R_{D^*} or $R_{D\pi}$: Closing the prediction gap?

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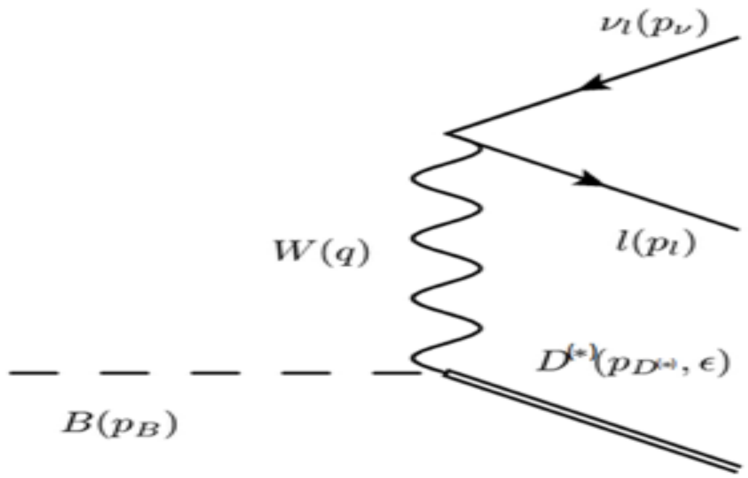
Evidence of LFU violation?

$$R_{D^{(*)}} \equiv \frac{\mathrm{Br}(B \to \tau\nu_\tau D^{(*)})}{\mathrm{Br}(B \to l\nu_l D^{(*)})}$$

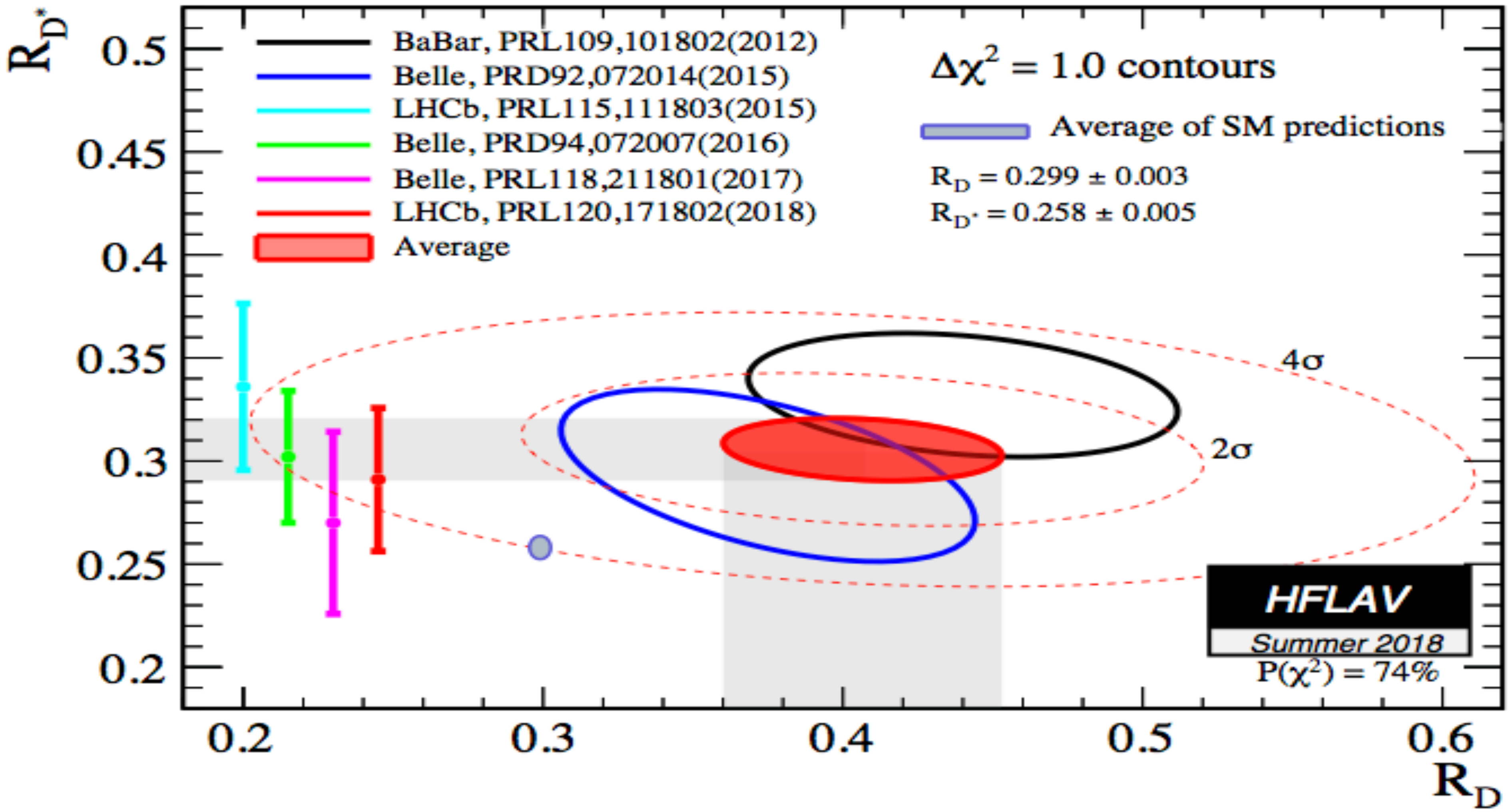


Experiment	R	Stat	Syst
BABAR12	0.332	0.024	0.018
BELLE15	0.293	0.038	0.015
LHCb15	0.336	0.027	0.03
BELLE16	0.302	0.03	0.011
BELLE17	0.27	0.035	0.028
LHCb18	0.291	0.019	0.026
Average HFLAV	0.306	0.013	0.007

$R_{D^*}^{expWA}$ deviates by approx. 3.7 σ $R_{D^*}^{SM}$

What are the considerations in the SM prediction?

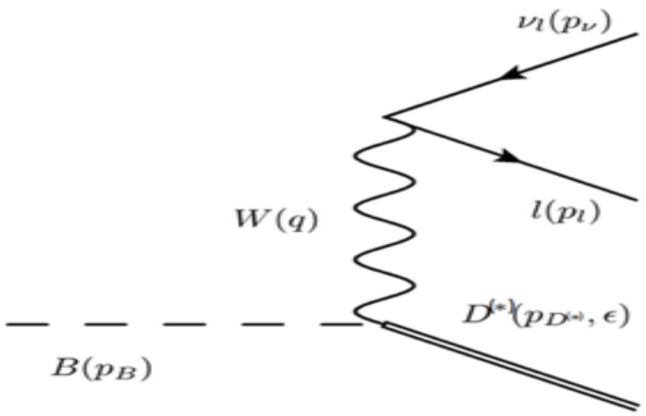
Evidence of LFU violation?



Y. Amhis et al. (HFLAV), Eur. Phys. J. C77, 895 (2017), 1612.07233. https://hflav.web.cern.ch
See Befani, S. et al J. Phys. G46(2019) no. 2, 023001 for a recent review

What are the considerations in the SM prediction?

3-body decay Standard model calculation



$$M_3 = \frac{G_F}{\sqrt{2}} V_{cb} J^\lambda l_\lambda$$ Leptonic current $$l_\lambda \equiv \bar{u}_l \gamma_\lambda (1-\gamma^5) v_\nu$$

Parametrization of the hadronic vertex *WSB ZPC 29 637(1985).*

Form factors param. *Falk A and Neubert, M. PRD 47 2965 (93) Caprini I. et al Nucl. Phys. B 530 (1998) 15*

$$\begin{aligned}
&\langle D^*(p_{D^*},\epsilon_\mu)|J^\lambda|B(p_B)\rangle \\
&= \frac{2i\underline{V}(q^2)}{m_B+m_{D^*}}\epsilon^{\lambda\mu\alpha\beta}\epsilon^*_\mu(p_B)_\alpha(p_{D^*})_\beta - 2m_{D^*}\underline{A}_0(q^2)\frac{q^\lambda q\cdot\epsilon^*}{q^2} \\
&\quad -(m_B+m_{D^*})\underline{A}_1(q^2)\left(\epsilon^{*\lambda}-\frac{q^\lambda q\cdot\epsilon^*}{q^2}\right) \\
&\quad +\frac{\underline{A}_2(q^2)q\cdot\epsilon^*}{m_B+m_{D^*}}\left((p_B+p_{D^*})^\lambda - \frac{m_B^2-m_{D^*}^2}{q^2}q^\lambda\right),
\end{aligned}$$

- V, A0, A1, A2 have been reconstructed by Belle using HQET analysis, but only for e and μ measurements - not τ! W. *Dungel et al. (Belle Collaboration), Phys. Rev. D 82, 112007 (2010).*
- A0 is heavily suppressed for e and μ since it represents a longitudinal state of the lepton-neutrino system
- Instead, A0 is derived from A2 using HQET approximation. A direct measurement from τ data could test it!

Form factors measurement

Dungel et al. (Belle Collaboration), Phys. Rev. D 82, 112007 (2010).

Using Caprini-Lellouch-Neubert (CLN) parametrization *Caprini I. et al Nucl. Phys. B 530 (1998) 15*

$$V(q^2) = R_1(w)\frac{h_{A_1}}{R_{D^*}},$$

$$A_0(q^2) = R_0(w)\frac{h_{A_1}}{R_{D^*}},$$

$$A_2(q^2) = R_2(w)\frac{h_{A_1}}{R_{D^*}}.$$

$$h_{A_1}(w) = \frac{A_1(q^2)}{R_{D^*}}\frac{2}{w+1}$$

$$w \equiv 1 - \frac{1}{2}\left(\frac{p_B}{m_B} - \frac{p_{D^*}}{m_{D^*}}\right)^2 = \frac{p_B \cdot p_{D^*}}{m_B m_{D^*}} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

Kinematical parameter.

$$R_{D^*} \equiv 2\sqrt{m_B m_{D^*}}/(m_B + m_{D^*})$$

Isgur-Wise function

	Belle	Average
$h_{A_1}(1)\lvert V_{cb}\rvert$	$(34.6 \pm 0.2 \pm 1.0) \times 10^{-3}$	$(35.61 \pm 0.43) \times 10^{-3}$
ρ^2	$1.214 \pm 0.034 \pm 0.009$	1.205 ± 0.026
$R_1(1)$	$1.401 \pm 0.034 \pm 0.018$	1.404 ± 0.032
$R_2(1)$	$0.864 \pm 0.024 \pm 0.008$	0.854 ± 0.020

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2,$$
$$R_0(w) = R_0(1) - 0.11(w-1) + 0.01(w-1)^2,$$
$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2, \text{ and}$$
$$h_{A_1}(w) = h_{A_1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right],$$
$$\text{with } z \equiv \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}},$$

F. Falk and M. Neubert, Phys. Rev. D 47, 2965 (1993);
M. Neubert, Phys. Rev. D 46, 2212 (1992).

HQET and leading corrections

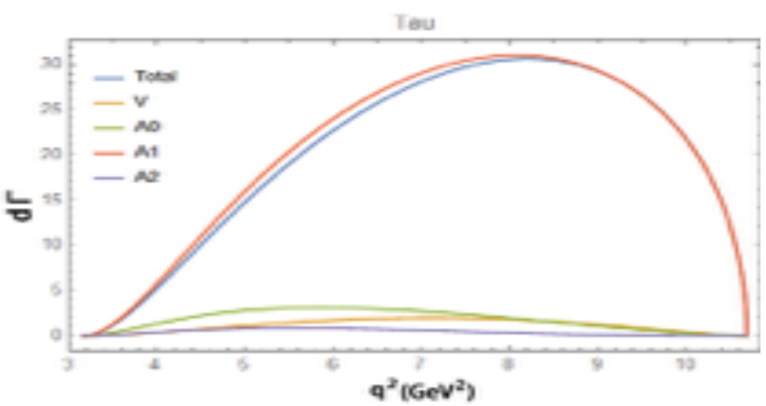
$$\boxed{\frac{R_2(1)(1 - m_{D^*}/m_B) + (m_{D^*}/m_B)\left[R_0(1)(1 + m_{D^*}/m_B) - 2\right]}{(1 - m_{D^*}/m_B)^2} = 0.97}$$

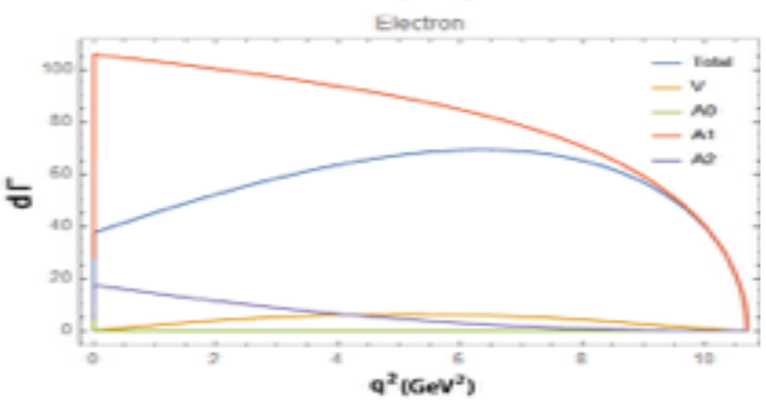
$R_2(1)$ = 0.80 Th.vs $R_2(1)$=0.864 Exp.

0.252 ± 0.003	S. Fajfer, S. et al. PRD 85, 094025 (2012) (CLN)

Corrections from form factors parametrization?

- Form factors are evaluated in different phase space regions.





Form factors contributions to the differential decay width

Including corrections to dispersive bounds on form-factors. Boyd-Grinstein-Lebed (BGL) parametrization *C.G. Boyd, B. Grinstein and R.F. Lebed,, PRD 56 (1997) 6895*

$$\sqrt{M_B M_{D^*}}^{-1}\langle D^*(\varepsilon,p')|V_\mu|B(p)\rangle = \varepsilon_{\mu\nu\rho\sigma}\,\varepsilon^{*\nu}v'^{\rho}v^{\sigma}\,h_V(w),$$

$$\sqrt{M_B M_{D^*}}^{-1}\langle D^*(\varepsilon,p')|A_\mu|B(p)\rangle = -i(w+1)\,\varepsilon^*_\mu\,h_{A_1}(w)+i(\varepsilon^* v)\,v_\mu\,h_{A_2}(w)+i(\varepsilon^* v)\,v'_\mu\,h_{A_3}(w),$$

- Different parametrizations, NLO corrections and theoretical restrictions for the form factors have been studied

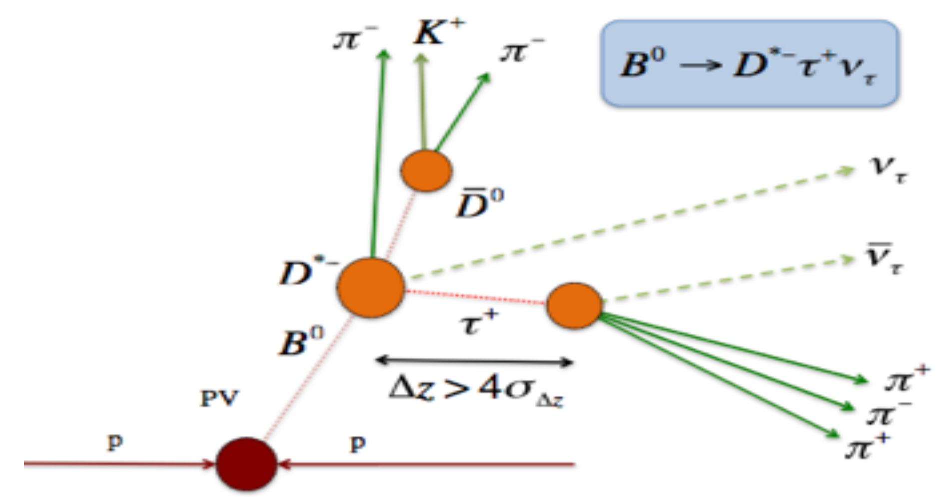
R	
0.260 ± 0.008	Bigi, D. et al. JHEP 11(2017)06 (BGL, LCSR)
0.257 ± 0.003	Berlochner, F. et al. PRD 95, 115008 (2017) newfit, QCDSR
0.259 ± 0.006	Jaiswal, S. et al. JHEP 12 (2017)060 CLN
0.257 ± 0.005	Jaiswal, S. et al. JHEP 12 (2017)060 BGL

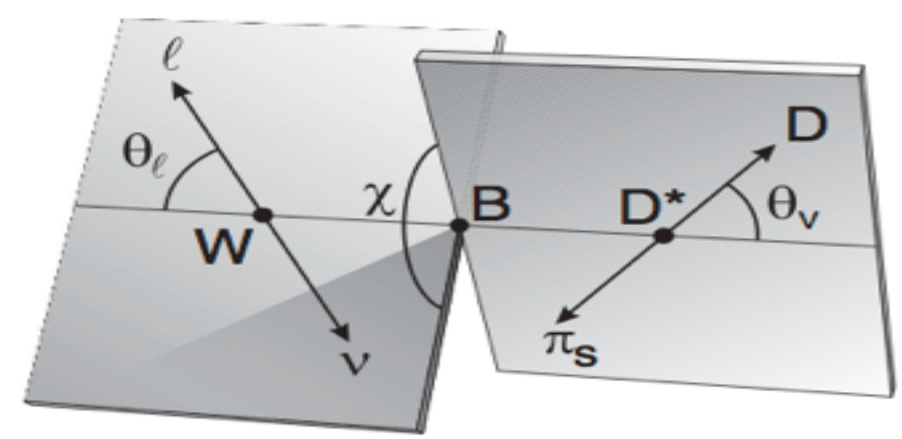
Form factors from Lattice
Kaneko K, JLQCD Coll arXiv: 1811.00794v1 [hep-lat]

0.256 ± 0.020	Gubernari, N. et al. JHEP 01(2019)150 LCSR+Lattice

$B \rightarrow D^* l \nu$ reconstruction

- LHCb
  - Uses Neutral B's (charged D*)
  - D* -> Dπ, $\Delta M = M_{D^*} - M_D < 2$ MeV/c2
  - D -> Kπ,
  - τ, leptonic and hadronic modes (π)
- Belle
  - Uses Neutral and Charged B's
  - D* -> Dπ, Dγ, $\Delta M = M_{D^*} - M_D < 3\ \sigma$
  - D -> Kπ, Kππ
  - τ, leptonic and hadronic modes (π, ρ)
- BaBar
  - Uses Neutral and Charged B's
  - D* -> Dπ, Dγ, $\Delta M = M_{D^*} - M_D < 4\ \sigma$
  - D -> Kπ, Kππ, Kπππ, KKπ…
  - τ, leptonic modes





D* is detected through its daughter particles

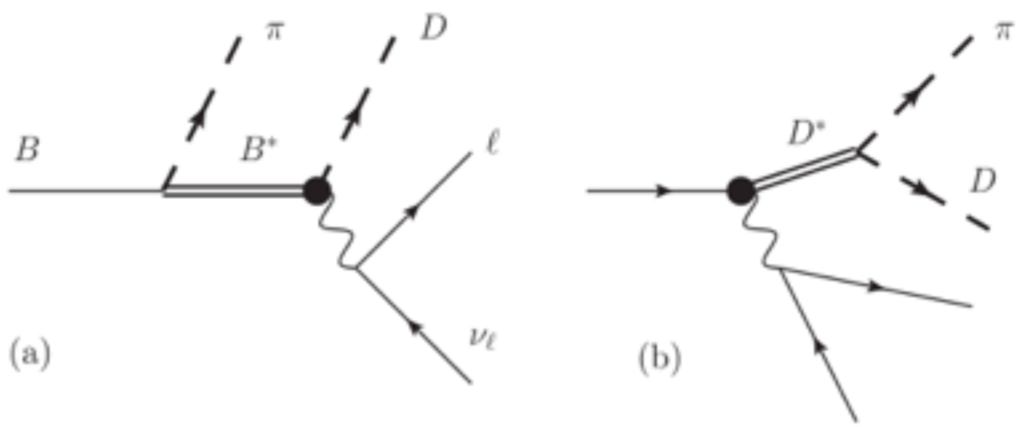
$Br(D^{*+} \to D\pi) = 98\ \%$
$Br(D^{*0} \to D\pi) = 64.7\ \%$
$Br(D^{*0} \to D\gamma) = 35.3\ \%$

M. Tanabashi et al. (PDG) PRD 98, 030001 (2018).

4-body decay Corrections from excited B's intermediate states?

From R_{D^*} to $R_{D\pi}$

$$R_{D\pi} \equiv \frac{BR(B \to \tau \nu_\tau \pi D)}{BR(B \to l \nu_\pi D)}$$



C. S. Kim, et al. PRD 95, 013003 (2017).

Observation of width effects in the D*π system
le Yaouanc et al. arXiv:1806.09853 [hep-ph]

Peter Lichard arXiv:hep-ph/9811493

B* is off-shell. The D* propagator includes a finite width because it can be on-shell.

$$\left[\frac{N_{D^*}^{\nu\beta}(p_1+p_2)}{(p_1+p_2)^2 - m_{D^*}^2 + i m_{D^*}\Gamma_{D^*}}\right]$$

$$N_{V^*}^{\nu\beta}(q) = T_{\nu\beta}(q) + L_{\nu\beta}(q)(m_{V^*}^2 - q^2)/m_{V^*}^2$$

transverse longitudinal

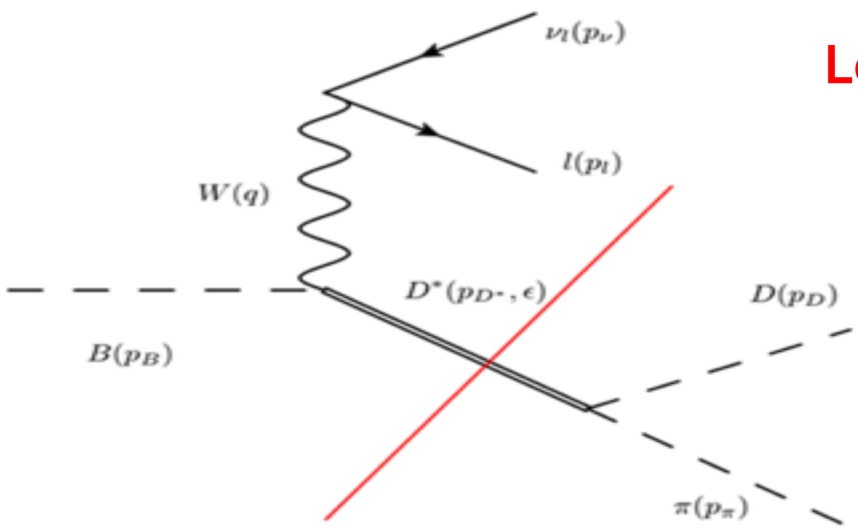
projectors

Interference is null in the narrow width approx. Explored the D-π system around m_{D^*}

0.25 3(2) muon***(e)***	C. S. Kim et al. PRD 95, 013003 (2017) CLN

4-body decay Corrections from D* as intermediate state?

J. E. Chavez-Saab and Genaro Toledo PRD 98, 056014 (2018).



Longitudinal dof, finite decay width, interferences…

$$M = M_{3\mu} D^{\mu\nu} M_{2\nu},$$

$$M_3^\mu = \frac{G_F}{\sqrt{2}} V_{cb} J^{\lambda\mu} l_\lambda$$

$$J^\lambda = J^{\lambda\mu}\, \epsilon_\mu$$

Consider hadronic vertex as in the 3-body decay. Additional structures might be important.

$$M_{2\nu} = -ig(p_D - p_\pi)_\nu$$

2-body decay vertex

$D^{\mu\nu}$ is the D^* propagator

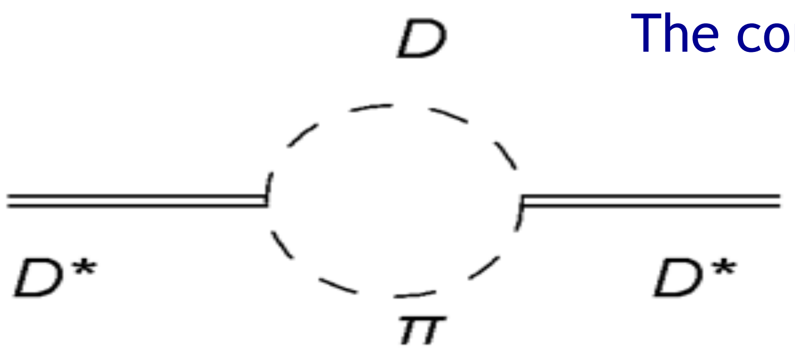
Proper description of unstable states is important. As it may break EM gauge invariance

We describe it in a similar way to the W gauge boson at the one loop level.

U. Baur and D. Zeppenfeld PRL 75(1995)1002; E.N. Argyres et al PLB 358(1995)339; M. Beuthe et al. NPB 498 55(1997)

Absorptive corrections to the propagator

The absorptive contribution due to the bosons in the loop of the propagator and vertex introduces transverse and longitudinal corrections. G.Lopez Castro and GT PRD 61 (00)033007; L.A. Jimenez Pérez and GT JPG 44 125003 (2017)



The corrected propagator, split in Transverse (T) and Longitudinal (L) is:

$$D^{\mu\nu} = \frac{-iT^{\mu\nu}}{p_{D^*}^2 - m_{D^*}^2 + i\mathrm{Im}\Pi_T} + \frac{iL^{\mu\nu}}{m_{D^*}^2 - i\mathrm{Im}\Pi_L},$$

$$T^{\mu\nu} \equiv g^{\mu\nu} - \frac{p_{D^*}^\mu p_{D^*}^\nu}{p_{D^*}^2} \qquad L^{\mu\nu} \equiv \frac{p_{D^*}^\mu p_{D^*}^\nu}{p_{D^*}^2}$$

where the absorptive functions are: $\mathrm{Im}\Pi_T = \sqrt{p_{D^*}^2}\Gamma_{D^*}(p_{D^*}^2)$ introduces the finite decay width

the longitudinal correction $Im\Pi_L = -\frac{g^2\lambda^{1/2}(p_{D^*}^2, m_D^2, m_\pi^2)}{16\pi}\left(\frac{m_D^2 - m_\pi^2}{p_{D^*}^2}\right)^2$

is proportional to $\sim \frac{m_D^2 - m_\pi^2}{m_{D^*}^2}$ $= \Delta^2 = 0.86$

Narrow width approximation

$$|p_{D^*}^2 - m_{D^*}^2 + i m_{D^*}\Gamma(p_{D^*}^2)|^{-2} \approx \frac{\pi}{m_{D^*}\Gamma_{D^*}}\delta(p_{D^*}^2 - m_{D^*}^2)$$

- Transverse $$|M_T|^2 = M_{3\mu}M_{3\alpha}^* T^{\mu\nu}T^{\alpha\beta}M_{2\nu}M_{2\beta}^* \frac{\pi\delta(p_{D^*}^2 - m_{D^*}^2)}{m_{D^*}\Gamma_{D^*}}$$ $$\Gamma_{D^*} \equiv \Gamma_{D^*}(m_{D^*}^2)$$

- Longitudinal $$M_L = igM_{3\mu}\frac{p_{D^*}^\mu}{p_{D^*}^2}\frac{m_D^2 - m_\pi^2}{m_{D^*}^2 - i\mathrm{Im}\Pi_L}$$ $$|M|_L^2 = |M_3^\mu L_{\mu\nu} M_2^\nu|^2 \frac{1}{m_{D^*}^4 + (Im\Pi_L)^2}.$$

- Interference $$\frac{(q^2 - m_{D^*}^2 + i m_{D^*}\Gamma_{D^*})}{m_{D^*}^2 - iIm\Pi_L} T^{\mu_1\nu_1}L_{\mu_2\nu_2}\frac{\pi}{m_{D^*}\Gamma_{D^*}}\delta(q^2 - m_{D^*}^2)$$

The interference between T and L may be relevant. Not considered in earlier calculations of $R_{D\pi}$

We explored the longitudinal contribution around

$$(p_D + p_\pi)^2 = (m_{D^*} \pm \delta)^2 \qquad \delta \text{ is in the range } \Gamma_{D^*}/2 \text{ to } 1 \text{ MeV.}$$

for $R_{D\pi}$

We reported *PRD 98, 056014 (2018).* $(\delta = \Gamma_{D^*})$,

Br (in %)	Transversal	Longitudinal	Interference
Electron	4.6(3)	$5.0(3) \times 10^{-6}$	$7.6(6) \times 10^{-8}$
Muon	4.6(3)	$5.0(3) \times 10^{-6}$	$1.6(1) \times 10^{-3}$
Tau	1.16(8)	$1.1(6) \times 10^{-6}$	$1.02(7) \times 10^{-1}$
$R^e_{D\pi}$	0.252	0.252	0.274 (3)
$R^\mu_{D\pi}$	0.252	0.252	0.275 (3)

$R_{D\pi}$ values as each contribution is added from left to right.

Independent of the value of δ < 1 MeV at the current precision.

Errata

Bug found in the transcription to integration code

$\boxed{R_{D\pi}=0.253 \pm 0.003}$

Other corrections?

Corrections from excited Charmed mesons?

we also explored the scalar D*(2400) contribution. The interference effect is negligible in $R_{D\pi}$

Information on the scalar contributions
K. Abe, et al. Belle Collaboration PRD 69, 112002 (2004)
Bernlochner F. et al. PRD 95 014022(2017)
Celis, A. et al. PLB 771 (2017) 168.

Radiative corrections?

- Radiative corrections may be important when measurements at the few percent level become available

Tostado, S. L., et al. EPJC (2016) 76:495
Stefan de Boer PRL 120 261804(2018)

R_{D^*} SM prediction

R	Reference
0.259 ± 0.006	Jaiswal, S. et al. JHEP 12 (2017)060 CLN
0.260 ± 0.008	Bigi, D. et al. JHEP 11(2017)06 (BGL, LCSR)
0.257 ± 0.003	Berlochner, F. et al. PRD 95, 115008 (2017) newfit, QCDSR
0.257 ± 0.005	Jaiswal, S. et al. JHEP 12 (2017)060 BGL
0.256 ± 0.020	Gubernari, N. et al. JHEP 01(2019)150 LCSR+Lattice
0.252	Chuan -Hung, C. et al. JHEP 10(2006) 053 (LFQM)
0.252 ± 0.003	S. Fajfer, S. et al. PRD 85, 094025 (2012) (CLN)
R	
0.253	C. S. Kim et al. PRD 95, 013003 (2017) CLN
0.253 ± 0.003	This work, J. Chavez-Saab, M. Sánchez and G. Toledo, CLN. Corrected

$R_{D^*}^{SM} = 0.258 \pm 0.01$

Taking these values for the exp. average and SM prediction
the discrepancy is about 3.7 σ

Experimental Average **HFLAV**	0.306	± 0.013	± 0.007

Conclusions

- By considering $R_{D\pi}$, the SM model prediction is found to be consistent with R_{D^*} estimates when including intermediate states.

- The SM prediction could be refined further with a more careful analysis of the BD*W vertex.
  - τ data could provide a better approximation of A0
  - form factors parametrizations and HQET assumptions.

- Correlations with other observables and implications on scenarios for new physics may provided hints on remaining discrepancies.
  - see David Straub talk

Measurement of R(D) and R(D*) with a semileptonic tag at Belle

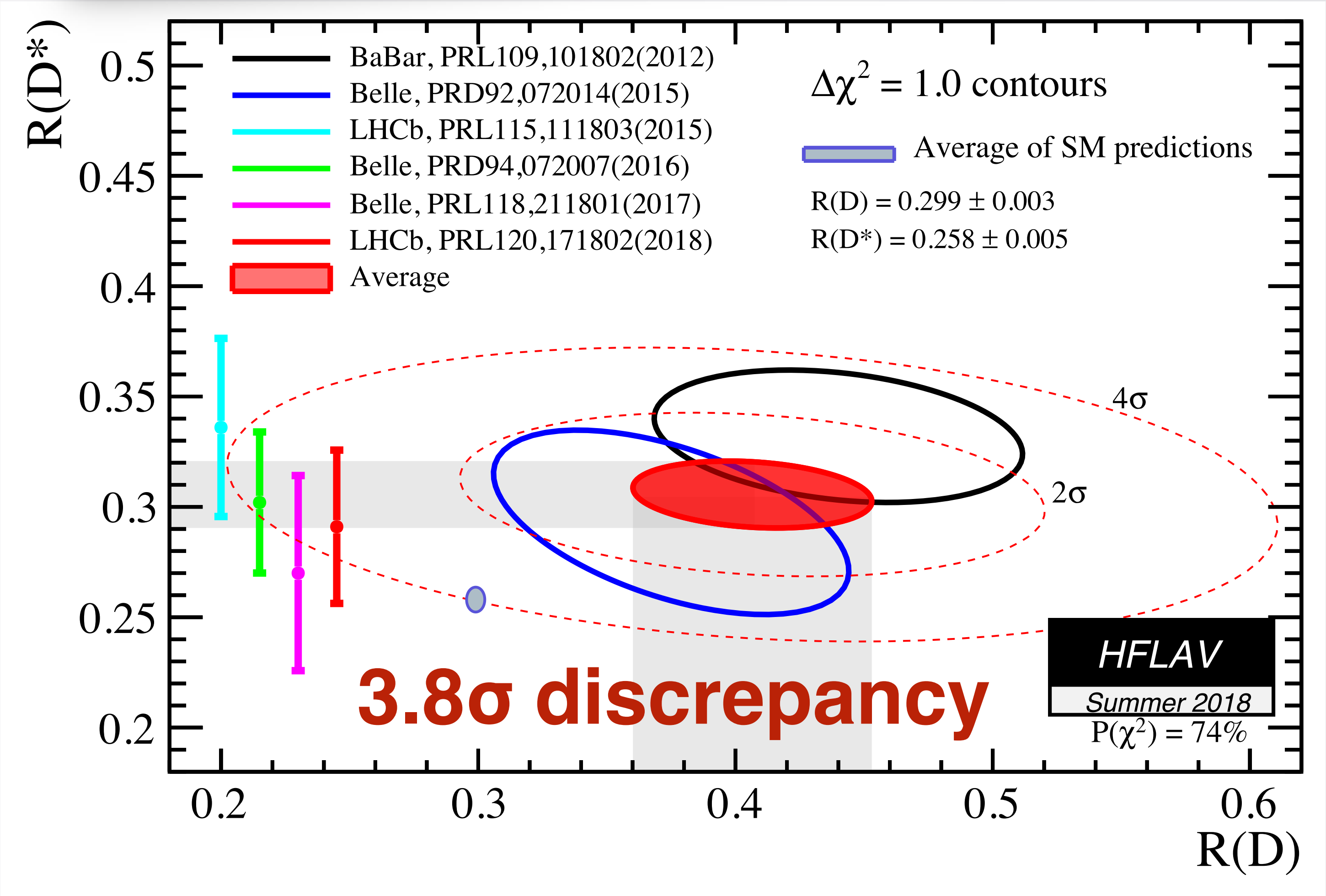
Giacomo Caria
on behalf of the Belle collaboration

54th Rencontres de Moriond, EW
22/03/2019

BELLE

THE UNIVERSITY OF MELBOURNE

The R(D) and R(D*) puzzles



$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+\ell^-\bar{\nu}_\ell)}$$

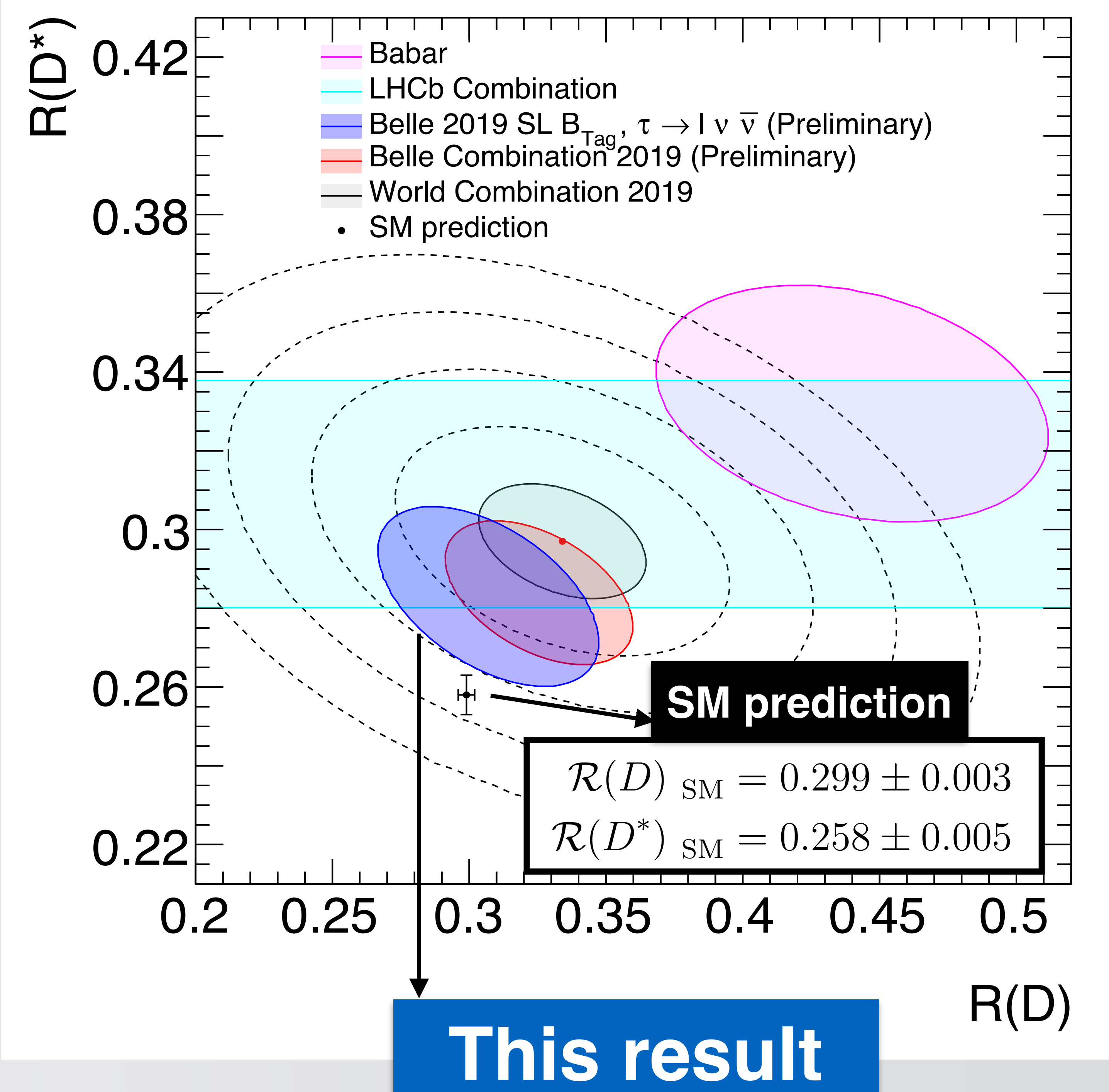
$$R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell)}$$

where ℓ = e,μ

Experiment	Tag method	τ mode	R(D)	R(D*)
Babar '12	Hadronic	ℓ ν ν	**0.440 ± 0.058 ± 0.042**	0.332 ± 0.024 ± 0.018
Belle '15	Hadronic	ℓ ν ν	**0.375 ± 0.064 ± 0.026**	0.293 ± 0.038 ± 0.015
LHCb '15	-	ℓ ν ν	-	0.336 ± 0.027 ± 0.030
Belle '16	**Semileptonic**	ℓ ν ν	-	0.302 ± 0.030 ± 0.011
Belle '17	Hadronic	π ν, ρ ν	-	0.270 ± 0.035 ± 0.027
LHCb '18	-	π π π	-	0.291 ± 0.019 ± 0.029
Average	-	-	**0.407 ± 0.039 ± 0.024**	0.306 ± 0.013 ± 0.007
SM			**0.299 ± 0.003**	0.258 ± 0.005

Conclusion / Preliminary $R(D^{(*)})$ averages

- **Most precise measurement** of R(D) and R(D*) to date
- First **R(D)** measurement performed with a **semileptonic tag**
- Results **compatible with SM** expectation within **1.2σ**
- **R(D) - R(D*) Belle average** is now within **2σ** of the SM prediction
- **R(D) - R(D*) exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**



$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

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Search for B $\rightarrow \ell\nu\gamma$ and B $\rightarrow \mu\nu_\mu$ and Test of Lepton Universality with R(K*) at Belle

Moriond EW 2019

Markus Prim for the Belle Collaboration | 22nd March 2019

INSTITUT FÜR EXPERIMENTELLE TEILCHENPHYSIK (ETP)

$R(K^*)$

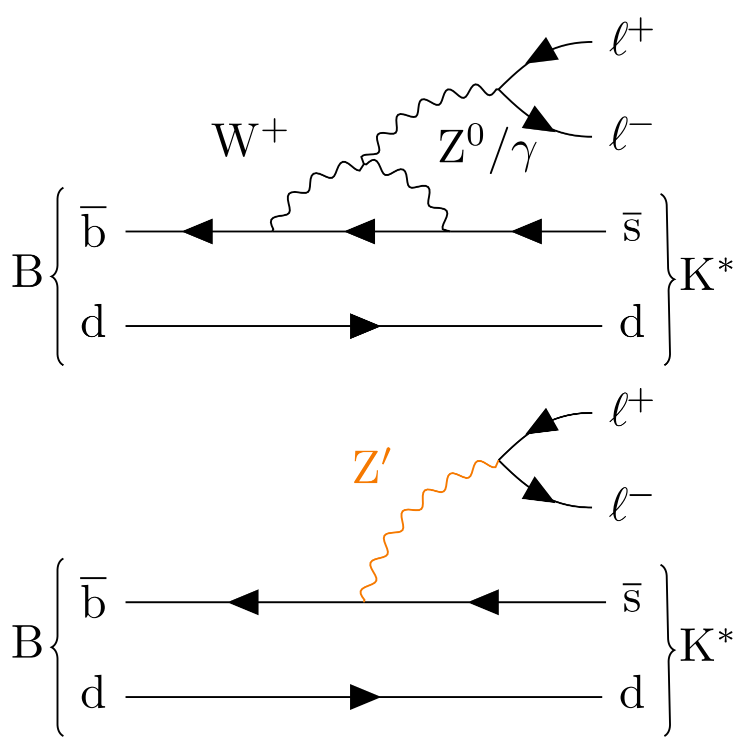
- Test of lepton flavor universality via:

$$R_{K^*} = \frac{\mathcal{B}(B \to K^* \mu^+ \mu^-)}{\mathcal{B}(B \to K^* e^+ e^-)} \approx 1$$

- Clean theoretical predictions.
- Currently $\mathcal{O}(2.3\sigma)$ tension.
- New physics can change this ratio.
- Decay modes used in this analysis:

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

$$K^{*0} \to K^+ \pi^-$$
$$K^{*+} \to K^+ \pi^0$$
$$K^{*+} \to K^0_S \pi^+$$



$R(K^*)$: (Preliminary) Result

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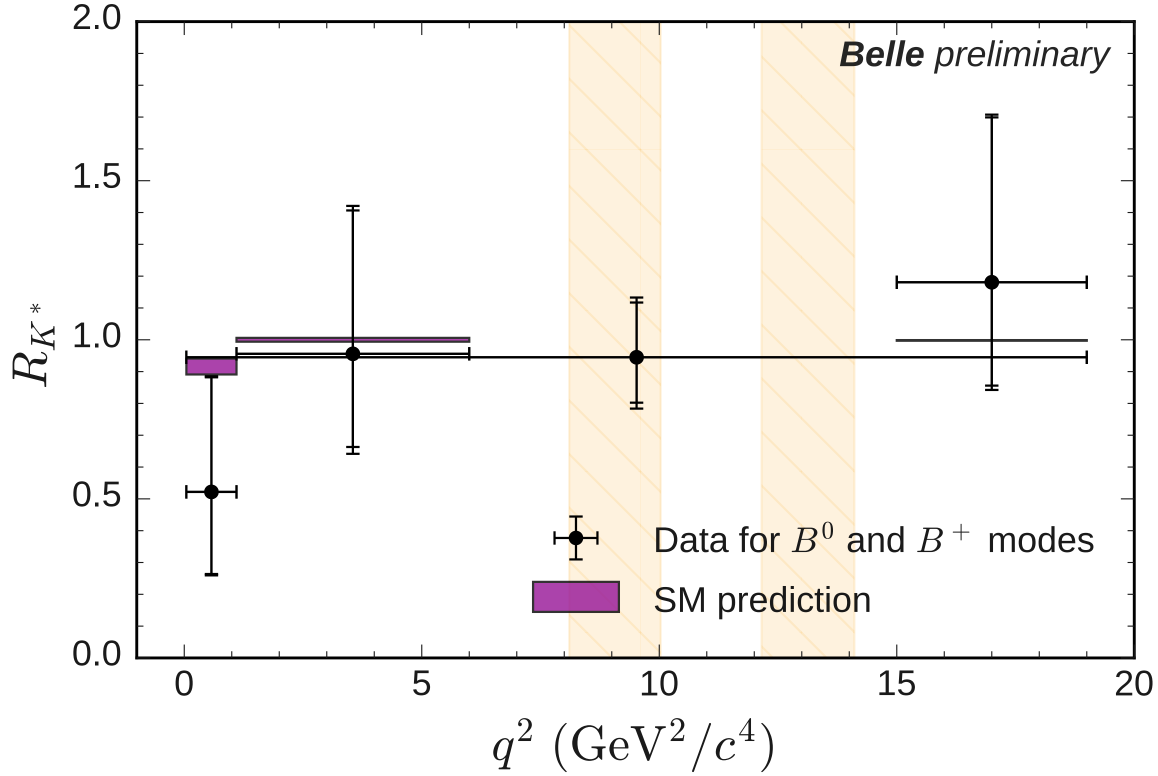

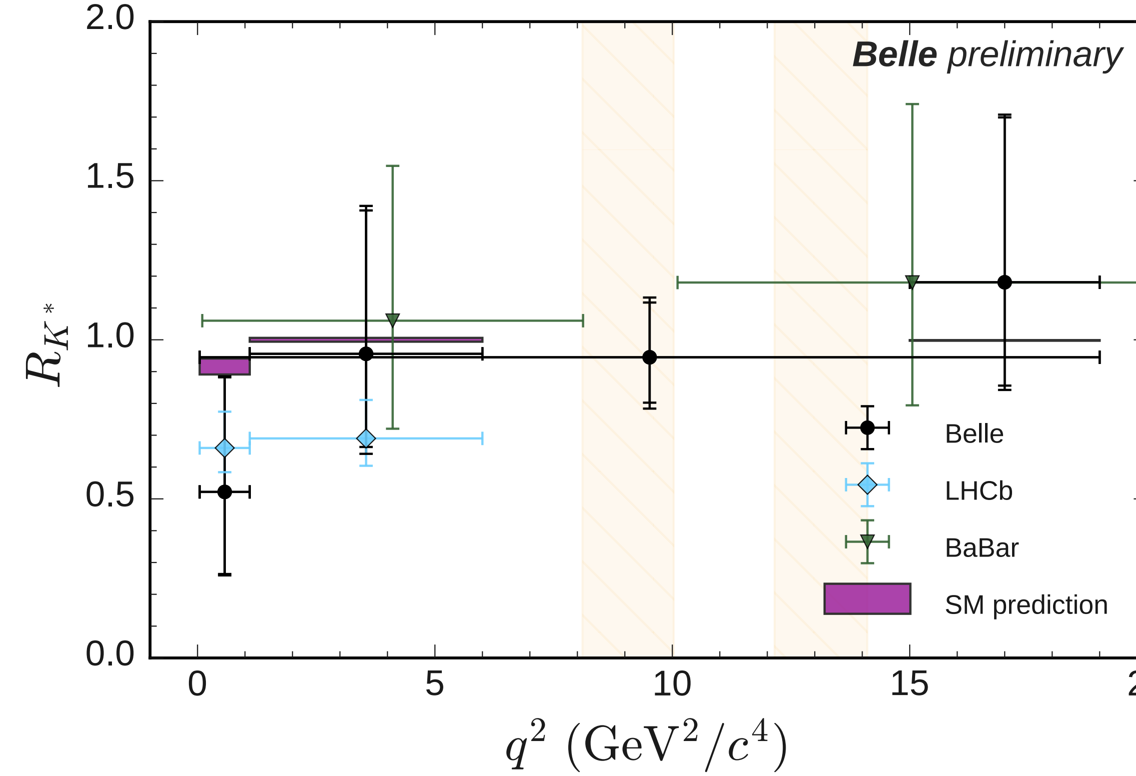

q^2 in GeV^2/c^4	All modes	B^0 modes	B^+ modes
[0.045, 1.1]	$0.52^{+0.36}_{-0.26} \pm 0.05$	$0.46^{+0.55}_{-0.27} \pm 0.07$	$0.62^{+0.60}_{-0.36} \pm 0.10$
[1.1, 6]	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.18$
[0.1, 8]	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.08$	$0.96^{+0.56}_{-0.35} \pm 0.14$
[15, 19]	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
[0.045,]	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.07$

- All measured values are in accordance with the SM and other recent measurements.
- First measurement of R(K^{*+}).