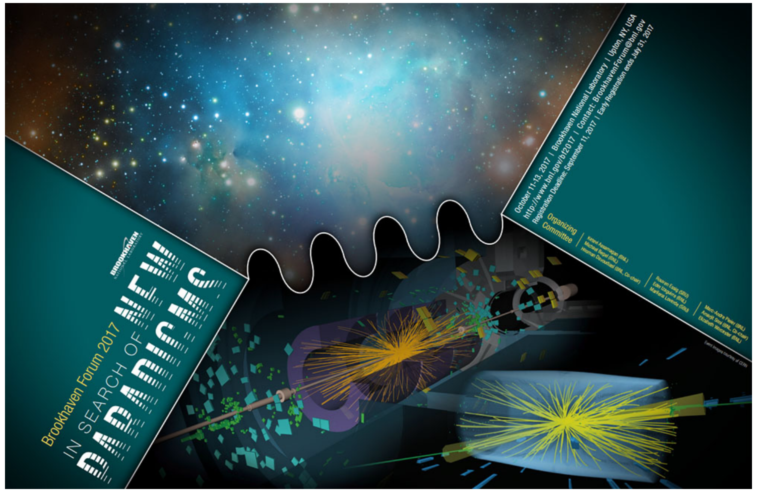
$R_{K^{(*)}}$ & $R_{D^{(*)}}$ at Belle

Bilas Pal, on behalf of the Belle Collaboration
University of Cincinnati

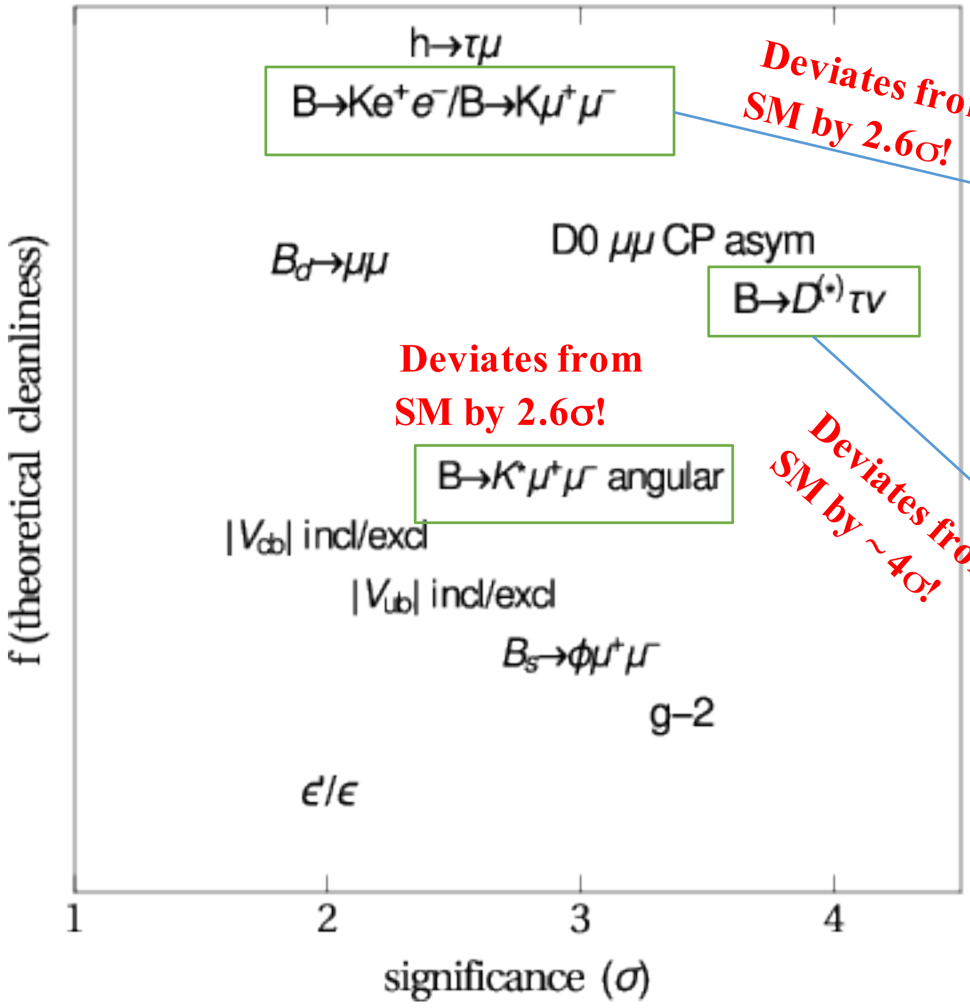
Brookhaven Forum 2017: In Search of New Paradigms

11-13 Oct, 2017



Status of Flavor Anomalies

Z. Ligeti: arXiv:1704.02938[hep-ph]

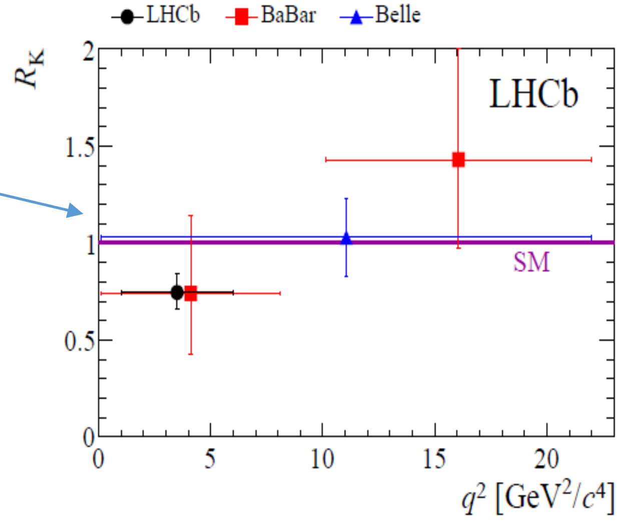


Deviates from SM by 2.6σ!

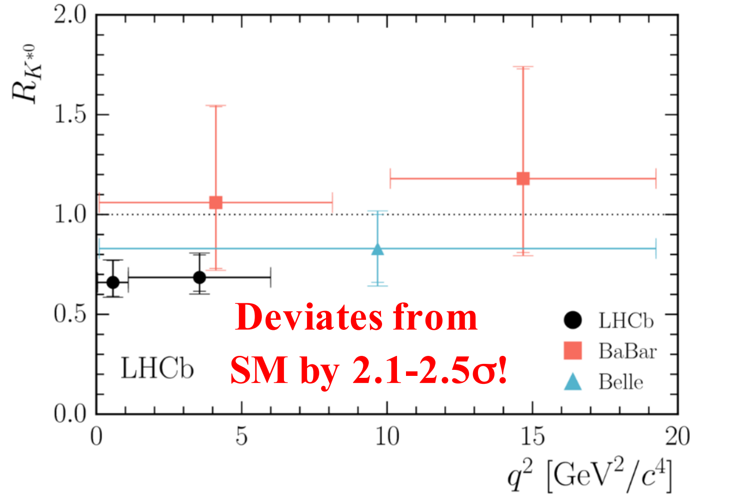
Deviates from SM by 2.6σ!

Deviates from SM by ~4σ!

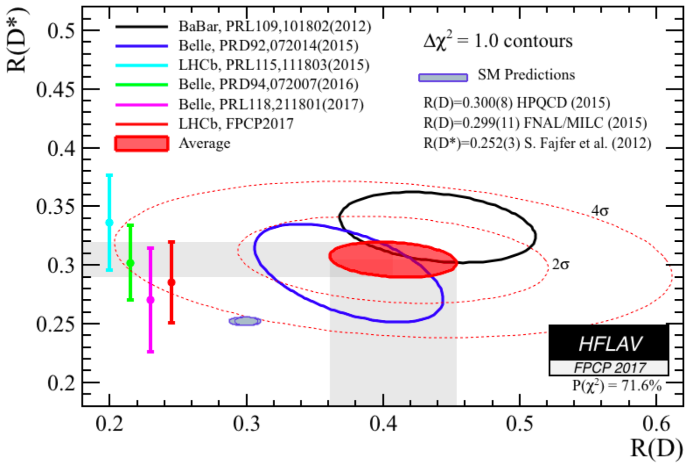
LHCb: PRL 113, 151601 (2014)
BaBar: PRD 86, 032012 (2012)
Belle: PRL 103, 171801 (2009)



LHCb: arXiv:1705.05802
BaBar: PRD 86, 032012 (2012)
Belle: PRL 103, 171801 (2009)

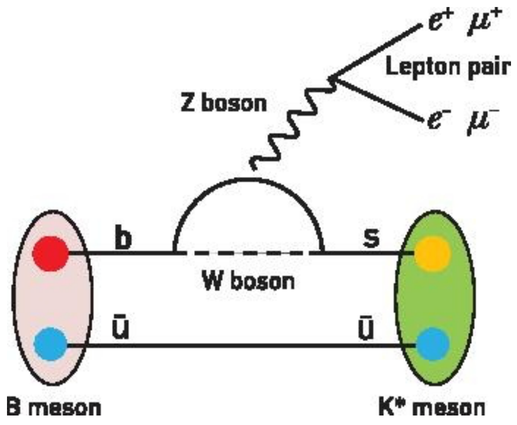


Deviates from SM by 2.1-2.5σ!



$R_{K^{(*)}}$ at Belle

J.T. Wei et al,
PRL 103, 171801 (2009)



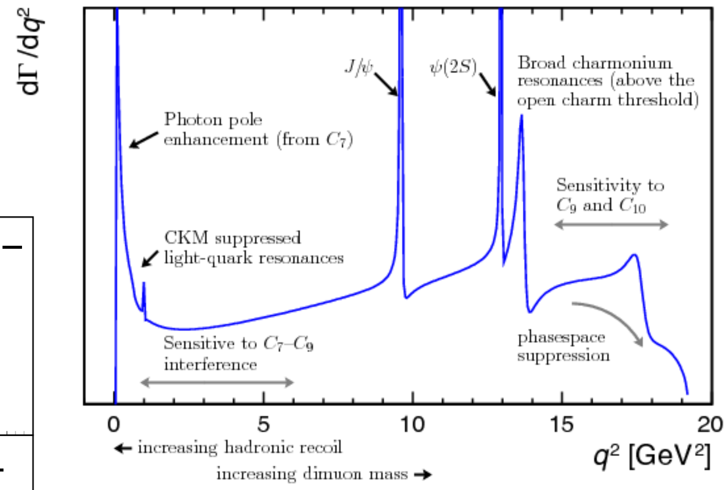
- Decays involved are $B \rightarrow K^{(*)} l^+ l^-$
  - Mediated via Electroweak Penguin process
  - Possibility of having non-SM particle in the loop
  - Two charged lepton in the final state allow for clean event selection
- Currently available Belle results are with 605 fb^{-1} of data and the measurements of $\boldsymbol{R_K}$ and $\boldsymbol{R_{K^*}}$ were performed in full q^2 range.
- We measured

$$R_K = \frac{B(B \rightarrow K\mu^+\mu^-)}{B(B \rightarrow Ke^+e^-)} = 1.03 \pm 0.19 \pm 0.06$$

And

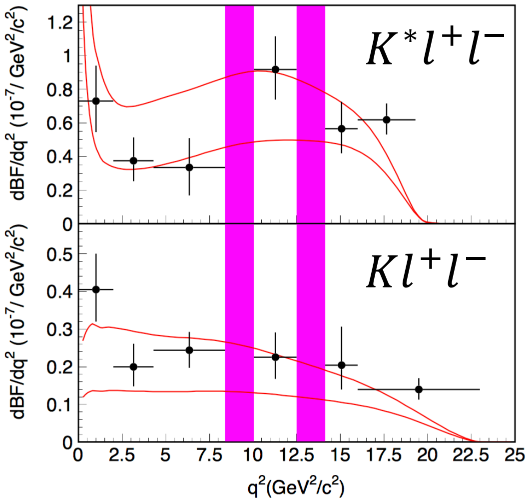
$$R_{K^*} = \frac{B(B \rightarrow K^*\mu^+\mu^-)}{B(B \rightarrow K^*e^+e^-)} = 0.83 \pm 0.17 \pm 0.08$$

T. Blake et al., arXiv: 1606.00916



Mode	$\mathcal{B}$ (10^{-7})
$K^{*+}\mu^+\mu^-$	$11.1^{+3.2}_{-2.7}\pm1.0$
$K^{*0}\mu^+\mu^-$	$10.6^{+1.9}_{-1.4}\pm0.7$
$K^{*}\mu^+\mu^-$	$11.0^{+1.6}_{-1.4}\pm0.8$
$K^{*+}e^+e^-$	$17.3^{+5.0}_{-4.2}\pm2.0$
$K^{*0}e^+e^-$	$11.8^{+2.7}_{-2.2}\pm0.9$
$K^{*}e^+e^-$	$13.9^{+2.3}_{-2.0}\pm1.2$

$K^{+}\mu^+\mu^-$	$5.3^{+0.8}_{-0.7}\pm0.3$
$K^{0}\mu^+\mu^-$	$4.4^{+1.3}_{-1.1}\pm0.3$
$K\mu^+\mu^-$	$5.0^{+0.6}_{-0.6}\pm0.3$
$K^{+}e^+e^-$	$5.7^{+0.9}_{-0.8}\pm0.3$
$K^{0}e^+e^-$	$2.0^{+1.4}_{-1.0}\pm0.1$
Ke^+e^-	$4.8^{+0.8}_{-0.7}\pm0.3$



$R_{K^{(*)}}$ at Belle

Wei et al,
PRL 103, 171801 (2009)

- Decays involved are $B \to K^{(*)} l^+ l^-$
  - Mediated via Electroweak Penguin process
  - Possibility of having non-SM particle in the loop
  - Two charged lepton in the final state allow for clean event selection
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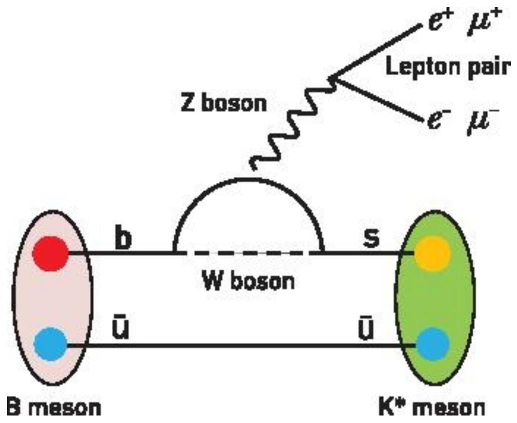
- We measured



$$R_K = \frac{B(B \to K\mu^+\mu^-)}{B(B \to Ke^+e^-)} = 1.03 \pm 0.19 \pm 0.06$$

And

$$R_{K^*} = \frac{B(B \to K^*\mu^+\mu^-)}{B(B \to K^*e^+e^-)} = 0.83 \pm 0.17 \pm 0.08$$

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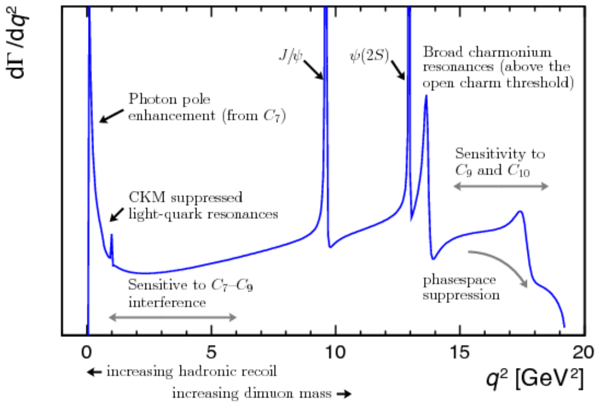
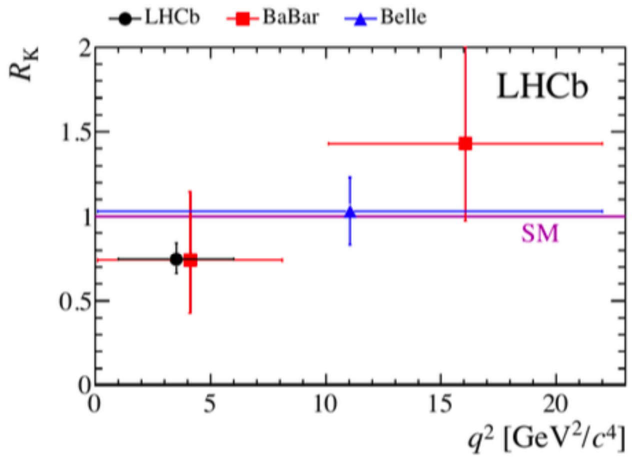
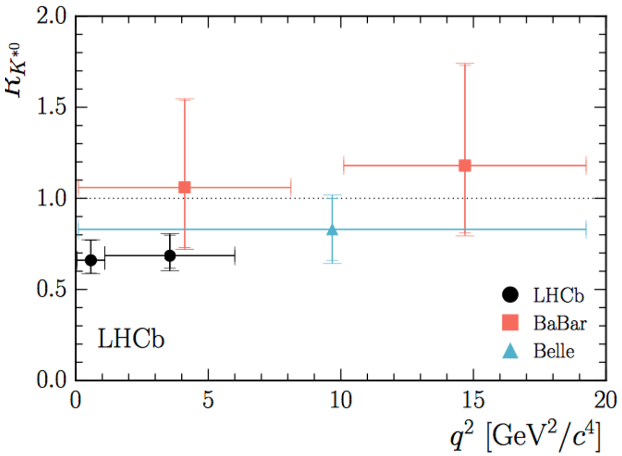






An analysis is ongoing in Belle, and a sensitivity study is also ongoing in Belle II. Belle II expect to have similar sensitivity of current LHCb on 2020 – 2021 with 3-10/ab data for these measurements!

Angular analysis of $B \to K^{*} l^{+} l^{-}$

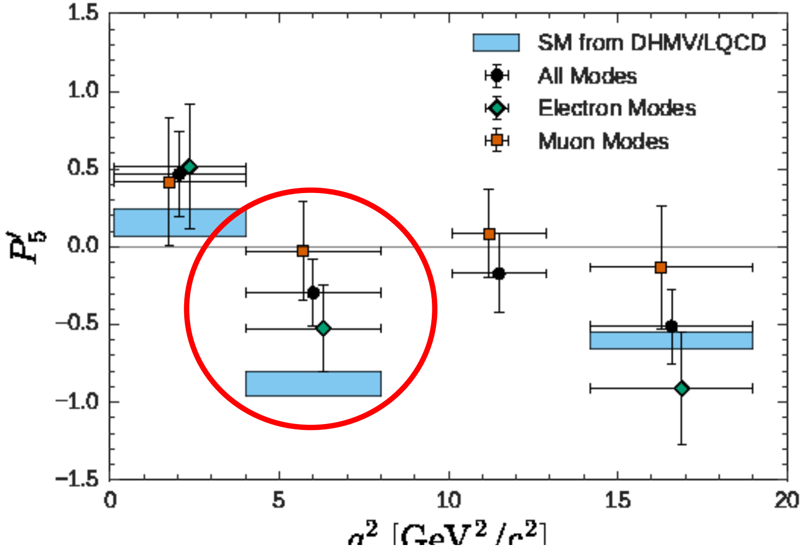
S. Wehle et al,
PRL 118, 111801 (2017)

- $(F_L, A_{FB}\ and\ S_i)$ are the observables
- A cleaner set of observables can be built, where the hadronic form factor uncertainties cancel at the leading order, e.g. $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$
- Most angular observables agree with SM
- Deviation in P_5' near $q^2 \approx 6\ GeV^2$

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

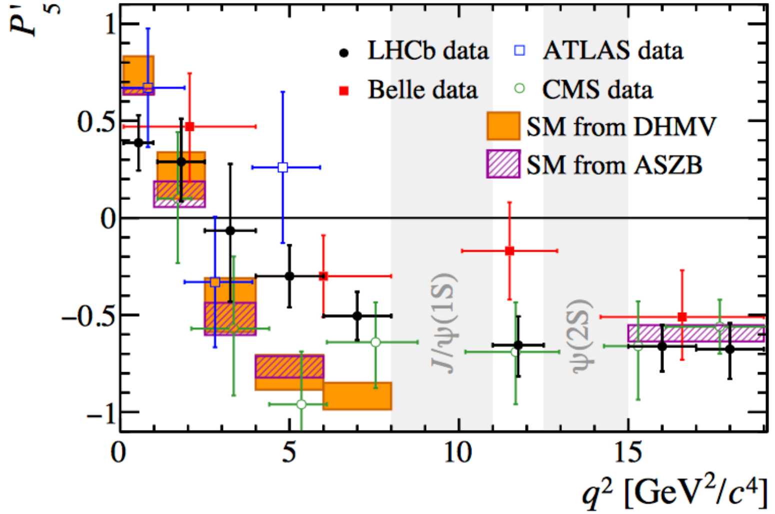
Fraction of longitudinal polarisation of the K*

Forward-backward asymmetry of the dilepton system



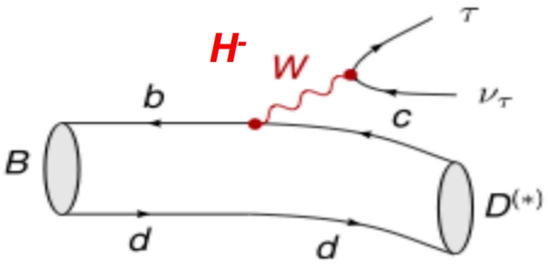
2.6σ deviation for K*μμ
1.1σ deviation for K*ee

Other experiments also show similar order tension in P_5' with SM predictions.



$R_{D^{(*)}}$ at Belle

- Decays involved are $B \to D^{(*)}\tau\nu$ and $B \to D^{(*)}l\nu$
  - They are not rare decays, tree level transition, mediated via a W in the SM, BF ~ 1-5%
  - $B \to D^{(*)}\tau\nu$ can also receive contribution from charged Higgs (which appears in SUSY, 2HDM)
  - Leptoquark may also contribute to this process.



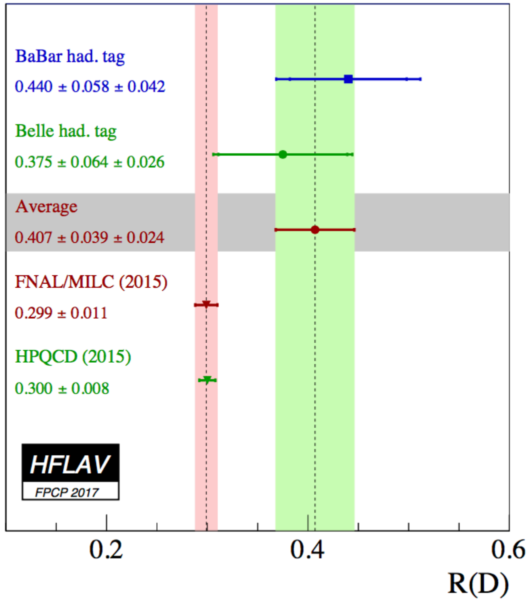
Define ratios:

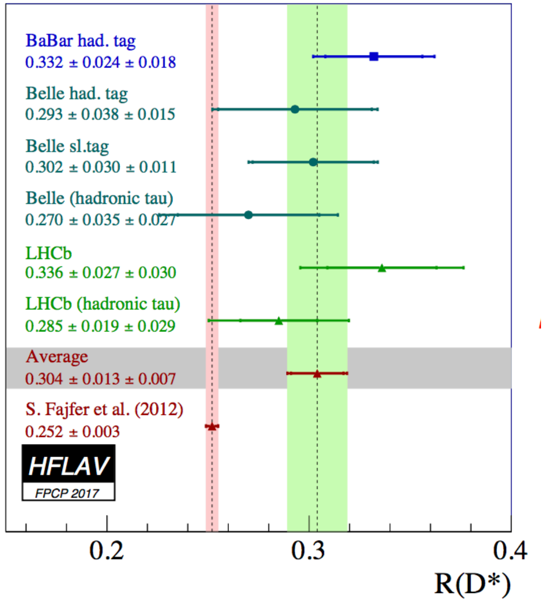
$$\mathcal{R}_{D^*} \equiv \frac{\mathcal{B}(B \to D^*\tau\nu)}{\mathcal{B}(B \to D^*\ell\nu)} \qquad \mathcal{R}_{D} \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$$

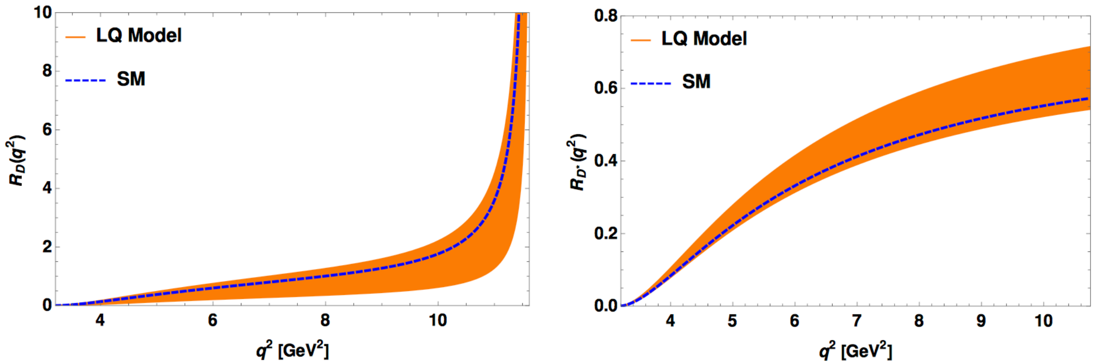
Measured ratios are traditionally been above the SM prediction

BaBar repoted the first discrepancy, confirmed by Belle and LHCb

May be the first sign of New Physics!!!







Sahoo, Mohanta & Giri, PRD 95, 035027 (2017)

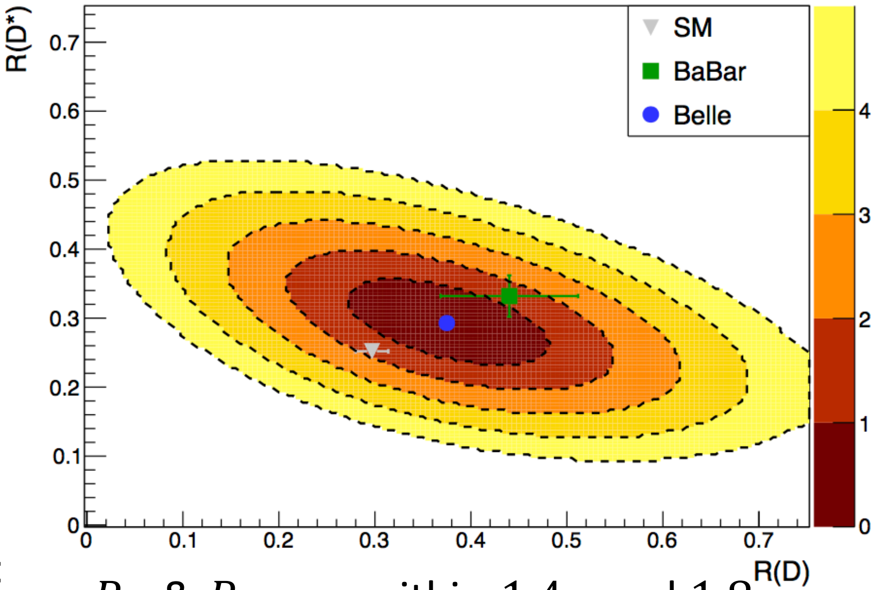
$R_{D^{(*)}}$ using Hadronic tag

M. Huschle et al, PRD 92, 072014 (2015)

- Fully reconstructed hadronic decays on tag side (1149 B final states)
- τ lepton is reconstructed in the leptonic decays $\tau \to l\nu\nu, l \equiv e, \mu$; so that signal and normalization modes have the same detectable final state particles.
- 4 signal samples $D^+l, D^0l, D^{*+}l, D^{*0}l$
- Calculate missing mass squared: $M^2_{miss} = (P_{Beam} - P_D - P_l)^2$;
  - Low-M^2_{miss} region is dominated by the lepton normalization and has essentially no sensitivity to to the τ signal
    - Fit M^2_{miss} directly for lepton normalization yields
  - High-M^2_{miss} region sensitive to the τ signal
    - Discrimination power in M^2_{miss} between the τ signal and D^{**} background is less
    - Fit a NN spectrum to obtain the τ signal yield: NN has 8 input variables, most discrimination power comes from E_{ECL} (unassociatec energy in calorimeter) and p^*_l (lepton momentum in CM frame)
    - Fit actually modified NN output: $O'_{NB} = \log\left(\frac{O_{NN} - O_{min}}{O_{max} - O_{NN}}\right)$

$$\mathcal{R}_{D^*} = 0.293 \pm 0.038 \pm 0.015$$
$$\mathcal{R}_D = 0.375 \pm 0.064 \pm 0.026$$

$$\mathcal{R}_{D^*} \equiv \frac{\mathcal{B}(B \to D^*\tau\nu)}{\mathcal{B}(B \to D^*\ell\nu)} \qquad \mathcal{R}_D \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$$



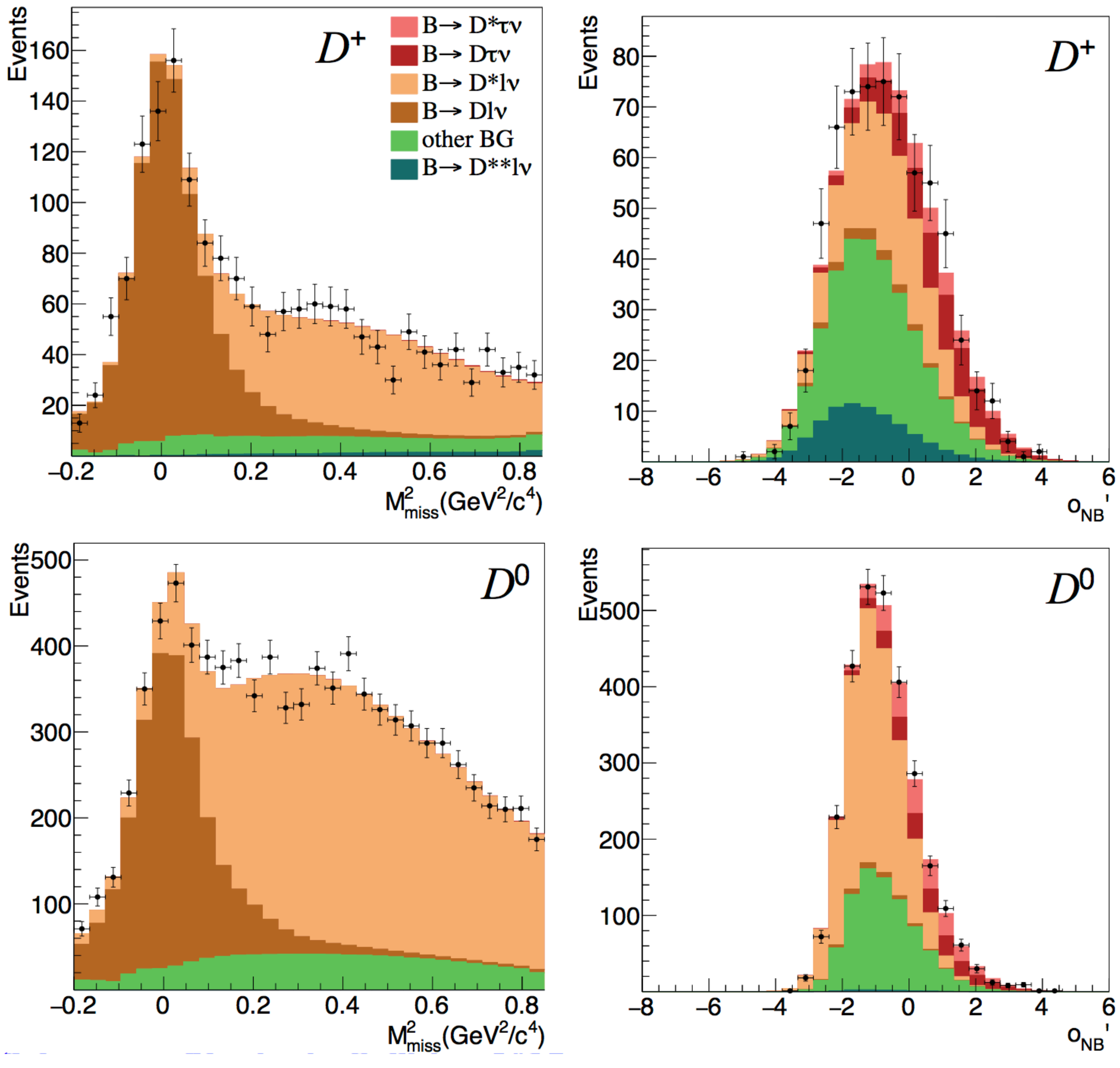
R_D & R_{D^*} are within 1.4σ and 1.8σ higher than the SM predictions!

$$\mathcal{R}^{SM}_{D^*} = 0.252 \pm 0.003$$
$$\mathcal{R}^{SM}_D = 0.297 \pm 0.017$$

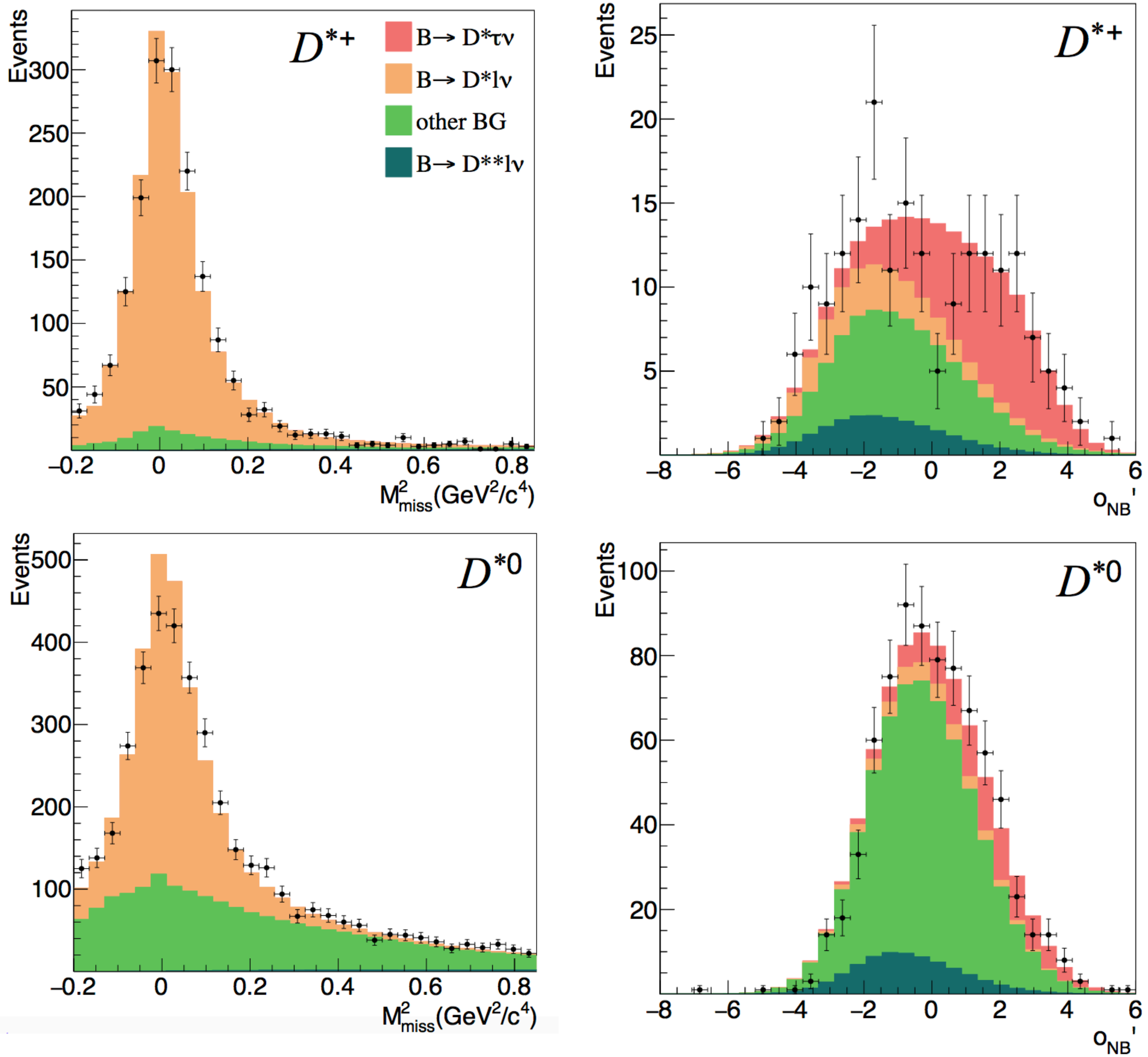
Fajfer, Kamenik & Nisadizc, PRD 85, 094025 (2012);
Kamenik and Mescia, PRD 78, 014003 (2008)

$R_{D^{(*)}}$ using Hadronic tag

$M^2_{miss} < 0.85$ $\quad$ $M^2_{miss} > 0.85$



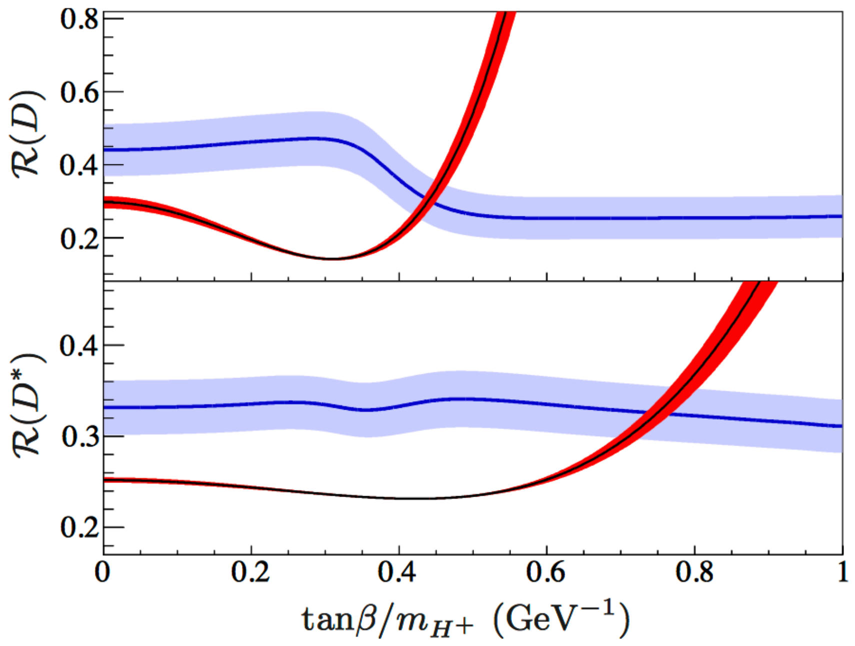
$M^2_{miss} < 0.85$ $\quad$ $M^2_{miss} > 0.85$



Constraint on Type II charged Higgs

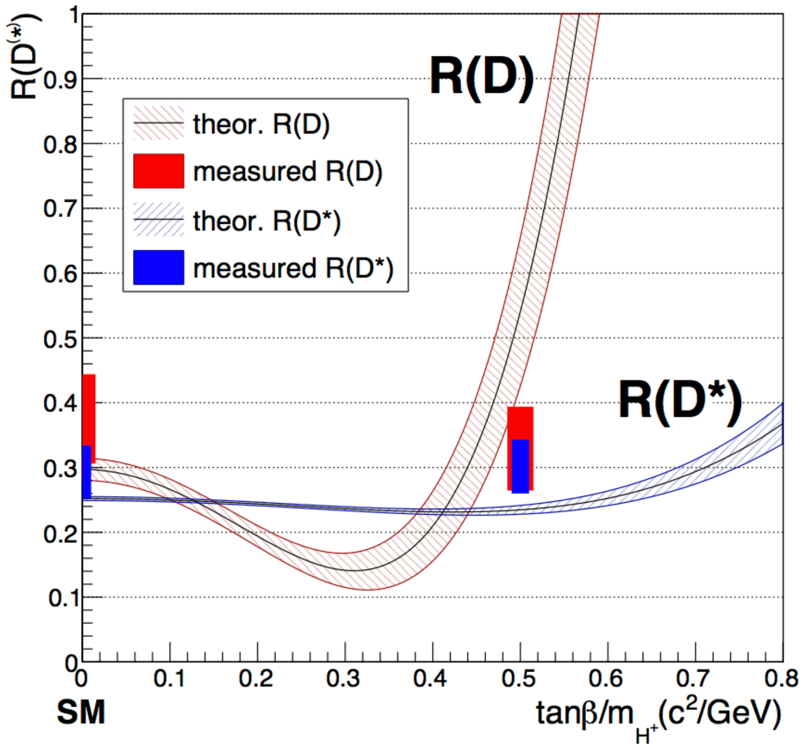
BaBar's measurements were notably higher than SM and disfavored Type-II 2HDM

$$\mathcal{R}_{D^*} = 0.332 \pm 0.024 \pm 0.018$$
$$\mathcal{R}_{D} = 0.440 \pm 0.058 \pm 0.042$$



J.P. Lees et al, PRD 88, 072012 (2013)

Belle's measurements are compatible with Type-II 2HDM in the region $\frac{\tan\beta}{m_{H^+}} = 0.5$

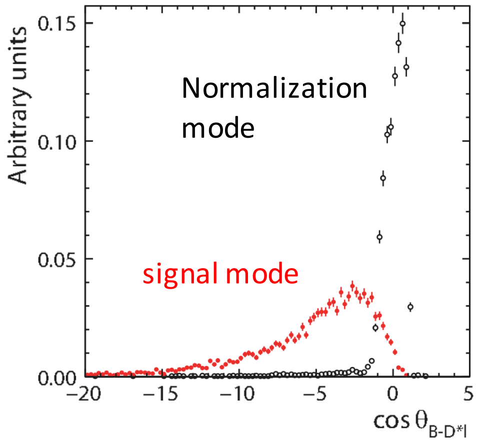


R_{D^*} with semileptonic tag

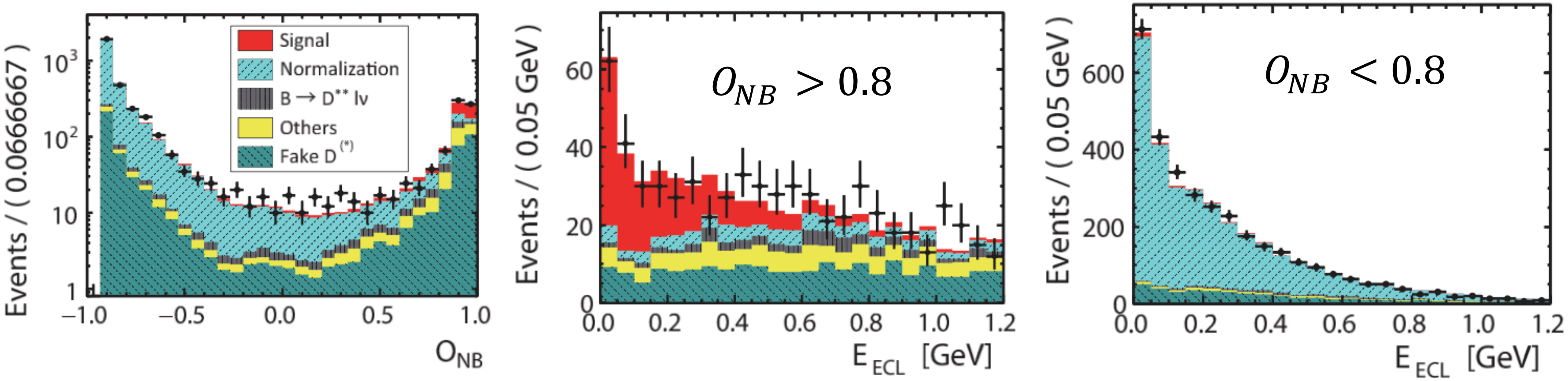
- Only neutral modes: signal $\overline{B^0} \rightarrow D^{*+}\tau\nu$ and normalization $\overline{B^0} \rightarrow D^{*+}l\nu$
- Tag side $\overline{B^0} \rightarrow D^{*+}l\nu$ (for normalization channel, both signal and tag sides decay to $D^{*}l\nu$)
  - More efficient than hadronic tag, but challenging as neutrino also in Tag side
  - Use

$$\cos\theta_{B\text{-}D^*\ell} \equiv \frac{2E_{\mathrm{beam}}E_{D^*\ell} - m_B^2c^4 - M_{D^*\ell}^2c^4}{2|\vec{p}_B|\cdot|\vec{p}_{D^*\ell}|c^2},$$

to distinguish signal and normalization.



- 2D fit to the variables E_{ECL} and O_{NB}; the input variables to NB are M_{miss}^2, visible energy (total energy of $B_{tag} + B_{sig}$) and $\cos\theta_{B-D^*l}$



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

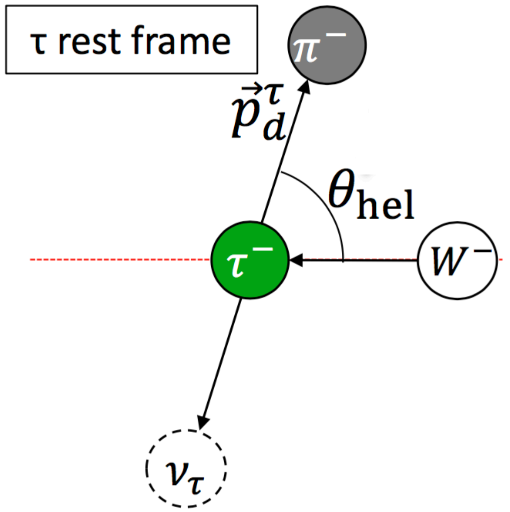
1.6σ higher than SM predictions!

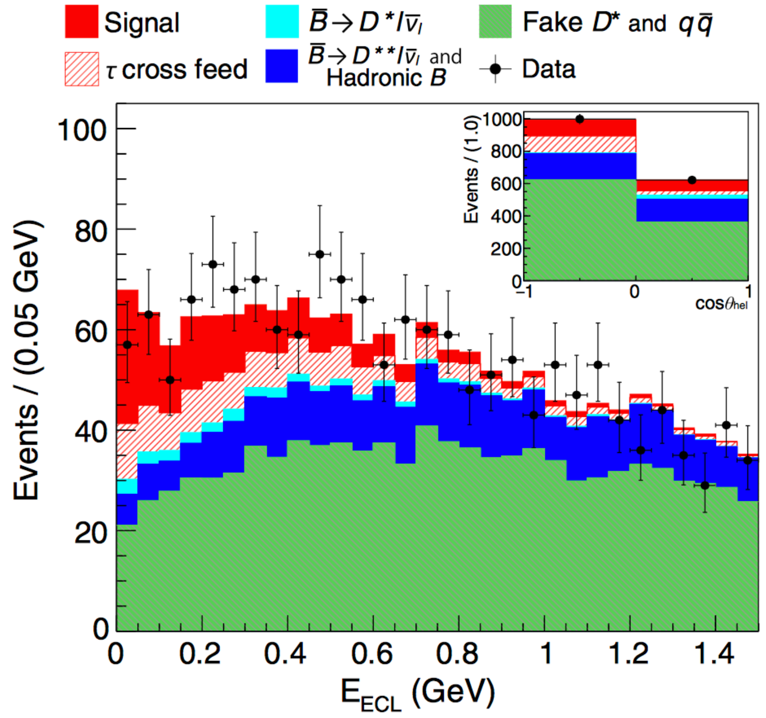
Y. Sato et al, PRD 94, 072007 (2016)

First measurement of R_{D^*} using the semileptonic tagging.

R_{D^*} using Hadronic tag

- Hadronic tagging (1104 B final states)
- Hadronic τ decays: $\tau \to \pi\nu, \rho\nu$
- Measure also the τ lepton polarization $P_\tau = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ - \Gamma^-}$ via the helicity angle, $\frac{d\Gamma}{d\, cos\theta_h} \propto 1 + \alpha P_\tau cos\theta_h$; $[\alpha = 1\ (\sim 0.45)$ for $\tau \to \pi\nu\ (\rho\nu)]$
- 2D fit to the variables E_{ECL} and $\cos\theta_h$ for signal extraction
- For normalization mode, fit to M^2_{miss} is used





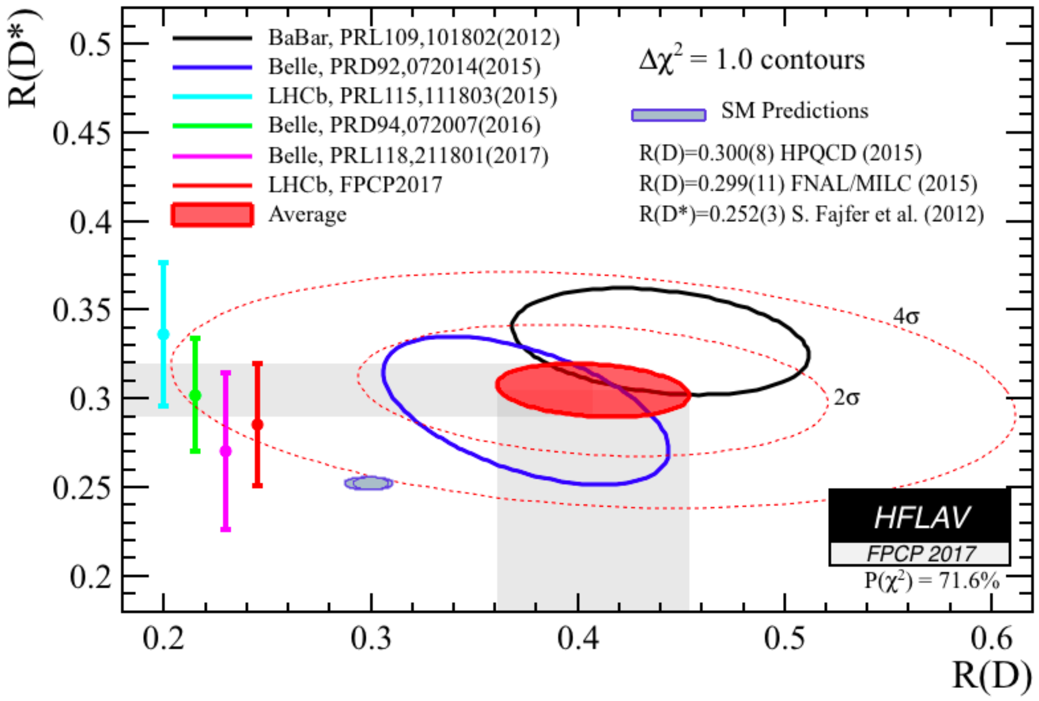
This is the first observation of $\bar{B} \to D^* \tau\nu$ decays using only hadronic τ decays: $\sim 7\sigma$ significance

$$\mathcal{R}_{D^*} = 0.270 \pm 0.035\ ^{+0.028}_{-0.025}$$
$$P_\tau(D^*) = -0.38 \pm 0.51\ ^{+0.21}_{-0.16} \quad \text{SM: -0.497}$$

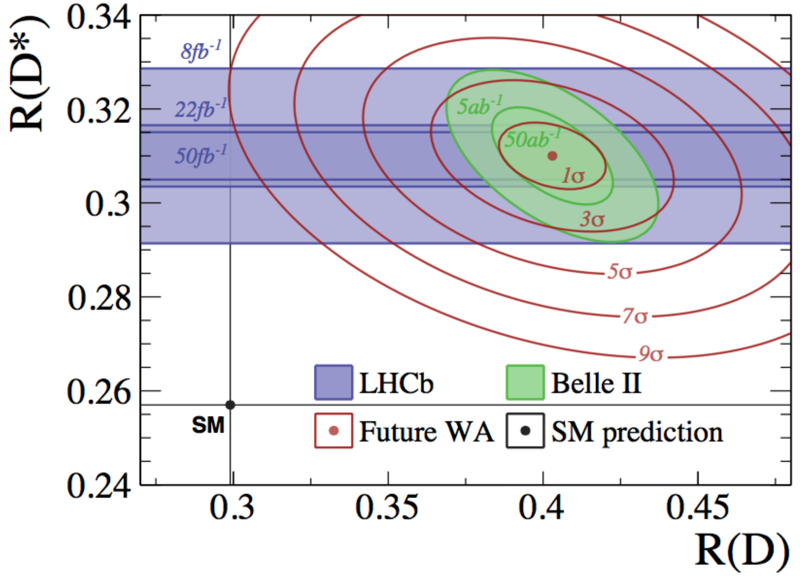
Consistent with SM!

S. Hirose et al, PRL118, 211801 (2017)

Summary of $R_{D^{(*)}}$



This may be the first sign of Physics beyond the SM. LHCb run II and Belle II should resolve this.



Current world average is ~ 4σ higher than the SM predictions

Albrecht et. al, arXiv:1709.10308[hep-ph]

SM Predictions:

R(D) =0.297 +- 0.017 [Kamenik & Mescia, PRD 78, 014003 (2008)]
R(D)=0.252 +- 0.003 [Fajfer et al., PRD 85, 094025 (2012)]*

More Recent SM Predictions (Lattice):

R(D) =0.299 +- 0.011 [Bailey et al. (FNAL/MILC), arXiv:1503.07237]
R(D) =0.300 +- 0.008 [Na et al. (HPQCD), arXiv:1505.03925]

Summary

- We have presented the recent results of $R_{K^{(*)}}$,$R_{D^{(*)}}$ and P_5' measured at Belle
- Observables $R_{D^{(*)}}$ and P_5' are traditionally above the SM predictions and are consistent with other experiments
- A Belle analysis is ongoing to measure $R_{K^{(*)}}$
- First data from Belle II will be available in 2019: Belle II and LHCb run II will clarify many of the flavor anomalies currently we are seeing at the level of 2 – 4 standard deviations!