Studies of electroweak-penguin and other rare B decays at Belle

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for the Belle Collaboration

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Outline

- Introduction
- Recent studies of electroweak penguin B decays:
  - → $B \to K^*\gamma$
  - → $B \to K^* l^+ l^-$
  - → $B \to h^{(*)}\nu\nu$
- Search for $B^- \to \mu^- \nu_\mu$
- Summary

The Belle experiment

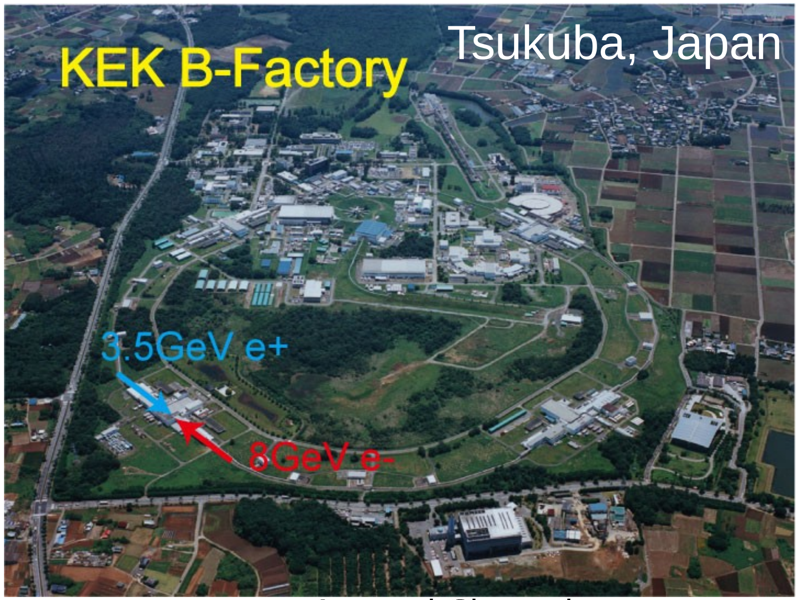
- Operating at the KEKB collider (1999-2010).
- Asymmetric beam energy:

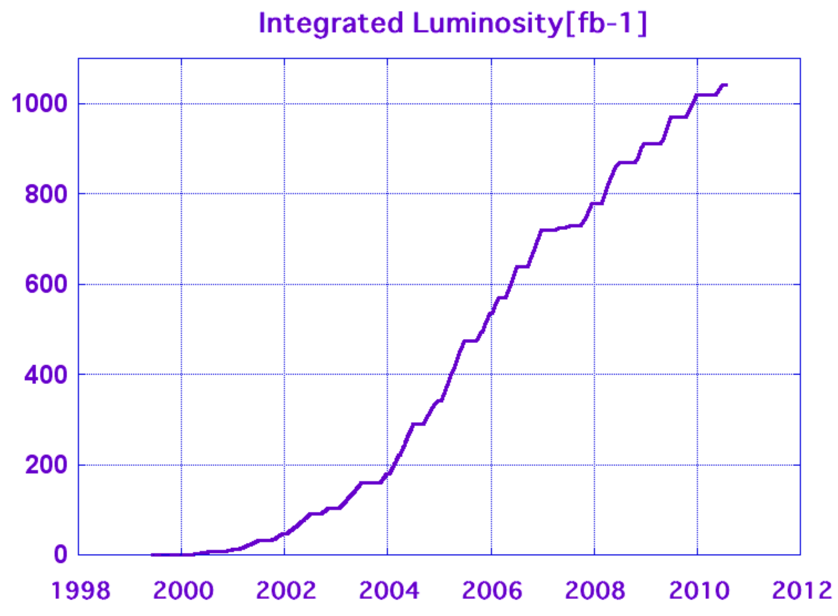
$$8.0 \text{ GeV} \;\; e^- \text{ on } 3.5 \text{ GeV} \;\; e^+$$

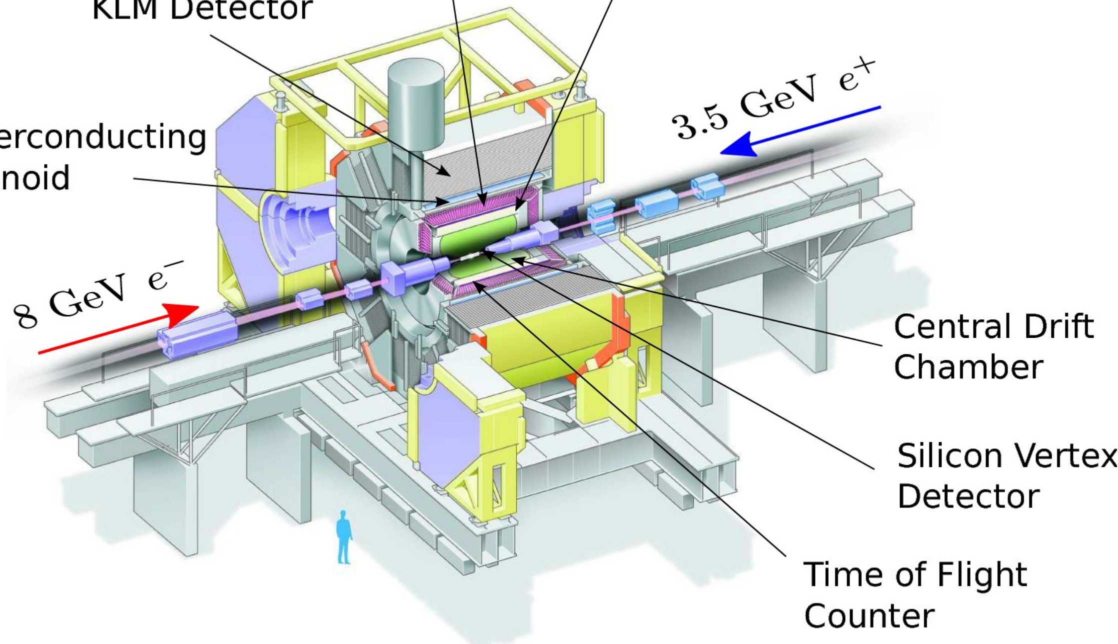
- Boosted B meson pair produced in

$$e^- \longrightarrow\longleftarrow e^+ \Rightarrow \Upsilon(4S) \Rightarrow B\bar{B}$$

- Collected about 772M BB pairs.



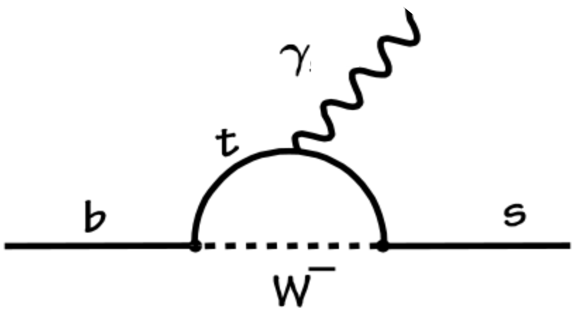


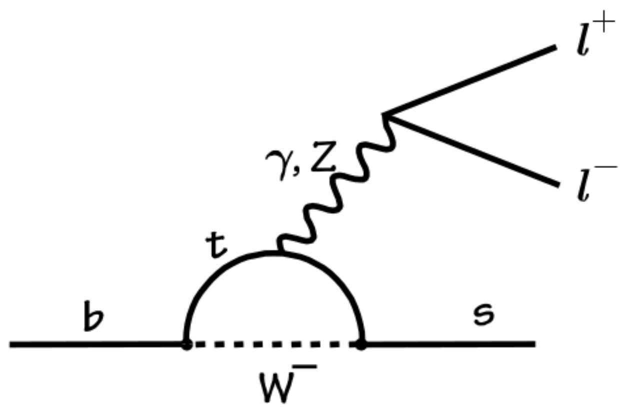


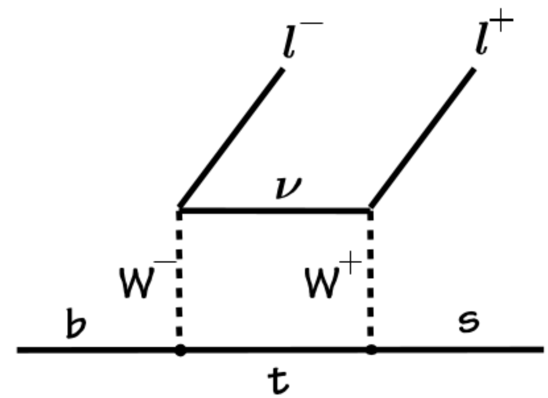
NP in radiative and EW penguins

- FCNC processes: suppressed in the SM; only via loop and box diagrams

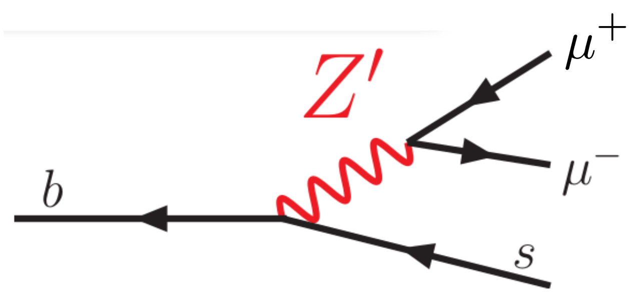
$b \to s\gamma$ $b \to s l^+ l^-$ $b \to s\nu\nu$ $\mathcal{B} \sim 10^{-5}$ and less







- High sensitivity to potential NP contributions in loops or new tree diagrams → enhancing/suppressing decay rates, inducing lepton flavor violation, affecting angular distributions, ...



NP in radiative and EW penguins

- Effective field theory description (NP model independend):

left-hand right-hand

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

$\mathcal{C}_i$ - Wilson coefficients → short distance

$\mathcal{O}_i$ - operator matrix elements → long dist.

- radiative and EW penguins sensitive to

$\mathcal{C}_7^{(,)}, \mathcal{O}_7 \sim (s_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$ **Photon penguin**

$\mathcal{C}_9^{(,)}, \mathcal{O}_9 \sim (\bar{s}_L \gamma_\mu b_L)(\bar{l}\gamma^\mu l)$ **EW vector**

$\mathcal{C}_{10}^{(,)}, \mathcal{O}_{10} \sim (\bar{s}_L \gamma_\mu b_L)(\bar{l}\gamma_5 \gamma^\mu l)$ **EW axial-vector**

- NP can contribute to $\boxed{\mathcal{C}_i \rightarrow \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}}$ $\boxed{\mathcal{C}'_i \rightarrow \mathcal{C}_i'^{SM} + \mathcal{C}_i'^{NP}}$

↳ m_s/m_b suppressed

- different observables sensitive to different combinations of $\mathcal{C}_i$'s

→ pinpoint NP contributions by measuring many observables

→ exploiting the power of global fits to see their "effective" nature

$b \to s\gamma$ Measurement of $B \to K^*\gamma$

- Theoretically the cleanest of exclusive $b \to s\gamma$ decay ($\mathcal{B} \sim 4 \times 10^{-5}$)
- Still large uncertainties arise from the form factors

→ relatively weak constraints on NP from $\mathcal{B}$ measurements (compared to $\mathcal{B}(b \to X_s\gamma)$)

- Ratios of $\mathcal{B}$ give theoretically and experimentally cleaner observables.

In this analysis we measure (beside $\mathcal{B}$):

Isospin asymmetry

$$\Delta_{0+} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)}$$

CP violation

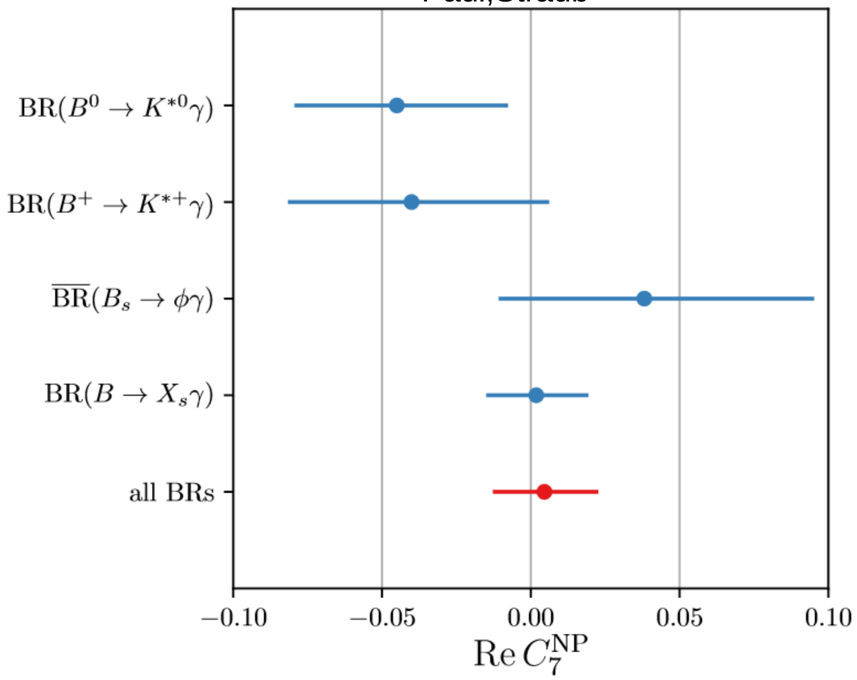
$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{K}^*\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\bar{B} \to \bar{K}^*\gamma) + \Gamma(B \to K^*\gamma)}$$

Difference & average of CPV in isospin

$$\Delta A_{CP} = A_{CP}(B^+ \to K^{*+}\gamma) - A_{CP}(B^0 \to K^{*0}\gamma),$$

$$\bar{A}_{CP} = \frac{A_{CP}(B^+ \to K^{*+}\gamma) + A_{CP}(B^0 \to K^{*0}\gamma)}{2},$$

Paul,Straub arXiv:1608.02556



$b \to s\gamma$ Measurement of $B \to K^*\gamma$

- Reconstructed modes

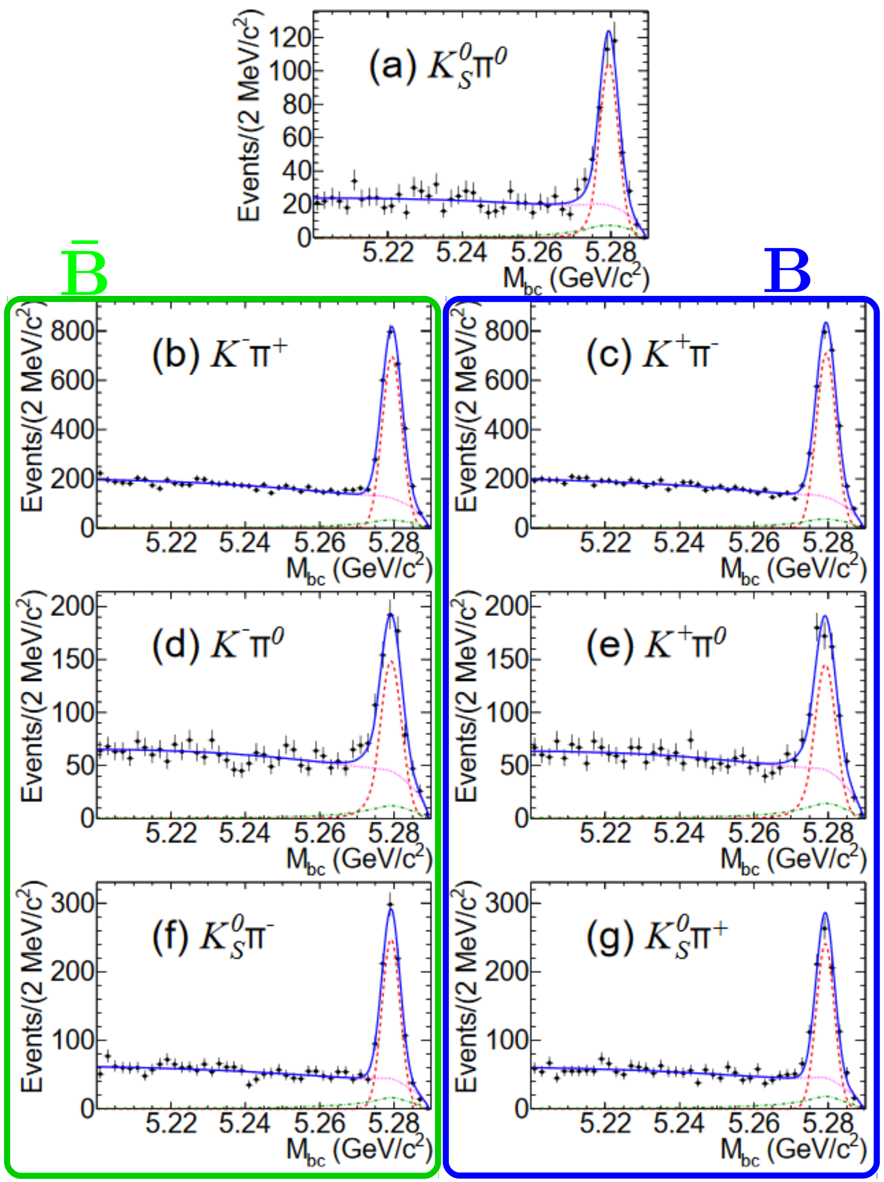
$$K^* \to K_S^0\pi^0,\ K^+\pi^-,\ K^+\pi^0,\ K_S^0\pi^+$$

- Main backgrounds

$ee \to q\bar{q}$ → NeuroBayes using event shape vars.

$B\bar{B}$ → π^0, η veto ($m_{\gamma\gamma}$)

- Simultaneous fit to m_{bc} distribution in 7 categories to extract B and asymmetries



Fit results

$$\mathcal{B}(B^0 \to K^{*0}\gamma) = (3.96 \pm 0.07 \pm 0.14) \times 10^{-5},$$
$$\mathcal{B}(B^+ \to K^{*+}\gamma) = (3.76 \pm 0.10 \pm 0.12) \times 10^{-5},$$
$$A_{CP}(B^0 \to K^{*0}\gamma) = (-1.3 \pm 1.7 \pm 0.4)\%,$$
$$A_{CP}(B^+ \to K^{*+}\gamma) = (+1.1 \pm 2.3 \pm 0.3)\%,$$
$$A_{CP}(B \to K^{*}\gamma) = (-0.4 \pm 1.4 \pm 0.3)\%,$$
$$\Delta_{0+} = (+6.2 \pm 1.5 \pm 0.6 \pm 1.2)\%,$$
$$\Delta A_{CP} = (+2.4 \pm 2.8 \pm 0.5)\%,$$
$$\bar{A}_{CP} = (-0.1 \pm 1.4 \pm 0.3)\%,$$

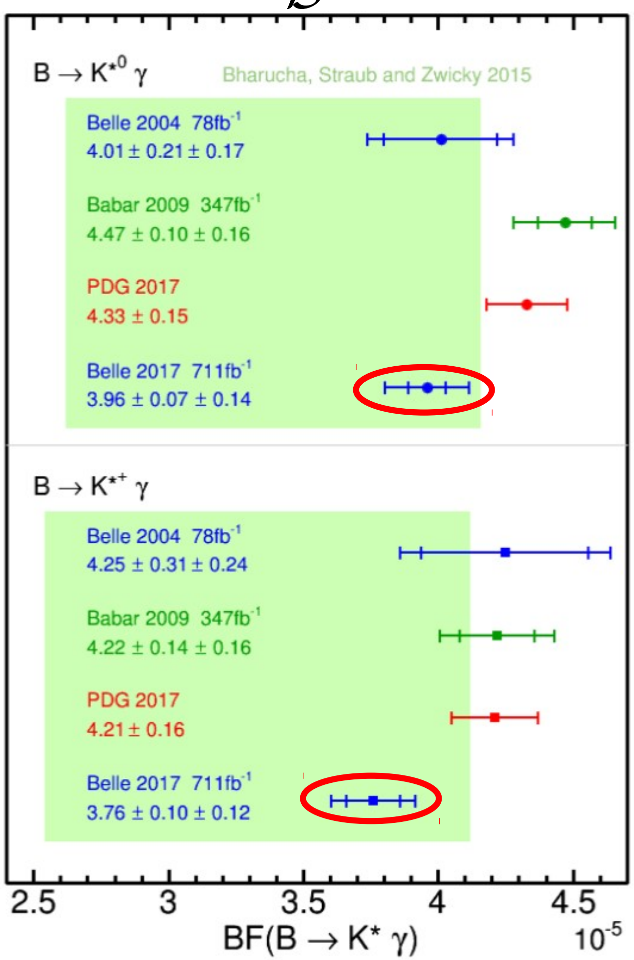
$b \to s\gamma$ Measurement of $\mathrm{B} \to \mathrm{K}^*\gamma$

PRL 119, 191802 (2017)

arXiv:1707.00394

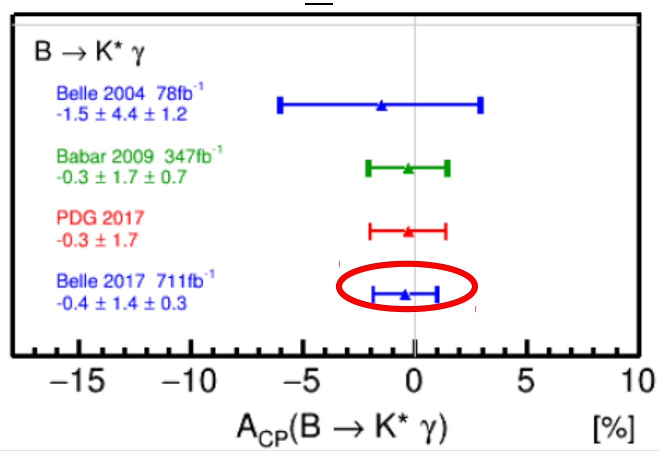
- comparison with previous measurements

$\mathcal{B}$



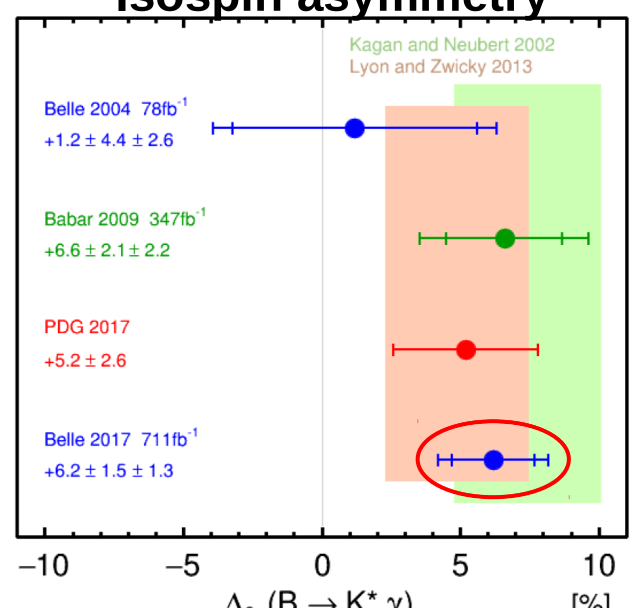
- consistent w/ previous measurements
- uncertainty systematics dominated

A_CP



- Most precise to date
- Consistent with SM
- Strong constraints on $\mathrm{Im}(\mathcal{C}_7)$

Isospin asymmetry



First evidence of isospin violation in $b \to s$

3.1σ

- great prospects for improving asymmetries precision at Belle II

$b \to s l^+ l^-$ Measurement of $\mathbf{B \to K^* l^+ l^-}$

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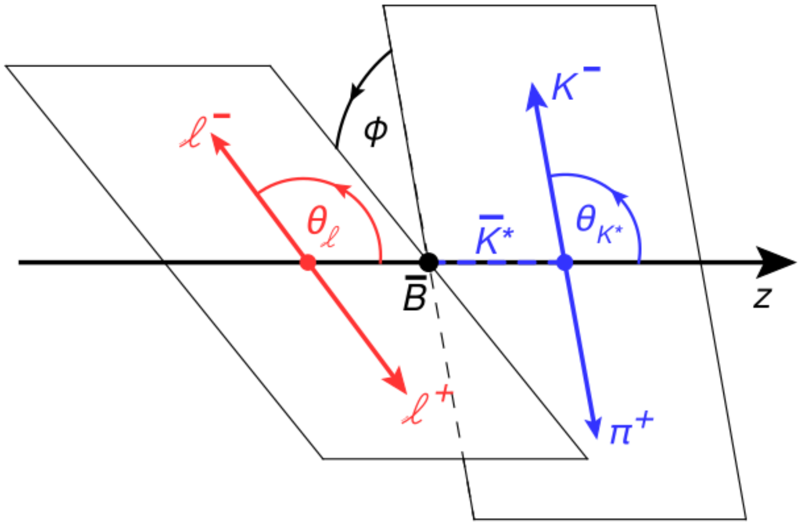
- $\mathcal{B}$ two orders of mag. lower than $b \to s\gamma$



- But additional degrees of freedom:
  - → Final state fully specified by 4 variables: $q^2 = m_{ll}^2,\ \theta_l,\ \theta_K$ and ϕ

- Measure the differential decay rate:

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\ \mathrm{d}\cos\theta_K\ \mathrm{d}\phi\ \mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

to determine the observables $F_L(q^2),\ S_i(q^2)$

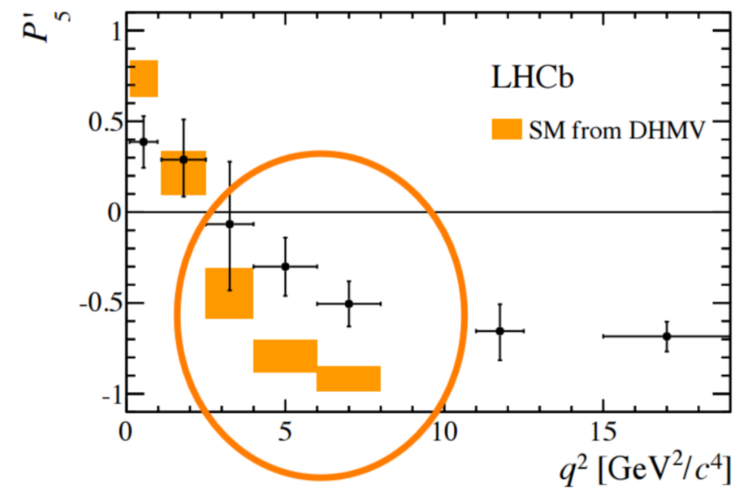
S. Descotes-Genon et al. JHEP 05 (2013) 137

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

Optimized observables, largely free of form factor uncertainties

$b \to s l^+ l^-$ Measurement of $B \to K^* l^+ l^-$

- LHCb finds 3.4 deviation from the SM value in P_5',



[LHCb, JHEP 02 (2016) 104]

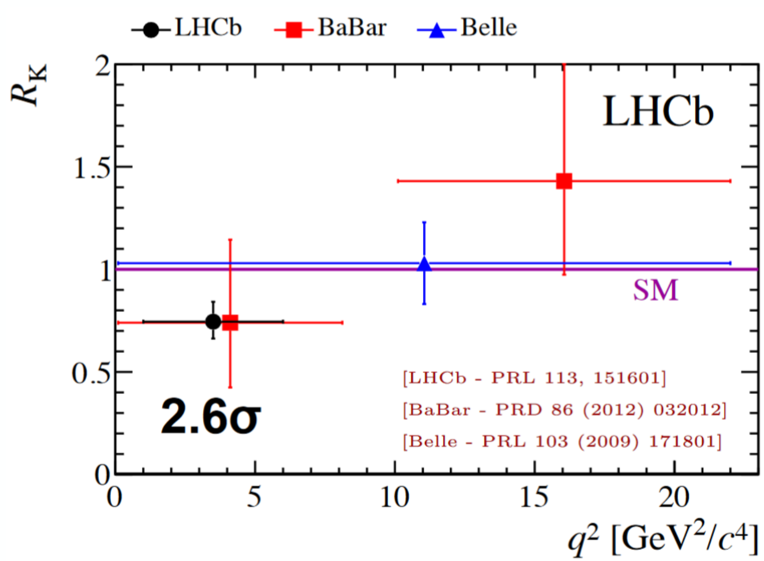
→ NP in $\mathcal{C}_9$?!

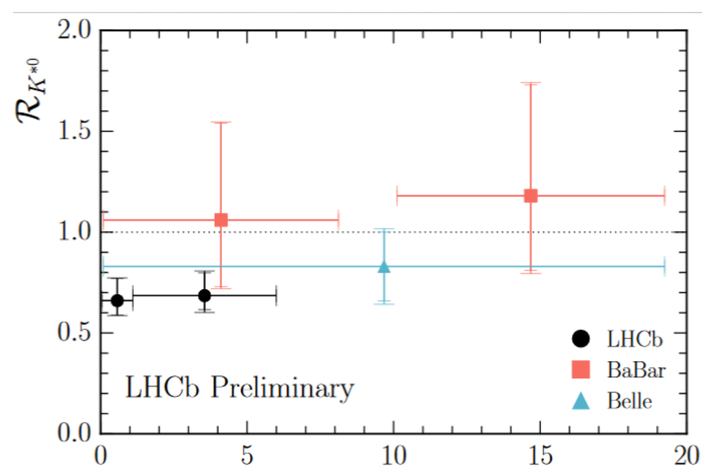
→ or contribution from charm loops?

- Lepton flavor universality (LFU) observables theoretically much cleaner

→ Notable deviations observed in

$$R_K = \frac{\mathrm{Br}(B \to K \mu^+ \mu^-)}{\mathrm{Br}(B \to K e^+ e^-)} \qquad R_{K^*} = \frac{\mathrm{Br}(B \to K^* \mu^+ \mu^-)}{\mathrm{Br}(B \to K^* e^+ e^-)}$$





- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

$b \to s l^+ l^-$ Measurement of $B \to K^* l^+ l^-$

- **We perform a test of LFU in angular observables, by measuring:**

$$P'^{\mu}_{4,5},\ P'^{e}_{4,5} \text{ and } Q_{4,5} = P'^{e}_{4,5} - P'^{\mu}_{4,5}$$

- reconstructed modes:

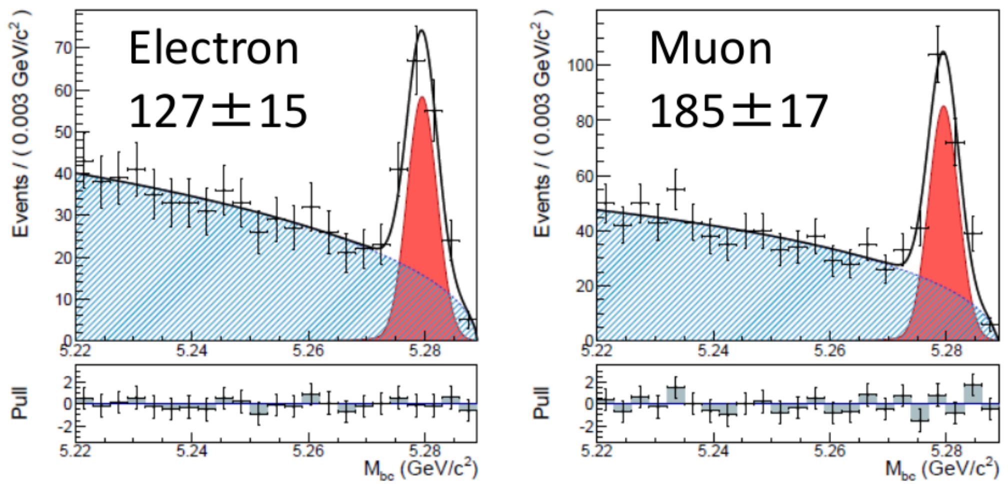
$$B^+ \to K^{*+} l^+ l^-,\ K_S^{*+}\pi^+, K^+\pi^0$$

$$B^0 \to K^{*0} l^+ l^-,\ K^{*0+}\pi^-$$

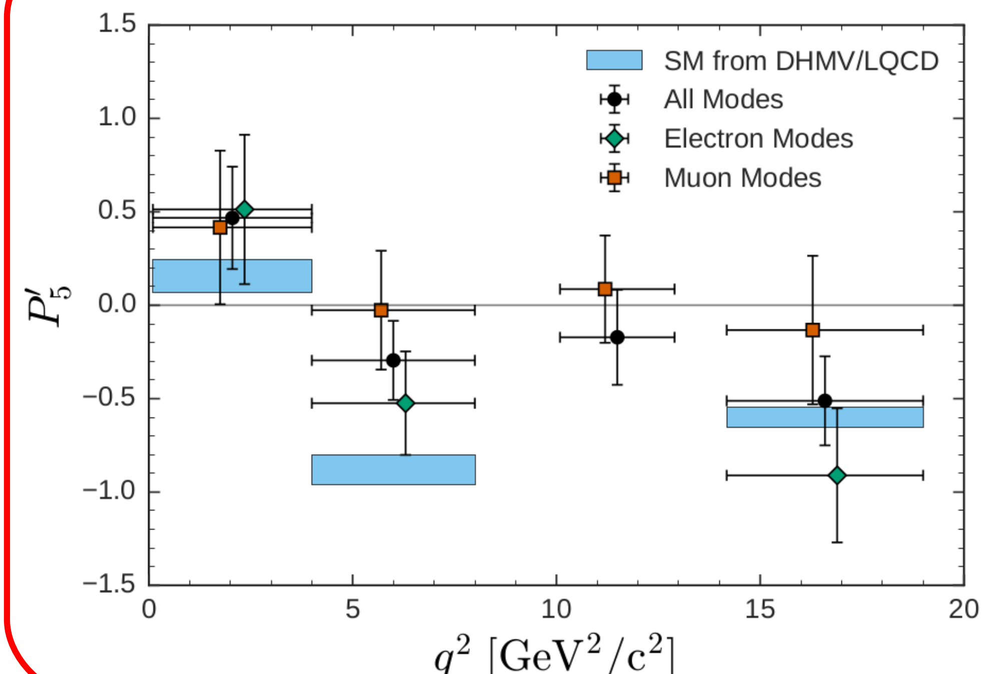
- Fit m_{bc} distribution for the signal yield

- Due to small statistics the data folding technique is applied

(exploit the symmetries of trig.functions, to cancel terms of not primary intereset in diff. rate)

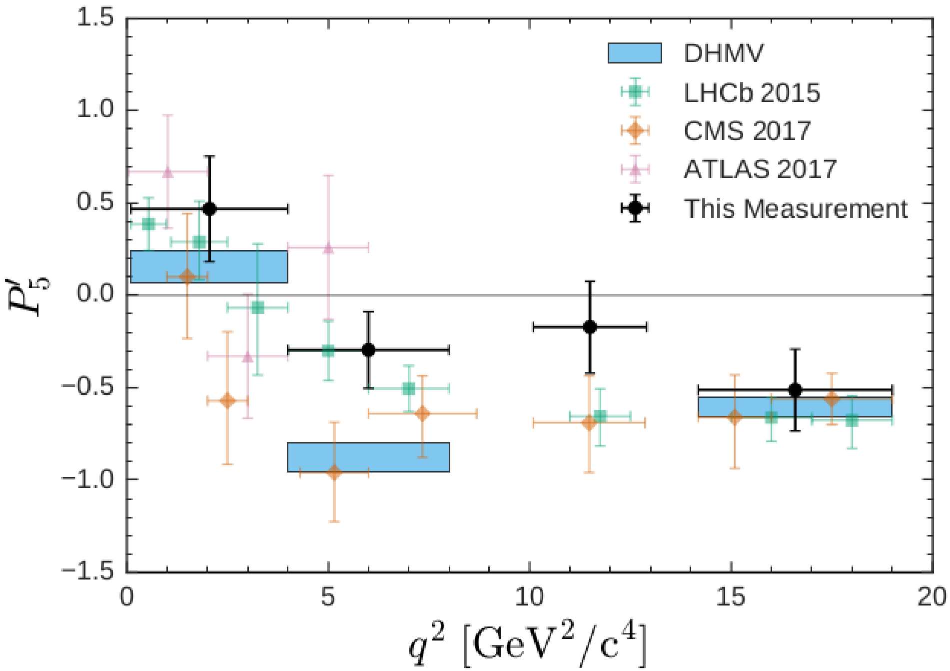


Fit result

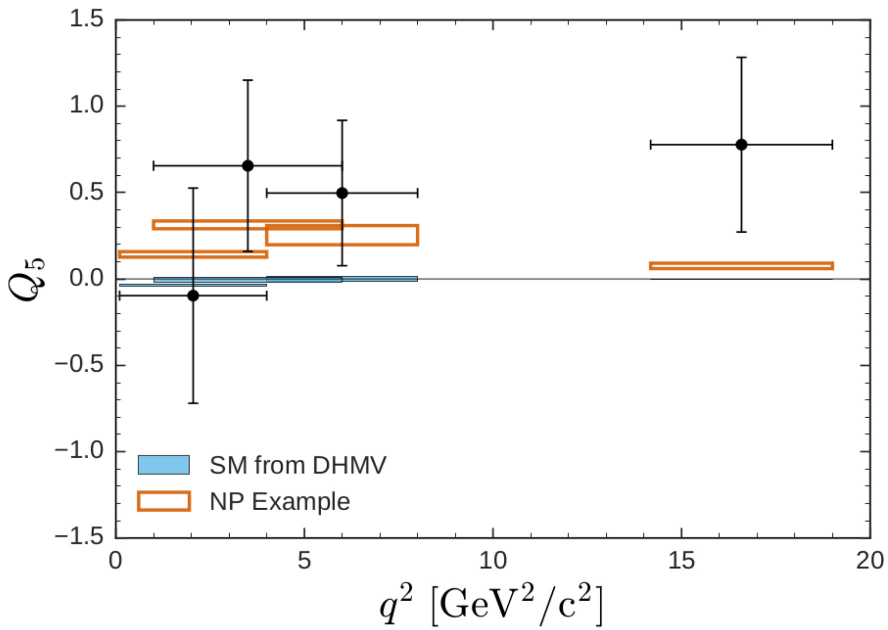


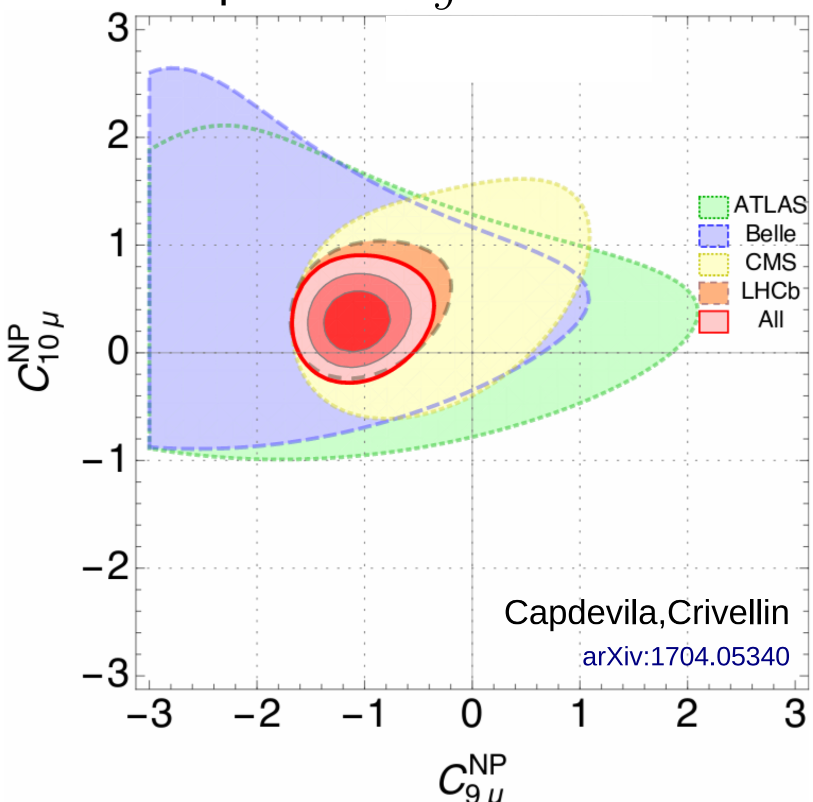
$b \to sl^+l^-$ Measurement of $\mathrm{B} \to \mathrm{K}^*\mathrm{l}^+\mathrm{l}^-$

Phys. Rev. Lett. 118, 111801



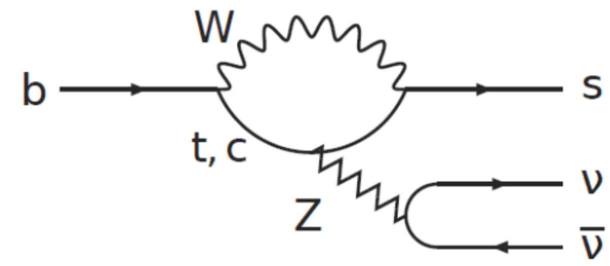
- Results compatible with the SM
- In the q^2 region of P_5' anomaly 2.5σ deviation from the SM is observed
  (driven by the muon final state, like in LHCb)
- Statisticaly limited → Belle II (esp. Q_5)
- Global fits point to $\mathcal{C}_9^{NP} \sim -1$



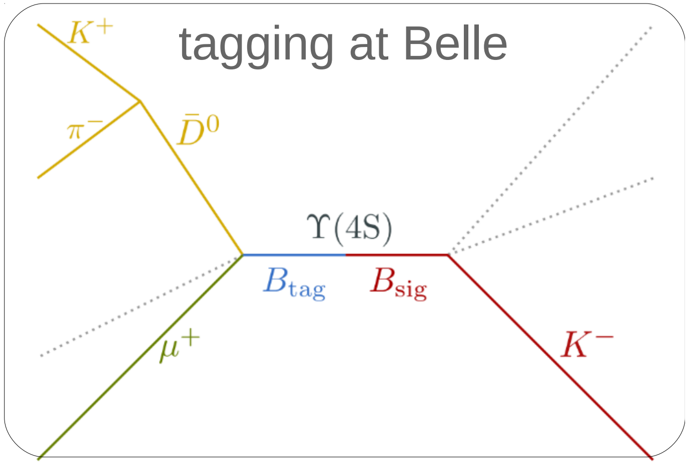


$b \to s\nu\nu$ Search for B $\to$ h$^{(*)}\nu\nu$

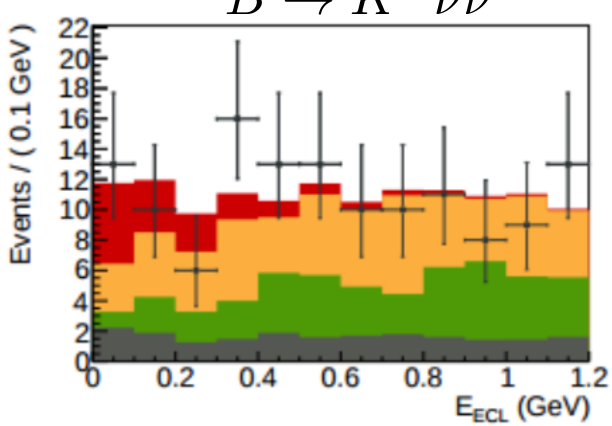
- via Z^0 penguin and WW box diagram
- sensitive to NP contributions in $\mathcal{C}_9, \mathcal{C}_{10}$
- no contribution from charm loops → theoretically very clean



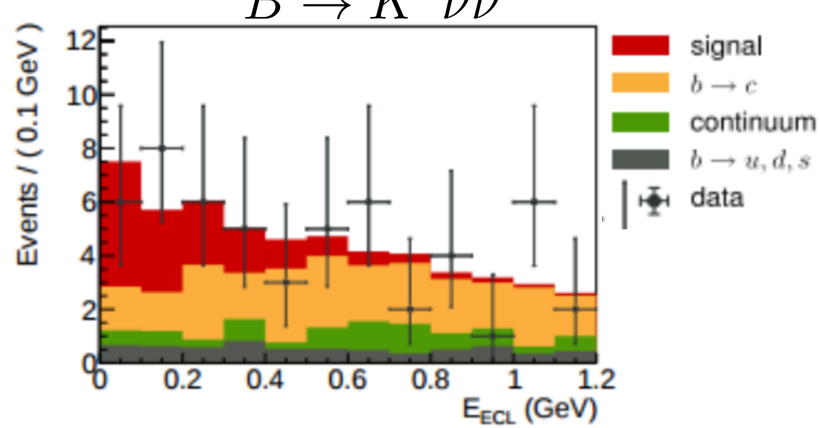
- Event reconstruction:
  - → $h^{(*)} = K^+, K^0_S, K^{*+}, K^{*0}, \pi^+, \pi^0, \rho^+, \rho^0$
  - → **semi-leptonic tagging**
    - → tag B reconstructed in $B \to D^{(*)} l \nu$ using NeuroBayes
    - → remaining particles used for $h^{(*)}$
- Signal extracted from extra energy in ECL



$B \to K^+\nu\nu$



$B \to K^*\nu\nu$



$b \to s\nu\nu$ Search for B $\to$ h$^{(*)}\nu\nu$

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Phys. Rev. D 96, 091101,

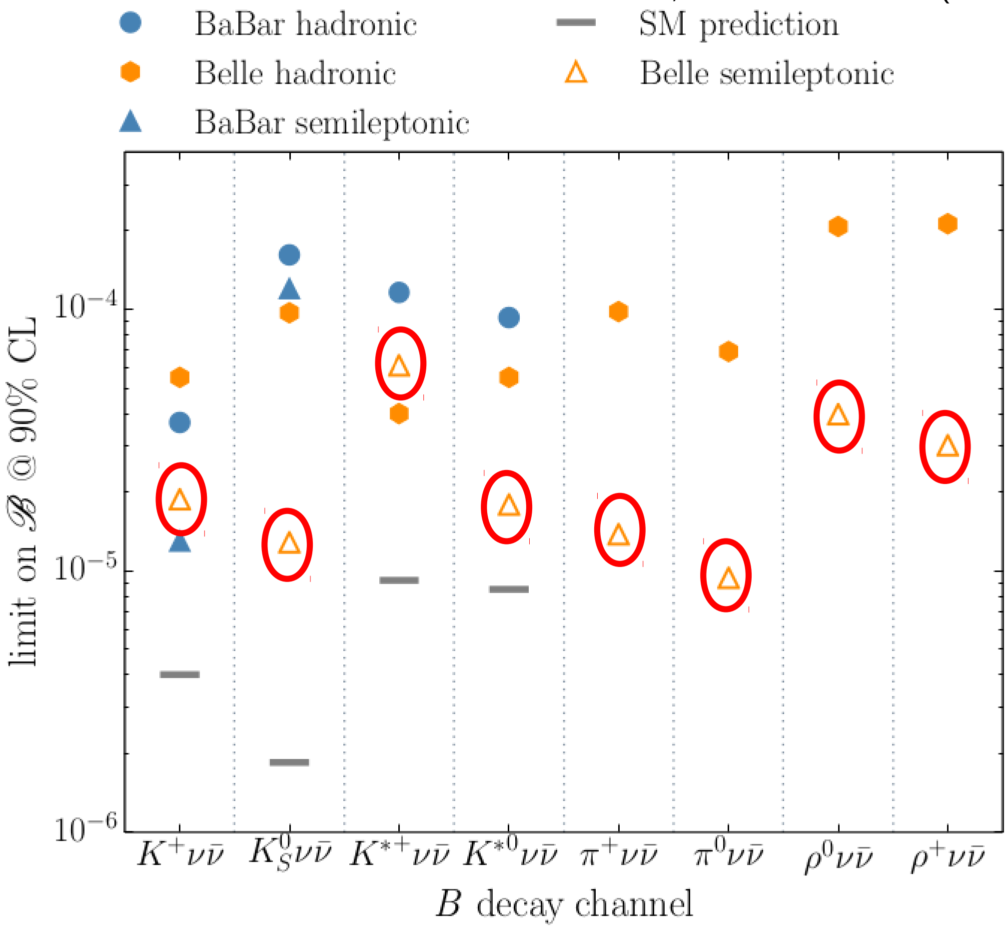
arXiv:1702.03224

- Fit results

Channel	Observed signal yield	Significance
$K^+\nu\bar{\nu}$	$17.7 \pm 9.1 \pm 3.4$	$1.9\,\sigma$
$K^0_S\,\nu\bar{\nu}$	$0.6 \pm 4.2 \pm 1.4$	$0.0\,\sigma$
$K^{*+}\nu\bar{\nu}$	$16.2 \pm 7.4 \pm 1.8$	$2.3\,\sigma$
$K^{*0}\nu\bar{\nu}$	$-2.0 \pm 3.6 \pm 1.8$	$0.0\,\sigma$
$\pi^+\nu\bar{\nu}$	$5.6 \pm 15.1 \pm 5.9$	$0.0\,\sigma$
$\pi^0\nu\bar{\nu}$	$0.2 \pm 5.6 \pm 1.6$	$0.0\,\sigma$
$\rho^+\nu\bar{\nu}$	$6.2 \pm 12.3 \pm 2.4$	$0.3\,\sigma$
$\rho^0\nu\bar{\nu}$	$11.9 \pm 9.0 \pm 3.6$	$1.2\,\sigma$

Worlds most stringent upper limits in several modes

A. Buras, et al. JHEP 02 184 (2015)



- upper limit on $\mathcal{B}(B \to K^{*0}\nu\nu)$ only factor 2 above the SM expected!

- Measurable at Belle II !

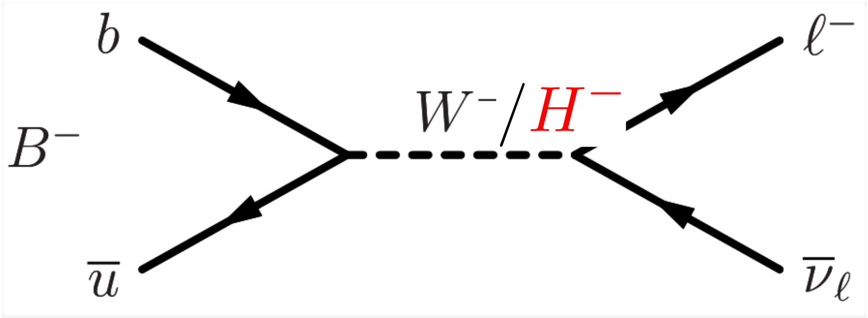
$B \to \mu\nu$ untagged measurement

- Due to helicity suppression very rare

$$\mathcal{B}(B \to \tau\nu) \gg \mathcal{B}(B \to \mu\nu) \gg \mathcal{B}(B \to e\nu)$$

+ Good SM prediction $\to$ NP sensitive

$$\mathcal{B}^{\mathrm{SM}}(B \to \mu\nu) = (3.8 \pm 0.31) \times 10^{-7}$$

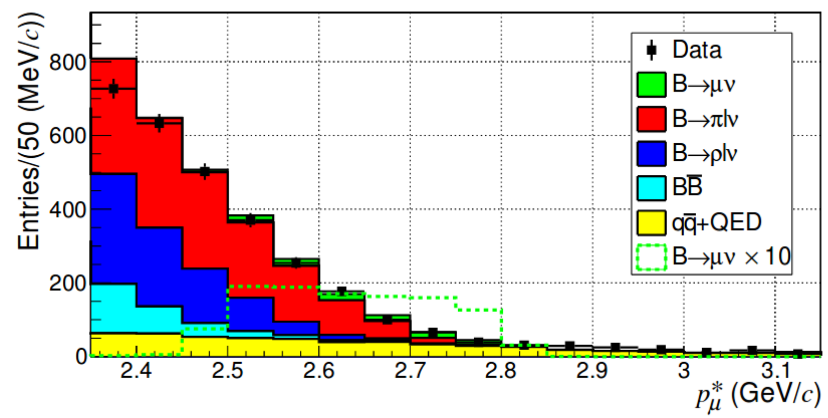


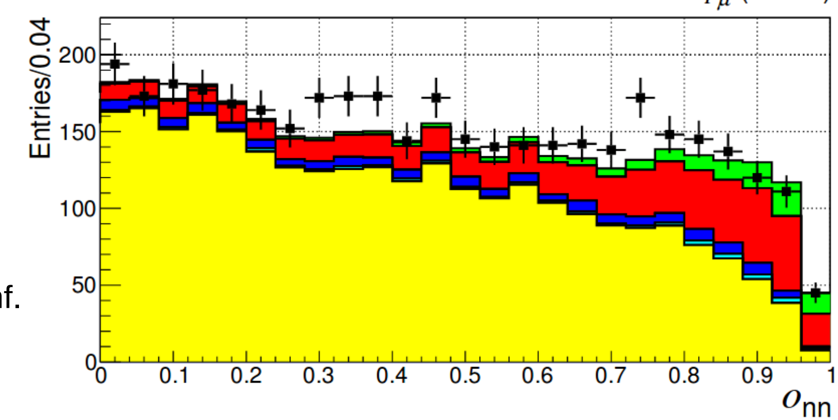
- most stringent limit from BaBar: $\mathcal{B} < 1.0 \times 10^{-6}$

Phys. Rev. D79, 091101 (2009)

- using **un-tagged** approach: all particles in event exept signal μ belong to the 2nd B.

- Neural network + p_μ^* to discriminate sig./bkg.





- Fit result

$$\mathcal{B}(B \to \mu\nu) = (6.46 \pm 2.22 \pm 1.6) \times 10^{-7}$$

2.4 σ excess above bkg level

$\mathcal{B} \in [2.9, 10.7] \times 10^{-7}$ at 90% conf.

arXiv:1712.04123, submitted to PRL

Summary and prospects

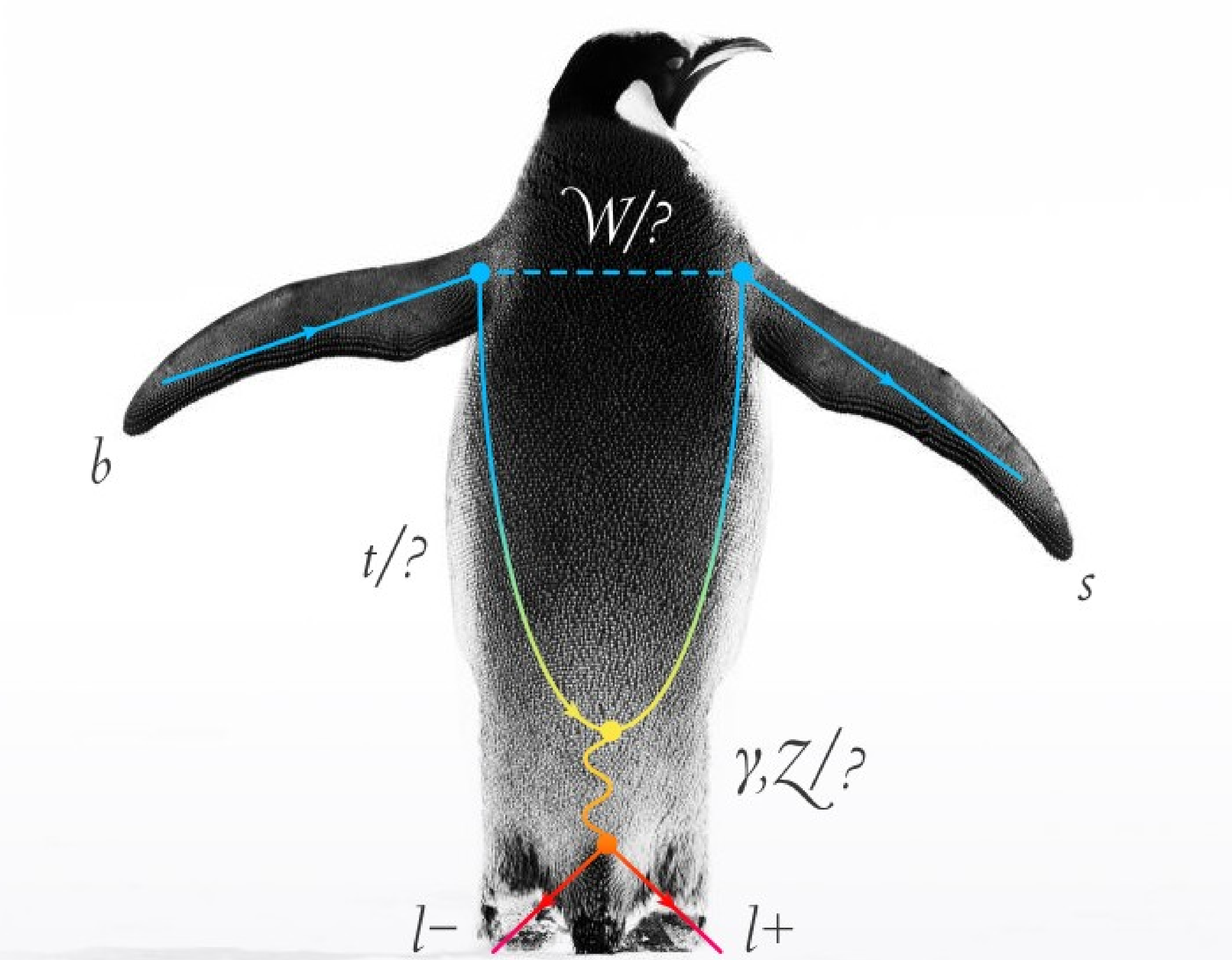
- We presented results of some of the recent measurements of B decays sensitive to NP

- Measurements presented are consistent with the SM, as well as with the previous results. The largest deviation from the SM is at the level of 2.6 σ, in $q^2 = 4-8\mathrm{GeV}$ bin of P_5' for muon channel (consistent with the LHCb anomaly)

- The Belle physics program is very much alive and new results on this topics are expected for summer conferences ($R(K^{(*)})$, $B \to K^{(*)}ll'$, $B \to X_s\gamma$, $R(D^{(*)})$)

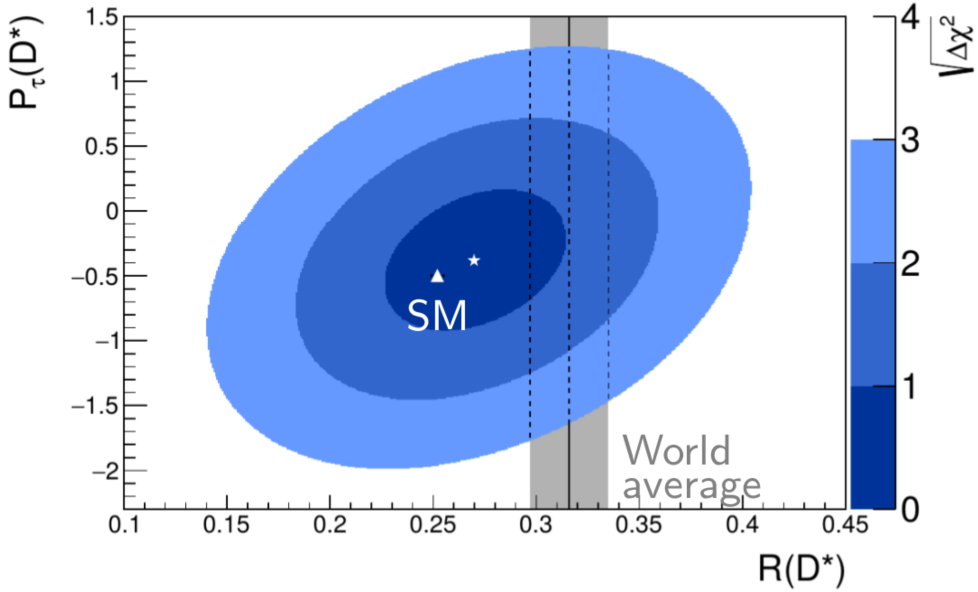
- On a longer term → expect great contributions from the Belle II experiment

→ **First collisions in the coming weeks!**



Quanta Magazine. Source photo: Christopher Michel

$R(D^*)$ and τ polarization in $B \to D^{(*)}\tau\nu$



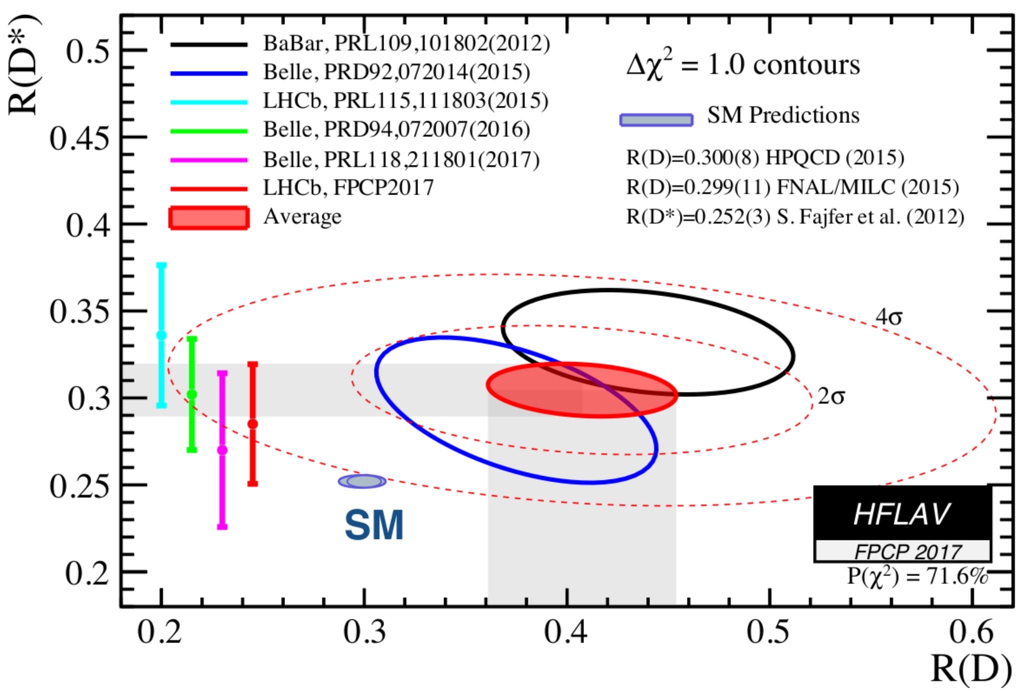
Phys. Rev. Lett. 118, 211801

arXiv:1612.00529

$$R(D^*) = 0.270 \pm 0.035^{+0.028}_{-0.025}$$

$$P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}$$

- consistent with the SM
- consistent with previous measurements



- combined with measurements from BaBar and LHCb $\sim 4\sigma$ discrepancy from the SM prdictions

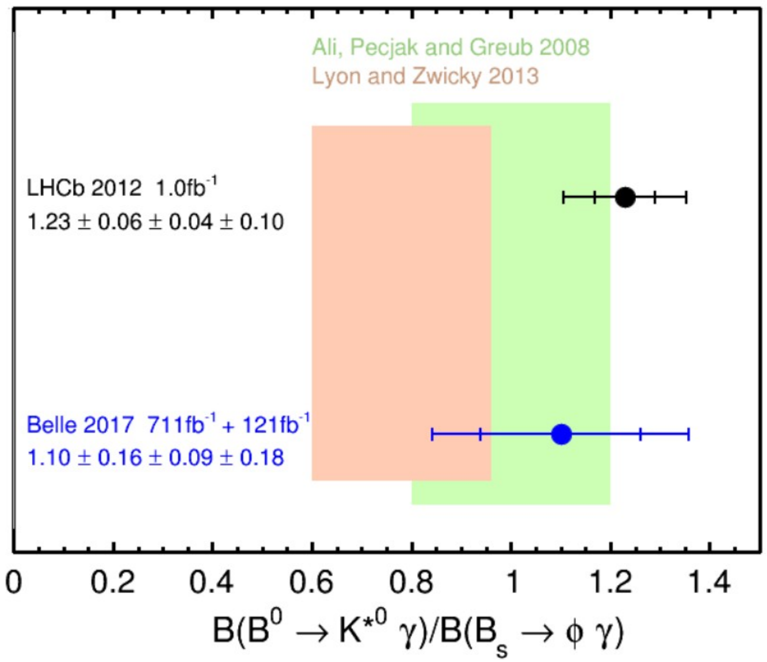
$B \to K^* \gamma$

Using previous Belle measurement of

$\mathcal{B}(B_S^0 \to \phi\gamma)$ PRD 91 01101 (2015)

we obtain the ratio

$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.10 \pm 0.16 \pm 0.09 \pm 0.18$$



Systematic uncertainties

$\mathcal{B}(B \to K^*\gamma)$

γ detection eff. – 2.0%

$\#$ of $B\bar{B}$ – 1.4%

π^0 detection eff. – 1.3%

peaking bkg. yield – 1.1 – 1.6%

Δ_{0+}

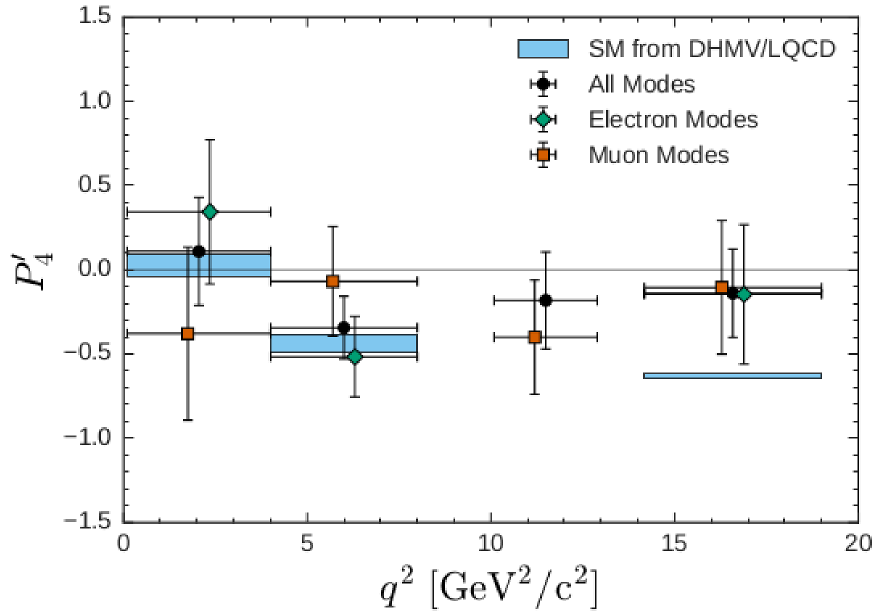
f_{+-}/f_{00} – 1.6%

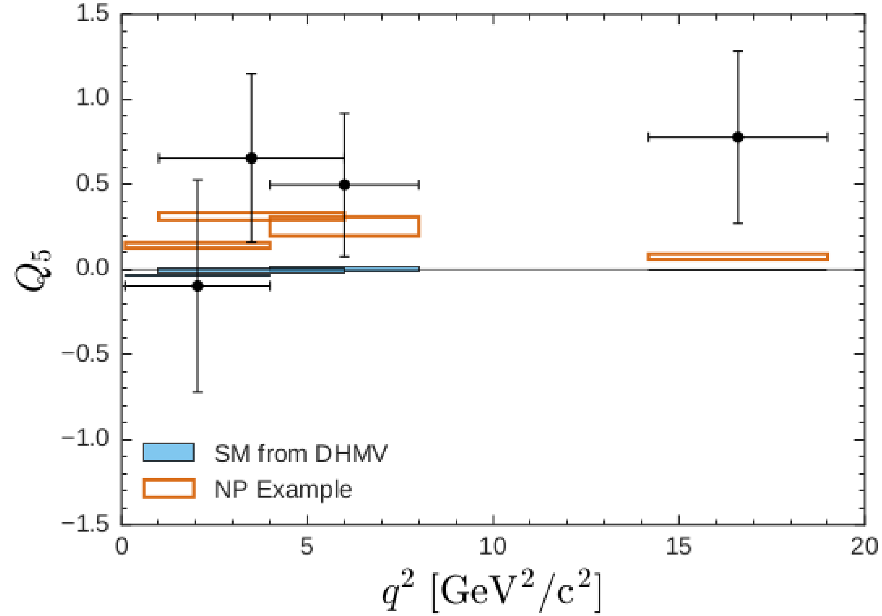
PID – 0.38%

A_{CP}

Charged hadron det. asymmetry

$\mathbf{B \rightarrow K^{*} l^{+} l^{-}}$





q^2 in GeV$^2/c^2$	P'_4	$P^{e\prime}_4$	$P^{\mu\prime}_4$	P'_5	$P^{e\prime}_5$	$P^{\mu\prime}_5$
[1.00, 6.00]	$-0.45^{+0.23}_{-0.22} \pm 0.09$	$-0.72^{+0.40}_{-0.39} \pm 0.06$	$-0.22^{+0.35}_{-0.34} \pm 0.15$	$0.23^{+0.21}_{-0.22} \pm 0.07$	$-0.22^{+0.39}_{-0.41} \pm 0.03$	$0.43^{+0.26}_{-0.28} \pm 0.10$
[0.10, 4.00]	$0.11^{+0.32}_{-0.31} \pm 0.05$	$0.34^{+0.41}_{-0.45} \pm 0.11$	$-0.38^{+0.50}_{-0.48} \pm 0.12$	$0.47^{+0.27}_{-0.28} \pm 0.05$	$0.51^{+0.39}_{-0.46} \pm 0.09$	$0.42^{+0.39}_{-0.39} \pm 0.14$
[4.00, 8.00]	$-0.34^{+0.18}_{-0.17} \pm 0.05$	$-0.52^{+0.24}_{-0.22} \pm 0.03$	$-0.07^{+0.32}_{-0.31} \pm 0.07$	$-0.30^{+0.19}_{-0.19} \pm 0.09$	$-0.52^{+0.28}_{-0.26} \pm 0.03$	$-0.03^{+0.31}_{-0.30} \pm 0.09$
[10.09, 12.90]	$-0.18^{+0.28}_{-0.27} \pm 0.06$	-	$-0.40^{+0.33}_{-0.29} \pm 0.09$	$-0.17^{+0.25}_{-0.25} \pm 0.01$	-	$0.09^{+0.29}_{-0.29} \pm 0.02$
[14.18, 19.00]	$-0.14^{+0.26}_{-0.26} \pm 0.05$	$-0.15^{+0.41}_{-0.40} \pm 0.04$	$-0.10^{+0.39}_{-0.39} \pm 0.07$	$-0.51^{+0.24}_{-0.22} \pm 0.01$	$-0.91^{+0.36}_{-0.30} \pm 0.03$	$-0.13^{+0.39}_{-0.35} \pm 0.06$