New results on $R(D)$ and $R(D^*)$ from Belle

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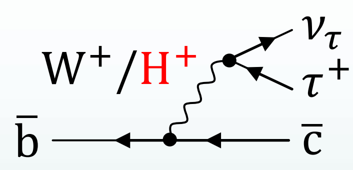
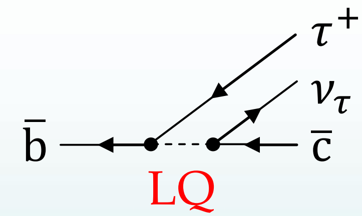
for the Belle collaboration

Physics motivation

New physics search in the tree level

- $R\left(D^{(*)}\right) = \frac{\mathcal{B}(B \to D^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \to D^{(*)} \ell \nu_\ell)} \quad (\ell = e \text{ or } \mu)$
  - Partial cancellation of theoretical uncertainties related to hadronic effects and measurement systematics.



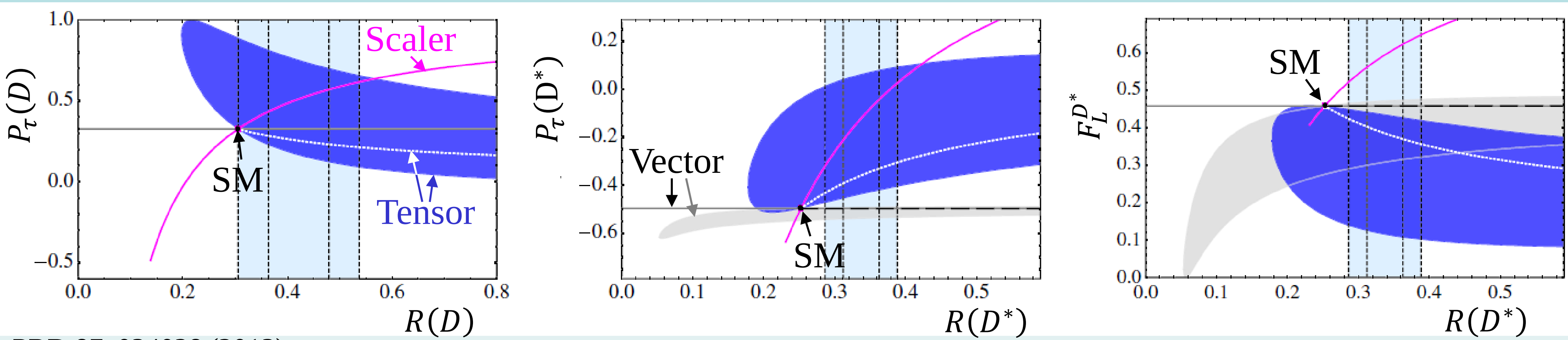


- $P_\tau\left(\mathrm{D}^{(*)}\right) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$

  $\Gamma^\pm$: decay rate for τ helicity $\pm\frac{1}{2}$

- $F_L^{D^*} = \frac{\Gamma(D_L^*)}{\Gamma(D_T^*) + \Gamma(D_L^*)}$

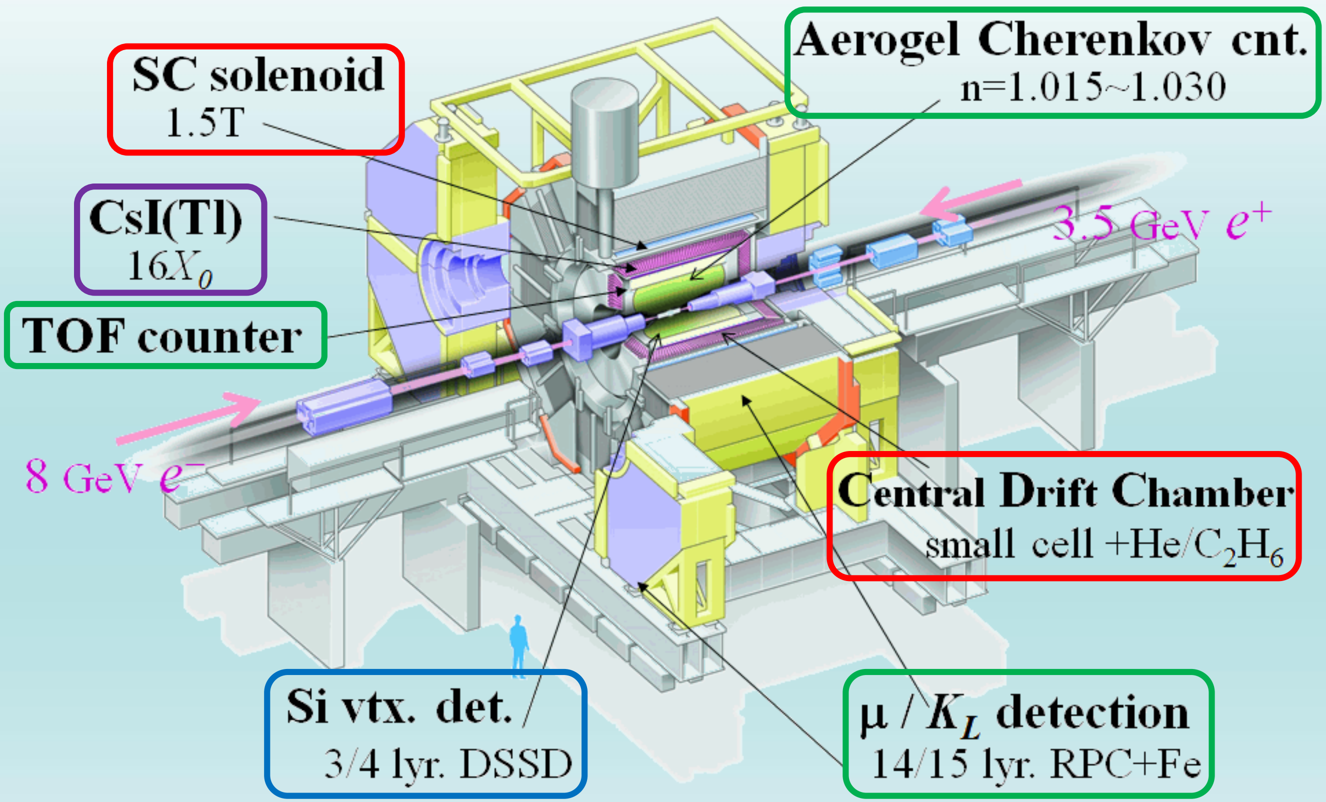
  $\Gamma\left(D^*_{T/L}\right)$: decay rate of $B \to D^*_{T/L} \tau \nu_\tau$



PRD 87, 034028 (2013)

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.

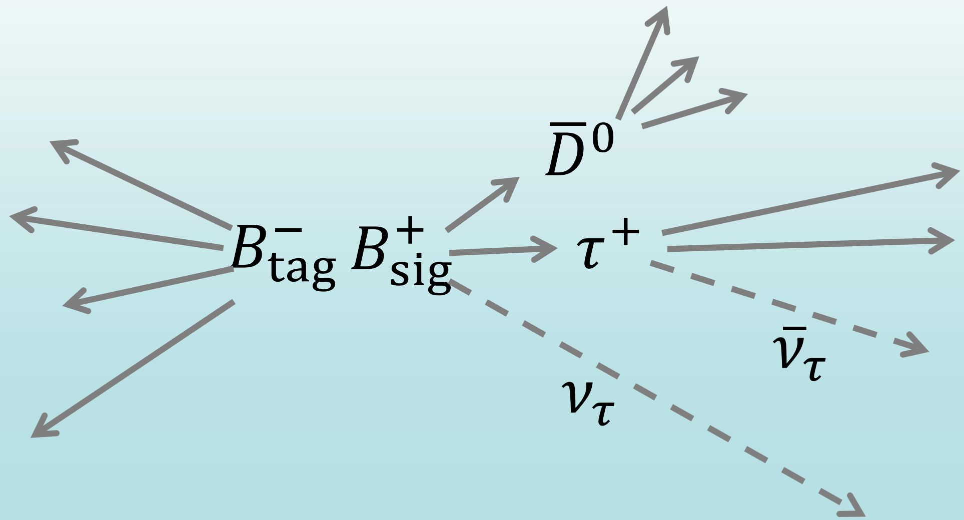
$B \to D^{(*)}\tau\nu$ reconstruction in Belle

- In SM, $BF(B^+ \to \bar{D}^0\tau^+\nu_\tau) = 0.66\%$ and $BF(B^+ \to \bar{D}^{*0}\tau^+\nu_\tau) = 1.23\%$
- Difficult of reconstruction due to multiple neutrinos

  → Need full reconstruction of the event

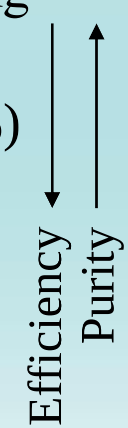
  – Suppress non-$B\bar{B}$ bkgd. and misreconstructed events

  → quite low efficiency



Reconstruct one of the B's decaying

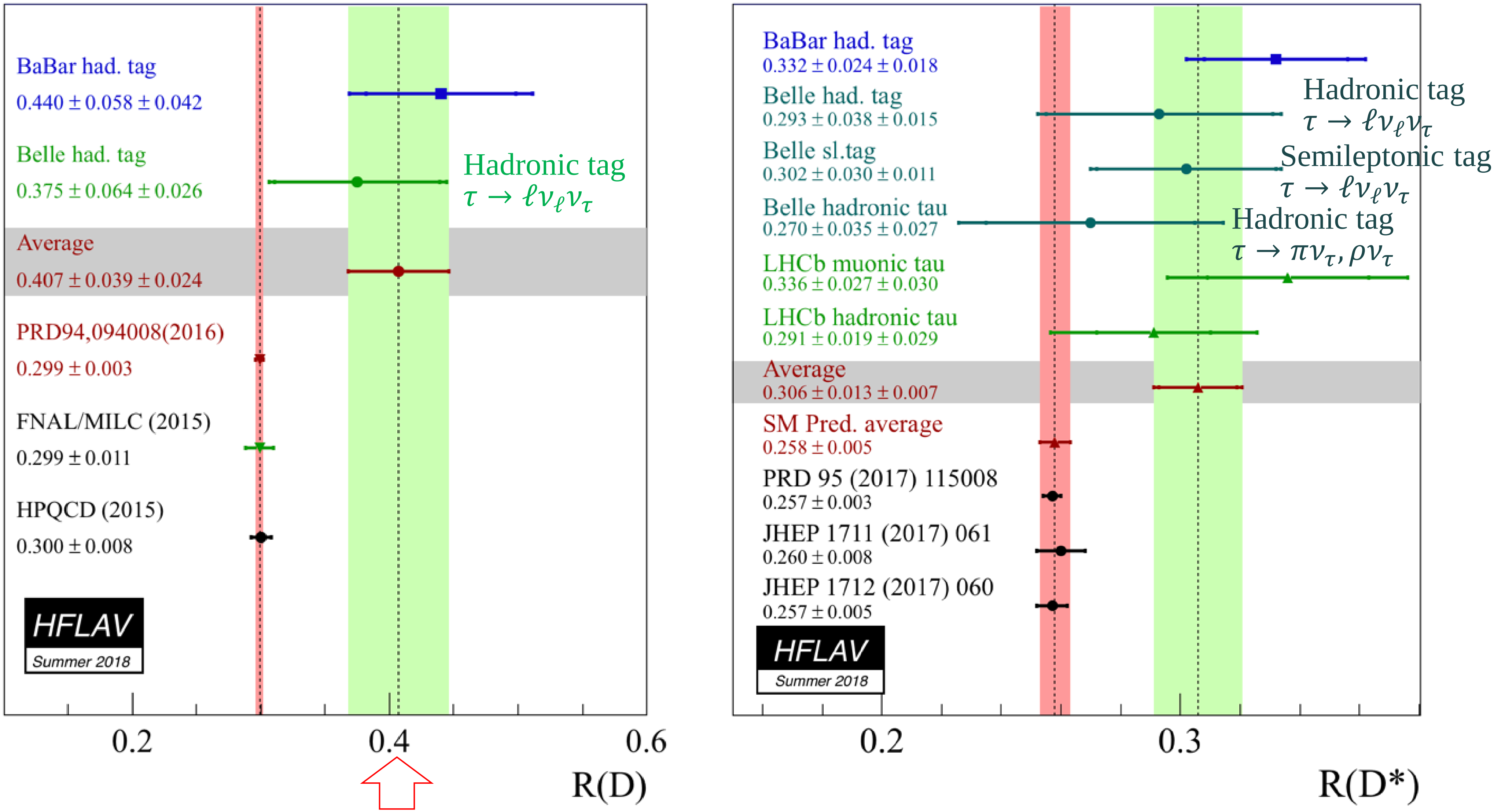
1. Hadronically ($\varepsilon_{\mathrm{sig}} \approx 0.2\%$)
2. Semileptonically ($\varepsilon_{\mathrm{sig}} \approx 0.5\%$)
3. Inclusively ($\varepsilon_{\mathrm{sig}} \approx$ a few %)



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 $R(D^*)$

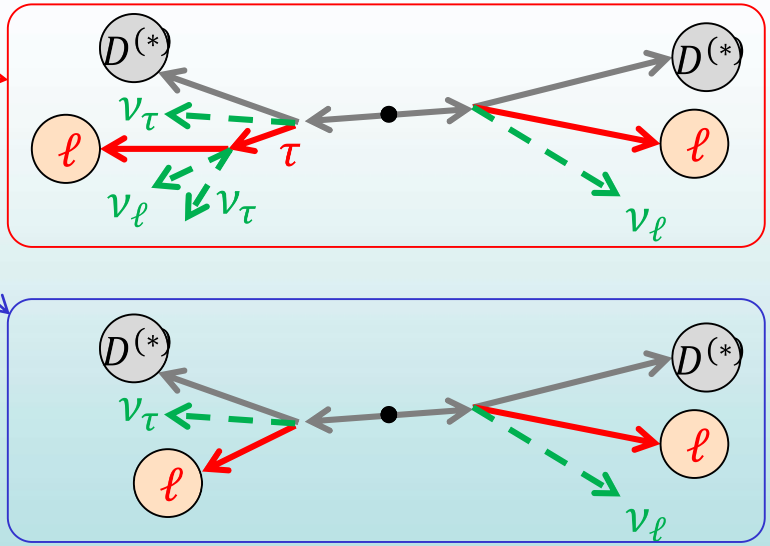


Only two (direct) measurements with hadronic tag
→ $R(D)$ with semileptonic tag will be added.

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

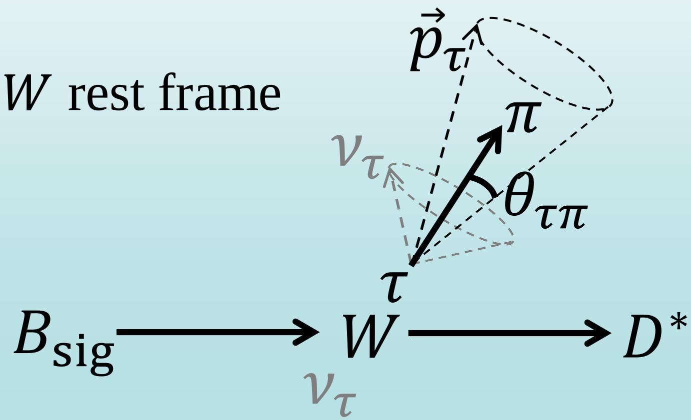
Polarization measurements

Angular distribution of τ decay

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

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

W rest frame



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

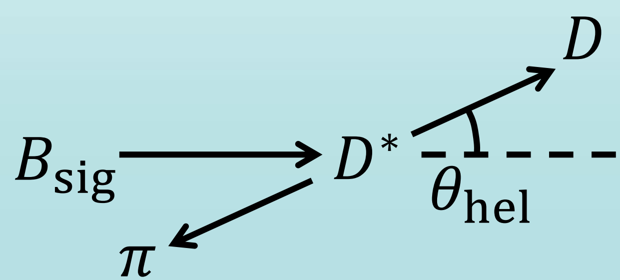
$$\cos\theta_{\tau\pi} = \frac{2E_\tau E_\pi - m_\tau^2 - m_\pi^2}{2|\vec{p}_\tau||\vec{p}_\pi|}$$

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

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

D^* rest frame



[Pros]

– All τ decays are useful.

– Not affected by cross-feeds of τ decays.

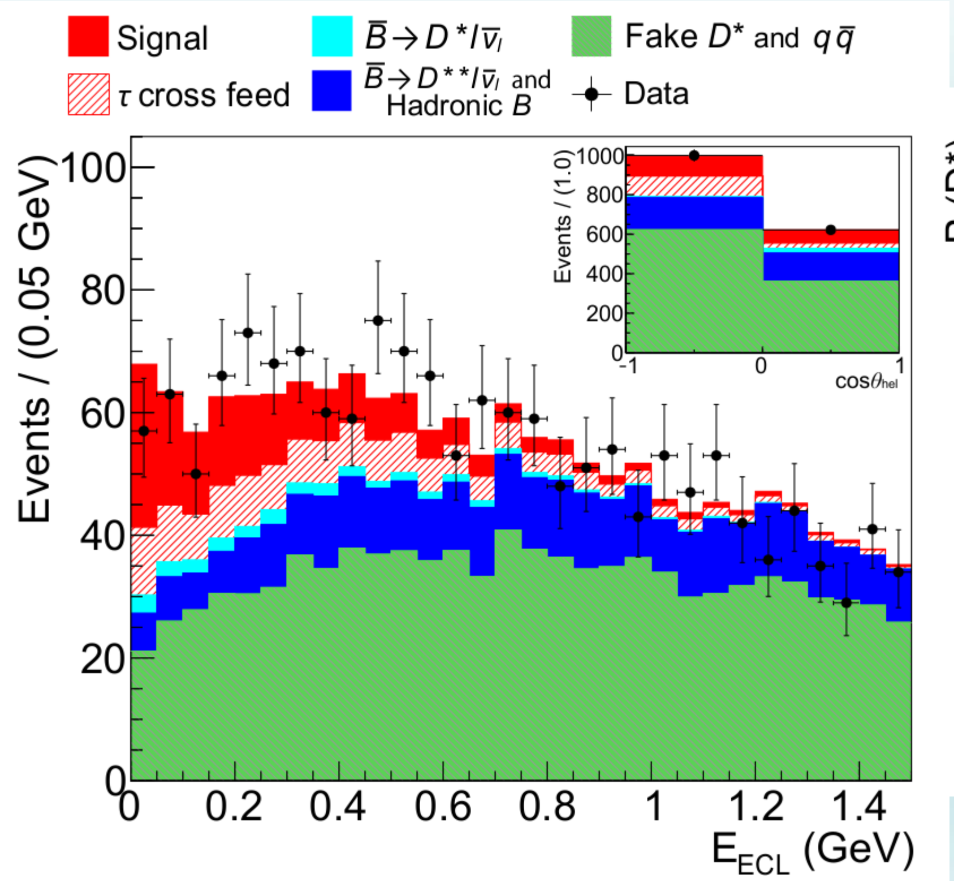
[Cons]

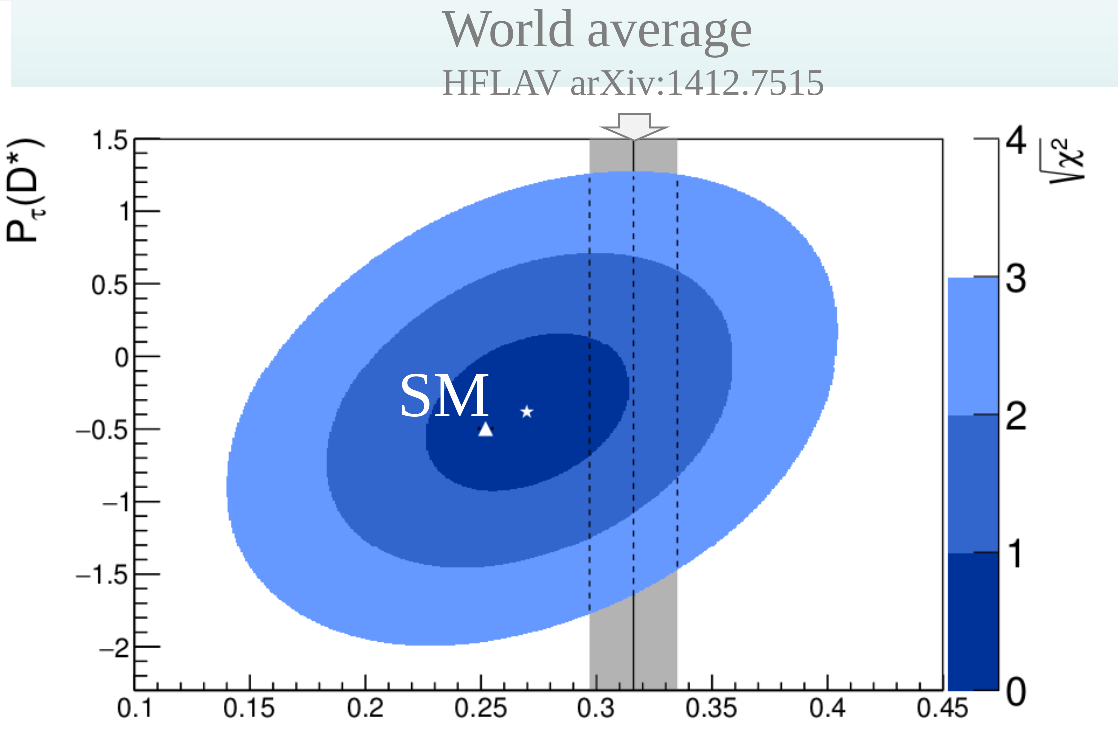
– Strong dependence of acceptance on $\cos\theta$ and q^2.

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

PRL 118, 211801 (2017)

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



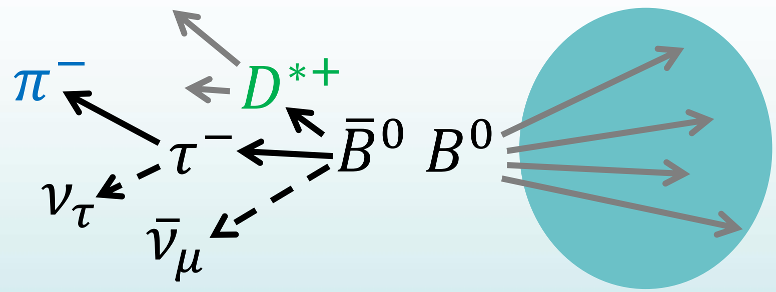


SM prediction
PRD 85, 094025 (2012); PRD 87, 034028 (2013)

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

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

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



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

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

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

- Expect ~300 signal events → Statistical error of $F_L^{D^*} \sim \pm\, 0.1$ and ~100 for $\tau^- \to \pi^-\bar{\nu}_\tau$ → Statistical error of $P_\tau(D^*) \sim \pm\, 0.8$

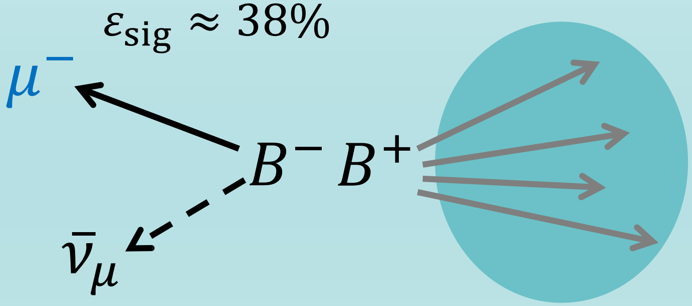
Close to opening the blinded signal box

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

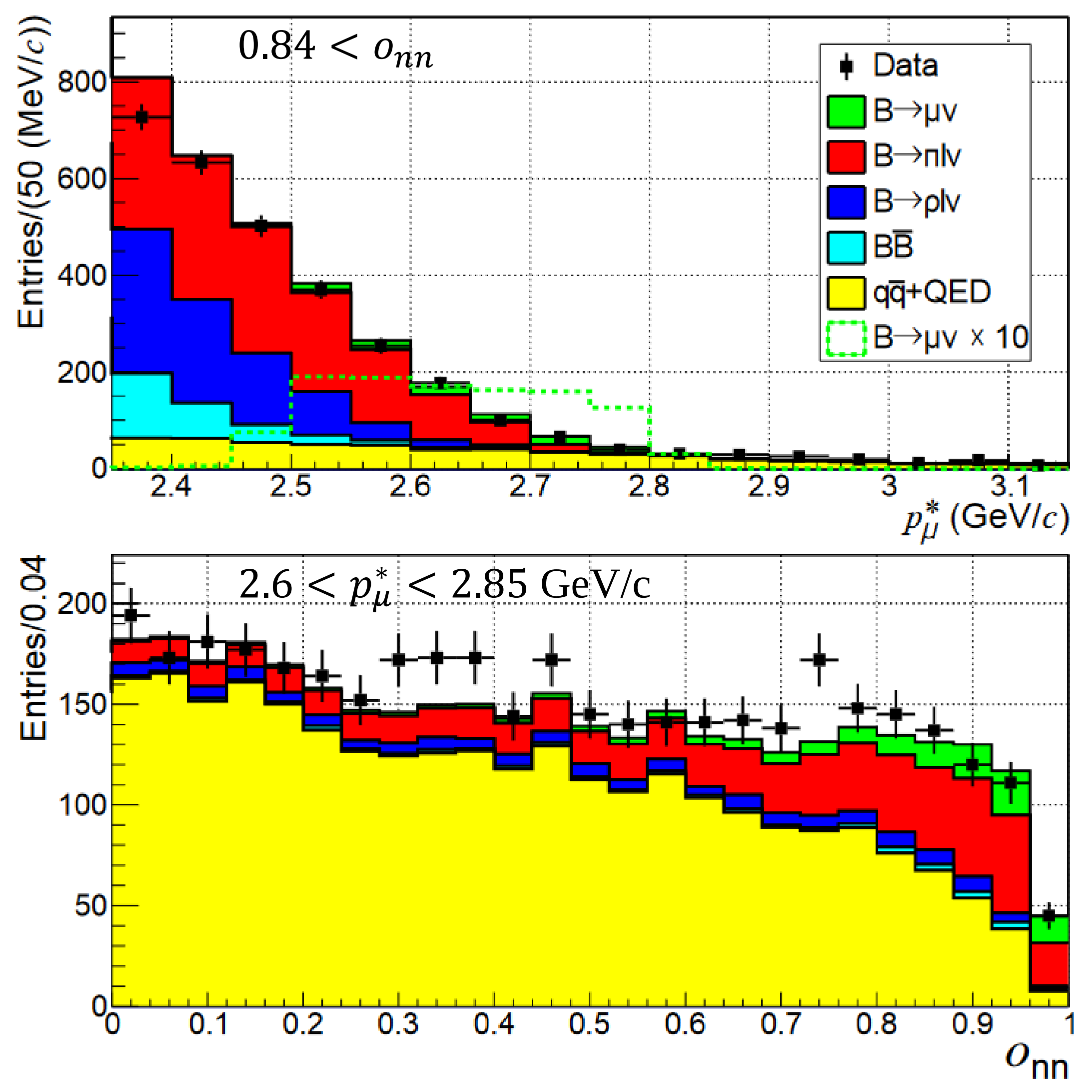
arXiv:1712.04123

- 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



Summary

- $R(D)$, $R(D^*)$, $P_\tau(\mathrm{D}^*)$ and $F_L^{D^*}$ are good probes for new physics.
  - Precise theoretical prediction and small measurement systematics for R.
  - Combined measurement of R and polarization could discriminate the type of new physics.
  - The measurement sensitivity is limited by the statistics.
- Belle is still active in producing new results:
  - $R(D)$ and $R(D^*)$ with semileptonic tag and a higher efficiency
  - $P_\tau(D^*)$ and $F_L^{D^*}$ with inclusive tag

  These results will appear in this summer.

- $B \to \ell\nu_\mu$ is also sensitive to new physics and $\frac{\mathcal{B}(B^-\to\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^-\to\mu^-\bar{\nu}_\mu)}$ will provide additional insight on the $R(D^{(*)})$ tension.
  - $\mathcal{B}(B^- \to \mu^-\bar{\nu}_\mu) = (6.46 \pm 2.22 \pm 1.60) \times 10^{-7}$ (2.4σ significance) with 711 fb^{-1} data → Promising at Belle II 50 ab^{-1} data