

Recent Results on Semileptonic B Decays at Belle & BaBar

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HELMHOLTZ RESEARCH FOR
GRAND CHALLENGES



Content

Analyses covered in this talk

$b \rightarrow u$

- Measurement of **partial** branching fractions of inclusive $B \rightarrow X_u \ell^+ \nu$ decays with hadronic tagging



PRD 104 , 012008 (2021)

- Measurement of **differential** branching fractions of inclusive $B \rightarrow X_u \ell^+ \nu$ decays



arXiv:2107.13855,
submitted to PRL

$b \rightarrow c$

- Measurements of **q^2 moments** of inclusive $B \rightarrow X_c \ell^+ \nu$ decays with hadronic tagging



arXiv:2109.01685,
submitted to PRD

- Extraction of **form factors** from a four-dimensional **angular analysis** of $B \rightarrow D^* \ell^+ \nu$



BABAR PRL 123, 091801 (2019)

$\Delta\mathcal{B}(B \rightarrow X_u \ell^+ \nu)$ and $|V_{ub}^{\text{incl.}}|$

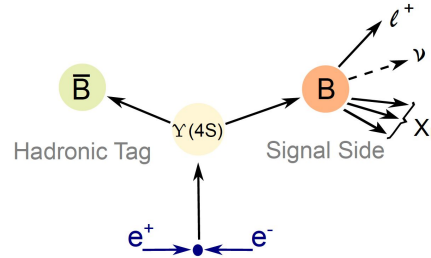


PRD 104 , 012008 (2021)

Inclusive $B \rightarrow X_u e^+ \nu$

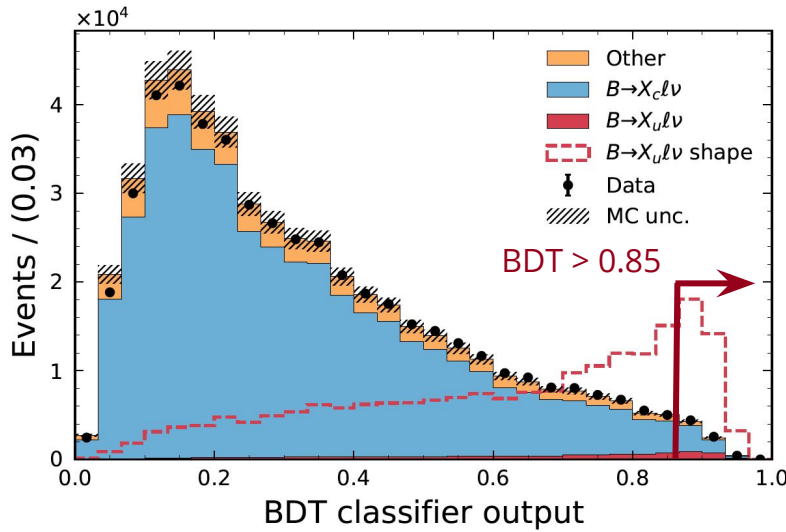
Event reconstruction

- Using **full Belle** dataset of **711 fb⁻¹**
- Hadronic tagging** with Neural Networks (~ 0.2-0.3% efficiency)
- Use **machine learning (BDT)** to suppress backgrounds with 11 training features, e.g. $MM^2, \#K^\pm, \#K_s$, etc.



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

→ Allows to reconstruct X_u



Reconstructed kinematic variables

- Hadronic system X :

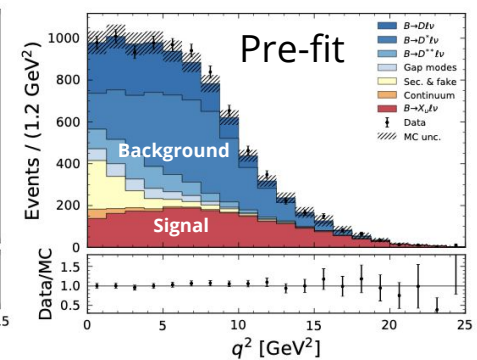
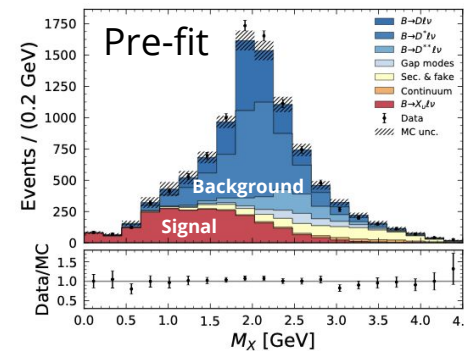
$$p_X = \sum_i (\sqrt{m_\pi^2 + |\mathbf{p}_i|^2}, \mathbf{p}_i) + \sum_i (E_i, \mathbf{k}_i)$$

- Missing mass squared:

$$MM^2 = (P_{Y(4S)} - P_{\text{tag}} - P_X - P_l)^2$$

- Leptonic system:

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



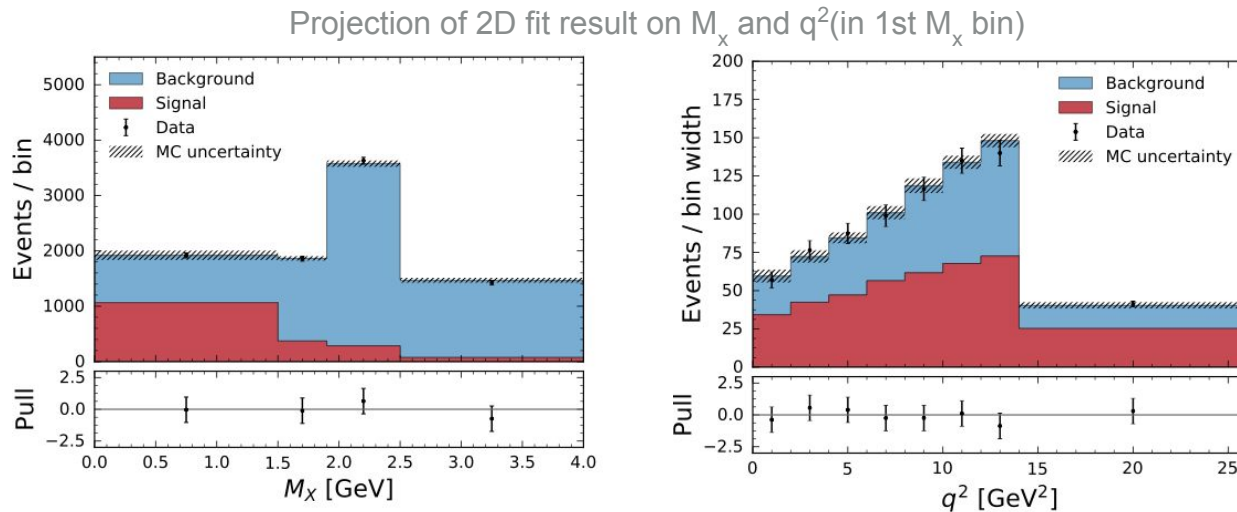
Partial Branching Fractions of $B \rightarrow X_u \ell^+ \nu$

- Extract signal using binned likelihood in **3 phase space (PS) regions**:

- $E_\ell^B > 1 \text{ GeV}$ (covers 86% of available signal PS)
- $E_\ell^B > 1 \text{ GeV}, M_X < 1.7 \text{ GeV}$ (56%)
- $E_\ell^B > 1 \text{ GeV}, M_X < 1.7 \text{ GeV}, q^2 > 8 \text{ GeV}^2$ (31%)

→ Fit either E_ℓ^B, M_X, q^2 or 2D ($M_X : q^2$)

- Signal yields further corrected for efficiency & acceptance in 3 PS regions
- Split results on e, μ, B^0, B^+ modes are provided for $E_\ell^B > 1 \text{ GeV}$ region



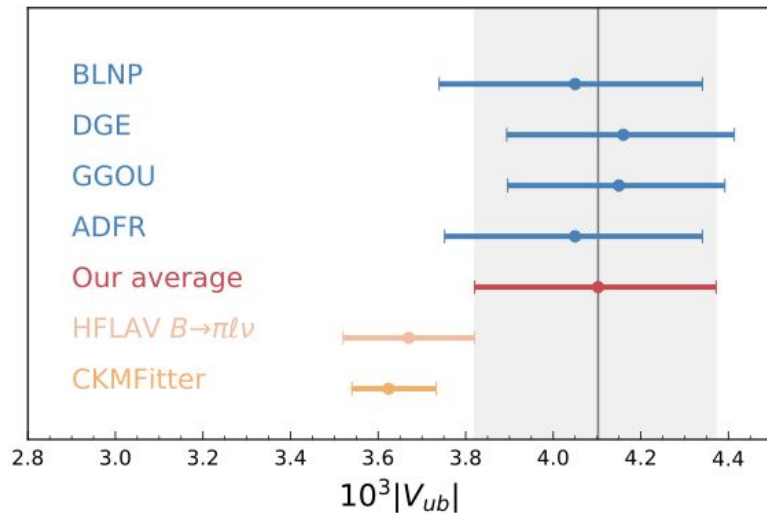
$$\mathcal{B}(E_\ell^B > 1 \text{ GeV}) = (1.59 \pm 0.07_{\text{stat}} \pm 0.16_{\text{sys}}) \times 10^{-3}$$

based on 2D fit

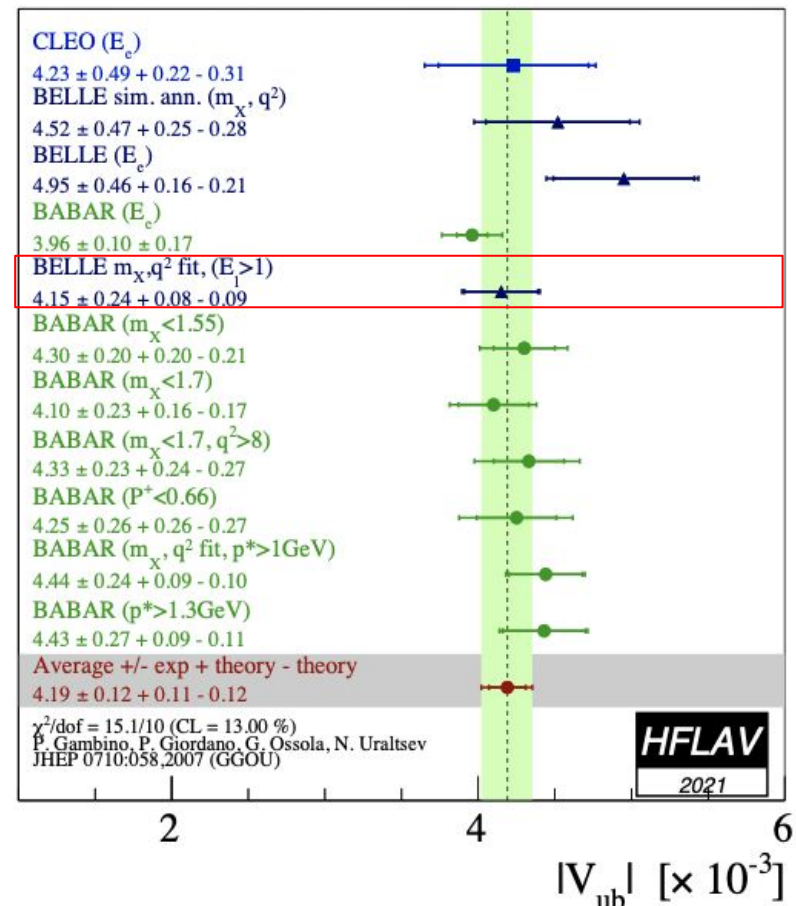
Inclusive $|V_{ub}|$

- Convert partial BF in $E_p^B > 1$ GeV of 2D fit result to $|V_{ub}|$
- Based on **four** calculations of the **decay rate**

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



Comparisons based on GGOU



Our average:

$$|V_{ub}| = (4.10 \pm 0.09_{\text{stat}} \pm 0.22_{\text{sys}} \pm 0.15_{\text{theo}}) \times 10^{-3}$$

compatible with excl. and CKM expectation within **1.3 σ** and **1.6 σ** respectively

Differential $\Delta\mathcal{B}(B \rightarrow X_u \ell^+ \nu)$



arXiv:2107.13855, submitted to PRL

Differential BF of $B \rightarrow X_u \ell^+ \nu$

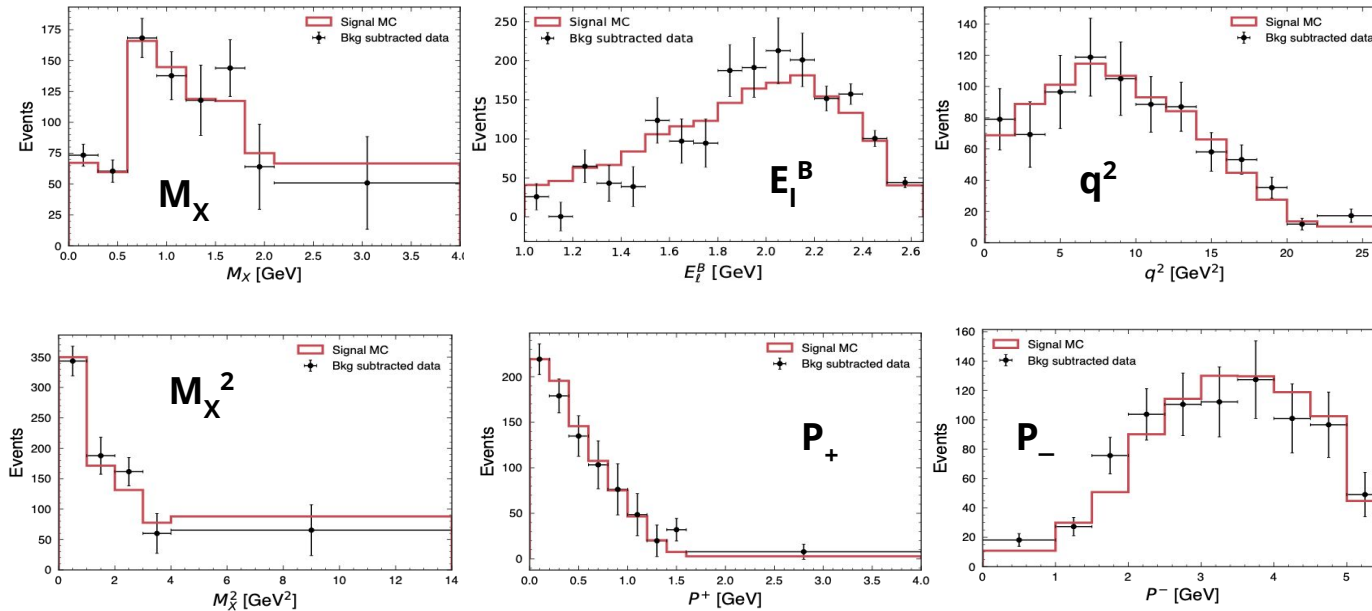
Preliminary

Background-subtracted spectra

- We measure the following 6 kinematic variables in the phase space of $E_l^B > 1$ GeV:

$$q^2, \quad E_l^B, \quad M_X, \quad M_X^2, \quad P_+, \quad P_- \quad (\text{light-cone momenta: } P_{\pm} = E_X \mp |\mathbf{p}_X|)$$

- Selection and reconstruction inherited from the partial BR measurement presented previously
- Additional selections on $|\mathbf{E}_{\text{miss}} - \mathbf{P}_{\text{miss}}| < 0.1$ GeV and reconstructed $M_X < 2.4$ GeV to improve resolution and reduce background shape uncertainty
- Background subtraction done via M_X fit; subtracted spectra are shown as below



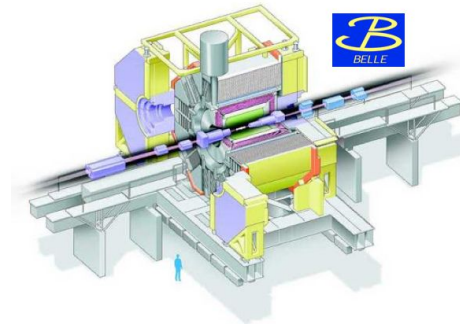
- Full bkg-sub. uncertainties are propagated

- Overlaid MC signal hybrid X_u (& normalised to fitted signal yields)

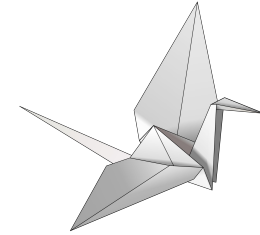
Unfolding



X: true distribution



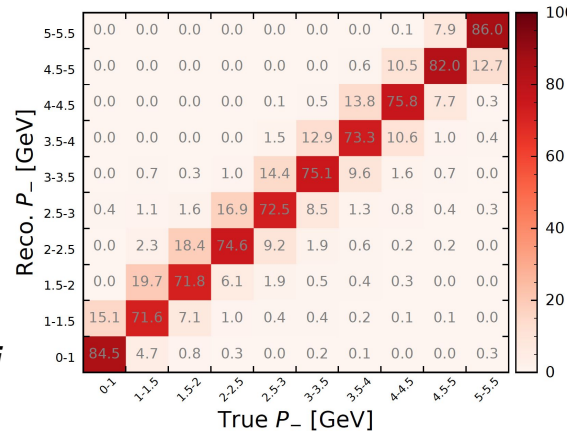
M: detector response



Y: measured distribution



- The detector response is represented by a migration matrix M
- $M(i, j)$ indicates the probability (%) to observe an event in bin i if it had a generator-level value in bin j



$$MX = Y$$

Direct solution for X is

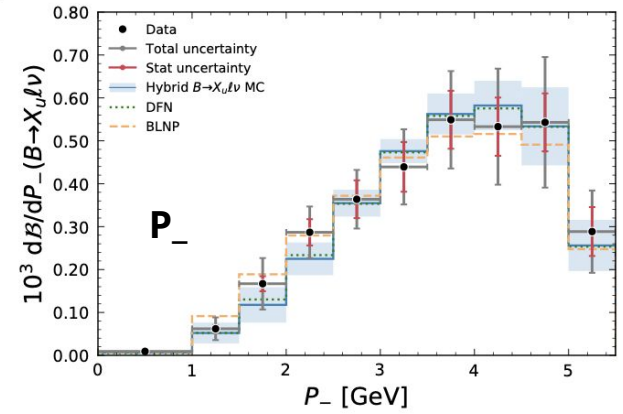
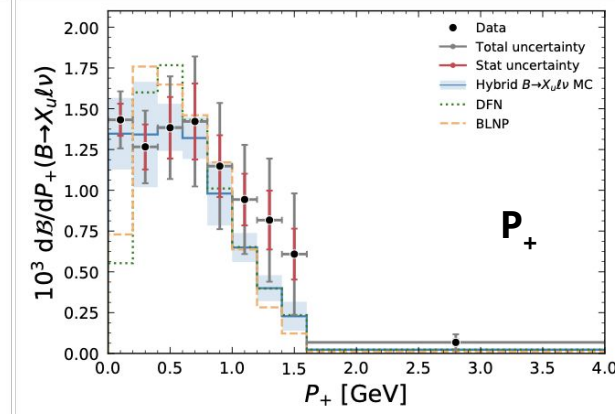
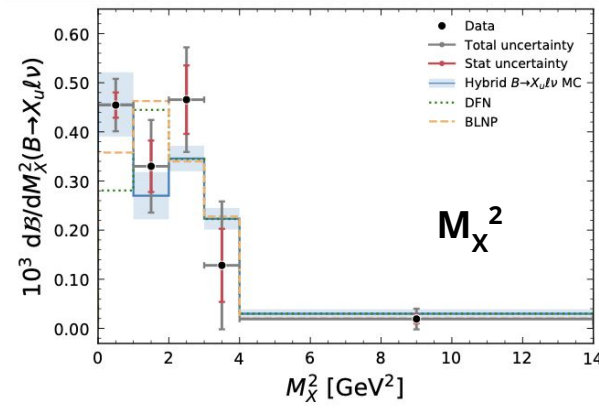
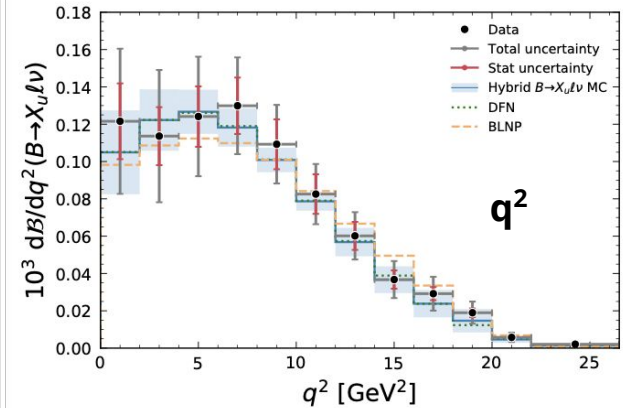
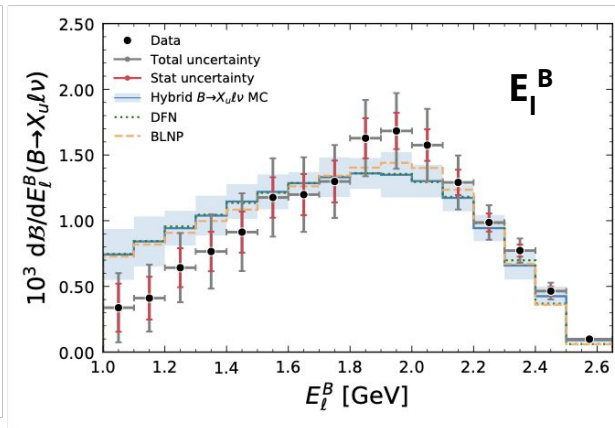
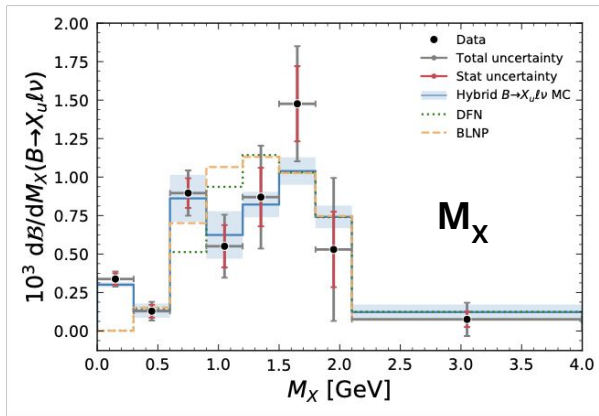
$$X = M^{-1}Y$$

- **Singular-Value-Decomposition (SVD)** [NIMA 372:469(1996)] is used in this analysis

Differential Spectra of $B \rightarrow X_u \ell^+ \nu$

Preliminary

- Convert unfolded yield to $\Delta\mathcal{B}$ in each bin considering reco. efficiency & acceptance
- Differential branching fractions ($E_1^B > 1$ GeV) are measured **for the first time**
- Necessary input for future **model-independent** determinations of $|V_{ub}|$ (e.g. NNVub, SIMBA)



All MC shapes are normalised to 1.59×10^{-3} [Belle, PRD 104, 012008 (2021)]

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



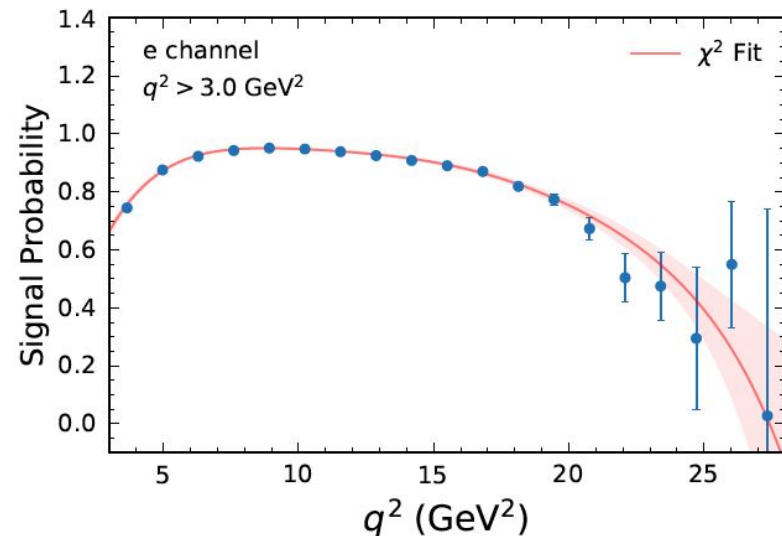
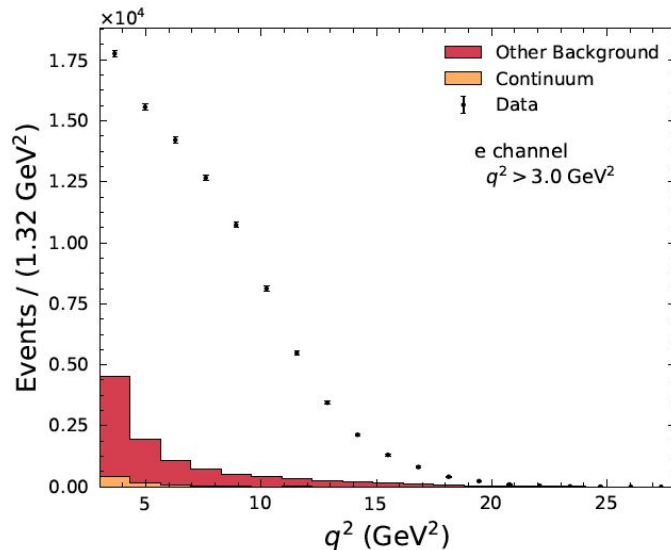
arXiv:2109.01685, submitted to PRD

q2 Moments of $B \rightarrow X_c \ell^+ \nu$

Preliminary

Open a new avenue for inclusive $|V_{cb}|$

- Novel theoretical approach introduced in [JHEP 02, 177 (2019)]
- #non-perturbative matrix elements reduced $13 \rightarrow 8$ at $1/m_b^4$
- Measurements using **full Belle** dataset and **hadronic tagging** with Neural Networks
- Analysis separated on e and μ modes
- Background suppressed in M_X and convert to signal probability ω on q^2

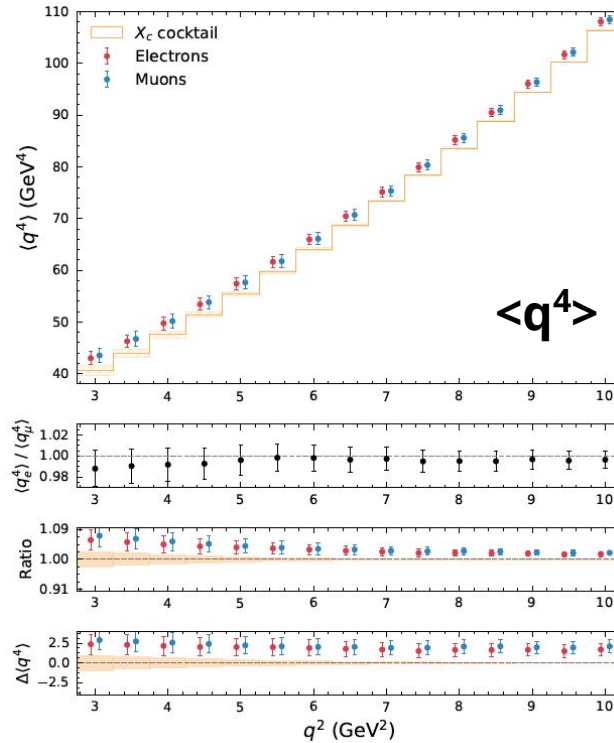
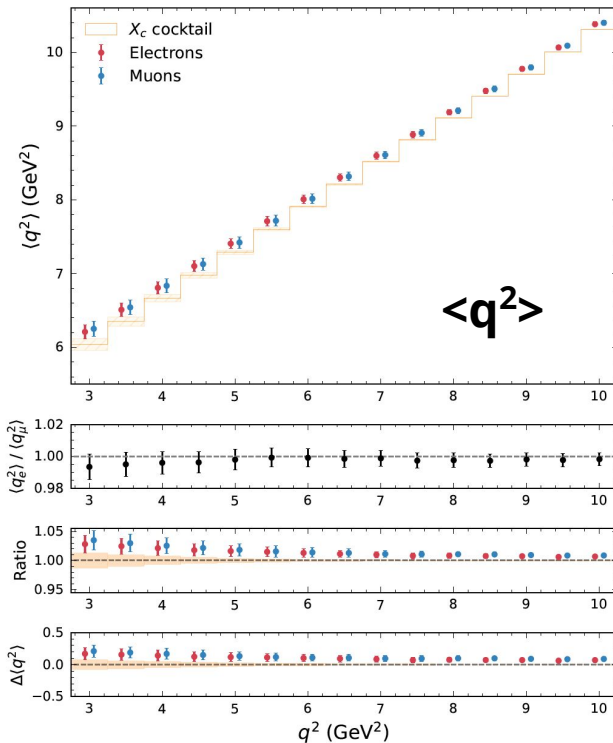


q² Moments of B → X_c ℓ⁺ ν

Preliminary

- $\langle q^{2m} \rangle$ (m=1~4) measured at a progression of cuts on q^2
- **Linear calibration** for resolution distortions
- **Correct** for selection effects, acceptance & residual bias
- Central moments are also provided

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



Based on the measured moments, theorists are working on $|V_{cb}|$ extraction right now.

Preliminary result in R. van Tonder's Moriond-EW'21 [talk](#)

$$|V_{cb}| \times 10^3 = 41.7 \pm 1.2$$

← lepton flavor universality

← Measured / Simulated

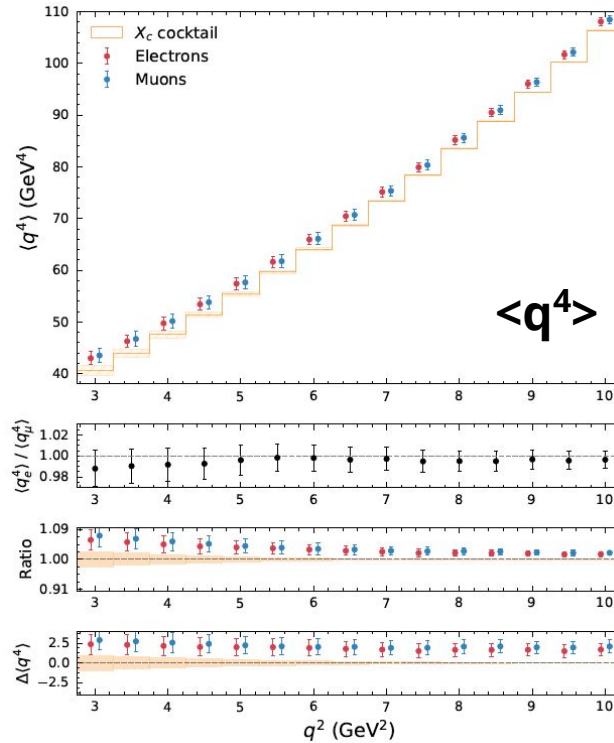
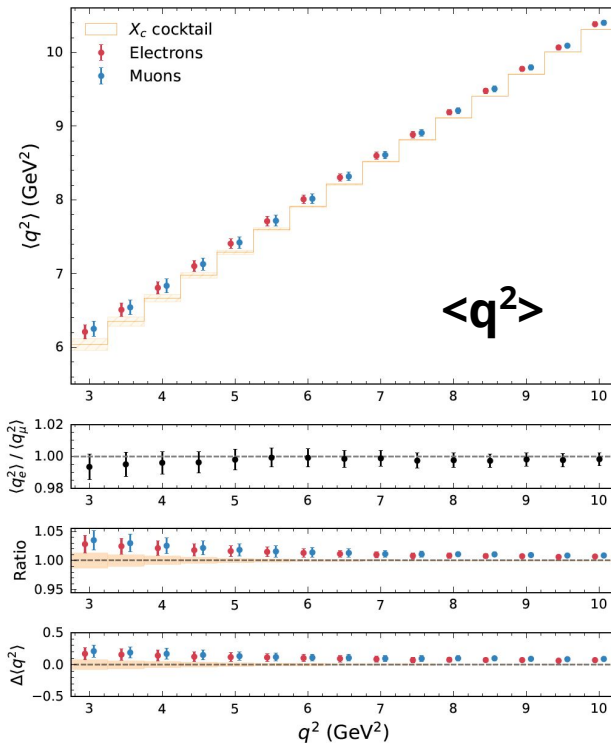
← Measured - Simulated

q² Moments of B → X_c ℓ⁺ ν

Preliminary

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Belle2 result is on the way!!

← lepton flavor universality

← Measured / Simulated

← Measured - Simulated

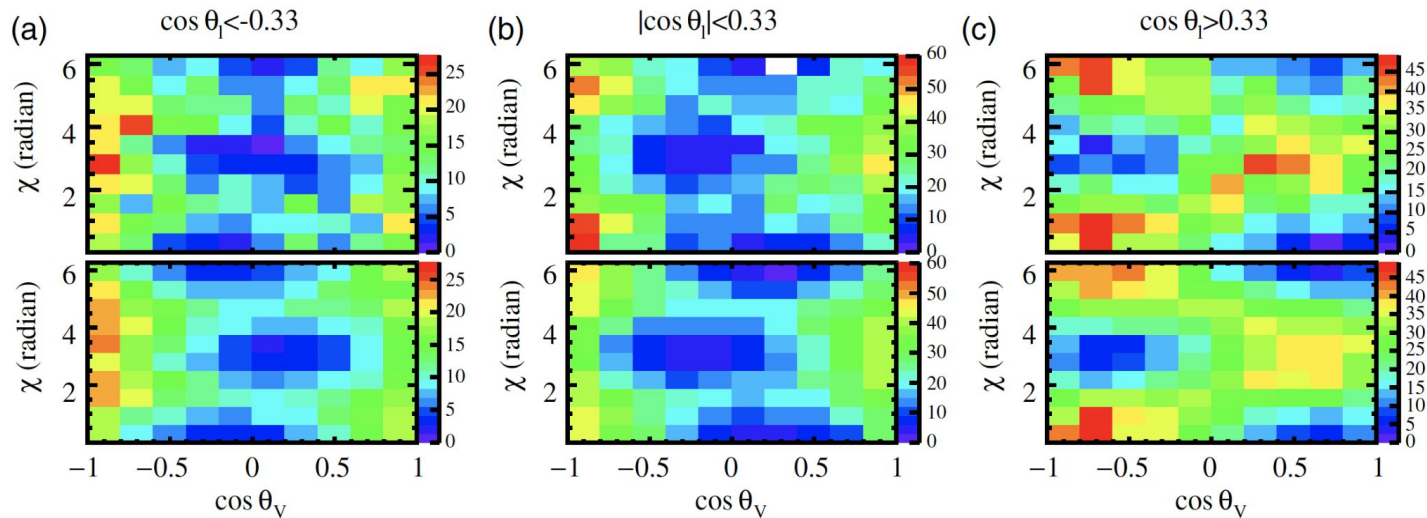
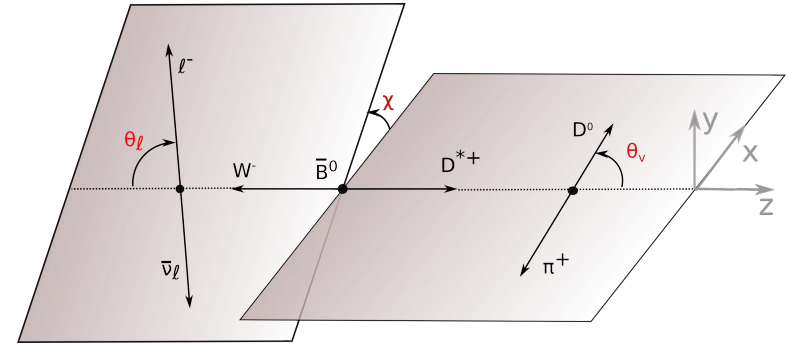
4D Angular Analysis of $B \rightarrow D^* \ell^+ \nu$



BABAR PRL 123, 091801 (2019)

Angular Analysis of $B \rightarrow D^* \ell^+ \nu$

- Use 471 fb^{-1} collected at **BaBar** and apply hadronic tagging
- **4D** ($q^2, \cos\theta_1, \cos\theta_\nu, \chi$) decay rate
- Extracted $|V_{cb}| = (38.36 \pm 0.90) \times 10^{-3}$

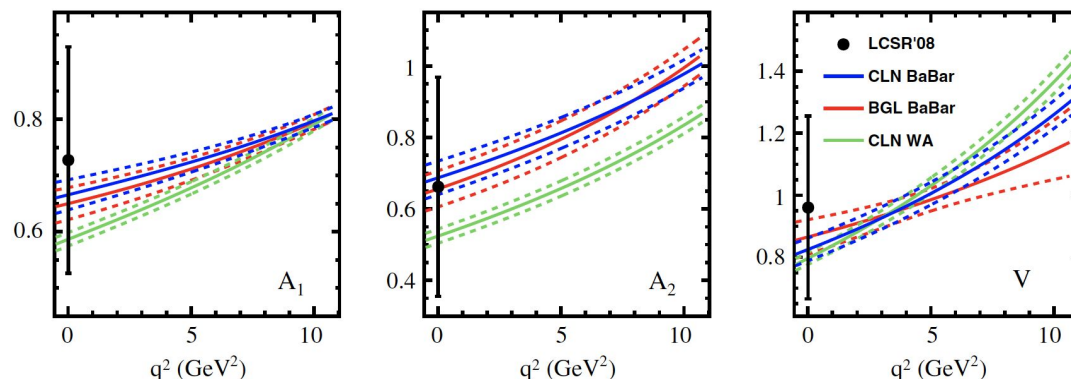


q^2 -integrated comparison:

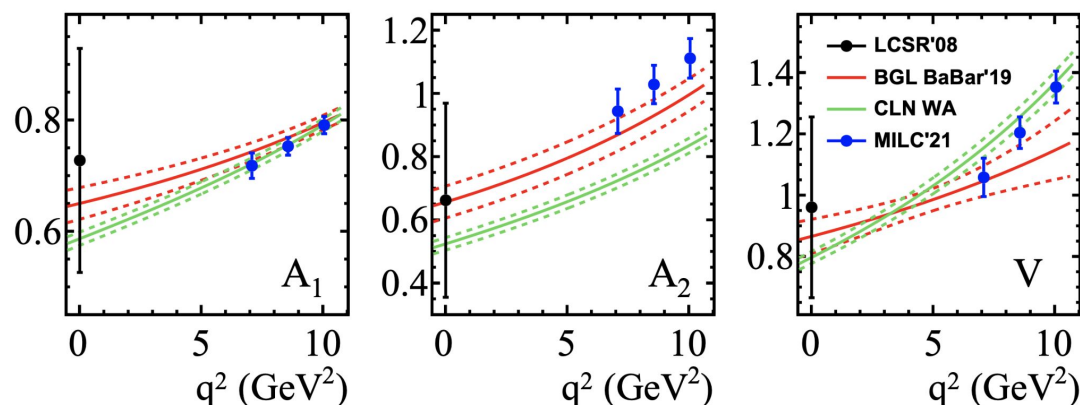
data (up row) and
reweighted MC based on
fitted BGL form factors (low
row)

Form Factors of $B \rightarrow D^* \ell^+ \nu$

- Extracted conventional axial-vector and vector form factors
- Fit to **BGL** and **CLN** parameterisations \rightarrow fairly compatible results
- New version of results with higher truncation and w/o unitarity constraint would be provided

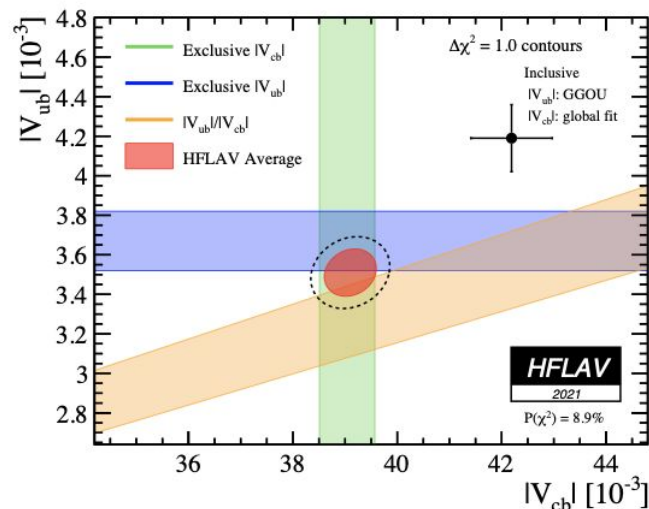


- Comparisons including **new LQCD results** taken from Biplab Dey's EPS-HEP'21 [talk](#)
- Sizeable discrepancy seen on **A₂** with **world averaged CLN** (HFAG2017)



Summary

- Several semileptonic B decays measured at the B-factories recently
- These new results will be very helpful to examine the **Vxb puzzles**
- Continuous efforts from experiment and theory are still needed
- Beyond these important results, the accumulated knowledge on MC modelling, analysis techniques, etc. will be beneficial for future measurements by e.g. **Belle II** or **LHCb**



Vxb puzzles: $\sim 3\sigma$ tension between excl. & incl. determinations



Thank You

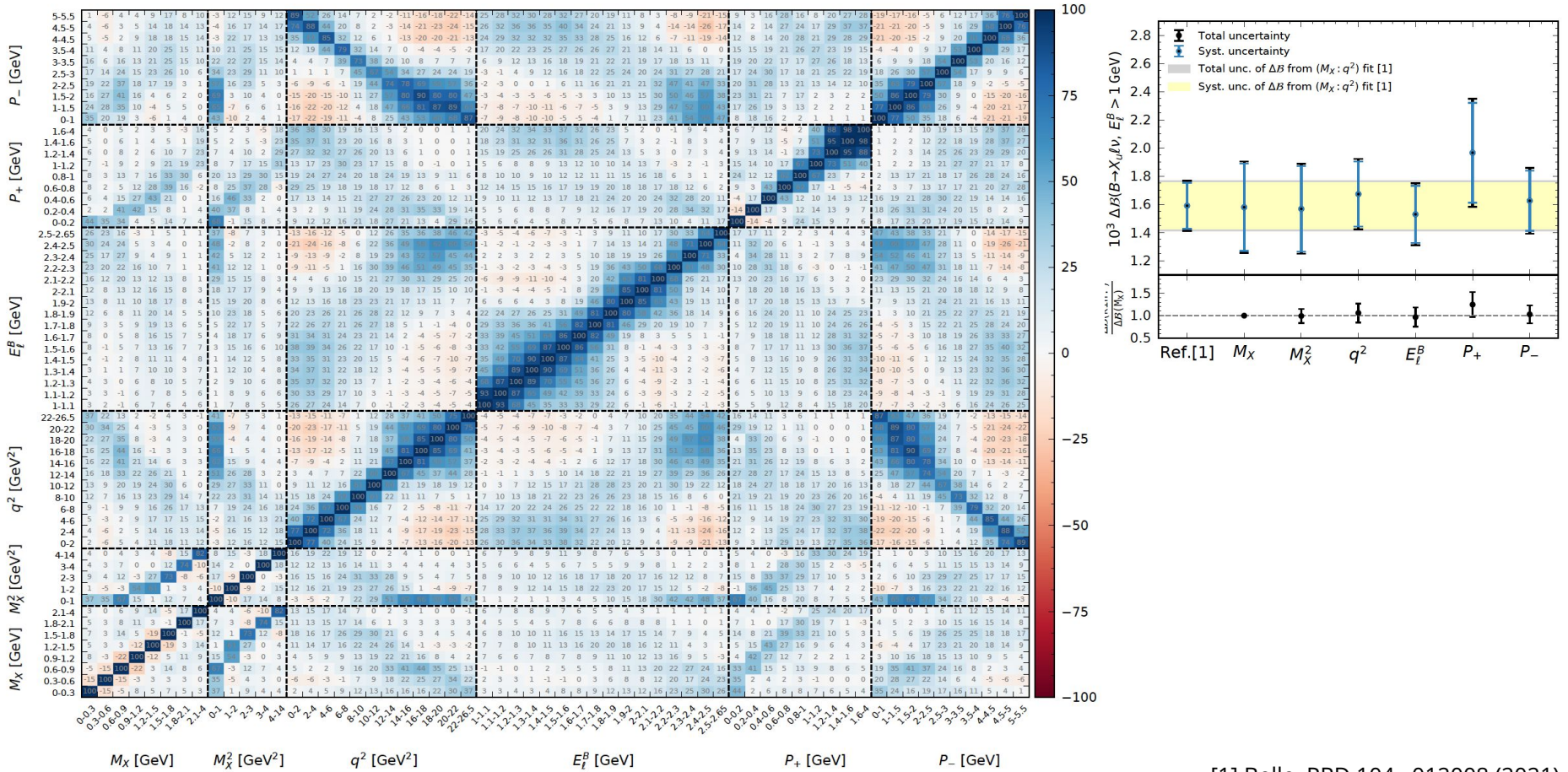
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Backup

Correlations of All Measured $\Delta\mathcal{B}$

Preliminary

- Full experimental correlations of differential $\Delta\mathcal{B}$ are extracted (important for global fit)
- Summed $\Delta\mathcal{B}$ agree well with $(1.59 \pm 0.07 \pm 0.16) \times 10^{-3}$ from $(M_X; q^2)$ fit result of [1]



[1] Belle, PRD 104, 012008 (2021)