Measurements of lepton flavor non-universality in B decays at Belle

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for the Belle Collaboration

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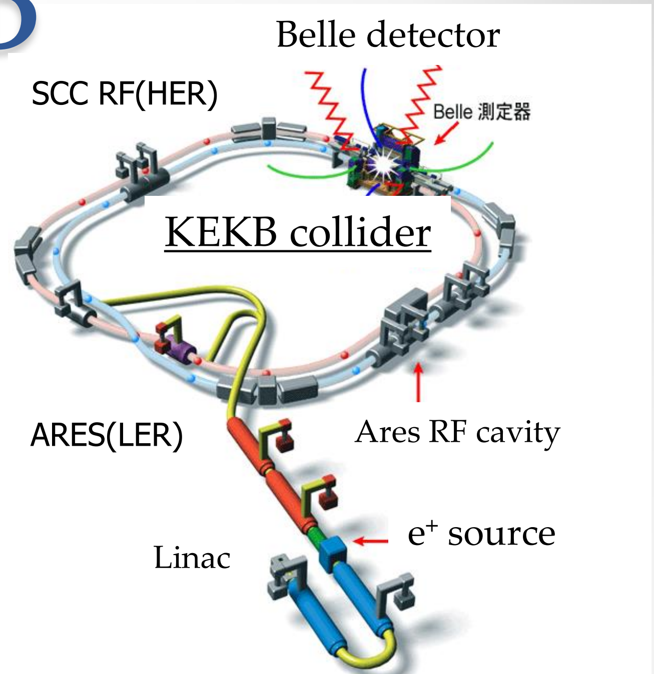
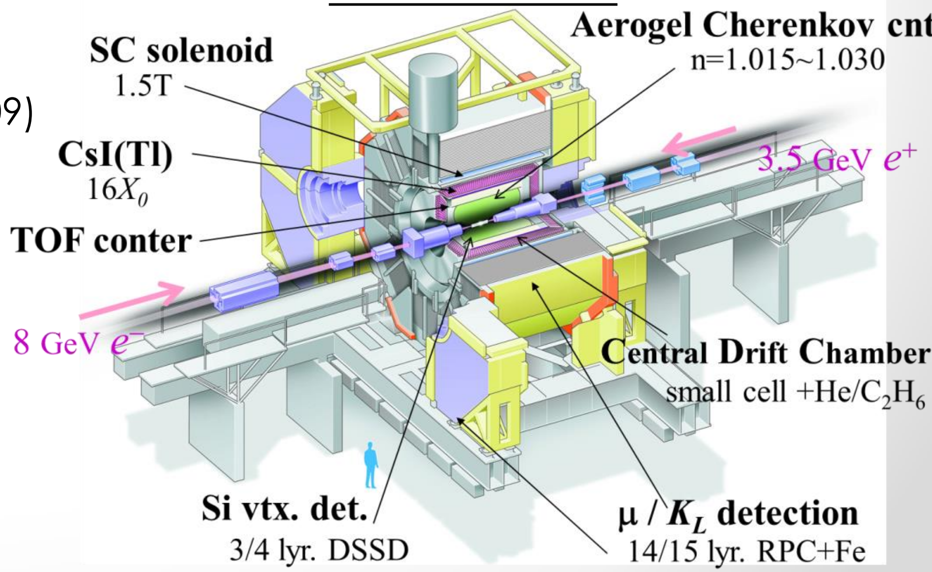
25th Anniversary of the Rencontres du Vietnam

Outline

- R(D) and R(D*) measurement with B→D(*)$\tau\nu$
- Test of lepton universality in B→K*ll
- Search for Lepton flavor violating decay B→K*μe

Belle and KEKB

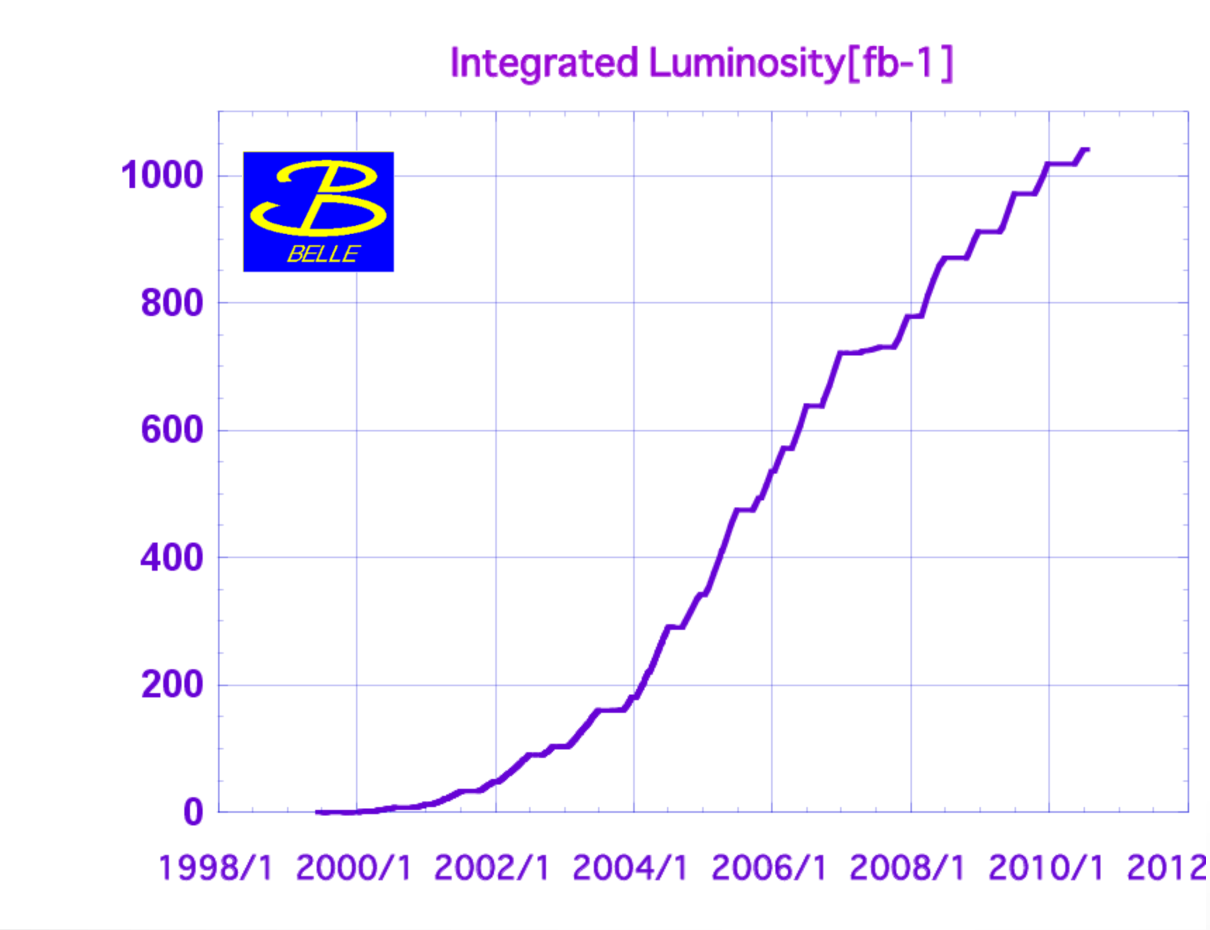




- KEKB
  - Achieved World Highest Luminosity (as of 2009)
    - L = 2.1 * 10^{34} /cm^2/sec ~ 20 $B\overline{B}$ pairs / sec
  - Asymmetric energy to boost B mesons
    - 8.0GeV e^- × 3.5GeV e^+
- Belle
  - Multi-purpose 4π detector
  - Vertexing, tracking, EM calorimeter, PID
- Data taking for 1999-2010

Belle Integrated Luminosity

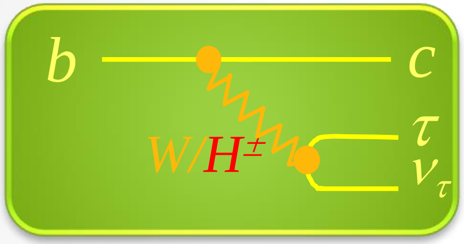
- The world largest integrated luminosity of > 1ab^{-1}
- 711 fb^{-1} on Υ(4S) resonance → **772×10^6 $B\bar{B}$ pairs**



On resonance:
Υ(5S): 121 fb^{-1}
Υ(4S): 711 fb^{-1}
Υ(3S): 3 fb^{-1}
Υ(2S): 25 fb^{-1}
Υ(1S): 6 fb^{-1}
Off reson./scan:
~100 fb^{-1}

Semi-tauonic B decay: $B \to D^{(*)}\tau\nu$

- Sensitive to new physics



Ratio of τ to μ,e could be reduced/enhanced

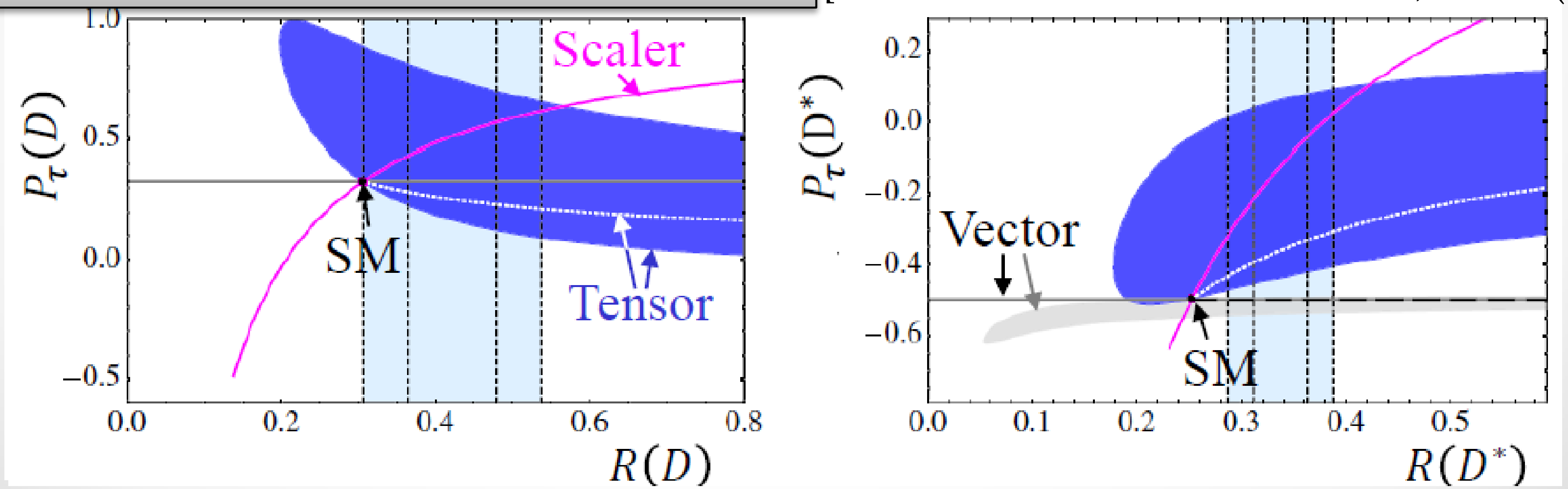
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

Polarization of tau could probe the NP model

$$P_\tau(D^{(*)}) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

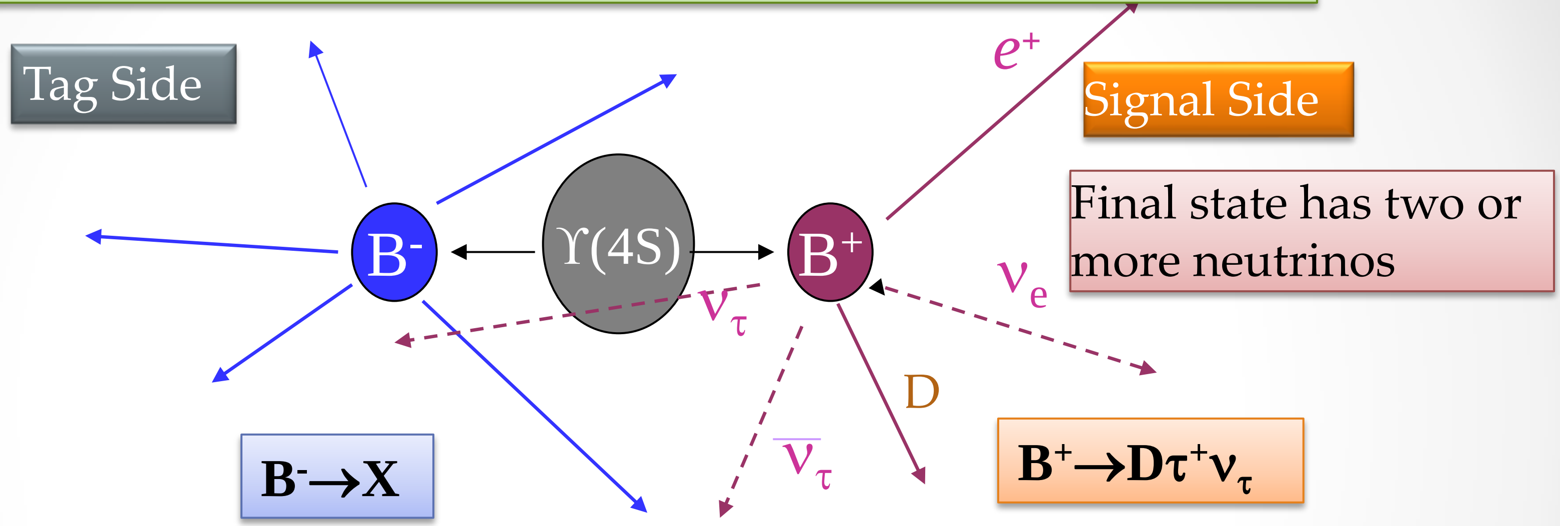
NP model (vector, scalar, tensor) dependence

[M. Tanaka and R. Watanabe PRD 87, 034028 (2013)]



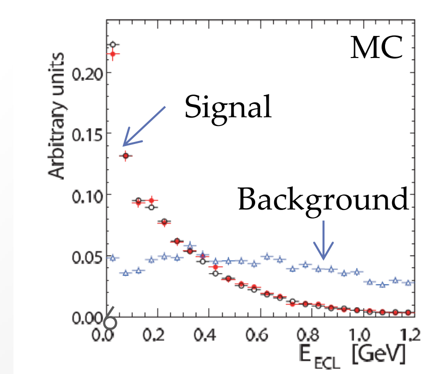
$B \to D^{(*)}\tau\nu$ Analysis at Belle

Utilize the B factory specific feature :
only one B-meson pair is produced



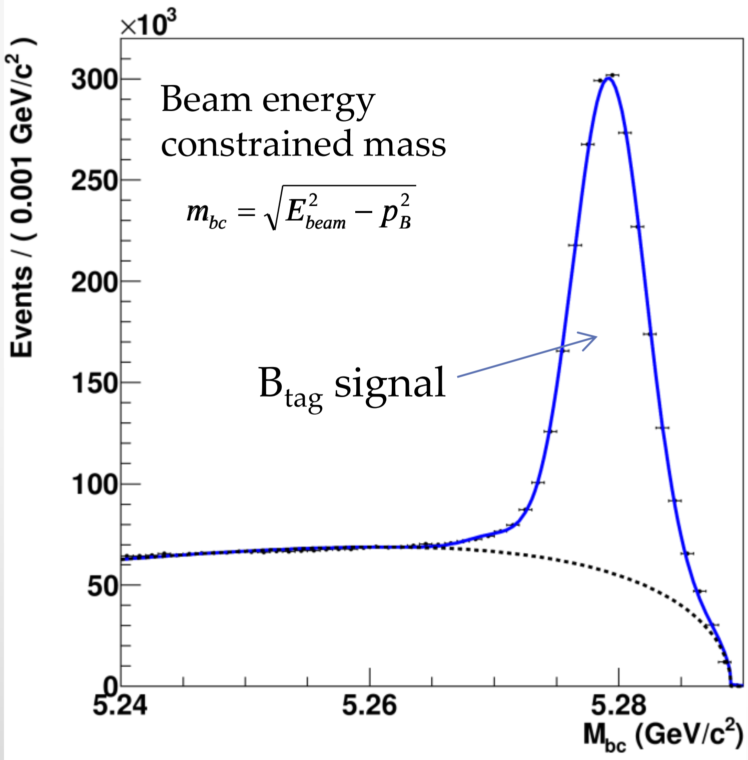
Tag B pair event by reconstructing one B meson in hadronic or semileptonic B Decay
→ Provide pure single B event

Require **no** particle remains after removing products of tagging B and the particle(s) from signal decays
← Remaining energy in the calorimeter (E_{ECL})

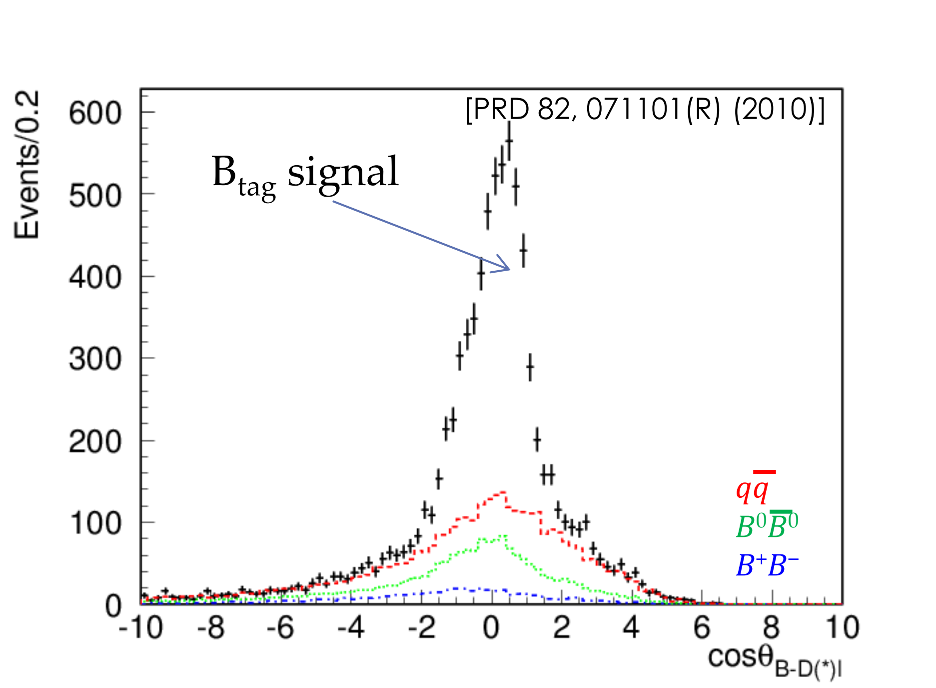


Tagging Methods

- <u>Hadronic Tag</u>
  - Fully reconstruct in B→DX decays
    - ~1100 exclusive decay channels [NIM A 654, 432 (2011)]
  - Tagging efficiency ~ 0.2 %
  - Less background



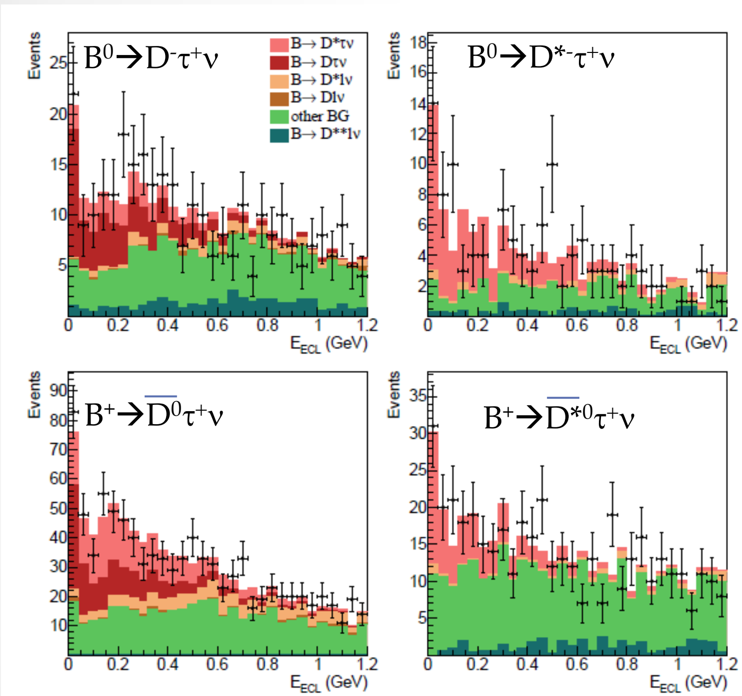
- <u>Semileptonic Tag</u>
  - Reconstruct $B \rightarrow D^{(*)} l \nu$
    - $E_B = E_{beam}$
    - Undetected neutrino mass ~ 0
  - Tagging efficiency ~ 0.5%
  - More background



$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\rm beam}^{\rm cms}E_{D^{(*)}\ell}^{\rm cms} - m_B^2 - M_{D^{(*)}\ell}^2}{2P_B^{\rm cms}\cdot P_{D^{(*)}\ell}^{\rm cms}}$$

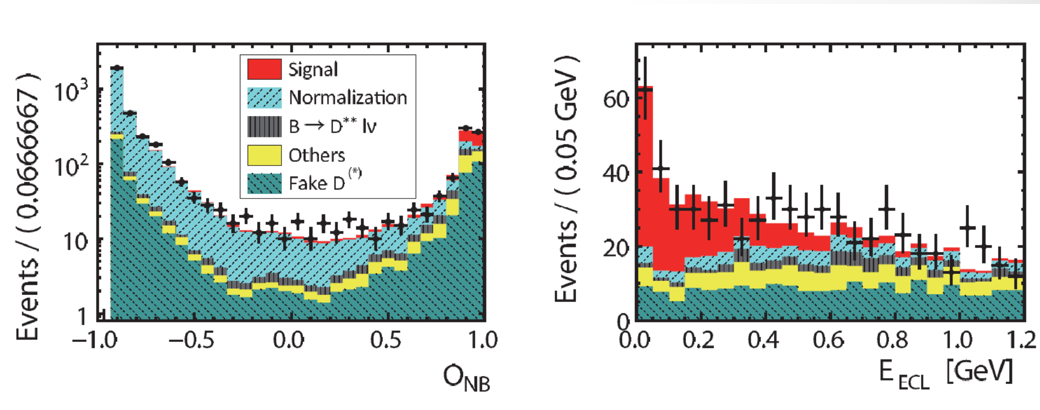
Results with leptonic tau decays

Hadronic Tag [PRD92,072014(2015)]



$$R(D) = 0.375 \pm 0.064 \pm 0.026$$
$$R(D^*) = 0.293 \pm 0.038 \pm 0.015$$

Semileptonic Tag [PRD94,072007(2016)]



$$\mathcal{R}(D^*) = 0.302 \pm 0.030 \pm 0.011$$

Consistent with, but higher than the SM predictions:
R(D) = 0.299 +- 0.003
R(D*) = 0.258 +- 0.005
[SM average of HFLAV Summer 2018]

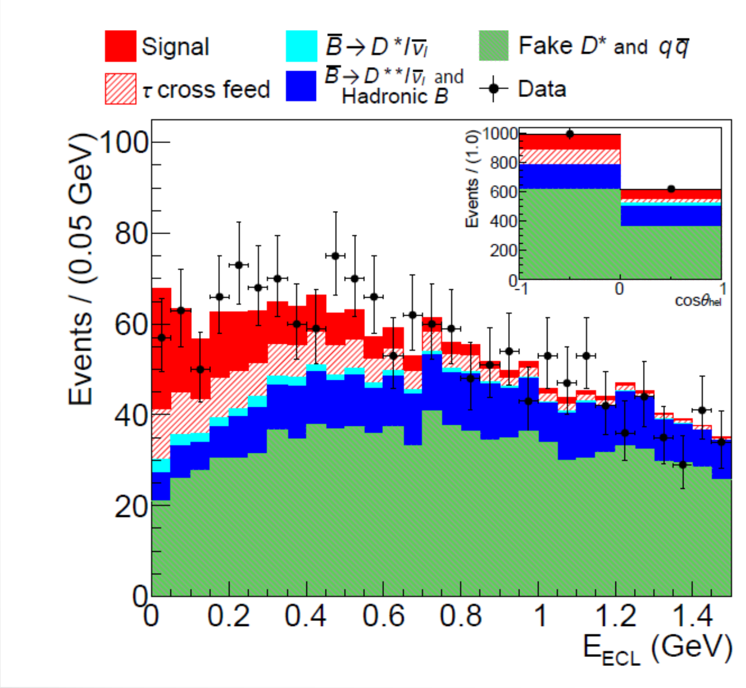
Results of Polarization Measurement

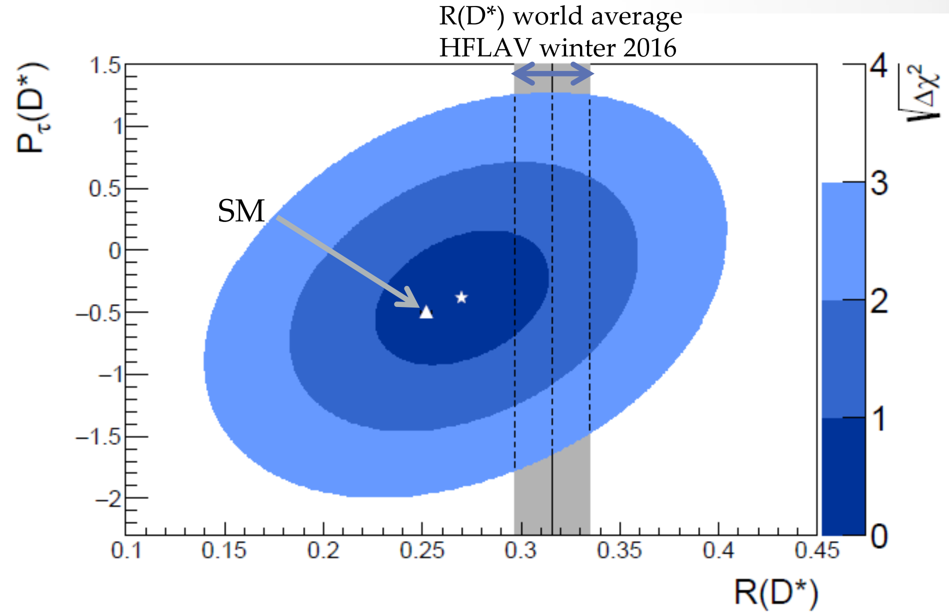
[PRL118, 211801 (2017) PRD97, 012004 (2018)]

- Hadronic tag
- Two body tau decays : $\tau \rightarrow \pi\nu, \rho\nu$
  - Helicity angle sensitive to the tau polarization

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{hel}} = \frac{1}{2}(1 + \alpha \cdot \mathcal{P}_\tau \cos\theta_{hel})$$

$$\alpha = \begin{cases} 1 & \text{for } \tau \to \pi^-\nu \\ 0.45 & \text{for } \tau \to \rho^-\nu \end{cases}$$

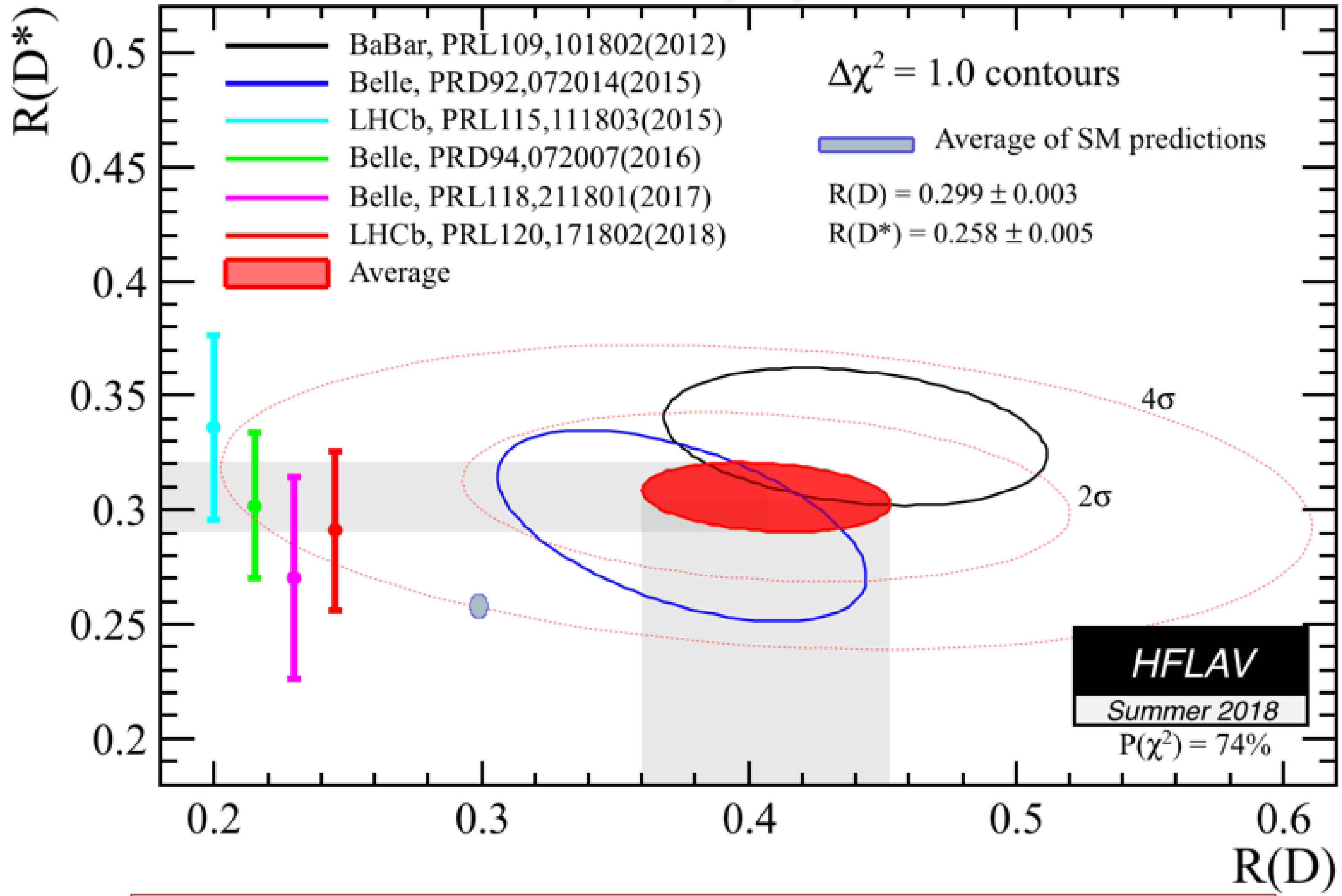




$$R(D^*) = 0.270 \pm 0.035(\text{stat})^{+0.028}_{-0.025}(\text{syst}),$$

$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat})^{+0.21}_{-0.16}(\text{syst}),$$

Current B→D(*)τν Situation



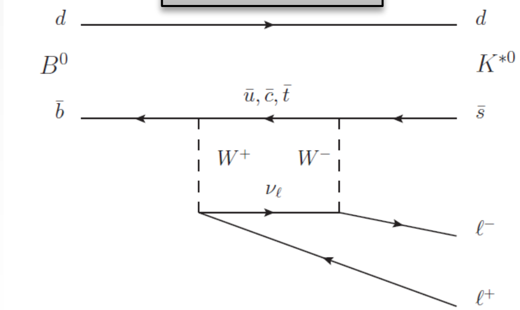
3.8 σ deviation from the SM prediction !

Additional Belle results will come soon

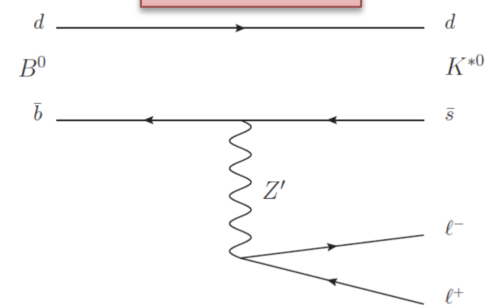
Belle II has started → Significant improvement in near future

Lepton Universality in B→K*ll

SM Example



NP Example

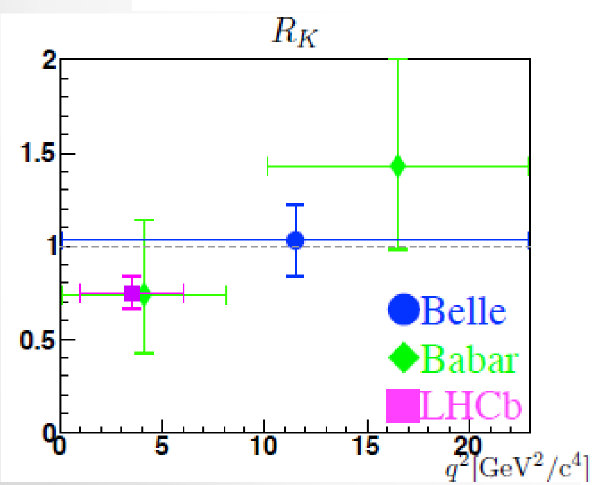


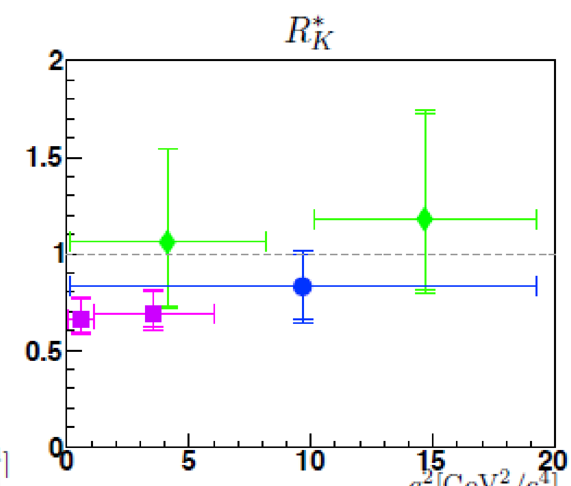
- LHCb reported 2.6 σ tension in [PRL 113,151601(2014), JHEP 08(2017), 055]

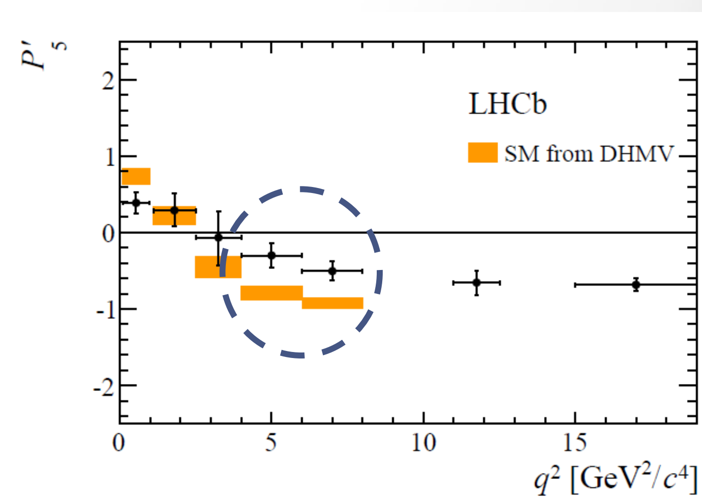
$$R_K \equiv \frac{\mathcal{B}(B \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B \to K^+ e^+ e^-)} \quad R_K^* \equiv \frac{\mathcal{B}(B \to K^* \mu^+ \mu^-)}{\mathcal{B}(B \to K^* e^+ e^-)}$$

- also in angular observable [JHEP 02(2016), 104]

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}} \qquad \frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2} \frac{\mathrm{d}^4\Gamma}{\mathrm{dcos}\theta_L \mathrm{dcos}\theta_K \mathrm{d}\phi \mathrm{d}q^2} : \theta_K, \theta_L, \phi, F_L, S_i$$





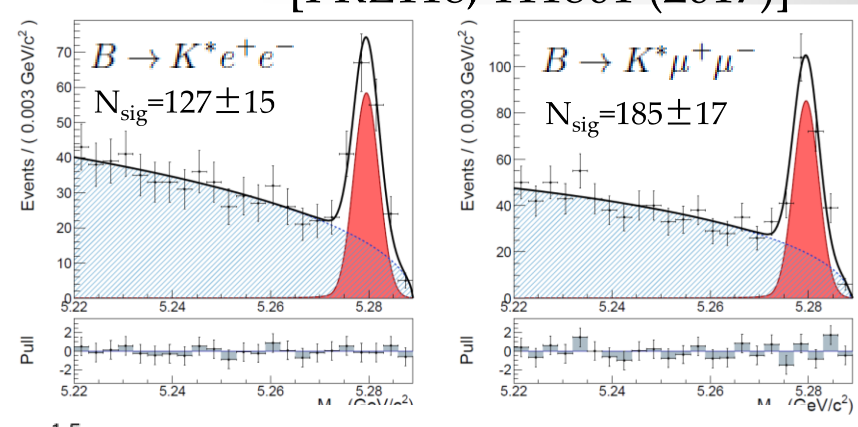


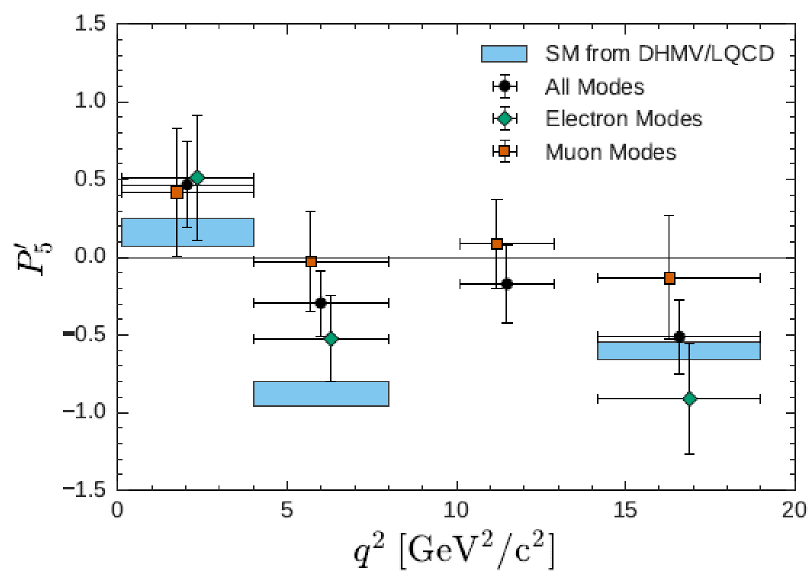
B→K*ll Angular Analysis Results

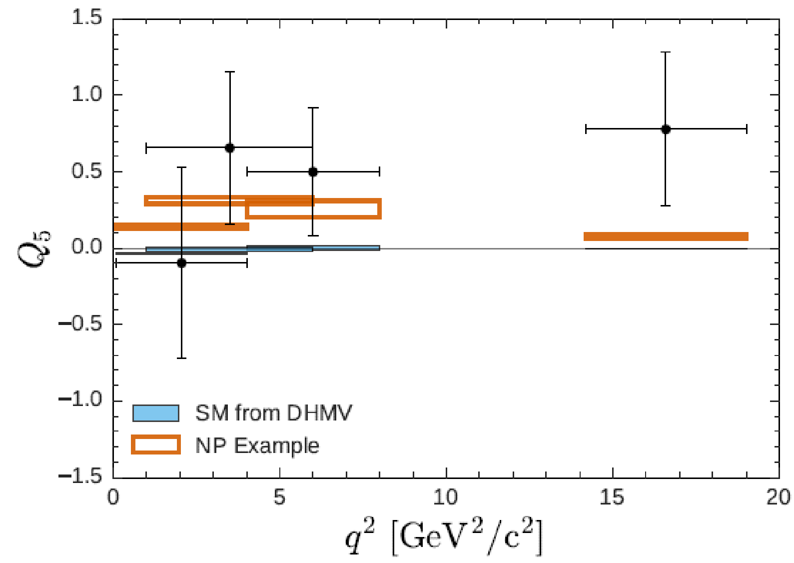
[PRL118, 111801 (2017)]

- B→K*μμ, K*ee reconstructed with Belle full data
- Angular analysis performed in four bins to obtain angular obsearvables
  - P'_i
  - the difference between the lepton flavors

$$Q_i = P_i^{\mu} - P_i^{e}$$

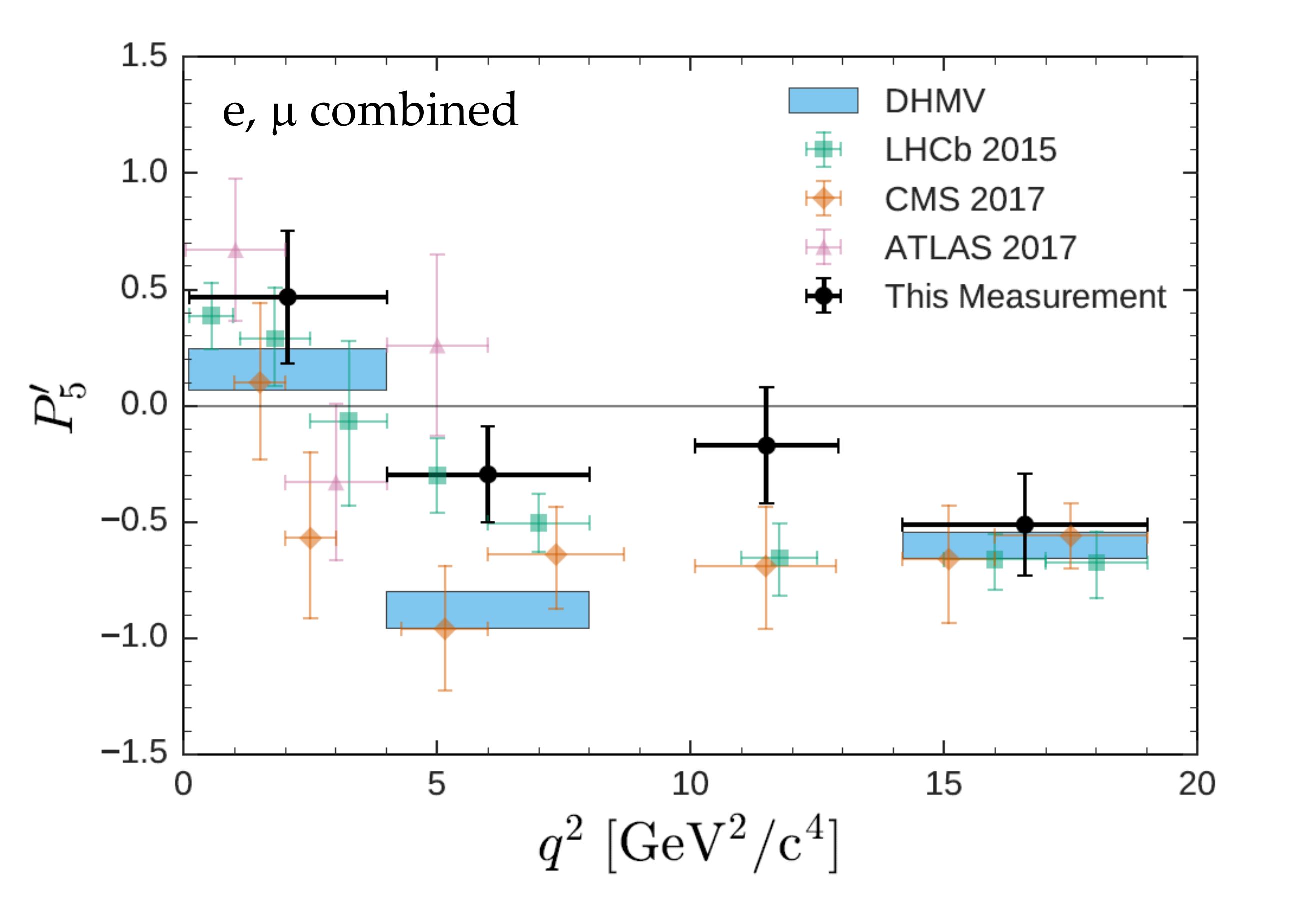






<u>Largest deviation in P'_5 of muon mode with 2.6σ</u>

Comparison with other measurements

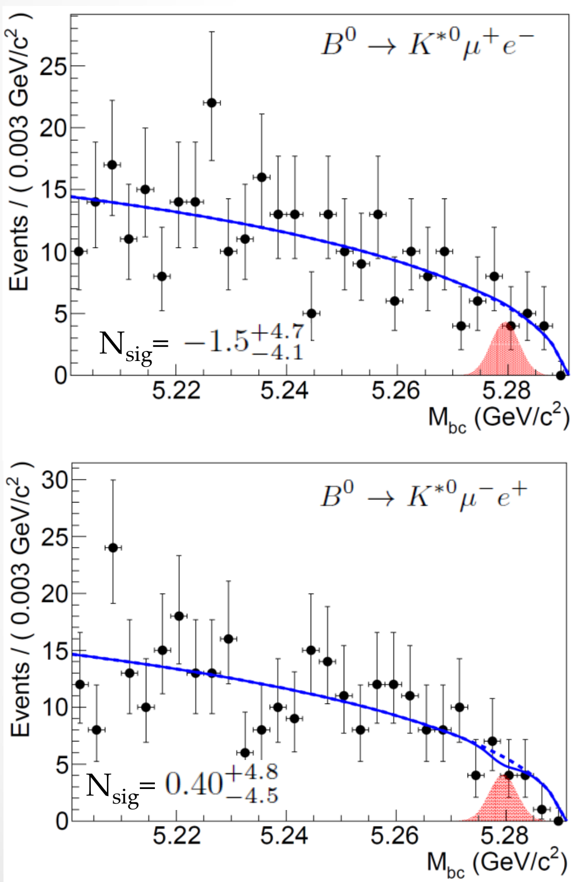


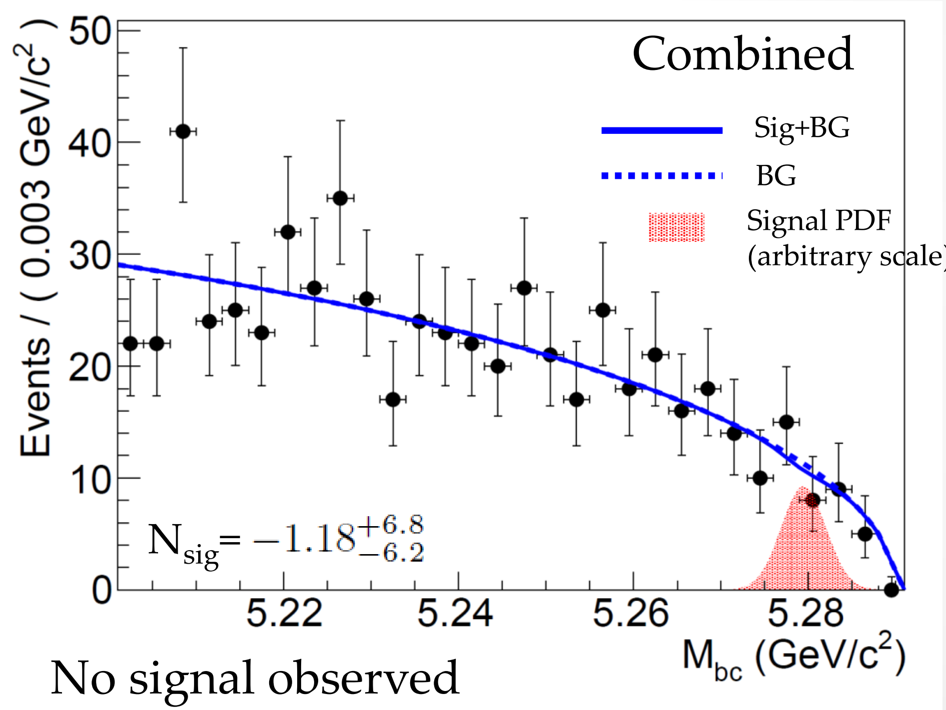
- Measurements are compatible with the SM
- Similar central values for the P'_5 anomaly with 2.5s tension

Search for lepton flavor violating decay $B^0 \rightarrow K^{*0}\mu e$

- **2018 New Belle Result with 772M $B\bar{B}$**

[arXiv:1807.03267 submitted to PRD]





No signal observed

Set most stringent limit of these decays

$$\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+ e^-) < 1.2 \times 10^{-7}$$
$$\mathcal{B}(B^0 \rightarrow K^{*0}\mu^- e^+) < 1.6 \times 10^{-7}$$
$$\mathcal{B}(B^0 \rightarrow K^{*0}\mu^\pm e^\mp) < 1.8 \times 10^{-7}$$

Summary

- Belle measured lepton universality using the data sample of the world largest luminosity
- **Tensions from the SM** exist in the measurements of B→D(*)$\tau\nu$ and B→K*ll
- New search for the LFV decay B→K*μe has been performed and set the most stringent limits
- Still need more results to be conclusive
    - Still some more analyses on going at Belle
    - Significant improvement from BelleII in near future

B→D(*)τν Systematic Errors

Hadronic Tag

TABLE IV. Overview of relative systematic uncertainties in percent. The last column gives the correlation between $R(D)$ and $R(D^*)$.

	$R(D)$ [%]	$R(D^*)$ [%]	Correlation
$D^{(*(*))}\ell\nu$ shapes	4.2	1.5	0.04
D^{**} composition	1.3	3.0	-0.63
Fake D yield	0.5	0.3	0.13
Fake ℓ yield	0.5	0.6	-0.66
D_s yield	0.1	0.1	-0.85
Rest yield	0.1	0.0	-0.70
Efficiency ratio f^{D^+}	2.5	0.7	-0.98
Efficiency ratio f^{D^0}	1.8	0.4	0.86
Efficiency ratio $f_{\rm eff}^{D^{*+}}$	1.3	2.5	-0.99
Efficiency ratio $f_{\rm eff}^{D^{*0}}$	0.7	1.1	0.94
CF double ratio g^+	2.2	2.0	-1.00
CF double ratio g^0	1.7	1.0	-1.00
Efficiency ratio $f_{\rm wc}$	0.0	0.0	0.84
$M^2_{\rm miss}$ shape	0.6	1.0	0.00
$o'_{\rm NB}$ shape	3.2	0.8	0.00
Lepton PID efficiency	0.5	0.5	1.00
Total	7.1	5.2	−0.32

Semileptonic Tag

TABLE I. Summary of the systematic uncertainties on $\mathcal{R}(D^*)$ for electron and muon modes combined and separated. The uncertainties are relative and are given in percent.

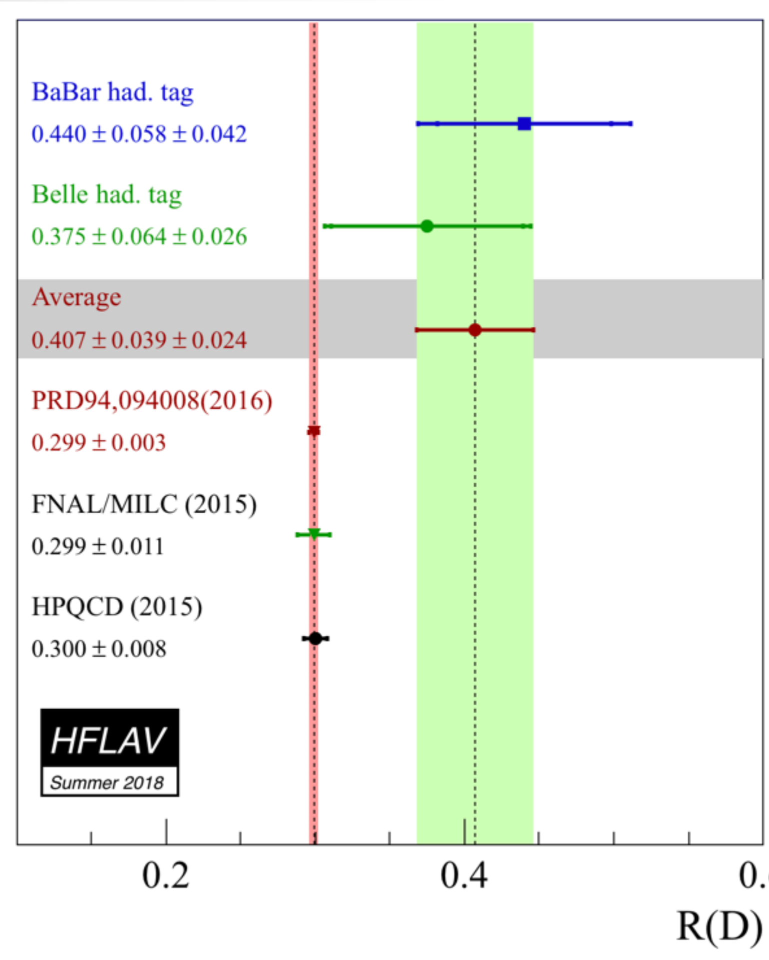
	$\mathcal{R}(D^*)$ [%]		
Sources	$\ell^{\rm sig} = e, \mu$	$\ell^{\rm sig} = e$	$\ell^{\rm sig} = \mu$
MC size for each PDF shape	2.2	2.5	3.9
PDF shape of the normalization in $\cos\theta_{B\text{-}D^*\ell}$	$^{+1.1}_{-0.0}$	$^{+2.1}_{-0.0}$	$^{+2.8}_{-0.0}$
PDF shape of $B \to D^{**}\ell\nu_\ell$	$^{+1.0}_{-1.7}$	$^{+0.7}_{-1.3}$	$^{+2.2}_{-3.3}$
PDF shape and yields of fake $D^{(*)}$	1.4	1.6	1.6
PDF shape and yields of $B \to X_c D^*$	1.1	1.2	1.1
Reconstruction efficiency ratio $\varepsilon_{\rm norm}/\varepsilon_{\rm sig}$	1.2	1.5	1.9
Modeling of semileptonic decay	0.2	0.2	0.3
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.2	0.2	0.2
Total systematic uncertainty	$^{+3.4}_{-3.5}$	$^{+4.1}_{-3.7}$	$^{+5.9}_{-5.8}$

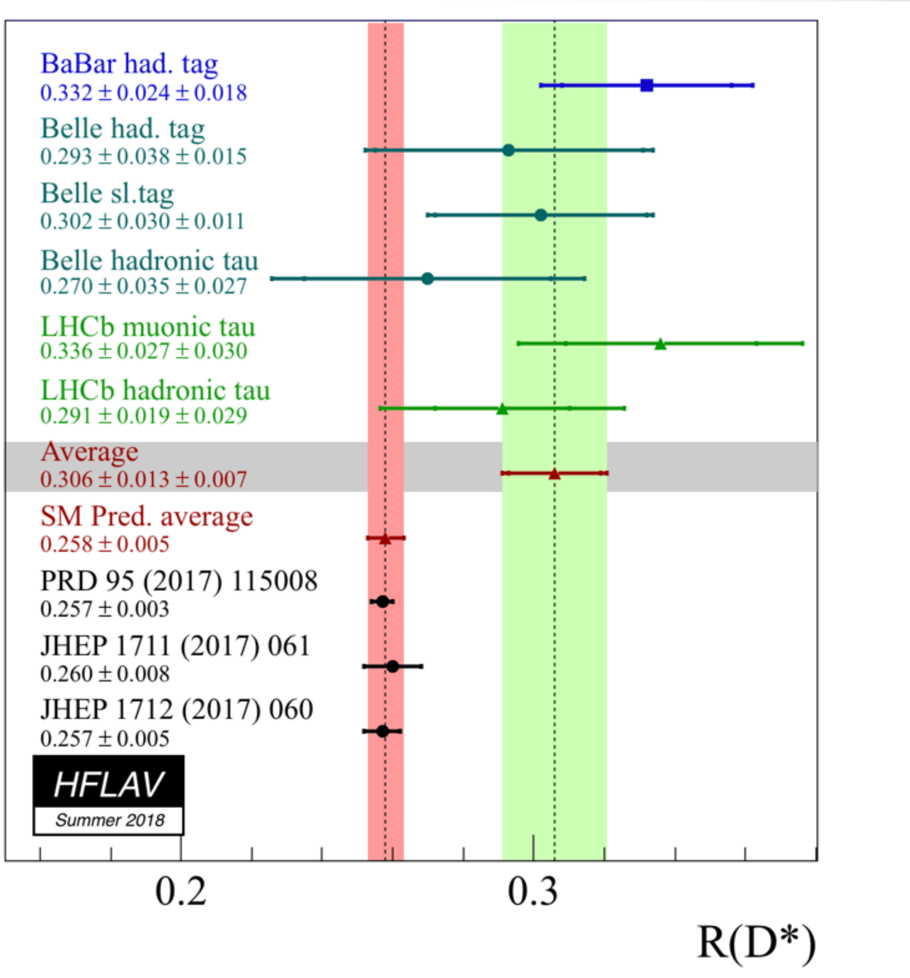
Hadronic Tag, hadronic tau decay

TABLE II. The systematic uncertainties in $R(D^*)$ and $P_\tau(D^*)$, where the values for $R(D^*)$ are relative errors. The group "common sources" identifies the common systematic uncertainty sources in the signal and the normalization modes, which cancel to a good extent in the ratio of these samples. The reason for the incomplete cancellation is described in the text.

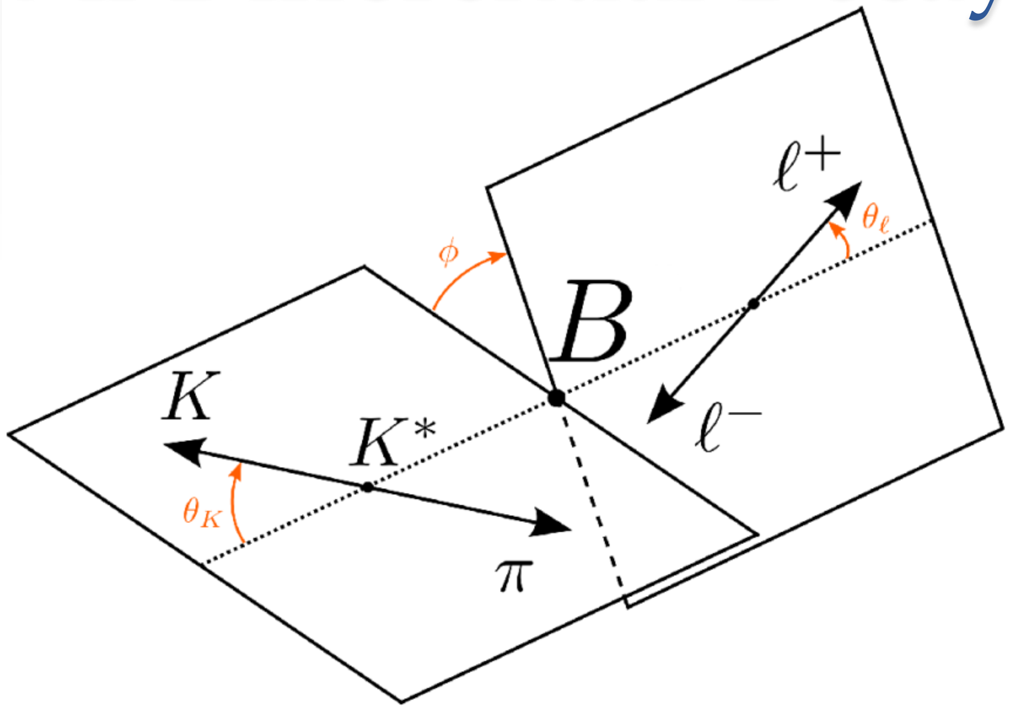
Source	$R(D^*)$	$P_\tau(D^*)$
Hadronic B composition	$^{+7.7\%}_{-6.9\%}$	$^{+0.134}_{-0.103}$
MC statistics for PDF shape	$^{+4.0\%}_{-2.8\%}$	$^{+0.146}_{-0.108}$
Fake D^*	3.4%	0.018
$\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$	2.4%	0.048
$\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau$	1.1%	0.001
$\bar{B} \to D^{*}\ell^-\bar{\nu}_\ell$	2.3%	0.007
τ daughter and ℓ^- efficiency	1.9%	0.019
MC statistics for efficiency estimation	1.0%	0.019
$\mathcal{B}(\tau^- \to \pi^-\nu_\tau, \rho^-\nu_\tau)$	0.3%	0.002
$P_\tau(D^*)$ correction function	0.0%	0.010
Common sources		
Tagging efficiency correction	1.6%	0.018
D^* reconstruction	1.4%	0.006
Branching fractions of the D meson	0.8%	0.007
Number of $B\bar{B}$ and $\mathcal{B}(\Upsilon(4S) \to B^+B^-$ or $B^0\bar{B}^0)$	0.5%	0.006
Total systematic uncertainty	$^{+10.4\%}_{-9.4\%}$	$^{+0.21}_{-0.16}$

R(D) and R(D*) Measurements





B→K*ll Differential Decay Rate



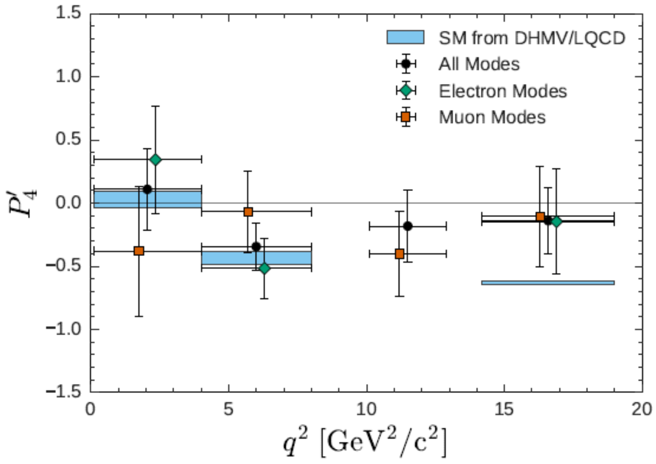
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi + S_4\sin2\theta_K\sin2\theta_\ell\cos\phi$$
$$+ S_5\sin2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin2\theta_K\sin2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big],$$

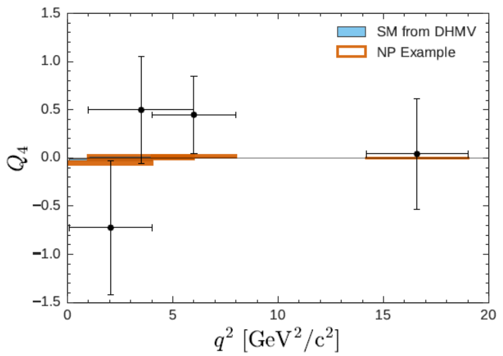
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

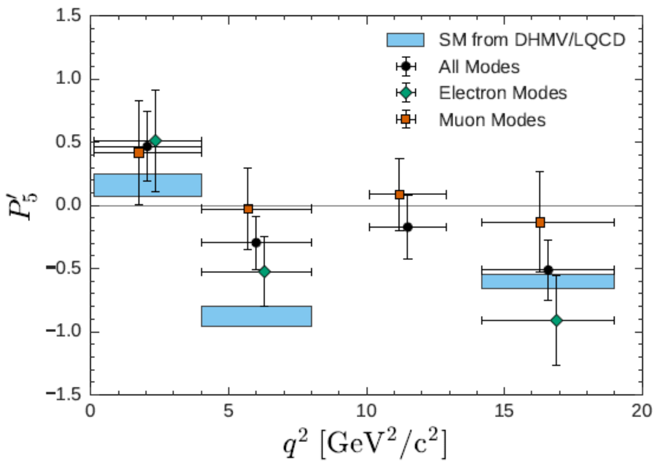
B→K*ll Results and Syst. Errors.

TABLE I. Fit results for P_4' and P_5' for all decay channels and separately for the electron and muon modes. The first uncertainties are statistical and the second systematic.

q^2 in GeV^2/c^2	P_4'	$P_4^{e\prime}$	$P_4^{\mu\prime}$	P_5'	$P_5^{e\prime}$	$P_5^{\mu\prime}$
[1.00, 6.00]	$-0.45^{+0.23}_{-0.22} \pm 0.09$	$-0.72^{+0.40}_{-0.39} \pm 0.06$	$-0.22^{+0.35}_{-0.34} \pm 0.15$	$0.23^{+0.21}_{-0.22} \pm 0.07$	$-0.22^{+0.39}_{-0.41} \pm 0.03$	$0.43^{+0.26}_{-0.28} \pm 0.10$
[0.10, 4.00]	$0.11^{+0.32}_{-0.31} \pm 0.05$	$0.34^{+0.41}_{-0.45} \pm 0.11$	$-0.38^{+0.50}_{-0.48} \pm 0.12$	$0.47^{+0.27}_{-0.28} \pm 0.05$	$0.51^{+0.39}_{-0.46} \pm 0.09$	$0.42^{+0.39}_{-0.39} \pm 0.14$
[4.00, 8.00]	$-0.34^{+0.18}_{-0.17} \pm 0.05$	$-0.52^{+0.24}_{-0.22} \pm 0.03$	$-0.07^{+0.32}_{-0.31} \pm 0.07$	$-0.30^{+0.19}_{-0.19} \pm 0.09$	$-0.52^{+0.28}_{-0.26} \pm 0.03$	$-0.03^{+0.31}_{-0.30} \pm 0.09$
[10.09, 12.90]	$-0.18^{+0.28}_{-0.27} \pm 0.06$	-	$-0.40^{+0.33}_{-0.29} \pm 0.09$	$-0.17^{+0.25}_{-0.25} \pm 0.01$	-	$0.09^{+0.29}_{-0.29} \pm 0.02$
[14.18, 19.00]	$-0.14^{+0.26}_{-0.26} \pm 0.05$	$-0.15^{+0.41}_{-0.40} \pm 0.04$	$-0.10^{+0.39}_{-0.39} \pm 0.07$	$-0.51^{+0.24}_{-0.22} \pm 0.01$	$-0.91^{+0.36}_{-0.30} \pm 0.03$	$-0.13^{+0.39}_{-0.35} \pm 0.06$







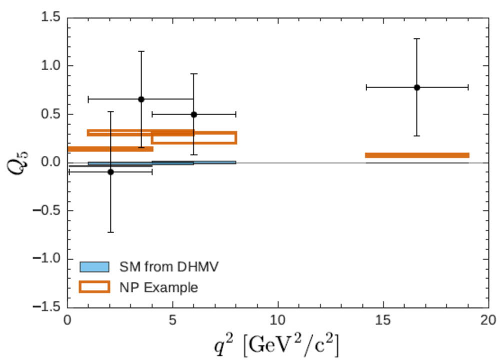


TABLE II. Results for the lepton-flavor-universality-violating observables Q_4 and Q_5. The first uncertainty is statistical and the second systematic.

q^2 in GeV^2/c^2	Q_4	Q_5
[1.00, 6.00]	$0.498 \pm 0.527 \pm 0.166$	$0.656 \pm 0.485 \pm 0.103$
[0.10, 4.00]	$-0.723 \pm 0.676 \pm 0.163$	$-0.097 \pm 0.601 \pm 0.164$
[4.00, 8.00]	$0.448 \pm 0.392 \pm 0.076$	$0.498 \pm 0.410 \pm 0.095$
[14.18, 19.00]	$0.041 \pm 0.565 \pm 0.082$	$0.778 \pm 0.502 \pm 0.065$

B→K*μe Upper Limits