Belle II status and prospects for studies of charged currents

May 15, 2023

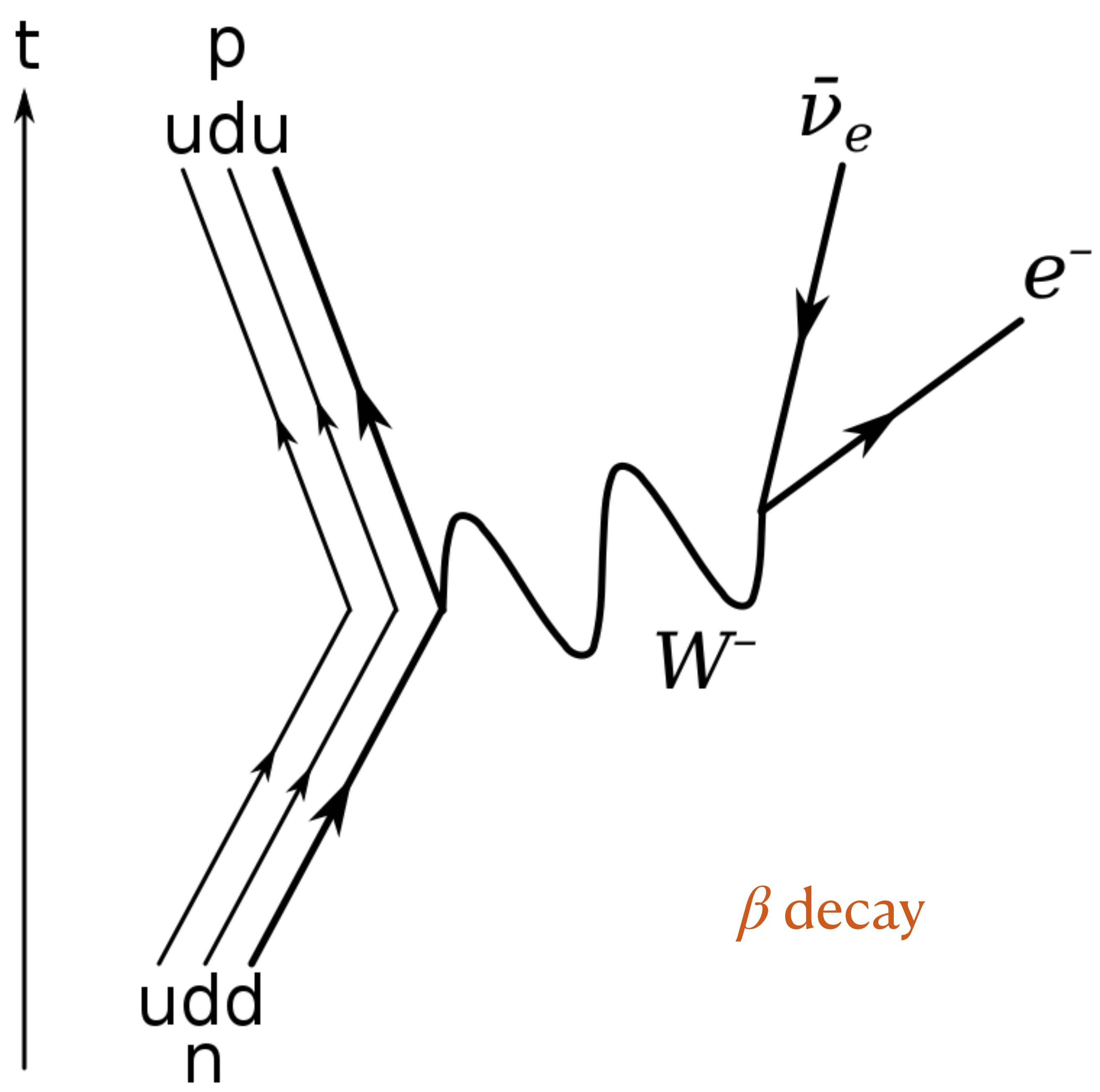
Sourav Dey
on behalf of the Belle II Collaboration

Belle II

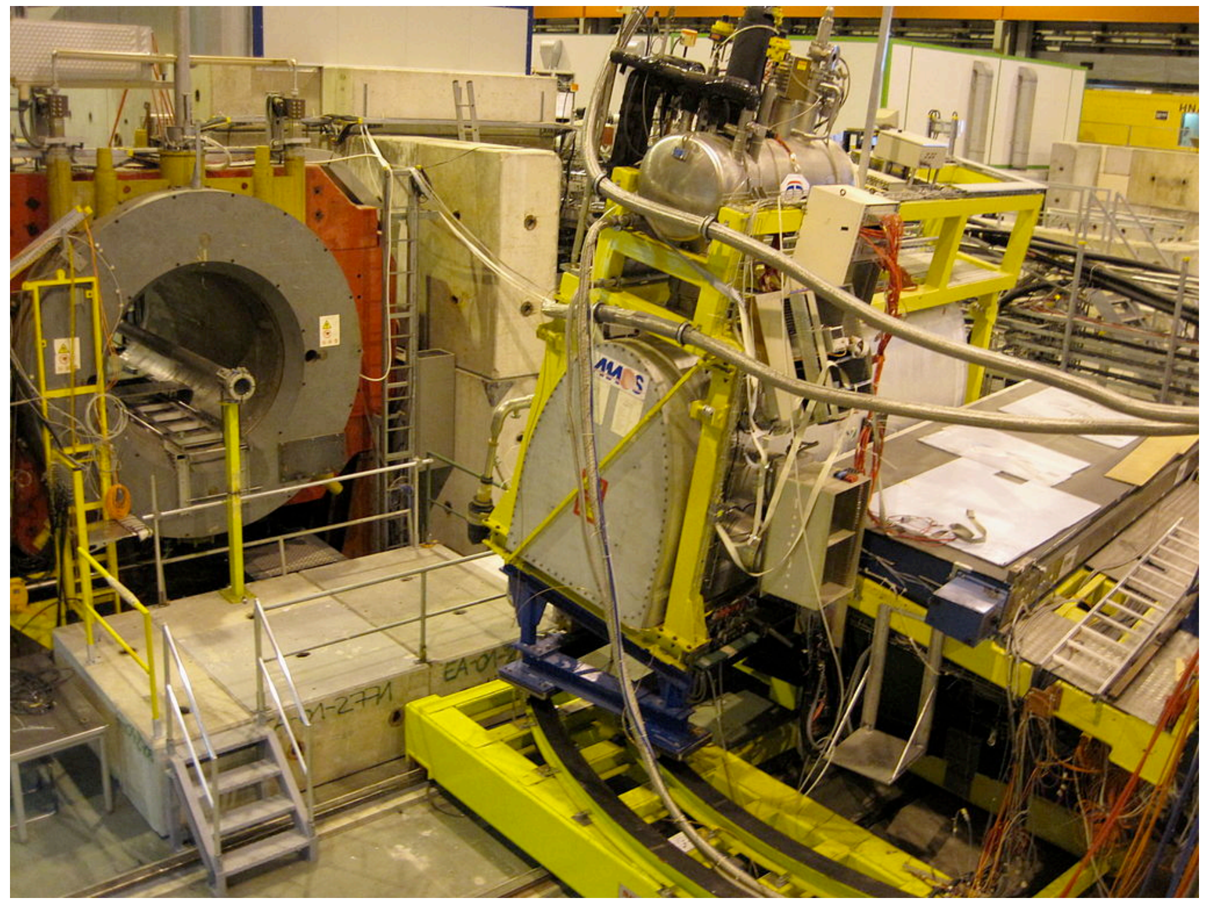
TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Charged Currents

- Exchange of W bosons
- Verified mediators of neutrino absorption and emission
- Unambiguous signals of W bosons first seen in UA1 and UA2 experiments at Super Proton Synchrotron in CERN(1983)
- $b \to c, d \to u$ etc. Change of flavor
- Belle II prospects(covered in this talk):
  - $b \to c$ anomalies
  - Light lepton Universality tests
  - $|V_{cb}|$ measurement

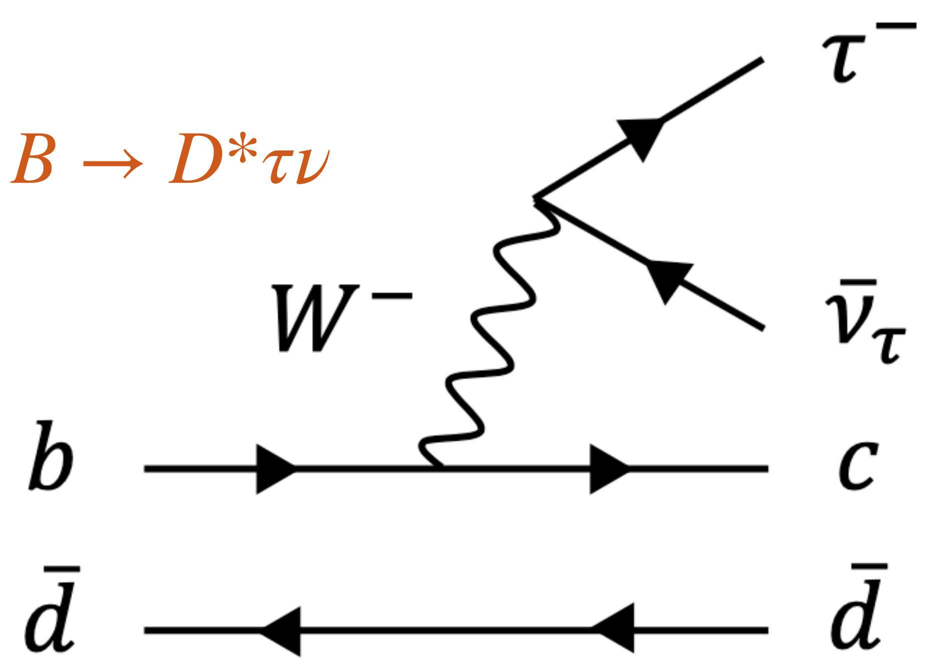


β decay

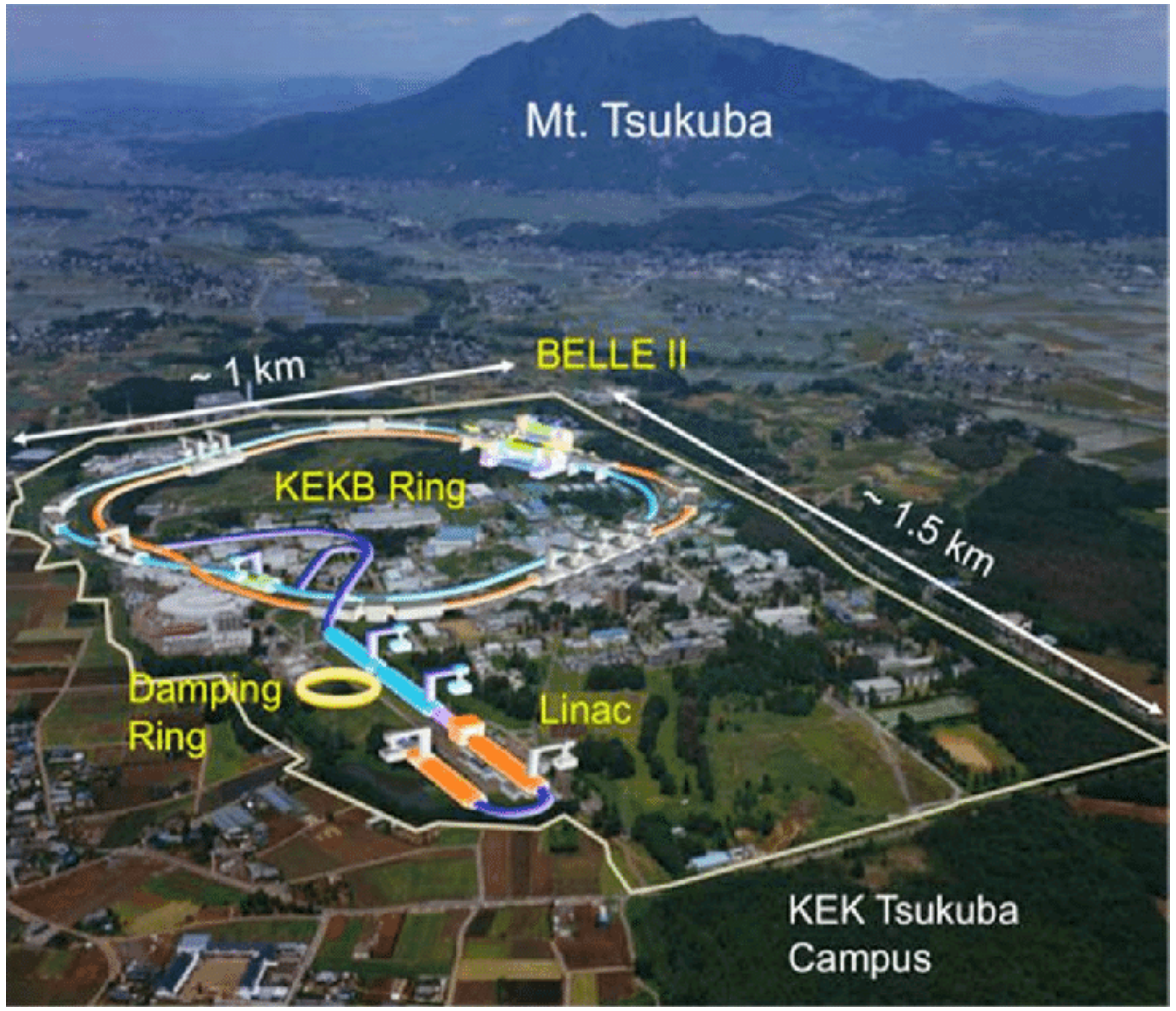


SPS, CERN

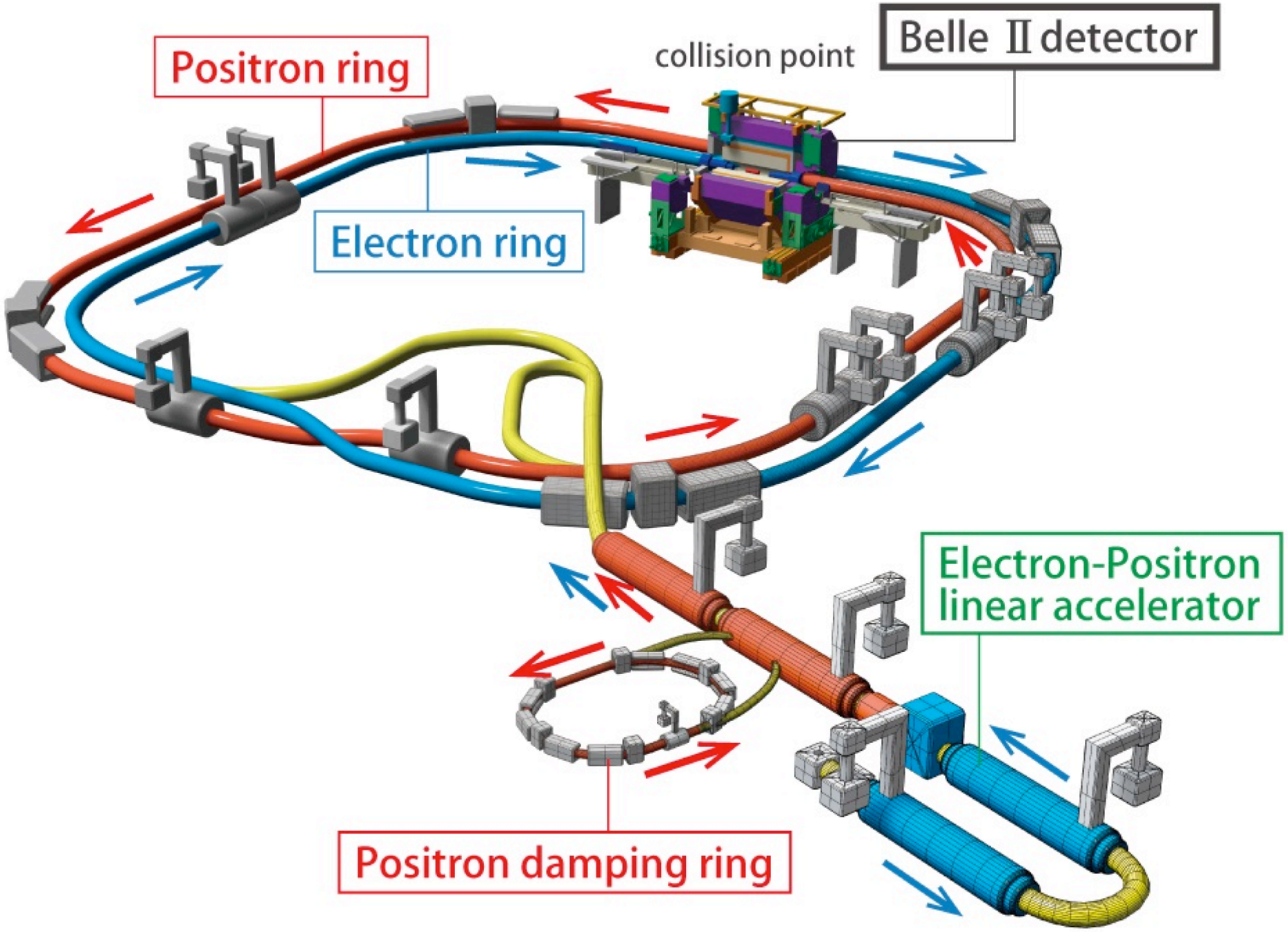
$B \to D^* \tau \nu$



SuperKEKB



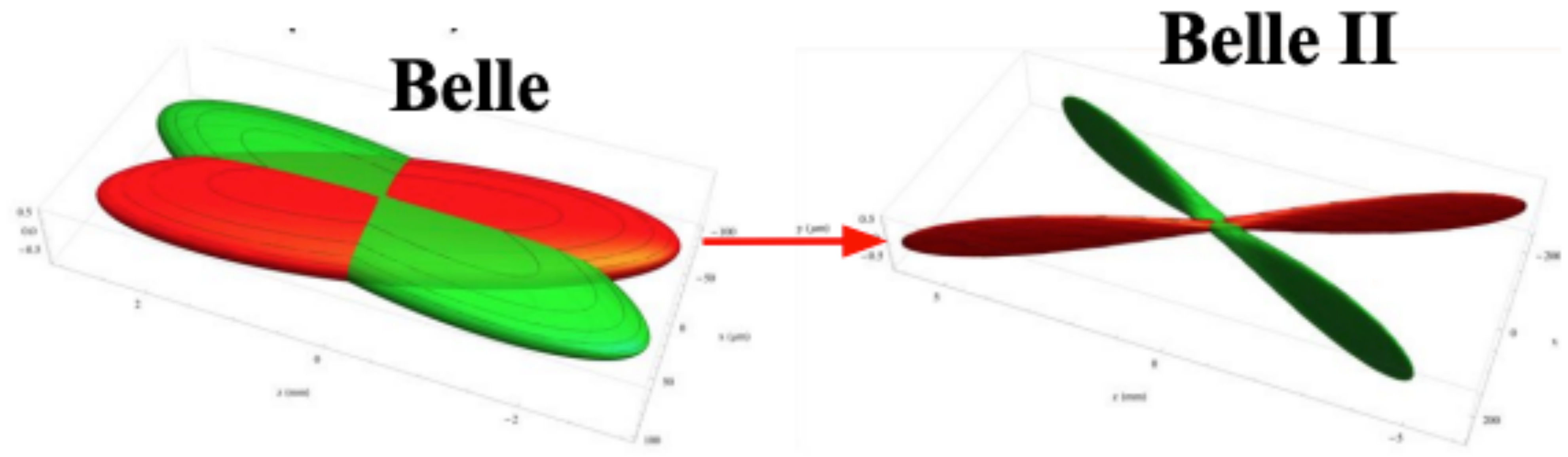
Mt. Tsukuba
~ 1 km
BELLE II
KEKB Ring
~ 1.5 km
Damping Ring
Linac
KEK Tsukuba Campus

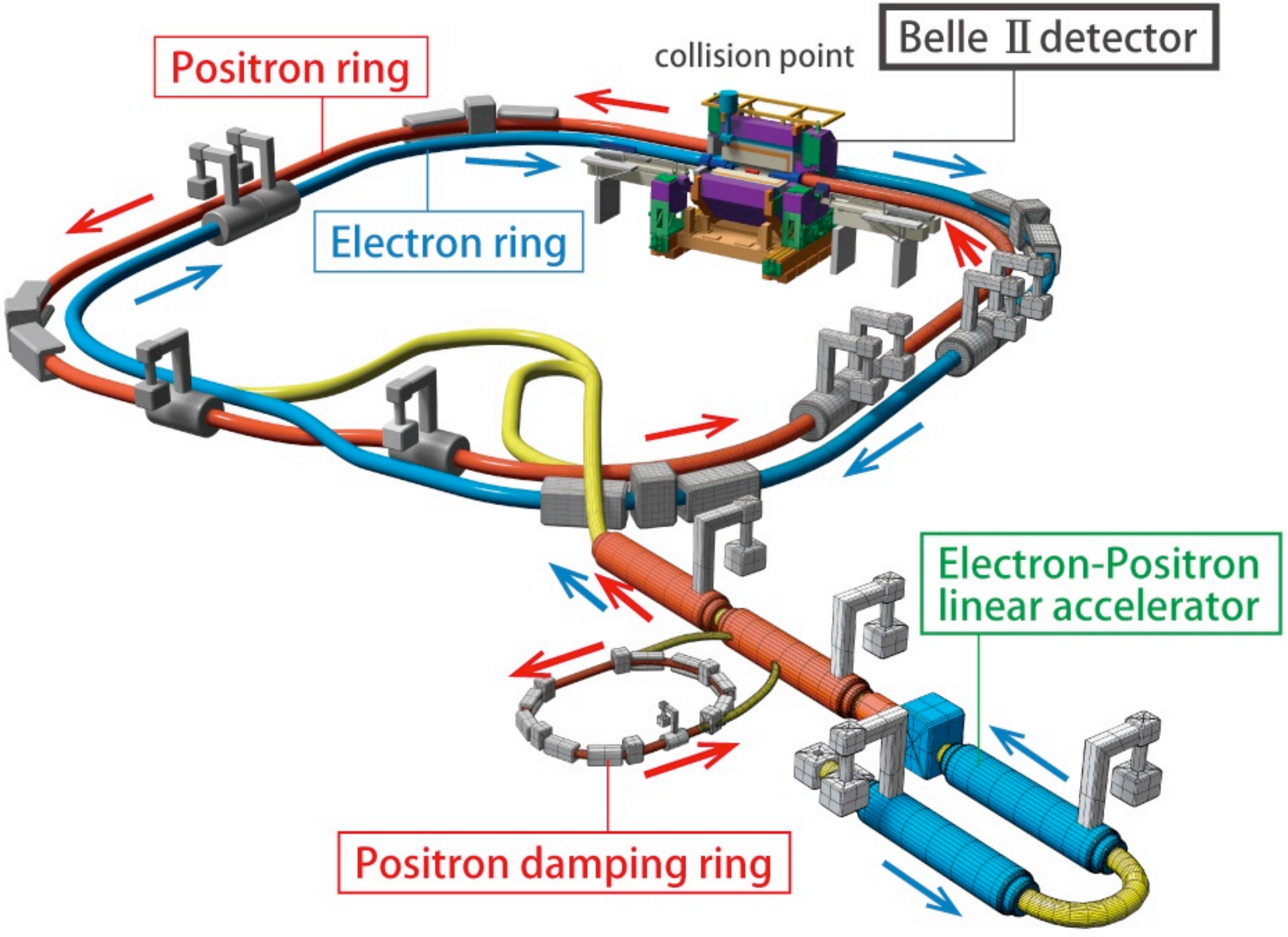


Positron ring
collision point
Belle II detector
Electron ring
Electron-Positron linear accelerator
Positron damping ring

SuperKEKB

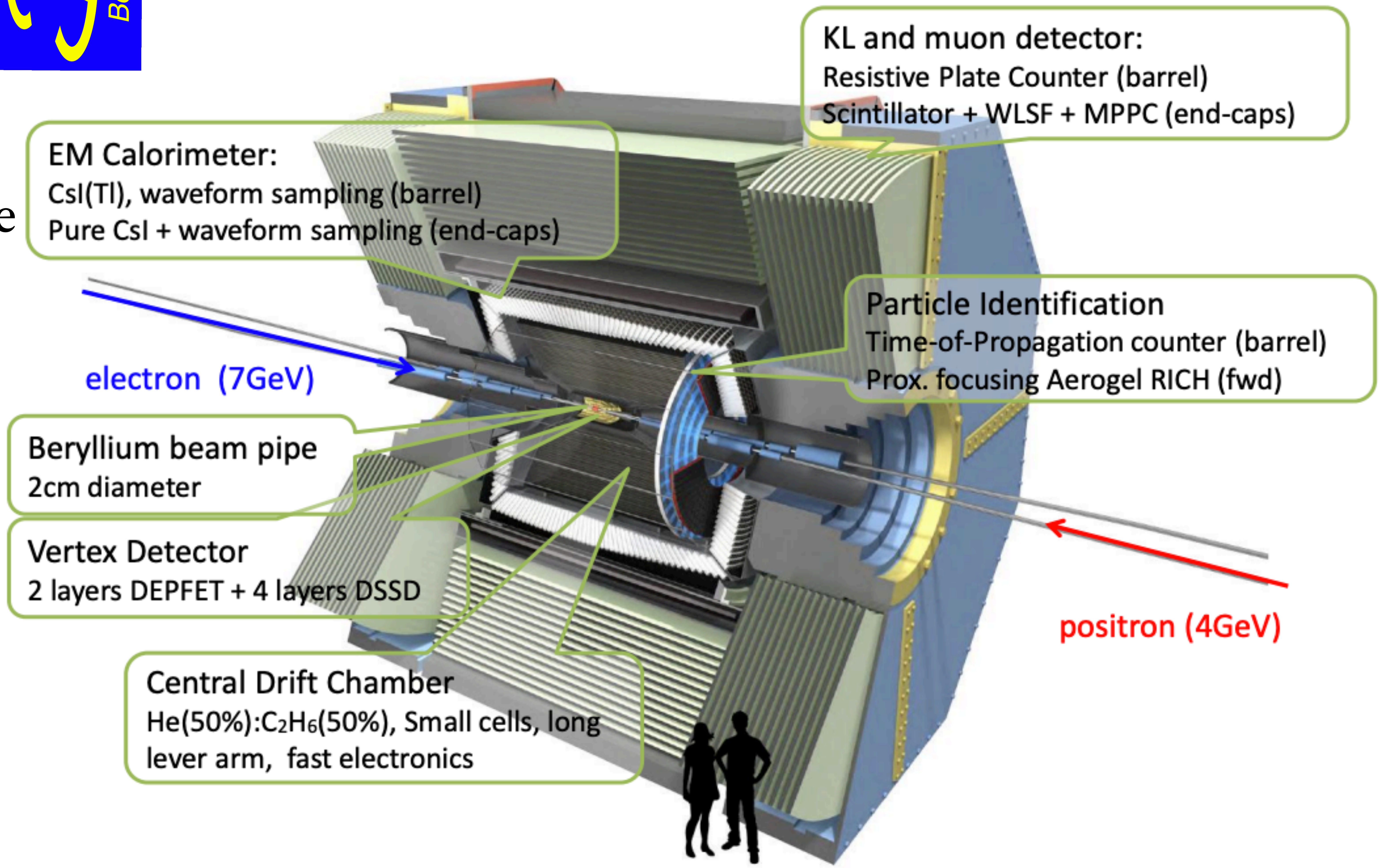
- 40 times larger luminosity than previous generation KEKB
- using nano-beam scheme with a tiny beam spot:
  - 60 nm x 10 μm x few 100 μm in y, x, z
- a few hundred atomic layers in y





The Belle II Detector

- SuperKEKB collides electron and positrons
- $\sqrt{s} = 10.58$ GeV : mass of $\Upsilon(4S)$
- $B\bar{B}$ pair production with a boost of the center-of-mass system: asymmetric collider
- B mesons can decay in a number of ways: prospect for studying a vast region of particle physics (Precision studies of B, charm, and tau physics, QCD and exotic hadrons, searches for BSM particles etc.)



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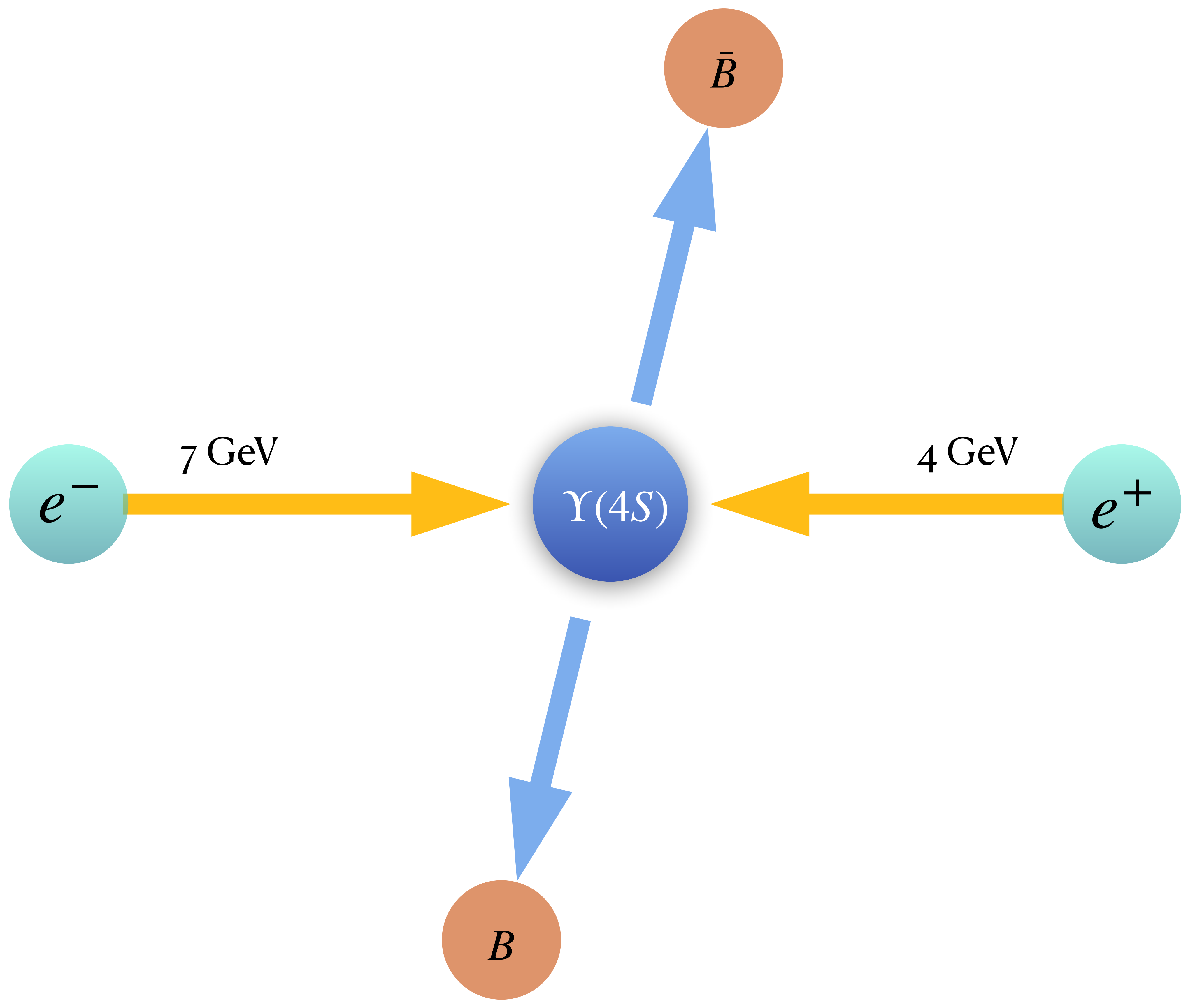
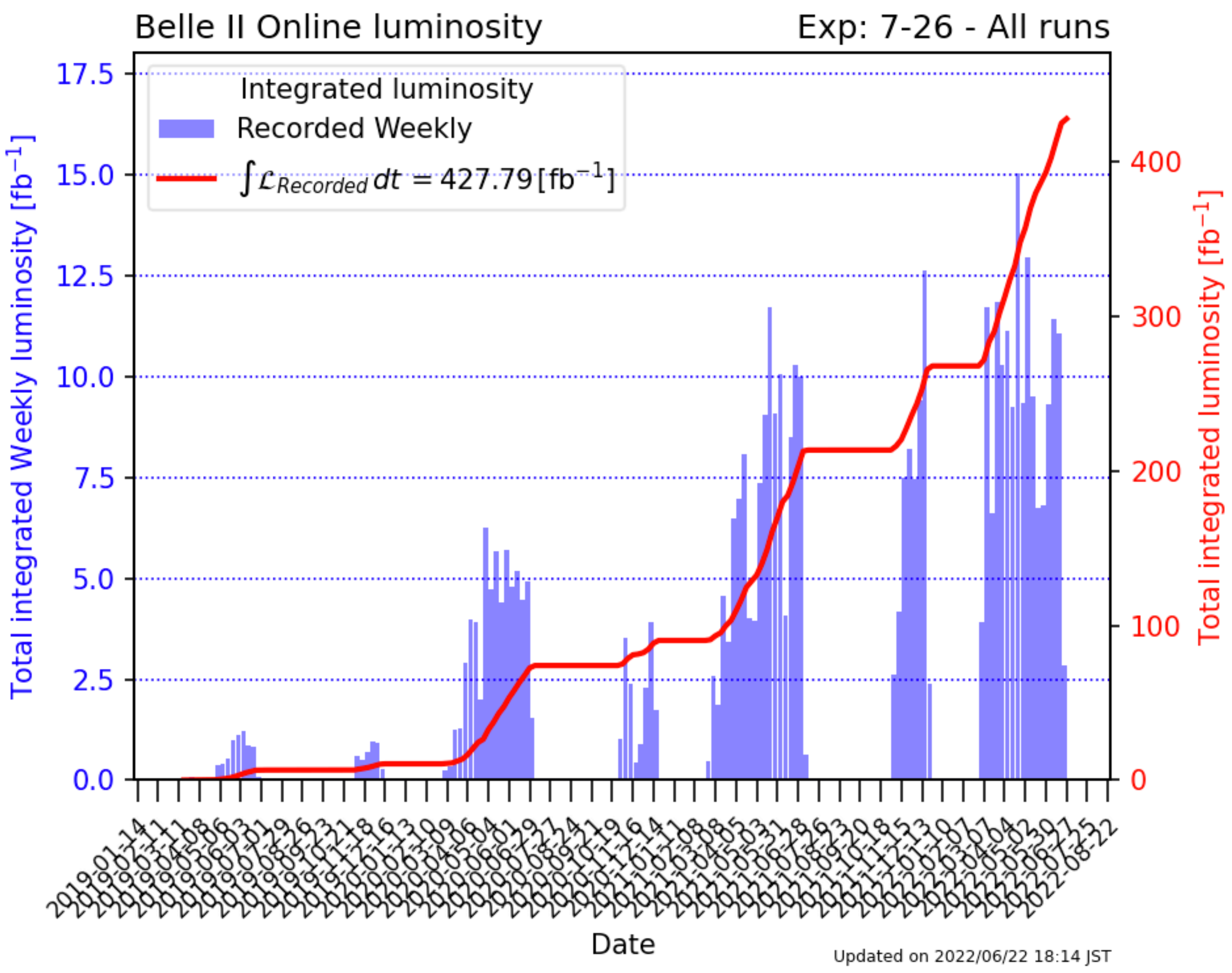
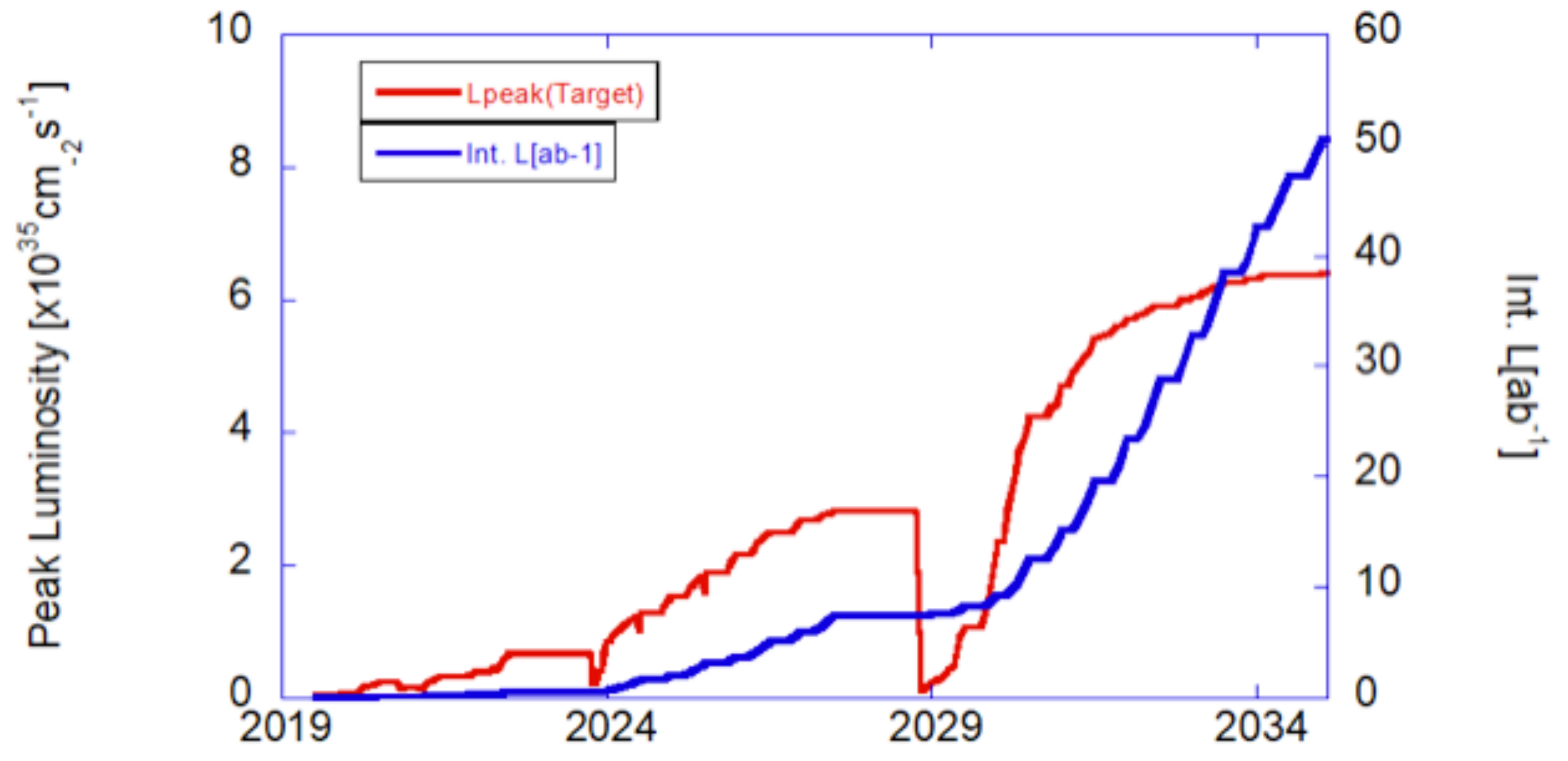


Luminosity





- Design integrated luminosity 50 ab^{-1}
- Regular data-taking since April 2019
- Current integrated luminosity 424 fb^{-1}
- Peak luminosity recorded : $4.7 \times 10^{34}\mathrm{cm}^{-1}\mathrm{s}^{-1}$
- At present, we have a long shutdown for accelerator and detector upgrades, will resume data taking in late 2023

Light-Lepton Universality Test : $R(X_{e/\mu})$ Measurement

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arXiv:2301.08266

- Excellent sensitivity to potential lepton-universality-violating (LUV) physics
- Previous direct searches
  - BR ratio in a single exclusive charmed hadron decay mode [Phys. Rev. D 100, 052007 (2019).]
  - the shapes of kinematic distributions of all decays to charmed hadrons [Phys. Rev. D 104, 112011 (2021)]
- First measurement of the inclusive branching fraction ratio .
- The most precise test of $e - \mu$ universality in semi-leptonic B-meson decays to date

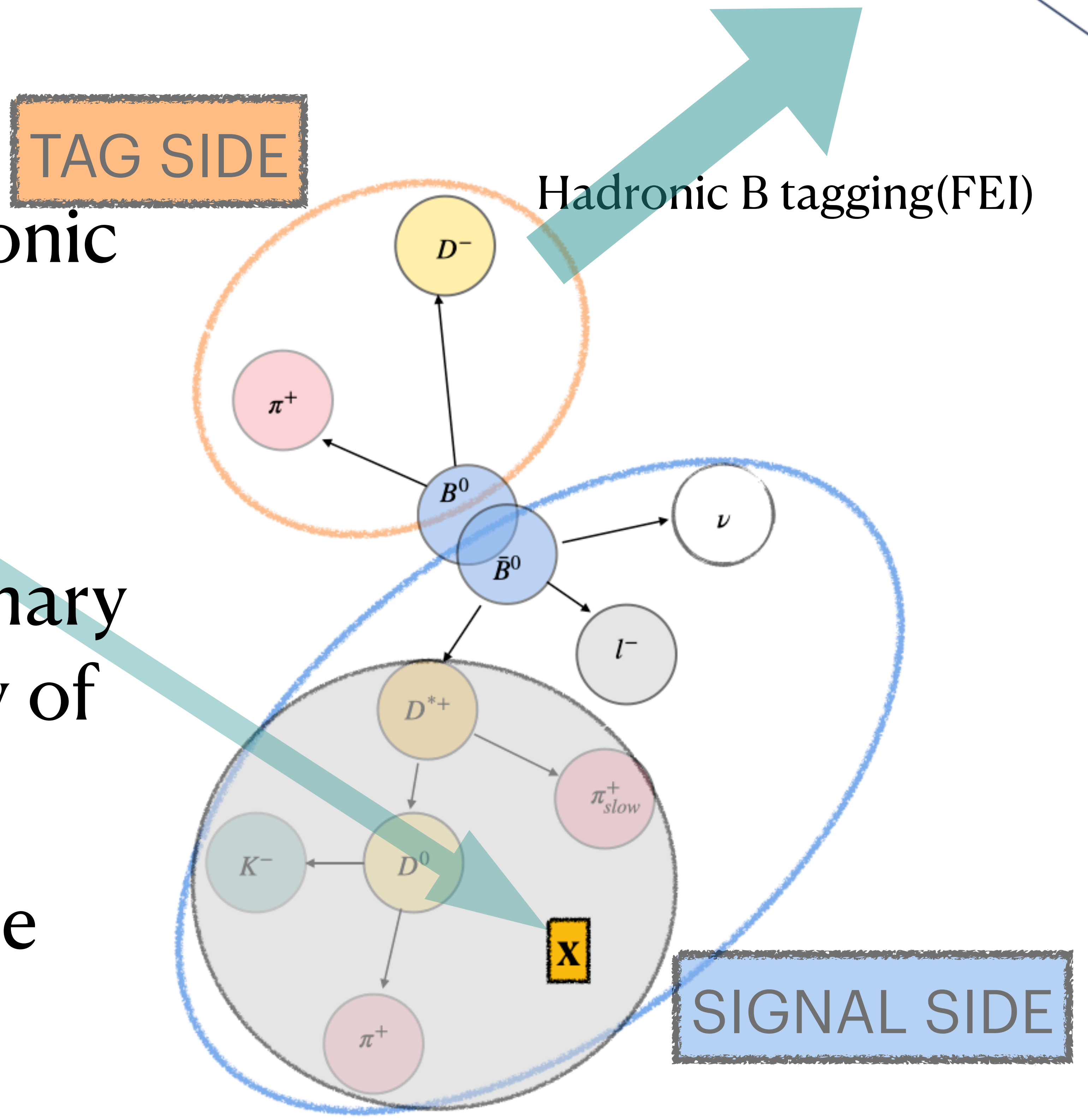
$$\boxed{R(X_{e/\mu}) = \frac{\mathcal{B}(\bar{B} \to X e^- \bar{\nu}_e)}{\mathcal{B}(\bar{B} \to X \mu^- \bar{\nu}_\mu)}}$$

This analysis uses:

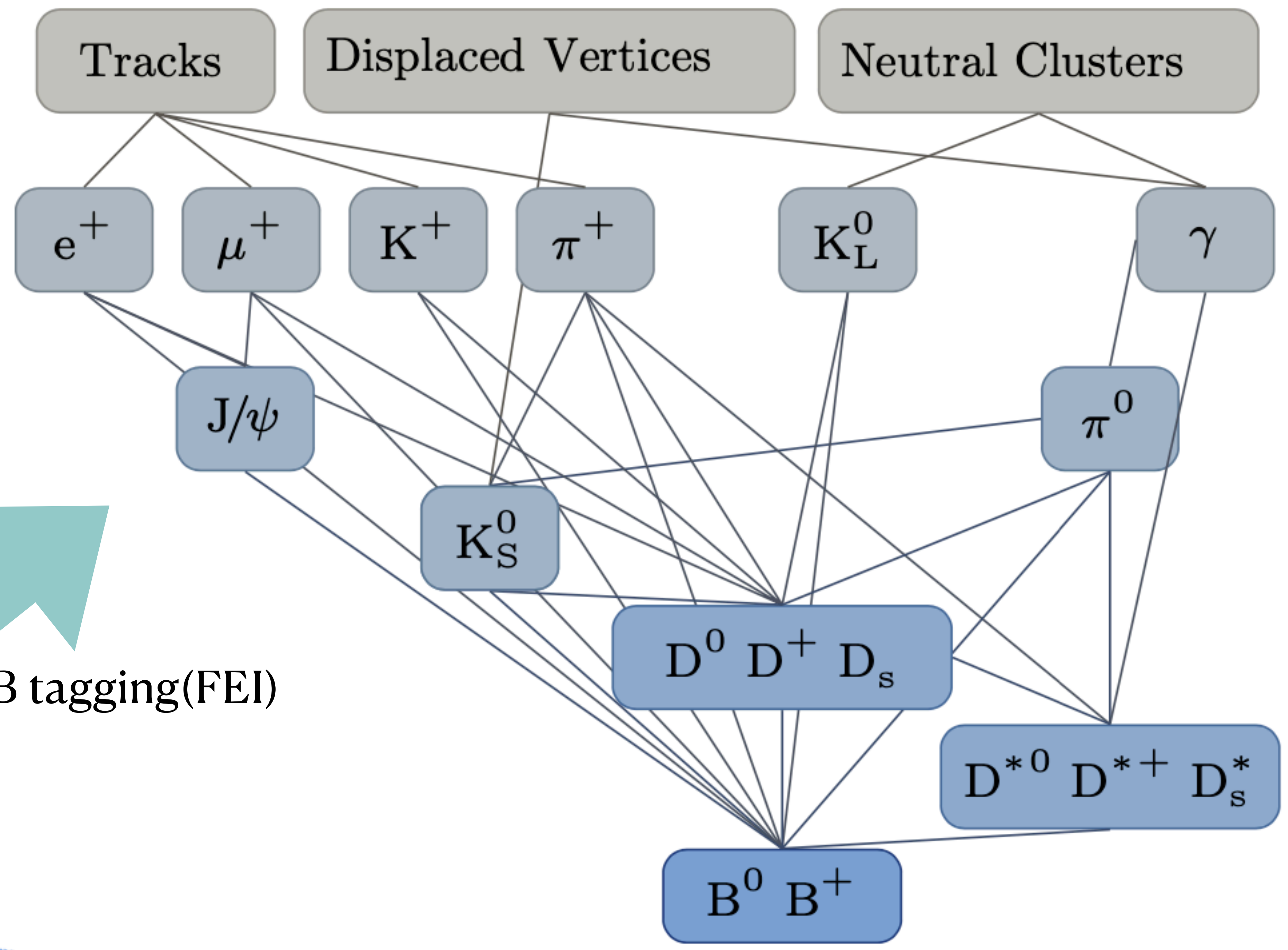
- Belle II collision data from 2019 and 2021 at a center-of-mass energy of $\sqrt{s} = 10.58$ GeV,
- Integrated luminosity 189 fb^{-1}, ~ 198×10^6 BB pairs.
- Additional 18 fb^{-1} off-resonance collision data below the $\Upsilon(4S)$ resonance, for backgrounds from continuum processes $e^+e^- \to q\bar{q}$, where q =u,d,s, or c quarks

Light-Lepton Universality Test : $R(X_{e/\mu})$ Measurement

- X the generic hadronic final state of the semi-leptonic decay of any flavor of B meson originating from $b \to c l \nu$ or $b \to u l \nu$ quark transitions
- Tag-side B mesons decay in fully hadronic modes(FEI)
- Lepton charge requirement:
  - corresponds to the charge of a primary lepton from the semi-leptonic decay of a signal B meson
  - that signal B meson has the opposite flavor to the tag B candidate



Inclusive signal modes

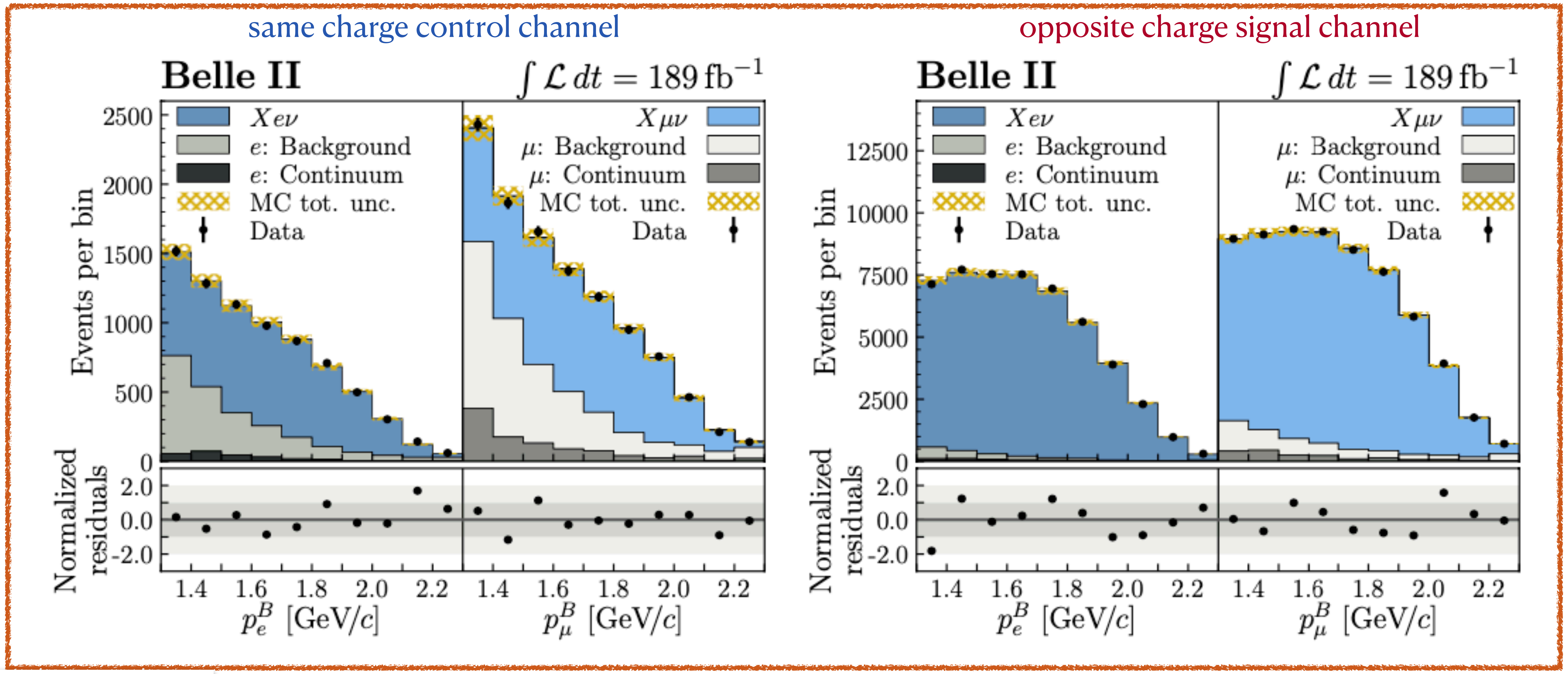


(Full Event Interpretation(FEI))

- MVA based approach
- reconstructs more than 100 explicit decay channels

https://doi.org/10.1007/s41781-019-0021-8

Light-Lepton Universality Test : $R(X_{e/\mu})$ Measurement



Simultaneous binned template fits to the p_e^B and p_μ^B spectra

(p_e^B = momentum of e in B rest frame etc.)

Source	Uncertainty [%]
Sample size	1.0
Lepton identification	1.9
$X_c \ell \nu$ branching fractions	0.1
$X_c \ell \nu$ form factors	0.2
Total	2.2

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

$$R(X_{e/\mu} \mid p_l^B > 1.3\ GeV/c) = 1.031 \pm 0.010(\text{stat}) \pm 0.019(\text{syst})$$

Consistent with Standard Model $R(X_{e/\mu})_{SM}$[1] by 1.2σ and the exclusive Belle $R(D^*{}_{e/\mu})$ [2],[3] measurement

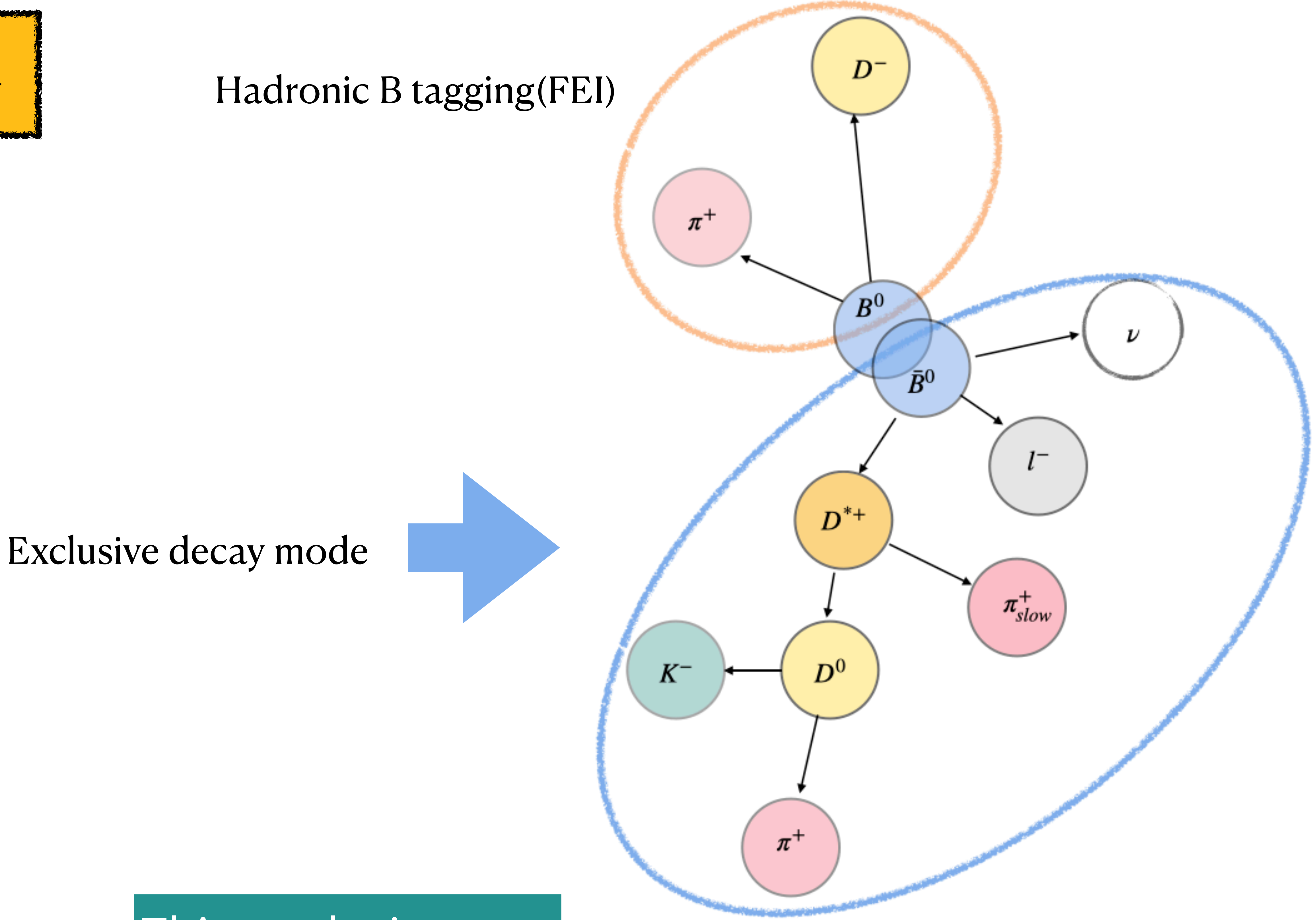
[1] J. High Energy Phys. 11, 007 (2022), [2] Phys. Rev. D 100, 052007 (2019), [3] arXiv:2301.07529

Light-Lepton Universality Test: Angular Asymmetry

Light-Lepton Universality Test: Angular Asymmetry

arXiv:2301.04716

- $\bar{B}^0 \to D^{*+} l^- \nu$ channel is used and reconstructed exclusively
- First dedicated light-lepton LU test using a complete set of angular asymmetry observables
  - designed to cancel most theoretical and experimental uncertainties
  - highly sensitive to LUV
- lepton universality is tested by comparing five angular asymmetries of e and μ



This analysis uses:

- Belle II collision data from 2019 and 2021 at a center-of-mass energy of $\sqrt{s} = 10.58$ GeV,
- Integrated luminosity 189 fb^{-1}, ~ 198×10^6 BB pairs.

Light-Lepton Universality Test: Angular Asymmetry

recoil parameter

$$w \equiv \frac{m_B^2 + m_{D^*}^2 - q^2c^2}{2m_B m_{D^*}}$$

$m_B = B$ mass

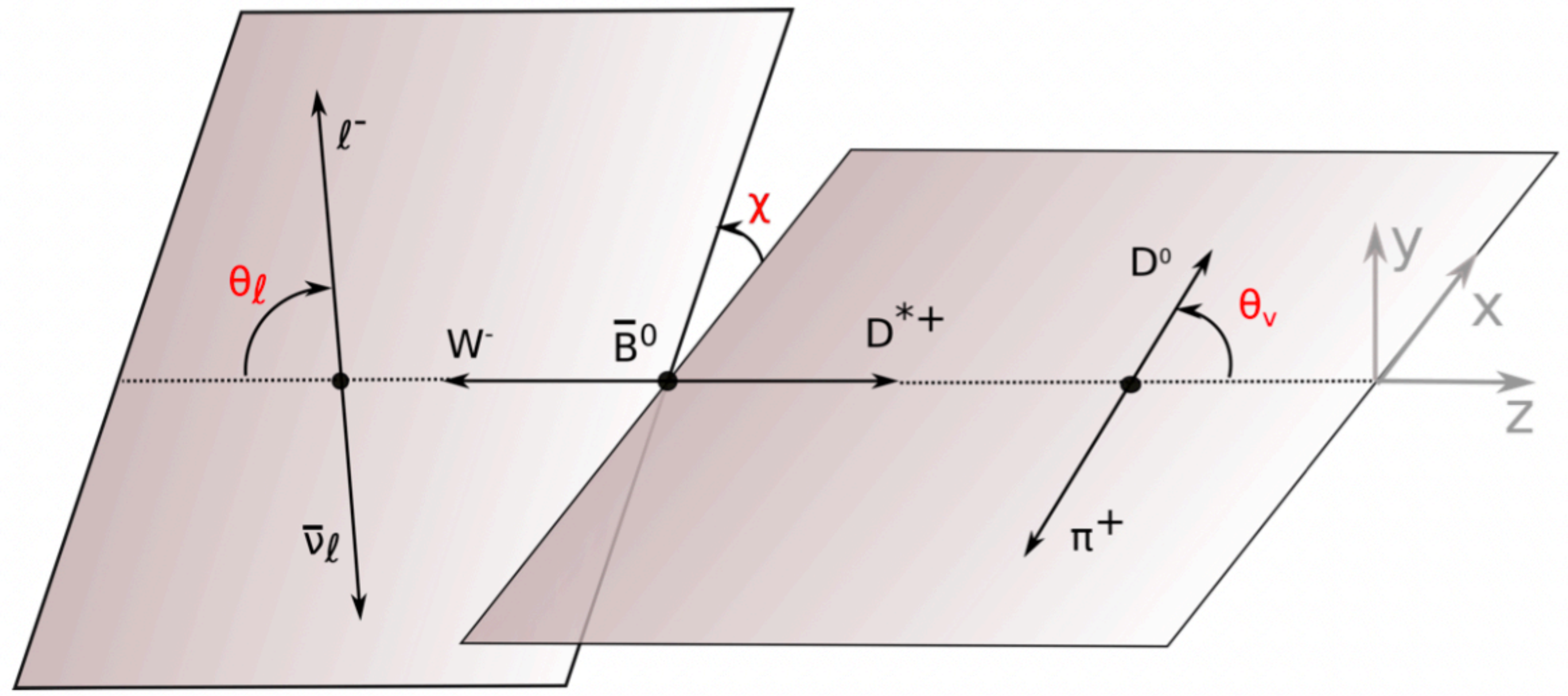
$m_{D^*} = D^*$ mass

$q =$ the four-vector of the momentum transferred from to the dilepton system

$\theta_l =$ The angle between the direction of the charged lepton in the virtual W frame and the W in the B frame

$\theta_V =$ The angle between the D in the D^* frame and the D^* in the B frame

$\chi =$ The angle between the decay planes formed by the virtual W and the D^* in the B frame



- Due to the spin of the final-state D^*, much of the properties of the V –A coupling and the spin of the virtual W are encoded in angular distributions of the final-state particles
- Fully characterized by four parameters

Light-Lepton Universality Test: Angular Asymmetry

- Angular Observable:

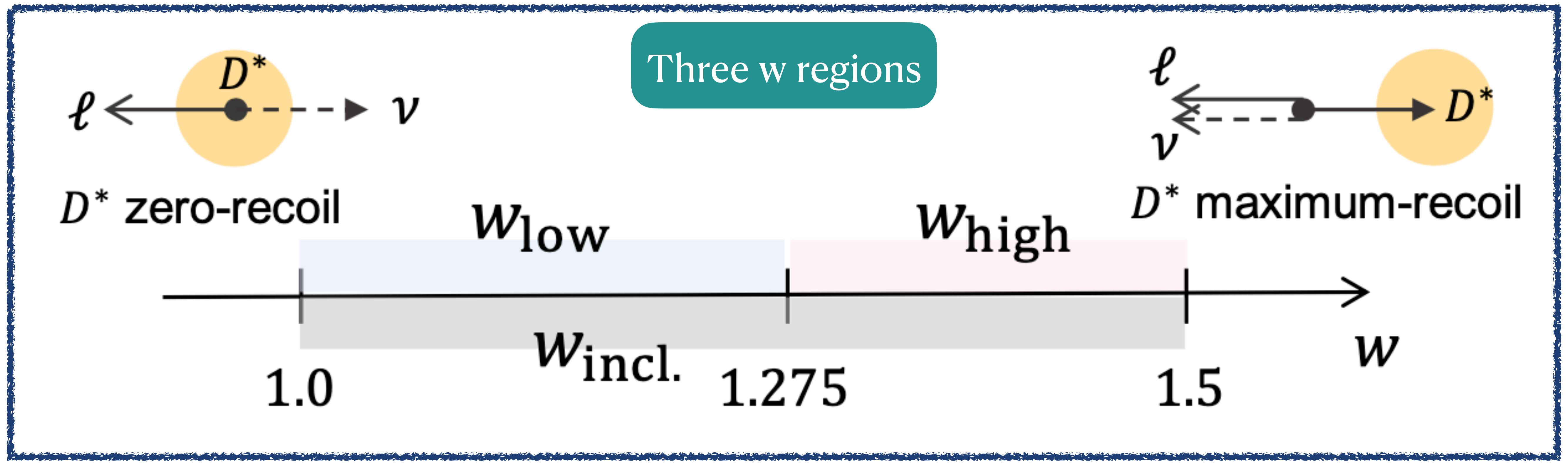
$$\mathcal{A}_x(w) = \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] dx \,\frac{d^2\Gamma}{dw\,dx}$$

$$A_{FB} : x = \cos\theta_l$$
$$S_3 : x = \cos 2\chi$$
$$S_5 : x = \cos\chi \cos\theta_v$$
$$S_7 : x = \sin\chi \cos\theta_V$$
$$S_9 : x = \sin 2\chi$$

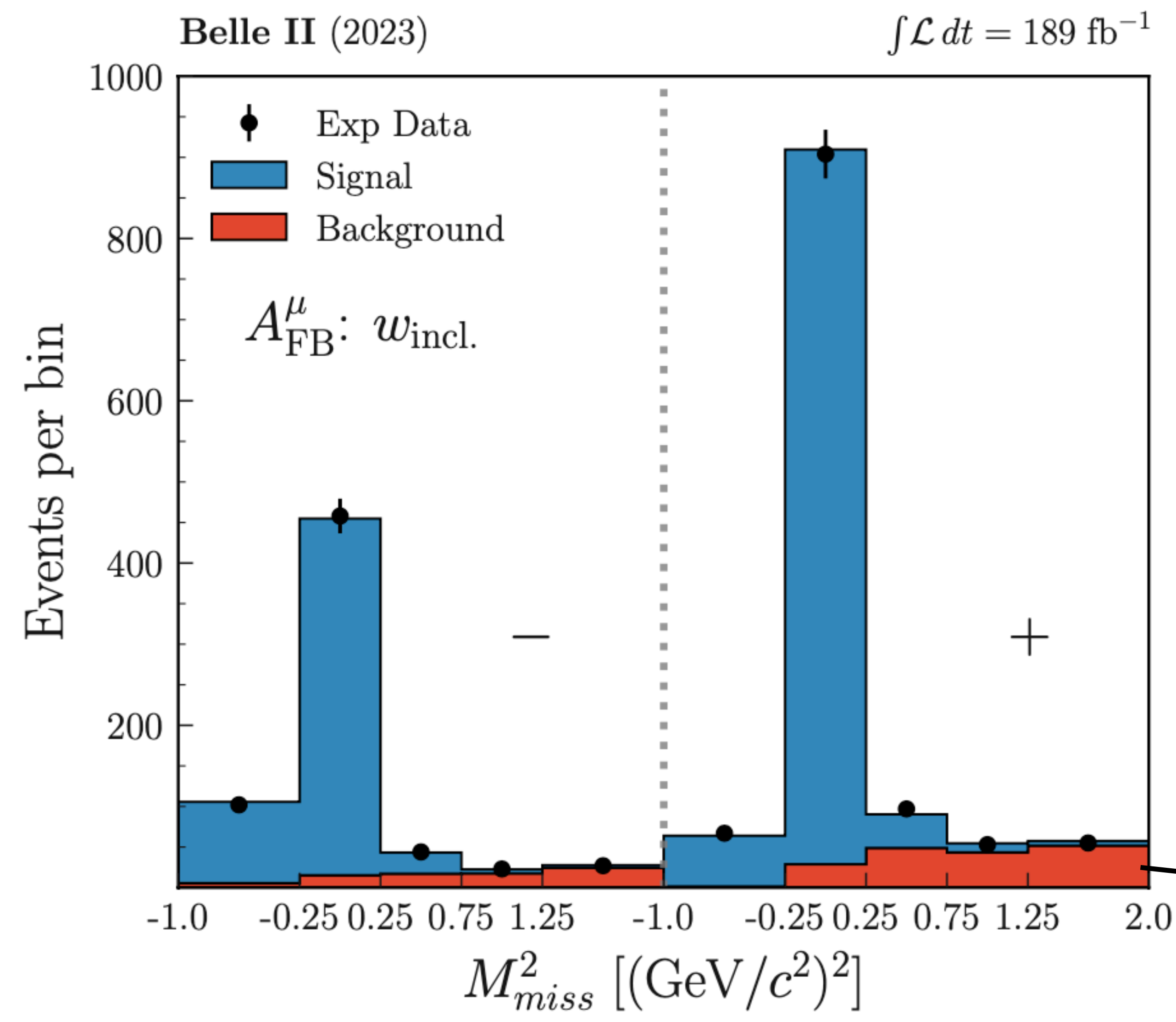
- theoretically and experimentally clean probes of LUV

$$\Delta\mathcal{A}_x(w) = \mathcal{A}_x^{\mu}(w) - \mathcal{A}_x^{e}(w)$$

- Most uncertainties cancel
  - experimental uncertainties cancel in the asymmetries $\mathcal{A}$
  - hadronic uncertainties in the form factors, largely cancel in $\Delta\mathcal{A}$



Light-Lepton Universality Test: Angular Asymmetry : Results

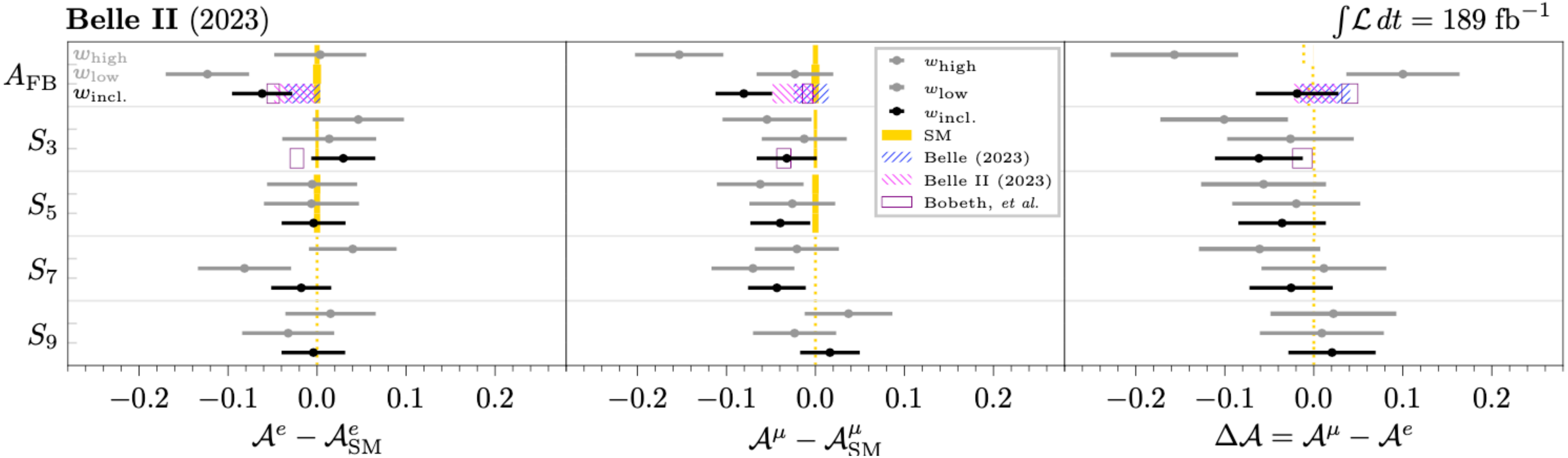


For each asymmetry A_X and w range, signal candidates separated into + and – categories based on the measured value of x. Numbers of signal events determined with binned maximum-likelihood fit of M^2_{miss}

No evidence of deviation from the standard model has been observed up to P values of 0.12

mostly $B \to D^{**} l\nu$

$$M^2_{\mathrm{miss}} \equiv \left(p_{e^+e^-} - p_{B_{\mathrm{tag}}} - p_{D^*} - p_{\ell}\right)^2$$



Determination of $|V_{cb}|$ using $\bar{B}_0 \rightarrow D^{*+} l^- \bar{\nu}_l$

Determination of $|V_{cb}|$ using $\bar{B}_0 \to D^{*+} l^- \bar{\nu}_l$

- The non-perturbative physics:

$$\frac{d^4\Gamma}{dw\ d\cos\theta_l\ d\cos\theta_V d\chi} \propto |V_{cb}|^2 \times |F(w, \cos\theta_l, \cos\theta_V, \chi)|^2$$

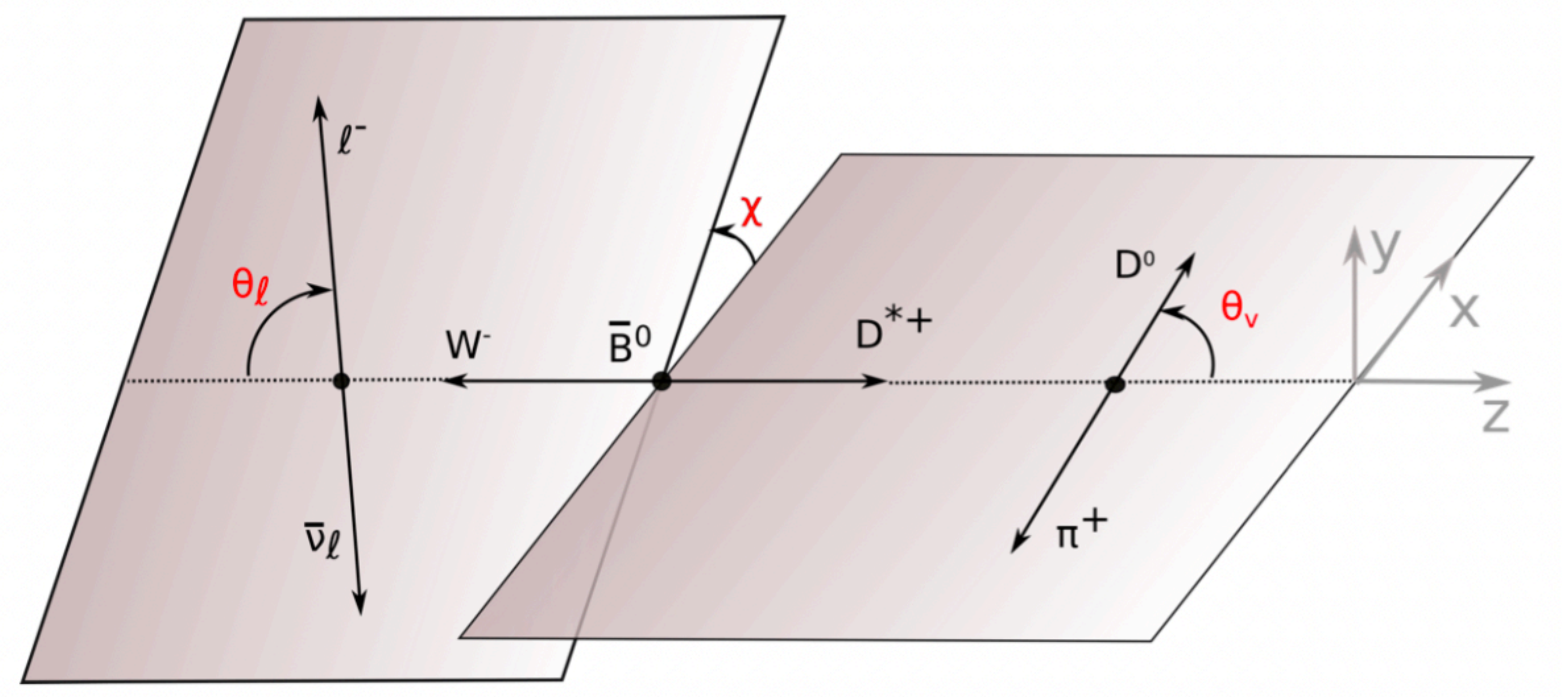
- is parametrized by three form factors as a function of

$$w = \frac{p_B \cdot p_{D^*}}{m_B m_{D^*}} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

- The neutrino direction is reconstructed inclusively using the known angle $\cos\theta_{BY}$ between the B and the $Y = D^* + l$ direction

$$\cos\theta_{BY} = \frac{2E_B^{CM}E_Y^{CM} - m_B^2c^4 - m_Y^2c^4}{2|\vec{p}_B^{CM}||\vec{p}_Y^{CM}|c^2}$$

- Signal yields in bins of kinematic variables w, $\cos\theta_l$, $\cos\theta_V$ and χ are determined bin by bin independently by 2D fits of $\cos\theta_{BY}$ and $\Delta M = M(D^*) - M(D^0)$



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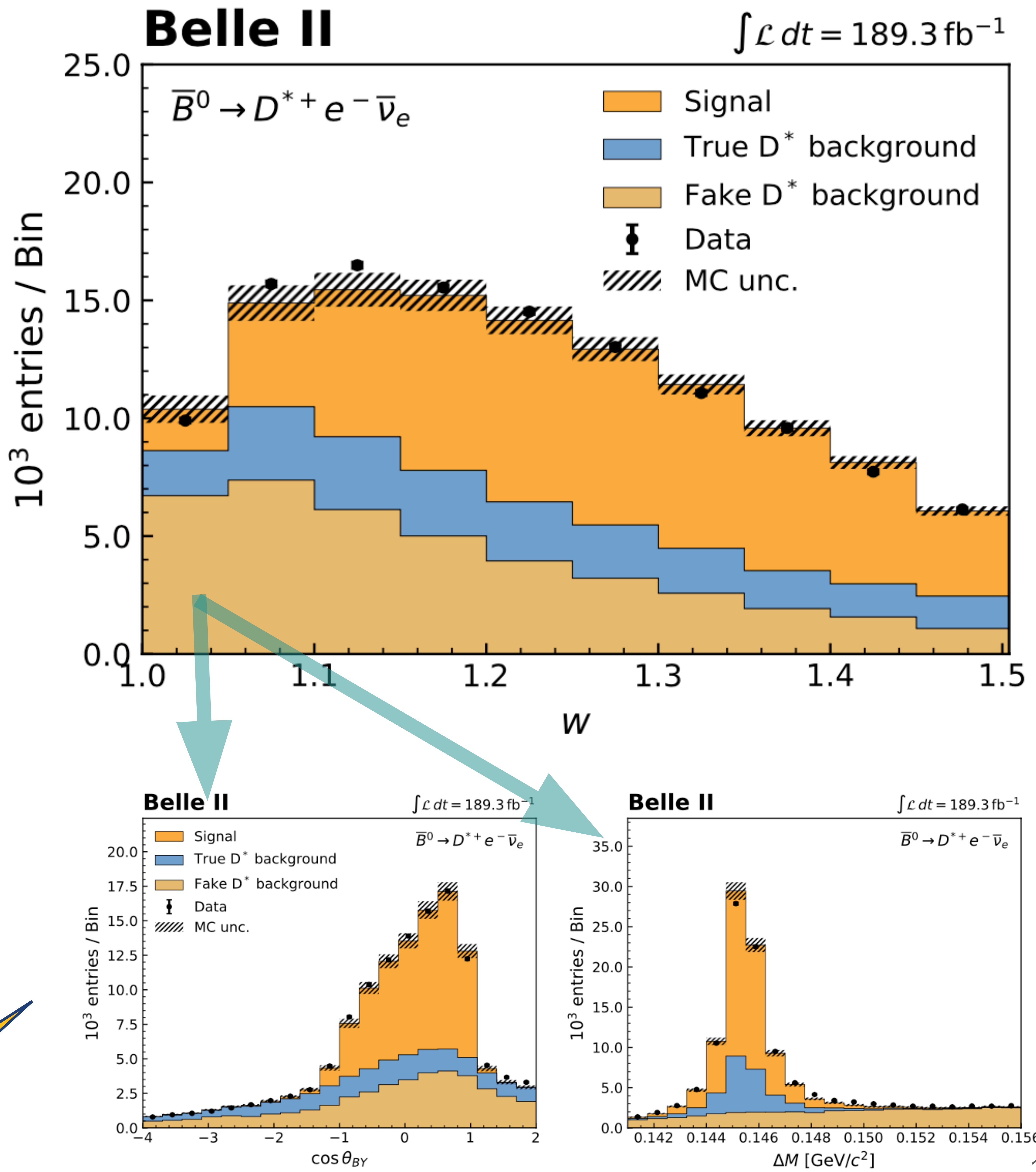
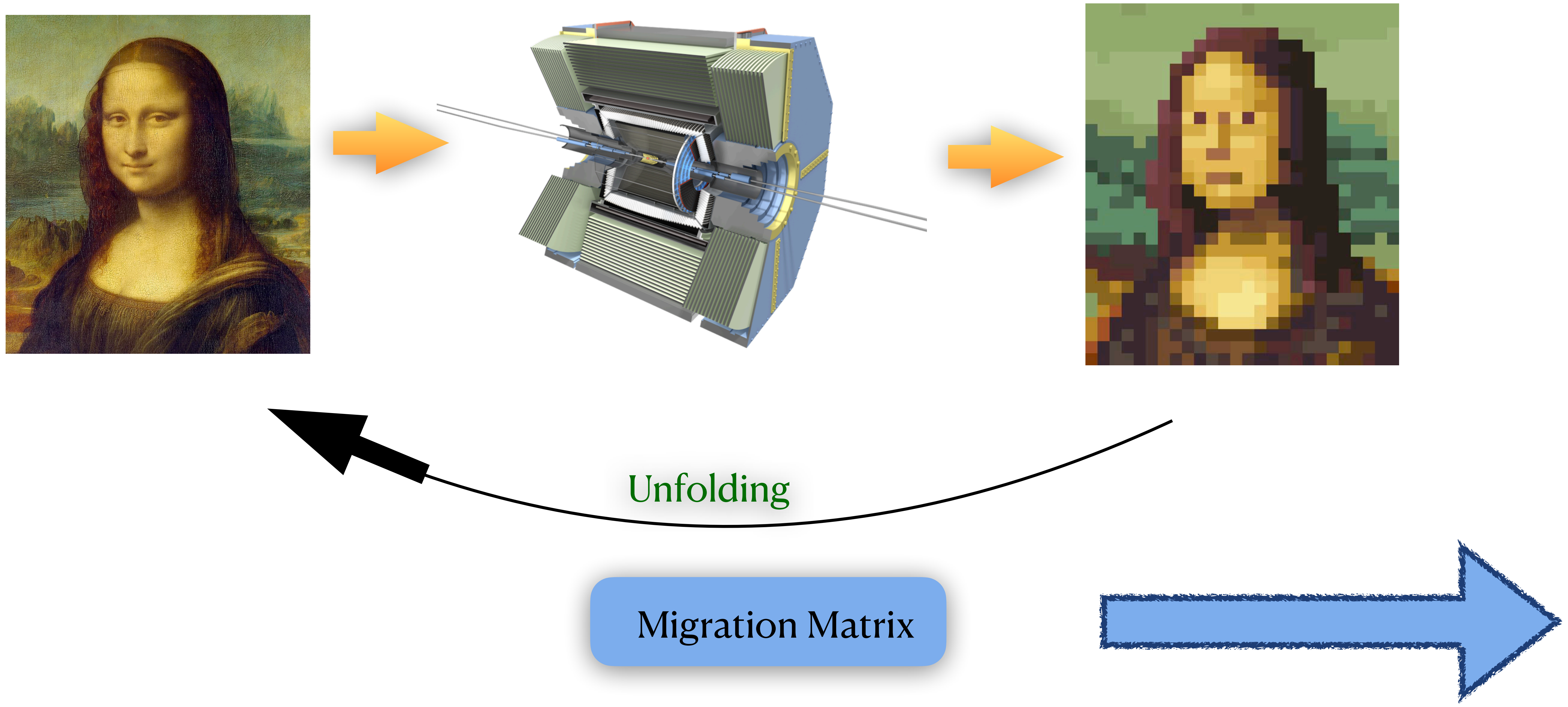
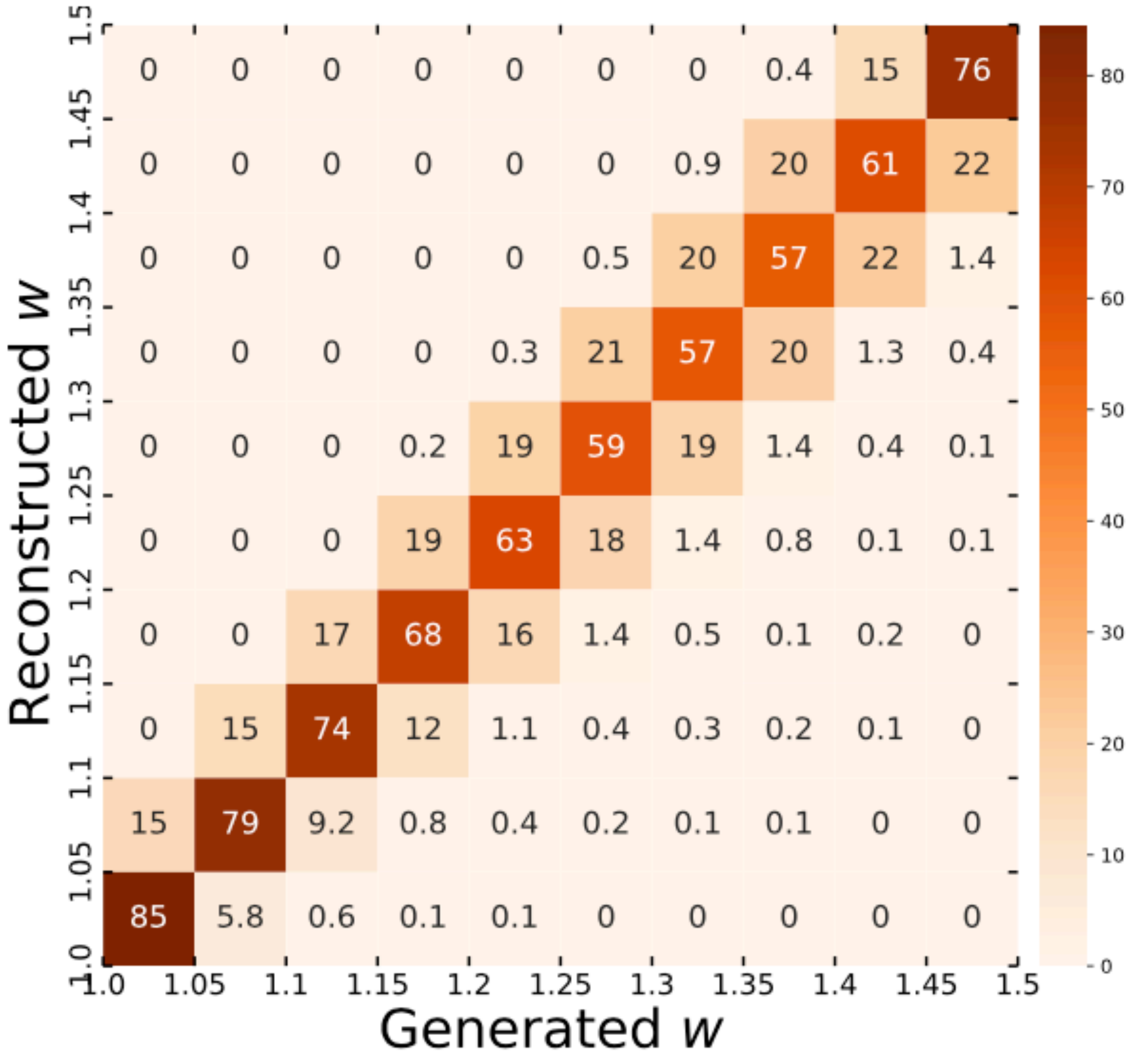
An example only: done for all the bins, for all the kinematic variables



- Bin-to-bin migration is corrected with SVD (Singular Value Decomposition) unfolding method [arXiv:hep-ph/9509307]



$\mathscr{M}_{ij} = \mathscr{P}$(measured value in bin i | true value in bin j)



Determination of $|V_{cb}|$ using $\bar{B}_0 \to D^{*+} l^- \bar{\nu}_l$

- $|V_{cb}|$ value is determined from measured partial rates $\Delta\Gamma$

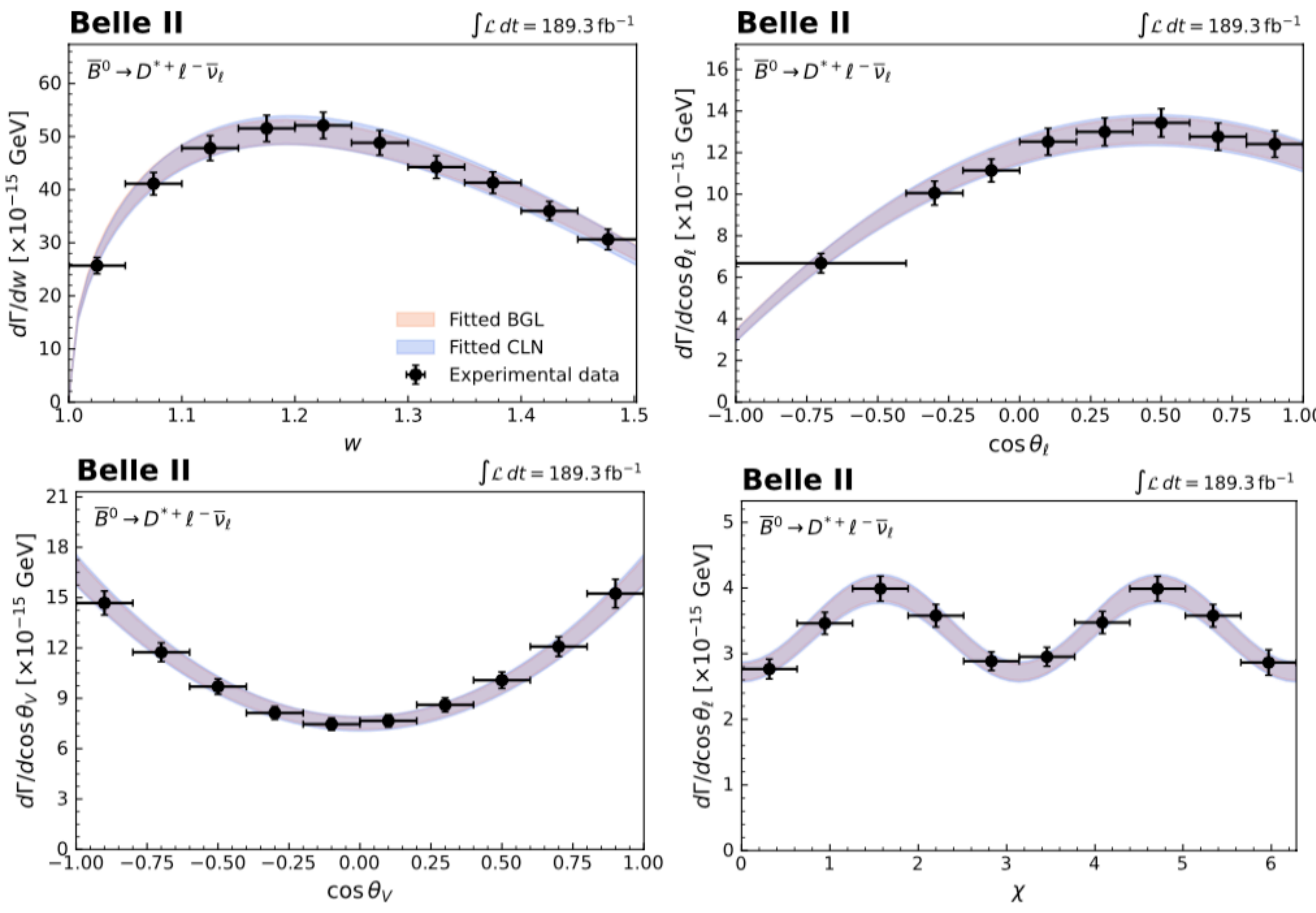
Boyd-Grinstein-Lebed parameterization

$$|V_{cb}|_{BGL} = (40.9 \pm 0.3_{stat} \pm 1.0_{sys} \pm 0.6_{theo}) \times 10^{-3}$$

Caprini-Lellouch-Neubert parameterization

$$|V_{cb}|_{BGL} = (40.4 \pm 0.3_{stat} \pm 1.0_{sys} \pm 0.6_{theo}) \times 10^{-3}$$

results agree well with the standard-model expectations, give no evidence for LUV



To be submitted to PRD

To sum up...

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

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Caprini-Lellouch-Neubert parameterization

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- The results shown in this presentation agree with SM
- No evidence of LUV(yet)