Belle status and Belle II prospect for $B \to D^{(*)}\tau\nu$ and related topics

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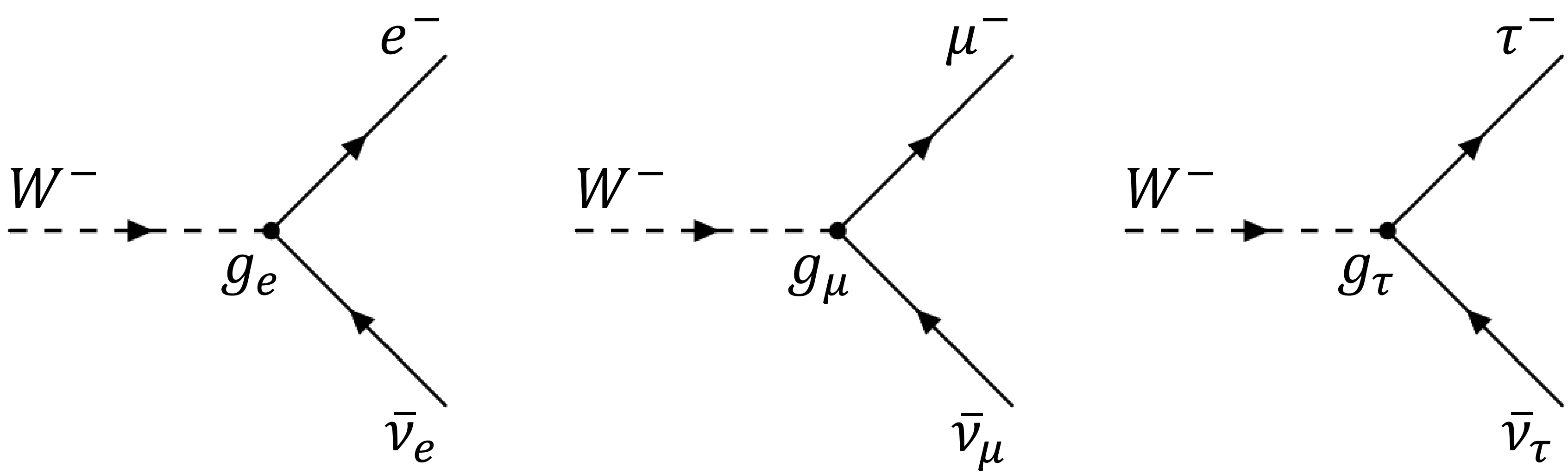
Nov. 15, 2018

WPI-next Mini-workshop
"Hints for New Physics in Heavy Flavors"

Lepton flavor universality

- In the Standard Model, the electroweak couplings between leptons and gauge bosons do not depend on the lepton flavor.
  - The difference of the branching fraction comes from the difference of the mass, i.e. helicity suppression and phase space.



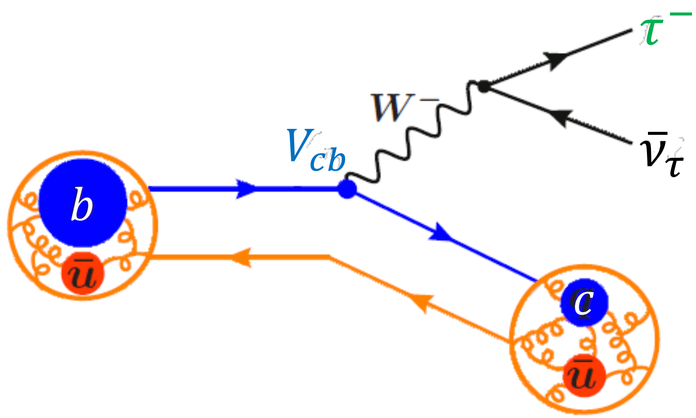
$$g_e = g_\mu = g_\tau$$

Tests of lepton flavor universality

- Decays of W/Z bosons
  - $\frac{\Gamma_{\mu\mu}}{\Gamma_{ee}} \equiv \frac{\mathcal{B}(Z\to\mu^+\mu^-)}{\mathcal{B}(Z\to e^+e^-)}$, $\frac{\Gamma_{\tau\tau}}{\Gamma_{ee}} \equiv \frac{\mathcal{B}(Z\to\tau^+\tau^-)}{\mathcal{B}(Z\to e^+e^-)}$ by LEP [Phys. Rep. 427 (2006) 257]
  - $R_Z \equiv \frac{\sigma_Z\cdot\mathcal{B}(Z\to e^+e^-)}{\sigma_Z\cdot\mathcal{B}(Z\to\mu^+\mu^-)}$, $R_W \equiv \frac{\sigma_{W^\pm}\cdot\mathcal{B}(W^\pm\to e\nu)}{\sigma_{W^\pm}\cdot\mathcal{B}(W^\pm\to\mu\nu)}$ by ATLAS [Phys. Rev. D85, 072004 (2012)]
  - $\mathcal{B}\,(W \to \ell\nu)$ $(\ell = e, \mu, \tau)$ by LEP [Phys. Rep. 532 (2013) 119]
  - $\frac{\mathcal{B}(W\to e\nu)}{\mathcal{B}(W\to\mu\nu)}$ by CDF,D0, LEP, ATLAS, LHCb [JHEP 10 (2016) 030]
- Decays of leptons
  - (g_τ/g_μ), (g_τ/g_e), (g_μ/g_e) from $\Gamma(\tau \to \mu\nu\nu)$, $\Gamma(\tau \to e\nu\nu)$, $\Gamma(\mu \to e\nu\nu)$
  - $(g_\tau/g_\mu)_\pi$, $(g_\tau/g_\mu)_K$ from $\frac{\Gamma(\tau\to h\nu)}{\Gamma(h\to\mu\nu)}$, $\frac{\Gamma(\tau\to h\nu)}{\Gamma(h\to e\nu)}$
- Decays of light mesons
  - $R_{e/\mu} = \frac{\Gamma(\pi\to e\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))}$ by PIENU [Phys. Rev. Lett. 115, 071801 (2015)]
  - $R_K = \frac{\Gamma(K\to e\nu)}{\Gamma(K\to\mu\nu)}$ by KLOE, NA62 [Phys. Lett. B719, 326 (2013)], et al.

All consistent with SM except for $B(W \to \tau\nu_\tau)$

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



Sensitive to new physics because the massive 3rd generation b quark and τ lepton are involved.

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} \Big\{ [\bar{c}\gamma^\mu(1-\gamma_5)b][\bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau] \quad \text{... SM } (W^\pm)$$

$$- \frac{m_b m_\tau}{m_B^2} \bar{c}[g_S + g_P\gamma_5]b[\bar{\tau}(1-\gamma_5)\nu_\tau] \Big\} \quad \text{... New Physics } (H^\pm)$$

$$+\text{h.c.}$$

Flavor-dependent coupling to the fermions

$$\frac{d\Gamma(B^- \to D^0 \ell^- \bar{\nu})}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2 (w^2 - 1)^{3/2} |\eta_{\text{EW}}|^2 |V_{cb}|^2 |\mathcal{G}(w)|^2$$

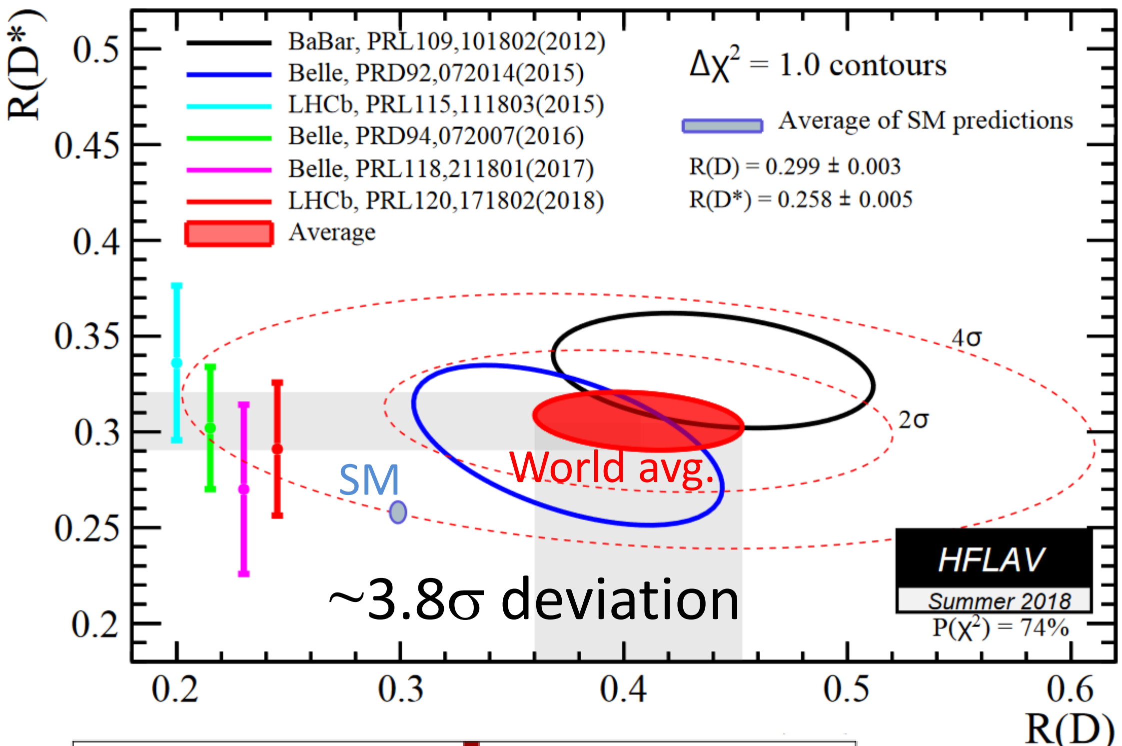
$$\frac{d\Gamma(B^- \to D^{*0} \ell^- \bar{\nu})}{dw} = \frac{G_F^2 m_{D^*}^3}{4\pi^3}(m_B - m_{D^*})^2 (w^2 - 1)^{1/2} |\eta_{\text{EW}}|^2 |V_{cb}|^2 \chi(w) |\mathcal{F}(w)|^2$$

Sizable uncertainties on $|V_{cb}|$ and the form factors

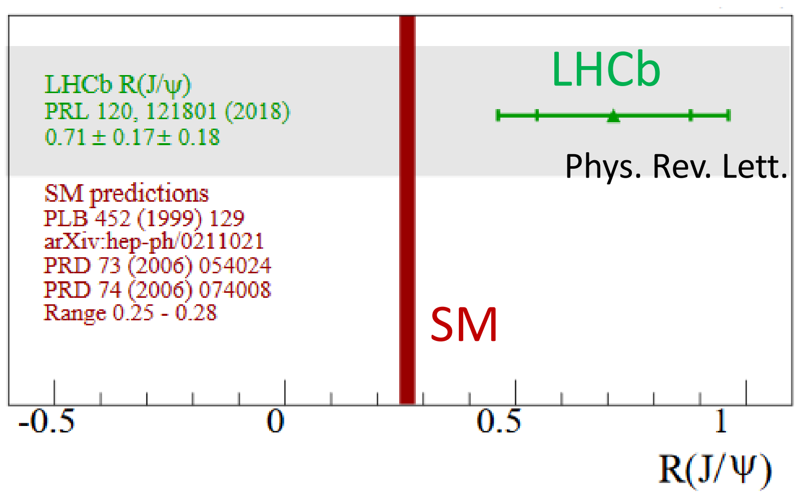
Hint of new physics in $b \to c\ell\nu$ tree decays

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

Useful observable to probe new physics since the uncertainties on $|V_{cb}|$ and the form factors as well as the experimental systematics cancel out



$$R(J/\Psi) = \frac{\Gamma(B_c \to J/\Psi\tau\nu)}{\Gamma(B_c \to J/\Psi\mu\nu)}$$



Phys. Rev. Lett. 120, 121801 (2018)

Deviation also in

$$R(K^{(*)}) = \frac{\Gamma(B \to K^{(*)}\mu\mu)}{\Gamma(B \to K^{(*)}ee)}$$

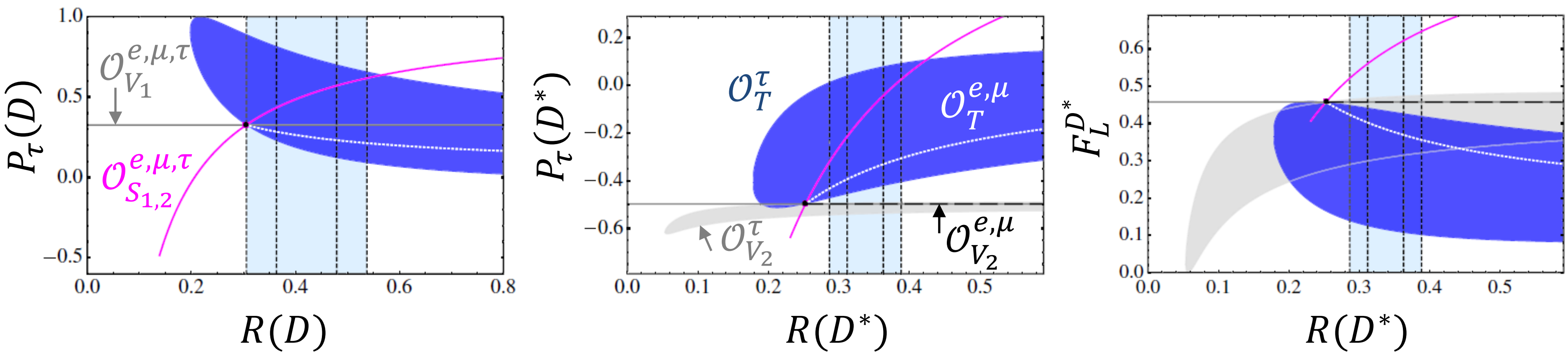
… $b \to s\ell\ell$ penguin decays

D^* and τ polarizations in $B \to D^*\tau\nu$

Observable which could distinguish the type of new physics:
Longitudinal polarizations

- $P_\tau(D^*) = \frac{\Gamma^+(D^*) - \Gamma^-(D^*)}{\Gamma^+(D^*) + \Gamma^-(D^*)}$ $\Gamma^\pm(D^*)$: decay rate with τ helicity $\lambda_\tau = \pm\frac{1}{2}$
- $F_L^{D^*} = \frac{\Gamma(D_L^*)}{\Gamma(D_L^*) + \Gamma(D_T^*)}$ $\Gamma(D_{L(T)}^*)$: decay rate of longitudinally (transversely) polarized D^*

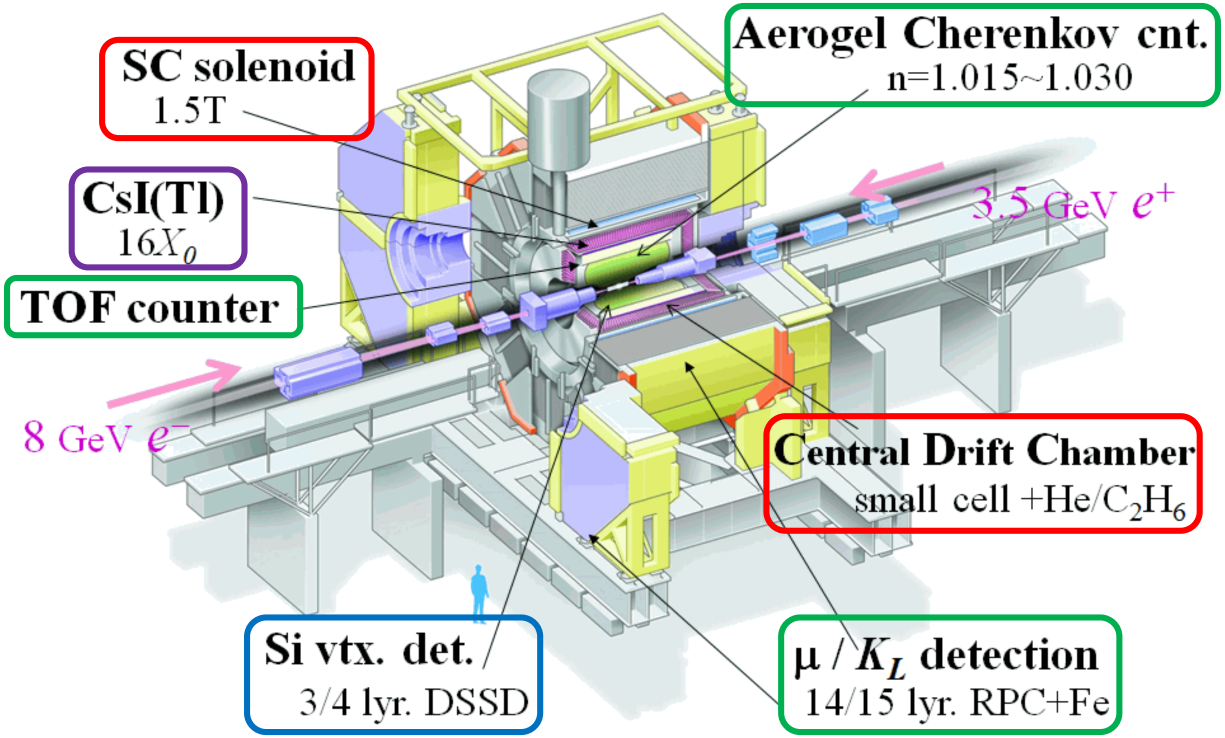
New physics scenarios [Phys. Rev. D 87, 034028 (2013)]



Belle measured $R(D)$, $R(D^*)$ and $P_\tau(D^*)$, and is still active in producing new results.

The Belle experiment

- Collected 772 x 10^6 $B\bar{B}$ events at KEKB factory (1998-2010), asymmetric e^+e^- collider at $\sqrt{s} = 10.58$ GeV, in Japan.
  - $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ (very clean and well-known initial state)



Hermetic spectrometer capable of

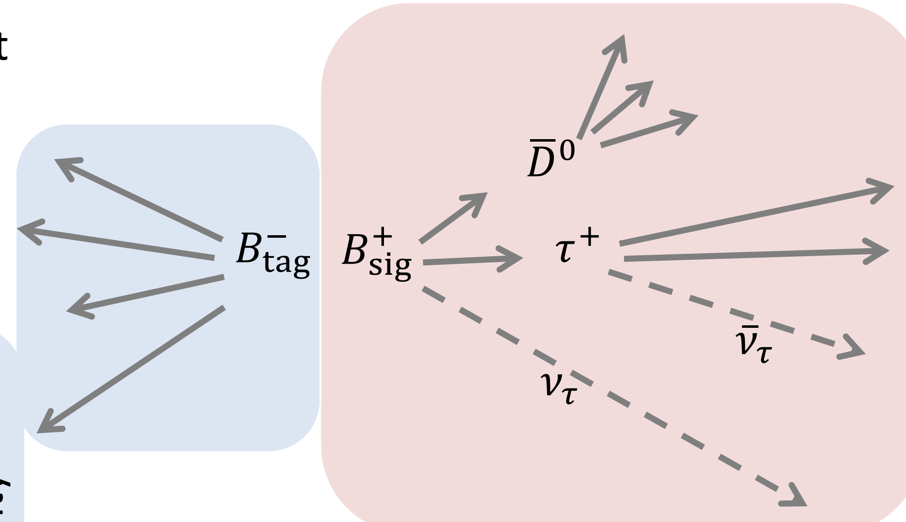
- Tracking and momentum meas. of charged tracks
- Vertex meas.
- Particle ID
- γ energy meas.

$B \to D^{(*)}\tau\nu$ reconstruction in Belle

- Not a rare decay
  - In SM, $\mathcal{B}(B^+ \to \bar{D}^0\tau^+\nu_\tau) = 0.66\%$ and $\mathcal{B}(B^+ \to \bar{D}^{*0}\tau^+\nu_\tau) = 1.23\%$
- but reconstruction of τ is challenging due to multiple neutrinos and need a high statistics..

  → Need full reconstruction of the event
  - Suppress non-$B\bar{B}$ bkgd. and misreconstructed events

  → quite low efficiency



Reconstruct one of the B's decaying

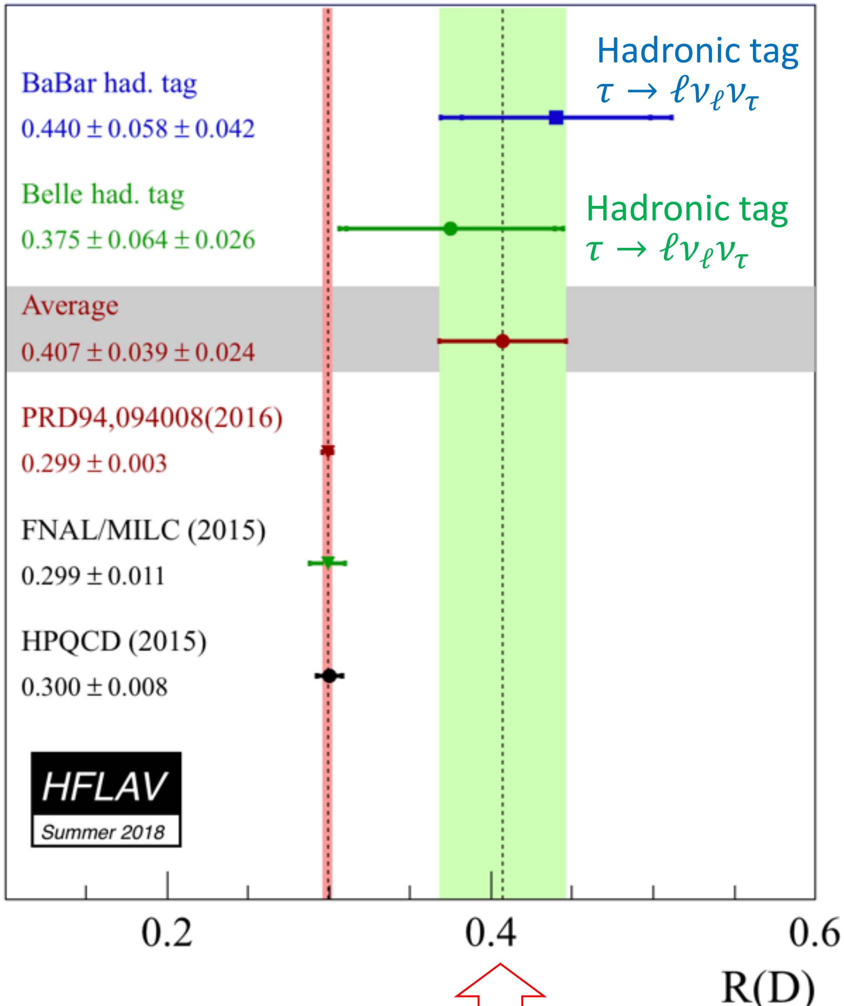
1. Hadronically ($\varepsilon_{\rm sig} \approx 0.2\%$)
2. Semileptonically ($\varepsilon_{\rm sig} \approx 0.5\%$)
3. Inclusively ($\varepsilon_{\rm sig} \approx$ a few %)

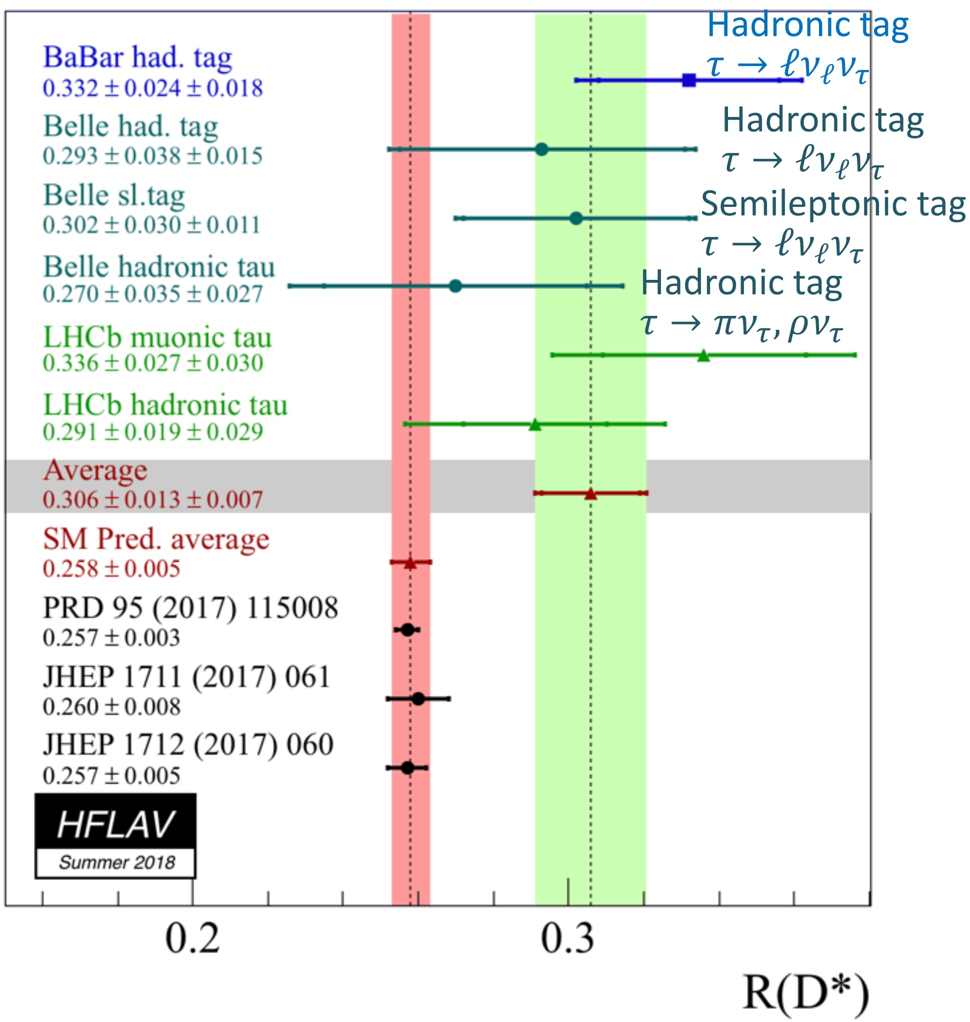
Efficiency ↓ Purity ↑

Select the other B of the signal decay with

- a $D^{(*)}$
- a charged daughter of τ
  1. Leptonic τ decay
  2. Hadronic τ decay

Previous results on $R(D)$ and $R(D^*)$





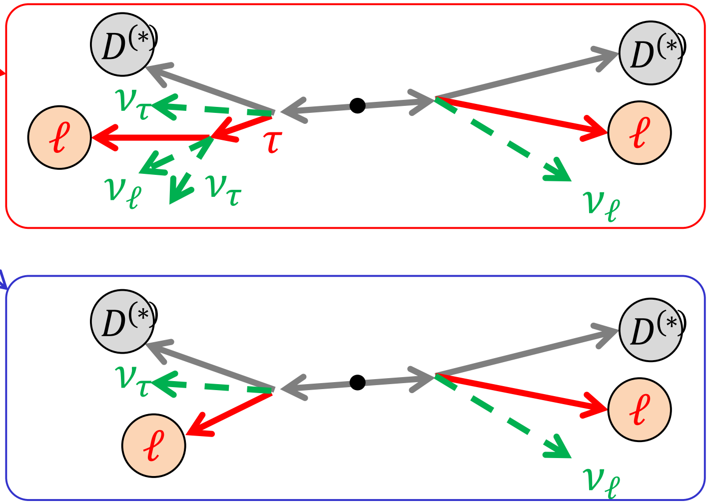
Only two (direct) measurements with hadronic tag

→ $R(D)$ with semileptonic tag will be added.

$B \to D^{(*)}\tau\nu$ with semileptonic tag

- Simultaneous measurement of $R(D)$ and $R(D^*)$

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)} = \frac{\text{signal}}{\text{normalization}}$$



  - In the previous result only $B^0\bar{B}^0 \to (D^{*-}\ell^+)(D^{*+}\ell^-)$
  - Add $B^0\bar{B}^0 \to (D^{(*)-}\ell^+)(D^{(*)+}\ell^-)$ and $B^+B^- \to (\bar{D}^{(*)0}\ell^+)(D^{(*)0}\ell^-)$

- Analysis with the Belle II software framework
  - To reconstruct B_{tag} we can exploit FEI (Full Event Interpretation; Multivariate analysis with Boosted-Decision Tree classifier) → higher efficiency

Close to opening the blinded signal box

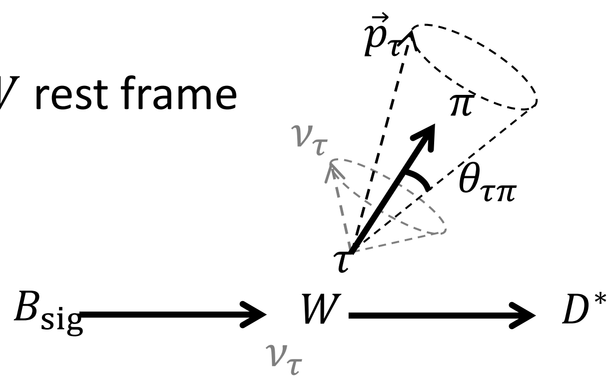
Polarization measurements

Angular distribution of τ decay

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\mathrm{hel}}} = \frac{1}{2}\left[1 + \alpha P_\tau(D^*)\cos\theta_{\mathrm{hel}}\right]$$

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

W rest frame



$\vec{p}_\tau$ can be constrained to lie on the cone with a half apex angle $\theta_{\tau\pi}$:

$$\cos\theta_{\tau\pi} = \frac{2E_\tau E_\pi - m_\tau^2 - m_\pi^2}{2|\vec{p}_\tau||\vec{p}_\pi|}$$

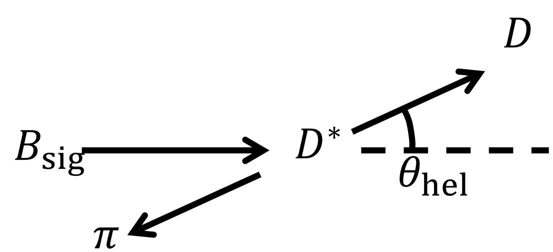
Boost in an arbitrary direction on the cone to translate $\cos\theta_{\tau\pi}$ to $\cos\theta_{\mathrm{hel}}$ in the τ rest frame.

Angular distribution of D^* decay

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\mathrm{hel}}} = \frac{3}{4}\left[2F_L^{D^*}\cos^2\theta_{\mathrm{hel}} + F_T^{D^*}\sin^2\theta_{\mathrm{hel}}\right]$$

$$(F_L^{D^*} + F_T^{D^*} = 1)$$

D^* rest frame



[Pros]

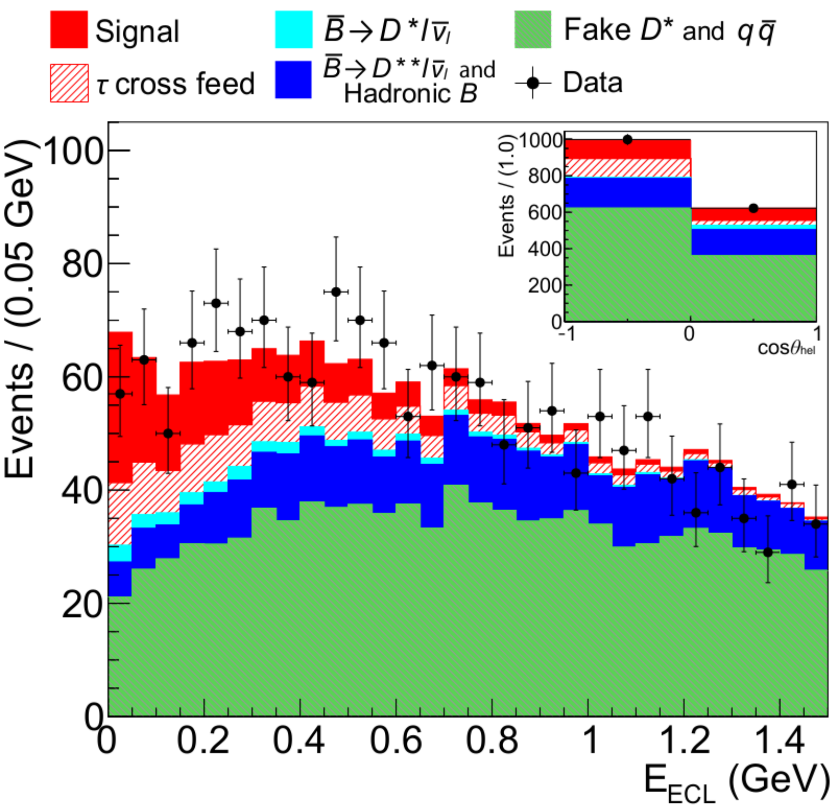
- All τ decays are useful.
- Not affected by cross-feeds of τ decays.

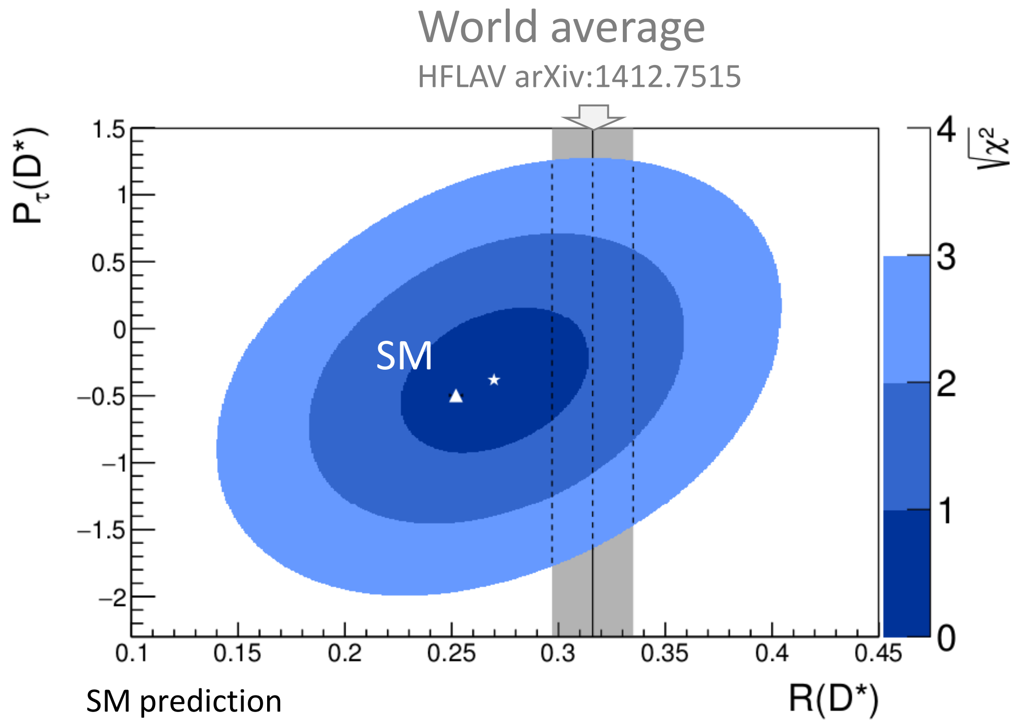
[Cons]

- Strong dependence of acceptance on $\cos\theta_{\mathrm{hel}}$ and q^2.

Result on $P_\tau(D^*)$

- Hadronic tag
- Two-body τ decays ($\tau \to \pi\nu_\tau, \rho\nu_\tau$)





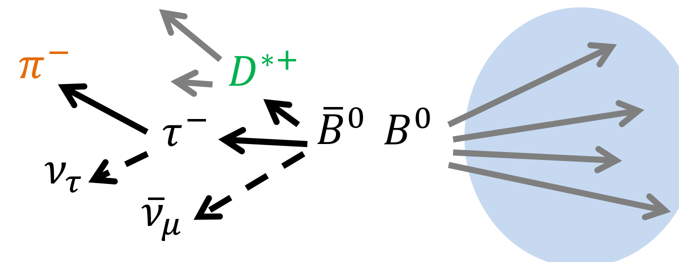
SM prediction
PRD 85, 094025 (2012); PRD 87, 034028 (2013)

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

PRL 118, 211801 (2017)

$P_\tau(D^*)$ and $F_L^{D^*}$ with inclusive tag

- Select candidates for $B_{\rm sig}$ daughters; $D^{*+} + (\ell^- \text{ or } \pi^-)$.
  - $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$
    - $D^{*+} \to D^0\pi^+$
      - $D^0 \to K^-\pi^+,\ K^-\pi^+\pi^0,\ K^-\pi^+\pi^-\pi^+$
    - $\tau^- \to \ell^-\nu_\tau\bar{\nu}_\tau,\ \pi^-\bar{\nu}_\tau$

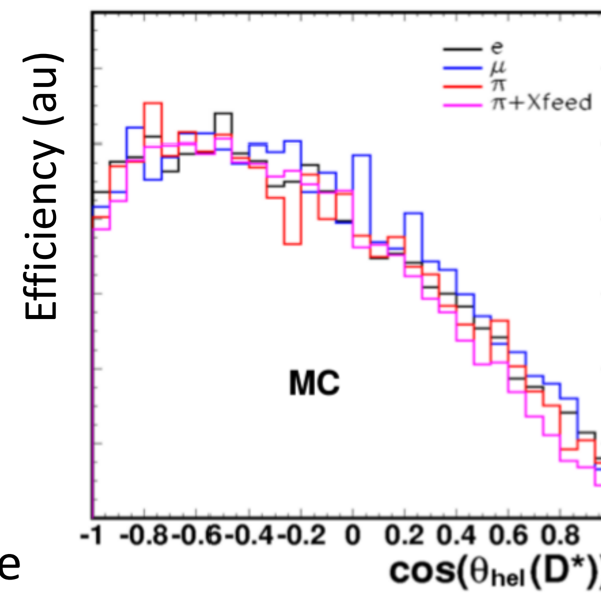


- Reconstruct $B_{\rm tag}$ inclusively from all the remaining particles.
  - Proper assignment of the particles without missing should lead to

$$M_{\rm tag} \equiv \sqrt{E_{\rm beam}^2 - |\vec{p}_{\rm tag}|^2} \approx M_B$$

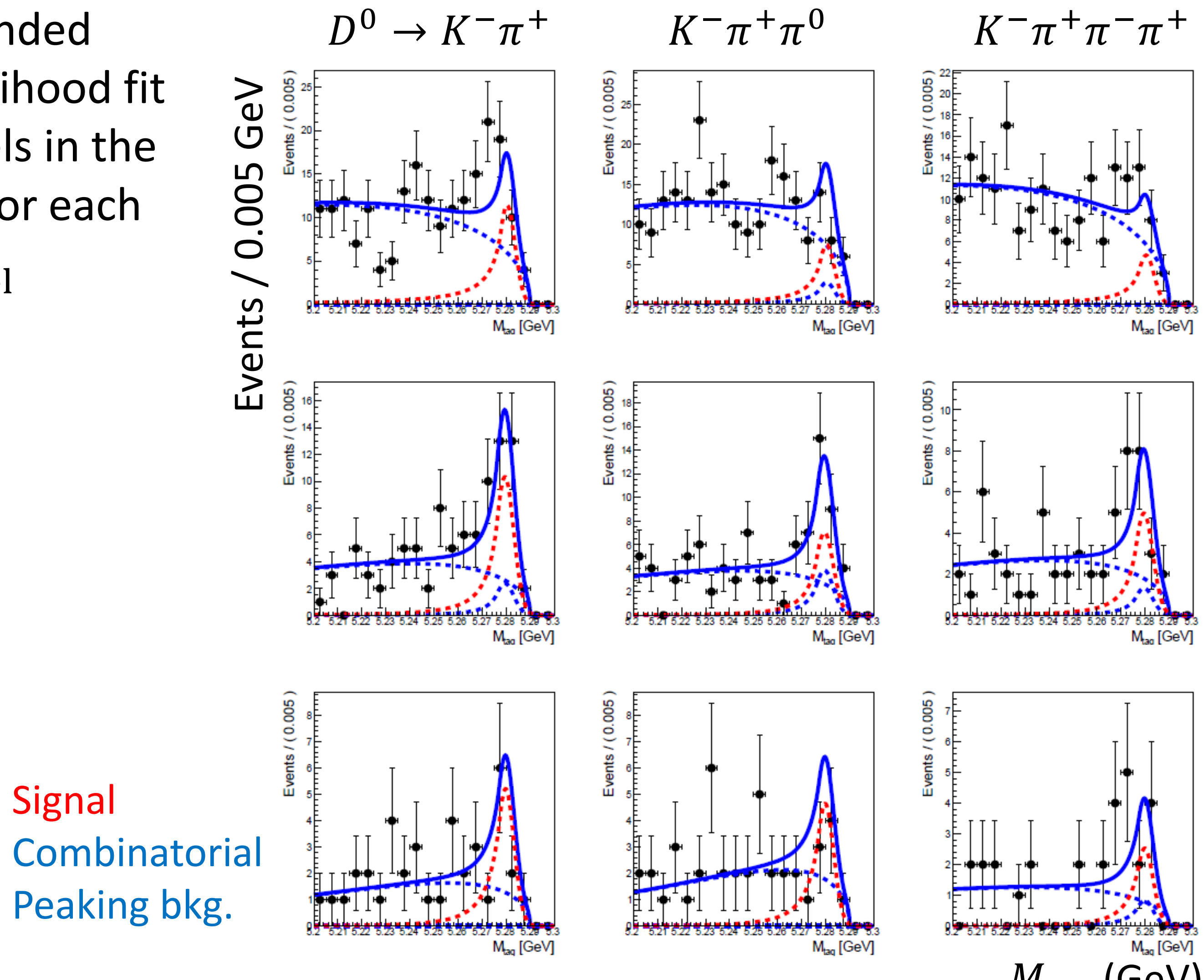
$$\Delta E_{\rm tag} \equiv E_{\rm tag} - E_{\rm beam} \approx 0$$

- Use only $\cos\theta_{\rm hel} < 0$ for $F_L^{D^*}$ meas.
  - Strong dependence of the efficiency on $\cos\theta_{\rm hel}$ due to the slow π from D^*, which is softer at a larger $\cos\theta_{\rm hel}$.
  - Correct signal yield for the efficiency/acceptance



Signal extraction for $F_L^{D^*}$ measurement

Simultaneous extended unbinned max likelihood fit to all 9 sub-channels in the M_{tag} distrbutions for each of 3 bins of $\cos\theta_{\text{hel}}$



$(-1.0 < \cos\theta_{\text{hel}}(D^*) < -0.67)$

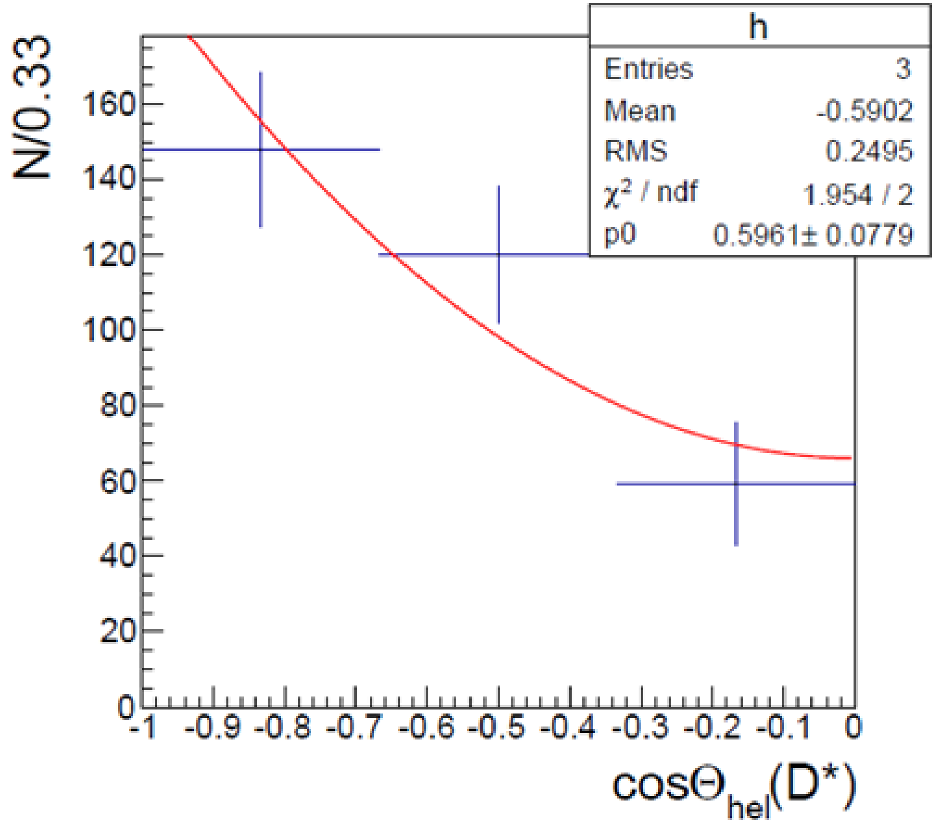
Result on $F_L^{D^*}$ presented at CKM2018

$F_L^{D^*} = 0.60 \pm 0.08(\mathrm{stat}) \pm 0.035(\mathrm{syst})$

cf. in SM

- $F_L^{D^*} = 0.46 \pm 0.03$ [Phys. Rev. D 95, 115038 (2017)]
- $F_L^{D^*} = 0.441 \pm 0.006$ [arXiv:1808.03565]

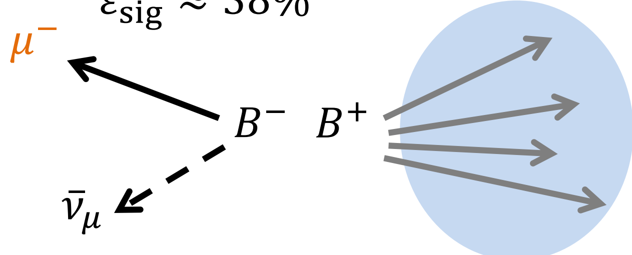
Consistent with SM within 2σ



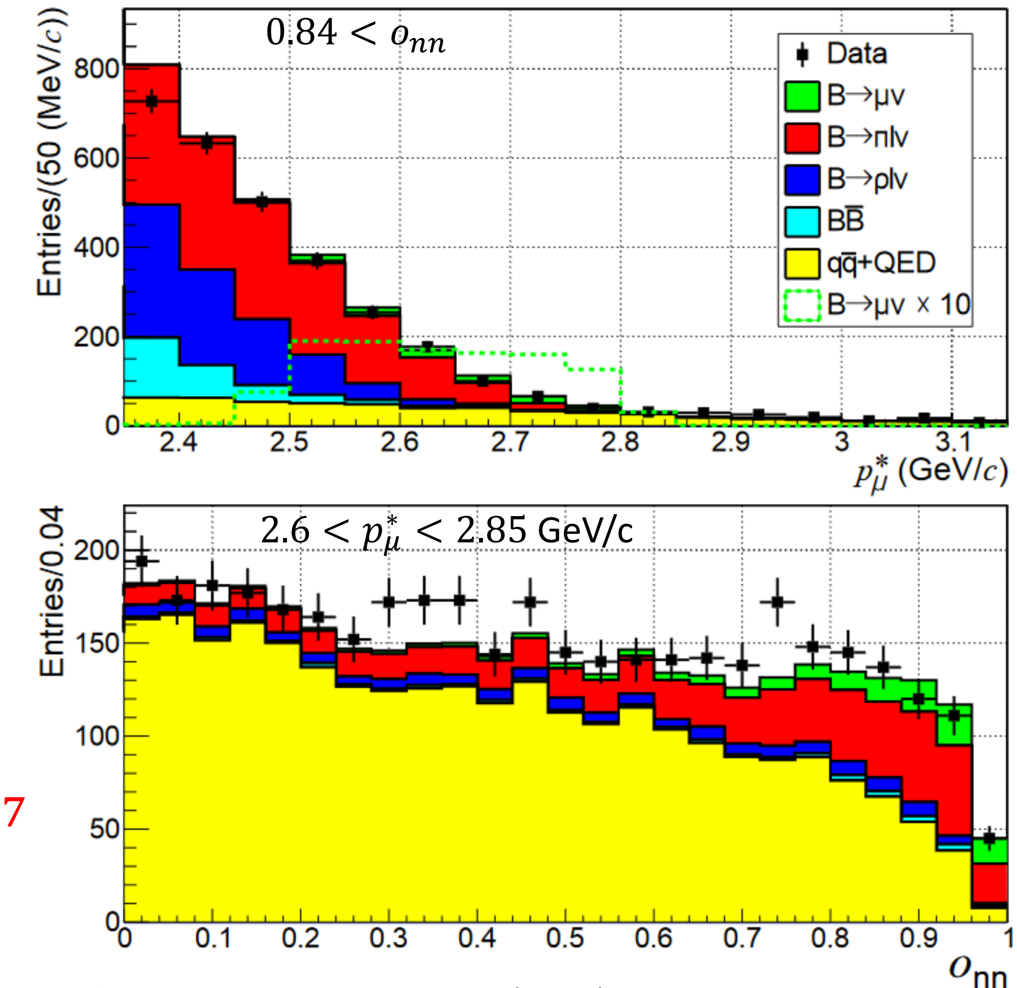
Search for $B \to \mu\nu_\mu$

- In SM $\mathcal{B}(B^- \to \mu^-\bar{\nu}_\mu) = \frac{G_F^2 m_B m_\mu^2}{8\pi}\left(1 - \frac{m_\mu^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B = (3.80 \pm 0.31) \times 10^{-7}$
- More precise SM prediction of $\frac{\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^- \to \mu^-\bar{\nu}_\mu)}$ than $R(D^{(*)})$
- Untagged (inclusive) method
  - Select a muon and check that the rest of event resembles B

$\varepsilon_{\text{sig}} \approx 38\%$



$\mathcal{B}(B^- \to \mu^-\bar{\nu}_\mu) =$
$(6.46 \pm 2.22 \pm 1.60) \times 10^{-7}$
Significance: 2.4σ
$[2.9, 10.7] \times 10^{-7}$ at 90% CL



Phys. Rev. Lett. 121, 031801 (2018)

Prospects for $B \to D^{(*)}\tau\nu$ at Belle II

Composition of the systematic uncertainties in each Belle analysis

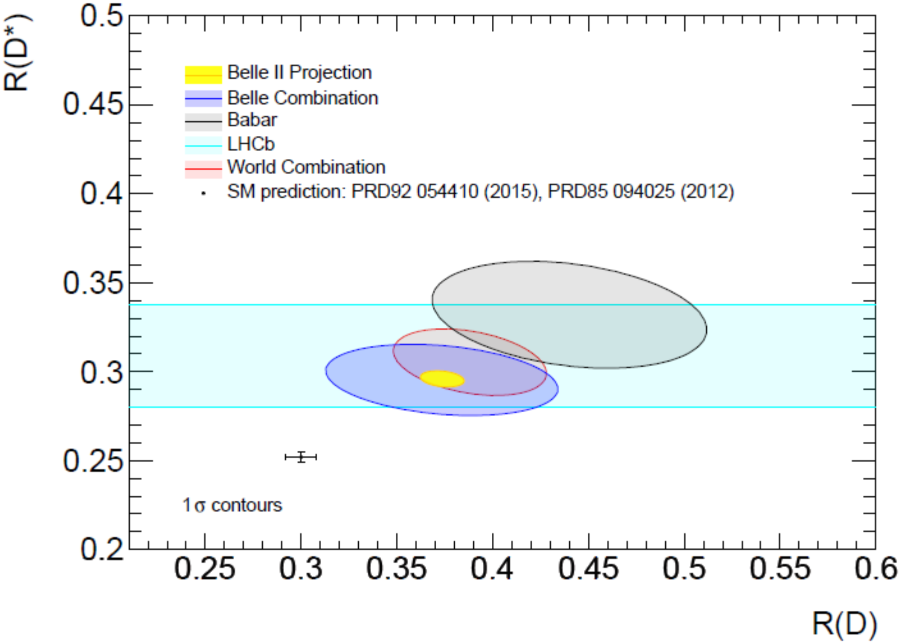
Source	Belle (Had, ℓ^-) R_D	Belle (Had, ℓ^-) R_{D^*}	Belle (SL, ℓ^-) R_{D^*}	Belle (Had, h^-) R_{D^*}
MC statistics	4.4%	3.6%	2.5%	$^{+4.0}_{-2.9}$%
$B \to D^{**}\ell\nu_\ell$	4.4%	3.4%	$^{+1.0}_{-1.7}$%	2.3%
Hadronic B	0.1%	0.1%	1.1%	$^{+7.3}_{-6.5}$%
Other sources	3.4%	1.6%	$^{+1.8}_{-1.4}$%	5.0%
Total	7.1%	5.2%	$^{+3.4}_{-3.5}$%	$^{+10.0}_{-9.0}$%

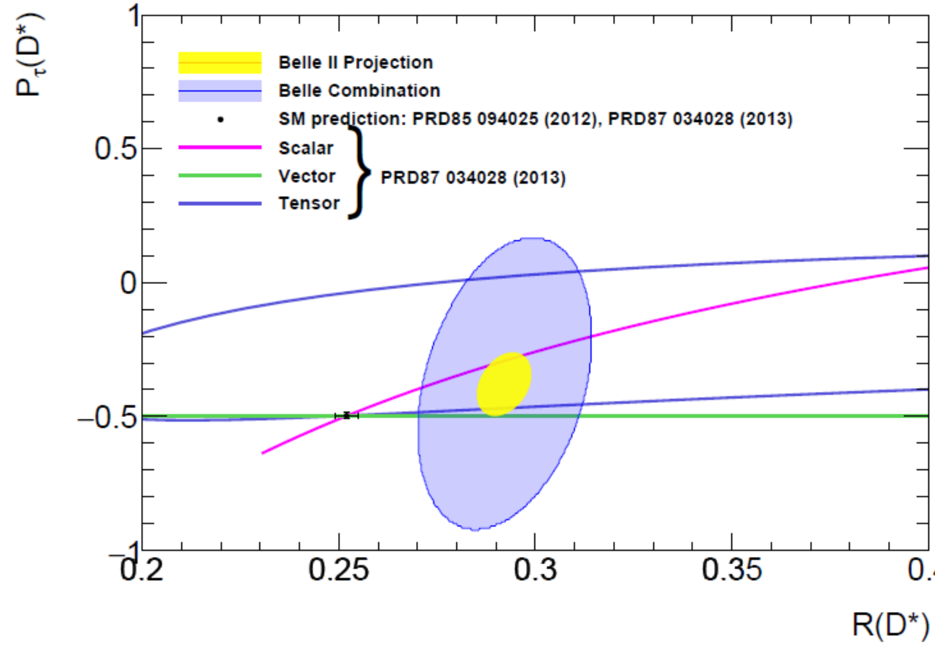
"The Belle II Physics Book", arXiv:1808.10567

- The uncertainty due to the MC statistics is reducible.
  - MC stat affects the estimation of the reconstruction efficiency, understanding of small cross-feed components and PDFs for the fit.
- The uncertainties from $\mathcal{B}(B \to D^{**}\ell\nu_\ell)$, D^{**} decays and hadronic B decays have to be reduced.
  - Need dedicated measurements of $B \to D^{**}\ell\nu_\ell$ and hadronic B decays with a large data sample.

Prospects for $B \to D^{(*)}\tau\nu$ at Belle II

- Belle 0.772 x 10^9 $B\bar{B}$ → Belle II ~50 x 10^9 $B\bar{B}$ (50 ab^{-1} in 6 yrs)





Expected precision (stat and syst)

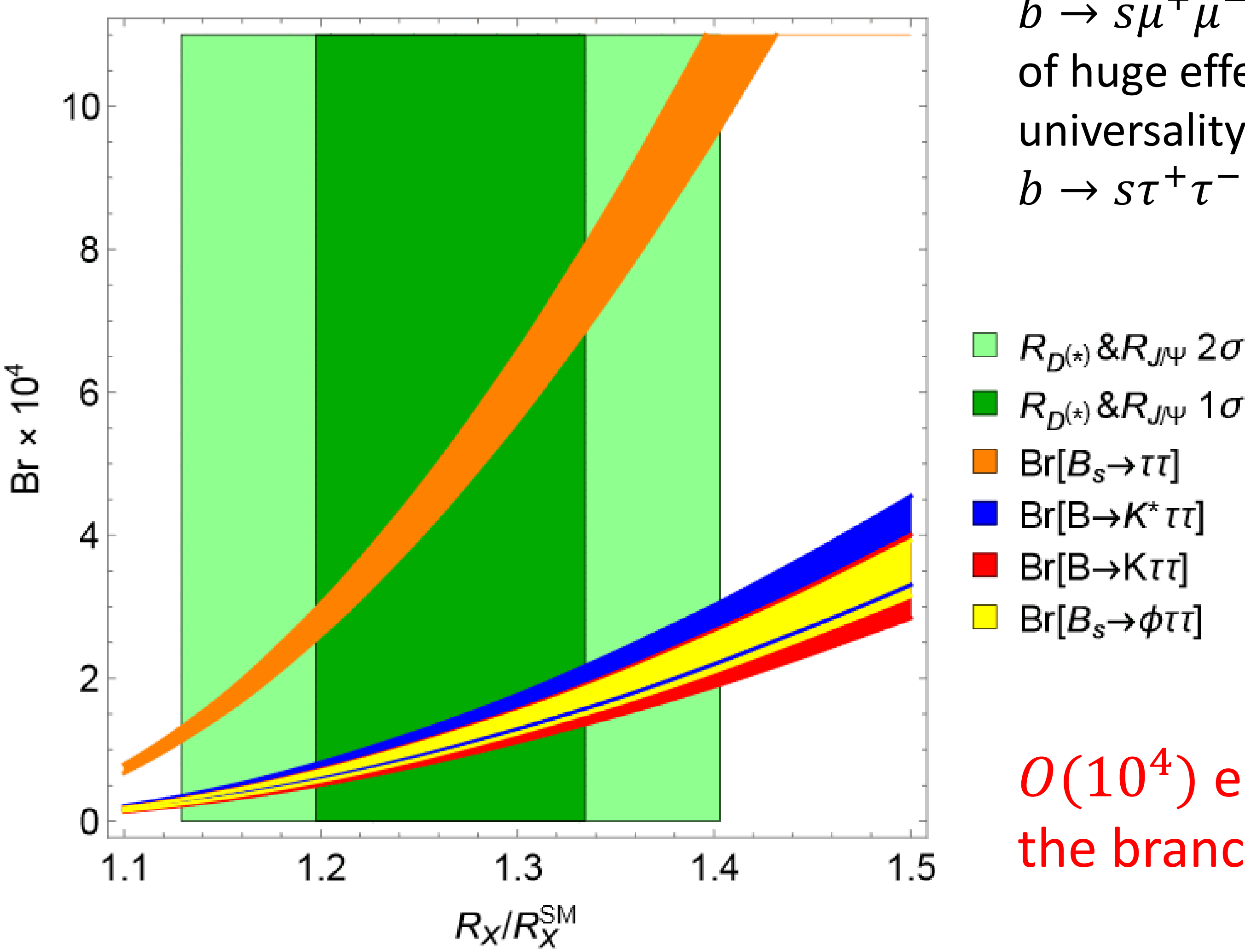
	$5\ ab^{-1}$	$50\ ab^{-1}$
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

In addition, q^2 and other distributions of kinematic observables to discriminate the new physics scenarios.

“The Belle II Physics Book”, arXiv:1808.10567

Search for $b \to s\tau^+\tau^-$ at Belle II

Phys. Rev. Lett. 120, 181802 (2018)



The anomalies seen in $R(D^{(*)})$, $R(J/\psi)$, $R(K^{(*)})$ and $b \to s\mu^+\mu^-$ suggest a possibility of huge effects of lepton flavor universality violation in $b \to s\tau^+\tau^-$ (FCNC penguin).

$O(10^4)$ enhancement of the branching fractions

Summary

- The anomalies in the semileptonic B decays could be a hint for new physics.
- $R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$ and the polarizations of D^* and τ in $B \to D^{(*)}\tau\nu$ are useful observable to probe new physics.
- Belle measured those observables with different tagging methods, and the following new results will come out soon:
  - $R(D)$ and $R(D^*)$ with semileptonic tag
  - $P_\tau(D^*)$ with inclusive tag
- Belle II will also play an important role on the $B \to D^{(*)}\tau\nu$ measurements with x50 data.