Semi-leptonic and leptonic decays with τ at Belle II

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On behalf of the Belle II collaboration

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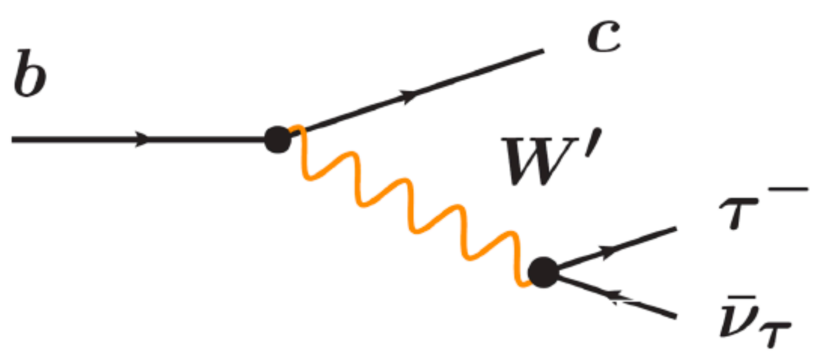
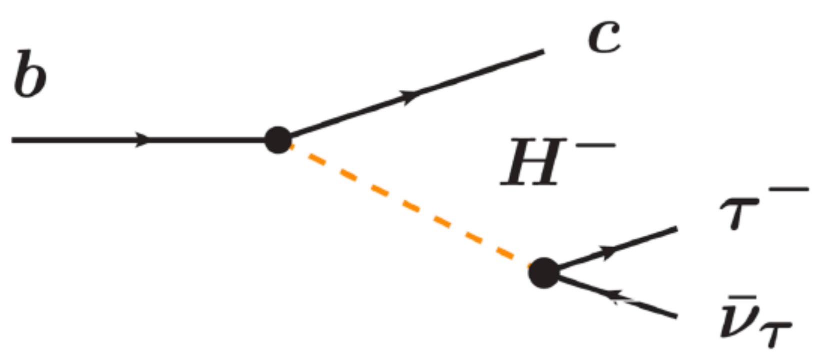
B-anomalies

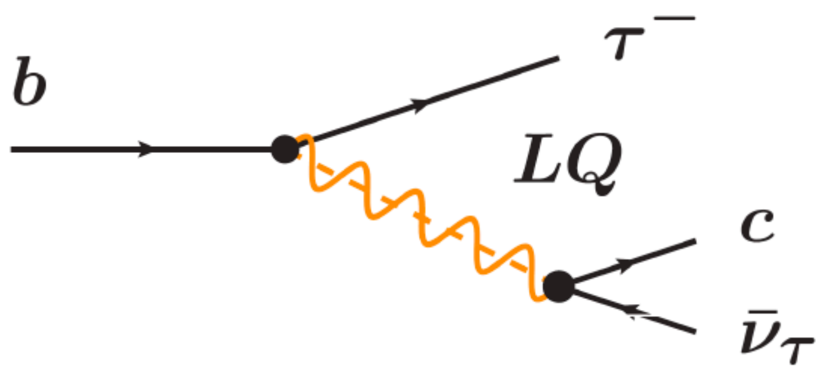
- Discrepancies with the Standard Model have been observed in multiple tests of lepton flavour universality.

R(D)-R(D*) : 3.1σ **R(K)-R(K*) : 3.1σ** etc..

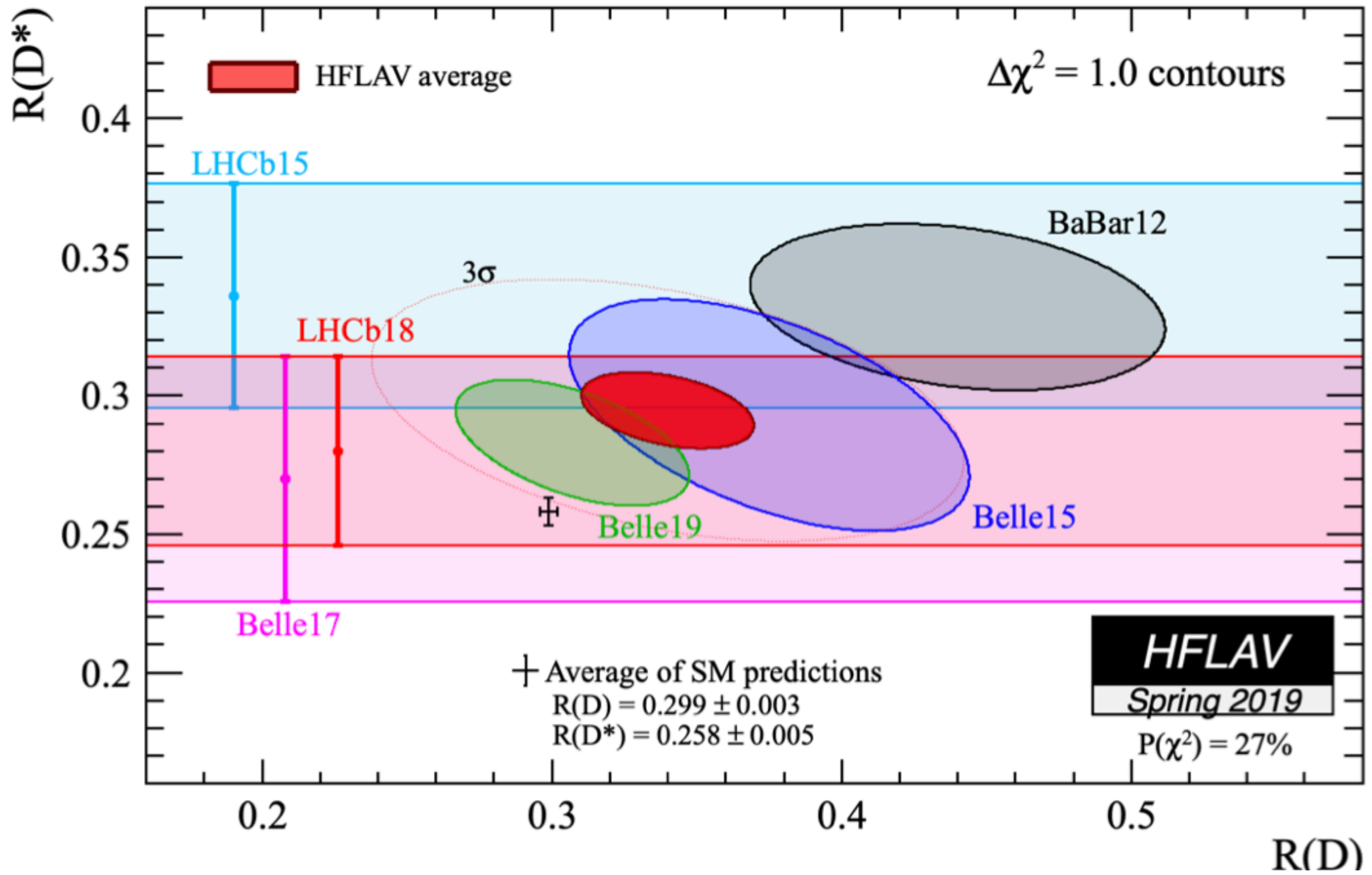
- Various new physics explanations have been hypothesized.

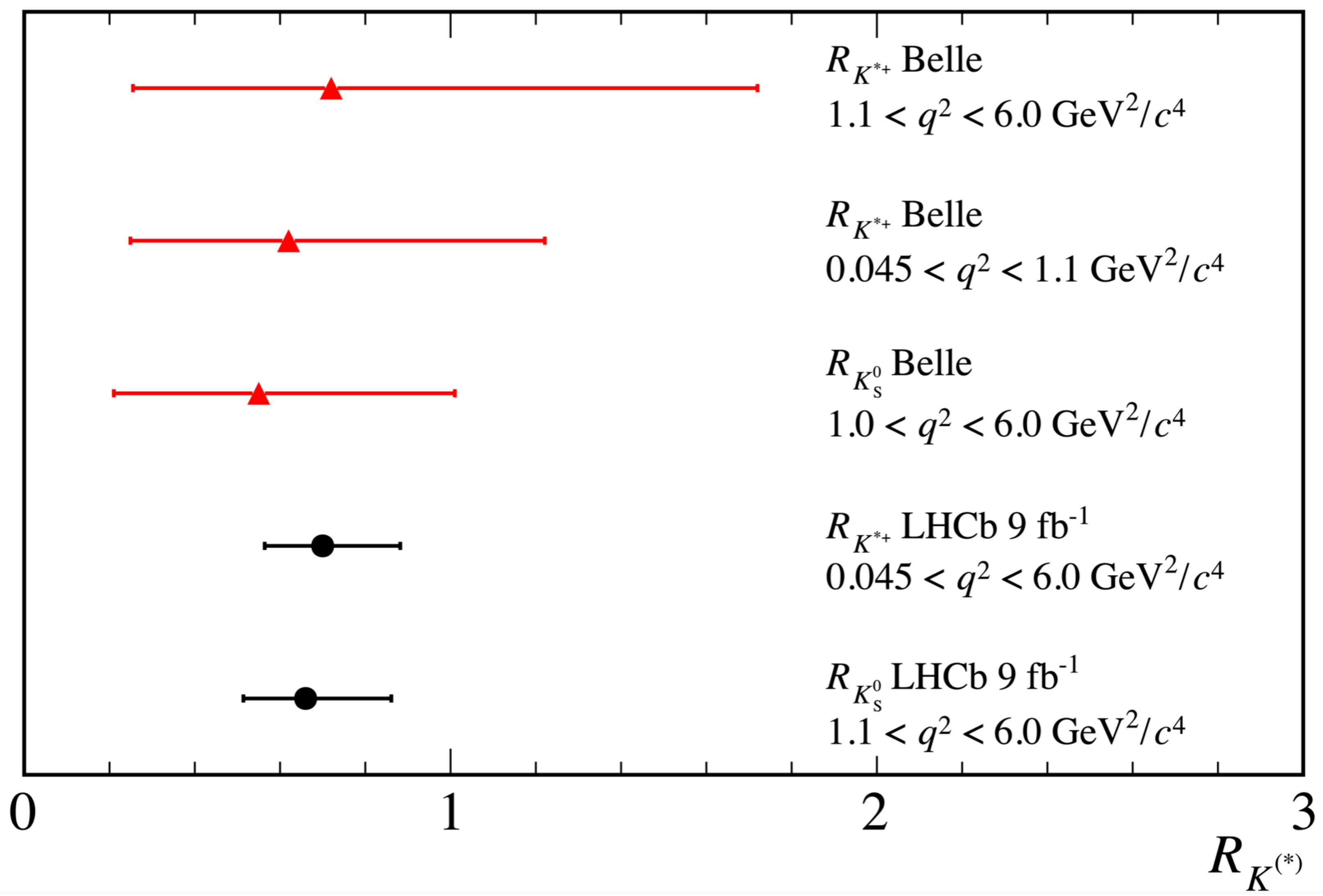






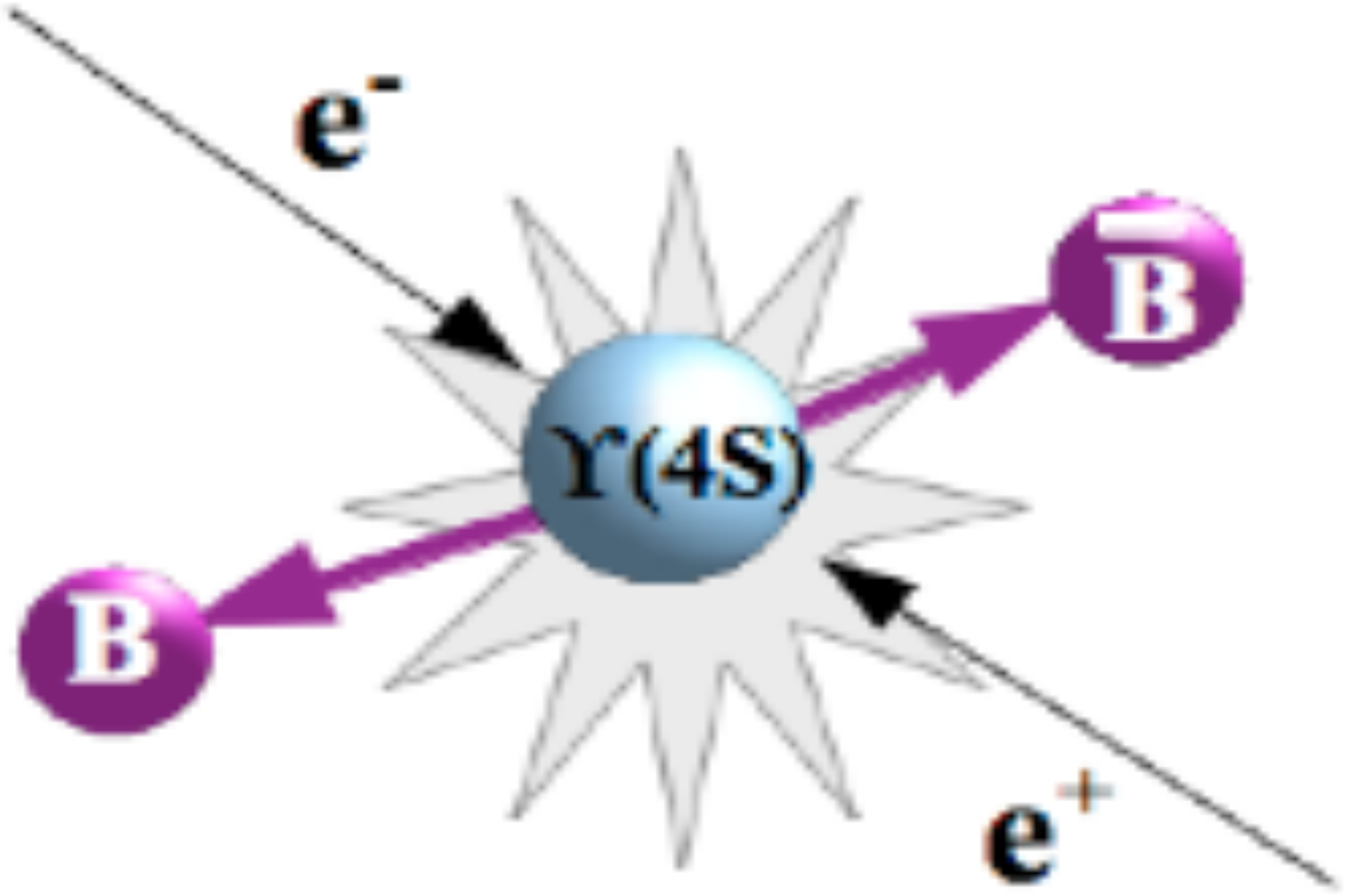
Semi-leptonic decays with tau prevail as an excellent avenue for what may lie beyond the SM.



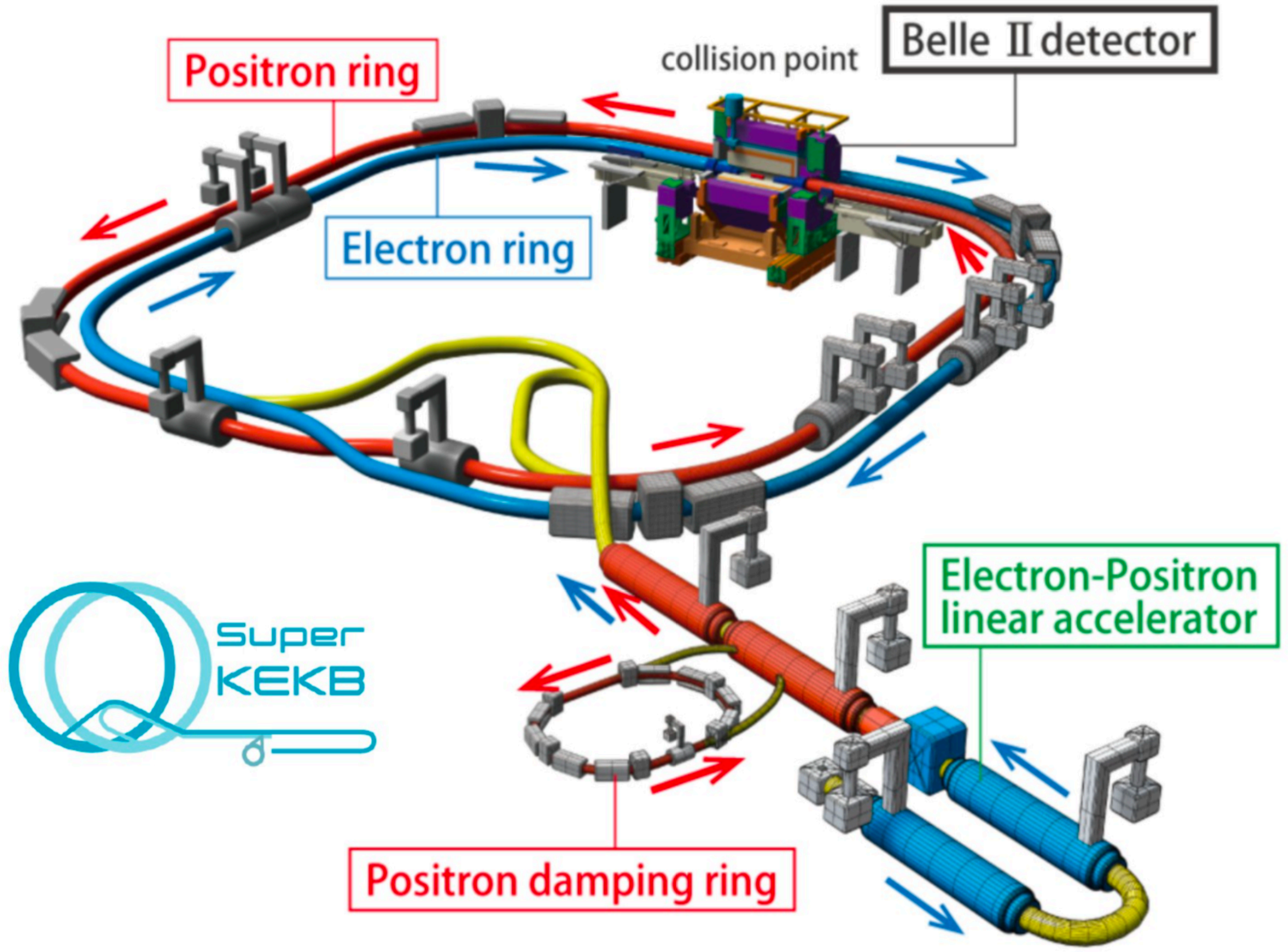


Belle II experiment

- A *B* meson factory in Tsukuba, Japan based on the SuperKEKB accelerator complex.
- Upgrade of its predecessor Belle at KEKB.



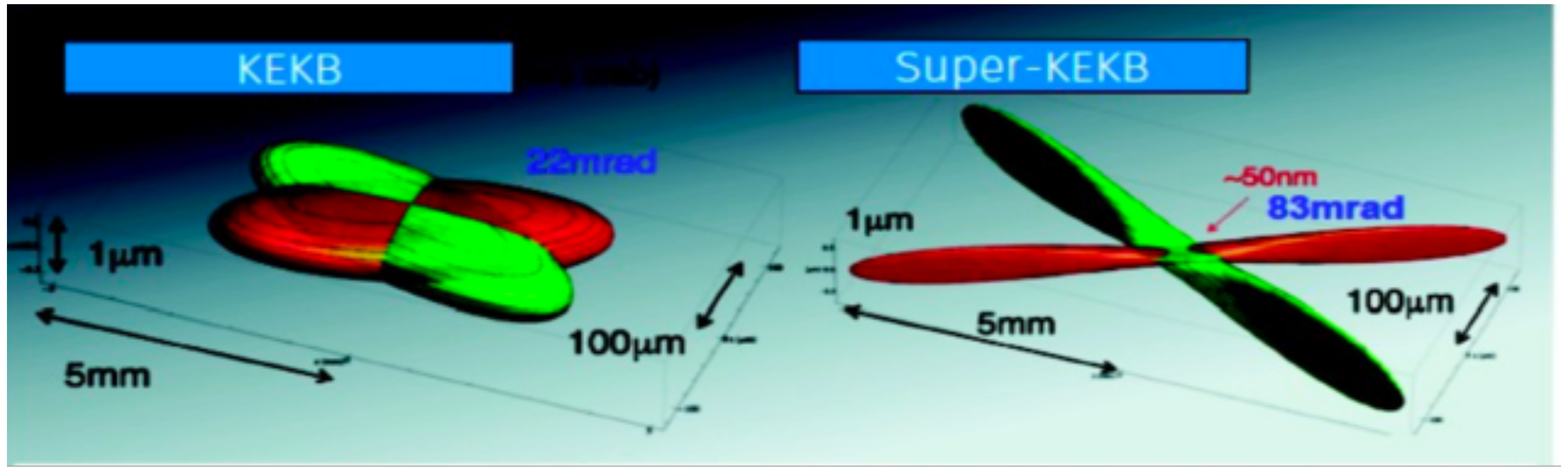
- Target luminosity: 50 ab^{-1}, 50 x the Belle dataset.
  - a (Super) *B*-factory (~1.1 x 10^9 $B\bar{B}$ pairs per ab^{-1})
  - a (Super) charm factory (~1.3 x 10^9 $c\bar{c}$ pairs per ab^{-1})
  - a (Super) τ factory (~0.9 x 10^9 $\tau\bar{\tau}$ pairs per ab^{-1})



- *B* physics:
  - CPV: $B \to J/\Psi K_s^0$, ϕK^0
  - Rare *B* decays: $B \to K\nu\bar{\nu}, K\tau\tau$
- Lepton flavour violation:
  - $\tau \to \mu\gamma$
- Charm Physics: *D* mixing

Belle II experiment

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



beam current

$$\mathcal{L} = \frac{\gamma_{e^\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{e^\pm}\xi_y^{e^\pm}}{\beta_y^{*e^\pm}}\left(\frac{R_L}{R_{\xi_y}}\right)$$

vertical beam size

- Improvements the Belle II detector :

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

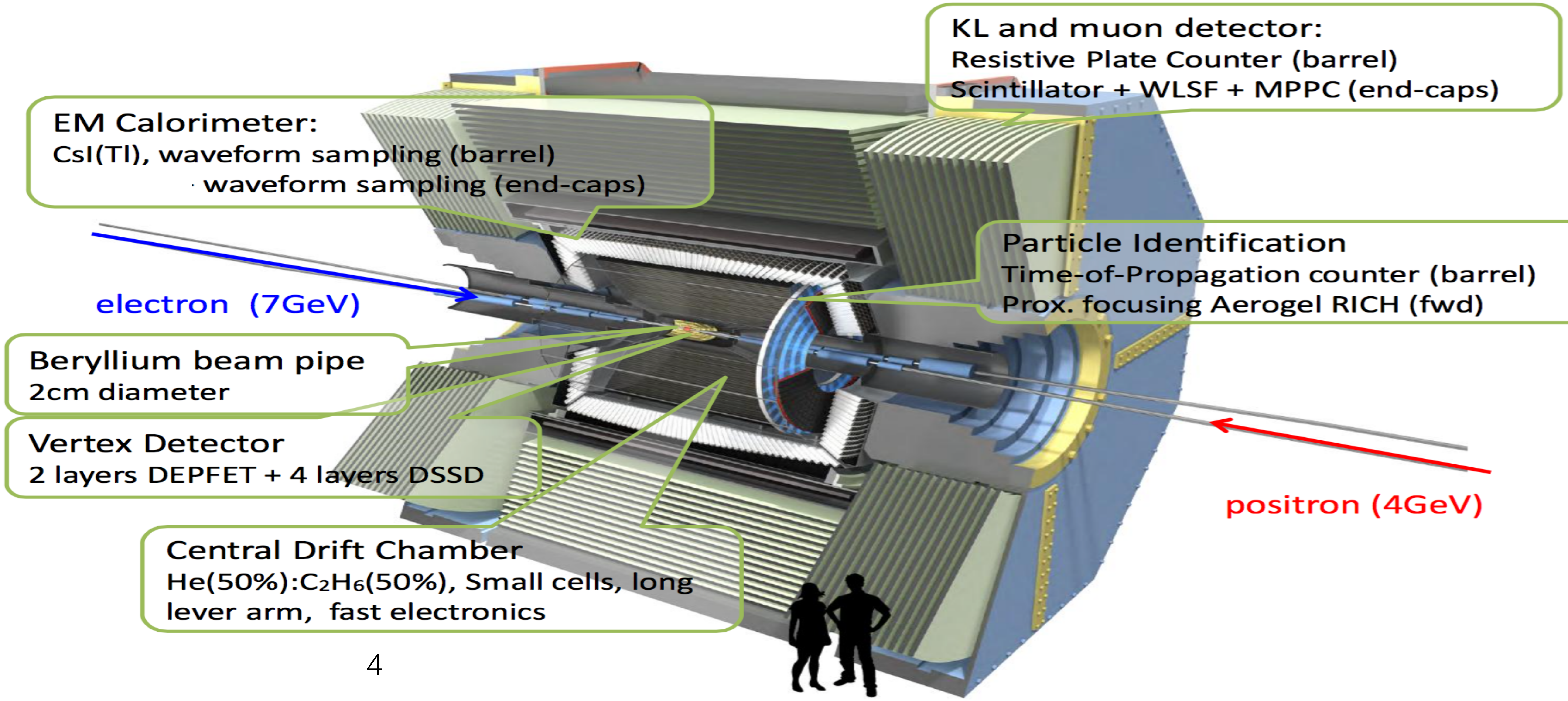
Vertexing: new 2 layers of pixels, upgraded 4 double-sided layers of silicon strips

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

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

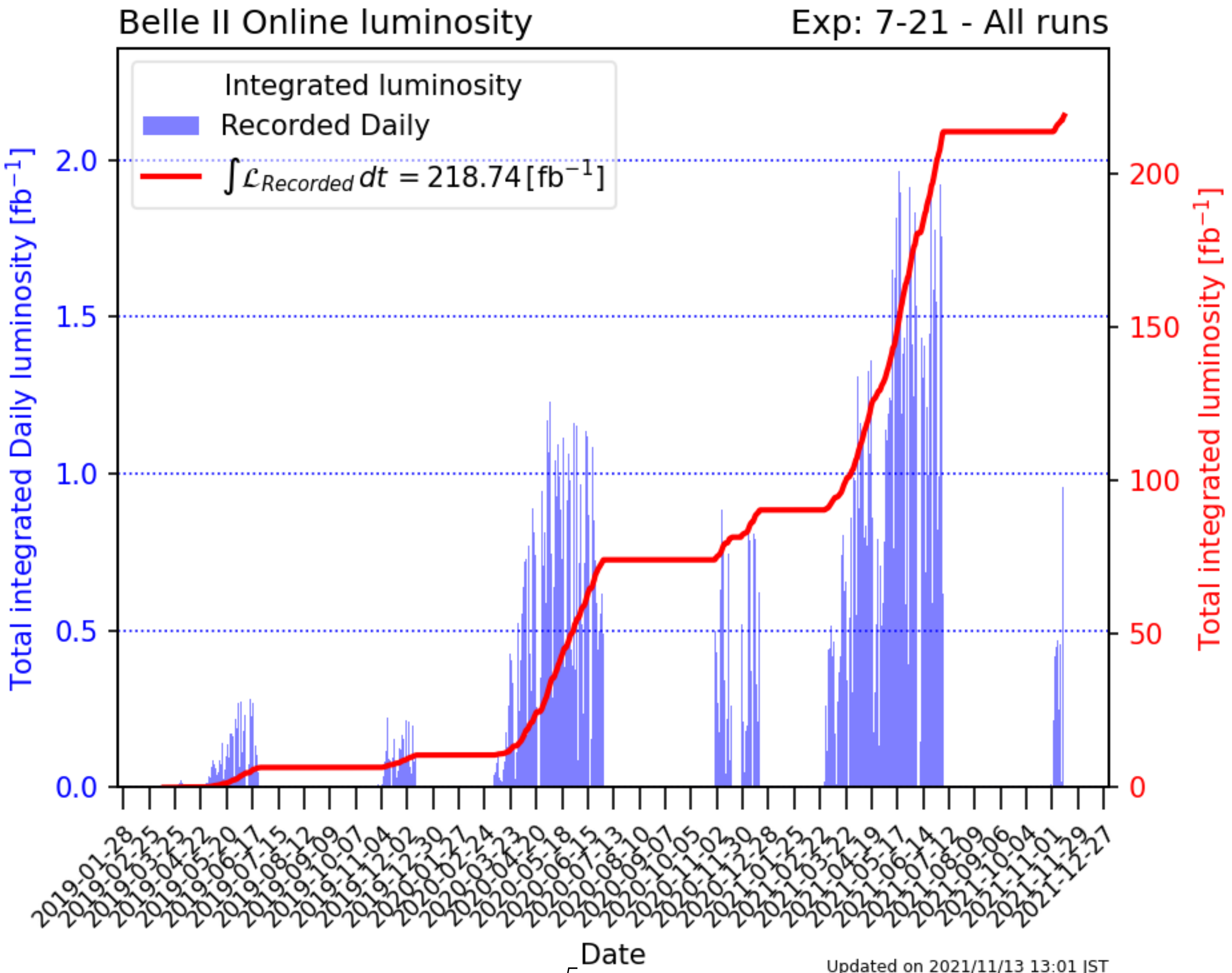
EM calorimetry: upgrade of electronics and processing with legacy CsI(Tl) crystals

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



Current Belle II dataset

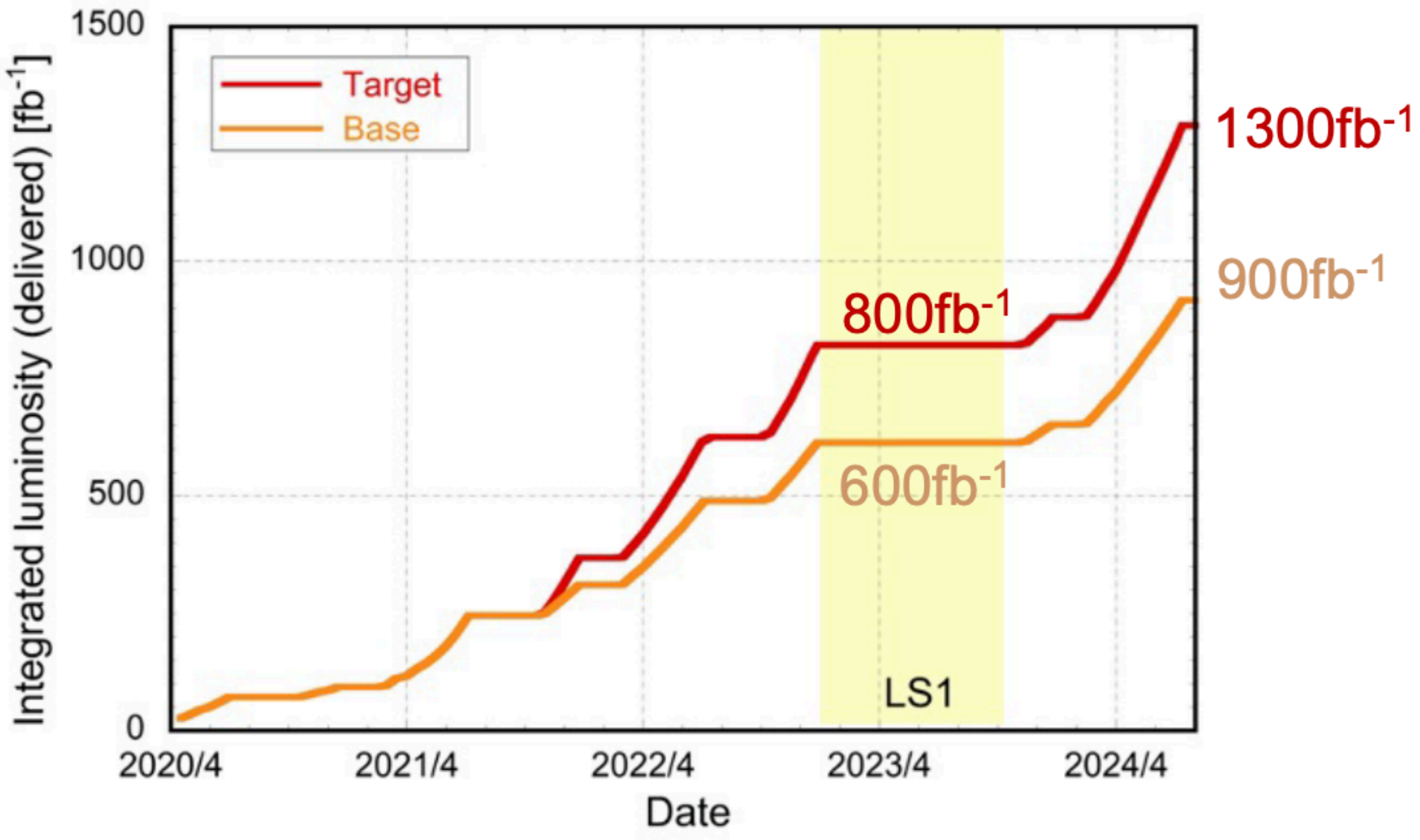
Belle II continued taking data during the pandemic!



Semi-tauonic Agenda

- Belle II will collect up to 800 fb^{-1} before its first shutdown .
- The collected data will be used to confirm the current *B*-anomalies and to present first novel results in the semi-tauonic sector.

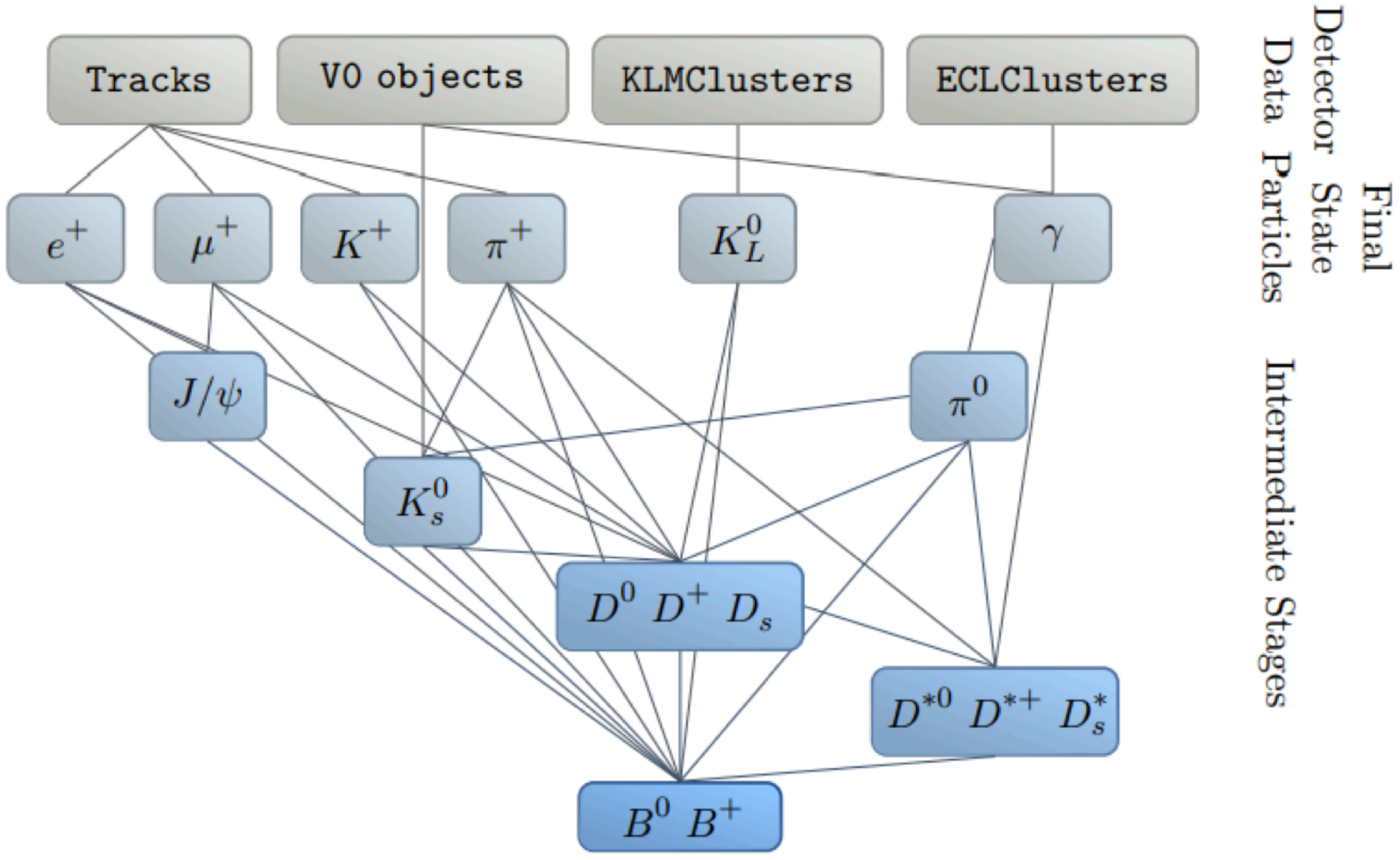
- Planned measurements in progress:
  - $R(D) - R(D^*)$:
    - With hadronic and semi-leptonic tagging, hadronic and leptonic tau decays.
    - Confirm anomaly using data collected before long shut down 1 and measure tau polarization.
    - First results by Summer 2022.
  - $B \to X\tau\nu$
    - Novel measurement with hadronic tagging .
    - First results by end of 2022 with O(400) fb^{-1} at least.
  - $B \to \tau\nu$
    - Unique capability of Belle II.
    - First results by end of 2022 with O(500) fb^{-1} or more.

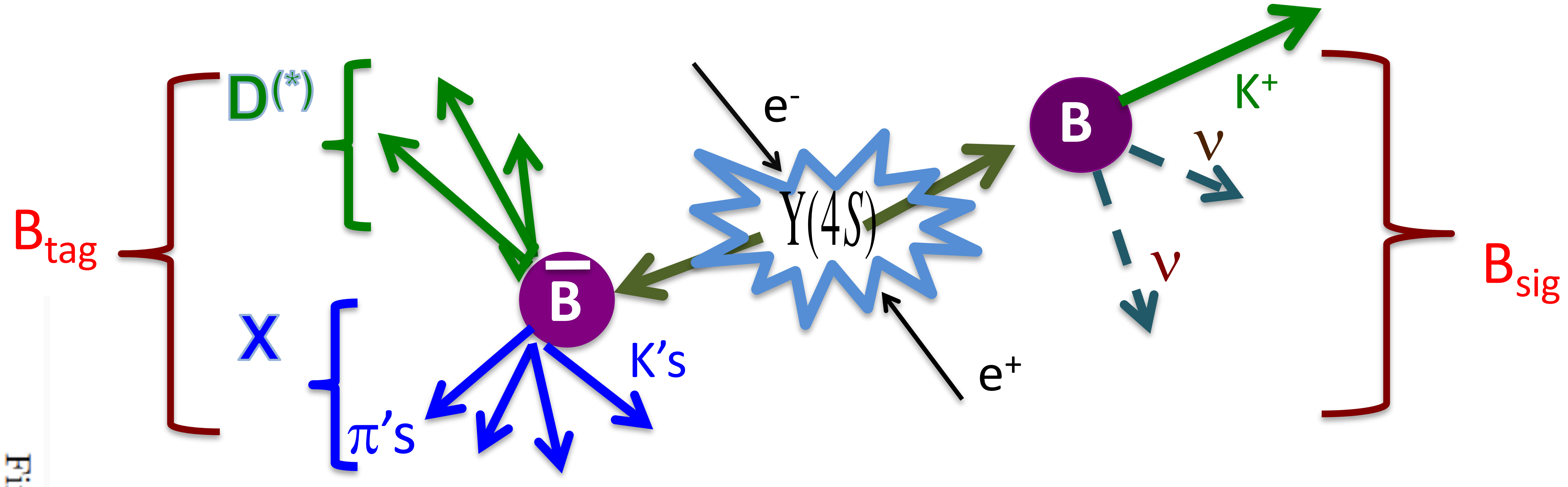


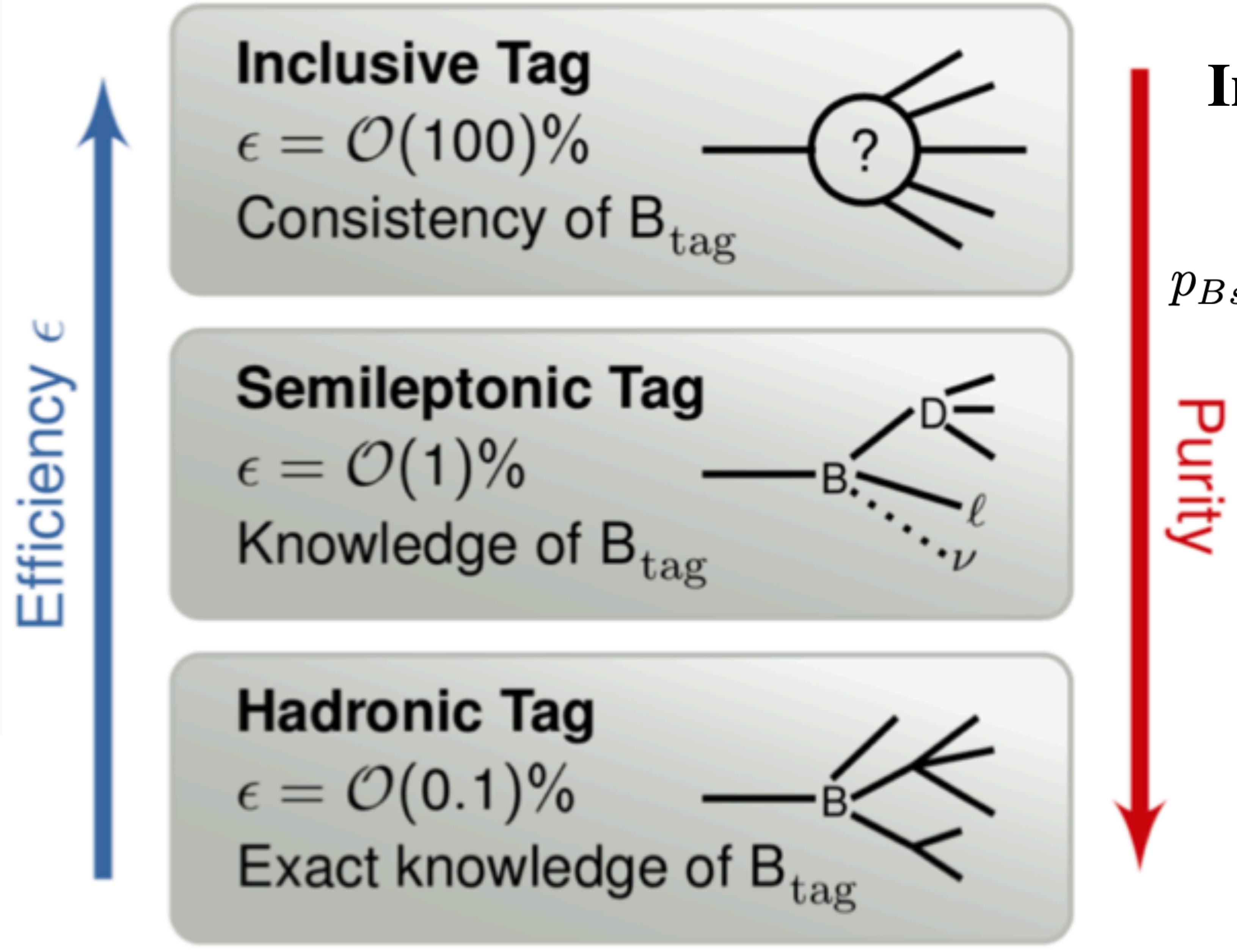
Preparing the toolkit

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.







Infer momentum and direction of signal B candidate:

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

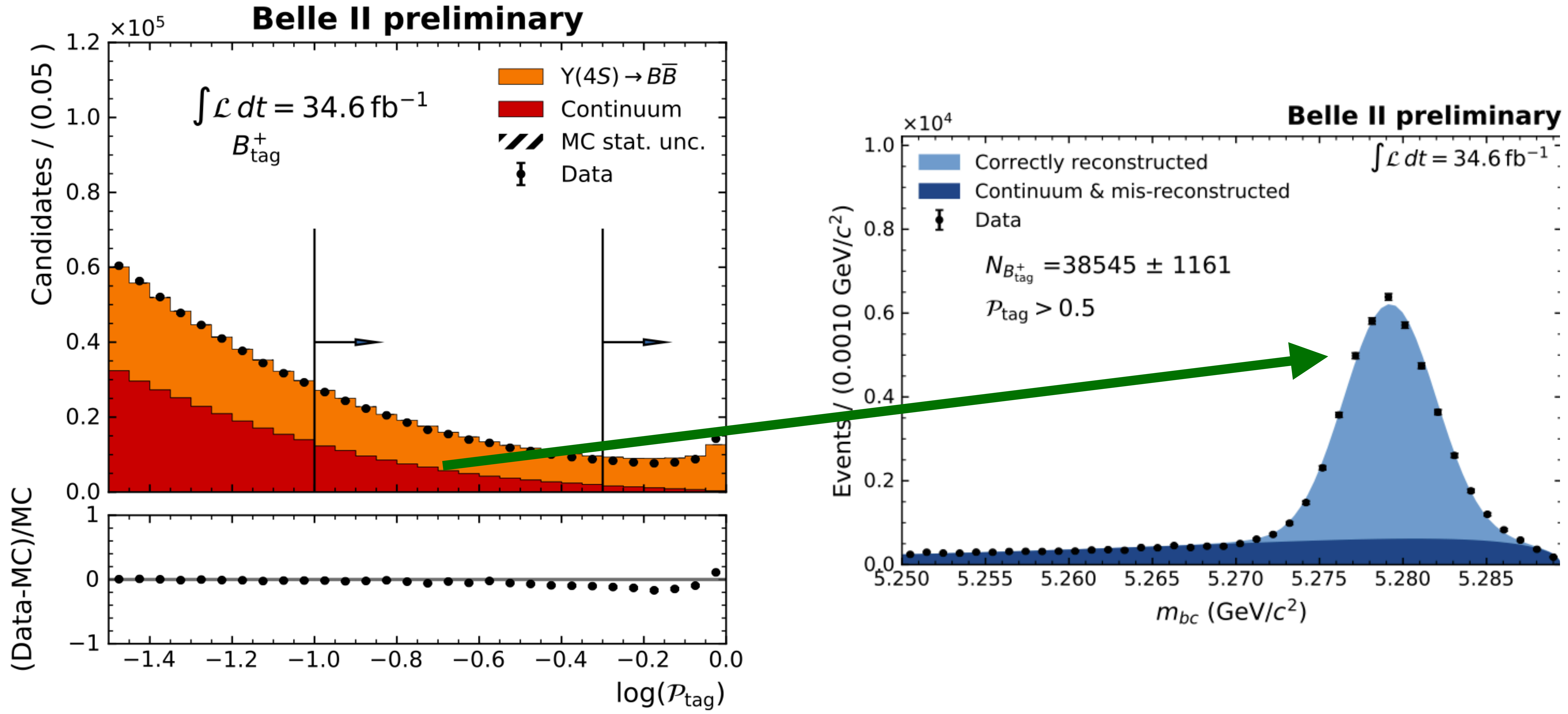
Ideal for decays with neutrinos, missing energy signatures!

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

B-tagging at Belle II

arXiv:2008.06096

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



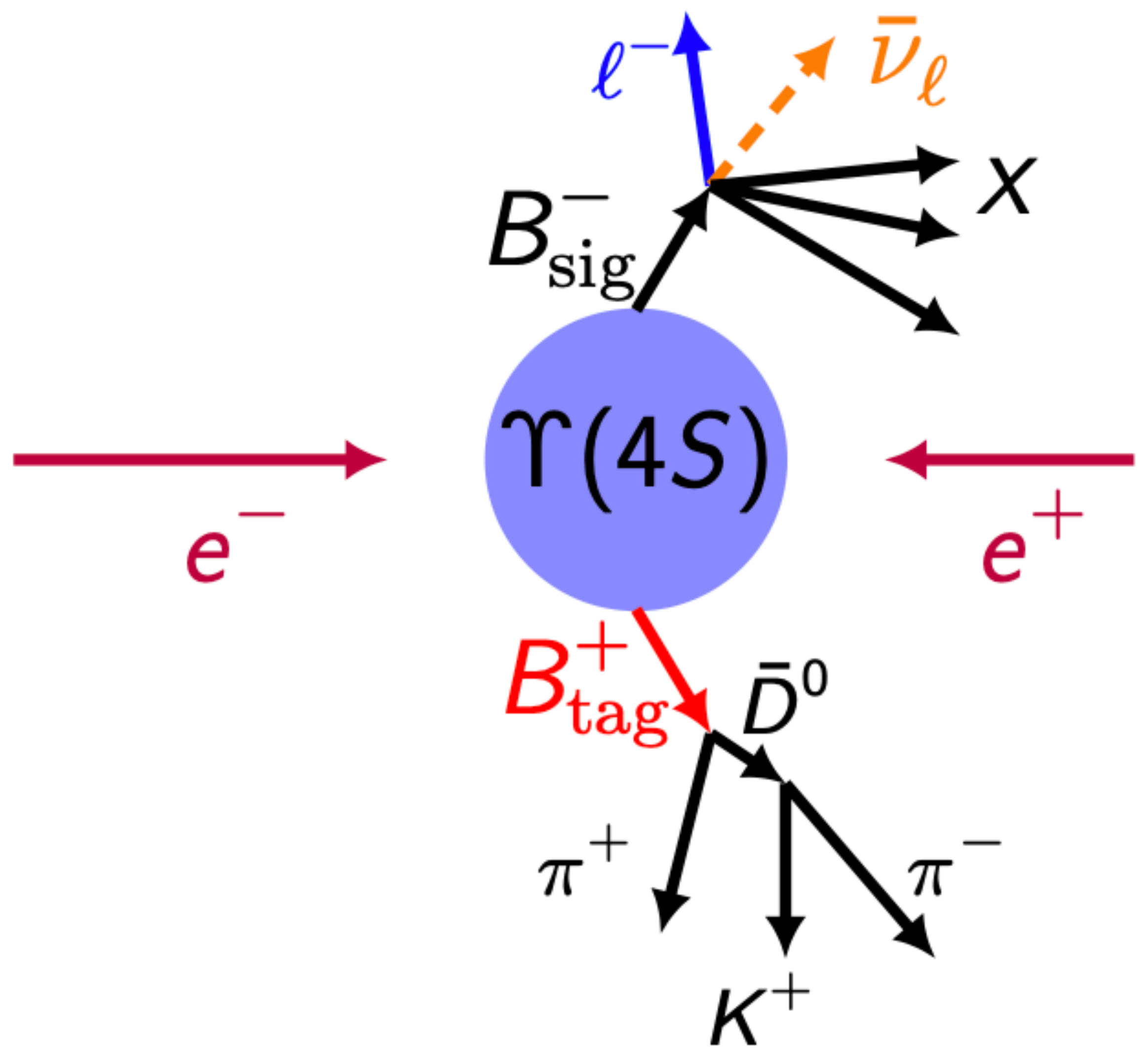
- 30-50% improvement in efficiency compared to Full Reconstruction at Belle.

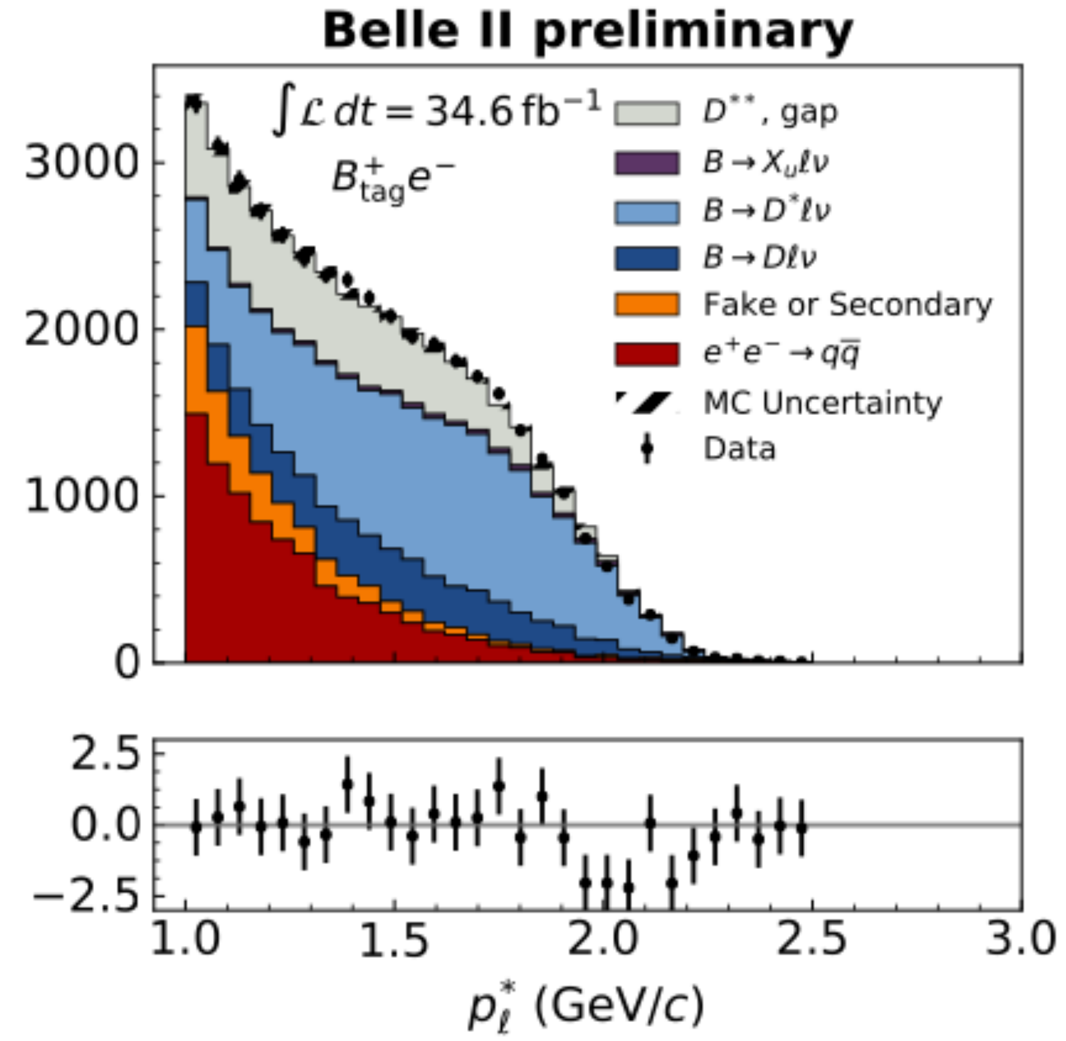
	$B^{\pm}$	B^0
Hadronic		
FEI with FR channels	0.53 %	0.33 %
FEI	0.76 %	0.46 %
FR	0.28 %	0.18 %
SER	0.4 %	0.2 %

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

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

- $B \to X\ell\nu$ channel employed to calibrate the hadronic FEI and account for data-MC differences.
- Calibration determined as $N^{X\ell\nu}_{Data}/N^{X\ell\nu}_{MC}$ after selecting signal side B

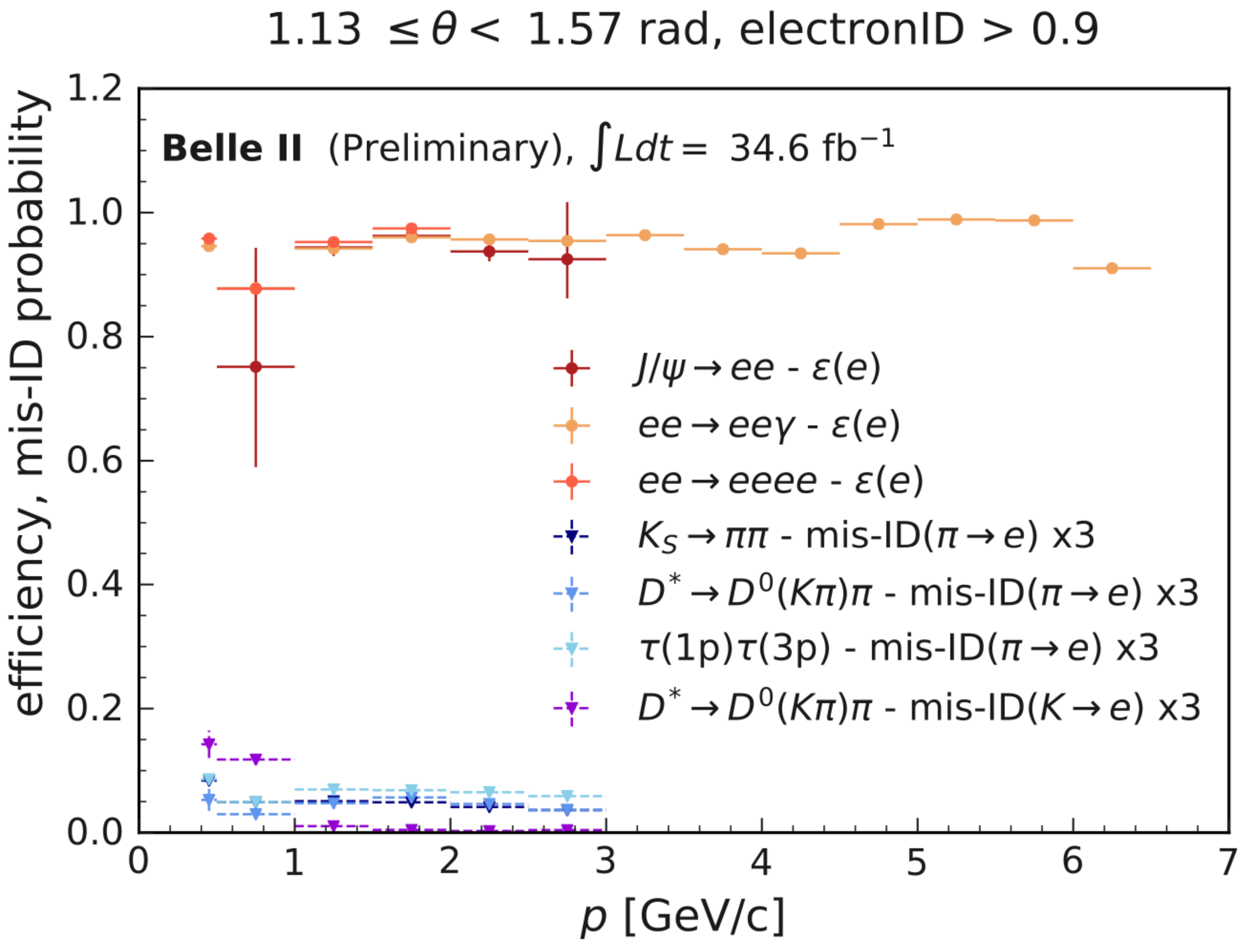




- Hadronic FEI calibration strategy has been established.
- Semi-leptonic FEI calibration and performance studies in progress for Summer 2022.

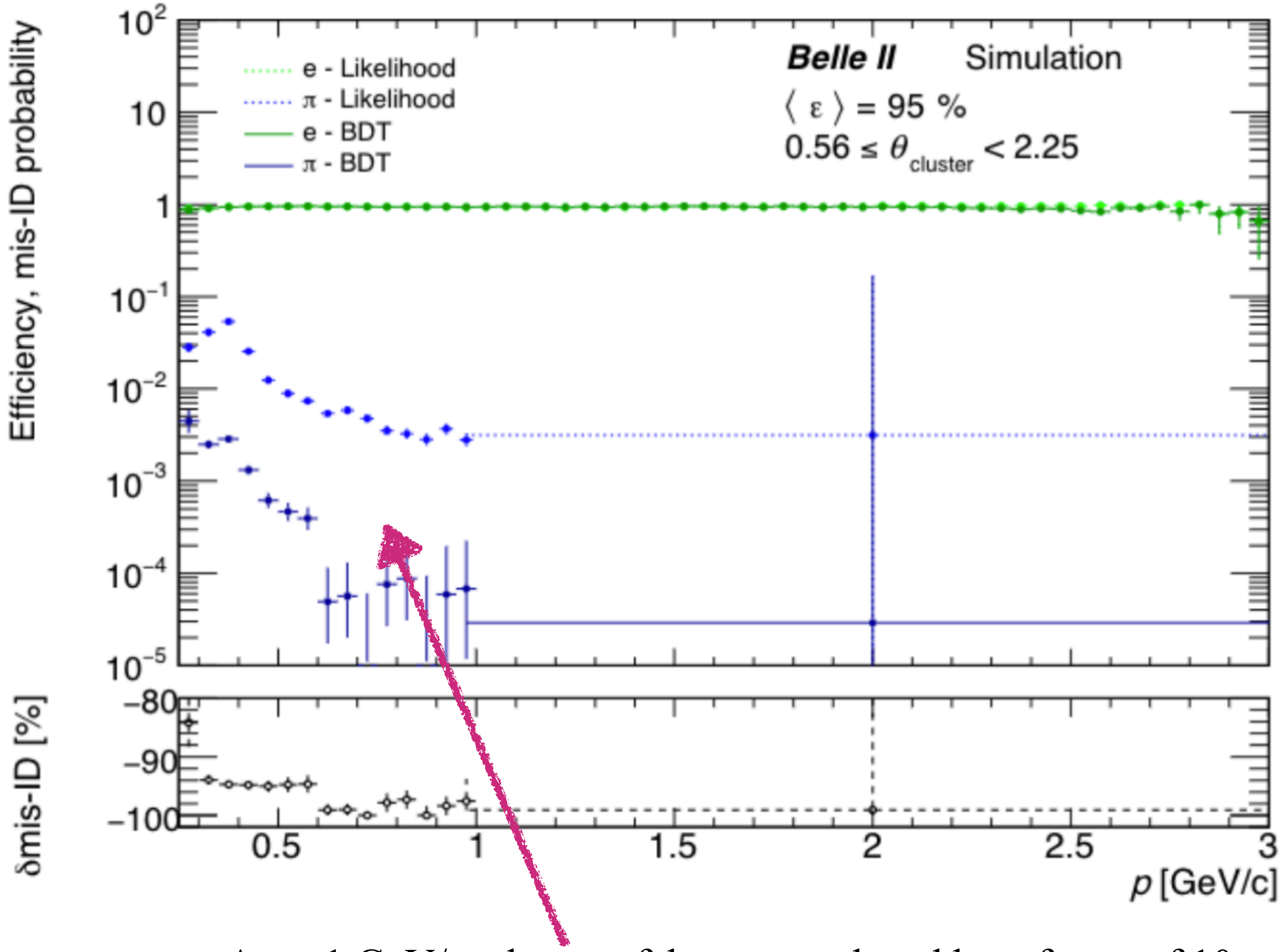
Lepton Identification

- 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 $\mathscr{L} > 0.9$

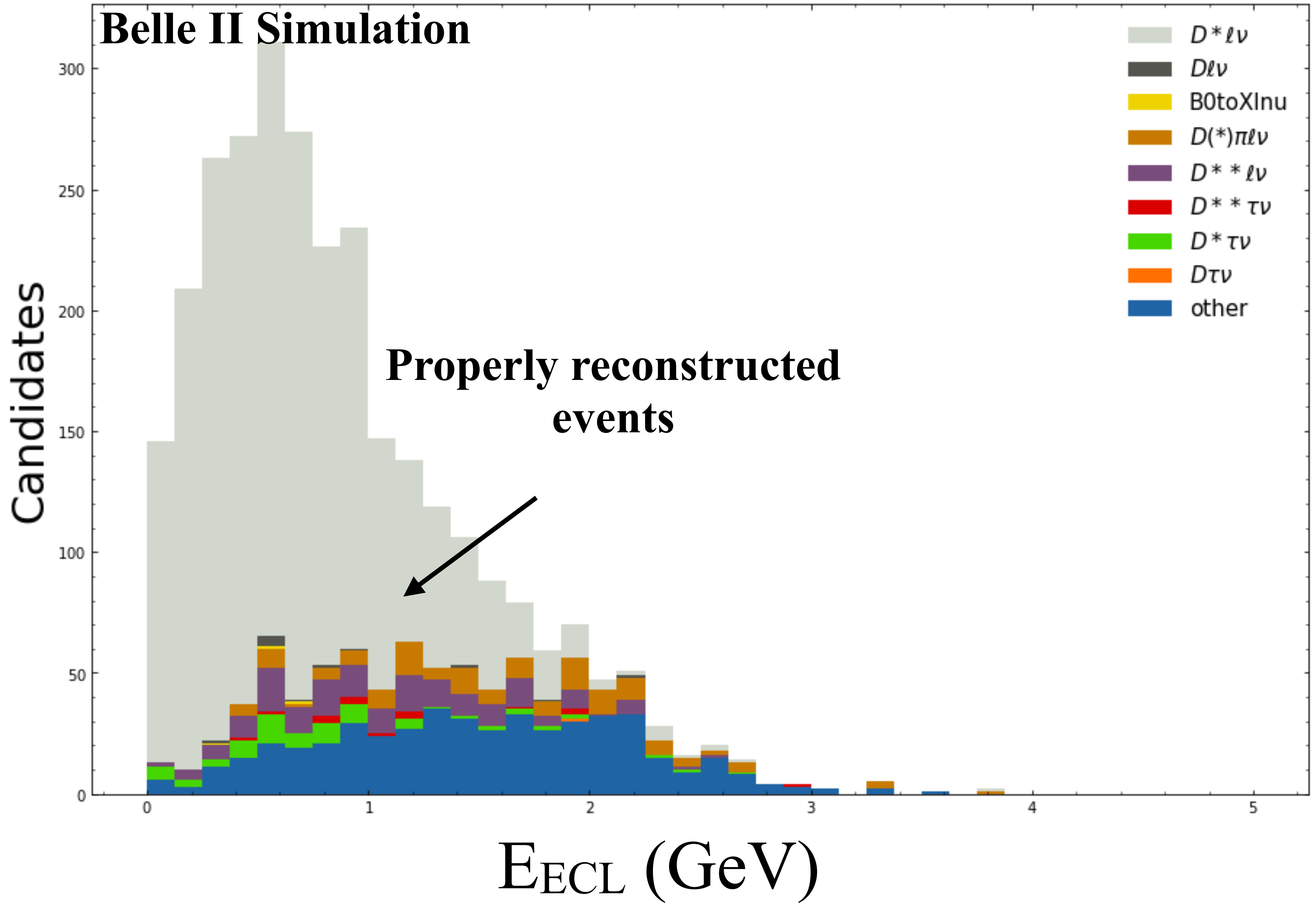
- Fake rates improved for low momenta using Boosted Decision Tree PID with ECL shower shape variables to separate between lepton and hadrons.



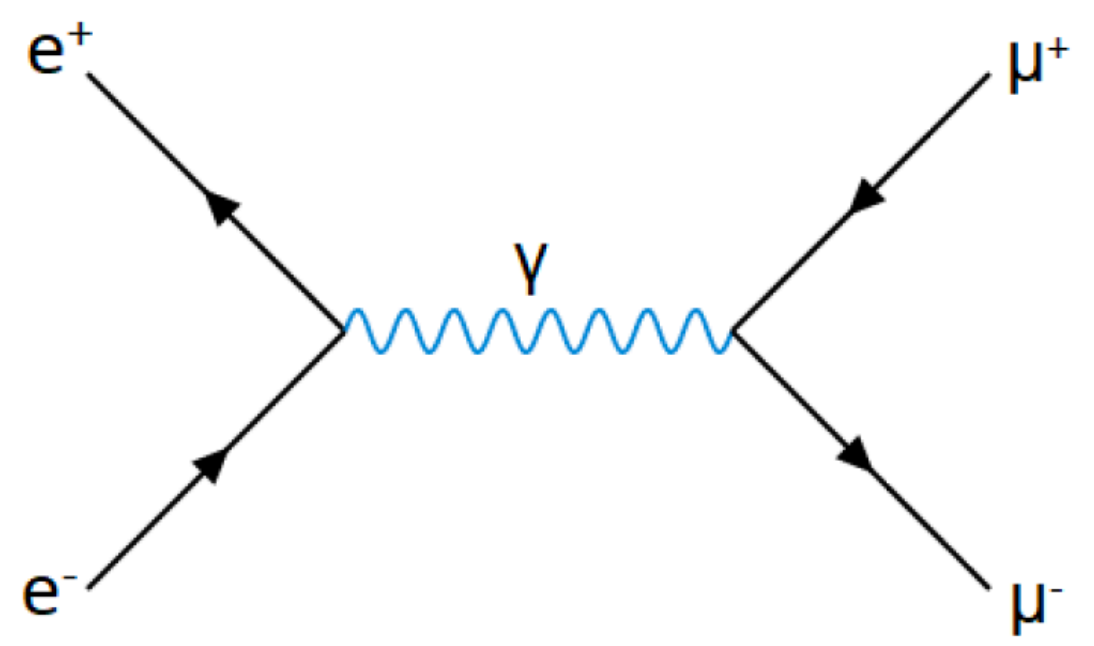
At p<1 GeV/c, electron fake rates reduced by a factor of 10.

EECL

- EECL is a key variable for many semi-leptonic and missing energy analyses, specifically $B \to D^* \tau \nu_\tau$.
- It is defined as the sum energy of all neutral clusters in the event after the full signal selection is applied: $B_{\rm sig}$+ $B_{\rm tag}$.



- Different contributions to EECL :
  - Mis-reconstructed candidates
  - Hadronic split-offs
  - Beam background contributions



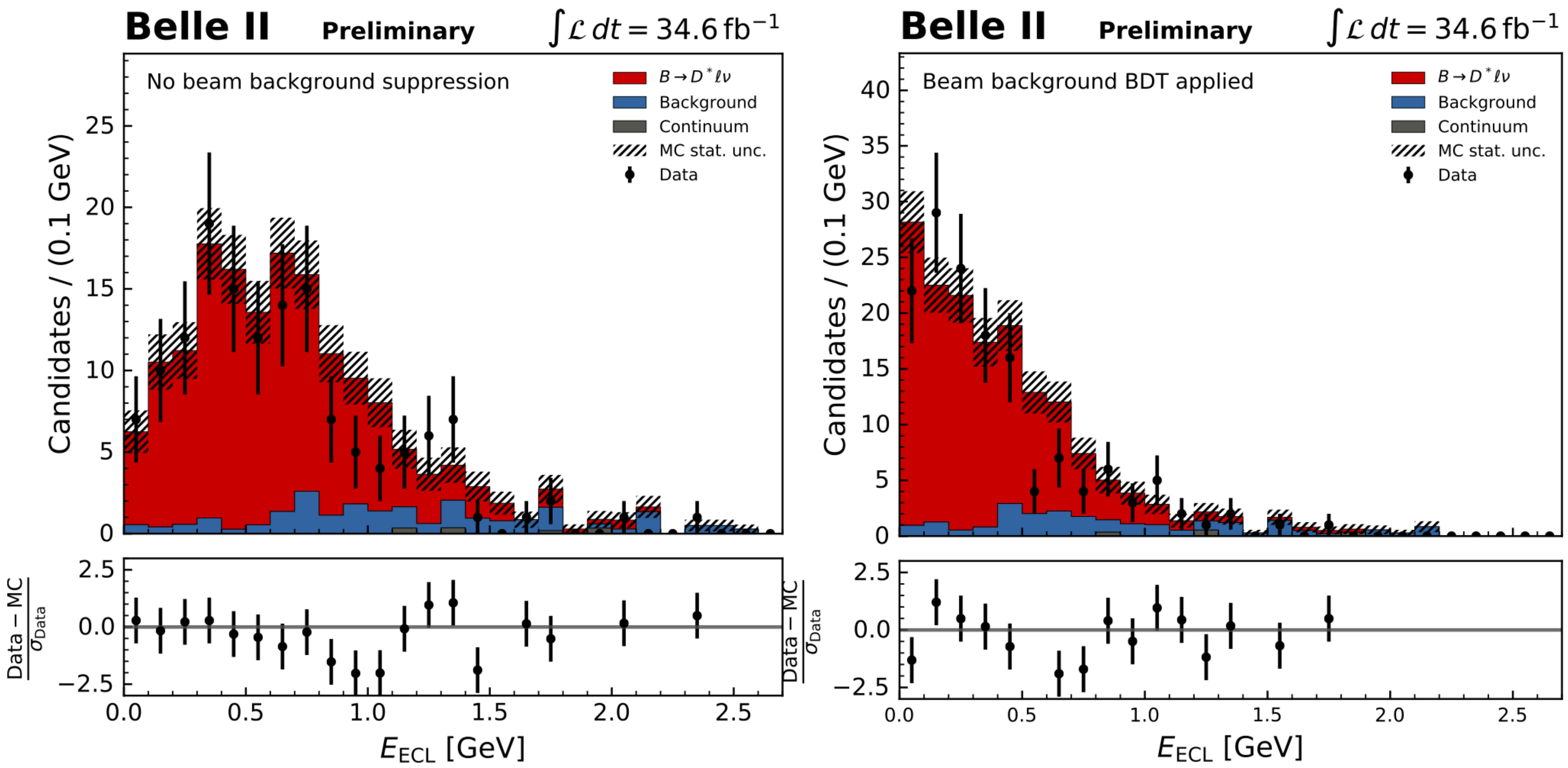
Develop a multi-variate algorithm (BDT) to suppress beam background contributions.

Employ shower shape variables to separate between clusters resulting from real photons and those that are related to beam backgrounds.

Isolate beam background photons from $e^+e^- \to \mu^+\mu^-$ events in data and train against simulated photons from $B\bar{B}$ events.

E_{ECL}

- Beam background BDT tested on E_{ECL} distribution of $B^0 \to D^{(*+)}\ell^-\nu_\ell$ events.



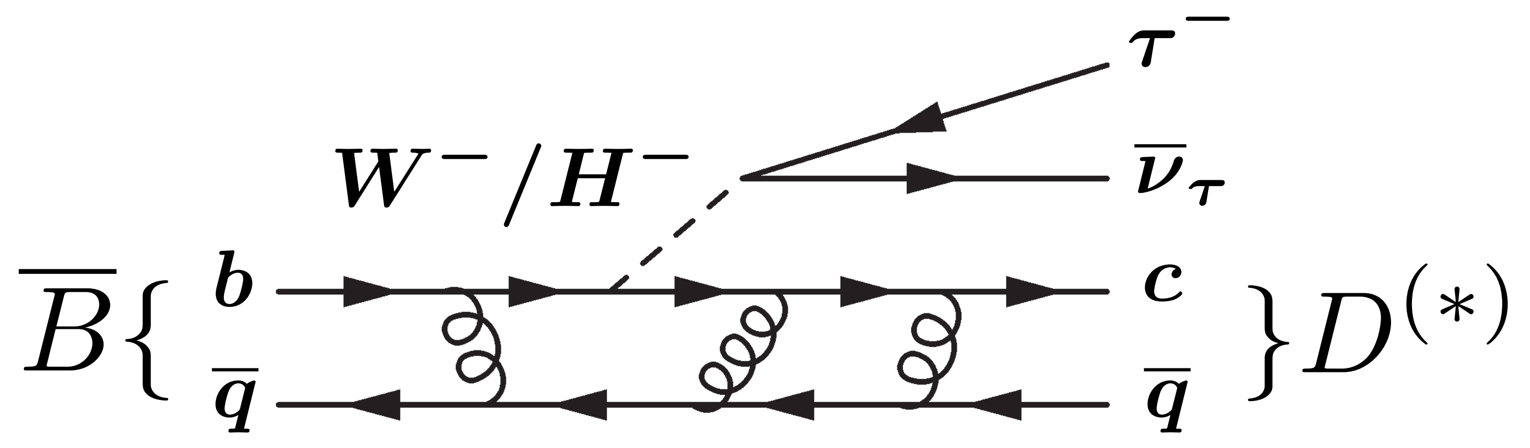
- Similar effort in progress and targeting summer 2022 for the suppression of hadronic split offs in E_{ECL}.

Now, the setup

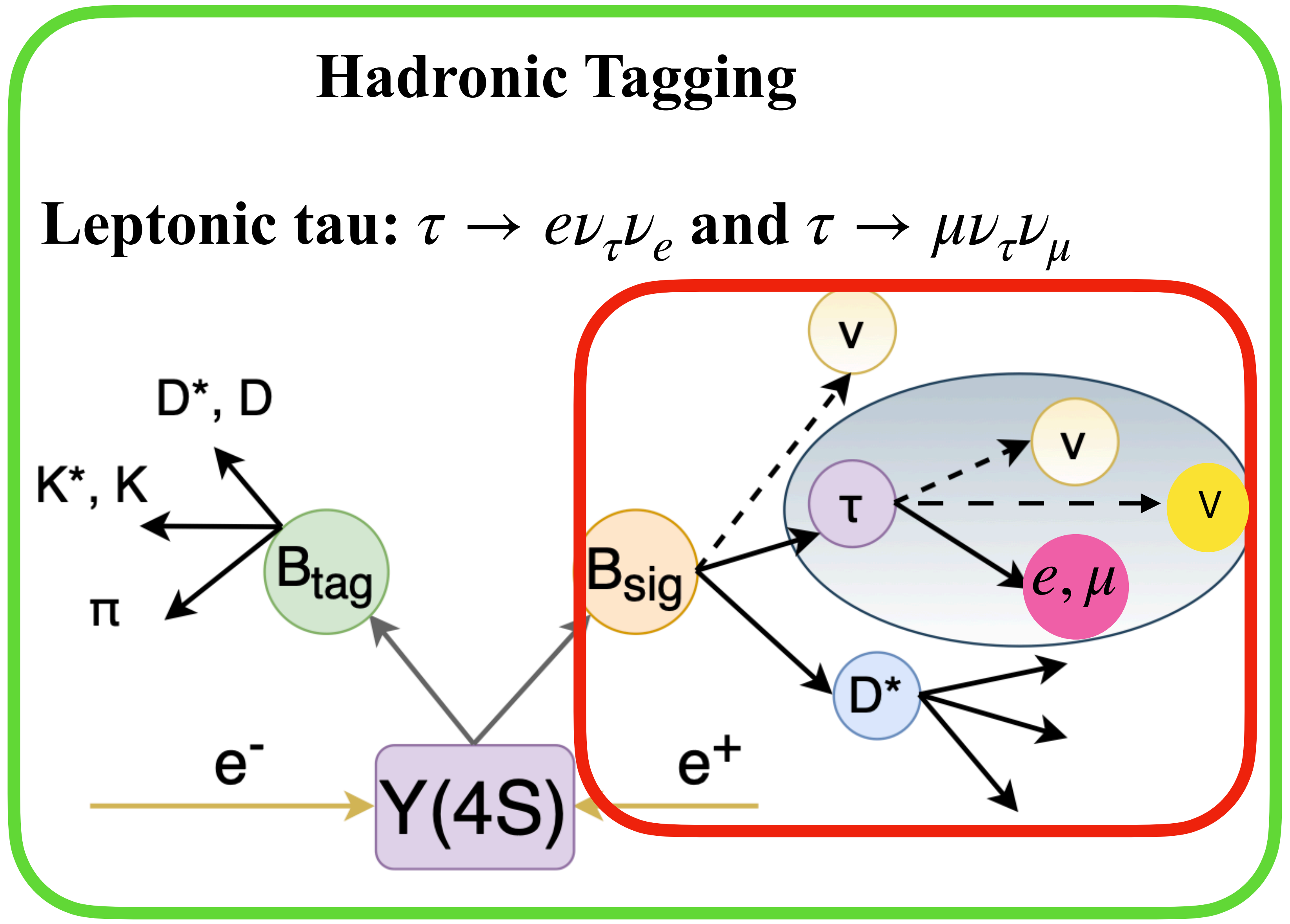
$R(D)$ and $R(D^*)$

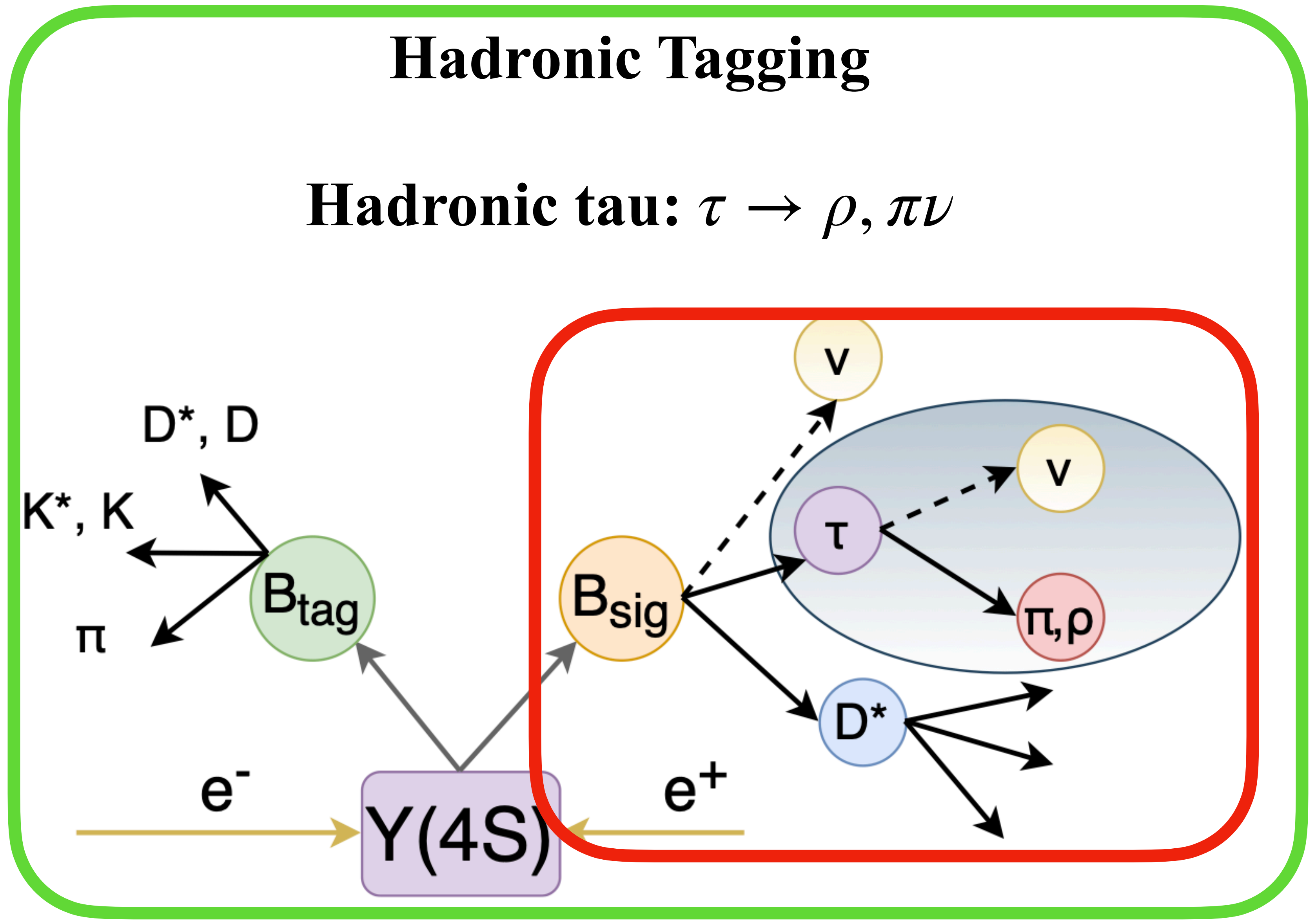
- One of the high priority analyses for Belle II.

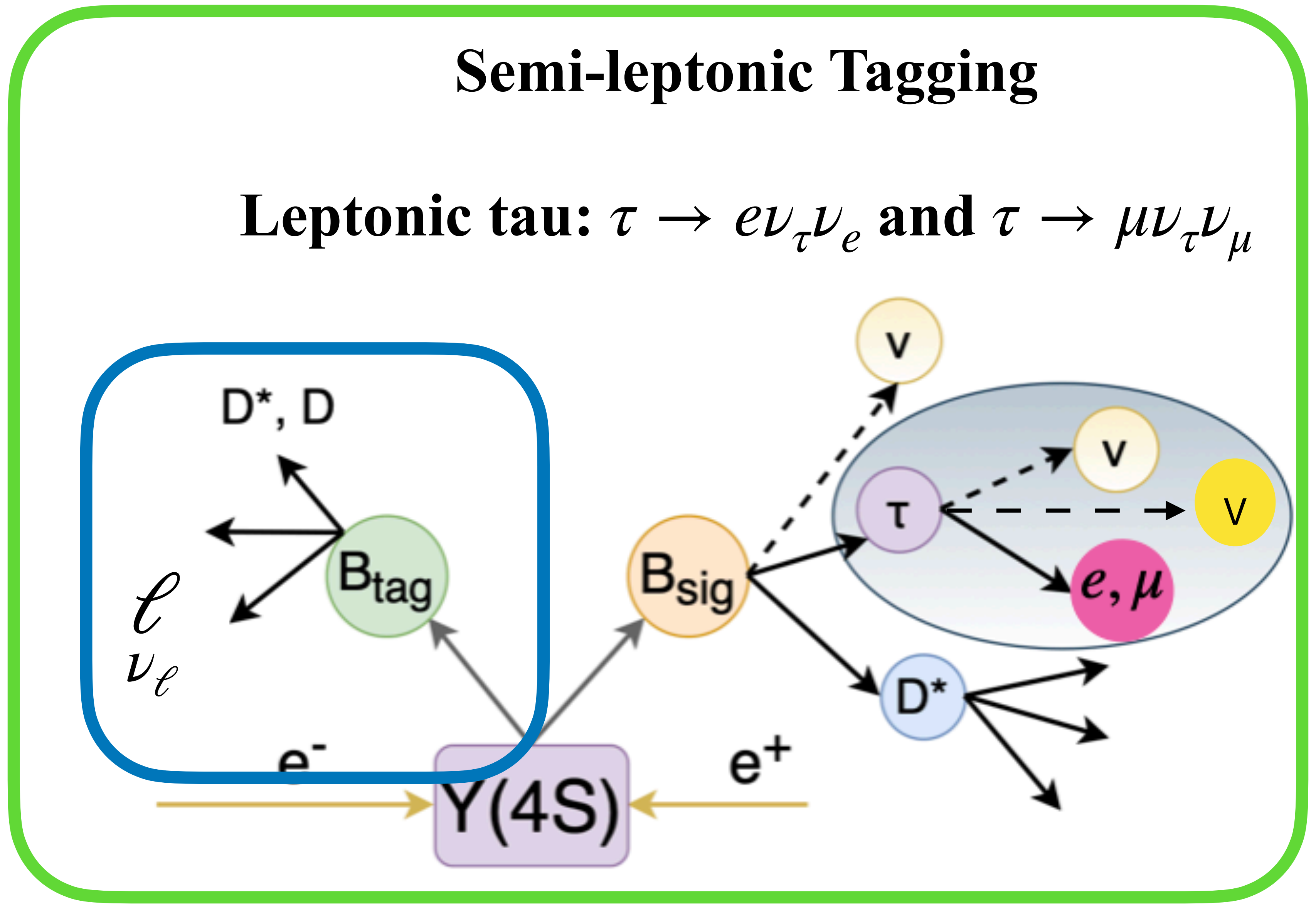
$$R(D) = \frac{\mathcal{B}(\bar{B} \to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+\ell^-\bar{\nu}_\ell)} \quad \text{and} \quad R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell)}$$



- 3 ongoing measurements planned in the short term:







Initial plan: confirm anomaly with ~0.5 ab[-1] of Belle II data.

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

- One of the high priority analyses for Belle II.

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

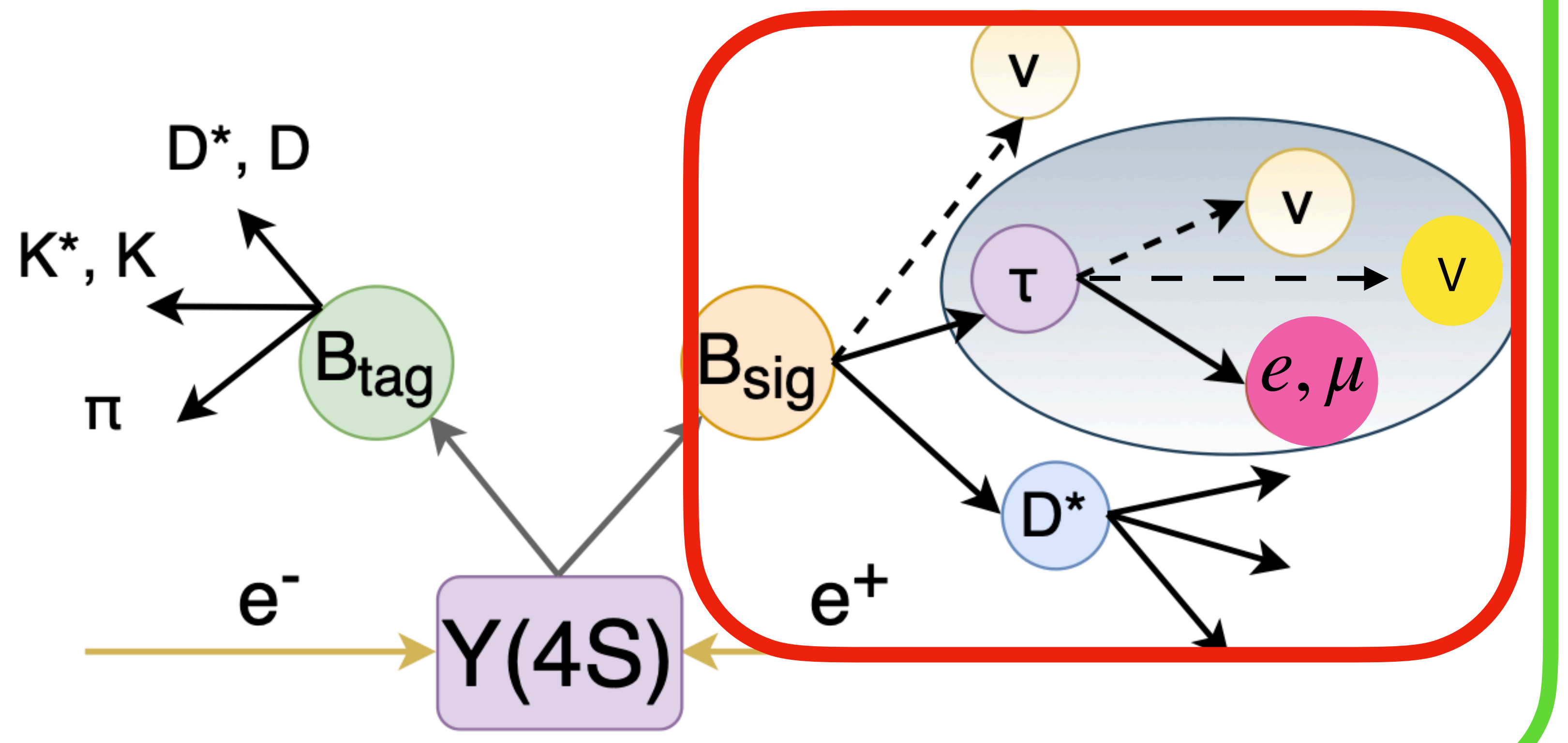
Normalization mode

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

- 3 ongoing measurements planned before the long shut down:

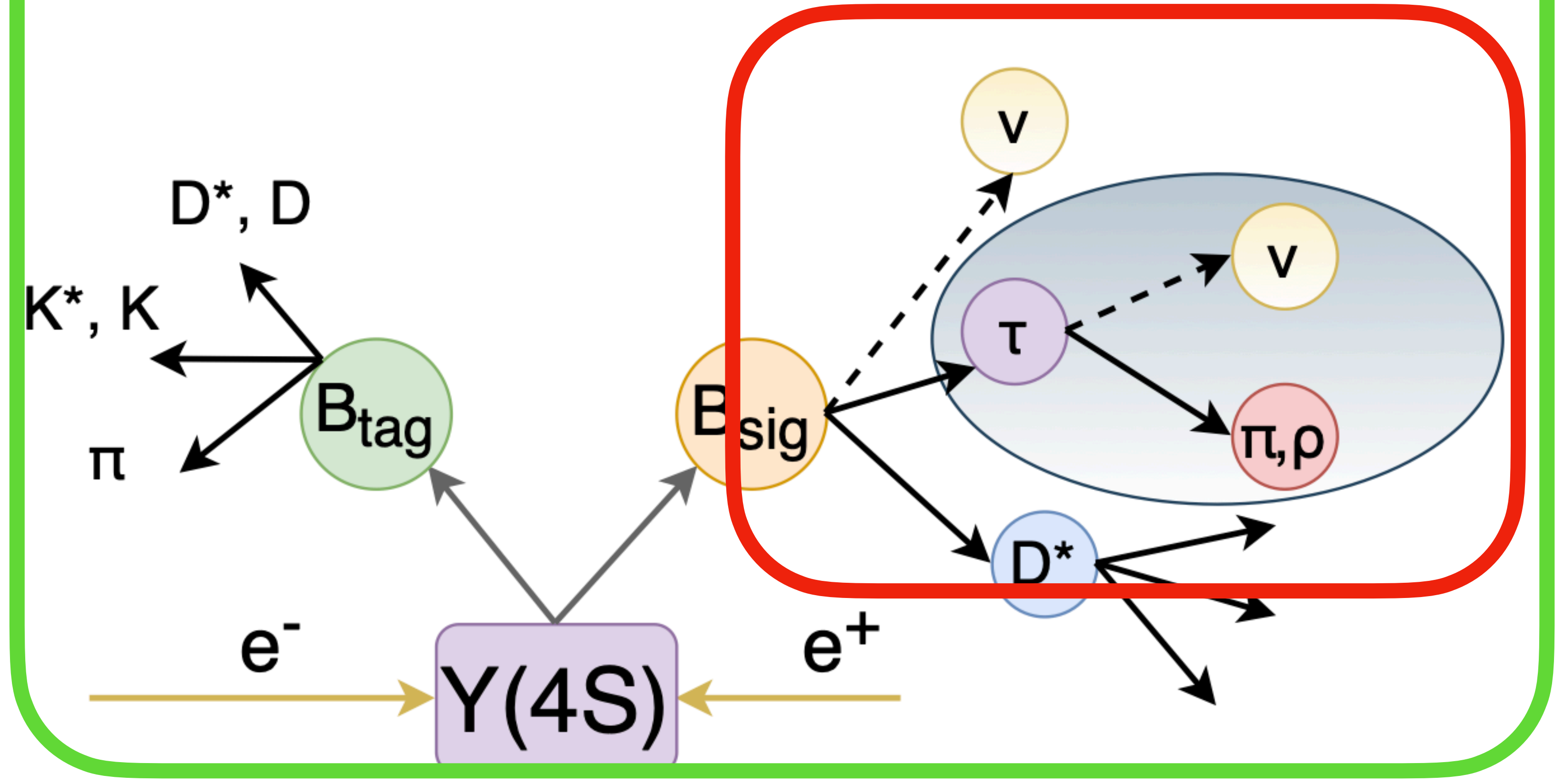
Hadronic Tagging

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



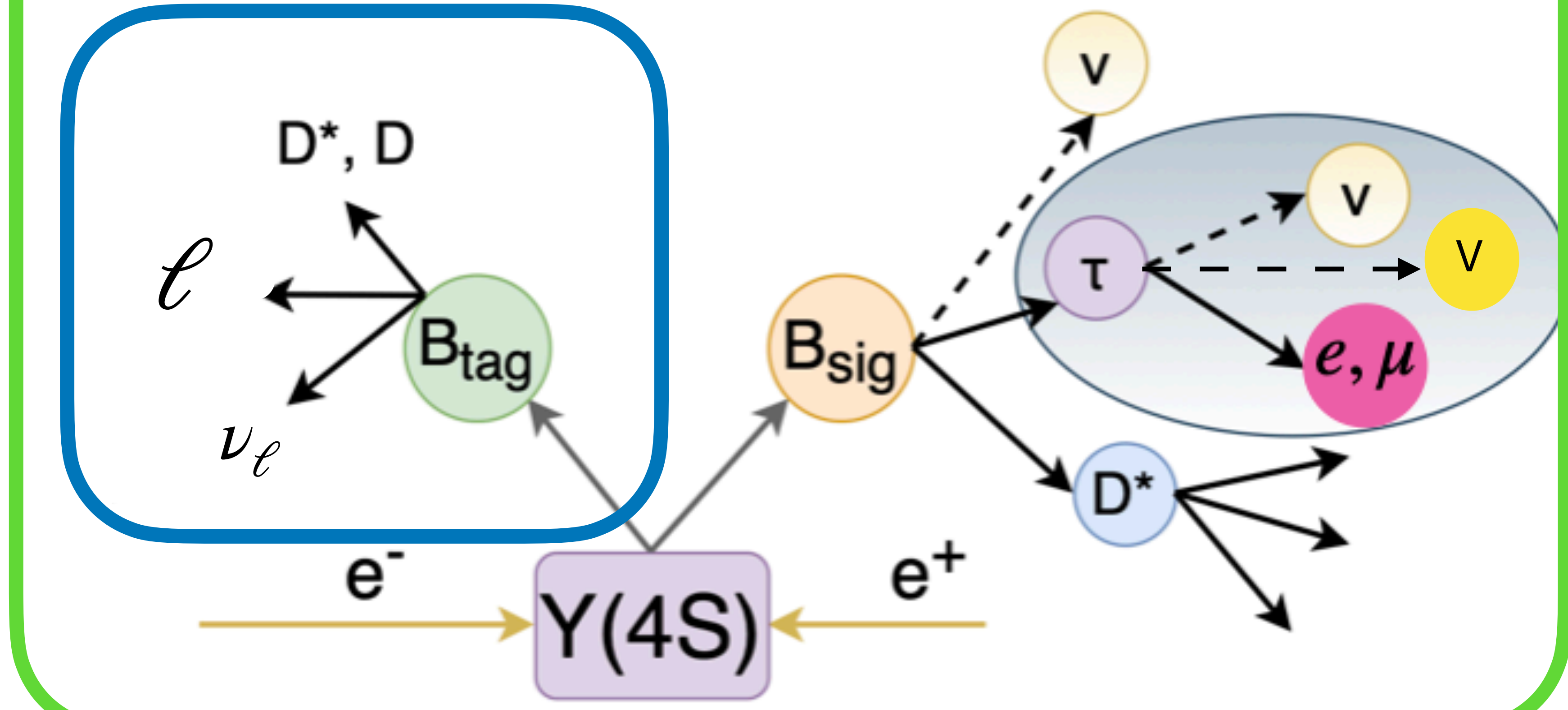
Hadronic Tagging

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



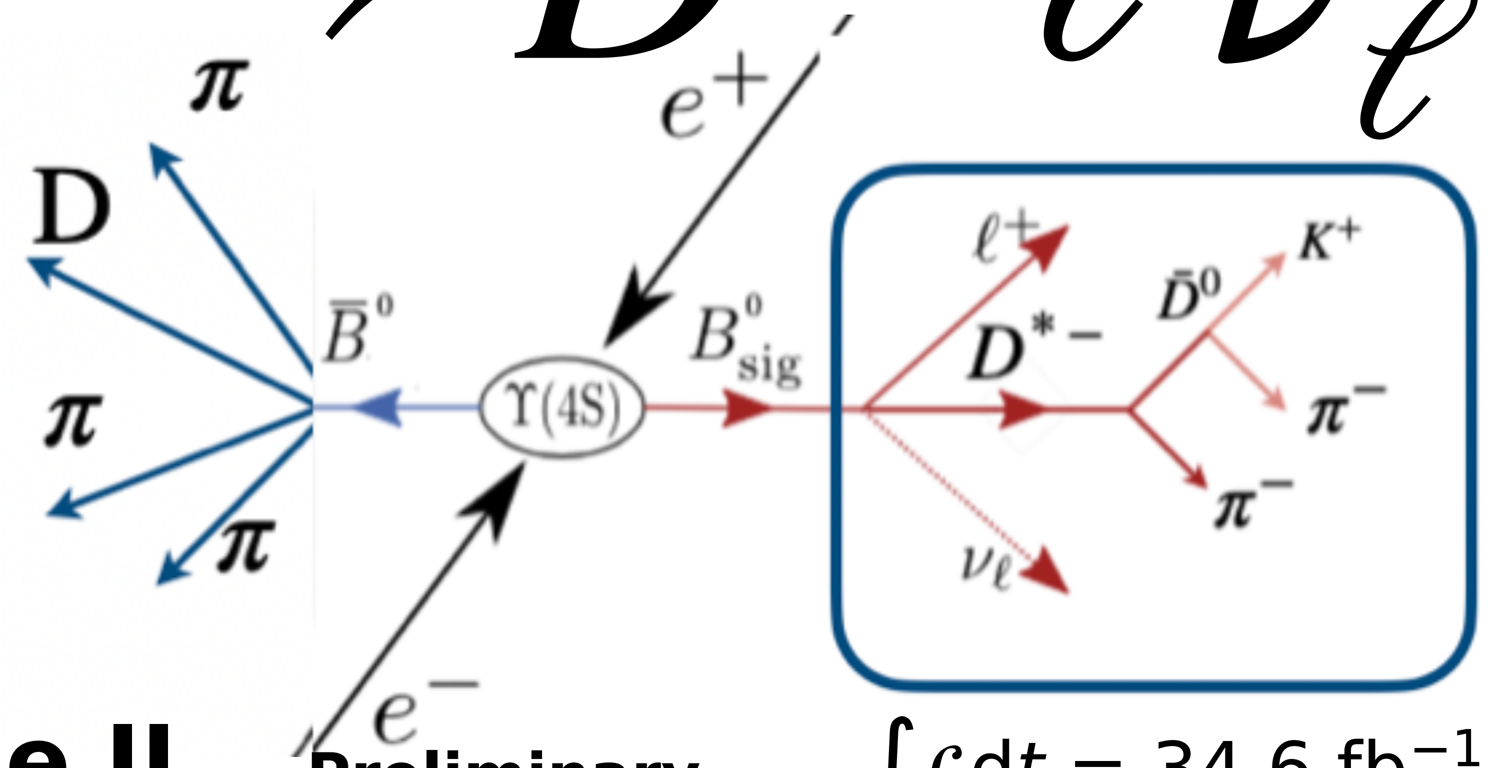
Semi-leptonic Tagging

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



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

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



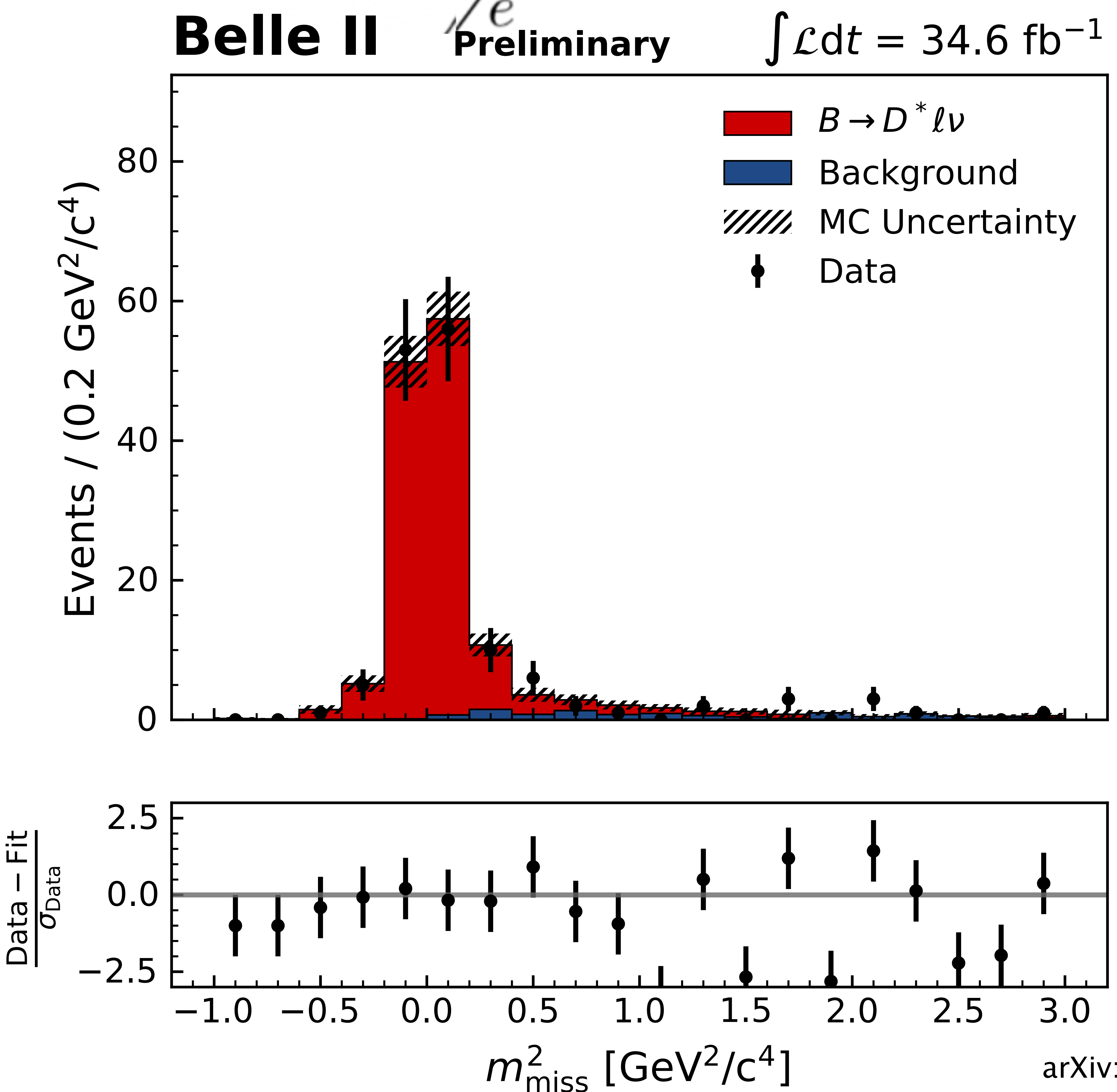
- Identify B_{tag} candidate and reconstruct D^0 meson from oppositely charged tracks with $1.858 < M_D < 1.878$ GeV/c^2 .
- Combine D^0 and π_s to form D^{*+} with $0.143 < \Delta M < 0.148$ GeV/c^2
- Identify high momentum lepton with $p_l^* > 1.0$ GeV/c and combine with D^{*+} .
- Extract signal yield using a fit to signal + background in m^2_{miss}:

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

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

In agreement with world average!

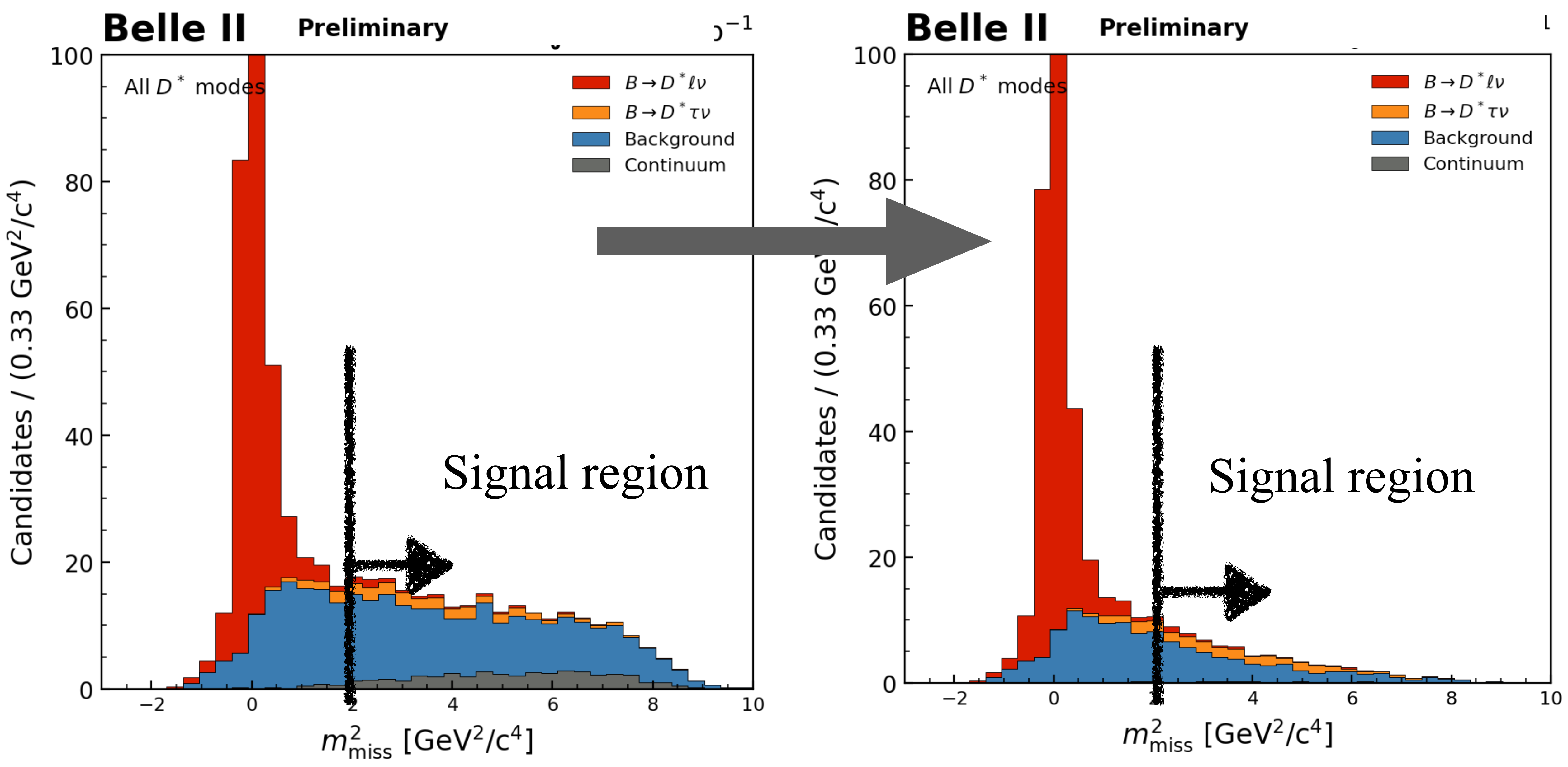
$$\mathscr{B}(\bar{B}^0 \to D^{*+}\ell\nu_\ell) = (5.05 \pm 0.14)\,\%$$

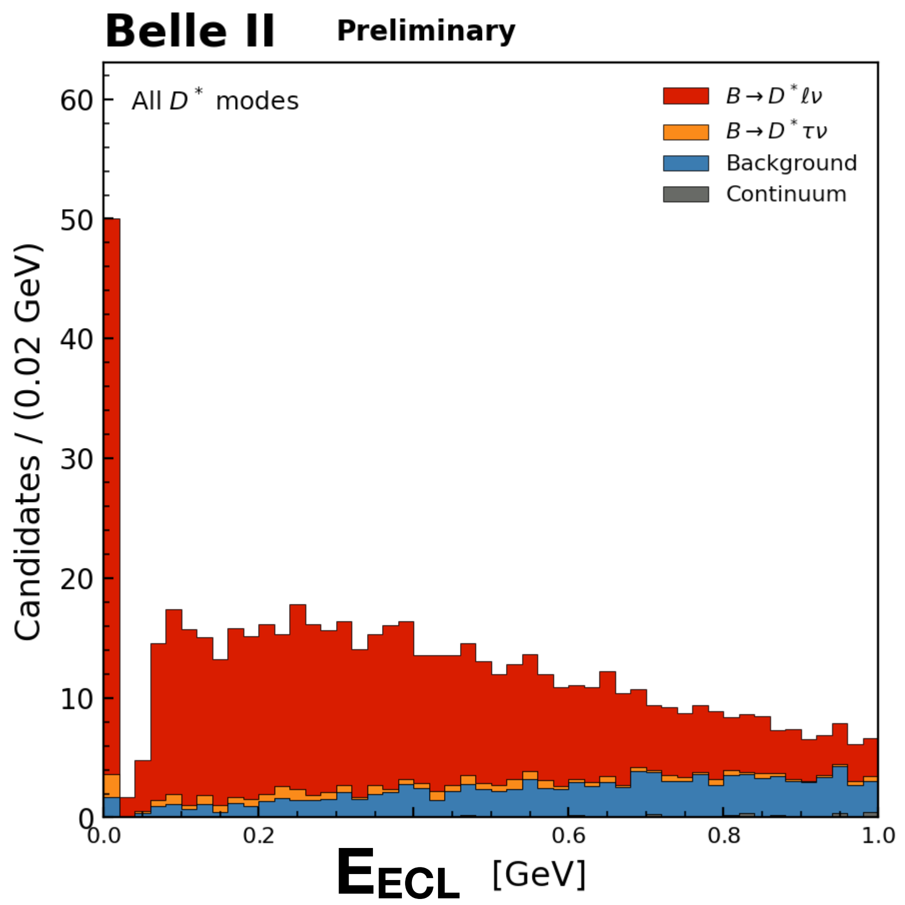


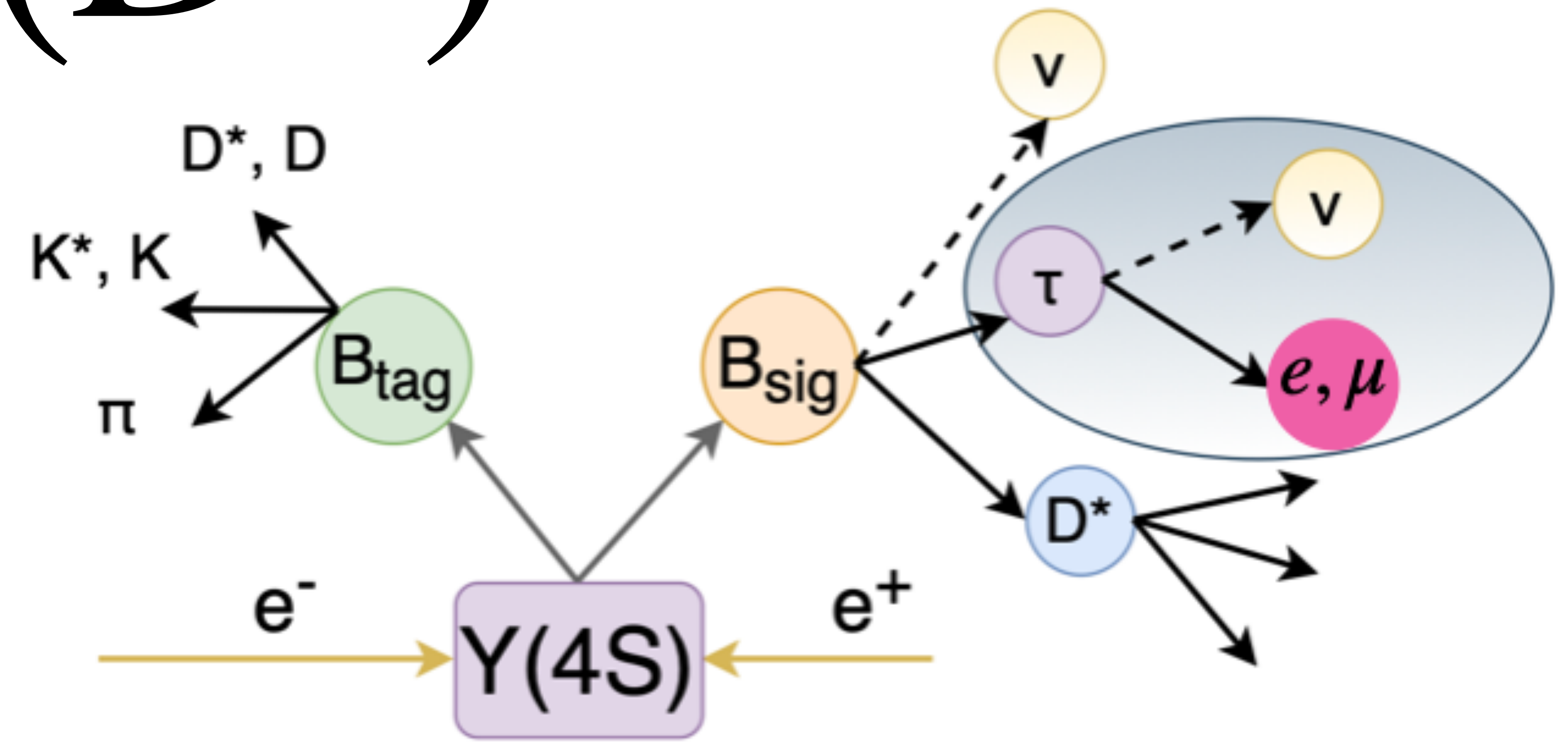
arXiv:2008.10299

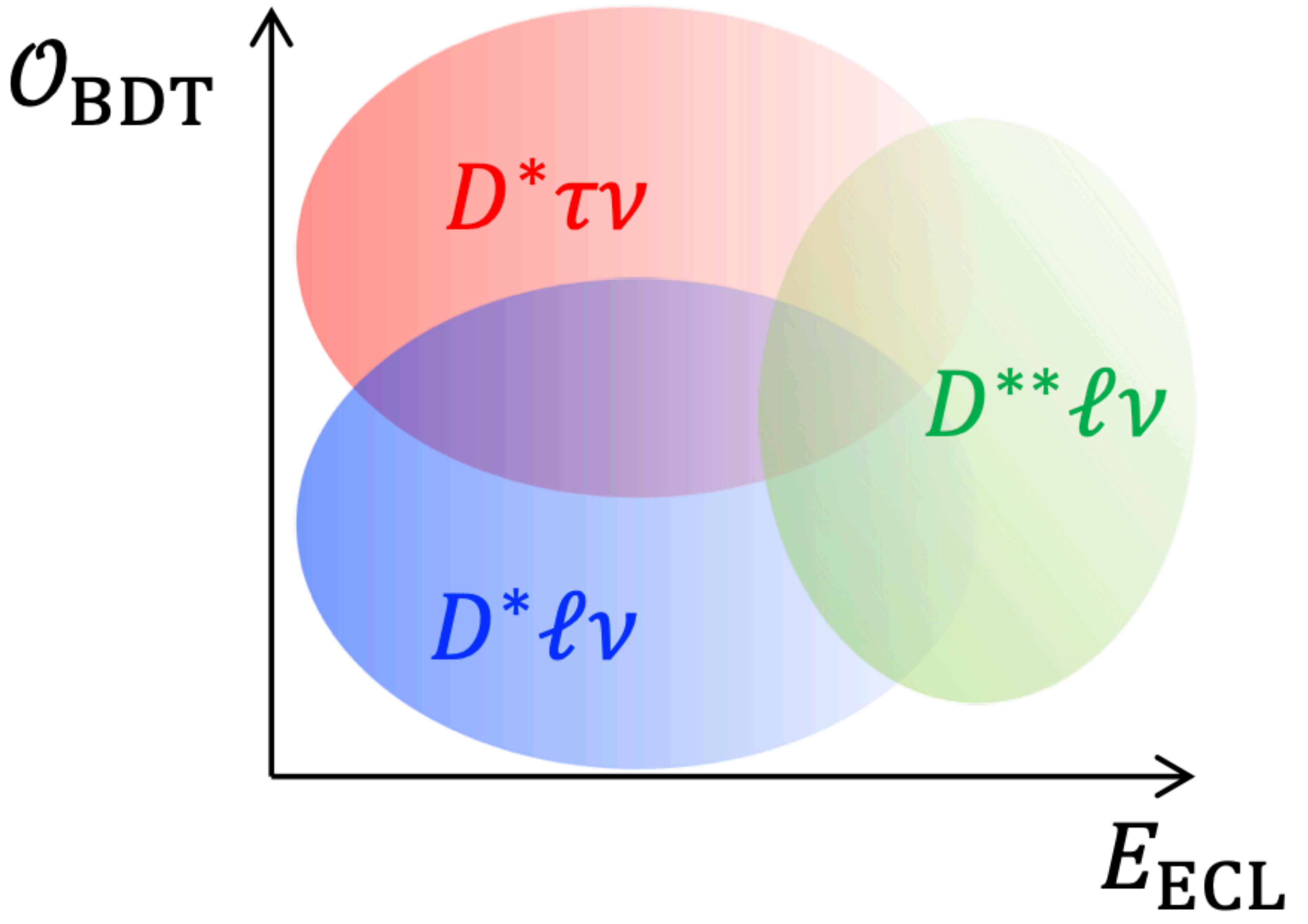
$R(D)$ and $R(D^*)$

- Boosted decision tree $\mathcal{O}(BDT)$ developed to suppress leading background contributions from semi-leptonic decays with D^{**} and hadronic B decays.









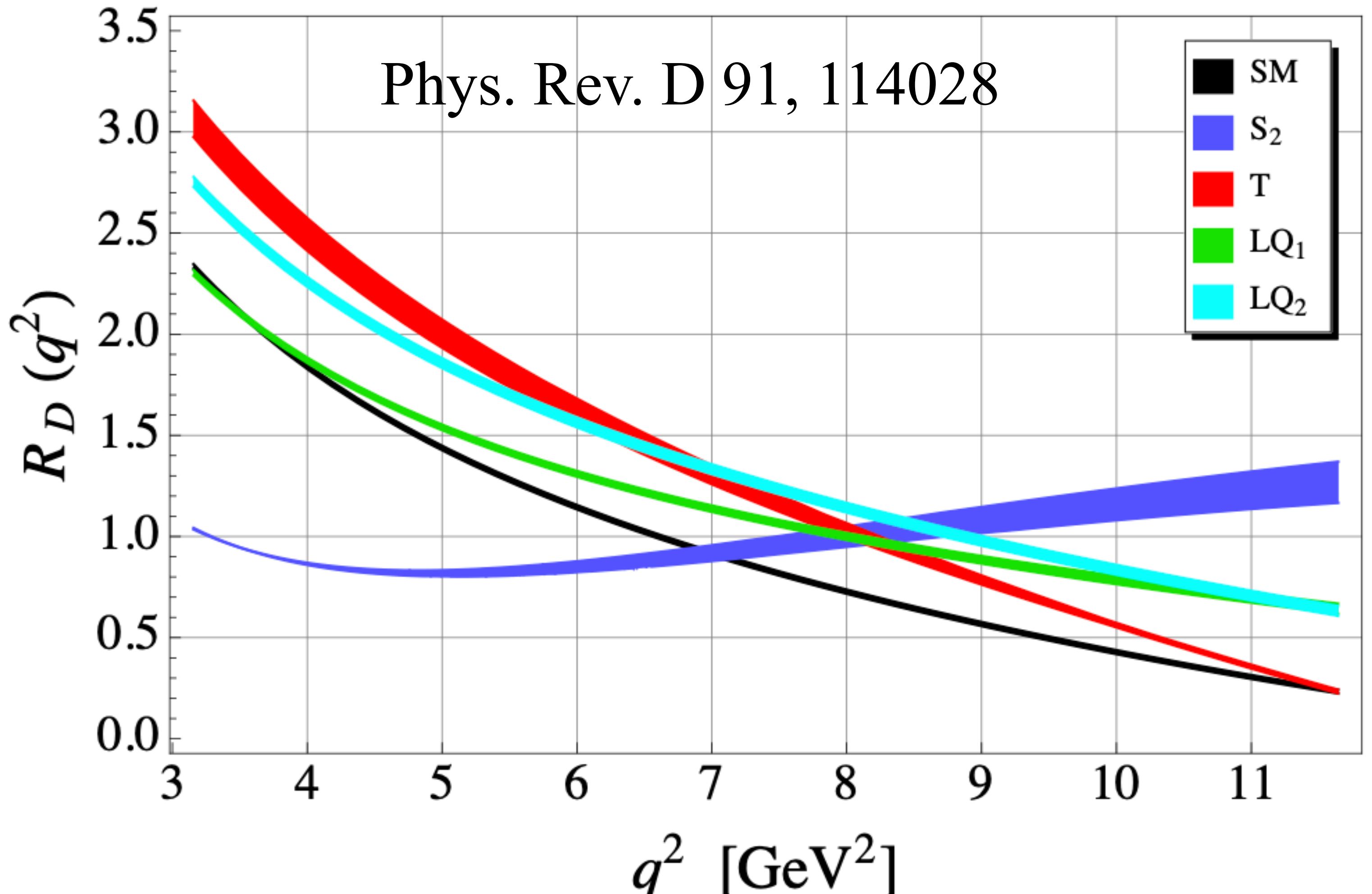
- Extract signal yield using key variables like: $M_\nu^2, p_\ell^*, E_{ECL}$

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

- Previous BaBar and Belle measurements have leading systematics from the tricky $B \to D^{**}$ background and the size of the MC samples.

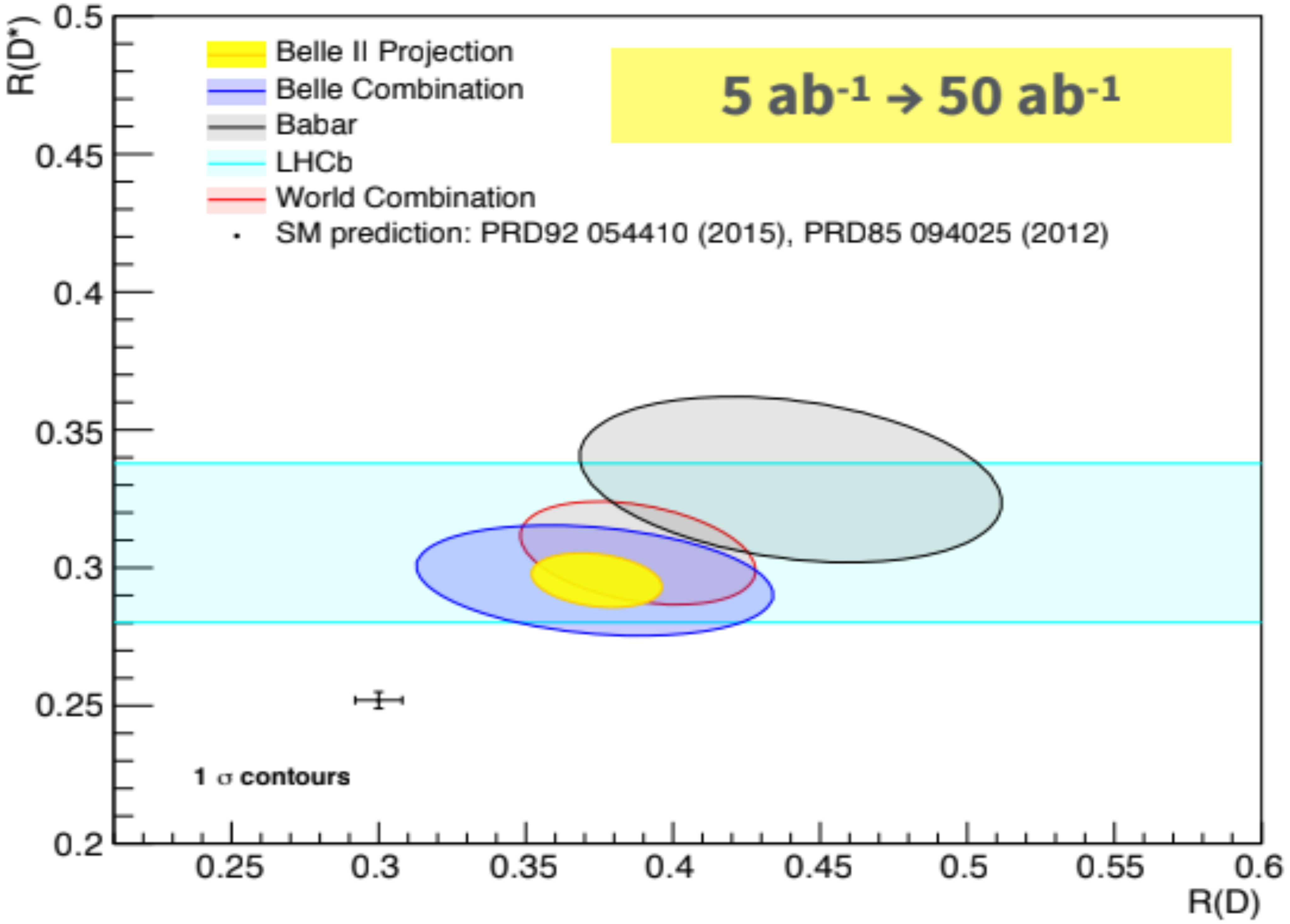
Source	Belle (Had, ℓ^-) R_D	Belle (Had, ℓ^-) R_{D^*}	Belle (SL, ℓ^-) R_{D^*}	Belle (Had, h^-) R_{D^*}
MC statistics	4.4%	3.6%	2.5%	$^{+4.0}_{-2.9}$%
$B \to D^{**}\ell\nu_\ell$	4.4%	3.4%	$^{+1.0}_{-1.7}$%	2.3%
Hadronic B	0.1%	0.1%	1.1%	$^{+7.3}_{-6.5}$%
Other sources	3.4%	1.6%	$^{+1.8}_{-1.4}$%	5.0%
Total	7.1%	5.2%	$^{+3.4}_{-3.5}$%	$^{+10.0}_{-9.0}$%

- More precise measurements of the $B \to D^{**}$ branching fraction in preparation.
- Plan to also measure the tau polarization and the q^2 dependent R(D) as the size of the dataset increases



	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

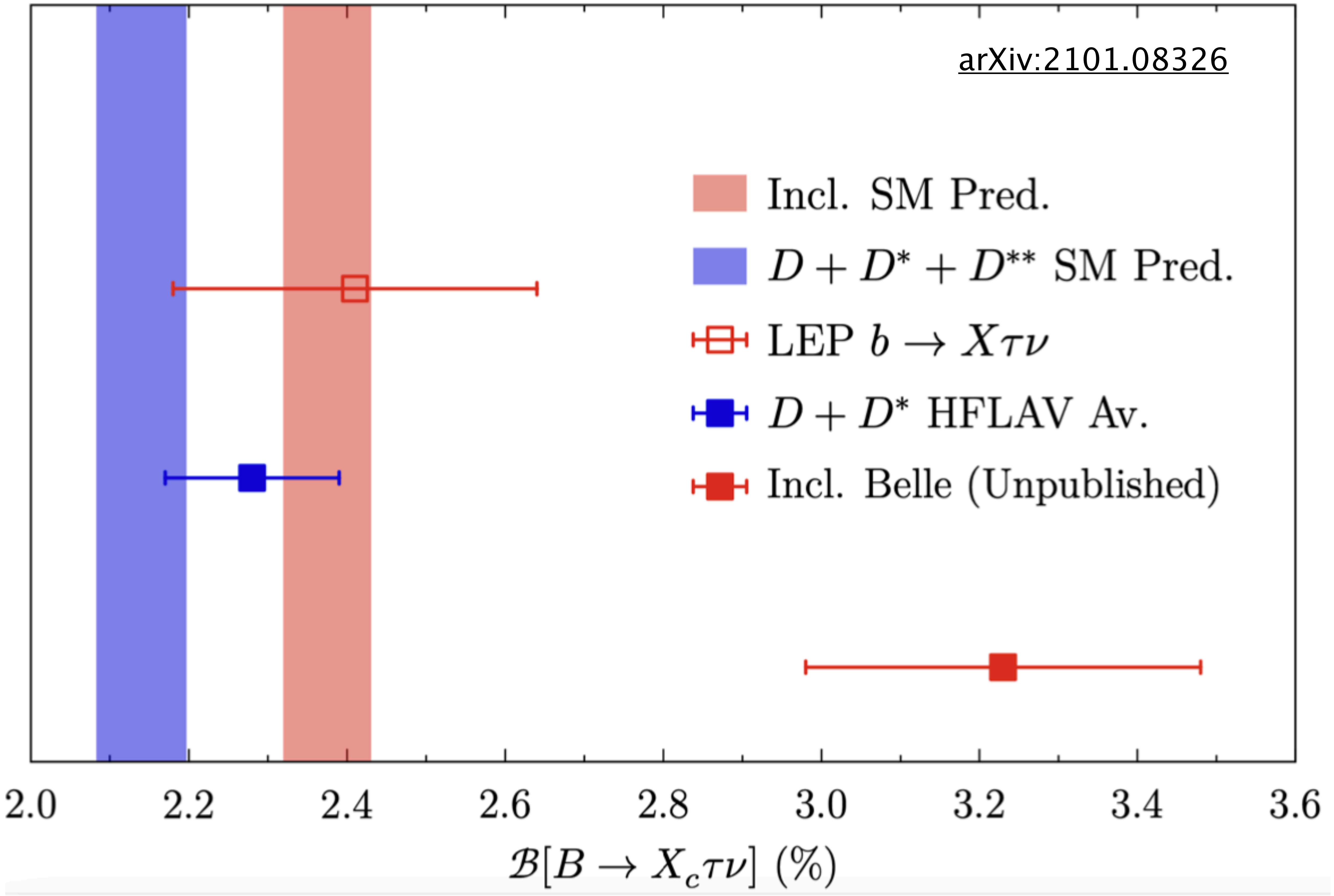
Statistical + systematic

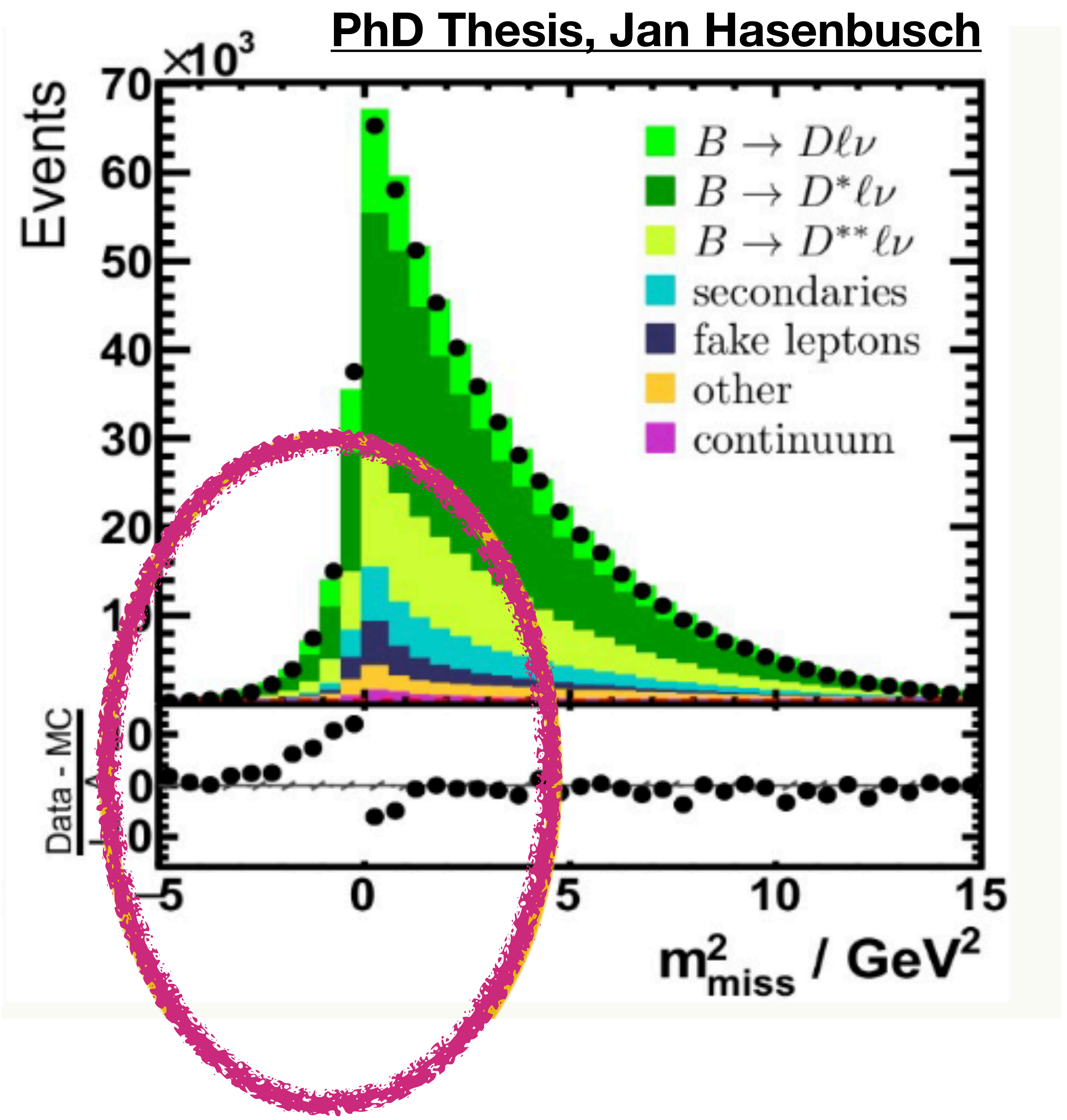


arXiv:1808.10567

$B \to X\tau\nu$

- Inclusive branching fraction is an important piece of the puzzle, complementary to exclusive D or D* decays.
- Most recent result since 2001.

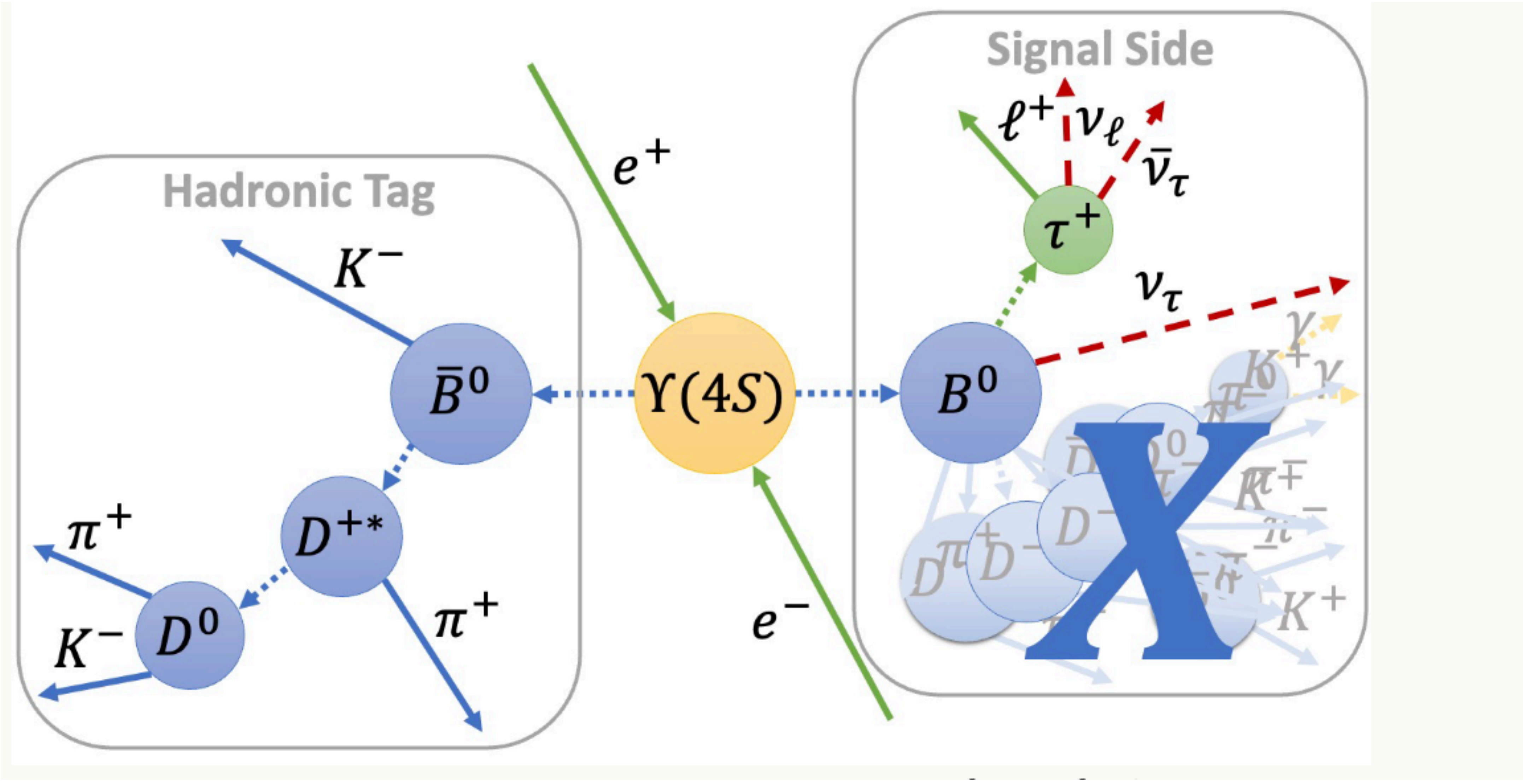




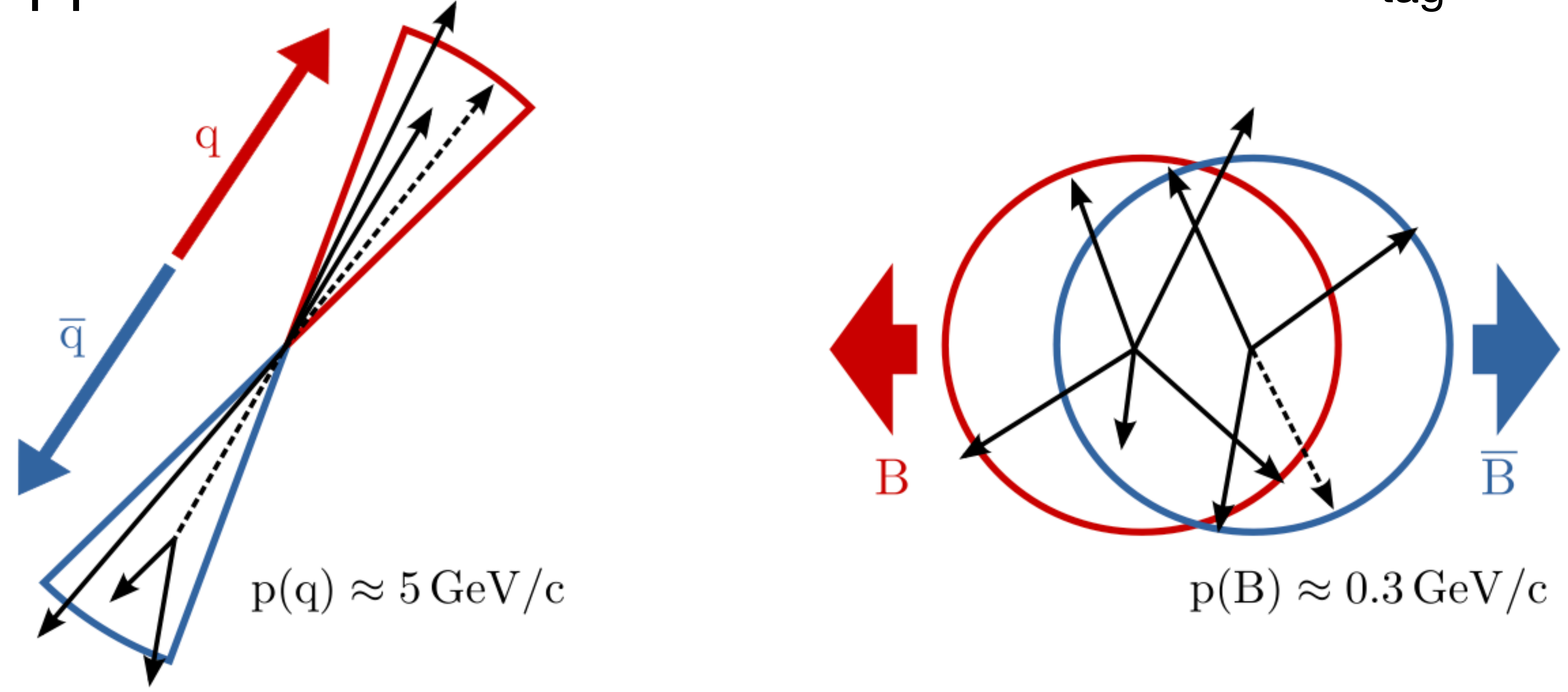
- Measurement sensitive to the modelling of signal and background semi-leptonic processes.
- Improved lepton identification and reduce fake rate at low momentum is critical.

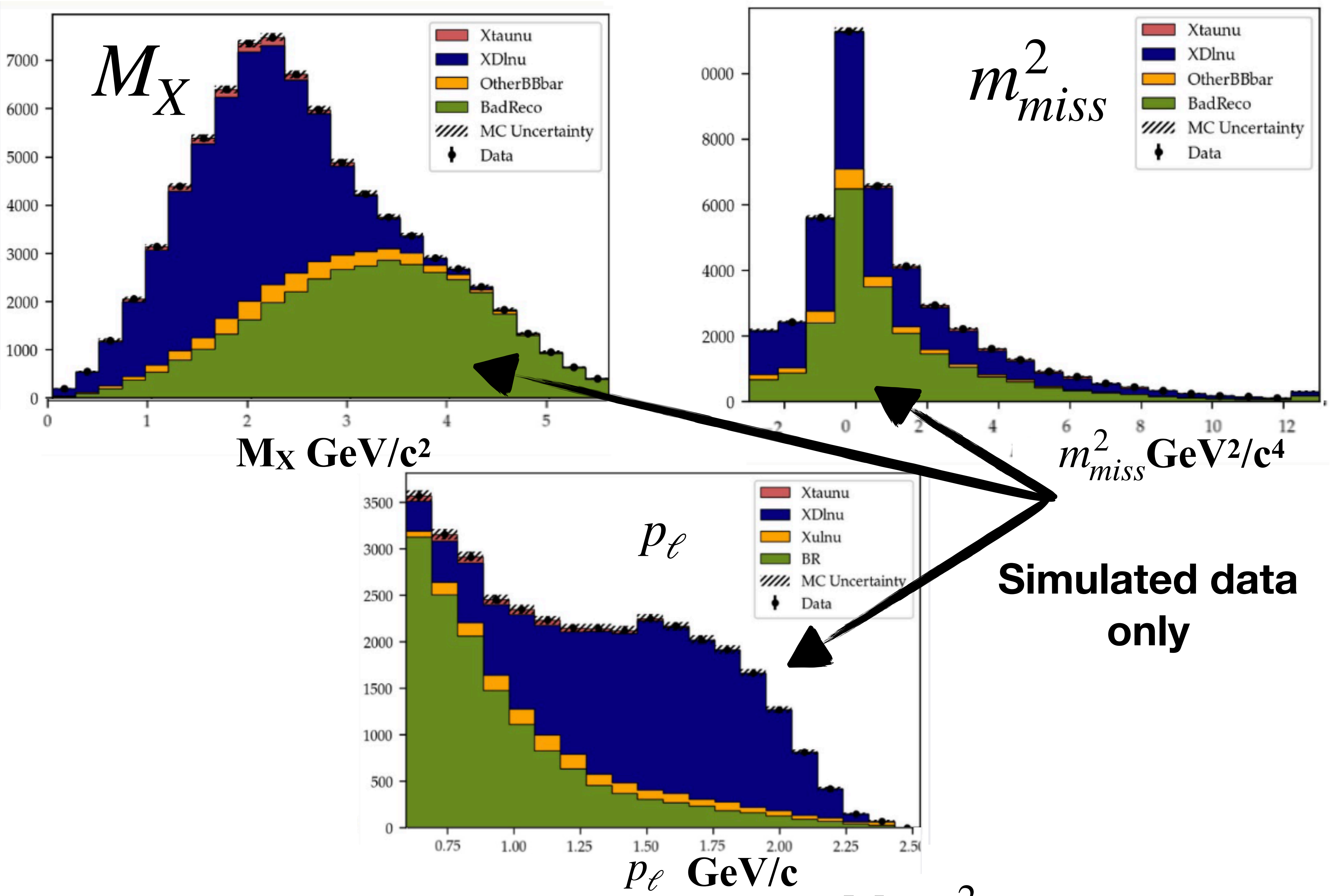
$B \to X\tau\nu$

- Use hadronic *B* tagging with leptonic decays of tau.



- Suppress continuum events and reconstruct B_{tag} + lepton.

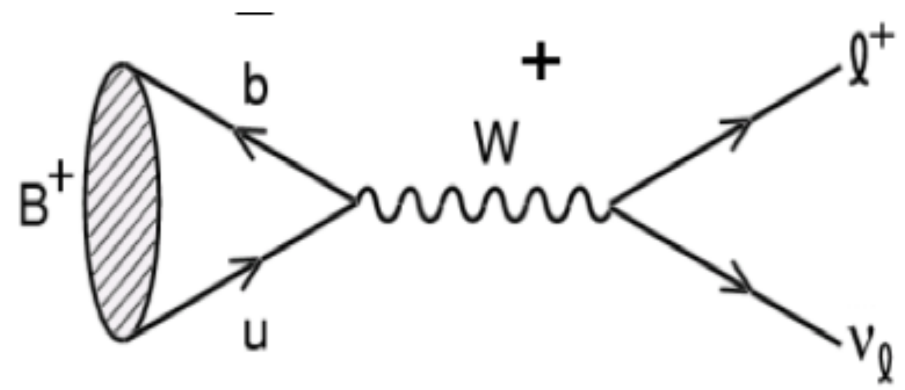


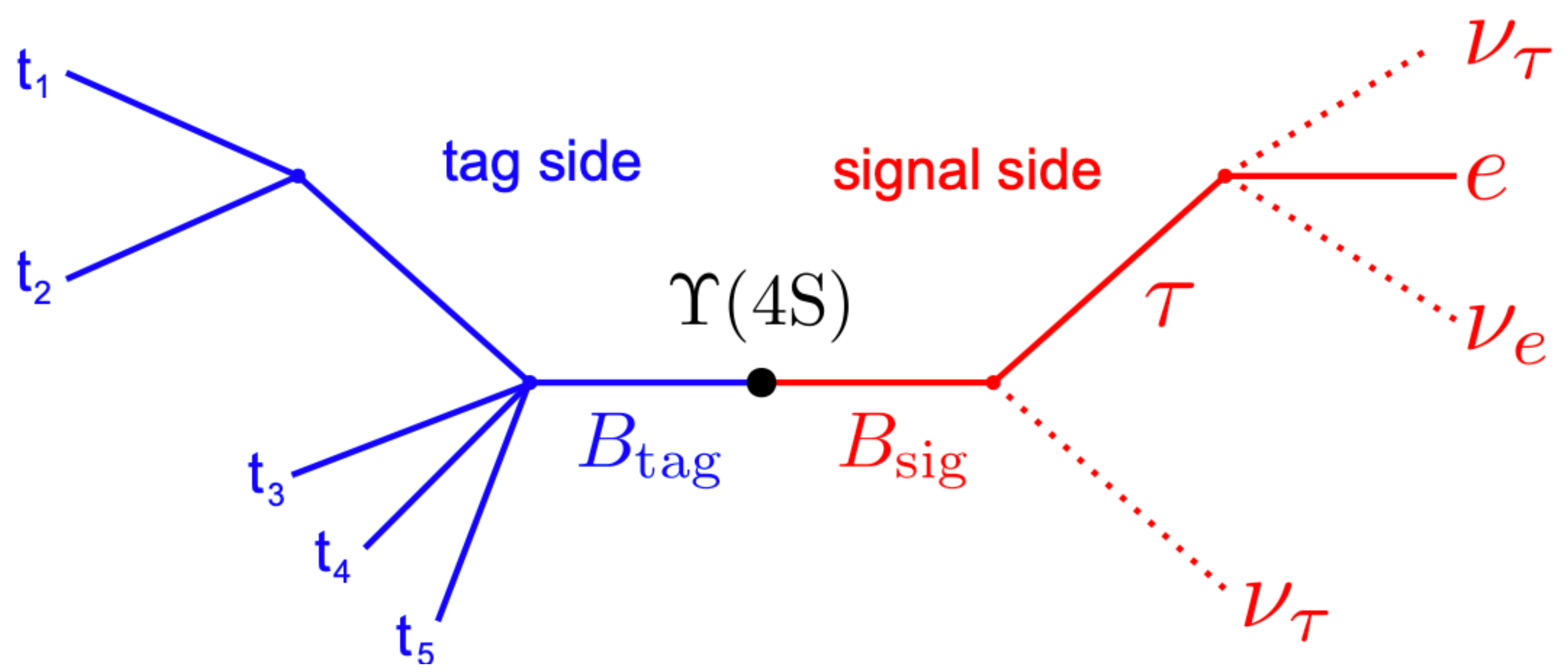


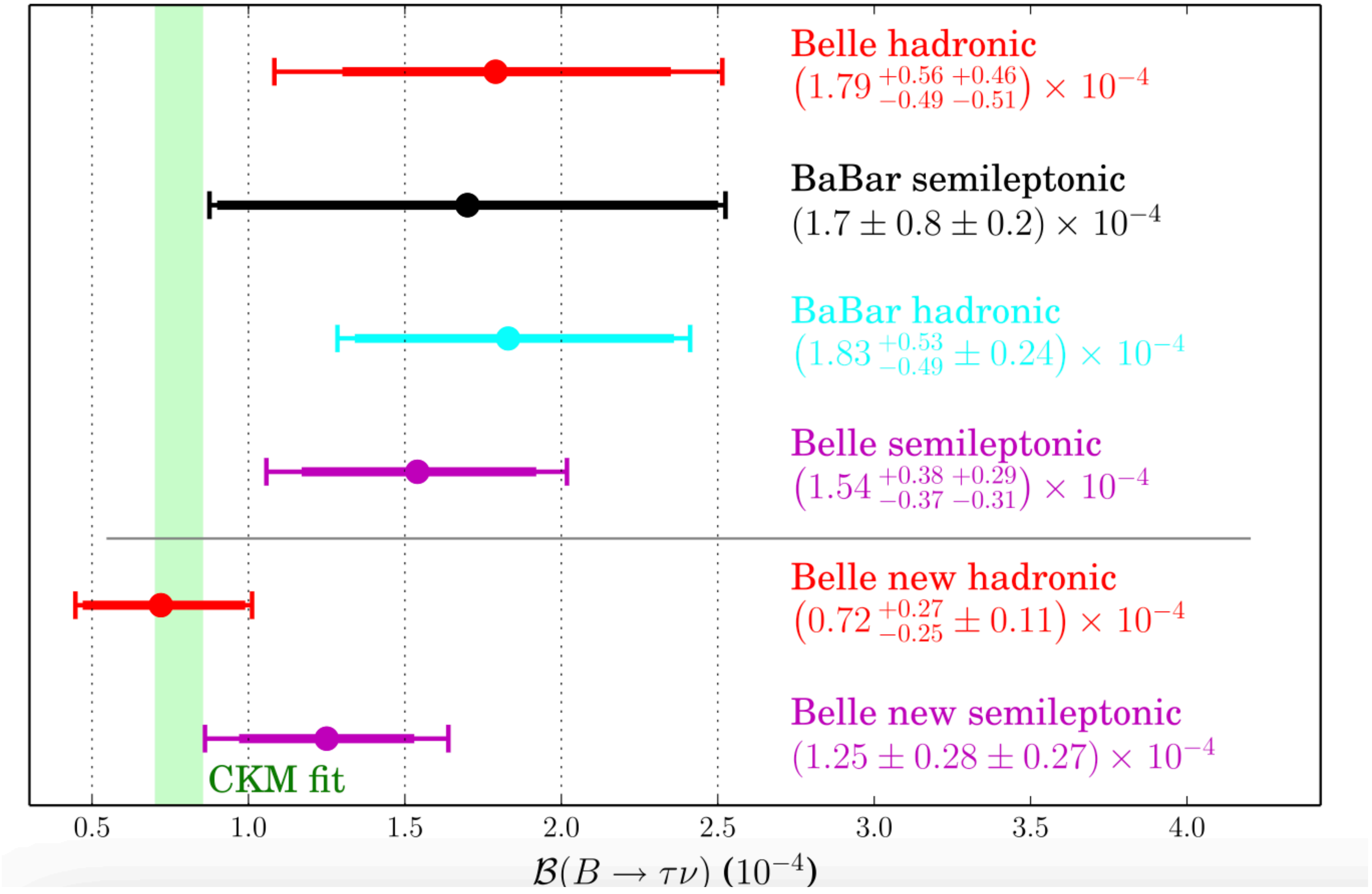
- Extract yields using quantities like M_X,m^2_{miss}, and p_ℓ
- Tools in development to understand and address any mismodeling in m^2_{miss} .
- First measurement with O(500) fb^{-1} of data is expected before long shut down.

$B \to \tau\nu$

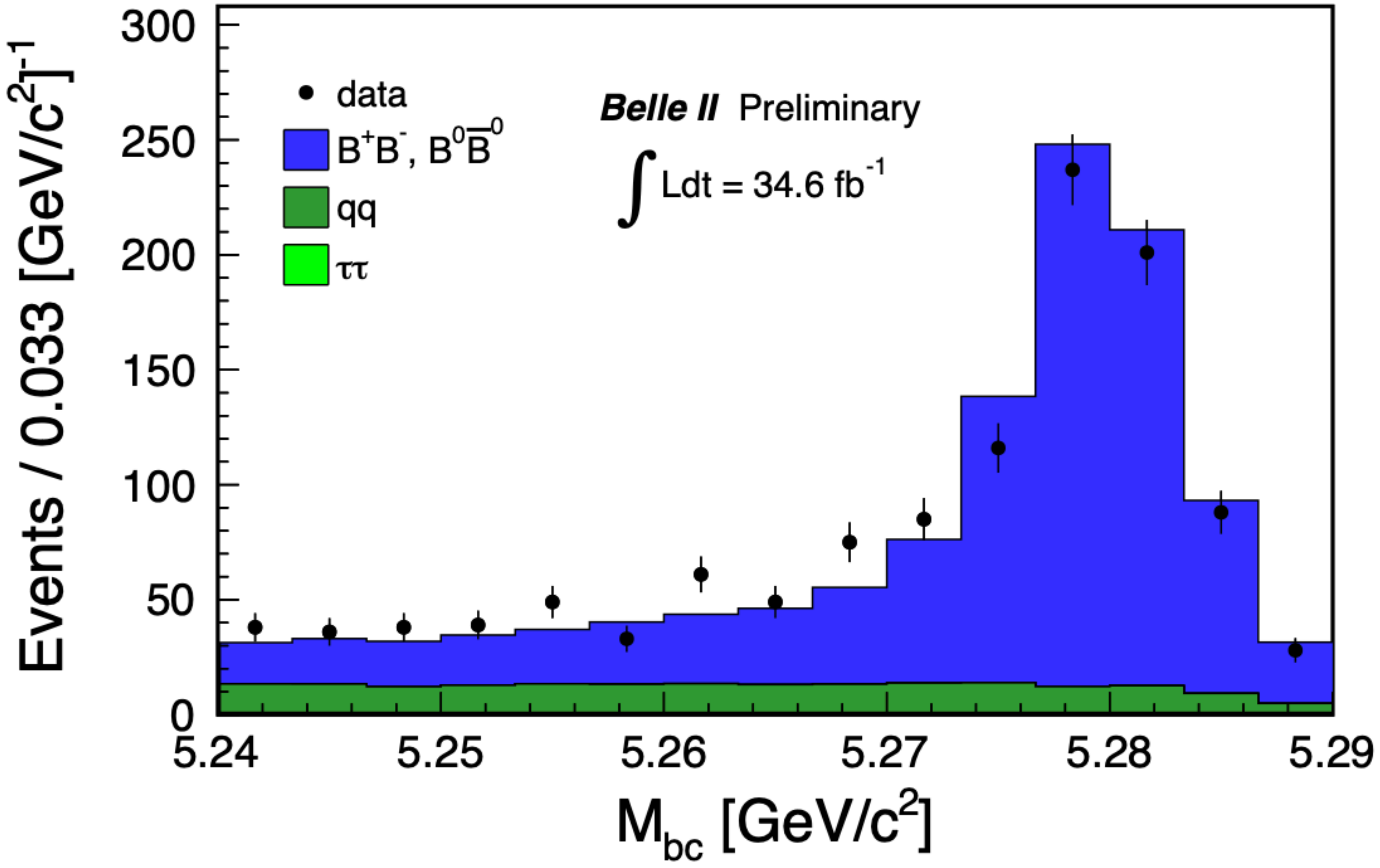
- High priority analysis for Belle II.
- Can provide orthogonal information on $|V_{ub}|$.







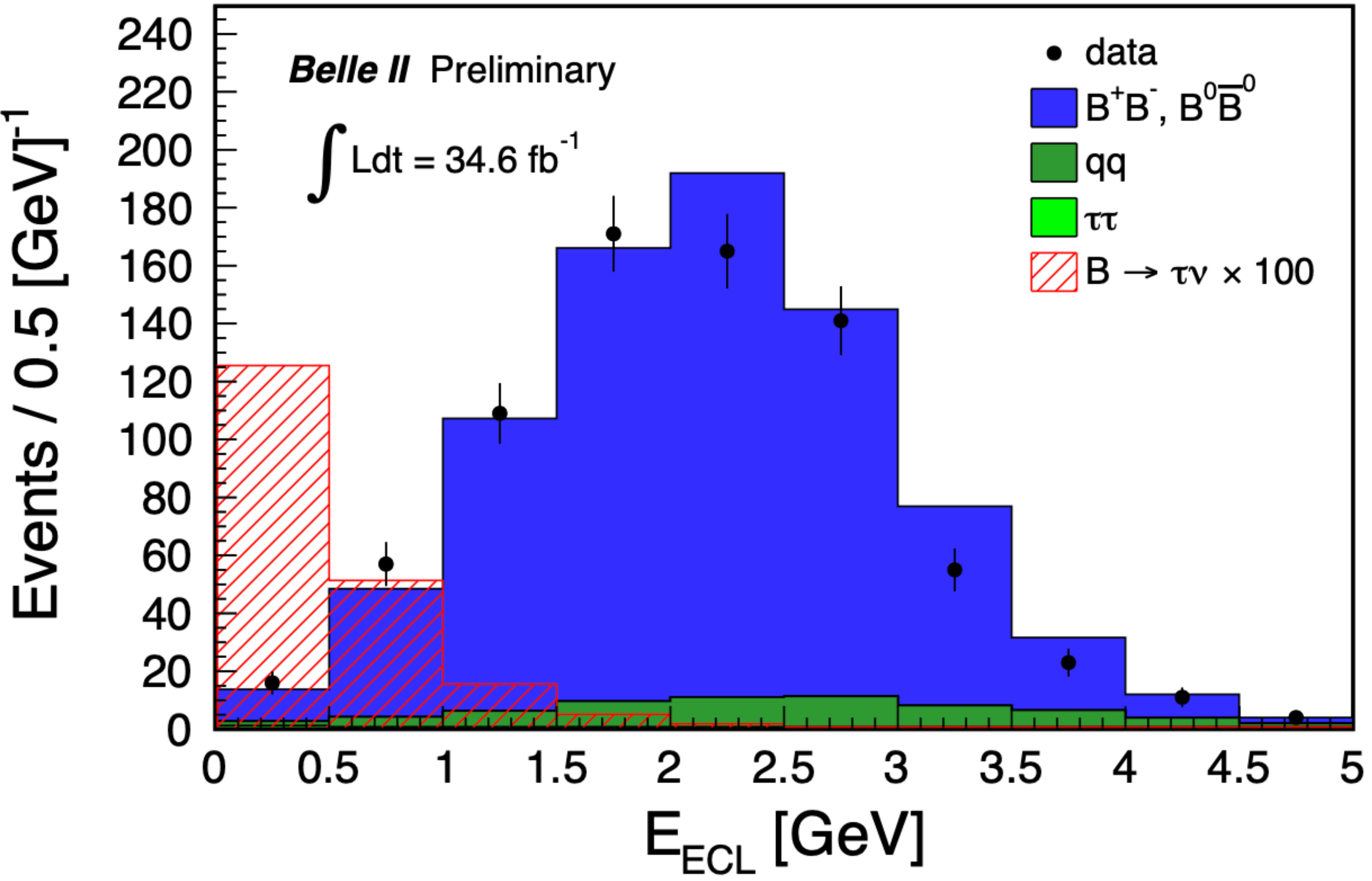
- Hadronic tagged measurement with leptonic τ decay.

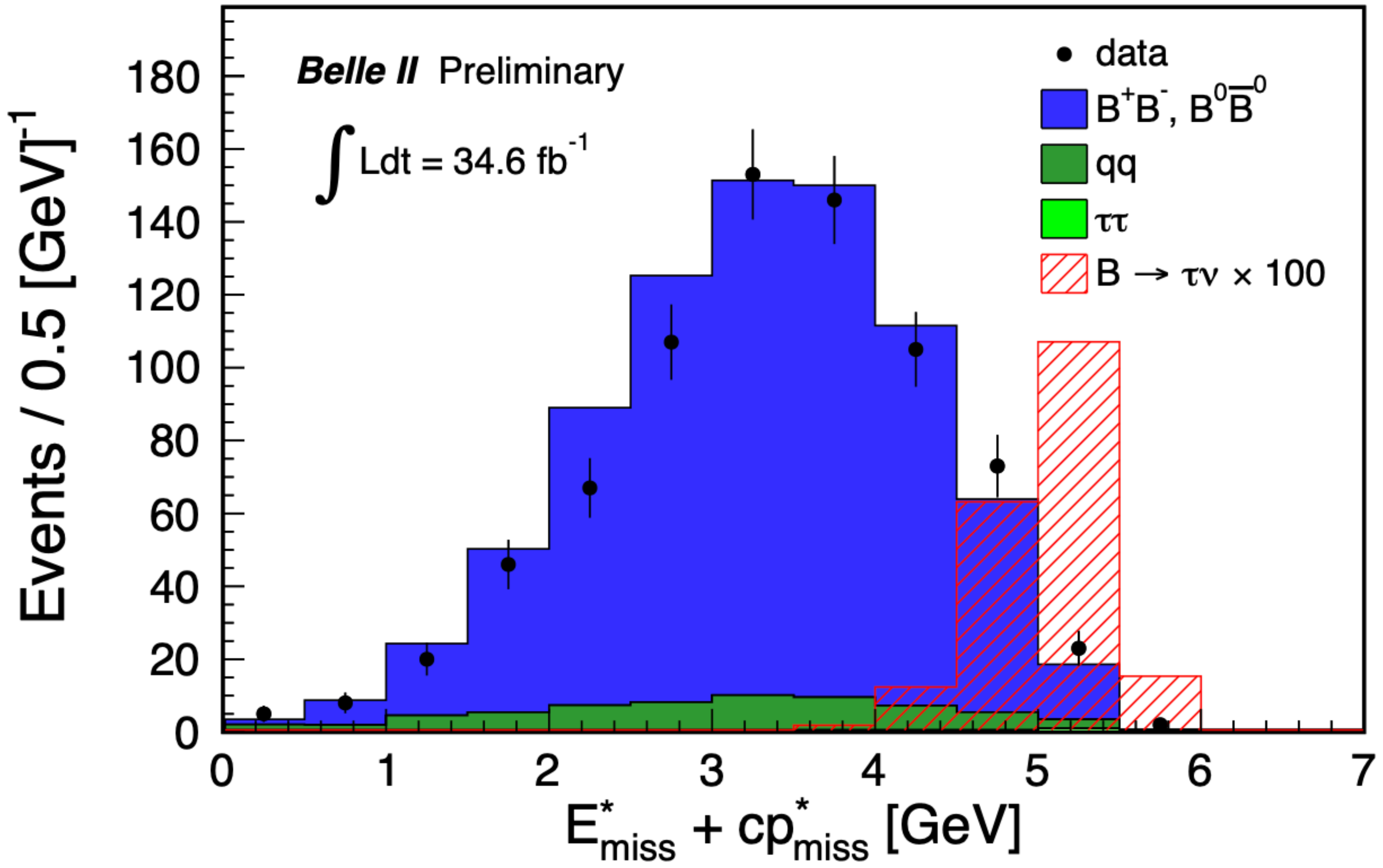


- Identify B_{tag} + lepton and suppress continuum events.

$B \to \tau\nu$

- Reasonable data-MC agreement and correct modeling of backgrounds for key variables.





	Integrated Luminosity (ab^{-1})	1	5	50
hadronic tag	statistical uncertainty (%)	29	13	4
	systematic uncertainty (%)	13	7	5
	total uncertainty (%)	32	15	6
semileptonic tag	statistical uncertainty (%)	19	8	3
	systematic uncertainty (%)	18	9	5
	total uncertainty (%)	26	12	5

- E_{ECL} affected by beam background contributions.
- Impact mitigated by optimizing selections on clusters in the rest-of-event.

- Improved precision with increasing data set to come.
  - First results expected with O(500) fb^{-1}.

Outlook

- Belle II is getting ready for a range of results in the semi-tauonic sector.
- Confirmation of the B anomalies and more precise measurements as the size of the data set increases.
- Improvements in B-tagging, lepton identification, background modelling, and beam background suppression are ready.
- On the hunt for new physics!!!

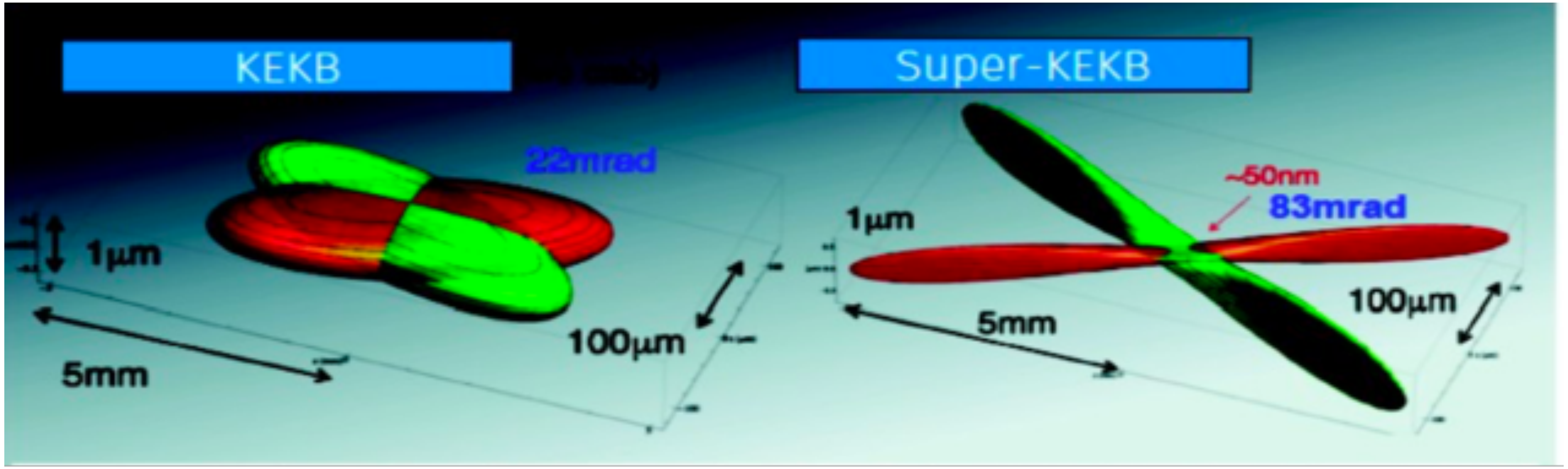
Beam Backgrounds

Sources of beam backgrounds:

• Touschek scattering: Coulomb scattering between 2 particles in the same beam bunch.

• Beam-case: scattering off residual gas atoms in the beam pipe

• Synchrotron radiation: photons emitted when electrons are bent by magnetic fields



$B \to X\tau\nu$

- Leading systematic uncertainties:
  - Statistical
  - Luminosity
  - PID weights
  - FEI calibration
  - $X_u\ell\nu$ BRs (FFs)
  - $X_u\tau\nu$ BRs (FFs)
  - $X_c\ell\nu$ BRs
  - $X_c\ell\nu$ FFs
  - $X_c\tau\nu$ BRs
  - $X_c\tau\nu$ FFs

$B \to X[\tau \to e\nu\nu]\nu$

Error source	Relative ratio of final uncertainty / %		
	Fakes & Other	$X\ell\nu$	$X\tau\nu$
Total rel. Unc.	**2.3**	**1.1**	**13.4**
Statistical	14.6	23.0	35.1
"Fit"	11.5	7.1	39.3
FEI, Lumi	0.0	0.0	0.3
PID	0.5	1.0	**7.4**
$\mathcal{B}$ total	**54.7**	**60.3**	**14.7**
$\mathcal{B}(D\ell\nu)$	0.5	0.3	0.0
$\mathcal{B}(D^*\ell\nu)$	0.8	1.7	1.1
$\mathcal{B}(D^{**}\ell\nu)$	1.8	4.5	4.1
$\mathcal{B}(D\pi\pi\ell\nu)$	**34.9**	**29.7**	0.2
$\mathcal{B}(D\eta\ell\nu)$	**36.1**	**48.4**	**10.3**
$\mathcal{B}(D_sK\ell\nu)$	0.6	0.5	0.1
$\mathcal{B}$ corr.	-20.0	-24.8	-1.1
Total corr.	18.6	8.5	3.2