Semileptonic B decays — results and plans at Belle II

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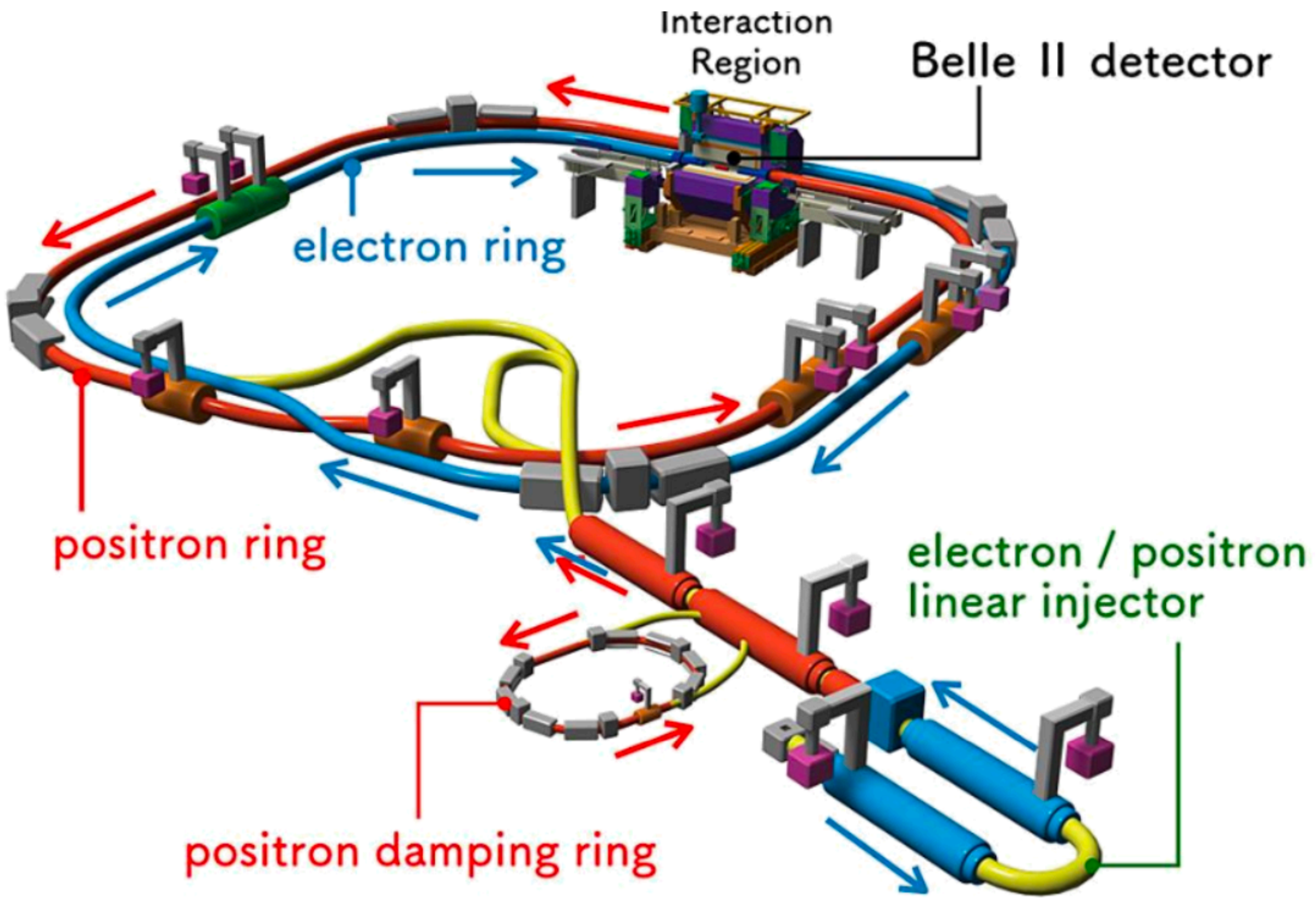
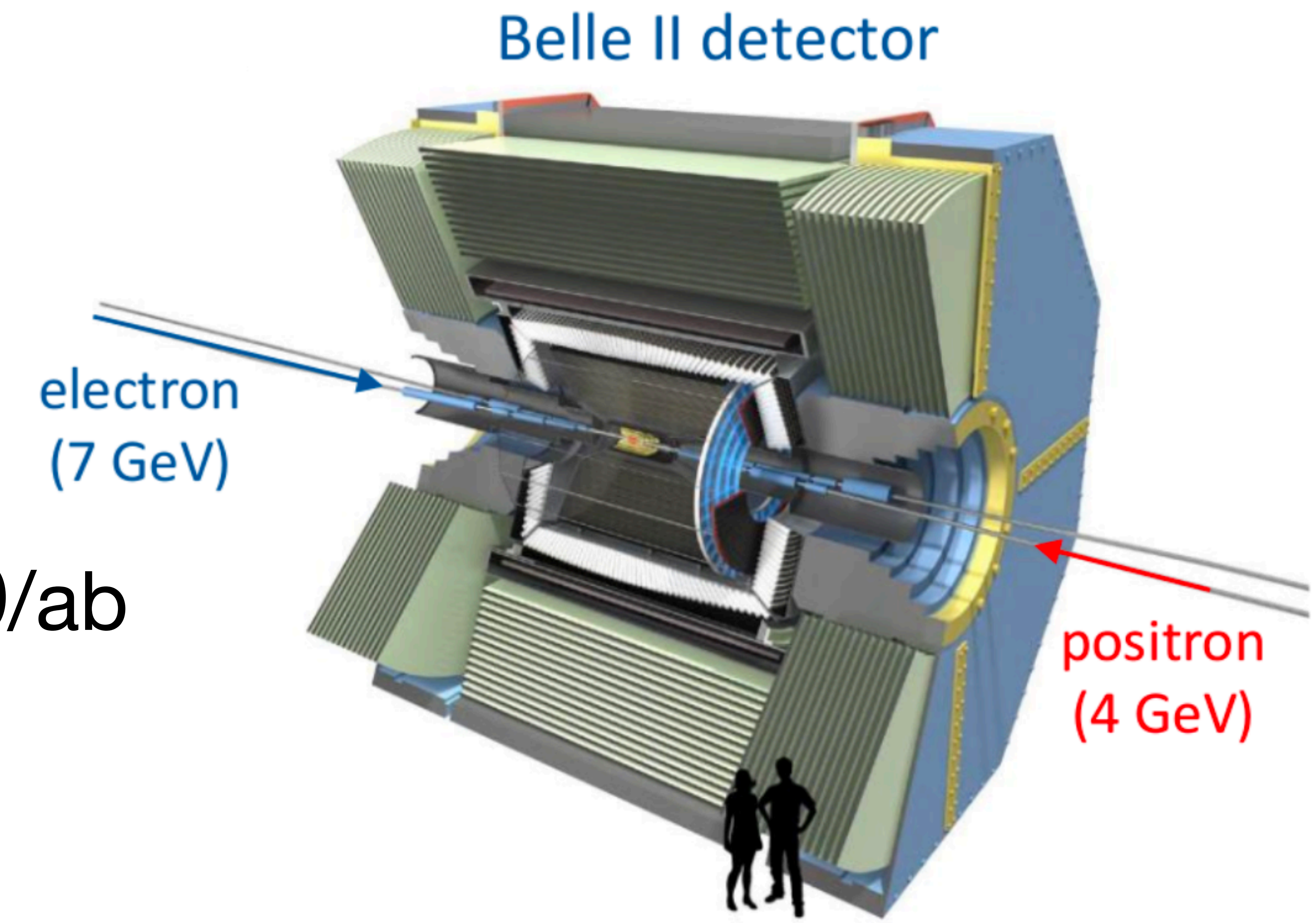
Semileptonic B decays at the junction of experiment and theory
Torino, Jun 12-13, 2025

Belle II @ SuperKEKB

- Luminosity frontier experiment to search for Physics beyond the Standard Model
  - e^+e^- asymmetric collision at the $\Upsilon(4S)$
  - High current / nano-beams, challenging background conditions
- Luminosity targets to achieve physics goals:
  - $\mathscr{L} = 6 \times 10^{35}$ cm^{-2} s^{-1}, $\int \mathscr{L} dt = 50$/ab



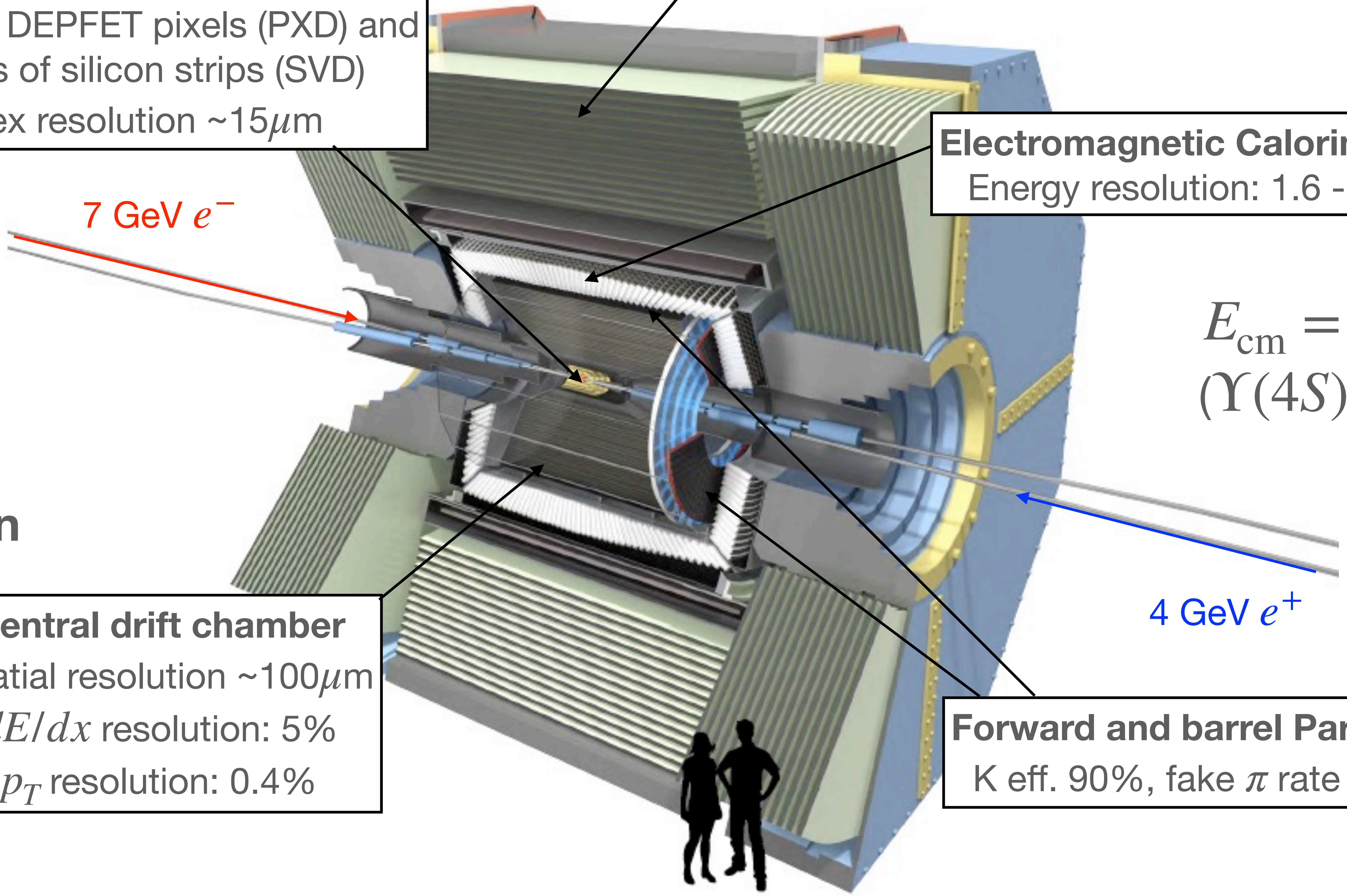


The Belle II detector

KEK
Tsukuba, Japan

KLM
Instrumented flux return

Vertex detector
2 layers of DEPFET pixels (PXD) and
4 layers of silicon strips (SVD)
Vertex resolution ~15μm

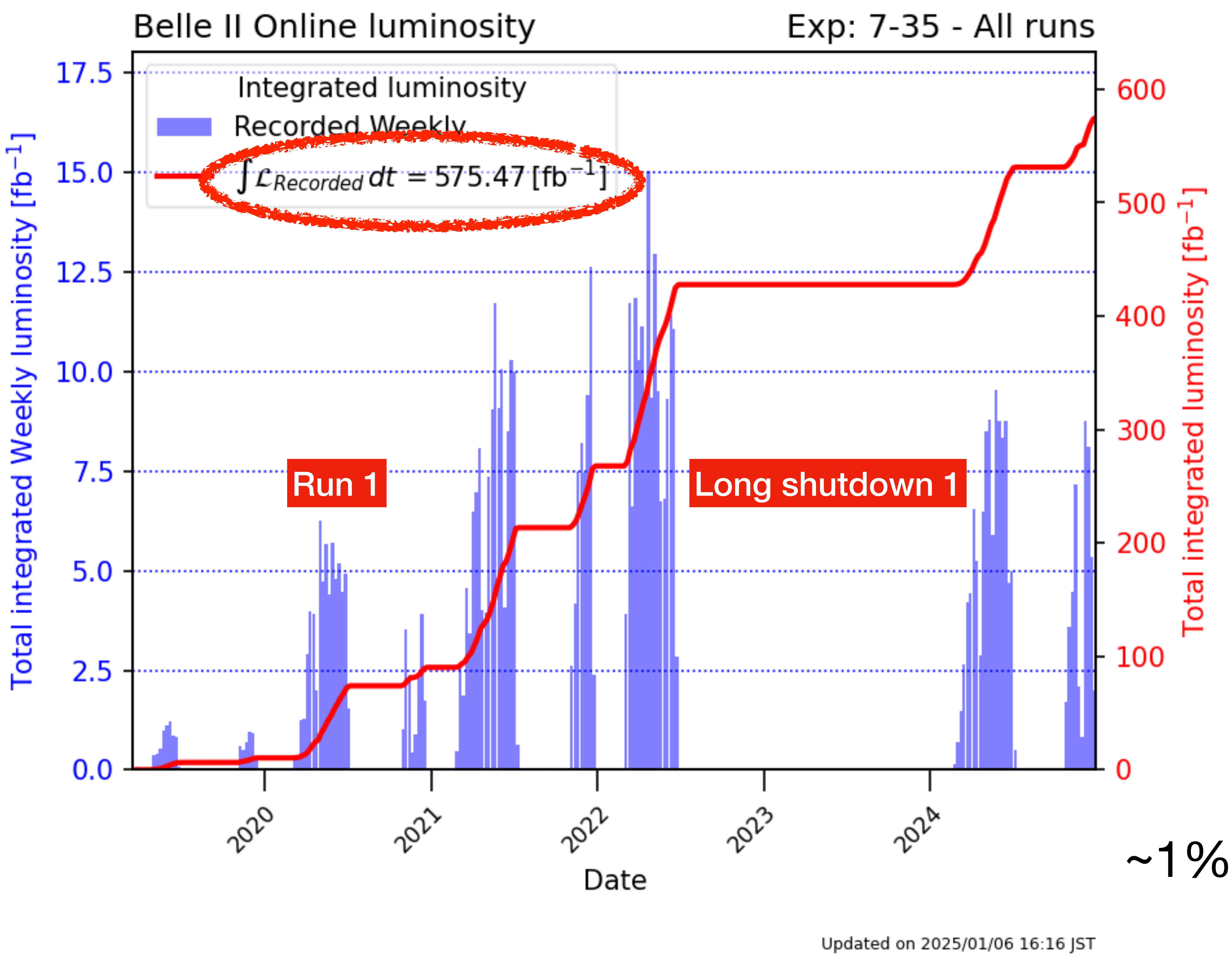


Electromagnetic Calorimeter
Energy resolution: 1.6 - 4%

$E_{\rm cm} = 10.58$ GeV
($\Upsilon(4S)$ resonance)

Central drift chamber
Spatial resolution ~100μm
dE/dx resolution: 5%
p_T resolution: 0.4%

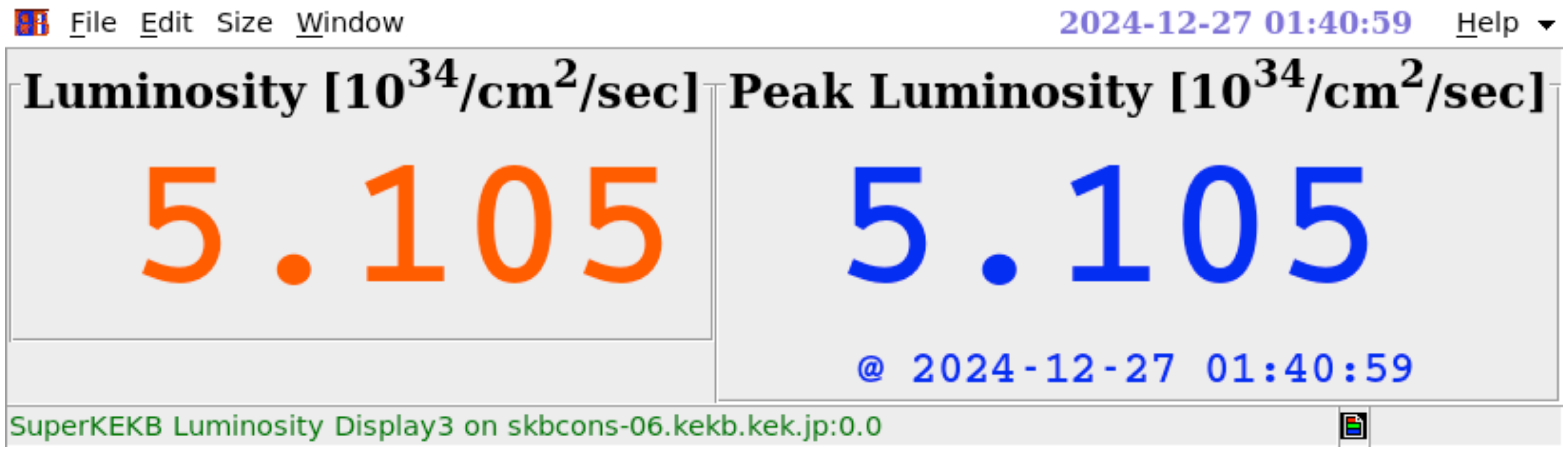
Forward and barrel Part. Id.
K eff. 90%, fake π rate 5%



~1% of 50/ab target

New luminosity record

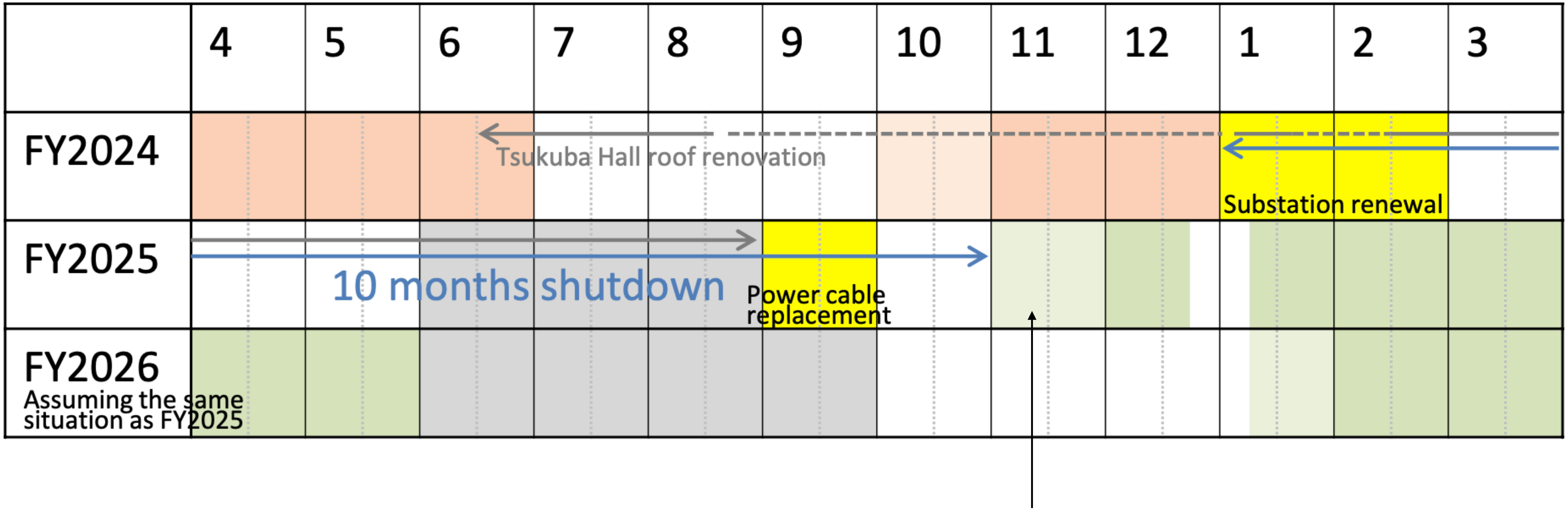
Dec 27, 2024



2025c operation schedule

[Baseline]

Faint colors for the machine start-up time

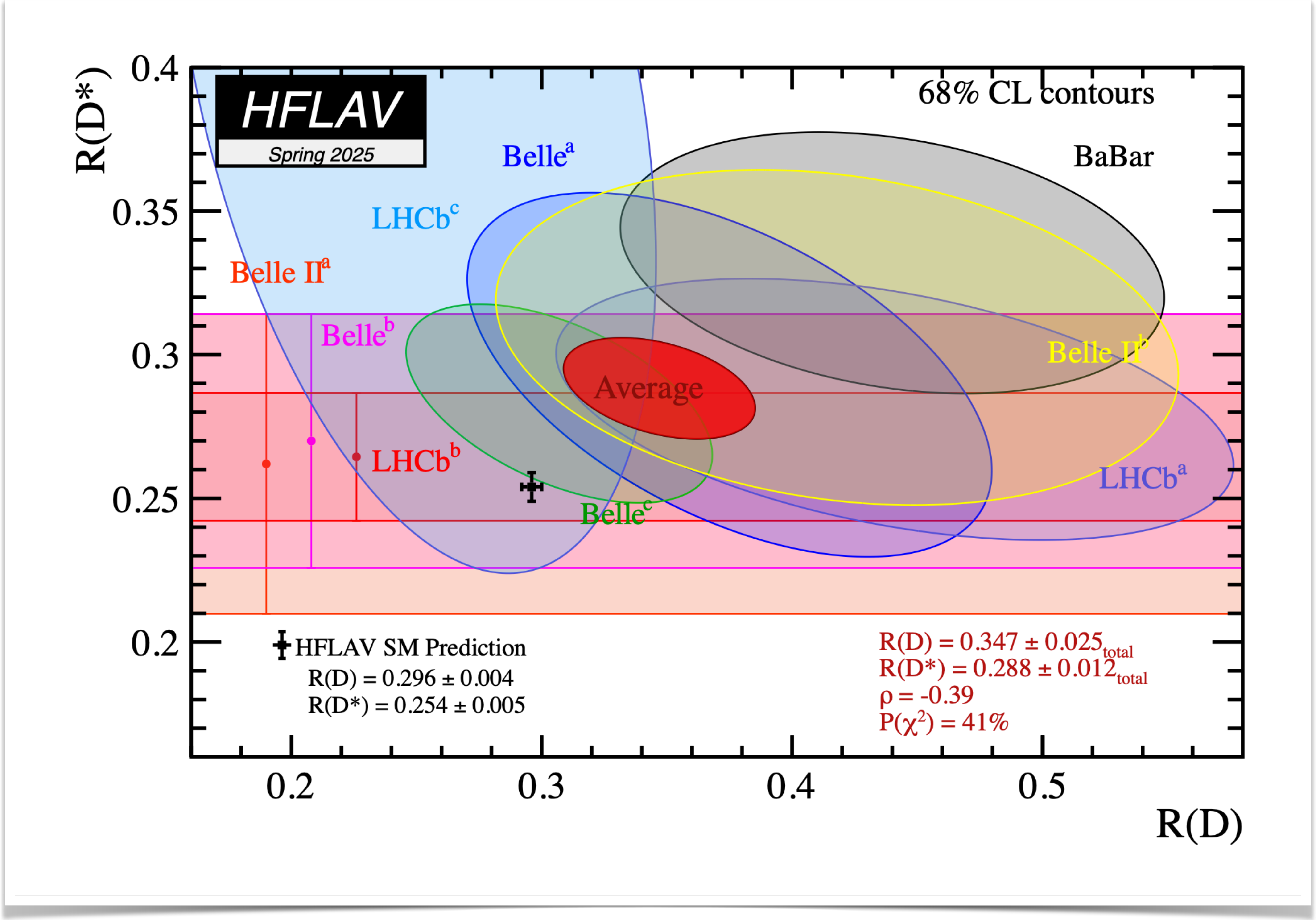


MR start at Nov 5 at the earliest

What I'm going to talk about

- New Belle II $B \to D\ell\nu$ result and impact on $|V_{cb}|$
  - Shown at Moriond EW 2025, collaboration paper in '48h display'
- My view on $|V_{cb}|$ inclusive and what we plan to do about it
  - Towards an untagged measurement of the inclusive semileptonic branching fraction

What I'm not going to talk about



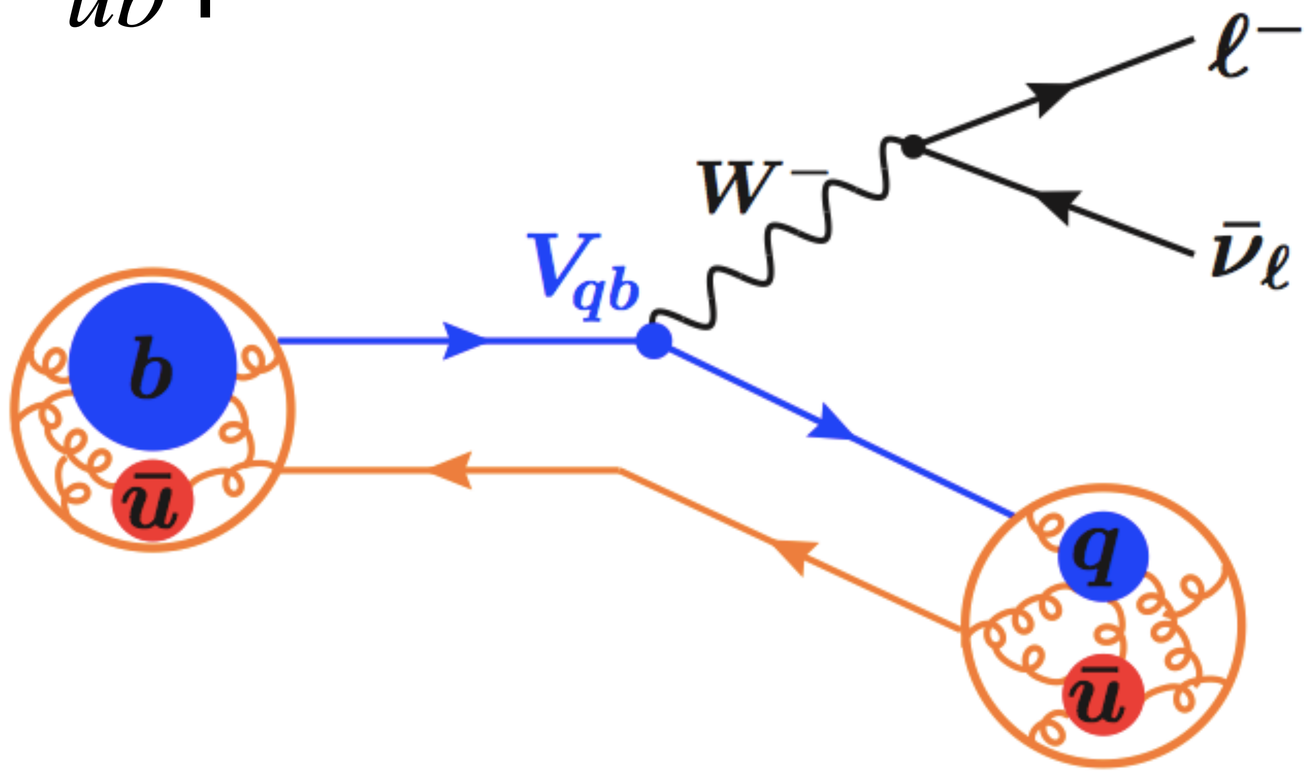
3.8σ difference to SM

https://hflav-eos.web.cern.ch/hflav-eos/semi/spring25/html/RDsDsstar/RDRDs.html

Semileptonic B decays

Determination of the CKM elements $|V_{cb}|$ and $|V_{ub}|$

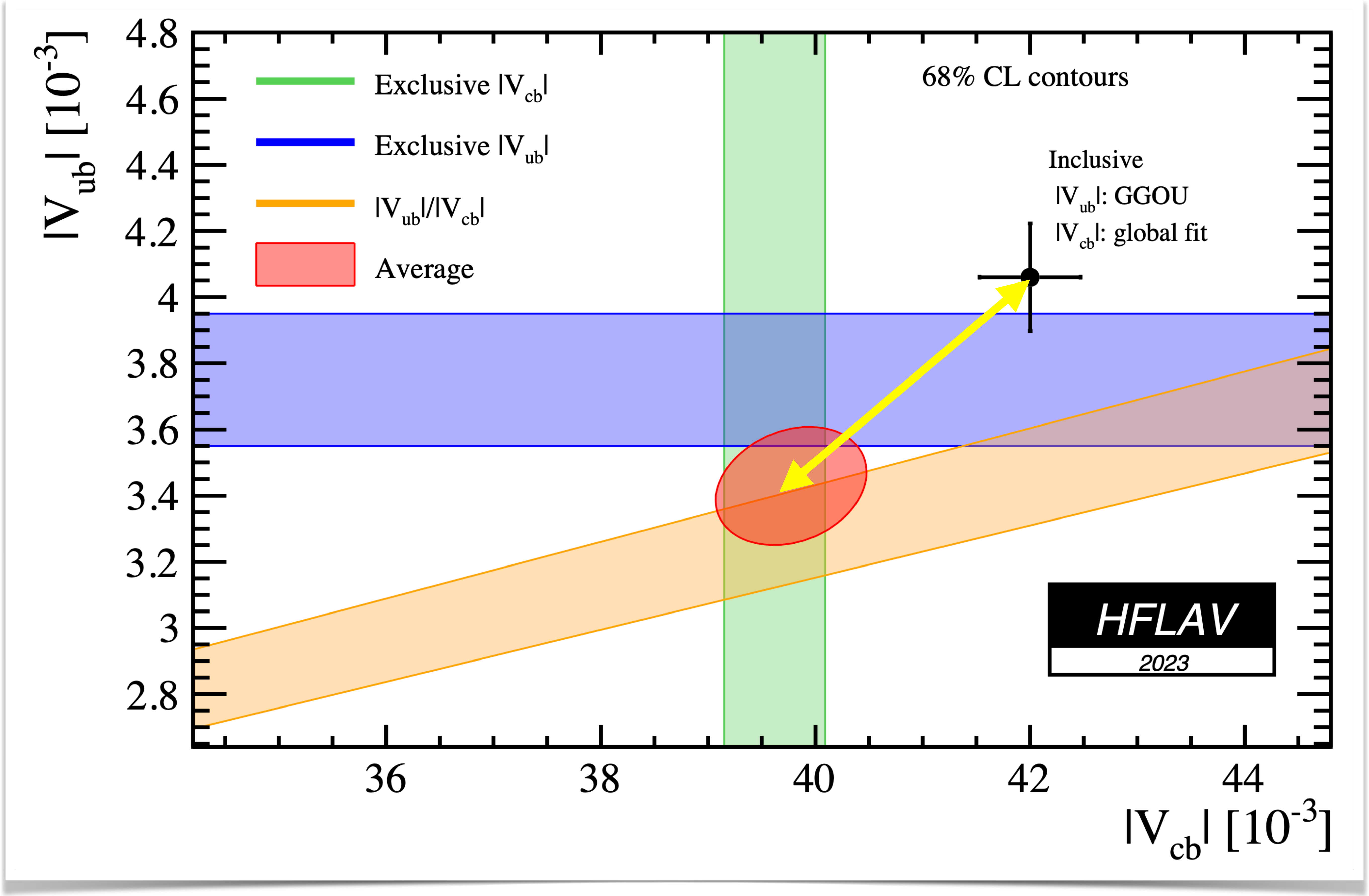
- SL B decays are studied to determine the CKM elements $|V_{cb}|$ and $|V_{ub}|$
  - $|V_{xb}|$ are limiting the global constraining power of UT fits
  - Important inputs in predictions of SM rates for ultrarare decays such as $B_s \to \mu\nu$ and $K \to \pi\nu\nu$
- The determinations can be
  - *Exclusive* — from a single final state
  - *Inclusive* — sensitive to all SL final states



$$d\Gamma \propto G_F^2 |V_{qb}|^2 \left| L_\mu \langle X | \bar{q}\gamma_\mu P_L b | B \rangle \right|^2$$

	Experiment	Theory
Exclusive $\lvert V_{cb}\rvert$	$B \to Dl\nu$, $D^*l\nu$ (low backgrounds)	Lattice QCD, light cone sum rules
Inclusive $\lvert V_{cb}\rvert$	$B \to Xl\nu$ (higher background)	Operator product expansion

Inclusive/exclusive anomaly



~3σ difference between *inclusive* and *exclusive* $|V_{xb}|$

“Once you eliminate the impossible, whatever remains, no matter how improbable, must be the truth.”

Sir Arthur Conan Doyle a.k.a. Sherlock Holmes

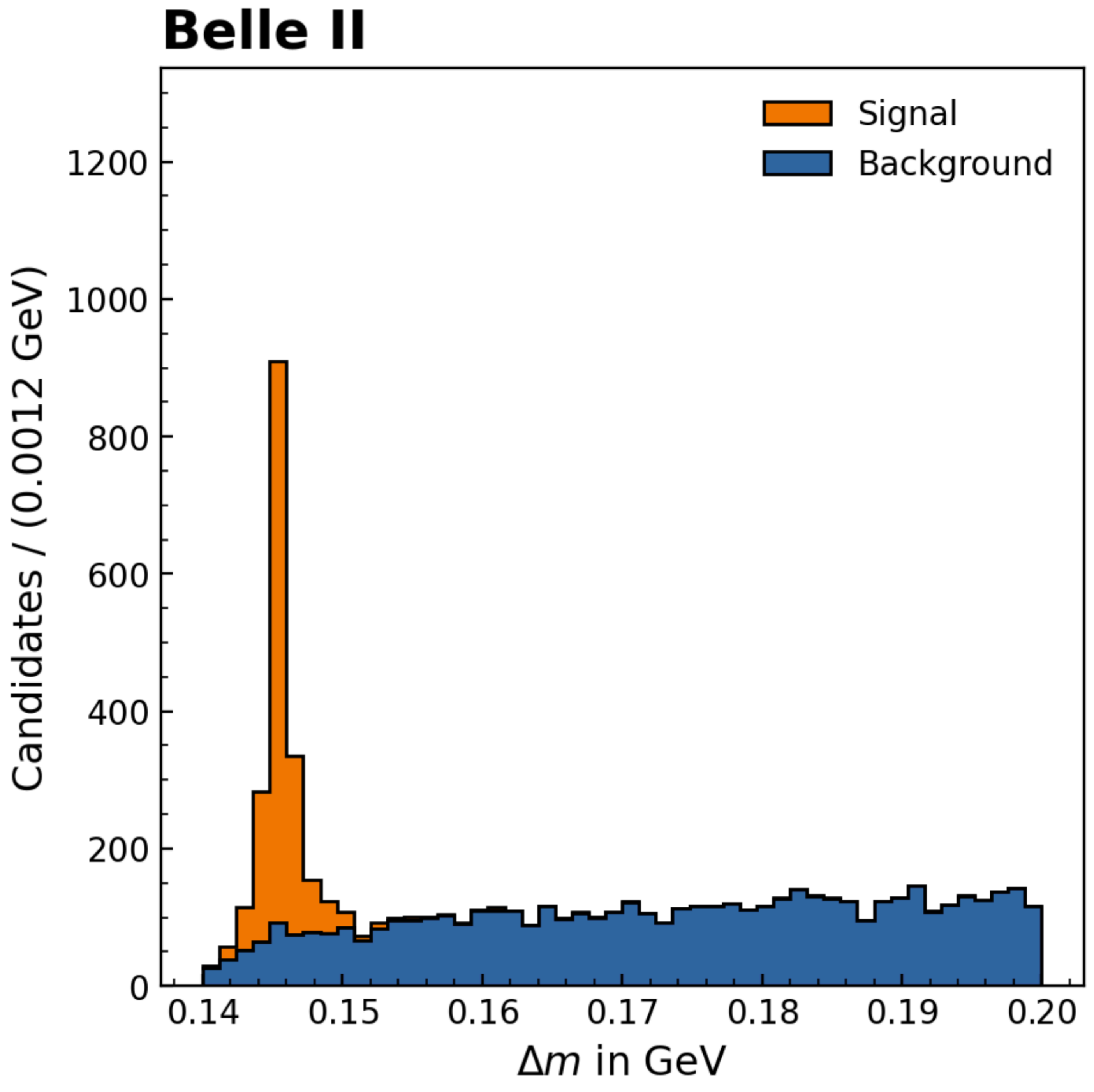
$|V_{cb}|$ exclusive status circa 2020

- Dominated by $B^0 \to D^{*-}\ell^+\nu$
  - $|V_{cb}| = (38.4 \pm 0.2 \pm 0.6 \pm 0.6) \cdot 10^{-3}$ ~2% uncertainty
    [PRD 100, 052007 (2019)]
- Extractions from $B \to D\ell\nu$ significantly less precise
  - $|V_{cb}| = (39.86 \pm 1.33) \cdot 10^{-3}$ ~3% uncertainty
    [PRD 93, 032006 (2016)]

Possible issues

$B^0 \to D^{*-}\ell^+\nu$

- Experimental
  - Slow pion from $D^{*+} \to D^0\pi^+$
  - Only one isospin state accessible (Coulomb correction)
- Theory
  - Three form-factors
  - Uncertainties BGL truncation



$$g(z) = \frac{1}{P_g(z)\phi_g(z)} \sum_{n=0}^{n_a-1} a_n z^n,$$

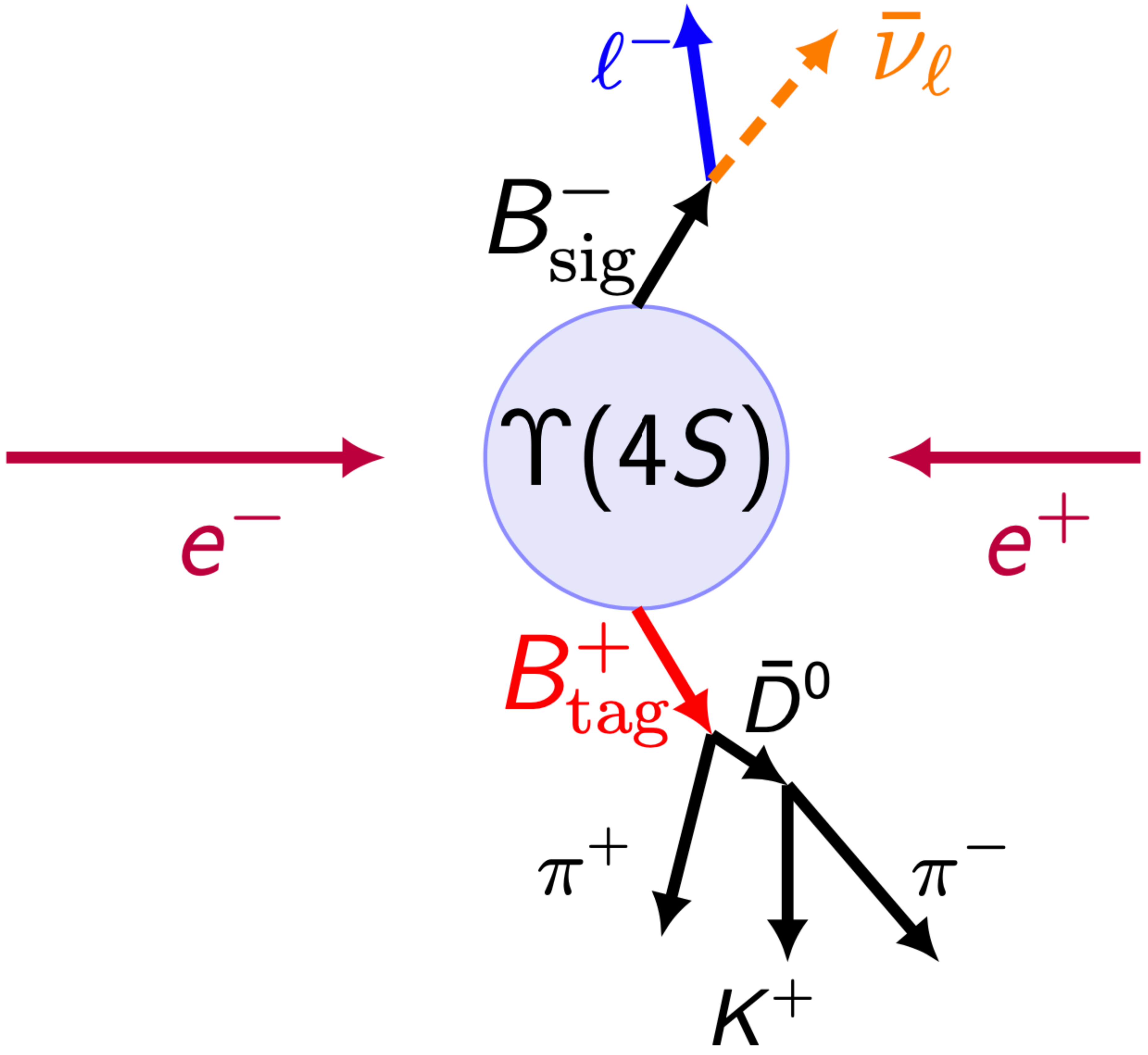
$$f(z) = \frac{1}{P_f(z)\phi_f(z)} \sum_{n=0}^{n_b-1} b_n z^n, \qquad z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}$$

$$\mathcal{F}_1(z) = \frac{1}{P_{\mathcal{F}_1}(z)\phi_{\mathcal{F}_1}(z)} \sum_{n=0}^{n_c-1} c_n z^n,$$

Possible issues tagging

Untagged:
only B_{sig} is reconstructed

high signal yield (+)
high backgrounds (-)
poor neutrino reconstruction (-)

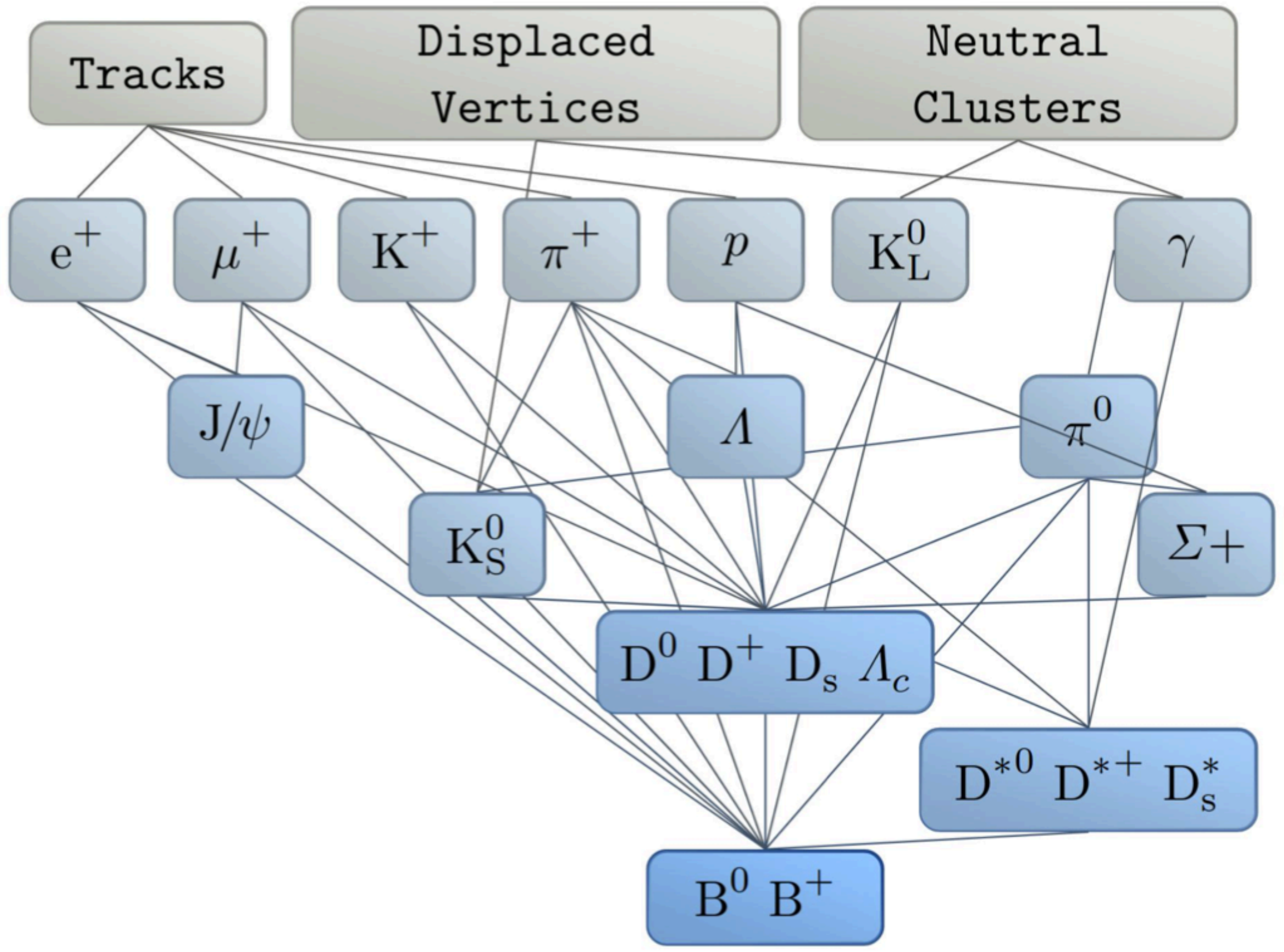


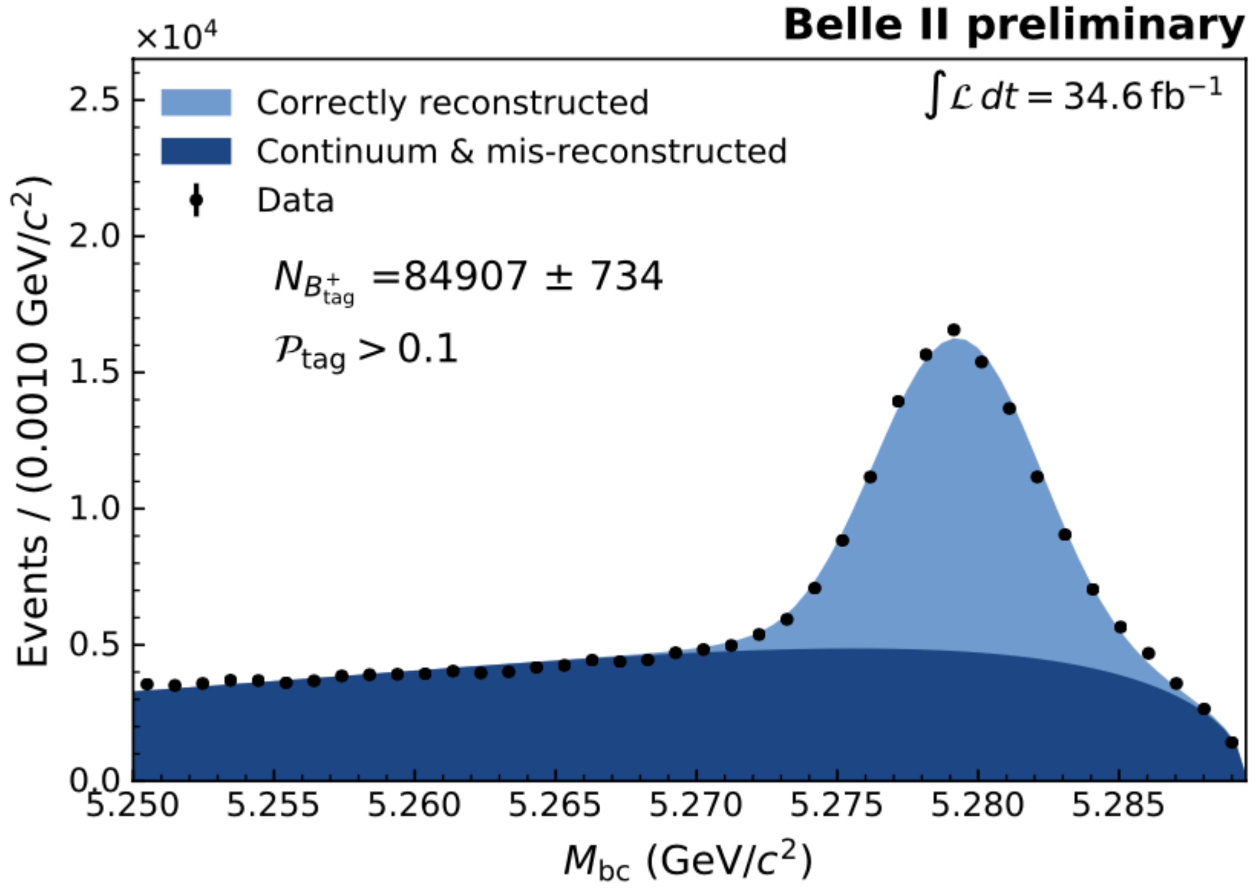
Tagged:
B_{sig} and B_{tag} are reconstructed

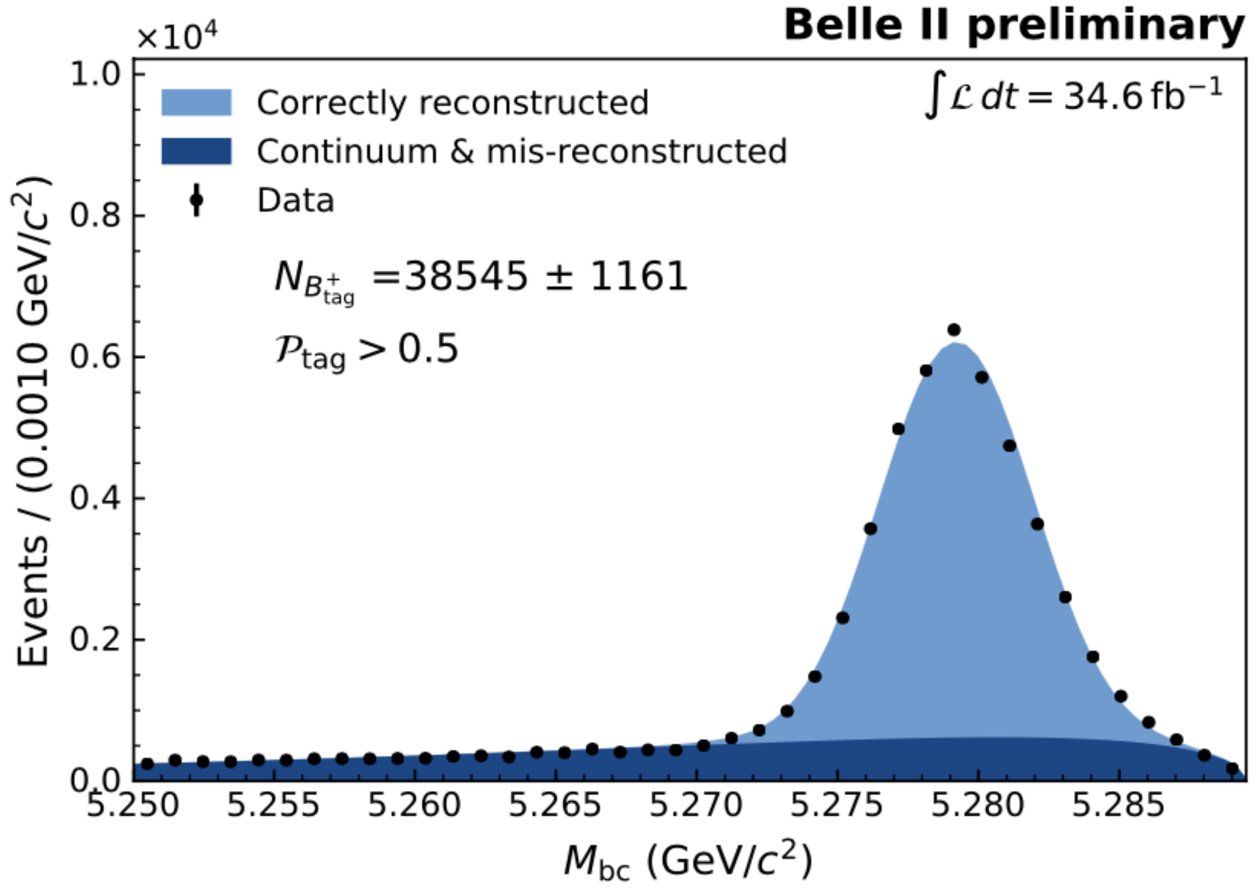
signal yield $O(10^3)$ lower (-)
low backgrounds (+)
good neutrino reconstruction (+)
tag calibration (-)

Hadronic tagging at Belle II

Comput Softw Big Sci (2019) 3: 6.







$$M_{bc} = \sqrt{E_{beam}^2/4 - (p_{B_{\mathrm{tag}}}^{\mathrm{cm}})^2} > 5.27\ \mathrm{GeV}/c^2$$

- The hadronic FEI employs over 200 boosted decision trees to reconstruct 10000 B decay chains
  - $\epsilon_{B^+} \approx 0.5\,\%$, $\epsilon_{B^0} \approx 0.3\,\%$ at low purity (about 50% increase with respect to the Belle tag)

Thus we need…

Belle II $B \to D\ell\nu$ untagged

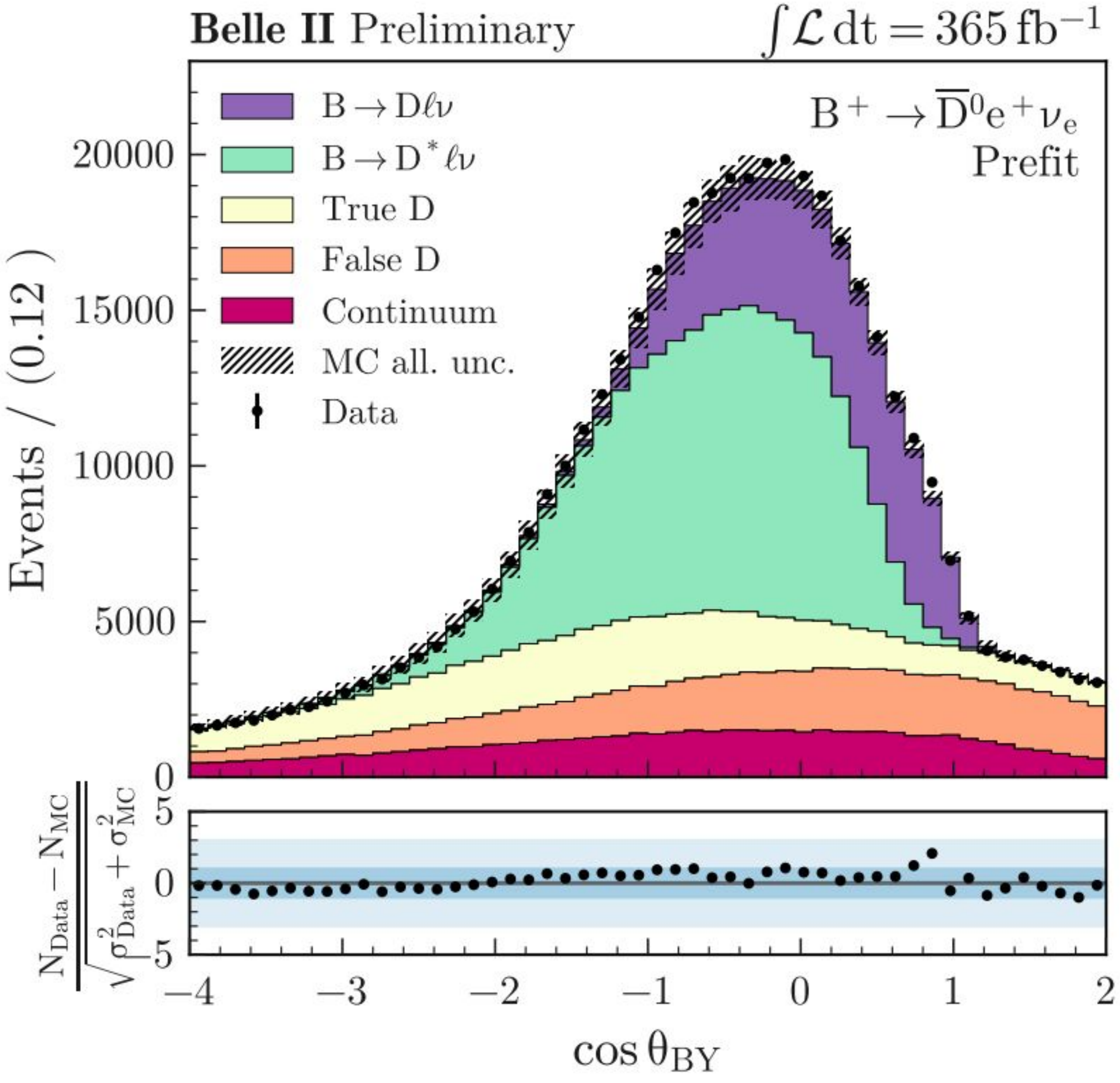
[Moriond EW 2025, paper to be submitted]

Signal reconstruction

Preliminary

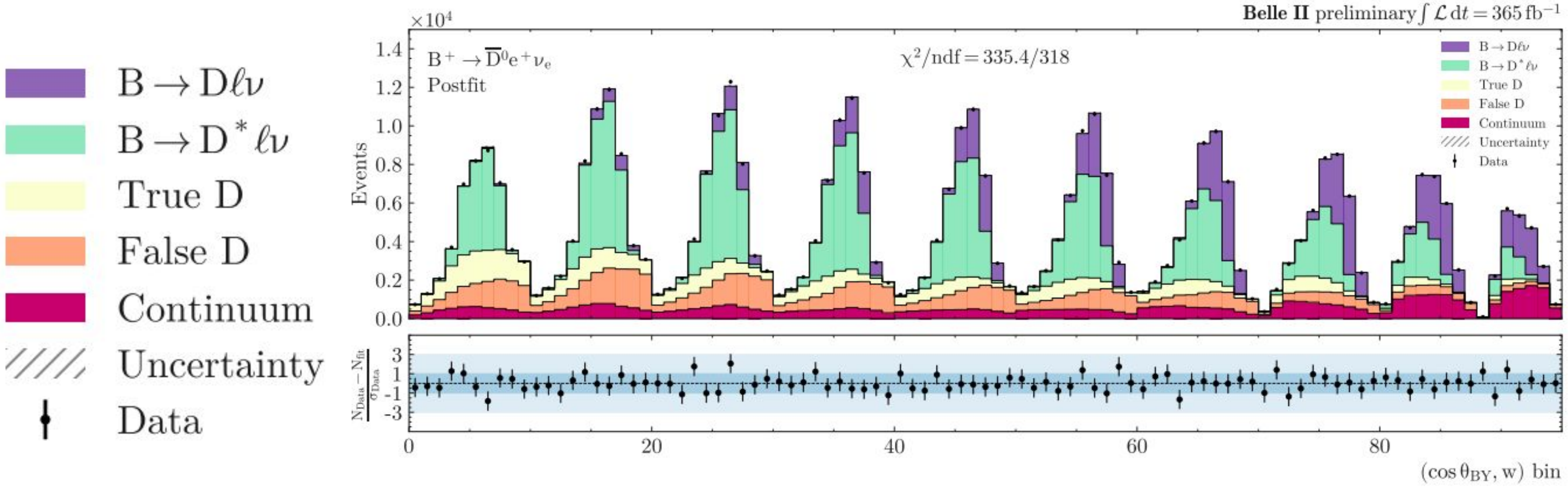
- The Belle II measurement is performed using B^0 and B^+ decays **without explicitly reconstructing the partner *B* meson** from the $\Upsilon(4S) \to B\bar{B}$ decay
  - $D^- \to K^+ \pi^- \pi^-$ and $D^0 \to K^- \pi^+$
- The signal is extracted using the **$\cos\theta_{BY}$ variable** where Y represents the Dl system

$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - M_Y^2}{2|p_B^*||p_Y^*|}$$



Binning in $w = v \cdot v'$

- The signal is **extracted from a 2D binned template fit of $\cos\theta_{BY}$:w** split in 10 bins each
- The fit is performed simultaneously on **4 separate channels D^0e^-, $D^0\mu^-$, D^+e^- and $D^+\mu^-$** to extract the individual **branching fractions** and a **lepton flavour universality test**



10 $\cos\theta_{BY}$ distributions in 10 w bins

arXiv:2411.18639

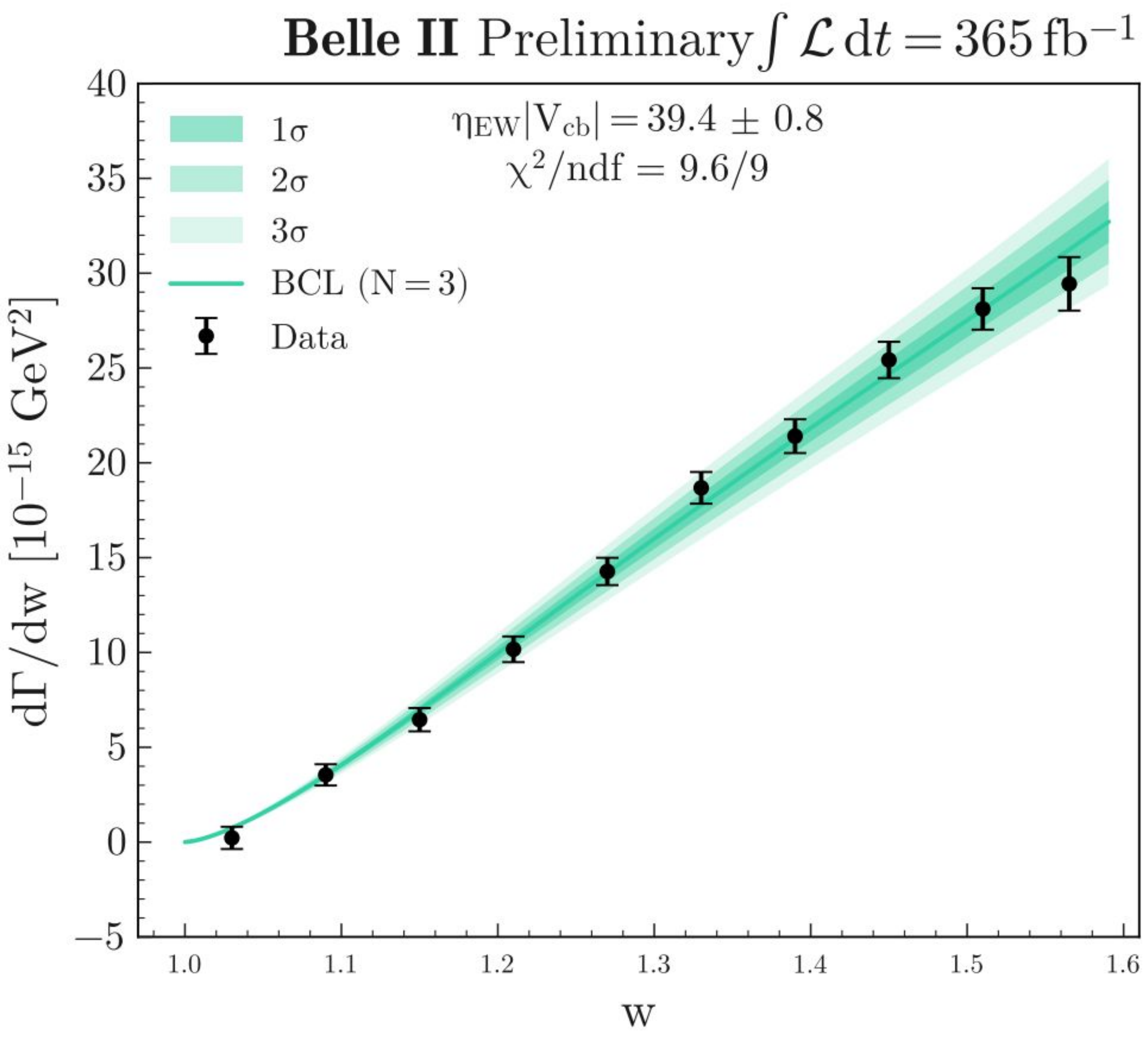
Preliminary

	Belle II	HFLAV
$\mathcal{B}(B \to D^-\ell^+\nu)$	$2.06 \pm 0.12\%$	$2.12 \pm 0.06\%$
$\mathcal{B}(B \to \bar{D}^0\ell^+\nu)$	$2.31 \pm 0.10\%$	$2.21 \pm 0.06\%$

$$\frac{\mathcal{B}(B \to De\nu)}{\mathcal{B}(B \to D\mu\nu)} = 1.02 \pm 0.03$$

Determination of $|V_{cb}|$

- The differential decay rate ***ΔΓ/Δw*** in 10 *w* bins is obtained from the **same fit**
- The obtained values of ***ΔΓ/Δw*** **are fitted** to the differential rate expressed using the Bourrely, Caprini, Lellouch (BCL) form factor parametrisation with a χ^2 fit with lattice QCD constraints → **extraction of $|V_{cb}|$ and BCL form factor parameters**



Measured values

Predicted values

$$\chi^2 = \sum_{i,j}^{10} \left(\boxed{\frac{\Delta\Gamma_i}{\Delta w}} - \boxed{\frac{\Delta\Gamma_{i,\mathrm{BCL}}}{\Delta w}} \right) \mathbf{C}_{ij}^{-1} \left(\frac{\Delta\Gamma_j}{\Delta w} - \frac{\Delta\Gamma_{j,\mathrm{BCL}}}{\Delta w} \right)$$
$$\boxed{+ \sum_{k,l}^{5} (c_k - c_{k,\mathrm{FLAG}}) \mathbf{D}_{kl}^{-1} (c_l - c_{l,\mathrm{FLAG}})}$$

LQCD constraints (FNAL/MILC + HPQCD)

$$|V_{cb}|_{BCL} = (39.2 \pm 0.8) \times 10^{-3}$$

$|V_{cb}|_{\mathrm{excl.}} = (39.77 \pm 0.46) \times 10^{-3}$ $|V_{cb}|_{\mathrm{incl.}} = (41.97 \pm 0.48) \times 10^{-3}$

Preliminary

Result for BCL expansion

BCL expansion: PRD 79, 013008 (2009)

$$r = M_D/M_B \qquad \mathcal{G}^2(w) = \frac{4r}{(1+r)^2} f_+^2(w) \qquad f_0(w_{\max}) = f_+(w_{\max})$$

$$f_+(q^2) = \frac{1}{1-q^2/M_+^2} \sum_{k=0}^{N-1} a_k \left[z^k - (-1)^{k-N} \frac{k}{N} z^N \right] \qquad f_0\left(q^2\right) = \frac{1}{1-q^2/M_0^2} \sum_{k=0}^{N-1} b_k z^k$$

	Values	Correlation coefficients				
a_0^+	0.8959(92)	1	0.26	-0.38	0.95	0.51
a_1^+	-8.03(15)		1	0.17	0.33	0.86
a_2^+	49.3(31)			1	-0.31	0.16
a_0^0	0.7813(73)				1	0.47
a_1^0	-3.38(15)					1

Preliminary

Measured parameters of the N = 3 BCL expansion

Systematic uncertainty $|V_{cb}|$

Fractional contributions to the total relative uncertainty of $|V_{cb}|$

$|V_{cb}|$ = (39.2 ± 0.4 (stat.) ± 0.6 (syst.) ± 0.5 (theo.)) × 10^{-3}

Preliminary

	Uncertainty [%]
Statistical uncertainty	0.9
MC Stat. Error	0.5
N_{bb}	0.5
f_{00}/f_{+-}	0.1
$f_{\not{B}}$	0.3
$\mathcal{B}(D \to K\pi(\pi))$	0.3
Selection	0.5
$\mathcal{B}(B \to X_c \ell\nu)$	0.3
Lepton identification	0.2
Kaon identification	0.5
Tracking efficiency	0.3
Signal PDF	0.4
$B \to D^* \ell\nu$ form factor	0.1
w background modelling	0.5
Background reweighing	0.3
$\tau_{B^{0/\pm}}$	0.1
Total Systematic	1.5
Lattice QCD inputs	1.2
Long-distance QED	0.4
Total theory	1.3
Total	2.1

Electroweak and QED corrections

- Short-distance electroweak corrections are well understood
  - η_{EW} = (1.0066 ± 0.0002) [Nucl. Phys. B 196, 83 (1982)]

- Long-distance QED corrections arise from photon exchange between the *D* meson and the charged lepton (Coulomb correction)
  - $\delta_{Coulomb} = (1 + \alpha\pi) = 1.023$ [Phys. Rev. D 41, 1736 (1990)]
  - A nuisance parameter θ is introduced to take into account the isospin-breaking effect of the Coulomb correction which modifies the *B* lifetime ratio
    - $\tau_{0+} \rightarrow \tau_{0+}(1 + \alpha\pi\theta)$
  - This is an important information that cannot be accessed in $B \rightarrow D^* l \nu$ measurements where the D^* is usually reconstructed via $D^* (\rightarrow D^0 \pi^+)$

Intermediate summary:
The goal of the research was reached but it did not bring us closer to understanding the issue…

Another idea is that the problem lies with the…

Inclusive semileptonic BR

$|V_{cb}|$ from inclusive decays

$B \to Xl\nu$

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2\left(1 + \frac{c_5(\mu)\langle O_5\rangle(\mu)}{m_b^2} + \frac{c_6(\mu)\langle O_6\rangle(\mu)}{m_b^3} + \mathcal{O}\left(\frac{1}{m_b^4}\right)\right)$$

- Based on the Operator Product Expansion (OPE)
- $\langle O_i \rangle$: hadronic matrix elements (non-perturbative)
  c_i: coefficients (perturbative)
- Parton-hadron duality → the hadronic ME depend only on the initial state

	Kinetic [JHEP 1109 (2011) 055]	1S [PRD70, 094017 (2004)]
O(1)	m_b, m_c	m_b
$O(1/m^2_b)$	μ^2_π, μ^2_G	λ_1, λ_2
$O(1/m^3_b)$	ρ^3_D, ρ^3_{LS}	ρ_1, $\tau_{1\text{-}3}$

Recent results for $|V_{cb}|$ inclusive

OPE-based analyses

- E_ℓ and M_X^2 moments
  [M. Bordone, B. Capdevila, and P. Gambino, Phys. Lett. B 822 (2021) 136679]

$$\boxed{|V_{cb}| = (42.16 \pm 0.30(th) \pm 0.32(exp) \pm 0.25(\Gamma)) \times 10^{-3} \qquad \mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu}_\ell) = (10.66 \pm 0.15)\%}$$

- q^2 moments ($\mathscr{B}_{\mathrm{SL}}$ is input)
  [F. Bernlochner et al., JHEP 10 (2022) 068]

$$\boxed{|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3} \qquad \mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu}_\ell) = (10.48 \pm 0.13)\%}$$

- E_ℓ, M_X^2 and q^2 moments
  [M. Bordone, B. Capdevila, and P. Gambino, Phys. Lett. B 822 (2021) 136679]

$$\boxed{|V_{cb}| = (41.97 \pm 0.27(\mathrm{exp}) \pm 0.31(\mathrm{th}) \pm 0.25(\Gamma)) \times 10^{-3} \qquad \mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu}_\ell) = (10.63 \pm 0.15)\%}$$

Rescaling JHEP 10 (2022) 068 to the same $\mathscr{B}_{\rm SL}$

- q^2 moments ($\mathscr{B}_{\rm SL}$ is input)
  [F. Bernlochner et al., JHEP 10 (2022) 068]

$$\boxed{|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}}$$

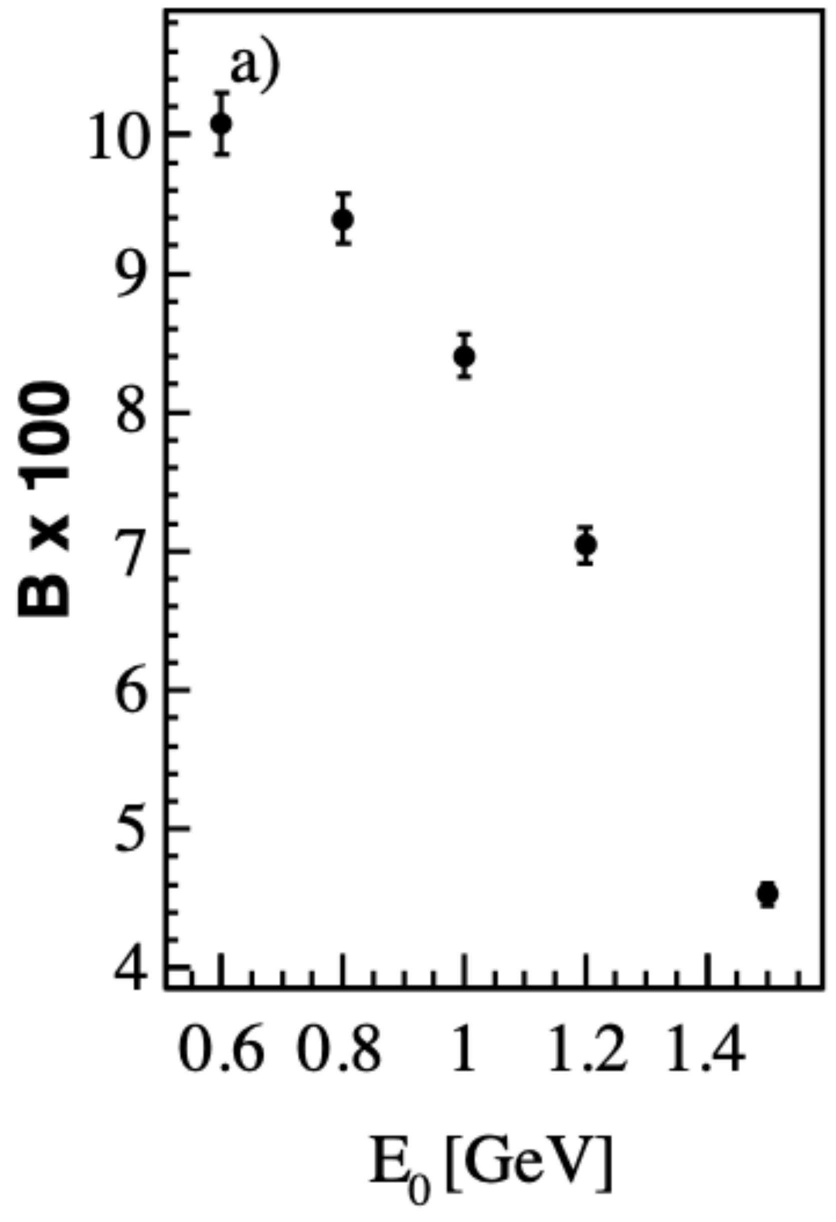
$$\mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu}_\ell) = (10.48 \pm 0.13)\%$$

$$\boxed{(41.99 \pm 0.65) \times 10^{-3}}$$

$$\mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu}_\ell) = (10.63 \pm 0.19)\%$$

Partial BR measurements

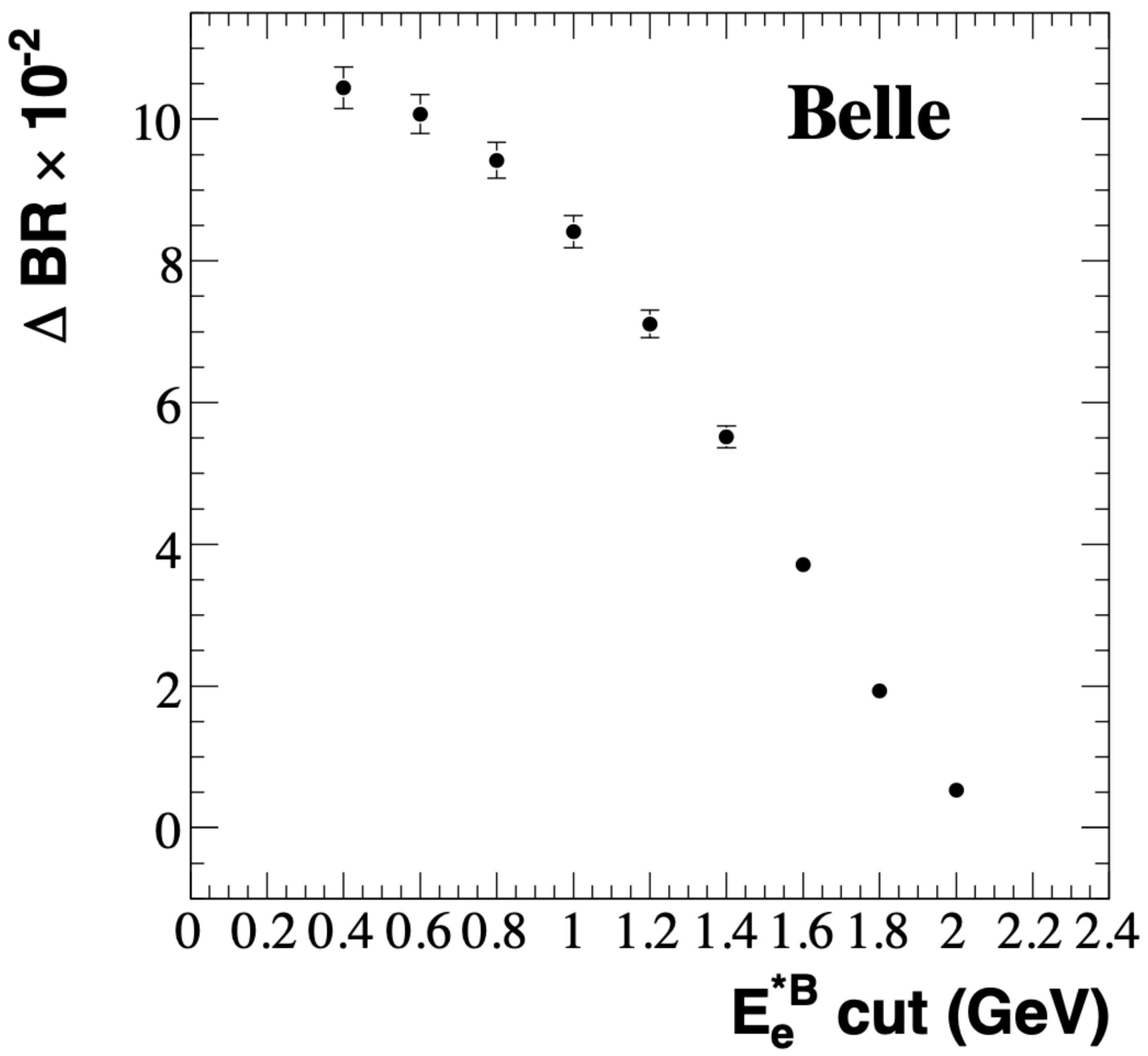
Inputs to global analyses



BaBar
Double semileptonic decays
[Phys.Rev. D81 (2010) 032003]

E_0[GeV]	$\mathcal{B}[10^{-2}]$
0.6	$10.30 \pm 0.06 \pm 0.24$
0.8	$9.61 \pm 0.05 \pm 0.20$
1.0	$8.65 \pm 0.04 \pm 0.17$
1.2	$7.31 \pm 0.04 \pm 0.14$
1.5	$4.79 \pm 0.03 \pm 0.09$

(2004 table)

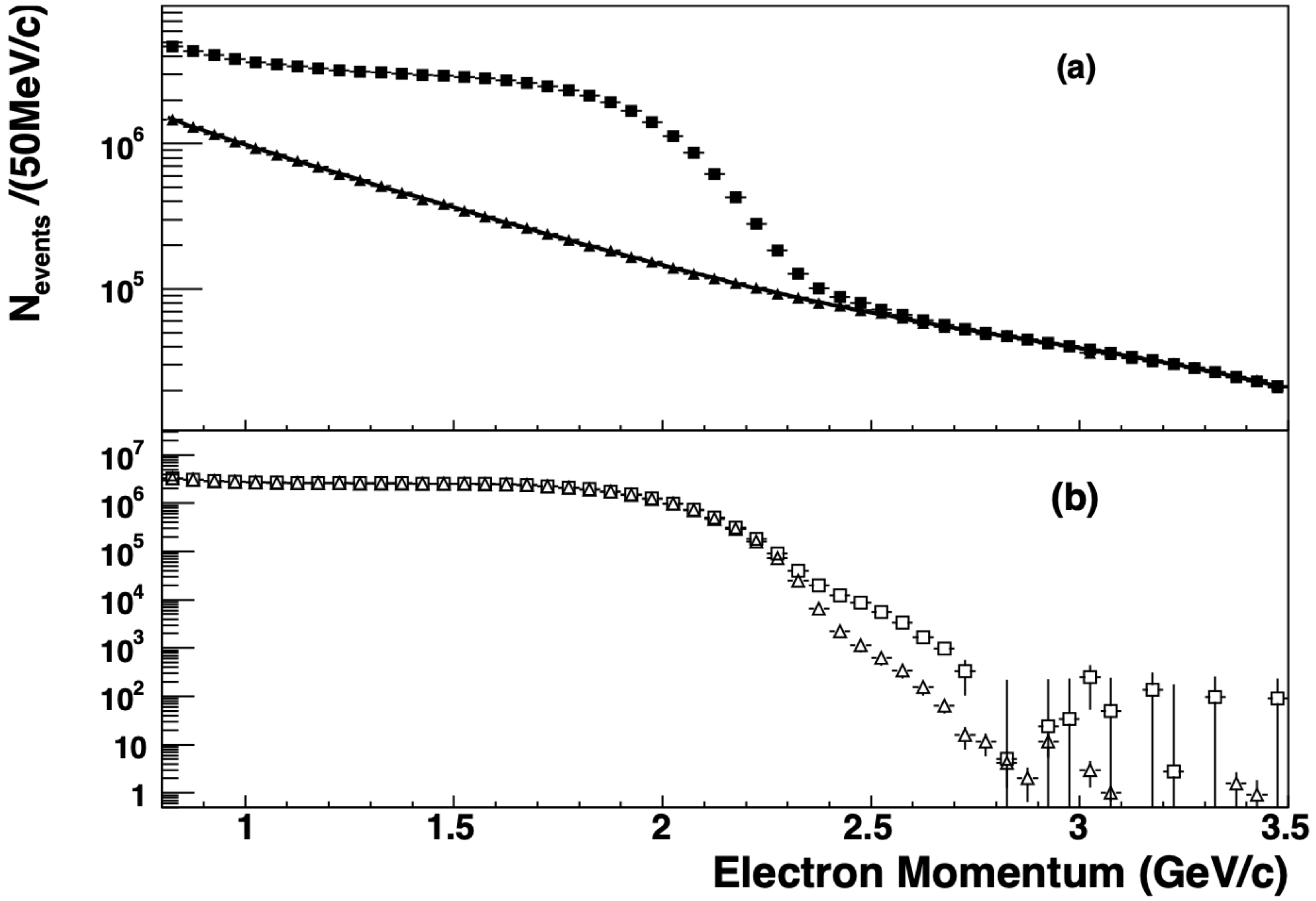


Belle
Hadronic tag
[Phys.Rev. D75 (2007) 032001]

$E_{\rm cut}$[GeV]	$\Delta\mathcal{B}\ [10^{-2}]$
0.4	$10.44 \pm 0.19 \pm 0.22$
0.6	$10.07 \pm 0.18 \pm 0.21$
0.8	$9.42 \pm 0.16 \pm 0.19$
1.0	$8.41 \pm 0.15 \pm 0.17$
1.2	$7.11 \pm 0.13 \pm 0.14$
1.4	$5.52 \pm 0.11 \pm 0.11$
1.6	$3.71 \pm 0.09 \pm 0.07$
1.8	$1.93 \pm 0.06 \pm 0.04$
2.0	$0.53 \pm 0.02 \pm 0.02$

Phys.Rev.D 95 (2017) 7, 072001

BaBar publication on $|V_{ub}|$ inclusive



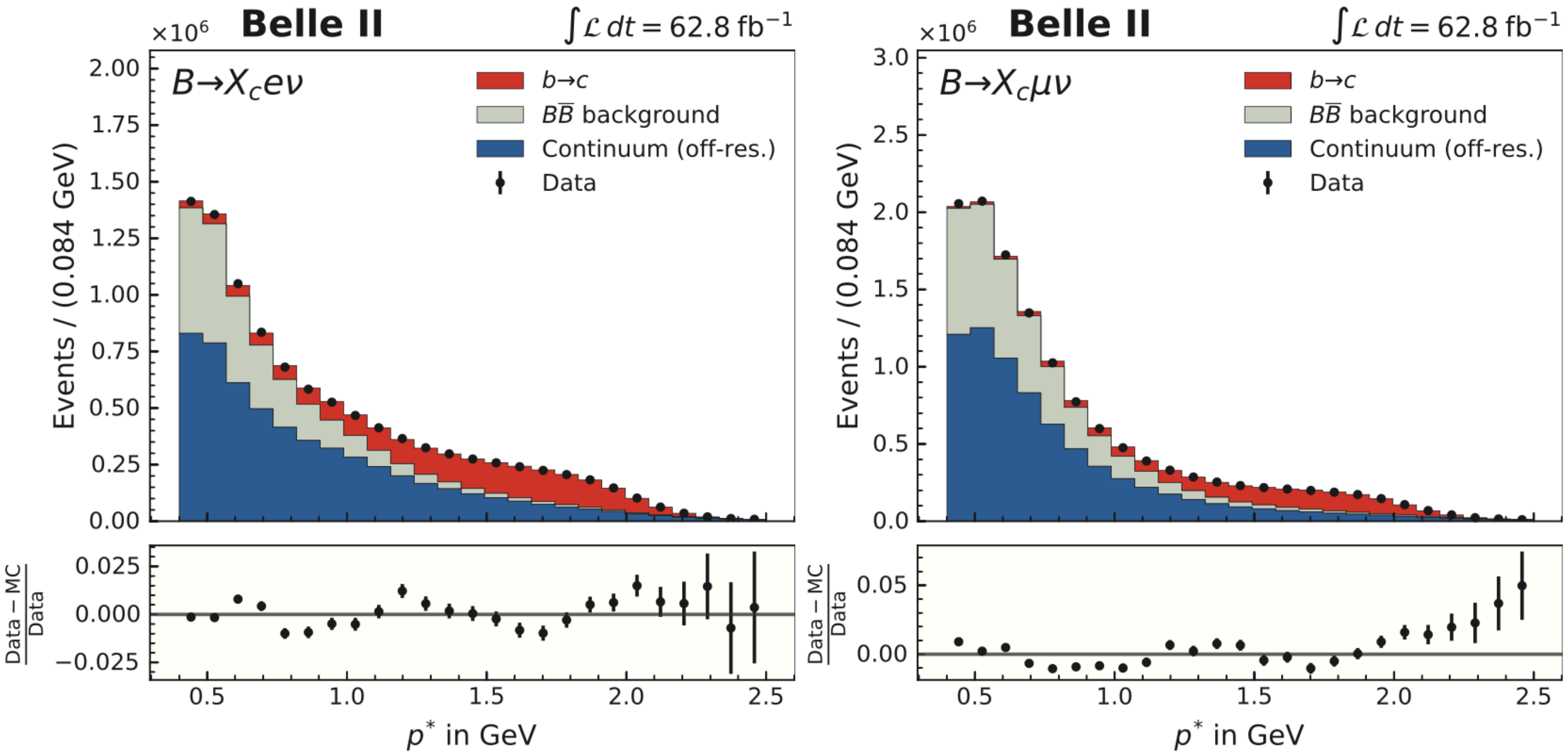
$$\boxed{\mathcal{B}(B \to Xe\nu) = (10.34 \pm 0.04_{\mathrm{stat}} \pm 0.26_{\mathrm{syst}})\%}$$

Revisiting the measurement of $\mathscr{B}_{\mathrm{SL}}$

- There is ample motivation for revisiting the measurement of the inclusive, semileptonic BR measurement
  - Only few recent measurements, issue with consistency?
  - $\mathscr{B}_{\mathrm{SL}}$ has a very significant impact on the value of $|V_{cb}|$ inclusive
- A new measurement should be inclusive to avoid issues with tagging
  - Requires excellent understanding of backgrounds and detector systematics

Belle II $B \to X\ell\nu$ inclusive [arXiv:2111.09405]

Preliminary conference result



- Pure inclusive measurement seems hard due to significant backgrounds, double-tag measurement a la BaBar?

Summary

- $|V_{cb}|$ *exclusive*
  - The new Belle II measurement of $B \to D\ell\nu$ shows no major surprise but strengthens the confidence in the present value for $|V_{cb}|$ exclusive
  - The collaboration paper should be submitted to the journal in a couple of days, detailed spectral data will be uploaded to HepData prior to submission
- $|V_{cb}|$ *inclusive*
  - Imho the inclusive, semileptonic BR did not receive enough experimental scrutiny though it could play a major role in understanding the exclusive-inclusive puzzle
  - Work towards an untagged measurement is underway in my group but please don't expect results soon as this will be a challenging task

Backup