Heavy Flavor Rare Decays

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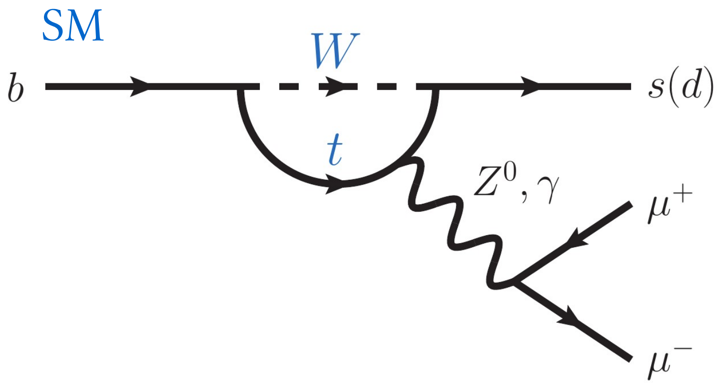
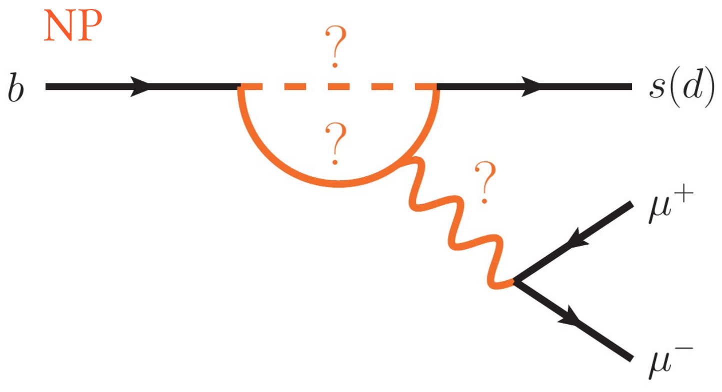
Particle Physics on the Verge of Another Discovery ?

Aspen, January 14, 2016

Why heavy flavor rare decays ?





Flavor physics :

- many possible measurements
- precise SM predictions
- possible New Physics (NP) virtual contribution in loops
- particle not on shell → potentially sensitive above the reach of direct search

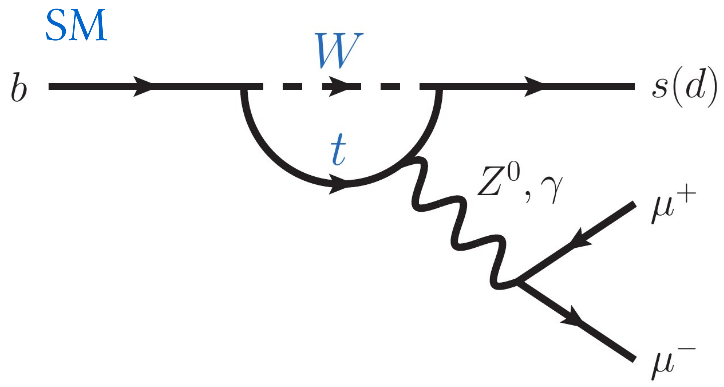
Rare decays :

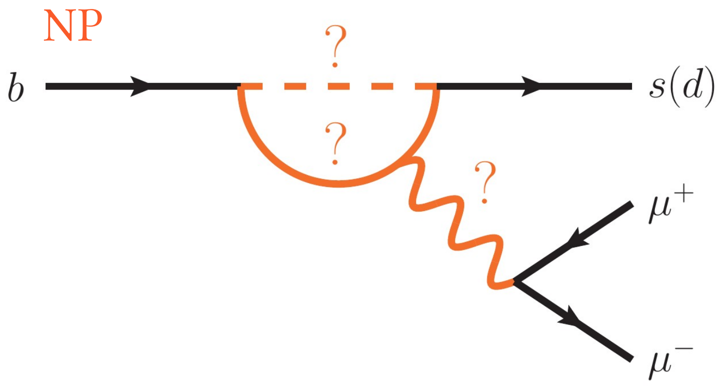
- Flavor Changing Neutral Current (FCNC) are highly suppressed in SM
- NP amplitudes enter at the same level as SM

This talk :

- focus on $b \to s$ transitions

Why heavy flavor rare decays ?





NP can modify a range of observables

- → branching fractions
- → angular distributions
- → CP/isospin asymmetries

Different types of decays give access to different observables

- → sensitive to different NP contributions

Correlations between the observables allow to identify the type of new physics involved

- → important to measure all possible observables

Model independent analysis of $b \to s$ transitions

$M_{Z,W,t} \gg m_b$ → low energy effective theory :

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

left-handed part

right-handed part
suppressed in SM

i = 1,2...... tree
i = 3-6,8 .. gluon penguin
i = 7 .... photon penguin
i = 9,10 ... electroweak penguin
i = S .... Scalar penguin
i = P .... Pseudo scalar penguin

- Local operators O_i depends on hadronic form factor
  - → (dominant) source of theoretical uncertainties
- Wilson coefficients C_i describe the short distance effect
  - → can be modify by new physics : $C = C^{\text{SM}} + C^{\text{NP}}$

    (including operators not present or suppressed in the SM)

Model independent analysis of $b \to s$ transitions

$M_{Z,W,t} \gg m_b$ → low energy effective theory :

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

left-handed part

right-handed part
suppressed in SM

i = 1,2...... tree
i = 3-6,8 .. gluon penguin
i = 7 .... photon penguin
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↘ In this talk :

- Dilepton decays : C_{10}, C_S, C_P
- $b \to s\ell\ell$ decays : C_7, C_9, C_{10}
- Radiative decays $b \to s\gamma$: C_7
- Non-universal lepton couplings
- Exotic searches

↘ include results from ATLAS, CMS and (mostly) LHCb
(unless stated otherwise : all results with complete LHC run I statistics)

Dilepton Decays

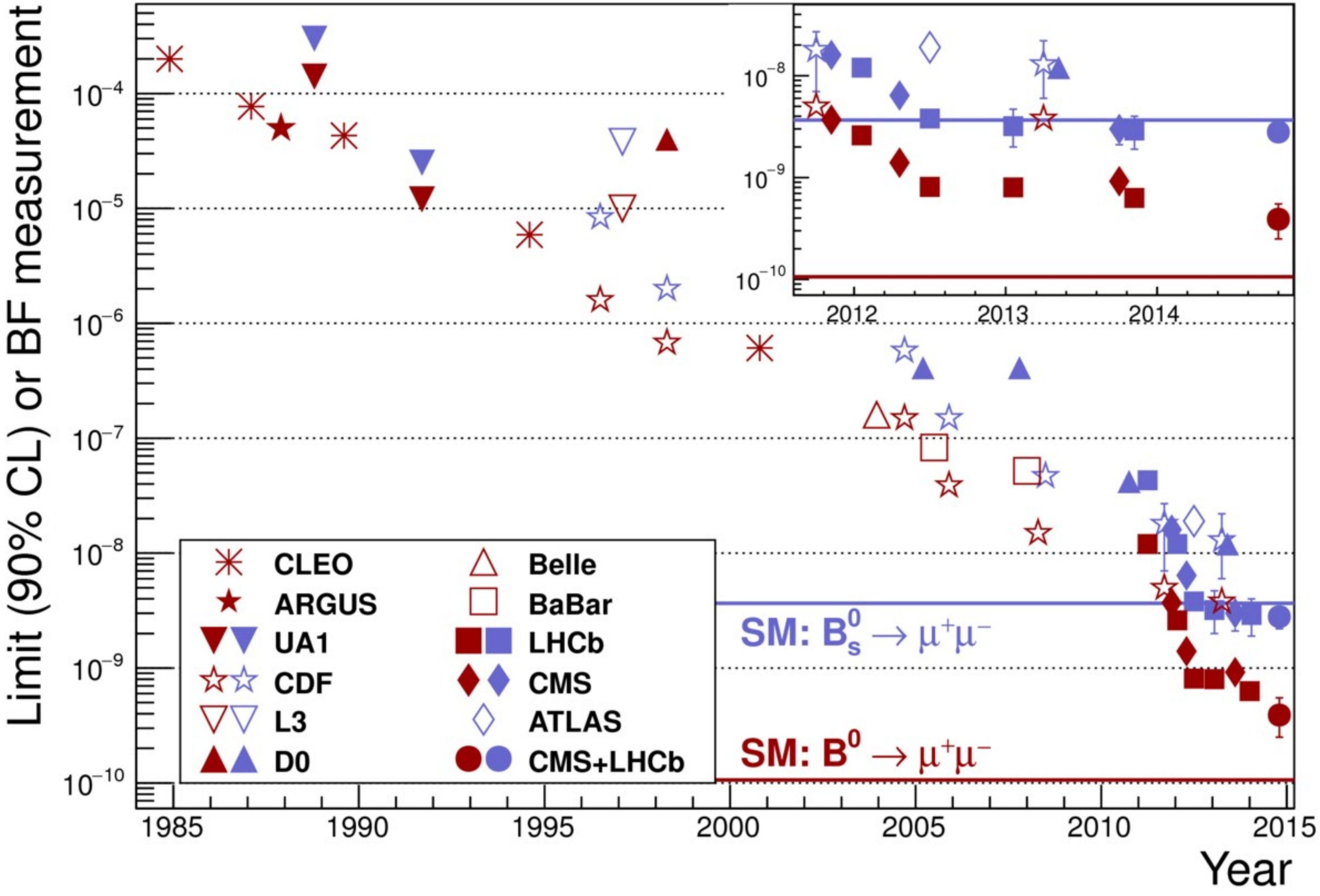
- $B_s^0 \rightarrow \mu^+\mu^-$ & $B^0 \rightarrow \mu^+\mu^-$

$B^0_s \to \mu^+\mu^-$ & $B^0 \to \mu^+\mu^-$

[Nature 522 (2015) 68]

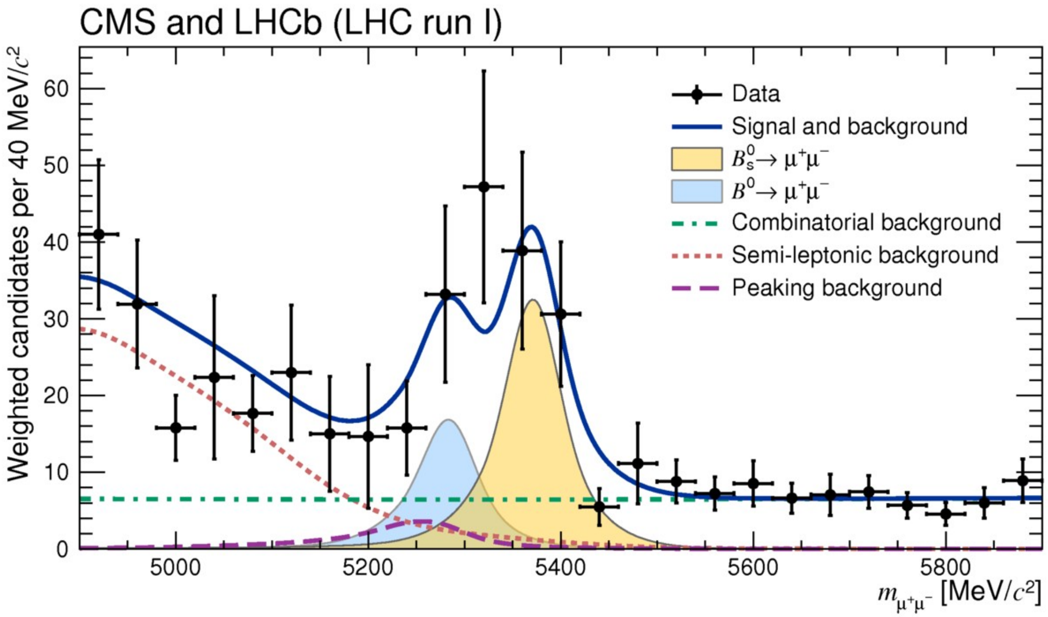
Exceedingly rare in the MS (loop & CKM suppressed + helicity suppressed)

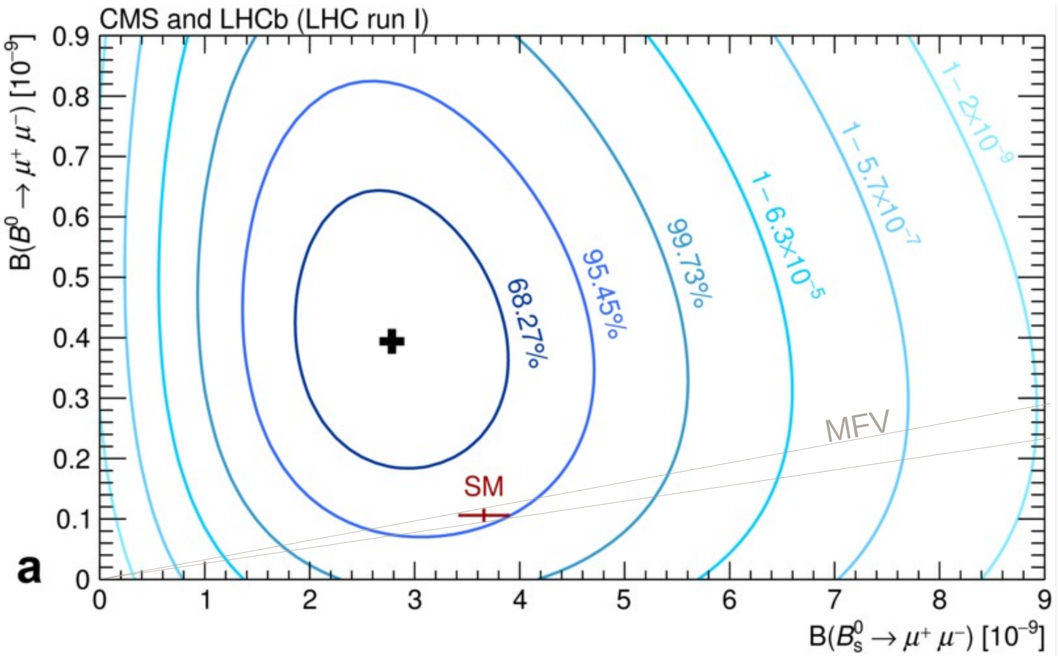
Not necessarily the same in extended models ...



$B_s^0 \to \mu^+\mu^-$ & $B^0 \to \mu^+\mu^-$

[Nature 522 (2015) 68]





CMS + LHCb combined result :

$$\bar{\mathcal{B}}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9},$$
$$\bar{\mathcal{B}}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}.$$

In agreement with SM : [Bobeth C. *et al*, Phys. Rev. Lett. 112 (2014) 101801]

$$\bar{\mathcal{B}}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9},$$
$$\bar{\mathcal{B}}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}.$$

↘ deviations are still possible

$b \to d\ell\ell$ Decays

- Branching fraction & CP asymmetries

  → $B^{+} \longrightarrow \pi^{+} \mu^{+} \mu^{-}$

$b \to s\ell\ell$ Decays

- Branching fractions & isospin asymmetries

  → $B^{0} \longrightarrow K^{(*)} \mu^{+} \mu^{-}$

- Branching fractions & angular analysis

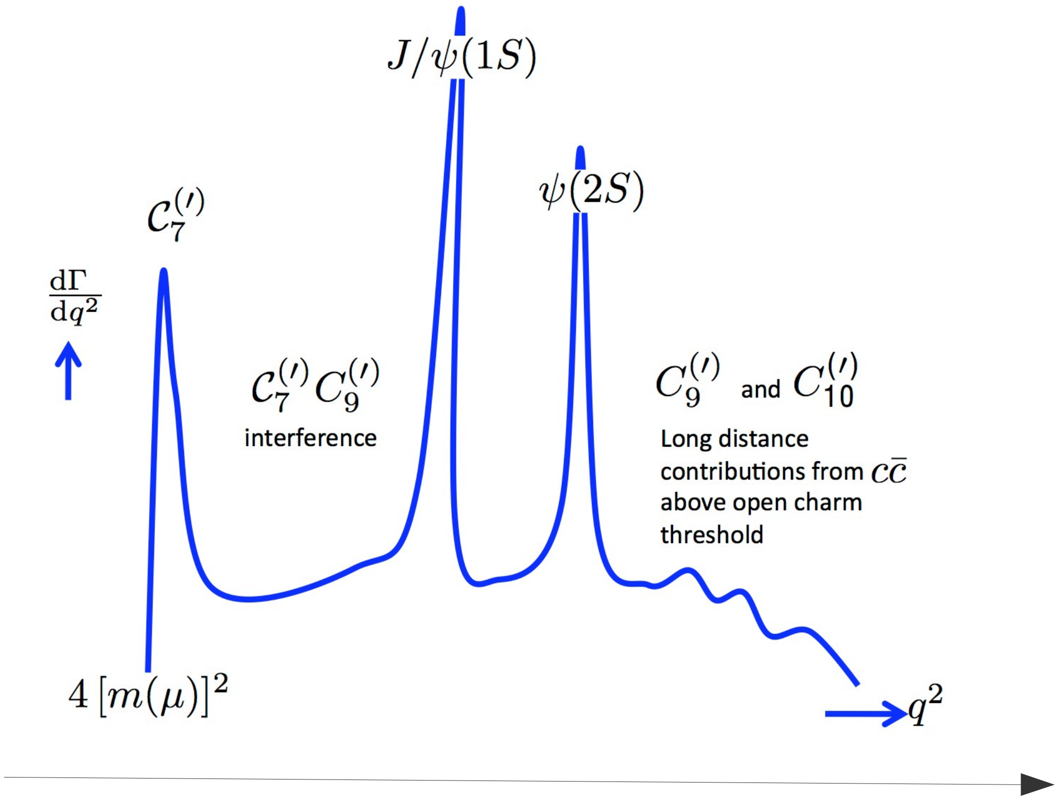
  → $B^{0} \longrightarrow K^{*0} \mu^{+} \mu^{-}$

  → $B_{s}^{0} \longrightarrow \Phi \ \mu^{+} \mu^{-}$

  → $\Lambda_{b}^{0} \longrightarrow \Lambda^{0} \ \mu^{+} \mu^{-}$

  → $B^{0} \longrightarrow K^{*0} \ e^{+} e^{-}$

Kinematic regimes in $B \to V\ell\ell$



$q^2 = m(\ell\ell)^2$

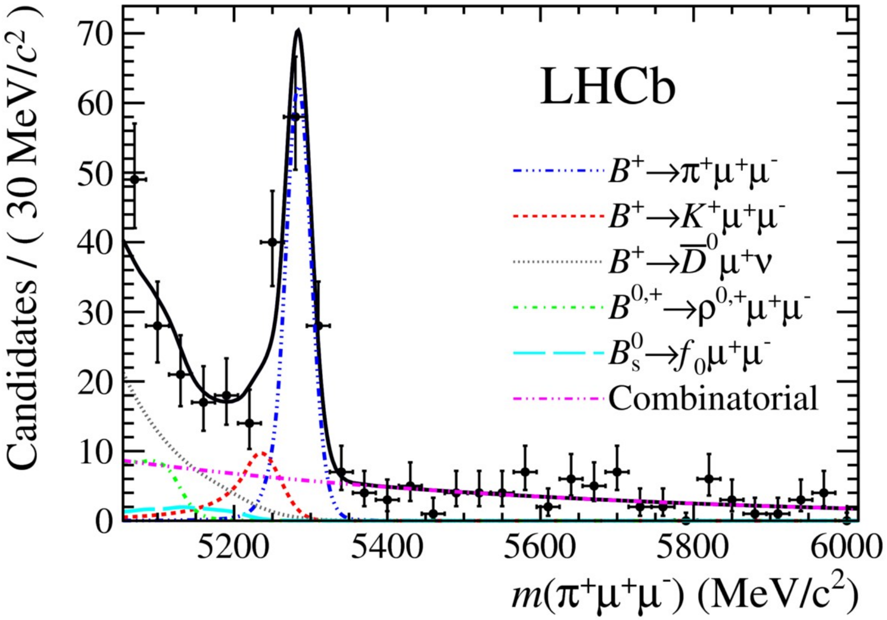
- Low q^2 (= large recoil)
- QCD factorization applies
- Form factors computed using LCSR method

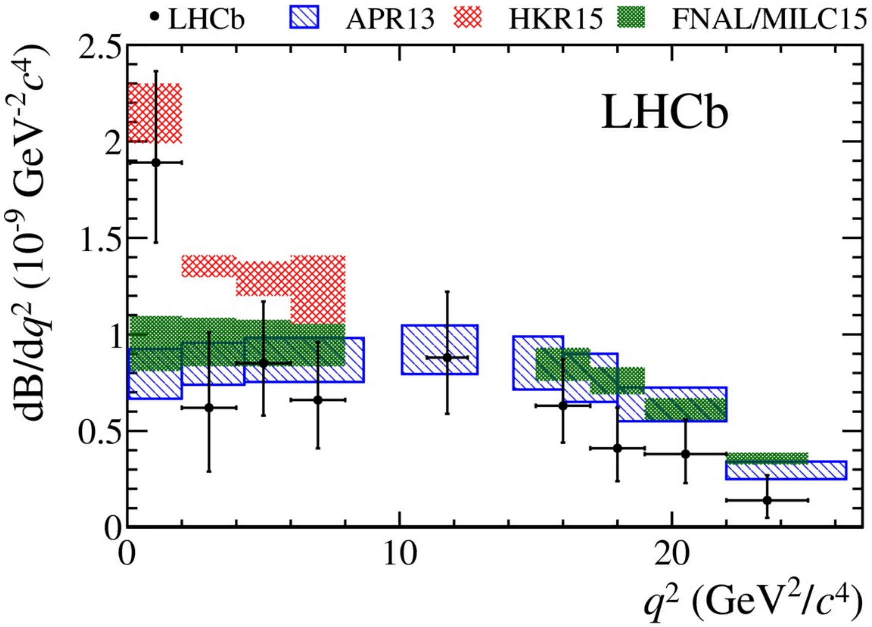
- High q^2 (= low recoil)
- OPE in $1/m_b$ applies
- Form factors from lattices

↘ Need to study these 2 regimes separately

$B^{+}\to\pi^{+}\mu^{+}\mu^{-}$: branching fraction and CP asymmetry

[JHEP10(2015)034]





SM predictions based upon: PRD89 (2014) 094021, arXiv:1506.07760, arXiv:1507.01618

Branching fraction in agreement with SM predictions

CP asymmetry :

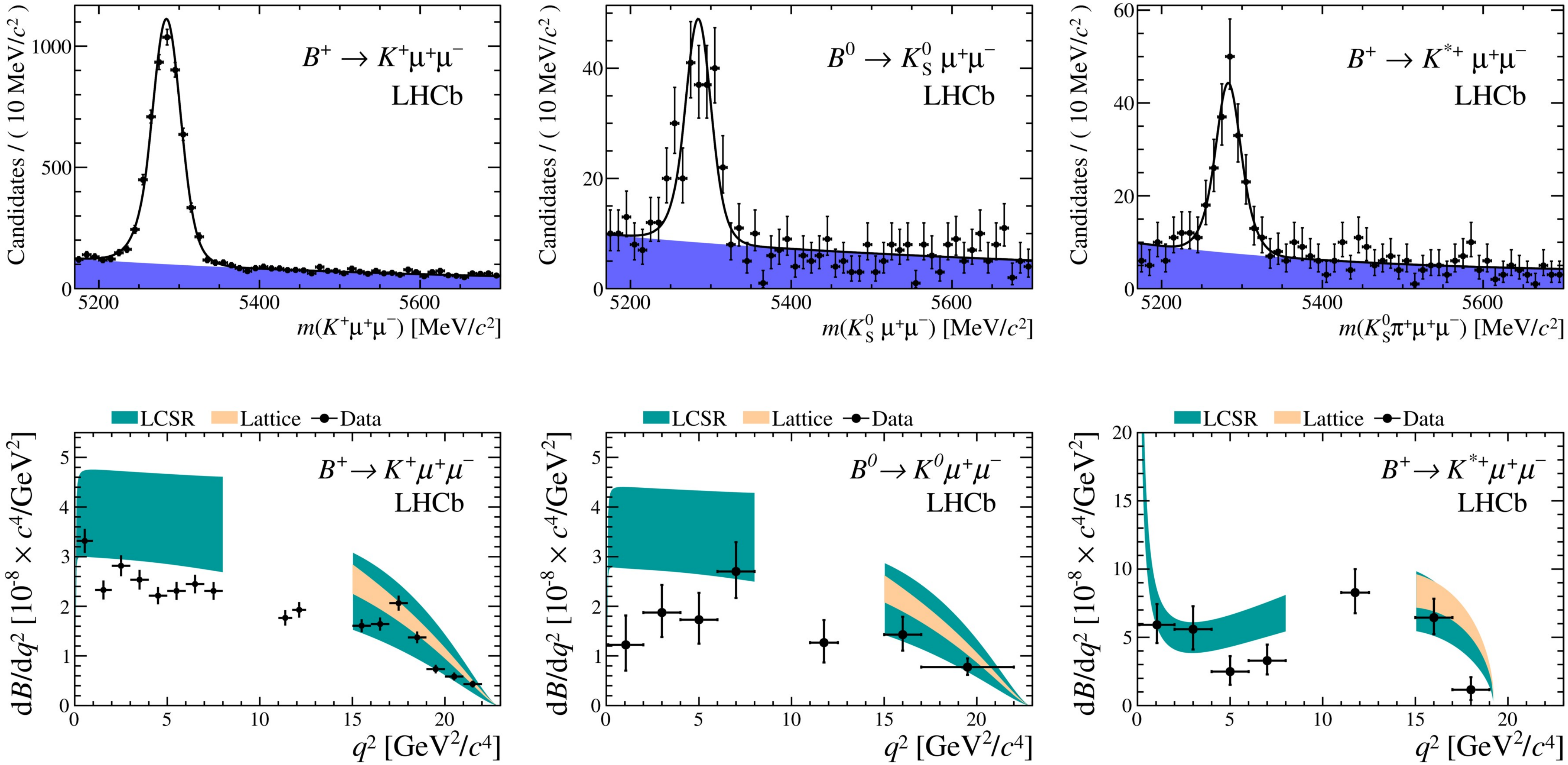
- $\mathcal{A}_{CP}(B^{\pm}\to\pi^{\pm}\mu^{+}\mu^{-}) = -0.11 \pm 0.12\,(\mathrm{stat}) \pm 0.01\,(\mathrm{syst})$
- in agreement with SM prediction [PRD92,074020(2015)]

Determination of $|V_{td}/V_{ts}|$

- compatible with previous measurements

$B \to K^{(*)} \mu^+ \mu^-$: branching fractions

[JHEP 06 (2014) 133]



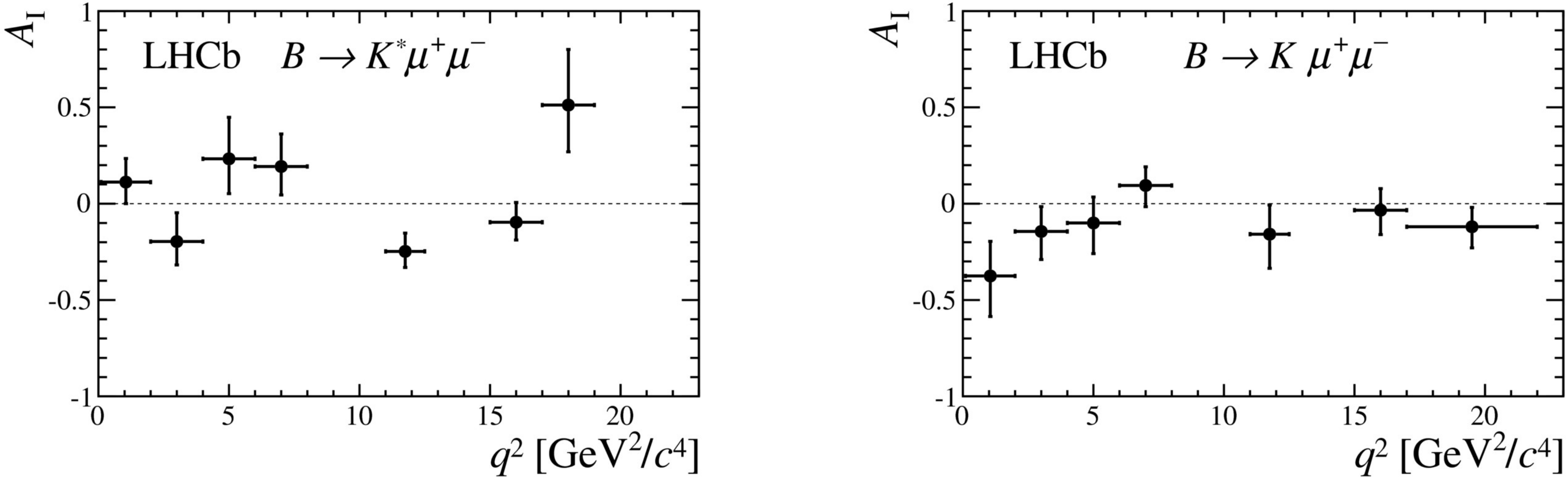
SM predictions based upon: JHEP 07 (2011) 067, JHEP 01 (2012) 107, PRL 111 (2013) 162002, PRL 112 (2014) 212003

- Measurements systematically lower than SM predictions ?

$B \to K^{(*)}\mu^+\mu^-$: isospin asymmetry

[JHEP 06 (2014) 133]

$$A_{\mathrm{I}} = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

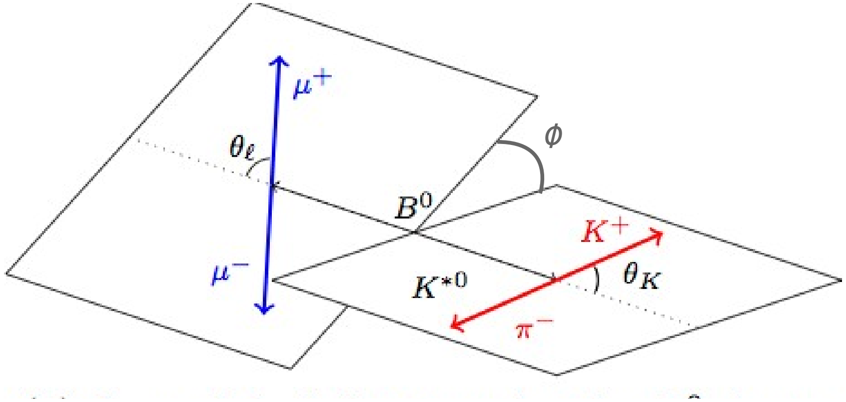


- A_{I} consistent with 0 across the full q^2 window (in the SM, expect ~+10% as $q^2 \to 0$ for $B \to K^*$ decays)

[PLB 539:227 (2002), JHEP 01 (2003) 074]

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

Decay described by 3 angles and q^2 ($m^2_{\mu\mu}$)



$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\big]$$

F_L, A_FB and S_i are determined in bins of q^2

- → depend on C_7, C_9, C_{10}
- → depend on hadronic form factors

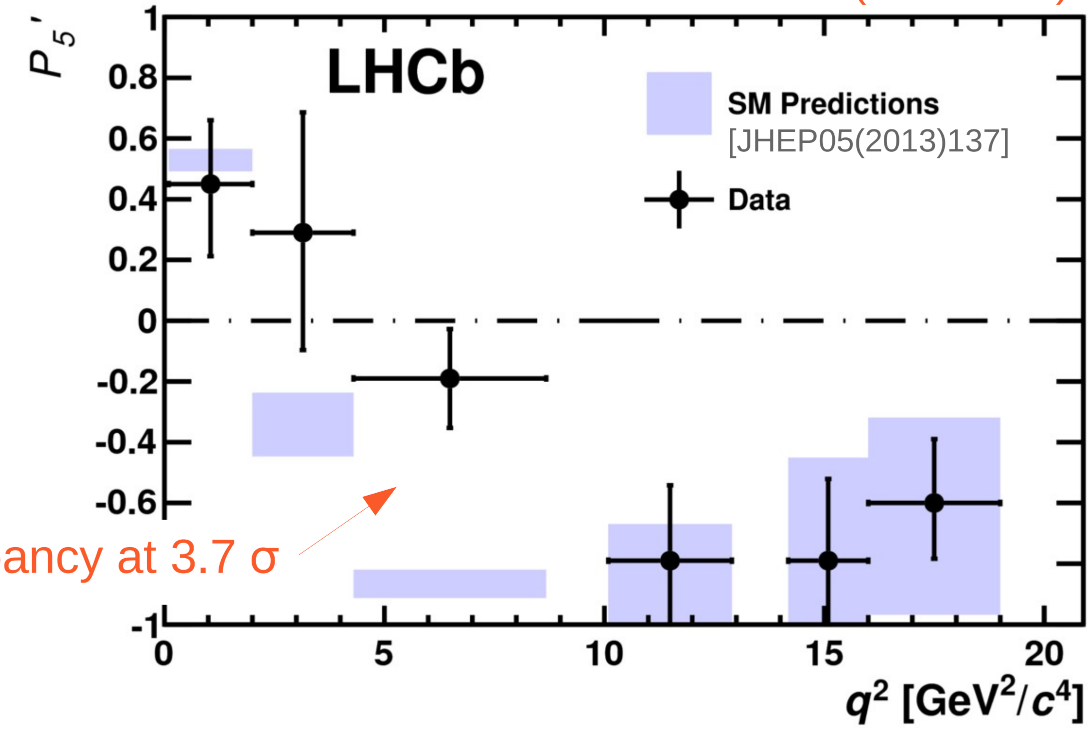
Angular analysis of the $B^0 \to K^{*0} \mu^+ \mu^-$ decay

[PRL 111 (2013) 191801]

Set of optimised variables where the leading form factor uncertainties cancel

→ ex : $P_5' = \dfrac{S_5}{\sqrt{F_L(1-F_L)}}$

1 fb^{-1} (2011 data)



Local discrepancy at 3.7 σ

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

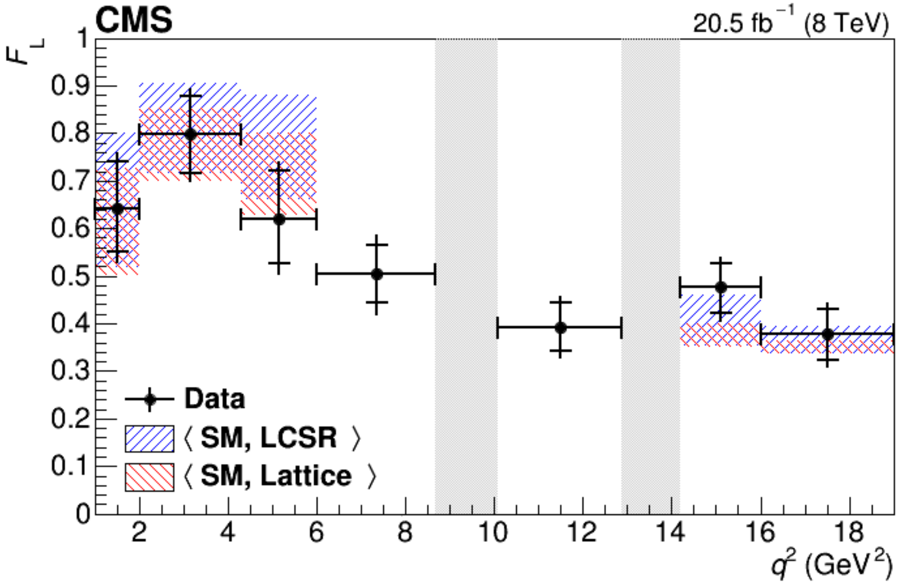
[PLB 753(2016)424]

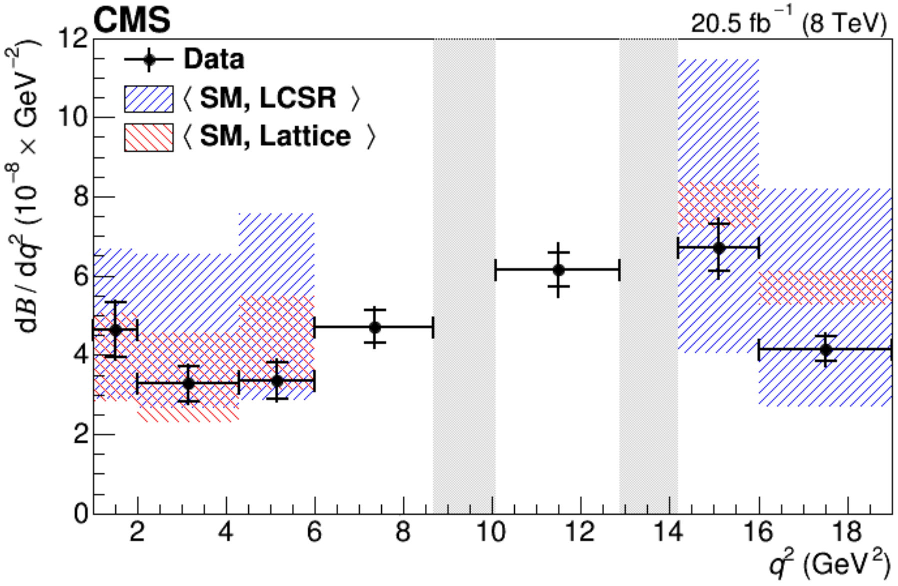
CMS result on 2012 data (8 TeV)

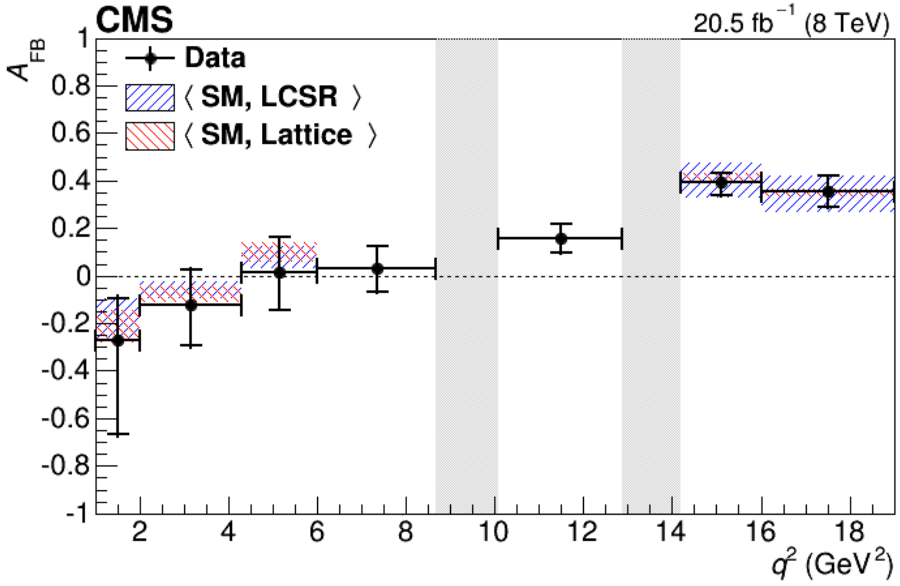
- → 20.5 fb^{-1}
- → 1400 signal events
- → integrated over Φ
- → fit s-wave component : F_s and A_s
- → determine : $d\mathcal{B}/dq^2$, A_{FB}, F_L

SM,LCSR ← [JHEP 09 (2010) 089, JHEP 02 (2013) 010]

SM,Lattice ← [PRD 89 (2014) 094501]





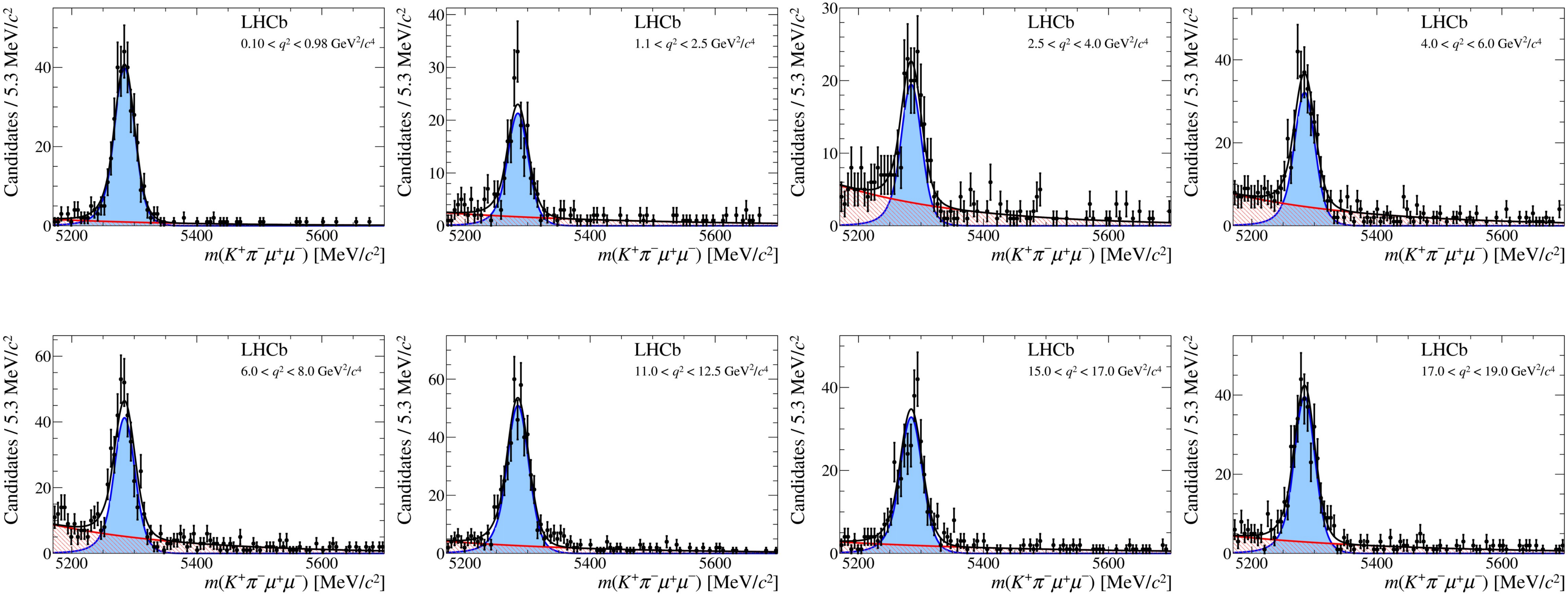


Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay

[arXiv: 1512.04442]
(submitted to JHEP)

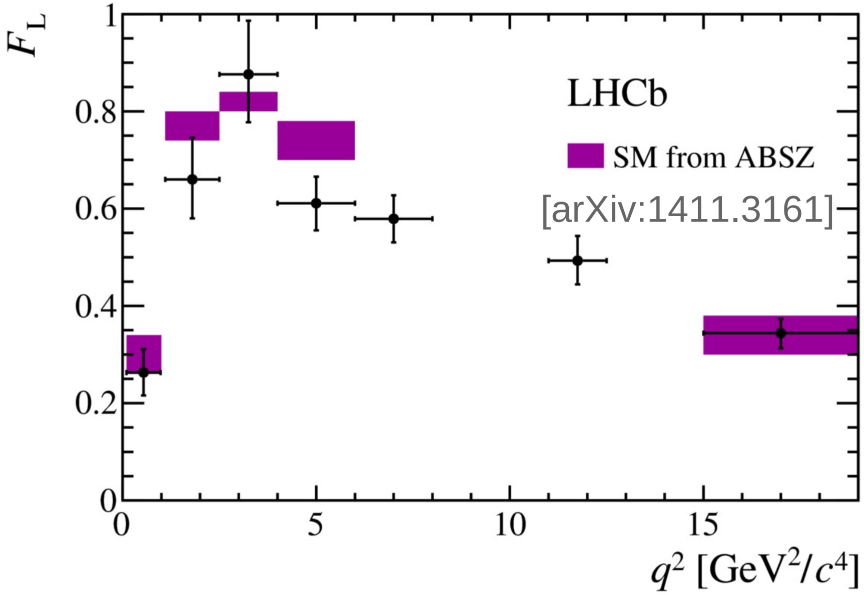
LHCb updated result on 3/fb (run I)

- 2398 ± 57 signal events
- ($K\pi$) S-wave contribution taken into account by fitting simultaneously the $K\pi$ mass
- Angular observables extracted from likelihood fit in decay angles and $m_{K\pi\mu\mu}$ in q^2 bins

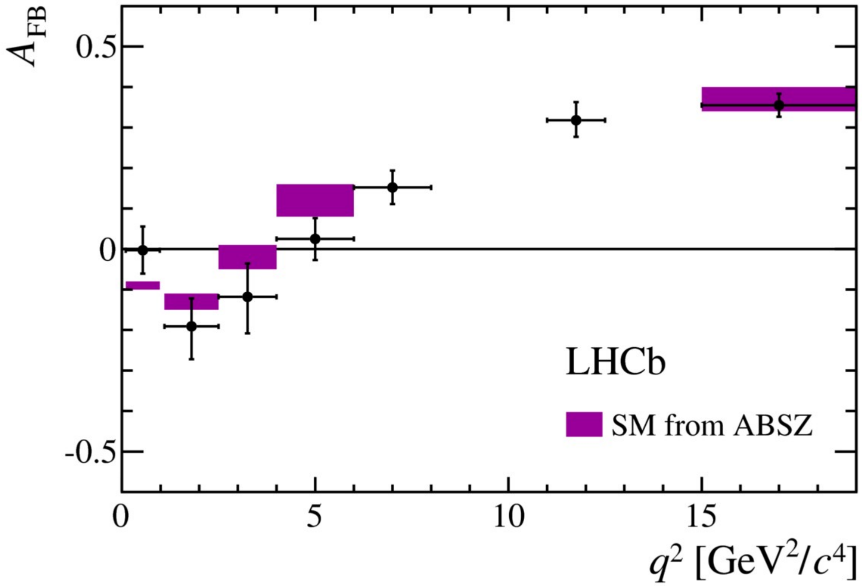


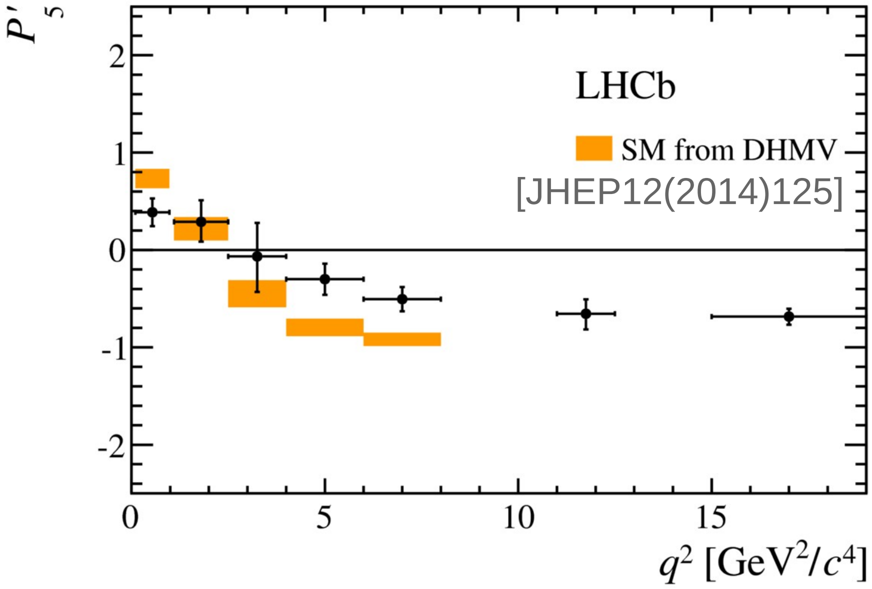
Angular analysis of the $B^0 \to K^{*0} \mu^+ \mu^-$ decay

[arXiv:1512.04442]
(submitted to JHEP)



[arXiv:1411.3161]





[JHEP12(2014)125]

A_{FB} systematically below SM predictions

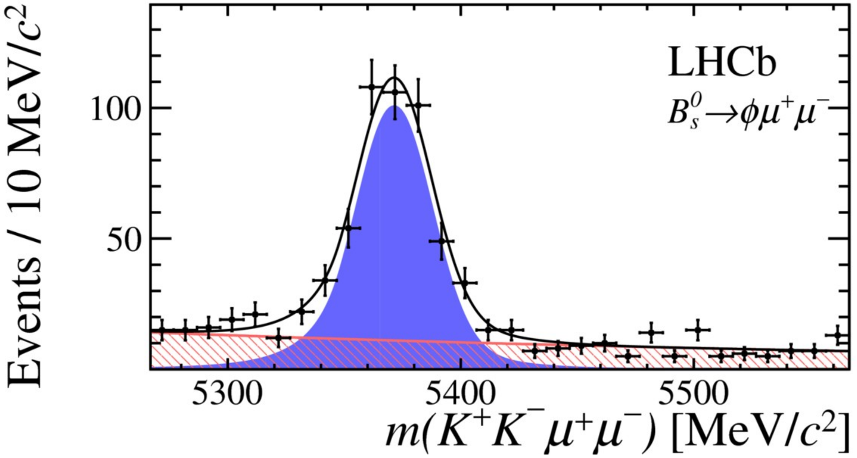
Discrepancy in P'_5 still there at 3.7 σ

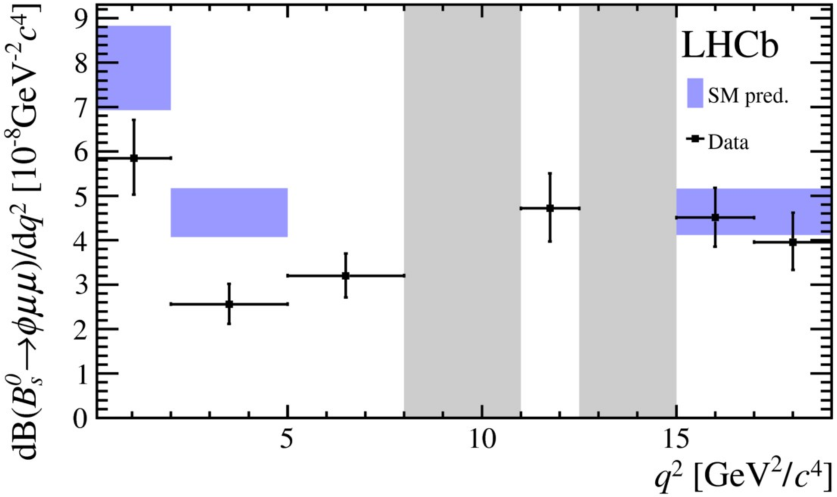
Angular analysis of the $B_s^0 \to \Phi\mu^+\mu^-$ decay

[JHEP 09 (2015) 179]

- Similar to $B_d^0 \to K^{*0}\mu^+\mu^-$
  - → but not self tagged
- Narrow Φ resonance gives clean signal
- 432 ± 24 signal events
- Full angular analysis performed

↘ At low q^2, BR is also below SM ($3.3\,\sigma$ in $1 < q^2 < 6\,\mathrm{GeV}^2$)





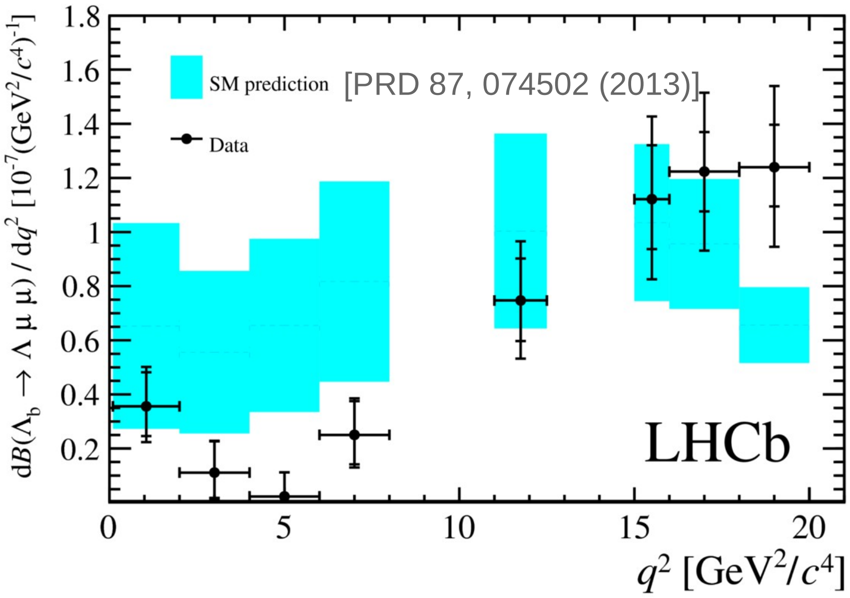
SM predictions based upon:
EPJ.C75(2015)382, arXiv:1503.05534

Angular analysis of the $\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-$ decay

[JHEP 06 (2015) 115]

Baryonic system provides sensitivity to additional observables

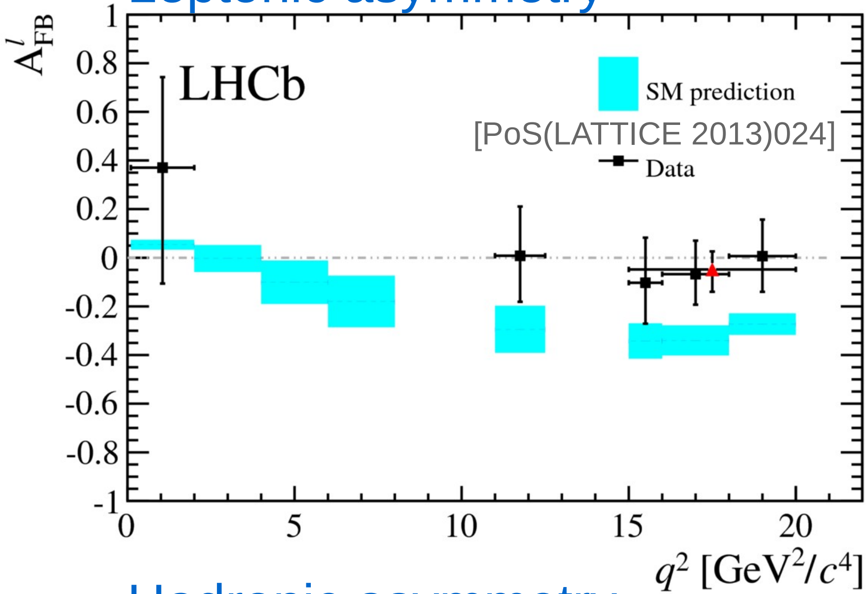
Rate still too low to perform a full angular analysis but forward-backward asymmetries are measured fitting one dimensional angular distributions



[PRD 87, 074502 (2013)]

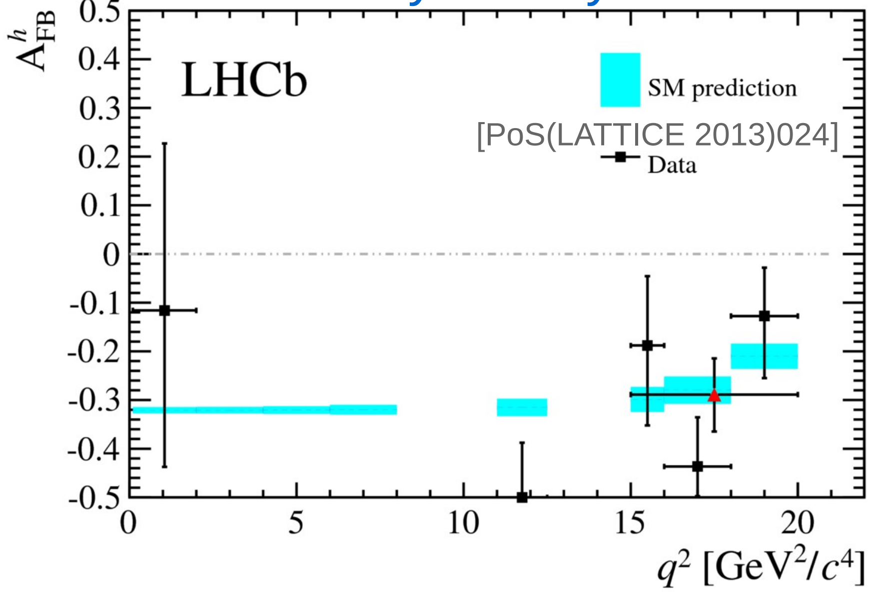
↘ Again, *BR* is below prediction at low q^2

Leptonic asymmetry



[PoS(LATTICE 2013)024]

Hadronic asymmetry



[PoS(LATTICE 2013)024]

Angular analysis of the $B^0 \to K^{*0} e^+ e^-$ decay

[JHEP 04 (2015) 064]

At small q^2 values, sensitive to photon polarization, which is predominantly left-handed in the SM

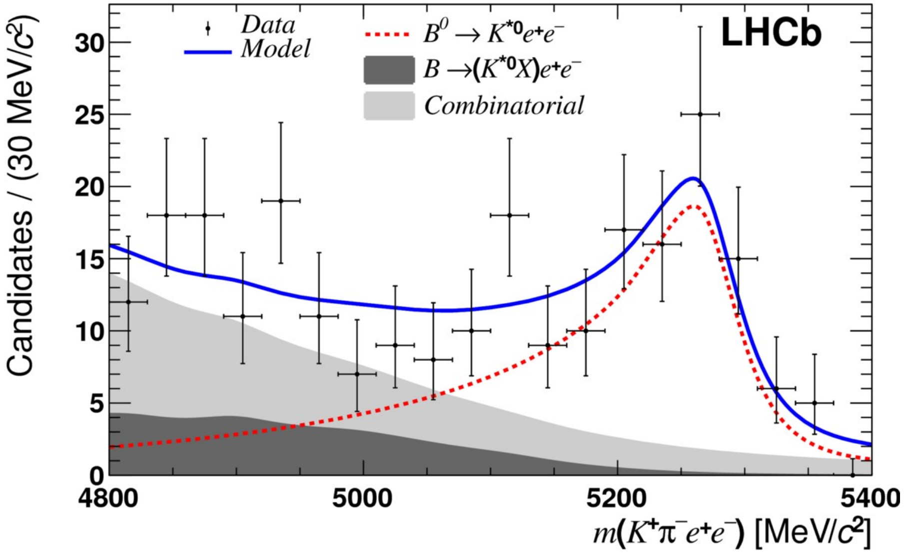
Measurement of F_L , $A_T^{(2)}$, A_T^{Im}, A_T^{Re} in the effective q^2 range [0.0020 ;1.120] GeV^2 /c^4

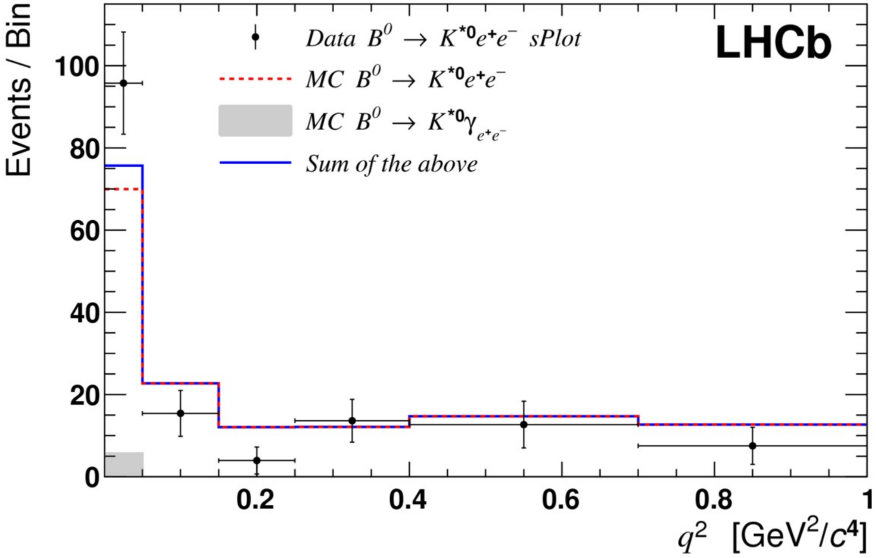
$$\begin{aligned} F_L &= 0.16 \pm 0.06 \pm 0.03 \\ A_T^{(2)} &= -0.23 \pm 0.23 \pm 0.05 \\ A_T^{\mathrm{Im}} &= +0.14 \pm 0.22 \pm 0.05 \\ A_T^{\mathrm{Re}} &= +0.10 \pm 0.18 \pm 0.05 \end{aligned}$$

- in agreement with SM
- constraints on C_7 competitive with radiative decays

$$A_T^{(2)}(q^2 \to 0) = \frac{2\mathcal{R}e(\mathcal{C}_7 \mathcal{C}_7'^*)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

$$A_T^{\mathrm{Im}}(q^2 \to 0) = \frac{2\mathcal{I}m(\mathcal{C}_7 \mathcal{C}_7'^*)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$



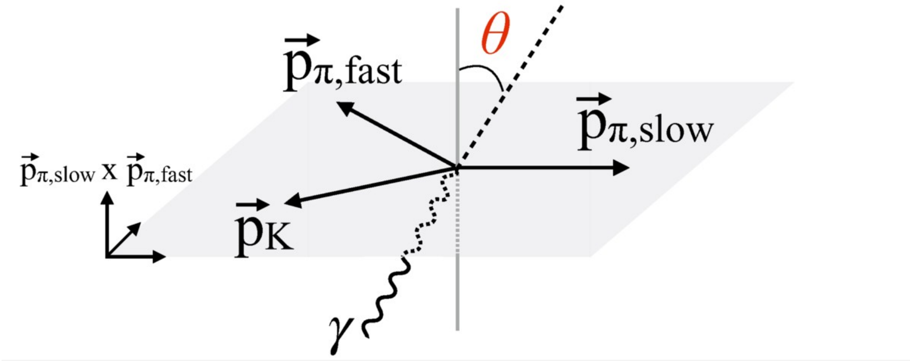


Radiative decays : $b \rightarrow s\gamma$

- Photon polarisation in $B^+ \rightarrow K^+\pi^+\pi^-\gamma$ decays

Photon polarisation in $B^+ \to K^+\pi^+\pi^-\gamma$ decays

[PRL112 (2014) 161801]

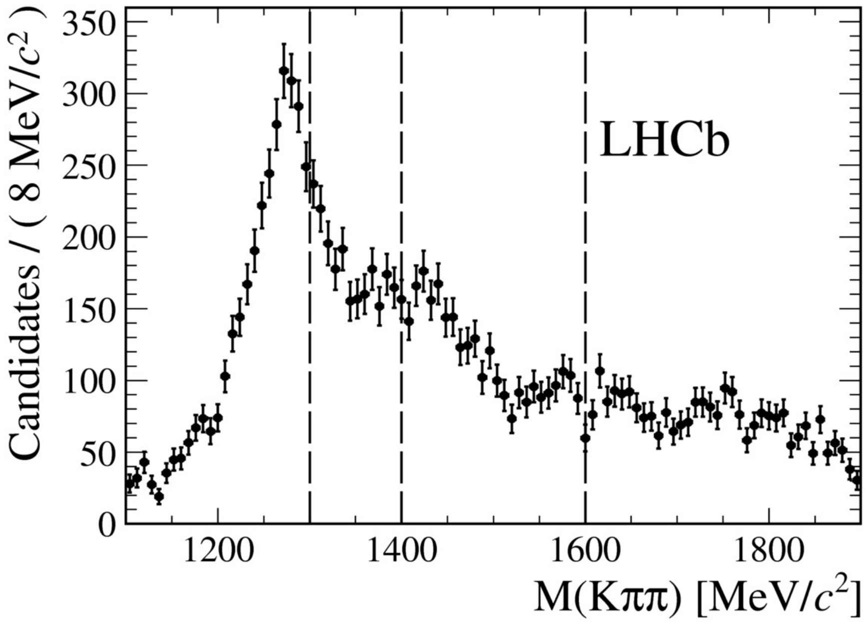


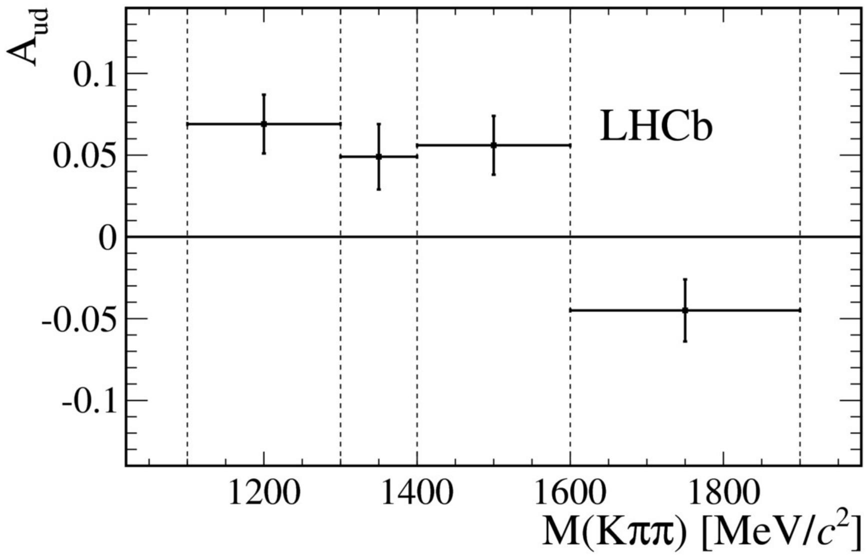
Photon polarisation (λ_γ) sensitive to C_7/C_7'

Measure up-down asymmetry A_{ud}

- → $\lambda_\gamma \propto A_{ud}$
- → $\lambda_\gamma \neq 0$ at 5.2 σ level

↘ need deeper understanding of the $K\pi\pi$ structure to determine C_7/C_7'





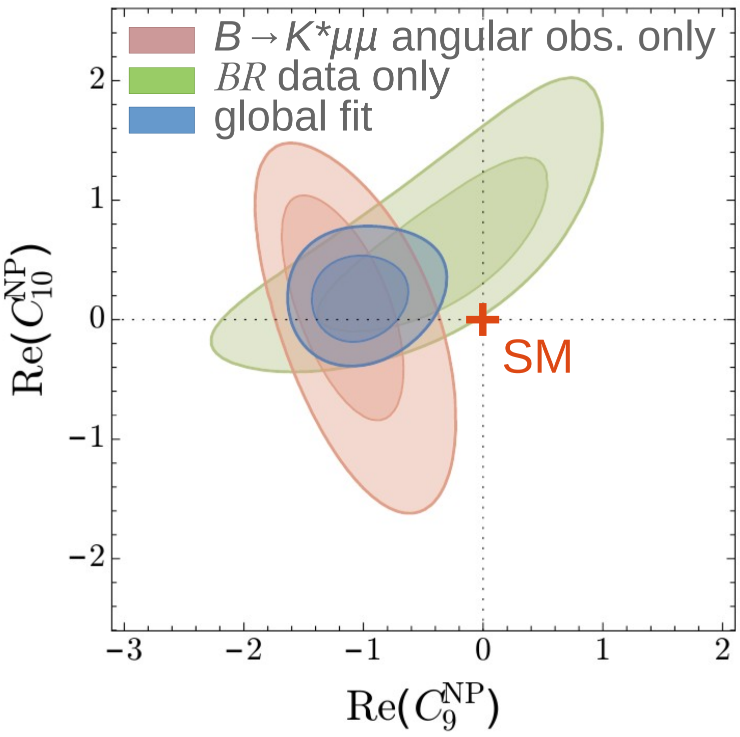
Interpretation

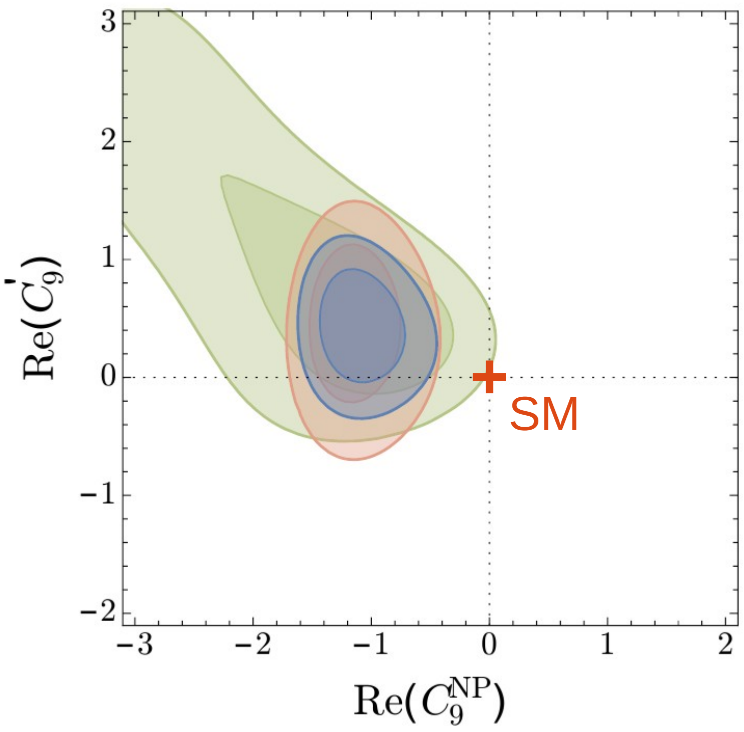
- Wilson coefficients fits

Interpretation : Wilson coefficients fits

[arXiv:1503.06199]

Global fit (76 observables) : W. Altmannshofer and D. Straub





The fit prefers

C_9^{NP} ~ -1.1

by 3.7 σ

Lot of interests from the theoretical side

- NP or underestimated effects ? (see Wolfgang's talk in this session)
  [EPJC(2015)75:382, JHEP12(2014)125, arXiv:1512.07157, …]
- BSM models
  (see Andrea's talk on Tuesday)

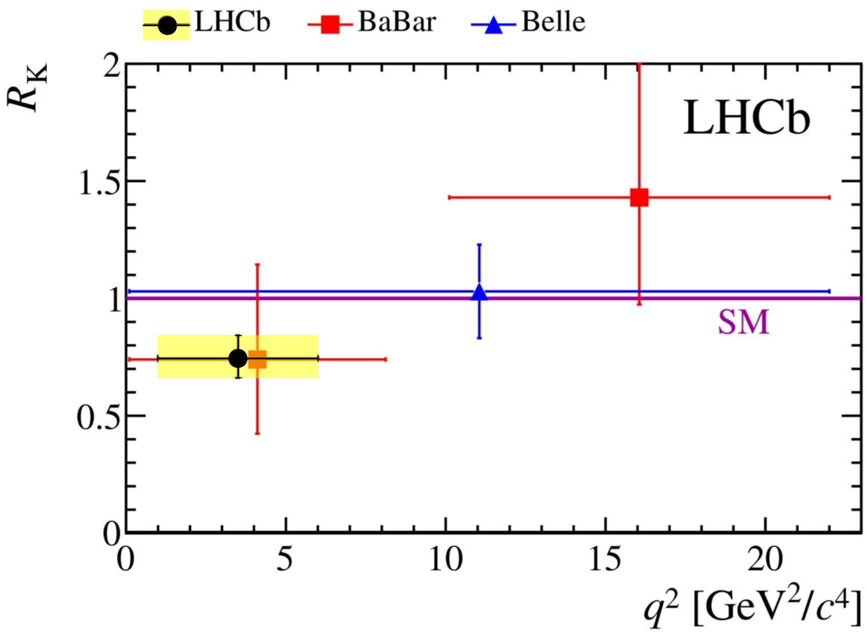
Lepton Non-universality Tests

- R_{K}
- $R(\mathrm{D})$ & $\mathrm{R}(\mathrm{D}^*)$

$B^+ \rightarrow K^+\ell^+\ell^-$

[PRL 113 (2014) 151601]

$$R_K = \frac{\Gamma(B^+ \rightarrow K^+\mu^+\mu^-)}{\Gamma(B^+ \rightarrow K^+e^+e^-)}$$



In SM: $R_K = 1$

LHCb measurement in $1 < q^2 < 6$ GeV^2/c^4 :

$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

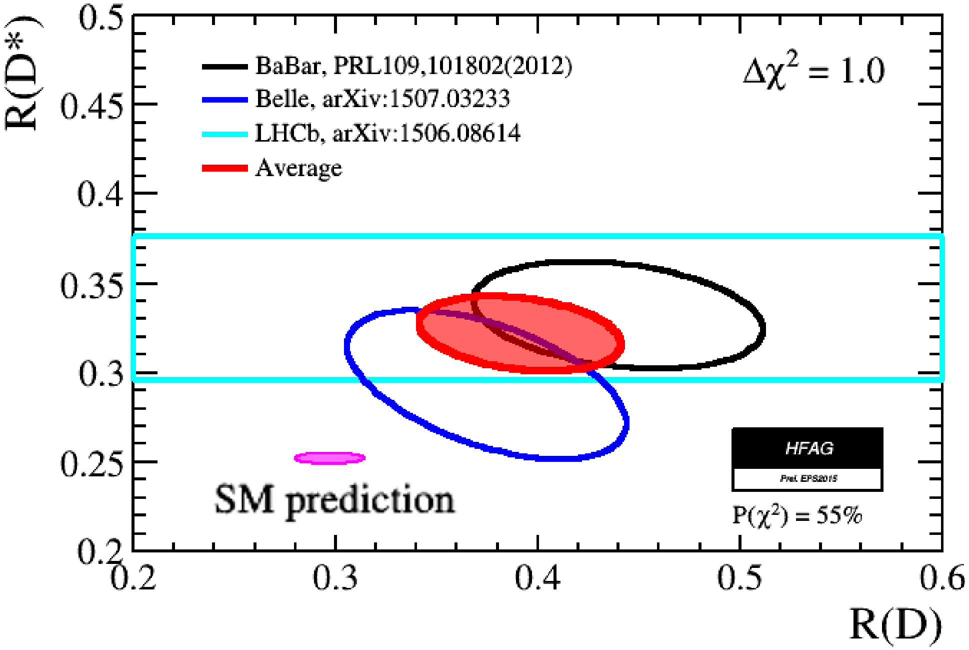
- → 2.6 σ from SM
- → electron mode is in agreement with SM
- → deficit of muon mode again

BaBar [PRL 109, 101802 (2012), PRD 88, 072012 (2013)]
Belle [PRD 92, 072014 (2015)]
LHCb [PRL 115 (2015) 112001]

$B \to D\tau\nu$

$$R(D) = \frac{B(B^0 \to D^+\tau^-\upsilon)}{B(B^0 \to D^+\mu^-\upsilon)} \qquad R(D^*) = \frac{B(B^0 \to D^{*+}\tau^-\upsilon)}{B(B^0 \to D^{*+}\mu^-\upsilon)}$$

[HFAG average]



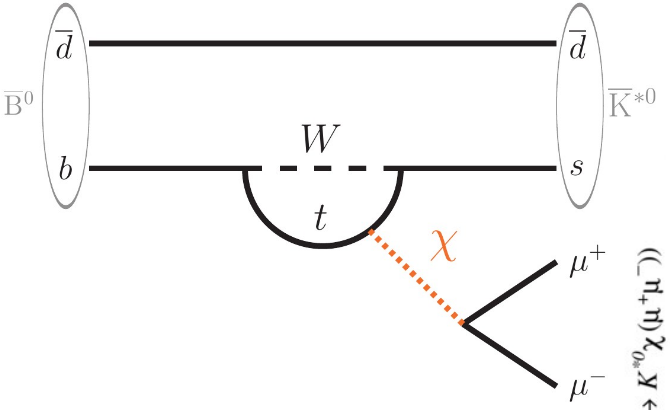
- Average is 3.9 σ away from SM

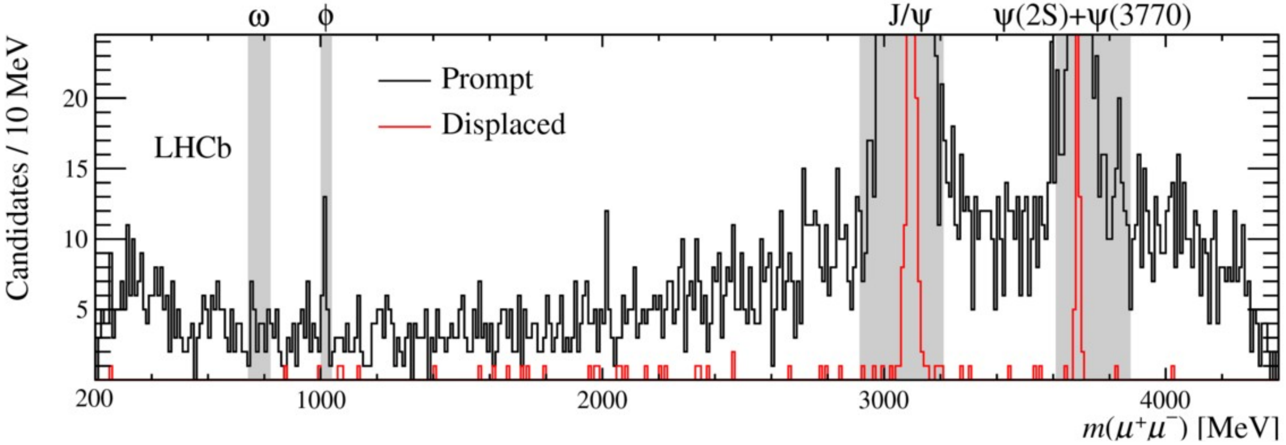
Exotic searches

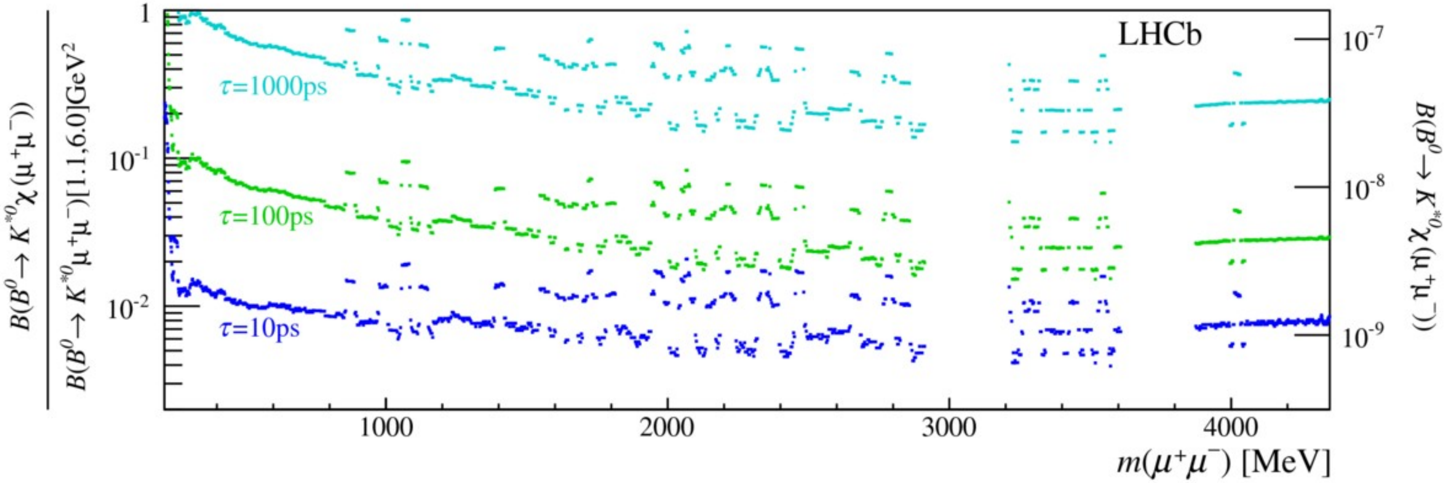
- Search of hidden-sector bosons

Hidden-sector bosons in $B^0\!\to K^{*0}\mu^+\mu^-$ decays

[PRL 115 (2015) 161802]







Search for $B^0 \to K^{*0}\chi(\mu\ \ \mu$

- limits O(10^{-9}) for lifetimes < 100 ps of a large $m(\mu\mu)$ range
- constraints on models predicting low mass bosons such as
  - dark matter with axion states ([PRD81 (2010) 034001])
  - inflaton ([PLB736 (2014) 494])

Conclusion

Heavy flavor rare decays is very rich sector

- lot's of variables to measure
- lot's of measurements already

Model independent analysis can be done to reveal possible NP effect

Some tension between the data and the SM is seen, mainly

- P_5' angular observable in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- R_K, $R(D)$ ratio in lepton universality tests

Need to improve both on theory and experimental sides to conclude

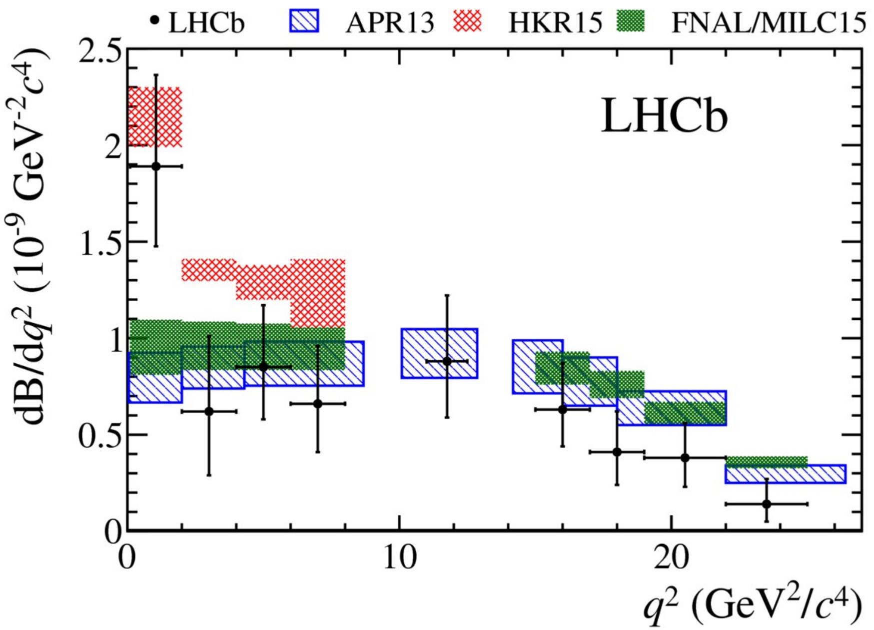
- After LHC run II : expect error bars ÷ 2 (LHCb)

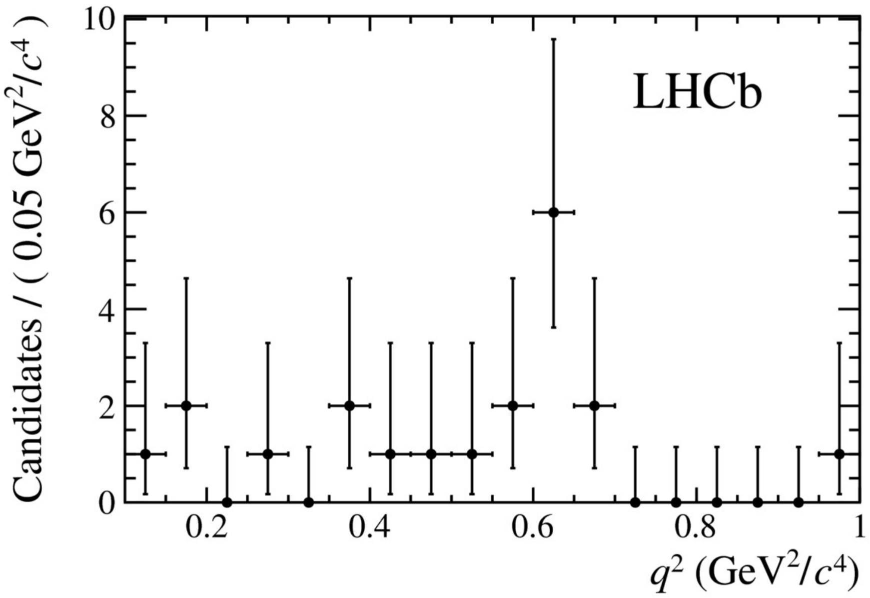
BACKUP

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

$B \to \pi^+\mu^+\mu^-$: branching fractions and CP asymmetry

HKR15 takes into account low q^2 resonance for which we see a hint





$$\mathcal{B}(B^\pm \to \pi^\pm\mu^+\mu^-) = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$$

$$\mathcal{A}_{CP}(B^\pm \to \pi^\pm\mu^+\mu^-) = -0.11 \pm 0.12 \pm 0.01$$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.24^{+0.05}_{-0.04} \quad \left\{\begin{array}{l} 1.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4 \\ 15.0 < q^2 < 22.0\,\mathrm{GeV}^2/c^4 \end{array}\right.$$

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

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

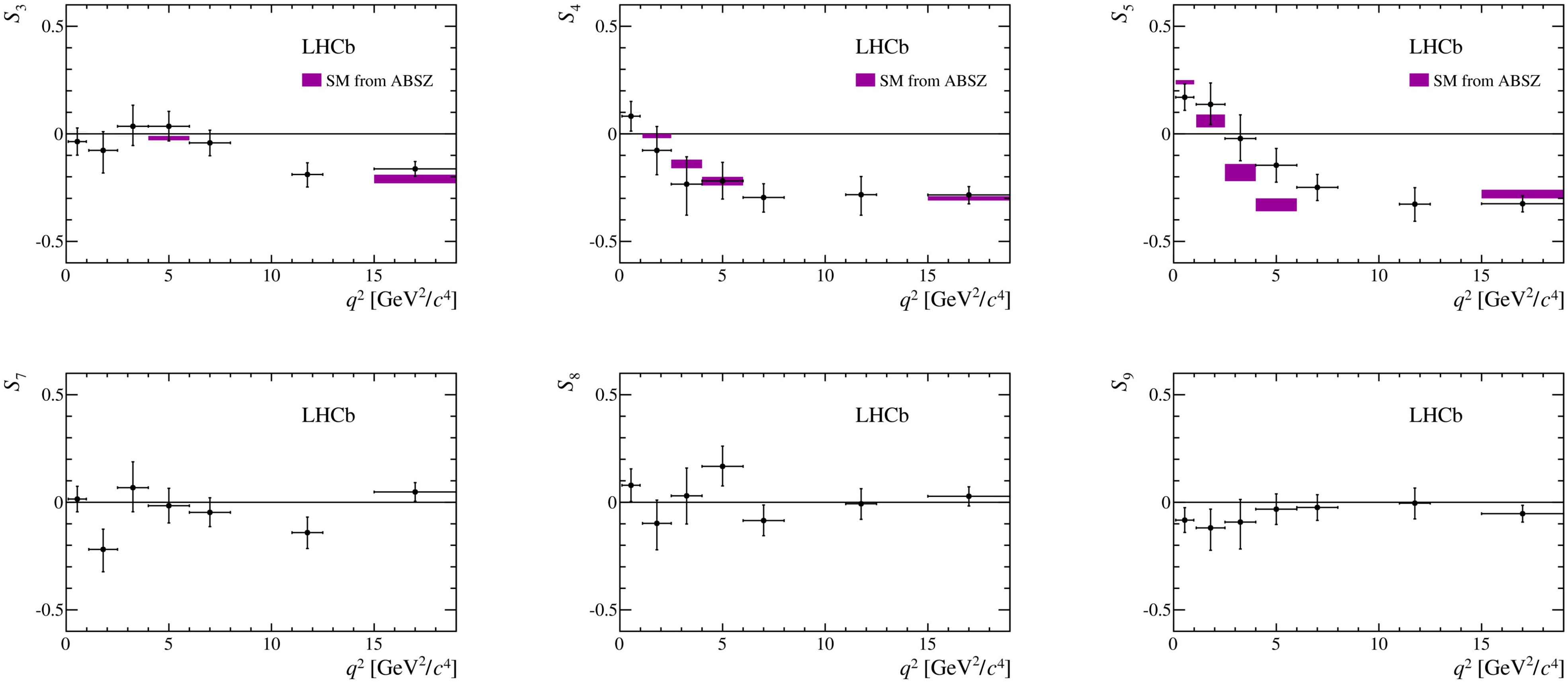
[arXiv: 1512.04442]

$$\begin{aligned}\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[&\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell \\ &- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\ &+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi \\ &+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi \\ &+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]\end{aligned}$$

$$\begin{aligned}\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{S+P}} = \;&(1-F_{\mathrm{S}})\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} \\ &+\frac{3}{16\pi}F_{\mathrm{S}}\sin^2\theta_l \\ &+\frac{9}{32\pi}(S_{11}+S_{13}\cos 2\theta_l)\cos\theta_K \\ &+\frac{9}{32\pi}(S_{14}\sin 2\theta_l+S_{15}\sin\theta_l)\sin\theta_K\cos\phi \\ &+\frac{9}{32\pi}(S_{16}\sin\theta_l+S_{17}\sin 2\theta_l)\sin\theta_K\sin\phi\,,\end{aligned}$$

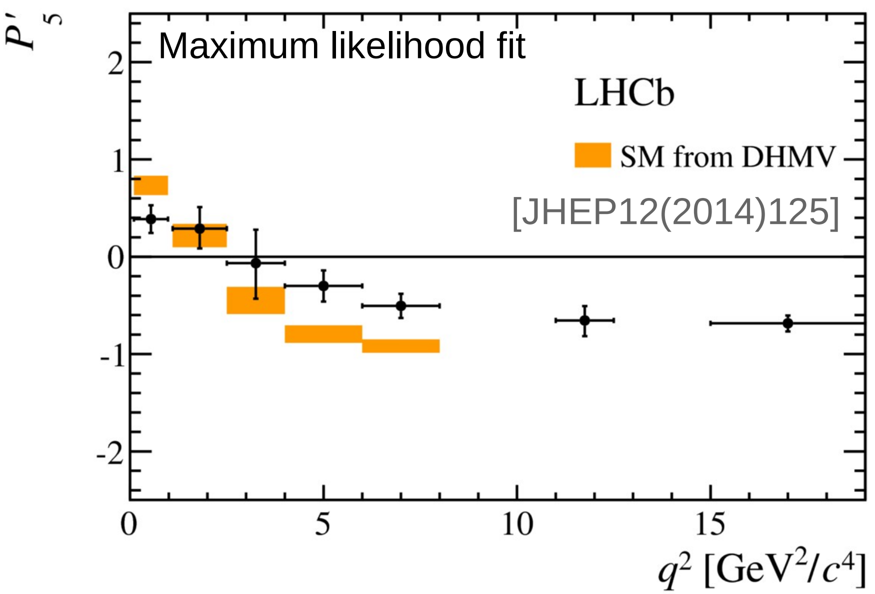
Angular analysis of the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay

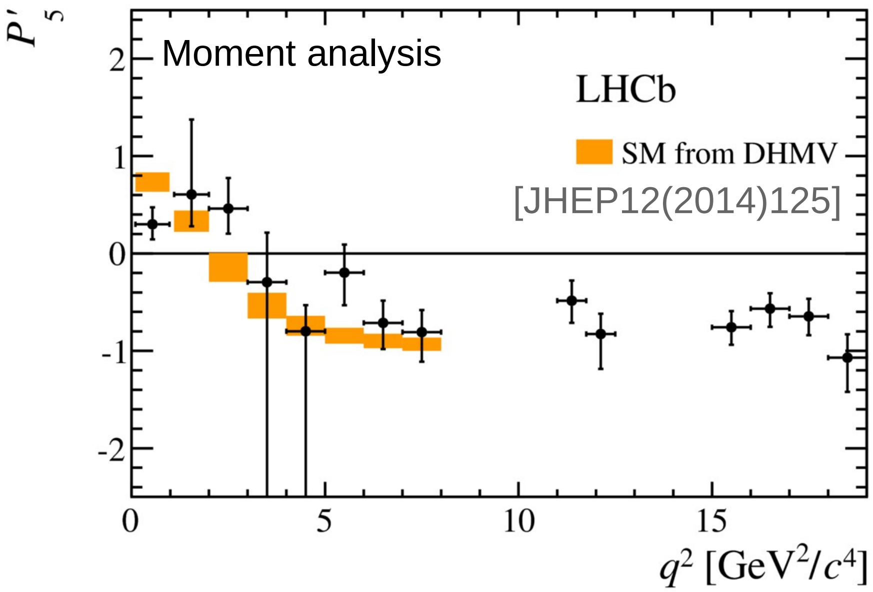
[arXiv: 1512.04442]



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

[arXiv: 1512.04442]



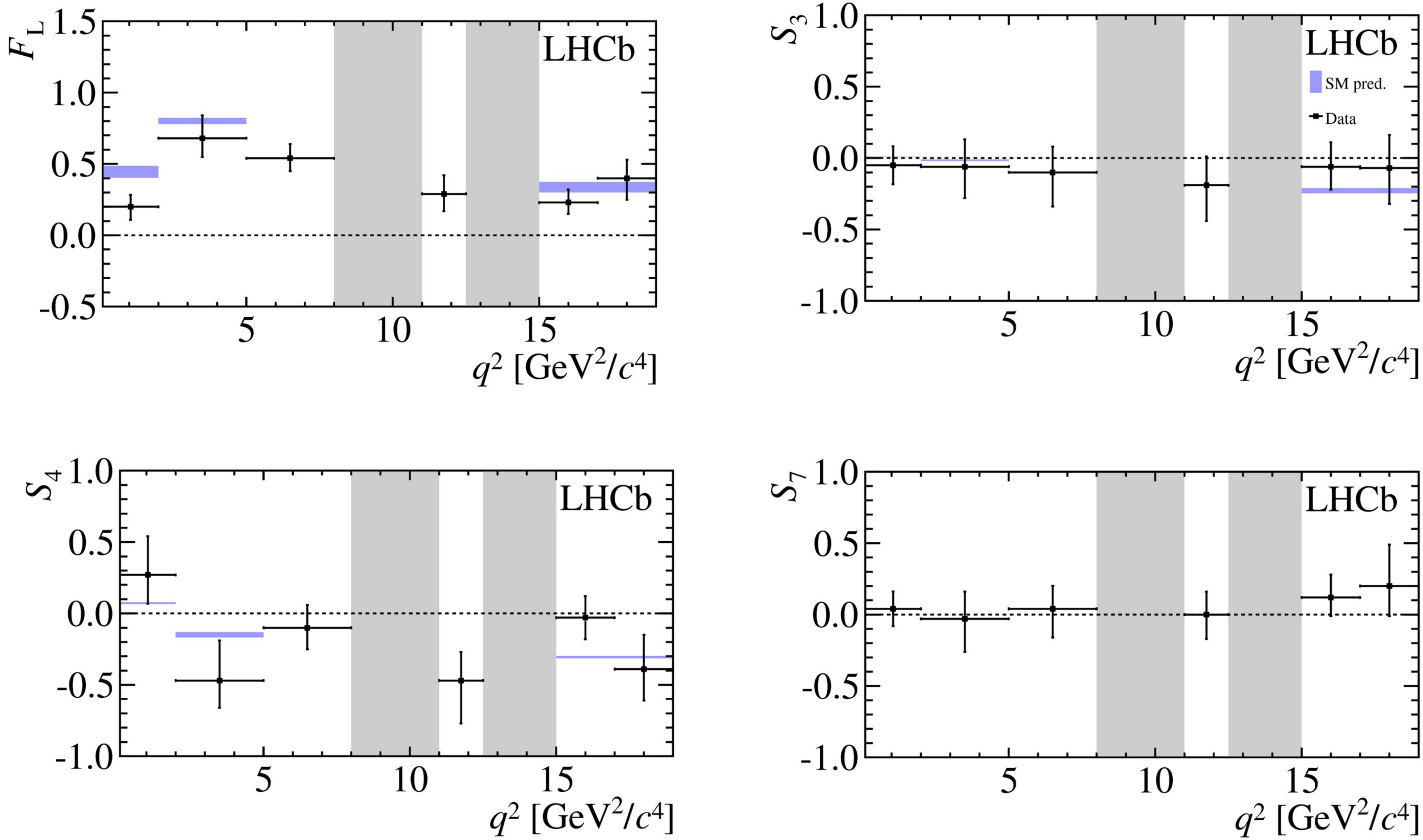


Theory predictions from Descotes-Genon *et al* [JHEP 12 (2014) 125]

$B^0_s \rightarrow \Phi \mu^+\mu^-$

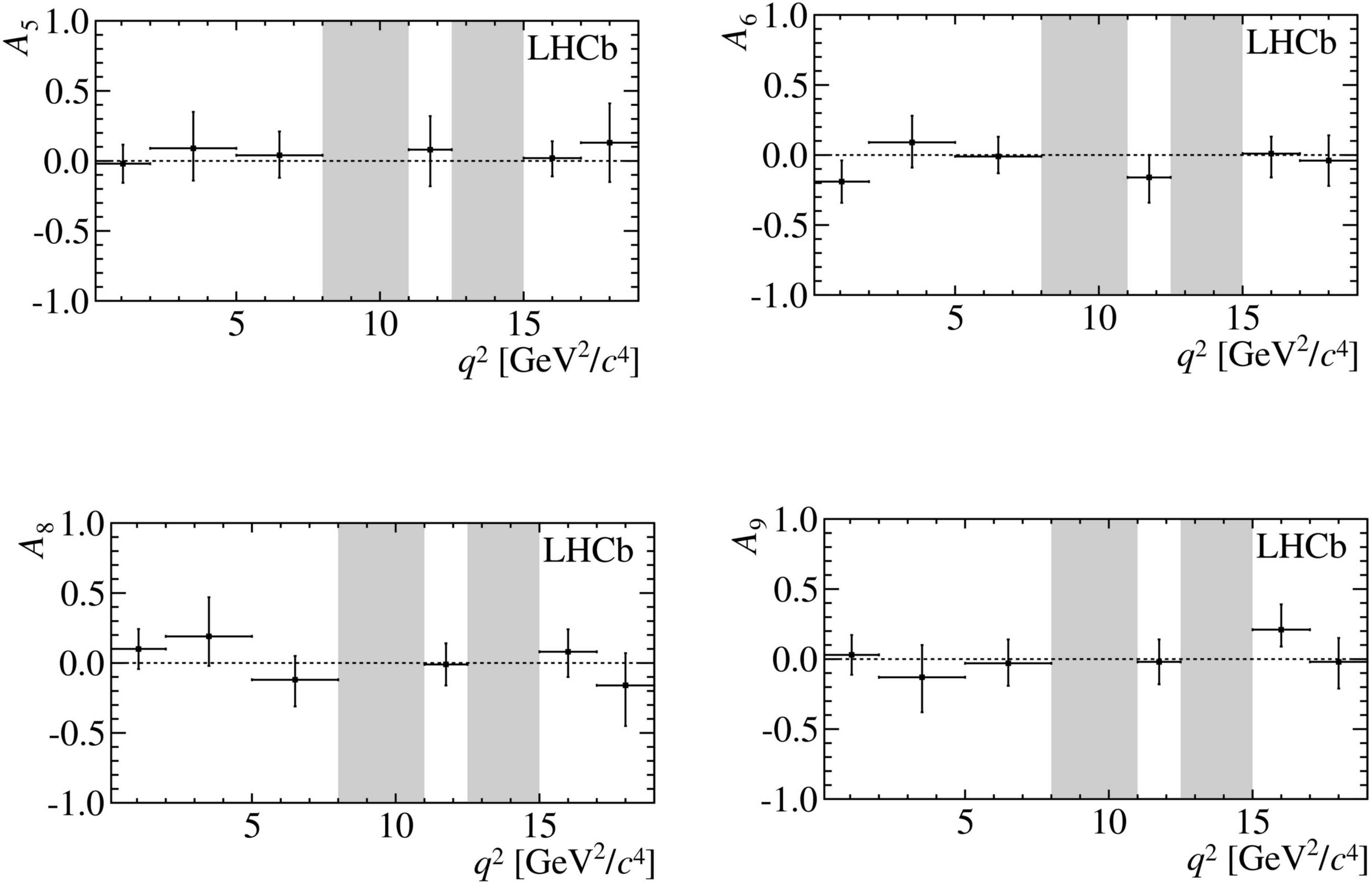
Angular analysis of the $B_s^0 \to \Phi\mu^+\mu^-$ decay

[JHEP 09 (2015) 179]



Angular analysis of the $B_s^0 \to \Phi\mu^+\mu^-$ decay

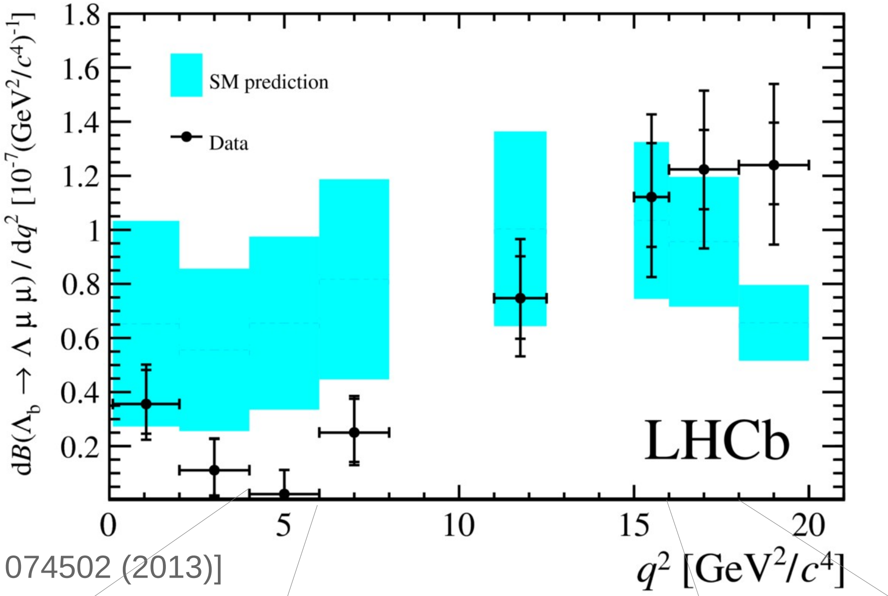
[JHEP 09 (2015) 179]



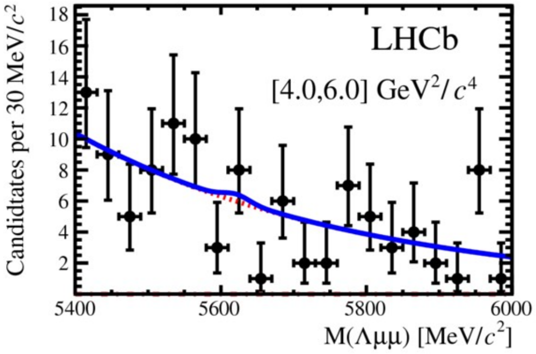
$\Lambda_b^0 \rightarrow \Lambda^0 \mu^+ \mu^-$

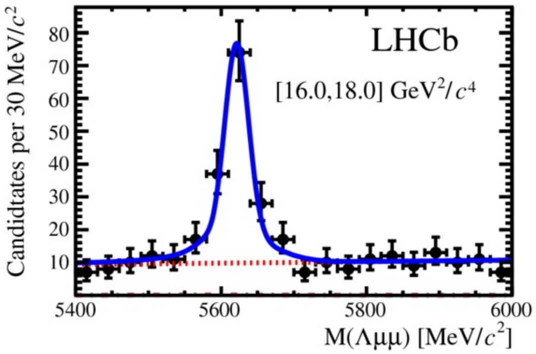
Angular analysis of the $\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-$ decay

[JHEP 06 (2015) 115]



[PRD 87, 074502 (2013)]





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

Angular analysis of the $B^0 \to K^{*0} e^+ e^-$ decay

[JHEP 04 (2015) 064]

$$F_{\mathrm{L}} = \frac{|A_0|^2}{|A_0|^2 + |A_{||}|^2 + |A_\perp|^2}$$

$$A_{\mathrm{T}}^{(2)} = \frac{|A_\perp|^2 - |A_{||}|^2}{|A_\perp|^2 + |A_{||}|^2}$$

$$A_{\mathrm{T}}^{\mathrm{Re}} = \frac{2\mathcal{R}e(A_{||L}A^*_{\perp L} + A_{||R}A^*_{\perp R})}{|A_{||}|^2 + |A_\perp|^2}$$

$$A_{\mathrm{T}}^{\mathrm{Im}} = \frac{2\mathcal{I}m(A_{||L}A^*_{\perp L} + A_{||R}A^*_{\perp R})}{|A_{||}|^2 + |A_\perp|^2}$$