Electroweak Penguin Decays at LHCb

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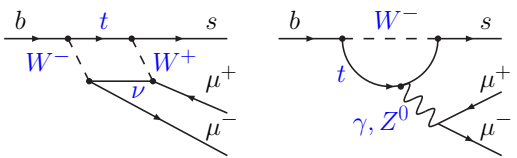
Electroweak penguin (EWP) decays

- flavour-changing neutral currents (FCNC) decays are forbidden at tree level (in SM)
- but FCNC are possible via quark loops:

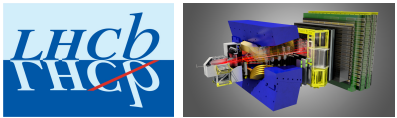


- decays are loop suppressed $\rightarrow$ rare decays with $\mathcal{BF}$ in SM of about $10^{-6} - 10^{-8}$
- contributions from new physic (NP) models can enter these quark loops
  - Leptoquarks[PRD99(2019)055025], Z'[Eur.Phys.J.C75(2015)382] and others
- tensions to the SM predictions have been observed $\rightarrow$ *flavour anomalies*

Electroweak penguin decays at LHCb

- LHCb provides the perfect working environment for Electroweak penguin decays
  - **decay attributes:**
  - ▷ purely charged particle final state
  - ▷ semi-leptonic decays without neutrinos
  - ▷ huge cross-section at pp collisions
  - **detector characteristics:**
  - ▷ high trigger efficiencies and precise momentum resolution
  - ▷ single particle identifications

→ large data-set of produced $b\bar{b}$ pairs



[2008 JINST 3 S08005] [Int.J.Mod.Phys.A 30,1530022(2015)]

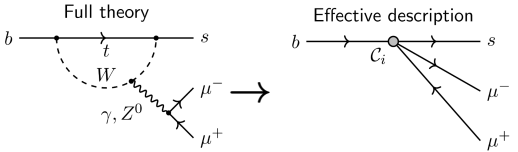
Experimental probes in EWP

- (differential) branching fractions
- tests of CP conservation
- angular observables
- Lepton-Flavour Universality tests

→ LFU talk by C. Benito tomorrow 9:28am

Effective Field Theories and Wilson coefficients

Effective field theories:

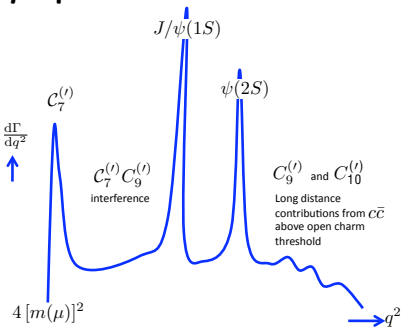


$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{\text{CKM}} \sum_i \mathcal{C}_i \mathcal{O}_i$$

- Fermion operators $\mathcal{O}_i$ and Wilson coefficients $\mathcal{C}_i$

→ Wilson coefficients allow for **model independent comparison** of different EWP measurements

q^2 spectrum:

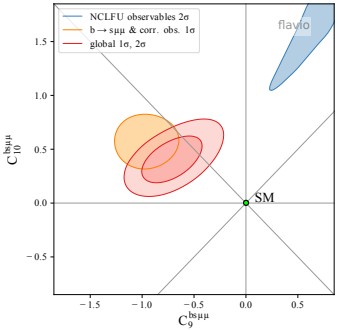


left-handed: $\mathcal{C}_i$
right-handed: $\mathcal{C}_i'$
photon: $\mathcal{C}_7$
(axial) vector: $(\mathcal{C}_{10})\ \mathcal{C}_9$

Flavour anomalies

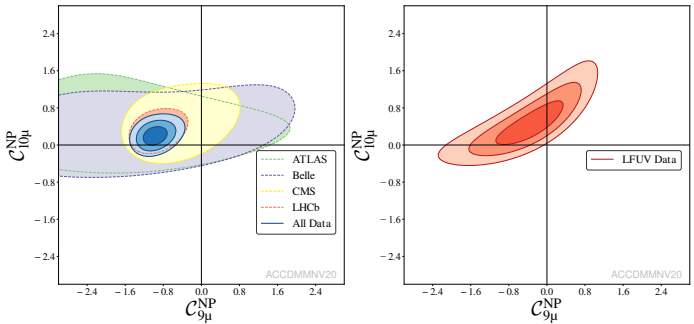
- combine all $bs\mu\mu$ measurements ($\mathcal{B}$, angular analysis and LFU tests), fit for underlying Wilson coefficients
- plot shows NP contribution to muonic $\mathcal{C}_9$ and $\mathcal{C}_{10}$ and their tensions to SM prediction

anomalies after Moriond 2019



modified from [Eur.Phys.J.C80(2020)252]

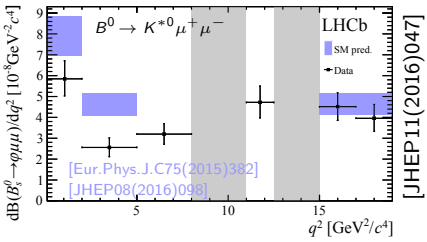
anomalies in 2020



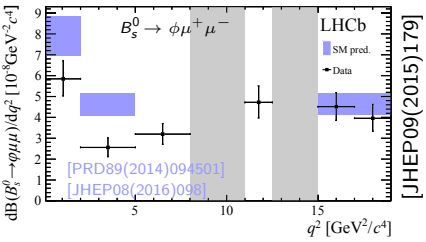
central and right plot from [arXiv:1903.09578]v6

Differential branching fractions of electroweak penguin decays

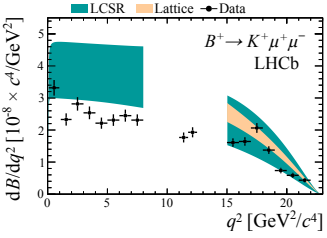
Differential branching fractions are measured consistently lower than SM predictions

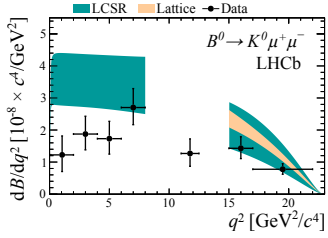


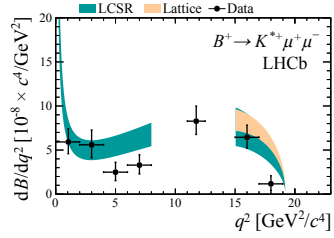
[JHEP11(2016)047]



[JHEP09(2015)179]



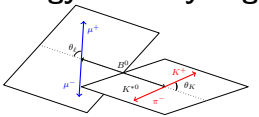




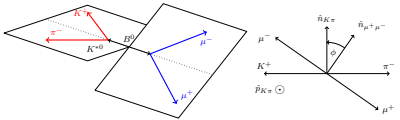
[JHEP06(2014)133]
[PRD71(2005)014029]
[JHEP09(2010)089]
[PRD88(2013)054509]
[PRD89(2014)094501]
[PRL111(2013)162002]
[PRL112(2014)212003]

What are angular analyses?

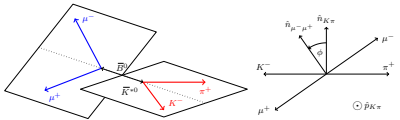
topology of decay angles



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



(b) ϕ definition for the B^0 decay



(c) ϕ definition for the $\overline{B}^0$ decay

leptonic and hadronic decay part

- decay kinematic parametrization using 3 angles:
  - θ_K, θ_L, ϕ (*see left*)
- plus squared momentum transfer of di-leptons, q^2

Angular differential decay rate:

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2 d\cos\theta_K d\cos\theta_L d\phi} =$$

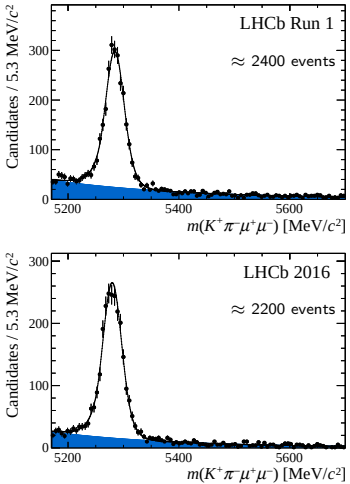
$$\frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_L - F_L\cos^2\theta_K\cos 2\theta_L$$
$$+S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_L\cos\phi$$
$$+S_5\sin 2\theta_K\sin\theta_L\cos\phi + \tfrac{3}{4}A_{FB}\sin^2\theta_K\cos\theta_L$$
$$+S_7\sin 2\theta_K\sin\theta_L\sin\phi + S_8\sin 2\theta_K\sin 2\theta_L\sin\phi$$
$$+S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Big]$$

- angular observables F_L, A_{FB} and S_x

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

- 4 charged particle final state via $K^{*0} \to K^+\pi^-$
- LHCb measured this decay two times:
  2011 data [JHEP08(2013)131]
  full Run 1 [JHEP02(2016)104]
- existing tension to SM (prominent in $P_5^{(\prime)}$)

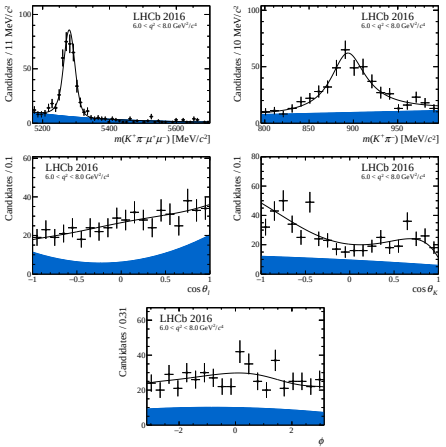
- **now:** update including 2016 data
- $\to$ doubling the event statistics
  [PRL125(2020)011802]



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

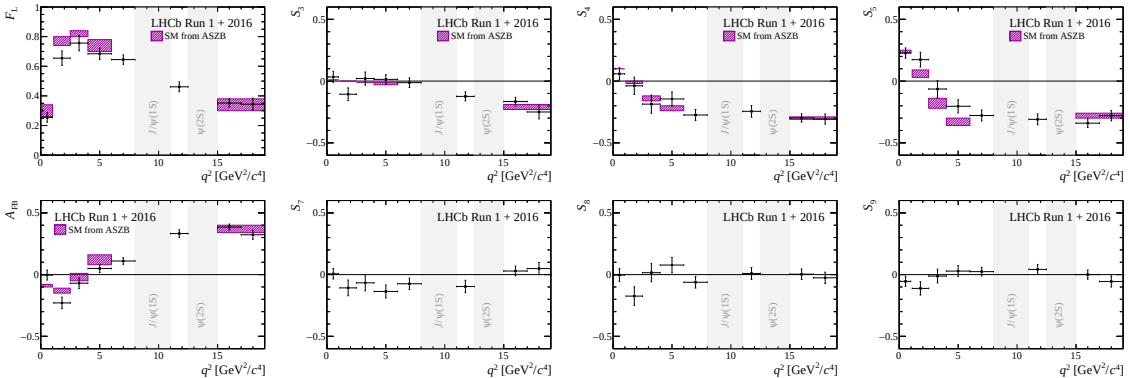
- 5D fit: invariant mass of B^0 and K^{*0} and three angles $\cos\theta_L$, $\cos\theta_K$ and ϕ
- fitting K^{*0} dimension improves constraints on S-wave fraction
- 8 q^2 bins
  - excluding ϕ (1020), J/ψ and $\psi(2S)$ regions
- a 4D (q^2 and angles) acceptance correction is convoluted into the fit PDF
- simultaneous fit of Run 1 and 2016 data samples

Fit projections in $[6.0 - 8.0]\,\mathrm{GeV}^2/c^2$ (2016)



[PRL125(2020)011802]

$B^0 \to K^{*0}\mu^+\mu^-$: Resulting values of angular observables

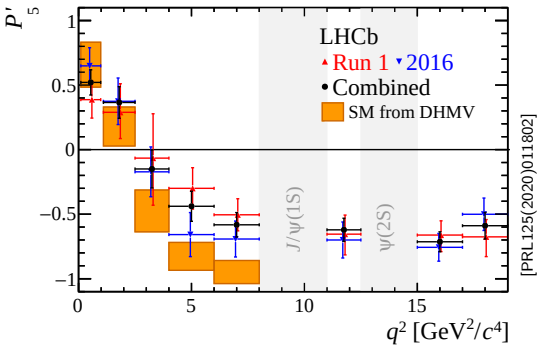


[PRL125(2020)011802]

- angular observables obtained by simultaneous fit to Run 1 + 2016 data $(4.7\,\text{fb}^{-1})$

SM predictions by **[JHEP08(2016)098]**[arXiv:1503.0553] and **[Eur.Phys.J.C75(2015)382]**[arXiv:1411.3161]

$B^0 \to K^{*0}\mu^+\mu^-$: Less form-factor dependent observables, i.e. P_5'



SM predictions by **[JHEP12(2014)125]**[arXiv:1407.8526] and **[JHEP09(2010)089]**[arXiv:1006.4945]

Trends of all observables in backup slides

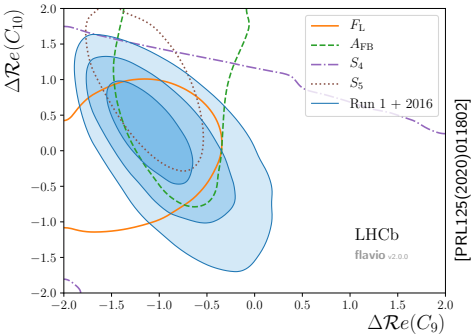
$$P_5' = \frac{S_5}{F_L\sqrt{1-F_L}}$$

- in $P^{(\prime)}$ observables hadronic form-factors cancel out (to first order)
- behaviour of the tension in P_5':
  - values move closer to SM predictions
  - but with higher precision

  $\rightarrow$ tension with almost identical significance
- local discrepancies to SM are:
  - $q^2 = [4.0 - 6.0]$: 2.5σ
  - $q^2 = [6.0 - 8.0]$: 2.9σ
- *global evaluation on next slides*!

$B^0 \to K^{*0}\mu^+\mu^-$: Global fits to $\mathcal{C}_9$ and $\mathcal{C}_{10}$

- Global fit to obtain Wilson coefficients from results of angular observables
- overall very consistent picture between individual observables, i.e. A_{FB}, F_L and S_5
- results of the *non-SM* part of Wilson coefficients $\Delta\mathcal{C}_i = \mathcal{C}_i - \mathcal{C}_i^{SM}$ for $\mathcal{C}_9$ and $\mathcal{C}_{10}$:

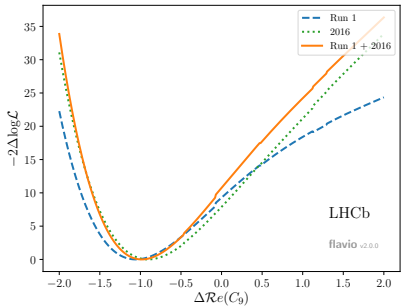


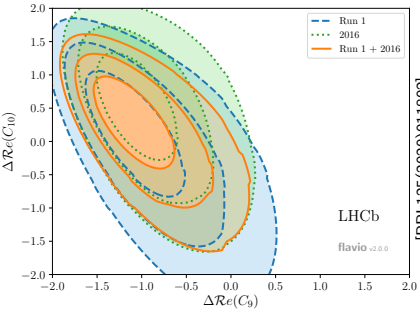
[PRL125(2020)011802]

all global fit (plots) generated using FLAVIO by D. Straub et al. [arXiv:1810.08132]

$B^0 \to K^{*0}\mu^+\mu^-$: Global fits to $\mathcal{C}_9$ and $\mathcal{C}_{10}$

- consistent results between Run 1 and 2016
- global fit clearly favours $\Delta\mathcal{C}_9 \approx -1.0$ scenario over SM value
- global discrepancy to SM is 3.3σ
- deviations are compatible with anomalies observed in LFU tests





[PRL125(2020)011802]

all global fit (plots) generated using FLAVIO by D. Straub et al. [arXiv:1810.08132]

Angular analysis of $B^0 \to K^{*0} e^+ e^-$ at very low q^2 at LHCb **!NEW!**

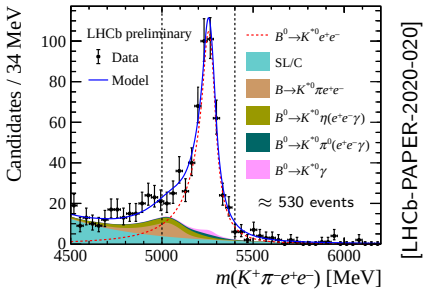
- ... same decay as before, but electrons instead of muons
- fit in one very low q^2 bin:

  [0.0008, 0.257] GeV^2/c^2
- update of Run 1 analysis

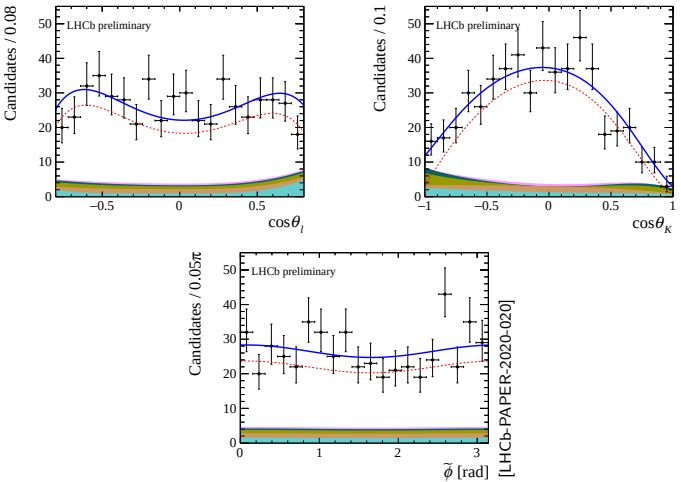
  [JHEP04(2015)064]
- **now** Full Run 1 + 2:
  - increased signal purety
  - lower q^2 reached
  - Run 2 has improved electron triggers
- folding $\tilde{\phi} = \phi + \pi$ if $\phi < 0$

Folded angular decay rate:

$$\begin{aligned}
&\tfrac{3}{4}(1 - F_L)\sin^2\theta_K + F_L\cos^2\theta_K \\
&+\tfrac{1}{4}(1 - F_L)\sin^2\theta_K\cos 2\theta_L - F_L\cos^2\theta_K\cos 2\theta_L \\
&+\tfrac{1}{2}(1 - F_L)\,A_T^{(2)}\sin^2\theta_K\sin^2\theta_L\cos 2\tilde{\phi} \\
&+(1 - F_L)\,A_T^{Re}\sin^2\theta_K\cos\theta_L \\
&+\tfrac{1}{2}(1 - F_L)\,A_T^{Im}\sin^2\theta_K\sin^2\theta_L\sin 2\tilde{\phi}
\end{aligned}$$



$B^0 \to K^{*0} e^+ e^-$: Angular fit projections and results



Angular fit performed in smaller mass window $[5000 - 5400]\,\mathrm{MeV}/c^2$

Angular observable results:

$$F_L = 0.044 \pm 0.026 \pm 0.014$$
$$A_T^{Re} = -0.064 \pm 0.077 \pm 0.015$$
$$A_T^{(2)} = +0.106 \pm 0.103^{+0.016}_{-0.017}$$
$$A_T^{Im} = +0.015 \pm 0.102 \pm 0.012$$

All values in agreement with SM predictions

see talk M. Borsato at 9:00am for more details and C_7 / C_7'

Conclusion

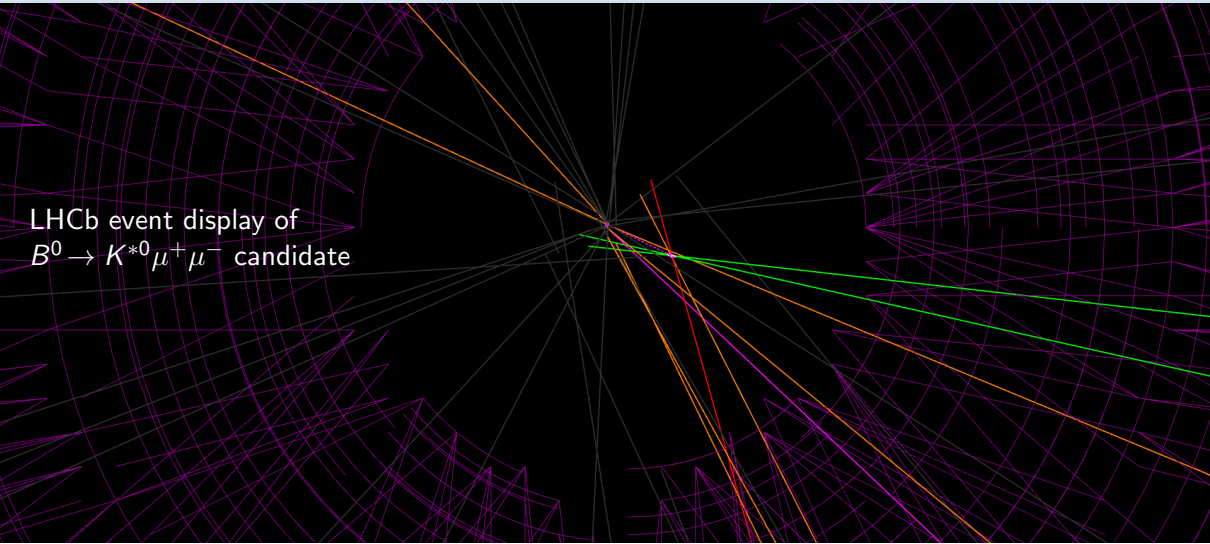
- differential branching fractions are measured consistently low
- tensions in $P_5^{(\prime)}$ and $\mathcal{C}_9$ persist after $B^0 \to K^{*0}\mu^+\mu^-$ 2016 update
- in general, the anomalies in muonic electroweak penguin decays are consistent with a NP scenario of $\Delta\mathcal{C}_9 = -1.0$
- LHCb is ramping up the analyses with electrons
- exciting times ahead with an updated LHCb detector and Belle II start-up

Further LHCb penguin presentations at ICHEP2020:

- *Purely Leptonic Rare decays at LHCb* by L. Yeomans last Tuesday 3:30pm
- *Rare Radiative decays at LHCb* by M. Borsato today at 9:00am
- *Lepton Flavour Universality tests in EWP decays at LHCb* by C. Benito tomorrow at 9:28am

A full list of all publications on electroweak penguin decays results including LFU tests at LHCb can be found at http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_RD.html

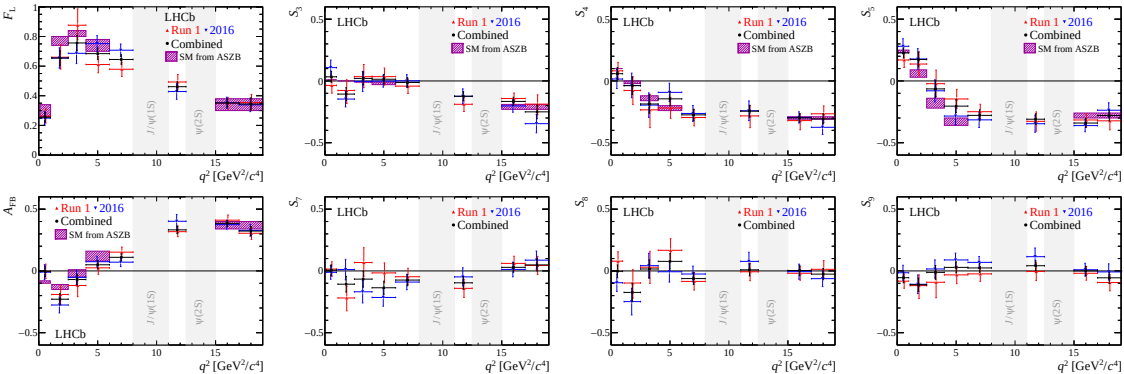
Thank you for your attention



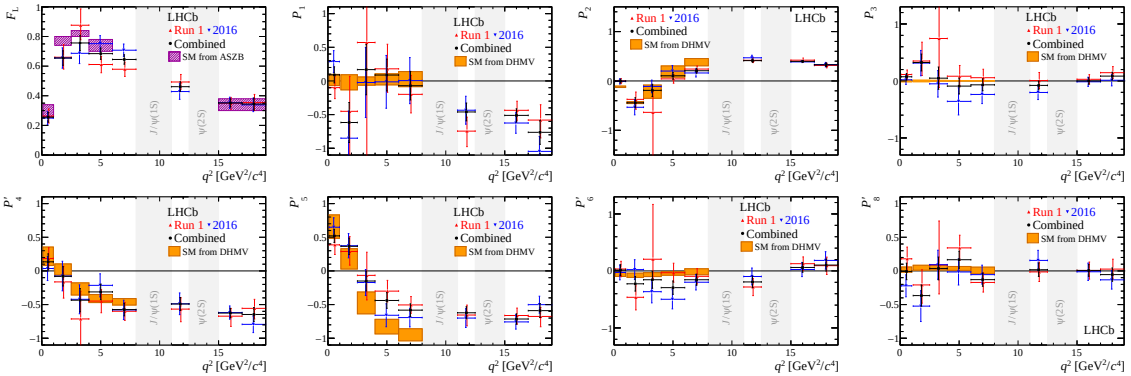
Backup slides

Backup

$B^0 \to K^{*0}\mu^+\mu^-$: Comparison of angular obserables Run 1 and 2016



$B^0 \to K^{*0}\mu^+\mu^-$: Trend of all $P^{(\prime)}$ obserables



$B^0 \to K^{*0}\mu^+\mu^-$: Systematic uncertainty summary

Source	F_L	A_{FB}, 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	< 0.03	< 0.09
$m(K^+\pi^-)$ model	< 0.01	< 0.01	< 0.02
Background model	< 0.01	< 0.01	< 0.03
Peaking backgrounds	< 0.02	< 0.02	< 0.03
$m(K^+\pi^-\mu^+\mu^-)$ model	< 0.01	< 0.01	< 0.02
$K^+\mu^+\mu^-$ veto	< 0.01	< 0.01	< 0.01
Trigger	< 0.01	< 0.01	< 0.01
Bias correction	< 0.02	< 0.02	< 0.04