Recent Belle II results on the CKM parameters $|V_{cb}|$ and $|V_{ub}|$

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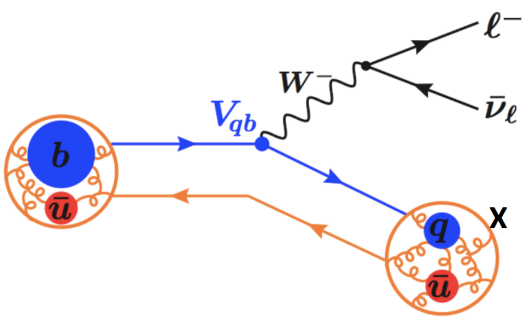
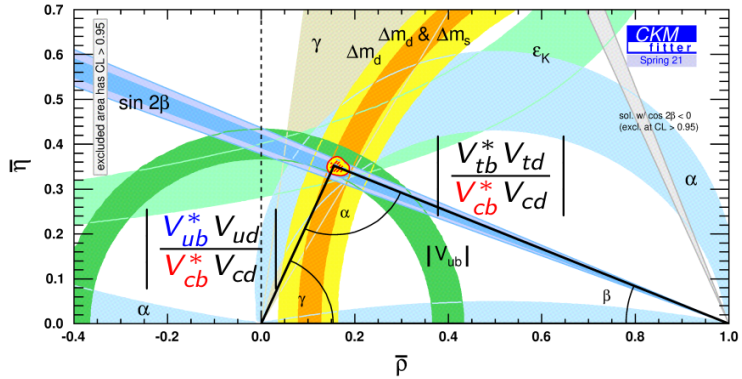
Project P34529-N

Status of $|V_{cb}|$ and $|V_{ub}|$



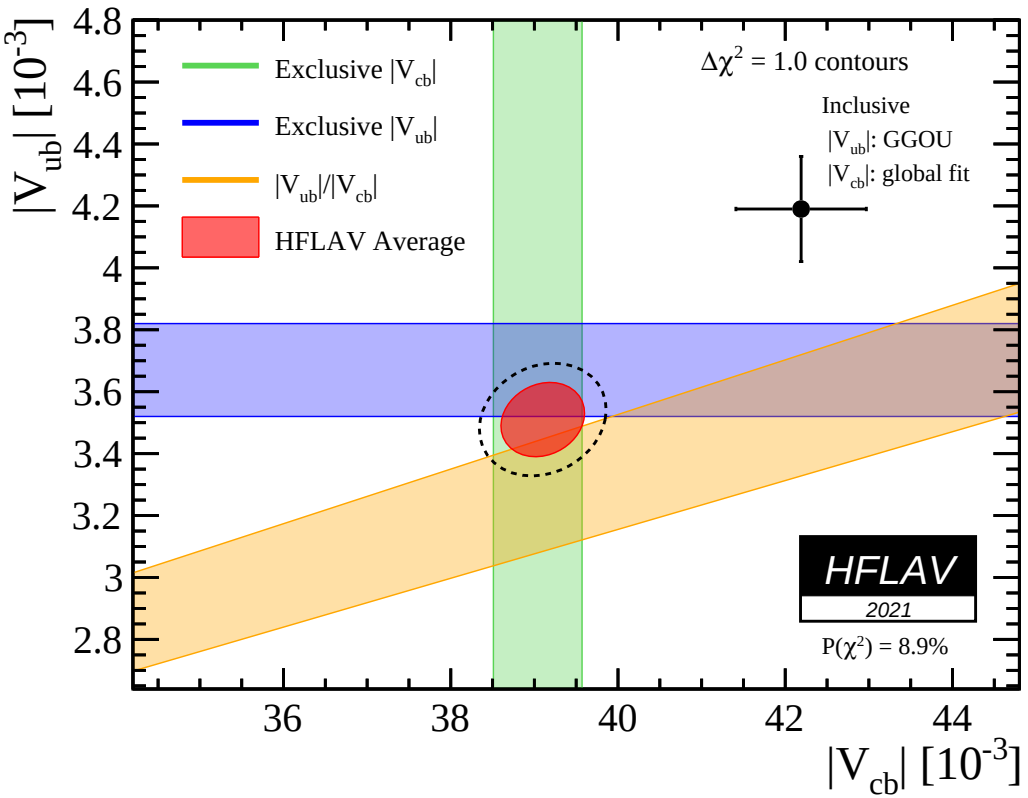


- $|V_{cb}|$ and $|V_{ub}|$ constrain the SM through unitarity triangle
- Important input in SM predictions
- Semileptonic B decays are studied to measure $|V_{cb}|$ and $|V_{ub}|$
  - Factorizable leptonic and hadronic currents

- **Exclusive**: Reconstruct specific final states
- *i.e.:*
  - $|V_{cb}| : B \to D^{(*)}\ell\nu$
  - $|V_{ub}| : B \to \pi\ell\nu$
- Theory input: Lattice QCD (LQCD)

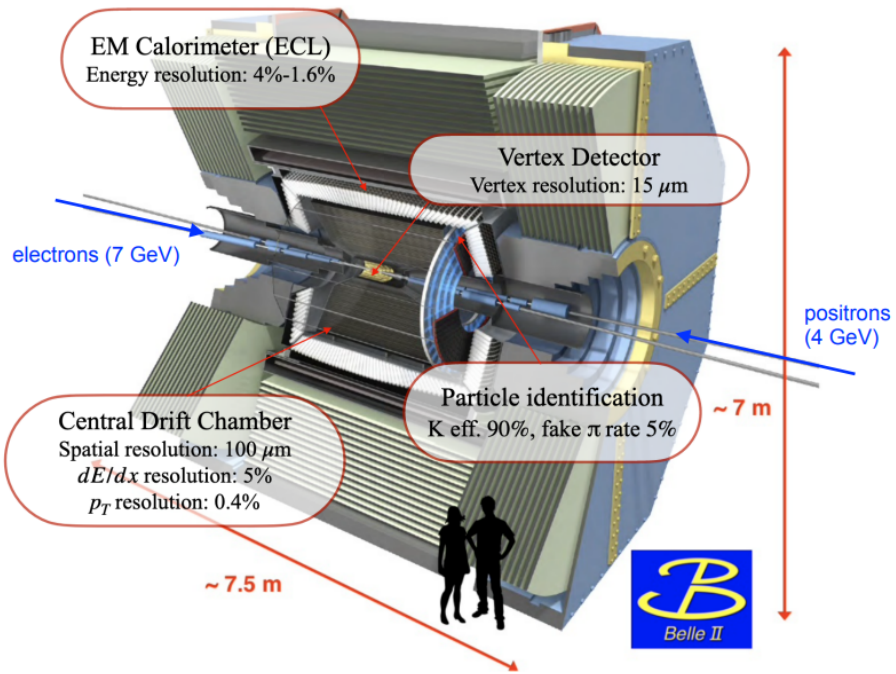
- **Inclusive**: Measure general $X\ell\nu$ decay
- *i.e.:*
  - $|V_{cb}| : B \to X_c\ell\nu$
  - $|V_{ub}| : B \to X_u\ell\nu$
- Theory input: Heavy Quark Expansion Theory (HQET)

Status of $|V_{cb}|$ and $|V_{ub}|$



- $\sim 3\sigma$ discrepancy between inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$ measurements
- Limiting factor in precision flavor physics

Belle II

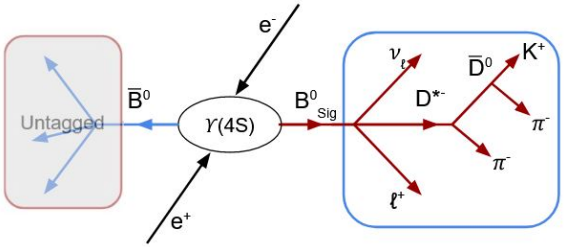


[Belle II TDR: arXiv:1011.0352]

- **Belle II:**
  - Hermetic detector
    - 3-dimensional missing momentum measurements
    - Important for studying events with missing energy
  - Excellent particle identification
  - high γ detection efficiency
- Collected data:
  - **362 fb^{-1}** @ $\Upsilon(4S)$
  - Results shown today: 189 fb^{-1}

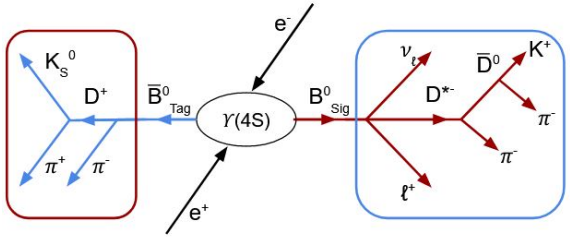
Untagged vs Tagged

Untagged



- Reconstruct only B_{sig}
- High efficiency, high backgrounds

Tagged



- B_{sig} and B_{tag} are reconstructed
- Tag can be hadronic or semileptonic
- Precisely determine missing neutrino momentum

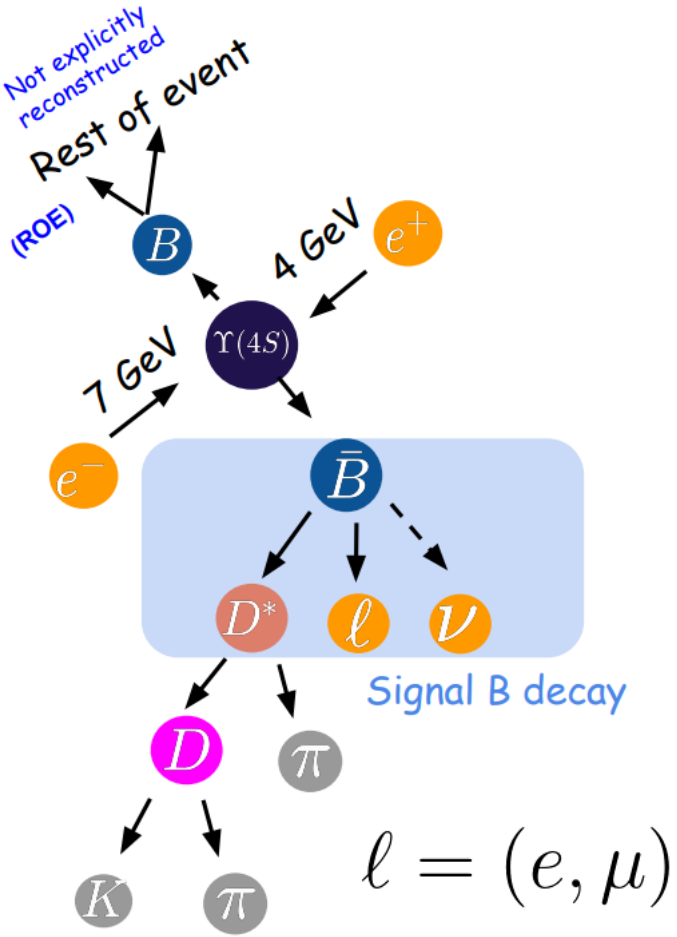
Terminology

- **Untagged - Tagged**
  - Only one or both B mesons reconstructed per event
- **Exclusive - Inclusive**
  - Reconstruction of $B_{sig} \to$ specific decay or $B_{sig} \to X\ell\nu$

	V_{cb}	V_{ub}
Exclusive	Untagged $D^*\ell\nu$ Tagged $D^*\ell\nu$ Untagged $D\ell\nu$	Untagged $\pi\ell\nu$ Tagged $\pi\ell\nu$

Untagged $B \to D^* \ell \nu$

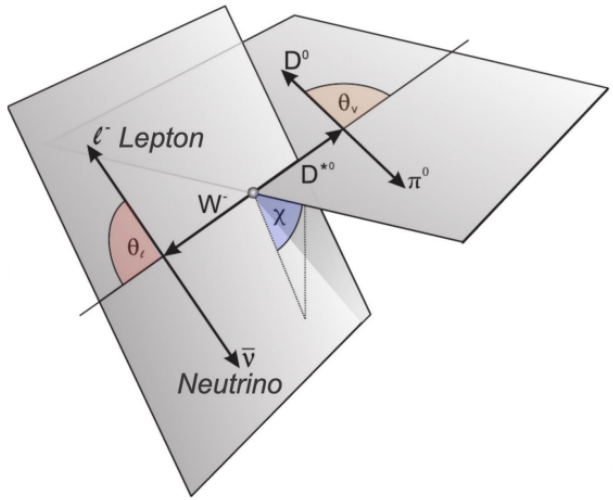
[to be submitted to Phys. Rev. D]



$$\ell = (e, \mu)$$

- Reconstruct neutral B mode $B^0 \to D^{*+} \ell^- \nu$

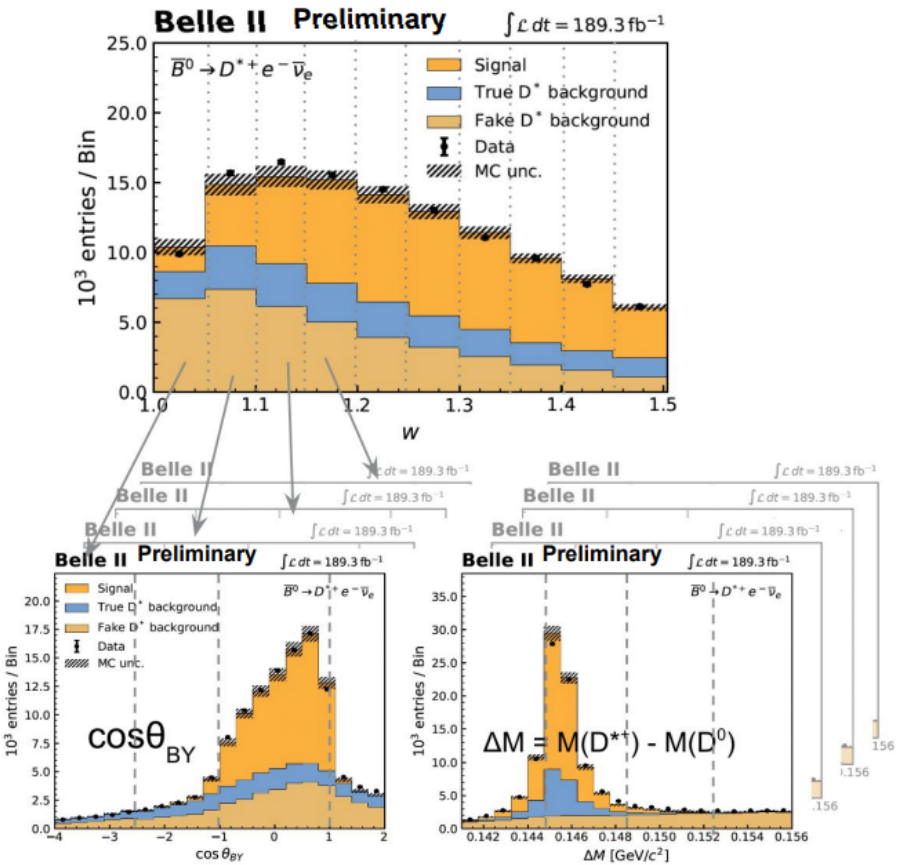
$$\frac{d^4\Gamma}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} \propto |V_{cb}|^2 F^2(w, \cos\theta_\ell, \cos\theta_V, \chi)$$



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

- Measure partially differential rates
- Fit form factors to decay rates

Signal extraction



- 2-dimensional fit in $\cos\theta_{BY}$ and $\Delta M = M(K\pi\pi_s) - M(K\pi)$
- Independent fits in 10 (8) bins of w, θ_V, χ (θ_ℓ)
- Template fit with 3 components

- Partial decay rates are determined from the unfolded yields

$$\Delta\Gamma_i = \frac{y_i^{\text{unfolded}}}{\epsilon_i N_{B^0} \mathcal{B}(D^{*+} \to D^0\pi^+)\mathcal{B}(D^0 \to K^-\pi^+)\tau_{B^0}}$$

reco. eff & acc.

input of PDG2022

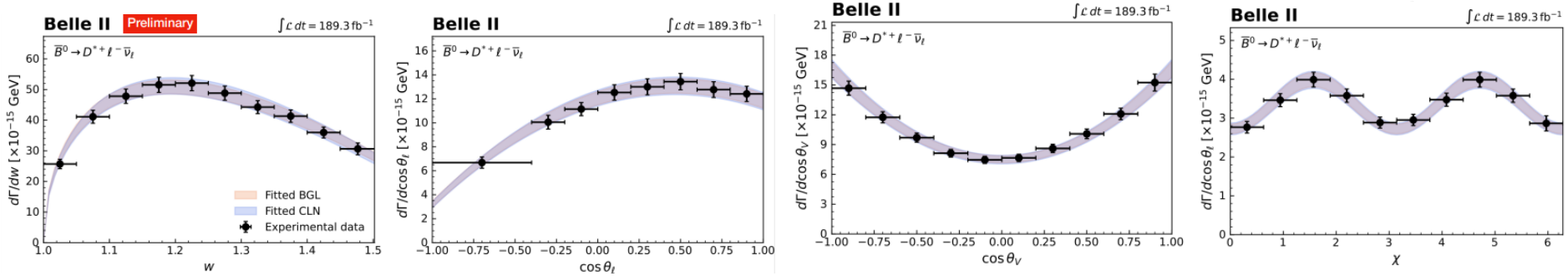
$|V_{cb}|$ extraction

- Fit form factor to measured differential decay widths including full correlation matrix
- BGL truncation order from Nested Hypothesis Test [Phys. Rev. D100, 013005 (2019)]

Relative uncertainty (%) Preliminary

	$\tilde{a}_0$	b_0	$\tilde{b}_1$	$\tilde{c}_1$
Statistical	3.3	0.7	44.8	35.4
Finite MC samples	3.0	0.7	39.4	33.0
Signal modelling	3.0	0.4	40.0	30.8
Background subtraction	1.2	0.4	24.8	18.1
Lepton ID efficiency	1.5	0.3	3.1	2.5
Slow pion efficiency	1.5	1.5	18.4	22.0
Tracking of K, π, ℓ	0.5	0.5	0.6	0.5
$N_{B\bar{B}}$	0.8	0.8	1.1	0.8
$f_{+-}/f00$	1.3	1.3	1.7	1.3
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.4	0.4	0.5	0.4
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.4	0.4	0.5	0.4
B^0 lifetime	0.1	0.1	0.2	0.1
Total	6.1	2.5	78.3	64.1

BGL fit results (LQCD at $w = 1.0$)



$$|V_{cb}|_{\text{BGL}} = (40.9 \pm 0.3_{\text{stat}} \pm 1.0_{\text{sys}} \pm 0.6_{\text{theo}}) \times 10^{-3}$$

World-average exclusive $D^* \ell\nu$: [arXiv:2206.07501]

$$(38.5 \pm 0.4_{\text{exp}} \pm 0.6_{\text{th}}) \times 10^{-3}$$

Other results

- Other extractable results from this analysis:

$$|V_{cb}|_{\text{BGL, LQCD @ w} > 1.0} = (40.0 \pm 1.2) \times 10^{-3}$$
$$|V_{cb}|_{\text{CLN}} = (40.4 \pm 0.3_{\text{stat}} \pm 1.0_{\text{sys}} \pm 0.6_{\text{theo}}) \times 10^{-3}$$

$$\mathcal{B}(B^0 \to D^{*+}\ell^-\nu) = (4.94 \pm 0.02_{\text{stat}} \pm 0.22_{\text{sys}})\%$$

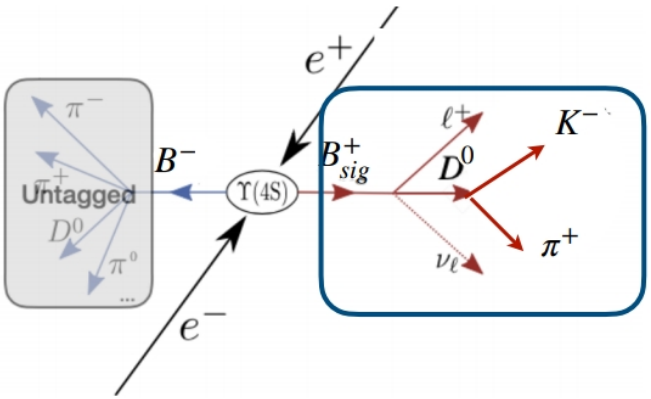
HFLAV average: $(4.97 \pm 0.12)\%$ [arXiv:2206.07501]

$$\mathcal{R}_{e/\mu} = 1.001 \pm 0.009_{\text{stat}} \pm 0.021_{\text{sys}}$$
$$\Delta\mathcal{A}_{fb} = (-4 \pm 16_{\text{stat}} \pm 18_{\text{sys}}) \times 10^{-3}$$

↪ See Peter Lewis' talk for a dedicated measurement

Untagged $|V_{cb}|$ via $B \to D\ell\nu$

[arXiv:2210.13143]

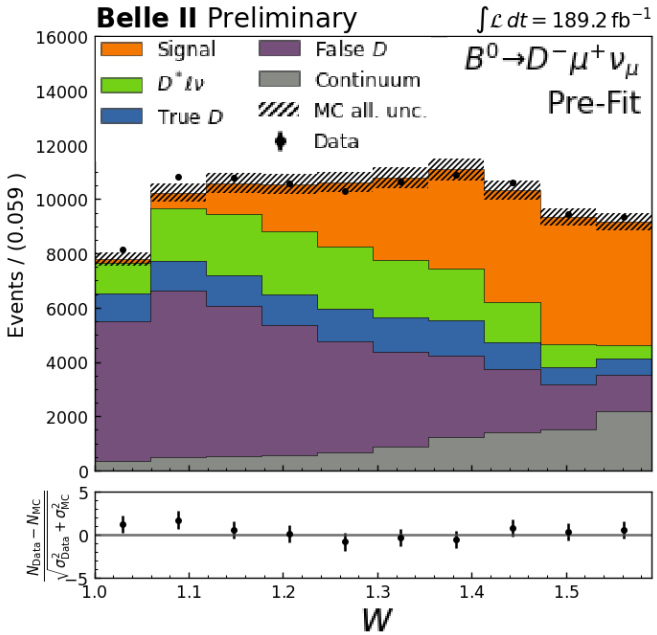


- Reconstruct both charged and neutral B modes
- $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$

Key differences to $D^*\ell\nu$

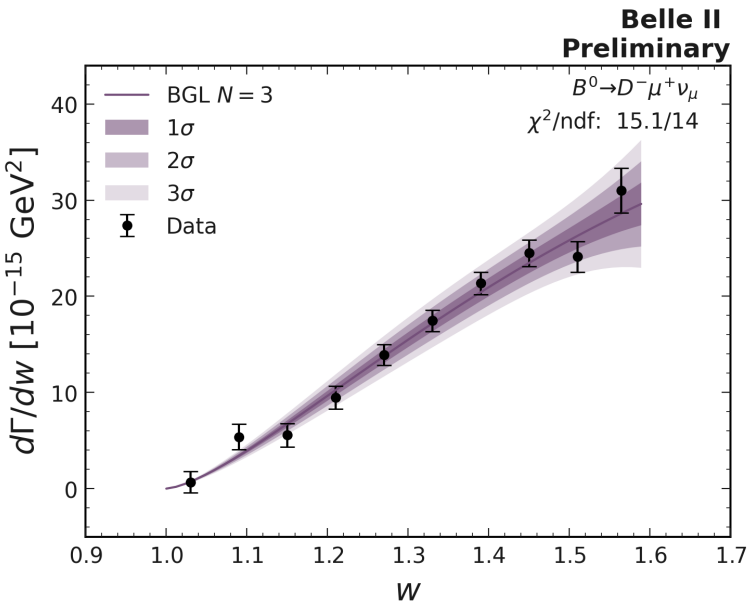
- Scalar meson, one form factor and one kinematic variable w
- No slow π dependence
- More backgrounds

B^0 mode



Untagged $|V_{cb}|$ via $B \to D\ell\nu$

- Signal yields from independent fits to $\cos\theta_{BY}$ in 10 w bins
- Fit BGL form factors up to $N = 3$ to partial decay rates
- FNAL/MILC [Phys. Rev. D 92, 034506] and HPQCD Lattice QCD [Phys. Rev. D 92, 054510 (2015)] as nuisance parameters



$$|V_{cb}| = (38.3 \pm 1.2) \times 10^{-3}$$

World-average exclusive $D\ell\nu$: [arXiv:2206.07501]

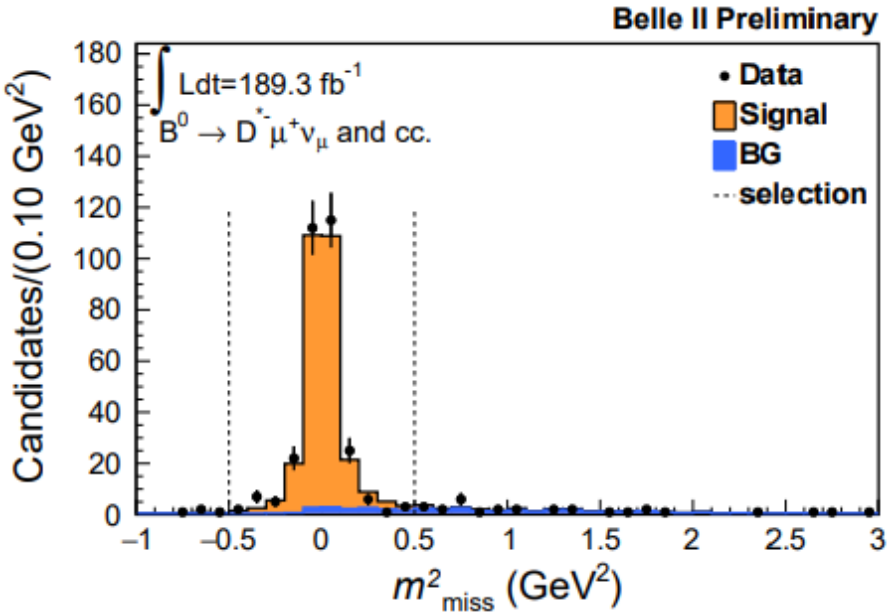
$(39.1 \pm 0.9_{\text{exp}} \pm 0.4_{\text{th}}) \times 10^{-3}$

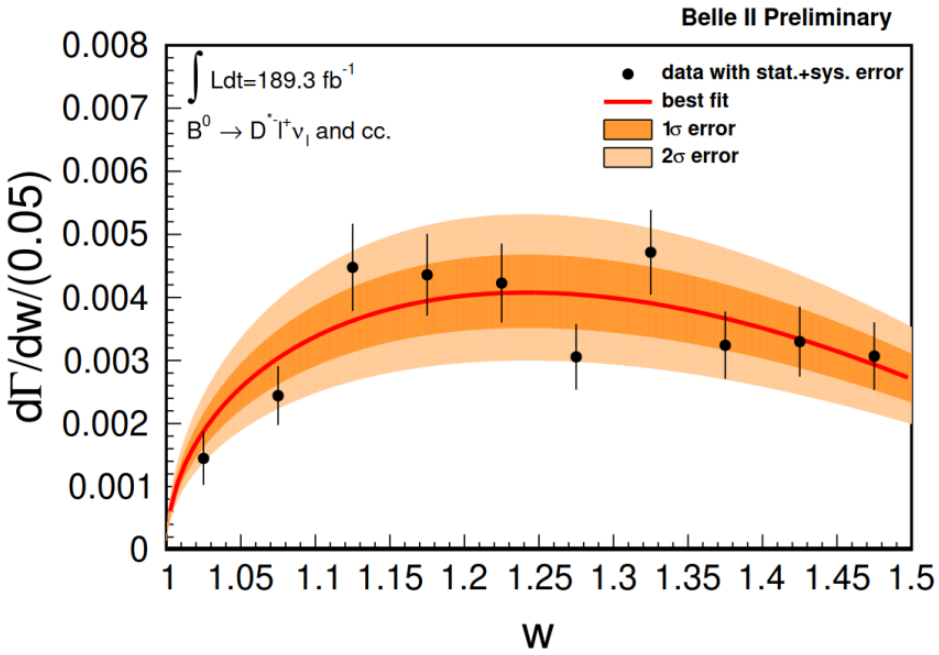
- $\sim 3\%$ error, comparable to the past measurements

Tagged $|V_{cb}|$ via $B \to D^* \ell \nu$

[arXiv:2301.04716]

- Tagged measurement of $B^0 \to D^{*\pm} \ell \nu$ with $\ell = (e, \mu)$
- Fit CLN parametrized form factor [NPB530, 153 (1998)] to differential decay rates





$$|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$$

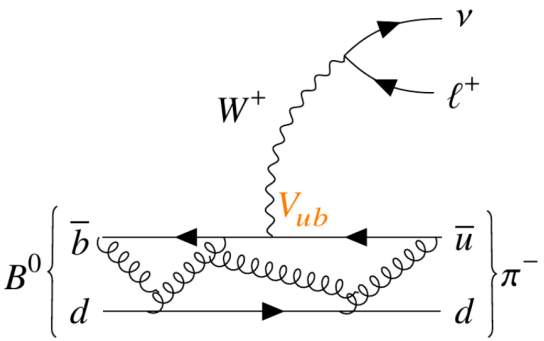
World-average exclusive $D^* \ell \nu$: [arXiv:2206.07501]

$$(38.46 \pm 0.40_{\text{exp}} \pm 0.55_{\text{th}}) \times 10^{-3}$$

- Major systematic errors: slow π efficiency and tag calibration

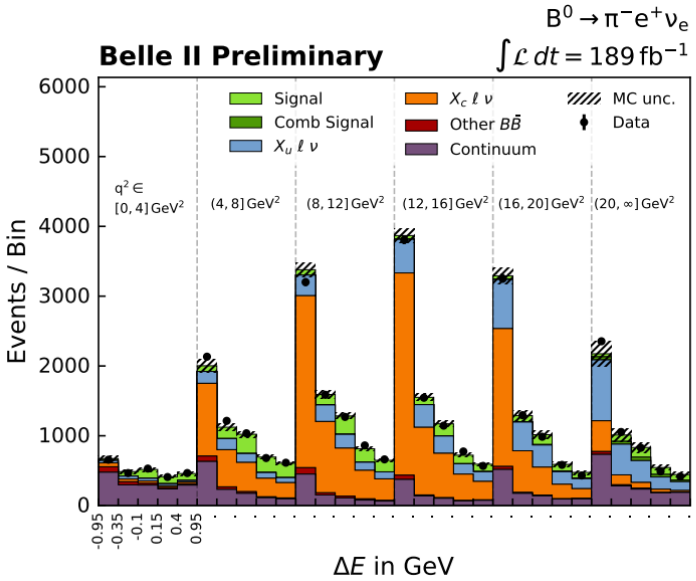
Untagged $|V_{ub}|$ via $B \to \pi \ell \nu$

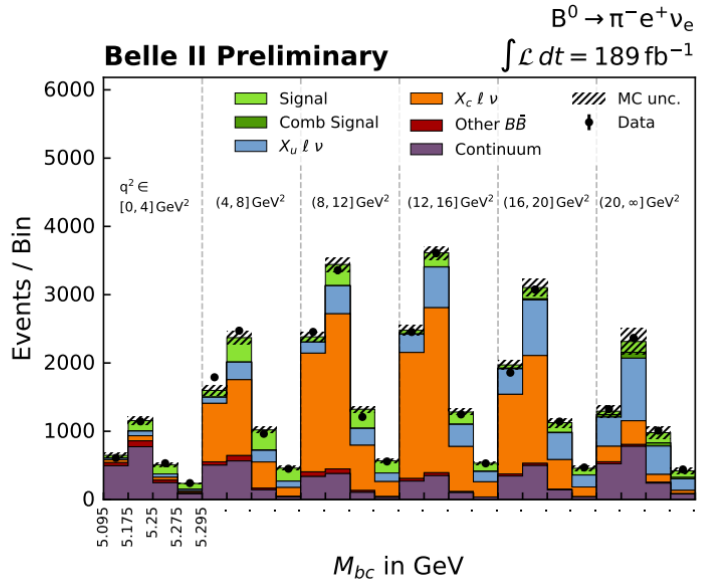
arXiv:2210.04224



$q^2 = (p_B - p_\pi)^2$

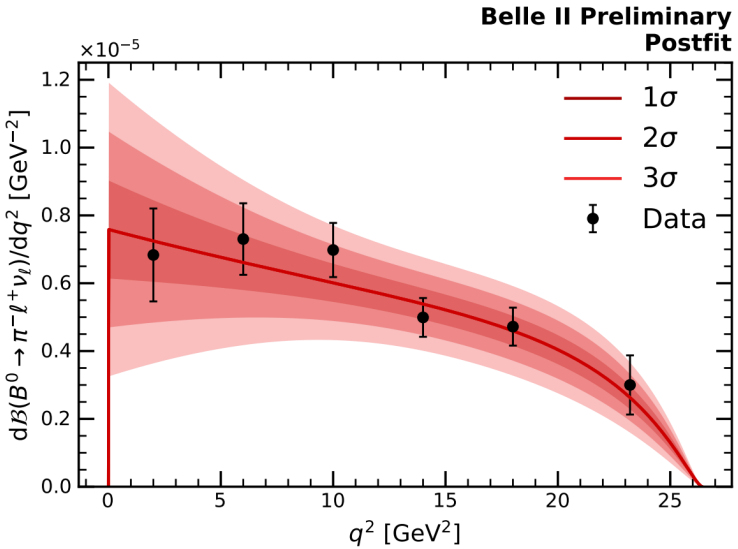
- Reconstruct $B^0 \to \pi^\pm \ell \nu$ with $\ell = (e, \mu)$
- 2 dimensional fit to $M_{bc} = \sqrt{E^{*2}_{\text{beam}} - |\vec{p}^{\,*}_B|^2}$ and $\Delta E = E^*_B - E^*_{\text{beam}}$ in 6 bins of q^2
- Bin-by-bin unfolding to correct migration





Untagged $|V_{ub}|$ via $B \to \pi \ell \nu$

- BCL extraction of V_{ub}:
  - Fit form factor to measured differential rates in bins of q^2
  - Input LQCD inputs $f_+(q^2)$ as nuicance parameters (FNAL/MILC [Phys. Rev. D 92, 014024])



Preliminary

Systematic uncertainties on the yields (%)

Source	$B^0 \to \pi^- e^+ \nu_e$						$B^0 \to \pi^- \mu^+ \nu_\mu$					
	$q1$	$q2$	$q3$	$q4$	$q5$	$q6$	$q1$	$q2$	$q3$	$q4$	$q5$	$q6$
Detector	1.2	1.0	1.1	1.4	2.3	2.4	2.3	3.2	3.3	1.2	1.9	3.8
MC sample size	4.0	2.0	2.4	2.8	3.9	5.6	3.9	2.0	2.3	2.7	3.4	4.8
Continuum	13.1	5.5	4.4	7.8	10.5	33.9	53.3	8.8	3.2	4.5	8.0	11.4
$B \to \rho \ell \nu$	9.5	12.5	9.7	6.9	3.4	12.9	8.7	11.6	8.6	6.3	3.3	14.3
$B \to X_u \ell \nu$	3.3	1.9	2.1	2.1	1.8	3.7	3.4	2.3	2.0	2.3	2.1	6.0
$B \to X_c \ell \nu$	2.3	3.0	1.1	0.8	0.5	2.4	2.4	1.5	1.5	0.8	0.5	2.2
Total syst.	17.2	14.3	11.2	11.1	12.0	37.0	53.4	15.2	10.3	8.7	9.7	20.3
Stat.	10.2	6.01	6.86	8.08	10.3	13.2	10.4	6.0	6.4	7.8	9.7	13.4
Total	20.2	15.5	13.2	13.7	15.9	39.2	54.5	16.4	12.2	11.6	13.7	24.3

$$|V_{ub}| = (3.55 \pm 0.12_{\text{stat}} \pm 0.13_{\text{sys}} \pm 0.17_{\text{theo}}) \times 10^{-3}$$

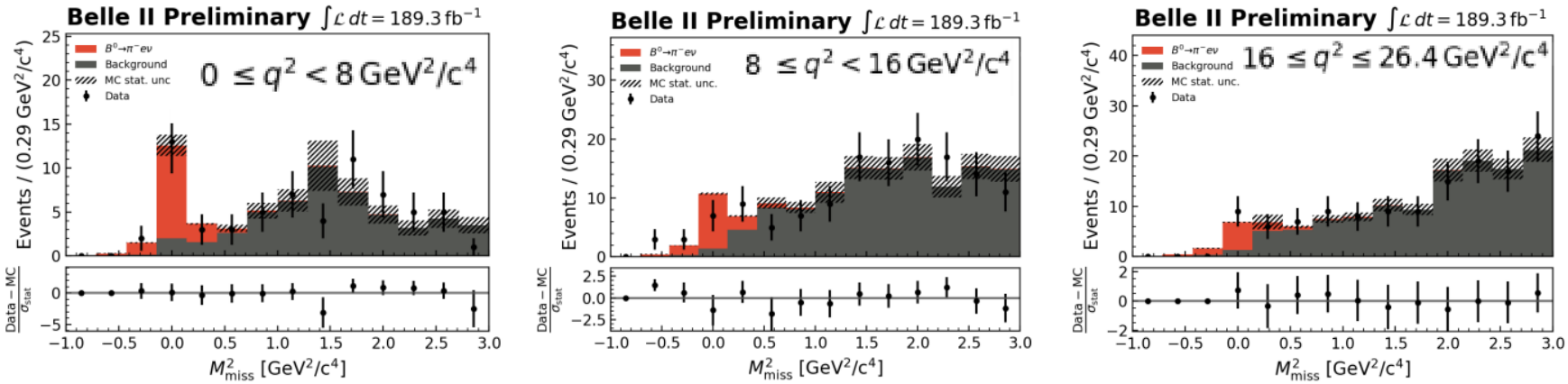
World-average exclusive $\pi \ell \nu$: $(3.67 \pm 0.15) \times 10^{-3}$ [arXiv:2206.07501]

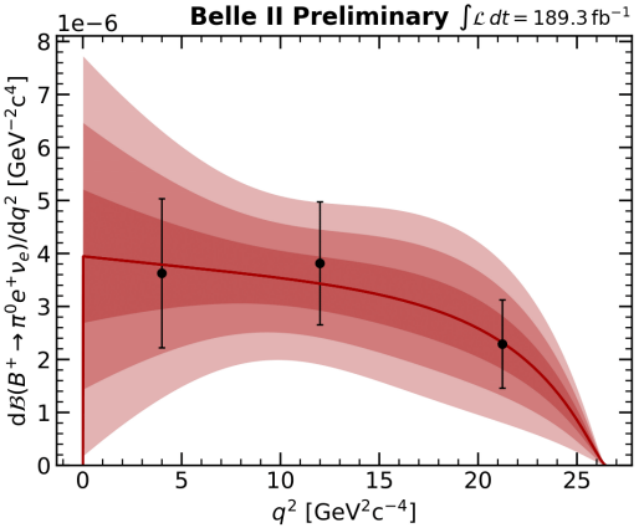
Tagged $|V_{ub}|$ via $B \to \pi e \nu$

arXiv:2206.08102

- Measure e modes with hadronic FEI

$B^0 \to \pi^- e^+ \nu_e$





- BCL expansion fit
- Leading systematic: tag calibration

$$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$$

World-average exclusive $\pi \ell \nu$:

[arXiv:2206.07501] $(3.67 \pm 0.15) \times 10^{-3}$

Outlook

- $|V_{cb}|$ and $|V_{ub}|$ play an important role in constraining the Standard Model
- Presented first preliminary exclusive measurements at Belle II
- Competitive precision with 189 fb^{-1} collected
  - Updates with more data in progress

	$\lvert V_{cb}\rvert \times 10^3$	Reference
Untagged $B \to D^* \ell\nu$	40.9 ± 1.2 (BGL)	To be submitted to PRD
Untagged $B \to D \ell\nu$	38.3 ± 1.2 (BGL)	[arXiv:2210.13143]
Tagged $B \to D^* \ell\nu$	37.9 ± 2.7 (CLN)	[arXiv:2301.047169]

	$\lvert V_{ub}\rvert \times 10^3$	Reference
Untagged $B \to \pi \ell\nu$	3.55 ± 0.25	[arXiv:2210.04224]
Tagged $B \to \pi e\nu$	3.88 ± 0.45	[arXiv:2206.08102]

World averages [HFLAV 2021]

$|V_{cb}|_{\text{excl.}} = (39.1 \pm 0.5) \times 10^{-3}$

$|V_{ub}|_{\text{excl.}} = (3.51 \pm 0.12) \times 10^{-3}$

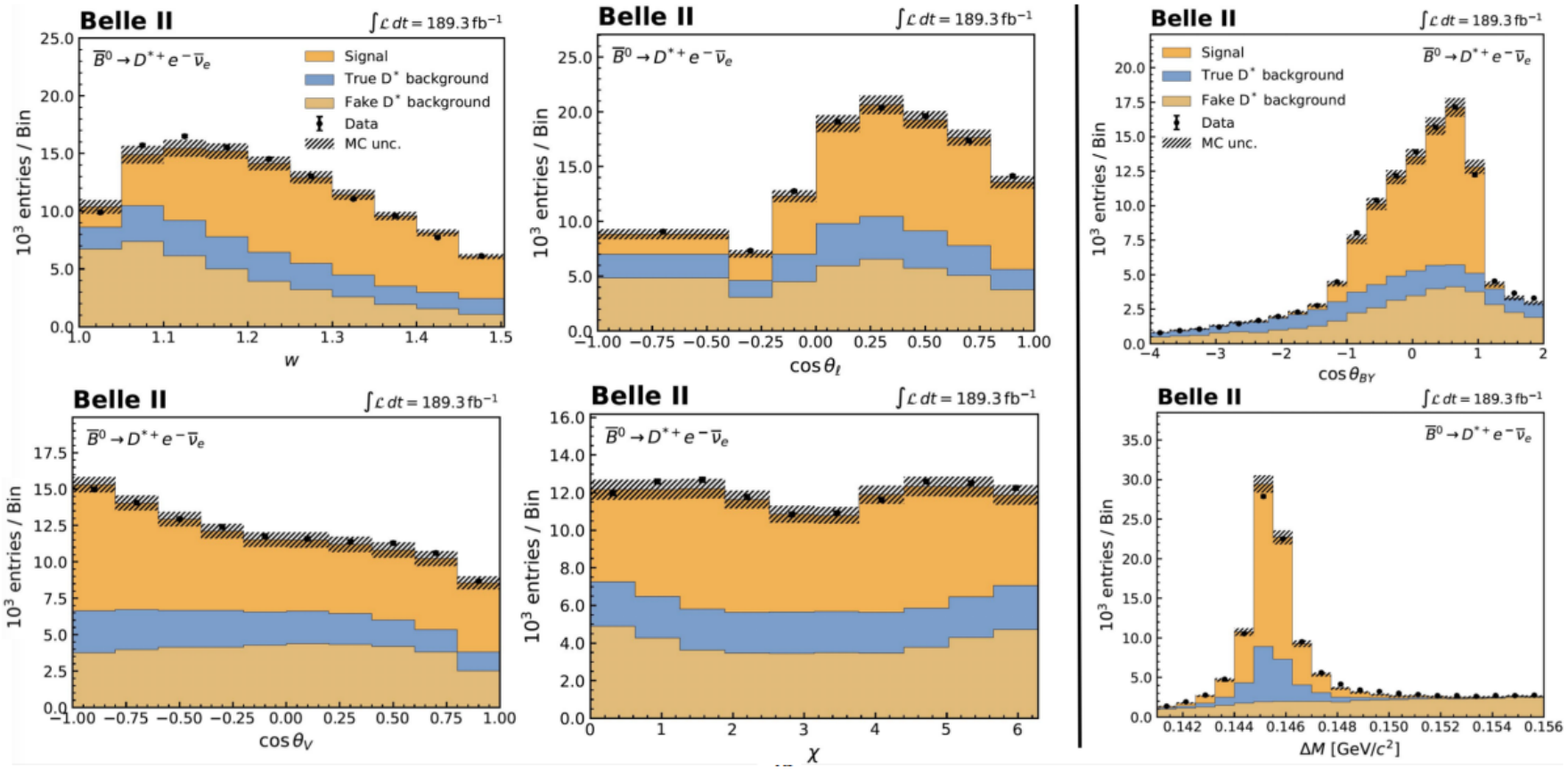
- New inclusive measurements in progress

Backup

$D^*\ell\nu$ Data-MC comparison

- e mode

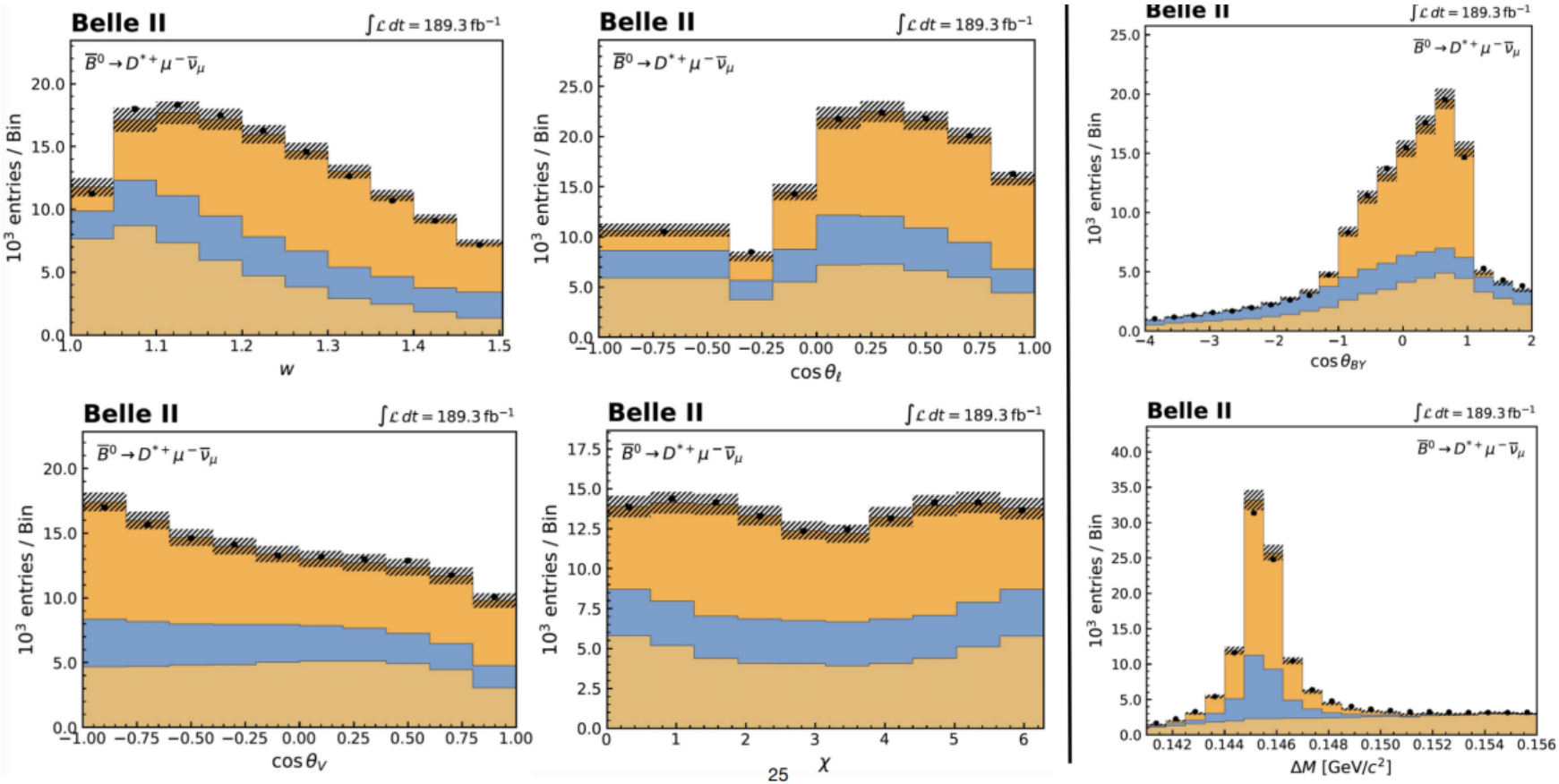
Preliminary



$D^*\ell\nu$ Data-MC comparison

- μ mode

Preliminary



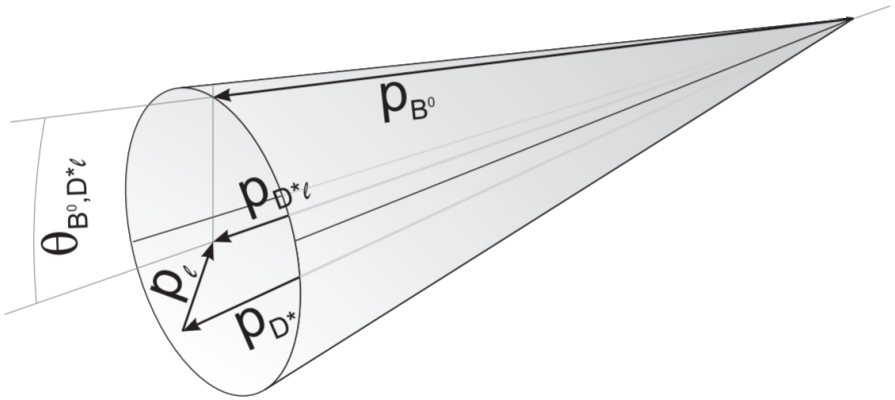
Kinematic variable construction

- How to reconstruct $w, \theta_\ell, \theta_V, \chi$?
- What we know about B:

$$E_B^* = \frac{E_{Beam}^*}{2} \qquad |\vec{p}_B^*| = \sqrt{(E_{Beam}^*)^2 - m_{B^0}^2}$$

- From reconstructed ℓ and D^*:

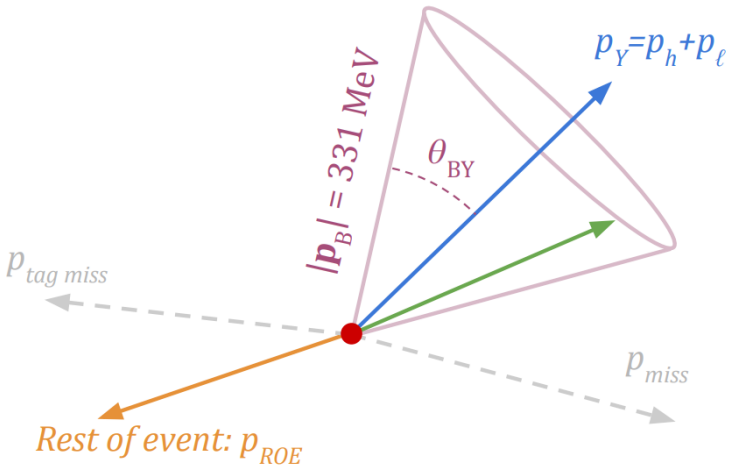
$$\cos\theta_{BY} = \frac{2\,E_B^* E_Y^* - m_B^2 - m_Y^2}{2|p_B^*||p_Y^*|},\ Y = \text{Combined } D^*\ \ell \text{ system}$$



- For kinematic variables, need direction on this cone

Kinematic variable construction

- Novel approach : (extension of BaBar's diamond frame [Phys. Rev. D 74, 092004])



- Calculate $\cos\theta_{BY}$ from reconstructed D^* and ℓ
- $B\overline{B}$ production: angularly distributed according to $\sin^2\theta_B$
- Sum up left-over tracks and clusters as Rest-of-Event (ROE) and calculate momentum p^*_{ROE}
- Likely direction on $\cos\theta_{BY}$ cone: Back-to-back with ROE
- Weighted average over 10 uniformly distributed vectors on cone
- Each vector has weight combining ROE and kinematic information:

$$\frac{1}{2}(1 - \hat{p}_{\mathrm{ROE}} \cdot \hat{p}_{\mathrm{B}})\ \sin^2\theta_B$$

↪ Improved resolution compared to previous methods!

Nested Hypothesis

- BGL truncation order from Nested Hypothesis Test [Phys. Rev. D100, 013005 (2019)]
  - Expand BGL order by one if χ^2 decreases by at least 1
  - Reject if maximum correlation between 2 parameters > 0.95

(n_a, n_b, n_c)	$\lvert V_{cb}\rvert \times 10^3$	χ^2	Ndf	$\rho_{\max}$
$(1,1,2)$	40.3 ± 1.1	41.4	32	0.3
$(2,1,2)$	40.2 ± 1.1	38.4	31	0.97
(1, 2, 2)	**40.9±1.2**	**39.8**	**31**	**0.56**
$(1,1,3)$	40.2 ± 1.1	40.5	31	0.97
$(2,2,2)$	40.1 ± 1.3	38.4	30	0.99
$(1,3,2)$	39.7 ± 1.4	37.4	30	0.98
$(1,2,3)$	40.7 ± 1.2	39.5	30	0.97