Radiative and EWP B decays at B-factories

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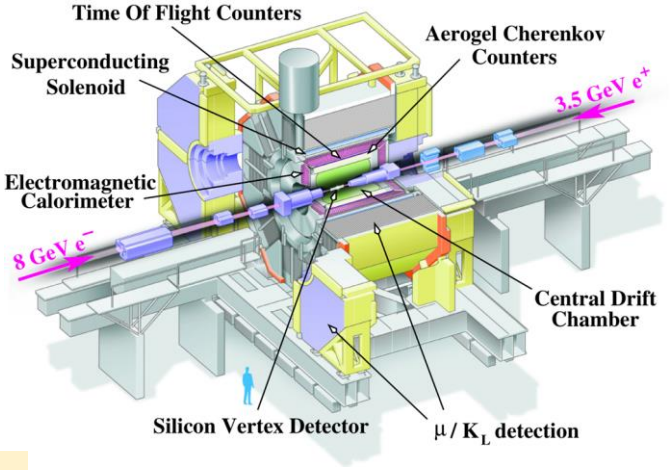
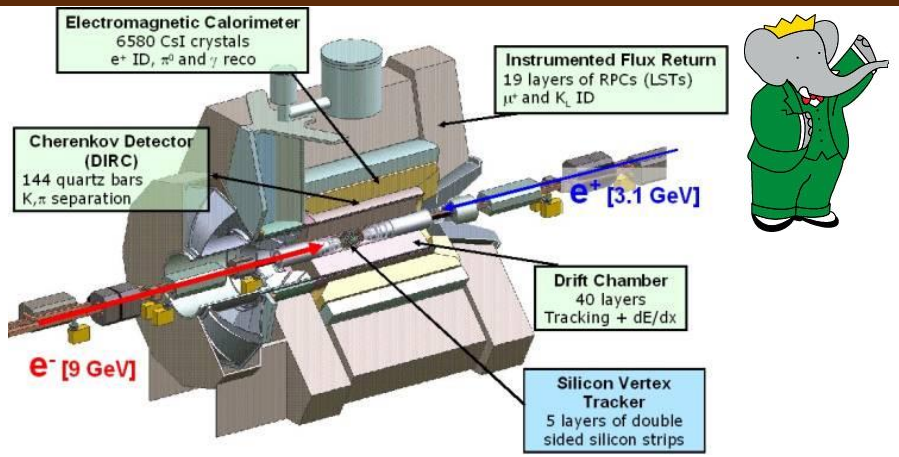
B-factories

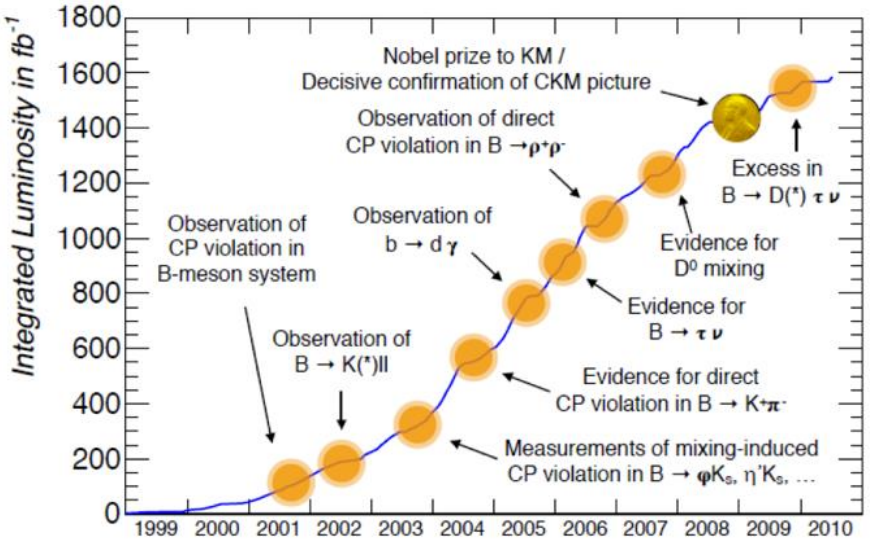




Success

(Belle and BaBar) had a successful operational period with a total recorded sample over 1.5 ab^{-1} (1.25 x 10^9 B-meson pairs).

- Observation of CPV in B meson system and confirmation of CKM picture.
- Still room for NP searches.



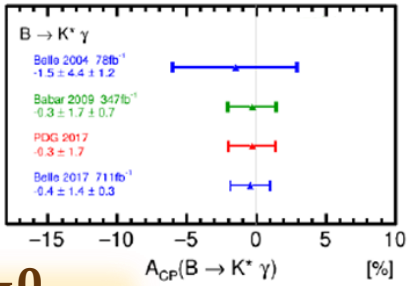
Advantages

- Very clean sample of quantum correlated B-meson pairs.
- Low background environment → efficient reconstruction of neutrals (π^0, η, ..)
- Dalitz plot analyses, missing mass analyses straight-forward.

Outline

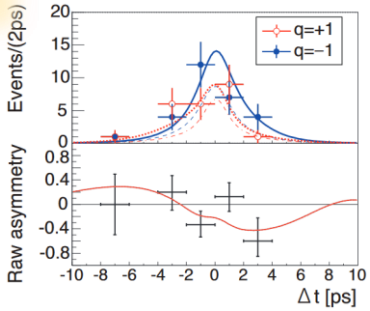
Measurement of B → K*γ

- Isospin asymmetry, A_{CP} and BF measurements .
- **Phys. Rev. Lett. 119, 191802 (2017)**



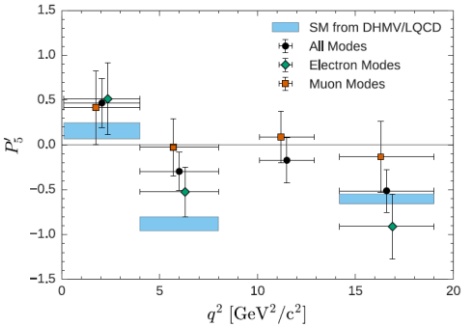
Measurement of time-dep. CP asymmetries $B^0 \rightarrow K^0_S \eta\gamma$

- Obtained CP Violation parameters.
- **arXiv 1803.07774 (accepted in PRD)**



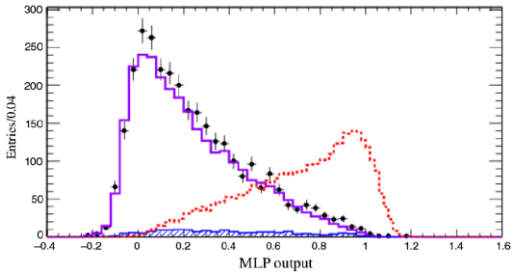
Angular Analysis of $B \rightarrow K^* \ell^+ \ell^-$

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



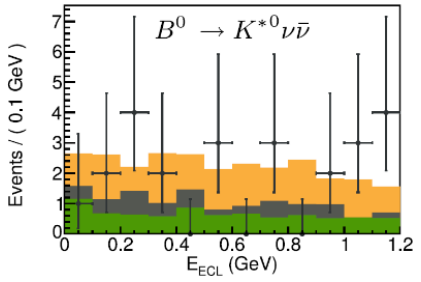
Search for the $B^+ \rightarrow K^+ \tau^+ \tau^-$

- Based on 471M $B\overline{B}$ pairs from BaBar.
- **Phys. Rev. Lett. 118, 031802 (2017)**



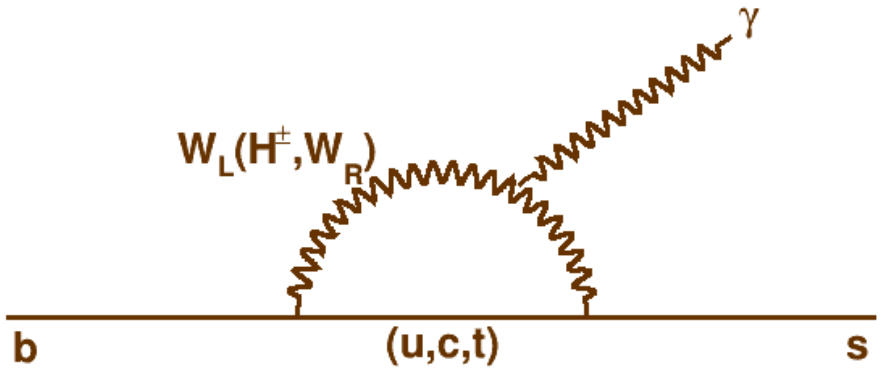
Search for $B \rightarrow h^{(*)}\nu\nu$

- Searched with Semi-leptonic tagging method.
- **Phys. Rev. D 96, 091101(R) (2017)**



$B \rightarrow K^*\gamma$

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



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

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

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

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

- Ratios of BF cancels important uncertainties (including the form-factor related).
- CP asymmetry (A_{CP}):

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

- Isospin asymmetry (Δ_{0+}):

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

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

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

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

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

Reconstruction of B → K*γ

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

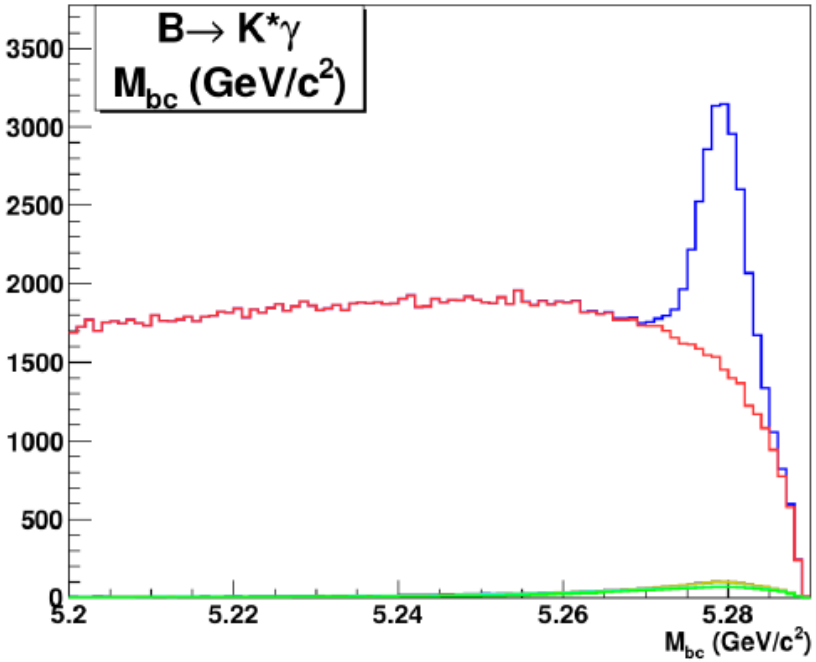
  Self-tagging

- Signal Selection:
  - -0.2 GeV < ΔE < 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 → $X_s\gamma$
Rare B other than $X_s\gamma$



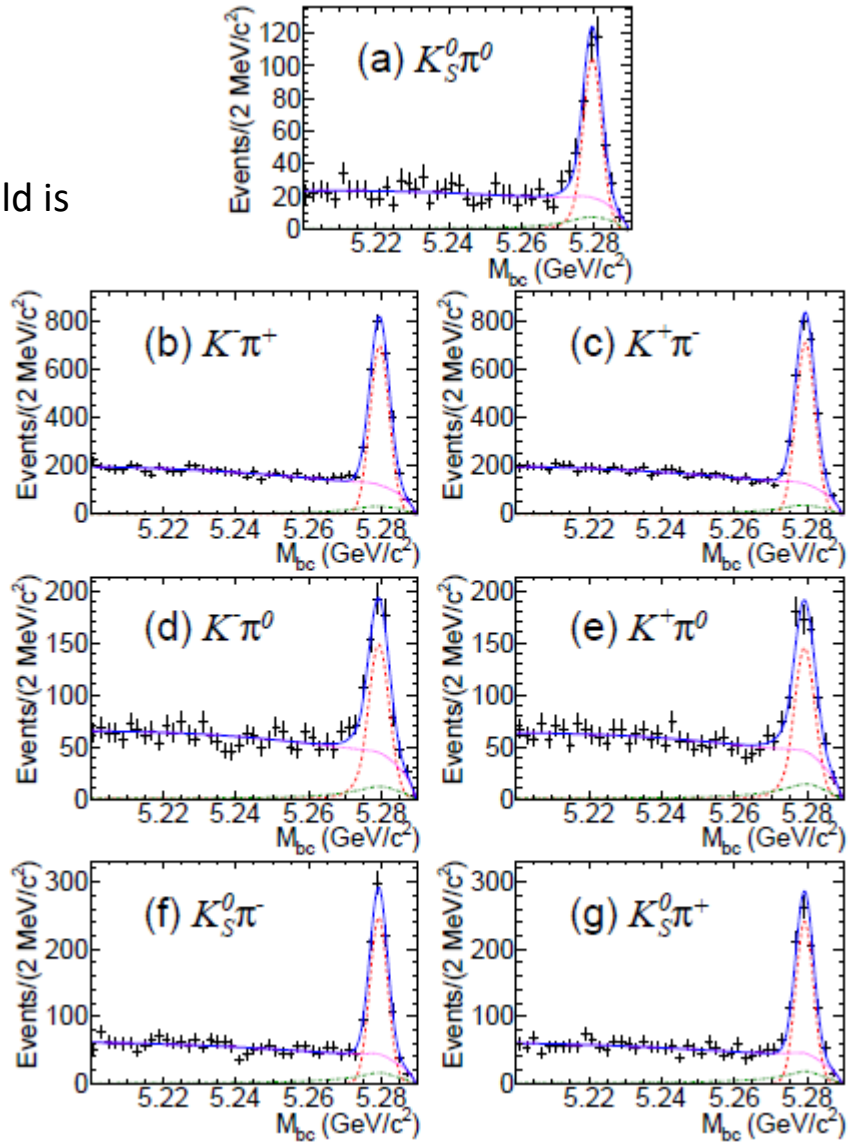
$M_{\rm bc}$ distribution summed four channels "with" $M(K\pi)$ selection after $\pi^0\eta$ veto

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

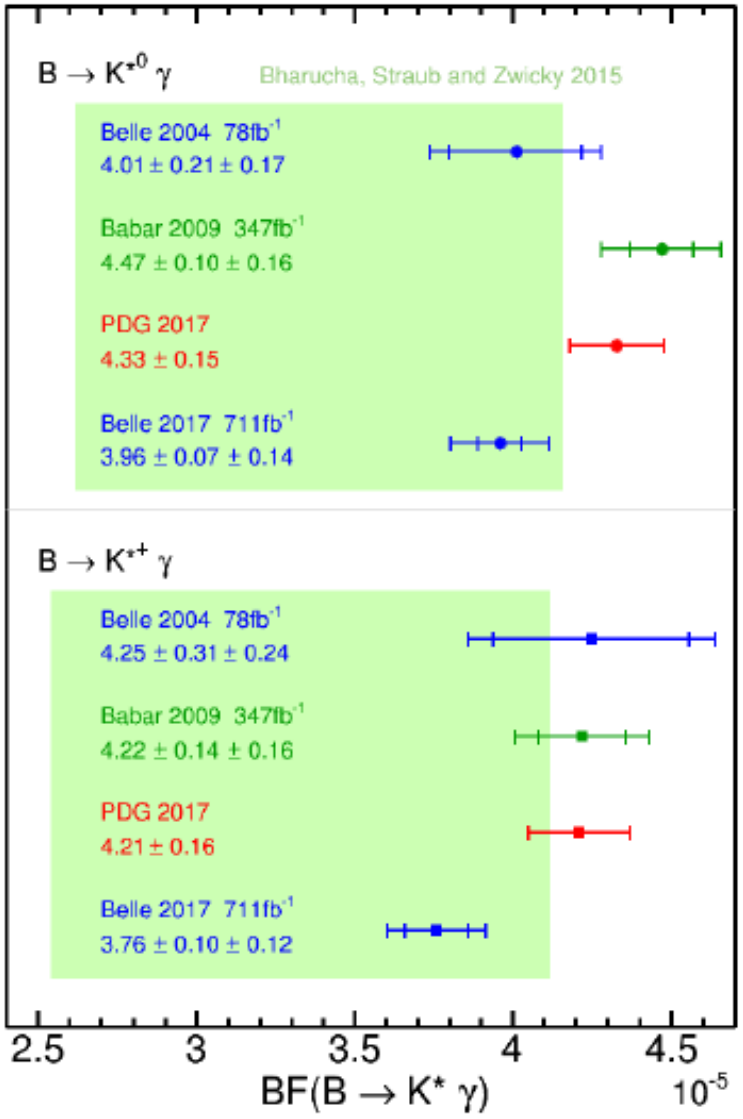
- BF, A_{CP} , Δ_{0+} and ΔA_{CP} is extracted in simultaneous fit performed to seven M_{bc} distributions with the likelihood:

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



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

- 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($B \rightarrow K^*\gamma$) and splits the difference between theory and experiment.



Belle measurement from 121 fb^{-1} of data at Υ(5S) for BF ($B_s \rightarrow \phi\gamma$) is used for the:
$BF(B^0 \rightarrow K^{*0}\gamma)/BF(B_s \rightarrow \phi\gamma) = 1.10 \pm 0.16 \pm 0.09 \pm 0.18$

Belle result is consistent with **LHCb** [Nucl. Phys. B 867, 1 (2013)], and theoretical predictions [Eur. Phys. J. C 55, 577 (2008)] and [Phys. Rev. D 88, 094004 (2013)]

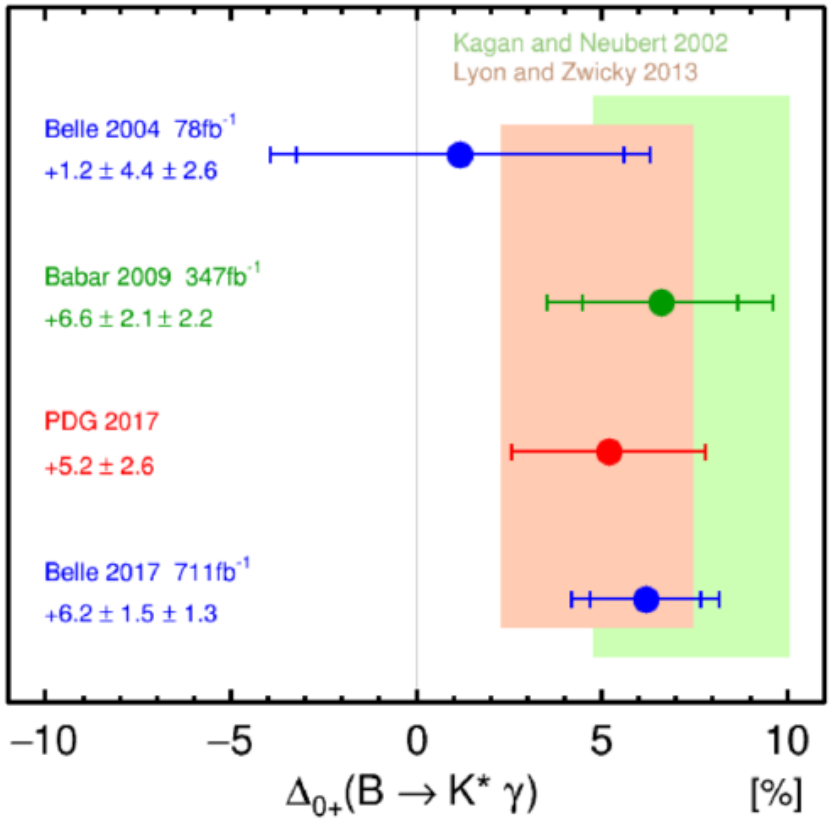
Result: Δ_{0+}

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

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

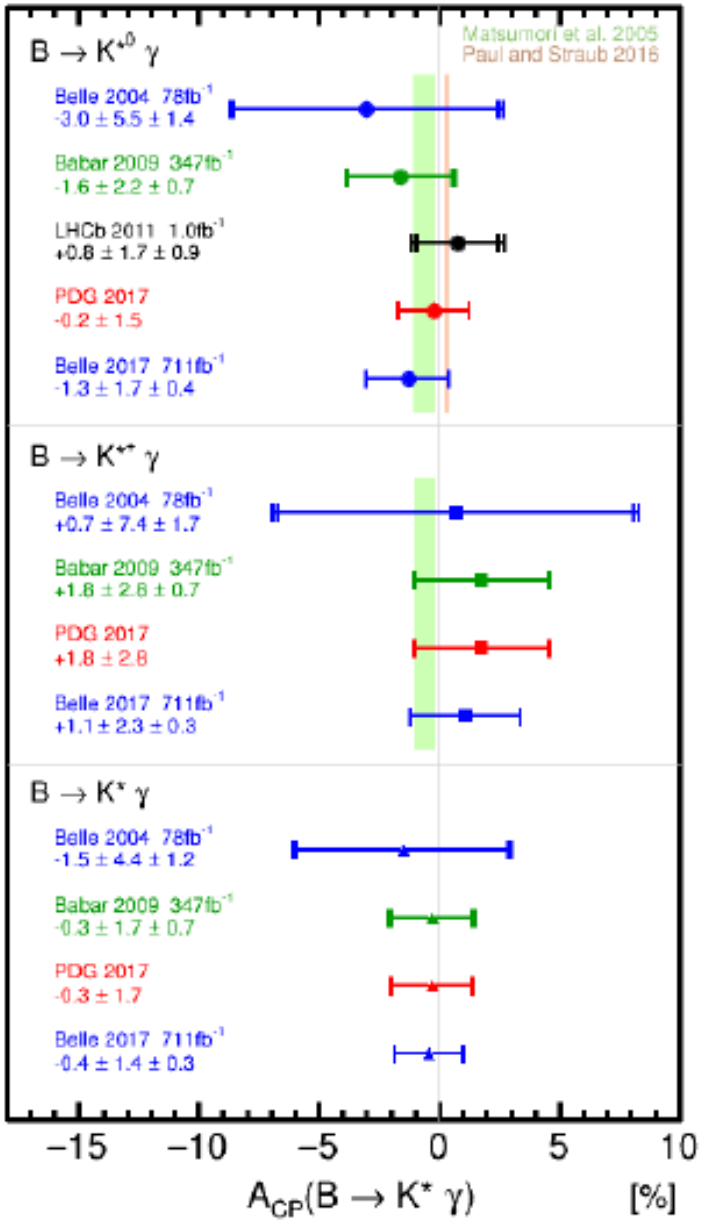
- Dominant uncertainties are statistical one and due to f_{+-}/f_{00}.

- 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.

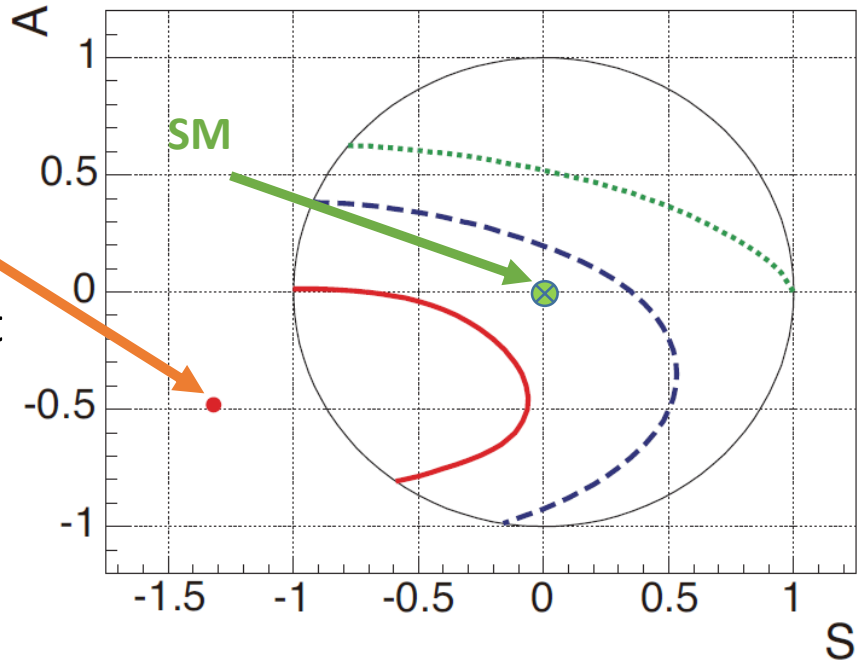


Measurement of time-dep. CP asymmetries $B^0 \to K^0_S \eta\gamma$

- Mixing-induced CP asymmetry in an exclusive $b \to s\gamma$ CP eigenstate mode such as $B^0 \to K^0_S \pi^0 \gamma$, $\mathbf{B^0 \to K^0_S \eta\gamma}$, $B^0 \to K^0_S \rho^0 \gamma$ and $B^0 \to K^0_S \phi\gamma$ is an excellent probe for particular class of NP scenario.
- In the SM, expected asymmetry $|S_{CP}| \approx \frac{2m_s}{m_b}\sin(2\phi_1)$ ~ a few %.
- New physics with right handed current increases the fraction of right handed photon.
  - Interfere with the SM occurs and large TDCPV possible

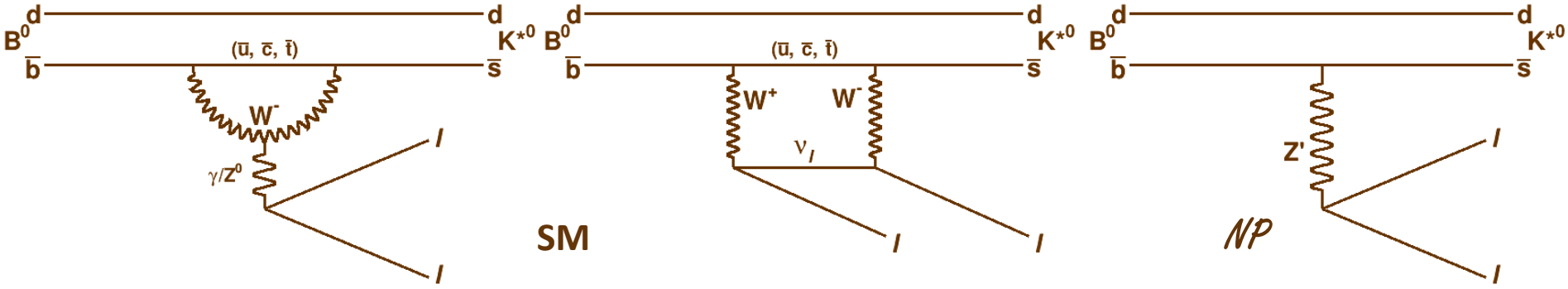
S = −1.32 ± 0.77(stat.) ± 0.36 (syst.)
A = −0.48 ± 0.41(stat.) ± 0.07(syst.)

This result is out of physical boundary but consistent with the null-asymmetry hypothesis within 2σ as well as with the SM predictions



Belle [arXiv 1803.07774 (accepted in PRD)]

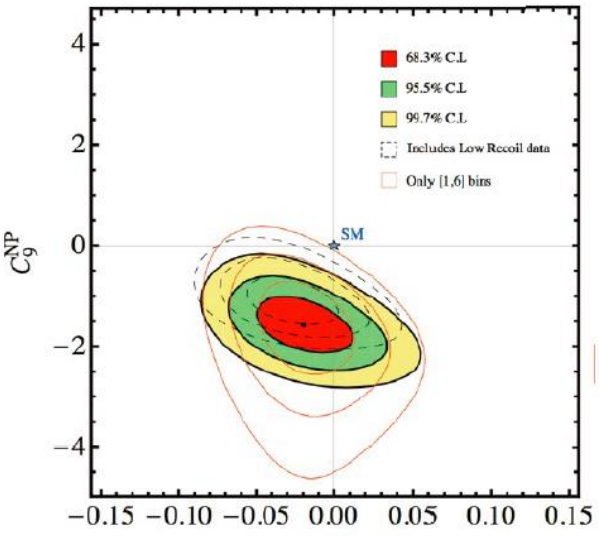
Angular Analysis of $B \to K^* \ell^+ \ell^-$



- 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 $B^0 \to K^{*0}\mu^+\mu^-$.

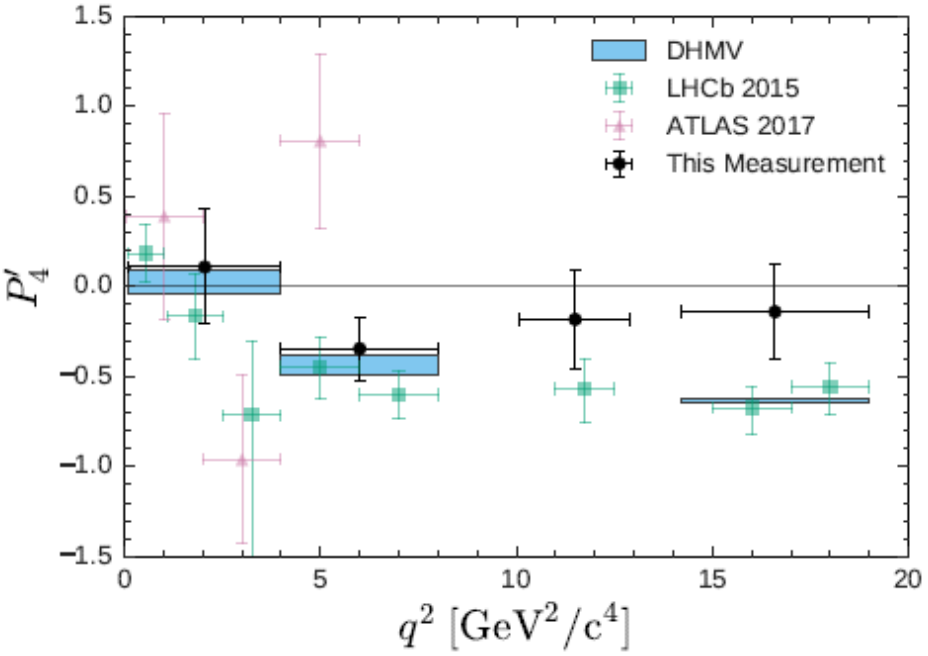
- Global fit to radiative and EW penguin B decays gives Wilson coefficient C_9^{NP} deviated about -1 from SM values

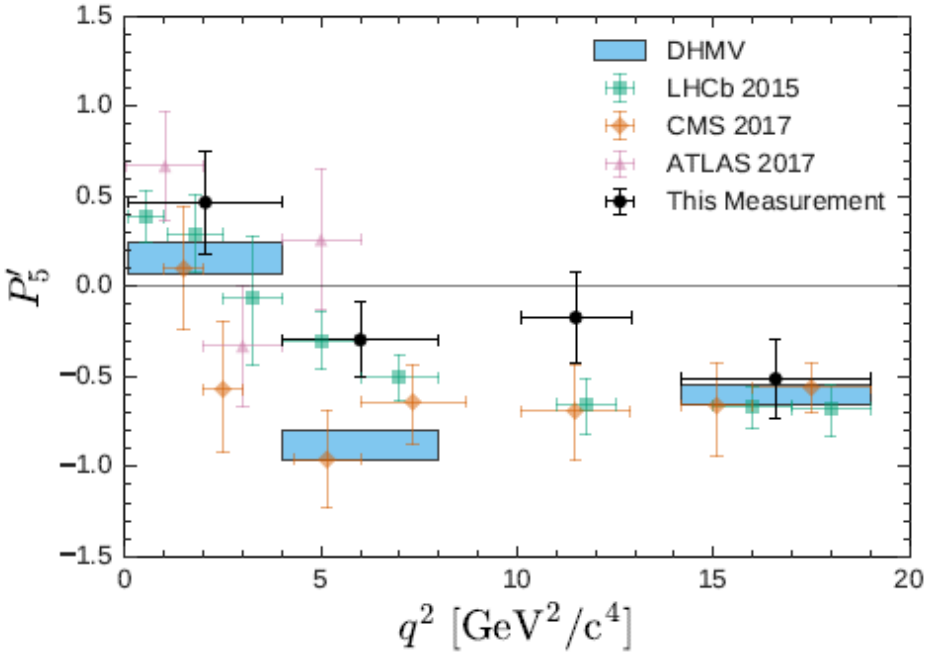
- Motivates to check lepton flavor dependence in angular analysis.



Descotes-Genon, Matias, and Virto
PRD 88 074002 (2013)

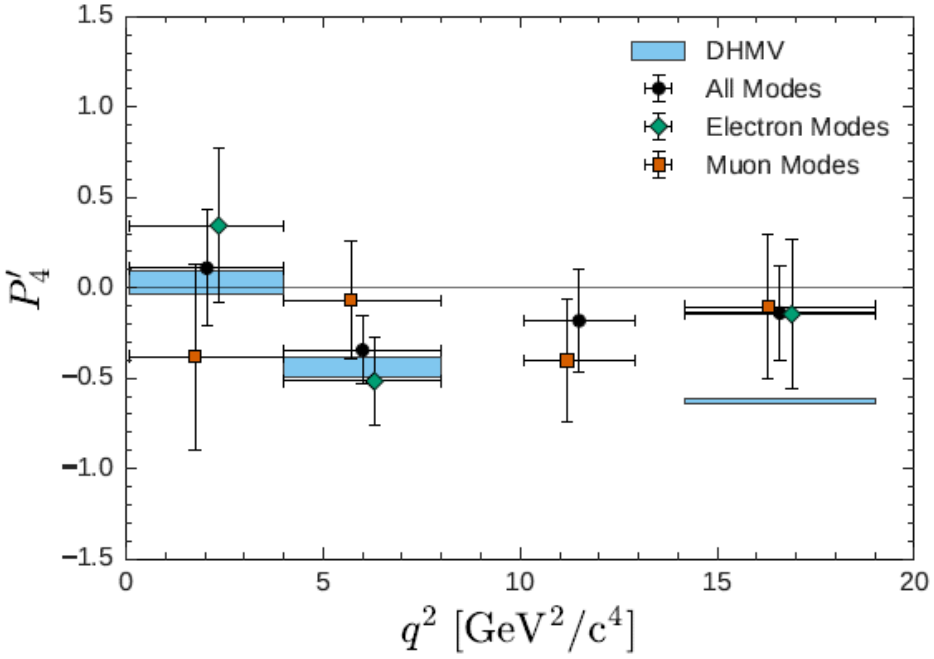
Result P_5': for Combined Data

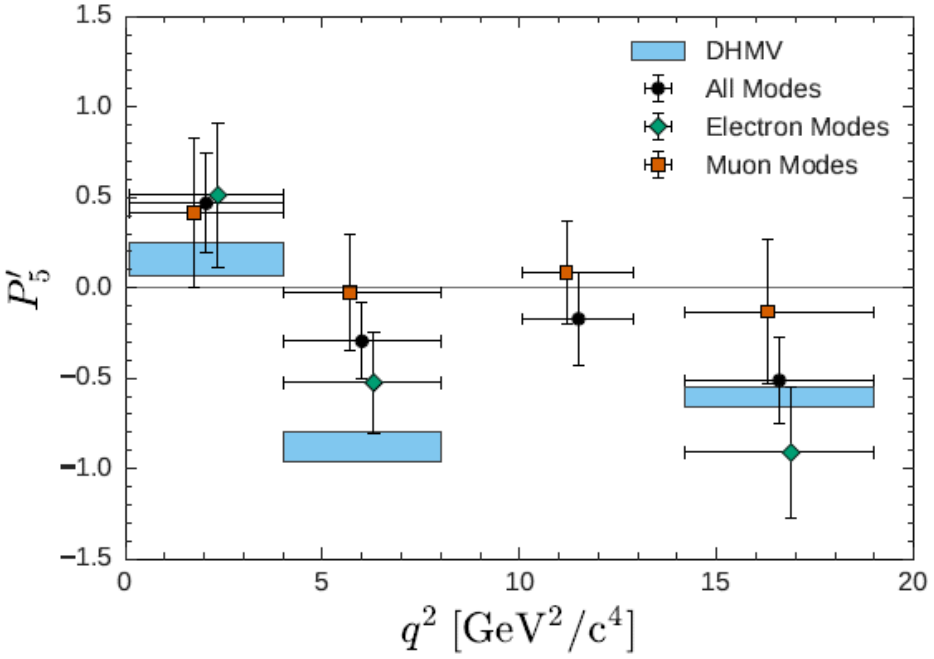




- Measurements are compatible with the SM.
- Similar central values for the P_5' anomaly with 2.5σ tension.

Result - Separate Lepton Flavor!

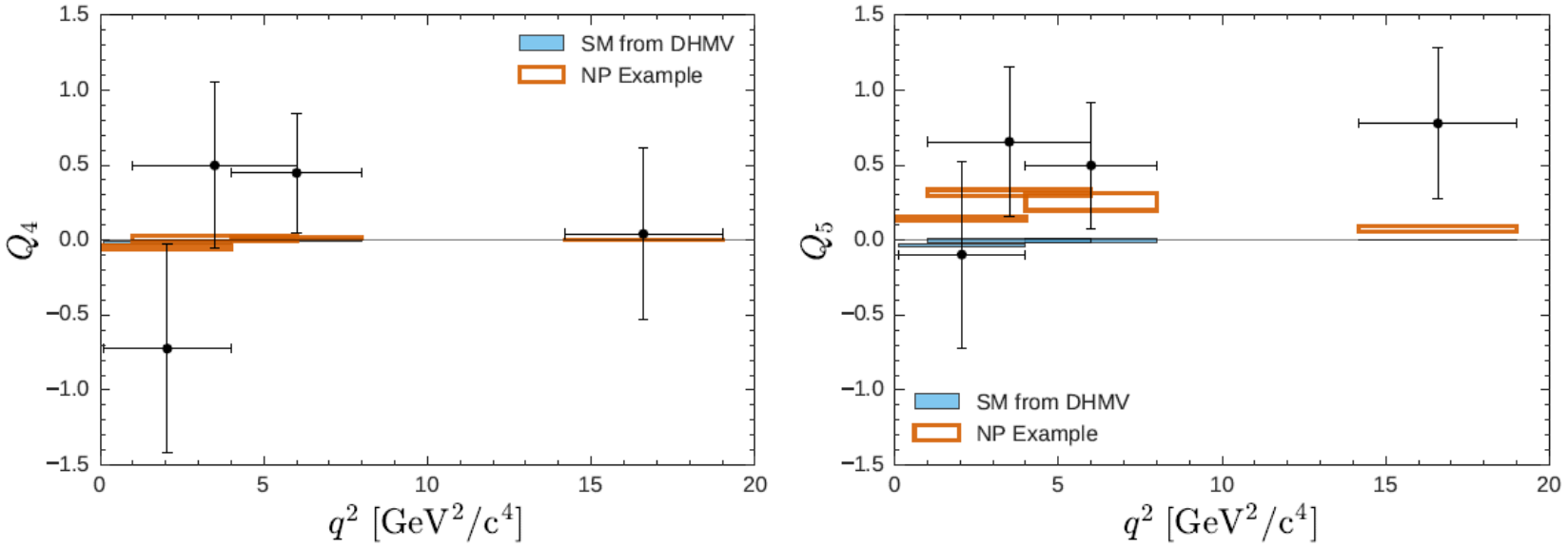




- The Largest deviation in the muon mode with 2.6σ.
- Electron mode is deviating with 1.1σ.

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.

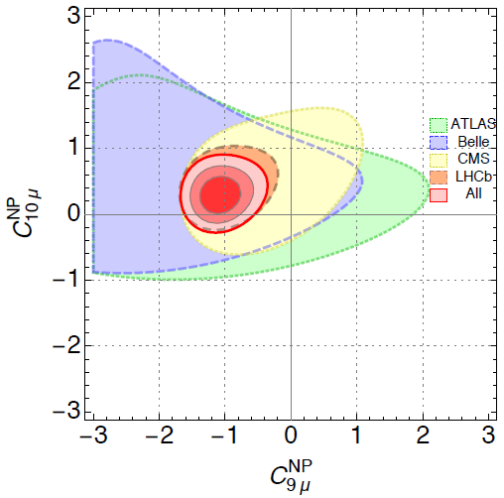


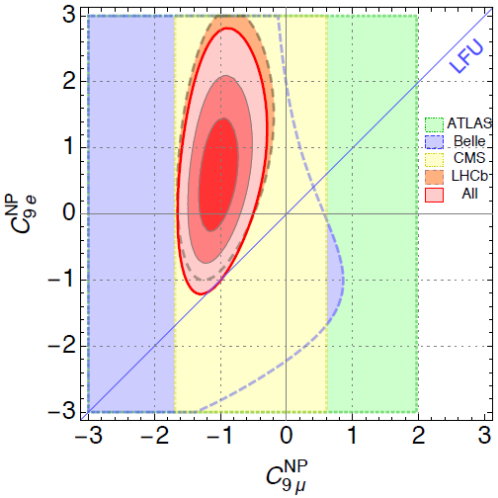
- No significant deviation from zero is discerned.
- Q_4 and Q_5 observables in agreement with SM and favoring NP scenario.

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

Global fits to b→s

- Including P_i', Q_i, b→sγ, R[$K^{(*)}$], B_s →μμ

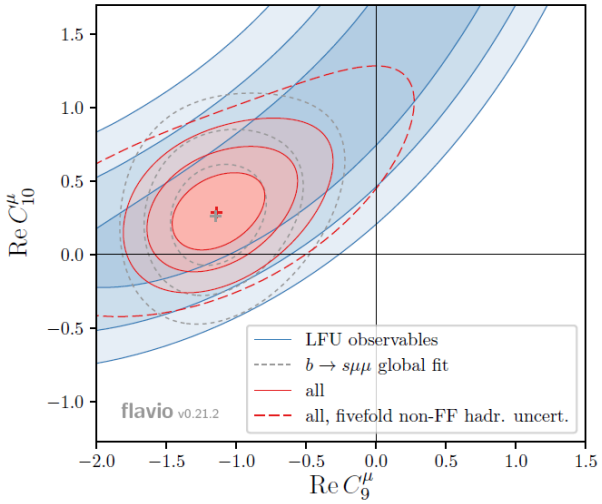


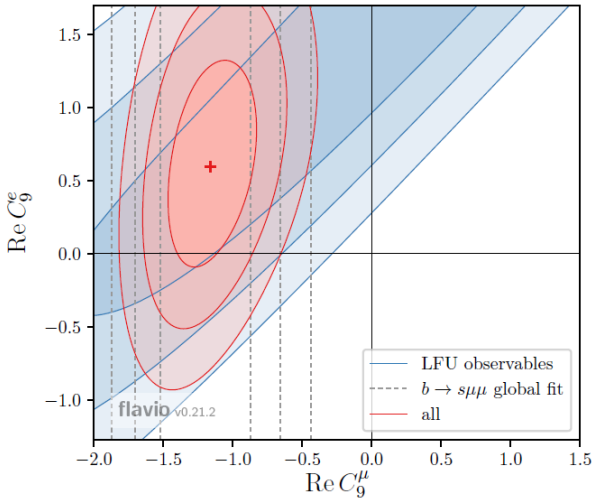


Capdevila, Crivellin, Descotes-Genon, Matias, and Virto
JHEP 1801 (2018) 093

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

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



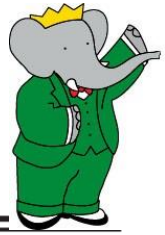


Altmannshofer, Stangl, and Straub
Phys. Rev. D 96, 055008 (2017)

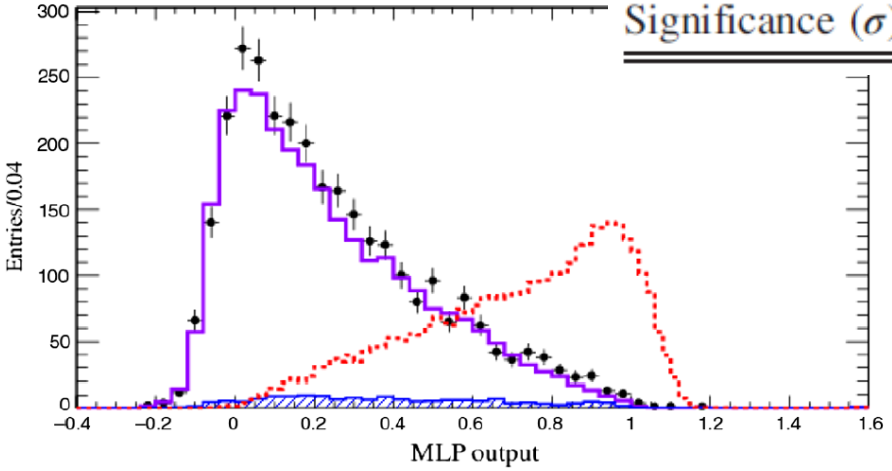
A combined fit singles out NP in the Wilson coefficient C_9^{μ} as a possible explanation.

Search for the $B^+ \to K^+ \tau^+ \tau^-$

- The decay $B^+ \to K^+\tau^+\tau^-$ is the third family equivalent of $B^+ \to K^+\ell^+\ell^-$; may provide additional sensitivity to NP.
- An important potential contribution to this decay is from neutral Higgs boson couplings, where the lepton-lepton-Higgs vertices are proportional to the mass squared of the lepton.
- Analysis based on the 424 fb^{-1} (471M $B\overline{B}$ pairs) data sample at BaBar.
- Hadronic B-tagging technique is employed. ($\tau^+ \to \mu^+\nu_\mu\overline{\nu_\tau}$ and $\tau^+ \to e^+\nu_e\overline{\nu_\tau}$)



Signal with arbitrary norm.
Combinatorial.
Peaking in M_{bc}
Data



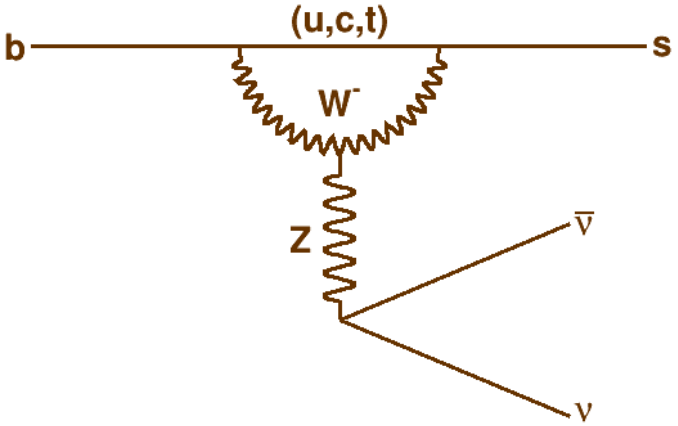
	e^+e^-	$\mu^+\mu^-$	$e^+\mu^-$
$N^i_{\rm bkg}$	$49.4 \pm 2.4 \pm 2.9$	$45.8 \pm 2.4 \pm 3.2$	$59.2 \pm 2.8 \pm 3.5$
$\epsilon^i_{\rm sig}(\times 10^{-5})$	$1.1 \pm 0.2 \pm 0.1$	$1.3 \pm 0.2 \pm 0.1$	$2.1 \pm 0.2 \pm 0.2$
$N^i_{\rm obs}$	45	39	92
Significance (σ)	−0.6	−0.9	3.7

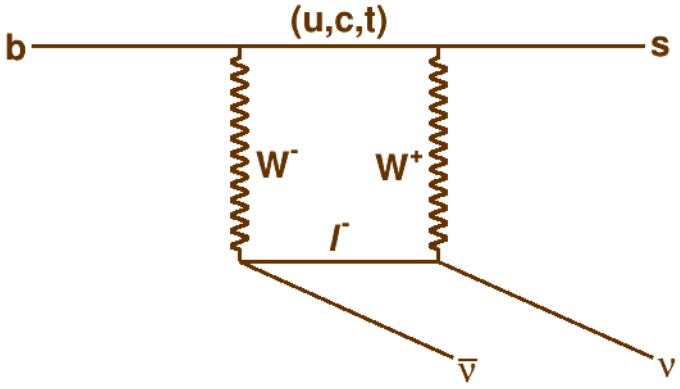
The UL on the BF ($B^+ \to K^+\ell^+\ell^-$) with all the 3 modes combined at 90% CL is: $< 2.25 \times 10^{-3}$.

BaBar [Phys. Rev. Lett. 118, 031802 (2017)]

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

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





Belongs to the theoretically cleanest modes in the field of FCNC processes

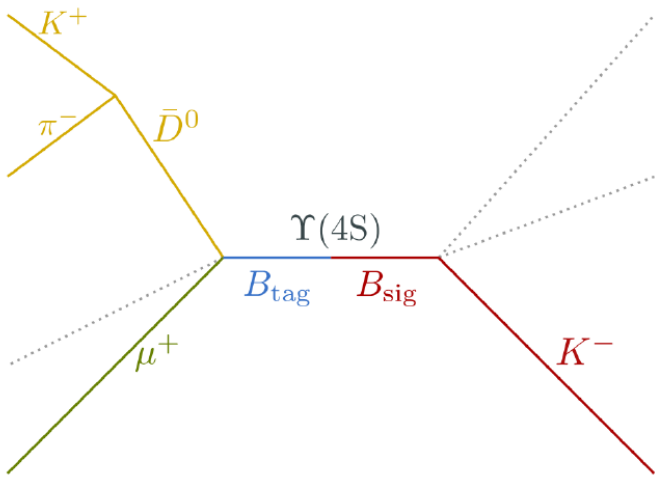
- SM prediction for the BF ranges from 1.2×10^{-7} ($B \to \pi^0\nu\nu$) to 9.2×10^{-6} ($B \to K^{*+}\nu\nu$).
  [A. Buras *et al.* J. High Energy Phys. 02 (2015) 184; C. Hambrock *et al.* Phys. Rev. D 92, 074020 (2015).]

- 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)]

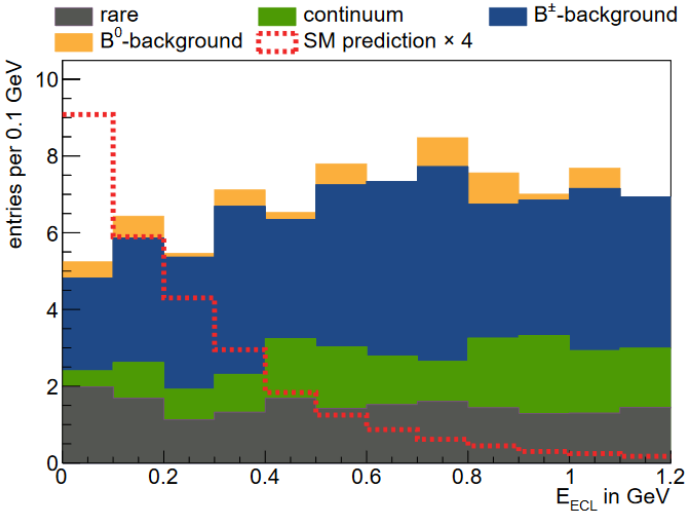
Reconstruction of $B \to h^{(*)}\nu\nu$

- 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_{tag}) decay product to form an $\Upsilon(4S)$ candidate.
- No additional charged track, π^0 or K_L^0.
- Continuum events are suppressed with the event shape variables.
- Signal extracted in extra (additional) energy in the calorimeter

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

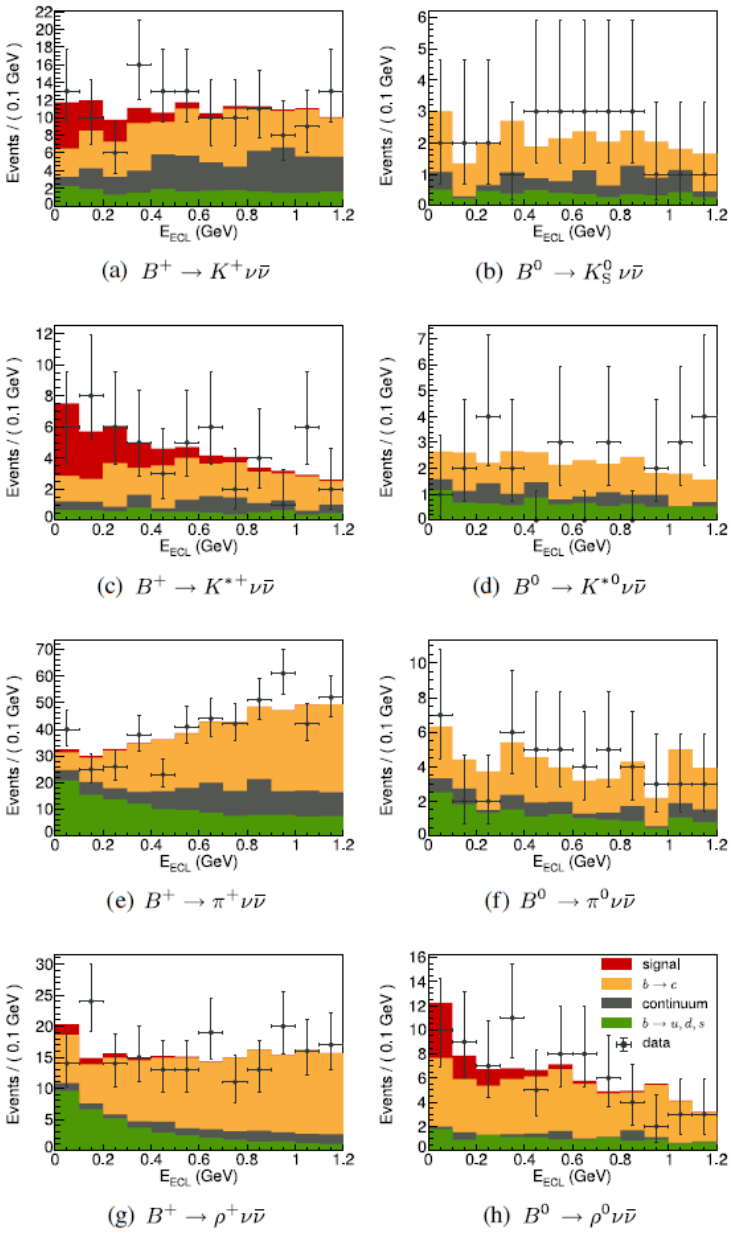


Results

- Signal Extraction:
  - Fit with template histograms.
  - **Signal** and Background (**b→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

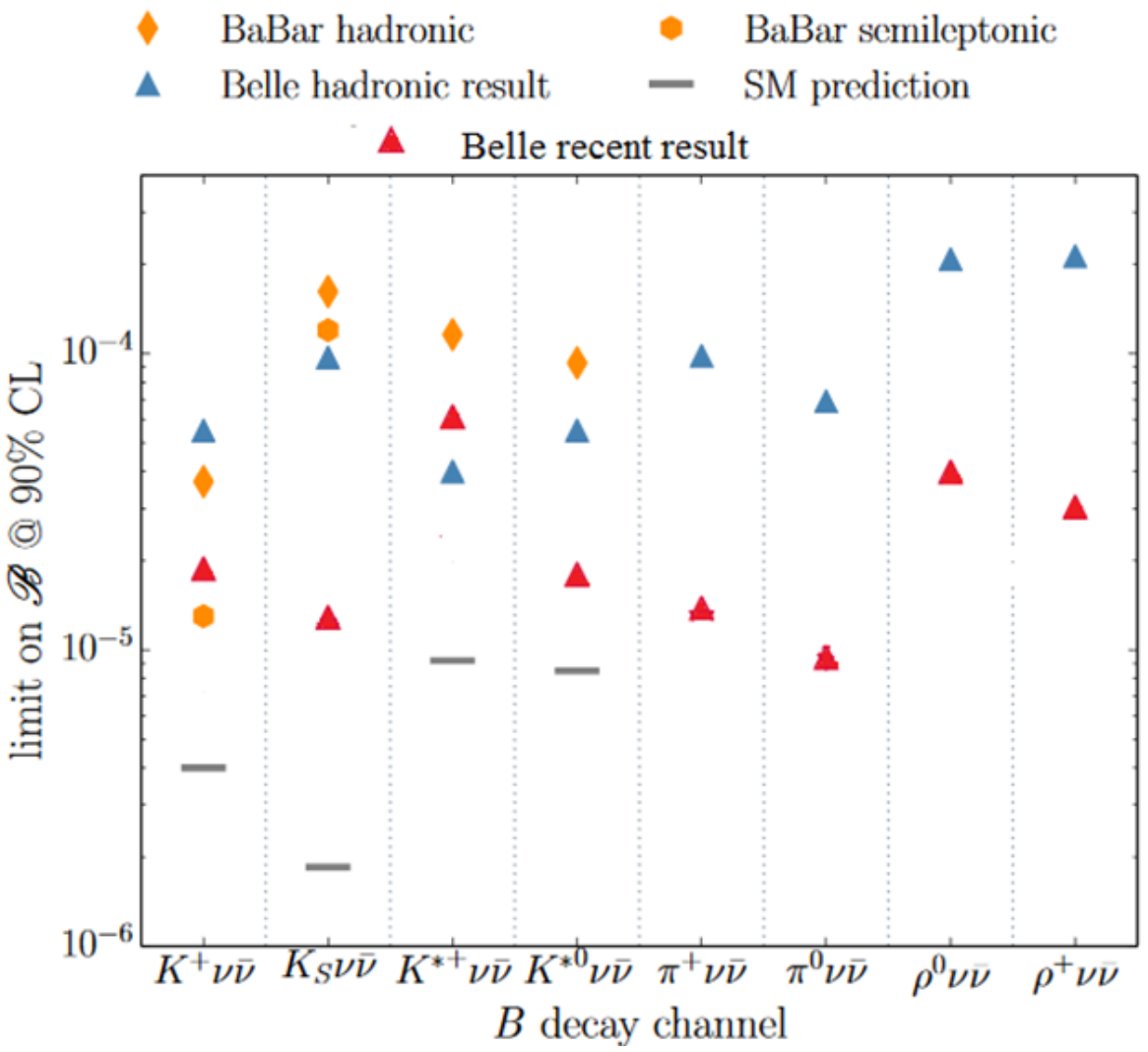


(a) $B^+ \to K^+\nu\bar{\nu}$ (b) $B^0 \to K^0_S\nu\bar{\nu}$ (c) $B^+ \to K^{*+}\nu\bar{\nu}$ (d) $B^0 \to K^{*0}\nu\bar{\nu}$ (e) $B^+ \to \pi^+\nu\bar{\nu}$ (f) $B^0 \to \pi^0\nu\bar{\nu}$ (g) $B^+ \to \rho^+\nu\bar{\nu}$ (h) $B^0 \to \rho^0\nu\bar{\nu}$

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

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.



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

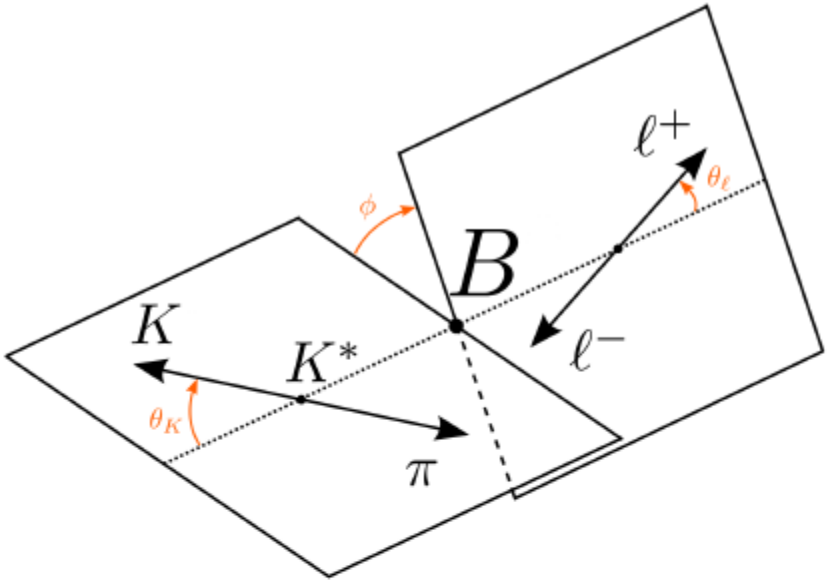
- First Lepton Flavor dependent angular analysis of $B \to K^*\ell^+\ell^-$ performed.
  - Consistent with both SM and NP with $C_{9\mu}^{NP} \approx -1.1$.

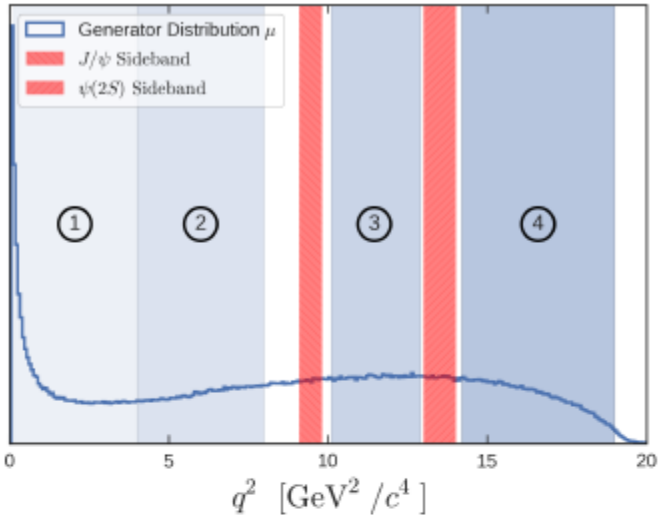
- $B^+ \to K^+\tau^+\tau^-$ is searched for the first time, using full dataset collected at BaBar. No significant signal is observed and UL is derived $< 2.25 \times 10^{-3}$ (90% CL).

- 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.

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

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

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

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

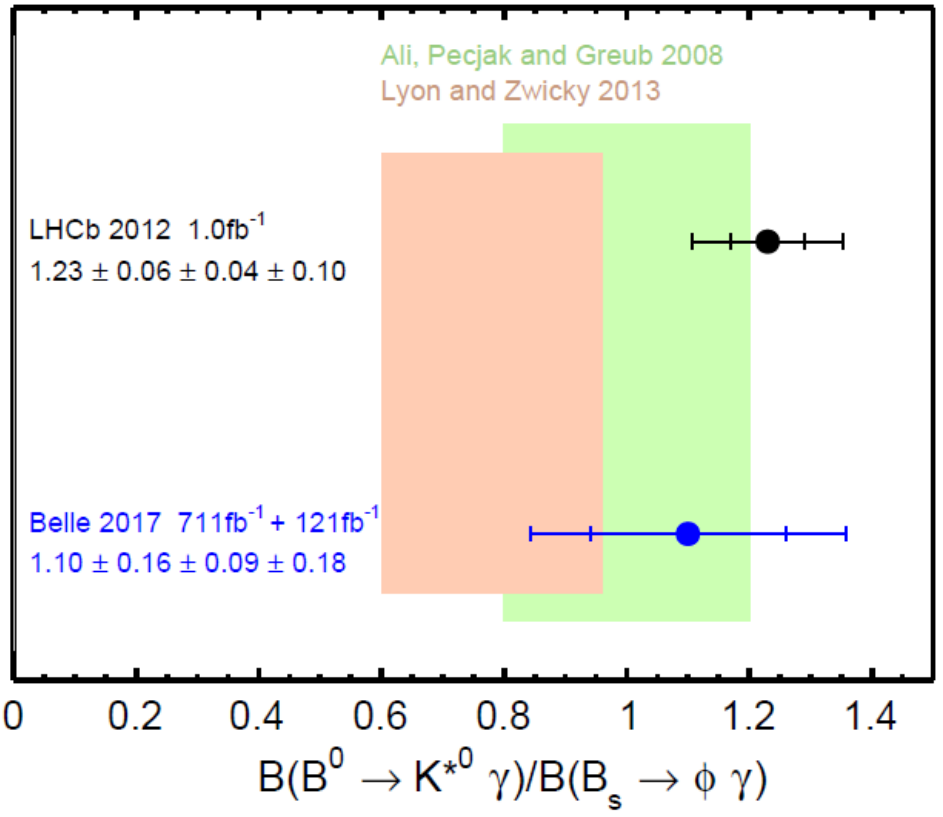
are considered to be largely free from form-factor uncertainties (J. High Energy Phys. 05 (2013) 137).

- Transverse polarization asymmetry

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

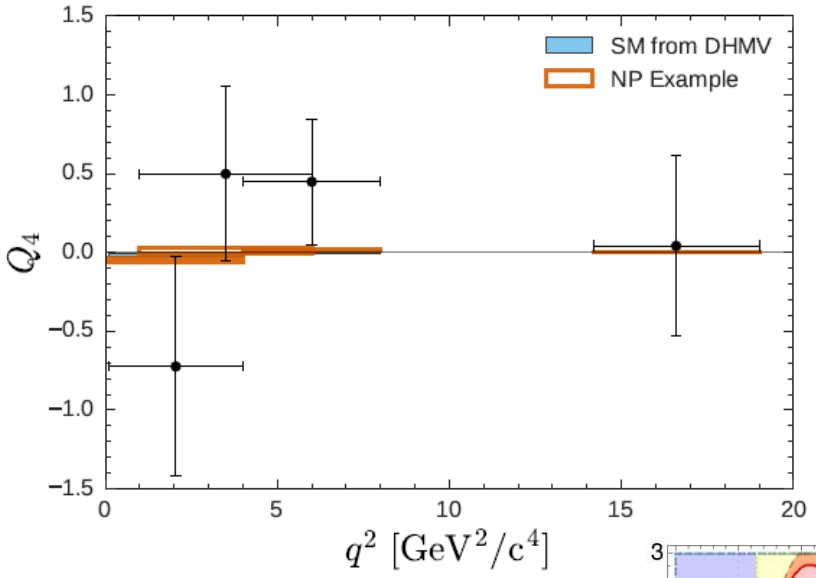
Result : BF($B^0 \to K^{*0}\gamma$)/BF($B_s \to \phi\gamma$)

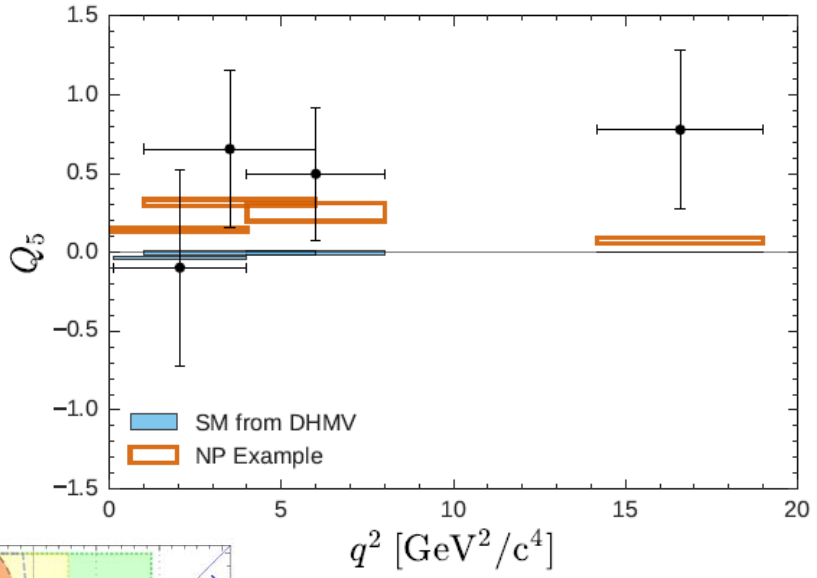
- Belle measurement from 121 fb^{-1} of data at $\Upsilon(5S)$ for BF ($B_s \to \phi\gamma$) is used. [Phys. Rev. D 91, 011101 (2015)]
- Only $K^{*0} \to K^+\pi^-$ mode is used to cancel common systematics
- BF($B^0 \to K^{*0}\gamma$)/BF($B_s \to \phi\gamma$) : $1.10 \pm 0.16 \pm 0.09 \pm 0.18$
- **Belle** 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)]



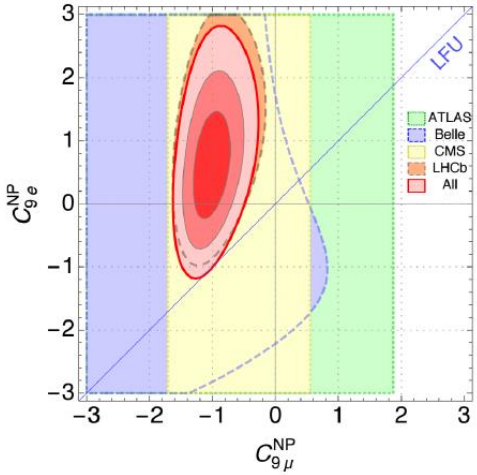
Result - Separate Lepton Flavor!

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



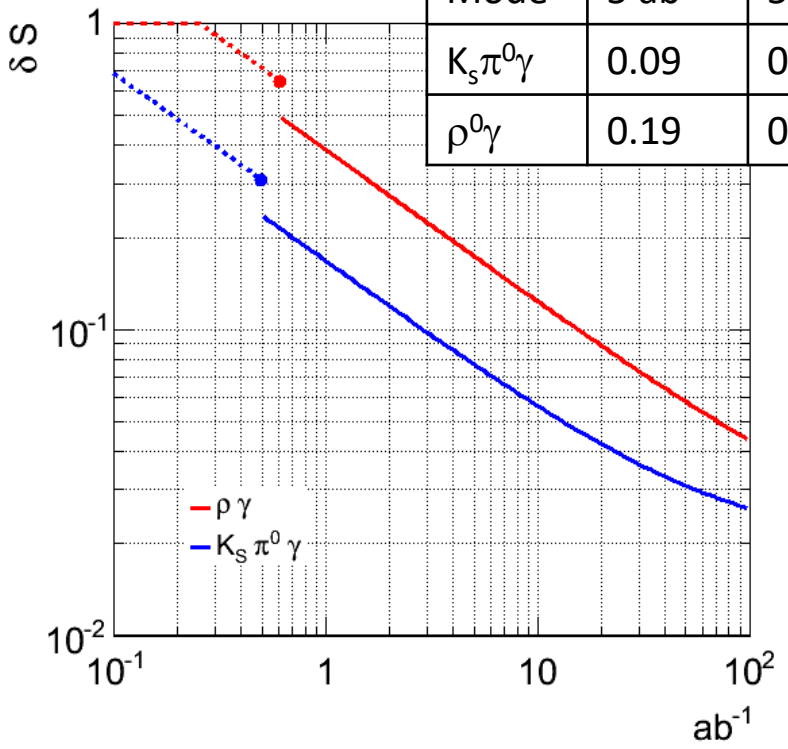
Capdevila, Crivellin, Descotes-Genon, Matias, Virto, arXiv:1704.05340

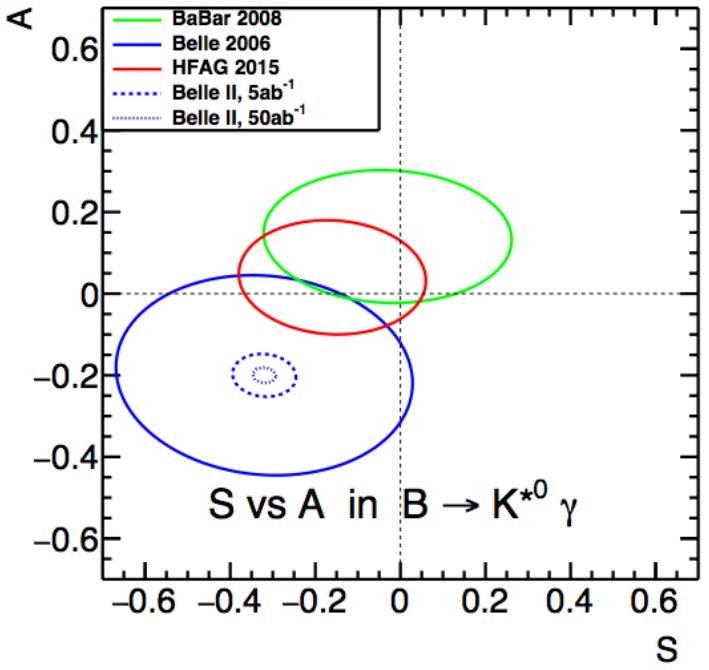
Time dependent CPV

- At Belle II, significant improvement in the determination of $A_{CP}(t)$ in $K_s\pi^0\gamma$ is expected.
  - → Belle II vertex detector is larger than Belle (6cm → 11.5cm).
  - → 30% more Ks with vertex hits available.
  - → Effective tagging efficiency is 13% better (conservative estimation).

- Expected errors for ***S*** measurements of $K_s\pi^0\gamma$ and $\rho^0\gamma$.

Mode	5 ab^{-1}	50 ab^{-1}
$K_s\pi^0\gamma$	0.09	0.030
$\rho^0\gamma$	0.19	0.064





16σ deviation with 50 ab^{-1}.