Measurements of $\mathcal{R}(D)$ and $\mathcal{R}(D^{*})$ at Belle II

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

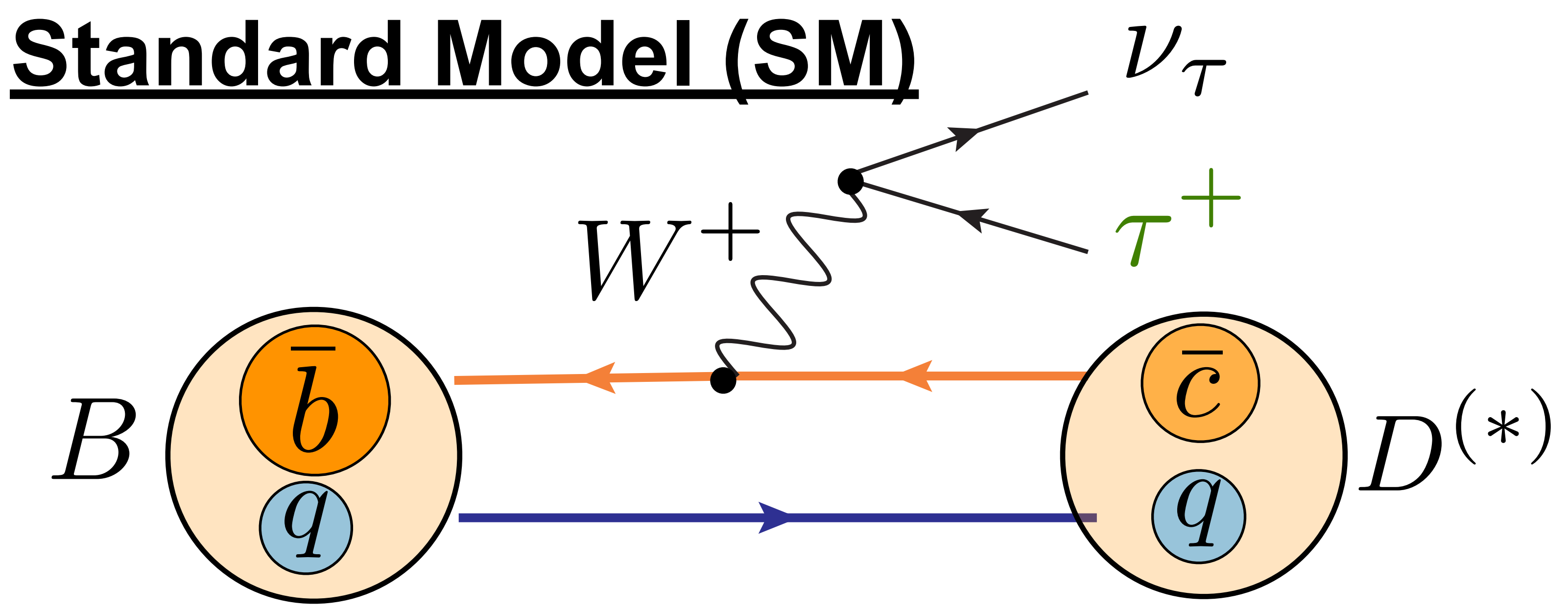
- Sensitive probes for New Physics (NP) (leptoquarks, two Higgs doublets etc.)
- NP could impact
  - observed lepton flavour universality (**LFU**) **ratios**,

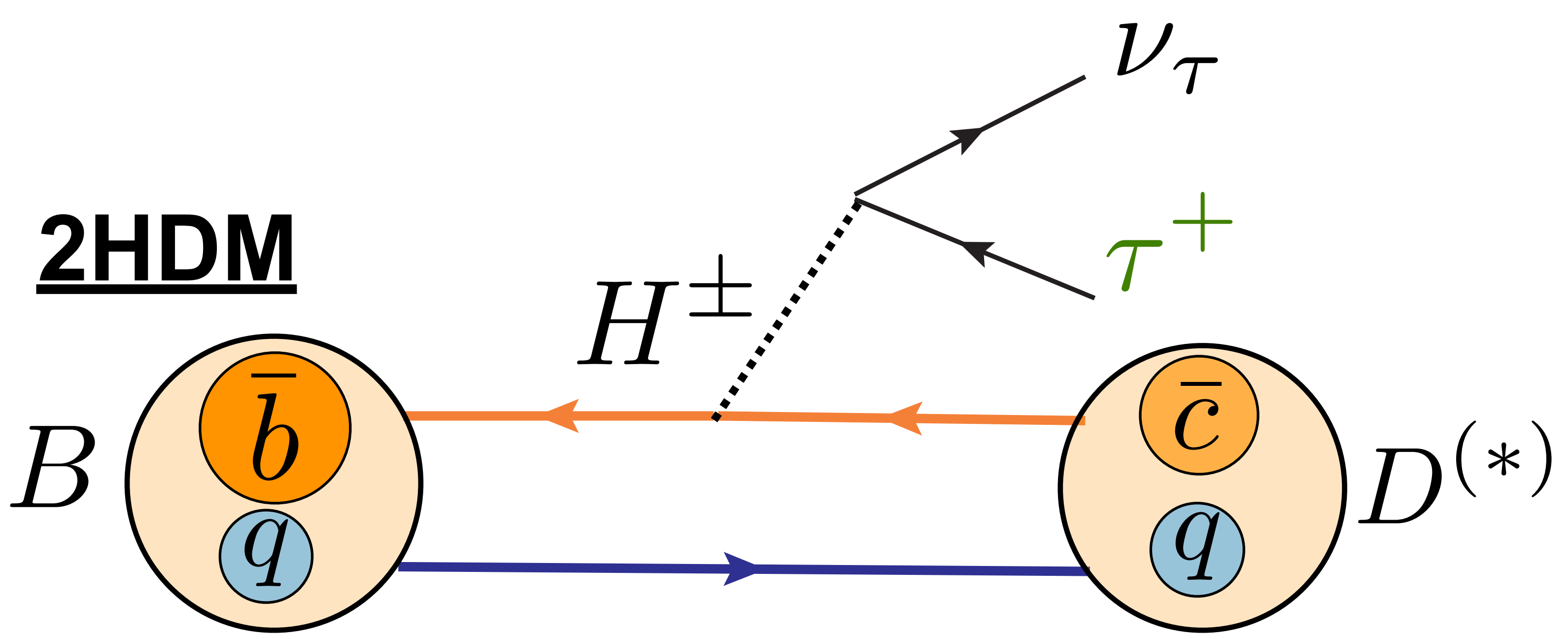
$$\mathcal{R}(D) \equiv \frac{\mathcal{B}(B \to D\tau^+\nu_\tau)}{\mathcal{B}(B \to D\ell^+\nu_\ell)}$$

$$\mathcal{R}(D^*) \equiv \frac{\mathcal{B}(B \to D^*\tau^+\nu_\tau)}{\mathcal{B}(B \to D^*\ell^+\nu_\ell)}$$

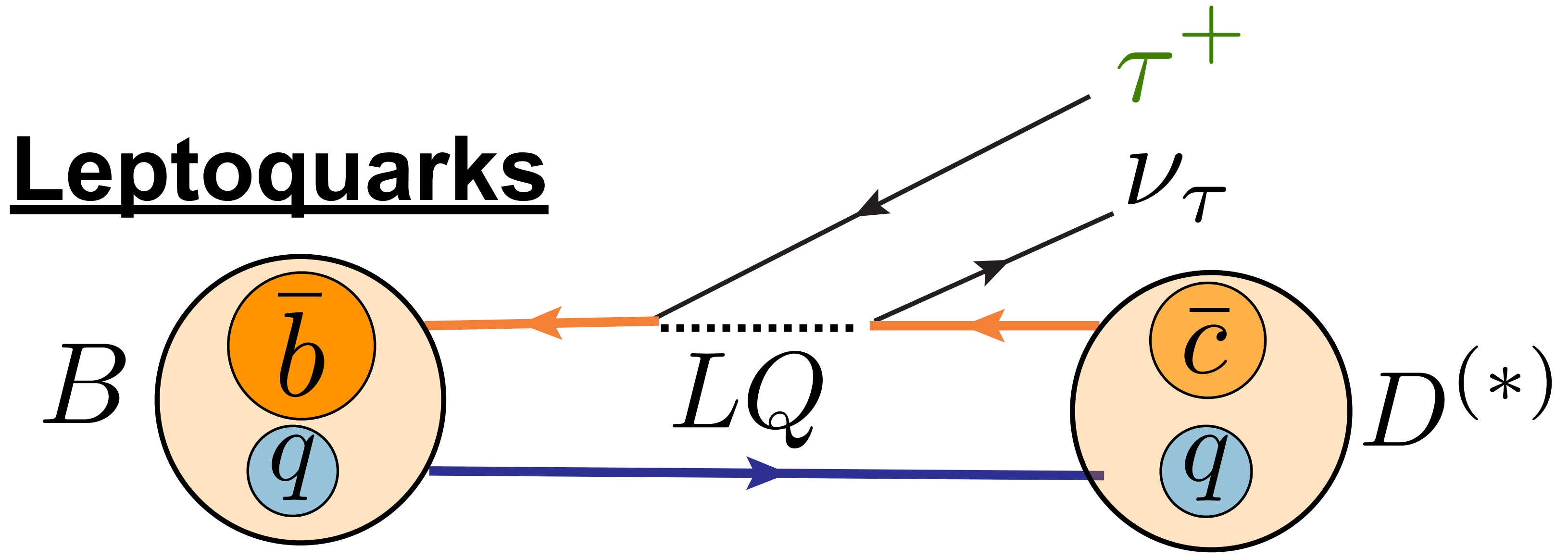
(where $\ell = e$ and μ)

$\mathcal{B}(B \to D^{(*)}\ell\nu) =$ average of electron and muon modes





[Front. Phys. 80, 1 (2000)]



[Phys. Lett. B 191, 442 (1987); 448, 320(E) (1999)]

$(q = u, d)$

$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

- Ratios of branching fractions:

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

- Some common systematics are cancelled out
  - Theoretical uncertainty of form factors
  - Uncertainty of $|V_{cb}|$
  - Experimental uncertainty of efficiencies

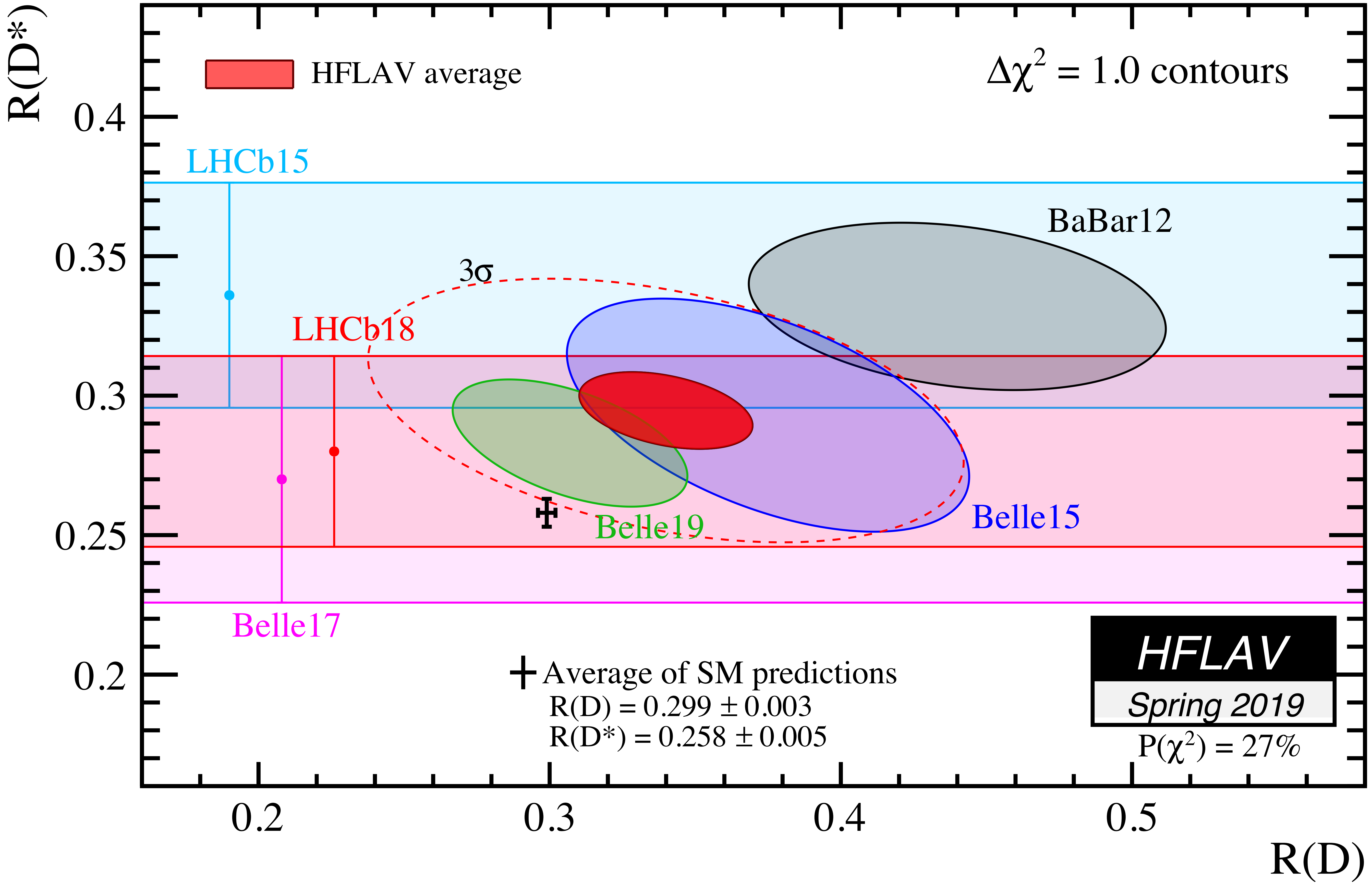
Theory average:

$\mathcal{R}(D)^{SM} = 0.299 \pm 0.003$

$\mathcal{R}(D^*)^{SM} = 0.258 \pm 0.005$

[Phys.Rev. D94 9, 094008 (2016), Phys.Rev. D95 11, 115008 (2017)]
[JHEP 1711 061 (2017), JHEP 1712 060 (2017)]

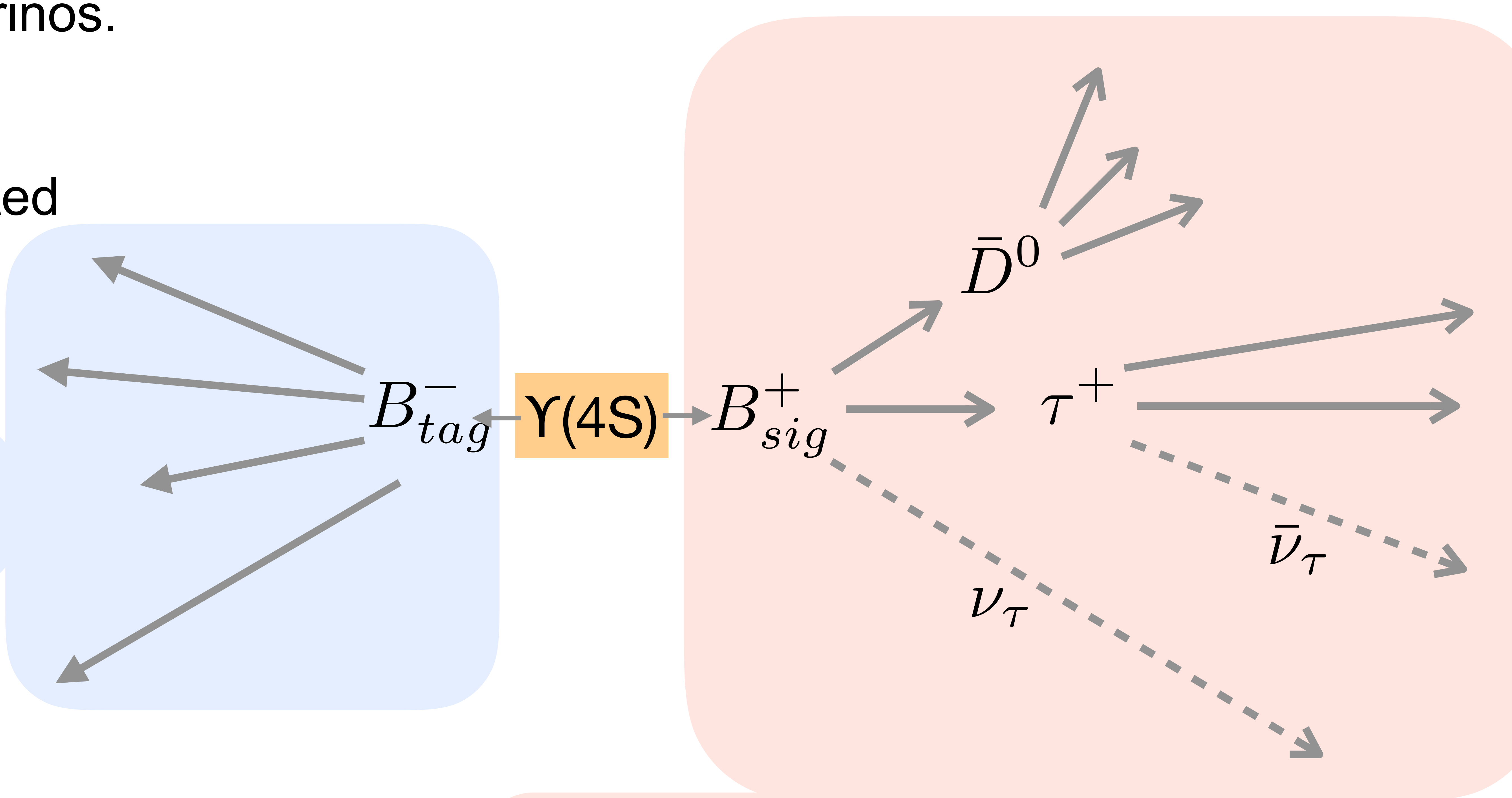
With current data from Belle, LHCb and BaBar:



- Latest **Belle** measurement brings down to the world average discrepancy from 3.8σ (HFAV 2018) to 3.1σ.

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

- Not a rare decay:
  - In SM, $\mathcal{B}(B^+ \to \bar{D}^0 \tau^+ \nu_\tau) = 0.66\%$ and $\mathcal{B}(B^+ \to \bar{D}^{*0} \tau^+ \nu_\tau) = 1.23\%$
- Reconstruction of τ is challenging due to multiple neutrinos.
  - Need full reconstruction of the event.
    - Suppress non-$B\bar{B}$ background and mis-reconstructed events.
  - Need a high statistics.

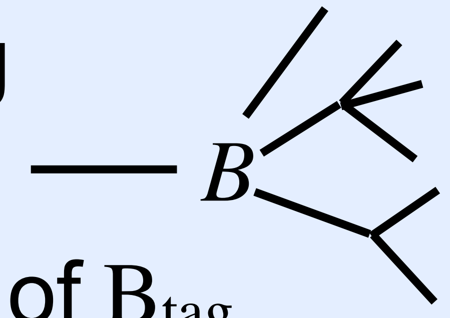


the companion B meson (B_{tag}) reconstruction (Tagging)

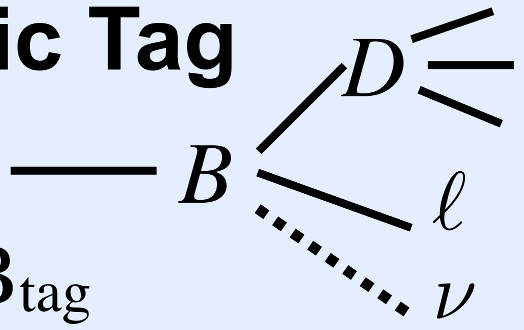
Efficiency ε: low → high

Purity: high → low

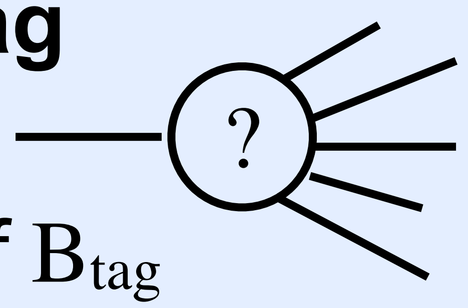
- **Hadronic Tag**
  $\varepsilon = \mathcal{O}(0.1)\%$
  Exact knowledge of B_{tag}



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



- **Inclusive Tag**
  $\varepsilon = (100)\%$
  Consistency of B_{tag}



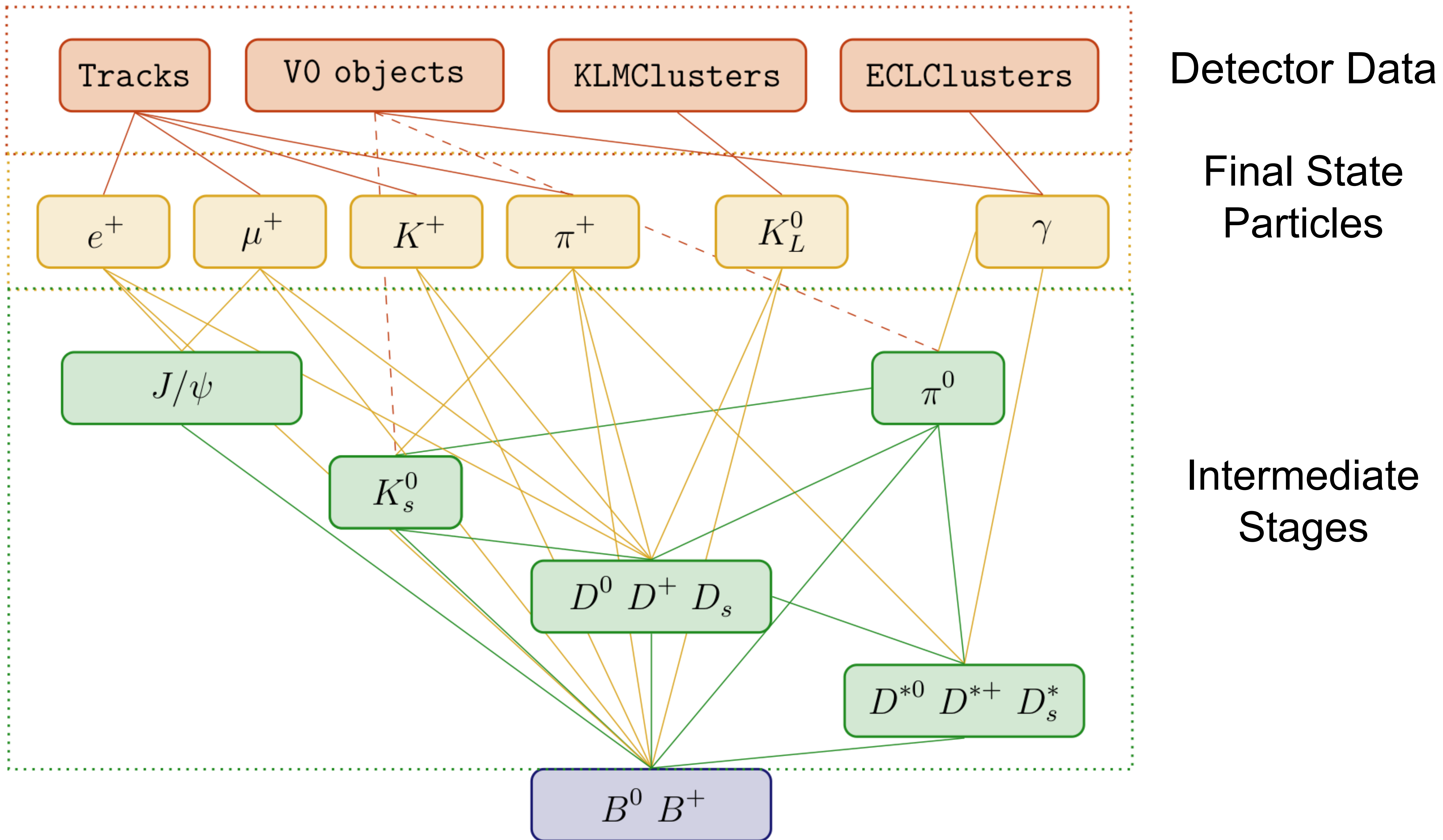
select the B_{sig} decay with

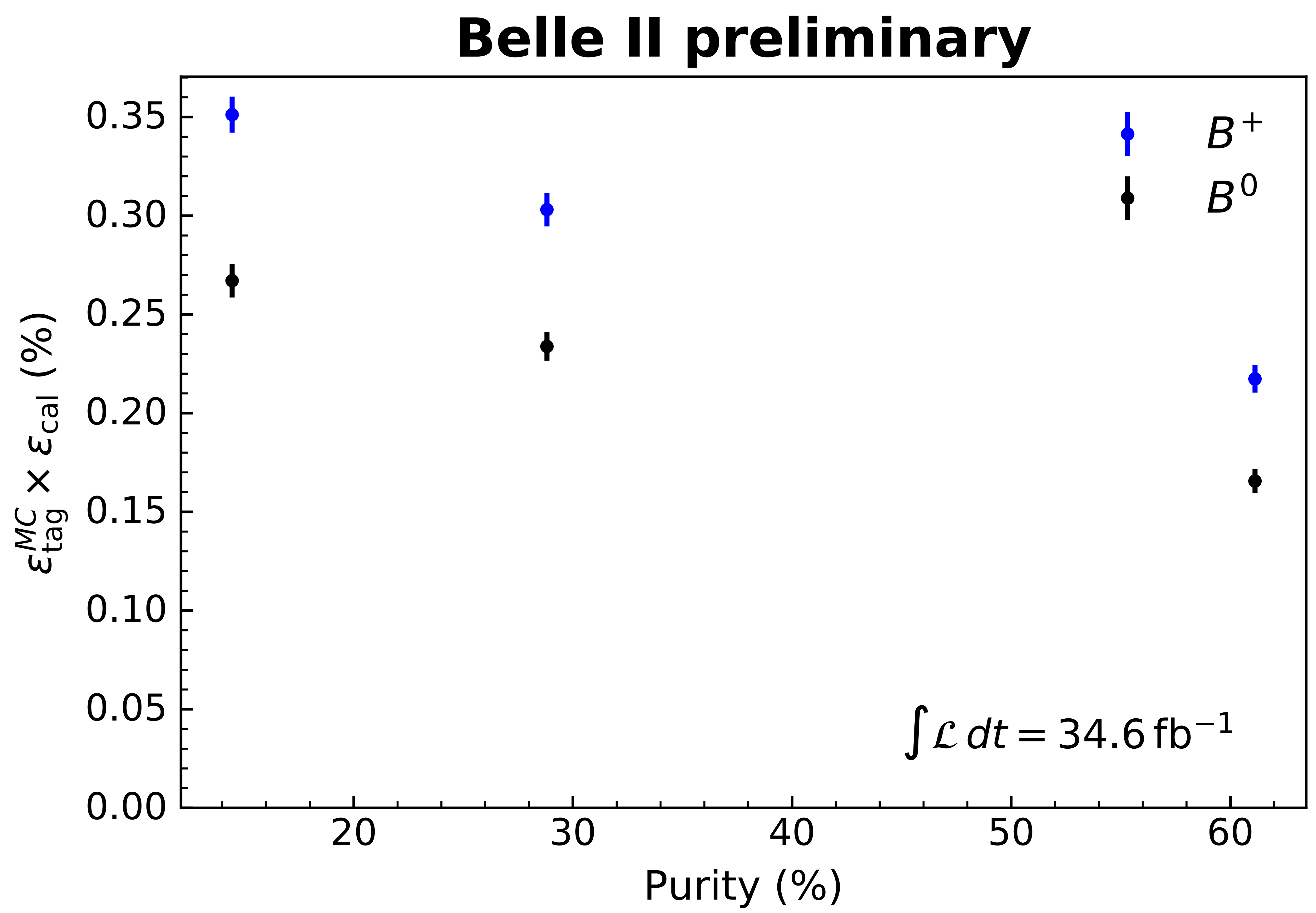
- a $D^{(*)}$
- a charged daughter of τ
  - Leptonic τ decay
  - Hadronic τ decay

Full Event Interpretation: B Tagging Software at Belle II

- FEI (Full Event Interpretation): Multivariate analysis with Boosted-Decision Tree (BDT) classifier.
  - The most evolved version of B tagging software developed for Belle II.
  - $\mathcal{O}(200)$ BDT classifiers trained on $\mathcal{O}(10{,}000)$ B decay channels to identify the B_{tag}.
- FEI was successfully used in **recent Belle $\mathcal{R}(D^{(*)})$ measurement with a semileptonic tagging method.** *[Phys. Rev. Lett. 124, 161803 (2020)]*

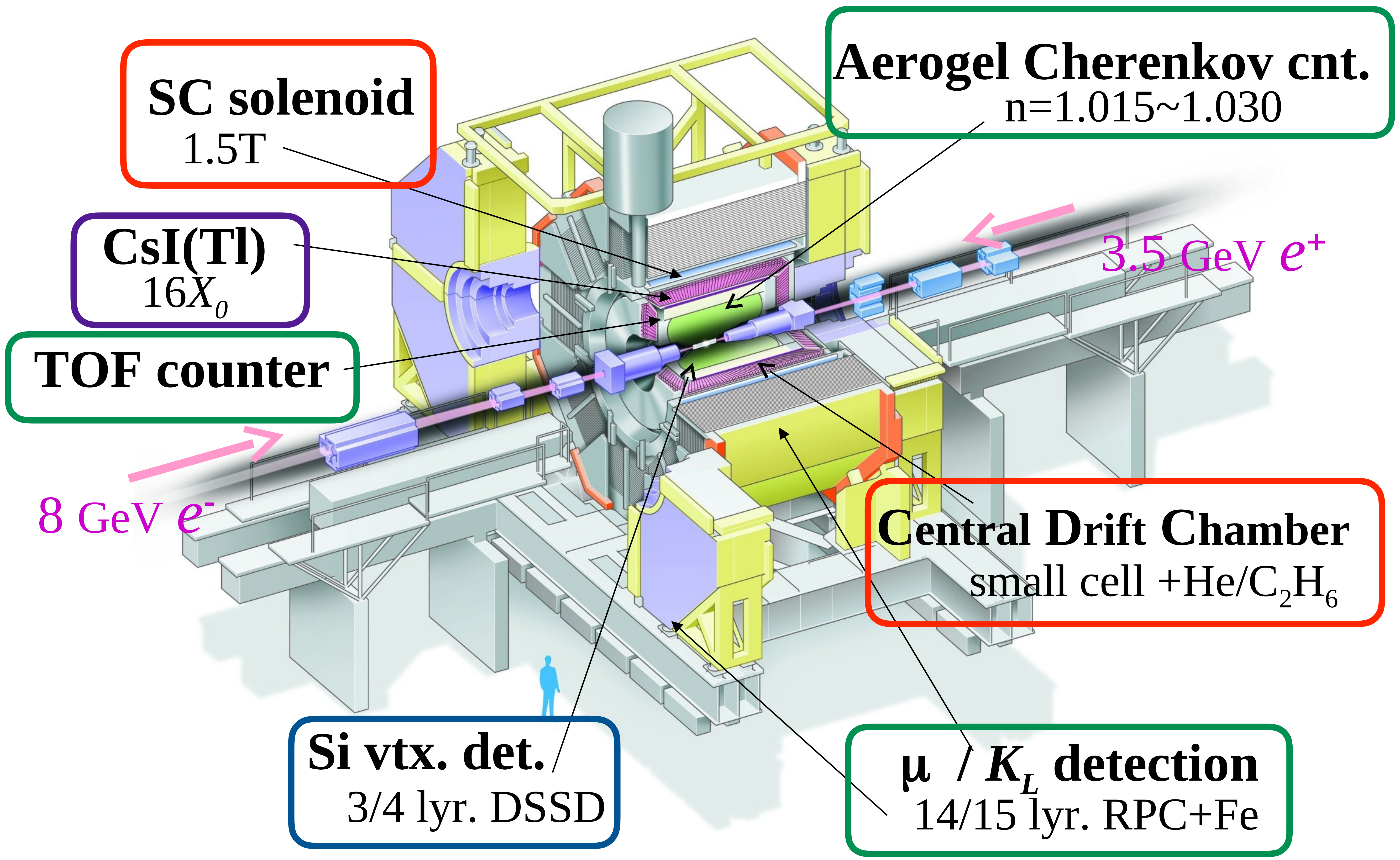
[Comput. Softw. Big Sci. 3, 6 (2019)]





Recent $\mathcal{R}(D^{(*)})$ Measurements at *Belle*

Belle @ KEKB



- Collected 772 x 10^6 $B\bar{B}$ events at **KEKB** factory (1999-2010),
  - 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 measurement of charged tracks
  - Vertex measurement
  - Particle ID

Recent $\mathcal{R}(D^{(*)})$ Measurement in Belle with Semileptonic Tagging

- **Analysis with the *Belle II* software framework.**
- 772 x 10^6 $B\overline{B}$ events
- 4 data samples: $D^+ \ell^-$, $D^0 \ell^-$, $D^{*+} \ell^-$, $D^{*0} \ell^-$

combined reconstructed branching fractions

- $\boldsymbol{D^0}$ $(K\pi\pi^0, K\pi\pi\pi, K\pi, K_S\pi\pi, K_S\pi^0, K_SKK, KK, \pi\pi)$, → 30% for $\boldsymbol{D^0}$
- $\boldsymbol{D^+}$ $(K\pi\pi, K_S\pi\pi^0, K_S\pi\pi\pi, K_S\pi, KK\pi, K_SK)$, → 22% for $\boldsymbol{D^+}$
- D^{*+} $(D^0\pi, D^+\pi^0)$, D^{*0} $(D^0\pi^0)$

$B^{\pm/0} \to D^{(*)}\tau(\ell\nu\nu)\nu$

signal mode

← B-signal — $\Upsilon(4S)$ — B-tag →

$B^{\pm/0} \to D^{(*)}\ell\nu$

Using a hierarchical algorithm based on Fast BDT

$B^{\pm/0} \to D^{(*)}\ell\nu$

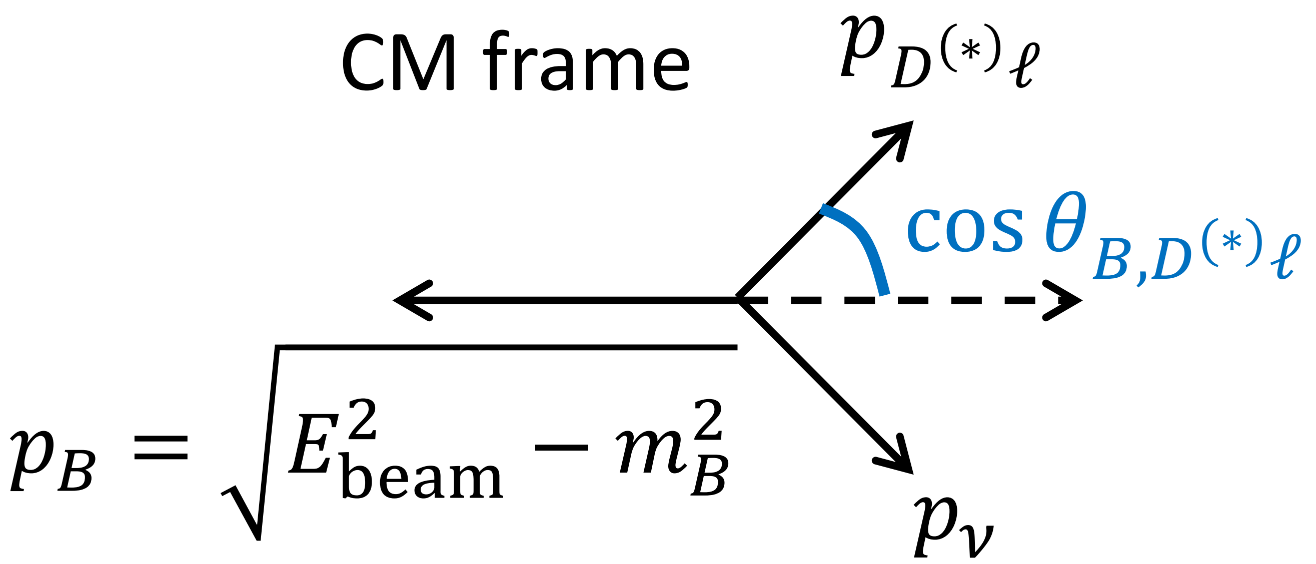
normalization mode

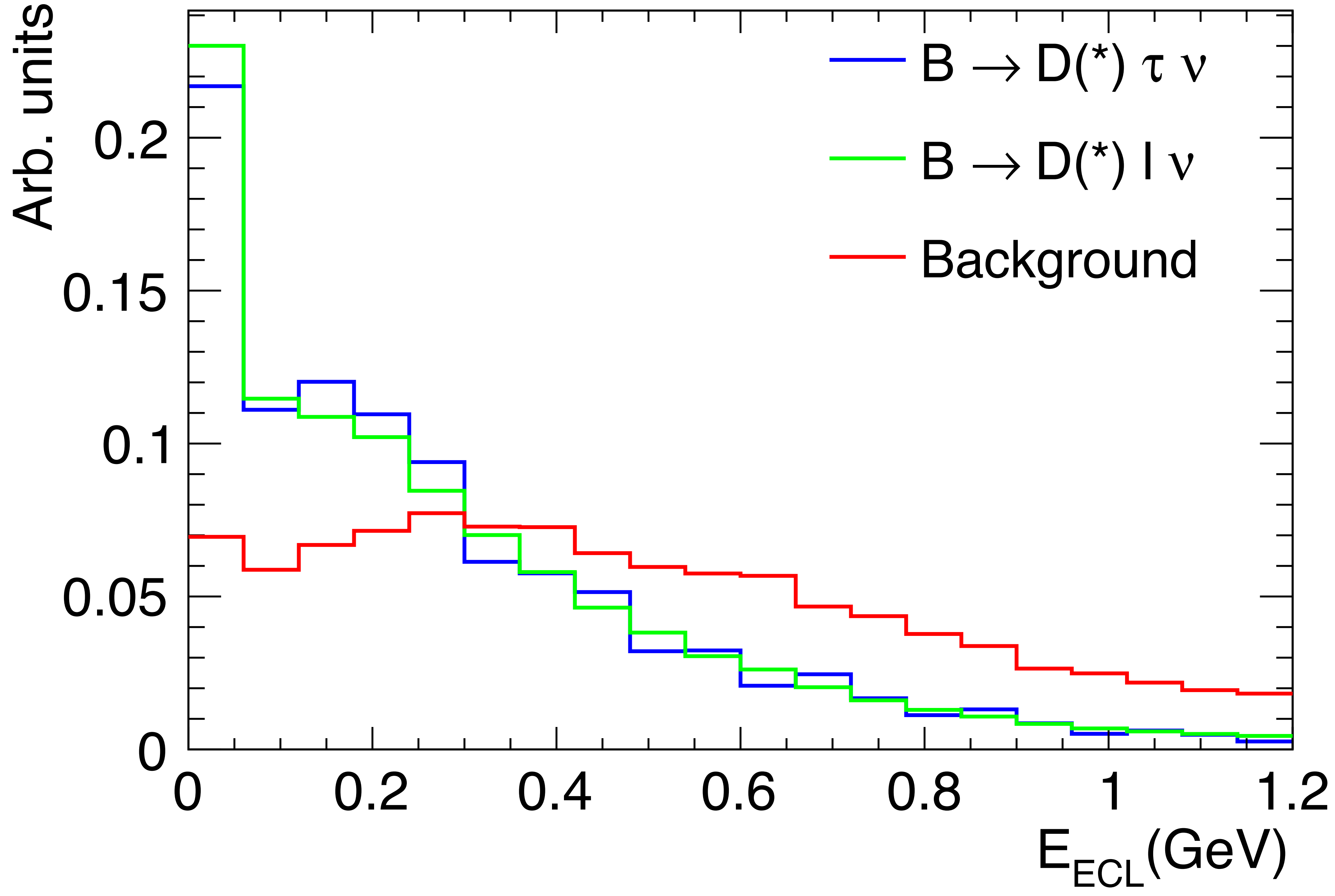
(where $\ell = e$ and μ)

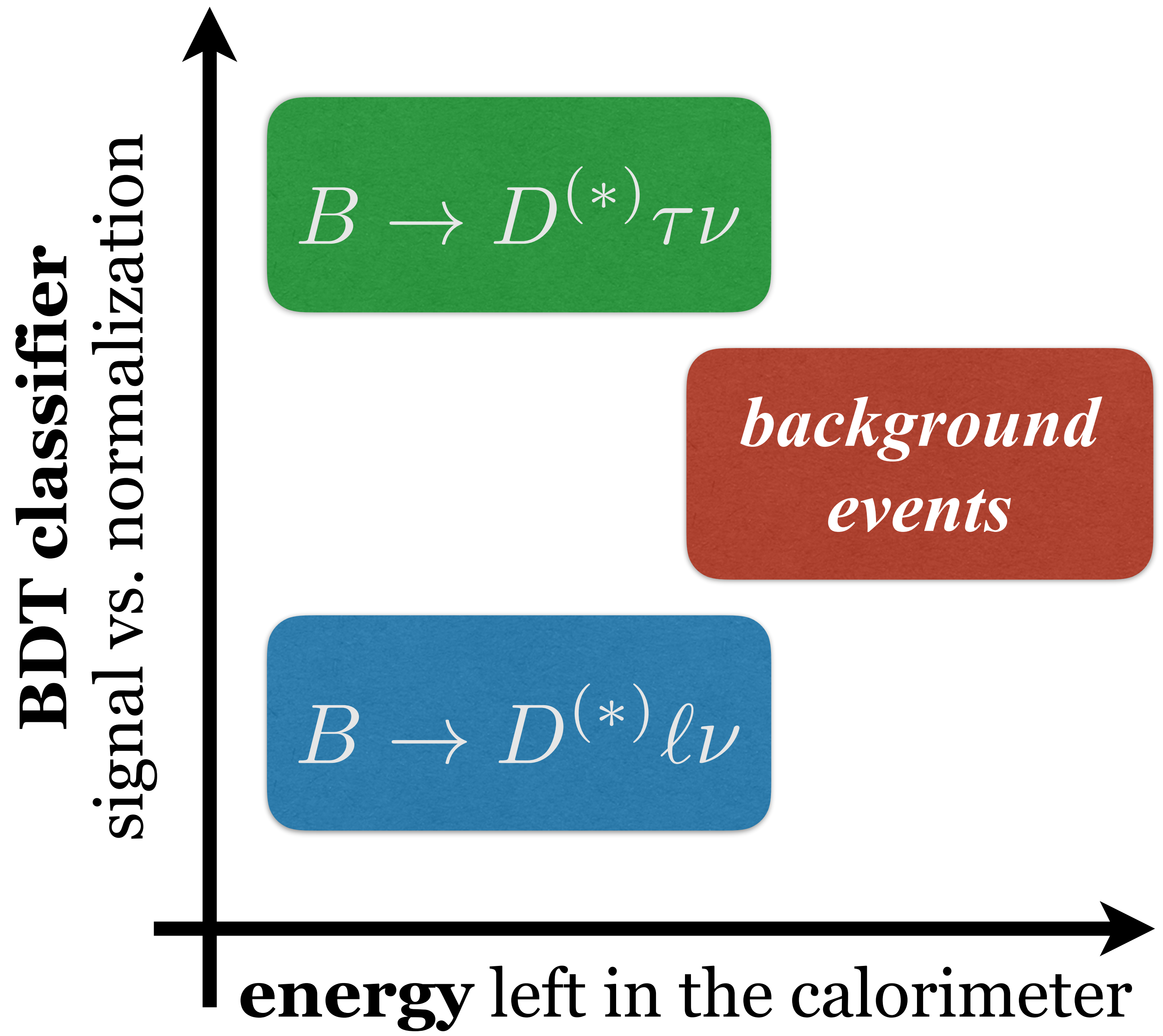
- **"B-tag" and "B-signal" are required to be of opposite flavor**

Key Observables

- E_{ECL} : Energy deposited in the **Electromagnetic Calorimeter (ECL)** not associated with reconstructed particles.
  - Signal ($B \to D^{(*)} \tau \nu$) and normalization ($B \to D^{(*)} \ell \nu$) events **peak near zero in E_{ECL}** ,
- **BDT classifier output** (based on the XGBoost package): "**class**"
  - To separate reconstructed signal and normalization
  - Input variables:
    - visible energy,
    - $m^2_{miss} = (E_{beam} - E_{D^{(*)}} - E_\ell)^2 - (p_{D^{(*)}} + p_\ell)^2$
    - $cos\theta_{B,D^{(*)}\ell} \equiv \dfrac{2E_{beam}E_{D^{(*)}\ell} - m_B^2 - m^2_{D^{(*)}\ell}}{2|p_B||p_{D^{(*)}\ell}|}$

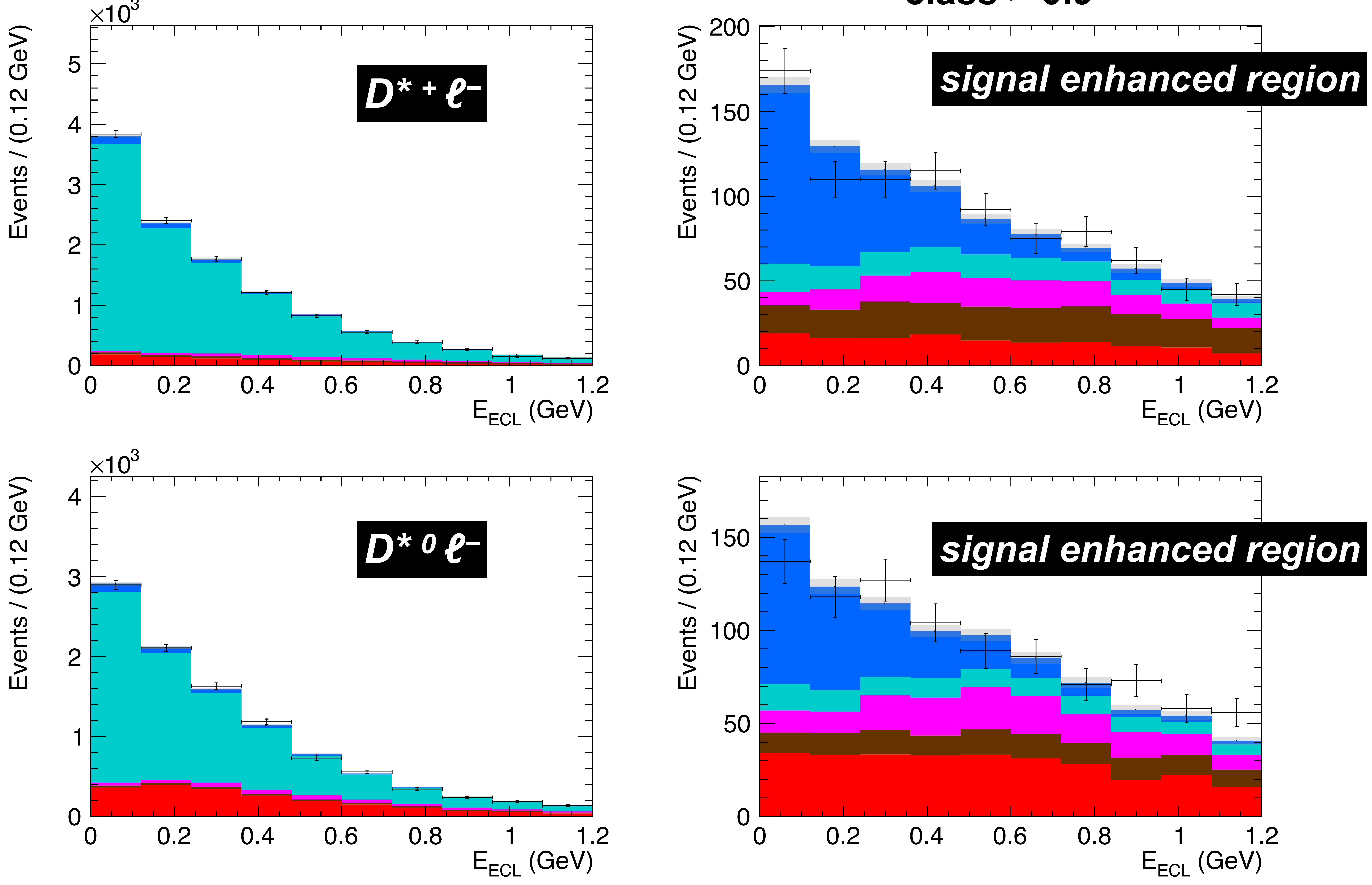


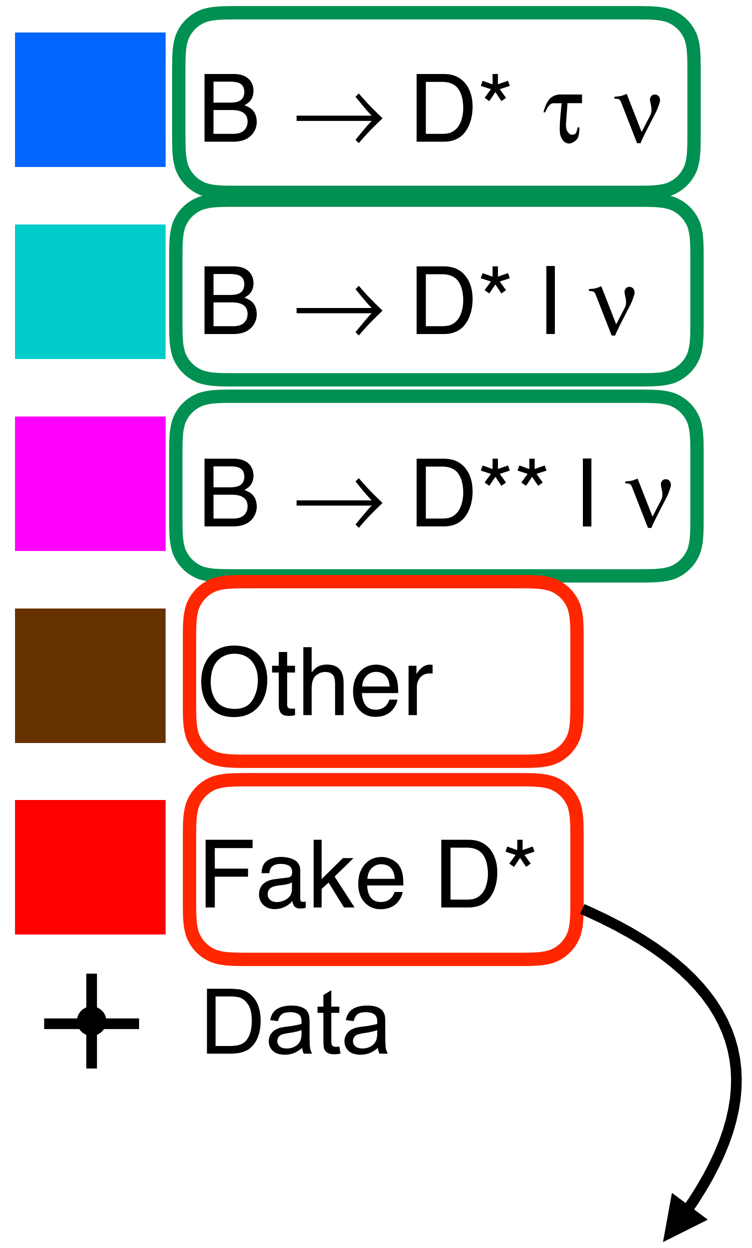




Fit Results ($D^* \ell^-$ sample)

class > 0.9





Calibrated with M(D*) - M(D) sidebands

Component types:

- floating
- correlated
- fixed

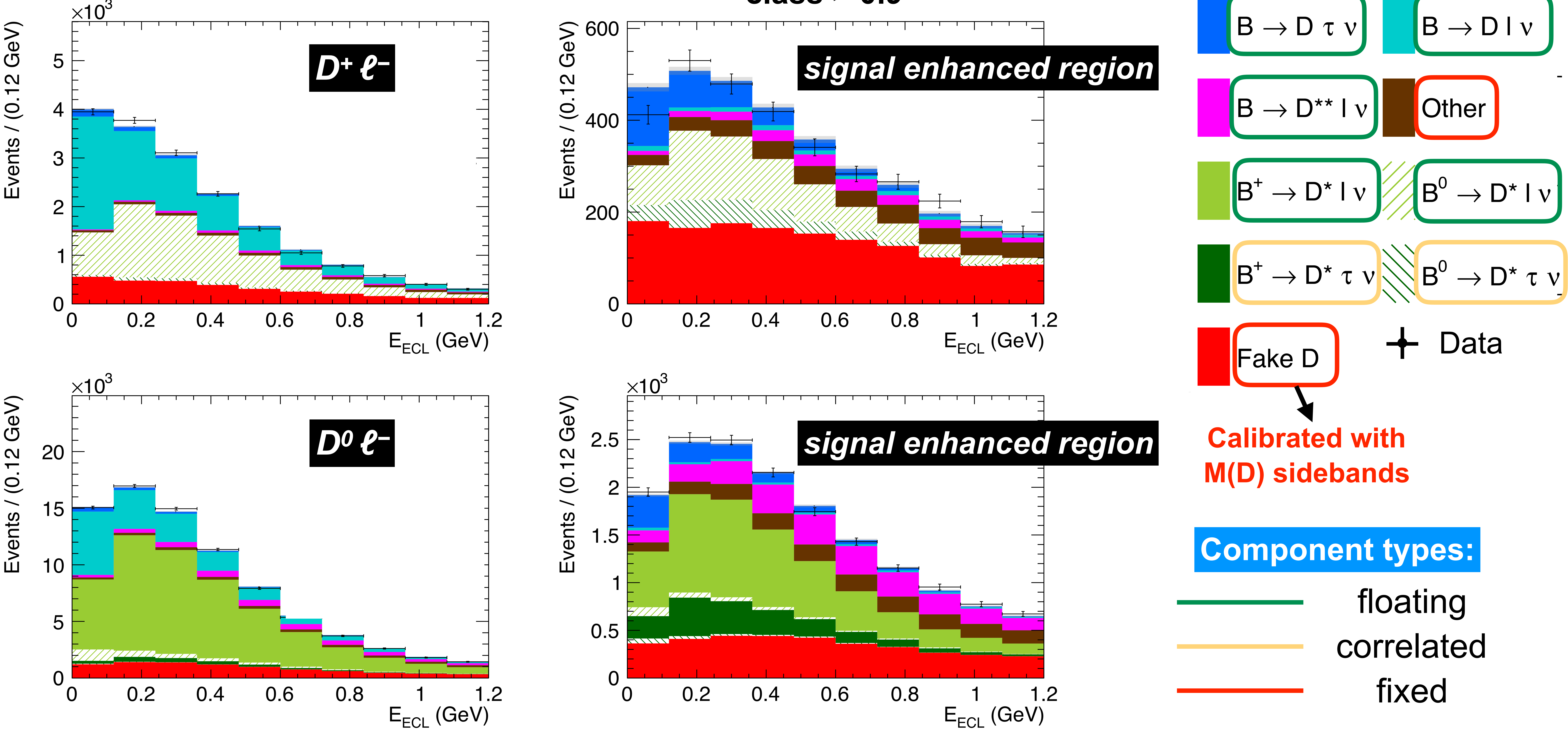
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)} = \frac{1}{2\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)} \cdot \frac{\epsilon_{\rm norm}}{\epsilon_{\rm sig}} \cdot \frac{N_{\rm sig}}{N_{\rm norm}}$$

MC: $\frac{\epsilon_{\rm norm}}{\epsilon_{\rm sig}}$

$\frac{N_{\rm sig}}{N_{\rm norm}}$ → Fit to PDFs to the data

Fit Results ($D\,\ell^-$ sample)

class > 0.9



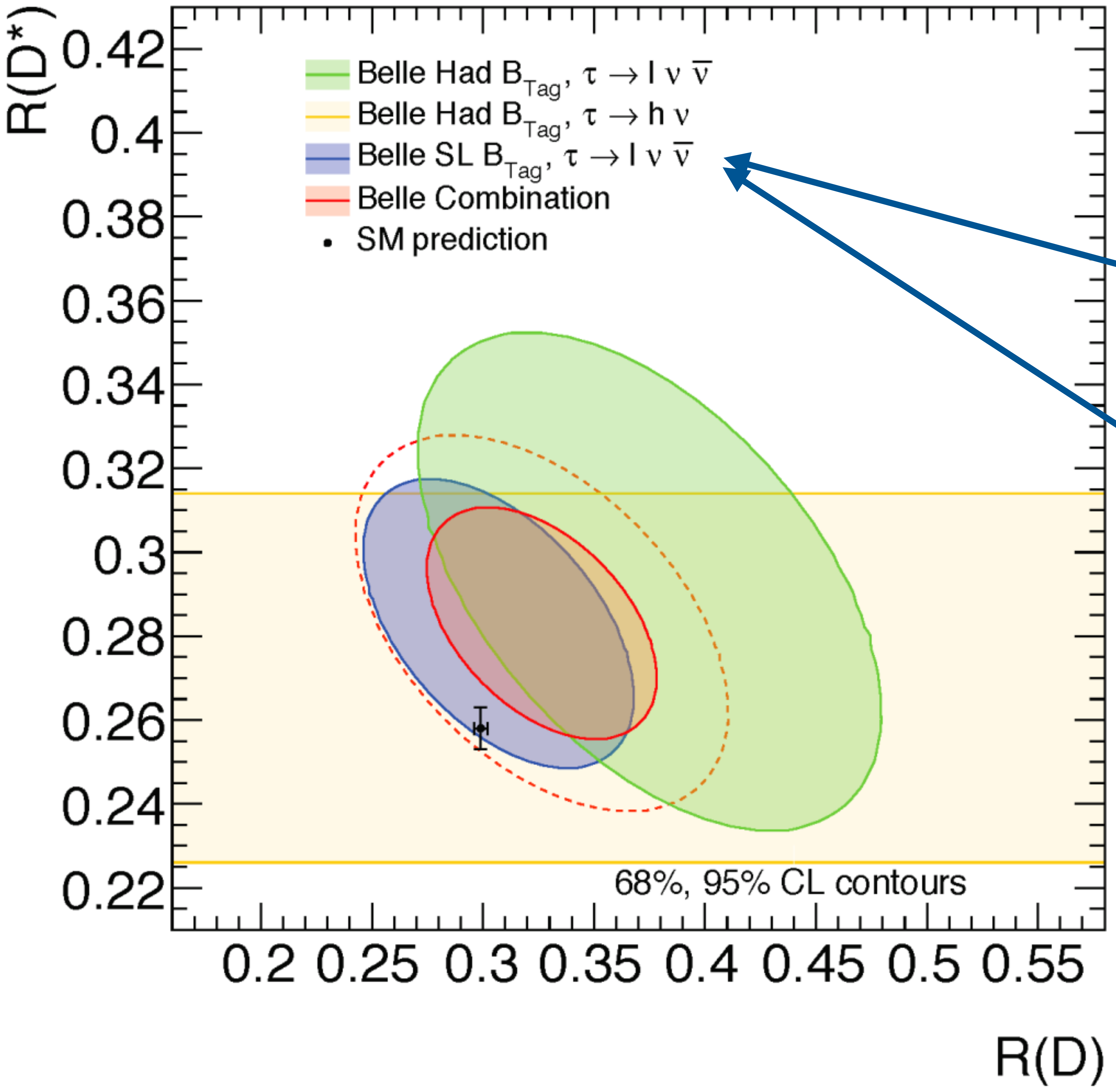
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)} = \frac{1}{2\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)} \cdot \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}} \cdot \frac{N_{\text{sig}}}{N_{\text{norm}}}$$

MC

Fit to PDFs to the data

Result on $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

Phys. Rev. Lett. 124, 161803 (2020)



- Most precise measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$.
- First $\mathcal{R}(D)$ result with a semileptonic tag.

$\mathcal{R}(D)$ = 0.307 ± 0.037 ± 0.016 — Agrees with SM within 0.2 σ

$\mathcal{R}(D^*)$= 0.283 ± 0.018 ± 0.014 — Agrees with SM within 1.1 σ

- The combined result agrees with the SM prediction within 0.8 σ.
- The results of this analysis, together with past Belle results combined gives compatibility with the SM within 1.6 σ.

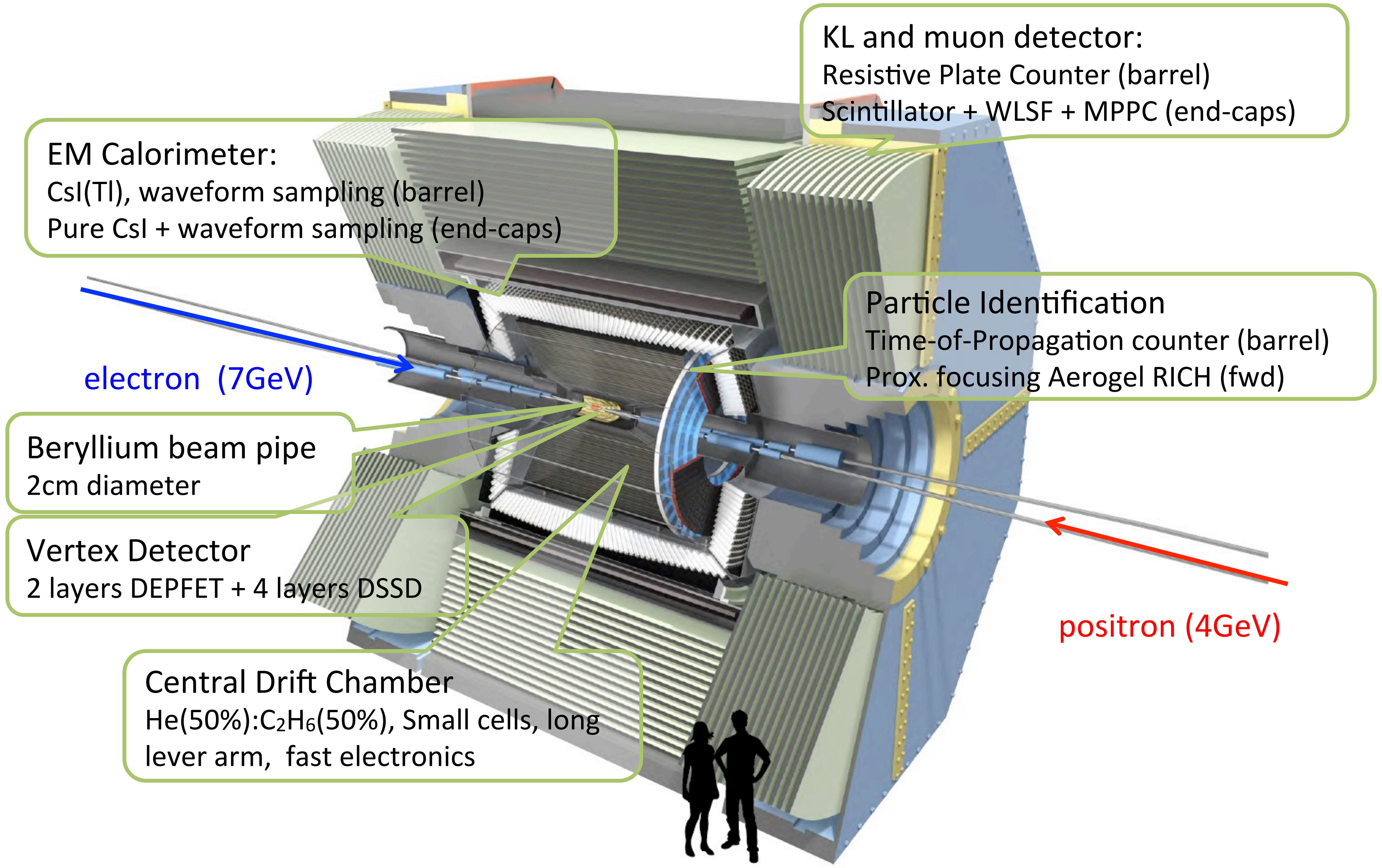
$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ Status

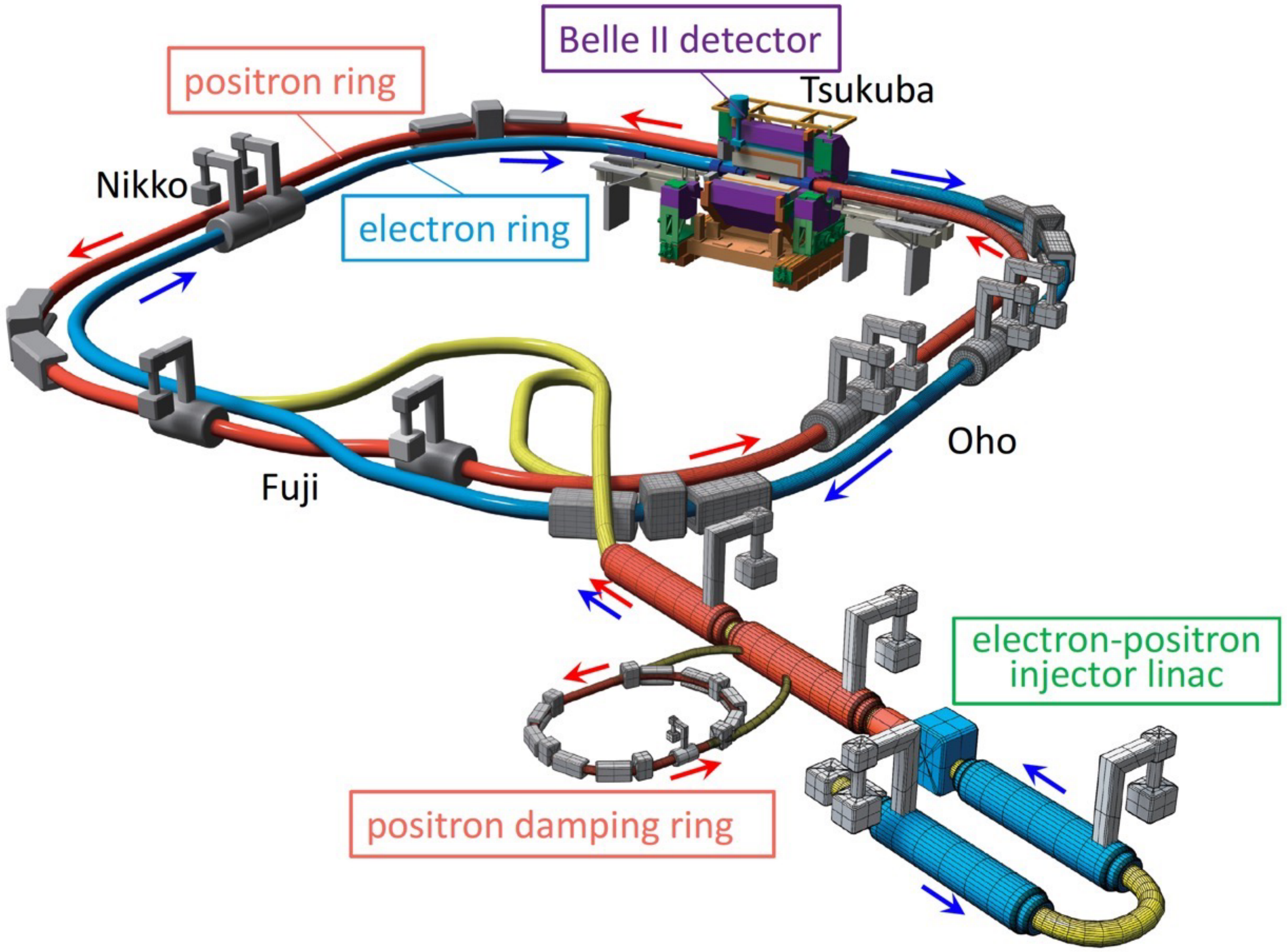
Experiment	Tag Method	τ Mode	R(D)	R(D*)	
BABAR '12	Hadronic	$\ell\nu\nu$	0.440 ± 0.058 ± 0.042	0.332 ± 0.024 ± 0.018	
Belle '15	Hadronic	$\ell\nu\nu$	0.375 ± 0.064 ± 0.026	0.293 ± 0.038 ± 0.015	
LHCb '15	-	$\ell\nu\nu$	-	0.336 ± 0.027 ± 0.030	
Belle '16	Semileptonic	$\ell\nu\nu$	-	0.302 ± 0.030 ± 0.011	B^0
Belle '17	Hadronic	$\pi\nu, \rho\nu$	-	0.270 ± 0.035 ± 0.027	
LHCb '18	-	$\pi\pi\pi\nu$	-	0.291 ± 0.019 ± 0.029	
Belle '19	Semileptonic	$\ell\nu\nu$	0.307 ± 0.037 ± 0.016	0.283 ± 0.018 ± 0.014	B^0 B^+
AVERAGE (2019)	-	-	0.340 ± 0.027 ± 0.013	0.295 ± 0.011 ± 0.008	
SM			0.299 ± 0.003	0.258 ± 0.005	

Experimental world average tension with SM prediction decreases from 3.8σ (Avg. 2018) to 3.1σ.

Prospects for $\mathcal{R}(D^{(*)})$ Measurements at *Belle II*

Belle II @ SuperKEKB

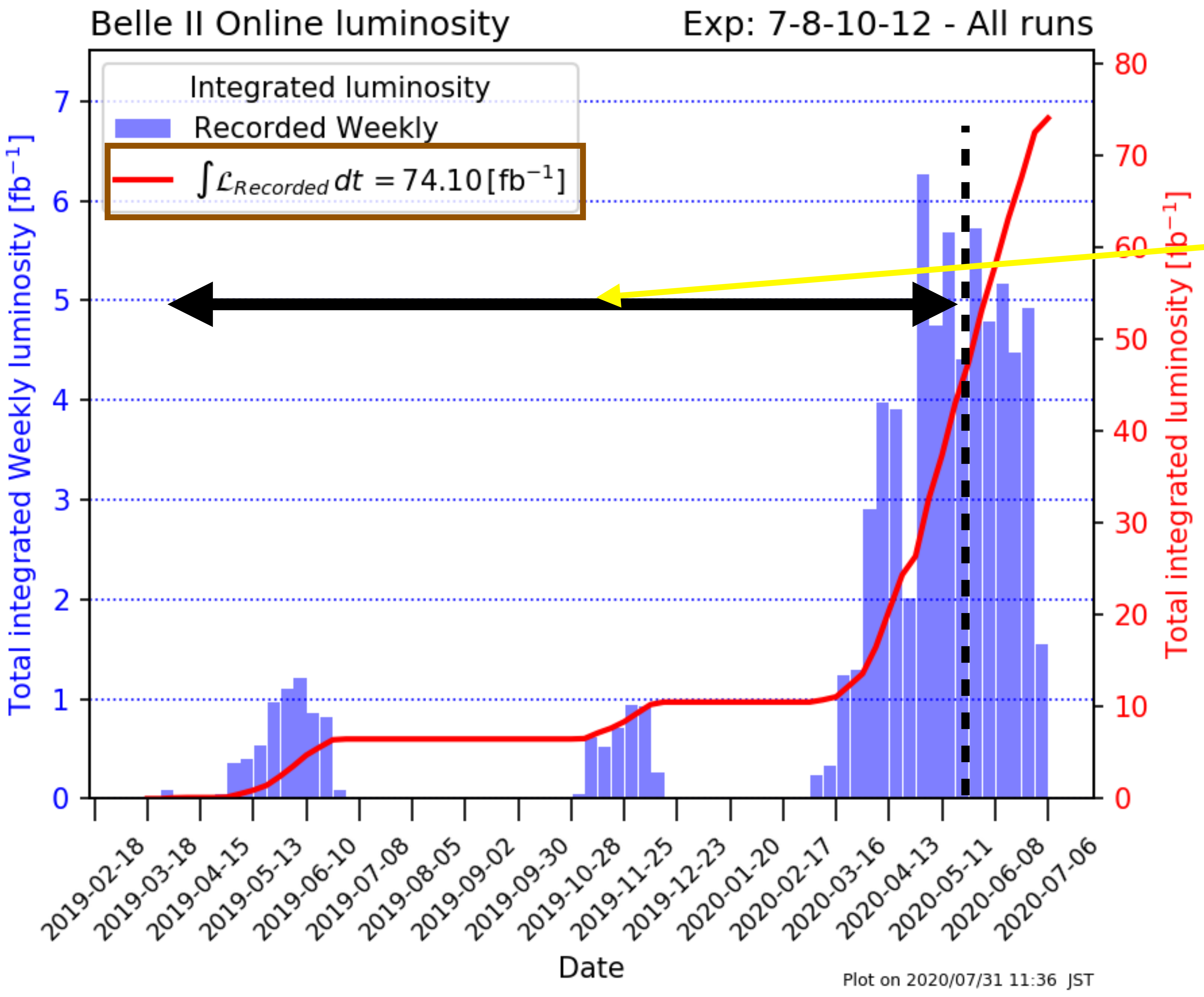




- ***SuperKEKB***: 40 x higher instantaneous luminosity than KEKB → $\mathcal{L} = 6 \times 10^{35}$ cm^{-2}s^{-1}
- ***Belle II:*** major upgrade of the ***Belle*** detector.
  - Improved reconstruction algorithm, e.g. tracking, vertexing and particle identification.

Covered by Toru Iijima "Belle II: Status and Highlights" on Monday September 21, 2020

Current Belle II Dataset



Data sample used in the studies presented today:

$$\int \mathcal{L} dt = 34.6 fb^{-1}$$

- **Current data sample is too limited for semitauonic *B* measurements.**
  - Studied data/MC comparisons to show the detector performance
  - Rediscovery of $\overline{B}^0 \to D^{*+}\ \ell\ \nu$.
- Expecting the first measurements with τ's with $\mathcal{O}(200\ fb^{-1})$ in 2021.

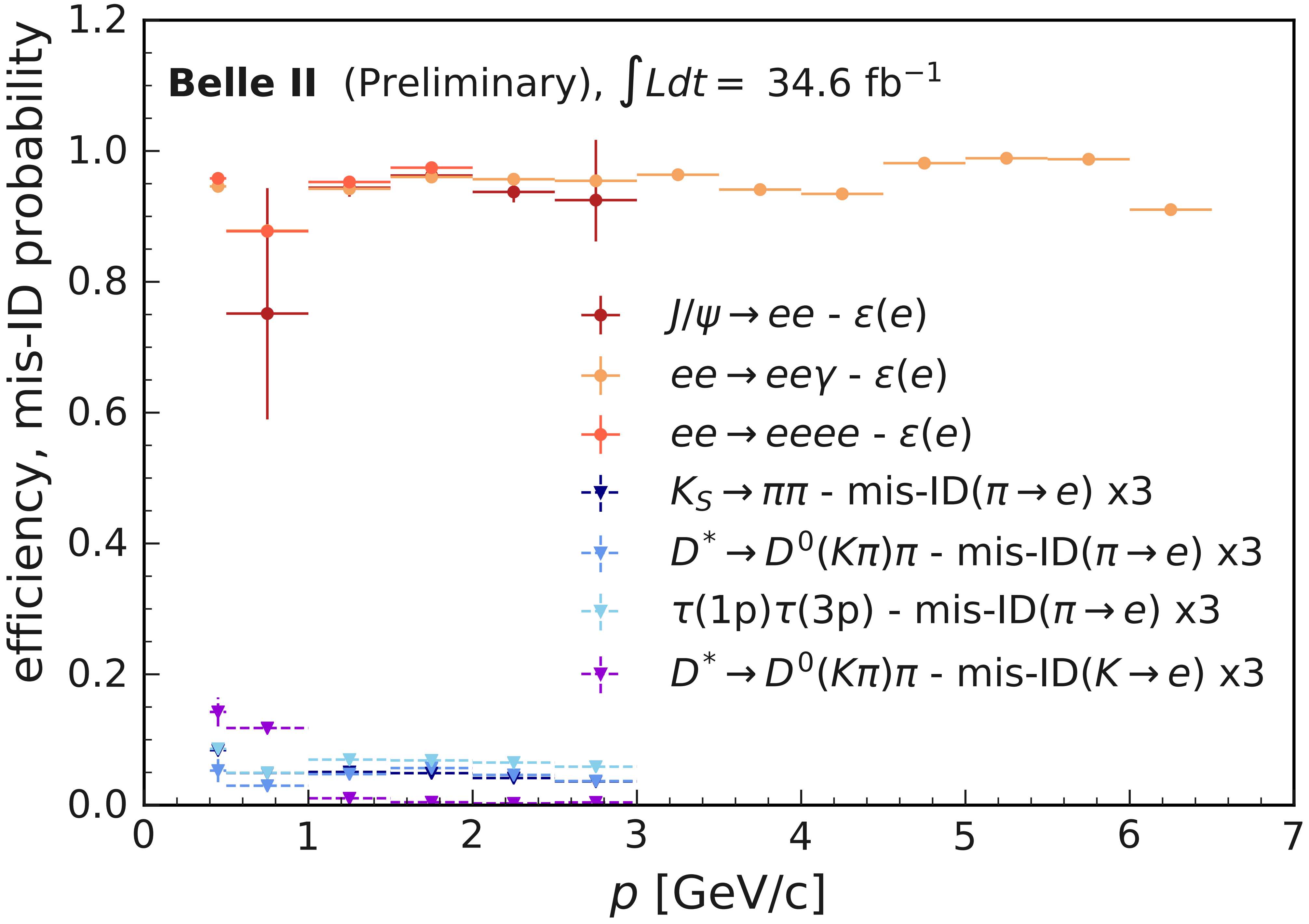
Lepton Identification Performance in 2020 Data

- $B \to D^{(*)} \tau \nu$ analyses essentially depend on how well we identify leptons.

Efficiencies and mis-identification rates for a representative bin in the detector "barrel" region

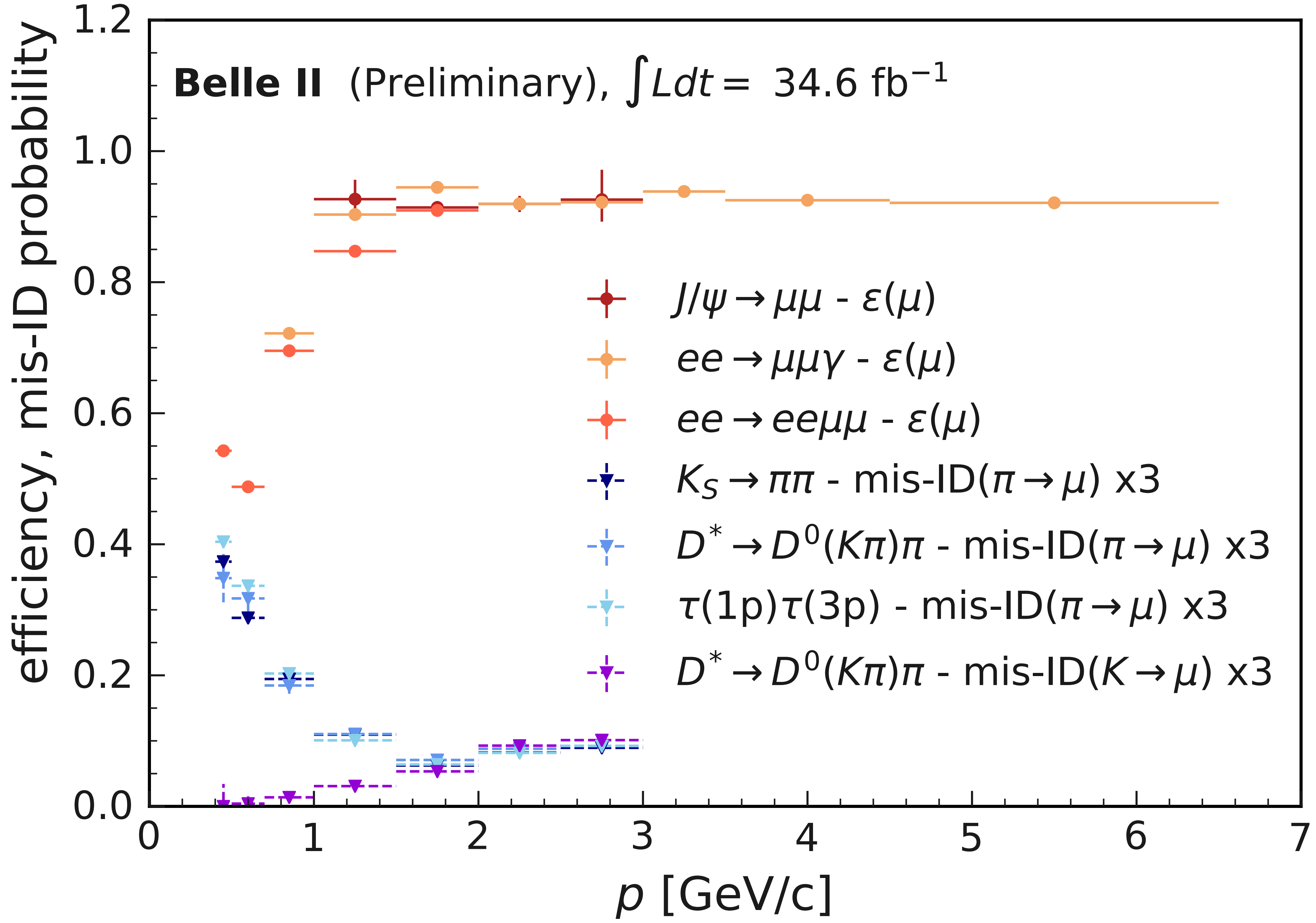
electrons

1.13 $\leq \theta <$ 1.57 rad, electronID > 0.9



muons

0.82 $\leq \theta <$ 1.16 rad, muonID > 0.9

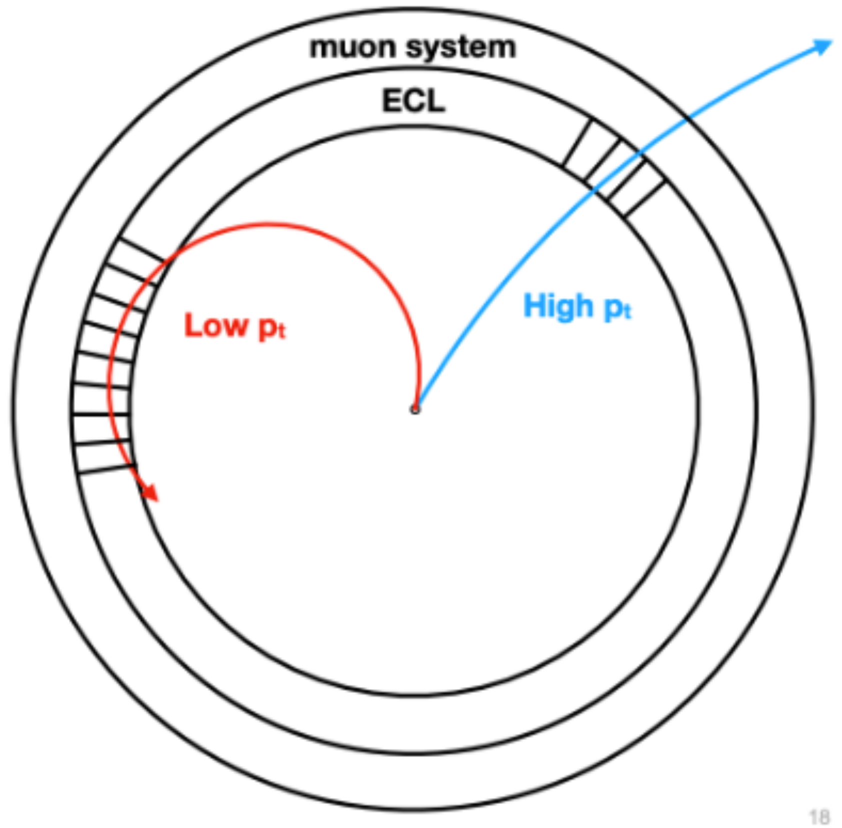


- e, $\mathcal{L}_{\text{ratio}} > 0.9, p > 1$ GeV/c $\to$ ⟨efficiency⟩ of 94% for 2% pion mis-id probability.
- μ, $\mathcal{L}_{\text{ratio}} > 0.9, p > 1$ GeV/c $\to$ ⟨efficiency⟩ of 90% for 4% pion mis-id probability.

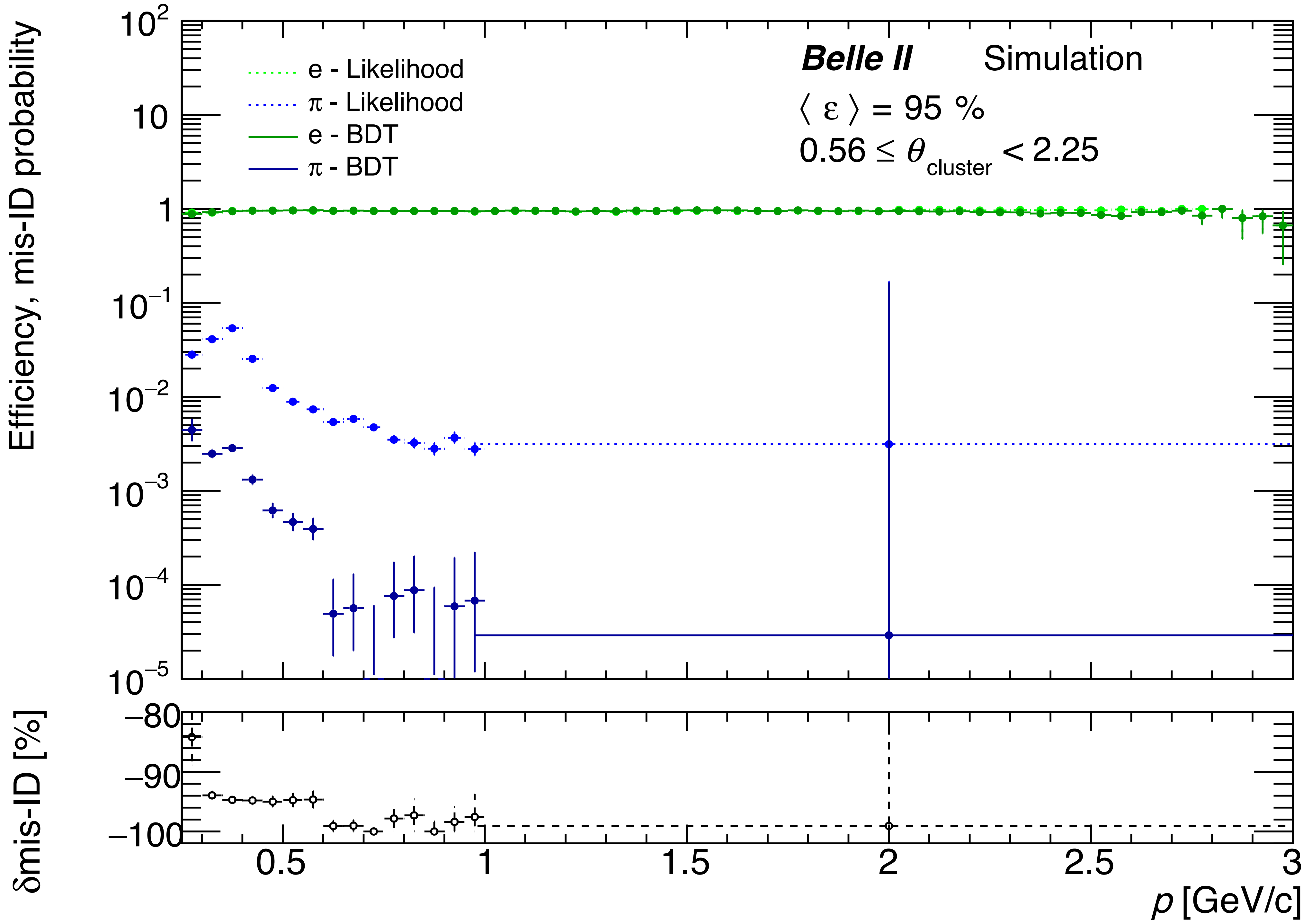
Likelihood ($\mathcal{L}$) ratio
(with inputs from all sub-detectors)

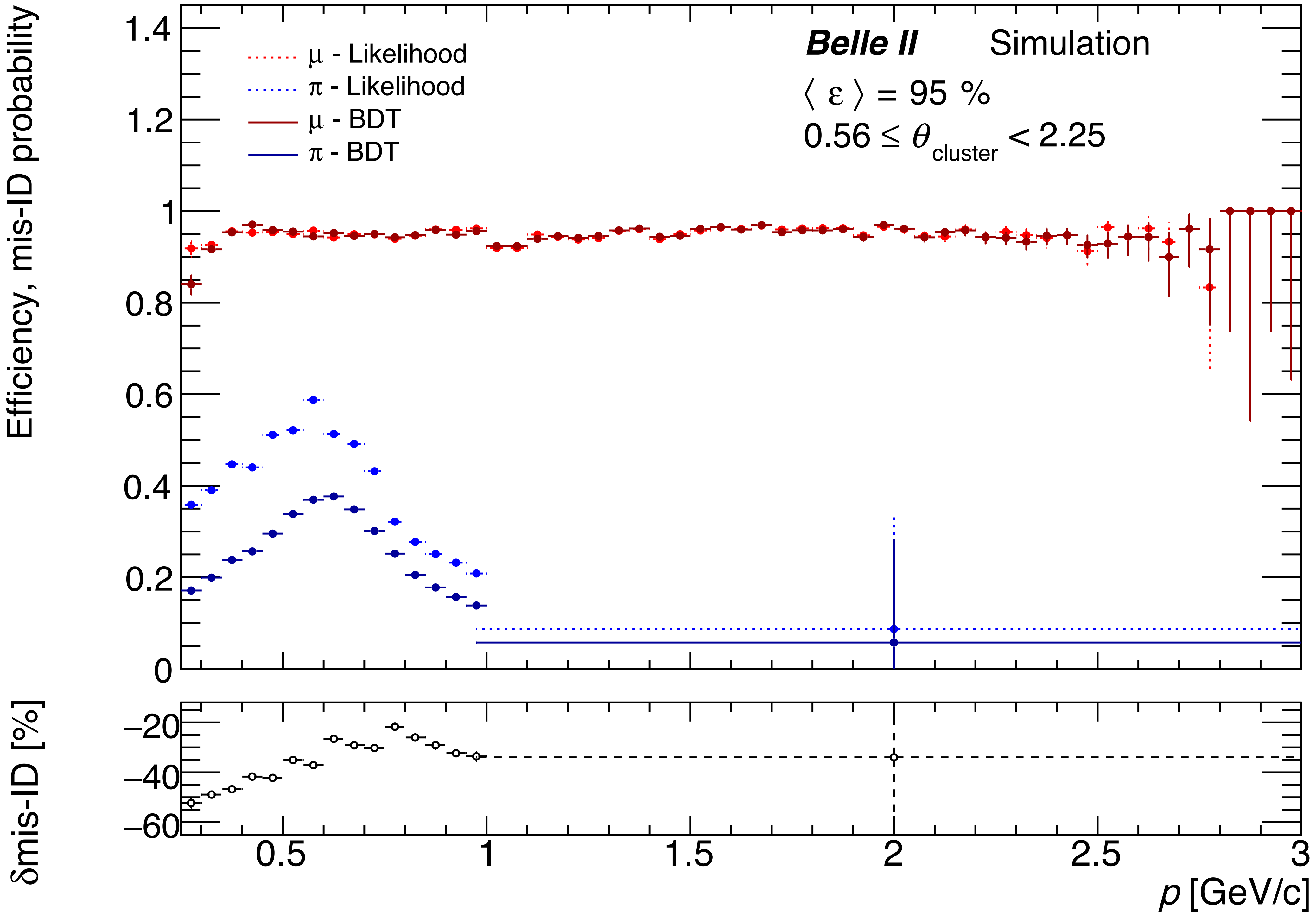
$$\ell ID = \frac{\mathcal{L}_\ell}{\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p}$$

Improving Lepton Identification Using the ECL



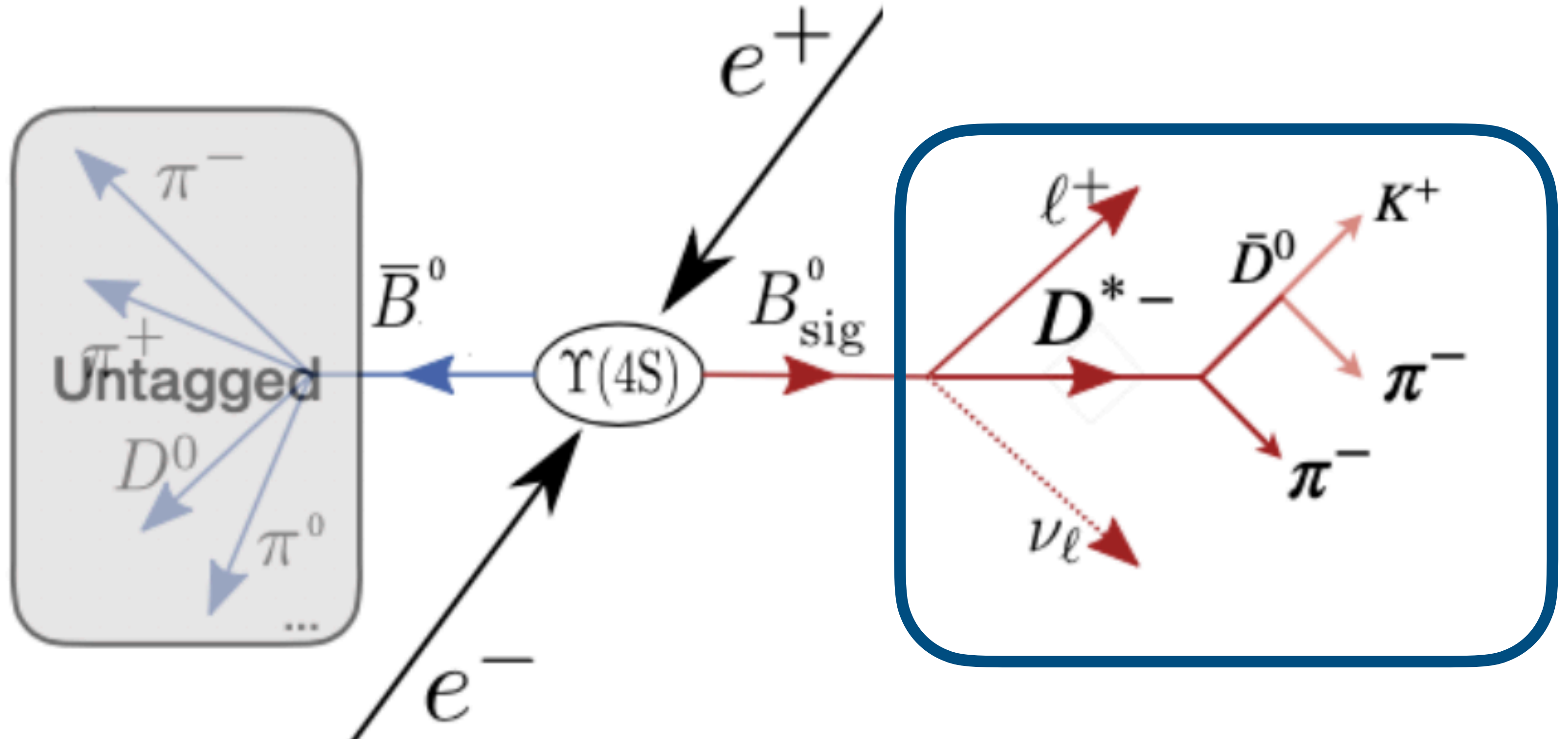
- At low momentum, muons do not reach the dedicated muon detector (KLM) and electrons suffer significant energy losses due to bremsstrahlung.
- To improve lepton-hadron separation:
  - combine several calorimetric observables (lateral shower shapes, extrapolated track depth in the ECL...) in a BDT.

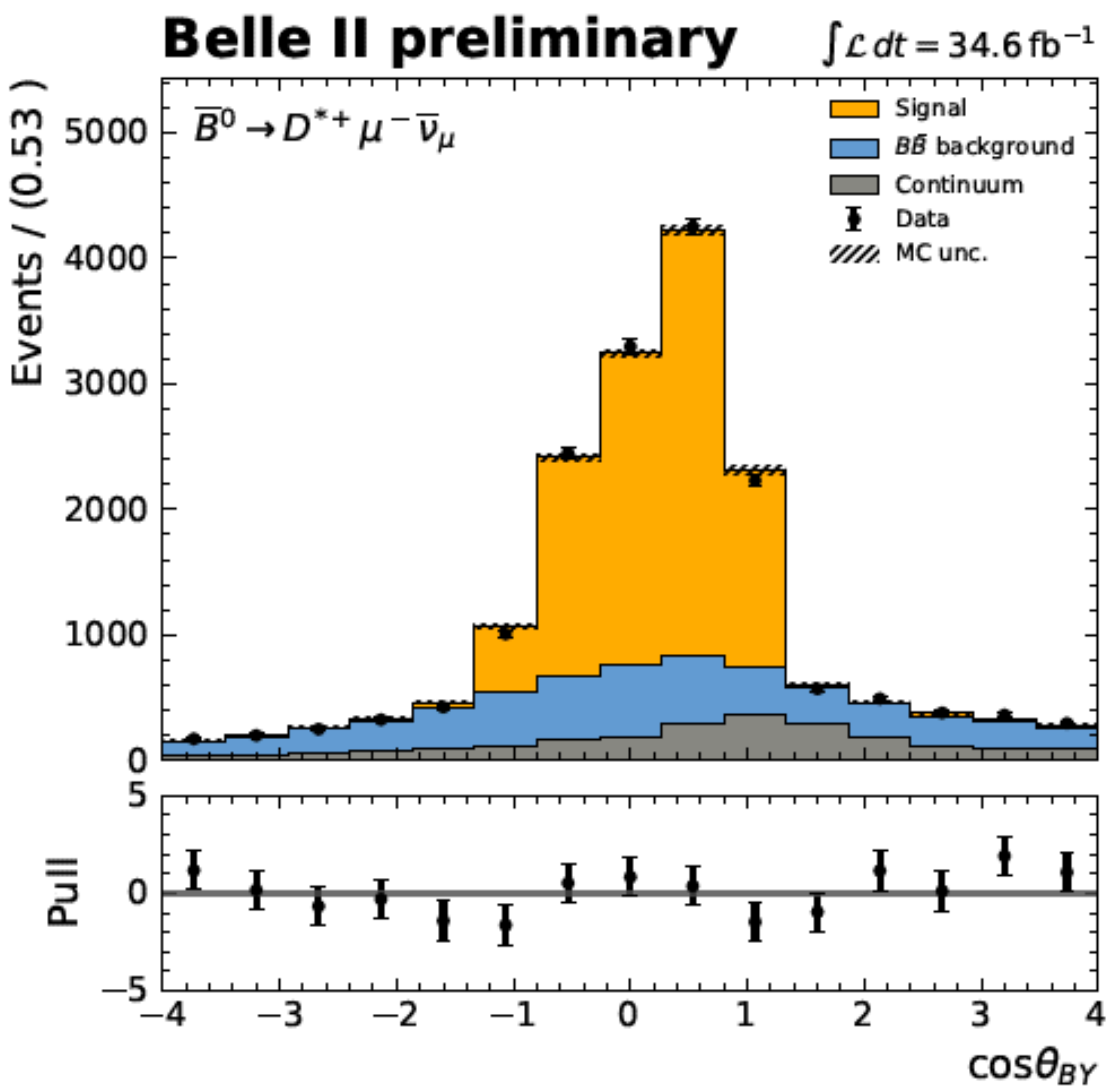


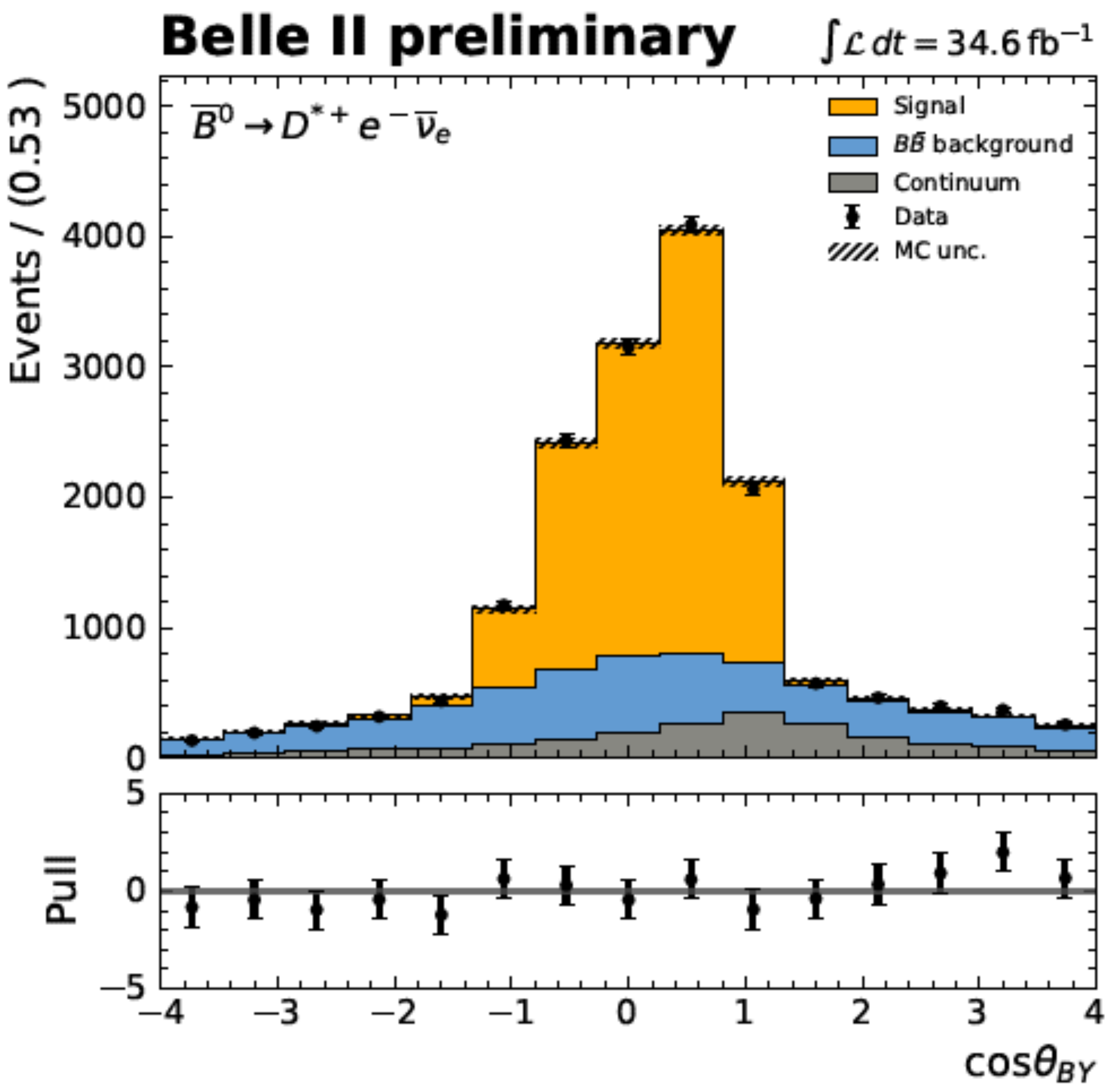


- A factor of 10 reduction in $\pi \to e$ fake rate, and a factor of 2 in $\pi \to \mu$ fake rate for $p < 1$ GeV/c (MC).

Rediscovery of $\bar{B}^0 \rightarrow D^{*+}\ \ell\ \nu_\ell$ (Untagged)







- Signal yield extraction using a fit to $cos\theta_{BY}$.

$$cos\theta_{BY} = \frac{2E^*_B E^*_Y - m^2_B - m^2_Y}{2|p^*_B||p^*_Y|}$$

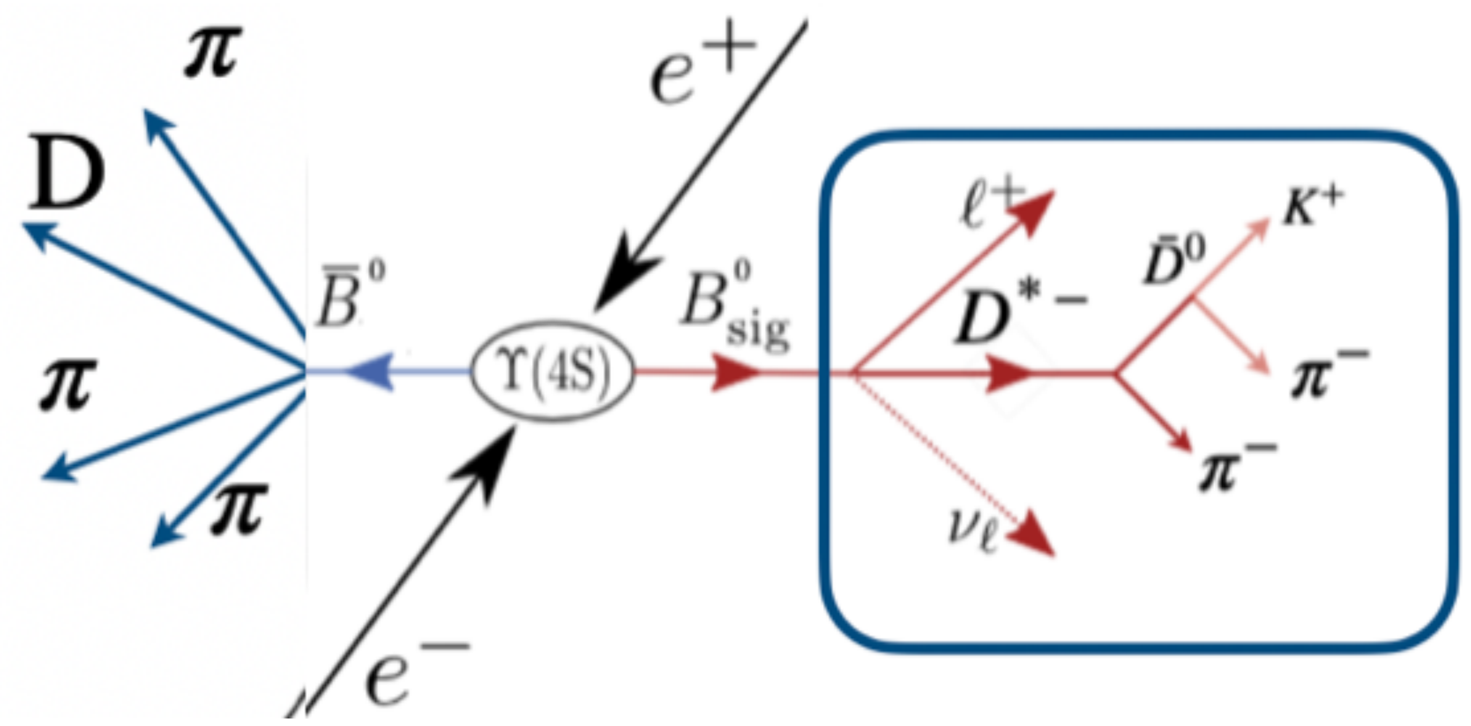
$$\mathcal{B}(\bar{B}^0 \rightarrow D^*\ell\bar{\nu}) = (4.60 \pm 0.05(stat) \pm 0.18(sys) \pm 0.45\pi_s)\%$$

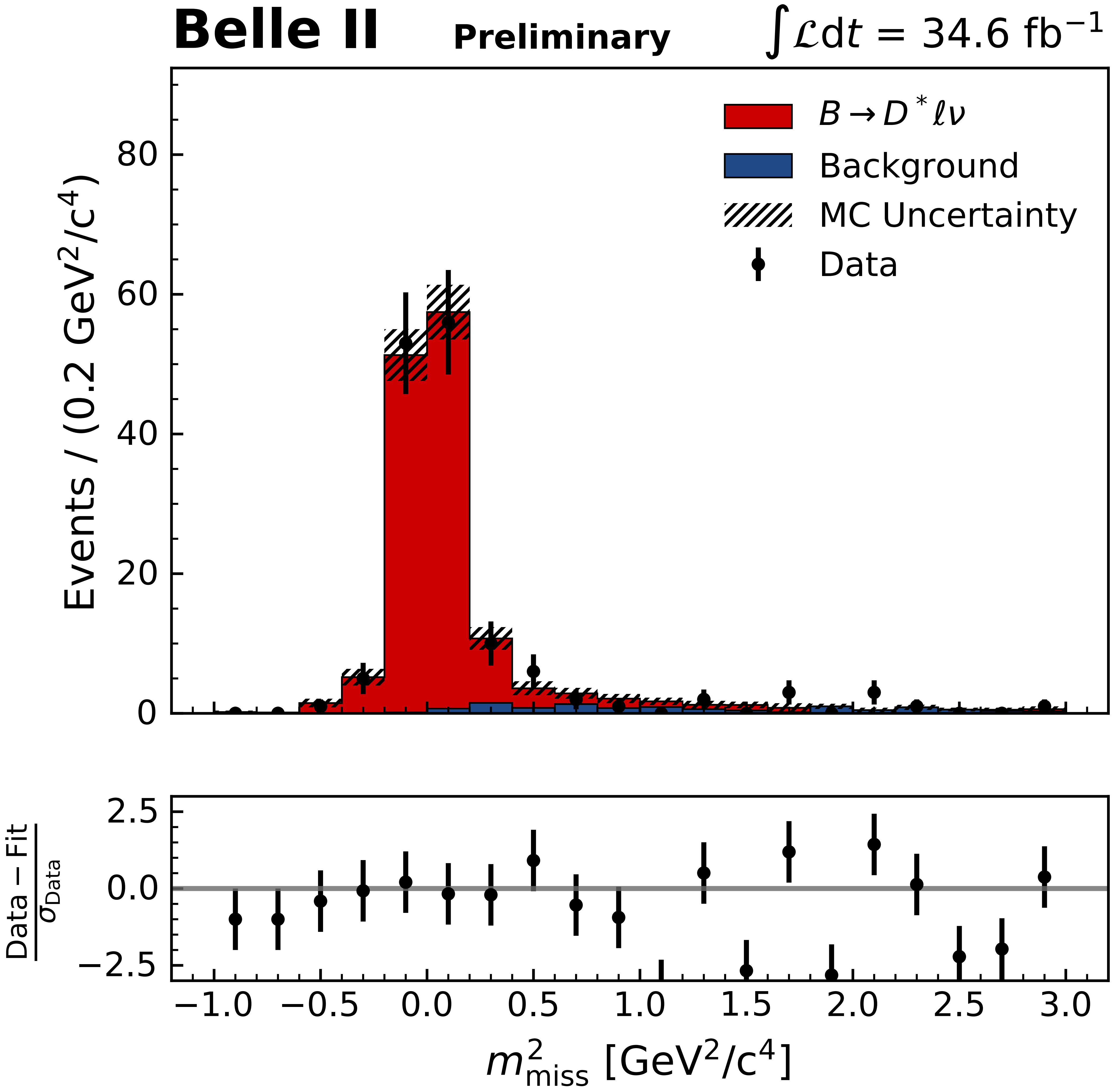
Compatible with current world average!

$$\mathcal{R}_{e\mu} = \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}e^-\bar{\nu}_e)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu)} = 0.99 \pm 0.03$$

$$\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\ell\bar{\nu}) = (5.05 \pm 0.14)\%$$

Rediscovery of $\bar{B}^0 \to D^{*+} \ell \nu_\ell$ (with hadronic tag)





- Signal yield extraction with fit to m^2_{miss}

$$m^2_{miss} = (p_{e^+e^-} - p_{B_{tag}} - p_{D^*} - p_l)^2$$

$$\mathcal{B}(\bar{B}^0 \to D^{*+} \ell \bar{\nu}) = (4.51 \pm 0.41(stat) \pm 0.27(syst) \pm 0.45(\pi_s))\%$$

Compatible with current world average! $\mathcal{B}(\bar{B}^0 \to D^{*+} \ell \bar{\nu}) = (5.05 \pm 0.14)\%$

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

- Additional distributions of observables to discriminate NP scenarios:
  - Polarizations $\mathcal{P}_\tau(D^*)$ and $\mathcal{P}_{D^*}$ ($\tau \to \pi\nu$, $\tau \to \rho\nu$)

$$P_\tau(D^{(*)}) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} \qquad P_{D^*} = \frac{\Gamma_L}{\Gamma_L + \Gamma_T}$$

$\Gamma^{+(-)}$: the decay rate with the tau helicity +1/2 (-1/2)

$\Gamma_{L(T)}$: the decay rate with longitudinally (transversely) polarized D^*

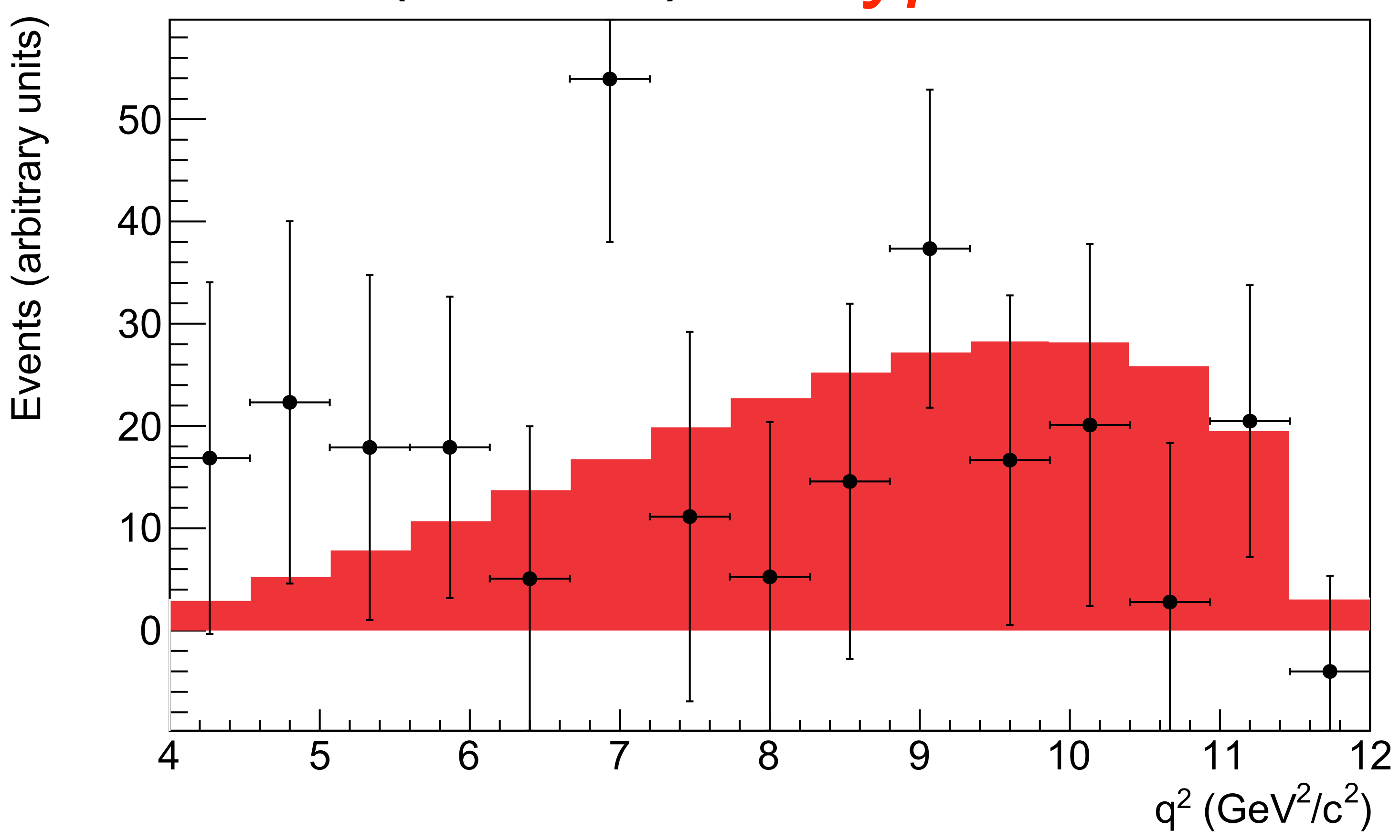
[Belle PRD 97, 012004 (2018)]   [BELLE-CONF-1805, 1903.03102]

  - Kinematic distributions ($q^2=(p_\tau + p_\nu)^2$ and p^*_ℓ)

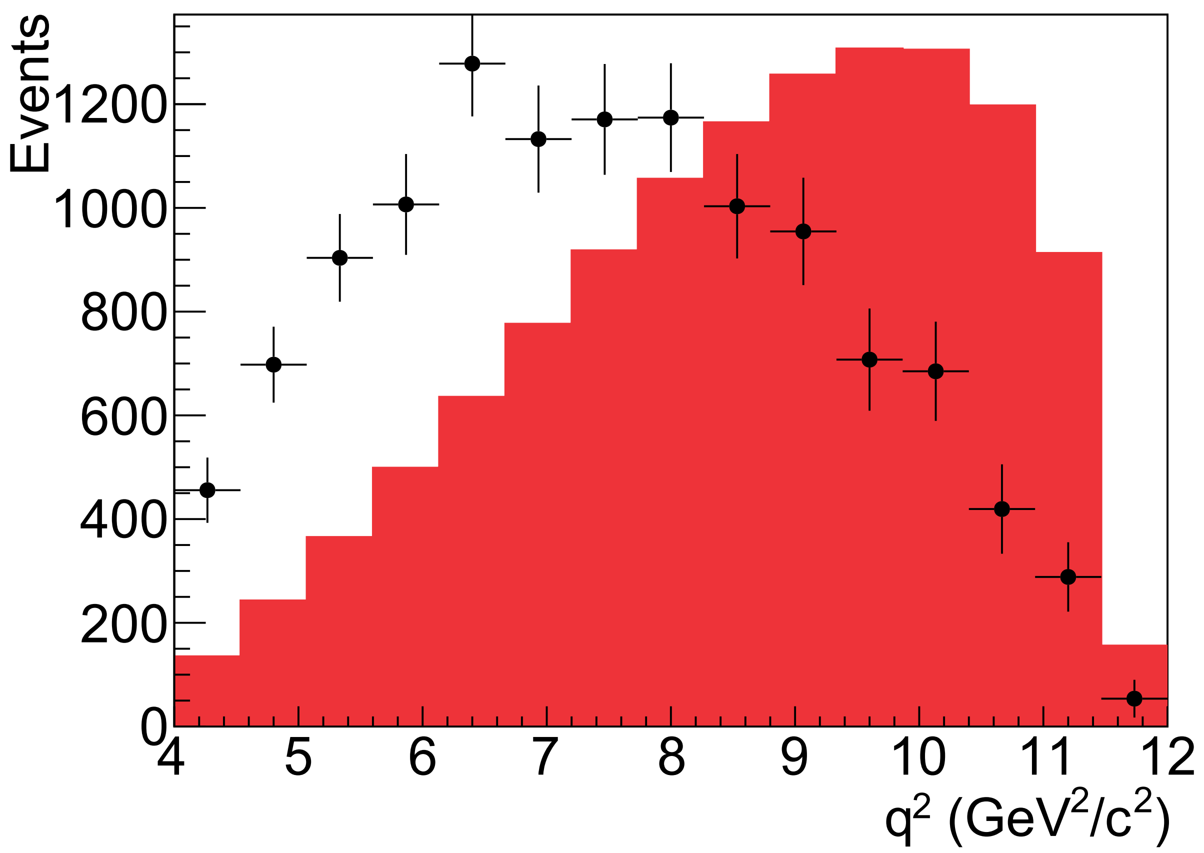
$B \to D\tau(\to \ell\nu\nu)\nu$ (with hadronic tagging), q^2 distribution

[Belle II Physics Book; PETP 2019, 123C01 (2019)]

Belle (771 fb^{-1}) type II 2HDM



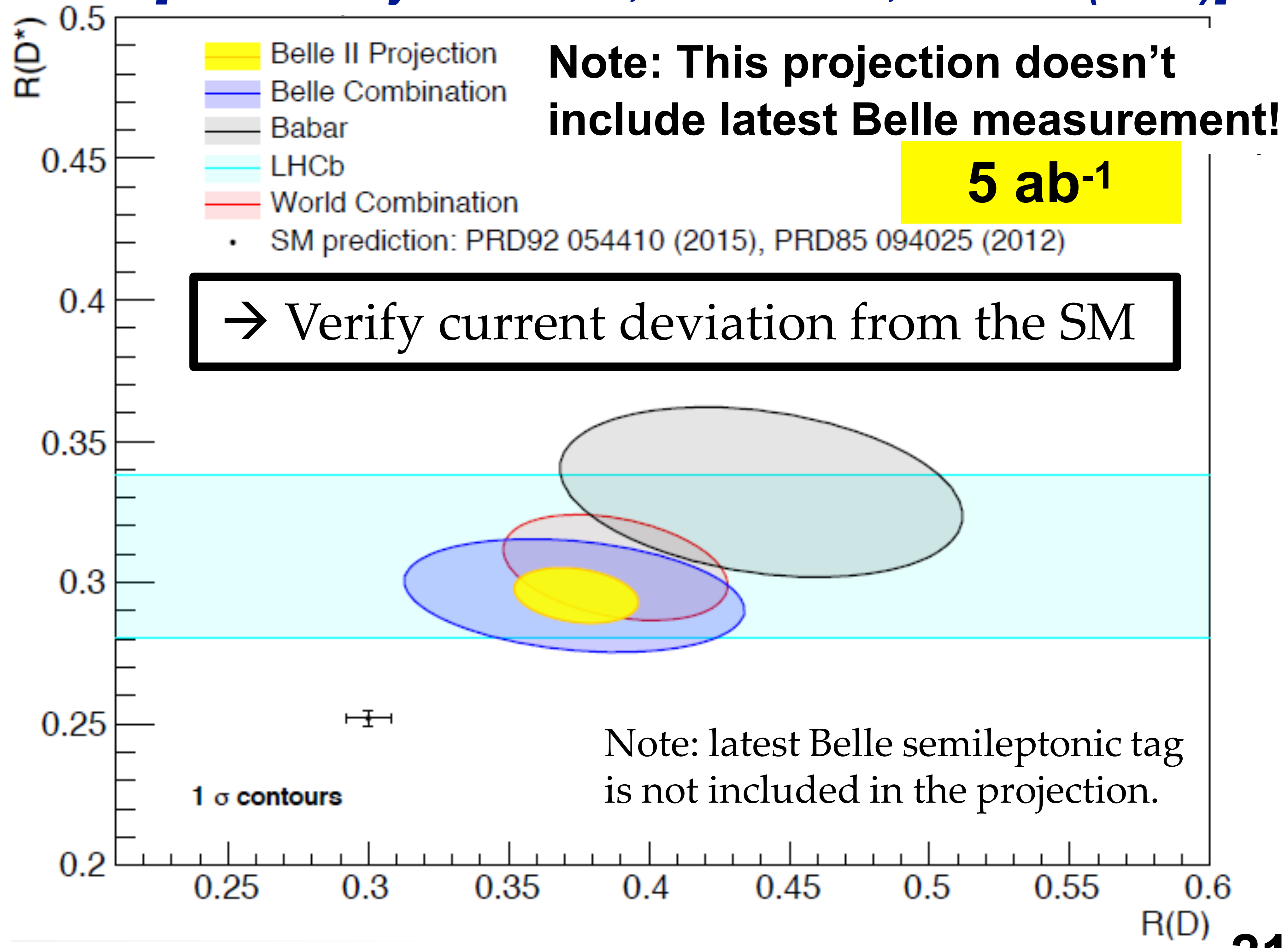
Belle II (SM 50 ab^{-1}) type II 2HDM



Expected precision (stat and syst) for Belle II

	5 ab^{-1}	50 ab^{-1}
$\mathcal{R}(D)$	(±6.0 ± 3.9)%	(±2.0 ±2.5)%
$\mathcal{R}(D^*)$	(±3.0 ± 2.5)%	(±1.0 ± 2.0)%
$\mathcal{P}_\tau(D^*)$	±0.18 ± 0.08	±0.06 ± 0.04

[Belle II Physics Book; PETP 2019, 123C01 (2019)]



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[Belle PRD 97, 012004 (2018)] *[BELLE-CONF-1805, 1903.03102]*

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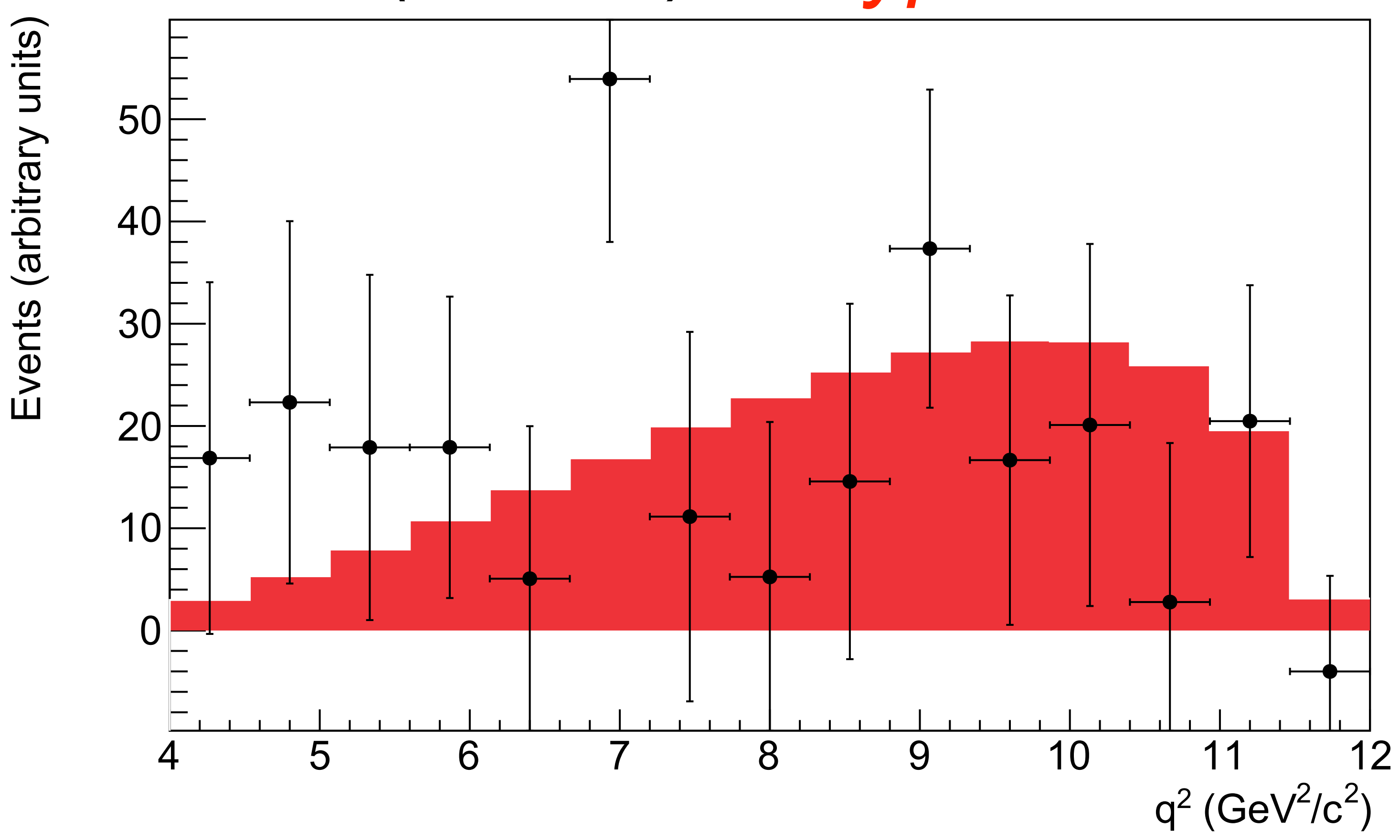
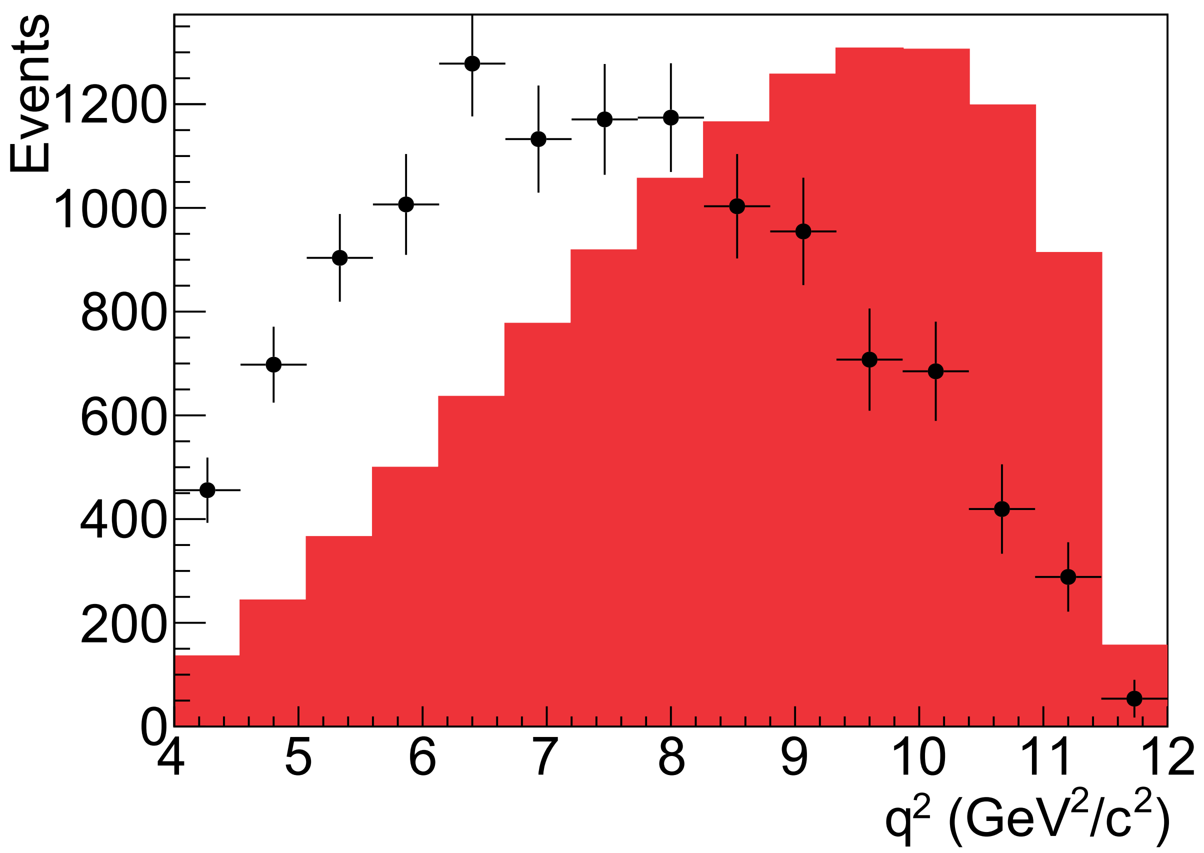
$B \to D\tau(\to \ell\nu\nu)\nu$ (with hadronic tagging), q^2 distribution

[Belle II Physics Book; PETP 2019, 123C01 (2019)]

Belle (771 fb^{-1}) *type II 2HDM*



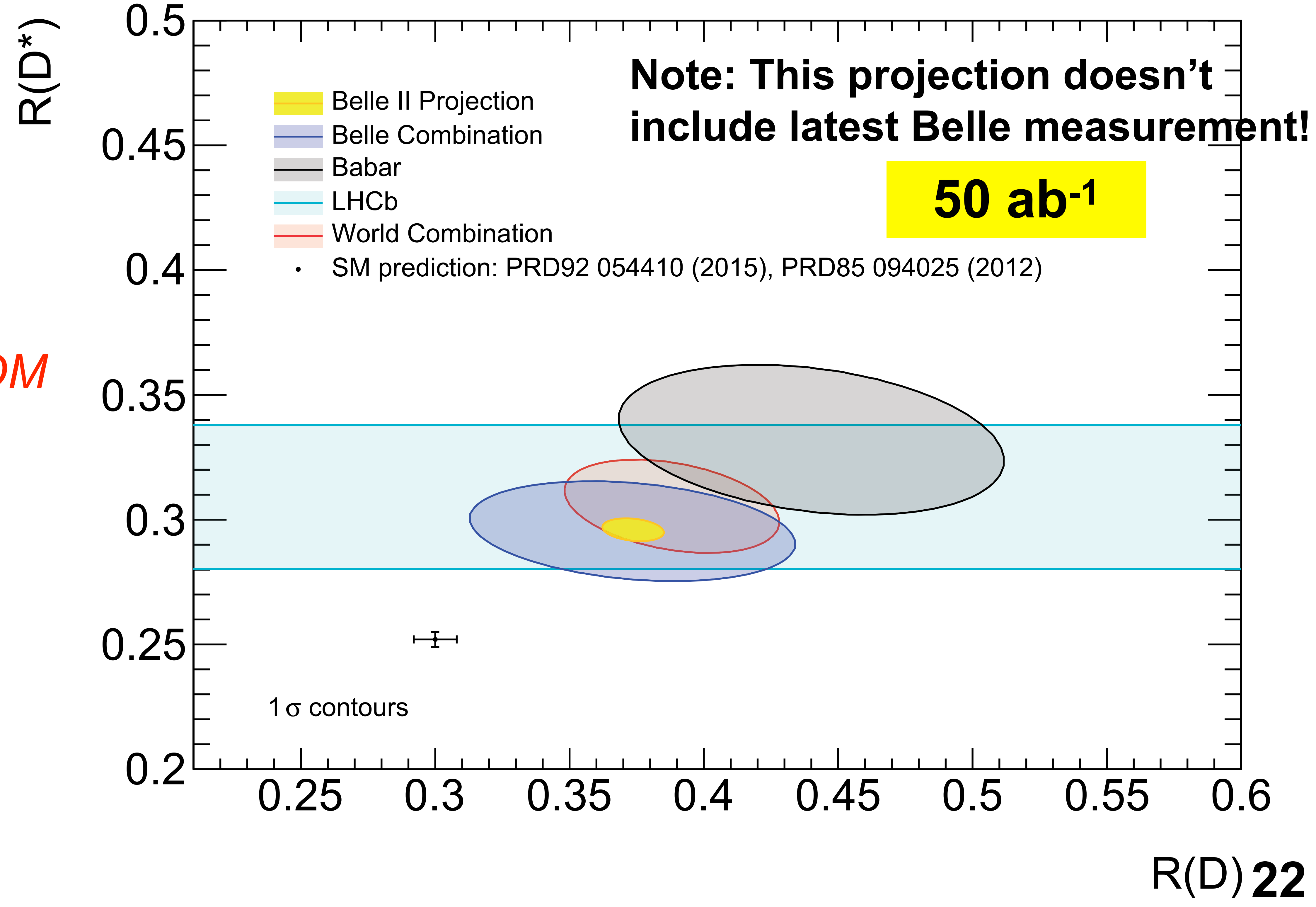
Belle II (SM 50 ab^{-1}) *type II 2HDM*



Expected precision (stat and syst) for Belle II

	5 ab^{-1}	50 ab^{-1}
$\mathcal{R}(D)$	(±6.0 ± 3.9)%	(±2.0 ±2.5)%
$\mathcal{R}(D^*)$	(±3.0 ± 2.5)%	(±1.0 ± 2.0)%
$\mathcal{P}_\tau(D^*)$	±0.18 ± 0.08	±0.06 ± 0.04

[Belle II Physics Book; PETP 2019, 123C01 (2019)]

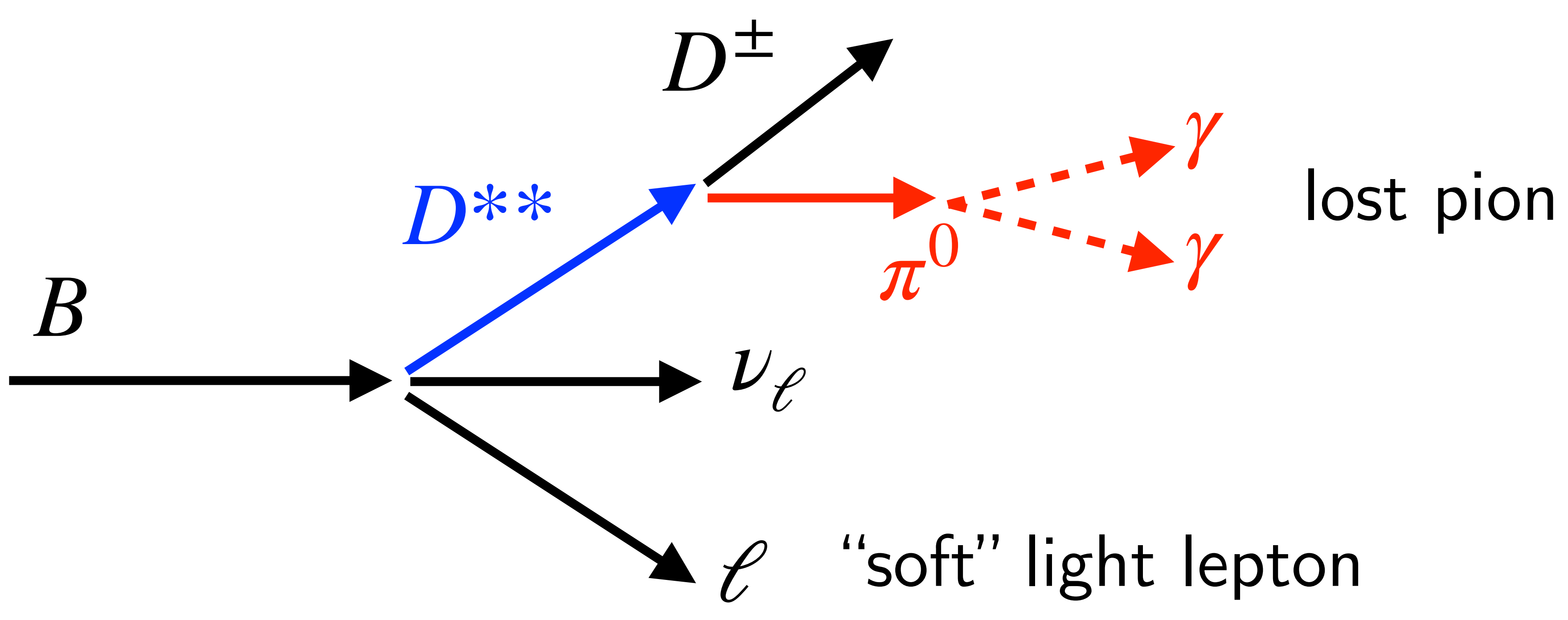


Prospects for $B \to D^{(*)} \tau \nu$ at Belle II

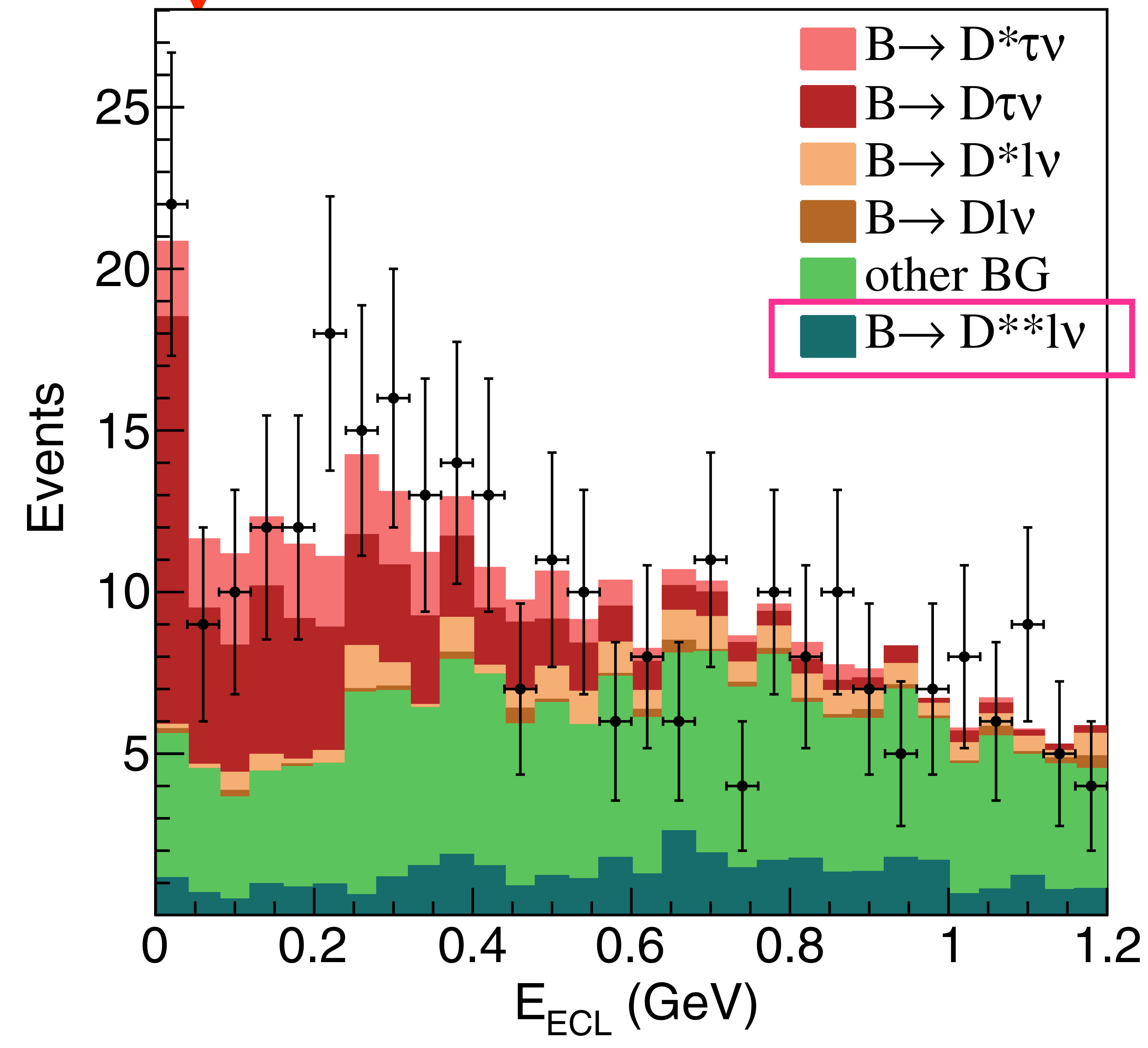
Composition of the systematic uncertainties in each Belle analysis [Belle II Physics Book; PETP 2019, 123C01 (2019)]

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%	$^{+3.4}_{-3.5}$%	$^{+10.0}_{-9.0}$%

[PRD 92, 072014 (2015)] [PRD 94, 072007 (2016)] [PRL 118, 211801 (2017)]



[Phys. Rev., D92(7), 072014 (2015)]



- "Soft" light lepton in $B \to D^{**}\ell\nu_\ell$ resembles one created from τ,
  - need dedicated measurements of $B \to D^{**}\ell\nu_\ell$ with a large data sample.

Conclusions

- Belle recently provided the most precise measurements of $\mathcal{R}(D)$ and $\mathcal{R}(D*)$,
  - the first measurement of $\mathcal{R}(D)$ based on a semileptonic tagging,
  - reduces the tension between SM and world average.

- Belle II collected ≈ 74 fb^{-1} of data,
  - preliminary lepton identification studies present good performance,
  - physics analyses will test the new developments soon.

- Expecting first measurements of semi-tauonic *B* meson decays at Belle II in 2021.

- $\mathcal{R}(D)$ and $\mathcal{R}(D*)$: Expecting $\mathcal{O}(5\%)$ precision (total uncertainty) with 5 ab^{-1} Belle II data

Extra

Recent $\mathcal{R}(D^{(*)})$ Measurement in Belle with Semileptonic Tagging

- 2D extended maximum-likelihood fit performed simultaneously.
- Fit components are:
  - Signal: *Free*
  - Normalization: *Free*
  - $B \to D^{**} \ell \nu$: *Free*
  - Fake $D^{(*)}$: *Fixed* (calibrated using the sidebands)
  - Feed-down for normalization: *Free*
    - $B^+ \to D^0 \ell \nu$: $B^+ \to (D^{*0} \to D^0 \pi^0 / \gamma) \ell \nu$, $B^0 \to (D^{*+} \to D^0 \pi^+) \ell \nu$
    - $B^0 \to D^+ \ell \nu$: $B^0 \to (D^{*+} \to D^+ \pi^0) \ell \nu$
  - Feed-down for signal: *Constrained*
    - $N_{feed\text{-}down} = K . N^{D^* \ell}$ (K: *Fixed* to MC)
  - $N_{\text{feed-down}} = K \cdot N^{D^* l}$ (K: *Fixed* to MC)
  - Other backgrounds: *Fixed* to MC
    - Continuum, fake lepton, $B \to D^* D^{(*)}$, etc.

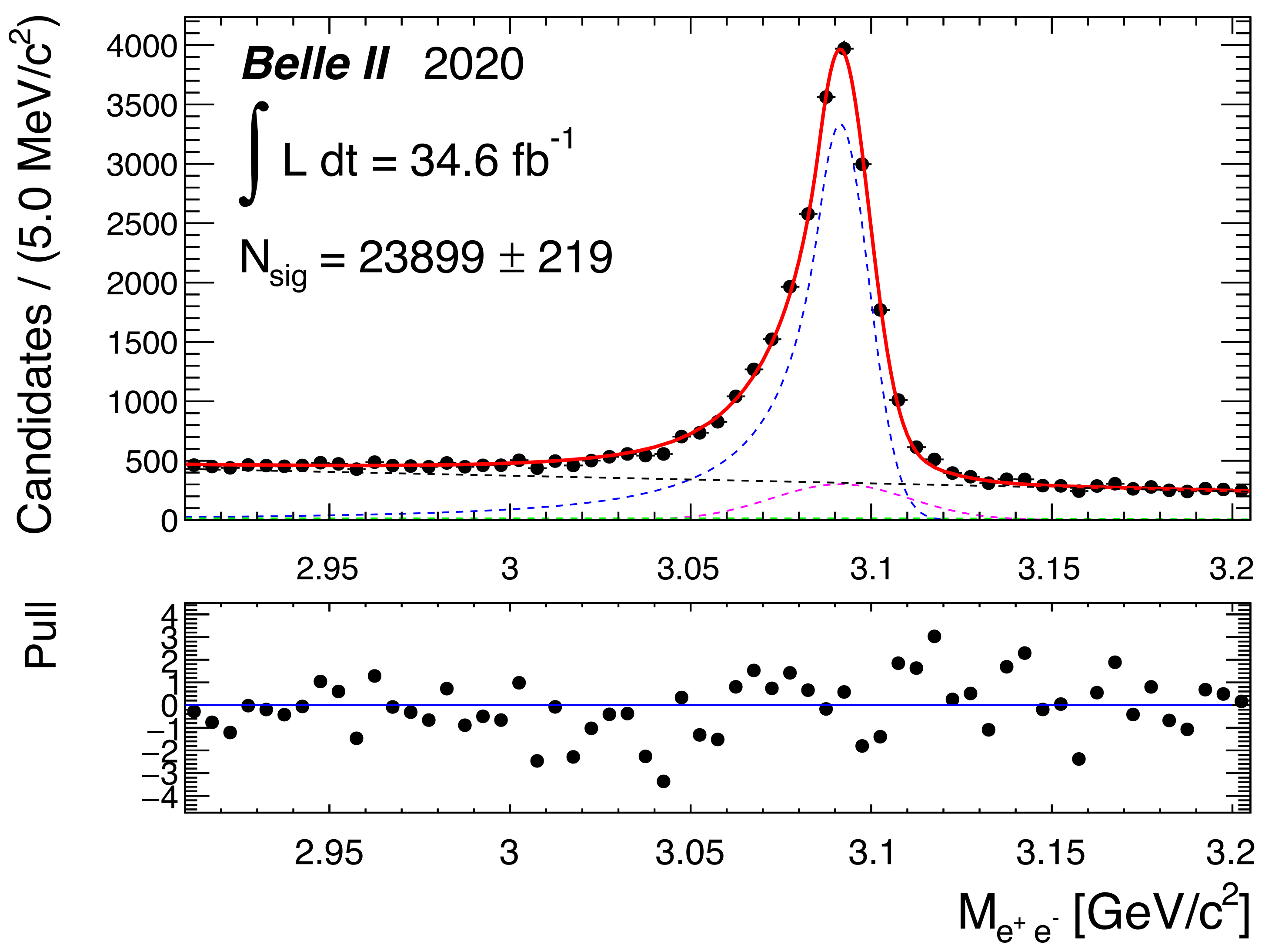
Lepton Identification Performance in 2020 Data

- Lepton id and hadron mis-id performance in simulation calibrated to data using complementary set of decay channels.

BELLE2-NOTE-PL-2020-027 ***(https://docs.belle2.org/record/2062?ln=en)***

Lepton ID efficiency	Hadron mis-id.
$J/\psi \to \ell\ell$	$K_S \to \pi\pi$
$ee \to ee\ell\ell$	$ee \to \tau(1\text{-}p)\tau(3\text{-}p)$
$ee \to ee(\gamma)$	$D^{*+} \to D^0(K^-\pi^+)\pi^+$
$ee \to \mu\mu\gamma$	$D^{*+} \to D^0(K^-\pi^+)\pi^+$

$J/\psi \to e^+e^-$



$J/\psi \to \mu^+\mu^-$