



名古屋大学
高等研究院

DMNet



A test of lepton flavor universality by semi-leptonic B decay at Belle II

Qi-Dong Zhou (周启东)

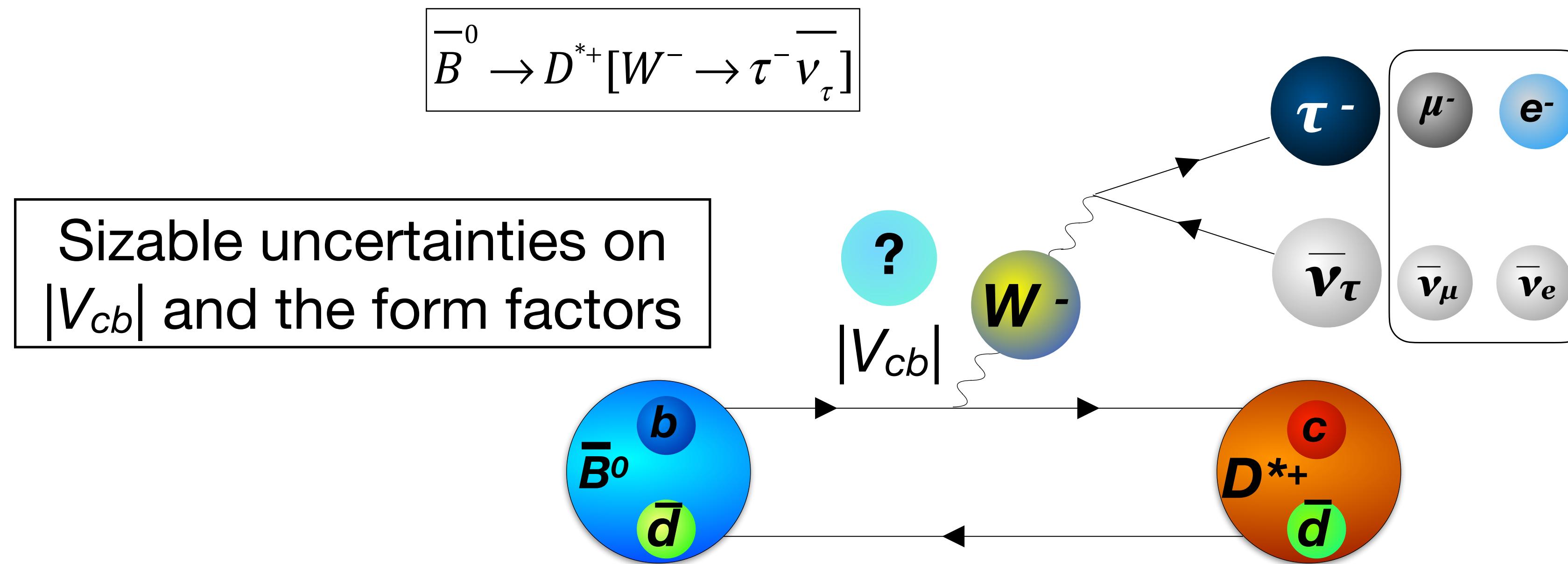
名古屋大学 高等研究院/素粒子宇宙起源研究所

(2023年5月 入职山东大学 前沿交叉科学青岛研究院)



4月 20-23 2023, 华中科技大学（东湖宾馆），武汉
第五届重味物理和量子色动力学研讨会

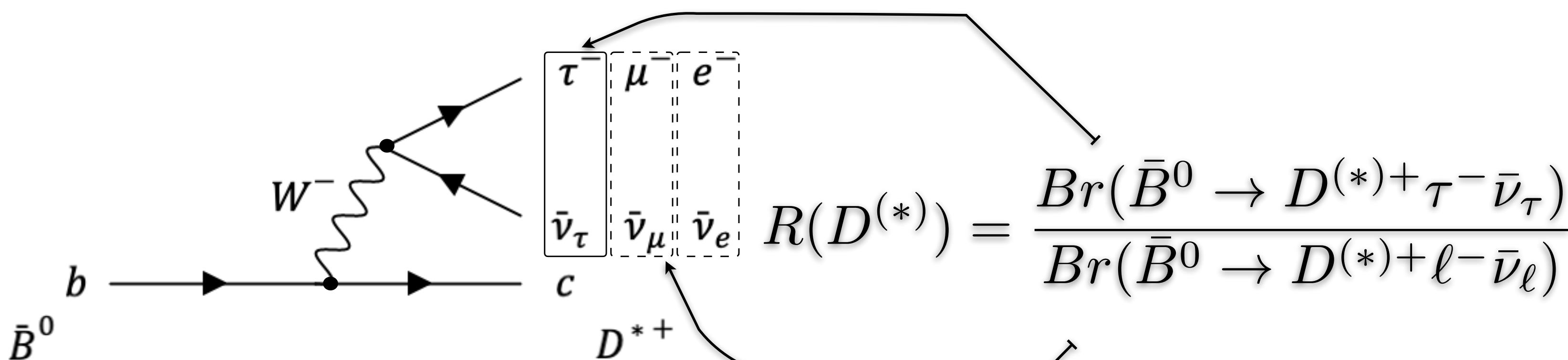
Semi-tauonic B decay: $B \rightarrow D^{(*)}\tau\nu$



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

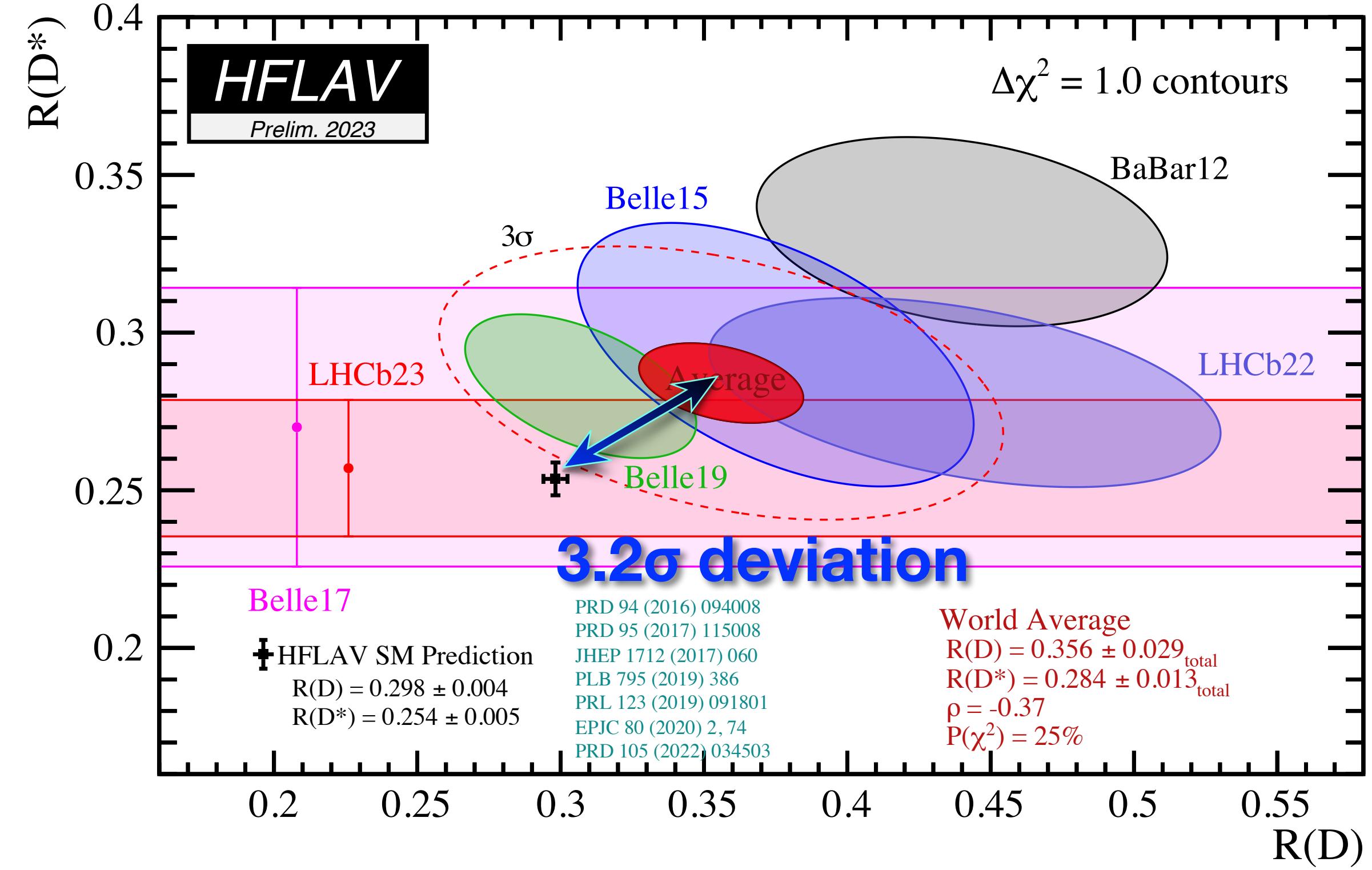
- Universality of the lepton coupling to the W gauge boson (Symmetry)
 - Lepton Flavor Universality (LFU) is fundamental axiom of Standard Model (SM)
- $B \rightarrow D^{(*)}\tau\nu$ sensitive to New physics (NP) because the massive 3rd generation **b quark** and **τ lepton** are involved
 - Flavor-dependent coupling to fermions could violates LFU

$R(D)$ and $R(D^*)$ anomaly



- Charged lepton mass changes **kinematics** and modifies **form factors** in the hadronization
- QED corrections depend on lepton velocity (τ vs. (e, μ))

- Ratio of branch fractions cancel out most of the uncertainties on $|V_{cb}|$, form factors and the experimental systematics



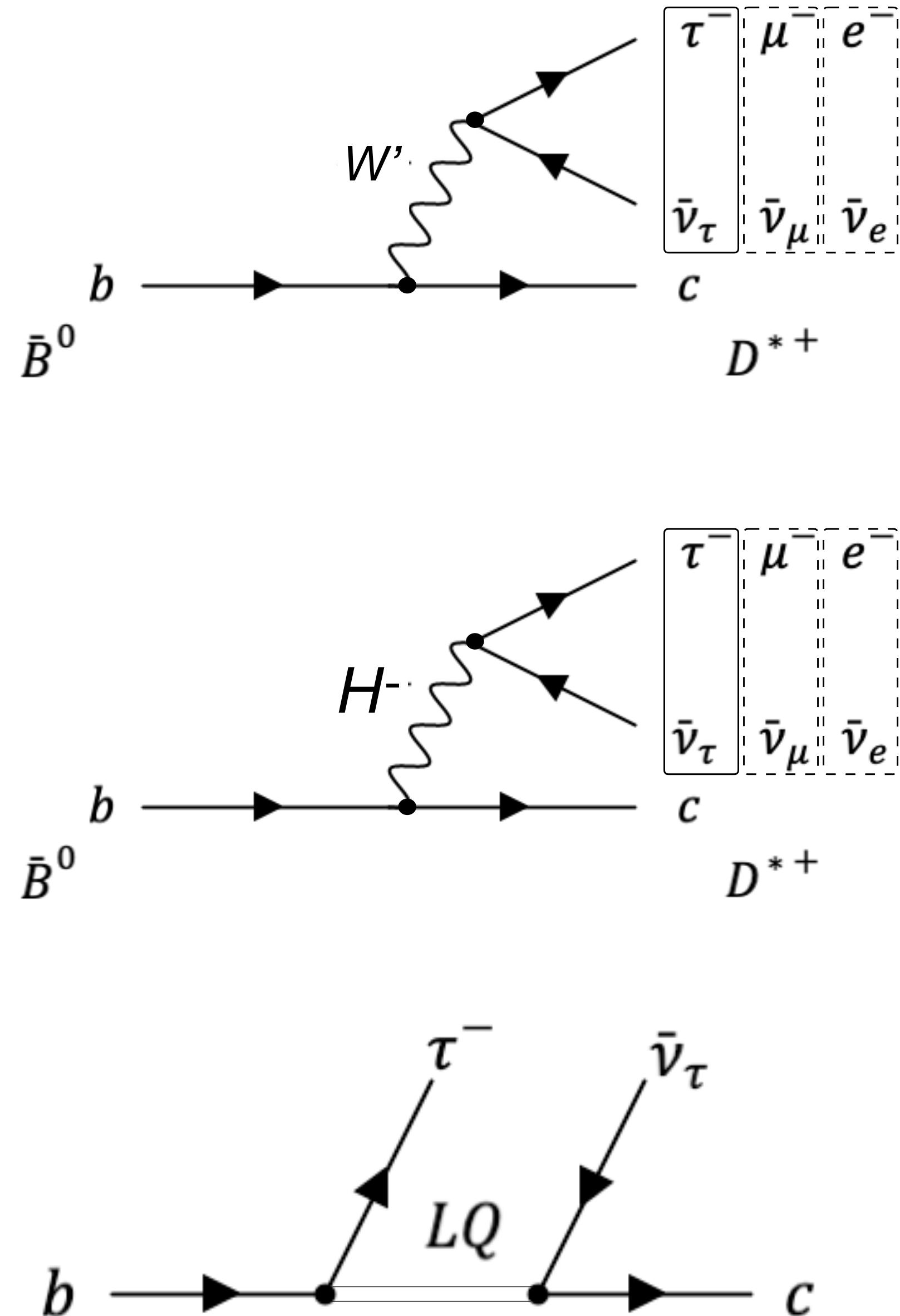
$3.8\sigma \rightarrow 3.1\sigma \rightarrow 3.3\sigma \rightarrow 3.2\sigma \rightarrow 3.2\sigma$

LHCb18 Belle19 2021 LHCb22 LHCb23

New physics scenarios

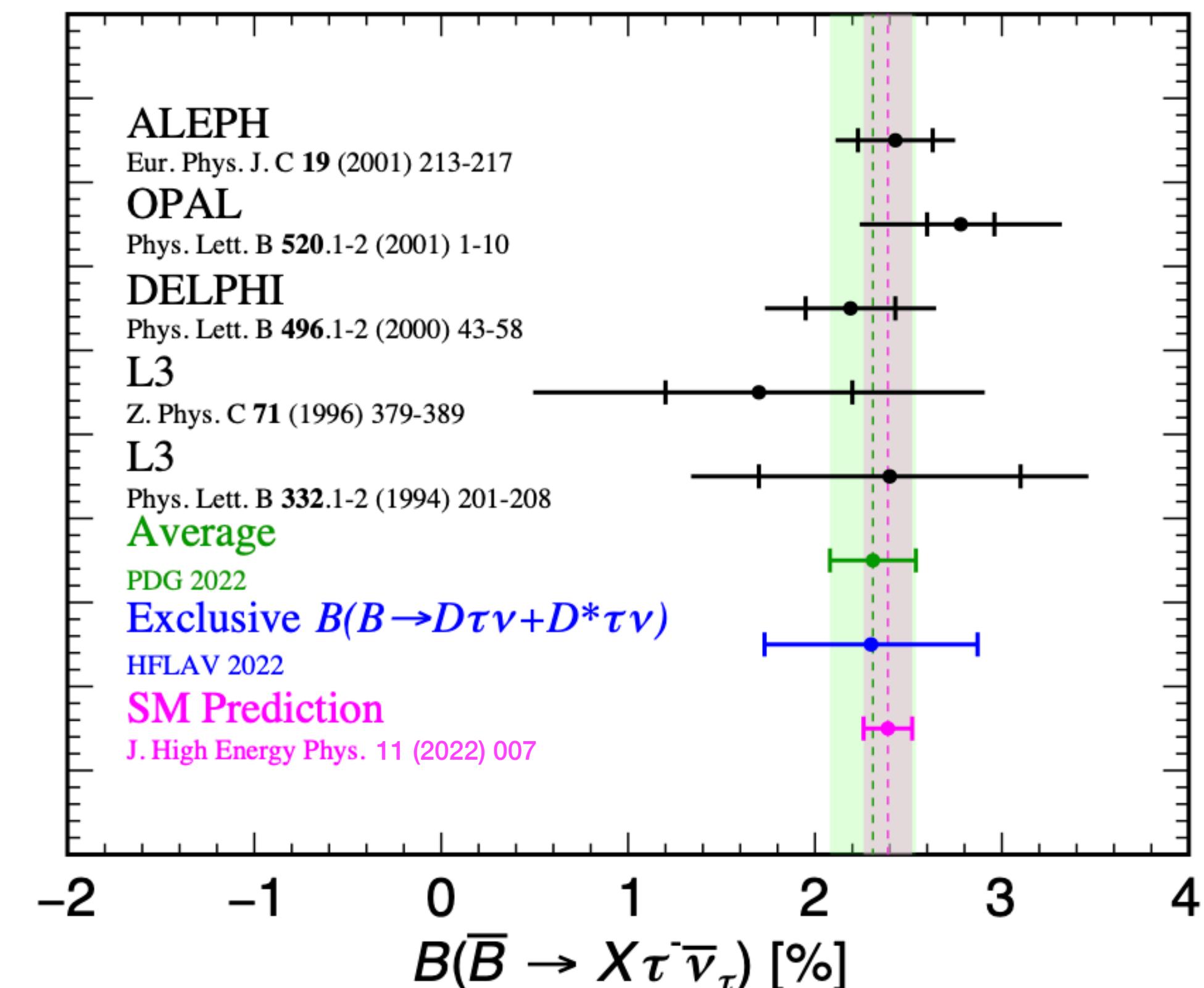
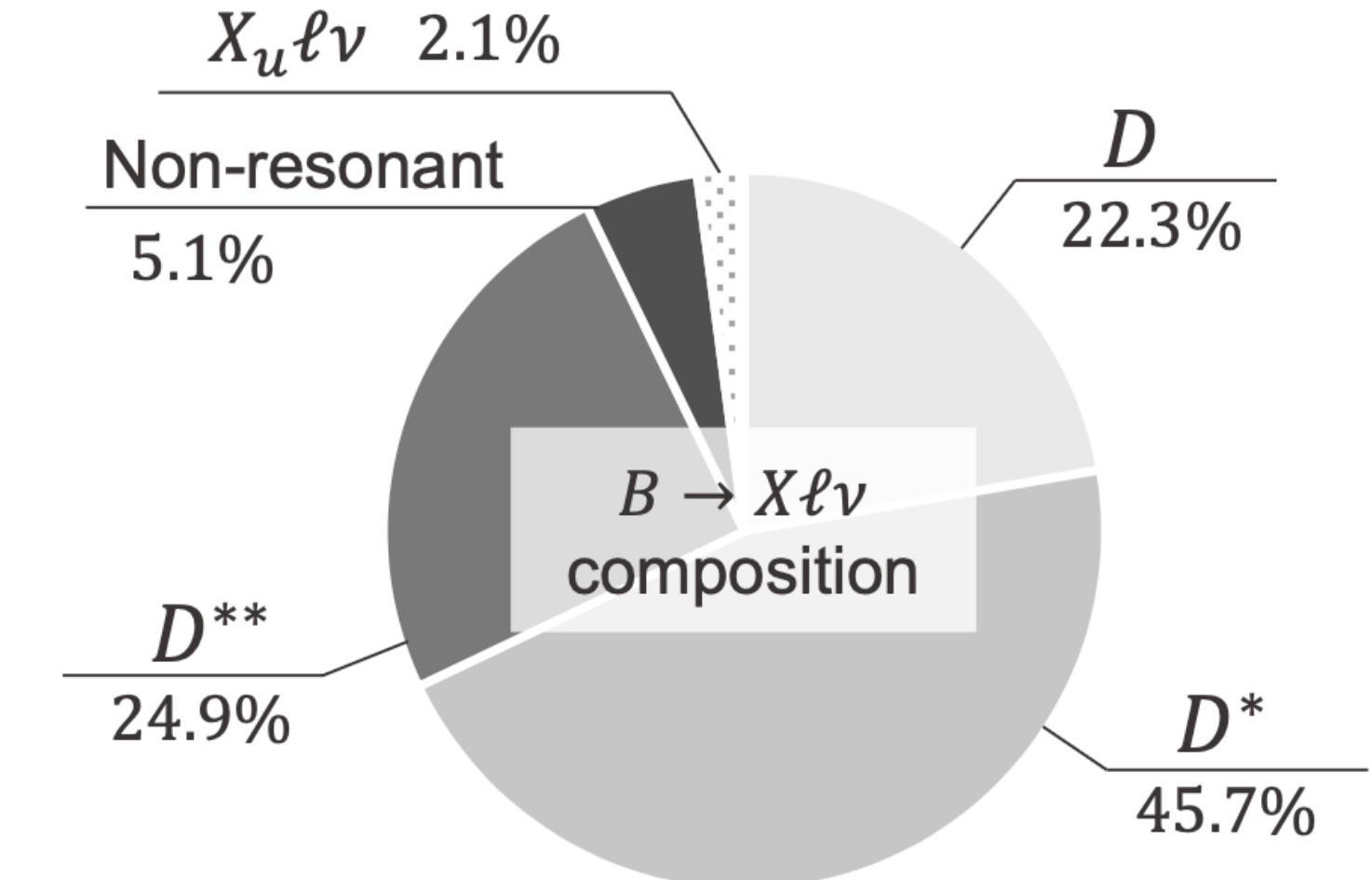
In general, there are three typical candidate scenarios to explain the anomaly observed in $R(D^{(*)})$

- Heavy vector bosons
 - Constrained from $W' \rightarrow \tau\nu$ and $Z' \rightarrow \tau\tau$ search
- Charged Higgs
 - Constrained from $B_c \rightarrow \tau\nu$ and $H^\pm \rightarrow \tau\nu$, still allowed
 - Previously, it was rejected by $B_c \rightarrow \tau\nu$ measurement, however, recovered by recalculating the B_c lifetime.
[arXiv:2201.06565](https://arxiv.org/abs/2201.06565)
- Leptoquark
 - $gg \rightarrow LQ \ LQ^*$, still broad parameter regions are allowed



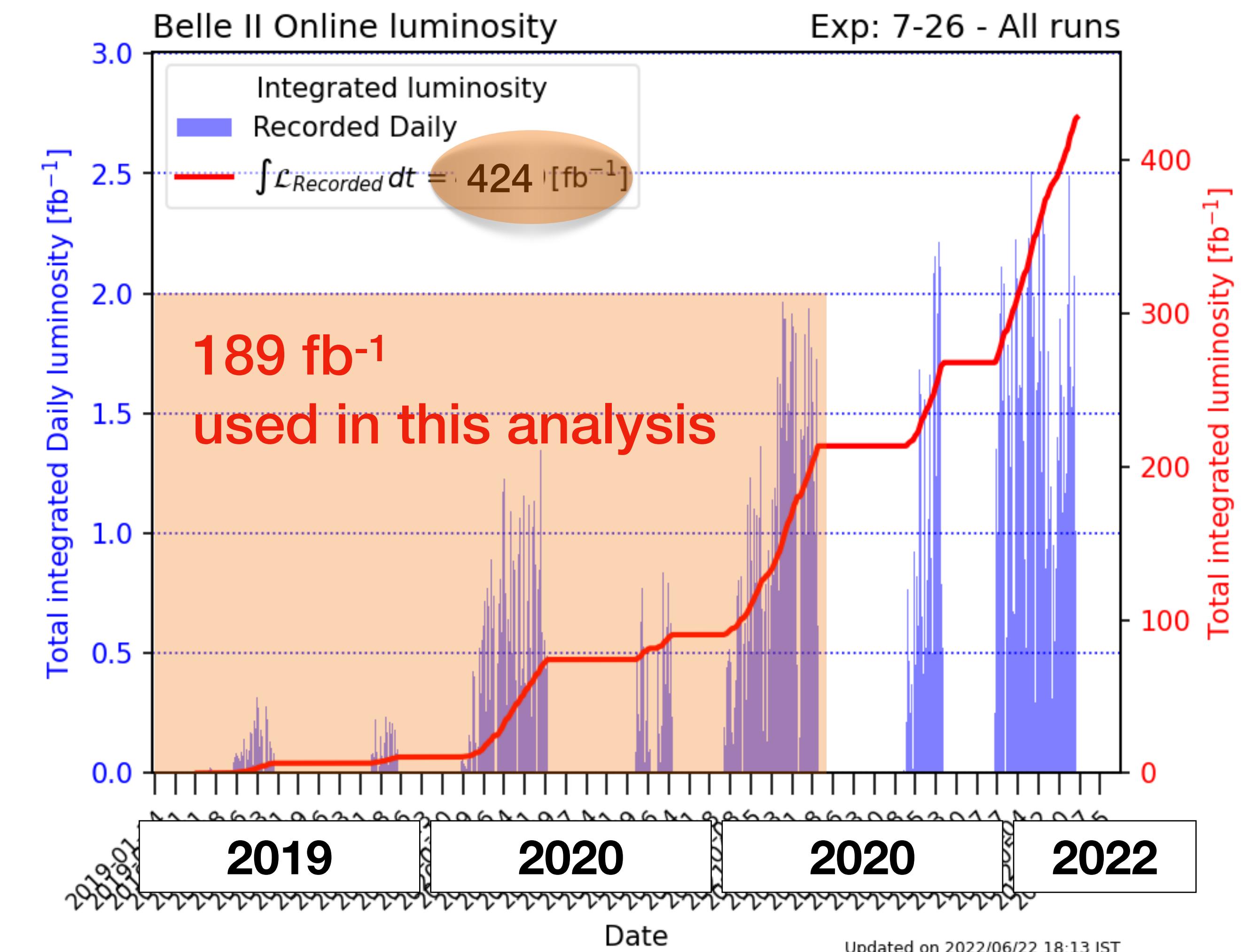
LFU test by $R(X_{\tau/\ell})$ measurement

- Breakdown of $B \rightarrow Xl\nu$ branching fractions
 - ~ 2/3 overlap with D and D^*
 - ~ 3/4 D decay to $\nu, K_L^0, n\pi \dots$
 - ~ 1/3 contribution from D^{**} and nonresonant X_c
- Multiple LEP experiments measured $Br(B \rightarrow X\tau\nu)$
 - $Br(B \rightarrow X\tau\nu)$ are completely saturated by D/D^* BFs
→ An update measurement is needed
- $R(X)$ is critical cross-check of $R(D^{(*)})$, a partially complementary test of LFU
- $R(X_{\tau/\ell}) = \frac{Br(\bar{B} \rightarrow X\tau^-\bar{\nu}_\tau)}{Br(\bar{B} \rightarrow X\ell^-\bar{\nu}_\ell)}$
- $R(X)$ has never been measured



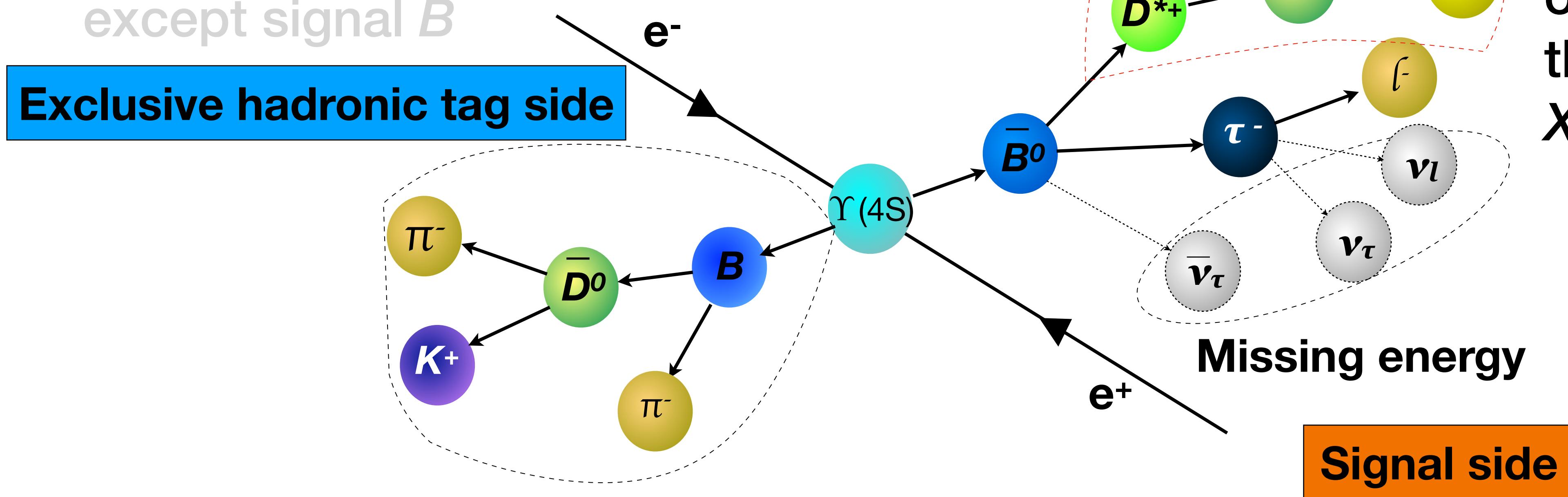
Status of B anomaly measurements at Belle II

- 424 fb^{-1} until Long Shutdown (LS) 1,
~363 fb^{-1} on $\gamma(4S)$
 - Belle: 1 ab^{-1}
- First $R(X_{e/\mu})$ result at Belle II using 189 fb^{-1} data-set
- First $R(D^*)$ measurement at Belle II using 189 fb^{-1} data-set targeting the end of spring 2023
- Other three $R(D^{(*)})$ and a $R(X_{\tau/\ell})$ analyses with different tagging methods are on-going



Tagging methods

- B tagging is necessary to measure $B \rightarrow X / D^* \tau \nu$, $B \rightarrow X / D^* l \nu$ ($\nu \geq 2$) simultaneously
- Hadronic tag
- Exclusive tag
 - Fully reconstruct $B \rightarrow D^{(*)}(/J/\psi/\Lambda)X$
 - Tagging efficiency 0.2~0.4%
 - less background
- Inclusive tag
 - Reconstruct tag B with all particles except signal B



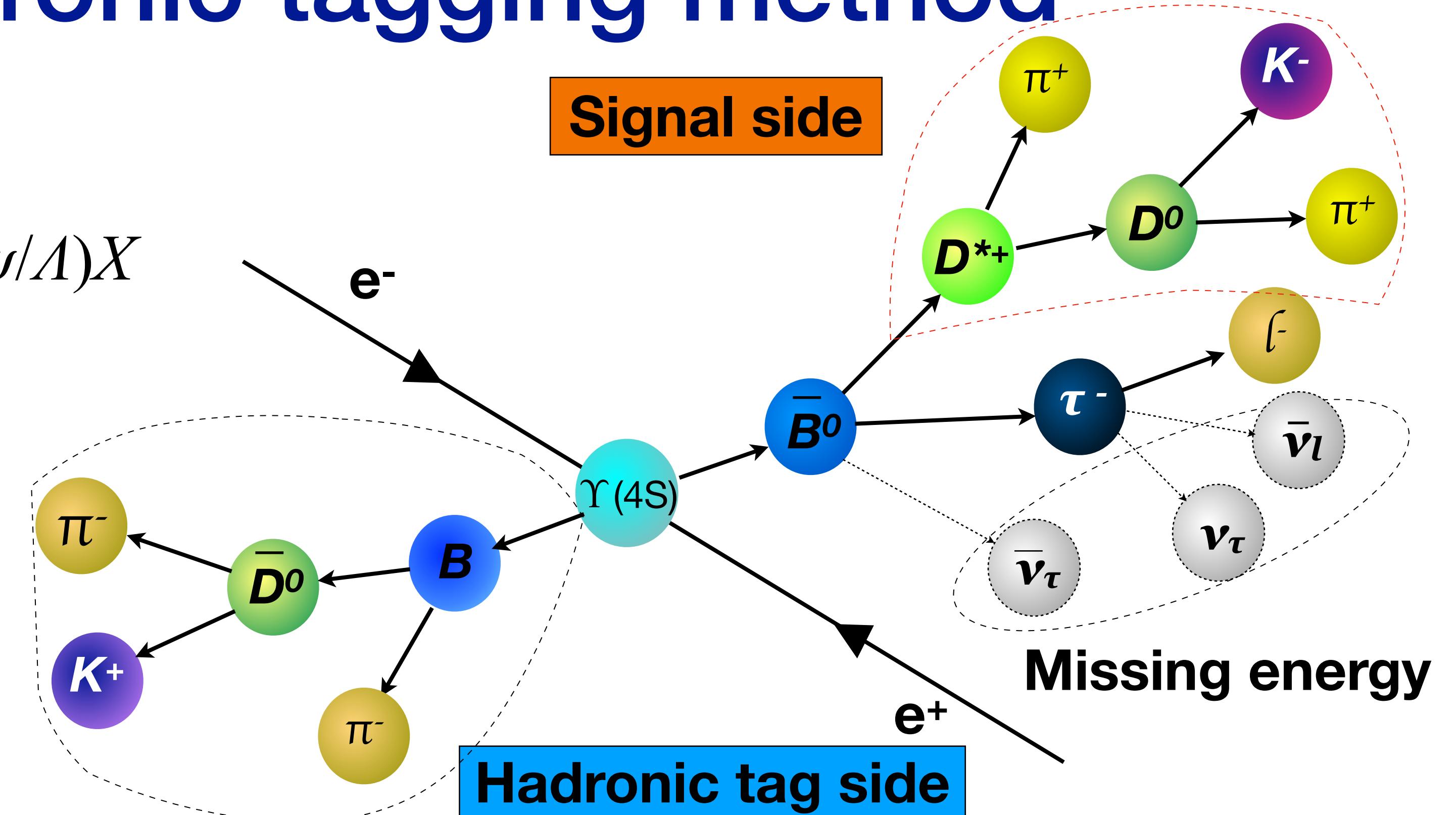
- Semileptonic tag

- Reconstruct $B \rightarrow D^{(*)} l \nu$
- Tagging efficiency $\sim 0.5\%$
- More background

X : reconstruct other particles than a lepton as X on signal side

Exclusive hadronic tagging method

- Hadronic tag
- Exclusive tag
 - Fully reconstruct $B \rightarrow D^{(*)}(/J/\psi/\Lambda)X$
 - Tagging efficiency 0.2~0.4%
 - less background



- Fully reconstruct one of the B mesons (B tag), possible to measure momentum of other B meson (B signal)
- Indirectly measure missing momentum of neutrinos in signal B decays
- $M_{\text{miss}}^2 = (p_{\text{beam}} - p_{B\text{tag}} - p_{D^{(*)}} - p_\ell)^2$
- E_{ECL} unassigned neutral energy in the calorimeter $E_{\text{ECL}} = \sum_i E_i^\gamma$

} Fitting variables for yields determination

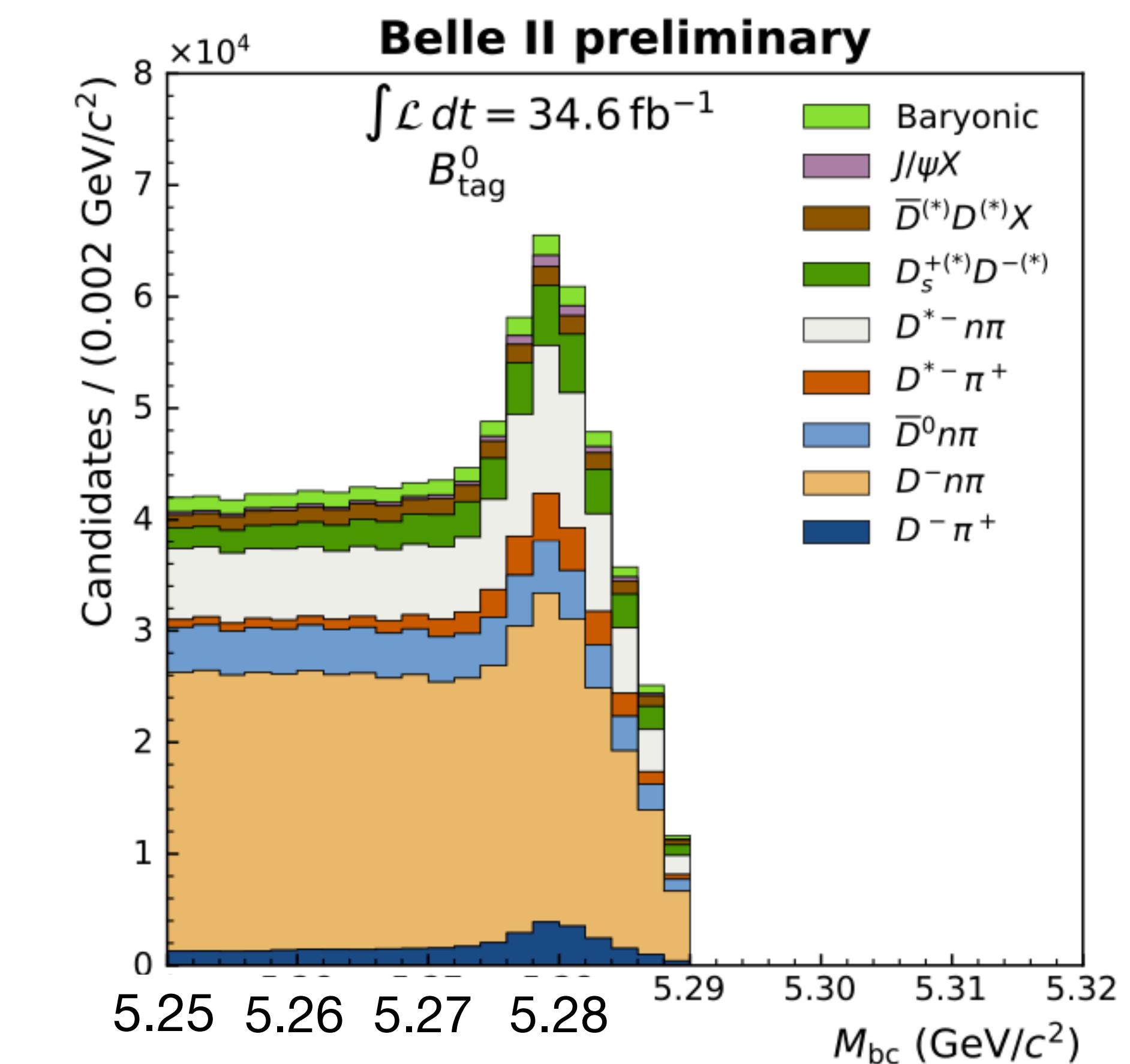
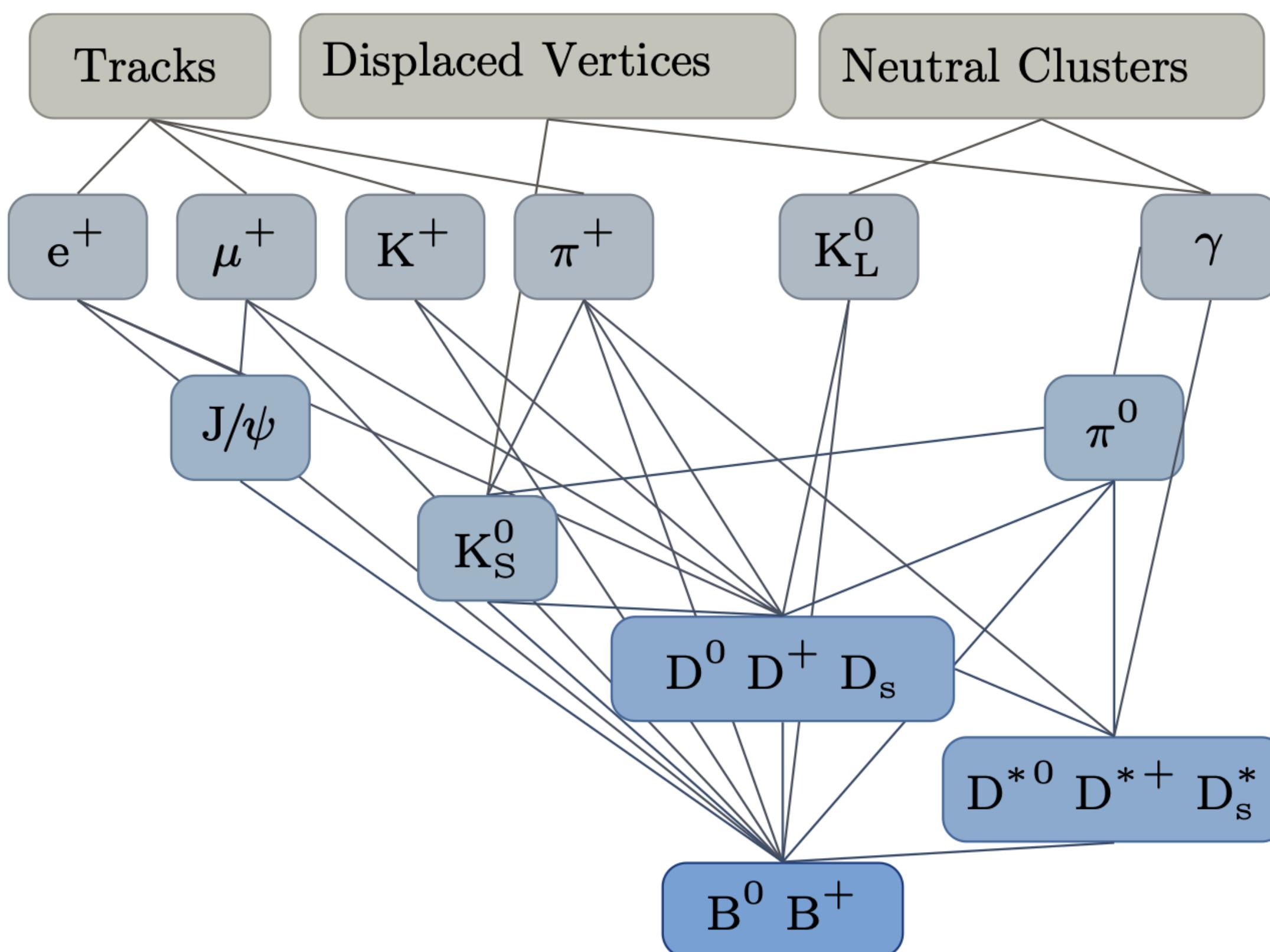
Hadronic tag reconstruction at Belle II

- Hadronic tagging reconstruction : Full Event Interpretation (FEI) trained 200 Boost Decision Tree (BDT) to reconstruct ~100 decay channels, ~10,000 B decay chains

[arXiv:2008.06096](https://arxiv.org/abs/2008.06096)

- $\varepsilon=0.30\%$ for B^\pm **10-30% increased**
- $\varepsilon=0.23\%$ for B^0
- $\varepsilon=0.28\%$ for B^\pm @Belle
- $\varepsilon=0.18\%$ for B^0 @Belle

Comp. and Soft. For Big Sci. 3, 6 (2019)

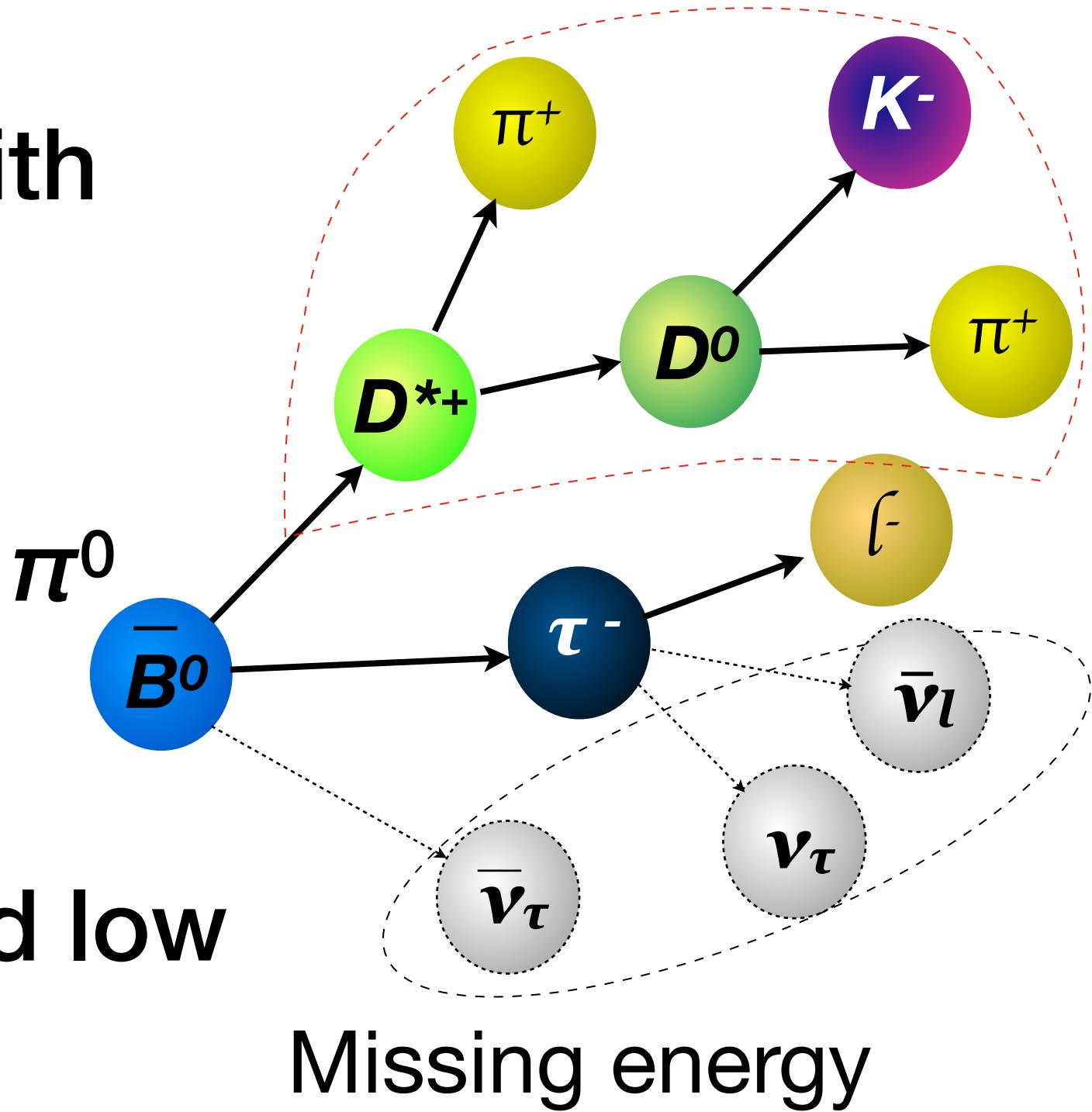


$$m_{bc} = \sqrt{(E_{\text{beam}}^*)^2 - (p_B^*)^2}$$

Signal side reconstruction

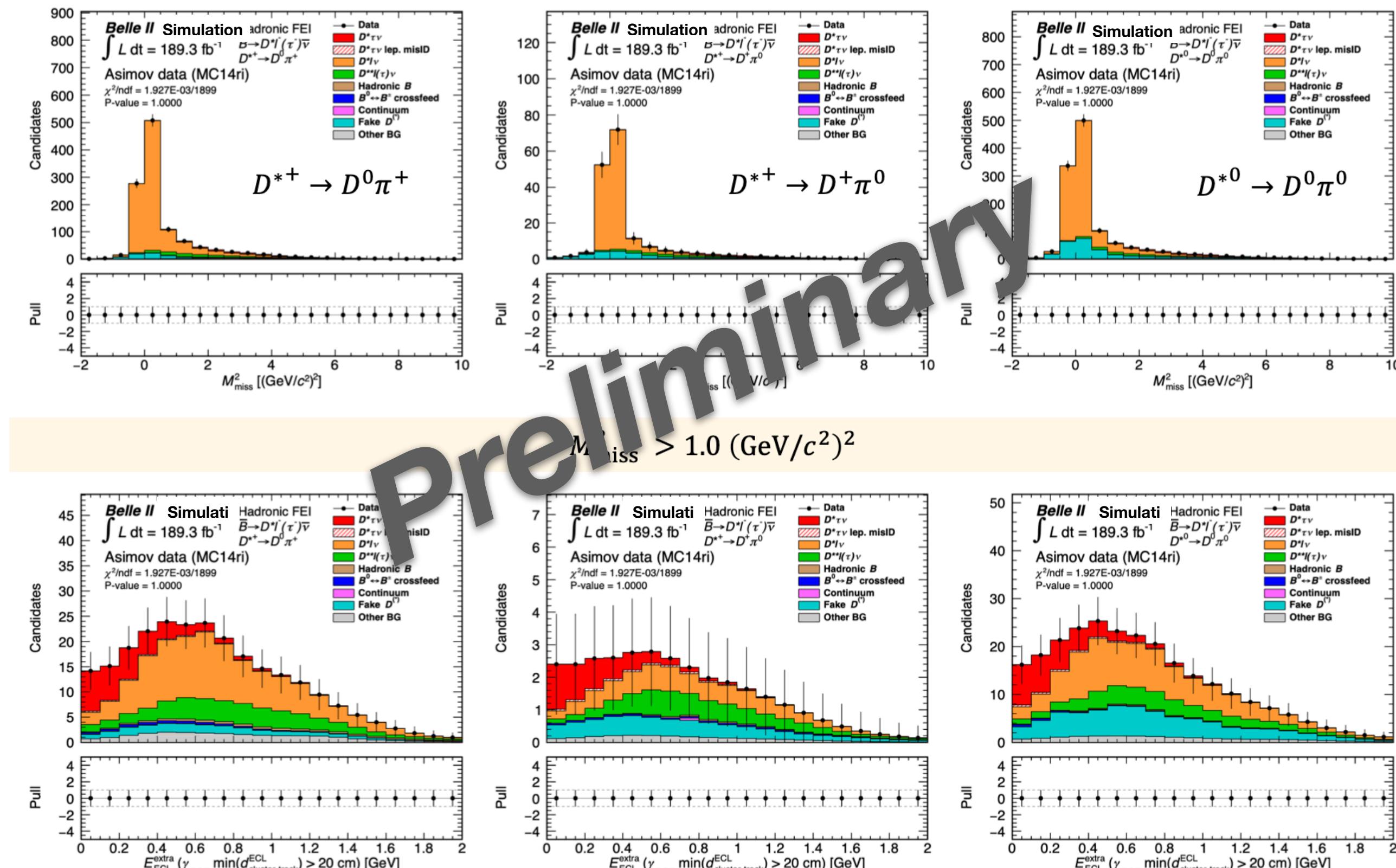
D^* decays	D decays
$D^{*+} \rightarrow D^0\pi^+$	$D^0 \rightarrow K^-\pi^+\pi^0$
	$D^0 \rightarrow K^-\pi^+\pi^-\pi^+$
	$D^0 \rightarrow K_S^0\pi^+\pi^-\pi^0$
	$D^0 \rightarrow K^-\pi^+$
	$D^0 \rightarrow K_S^0\pi^+\pi^-$
	$D^0 \rightarrow K_S^0\pi^0$
	$D^0 \rightarrow K^-K^+$
	$D^0 \rightarrow \pi^+\pi^-$
$D^{*+} \rightarrow D^+\pi^0$	$D^+ \rightarrow K^-\pi^+\pi^+$
	$D^+ \rightarrow K_S^0\pi^+$
	$D^+ \rightarrow K^-K^+\pi^+$
	$D^+ \rightarrow K_S^0K^+$
$D^{*0} \rightarrow D^0\pi^0$	$D^0 \rightarrow K^-\pi^+\pi^0$
	$D^0 \rightarrow K^-\pi^+\pi^-\pi^+$
	$D^0 \rightarrow K_S^0\pi^+\pi^-\pi^0$
	$D^0 \rightarrow K^-\pi^+$
	$D^0 \rightarrow K_S^0\pi^+\pi^-$
	$D^0 \rightarrow K_S^0\pi^0$
	$D^0 \rightarrow K^-K^+$
	$D^0 \rightarrow \pi^+\pi^-$

- Reconstruct $B \rightarrow D^*\tau\nu$ and $B \rightarrow D^*l\nu$ with same selections
- τ lepton reconstruct with $\ell(e, \mu)\nu\nu$
- D meson reconstruct with $K^\pm, \pi^\pm, K_s, \pi^0$
 - 8 D^0 modes ($\text{Br} \sim 36\%$)
 - 4 D^+ modes ($\text{Br} \sim 12.3\%$)
- D^* meson reconstruct with D^+/D^0 and low momentum π^+/π^0
 - $D^{*+} \rightarrow D^0\pi^+ / D^+\pi^0$ ($\text{Br} \sim 98\%$)
 - $D^{*0} \rightarrow D^0\pi^0$ ($\text{Br} \sim 65\%$)
- Both neutral and charged B^\pm/B^0 mesons reconstruct with D^{*+}/D^{*0} and $\tau/\ell = (e, \mu)$



Belle II $R(D^*)$ sensitivity at 189 fb⁻¹

- Extracting $B \rightarrow D^* \tau \nu$, $B \rightarrow D^* l \nu$ yields by a two-dimensional simultaneously fit
 - $M_{\text{miss}}^2 = (p_{\text{beam}} - p_{B\text{tag}} - p_{D^{(*)}} - p_l)^2$
 - E_{ECL} unassigned neutral energy in the calorimeter
- The fit returns $R(D^*) = 0.254$, statistical uncertainty is +17/-16% at 189 fb⁻¹
- Belle '15 statistical uncertainty is 13% (15%@ $R(D^*) = 0.254$)



$$R(D^*) = 0.254^{+0.043}_{-0.040} \left(\begin{array}{l} +17\% \\ -16\% \end{array} \right)$$

Preliminary systematic uncertainties

- Each source of the uncertainty changes the PDF shape, consequently modify the fitted $R(D^*)$ value

Source	Uncertainty	
Statistical uncertainty	+0.043	+17%
	-0.040	-16%
E_{ECL} PDF shape	+0.028	+10.8%
	-0.015	-8.0%
MC statistics	+0.010	+4.1%
	-0.007	-2.7%
$B \rightarrow D^{**} l \nu$ branching ratios	+0.012	+2.7%
	-0.010	-1.9%
...		

Statistical uncertainty dominated

- Currently, finalize the systematics uncertainty
 - Especially, checking the $B \rightarrow D^{**} l \nu$ modeling
 - Result coming soon, stay tuned

Light-lepton universality test $R(X_{e/\mu})$

[arXiv:2301.08266](https://arxiv.org/abs/2301.08266)

- Test light-lepton universality by measuring $R(X_{e/\mu}) = \frac{Br(\bar{B} \rightarrow X e^- \bar{\nu}_e)}{Br(\bar{B} \rightarrow X \mu^- \bar{\nu}_\mu)}$

- $R(X)$ has never been measured

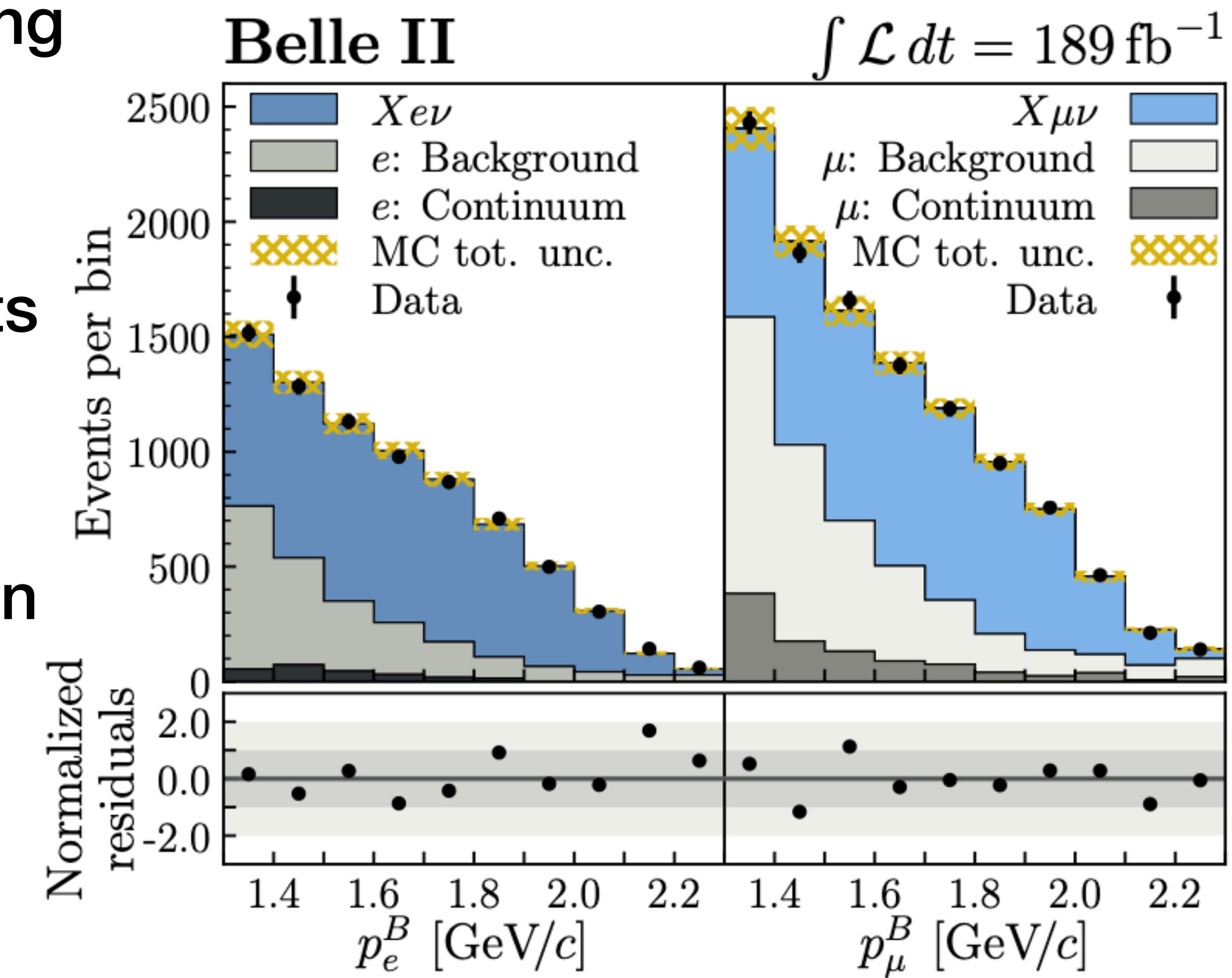
- Approach employed at Belle II: M_X reweighting

- Events weights from data/MC ratio in M_X distribution, applied to all events

- q^2, M_{miss}^2 can be expressed by reliable parts and M_X part

- Signal yields are extracted by a binned maximum-likelihood simultaneous fit to lepton momentum

Control channel ($B^0 \bar{B}^0 / B^+ \bar{B}^-$)



Light-lepton universality test $R(X_{e/\mu})$

[arXiv:2301.08266](https://arxiv.org/abs/2301.08266)

- First $R(X_{e/\mu})$ measurement

$$R(X_{e/\mu}) = 1.033 \pm 0.010 \text{ (stat)} \pm 0.019 \text{ (syst)}$$

- Most precise BF based LFU test of e- μ universality with semileptonic B decays to date

- Consistent with SM value by 1.2σ

$$R(X_{e/\mu})_{\text{SM}} = 1.006 \pm 0.001 \quad \text{JHEP 11 (2022) 007}$$

- Compatible with exclusive Belle measurements

[PRD 100, 052007 \(2019\)](https://doi.org/10.1103/PRD.100.052007)

$$R(D^*_{e/\mu}) = 1.01 \pm 0.01 \text{ (stat)} \pm 0.03 \text{ (syst)}$$

$$R(D^*_{e/\mu}) = 0.990 \pm 0.021 \text{ (stat)} \pm 0.023 \text{ (syst)}$$

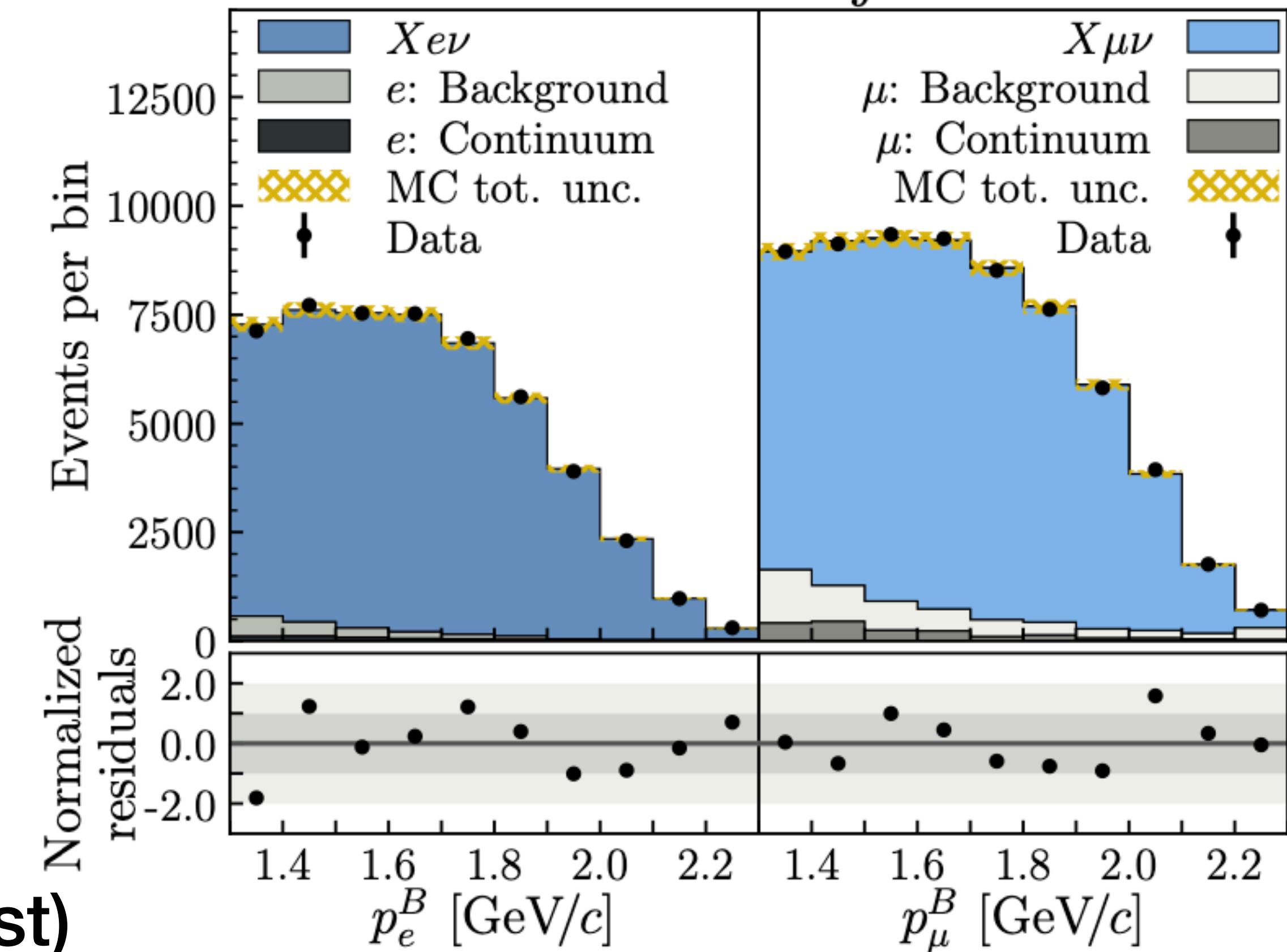
[arXiv:2301.07529](https://arxiv.org/abs/2301.07529)

- NOTE: $R(X_{e/\mu})$ result will have a update soon, but will not change the conclusion

Signal channel ($B^0 \bar{B}^0 / B^+ B^-$)

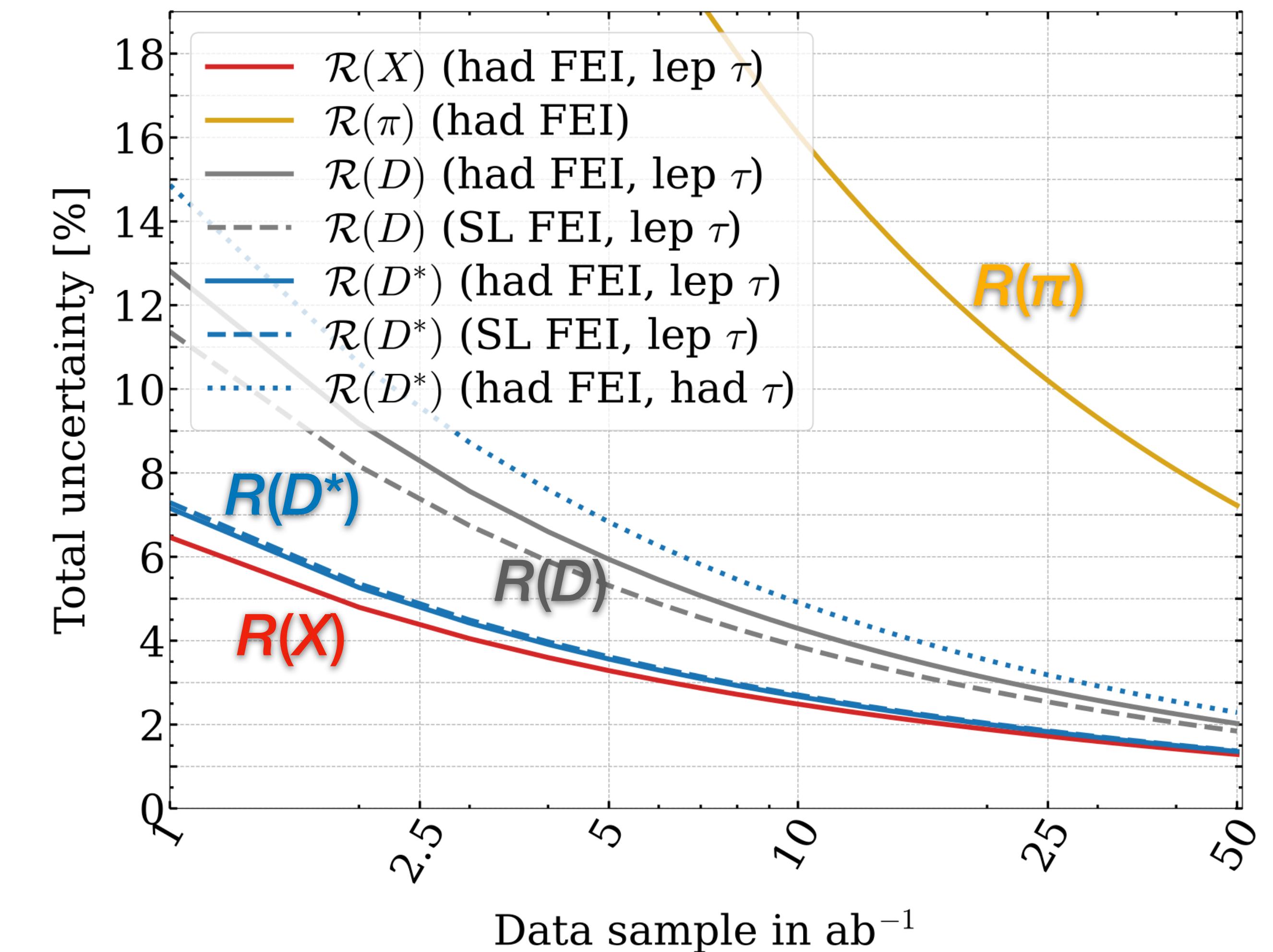
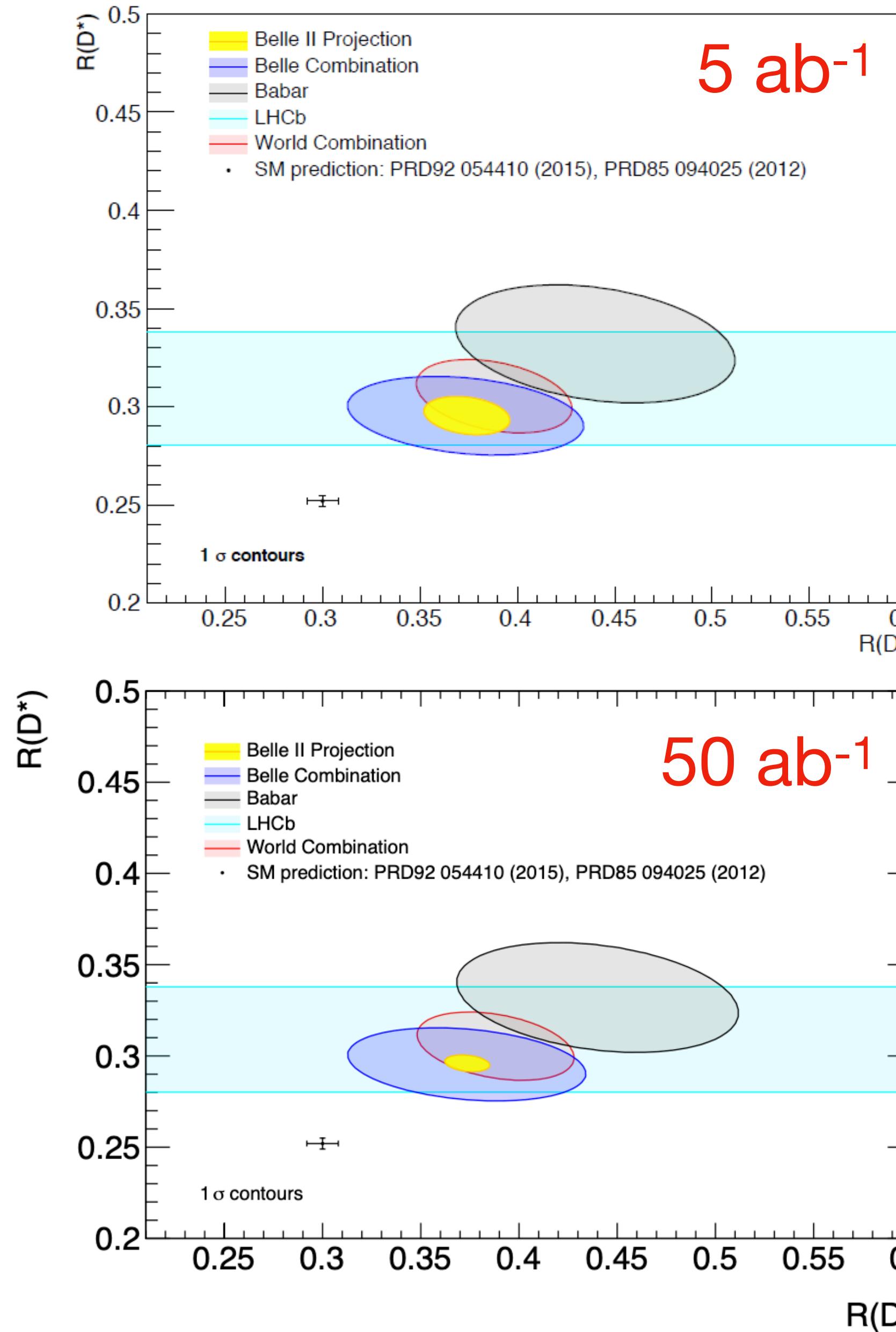
Belle II

$$\int \mathcal{L} dt = 189 \text{ fb}^{-1}$$



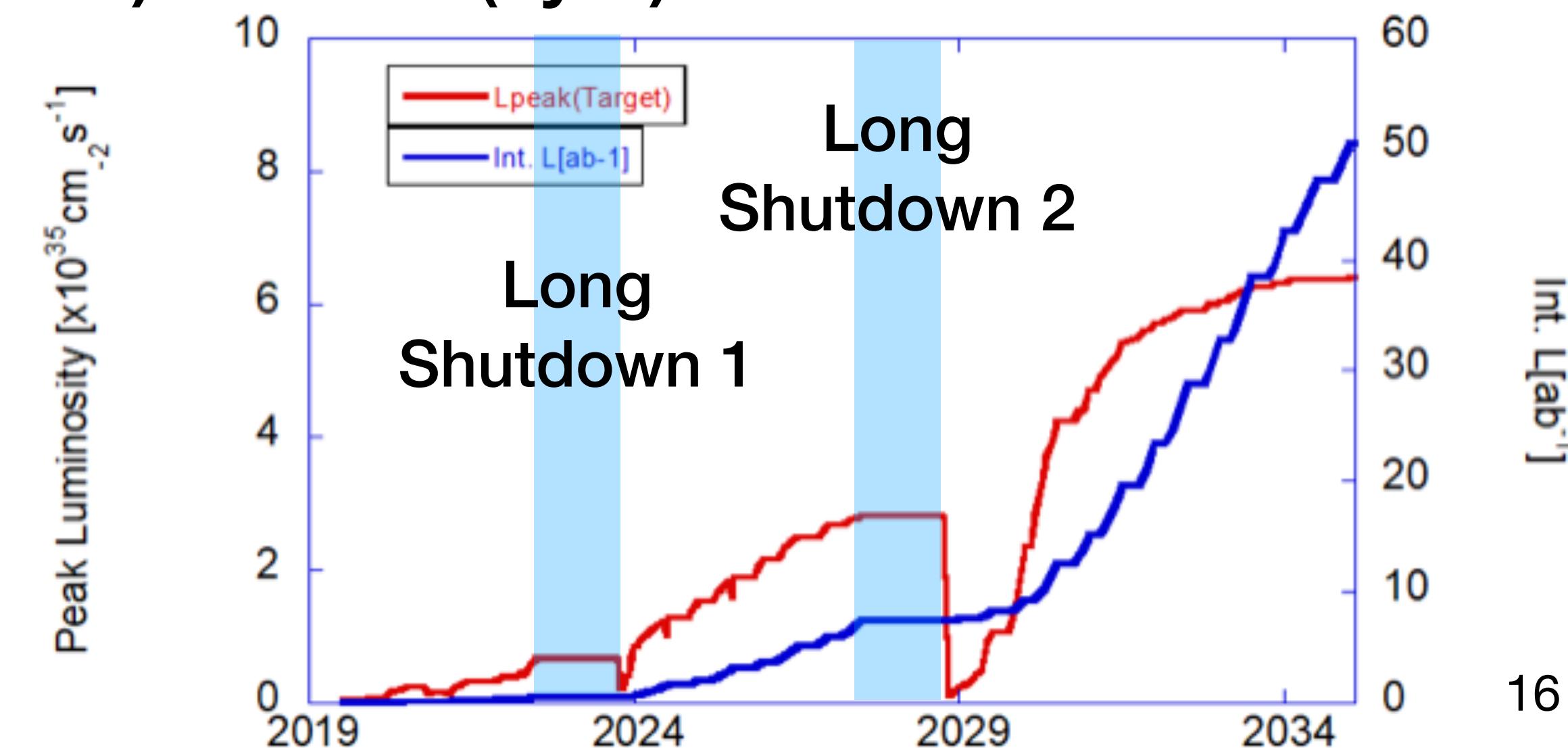
Expected sensitivity anomaly measurement at Belle II

The Belle II Physics Book, PTEP 2019, 123C01



Summary and prospects

- $R(D^*)$ shows 3.2σ deviation between experimental average value and standard model prediction
 - Hint of Lepton Flavor Universality Violation
- Belle II performed $R(D^*)$ and $R(X_{e/\mu})$ with hadronic tagging based on **189 fb $^{-1}$** data
 - Expected statistical uncertainty of $R(D^*)$ is **+17/-16%** at 189 fb $^{-1}$
 - Evaluated most of the systematic uncertainty for $R(D^*)$, <- statistical uncertainty dominated, result coming soon
 - First measurement of $R(X_{e/\mu}) = 1.033 \pm 0.010$ (stat) ± 0.019 (syst)
 - Consistent with SM by 1.2σ
- SuperKEKB/Belle II will resume operation in winter of 2023



Thank you