Semileptonic *B* decays from Belle and Belle II:

$|V_{xb}|$ and tests of lepton universality

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for the Belle & Belle II Collaborations

March 28th, Moriond EW 2024

BELLE

Belle II

DESY.

Measurements covered in this talk

All results are new since Moriond 2023

Lepton-Flavor universality tests

- $R(D^*_{\tau/\ell}) = \dfrac{\mathcal{B}(B \to D^*\tau\nu)}{\mathcal{B}(B \to D^*\ell\nu)}$ **Updated!**
- $R(X_{\tau/\ell}) = \dfrac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)}$

CKM matrix elements $|V_{cb}|$ & $|V_{ub}|$

- Simultaneous $B \to (\pi, \rho)\ell\nu$, untagged **New!!**
- Angular coefficients of $B \to D^*\ell\nu$
- Simultaneous inclusive and exclusive $|V_{ub}|$
- Ratio of inclusive $|V_{ub}|$ and $|V_{cb}|$

Belle II: Full or half of Run1 data of 364 fb^{-1}

BELLE: Full data of 711 fb^{-1}

Other B-flavor topics from Belle II were presented by P. Goldenzweig, N. Rout, S. Moneta, P. Stavroulakis, S.P. Lin.

Lepton-Flavor universality

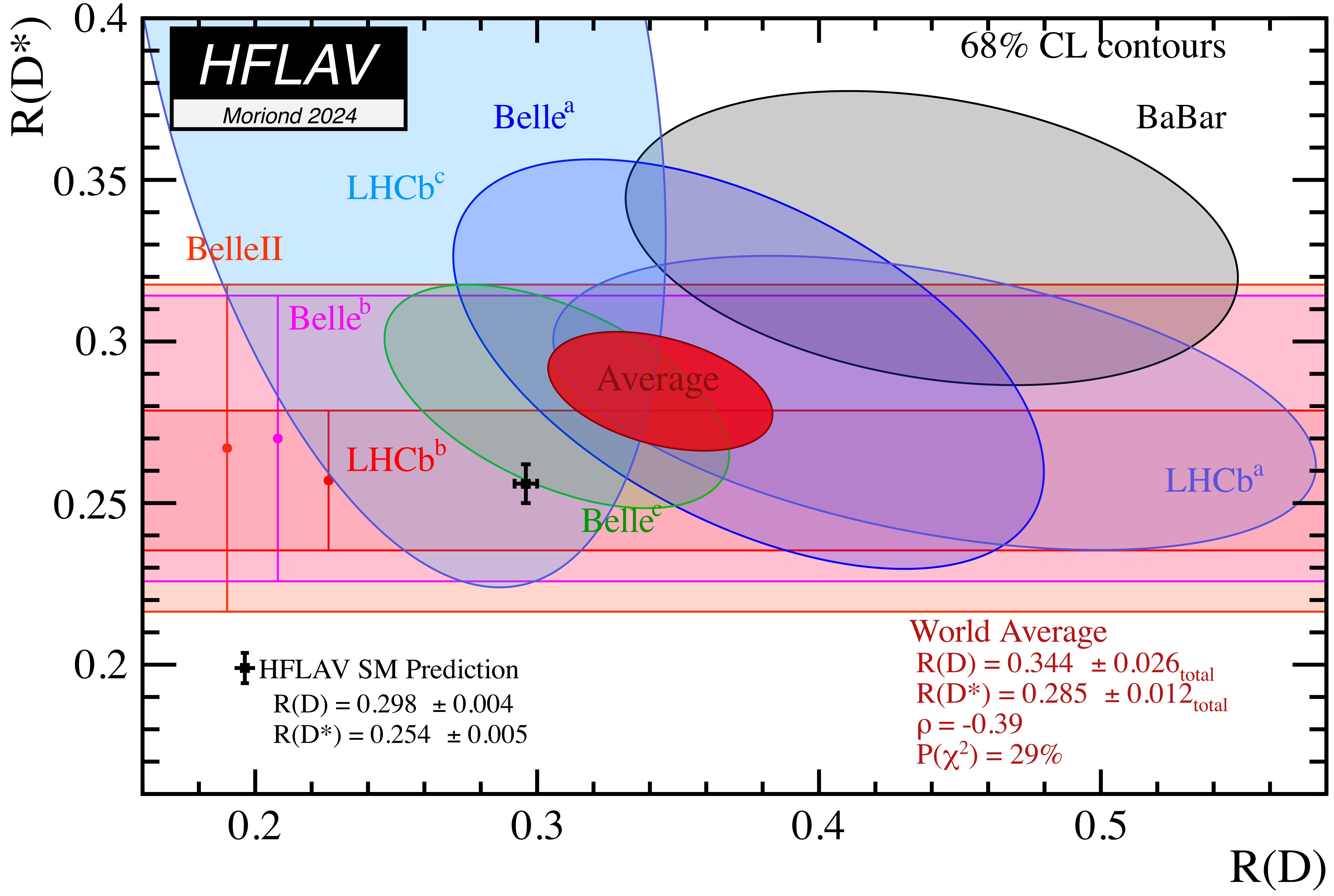
- In SM, the W boson couples equally to τ, μ, e => **Lepton-Flavor Universality (LFU)**
- Semileptonic B decays are sensitive to new physics beyond SM
- **Ratio measurements** provide stringent LFU tests: branching fractions, angular asymmetry, etc.
  - Normalization ($|V_{xb}|$) cancels
  - Part of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

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

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

final state can involve different hadrons

Tension of $R(D^{(*)})$ with SM ~3σ



R(D*) using hadronic B tagging at Belle II

arXiv:2401.02840
Preliminary

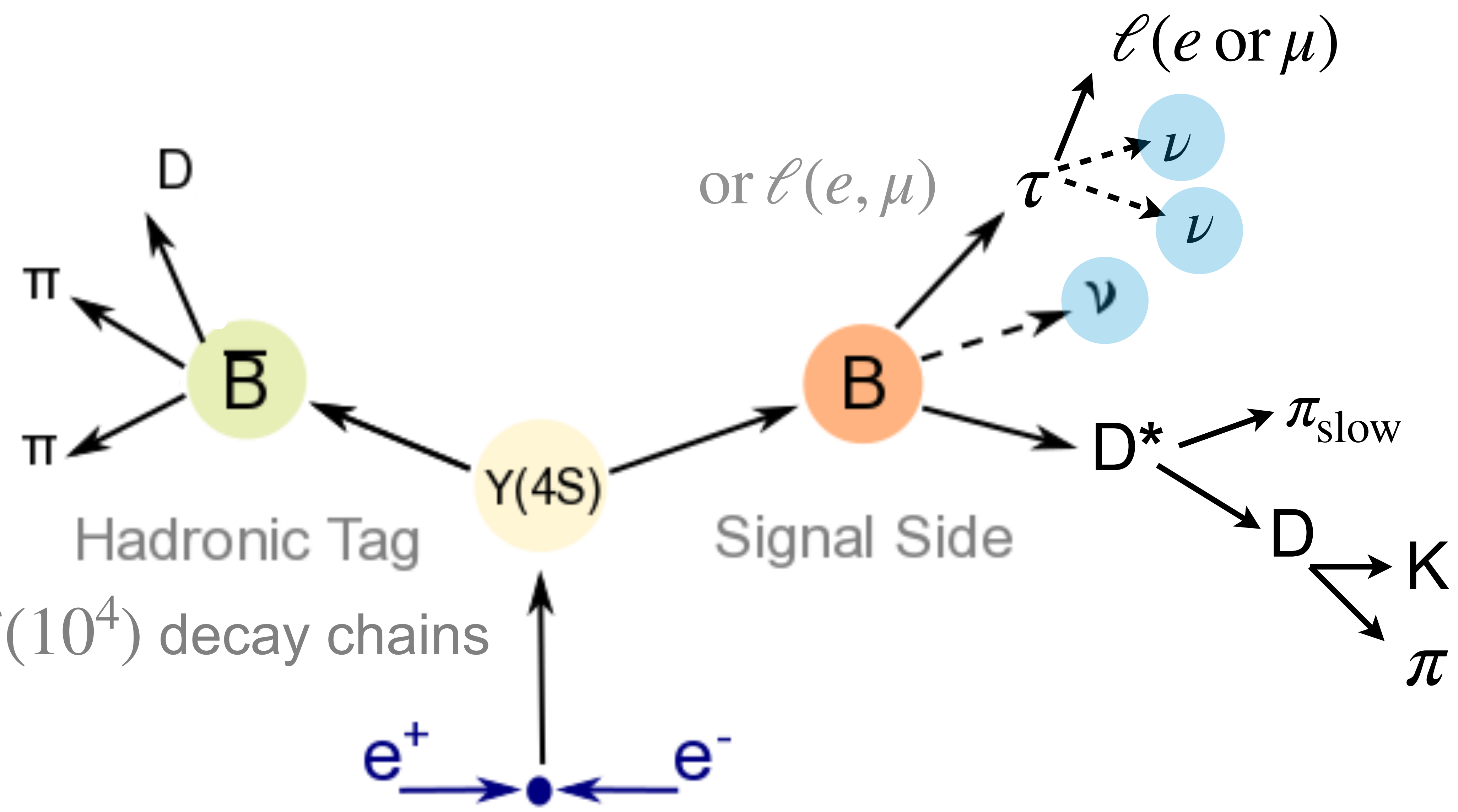
- Use 189 fb^{-1} dataset with hadronic tagging strategy
- Signal decays: $B \to D^*(\tau, \ell)\nu,\ D^{*+} \to D^0\pi^+, D^+\pi^-$ and $D^{*0} \to D^0\pi^0$, and leptonic τ decays
- Data-driven validation of modelling in sideband regions
- Extract R(D*) using 2D fit on M^2_{miss} and residual energy in the calorimeter E_{ECL}

Reconstruct B_{tag}

Full Event Interpretation

Comput.Softw.Big Sci. 3 (2019) 1, 6

$\epsilon(B^+) \approx 0.35\,\%$ $\epsilon(B^0) \approx 0.27\,\%$



$D^{*+} \to D^0\pi^+/D^+\pi^0$: $\mathcal{B}$~98%
$D^{*0} \to D^0\pi^0$: $\mathcal{B}$~65%

Eight D^0 modes: $\mathcal{B}$~36%,
Three D^+ modes: $\mathcal{B}$~12%

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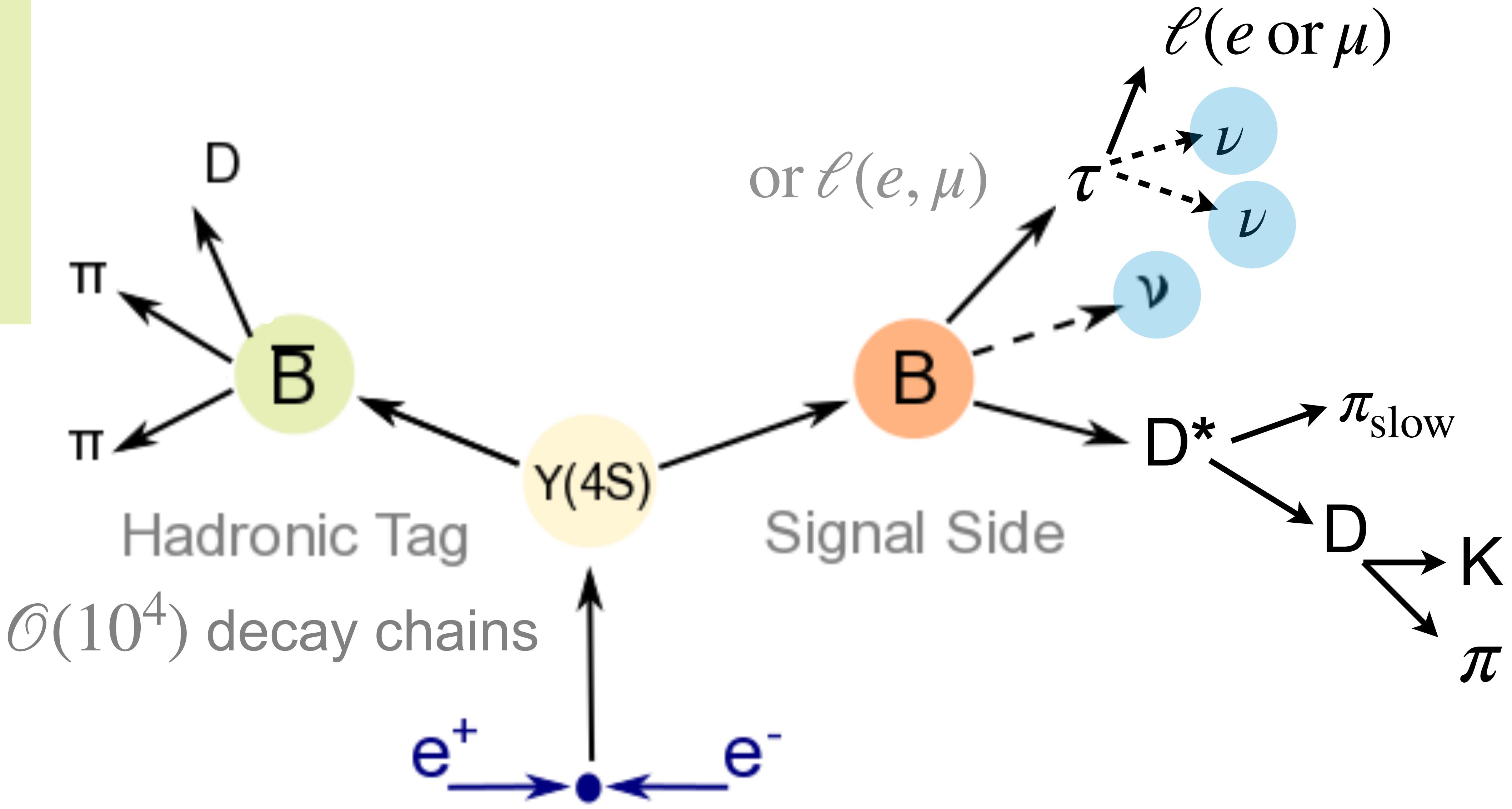
Reconstruct B$_{\rm tag}$

Full Event Interpretation

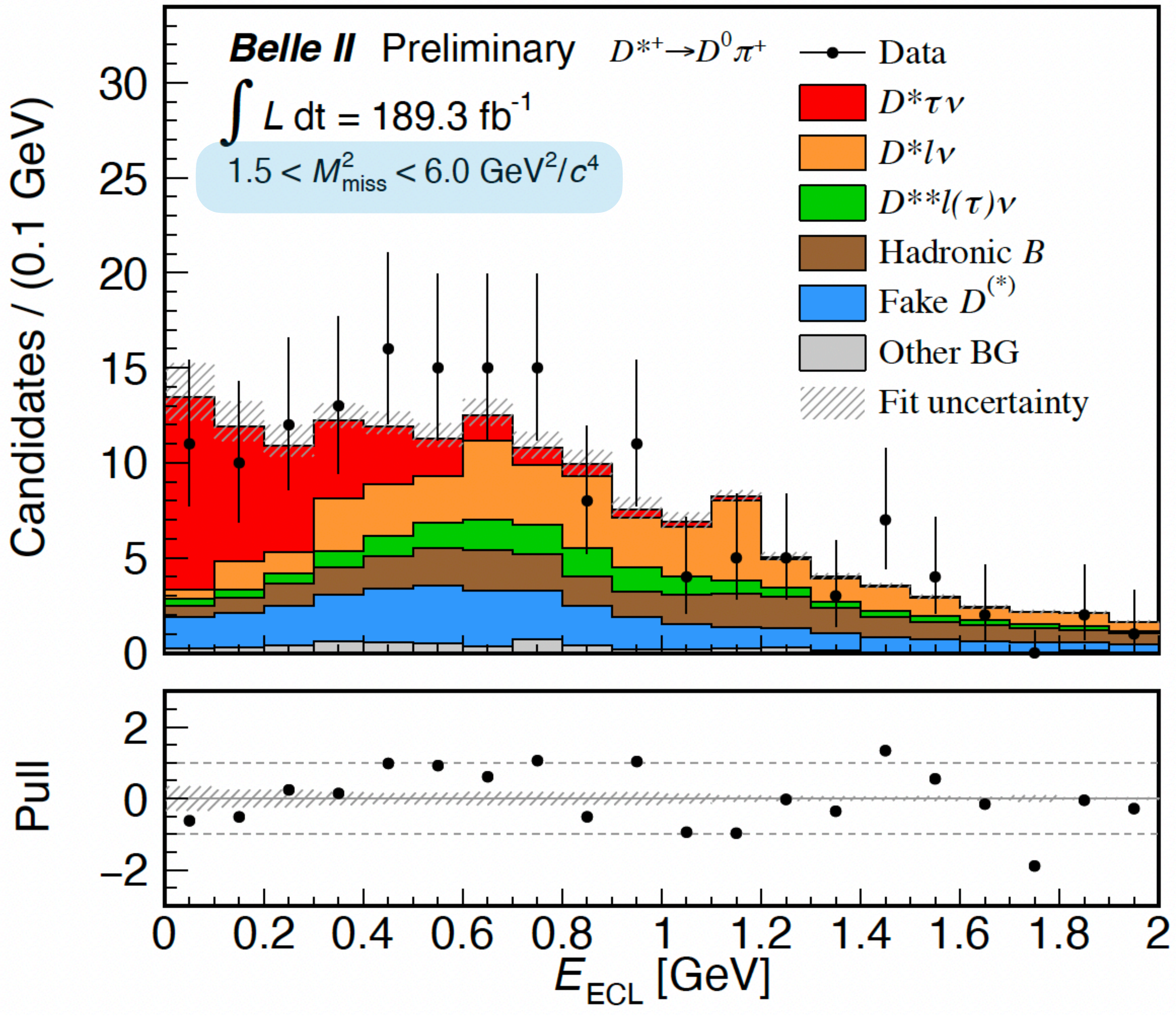
Comput.Softw.Big Sci. 3 (2019) 1, 6

$\epsilon(B^+) \approx 0.35\,\%$ $\epsilon(B^0) \approx 0.27\,\%$

In the rest of event (ROE), require no remaining tracks/π^0.



$D^{*+} \to D^0\pi^+$



$$M^2_{\rm miss} = (E^*_{\rm beam} - E^*_{D^*} - E^*_\ell)^2 - (-\vec{p}^{\,*}_{B_{\rm tag}} - \vec{p}^{\,*}_{D^*} - \vec{p}_\ell^{\,*})^2$$

R(D*) using hadronic B tagging at Belle II

arXiv:2401.02840
Preliminary

$$R(D^*) = 0.262\ ^{+0.041}_{-0.039}(\text{stat})\ ^{+0.035}_{-0.032}(\text{syst})$$

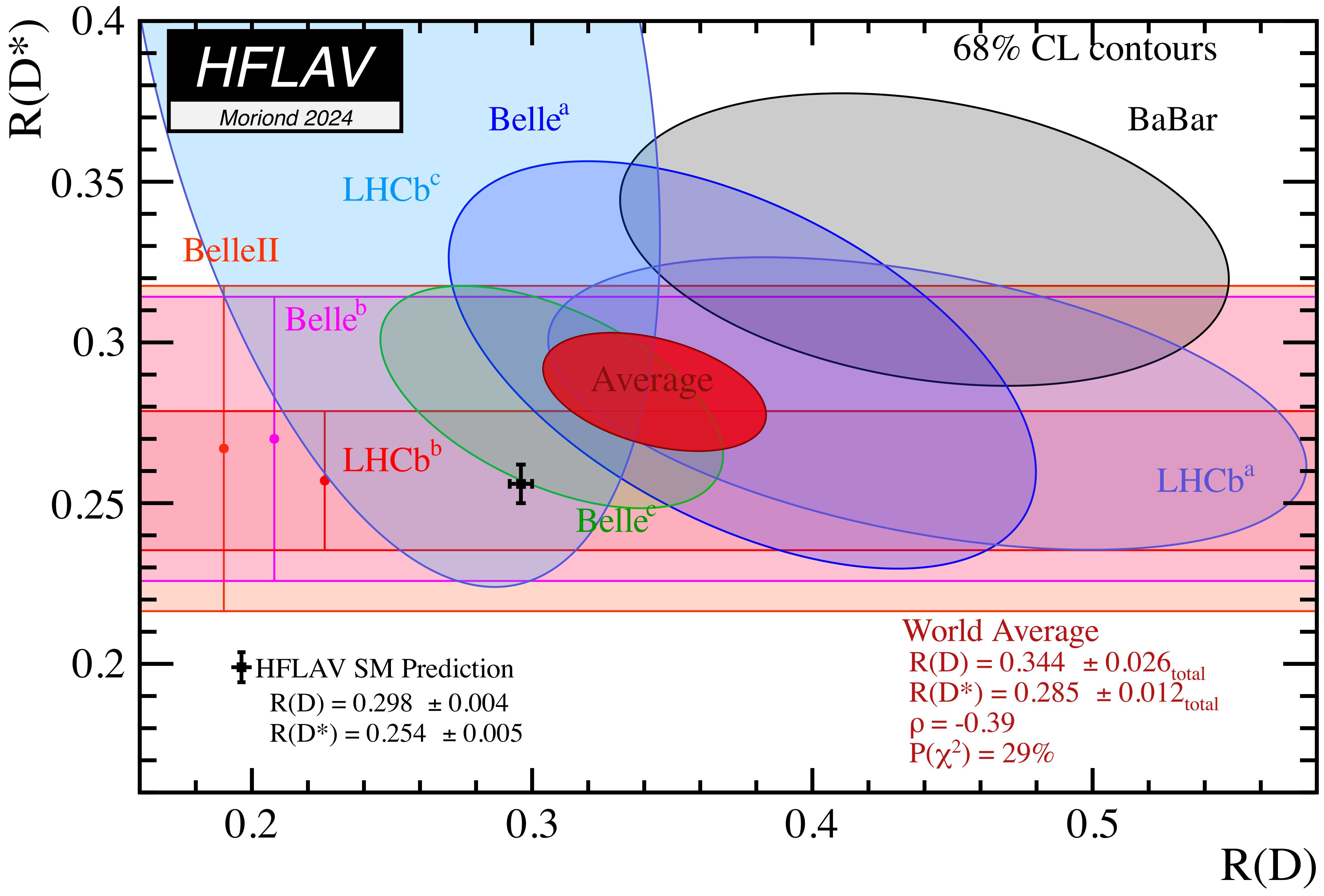
comparable stat. precision as Belle

dominant by PDF shapes, MC sample size

consistent with SM predictions [HFLAV 23]

- Previous version presented in Lepton Photon 2023
- Minor updates applied

Update to full Run1 dataset and include R(D) is ongoing

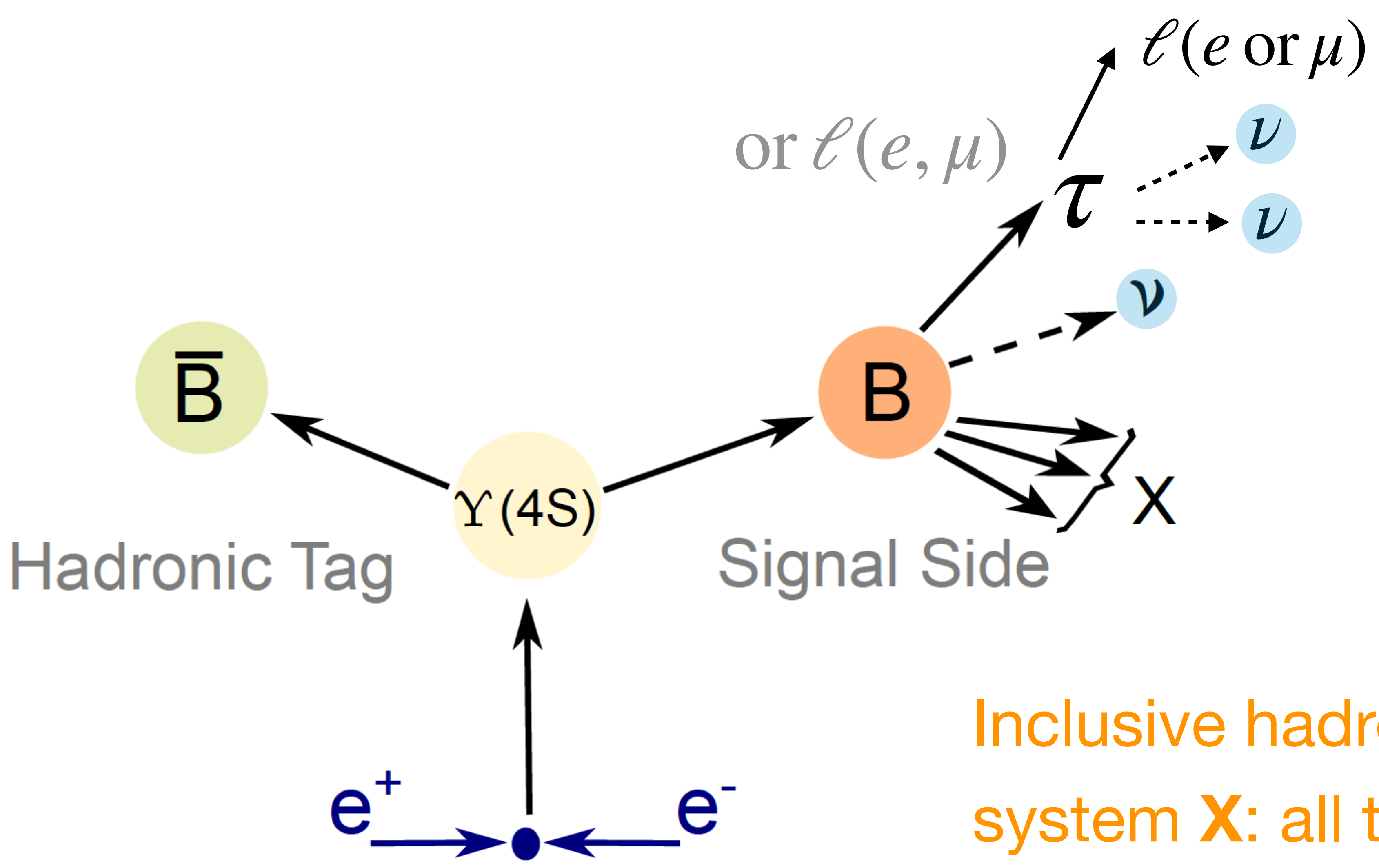


First measurement of $R(X)_{\tau/\ell}$

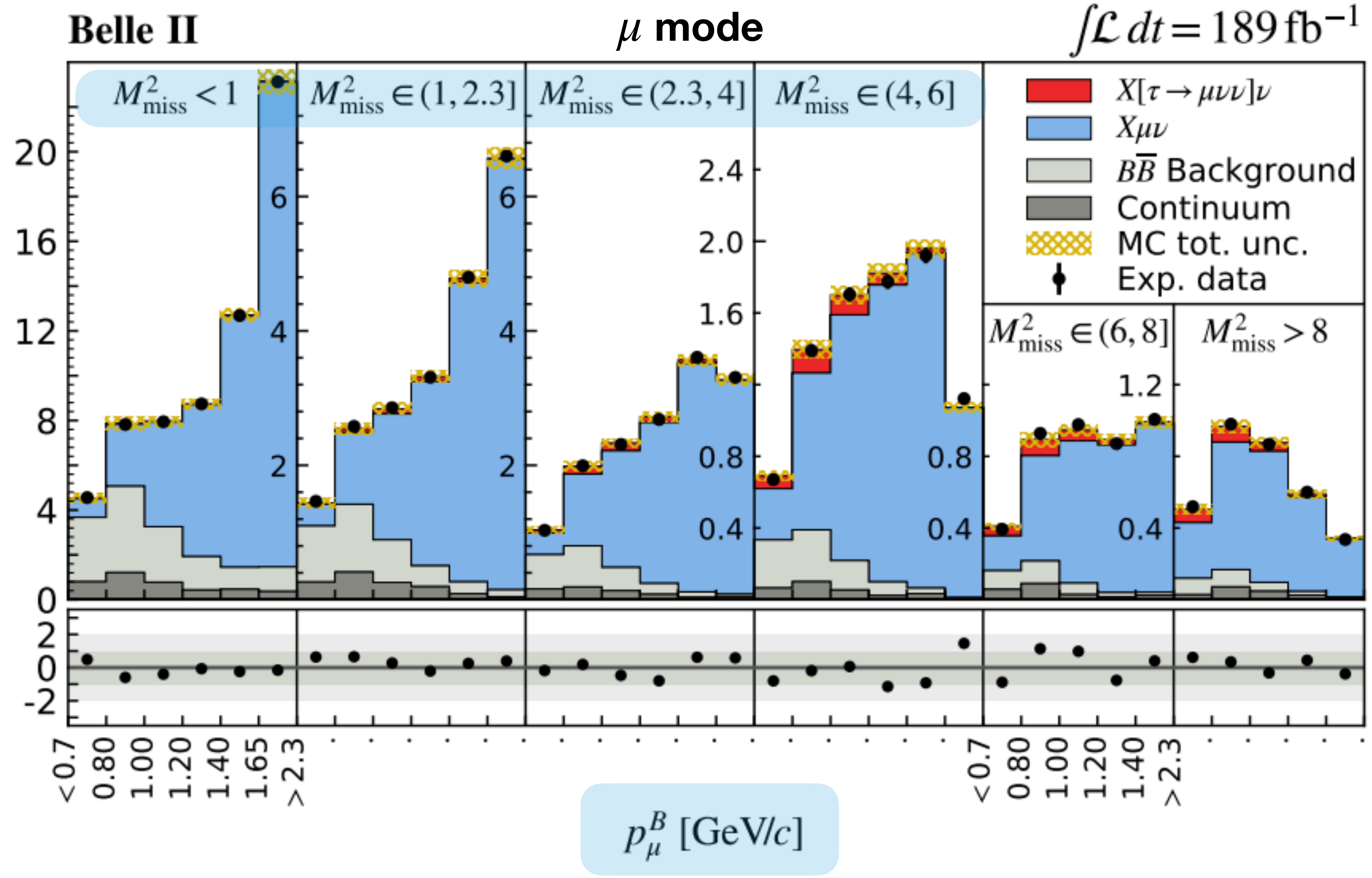
arXiv:2311.07248
Preliminary

- Use 189 fb^{-1} dataset with hadronic tagging and leptonic τ decay
- Data-driven signal modelling correction with sideband regions
- Extract signal events simultaneously for e and μ modes on $(M^2_{\text{miss}}, p^B_\ell)$

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



Inclusive hadronic system **X**: all tracks & neutrals in ROE



First measurement of $R(X)_{\tau/\ell}$

arXiv:2311.07248
Preliminary

- World's first inclusive measurement at *B*-factory with $\Upsilon(4S)$
- Consistent with SM expectations, e.g. R(X)=0.223 ± 0.005 [JHEP11(2022)007]

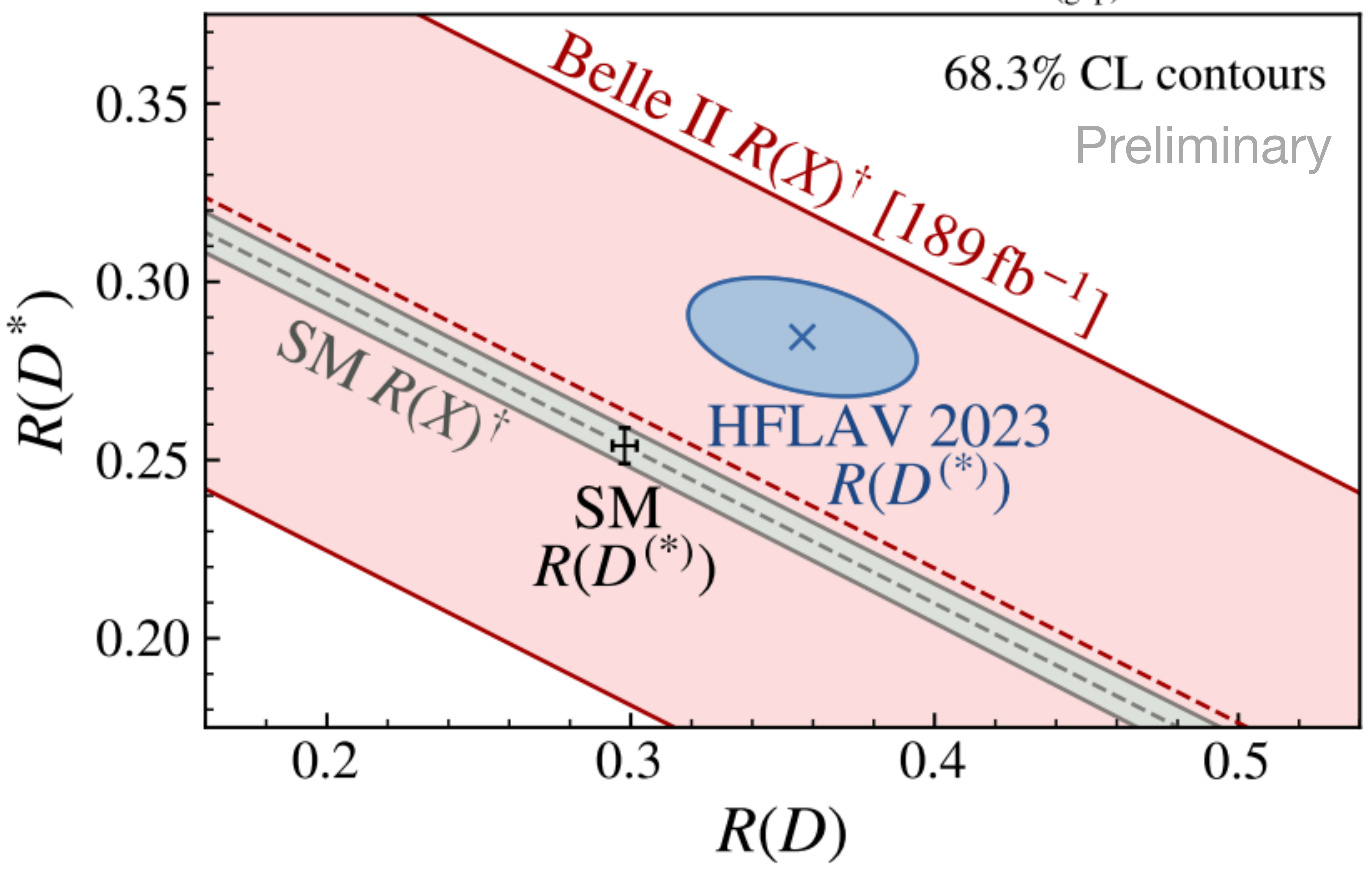
$$R(X_{\tau/e}) = 0.232 \pm 0.020\ (\text{stat}) \pm 0.037\ (\text{syst})$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.027\ (\text{stat}) \pm 0.050\ (\text{syst})$$

$$R(X_{\tau/\ell}) = 0.228 \pm 0.016\ (\text{stat}) \pm 0.036\ (\text{syst})$$

dominated by gap modes branching fraction, $B \to D^*$ form factors, background shape

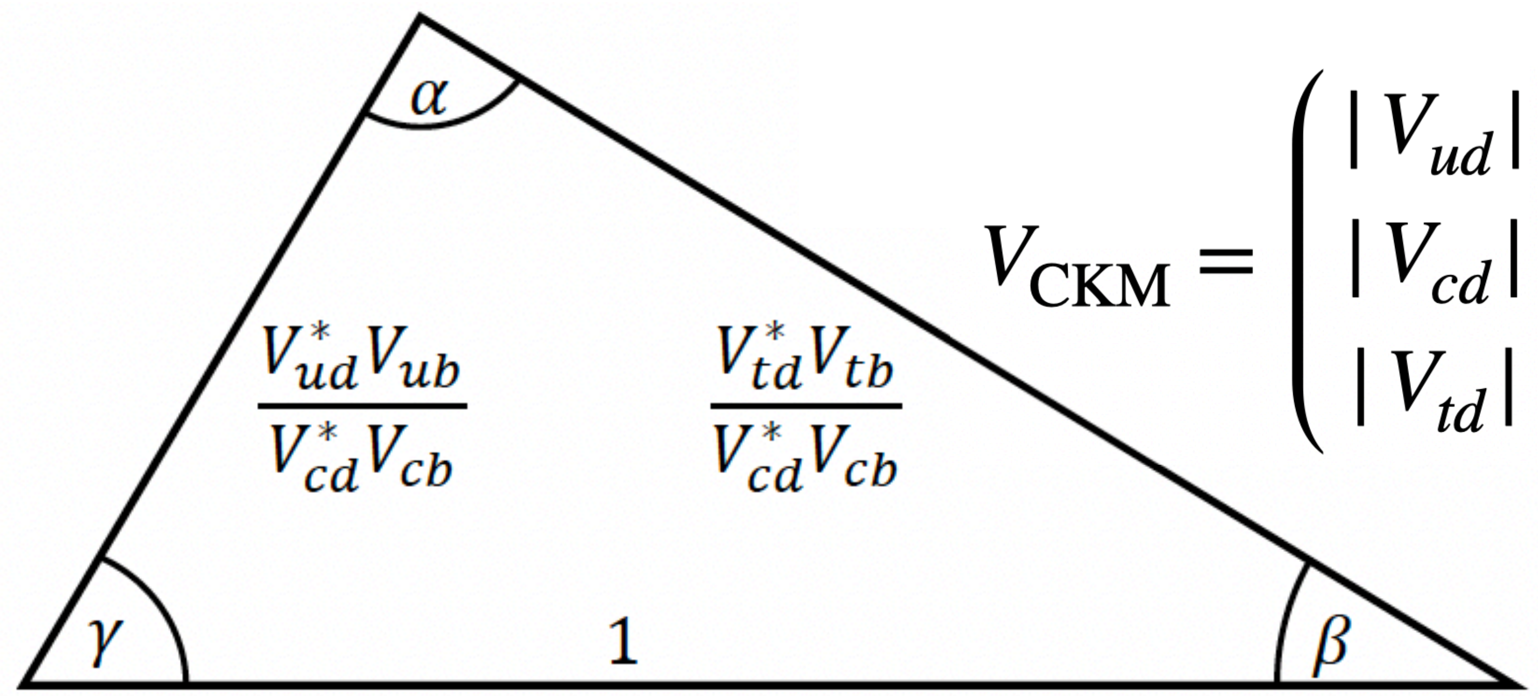
$R(X)^{\dagger} \cdot \mathcal{B}(B \to X\ell\nu) = [x \text{ axis}] \cdot \mathcal{B}(B \to D\ell\nu) + [y \text{ axis}] \cdot \mathcal{B}(B \to D^*\ell\nu)$

† = with expected SM contributions of $D^{**}_{(\text{gap})}, X_u$ removed



|Vcb| & |Vub|

- 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



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

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

Exclusive

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

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

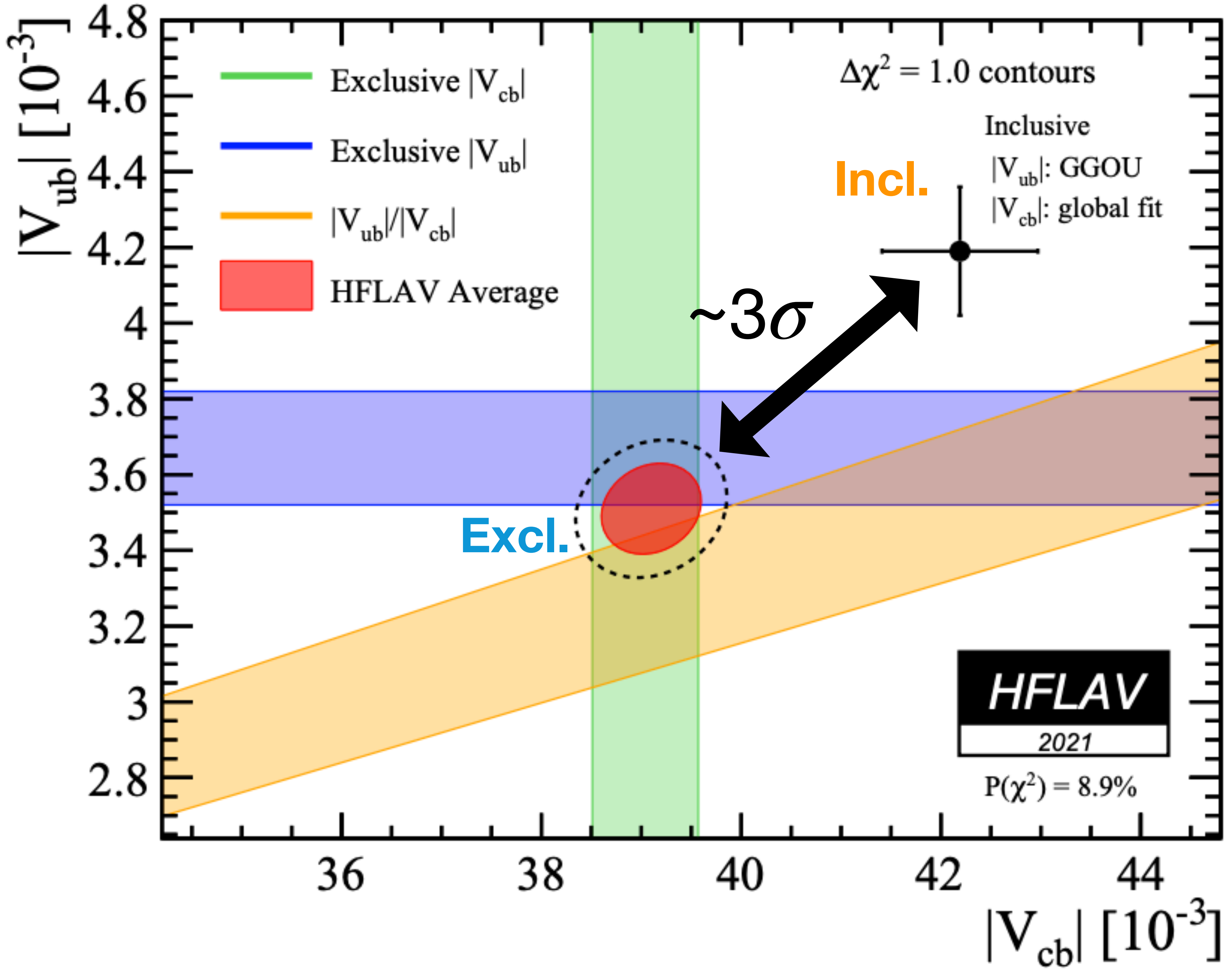
Form factor f (LCSR, LQCD)

Inclusive

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

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

+ Shape Function / Fermi Motion (OPE)



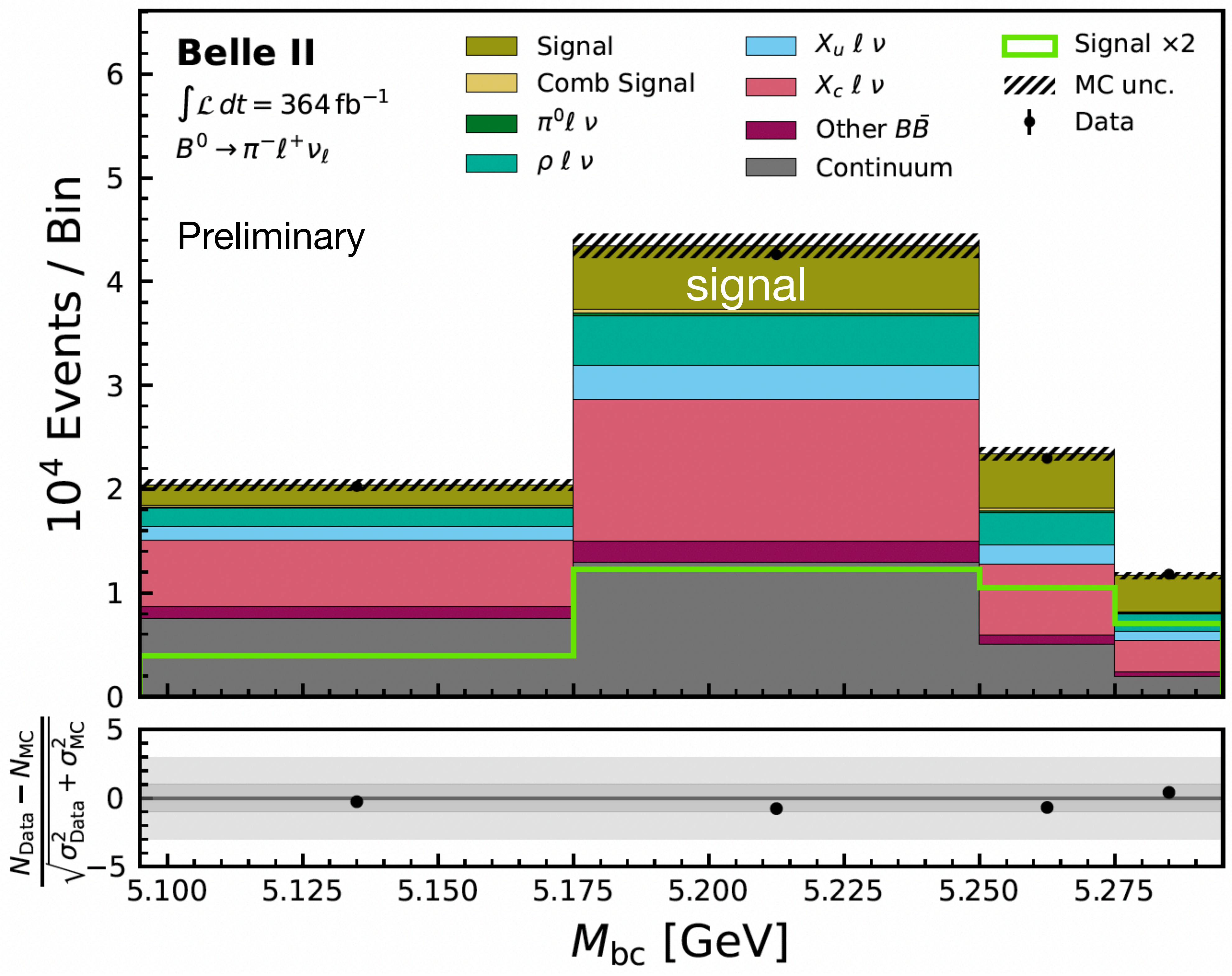
Simultaneous measurements of $B^0 \to \pi^- \ell^+ \nu$, $B^+ \to \rho^0 \ell^+ \nu$

Preliminary

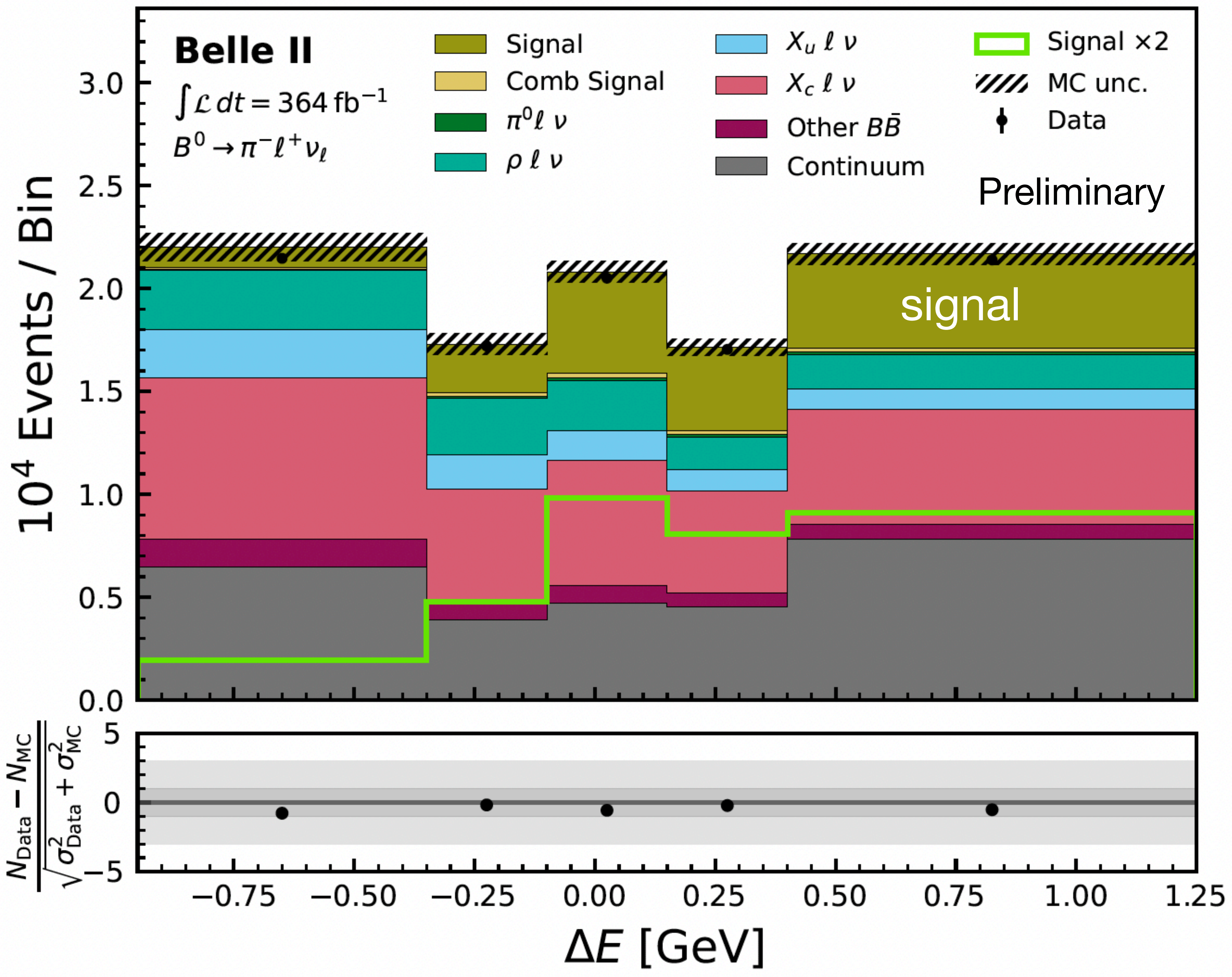
NEW!!

- Full **Run1** data of 364 fb^{-1} with untagged analysis strategy
- Novel method to simultaneously extract signals in 2D grid of beam-constrained mass M_{bc} and energy difference ΔE **for each bin of** q^2 : **13** bins for π mode, **10** bins for ρ mode

$$M_{bc} = \sqrt{E^{*2}_{\text{beam}} - |\vec{p}^{\,*}_B|^2}$$



$$\Delta E = E^*_B - E^*_{\text{beam}}$$



Simultaneous measurements of $B^0 \to \pi^-\ell^+\nu$, $B^+ \to \rho^0\ell^+\nu$

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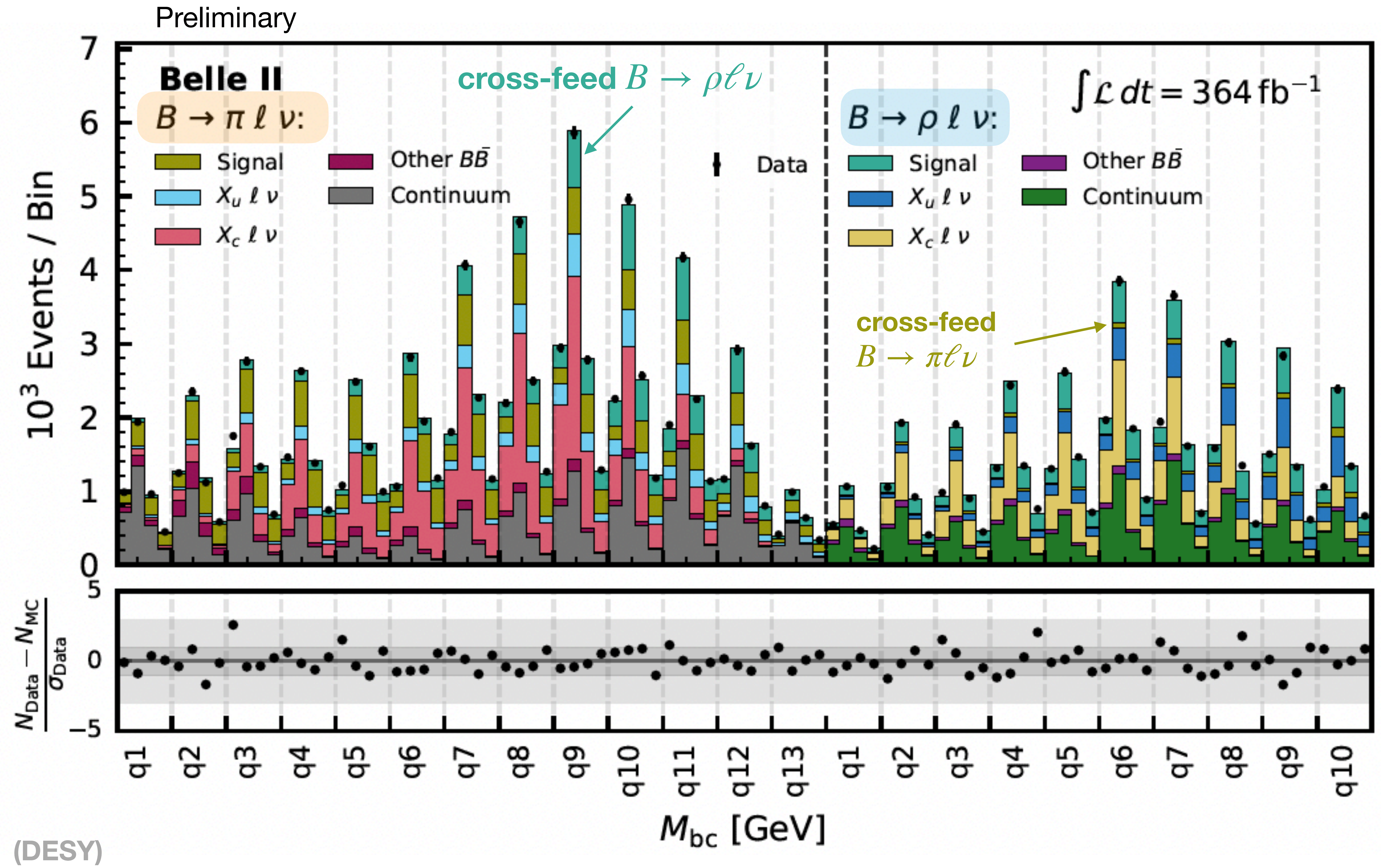

- Cross-feed signals are linked in two modes
- Dominant backgrounds are from $B \to X_c\ell\nu$ decays and continuum ($e^+e^- \to q\bar{q}$)

Simultaneous measurements of $B^0 \to \pi^- \ell^+ \nu$, $B^+ \to \rho^0 \ell^+ \nu$

Belle II

Preliminary

NEW!!

- Partial branching factions in each q^2 bin obtained with fitted yields and efficiency corrections
- Total BR is a sum of partial bins

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.516 \pm 0.042 \pm 0.059) \times 10^{-4}$$

$$\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.625 \pm 0.079 \pm 0.180) \times 10^{-4}$$

stat syst

Consistent with world averages

Compatible precision as Belle/BaBar

Simultaneous measurements of $B^0 \to \pi^- \ell^+ \nu$, $B^+ \to \rho^0 \ell^+ \nu$

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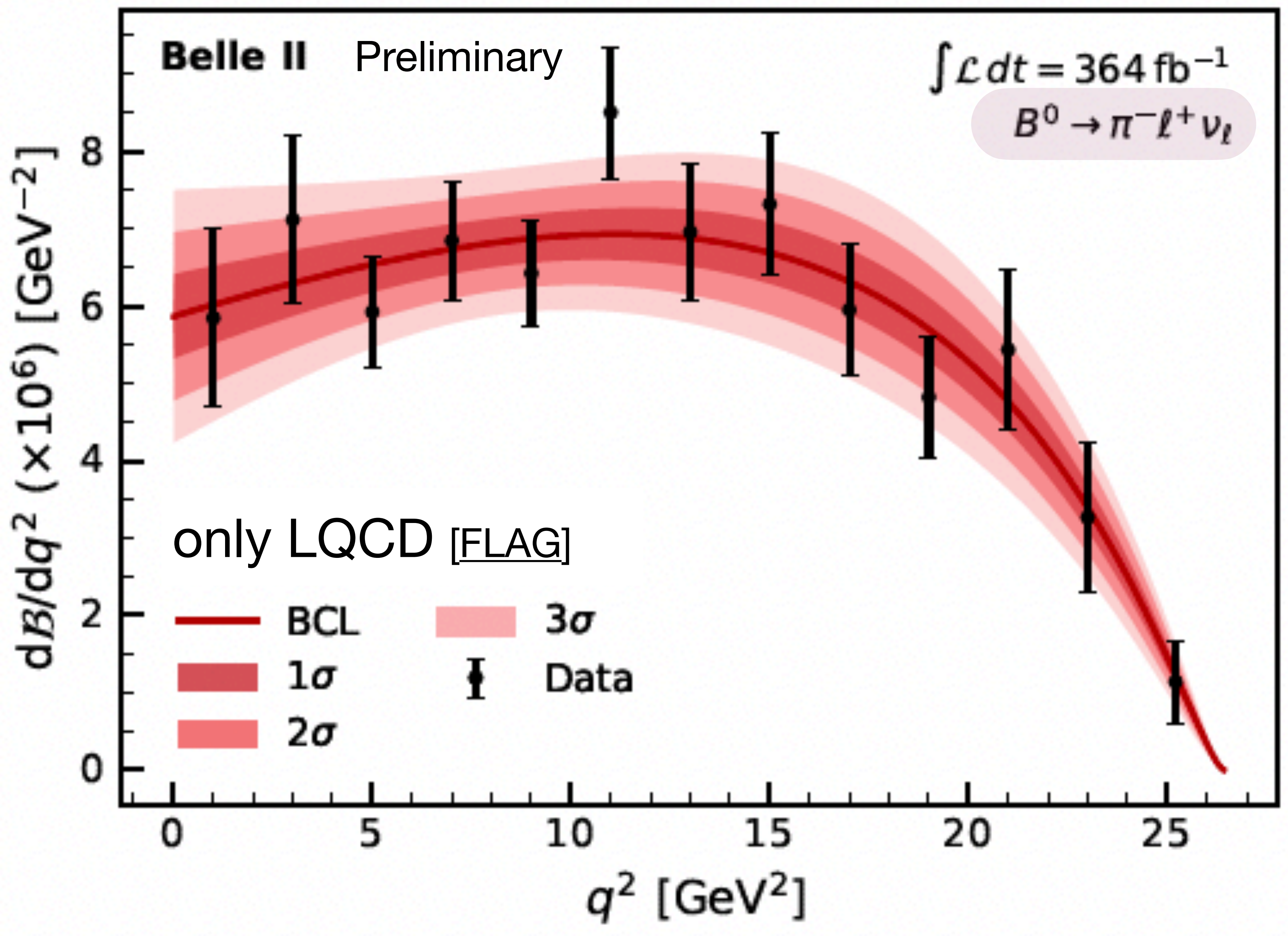
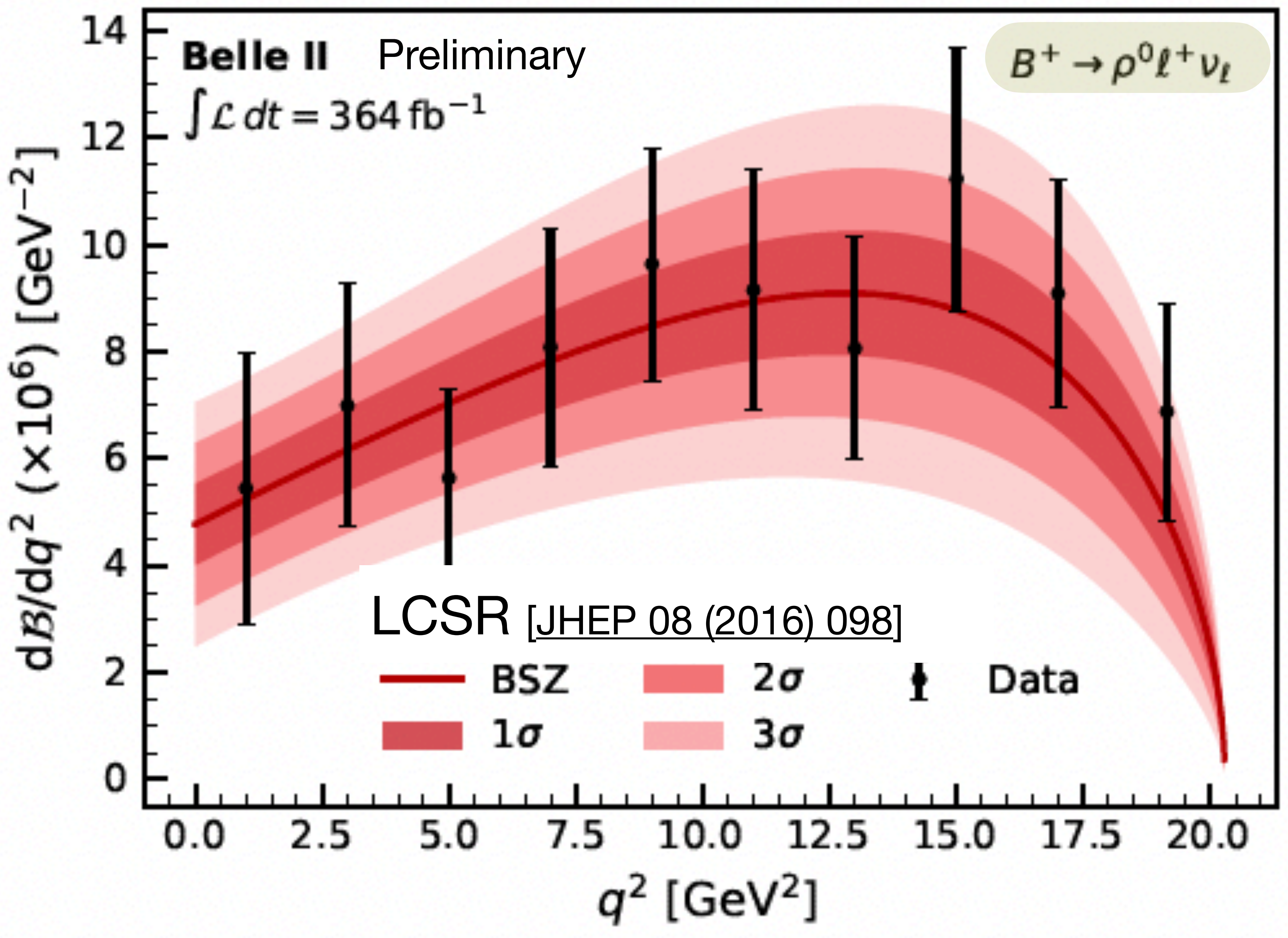
stat syst

Consistent with world averages

Compatible precision as Belle/BaBar

- Extracted $|V_{ub}|$ with lattice QCD and/or light-cone sum rules (LCSR) constraints of form factors





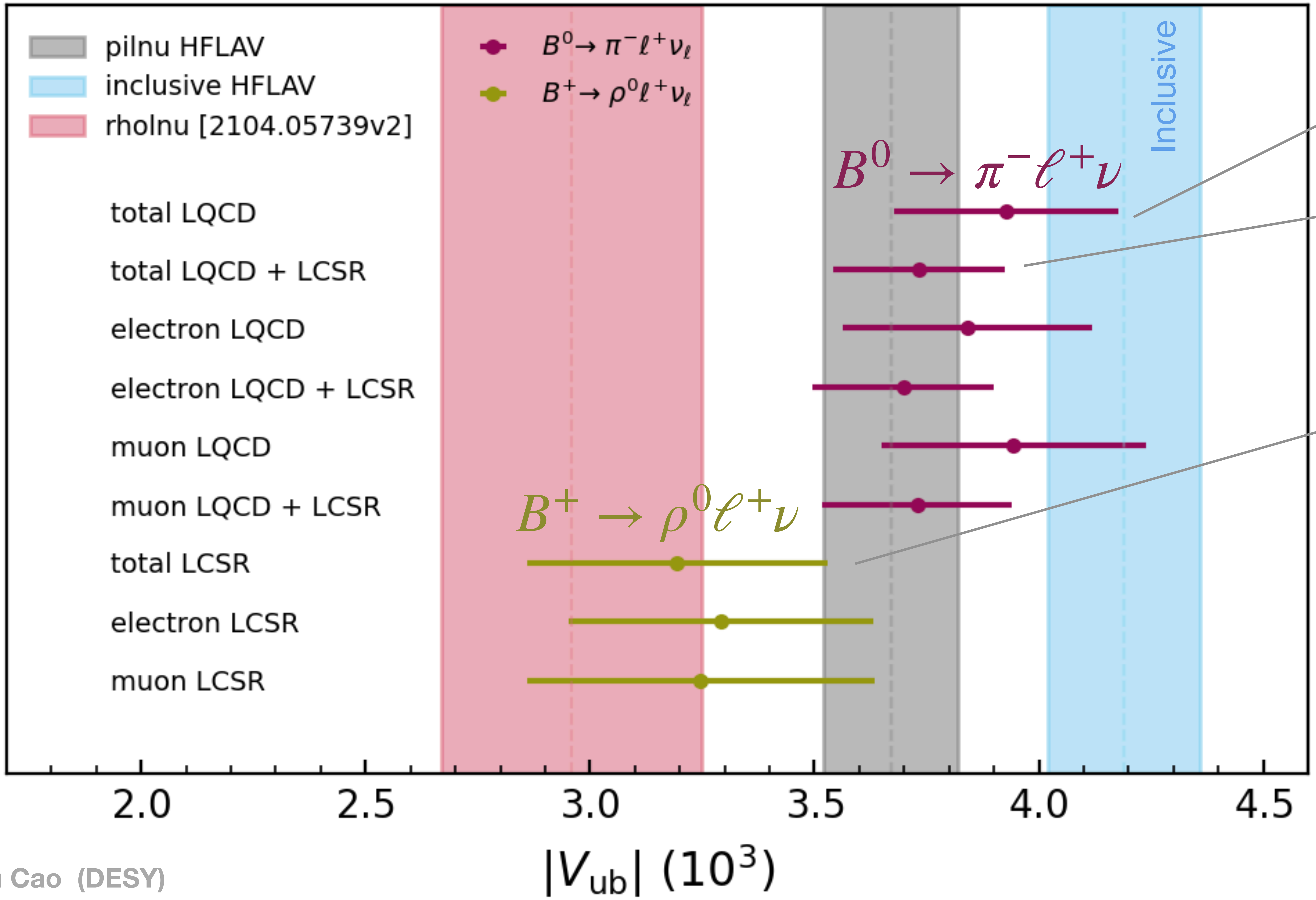
Simultaneous measurements of $B^0 \to \pi^- \ell^+ \nu$, $B^+ \to \rho^0 \ell^+ \nu$

- Further split into e and μ modes to provide cross check
- Additional stability tests done by removing higher/lower q^2 bins

Preliminary

NEW!!

Preliminary



$$|V_{ub}|_{B\to\pi\ell\nu_\ell} = (3.93 \pm 0.09 \pm 0.13 \pm 0.19) \times 10^{-3}$$
stat syst theo

LQCD

$$|V_{ub}|_{B\to\pi\ell\nu_\ell} = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$$

LQCD+LCSR

$$|V_{ub}|_{B\to\rho\ell\nu_\ell} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$$

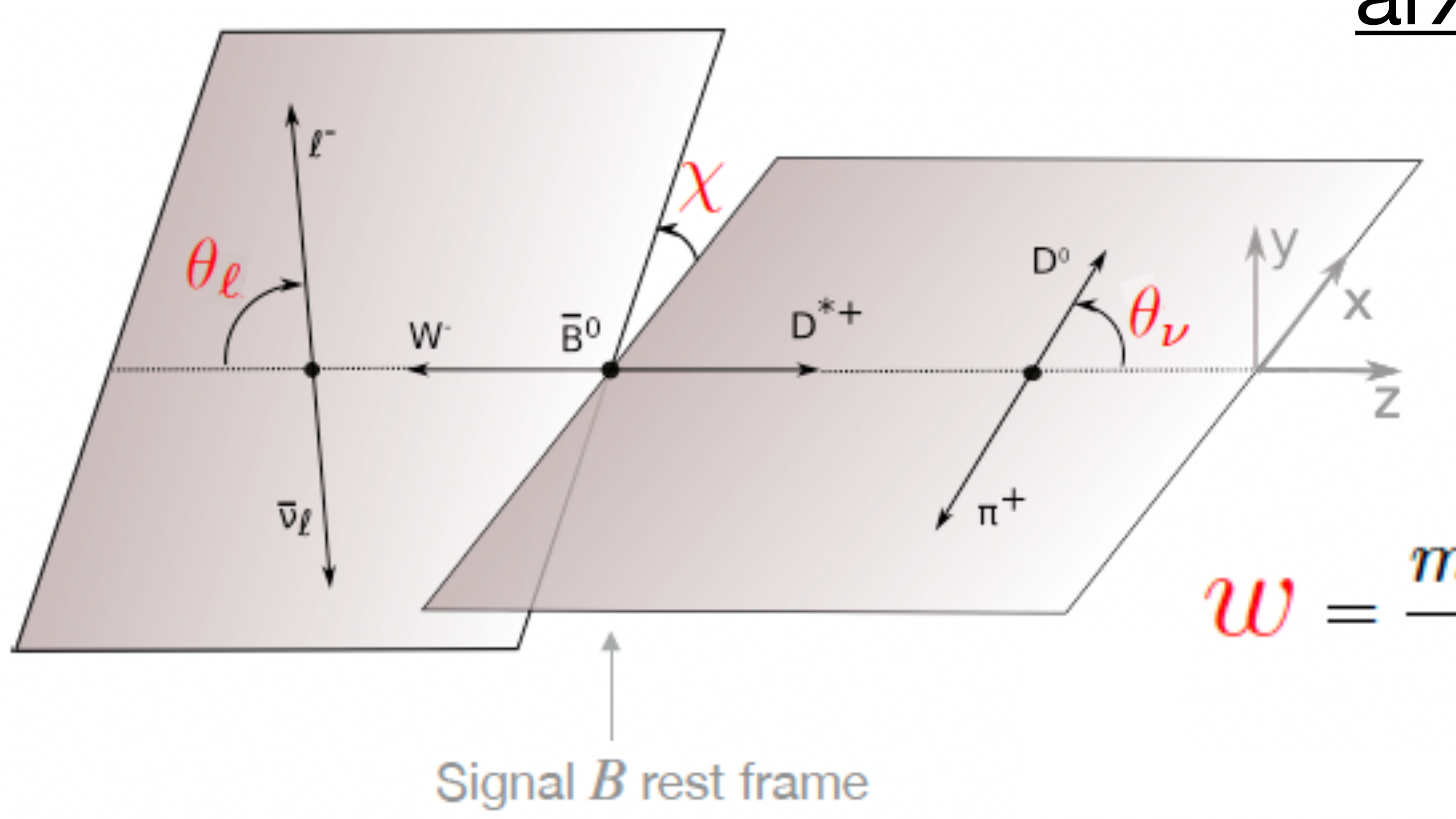
LCSR

- Leading systematic unc. are the modelling of continuum and non-resonant $B \to X_u \ell \nu$ decays
- Overall **theoretical** uncertainty dominating

Angular coefficients of $B \to D^* \ell \nu$ and $|V_{cb}|$

[arXiv: 2310.20286](https://arxiv.org/abs/2310.20286)
Preliminary

- Full Belle data set of 711 fb^{-1} for $B^{\pm,0}, \ell = e, \mu$
- **Hadronic tagging** and background subtracted via fitting M^2_{miss}
- Measured **12 angular coefficients J_i in four bins of w**
  => 4D differential decay rate
  - **Advantage**: captures the full differential information; linear combination of J_i provide SM tests
- **Extract $|V_{cb}|$ with external constraint on normalization** [HFLAV 2021] **+ LQCD beyond zero-recoil**
- Can also test **LFU** via $\Delta = J_i^e - J_i^\mu$



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

Phys.Rev.D 90 (2014) 9, 094003

$$J_i = J_i(w)$$

$$\bar{J}_i = \frac{1}{N_i} \sum_{j=1}^{8} \sum_{k,l=1}^{4} \eta^{\chi}_{i,j} \eta^{\theta_\ell}_{i,k} \eta^{\theta_V}_{i,l} \left[\chi^{(j)} \otimes \chi^{(k)} \otimes \chi^{(l)} \right]$$

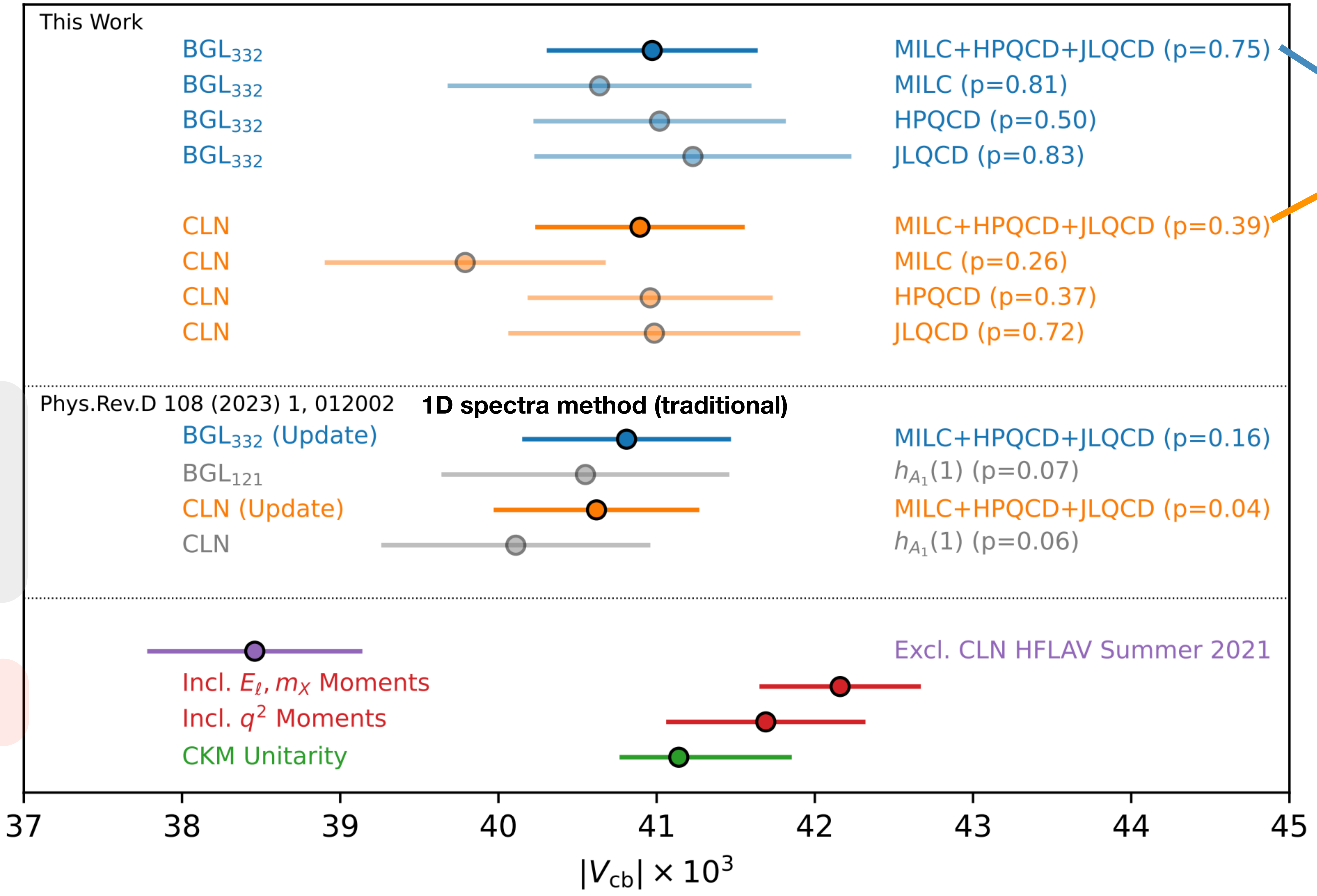
Normalization — Weights — Unfolded Yields

$$\frac{\mathrm{d}\Gamma(\bar{B} \to D^* \ell \bar{\nu}_\ell)}{\mathrm{d}w\, \mathrm{d}\cos\theta_\ell\, \mathrm{d}\cos\theta_V\, \mathrm{d}\chi} = \frac{2 G_F^2 \eta_{EW}^2 |V_{cb}|^2 m_B^4 m_{D^*}}{2\pi^4} \times \Big(J_{1s} \sin^2\theta_V + J_{1c} \cos^2\theta_V$$
$$+ (J_{2s} \sin^2\theta_V + J_{2c} \cos^2\theta_V) \cos 2\theta_\ell + J_3 \sin^2\theta_V \sin^2\theta_\ell \cos 2\chi$$
$$+ J_4 \sin 2\theta_V \sin 2\theta_\ell \cos\chi + J_5 \sin 2\theta_V \sin\theta_\ell \cos\chi + (J_{6s} \sin^2\theta_V + J_{6c} \cos^2\theta_V) \cos\theta_\ell$$
$$+ J_7 \sin 2\theta_V \sin\theta_\ell \sin\chi + J_8 \sin 2\theta_V \sin 2\theta_\ell \sin\chi + J_9 \sin^2\theta_V \sin^2\theta_\ell \sin 2\chi \Big).$$

Angular coefficients of $B \to D^* \ell \nu$ and $|V_{cb}|$

arXiv: 2310.20286
Preliminary

- Obtained $|V_{cb}|$ **agrees** with the result of fitting 1D partial rates from the same data set [PRD 108 (2023) 012002], and the p-values of fits are improved
- Also **agrees** with the latest & most precise determinations of $|V_{cb}|$ from **inclusive mode**



$$|V_{cb}| = (41.0 \pm 0.3 \pm 0.4 \pm 0.5) \times 10^{-3}\ (\mathrm{BGL}_{332})$$

$$|V_{cb}| = (40.9 \pm 0.3 \pm 0.4 \pm 0.4) \times 10^{-3}\ (\mathrm{CLN})$$

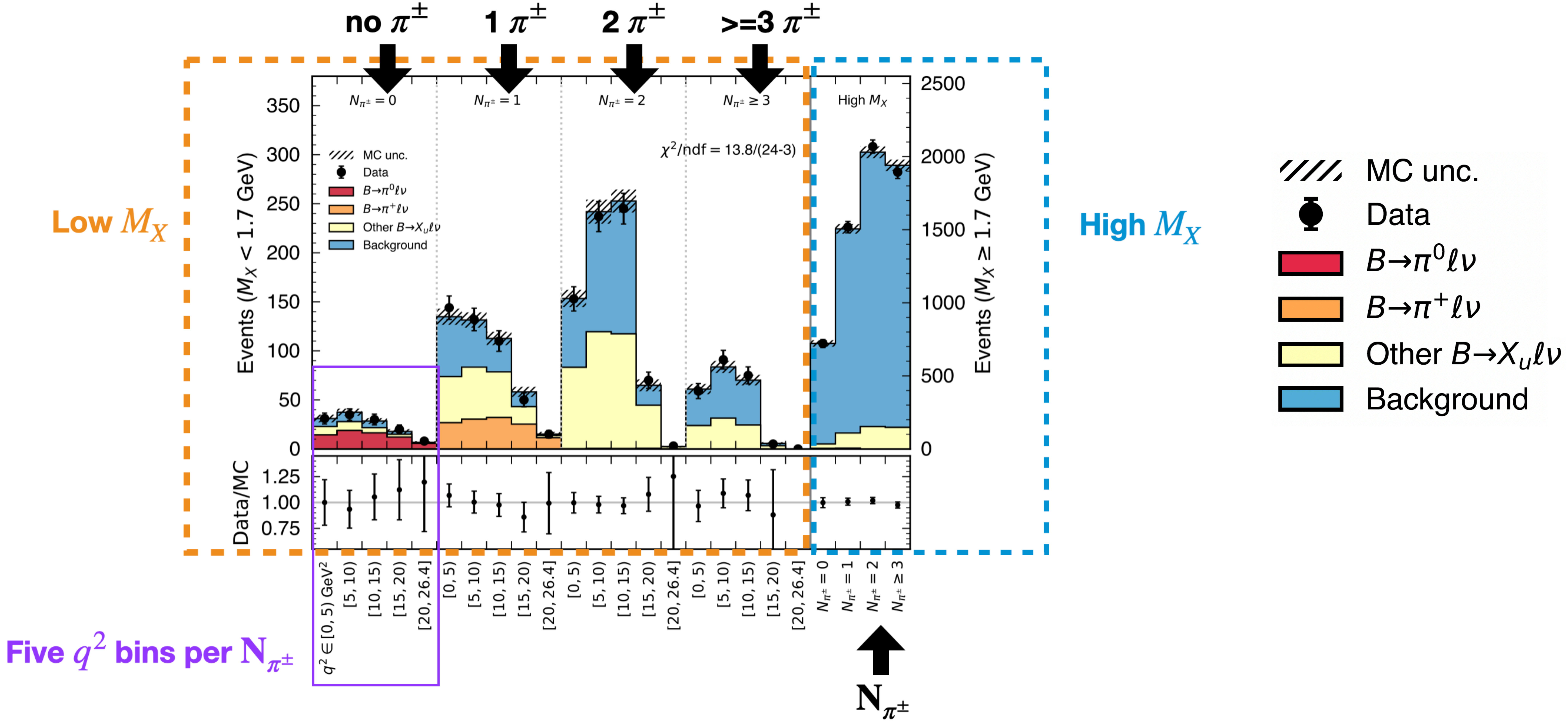
stat syst theo

- BGL truncation based on **nested hypothesis test**
- **Systematic** uncertainty dominated by limited sample size for deriving migration & efficiency corrections, branching fractions of D decay, etc.

First simultaneous determinations of incl. & excl. $|V_{ub}|$

PRL 131, 211801 (2023)

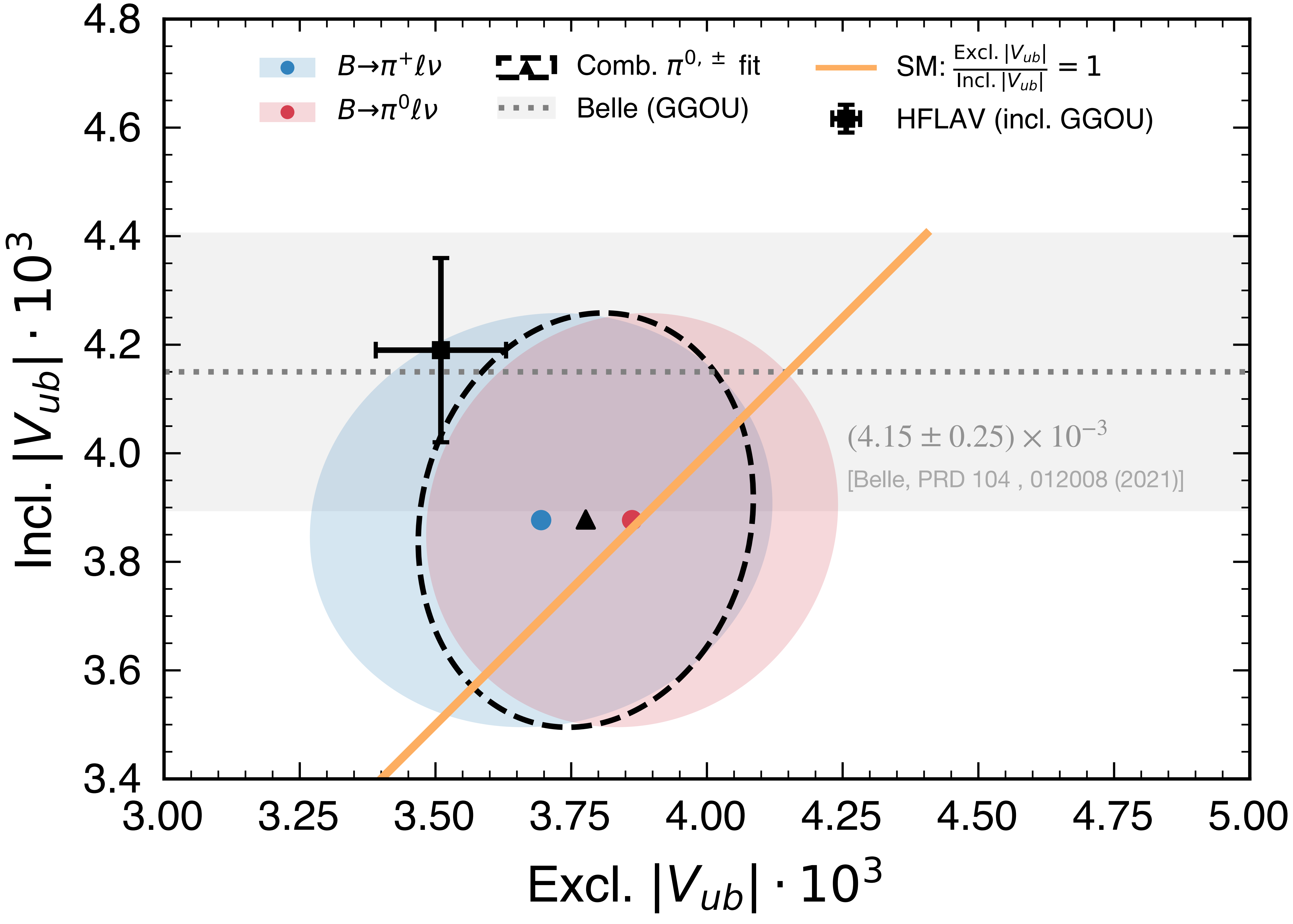
- Inherit **same analysis strategy** in the inclusive $|V_{ub}|$ measurement [Belle, PRD 104 , 012008 (2021)]
- Extract signal in q^2 and charged pion multiplicity $N_{\pi^\pm}$ for $B \to \pi\ell\nu$ and $B \to X_u\ell\nu$ simultaneously
- **Normalizations** and **$B \to \pi\ell\nu$ form factor (q^2 shape) determined by fit**



First simultaneous determinations of incl. & excl. $|V_{ub}|$

PRL 131, 211801 (2023)

- Various fit scenarios applied:
  - Input BCL constraint: **LQCD + exp.** or only LQCD [FLAG: EPJC 82, 869 (2022)]
  - **Combined** or separate $B \to \pi^+ \ell \nu$, $B \to \pi^0 \ell \nu$ (isospin relation)



Excl. $(3.78 \pm 0.23_{\text{stat}} \pm 0.16_{\text{syst}} \pm 0.14_{\text{theo}}) \times 10^{-3}$

Incl. $(3.88 \pm 0.20_{\text{stat}} \pm 0.31_{\text{syst}} \pm 0.09_{\text{theo}}) \times 10^{-3}$

Ratio $0.97 \pm 0.12 \quad (\rho = 0.11)$ compatible with the world average within 1.2σ

Weighted average of excl. & incl.

$$\left|V_{ub}\right| = (3.84 \pm 0.26) \times 10^{-3}$$

This is consistent with CKM global fit (w/o $|V_{ub}|$)**:**

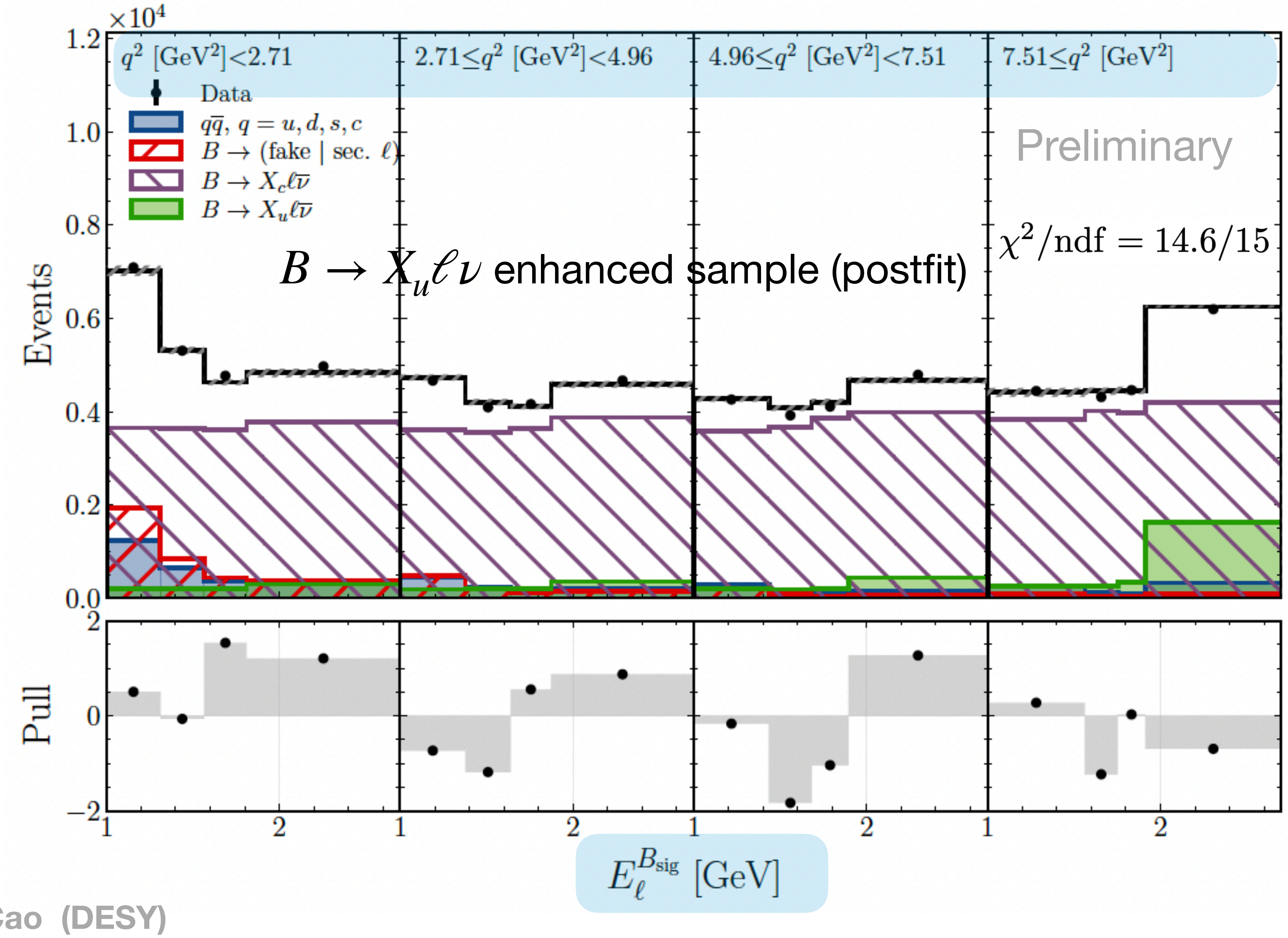
$(3.64 \pm 0.07) \times 10^{-3}$ **within 0.8σ**

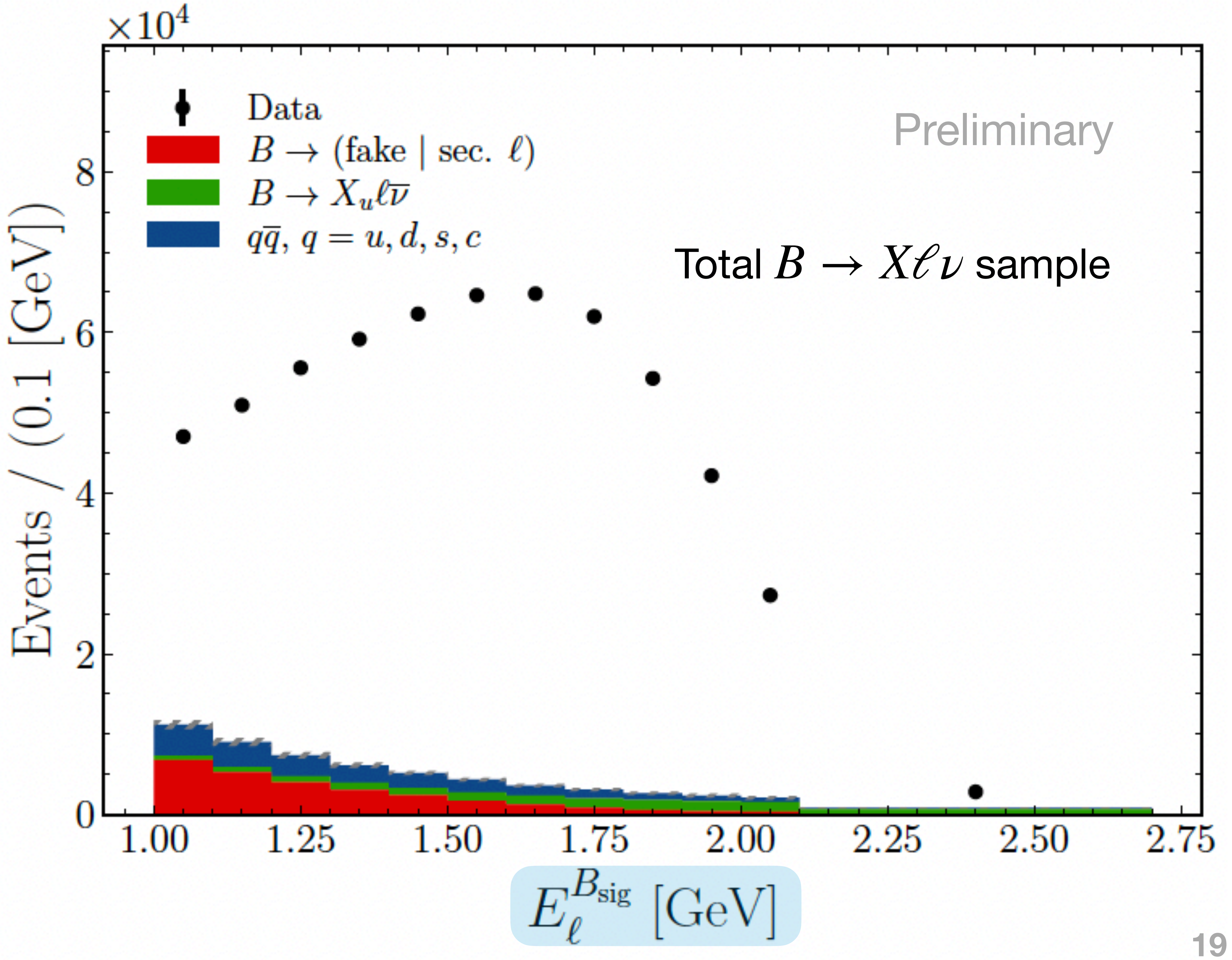
Ratio of inclusive $\Delta\mathscr{B}(B \to X_u \ell \nu)$ and $\Delta\mathscr{B}(B \to X_c \ell \nu)$

arXiv: 2311.00458

Preliminary

- Full Belle dataset of 711 fb^{-1} with **hadronic tagging** using Belle II tool (FEI [Comput.Softw.Big Sci. 3 (2019) 1, 6])
- Split into $B \to X_u \ell \nu$ **enhanced** and **depleted** sub-samples based on $N_{(K^\pm, K_s)}$, apply data-driven $B \to X_c \ell \nu$ modelling using $B \to X_u \ell \nu$ depleted sample
- $B \to X_u \ell \nu$ yields extracted in $(q^2 : E_\ell^B)$ spectra in the enhanced sample via a binned likelihood fit
- $B \to X_c \ell \nu$ yields obtained by subtracting other contributions from total $B \to X \ell \nu$





Ratio of partial BFs and inclusive $|V_{ub}|/|V_{cb}|$

arXiv: 2311.00458

Preliminary

- Measured partial phase space region of $E_\ell^B > 1\,\mathrm{GeV}$
- Phase space coverages: $\epsilon_\Delta^u = 86\,\%$, $\epsilon_\Delta^c = 78\,\%$
- Unfolded differential ratios on E_ℓ^B, q^2 also provided

$$\frac{\Delta\mathcal{B}(B \to X_u \ell \nu)}{\Delta\mathcal{B}(B \to X_c \ell \nu)} = 1.96(1 \pm 8.4\%_{\mathrm{stat}} \pm 7.9\%_{\mathrm{syst}}) \times 10^{-2}$$

dominated by $B \to X_u \ell \nu$ modelling, fake leptons and secondary decays

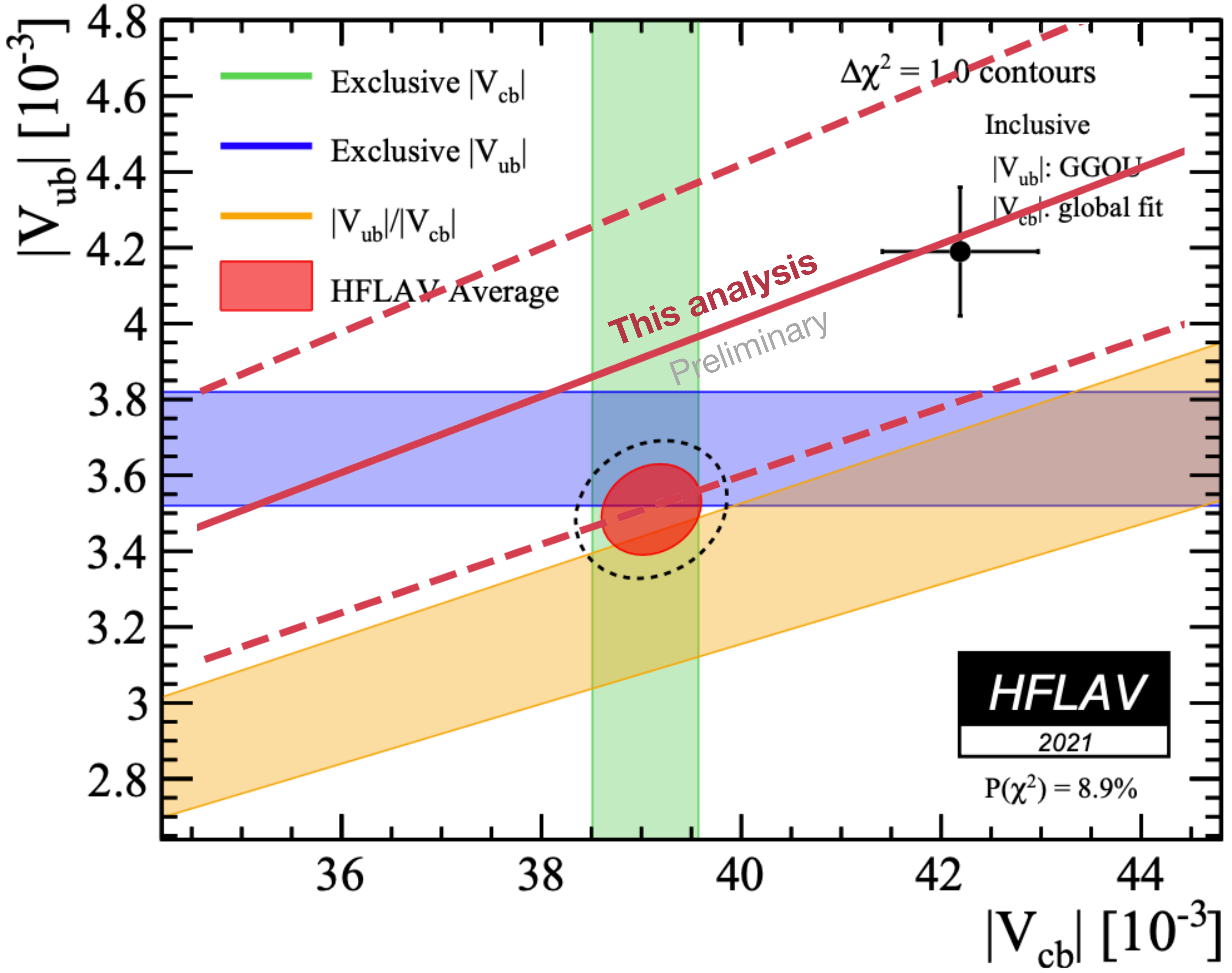
$$|V_{ub}| = \sqrt{\frac{1}{\tau_B \Delta\Gamma(B \to X_u \ell \nu)} \frac{\Delta\mathcal{B}(B \to X_u \ell \nu)}{\Delta\mathcal{B}(B \to X_c \ell \nu)} \Delta\mathcal{B}(B \to X_c \ell \nu)}$$

WA: (8.55 ± 0.16)%

$$\frac{|V_{ub}|}{|V_{cb}|} = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell \nu)}{\Delta\mathcal{B}(B \to X_c \ell \nu)} \frac{\Delta\Gamma(B \to X_c \ell \nu)}{\Delta\Gamma(B \to X_u \ell \nu)}}$$

Theo. input: $\Delta\Gamma(B \to X_u \ell \nu) = 58.5^{+2.7}_{-2.3}\,\mathrm{ps}^{-1}$ [JHEP 10 (2007) 058]

$\Delta\Gamma(B \to X_c \ell \nu) = 29.7 \pm 1.2\,\mathrm{ps}^{-1}$ [EPJ C 81, 226 (2021)]



Summary

- Many new semileptonic B decay results from Belle (II)
  - **R(D*) and R(X) LFU tests consistent with SM**
  - Long-standing **$|V_{xb}|$** puzzle still remains, especially for **$|V_{cb}|$**

- Continuous efforts from **experiment** and **theory** ALWAYS needed
  - **Higher precision** expected at Belle II for next round of new results
  - Some **systematic** error could be reduced with improved **modelling**
  - **Theoretical** error plays the leading role in some results

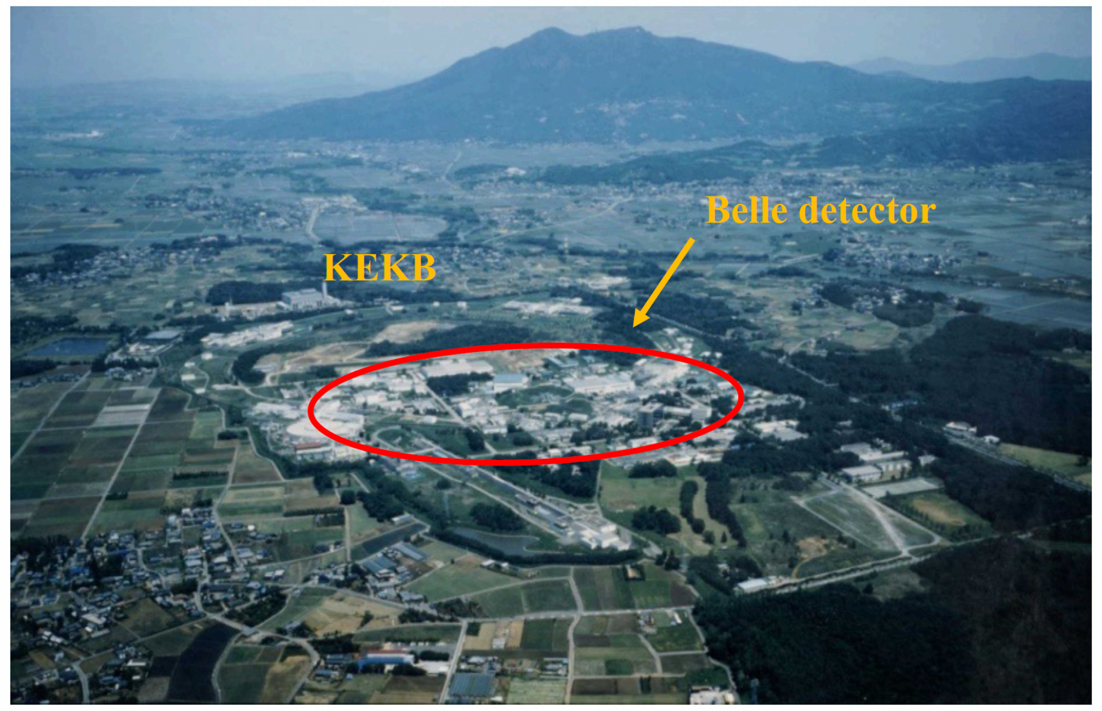
- Beyond these important results, the accumulated knowledge (MC modeling, analysis techniques, etc.) will be beneficial for future measurements by e.g. Belle II or LHCb

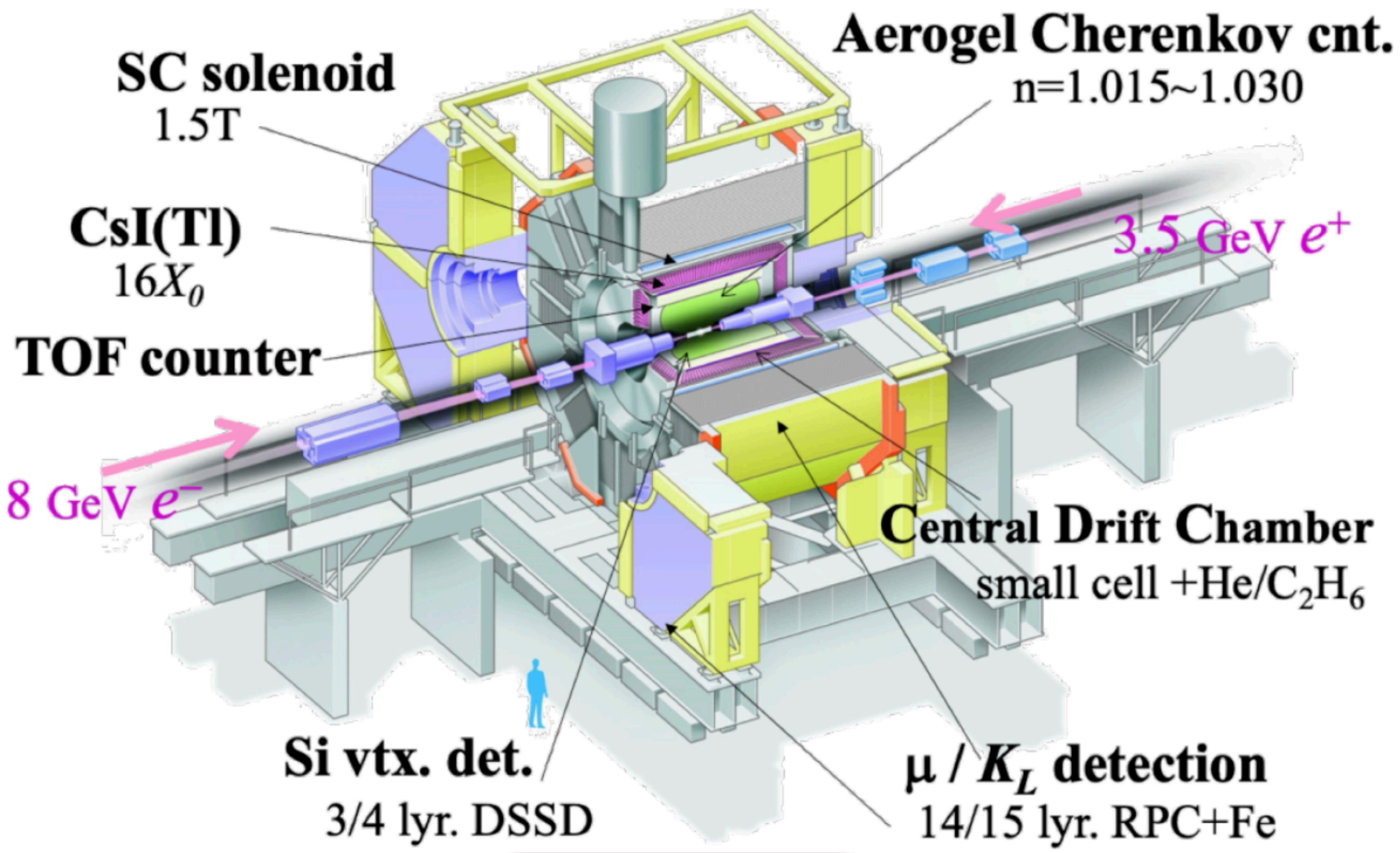
More are on the way…

Backup Slides

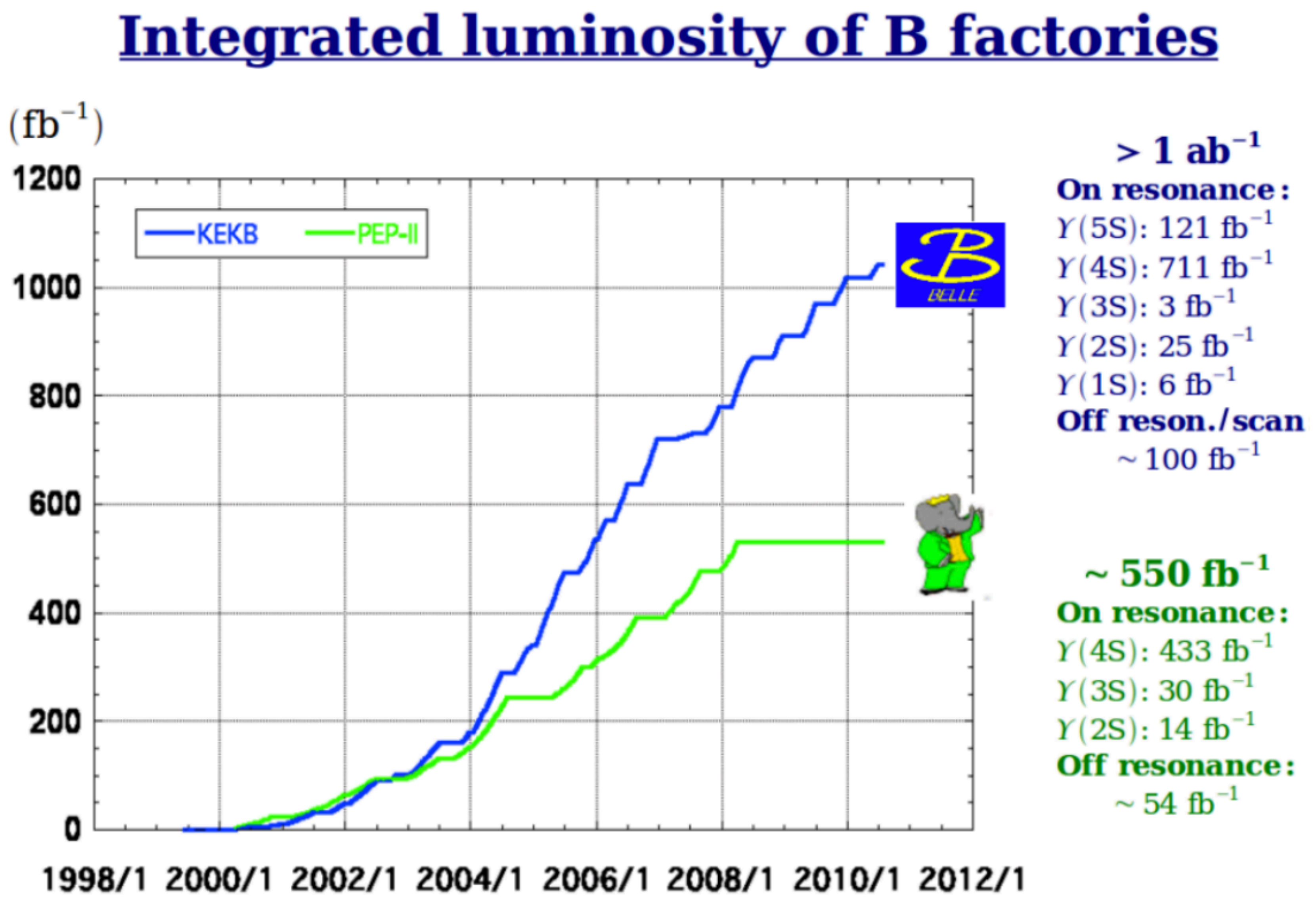
Belle Experiment

- KEKB is an asymmetric-energy e^+e^- collider operating near $\Upsilon(4S)$ mass peak
- Belle detector: nearly 4π coverage, good performances on momentum/vertex resolution, particle identification
- Unique advantages for analysing inclusive decays and process involving multiple neutrals



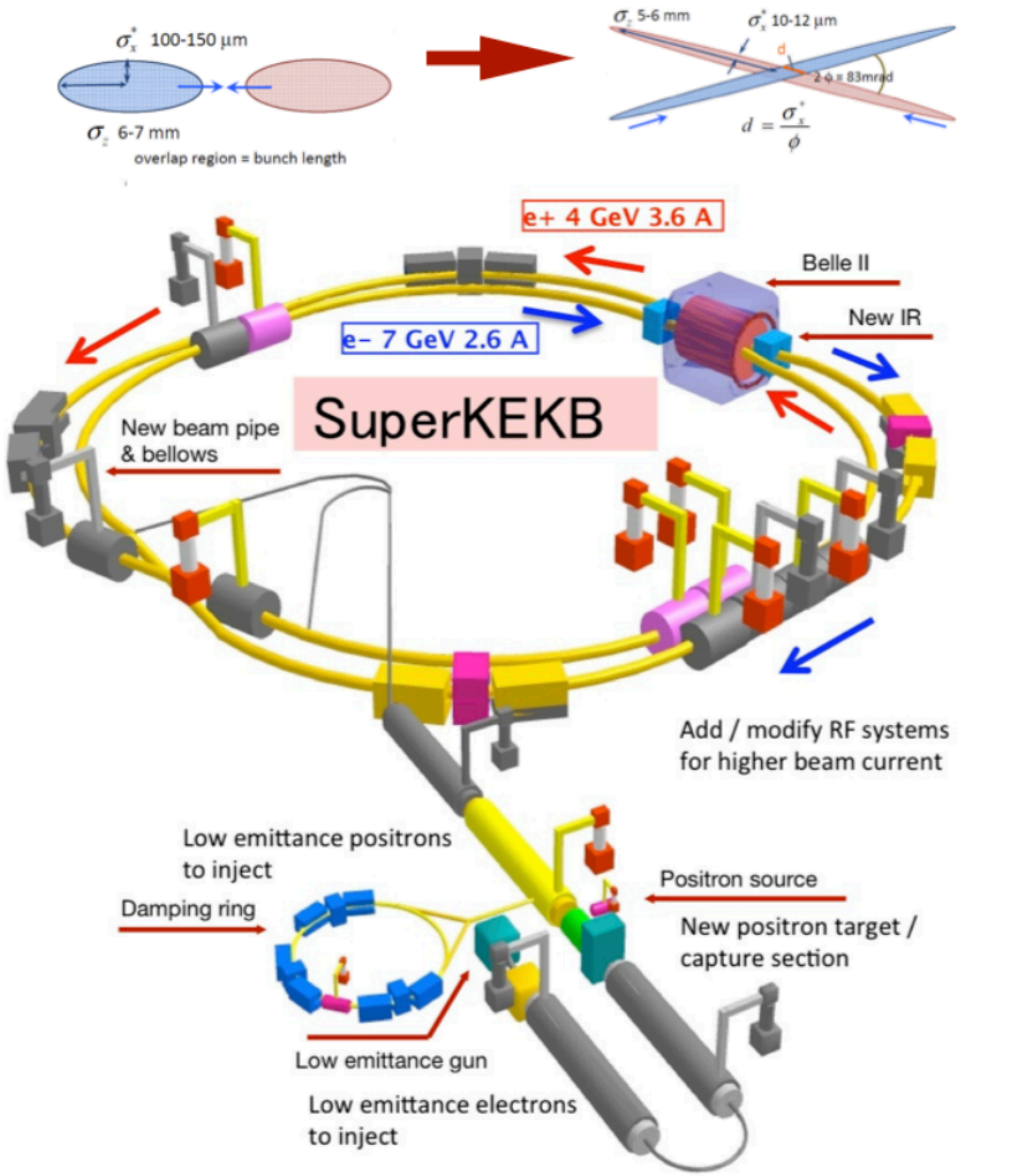


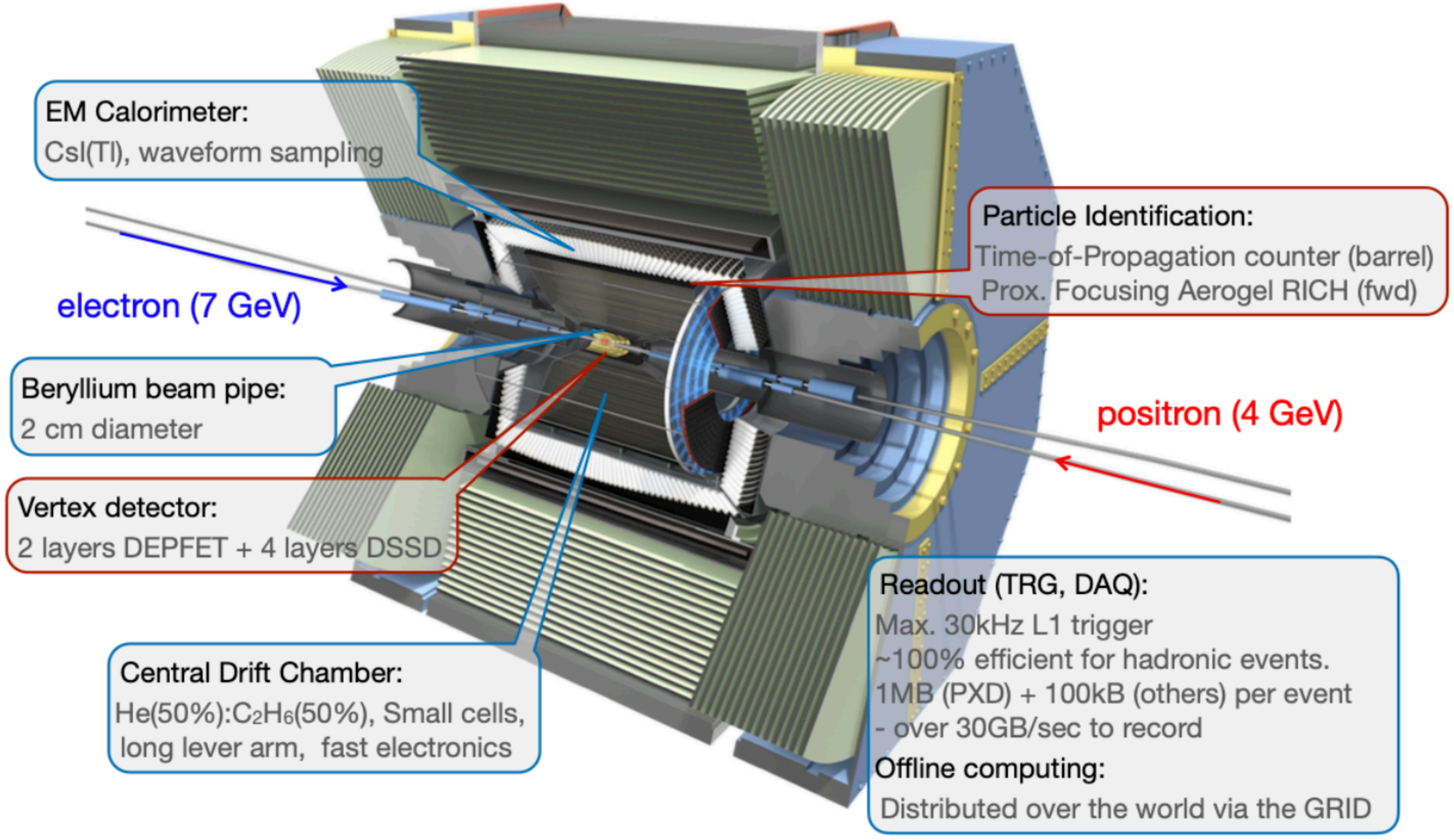
PEAK
L = 2.1 x 10^{34}/cm^2/sec



Belle II Experiment

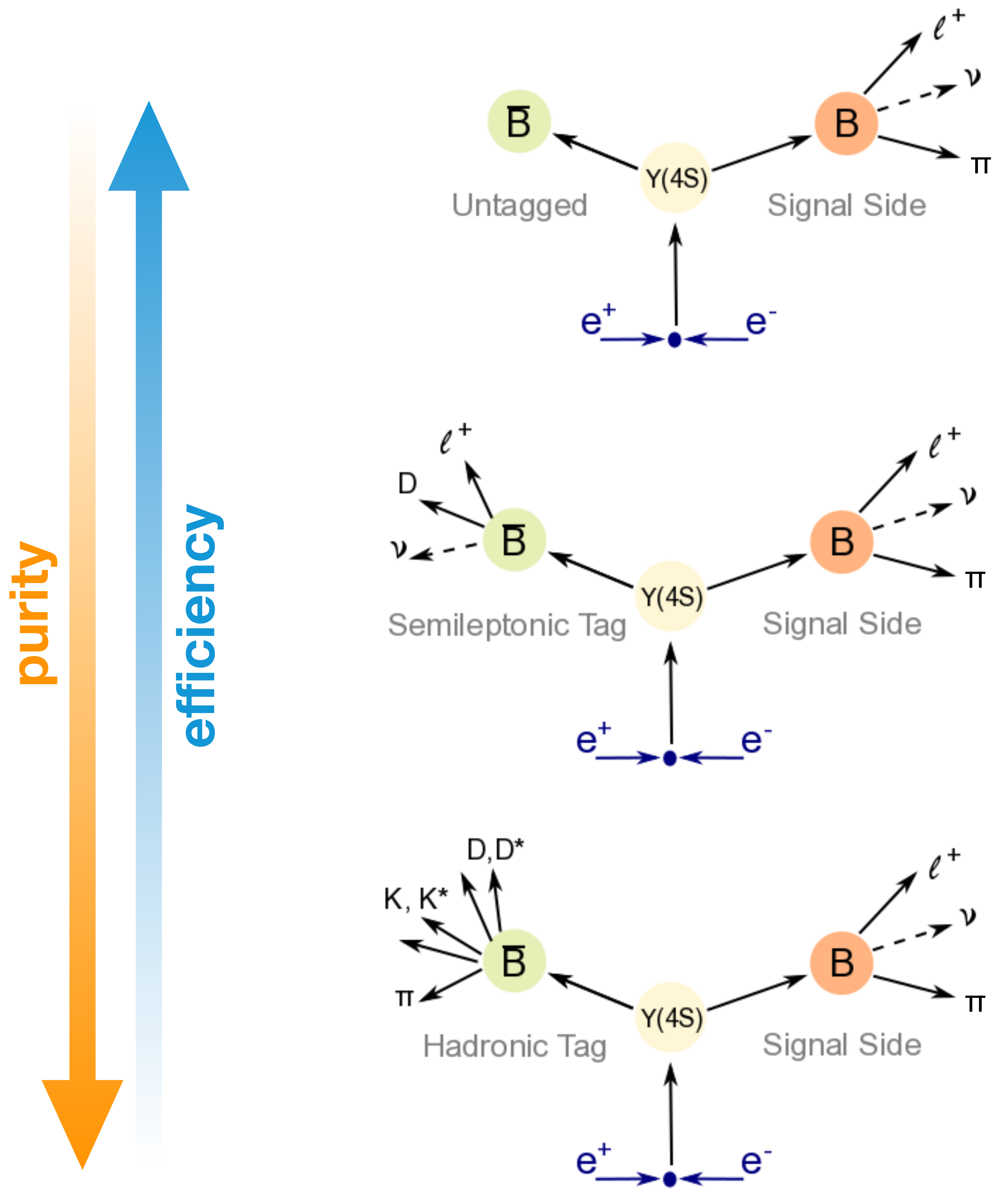
Upgraded detector and accelerator





arXiv:1011.0352 [physics.ins-det]

Backup: Tagging vs. Untagging



- Untagged
  - 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: R(D*) using hadronic B tagging at Belle II

arXiv:2401.02840
Preliminary

Table VII. Observed (expected) yields of the signal and normalization modes. The index i designates the fit category for the three D^* decays. Only statistical uncertainties are given.

Parameter	Observed (expected) yield		
	$D^{*+} \to D^0\pi^+$	$D^{*+} \to D^+\pi^0$	$D^{*0} \to D^0\pi^0$
$N^i_{D^*\tau\nu} + N^i_{D^*\tau\nu,\ell\text{-misID}}$	50.9 ± 7.8	7.8 ± 1.2	49.2 ± 7.5
$N^i_{D^*\ell\nu}$	1084.6 ± 36.7 (1041.0 ± 11.2)	137.9 ± 6.6 (133.2 ± 4.3)	940.9 ± 36.0 (927.2 ± 10.7)

$$\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell) = (5.27\ ^{+0.25}_{-0.24})\ \%,$$

$$\mathcal{B}(B^- \to D^{*0}\ell^-\overline{\nu}_\ell) = (5.50\ ^{+0.28}_{-0.27})\ \%.$$

Table VIII. Summary of systematic uncertainties on $R(D^*)$.

Source	Uncertainty
PDF shapes	$^{+9.1\%}_{-8.3\%}$
Simulation sample size	$^{+7.5\%}_{-7.5\%}$
$\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell$ branching fractions	$^{+4.8\%}_{-3.5\%}$
Fixed backgrounds	$^{+2.7\%}_{-2.3\%}$
Hadronic B decay branching fractions	$^{+2.1\%}_{-2.1\%}$
Reconstruction efficiency	$^{+2.0\%}_{-2.0\%}$
Kernel density estimation	$^{+2.0\%}_{-0.8\%}$
Form factors	$^{+0.5\%}_{-0.1\%}$
Peaking background in ΔM_{D^*}	$^{+0.4\%}_{-0.4\%}$
$\tau^- \to \ell^-\nu_\tau\overline{\nu}_\ell$ branching fractions	$^{+0.2\%}_{-0.2\%}$
$R(D^*)$ fit method	$^{+0.1\%}_{-0.1\%}$
Total systematic uncertainty	$^{+13.5\%}_{-12.3\%}$

Backup: First Measurement of $R(X)_{\tau/\ell}$

arXiv:2311.07248
Preliminary

Table I: Relative statistical and systematic uncertainties on the value of $R(X_{\tau/\ell})$.

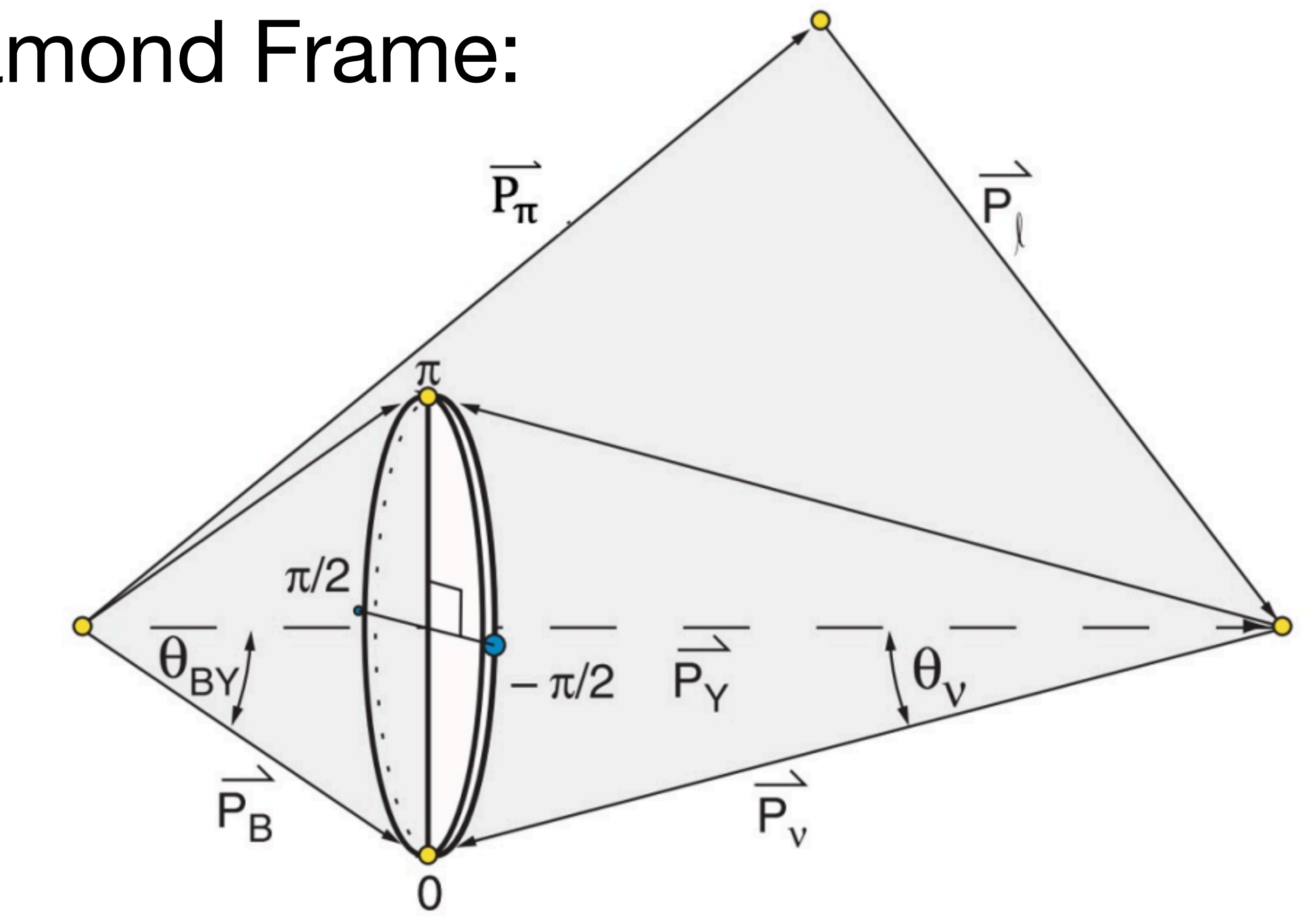
Source	Uncertainty [%]		
	e	μ	ℓ
Experimental sample size	8.8	12.0	7.1
Simulation sample size	6.7	10.6	5.7
Tracking efficiency	2.9	3.3	3.0
Lepton identification	2.8	5.2	2.4
$X_c\ell\nu$ M_X shape	7.3	6.8	7.1
Background (p_ℓ, M_X) shape	5.8	11.5	5.7
$X\ell\nu$ branching fractions	7.0	10.0	7.7
$X\tau\nu$ branching fractions	1.0	1.0	1.0
$X_c\tau(\ell)\nu$ form factors	7.4	8.9	7.8
Total	18.1	25.6	17.3

Backup: Simultaneous measurements of $B^0 \to \pi^- \ell^+ \nu$, $B^+ \to \rho^0 \ell^+ \nu$

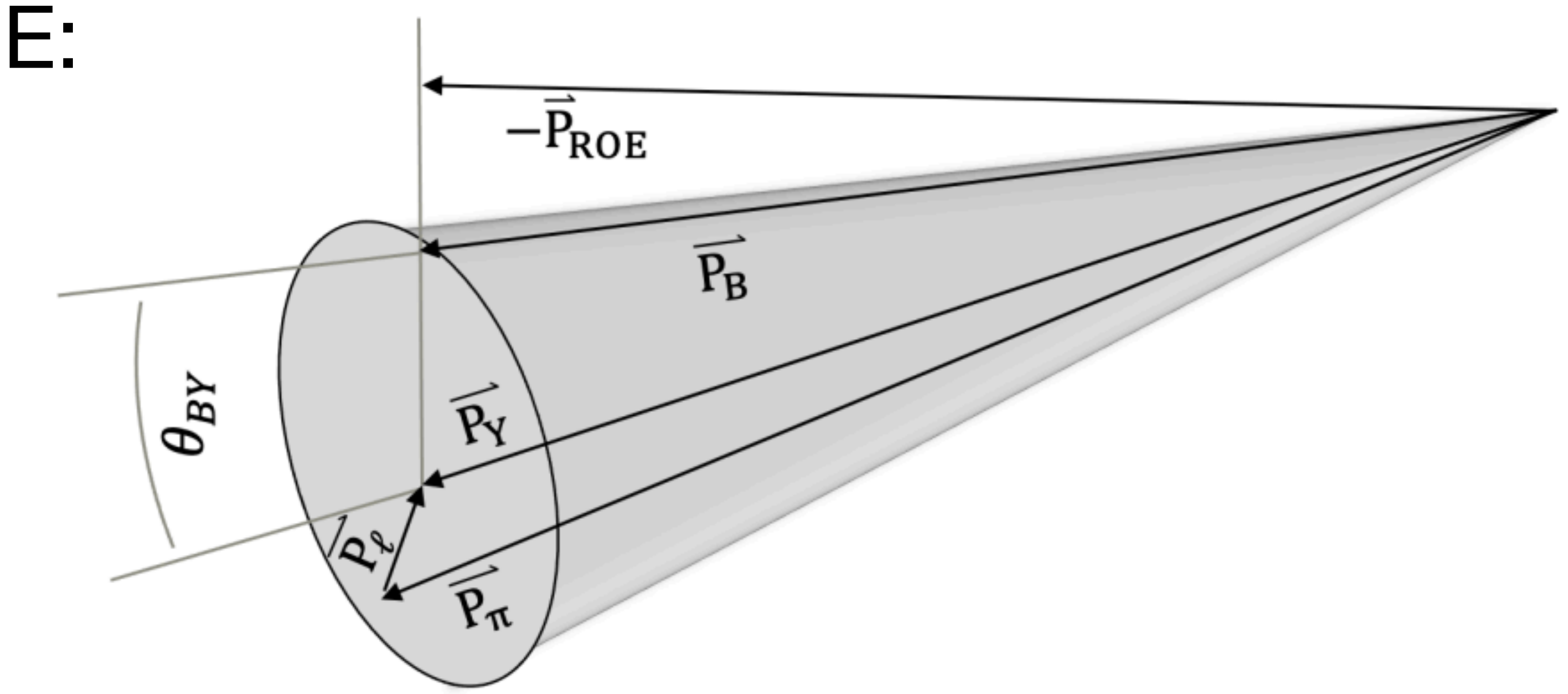
Preliminary

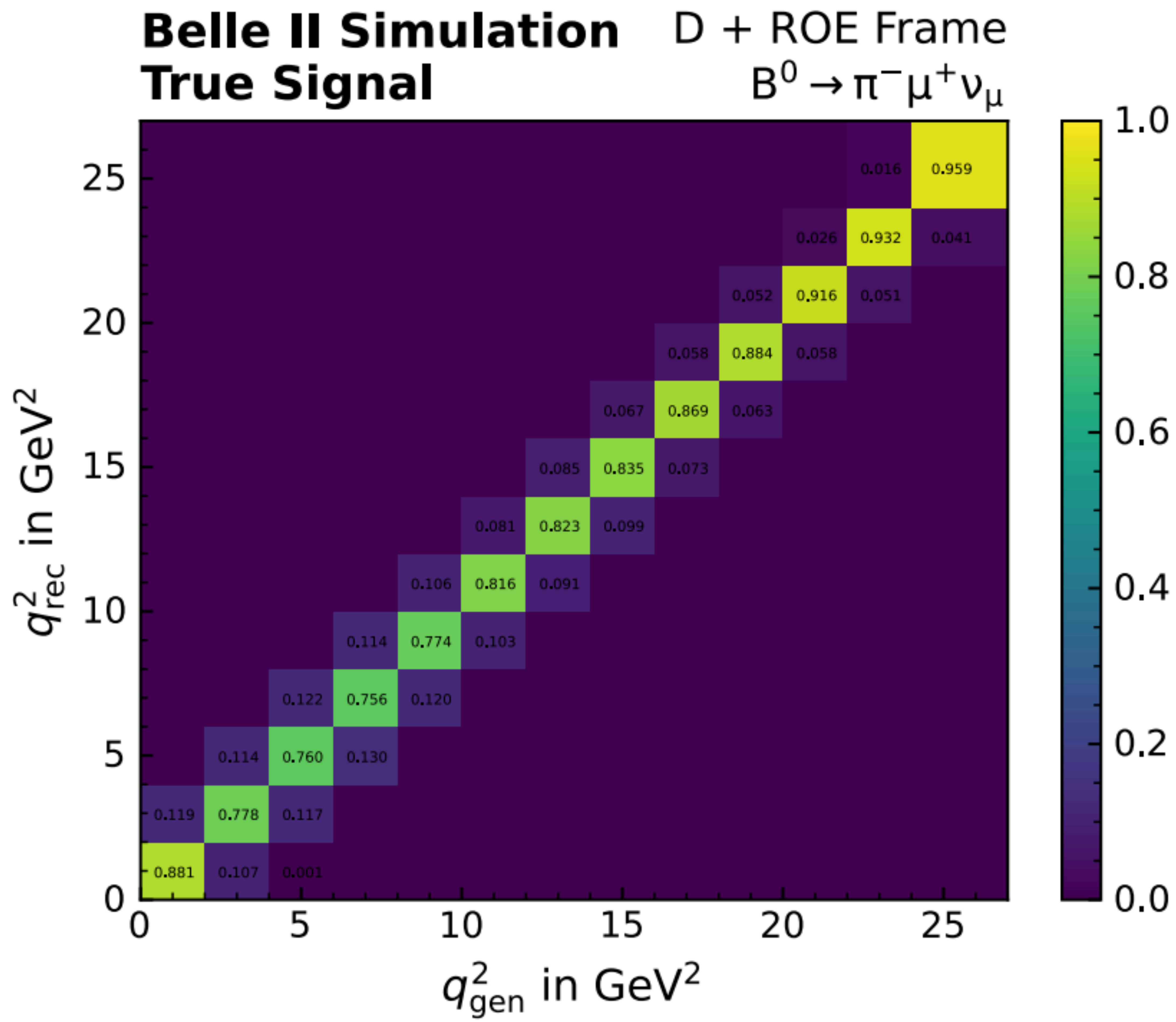
- Reconstruct q² based on Diamond Frame (BaBar's approach) and the rest of even method (Belle's approach)

Diamond Frame:



ROE:



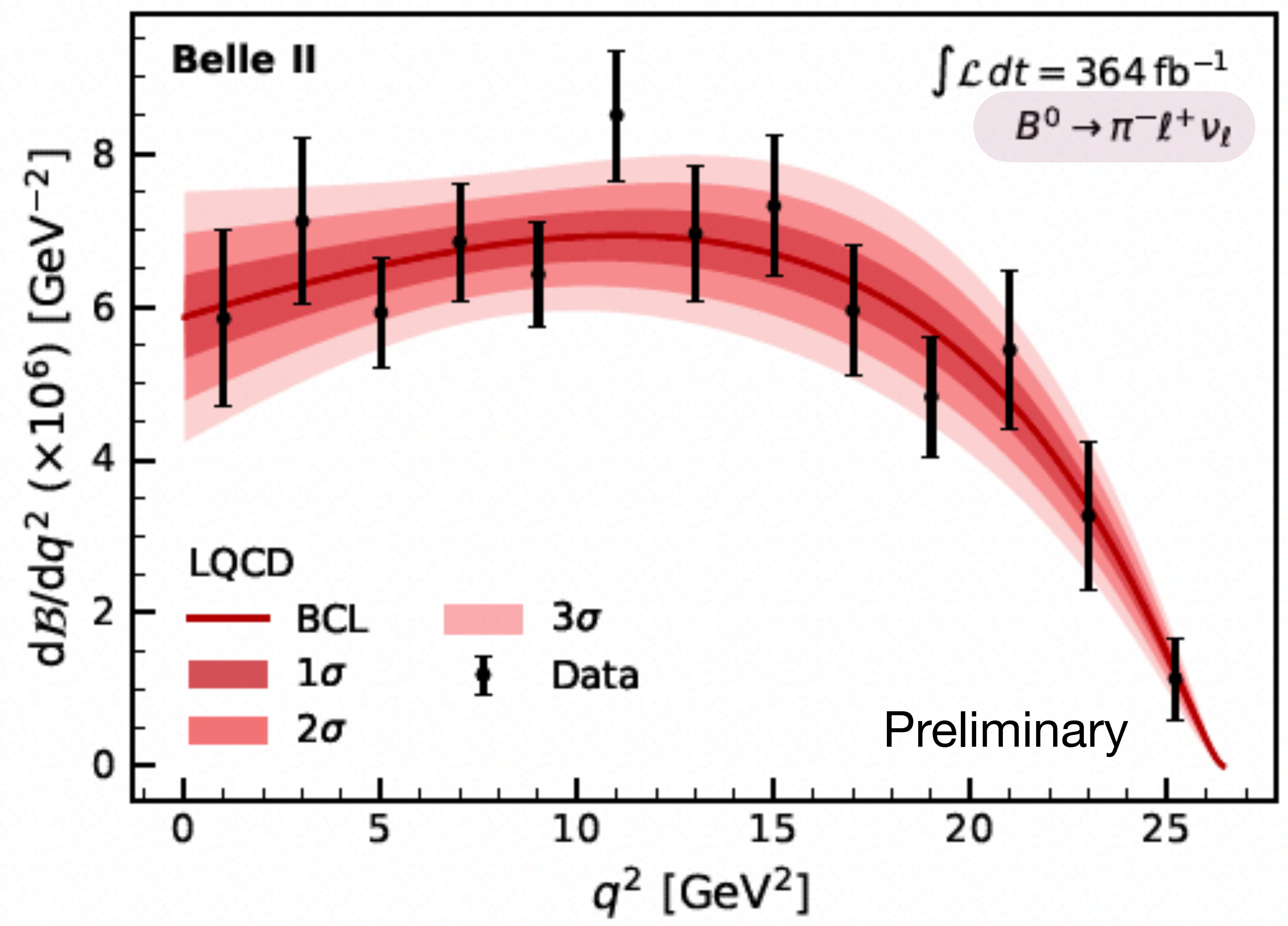


Backup: Simultaneous measurements of $B^0 \to \pi^- \ell^+ \nu$, $B^+ \to \rho^0 \ell^+ \nu$

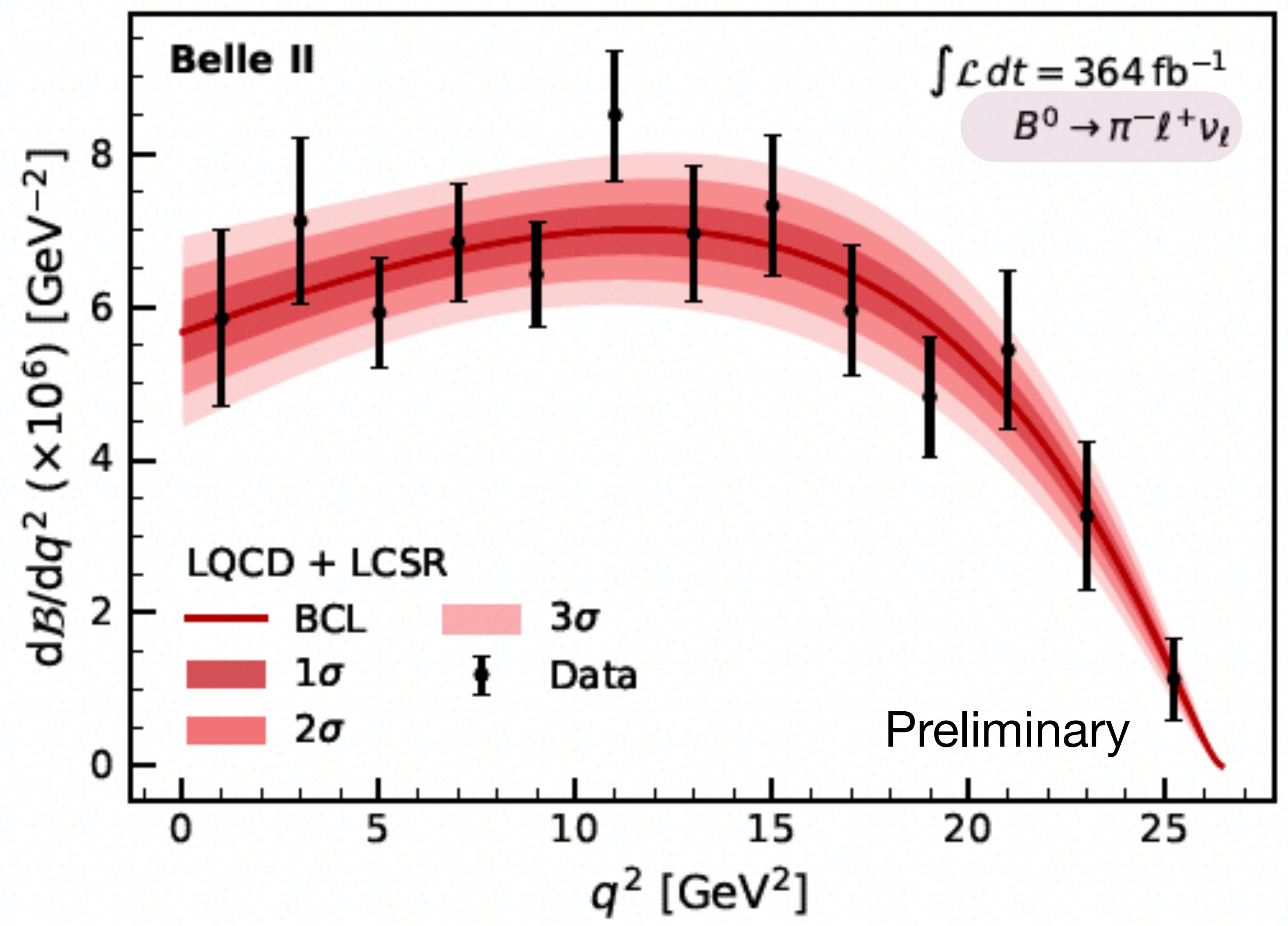
- Extracted $|V_{ub}|$ with lattice QCD and/or light-cone sum rules (LCSR) constraints of form factors

Preliminary

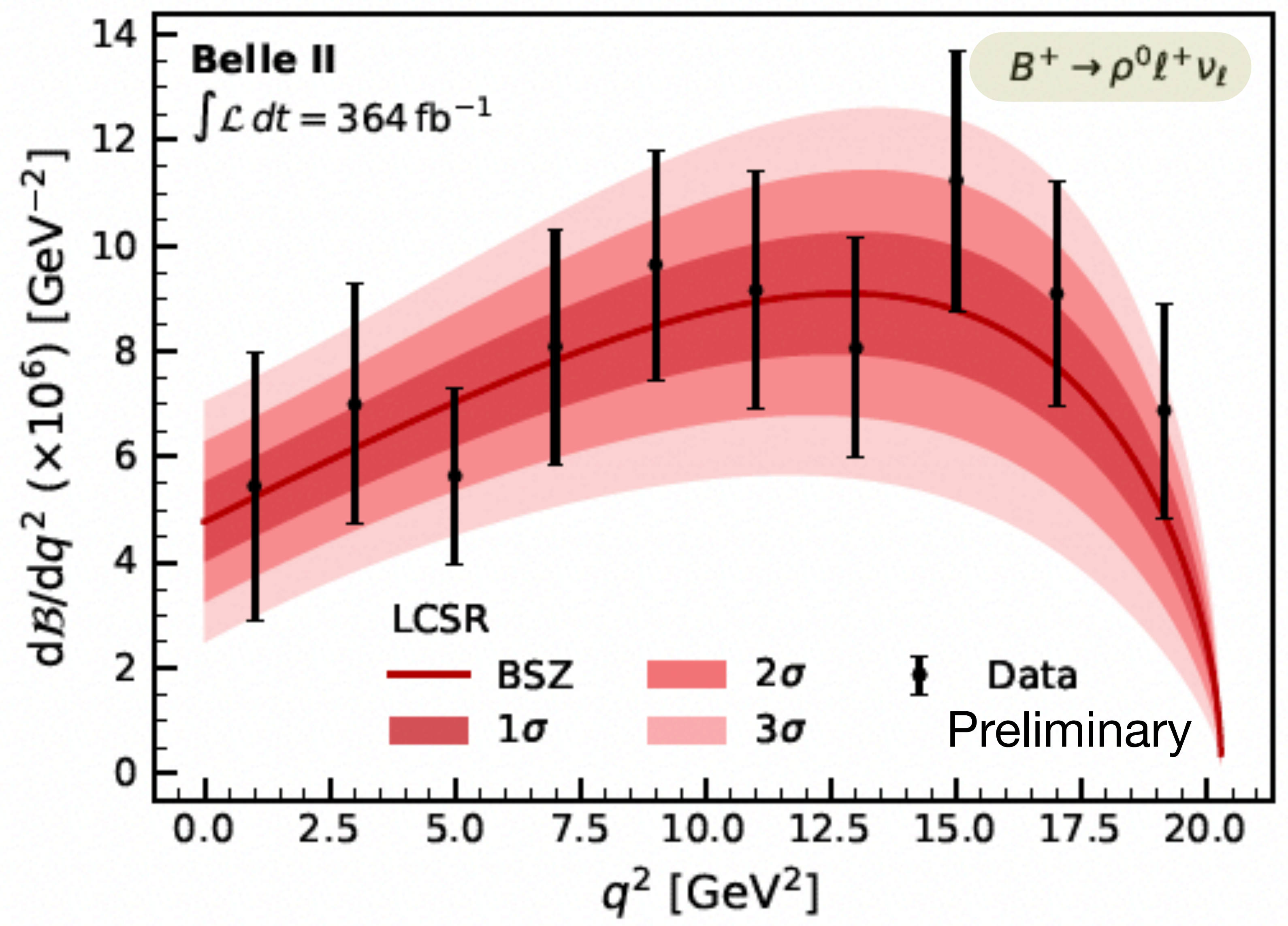
only LQCD [FLAG]



LQCD [FLAG] + LCSR [JHEP 07 (2021) 036]



LCSR [JHEP 08 (2016) 098]



		$B^0 \to \pi^- \ell^+ \nu_\ell$	
		LQCD	LQCD + LCSR
$\lvert V_{ub}\rvert$ (10^{-3})		3.93 ± 0.25	3.73 ± 0.19
$f_+(q^2)$	b_0^+	0.42 ± 0.02	0.45 ± 0.02
	b_1^+	-0.52 ± 0.05	-0.52 ± 0.05
	b_2^+	-0.81 ± 0.21	-1.02 ± 0.18
$f_0(q^2)$	b_0^0	0.02 ± 0.25	0.59 ± 0.02
	b_1^0	-1.43 ± 0.08	-1.39 ± 0.07
χ^2/ndf		8.387/7	8.359/7

		$B^+ \to \rho^0 \ell^+ \nu_\ell$
		LCSR
$\lvert V_{ub}\rvert$ (10^{-3})		3.19 ± 0.33
$A_1(q^2)$	$b_0^{A_1}$	0.27 ± 0.03
	$b_1^{A_1}$	0.34 ± 0.13
$A_2(q^2)$	$b_0^{A_2}$	0.29 ± 0.03
	$b_1^{A_2}$	0.66 ± 0.17
$V(q^2)$	b_0^V	0.33 ± 0.03
	b_1^V	-0.93 ± 0.17
χ^2/ndf		3.850/3

Backup: Simultaneous measurements of $B^0 \to \pi^- \ell^+ \nu$, $B^+ \to \rho^0 \ell^+ \nu$

Preliminary

- Uncertainties in % on the partial BRs

	$B^0 \to \pi^- \ell^+ \nu_\ell$												
Source	$q1$	$q2$	$q3$	$q4$	$q5$	$q6$	$q7$	$q8$	$q9$	$q10$	$q11$	$q12$	$q13$
Detector effects	2.0	0.9	1.1	1.0	1.0	1.1	1.1	1.0	0.9	1.2	2.3	4.1	5.8
Beam energy	0.6	0.8	0.7	0.8	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.6	0.7
Simulated sample size	4.7	3.8	3.3	3.2	3.2	2.9	3.8	3.7	4.0	4.5	5.9	8.0	13.6
BDT efficiency	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Physics constraints	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Signal model	0.1	0.1	0.2	0.1	0.0	0.2	0.2	0.4	0.3	0.8	0.9	0.2	4.9
ρ lineshape	0.1	0.1	0.3	0.3	0.2	0.1	0.3	0.1	0.3	0.1	0.2	0.2	0.6
Nonres. $B \to \pi\pi\ell\nu_\ell$	0.5	0.6	0.4	0.4	0.5	1.0	1.2	1.0	0.8	1.8	1.2	2.3	14.3
DFN parameters	0.8	0.4	1.5	1.6	1.4	1.7	1.2	0.1	0.7	1.2	2.9	3.5	3.7
$B \to X_u\ell\nu_\ell$ model	0.2	0.4	0.3	0.4	0.2	0.9	1.1	1.2	1.0	1.3	1.6	0.7	8.7
$B \to X_c\ell\nu_\ell$ model	1.4	2.0	1.7	1.3	1.3	1.4	1.8	1.6	1.3	1.4	1.1	0.5	1.7
Continuum	15.1	11.3	7.6	7.1	5.8	5.7	8.1	8.3	9.6	10.4	14.5	23.8	34.4
Total syst.	16.4	12.6	9.3	8.7	7.7	7.7	10.0	9.9	11.1	12.2	16.6	26.0	41.6
Stat.	11.0	8.8	7.9	7.0	7.5	6.4	7.9	7.7	9.1	10.7	9.6	14.6	22.6
Total	19.7	15.4	12.2	11.2	10.7	10.0	12.7	12.6	14.4	16.3	19.1	29.8	47.3

	$B^+ \to \rho^0 \ell^+ \nu_\ell$									
Source	$q1$	$q2$	$q3$	$q4$	$q5$	$q6$	$q7$	$q8$	$q9$	$q10$
Detector effects	2.8	2.0	1.6	1.1	1.7	1.9	2.4	1.4	1.4	1.6
Beam energy	2.1	1.9	1.9	1.5	1.3	1.1	1.0	0.9	0.8	0.5
Simulated sample size	14.1	7.8	7.4	6.3	6.3	5.2	6.4	5.6	6.2	7.3
BDT efficiency	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Physics constraints	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Signal model	0.7	0.2	0.2	0.2	0.3	0.4	0.5	0.3	1.8	2.4
ρ lineshape	1.7	1.6	2.0	1.0	1.9	1.8	1.4	0.9	1.6	1.7
Nonres. $B \to \pi\pi\ell\nu_\ell$	5.6	6.3	6.7	8.6	9.3	10.7	10.1	7.0	7.8	11.8
DFN parameters	3.6	5.5	4.1	3.5	1.1	1.2	2.7	1.7	1.9	2.3
$B \to X_u\ell\nu_\ell$ model	1.7	3.0	3.8	5.0	5.8	6.1	6.3	1.9	7.2	12.4
$B \to X_c\ell\nu_\ell$ model	1.8	1.9	1.7	1.1	1.4	1.7	0.9	0.9	1.9	2.6
Continuum	31.5	24.3	17.0	19.6	13.2	14.8	16.0	16.6	15.2	18.7
Total syst.	35.6	27.5	21.0	23.5	18.8	20.5	21.6	19.4	20.2	27.0
Stat.	30.0	17.5	20.8	14.4	12.4	13.6	14.1	10.4	12.2	11.8
Total	46.6	32.6	29.6	27.6	22.6	24.6	25.8	22.0	23.6	29.5

Backup: Simultaneous measurements of $B^0 \to \pi^- \ell^+ \nu$, $B^+ \to \rho^0 \ell^+ \nu$

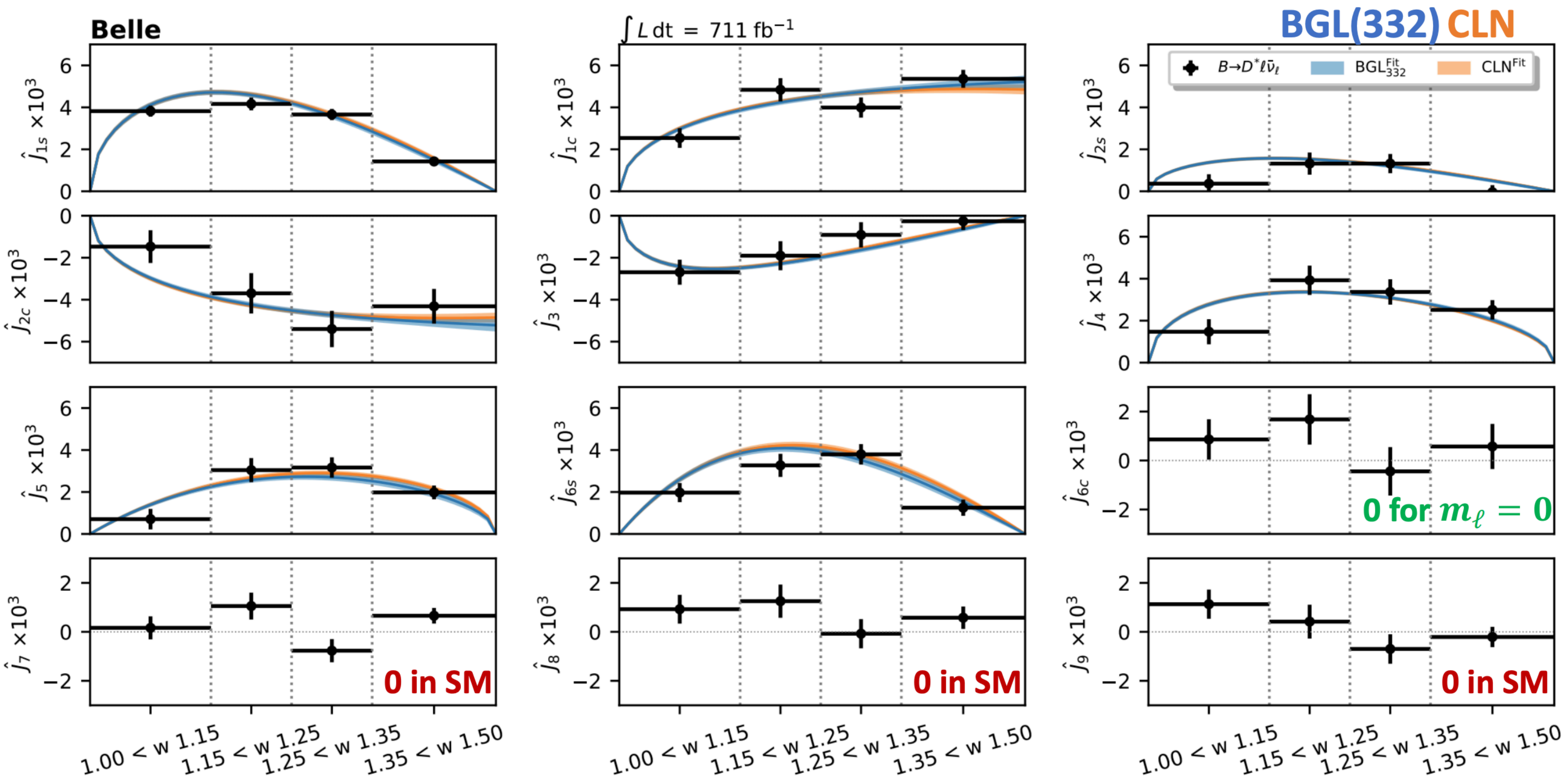
Preliminary

- Uncertainties in % on $|V_{ub}|$

	$B^0 \to \pi^- \ell^+ \nu_\ell$		$B^+ \to \rho^0 \ell^+ \nu_\ell$
	LQCD	LQCD + LCSR	LCSR
Detector effects	0.64	0.24	0.44
Beam energy	0.05	0.03	0.09
Simulated sample size	1.51	0.78	1.41
BDT efficiency	0.31	0.21	0.28
Physics constraints	0.61	0.43	0.88
Signal model	0.38	0.13	0.41
ρ lineshape	0.26	0.21	0.13
Nonres. $B \to \pi\pi\ell\nu_\ell$	0.43	0.11	1.97
DFN parameters	0.64	0.32	0.88
$B \to X_u \ell \nu_\ell$ model	0.61	0.40	1.56
$B \to X_c \ell \nu_\ell$ model	0.51	0.43	0.50
Continuum	2.39	1.37	4.91
Total syst.	3.26	1.91	5.33
Stat.	2.31	1.82	3.76
Theory	4.83	4.29	8.15
Total	6.40	5.13	10.34

Backup: Angular Coefficients of $B \to D^* \ell \nu$

arXiv: 2310.20286
Preliminary

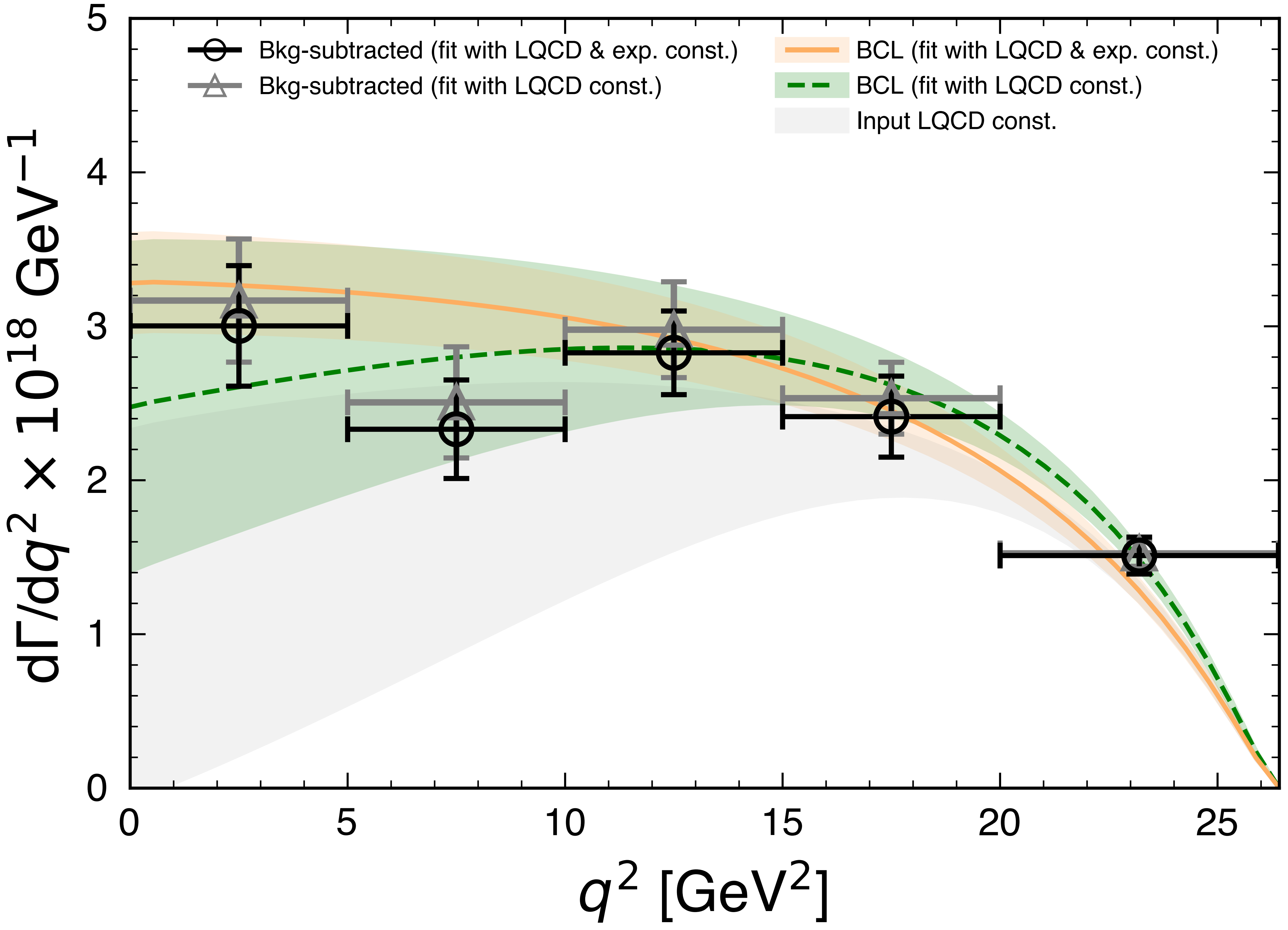


Backup: First Simultaneous Determination of Incl. & Excl. $|V_{ub}|$

- Various fit scenarios applied:
  - **Combined** or separate $B \to \pi^+\ell\nu$, $B \to \pi^0\ell\nu$ (isospin relation)
  - Input BCL constraint: **LQCD + exp.** or **only LQCD** [FLAG: Eur. Phys. J. C 82, 869 (2022)]

PRL 131, 211801 (2023)

q^2 spectra with **fitted BCL para.** (linked $\pi^{0,\pm}$)



Points: subtract other $B \to X_u\ell\nu$ and background in data, and apply unfolding + eff. correction

Fitted BCL parameters (LQCD + exp.)

	$\|V_{ub}\| \times 10^3$	a_0^+	a_1^+	a_2^+	a_0^0	a_1^0
Central	3.777	0.414	-0.493	-0.297	0.500	-1.426
Uncertainty	0.309	0.014	0.053	0.180	0.023	0.054
$\|V_{ub}\|$	1.000	-0.452	-0.168	0.232	-0.109	-0.105
a_0^+		1.000	0.151	-0.451	0.259	0.142
a_1^+			1.000	-0.798	-0.096	0.214
a_2^+				1.000	0.012	-0.097
a_0^0					1.000	-0.451
a_1^0						1.000

Backup: First Simultaneous Determination of Incl. & Excl. $|V_{ub}|$

PRL 131, 211801 (2023)

Leading Systematic Uncertainties

Sources	Relative Syst. Uncertainty
Exclusive mode	$\mathscr{B}(B \to \pi \ell \nu)$
Tagging efficiency	4.1%
$B \to X_u \ell \nu$ modelling	3.5%
$B \to X_c \ell \nu$ modelling	1.2%
Inclusive mode	$\Delta\mathscr{B}(B \to X_u \ell \nu)$
$B \to X_u \ell \nu$ modelling	10.9%
Fragmentation	5.3%
$B \to X_c \ell \nu$ modelling	2.8%

Backup: Other Recent Results from Belle II

LFU Tests	References
$R(X_{e/\mu})$	Phys. Rev. Let. 131, 05184 (2023)
$B^0 \to D^{*-}\ell^+\nu\ (\ell = e, \mu)$ angular asymmetries	Phys. Rev. Let. 131, 181801 (2023)

	$\lvert V_{cb}\rvert \times 10^3$	References
$B^0 \to D^{*-}\ell^+\nu$, untagged	**40.57 ± 1.16 (BGL)**	Phys. Rev. D 108, 092013 (2023)
$B^0 \to D^{*-}\ell^+\nu$, tagged	**37.9 ± 2.7 (CLN)**	arXiv:2301.04716
$B \to D\ell\nu$, untagged	**38.28 ± 1.16 (BGL)**	arXiv:2210.13143
	$\lvert V_{ub}\rvert \times 10^3$	
$B \to \pi e\nu$, tagged	**3.88 ± 0.45**	arXiv:2206.08102
$B \to \pi\ell\nu$, untagged	**3.55 ± 0.25**	arXiv:2210.04224

Preliminary

Preliminary

More are on the way…