Semileptonic B decays at Belle II & Belle

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for SUSY 2023 (July 17-21, 2023)

Outline

- The cram course
  - for Belle II and Belle experiments (details in Appendix 0)
- on V_{xb} $(x = c, u)$ tensions
  - V_{ub} from exclusive $B \to \pi \ell^+ \nu$ (Belle II)
  - simultaneous (inclusive & exclusive) V_{ub} (Belle)
- on LFU test
  - inclusive ratio $R(X_{e/\mu})$ (Belle II)
  - First Belle II result on $R(D^*)$
- Closing remarks

The cram course

for *B*-mesons @ Belle & Belle II

$$e^- \xrightarrow{8\ \text{GeV}} (\star) \xleftarrow{3.5\ \text{GeV}} e^+$$

(1999-2010)

$$e^- \xrightarrow{7\ \text{GeV}} (\star) \xleftarrow{4\ \text{GeV}} e^+$$

(since 2019)

See Appendix 0 (p.25-31) for more

- $\sqrt{s} = 10.58\ \text{GeV} = m(\Upsilon(4S))$ for both
- Use $\Upsilon(4S) \to B\overline{B}$
- ∃ continuum underneath $\Upsilon(4S)$

Belle II Physics Mind-map

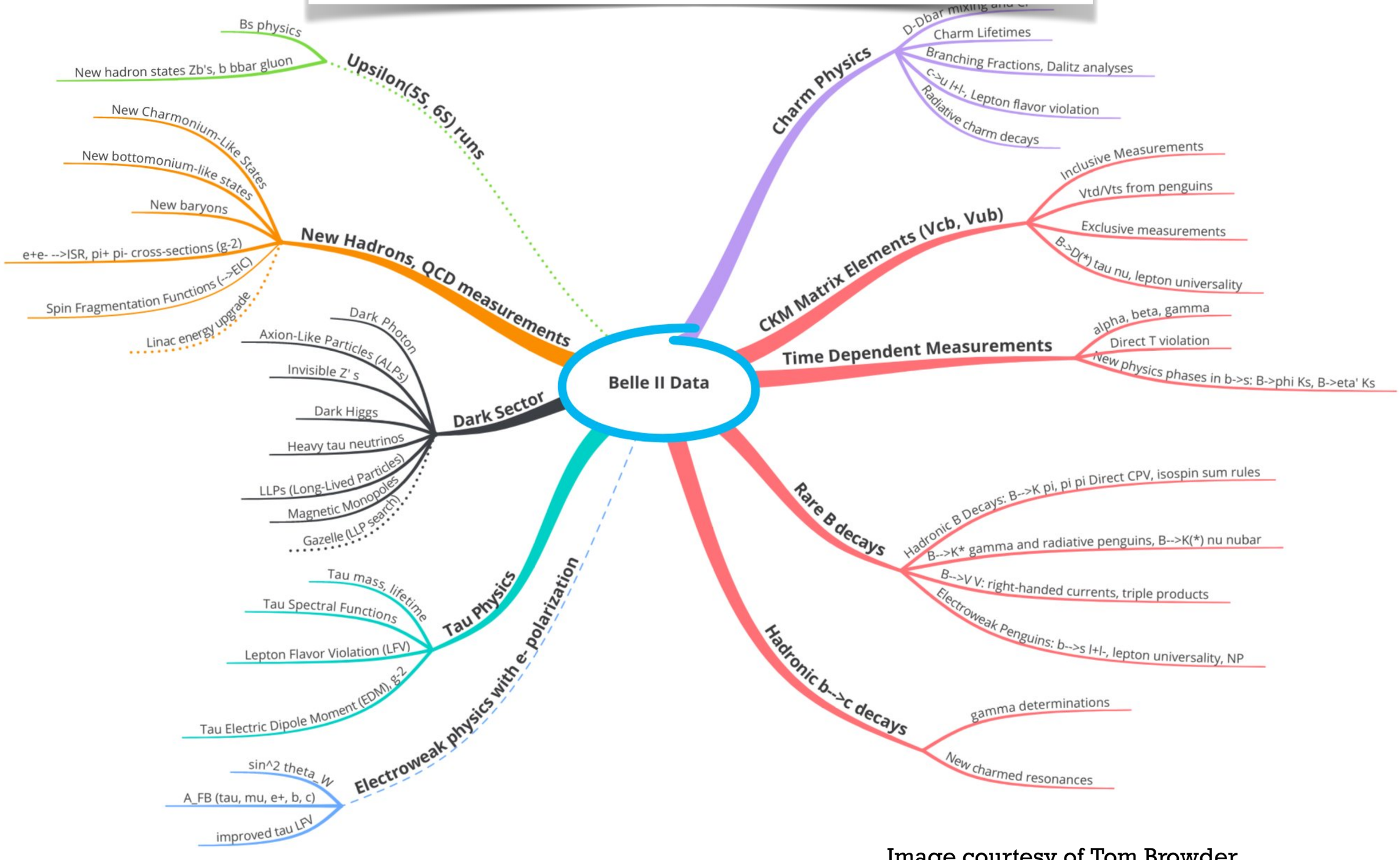


Image courtesy of Tom Browder

Belle II Physics Mind-map

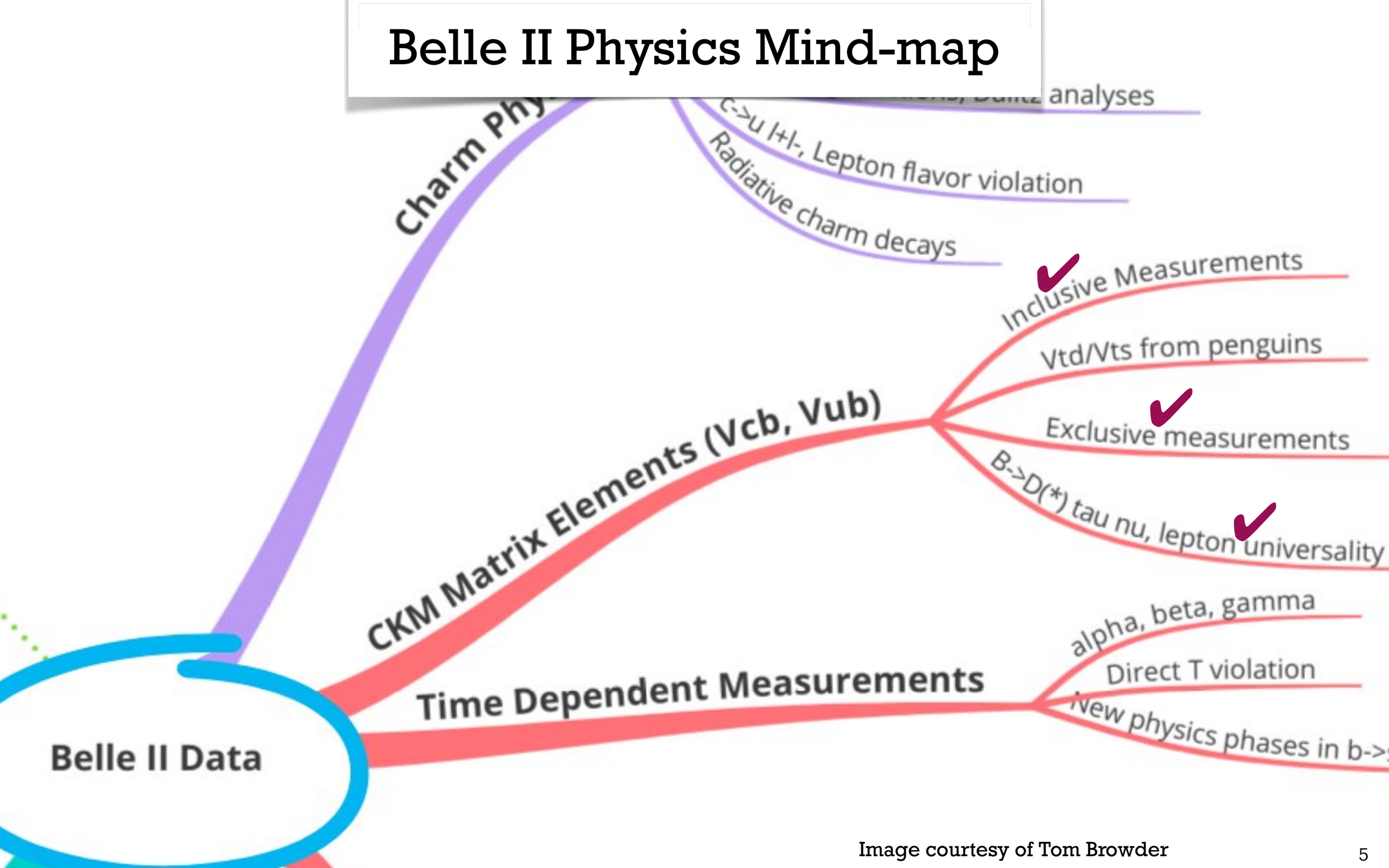
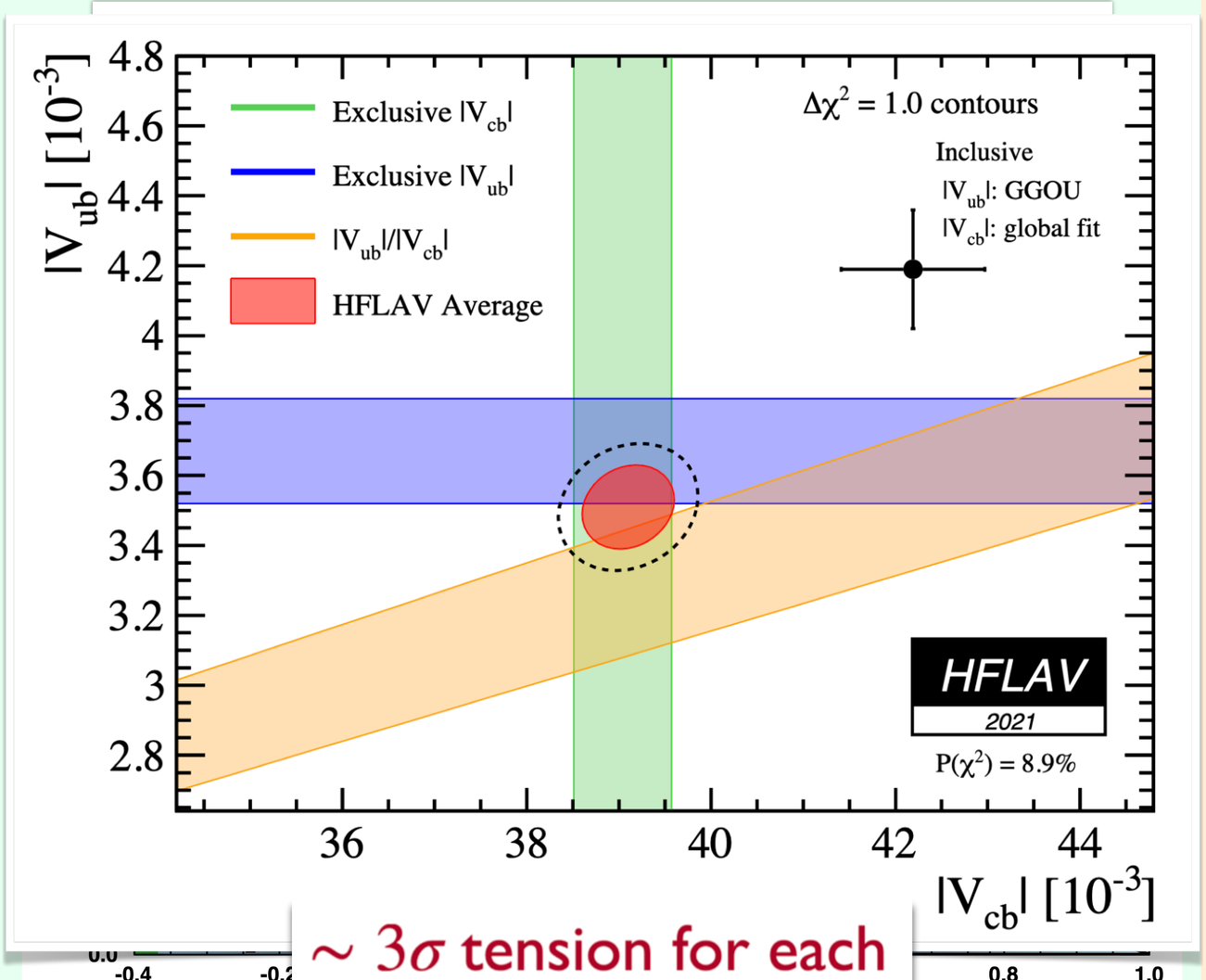


Image courtesy of Tom Browder

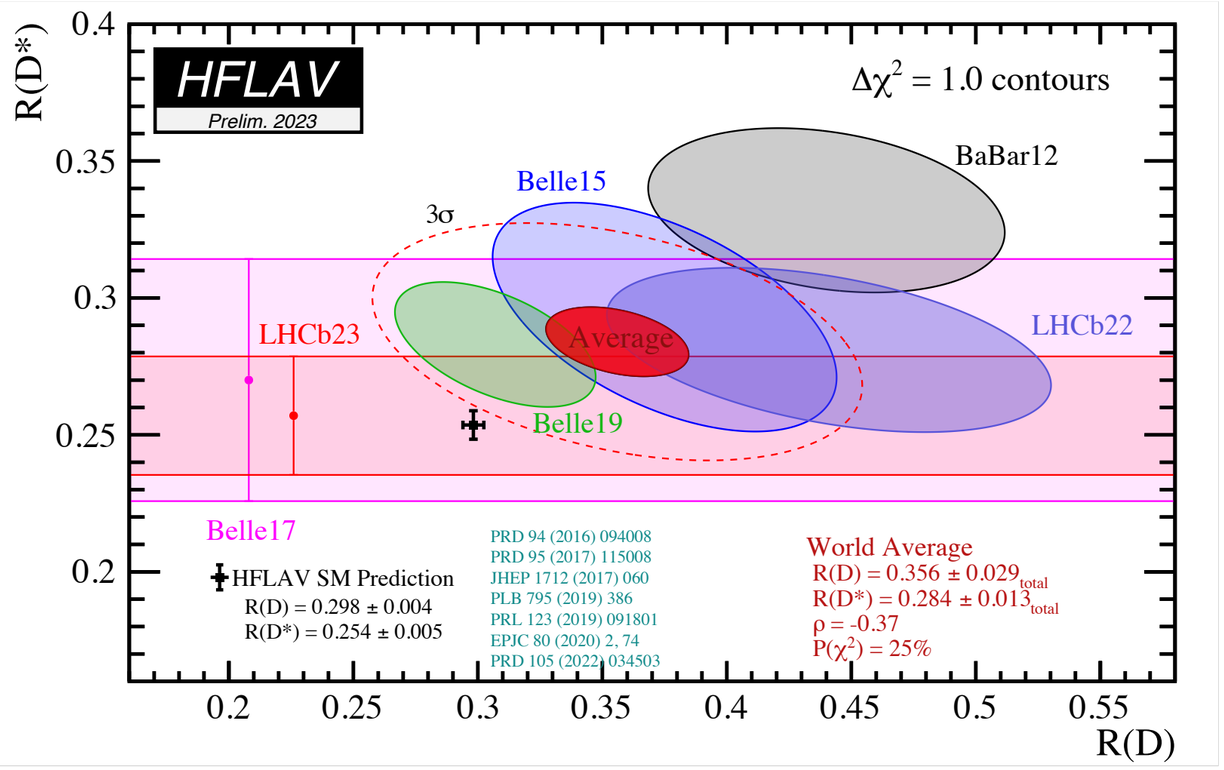
tensions in semileptonic B decays

Precision measurements of CKM UT



~ 3σ tension for each ($|V_{cb}|$, $|V_{ub}|$)

Test of lepton universality in $R(D^{(*)})$



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

on V_{xb} $(x = c, u)$ tensions

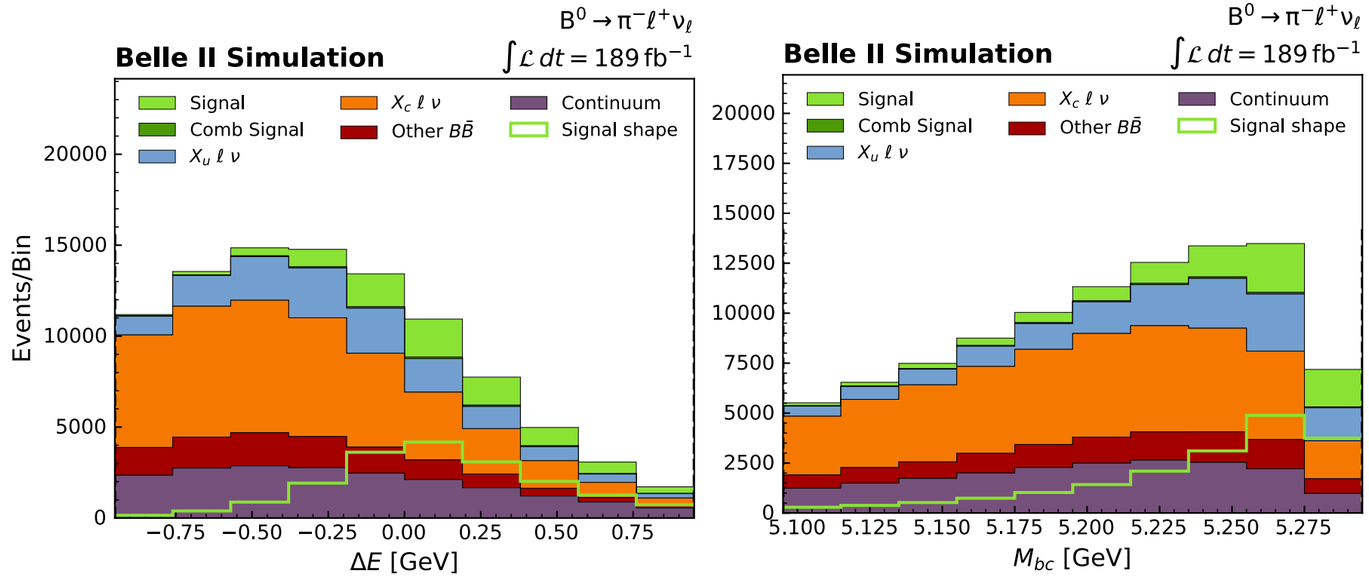
- $|V_{cb}|$ from exclusive B decays (Belle, Belle II) — Appendix 1 in the back-up slides
- $|V_{ub}|$ from exclusive $B^0 \to \pi^- \ell^+ \nu$ (Belle II)
- Simultaneous (incl. & excl.) $|V_{ub}|$ (Belle)

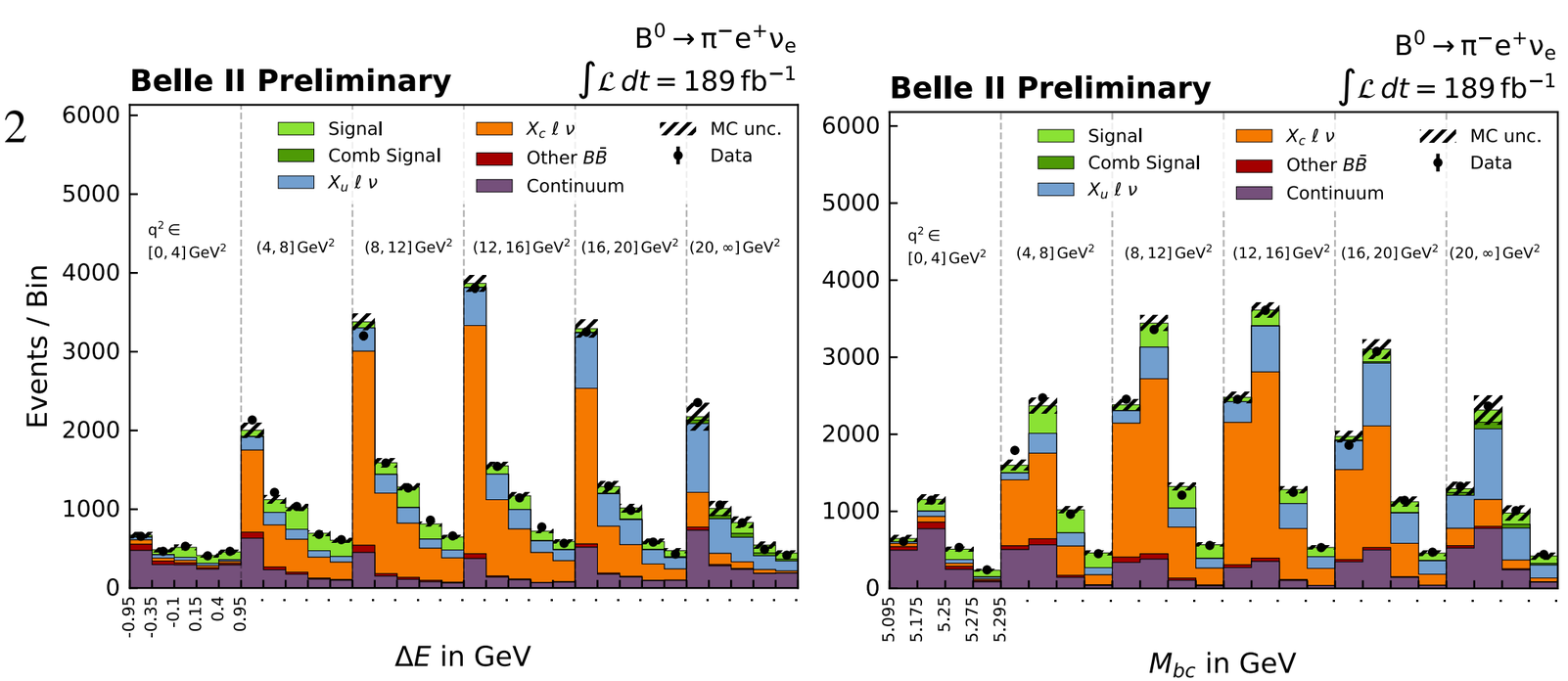
$B^0 \to \pi^- \ell^+ \nu$ for $|V_{ub}|$ (untagged)

arXiv:2210.04224

- Belle II dataset of $\mathscr{L}_{\text{int}} = 189\ \text{fb}^{-1}$
- "untagged" analysis
  - aiming at highest signal efficiency
  - instead of tagging, just measure ROE for background suppression using $(E, \vec{p})$ cons.
- suppress $q\bar{q}$ & combinatoric backgrounds via BDT
- measure partial BF in 6 bins of q^2
  - signal extraction by binned 2D fit to $(M_{bc}, \Delta E)$

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.426 \pm 0.056 \pm 0.125) \times 10^{-4}$$





$B^0 \to \pi^- \ell^+ \nu$ for $|V_{ub}|$ (untagged)

arXiv:2210.04224

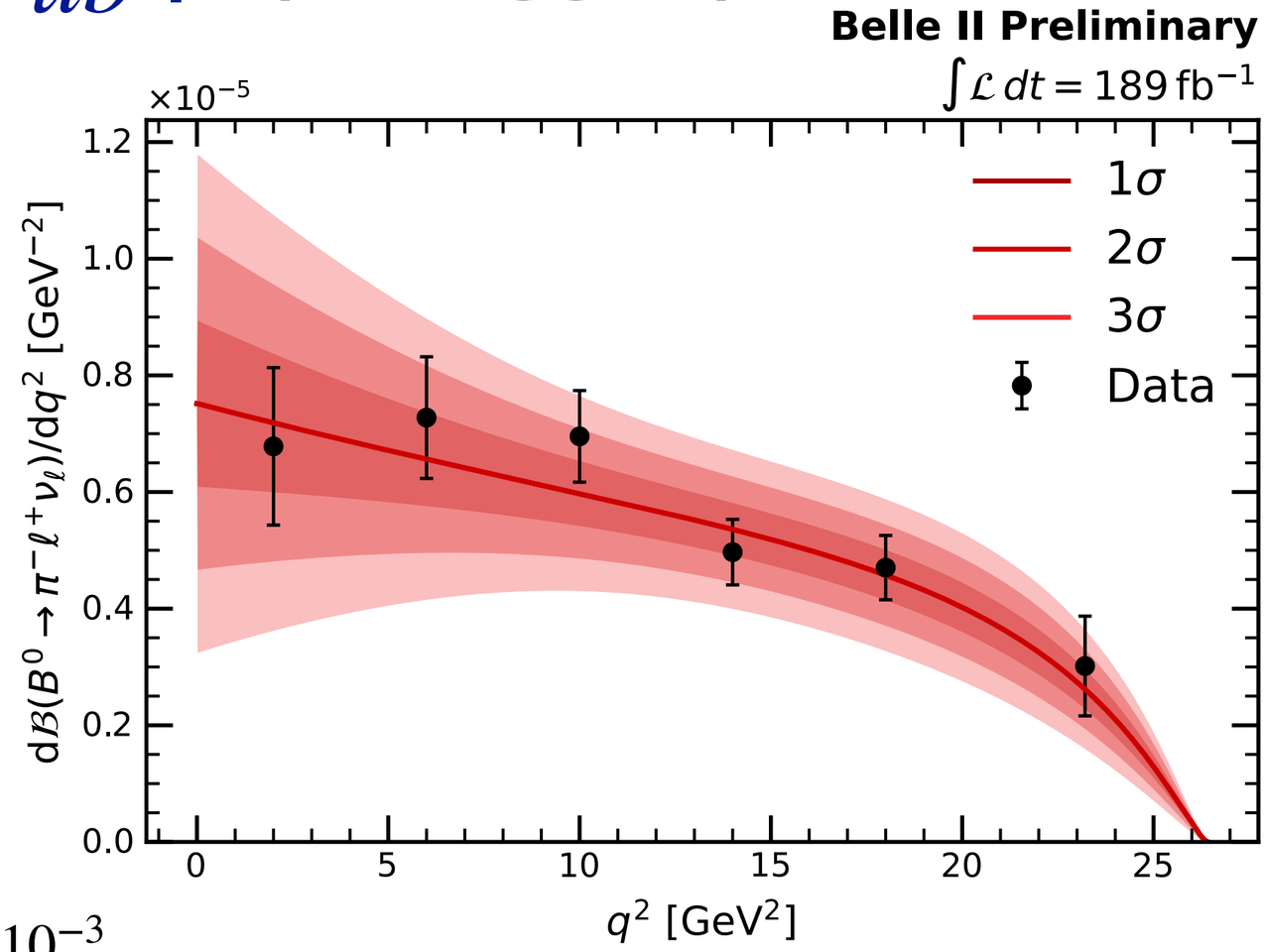
- Extract $|V_{ub}|$ from the partial BF

$$\frac{d\Gamma(B \to \pi \ell^+ \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 |p_\pi|^3 |f_+(q^2)|^2$$

in the limit $m_\ell^2 = 0$

- BCL expansion for $|V_{ub}|$
  - Lattice QCD input from FNAL/MILC on the eight BCL parameters

Bourrely, Lellouch, Caprini, PRD **79**, 013008 (2009)



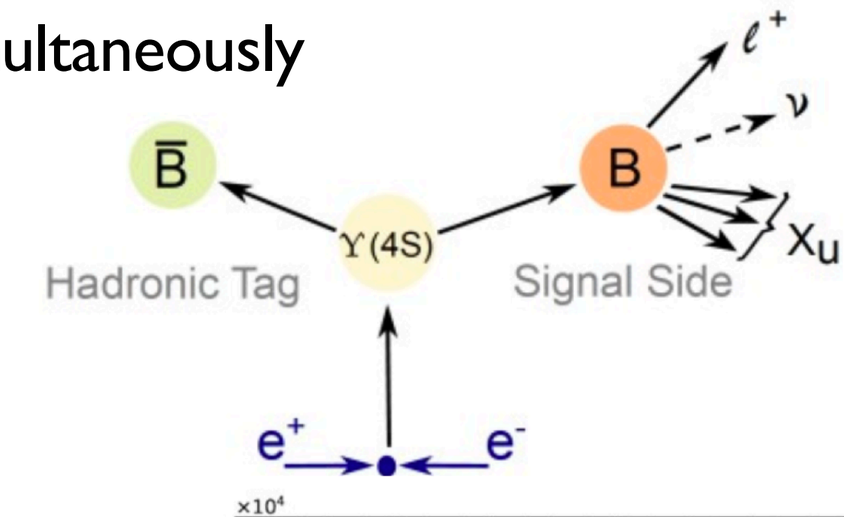
$$|V_{ub}|_{B^0 \to \pi^- e^+ \nu} = (3.60 \pm 0.18 \pm 0.14 \pm 0.18) \times 10^{-3}$$
$$|V_{ub}|_{B^0 \to \pi^- \mu^+ \nu} = (3.71 \pm 0.16 \pm 0.15 \pm 0.17) \times 10^{-3}$$

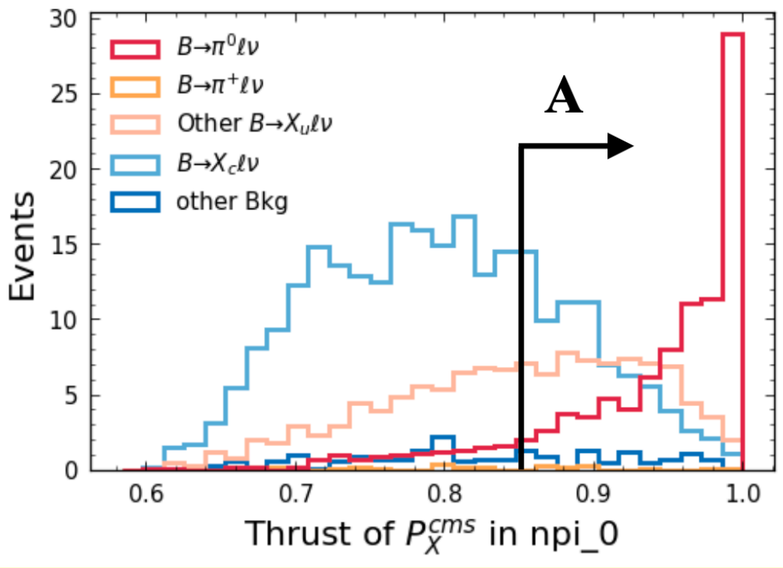
$$|V_{ub}|_{B^0 \to \pi^- \ell^+ \nu} = (3.55 \pm 0.12 \pm 0.13 \pm 0.17) \times 10^{-3}$$

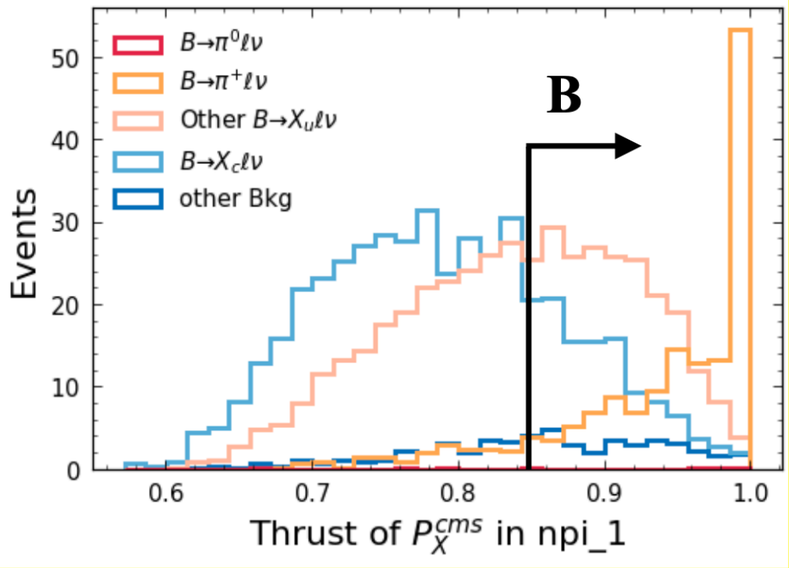
Simultaneous (incl. & excl.) $|V_{ub}|$

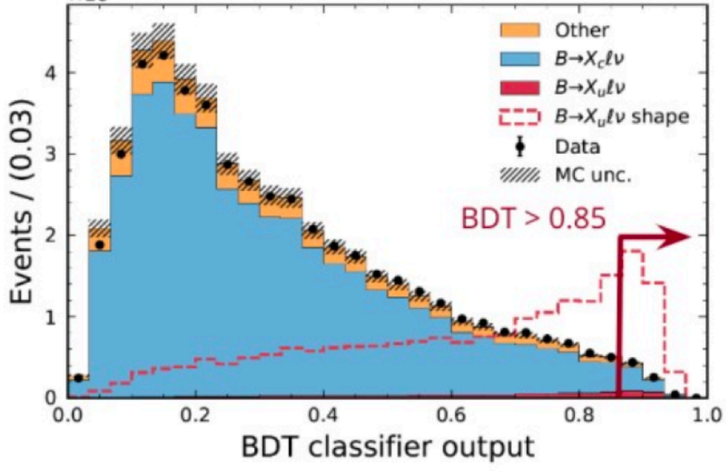
arXiv:2303.17309
submitted to PRL

- Measure $B \to X_u \ell^+ \nu, B^0 \to \pi^- \ell^+ \nu, B^+ \to \pi^0 \ell^+ \nu$ simultaneously
- B-tagging by hadronic decays
  - ANN-based tagging of companion B
  - allows reconstruction of X_u in $B \to X_u \ell^+ \nu$
- $b \to c$ is suppressed using M_X, and further by BDT
  - 11 features for training (M_{m}^2, χ^2_{vtx}, $N(K'\mathrm{s})$, etc.)
- use X_u thrust in the CM frame, for $B \to \pi \ell^+ \nu$ significance







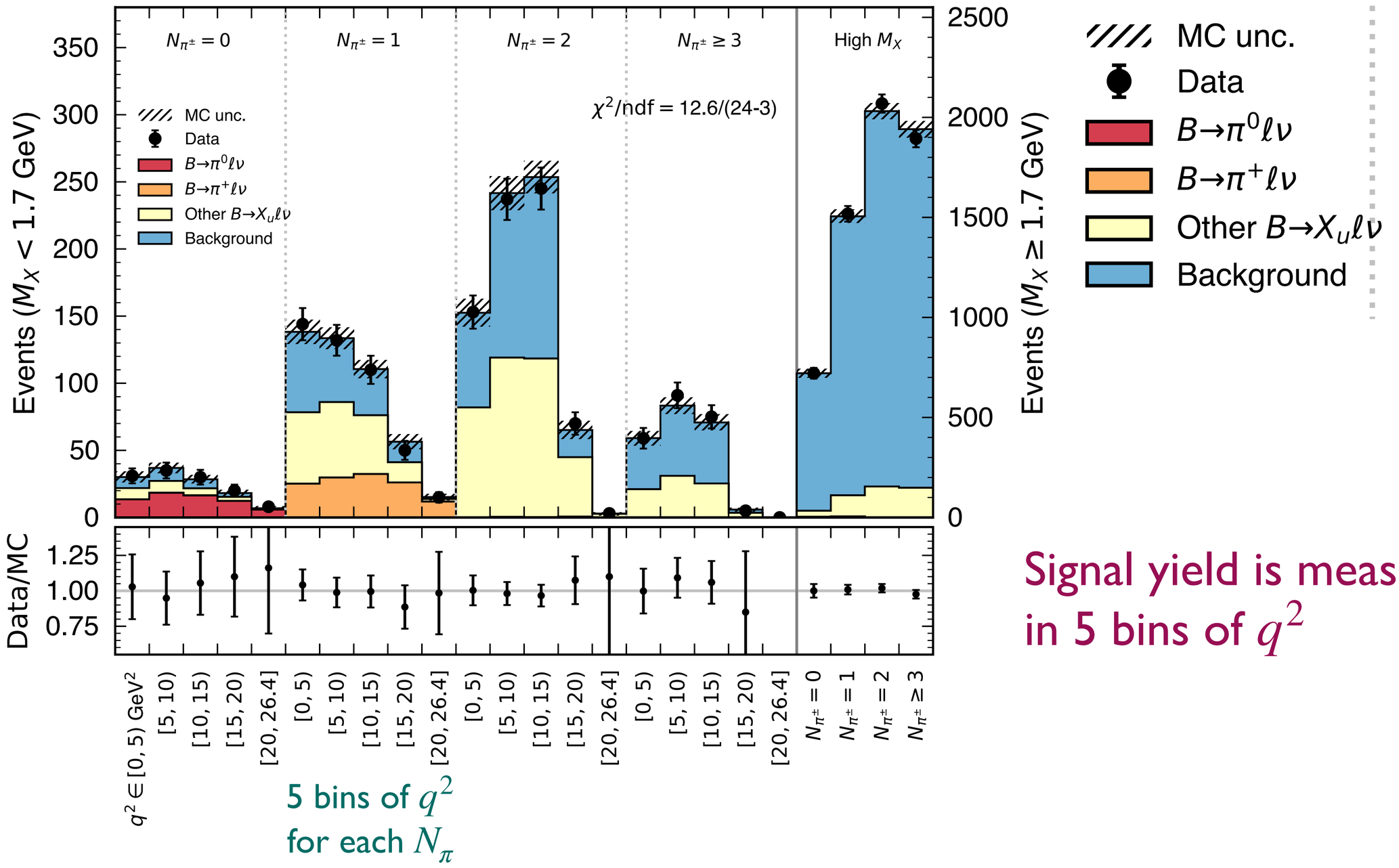


Simultaneous (incl. & excl.) $|V_{ub}|$

arXiv:2303.17309
submitted to PRL

Full Belle dataset

$\mathscr{L}_{\rm int} = 711\ {\rm fb}^{-1}$

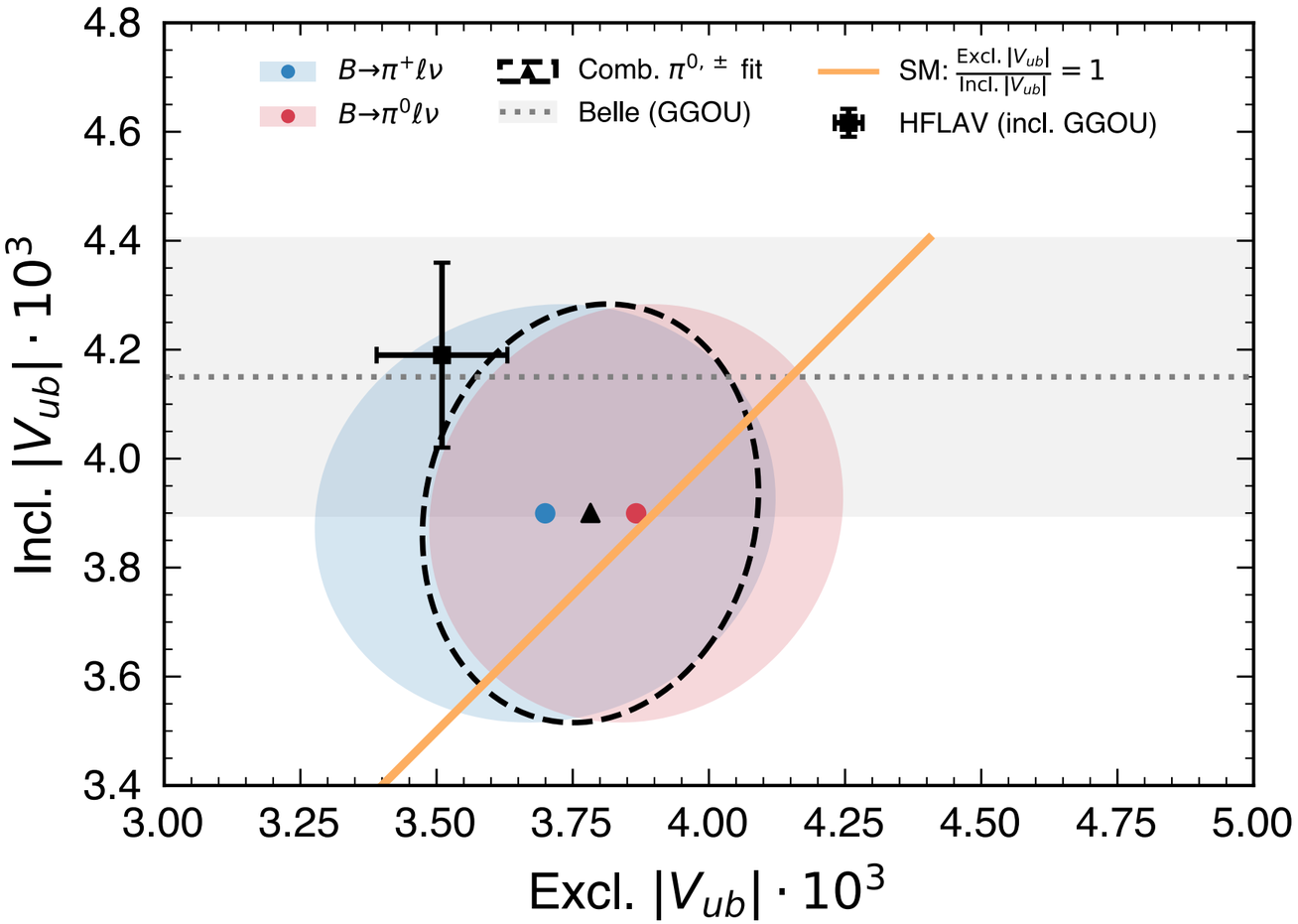


5 bins of q^2
for each N_π

Signal yield is measured
in 5 bins of q^2

Simultaneous (incl. & excl.) $|V_{ub}|$

arXiv:2303.17309
submitted to PRL



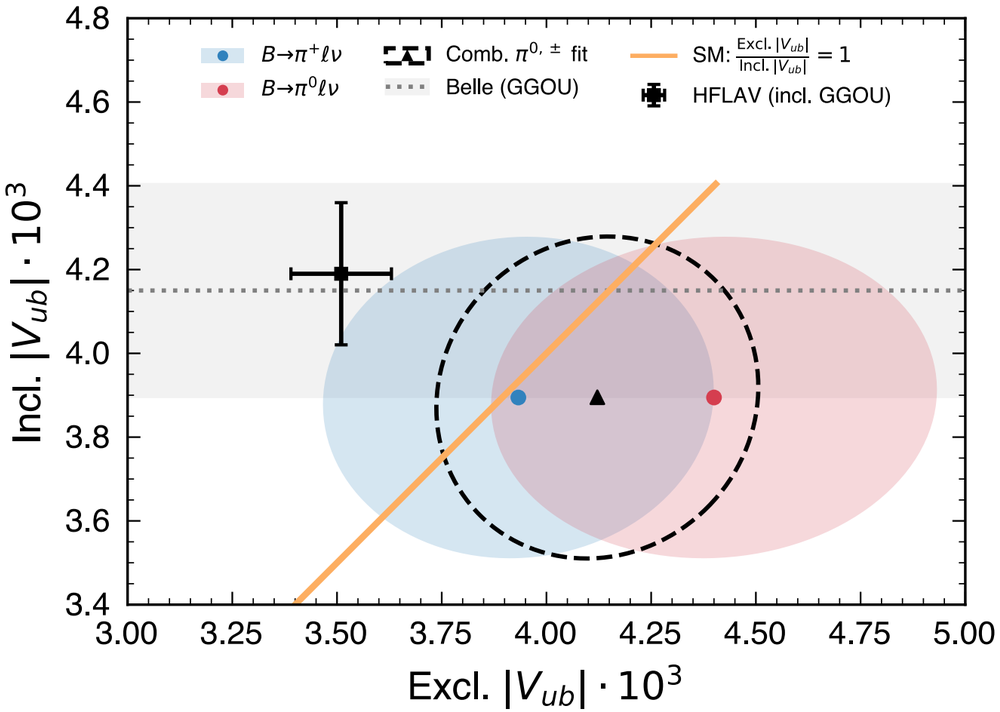
- $|V_{ub}|$ results from fits using LQCD and experimental constraints for the $B \to \pi^+ \ell \nu$ form-factor (*left*)

$$\left|V_{ub}^{\text{excl.}}\right| = (3.78 \pm 0.23 \pm 0.16 \pm 0.14) \times 10^{-3}$$
$$\left|V_{ub}^{\text{incl.}}\right| = (3.90 \pm 0.20 \pm 0.32 \pm 0.09) \times 10^{-3}$$

±(stat) ±(syst) ±(theory)

$$\left|V_{ub}^{\text{excl.}}\right| / \left|V_{ub}^{\text{incl.}}\right| = 0.97 \pm 0.12$$

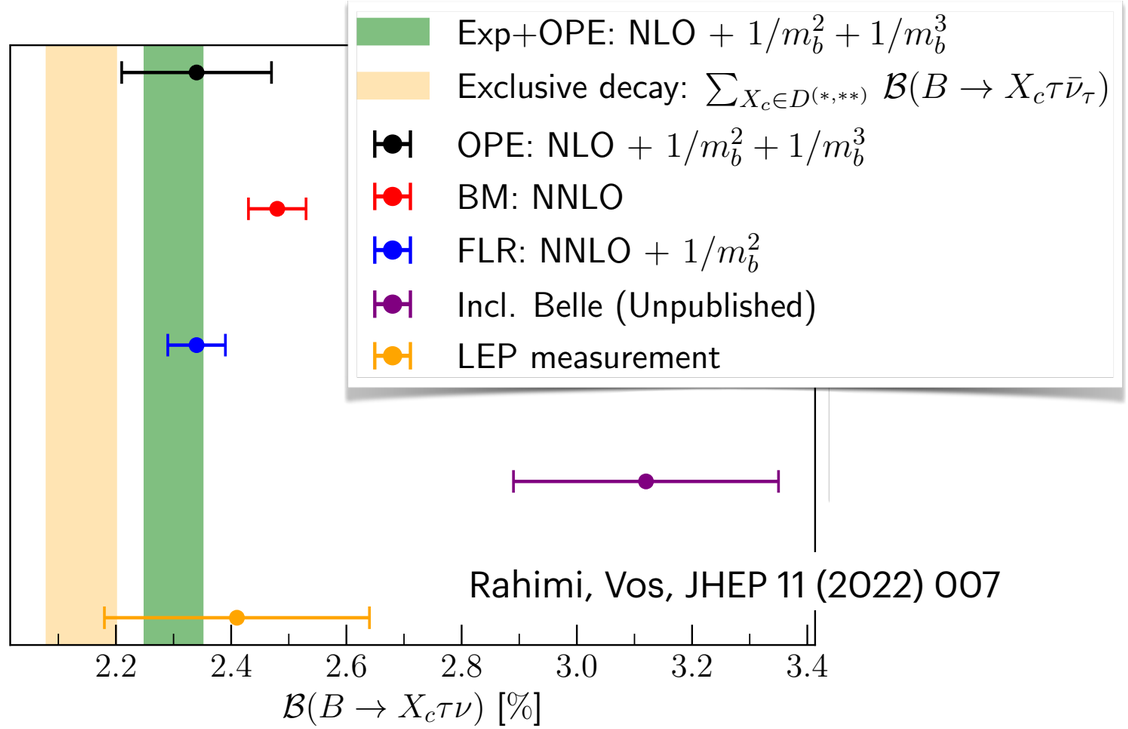
- $|V_{ub}|$ from fits using LQCD, but w/ o form-factor constraints (*right*)



on the LFU test

LFU test with inclusive $B \to X\ell\nu$

- ***inclusive*** study — complementary to ***exclusive*** studies
  - existing $R(D^{(*)})$ are all from exclusive analyses
- one of the unique and high-profile goals of Belle II
- last measured by LEP (!)
- As a first step towards measuring $R(X_{c,\tau/\ell})$, we measure $R(X_{e/\mu})$ at Belle II



- $R(X_{c,\tau/\ell})_{\mathrm{SM}} = 0.223 \pm 0.004$

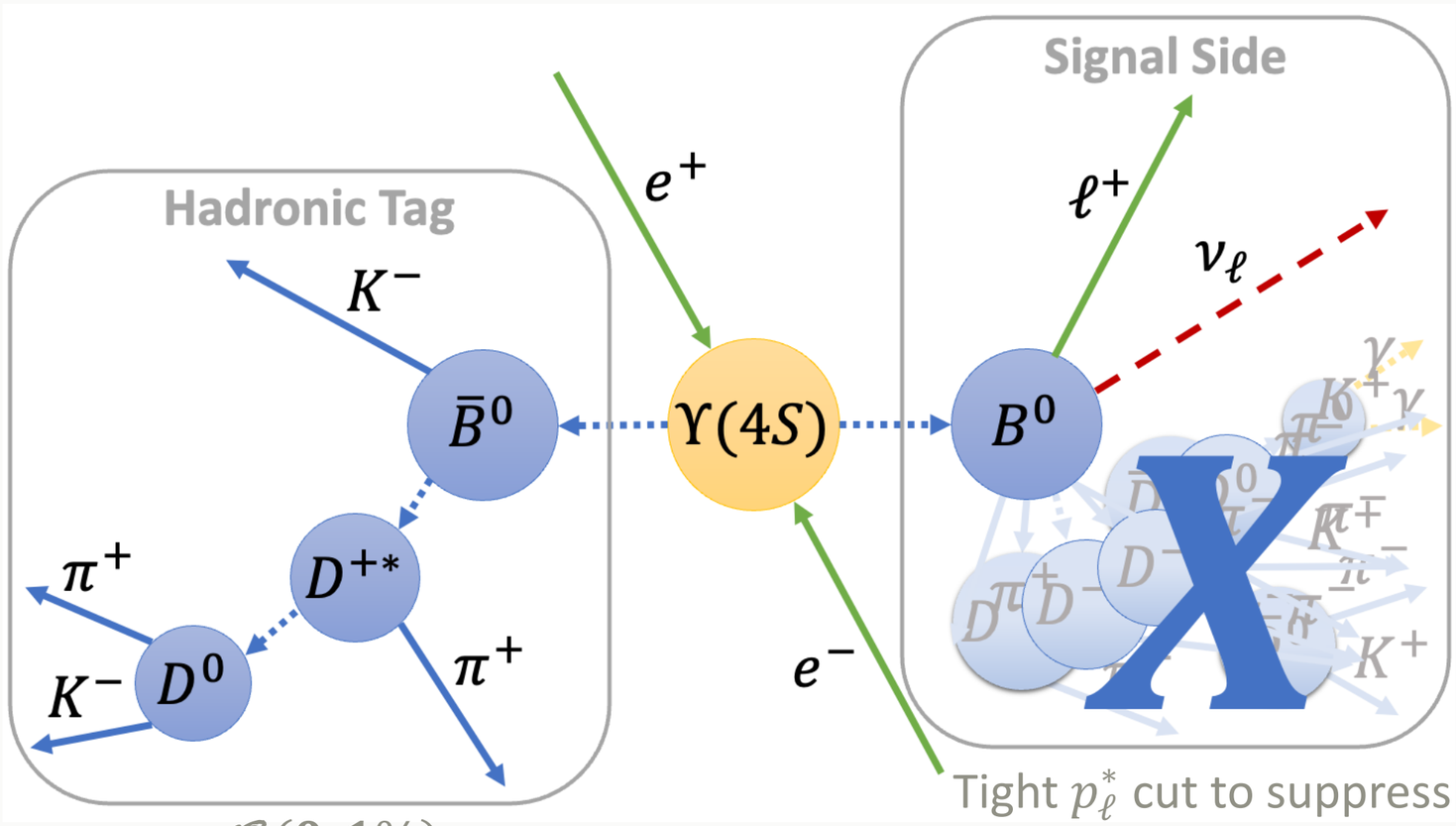
Feytsis, Ligeti, Ruderman, PRD 92, 054018 (2015)

- $R(X_{e/\mu})_{\mathrm{SM}} = 1.006 \pm 0.001$

Rahimi, Vos, JHEP 11 (2022) 007

LFU test with inclusive $B \to X\ell\nu$

arXiv:2301.08266
accepted to PRL



- **Reconstruct**
  $\Upsilon(4S) \to B^-_{\rm tag}\ell^+X$
  $\Upsilon(4S) \to \bar{B}^0_{\rm tag}\ell^+X$
- $p^*_\ell > 1.3$ GeV
- **Only basic quality cuts on tracks and calorimeter signals**
- **Tight constraints on tag quality**

$\epsilon = \mathcal{O}(0.1\%)$

Precise knowledge of $B_{\rm tag}$ kinematics

Tight p^*_ℓ cut to suppress
- hadrons faking leptons ("**fakes**")
- secondary leptons from $b \to c \to (\ell, s)$ cascades ("**secondaries**")
- $B \to X\tau\nu$

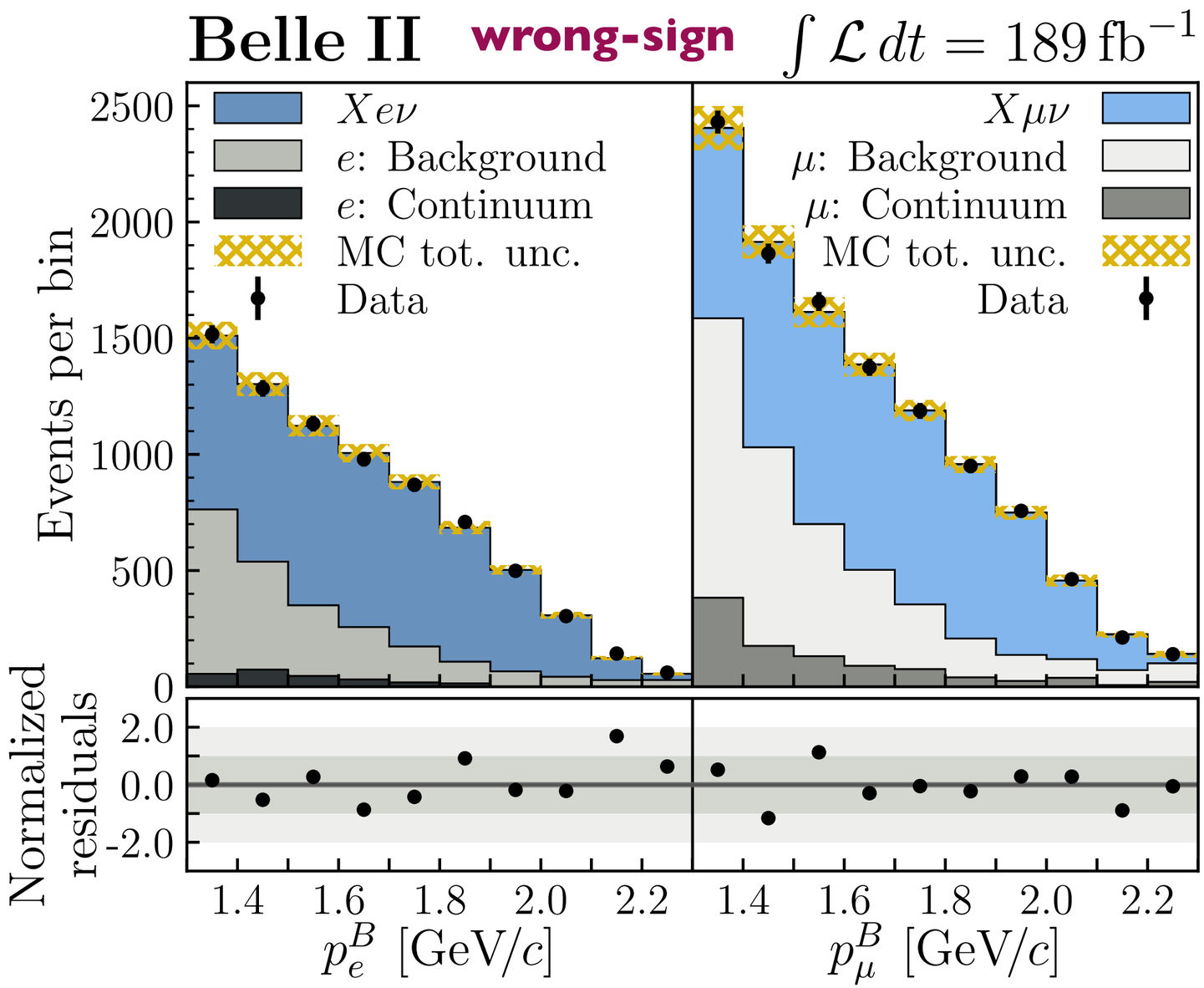
[53% (e) / 66% (μ) of selected B $\to X\ell\nu$ is retained]

See p.31 for FEI as hadronic B-tagging tool.

slide taken from Belle II ICHEP2022 talk by H. Junkerkalefeld

LFU test with inclusive $B \to X\ell\nu$

arXiv:2301.08266
accepted to PRL

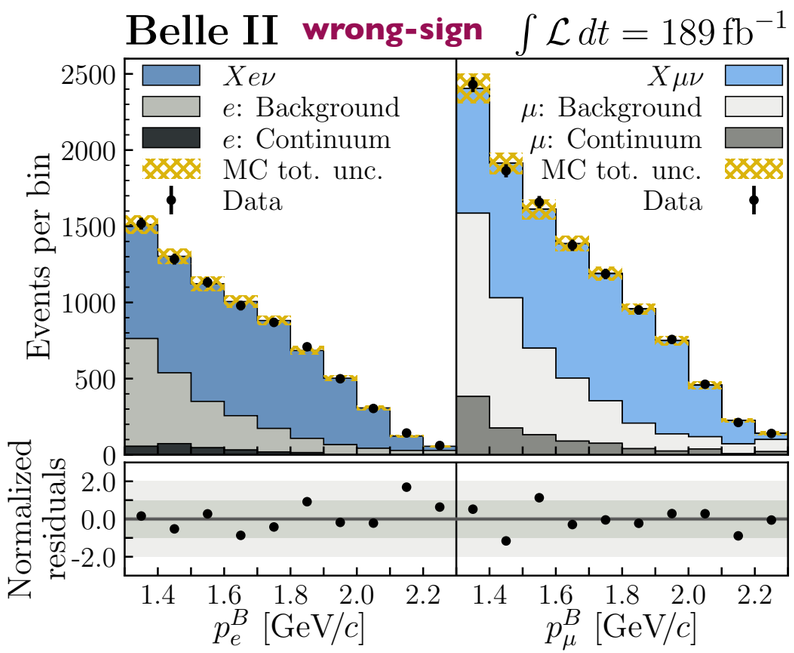


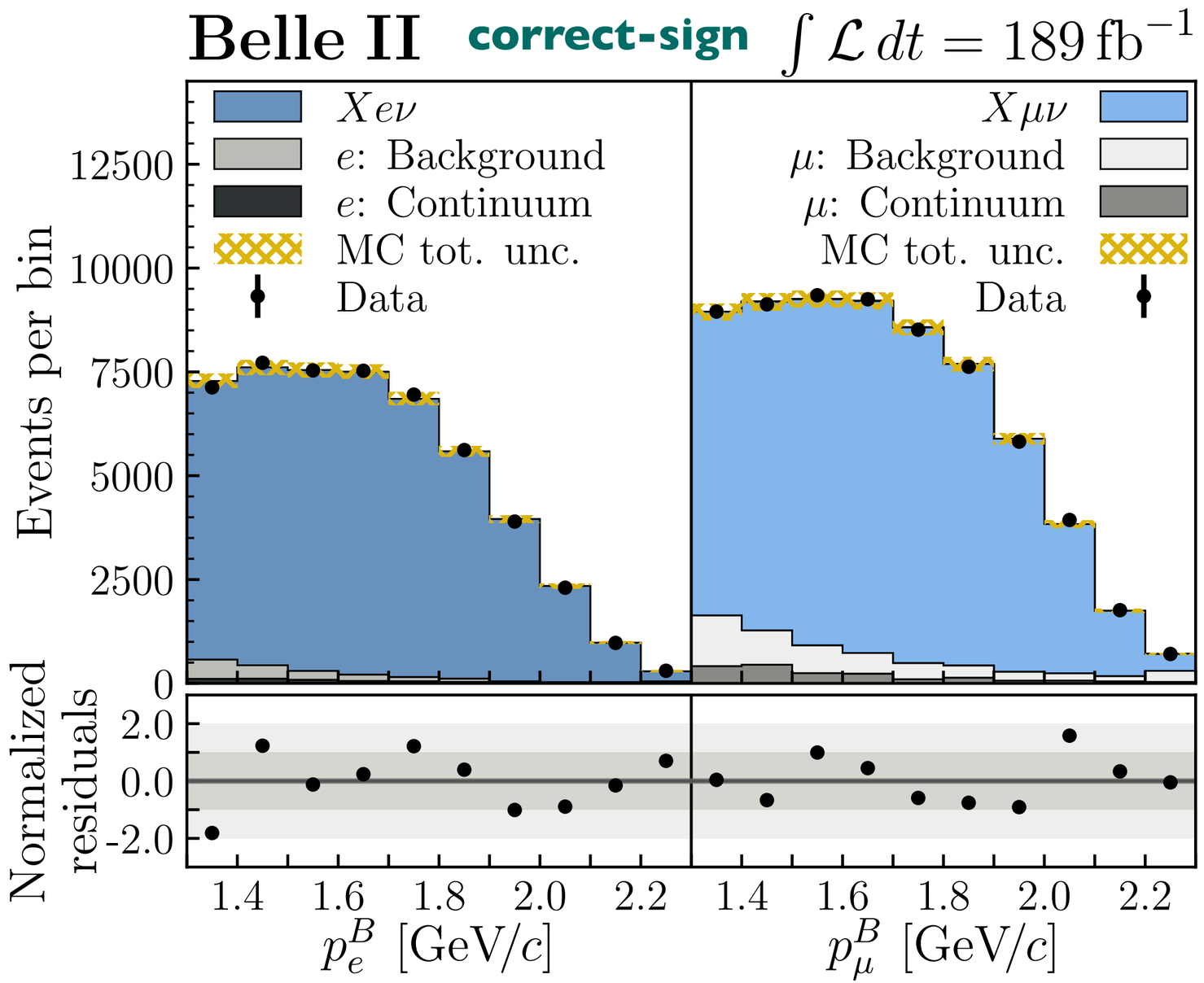
Signal extraction by fitting p_ℓ^B

- Continuum bkgd. is Gaussian-constrained by off-resonance data
- Exploit $B_{\text{tag}} - \ell$ charge correlation
  - ✓ For B^+_{tag}, signal lepton is ℓ^-
  - ✓ For B^0_{tag}, signal lepton is ℓ^-, except for $B\overline{B}$ mixing
- ✓ Fake & secondary leptons are Gaussian-constrained by simulatenously fitting the p_ℓ^B in wrong-sign sample (*left*)

LFU test with inclusive $B \to X\ell\nu$

arXiv:2301.08266
accepted to PRL





$$R(X_{e/\mu}) = 1.007 \pm 0.009 \pm 0.019$$

the most precise BF-based LFU test, and consistent with SM

$R(D^*)$ from Belle II

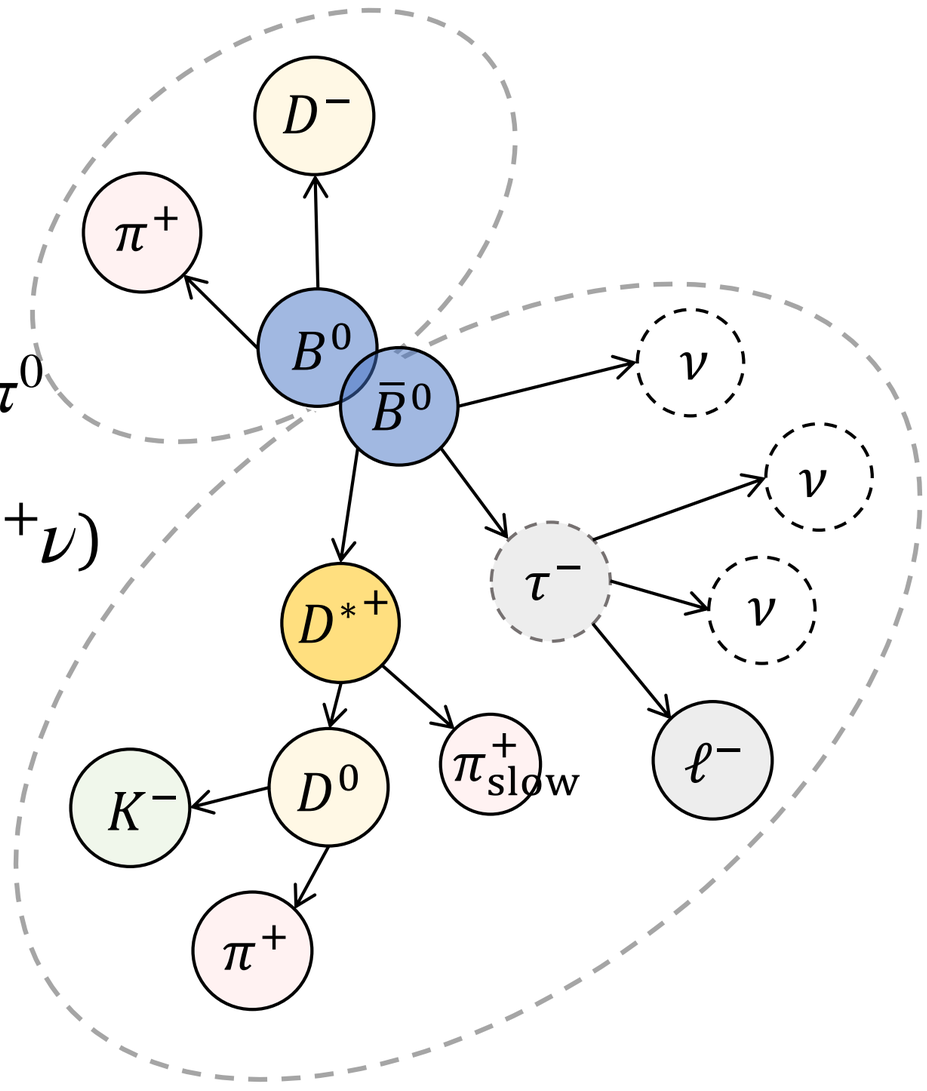
New for July, 2023
Preliminary

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

- First $R(D^*)$ result from Belle II
- Analysis features
  - Use hadronic B-tagging with FEI (slide 31)
  - leptonic τ decays, $\tau^+ \to \ell^+ \nu_\ell \bar{\nu}_\tau$
  - three D^* modes: $D^{*+} \to D^0\pi^+$, $D^+\pi^0$ and $D^{*0} \to D^0\pi^0$
- Signal ($B \to D^* \tau^+ \nu$) & Normalization ($B \to D^* \ell^+ \nu$)
  - extracted simultaneously
  - by fitting 2D $(M^2_{\rm miss}, E_{\rm ECL})$

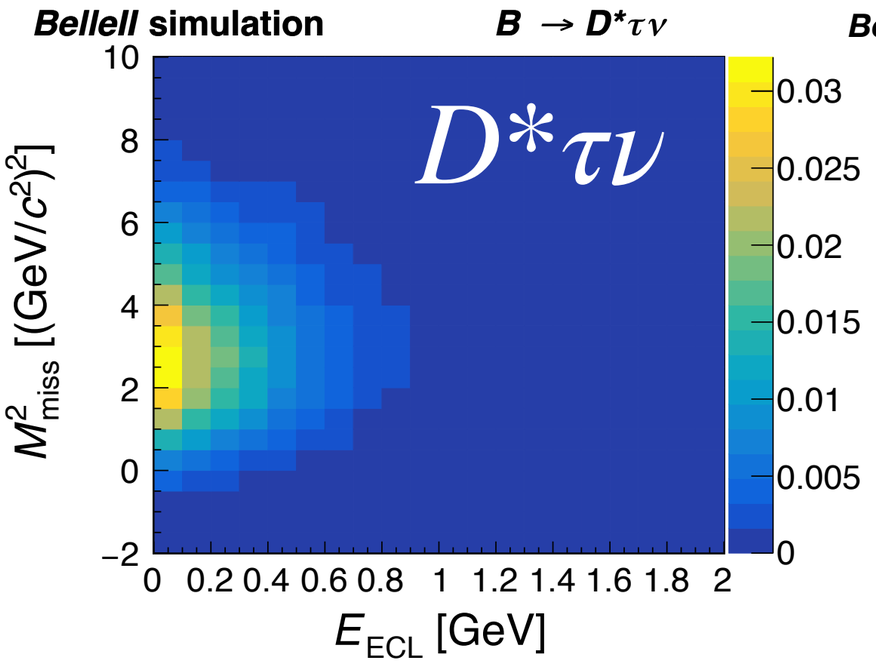
$$M^2_{\rm miss} \equiv (p_{e^+e^-} - p_{B_{\rm tag}} - p_{D^*} - p_\ell)^2$$

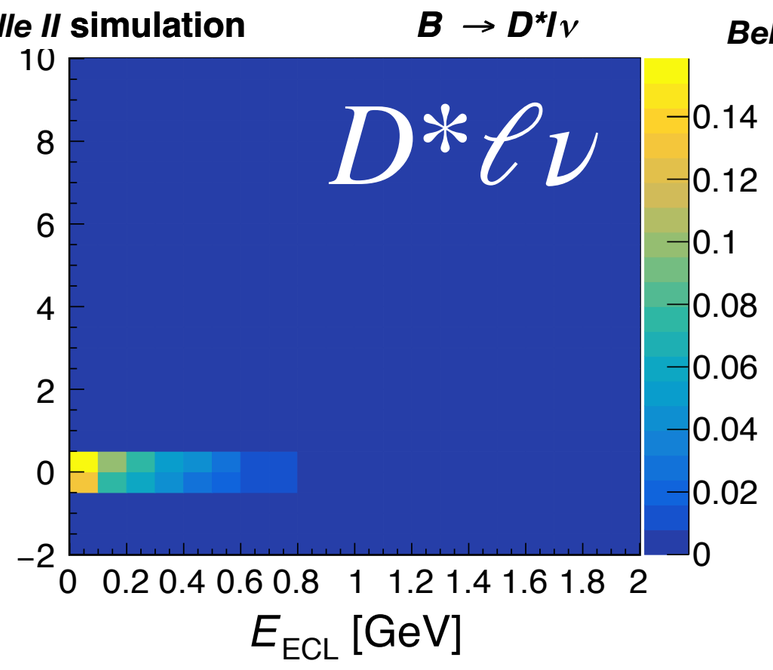
$E_{\rm ECL}$ = extra energy (unmatched) in the EM calorimeter

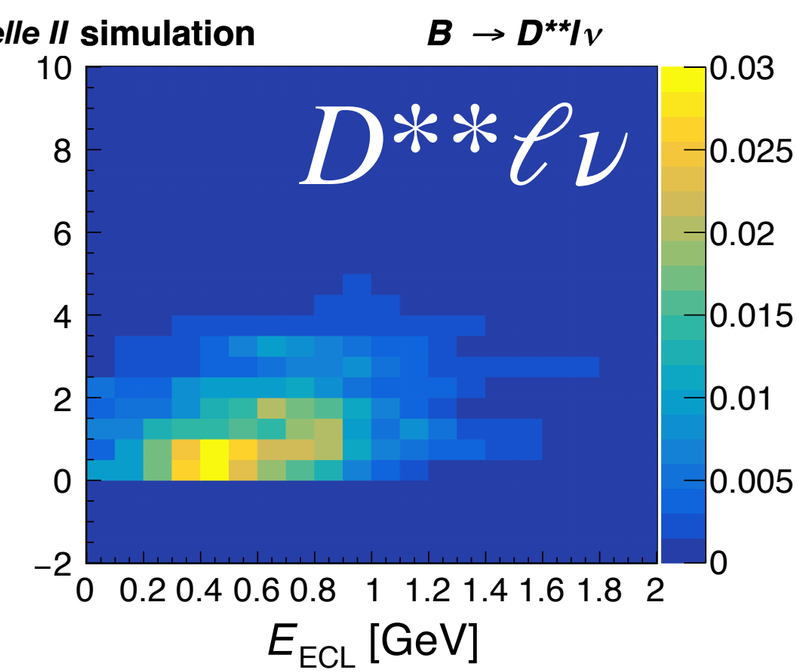


$R(D^*)$ from Belle II

New for July, 2023
Preliminary







- Signal ($B \to D^*\tau^+\nu$) & Normalization ($B \to D^*\ell^+\nu$)
  - extracted simultaneously
  - by fitting 2D $(M^2_{\text{miss}}, E_{\text{ECL}})$

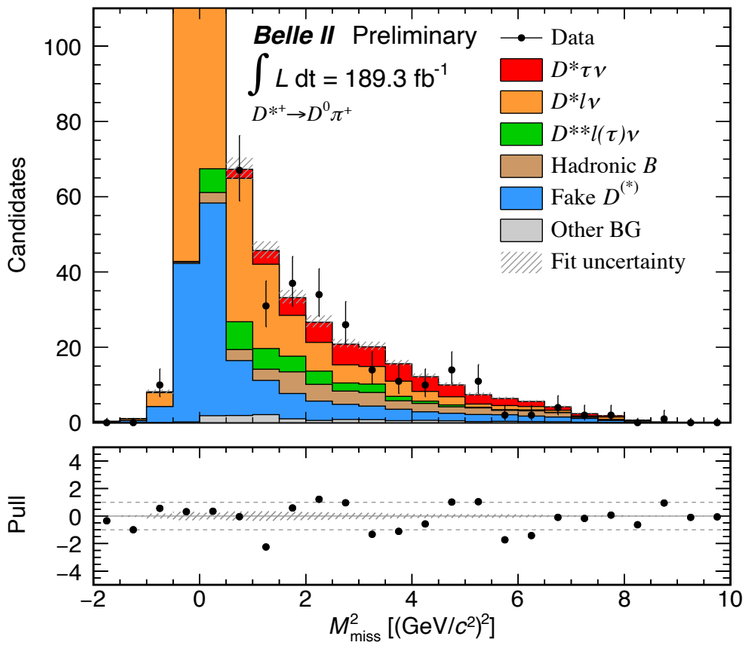
$$M^2_{\text{miss}} \equiv (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_\ell)^2$$

$E_{\text{ECL}} =$ extra energy (unmatched) in the EM calorimeter

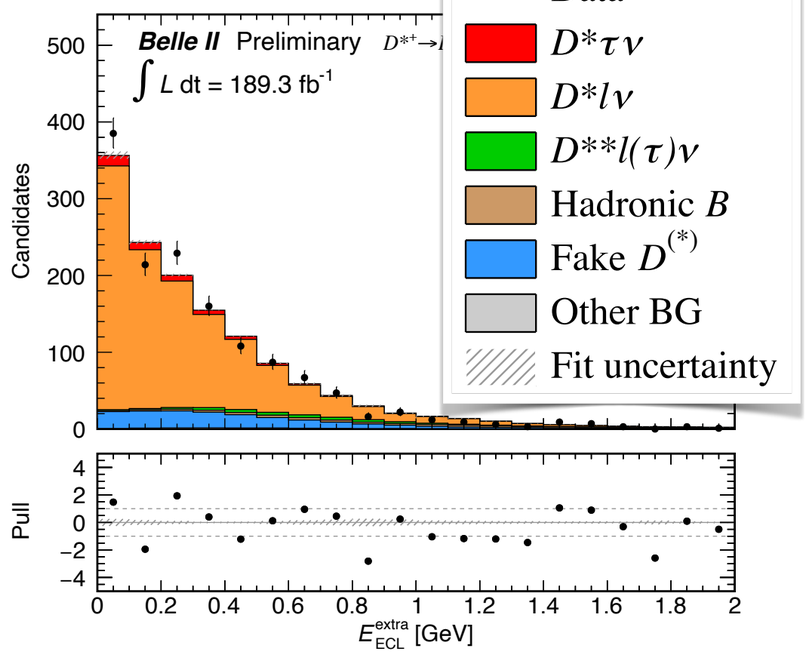
$R(D^*)$ from Belle II

$\mathscr{L}_{\rm int} = 189\ {\rm fb}^{-1}$ New for July, 2023 *Preliminary*

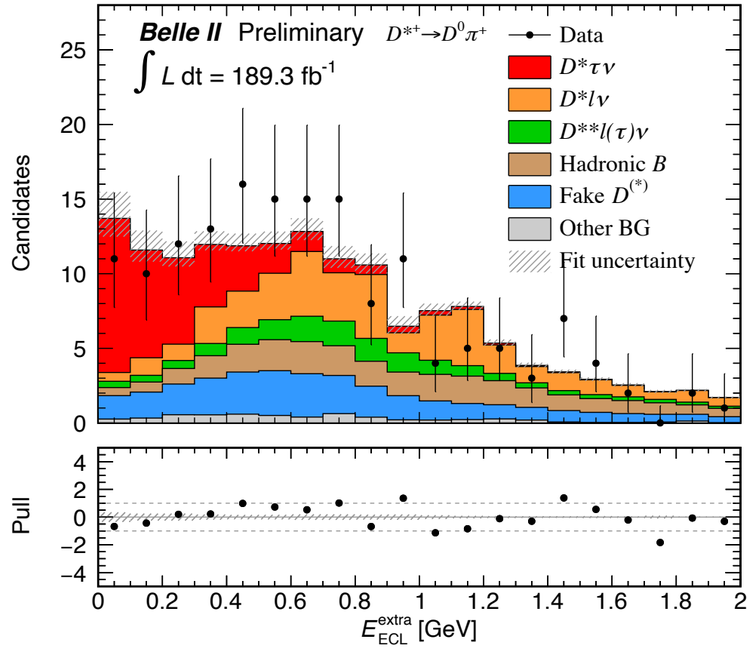
- Fit projections for the sub-mode $D^{*+} \to D^0\pi^+$



$M^2_{\rm miss}$ (peak-bin yield ~O(600))



$E_{\rm ECL}$ for entire $M^2_{\rm miss}$ region



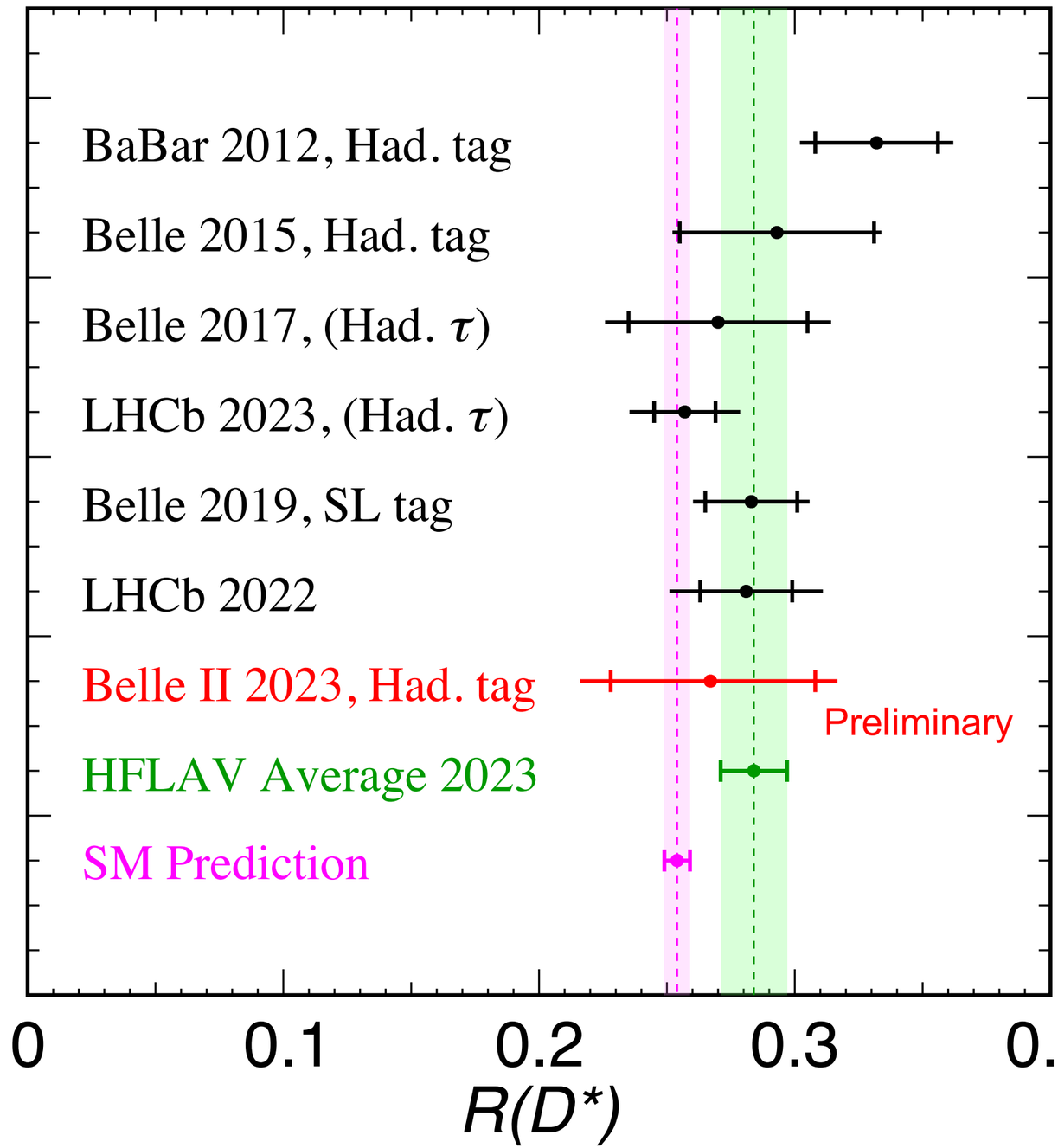
$E_{\rm ECL}$ for signal-enhanced region
$1.5 < M^2_{\rm miss} < 6.0\ {\rm GeV}^2$

$$R(D^*) = 0.267^{+0.041+0.028}_{-0.039-0.033}$$

- Systematics
  - dominant sources: $E_{\rm ECL}$ PDF shape, MC statistics

$R(D^*)$ from Belle II

New for July, 2023
Preliminary



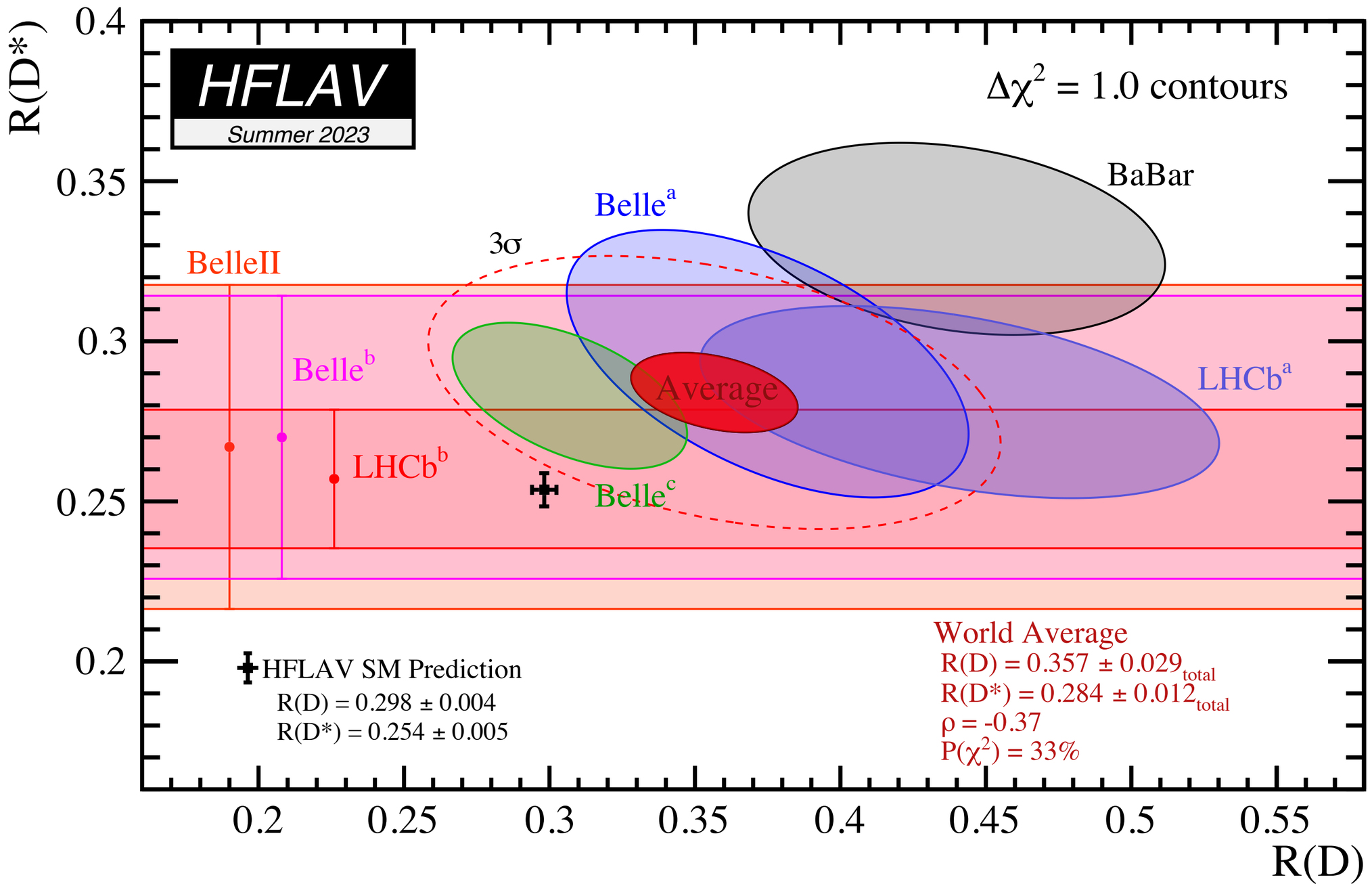
	$5\ \text{ab}^{-1}$	$50\ \text{ab}^{-1}$
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

Belle II expected precision, from
The Belle II Physics Book, PTEP 2019 (2019) 123C01

new Belle II result is consistent with both the SM and the HFLAV average

$$R(D^*) = 0.267^{+0.041\,+0.028}_{-0.039\,-0.033}$$

$R(D)$ vs. $R(D^*)$, updated



Closing remarks

- Precise determination of the CKM matrix elements is crucial for testing the Standard Model. The magnitudes of these elements, in particular, V_{cb} and V_{ub}, are best measured by using B-meson semileptonic decays.
- Moreover, semileptonic B-meson decays provide a great testing ground for lepton universality of charged-current weak interaction processes.
- We reported recent unique and/or competitive results of inclusive and exclusive B-meson semileptonic decays, from the Belle II and Belle experiments.
- For some of these results, tag-side reconstruction of a companion B-meson decay has been exploited, which is now a unique feature of Belle II.
- For bottom line, using $189\ \mathrm{fb}^{-1}$ data sample, Belle II has made 1) precise measurement of inclusive ratio, $R(X_{e/\mu})$ and 2) its first contribution to $R(D^*)$.

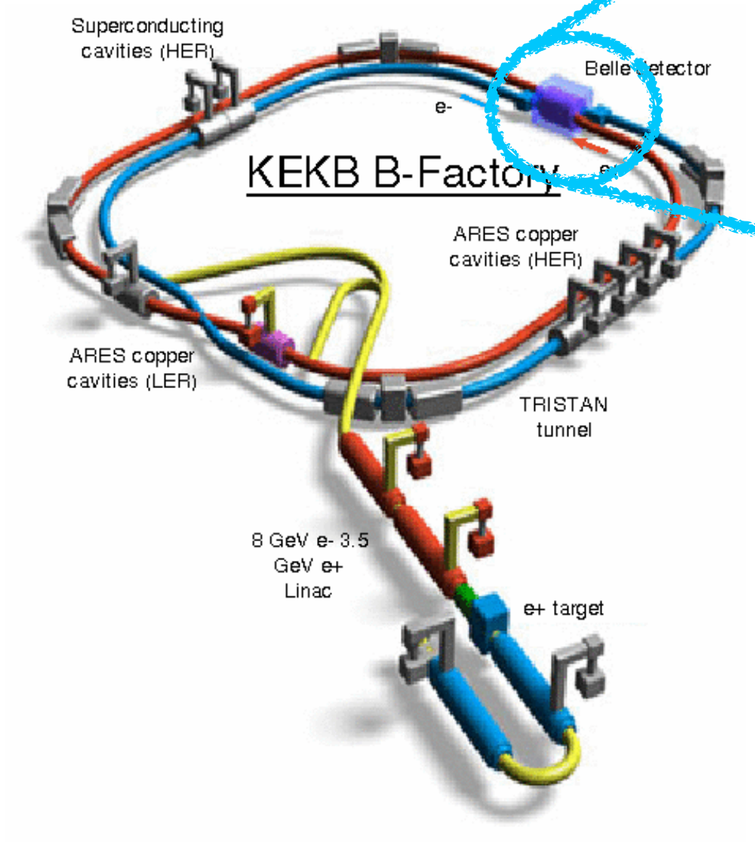
Thank you!

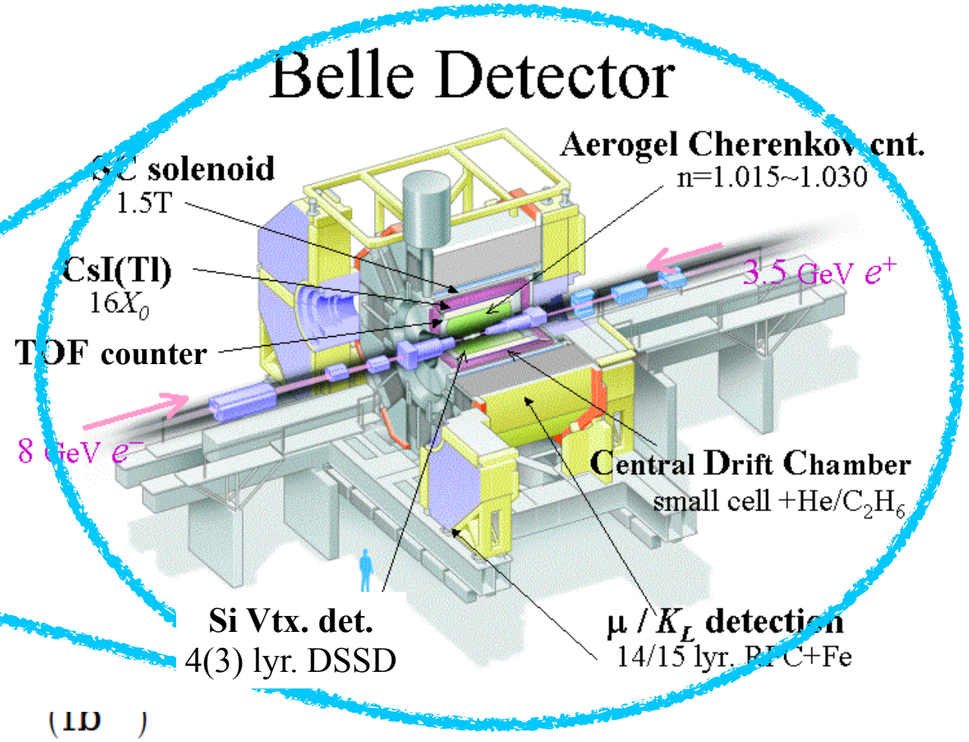
Appendices

Appendix O The apparatuses

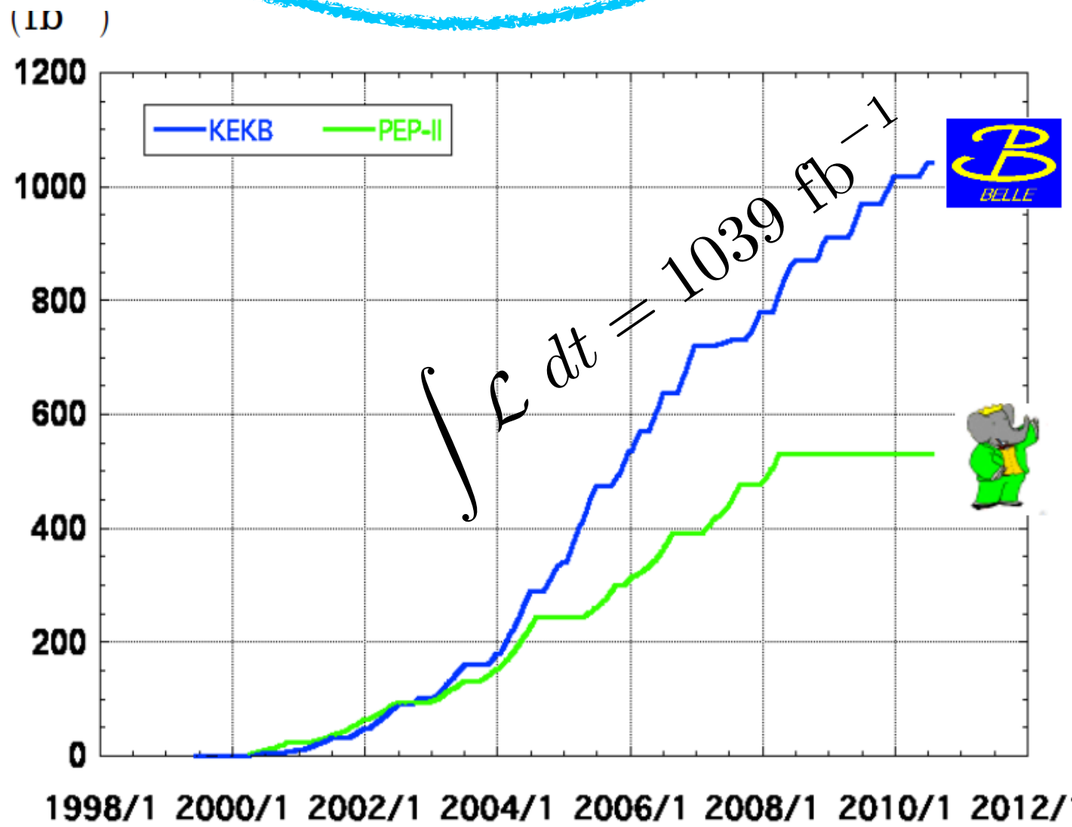
22 countries
100 institutions
~450 members

$$\mathcal{L}_{\rm peak} = 21.1\ {\rm nb}^{-1}{\rm s}^{-1}$$





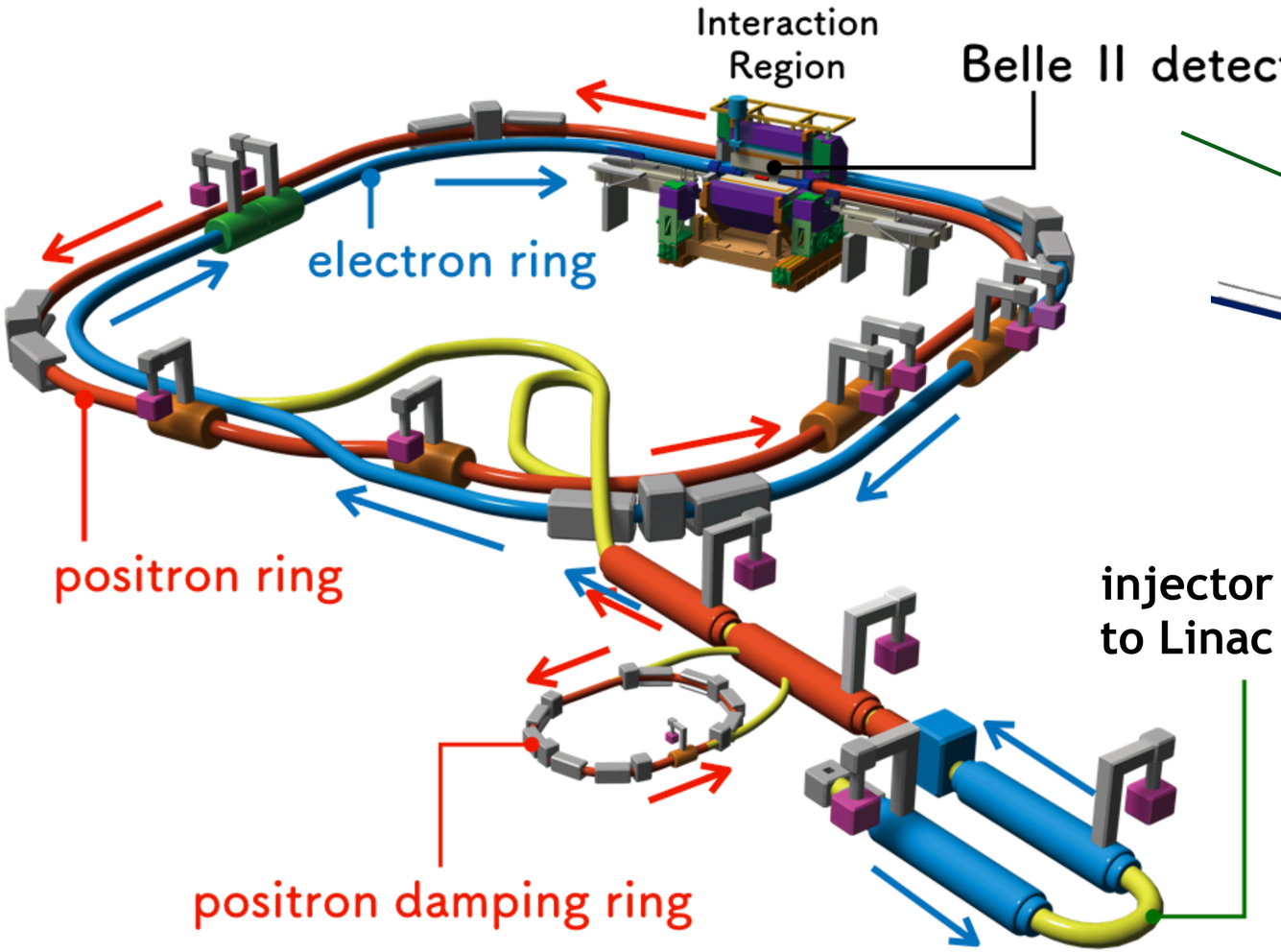
$$e^- \xrightarrow{\text{8 GeV}} (\star) \xleftarrow{\text{3.5 GeV}} e^+$$



> 1 ab^{-1}
On resonance:
Υ(5S): 121 fb^{-1}
Υ(4S): 711 fb^{-1}
Υ(3S): 3 fb^{-1}
Υ(2S): 25 fb^{-1}
Υ(1S): 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

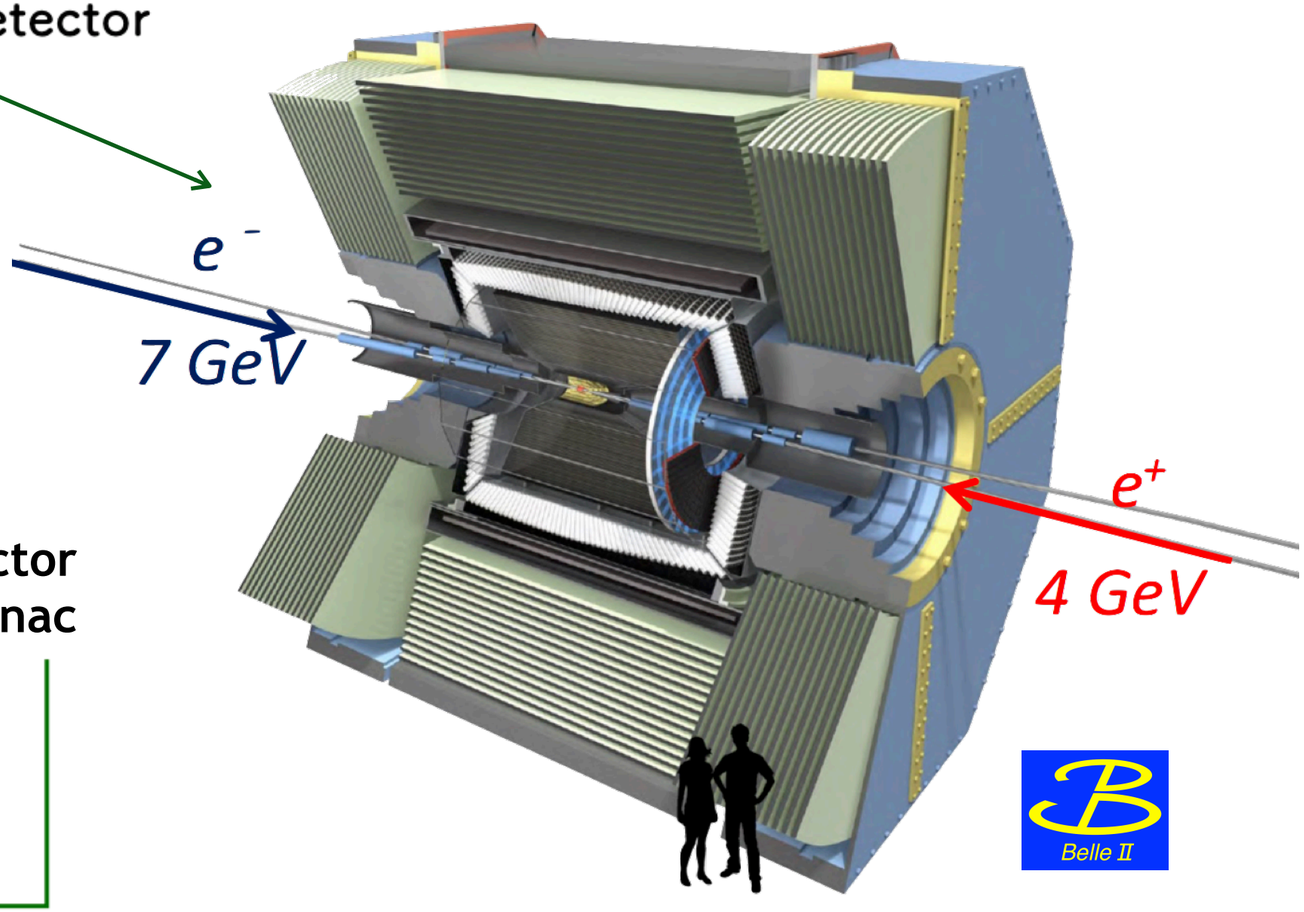
~ 550 fb^{-1}
On resonance:
Υ(4S): 433 fb^{-1}
Υ(3S): 30 fb^{-1}
Υ(2S): 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

SuperKEKB



$$e^- \xrightarrow{7\ \text{GeV}} (\star) \xleftarrow{4\ \text{GeV}} e^+$$

Belle II



$$\mathcal{L} = 6.5 \times 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$$

$$\int^{\text{goal}} \mathcal{L}\ dt = 50\ \text{ab}^{-1}$$

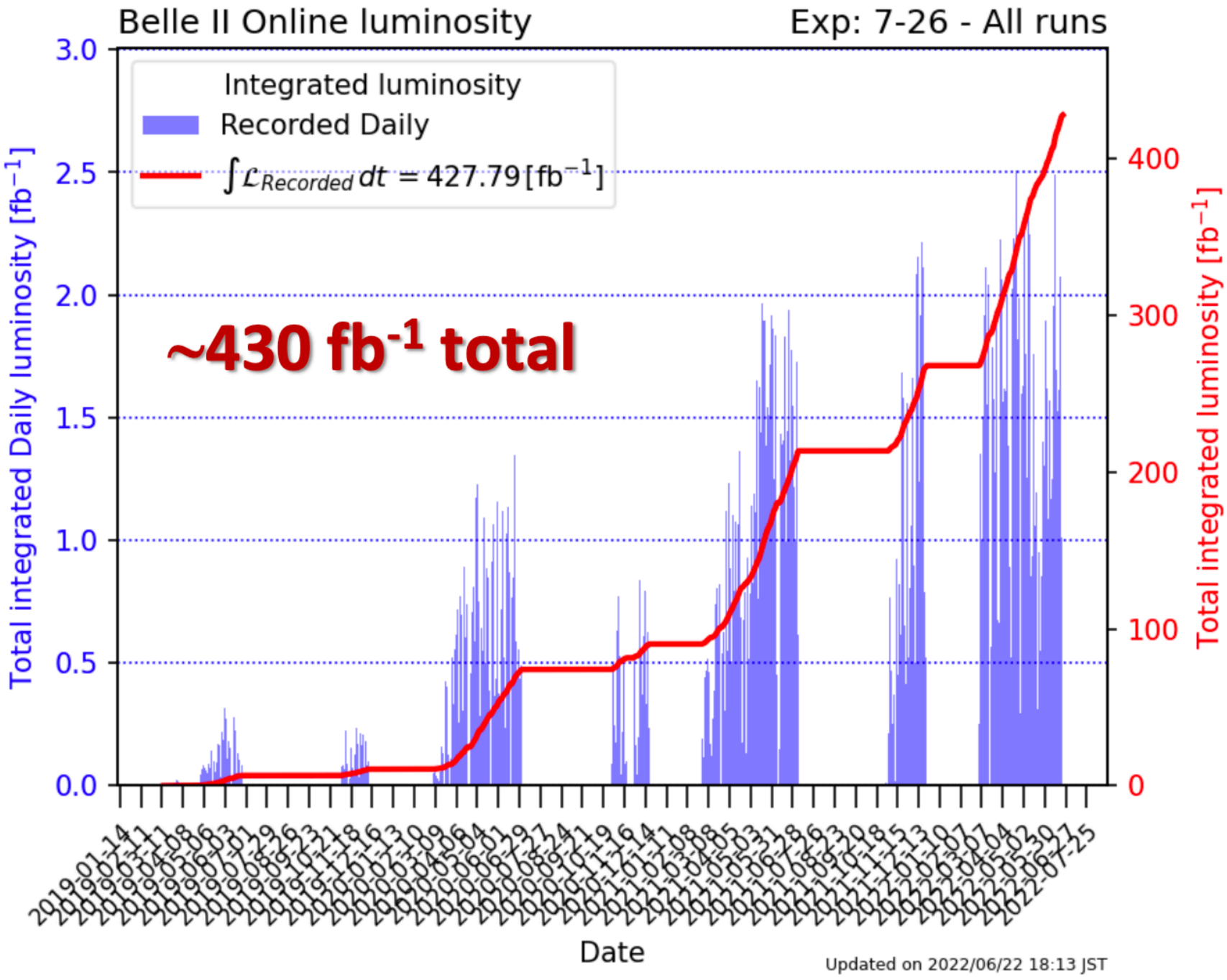
Belle II

Collected luminosity before LS1 (2019-2022)

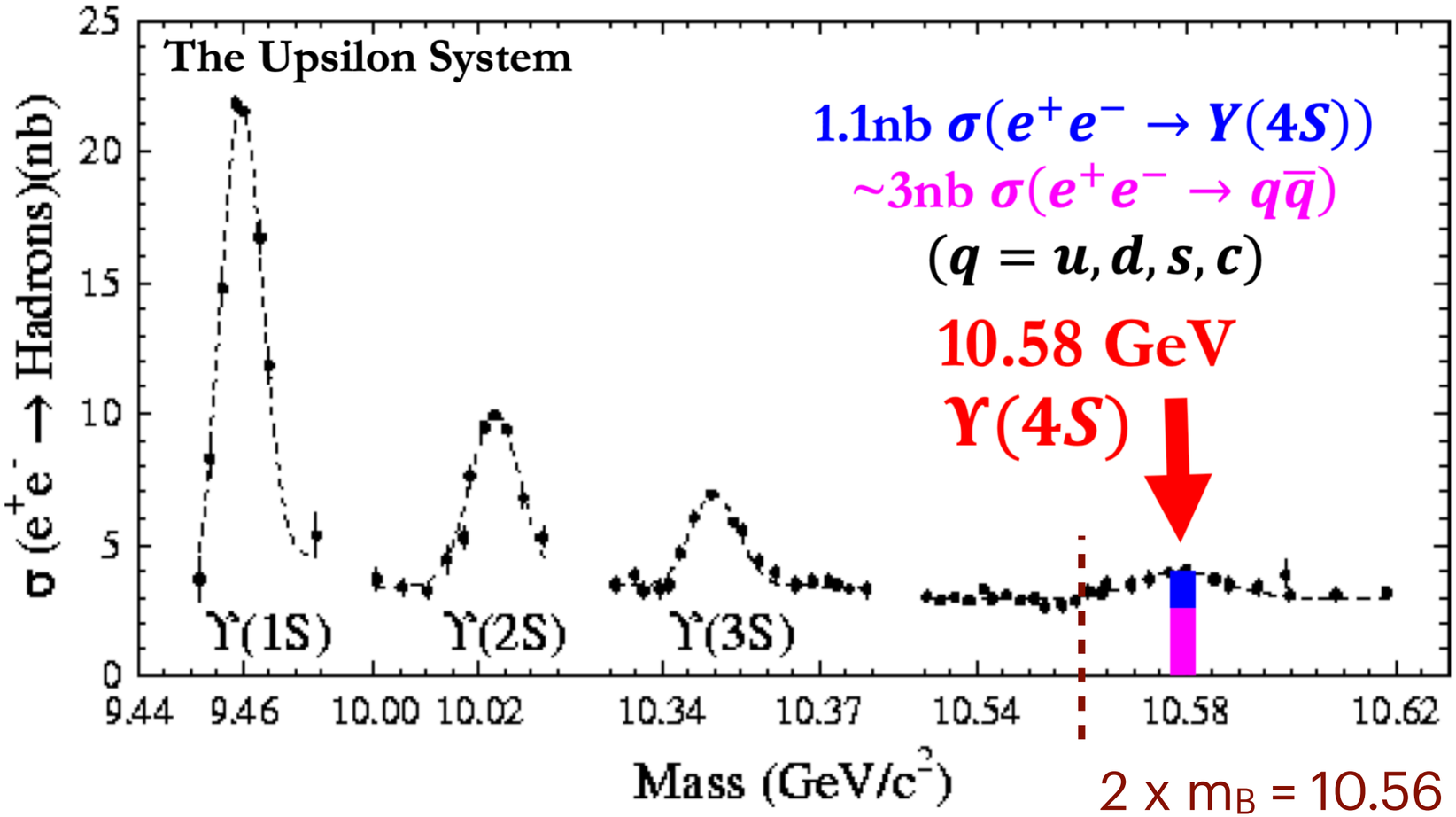
Belle II was in operation through the Pandemic era, with modified working mode in accordance with the anti-pandemic policy.

peak luminosity world record

$4.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



$e^+e^- \to \Upsilon(4S)$ as a B-factory

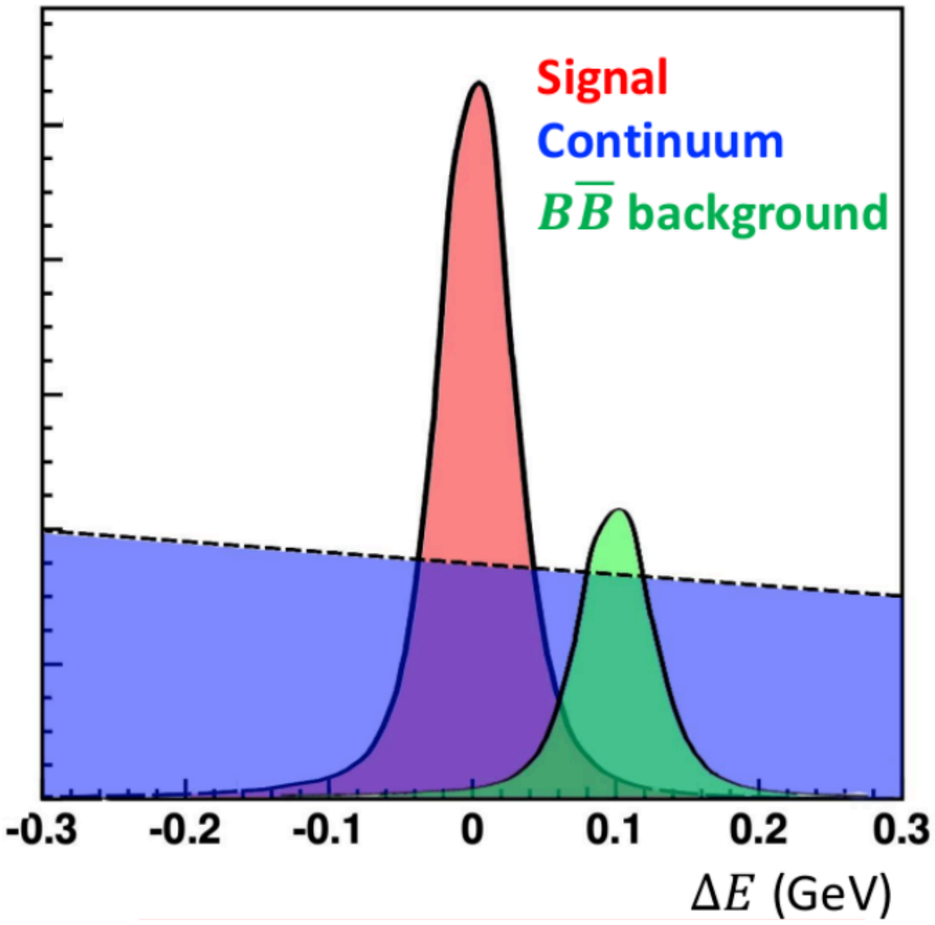


- $\mathcal{B}(\Upsilon(4S) \to B\overline{B}) > 96\%$, with $p_B^{CM} \sim 0.35$ GeV/c
- nothing else but $B\overline{B}$ in the final state

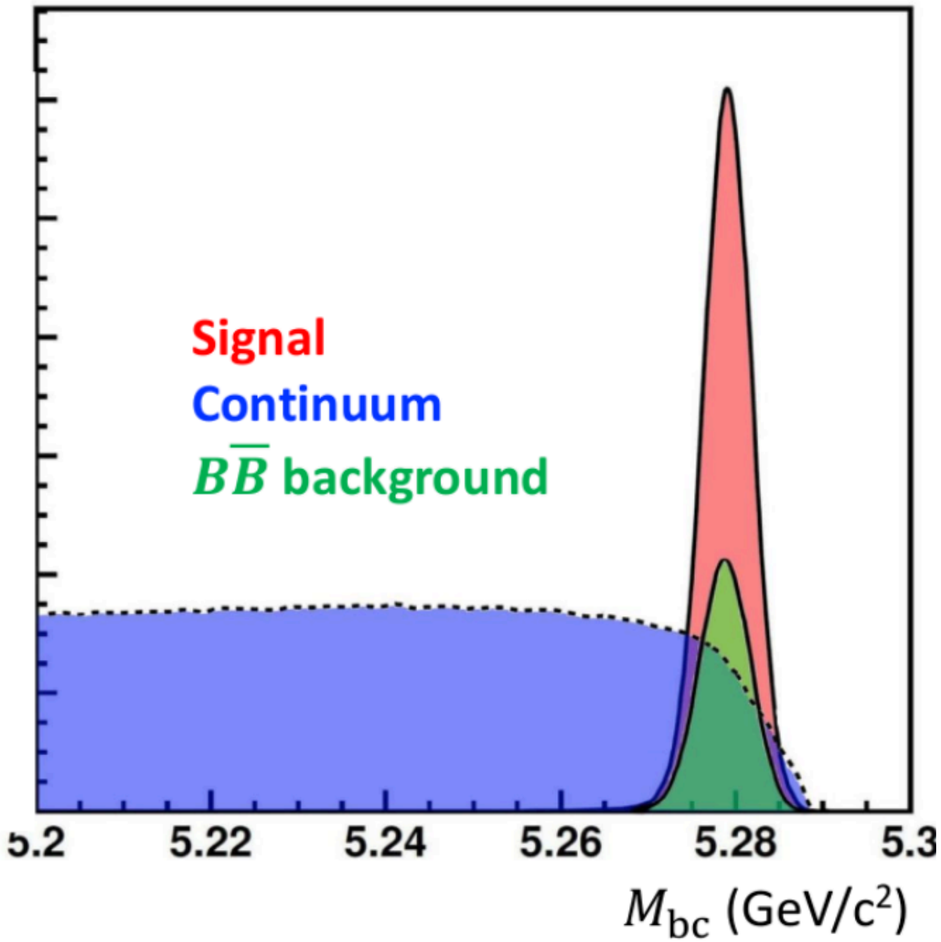
  $\therefore$ if we know $(E, \vec{p})$ of one B, the other B is also constrained

Key variables of *B* decays

$$\Delta E = E_B^* - \sqrt{s}/2$$

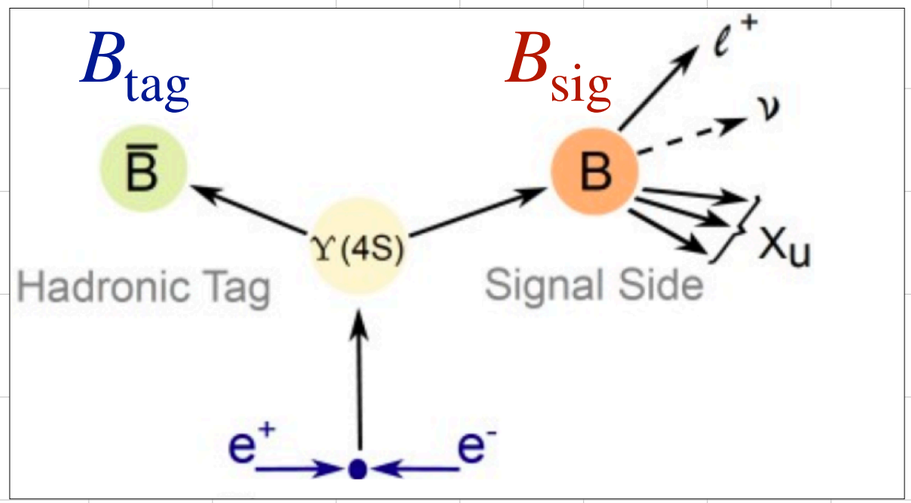


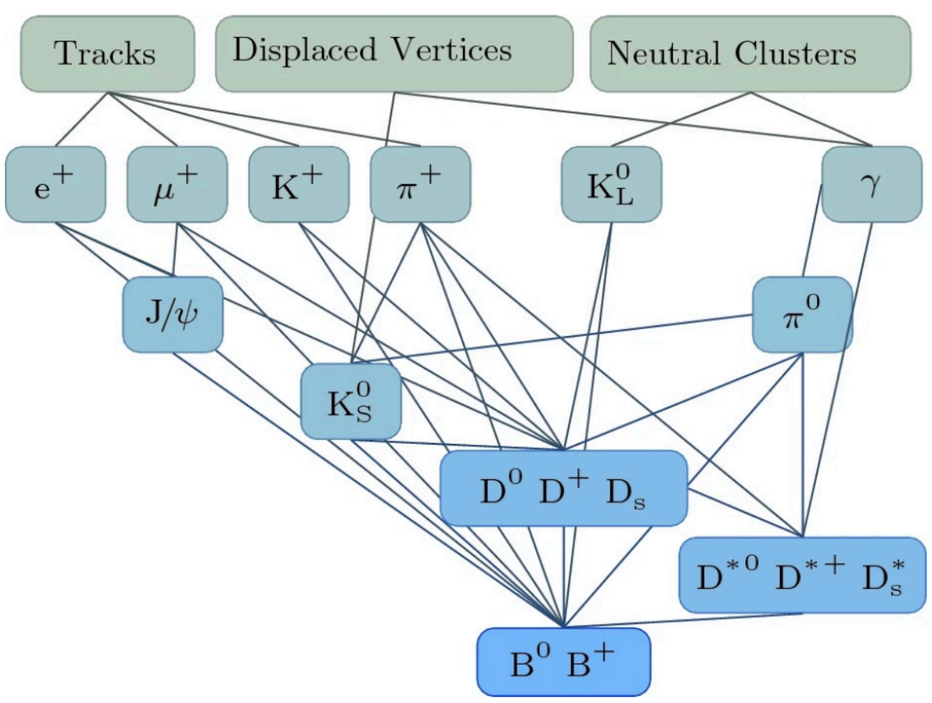
$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - \vec{p}_B^{*2}}$$

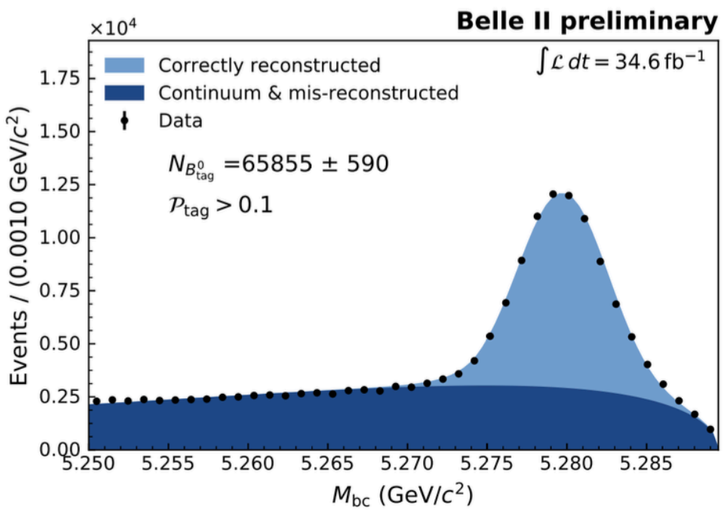


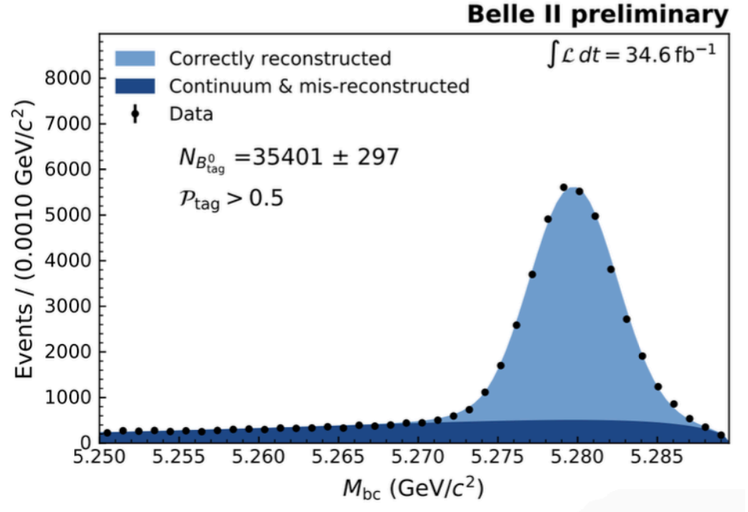
Full Event Interpretation (FEI)

- FEI algorithm to reconstruct B_{tag}
  - uses ~200 BDT's to reconstruct $\mathcal{O}(10^4)$ different B decay chains
  - assign signal probability of being correct B_{tag}









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arXiv:2008.060965

Appendix 1 Exclusive

$B \to D^{(*)}\ell^+\nu$ for V_{cb}

$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$

- Differential shapes (*normalized*) of $B \to D^* \ell^+ \nu$
  - as input to determine the non-perturbative form factor
  - once FF shape is known, it can be combined with L-QCD (or other methods) for the absolute normalization to determine $|V_{cb}|$

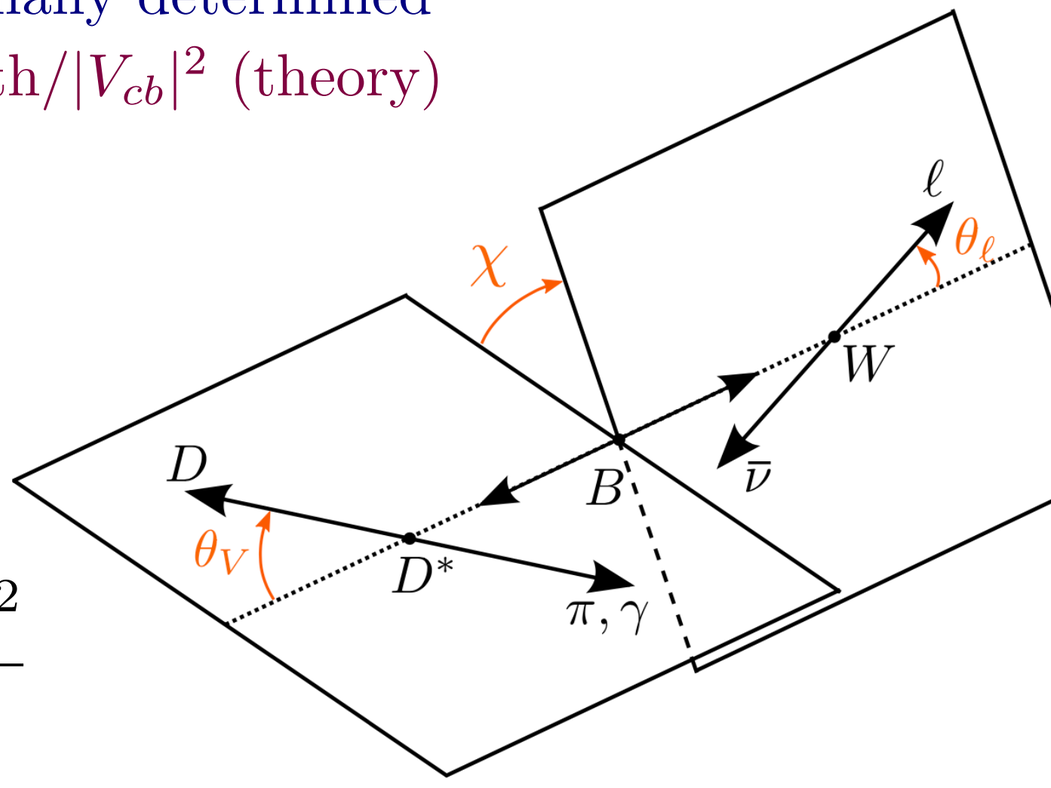
$$|V_{cb}| = \sqrt{\frac{\mathcal{B}(B \to D^* \ell \bar{\nu}_\ell)}{\tau_B \, \Gamma(B \to D^* \ell \bar{\nu}_\ell)}}$$

$\mathcal{B}$ – externally determined

Γ = decay width/$|V_{cb}|^2$ (theory)

  - use hadronic B-tagging via FEI
  - L-QCD at zero recoil ($w = 1$) is used for $|V_{cb}|$

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

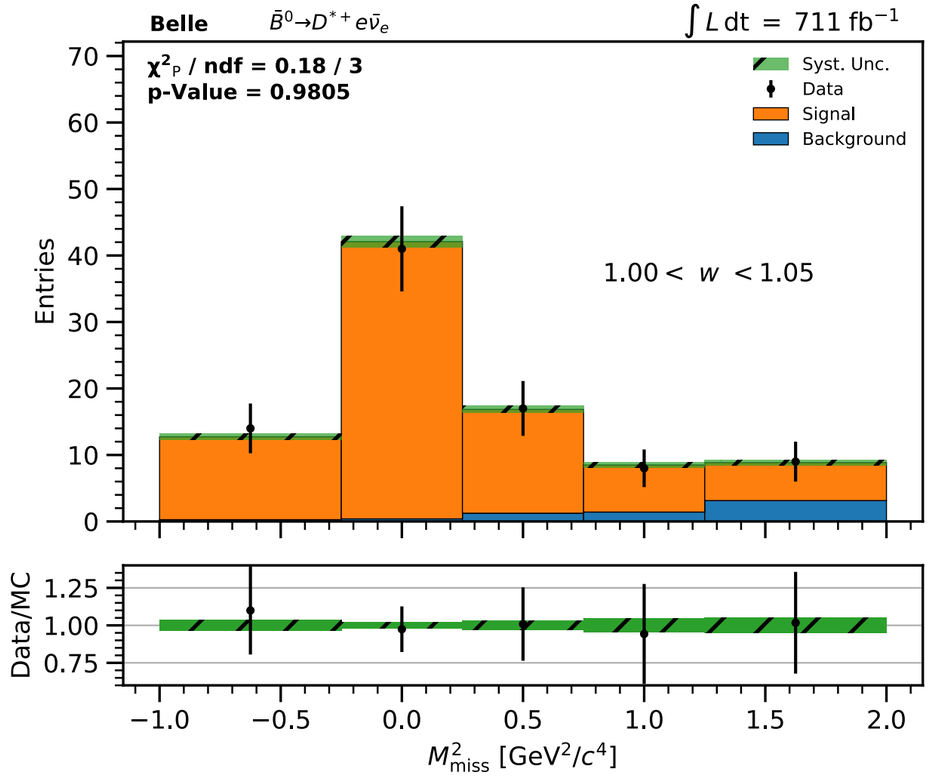


$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$

arXiv:2301.07529
submitted to PRD

w $\cos\theta_\ell$ $\cos\theta_V$ χ

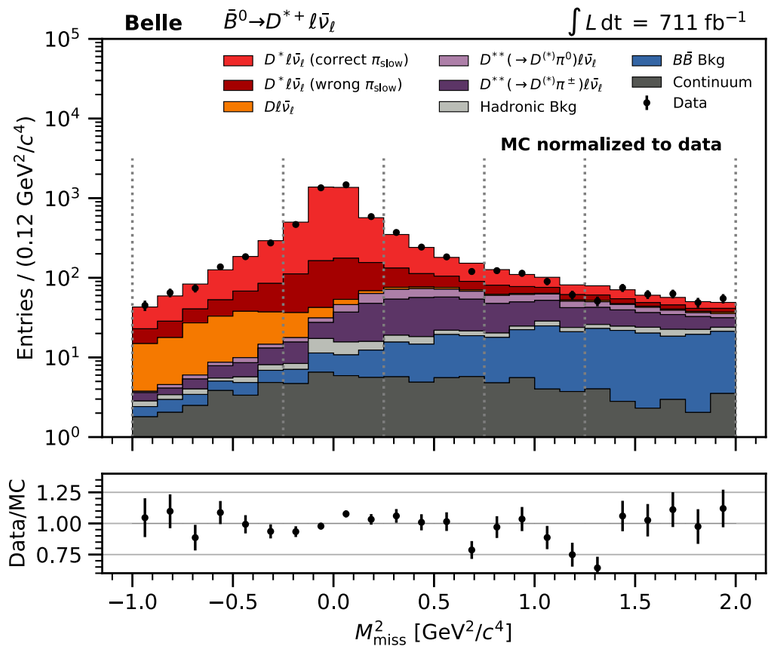
- Full correlations b/w the projections are also determined
- Bkgd. subtraction, with binned likelihood fits to $M^2_{\rm miss}$

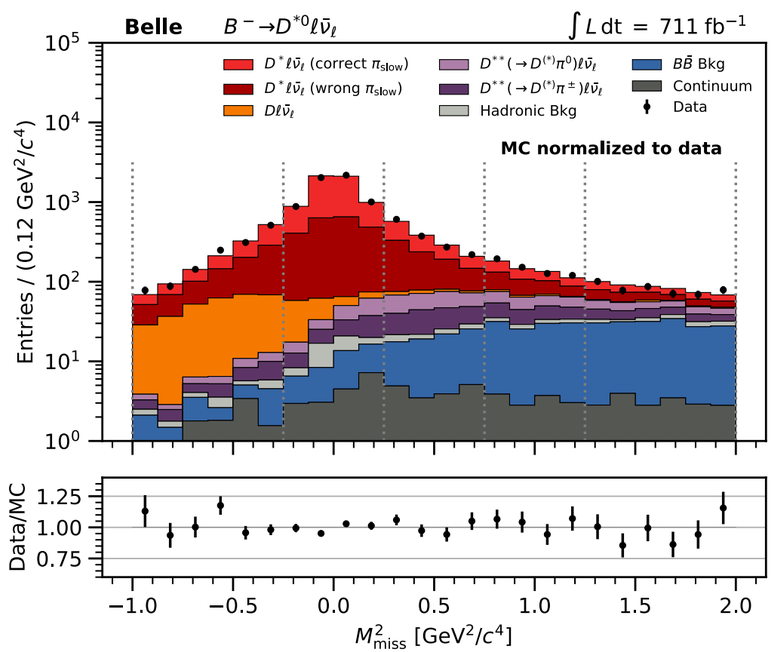


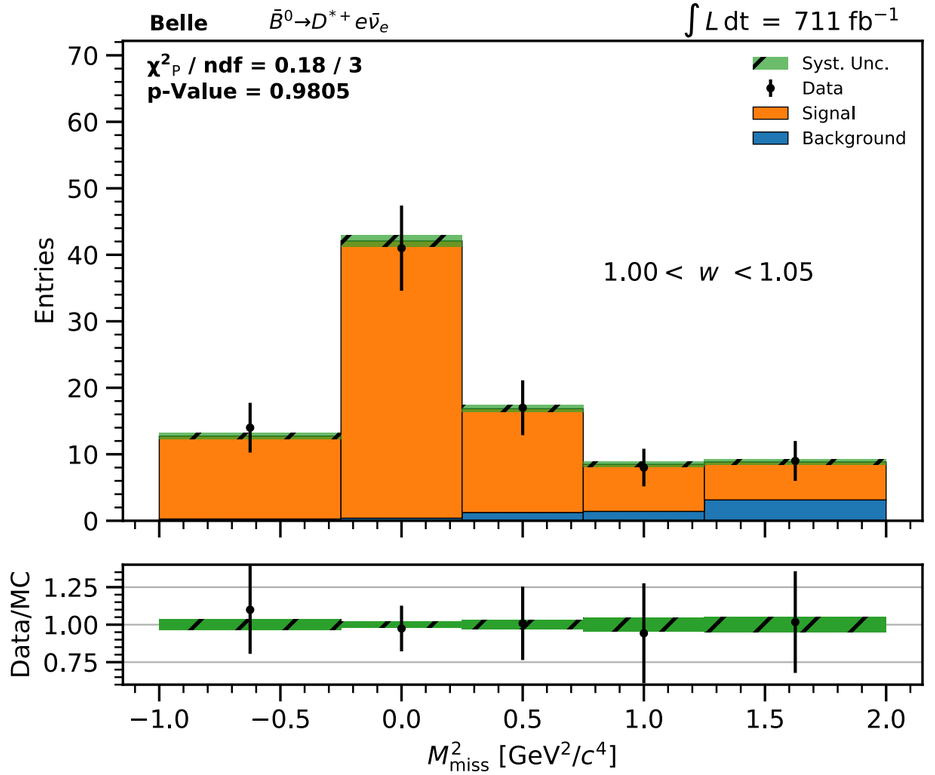
arXiv:2301.07529
submitted to PRD

$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$

background subtraction, with binned likelihood fits to $M^2_{\rm miss}$

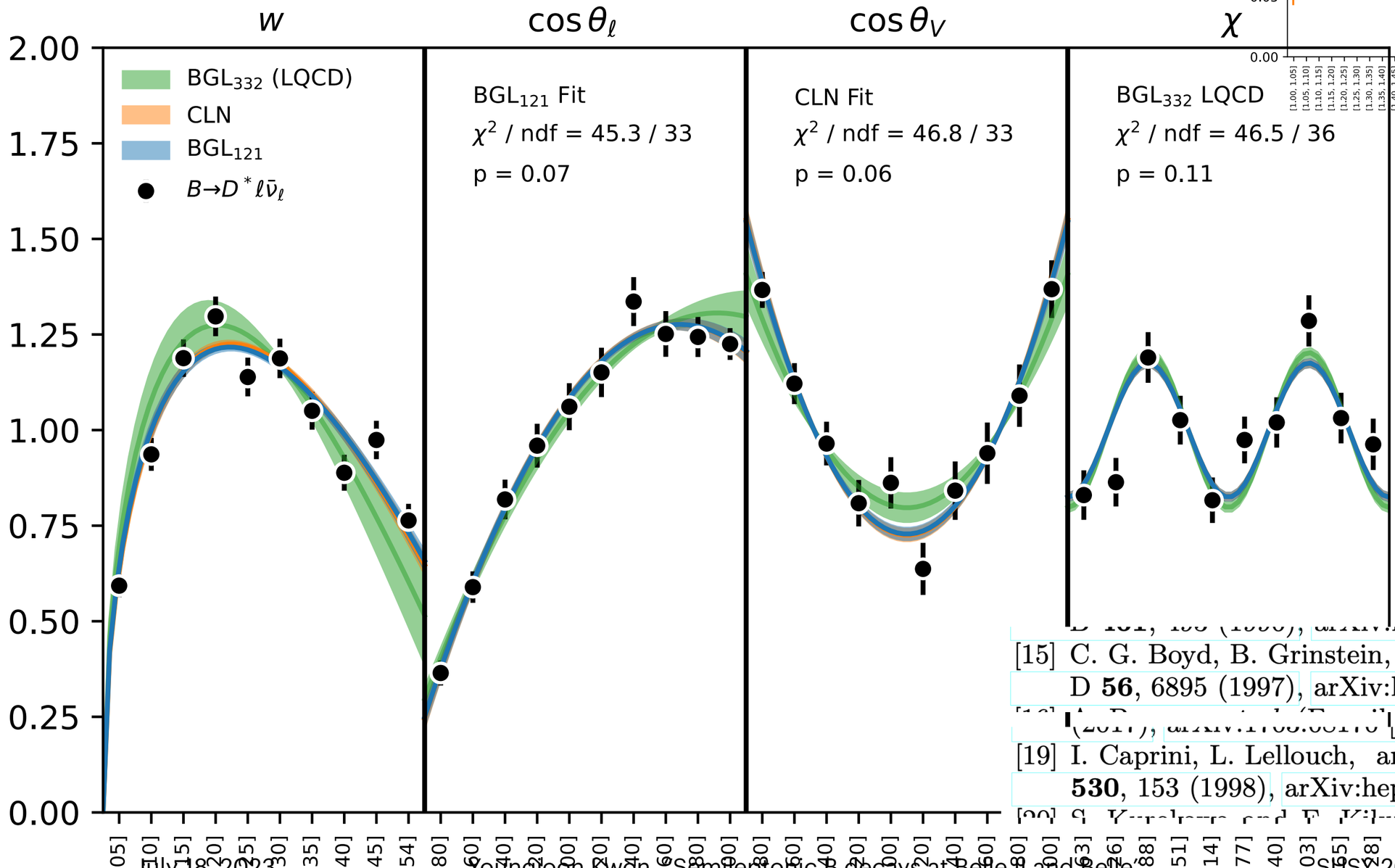


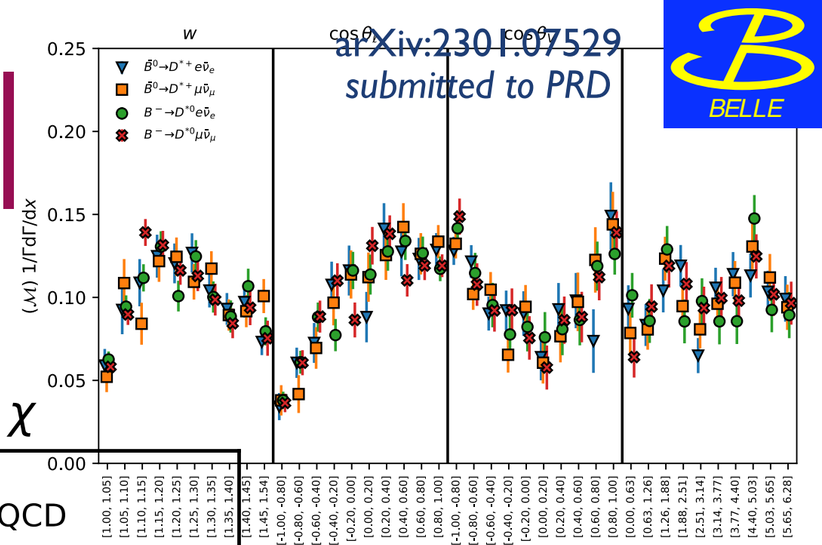




$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$

fitted shapes to BGL & CLN models





arXiv:2301.07529
submitted to PRD

BELLE

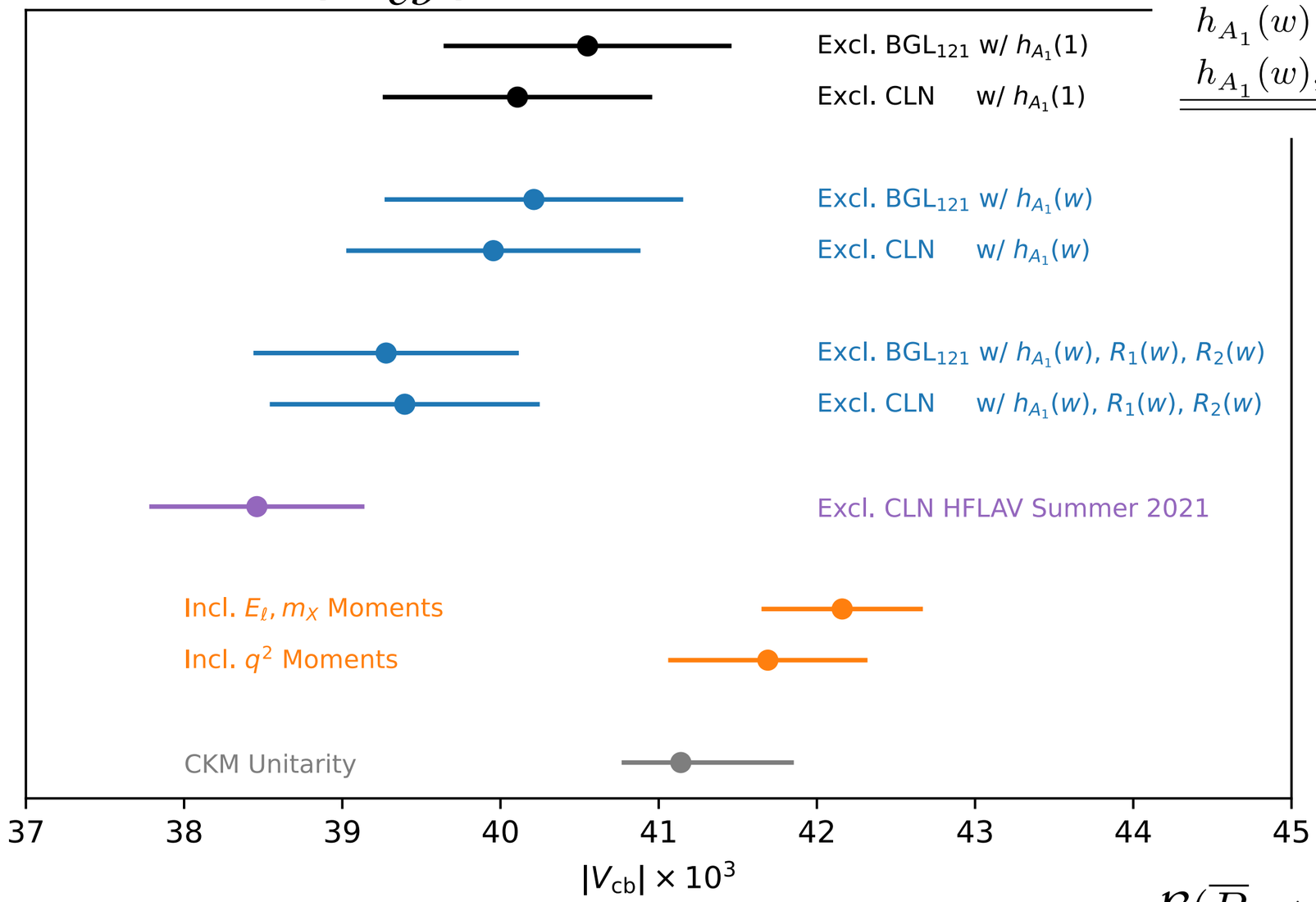
[15] C. G. Boyd, B. Grinstein, and R. F. Lebed, Phys. Rev. D **56**, 6895 (1997), arXiv:hep-ph/9705252.

[19] I. Caprini, L. Lellouch, and M. Neubert, Nucl. Phys. B **530**, 153 (1998), arXiv:hep-ph/9712417.

$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$

arXiv:2301.07529
submitted to PRD

$|V_{cb}|$ and other results



	BGL_{121}	CLN
$h_{A_1}(1)$	40.6 ± 0.9	40.1 ± 0.9
$h_{A_1}(w)$	40.2 ± 0.9	40.0 ± 0.9
$h_{A_1}(w),\ R_1(w),\ R_2(w)$	39.3 ± 0.8	39.4 ± 0.9

$$\Delta A_{\mathrm{FB}} = A_{\mathrm{FB}}^{\mu} - A_{\mathrm{FB}}^{e}$$

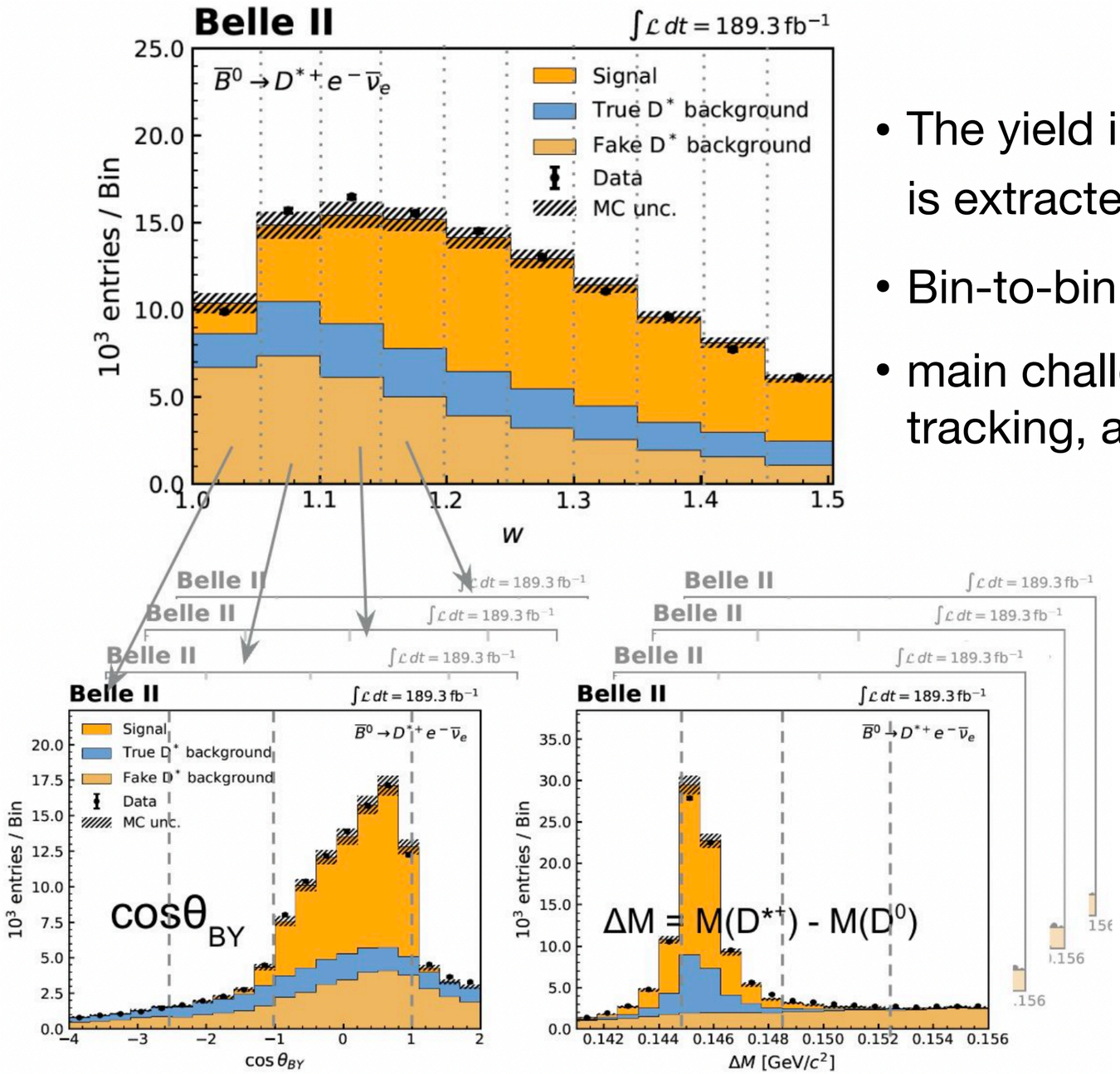
	ΔA_{FB}
$\bar{B}^0 \to D^{*+} \ell \bar{\nu}_\ell$	$0.062 \pm 0.044 \pm 0.011$
$B^- \to D^{*0} \ell \bar{\nu}_\ell$	$-0.003 \pm 0.033 \pm 0.009$
$B \to D^* \ell \bar{\nu}_\ell$	$0.022 \pm 0.026 \pm 0.007$

$$\Delta F_L = F_L^{\mu} - F_L^{e}$$

	$\Delta F_L^{D^*}$
$\bar{B}^0 \to D^{*+} \ell \bar{\nu}_\ell$	$0.032 \pm 0.033 \pm 0.010$
$B^- \to D^{*0} \ell \bar{\nu}_\ell$	$0.025 \pm 0.035 \pm 0.010$
$B \to D^* \ell \bar{\nu}_\ell$	$0.034 \pm 0.024 \pm 0.007$

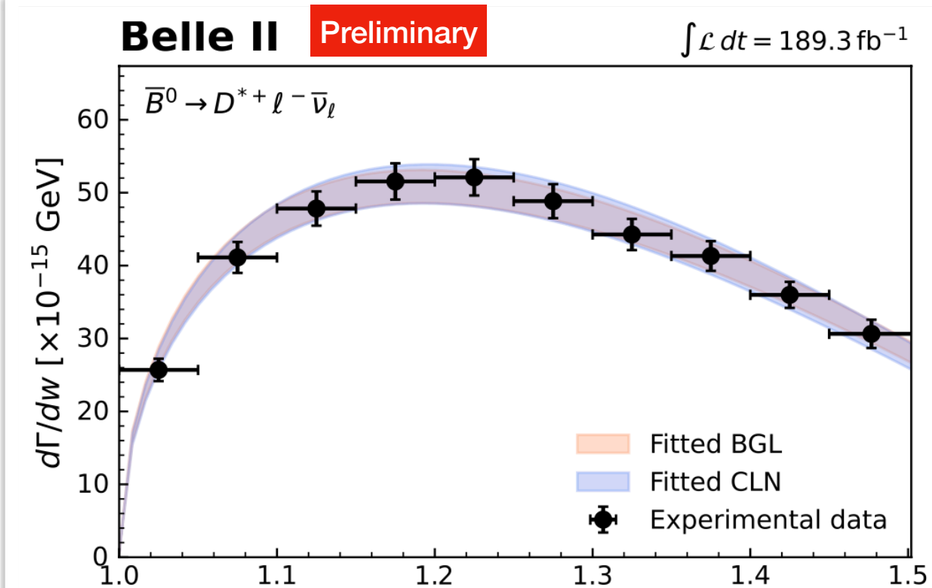
$$R_{e/\mu} = \frac{\mathcal{B}(\overline{B} \to D^* e \bar{\nu}_e)}{\mathcal{B}(\overline{B} \to D^* \mu \bar{\nu}_\mu)} = 0.990 \pm 0.021 \pm 0.023$$

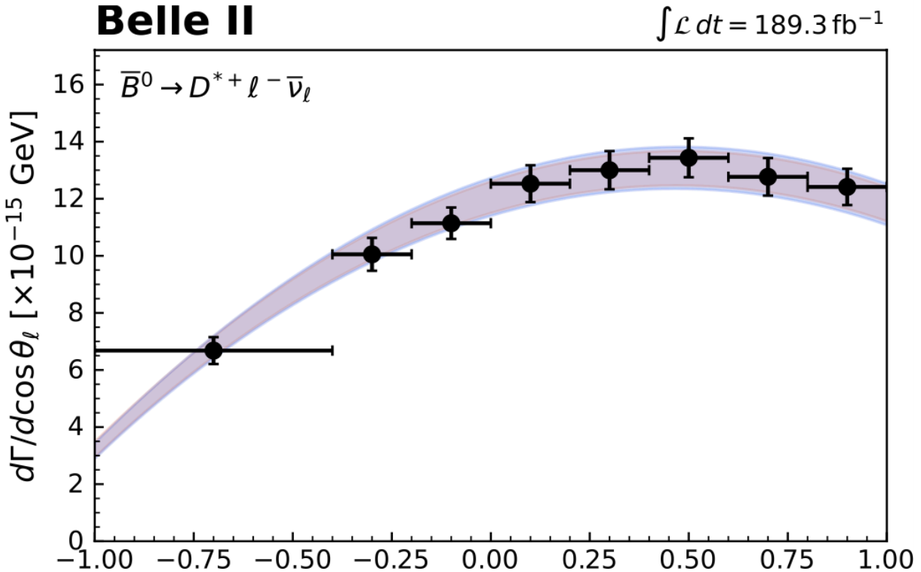
$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$ from Belle II

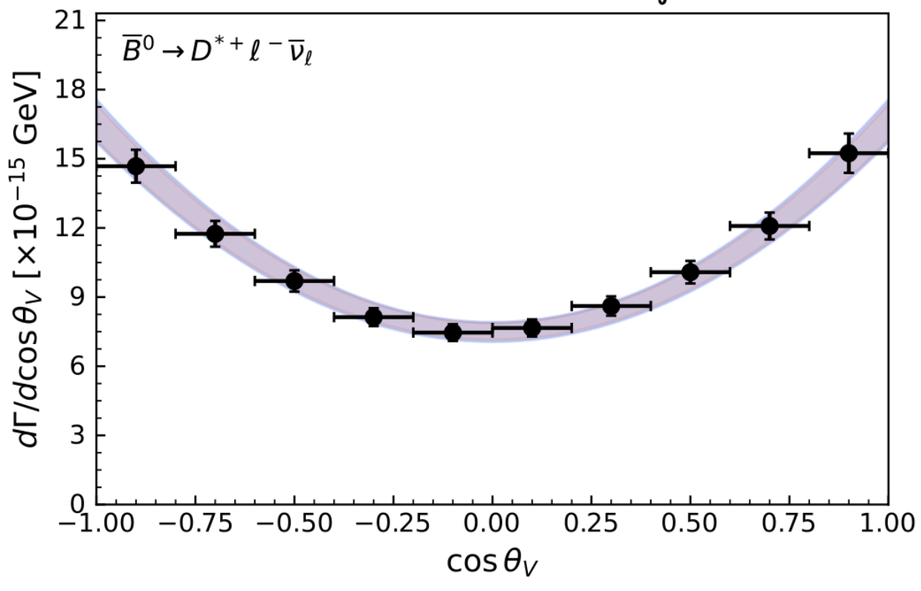


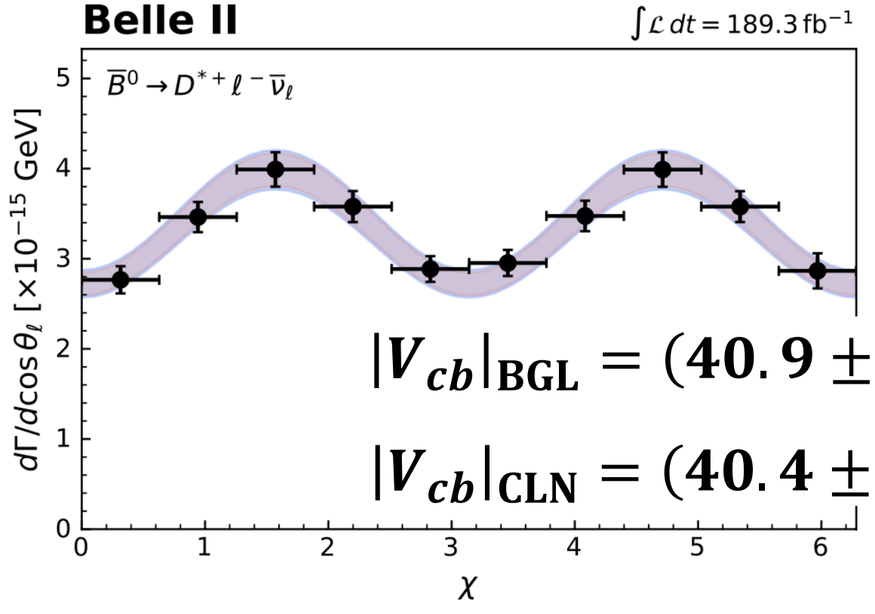
- The yield in 10 (8) bin of w and the three cosine angles is extracted by fitting $\cos\theta_{BY}$ and ΔM for D^*
- Bin-to-bin migration is corrected with SVD unfolding
- main challenges: background modeling, slow-pion tracking, and stat. correlations b/w bins

$B \to D^* \ell^+ \nu$ shapes & $|V_{cb}|$ from Belle II









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

(QCD input)

$$|V_{cb}|_{\text{CLN}} = (40.4 \pm 0.3 \pm 1.0 \pm 0.6) \times 10^{-3}$$