Overview of R(D) and R(D*)

Flavour Physics and CP Violation Conference

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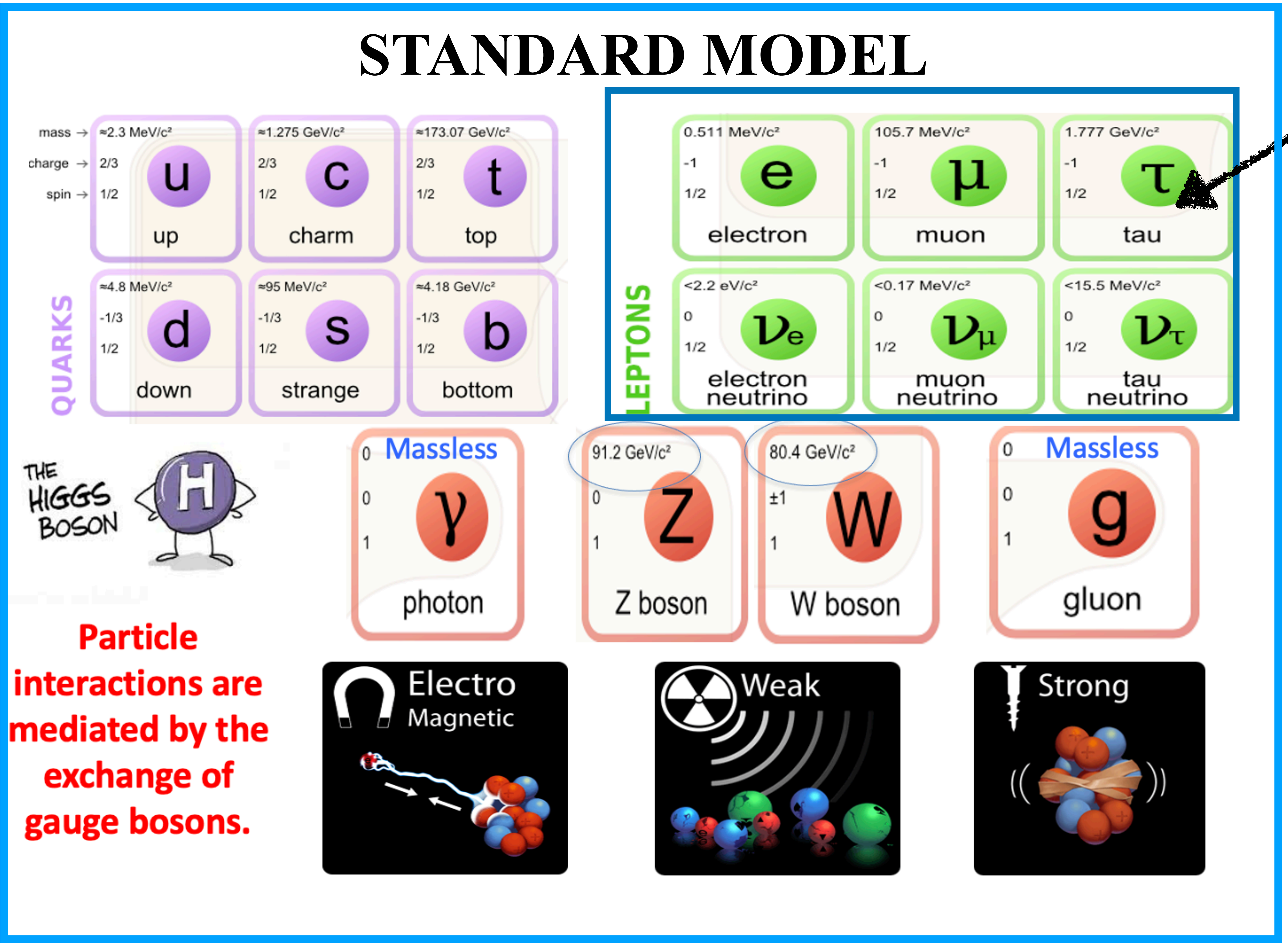
May 23, 2022

On behalf of the Belle, Belle II and LHCb collaborations

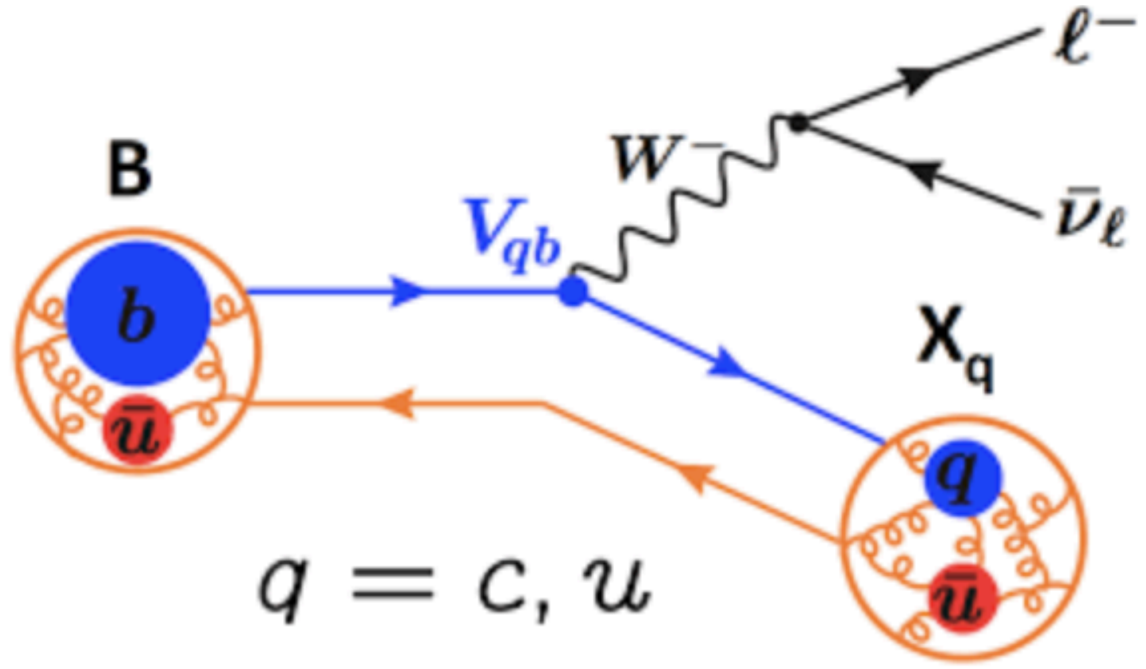
Lepton Flavour Universality



- **Lepton Flavour Universality**: gauge interactions of the three generations of leptons are identical once the mass difference is accounted for.

- **Violation of LFU is a clear signal of new physics** and hence the search for such signals in leading particle physics experiments.

- **Semileptonic *B* decays: an excellent probe** for SM precision measurements ($|V_{cb}|$ and $|V_{ub}|$) and an invaluable portal for lepton flavour universality tests.



Discrepancies with the Standard Model have been observed in multiple LFU tests: **R(D)-R(D*) : 3.1σ** **R(K)-R(K*) : 3.1σ** etc..

R(D) and R(D*)

- R(D) and R(D*) are defined as the ratio of the semitauonic decay $B \to D^*\tau\nu$ to the lighter lepton counterparts $B \to D^*\ell\nu, \ell = e, \mu$.

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

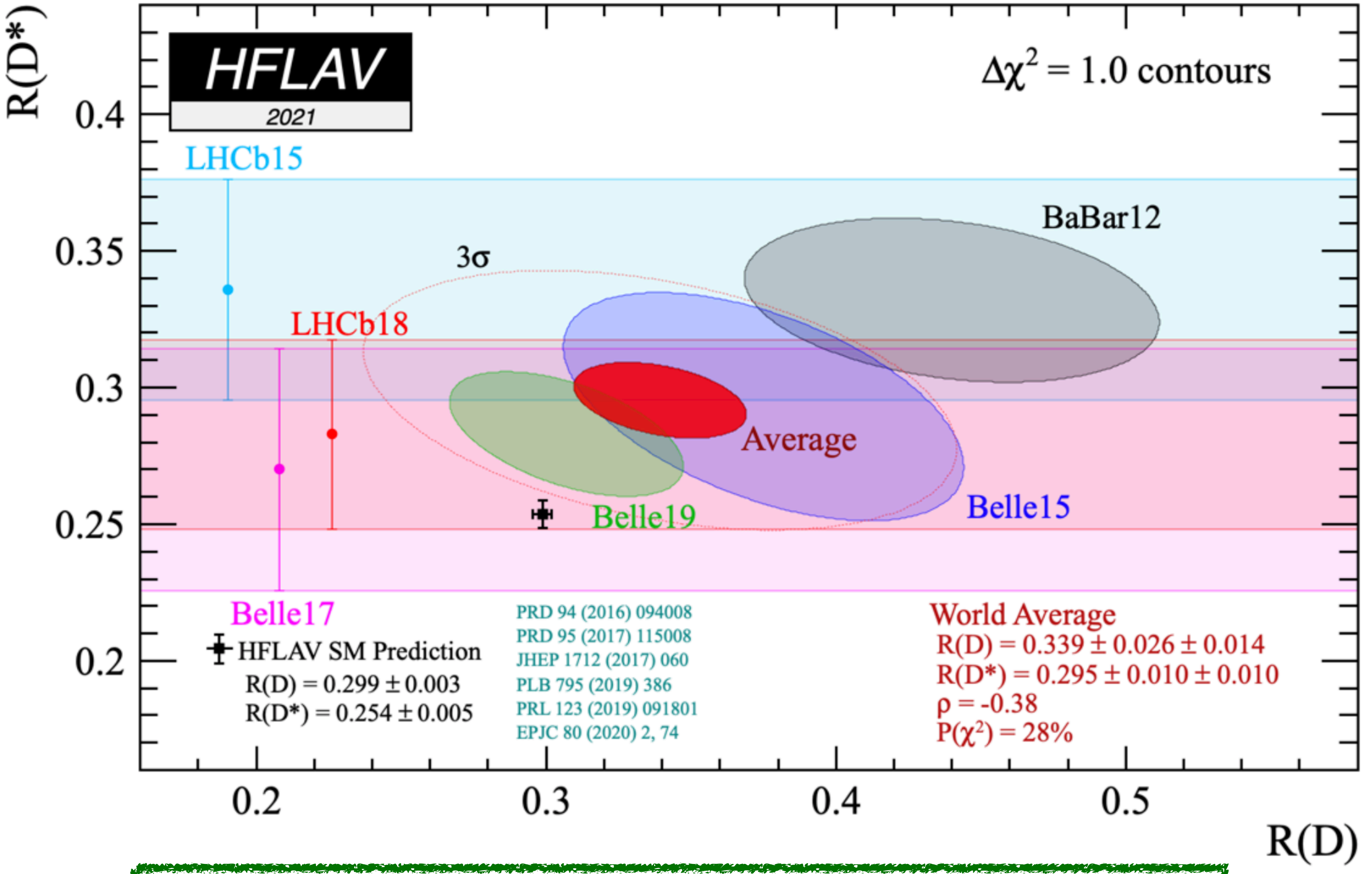
- Determined to high precision in the SM:

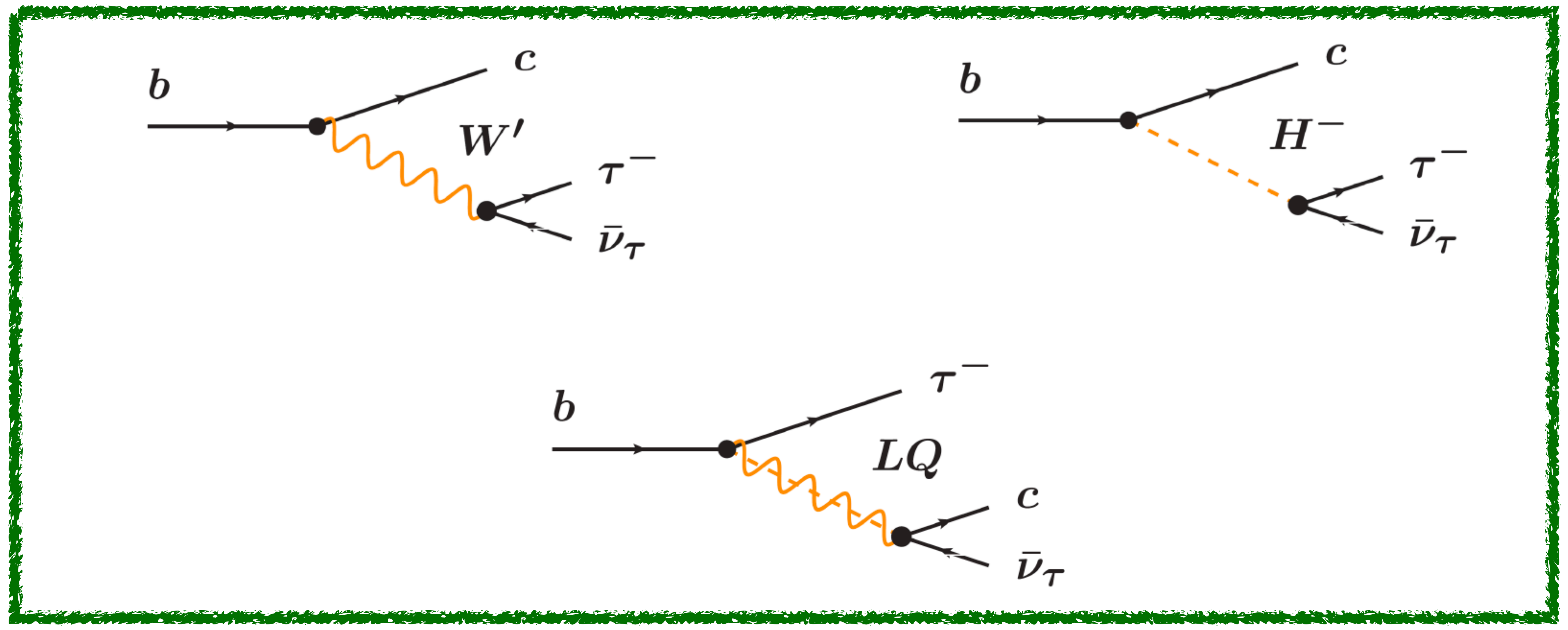
$$R(D^*)^{\rm SM} = 0.254 \pm 0.005 \qquad R(D)^{\rm SM} = 0.299 \pm 0.003$$

- Ratio allows for many uncertainties to cancel.

- **Measurement has been performed by BaBar, Belle, and LHCb and showed a combined 3.1σ deviation from the SM.**

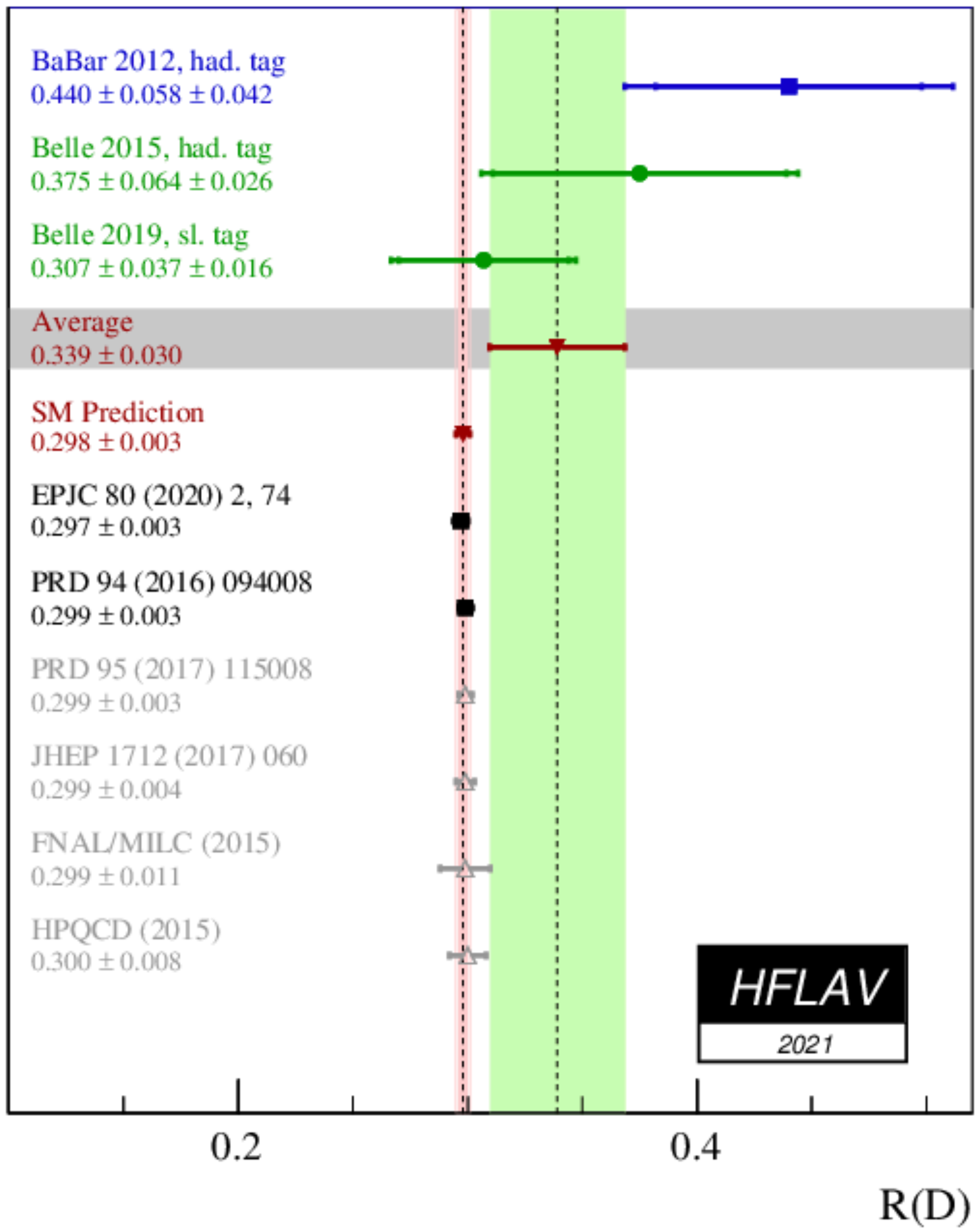
- Various new physics scenarios predict deviation from the SM.

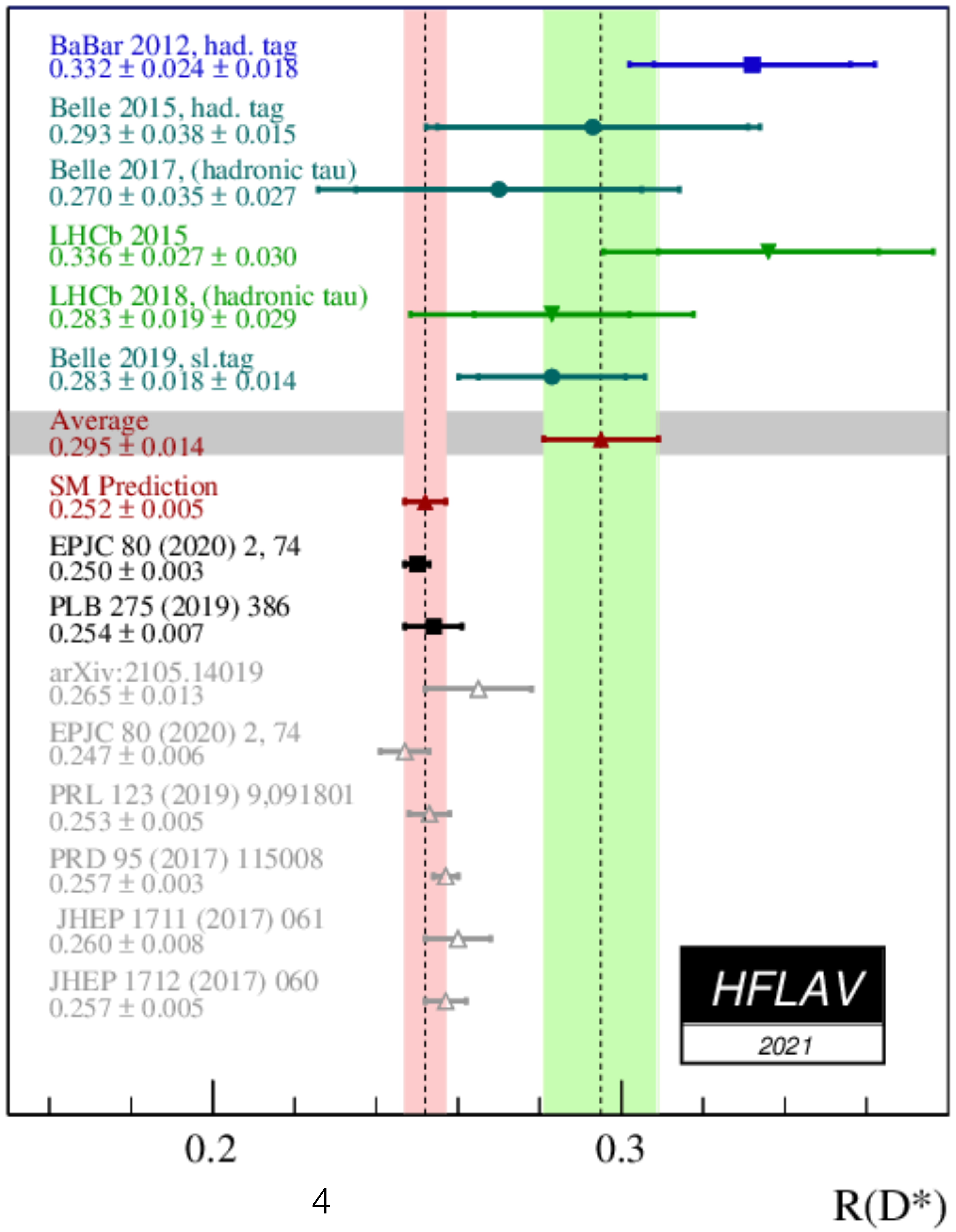




R(D) and R(D*)

- Wide range of measurements at the *B*-factories and LHCb with hadronic and/or leptonic τ decays.
- Final state cannot be fully reconstructed due to lepton neutrinos.





***B*-factories:** hadronic or semileptonic *B* tagging to exploit the full event kinematics and identify missing energy components.

LHCb: excellent vertexing to suppress leading backgrounds and approximate B_{sig} kinematics.

LHCb

$R(D^*)$ **muonic with** $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$

Phys. Rev. Lett. **115** 112001 (2015)

$R(D^*)$ **hadronic with** $\tau^+ \rightarrow \pi^+ \pi^- \pi^+ (\pi^0) \bar{\nu}_\tau$

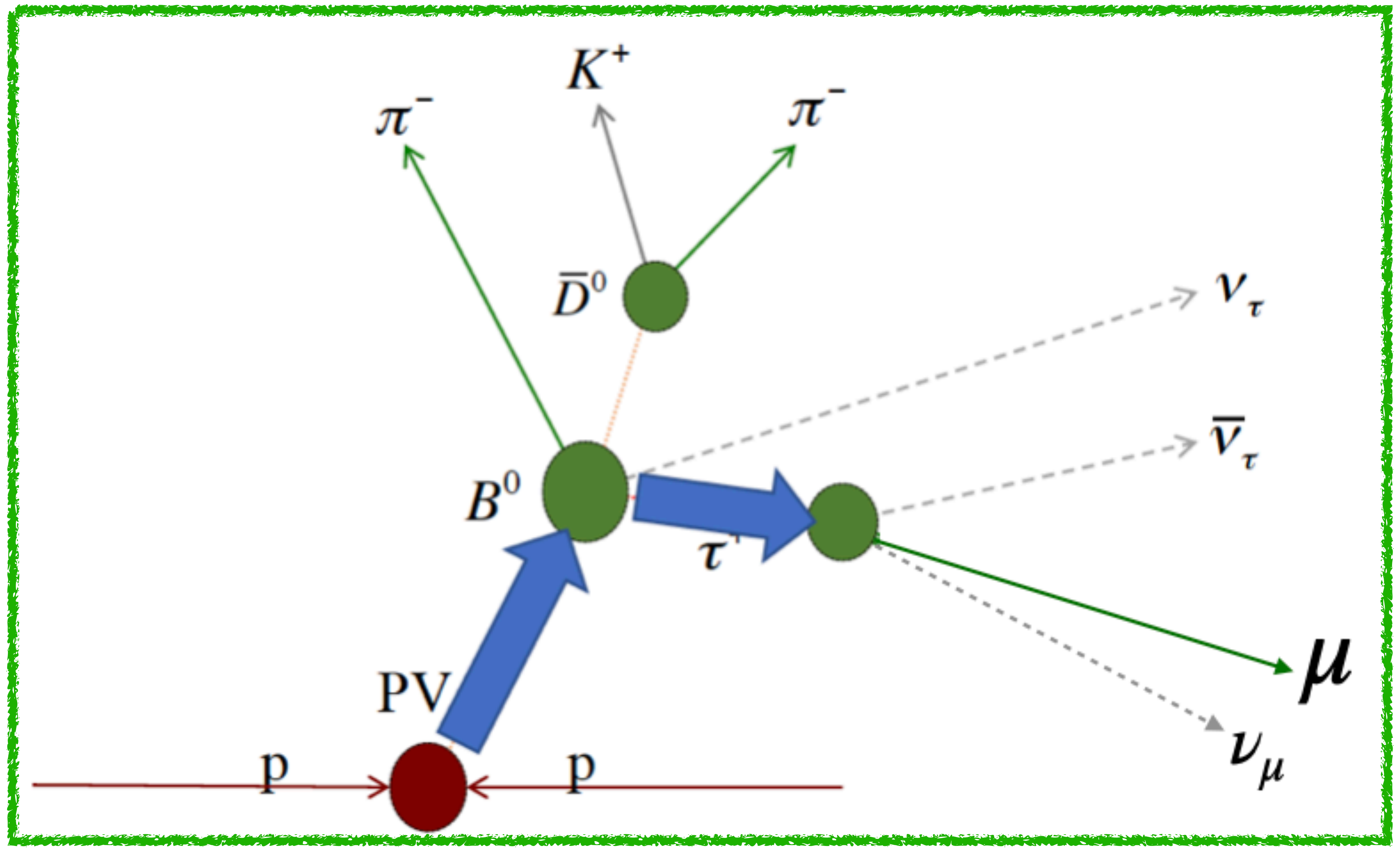
Phys. Rev. Lett. **120** 171802 (2018)   Phys. Rev. D **97** 072013 (2018)

R(D*) muonic

Phys. Rev. Lett. **115** 112001 (2015)

- Measurement performed with 3.0 fb^{-1} of LHCb data collected during 2011-2012.
- Common reconstruction procedure for both the signal mode $\bar{B}^0 \rightarrow D^{*+}\tau^-\nu_\tau$ and normalization mode $\bar{B}^0 \rightarrow D^{*+}\mu^-\nu_\mu$.

$$R(D^*) = \frac{\mathscr{B}(\bar{B} \rightarrow D^{*+}\tau^-\bar{\nu}_\tau)}{\mathscr{B}(\bar{B} \rightarrow D^{*+}\mu^-\bar{\nu}_\mu)}$$



- MVA algorithm developed to distinguish whether a charged track originated from the B_{sig} or the rest of event.
  - Based on track separation from PV, track angle, etc…
- Separation of signal and normalization using: E_μ^*, m_{miss}^2, q^2 in the B rest frame:

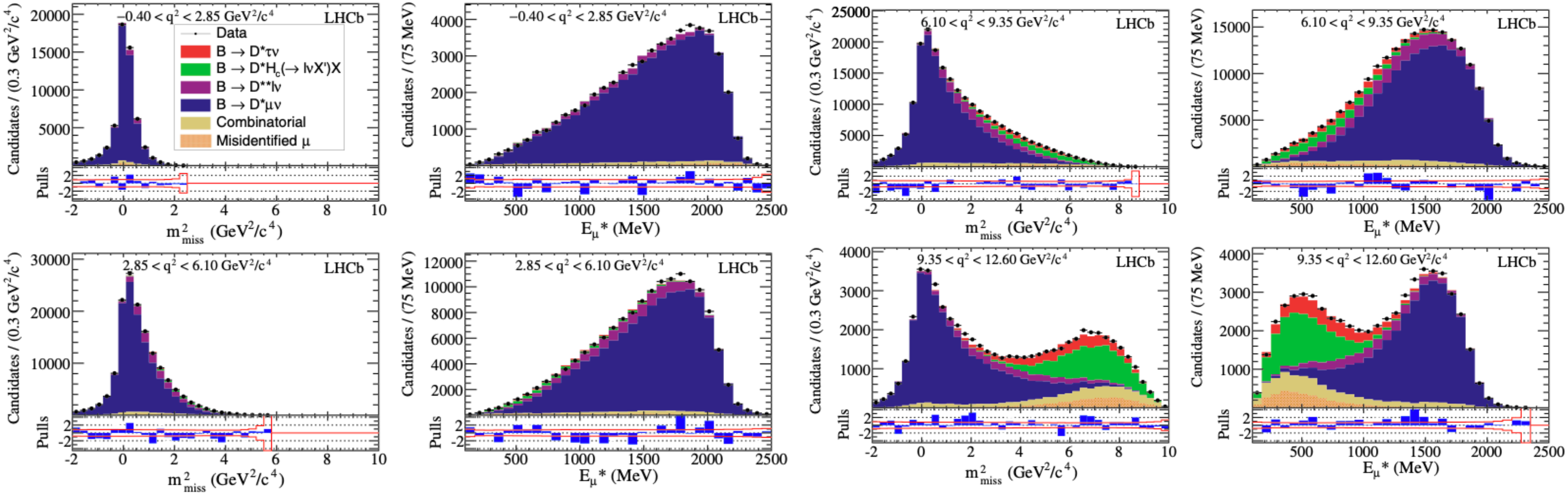
$$q^2 = (p_B - p_D)^2 \text{ and } m_{miss}^2 = (p_B - p_{D^*} - p_\mu)^2$$

- B rest frame determined using:
  - the unit vector from the PV to the B decay vertex
  - p_z of B given by $(p_B)_z = (m_B/m_{reco})(p_{reco})_z$

Phys. Rev. Lett. **115** 112001 (2015)

R(D*) muonic

- Challenging backgrounds:
  - Semileptonic decays to excited charm states: $B \to D^{(**)}\ell\nu$
  - Double charm B decays: $B \to D^{(*)}H_c X, H_c \to \mu\nu_\mu X$
  - B decays with hadrons misidentified muons
- Maximum likelihood fit of m^2_{miss}, E^*_μ, and q^2 to extract relative signal, normalization and background contributions.



Phys. Rev. Lett. **115** 112001 (2015)

R(D*) muonic

- Main systematic uncertainties from the limited size of the MC samples.
- Kinematic distribution for events with hadrons misidentified as muons are determined from control samples.

$$R(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$$

- **Result is 1.7 sigma over the SM.**
- **First measurement of R(D*) at a hadronic collider.**
- Improved modeling of background events can decreas systematic uncertainty in future results.
- **Future simultaneous measurement of R(D) and R(D*) at LHCb with Run1 data and Run 2 data , i. 4 times the available statistics.**
- **Full angular analysis of** $B^0 \to D^{*-}\mu^+\nu_\mu$ **and** $B^0 \to D^{*-}\tau^+\nu_\tau$

Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$B^0 \to D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors	0.6
$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{**}\mu^-\bar{\nu}_\mu)$	0.5
$\bar{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\bar{B} \to D^{**}(\to D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors	0.3
$\bar{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**

Normalization uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

LHCb

$R(D^*)$ **muonic with** $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$

Phys. Rev. Lett. **115** 112001 (2015)

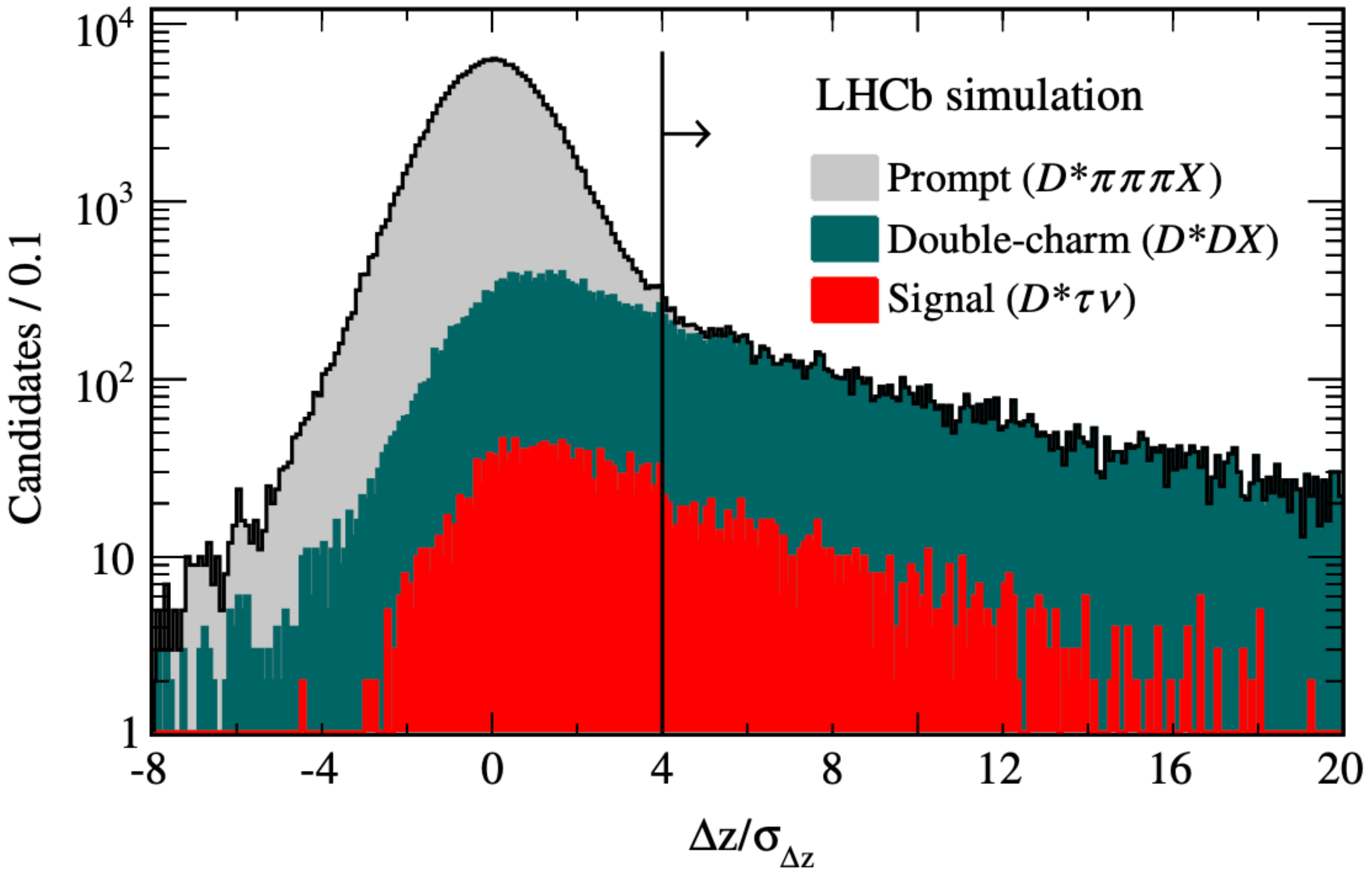
$R(D^*)$ **hadronic with** $\tau^+ \to \pi^+ \pi^- \pi^+ (\pi^0) \bar{\nu}_\tau$

Phys. Rev. Lett. **120** 171802 (2018) Phys. Rev. D **97** 072013 (2018)

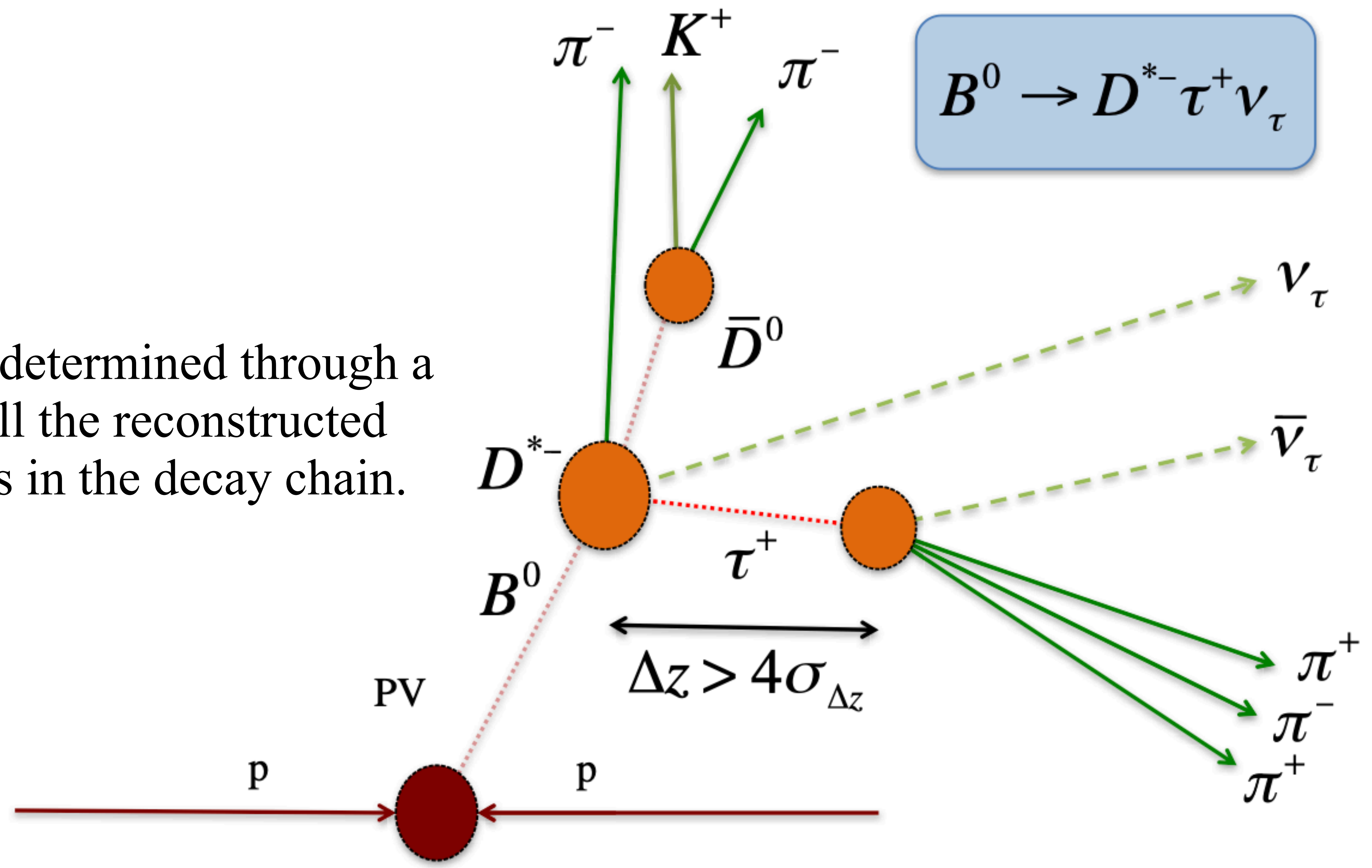
Phys. Rev. Lett. **120** 171802 (2018)

R(D*) hadronic

- Measure $\kappa(D^*) = \frac{\mathscr{B}(B^0 \to D^{-*}\tau^+\nu_\tau)}{\mathscr{B}(B^0 \to D^{*-}3\pi)} = \frac{N_{sig}}{N_{norm}} \frac{\epsilon_{sig}}{\epsilon_{norm}} \frac{1}{\mathscr{B}(\tau^+ \to 3\pi\bar{\nu}_\tau) + \mathscr{B}(\tau^+ \to 3\pi\pi^0\bar{\nu}_\tau)}$.
- Convert it to R(D*) via $R(D^*) = \kappa(D^{*-}) \times \frac{\mathscr{B}(B^0 \to D^{*-}3\pi)}{\mathscr{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$.
- Large backgrounds originating from $B \to D^*3\pi X$ and $B \to DD^{(*)}$
  - ~ 100x the signal
  - Reduced by requiring $\Delta z/\sigma_z > 4$



B vertex determined through a fit of all the reconstructed particles in the decay chain.



Momentum of τ can be determined up to two fold ambiguity using:
- Unit-vector between B^0 vertex and PV
- Unit vector between 3π vertex and B^0 vertex

Phys. Rev. Lett. **120** 171802 (2018)

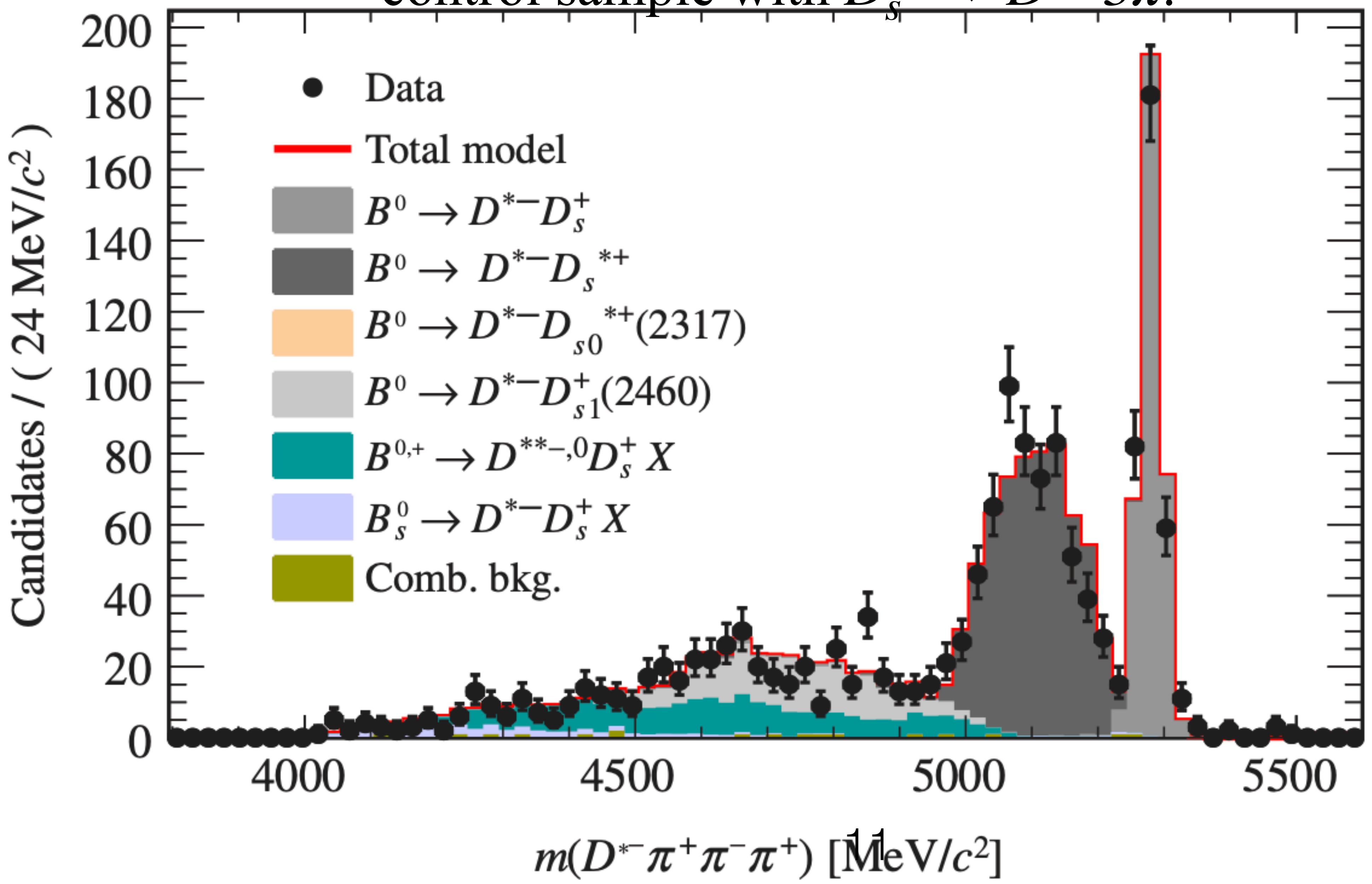
R(D*) hadronic

- $B \to D^{(*)}D^{(*)}$(X) backgrounds suppressed using MVA :
  - Different resonant structures of τ and D_s^+ decays
  - Neutral isolation
  - Kinematic properties : $m(\pi^+\pi^-)$, $m(D^{(*-)}\pi^+\pi^-\pi^+)$,etc..

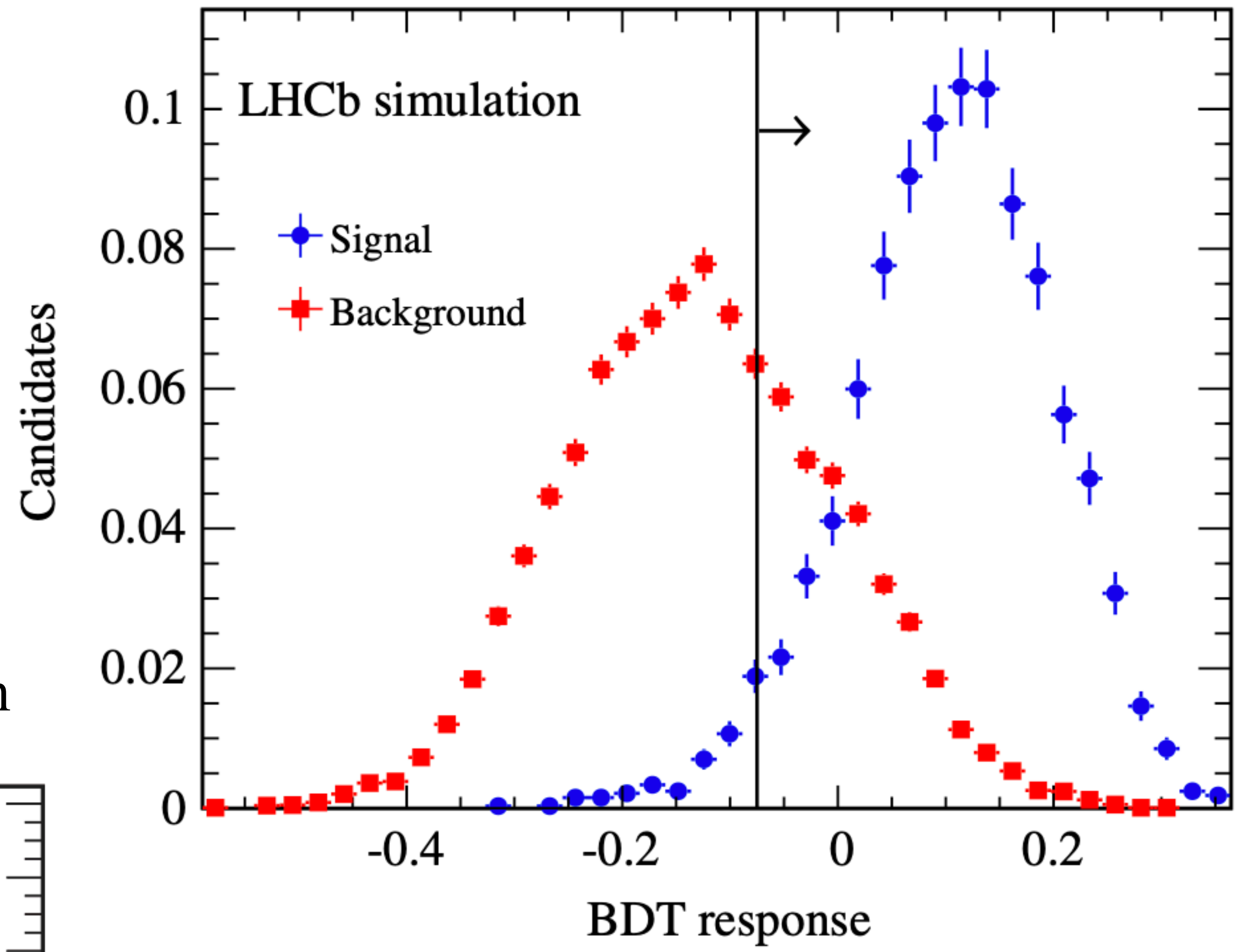
- Remaining backgrounds from:
  - $X_b \to D^{(*-)}D_s^+(X)$
  - $X_b \to D^{(*-)}D^+(X)$
  - $X_b \to D^{(*-)}D^0X$
  - Combinatorial
  - $X_b \to D^{**}\tau\nu$

Related to the signal yield by a proportionality factor of: 0.110 ± 0.044

Main double charm background:
Corrections and Relative yields determined from control sample with $D_s^+ \to D^{*-}3\pi$:



Signal region: BDT>-0.075

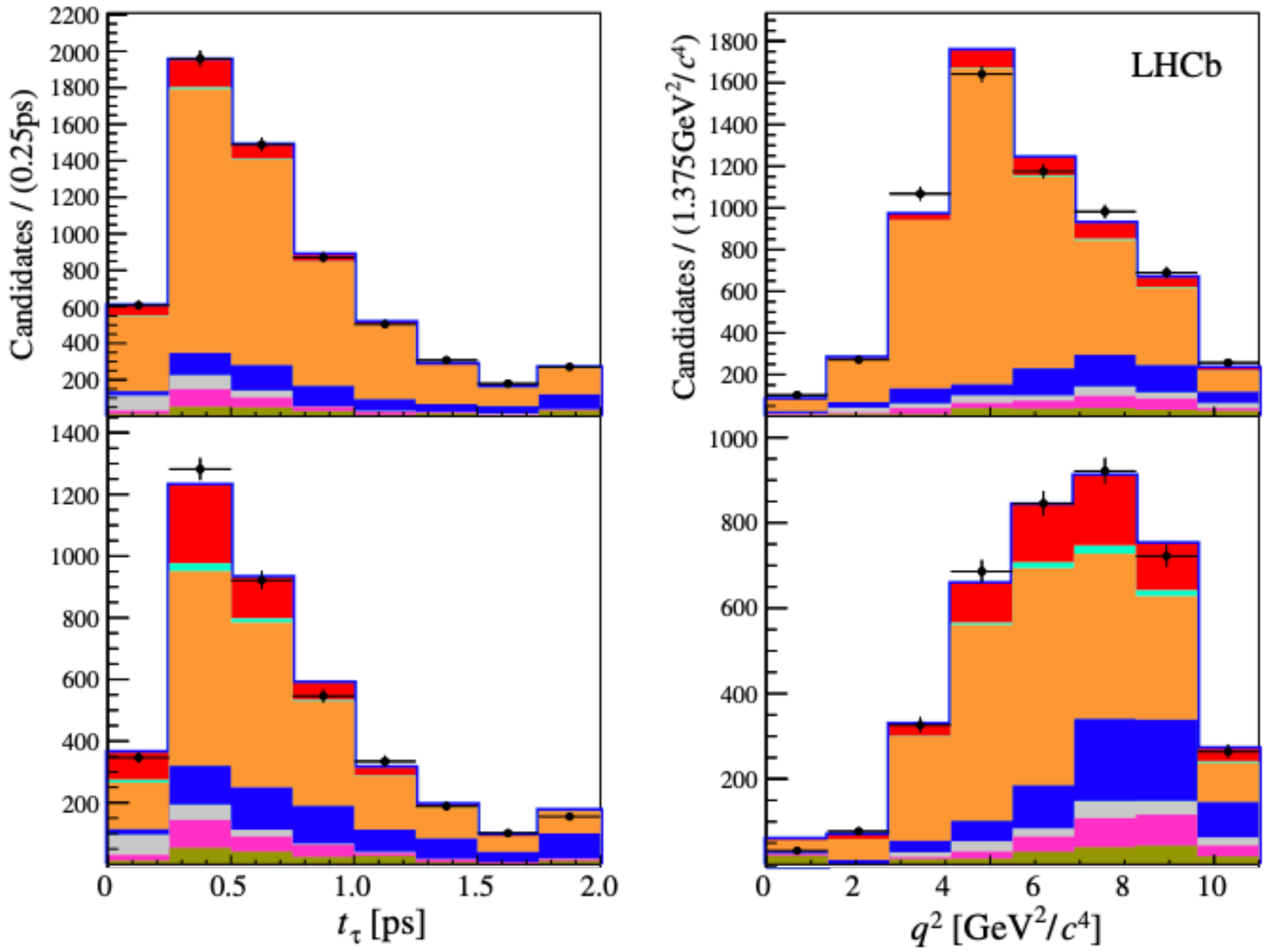


Template shapes, yield, or relative yield of remaining background contributions also examined via control mode samples.

R(D*) hadronic

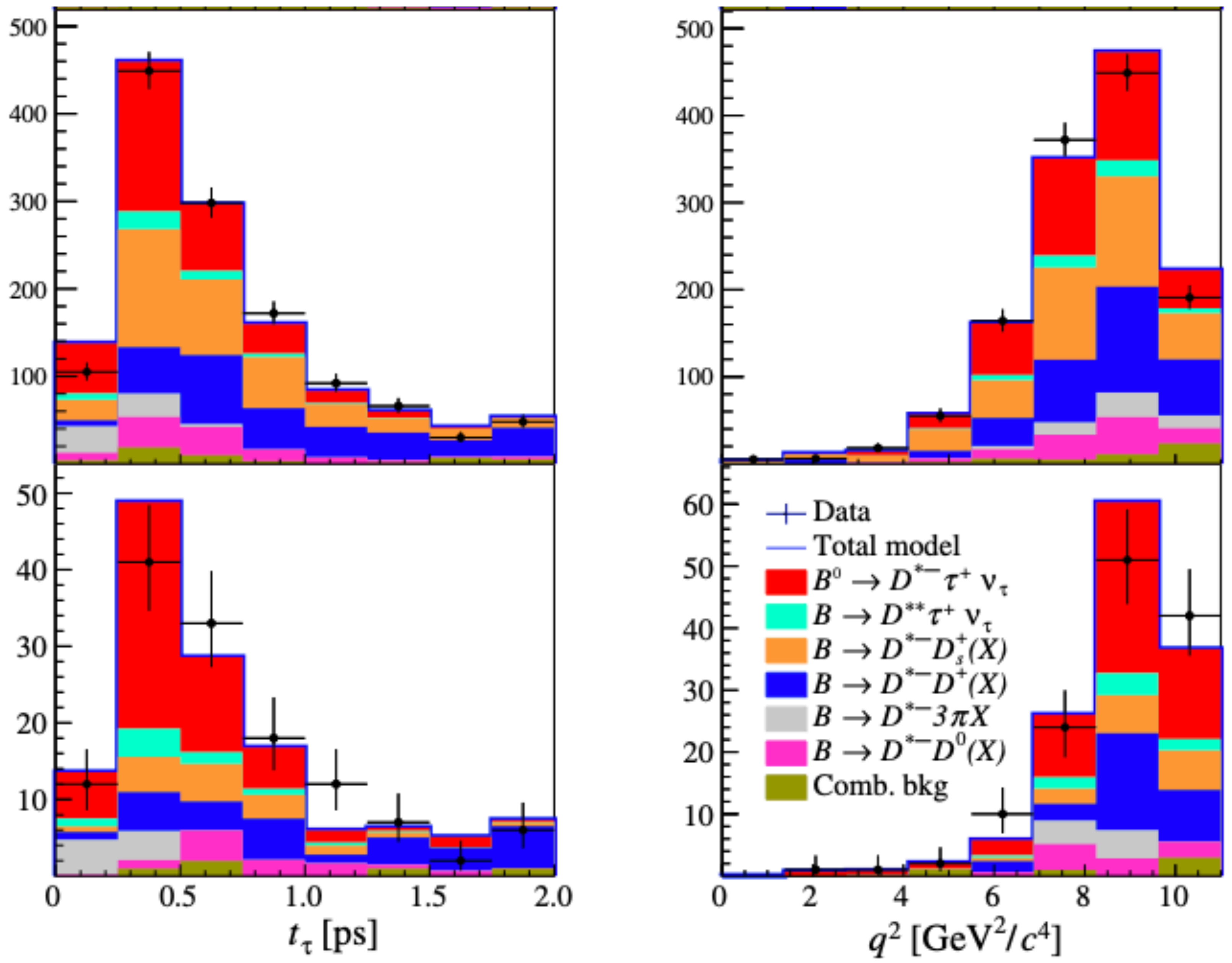
Phys. Rev. Lett. **120** 171802 (2018)

- Signal yield extracted via a 3 dimensional fit to t_τ decay time and q^2 in 4 bins of the BDT output.



Signal yield increases with BDT output.

$B \to D^{(*-)} D_s^+(X)$ background decreases



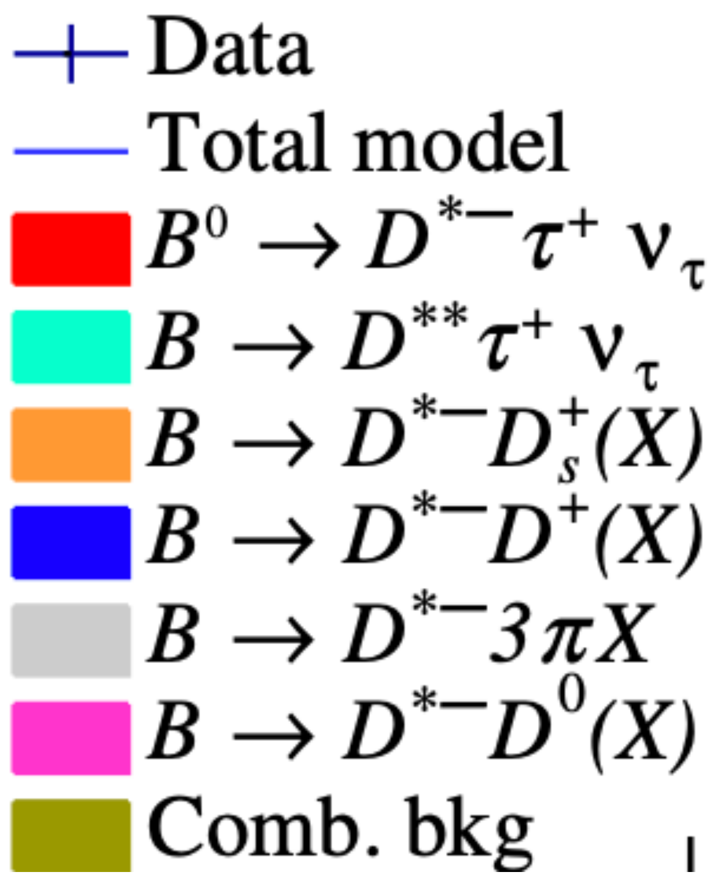
- $N_{sig} = 1296 \pm 86$
- $N_{norm} = 17660 \pm 158$

$$\mathcal{K}(D^{*-}) = 1.97 \pm 0.13(\text{stat}) \pm 0.18(\text{syst})$$

$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau = [1.42 \pm 0.094(\text{stat}) \pm 0.129(\text{syst}) \pm 0.054(\text{ext})] \times 10^{-2}$$

$$\mathcal{R}(D^{*-}) = 0.291 \pm 0.019(\text{stat}) \pm 0.026(\text{syst}) \pm 0.013(\text{ext})$$

Limited knowledge of the external branching fraction



R(D*) hadronic

Phys. Rev. Lett. **120** 171802 (2018)

- Leading systematic uncertainties:
  - Simulated sample size.
  - Knowledge of the D_s^+ decay model.
  - Difference in trigger efficiency for signal and normalization modes.

- First result on R(D*) with hadronic tau at the LHC, 1.1σ above the SM expectation.

Combined with R(D*) muonic from the LHC:

$$R(D^*) = 0.31 \pm 0.0160(\text{stat}) \pm 0.021(\text{sys})$$

2.2σ above the SM.

- External measurements of the double charm decays can decrease the systematic uncertainty.

- Future R(D*) measurement using Run 2 data, increased statistics will allow for higher statistics in the control samples.

- Planned measurement of longitudinal D* polarisation in $B^0 \to D^{*-}\tau^+\nu_\tau$

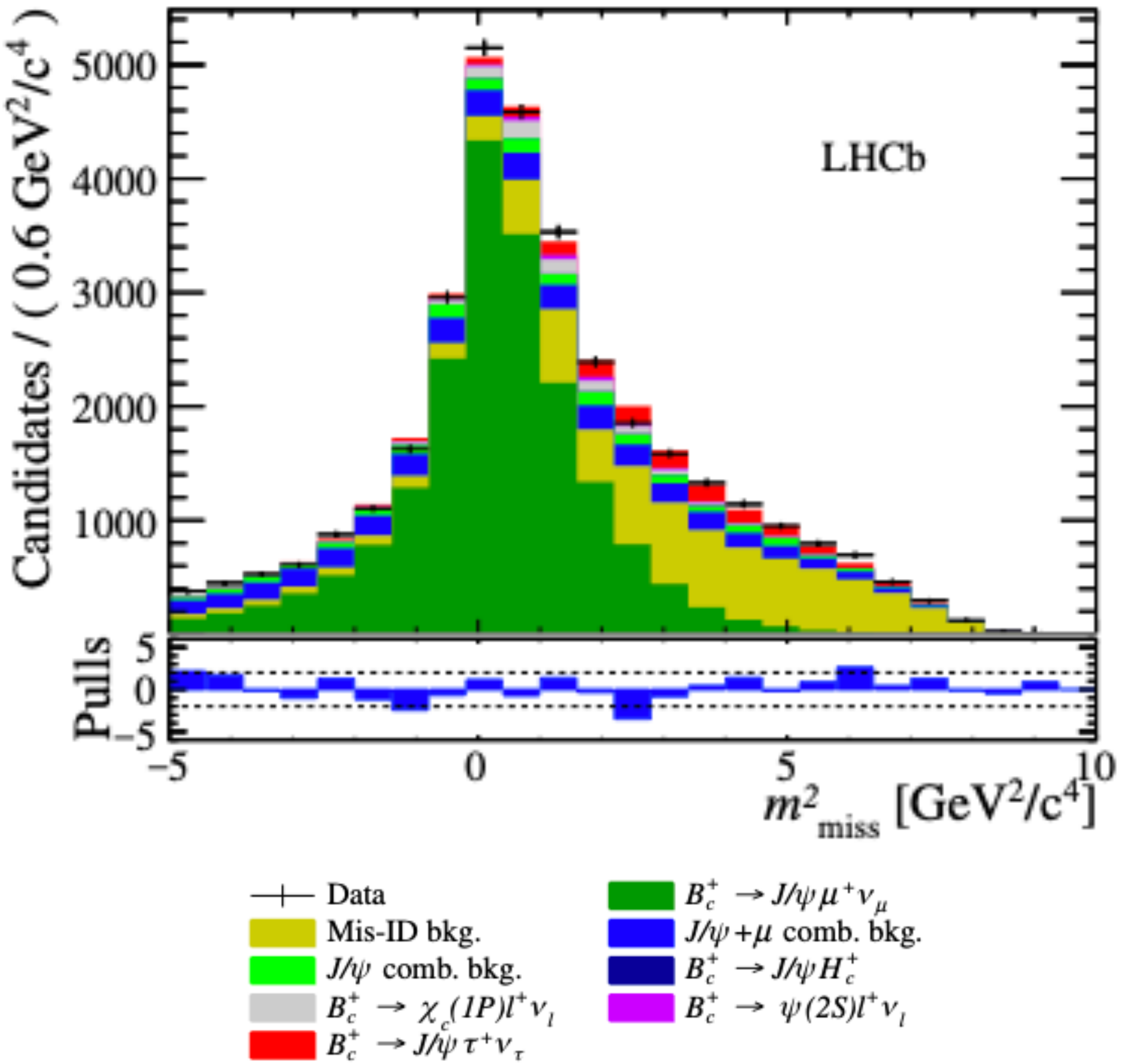
Source	$\delta R(D^{*-})/R(D^{*-})$ [%]
Simulated sample size	4.7
Empty bins in templates	1.3
Signal decay model	1.8
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feeddowns	2.7
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-}D_s^+X$, $B \to D^{*-}D^+X$, $B \to D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-}3\pi X$ background	2.8
Efficiency ratio	3.9
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Total uncertainty	9.1

More LFU tests: $R(J/\psi)$ and $R(\Lambda_c)$

- LHCb has also measured $R(J/\psi) = \dfrac{\mathcal{B}(B_c \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c \to J/\psi\mu^+\nu_\mu)}$, with $\tau \to \mu^+\nu_\mu\nu_\tau$

$$R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{sys})$$

- First observation of $\mathcal{B}(B_c \to J/\psi\tau^+\nu_\tau)$ with 3.1σ significance.
- The **result is 2σ above the SM.**
- Large uncertainty from unknown form factors of B_c decay.



PRL 120, 121801 (2018)

More LFU tests: $R(J/\psi)$ and $R(\Lambda_c)$

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$$R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{sys})$$

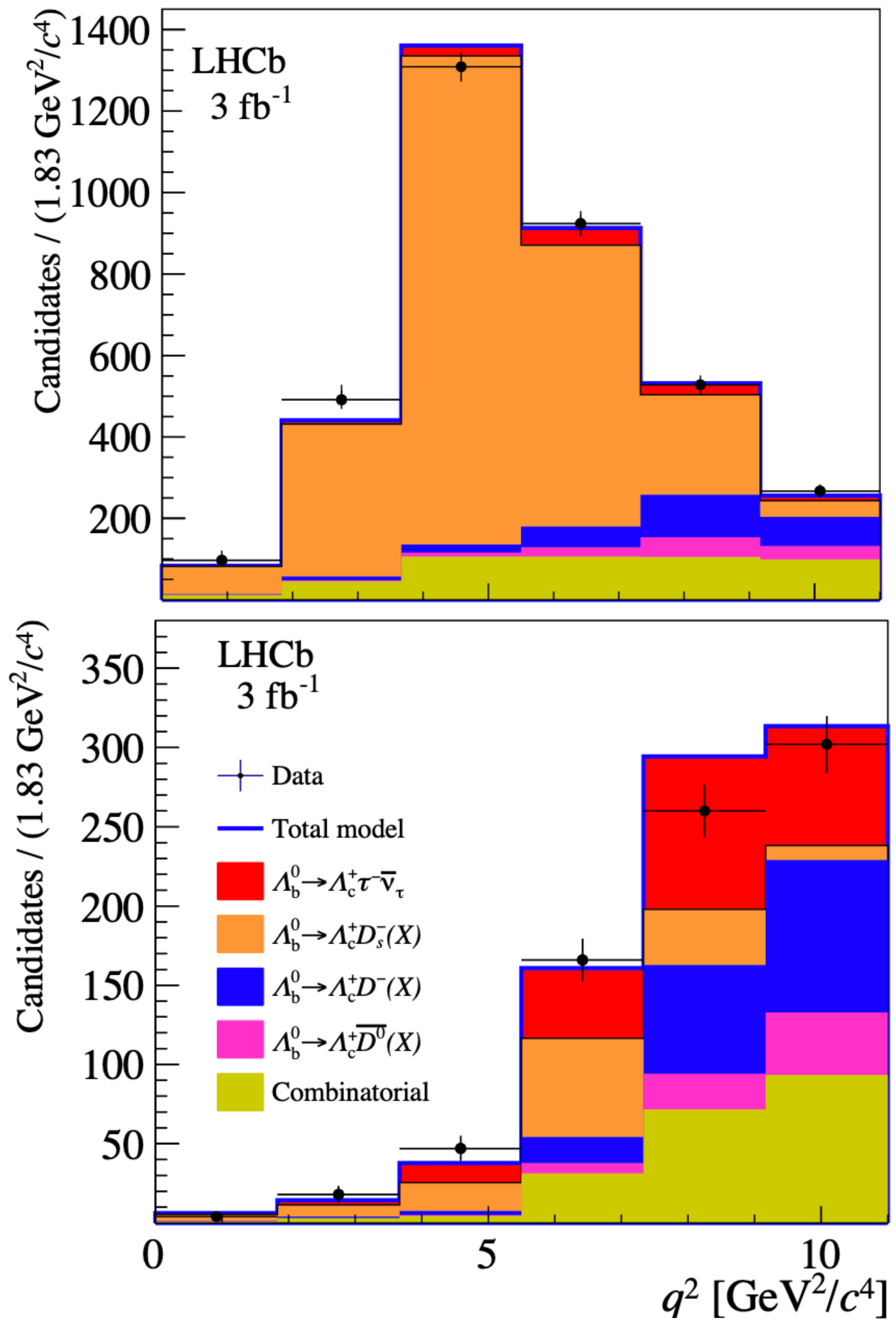
- First observation of $\mathcal{B}(B_c \to J/\psi\tau^+\nu_\tau)$ with 3.1σ significance.
- The **result is** 2σ **above the SM.**
- Large uncertainty from unknown form factors of B_c decay.

NEW:

- $R(\Lambda_c^+) = \dfrac{\mathcal{B}(\Lambda_b \to \Lambda_c\tau^+\nu_\tau)}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu^+\nu_\mu)}$, with $\tau \to \pi^+\pi^-\pi^+\nu_\tau$
- **First observation of** $\mathcal{B}(\Lambda_b \to \Lambda_c\tau^+\nu_\tau)$ **with 6.1σ significance.**
- $R(\Lambda_c^+) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$

agrees with the SM prediction of $R(\Lambda_c^+) = 0.324 \pm 0.004$.

- Largest systematic uncertainty from the template shapes of background modes.
- Additional systematic uncertainty from external branching fractions.
- Constrains NP models that predicts high values of $R(\Lambda_c^+)$



Phys. Rev. Lett. 128, 191803 (2022)

R(D) and R(D*) at Belle

Hadronic tagging with leptonic tau decays
Phys. Rev. D **92**, 072014 (2015)

Hadronic tagging with hadronic tau decays
Phys. Rev. Lett. **118,** 211801 (2017)

Semileptonic tagging with leptonic tau decays
Phys. Rev. Lett. **124**, 161803, 2020

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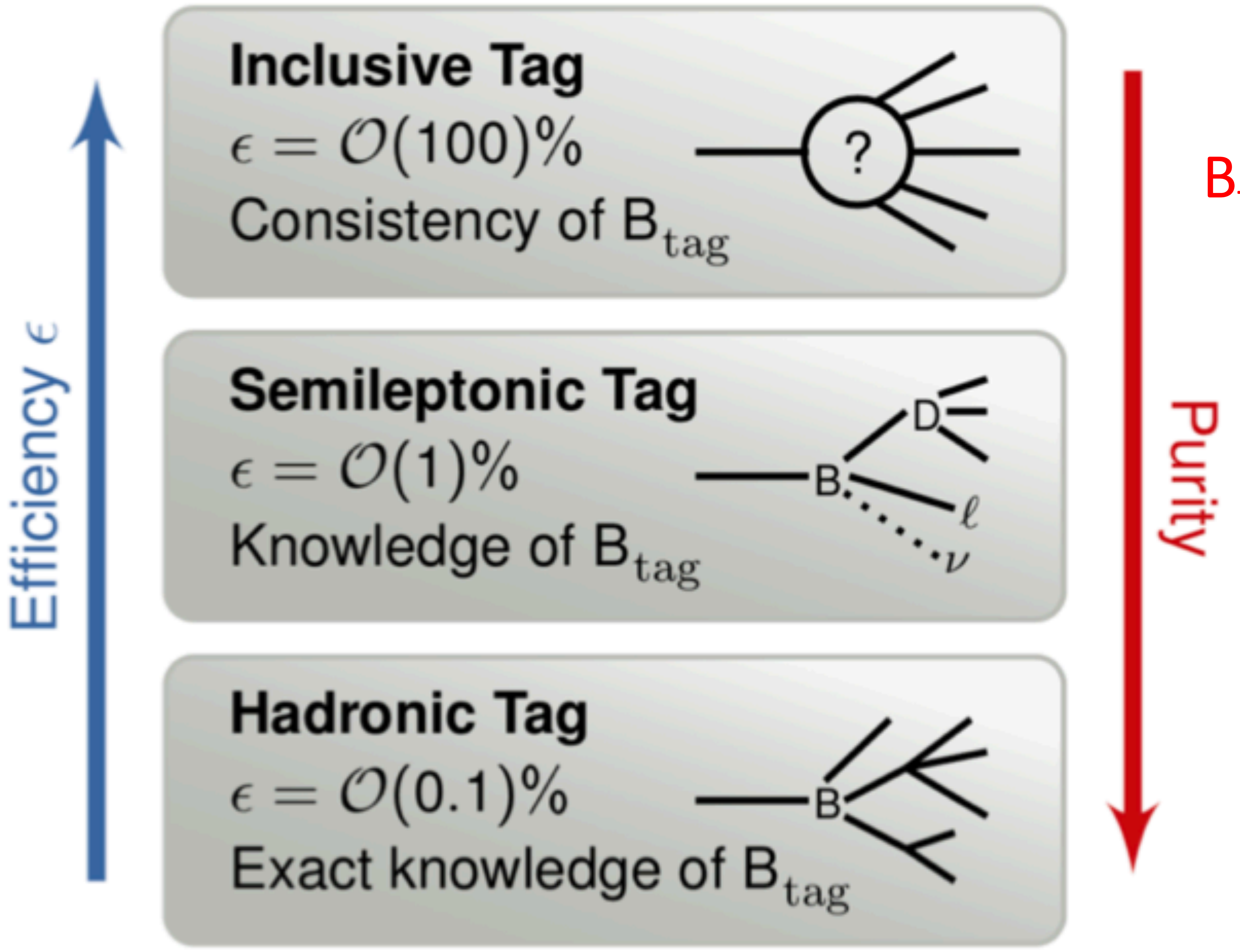
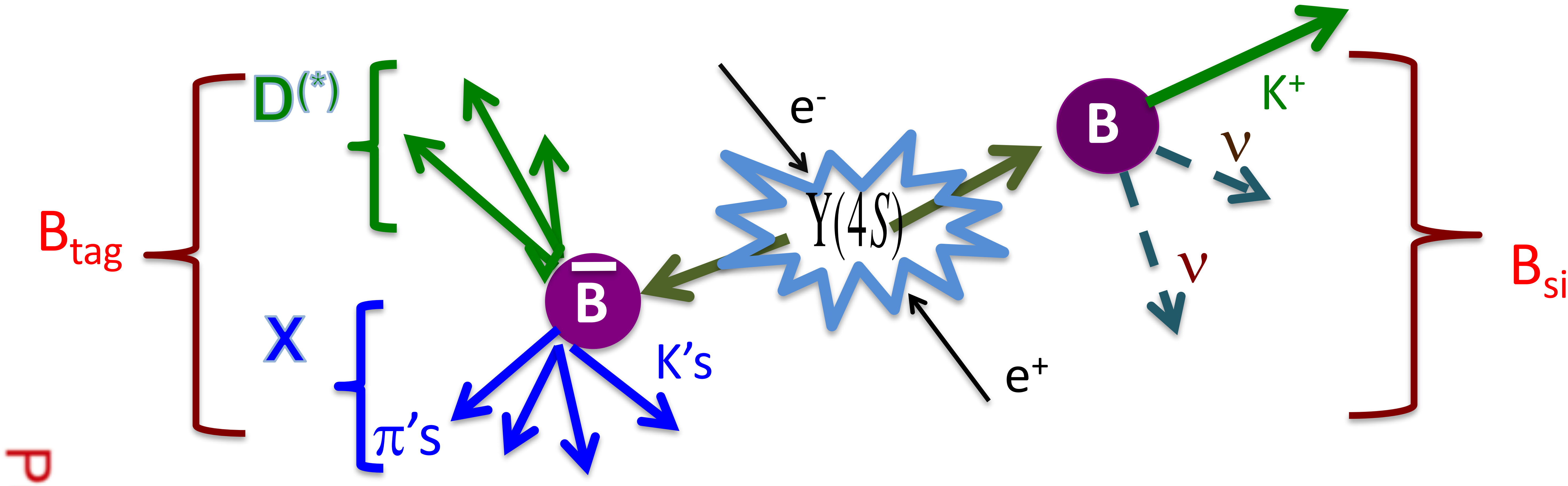
Phys. Rev. Lett. **124**, 161803, 2020

R(D) and R(D*) at B-factories

- The B-factories employ *B*-tagging to measure R(D) and R(D*).
- $\Upsilon(4S)$ produced almost at rest, and instantly decays into a pair of B mesons.
- Exclusive reconstruction of one of the *B* mesons, B_{tag}, using hadronic and semi-leptonic modes.





Infer momentum and direction of signal *B* candidate:

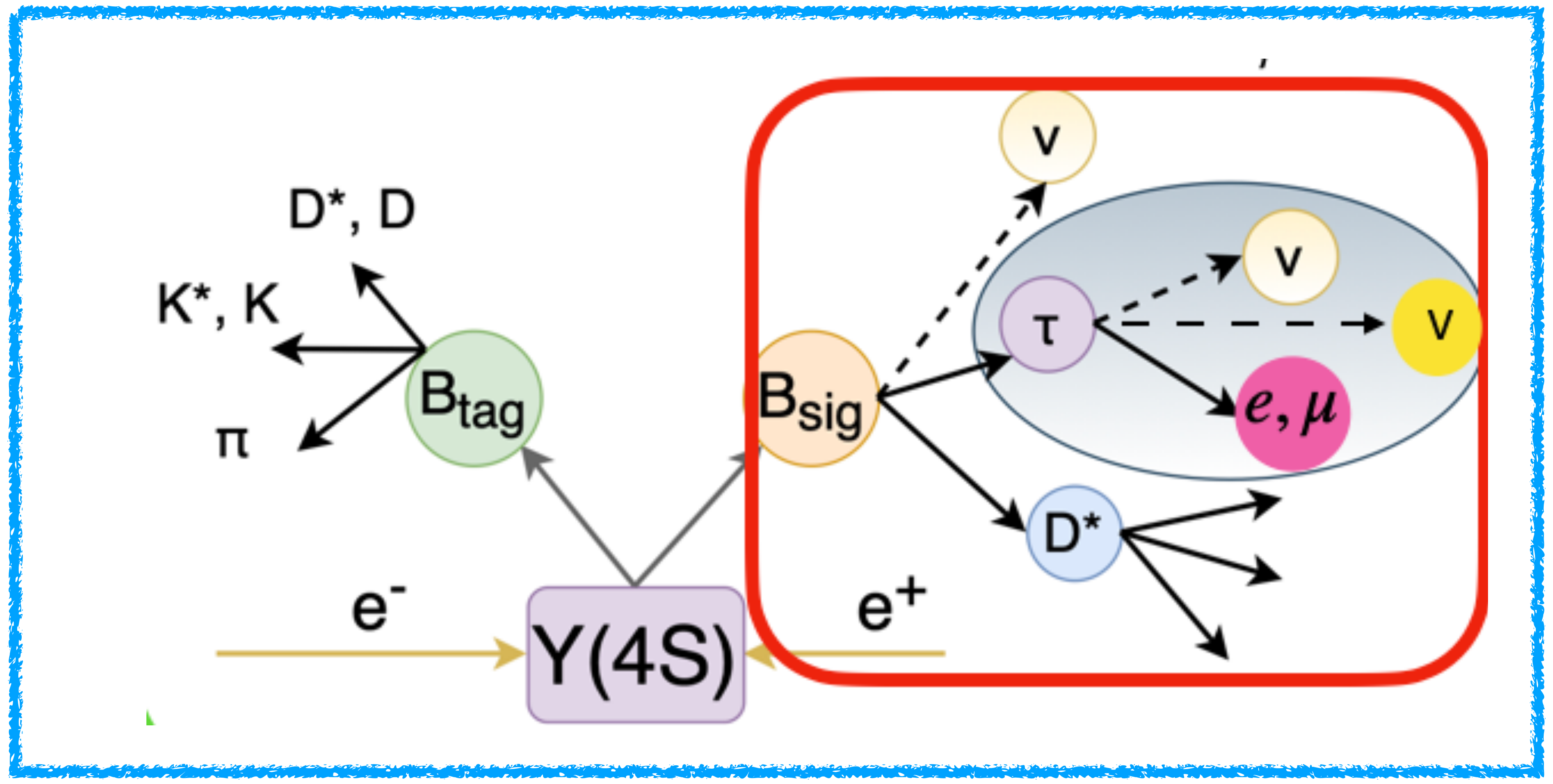
$$p_{B\,sig} \equiv (E_{B\,sig}, \vec{p}_{B\,sig}) = \left(\frac{m_{\Upsilon(4S)}}{2}, -\vec{p}_{B\mathrm{tag}}\right)$$

Ideal for decays with neutrinos, missing energy signatures!

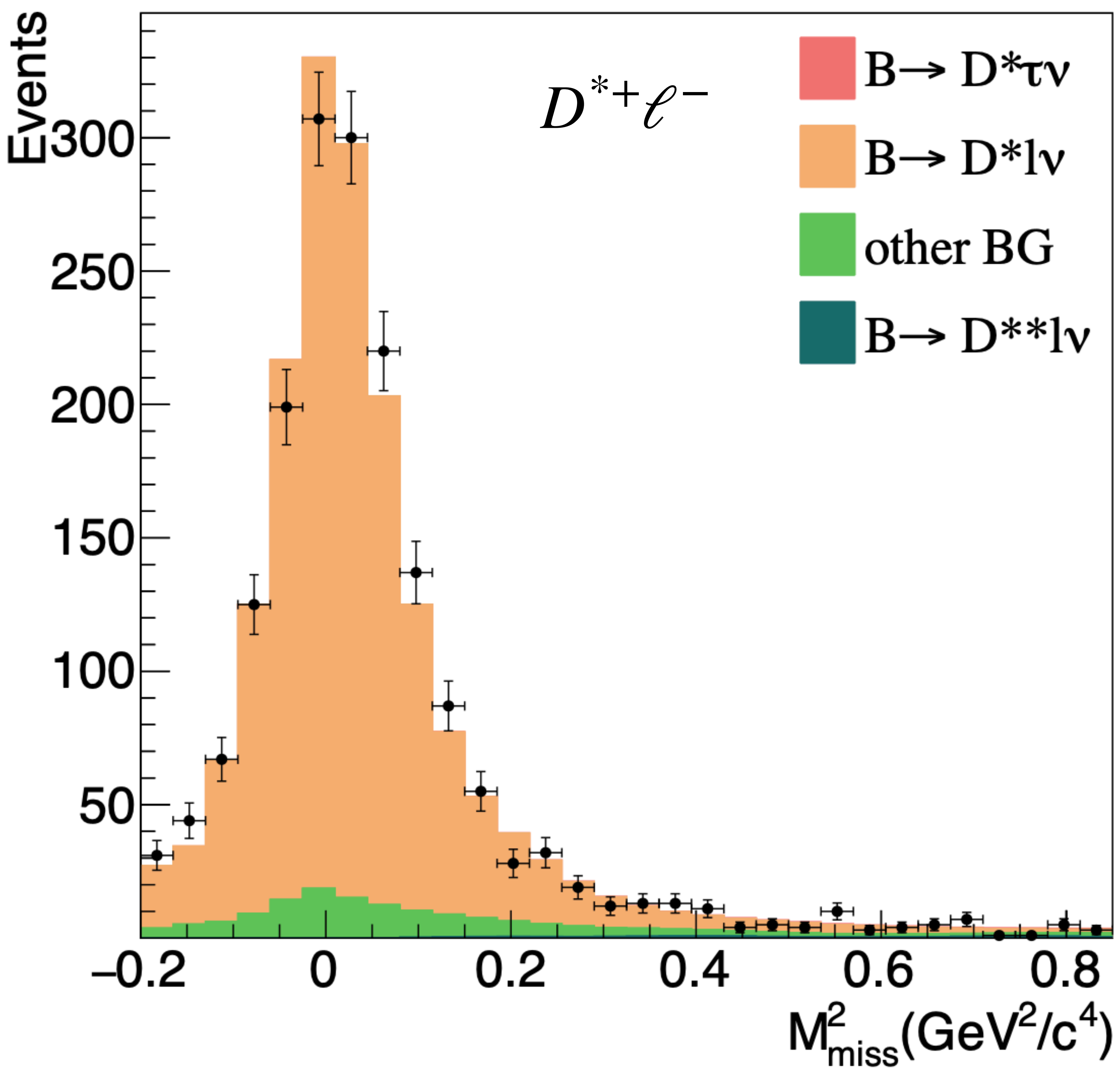
Phys. Rev. D **92**, 072014 (2015)

R(D) and R(D*) with Hadronic Tagging

- Measured using 711 fb^{-1} of Belle data
- Reconstruct first *B* exclusively via 1149 hadronic modes in a hierarchal approach.
    - Efficiency of 0.3% for B$^+$ and 0.2% for B^0.



$$m^2_{\rm miss} = \left(p_{e^+e^-} - p_{B_{\rm tag}} - p_{D^*} - p_\ell\right)^2$$



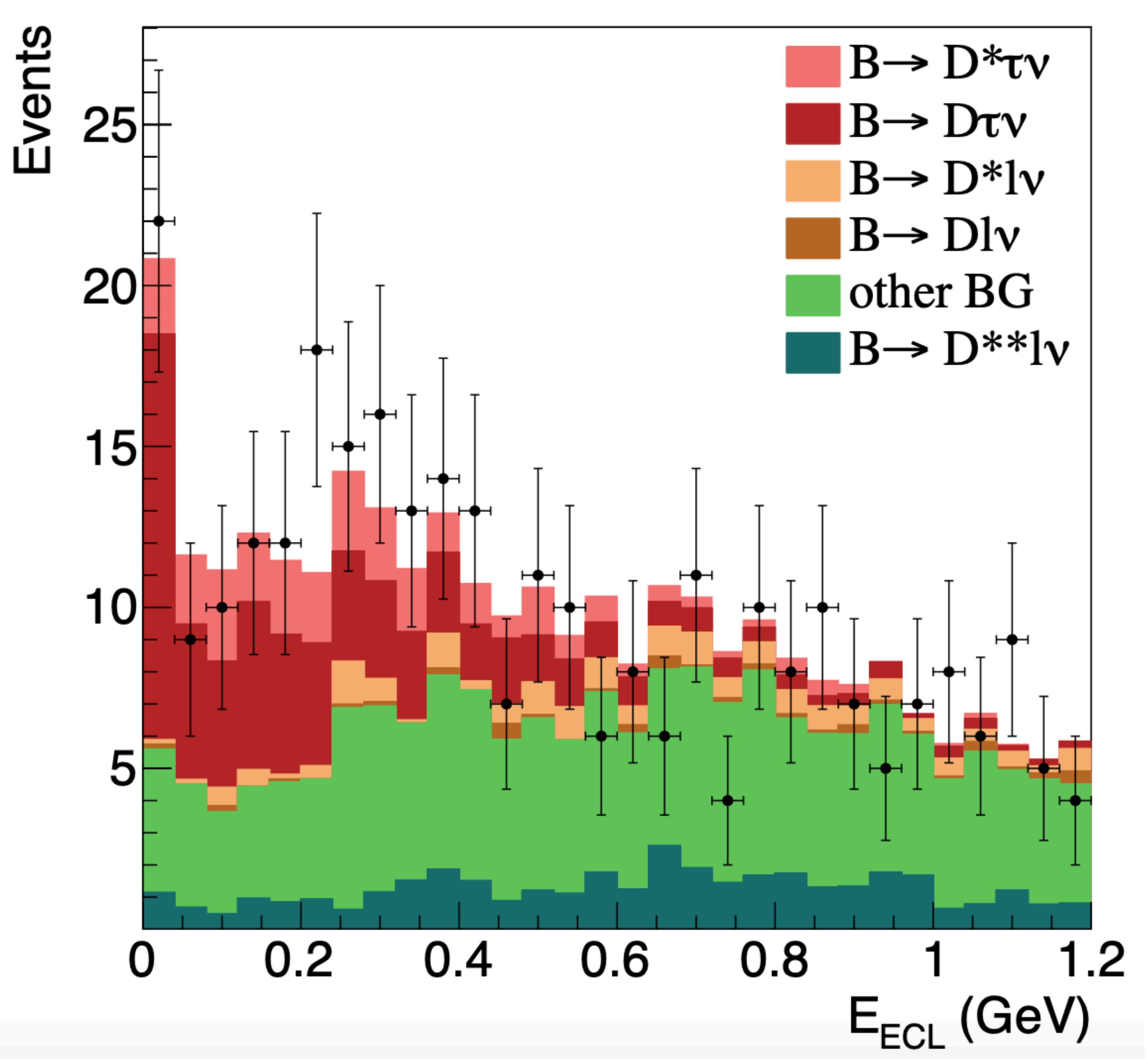
- Remaining information, tracks and cluster, are used for signal and normalisation reconstruction.
- Reconstruct D^0, D$^+$ D^{*0}, D^{*+} via multiple modes.
- Combine with lepton and determine m^2_{miss}.

- Exact determination of q^2 and m^2_{miss} .
- Region below m^2_{miss}<0.85 GeV^2/c^4 is dominated by normalisation mode.

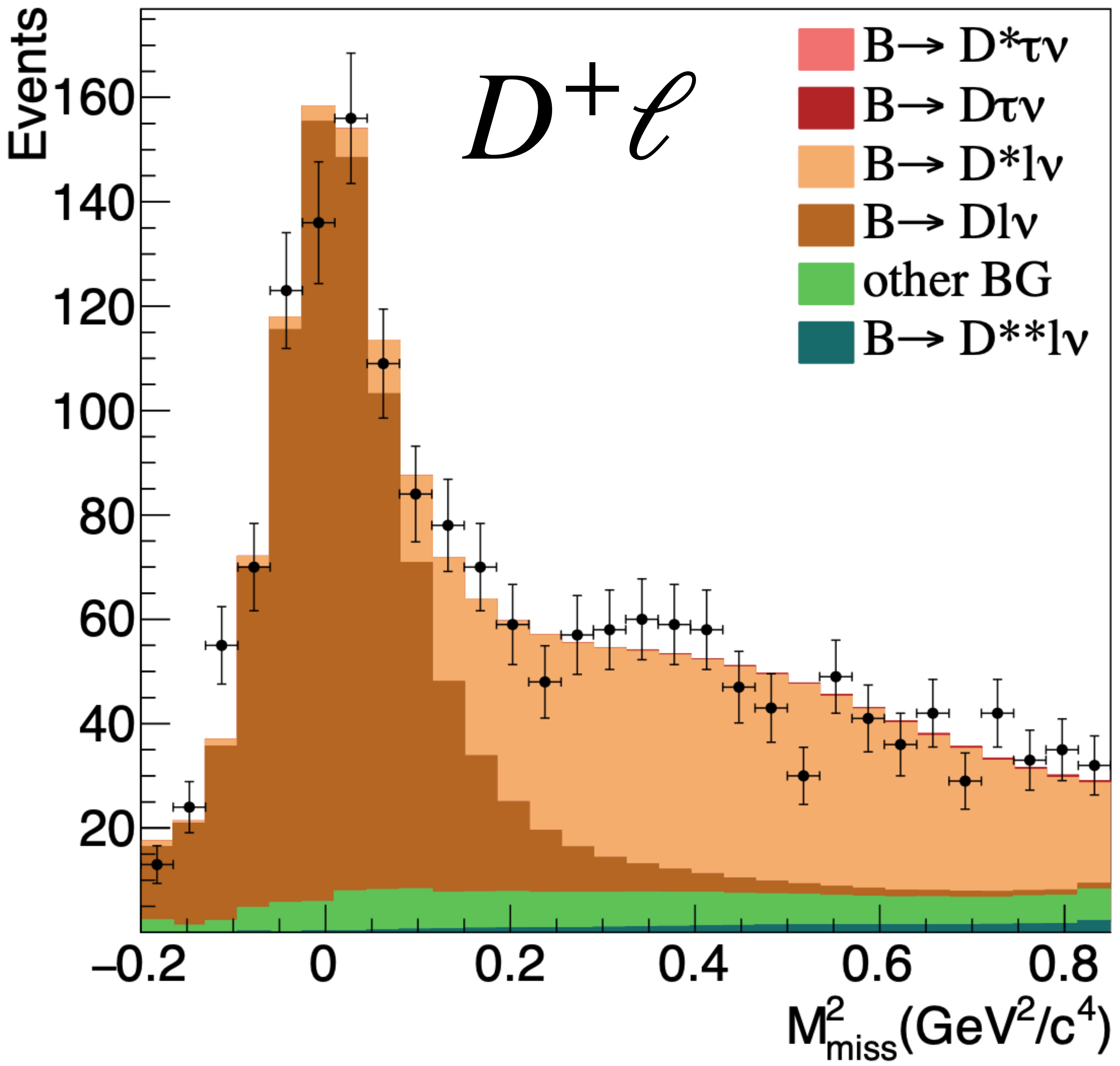
Phys. Rev. D **92**, 072014 (2015)

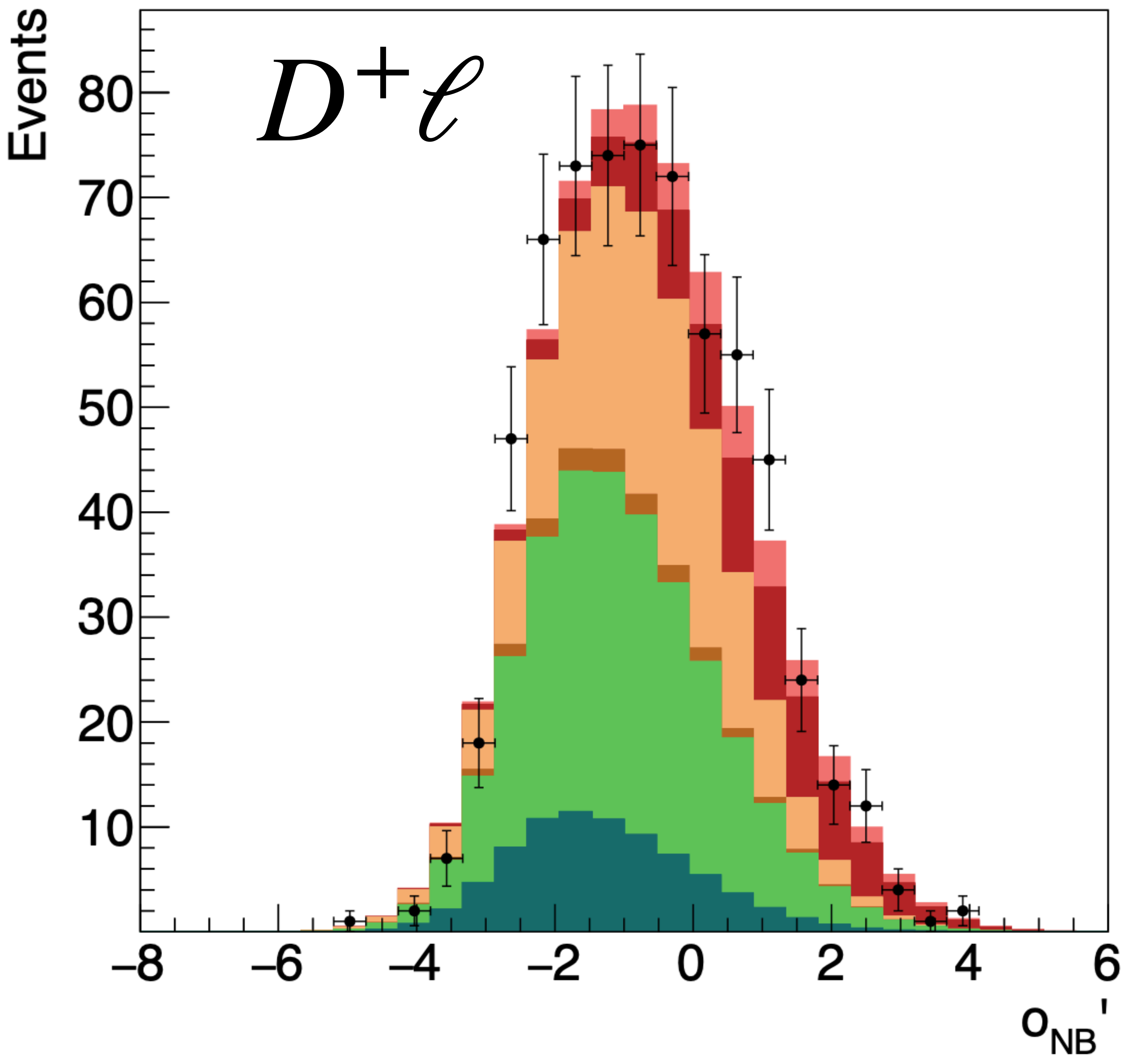
R(D) and R(D*) with Hadronic Tagging

- Large crossfeed from $D^*\ell$ to $D\ell$ samples, added to the total signal and normalisation yields.
- Challenging $B \rightarrow D^{(**)}\ell\nu$ with the same signature in the higher m^2_{miss} region as the signal.
- Train BDT O'_{NB} for 4 samples $D^{*+}\ell, D^{*0}\ell, D^{+}\ell, D^{0}\ell$, with main discriminating variable is E_{ECL}.



E_{ECL} the sum energy of all neutral clusters in the event after the full signal selection is applied: B_{sig}+ B_{tag}.





Simultaneous fit to:

m^2_{miss} in m^2_{miss}<0.85 GeV²/c⁴ to extract normalisation yield

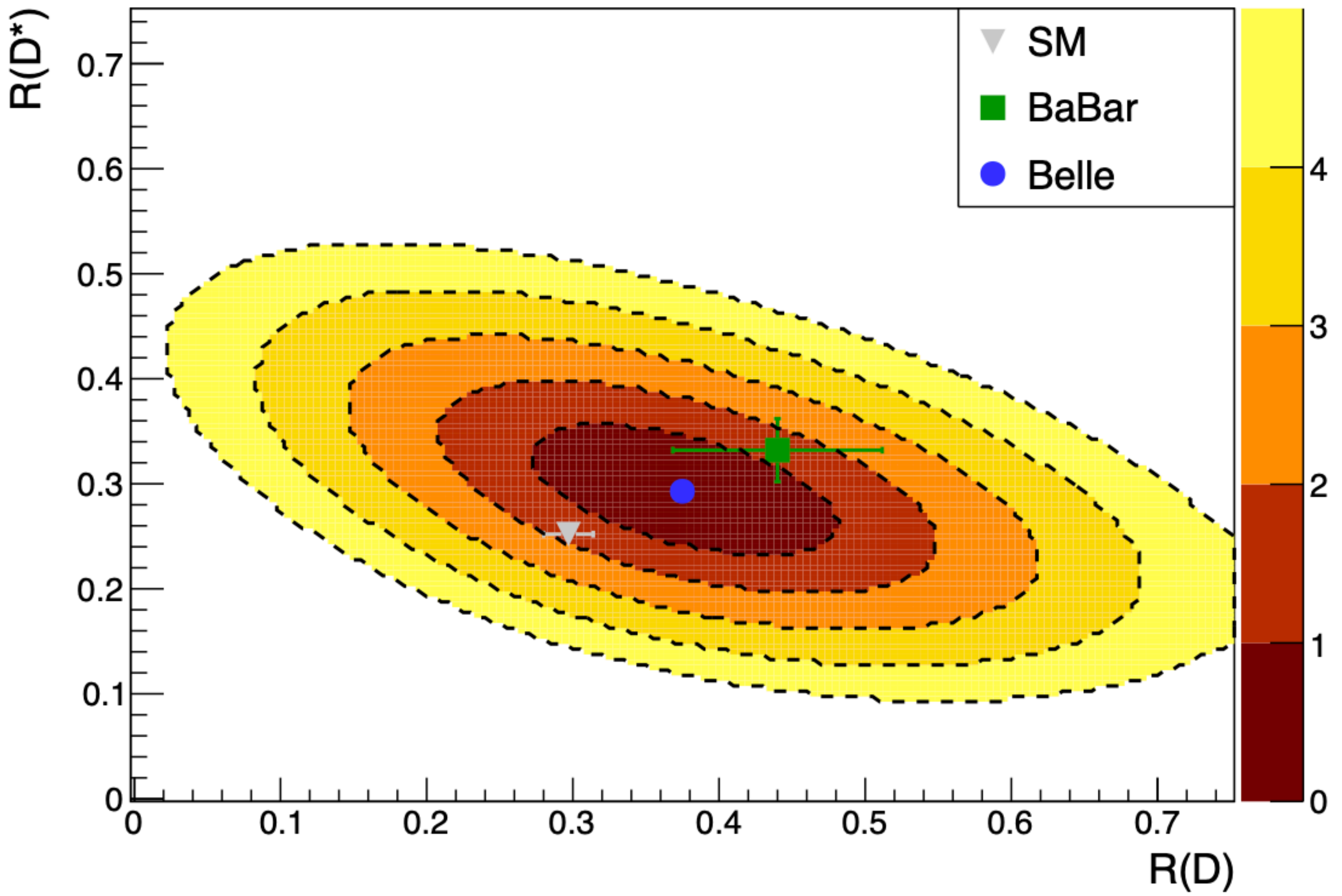
O'_{NB} in m^2_{miss}>0.85 GeV²/c⁴ to extract signal and background yields.

Phys. Rev. D **92**, 072014 (2015)

R(D) and R(D*) with Hadronic Tagging

- Leading systematic uncertainties:
- Final result:
  - modelling and composition of the $B \to D^{(**)}\ell\nu$ background.
  - Shape of the BDT output
  - Fixed factors in the fit, determined from simulation.

R(D) = 0.375 ± 0.064 ± 0.026
R(D∗) = 0.293 ± 0.038 ± 0.015



	$R(D)$ [%]	$R(D^*)$ [%]	Correlation
$D^{(*(*))}\ell\nu$ shapes	4.2	1.5	0.04
D^{**} composition	1.3	3.0	-0.63
Fake D yield	0.5	0.3	0.13
Fake ℓ yield	0.5	0.6	-0.66
D_s yield	0.1	0.1	-0.85
Rest yield	0.1	0.0	-0.70
Efficiency ratio f^{D^+}	2.5	0.7	-0.98
Efficiency ratio f^{D^0}	1.8	0.4	0.86
Efficiency ratio $f_{\rm eff}^{D^{*+}}$	1.3	2.5	-0.99
Efficiency ratio $f_{\rm eff}^{D^{*0}}$	0.7	1.1	0.94
CF double ratio g^+	2.2	2.0	-1.00
CF double ratio g^0	1.7	1.0	-1.00
Efficiency ratio $f_{\rm wc}$	0.0	0.0	0.84
$M^2_{\rm miss}$ shape	0.6	1.0	0.00
$o'_{\rm NB}$ shape	3.2	0.8	0.00
Lepton PID efficiency	0.5	0.5	1.00
Total	7.1	5.2	−0.32

Compared with previous BaBar measurement using hadronic tagging and leptonic tau decays.

PRL 100, 101802 (2012), PRD 88, 072012 (2013)

Phys. Rev. D **92**, 072014 (2015)

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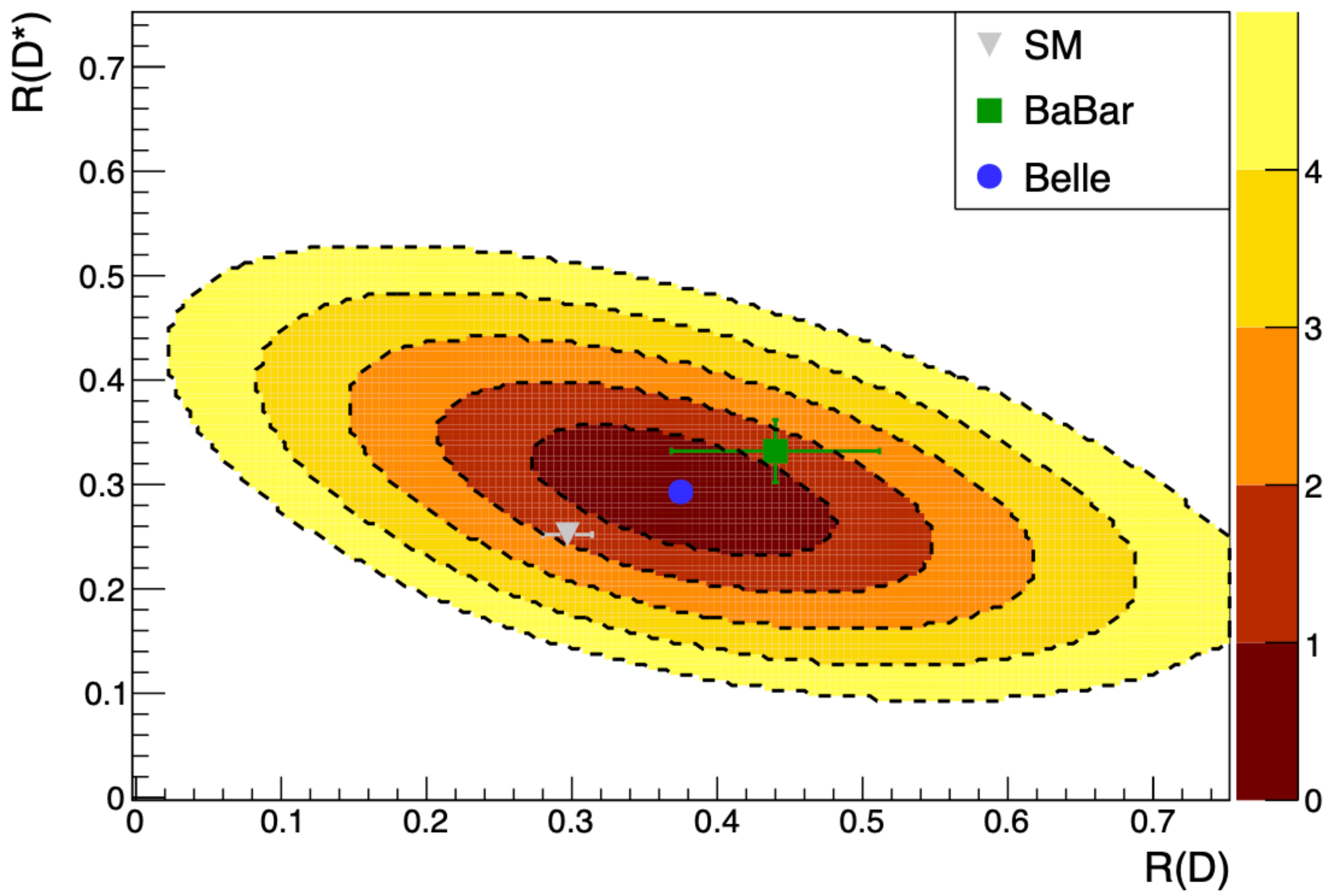
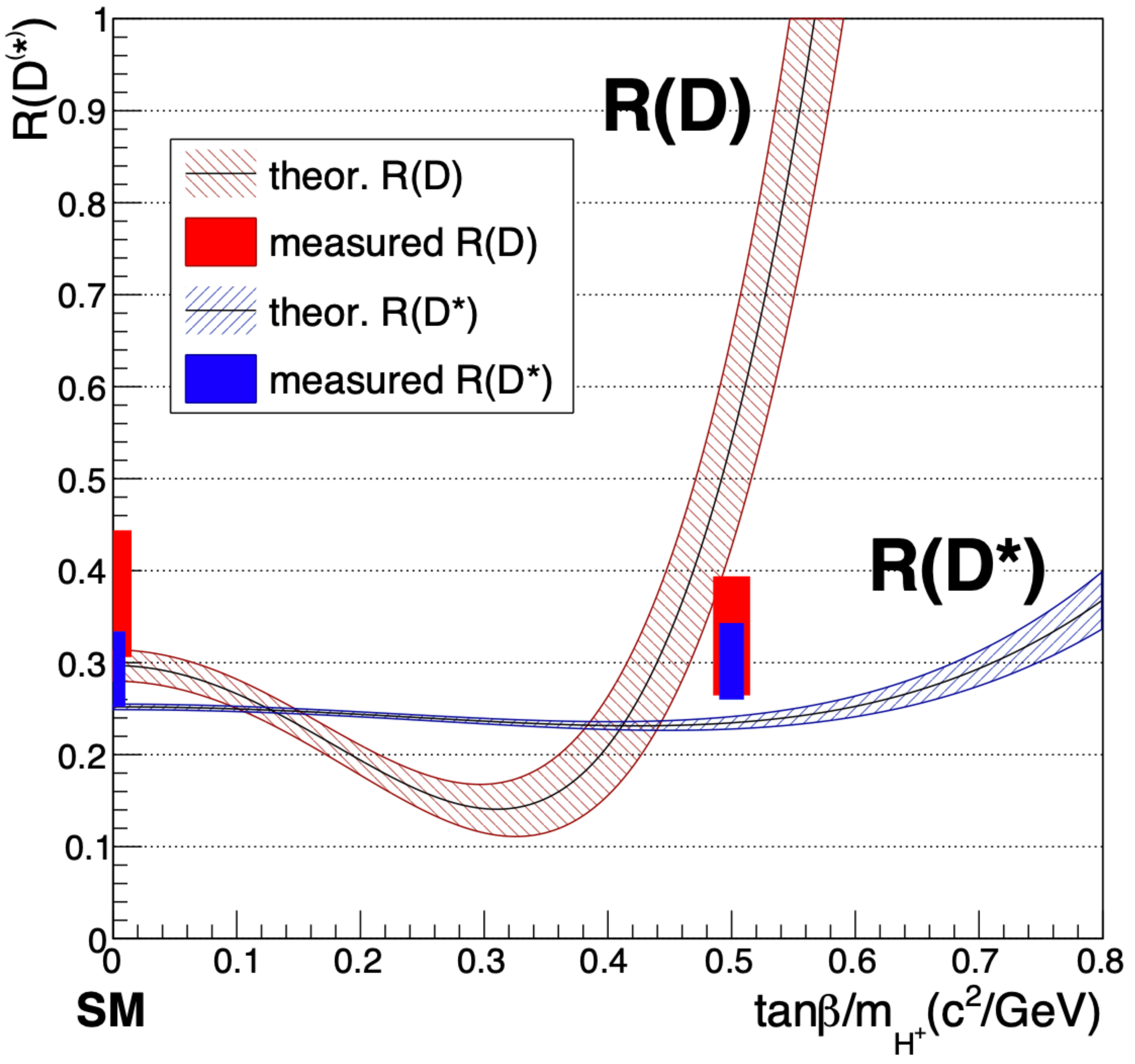
R(D*) = 0.293 ± 0.038 ± 0.015





Compatible with type II 2HDM in the region
$\tan\beta/m_{H^+}$ 0.45(c^2/GeV)

R(D) and R(D*) at Belle

Hadronic tagging with leptonic tau decays
Phys. Rev. D **92**, 072014 (2015)

→ Hadronic tagging with hadronic tau decays
Phys. Rev. Lett. **118,** 211801 (2017)

Semileptonic tagging with leptonic tau decays
Phys. Rev. Lett. **124**, 161803, 2020

R(D*) & Tau Polarization

Phys. Rev. Lett. 118 211801 (2017)

- Measure τ polarisation with $\tau^- \to \pi^- \nu_\tau$ and $\tau^- \to \rho^- \nu_\tau$ using the full Belle dataset.

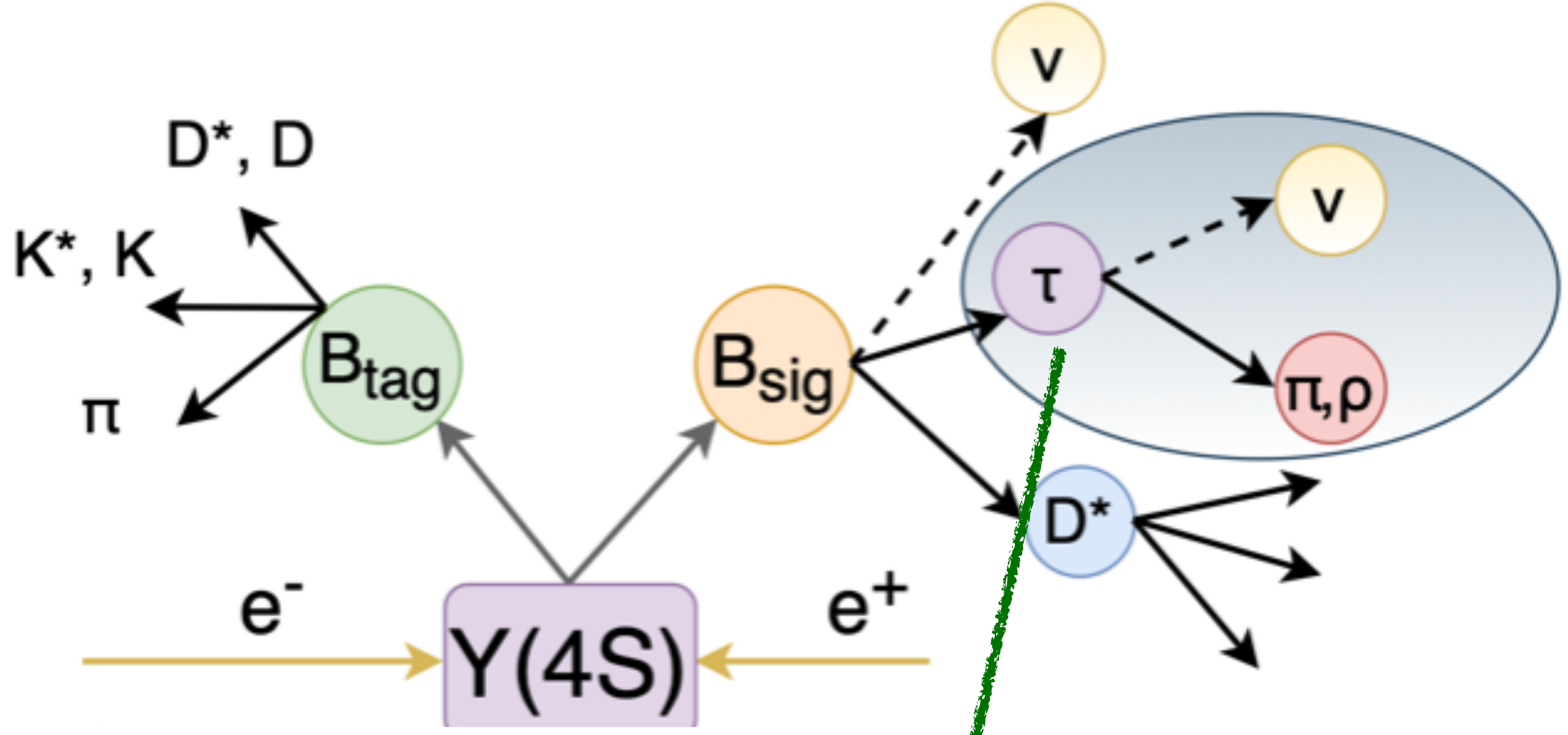
$$P_\tau(D^{(*)}) = \frac{\Gamma^+(D^{(*)}) - \Gamma^-(D^{(*)})}{\Gamma^+(D^{(*)}) + \Gamma^-(D^{(*)})}$$

- Sensitive to new physics contributions.
- SM predicts:
  - $P_\tau(D) = 0.325 \pm 0.009$
  - $P_\tau(D^*) = -0.497 \pm 0.013$
- Can be measured via:

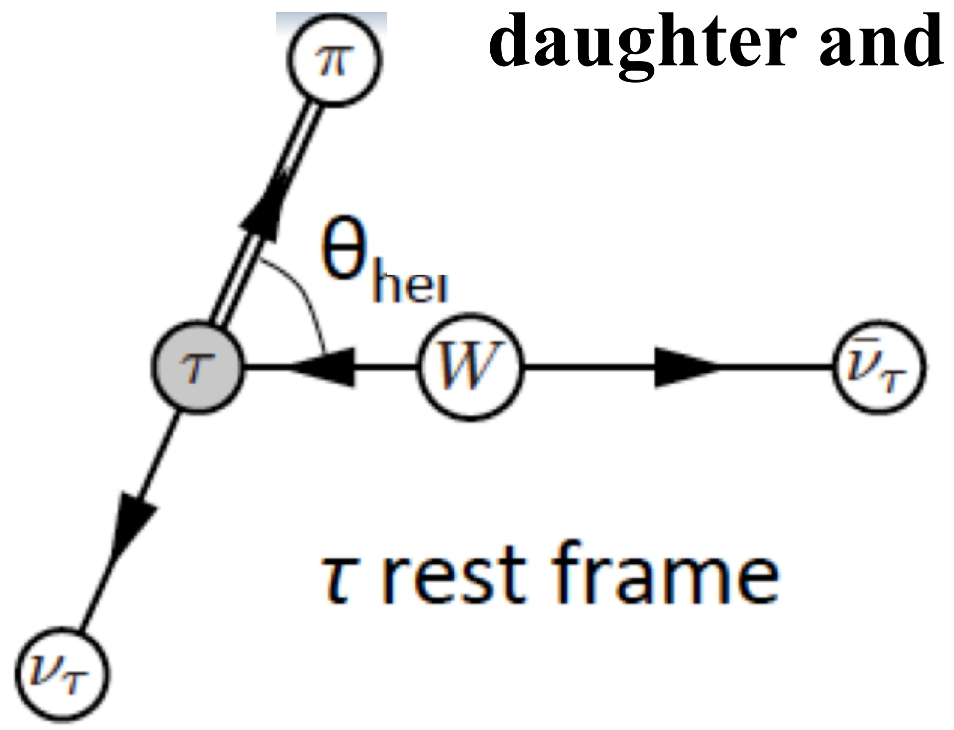
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\text{hel}}} = 1 + \alpha P_\tau \cos\theta_{\text{hel}}$$

  - $\alpha = 1$ for $\tau^- \to \pi^- \nu_\tau$
  - $\alpha = 0.45$ for $\tau^- \to \rho^- \nu_\tau$

Employ a hadronic tag analysis to determine the B_{sig} 4-vector and the $\tau\nu_\tau$ frame



Angle between the τ daughter and the W



τ rest frame

$$\cos\theta_{\text{hel}}(\tau) = 1 - \frac{2m_\tau^2 M_M^2}{(M_W^2 - m_\tau^2)(m_\tau^2 - m_h^2)}$$

Phys. Rev. Lett. 118 211801 (2017)

R(D*) & Tau Polarization

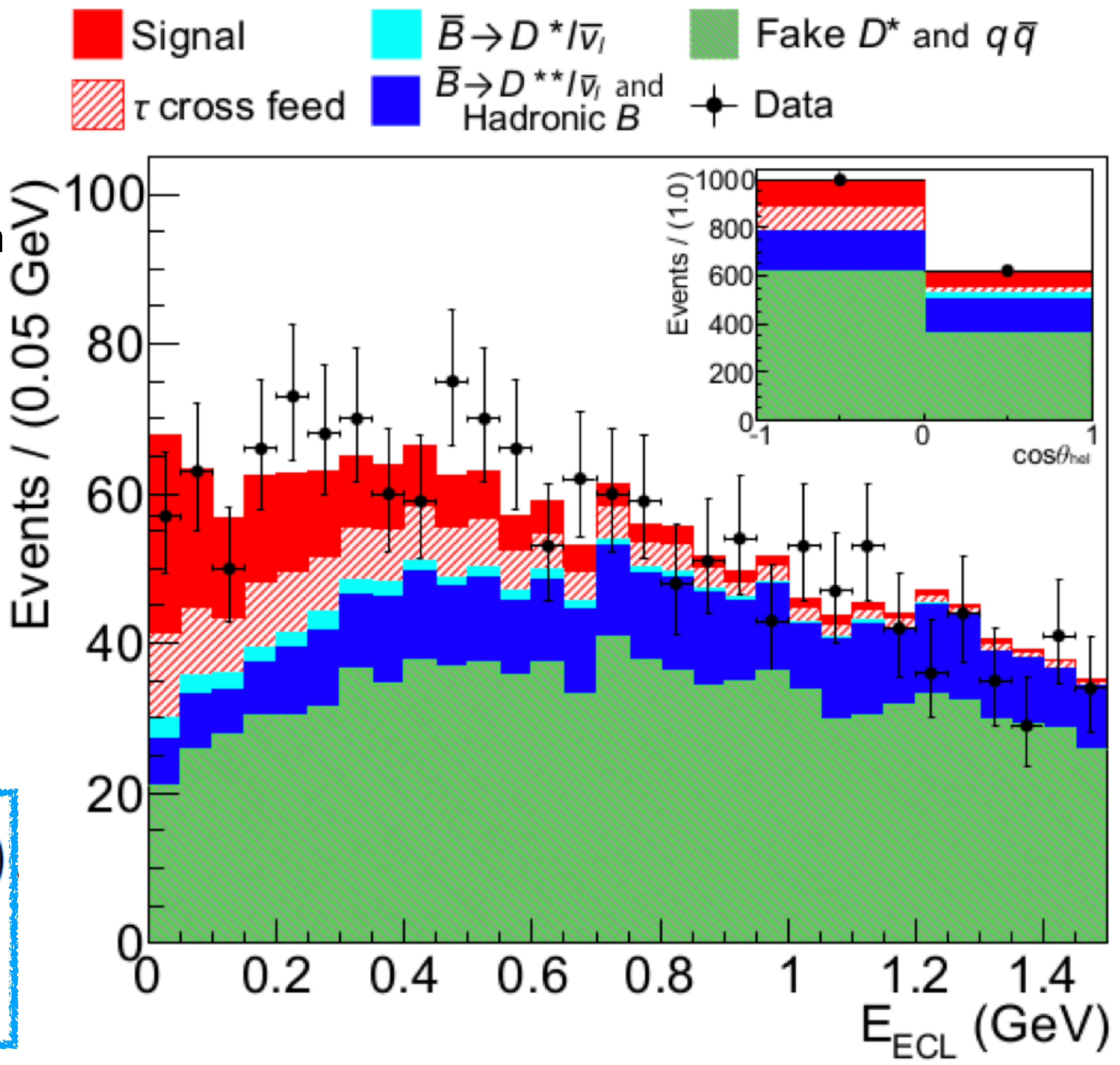
- Divide signal sample into 2 regions:
  - $\cos\theta_{\text{hel}}$>0 forward
  - $\cos\theta_{\text{hel}}$<0 backward

- Extract signal and background yields in a simultaneous fit to E_{ECL} in 8 samples:

$$(B^-, B^0) \times (\pi^-\nu_\tau, \rho\nu_\tau) \times (\text{backward}, \text{forward})$$

- $$P_\tau(D^*) = \frac{[2(N^F_{sig} - N^B_{sig})]}{[\alpha(N^F_{sig} + N^B_{sig}]} \quad \text{and} \quad R(D^*) = \frac{\epsilon_{norm} N_{sig}}{\mathcal{B}_\tau \epsilon_{sig} N_{norm}}$$

$$R(D^*) = 0.270 \pm 0.035(\text{stat})^{+0.028}_{-0.025}(\text{syst})$$
$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat})^{+0.21}_{-0.16}(\text{syst}),$$



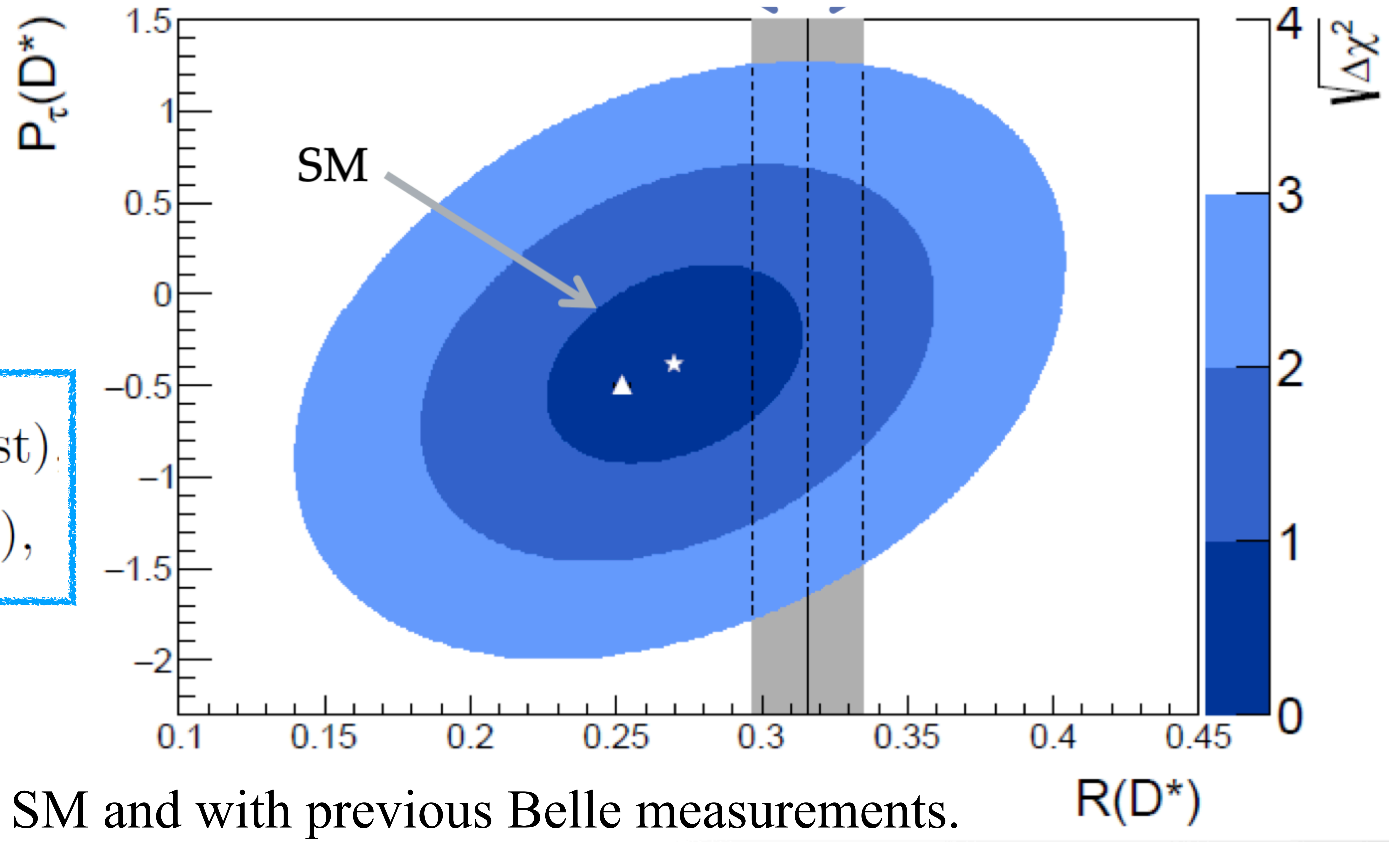
R(D*) & Tau Polarization

Phys. Rev. Lett. 118 211801 (2017)

Leading systematic uncertainties:

- Hadronic *B* decay decomposition
- Limited size of MC sample
- Fake D* component shape and yield

$$R(D^*) = 0.270 \pm 0.035(\mathrm{stat})^{+0.028}_{-0.025}(\mathrm{syst}),$$
$$P_\tau(D^*) = -0.38 \pm 0.51(\mathrm{stat})^{+0.21}_{-0.16}(\mathrm{syst}),$$



Result agrees with the SM and with previous Belle measurements.

First measurement of tau polarization:

$$P_\tau(D^*) > +0.5 \text{ at } 90\% \text{ CL}$$

R(D) and R(D*) at Belle

Hadronic tagging with leptonic tau decays
Phys. Rev. D **92**, 072014 (2015)

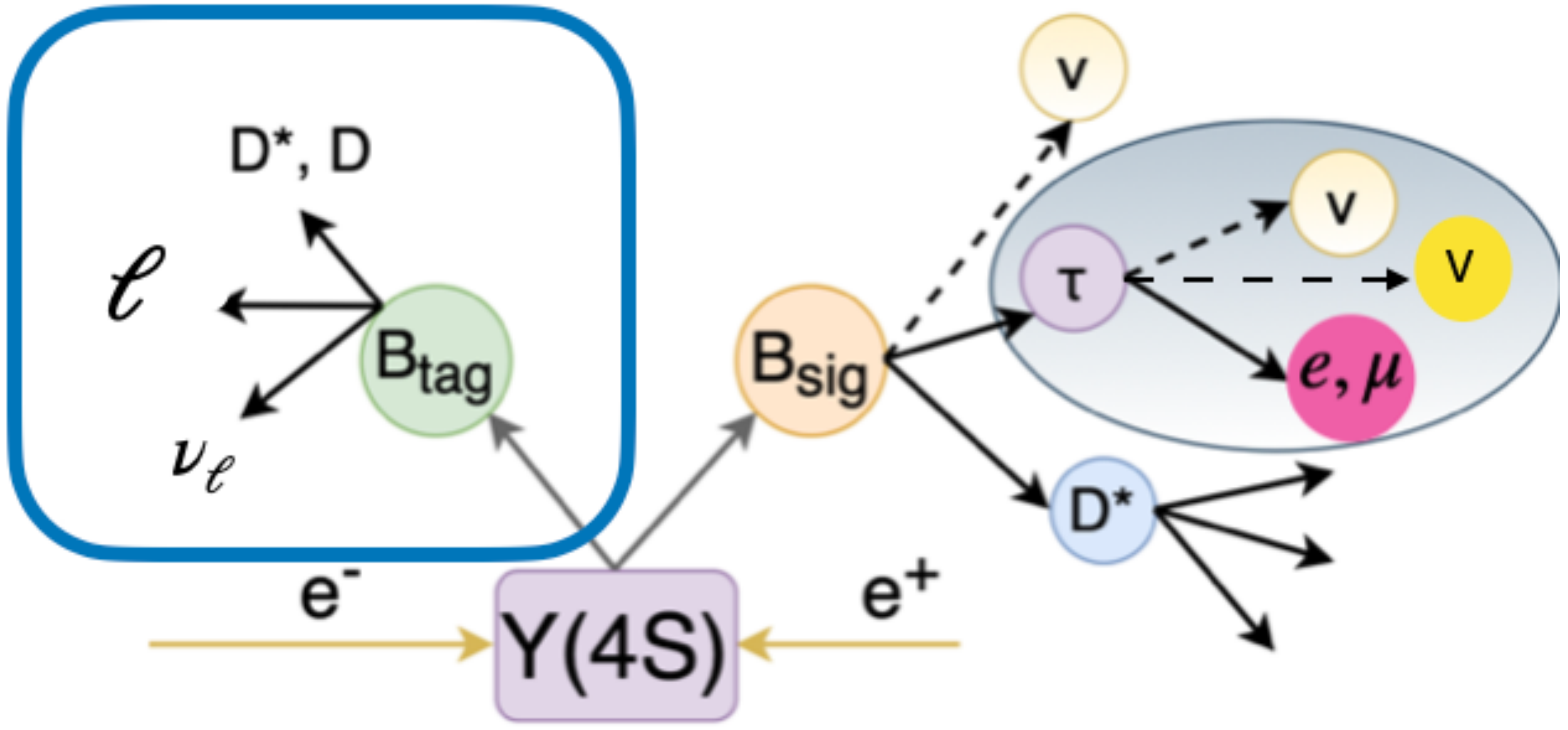
Hadronic tagging with hadronic tau decays
Phys. Rev. Lett. **118,** 211801 (2017)

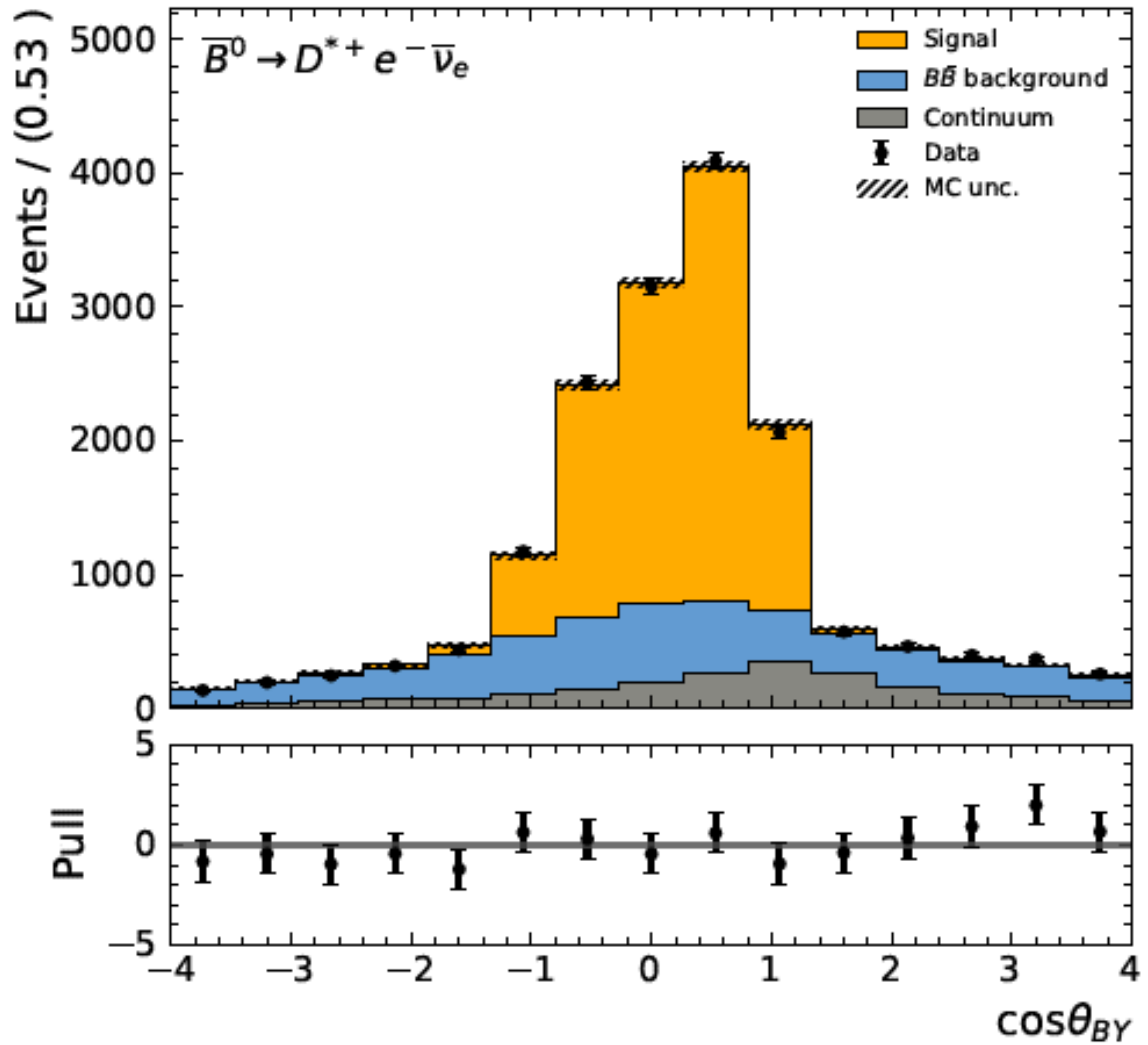
Semileptonic tagging with leptonic tau decays
Phys. Rev. Lett. **124**, 161803, 2020

Phys. Rev. Lett. **124**, 161803, 2020

R(D) and R(D*) with Semileptonic Tagging

- Based on a data sample with 772 x 10⁶ $B\bar{B}$ pairs
- Measure $R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^{(*+)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*+)}\ell^-\bar{\nu}_\ell)}$ with $\tau^+ \to \ell^+\nu_\ell\bar{\nu}_\tau$
- Use semileptonic tagging with a hierarchical based on a BDT classifier that reconstructs $D^{(*)}\ell\bar{\nu}_\ell$ and $D\ell\bar{\nu}_\ell$.



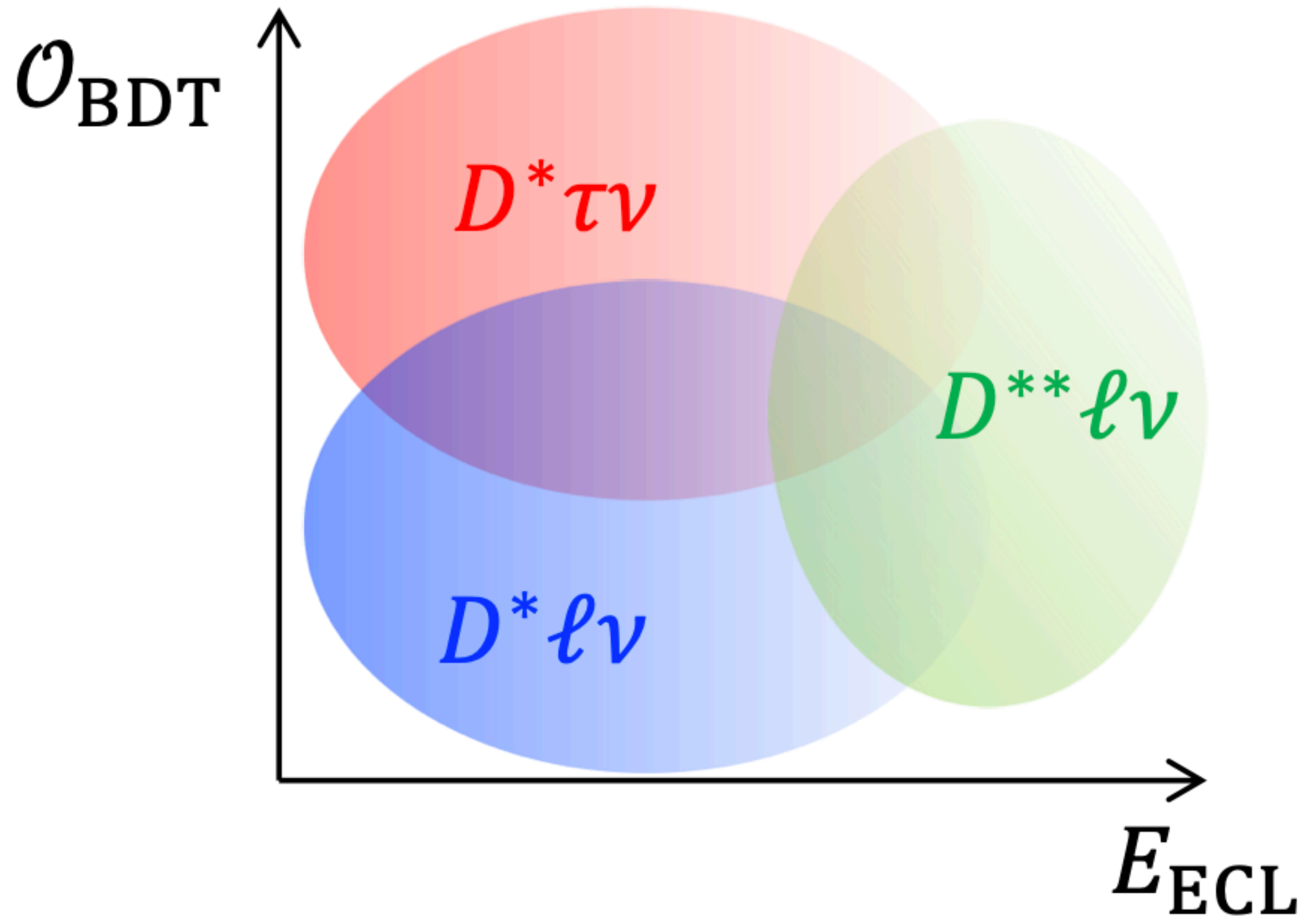


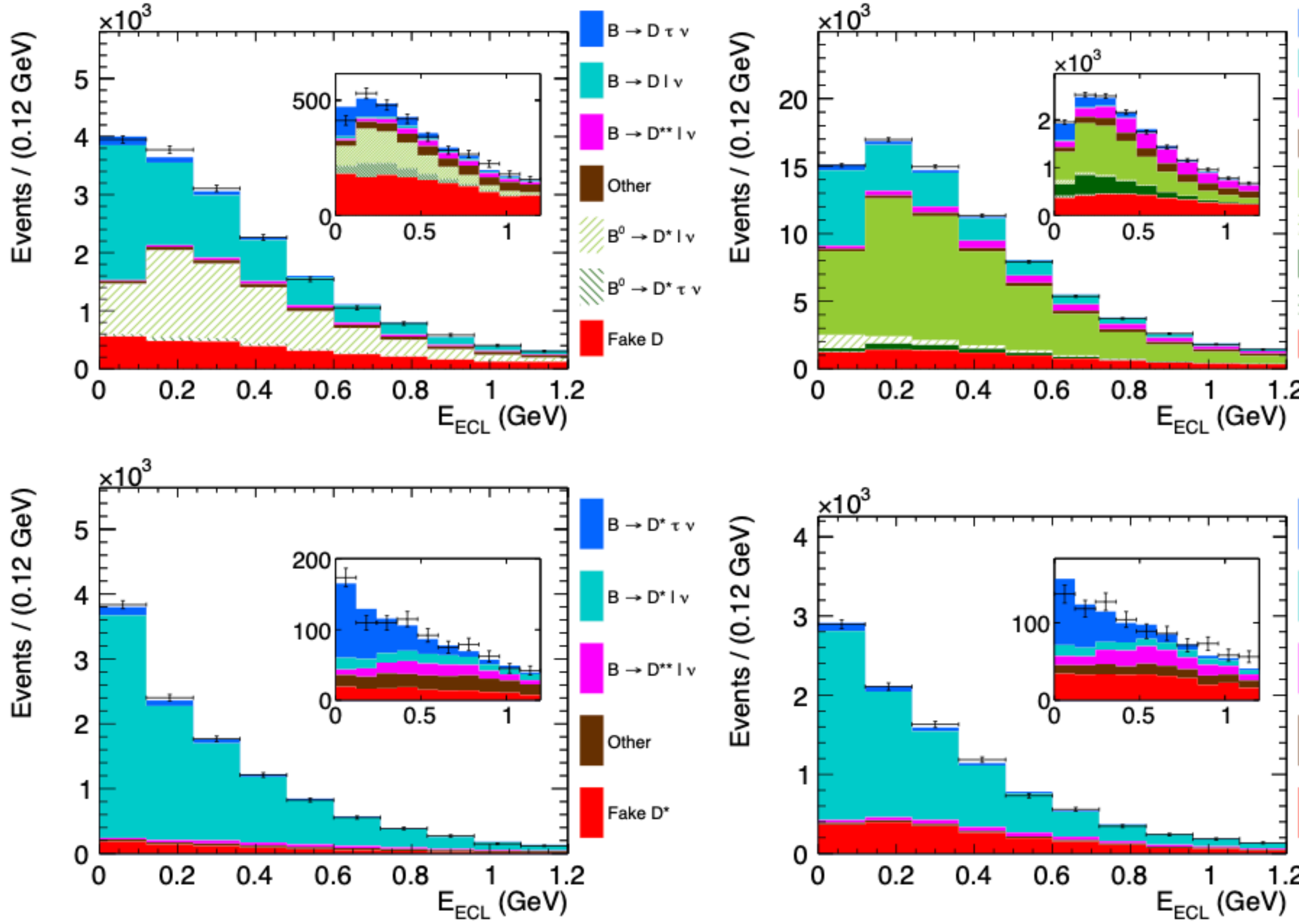
- Separate well reconstructed B_{tag} candidates with $cos\theta_{B,D^*\ell} = \frac{2E_{beam}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2}{2|p_B||p_{D^{(*)}\ell}|}$
- Reconstruct signal side $D^*\ell$ using a list of D^0 and D^+ modes
- Suppress background events using E_{ECL}<1.2 GeV.
- Develop MVA to separate between signal and normalization from backgrounds based on variables such as m_{miss}^2 and E_{vis} .

Phys. Rev. Lett. **124**, 161803, 2020

R(D) and R(D*) with Semileptonic Tagging

- Extra signal and normalization yields from a fit O_{cls} and E_{ecl} in four samples: $D^{*+}\ell, D^{*0}\ell, D^{+}\ell, D^{0}\ell$
- Feed down from D*l to Dl sample is large and left free in the fit .
- Background yield from $B \to D^{(**)}\tau\nu$ is left free in the fit. Other backgrounds are fixed to their MC expectation.
- Fake D*: yield of fake or misreconstructed D* mesons, determined using sideband data.





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

Phys. Rev. Lett. **124**, 161803, 2020

R(D) and R(D*) with Semileptonic Tagging

- Leading uncertainties
  - Limited MC sample size:
    - PDF shapes in the final fit
    - Efficiency ratio of signal to normalization events
    - Reconstruction efficiency of feed down yield.
  - Limited knowledge of $B \to D^{(**)}\ell\nu$ branching fractions

$$R(D^*) = 0.283 \pm 0.018 \pm 0.014$$
$$R(D) = 0.307 \pm 0.037 \pm 0.016$$

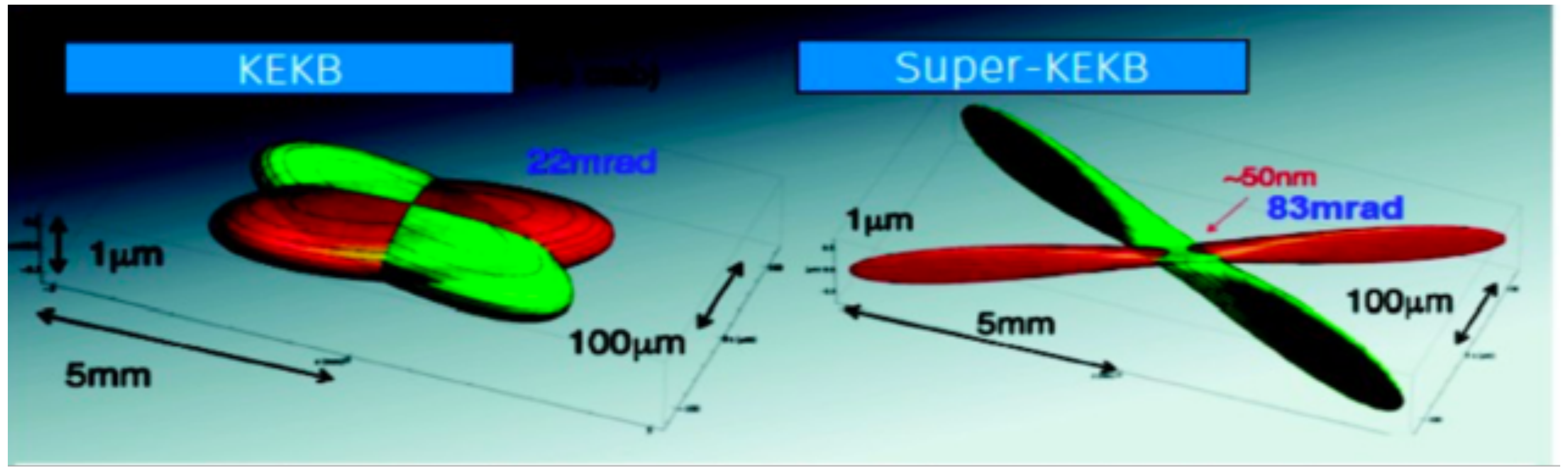
- Most precise measurement performed to date!
- In agreement with the SM within 0.2σ and 1.1σ.

Source	$\Delta\mathcal{R}(D)$ (%)	$\Delta\mathcal{R}(D^*)$ (%)	Correlation
D^{**} composition	0.76	1.41	−0.41
PDF shapes	4.39	2.25	−0.55
Feed-down factors	1.69	0.44	0.53
Efficiency factors	1.93	4.12	−0.57
Fake $D^{(*)}$ calibration	0.19	0.11	−0.76
B_{tag} calibration	0.07	0.05	−0.76
Lepton efficiency and fake rate	0.36	0.33	−0.83
Slow pion efficiency	0.08	0.08	−0.98
B decay form factors	0.55	0.28	−0.60
Luminosity, f^{+-}, f^{00} and $\mathcal{B}(\Upsilon(4S))$	0.10	0.04	−0.58
$\mathcal{B}(B \to D^{(*)}\ell\nu)$	0.05	0.02	−0.69
$\mathcal{B}(D)$	0.35	0.13	−0.65
$\mathcal{B}(D^*)$	0.04	0.02	−0.51
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.15	0.14	−0.11
Total	5.21	4.94	−0.52

Belle II

Belle II experiment

- Luminosity projected to be 30 x larger than that of Belle.
  - 20x smaller vertical beam size.
  - 1.5 x beam current.



- Improvements the Belle II detector :

Central beam pipe: decreased diameter from 3cm to 2cm (Beryllium)

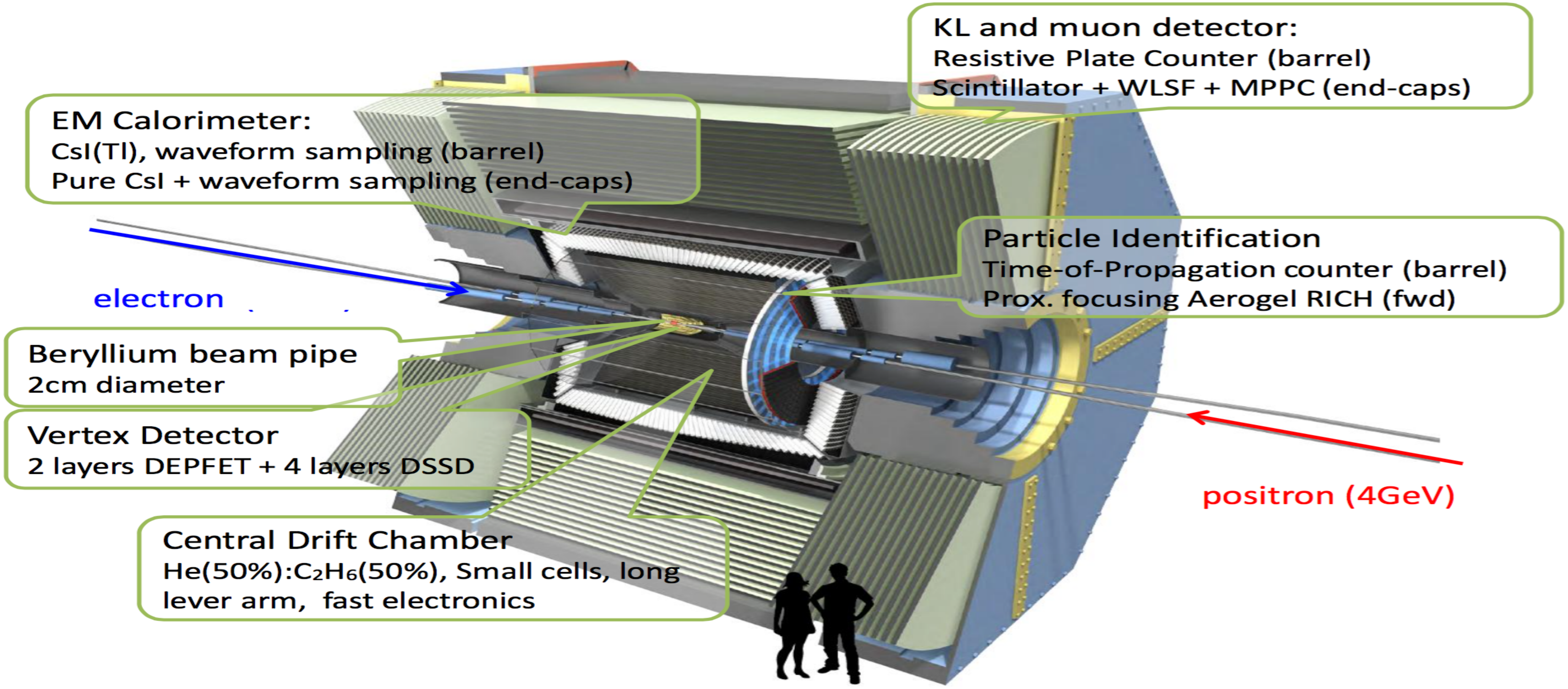
Vertexing: new 2 layers of pixels, upgraded 4 double-sided layers of silicon strips

Tracking: drift chamber with smaller cells, longer lever arm, faster electronics

PID: new time-of-flight (barrel) and proximity focusing aerogel (endcap) Cherenkov detectors

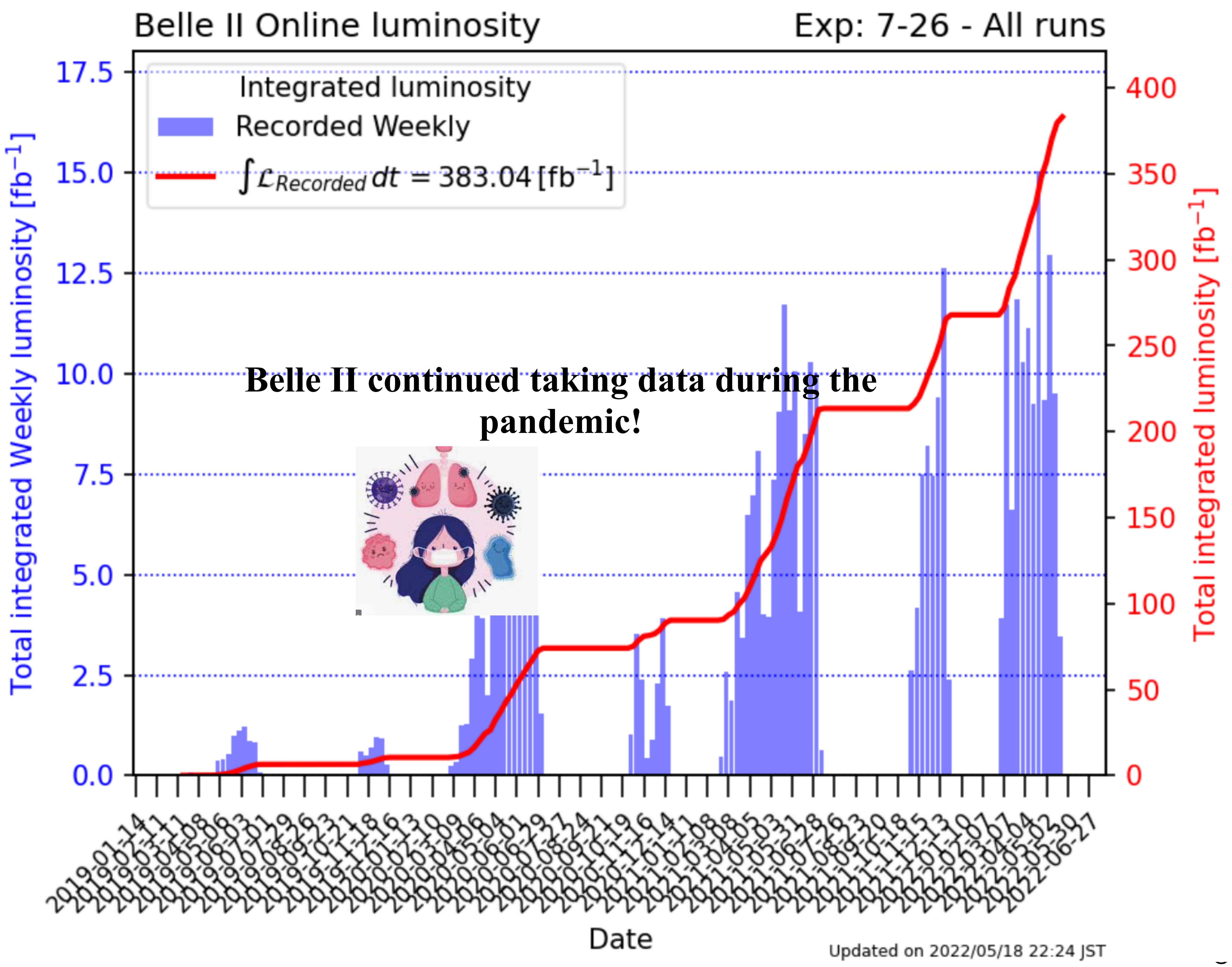
EM calorimetry: upgrade of electronics and processing with legacy CsI(Tl) crystals

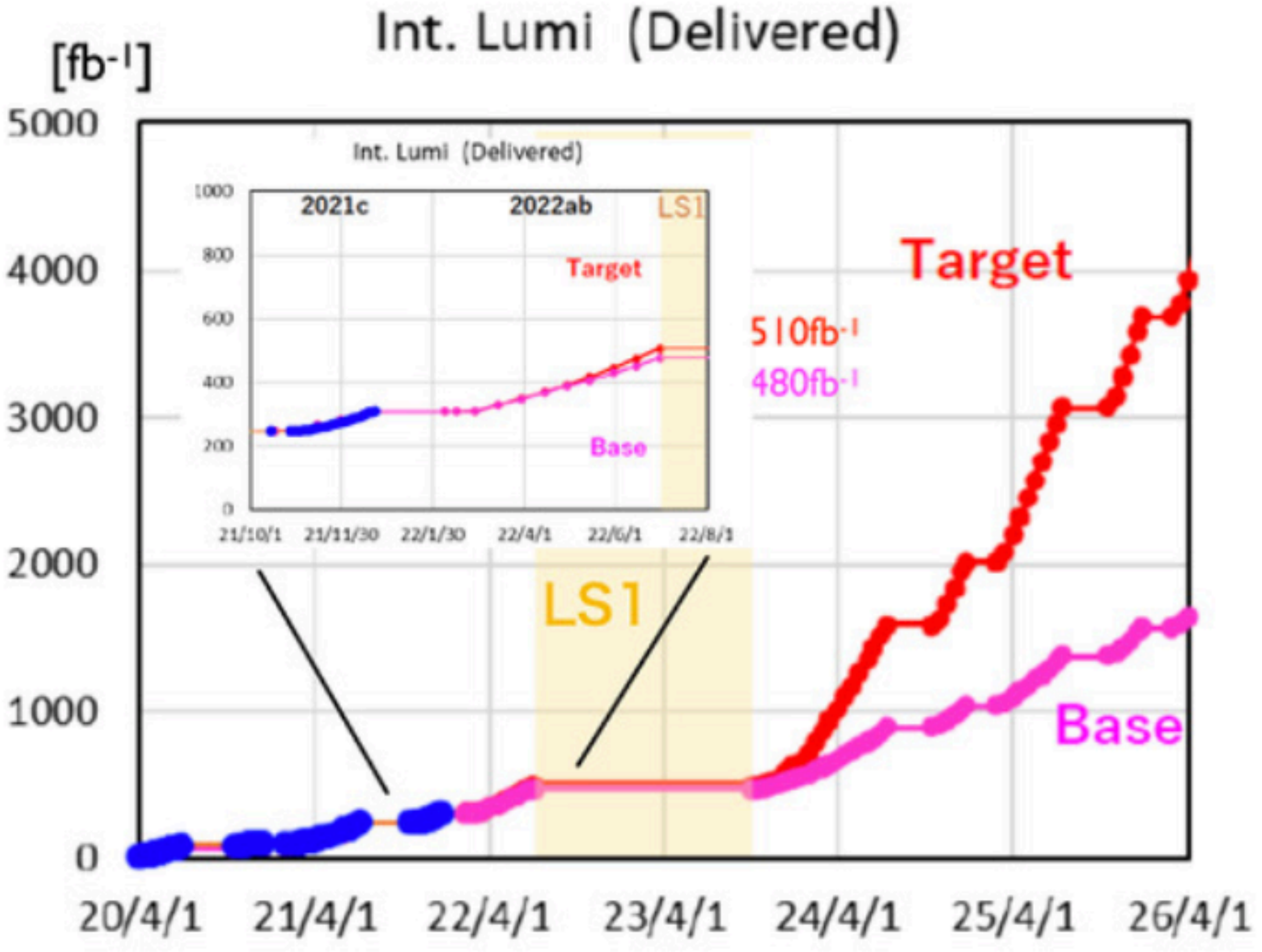
K_L and μ: scintillators replace RPCs (endcap and inner two layers of barrel)



Belle II dataset

- Belle II started data-taking in March 2019 and has now collected ~380 fb-1.



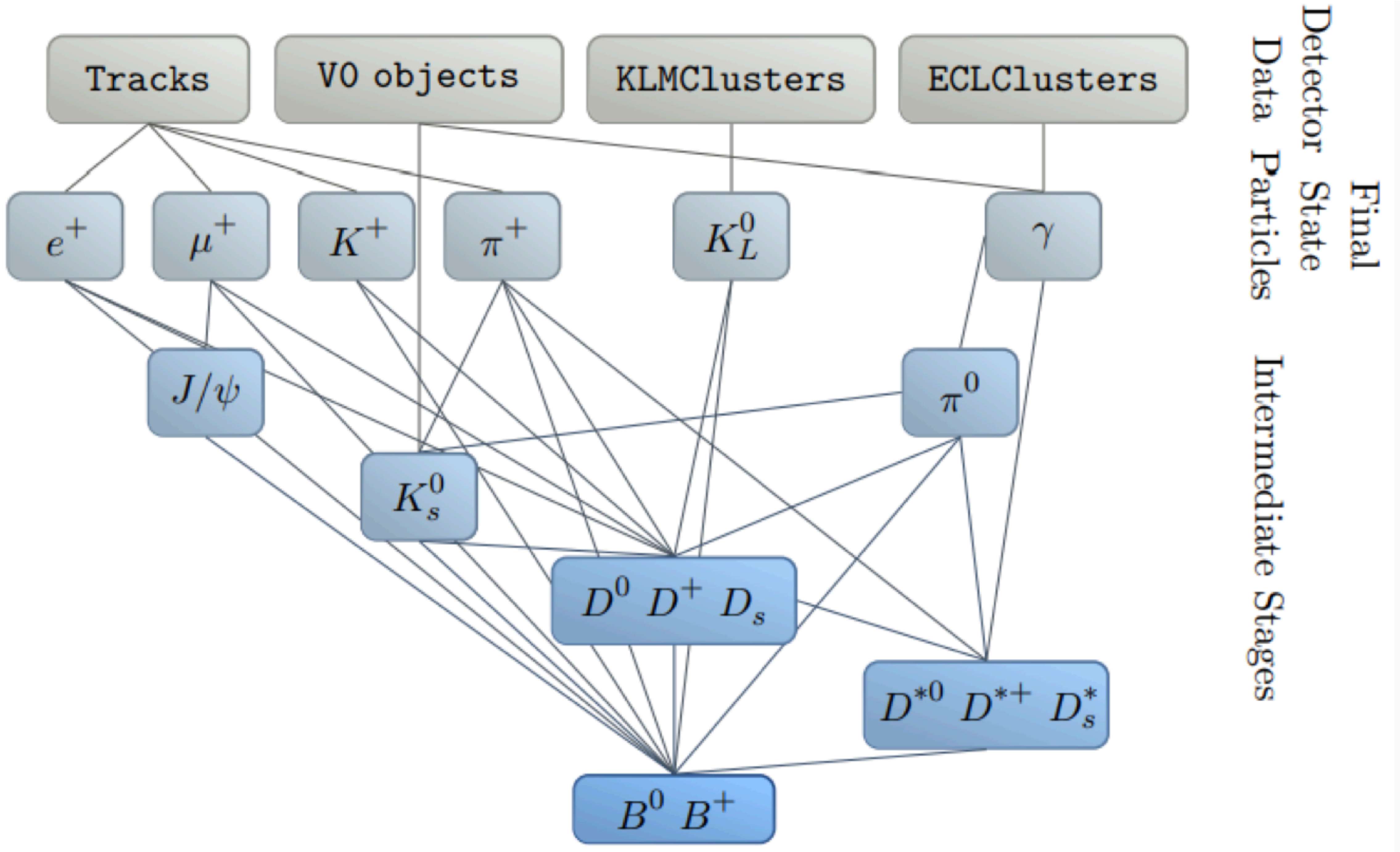


- Belle II will collect up to 510 fb^{-1} before its first shutdown .
- Plan to confirm the current *B*-anomalies, R(D) and R(D*), and to present first novel results R(X).

Preparing the toolkit

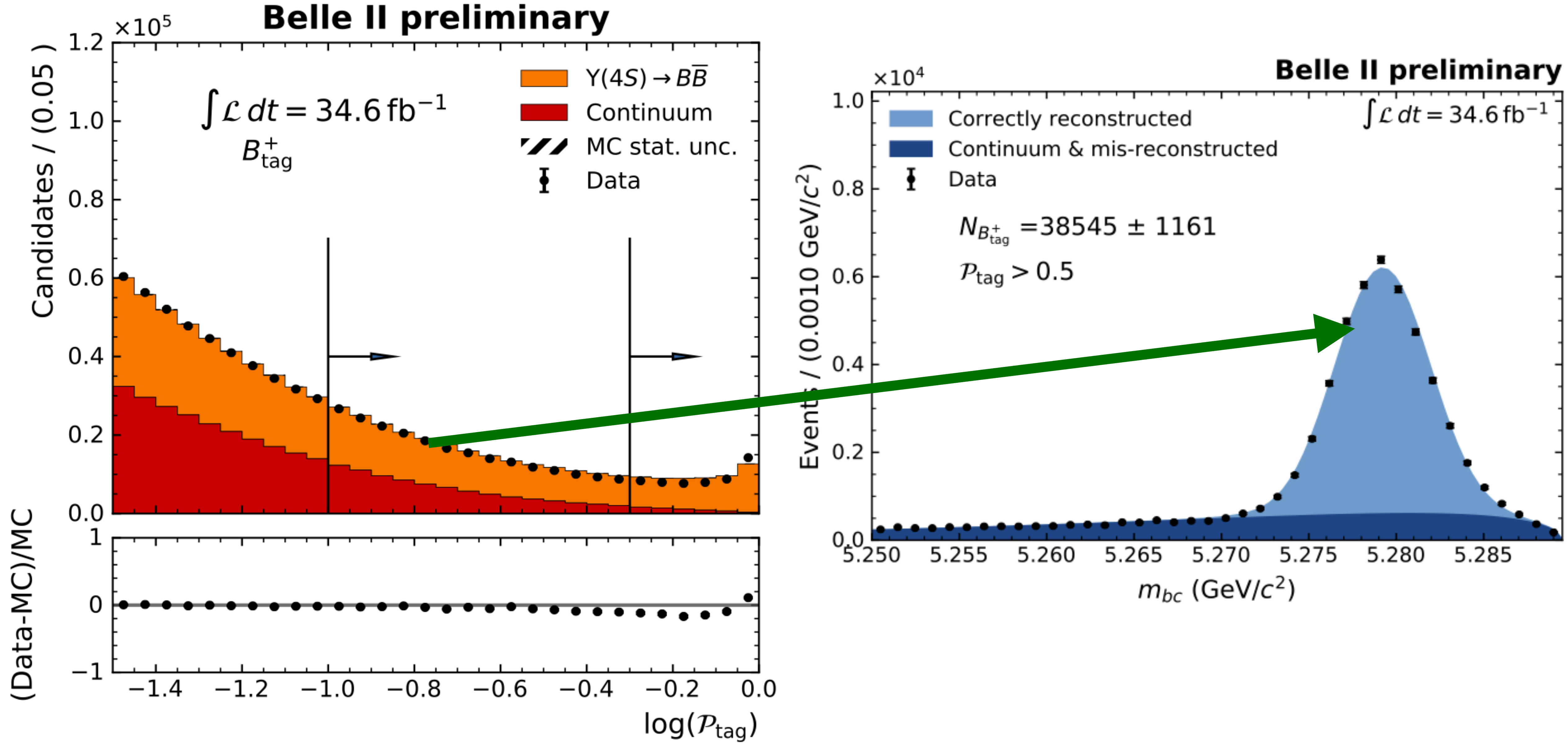
B-tagging at Belle II

- Exclusive reconstruction of B mesons using hadronic and semi-leptonic modes.
- Achieved using the Full Event Interpretation (FEI), a multivariate algorithm based on a hierarchal approach.



- Employs over 200 Boosted Decision Trees to reconstruct ~10000 B decay chains.

- Outputs a signal probability which separates correctly reconstructed B mesons.



- 30-50% improvement in efficiency compared to Full Reconstruction at Belle.

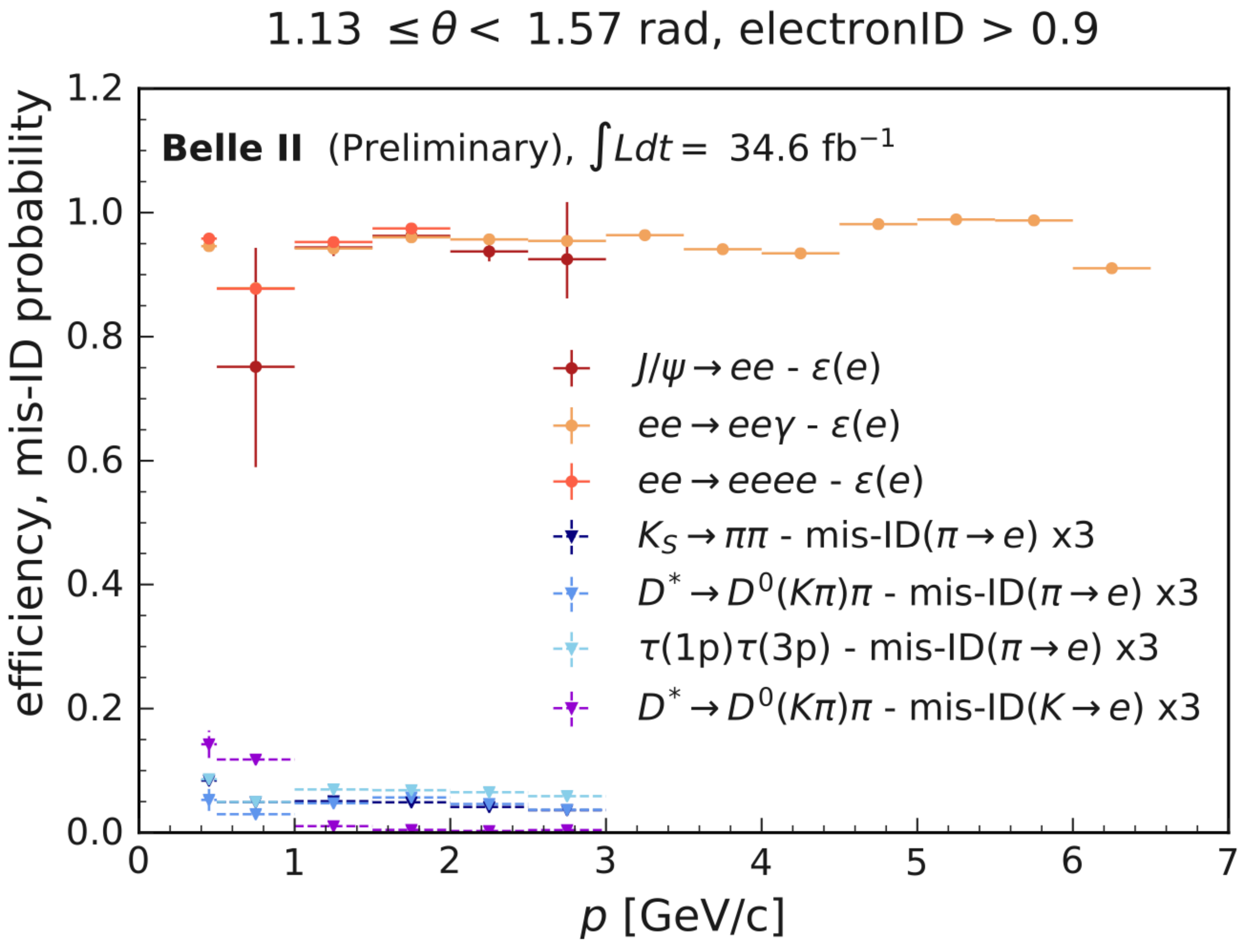
	B$^\pm$	B^0
Hadronic		
FEI with FR channels	0.53 %	0.33 %
FEI	0.76 %	0.46 %
FR	0.28 %	0.18 %
SER	0.4 %	0.2 %

	B$^\pm$	B^0
Semileptonic		
FEI	1.80 %	2.04 %
FR	0.31 %	0.34 %
SER	0.3 %	0.6 %

Comp. Softw. Big. Sci. 3 (2019)

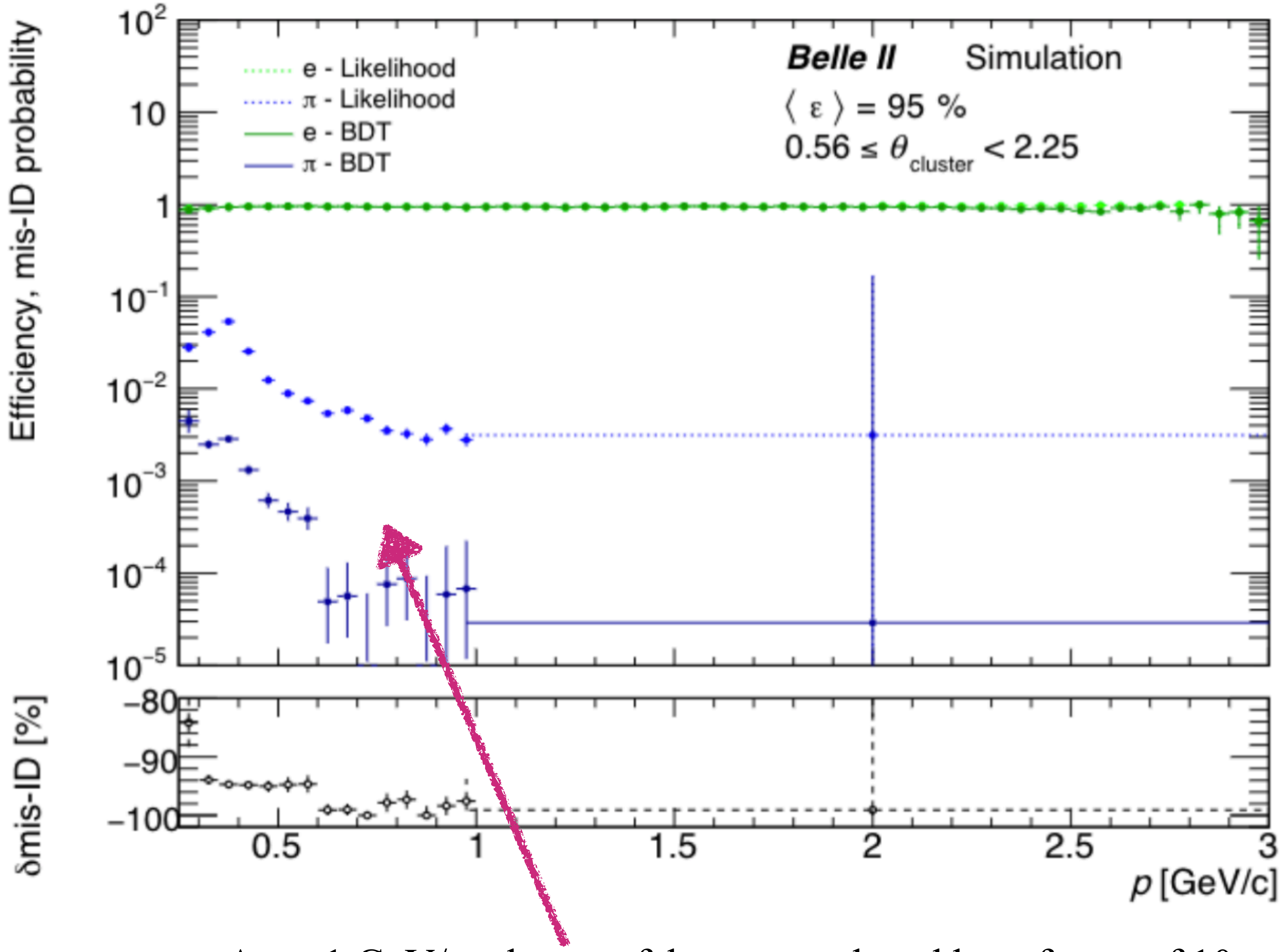
Lepton Identification

- Belle II has global particle identification based on almost all detector subsystem inputs.
- PID performance and fake rate evaluated in bins of the polar angle using standard candle processes.



e.g. electron efficiency of 94% and pion misID at 2% for $\mathscr{L} > 0.9$

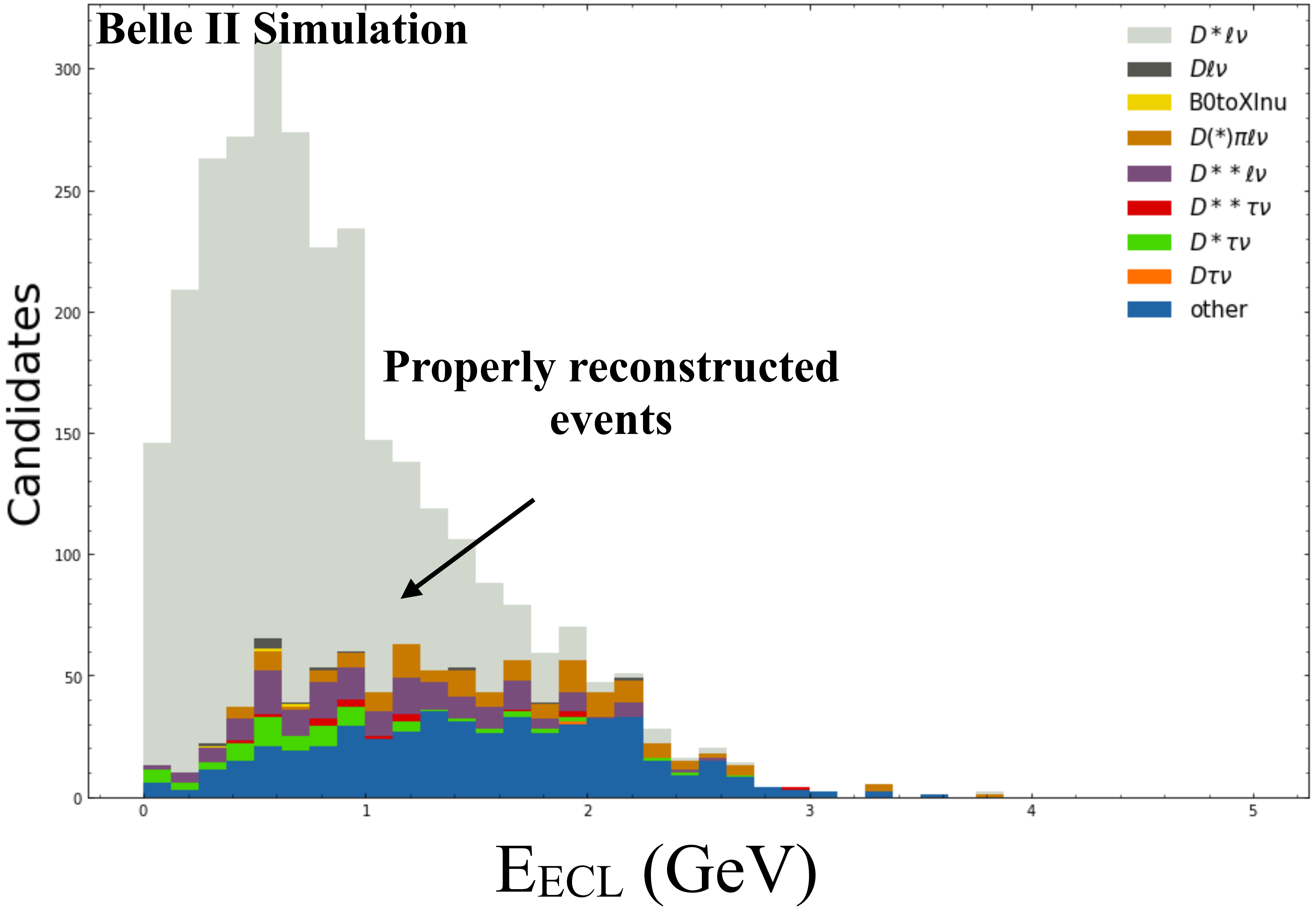
- Fake rates improved for low momenta using Boosted Decision Tree PID with ECL shower shape variables to separate between lepton and hadrons.

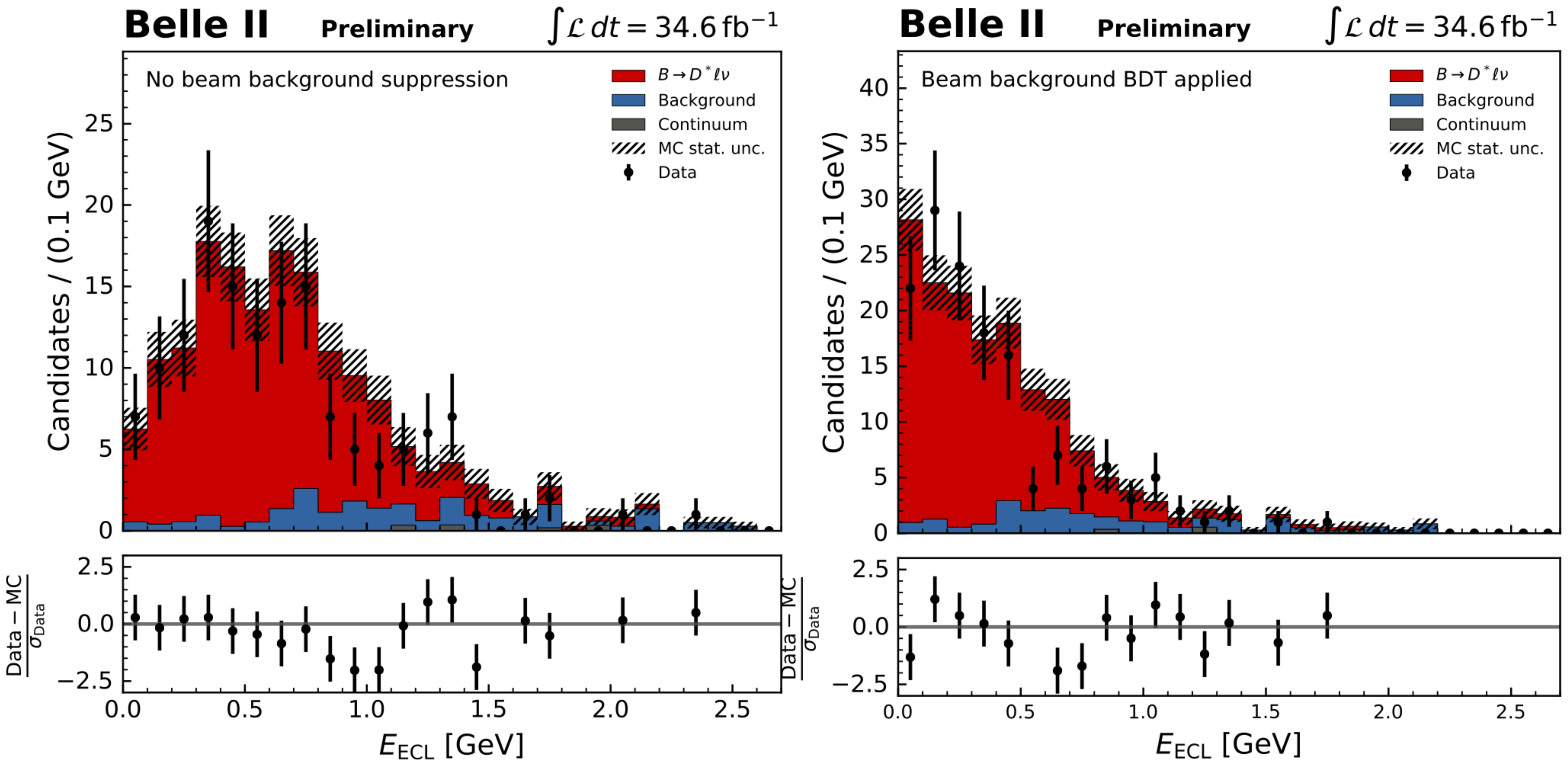


At p<1 GeV/c, electron fake rates reduced by a factor of 10.

E_{ECL}

- E_{ECL} is a key variable for many semi-leptonic and missing energy analyses, specifically $B \to D^* \tau \nu_\tau$.





Develop a multi-variate algorithm (BDT) to suppress beam background and fake photon or hadronic shower split-off contributions.

- Different contributions to E_{ECL} :
  - Mis-reconstructed candidates
  - Hadronic split-offs
  - Beam background contributions

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

- One of the high priority analyses for Belle II.

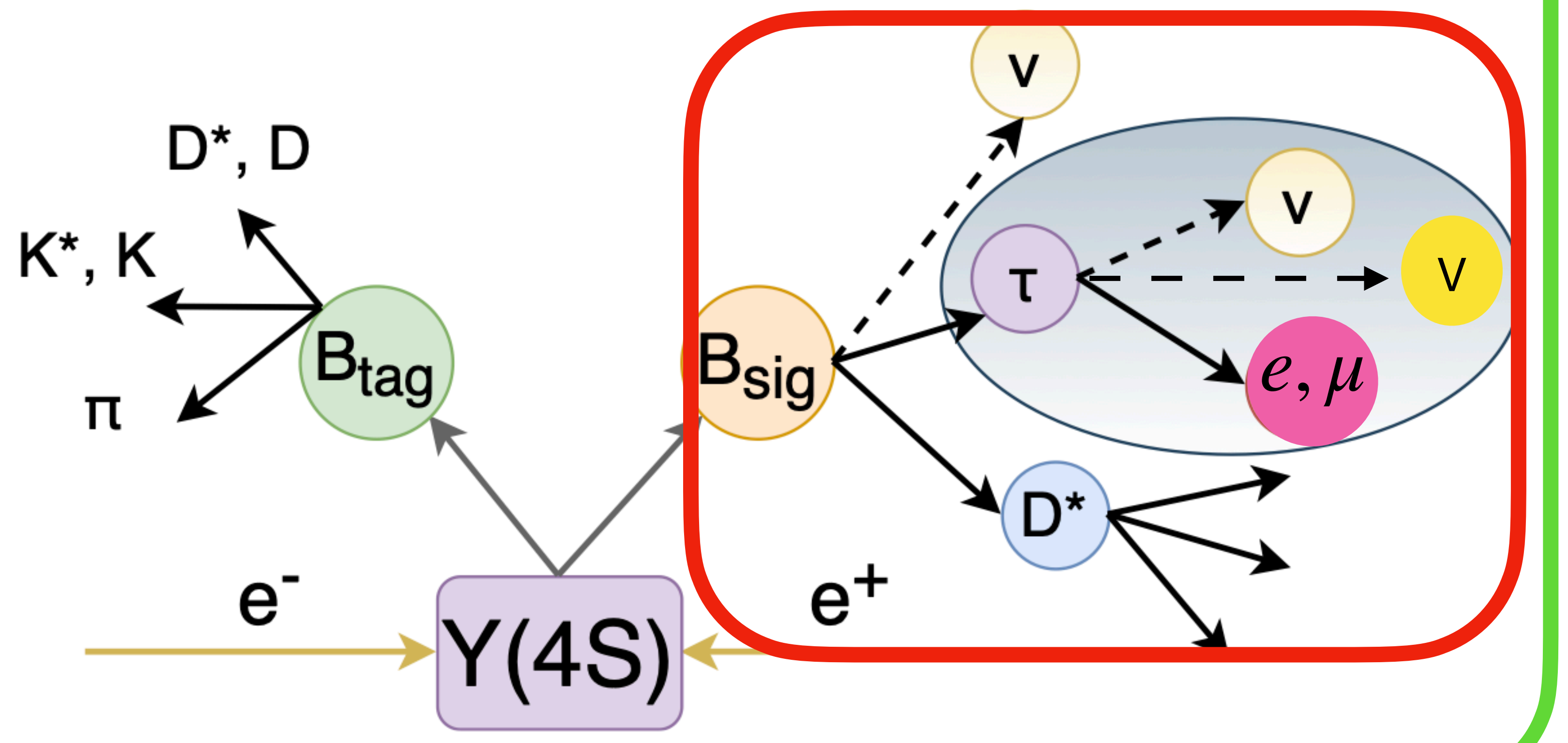
$$R(D) = \frac{\mathscr{B}(\bar{B} \to D^+\tau^-\bar{\nu}_\tau)}{\mathscr{B}(\bar{B} \to D^+\ell^-\bar{\nu}_\ell)} \quad \text{and} \quad R(D^*) = \frac{\mathscr{B}(\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathscr{B}(\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell)}$$

→ **Measure branching fraction of normalization mode to test Belle II data and analysis's chain.**

- 3 ongoing measurements planned before the long shut down of Belle II planned in 2022-2023:

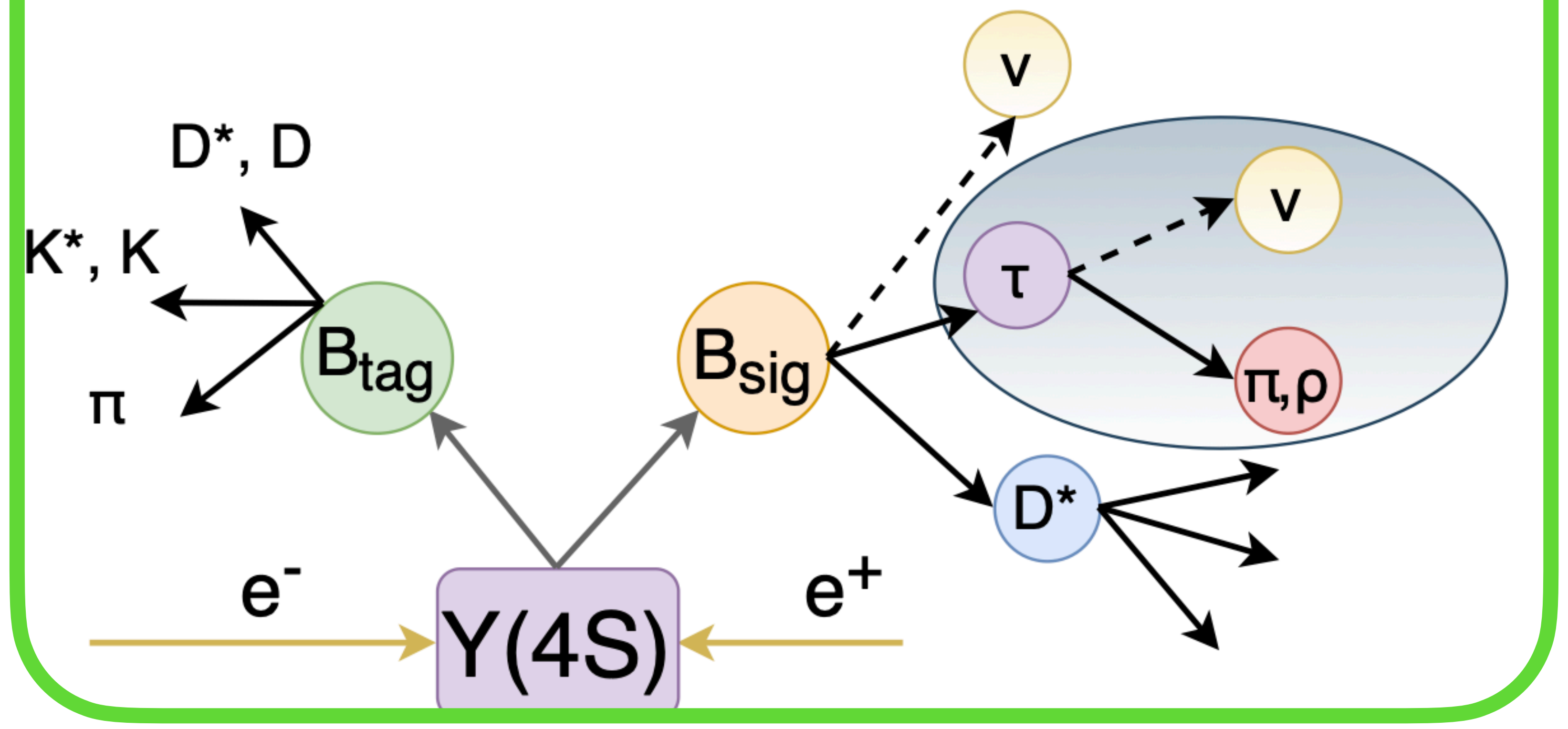
Hadronic Tagging

Leptonic tau: $\tau \to e\nu_\tau\nu_e$ **and** $\tau \to \mu\nu_\tau\nu_\mu$



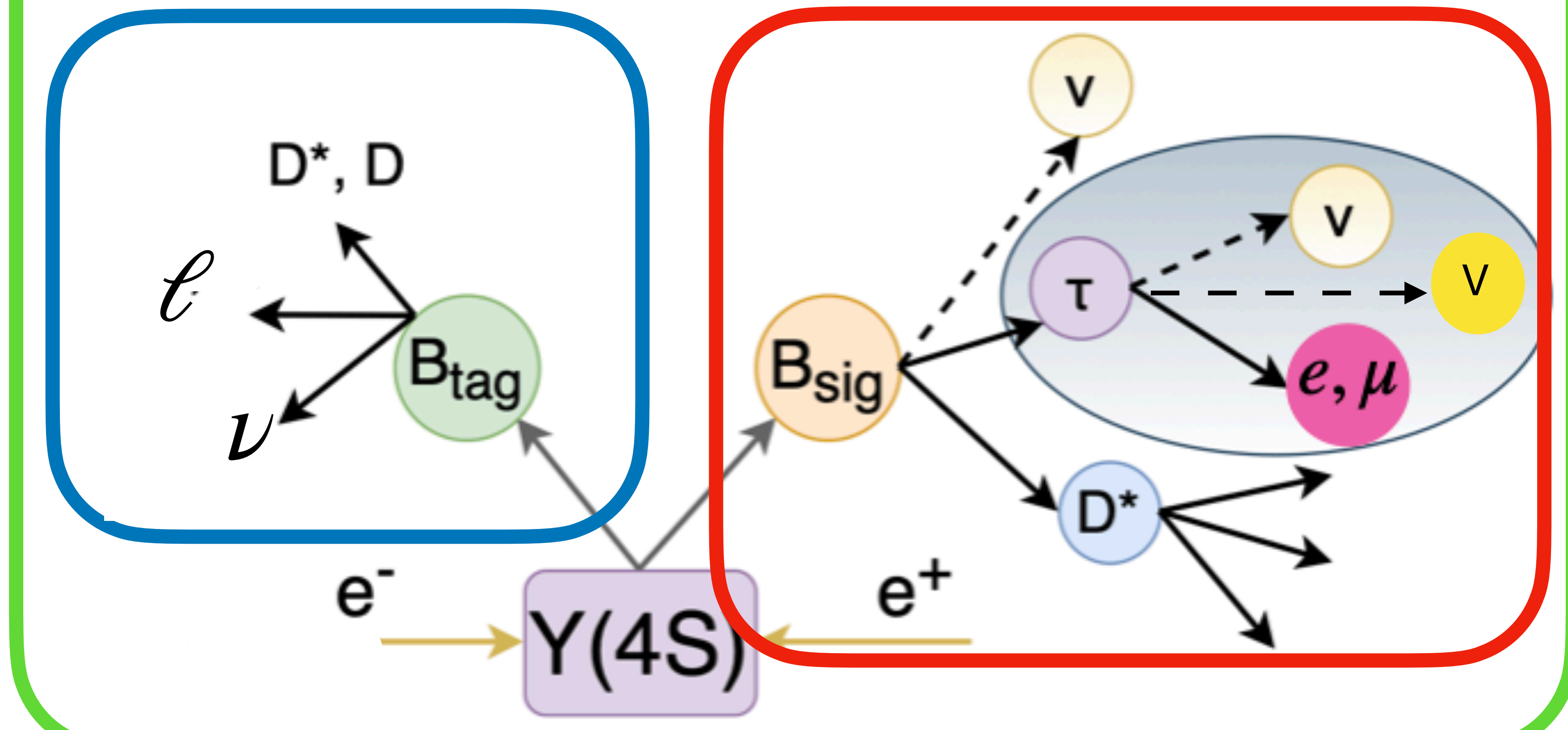
Hadronic Tagging

Hadronic tau: $\tau \to \rho, \pi\nu$



Semi-leptonic Tagging

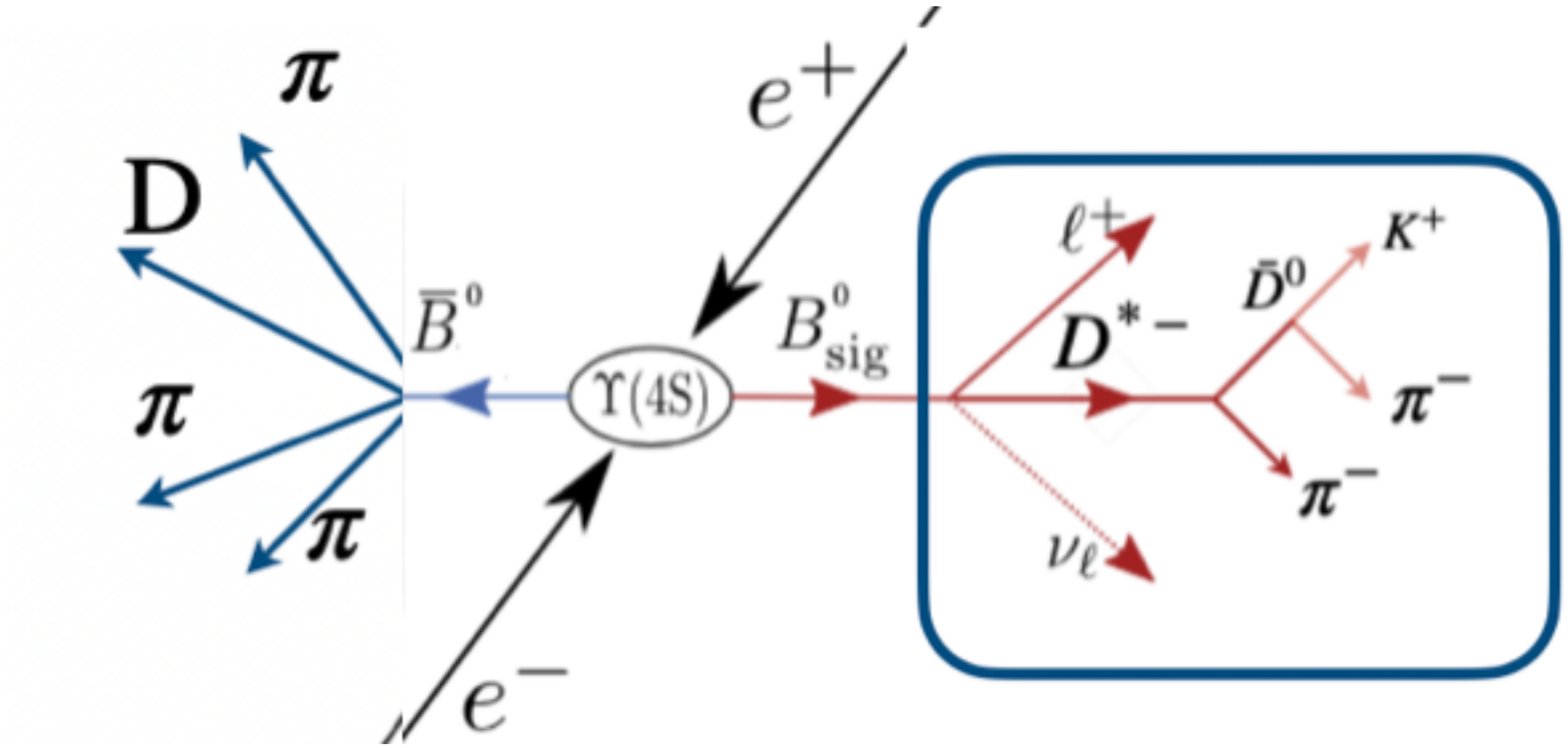
Leptonic tau: $\tau \to e\nu_\tau\nu_e$ **and** $\tau \to \mu\nu_\tau\nu_u$



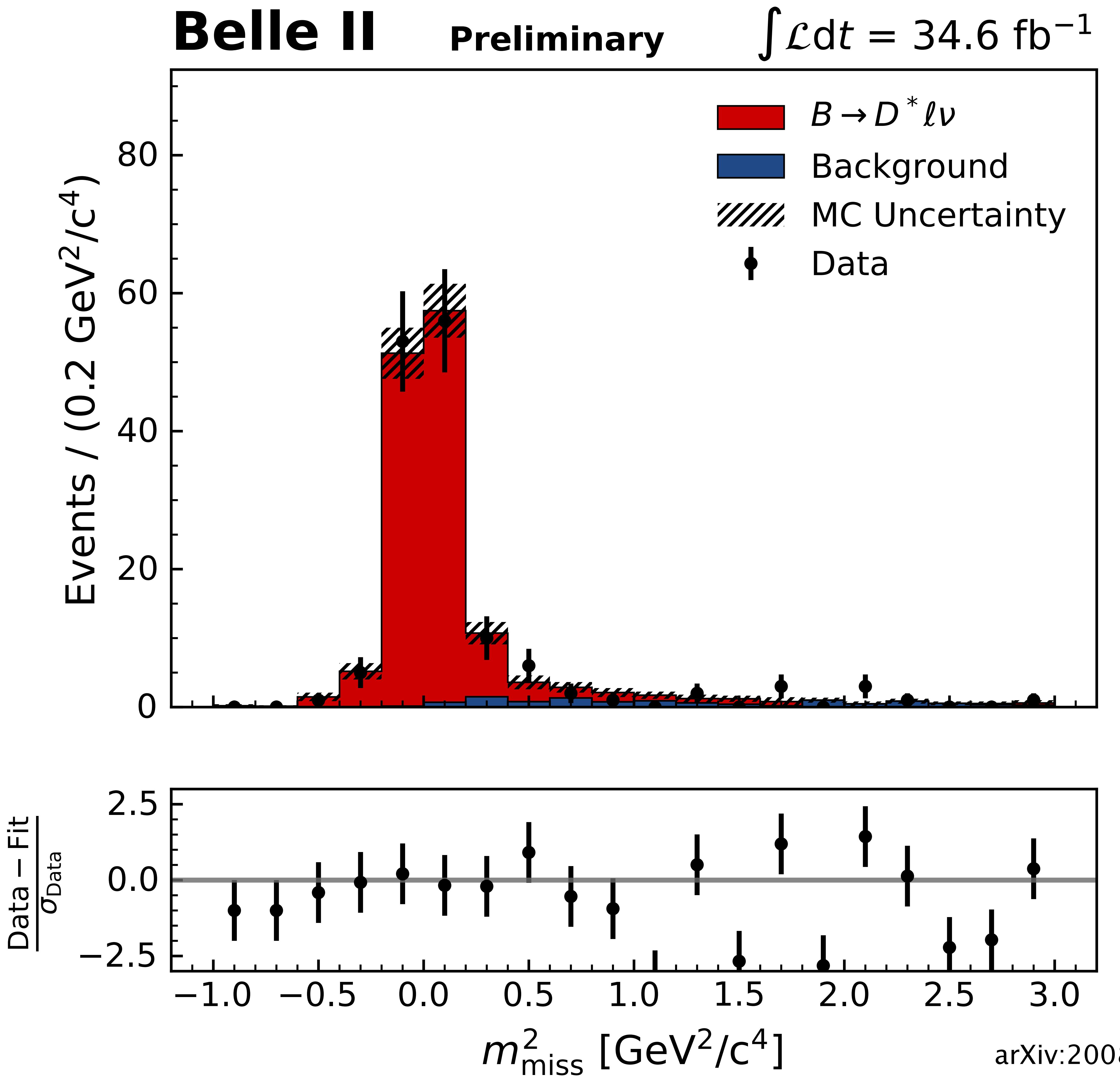
ν_ℓ

Initial plan: confirm anomaly with ~0.5 ab⁻¹ of Belle II data.

Tagged Exclusive $B^0 \to D^{*+} \ell \nu_\ell$



$$m^2_{\text{miss}} = \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_\ell\right)^2$$



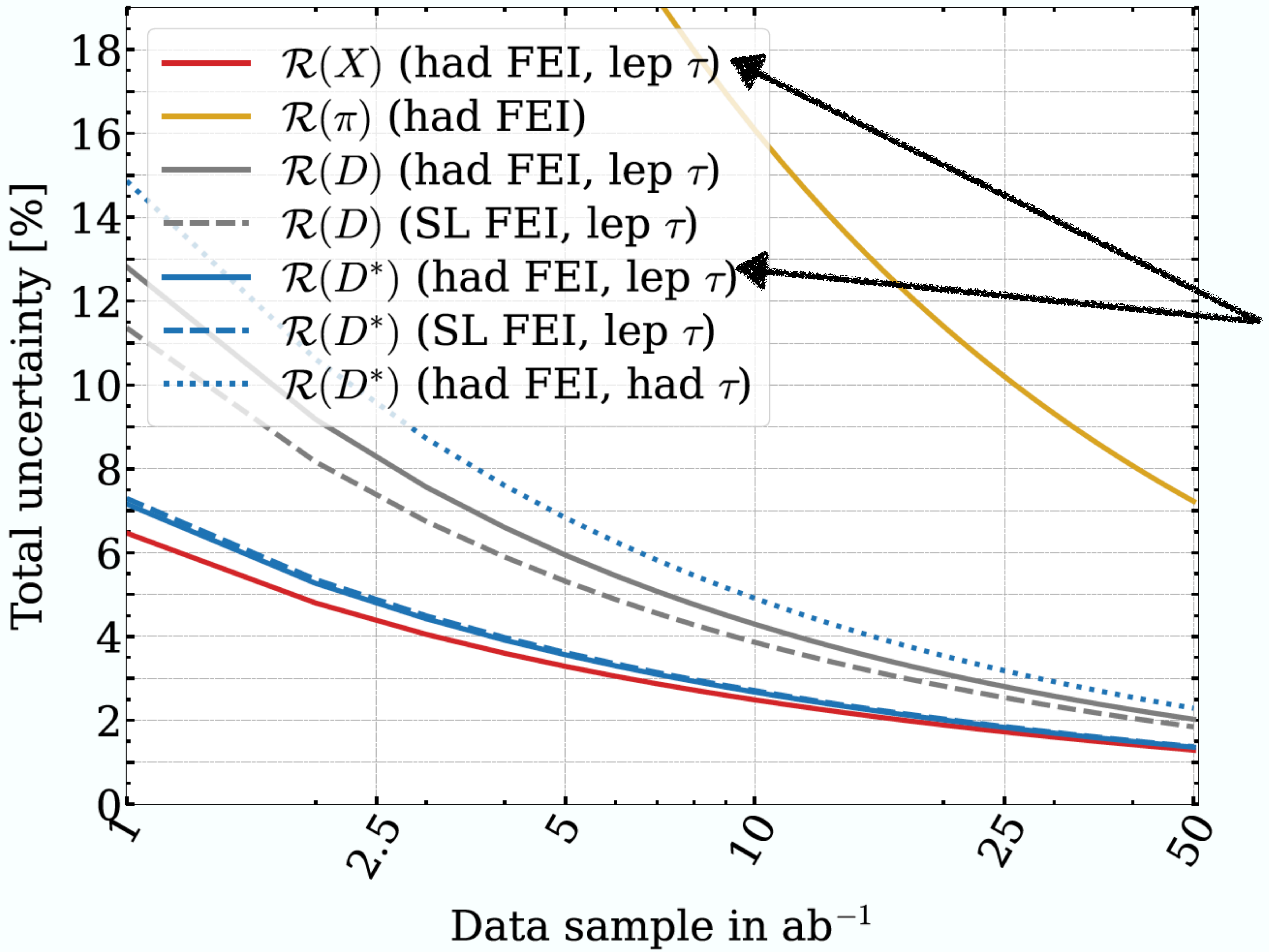
$$\mathscr{B}(\bar{B}^0 \to D^{*+}\ell\nu_\ell) = (4.51 \pm 0.41_{stat} \pm 0.27_{syst} \pm 0.45_{\pi_s})\,\%$$

In agreement with world average!

$$\mathscr{B}(\bar{B}^0 \to D^{*+}\ell\nu_\ell) = (5.05 \pm 0.14)\,\%$$

arXiv:2008.10299

Belle II Agenda



First results planned by Summer 2022.

Conclusion

- R(D) and R(D*) is a stringent test of Lepton Flavour Universality and a valuable portal for what lies beyond the SM.
- Future measurements planned:
  - LHCb: R(D), R(D*), R(J/ψ), R(Λ_c)
  - Belle II: R(D), R(D*), R(X)
  - BaBar: R(D) and R(D*) with semileptonic tagging (Talk by Yinxuan Li)
- Combined with angular analyses measurements of $B \to D^*\ell\nu$ and $B \to D^*\tau\nu$ decays, we should be zooming in on the New Physics if it is there.