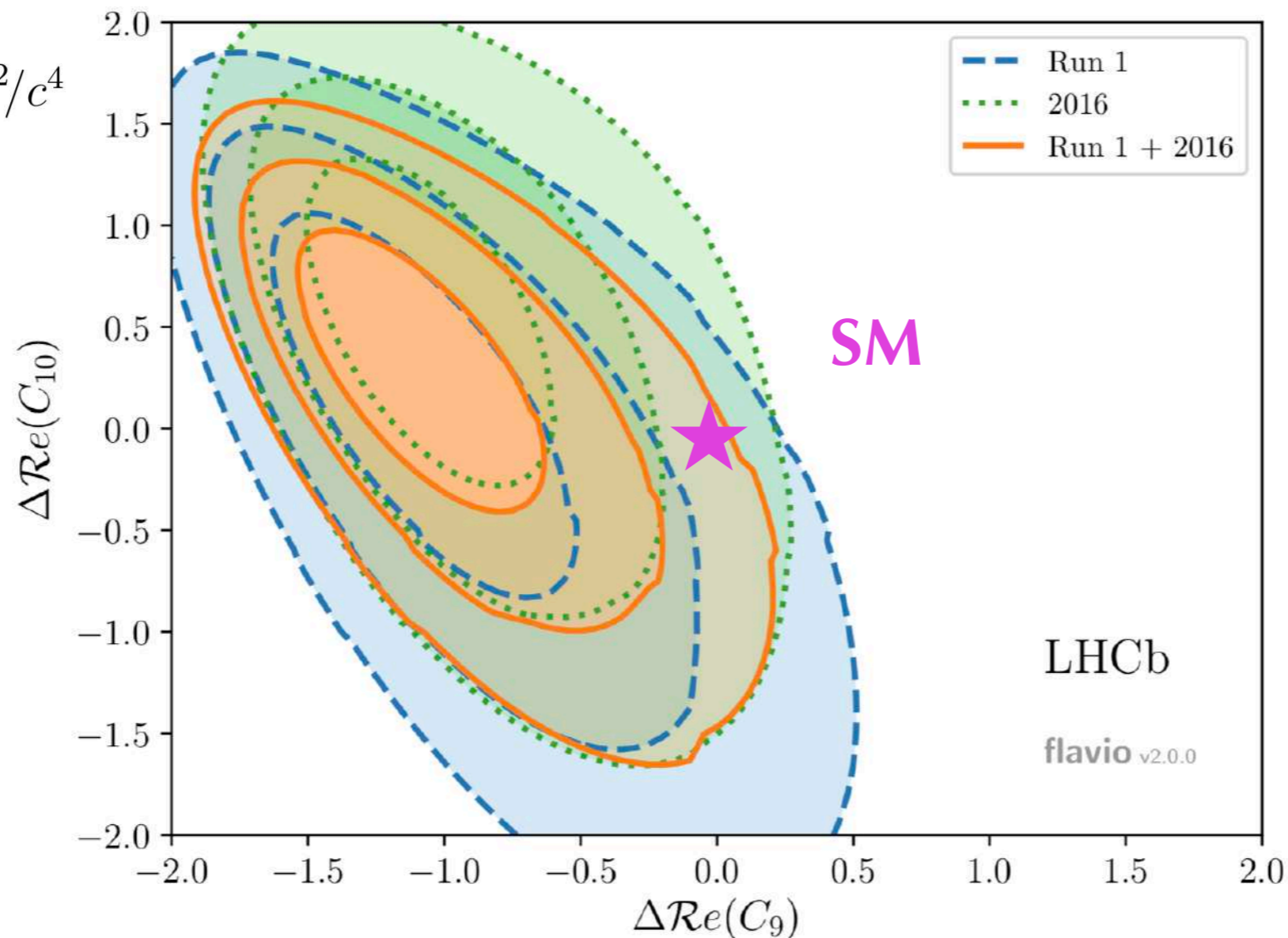
Varying $Re(C_9)$ and $Re(C_{10})$

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 illustrative purposes and contains no systematic uncertainties or bias and coverage corrections

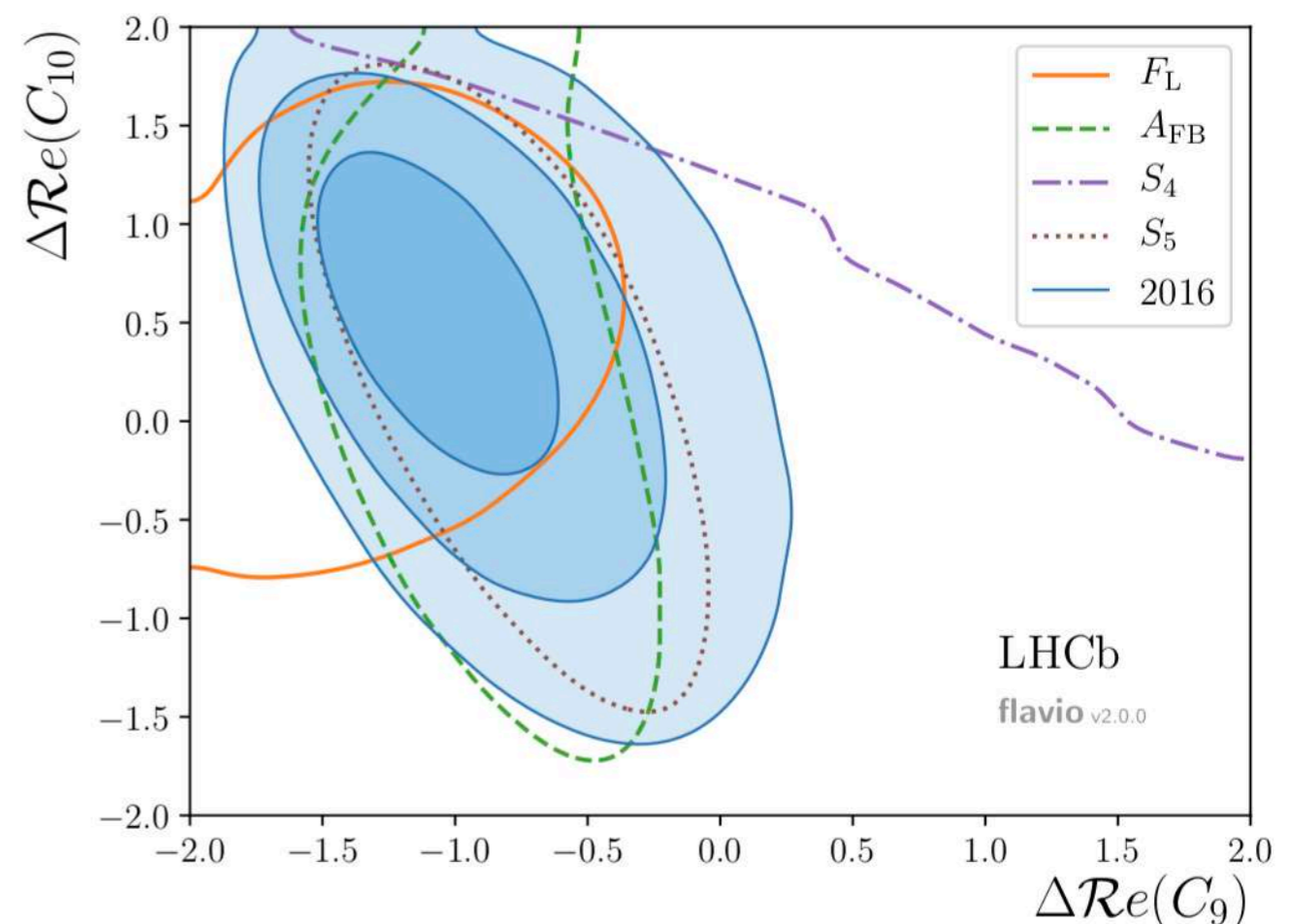
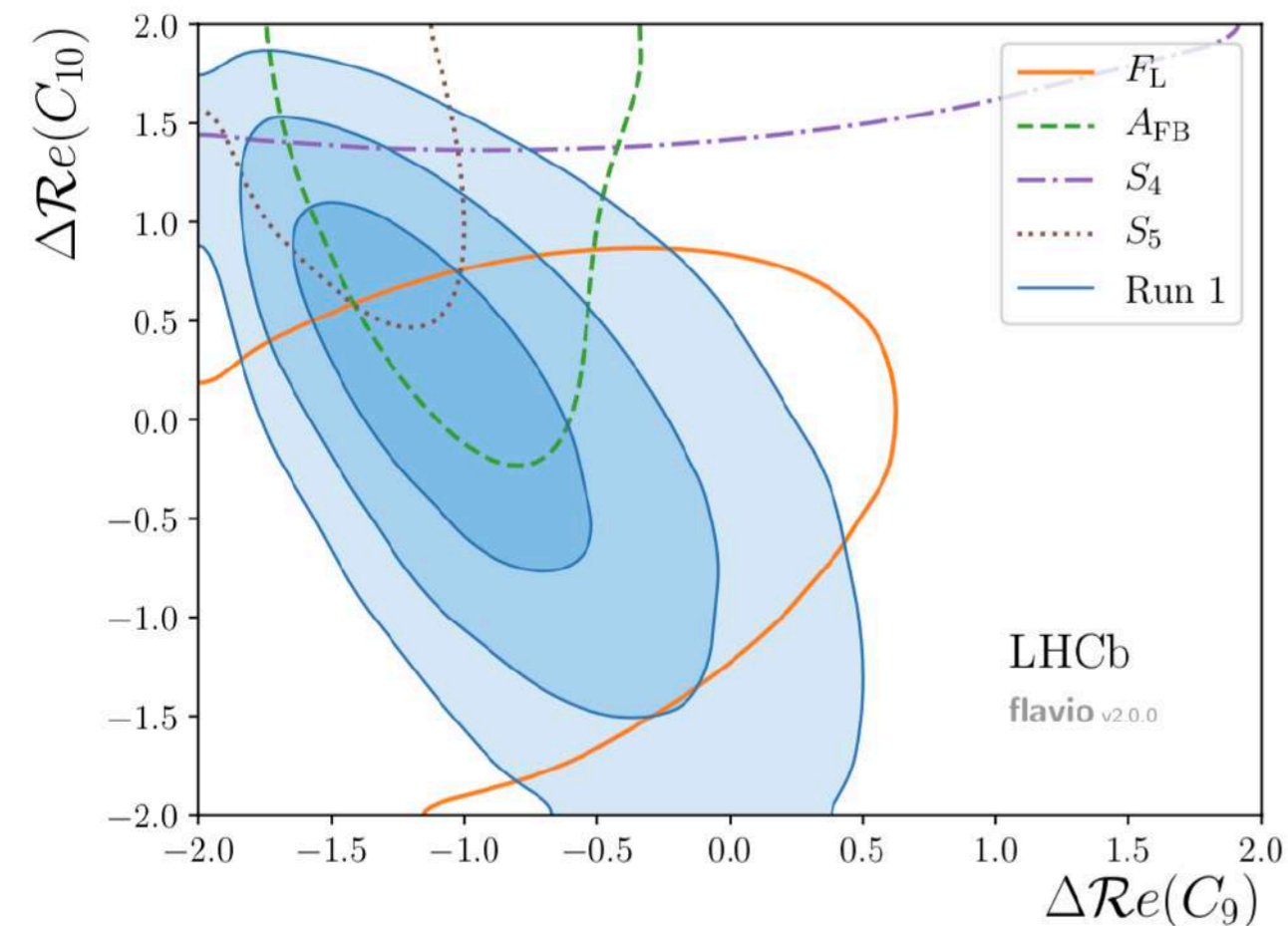
Varying $Re(C_9)$ and $Re(C_{10})$

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

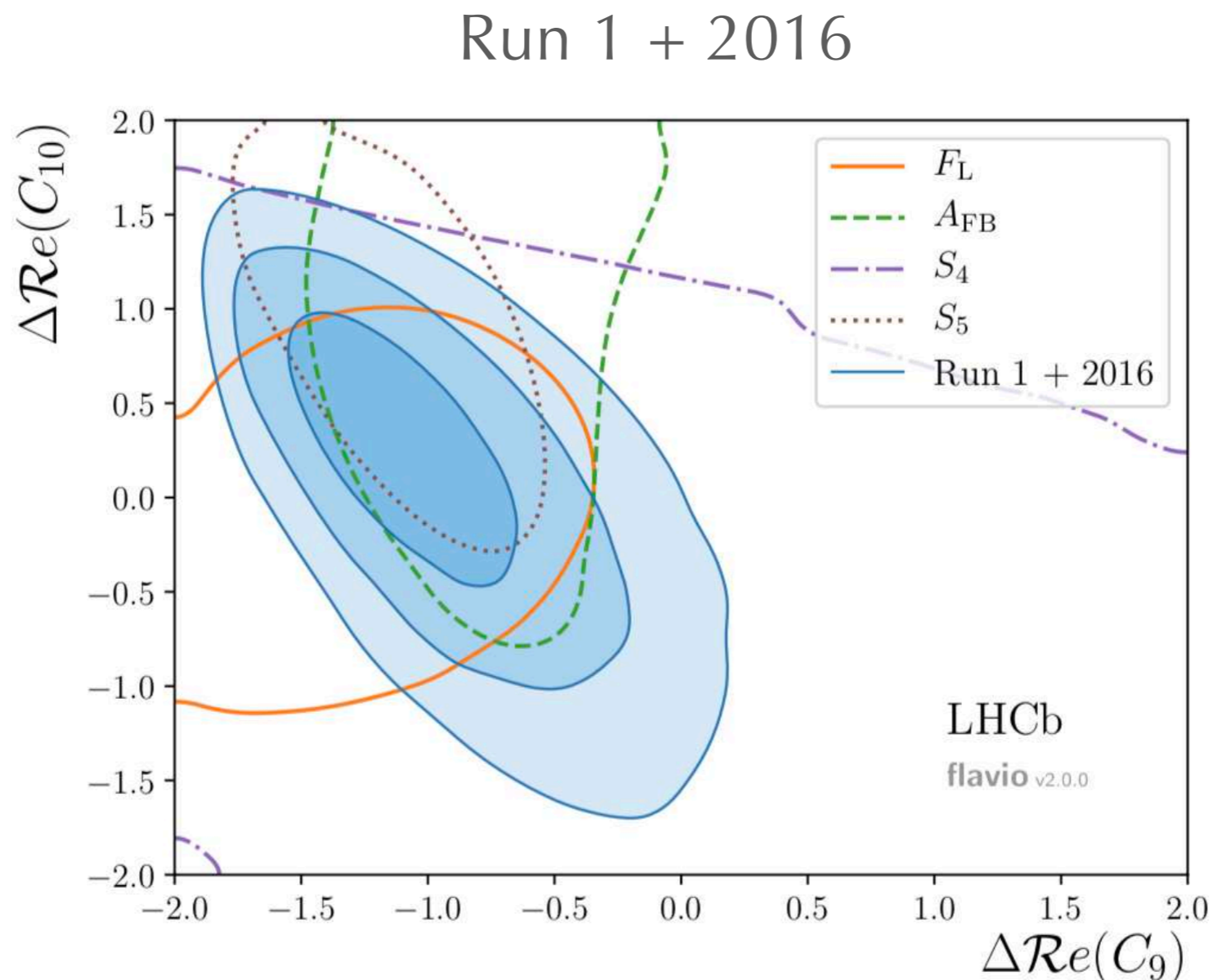


Disclaimer: 2016-only data is for illustrative purposes and contains no systematic uncertainties or bias and coverage corrections

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



Varying $Re(C_9)$ only

Varying $Re(C_9)$ only

- When varying only $Re(C_9)$ significances are as follows

Run 1 and 2016 in good agreement

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

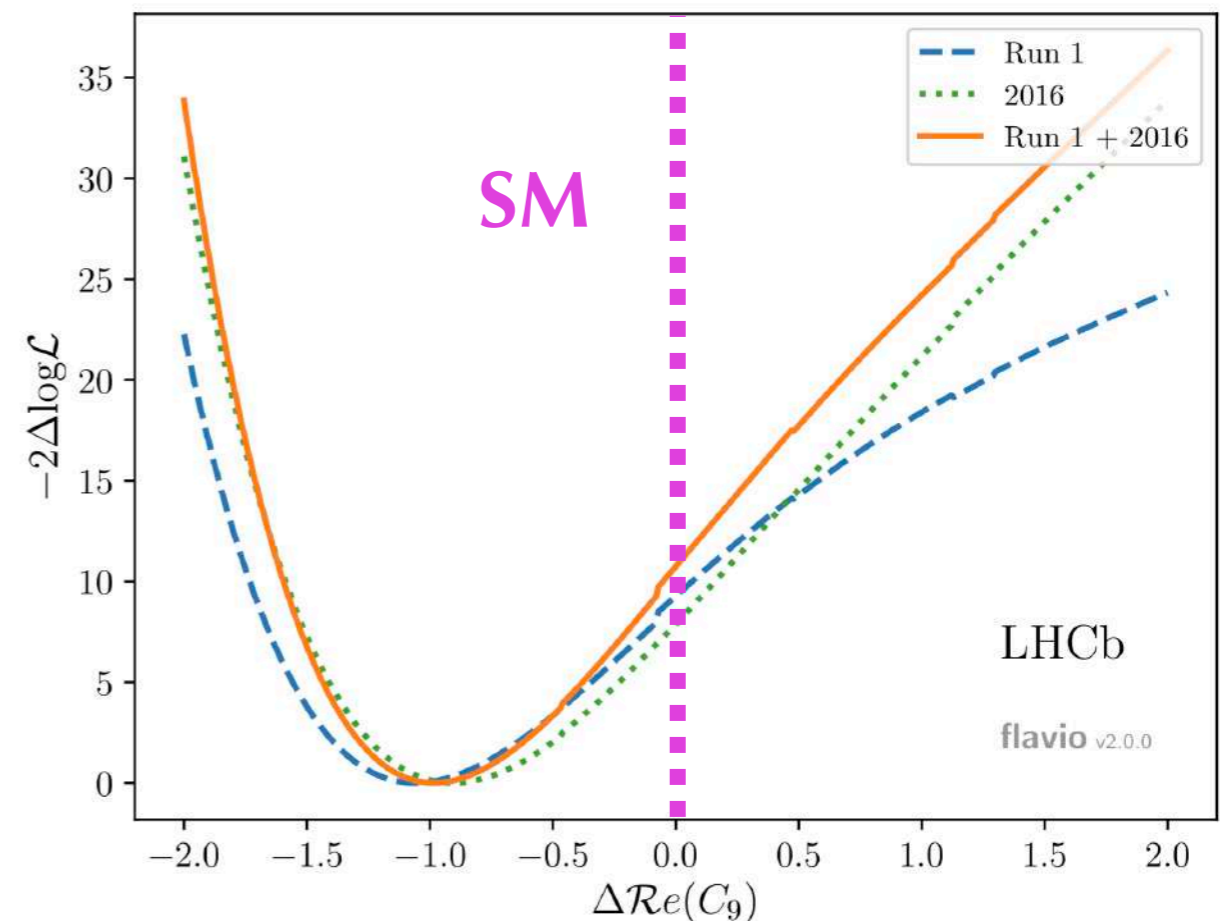
- Run 1: 3.0σ (previous nuisances 3.4σ)

- Run 1 + 2016: 3.3σ

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

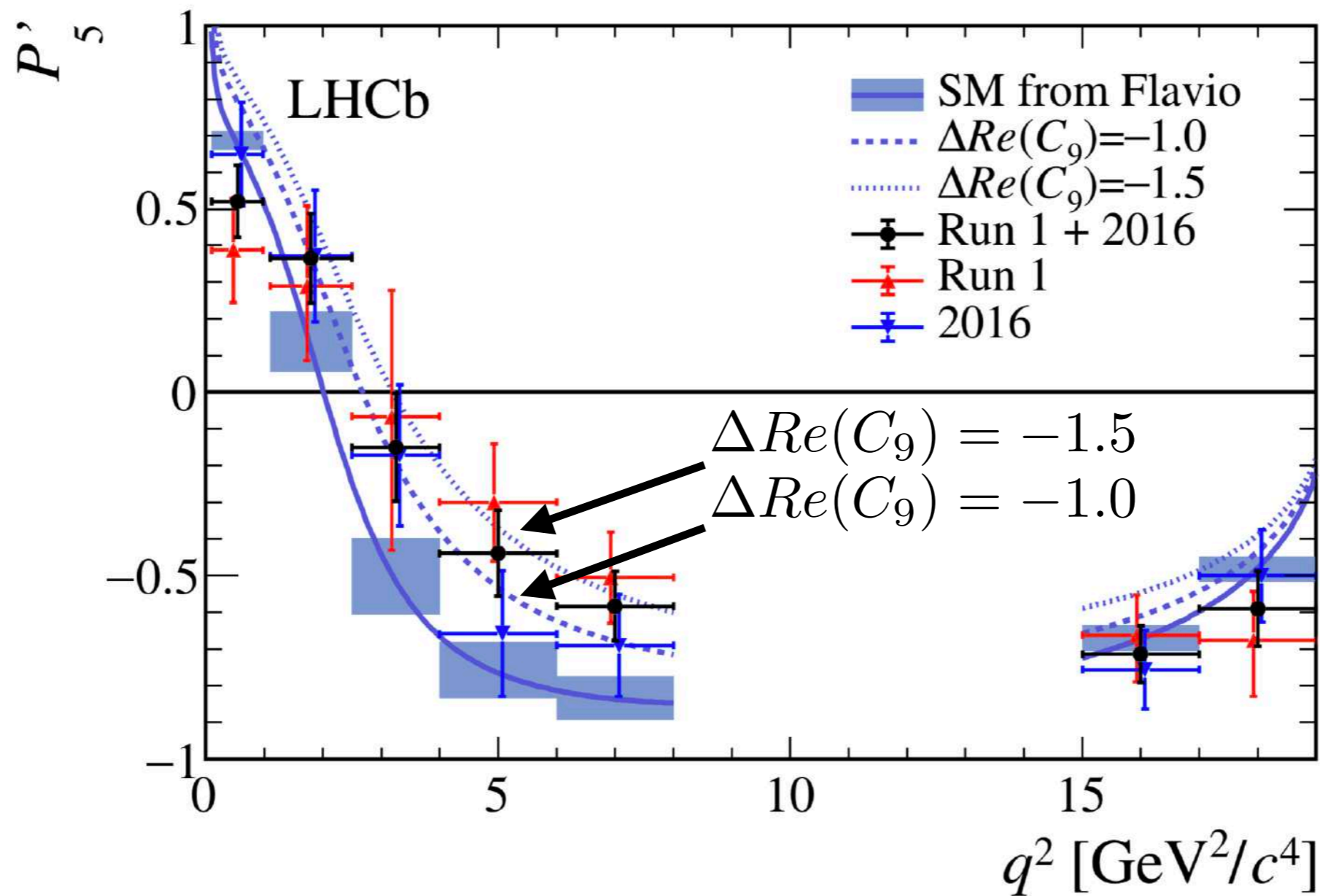
- Run 1: 2.4σ

- Run 1 + 2016: 2.7σ



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

Conclusions

- An angular analysis of the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ has been performed, using data collected during Run 1 data taking and 2016
- Tension is confirmed with 2016 data
- The exact significance of the discrepancy depends on the nuisance parameters chosen and q^2 bins fitted
- Paper will appear on CDS and arXiv shortly
- Update with full Run 2 is underway

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)



CERN-EP-2020-027
LHCb-PAPER-2020-002
March 5, 2020

Measurement of CP -averaged observables in the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay

LHCb collaboration[†]

Abstract

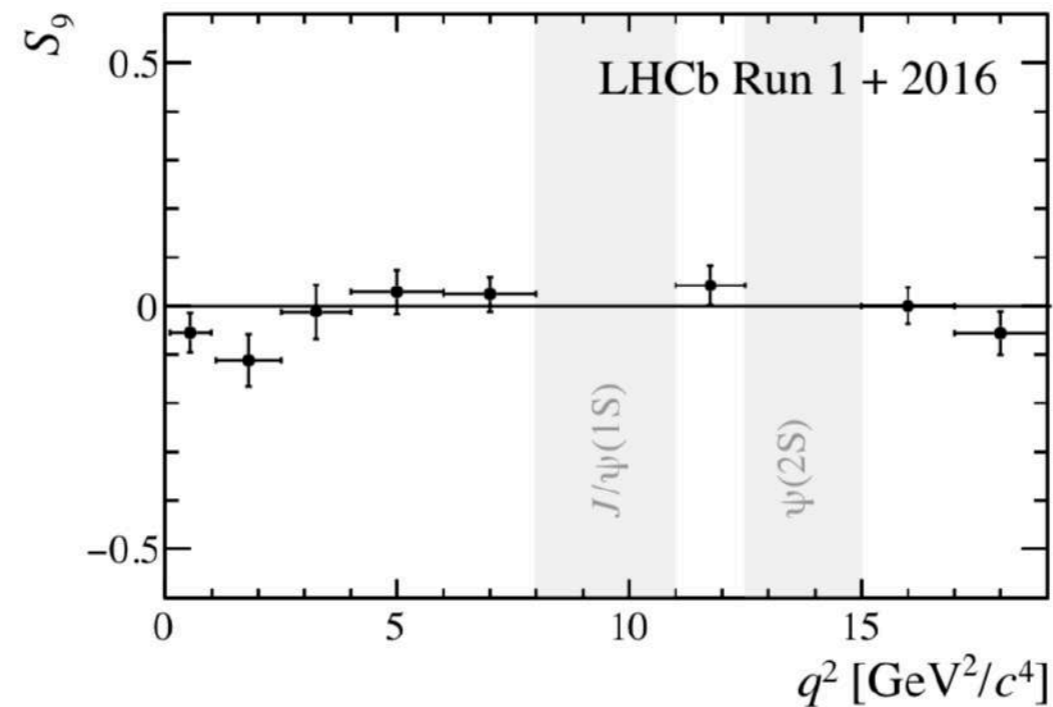
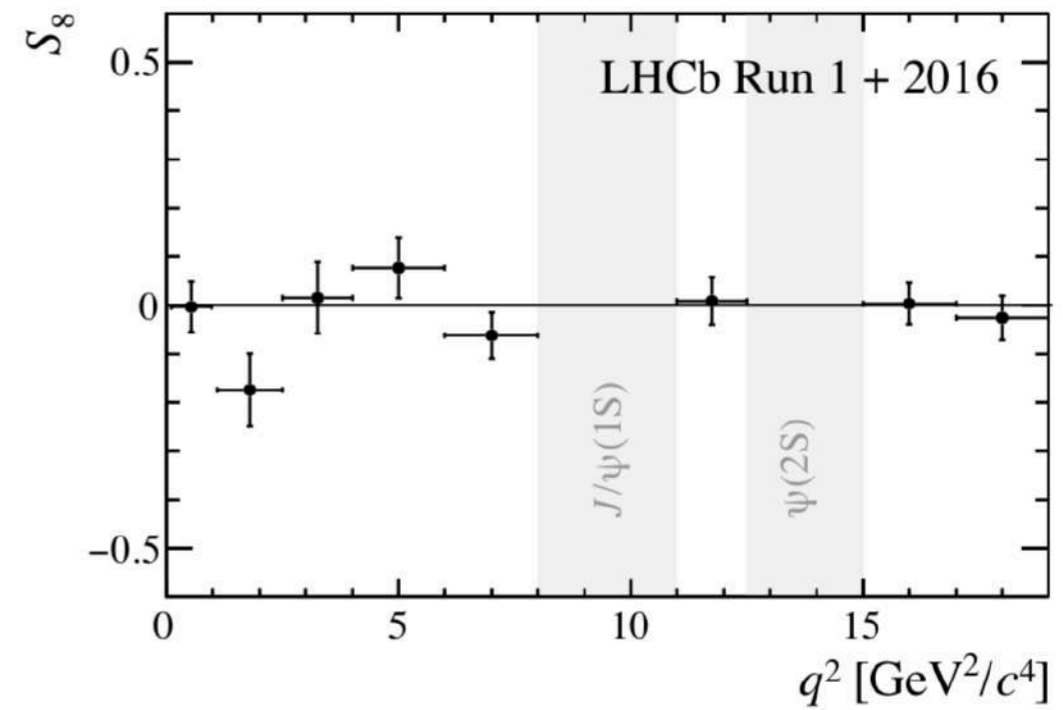
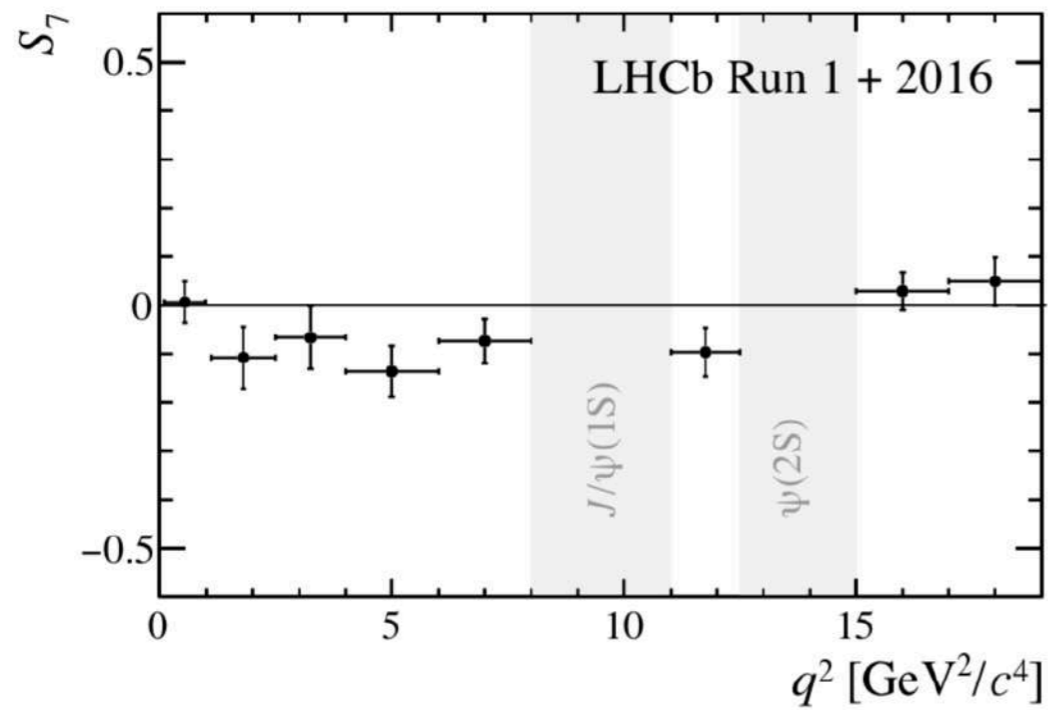
An angular analysis of the $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\mu^+\mu^-$ decay is presented using a data set corresponding to an integrated luminosity of 4.7 fb^{-1} of pp collision data collected with the LHCb experiment. The full set of CP -averaged observables are determined in bins of the invariant mass squared of the dimuon system. Contamination from decays with the $K^+\pi^-$ system in an S-wave configuration is taken into account. The tension seen between the previous LHCb results and the Standard Model predictions persists with the new data. The precise value of the significance of this tension depends on the choice of theory nuisance parameters.

Submitted to Phys. Rev. Lett.

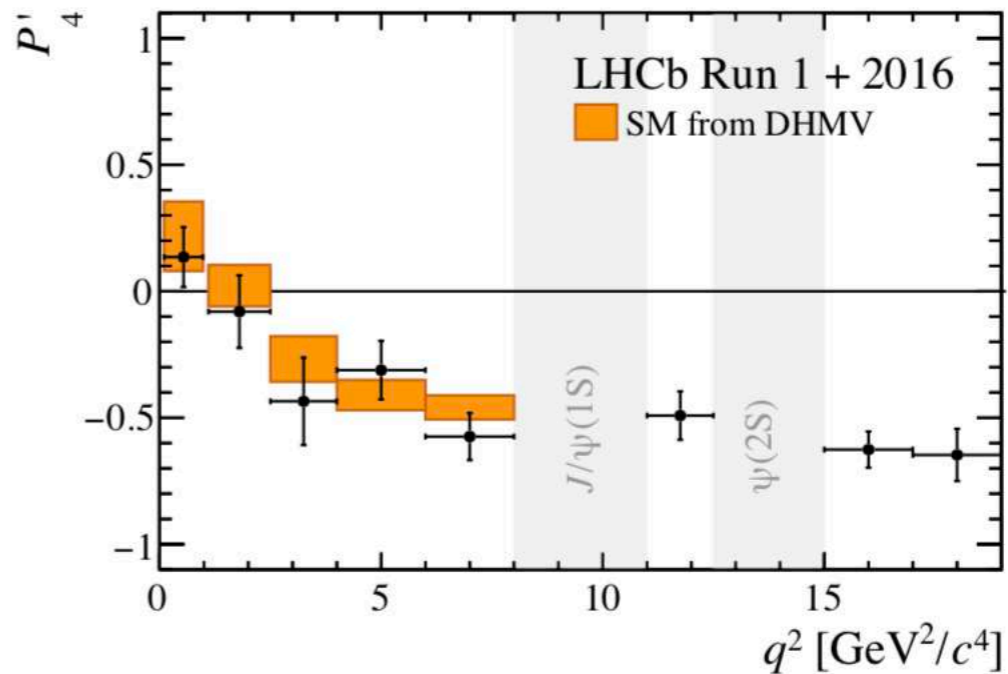
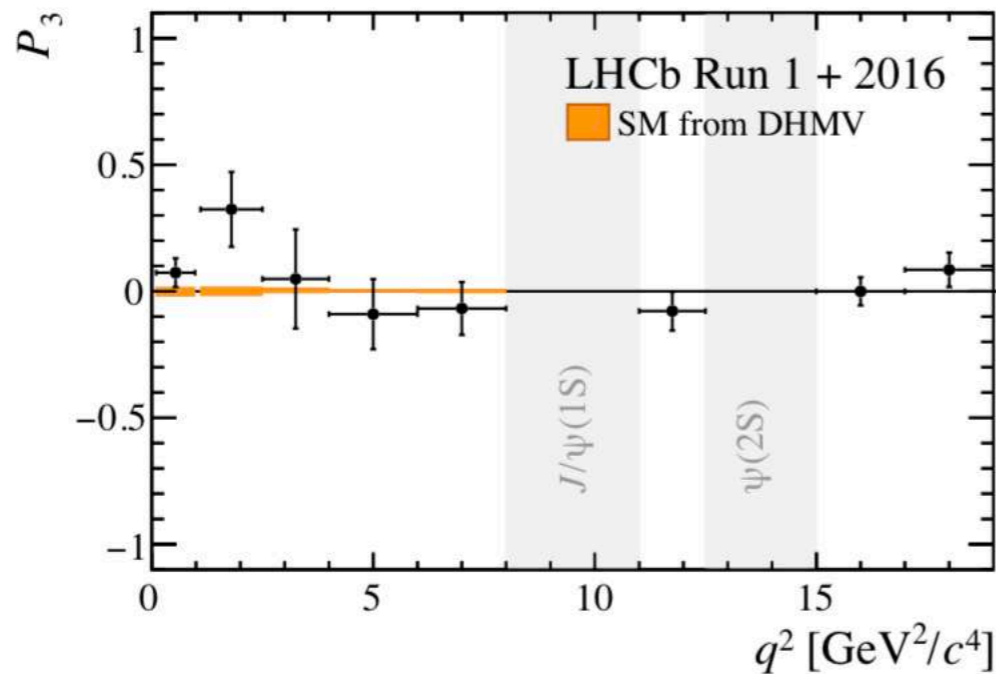
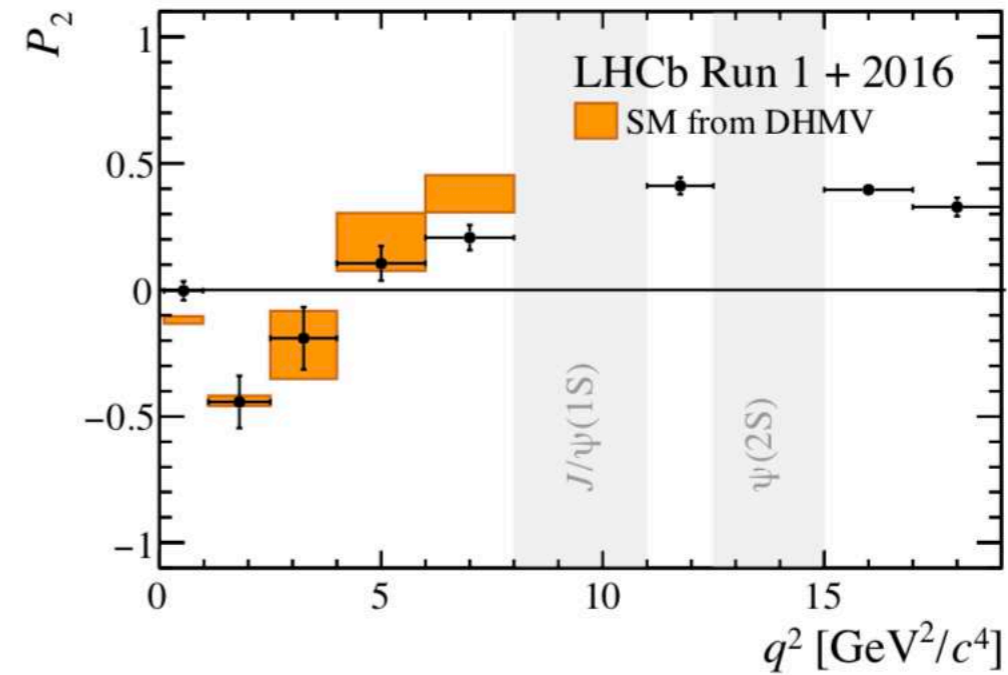
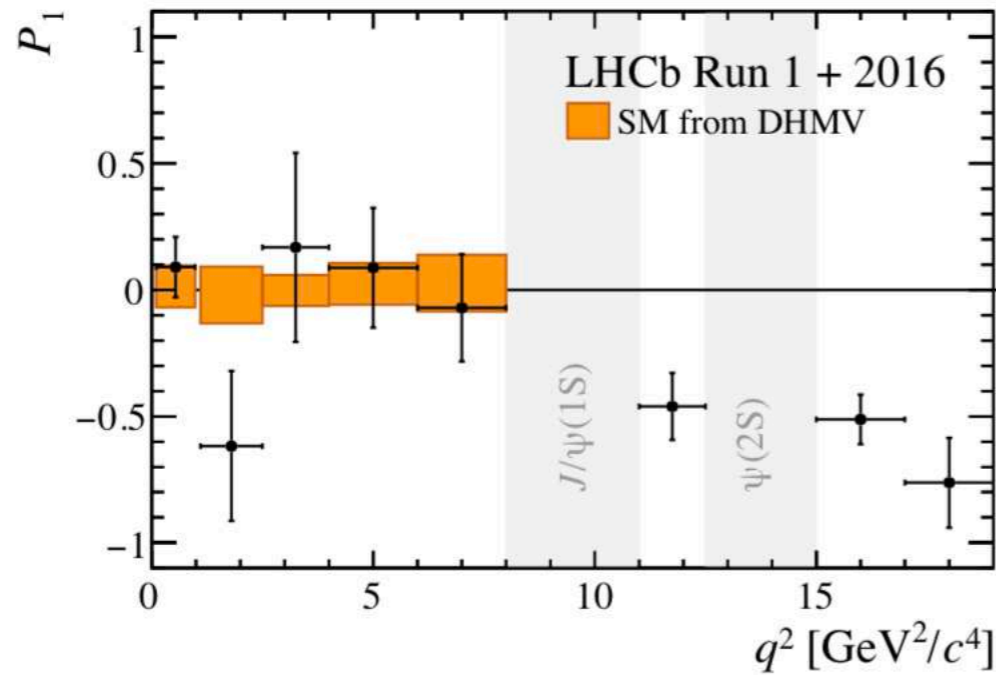
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Back up slides

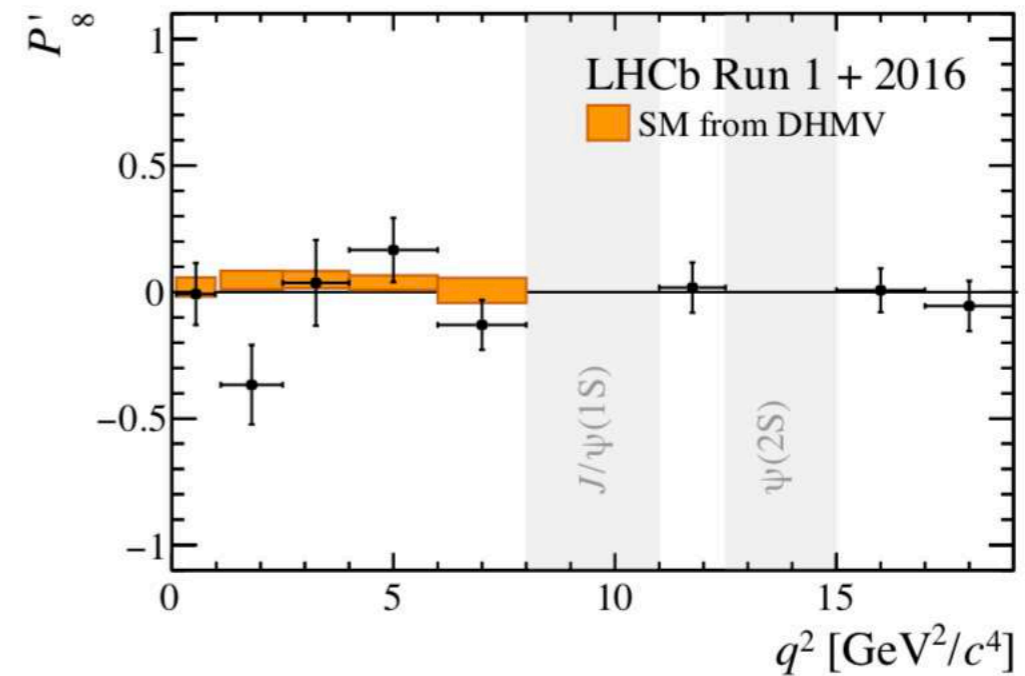
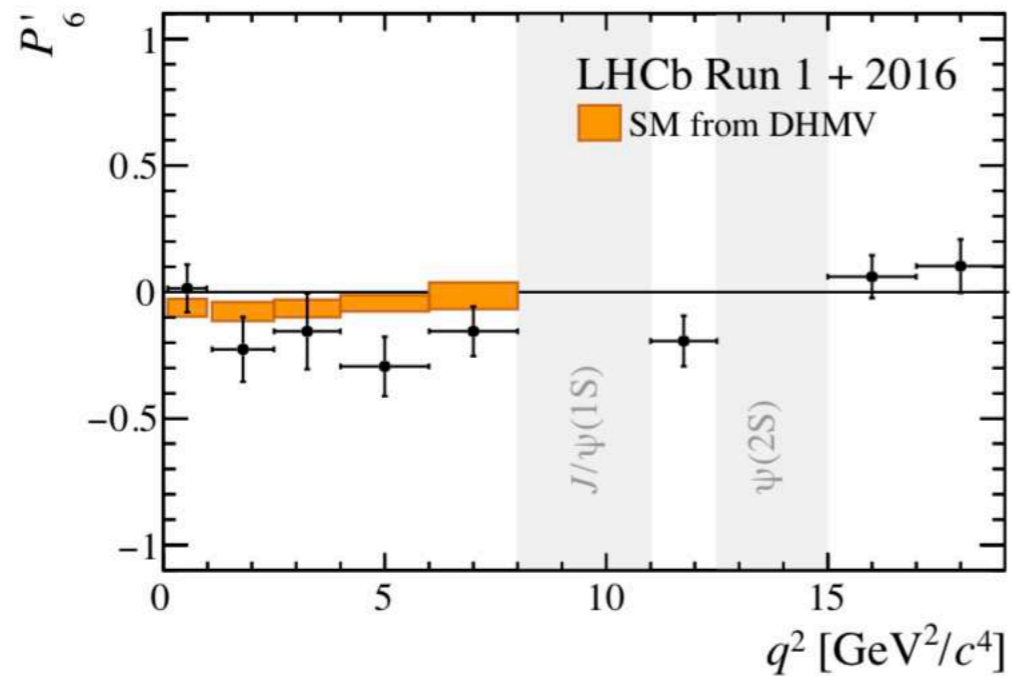
CP-averaged observables



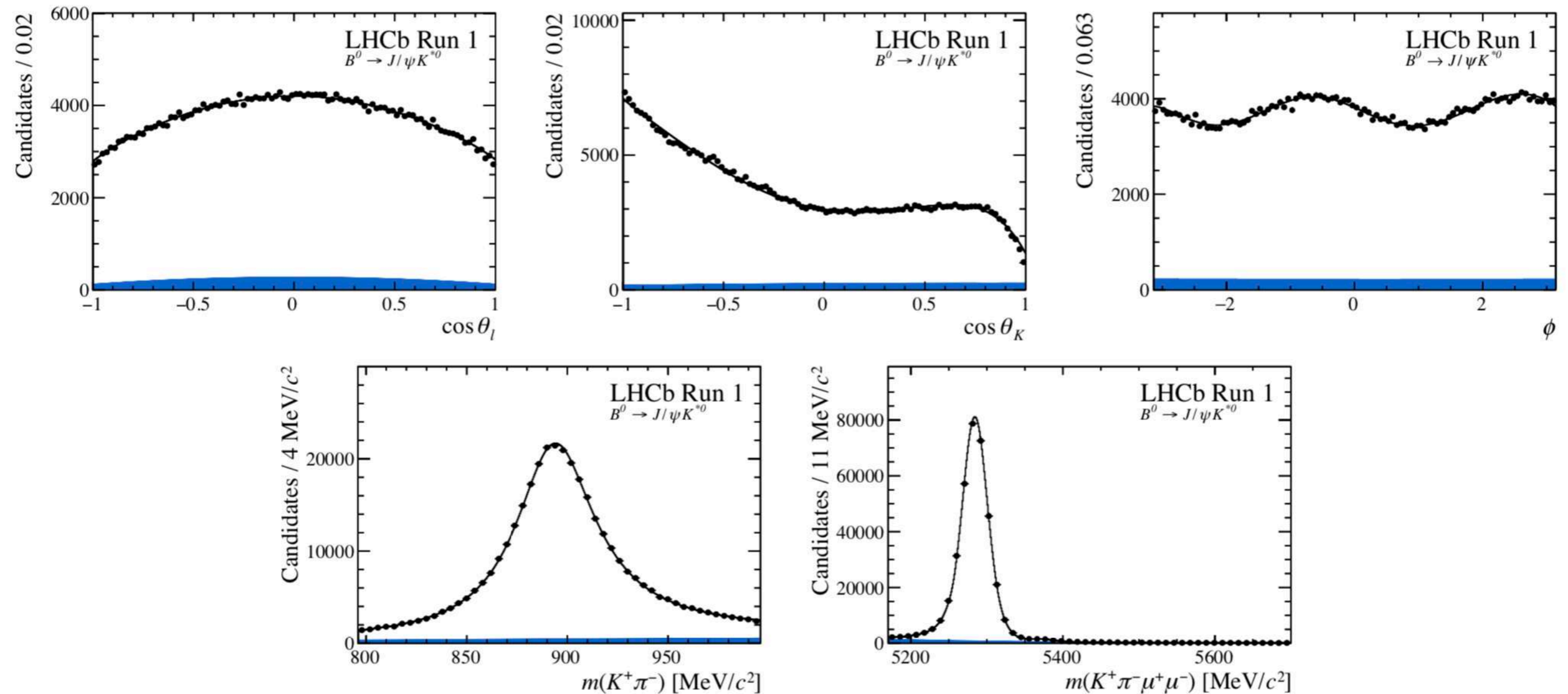
CP-averaged observables



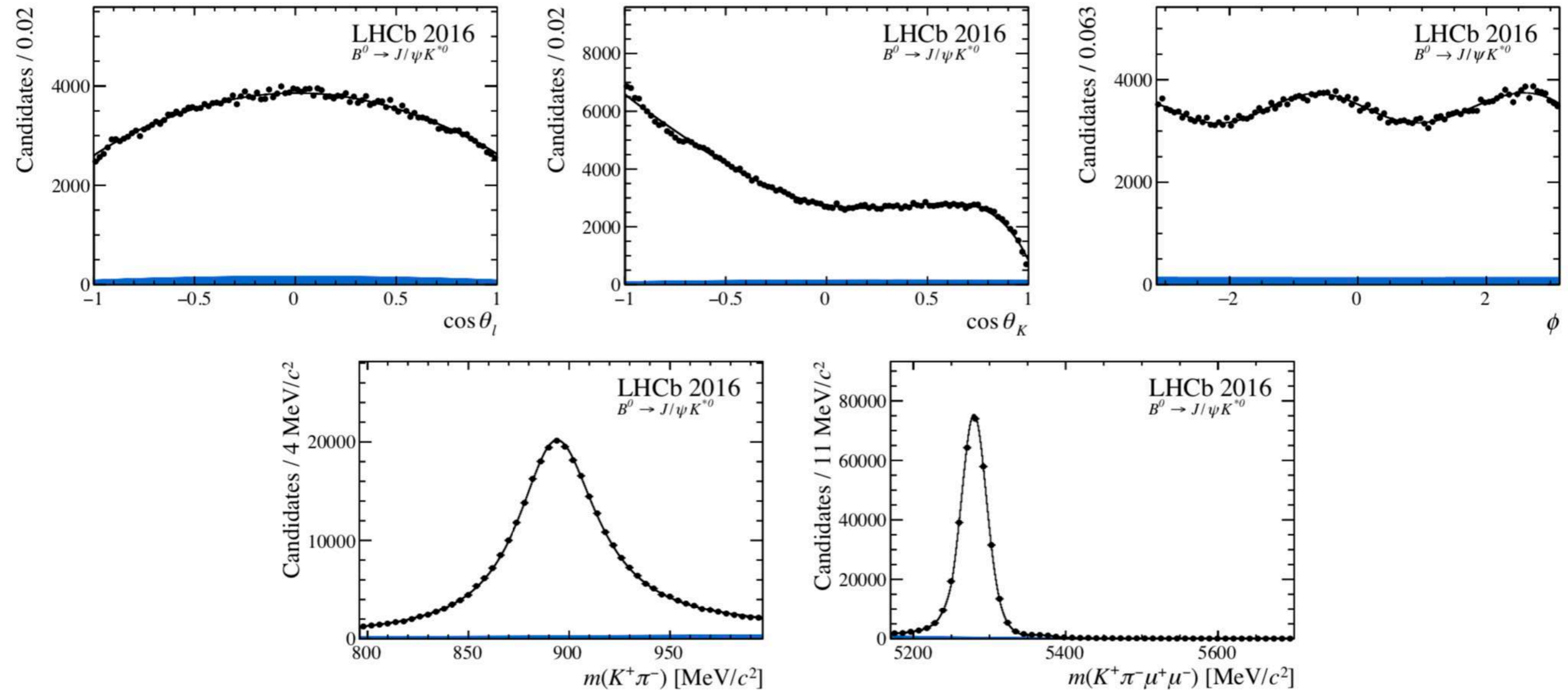
CP-averaged observables



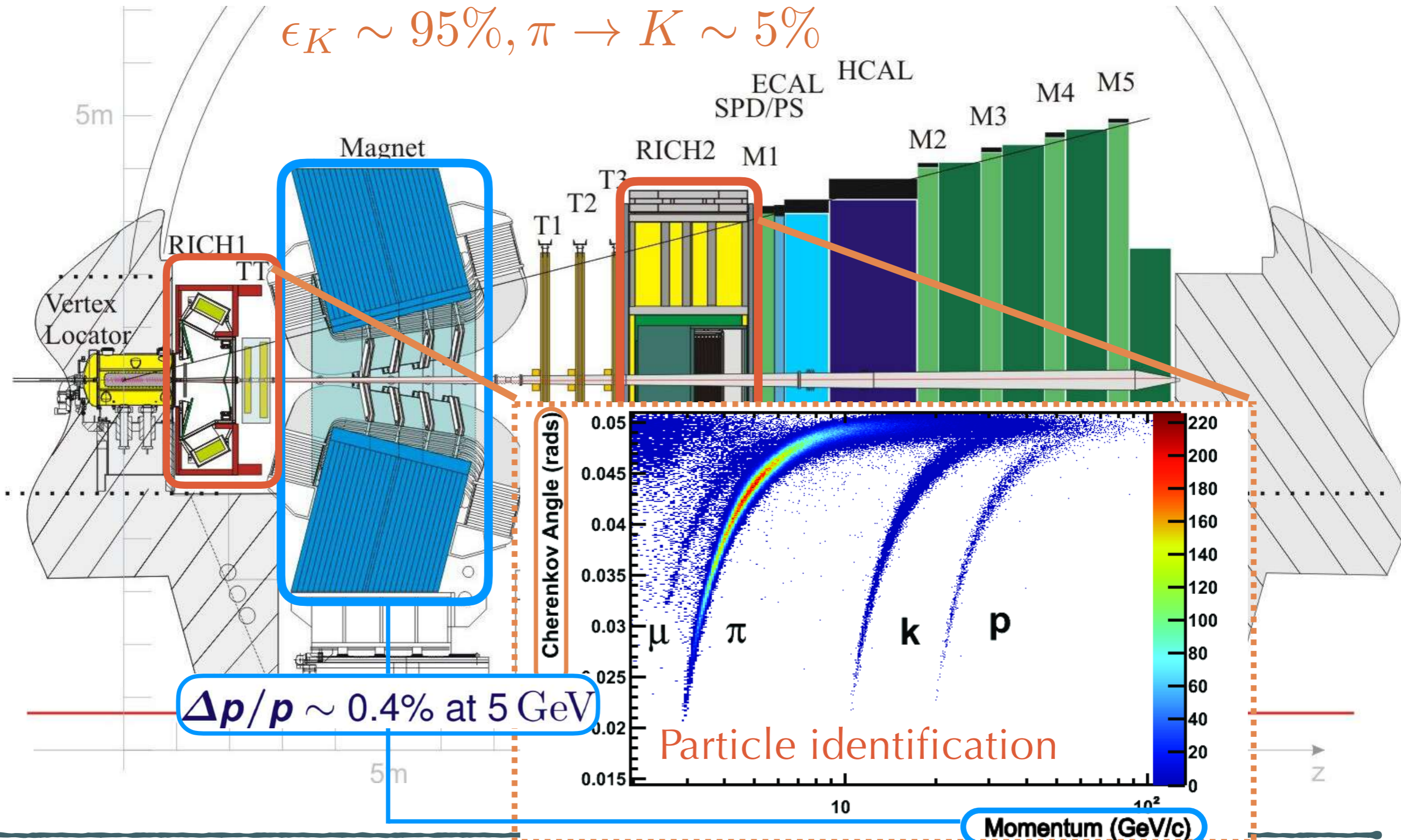
Control channel projections



Control channel projections

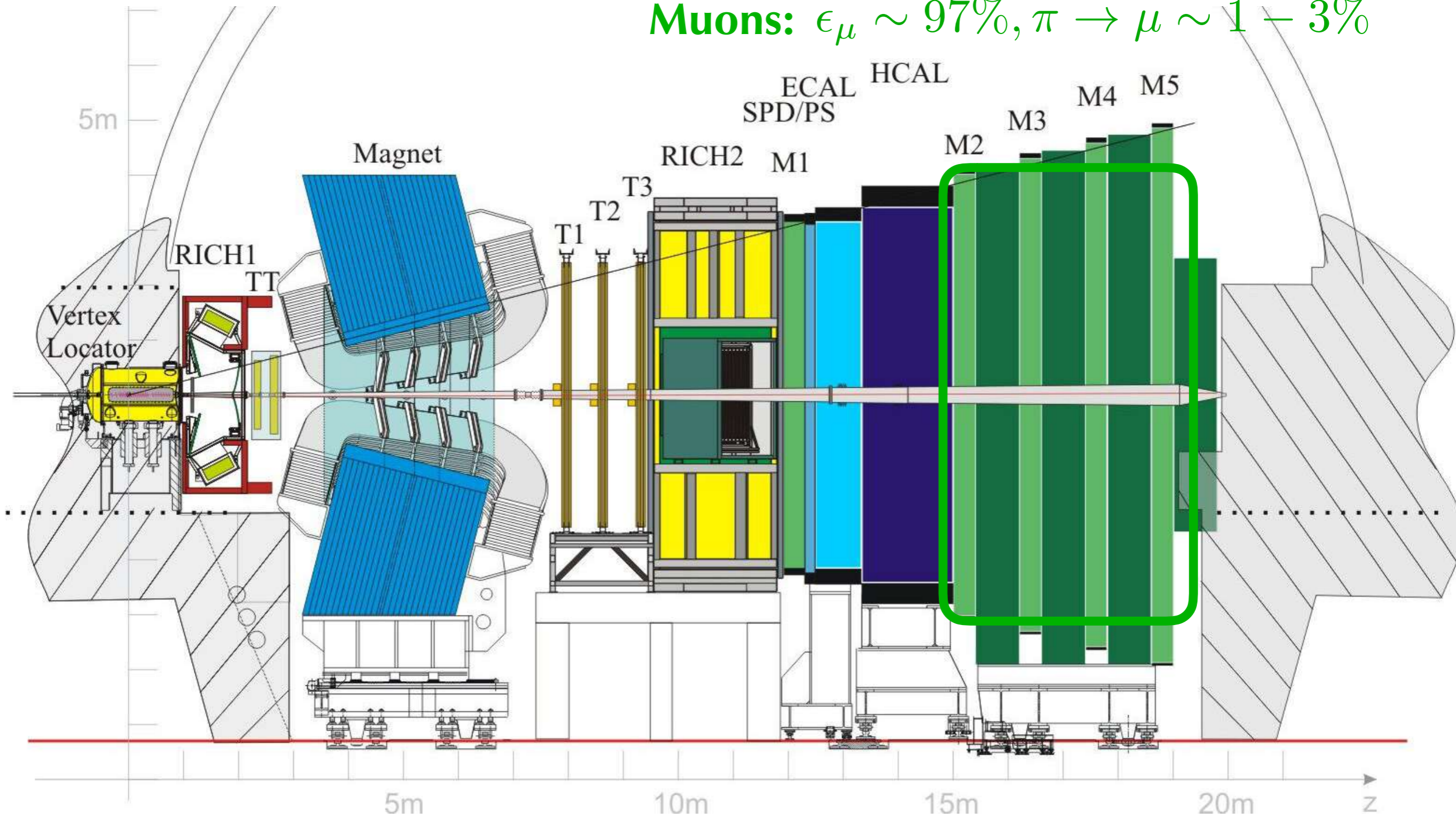


The LHCb experiment



The LHCb experiment

Muons: $\epsilon_{\mu} \sim 97\%$, $\pi \rightarrow \mu \sim 1 - 3\%$



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

$$\frac{d^4\Gamma[\bar{B}^0 \rightarrow \bar{K}^{*0} \mu^+ \mu^-]}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi} \sum_i \underbrace{I_i(q^2)}_{\text{angular coefficients}} \underbrace{f_i(\vec{\Omega})}_{\text{angular functions}}$$

angular coefficients angular functions

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