# Impact of CP-asymmetric (angular) observables on the [b->sll] BSM model landscape

*Beyond the Flavour Anomalies II*

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## Outline

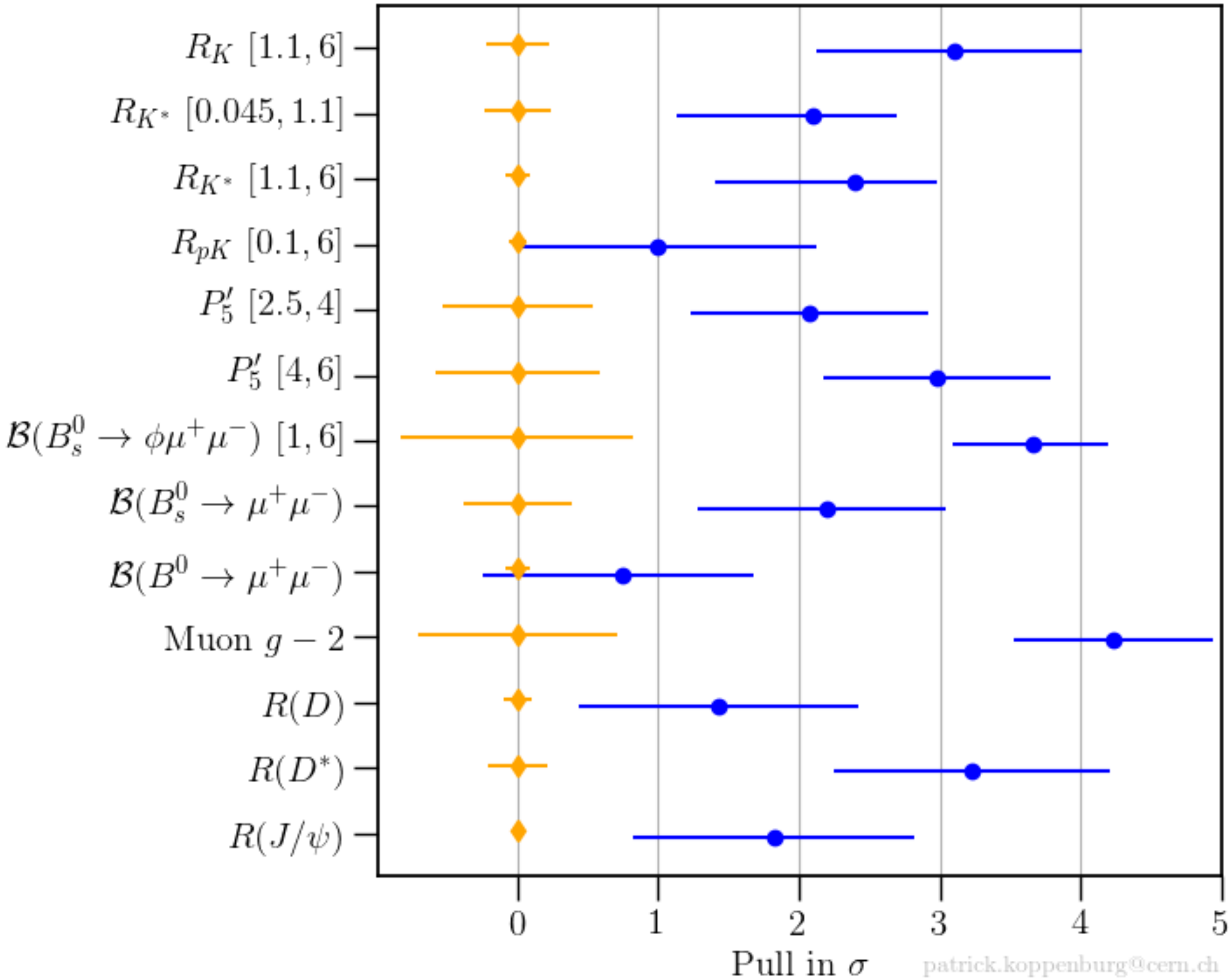
1. CP-asymmetric observables and experimental results to date -> Eluned

2. Impact of observables on distinguishing NP models + new observables -> Aleks

3. Conclusions/experimental prospects -> Eluned

# The current [ $b \to s\ell^+\ell^-$ and friends] landscape

Tensions in CP-averaged observables…what about CP-asymmetric?

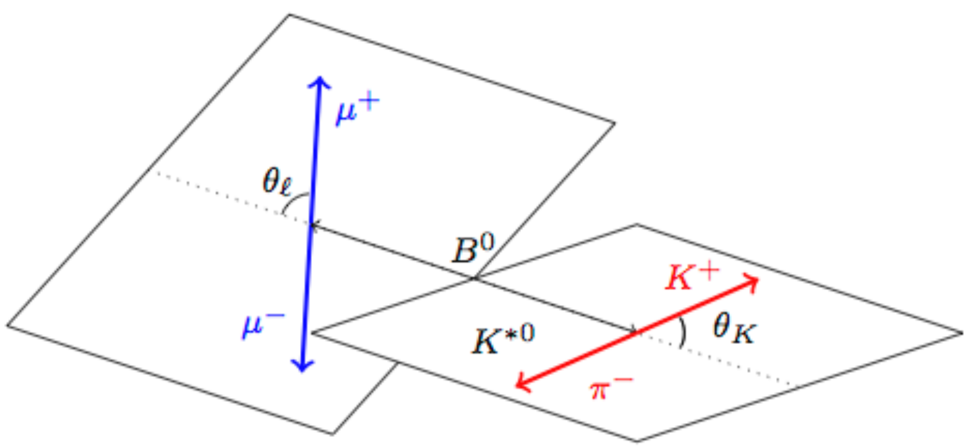



Propaganda plot by
Patrick Koppenberg

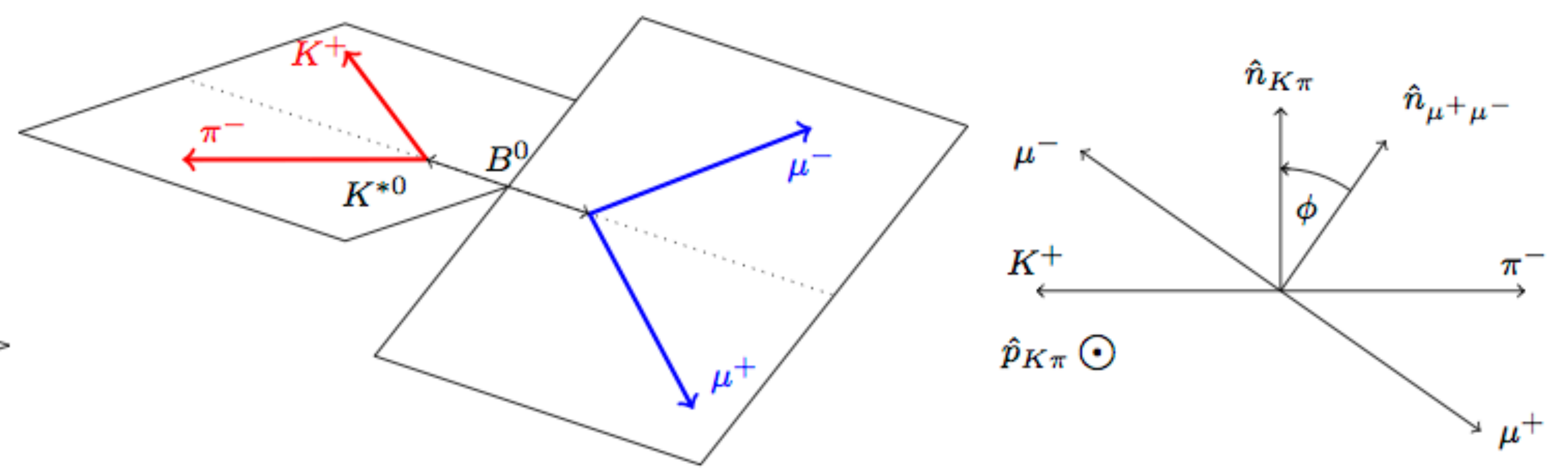
# $B \to V\ell^+\ell^-$ decays: angular analysis

Ignoring meson width, decays described by: $\overrightarrow{\Omega} = (\cos\theta_l, \cos\theta_k, \phi), q^2$

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




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




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

- Other $B \to V\ell^+\ell^-$ decay examples: $B^+ \to K^{*+}\ell^+\ell^-$, $B^0_s \to \phi\ell^+\ell^-$
- Complex amplitudes of vector meson, $A^{L,R}_{0,\perp\|}$, **better accessed using angular analysis**

# $B \to V\ell^+\ell^-$ decays: angular analysis

- Angular description of the decay given as

Angular coefficients

Angular functions

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

$$\frac{d^4\Gamma[B \to V\mu^+\mu^-]}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi} \sum_i \bar{I}_i(q^2) f_i(\vec{\Omega})$$

- Expanding:

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

**12 terms with different [CP] [T] parity**

# CP asymmetric angular observables

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

CP-averaged

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

CP-asymmetries

- Why study CP-asymmetric *angular* observables?
  - **Theory** Sensitive to CP-violating phases (small in the SM)
  - **Experiment** unlike $A_{CP}$, (most) angular observables are not sensitive to *particle/anti-particle asymmetries in production*

# $B \to V\ell^+\ell^-$: CP parity of observables

- Combination and CP-parity of amplitudes upon which each observable is dependent dictate the CP-parity of $I_i(q^2)$

Same CP-parity for B/Bbar

$$I^{(a)}_{1,2,3,4,7} \longrightarrow \bar{I}^{(a)}_{1,2,3,4,7}\,,$$

Different CP-parity for B/Bbar

$$I^{(a)}_{5,6,8,9} \longrightarrow -\bar{I}^{(a)}_{5,6,8,9}\,,$$

- The B flavour for $B \to V(\to M_1 M_2)\ell^+\ell^-$ decays, where $M_1 M_2$ is a CP-eigenstate, can only be accessed with flavour tagging
- **Counter-intuitive:** taking the untagged CP-averaged rate gives the CP-asymmetries $A_{5,6,8,9}$

# $B \to V\ell^+\ell^-$ : T-parity of observables

**T-parity** *(reverse the sign of all particles spin and momenta)*

- Dictates dependence on weak, $\Delta_W$, and strong, $\Delta_S$ phases

| T-odd | T-even |
| --- | --- |
| [odd under $\phi \to -\phi$] | [even under $\phi \to -\phi$] |
| $\propto \cos\Delta_S \sin\Delta_W$ | $\propto \sin\Delta_S \sin\Delta_W$ |
| Asymmetries associated with | Asymmetries associated with |
| $I_{7,8,9}$ | $I_{1-6}$ |

- **strong phase small**, **T-odd** observables more sensitive to CP-violating effects (expected at low $q^2$)
- **strong phase large**, **T-even** observables more sensitive (this is the case e.g. near charmonium resonances )

# $B \to P\ell^+\ell^-$ decays: angular analysis

- $b \to s\ell^+\ell^-$ transitions with pseudoscalar mesons are described by a single angle: $\cos(\theta_l)$
- Full decay rate dependent on just 3 terms

$$\frac{d^2\Gamma[B \to P\ell^+\ell^-]}{dq^2 d\cos\theta_l} = \sum_{i=0,1,2} G_i P_i(\cos\theta_l)$$

- CP-parity, all T-even

$$G_{0,2} \to \bar{G}_{0,2} \qquad G_1 \to -\bar{G}_1$$

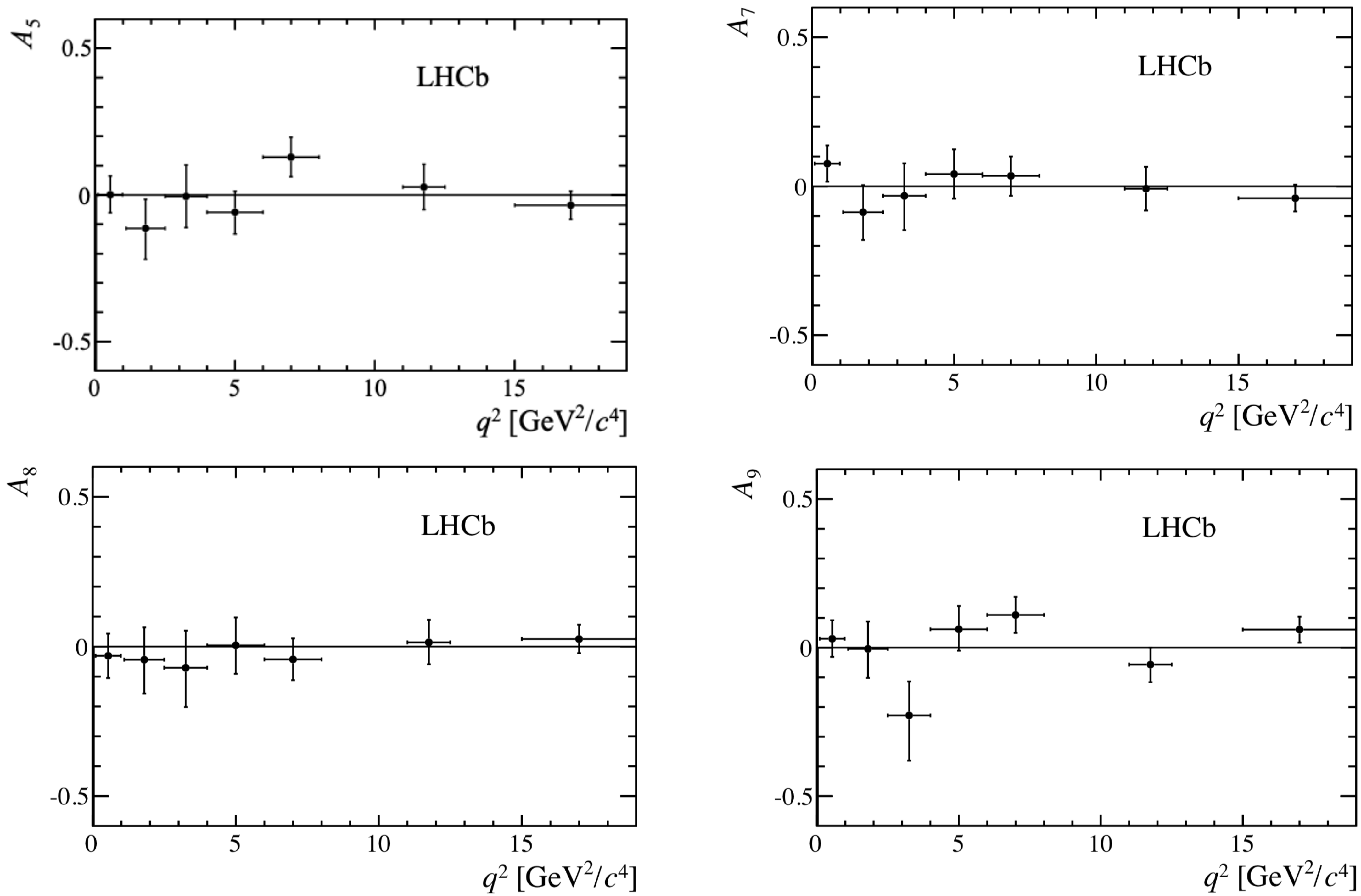
- $G_0$ corresponds to integrated decay rate

# Some examples of measurements to date

discussed here

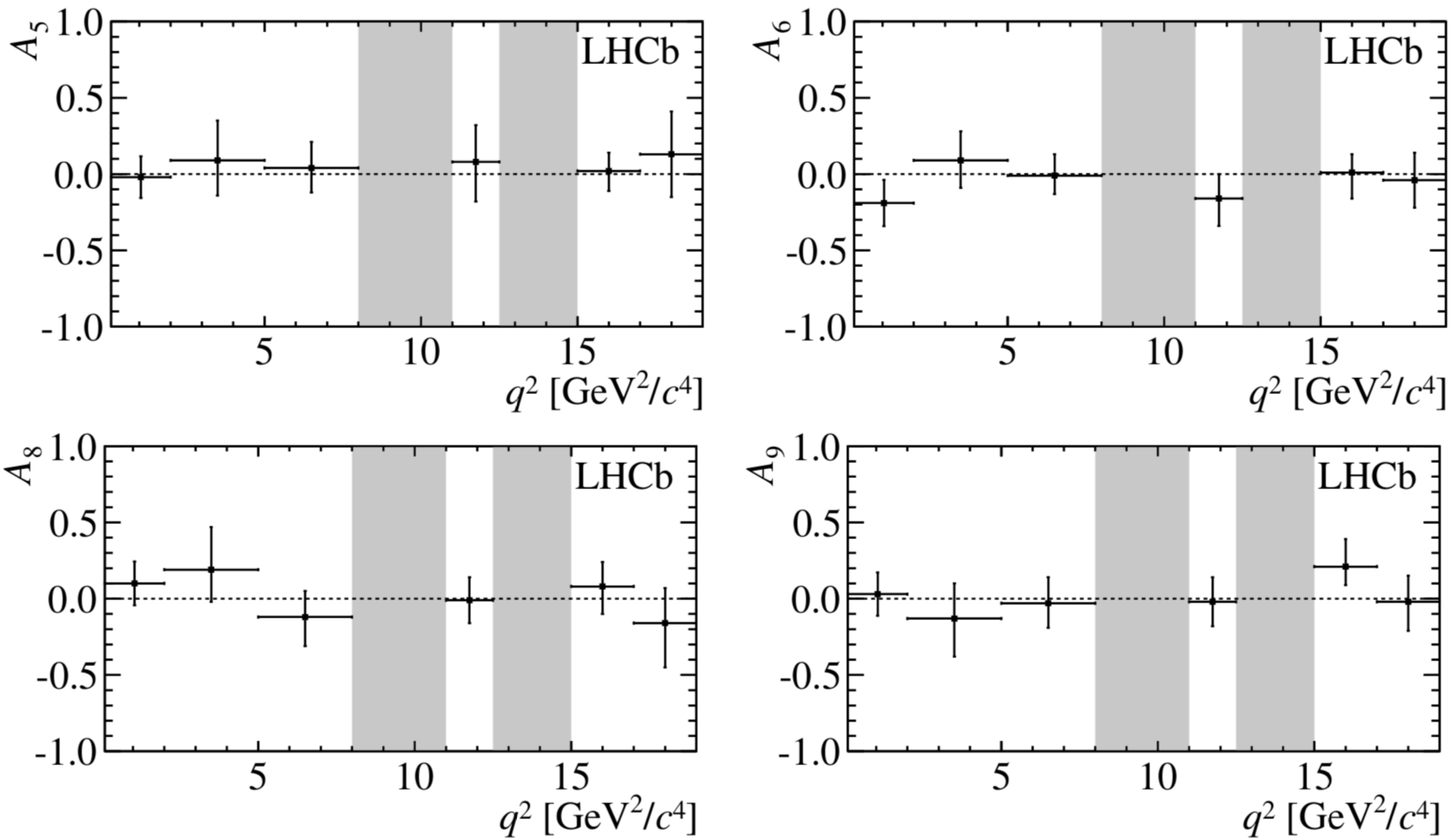
| | |
|---|---|
| ➤ JHEP 06 (2017) 108 | $\mathcal{A}_{CP}(\Lambda_b^0 \to pK\mu\mu)$ +triple products |
| ➤ JHEP 02 (2016) 104 | $B^0 \to K^{*0}\mu^+\mu^-$ Angular analysis |
| ➤ JHEP 10 (2015) 034 | $\mathcal{A}_{CP}(B^+ \to \pi^+\mu^+\mu^-)$ (b->dll) |
| ➤ JHEP 09 (2015) 179 | $B_s^0 \to \phi\mu^+\mu^-$ Angular analysis |
| ➤ JHEP 09 (2014) 177 | $\mathcal{A}_{CP}(B \to K^{(*)}\mu\mu)$ |

# $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$ JHEP 02 (2016) 104



# $B_s^0 \to \phi(\to KK)\mu\mu$

JHEP 09 (2015) 179

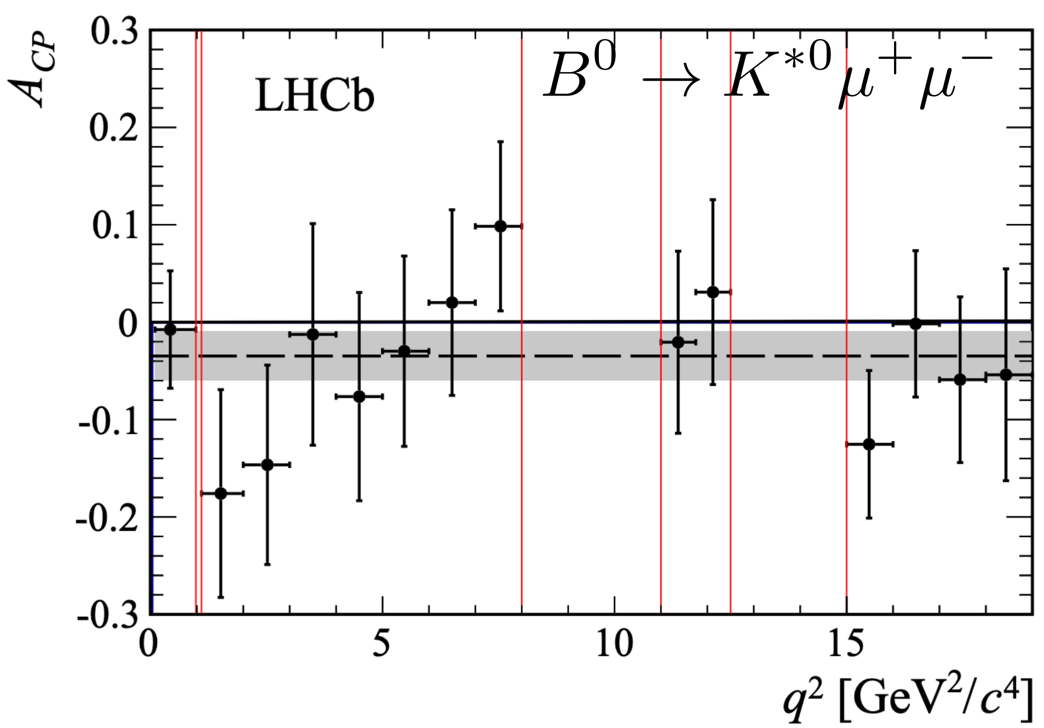


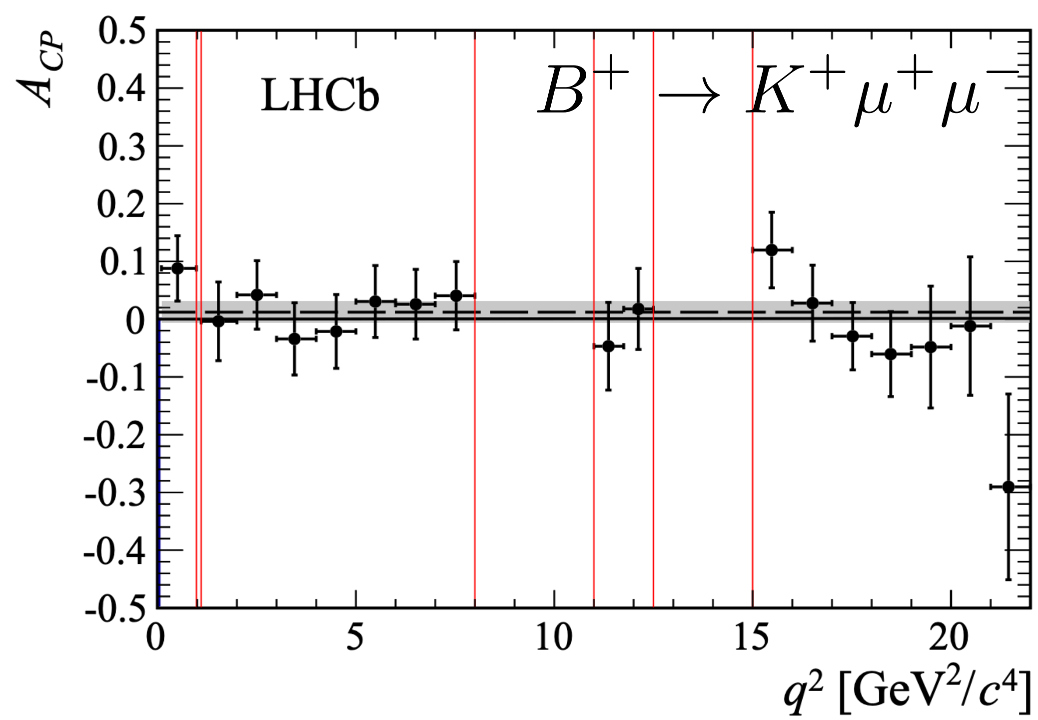
# Direct asymmetries

JHEP 09 (2014) 177

$$A_{CP} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

**T-even**, want large strong phase!




- Extracted using

$$\mathcal{A}_{CP}(B \to K^{(*)}\mu^+\mu^-) = \mathcal{A}_{\rm raw}(B \to K^{(*)}\mu^+\mu^-) - \mathcal{A}_{\rm raw}(B \to J/\psi\, K^{(*)})$$

Splitting accord to kaon charge and fitting the B mass to in bins to get yields

*Eur.Phys.J.C* 77 (2017) 3, 161

# Measuring the strong phase from charm-loops.

- Measurements fitting the whole q2 range give access to strong phase of charmonium modes
- Express charmonium mode contribution as

relative phase

$$C_9^{eff} = C_9 + \sum_j \eta_j e^{i\delta_j} A_j^{res}(q^2)$$

magnitude lineshape

$$j \in \{J/\psi, \psi(2S), \psi(3770), \psi(4040), \psi(4160), \psi(4415)\}$$

- Fit for relative strong phase, increased precision on strong phases gives better access to CP-violating weak phase
- Relative phase for J/psi found to be ~ $\pm\pi/2$

# Complex Wilson coefficients in $b \to s\mu\mu$?

Effective Hamiltonian:

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

$$\mathcal{O}_7 = \frac{em_b}{4\pi}(\bar{s}_R\sigma_{\mu\nu}b_R)F^{\mu\nu}$$

$$\mathcal{O}_{9(10)} = \frac{e^2}{(4\pi)^2}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}\gamma^\mu(\gamma^5)\mu)$$

Analyses of rare *B* decay discrepancies:

$$C_i = C_i^{\text{SM}} + \delta C_i$$

- Various NP scenarios possible

J. Aebischer et al. Eur. Phys. J. C 79 509 (2019)

M. Algueró et al. Eur. Phys. J. C 79 714 (2019) Update: 2104.08921

A. Arbey et al. Phys. Rev. D 100 015045 (2019)

A. Biswas et al. 2004.14687

L.-S. Geng et al. 2103.12738

T. Hurth et al. 2104.10058

- Could CPV observables help at disentangling various NP scenarios/models?

A. K. Alok, B. Bhattacharya, D. Kumar, J. Kumar, D. London, and S. U. Sankar, Phys. Rev. D 96, 015034 (2017)

W. Altmannshofer and P. Stangl, 2103.13370

- What new and improved observables could we use to further pinpoint CPV in $b \to s\mu\mu$?

S. Descotes-Genon, M. Novoa-Brunet and K. K. Vos, JHEP 02 (2021) 129

D. Bečirević, S. Fajfer, N. Košnik and A. Smolkovič, Eur. Phys. J. C 80 (2020) 940

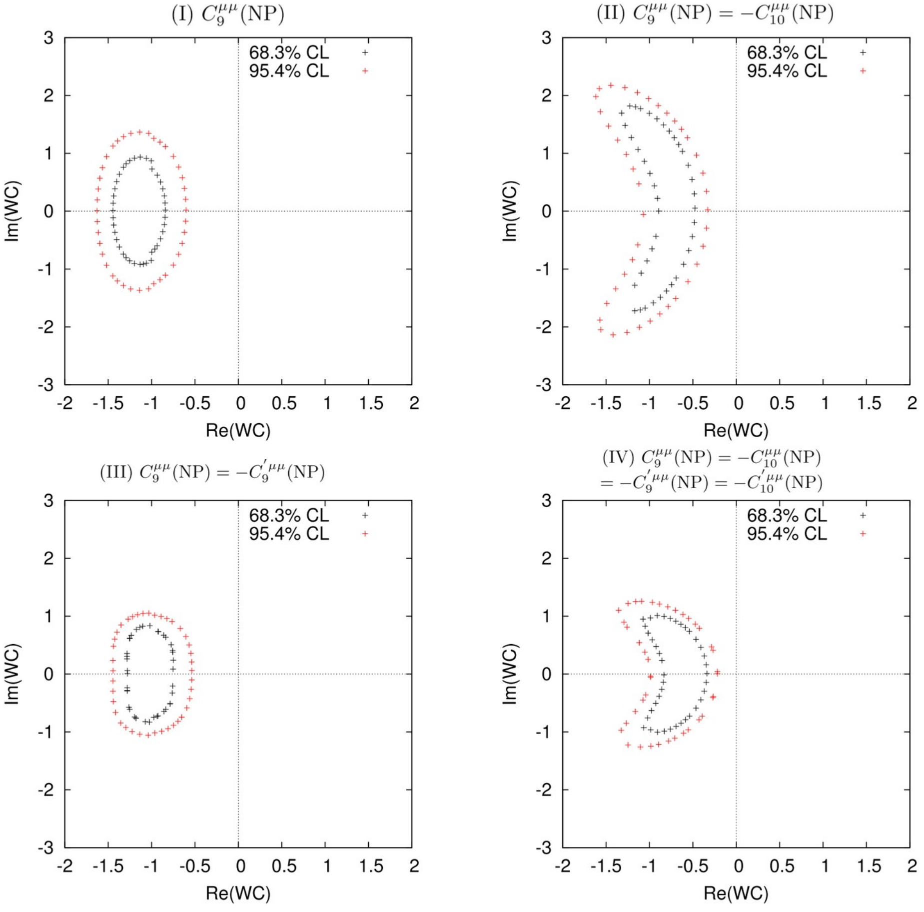
| | all rare $B$ decays | |
|---|---|---|
| Wilson coefficient | best fit | pull |
| $C_9^{bs\mu\mu}$ | $-0.82^{+0.14}_{-0.14}$ | $6.2\sigma$ |
| $C_{10}^{bs\mu\mu}$ | $+0.56^{+0.12}_{-0.12}$ | $4.9\sigma$ |
| $C_9^{\prime bs\mu\mu}$ | $-0.09^{+0.13}_{-0.13}$ | $0.7\sigma$ |
| $C_{10}^{\prime bs\mu\mu}$ | $+0.01^{+0.10}_{-0.09}$ | $0.1\sigma$ |
| $C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$ | $-0.06^{+0.11}_{-0.11}$ | $0.5\sigma$ |
| $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ | $-0.43^{+0.07}_{-0.07}$ | $6.2\sigma$ |

W. Altmannshofer and P. Stangl, 2103.13370

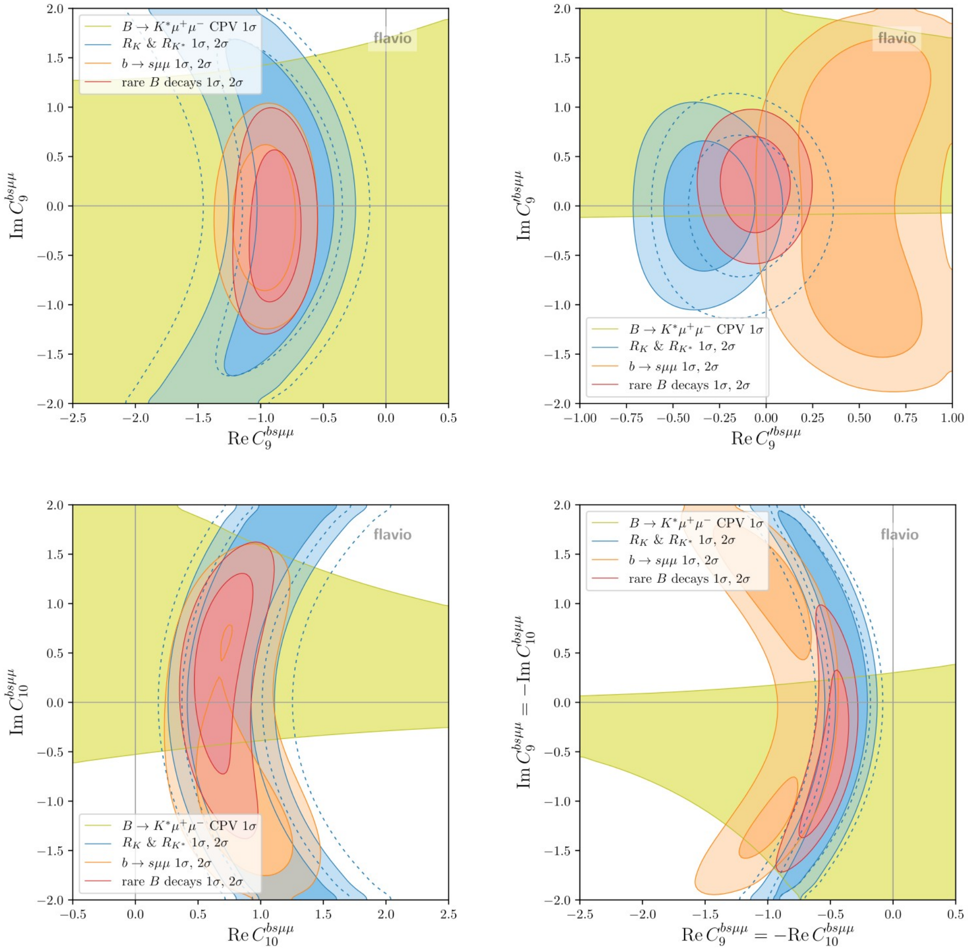
# Discriminating power of CPV observables

various BR, angular, LFUV obs. in fit: $B \to K\mu\mu, B \to \phi\mu\mu, B_s \to \mu\mu, R_{K^{(*)}}, \ldots$

A. K. Alok, B. Bhattacharya, D. Kumar, J. Kumar, D. London, and S. U. Sankar, Phys. Rev. D 96, 015034 (2017)

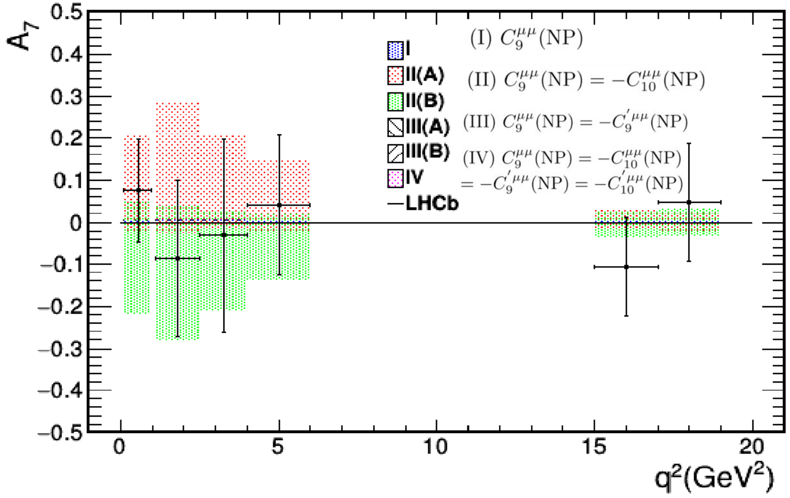


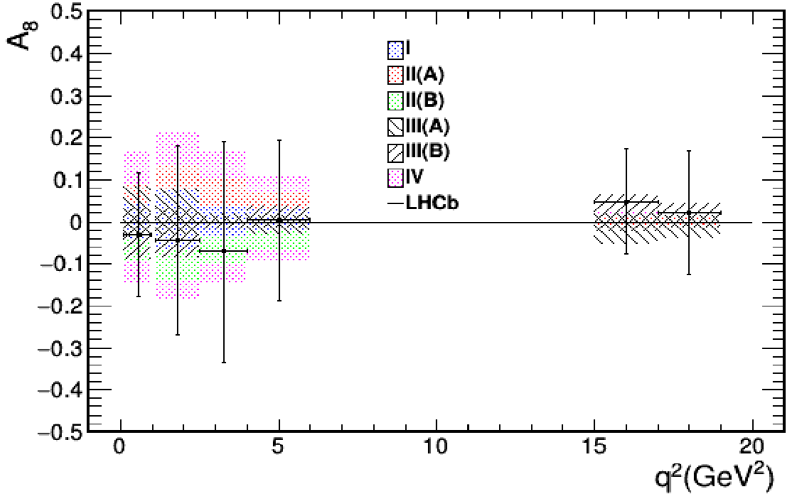

W. Altmannshofer and P. Stangl, 2103.13370

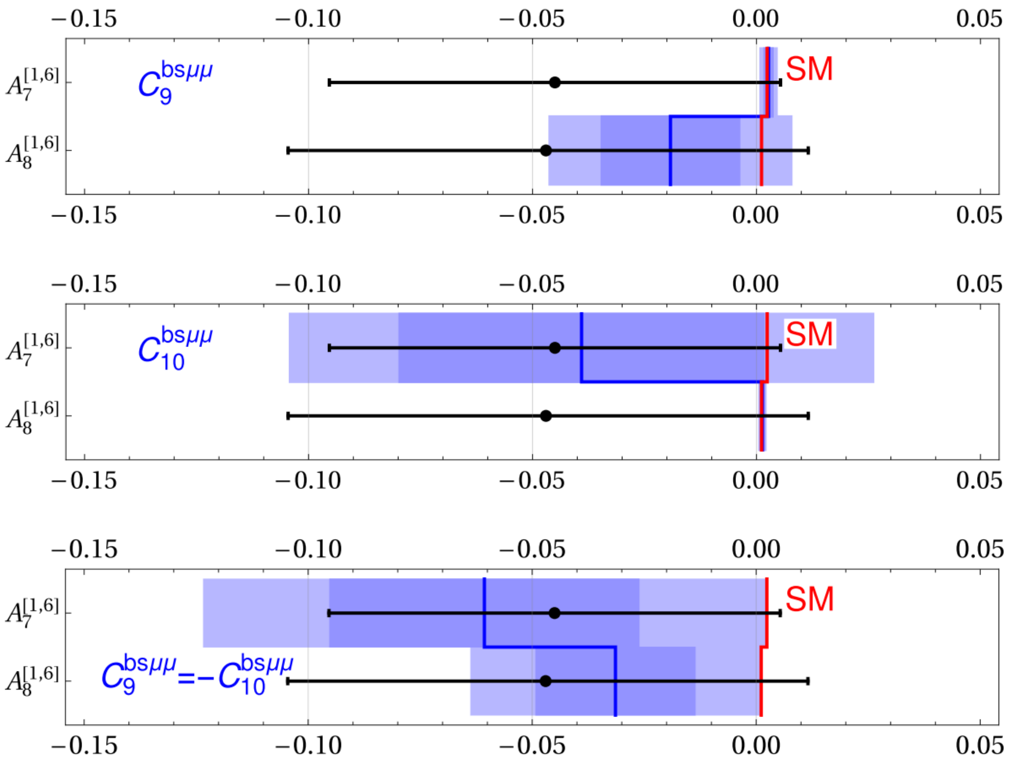


# Predictions of CPV observables in $B^0 \to K^{*0}\mu\mu$ hint at discriminating power among scenarios:

A. K. Alok, B. Bhattacharya, D. Kumar, J. Kumar, D. London, and S. U. Sankar, Phys. Rev. D 96, 015034 (2017)




W. Altmannshofer and P. Stangl, 2103.13370

$A_3$-$A_6$ direct CPA

$A_7$-$A_9$ triple product CPA

$A_7$ very sensitive to Im$C_{10}$

C. Bobeth, G. Hiller and G. Piranishvili, JHEP 0807, 106 (2008)

# New and improved observables?

S. Descotes-Genon, M. Novoa-Brunet and K. K. Vos,
JHEP 02 (2021) 129

D. Bečirević, S. Fajfer, N. Košnik and A. Smolkovič,
Eur. Phys. J. C 80 (2020) 940

# Time-dependent angular analysis of $B_d \to K_S \ell\ell$

S. Descotes-Genon, M. Novoa-Brunet and K. K. Vos,
JHEP 02 (2021) 129

Main idea: Consider interference between decay and mixing

$$\frac{d\Gamma\left(B_d(t) \to K_S \ell\ell\right) - d\Gamma\left(\bar{B}_d(t) \to K_S \ell\ell\right)}{ds\, d\cos\theta_\ell} = \left[G_0 - \widetilde{G}_0\right](t) + \left[G_1 - \widetilde{G}_1\right](t)\cos\theta_\ell + \left[G_2 - \widetilde{G}_2\right](t)\frac{1}{2}\left(3\cos^2\theta_\ell - 1\right)$$

$$G_i(t) - \widetilde{G}_i(t) = e^{-\Gamma t}\left[(G_i - \widetilde{G}_i)\cos(x\Gamma t) - s_i \sin(x\Gamma t)\right] \qquad x \equiv \Delta m/\Gamma$$

After time integration:

$$\langle \Delta_i \rangle_{\text{Hadronic}} \equiv \frac{\langle G_i - \widetilde{G}_i \rangle_{\text{Hadronic}}}{\langle d(\Gamma + \bar{\Gamma})/dq^2 \rangle_{\text{Hadronic}}}$$

Measure:

$$\langle \Delta_i \rangle^{K_S}_{\text{Hadronic}} = \frac{1}{1+x^2}\langle \Delta_i \rangle^{K^\pm} - \frac{x}{1+x^2}\sigma_i \qquad \sigma_i = \frac{s_i}{2\Gamma_\ell} \qquad i = 0, 1, 2$$

Extract:

$$\frac{1}{1+x^2} = 0.6284(24)\,, \qquad \frac{x}{1+x^2} = 0.4832(6)$$

$s_i$ accessible even after bypassing the study of time dependence

Flavor tagging needed

Similar approaches for B → V in

S. Descotes-Genon and J. Virto,
JHEP 04 (2015) 045

C. Bobeth, G. Hiller and G. Piranishvili,
JHEP 07 (2008) 106

S. Descotes-Genon, M. Novoa-Brunet and K. K. Vos, JHEP 02 (2021) 129

# Sensitivity to complex Wilson coefficients:

$$\text{Scenario 1}: \mathcal{C}_{9\mu}^{\rm NP} = -1.12 + i1.00\,,$$
$$\text{Scenario 2}: \mathcal{C}_{9\mu}^{\rm NP} = -1.14 - i0.22\,, \qquad \mathcal{C}_{9'\mu}^{\rm NP} = 0.40 - i0.38\,,$$
$$\text{Scenario 3}: \mathcal{C}_{9\mu}^{\rm NP} = -1.13 - i0.12\,, \qquad \mathcal{C}_{9'\mu} = 0.52 - i1.80\,, \qquad \mathcal{C}_{10\mu}^{\rm NP} = 0.41 + i0.13$$

| Observable | SM | Scen. 1 | Scen. 2 | Scen. 3 | $C_S = 0.2$ | $C_T = 0.2$ |
|---|---|---|---|---|---|---|
| $\sigma_0$ | 0.368(5) | 0.273(6) | 0.402(5) | 0.43(1) | 0.368(5) | 0.368(5) |
| $\sigma_2$ | −0.359(5) | −0.266(6) | −0.392(4) | −0.415(9) | −0.359(5) | −0.357(5) |
| $R_S$ | −0.107(4) | 0.69(2) | −0.39(2) | −0.59(9) | −0.105(4) | −0.107(4) |
| $R_{T_t}$ | 0.035(1) | −0.225(8) | 0.128(7) | 0.19(3) | 0.035(1) | 0.036(1) |
| $R_W \times 10^2$ | −0.179(8) | 1.09(4) | −0.63(4) | −1.0(1) | −0.01(1) | 0.04(3) |

$q^2 \in [1, 6]$ GeV

$$R_S \equiv \frac{2}{\sin\phi}(-\sigma_2 + 2\sigma_0) - F_H^\ell + 3$$

$$\frac{d^2\Gamma(B^- \to K^-\ell\ell)}{dq^2\; d\cos\theta_\ell} + \frac{d^2\Gamma(B^+ \to K^+\ell\ell)}{dq^2\; d\cos\theta_\ell} = 2\Gamma_\ell\left[\frac{1}{2}F_H^\ell + A_{FB}^\ell\cos\theta_\ell + \frac{3}{4}(1-F_H^\ell)(1-\cos^2\theta_\ell)\right]$$

$$\sigma_i = \frac{s_i}{2(G_0 + \bar{G}_0)} = \frac{s_i}{2\Gamma_\ell}$$

$$R_{T_t} \equiv \frac{2}{\sin\phi}\sigma_2 + F_H^\ell - 1$$

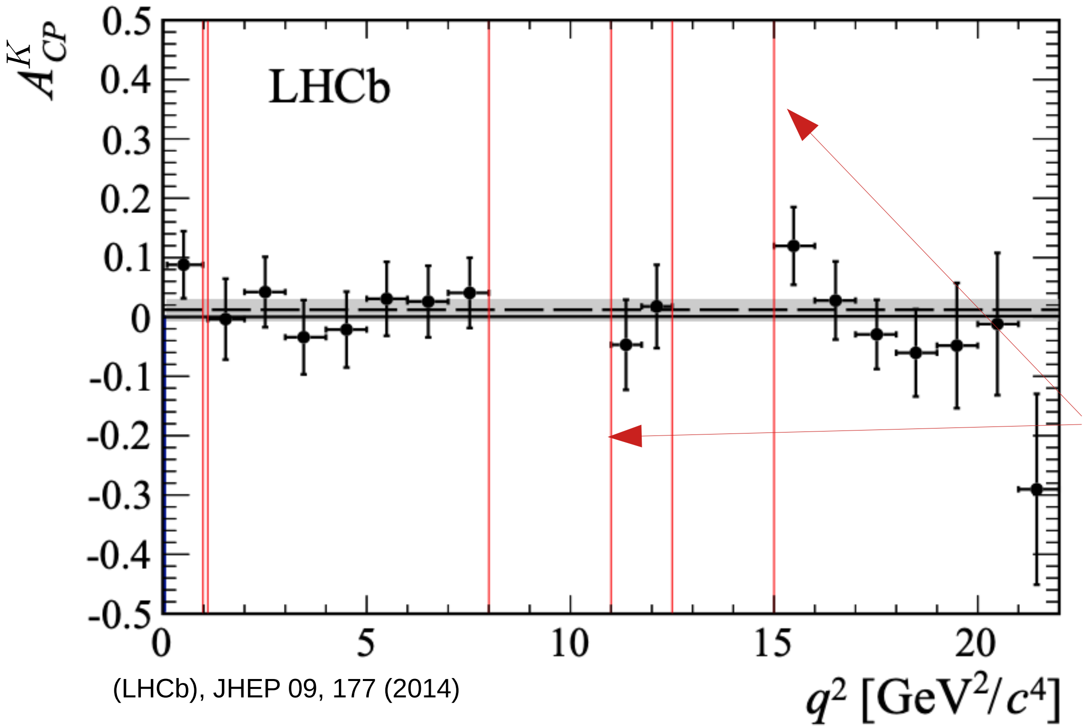
$$R_W \equiv R_S + 3R_{T_t}$$

$$\frac{q}{p} = e^{i\phi}$$

$$F_H^\ell = 1 + \frac{G_2 + \bar{G}_2}{G_0 + \bar{G}_0}$$

# Resonantly enhanced $\mathcal{A}_{\rm CP}$ in $B \to K\mu^+\mu^-$

D. Bečirević, S. Fajfer, N. Košnik and A. Smolkovič,
Eur. Phys. J. C 80 (2020) 940




(LHCb), JHEP 09, 177 (2014)

$$\mathcal{A}_{\rm CP}^{K^{(*)}} = \frac{\mathcal{B}(\overline{B} \to \overline{K}^{(*)}\mu\mu) - \mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(\overline{B} \to \overline{K}^{(*)}\mu\mu) + \mathcal{B}(B \to K^{(*)}\mu\mu)}$$

Regions around $q^2 \approx m^2_{J/\psi,\psi(2S)}$ not measured

We argue $\mathcal{A}_{\rm CP}$ is significantly enhanced in these regions, effective probe of ${\rm Im}\,\delta C_9$

To predict $\mathcal{A}_{\rm CP}$ we need a handle on strong phases.

Similar approach for $B \to K^*\mu\mu$ in

T. Blake et al. Eur. Phys. J. C 78, 453 (2018)

Resonant amplitudes, eg. $B \to K(J/\psi \to \mu\mu)$ provide a source.

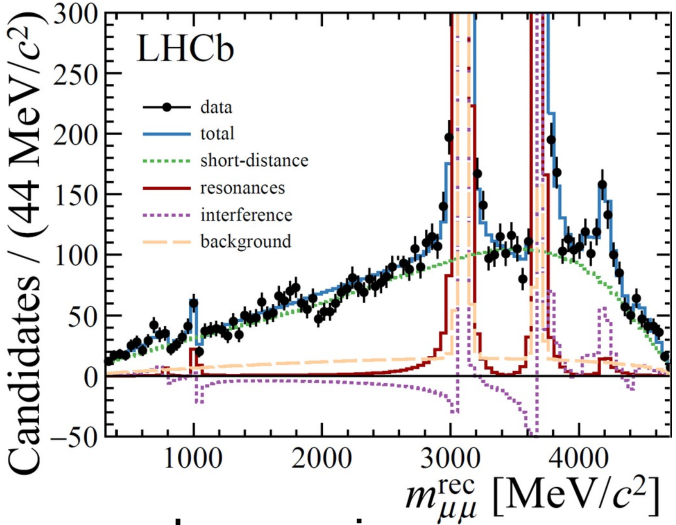
# LHCb fit to a phenomenological model:

(LHCb), Eur. Phys. J. C 77, 161 (2017)

source of strong phases

$$C_9^{\mathrm{eff}}(q^2) = C_9 + C_9^{\mathrm{res}}(q^2) = C_9 + \sum_j \frac{m_j\,\Gamma_j\,\eta_j\,e^{i\delta_j}}{m_j^2 - q^2 - i\,m_j\Gamma_j(q^2)}$$

$$j \in \{J/\psi, \psi(2S), \psi(3770), \psi(4040), \psi(4160), \psi(4415)\}$$




# For narrow charmonia:

$$\eta_{J/\psi} \approx 8.5 \times 10^3$$
$$\eta_{\psi(2S)} \approx 1.4 \times 10^3$$
$$\delta_{J/\psi}, \delta_{\psi(2S)} \approx \pm\pi/2$$

Caveat: 4 degenerate fit solutions

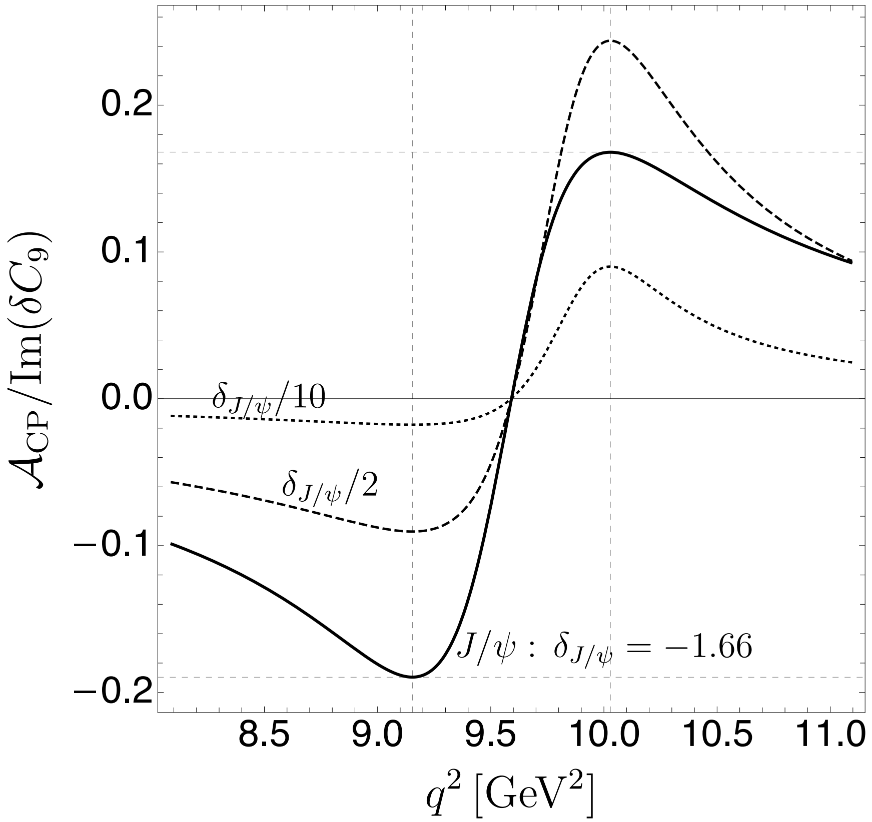
# $\mathcal{A}_{\mathrm{CP}}$ near narrow resonances:

$$C_9^{\mathrm{res}}(q^2) \approx \frac{m_j\Gamma_j\eta_j e^{i\delta_j}}{m_j^2 - q^2 - i m_j\Gamma_j}$$

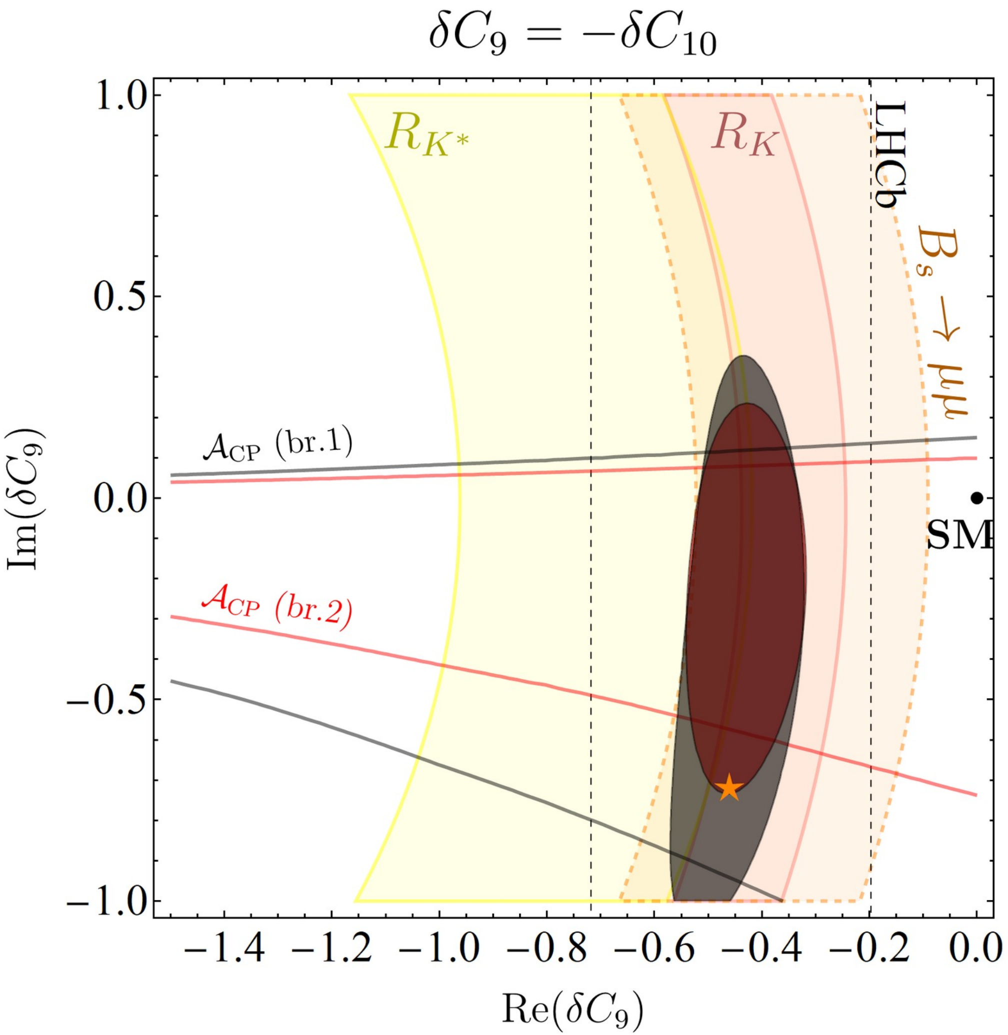
$A, B = \mathrm{const.}$

$x \equiv (q^2 - m_j^2)/(m_j\Gamma_j)$

$$\mathcal{A}_{\mathrm{CP}}(q^2) = \mathrm{Im}(\delta C_9)\,\frac{2\eta_j\,(\cos\delta_j - x\sin\delta_j)}{\eta_j^2 - 2\eta_j B\,[\sin\delta_j + x\cos\delta_j] + A\,[1+x^2]}$$



# Constraints in the complex plane




CP even

$$R_K = 0.846^{+0.044}_{-0.041}$$

(LHCb), Phys. Rev. Lett. 113, 151601 (2014)
(LHCb), Phys. Rev. Lett. 122, 191801 (2019)
(LHCb) 2103.11769

$$R_{K^*} = 0.69^{+0.12}_{-0.09}$$

(LHCb), JHEP 08, 055 (2017)

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.85^{+0.34}_{-0.31}) \times 10^{-9}$$

CERN-LHCb- CONF-2020-002
(LHCb), M. Santimaria, LHC Seminar
(see talk by Peter Stangl and Quim Matias)

CP odd $\{$ $\mathcal{A}^K_{\rm CP}$ from 6 bins with $q^2 \in [2,8]$ GeV²

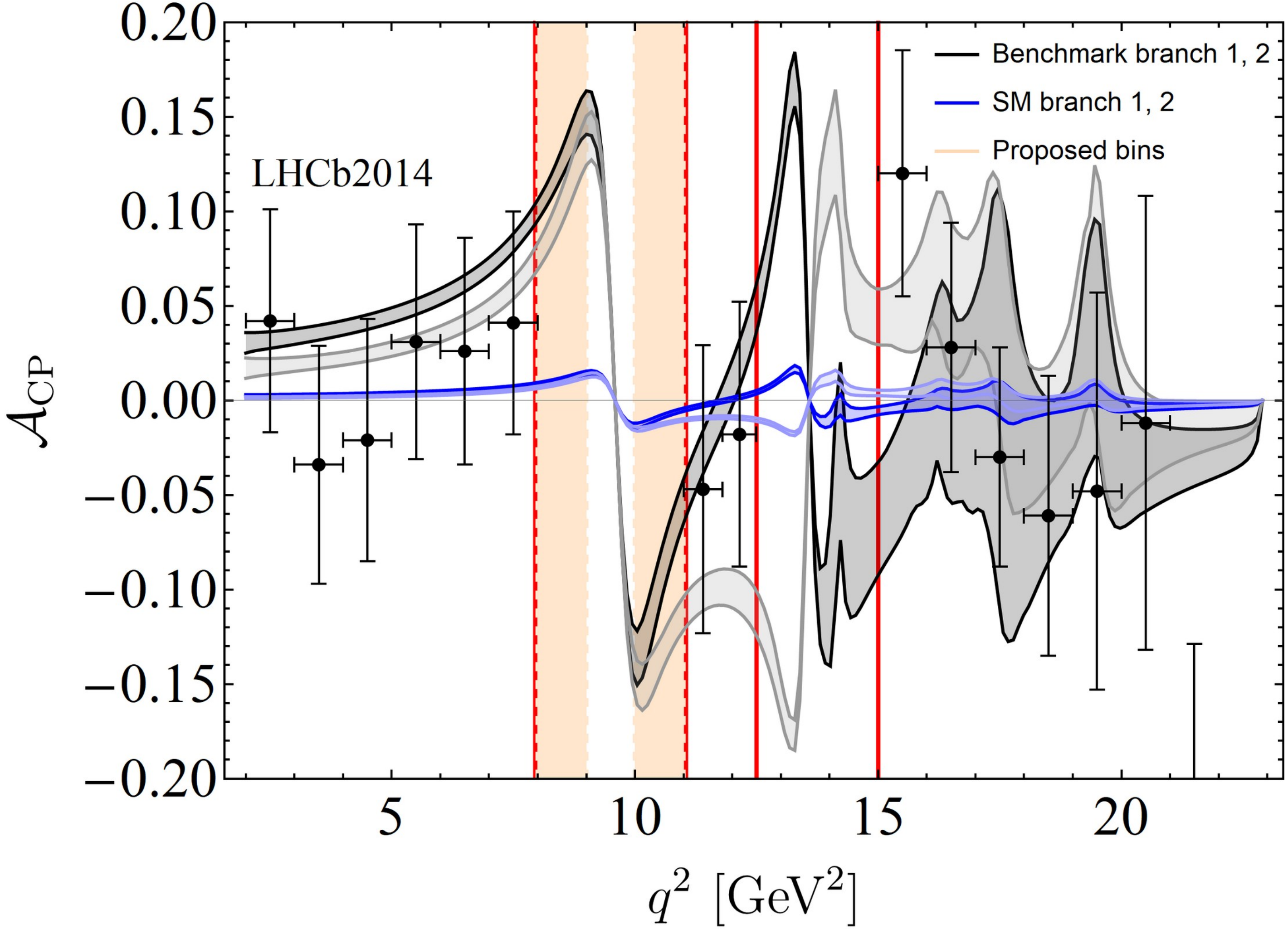
(LHCb), JHEP 09, 177 (2014)

(br. 1, 2 with $\delta_{J/\psi} < 0$)

Benchmark point:

★ $\delta C_9 = -\delta C_{10} = -0.46 - 0.71i$

Prediction using the benchmark: $\delta C_9 = -\delta C_{10} = -0.46 - 0.71i$




$\mathcal{A}_{\rm CP}$ maximal in blinded regions!

# Summary

- Large values of $\mathrm{Im}\delta C_9$ consistent with data, assumptions of $\delta C_9 \in \mathbb{R}$ should be experimentally scrutinized

- CPV (angular) observables show discriminating power among various BSM scenarios, e.g. $\mathrm{Im}C_9 \Rightarrow A_8$
  $\mathrm{Im}C_{10} \Rightarrow A_7$

  A. K. Alok, B. Bhattacharya, D. Kumar, J. Kumar, D. London, and S. U. Sankar, Phys. Rev. D 96, 015034 (2017)

  W. Altmannshofer and P. Stangl, 2103.13370

- New observables in time-dependent angular analysis of $B_d \to K_S \ell\ell$ ($R_S, R_{T_t}, \ldots$) show promising sensitivity to complex scenarios

  S. Descotes-Genon, M. Novoa-Brunet and K. K. Vos, JHEP 02 (2021) 129

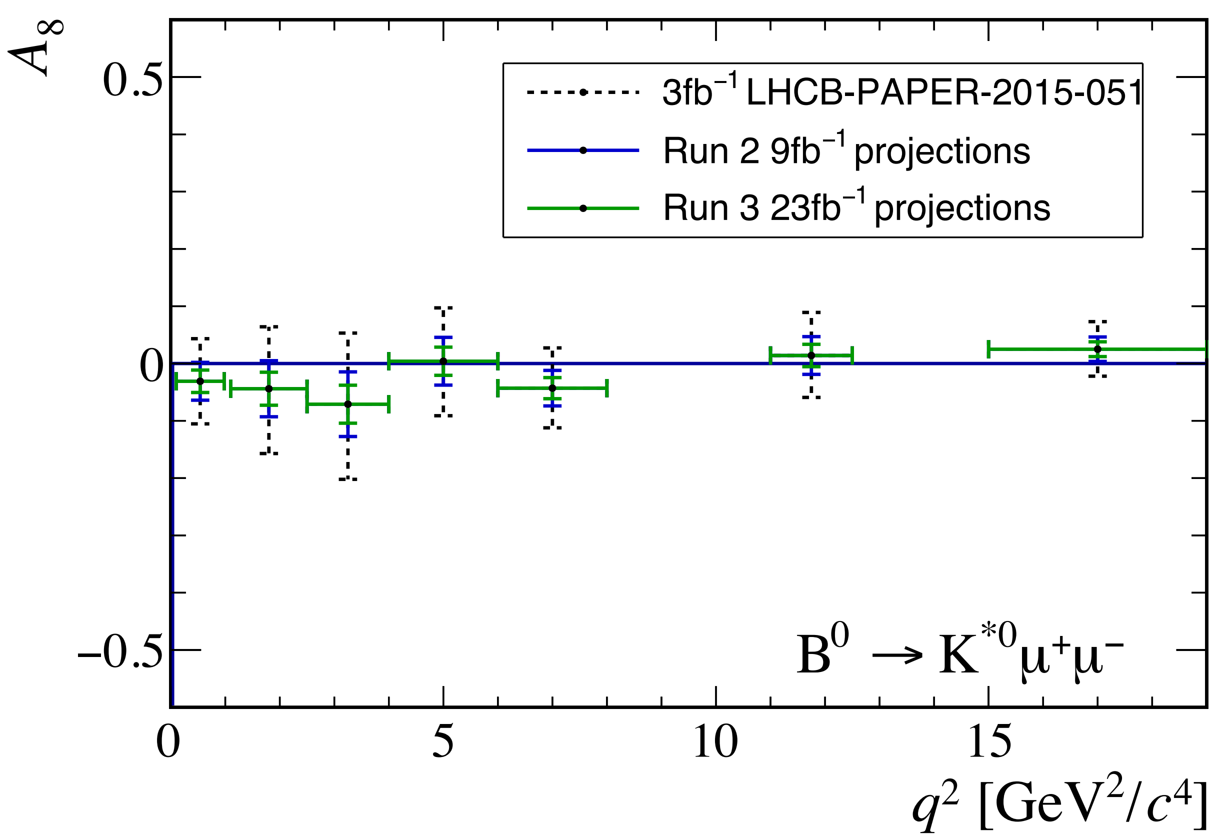
- Direct $\mathcal{A}_{\rm CP}$ in $B \to K\mu^+\mu^-$ near narrow charmonia significantly enhanced, promising probe of presence of NP weak phases

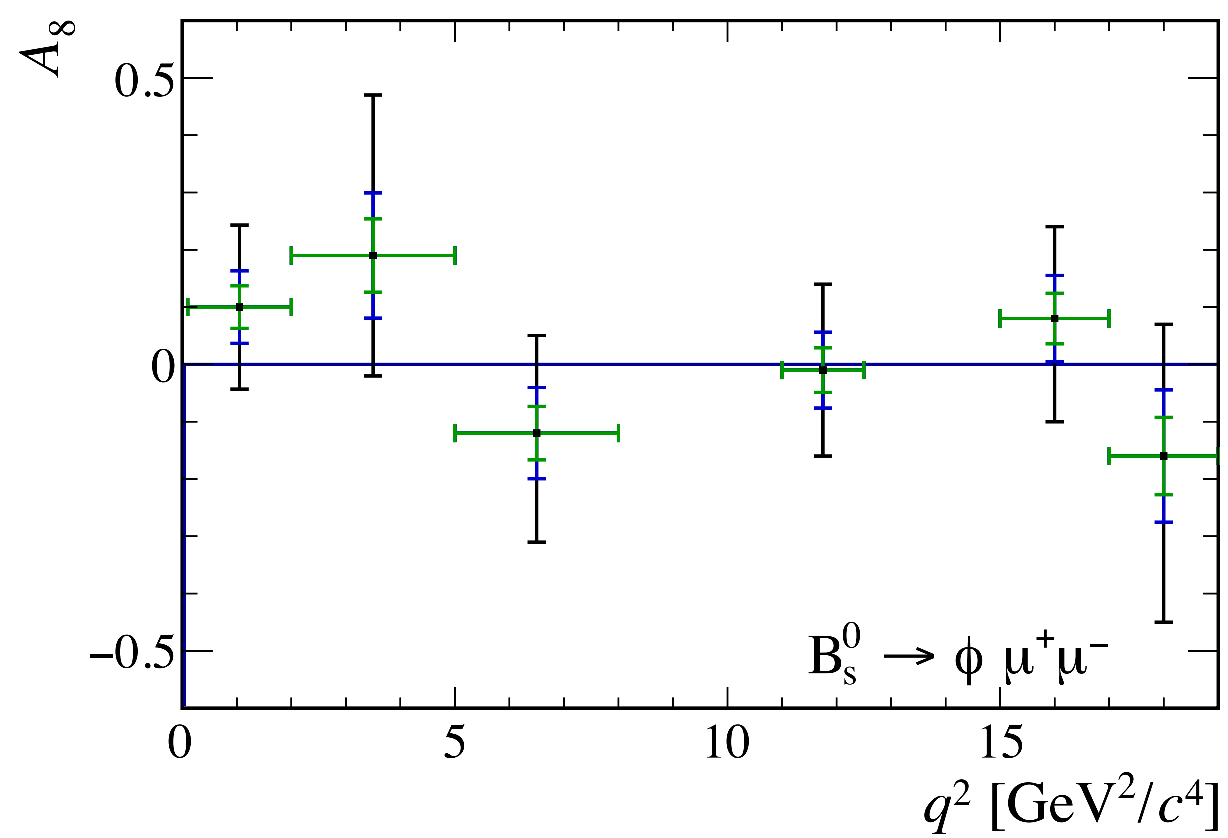
  D. Bečirević, S. Fajfer, N. Košnik and A. Smolkovič, Eur. Phys. J. C 80 (2020) 940

  Bins of $q^2 \sim [8,9],[10,11]\ \mathrm{GeV}^2$ especially interesting

# Conclusions/experimental prospects

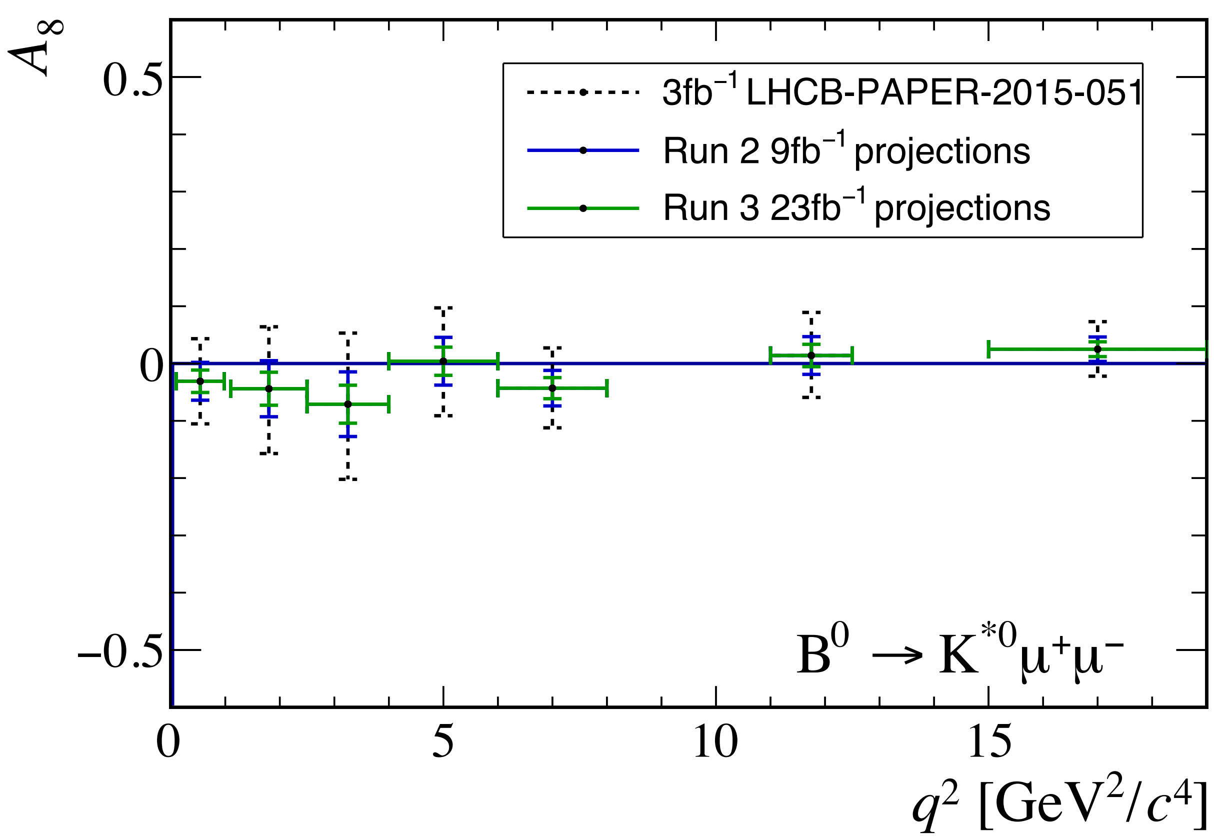
# LHCb and Belle II by ~ 2025-2030

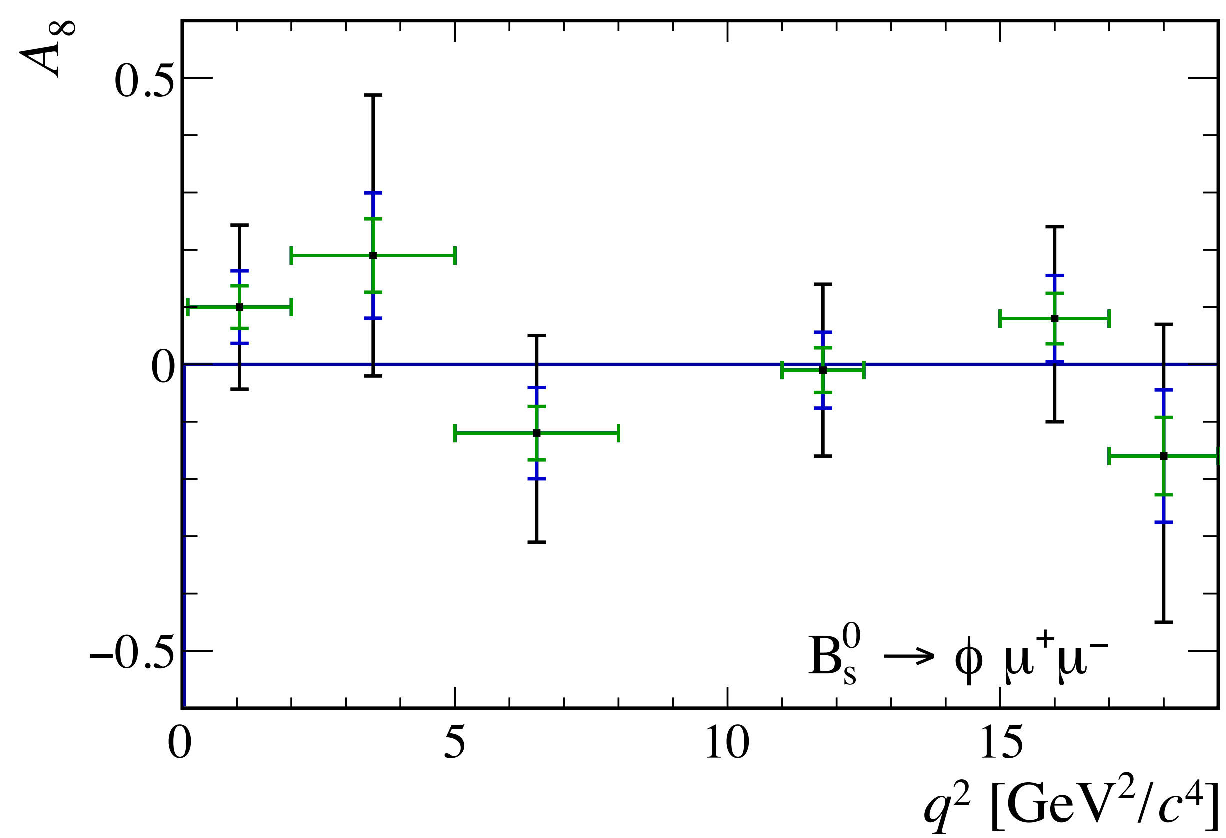



- Similar sensitivity to $b \to s\mu^+\mu^-$ $A_i$ observables expected by LHCb (Belle II) with 23 fb-1 (50 ab -1) for $B^0$ decays
- Angular analysis of $B^0 \to K^{*0}e^+e^-$ ongoing at LHCb, Belle II will provide *improved sensitivity to electron modes*

# LHCb by ~ 1 year



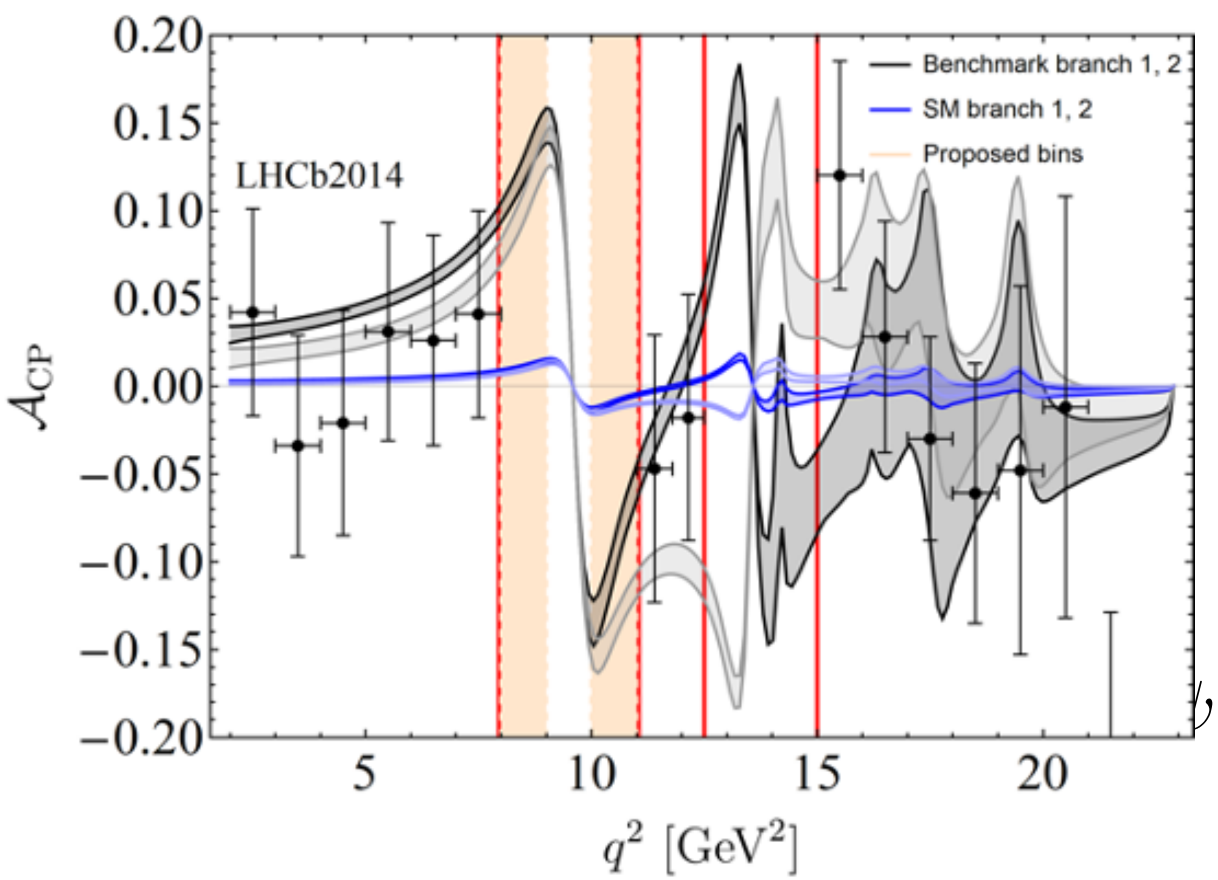

- Angular analysis of $B_s^0 \to \phi\mu^+\mu^-$ by summer conferences/sooner
- Our measurement of $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$being presented next week at SM@LHC workshop
- Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ with CP-asymmetries following soon

# Flavour tagging $b \to s\mu^+\mu^-$ decays

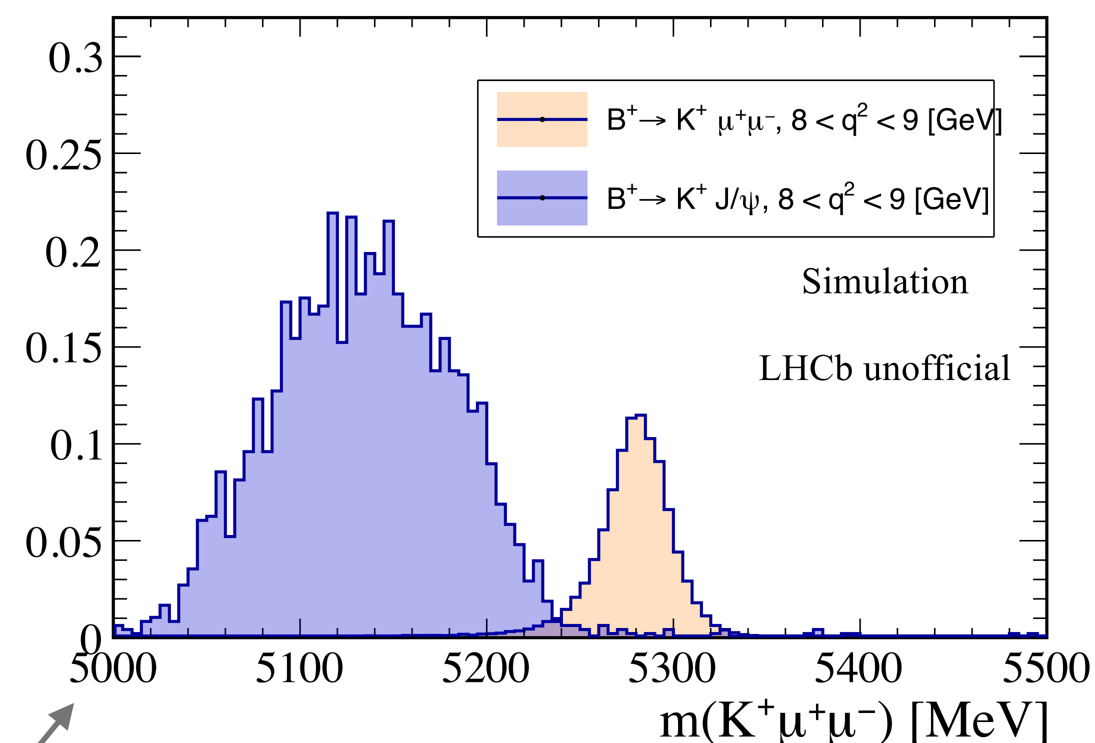
| Yields, $\epsilon_{tag} \equiv 5\%$ | | Run 1 observed | | Run 3 expected | |
|---|---|---|---|---|---|
| | | Full $q^2$ | $1.1 < q^2 < 6.0$ | Full $q^2$ | $1.1 < q^2 < 6.0$ |
| $B_s^0 \to \phi(1020)\mu^+\mu^-$ | untagged | 432 | 101 | 5230 | 1220 |
| | tagged | 22 | 5 | 262 | 60 |
| $B_d^0 \to K_s\mu^+\mu^-$ | untagged | 176 | 70 | 2200 | 850 |
| | tagged | 9 | 4 | 110 | 43 |

- Observables dependent on interference between mixing and decay can only be accessed using flavour-tagging
- Tagged angular analysis possible by end of Run 3 (2025) in wider q2 bins at LHCb, full lifetime + angular analysis still somewhat limited
- Effective tagging power at Belle II ~ 30% -> better sensitivity to CP-eigenstates, particularly from $B^0$ decays

# Measuring $A_{CP}$ close to the pole




Schematic purposes only



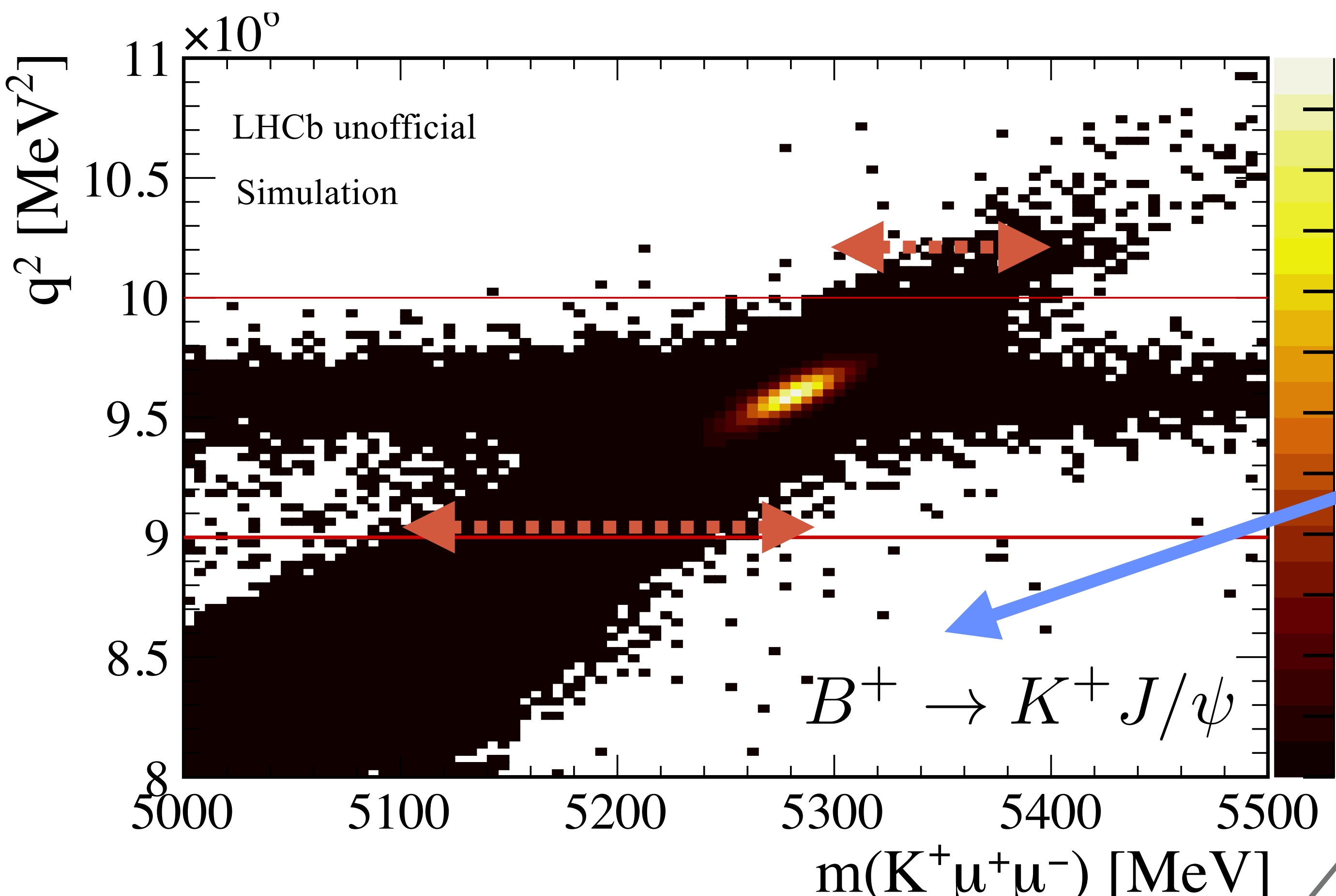

Want to be sensitive to interference from charmonium amplitude in this region

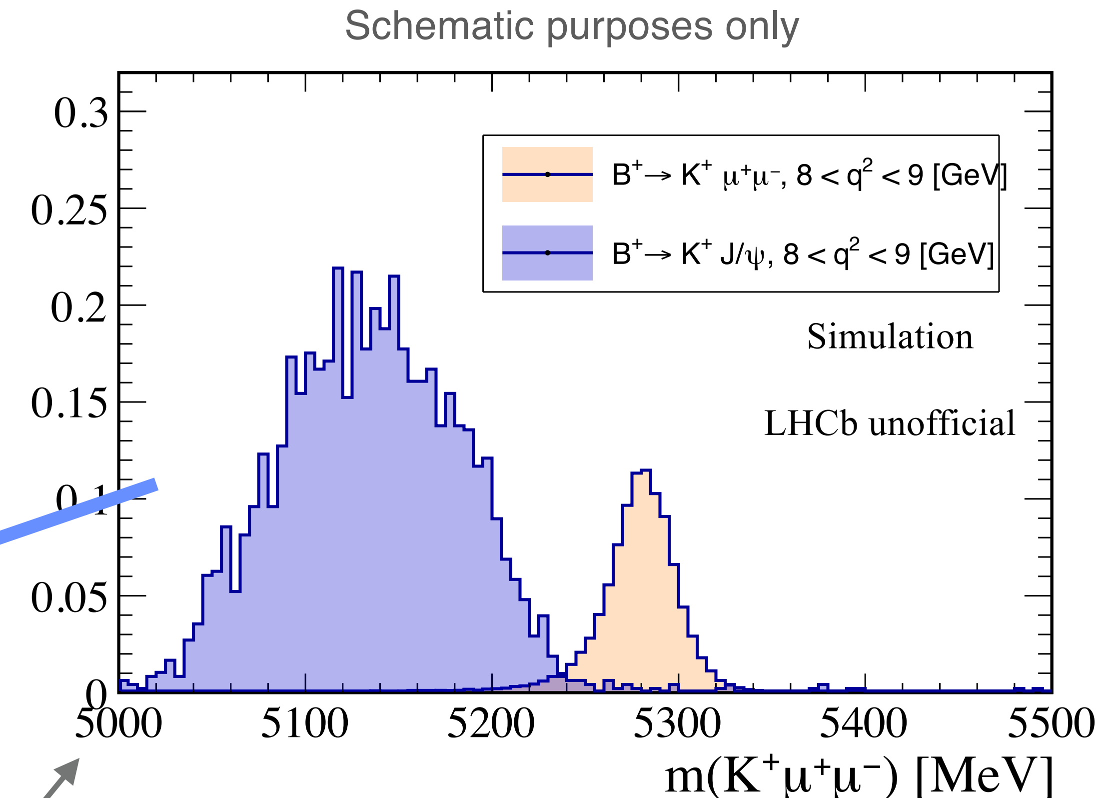
**But** don't want to measure effects from KJpsi with incorrect momenta

## 2 options

- Integrated over $q^2$ - "fit & count"
- CP-asymmetric differential rate over full $q^2$ in similar idea to Eur. Phys. J. C 77 (2017)

# Measuring $A_{CP}$ close to the pole




## 2 options

- Integrated over $q^2$ - "fit & count"
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Want to be sensitive to interference from charmonium amplitude in this region

**But** don't want to measure effects from KJpsi with incorrect momenta

# Potential discussion points

- We may be throwing useful information away by leaving asymmetries out in global fits as a standard model
- Are there any obvious reasons why asymmetries aren't generally include in global fits (other than the argument that "they don't matter") e.g. experimental correlations?
- Prospects for Belle II for measuring flavour-tagged CP-eigenstates?

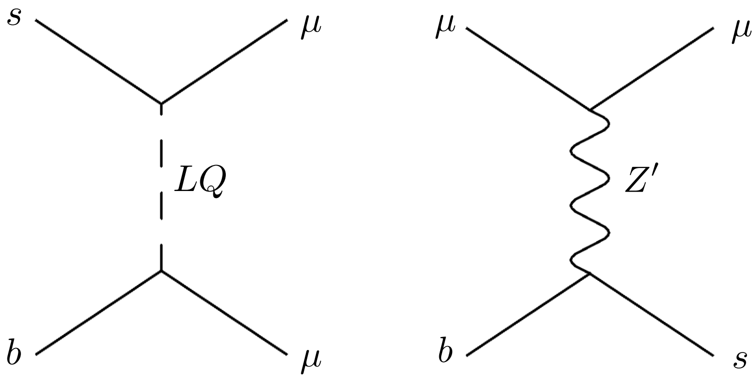
# Back ups

# Discriminating power of CPV observables
## - model dependent approach -

In * minimal tree-level LQ and *Z'* models were considered:

All possible scalar and vector LQ states, e.g.:

$$\mathcal{L}_{S_3} = y'_{\ell q} \bar{\ell}^c_L i\tau_2 \vec{\tau} q_L \cdot \vec{S}_3 \qquad \mathcal{L}_{U_3} = g'_{\ell q} \bar{\ell}_L \gamma_\mu \vec{\tau} q_L \cdot \vec{U}_3^\mu$$




Two couplings active for *Z':*

$$\mathcal{L}^{eff}_{Z'} = -\frac{g_L^{bs} g_L^{\mu\mu}}{M^2_{Z'}} (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma^\mu P_L \mu) - \frac{(g_L^{bs})^2}{2M^2_{Z'}} (\bar{s}\gamma^\mu P_L b)(\bar{s}\gamma^\mu P_L b) - \frac{(g_L^{\mu\mu})^2}{M^2_{Z'}} (\bar{\mu}\gamma^\mu P_L \mu)(\bar{\nu}_\mu \gamma^\mu P_L \nu_\mu)$$

Additional constraints available:

$$\mathcal{B}(B \to K\nu\bar{\nu}) < 1.6 \times 10^{-5}$$
$$\mathcal{B}(B \to K^*\nu\bar{\nu}) < 2.7 \times 10^{-5}$$

Belle, Phys.Rev.D 96 (2017) 9, 091101

not yet stringent enough

Neutrino trident production

$$\nu_\mu N \to \nu_\mu N \mu^+ \mu^-$$

S. R. Mishra et al.
Phys. Rev. Lett. 66, 3117

$$|g_L^{\mu\mu}| \leq 1.25$$

$B_s - \bar{B}_s$ mixing

constrains $g_L^{bs} \in \mathbb{C}$
via $\Delta M_s, \varphi_s$

See e.g. hflav

* A. K. Alok, B. Bhattacharya, D. Kumar, J. Kumar, D. London, and S. U. Sankar, Phys. Rev. D 96, 015034 (2017)

Fit with LQs (one-by-one) shows:

$S_3(\bar{3}, 3, 1/3), U_1(\bar{3}, 1, -2/3), U_3(\bar{3}, 3, -2/3)$

can explain *B* discrepancies, give the same fit results in terms of their couplings

A. K. Alok, B. Bhattacharya, D. Kumar, J. Kumar, D. London, and S. U. Sankar, Phys. Rev. D 96, 015034 (2017)

E.g.:

$M_{LQ} = 1$ TeV

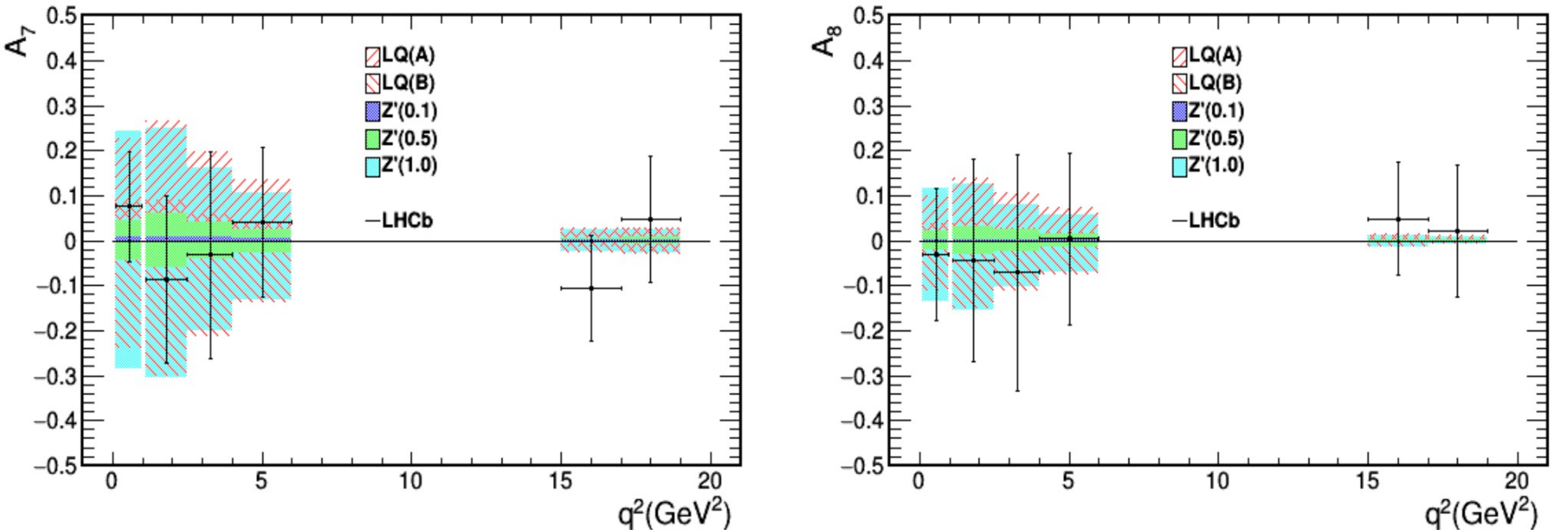
| LQ | Coupling | [Re(coupling), Im(coupling)] $\times 10^3$ | pull |
|---|---|---|---|
| $\vec{\Delta}'_{1/3}$ $[S_3]$ | $y'^{\mu b}_{\ell q}(y'^{\mu s}_{\ell q})^*$ | (A) $[(1.5 \pm 0.5), (-1.9 \pm 1.2)]$ | 4.2 |
| | | (B) $[(1.4 \pm 0.5), (1.7 \pm 1.3)]$ | 4.0 |

Fit with *Z'* shows:

$M_{Z'} = 1$ TeV

| $g_L^{\mu\mu}$ | [Re($g_L^{bs}$),Im($g_L^{bs}$)]$\times 10^3$ | pull |
|---|---|---|
| 0.01 | $[(-2.4 \pm 2.1), (-0.1 \pm 0.7)]$ | 0.8 |
| 0.05 | $[(-3.9 \pm 1.2), (0.0 \pm 0.5)]$ | 2.3 |
| 0.1 | $[(-4.3 \pm 1.0), (0.0 \pm 0.4)]$ | 3.3 |
| 0.2 | $[(-3.9 \pm 0.8), (0.0 \pm 0.5)]$ | 4.0 |
| 0.4 | $[(-2.1 \pm 0.5), (-0.1 \pm 0.8)]$ | 4.2 |
| 0.5 | $[(-1.8 \pm 0.5), (-0.1 \pm 0.9)]$ | 4.0 |
| 0.8 | $[(-1.1 \pm 0.3), (-0.1 \pm 1.5)]$ | 4.0 |
| 1.0 | $[(-0.8 \pm 0.3), (-0.4 \pm 3.1)]$ | 4.0 |

## Predictions of CPV:



# Time-dependent angular analysis of $B_d \to K_S \ell\ell$

S. Descotes-Genon, M. Novoa-Brunet and K. K. Vos,
JHEP 02 (2021) 129

| Observable | SM | Scen. 1 | Scen. 2 | Scen. 3 | $C_S = 0.2$ | $C_T = 0.2$ |
|---|---|---|---|---|---|---|
| $\sigma_0$ | 0.368(5) | 0.273(6) | 0.402(5) | 0.43(1) | 0.368(5) | 0.368(5) |
| $\sigma_2$ | −0.359(5) | −0.266(6) | −0.392(4) | −0.415(9) | −0.359(5) | −0.357(5) |
| $R_S$ | −0.107(4) | 0.69(2) | −0.39(2) | −0.59(9) | −0.105(4) | −0.107(4) |
| $R_{T_t}$ | 0.035(1) | −0.225(8) | 0.128(7) | 0.19(3) | 0.035(1) | 0.036(1) |
| $R_W \times 10^2$ | −0.179(8) | 1.09(4) | −0.63(4) | −1.0(1) | −0.01(1) | 0.04(3) |

$$\sigma_i = \frac{s_i}{2(G_0 + \bar{G}_0)} = \frac{s_i}{2\Gamma_\ell}, \qquad \rho_i = \frac{s_i}{2(G_i + \bar{G}_i)}$$

$$\rho_0 = \rho_2 = \sigma_0 = -\frac{\sin\phi}{2}, \qquad \sigma_1 = 0, \qquad \phi = -2\beta$$

$$R_S \equiv \frac{2}{\sin\phi}(-\sigma_2 + 2\sigma_0) - F_H^\ell + 3$$

$$R_{T_t} \equiv \frac{2}{\sin\phi}\sigma_2 + F_H^\ell - 1$$

$$R_W \equiv R_S + 3R_{T_t}$$

$$\frac{q}{p} = e^{i\phi}$$

- Do $\sigma_0, \sigma_1, \rho_2$ obey the simple relations , directly related to $B_d$-$\bar{B}_d$ mixing? If yes, NP enters only the SM and chirally flipped operators $\mathcal{O}_{7('),9('),10(')}$ with real contributions, in agreement with the NP scenarios currently favoured by global fits to $b \to s\ell\ell$ data.

- Do $\sigma_0$, $\sigma_2$, $R_S$ and/or $R_{T_t}$ deviate from their SM expectations? If yes, it means that NP enters with imaginary contributions, odd under CP-conjugation.

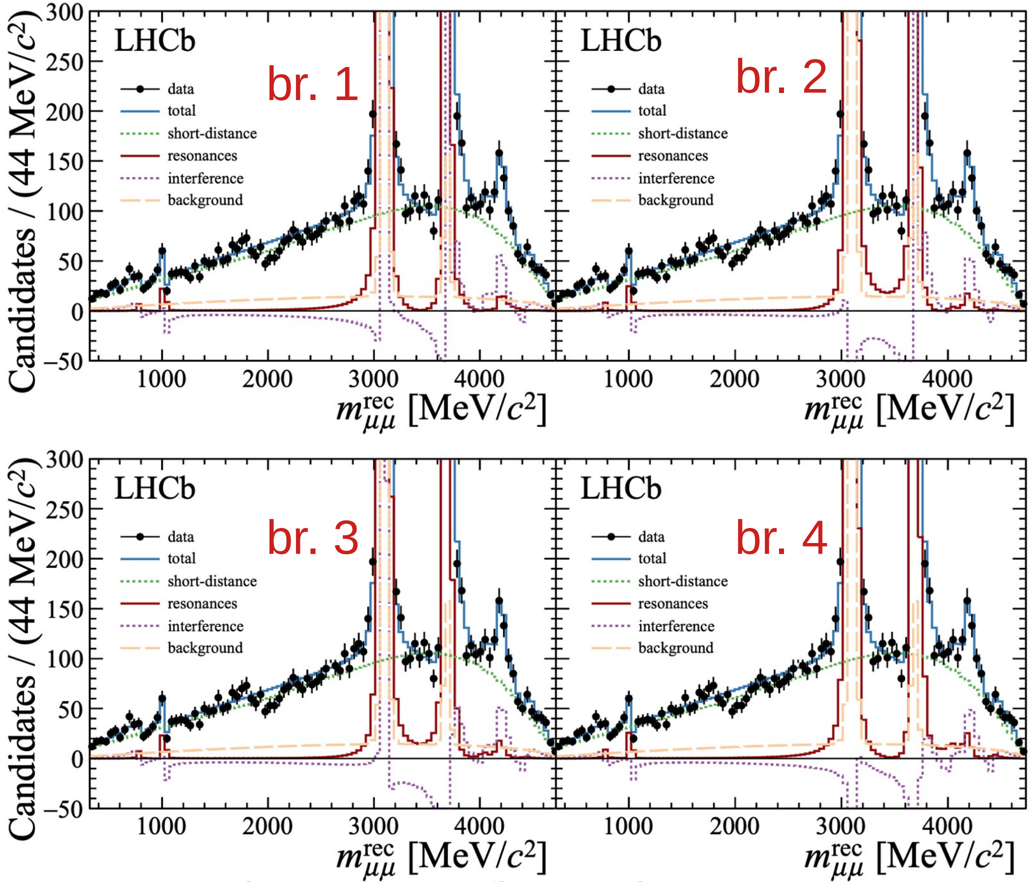
- Does $R_W$ deviate from its SM expectation, but are $\sigma_0$, $\sigma_2$, $R_S$ and $R_{T_t}$ close to the SM? If yes, it means that NP enters through scalar and tensor contributions. Complementary information is then obtained through $F_H^\ell$.

# LHCb provides a fit to a phenomenological model:

(LHCb), Eur. Phys. J. C 77, 161 (2017)

$$C_9^{\rm eff}(q^2) = C_9 + C_9^{\rm res}(q^2) = C_9 + \sum_j \frac{m_j\,\Gamma_j\,{\color{red}\eta_j\,e^{i\delta_j}}}{m_j^2 - q^2 - i\,m_j\Gamma_j(q^2)}$$

$$j \in \{J/\psi, \psi(2S), \psi(3770), \psi(4040), \psi(4160), \psi(4415)\}$$




Source of strong phases

For narrow charmonia:

$$\eta_{J/\psi} \approx 8.5 \times 10^3$$
$$\eta_{\psi(2S)} \approx 1.4 \times 10^3$$
$$\delta_{J/\psi}, \delta_{\psi(2S)} \approx \pm\pi/2$$

Caveat: 4 degenerate fit solutions

# Resonant regions

Consider $q^2$ region close to one isolated resonance:

$A, B = \text{const.}$
$x \equiv (q^2 - m_j^2)/(m_j\Gamma_j)$

$$C_9^{\text{res}}(q^2) \approx \frac{m_j \Gamma_j \eta_j e^{i\delta_j}}{m_j^2 - q^2 - i m_j \Gamma_j} \Rightarrow$$

$$\boxed{\mathcal{A}_{\text{CP}}(q^2) = \text{Im}(\delta C_9)\, \frac{2\eta_j\left(\cos\delta_j - x\sin\delta_j\right)}{\eta_j^2 - 2\eta_j B\left[\sin\delta_j + x\cos\delta_j\right] + A\left[1 + x^2\right]}}$$

$$\frac{d\bar{\Gamma}}{dq^2} - \frac{d\Gamma}{dq^2} = \frac{4\mathcal{N}\lambda}{3}\left[f_+(q^2)\right]^2 \text{Im}(C_9^{\text{res}}(q^2))\, \text{Im}(\delta C_9)$$

strong weak

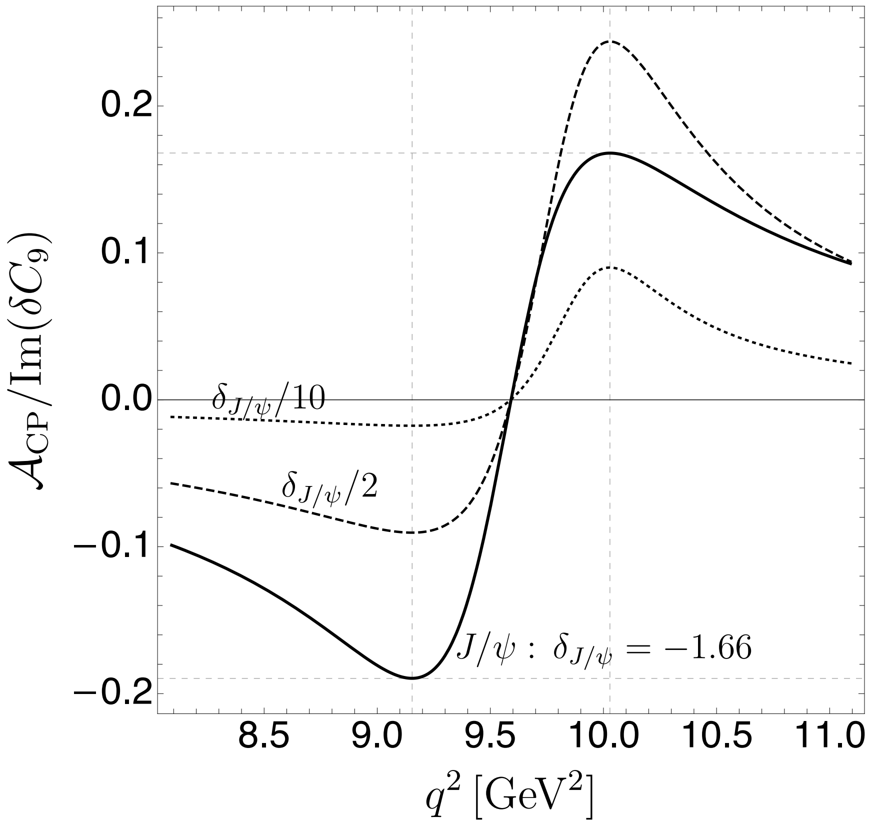
Focusing on $J/\psi$:

- Large $\eta_j$ and $\delta_j$ close to $\pm\pi/2$
- $\mathcal{A}_{\text{CP}}$ : - suppressed at resonant peak
  - enhanced away from peak
  - antisymmetric wrt. peak

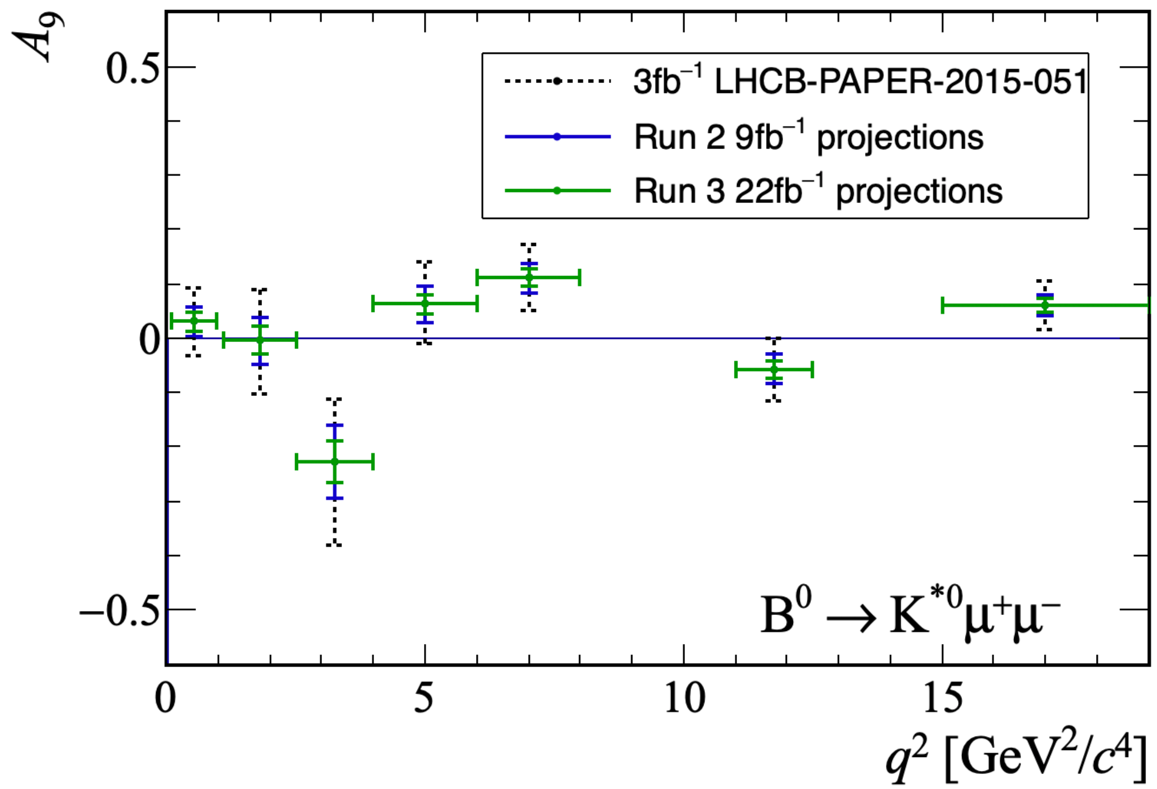
Maximal asymmetry at:

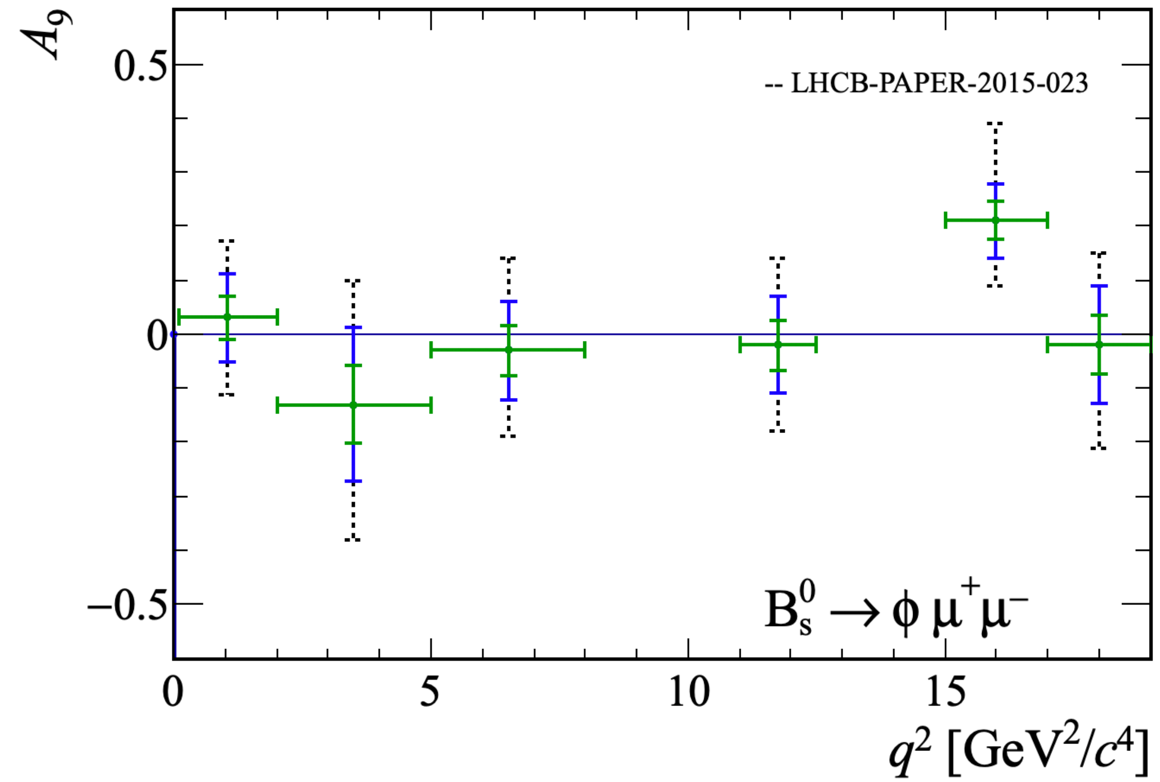
$$q_{1,2}^2 = m_j^2 \pm m_j\Gamma_j\left(\frac{\eta_j}{\sqrt{A}} + \frac{B}{\sqrt{A}\sin\delta_j}\right) + m_j\Gamma_j\cot\delta_j$$

$$\mathcal{A}_{\text{CP}}\left(q_{1,2}^2\right) = \text{Im}(\delta C_9)\, \frac{\sin\delta_j}{\pm\sqrt{A} + B\cos\delta_j}$$



# LHCb and Belle II by ~ 2025




- Similar sensitivity to $b \to s\mu^+\mu^-$ $A_i$ observables expected by LHCb (Belle II) with 23 fb-1 (50 ab -1) for $B^0$ decays
- Angular analysis of $B^0 \to K^{*0}e^+e^-$ ongoing at LHCb, Belle II will provide *improved sensitivity to electron modes*

# CP asymmetries in angular observables

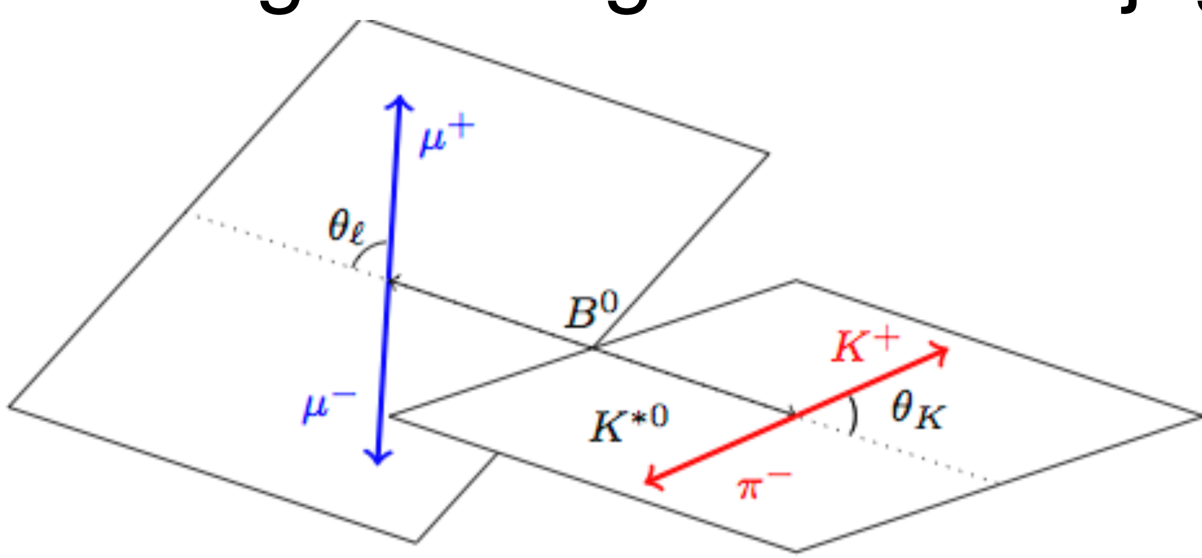
- Swapping $B^0 \to K^{*0}\mu\mu \leftrightarrow \overline{B}^0 \to \overline{K}^{*0}\mu\mu$

$a = s, c$

$$I^{(a)}_{1,2,3,4,7} \longrightarrow \bar{I}^{(a)}_{1,2,3,4,7}\,, \qquad I^{(a)}_{5,6,8,9} \longrightarrow -\bar{I}^{(a)}_{5,6,8,9}\,,$$

CP-odd

- Why the minus sign?
  - $\theta_l$ is defined always relative to the **positive muon**
  - $\theta_K$ is defined always relative to the **kaon**, which changes charge in the conjugate

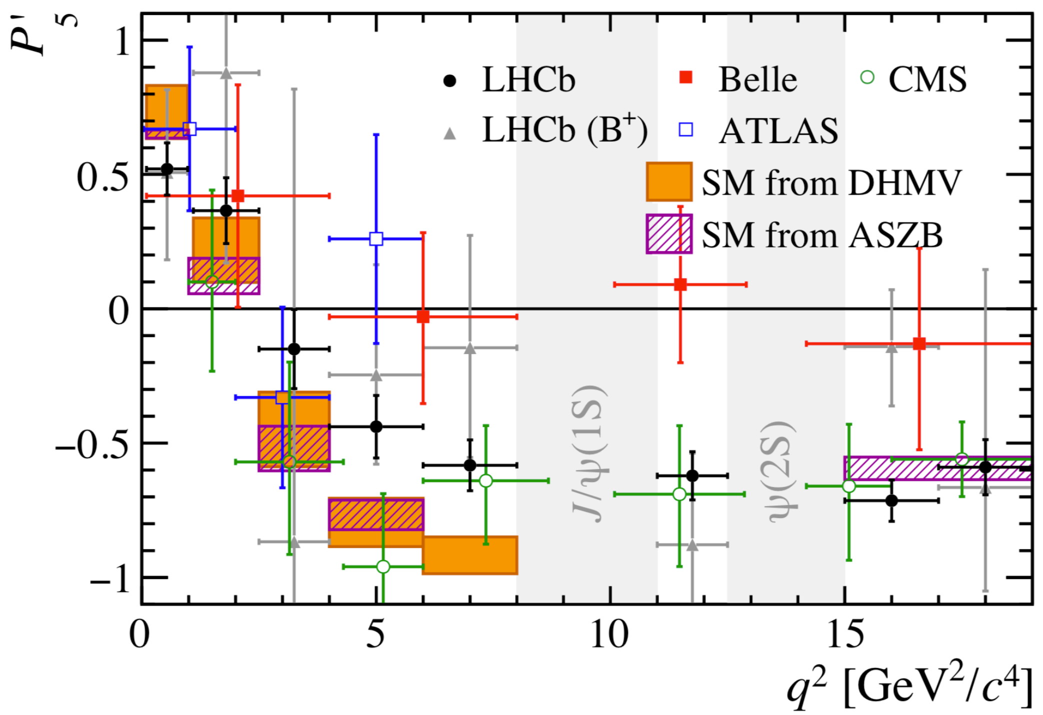



(a) $\theta_K$ and $\theta_\ell$ definitions for the $B^0$ decay

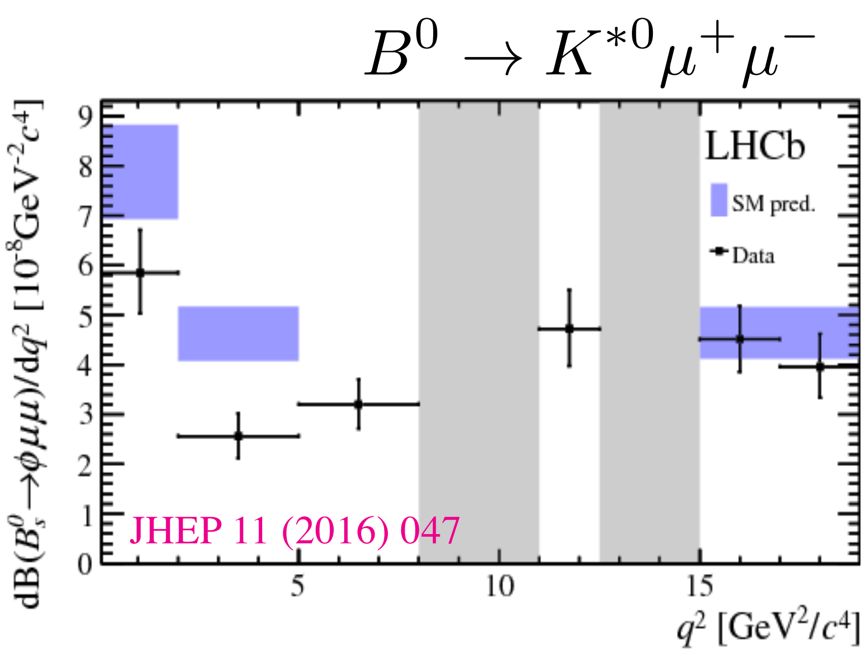
$$\theta_l \to \theta_l - \pi$$

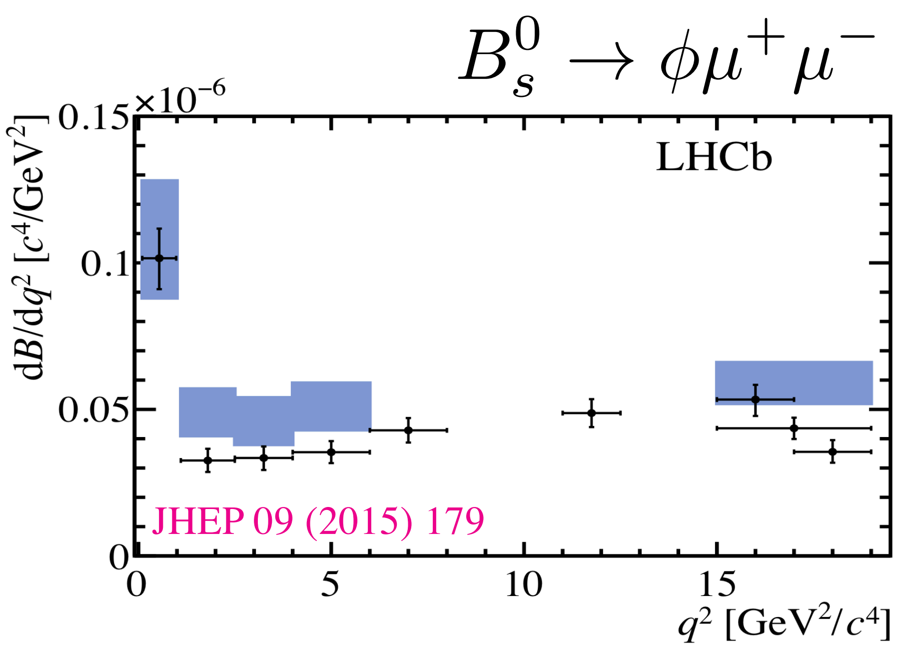
$$\phi \to -\phi$$

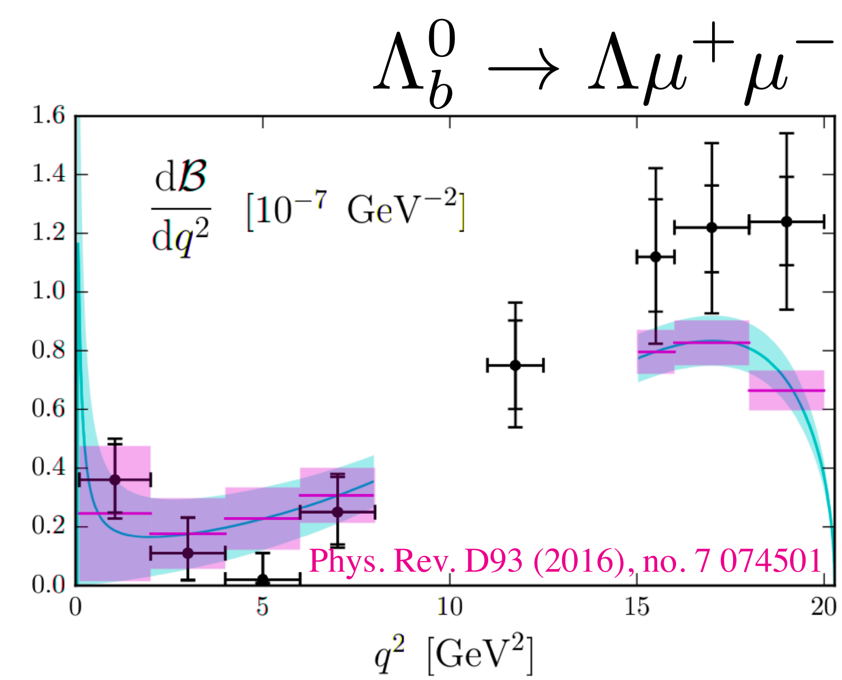
# The current [b->sll and friends] landscape




RK LHCb + Belle plot here

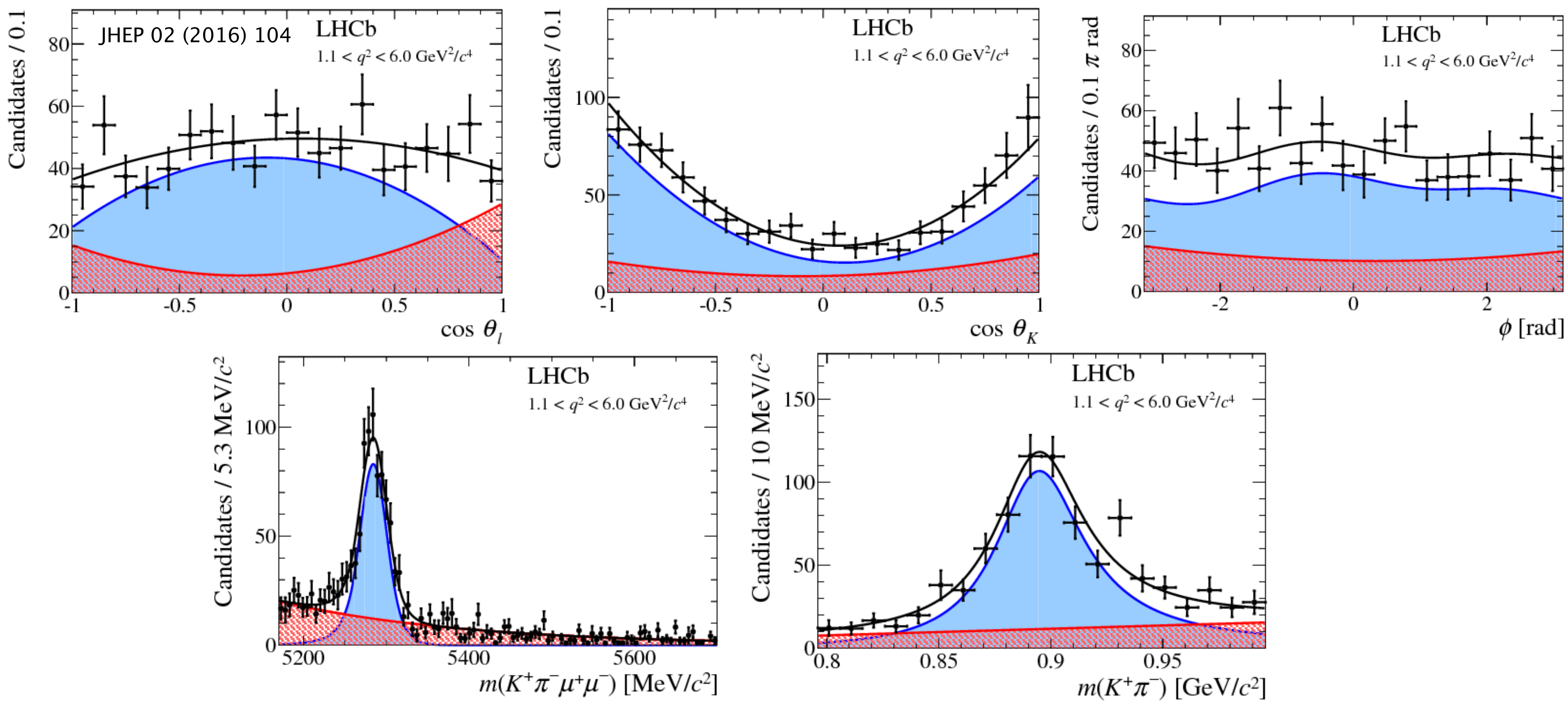


# Extraction of $\mathcal{A}_i$: $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$

- Perform unbinned maximum likelihood fit to determine angular observables
- Use reconstructed B mass for signal/background separation
- Use reconstructed $m_{K\pi}$ mass to constrain non-resonant S-wave



# Aside: angular acceptance

- The reconstruction and selection efficiency must be calculated as a function of angles and $q^2$ .
- Efficiency can be parametrise 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 MC samples

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

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

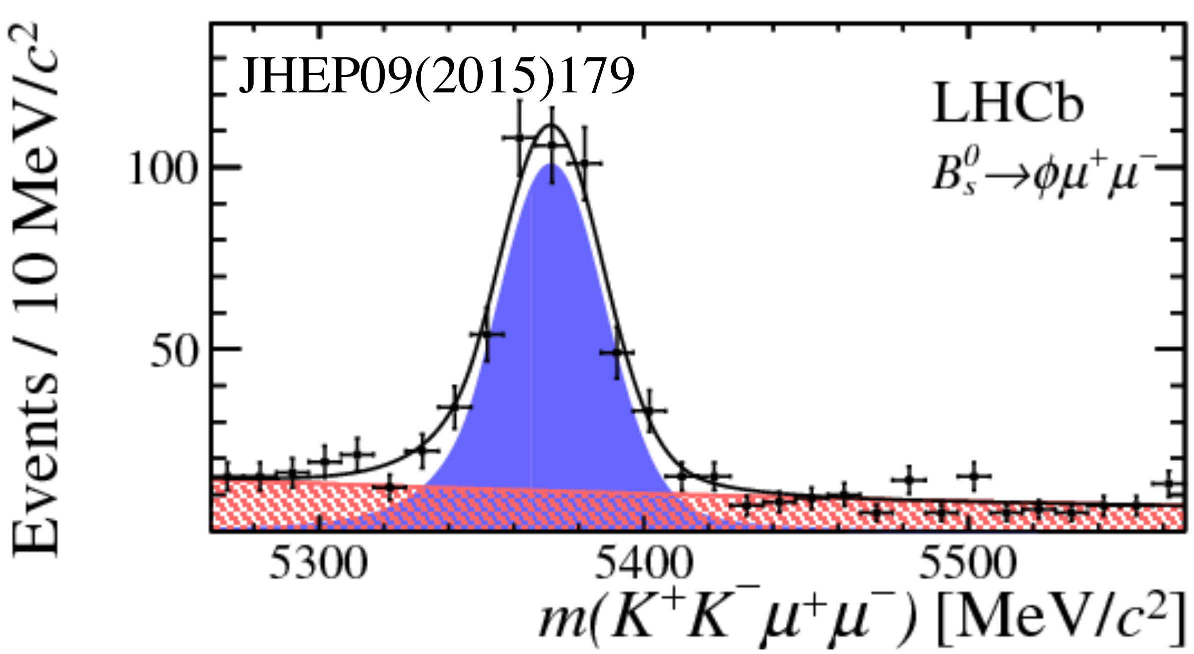
JHEP 02 (2016) 104

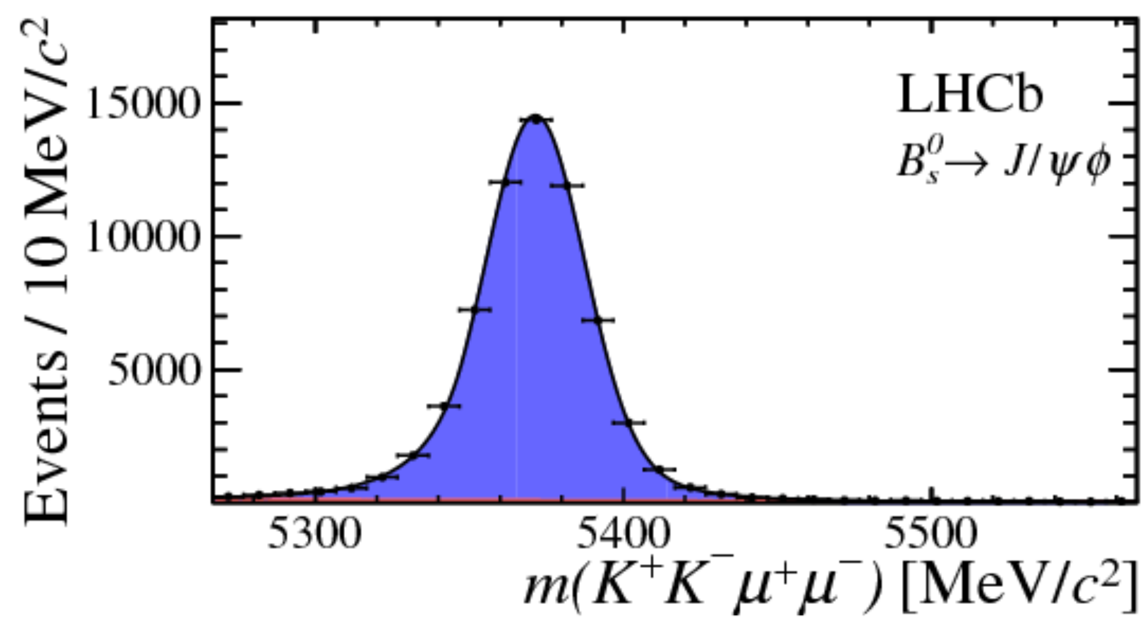
| Source | $F_L$ | $S_3$–$S_9$ | $A_3$–$A_9$ | $P_1$–$P'_8$ | $q_0^2$ GeV$^2/c^4$ |
|---|---|---|---|---|---|
| Acceptance stat. uncertainty | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ | 0.01 |
| Acceptance polynomial order | $< 0.01$ | $< 0.02$ | $< 0.02$ | $< 0.04$ | 0.01–0.03 |
| Data-simulation differences | 0.01–0.02 | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.02$ |
| Acceptance variation with $q^2$ | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ | – |
| $m(K^+\pi^-)$ model | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.03$ | $< 0.01$ |
| Background model | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.02$ | 0.01–0.05 |
| Peaking backgrounds | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ | 0.01–0.04 |
| $m(K^+\pi^-\mu^+\mu^-)$ model | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.02$ | $< 0.01$ |
| Det. and prod. asymmetries | – | – | $< 0.01$ | $< 0.02$ | – |

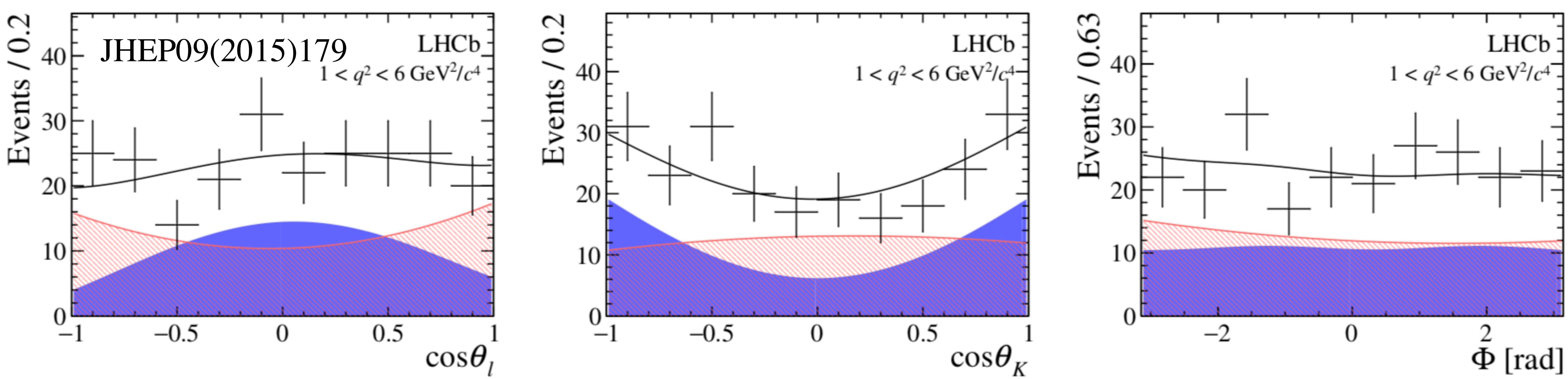
Systematic effects very small compared to stat.

Statistical errors ~ 0.05-0.150

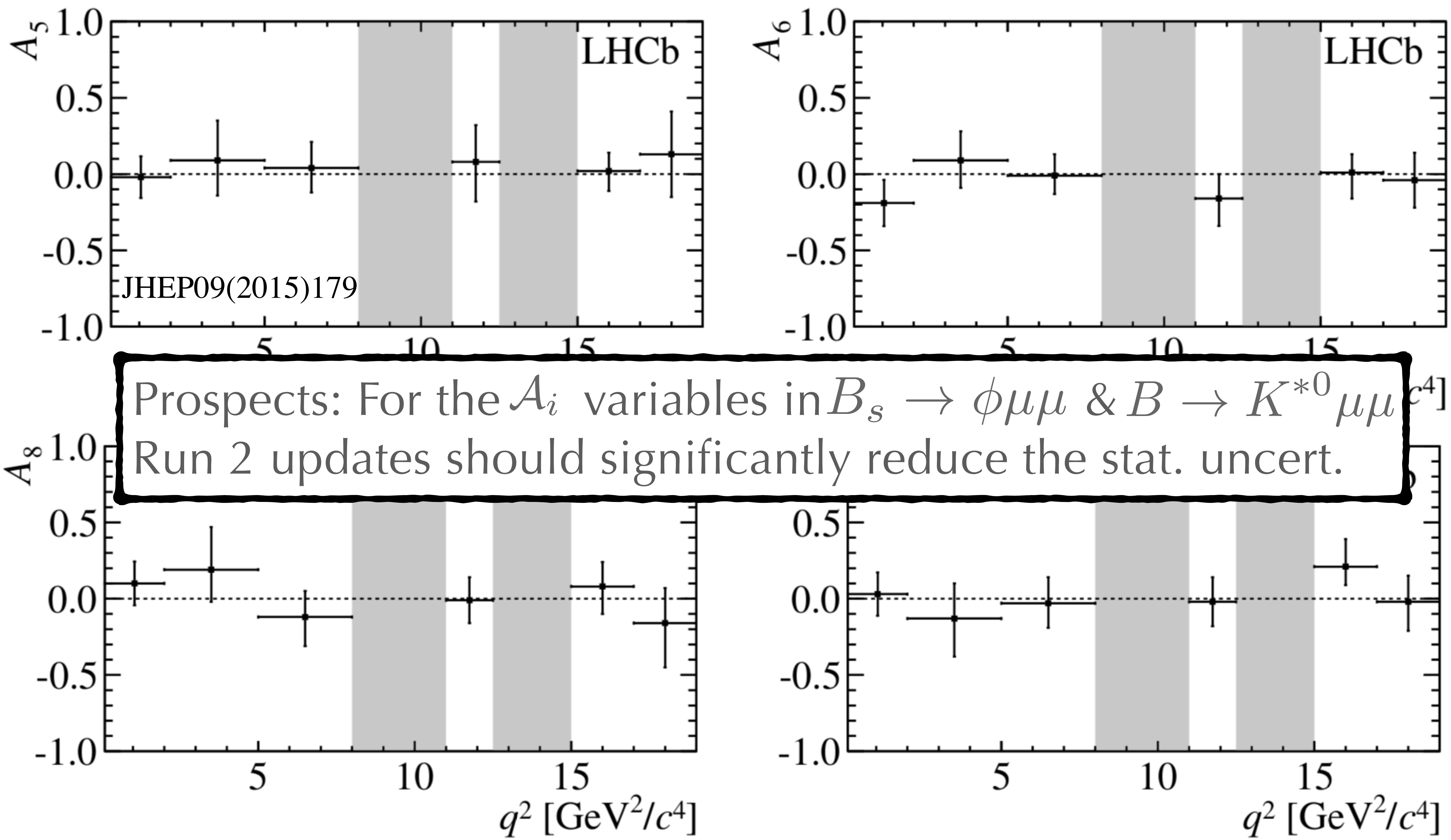
# Example: $B_s^0 \to \phi(\to KK)\mu\mu$



# Example: $B_s^0 \to \phi(\to KK)\mu\mu$



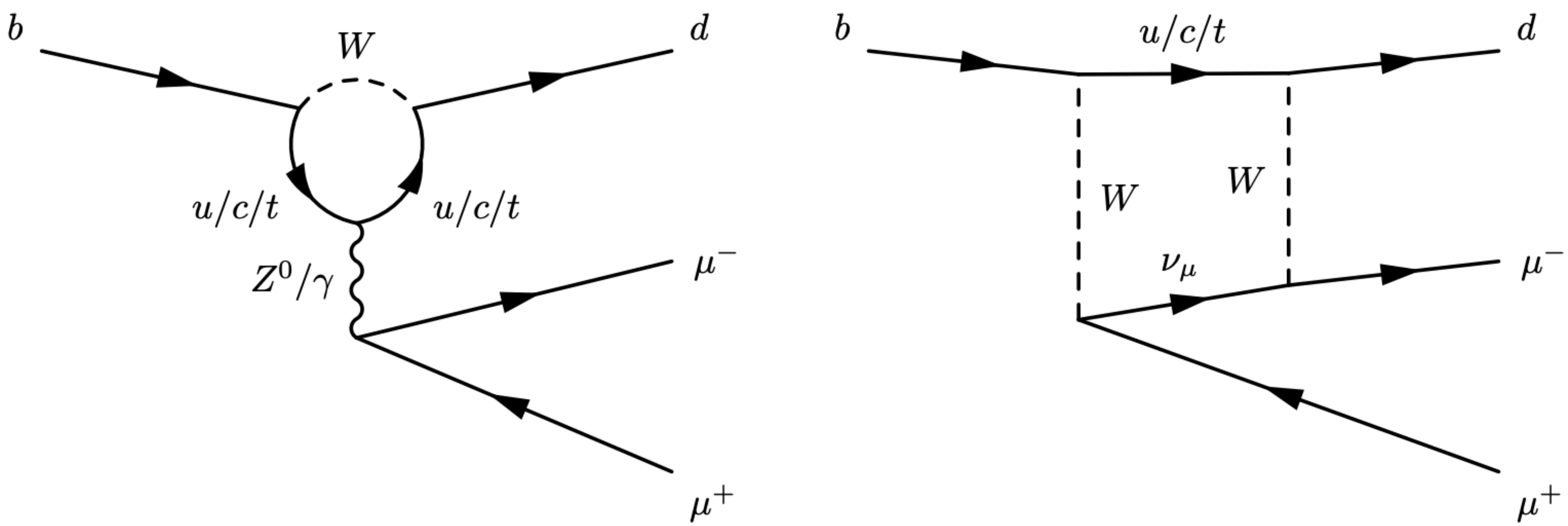

Prospects: For the $\mathcal{A}_i$ variables in $B_s \to \phi\mu\mu$ & $B \to K^{*0}\mu\mu$
Run 2 updates should significantly reduce the stat. uncert.

“

CP asymmetries in rates

$$A_{CP} = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$$

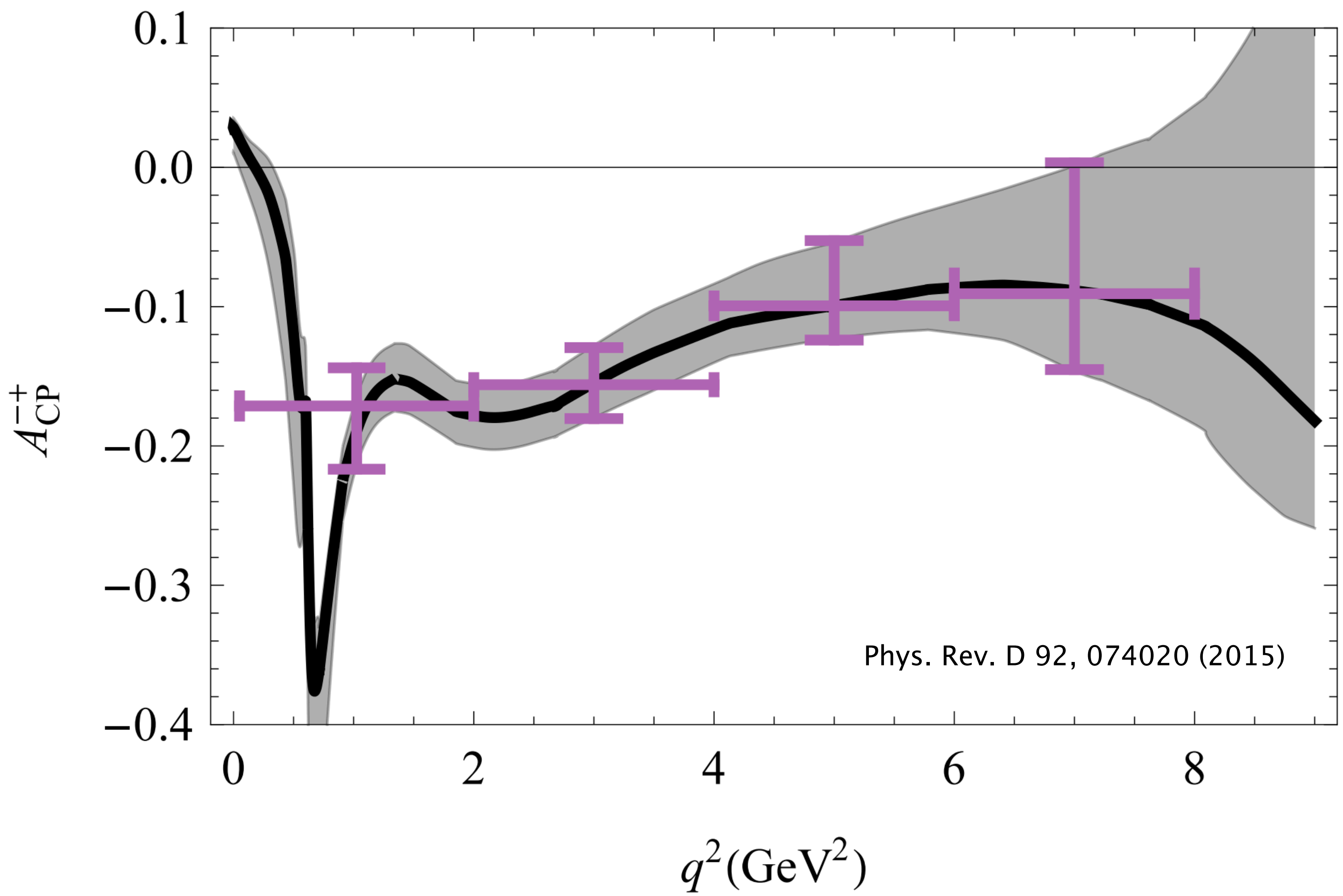
# $\mathcal{A}_{CP}(B^+ \to \pi^+\mu^+\mu^-)$




$b \to dll$ suppressed wrt $b \to sll$ by $\frac{V_{td}}{V_{ts}}$

$\mathcal{A}_{CP}(B^+ \to \pi^+\mu^+\mu^-)$ expected to be no vanishing

# $\mathcal{A}_{CP}(B^+ \to \pi^+\mu^+\mu^-)$




| Bin [GeV$^2$] | $[0.05, 2.0]$ | $[2.0, 4.0]$ | $[4.0, 6.0]$ | $[6.0, 8.0]$ | $[1.0, 6.0]$ |
|---|---|---|---|---|---|
| $\mathcal{A}_{CP}^{(-+)}$ | $-0.171^{+0.027}_{-0.045}$ | $-0.156^{+0.027}_{-0.024}$ | $-0.099^{+0.047}_{-0.025}$ | $-0.091^{+0.093}_{-0.053}$ | $-0.143^{+0.035}_{-0.029}$ |

# $\mathcal{A}_{CP}(B^+ \to \pi^+\mu^+\mu^-)$

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(B^- \to \pi^-\mu^+\mu^-) - \Gamma(B^+ \to \pi^+\mu^+\mu^-)}{\Gamma(B^- \to \pi^-\mu^+\mu^-) + \Gamma(B^+ \to \pi^+\mu^+\mu^-)}$$

$$\mathcal{A}_{\text{RAW}} \equiv \frac{\mathcal{N}(B^- \to \pi^-\mu^+\mu^-) - \mathcal{N}(B^+ \to \pi^+\mu^+\mu^-)}{\mathcal{N}(B^- \to \pi^-\mu^+\mu^-) + \mathcal{N}(B^+ \to \pi^+\mu^+\mu^-)}$$

Raw asymmetries, take from fits

$$\mathcal{A}_{CP}(B^\pm \to \pi^\pm\mu^+\mu^-) = \mathcal{A}_{\text{RAW}} - \mathcal{A}_{\text{P}} - \mathcal{A}_{\text{DET}},$$

Production asymmetry

$(-0.6 \pm 0.6)\%$

Detector asymmetries

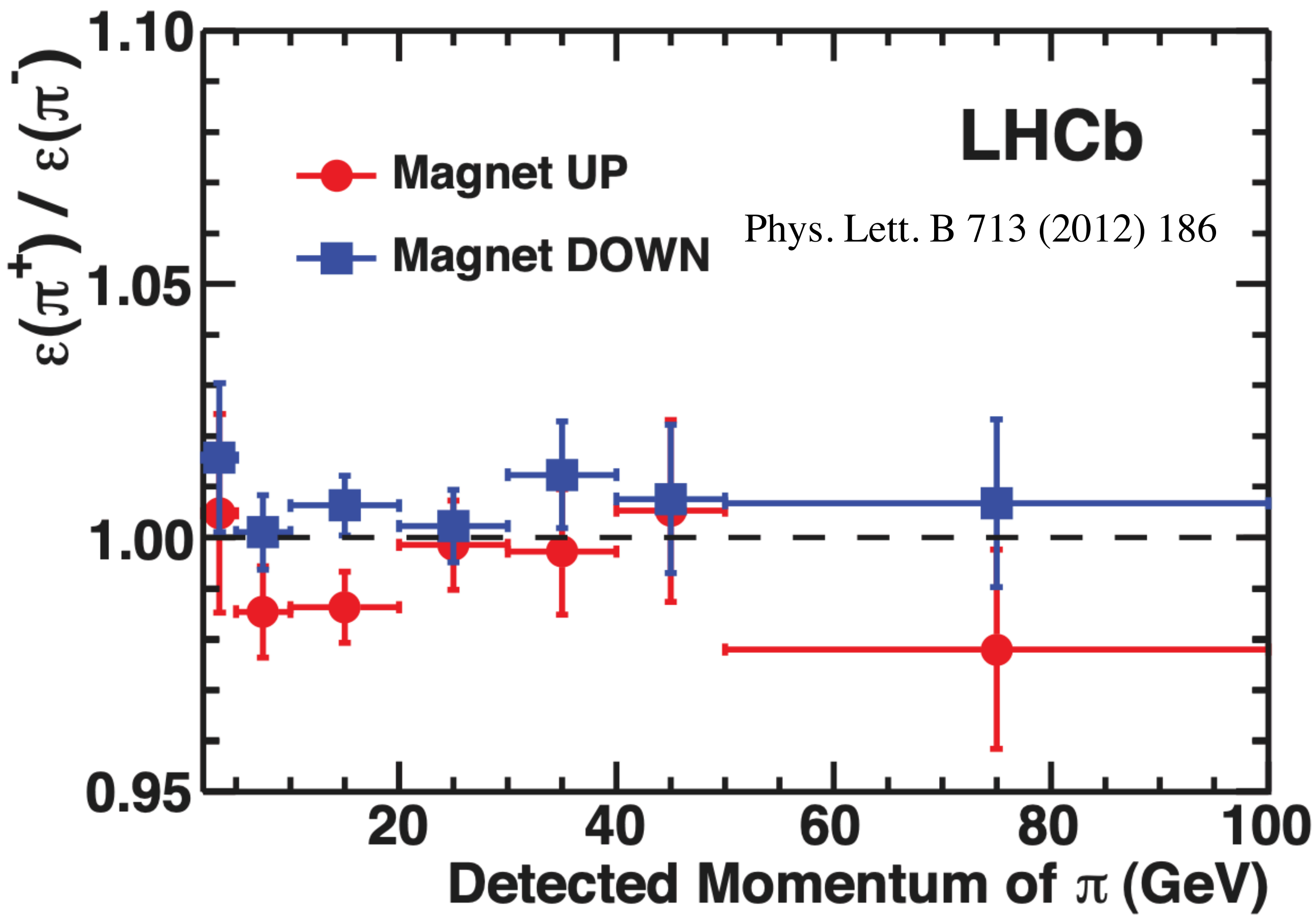
Phys. Rev. Lett. **114**, 041601

# $A_{CP}(B^+ \to \pi^+\mu^+\mu^-)$

Detector asymmetries: Phys. Lett. B 713 (2012) 186

$D^{*+} \to \pi_s^+ D^0 \quad D^0 \to K^-\pi^+\pi^+\pi^-$

Compare fully reconstructed $D^0$ to partially reconstructed (pion missing)

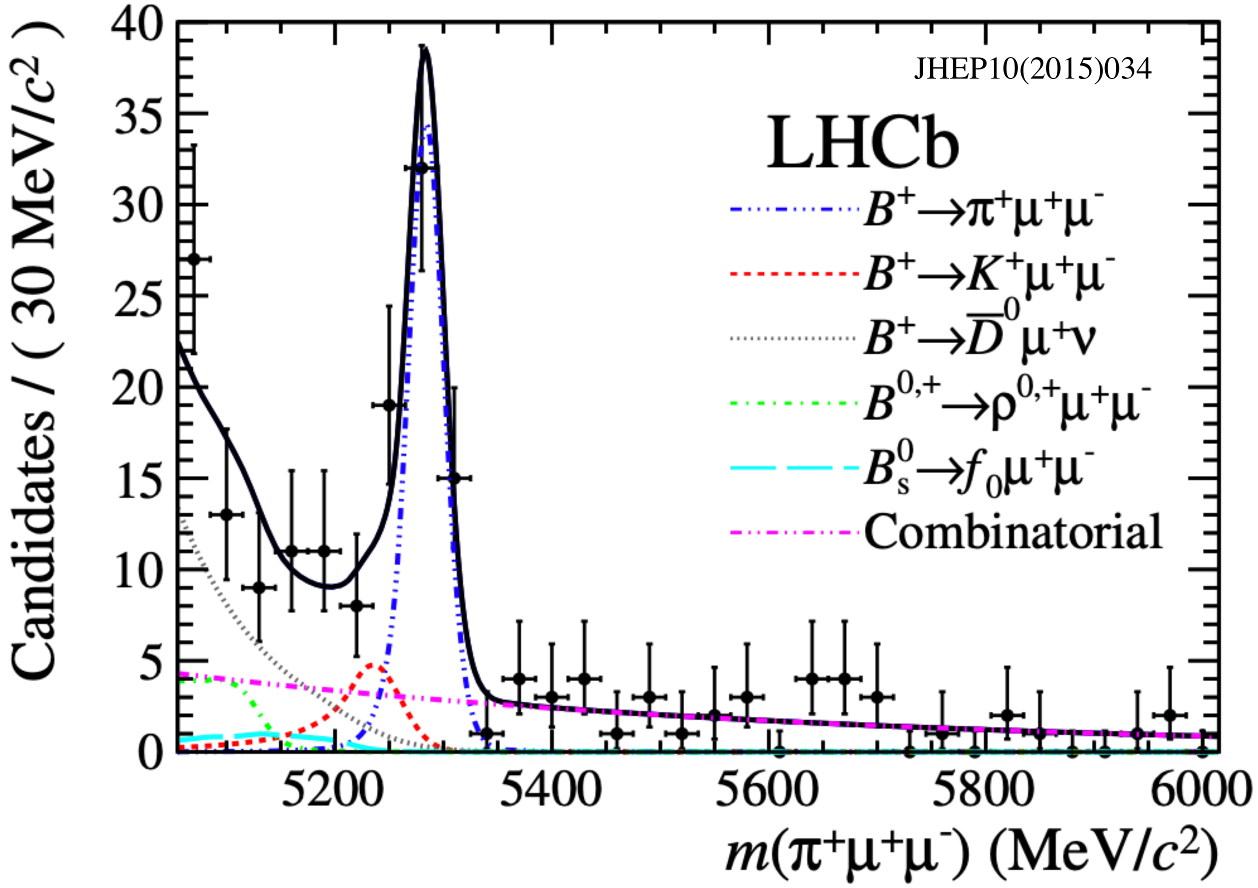


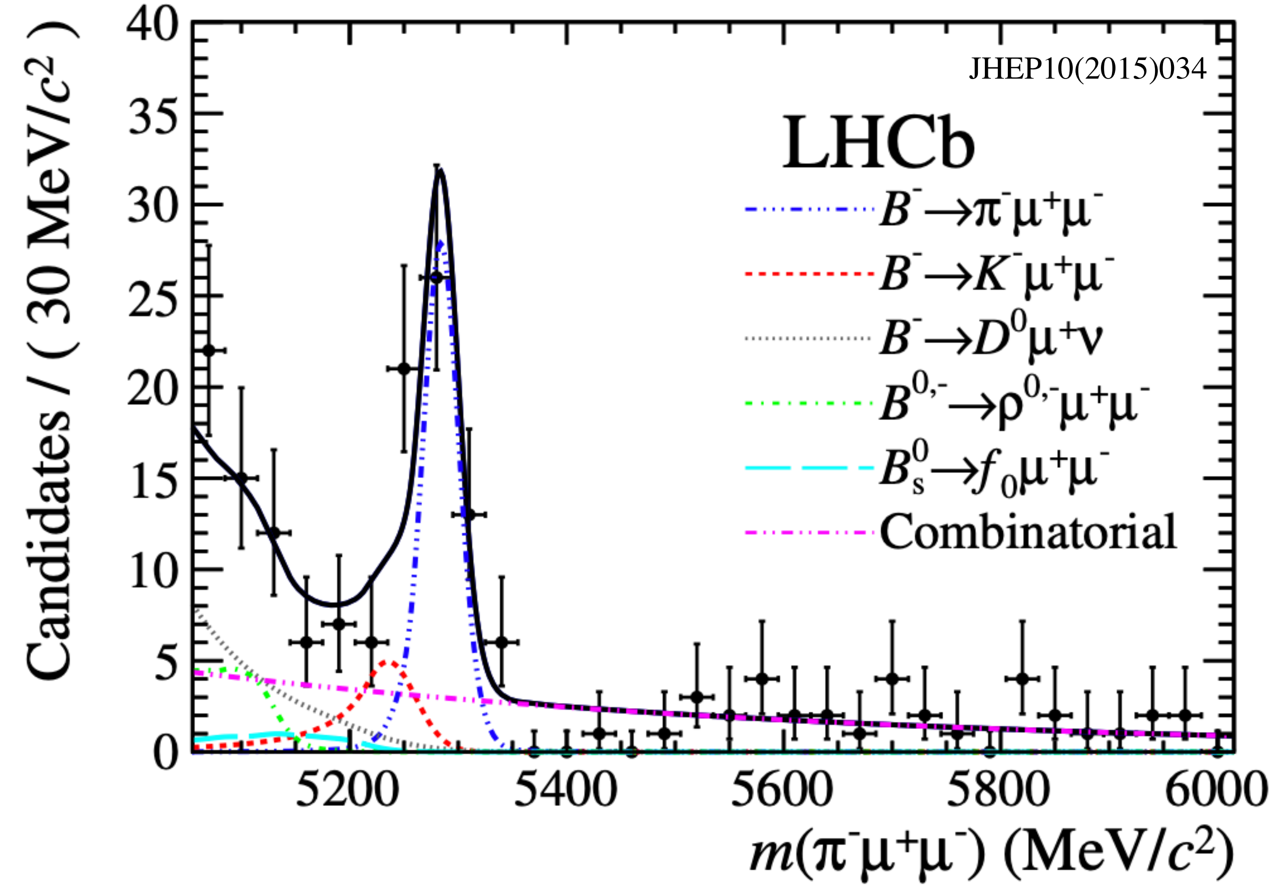

Binned in $p$, $p_t$ and azimuthal production angle

$$\epsilon_{\pi^+}/\epsilon_{\pi^-} = 0.9914 \pm 0.0040$$

$$\epsilon_{\pi^+}/\epsilon_{\pi^-} = 1.0045 \pm 0.0034$$

# $\mathcal{A}_{CP}(B^+ \to \pi^+\mu^+\mu^-)$

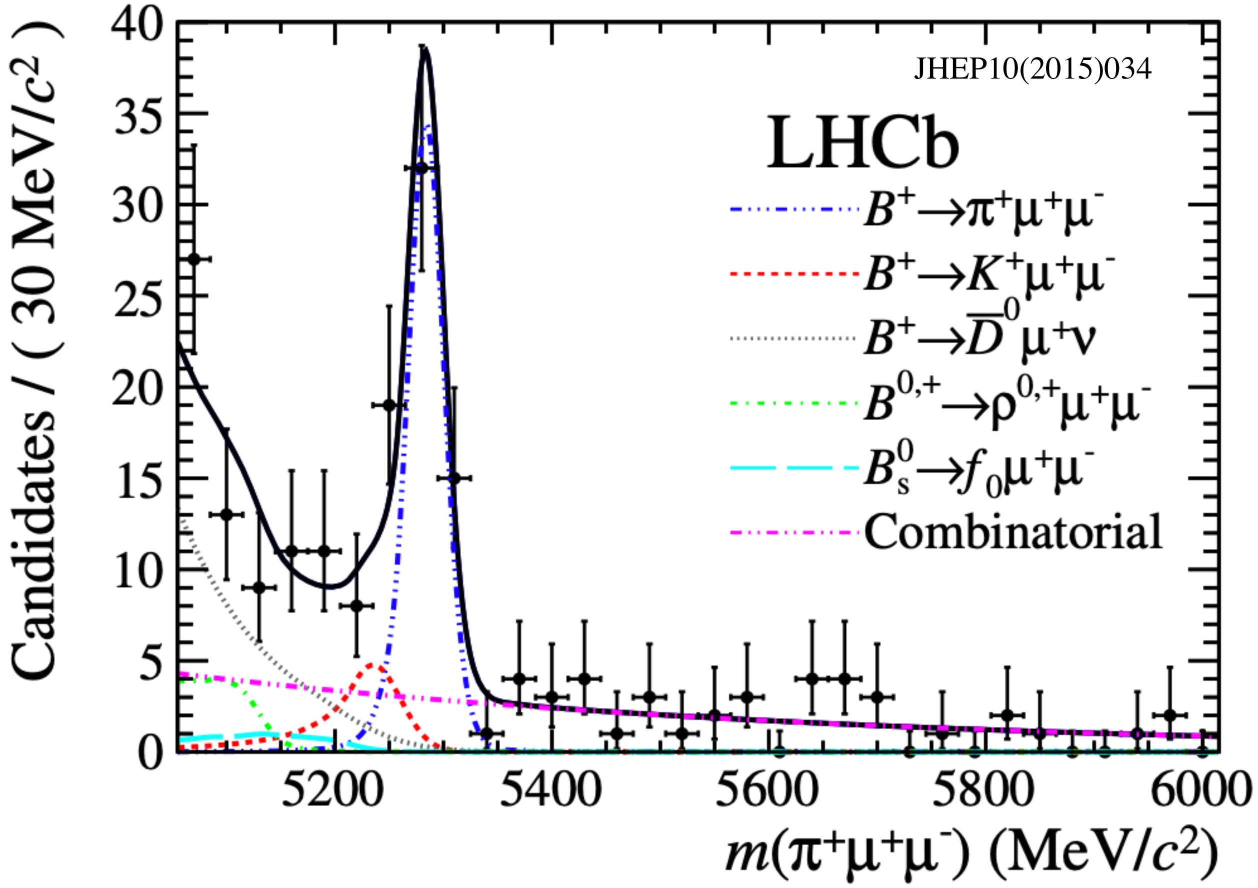


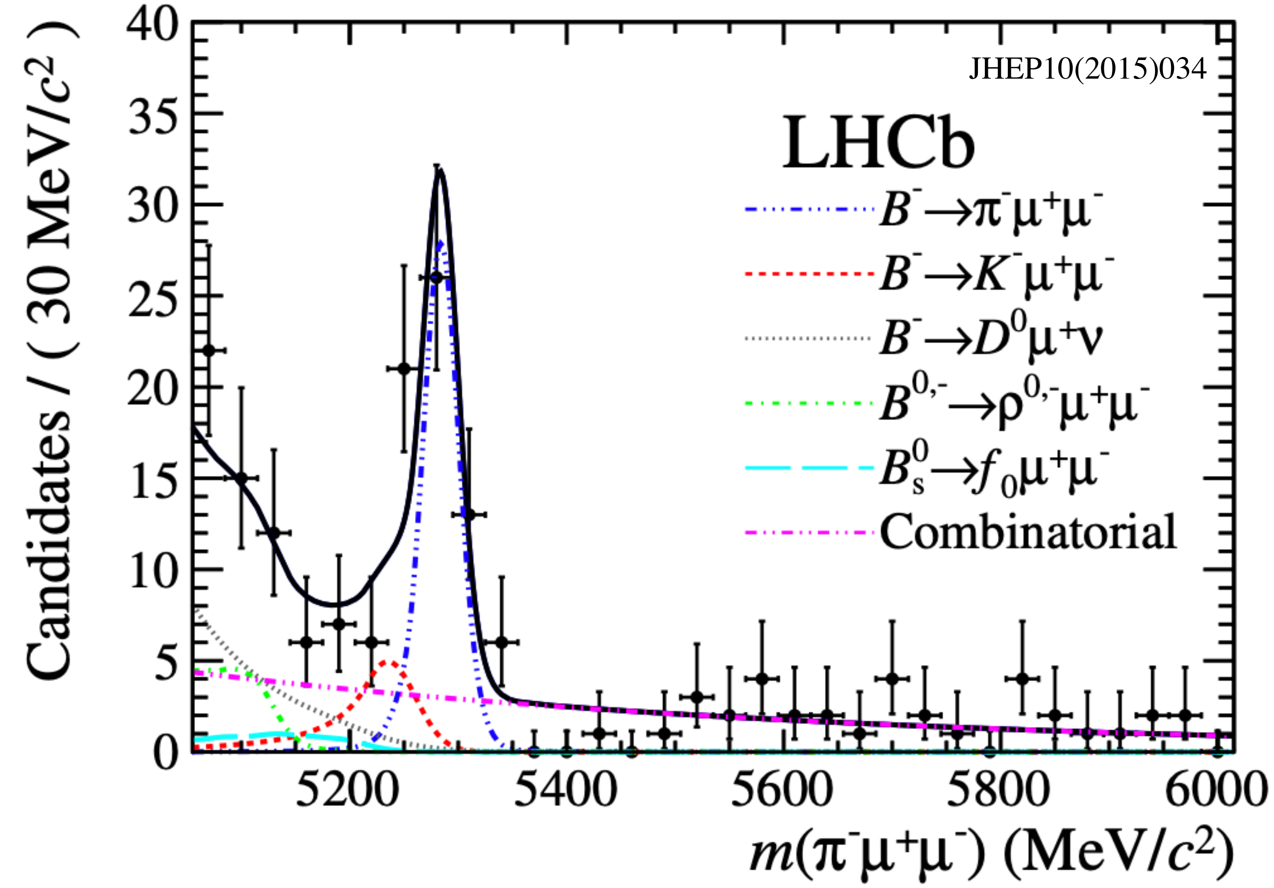




| $\mathcal{N}(B^\pm \to \pi^\pm\mu^+\mu^-)$ | $\mathcal{N}(B^+ \to \pi^+\mu^+\mu^-)$ | $\mathcal{N}(B^- \to \pi^-\mu^+\mu^-)$ |
|---|---|---|
| $92.7 \pm 11.5$ | $51.7 \pm 8.3$ | $41.1 \pm 7.9$ |

Simultaneous fit between $m(\pi^+\mu^+\mu^-)$ and $m(K^+\mu^+\mu^-)$ constrain cross-feed

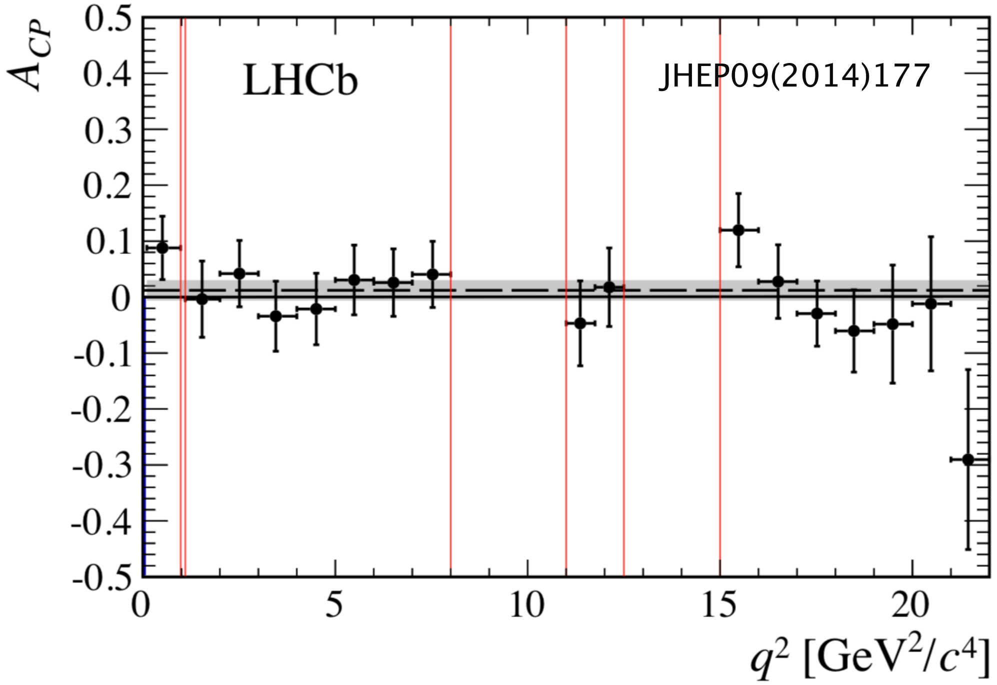
# $\mathcal{A}_{CP}(B^+ \to \pi^+\mu^+\mu^-)$

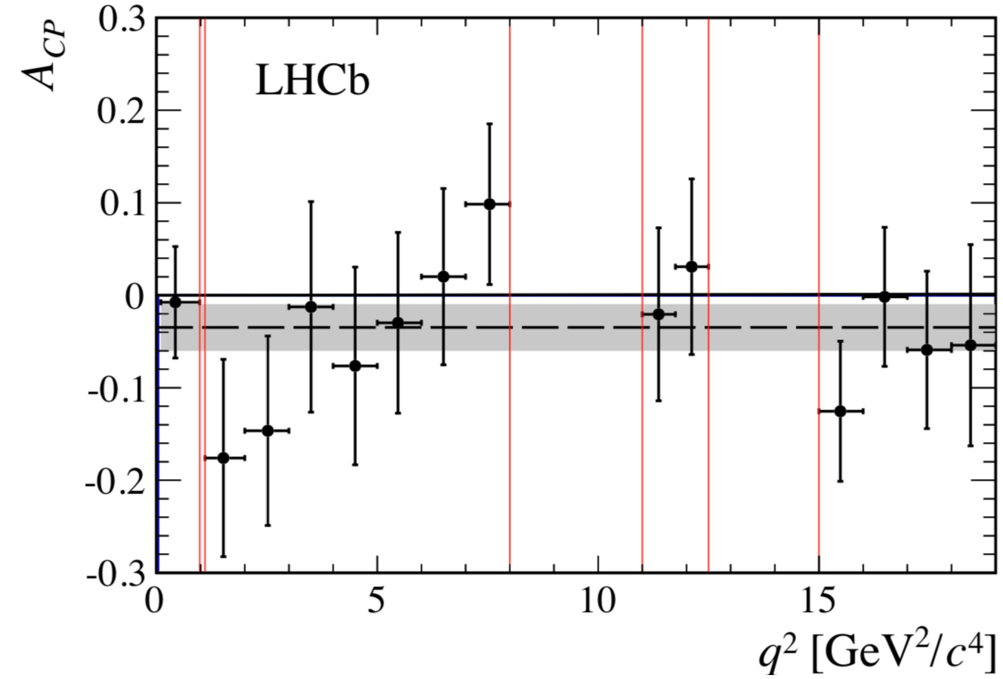



$$\mathcal{A}_{CP}(B^{\pm} \to \pi^{\pm}\mu^+\mu^-) = -0.11 \pm 0.12\,(\text{stat}) \pm 0.01\,(\text{syst})$$

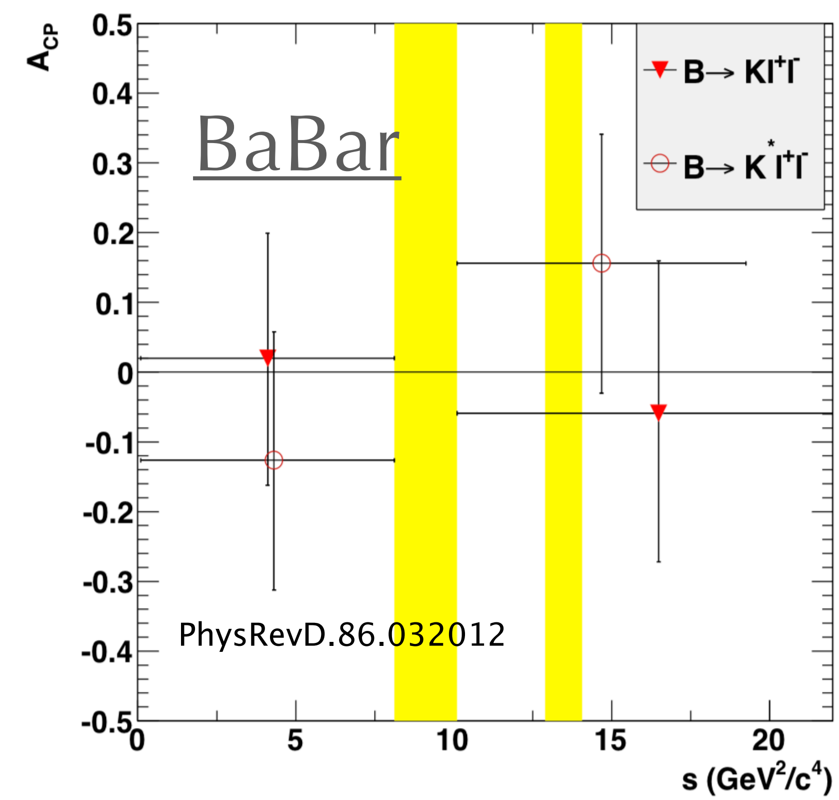
# $\mathcal{A}_{CP}$ in $B \to K^{(*)}ll$ decays




## LHCb

$$\mathcal{A}_{CP}(B^0 \to K^{*0}\mu^+\mu^-) = -0.035 \pm 0.024 \pm 0.003,$$
$$\mathcal{A}_{CP}(B^+ \to K^+\mu^+\mu^-) = \quad 0.012 \pm 0.017 \pm 0.001,$$

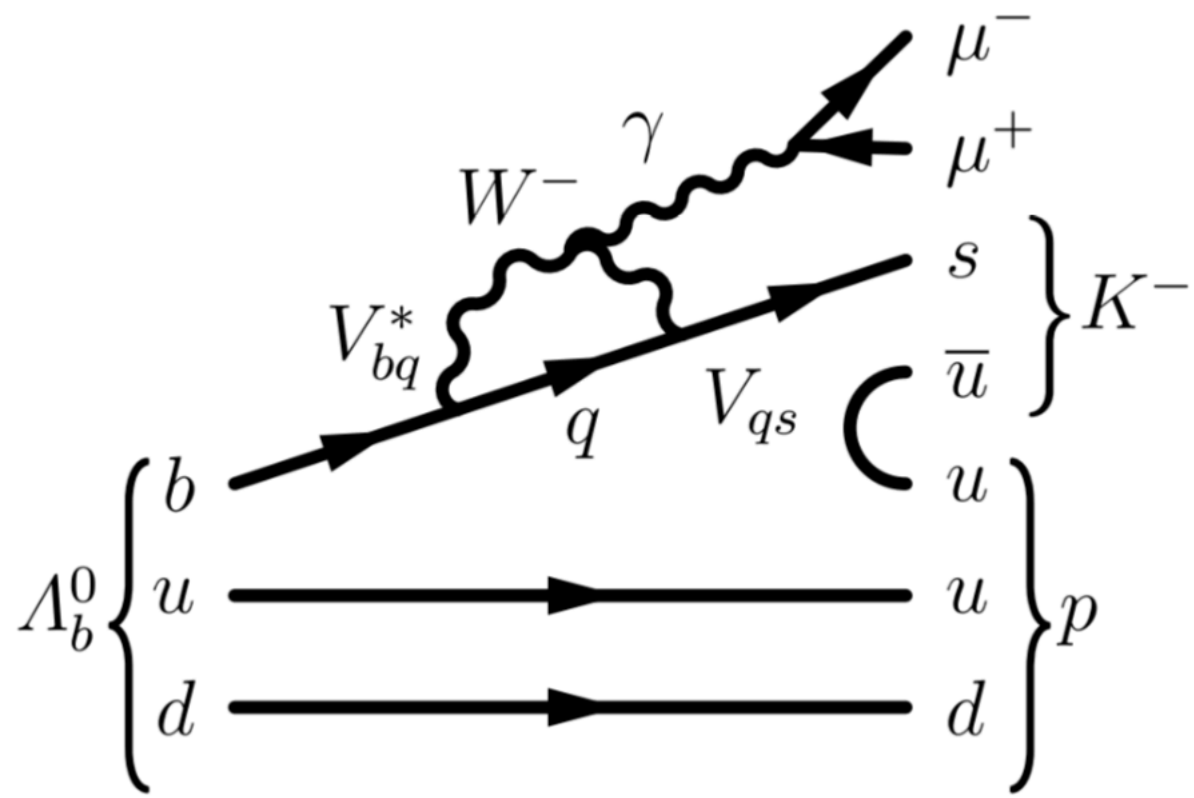



## Belle [Phys.Rev.Lett.103:171801,2009]

$$A_{CP}(K^*\ell^+\ell^-) \; = \; -0.10 \pm 0.10 \pm 0.01 \; ,$$
$$A_{CP}(K^+\ell^+\ell^-) \; = \; 0.04 \pm 0.10 \pm 0.02 \; .$$

CP asymmetries in baryons using rates and triple products

# $\Lambda_b^0 \to pK\mu\mu$




- $b \to sll$ transition in baryon sector
- CP asymmetries looked at in rates and triple products

# $\Lambda_b^0 \to pK\mu\mu$

*Expected to be small in the SM* [e.g. 10.1093/ptep/ptv017]

$$\mathcal{A}_{CP} = \mathcal{A}_{\mathrm{RAW}} - \boxed{\mathcal{A}_{\mathrm{P}}} - \boxed{\mathcal{A}_{\mathrm{DET}}},$$

- Detector asymmetries for final state well-measured
- Production asymmetries for $\Lambda_b$ measured at LHCb for first time in 2017, after this result
- Solution: measure $\Delta\mathcal{A}_{CP}$ between modes with same mother

$\boxed{\Lambda_b \to pKJ/\psi}$ Assume CP-conserving

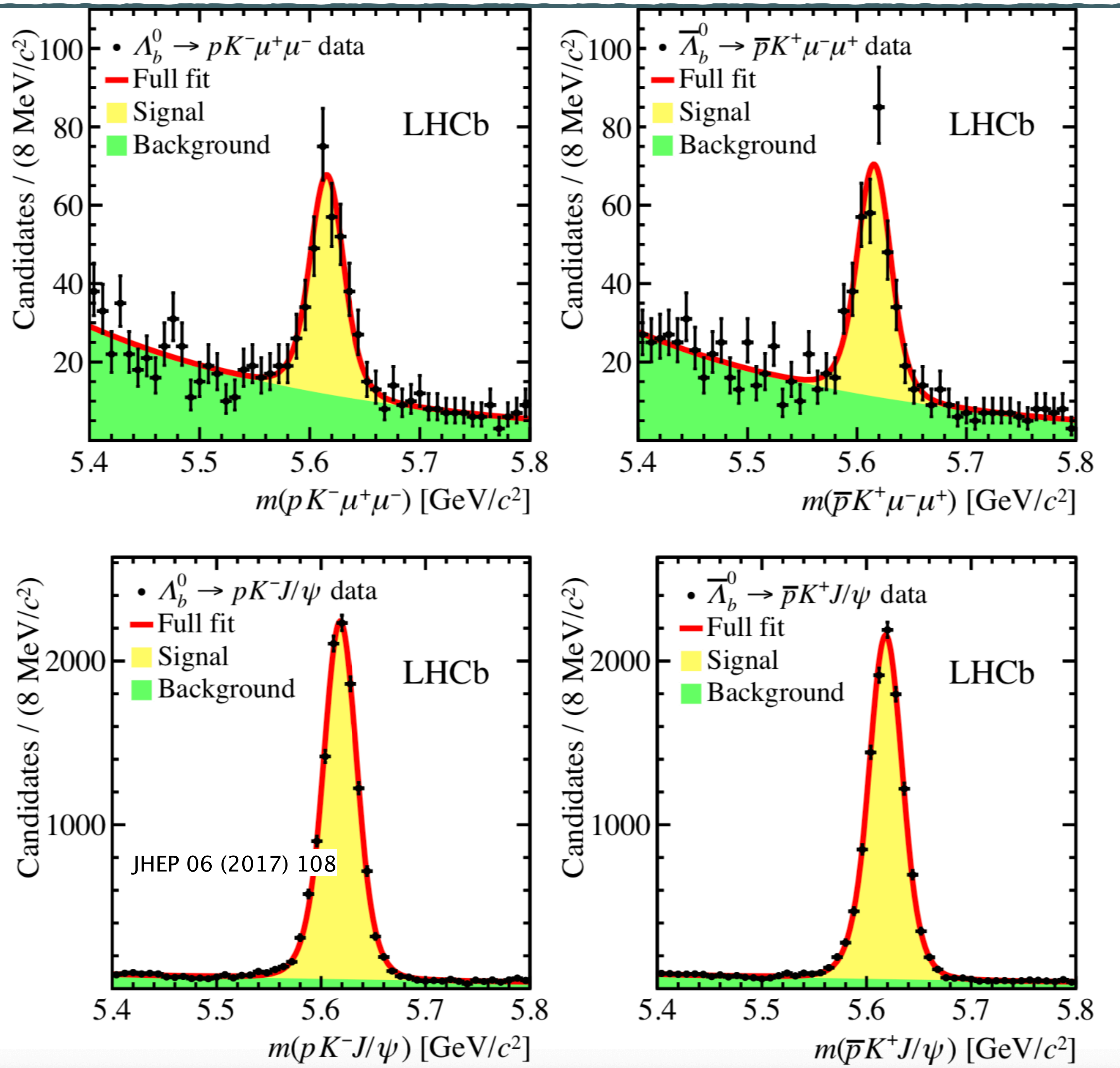
- M

$$\mathcal{A}_{\mathrm{raw}} \approx \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) + \boxed{\mathcal{A}_{\mathrm{prod}}(\Lambda_b^0)} - \boxed{\mathcal{A}_{\mathrm{reco}}(K^+) + \mathcal{A}_{\mathrm{reco}}(p)}$$

$$\begin{aligned}\Delta\mathcal{A}_{CP} &\equiv \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-J/\psi) \\ &\approx \mathcal{A}_{\mathrm{raw}}(\Lambda_b^0 \to pK^-\mu^+\mu^-) - \mathcal{A}_{\mathrm{raw}}(\Lambda_b^0 \to pK^-J/\psi).\end{aligned}$$

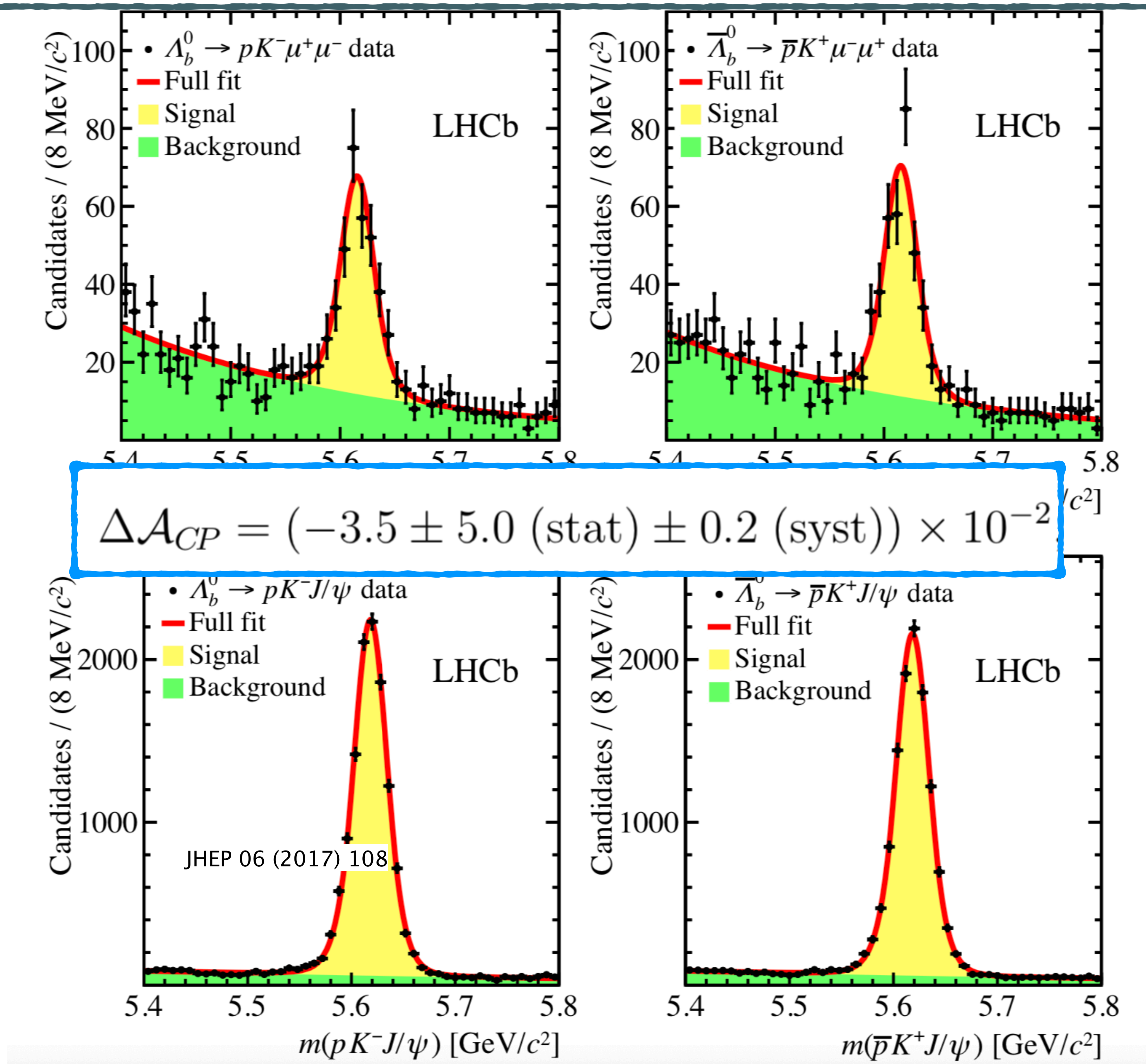
# $\Lambda_b^0 \to pK\mu\mu$

First observation, 600 events in total



# $\Lambda_b^0 \to pK\mu\mu$

First observation, 600 events in total




$$\Delta\mathcal{A}_{CP} = (-3.5 \pm 5.0\ (\text{stat}) \pm 0.2\ (\text{syst})) \times 10^{-2}$$

JHEP 06 (2017) 108

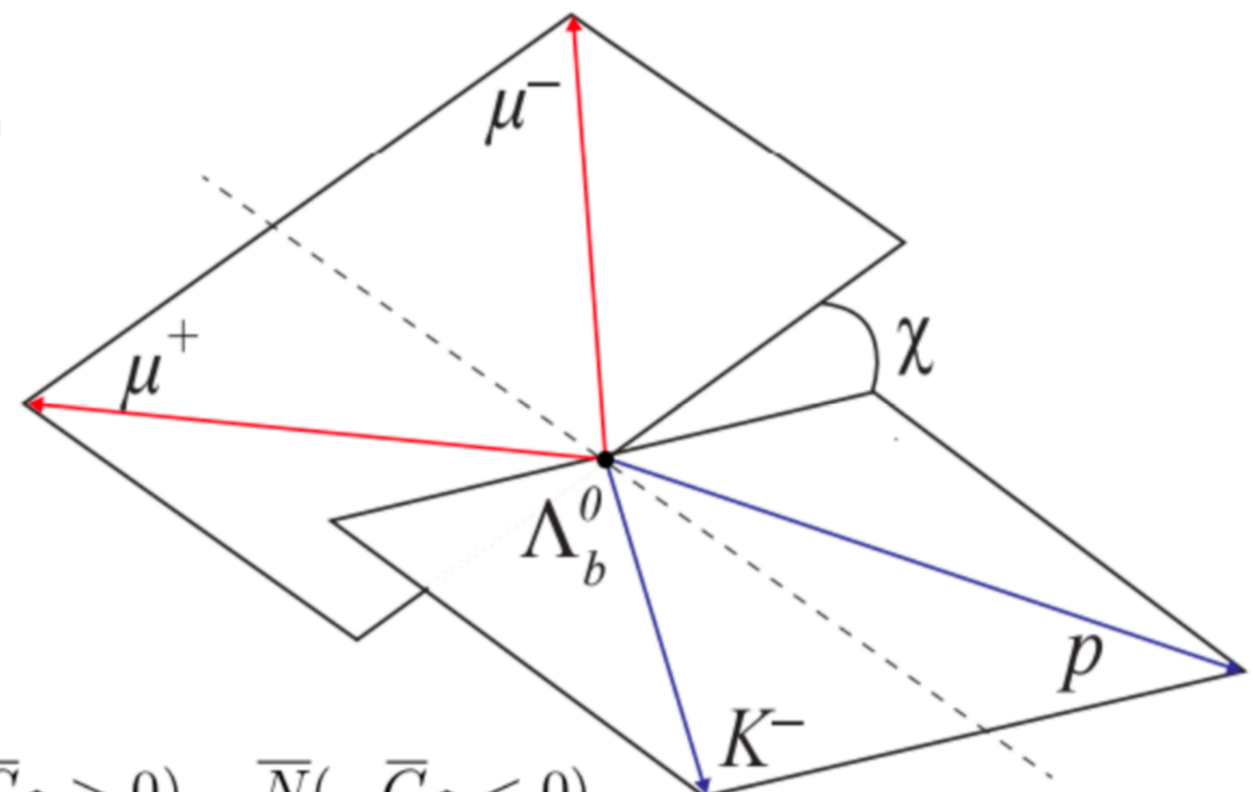
# $\Lambda_b^0 \to pK\mu\mu$

- Can also look at triple products (TP):

Triple product

proportional to

$$C_{\widehat{T}} \equiv \vec{p}_{\mu^+} \cdot (\vec{p}_p \times \vec{p}_{K^-}),$$
$$\overline{C}_{\widehat{T}} \equiv \vec{p}_{\mu^-} \cdot (\vec{p}_{\overline{p}} \times \vec{p}_{K^+}),$$




$$A_{\widehat{T}} \equiv \frac{N(C_{\widehat{T}} > 0) - N(C_{\widehat{T}} < 0)}{N(C_{\widehat{T}} > 0) + N(C_{\widehat{T}} < 0)}, \quad \overline{A}_{\widehat{T}} \equiv \frac{\overline{N}(-\overline{C}_{\widehat{T}} > 0) - \overline{N}(-\overline{C}_{\widehat{T}} < 0)}{\overline{N}(-\overline{C}_{\widehat{T}} > 0) + \overline{N}(-\overline{C}_{\widehat{T}} < 0)},$$

$$a_{CP}^{\widehat{T}\text{-odd}} \equiv \frac{1}{2}\left(A_{\widehat{T}} - \overline{A}_{\widehat{T}}\right), \qquad a_{P}^{\widehat{T}\text{-odd}} \equiv \frac{1}{2}\left(A_{\widehat{T}} + \overline{A}_{\widehat{T}}\right),$$

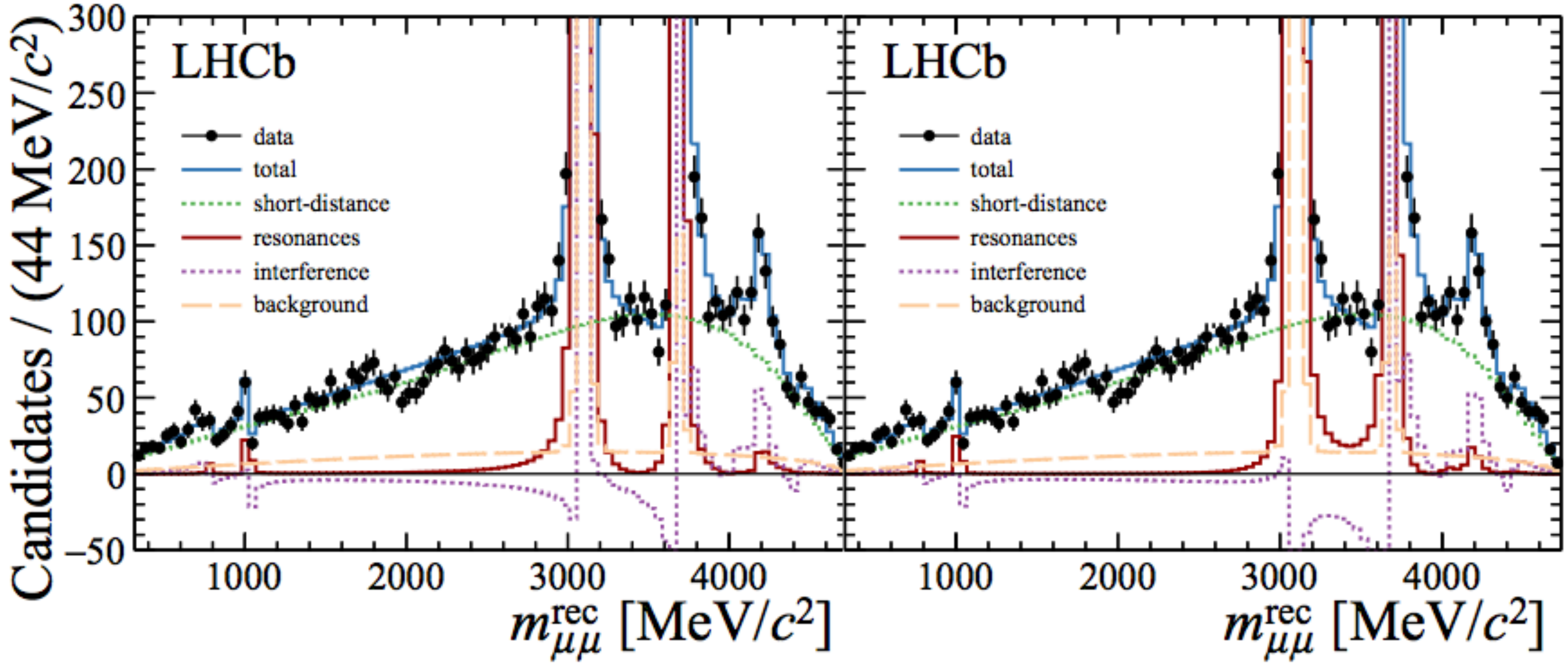
# $\Lambda_b^0 \to pK\mu\mu$

- Can also look at triple products (TP):
  - Triple products are CP-odd variables, which, because of how they are constructed, are not dependent on production effects
  - Non-zero triple product value -> CP-violation
- Also complement $\mathcal{A}_{CP}$ search for CP violation as:

| $\mathcal{A}_{CP}$ | Triple product |
|---|---|
| $\left.\frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi}\right\rvert_{CP-\mathrm{odd}}^{\widehat{T}-\mathrm{even}} \propto a_1^e a_2^e \sin(\delta_1^e - \delta_2^e)\sin(\phi_1^e - \phi_2^e),$ | $\left.\frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi}\right\rvert_{CP-\mathrm{odd}}^{\widehat{T}-\mathrm{odd}} \propto a_1^e a_1^o \cos(\delta_1^e - \delta_1^o)\sin(\phi_1^e - \phi_1^o),$ |
| Enhanced with large strong phase differences | Enhanced with small strong phase differences |

# Strong phase from charm-loops: $B^+ \to K^+\mu^+\mu^-$

- Strong phase relative to penguin mode from long-distance $B^+ \to K^+\psi_{1S,2S}(\to \mu^+\mu^-)$ contributions ~ $\pm\pi/2$
- Sign ambiguity may be resolvable with more data




*Eur.Phys.J.C* 77 (2017) 3, 161

# $\Lambda_b^0 \to pK\mu\mu$

- Can also look at triple products (TP):
  - Triple products are CP-odd variables, which, because of how they are constructed, are not dependent on production effects
  - Non-zero triple product value -> CP-violation
- Also complement $\mathcal{A}_{CP}$ search for CP violation as:

| $\mathcal{A}_{CP}$ | Triple product |
| --- | --- |

$$\frac{d\Gamma}{d\Phi}\bigg|^{\widehat{T}-\text{even}}_{CP-\text{odd}} \propto a_1^e a_2^e \sin(\delta_1^e - \delta_2^e) \sin$$

Enhanced with large strong phase d

$$a_{CP}^{\widehat{T}\text{-odd}} = (\quad 1.2 \pm 5.0\,(\text{stat}) \pm 0.7\,(\text{syst})) \times 10^{-2},$$

$$a_{P}^{\widehat{T}\text{-odd}} = (-4.8 \pm 5.0\,(\text{stat}) \pm 0.7\,(\text{syst})) \times 10^{-2}.$$

# Summary

- CP asymmetries offer good tests of the SM
- Different CP-violating observables are complementary with respect to both experimental effects and in relation to strong phase differences
- Angular CP-violating observables are effective at constraining Wilson Coefficient phases

Thank you for your attention!

# Expressions for Ai

JHEP 0807:106,2008

$$A_{\rm CP} = \mathcal{A}\frac{8\hat{m}_b}{3\hat{s}}{\rm Re}\bigg\{\frac{\xi_\parallel^2}{\xi_\perp^2}\frac{M_B^2}{M_{K^*}^2}\frac{(1-\hat{s})^2}{8}\left[\hat{m}_b\frac{|\mathcal{T}_\parallel^-|^2}{\xi_\parallel^2}-\frac{\mathcal{T}_\parallel^-}{\xi_\parallel}(C_9-C_9')^*\right]+\frac{\hat{m}_b}{\hat{s}}\frac{|\mathcal{T}_\perp^+|^2+|\mathcal{T}_\perp^-|^2}{\xi_\perp^2}$$
$$+\frac{\mathcal{T}_\perp^+-\mathcal{T}_\perp^-}{\xi_\perp}C_9^*+\frac{\mathcal{T}_\perp^++\mathcal{T}_\perp^-}{\xi_\perp}C_9'^*-(\delta_W\to-\delta_W)\bigg\}+\mathcal{O}\left(m_l^2/q^2\right), \qquad \text{(D.1)}$$

$$A_3 = \mathcal{A}\frac{2\hat{m}_b\beta_l}{\hat{s}}{\rm Re}\bigg\{\frac{\hat{m}_b}{\hat{s}}\frac{|\mathcal{T}_\perp^+|^2-|\mathcal{T}_\perp^-|^2}{\xi_\perp^2}+\frac{\mathcal{T}_\perp^+-\mathcal{T}_\perp^-}{\xi_\perp}C_9^*+\frac{\mathcal{T}_\perp^++\mathcal{T}_\perp^-}{\xi_\perp}C_9'^*-(\delta_W\to-\delta_W)\bigg\}, \qquad \text{(D.2)}$$

$$A_4^D = -\mathcal{A}^D\frac{\hat{m}_b\beta_l}{2\hat{s}}{\rm Re}\bigg\{\left(\frac{\mathcal{T}_\perp^-}{\xi_\perp}-\hat{s}\frac{\mathcal{T}_\parallel^-}{\xi_\parallel}\right)(C_9-C_9')^*-2\hat{m}_b\frac{\mathcal{T}_\perp^-(\mathcal{T}_\parallel^-)^*}{\xi_\perp\xi_\parallel}-(\delta_W\to-\delta_W)\bigg\}, \qquad \text{(D.3)}$$

$$A_5^D = -\mathcal{A}^D\frac{\hat{m}_b}{\hat{s}}{\rm Re}\bigg\{\left(\frac{\mathcal{T}_\perp^-}{\xi_\perp}-\hat{s}\frac{\mathcal{T}_\parallel^-}{\xi_\parallel}\right)C_{10}-\left(\frac{\mathcal{T}_\perp^-}{\xi_\perp}+\hat{s}\frac{\mathcal{T}_\parallel^-}{\xi_\parallel}\right)C_{10}'^*-(\delta_W\to-\delta_W)\bigg\}, \qquad \text{(D.4)}$$

$$A_6 = \mathcal{A}\frac{4\hat{m}_b}{\hat{s}}{\rm Re}\bigg\{\frac{\mathcal{T}_\perp^++\mathcal{T}_\perp^-}{\xi_\perp}C_{10}^*-\frac{\mathcal{T}_\perp^+-\mathcal{T}_\perp^-}{\xi_\perp}C_{10}'^*-(\delta_W\to-\delta_W)\bigg\}, \qquad \text{(D.5)}$$

# Expressions for Ai

JHEP 0807:106,2008

$$A_7^D = \mathcal{A}^D \frac{\hat{m}_b}{\hat{s}} \mathrm{Im}\left\{ (C_{10} - C'_{10}) \left( \frac{\mathcal{T}_\perp^-}{\xi_\perp} + \hat{s} \frac{\mathcal{T}_\parallel^-}{\xi_\parallel} \right)^* - (\delta_W \to -\delta_W) \right\}, \quad \text{(D.6)}$$

$$A_8^D = \mathcal{A}^D \frac{\beta_l}{2} \mathrm{Im}\left\{ \frac{2\hat{m}_b^2}{\hat{s}} \frac{\mathcal{T}_\perp^+ (\mathcal{T}_\parallel^-)^*}{\xi_\perp \xi_\parallel} - \frac{\hat{m}_b}{\hat{s}} \left[ \left( \frac{\mathcal{T}_\perp^+}{\xi_\perp} + \hat{s} \frac{\mathcal{T}_\parallel^-}{\xi_\parallel} \right) C_9^* - \left( \frac{\mathcal{T}_\perp^+}{\xi_\perp} - \hat{s} \frac{\mathcal{T}_\parallel^-}{\xi_\parallel} \right) C_9'^* \right] \right.$$
$$\left. + C_9 C_9'^* + C_{10} C_{10}'^* - (\delta_W \to -\delta_W) \right\}, \quad \text{(D.7)}$$

$$A_9 = -\mathcal{A}\, 2\beta_l \mathrm{Im}\left\{ \frac{2\hat{m}_b^2}{\hat{s}^2} \frac{\mathcal{T}_\perp^+ (\mathcal{T}_\perp^-)^*}{\xi_\perp^2} + \frac{\hat{m}_b}{\hat{s}} \left[ \frac{\mathcal{T}_\perp^+ - \mathcal{T}_\perp^-}{\xi_\perp} C_9^* - \frac{\mathcal{T}_\perp^+ + \mathcal{T}_\perp^-}{\xi_\perp} C_9'^* \right] \right.$$
$$\left. - C_9 C_9'^* - C_{10} C_{10}'^* - (\delta_W \to -\delta_W) \right\}, \quad \text{(D.8)}$$