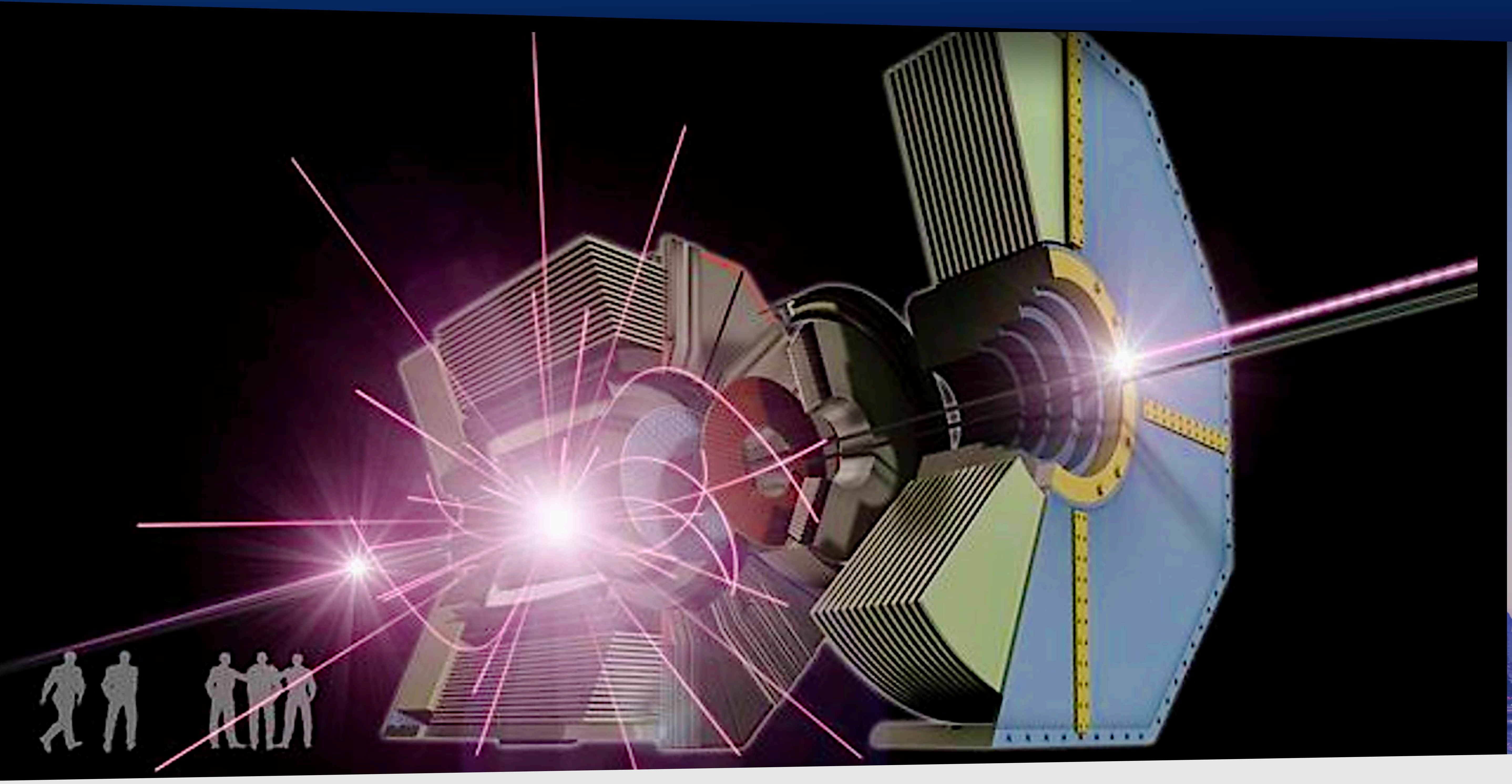
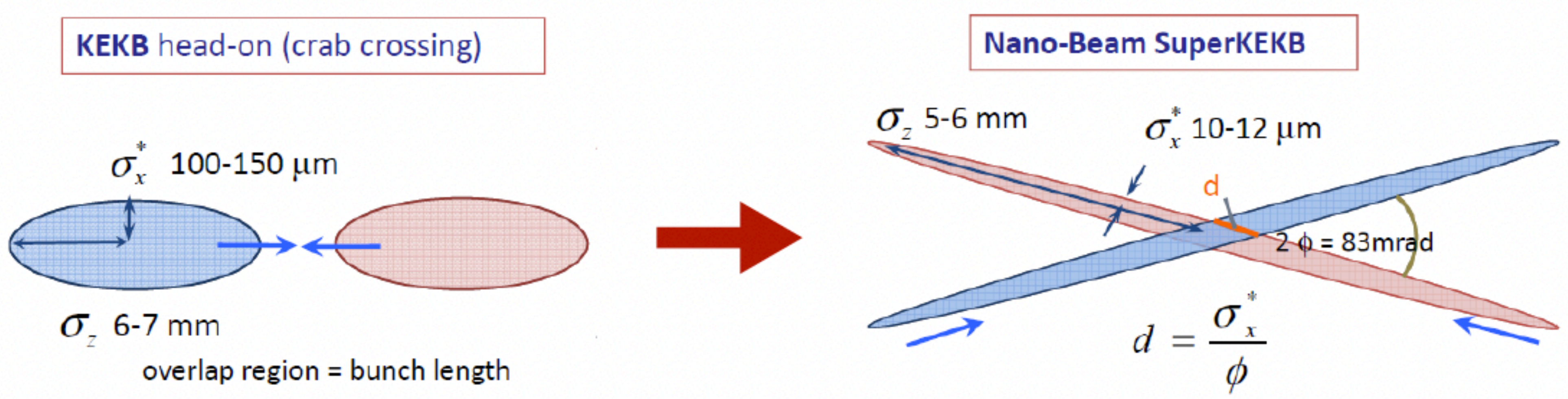
Highlights of B Physics Results from Belle II

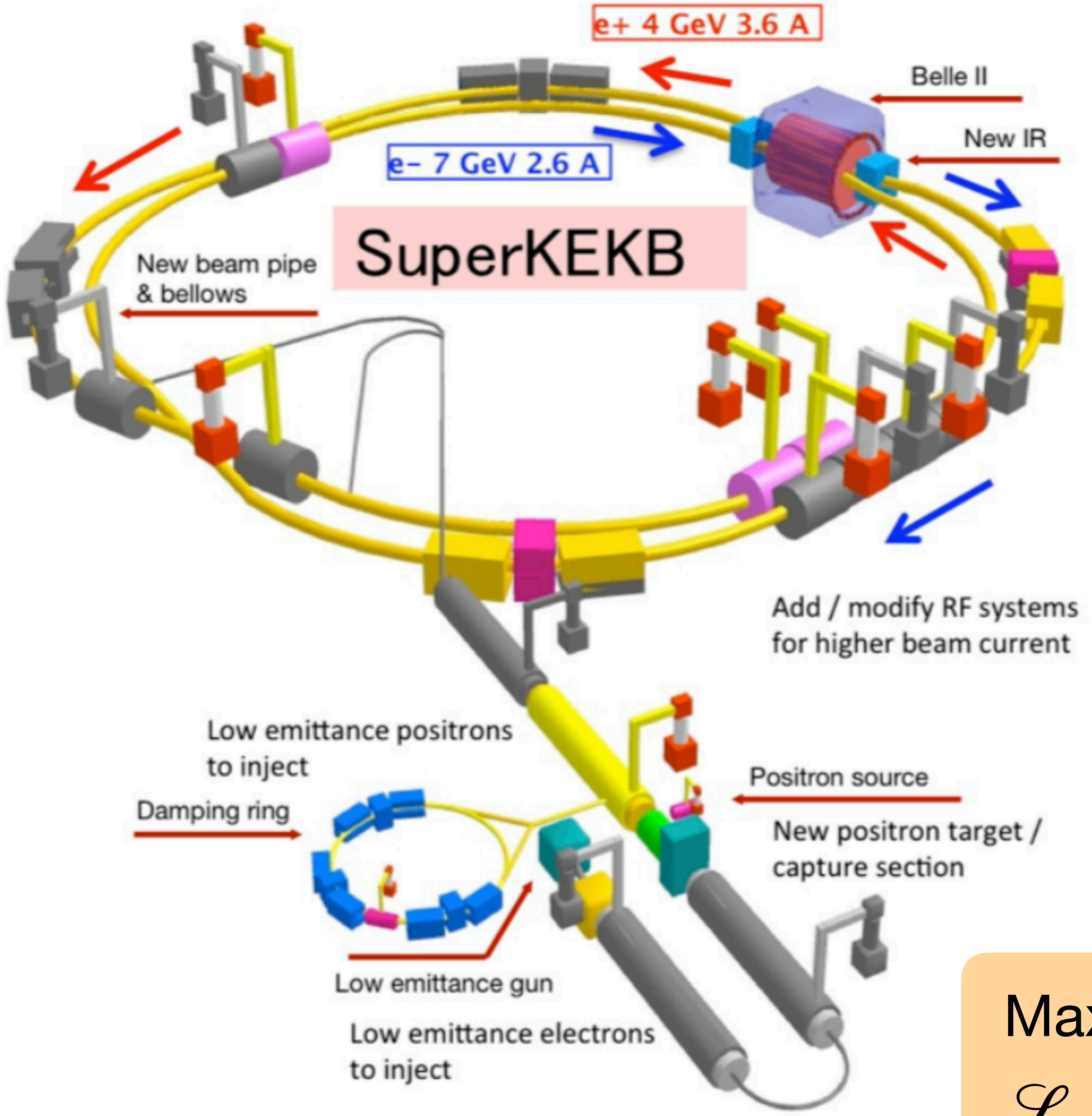


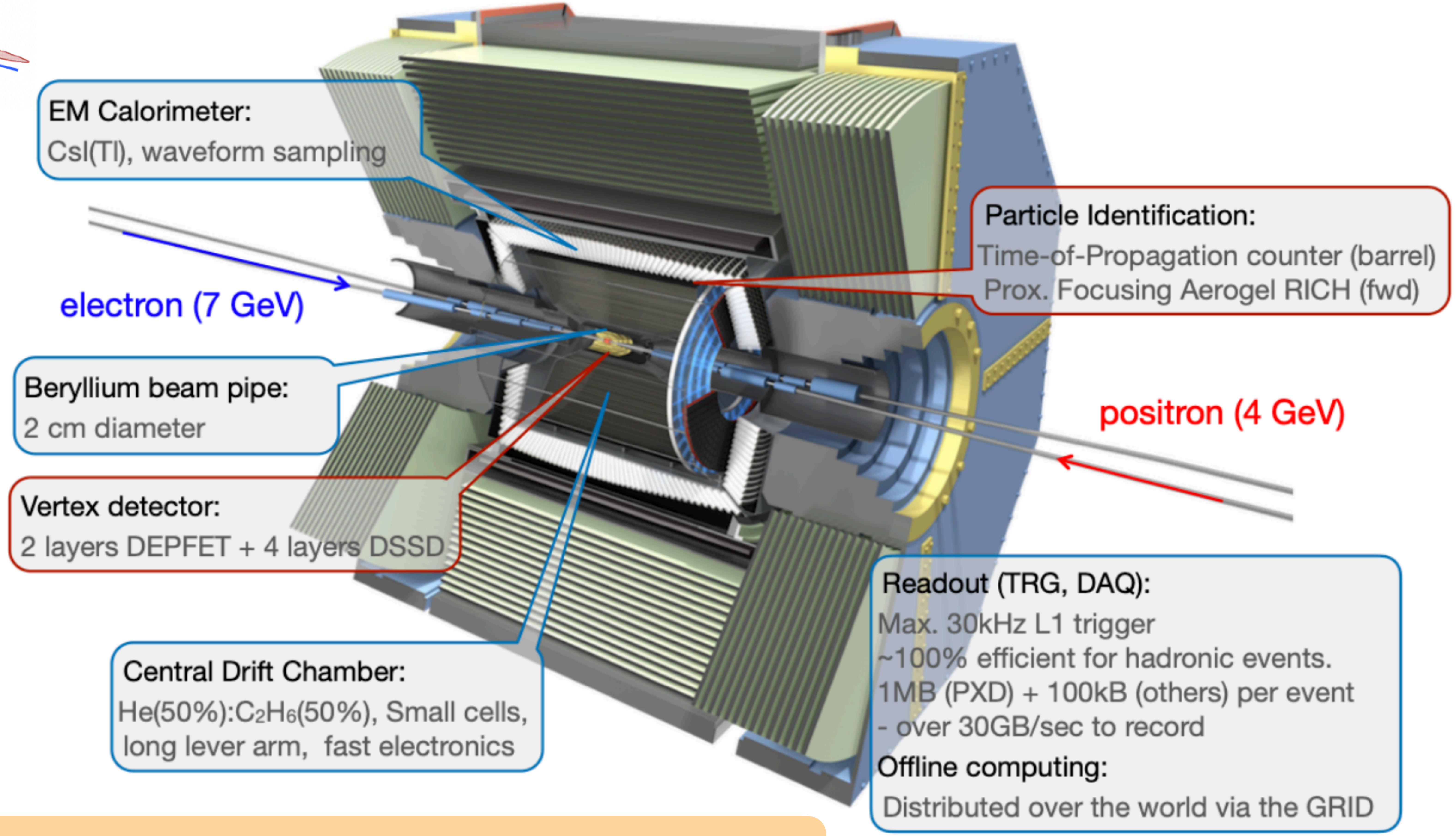
曹 璐

复旦大学 现代物理研究所

Belle II Experiment @ SuperKEKB







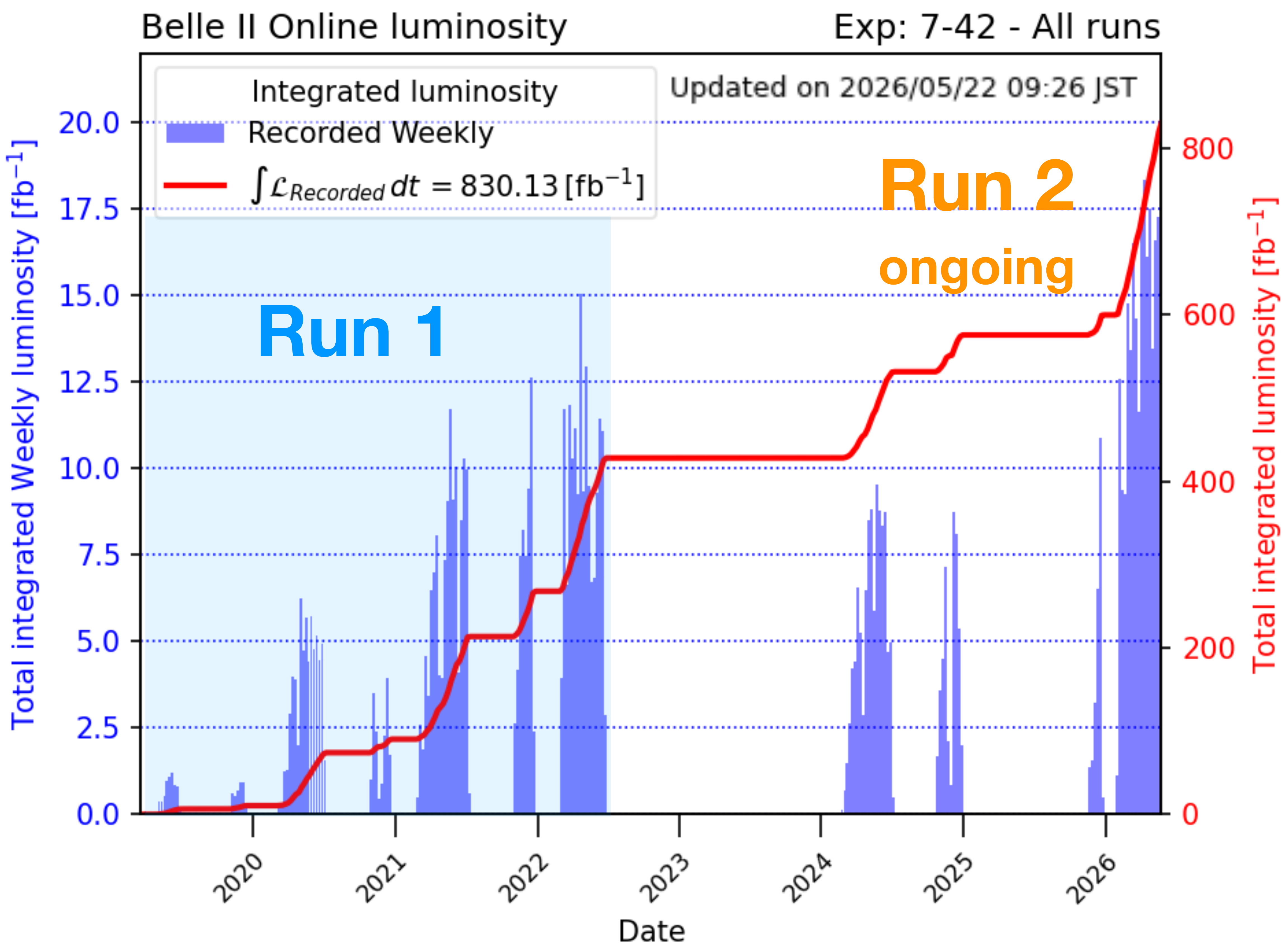
Max instantaneous luminosity:

$$\mathscr{L} = 5.244 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

New World Record @2026.03.19

Belle II Run Status

Belle II surpassed the Y(4S) luminosity of Belle 711 fb^{-1} last weekend and has now recorded the **largest** such dataset ever!!!



Run 1

- Total integrated luminosity: **424 fb-1**
- Total integrated luminosity at the Y(4S) resonance: **365 fb-1**
- Total integrated luminosity below Y(4S) resonance: **42 fb-1**
- Total integrated luminosity above Y(4S) resonance: **19 fb-1**

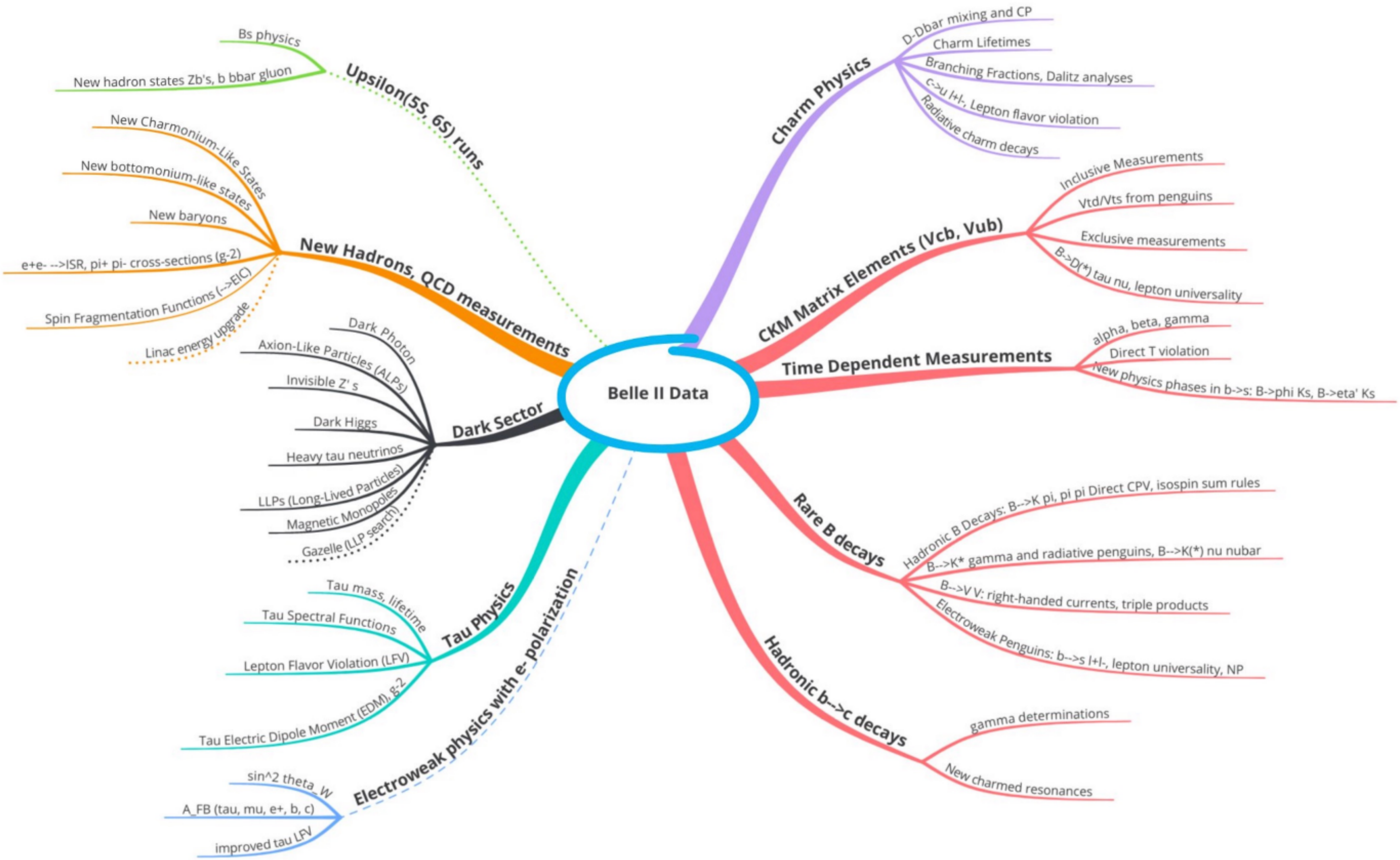
Run 2
2024-2025

- Total integrated luminosity: **175.40 fb-1**
- Total integrated luminosity at the Y(4S) resonance: **157.14 fb-1**
- Total integrated luminosity below the Y(4S) resonance: **18.26 fb-1**

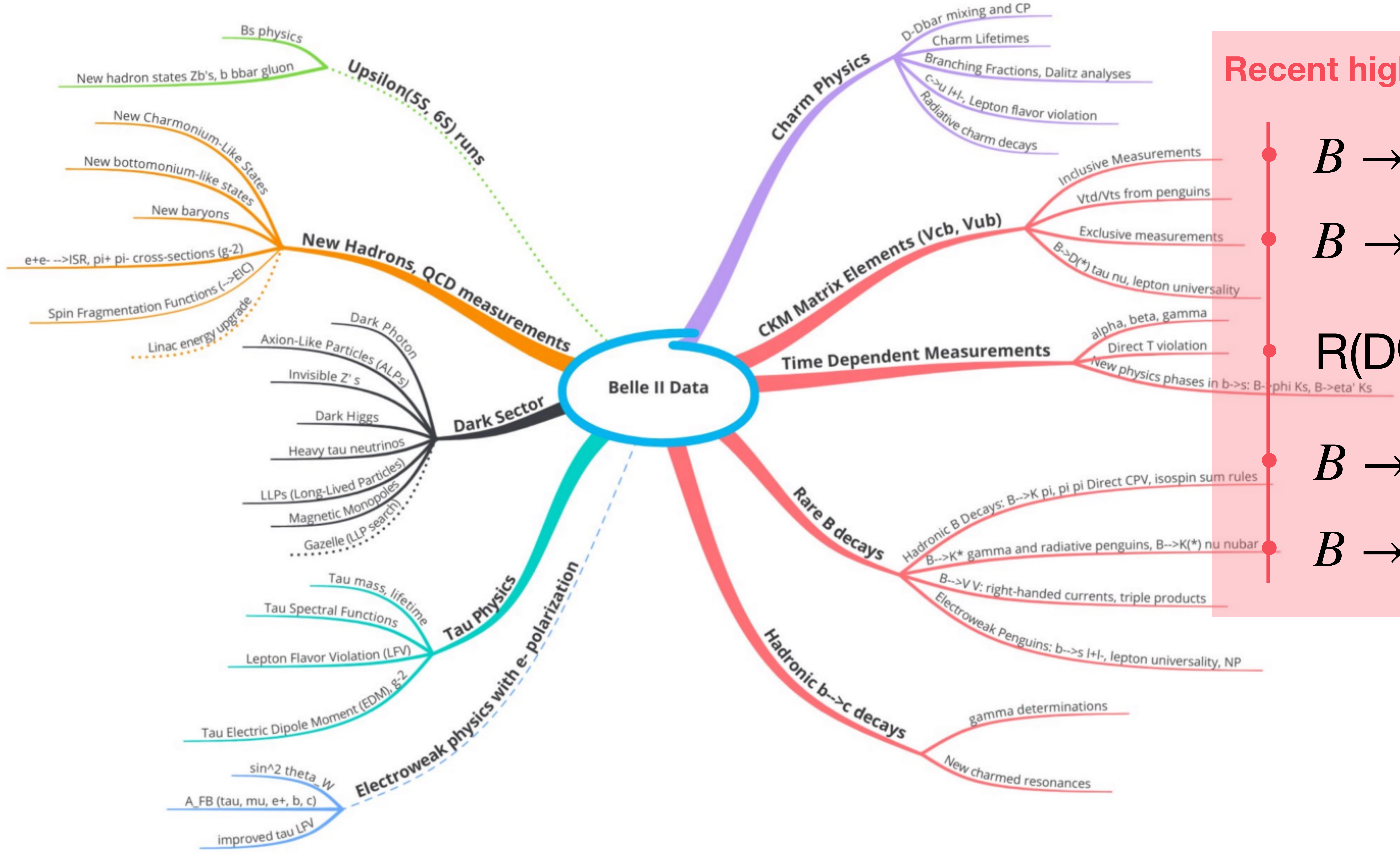
Up-to-date lumi.: https://www.belle2.org/info/luminosity_status/

Event display of ongoing data-taking: https://evdisp.belle2.org/

Results Covered in This Talk



Results Covered in This Talk



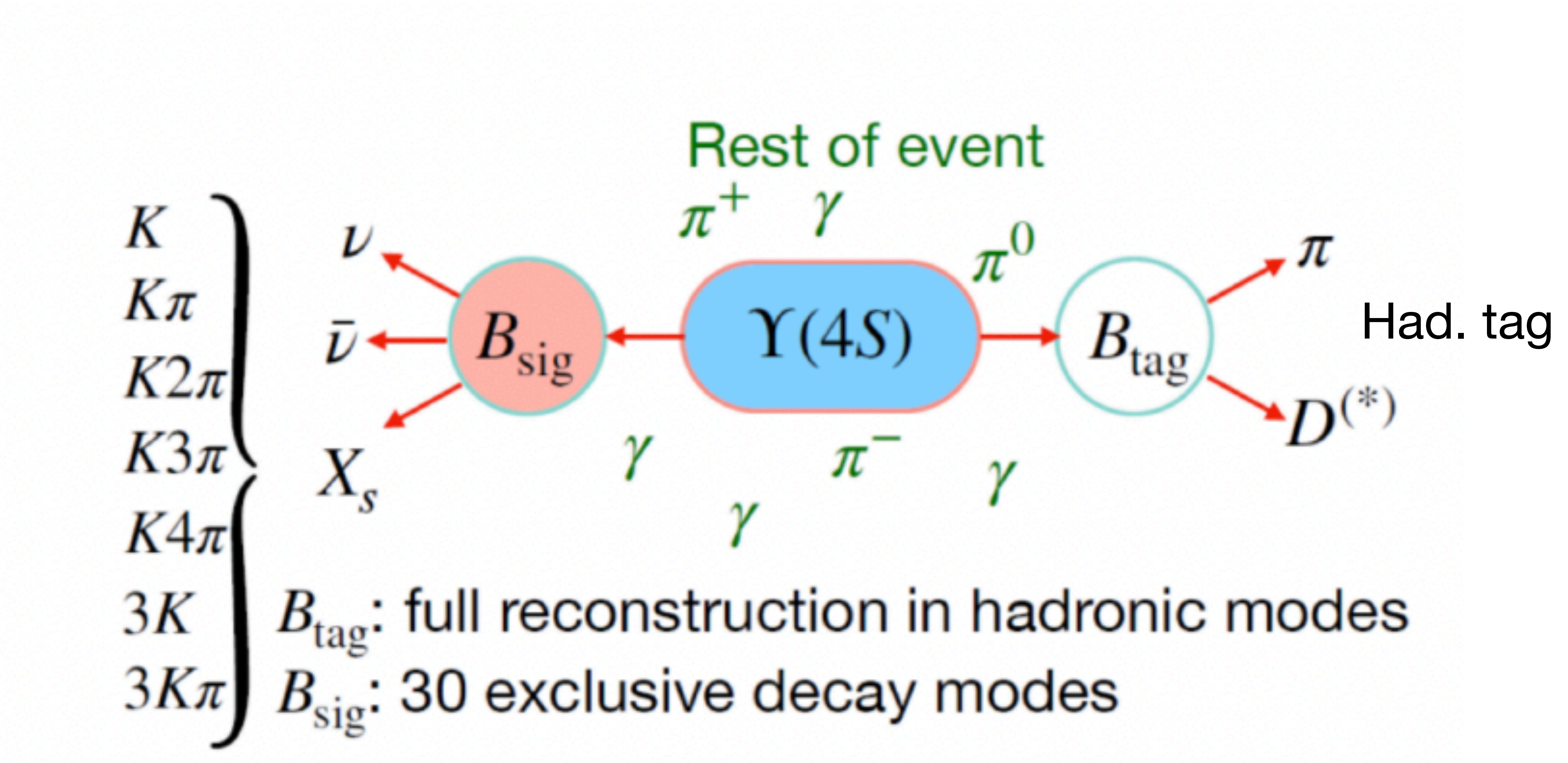
Recent highlights in B physics

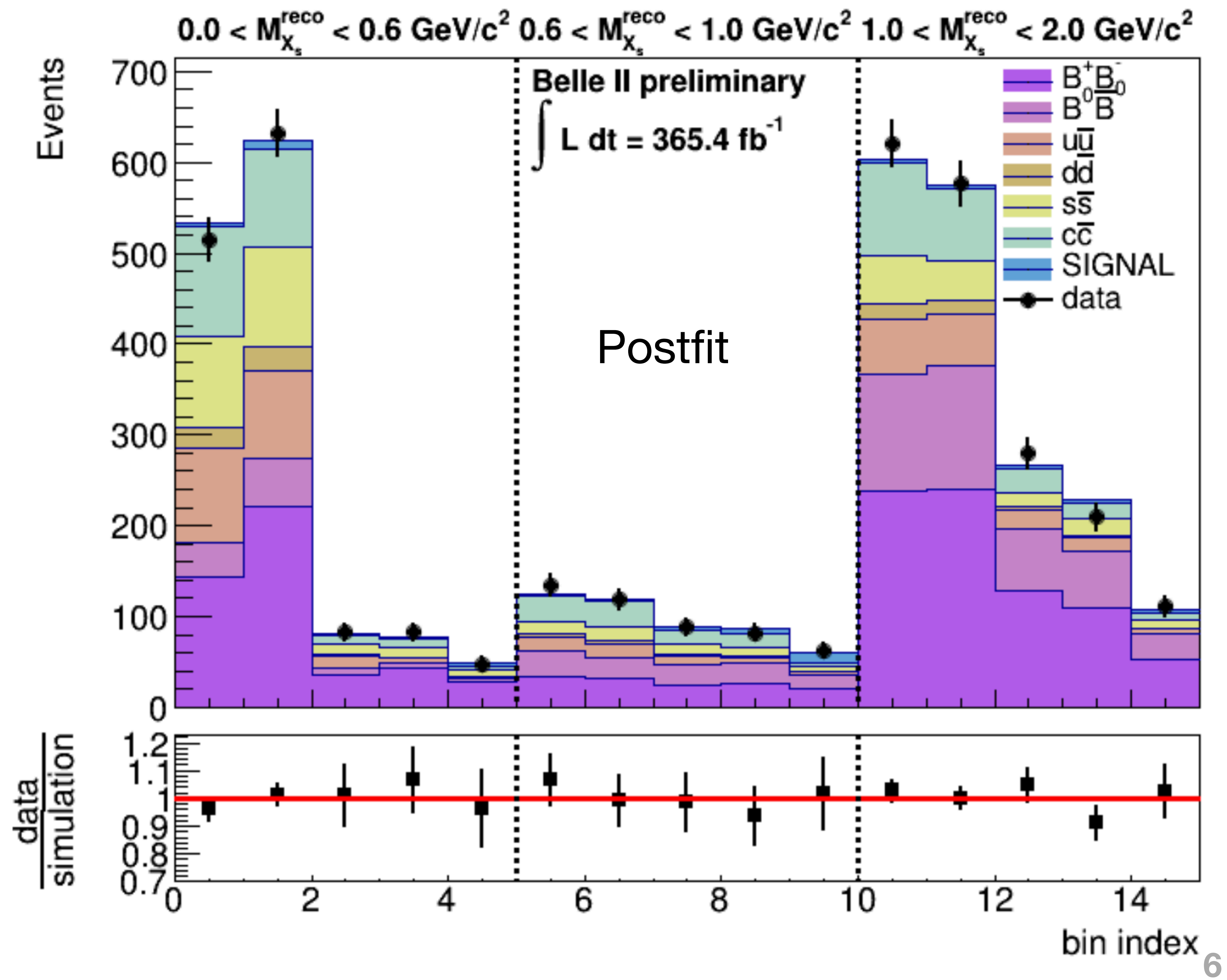
- $B \to X_u \ell \nu$
- $B \to \mu \nu$
- R(D$^{(*)}$) SL-tag, Had.-tag
- $B \to \pi^0 \pi^0$
- $B \to X_s \nu \bar{\nu}$

First Search for $B \to X_s \nu\bar{\nu}$

arXiv:2511.10980
Accepted by PRL

- Belle II Run1 dataset: 365 fb^{-1}
- Complementary to $B^+ \to K^+\nu\bar{\nu}$, sensitive to BSM contributions
- Sum of 30 exclusive modes: $B \to Kn\pi$ $(n \leq 4)$, $B \to 3K$, $B \to 3K\pi$
- Extract signal with 2D binned likelihood fit on BDT score and hadronic mass M_{X_s}





First Search for $B \to X_s \nu\bar{\nu}$

arXiv:2511.10980
Accepted by PRL

- No significant signal observed
- Upper limits set for each & full M_{Xs} regions
- Dominant syst uncertainties: MC size, bkg normalization

	M_{X_s} [GeV/c^2]	ϵ [10^{-3}]	N_{sig}	$\mathcal{B}$ [10^{-5}] central value	$\mathcal{B}$ [10^{-5}] UL$_{obs}$	$\mathcal{B}$ [10^{-5}] UL$_{exp}$ (expected from bkg-only hypothesis)
K	$[0, 0.6]$	2.93	6^{+18+19}_{-17-16}	$0.3 \pm 0.8^{+0.9}_{-0.7}$	2.2	2.0
K*	$[0.6, 1.0]$	1.32	36^{+27+31}_{-26-26}	$3.5^{+2.6+3.1}_{-2.5-2.6}$	9.5	6.6
other	$[1.0, m_B]$	0.62	24^{+44+62}_{-43-53}	$5.1^{+9.2+12.9}_{-8.8-11.0}$	31.2	26.7
	Full range	0.97	66^{+64+95}_{-62-81}	$8.8^{+8.5+12.6}_{-8.2-10.8}$	32.2	24.4

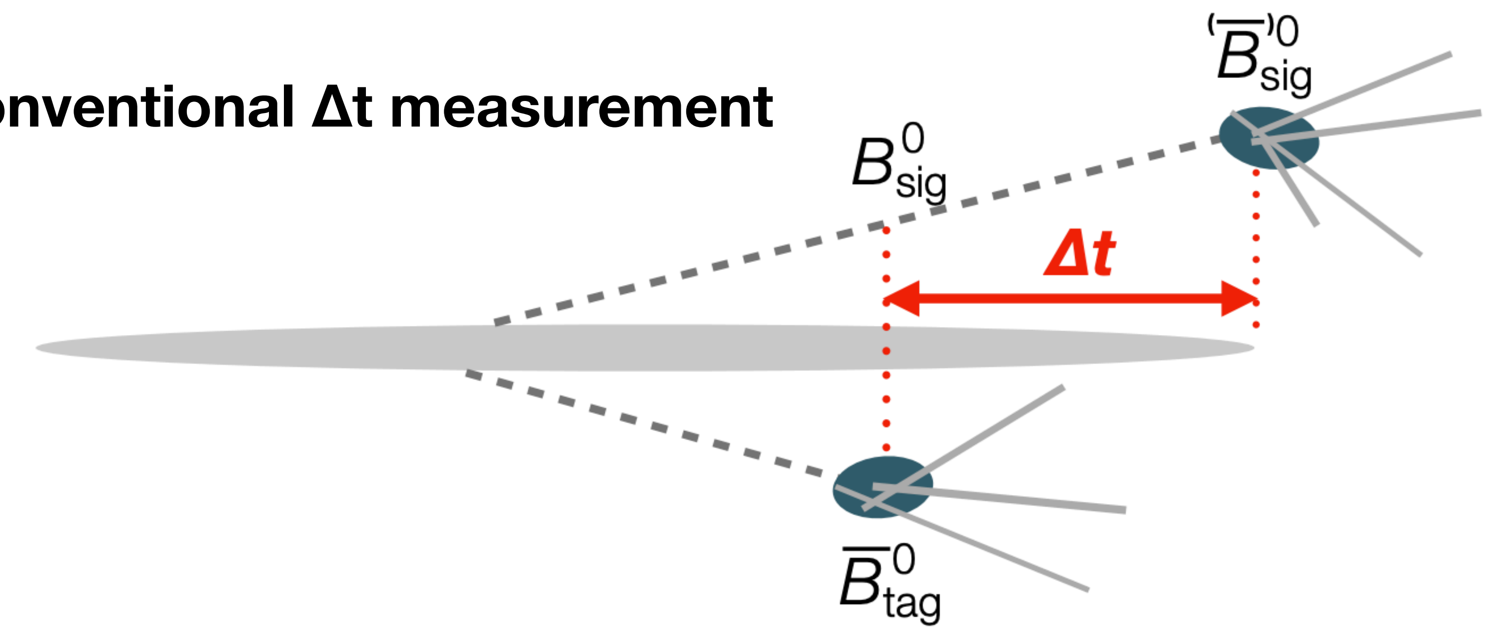
compatible with $B \to K\nu\bar{\nu}$ result

Mixing-Induced CP Violation in $B^0 \to \pi^0\pi^0$

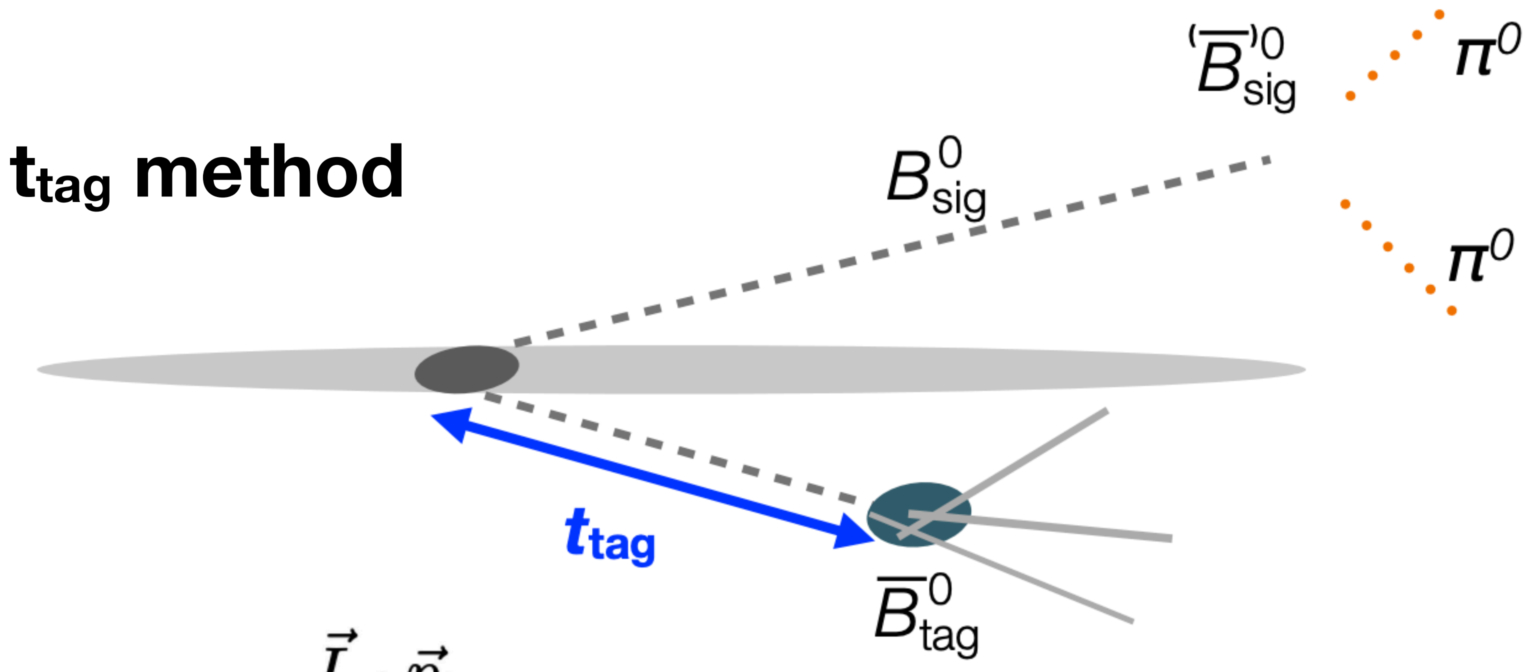
Preliminary

- Measure time-dependent asymmetry in B decays $$A_{CP}(t) = \frac{N(\overline{B}^0(t) \to f) - N(B^0(t) \to f))}{N(\overline{B}^0(t) \to f) + N(B^0(t) \to f))} \quad f = \pi^0\pi^0$$
- Built upon previous time-integrated Belle II analysis [PRD 111, L071102(2025)]
- Use novel approach to access TDCPV w/o vertex [PRD 112, 032011(2025)] **=> measure B-tag decay time instead**

Conventional Δt measurement



t_{tag} method

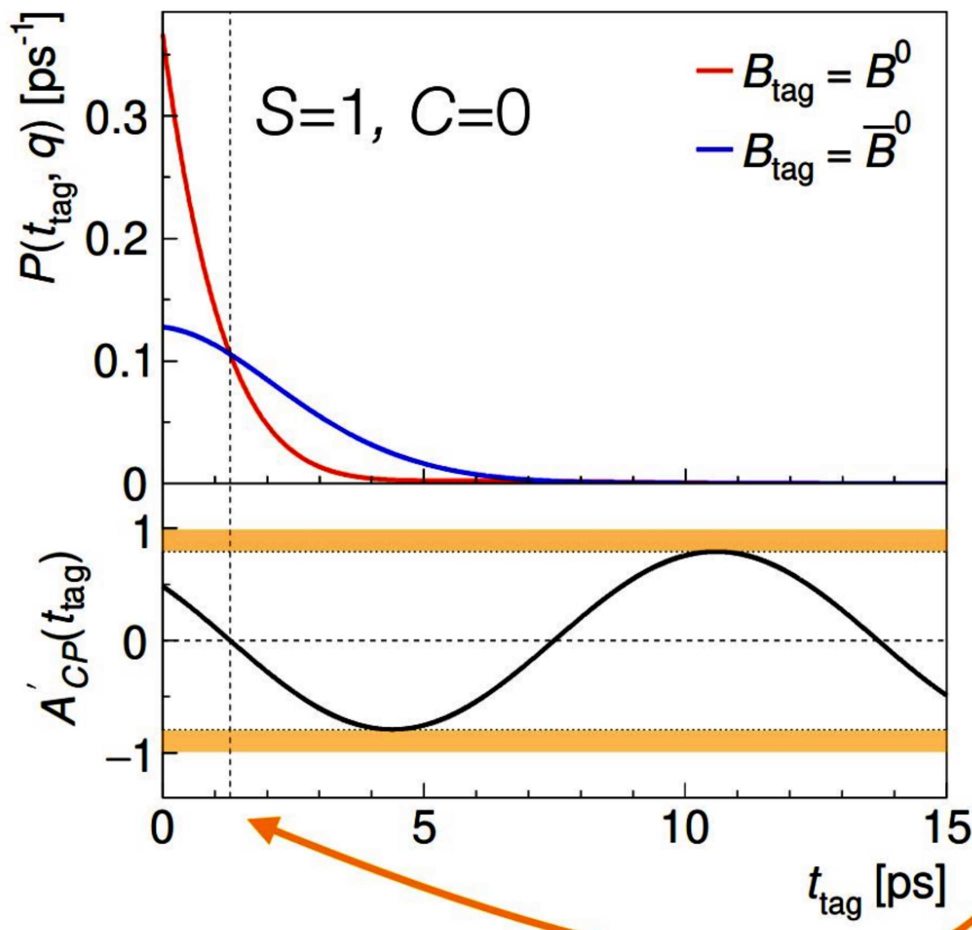


$$t_{tag} = m_B \frac{\vec{L} \cdot \vec{p}_{tag}}{|p_{tag}|^2}$$

$$\mathcal{P}(t_{tag}, t_{CP}, q) = \frac{e^{-\frac{t_{CP}+t_{tag}}{\tau}}}{2\tau^2}\Big(1 + q\big[S \sin \Delta m(t_{CP} - t_{tag}) - C \cos \Delta m(t_{CP} - t_{tag})\big]\Big)$$

Marginalizing over t_{CP}

$$\mathcal{P}(t_{tag}, q) = \frac{e^{-t_{tag}/\tau}}{2\tau}\Big(1 + q\big[S' \sin \Delta m(t_{tag} - \hat{t}) - C' \cos \Delta m(t_{tag} - \hat{t})\big]\Big),$$



$$\mathcal{A}'_{CP}(t_{tag}) = S' \sin \Delta m(t_{tag} - t_0) - C' \cos \Delta m(t_{tag} - t_0)$$

$$S' = -\frac{S}{\sqrt{1 + (\tau \Delta m)^2}} \approx \mathbf{-0.8\ S}$$

$$C' = \frac{C}{\sqrt{1 + (\tau \Delta m)^2}} \approx \mathbf{0.8\ C}$$

$$t_0 = \frac{1}{\Delta m} \arctan(\Delta m \tau) \approx \mathbf{1.3\ ps}$$

- High $\mathbf{t_{tag}}$ precision: 1.5 ps @ Belle II with PXD
- Technique validated with $B^0 \to J/\psi K^0_s$ for ϕ_1

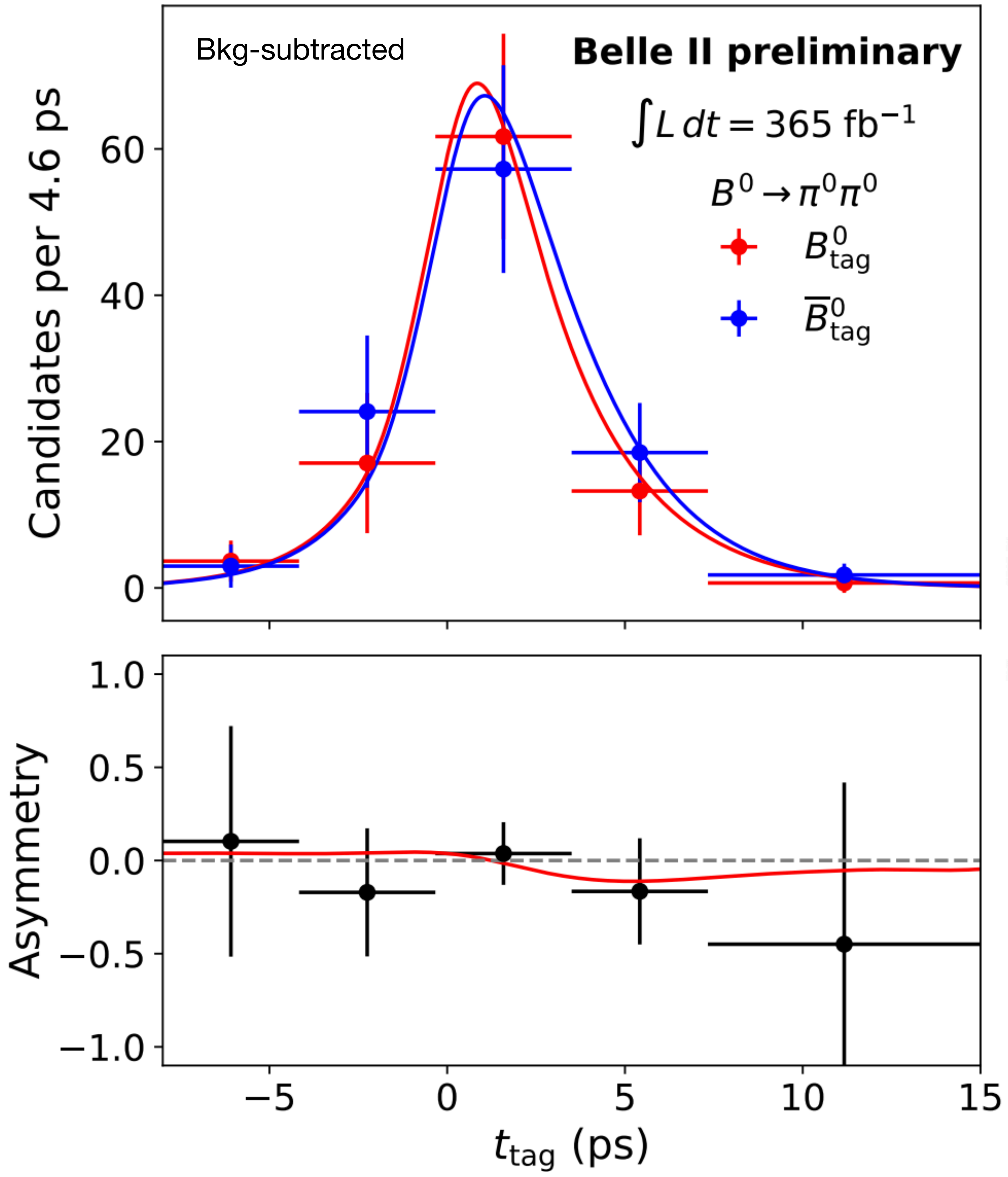
Mixing-Induced CP Violation in $B^0 \to \pi^0\pi^0$

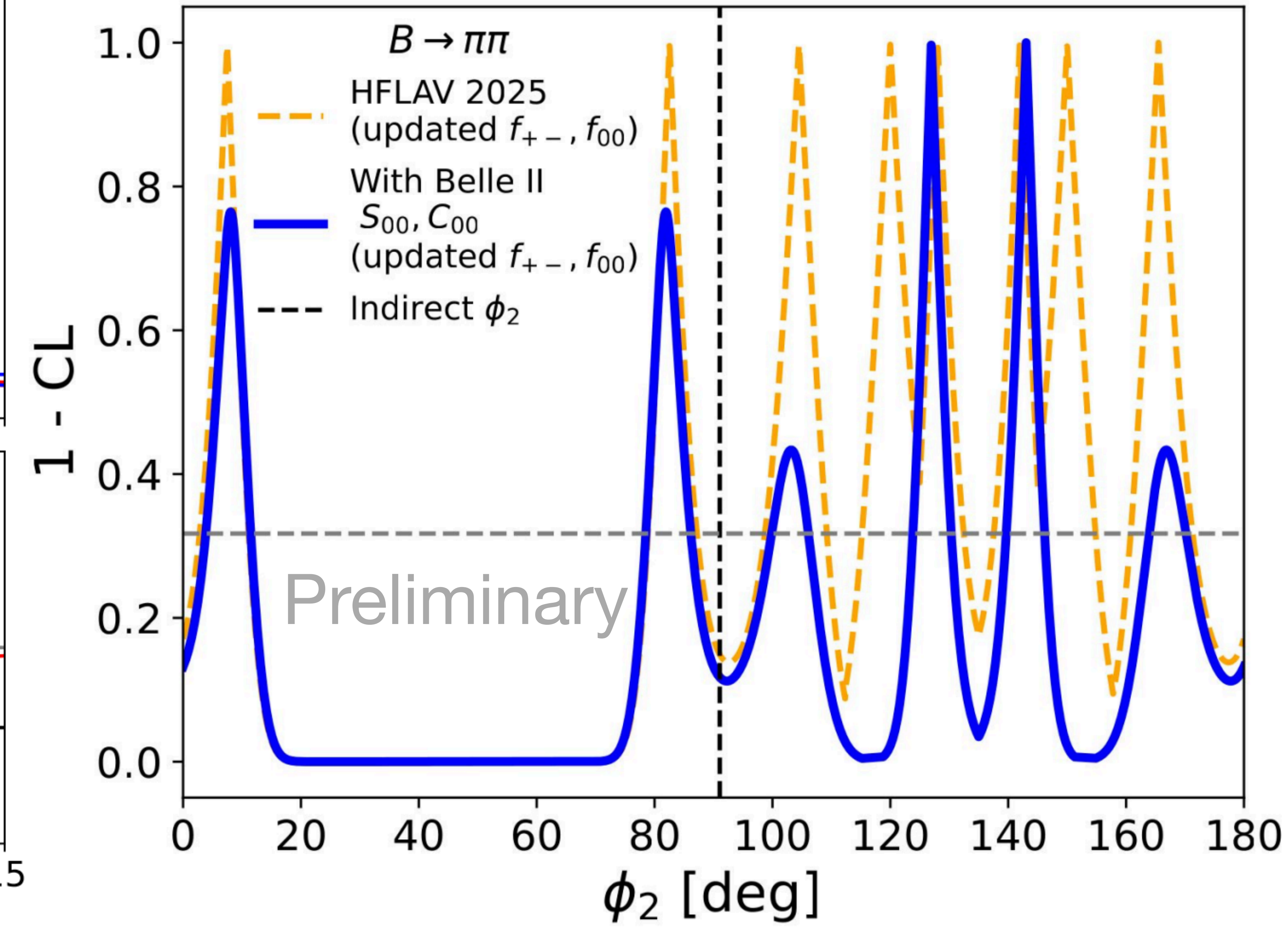
Preliminary

- First measurement of mixing induced CP-violation without signal vertex
- Would have required 20x more data if $A_{CP}(\Delta t)$, relies on π^0modes with vertex info
- Consistent with previous Belle II time-independent $C_{\pi^0\pi^0}$

Preliminary

$$S_{00} = 0.61^{+0.75}_{-0.79}\,(\text{stat}) \pm 0.11\,(\text{syst}),$$
$$C_{00} = 0.05 \pm 0.28\,(\text{stat}) \pm 0.07\,(\text{syst})$$





- Allowed 68% CL region interval in ϕ2 from B→ππ shrunk by 40%
- CKM-like ϕ2 solutions from ππ and ρρ are consistent with similar uncertainty

Lepton-Flavor Universality Test

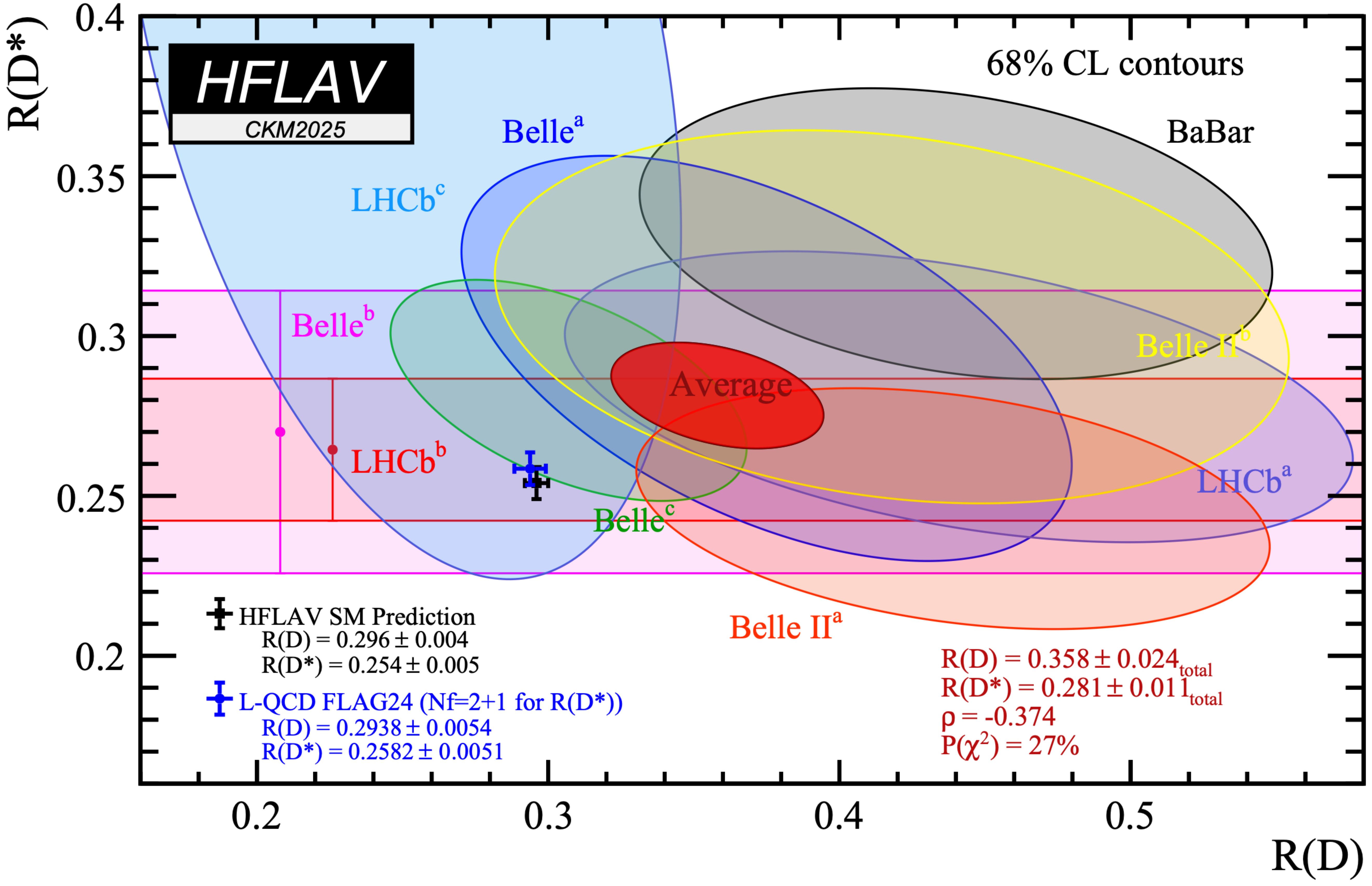
- In SM, the W boson couples equally to τ, μ, e => **Lepton-Flavor Universality (LFU)**
- Semileptonic B decays are sensitive to new physics beyond SM
- **Ratio measurements** provide stringent LFU tests: branching fractions, angular asymmetry, etc.
  - Normalization ($|V_{xb}|$) cancels
  - Part of theoretical, experimental uncertainties cancels

$$R(H_{\tau/\ell}) = \frac{\mathscr{B}(B \to H\tau\nu)}{\mathscr{B}(B \to H\ell\nu)}$$

$$H = D, D^*, X, \pi, \text{etc}. \quad \ell = e, \mu$$

final state can involve different hadrons

Tension of $R(D^{(*)})$ with SM_{HFLAV} ~3σ



Lepton-Flavor Universality Test

- In SM, the W boson couples equally to τ, μ, e => **Lepton-Flavor Universality (LFU)**
- Semileptonic B decays are sensitive to new physics beyond SM
- **Ratio measurements** provide stringent LFU tests: branching fractions, angular asymmetry, etc.
    - Normalization ($|V_{xb}|$) cancels
    - Part of theoretical, experimental uncertainties cancels

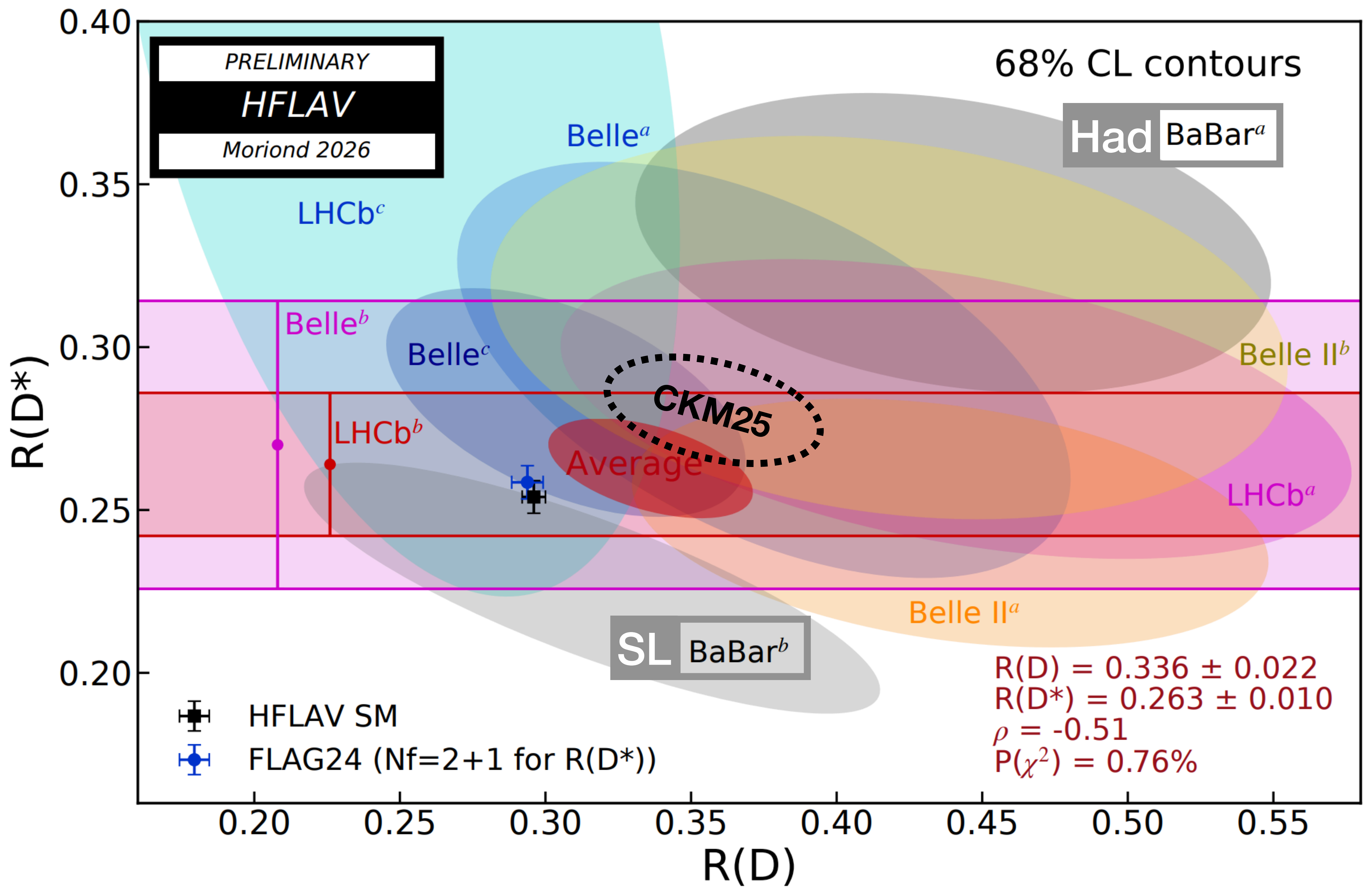
$$R(H_{\tau/\ell}) = \frac{\mathscr{B}(B \to H\tau\nu)}{\mathscr{B}(B \to H\ell\nu)}$$

$$H = D, D^*, X, \pi, \text{etc}. \quad \ell = e, \mu$$

final state can involve different hadrons

Tension of $R(D^{(*)})$ with SM$_{\text{HFLAV}}$ ~2σ

including new preliminary BaBar results



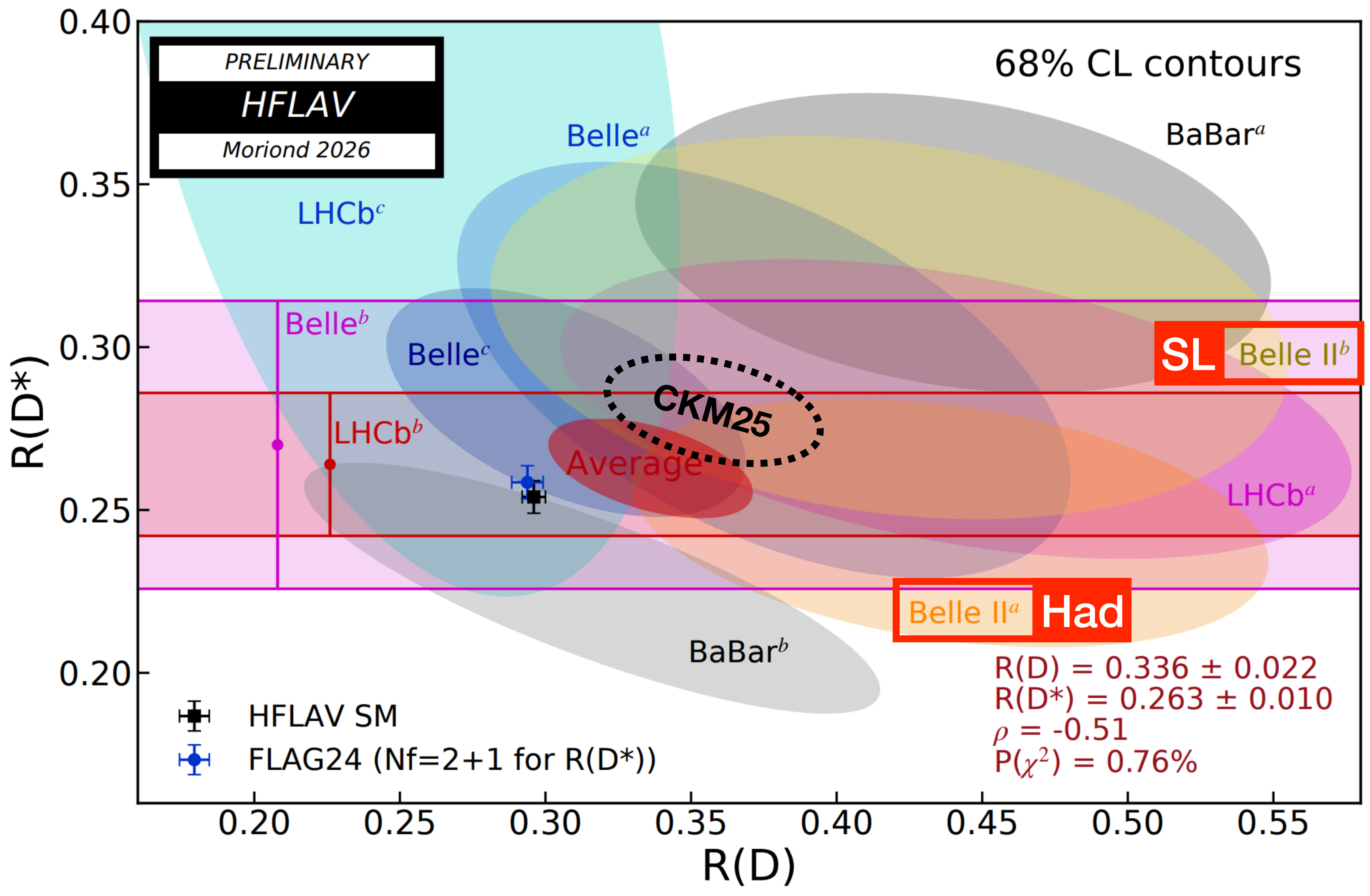
Lepton-Flavor Universality Test

- In SM, the W boson couples equally to τ, μ, e => **Lepton-Flavor Universality (LFU)**
- Semileptonic B decays are sensitive to new physics beyond SM
- **Ratio measurements** provide stringent LFU tests: branching fractions, angular asymmetry, etc.
  - Normalization ($|V_{xb}|$) cancels
  - Part of theoretical, experimental uncertainties cancels

$$R(H_{\tau/\ell}) = \frac{\mathscr{B}(B \to H\tau\nu)}{\mathscr{B}(B \to H\ell\nu)}$$

$$H = D, D^*, X, \pi, \text{etc}. \quad \ell = e, \mu$$

final state can involve different hadrons



Tension of $R(D^{(*)})$ with SM_{HFLAV} ~2σ

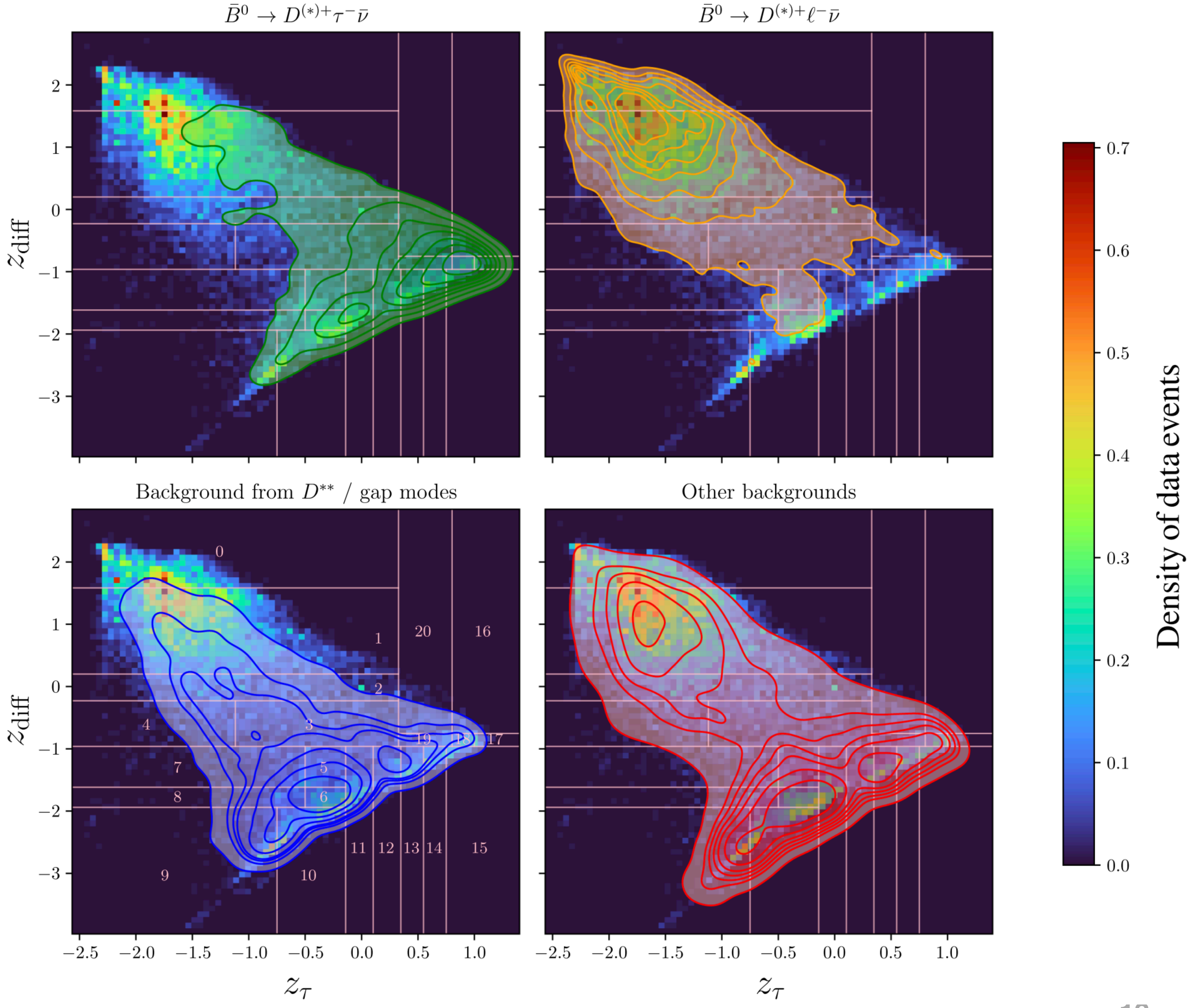
including new preliminary BaBar results

R(D(*)) with Semileptonic Tag

PRD 112, 032010 (2025)

- Belle II Run1 dataset: 365 fb^{-1}, only neutral B
- Reconstruct B$_{tag}$ from $B^0 \to D^{(*)}\ell\nu$ using SL-FEI [Comput.Softw.Big Sci. 3 (2019) 1, 6]
- Reconstruct tau via **leptonic** decays
- A multi-classification scores (p_τ, p_ℓ, p_{bkg}) transferred into 2D binned likelihood distributions Z_{diff}, Z_τ for signal extraction in 4 channels simultaneously
- R(D) and R(D*) directly included as free floating fit parameters

$$z_p = \mathrm{logit}(p) = \log\left(\frac{p}{1-p}\right)$$
$$z_{\mathrm{diff}} = z_l - z_{\mathrm{bkg}}$$



R(D(*)) with Semileptonic Tag

PRD 112, 032010 (2025)

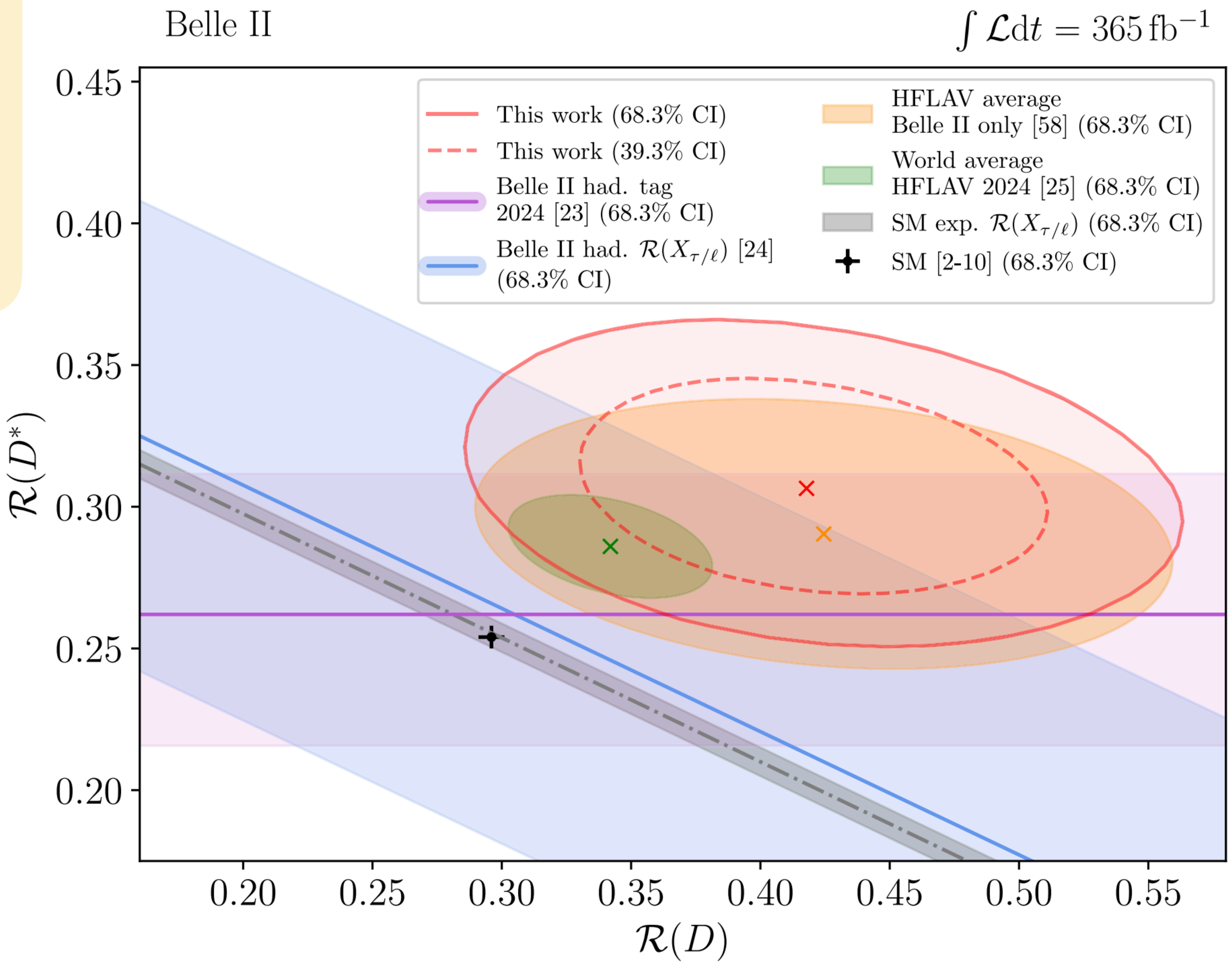
$$\mathcal{R}(D^+) = 0.418^{+0.075}_{-0.073}(\text{stat})^{+0.049}_{-0.056}(\text{syst})$$

$$\mathcal{R}(D^{*+}) = 0.306^{+0.035}_{-0.033}(\text{stat})^{+0.016}_{-0.018}(\text{syst})$$

$\rho = -0.24$

dominant by MC size, Xc gap modes, LID eff. & fakes

- Results are statistically limited
- Compatible with current world average within 0.6σ
- **Agrees with SM within 1.7σ**
- Several consistency checks have been performed (see backup)



R(D(*)) with Semileptonic Tag

PRD 112, 032010 (2025)

$$\mathcal{R}(D^+) = 0.418^{+0.075}_{-0.073}(\text{stat})^{+0.049}_{-0.056}(\text{syst})$$

$$\mathcal{R}(D^{*+}) = 0.306^{+0.035}_{-0.033}(\text{stat})^{+0.016}_{-0.018}(\text{syst})$$

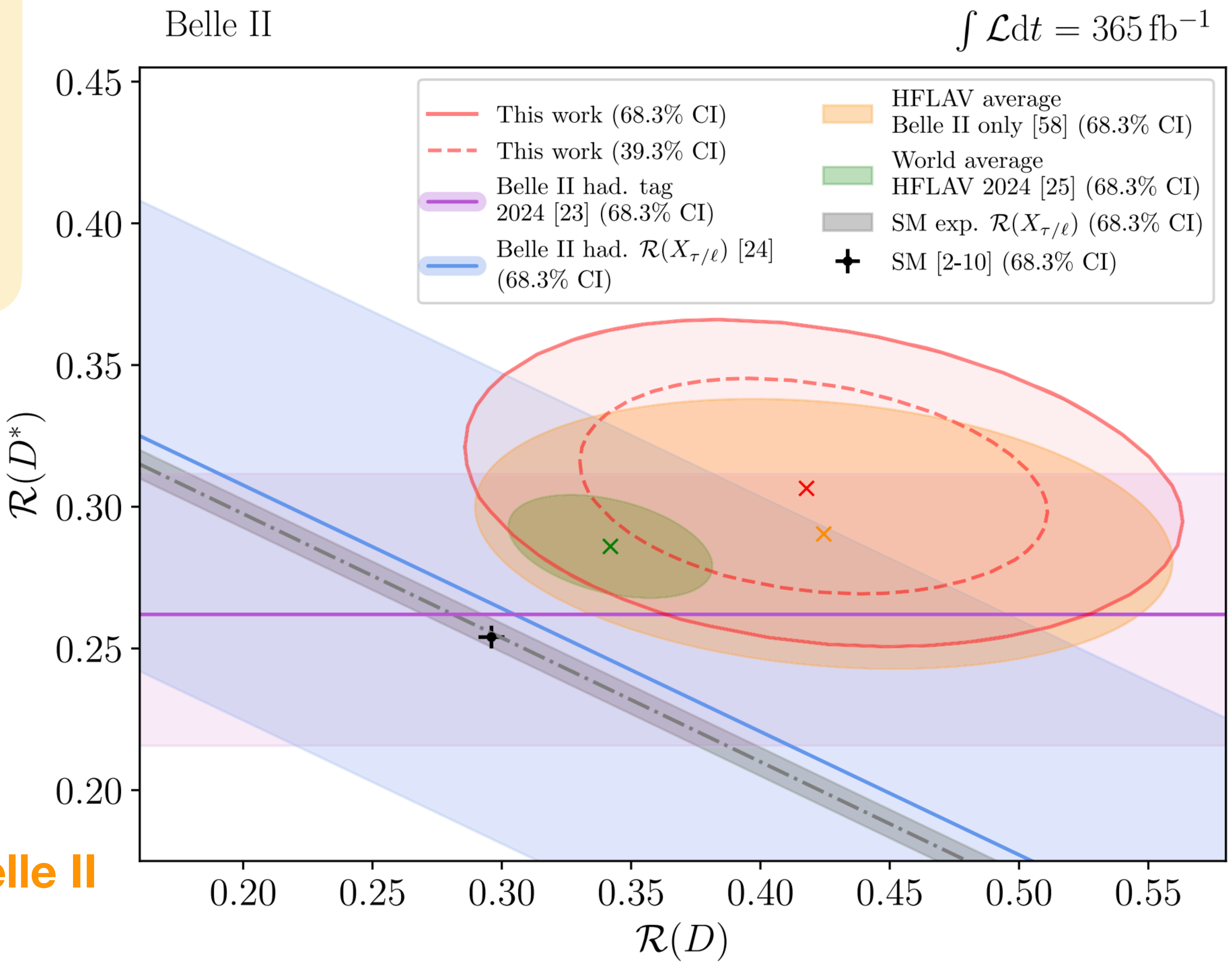
$$\rho = -0.24$$

dominant by MC size, Xc gap modes, LID eff. & fakes

- Results are statistically limited
- Compatible with current world average within 0.6σ
- **Agrees with SM within 1.7σ**
- Several consistency checks have been performed (see backup)

✓ **Demonstrate the SL tagging method at Belle II**

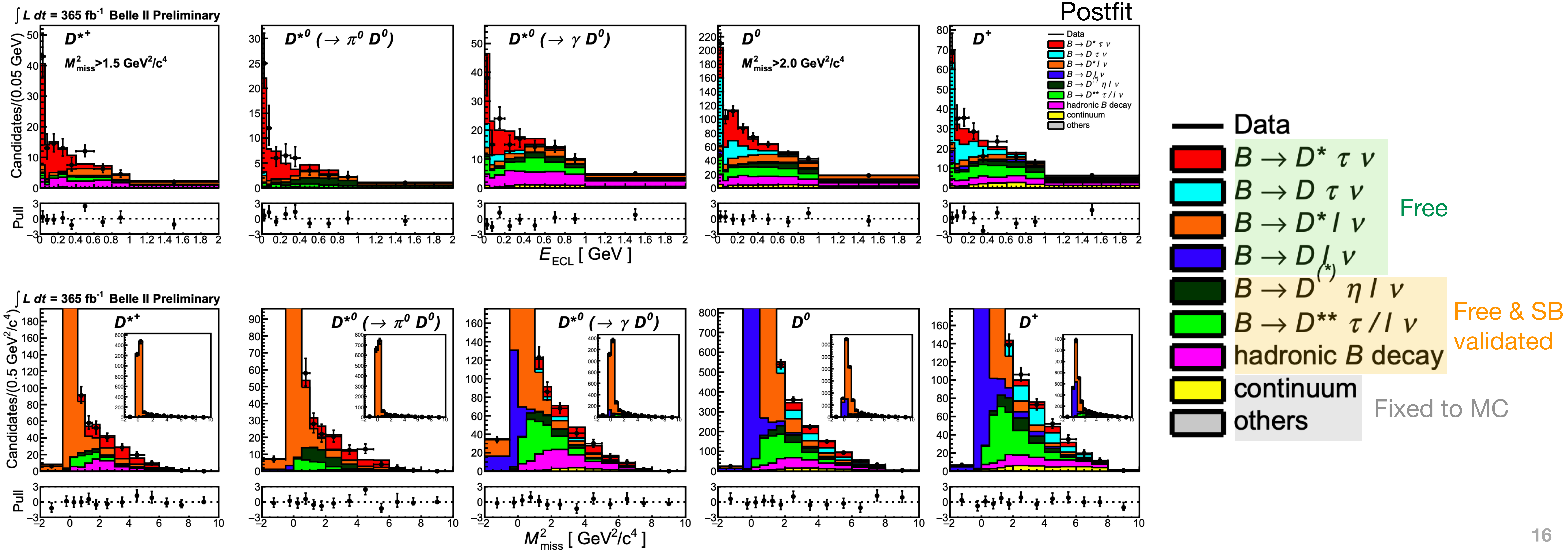
✓ **First Belle II R(D)-R(D*) result**



R(D(*)) with Hadronic Tag

Preliminary

- Run1 dataset: 365 fb^{-1}, supersedes previous had. R(D*) using 189 fb^{-1} [PRD 110, 072020 (2024)]
- Reconstruct **leptonic** tau decays
- 2D (E_{ECL} : M^2_{miss}) binned simultaneous fit in 5 channels



R(D^(*)) with Hadronic Tag

Preliminary

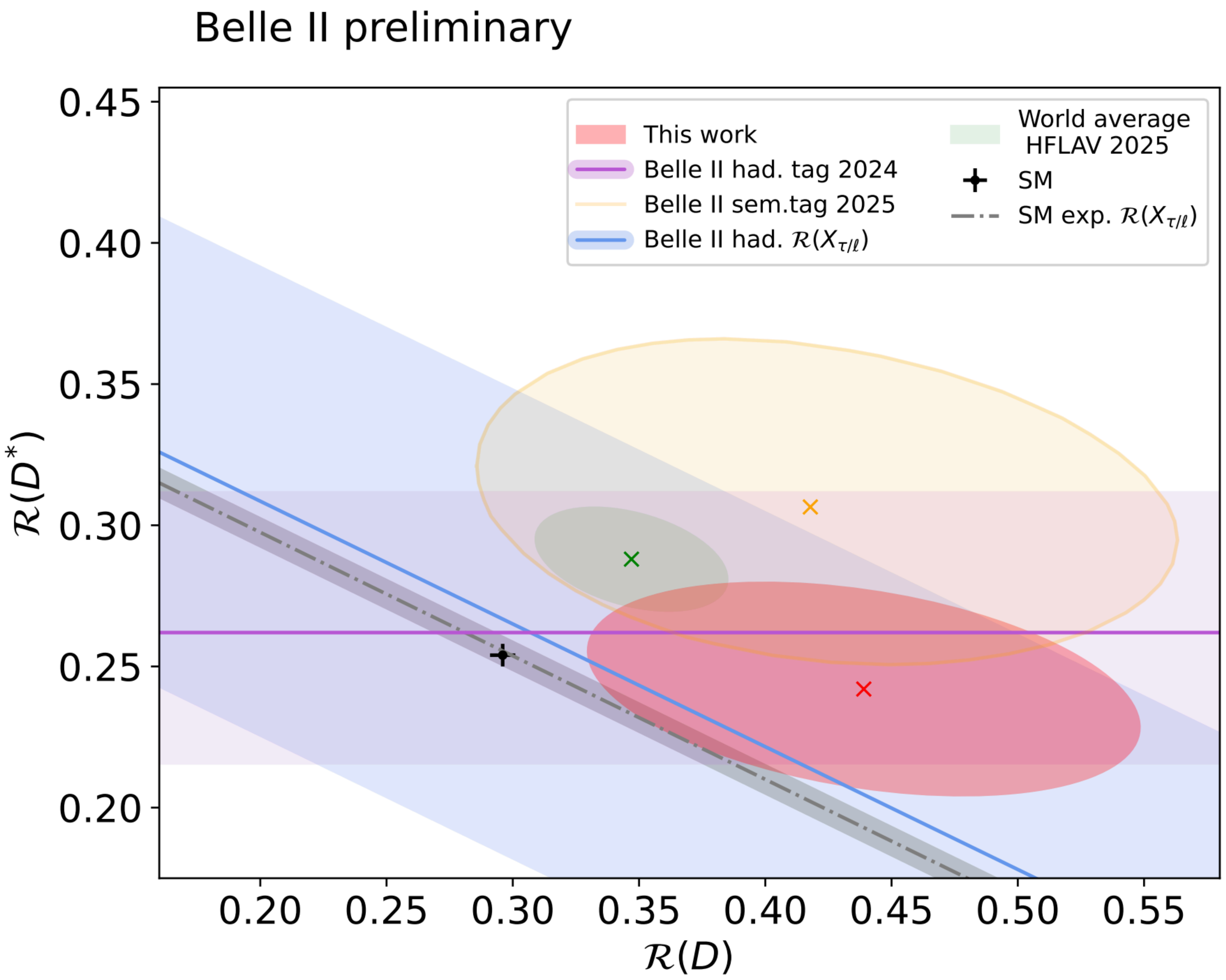
$$R(D^*) = 0.242 \pm 0.019(\text{stat}) \pm 0.016(\text{syst})$$
$$R(D) = 0.439 \pm 0.055(\text{stat}) \pm 0.046(\text{syst})$$

Preliminary

$$\rho_{\text{stat}} = -0.40, \rho_{\text{sys}} = -0.20$$

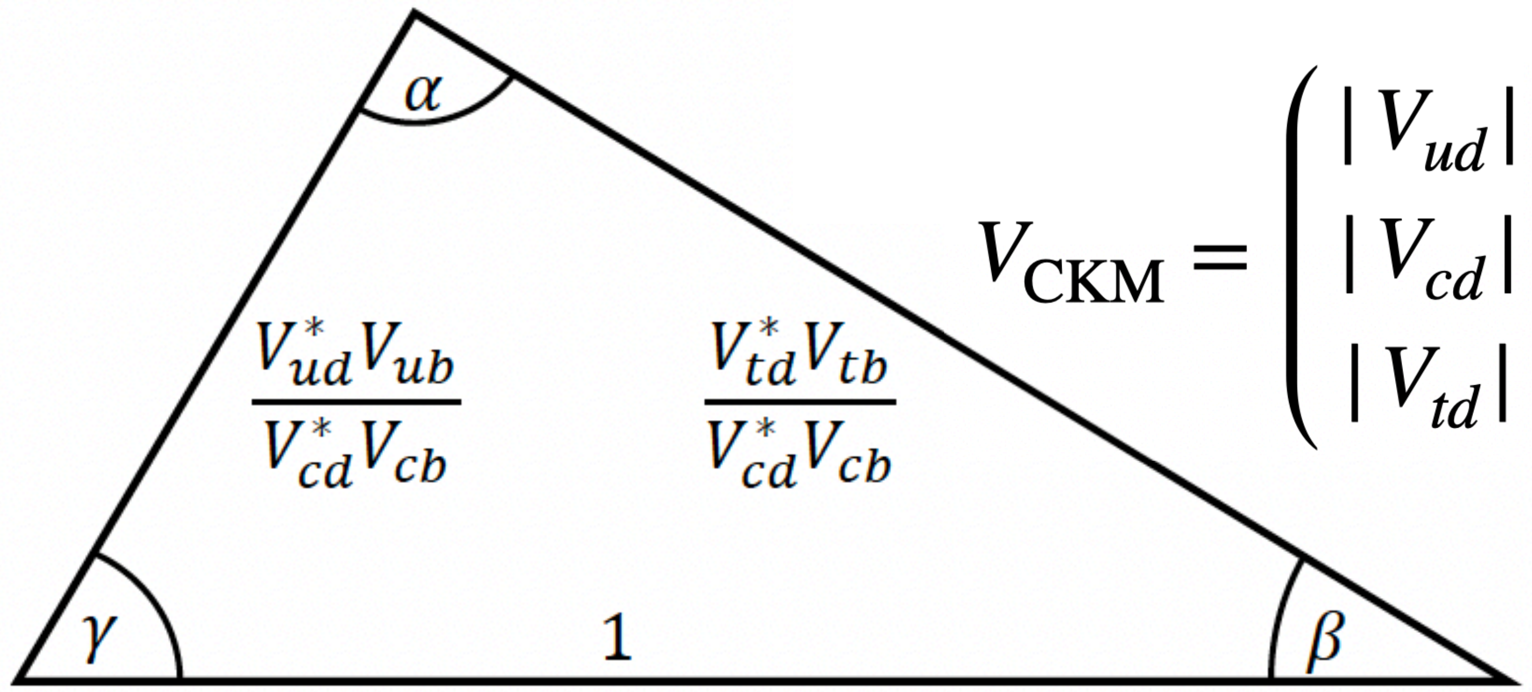
- Compatible with current world average within 1.3σ
- **Agrees with SM within 1.5σ**
  - **0.5σ for R(D*)**
  - **2.0σ for R(D)**
- Dominant syst. uncertainties: MC size, Xc gap modes, continuum bkg

✓ **Most precise R(D^(*)) with Had. tag**



$|V_{cb}|$ & $|V_{ub}|$

- Important to constrain CKM unitarity triangle & test SM
- Determinations via **inclusive** or **exclusive** semileptonic B decays
- Long-standing "**Vxb-puzzle**": discrepancy btw. inclusive and exclusive determinations



$$V_{\text{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix}$$

$$V_{\text{CKM}} V_{\text{CKM}}^\dagger = \mathbf{1}$$

Exclusive

$B \to \pi \ell \nu, B \to \rho \ell \nu, B \to D^{(*)} \ell \nu, \Lambda_b \to p \ell \nu$, etc.

$$\mathscr{B} \propto \left| V_{xb} \right|^2 f^2$$

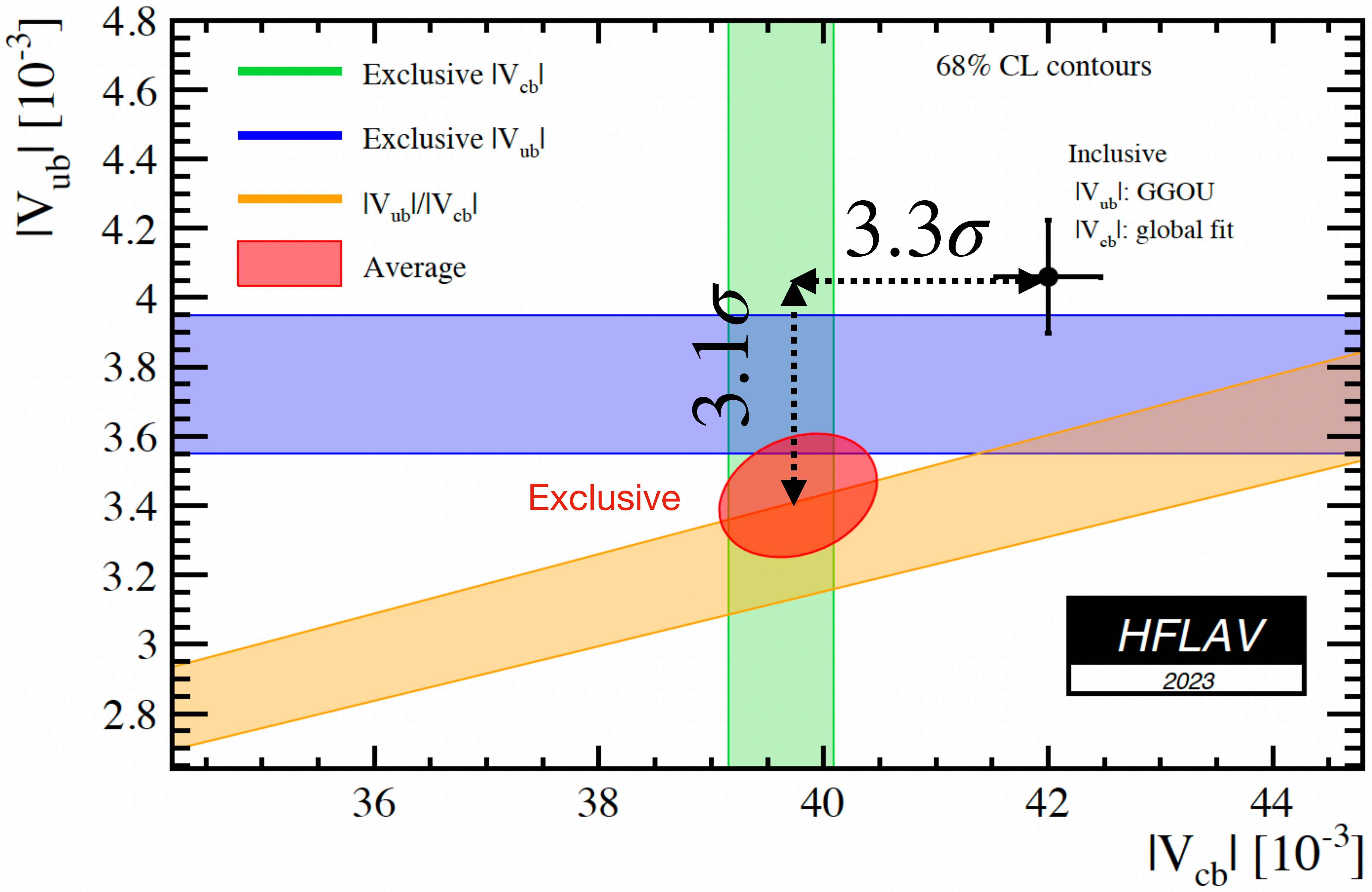
Form factor f (LCSR, LQCD)

Inclusive

$$B \to X_u \ell \nu, \;\; B \to X_c \ell \nu$$

$$\mathscr{B} \propto \left| V_{xb} \right|^2 \left[1 + \frac{c_5(\mu) \langle O_5 \rangle (\mu)}{m_h^2} + \frac{c_6(\mu) \langle O_6 \rangle (\mu)}{m_h^3} + O\left(m_b^4\right) \right] \qquad \left| V_{xb} \right| = \sqrt{\frac{\Delta \mathscr{B}}{\tau_B \cdot \Delta \Gamma}}$$

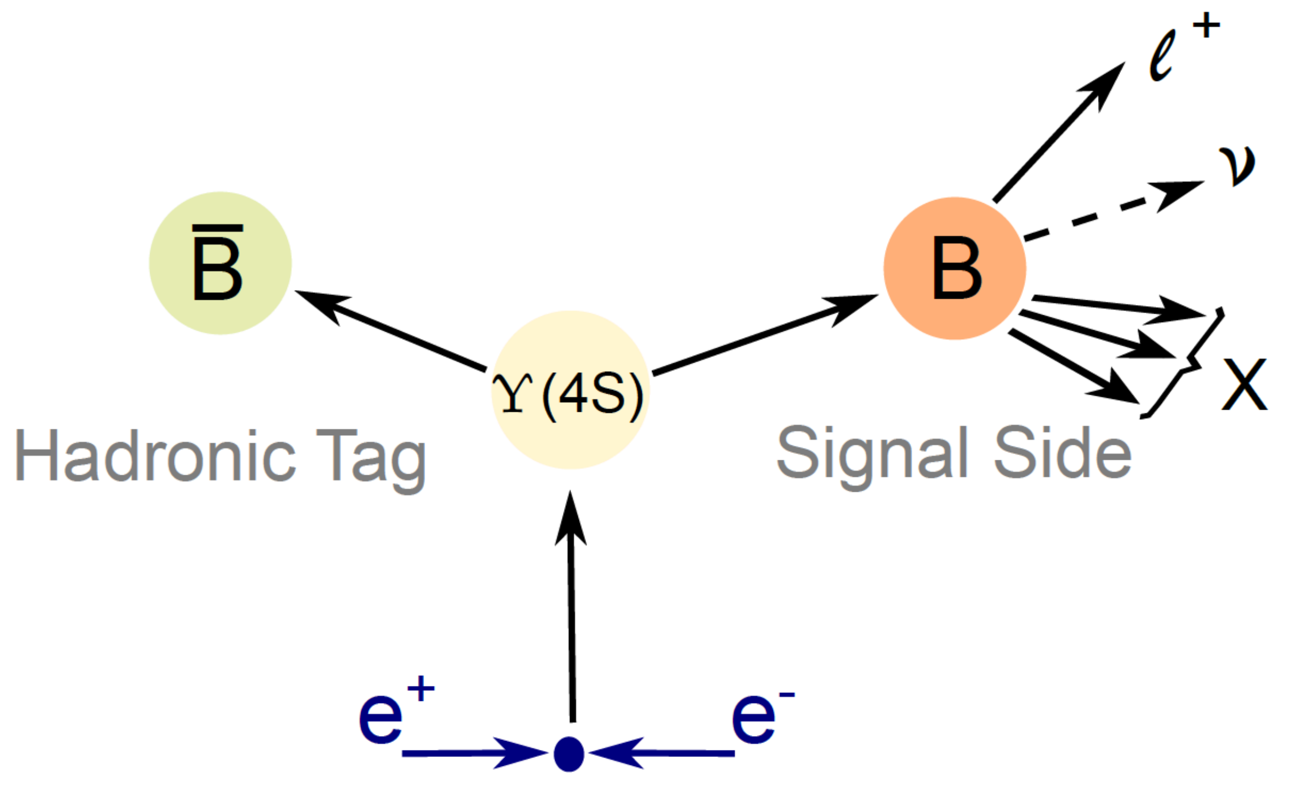
+ Shape Function / Fermi Motion (OPE)



$B \to X_u \ell \nu$ and Inclusive $|V_{ub}|$

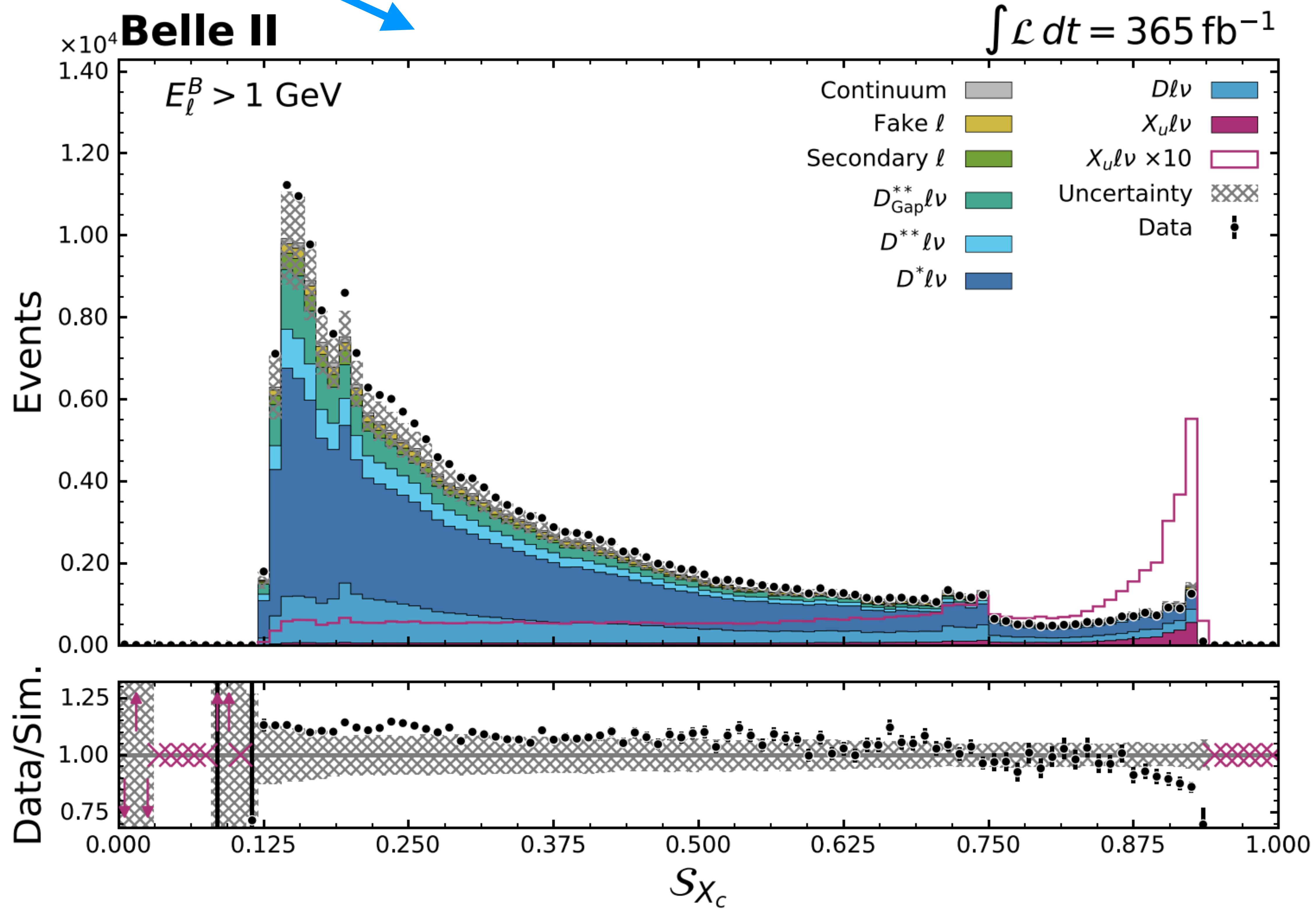
PRD 113, 032004 (2026)

- Run1 dataset: 365 fb^{-1}
- Use hadronic tag to fully reconstruct B_{tag}
- Two classifiers used to suppress continuum, $B \to X_c \ell \nu$



Can fully assign each final state particle to either the tag or signal side

Allows to reconstruct inclusive *X*



- Hadronic system *X*:

$$p_X = \sum_i \left(\sqrt{m_\pi^2 + |\mathbf{p_i}|^2}, \mathbf{p_i}\right) + \sum_i (E_i, \mathbf{k_i})$$

- Missing mass squared:

$$MM^2 = \left(P_{\Upsilon(4S)} - P_{\mathrm{tag}} - P_X - P_\ell\right)^2$$

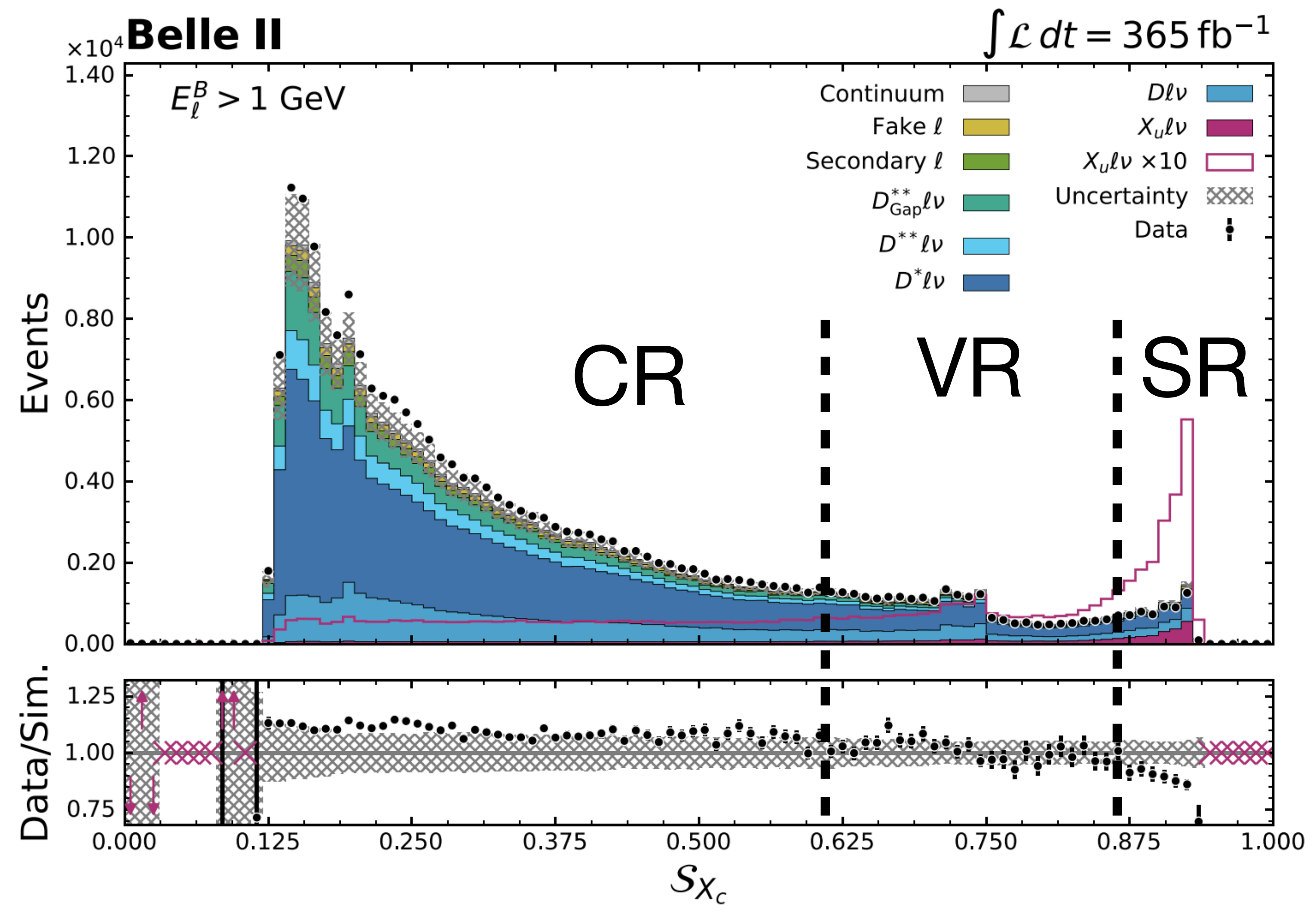
- Leptonic system:

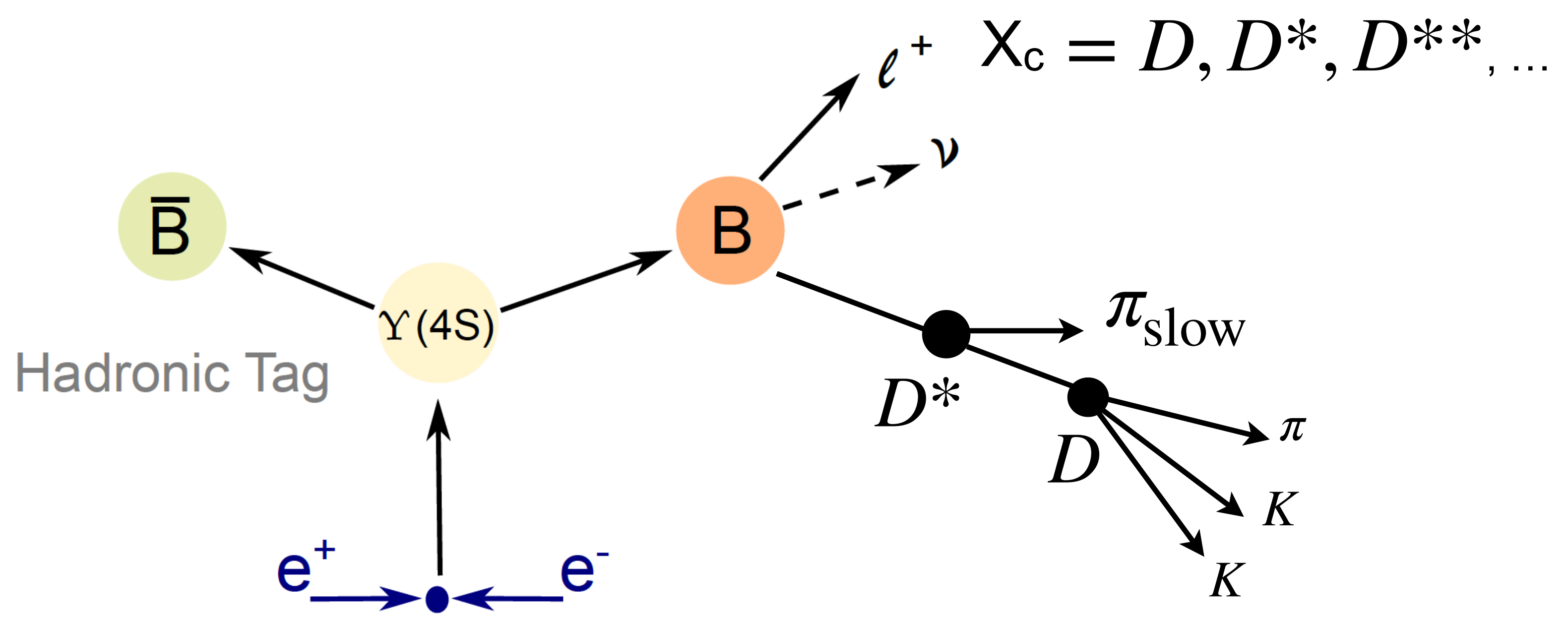
$$q^2 = (P_B - P_X)^2 = (P_l + P_\nu)^2$$

$B \to X_u \ell \nu$ and Inclusive |V$_{ub}$|

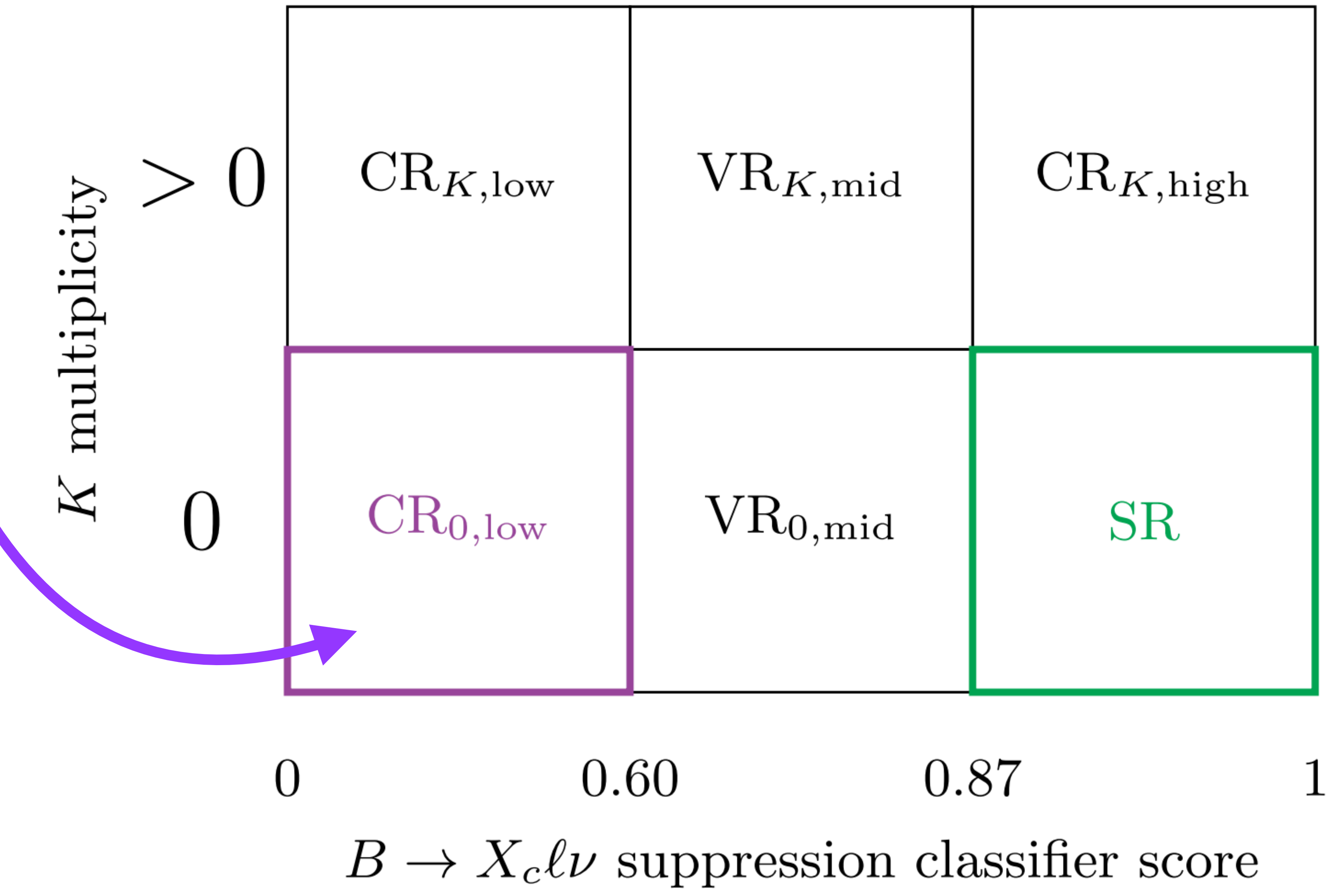
PRD 113, 032004 (2026)

- Based on $B \to X_c \ell \nu$ classifier, **Kaon veto** applied additionally to define validation/control regions
- MC normalisation of $B \to X_c \ell \nu$ in **SR** corrected via extrapolating CRs
- Simultaneous fit **CR** and **SR**, the high statistics of $B \to X_c \ell \nu$ in **CR** push the shape corrections to **SR**
- Systematics included as ~150 source-wise nuisances parameters and shared in **CR** & **SR**
- **VR** used as pseudo-SR for validating the method





Data-driven correction based on $B \to X_c \ell \nu$ enriched sideband

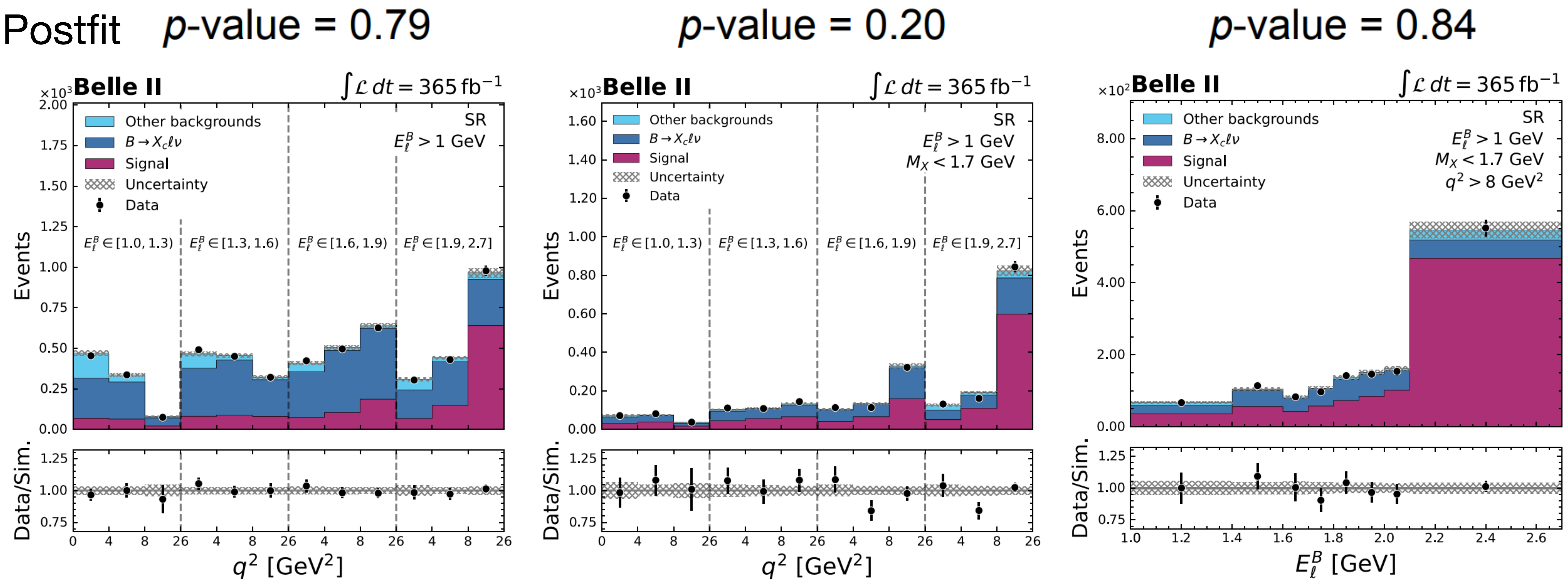


$B \to X_u \ell \nu$ and Inclusive $|V_{ub}|$

PRD 113, 032004 (2026)

- Measured $\Delta\mathscr{B}$ of 3 partial phase spaces
- Leading syst. uncertainties are from inclusive X_u modelling, fragmentation, $B \to X_c \ell \nu$ normalisation correction, fit bias correction

Postfit



$$\Delta\mathcal{B}(B \to X_u \ell \nu)_1 = (1.54 \pm 0.08 \pm 0.12) \times 10^{-3}$$

$$\Delta\mathcal{B}(B \to X_u \ell \nu)_2 = (0.95 \pm 0.05 \pm 0.10) \times 10^{-3}$$

$$\Delta\mathcal{B}(B \to X_u \ell \nu)_3 = (0.55 \pm 0.03 \pm 0.05) \times 10^{-3}$$

Consistent with previous measurements

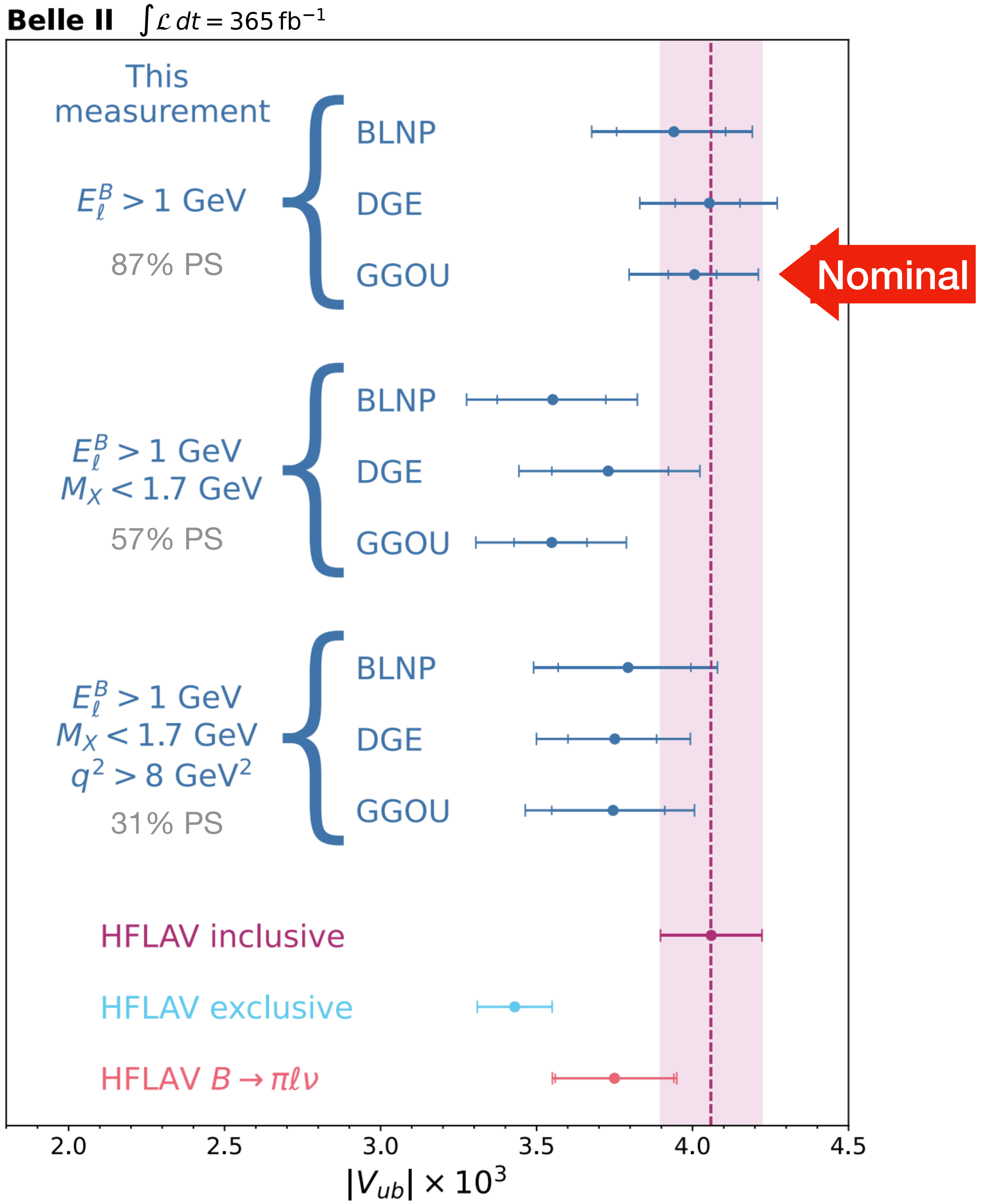
$B \to X_u \ell \nu$ and Inclusive |Vub|

PRD 113, 032004 (2026)

- With various theo. predictions on the decay rates, $\Delta\mathscr{B}$ converted to |Vub|

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell^+ \nu_\ell)}{\tau_B \cdot \Delta\Gamma(B \to X_u \ell^+ \nu_\ell)}}$$

- Nominal result agrees with inclusive WA and $|V_{ub}|_\pi$
- Achieved similar precision as the previous Belle measurement using 711fb^{-1} [PRD 104 , 012008 (2021)]
    - Higher tagging efficiency
    - Better D* reconstruction and discrimination

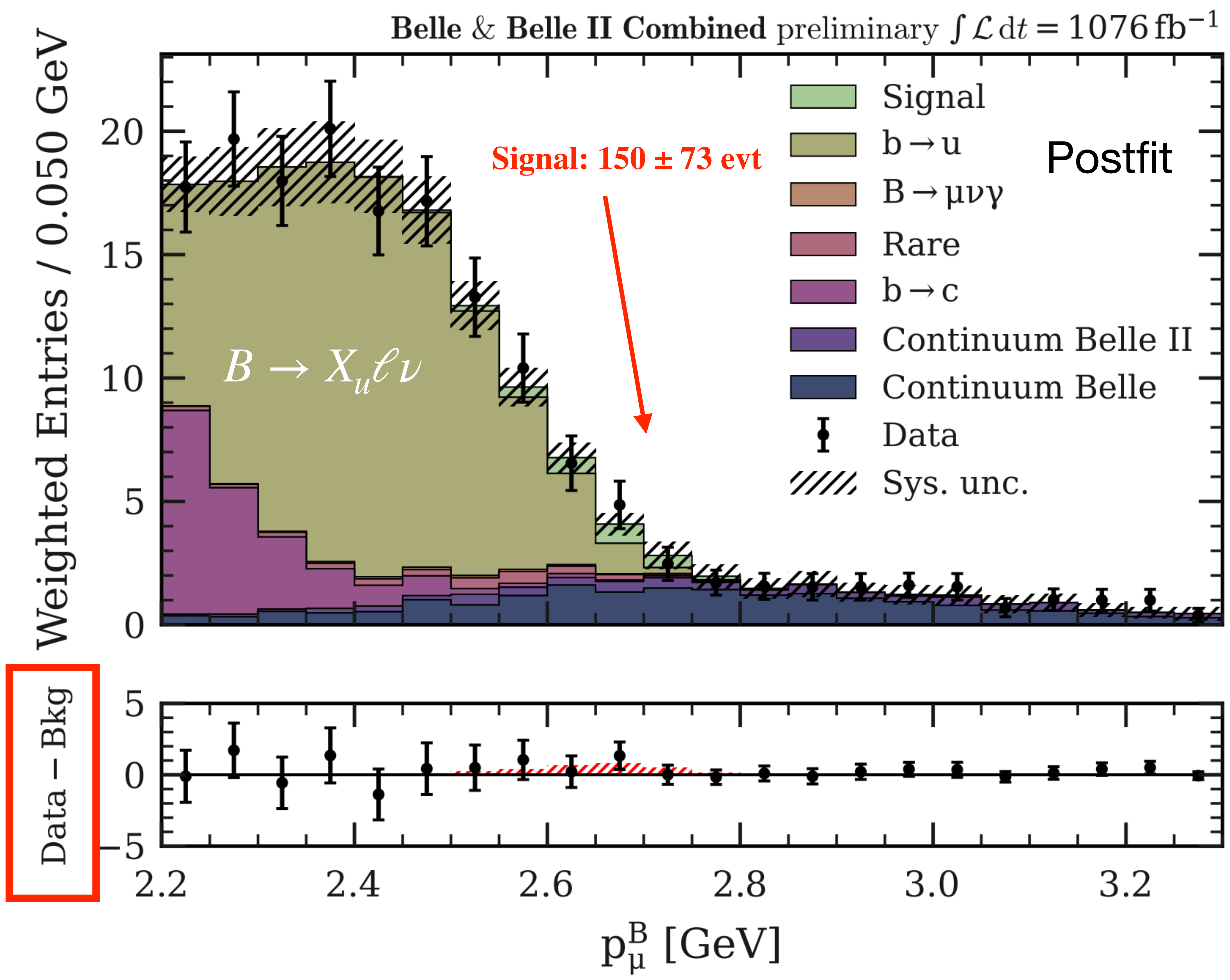


$B \to \mu\nu$ with Inclusive Tag at Belle+Belle II

arXiv:2602.09800

Accepted by PRD

- Combine **Belle II** 365fb^{-1}and **Belle** published result from 711fb^{-1} [PRD 101, 032007(2020)]
- **Inclusive tag**: tracks and clusters in the rest of event (ROE) used to reconstruct B$_{tag}$
- Signal extraction on p_μ^B after boosting muon to B$_{sig}$ rest frame



Observed significance relative to bkg-only hypothesis: 2.4σ

$$\mathcal{B}(B^+ \to \mu^+\nu_\mu) = (4.4 \pm 1.9 \pm 1.0) \times 10^{-7}$$

Upper limits (most stringent to date):

$$\mathcal{B}(B^+ \to \mu^+\nu_\mu) < 7.2 \times 10^{-7}$$ Bayesian

$$\mathcal{B}(B^+ \to \mu^+\nu_\mu) < 6.7 \times 10^{-7}$$ Frequentist

$$|V_{ub}| = \left(3.92\,^{+0.77}_{-0.96}\,(\text{stat.})\,^{+0.44}_{-0.49}\,(\text{sys.}) \pm 0.03\,(\text{theo.})\right) \times 10^{-3}$$

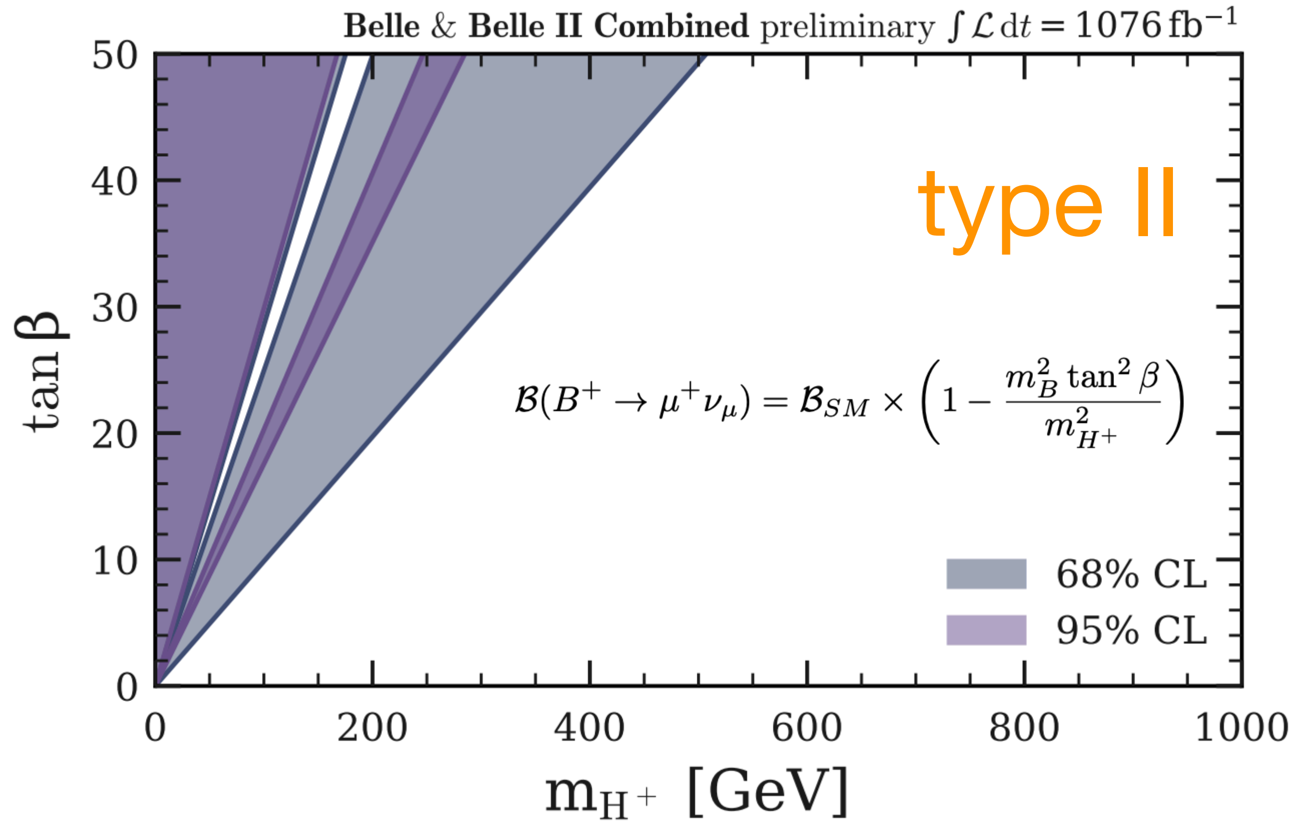
dominated by b->u modelling, cont. modelling

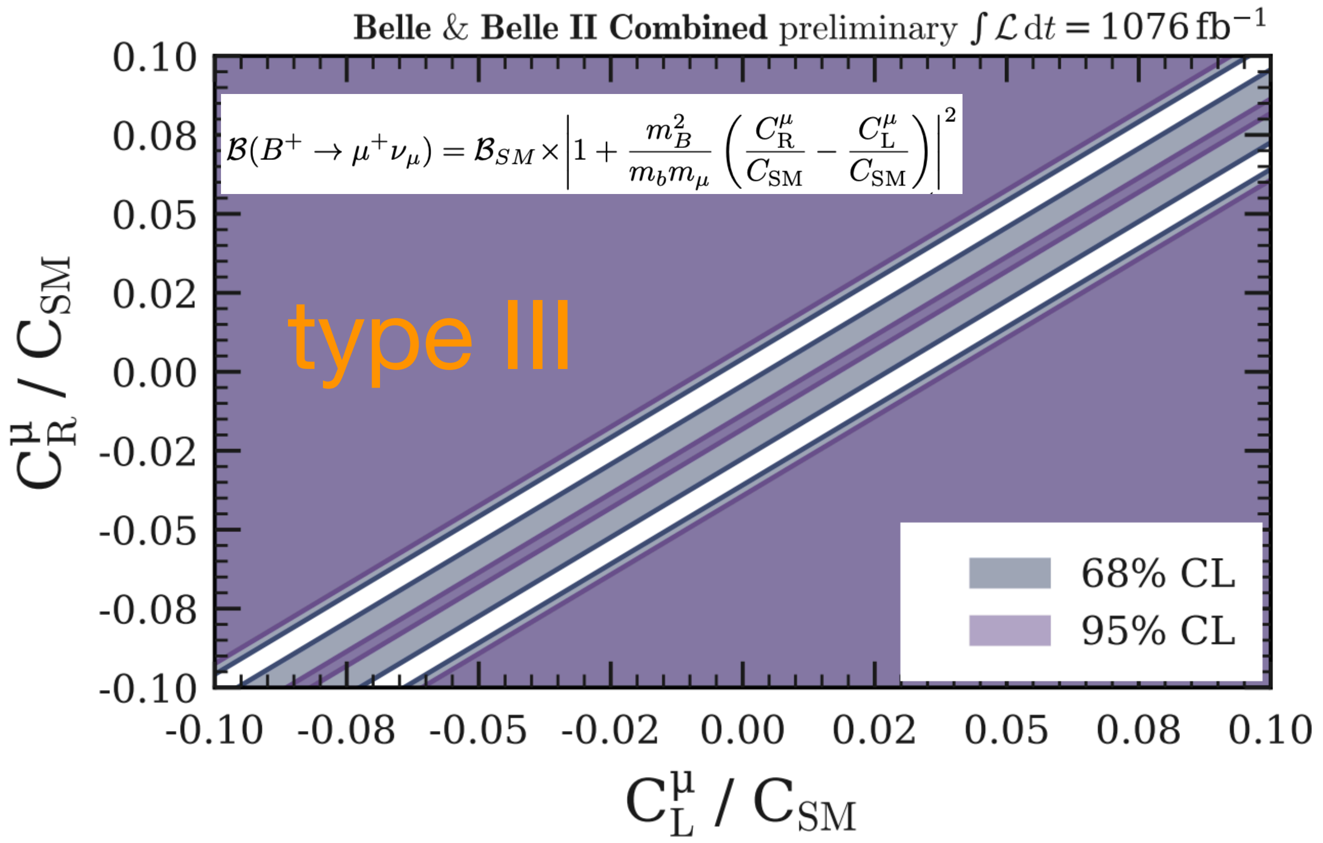
$B \to \mu\nu$ with Inclusive Tag at Belle+Belle II

arXiv:2602.09800
Accepted by PRD

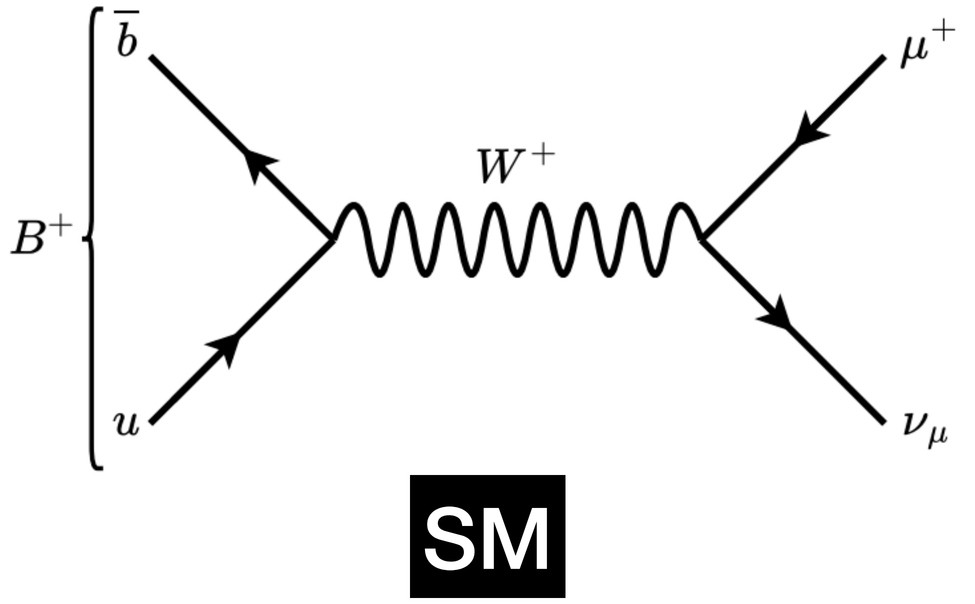
Further investigation:

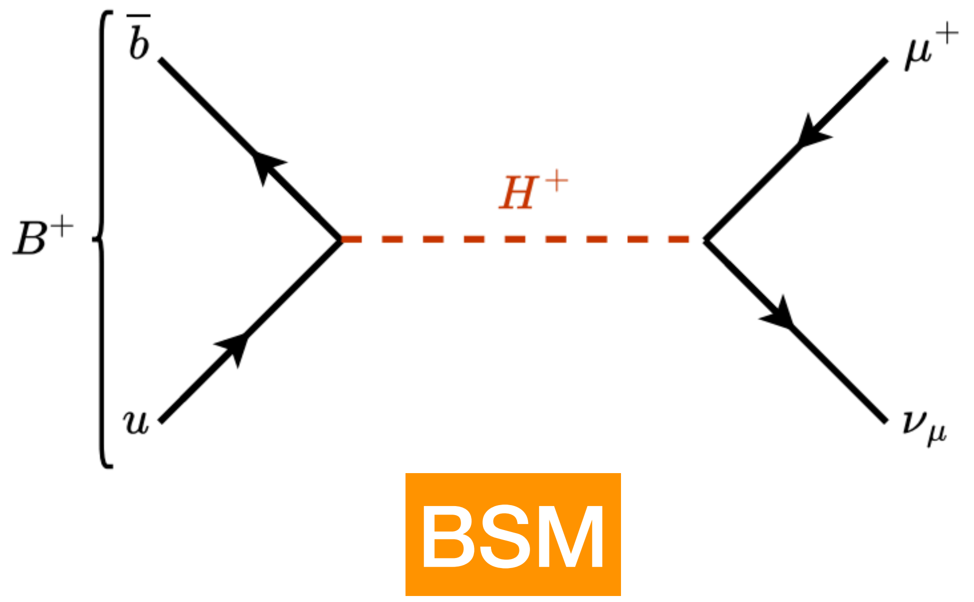
- Exclude parameter space for **type II & III 2HDM**
- Search for heavy neutrinos within m_N=0~1.5 GeV
- Extract $\Delta\mathscr{B}(B \to X_u\mu\nu)$ with $p_\mu^B > 2.2$ GeV
- Weak annihilation contribution in $\Delta\mathscr{B}(B \to X_u\mu\nu)$

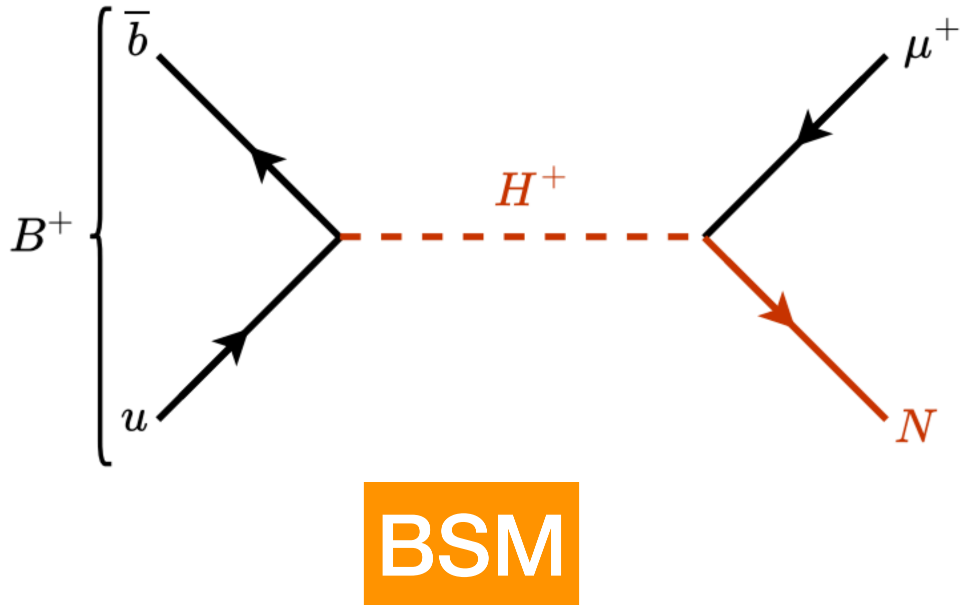


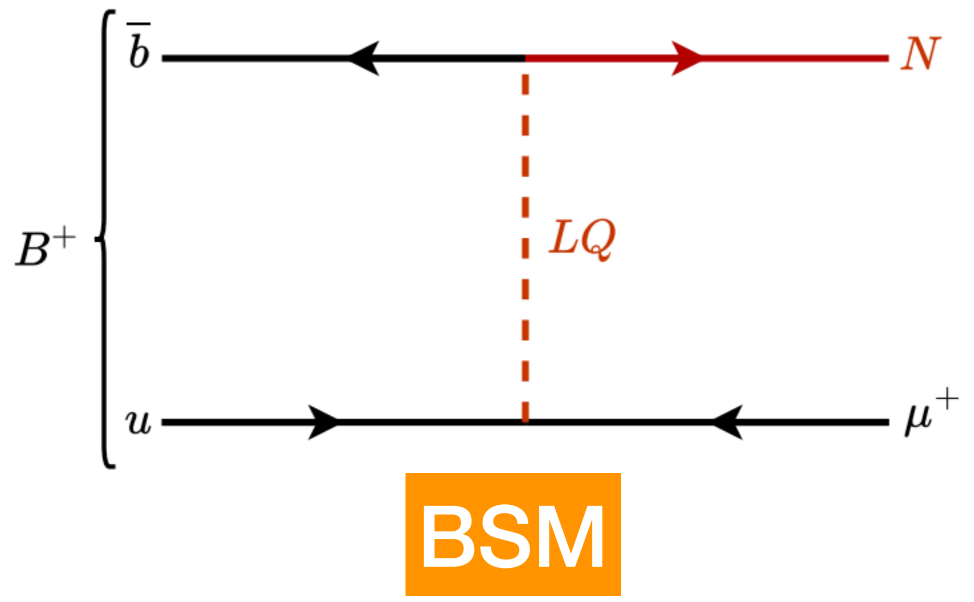


$$\mathcal{B}(B^+ \to \mu^+\nu_\mu) = \frac{G_F^2 m_B m_\mu^2}{8\pi}\left(1 - \frac{m_\mu^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_{B^+}$$







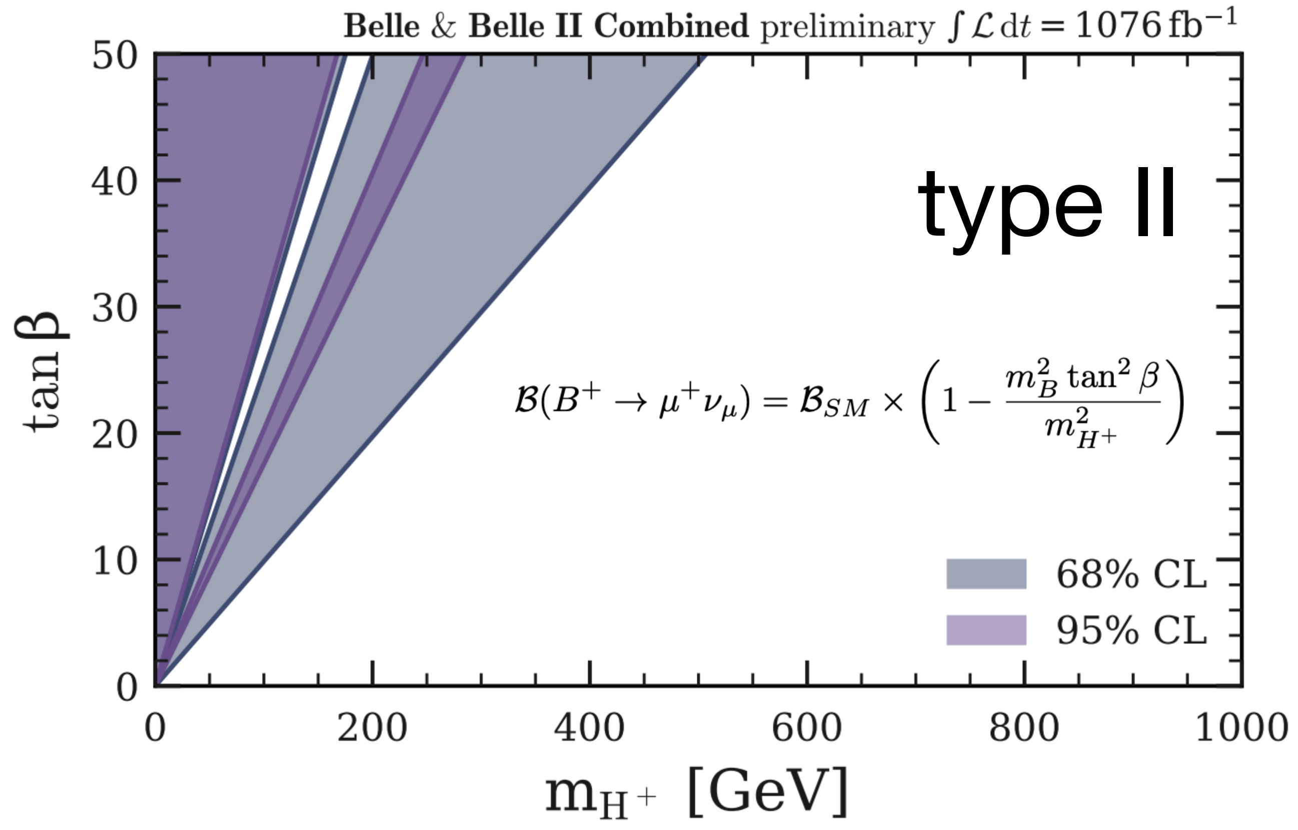


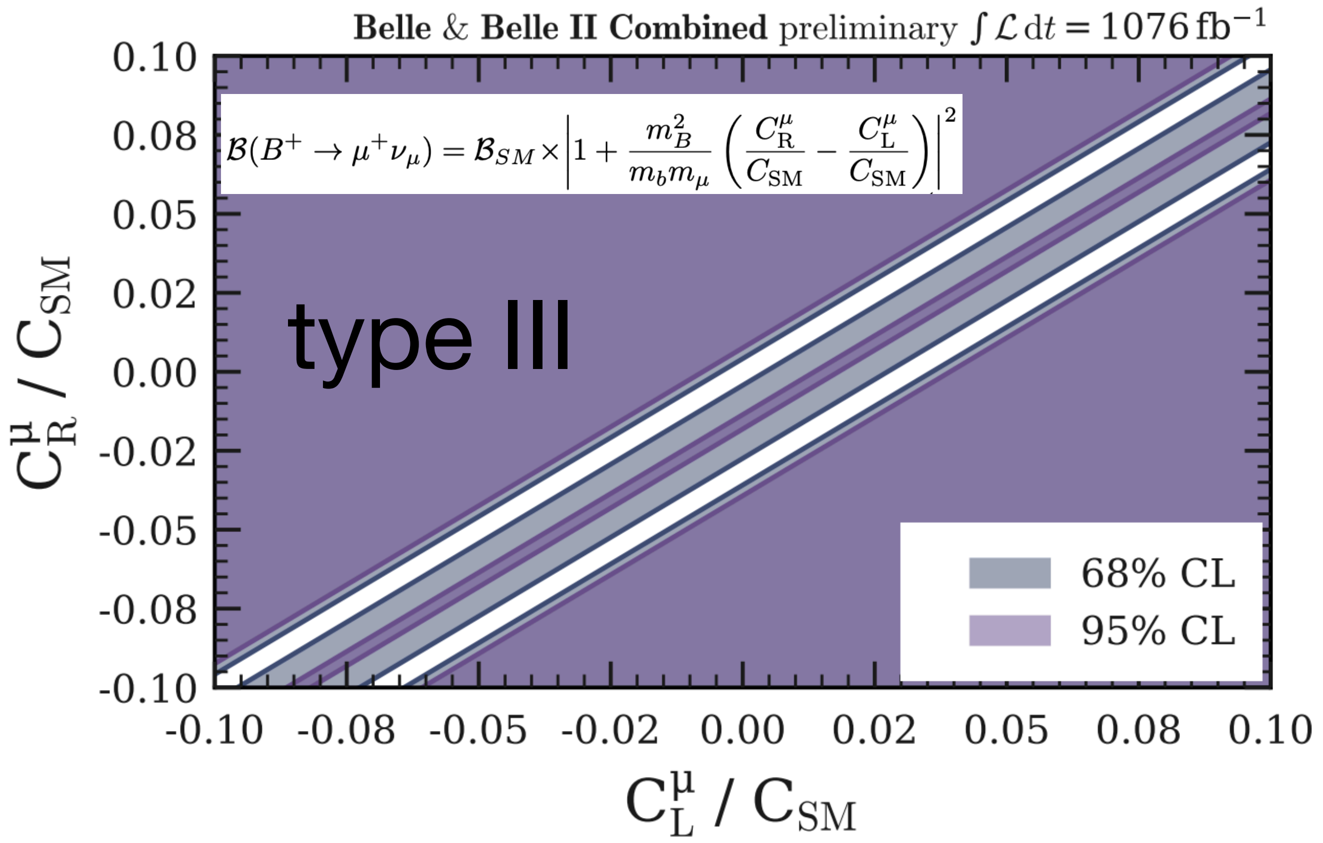
$B \to \mu\nu$ with Inclusive Tag at Belle+Belle II

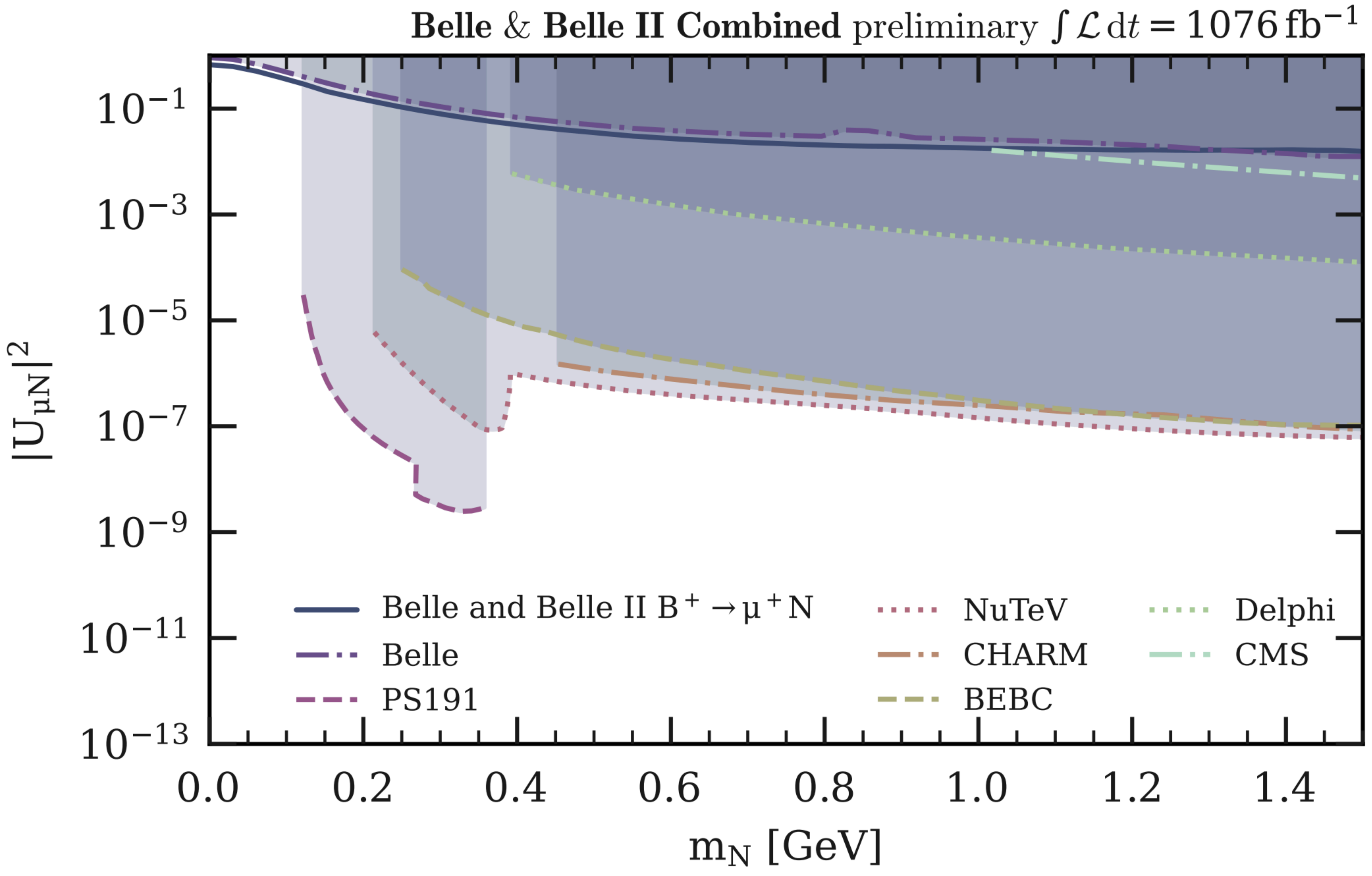
arXiv:2602.09800
Accepted by PRD

Further investigation:

- Exclude parameter space for type II & III 2HDM
- Search for **heavy neutrinos within m_N=0~1.5 GeV**
- Extract $\Delta\mathscr{B}(B \to X_u \mu\nu)$ with $p_\mu^B > 2.2$ GeV
- Weak annihilation contribution in $\Delta\mathscr{B}(B \to X_u \mu\nu)$







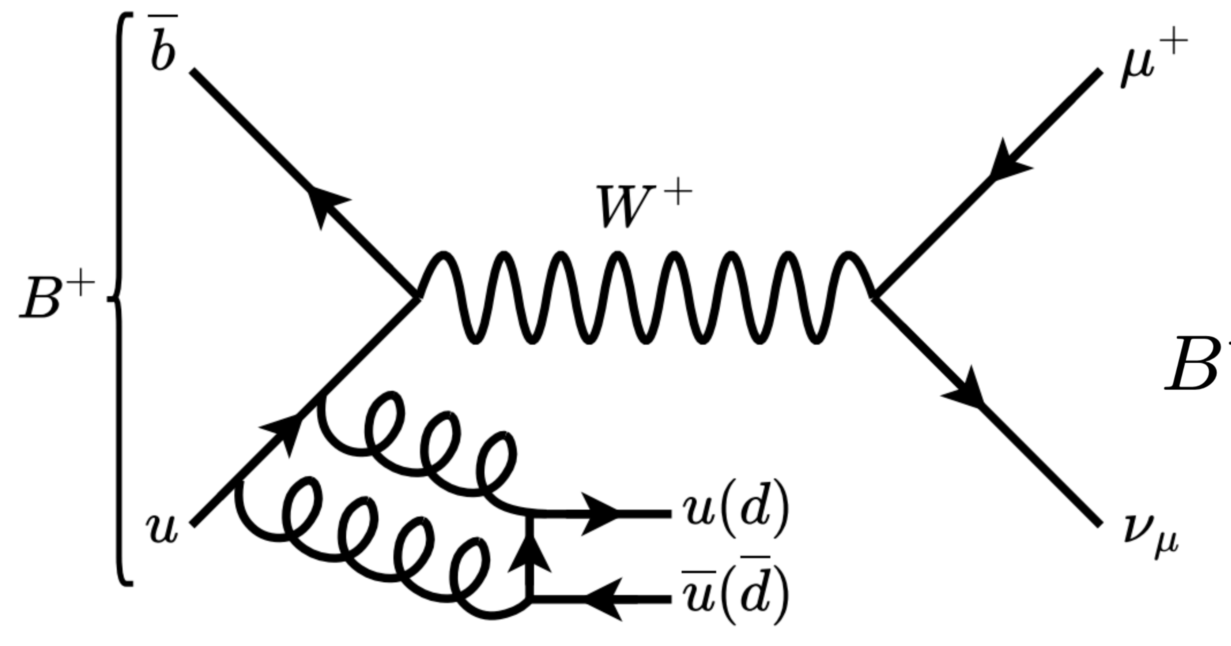
$B \to \mu\nu$ with Inclusive Tag at Belle+Belle II

arXiv:2602.09800

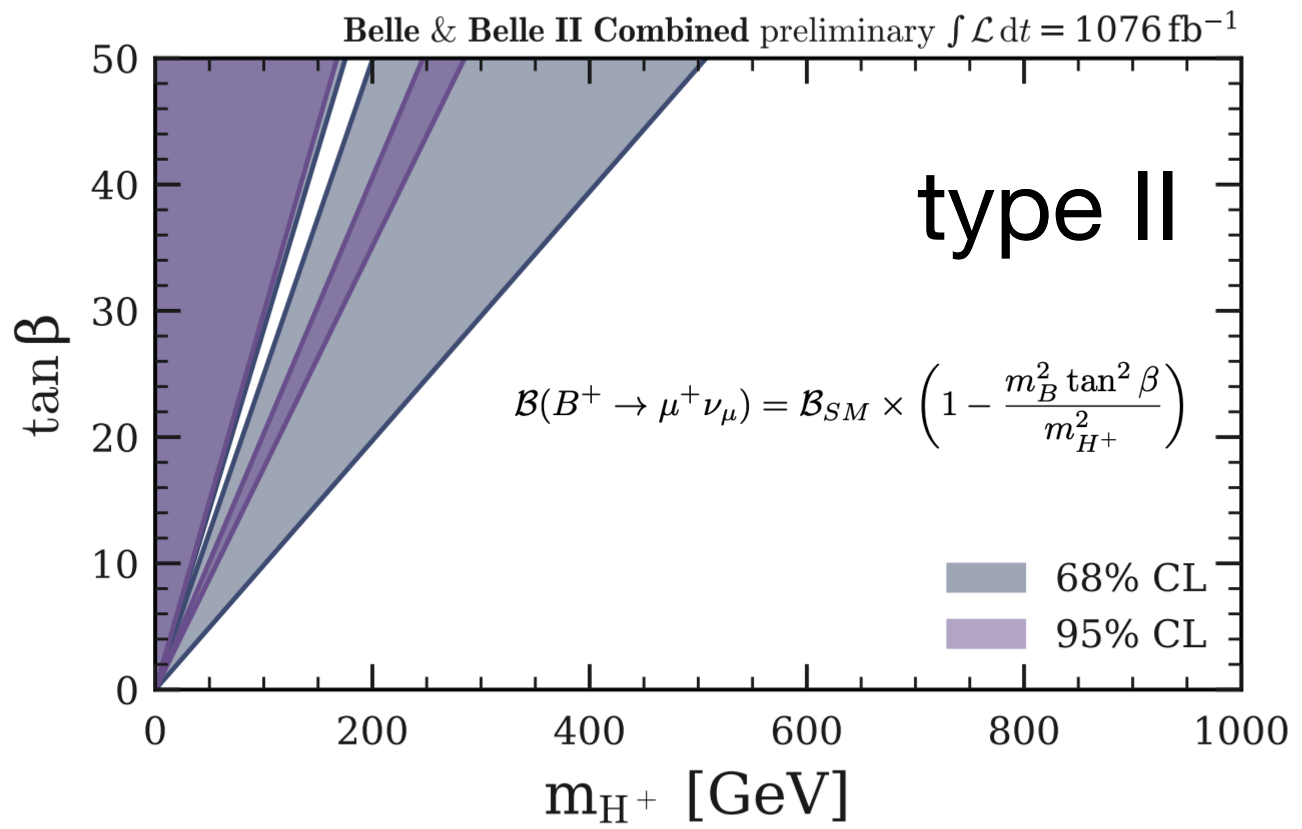
Accepted by PRD

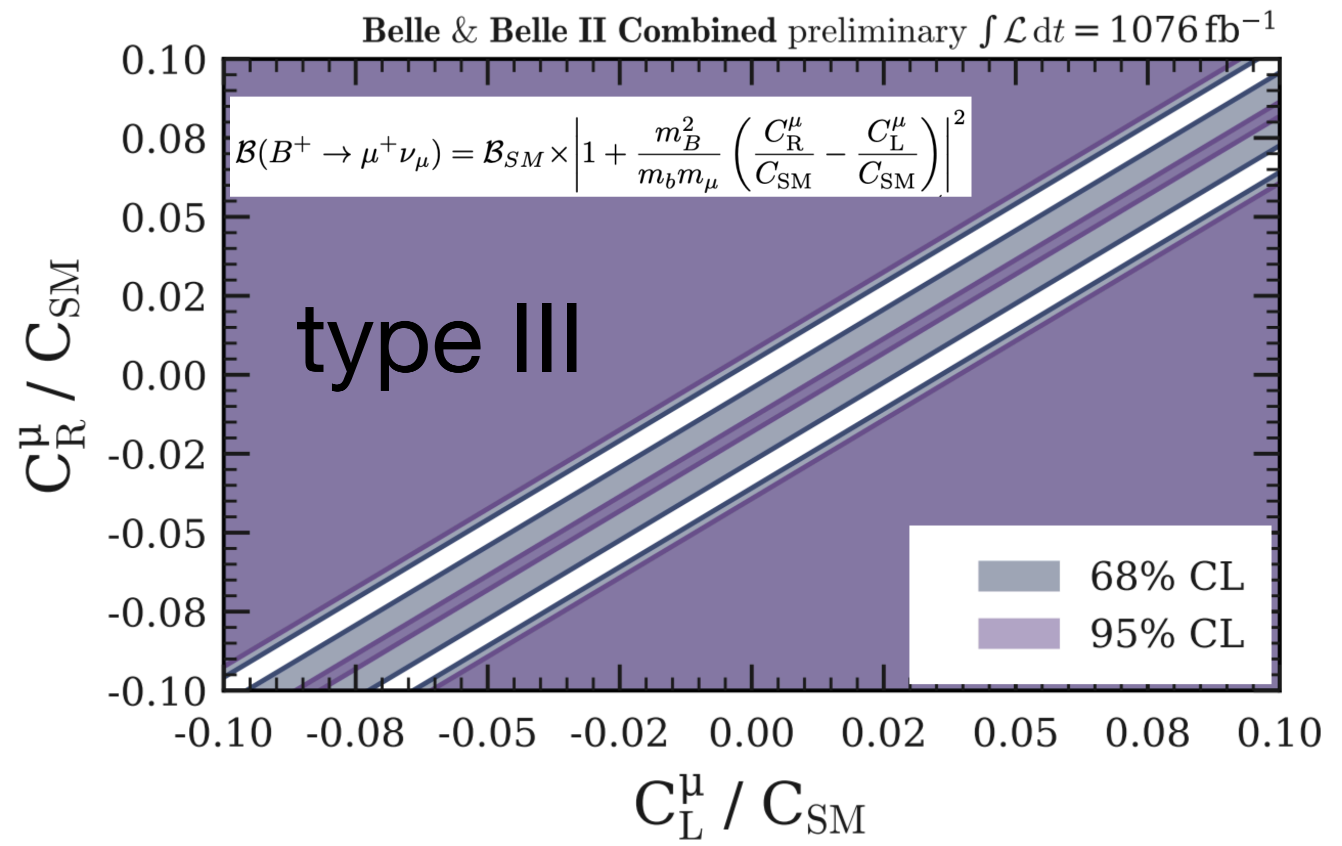
Further investigation:

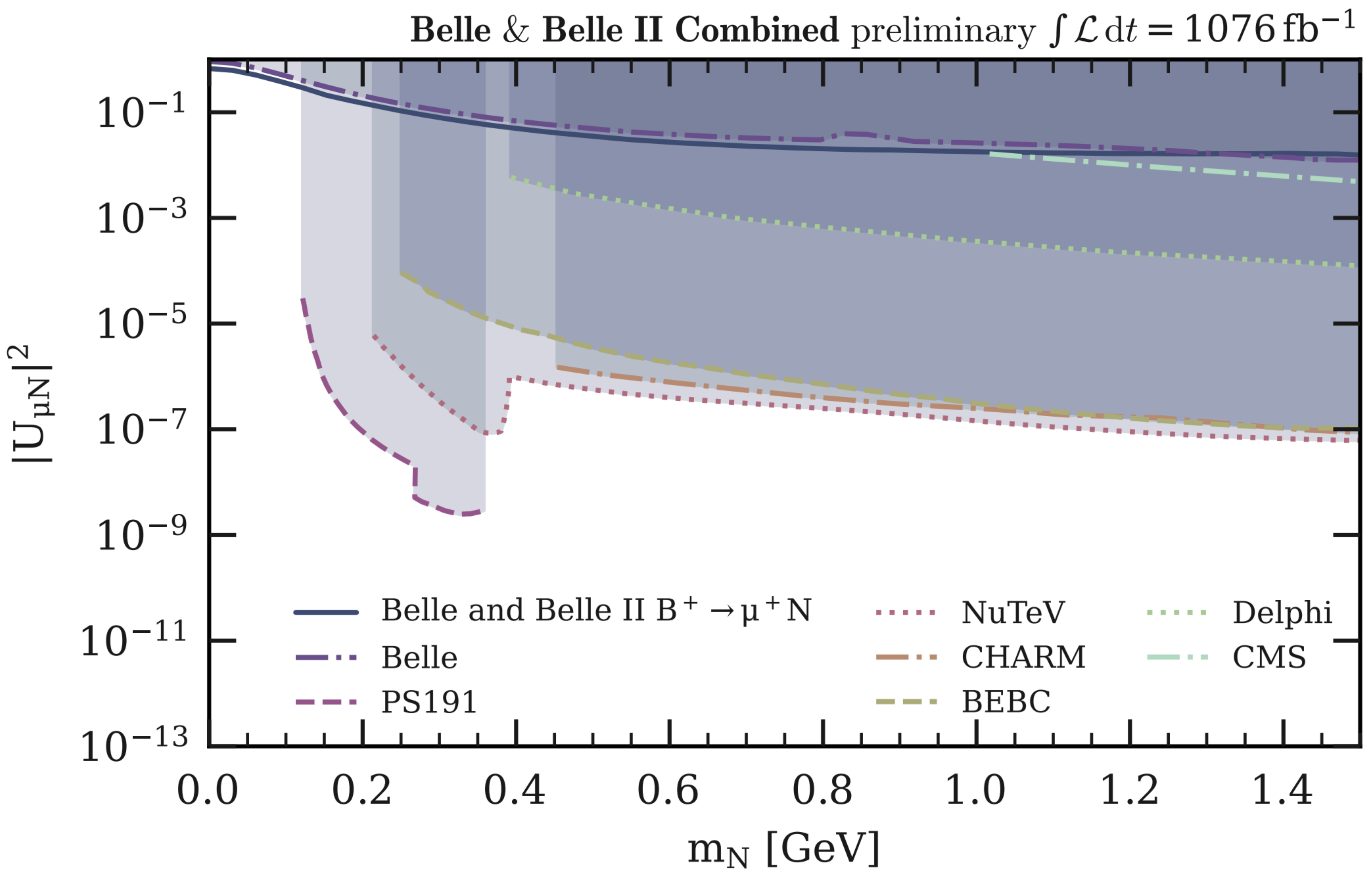
- Exclude parameter space for type II & III 2HDM
- Search for heavy neutrinos within m_N=0~1.5 GeV
- Extract $\Delta\mathscr{B}(B \to X_u \mu\nu)$ with $p_\mu^B > 2.2$ GeV **=> agrees with inclusive result**
- **Weak annihilation** contribution in $\Delta\mathscr{B}(B \to X_u \mu\nu)$

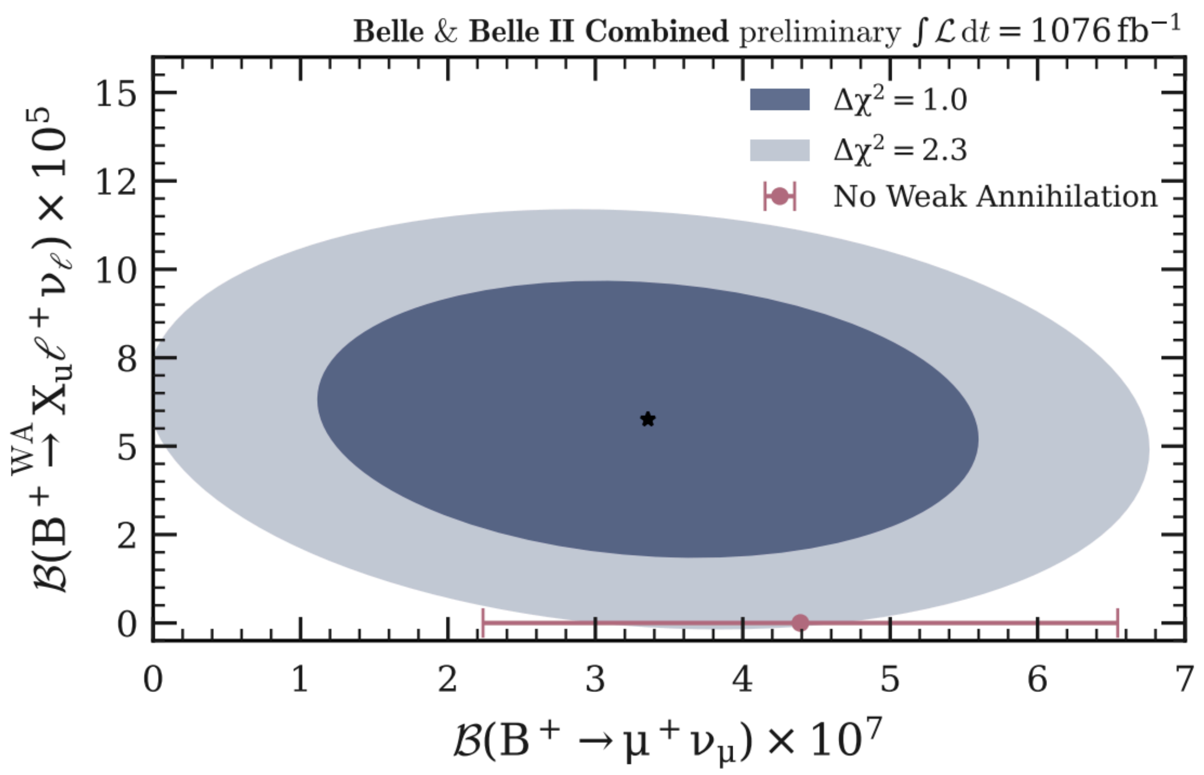


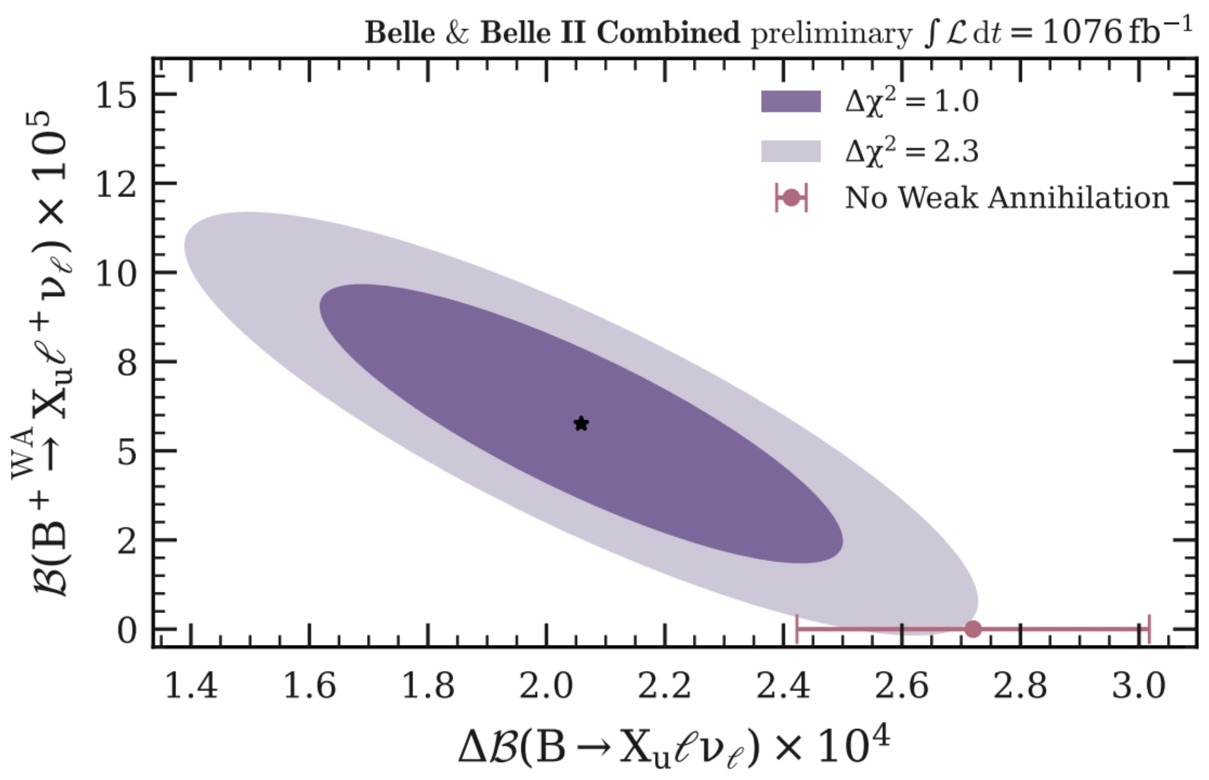
$B^+ \overset{\text{WA}}{\to} X_u \ell^+ \nu_\ell$











Summary & Outlook

- Belle II has been playing a crucial role in the B physics regime
- Many exciting new results are on the way using the existing largest ever B-factory dataset
- Cooperations are initiated on common issues (e.g. generators) with BESIII & LHCb

Upcoming:

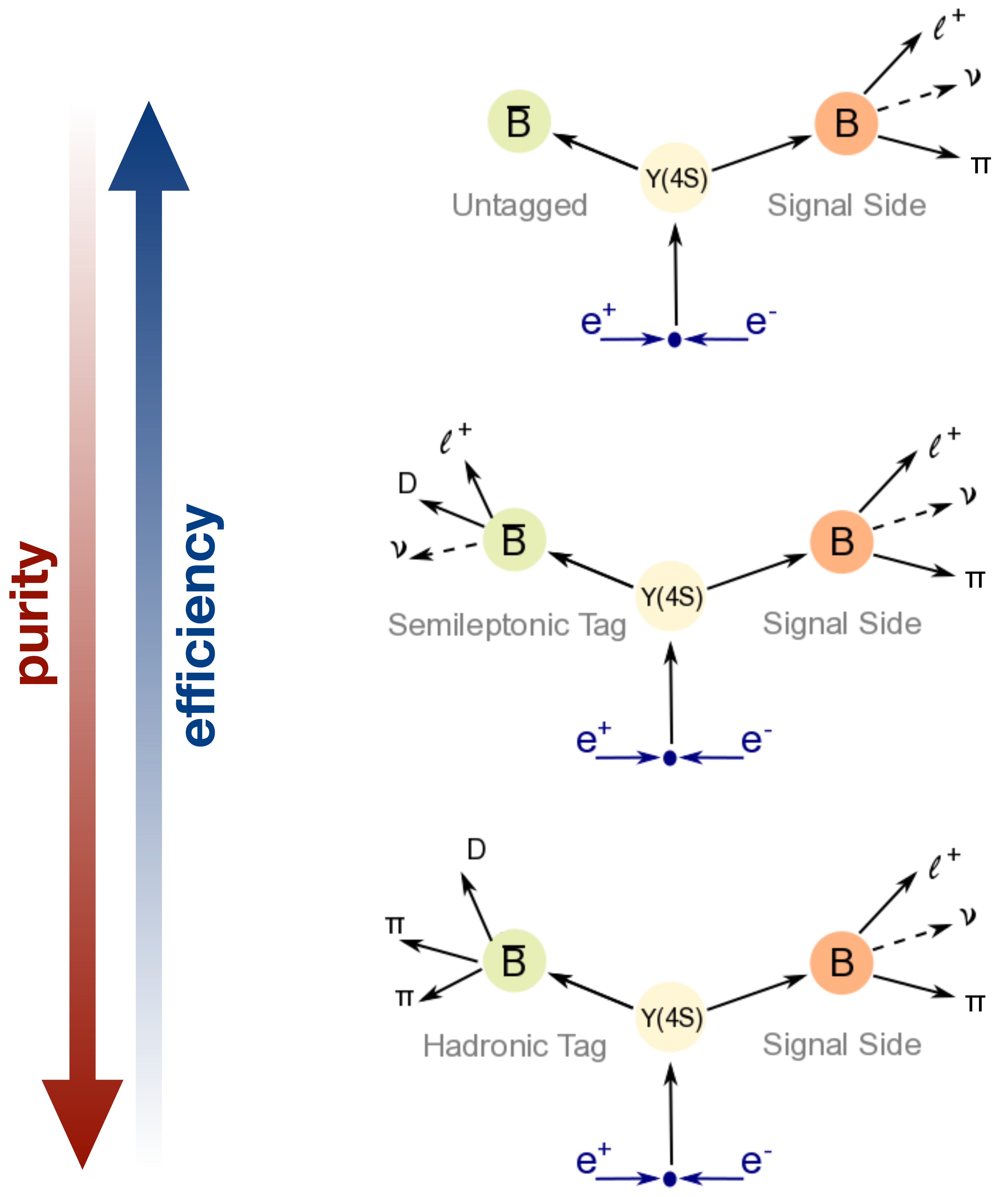
✳ Combined $B \to D\ell\nu$ and $B \to D^*\ell\nu$

✳ R(D*) & P_τ(D*) with 1-prong tau and had. tag

Recent highlights in B physics

- $B \to X_u \ell \nu$
- $B \to \mu\nu$
- R(D$^{(*)}$) SL-tag, Had.-tag
- $B \to \pi^0\pi^0$
- $B \to X_s \nu\bar{\nu}$

Backup: Tagging Techniques



- Untagged/Inclusive tag
  - Loose constraints on signal
  - Very large statistics, but also very large background
  - Efficiency $\epsilon \approx \mathcal{O}(100\%)$

- Semileptonic tag
  - Mid-range reconstruction efficiency
  - Due to multiple neutrinos, less information about B_{tag}

- Hadronic tag
  - Cleaner sample
  - Knowledge of $p(B_{sig})$
  - Low tag-side efficiency $\epsilon \approx \mathcal{O}(0.5\%)$

Backup: Mixing-Induced CP Violation in $B^0 \to \pi^0\pi^0$

Methodology: PRD 112, 032011(2025)

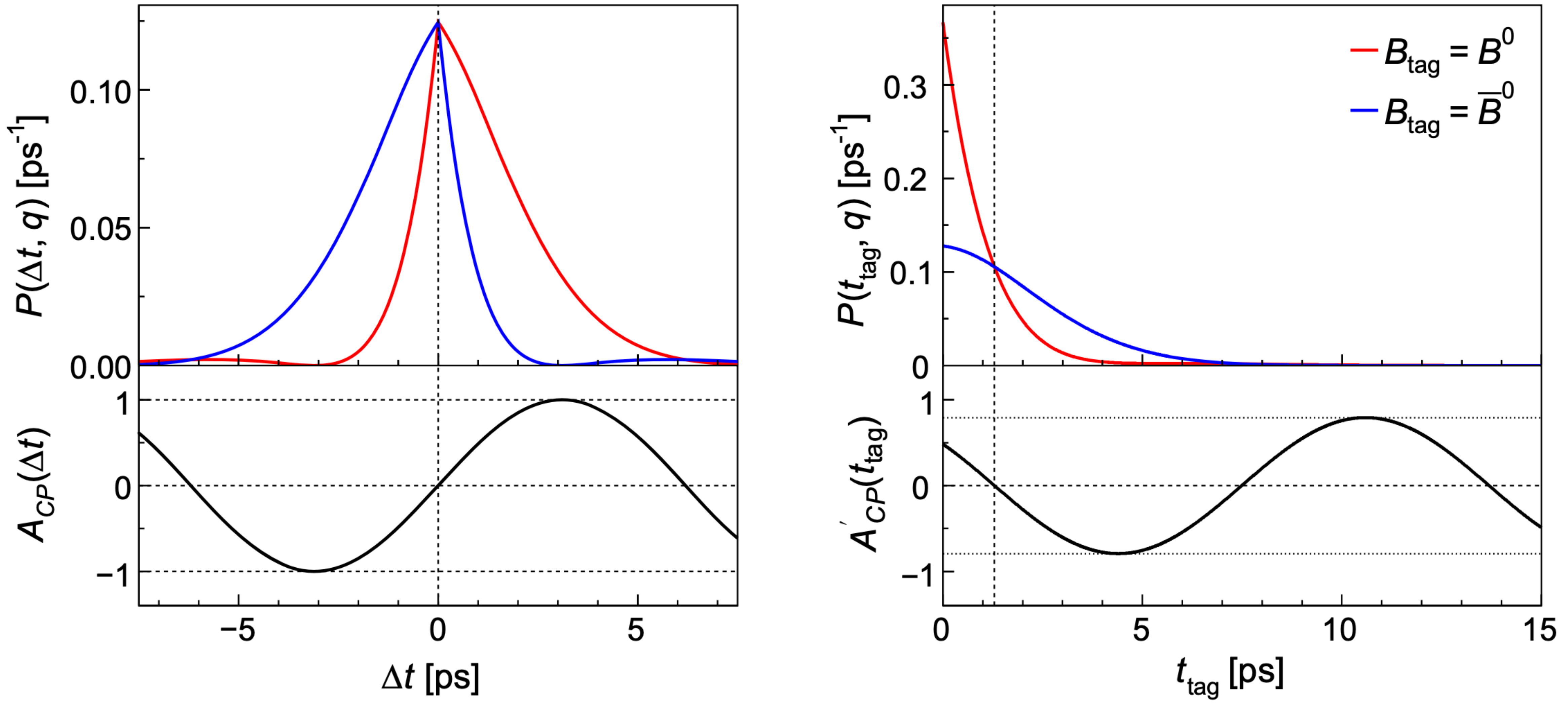


FIG. 1. Top panels: theoretical decay rates as a function of (left) Δt and (right) t_{tag}, for tagged (blue) B^0 and (red) $\bar{B}^0$ mesons assuming $S = 1.0$ and $C = 0.0$. Bottom panels: corresponding CP-violating decay-rate asymmetries (left) $\mathcal{A}_{CP}(\Delta t)$ and (right) $\mathcal{A}'_{CP}(t_{tag})$. The horizontal dashed lines show the maximum oscillation amplitudes. The vertical dashed line shows (left) the Δt origin and (right) the $\hat{t}$ value in Eq. (6). The decay time t_{tag} is non-negative by definition.

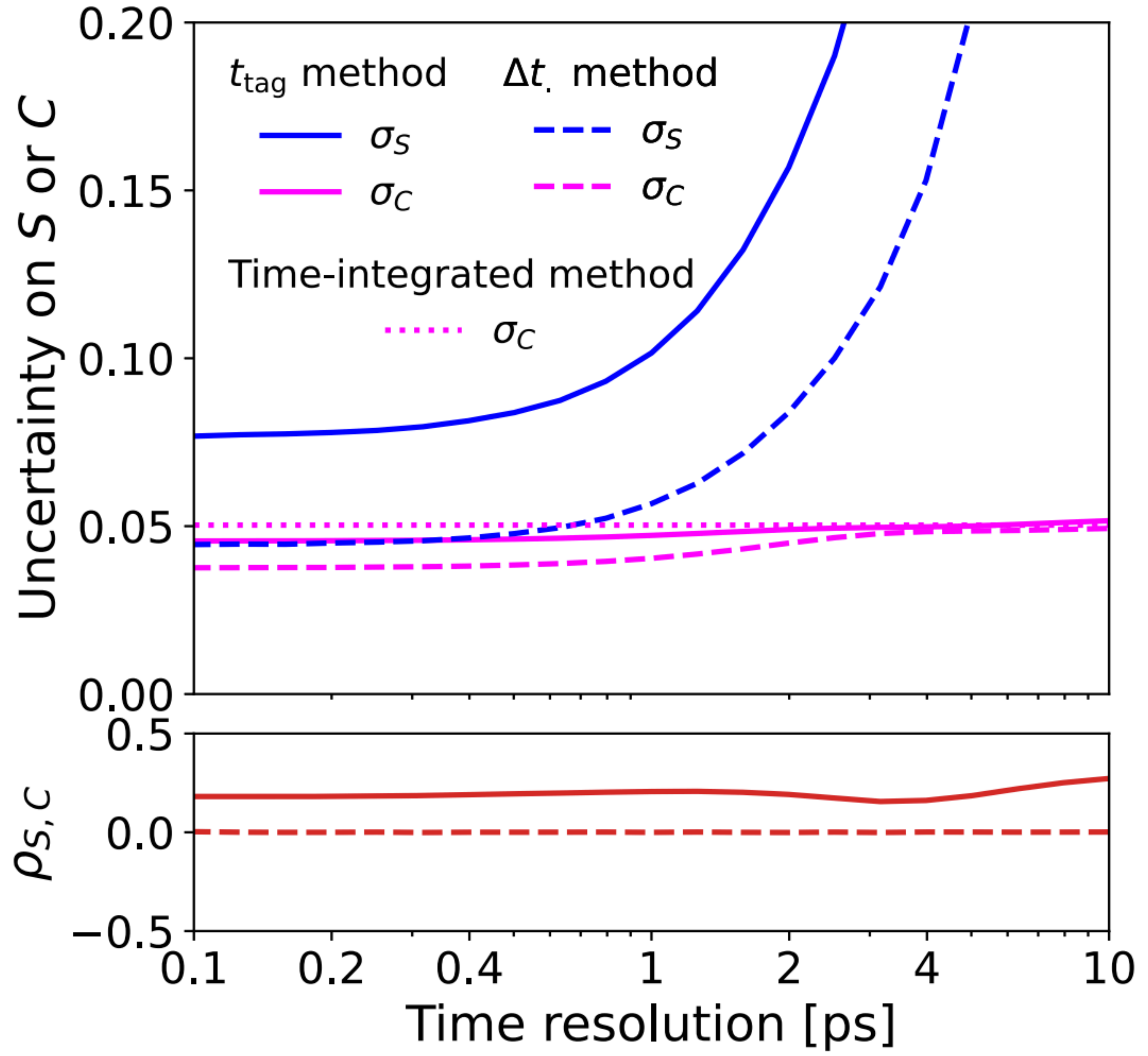


FIG. 2. Top panel: uncertainties on the CP-violating coefficients (blue) S and (magenta) C as functions of the resolution on (solid line) t_{tag} or (dashed line) Δt, for 10^3 perfectly tagged signal-only decays. Bottom panel: linear correlation between the coefficients.

Backup: First Search for $B \to X_s \nu\bar{\nu}$

arXiv:2511.10980

Accepted by PRL

TABLE I: Summary of the dominant systematic uncertainties and the total contribution from subdominant uncertainties on $\mathcal{B}(B \to X_s\nu\bar{\nu})$ in the entire M_{X_s} range. The impact on the branching fraction uncertainty $\sigma_{\mathcal{B}}$ from each source is estimated by fixing the corresponding nuisance parameter in the minimization procedure and subtracting its uncertainty in quadrature from the total uncertainty. Due to correlations among sources, the quadrature sum of individual uncertainties does not equal the total uncertainty.

Source	Impact on $\sigma_{\mathcal{B}}$ $[10^{-5}]$
Simulated-sample size	6.0
Background normalization	5.7
Branching fractions of major B-decays	2.3
Non-resonant $X_s\nu\bar{\nu}$ generation range	2.1
$\mathcal{O}_{\rm BDT}$ selection efficiency	2.0
Photon multiplicity correction	1.8
$q\bar{q}$ background efficiency	1.8
Other subdominant contributions	3.0
Total systematic sources	11.7

TABLE I: Summary of systematic uncertainties on the $\mathcal{B}(B \to X_s\nu\bar{\nu})$ in each M_{X_s} range. The impact on the branching fraction uncertainty $\sigma_{\mathcal{B}}$ from each source is estimated by fixing the corresponding nuisance parameter in the minimization procedure and subtracting its uncertainty in quadrature from the total uncertainty. Due to correlations among sources, the quadrature sum of individual systematic uncertainties does not equal the total systematic uncertainty. $M_{X_s}^{\rm max}$ is the mass of the B meson.

		Impact on $\sigma_{\mathcal{B}}$ $[10^{-5}]$			
Source	Uncertainty size	Full range	$[0, 0.6]$ GeV/c^2	$[0.6, 1.0]$ GeV/c^2	$[1.0, M_{X_s}^{\rm max}]$ GeV/c^2
Simulated-sample size	$O(1\%)$	6.0	0.4	1.5	6.3
Background normalization	20%	5.7	0.6	2.0	6.6
Branching fraction of major B-decay	$O(1\text{-}100\%)$	2.3	0.1	0.6	2.0
Non-resonant $X_s\nu\bar{\nu}$ generation point	9.1%	2.1	0.0	0.0	2.2
$\mathcal{O}_{\rm BDT}$ selection efficiency	$O(1\text{-}10\%)$	2.0	0.0	0.4	2.3
Photon multiplicity correction	$O(1\%)$	1.8	0.0	0.3	1.6
$q\bar{q}$ background efficiency	$O(10\%)$	1.8	0.1	0.2	1.8
Fitting bias	$O(5\%)$	1.5	0.2	0.2	1.5
Tagging efficiency	$O(1\text{-}30\%)$	1.1	0.1	0.3	0.8
Tagging efficiency from $B \to K^{(*)}J/\psi$ decay	$O(20\text{-}100\%)$	1.0	0.1	0.4	1.0
$\mathcal{O}_{\rm BDT}$ distribution shape for $q\bar{q}$ background	100% of weight	1.0	0.1	0.2	0.7
Branching fraction for $B \to X_s K_L^0 K_L^0$	100%	0.9	0.0	0.3	0.6
The number of $B\bar{B}$ pair	1.45%	0.7	0.0	0.1	0.6
Fermi motion momentum	$O(8\%)$	0.7	0.0	0.0	0.7
Fragmentation	$O(1\text{-}100\%)$	0.6	0.0	0.1	0.7
$B \to K^*$ form factor	$O(10\%)$	0.6	0.0	0.5	0.6
Branching fraction for $B \to X_s n\bar{n}$	100%	0.4	0.1	0.4	0.0
Fraction of $K\nu\bar{\nu}$, $K^*\nu\bar{\nu}$ decays	$O(5\%)$	0.4	0.1	0.3	0.4
b-quark mass parameter	3.2%	0.3	0.0	0.0	0.3
Branching fraction for $D \to XK_L^0$ from B meson	7.7%	0.3	0.0	0.1	0.2
Charged pion identification	$O(1\%)$	0.2	0.0	0.1	0.2
$B \to K$ form factor	$O(1\%)$	0.2	0.1	0.0	0.2
Tracking efficiency	0.27%	0.2	0.0	0.0	0.1
π^0 reconstruction efficiency	$O(1\%)$	0.1	0.0	0.0	0.1
Charged kaon identification	$O(1\%)$	0.1	0.0	0.0	0.1
K_S^0 reconstruction efficiency	$O(5\%)$	0.1	0.0	0.0	0.1
K_L^0 efficiency in the ECL	17%	0.1	0.0	0.0	0.1
Total systematic sources		11.7	0.8	2.8	11.9
Statistical uncertainty		8.3	0.8	2.6	9.0

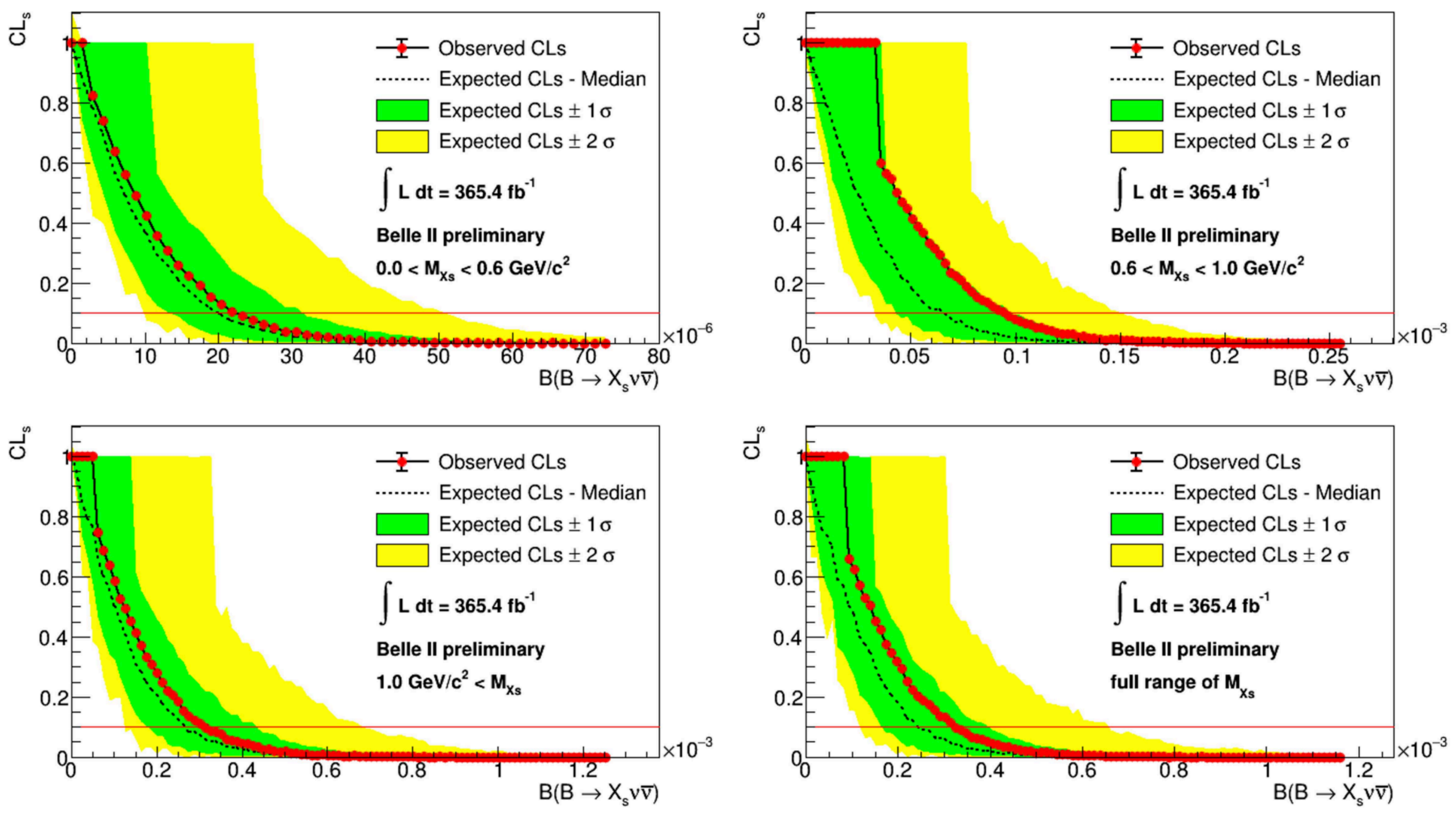


FIG. 1: CLs values as a function of the assumed branching fraction for $B \to Xs\nu\bar{\nu}$ in each M_{X_s} region. The red line indicates the 90% confidence level upper limits.

Backup: R(D(*)) with Semileptonic Tag

PRD 112, 032010 (2025)

TABLE I. Systematic uncertainties on $\mathcal{R}(D^+)$ and $\mathcal{R}(D^{*+})$ ranked by the magnitude of the uncertainty on $\mathcal{R}(D^+)$. The percentage values in brackets indicate the relative uncertainty.

Systematic uncertainty	$\Delta\mathcal{R}(D^+)$	$\Delta\mathcal{R}(D^{*+})$
Additive		
MC sample size	0.033 (7.9%)	+0.011(3.4%) −0.012(3.9%)
Gap $\mathcal{B}$	+0.014(3.4%) −0.038(9.1%)	0.001 (0.1%)
LID efficiency (μ)	+0.025(6.1%) −0.016(3.9%)	0.001 (0.1%)
Fake rates (e)	+0.016(3.7%) −0.008(2.0%)	0.002 (0.7%)
$\pi^\pm$ from $D^* \to D\pi$	0.003 (0.7%)	0.001 (0.1%)
Continuum fraction	+0.003(0.7%) −0.002(0.4%)	0.001 (0.2%)
Gap FFs	+0.003(0.6%) −0.001(0.3%)	0.001 (0.1%)
$\mathcal{B}(\bar{B} \to D^{**}\ell\bar{\nu}_\ell)$	0.002 (0.5%)	0.001 (0.1%)
$\bar{B} \to D^{**}\ell\bar{\nu}_\ell$ FFs	0.001 (0.3%)	0.001 (0.2%)
BDT modeling	0.001 (0.3%)	0.001 (0.2%)
$\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell/\tau\bar{\nu}_\tau$ FFs	0.001 (0.1%)	0.001 (0.3%)
LID efficiency (e)	0.001 (0.1%)	0.001 (0.3%)
Fake rates (μ)	0.001 (0.1%)	0.001 (0.1%)
Total additive uncertainty	+0.047(11.3%) −0.054(12.9%)	+0.011(3.6%) −0.012(4.0%)
Multiplicative		
$\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell/\tau\bar{\nu}_\tau$ FFs	0.009 (2.1%)	0.011 (3.5%)
MC sample size	0.007 (1.7%)	0.004 (1.2%)
LID efficiency (e)	0.001 (0.2%)	0.001 (0.2%)
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.001 (0.2%)	0.001 (0.2%)
LID efficiency (μ)	0.001 (0.1%)	0.001 (0.1%)
Tracking efficiency	0.001 (0.1%)	0.001 (0.1%)
$\pi^\pm$ from $D^* \to D\pi$	⋯	0.001 (0.2%)
Total multiplicative uncertainty	0.012 (2.8%)	0.011 (3.7%)
Total systematic uncertainty	+0.049(11.6%) −0.056(13.4%)	+0.016(5.2%) −0.018(5.8%)
Total statistical uncertainty	+0.075(17.9%) −0.073(17.5%)	+0.035(11.4%) −0.033(10.8%)
Total uncertainty	+0.089(21.4%) −0.092(22.0%)	+0.038(12.6%) −0.037(12.2%)

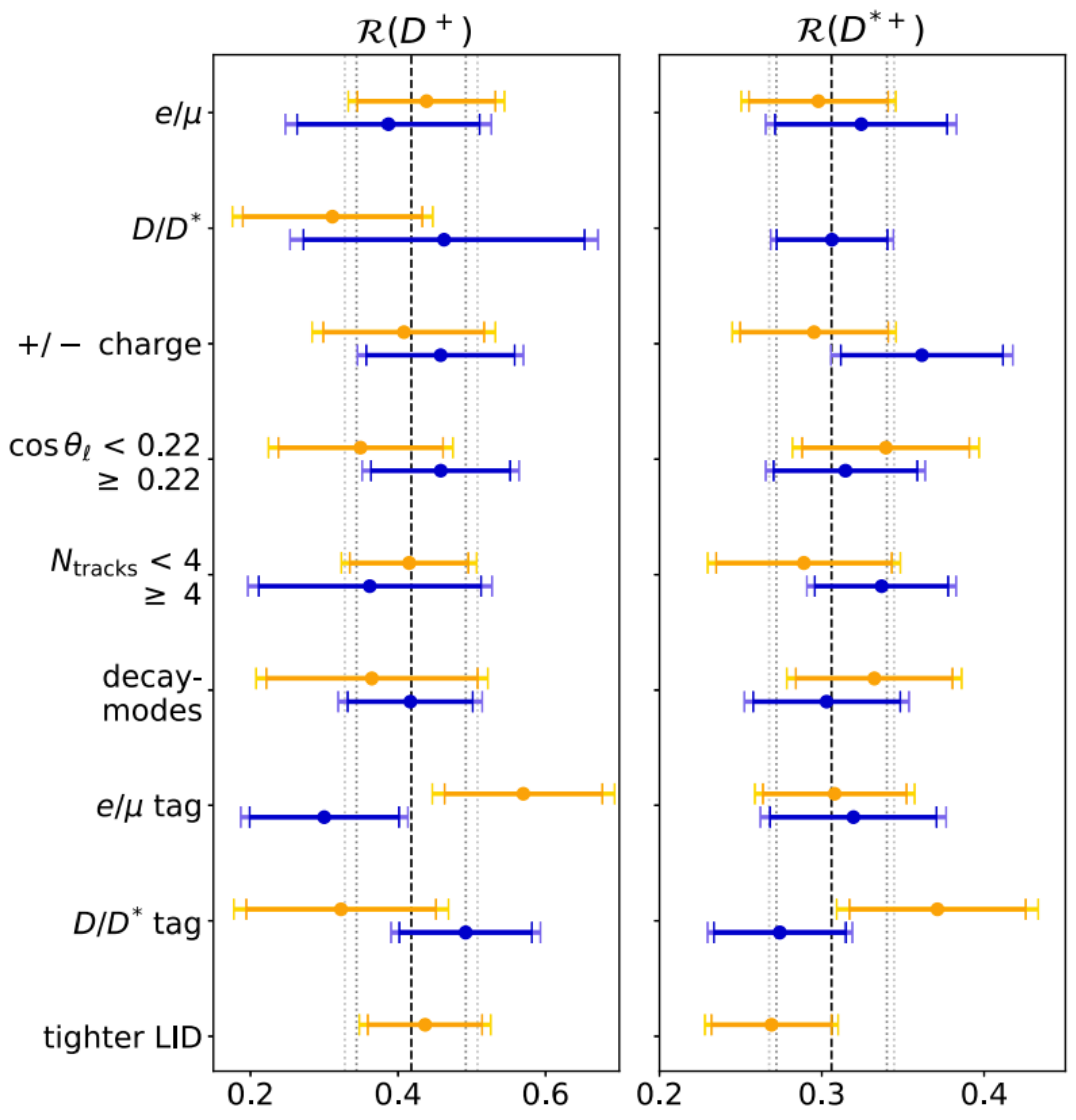


FIG. 6. Summary of the various consistency checks. The central values of each sample split fit (blue and orange error bars), along with the sizes of the statistical and total uncertainties are shown (inner and outer ticks). The nominal results Eqs. (8) and (9) are also shown (dashed black line) with statistical and total uncertainty (inner and outer gray line). The left column shows $\mathcal{R}(D)$, and the right column $\mathcal{R}(D^*)$.

Backup: R(D(*)) with Hadronic Tag

Preliminary

Table II. Summary of the systematic uncertainties on $R(D^{(*)})$ and their correlation (ρ). The description of each source is provided in the text.

Source	$R(D^*)$	$R(D)$	ρ
Simulation sample size	4.8%	8.4%	−0.44
gap-mode branching fraction	2.7%	3.1%	0.00
$\bar{B} \to D^{**}\tau^-/(\ell^-)\bar{\nu}_\ell$ branching fractions	0.3%	1.3%	0.25
Hadronic B decay branching fractions	1.6%	1.5%	−0.26
Form factors	0.5%	0.9%	−0.70
Fraction of misreconstructed $D^{(*)}$	0.5%	1.2%	0.00
Continuum background	2.4%	2.1%	0.93
Fit biases	0.3%	1.2%	0.00
Low-momentum π^0, γ efficiency	2.2%	2.4%	0.99
Other efficiency corrections	0.7%	1.4%	0.92
B-tagging efficiency in data	0.9%	1.8%	−1.00
B-tagging efficiency of $B \to D\tau\nu$	0.1%	1.8%	1.00
M^2_{miss} resolution	0.5%	0.8%	0.48
Total systematic uncertainty	6.7%	10.3%	−0.20
Statistical uncertainty	7.9%	12.5%	−0.40

Backup: $B \to X_u \ell \nu$ and Inclusive $|V_{ub}|$

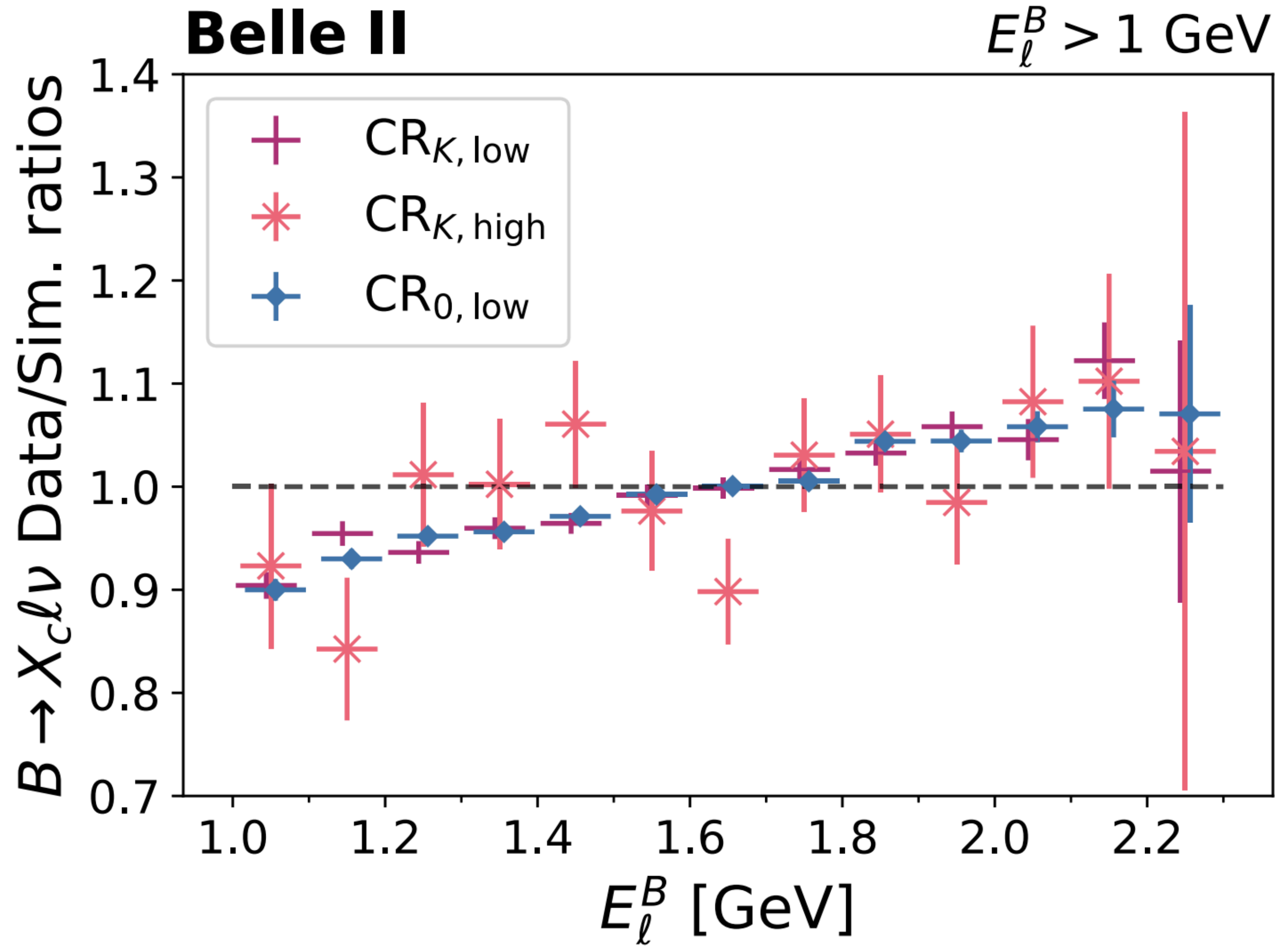
PRD 113, 032004 (2026)

TABLE I. Assumed branching fractions used for simulated semileptonic B decays.

	$\mathcal{B}$ (%)	
Decay mode	B^+	B^0
Incl. $B \to X_u \ell \nu$	0.192 ± 0.024	0.176 ± 0.022
$B \to \pi \ell \nu$	0.0078 ± 0.0003	0.0150 ± 0.0006
$B \to \rho \ell \nu$	0.0158 ± 0.0011	0.0294 ± 0.0021
$B \to \omega \ell \nu$	0.0119 ± 0.0009	$\cdots$
$B \to \eta \ell \nu$	0.0035 ± 0.0004	$\cdots$
$B \to \eta' \ell \nu$	0.0024 ± 0.0007	$\cdots$
Incl. $B \to X_c \ell \nu$	11.05 ± 0.16	10.27 ± 0.15
$B \to D \ell \nu$	2.27 ± 0.06	2.11 ± 0.05
$B \to D^* \ell \nu$	5.27 ± 0.12	4.90 ± 0.11
$B \to D_1 \ell \nu$	0.64 ± 0.10	0.59 ± 0.10
$B \to D_0^* \ell \nu$	0.13 ± 0.19	0.12 ± 0.18
$B \to D_1' \ell \nu$	0.28 ± 0.04	0.26 ± 0.04
$B \to D_2^* \ell \nu$	0.32 ± 0.03	0.30 ± 0.03
$B \to D_s K \ell \nu$	0.03 ± 0.01	$\cdots$
$B \to D_s^* K \ell \nu$	0.03 ± 0.02	$\cdots$
$B \to D \eta \ell \nu$	0.90 ± 0.90	0.86 ± 0.86
$B \to D^* \eta \ell \nu$	0.90 ± 0.90	0.86 ± 0.86
$B \to D \pi \pi \ell \nu$	0.07 ± 0.09	0.07 ± 0.08
$B \to D^* \pi \pi \ell \nu$	0.22 ± 0.10	0.20 ± 0.10

TABLE VIII. Breakdown of uncertainties added following the bias corrections described in Secs. V F and V G. In addition, we show the systematic, statistical, and total uncertainties of the corrected branching fractions.

	Relative uncertainty (%)		
	Fit 1	Fit 2	Fit 3
Fit bias	2.6	2.3	1.8
Composition uncertainty	1.3	5.7	0.2
$B \to X_c \ell \nu$ overestimation correction	2.6	0.4	1.3
Total systematic	7.9	10.5	9.7
Statistical	5.4	5.6	4.5
Total	9.6	11.9	10.7



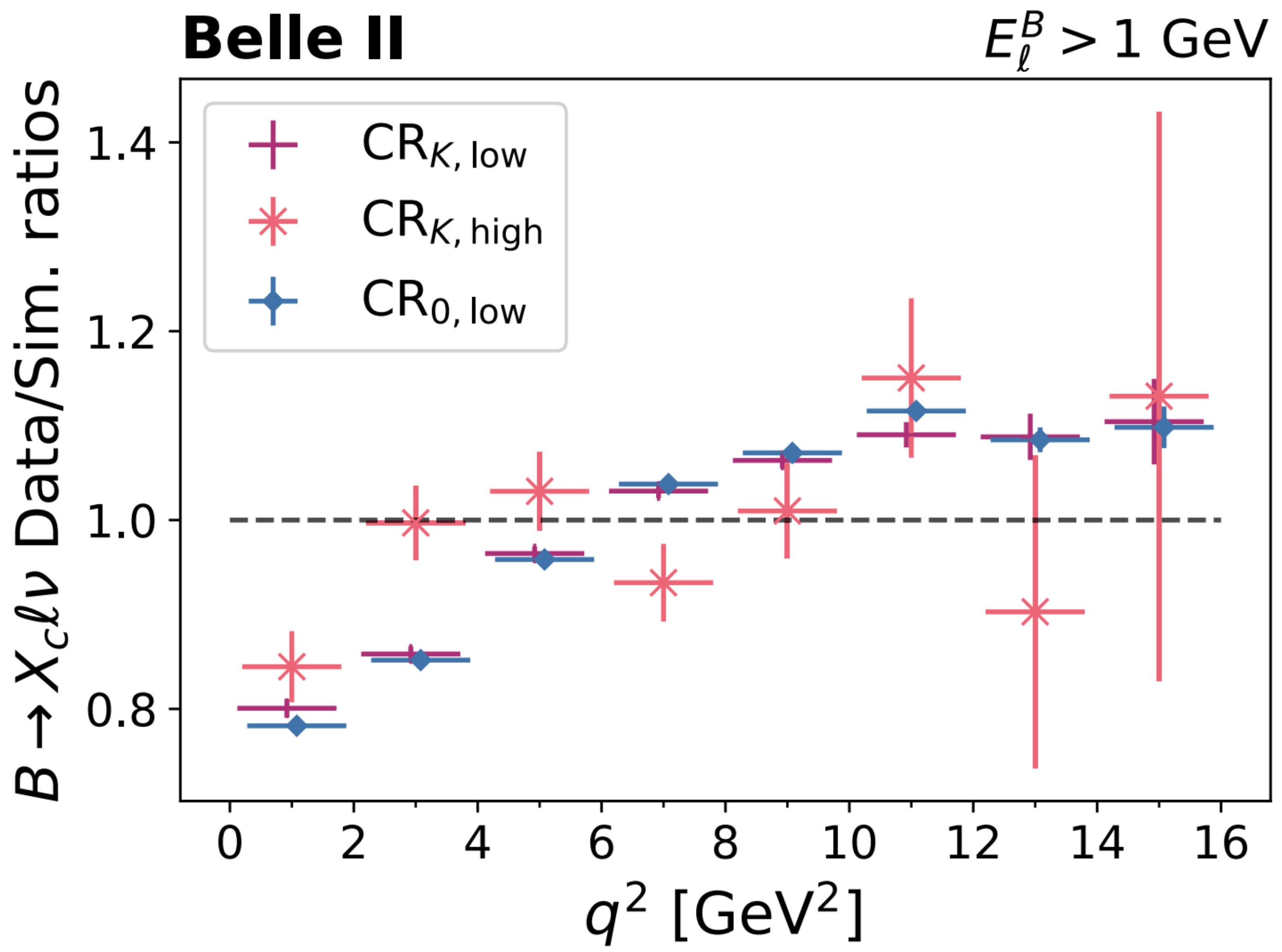


TABLE VII. Breakdown of the systematic uncertainties of the partial branching fraction obtained from each fit.

	Relative uncertainty (%)		
Uncertainty source	Fit 1	Fit 2	Fit 3
DFN parameters	4.4	4.5	5.7
DFN → BLNP	0.2	0.8	1.3
γ_S	1.7	2.1	2.1
$B \to \pi \ell \nu$ form factors	0.3	0.3	0.3
$B \to \rho \ell \nu$ form factors	0.3	0.3	0.2
$B \to \omega \ell \nu$ form factors	0.1	0.1	0.1
$B \to \eta/\eta' \ell \nu$ form factors	<0.1	<0.1	<0.1
$B^\pm \to X_u \ell \nu$ branching fractions	0.9	0.6	0.5
$B^0 \to X_u \ell \nu$ branching fractions	0.6	0.5	0.5
$B \to D^{**}_{\mathrm{Broad}}$ form factors	0.5	0.1	0.2
$B \to D^{**}_{\mathrm{Narrow}}$ form factors	0.1	<0.1	<0.1
$B \to D/D^* \ell \nu$ form factors	<0.1	<0.1	<0.1
$B^\pm \to X_c \ell \nu$ branching fractions	0.7	0.5	0.2
$B^0 \to X_c \ell \nu$ branching fractions	0.6	0.2	0.1
D decay branching fractions	0.1	0.3	0.1
SR $X_c \ell \nu$ normalization	1.6	3.5	3.4
CR $X_c \ell \nu$ normalization	0.9	1.1	0.4
Other backgrounds normalization	0.3	N/A	N/A
X_u fragmentation	0.3	4.4	3.9
$N_{\Upsilon(4S)}$	1.4	1.4	1.4
FEI	1.3	1.3	1.4
Slow pion efficiency	0.4	0.2	0.3
ℓ identification	0.7	0.7	0.6
$f^{\pm/00}$	0.6	0.7	0.6
Continuum calibration	0.2	0.2	0.2
Tracking	0.3	0.3	0.3
K_S^0 efficiency	0.1	0.1	<0.1
$K^\pm$ ID	<0.1	<0.1	<0.1
Simulated data statistics	1.1	1.1	0.8

Backup: $B \to \mu\nu$ with Inclusive Tag at Belle+Belle II

Table V: The uncertainties on the measured $B^+ \to \mu^+\nu_\mu$ branching fraction are shown. For definitions of additive and multiplicative errors see the text. FF denotes form factor, and BF denotes branching fraction.

Source	Fractional uncertainty
Additive uncertainties	
$b \to u$ modeling	17.4%
$B \to \pi\ell^+\nu_\ell$ FF	8.2%
$B \to \rho\ell^+\nu_\ell$ FF	8.9%
$B^+ \to \omega\ell^+\nu_\ell$ FF	4.5%
$B^+ \to \eta\ell^+\nu_\ell$ FF	0.2%
$B^+ \to \eta'\ell^+\nu_\ell$ FF	1.0%
$B \to \pi\ell^+\nu_\ell$ BF	4.8%
$B \to \rho\ell^+\nu_\ell$ BF	1.0%
$B^+ \to \omega\ell^+\nu_\ell$ BF	0.2%
$B^+ \to \eta\ell^+\nu_\ell$ BF	0.2%
$B^+ \to \eta'\ell^+\nu_\ell$ BF	0.1%
$B \to X_u\ell^+\nu_\ell$ BF	3.3%
DFN parameters	5.7%
Hybrid model	6.0%
MC sample size	5.6%
Continuum modeling	14.0%
Shape correction	4.1%
MC sample size	13.3%
$B^+ \to \mu^+\nu_\mu\gamma$ modeling	4.8%
$b \to c$ modeling	2.4%
Rare decay modeling	1.5%
$B^+ \to \mu^+\nu_\mu$ modeling	1.5%
Multiplicative uncertainties	
PID efficiency Belle	1.6%
Tracking efficiency Belle	0.3%
$N_{B\bar{B}}$ Belle	1.1%
PID efficiency Belle II	1.0%
Tracking efficiency Belle II	0.1%
$N_{B\bar{B}}$ Belle II	0.3%
f_{+0}	2.1%
Control channel efficiency ratios	3.2%
Total systematic uncertainty	23.6%
Total statistical uncertainty	42.9%

arXiv:2602.09800
Accepted by PRD