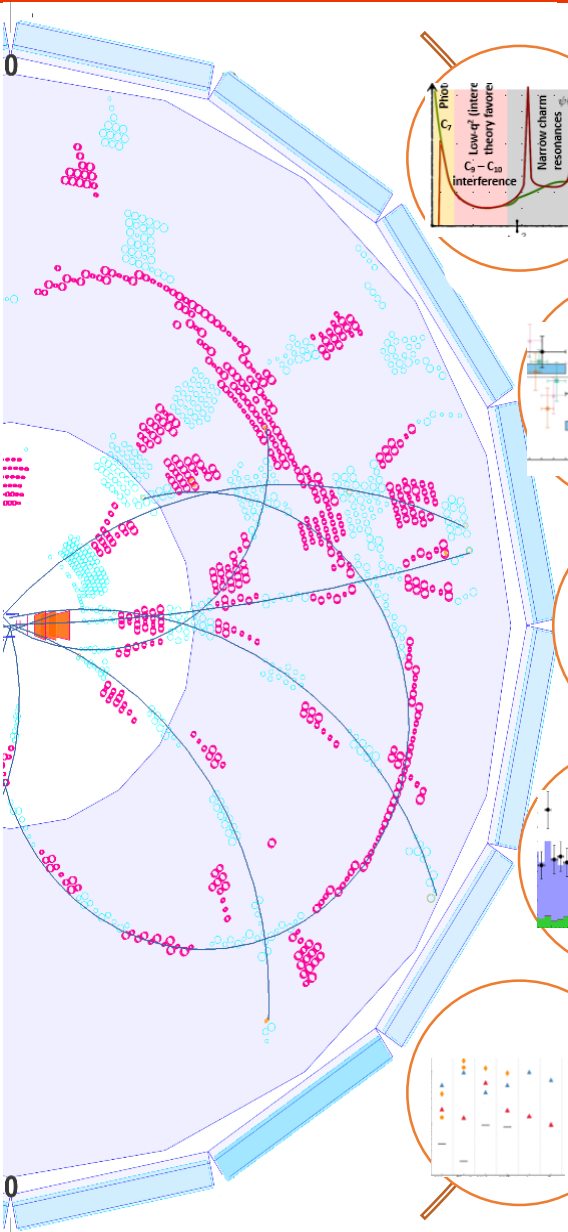
# Meet the Anomalies: Experimental Perspective on $b \to s \ell \ell$

**Saurabh Sandilya**

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

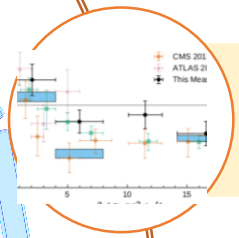
**Belle II Academy**
**March 22, 2021**

# Outline

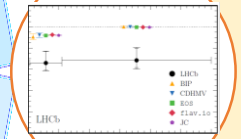




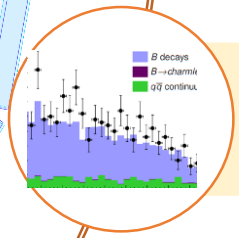

## Introduction



## Angular Analyses




## LFU ratios : R(K*) and R(K)




## LFV decays

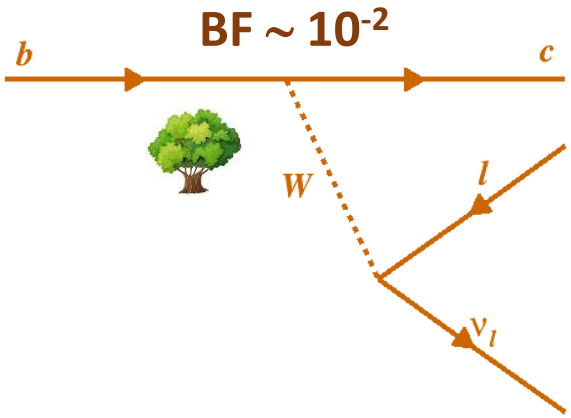


## Recent Belle II result : Search for $B \rightarrow K^{+}\nu\nu$

# Prologue : Anomalies in B-decays

- In the recent years, several discrepancies from the SM have been reported in the B-decays.

I **B-decays with $b \to c\ell\nu_\ell$ transitions:** Dominant decays of *b*-quarks are tree level transitions $b \to cW^{-*}$.

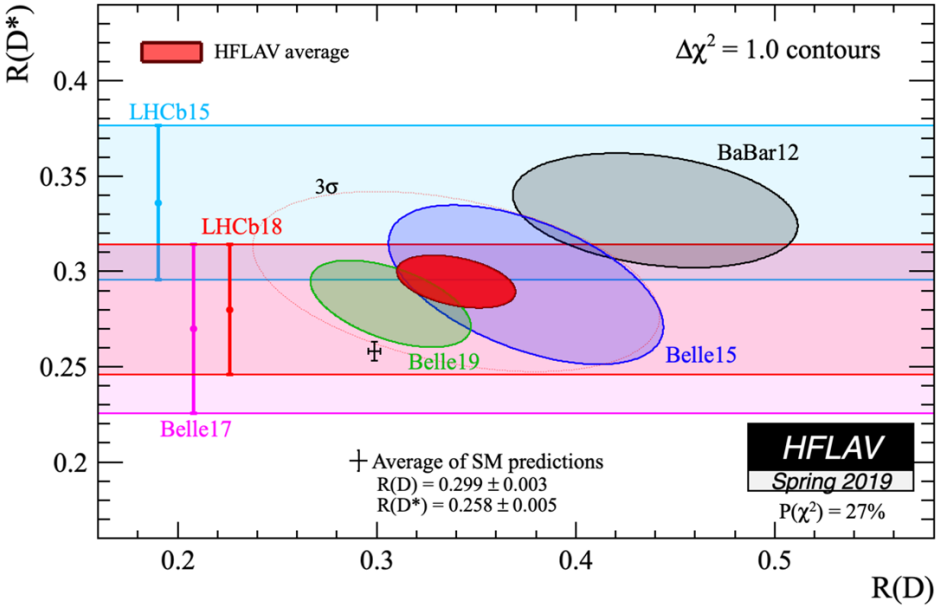



**Decays : $B \to D\ell\nu_\ell$ $B \to D^{(*)}\ell\nu_\ell$ $B_c \to J/\psi\ell\nu_\ell$**

**Variables :** R(D), R(D*), R(J/ψ)…

$$\mathcal{R}(D^{(*)}) = \frac{BF[\bar{B} \to D^{(*)}\tau^-\nu_\tau]}{BF[\bar{B} \to D^{(*)}\ell^-\nu_\ell]}$$

- $\mathcal{R}(D)$ - $\mathcal{R}(D^*)$ experimental world average tension with SM prediction decreases from 3.8 σ to 3.1σ

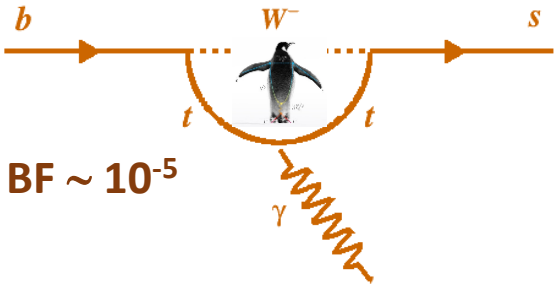



**Will be discussed on March 24th**

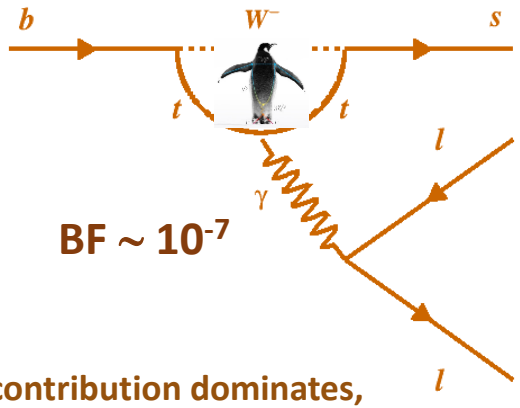
# Prologue : Anomalies in B-decays

- In the recent years, several discrepancies from the SM have been reported in the B-decays.

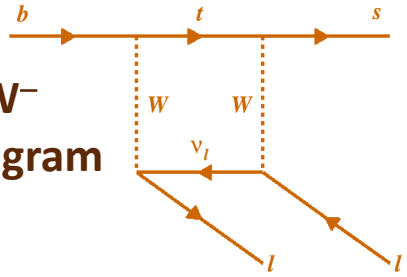
**III** **B-decays with b→sℓℓ transitions:** FCNCs and are forbidden in the SM at the tree level and can only occur at greatly suppressed rates through higher-order processes (penguin loops/box).




BF ~ $10^{-5}$




BF ~ $10^{-7}$




$W^+W^-$ Box Diagram

**a virtual t quark contribution dominates, with secondary contributions from virtual c and u quarks.**

# Prologue : Anomalies in B-decays

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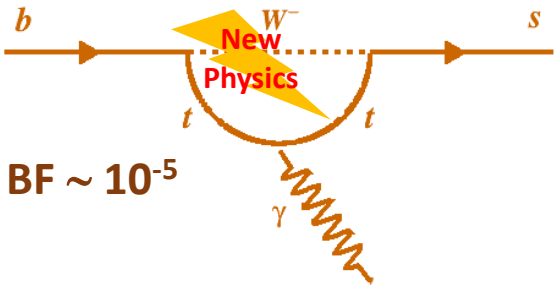
**B-decays with b→sℓℓ transitions:** FCNCs and are forbidden in the SM at the tree level and can only occur at greatly suppressed rates through higher-order processes (penguin loops/box).

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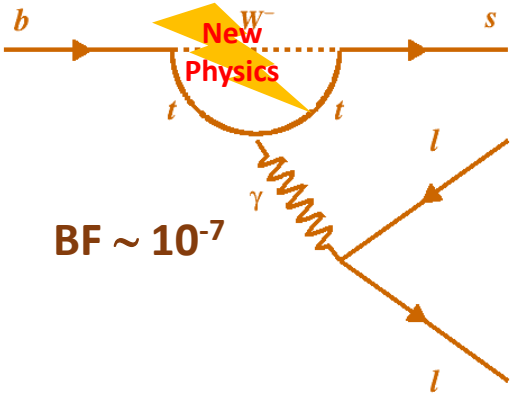


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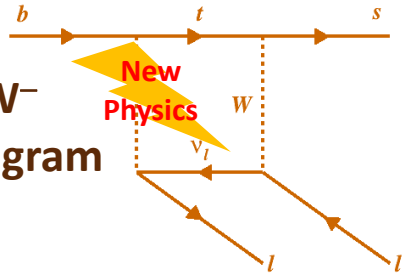



$W^+W^-$ Box Diagram

- **Sensitive to NP:** Interference from the 'possible' contribution from the BSM.
- **Decays of Interest:** $B \to K^{(*)} \ell\ell$, $B \to K^{(*)} \nu\nu$ , $B_{(s)} \to \ell\ell$
- **Variables:** Differential decay rates, LFU ratios (R(K), R(K*)), Angular observables $P_i$ , $Q_i$ …

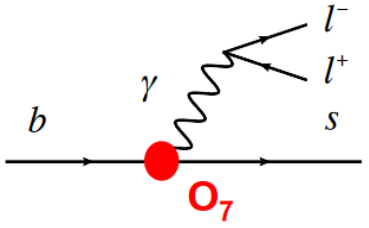
- Rich laboratory of NP studies on its own.

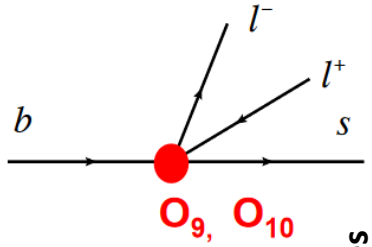
- The relevant effective Hamiltonian:

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C'_i O'_i) + \text{h.c.}$$

- The Operators which are most sensitive to the NP:

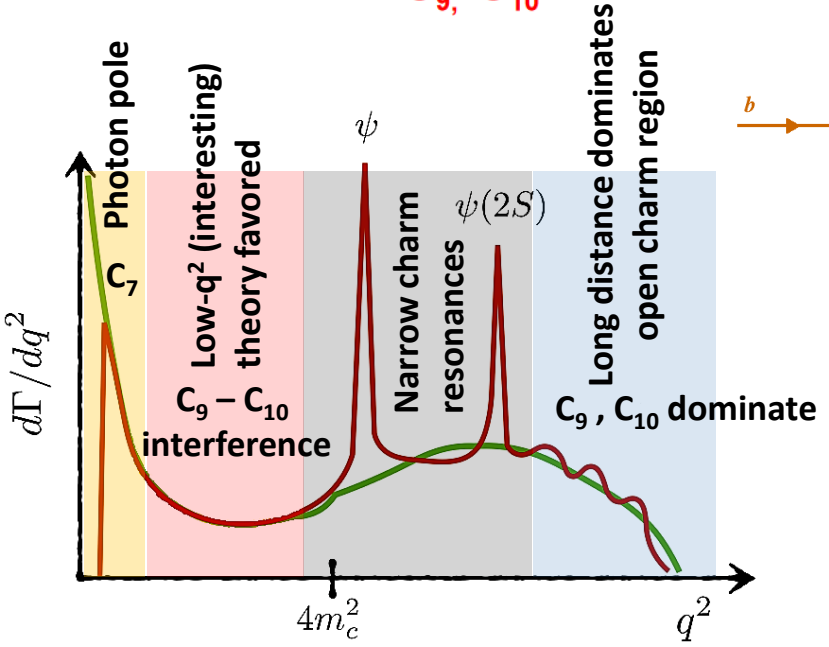
Dipole

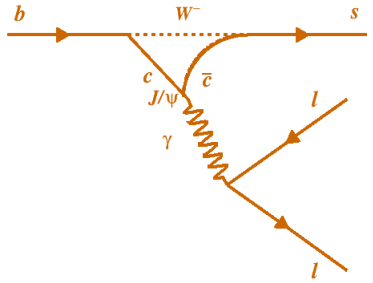


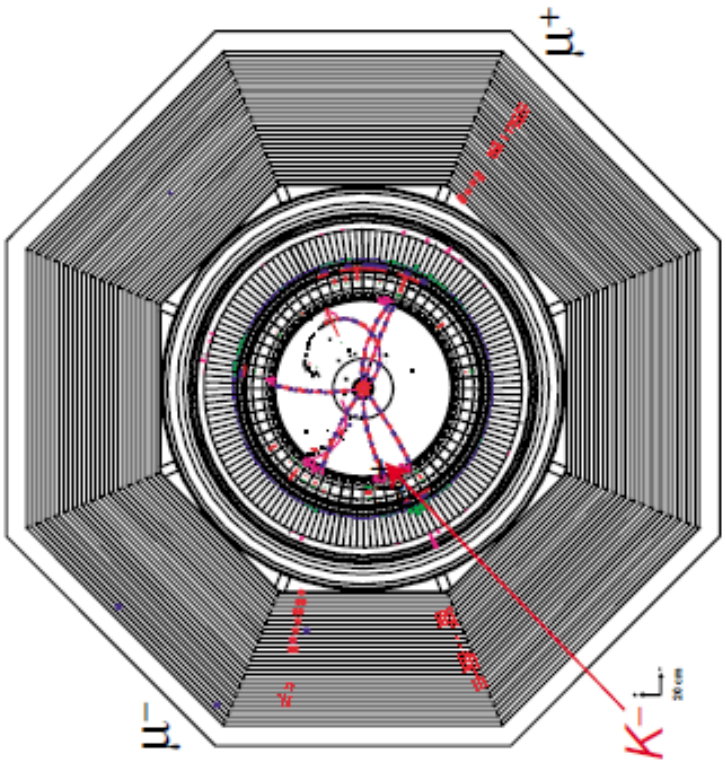

Four fermion

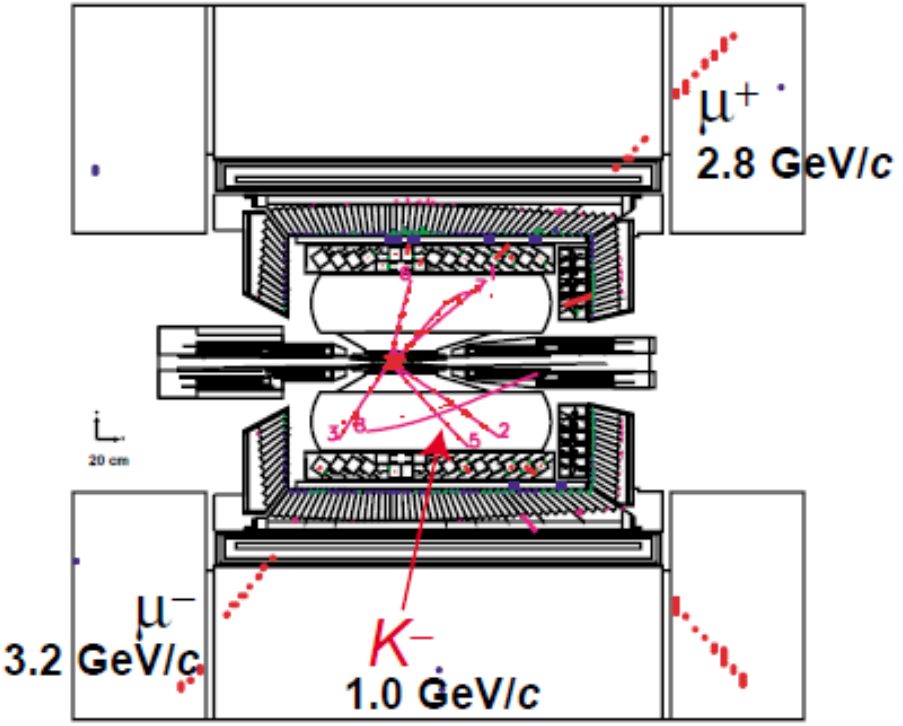
- Differential decay rate of $B \to K^{*0} \ell^+ \ell^-$ wrt to $q^2$ (dilepton invariant mass square)



## $B^+ \to K^+\mu^+\mu^-$ Event




Lepton Photon 01, 2001 July 23, Roma

# Differential BF for $B \to K^{(*)}\ell^+\ell^-$

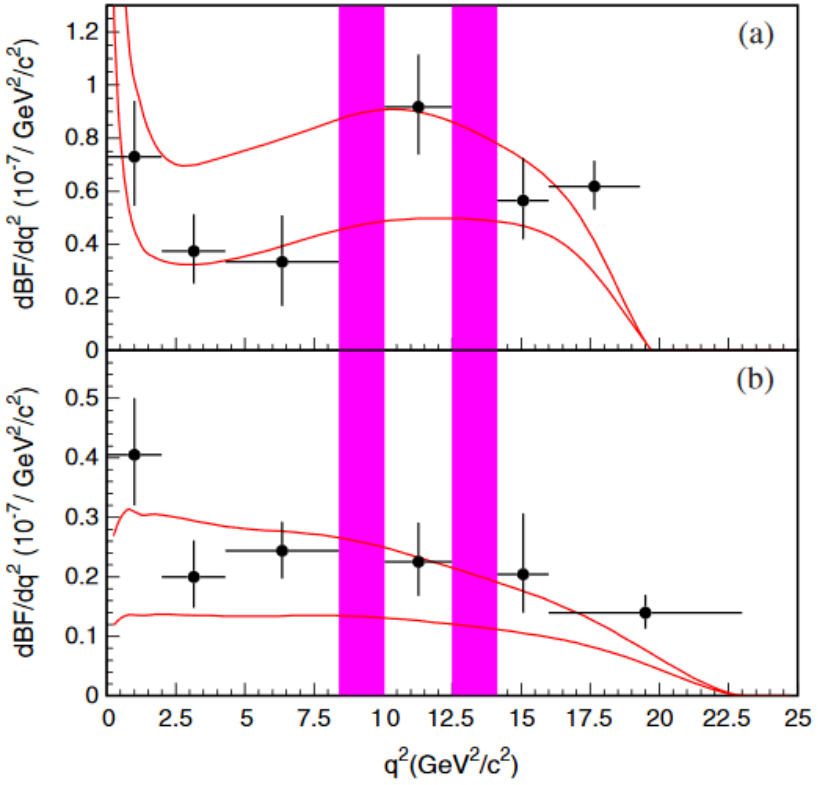
$B \to K^{(*)}\ell^+\ell^-$ based on 657 M BB pairs

- $\mu^+\mu^-$ and $e^+e^-$
- $K^+\pi^-$, $K^0_S\pi^+$, $K^+\pi^0$, $K^+$and $K^0_S$

**PRL103, 171801 (2009)**

- The differential branching fraction, isospin asymmetries ($A_I$) , K* longitudinal polarization ($F_L$) and lepton forward-backward asymmetry ($A_{FB}$) as a function of $q^2 \cong M_{\ell\ell}{}^2c^2$ .

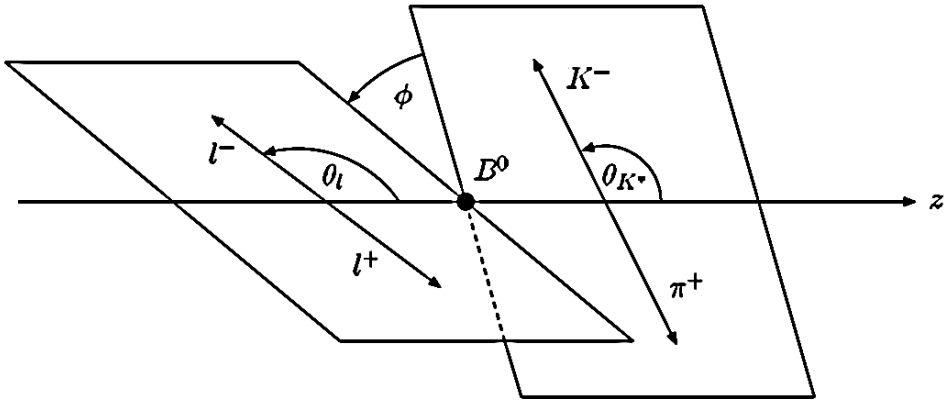
- Differential branching fractions for the (a) $B \to K^*\ell^+\ell^-$ (b) $B \to K\ell^+\ell^-$
- The solid curves show the SM theoretical predictions with the minimum and maximum allowed form factors



# Forward Backward asymmetry in $B \to K^* \ell^+ \ell^-$

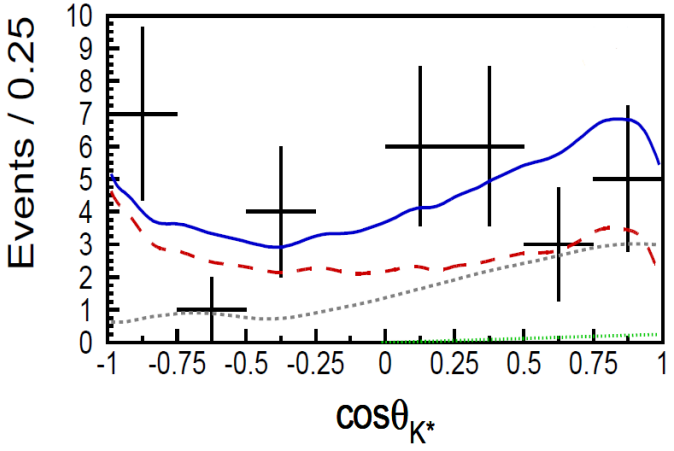
PRL103, 171801 (2009)

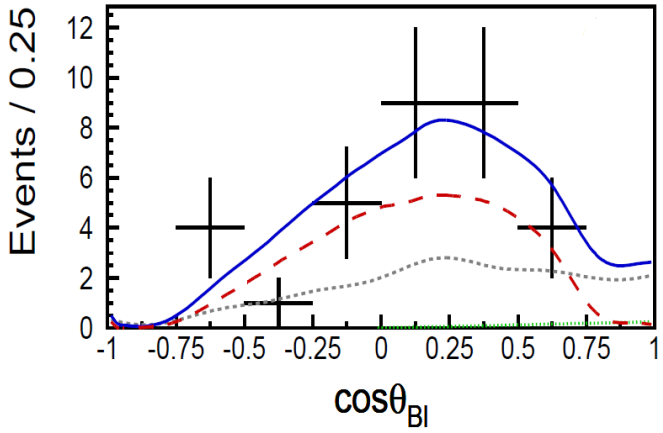
- $F_L$ and $A_{FB}$ are obtained from fit to $\cos\theta_{K^*}$ and $\cos\theta_{B\ell}$




- $\theta_{B\ell}$ = angle between $\ell^-$ and opposite to the B-direction in the $\ell^+\ell^-$ CM frame.
- $\theta_{K^*}$ = angle between $K^-$ and opposite to the B-direction in the K* CM frame.

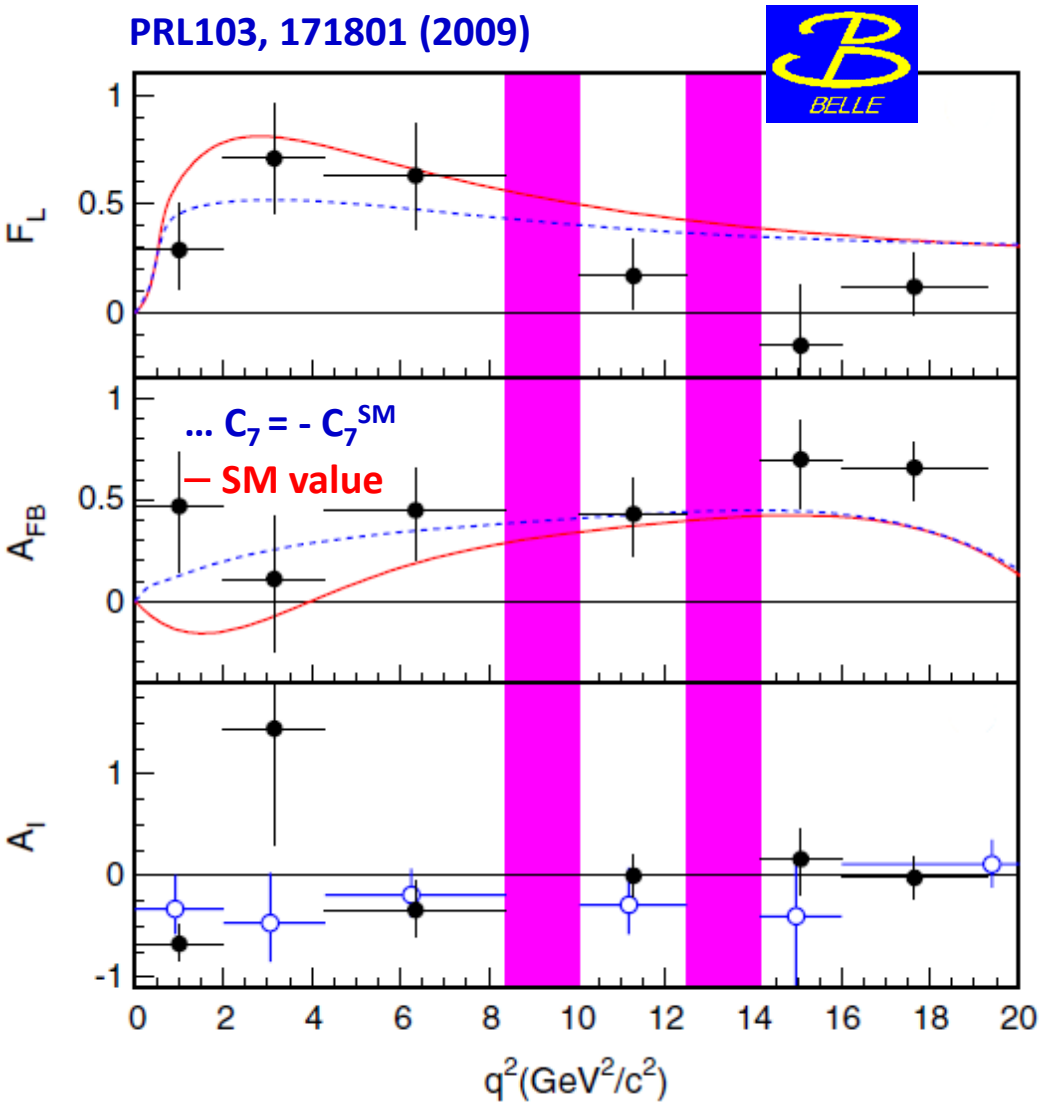
- **For illustration in $q^2 \in (0, 2.0)$ GeV$^2$/c$^2$**



# Forward Backward asymmetry in $B \to K^* \ell^+ \ell^-$

The Fit result for $F_L$ , $A_{FB}$ and isospin asymmetry as a function of $q^2$.




- The results as well as the SM curves are shown.
- Curves with case $C_7$ with reversed sign ($-C_7^{SM}$) are also superimposed
- The measured values do not reject this possibility.

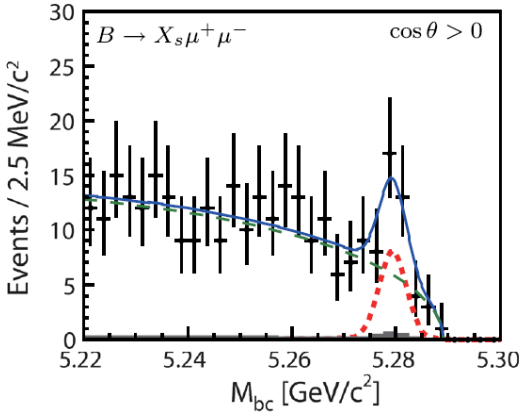
- The same analysis also measured the LFU ratios:

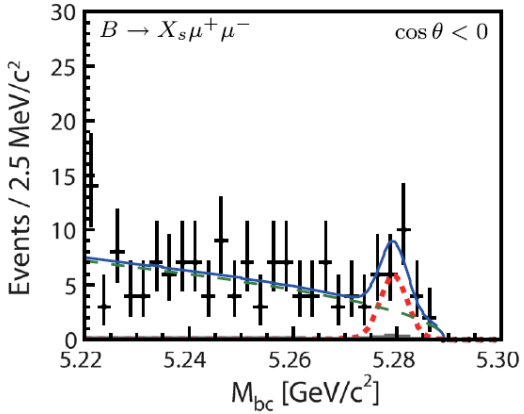
$R(K^*) = 0.83 \pm 0.17 \pm 0.08$

$R(K) = 1.03 \pm 0.19 \pm 0.06$

# Measurement of $A_{FB}(B \to X_s \ell^+ \ell^-)$

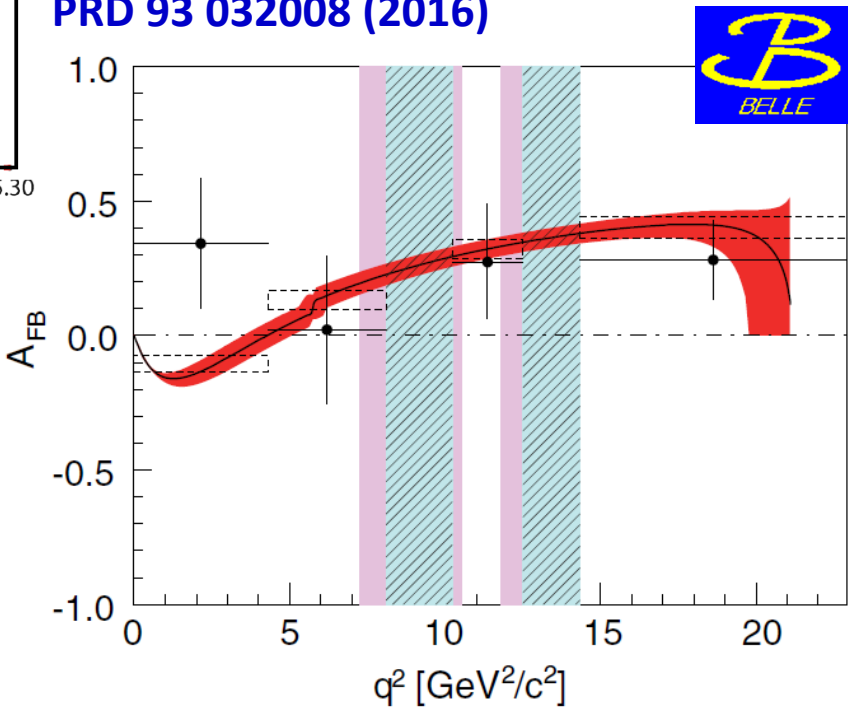
- Inclusive measurement is theoretically cleaner than the exclusive, but experimentally more challenging.
- Sum-of-exclusive technique (10 modes with $M[X_s] < 2.0$ GeV/$c^2$) used to measured $A_{FB}$ (corresponds to ~50% of the inclusive rate).




**← For illustration in $q^2 \in (1, 6)$ GeV²/c²**

**PRD 93 032008 (2016)**

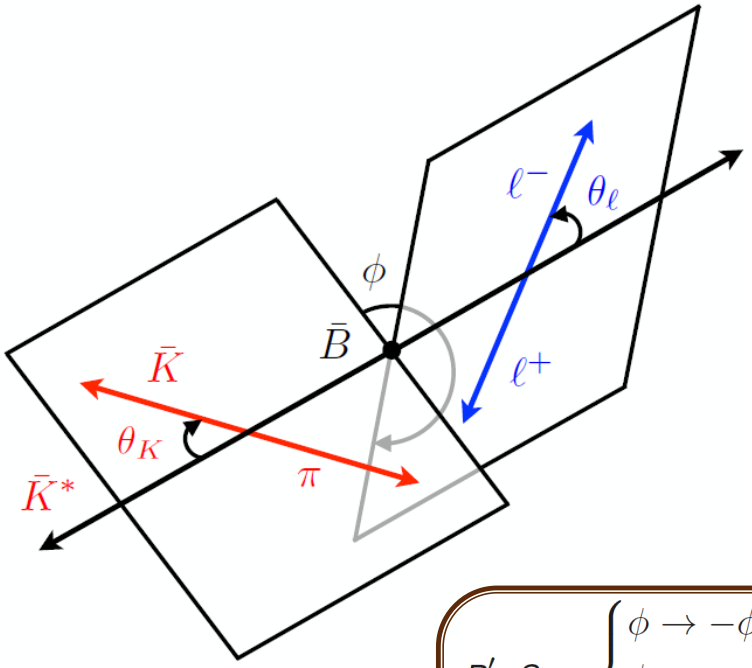



- The result is consistent with a SM prediction within error (1.8σ tension in low-$q^2$ ).
- Results are statistically dominated → Belle II

# Angular Analysis of $B \to K^* \ell^+ \ell^-$

The differential decay rate for $B \to K^* \ell^+ \ell^-$ can be written as

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




**JHEP 01 (2009) 019**

$$P_4', S_4: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_L > \pi/2 \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \pi/2, \end{cases}$$

$$P_5', S_5: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \pi/2, \end{cases}$$

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

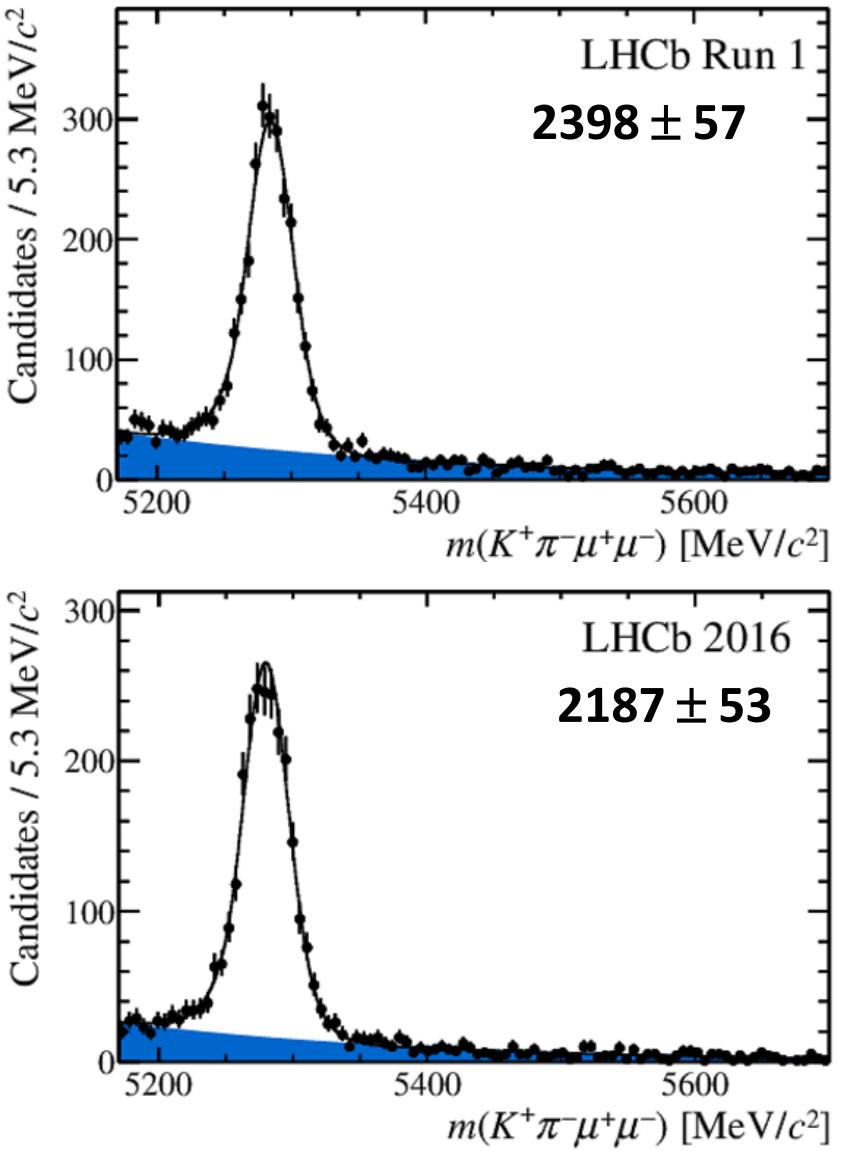
The observables are considered to be largely free from form-factor related uncertainties

**Introduced by LHCb in Phys. Rev. Lett. 111, 191801.**

# Angular Analysis of $B \to K^{*0} \ell^+ \ell^-$ at LHCb

- The data set corresponds to an integrated luminosity of 4.7 $fb^{-1}$.
- **$K^{*0}$** candidates with **$m(K^+\pi^-)$** $\in$ (795.9, 995.9) MeV/$c^2$
- Two opposite charged tracks (muons), combined with a **$K^{*0}$** candidate.
- The distribution of the invariant mass **$m(K^+\pi^-\mu^+\mu^-)$** is used as a discriminating variable
- 4D+1D fit : **$m(K^+\pi^-\mu^+\mu^-)$ , $\cos\theta_l$, $\cos\theta_K$, $\cos\phi$ and additionally $m(K^+\pi^-)$**
- For every $q^2$ bin, a fit is performed in both the standard and the optimized basis.

**Phys. Rev. Lett. 125 (2020) 011802**



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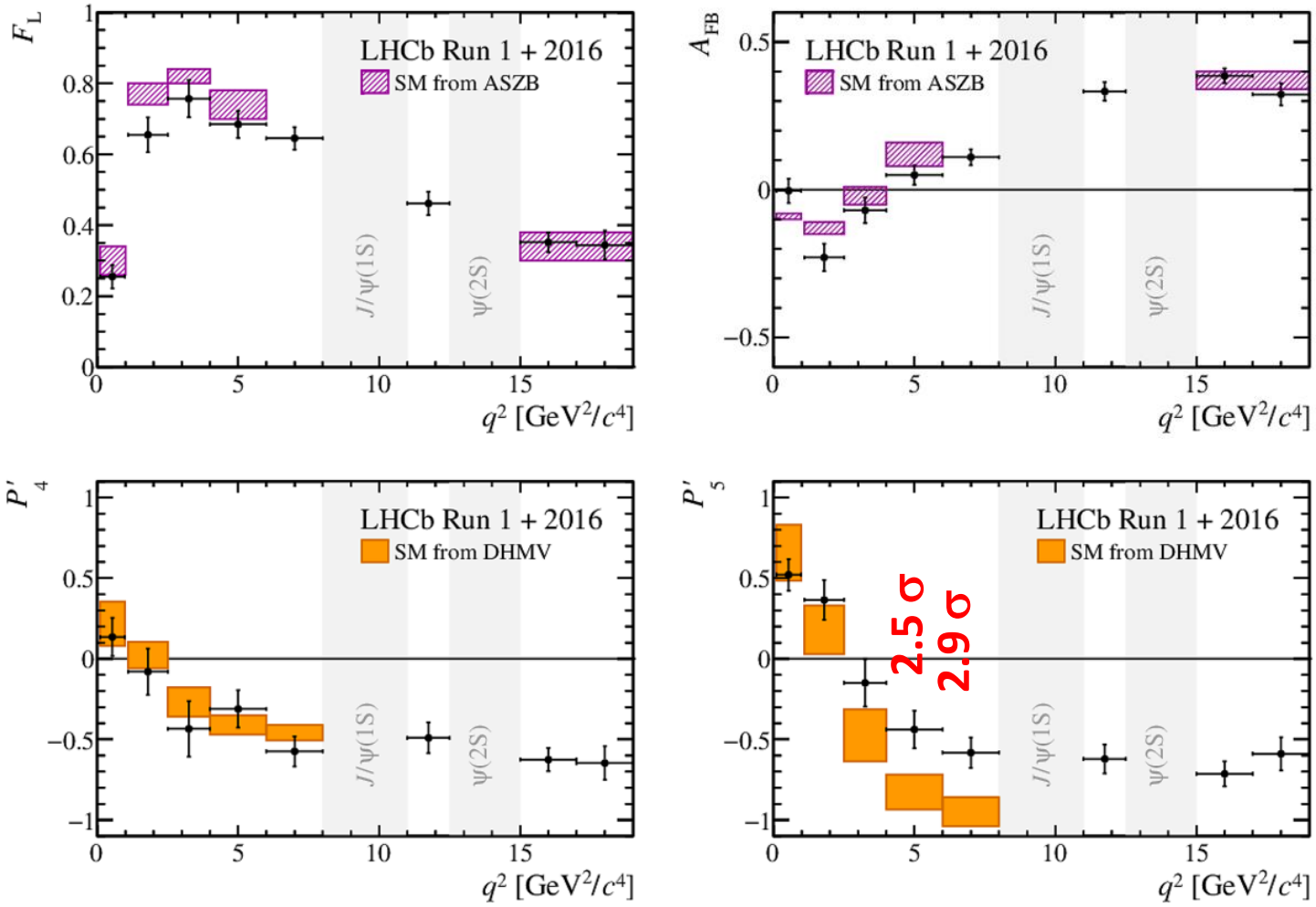
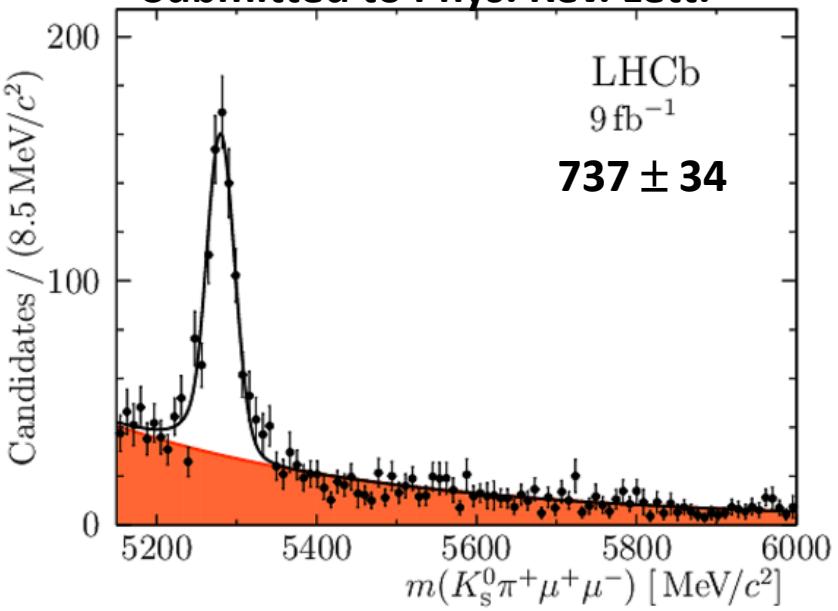


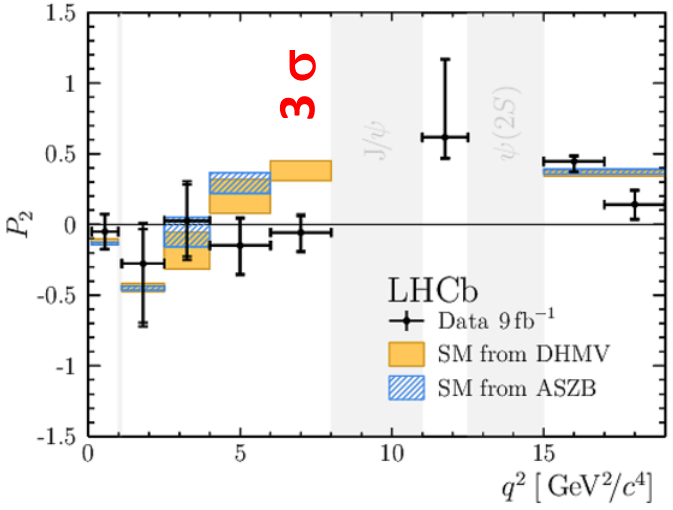

- The overall tension with the SM is observed to increase mildly.
- Discrepancy with the SM value of Re($C_9$) : 3σ with data set in previous analysis **[JHEP 02 (2016) 104]** which changes to 3.3 σ with Run1+2016

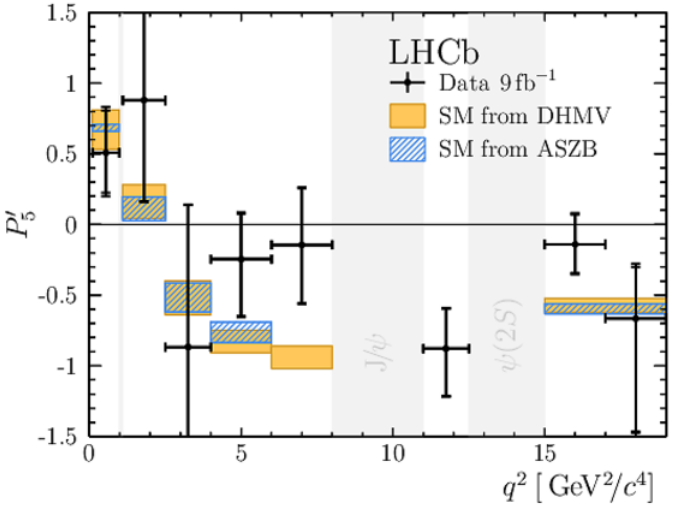
# Angular Analysis of $B^+ \to K^{*+}\ell^+\ell^-$ at LHCb

- The data set corresponds to an integrated luminosity of **9 fb$^{-1}$**.
- **$K^{*+}$** meson is reconstructed with **$K_S^0\pi^+$** within 100 MeV window of nominal **$K^{*+}$** nominal mass.
- The results from $B^+ \to K^{*+}\ell^+\ell^-$ confirm the global tension with respect to the SM predictions previously reported in the decay $B \to K^{*0}\ell^+\ell^-$

**Submitted to Phys. Rev. Lett.**



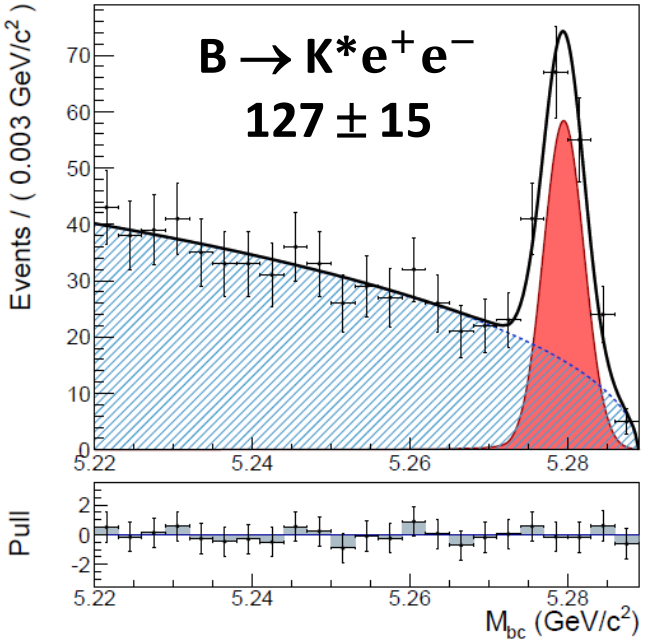



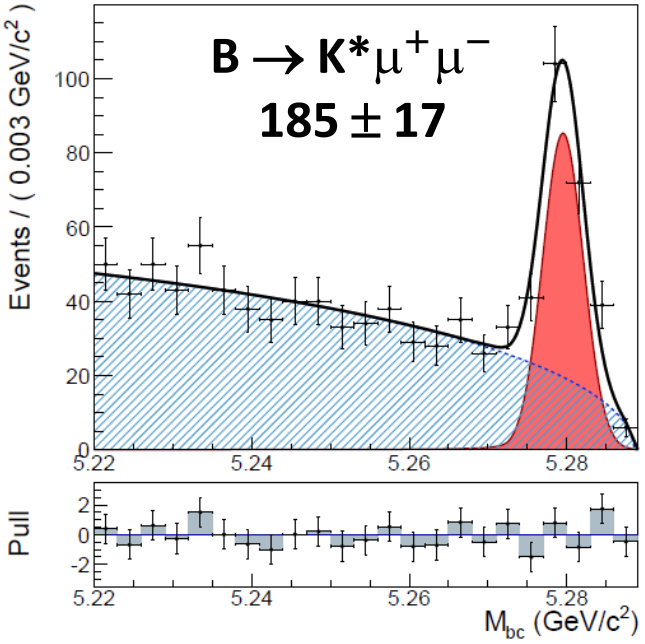

**pattern of deviations from the SM predictions in the observables $P_5'$**

# Angular Analysis of $B \to K^* \ell^+ \ell^-$ at Belle

Belle [Phys. Rev. Lett. 118, 111801 (2017)]

- Reconstructed $B^0$ and $B^+$ : $B \to K^*(892) \ell^+ \ell^-$
  - $K^*(892) \to K^+\pi^-$, $K^0_S\pi^+$, and $K^+\pi^0$
  - $\ell^+\ell^- \to \mu^+\mu^-$ and $e^+e^-$
- Signal is extracted in Beam Constrained Mass: $M_{bc} = \sqrt{E^2_{beam} - |\overrightarrow{p_B}|^2}$
- Signal pdf: **Crystal Ball** , Background pdf: **Argus shape**



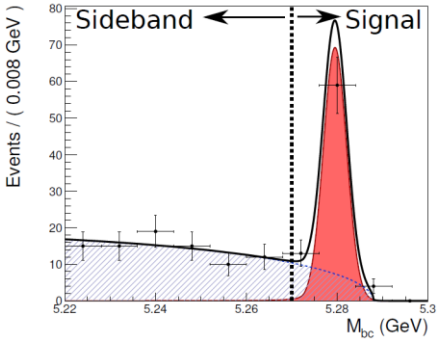



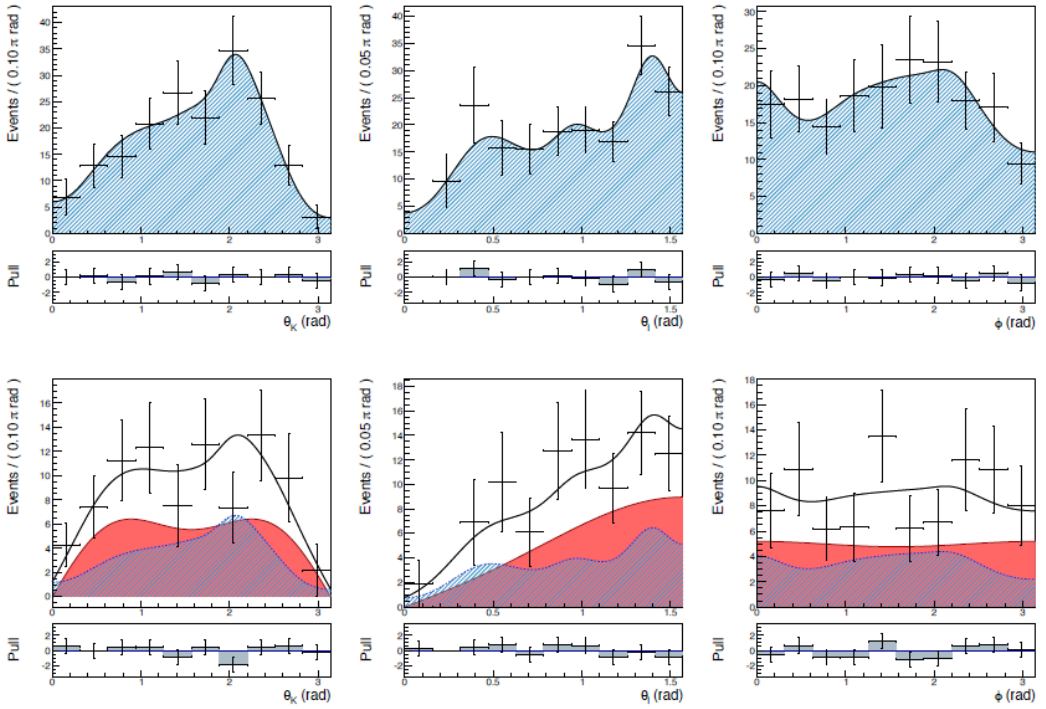
# Angular Analysis of $B \to K^* \ell^+ \ell^-$ at Belle

- Data is divided in the $q^2$ bins.

Belle [Phys. Rev. Lett. 118, 111801 (2017)]

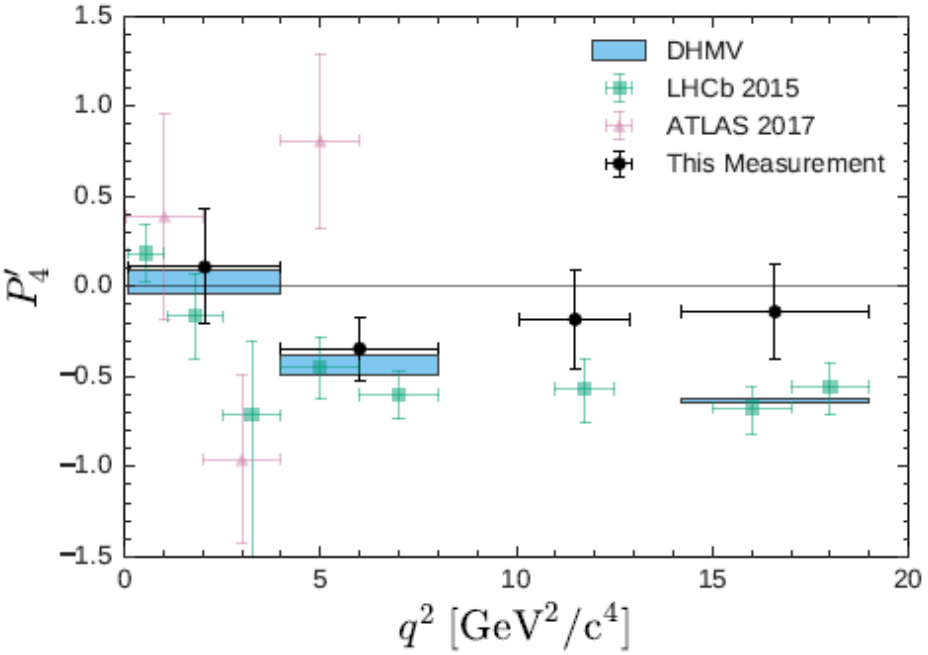
- Signal and background fraction is obtained by fitting $M_{bc}$ distribution
- The data is split into a sideband and signal region

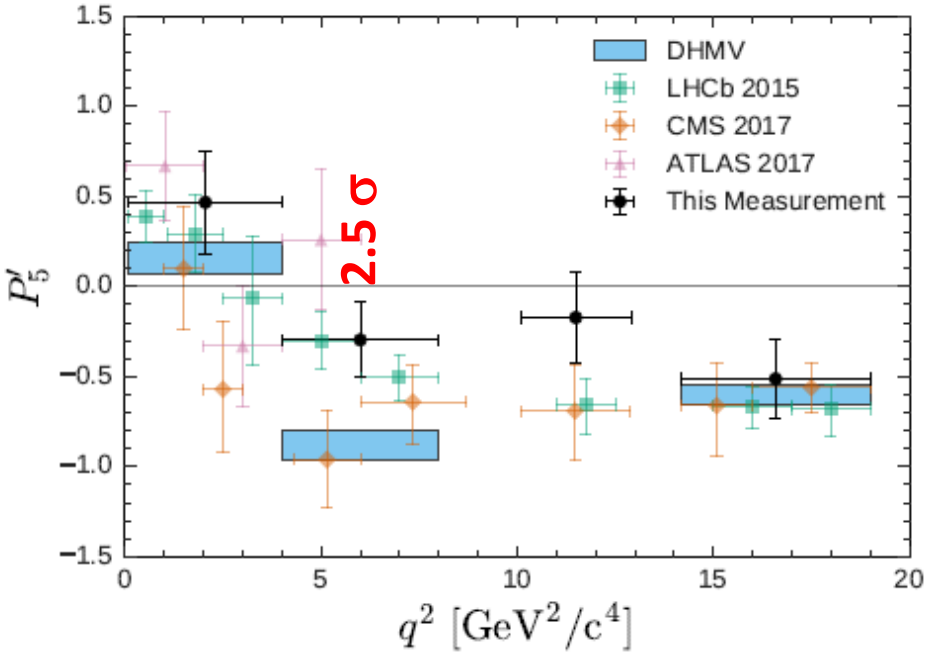



- Shape of the background can be determined in the sideband region
- Final fit in signal region for each transformation

# Result $P_5'$: for Combined Data

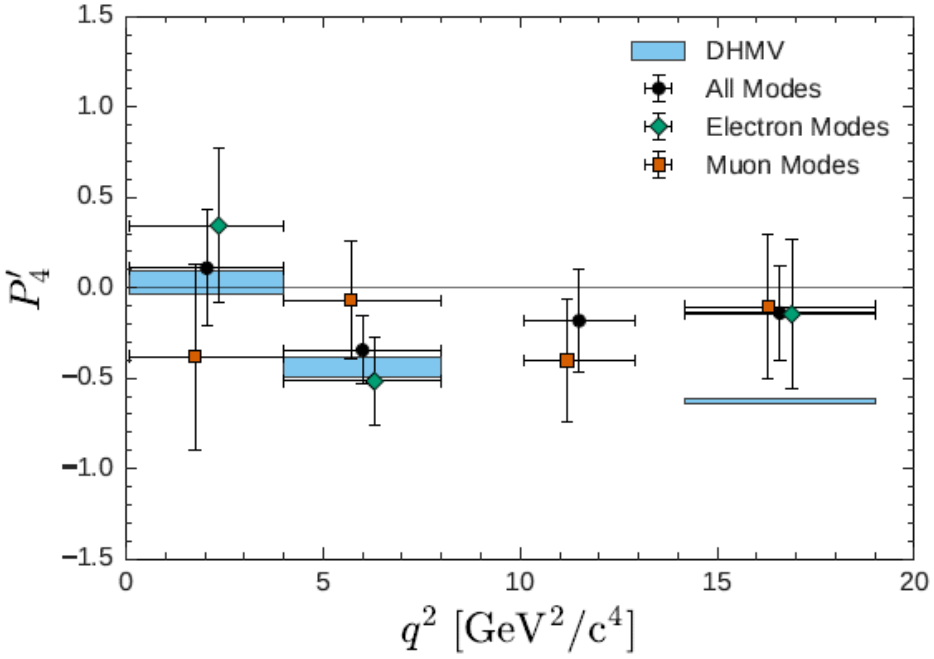


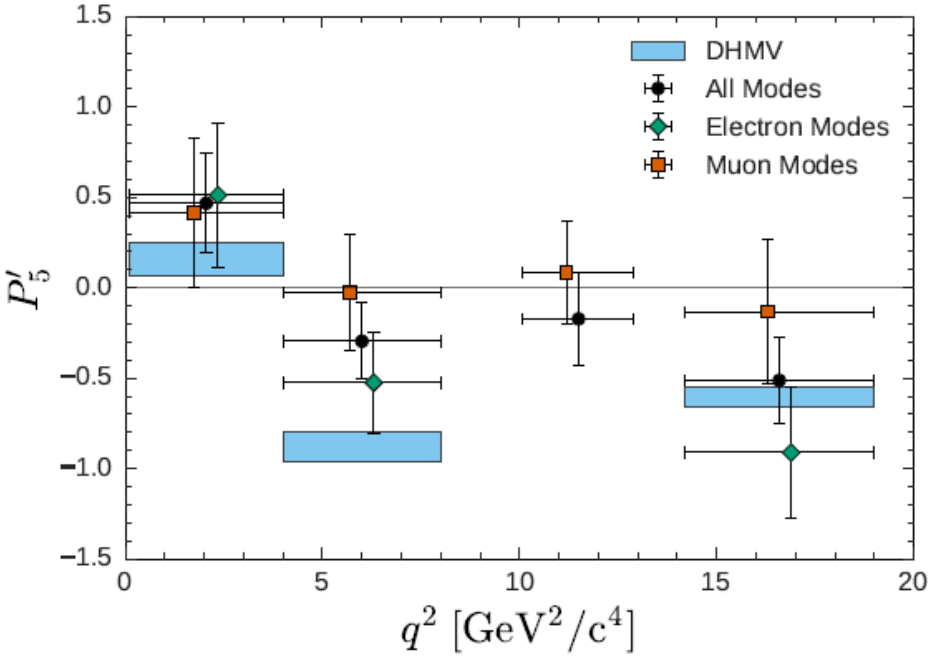




- Measurements are compatible with the SM.
- Similar central values for the $P_5'$ anomaly with 2.5σ tension.

**Belle [Phys. Rev. Lett. 118, 111801 (2017)]**

# Result - Separate Lepton Flavor!



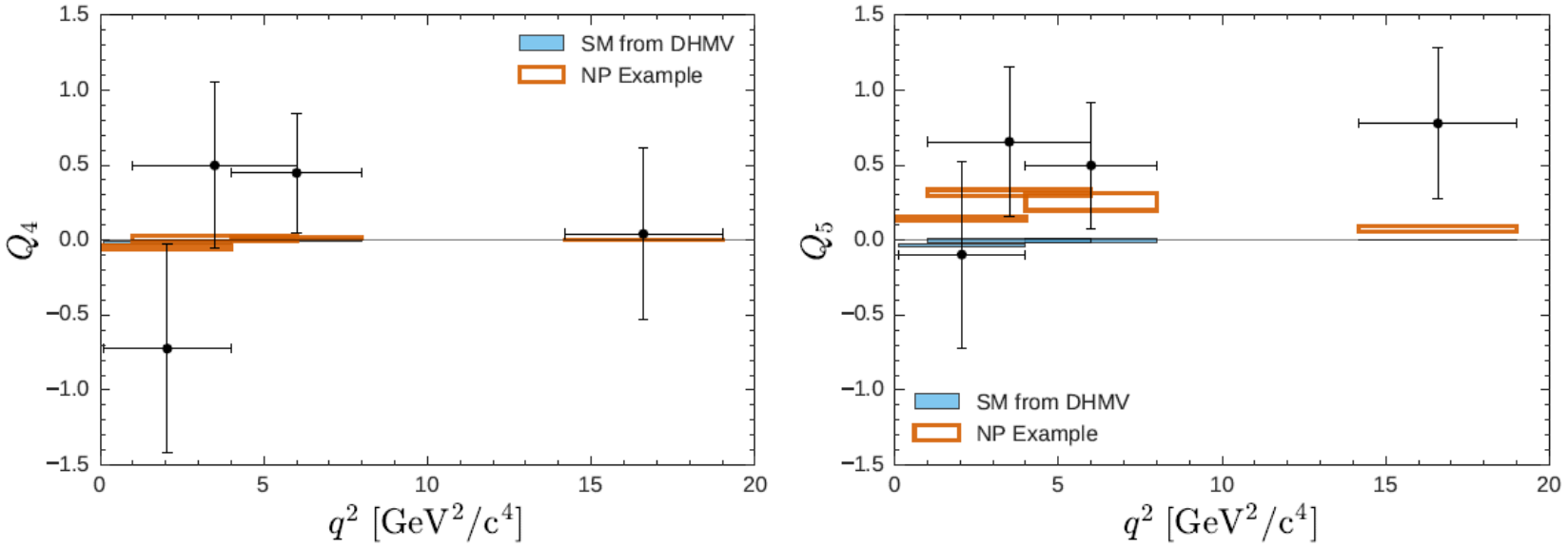

- The Largest deviation in the muon mode with 2.6σ.
- Electron mode is deviating with 1.1σ.

- With 2.8 ab$^{-1}$ the uncertainty on P'$_5$ (e & μ ) will be comparable to LHCb 3fb$^{-1}$ (μ only).

**Belle [Phys. Rev. Lett. 118, 111801 (2017)]**

# Result - Separate Lepton Flavor!

- Test lepton flavor universality.
- Observables $Q_i = P'^{\mu}_i - P'^{e}_i$. [JHEP 10, 075 (2016)]
- Deviation from zero very sensitive to NP.




- No significant deviation from zero is discerned.
- $Q_4$ and $Q_5$ observables in agreement with SM and favoring NP scenario.

**Belle [Phys. Rev. Lett. 118, 111801 (2017)]**

# Lepton Flavor Universality ratios : R(K/K*)

- In the SM, the coupling of gauge bosons to leptons is independent of lepton-flavor, a concept known as LFU.
- Experimental tests of LFU are excellent probes for New Physics.
- The Lepton Flavor universality can be tested very precisely with the ratios:

$$R_H[q_0^2, q_1^2] = \frac{\int_{q_0^2}^{q_1^2} dq^2 \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}}{\int_{q_0^2}^{q_1^2} dq^2 \frac{d\Gamma(B \to He^+e^-)}{dq^2}}; \; H = K, K^*, X_s$$

- In these ratios, hadronic uncertainties in theoretical predictions cancel and SM prediction is (very) close to unity. The uncertainity order of 1%
- Experimentally, many sources of systematic uncertainties are substantially reduced.

# Recent R(K*) measurement at Belle

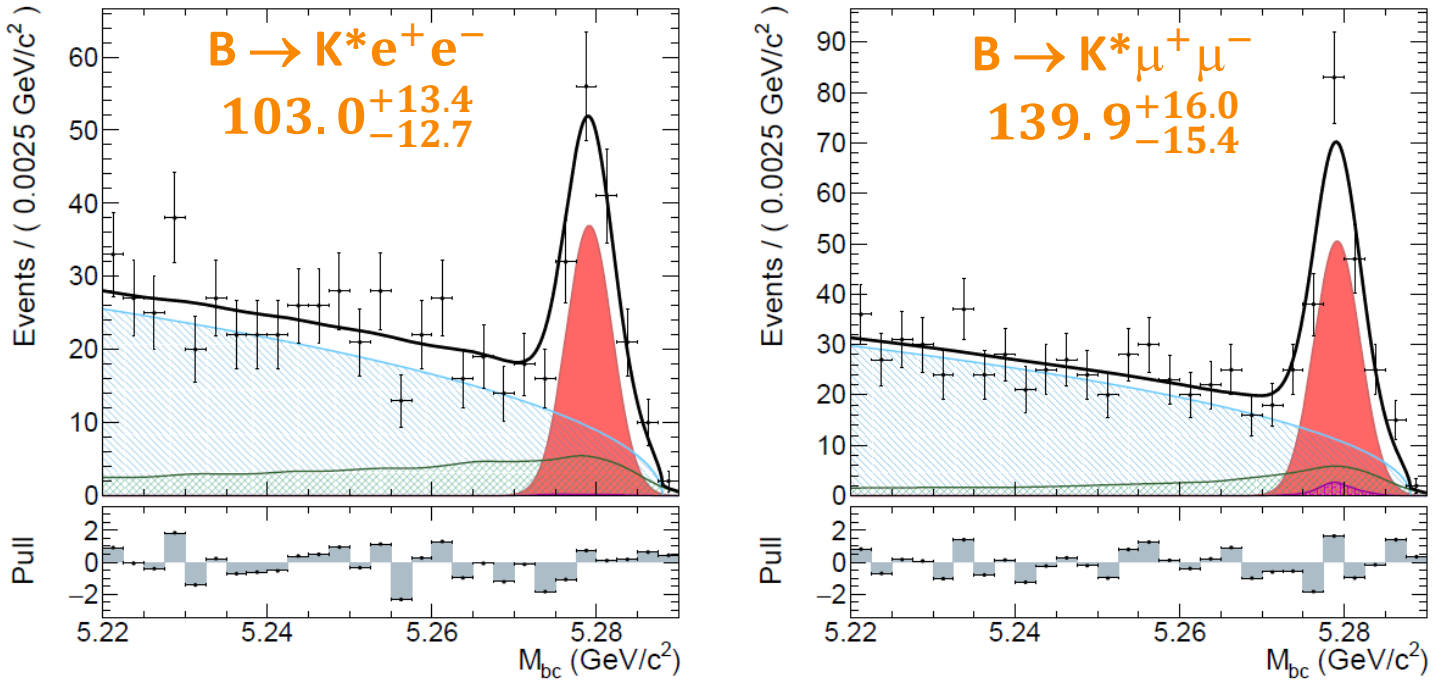
Belle [arXiv: 1904.02440]

- Reconstructed $B^0$ and $B^+$ : $B \rightarrow K^*(892)\ell^+\ell^-$
  - $\ell^+\ell^-$ → $\mu^+\mu^-$ and $e^+e^-$
  - $K^*(892)$ → $K^+\pi^-$, $K^0_S\pi^+$, and $K^+\pi^0$
- Full Belle data set **711 fb$^{-1}$**
- **Bremsstrahlung** losses are recovered in **electron** candidates.
- **Hierarchical NN Reconstruction :** A dedicated NN classier is trained with MC samples to identify each particle type used in the decay chain.
- To further suppress ($e^+e^- \rightarrow q\bar{q}$ ) background events, variables related to event shape variables, vertex information are used in the NN.
- Large irreducible background events arise from the decay **$B \rightarrow K^*J/\psi[\psi(2S)]$**, which are vetoed by applying criteria on di-lepton invariant mass.
- However, the decays $B \rightarrow K^*J/\psi[\psi(2S)]$ serve as a very good **Control Sample**.

$$\frac{BF[B \rightarrow K^* J/\psi(\rightarrow \mu^+\mu^-)]}{BF[B \rightarrow K^* J/\psi(\rightarrow e^+e^-)]} = 1.015 \pm 0.025 \pm 0.038$$

# Recent R(K*) measurement at Belle

- Signal is extracted in Beam Constrained Mass: $M_{bc} = \sqrt{E_{beam}^2 - |\overrightarrow{p_B}|^2}$
- Signal pdf: **Crystal Ball** , Combinatorial background pdf: **Argus shape.**
- For example, the fit presented below are for the **$q^2 > 0.045$ GeV$^2$/c$^4$**

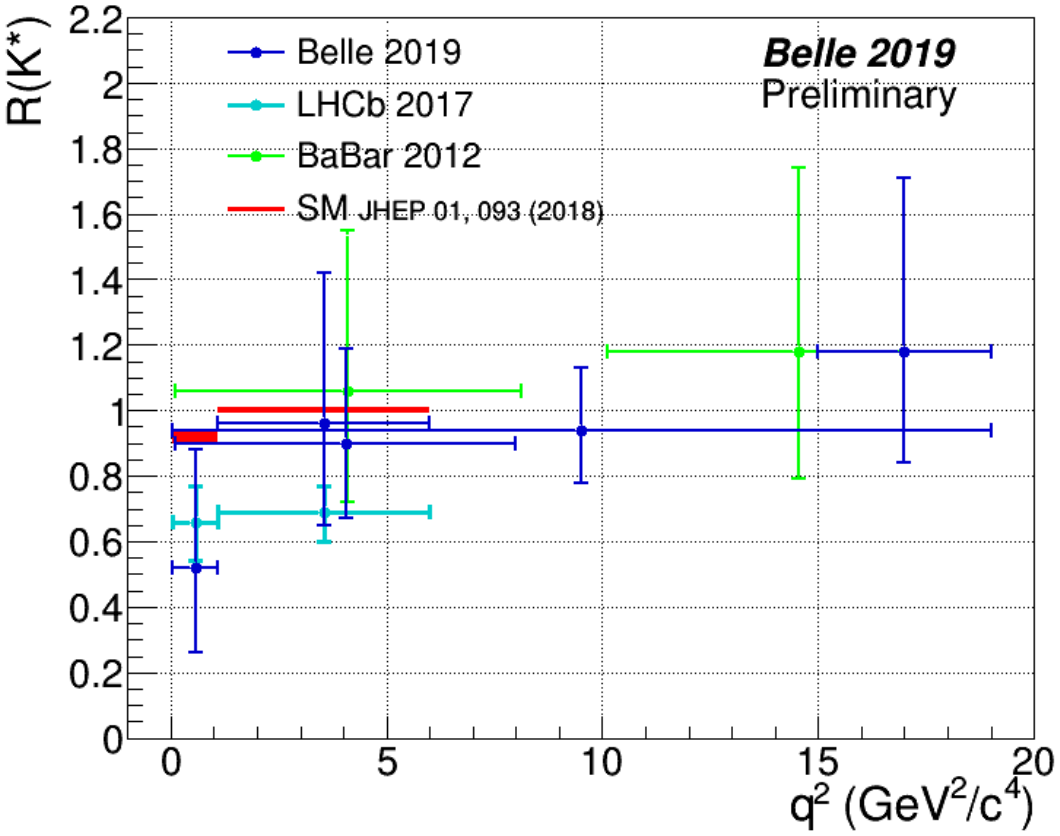



- Analysis is performed in several **$q^2$ bins** [0.045, 1.1], [1.1, 6.0], [0.1, 8.0 ], [15, 19], and > 0.045 GeV$^2$/c$^4$

Belle [arXiv: 1904.02440]

# Current R(K*) Status

- Belle also provided first measurement of $R(K^{*+})$.
- Latest R(K*) measurement from Belle are consistent with the SM as well as with the previous measurements from LHCb (and BaBar).




SM example: JHEP 1801 (2018) 093
for $q^2 \in (0.045,1.1)$ GeV$^2/c^4$ : $0.92 \pm 0.02$
for $q^2 \in (1.1,6.0)$ GeV$^2/c^4$ : $1.00 \pm 0.01$

- **LHCb measurements for R(K*):**

$0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03\ (\text{sys.})$
for $q^2 \in (0.045,1.1)$ GeV$^2/c^4$
2.1 – 2.3 σ from SM

$0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05\ (\text{sys.})$
for $q^2 \in (1.1,6.0)$ GeV$^2/c^4$
2.4 – 2.5 σ from SM

LHCb, JHEP08(2017)055

- **Belle measurements for R(K*):**

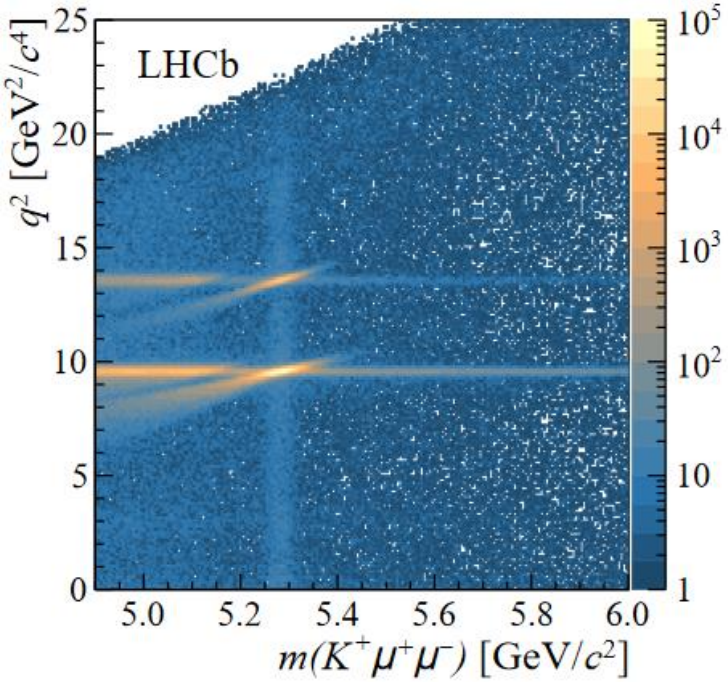
$0.52^{+0.36}_{-0.26}(\text{stat}) \pm 0.05\ (\text{sys.})$
for $q^2 \in (0.045,1.1)$ GeV$^2/c^4$

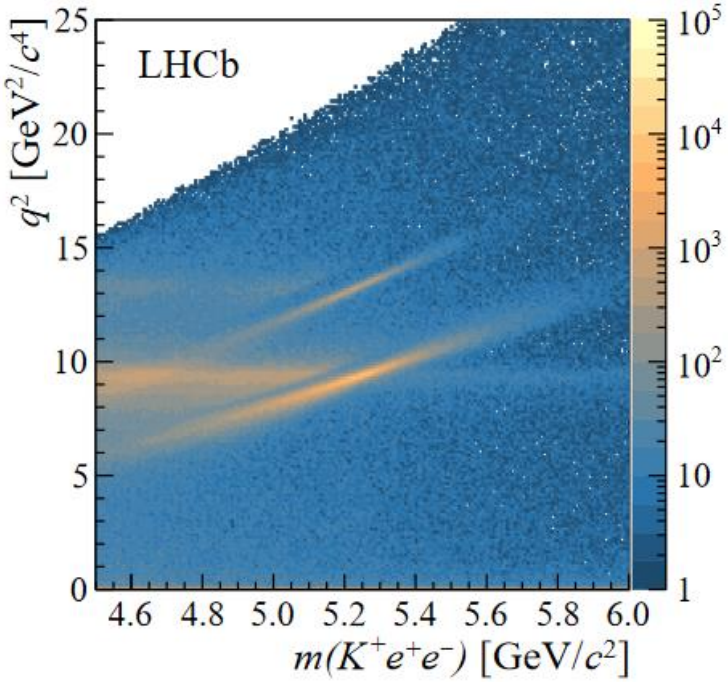
$0.96^{+0.29}_{-0.27}(\text{stat}) \pm 0.11\ (\text{sys.})$
for $q^2 \in (1.1,6.0)$ GeV$^2/c^4$

Belle [arXiv: 1904.02440]

# Recent R(K) measurement at LHCb

- **5 fb$^{-1}$** of pp collision at CM energy 7, 8 and 12 TeV.
- Reconstructed $B^+$ : $B^+ \rightarrow K^+ \ell^+ \ell^-$
  $\hookrightarrow \mu^+\mu^-$ and $e^+e^-$
- Significantly different reconstruction of decays with muons in the final state as compared to decays with electrons (brem losses and different trigger selection).



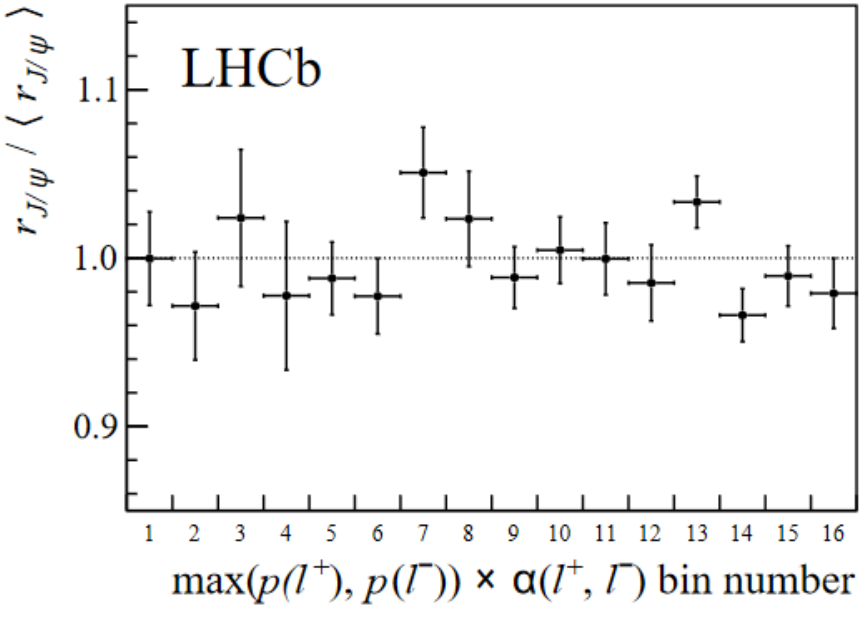



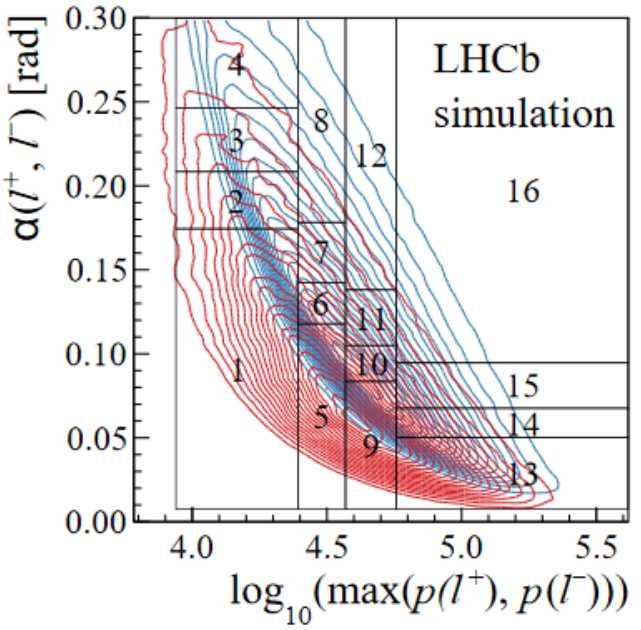
# Recent R(K) measurement at LHCb

- **Measure $R_K$ as a double ratio:**

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

- Several cross-checks are used to verify the analysis procedure.
  - Single ratio **r(J/ψ)** [=1.014 ± 0.035] is found to be consistent with **unity** (also as a function **momentum** of leptons and dilepton **opening angle**.)
  - Double ratio $\mathbf{R_K^{\psi(2S)}}$ [=0.986 ± 0.013] is determined close to 1.

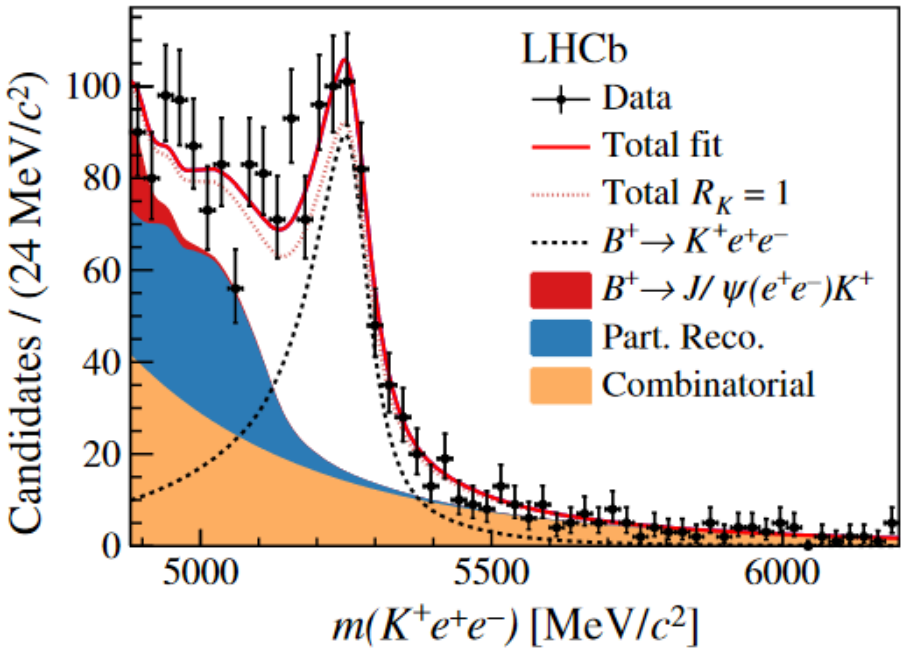


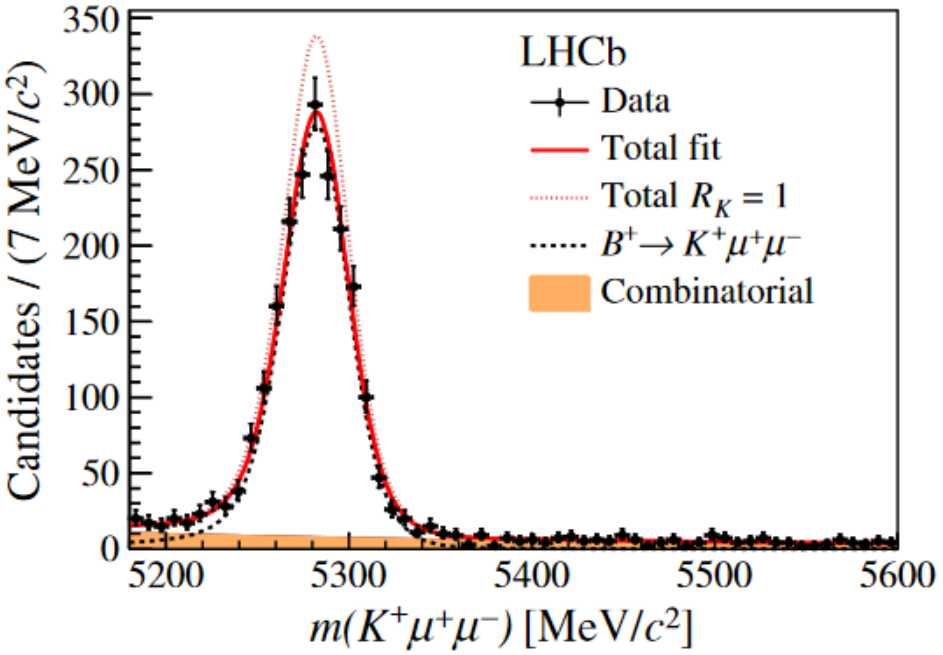




$B^+ \to K^+ \ell^+\ell^-$

$B^+ \to K^+ J/\psi\ (\ell^+\ell^-)$

# Recent R(K) measurement at LHCb




- A total of 1943 ± 49 $B^+ \to K^+\mu^+\mu^-$ decays are observed.
- The value of $R_K\ [q^2 \in (1.1, 6.0)\ GeV^2/c^4] = 0.846^{+0.060}_{-0.054}\,(stat.)^{+0.016}_{-0.014}\,(sys.)$
- Consistent with the Standard Model at the level of 2.5 σ.

# Recent R(K) measurement at Belle

JHEP03(2021)105

- Reconstructed $B^0$ and $B^+$ : $B \rightarrow K\ \ell^+\ell^-$
  - $\ell^+\ell^-$ → $\mu^+\mu^-$ and $e^+e^-$
  - K → $K^+$ and $K^0_S$
- Full Belle data set **711 fb$^{-1}$**
- Charged tracks are required to originate near the interaction region (except $K^0_S$) and further selected based on **particle identification**.
- **Bremsstrahlung** losses are recovered in **electron** candidates.
- A NN is trained with input variables related event shape, vertex quality and decay kinematics to suppress the **background from continuum and generic *B* decays**.
- Large irreducible background events arise from the decay **$B \rightarrow KJ/\psi[\psi(2S)]$**, which are vetoed by applying criteria on di-lepton invariant mass.
- Also a veto [$M_{K\pi} \notin (1.85,1.88)$ GeV/$c^2$ ] is applied to suppress events arising from the decay **$B^- \rightarrow D^0[K^-\pi^+]\ \pi^-$** due to particle mis-identification.
- The decays **$B \rightarrow KJ/\psi[\psi(2S)]$** served as a good **control sample.**

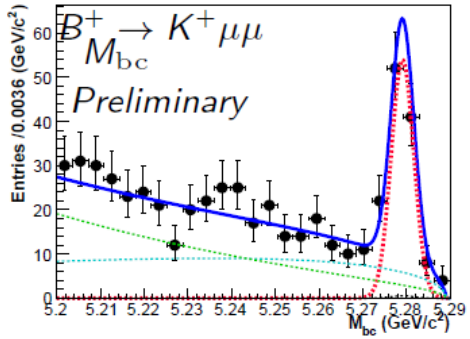
$$\frac{BF[B^+ \rightarrow K^+ J/\psi(\rightarrow \mu^+\mu^-)]}{BF[B^+ \rightarrow K^+ J/\psi(\rightarrow e^+e^-)]} = 0.992 \pm 0.011 \qquad \frac{BF[B^0 \rightarrow K^0_S J/\psi(\rightarrow \mu^+\mu^-)]}{BF[B^0 \rightarrow K^0_S J/\psi(\rightarrow e^+e^-)]} = 1.048 \pm 0.020$$

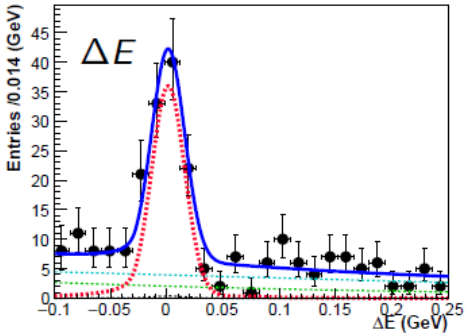
JHEP03(2021)105

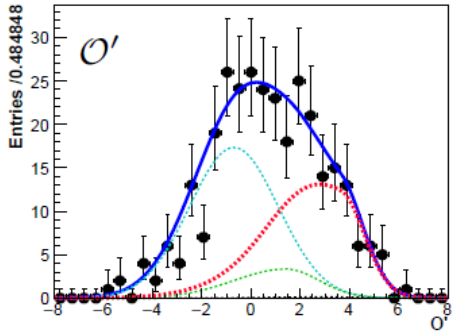
- The NN output (O) is translated to (O') using the formula:
- Requirement $O_{min} > -0.6$ reduces 75% bkg with 4-5% signal loss.

$$O' = \log \frac{O - O_{min}}{O_{max} - O}$$

- Extended maximum likelihood fit is performed in 3-dimensions: **$M_{bc}$ , $\Delta E$ ($E_B$ -$E_{beam}$), and O'.** (parameterized with MC, control samples and off-resonance data).
- For example, the fit presented below are for the **$q^2 > 0.1$ GeV$^2/c^4$**



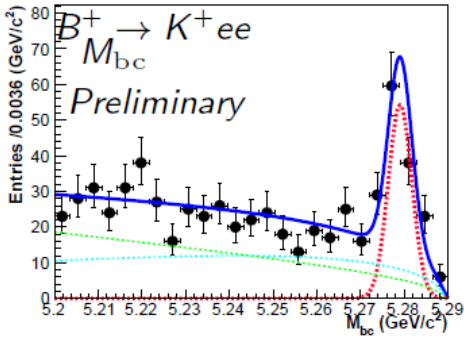



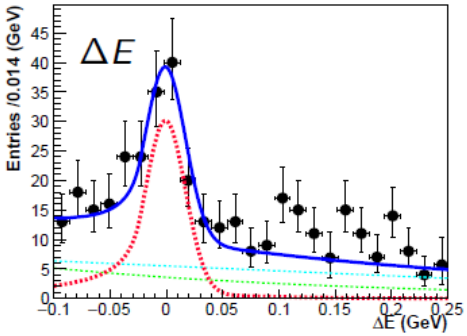

$B^+ \to K^+\mu^+\mu^-$

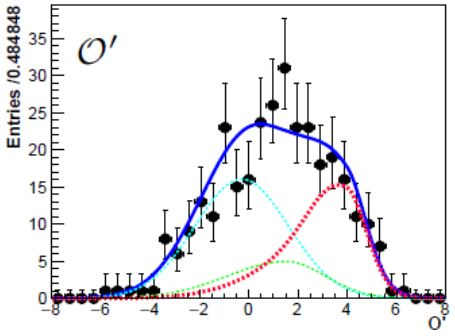
$137 \pm 14$

$B^0 \to K^0_S\mu^+\mu^-$

$27.3^{+6.6}_{-5.8}$




$B^+ \to K^+e^+e^-$

$138 \pm 15$

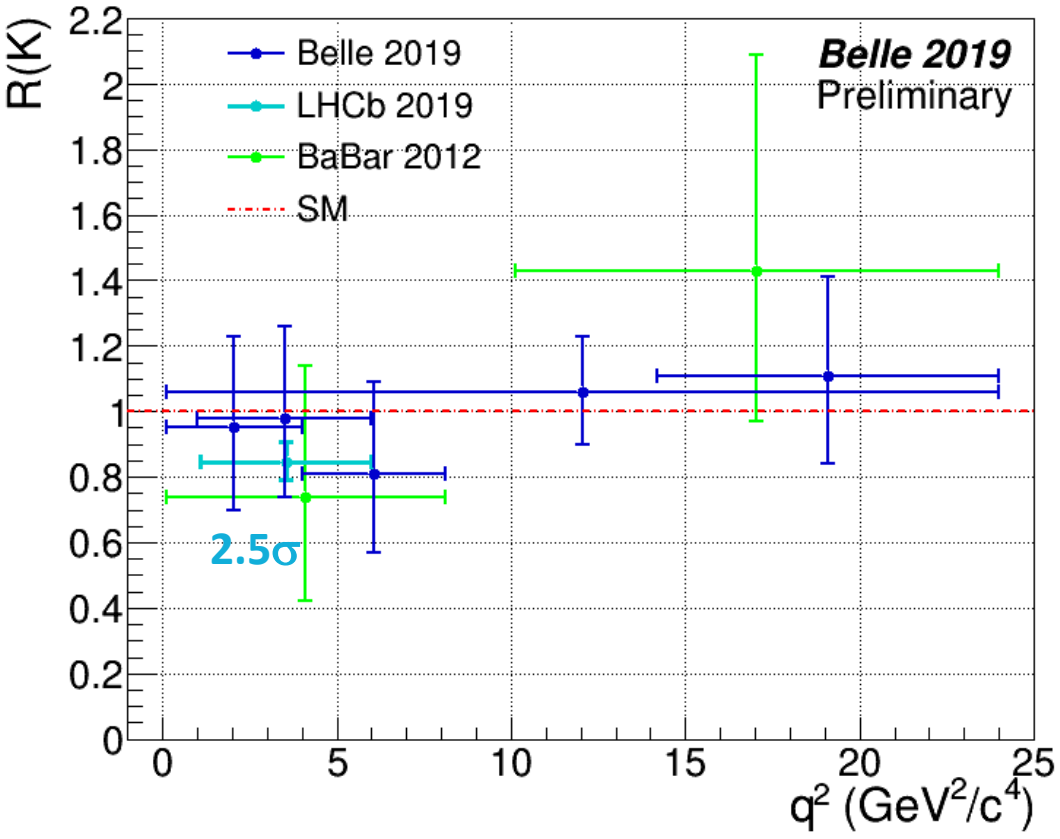
$B^0 \to K^0_S\mu^+\mu^-$

$21.8^{+7.0}_{-6.1}$

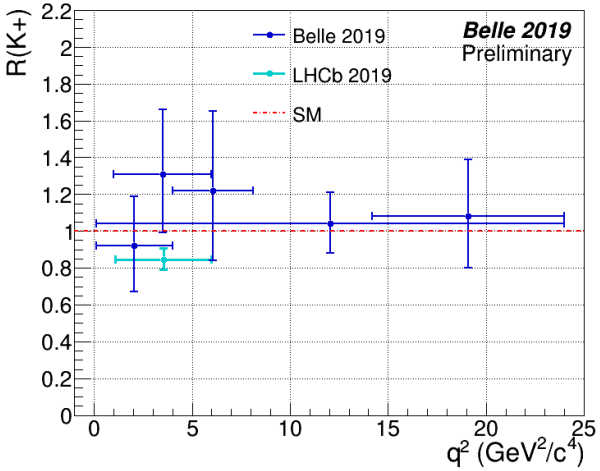
- The value of **$R_K$ [$q^2 \in (1.0, 6.0)$ GeV$^2/c^4$] = $0.98^{+0.27}_{-0.23}\,(\text{stat.}) \pm 0.06\,(\text{sys.})$**

# Current R(K) Status

- **Belle measured R(K) in several $q^2$ bins** and also reported first measurement of $R(K_s^0)$.
- In all the bins Belle's R(K) is **consistent with SM** value.




- **Belle measurement** R(K) $0.98^{+0.27}_{-0.23} \pm 0.06$ [in $q^2 \in (1.0, 6.0)$ GeV$^2$/c$^4$] **is consistent with LHCb measurement** of R(K) = $0.846^{+0.060\ +0.016}_{-0.054\ -0.014}$ [in $q^2 \in (1.1, 6.0)$ GeV$^2$/c$^4$].
- **LHCb measurement is compatible with SM at 2.5σ.**

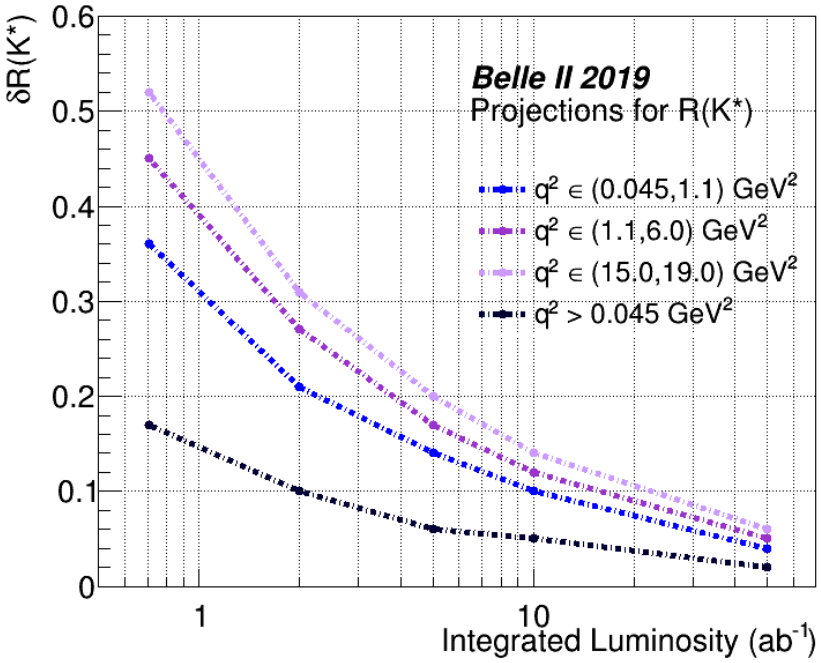


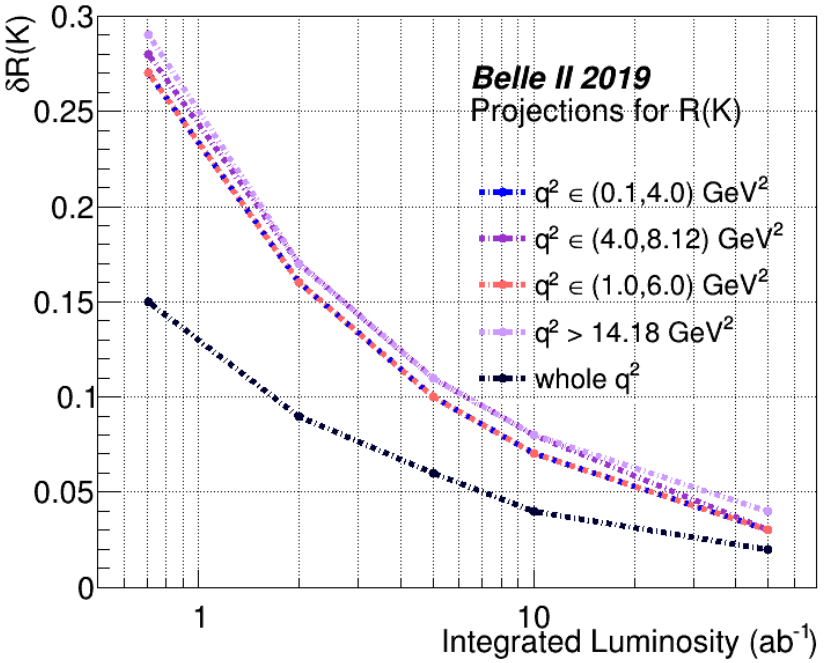

- In fact, Belle **R(K⁺) = $1.31^{+0.34}_{-0.31} \pm 0.07$** [in $q^2 \in (1.0, 6.0)$ GeV$^2$/c$^4$]

# Belle II Projections for R(K) and R(K*)

- Upcoming Belle II measurements will be helpful in reducing statistical uncertainties.
- Total uncertainties on R(K) and R(K*) measurements can reach down to below 5% with full data-set at Belle II.
- Uncertainties are still statistical dominant (total systematic is below 1% with dominating uncertainty from lepton identification ~ 0.4%)

**B2TIP report | arXiv:1808.10567**



# Recent A(I) measurement at Belle

**JHEP03(2021)105**

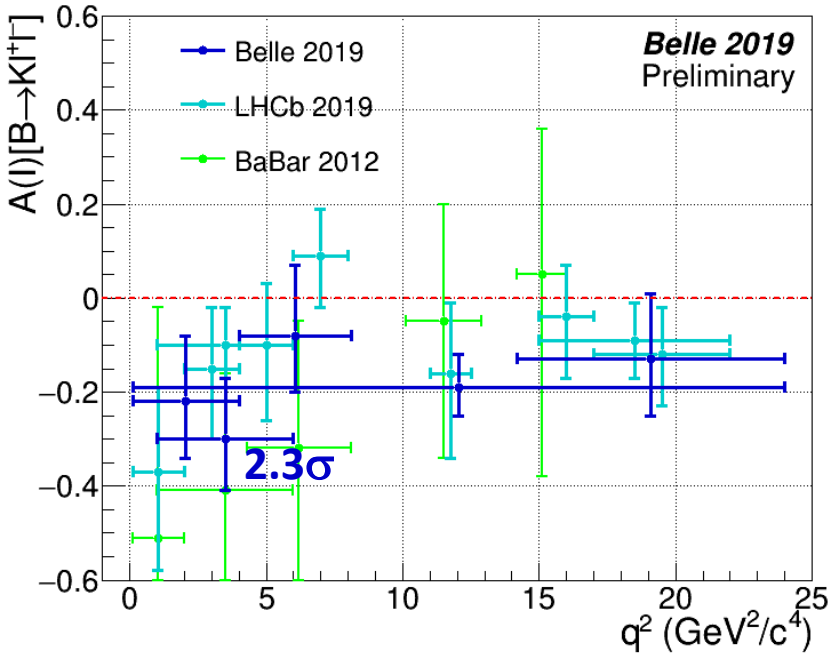
- Another theoretically clean observable is CP averaged isospin asymmetry:

$$A_I = \frac{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^0 \ell\ell) - \mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+ \ell\ell)}{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^0 \ell\ell) + \mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+ \ell\ell)}$$

The value of A(I) is expected to be close to zero in the SM.

J. Lyon and R. Zwicky,
Phys. Rev. D 88, 094004 (2013)

- Earlier, BaBar **[PRD 86, 032012 (2012)]**, Belle **[PRL103, 171801 (2009)]** and LHCb **[JHEP 06 (2014)133]** had reported A(I) to be significantly below zero, especially in the $q^2$ region below the J/ψ resonance.




- Belle's A(I) measurement is consistent with the previous measurements.
- In all bins A(I) is below zero.

JHEP03(2021)105

- Another theoretically clean observable is CP averaged isospin asymmetry:

$$A_I = \frac{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^0\ell\ell) - \mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\ell\ell)}{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^0\ell\ell) + \mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\ell\ell)}$$

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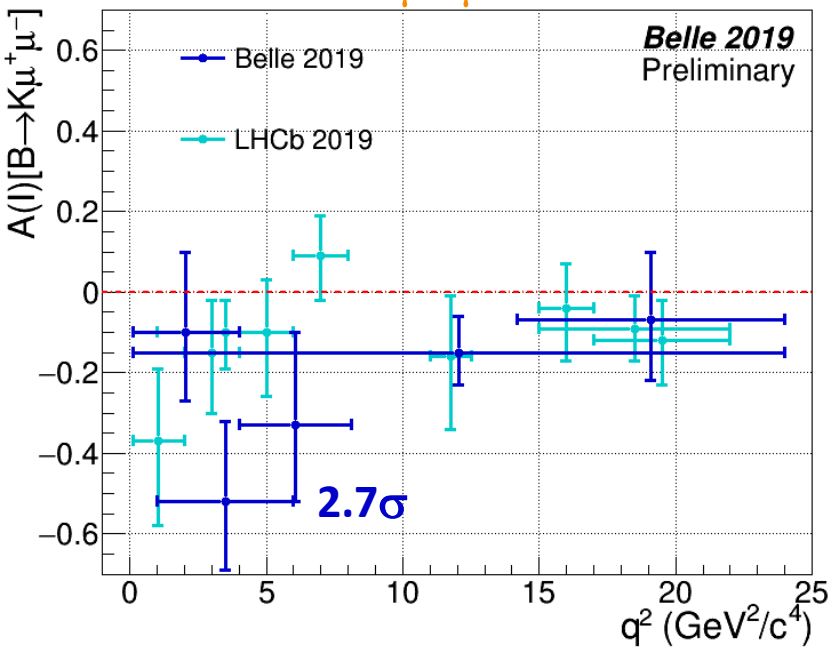
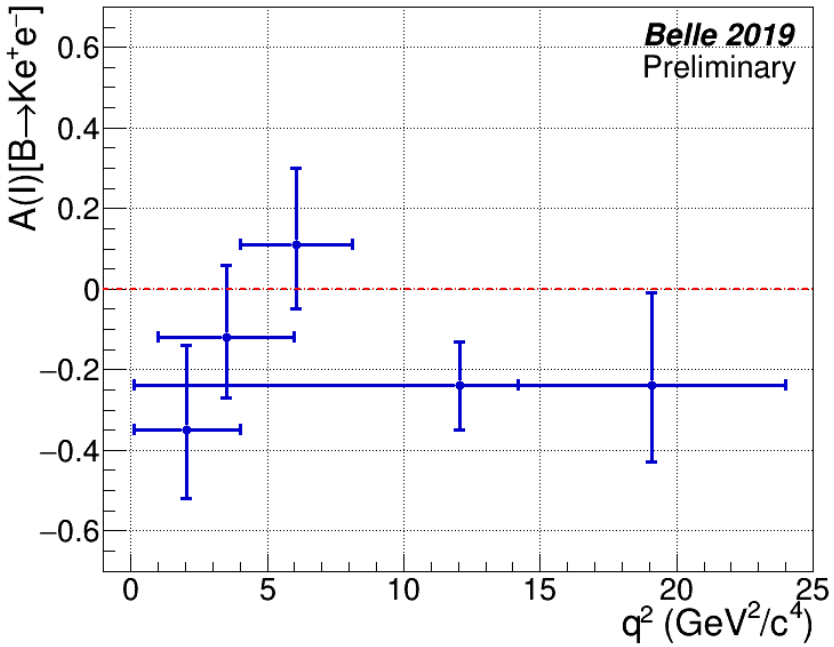
$B \to K\mu^+\mu^-$

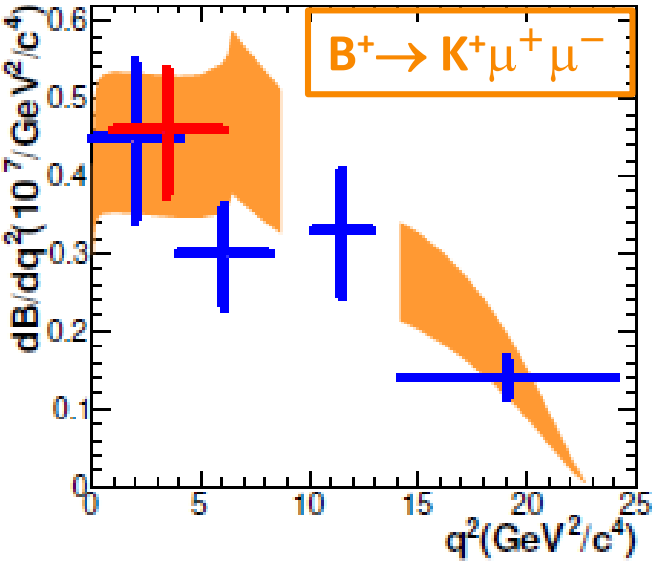


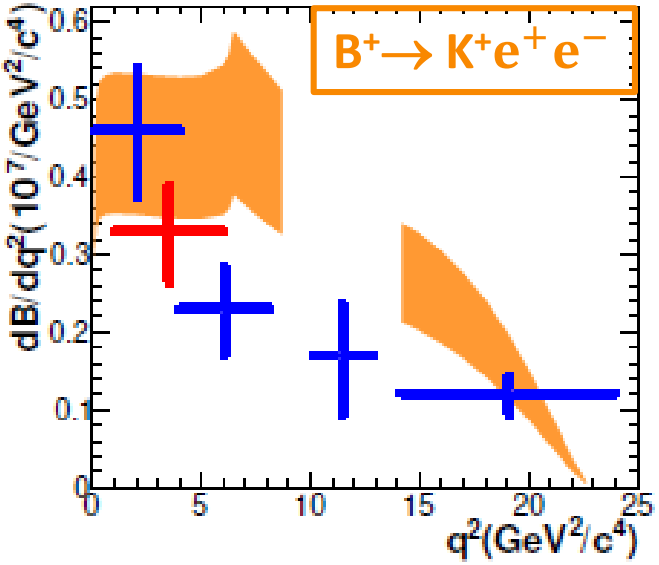

$B \to Ke^+e^-$

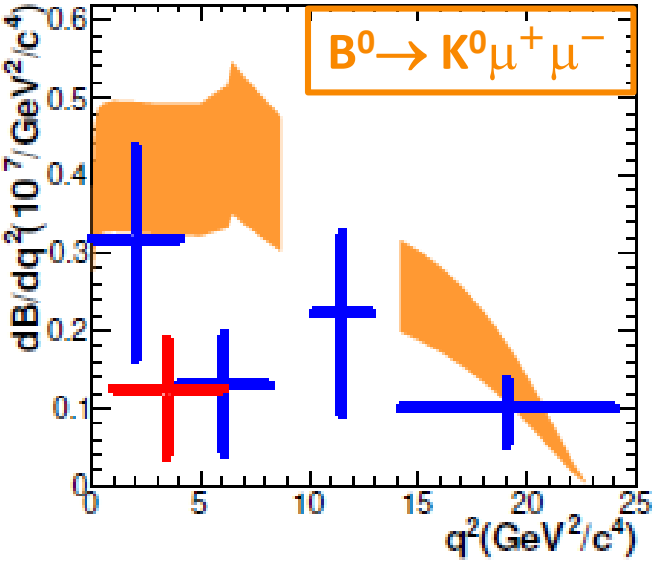


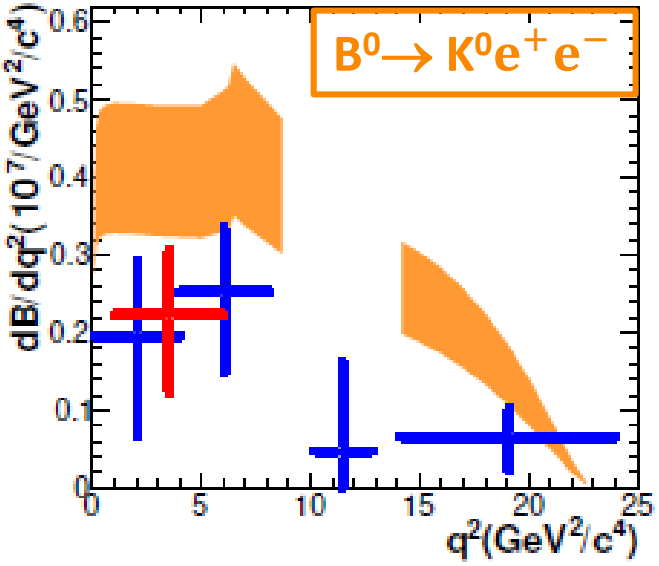
# Differential Branching Fraction measurement at Belle

**JHEP03(2021)105**

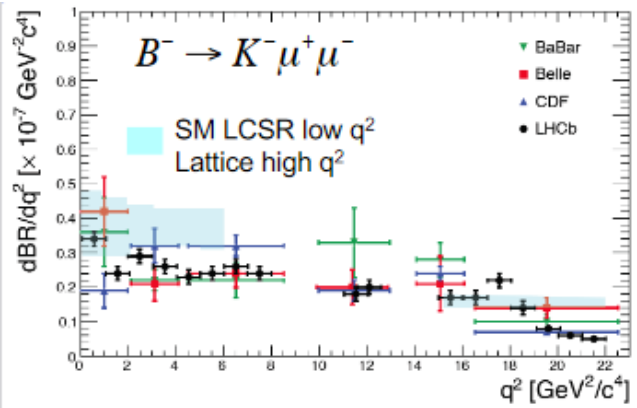


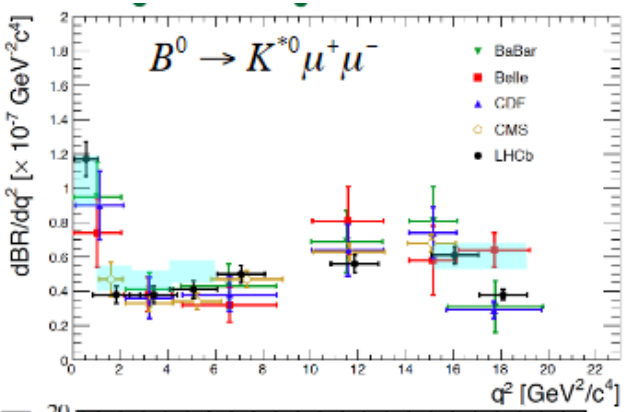



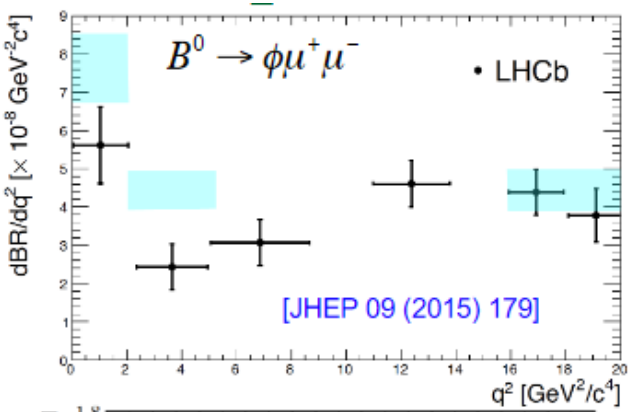



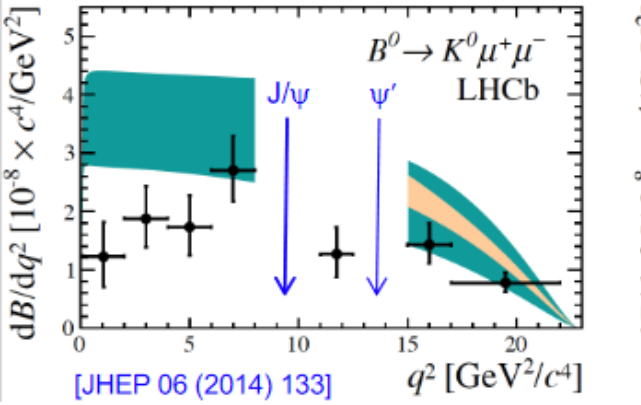



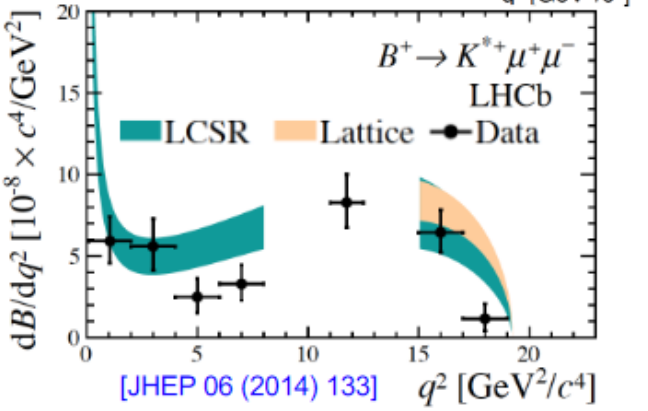
# Differential Branching Fraction measurement at LHCb

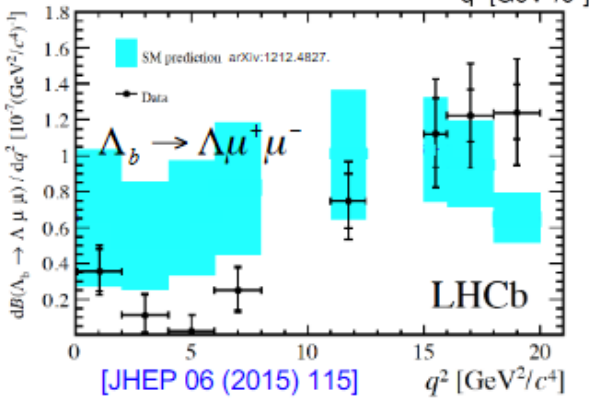


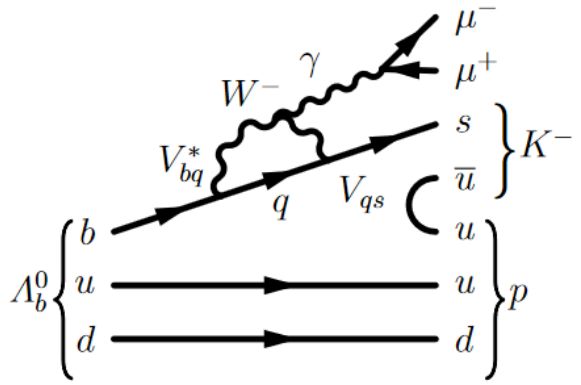



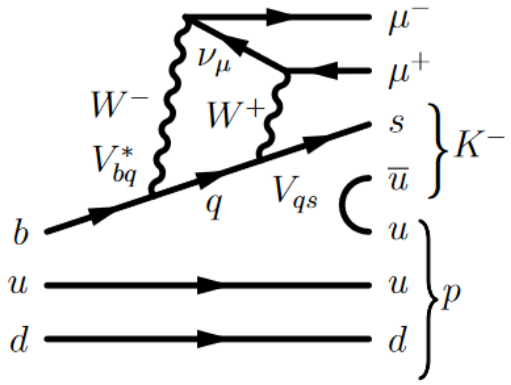



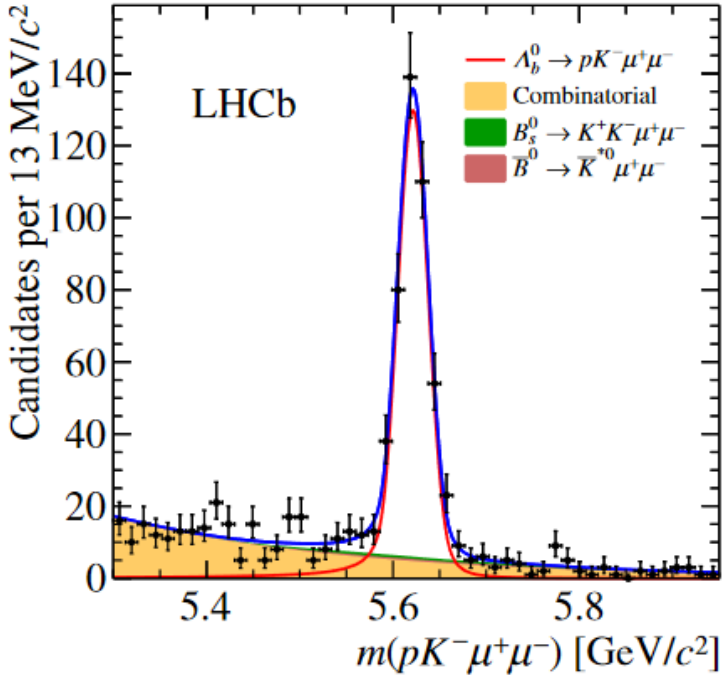



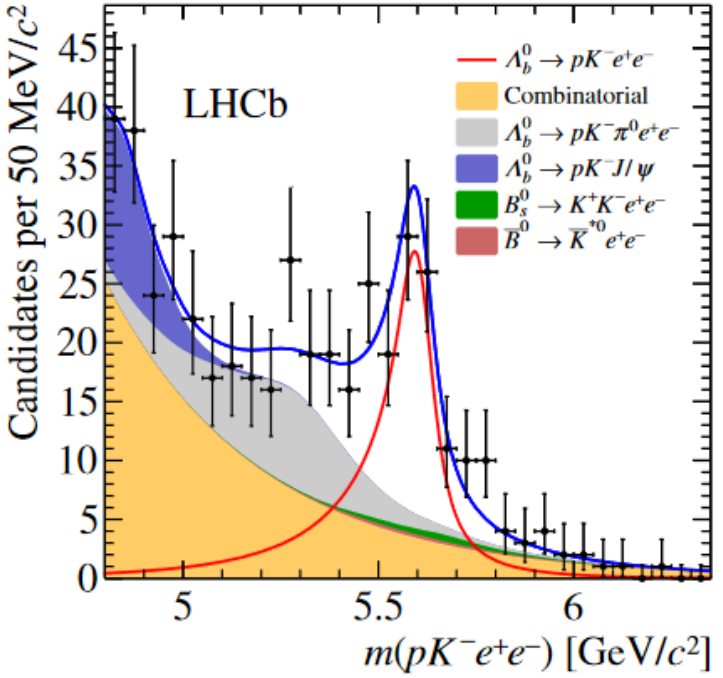

- Data generally below model predictions at low $q^2$

# LFU ratio for the decay $\Lambda_b^0 \to p\, K^- \ell\ell$ at LHCb




$$R_{pK}|_{0.1<q^2<6\ \mathrm{GeV}^2/c^4} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

# Search for LFV decay $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$

- Measurements have exhibited **possible deviations in R(K) and R(K*)** from LFU.
- **Violation of LFU** is accompanied by **LFV**.

**S. L. Glashow et.al PRL 114, 091801 (2015)**

- LFV decay $\mathbf{B^0 \to K^{*0}\mu^{\pm}e^{\mp}}$ is searched at **Belle**.

**Phys. Rev. D 98, 071101(R) 2018**

- $\mathbf{K^{\pm}}$, $\mathbf{\pi^{\pm}}$, $\mathbf{\mu^{\pm}}$ **and** $\mathbf{e^{\pm}}$ candidates are selected from tracks **near IP** and **satisfying PID** requirements. Inv. mass from K-$\pi$ should be within **100 MeV window around** $\mathbf{K^{*0}}$ nominal mass.

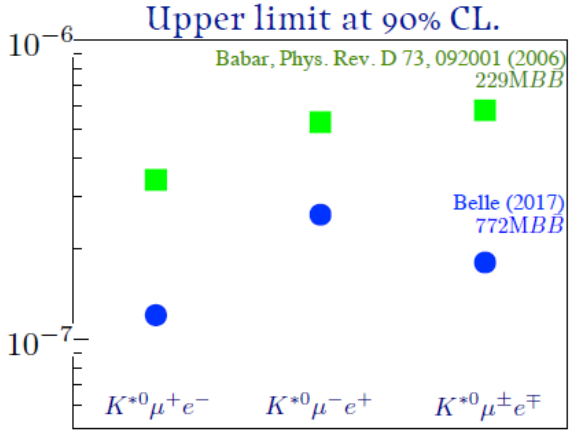
- **continuum** background events are suppressed using input variables based on event topology in a **NN**. Another NN is used to suppress background originating from **B-decays**. $\mathbf{B^0 \to K^{*0}J/\psi}$ was a good control sample and it is also used to **calibrate** the NNs.

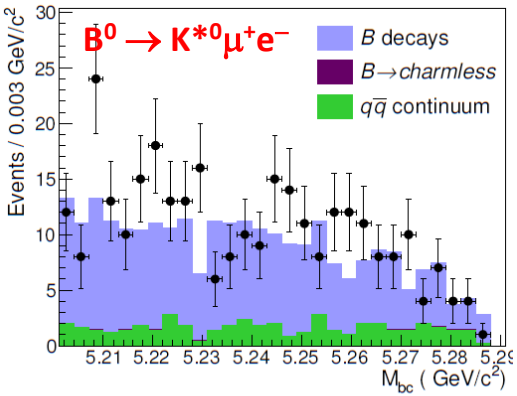
- **set of vetoes** applied to suppress events from $\mathbf{B^0 \to K^{*0}\,[K^+\pi^-]J/\psi[\ell^+\ell^-]}$ decays in which one of the **leptons is misidentified and swapped with the** $\mathbf{K^+}$ **or** $\mathbf{\pi^-}$.

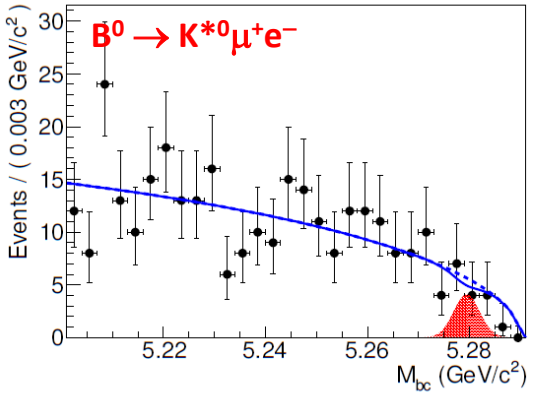
# Search for LFV decay $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$

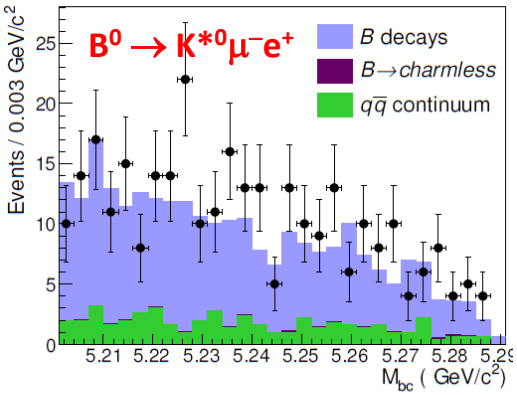
- **good agreement** between **data and MC** for both the **number of events observed** and the **shapes** of the distributions.
- **No signal** is observed → **UL** is derived.

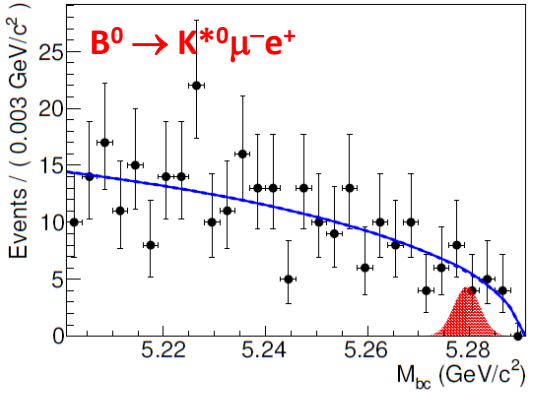
| Mode | ε (%) | $N_{sig}$ | $B^{UL}$ ($10^{-7}$) |
|---|---|---|---|
| $B^0 \to K^{*0}\mu^+e^-$ | 8.8 | $-1.5^{+4.7}_{-4.1}$ | 1.2 |
| $B^0 \to K^{*0}\mu^-e^+$ | 9.3 | $0.40^{+4.8}_{-4.5}$ | 1.6 |
| $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ | 9.0 | $-1.2^{+6.8}_{-6.2}$ | 1.8 |

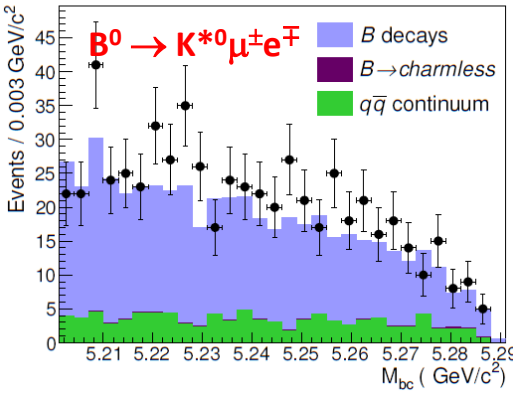


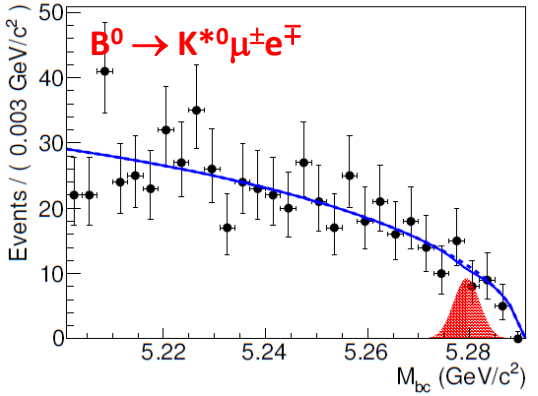



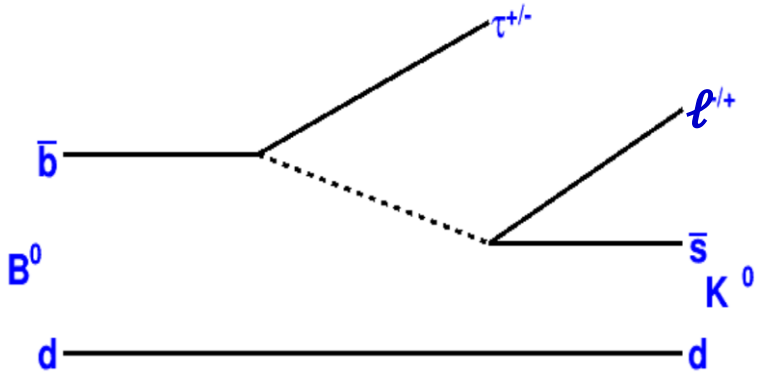



# Searches for LFV B decay with τ in the final state

- From the Lepto-quark model perspective LFV modes with τ in the final state is of particular interest as preserves the (lepton-quark) generation.



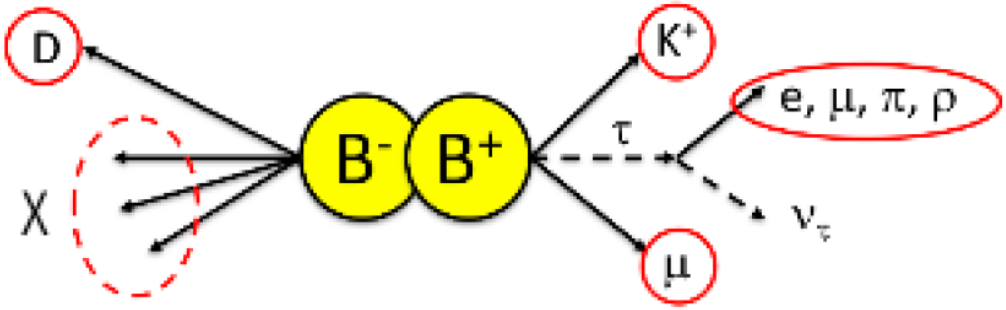

- Results from BaBar Collaboration [**Phys.Rev.D 86 (2012) 012004**] are based on hadronic $B_{tag}$ reconstruction method.

| Mode | $\mathcal{B}(B \to h\tau\ell)(\times 10^{-5})$ Central value | 90% C.L. UL |
|---|---|---|
| $B^+ \to K^+\tau\mu$ | $0.0^{+2.7}_{-1.4}$ | <4.8 |
| $B^+ \to K^+\tau e$ | $-0.6^{+1.7}_{-1.4}$ | <3.0 |
| $B^+ \to \pi^+\tau\mu$ | $0.5^{+3.8}_{-3.2}$ | <7.2 |
| $B^+ \to \pi^+\tau e$ | $2.3^{+2.8}_{-1.7}$ | <7.5 |

- Recently LHCb [**JHEP 06 (2020) 129**] also searched for the decay $B^+ \to K^+\tau^+\mu^-$ with 9 $fb^{-1}$ data.
- The four-momentum of the τ lepton is determined by using $B^+$ mesons from $B_{s2}^{*0} \to B^+K^-$ decays.
- No significant excess is observed, and an UL is set on the BF @ 90% CL : **$BF[B^+ \to K^+\tau^+\mu^-] < 3.9 \times 10^{-5}$**

# Searches for LFV B decay with τ in the final state @ Belle (II)

- Studies are ongoing in Belle (II) with hadronic tag (UL@95% CL estimated to be around $1 \times 10^{-5}$) .
- Can we do better ? Combining hadronic tag with an more inclusive tag?...
- Exploit the high BF of $B^+ \rightarrow \overline{D^0} X$
- Reconstruct $D^0$ + inclusive X




| | $B^+ \rightarrow$ | $B^0 \rightarrow$ |
|---|---|---|
| $D^0 X$ | $(8.6 \pm 0.7)\%$ | $(8.1 \pm 1.5)\%$ |
| $\overline{D}^0 X$ | $(79 \pm 4)\%$ | $(47.4 \pm 2.8)\%$ |
| $D^+ X$ | $(2.5 \pm 0.5)\%$ | $(< 3.9\%)$ |
| $D^- X$ | $(9.9 \pm 1.2)\%$ | $(36.9 \pm 3.3)\%$ |
| $D_s^+ X$ | $(7.9 \pm 1.4)\%$ | $(10 \pm 2)\%$ |
| $D_s^- X$ | $(1.10 \pm 0.40)\%$ | $(< 2.6\%)$ |
| $\Lambda_c^+ X$ | $(2 \pm 1)\%$ | $(< 3.1\%)$ |
| $\Lambda_c^- X$ | $(3 \pm 1)\%$ | $(5.0 \pm 2.0)\%$ |

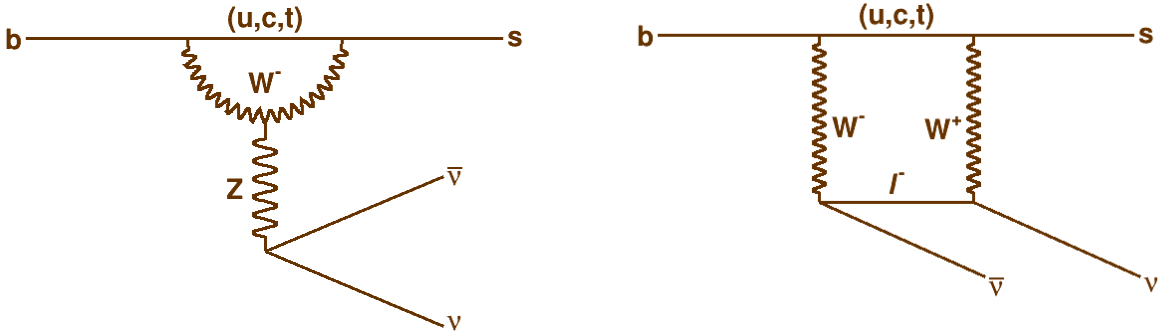
- Application in $B \rightarrow K \tau l$, where the topology with $K+l$ allows looser reconstruction in $B_{tag}$ side

1) D is reconstructed
2) Primary K and l, and τ decay prong are chosen
3) ''D + X'' provides the tag side B

**Snowmass meeting slides:** https://indico.fnal.gov/event/44442/

# Search for $B^+ \to K^+\nu\nu$ at Belle II

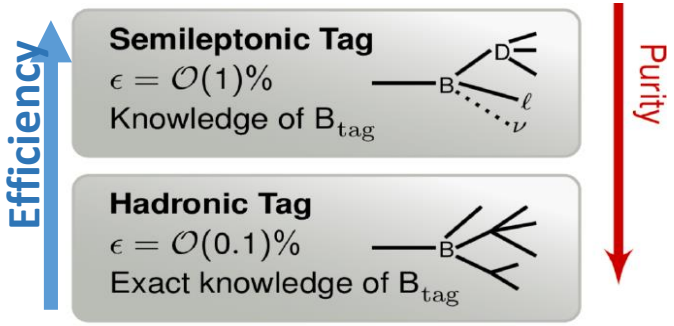
- Recent search for **$B \to K^+\nu\nu$** at **Belle II**, with early $e^+e^-$ collision data of just 63 $fb^{-1}$.
- Proceeds via penguin or box diagrams:




**Belongs to the theoretically cleanest modes in the field of FCNC processes.**
**As the transition mediates by a Z-boson alone**

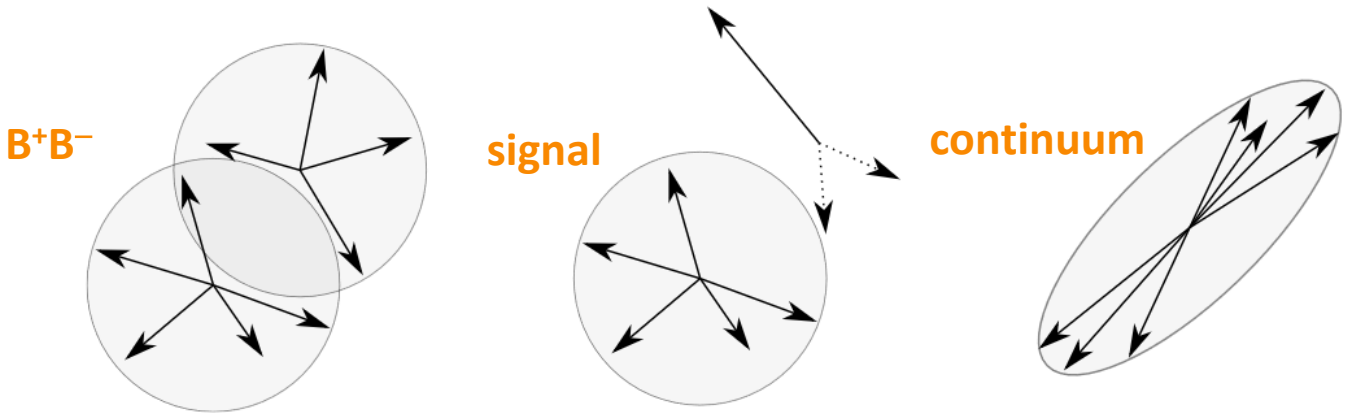
- SM prediction for the **$BF[B \to K^+\nu\nu]_{SM}$** is **$(4.6 \pm 0.5) \times 10^{-6}$** **[The Belle II Physics Book, Prog. Theor. Exp. Phys. 2019, 123C01].**
- Important test for NP models proposed to explain anomalies in b→sll.
- Experimentally challenging, tagging of companion B meson needed.
- **Belle** Hadronic tagging [**PRD87 111103 (2013)**] :
  **$< 5.5 \times 10^{-5}$ $(2.2 \times 10^{-5})$**
- **Belle** Semileptonic tagging [**PRD96 091101 (R) (2017)**] :
  **$< 1.9 \times 10^{-5}$ $(0.8 \times 10^{-5})$**
- **BaBar** Hadronic tagging [**PRD 87, 112005 (2013)**] :
  **$< 3.7 \times 10^{-5}$**
- **BaBar** Semileptonic tagging [**PRD 82, 112002 (2010)**] :
  **$< 1.3 \times 10^{-5}$**

**Tagging Methods:**



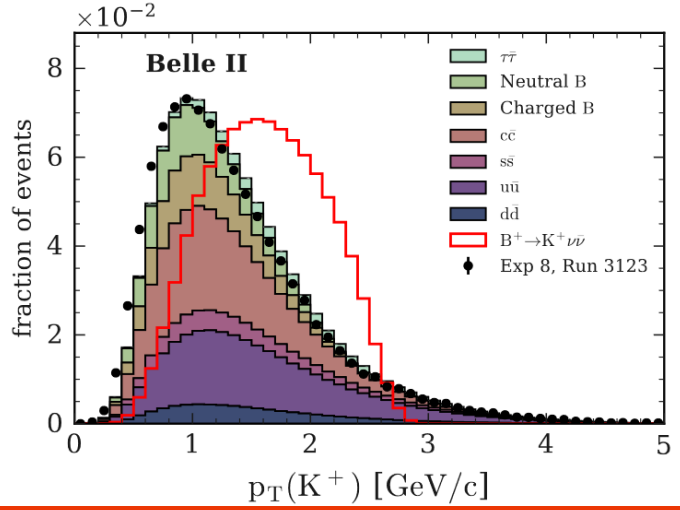
# Search for $B^+ \to K^+\nu\nu$ at Belle II

- In this search, an inclusive tagging approach is used, which benefits from larger signal efficiency (~4%) at the cost of higher background levels.



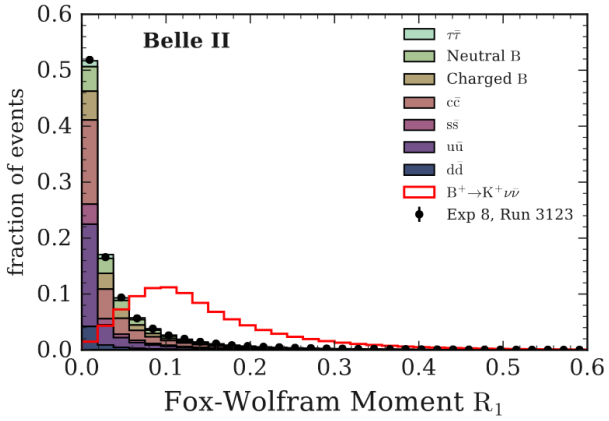

- The analysis method exploits the distinctive topological features of the decay to suppress backgrounds : generic B and continuum

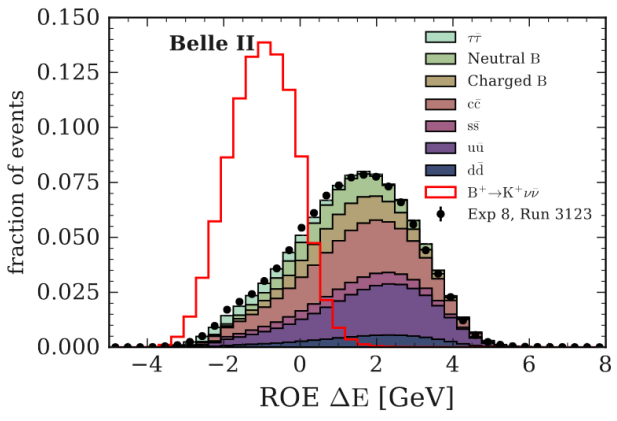
- Signal $K^+$ track as highest $p_T$ track in an event.
- The remaining track and cluster assigned to the other “B” and called “ROE” and a common vertex is fitted.

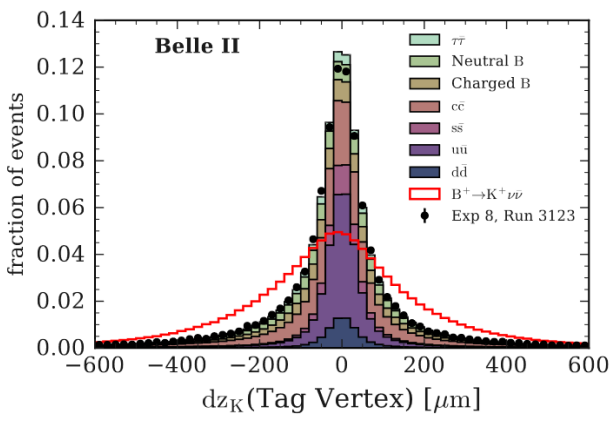


# Search for $B^+ \to K^+\nu\nu$ at Belle II

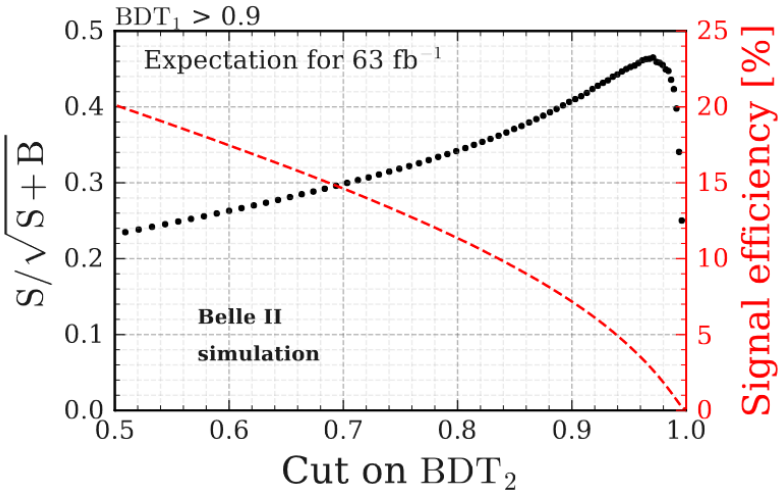
- Minimizing the background contamination with constraints on event topology, missing energy and vertex separation



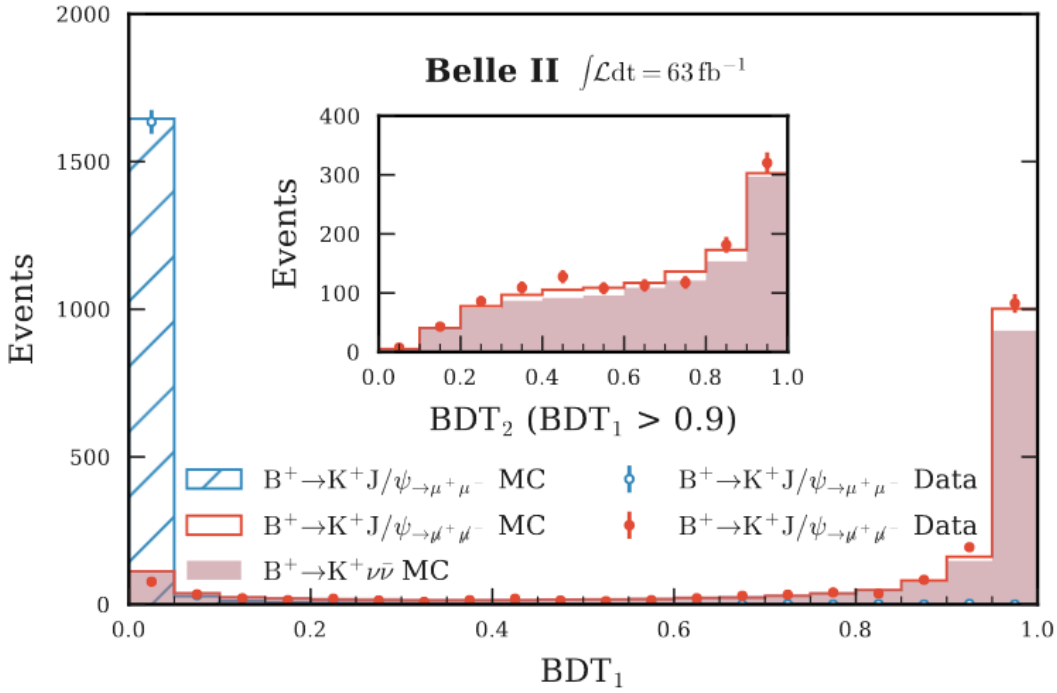




- $BDT_1$ is trained on 51 most discriminating variable w/o loss of performance and then $BDT_2$ is trained with the same set of variables but only on events with $BDT_1 > 0.9$
- The efficiency for the SM signal is 4.3% for the criteria on $BDT_2 > 0.95$.
- The efficiency is highest towards low $q^2$ ($q^2 \sim 0$, 10%) and drops to zero for $q^2 > 15 GeV^2/c^2$.



# Search for $B^+ \to K^+\nu\nu$ at Belle II

- The decay $B^+ \to K^+ J/\psi$ $[\to \mu^+\mu^-]$ is used to validate the analysis strategy.
- Events reconstructed ignoring the muons from $J/\psi$ to mimic missing momenta and K+ kinematics updated.




- The statistical analysis to determine the signal strength is performed with the **`pyhf`** package, which implements the **`Histfactory`** statistical model.
- The BF [$B \to K^+\nu\nu$ ] is computed using a ML fit to binned [in $p_T(K^+)$ and $BDT_2$ ] distribution of event counts.

# Search for $B^+ \to K^+\nu\nu$ at Belle II

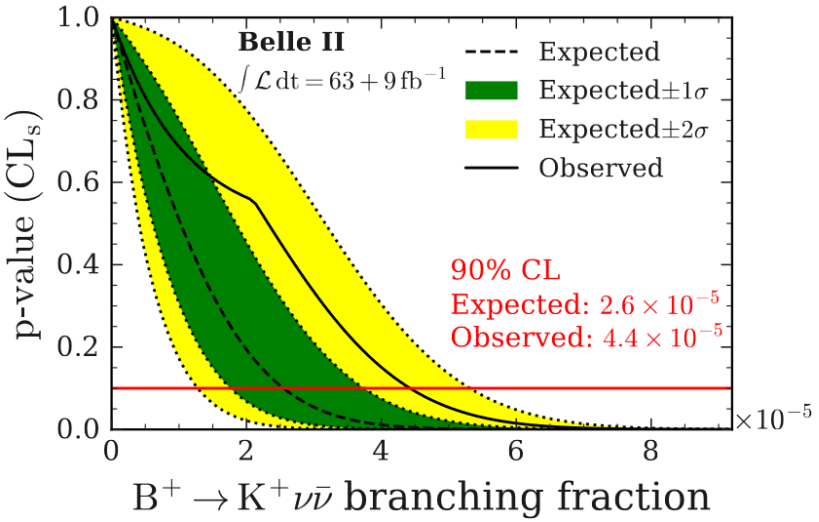
- Measured signal strength $\mu$:

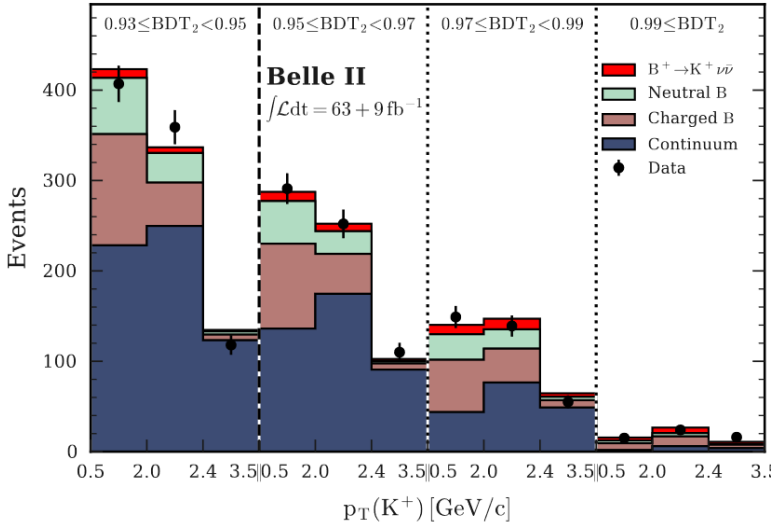
$$\mu = 4.2^{+2.9}_{-2.8}(\text{stat.})^{+1.8}_{-1.6}(\text{syst.}) = 4.2^{+3.4}_{-3.2}$$

Consistent with the bkg-only hypothesis ($\mu = 0$) at CL 1.3 $\sigma$

Consistent with the SM hypothesis ($\mu = 1$) at CL 1 $\sigma$

$$\text{BF}[B \to K^+\nu\nu] = 1.9^{+1.3}_{-1.3}(\text{stat.})^{+0.8}_{-0.7}(\text{syst.}) \times 10^{-5} = 1.9^{+1.6}_{-1.5} \times 10^{-5}$$




- As no significant signal is observed, **the observed UL $4.4 \times 10^{-5}$** (and expected $2.6 \times 10^{-5}$)is computed using $CL_s$ method at 90% confidence level

# Search for $B^+ \to K^+\nu\nu$ at Belle II

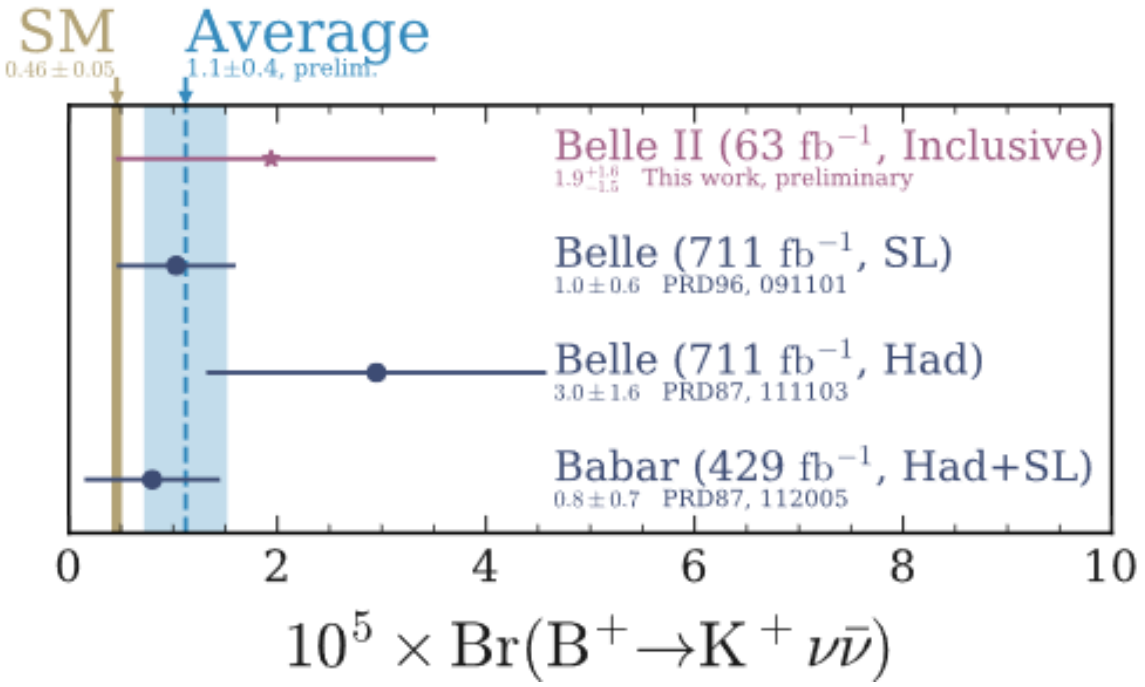
- Measured signal strength $\mu$:

$$\mu = 4.2^{+2.9}_{-2.8}(\text{stat.})^{+1.8}_{-1.6}(\text{syst.}) = 4.2^{+3.4}_{-3.2}$$

Consistent with the bkg-only hypothesis ($\mu = 0$) at CL 1.3 $\sigma$

Consistent with the SM hypothesis ($\mu = 1$) at CL 1 $\sigma$

BF[$B \to K^+\nu\nu$] = $1.9^{+1.3}_{-1.3}(\text{stat.})^{+0.8}_{-0.7}(\text{syst.}) \times 10^{-5} = 1.9^{+1.6}_{-1.5} \times 10^{-5}$

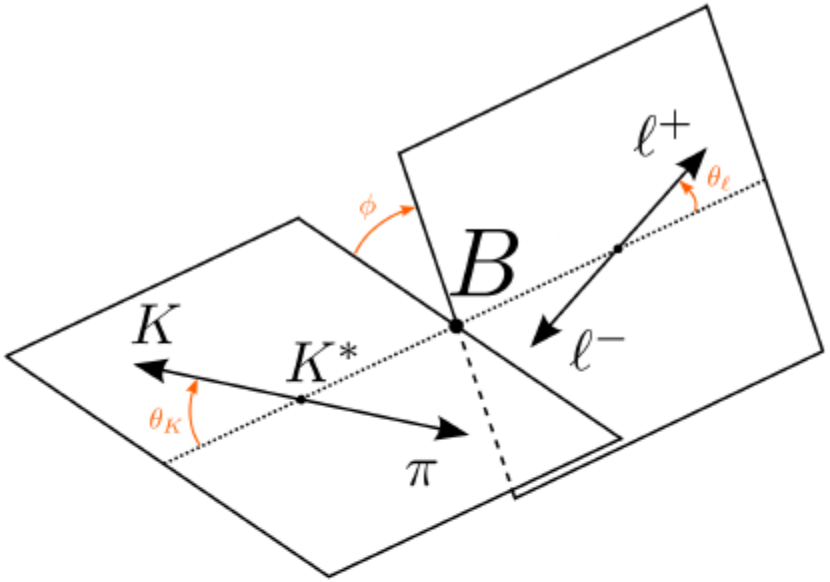


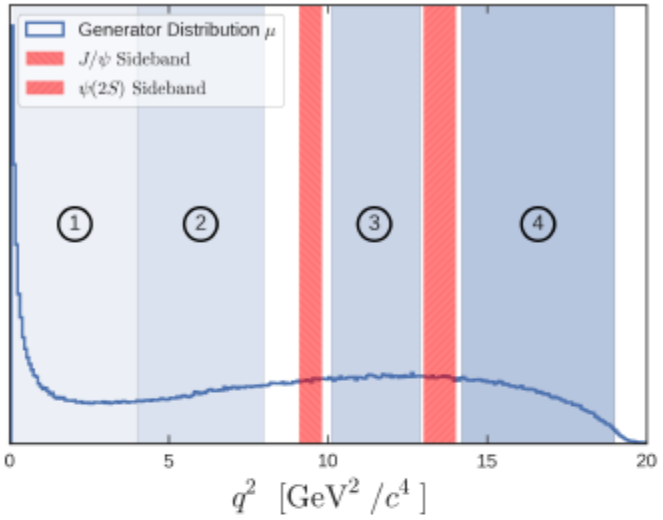
# Summary

- The decays $B \to K^{(*)}\ell^+\ell^-$ were first observed by Belle (2001).
- Anomalies at level of $3.3\sigma$ in angular analyses and suggests in the modes with muons.
- Lepton Flavor dependent angular analysis of $B \to K^*\ell^+\ell^-$ performed at Belle: Consistent with both SM and NP with $C_{9\mu}^{NP} \approx -1.1$.
- LFU ratios also confirm this hint of deviations with SM prediction in R(K) and R(K*)
- This also calls for searches for the LFV decay $B^0 \to K^{(*)}\ell\ell'$ (specially decays with $\tau$-lepton in the final states)
- Search for $B^+ \to K^+\nu\nu$ is performed based on inclusive tagging and the sensitivity with just 63 $fb^{-1}$ data is already close to previous searches with significantly large data-set
- Belle II has brighter prospects for EWP rare decays with its upcoming large data.

# Extra Slides

# Full Angular Analysis




The observables are depended on $q^2 = M^2_{\ell^+\ell^-}$

The differential decay rate for $B \to K^* \ell^+ \ell^-$ can be written as

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

# $P_5'$ asymmetries

1606.00999

## Inset 3: The $A_{\rm FB}$, $F_{\rm L}$ and $P_5'$ asymmetries

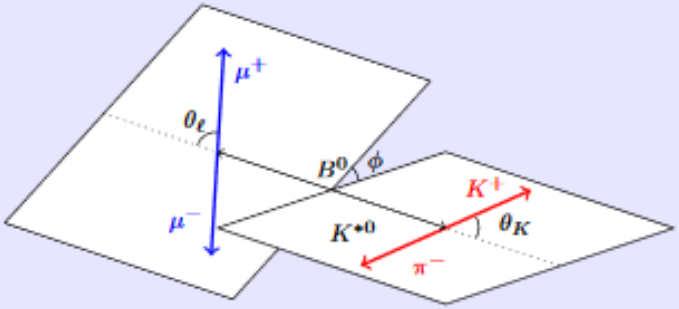



**Figure 11:** The angles $\theta_\ell$, $\theta_K$ and $\phi$ in the decay $B \to K^* \mu^+ \mu^-$. Figure by Thomas Blake.

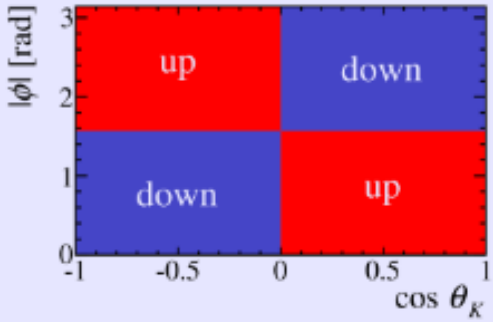



**Figure 12:** Definition of the $P_5'$ asymmetry.

In the decay $B^0 \to K^{*0}\mu^+\mu^-$, followed by $K^{*0} \to K^+\pi^-$, the direction of the four outgoing particles can be described by three angles, shown in Fig. 11. The forward-backward asymmetry $A_{\rm FB}$ is defined as the relative difference between the number of positive and negative leptons going along the direction of the $B^0$ meson in the rest frame of the two-lepton system. This corresponds to an asymmetry in the distribution of the $\theta_\ell$ angle. Similarly, the $K^{*0}$ polarisation fraction $F_{\rm L}$ depends on the angle $\theta_K$, defined analogously to $\theta_\ell$. Other asymmetries can be constructed from the other angles or combinations of them. The $P_5'$ asymmetry suggested by Ref. [101] is based on the angles $\theta_K$ and $\phi$. It is defined as the relative difference between the number of decays in the regions in red and blue in Fig. 12, divided by $\sqrt{F_{\rm L}(1-F_{\rm L})}$. Quantities based on several angles are more difficult to measure than single-angle ones as they require a better understanding of the reconstruction efficiencies depending on the kinematics of the outgoing particles.

# Folding Procedure

$$P_4', S_4: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_L > \pi/2 \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \pi/2, \end{cases}$$

$$P_5', S_5: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \pi/2, \end{cases}$$

- With a transformation of the angles, the dimension is reduced to three free parameters
- Each transformation remains three observables $S_j$, $F_L$ and $S_3$
- The observables

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

are considered to be largely free from form-factor uncertainties (J. High Energy Phys. 05 (2013) 137).

- Transverse polarization asymmetry

$$A_T^{(2)} = \frac{2S_3}{(1-F_L)}$$

# Belle II prospects for angular analysis