Status (Prospects) of $B \to K^{(*)}\ell^+\ell^-$ decays at Belle (II) & related topics

Saurabh Sandilya

University of Cincinnati
(On Behalf of the Belle and Belle II Collaboration)

Outline

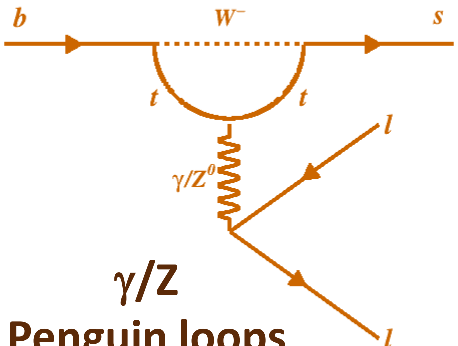
- **Introduction**
- **Forward Backward asymmetry in $B \to K^* \ell^+ \ell^-$ and $B \to X_s \ell^+ \ell^-$**
- **Lepton flavor separated angular analysis of $B \to K^{*0} \ell^+ \ell^-$ at Belle**
- **R(K*) and R(K) status**
- **Search for LFV decay $B \to K^{*0} \mu^+ e^-$**
- **Search for $B \to h^{(*)} \nu\nu$**

+ Belle II Prospects

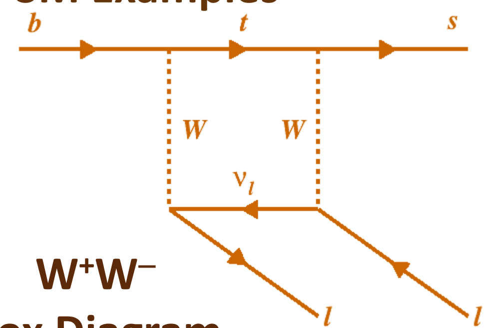
Introduction

- The decays such as $B \to K^{(*)} \ell^+ \ell^-$ are manifestations of quark level transitions $b \to s \ell^+ \ell^-$.
- These FCNC processes are forbidden in the SM at the tree level and can only occur at greatly suppressed rates through higher-order processes (penguin loops/box).

SM Examples



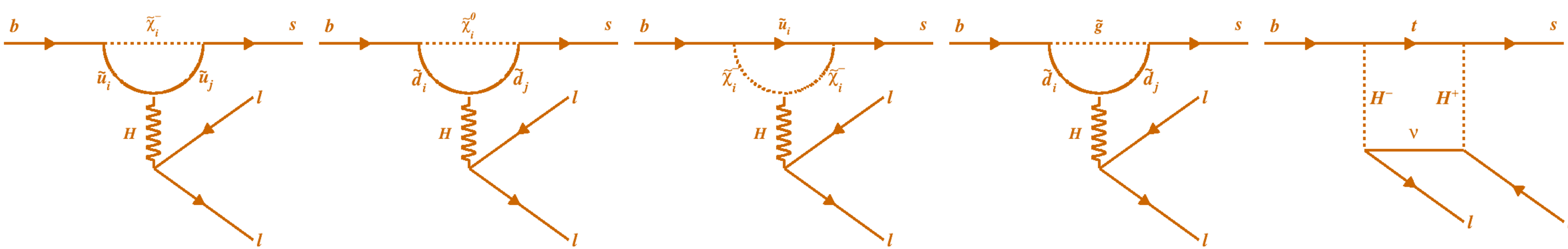
γ/Z
Penguin loops



W⁺W⁻
Box Diagram

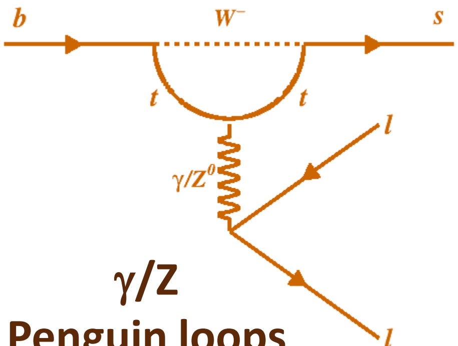
a virtual t quark contribution dominates, with secondary contributions from virtual c and u quarks.

- Sensitive to NP: Supersymmetry, 2HDM, Fourth generation, Extra-dimensions, Leptoquarks, Axions . .

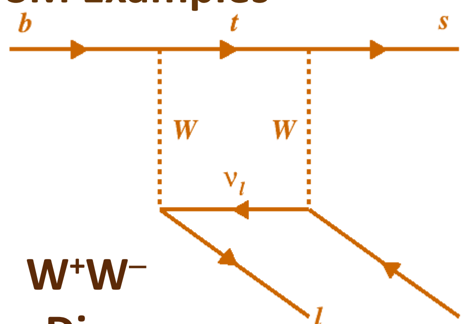


- The decays such as $B \to K^{(*)} \ell^+ \ell^-$ are manifestations of quark level transitions $b \to s \ell^+ \ell^-$.
- These FCNC processes are forbidden in the SM at the tree level and can only occur at greatly suppressed rates through higher-order processes (penguin loops/box).

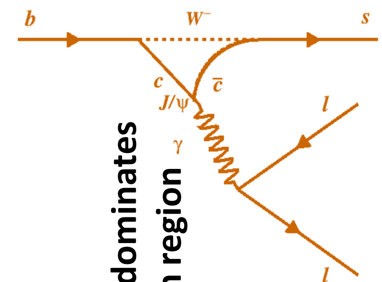
SM Examples



γ/Z
Penguin loops



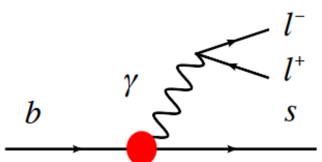
W⁺W⁻
Box Diagram



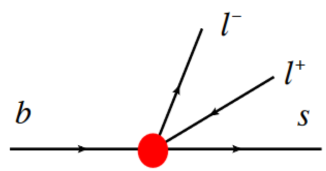
The relevant effective Hamiltonian: ↓

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

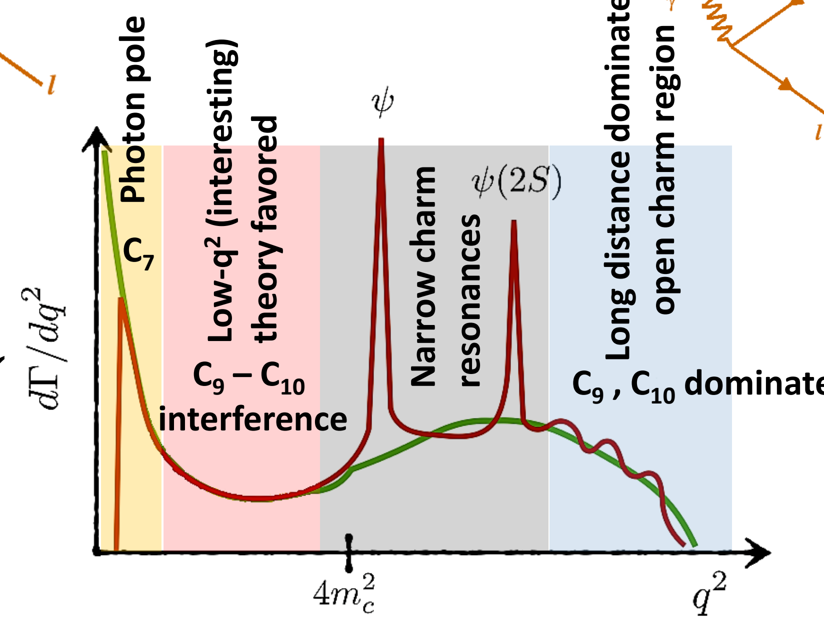
The Operators which are most sensitive to the NP: ↓



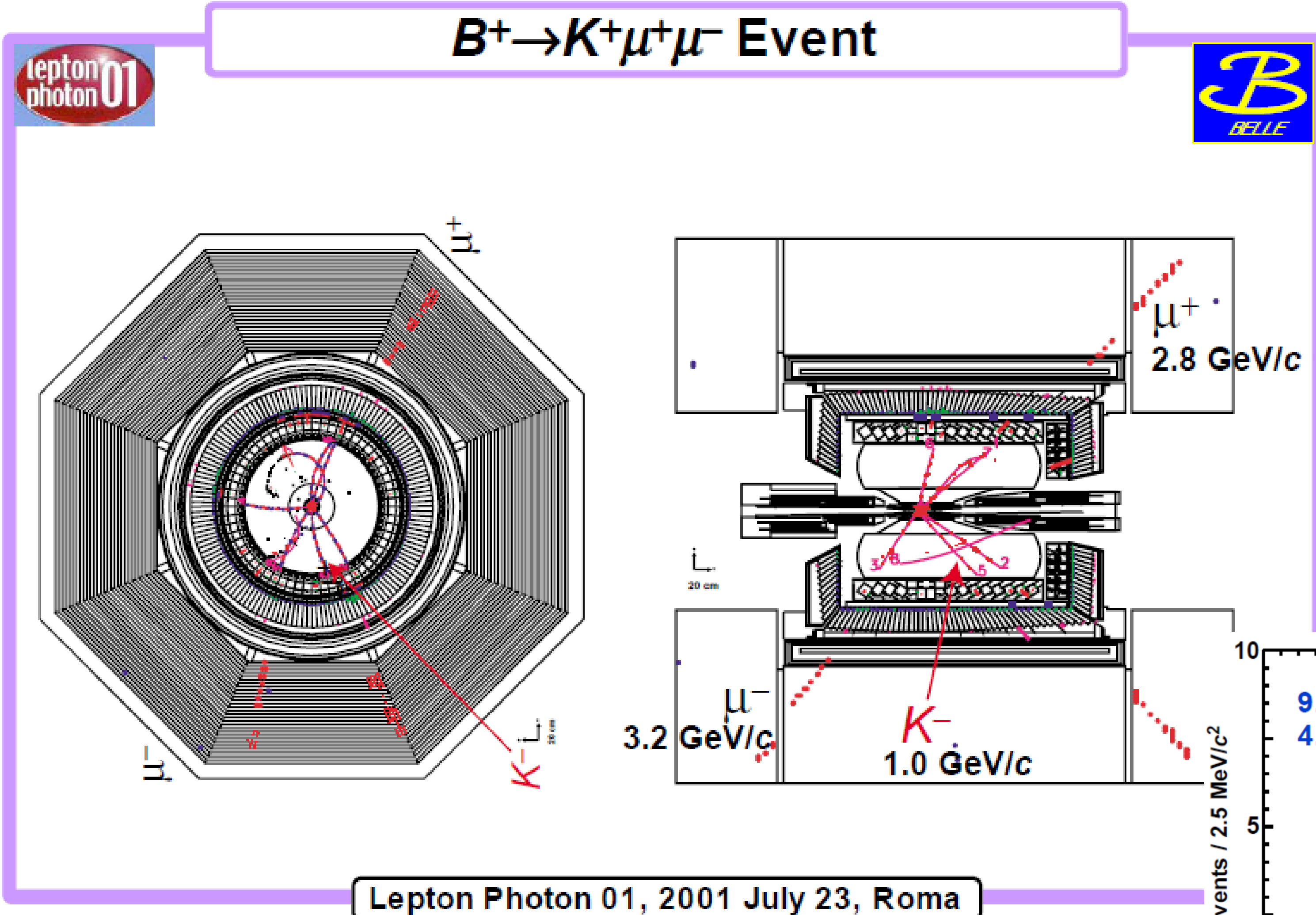
O_7
dipole



O_9, O_{10}
Four fermion

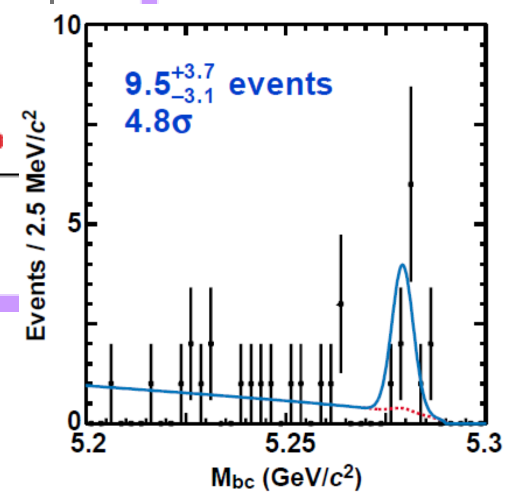


First observation of a $b \to s\ell^+\ell^-$ decay (LP-2001)



29.5 fb^{-1}

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



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

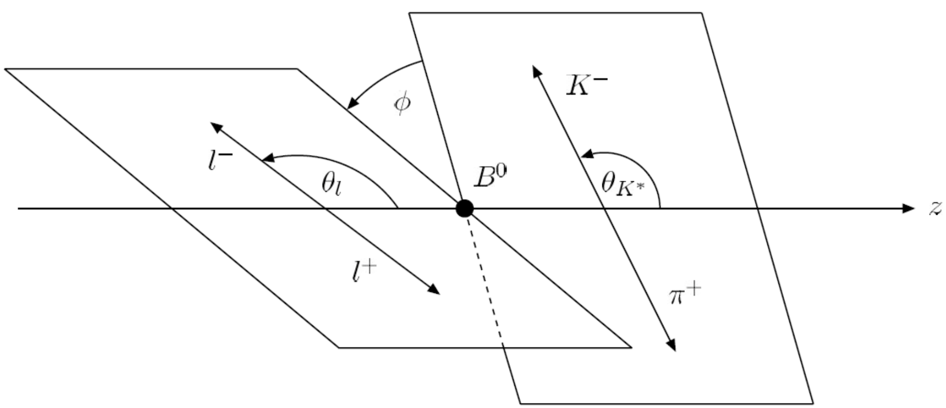
$B \to K^{(*)} \ell^+ \ell^-$ based on 657 M BB pairs

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

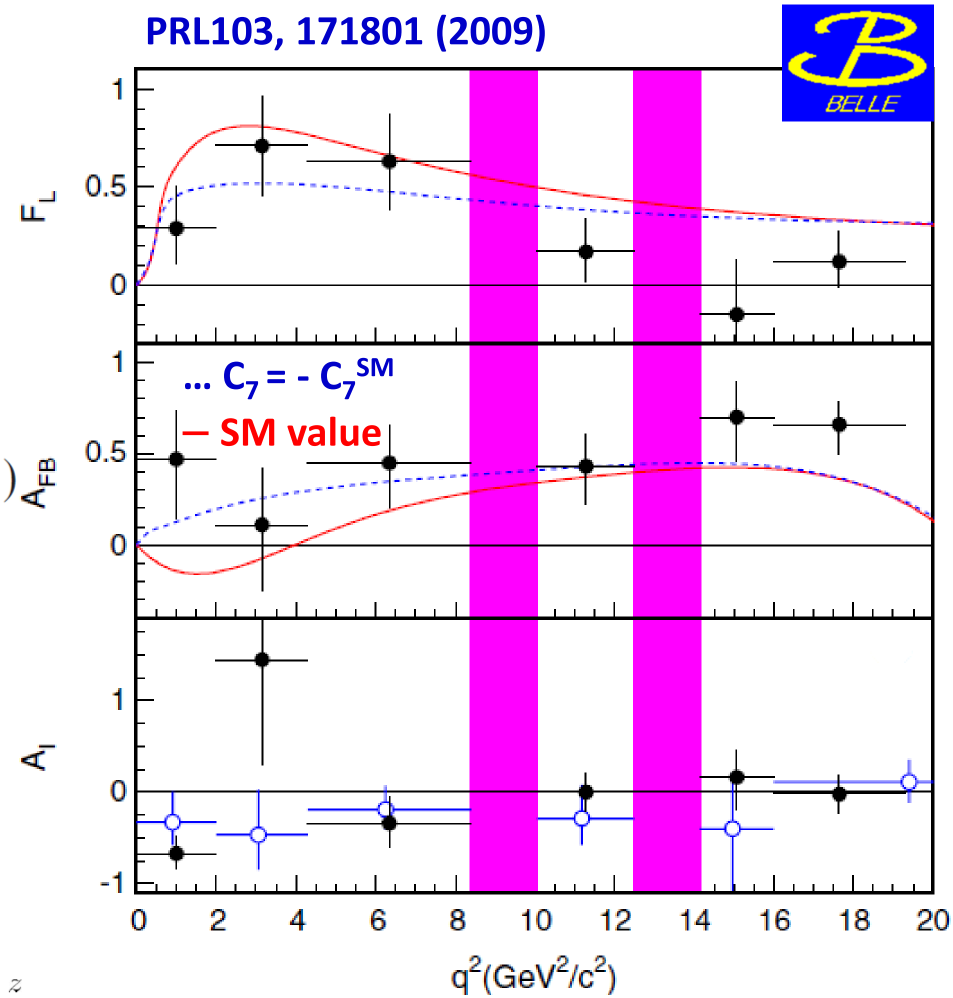
F_L and A_{FB} are obtained from fit to $\cos\theta_{K*}$ and $\cos\theta_{B\ell}$

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

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



PRL103, 171801 (2009)



R(K*) = 0.83 ± 0.17 ± 0.08
R(K) = 1.03 ± 0.19 ± 0.06

Pre-LHCb

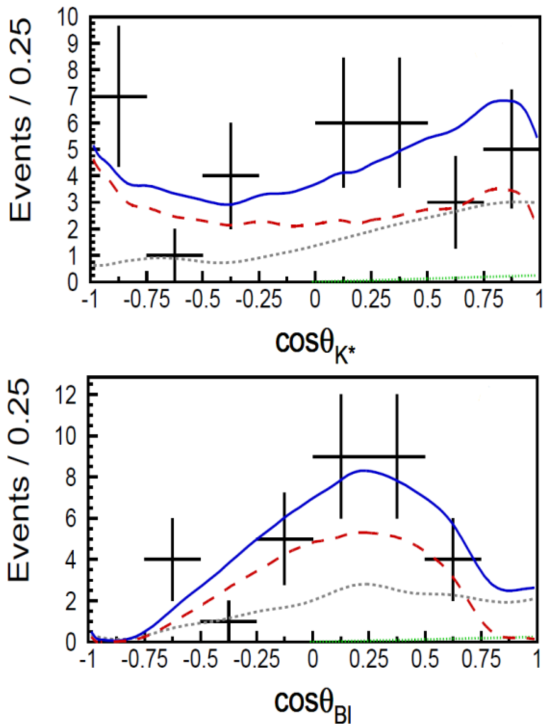
Forward Backward asymmetry in $B \to K^{*}\ell^{+}\ell^{-}$

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

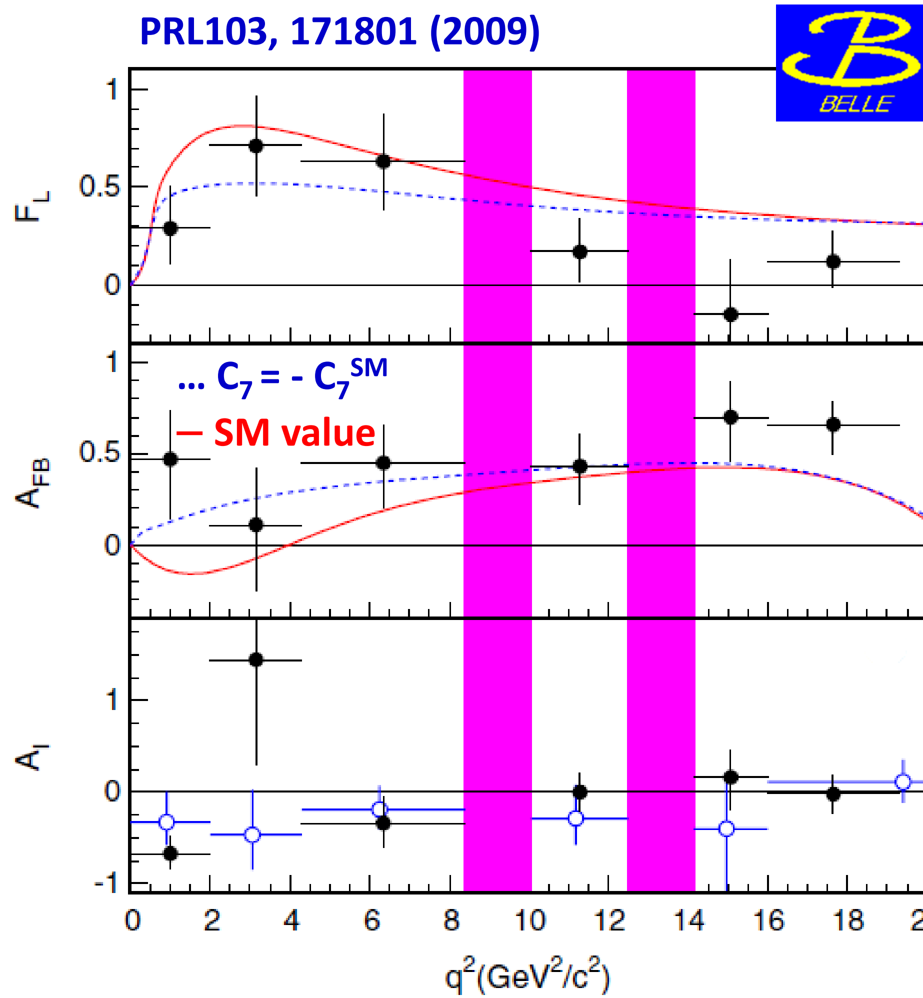
- $\ell^{+}\ell^{-} \to \mu^{+}\mu^{-}$ and $e^{+}e^{-}$
- $K^{(*)} \to K^{+}\pi^{-}, K^{0}_{S}\pi^{+}, K^{+}\pi^{0}, K^{+}$ and K^{0}_{S}

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



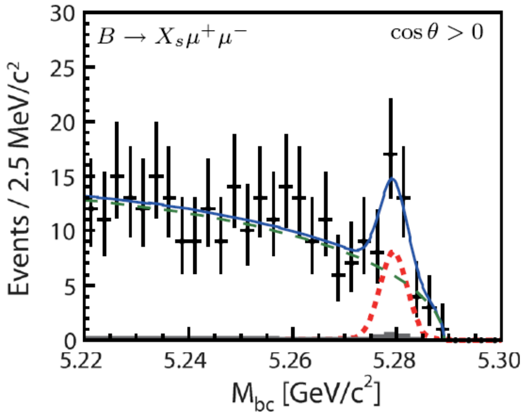
PRL103, 171801 (2009)

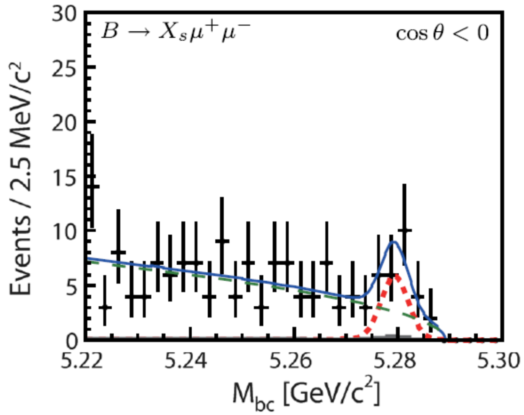


$R(K^*) = 0.83 \pm 0.17 \pm 0.08$

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

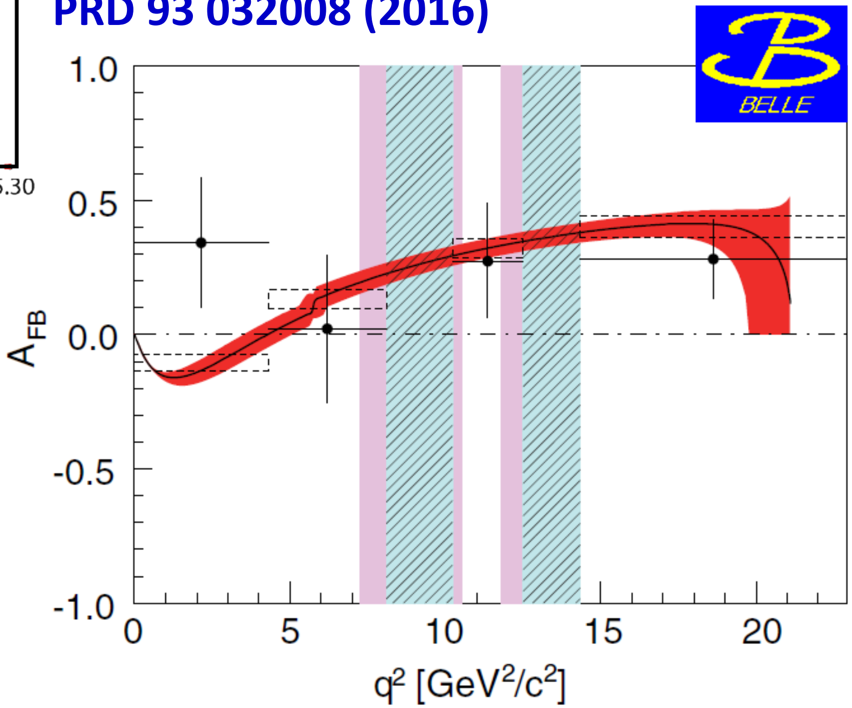
- Inclusive measurement is theoretically cleaner than the exclusive, but experimentally more challenging .
- Sum-of-exclusive technique (10 modes with $M[X_s] < 2.0$ GeV/c^2) used to measured A_{FB} (corresponds to ~50% of the inclusive rate).





← **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 $\rightarrow$ Belle II

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

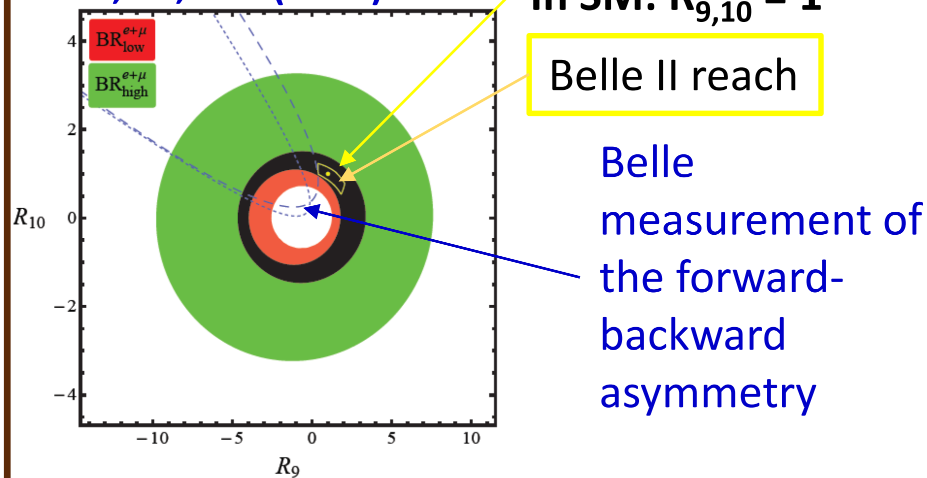
B2TIP report | arXiv:1808.10567

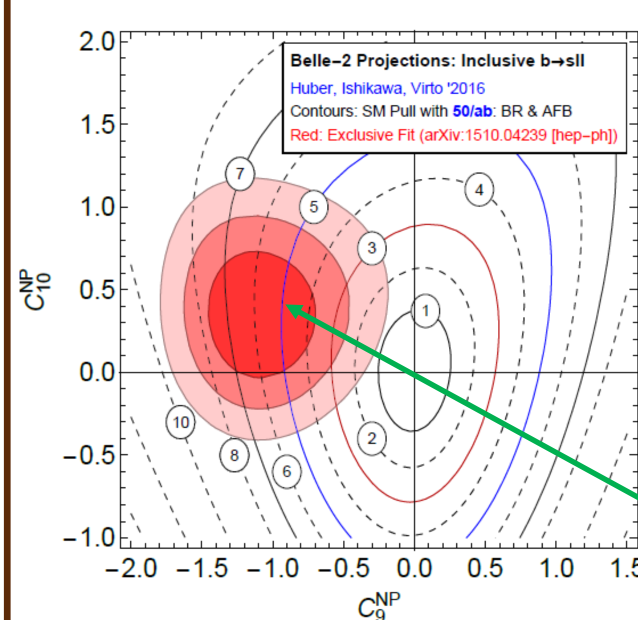
- In the beginning, Belle II will still have to rely on the sum-of-exclusive method but later fully inclusive analysis can also be attempted.

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

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

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

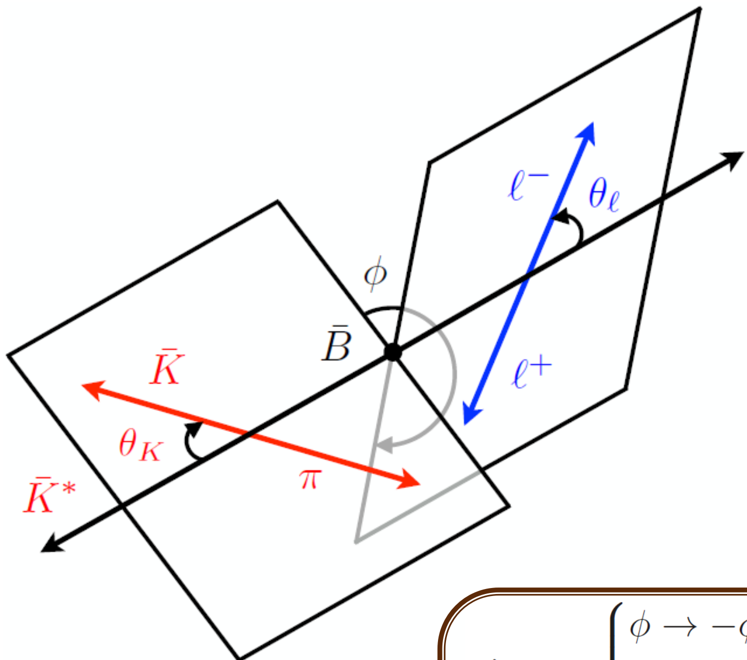




Exclusion contours in the C_9^{NP} - C_{10}^{NP} plane resulting from future BF and A_{FB} for $B \to X_s \ell^+ \ell^-$

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

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

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

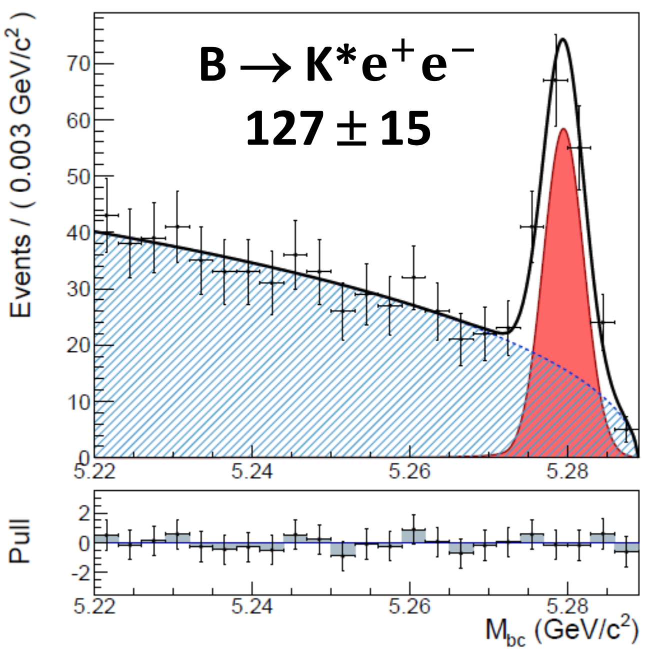
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

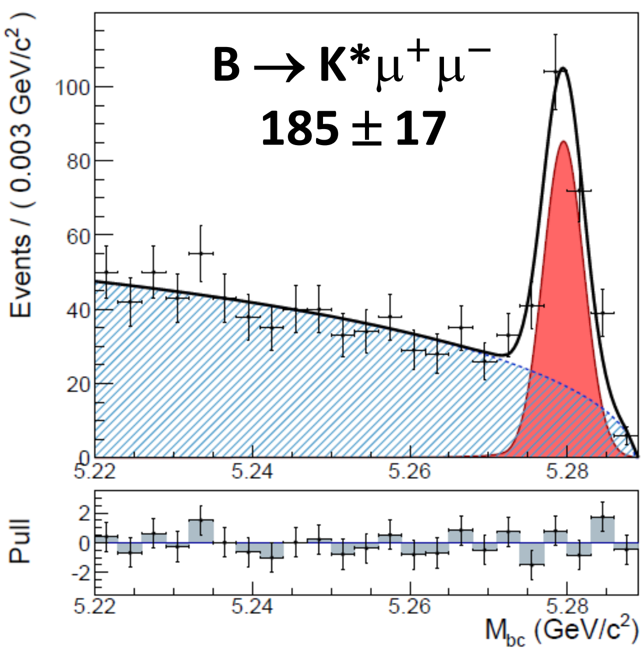
The observables are considered to be largely free from form-factor related uncertainties

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

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

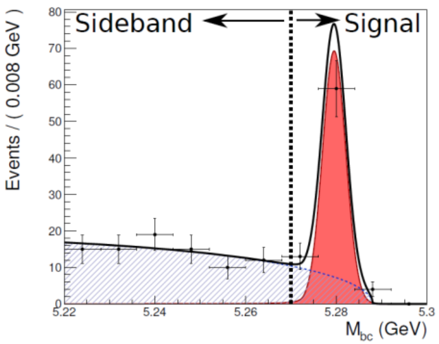
- Reconstructed B^0 and B^+ : B → K*(892)$\ell^+\ell^-$
  - $\ell^+\ell^-$ → $\mu^+\mu^-$ and e^+e^-
  - K*(892) → $K^+\pi^-$, $K^0_S\pi^+$, and $K^+\pi^0$
- Signal is extracted in Beam Constrained Mass: $M_{bc} = \sqrt{E^2_{beam} - |\overrightarrow{p_B}|^2}$
- Signal pdf: **Crystal Ball** , Background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

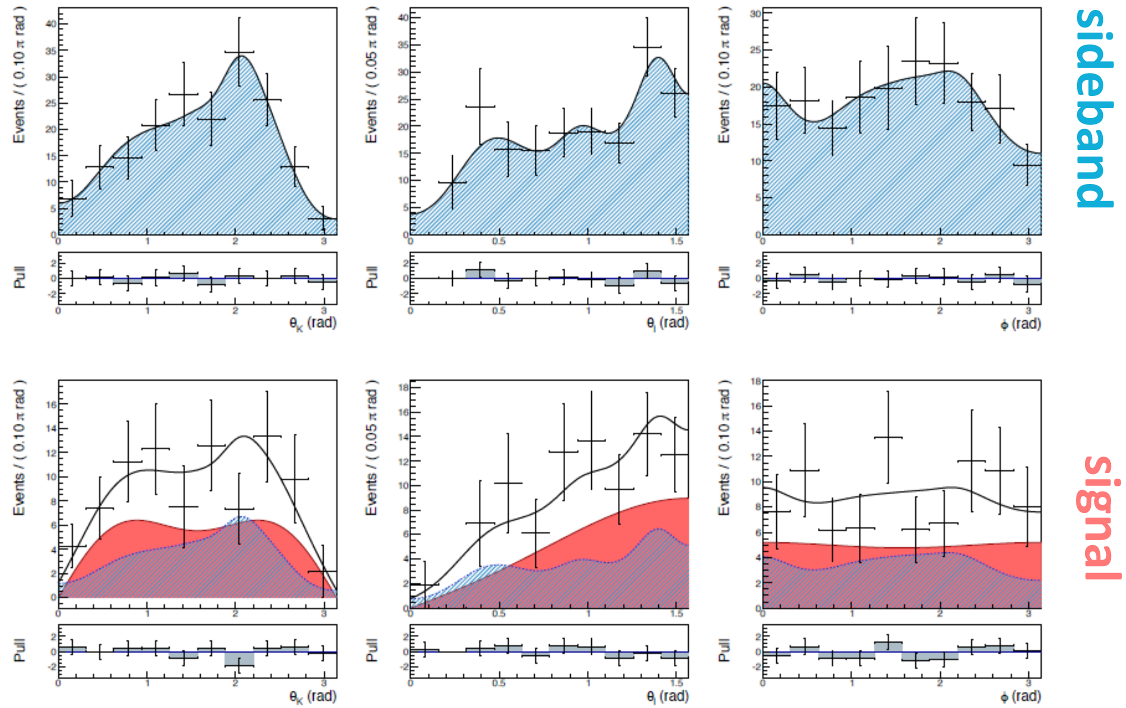




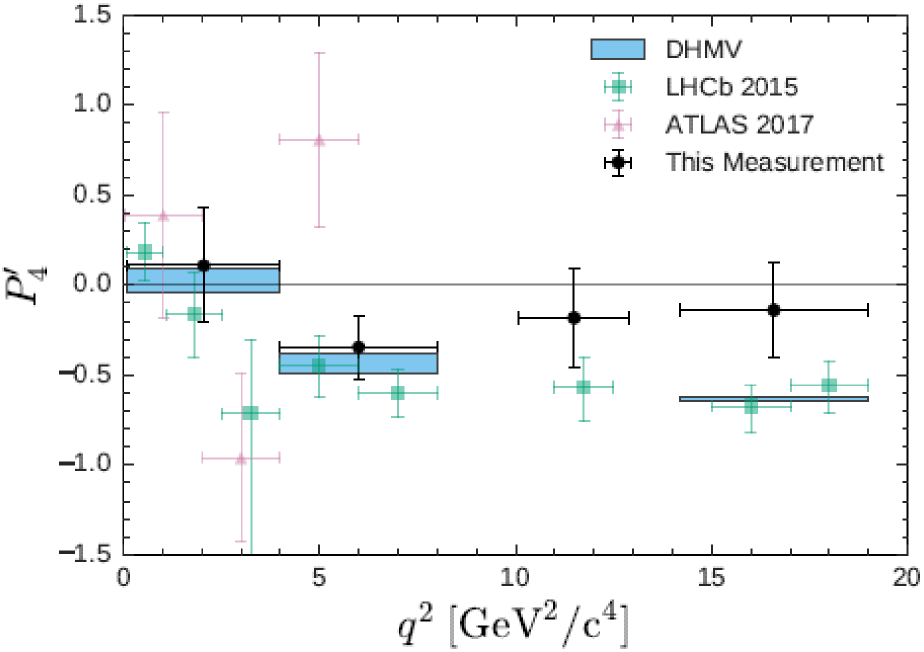
Belle [Phys. Rev. Lett. 118, 111801 (2017)]

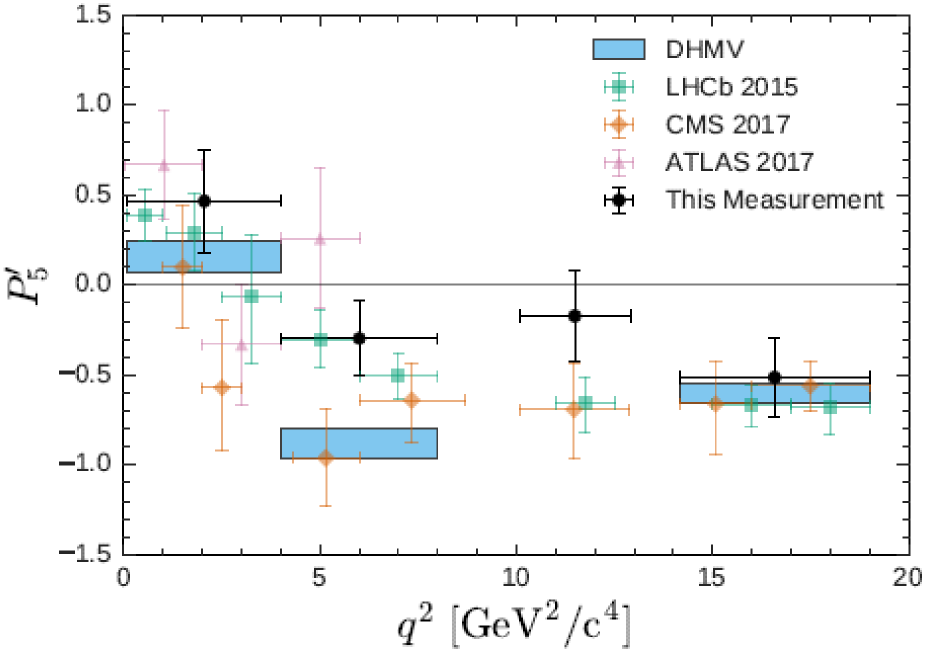
- Data is divided in the q^2 bins.
- Signal and background fraction is obtained by fitting M_{bc} distribution
- The data is split into a sideband and signal region





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

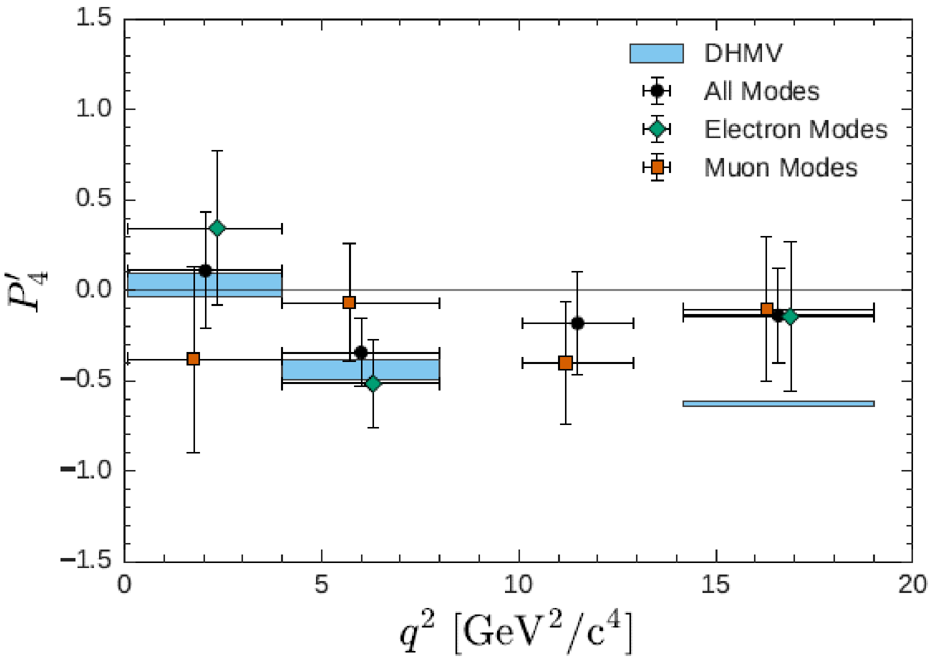


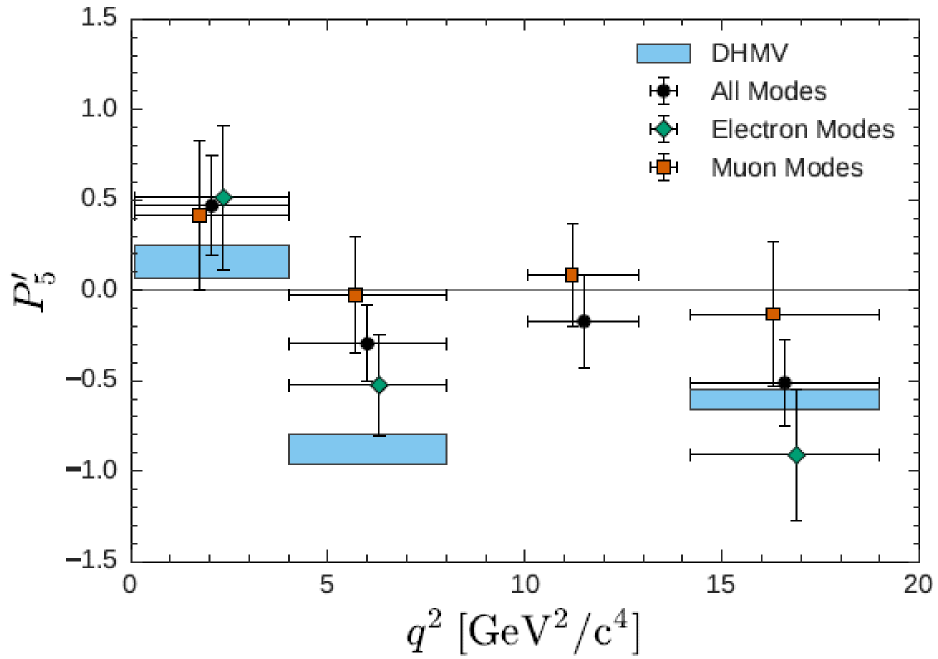


- Measurements are compatible with the SM.
- Similar central values for the P_5' anomaly with 2.5σ tension.

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

Result - Separate Lepton Flavor!



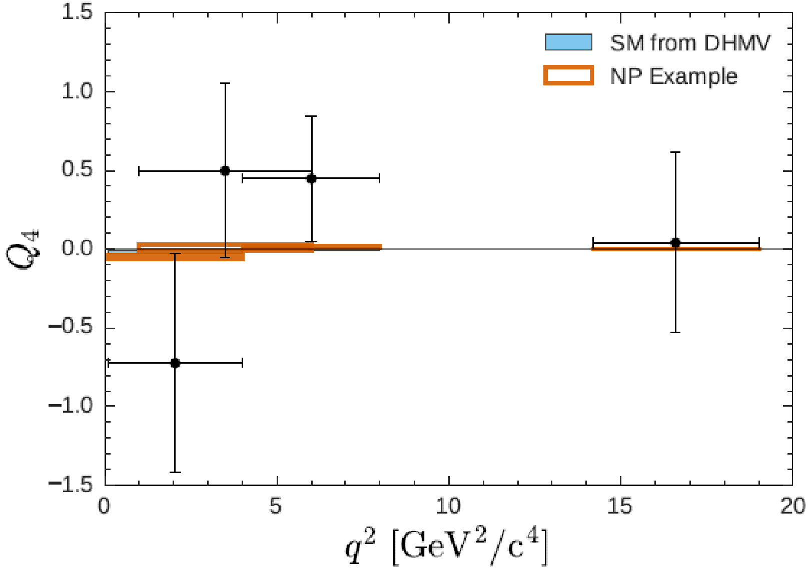


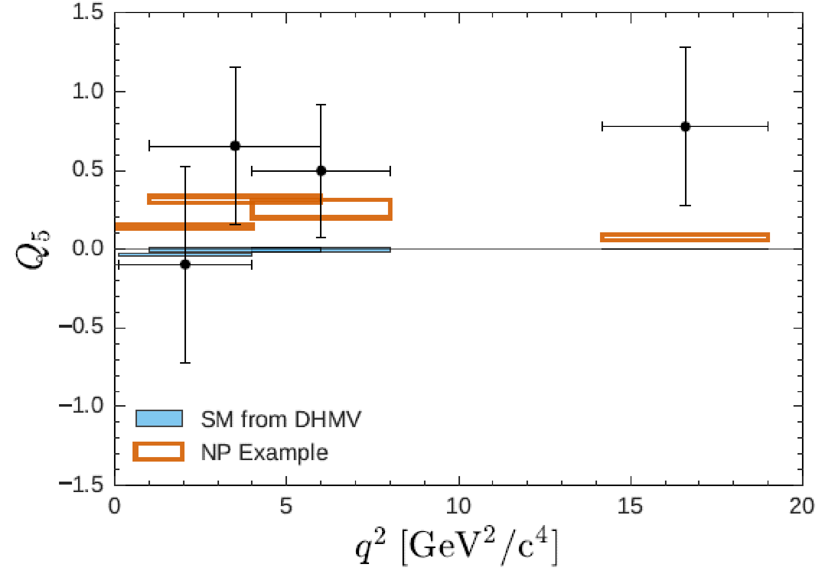
- The Largest deviation in the muon mode with 2.6σ.
- Electron mode is deviating with 1.1σ.

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.

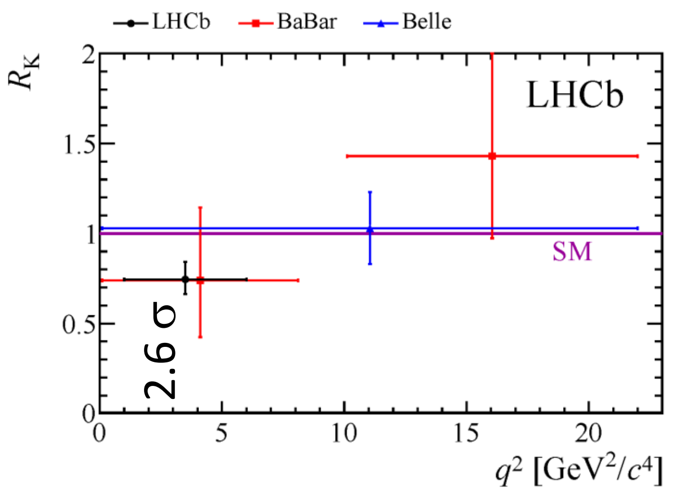
Belle [Phys. Rev. Lett. 118, 111801 (2017)]

- The Lepton Flavor universality can be tested very precisely with the ratios:

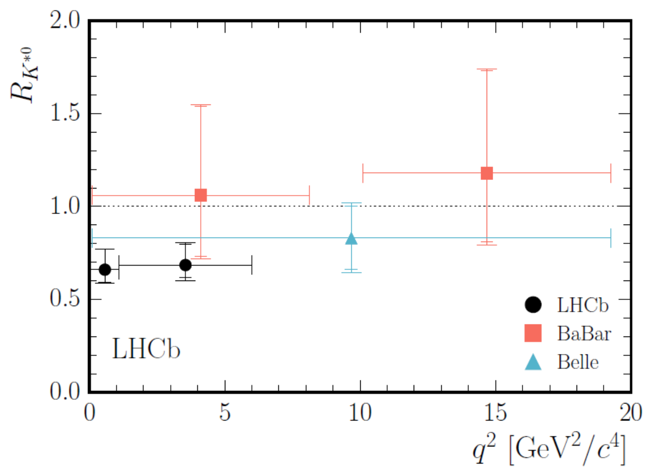
$$R_H[q_0^2, q_1^2] = \frac{\int_{q_0^2}^{q_1^2} dq^2 \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}}{\int_{q_0^2}^{q_1^2} dq^2 \frac{d\Gamma(B \to He^+e^-)}{dq^2}} \quad ; H = K, K^*, X_s$$

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

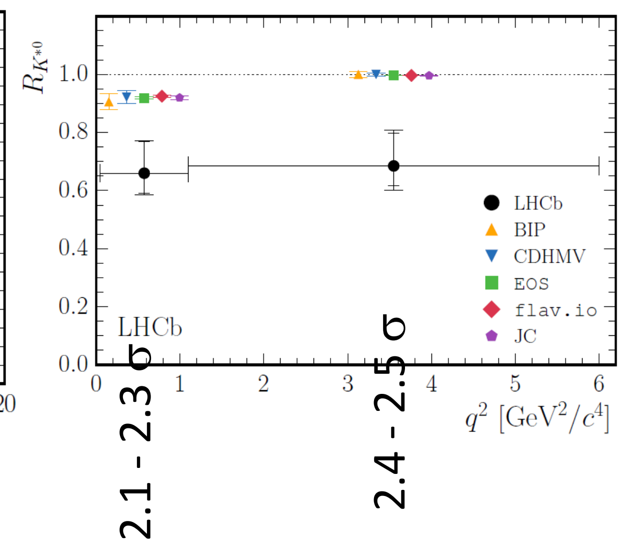
- Experimentally, many sources of systematic uncertainties are substantially reduced.



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]

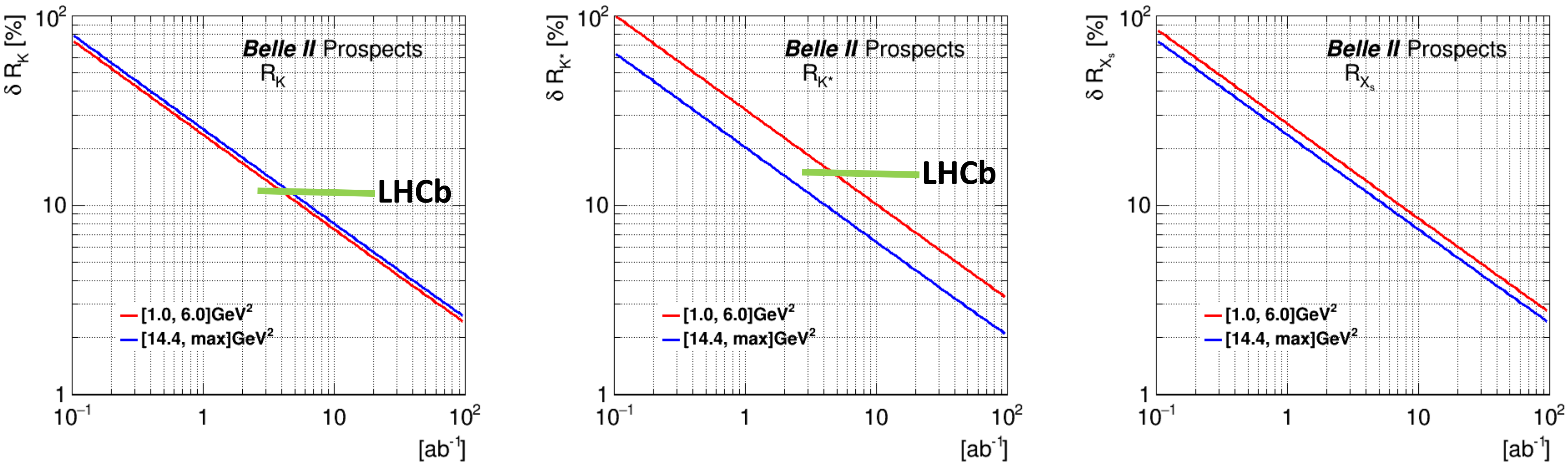
Belle II prospects for R(K/K*)

- The Lepton Flavor universality can be tested very precisely with the ratios:

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

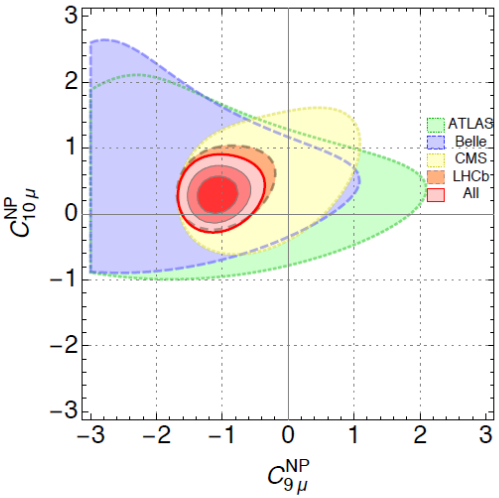
- In these ratios, hadronic uncertainties in theoretical predictions cancel and SM prediction is (very) close to unity.
- Experimentally, many sources of systematic uncertainties are substantially reduced.

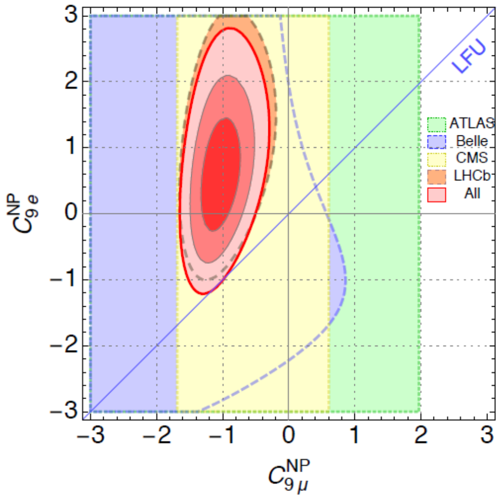
B2TIP report | arXiv:1808.10567



Global fits to b→s

- Including P_i', Q_i, $b \to s\gamma$, $R[K^{(*)}]$, $B_s \to \mu\mu$

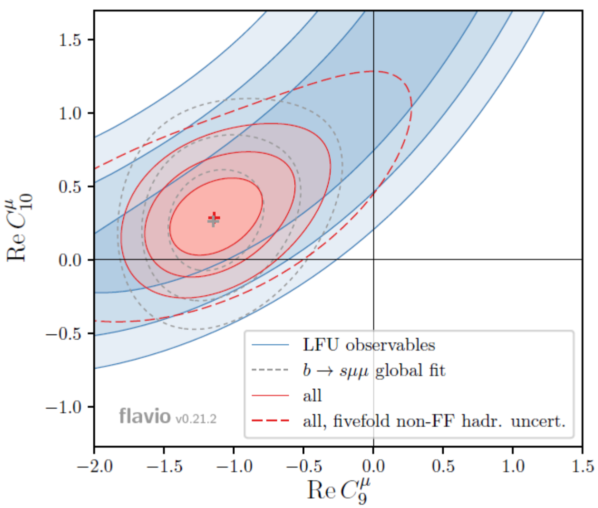


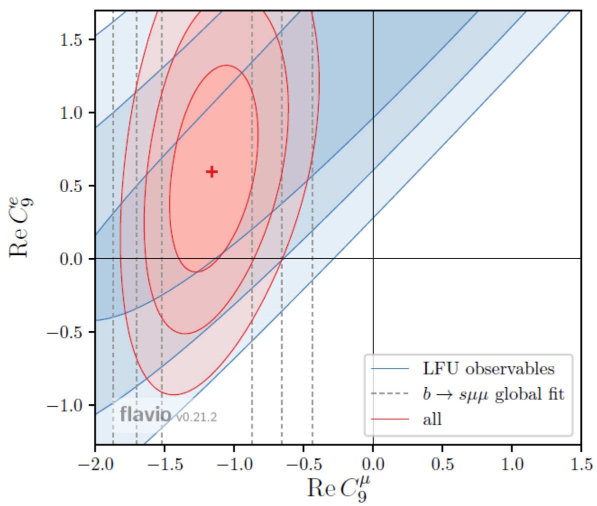


Capdevila, Crivellin, Descotes-Genon, Matias, and Virto
JHEP 1801 (2018) 093

suggests $C_{9\mu}^{NP} \approx -1.1$

- Including $R[K^{(*)}]$ and Belle's P_i', Q_i





Altmannshofer, Stangl, and Straub
Phys. Rev. D 96, 055008 (2017)

A combined fit singles out NP in the Wilson coefficient C_9^{μ} as a possible explanation.

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

- Measurements from the LHCb have exhibited **possible deviations in R(K) and R(K*)** from LFU.
  PRL 113, 151601 (2014), JHEP 08, 055 (2017)

- **Violation of LFU** is accompanied by **LFV**. **S. L. Glashow et.al PRL 114, 091801 (2015)**

- Recently, LFV decay $\mathbf{B^0 \to K^{*0}\mu^\pm e^\mp}$ is searched at **Belle**.
  Phys. Rev. D 98, 071101(R) 2018

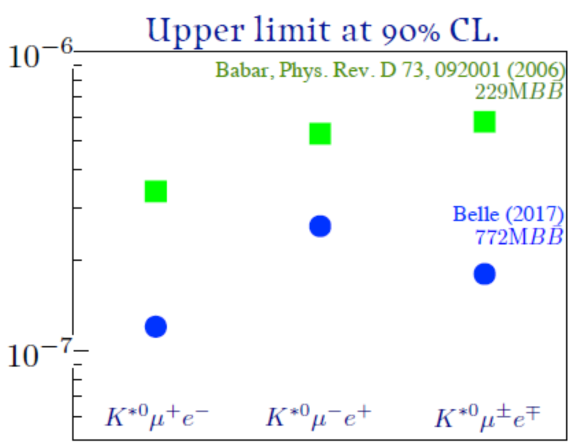
- $\mathbf{K^\pm, \pi^\pm, \mu^\pm}$ **and** $\mathbf{e^\pm}$ candidates are selected from tracks **near IP** and **satisfying PID** requirements. Inv. mass from K-π should be within **100 MeV window around** $\mathbf{K^{*0}}$ nominal mass.

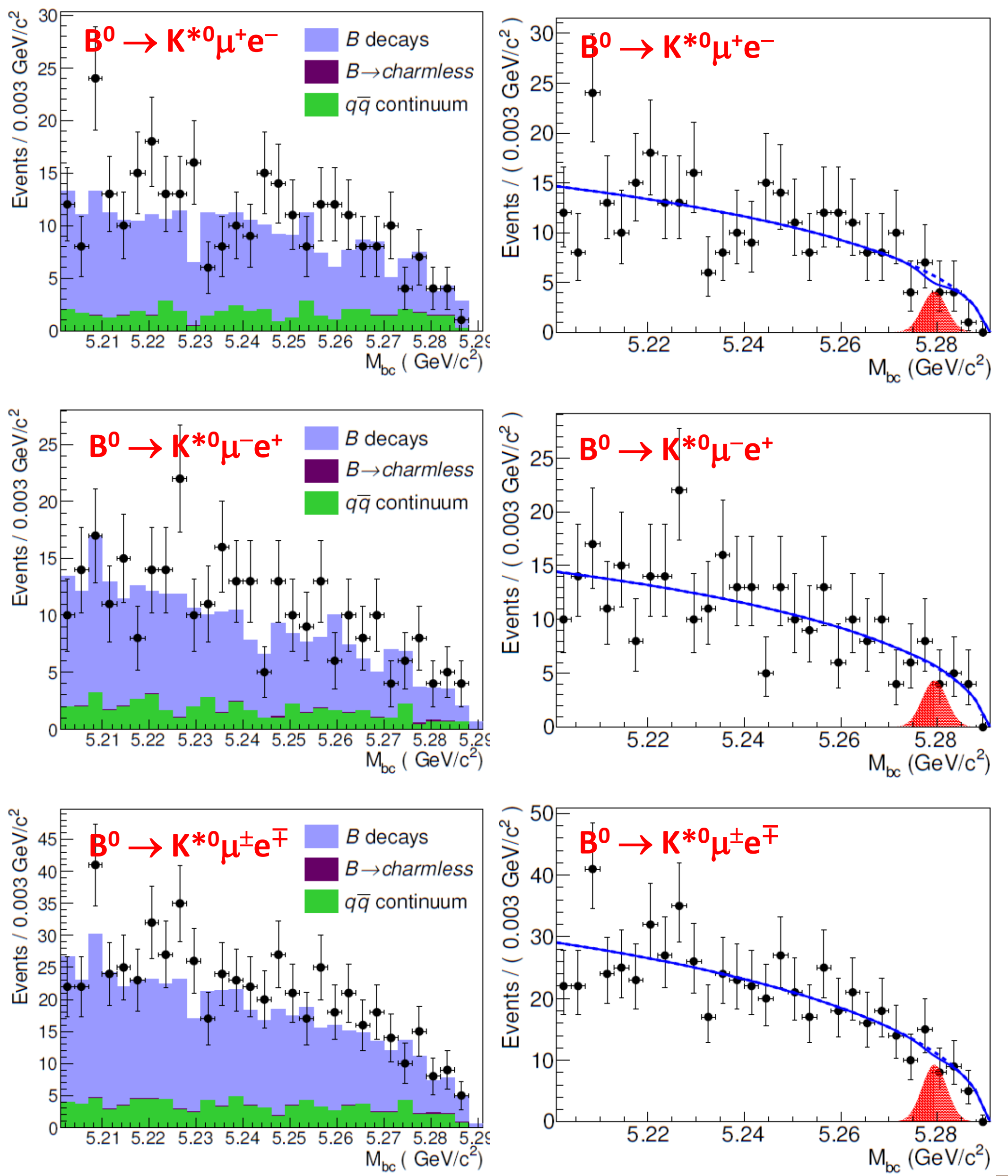
- **continuum** background events are suppressed using input variables based on event topology in a **NN**. Another NN is used to suppress background originating from **B-decays**. $\mathbf{B^0 \to K^{*0}J/\psi}$ was a good control sample and it is also used to **calibrate** the NNs.

- **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** $\mathbf{\pi^-}$**.**

- **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.

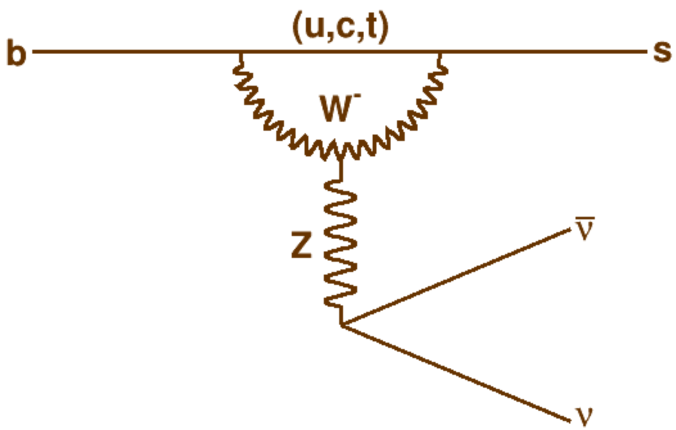
Mode	ε (%)	N_{sig}	B^{UL} (10^{-7})
$B^0 \to K^{*0}\mu^+e^-$	8.8	$-1.5^{+4.7}_{-4.1}$	1.2
$B^0 \to K^{*0}\mu^-e^+$	9.3	$0.40^{+4.8}_{-4.5}$	1.6
$B^0 \to K^{*0}\mu^\pm e^\mp$	9.0	$-1.2^{+6.8}_{-6.2}$	1.8

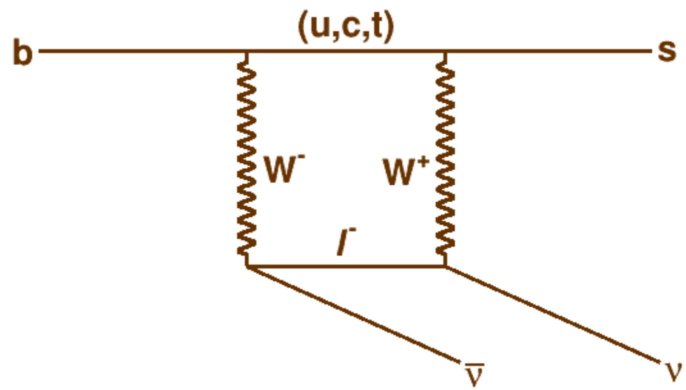




Search for $B \to h^{(*)}\nu\nu$

- Search for $B \to h^{(*)} \nu\nu$ at **Belle**, where $h = K^+, K^0_S, K^{*+}, K^{*0}, \pi^+, \pi^0\ \rho^+, \rho^0$
- Proceeds via penguin or box diagrams:





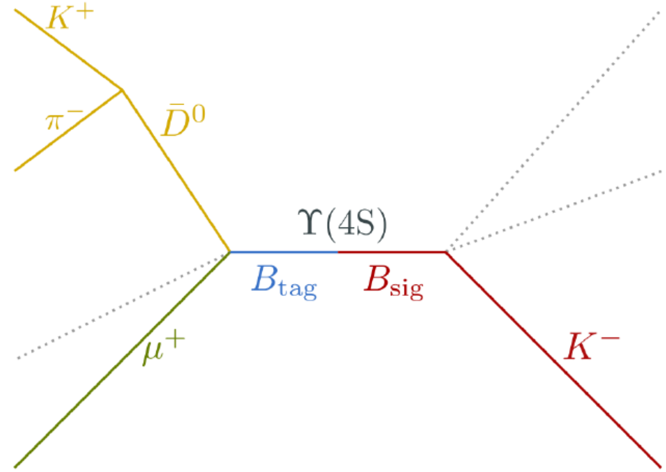
Belongs to the theoretically cleanest modes in the field of FCNC processes. As the transition mediates by a Z-boson alone

- SM prediction for the BF ranges from 1.2×10^{-7} ($B \to \pi^0\nu\nu$) to 9.2×10^{-6} ($B \to K^{*+}\nu\nu$).
  [A. Buras *et al.* J. High Energy Phys. 02 (2015) 184; C. Hambrock *et al.* Phys. Rev. D 92, 074020 (2015).]

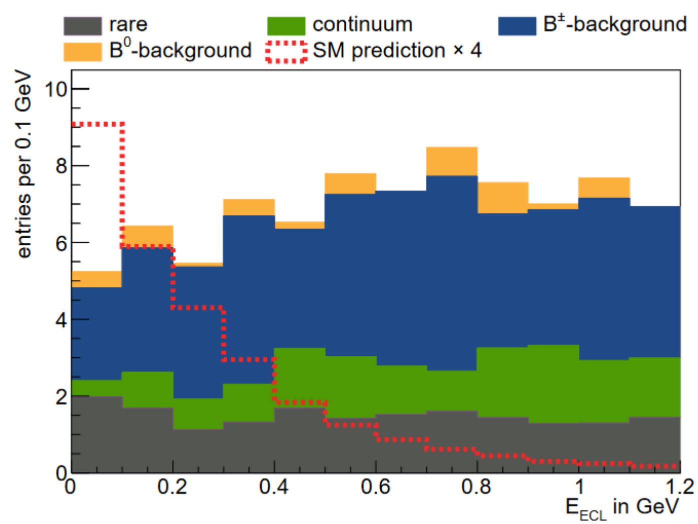
- Experimentally challenging, tagging of companion B meson needed.
  - measured at **Belle** using Hadronic tagging [**Phys.Rev.D87 111103 (2013)**].
  - measured at **BaBar** utilizing both hadronic [**Phys. Rev. D 87, 112005 (2013)**] and semileptonic tagging [**Phys. Rev. D 82, 112002 (2010)**]
  - Semileptonic tagging in this analysis.

Belle [Phys. Rev. D 96, 091101(R) (2017)]

- Semileptonic tagging for companion B (B_{tag}):
  - Hierarchical reconstruction of $B \to D^{(*)}\ell\nu$ using Neural Network.
  - 2 – 3 times efficient than hadronic tagging.
- B_{tag} candidate is combined with the reconstructed signal (B_{sig}) decay product to form an $\Upsilon(4S)$ candidate or signal event candidate.
- No additional charged track, π^0 or K_L^0 in an event.
- Continuum events are suppressed with the event shape variables.
- Signal extracted in extra (additional) energy in the calorimeter



for eg. $B^+ \to K^+\nu\nu$

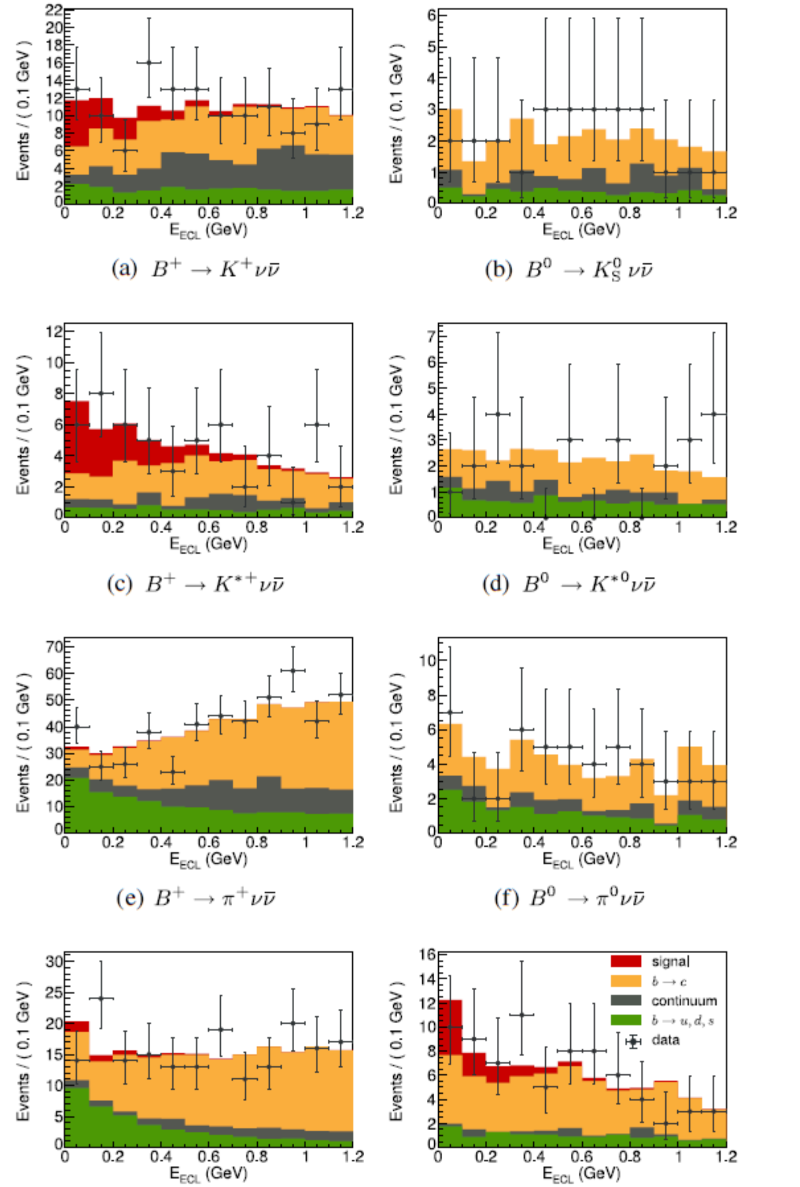


- Signal Extraction:
  - Fit with template histograms.
  - Signal and Background ($b \to c$, continuum, light quark pairs).
  - Relative fractions are fixed to MC values.

- No statistically significant signal yield observed.

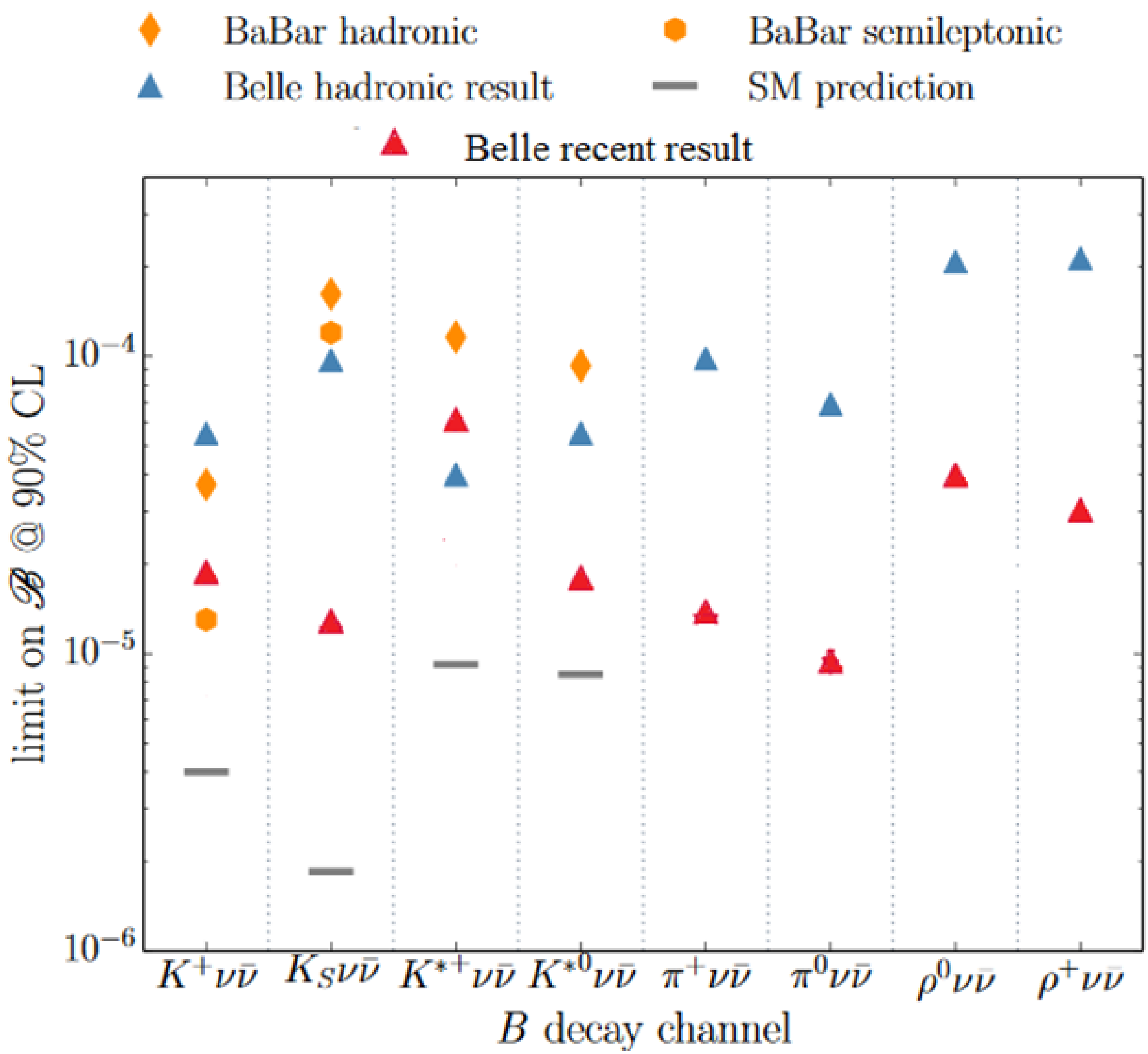
Channel	Observed signal yield	Significance
$K^{+}\nu\bar{\nu}$	$17.7 \pm 9.1 \pm 3.4$	1.9σ
$K^{0}_{S}\nu\bar{\nu}$	$0.6 \pm 4.2 \pm 1.4$	0.0σ
$K^{*+}\nu\bar{\nu}$	$16.2 \pm 7.4 \pm 1.8$	2.3σ
$K^{*0}\nu\bar{\nu}$	$-2.0 \pm 3.6 \pm 1.8$	0.0σ
$\pi^{+}\nu\bar{\nu}$	$5.6 \pm 15.1 \pm 5.9$	0.0σ
$\pi^{0}\nu\bar{\nu}$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

Belle [Phys. Rev. D 96, 091101(R) (2017)]



(a) $B^{+} \to K^{+}\nu\bar{\nu}$ (b) $B^{0} \to K^{0}_{S}\nu\bar{\nu}$
(c) $B^{+} \to K^{*+}\nu\bar{\nu}$ (d) $B^{0} \to K^{*0}\nu\bar{\nu}$
(e) $B^{+} \to \pi^{+}\nu\bar{\nu}$ (f) $B^{0} \to \pi^{0}\nu\bar{\nu}$
(g) $B^{+} \to \rho^{+}\nu\bar{\nu}$ (h) $B^{0} \to \rho^{0}\nu\bar{\nu}$

- Most stringent upper limits on BF[$B \to h^{(*)}\nu\nu$], where $h^{(*)} = K^+, K_s^0$, **K^{*0}**, π^+, π^0, ρ^+ and ρ^0 .
- Golden channel for Belle II.

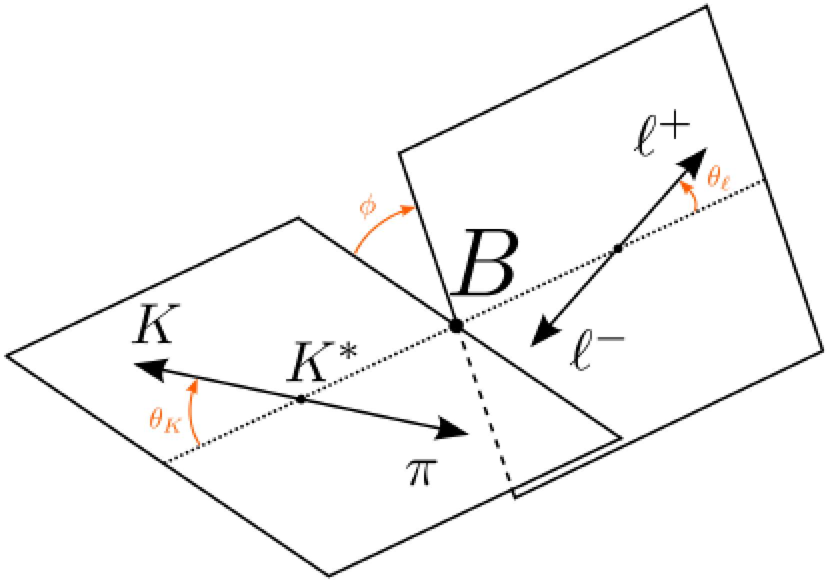


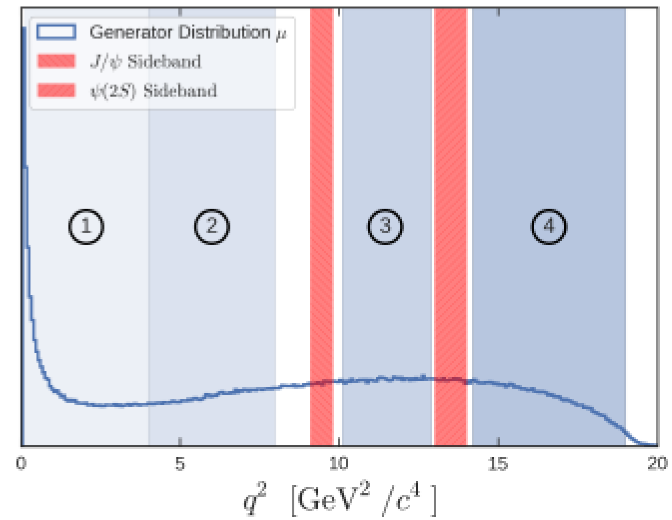
Summary

- The decays $B \rightarrow K^{(*)}\ell^+\ell^-$ were first observed by Belle (2001).
- First Lepton Flavor dependent angular analysis of $B \rightarrow K^*\ell^+\ell^-$ performed: Consistent with both SM and NP with $C_{9_\mu}^{NP} \approx -1.1$.
- Searched for the LFV decay $B^0 \rightarrow K^{*0}\mu^{\pm}e^{\mp}$ at Belle, and the most stringent limit derived.
- Search for $B \rightarrow h^{(*)}\nu\nu$ is performed. Most stringent limits till date in most channels. Close to SM prediction in $K^{(*)}$ mode. Golden channel for Belle II.
- Upcoming B-factory “Belle II” has brighter prospects for EWP decays.

ありがとう

Extra Slides





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

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

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