$|V_{cb}|$ and $|V_{ub}|$ at Belle II

Munira Khan on behalf of the Belle II collaboration

Belle II

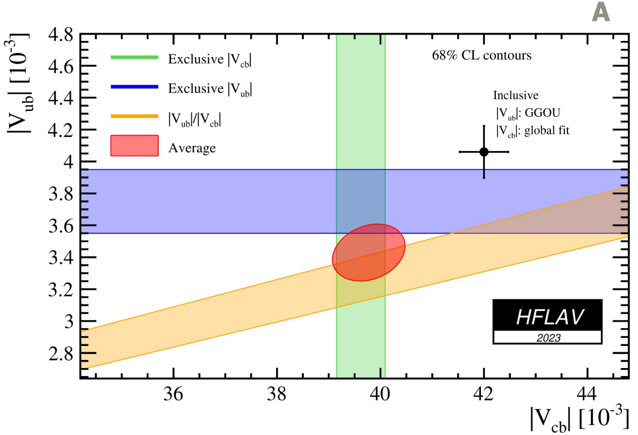
UNIVERSITÄT BONN

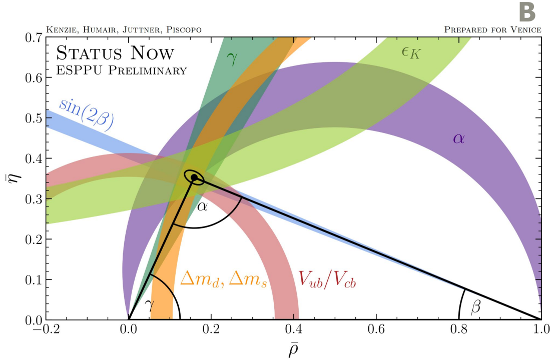
Bundesministerium für Bildung und Forschung

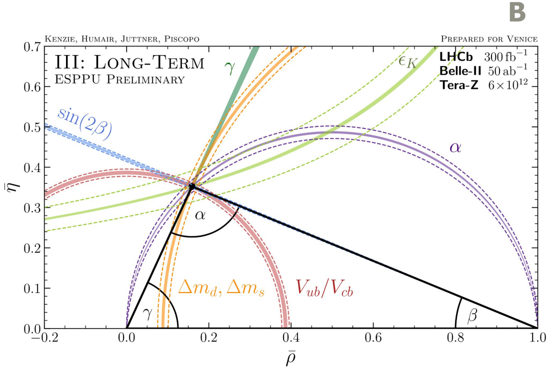
CKM matrix elements

- Precision measurement of CKM matrix elements are important inputs to SM and enable ways to test it
- Reducing the tension of inclusive vs exclusive determinations serves the scope of ESPP

→ Measurements of (semi-)leptonic decays at Belle II







A HFLAV 2023. arXiv:2411.18639 [hep-ex]
B https://agenda.infn.it/event/44943/contributions/263368/

Experimental site

SuperKEKB

B-factory experiment in Tsukuba, Japan

Asymmetric e^+e^- collider at Υ(4S) resonance

Luminosity record of 5.1 x 10^{34} cm^{-1} s^{-1}

Run 1 (2019 – 2022): 424 fb^{-1} of data, 365 fb^{-1} at Υ(4S)

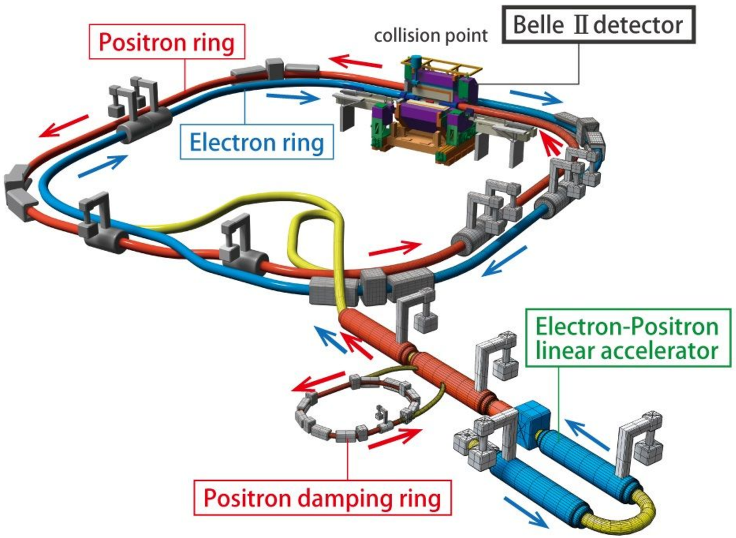
Run 2 (2024 – ongoing): 150 fb^{-1} of data

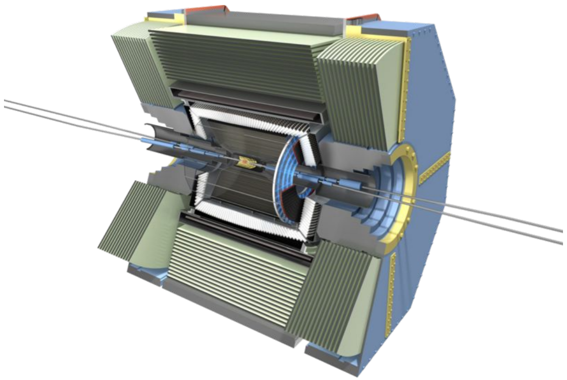
$\sigma(b\bar{b})$ ~ 1.1nb BB events

$\sigma(q\bar{q})$ ~ 3.7nb (q = u, d, s, c) continuum events

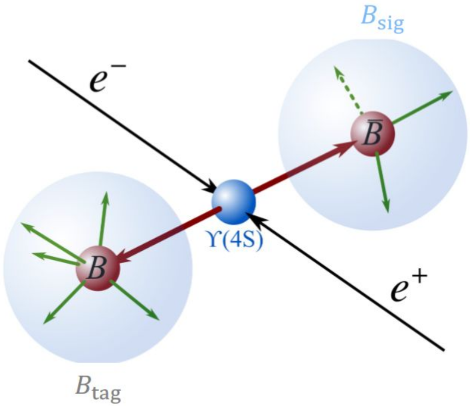
Belle II

- Hermetic & dedicated sub-detectors for tracking, PID and calorimetry
- Well-suited to inclusive measurements and analyses with missing particles



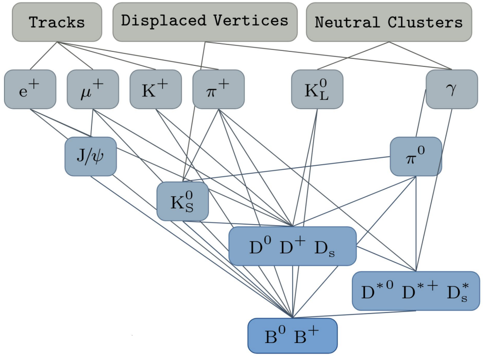


Events kinematics and tagging at Belle II

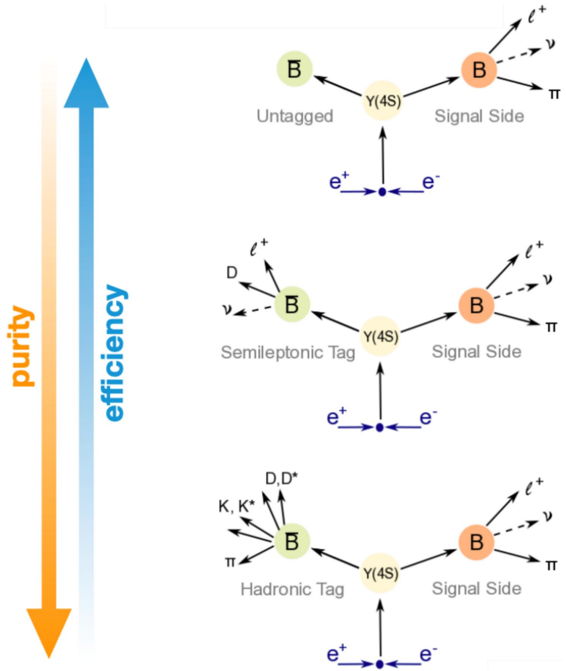


$$e^+e^- \to \Upsilon(4S) \to B_{\text{sig}} B_{\text{tag}}$$

Schematic Overview of Full Event Interpretation

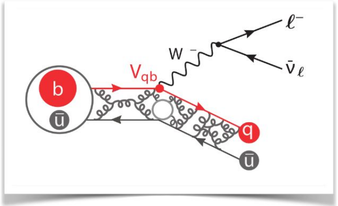


Comput Softw Big Sci 3, 6 (2019)



Strategy for event tagging

Inclusive vs Exclusive $|V_{qb}|$ determinations



Inclusive $|V_{ub}|$

$\bar{B} \to X_u \, \ell \, \bar{\nu}_\ell$

+ Fermi Motion / Shape Function

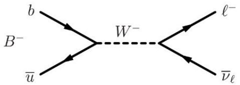
Inclusive $|V_{cb}|$

$\bar{B} \to X_c \, \ell \, \bar{\nu}_\ell$

Operator Product Expansion

$$\boxed{\mathcal{B} = |V_{qb}|^2 \left[\Gamma(b \to q \, \ell \, \bar{\nu}_\ell) + 1/m_{c,b} + \alpha_s + \ldots \right]}$$

'Leptonic' $|V_{ub}|$



$$\boxed{\mathcal{B} \propto |V_{ub}|^2 \, f_B^2 \, m_\ell^2}$$

B-Meson decay constant

Exclusive $|V_{ub}|$

$\bar{B} \to \pi \, \ell \, \bar{\nu}_\ell, \Lambda_b \to p \, \mu \, \bar{\nu}_\mu$

Exclusive $|V_{cb}|$

$\bar{B} \to D \, \ell \, \bar{\nu}_\ell, \bar{B} \to D^* \, \ell \, \bar{\nu}_\ell$

$$\boxed{\mathcal{B} \propto |V_{cb}|^2 \, f^2}$$

Form Factors

$\langle B | H_\mu | P \rangle = (p + p')_\mu \, f_+$

→ Long standing discrepancy between inclusive and exclusive determinations

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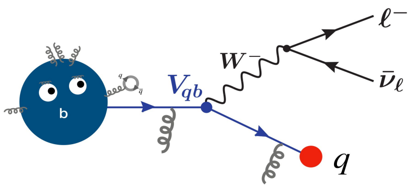
Measurements at Belle II



$|V_{cb}|$ Exclusive

- $B \to D l \nu$ (untagged)

  arXiv:2506.15256

- $B \to D^* l \nu$ (untagged)

  Phys.Rev.D 108 (2023) 9, 9

$|V_{cb}| = (40.13 \pm 0.27 \pm 0.93 \pm 0.58) \times 10^{-3}$

$|V_{cb}|$ Inclusive

- $B \to X_c \ell \nu$ (q^2 moments, had. tagged)

  Phys.Rev.D 107 (2023) 7, 072002

  J. High Energy Phys. 10 (2022) 068

- $B \to X_c \ell \nu$ (M_x moments, had. tagged)

  arXiv:2009.04493

$|V_{ub}|$ Exclusive

- $B^0 \to \pi^- \ell^+ \nu_\ell$ and $B^+ \to \rho^0 \ell^+ \nu_\ell$ (untagged)

  Phys.Rev.D 111 (2025) 11, 112009

- $B \to \tau \nu$

  arXiv:2502.04885

$|V_{ub}|$ Inclusive

- $B \to X_u \ell \nu$ partial branching fractions (had. tagged)

  Paper in preparation

arXiv:2506.15256
submitted to PRD

Exclusive $|V_{cb}|$

Determination of $|V_{cb}|$ using $B \to D\ell\nu_\ell$ decays at Belle II

arXiv:2506.15256
submitted to PRD

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

Advantages to $B \to D\ell\nu$: Depends only on one form factor

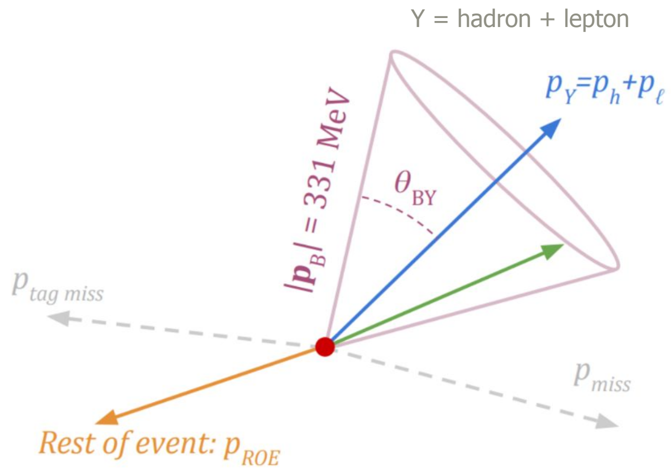
and one main background ($B \to D^*l\nu$ feed-down)

Differential measurement of using $w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$

through $\cos\theta_{BY} = \frac{2\,E_{\text{Beam}} E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$

Access B momentum direction via

- Calculating $w = v_B\, v_D$ for each potential direction of B momentum
- Calculating weights $u = \frac{1}{2}(1 - \hat{p}_B^* \cdot \hat{p}_{\text{ROE}}^*)\sin^2\theta_B^*$



arXiv:2506.15256
submitted to PRD

$B \to Dl\nu$ at Belle II

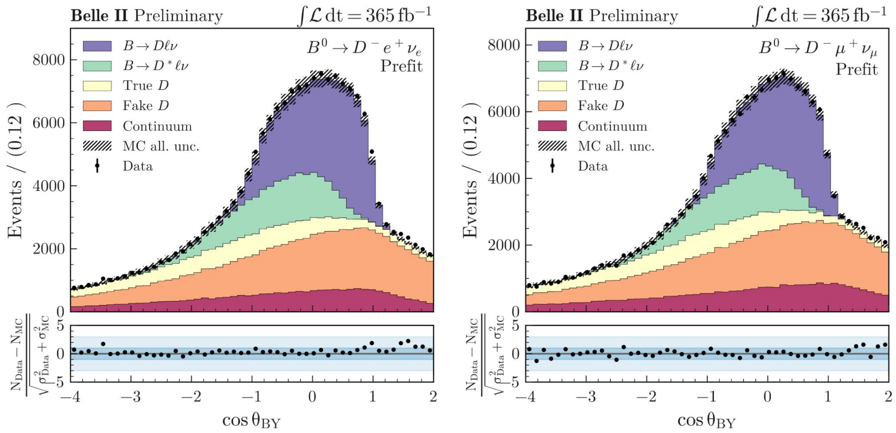
$$\cos\theta_{BY} = \frac{2\,E_{\mathrm{Beam}}E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$$

Reconstruct: $D^0 \to K^- \pi^+$ & $D^+ \to K^- \pi^+ \pi^+$ and lepton of matching charge (e, μ)

D* veto and selections to reduce other backgrounds

Several control samples validated and correction factors derived from some of them

Signal expected in $\cos\theta_{BY}$ = [-1, 1]



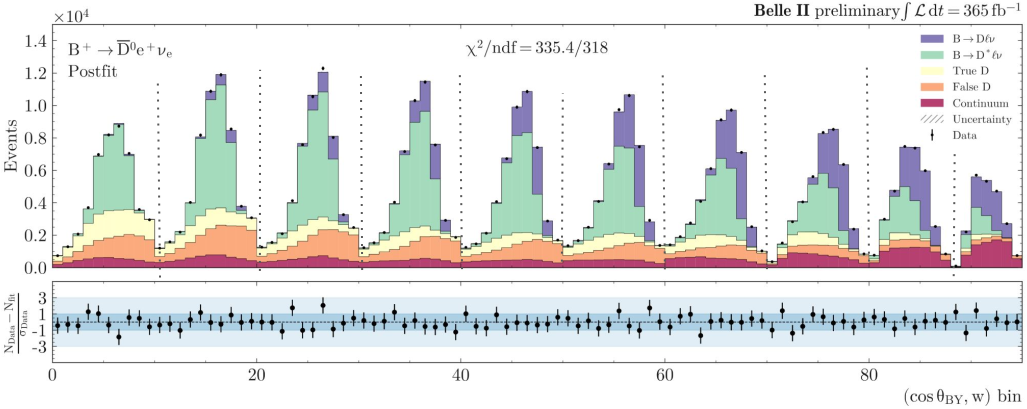
Signal extraction fit

arXiv:2506.15256
submitted to PRD

Maximum likelihood fit in 10 equal-width bins of $\cos\theta_{BY}$ and 10 bins of w

Five components:

- $B \to Dl\nu$ signal
- $B \to D^*l\nu$ feed-down
- Correctly reconstructed D
- Mis-reconstructed D
- ee $\to$ Lighter quarks and tau pairs



Bin-to-bin migration effects are accounted for by constructing signal templates based on generated values of w

$$\boxed{\mathcal{B}(B^0 \to D^-\ell^+\nu_\ell) = (2.06 \pm 0.05\,(\text{stat.}) \pm 0.10\,(\text{sys.}))\%}$$

$$\boxed{\mathcal{B}(B^+ \to \bar{D}^0\ell^+\nu_\ell) = (2.31 \pm 0.04\,(\text{stat.}) \pm 0.09\,(\text{sys.}))\%}$$

arXiv:2506.15256
submitted to PRD

$|V_{cb}|$ extraction and results

$$\boxed{\frac{d\Gamma(B\to \bar{D}\ell^+\nu_\ell)}{dw}} \propto (w-1)^{3/2}\boxed{\eta^2_{\text{EW}}\,(1+\delta_C^{+,0})}\boxed{\mathcal{G}^2(w)}\,|V_{cb}|^2$$

$\propto$ signal yield QED correction form factor

$$w = \frac{m_B^2+m_D^2-q^2}{2m_B m_D} \qquad q^2 = (p_B - p_D)^2$$

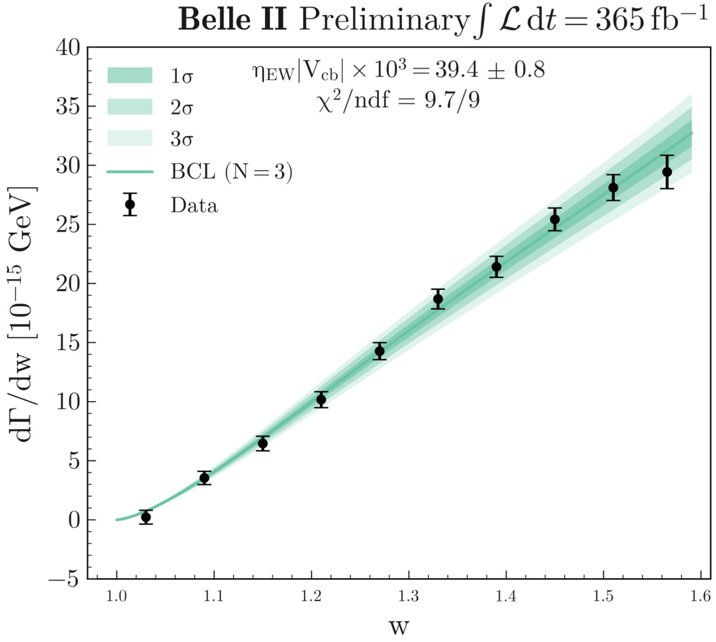
Two form factor models:

→ BCL (Bourrely, Caprini, Lellouch) parameterization [PRD 79, 013008 (2009)]

→ CLN (Caprini, Lellouch, Neubert) parameterization [Nucl. Phys. B 530, 153 (1998)]

$$|V_{cb}| = (39.2 \pm 0.4 \pm 0.6 \pm 0.5) \times 10^{-3}$$

The most precise measurement to date using $B \to D\ell\nu$!



Phys.Rev.D 111 (2025) 11, 112009

Exclusive $|V_{ub}|$

Determination of $|V_{ub}|$ from simultaneous measurements of untagged $B^0 \to \pi^- \ell^+ \nu_\ell$ and $B^+ \to \rho^0 \ell^+ \nu_\ell$ decays

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Analysis setup

Variables of interest: ΔE, M_{bc}, q^2

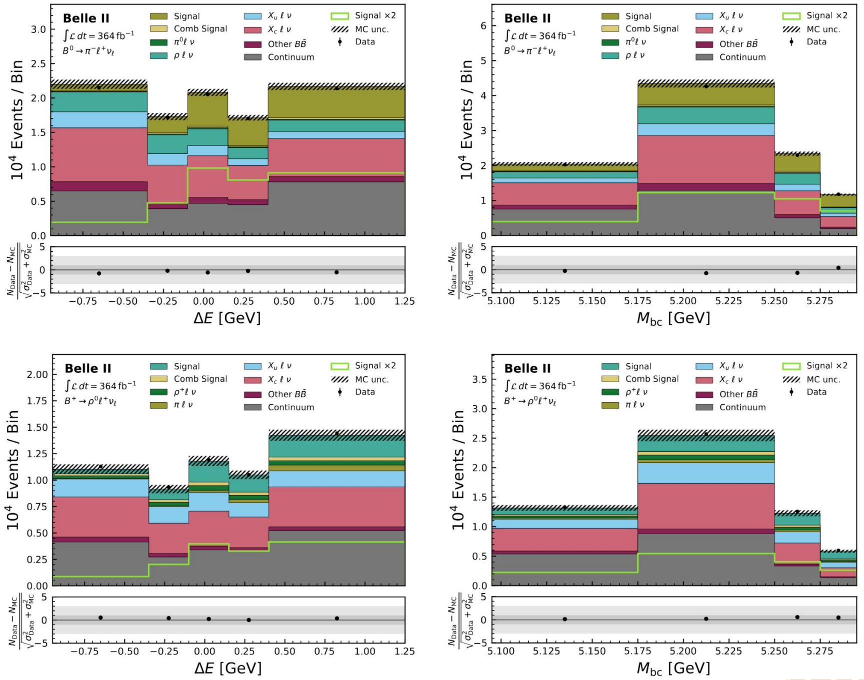
Signal components:

a. True Signal
b. Combinatorial Signal
c. Isospin-conjugate signal
d. Cross-feed signal

Background suppression:

BDTs for BB and continuum suppression trained wrt. on signal mode and q^2 bin

$\rightarrow$ 2 x (13 + 11) = 48 BDTs



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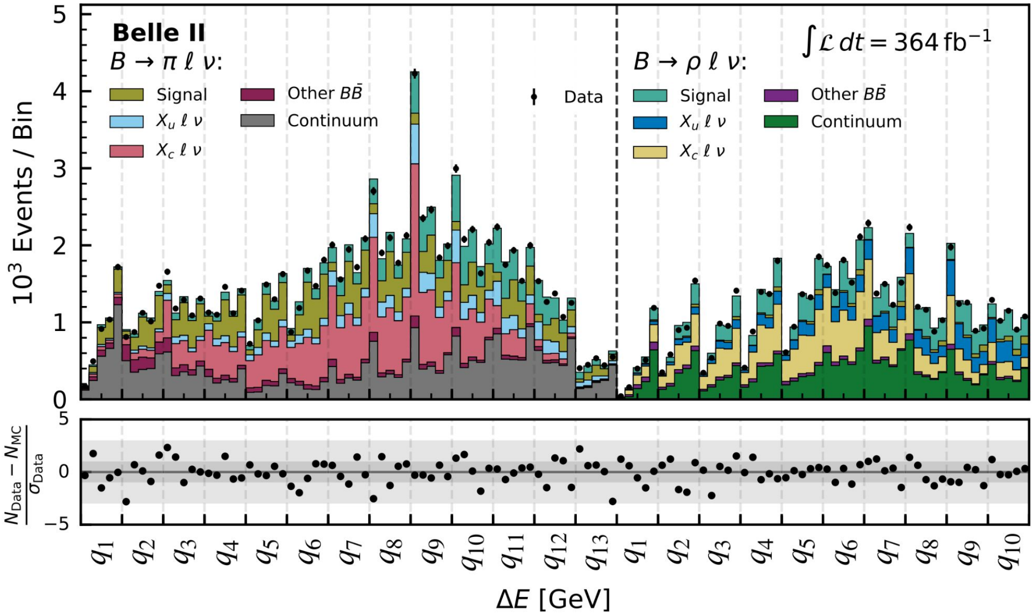
Fit results

Simultaneous 3D fit in 460 bins: (13+10) of q^2 x 5 of ΔE x 4 of M_{bc}



Signal yields are obtained in bins of true q^2

Total branching fraction as sum of partial ones obtained from fitted yields and efficiencies

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

→ Consistent with SM

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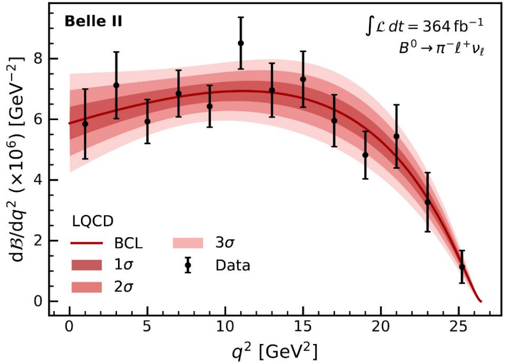
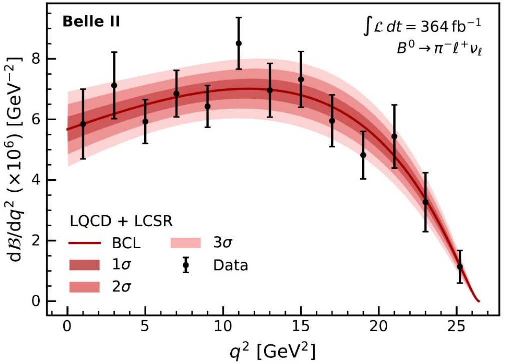
Determination of $|V_{ub}|$

Estimate $|V_{ub}|$ by minimizing $\chi^2 = \sum_{i,j=1}^{N} (\Delta B_i - \Delta\Gamma_i \tau) C_{ij}^{-1} (\Delta B_j - \Delta\Gamma_j \tau) + \chi^2_{theo}$

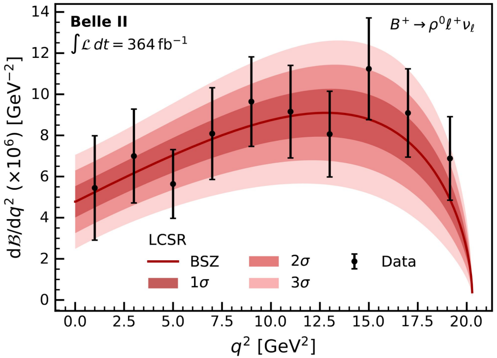
$B^0 \to \pi^- \ell^+ \nu$ (LQCD)



$B^0 \to \pi^- \ell^+ \nu$ (LQCD and LCSR)



$B^0 \to \rho^0 \ell^+ \nu$ (LCSR)



LQCD only

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

LQCD + LCSR

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

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

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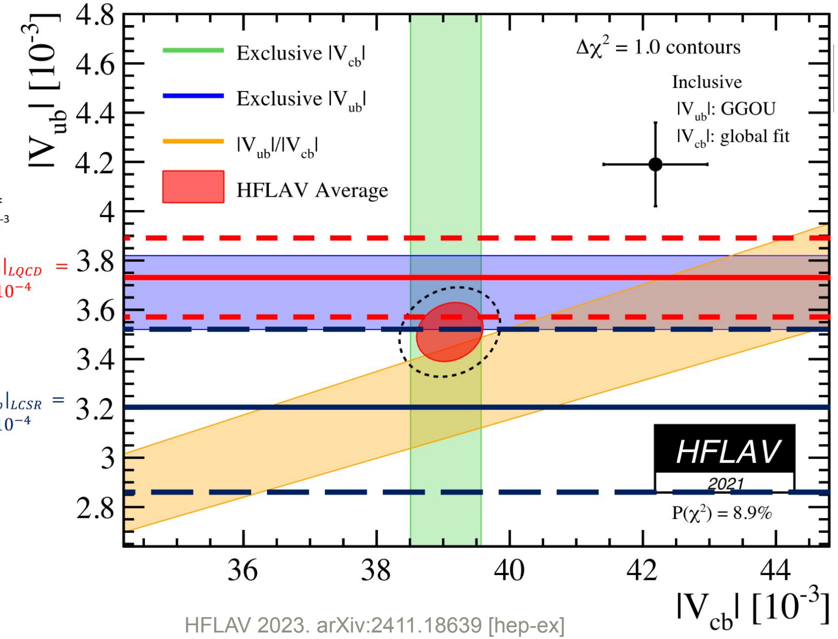
Exclusive $|V_{ub}|$ result

$|V_{ub}|$ excl. HFLAV = (3.67 +- 0.15) × 10^{-3}

$B^0 \to \pi^+ l\nu$: $|V_{ub}|_{LQCD}$ = (3.73 ± 0.16)×10^{-4}

$B^0 \to \rho^0 l\nu$: $|V_{ub}|_{LCSR}$ = (3.19 ± 0.33)×10^{-4}



HFLAV 2023. arXiv:2411.18639 [hep-ex]

Separate $|V_{ub}|$ extraction fits for π and ρ mode

Different theory calculations:

- only LQCD constraints
- LQCD + LCSR

Experimentally limited by size of off-resonance dataset and description of the non-resonant $B \to X_u \ell \nu$ backgrounds

Published in:
Phys.Rev.D 107 (2023) 7, 072002

Inclusive $|V_{cb}|$

Measurement of Lepton Mass Squared Moments in $B \to X_c \ell \nu$ decays with the Belle II Experiment

Inclusive $|V_{cb}|$

Published in:
Phys.Rev.D 107 (2023) 7, 072002

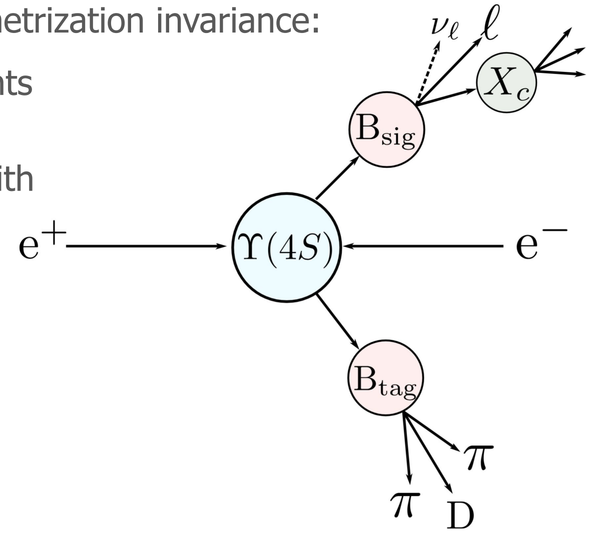
- Theory uncertainty on incl. $|V_{cb}|$ associated to truncation of the HQE and perturbative expansion
  $\rightarrow$ Measuring moments allows reduction of this uncertainty
- Reduced number of parameters by exploiting reparametrization invariance: not allowed for lepton-energy or hardon-mass moments

$$q^2 \equiv (p_\ell + p_\nu)^2 = (p_B - p_X)^2$$

$\rightarrow$ Novel method to determine $|V_{cb}|$ from q^2 moments with reduced number of parameters in the fit

[JHEP 02 (2019), 177]

$\rightarrow$ First result of q^2 moments from Belle II at 62 fb^{-1}



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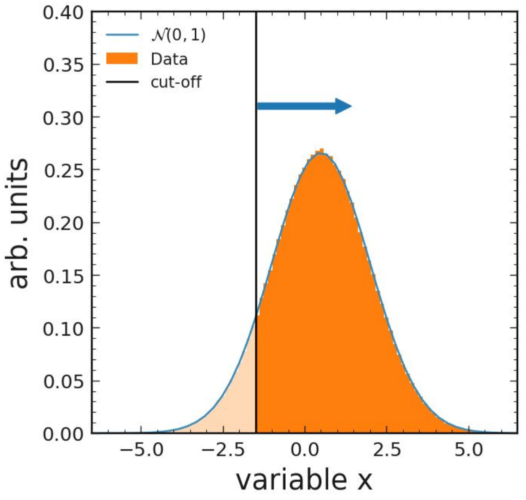
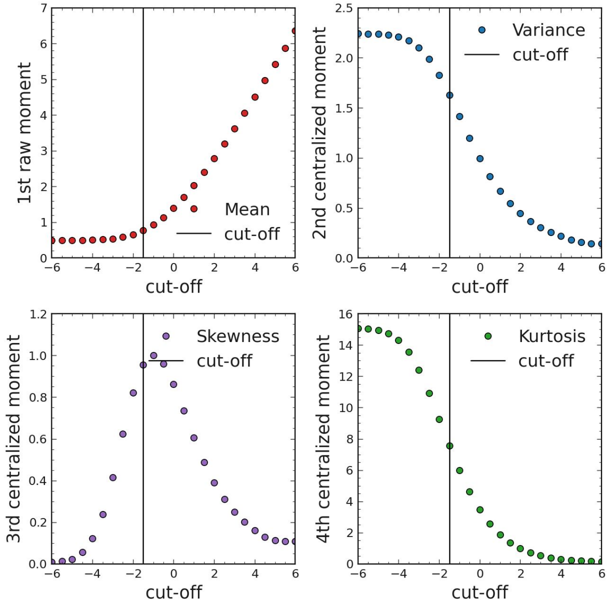
Inclusive $|V_{cb}|$

Moments measured w.r.t. various lower thresholds in the distribution





$$\mu_n = \int_{-\infty}^{-\infty} (x-c)^n f(x) dx$$

Raw moment: $c = 0$

Central moment: $c = \text{Mean}$

Reconstruction strategy

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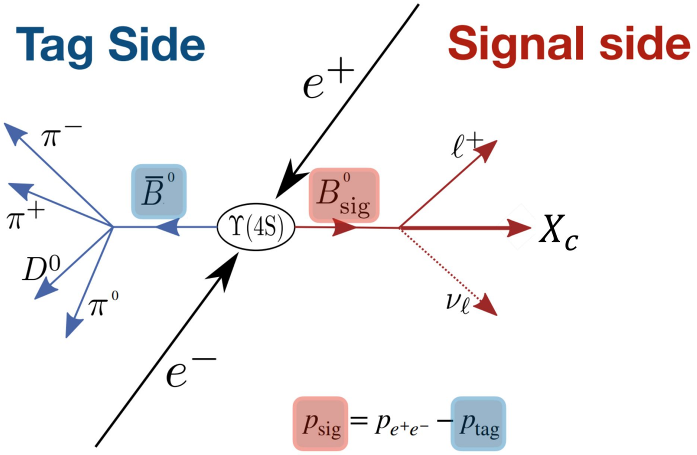
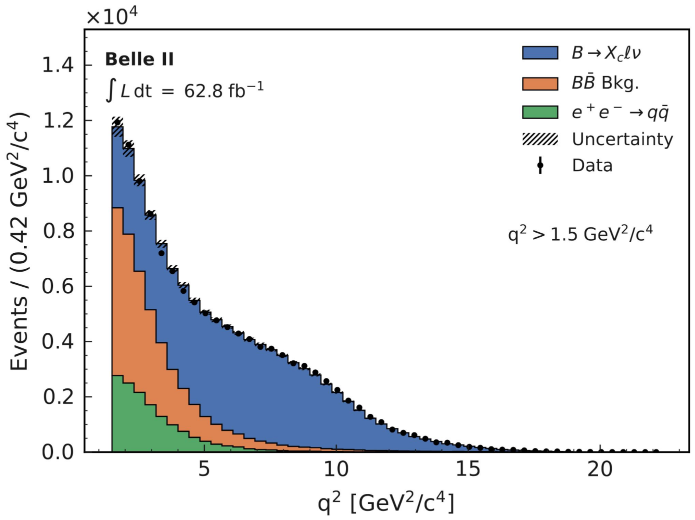
- Employ hadronic tagging to obtain full event kinematic information
- Kinematic fit to improve resolution in M_X and q^2

Variables of interest:

M_X, q^2





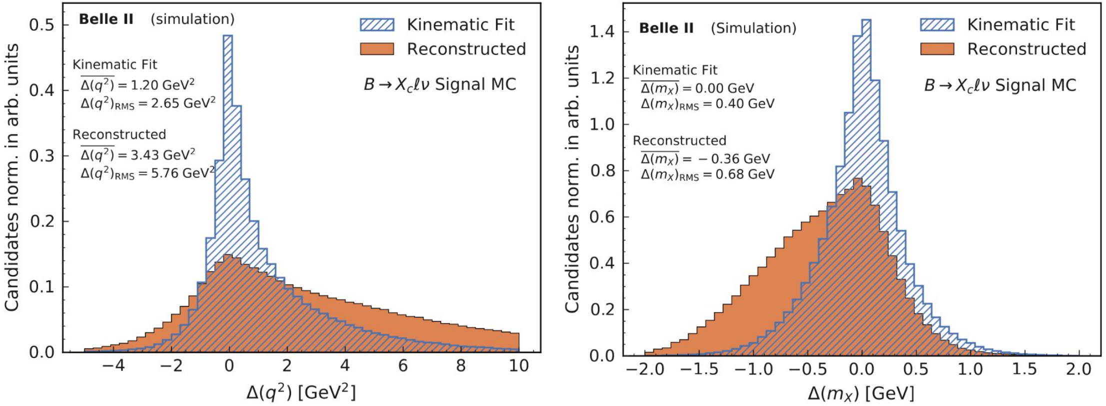
Kinematic Fit

Published in:
Phys.Rev.D 107 (2023) 7, 072002

Not sufficient resolution and bias for M_X and q^2 after reconstruction

Use kinematic constraints:

- B meson mass at 5.279 GeV
- No missing momentum
- Positive $M_x^{\ 2}$



✓ Improved resolution in M_X and q^2

Background subtraction fit

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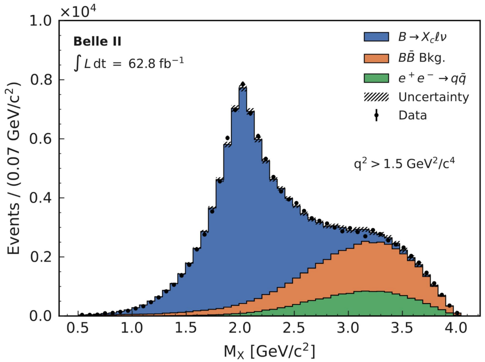

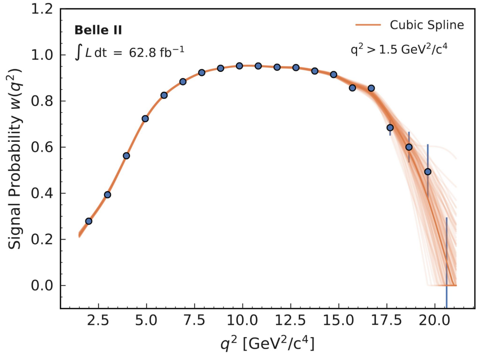

Event-wise master formula

$$\langle q^{2n} \rangle = \frac{\Sigma_{i=0}^{N_{data}} w(q_i^2) \times q_{calib,i}^{2n}}{\Sigma_{j=0}^{N_{data}} w(q_j^2)} \times \mathcal{C}_{calib} \times \mathcal{C}_{gen}$$

Fit to M_X to extract Signal and Background normalization

- Free floating signal-yield
- bin-wise nuisance parameters
- One fit for each lower threshold cut in q^2

→ Bin-wise signal probability

Cubic spline interpolation to obtain continuous signal probability functions

Calibration procedure

Published in:
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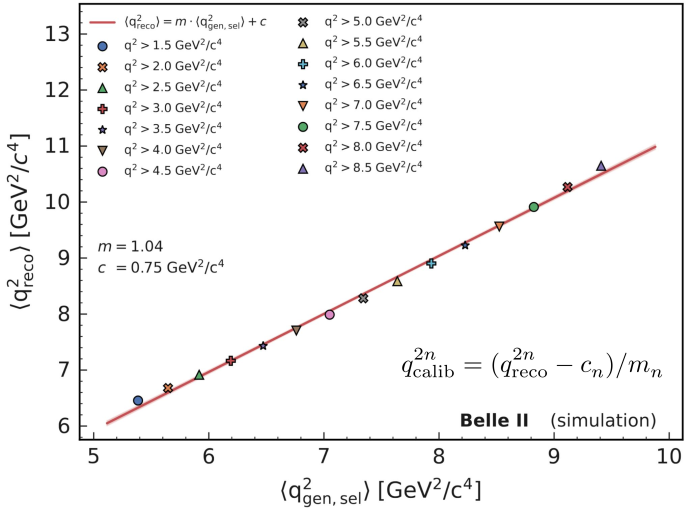
- Linear fit on MC to reconstructed moments vs generator-level moments
- For each moment & threshold cut, constant factors C_{calib} and C_{gen} correct further bias

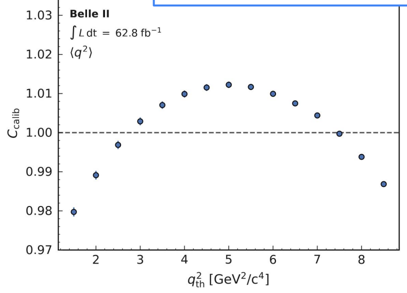


$$q^{2n}_{\mathrm{calib}} = (q^{2n}_{\mathrm{reco}} - c_n)/m_n$$

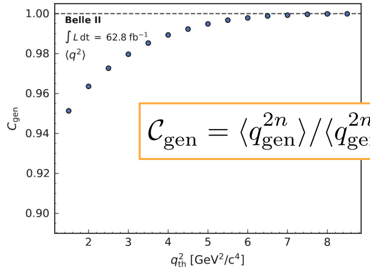
Event-wise master formula

$$\langle q^{2n} \rangle = \frac{\Sigma_{i=0}^{N_{data}} w(q_i^2) \times q^{2n}_{calib,i}}{\Sigma_{j=0}^{N_{data}} w(q_j^2)} \times \mathcal{C}_{calib} \times \mathcal{C}_{gen}$$

$$\mathcal{C}_{\mathrm{calib}} = \langle q^{2n}_{\mathrm{gen,sel}} \rangle / \langle q^{2n}_{\mathrm{calib}} \rangle$$



$$\mathcal{C}_{\mathrm{gen}} = \langle q^{2n}_{\mathrm{gen}} \rangle / \langle q^{2n}_{\mathrm{gen,sel}} \rangle$$



Systematic uncertainties

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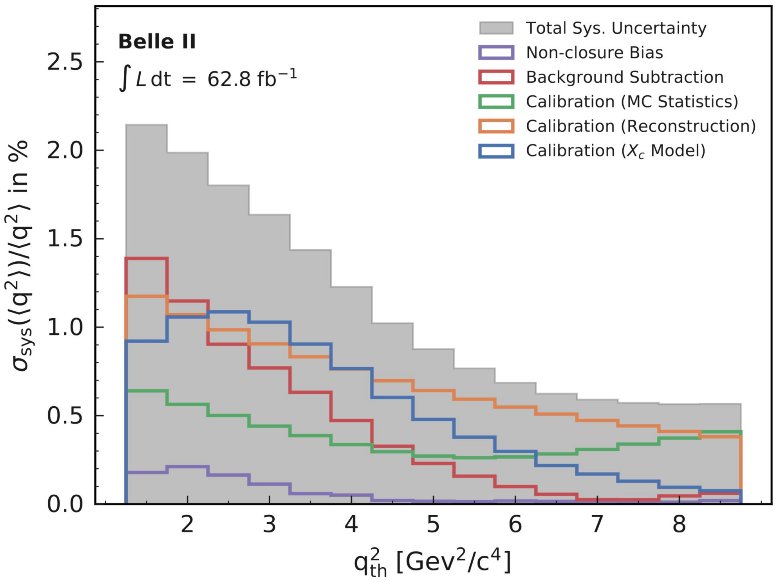
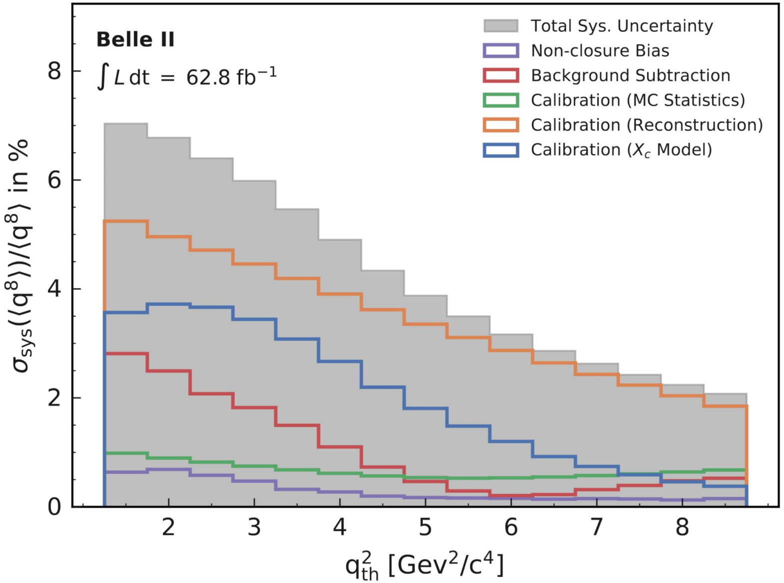
Systematics dependant on lower threshold cut and moment of q^2





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Results

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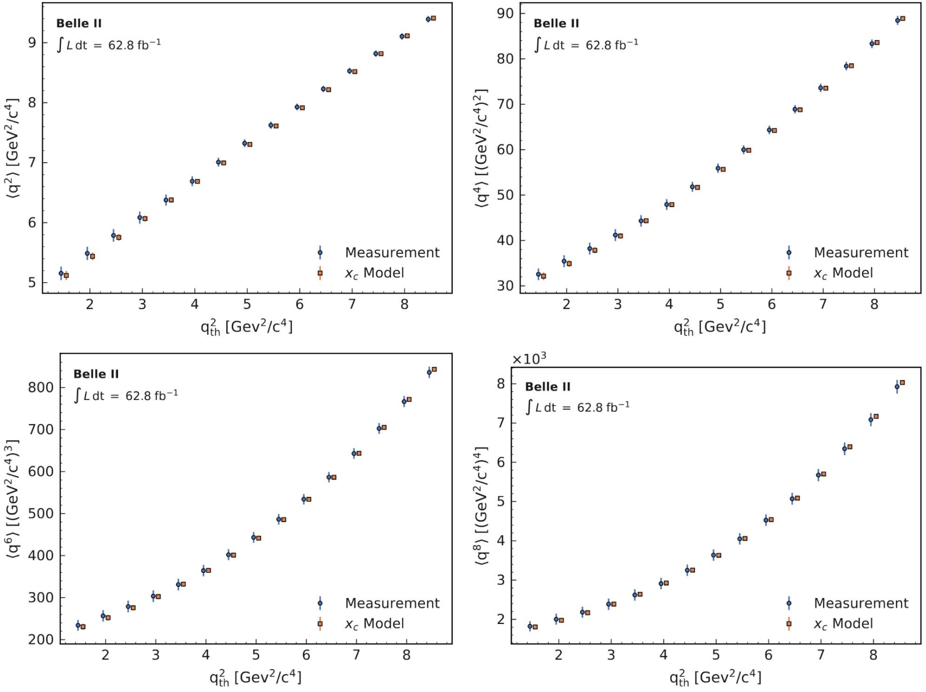


Extracted moments can be used in fit to determine value of $|V_{cb}|$

(Extracted $|V_{cb}|$ value combined with Belle result)

$$\boxed{|V_{cb}| = (41.70 \pm 0.69) \times 10^{-3}}$$

J. High Energy Phys. 10 (2022) 068

Paper to be submitted

Inclusive $|V_{ub}|$

Measurement of inclusive $B \to X_u \ell \nu$ partial branching fractions and $|V_{ub}|$ at Belle II

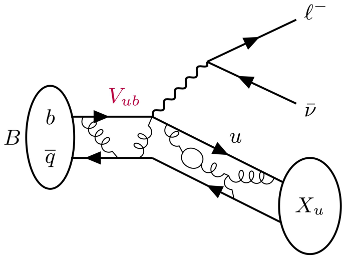
Paper to be submitted

Measurement outline

Kinematic selections break inclusivity requirement of the HQE and predictions of differential decay rates become necessary

→ Predictions rely on effective description of the b-quark motion inside the meson

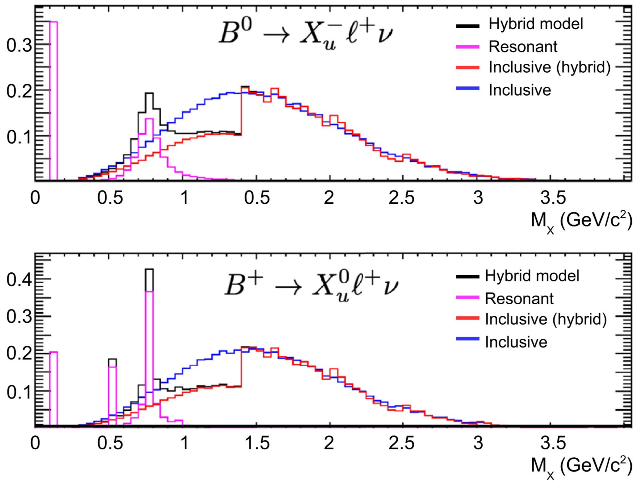
→ Shape functions



Three phase space regions

(87%, 57% and 32% of full available phase space)

Phys. J. C 80, 966 (2020)



Hybrid model approach to combine resonant and non-resonant modelling

3D re-weighting in E_ℓ^B, M_X, q^2

$$w_{ijk} = \frac{\Delta\mathcal{B}^{\text{inc}}_{ijk} - \Delta\mathcal{B}^{\text{exc}}_{ijk}}{\Delta\mathcal{B}^{\text{inc}}_{ijk}}$$

Paper to be submitted

Selections and modelling corrections

Hadronic tagging and inclusive reconstruction of X

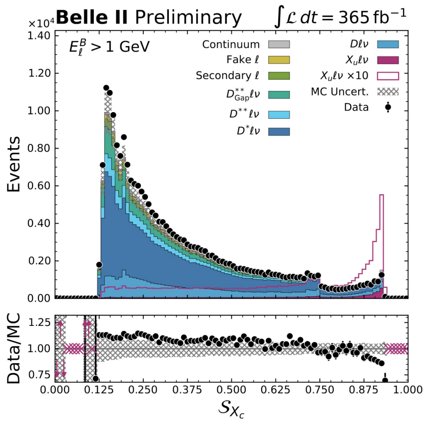
Variables of interest: E_ℓ^B, M_X, q^2

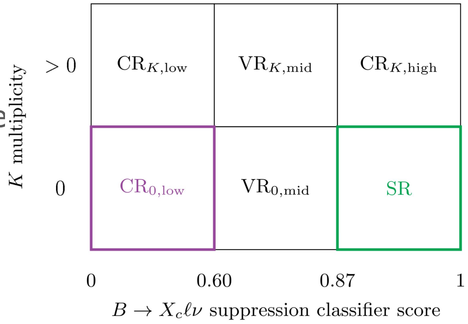
Background suppression

- BDT-based corrections to continuum shape and normalization
- ML-algorithm trained on nine kinematic variables to suppress $B \to X_c \ell\nu$ background

Modelling corrections to $B \to X_c \ell\nu$

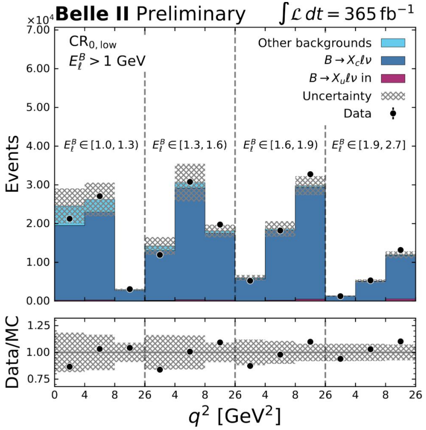
- mismodelling could not be attributed to a single source: normalization and shape correction are corrected separately: normalization from ABCD method
- Shape correction is directly implemented into the signal extraction procedure by simultaneously fitting $CR_{0,low}$ ($B \to X_c \ell\nu$ enriched region)

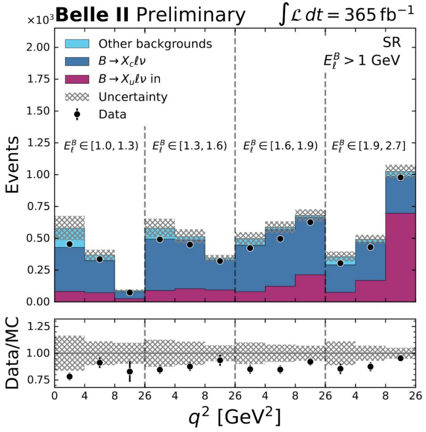




Paper to be submitted

Signal Extraction





Simultaneous fit in signal region (SR) and control region (CR)

2D fit in E_ℓ^B and q^2

Three templates:

Signal $B \to X_u \ell \nu$, $B \to X_c \ell \nu$ and other bkg.

Different phase-space selections

Phase space selections	Acceptance
$E_\ell^B > 1.0$ GeV	87%
$E_\ell^B > 1.0$ GeV $M_X < 1.7$ GeV	57%
$E_\ell^B > 1.0$ GeV $M_X < 1.7$ GeV $q^2 > 8$ GeV^2	31%

Unconstrained $B \to X_u \ell \nu$ normalization factor in SR (fixed in CR)

$\to$ Accounts for $B \to X_c \ell \nu$ mismodelling and correlations

Paper to be submitted

$|V_{ub}|$ determination

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

Three theoretical frameworks:

- BLNP [PRD 72, 073006 (2005)]
- Dressed Gluon Expansion [JHEP 10, 058 (2007)]
- Gambino, Giordano, Ossola and Uraltsev [JHEP 01, 097 (2006)]

Result in most inclusive phase space region (GGOU):

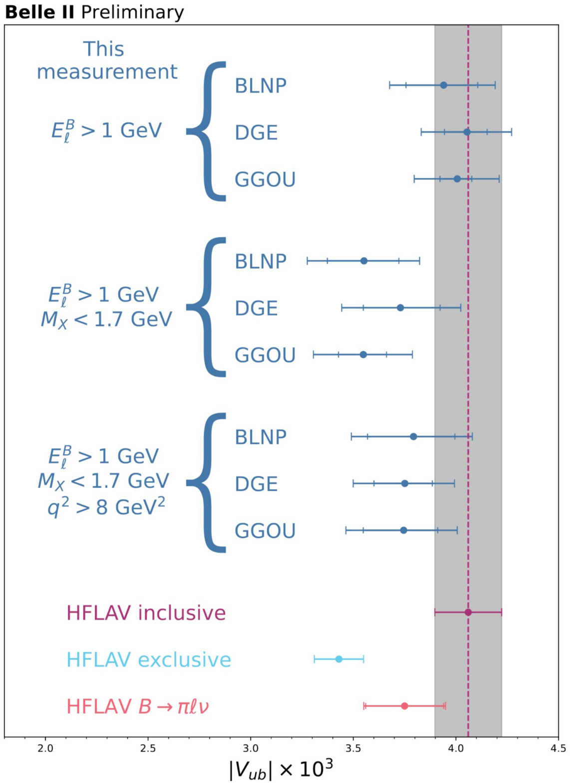
$$\Delta\mathcal{B}(B \to X_u \ell \nu) = (1.54 \pm 0.08 \pm 0.12) \times 10^{-3}$$

$$\boxed{|V_{ub}| = (4.01 \pm 0.11 \pm 0.16^{+0.07}_{-0.08}) \times 10^{-3}}$$

→ Consistent with inclusive HFLAV average, exceeds exclusive average

→ Competitive with Belle thanks to better tagging algorithm and more modern background suppression methods

→ Leading systematics: $B \to X_u \ell \nu$ modelling and corrections on $B \to X_c \ell \nu$ modelling



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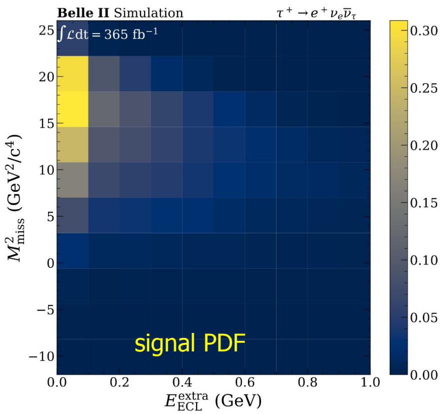
arXiv:2502.04885
submitted to PRD

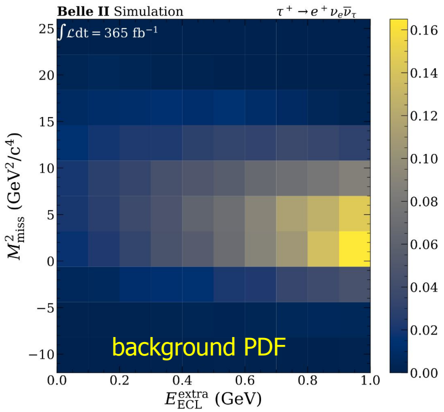
Exclusive $|V_{ub}|$

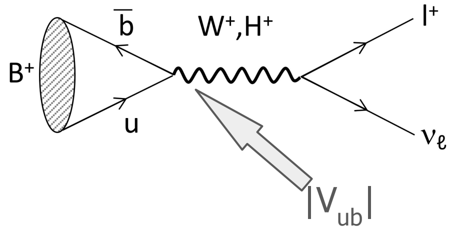
Measurement of $B \to \tau\nu$ branching fraction with a hadronic tagging method at Belle II

arXiv:2502.04885
submitted to PRD

Analysis setup







Clean in theory, experimentally challenging

Helicity suppressed in SM

Sensitive to NP contributions (e.g.charged Higgs)

Fully reconstruct Btag and analyse simultaneously for four tau decay modes:

$\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$, $\tau \to \pi\nu$, $\tau \to \rho\nu$ (72% of tau decay modes)

Reconstructing the Rest of the Event (ROE):

→ Sum of cleaned-up energy in calorimeter: E_{ECL}^{extra}

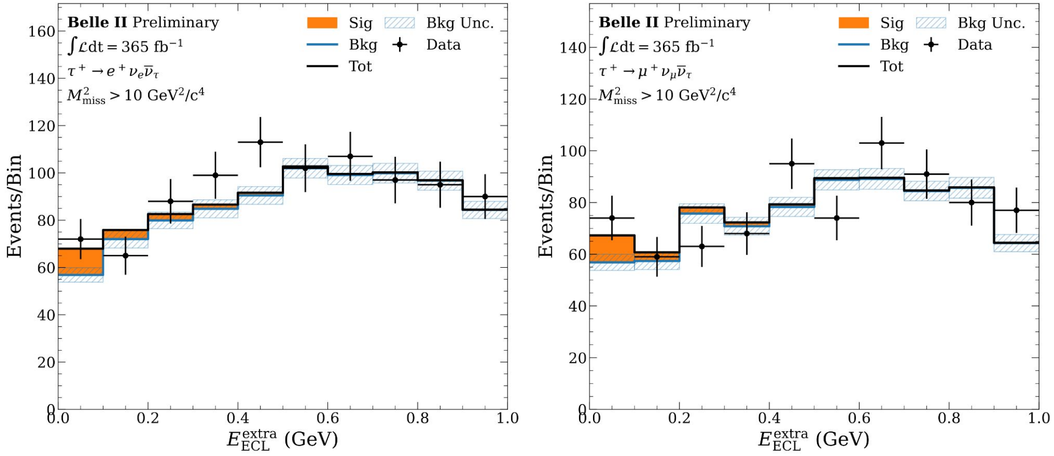
→ Missing mass of undetected particles: M^2_{miss}

Signal extraction procedure

arXiv:2502.04885
submitted to PRD

Suppress continuum background with two separate BDTs for hadronic and lepton decay modes

Signal yield extracted from simultaneous 2D binned likelihood fit on E_{ECL}^{extra} and M^2_{miss} to all four channels



Exclusive $|V_{ub}|$ result

arXiv:2502.04885
submitted to PRD

Branching fraction is measured with 3σ significance

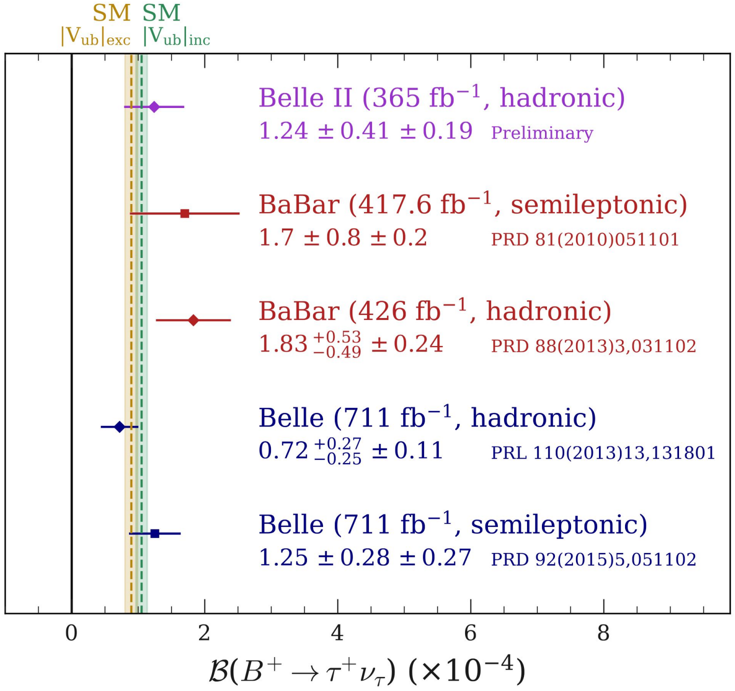
$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = [1.24 \pm 0.41(\text{stat.}) \pm 0.19(\text{syst.})] \times 10^{-4}$$

→ Consistent with current world average and SM prediction

$$|V_{ub}|_{B^+\to\tau^+\nu_\tau} = [4.41^{+0.74}_{-0.89}] \times 10^{-3}$$

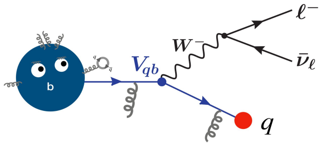
Uncertainty competitive with previous analysis despite lower statistics

→ Improved tagging algorithm and optimized selection



Summary and Outlook

Summary and Outlook



Several results from Belle II were presented

Results on moments at Belle II:

- q^2 moments (Phys.Rev.D 107 (2023) 7, 072002)
- M_x moments (arXiv:2009.04493)

Many ongoing measurements on moments:

- First simultaneous measurement of E_ℓ^B, q^2 and M_x moments in $B \to X_c \ell \nu$ decays

- q^2 and M_x moments in $B_s \to X_c \ell \nu$ decays

$|V_{cb}|$ Exclusive

- $B \to D l \nu$ (untagged)
  arXiv:2506.15256
  $|V_{cb}| = (39.2 \pm 0.4 \pm 0.6 \pm 0.5) \times 10^{-3}$
- $B \to D^* l \nu$ (untagged)
  Phys.Rev.D 108 (2023) 9, 9
  $|V_{cb}| = (40.13 \pm 0.27 \pm 0.93 \pm 0.58) \times 10^{-3}$

$|V_{cb}|$ Inclusive

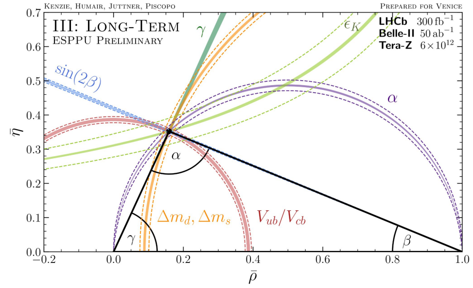
- $B \to X_c \ell \nu$ (q^2 moments, had. tagged)
  Phys.Rev.D 107 (2023) 7, 072002
  J. High Energy Phys. 10 (2022) 068
  $|V_{cb}| = (41.70 \pm 0.69) \times 10^{-3}$
- $B \to X_c \ell \nu$ (M_x moments, had. tagged)
  arXiv:2009.04493

$|V_{ub}|$ Exclusive

- $B^0 \to \pi^- \ell^+ \nu_\ell$ and $B^+ \to \rho^0 \ell^+ \nu_\ell$ (untagged)
  Phys.Rev.D 111 (2025) 11, 112009
  $|V_{ub}| = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$
- $B \to \tau \nu$
  arXiv:2502.04885
  $|V_{ub}| = (4.41 \pm 0.89) \times 10^{-3}$

$|V_{ub}|$ Inclusive

- $B \to X_u \ell \nu$ partial branching fractions (had. tagged)
  Paper in preparation
  $|V_{ub}| = (4.01 \pm 0.11 \pm 0.16) \times 10^{-3}$



Backup

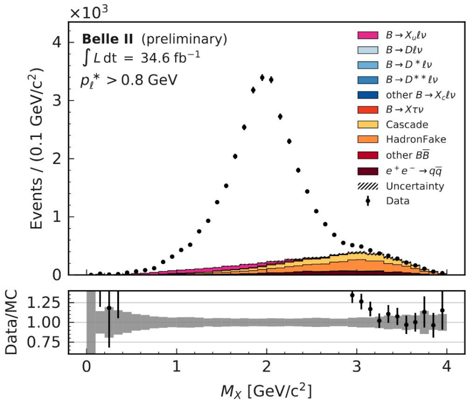
arXiv:2009.04493

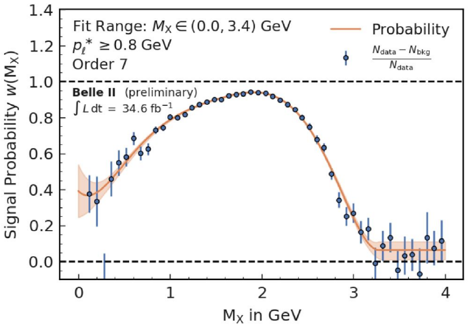
Inclusive $|V_{cb}|$

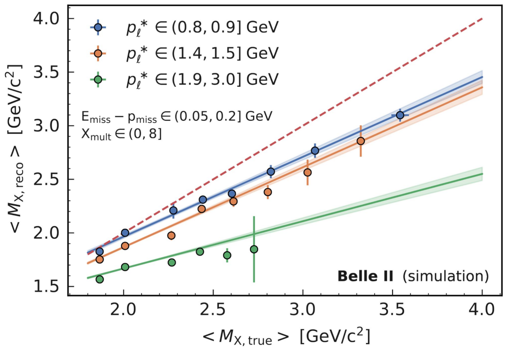
Measurement of Hadronic Mass Moments in $B \to X_c \ell \nu$ decays at Belle II

arXiv:2009.04493

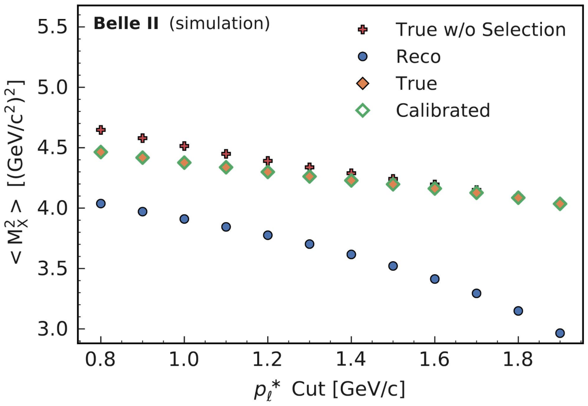
Background subtraction and calibration







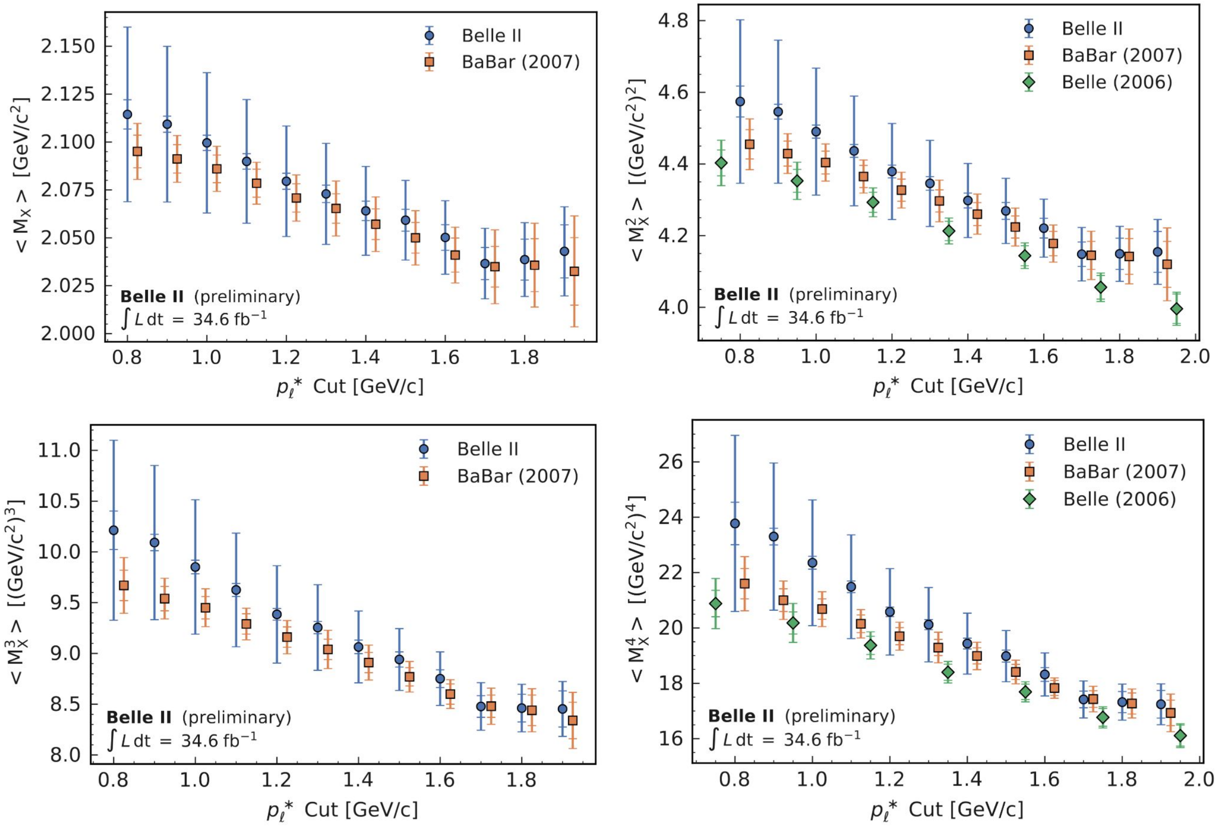
$$\langle M_X^n \rangle = \frac{\sum_i w_i(M_X) M_{X,\mathrm{calib}\,i}^{\;n}}{\sum_i w_i(M_X)} \times \mathcal{C}_{\mathrm{calib}} \times \mathcal{C}_{\mathrm{true}}$$



arXiv:2009.04493

Results

Consistent with previous results but non-competitive result at 32.6 fb^{-1}



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