Karlsruhe Institute of Technology

BELLE

Lepton Universality Violations in b $\rightarrow$ c Transitions

15th Recontres du Vietnam - 3 Neutrinos and Beyond

Markus Prim for the Belle Collaboration | 9th August 2019

INSTITUT FÜR EXPERIMENTELLE TEILCHENPHYSIK (ETP)

Lepton Flavor Universality in the Standard Model

- Leptons appear in the SM in the gauge and Yukawa sector.

Gauge sector

- $\mathcal{L}_{\text{SM}}^{\text{Gauge}} \subset i\left(\bar{L}_{\text{L}}^{i}\gamma^{\mu}D_{\mu}L_{\text{L}}^{i} + \bar{E}_{\text{R}}^{i}\gamma^{\mu}D_{\mu}E_{\text{R}}^{i}\right)$
- Gauge interactions are Lepton Flavor Universal

Yukawa sector

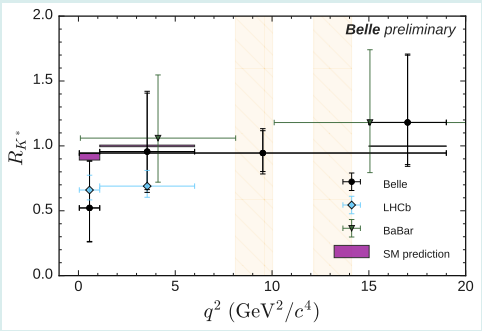
- $\mathcal{L}_{\text{SM}}^{\text{Yukawa}} \subset \left(Y_{ij}^{E}\bar{L}_{\text{L}}^{i}E_{\text{R}}^{j}H + \text{h.c.}\right)$
- Yukawa sector non-universal because of mass terms $m_e \neq m_\mu \neq m_\tau$ and Higgs interactions (negligible).

Testing the LFU in the Standard Model means testing the universality of the gauge interaction.

Lepton Flavor Universality Violation

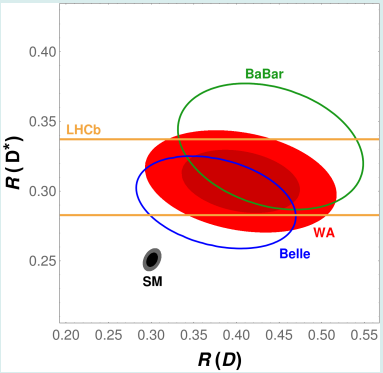
$b \to s\ell\ell$

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



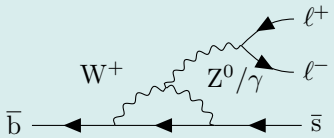
$b \to c\ell\nu$

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



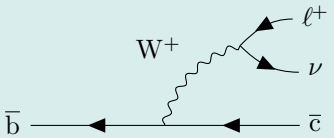
Lepton Flavor Universality Violation

$b \to s\ell\ell$



- neutral current (FCNC)
- Loop process in SM
- $\mu\mu$ vs. ee

$b \to c\ell\nu$



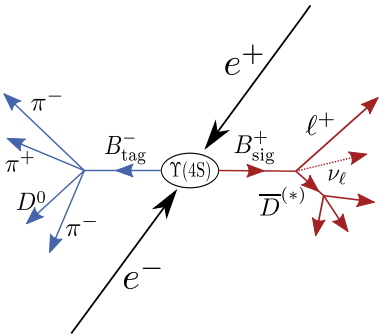
- charged current
- Tree level process in SM
- τ vs. $\ell = e, \mu$

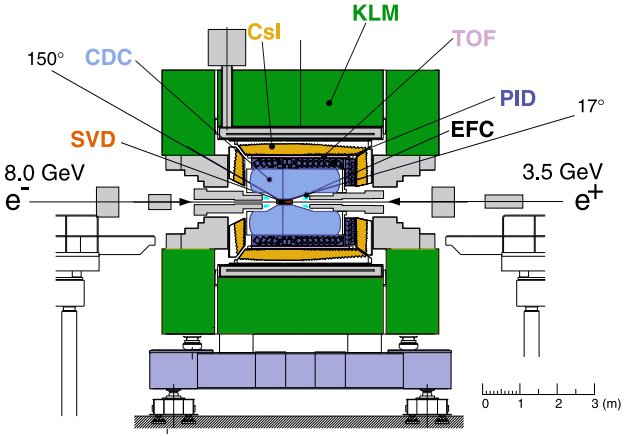
Today

Belle's latest R($D^{(*)}$)

arXiv:1904.08794

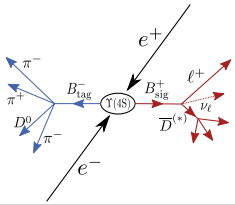
The Belle Experiment





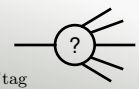
Belle recorded 711 fb^{-1} on the $\Upsilon(4S)$ resonance.

B-Tagging at Belle

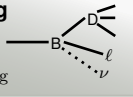


Efficiency ϵ

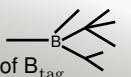
Inclusive Tag
$\epsilon = \mathcal{O}(100)\%$
Consistency of B_{tag}



Semileptonic Tag
$\epsilon = \mathcal{O}(1)\%$
Knowledge of B_{tag}



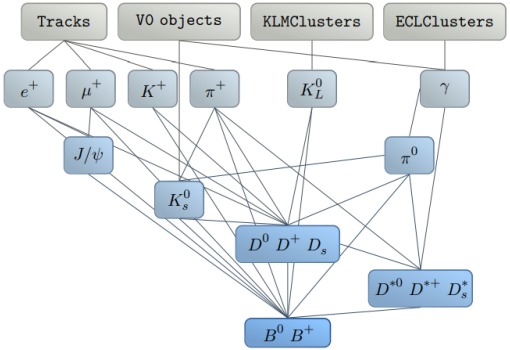
Hadronic Tag
$\epsilon = \mathcal{O}(0.1)\%$
Exact knowledge of B_{tag}



Purity

Exclusive Tagging: The Full Event Interpretation (FEI)

Keck, T., et al. Comput Softw Big Sci (2019)



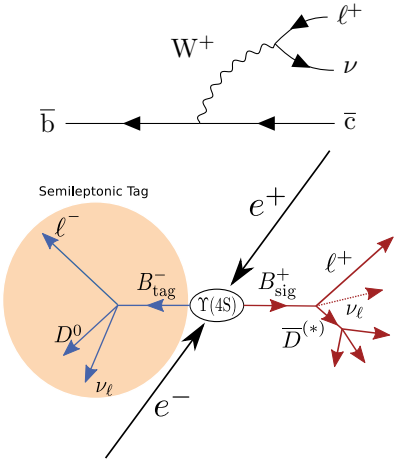
Automatic reconstruction of $\mathcal{O}(100)$ explicit decay channels, leading to $\mathcal{O}(10000)$ distinct decay chains.

Tag-Side Reconstruction and Selection

- B_{tag} is reconstructed in $D\ell\nu$ and $D^*\ell\nu$ decay chains (semileptonic tag).
- Good tags identified by classifier output.
- Veto for $B \to D^*\tau(\to \ell\nu\nu)\nu$ via

$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\text{beam}}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2}{2|\vec{p}_B||\vec{p}_{D^{(*)}\ell}|}.$$

- Correctly reconstructed B candidates are found in $\cos\theta_{B,D^{(*)}\ell} = [-1, 1]$.
- Mis-reconstructed $B \to D^*\tau(\to \ell\nu\nu)\nu$ decays have larger negative values.



Signal-Side Reconstruction and Selection

- Only consider $\tau \to \ell\nu\nu$.
- $D^{(*)}$ selection via reconstructed invariant mass and vertex fit (for channels without π^0).

$D^0 \to$	$\mathcal{B}$ (%)
$K^-\pi^+\pi^0$	14.4
$K^-\pi^+\pi^+\pi^-$	8.23
$K^-\pi^+$	3.95
$K^0_S\pi^+\pi^-$	2.80
$K^0_S\pi^0$	1.24
$K^0_S K^+ K^-$	4.42
K^+K^-	0.41
$\pi^+\pi^-$	0.15
Total	35.59

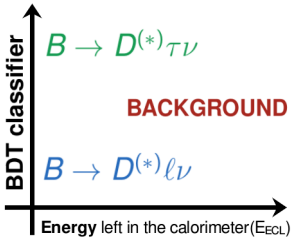
$D^+ \to$	$\mathcal{B}$ (%)
$K^-\pi^+\pi^+$	9.38
$K^0_S\pi^+\pi^0$	7.36
$K^0_S\pi^+\pi^+\pi^-$	6.25
$K^0_S\pi^+$	1.56
$K^-K^+\pi^+$	0.99
$K^0_S K^+$	0.30
Total	25.84

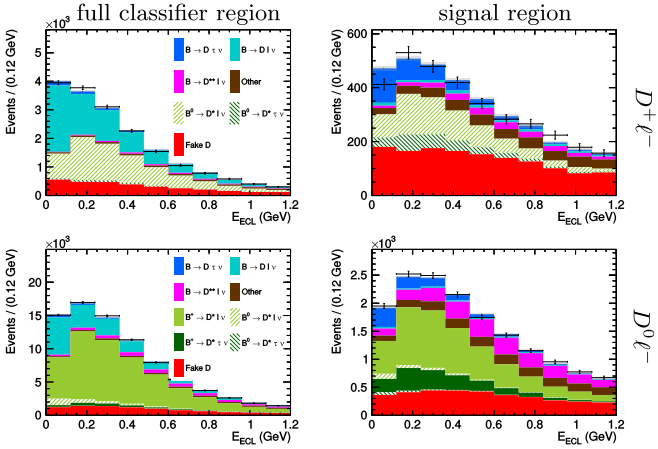
$D^{*+} \to$	$\mathcal{B}$ (%)
$D^0\pi^+$	67.7
$D^+\pi^0$	30.7
Total	98.4

$D^{*0} \to$	$\mathcal{B}$ (%)
$D^0\pi^0$	64.7
Total	64.7

Signal Extraction

- Signal extraction in a 2D plane:
- E_{ECL}
- $\mathcal{C}_{\mathrm{out}}$: BDT which discriminates between τ and ℓ mode. Input: $\cos\theta_{\mathrm{B,D}^{(*)}\ell}$, m^2_{miss}, E_{visible}





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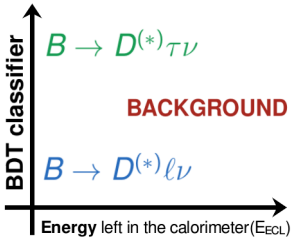
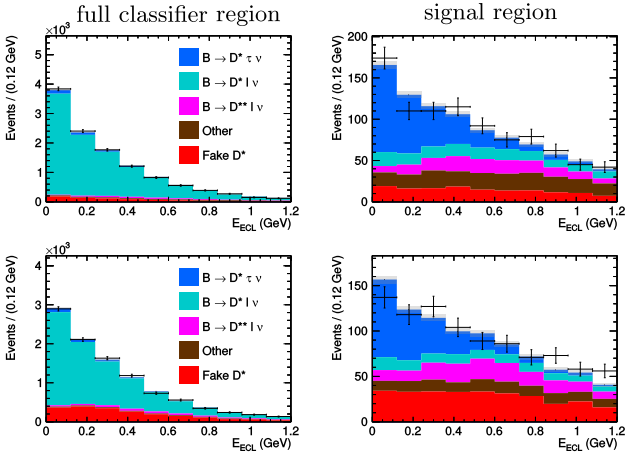




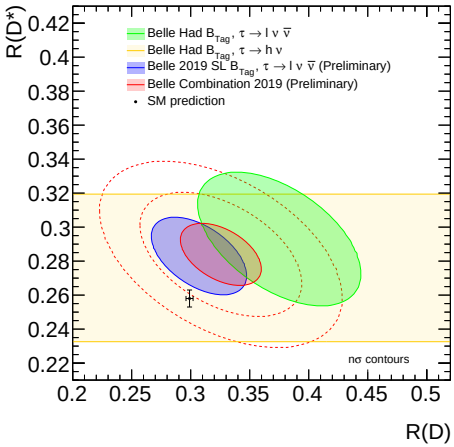
Systematics

Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)
D^{**} composition	0.76	1.41
Fake $D^{(*)}$ calibration	0.19	0.11
$W\mathrm{B}_{\mathrm{tag}}$ calibration	0.07	0.05
Feed-down factors	1.69	0.44
Efficiency factors	1.93	4.12
Lepton efficiency and fake rate	0.36	0.33
Slow pion efficiency	0.08	0.08
MC statistics	4.39	2.25
B decay form factors	0.55	0.28
Luminosity	0.10	0.04
$\mathcal{B}(B \to D^{(*)}\ell\nu)$	0.05	0.02
$\mathcal{B}(D)$	0.35	0.13
$\mathcal{B}(D^*)$	0.04	0.02
$\mathcal{B}(\tau \to \ell\nu\nu)$	0.15	0.14
Total	5.21	4.94

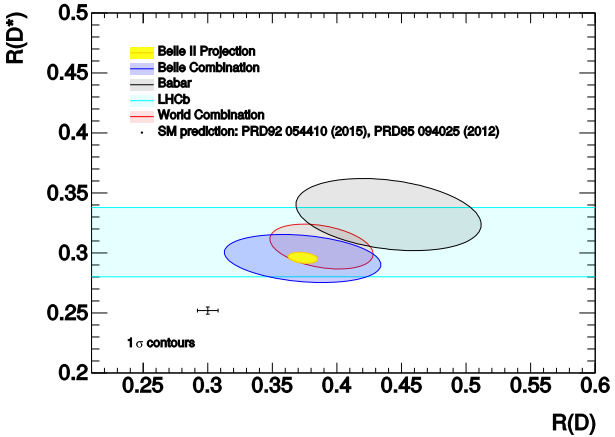
Results

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

- SM agreement: $1.2\,\sigma$.
- **First result for $\mathcal{R}(D)$ with semileptonic tagging.**
- **Most precise determination of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ to date.**



A Glimpse into the Future



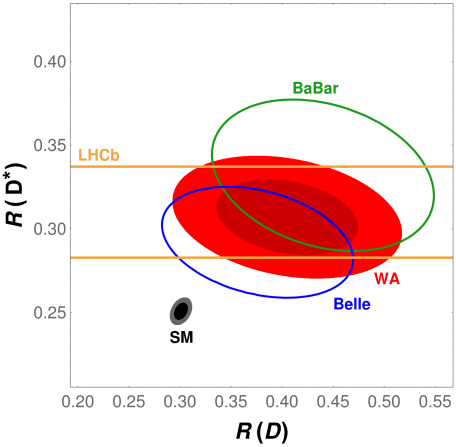
Belle II will pin down the flavor anomaly.

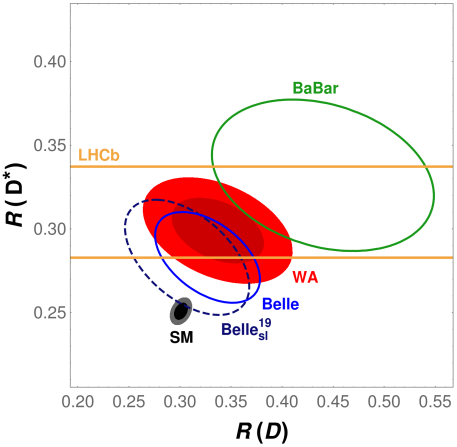
(Projection with old world average arXiv:1808.10567)

Theory Perspective to R($D^{(*)}$)

Excerpt of arXiv:1904.09311

New World Average





Effective Hamiltonian for $b \to c\ell\nu$ Transitions

$$\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + \mathcal{C}_{V_L}) \mathcal{O}_{V_L} + \mathcal{C}_{V_R} \mathcal{O}_{V_R} + \mathcal{C}_{S_R} \mathcal{O}_{S_R} + \mathcal{C}_{S_L} \mathcal{O}_{S_L} + \mathcal{C}_T \mathcal{O}_T \right] + \text{h.c.}$$

with the Fermi operators $\mathcal{O}_i$

$$\mathcal{O}_{V_{L,R}} = (\bar{c}\gamma^\mu b_{L,R}) (\bar{\ell}_L \gamma_\mu \nu_L), \quad \mathcal{O}_{S_{L,R}} = (\bar{c} b_{L,R}) (\bar{\ell}_R \nu_L), \quad \mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} b_L) (\bar{\ell}_R \sigma_{\mu\nu} \nu_L)$$

weighted by the Wilson coefficients $\mathcal{C}_i$, with

$$\mathcal{C}_{V_L}^{SM} = \mathcal{C}_{V_R}^{SM} = \mathcal{C}_{S_R}^{SM} = \mathcal{C}_{S_L}^{SM} = \mathcal{C}_T^{SM} = 0$$

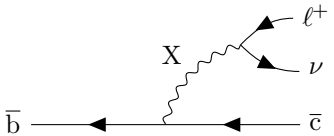
Assumptions:

- No light right-handed neutrinos.
- Possible NP contribution only in third generation of leptons.
- $\mathcal{C}_{V_R}$ are lepton-flavor universal.
- CP-conserving limit, i.e. Wilson coefficients are real.

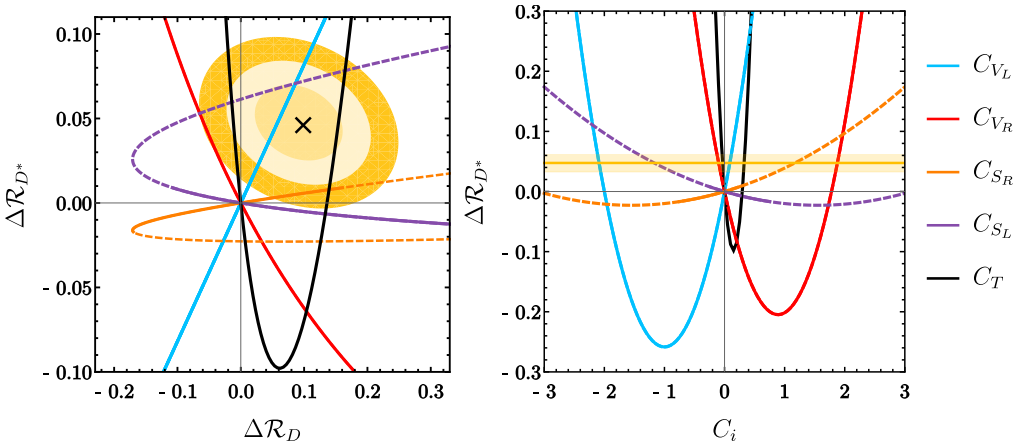
New Physics Scenarios

- NP models are usually include combinations of NP operators:

$$
\begin{aligned}
\mathrm{W}' &\to \mathcal{C}_{\mathrm{V_L}} \\
\mathrm{H}^- &\to \mathcal{C}_{\mathrm{S_L}}, \mathcal{C}_{\mathrm{S_R}}, \mathcal{C}_{\mathrm{T}} \\
\phi_{\mathrm{LQ}} &\to \mathcal{C}_{\mathrm{V_L}}, \mathcal{C}_{\mathrm{V_R}}, \mathcal{C}_{\mathrm{T}} \\
V^{\mu}_{\mathrm{LQ}} &\to \mathcal{C}_{\mathrm{V_L}}, \mathcal{C}_{\mathrm{S_R}}
\end{aligned}
$$

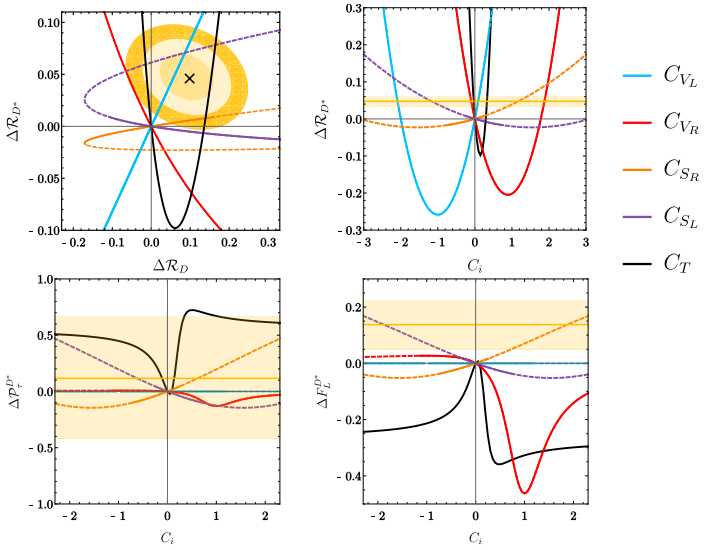


New Physics Influence on $\mathcal{R}(D^{(*)})$



(With old world average)

New Physics Influence on $\mathcal{R}(D^{(*)})$



- dashed line parts excluded by $\mathcal{B}(\mathrm{B_c^+} \to \tau\nu) < 10\,\%$
- caveat: acceptance and efficiency effects of NP not included in these scans

(With old world average)

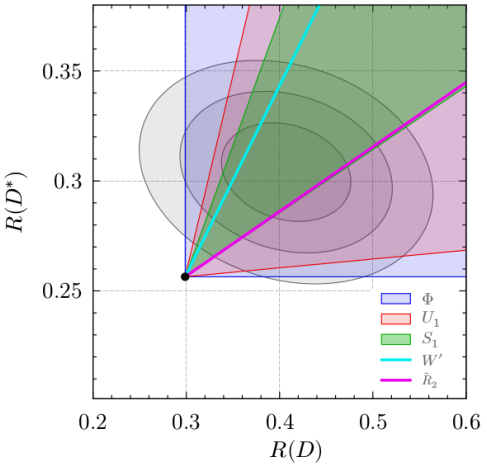
Theory Perspective to $R(D^{(*)})$ with Right-Handed Neutrinos

Excerpt of JHEP 1902 (2019) 119

Models and Their Influence

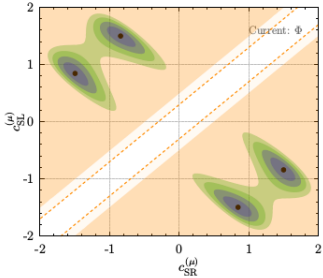
- New contribution from $b \to c\tau N_R$.
- EFT study of the lowest dimension electroweak operators that can account for the $\mathcal{R}(D^{(*)})$ anomalies.
- Models with tree-level mediator exchange:

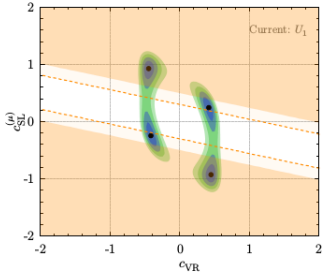
mediator	WCs
W'_μ	c_{VR}
Φ	$c_{\mathrm{SL}}(\mu), \quad c_{\mathrm{SR}}(\mu)$
U_1^μ	$c_{\mathrm{SL}}(\mu), \quad c_{\mathrm{VR}}$
$\tilde{R}_2$	$c_{\mathrm{SR}}(\mu) = 4r c_{\mathrm{T}}(\mu)$
S_1	$c_{\mathrm{VR}},\ c_{\mathrm{SR}}(\mu) = -4r c_{\mathrm{T}}(\mu)$

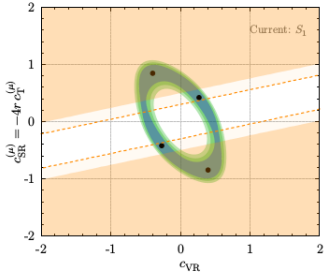


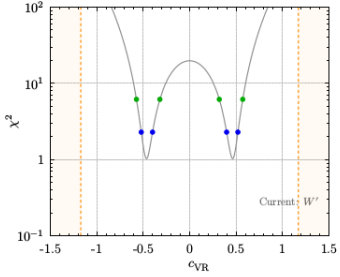
(With old world average.)

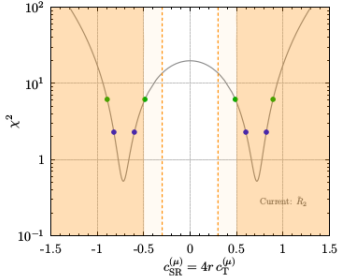
Best-Fit Points









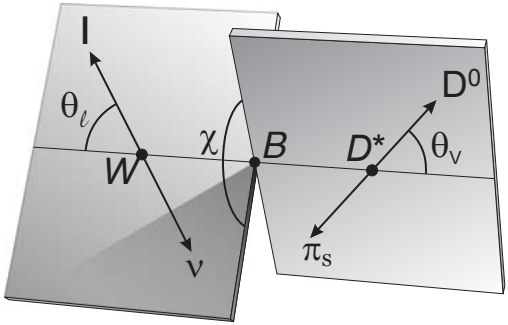


Belle's latest $B \to D^* \ell \nu$

arXiv:1809.03290 accepted by PRD

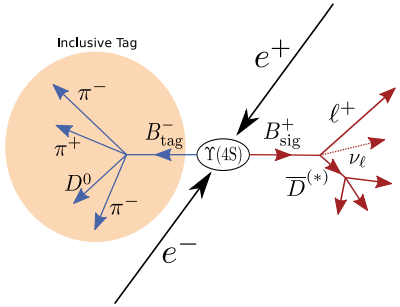
Motivation

- What if NP not only in $b \to c\tau\nu$ transitions?
- Investigate NP in the normalization mode of $\mathcal{R}(D^{(*)})$ analysis: $b \to c\ell\nu$.
- Angular observables are a powerful tool.
- Nota Bene: Presented Analysis is focused on V_{cb} extraction.



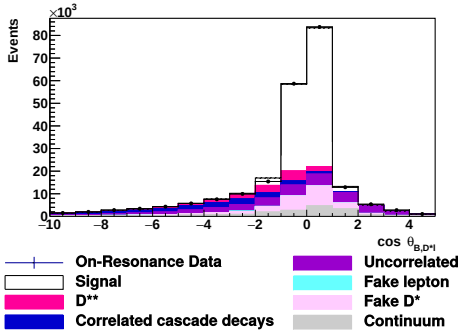
Event Reconstruction

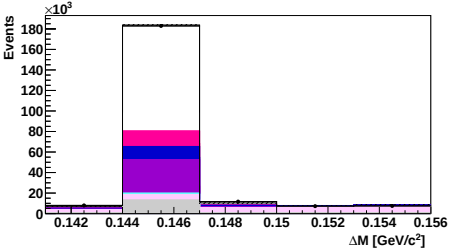
- In comparison to $\mathcal{R}(D^{(*)})$, no tag-side reconstruction.
- $\mathrm{B}_{\mathrm{tag}}$-momentum reconstructed via $\vec{p}_{\mathrm{incl.}} = \sum_i^{p_i}$.
  $\Rightarrow \vec{p}_{\mathrm{B_{sig}}} = -\vec{p}_{\mathrm{incl.}}$.
- Signal-side only reconstructed in cleanest mode:
  $\mathrm{B}^0 \to \mathrm{D}^{*-}(\to \overline{\mathrm{D}}^0(\to \mathrm{K}^+\pi^-)\pi^-)\ell\nu$
- $\mathcal{B} \approx 5\% \times 68\% \times 4\% \approx 0.14\%$

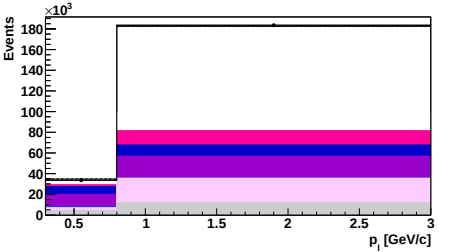


Background Estimation

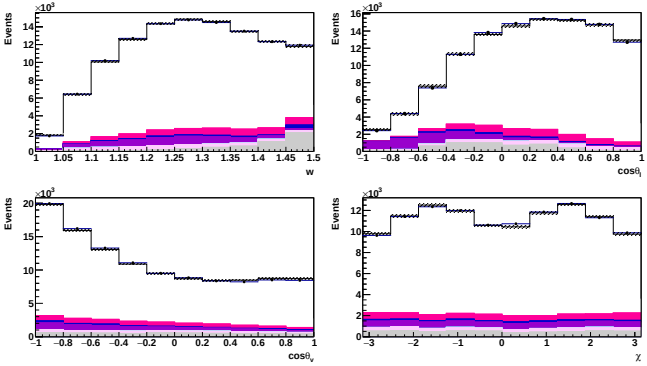
- $\cos\theta_{\mathrm{B,D}^*\ell} = \dfrac{2E_{\mathrm{beam}}E_{\mathrm{D}^*\ell} - m_{\mathrm{B}}^2 - m_{\mathrm{D}^*\ell}^2}{2|\vec{p}_{\mathrm{B}}||\vec{p}_{\mathrm{D}^*\ell}|}$
- $\Delta M = m_{\mathrm{D}^*} - m_{\mathrm{D}}$
- p_ℓ

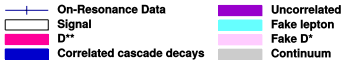


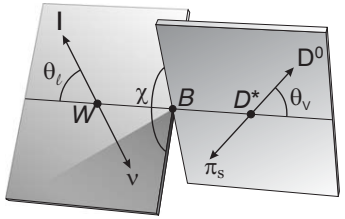




Differential Distributions

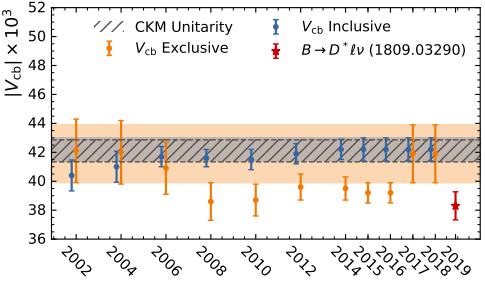






Results

$$V_{cb}^{CLN} = (38.4 \pm 0.2 \pm 0.6 \pm 0.6) \times 10^{-3}$$
$$V_{cb}^{BGL} = (38.3 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3}$$



Tension on V_{cb} between inclusive and exclusive determination is back.

$$\frac{\mathcal{B}(B^0 \to D^{*-} e^+ \nu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu)} = 1.01 \pm 0.01 \pm 0.03\,.$$

- Systematic uncertainty dominated by lepton identification.

Most stringent test of LFU in B decays to date.

Summary

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- Two new important results on LFU: τ vs. ℓ and e vs. μ in b $\to$ c$\ell\nu$ transitions.
- Tension on $\mathcal{R}(D^{(*)})$ reduced with new measurement.
- Belle's new analyses (will) have an important impact on the current (global) fits on LFU.
- Belle II will give a final answer on the $\mathcal{R}(D^{(*)})$ anomaly.
- There is an interplay between flavor anomalies and neutrino physics.