Recent Results on Radiative and Electroweak Penguin decays at Belle

Saurabh Sandilya

University of Cincinnati
(On Behalf of the Belle Collaboration)

Outline

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

- About nine times larger statistics than the previous Belle analysis.
- arXiv:1707.00394 [Submitted to Phy. Rev. Lett.]

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

- Lepton Flavor dependent angular analysis.
- Published recently in Phys. Rev. Lett. 118, 111801 (2017)

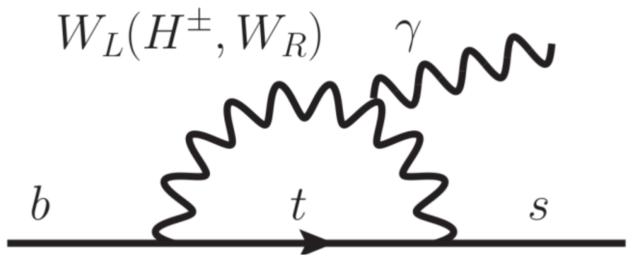
Search for $B \to h^{(*)}\nu\nu$

- Semi-leptonic tagging method used.
- arXiv:1702.03224 [Submitted to Phy. Rev. D]

All the analyses used a full data sample of $711 fb^{-1}$ containing 772 Million B-meson pairs.

$B \to K^*\gamma$

- The decay $B \to K^*\gamma$ proceeds dominantly via one loop electromagnetic penguin diagram so-called radiative penguin ($b \to s\gamma$) transition.



- These diagrams are sensitive to the particles from the NP models, that can also enter in to the loop.

- Among $b \to s\gamma$ transitions, $B \to K^*\gamma$ is one of the most important channel:
  - Cleanest exclusive decay among $B \to X_s\gamma$
  - Large BF: $\sim 4 \times 10^{-5} \to$ about 12% of inclusive $B \to X_s\gamma$

- The BFs give weak constraints on the NP as the SM predictions suffer from large uncertainties (~30 %) in the form factor.

Ratios with $B \to K^*\gamma$

- Ratios of BF cancels important uncertainties (including the form-factor related).

- CP asymmetry (A_{CP}):

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

- Isospin asymmetry (Δ_{0+}):

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

- Difference of CP asymmetry between charged and neutral B (ΔA_{CP}):

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

(ΔA_{CP} will be useful to identify NP once A_{CP} is observed)

- Ratio of the B.Fs. : $BF(B^0 \to K^{*0}\gamma)/BF(B_s \to \phi\gamma)$

Reconstruction of $B \rightarrow K^*\gamma$

- Four sub-decay modes:
  - K^{*0} : $K_s^0\pi^0$ $K^+\pi^-$
  - K^{*+} : $K_s^0\pi^+$ $K^+\pi^0$

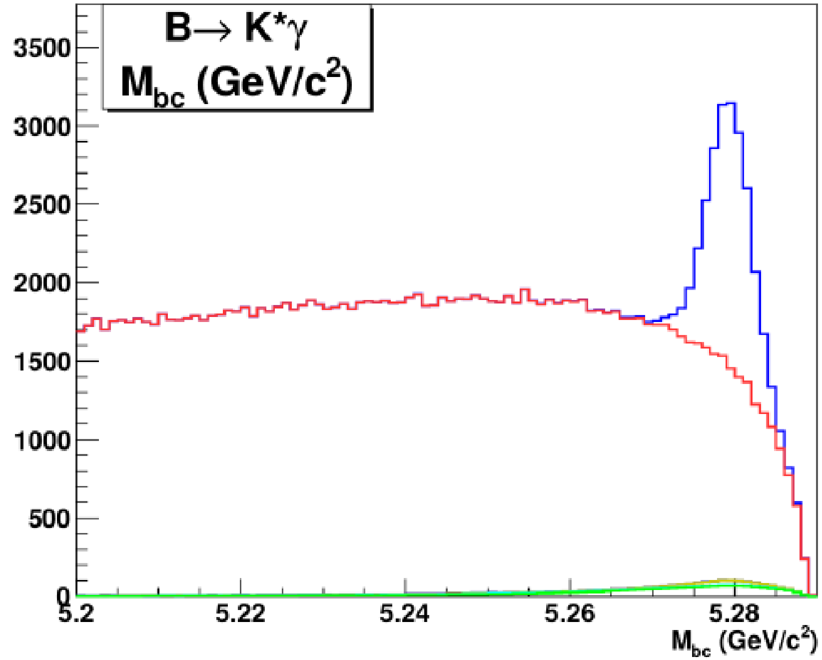
  Self-tagging

- Signal Selection:
  - -0.2 GeV $< \Delta E < 0.1$ GeV
  - 5.20 GeV/$c^2 < M_{bc} < 5.29$ GeV/c^2
  - $|M_{K\pi} - M_{K^*}| < 75$ MeV/c^2

- Background Suppresion:
  - Continuum: Neural network with event shape variables
  - photon selection with π^0 and η veto.

- Best candidate selection:
  - Number of candidates per event is 1.16 with MC.
  - Random candidate selection.

Signal
Continuum
$B \rightarrow X_s\gamma$
Rare B other than $X_s\gamma$



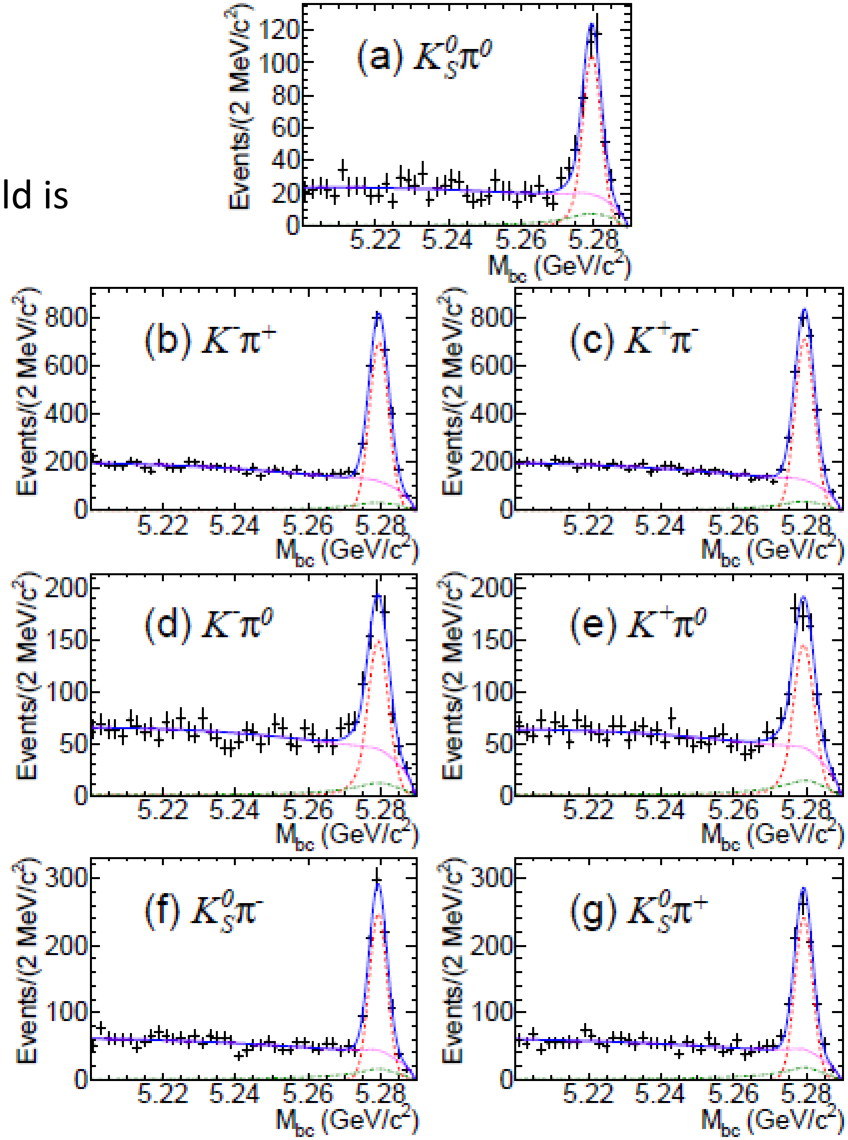
$M_{\rm bc}$ distribution summed four channels "with" $M(K\pi)$ selection after $\pi^0\eta$ veto

Extraction of BF, A_{CP} , Δ_{0+} , ΔA_{CP}

- Unbinned maximum likelihood fit to M_{bc} distributions:
  - Signal w/o π^0 (w/ π^0) : Gaussian (Crystal Ball)
  - Cross-feed : ARGUS + Bifurcated Gaussian (the yield is proportional to signal yield)
  - Continuum bkg : ARGUS
  - BB bkg : ARGUS + Bifurcated Gaussian

- BF, A_{CP} , Δ_{0+} and ΔA_{CP} is extracted in simultaneous fit performed to seven M_{bc} distributions with the likelihood:

$$
\begin{aligned}
&\mathcal{L}(M_{\rm bc}|\mathcal{B}^N, \mathcal{B}^C, A^N_{CP}, A^C_{CP}) \\
&= \Pi\mathcal{L}^{K^0_S\pi^0}(M_{\rm bc}|\mathcal{B}^N) \\
&\times \Pi\mathcal{L}^{K^-\pi^+}(M_{\rm bc}|\mathcal{B}^N, A^N_{CP}) \times \Pi\mathcal{L}^{K^+\pi^-}(M_{\rm bc}|\mathcal{B}^N, A^N_{CP}) \\
&\times \Pi\mathcal{L}^{K^-\pi^0}(M_{\rm bc}|\mathcal{B}^C, A^C_{CP}) \times \Pi\mathcal{L}^{K^+\pi^0}(M_{\rm bc}|\mathcal{B}^C, A^C_{CP}) \\
&\times \Pi\mathcal{L}^{K^0_S\pi^-}(M_{\rm bc}|\mathcal{B}^C, A^C_{CP}) \times \Pi\mathcal{L}^{K^0_S\pi^+}(M_{\rm bc}|\mathcal{B}^C, A^C_{CP}),
\end{aligned}
$$

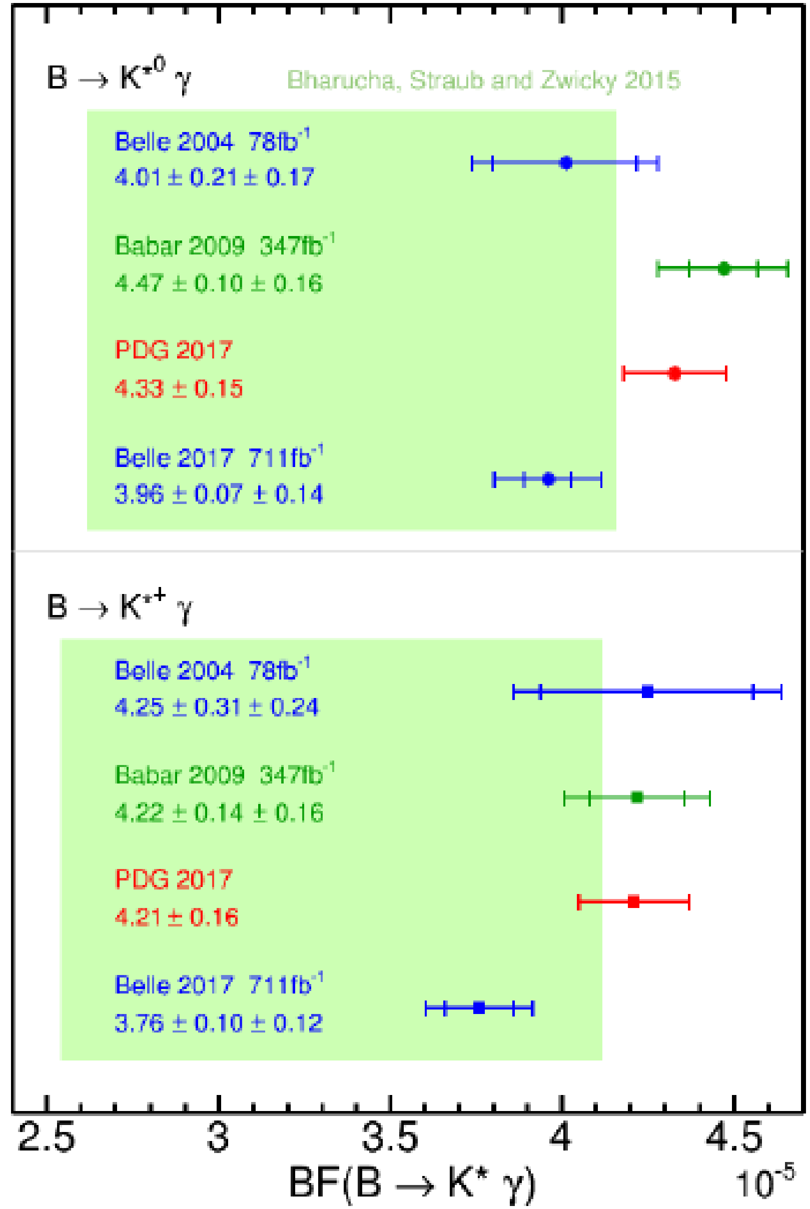


Result : BF ($B \to K^*\gamma$)

- New **Belle** result is consistent with the previous measurements
  - smaller (~10%) than **BaBar** [**Phys. Rev. Lett. 103, 211802 (2009)**] result which dominated the **PDG** average.

- Also consistent with the theoretical predictions by **Bharucha, Starub and Zwicky**. [**J. High Energy Phys. 08 (2016) 098.**]

- Most precise measurement of the BF($B \to K^*\gamma$) and splits the difference between theory and experiment.



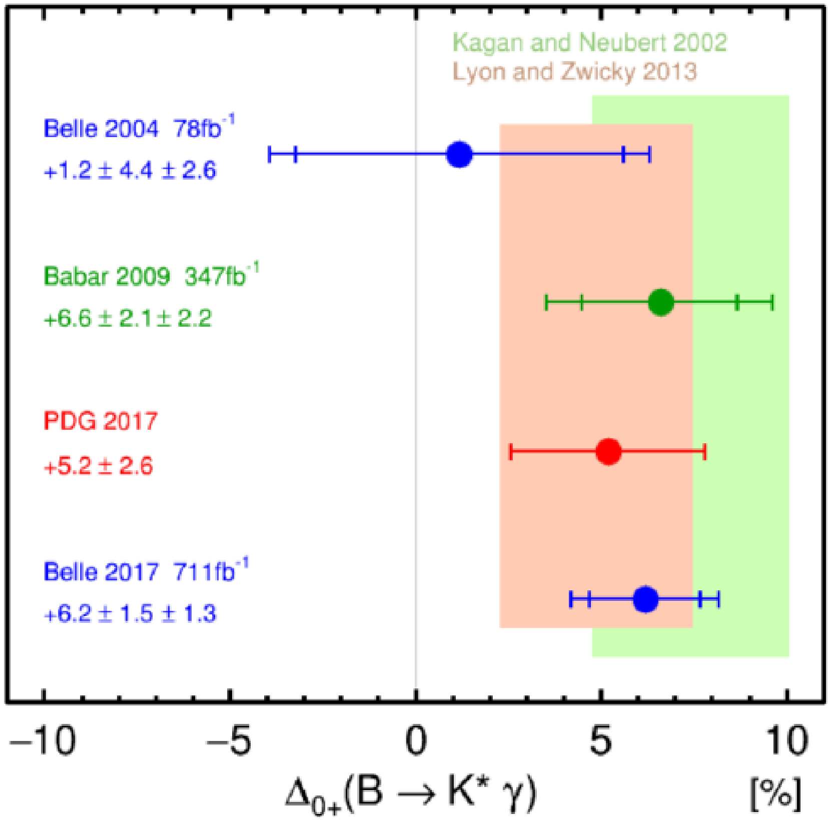
Result: Δ_{0+}

- First evidence of isospin violation in $b \to s$ transition with 3.1σ significance.

$$\Delta_{0+} = (+6.2 \pm 1.5(\text{stat}) \pm 0.6(\text{sys}) \pm 1.2(f_{+-}/f_{00}))\%$$

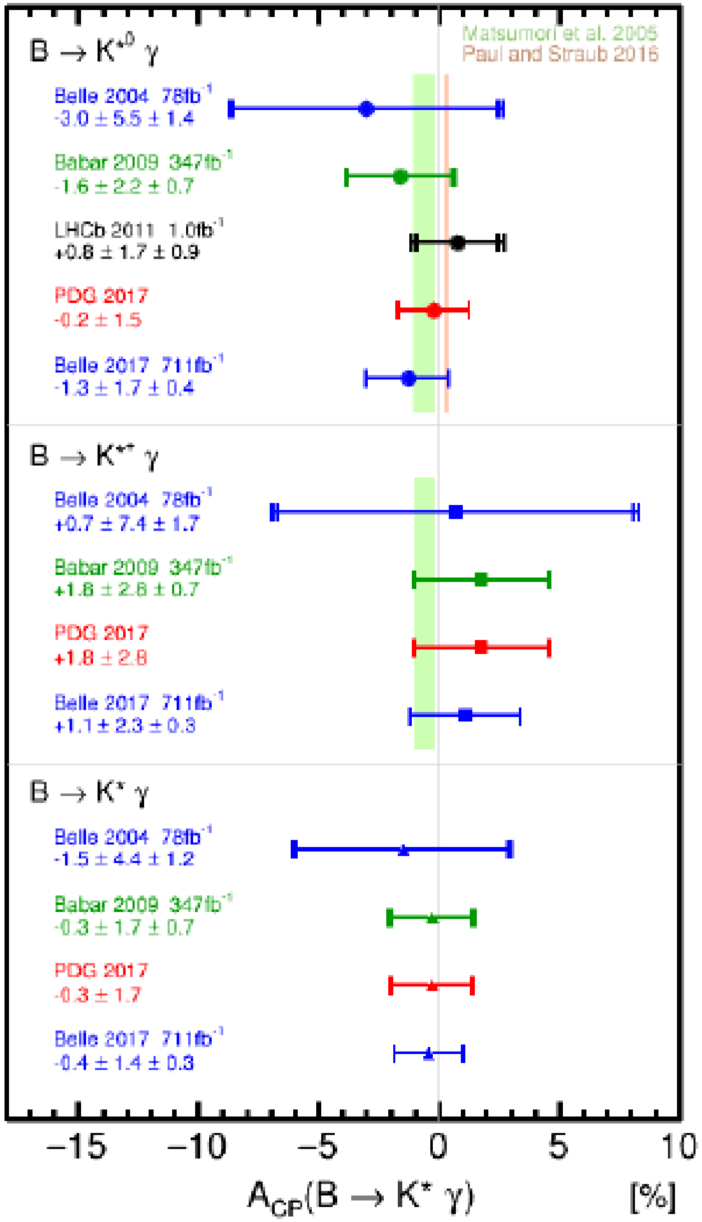
- Dominant uncertainties are statistical one and due to f_{+-}/f_{00}.

- New **Belle** result is consistent with **BaBar** [Phys. Rev. Lett. 103, 211802 (2009)], and also theoretical predictions within the SM by **Kagan and Neubert** [Phys. Lett. B 539, 227 (2002)] and **Lyon and Zwicky** [Phys. Rev. D 88, 094004 (2013)].



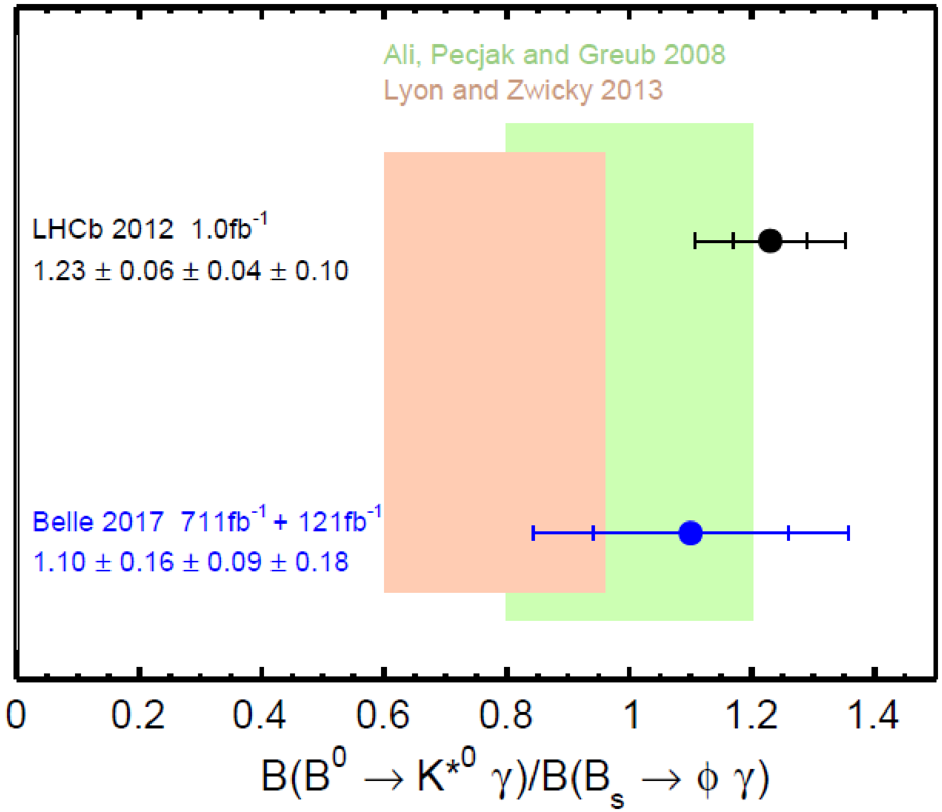
Result: A_{CP}

- New **Belle** results are most precise to date.
- Consistent with zero and previous measurements by **BaBar** [Phys. Rev. Lett. 103, 211802 (2009)] and **LHCb** [Nucl. Phys. B 867, 1 (2013)].
- Consistent with theoretical predictions within the SM by **Matsumori et al** [Phys. Rev. D 72, 014013 (2005)] and **Paul and Straub** [arXiv:1608.02556].
- $\Delta A_{CP} = (+2.4 \pm 2.8 \pm 0.5)\%$ consistent with zero.

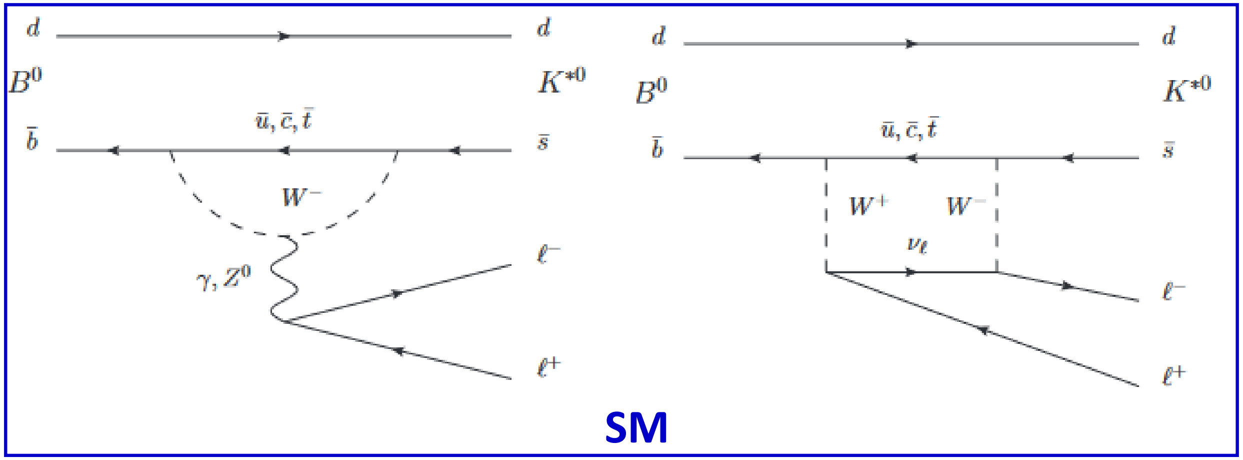


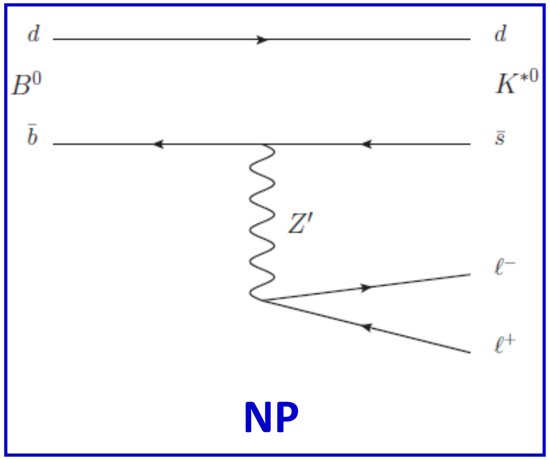
Result : BF($B^0 \to K^{*0}\gamma$)/BF($B_s \to \phi\gamma$)

- Belle measurement from 121 fb^{-1} of data at Υ(5S) for BF ($B_s \to \phi\gamma$) is used. [Phys. Rev. D 91, 011101 (2015)]
- Only $K^{*0} \to K^+\pi^-$ mode is used to cancel common systematics
- BF($B^0 \to K^{*0}\gamma$)/BF($B_s \to \phi\gamma$) : $1.10 \pm 0.16 \pm 0.09 \pm 0.18$
- **Belle** result is consistent with **LHCb** [Nucl. Phys. B 867, 1 (2013)], and theoretical predictions by **Ali, Pecjak and Greub** [Eur. Phys. J. C 55, 577 (2008)] and **Lyon and Zwicky** [Phys. Rev. D 88, 094004 (2013)]



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

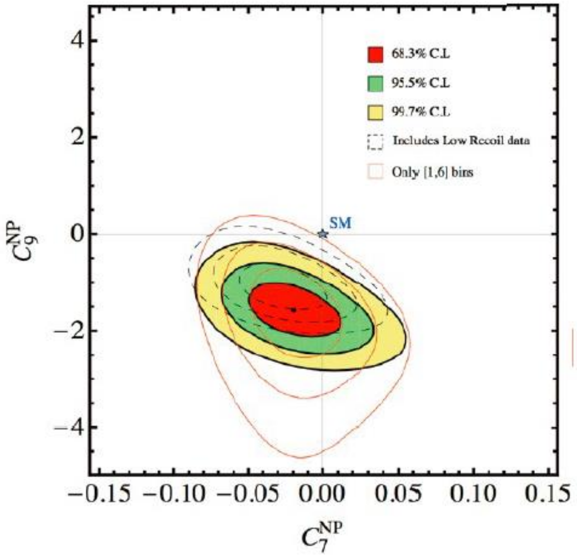




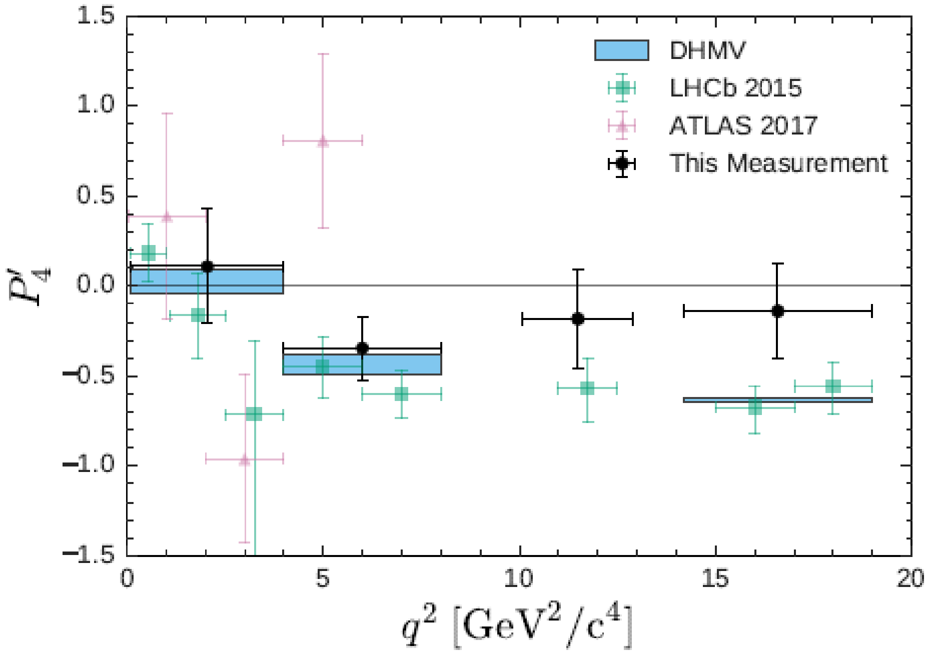
- LHCb reported 3.4σ deviation from a SM prediction in P_5' for $4 < q^2 < 8$ GeV^2/c^2 which was obtained from full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$.

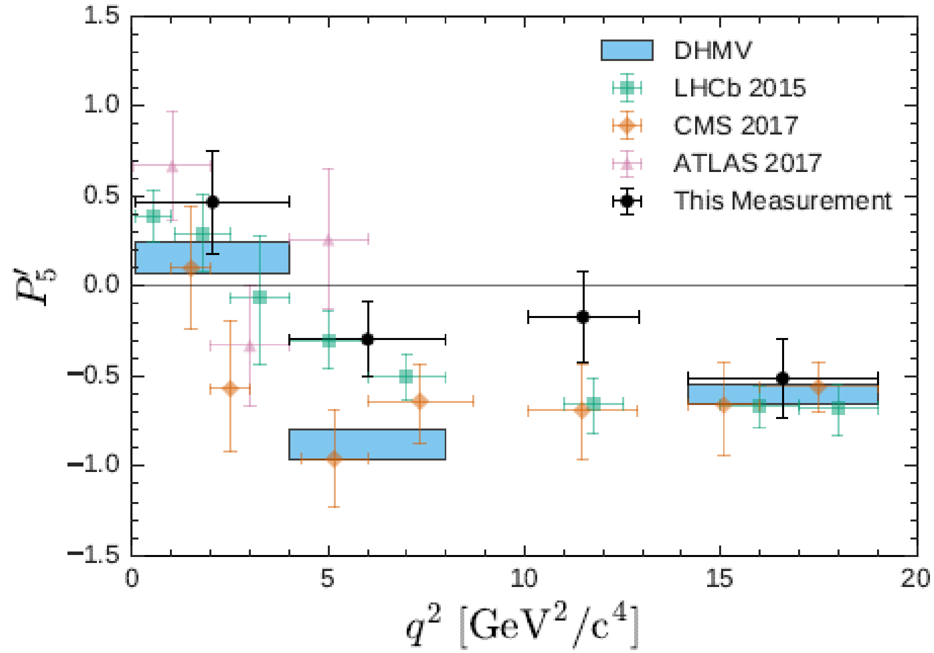
- Global fit to radiative and EW penguin B decays gives Wilson coefficient C_9^{NP} deviated about -1 from SM values

- Motivates to check lepton flavor dependence in angular analysis.



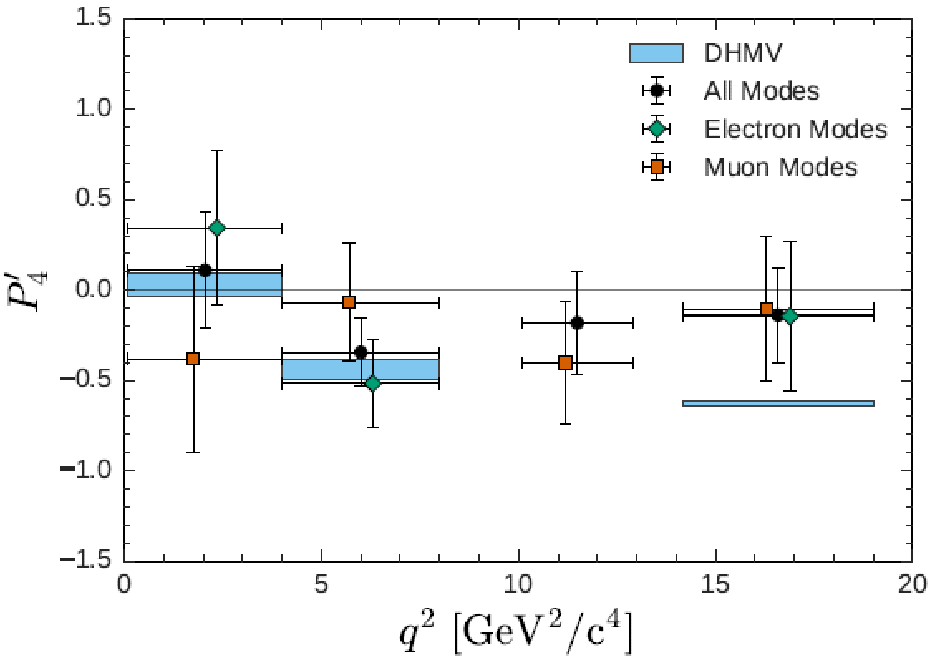
Result P_5': for Combined Data

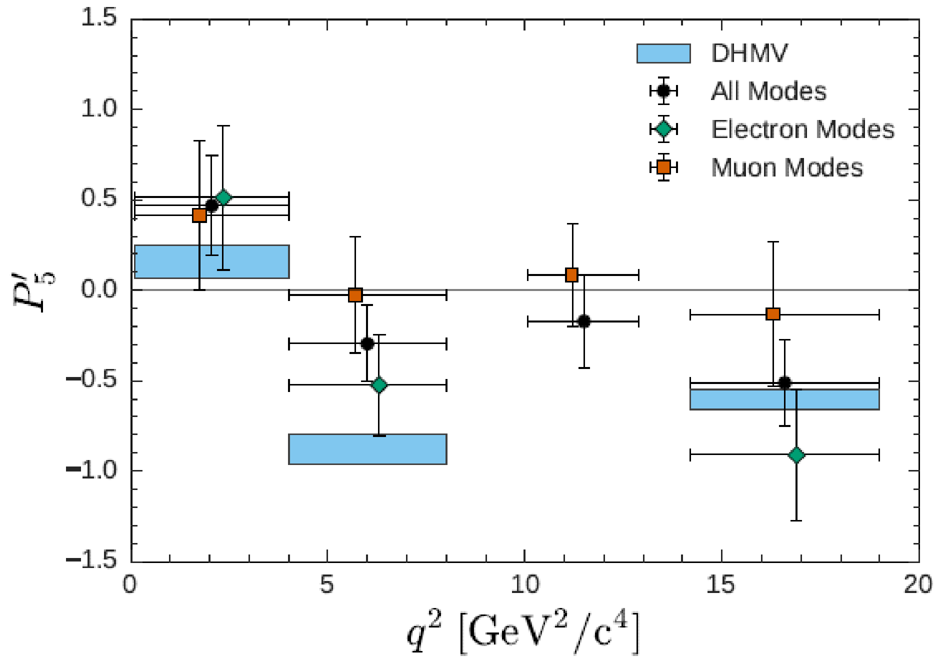




- Measurements are compatible with the SM.
- Similar central values for the P_5' anomaly with 2.5σ tension.

Result - Separate Lepton Flavor!

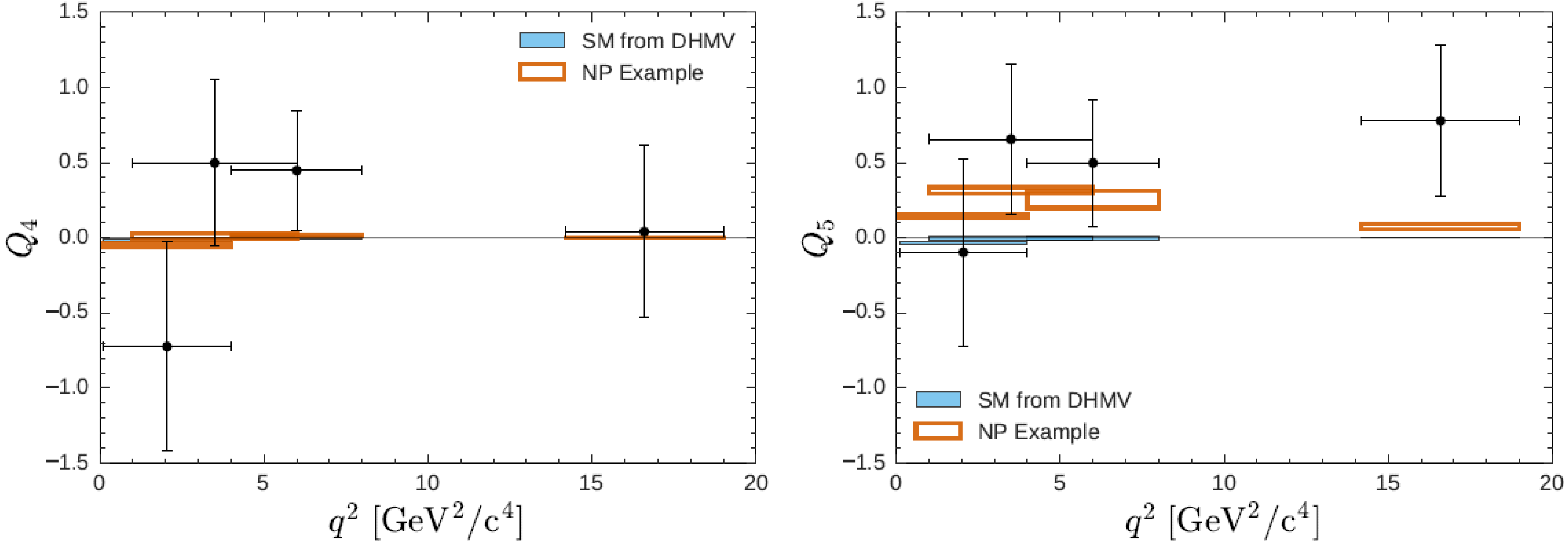




- The Largest deviation in the muon mode with 2.6σ.
- Electron mode is deviating with 1.1σ.

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.

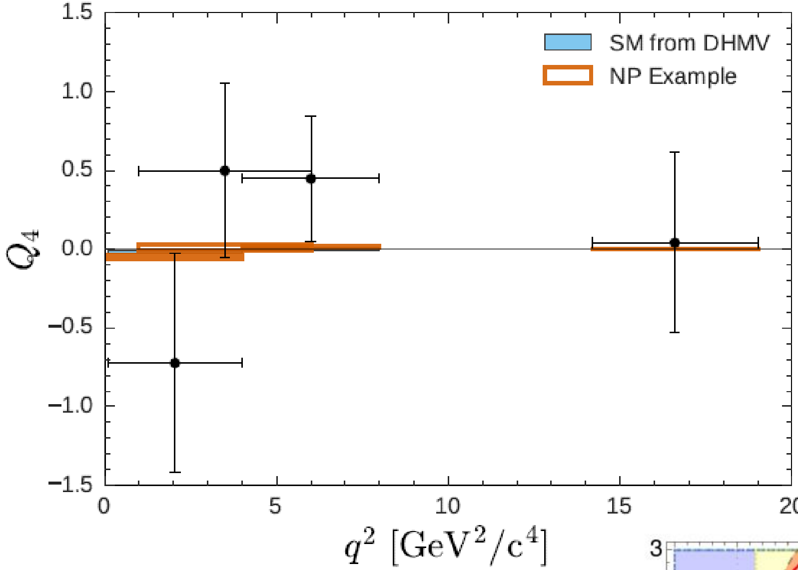


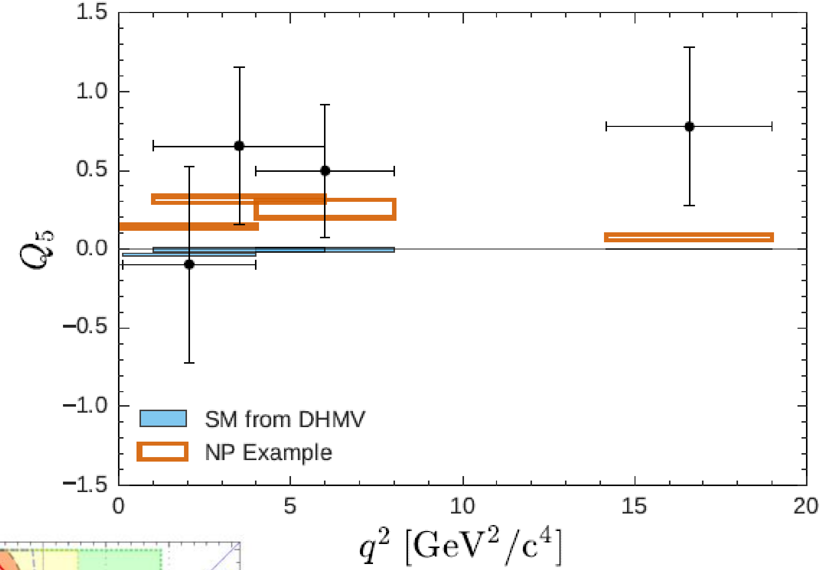
- No significant deviation from zero is discerned.
- Q_4 and Q_5 observables in agreement with SM and favoring NP scenario.

- Published recently in [Phys. Rev. Lett. 118, 111801 (2017)]

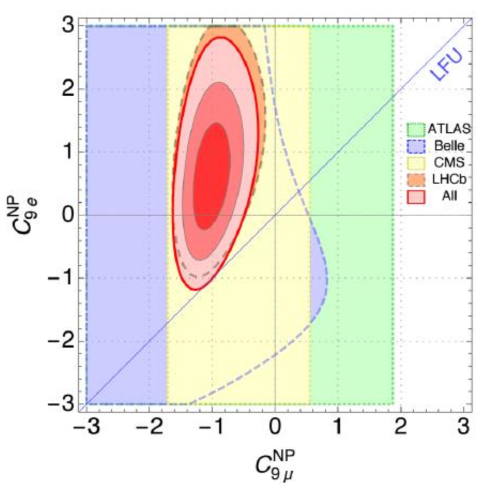
Result - Separate Lepton Flavor!

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





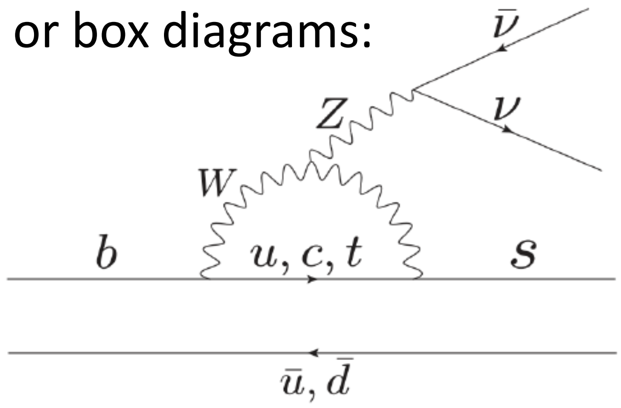
- Global fits including P_5' Q_5 $R(K^*)$, $B_s \to \mu\mu$, $b \to s\gamma$ suggests $C_{9\mu}^{NP} \approx -1.1$

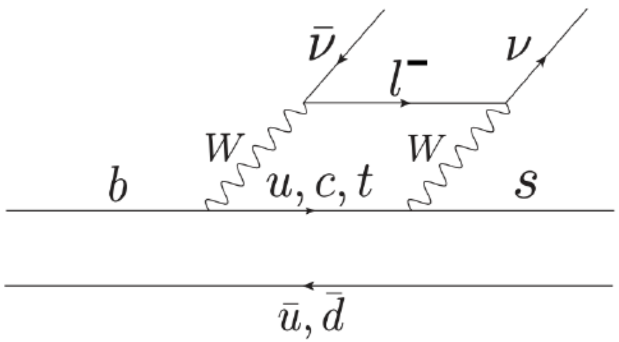


Capdevila, Crivellin, Descotes-Genon, Matias, Virto, arXiv:1704.05340

Search for B → $h^{(*)}\nu\nu$

- Proceeds via penguin or box diagrams:





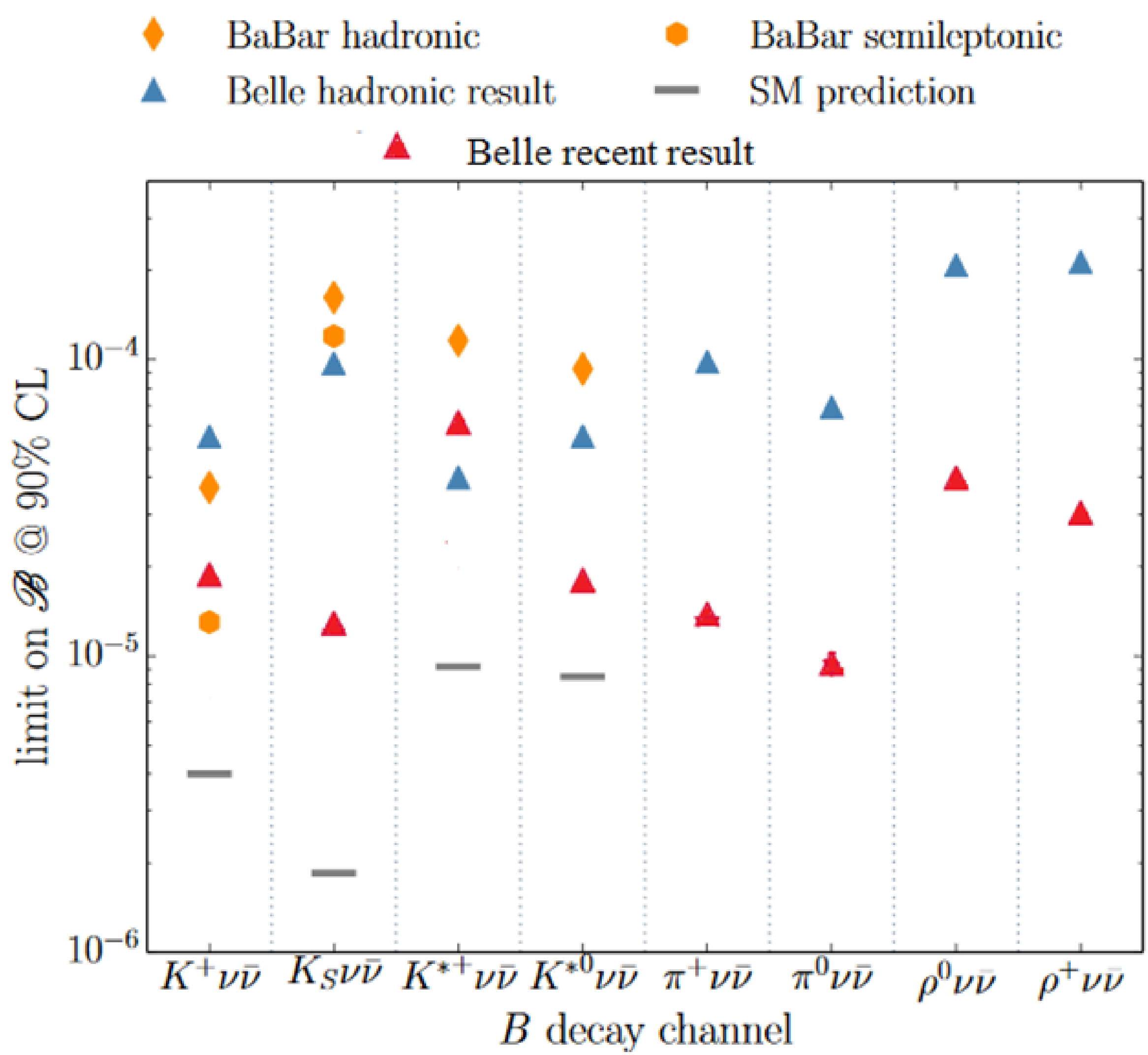
- Theoretically very clean channel (no charm loops)
- Experimentally challenging, tagging of companion B meson needed.
  - Hadronic tagging already measured at Belle. [Phys.Rev.D87 111103 (2013)].
  - Semileptonic tagging in this analysis.

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

Mode	$\mathcal{B}$ $[10^{-6}]$
$B^+ \to K^+\nu\bar{\nu}$	$3.98 \pm 0.43 \pm 0.19$
$B^0 \to K^0_S\nu\bar{\nu}$	$1.85 \pm 0.20 \pm 0.09$
$B^+ \to K^{*+}\nu\bar{\nu}$	$9.91 \pm 0.93 \pm 0.54$
$B^0 \to K^{*0}\nu\bar{\nu}$	$9.19 \pm 0.86 \pm 0.50$

Upper Limits

- Most stringent upper limits on BF[$B \rightarrow h^{(*)}\nu\nu$], where $h^{(*)} = K^+, K_s^0, K^{*0}, \pi^+, \pi^0, \rho^+$ and ρ^0 .
- Golden channel for Belle II.
- See S. Cunliffe's talk (previous speaker).



Summary

- New measurement of $B \to K^*\gamma$ performed.
  - First evidence for Isospin Violation in $b \to s$ transition with 3.1σ significance.
  - All the measurements are most precise to date.
  - Used to constrain new physics

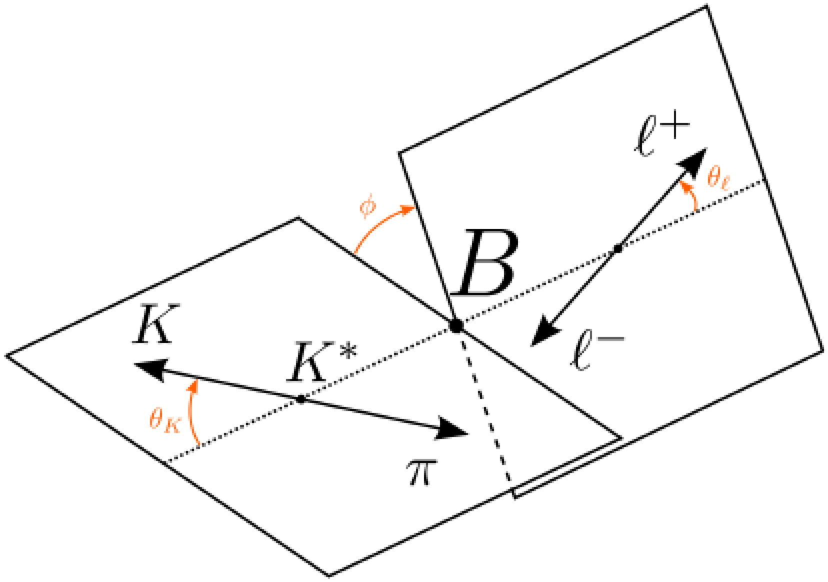
- First Lepton Flavor dependent angular analysis of $B \to K^*\ell^+\ell^-$ performed.
  - Consistent with both SM and NP with $C_{9\mu}^{NP} \approx -1.1$.

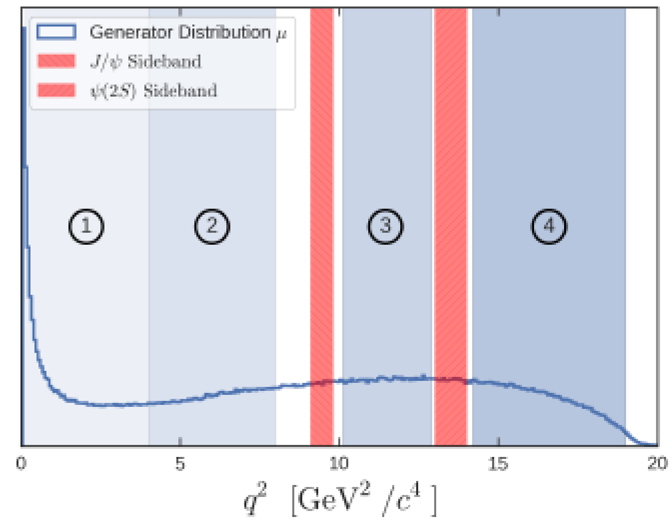
- Search for $B \to h^{(*)}\nu\nu$
  - Most stringent limits till date in most channels.
  - Close to SM prediction in $K^{(*)}$ mode.
  - Golden channel for Belle II.

- See Belle II Prospects in S. Cunliffe's talk (previous speaker)

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

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

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

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