Updates of V_{cb}, V_{ub} Tensions from Belle (II)

Youngjoon Kwon (Yonsei U.)

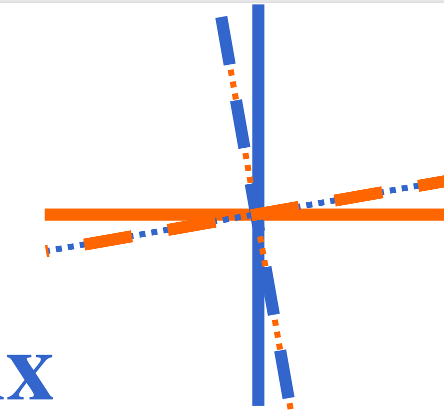
Nov. 5, 2024 @ Saga-Yonsei XXI

Fermions of SM

$$\begin{bmatrix} \nu_e \\ e^- \end{bmatrix}, \begin{bmatrix} \nu_\mu \\ \mu^- \end{bmatrix}, \begin{bmatrix} \nu_\tau \\ \tau^- \end{bmatrix}$$

$$\begin{bmatrix} u \\ d' \end{bmatrix}, \begin{bmatrix} c \\ s' \end{bmatrix}, \begin{bmatrix} t \\ b' \end{bmatrix}$$

Quark flavor mixing and CKM matrix



- For quarks,
  - weak interaction eigenstates ≠ mass eigenstates
  - mixing of quark flavors through a **unitary matrix**

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \left(V_{CKM}\right)\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

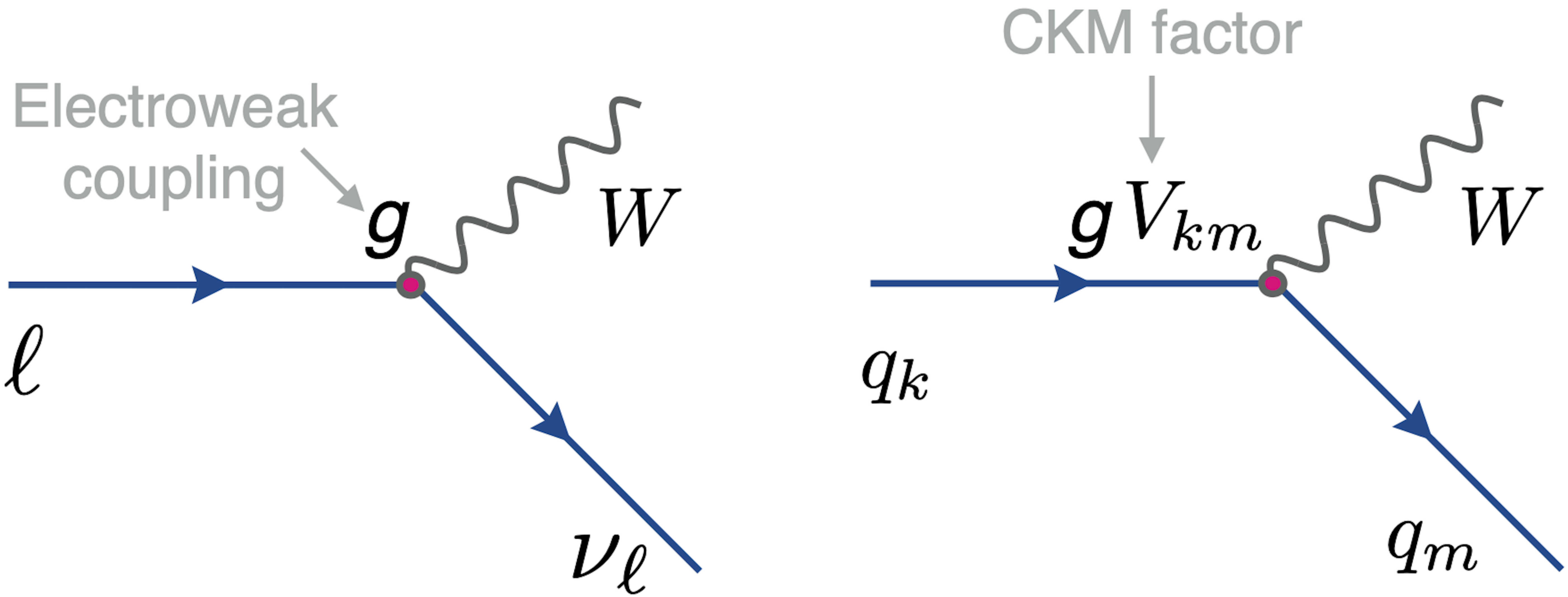
Wolfenstein parametrization

$$\mathbf{V}_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

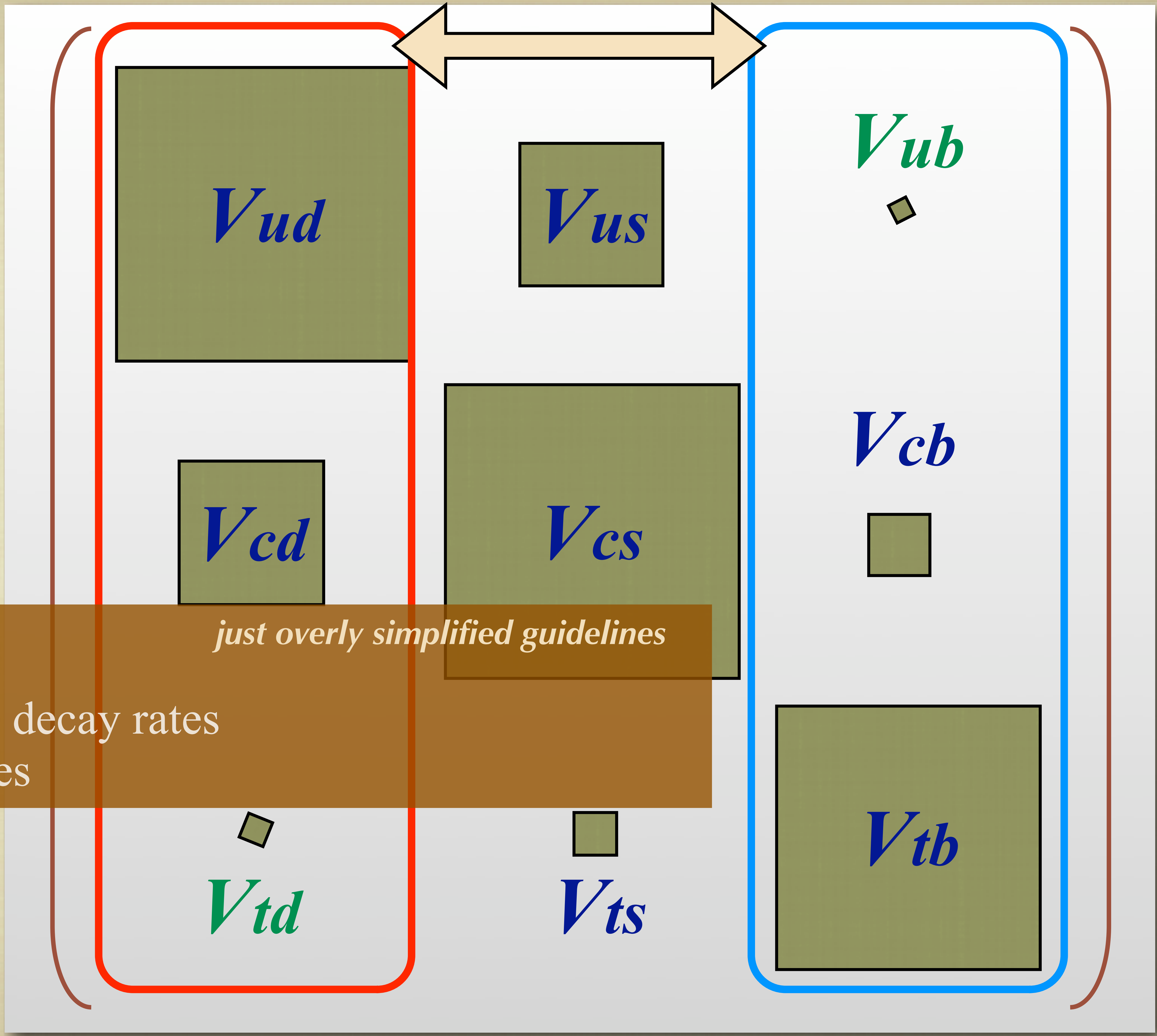
$|\lambda| \approx O(0.1)$

3 real parameters (λ, A, ρ) and 1 phase (η)

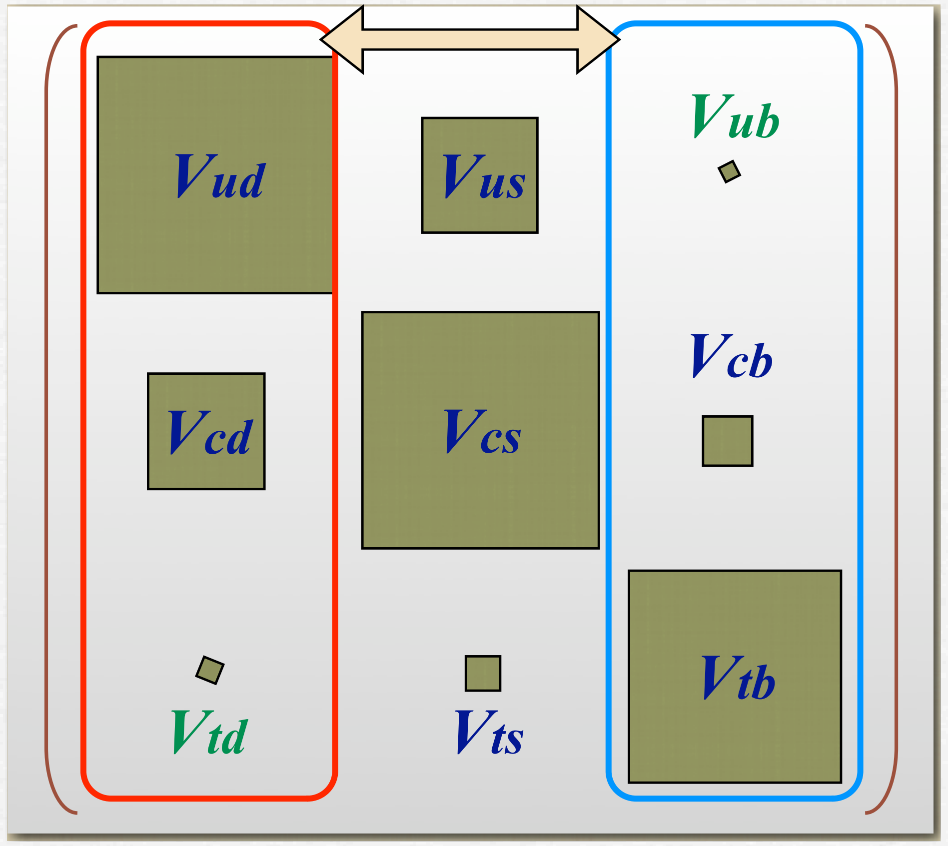
How fermions interact with $W^{\pm}$



Test Unitarity?

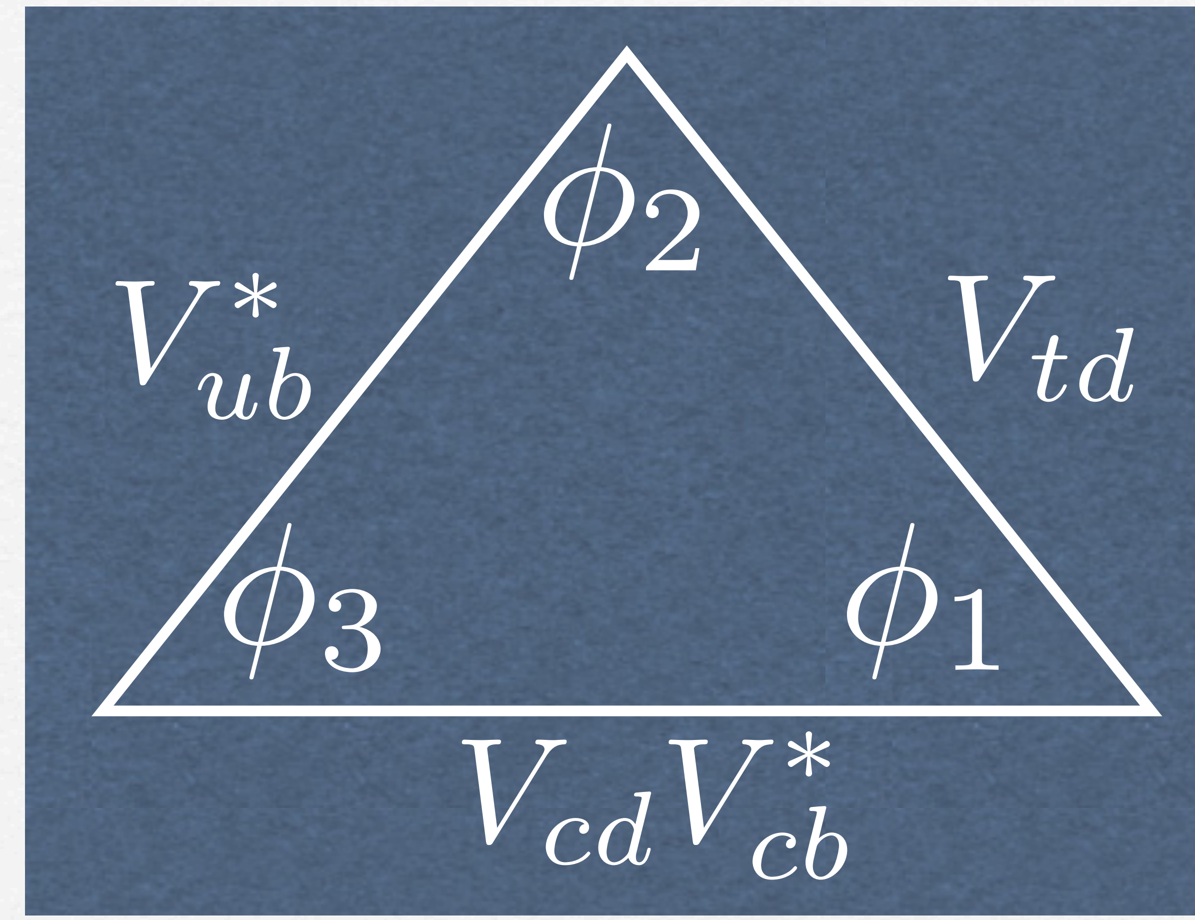


- $V = |V| exp(i\phi)$
  - $|V|$ from semi-leptonic decay rates
  - ϕ from *CP* asymmetries



$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

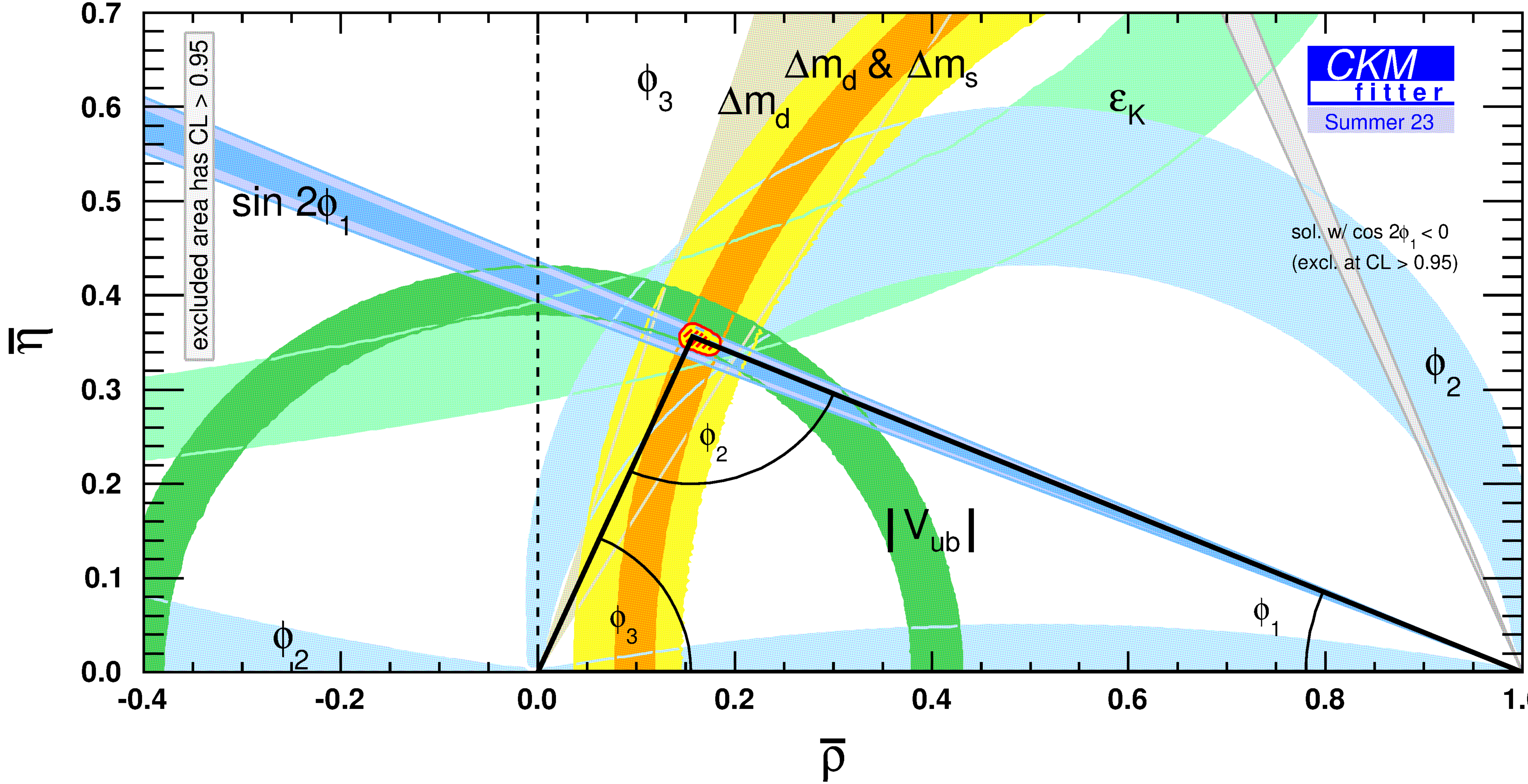
$$V_{ud} \cong V_{tb} \cong 1$$



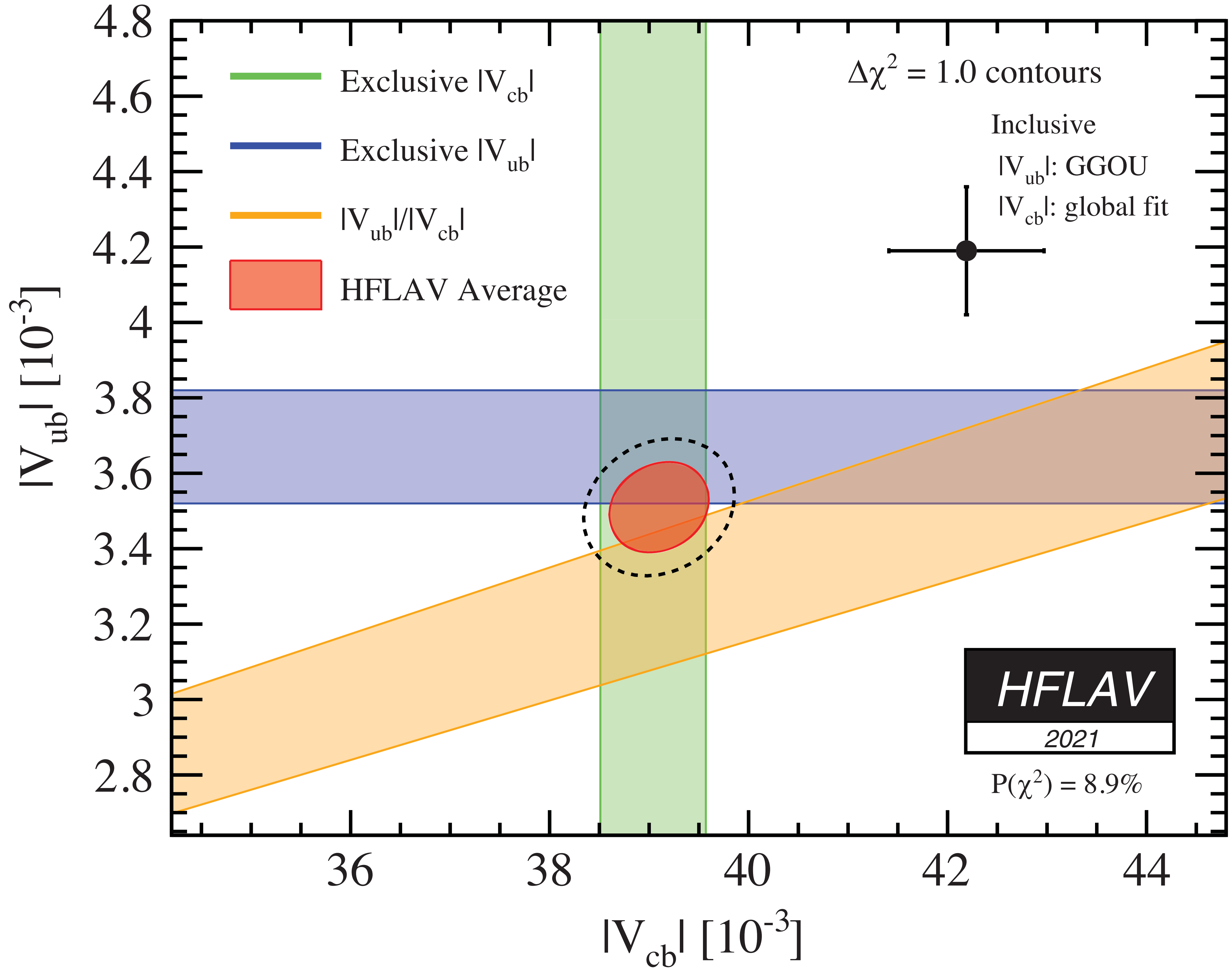
Unitarity triangle angles			
BABAR:	β	α	γ
BELLE:	ϕ_1	ϕ_2	ϕ_3
This talk:	易	難	魔

Z. Ligeti, from plenary talk @ ICHEP 2004

Current status of CKM unitarity



The V_{cb}, V_{ub} saga



The "CKM Brothers"

- Dr. Hyunki Jang (SNU)
- Dr. Jiwoo Nam (SKKU)

Belle Journal Publications | Physics Letters B | Vol 526, Iss

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Volume 526, Issues 3–4

Pages 173-450 (7 February 2002)

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Short communication ○ Abstract only

Determination of $|V_{cb}|$ using the semileptonic decay $\bar{B}^0 \to D^{*+} e^- \bar{\nu}$

Belle Collaboration, K. Abe, K. Abe, R. Abe, ... D. Žontar

Pages 247-257

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Short communication ○ Abstract only

Measurement of $B(\bar{B}^0 \to D^+ \ell^- \bar{\nu})$ and determination of $|V_{cb}|$

Belle Collaboration, K. Abe, K. Abe, R. Abe, ... D. Žontar

Pages 258-268

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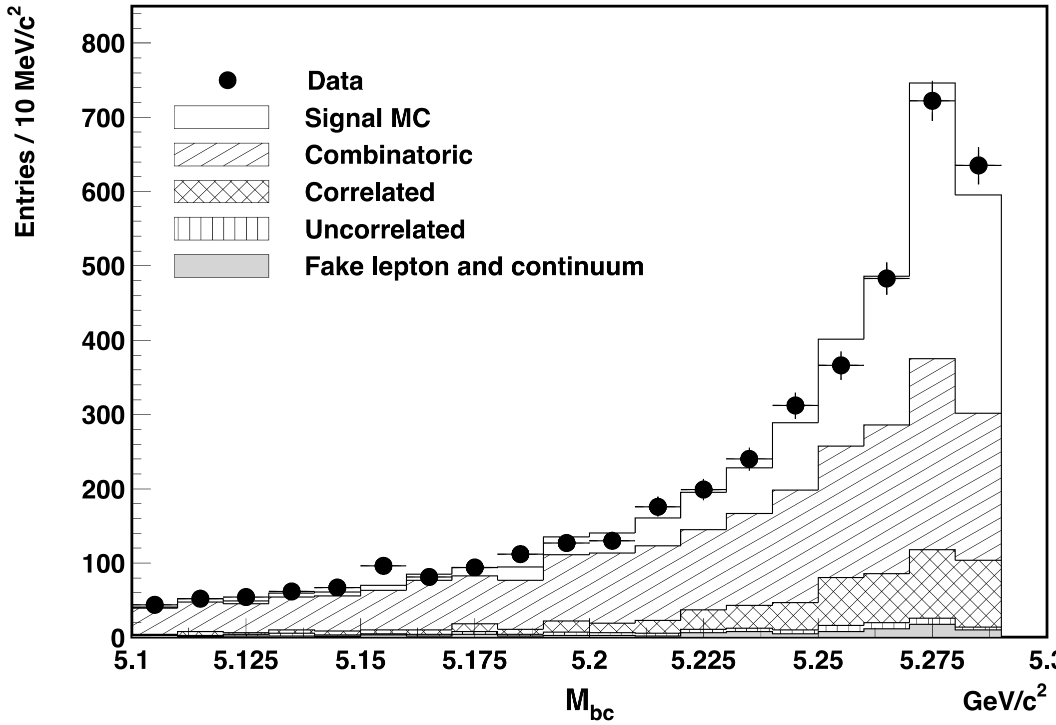
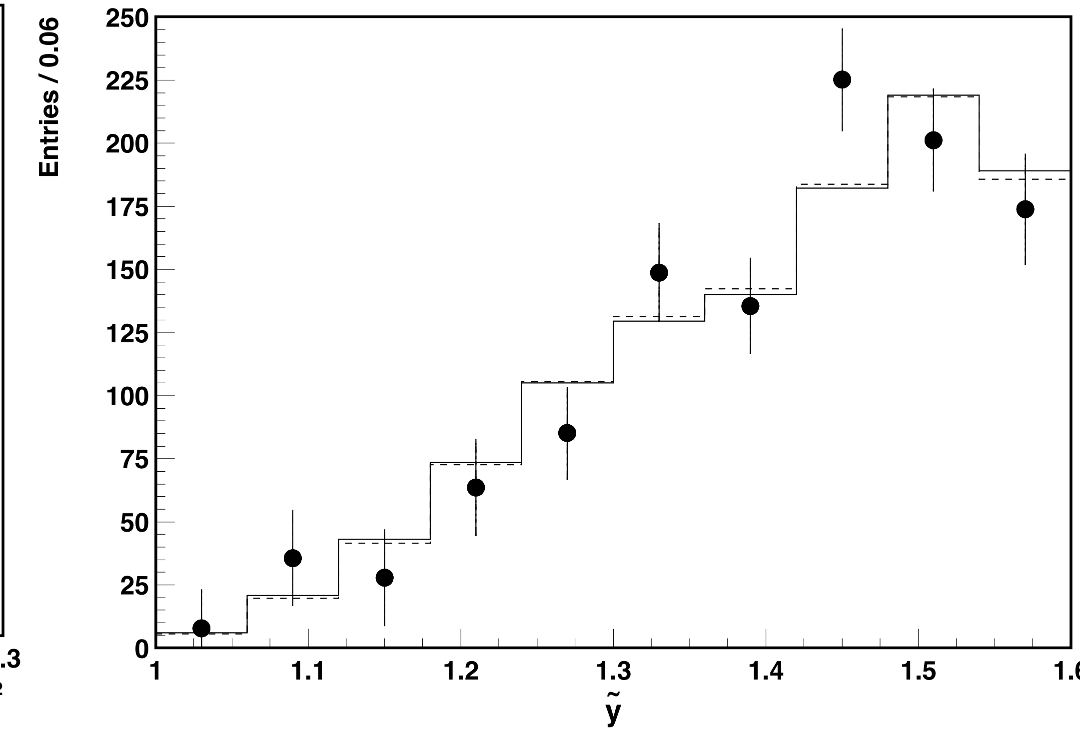
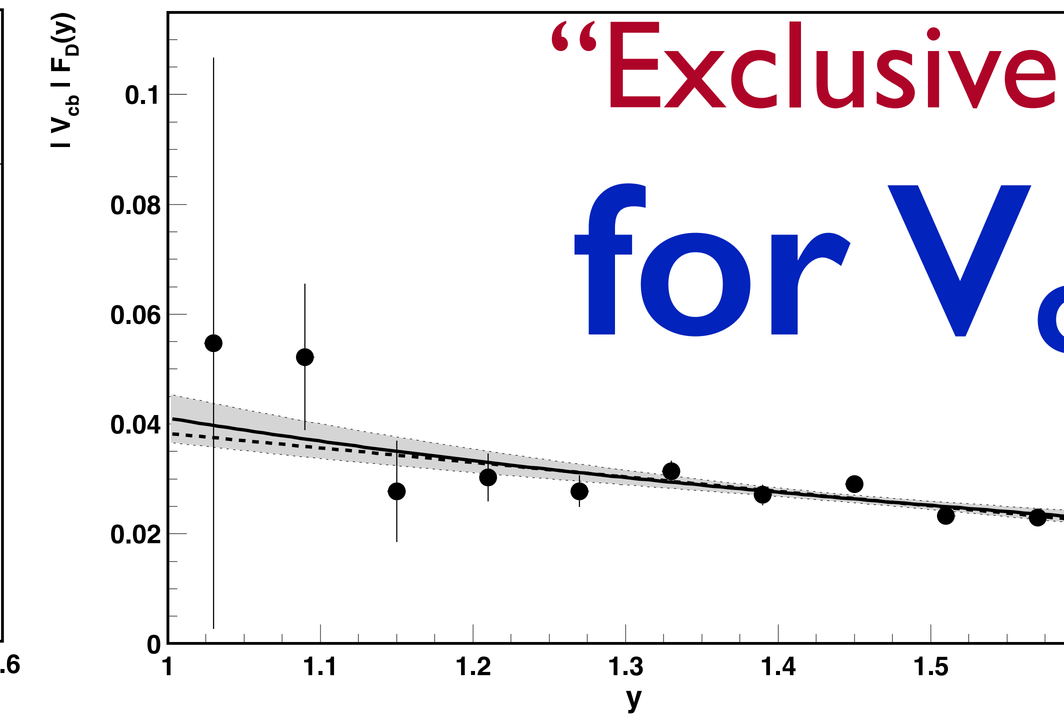
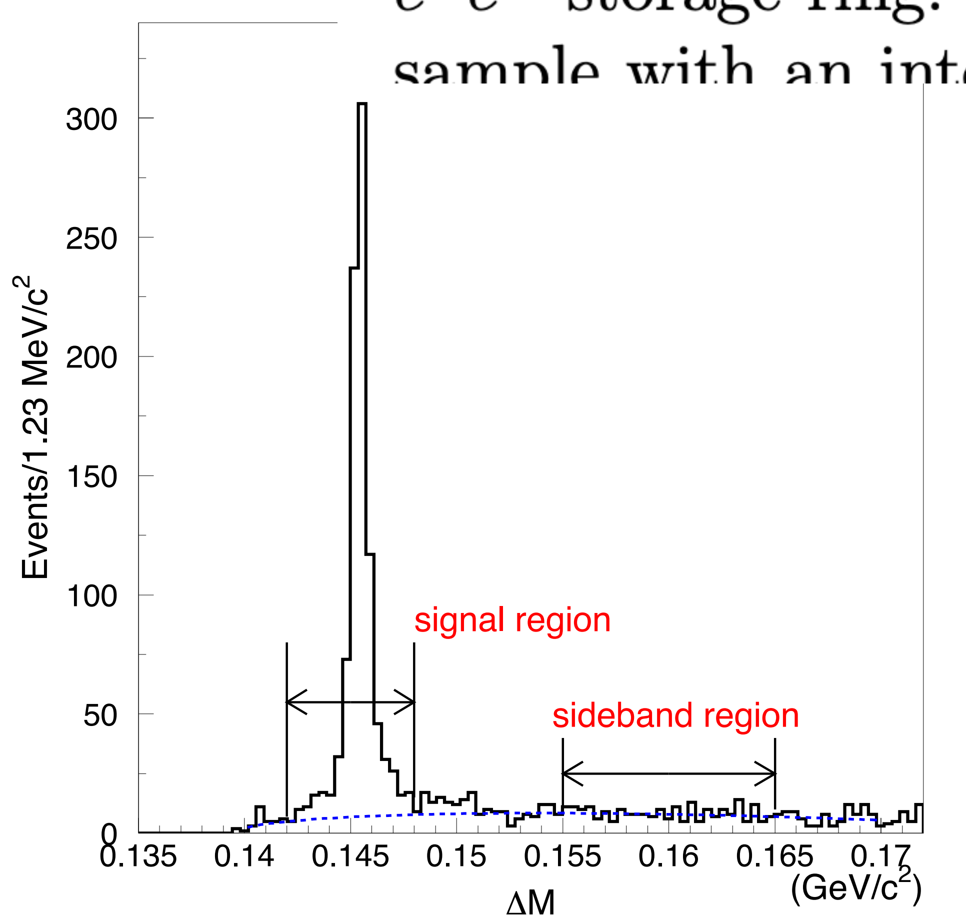
“Exclusive” for V_{cb}

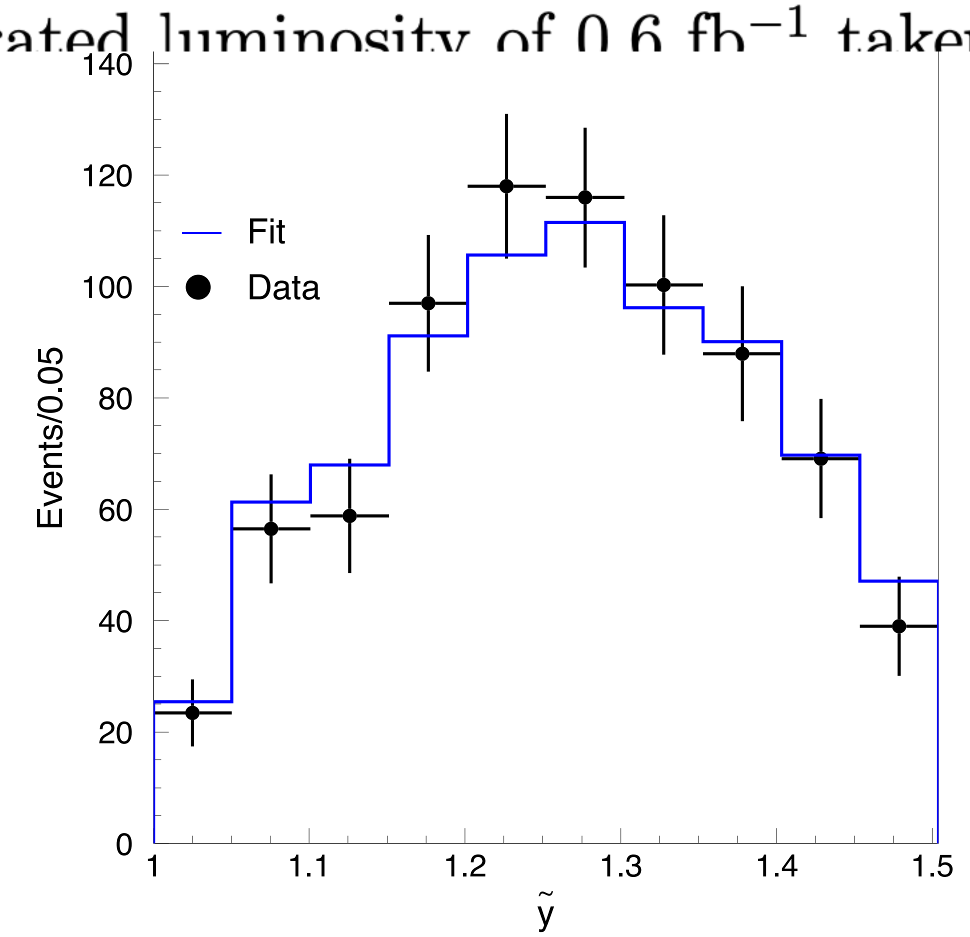


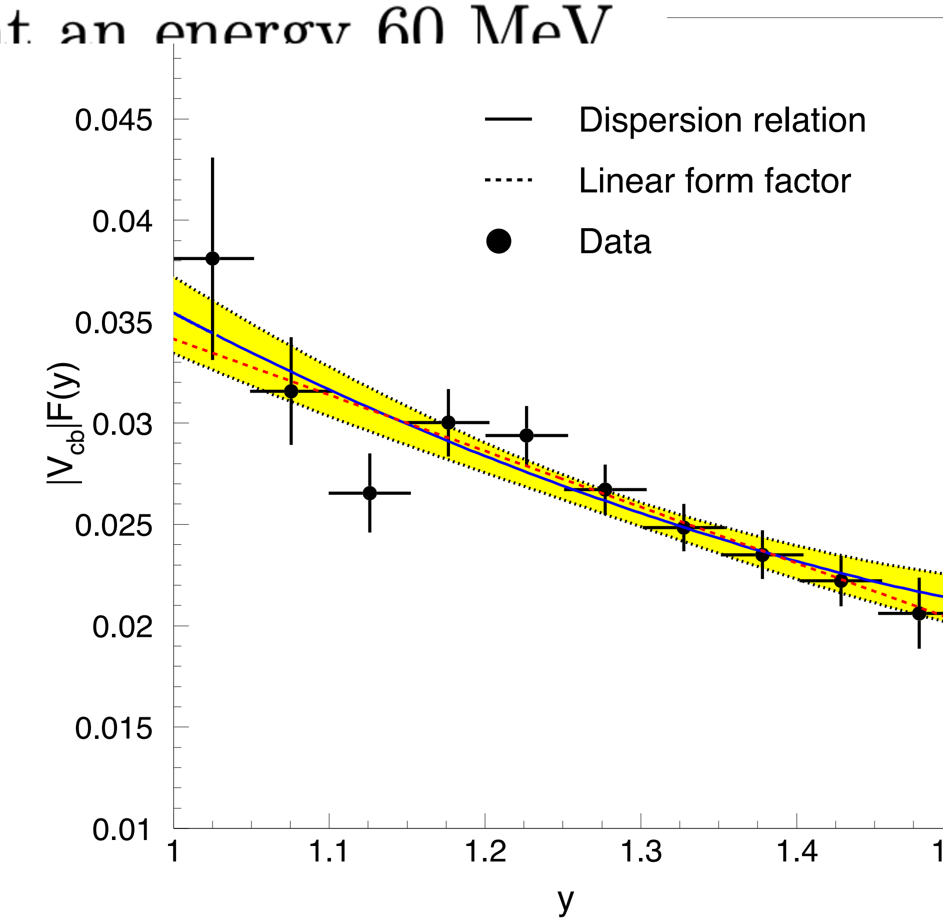




The data correspond to an integrated luminosity of 10.2 fb^{-1} accumulated at the $\Upsilon(4S)$ resonance with the Belle detector [15] at KEKB [16], an asymmetric e^+e^- storage ring. This corresponds to 10.8×10^6 $B\bar{B}$ events. An additional sample with an integrated luminosity of 0.6 fb^{-1} taken at an energy 60 MeV







Measurement of the inclusive semileptonic branching fraction of B mesons and $|V_{cb}|$

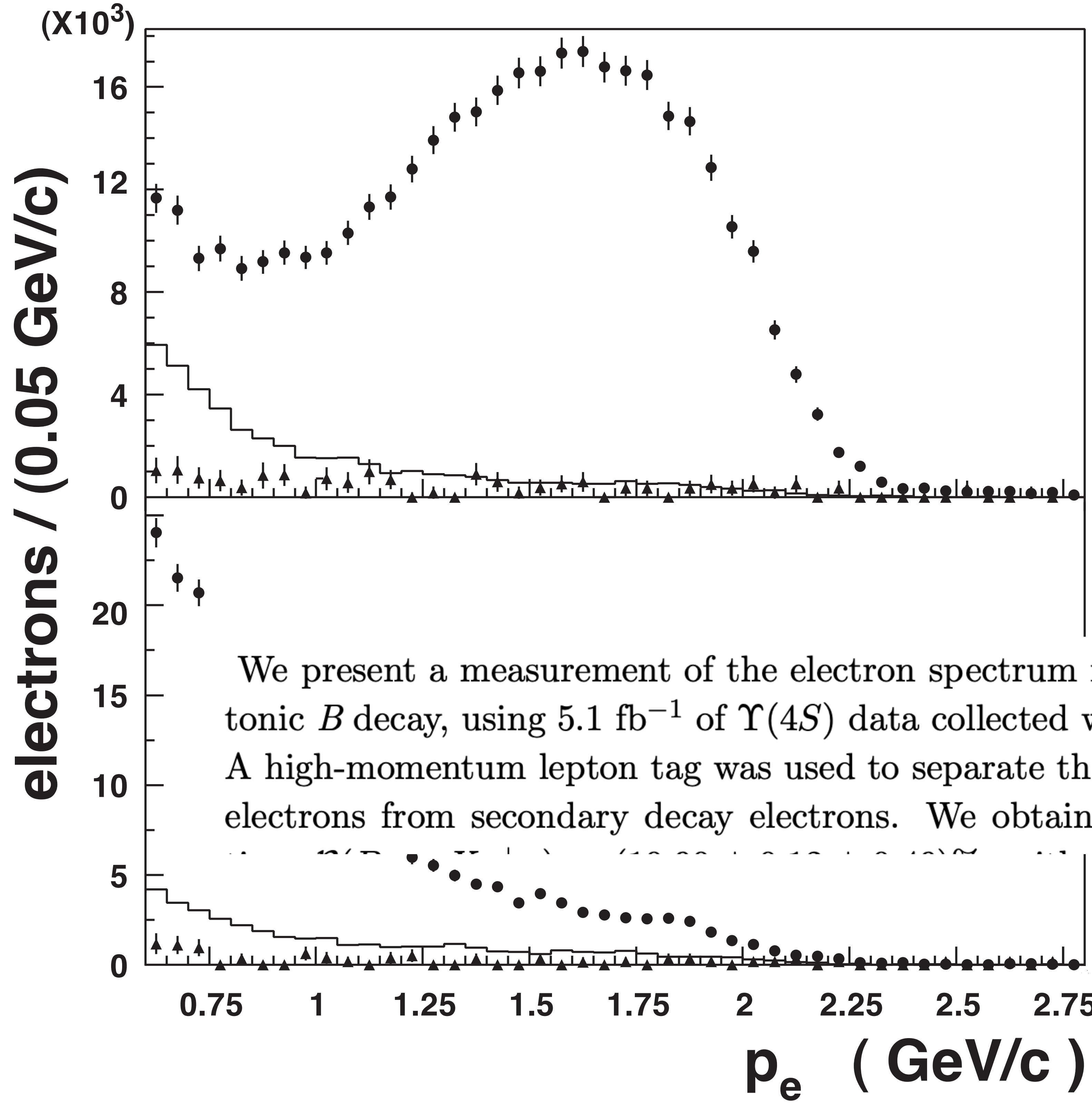
Belle Collaboration

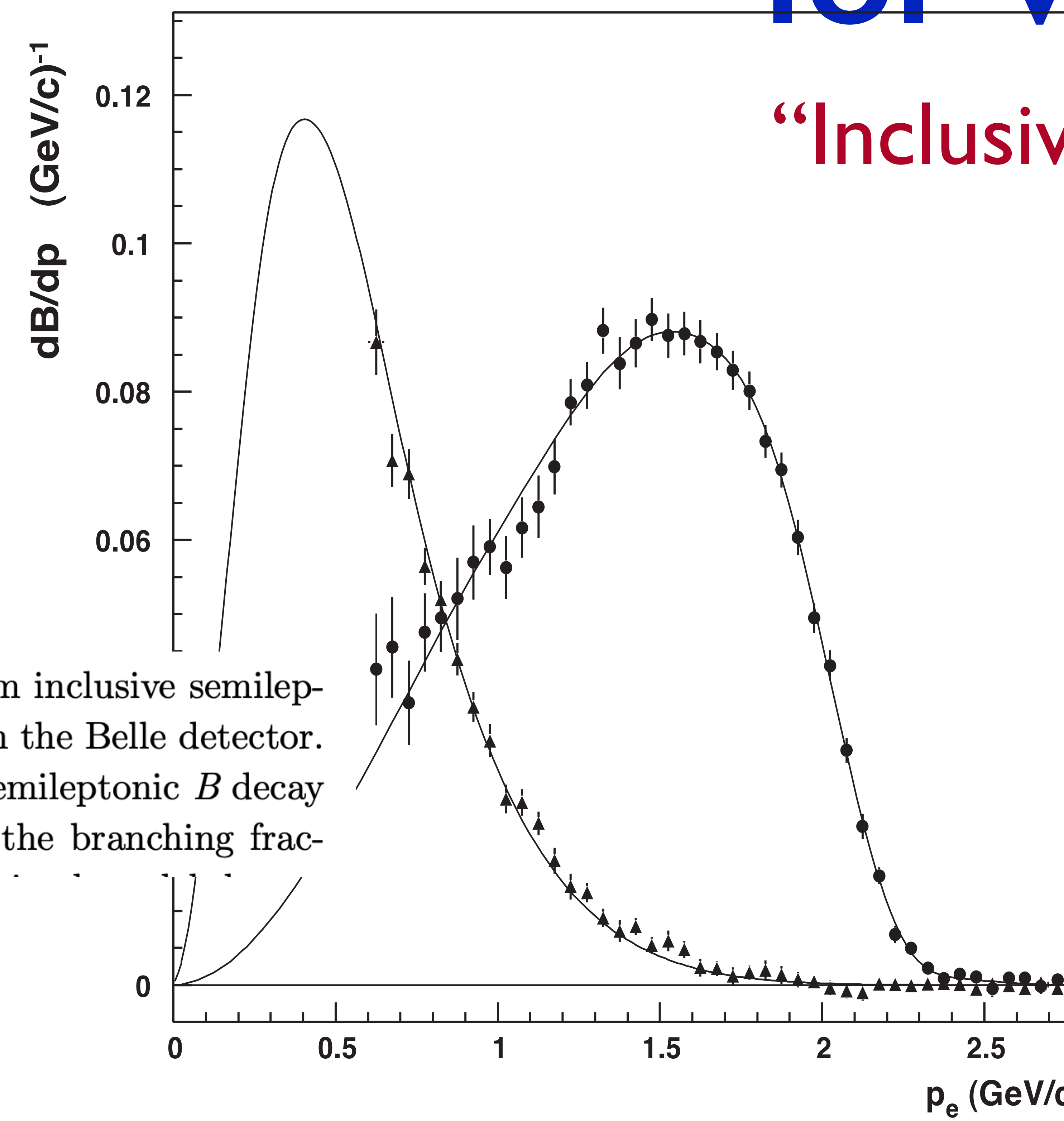
Physics Letters B

Volume 547, Issues 3–4, 7 November 2002, Pages 181-192

for V_{cb}

"Inclusive"





We present a measurement of the electron spectrum from inclusive semileptonic B decay, using 5.1 fb^{-1} of $\Upsilon(4S)$ data collected with the Belle detector. A high-momentum lepton tag was used to separate the semileptonic B decay electrons from secondary decay electrons. We obtained the branching frac-

First Measurement of the $B \to \pi \ell \nu$ and $B \to \rho(\omega) \ell \nu$ Branching Fractions

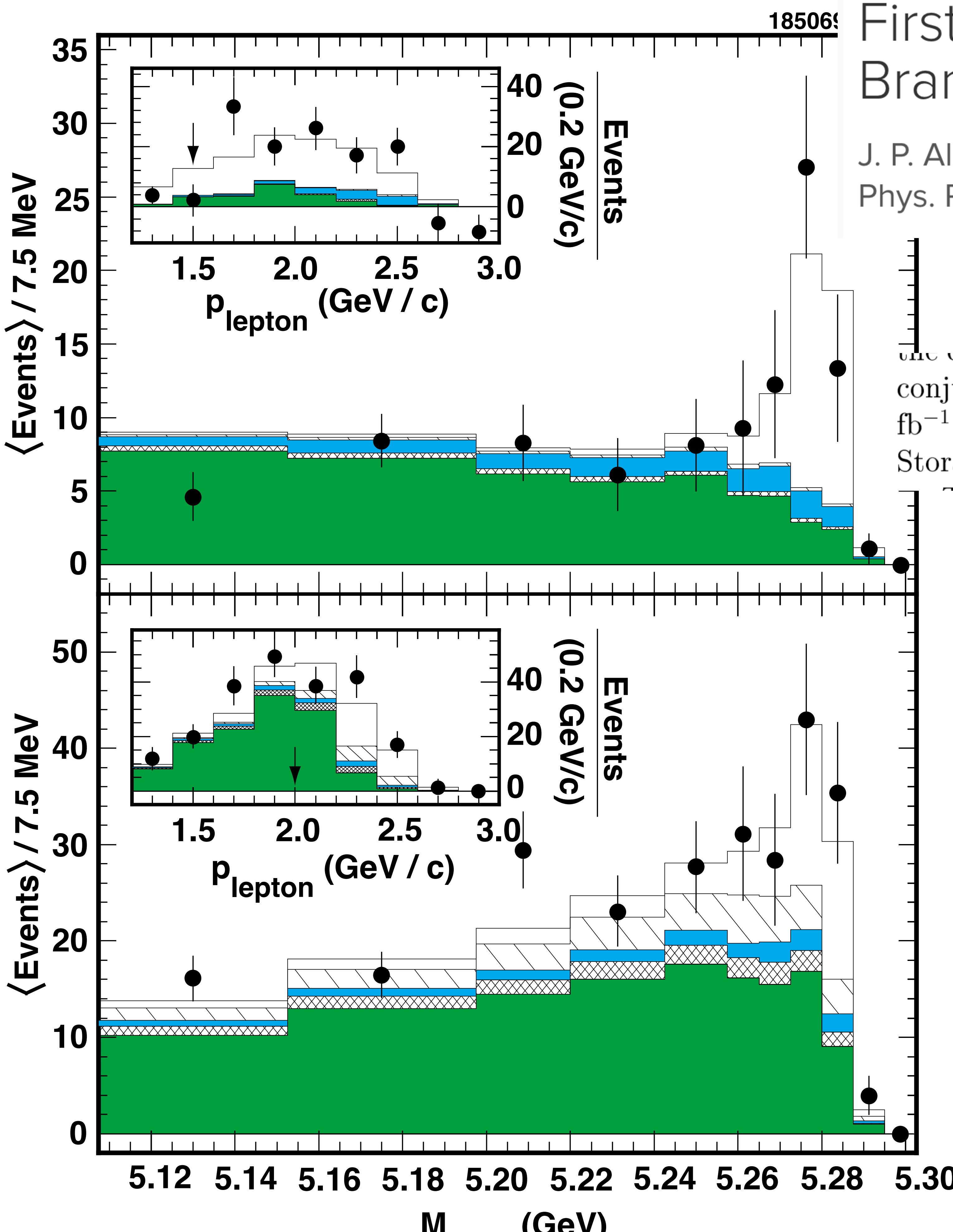
J. P. Alexander *et al.* (CLEO Collaboration)

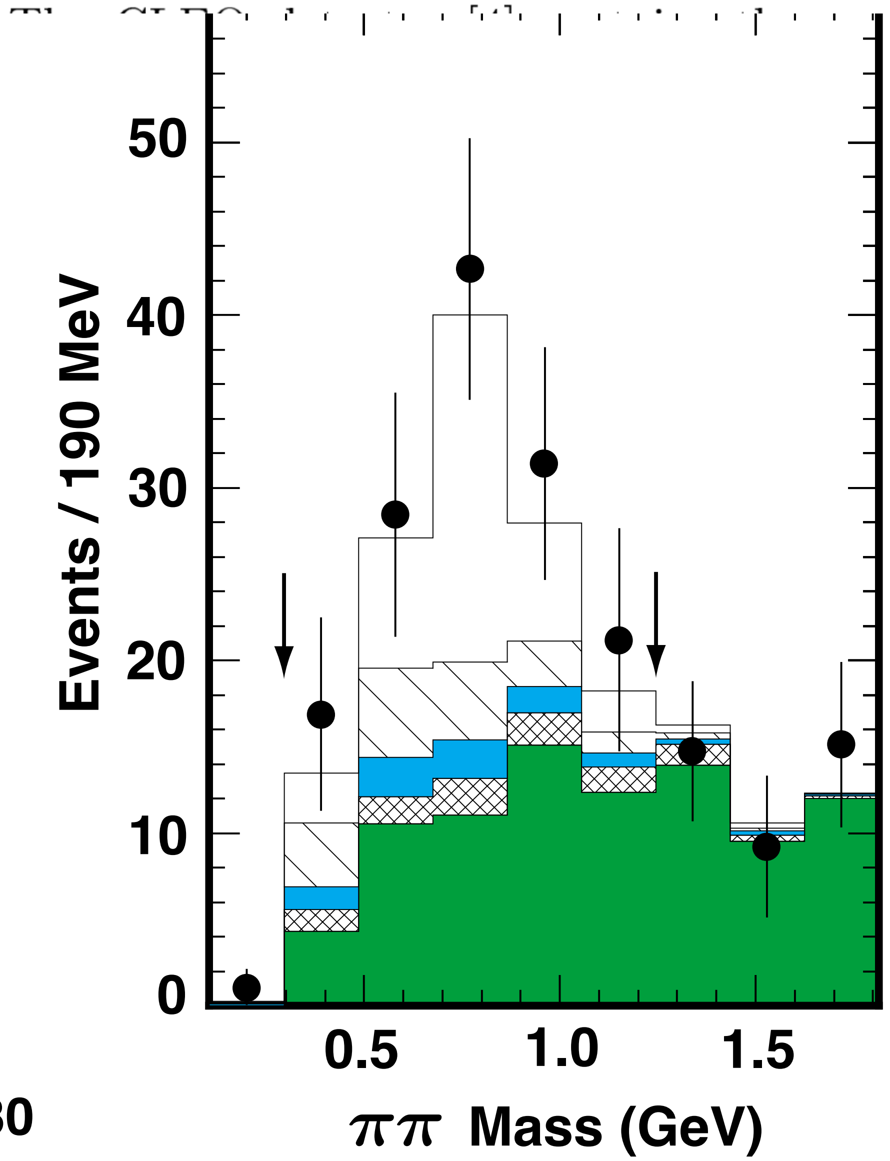
Phys. Rev. Lett. **77**, 5000 – Published 16 December 1996

for V_{ub}

"Exclusive"

conjugate modes, where $\ell = e$ or μ. The study is based on an $\Upsilon(4S)$ data sample of 2.66 fb^{-1} (2.84×10^6 $B\bar{B}$ pairs) accumulated by the CLEO experiment at the Cornell Electron Storage Ring (CESR).





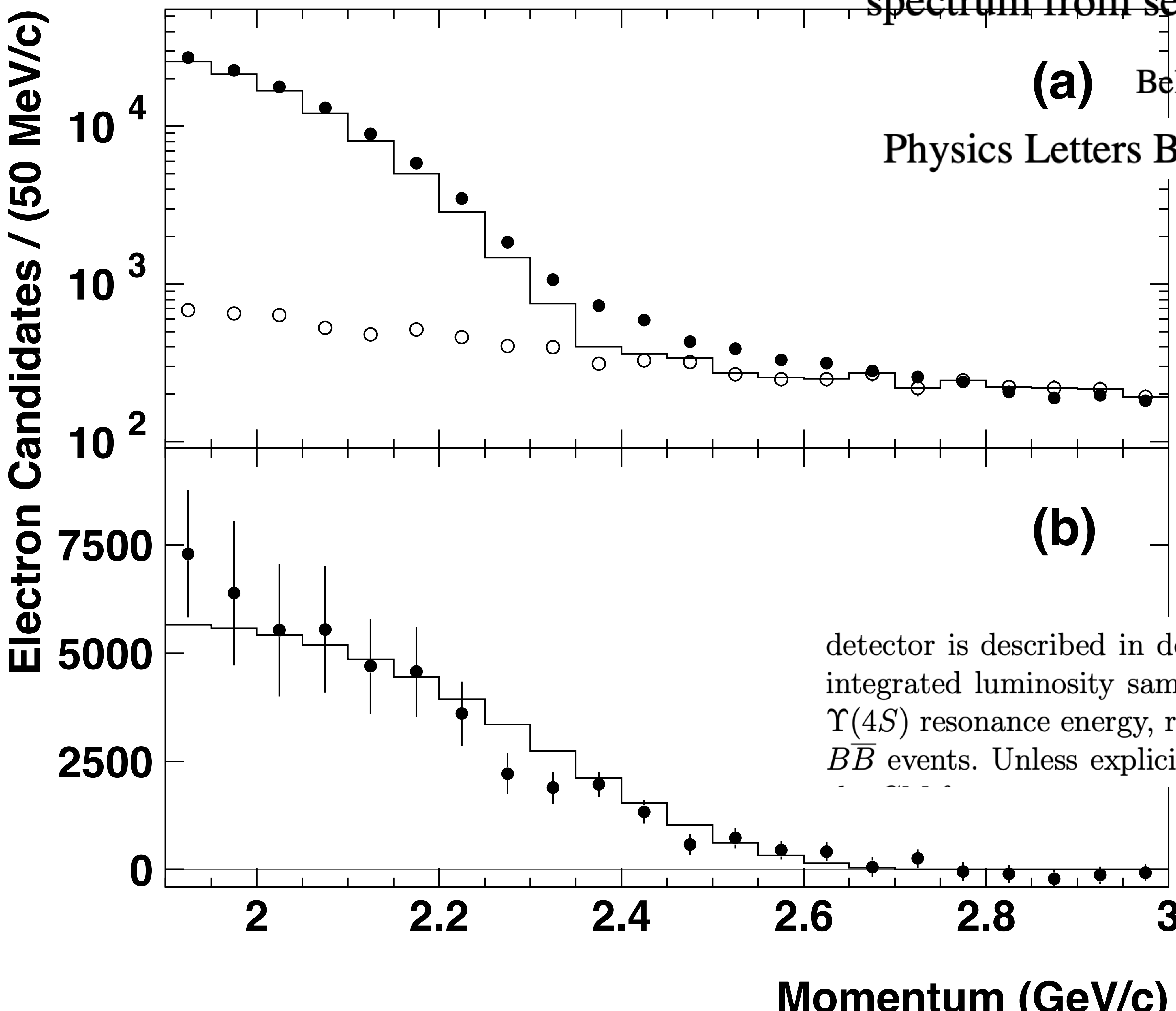
Measurement of $|V_{ub}|$ near the endpoint of the electron momentum spectrum from semileptonic B-meson decays

Belle Collaboration

Physics Letters B 621 (2005) 28–40

for V_{ub}

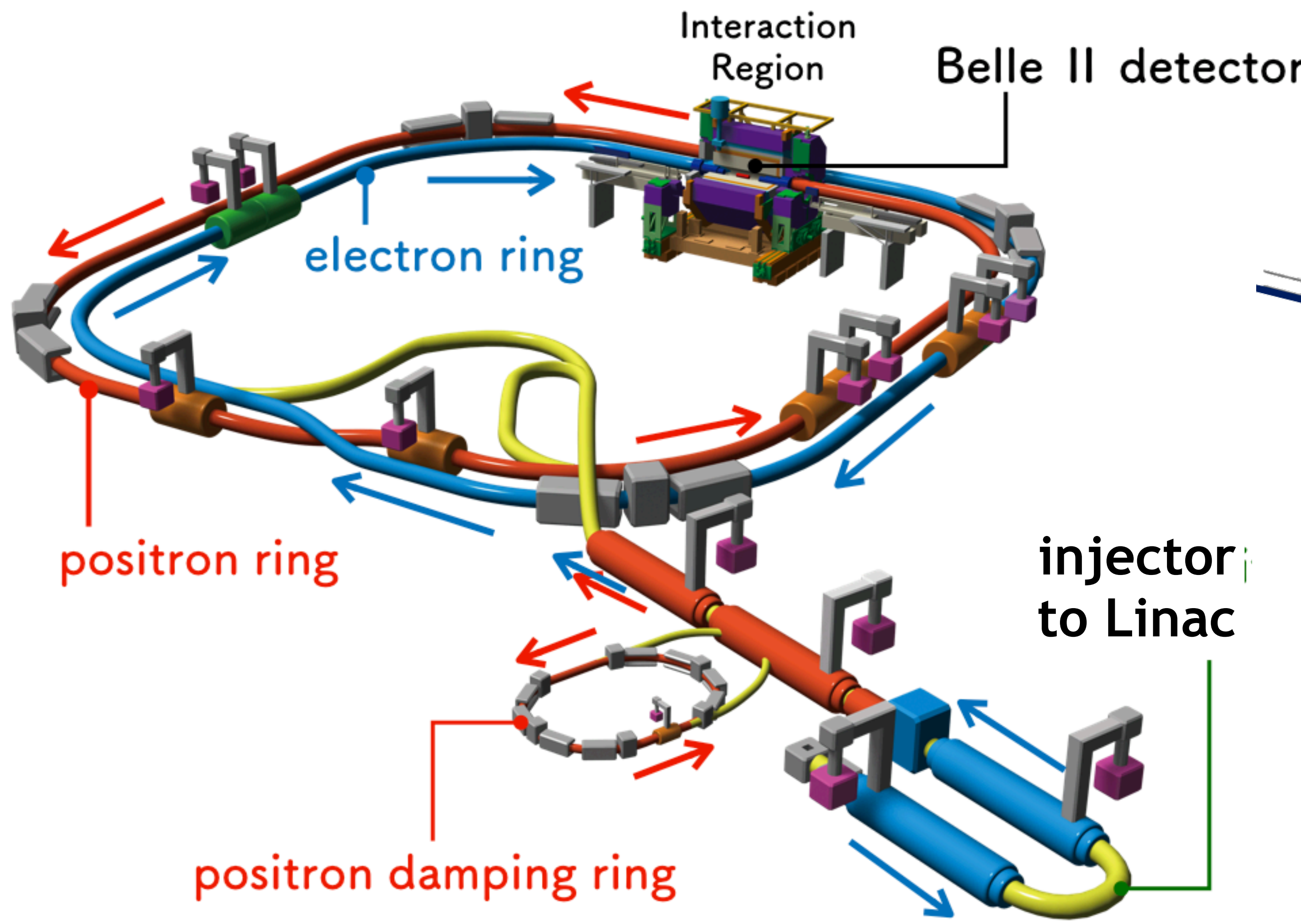
“Inclusive”

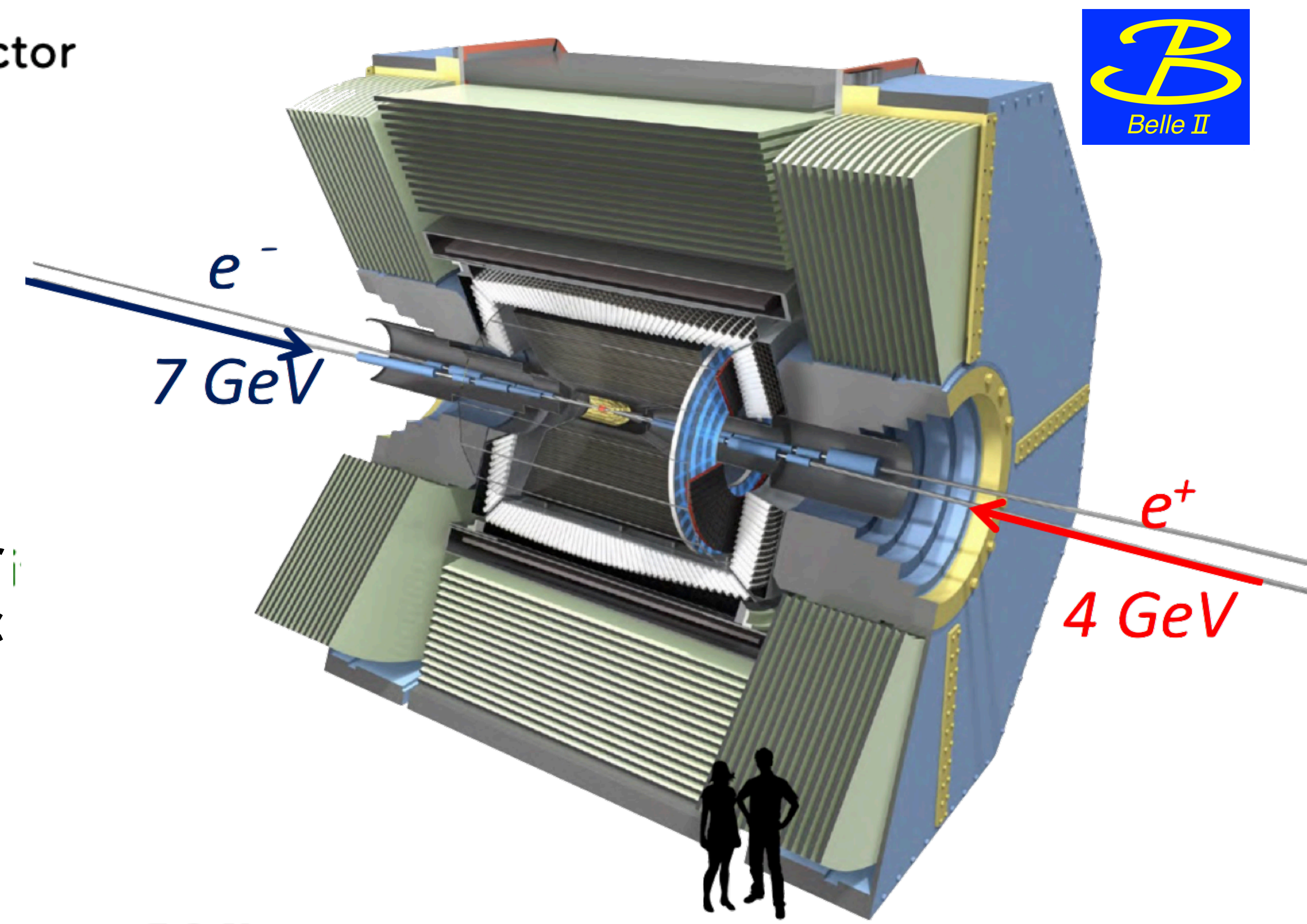


detector is described in detail elsewhere [27]. We use 27.0 fb^{-1} and 8.8 fb^{-1} integrated luminosity samples taken at (ON) and 60 MeV below (OFF) the $\Upsilon(4S)$ resonance energy, respectively. The ON sample consists of 29.4 million $B\overline{B}$ events. Unless explicitly stated otherwise, all variables are calculated in

SuperKEKB

Belle II





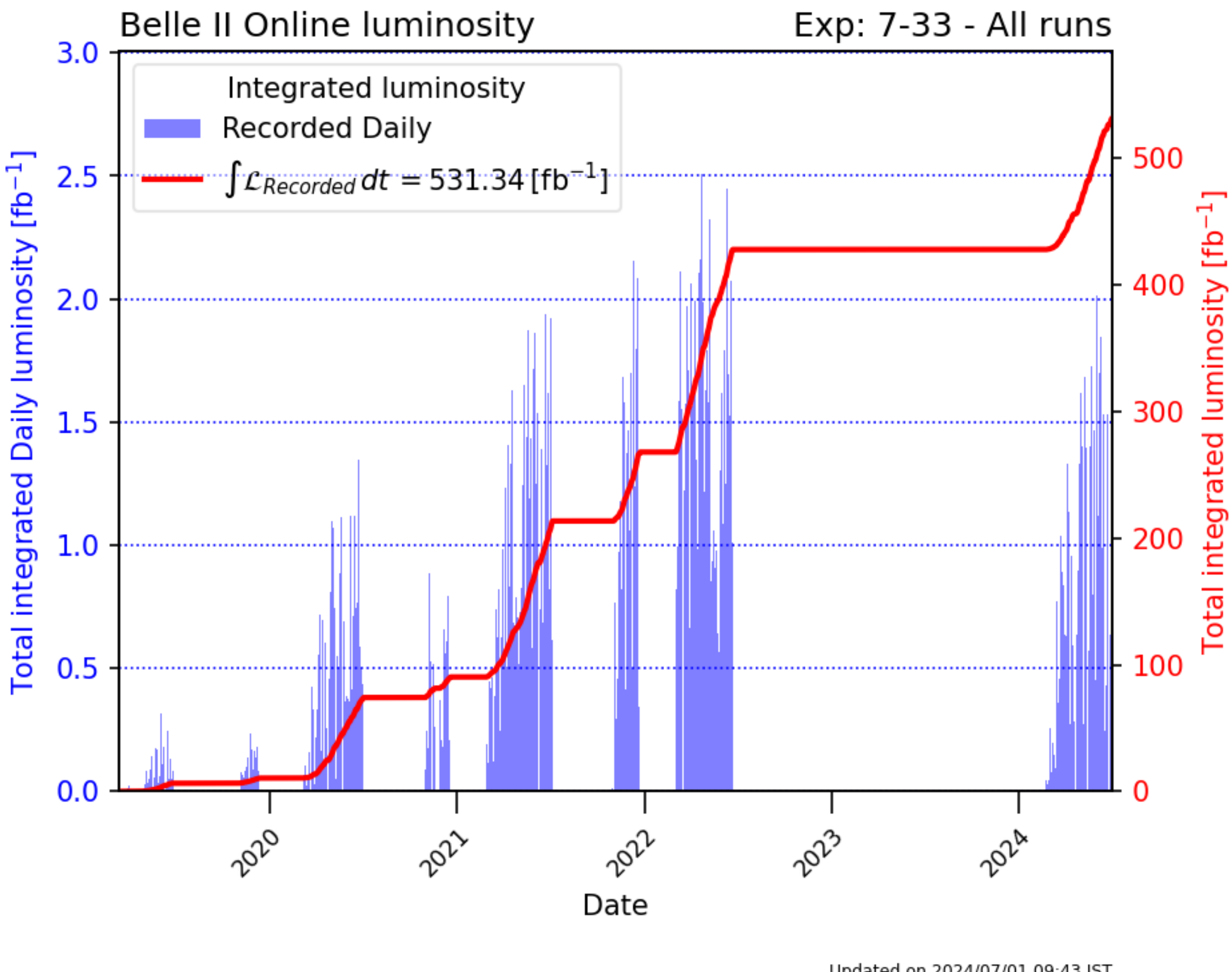
$$e^- \xrightarrow{7\text{ GeV}} (\star) \xleftarrow{4\text{ GeV}} e^+$$

$$\sqrt{s} = 10.58\text{ GeV} = m_{\Upsilon(4S)}c^2$$

We also have data taken off-resonance as well as energy scan around $\Upsilon(5S)$

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

  $\therefore$ if we know $(E, \vec{p})$ of one B, the other B is also constrained "B-tagging" *unique to e^+e^- B-factory*



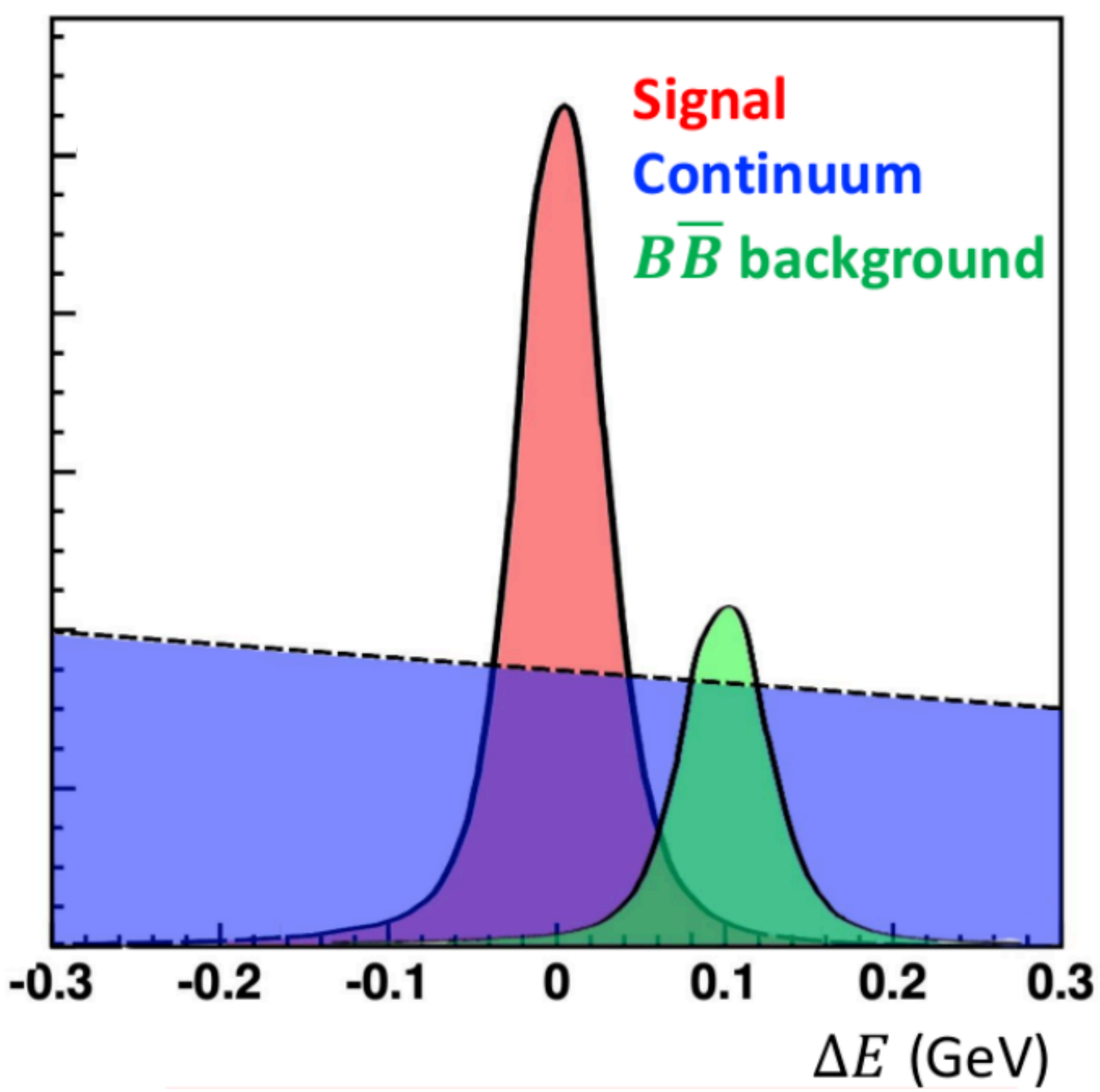
Belle (1999-2010) Luminosity

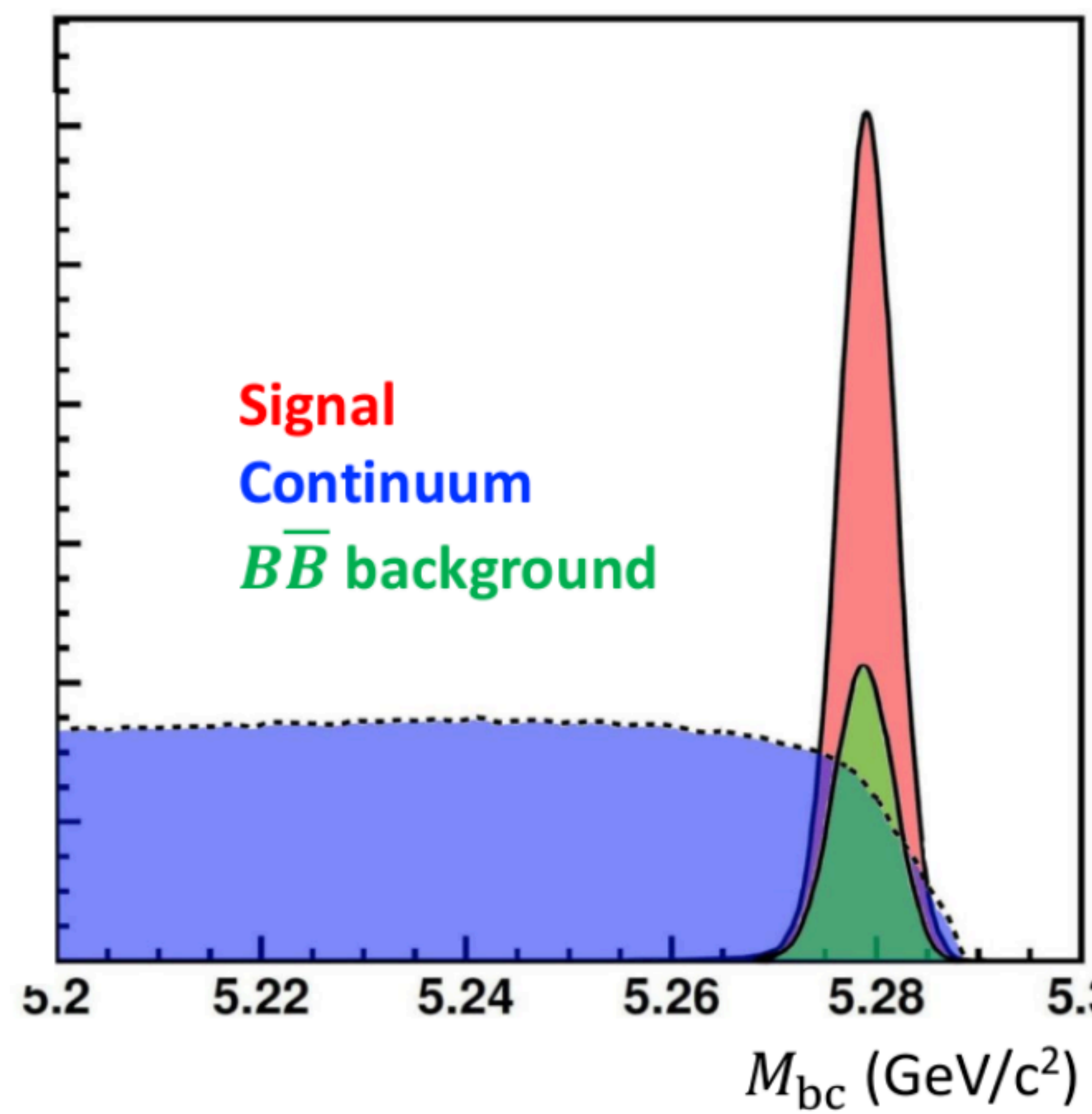
- $\int \mathscr{L}_{\text{total}} = 1039\ \text{fb}^{-1}$
- $\int \mathscr{L}_{\Upsilon(4S)} = 711\ \text{fb}^{-1}$

Key variables of B decays

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

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

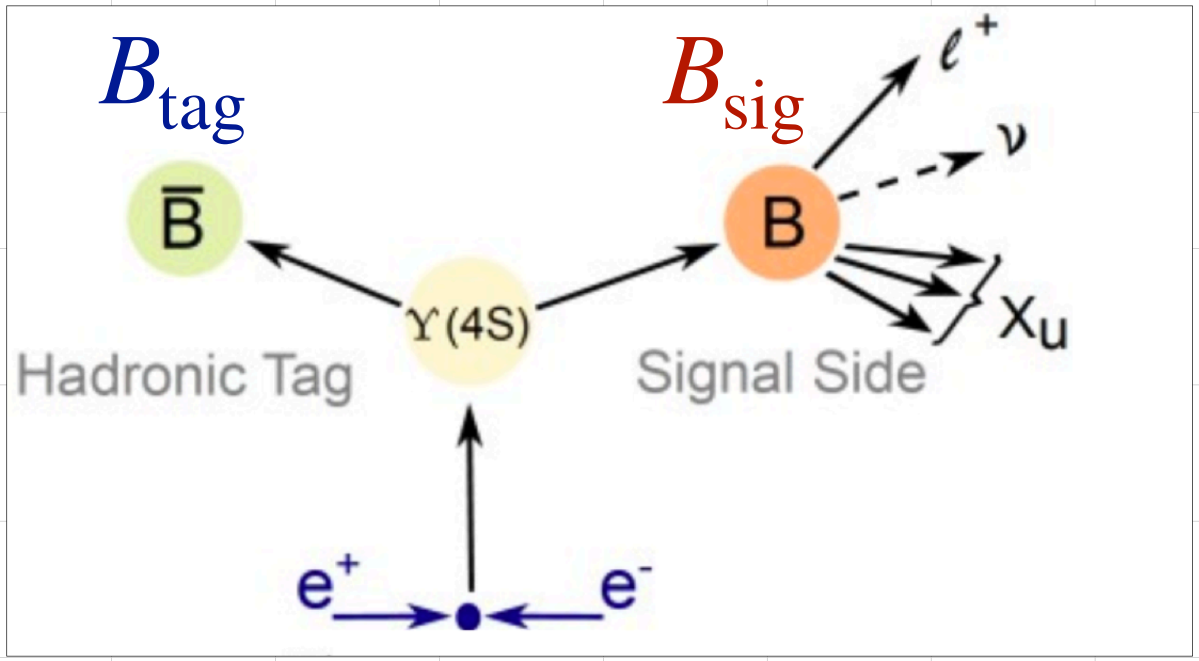




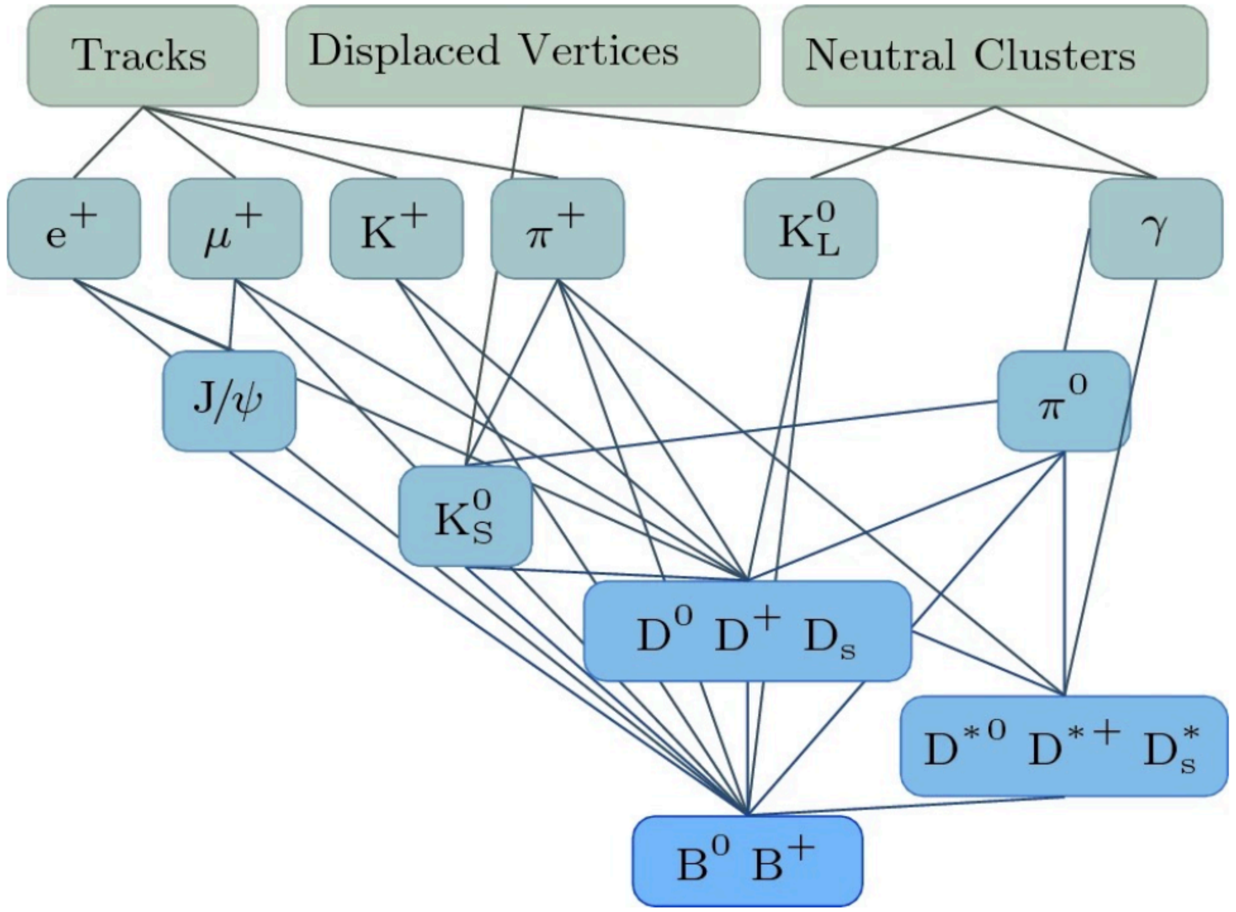
FEI

Full Event Interpretation

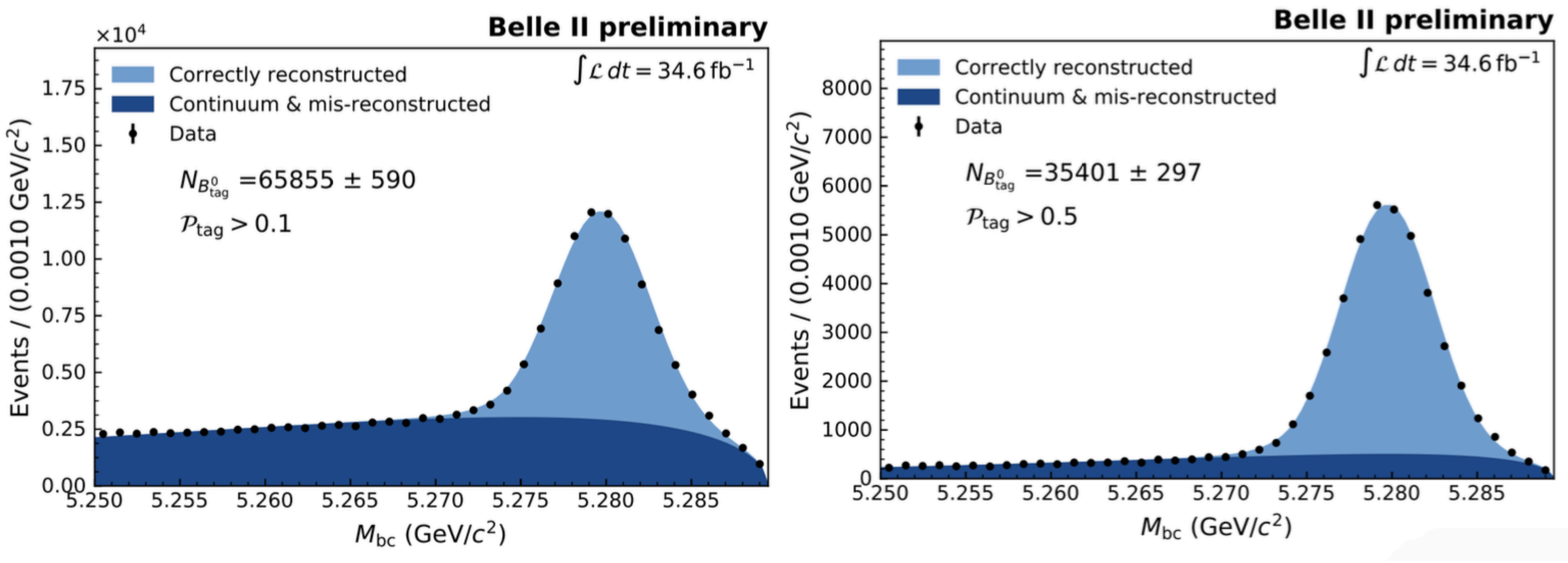
- FEI algorithm to reconstruct B_{tag}
  - uses ~200 BDT's to reconstruct $\mathcal{O}(10^4)$ different B decay chains
  - assign signal probability of being correct B_{tag}



Comput Softw Big Sci 3, 6 (2019)

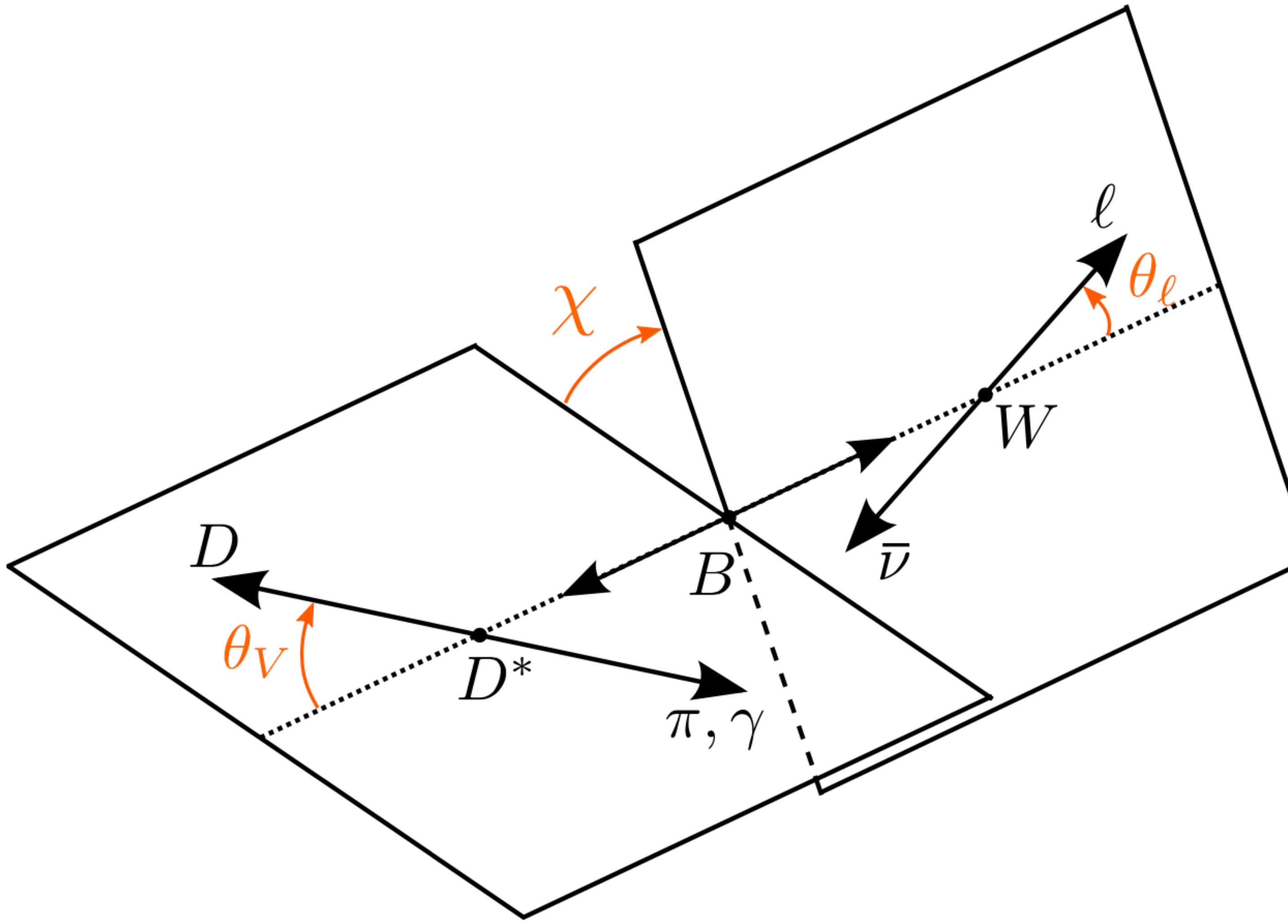


arXiv:2008.060965



$|V_{cb}|$ from angular coeff's of $B \to D^* \ell \nu$

- **Obtain the differential rates in three angles, θ_ℓ, θ_V, χ, and a kinematic variable, w.**
  - differential rates are expressed in terms of 12 functions J_i that depend only on w.
  - possible for SM test & LFU test
- **Belle data sample of $711\ \mathrm{fb}^{-1}$**



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

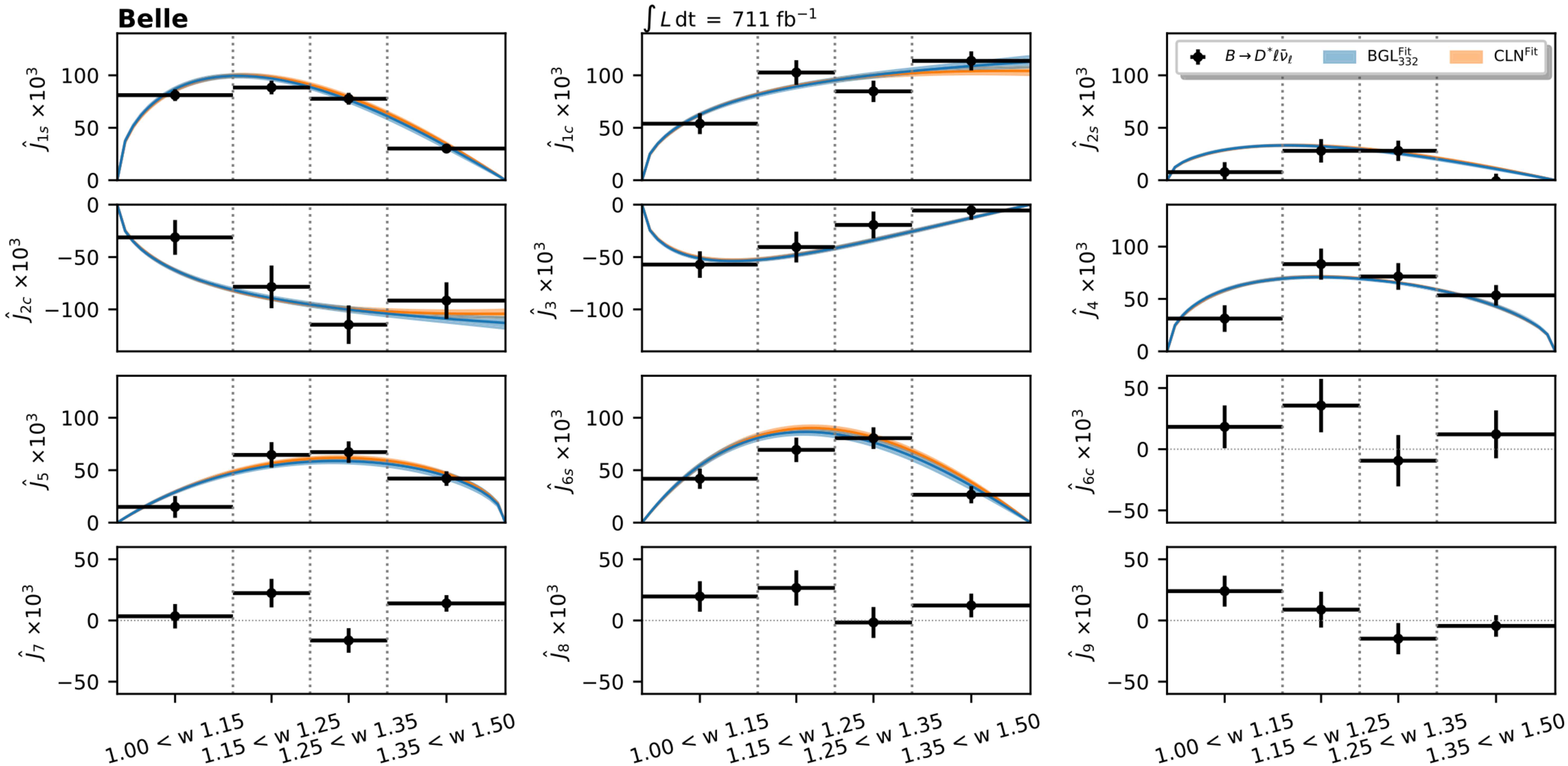
$$\frac{\mathrm{d}\Gamma(\bar{B} \to D^* \ell \bar{\nu}_\ell)}{\mathrm{d}w\, \mathrm{d}\cos\theta_\ell\, \mathrm{d}\cos\theta_\mathrm{V}\, \mathrm{d}\chi} = \frac{2 G_\mathrm{F}^2 \eta_\mathrm{EW}^2 |V_\mathrm{cb}|^2 m_B^4 m_{\mathrm{D}^*}}{2\pi^4} \times \Big(J_{1s} \sin^2\theta_\mathrm{V} + J_{1c}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

$|V_{cb}|$ from angular coeff's of $B \to D^*\ell\nu$

$$|V_{\rm cb}| = (40.7 \pm 0.3 \pm 0.4 \pm 0.5) \times 10^{-3} \qquad ({\rm BGL}_{332}),$$

$$|V_{\rm cb}| = (40.3 \pm 0.3 \pm 0.4 \pm 0.4) \times 10^{-3} \qquad ({\rm CLN}),$$

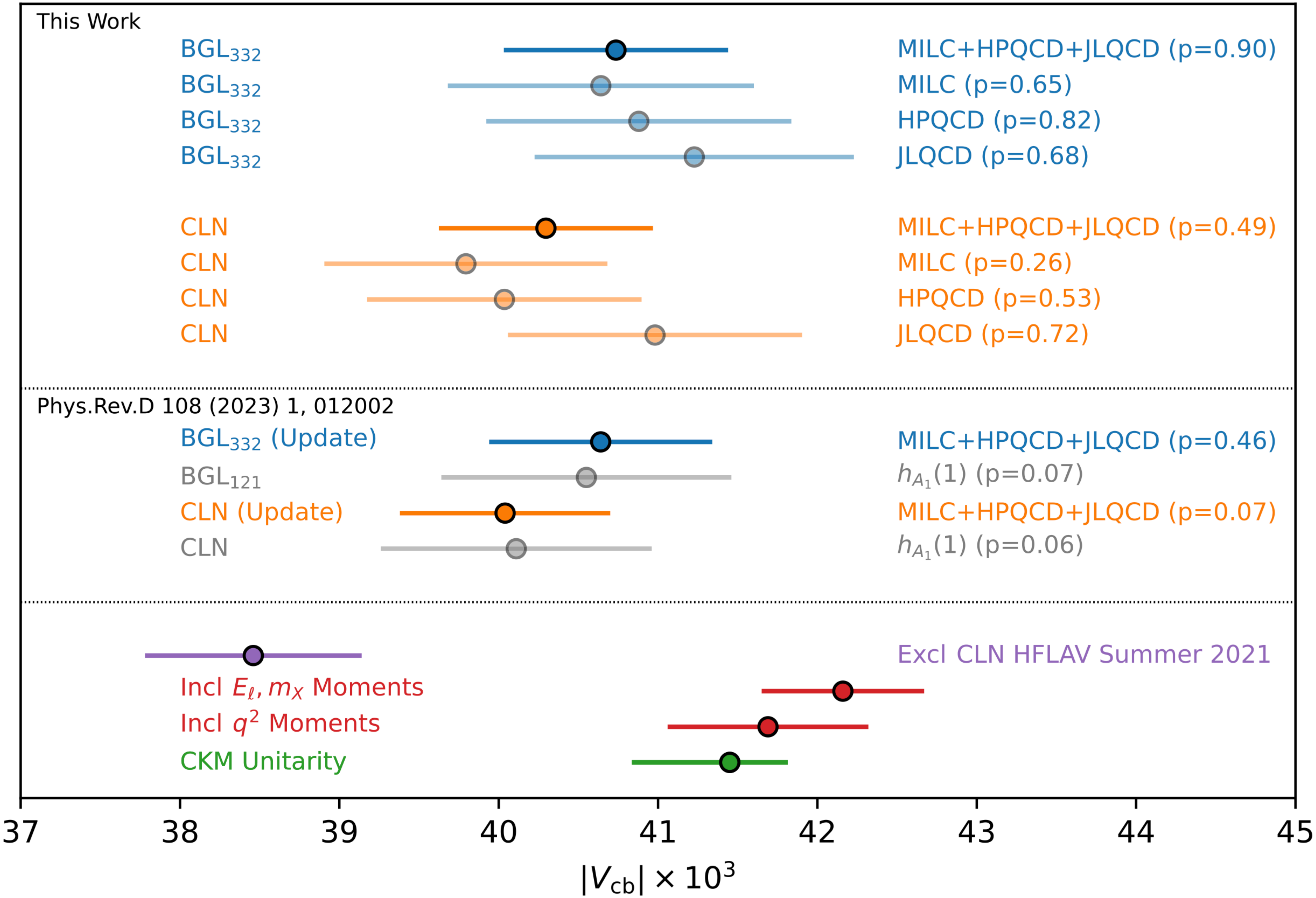
[17] C. G. Boyd, B. Grinstein, and R. F. Lebed, Nucl. Phys. B **461**, 493 (1996), arXiv:hep-ph/9508211.
[18] C. G. Boyd, B. Grinstein, and R. F. Lebed, Phys. Rev. D **56**, 6895 (1997), arXiv:hep-ph/9705252.
[16] I. Caprini, L. Lellouch, and M. Neubert, Nucl. Phys. B **530**, 153 (1998), arXiv:hep-ph/9712417.



$$|V_{\mathrm{cb}}| = (40.7 \pm 0.3 \pm 0.4 \pm 0.5) \times 10^{-3} \qquad (\mathrm{BGL}_{332}),$$

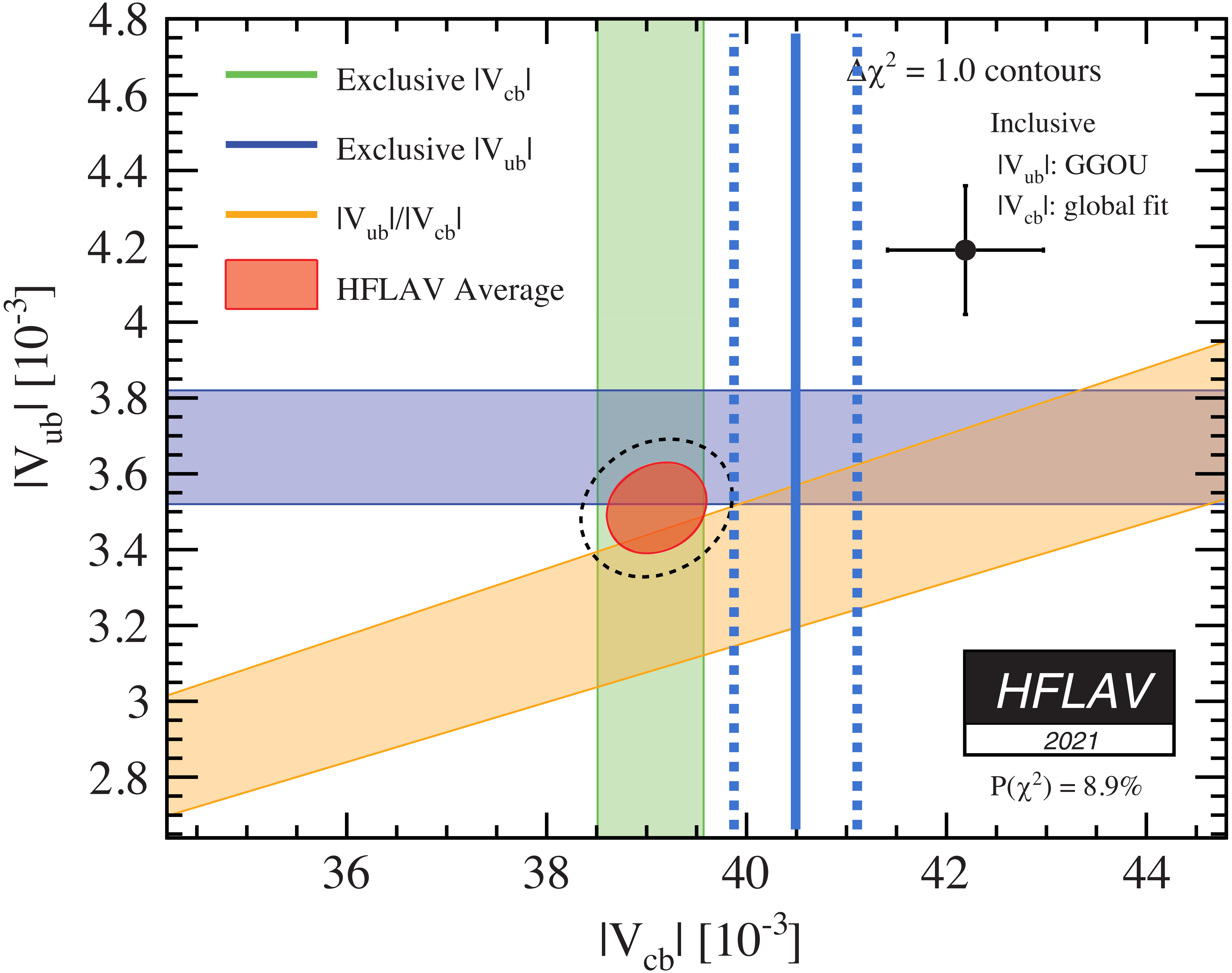
$$|V_{\mathrm{cb}}| = (40.3 \pm 0.3 \pm 0.4 \pm 0.4) \times 10^{-3} \qquad (\mathrm{CLN}),$$

$|V_{cb}|$ from angular coeff's of $B \to D^* \ell \nu$



PRL 133, 131801 (2024)

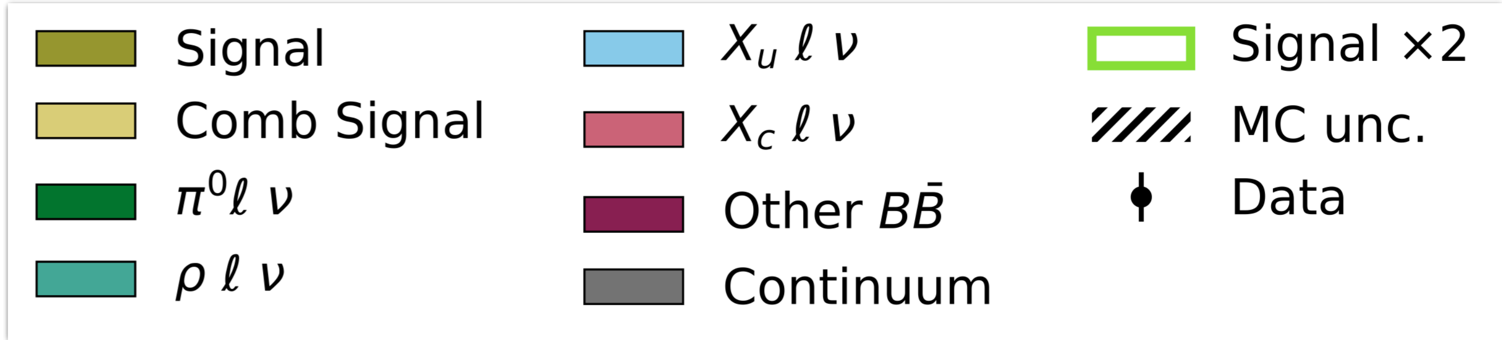
$|V_{cb}|$ from angular coeff's of $B \to D^*\ell\nu$

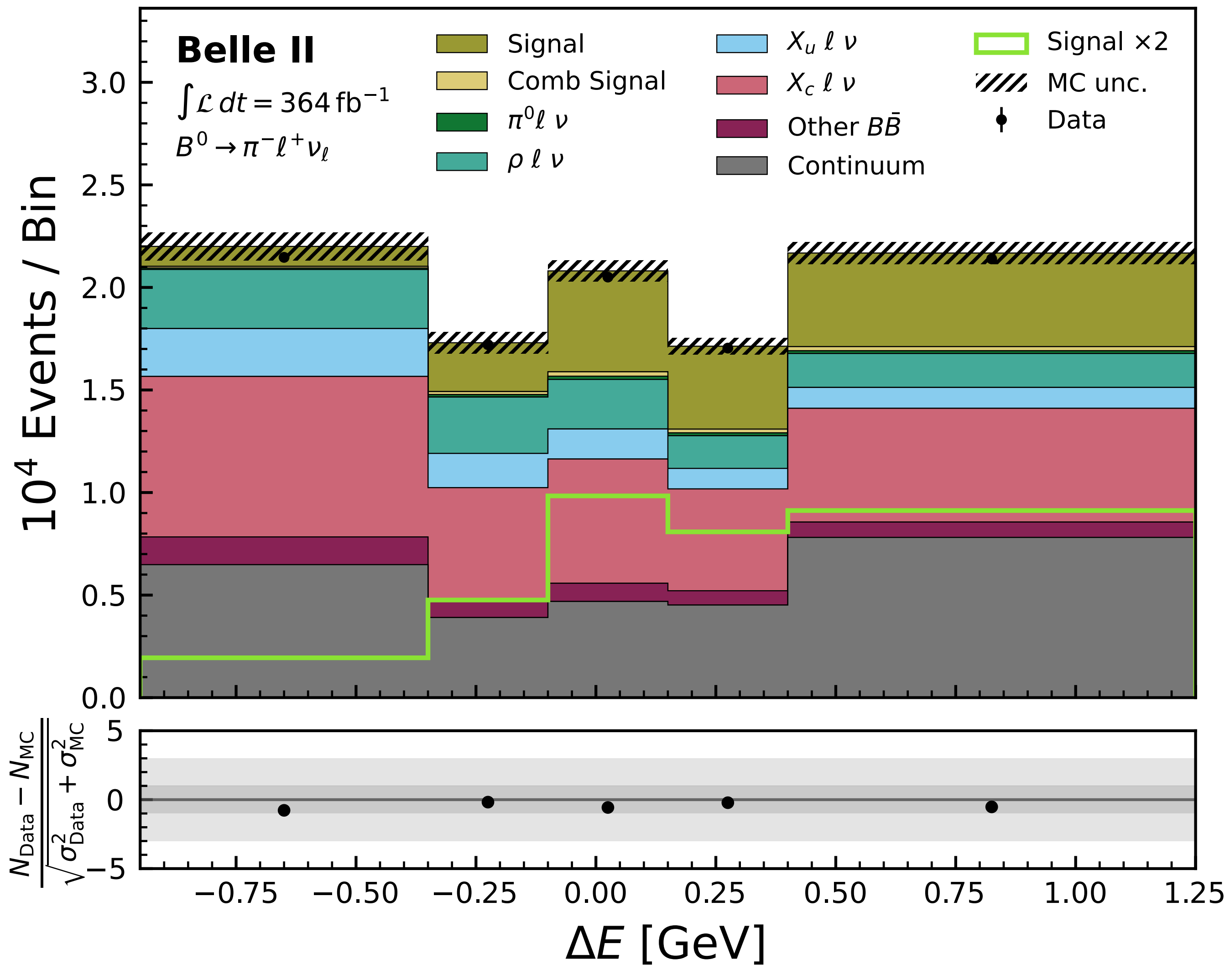


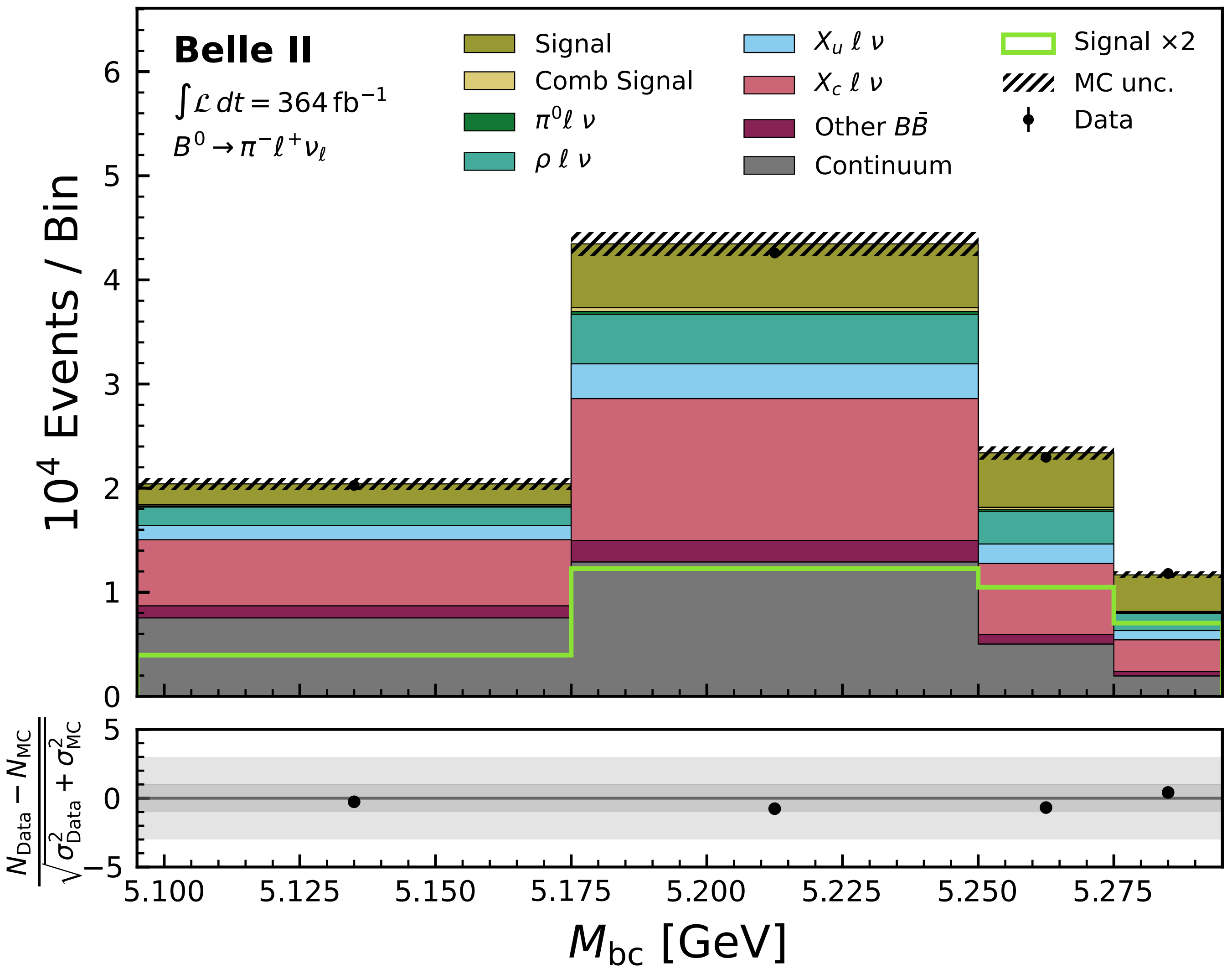
https://doi.org/10.48550/arXiv.2407.17403

$|V_{ub}|$ from $B^0 \to \pi^- \ell^+ \nu$ & $B^+ \to \rho^0 \ell^+ \nu$

- **Extract $|V_{ub}|$ by simultaneously fitting $B^0 \to \pi^- \ell^+ \nu$ & $B^+ \to \rho^0 \ell^+ \nu$**
- **Signal extraction in (13+10)x4x5 bins**
  - 13 (10) bins in q^2 for $B^0 \to \pi^- \ell^+ \nu$ ($\rho^0 \ell^+ \nu$)
  - 4 bins in $M_{\rm bc}$, 5 bins in ΔE







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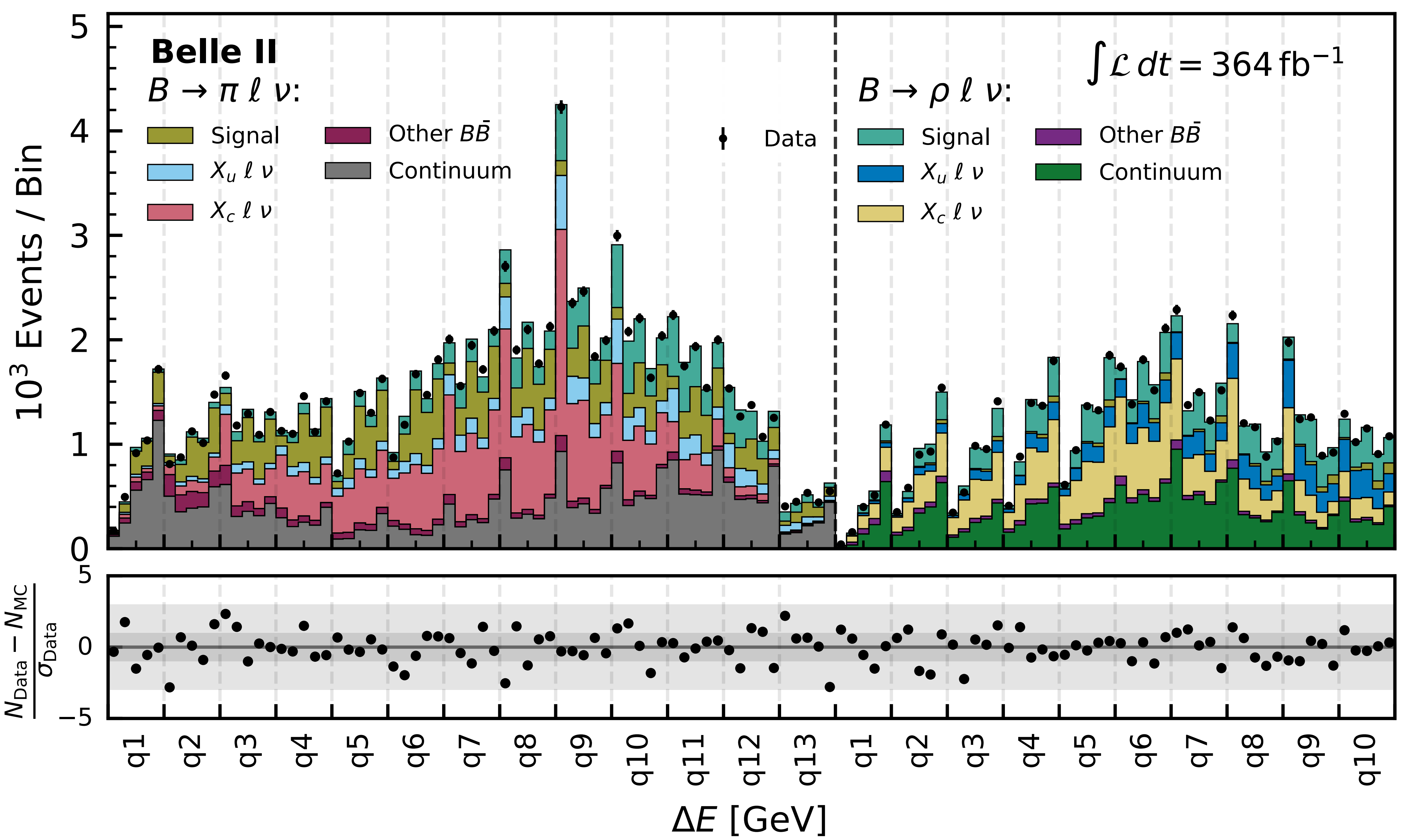
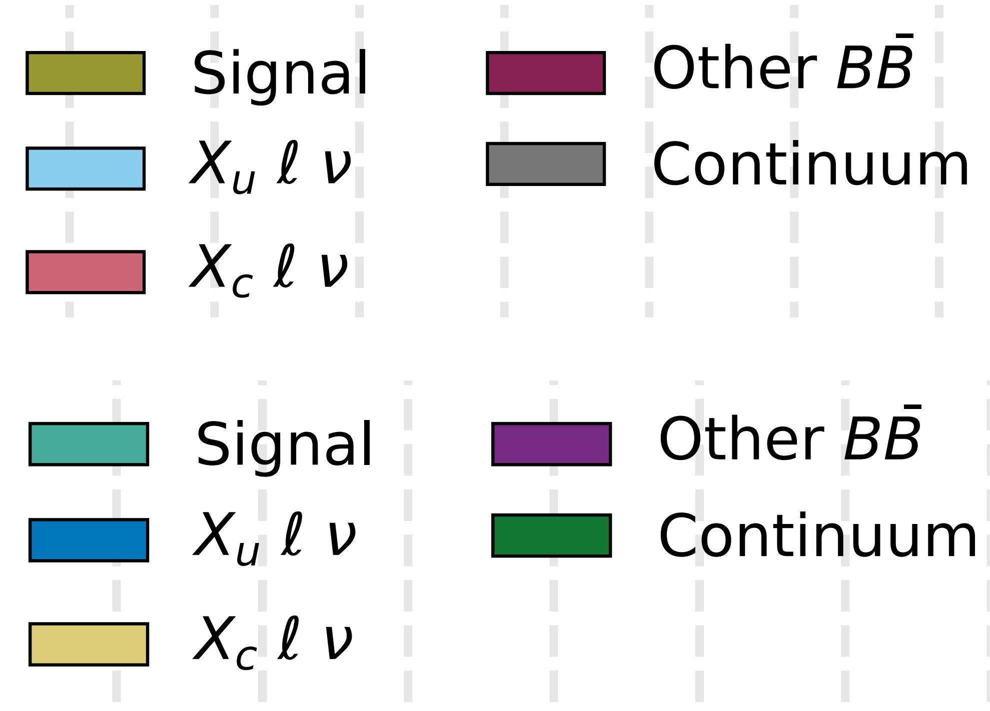
$|V_{ub}|$ from $B^0 \to \pi^- \ell^+ \nu$ & $B^+ \to \rho^0 \ell^+ \nu$





mode. The following are the labels and bin edges for the q^2 bins: $q1 : q^2 \in [0, 2]$, $q2 : [2, 4]$, $q3 : [4, 6]$, $q4 : [6, 8]$, $q5 : [8, 10]$, $q6 : [10, 12]$, $q7 : [12, 14]$, $q8 : [14, 16]$, $q9 : [16, 18]$, $q10 : [18, 20(20.3)]$, $q11 : [20, 22]$, $q12 : [22, 24]$, $q13 : [24, 26.4]$ GeV^2.

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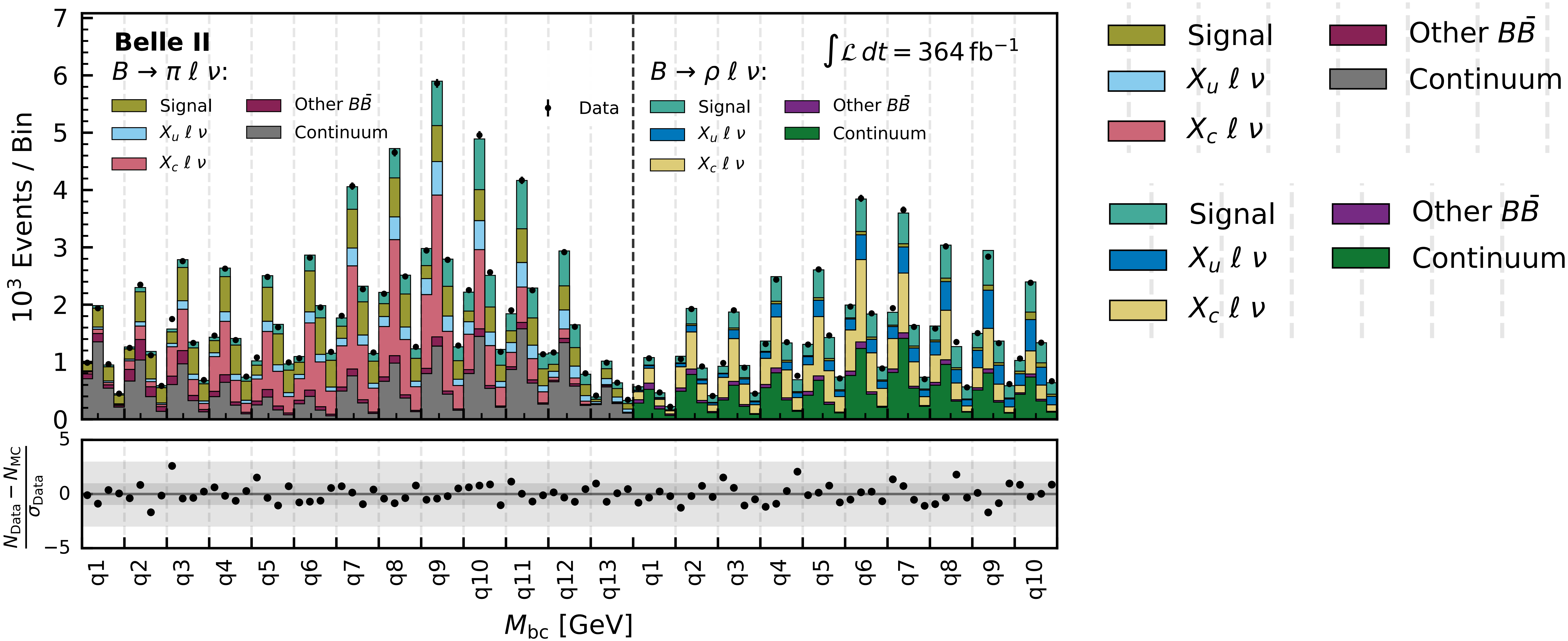
$|V_{ub}|$ from $B^0 \to \pi^- \ell^+ \nu$ & $B^+ \to \rho^0 \ell^+ \nu$



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$|V_{ub}|$ from $B^0 \to \pi^- \ell^+ \nu$ & $B^+ \to \rho^0 \ell^+ \nu$

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.516 \pm 0.042 \pm 0.059) \times 10^{-4}$$
$$\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.625 \pm 0.079 \pm 0.180) \times 10^{-4}$$

Total BF by integrating the $\Delta\mathscr{B}(q^2)$

$|V_{ub}|$ extracted separately from $\pi\ell\nu$ and $\rho\ell\nu$ mode using χ^2 fits to the measured q^2 spectra

$$\chi^2 = \sum_{i,j=1}^{N} (\Delta B_i - \Delta\Gamma_i \tau) C_{ij}^{-1} (\Delta B_j - \Delta\Gamma_j \tau) + \sum_m \chi^2_{Theory,m}$$

Form-factor coefficents:

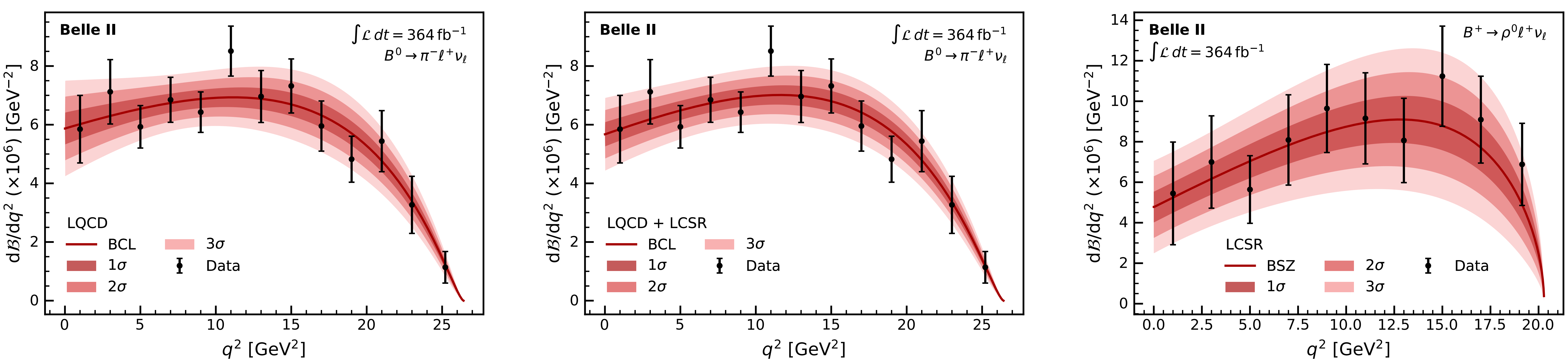
BCL for $B^0 \to \pi^- l^+ \nu_l$ — C. Bourrely, L. Lellouch and I. Caprini. PRD 79 (2009) 013008

BSZ for $B^+ \to \rho^0 l^+ \nu_l$ — A. Bharucha, D. M. Straub and R. Zwicky, JHEP 08 (2016) 98

$B^0 \to \pi^- \ell^+ \nu$ (LQCD) $\quad |V_{ub}|_{B\to\pi\ell\nu_\ell} = (3.93 \pm 0.09 \pm 0.13 \pm 0.19) \times 10^{-3}$

$B^0 \to \pi^- \ell^+ \nu$ (LQCD+LCSR) $\quad |V_{ub}|_{B\to\pi\ell\nu_\ell} = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$

$B^+ \to \rho^0 \ell^+ \nu$ (LCSR) $\quad |V_{ub}|_{B\to\rho\ell\nu_\ell} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$



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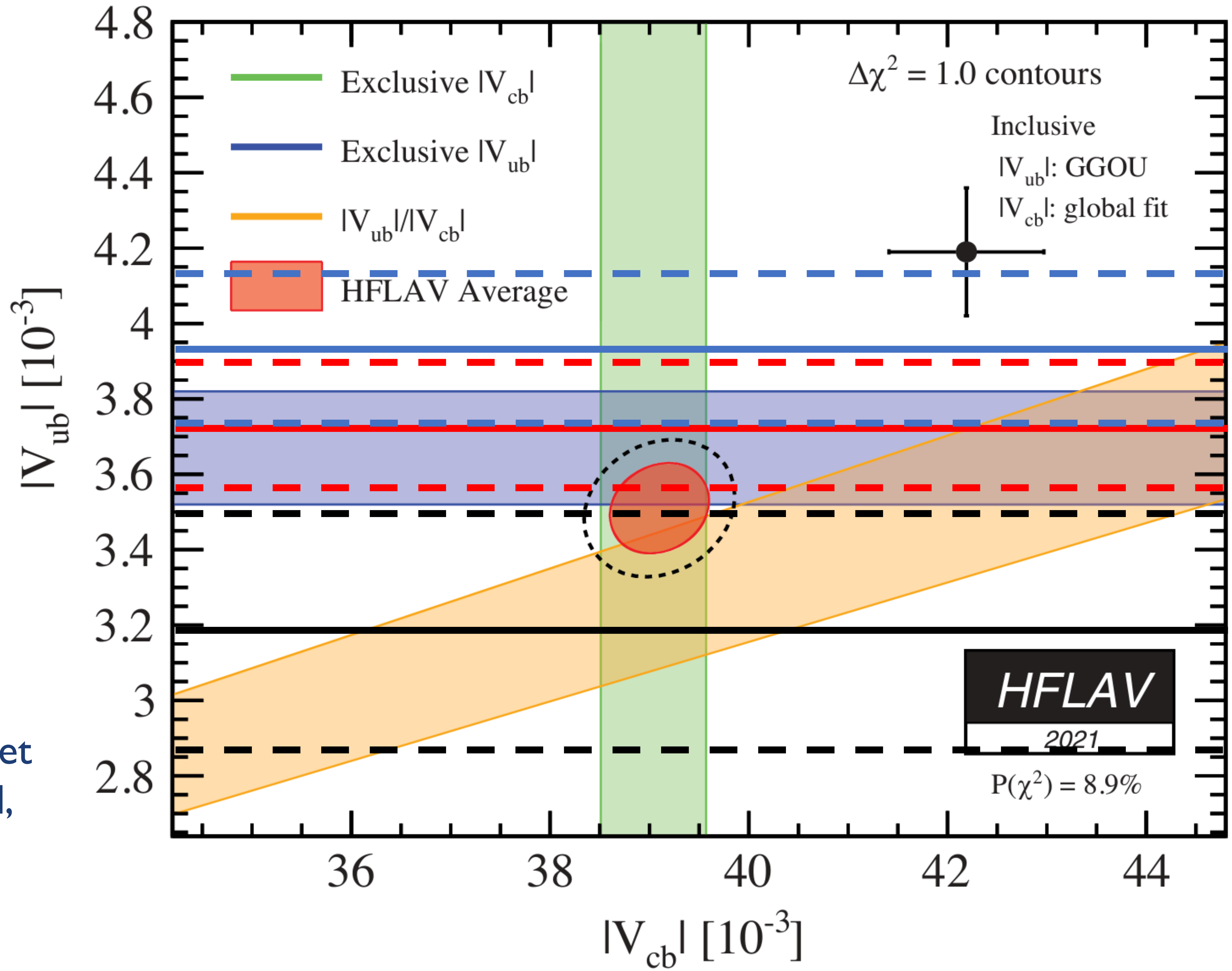
$$|V_{ub}|_{B\to\rho\ell\nu_\ell} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$$



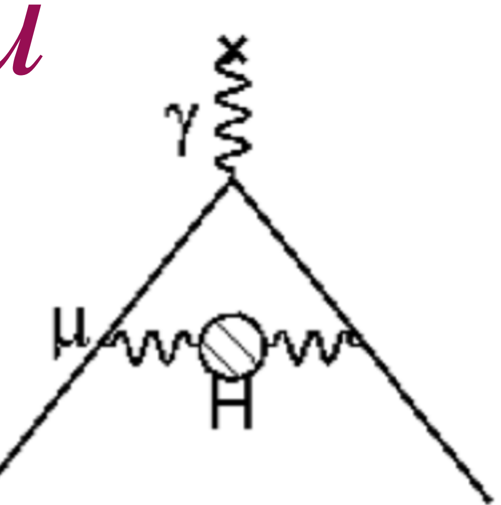
The results are limited by

- size of the off-resonance data set
- non-resonance $B \to X_u \ell \nu$ bkgd,

and reduce the tension against $|V_{ub}|$ inclusive

For 'light new physics'

$\sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^0)$ ***for*** a_μ^{HVP}



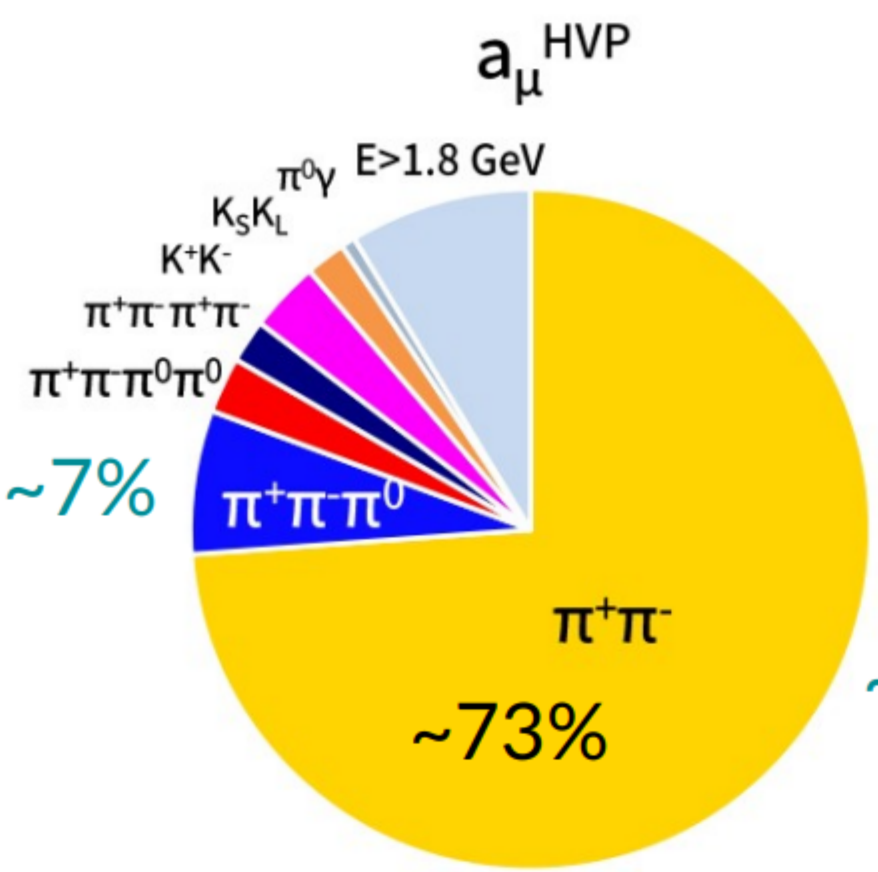
connections to muon (g-2)

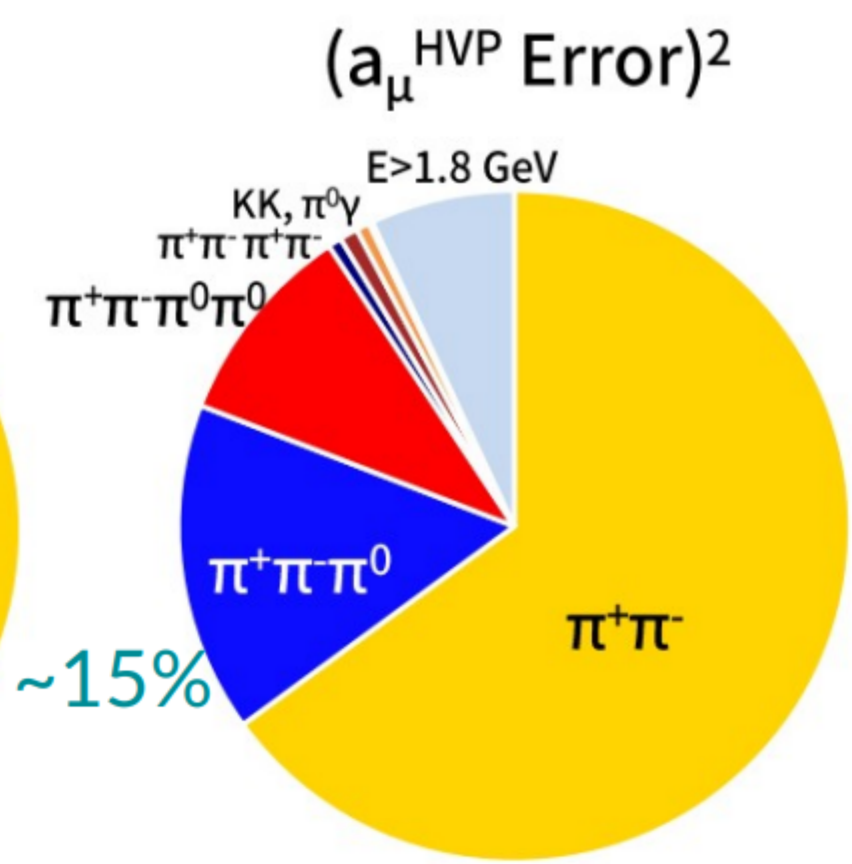
$$a_\mu = \frac{(g-2)_\mu}{2} = a_\mu^{\rm EW} + a_\mu^{\rm QED} + a_\mu^{\rm QCD}$$

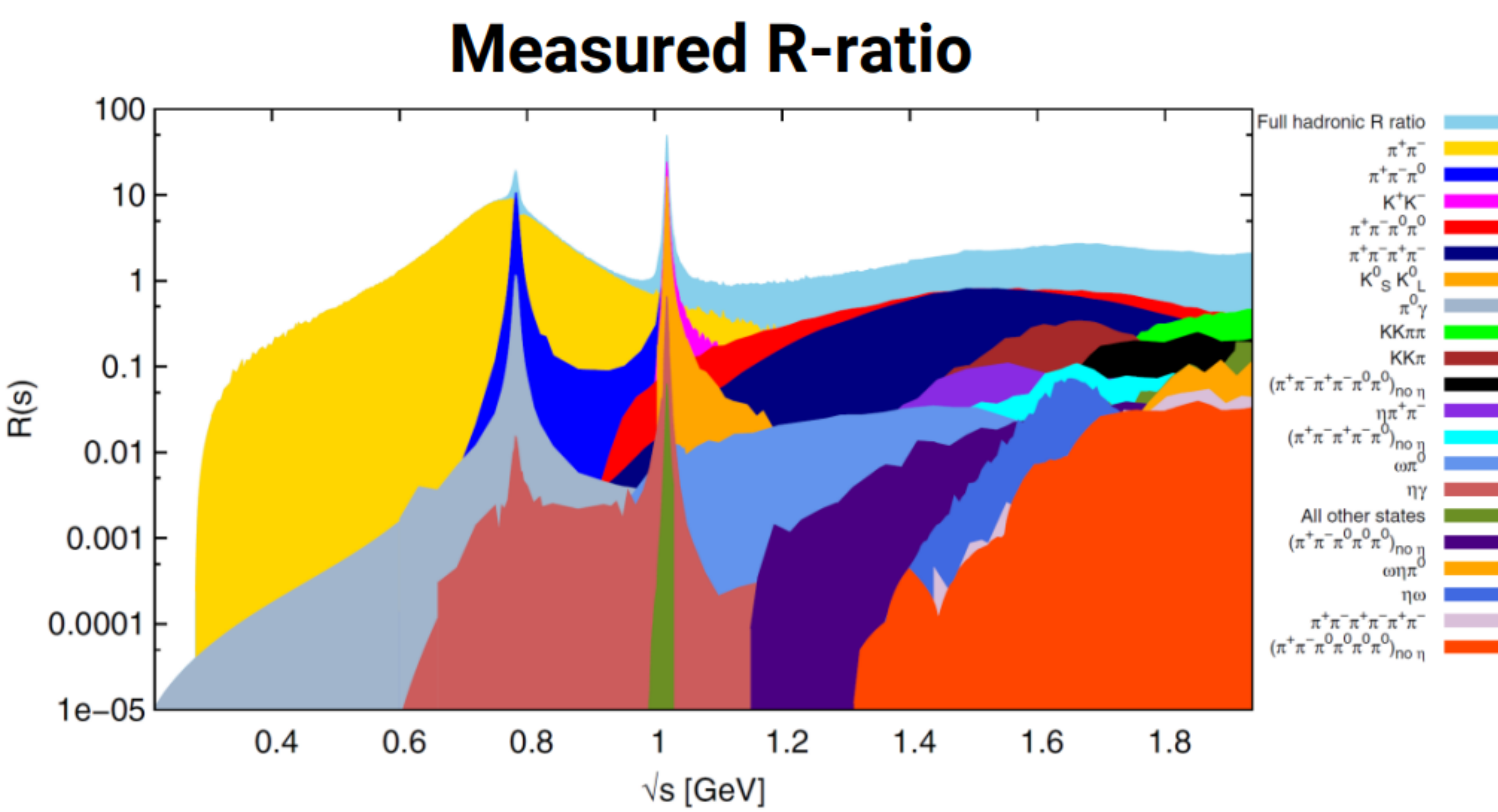
$$a_\mu^{\rm QCD} = a_\mu^{\rm HVP} + a_\mu^{\rm H,LBL}$$

(82%) (18%)

$$a_\mu^{\rm HVP,LO} = \frac{\alpha}{3\pi^2}\int_{m_\pi^2}^{\infty} \frac{K(s)}{s} R_{\rm had}(s)ds, \quad R_{\rm had}(s) = \frac{\sigma_0(e^+e^- \to \text{hadrons})}{\sigma_{\rm pt}(e^+e^- \to \mu^+\mu^-)};$$





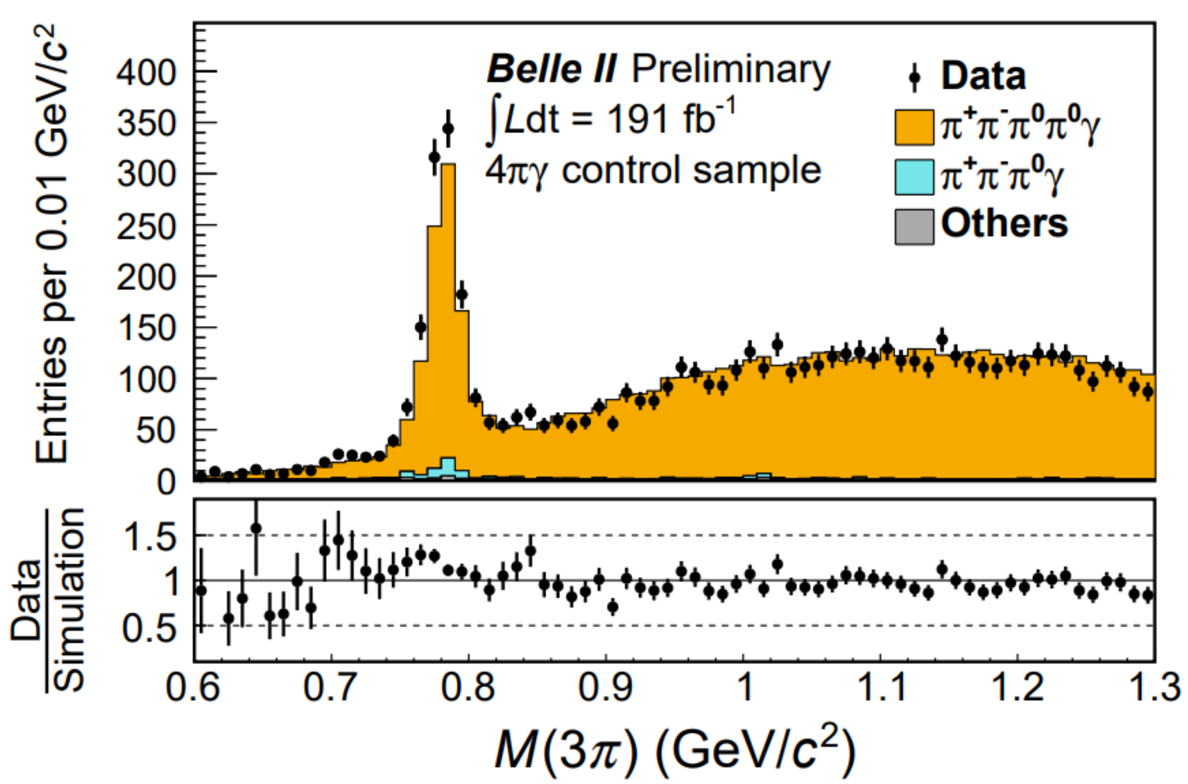


(a) The hadronic R-ratio.

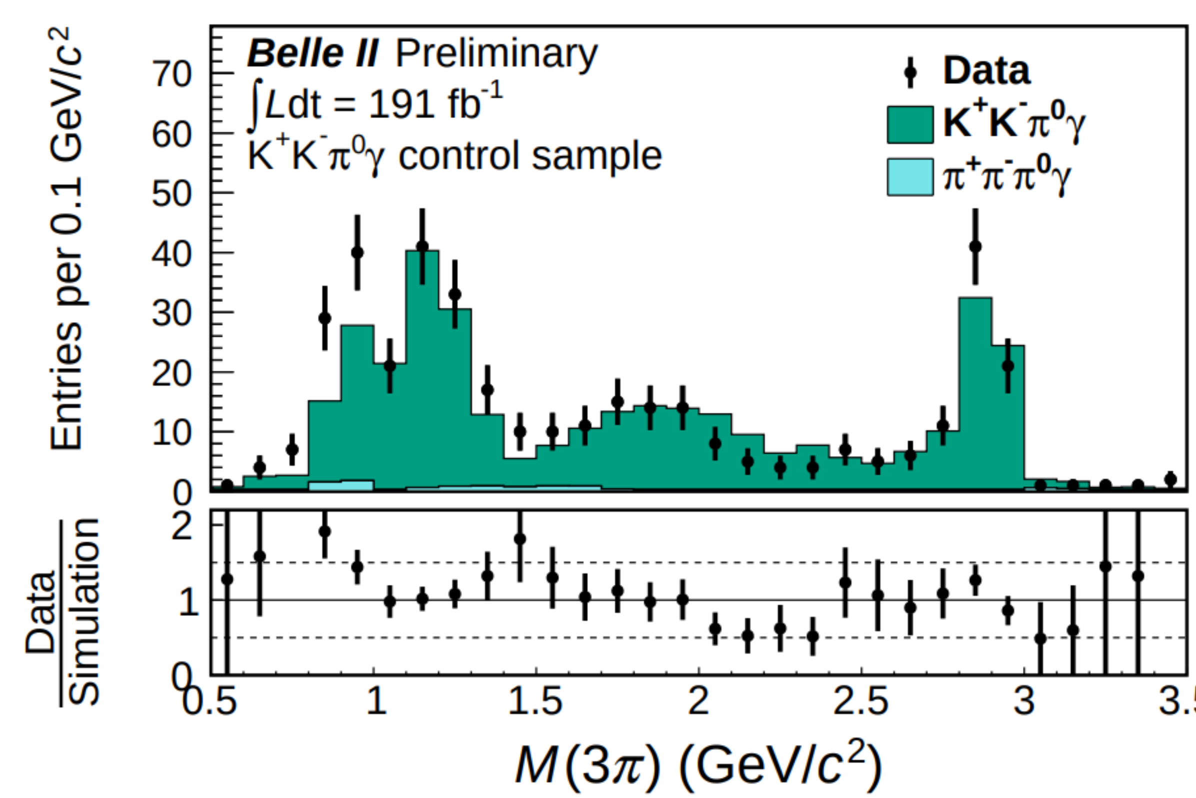
$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$

- Study $e^+e^- \to \pi^+\pi^-\pi^0$ decays in $\mathscr{L} = 191\ \text{fb}^{-1}$
- as a function of $\sqrt{s'}$ by using **ISR** technique
  - reconstruct $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{\text{ISR}}$, for $0.62 < \sqrt{s'} = M(3\pi) < 3.50$ GeV
- Kinematic fit for background suppression
  - constrain $(E, \vec{p})$ of $\pi^+\pi^-\pi^0\gamma_{\text{ISR}}$ to that of e^+e^- beams
- Validation ("scale factor") of backgrounds in control samples

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma$



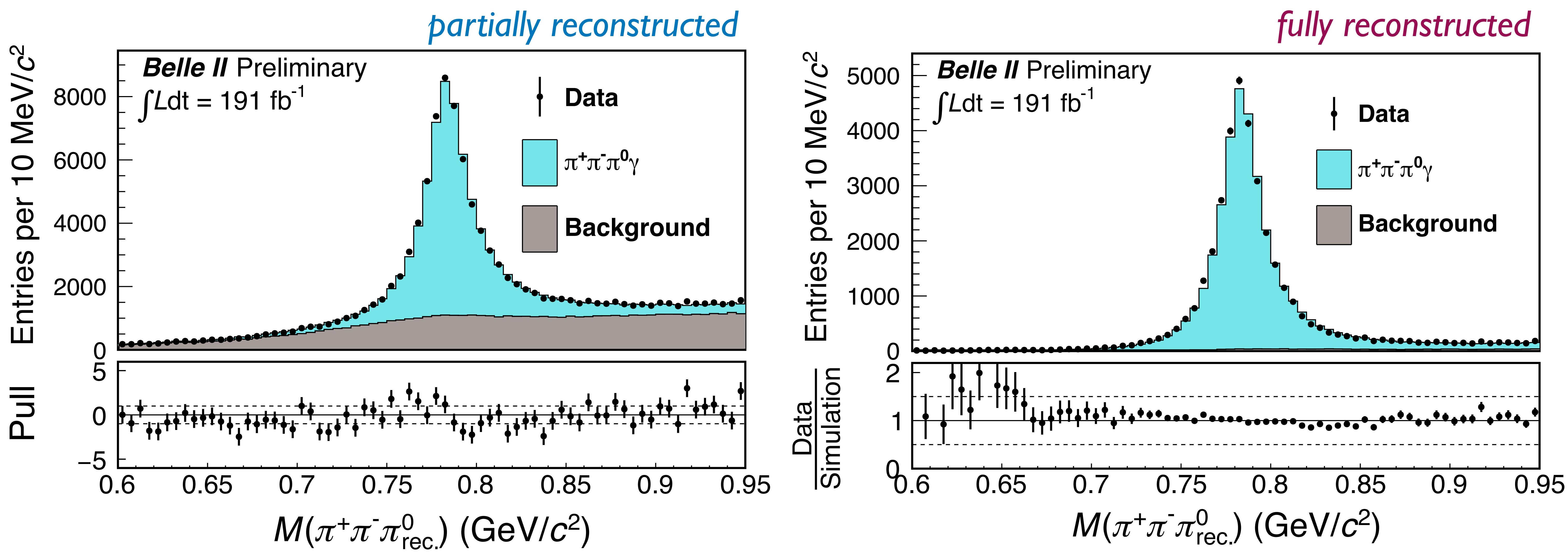
$e^+e^- \to K^+K^-\pi^0\gamma$



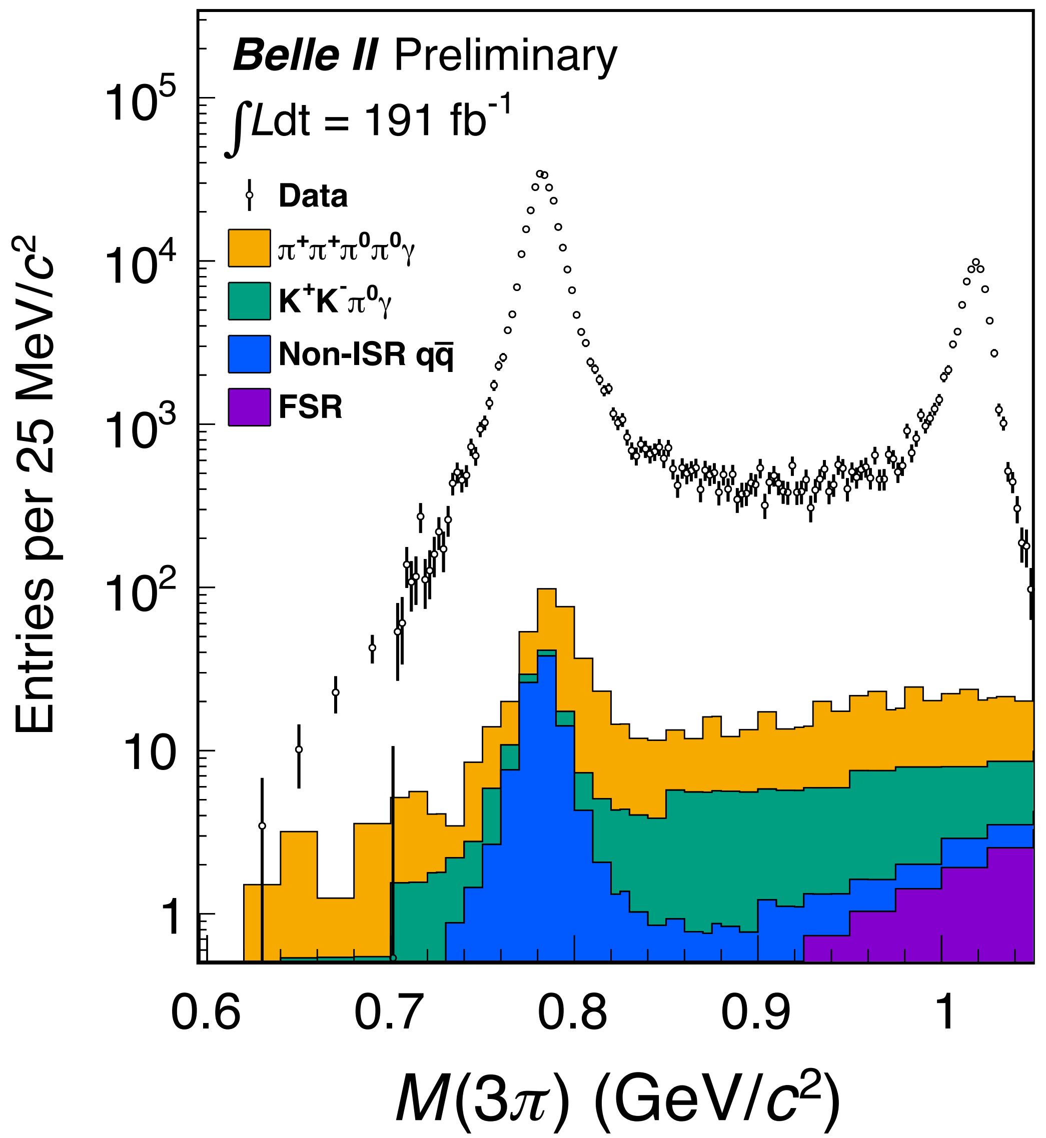
$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$

$$\varepsilon(\pi^0) = \frac{N_{\text{full}}(\gamma_{\text{ISR}}\pi^+\pi^-\pi^0)}{N_{\text{partial}}(\gamma_{\text{ISR}}\pi^+\pi^-)}$$

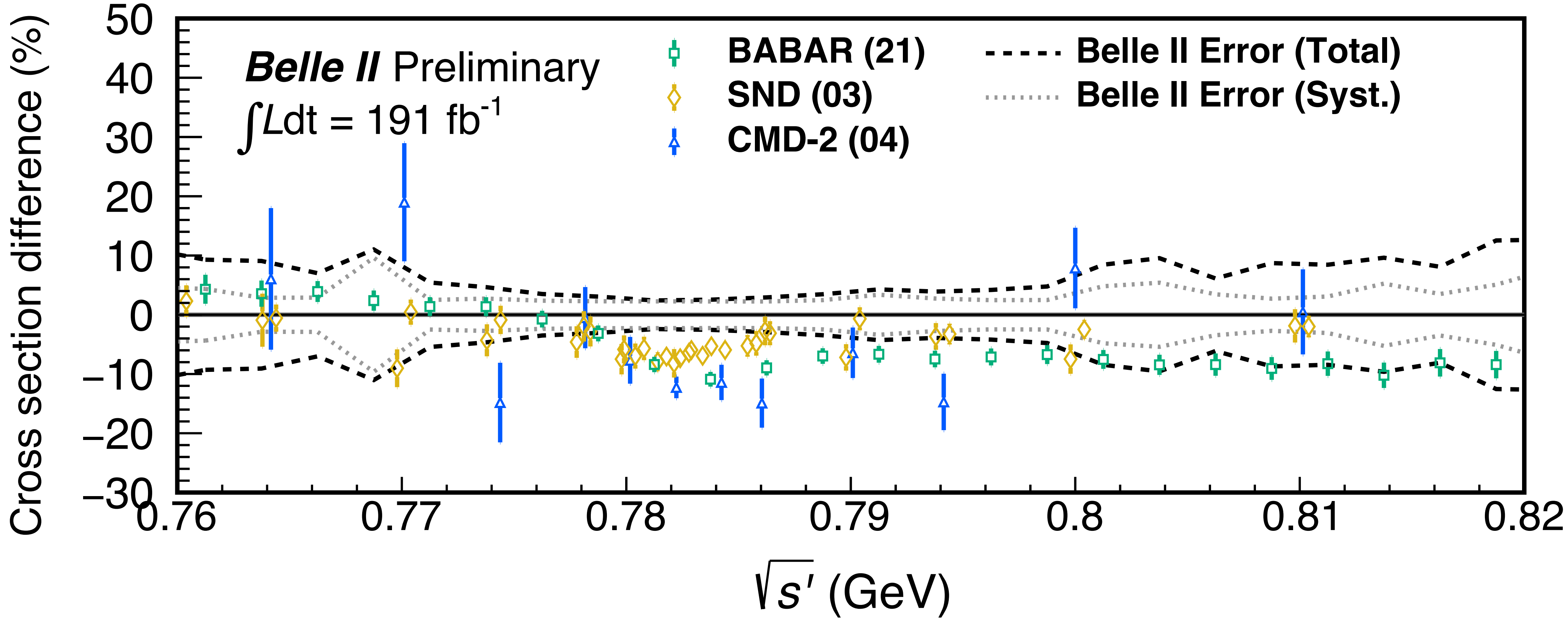
- π^0 efficiency as a major analysis challenge
- The $\varepsilon(\pi^0)$ is determined to an accuracy of ~1% by comparing full- and partial-reconstruction in the $\omega \to \pi^+\pi^-\pi^0$ region



$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$ Results



Differences of the measured cross section around the ω resonance



- $a_\mu^{3\pi}(0.62 - 1.8\ \mathrm{GeV}) = (48.91 \pm 0.23 \pm 1.07) \times 10^{-10}$
- main syst. uncertainties from efficiency and absence of NNLO in the MC
- 6.5% higher (2.5σ significant) than the global fit ➔ move to smaller 'anomaly'

$$a_\mu^{3\pi}(0.62\text{–}1.8\,\mathrm{GeV}) = (45.91 \pm 0.37 \pm 0.38) \times 10^{-10}.$$

Closing remarks

- Belle II has collected over $0.4\ \mathrm{ab}^{-1}$ data sample in its first 3 years of operation before LS1, and started Run 2 data-taking in Feb. this year.
- With the data set of ~1/2 the size of Belle, the physics precision of Belle II results are comparable or better in many analyses.
- Recent Belle II physics highlights include first evidence for $B^+ \to K^+\nu\bar{\nu}$, and inclusive test of LFU with $B \to X\tau\nu$. (PRD 109, 112006 (2024))
- Belle II started her endeavor to understand the 'Incl.-Excl. tension' on $|V_{ub}|$ and $|V_{cb}|$.
- After summer shutdown, Run 2 will resume very soon with the goal of collecting a several ab^{-1} data in the next few years. Please stay tuned!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자랑스러운 연세인 한강 작가의
노벨 문학상 수상을 축하합니다
Congratulations to Yonseian Han Kang
Winner of the 2024 Nobel Prize in Literature

Thank you!