



New results for semileptonic B decays from Belle

ICHEP 2022

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8th July 2022

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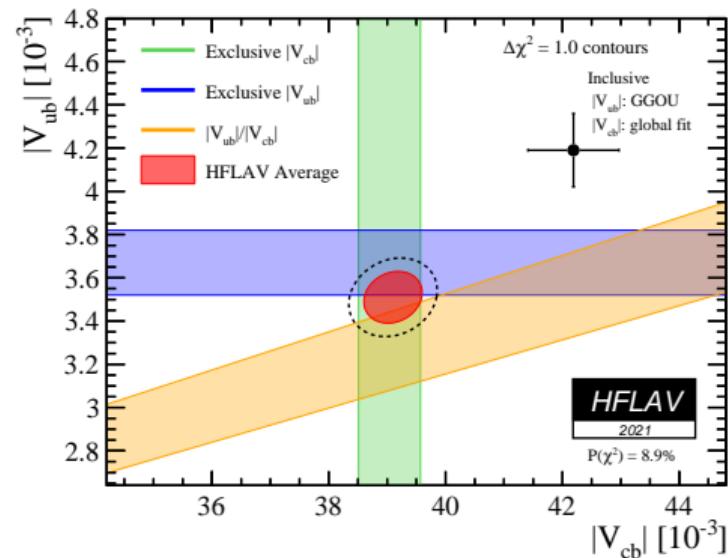
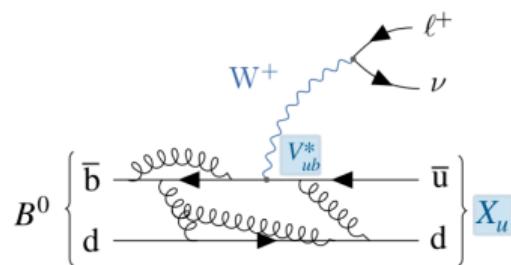


$|V_{ub}| - |V_{cb}|$ Puzzle

Long standing tension between **inclusive** and **exclusive** determinations of the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$.

Experimental difference:

- Reconstructing the hadronic system X_q
- Distinct systematics



Measurement of partial branching fractions of inclusive $B \rightarrow X_u \ell \nu$

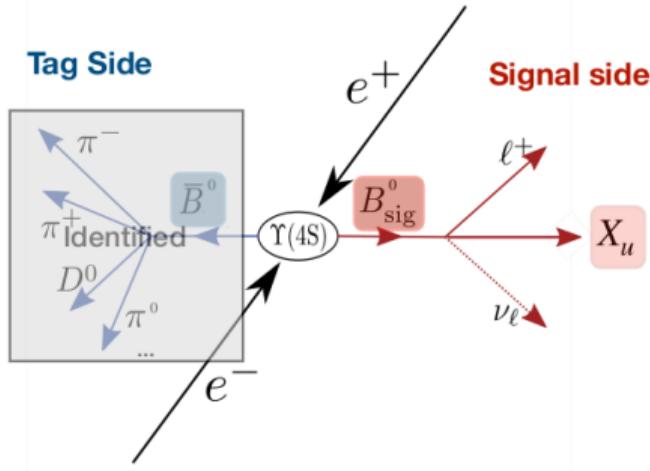
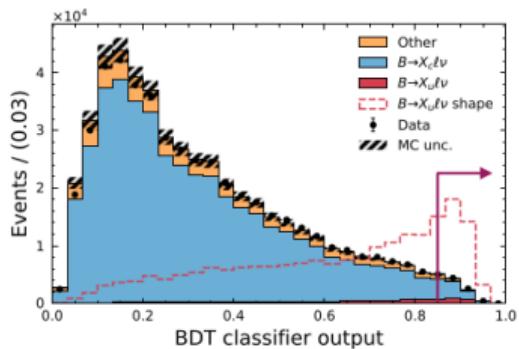
PRD 104, 012008 (2021), arXiv:2102.00020

Analysis Strategy

Use full Belle data set of 711/fb

Hadronic tagging with neural networks (ca. 0.2-0.3% efficiency)

Use machine learning (BDTs) to suppress backgrounds with 11 training features, e.g. m_{miss}^2 , #K $^\pm$, #Ks, etc.



Charged Tracks Neutral Clusters

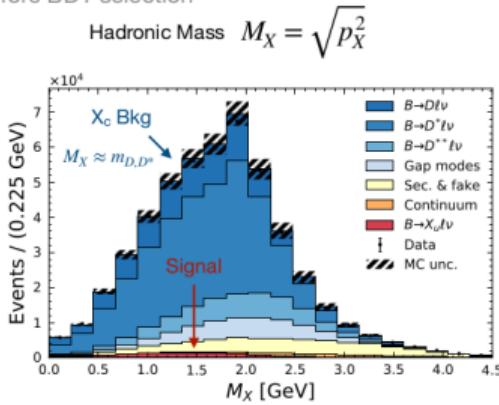
$$p_X = \sum_i \left(\sqrt{m_\pi^2 + |\mathbf{p}_i|^2}, \mathbf{p}_i \right) + \sum_j (E_j, \mathbf{k}_j)$$

$$q^2 = (p_{\text{sig}} - p_X)^2 \quad M_X = \sqrt{(p_X)^\mu (p_X)_\mu}$$

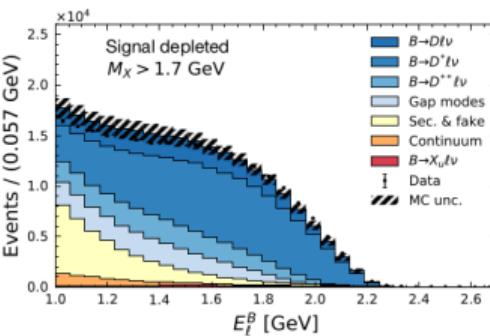
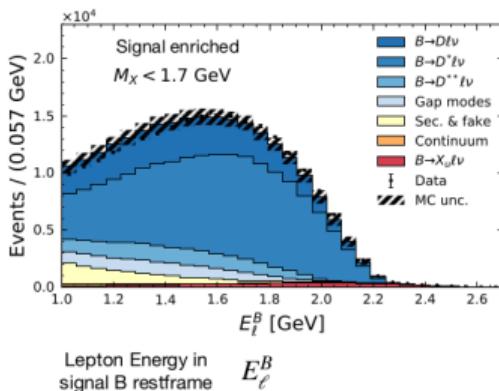
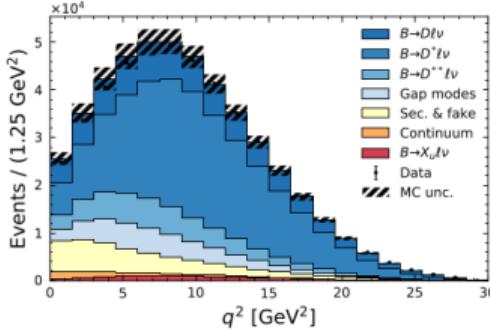
$$m_{\text{miss}}^2 = (p_{\text{sig}} - p_X - p_\ell)^2 \approx m_\nu^2 = 0 \text{ GeV}^2$$

Signal Enhancement

Before BDT selection



Four-momentum transfer squared $q^2 = (p_B - p_X)^2$



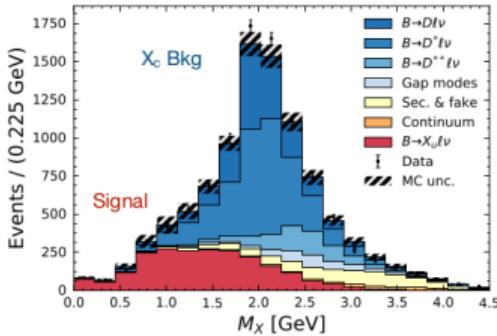
Lepton Energy in
signal B restframe

E_ℓ^B

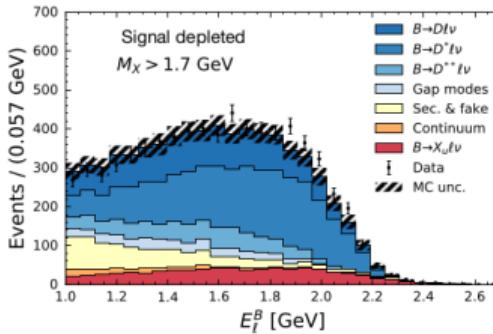
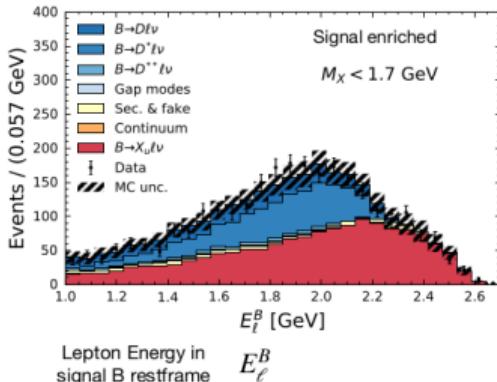
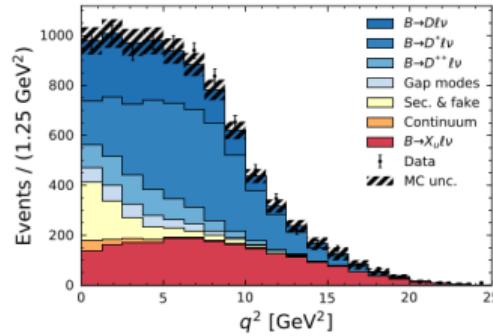
Signal Enhancement

After BDT selection

$$\text{Hadronic Mass } M_X = \sqrt{p_X^2}$$



$$\text{Four-momentum transfer squared} \quad q^2 = (p_B - p_X)^2$$



Lepton Energy in
signal B restframe
 E_ℓ^B

$|V_{ub}|$ Extraction

Fit kinematic distributions and measure [partial BF](#)

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

[3 phase-space regions](#)

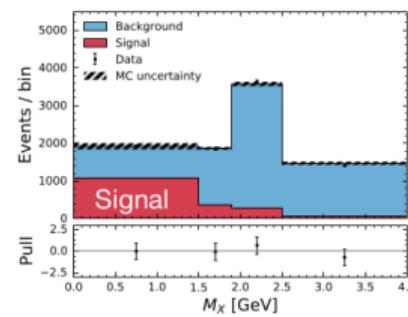
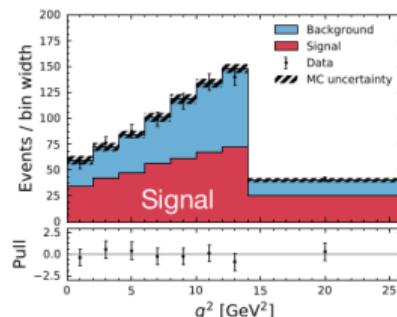
Phase-space region

$$M_X < 1.7 \text{ GeV}$$

$$M_X < 1.7 \text{ GeV}, q^2 > 8 \text{ GeV}^2$$

$$E_\ell^B > 1 \text{ GeV}$$

Example fit:



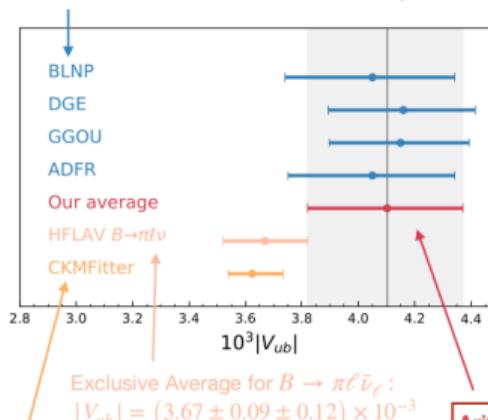
$|V_{ub}|$ Extraction

Fit kinematic distributions and measure **partial BF**

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

4 predictions of the partial rate

Result for most inclusive region with $E_\ell^B > 1$ GeV



3 phase-space regions

Phase-space region

$$M_X < 1.7 \text{ GeV}$$

$$M_X < 1.7 \text{ GeV}, q^2 > 8 \text{ GeV}^2$$

$$E_\ell^B > 1 \text{ GeV}$$

CKM Unitarity:
 $|V_{ub}| = (3.62^{+0.11}_{-0.08}) \times 10^{-3}$

Arithmetic average:
 $|V_{ub}| = (4.10 \pm 0.09 \pm 0.22 \pm 0.15) \times 10^{-3}$

Measurement of differential branching fractions of inclusive $B \rightarrow X_u \ell \nu$ decays

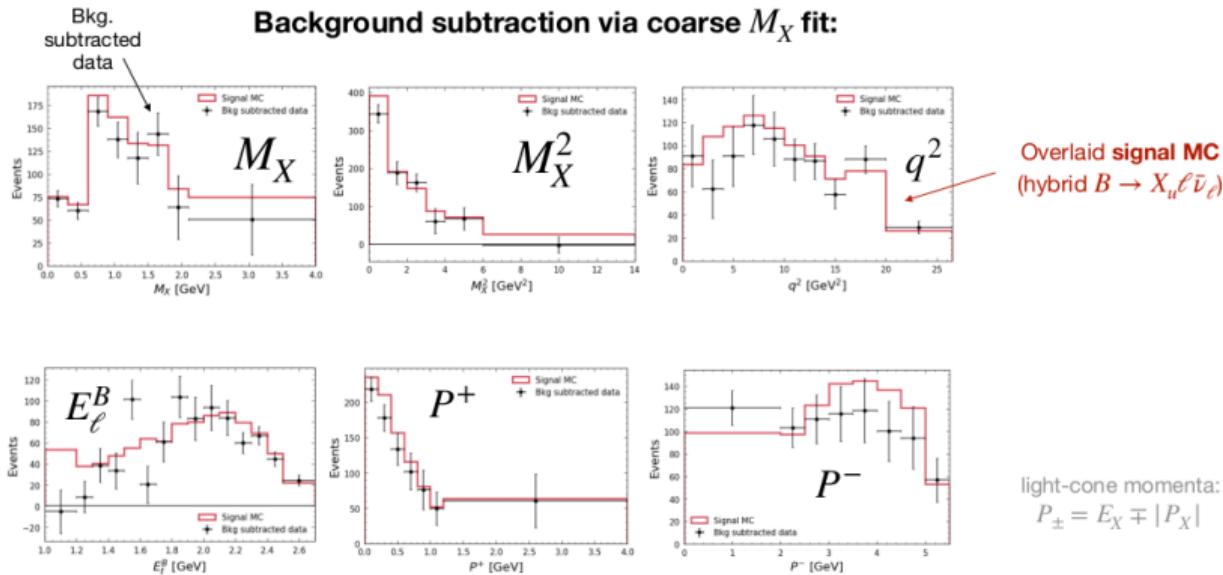
Phys. Rev. Lett. 127, 261801 (2021), arXiv:2107.13855

Differential branching fractions of inclusive $B \rightarrow X_u \ell \nu$

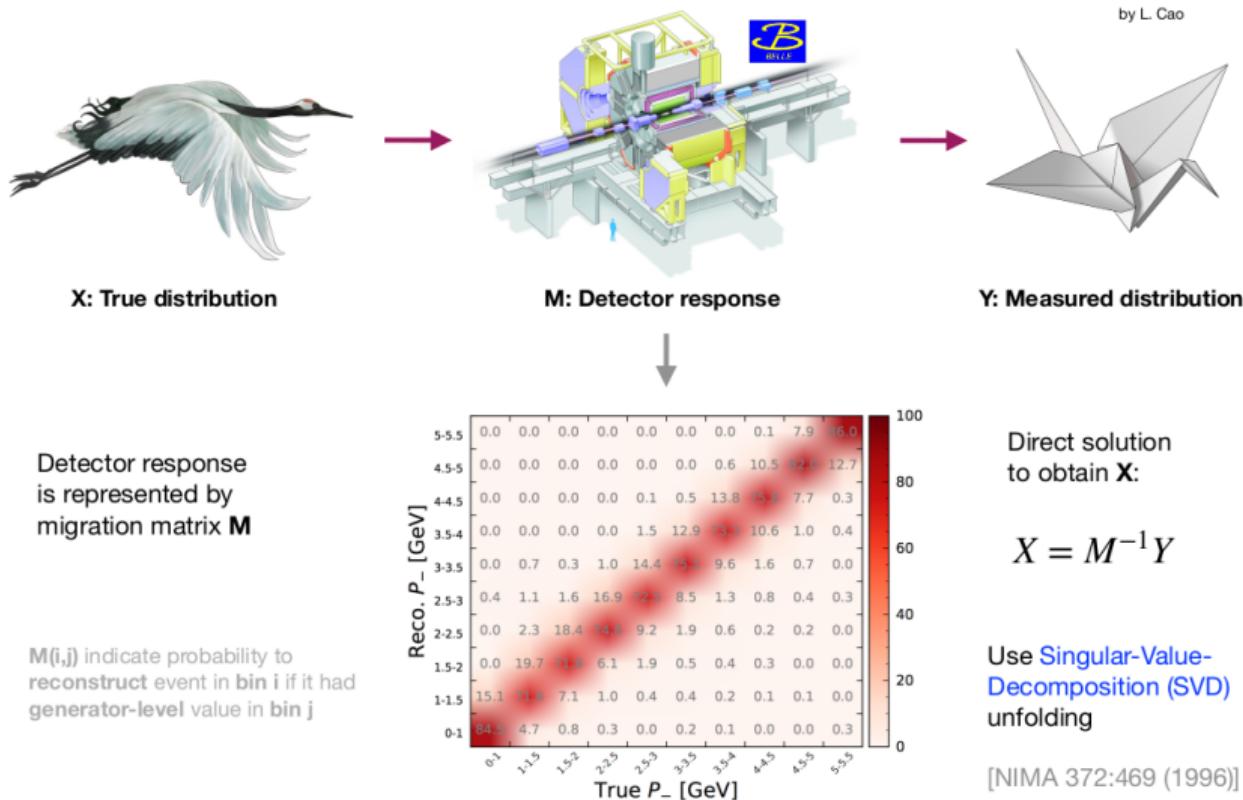
Measurement of **6 kinematic** variables **characterizing** $B \rightarrow X_u \ell \bar{\nu}_\ell$ in $E_\ell^B > 1$ GeV region of PS

Selection and reconstruction **analogous** to **partial BF** measurement

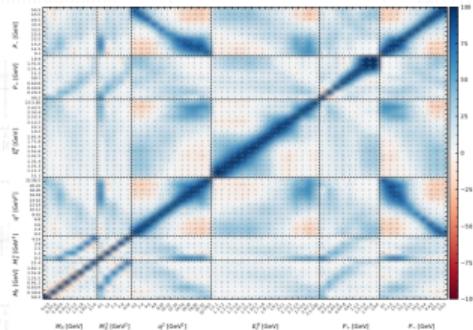
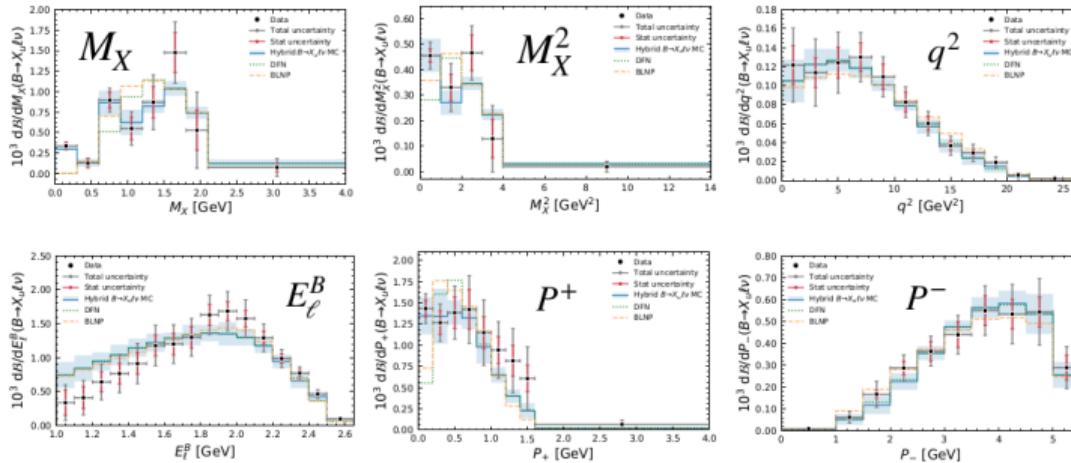
Apply **additional selections** to improve resolution and background shape uncertainties



Unfolding



Differential Spectra



- Full experimental correlation available
- Allows for model independent extraction of $|V_{ub}|$, e.g.:



P. Gambino, K. Healey, C. Mondino,
Phys. Rev. D 94, 014031 (2016),
[arXiv:1604.07598]



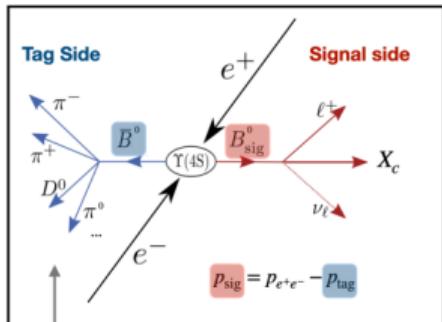
F. Bernlochner, H. Lacker, Z. Ligeti, I.
Stewart, F. Tackmann, K. Tackmann
Phys. Rev. Lett. 127, 102001 (2021)
[arXiv:2007.04320]

$B \rightarrow X_c \ell \nu$ q^2 **Moments**

PRD 104, 112011 (2021), arXiv:2109.01685

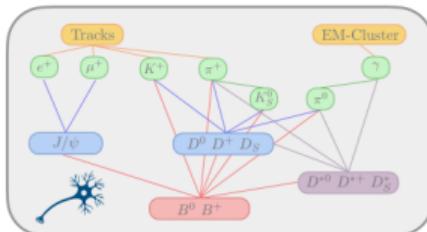
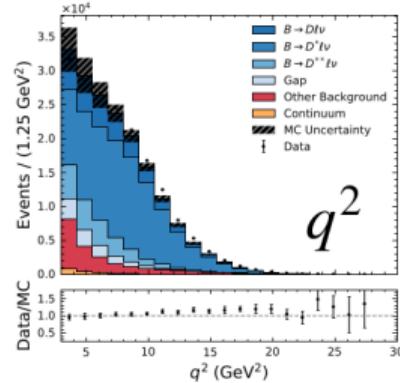
Measurement of the $B \rightarrow X_c \ell \nu$ q^2 Moments

Key-technique: hadronic tagging

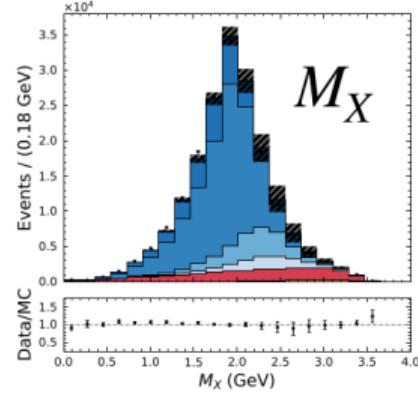


Can identify X_c constituents

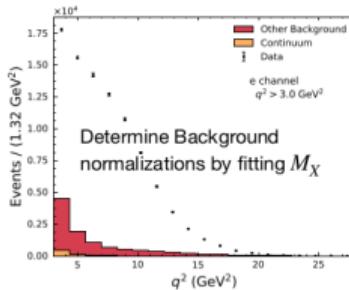
$$q^2 = (p_{\text{sig}} - p_{X_c})^2$$



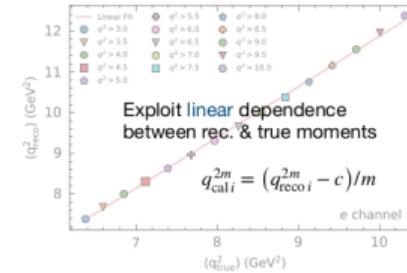
$$M_X = \sqrt{(p_{X_c})_\mu (p_{X_c})^\mu}$$



Measurement of the $B \rightarrow X_c \ell \nu$ q^2 Moments



Step #1: Subtract Background

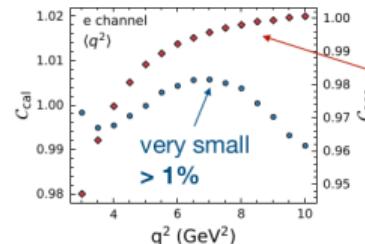


Step #2: Calibrate moment

Event-wise Master-formula

$$\langle q^{2m} \rangle = \frac{C_{\text{cal}} \cdot C_{\text{acc}}}{\sum_i^{\text{events}} w(q_i^2)} \times \sum_i^{\text{events}} w(q_i^2) \cdot q_{\text{cal}i}^{2m}$$

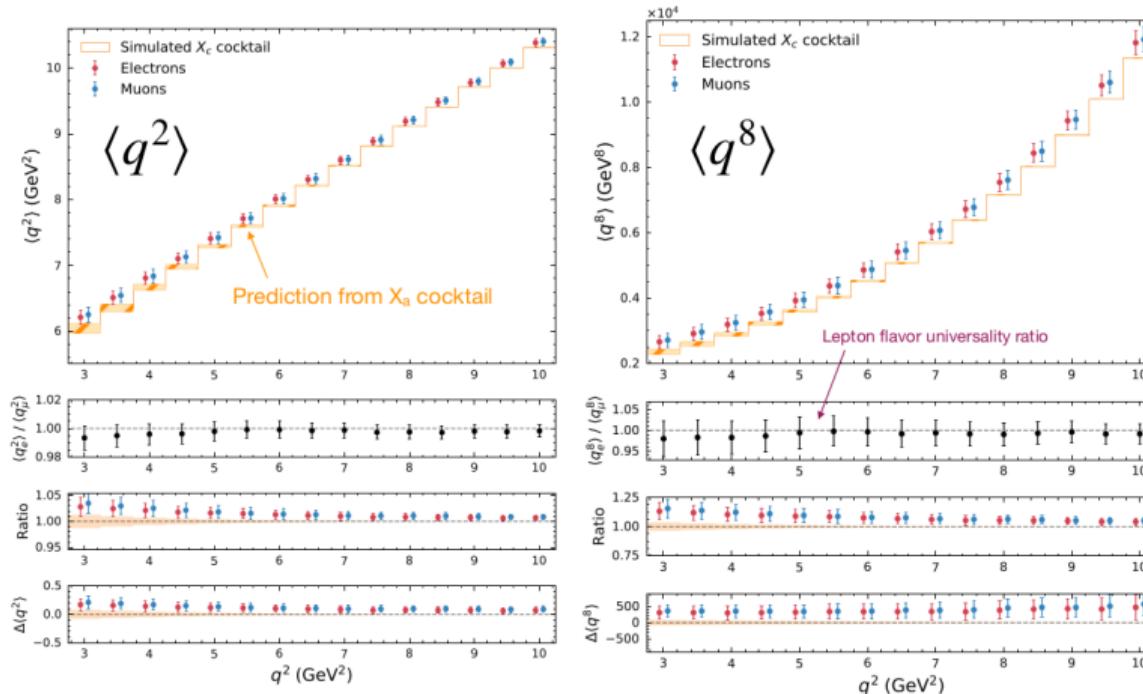
Step #3: If you fail, try again



Step #4: Correct for selection effects

Overall event reconstruction itself
also **biases** measured
moment by **1-2%**

Measured $B \rightarrow X_c \ell \nu$ Moments $\langle q^2 \rangle$ to $\langle q^8 \rangle$

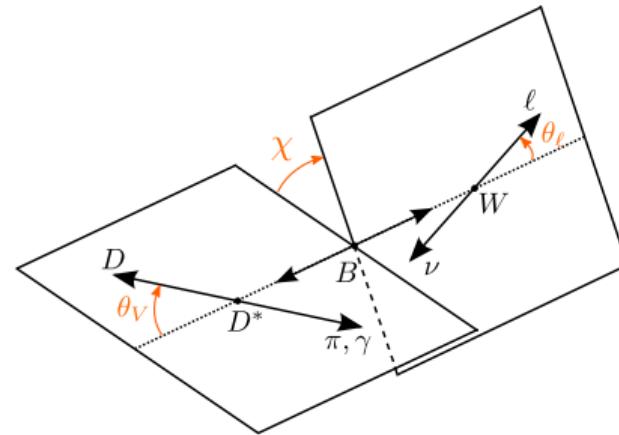
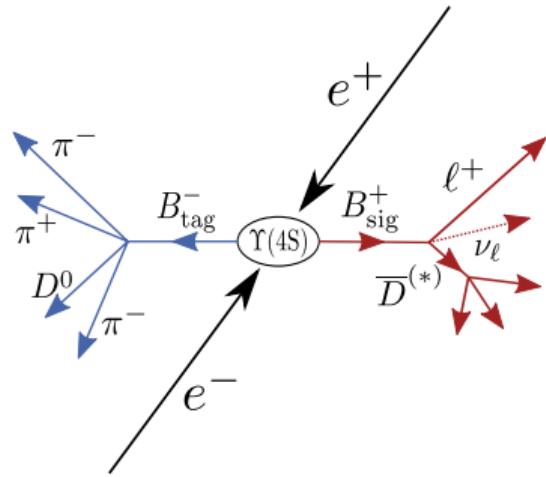


Extraction of $|V_{cb}|$ from measured moments is presented by Max Welsch.

Differential Measurement of $B \rightarrow D^* \ell \nu$ Decays

Teaser for an upcoming result

Differential Decay Rate of $B \rightarrow D^* \ell \nu_\ell$



$$\frac{d\Gamma_{B \rightarrow D^*(\rightarrow \dots) \ell \nu_\ell}}{dw d\cos\theta_\ell d\cos\theta_V d\chi} = \frac{6m_B m_{D^*}^2}{8(4\pi)^4} \sqrt{w^2 - 1} (1 - 2wr + r^2) G_F^2 |V_{cb}|^2 \times \mathcal{B}(D^* \rightarrow \dots)$$

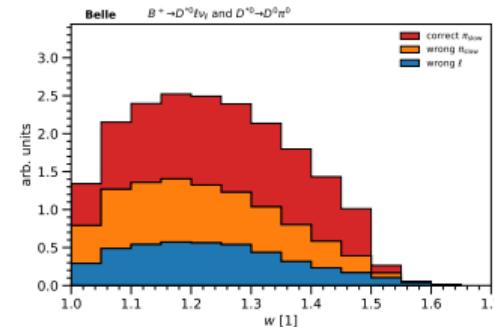
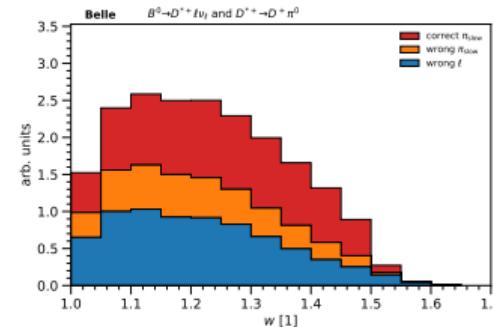
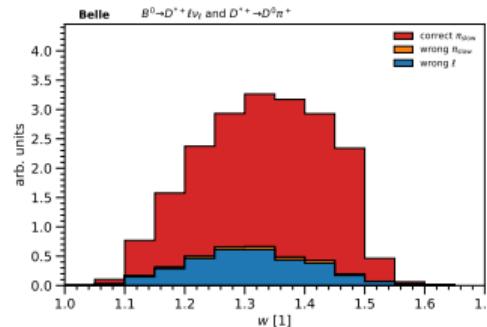
$$\begin{aligned} & \times \left((1 - \cos\theta_\ell)^2 \sin^2\theta_V H_+^2 + (1 + \cos\theta_\ell)^2 \sin^2\theta_V H_-^2 \right. \\ & + 4 \sin^2\theta_\ell \cos^2\theta_V H_0^2 - 2 \sin^2\theta_\ell \sin^2\theta_V \cos 2\chi H_+ H_- \\ & - 4 \sin\theta_\ell (1 - \cos\theta_\ell) \sin\theta_V \cos\theta_V \cos\chi H_+ H_0 \\ & \left. + 4 \sin\theta_\ell (1 + \cos\theta_\ell) \sin\theta_V \cos\theta_V \cos\chi H_- H_0 \right) \end{aligned}$$

$$r = m_{D^*}/m_B$$

$$w = (m_B^2 + m_{D^*}^2 - q^2)/(2m_B m_{D^*})$$

$$|V_{cb}| = \sqrt{\frac{\mathcal{B}(B \rightarrow D^* \ell \nu_\ell)}{\tau_B \Gamma(B \rightarrow D^* \ell \nu_\ell)}}$$

- We reconstruct the signal side in 4 distinct decay modes:
 - $\bar{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}_\ell$ with $D^{*+} \rightarrow D^0\pi^+$ and $D^{*+} \rightarrow D^+\pi^0$
 - $B^- \rightarrow D^{*0}\ell^-\bar{\nu}_\ell$ with $D^{*0} \rightarrow D^0\pi^0$
 - Each for e and μ separately
- B^+ mode adds $\approx 2\times$ the statistics of the B^0 mode.
- Neutral slow pions have a large fake rate, but probe the phase space $w \rightarrow 1$.



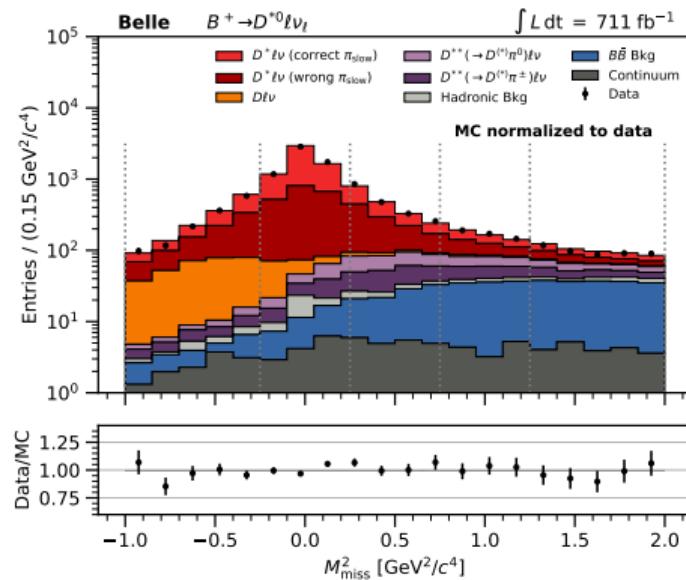
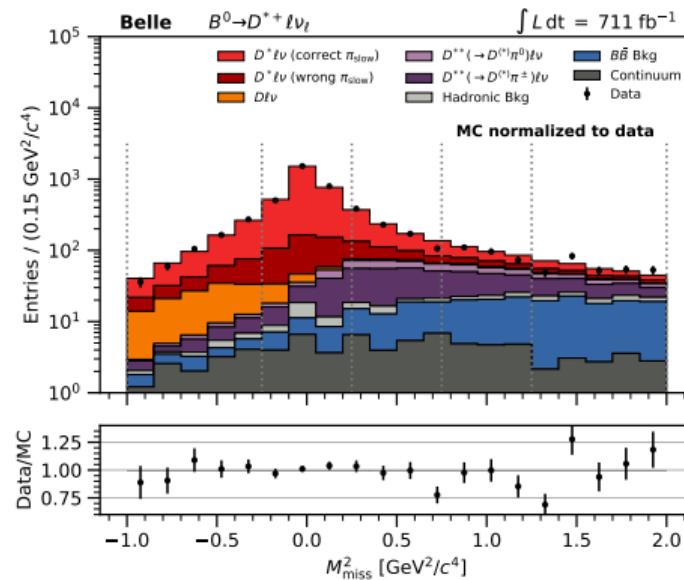
Background Subtraction

(Preliminary)

- Background subtraction using model-independent variable:

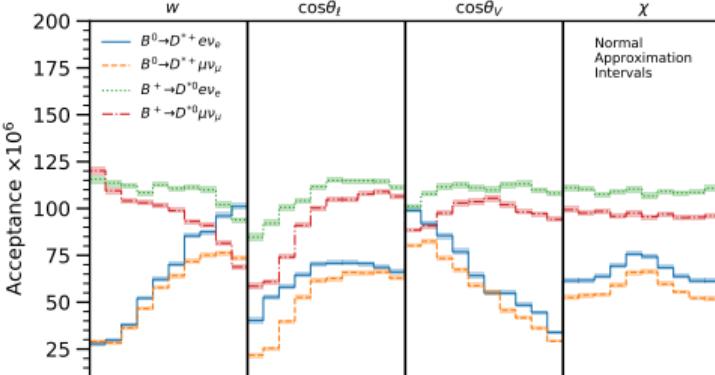
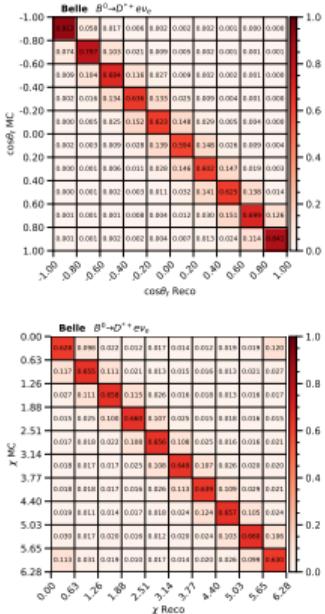
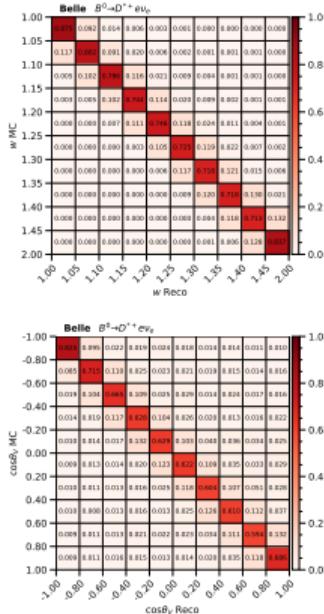
$$M_{\text{miss}}^2 = p_{\text{miss}}^2 = p_{e^+e^-} - p_{\text{tag}} - p_{D^*} - p_\ell \text{ in 10 bins of } w, \cos\theta_\ell, \cos\theta_V, \chi$$

- Good understanding of M_{miss}^2 .



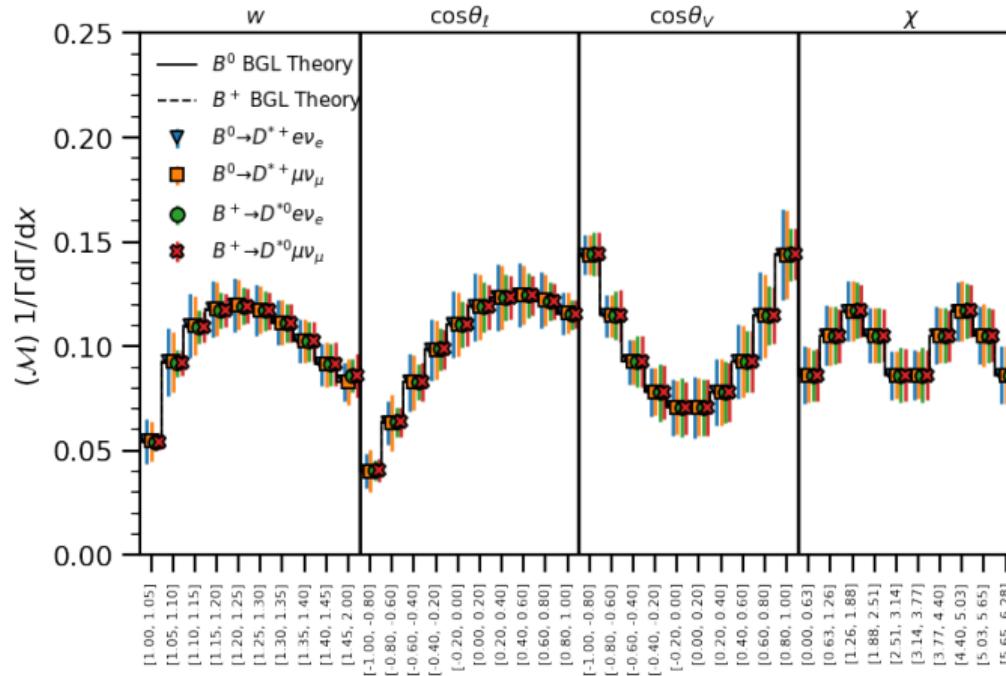
Unfolding and Acceptance Correction

(Preliminary)



Acceptance is different in B^+ and B^0
 → intrinsic cross-check for our understanding of systematics

Shape on Asimov Data (Simulation)



Allows determination of:

- Form Factors
- $|V_{cb}|$ w/ external input
- $F_L(D^*)$
- A_{FB}
- $R_{e\mu}(D^*)$

Summary & Conclusion



Belle is still actively pursuing the $|V_{ub}| - |V_{cb}|$ puzzle

- Partial and inclusive branching fractions of $B \rightarrow X_u \ell \nu$ decays
- q^2 moments of inclusive $B \rightarrow X_c \ell \nu$ decays
- Coming soon: Differential branching fraction of $B \rightarrow D^* \ell \nu$ decays

