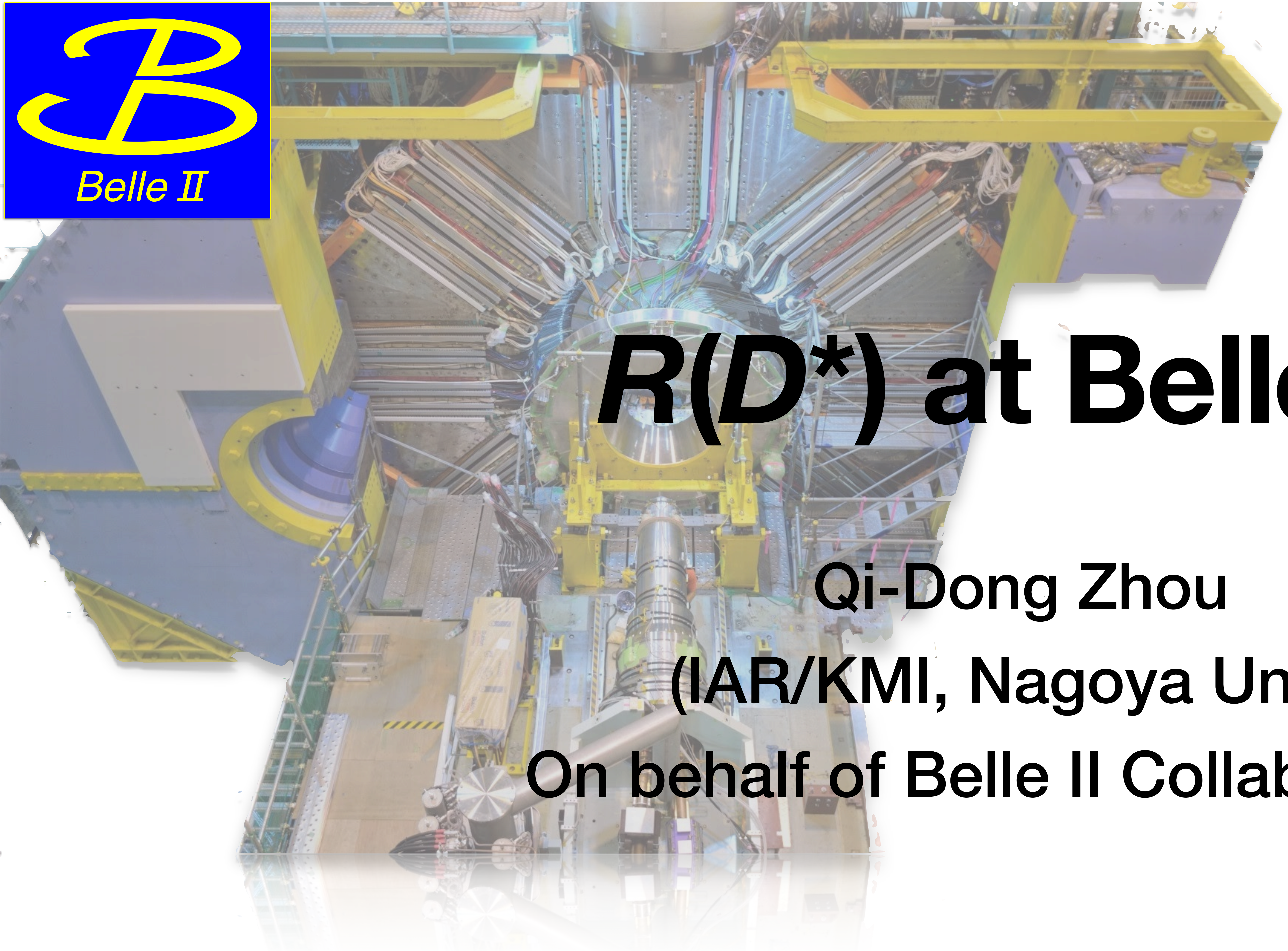


$R(D^*)$ at Belle II

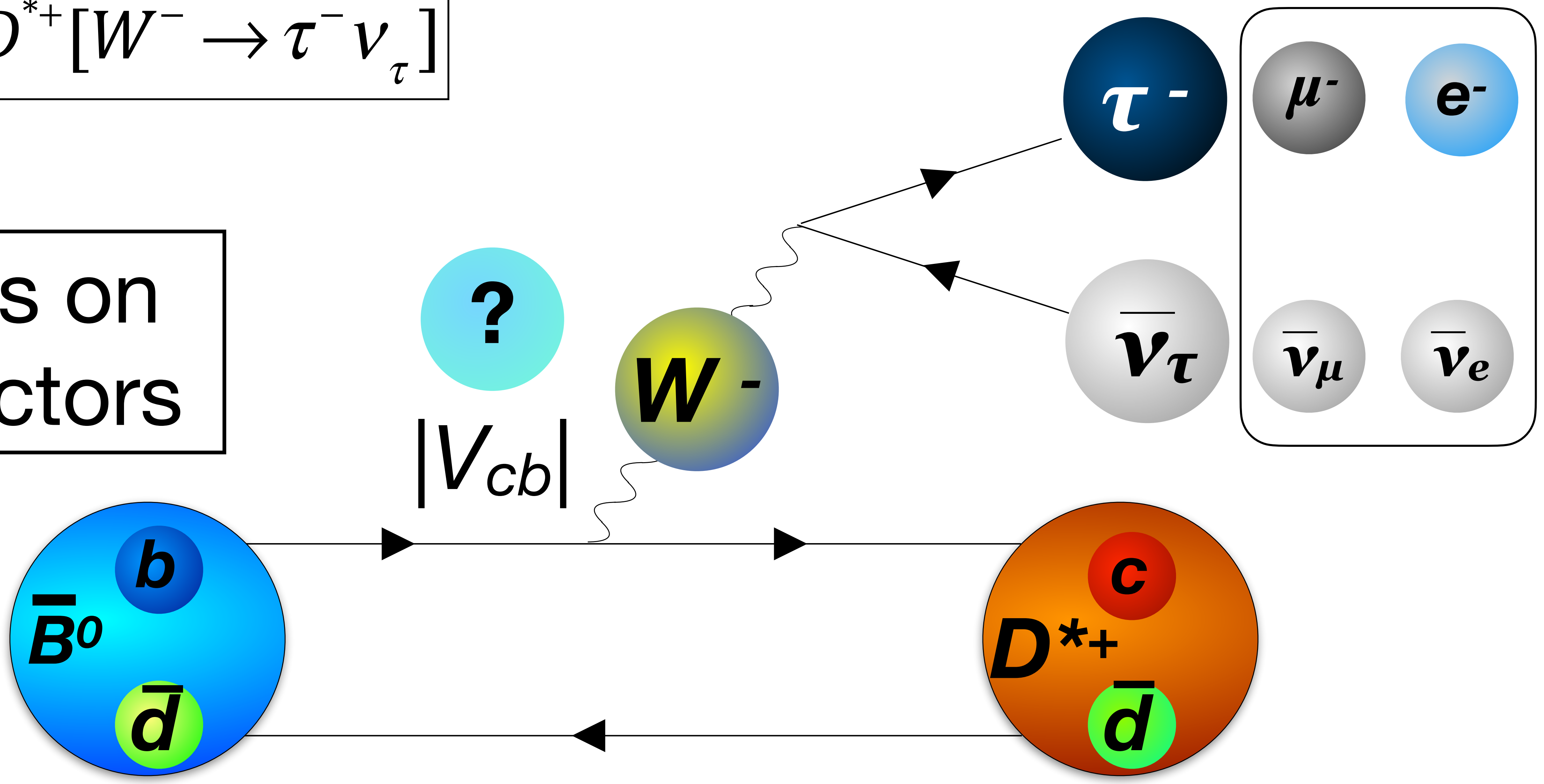
Qi-Dong Zhou
(IAR/KMI, Nagoya Univ.)
On behalf of Belle II Collaboration

Feb. 9 - 11, 2023, KEK Tsukuba Campus
Accomplishments and mysteries in quark flavor physics (KM 50) /
KEK Flavor Factories workshop (KEK-FF 2023)

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

$\overline{B}^0 \to D^{*+}[W^- \to \tau^- \overline{\nu}_\tau]$

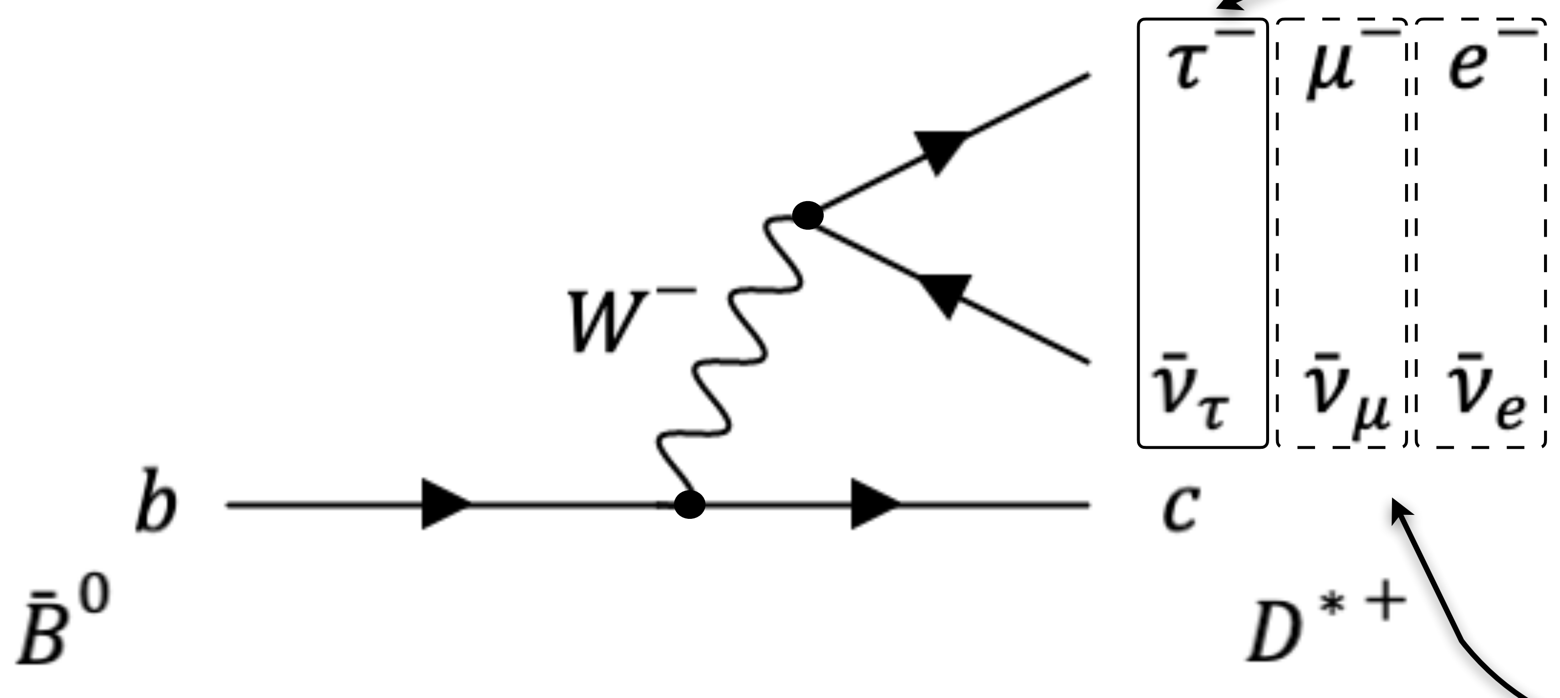
Sizable uncertainties on $|V_{cb}|$ and the form factors



- Universality of the lepton coupling to the *W* gauge boson (Symmetry)
  - Lepton Flavor Universality (LFU) is fundamental theory of Standard Model (SM)

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



$$R(D^{(*)}) = \frac{Br(\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau)}{Br(\bar{B}^0 \to D^{(*)+}\ell^-\bar{\nu}_\ell)}$$

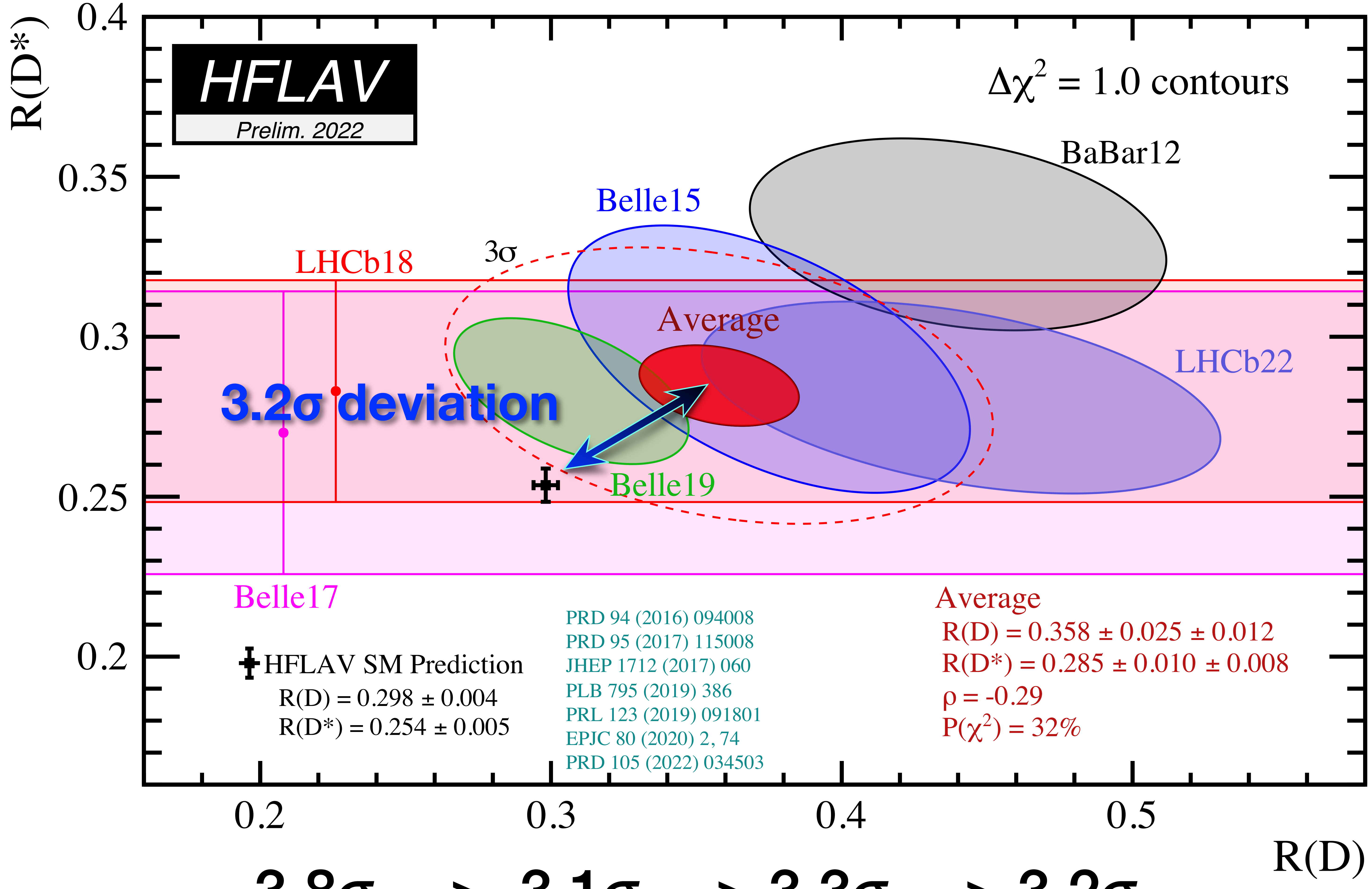
- Ratio of branch fractions cancel out most of the uncertainties on $|V_{cb}|$, form factors and the experimental systematics

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

Experiment	Tag method	τ decay	Correlation(stat/syst/total)	$R(D)$	$R(D^*)$
Babar '12	Hadronic	$\ell\nu\nu$	-0.45/-0.07/-0.27	0.440 ± 0.058 ± 0.042	0.332 ± 0.024 ± 0.018
Belle '15	Hadronic	$\ell\nu\nu$	-0.56/-0.11/-0.49	0.375 ± 0.064 ± 0.026	0.293 ± 0.038 ± 0.015
LHCb '15	-	$\mu\nu\nu$		-	0.336 ± 0.027 ± 0.030
Belle '16	Semileptonic	$\ell\nu\nu$		-	0.302 ± 0.030 ± 0.011
Belle '17	Hadronic	$\pi\nu,\rho\nu$		-	0.270 ± 0.035 $^{+0.028}_{-0.025}$
LHCb '18	-	$\pi\pi\pi\nu$		-	0.283 ± 0.019 ± 0.029
Belle '20	semileptonic	$\ell\nu\nu$	-0.53/-0.51/-0.51	0.307 ± 0.037 ± 0.016	0.283 ± 0.018 ± 0.014
LHCb '22	-	$\mu\nu\nu$	-0.49/ /-0.43	0.441 ± 0.060 ± 0.066	0.281 ± 0.018 ± 0.024
Average	-	-	-0.43/-0.07/-0.29	0.358 ± 0.025 ± 0.012	0.285 ± 0.010 ± 0.008
SM				0.298 ± 0.004	0.254 ± 0.005

R(*D*) and *R*(*D**) anomaly

	Correlation(stat/syst/total)	*R*(*D*)	*R*(*D**)
Average	-0.43/-0.07/-0.29	0.358 ± 0.025 ± 0.012	0.285 ± 0.010 ± 0.008
SM		0.298 ± 0.004	0.254 ± 0.005

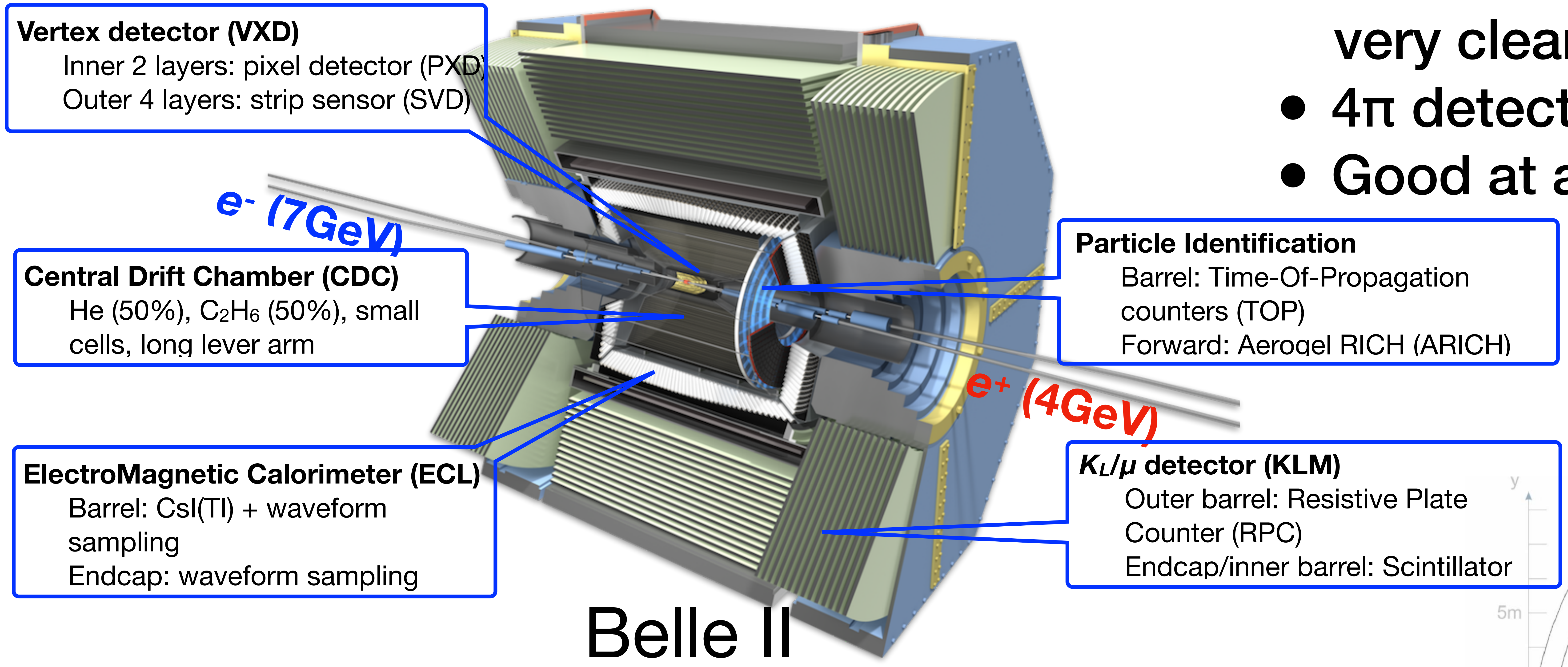


3.8σ —> 3.1σ —> 3.3σ —> 3.2σ

LHCb18 Belle19 2021 LHCb22

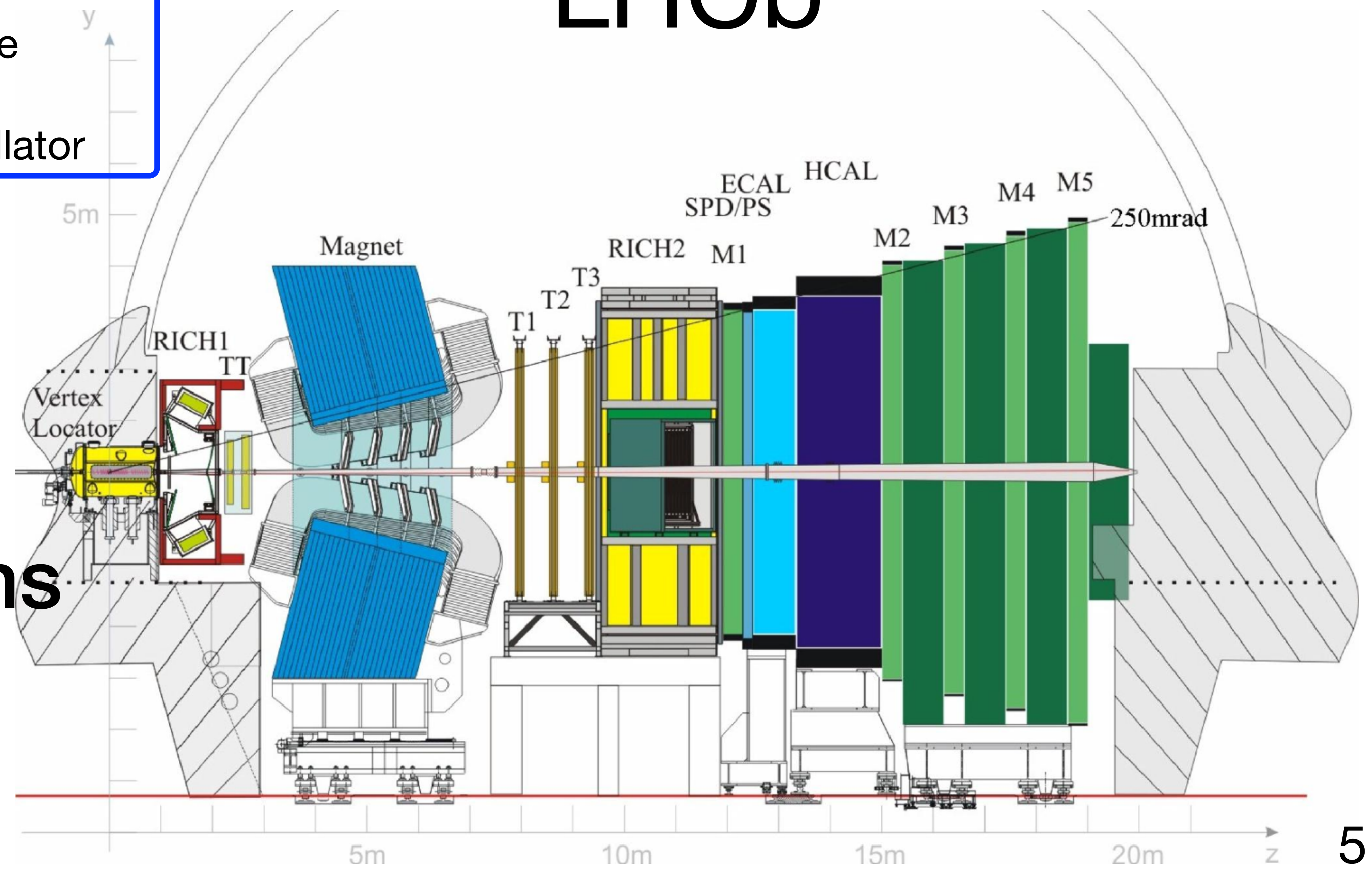
$R(D)$ and $R(D^*)$ experiments

- Experiments at B factory
  - $e^+e^- \to \Upsilon(4S) \to B\bar{B}$: very clean and well-known initial state
  - 4π detector surrounding the IP
  - Good at also measuring neutrals, π^0, γ



Belle II

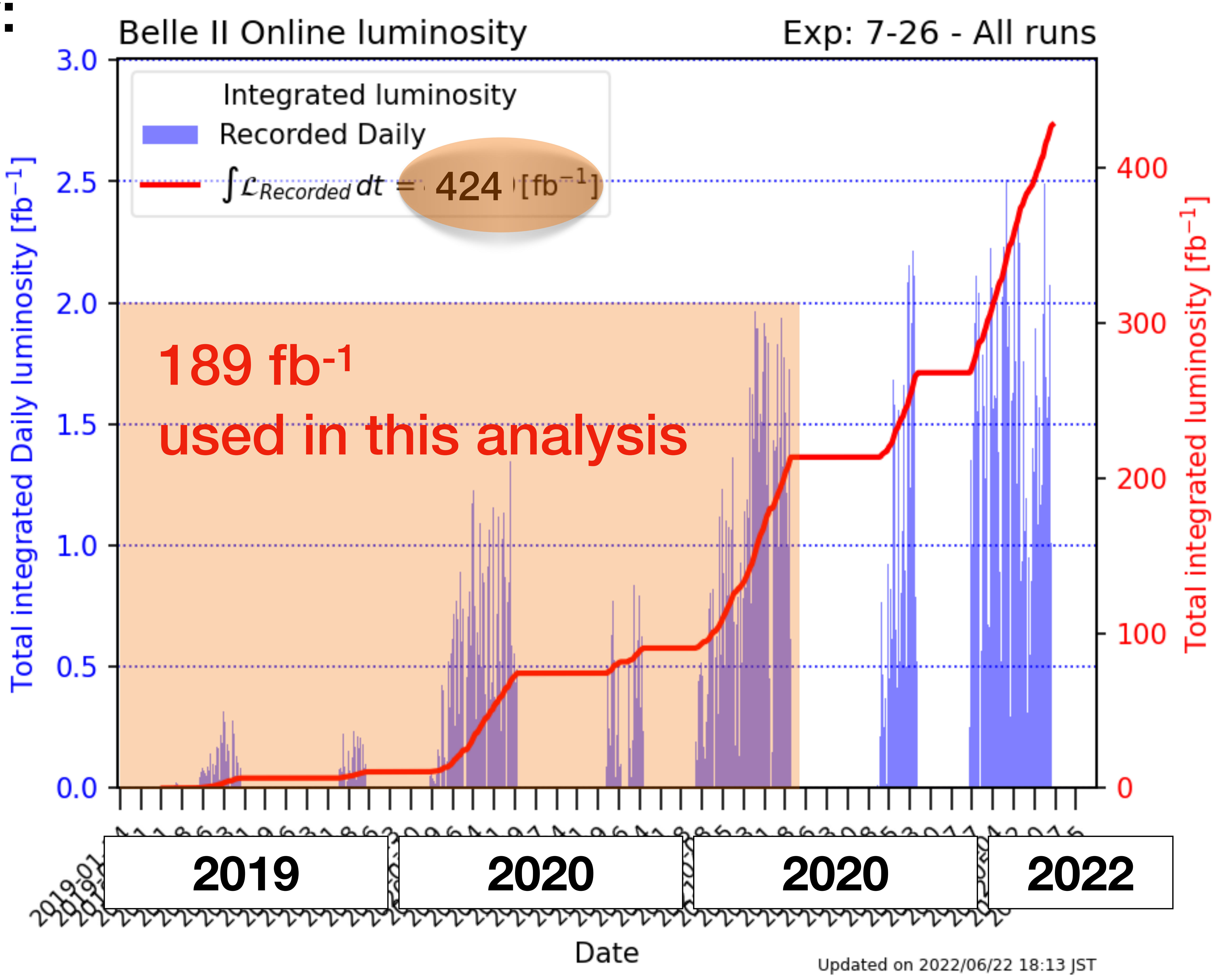
LHCb



- LHCb
  - Large amount of b hadrons produced in p-p collisions
  - Single arm detector covers forward region
  - Large boost, good separation of vertices

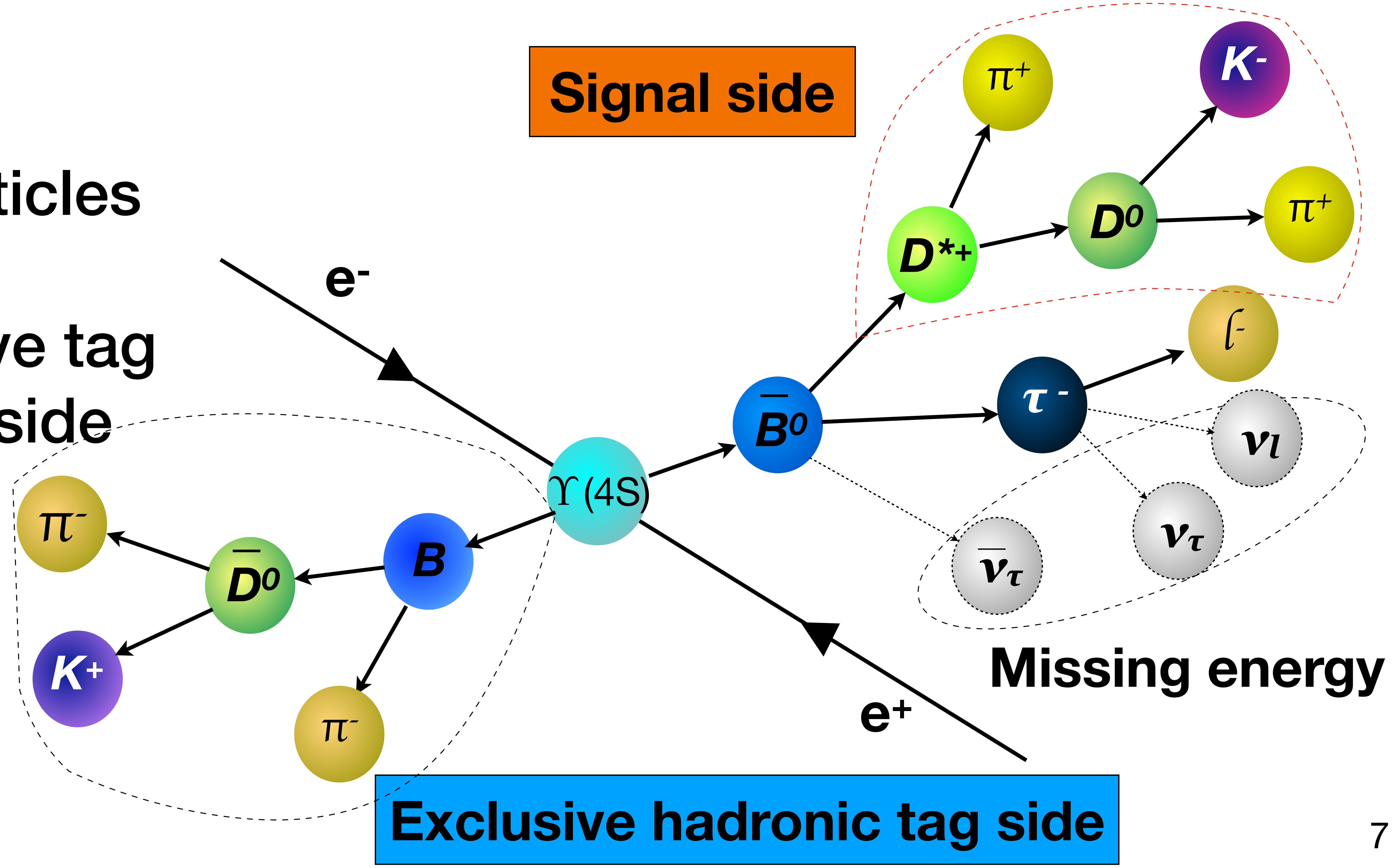
Data set for *R*(*D**) measurement

- World's highest instantaneous luminosity:
  $L = 4.7 \times 10^{34}\ cm^{-2}\ s^{-1}$
  KEKB record: $2.1 \times 10^{34}\ cm^{-2}\ s^{-1}$
- Belle II data taking efficiency ~90%
- 424 fb^{-1} until Long Shutdown (LS) 1, ~363 fb^{-1} on $\Upsilon(4S)$
  - Belle: 1 ab^{-1}
- First *R*(*D**) measurement at Belle II using 189 fb^{-1} data-set targeting the end of spring 2023



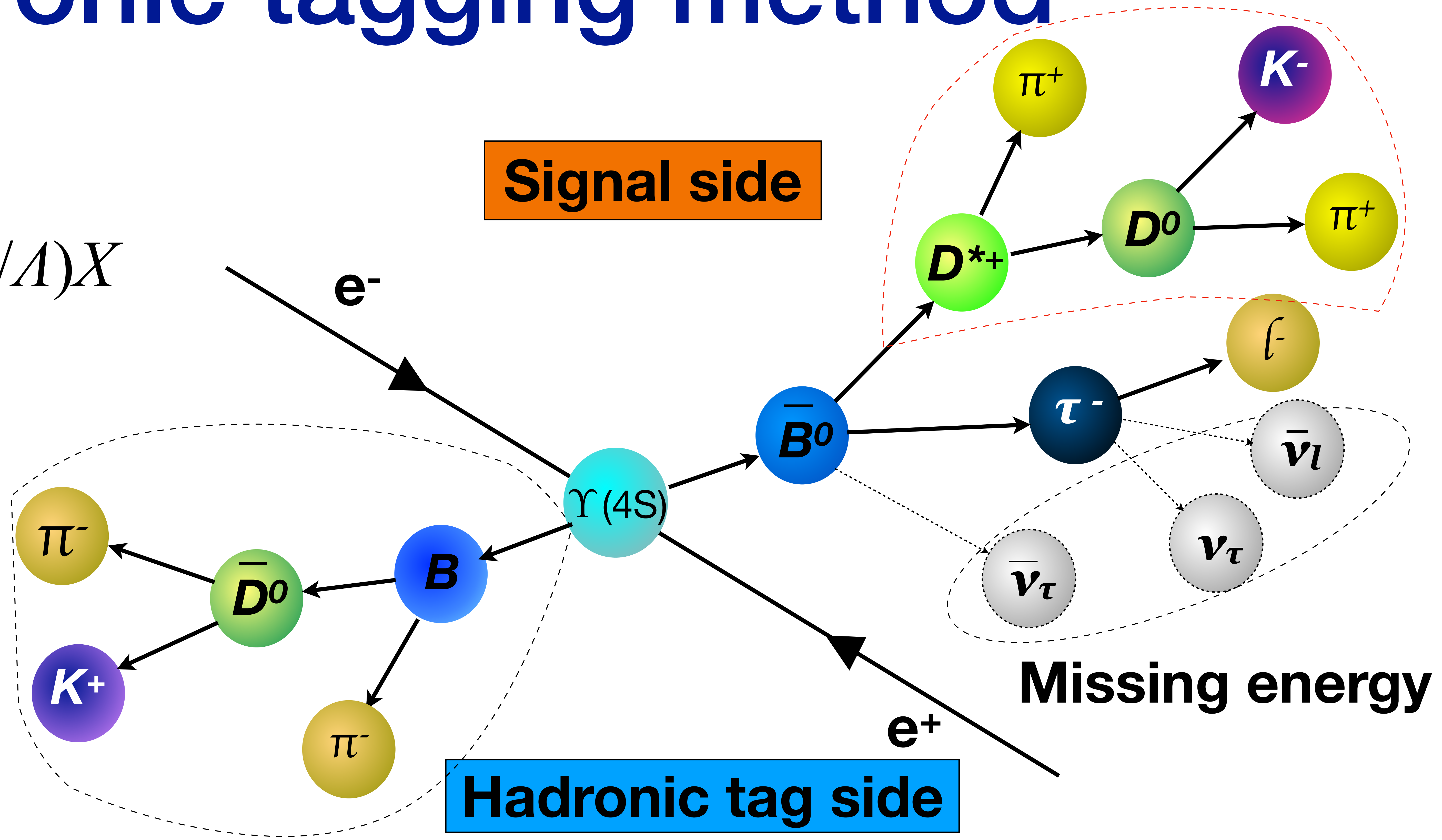
Tagging methods

- B tagging is necessary to measure $B\to D^*\tau\nu$, $B\to D^*l\nu$ ($\nu\geq 2$) simultaneously
- Hadronic tag
  - Exclusive tag
    - Fully reconstruct $B\to D^{(*)}(/J/\psi/\Lambda)X$
    - Tagging efficiency 0.2~0.4%
    - less background
  - Inclusive tag
    - Reconstruct tag *B* with all particles except signal *B*
    - Higher efficiency than exclusive tag
    - Low purity, need clean signal-side final state
- Semileptonic tag
  - Reconstruct $B\to D^{(*)}l\nu$
  - Tagging efficiency ~0.5%
  - More background



Exclusive hadronic tagging method

- <u>Hadronic tag</u>
  - <u>Exclusive tag</u>
    - Fully reconstruct $B \to D^{(*)}(/J/\psi/\Lambda)X$
    - 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
- $M^2_{\mathrm{miss}} = (p_{\mathrm{beam}} - p_{B\mathrm{tag}} - p_{D^{(*)}} - p_{\ell})^2$
- E_{ECL} unassigned neutral energy in the calorimeter $E_{\mathrm{ECL}} = \sum_i E_i^{\gamma}$

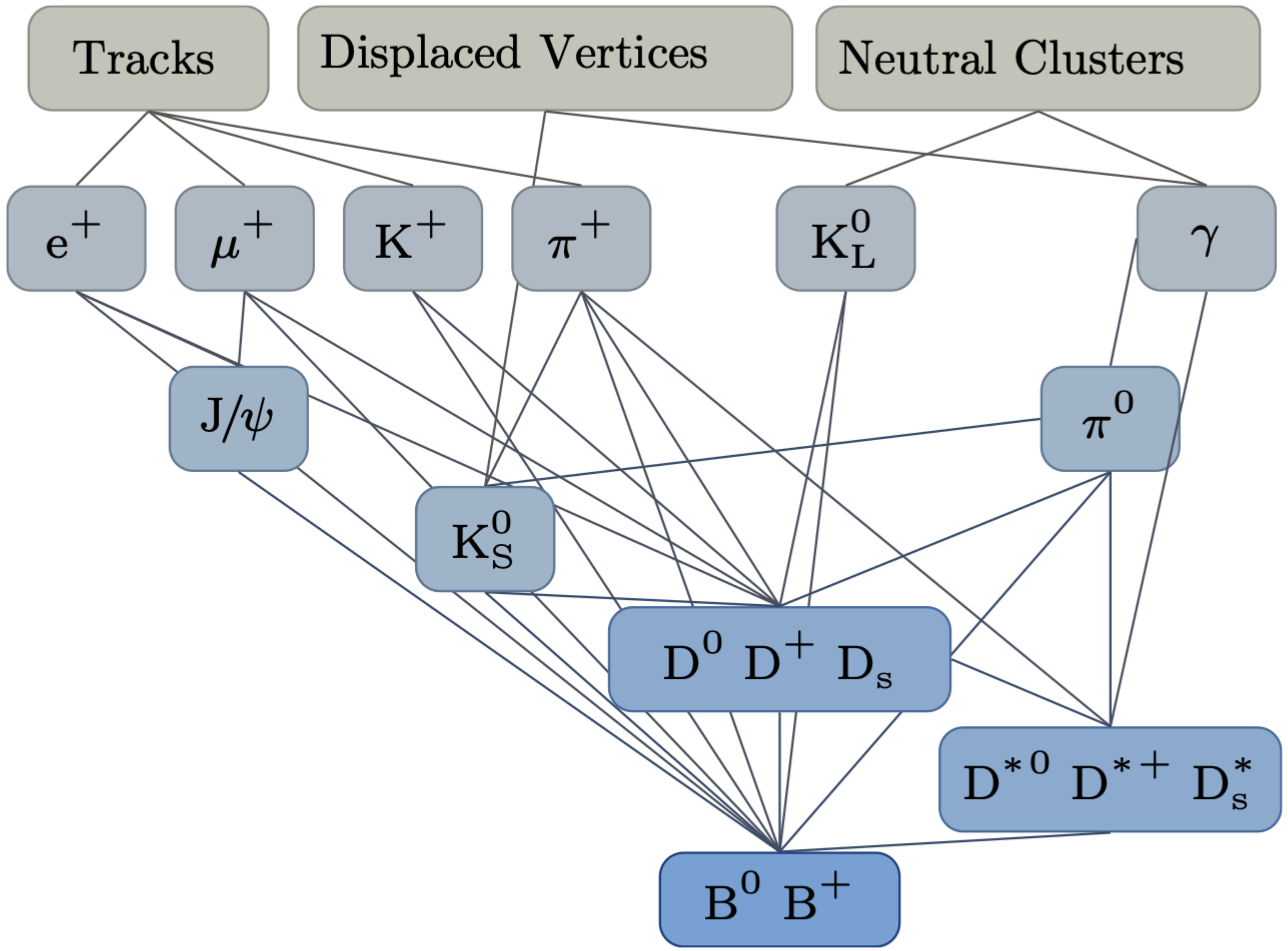
} Fitting variables for yields determination

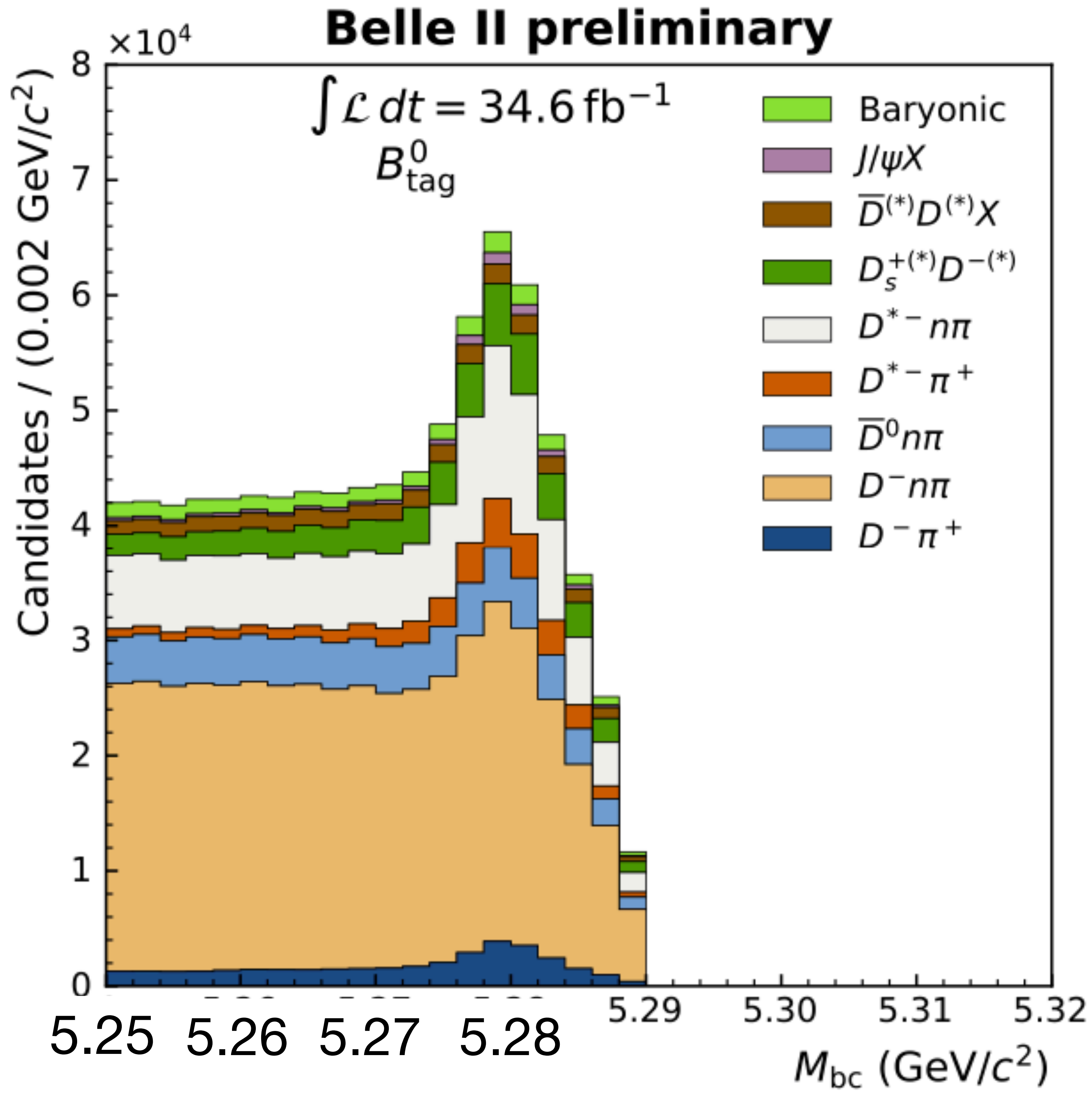
Hadronic tag reconstruction at Belle II

- Hadronic tagging reconstruction : Full Event Interpretation (FEI) trained 200 Boost Decision Tree (BDT) to reconstruct ~100 decay channels, ~10,000 *B* decay chains
  - ε=0.35% for $B^{\pm}$
  - ε=0.27% for B^{0}

arXiv:2008.06096

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



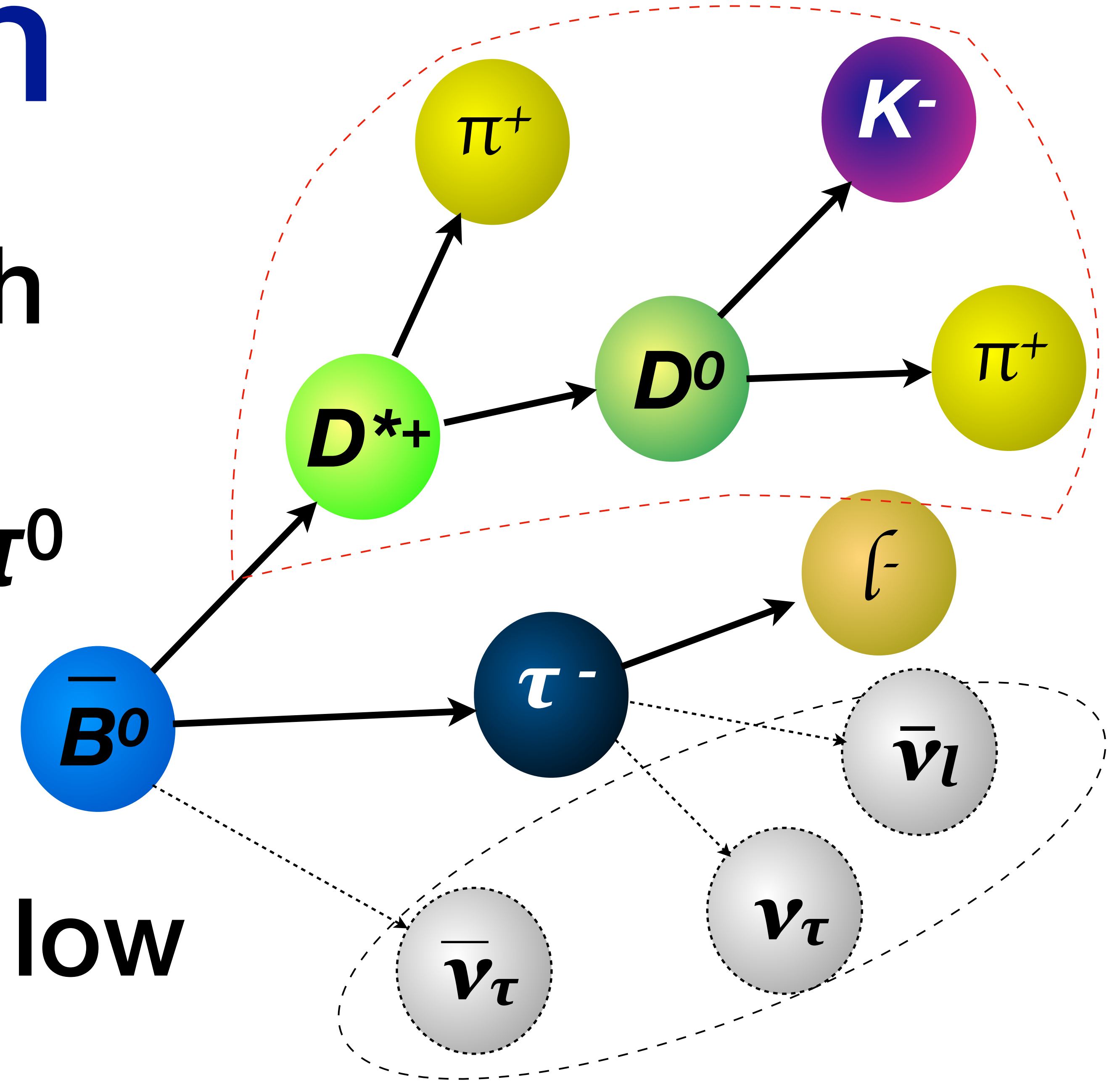


$$m_{\mathrm{bc}} = \sqrt{(E^*_{\mathrm{beam}})^2 - (p^*_B)^2}$$

Signal side reconstruction

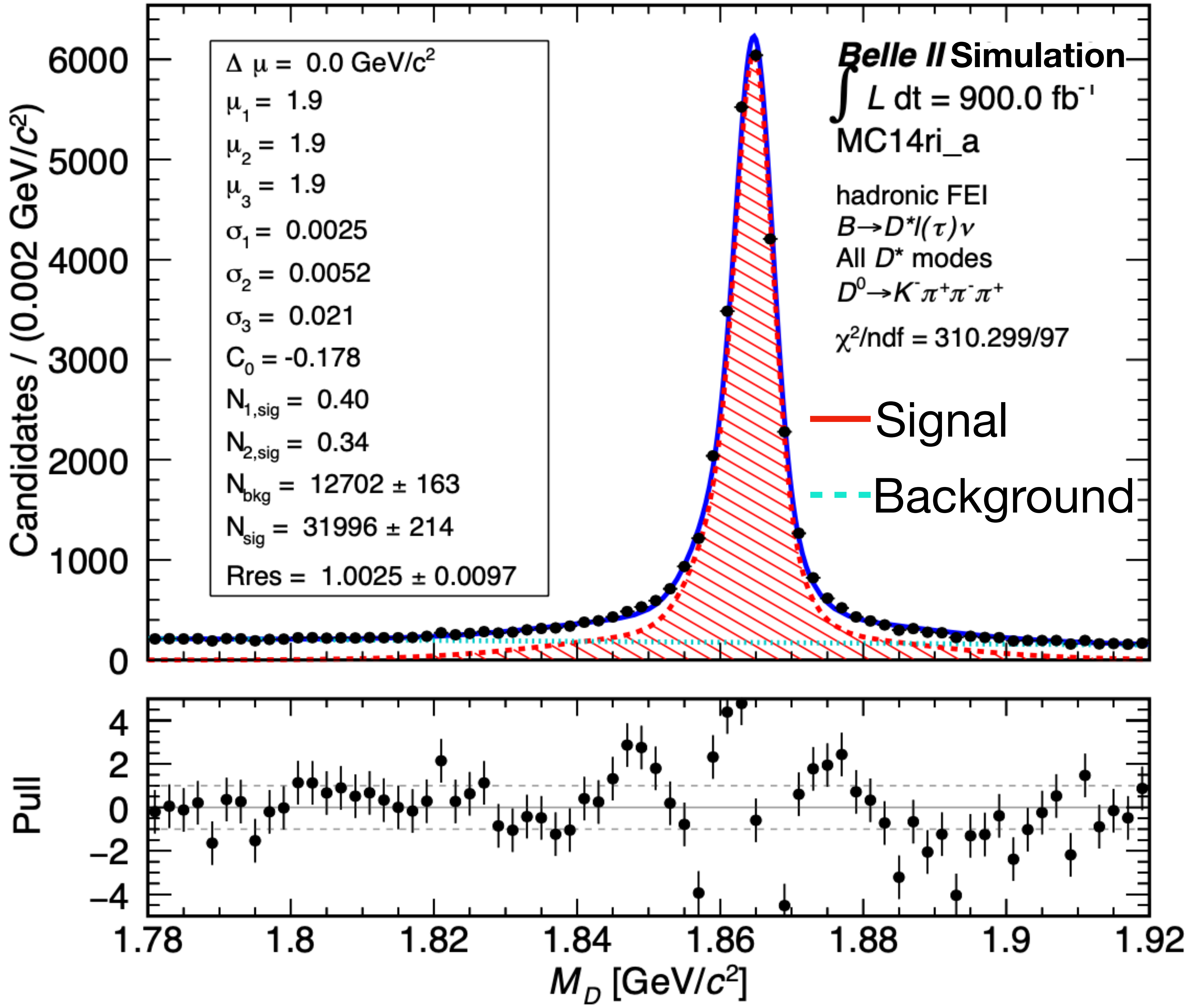
D^* decays	D decays
$D^{*+} \to D^0\pi^+$	$D^0 \to K^-\pi^+\pi^0$ $D^0 \to K^-\pi^+\pi^-\pi^+$ $D^0 \to K^0_S\pi^+\pi^-\pi^0$ $D^0 \to K^-\pi^+$ $D^0 \to K^0_S\pi^+\pi^-$ $D^0 \to K^0_S\pi^0$ $D^0 \to K^-K^+$ $D^0 \to \pi^+\pi^-$
$D^{*+} \to D^+\pi^0$	$D^+ \to K^-\pi^+\pi^+$ $D^+ \to K^0_S\pi^+$ $D^+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

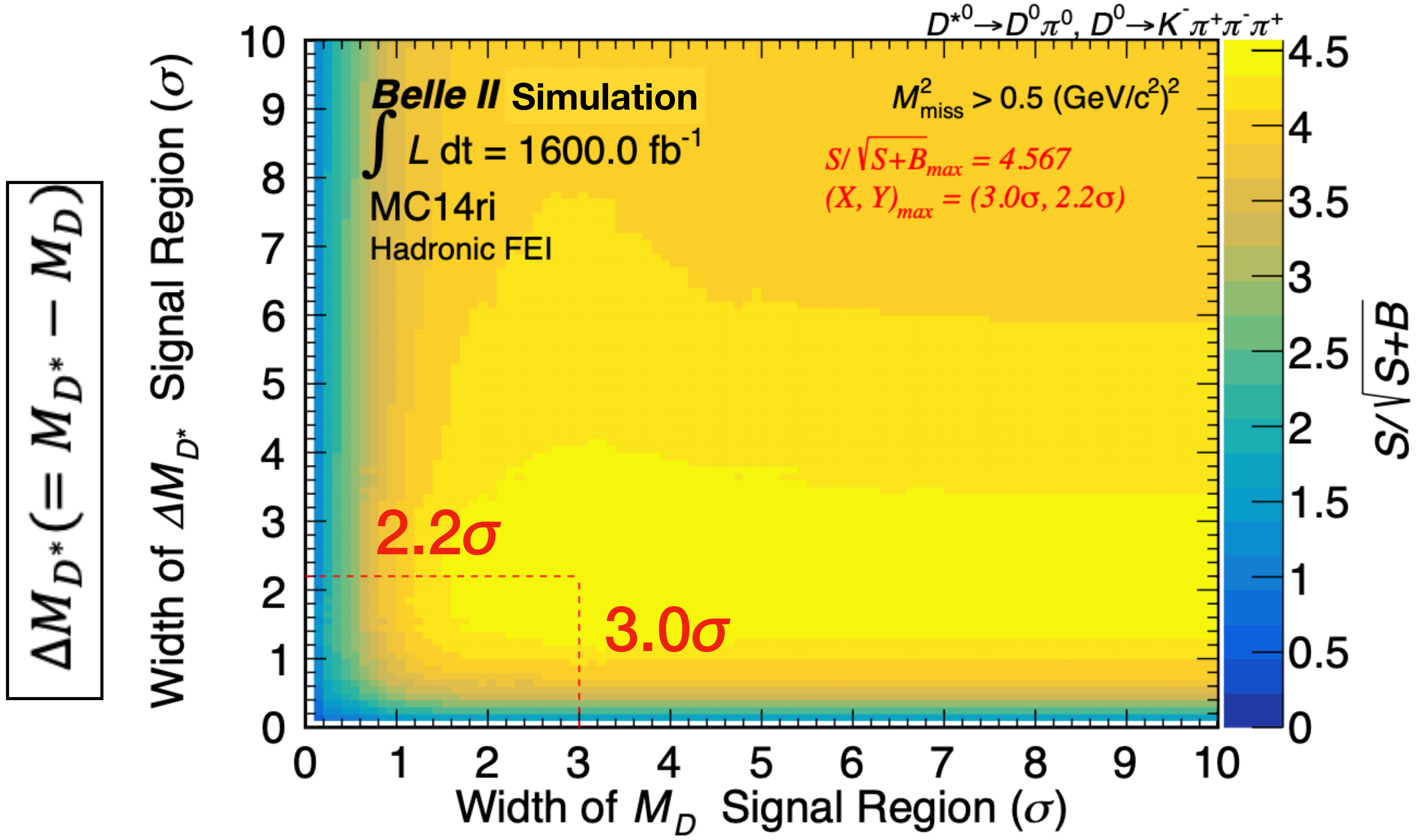
- Reconstruct $B \to D^*\tau\nu$ and $B \to D^*l\nu$ with same selections
- *D* meson reconstruct with $K^\pm$, $\pi^\pm$, K_s, π^0
  - 8 D^0 modes (Br ~36%)
  - 4 D^+ modes (Br ~12.3%)
- D^* meson reconstruct with D^+/D^0 and low momentum π^+/π^0
  - $D^{*+} \to D^0\pi^+/D^+\pi^0$ (Br ~98%)
  - $D^{*0}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



Missing energy

Improvement of reconstruction at Belle II



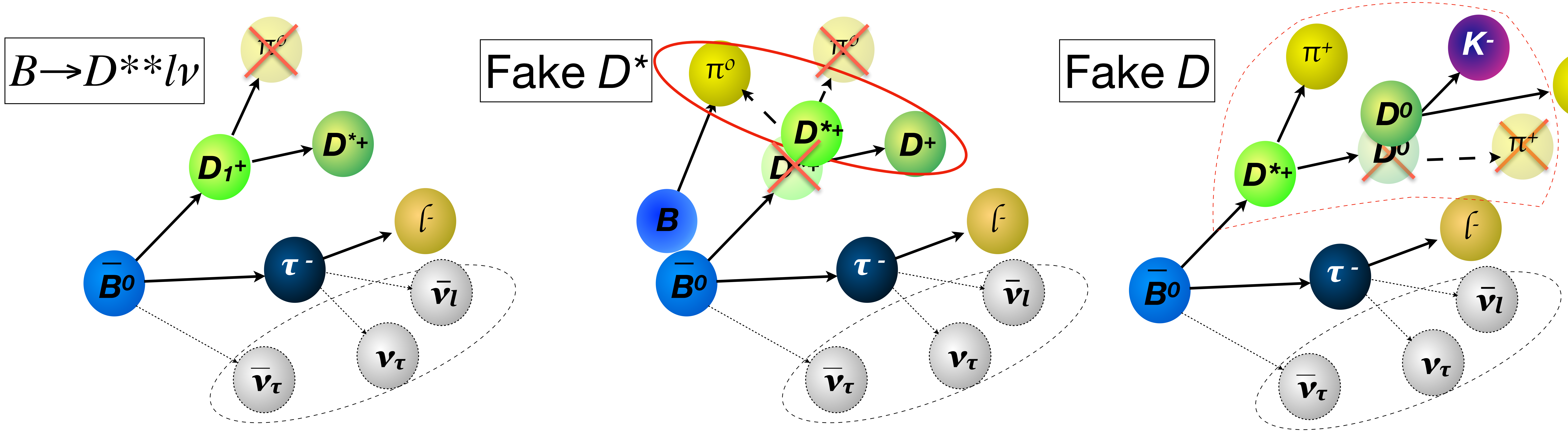


- Improve the reconstruction methodology at Belle II
  - Keep reasonably large reconstruction candidates
  - Found the maximum of FOM $N_{signal} / \sqrt{N_{signal} + N_{background}}$, by scanning the optimal selections
  - Improve 35% of FOM vs. Belle '15 hadronic tag $R(D^{(*)})$ analysis

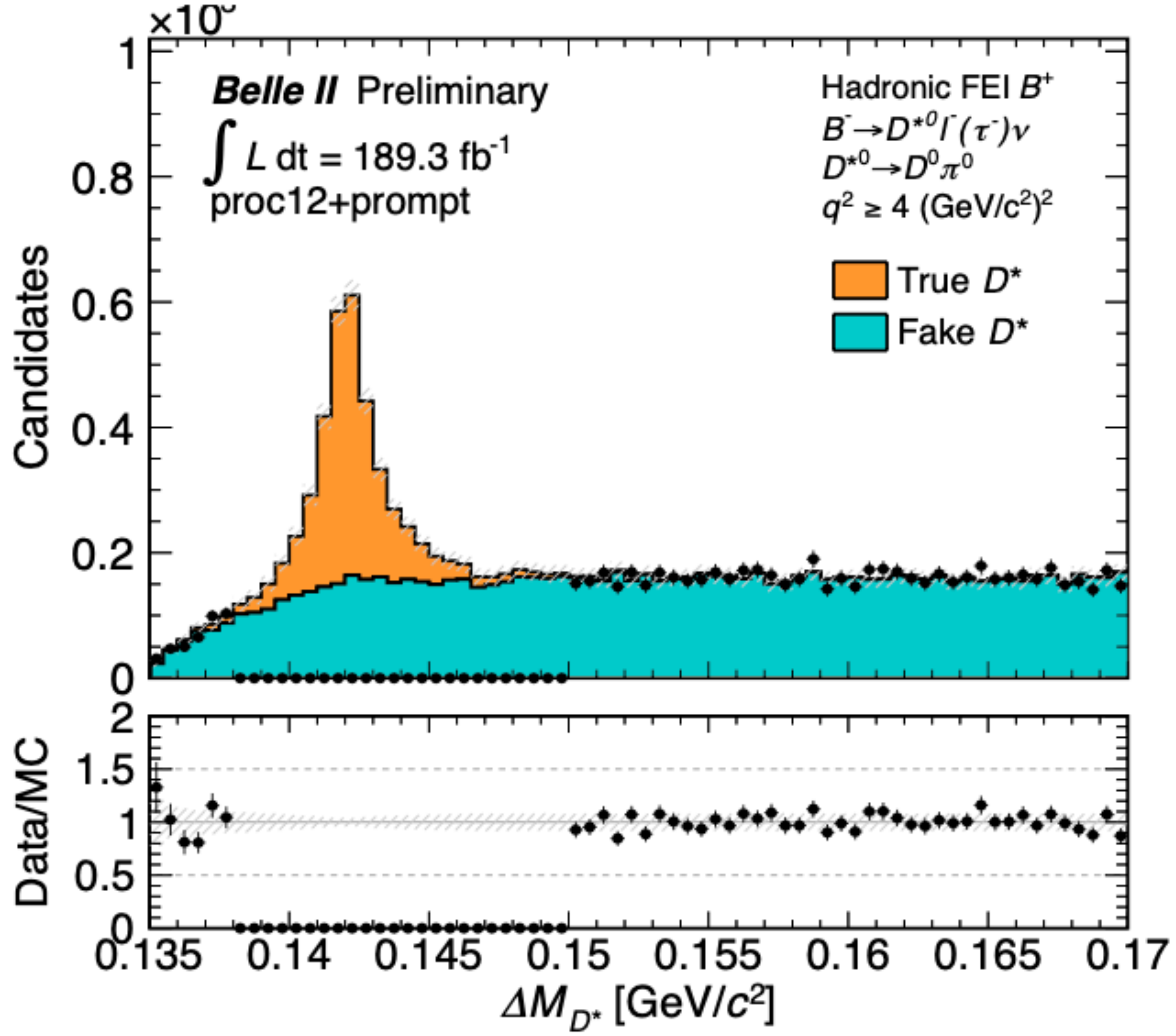
Dominant backgrounds

- Fraction of survived *B* candidates in each category after event selections are estimated based on Belle II MC simulation

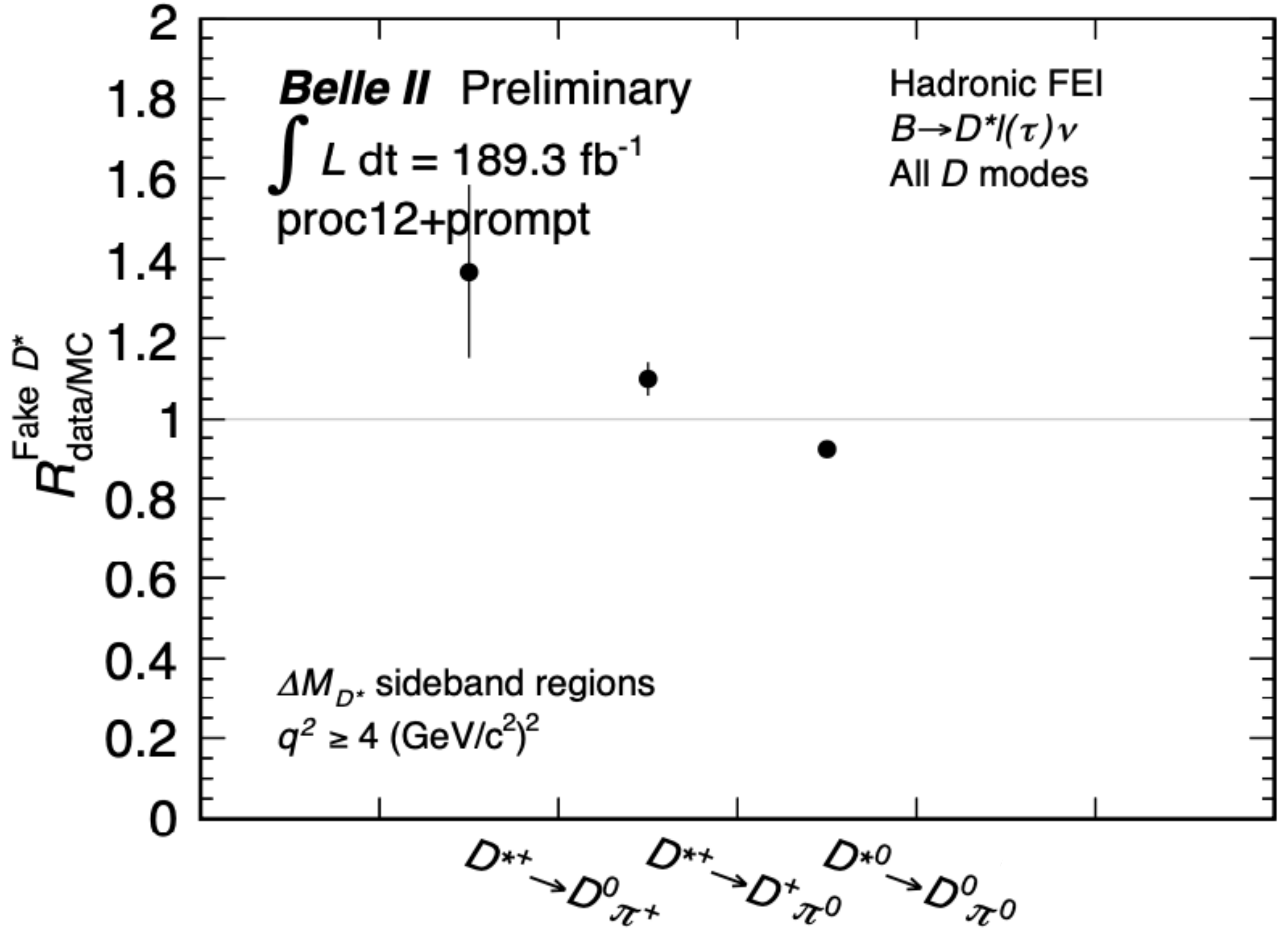
B condidates	$B \to D^* \tau \nu$	$B \to D^* l \nu$	Background Truth $D^{(*)}$	Background Fake $D^{(*)}$
			$B \to D^{**} l \nu$, $B \to D^{(*)} X$, $B^0 <-> B^\pm$, …	
B^0	2.7%	65.5%	12.5%	19.2%
$B^\pm$	1.7%	34.7%	5.9%	57.8%



Calibration of fake D^* background on ΔM_{D^*} sideband



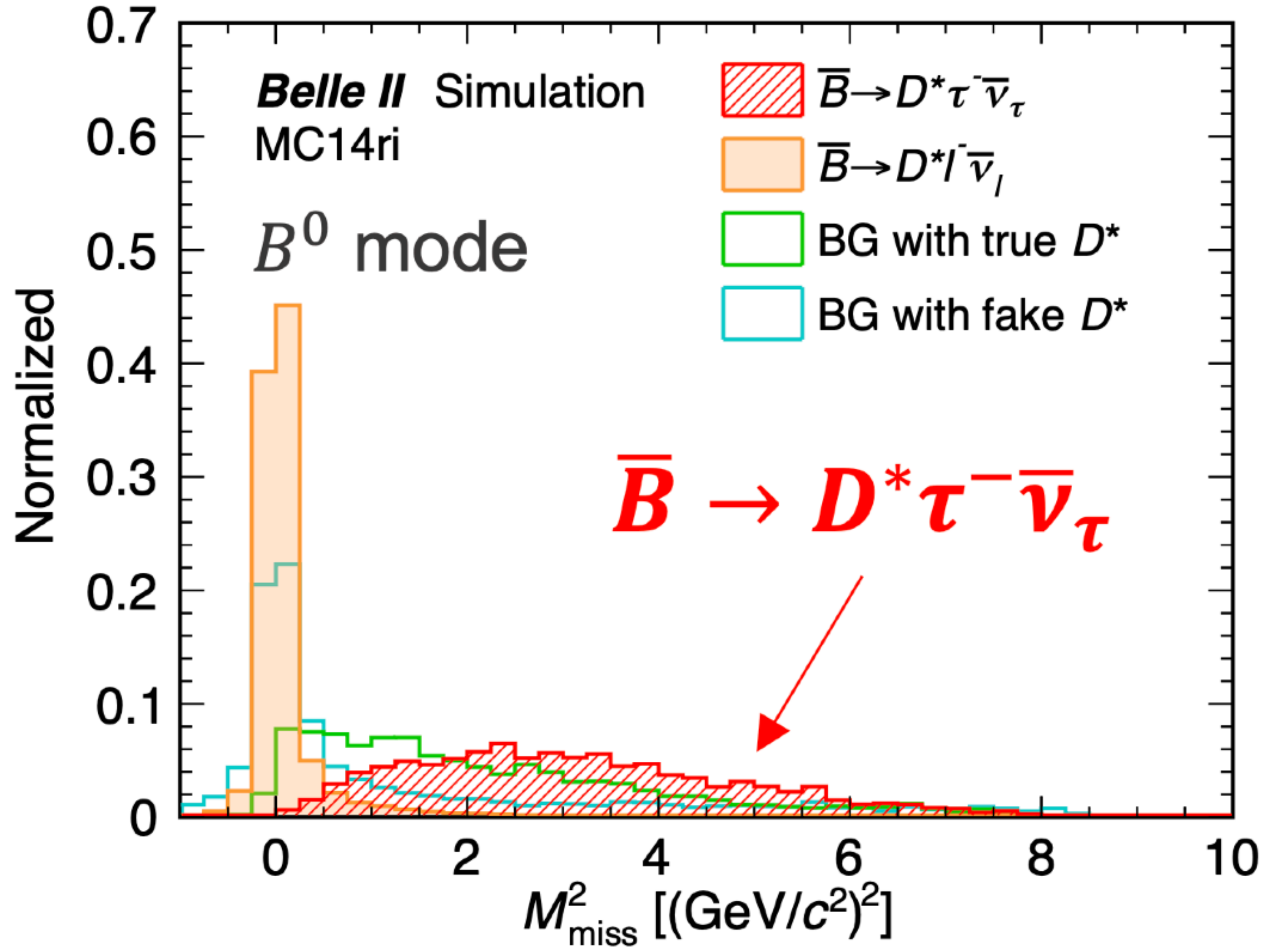
$$\Delta M_{D^*} (= M_{D^*} - M_D)$$

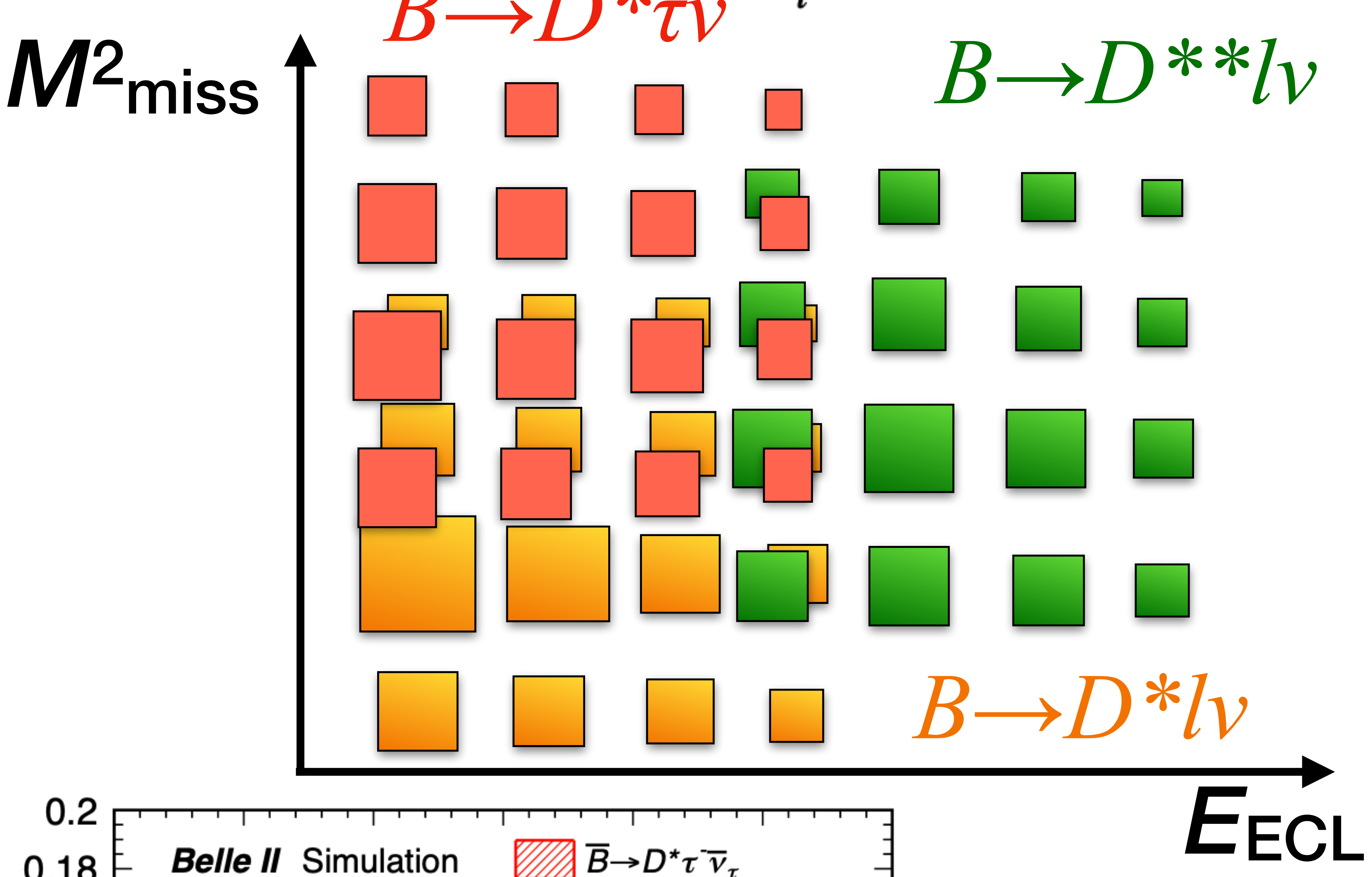


- Estimate the most dominate background (fake D^*) using ΔM_{D^*} sideband
  - Fit ΔM_{D^*} distribution at sideband, threshold or Chebychev functions
  - Obtain a calibration factor

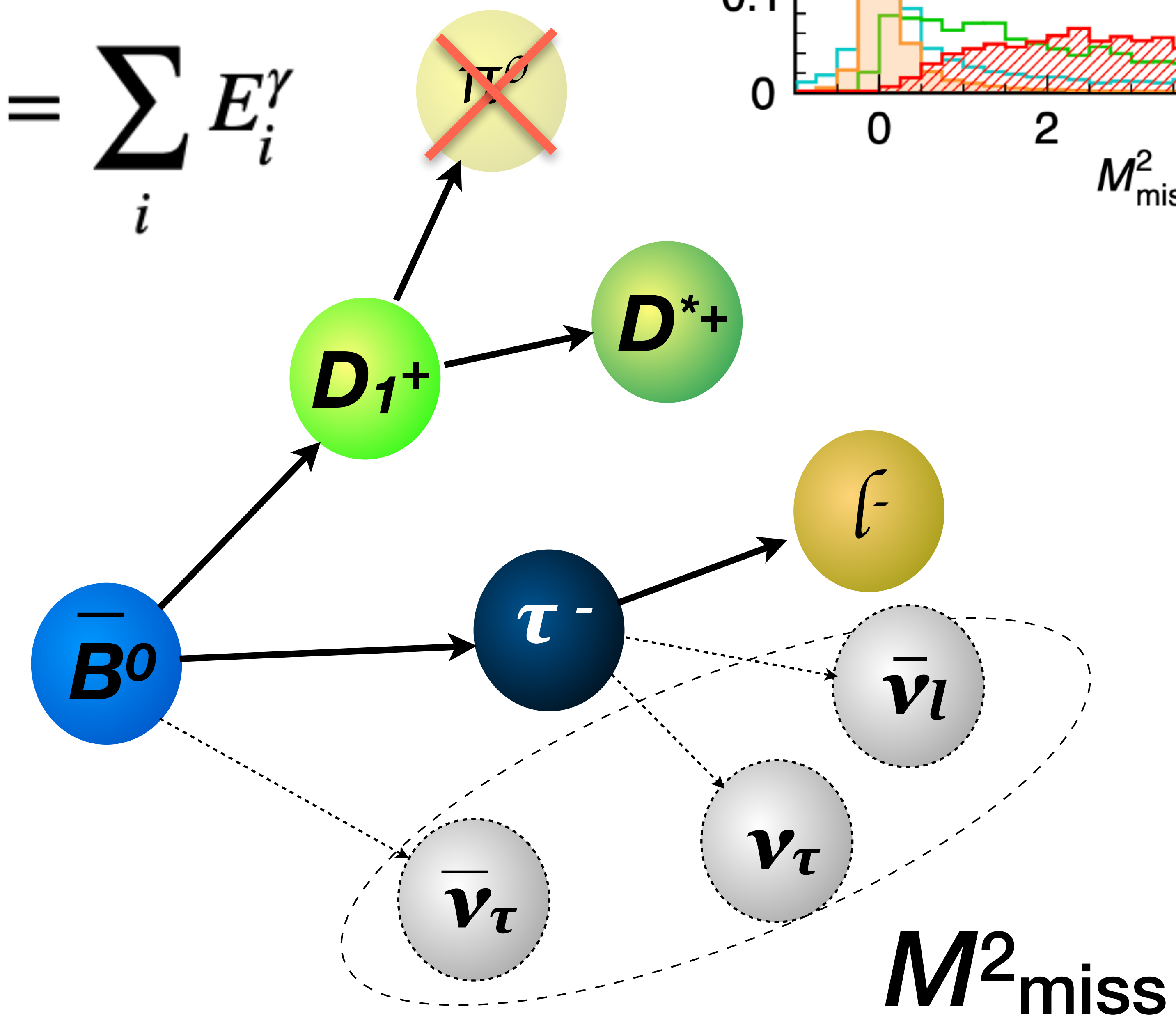
Fitting methodology and variables

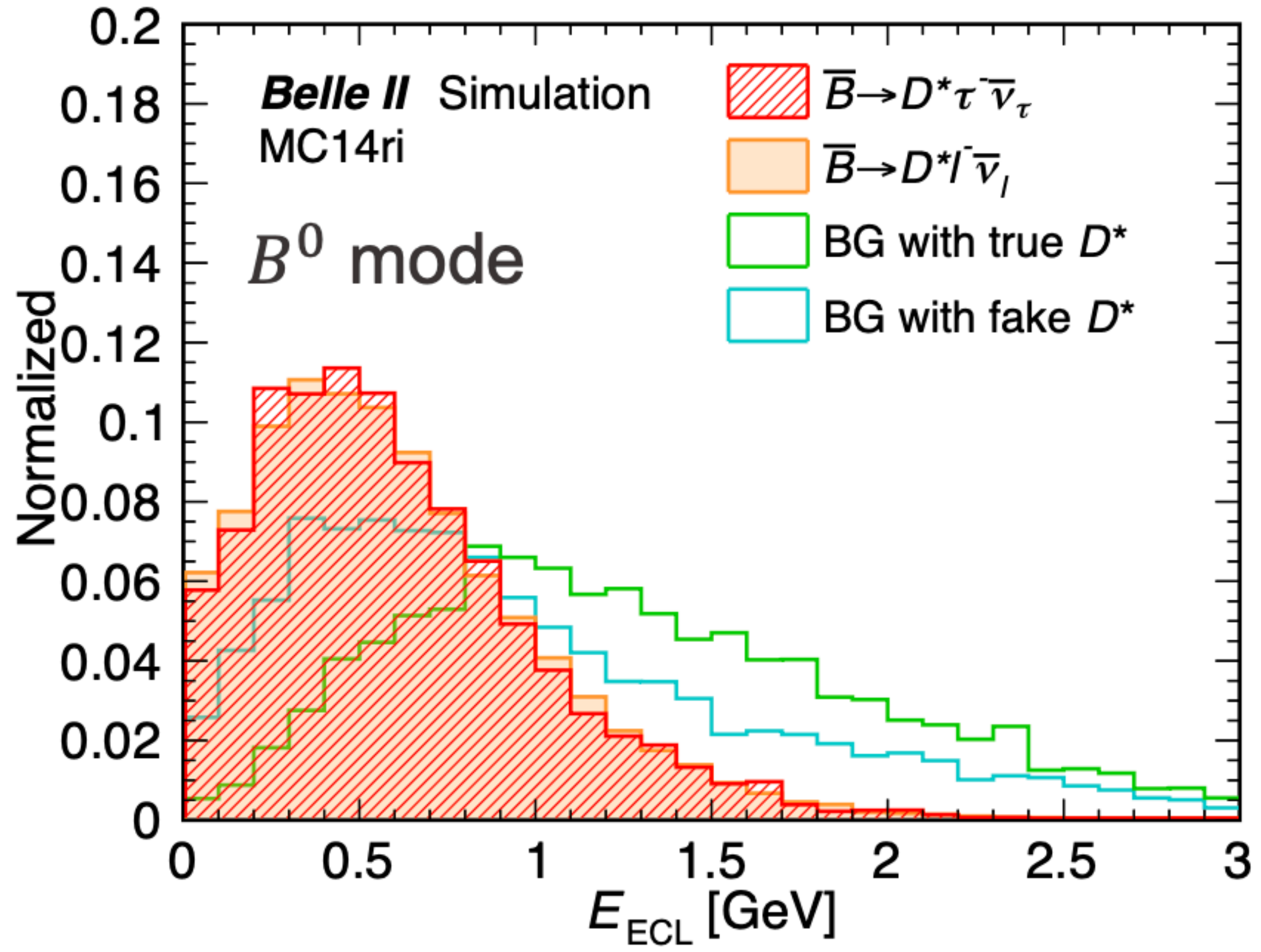
- Extracting $B \to D^*\tau\nu$, $B \to D^*l\nu$ yields by a two-dimensional simultaneously fit
  - $M^2_{\text{miss}} = (p_{\text{beam}} - p_{B\text{tag}} - p_{D(*)} - p_l)^2$
  - E_{ECL} unassigned neutral energy in the calorimeter $E_{\text{ECL}} = \sum_i E_i^\gamma$





$E_{\text{ECL}} = \sum_i E_i^\gamma$





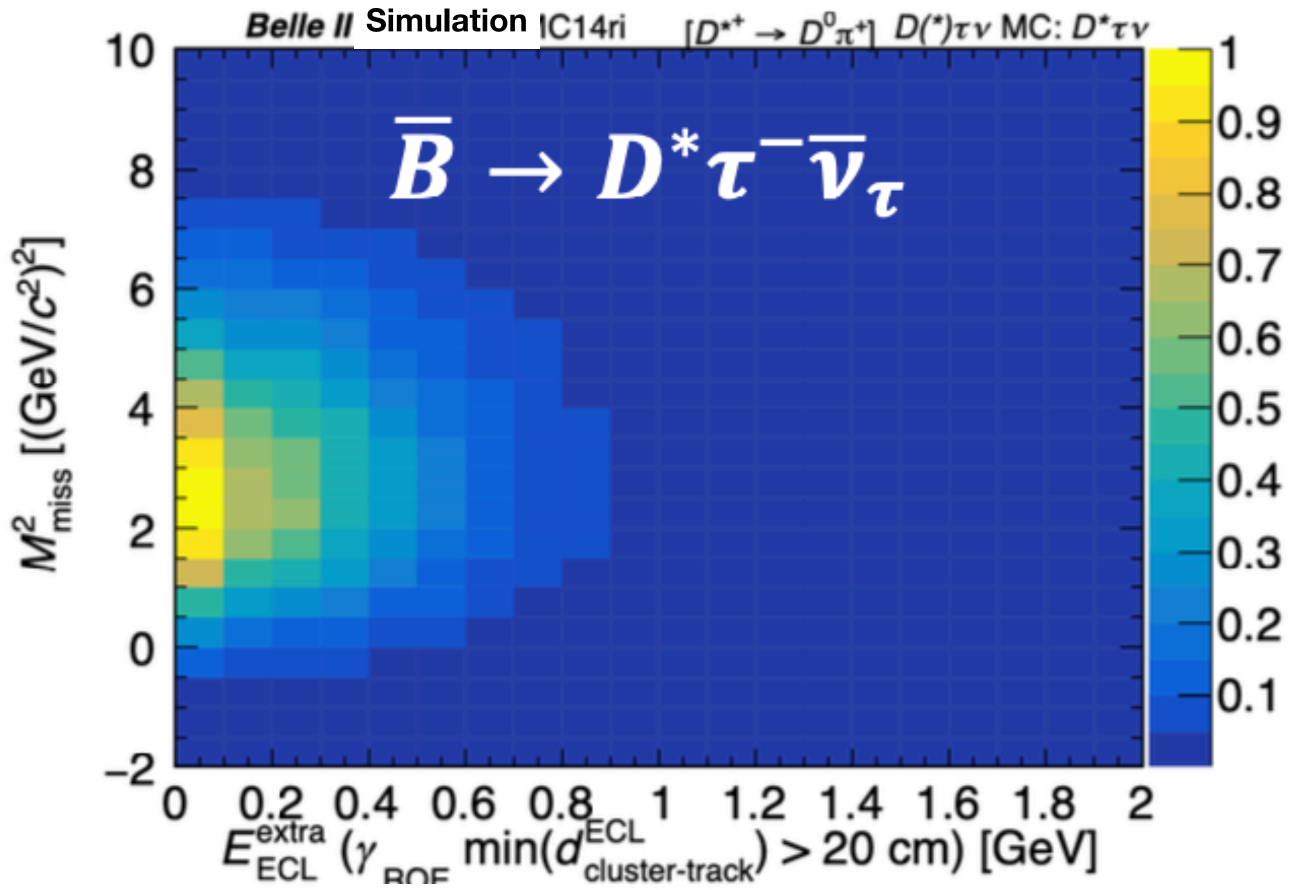
Fit configuration

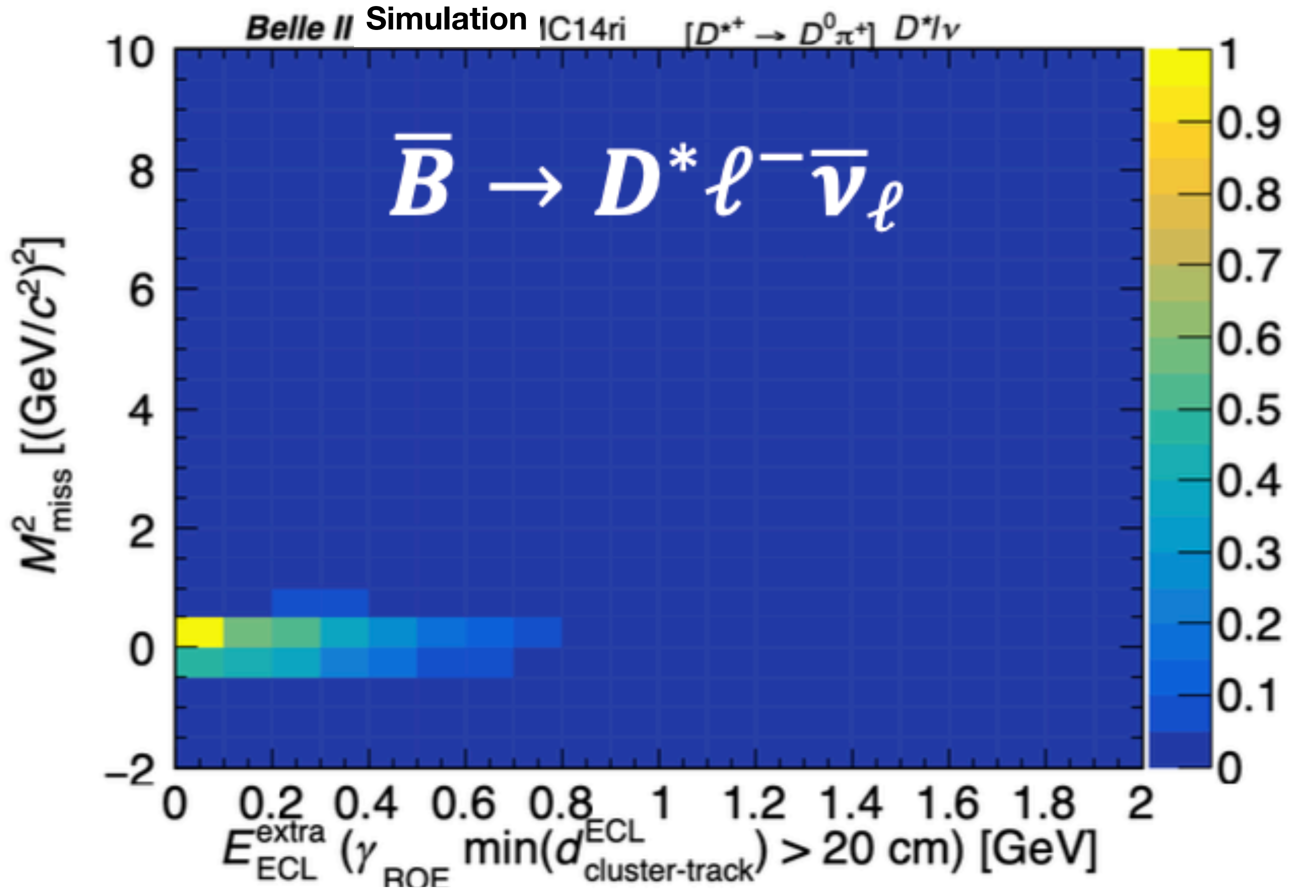
- PDFs in two dimensions with uniform 24 M^2_{miss} bins and 20 E_{ECL} bins after kernel density estimation
- $R(D^*)$ obtained by simultaneous fits among three D^* modes

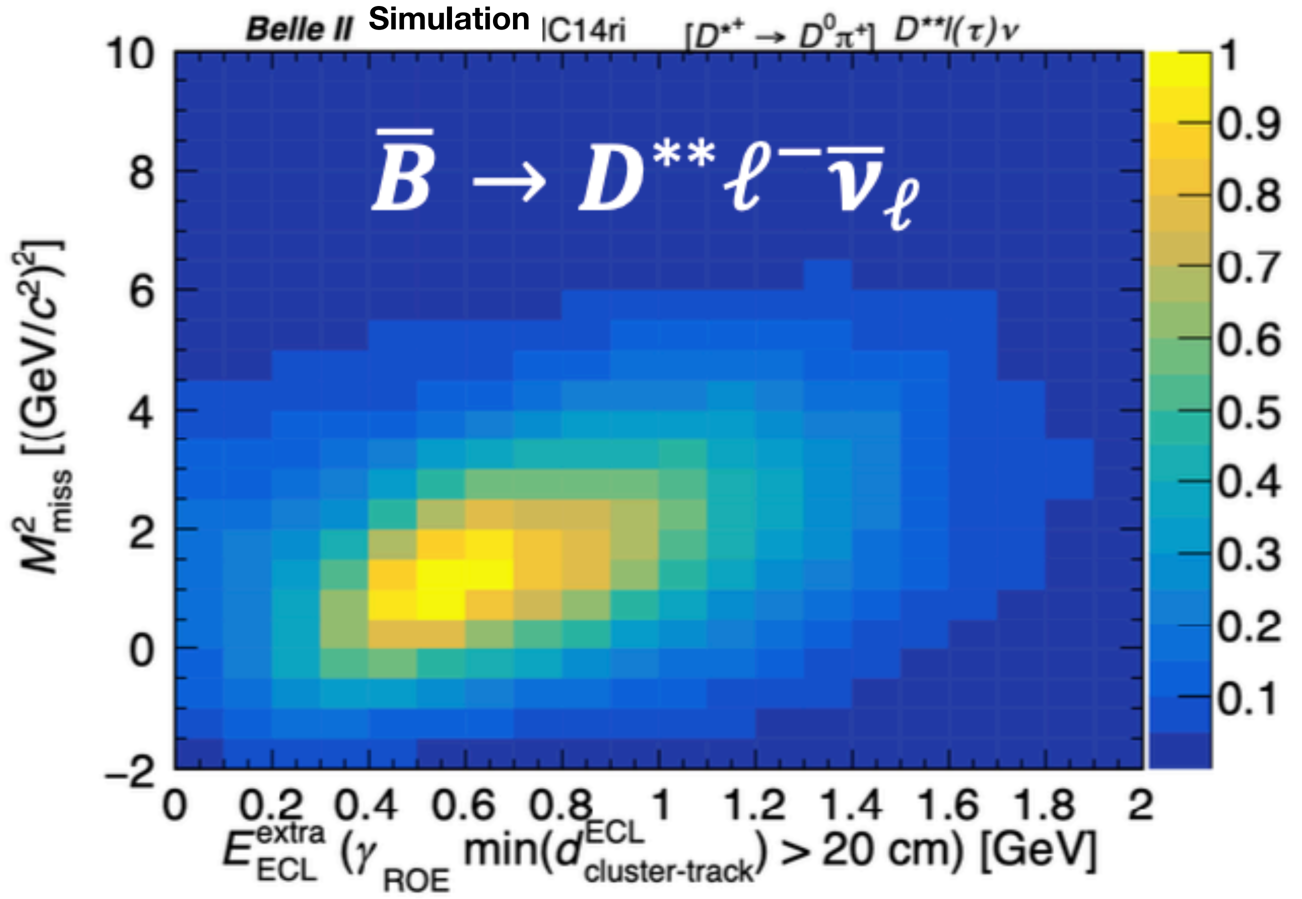
Signal mode $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$	
Signal mode $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ with misidentified lepton from τ	
Normalization mode $\bar{B} \to D^*\ell^-\bar{\nu}_\ell$	
Normalization mode $\bar{B} \to D^*\ell^-\bar{\nu}_\ell$ with misidentified lepton	
Backgrounds with true D^*	$\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$
	Hadronic B decays
	$B^0 \leftrightarrow B^\pm$ tag misidentification
	$q\bar{q}$ $(q = u, d, s, c)$
Background with fake D^*	

Constrain yields with sidebands

Fixed with MC yields



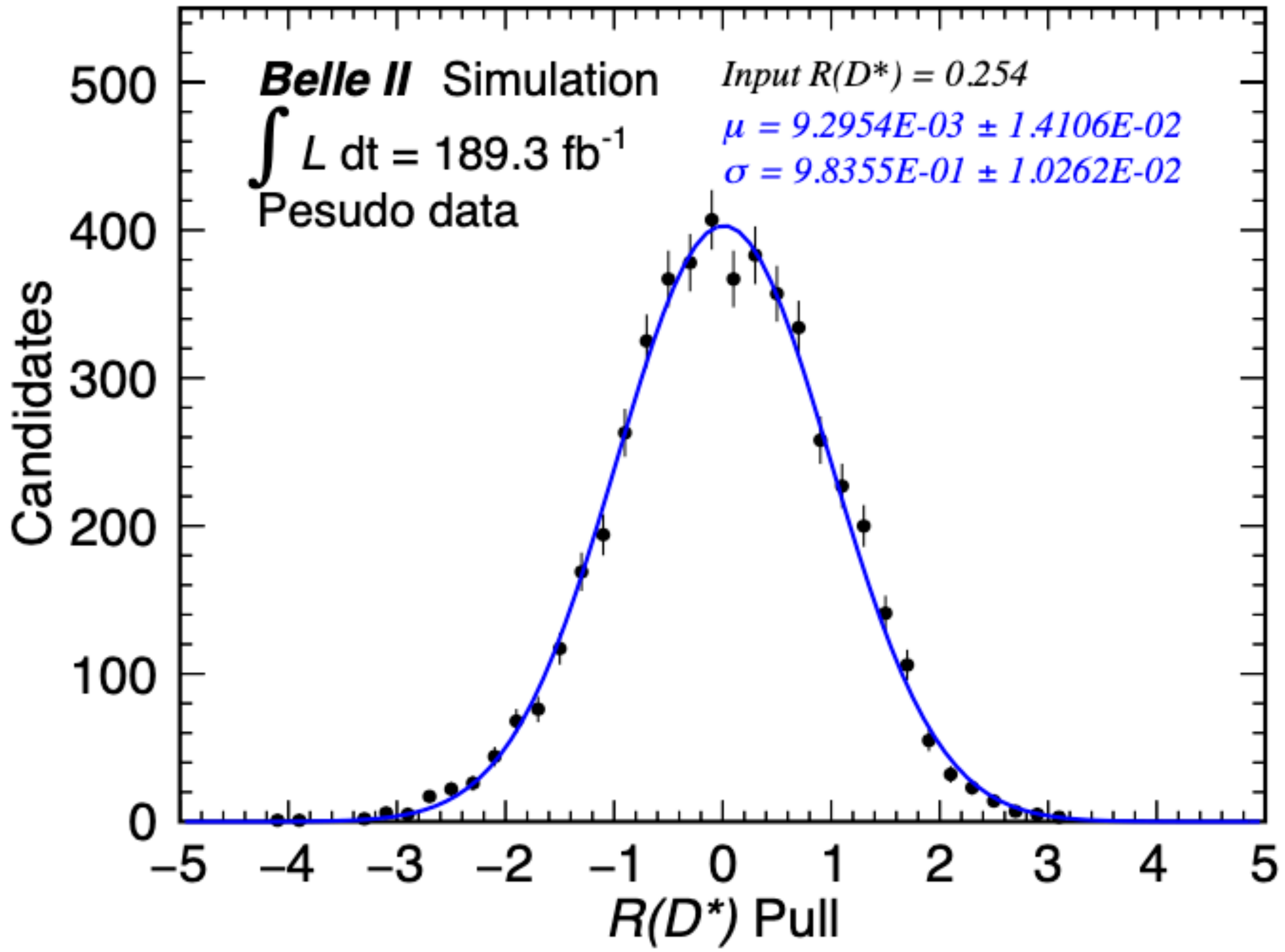




Fitter validation with pseudo data

- Producing 5000 random pseudo data set with 189 fb^{-1} based on PDF where *R*(*D**) = 0.254 (SM expectation)
- The fitter performance confirmed by *R*(*D**) pull distribution
- Linearity check of fitter has also been confirmed based on Asimov fit method, by scanned input *R*(*D**) in the range of 0.01 to 5.0

Eur.Phys.J.C71:1554,2011

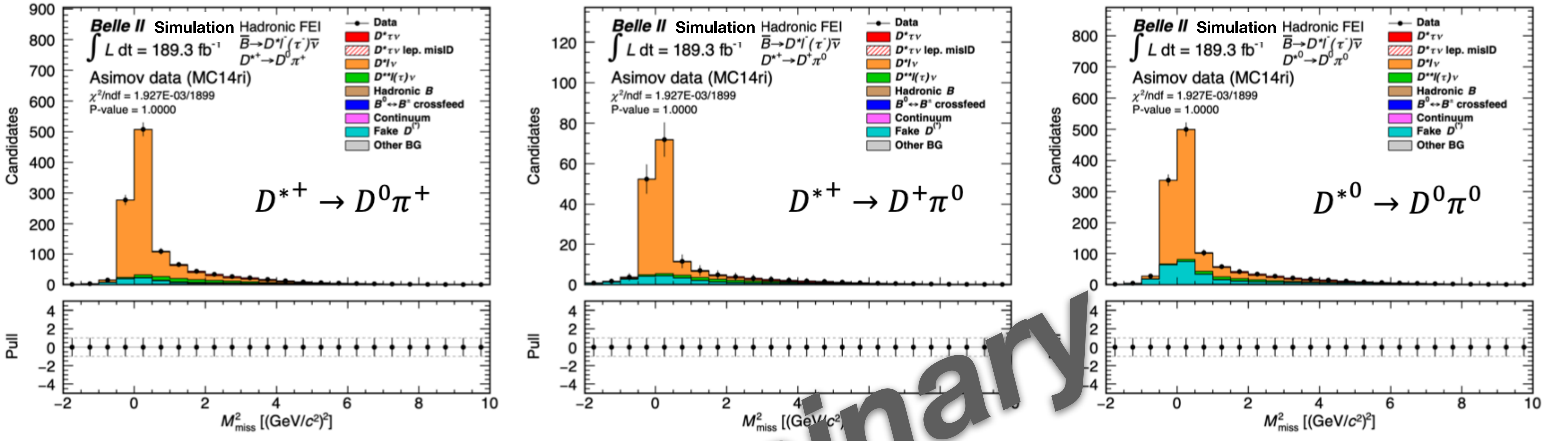


$\mu = 0.009 \pm 0.014$

$\sigma = 0.984 \pm 0.010$

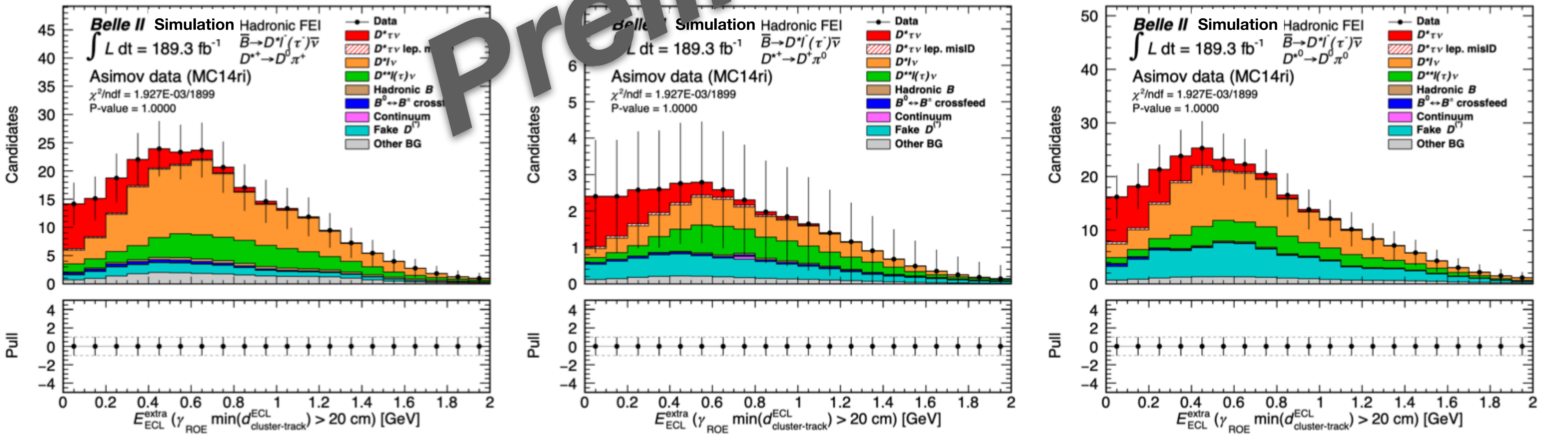
Belle II $R(D^*)$ sensitivity at 189 fb^{-1}

- Producing Asimov MC data set with 189 fb^{-1} based on PDF where $R(D^*)$ = 0.254 (SM expectation)
- The fit returns $R(D^*)$ = 0.254, statistical uncertainty is +18/-17% at 189 fb^{-1}
- Belle '15 statistical uncertainty is 13% (15%@ $R(D^*)$ = 0.254)



Preliminary

$M^2_{\rm miss} > 1.0\ (\mathrm{GeV}/c^2)^2$



$$R(D^*) = 0.254^{+0.046}_{-0.043}\ \left(^{+18}_{-17}\ ^{\%}_{\%}\right)$$

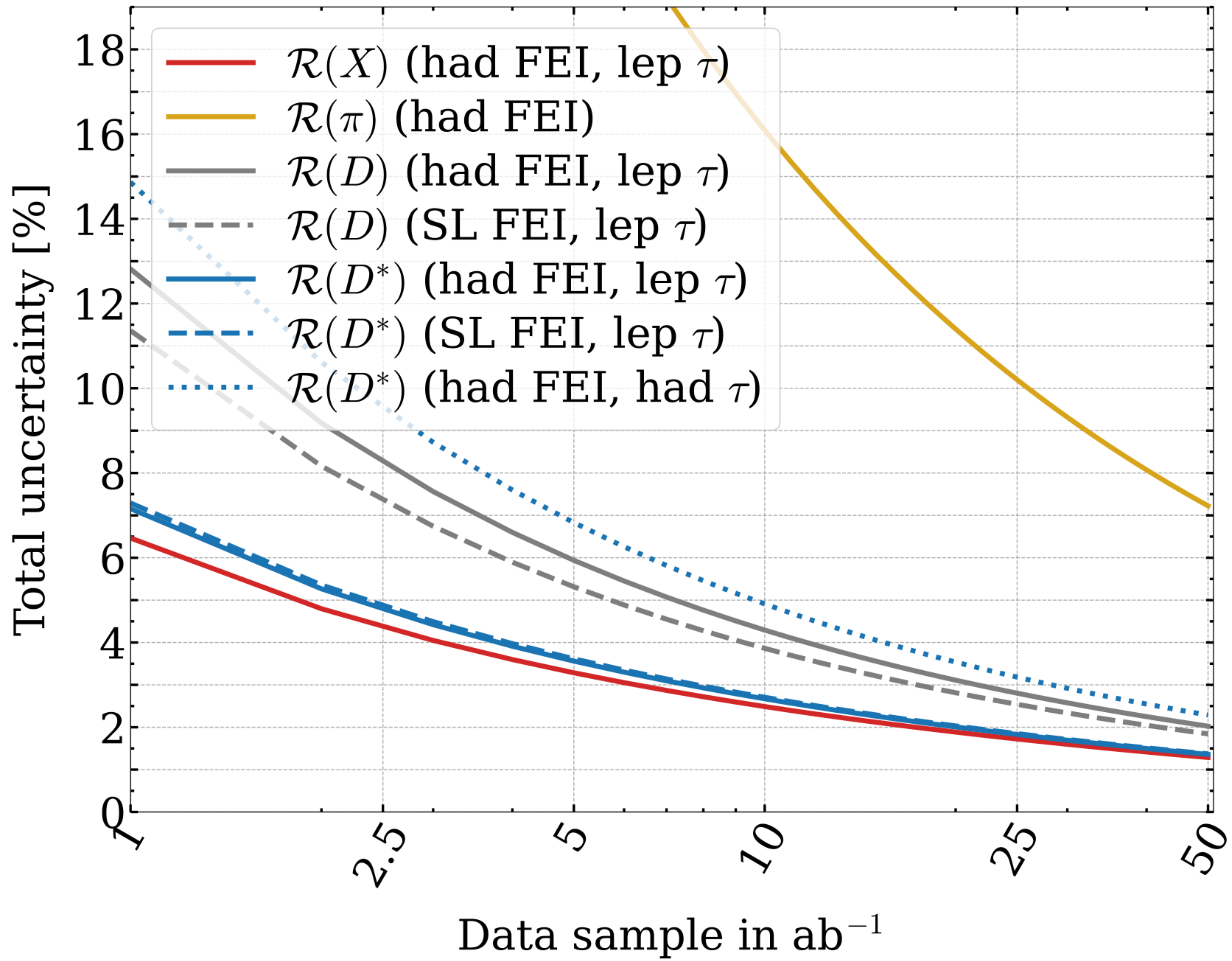
Preliminary systematic uncertainties

- Each source of the uncertainty changes the PDF shape, consequently modify the fitted $R(D^*)$ value
  - Generate PDFs by fluctuating one of the uncertainty sources
  - Fitting the fluctuated PDFs to the nominal pseudo data (un-fluctuated PDF)
  - Repeating the fit by 1000 times (fluctuate PDFs follow Gaussian) to obtain the $\Delta R(D^*)$
  - Asymmetric errors $\mu+\sigma$ and $\mu-\sigma$ from fitting $\Delta R(D^*)$ distribution as systematic uncertainties

Source	Uncertainty	
Statistical uncertainty	+0.046 -0.043	+18.1% -17.0%
MC statistics	+0.010 -0.007	+4.1% -2.7%
$B \to D^{**} l \nu$ branching ratios	+0.012 -0.010	+2.7% -1.9%
...		

Statistical uncertainty dominated

Expected sensitivity of *R*(*D**) at Belle II



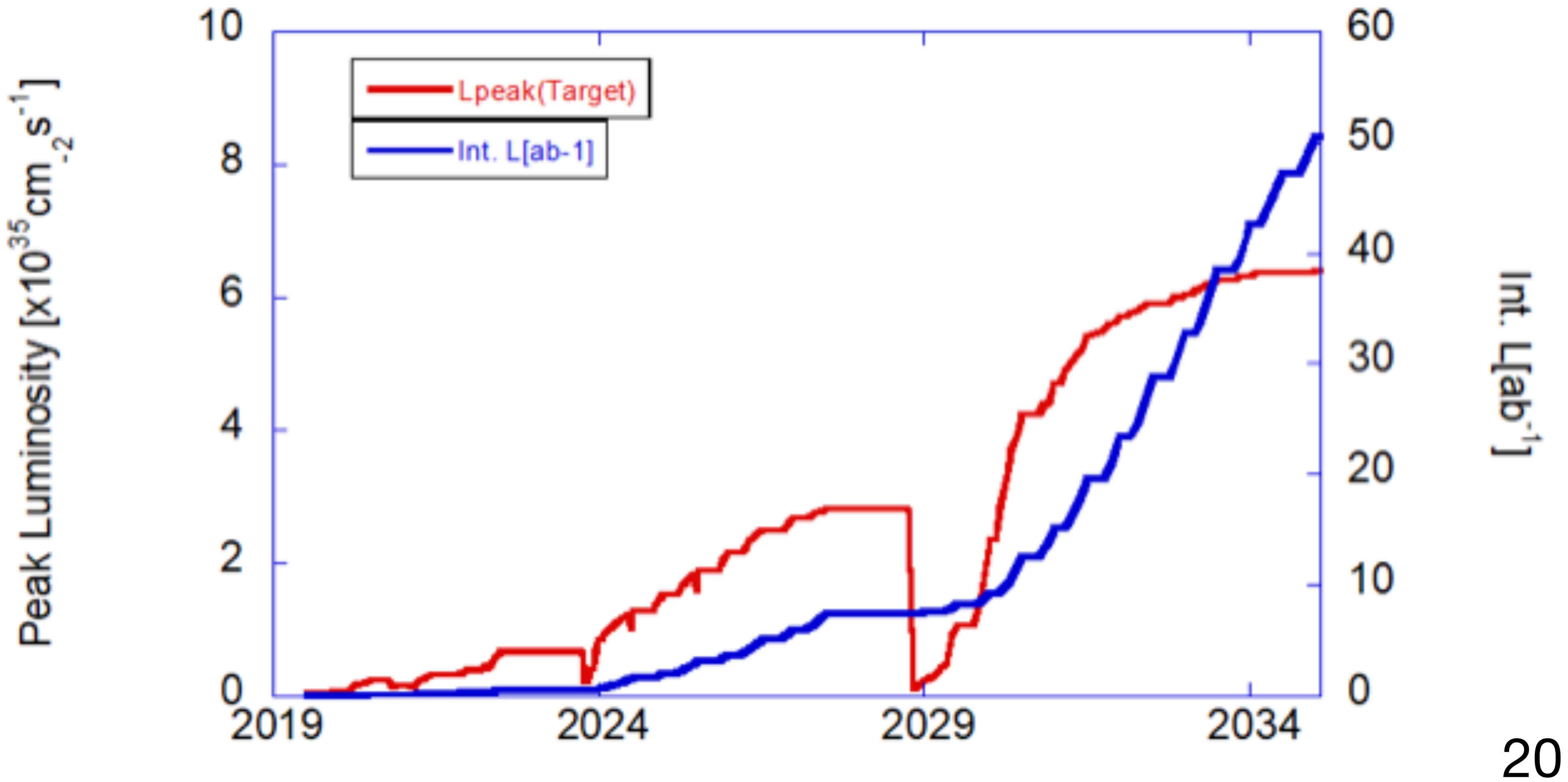
arXiv:2207.06307

Summary and prospects

- *R*(*D**) shows 3.2σ deviation between experimental average value and standard model prediction
  - Hint of Lepton Flavor Universality Violation

- Measurement of *R*(*D**) with hadronic tagging based on 189 fb^{-1} Belle II data
  - Established the analysis framework
  - Selection optimization improve FOM by 35% compare to Belle ’15 analysis
  - Expected statistical uncertainty is +18/-17% at 189 fb^{-1}
  - Evaluated most of the systematic uncertainty, <- statistical uncertainty dominated with 189 fb^{-1} data

- First *R*(*D**) measurement at Belle II using 189 fb^{-1} data-set targeting the end of spring 2023



Backup

Reconstruction selections

$B_{\rm tag}$	$\mathcal{P}_{B_{\rm tag}} > 0.001$ and $M_{{\rm bc},B_{\rm tag}} > 5.27$ GeV/c^2 and $-0.15 < \Delta E_{B_{\rm tag}} < 0.1$ GeV	Tag B meson
`good track`	$dr < 2.0$ and $\|dz\| < 4.0$ and $p_t > 0.1$ GeV/c	Tracks
# of tracks	The number of good tracks > 4	
π^+, K^+ from D	[`good track`] and nCDCHits > 20 and $\mathcal{P}_K^{\rm binary} > 0.1$, $\mathcal{P}_\pi^{\rm binary} > 0.1$	Hadrons
π^0	`pi0:eff40_May2020` and γ:|clusterTiming| < 200 ns	
K_S^0	`KS0:merged` and significanceOfDistance > 3 (before $B_{\rm sig}$ vertex fit)	
D	$1.78 < M_D < 1.92$ GeV/c^2	
$\gamma_{\rm low}$	`gamma:eff40_May2020` and |clusterTiming| < 200 ns	Neutrals
$\pi^0_{\rm slow}$	`pi0:eff50_May2020` and γ:|clusterTiming| < 200 ns	
$\pi^+_{\rm slow}$	$dr < 2.0$ and $\|dz\| < 4.0$ and $p > 0.05$ GeV/c	
D^*	$0.130 < \Delta M_{D^*} < 0.170$ GeV/c^2 ($0.100 < \Delta M_{D^*} < 0.190$ GeV/c^2) for $D^{*+}(D^{*0})$	
e, μ	[`good track`] and $\mathcal{P}_\mu^{\rm global} > 0.9$, $\mathcal{P}_e^{\rm global} > 0.9$	Leptons
$B_{\rm sig}$ vertex fit	1. `treeFit('B0(B+):sig', conf_level=0.0, ipConstraint=False, updateAllDaughters=True, massConstaint=[K_S0, pi0], path=path)`	Constraint $D^{(*)}$ daughter's masses to improve $D^{(*)}$ selections
	2. `treeFit('B0(B+):sig', conf_level=-1.0, ipConstraint=False, updateAllDaughters=True, massConstaint=[D*0, D*+, D0, D+, K_S0, pi0], path=path)`	Constraint $D^{(*)}$ masses additionally to improve $M^2_{\rm miss}$ resolution
		Vertex
ROE Charged	$\|dr\| < 5.0$ and $\|dz\| < 20.0$ and $p_t > 0.1$ GeV/c and nCDCHits > 0	
ROE Neutral	`gamma:eff40_May2020` and |clusterTiming| < 200 ns	Neutrals of Rest of event
ROE	roeCharge == 0 and ROE_nTracks == 0	

Belle II - LHCb comparison