Rare Decays and Lepton Flavor Universality Ratios

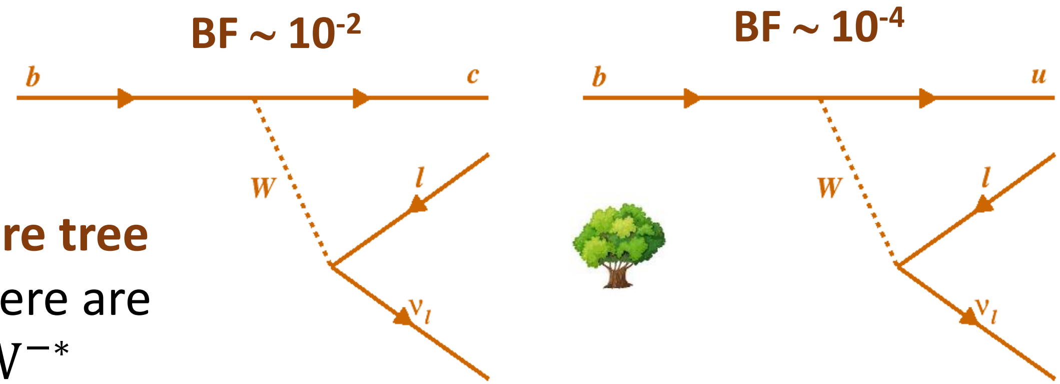
Saurabh Sandilya

University of Cincinnati

(Jul 29, 2019)

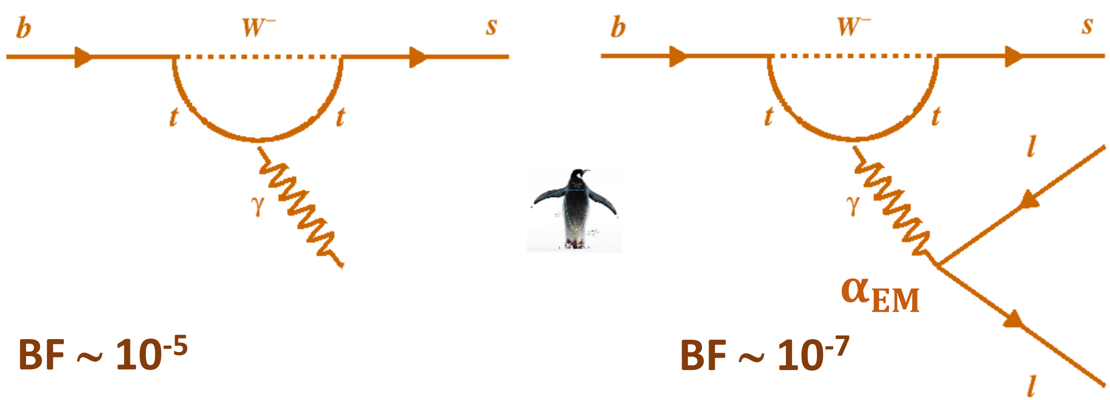
The APS Division of Particles & Fields (DPF) Meeting 2019

- We will focus on rare decays of mesons contains a *b*-quark : “*B*-mesons”

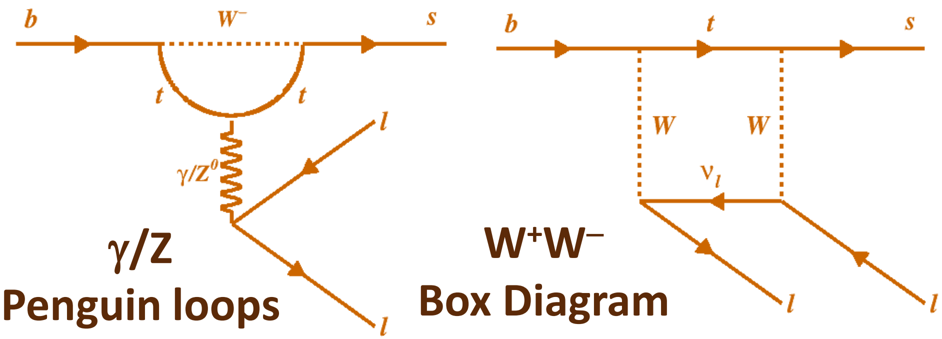


- **Dominant decays of *b*-quarks are tree level transitions $b \rightarrow cW^{-*}$.** There are also rare tree transition $b \rightarrow uW^{-*}$ (suppressed by $|V_{cb}/V_{ub}|^2$).

- $\boldsymbol{b \rightarrow s}$ (or, $b \rightarrow d$) quark level transitions are 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).



- **The decays such as $B \to K^{(*)} \ell^+ \ell^-$** are manifestations of quark level transitions $b \to s \ell^+ \ell^-$.

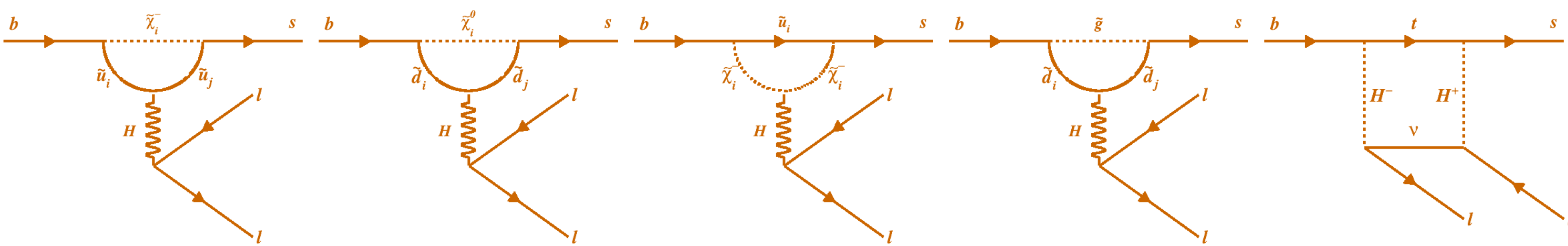


γ/Z Penguin loops

W⁺W⁻ Box Diagram

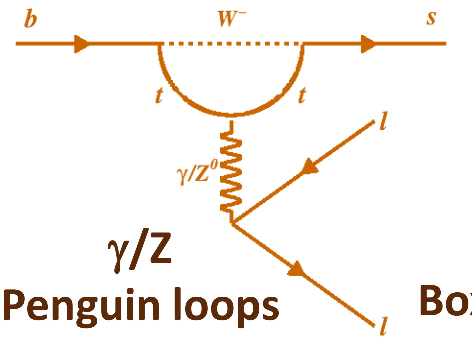
a virtual t quark contribution dominates, with secondary contributions from virtual c and u quarks.

- **Sensitive to NP:** Interference from the 'possible' contribution from the BSM.

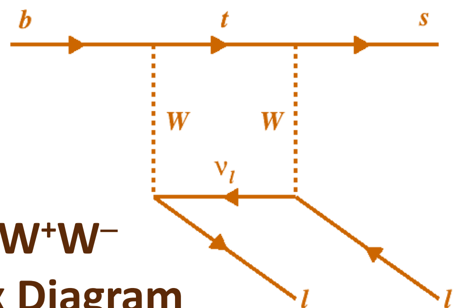


- These decays are rich laboratories of NP studies on its own and **offer hope of new physics.**

- **The decays such as $B \to K^{(*)} \ell^+\ell^-$** are manifestations of quark level transitions $b \to s\ell^+\ell^-$.

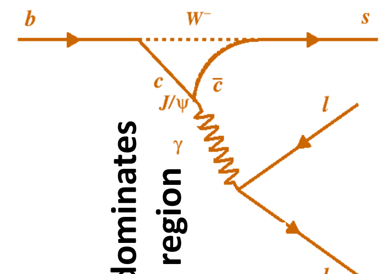


γ/Z
Penguin loops



W⁺W⁻
Box Diagram

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

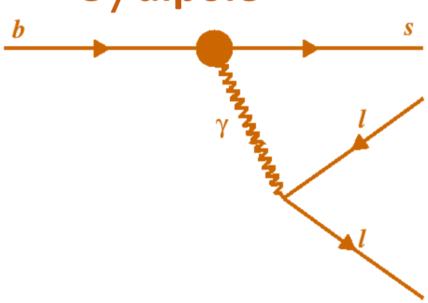


The relevant **effective Hamiltonian**:

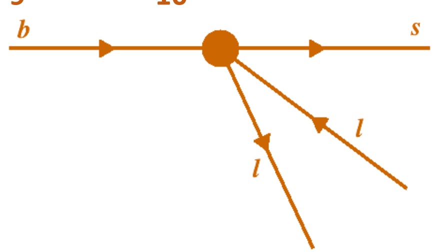
$$\mathbf{H_{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^{*} \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C'_i O'_i) + \text{h.c.}$$

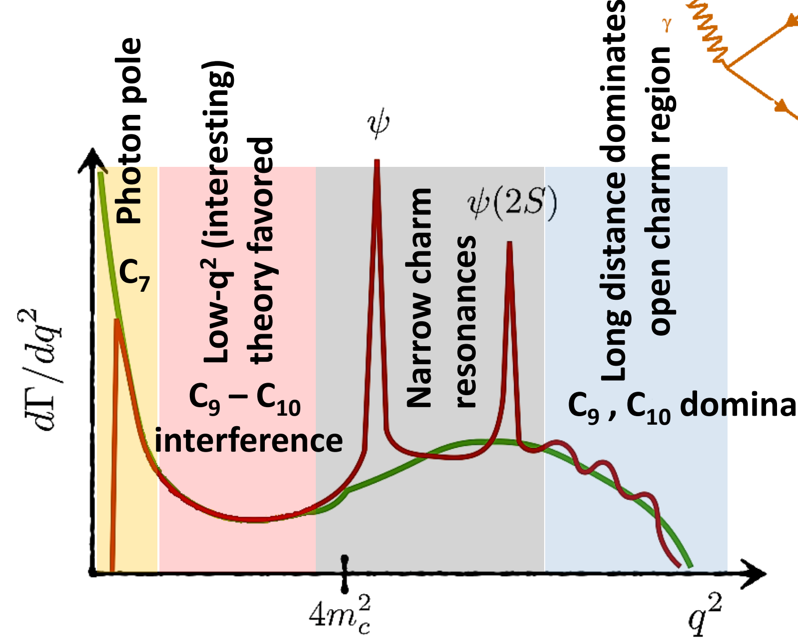
The Operators which are most sensitive to the NP:

O_7 dipole

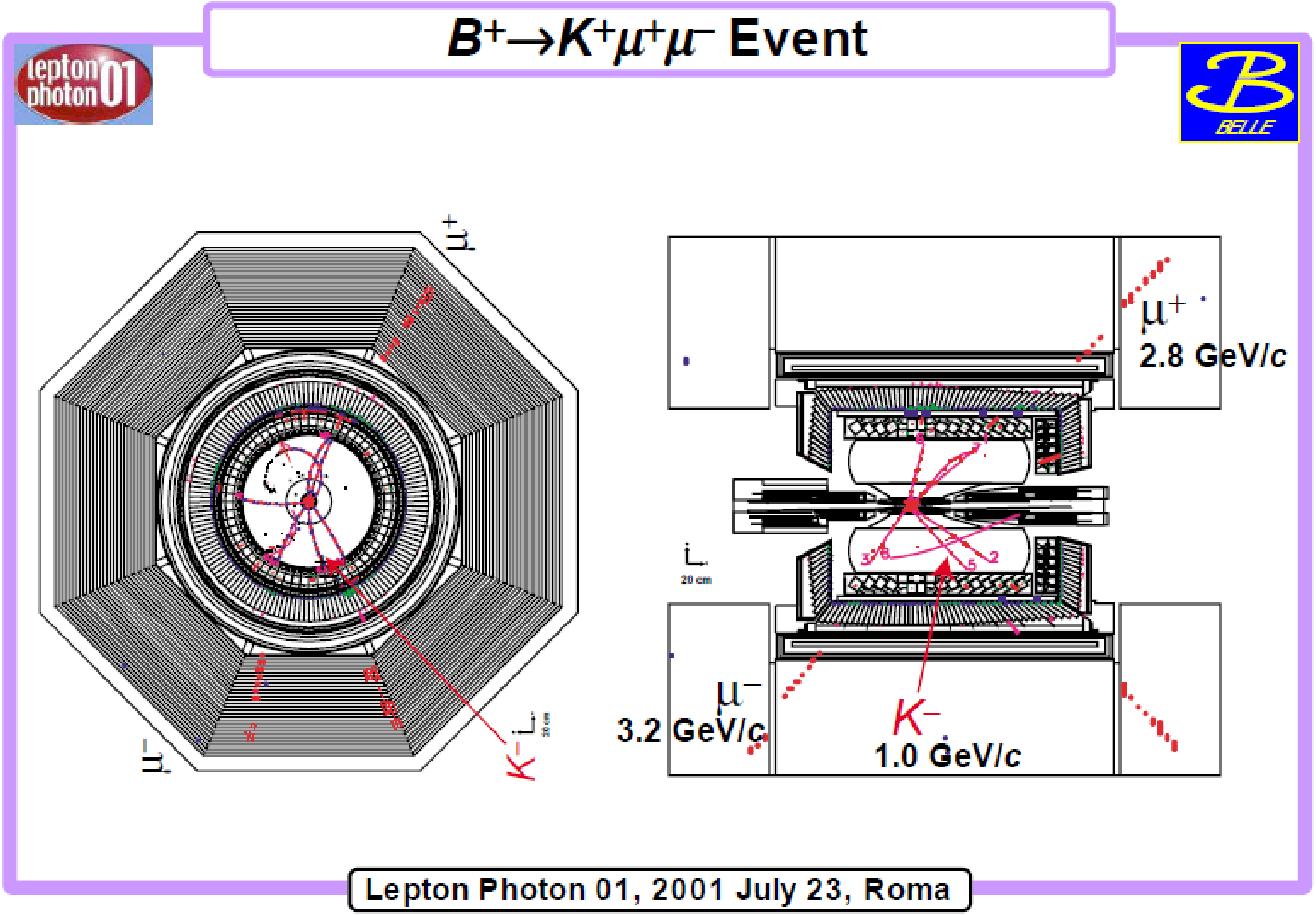


O_9 and O_{10} Four fermion



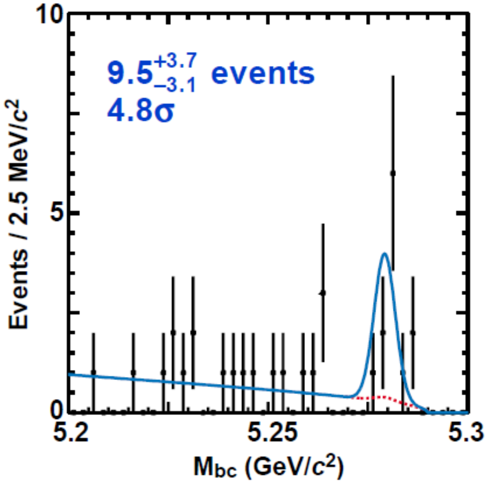


First observation of a b → $s\ell^+\ell^-$ decay (LP-2001)



29.5 fb^{-1}

$B^+ \to K^+\mu^+\mu^-$
$B^0 \to K_s^0\,\mu^+\mu^-$
combined



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

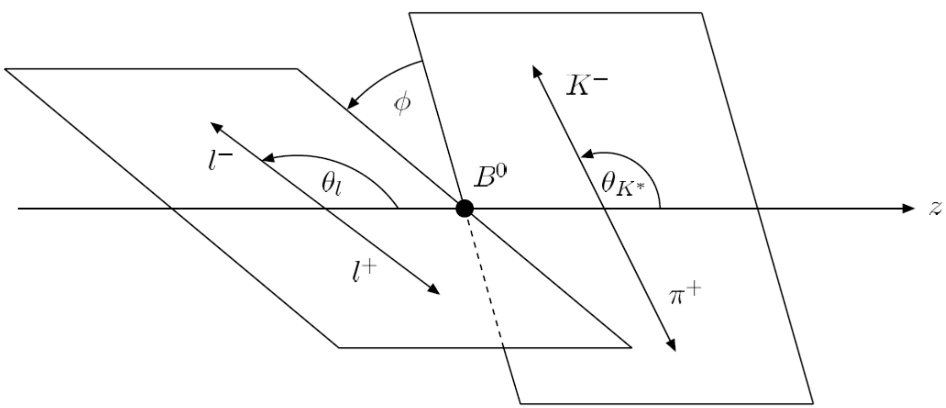
$B \rightarrow K^{(*)}\ell^+\ell^-$ based on 657 M BB pairs

- $\ell^+\ell^-$ → $\mu^+\mu^-$ and e^+e^-
- $K^{(*)}$ → $K^+\pi^-$, $K^0_S\pi^+$, $K^+\pi^0$, K^+ and K^0_S

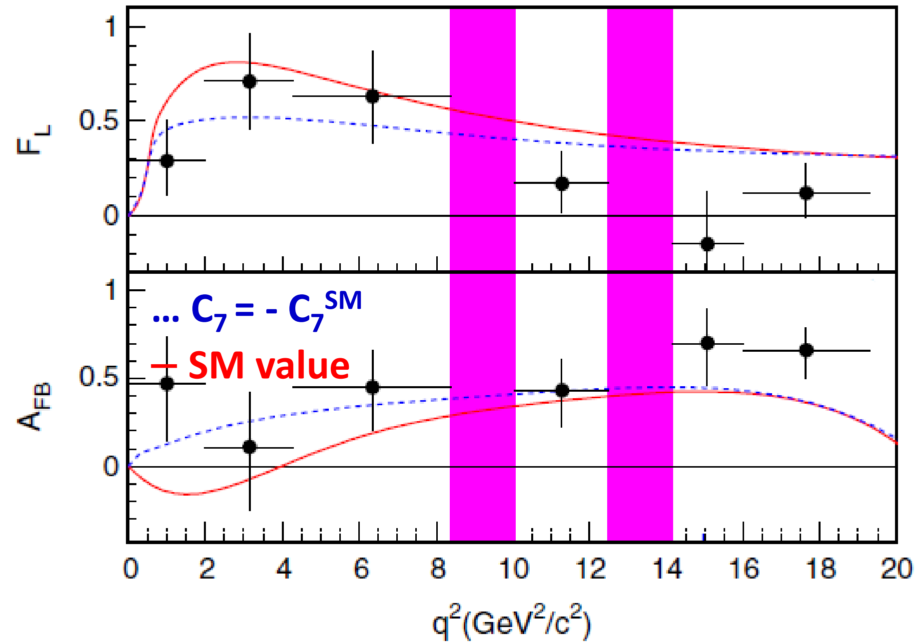
F_L and A_{FB} are obtained from fit to $\cos\theta_{K^*}$ and $\cos\theta_{B\ell}$

$$[\tfrac{3}{2}F_L\cos^2\theta_{K^*} + \tfrac{3}{4}(1 - F_L)(1 - \cos^2\theta_{K^*})]\epsilon(\cos\theta_{K^*})$$

$$[\tfrac{3}{4}F_L(1 - \cos^2\theta_{B\ell}) + \tfrac{3}{8}(1 - F_L)(1 + \cos^2\theta_{B\ell}) + A_{FB}\cos\theta_{B\ell}]\epsilon(\cos\theta_{B\ell})$$



Belle PRL103, 171801 (2009)



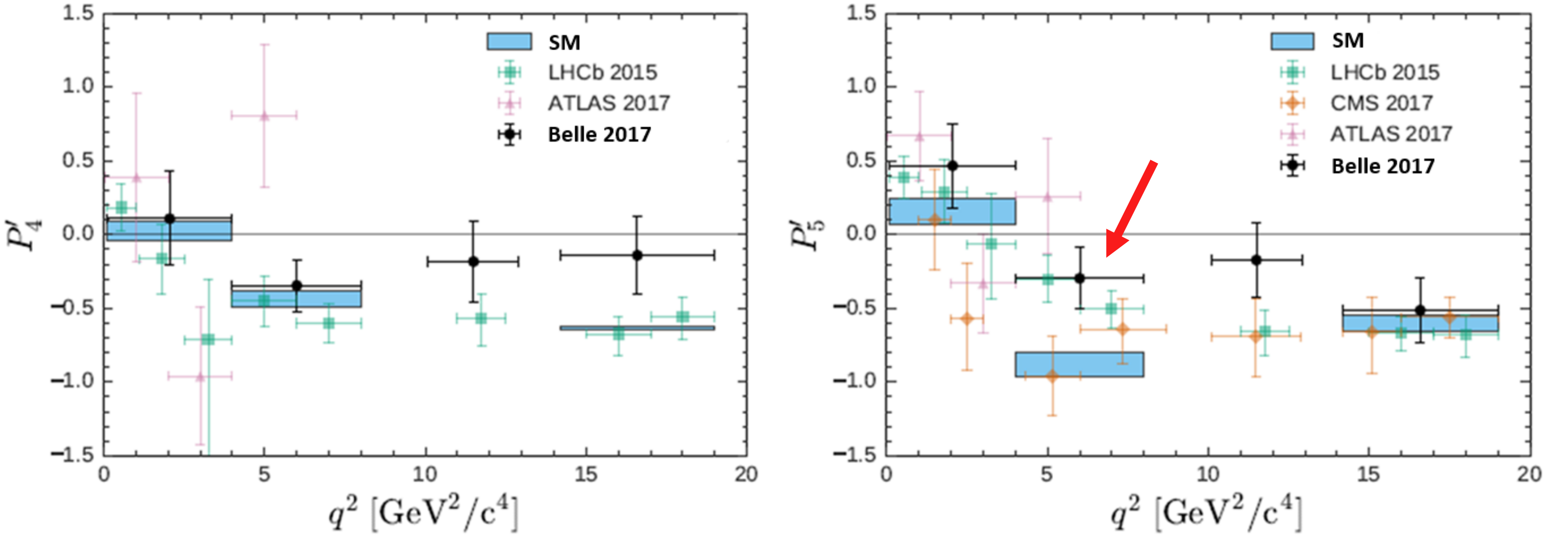
For full q^2 range:

$R(K^*) = 0.83 \pm 0.17 \pm 0.08$
$R(K) = 1.03 \pm 0.19 \pm 0.06$

Till last year

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

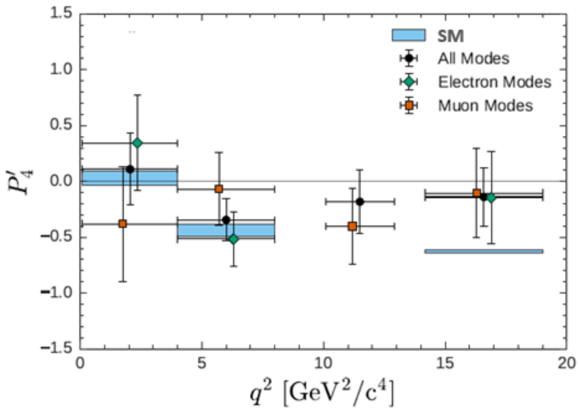
- A number of angular observables in $B \to K^* \ell^+ \ell^-$ decays can be theoretically predicted with good control of the relevant form factor uncertainties.
- The observables ***P_i'*** are considered to be largely free from form-factor related uncertainties (**Introduced by LHCb in PRL 111, 191801 (2013)**)

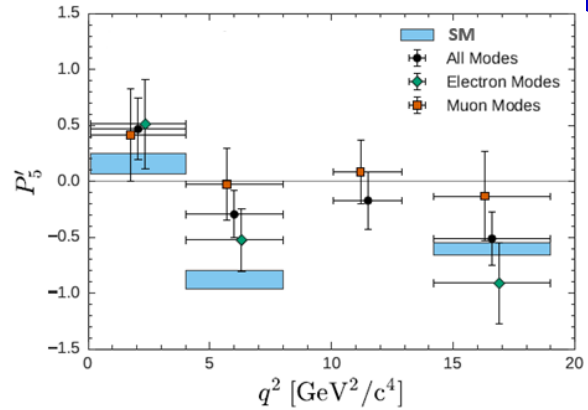


- Measurements are mostly compatible with the SM.
- LHCb observed deviation wrt SM predictions in P_5' with 3.7 σ .
- Belle observed similar central values for the P_5' anomaly $q^2 \in (1.1,6.0)$ GeV^2/c^4 with 2.5σ tension.

SM: S. Descotes-Genon, L. Hofer, J. Matias, and J. Virto JHEP10, 075 (2016).
R. R. Horgan, Z. Liu, S. Meinel, and M. Wingate PoS LATTICE2014, 372 (2015).
LHCb: JHEP02, 104 (2016) | Belle : Phys. Rev. Lett. 118, 111801 (2017)
CMS : Phys. Lett. B 781 517 (2018) | ATLAS : JHEP 10 (2018) 047

P_i' and Q_i' in separate lepton flavors

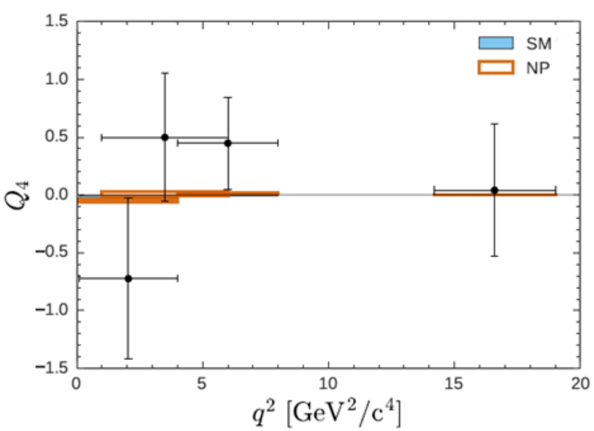


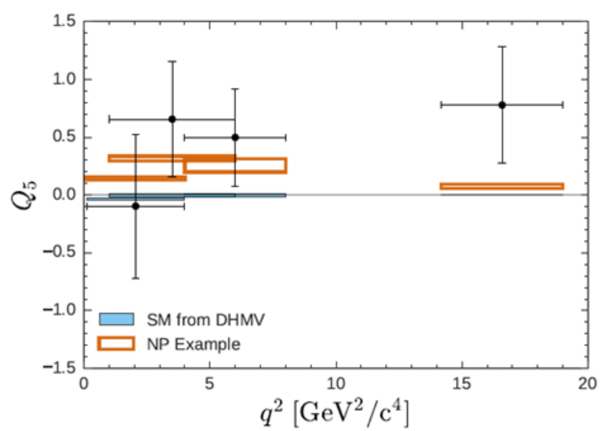


Belle [Phys. Rev. Lett. 118, 111801 (2017)]

- The Largest deviation in the **muon mode with 2.6σ**.
- **Electron mode** is deviating with **1.1σ**.
- Belle (II) is equally efficient in e & μ modes.

- With 2.8 ab^{-1} the uncertainty on P'_5 (e & μ) at Belle II will be comparable to LHCb 3fb^{-1} (μ only). **B2TIP report | arXiv:1808.10567**





- 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 seen.
- Q_4 and Q_5 observables in agreement with SM and central values favoring NP scenario.

Lepton Flavor Universality Ratios

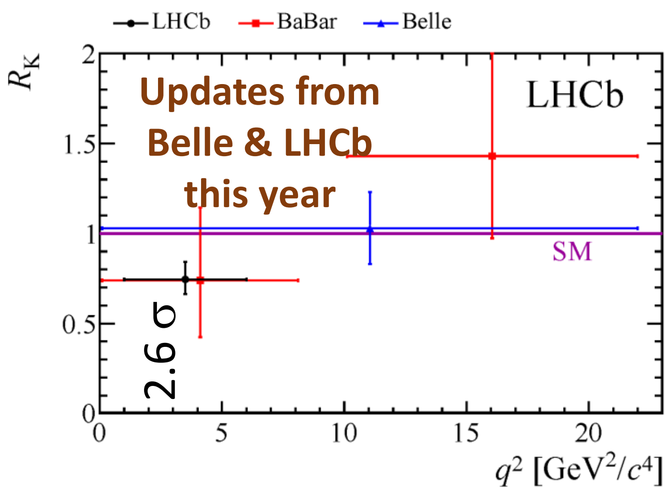
- The lepton flavor universality can be tested very precisely with the ratios:

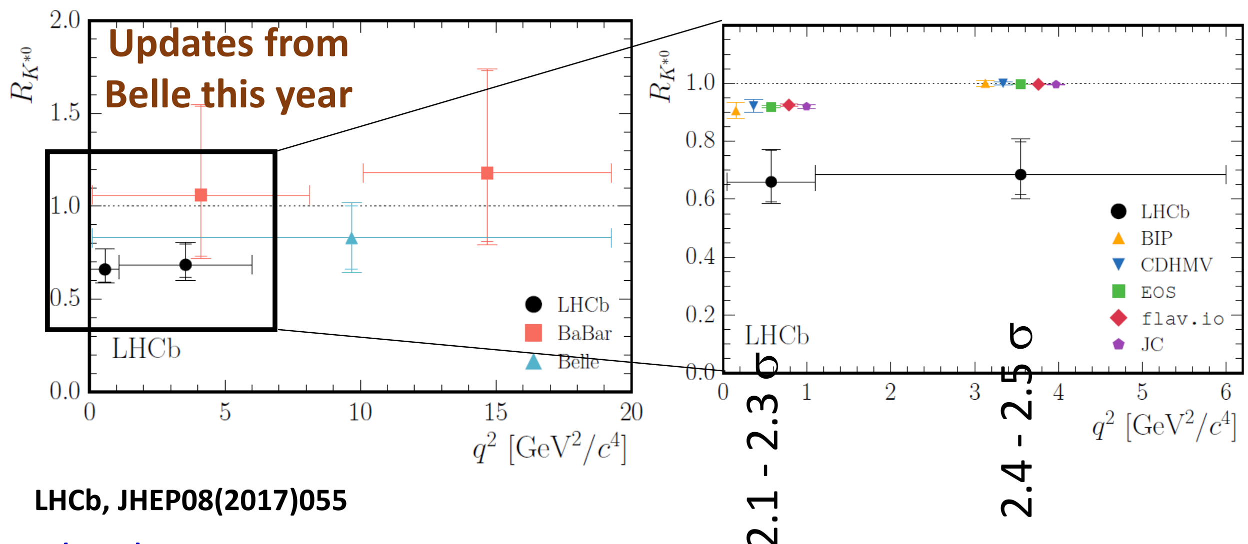
$$R_H[q_0^2, q_1^2] = \frac{\int_{q_0^2}^{q_1^2} dq^2 \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}}{\int_{q_0^2}^{q_1^2} dq^2 \frac{d\Gamma(B \to He^+e^-)}{dq^2}}; \ H = K, K^*$$

- In these ratios, hadronic uncertainties in theoretical predictions cancel and SM prediction is (very) close to unity.

- Experimentally, many sources of systematic uncertainties are also substantially reduced.

Status till last year 2018





LHCb, Phys. Rev. Lett. 113 (2014) 151601

LHCb, JHEP08(2017)055

Belle, Phys. Rev. Lett. 103 (2009) 171801

BaBar, Phys. Rev. D 86 (2012) 032012

[BIP, EPJC 76 440] [CDHMV, JHEP04(2017)016]
[EOS, PRD 95 035029] [flav.io, EPJC 77 377] [JC, PRD93 014028]

Recent R(K*) measurement at Belle

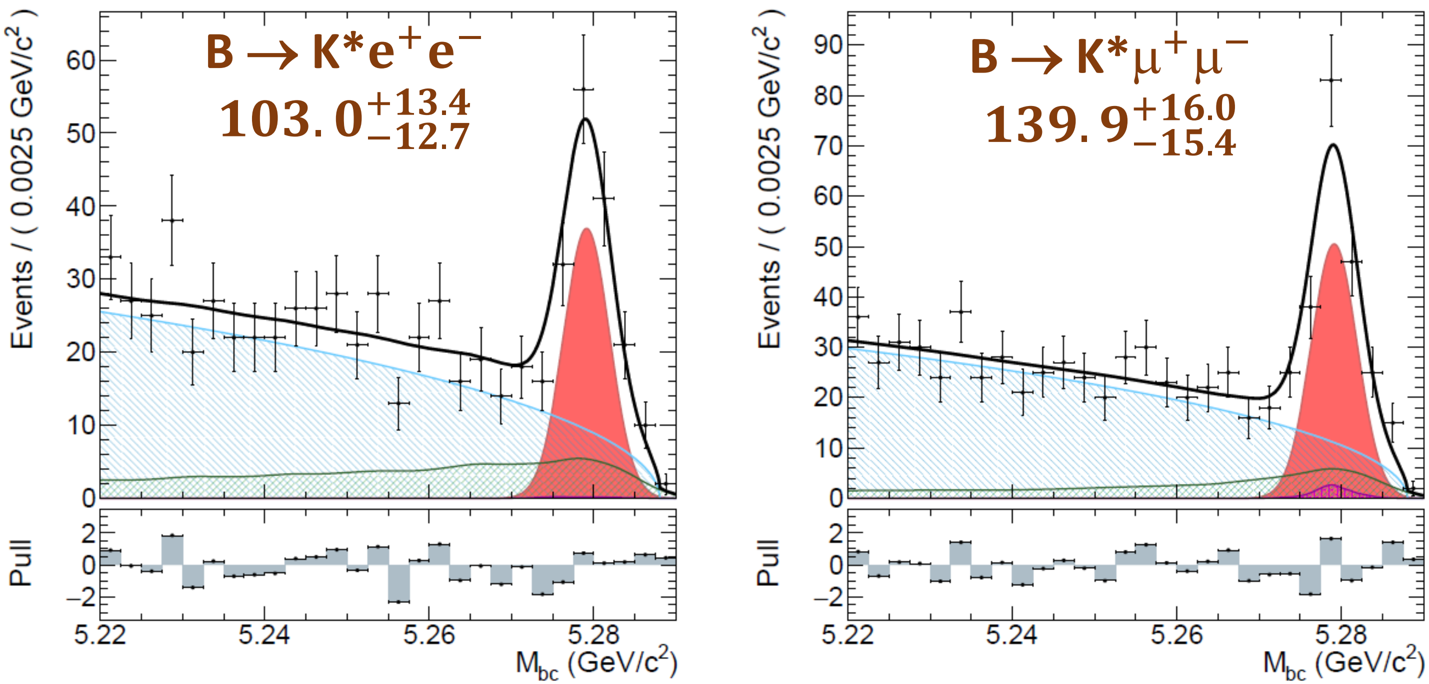
Belle [arXiv: 1904.02440]

- Reconstructed B^0 and B^+ : **B → K*(892)$\ell^+\ell^-$**
  - $\ell^+\ell^-$ → **$\mu^+\mu^-$ and e^+e^-**
  - K* → **$K^+\pi^-$, $K^0_S\pi^+$, 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 → K*J/ψ[ψ(2S)]**, which are vetoed by applying criteria on di-lepton invariant mass.
- However, the decays B → K*J/ψ[ψ(2S)] serve as a very good **Control Sample**.

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

Belle [arXiv: 1904.02440]

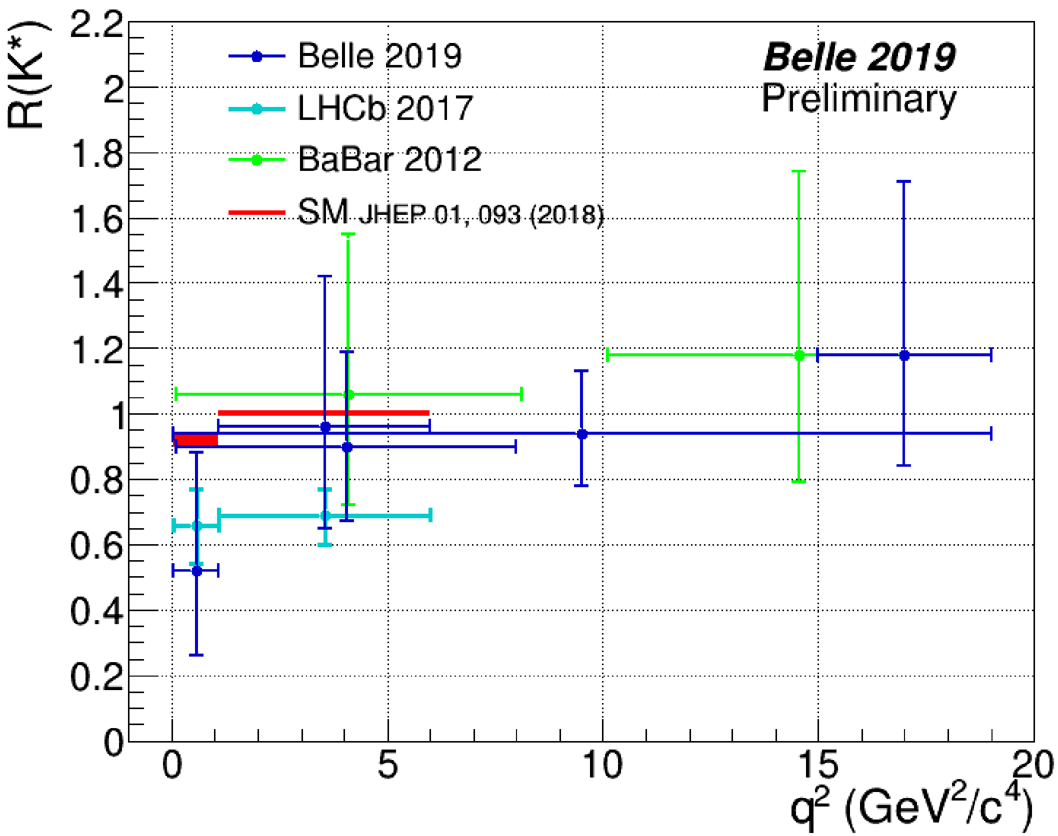
- Signal is extracted in Beam Constrained Mass: $M_{bc} = \sqrt{E_{beam}^2 - |\overrightarrow{p_B}|^2}$
- Signal pdf: **Crystal Ball** , Combinatorial background pdf: **Argus shape.**
- For example, the fit presented below are for the **$q^2 > 0.045$ GeV^2/c^4**



- 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

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 ± 0.02
for $q^2 \in (1.1, 6.0)$ GeV^2/c^4 : 1.00 ± 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]

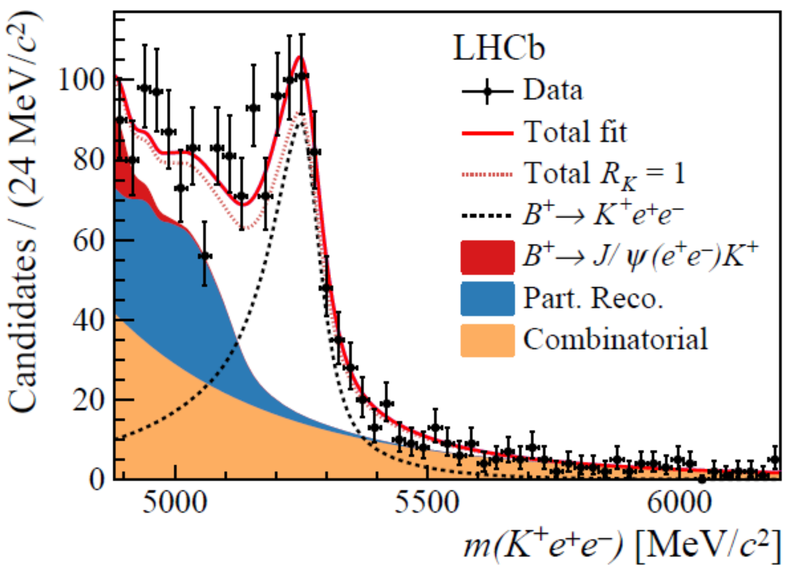
Recent R(K) measurement at LHCb

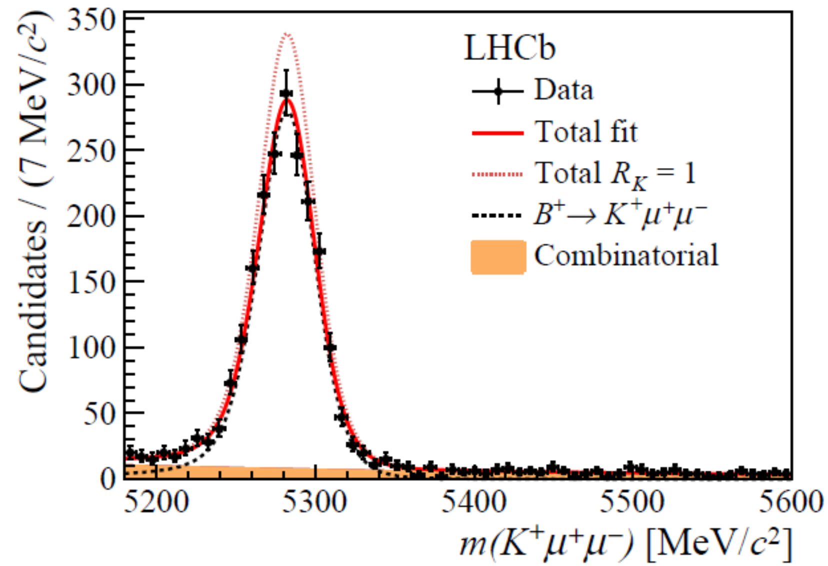
- Reconstructed B^+ : $B^+ \to K^+ \ell^+ \ell^-$ using 5 fb^{-1} of pp collision at CM energy 7, 8 and 12 TeV
  - $\ell^+\ell^- \to$ **$\mu^+\mu^-$ and e^+e^-**
- Significantly different reconstruction of decays with muons in the final state as compared to decays with electrons (brem losses and different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

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

- Several cross-checks are used to verify the analysis procedure.
  - Single ratio **$r(J/\psi)$** [=1.014 $\pm$ 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 $\pm$ 0.013] is determined close to 1.

- Reconstructed B^+ : $B^+ \rightarrow K^+ \ell^+ \ell^-$ using 5 fb^{-1} of pp collision at CM energy 7, 8 and 12 TeV
  $\hookrightarrow \mu^+\mu^-$ 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).





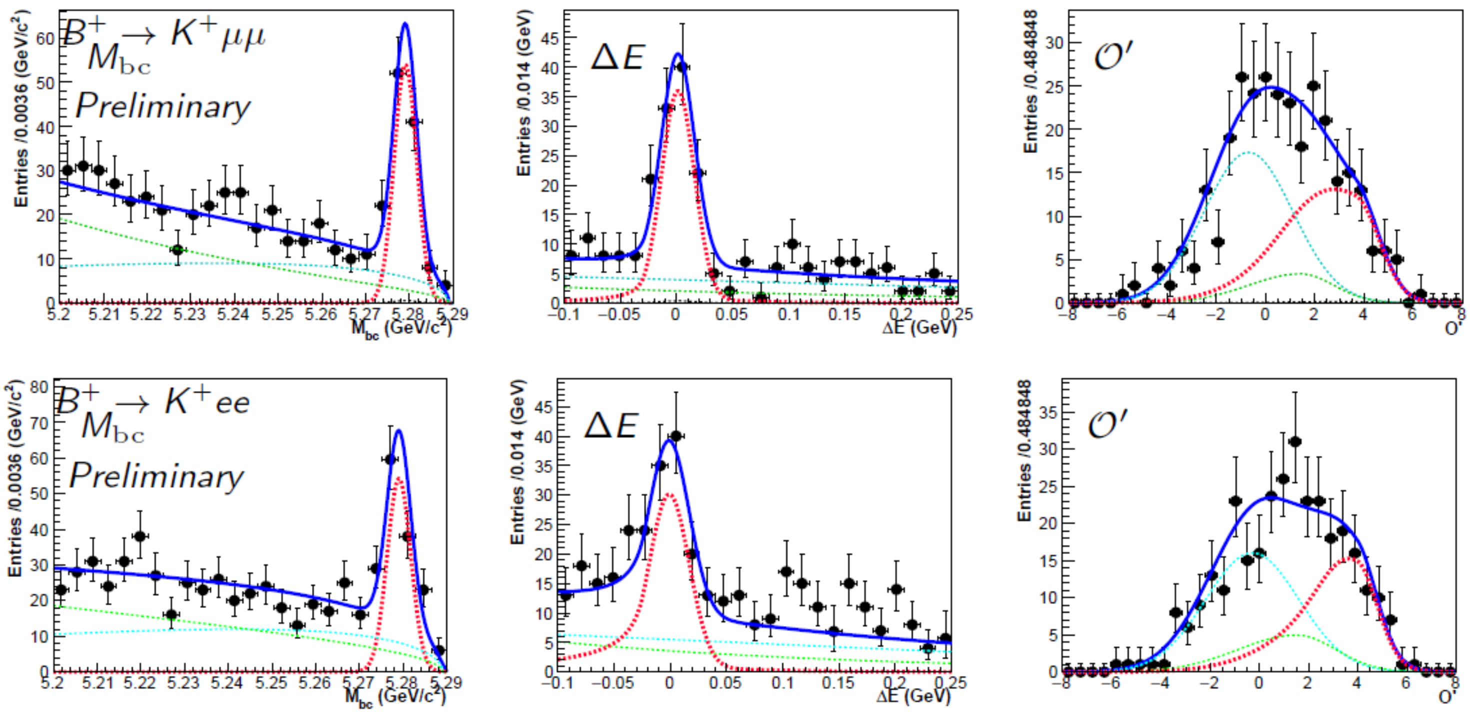
- A total of 1943 ± 49 $B^+ \rightarrow K^+\mu^+\mu^-$ decays are observed.
- The value of R_K [$q^2 \in (1.1, 6.0)$ GeV^2/c^4] = $0.846^{+0.060}_{-0.054}\,(\text{stat.})^{+0.016}_{-0.014}\,(\text{sys.})$

Recent R(K) measurement at Belle

- 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.**

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

- The NN output (O) is translated to (O') using the formula: $$O' = \log \frac{O - O_{min}}{O_{max} - O}$$
- Requirement O_{min} > -0.6 reduces 75% bkg with 4-5% signal loss.
- Extended maximum likelihood fit is performed in 3-dimensions: **M_{bc} , ΔE (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 ± 14

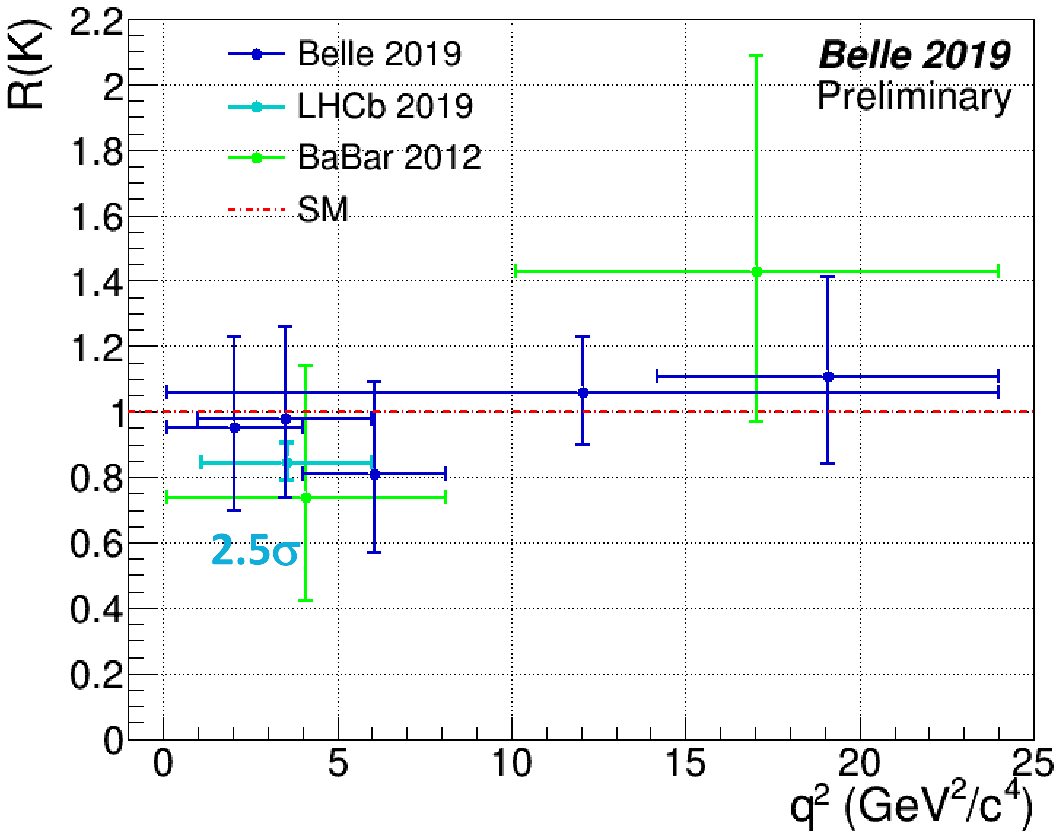
$B^0 \to K^0_s\mu^+\mu^-$
$27.3^{+6.6}_{-5.8}$

$B^+ \to K^+e^+e^-$
138 ± 15

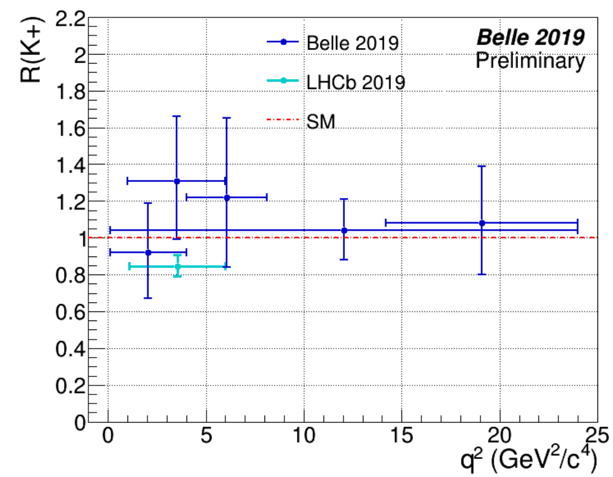
$B^0 \to K^0_s\mu^+\mu^-$
$21.8^{+7.0}_{-6.1}$

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

- **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) **=** $0.846^{+0.060}_{-0.054}\,^{+0.016}_{-0.014}$ [in $q^2 \in (1.1, 6.0)$ GeV^2/c^4].
- **LHCb measurement is compatible with SM at 2.5σ.**



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

Recent A(I) measurement at Belle

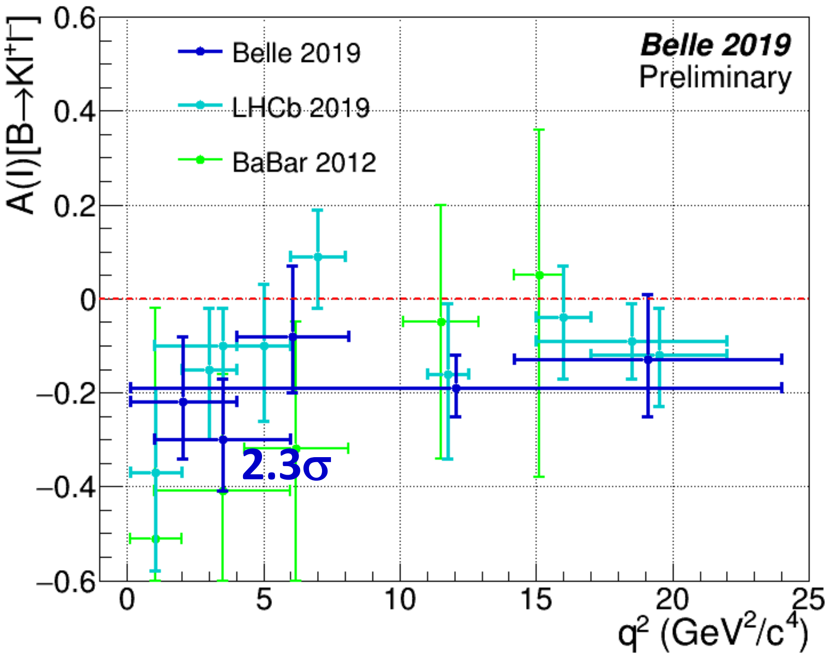
- Another theoretically clean observable is CP averaged isospin asymmetry:

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

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.

- Another theoretically clean observable is CP averaged isospin asymmetry:

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

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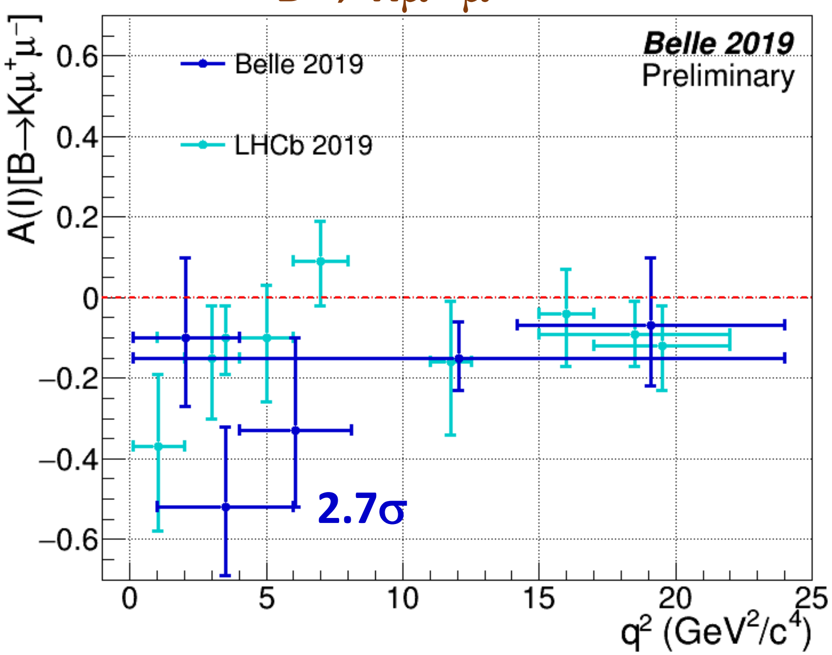
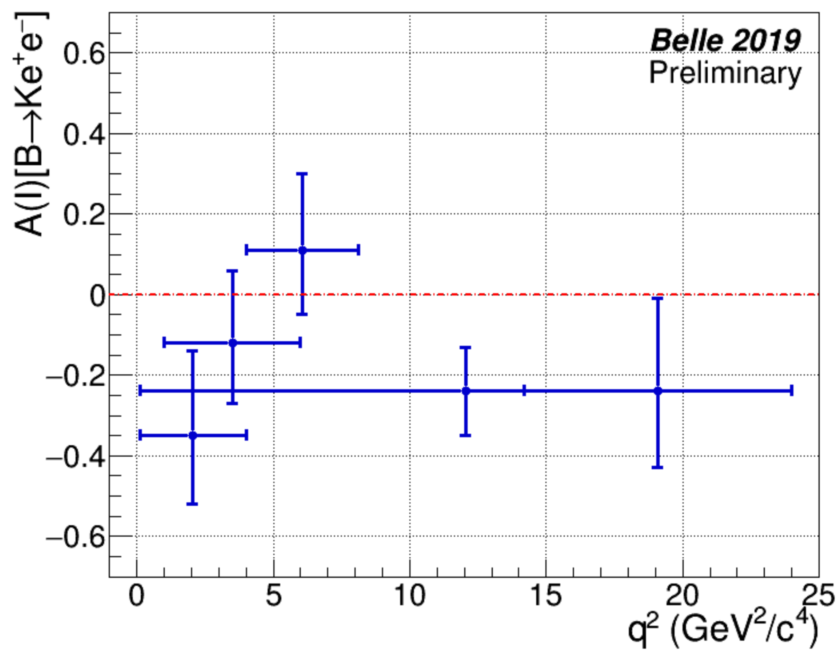
$B \to K\mu^+\mu^-$



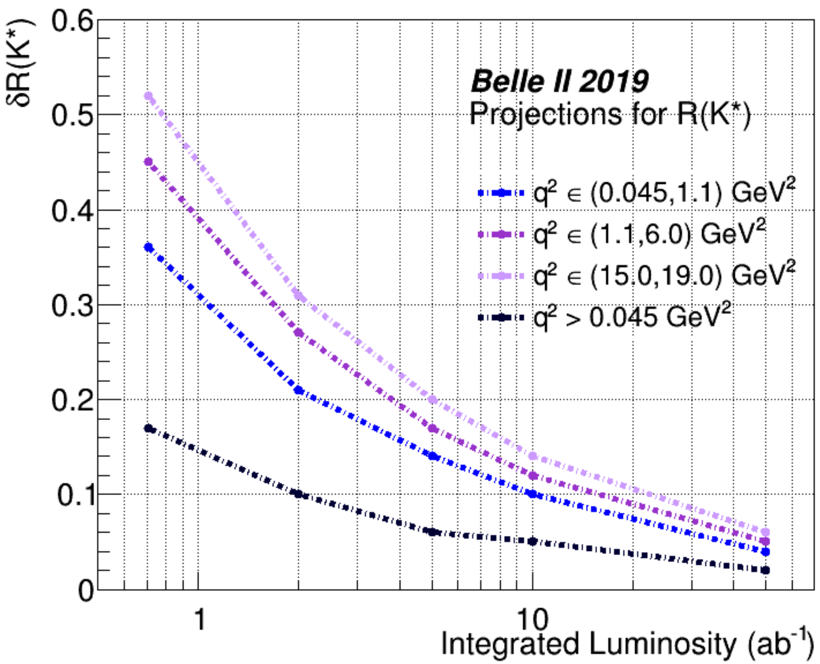
$B \to Ke^+e^-$

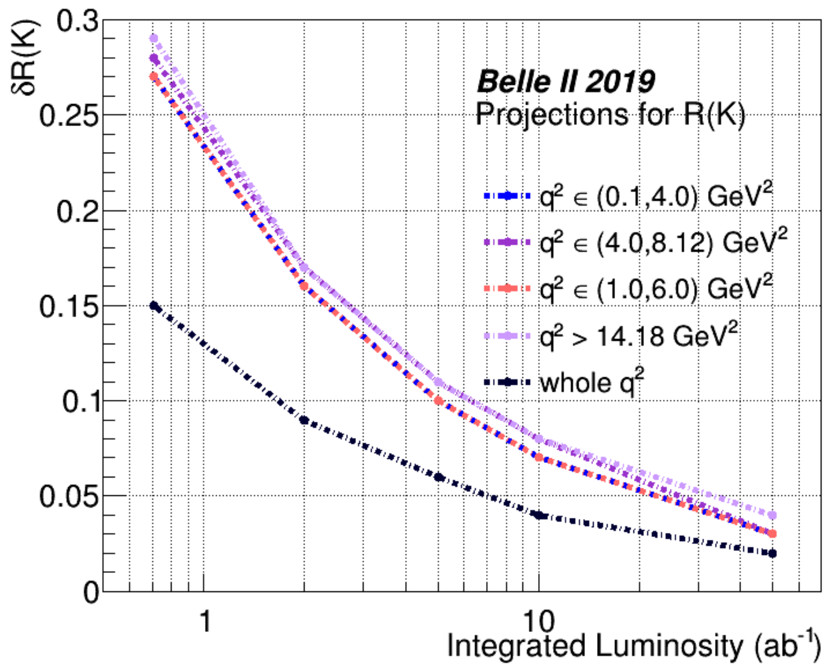


Belle II Projections for R(K) and R(K*)

- 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





Belle II Commissioning, First Results, and Future Prospects : Z. Liptak (Jul 31st)

Quark & Lepton Flavor Session

Summary

- The decays $B \to K^{(*)}\ell^+\ell^-$ are FCNC processes and is a laboratory of New Physics studies on its own.
- The ratio of branching fractions R(K) and R(K*) are theoretically as well as experimentally clean variables.
- Most precise results come from LHCb collaboration and reported (**this year: PRL122 (2019) 191801**) a deviation of 2.6σ in $q^2 \in (1.1, 6.0)$ GeV^2/c^4 for R(K) and similar deviations were reported earlier in R(K*) **JHEP08(2017)055**.
- Belle measurements of R(K*) (**arXiv:1904.02440**) and R(K) are compatible with both SM as well as with past measurements.
- Belle A(I) measurement for $B \to K\ell^+\ell^-$ is found significantly below zero (specially in $q^2 \in (1.0, 6.0)$ GeV^2/c^4 for decay $B \to K\mu^+\mu^-$ with deviation $\sim 2.7\sigma$).
- Belle II experiment has started physics runs and expected to accumulate larger data sample, which will be crucial for rare decays measurements.

No penguins were harmed in any of these measurements

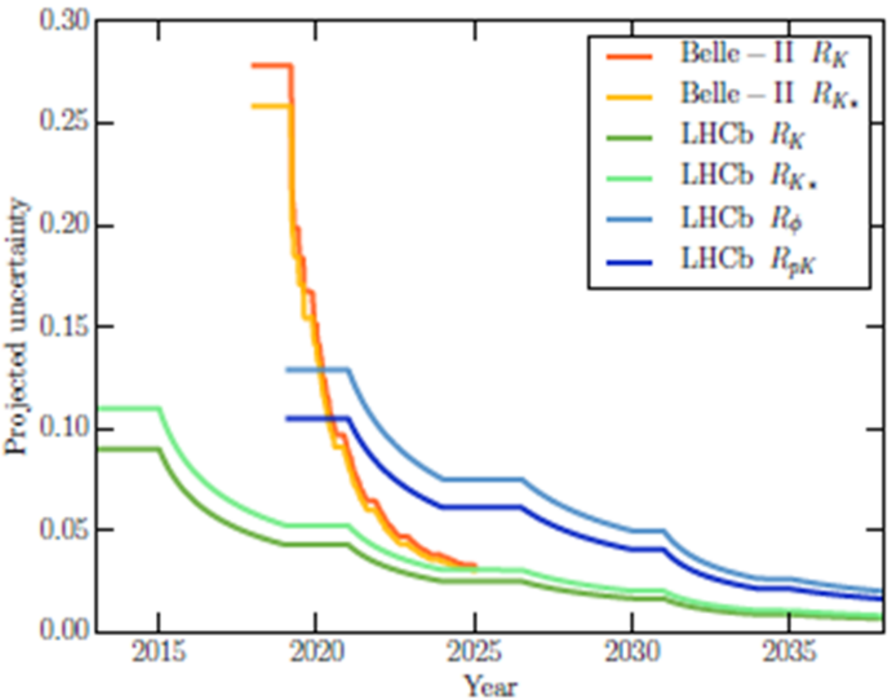
Extra Slides

LHCb prospects

Interplay between the **LHCb Upgrades** and **Belle II**.

Experiment	2018	2021	2024	2025	2037
Belle-II	—	$5\,ab^{-1}$		$50\,ab^{-1}$	
LHCb	$9\,fb^{-1}$		$23\,fb^{-1}$		$300\,fb^{-1}$

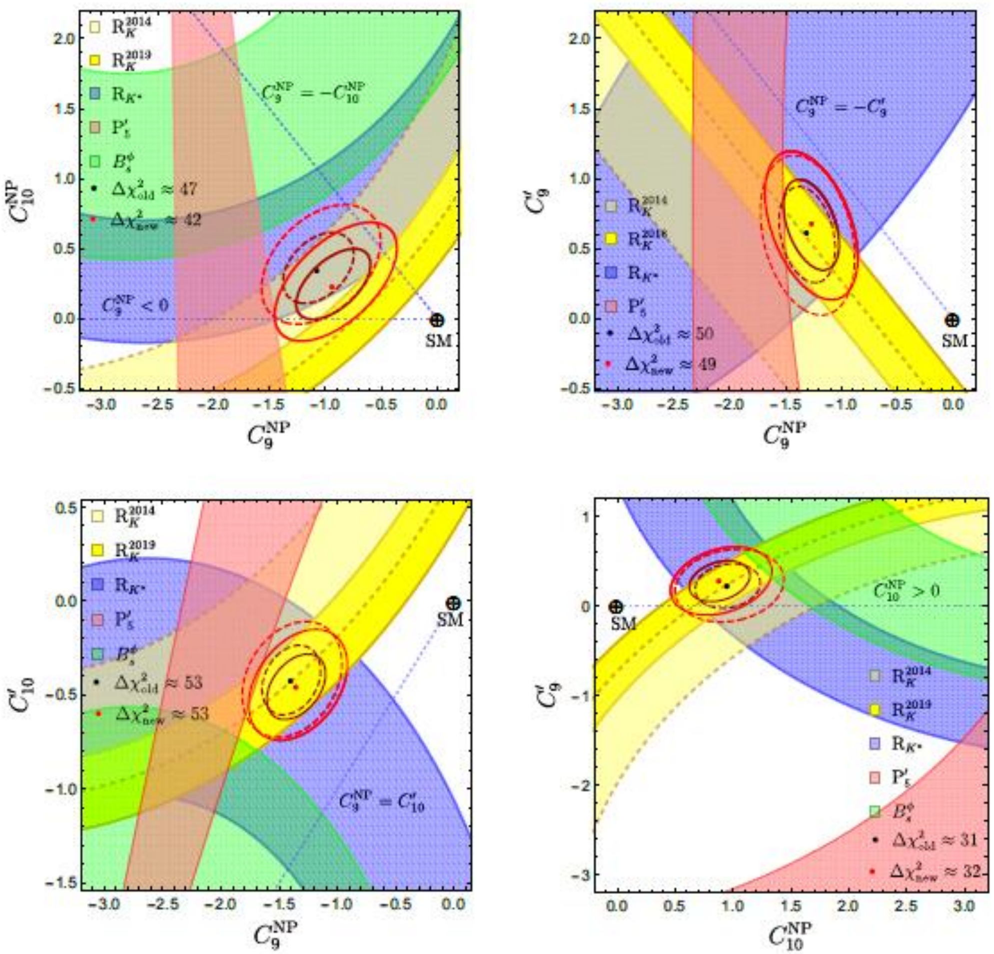
Large reduction of the uncertainty on the LFU measurements.



Yield	Run 1 result	$9\,fb^{-1}$	$23\,fb^{-1}$	$50\,fb^{-1}$	$300\,fb^{-1}$
$B^+ \to K^+e^+e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0}e^+e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B^0_s \to \phi e^+e^-$	–	80	230	530	3 300
$\Lambda^0_b \to pKe^+e^-$	–	120	360	820	5 000
$B^+ \to \pi^+e^+e^-$	–	20	70	150	900
R_X precision (stat.only)	Run 1 result	$9\,fb^{-1}$	$23\,fb^{-1}$	$50\,fb^{-1}$	$300\,fb^{-1}$
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

From slides of Julián García Pardiñas (Win 2019) & Vitalii Lisovskyi (EPSHEP 2019)

LHCb prospects



arXiv:1903.0961
[Alok, Amol, Shireen, Dinesh]

- analyze all the scenarios where the NP contributes to a pair of (O_9, O_{10}, O_9', O_{10}') operators at a time.
- Scenarios with new physics contributions to the (C_9^{NP}, C_9') or (C_9^{NP}, C_{10}') pair remain the most favored ones.

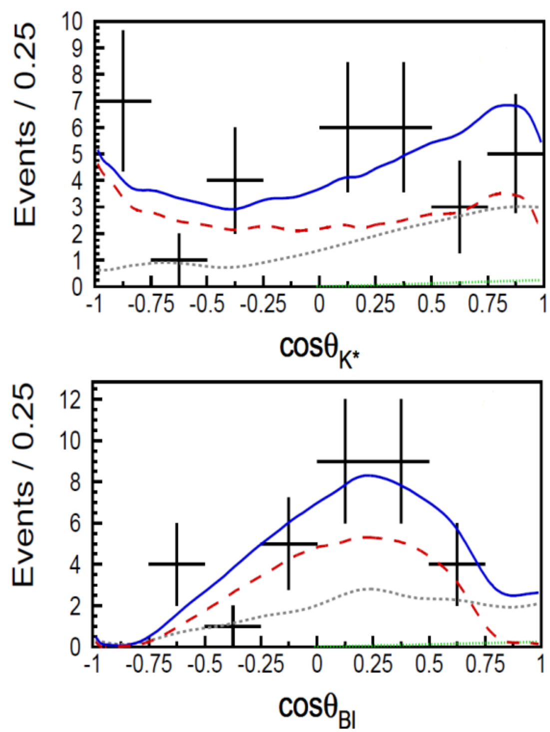
Forward Backward asymmetry in $B \to K^* \ell^+ \ell^-$

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

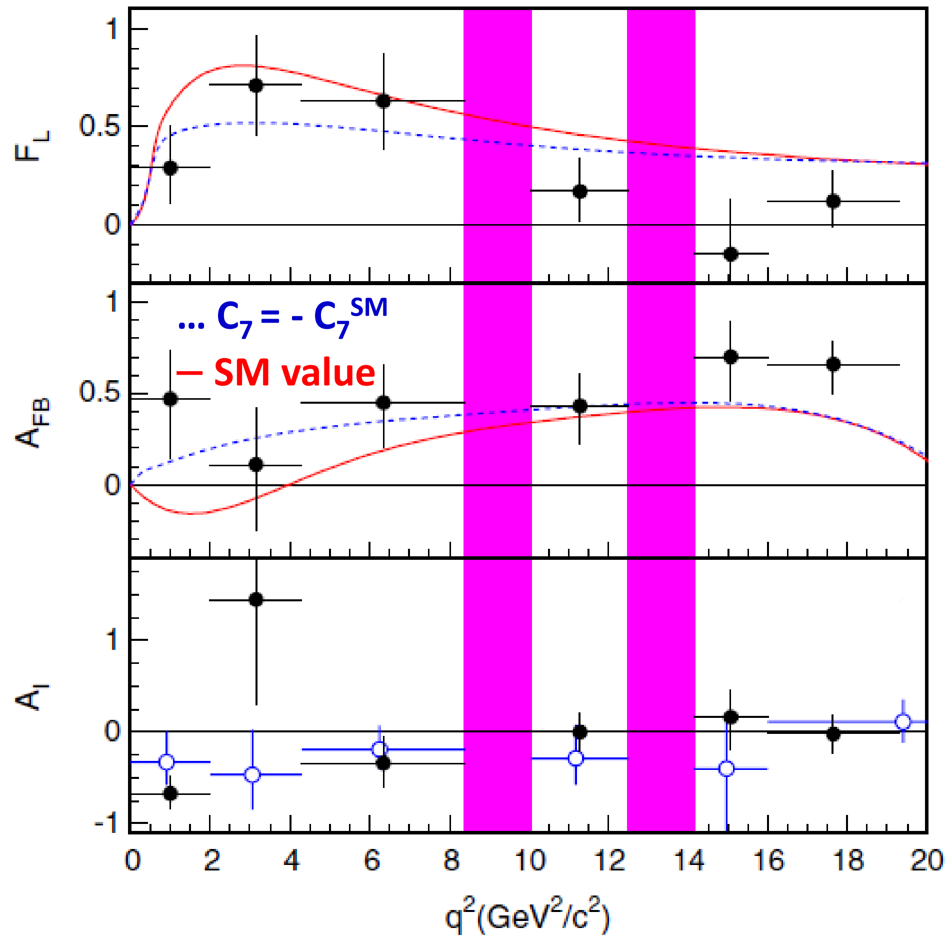
- $\mu^+\mu^-$ and e^+e^-
- $K^+\pi^-$, $K^0_S\pi^+$, $K^+\pi^0$, K^+ and K^0_S

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

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



PRL103, 171801 (2009)



$R(K^*) = 0.83 \pm 0.17 \pm 0.08$
$R(K) = 1.03 \pm 0.19 \pm 0.06$

Till this year

Belle II prospects for $B \to X_s \ell^+ \ell^-$

- Belle II can significantly improve upon this situation and with its expected larger statistics.

Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B \to X_s \ell^+ \ell^-)$ ($[1.0, 3.5]\ \mathrm{GeV}^2$)	29%	13%	6.6%
$\mathrm{Br}(B \to X_s \ell^+ \ell^-)$ ($[3.5, 6.0]\ \mathrm{GeV}^2$)	24%	11%	6.4%
$\mathrm{Br}(B \to X_s \ell^+ \ell^-)$ ($> 14.4\ \mathrm{GeV}^2$)	23%	10%	4.7%
$A_{\mathrm{FB}}(B \to X_s \ell^+ \ell^-)$ ($[1.0, 3.5]\ \mathrm{GeV}^2$)	26%	9.7%	3.1%
$A_{\mathrm{FB}}(B \to X_s \ell^+ \ell^-)$ ($[3.5, 6.0]\ \mathrm{GeV}^2$)	21%	7.9%	2.6%
$A_{\mathrm{FB}}(B \to X_s \ell^+ \ell^-)$ ($> 14.4\ \mathrm{GeV}^2$)	19%	7.3%	2.4%

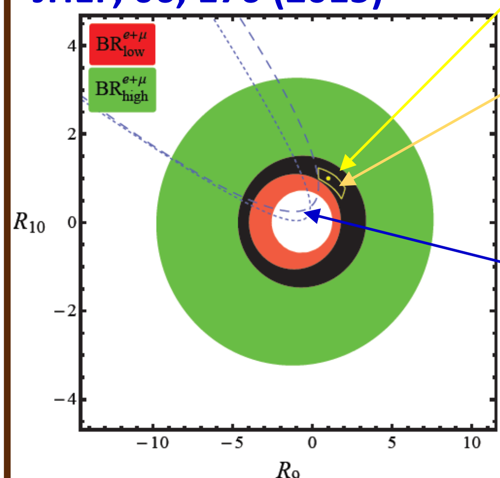
B2TIP report | arXiv:1808.10567

- In the beginning, Belle II will still have to rely on the sum-of-exclusive method but later fully inclusive analysis can also be attempted.

T. Huber et al., JHEP, 06, 176 (2015)

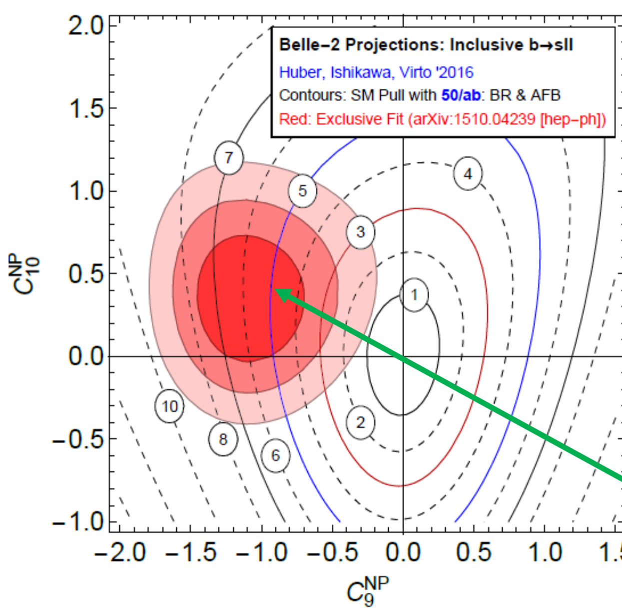
95% CL on the $\mathbf{R_{9,10}} = \frac{C_{9,10}}{C^{SM}_{9,10}}$

In SM: $R_{9,10}$ = 1



Belle II reach

Belle measurement of the forward-backward asymmetry

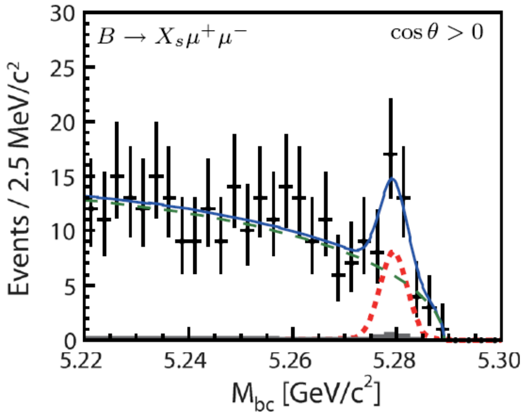


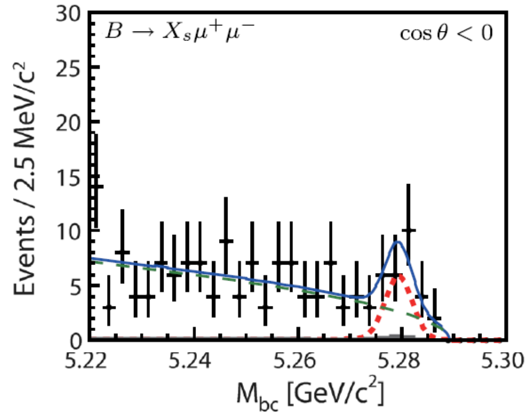
Exclusion contours in the C_9^{NP} - C_{10}^{NP} plane resulting from future BF and A_{FB} for
$B \to X_s \ell^+ \ell^-$

from global analysis

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

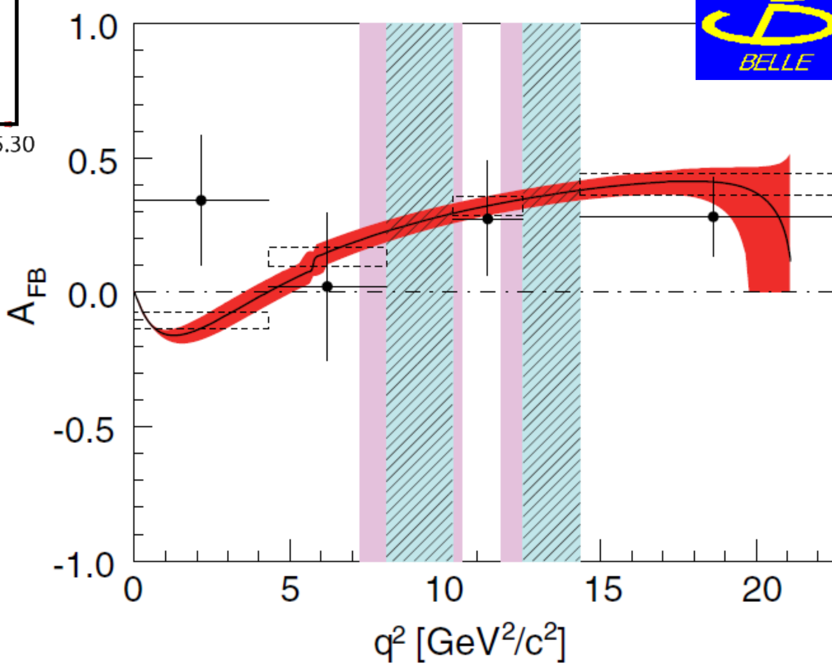
- Inclusive measurement is theoretically cleaner than the exclusive, but experimentally more challenging.
- Sum-of-exclusive technique (10 modes with $M[X_s] < 2.0$ GeV/c^2) used to measured A_{FB} (corresponds to ~50% of the inclusive rate).





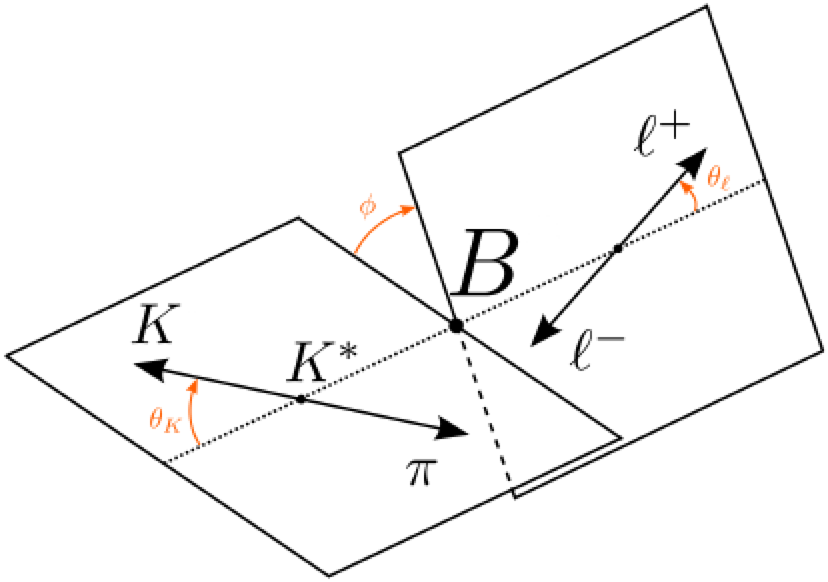
← For illustration in $q^2 \in (1, 6)$ GeV^2/c^2

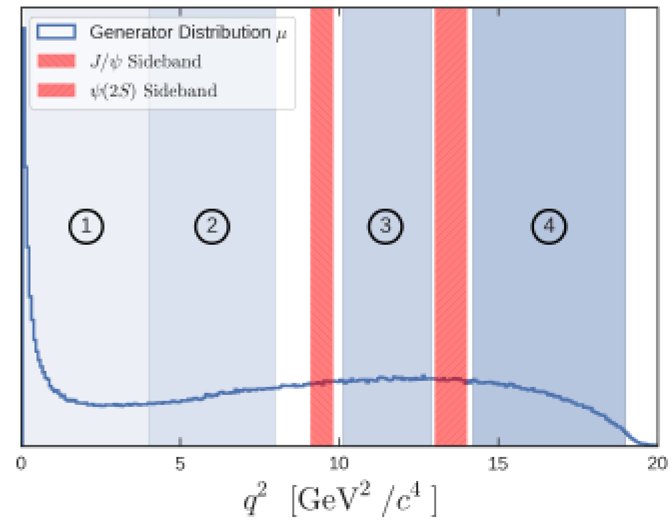
PRD 93 032008 (2016)



- The result is consistent with a SM prediction within error (1.8σ tension in low-q^2).
- Results are statistically dominated → Belle II (with its expected larger statistics).
- Also, fully inclusive analysis can also be attempted in Belle II.

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

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

1606.00999

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

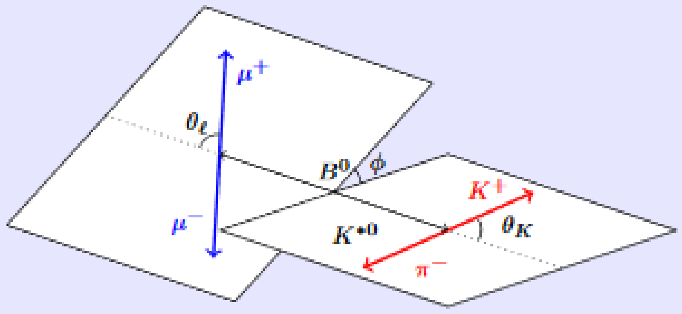


Figure 11: The angles θ_ℓ, θ_K and ϕ in the decay $B \to K^* \mu^+ \mu^-$. Figure by Thomas Blake.

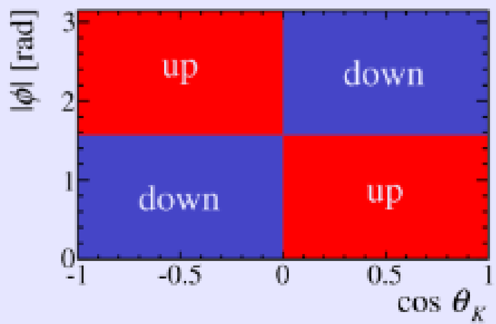
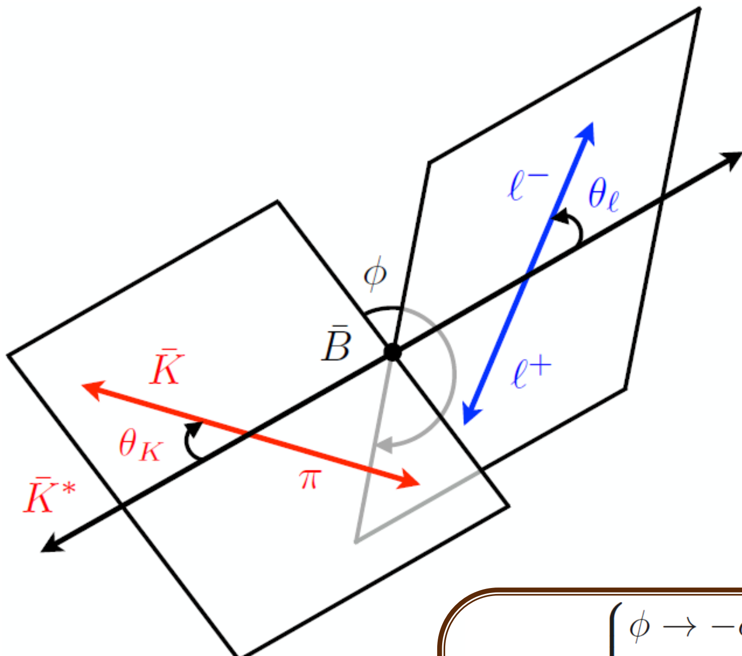


Figure 12: Definition of the P_5' asymmetry.

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 θ_ℓ angle. Similarly, the K^{*0} polarisation fraction $F_{\rm L}$ depends on the angle θ_K, defined analogously to θ_ℓ. 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 θ_K and ϕ. 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.

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

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



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.

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).

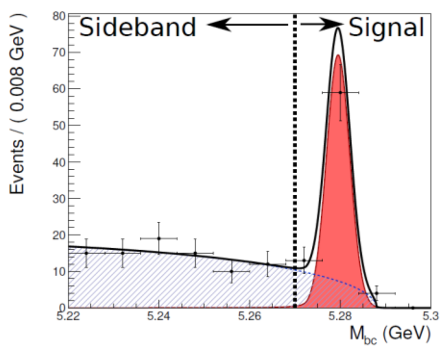
- Transverse polarization asymmetry

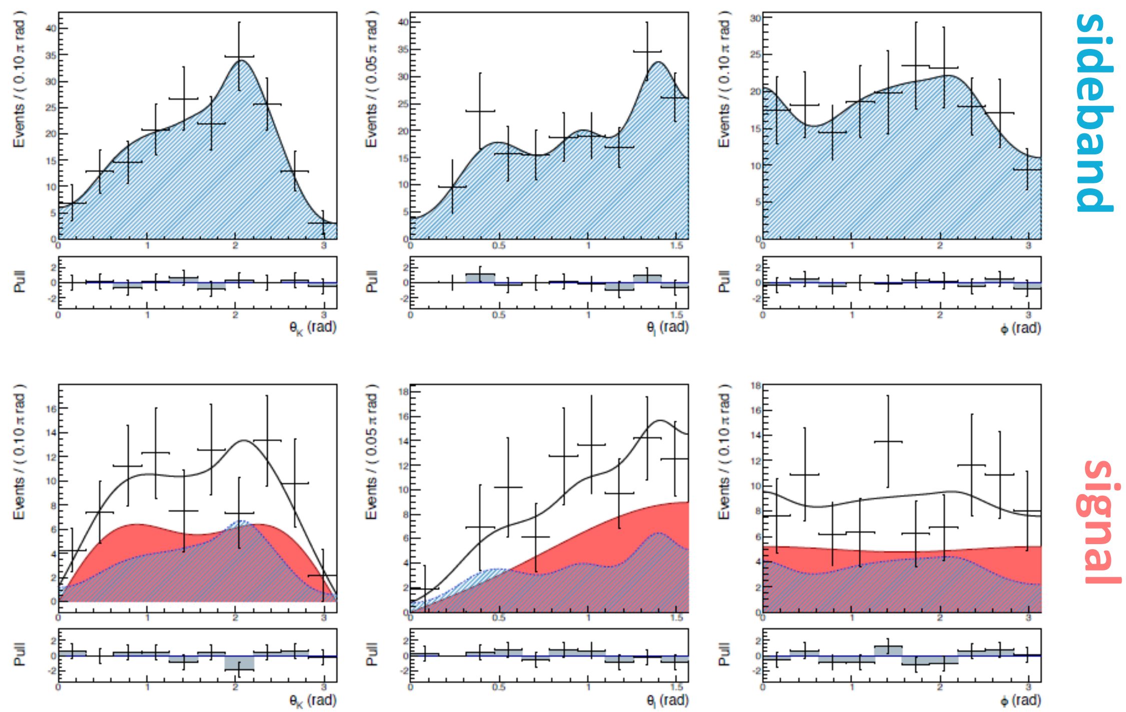
$$A_T^{(2)} = \frac{2S_3}{(1-F_L)}$$

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

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

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