MORIOND QCD: MARCH 28, 2023

SEMILEPTONIC B-MESON DECAYS INCLUDING $b \to c$ ANOMALIES AT BELLE II

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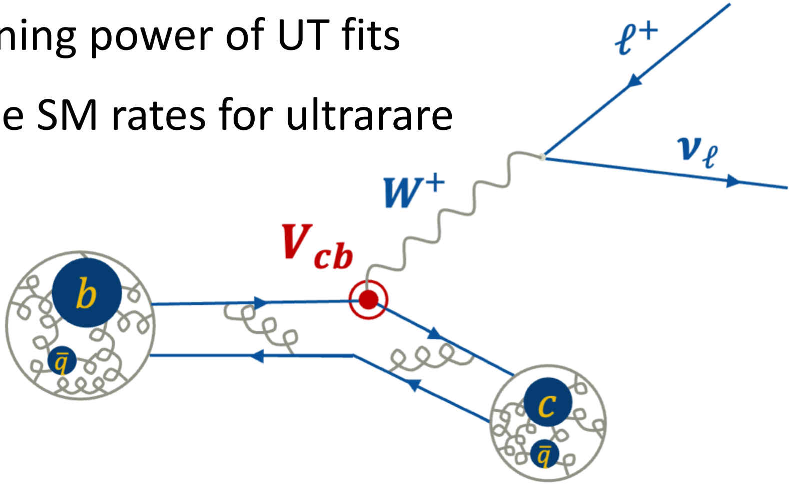
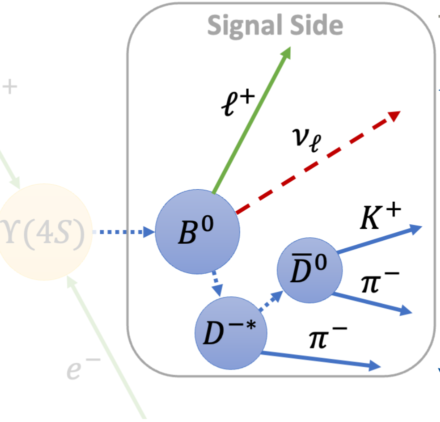
$|V_{cb}|$ & $|V_{ub}|$ MEASUREMENTS

- SL B decays are studied to **determine the CKM elements $|V_{cb}|$ and $|V_{ub}|$**
  - $|V_{xb}|$ are limiting the global constraining power of UT fits
  - Important inputs in predictions of the SM rates for ultrarare decays such as $K \to \pi\nu\nu$

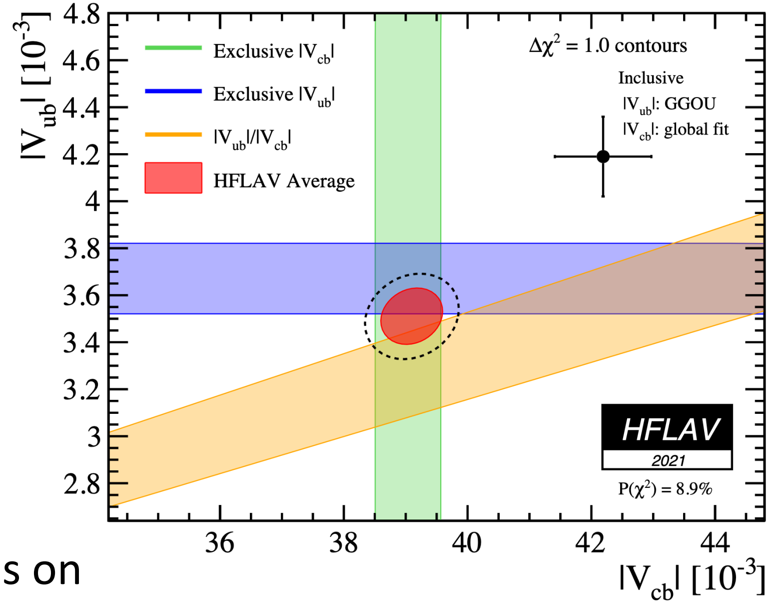


EXPERIMENTAL STATUS $|V_{cb}|$ AND $|V_{ub}|$

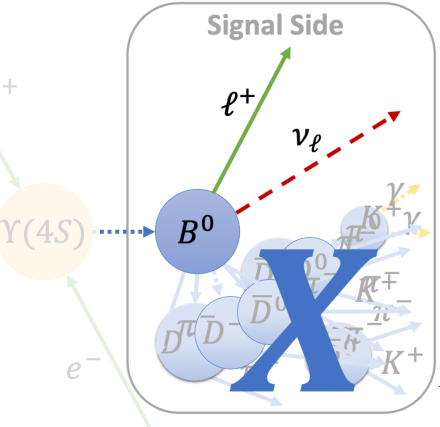


Experimentally clean
Theoretically challenging

- Determination of both $|V_{cb}|$ & $|V_{ub}|$ exhibit a discrepancy at the level of $\approx 3\,\sigma$ between **exclusive** (from a single final state) and **inclusive** (sensitive to all final states)

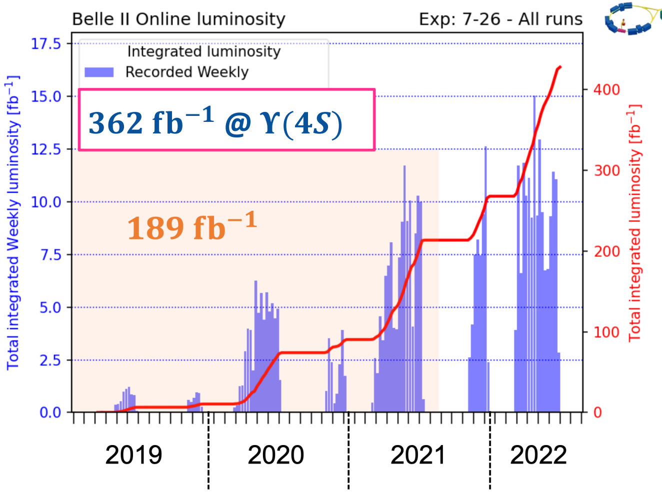


- The current experimental **focus** is on **understanding** the origin of **this discrepancy**, as this inconsistency limits the power of precision flavor physics

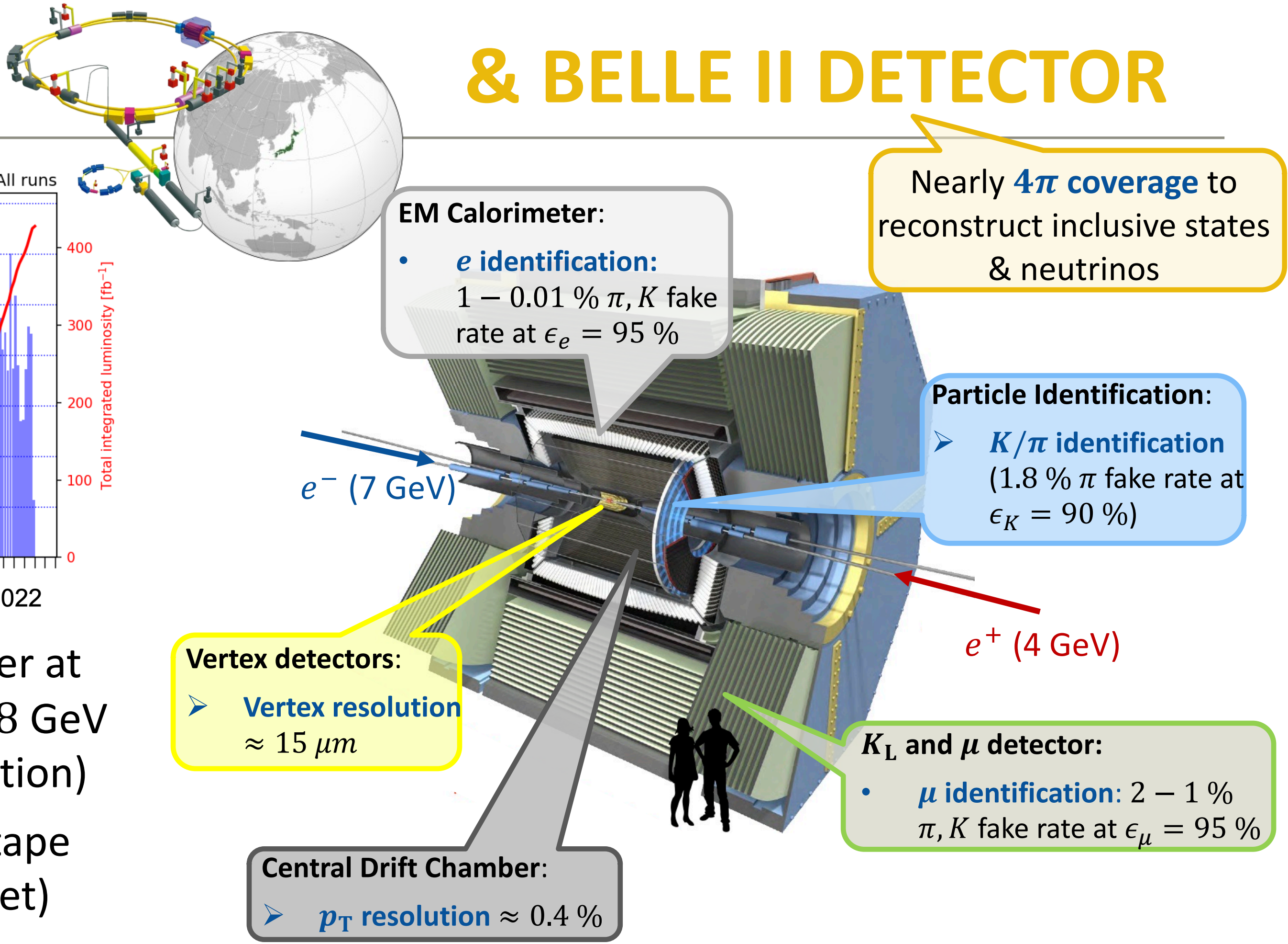


Experimentally challenging
Theoretically clean

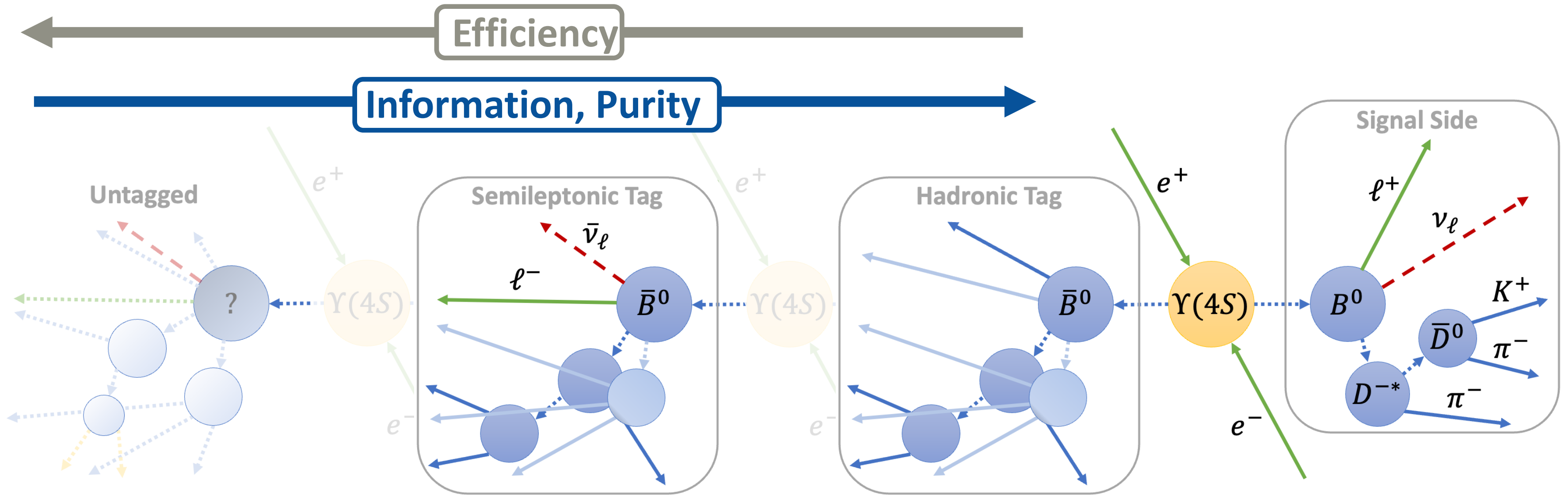
SUPERKEKB & BELLE II DETECTOR



- Asymmetric e^+e^- collider at (and near) $E_{c.m.} = 10.58$ GeV (resonant $\Upsilon(4S)$ production)
- $\int L\,dt = 424\ \mathrm{fb}^{-1}$ on tape (similar to BaBar's dataset)



B-MESON FLAVOR TAGGING



$\epsilon = \mathcal{O}(100\%)$

Only approximate kinematical information

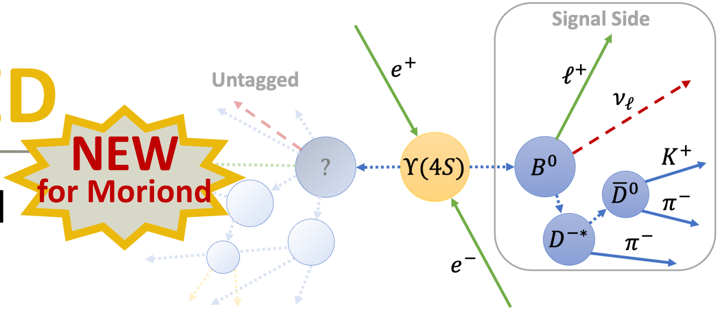
$\epsilon = \mathcal{O}(1\%)$

Rough knowledge of B_{tag} kinematics (missing $\boldsymbol{\nu}$)

$\epsilon = \mathcal{O}(0.1\%)$

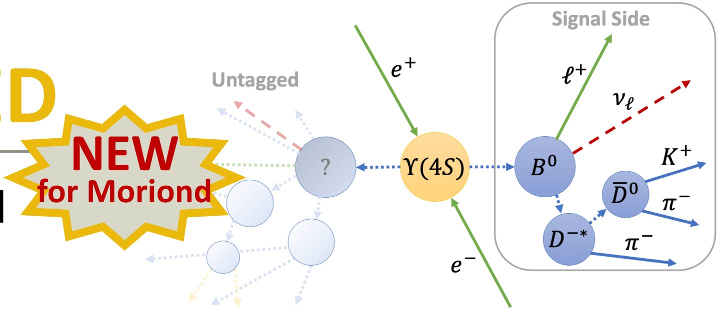
Exact knowledge of B_{tag} kinematics

$|V_{cb}|$: $B^0 \to D^{*-}\ell^+\nu$ UNTAGGED



- Challenging due to lack of clean kinematic signatures and missing knowledge of the B_{sig} direction

$|V_{cb}|$: $B^0 \to D^{*-}\ell^+\nu$ UNTAGGED



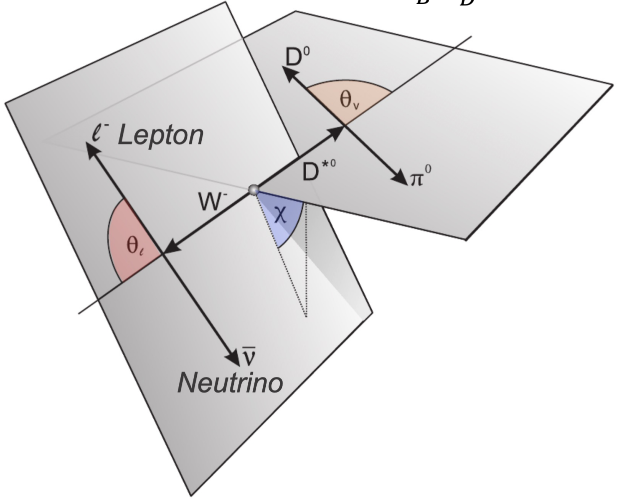
- Challenging due to lack of clean kinematic signatures and missing knowledge of the B_{sig} direction

$|V_{cb}|$ extraction and decay parametrization

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

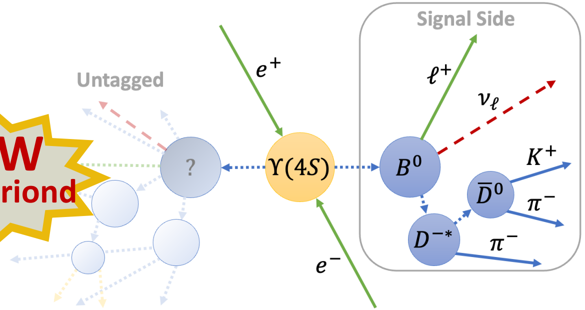
3 form factors as functions of w parametrize the non-perturbative physics

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



$|V_{cb}|$: $B^0 \to D^{*-}\ell^+\nu$ UNTAGGED

NEW for Moriond



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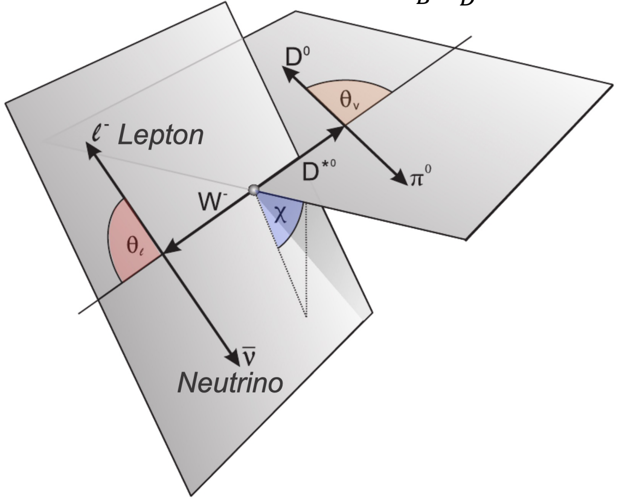


The $\boldsymbol{B_{\text{sig}}}$ **direction** is estimated in a **novel approach** using

- The known **angle $\cos\boldsymbol{\theta_{BY}}$** between the B_{sig} and the $Y = D^* + \ell$

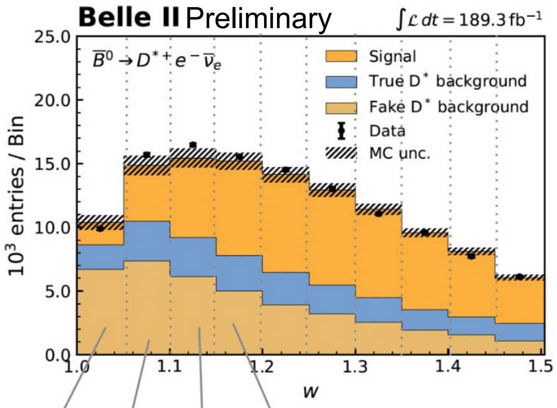
$$\cos\theta_{BY} = \frac{2E_B^{\text{c.m.}}E_Y^{\text{c.m.}} - m_B^2c^4 - m_Y^2c^4}{2|\vec{p}_B^{\,\text{c.m.}}||\vec{p}_Y^{\,\text{c.m.}}|c^2}$$

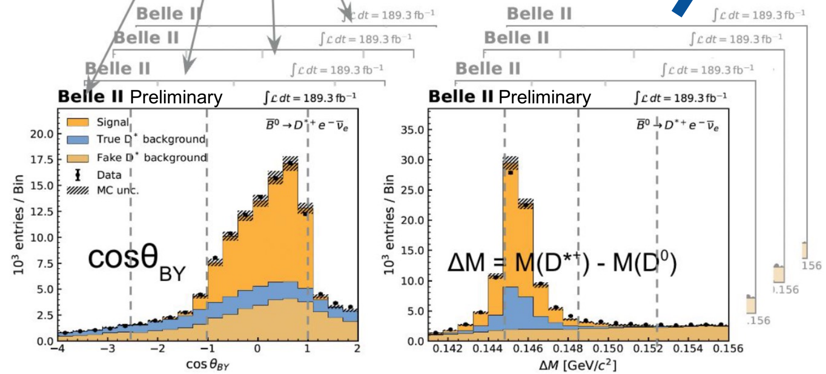
- **inclusive information** of the **untagged event side**
- the **angular distribution** of $\Upsilon(4S) \to B\bar{B}$ w.r.t. the beam axis

$|V_{cb}|$: $B^0 \to D^{*-}\ell^+\nu$ UNTAGGED

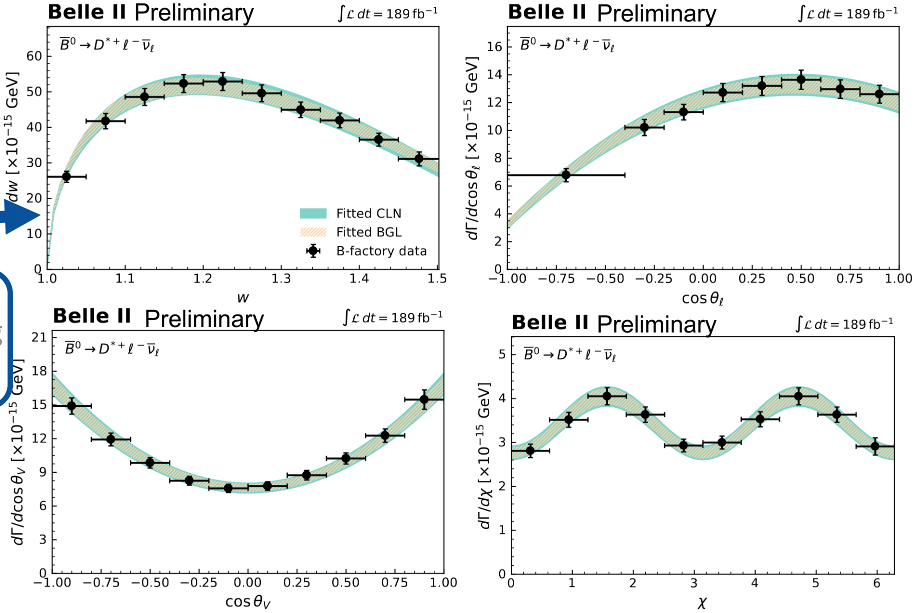
NEW for Moriond

- The yield is extracted in 10 (8) bins of w, $\cos\theta_\ell$, $\cos\theta_V$ and χ by **fitting $\cos\theta_{BY}$ and $\Delta M = M_{D^*} - M_D$**





Bin-to-bin migration corrected with SVD unfolding [arXiv:hep-ph/9509307](https://arxiv.org/abs/hep-ph/9509307)



$|V_{cb}|$: $B^0 \to D^{*-}\ell^+\nu$ UNTAGGED

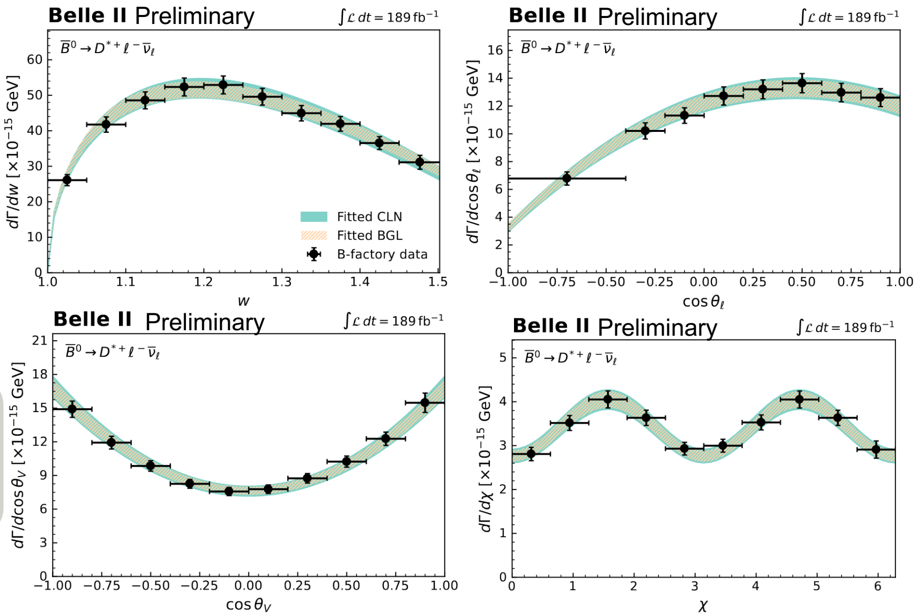
NEW for Moriond

BGL truncation order determined by Nested Hypothesis Test
Phys. Rev. D **100**, 013005

	Values	Correlations				χ^2/ndf
$\tilde{a}_0 \times 10^3$	0.89 ± 0.05	1.00	0.26	−0.27	0.07	40/31
$\tilde{b}_0 \times 10^3$	0.54 ± 0.01	0.26	1.00	−0.41	−0.46	
$\tilde{b}_1 \times 10^3$	-0.44 ± 0.34	−0.27	−0.41	1.00	0.56	
$\tilde{c}_1 \times 10^3$	-0.05 ± 0.03	0.07	−0.46	0.56	1.00	

LQCD input used for normalization **at zero recoil**
FNAL/MILC Phys. Rev. D **89**, 114504

$$|V_{cb}|_{\mathrm{BGL}} = \left(40.9 \pm 0.3^{\mathrm{stat}} \pm 1.0^{\mathrm{syst}} \pm 0.6^{\mathrm{theo}}\right) \times 10^{-3}$$
$$|V_{cb}|_{\mathrm{CLN}} = \left(40.4 \pm 0.3^{\mathrm{stat}} \pm 1.0^{\mathrm{syst}} \pm 0.6^{\mathrm{theo}}\right) \times 10^{-3}$$

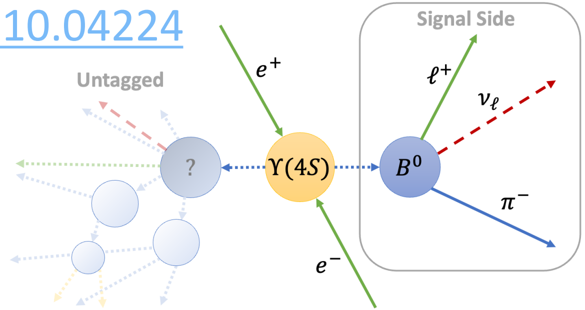


- In **good agreement** with **exclusive** and **inclusive** world averages
- FNAL/MILC predictions[1] of form factors beyond zero recoil probed but found to be in tension with fits at exp. favored BGL order. Suggested $|V_{cb}|$ value only shifts slightly.

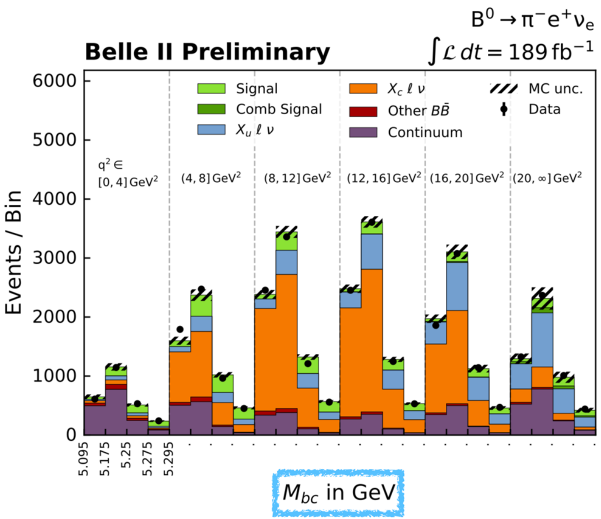
[1] = Eur. Phys. J. C **82**, 1141 (2022)

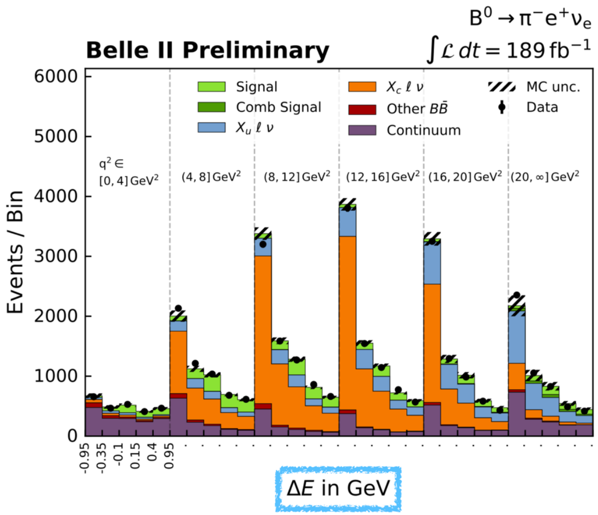
arXiv:2210.04224

$|V_{ub}|$: $B^0 \to \pi^- \ell^+ \nu$ UNTAGGED



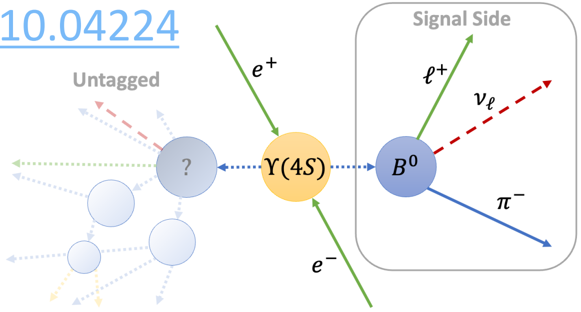
- Challenging due to low branching ratios, large backgrounds and lack of clean kinematic signatures
- Backgrounds suppressed using BDTs, B_{sig} direction derived inclusively
- The differential rates in **6 bins of q^2** are determined in a **fit to M_{bc} vs. ΔE**



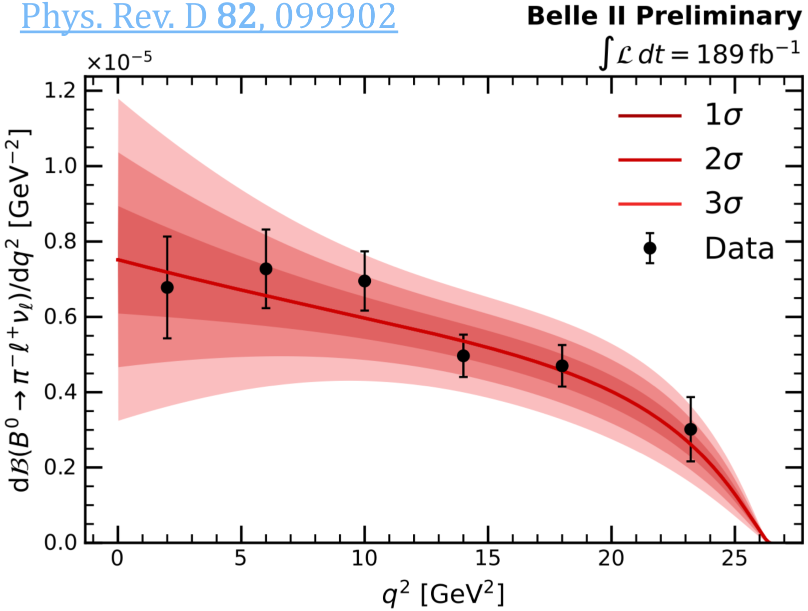


$|V_{ub}|$: $B^0 \to \pi^- \ell^+ \nu$ UNTAGGED

arXiv:2210.04224



$|V_{ub}|$ is determined in fit to BCL expansion
Phys. Rev. D **82**, 099902



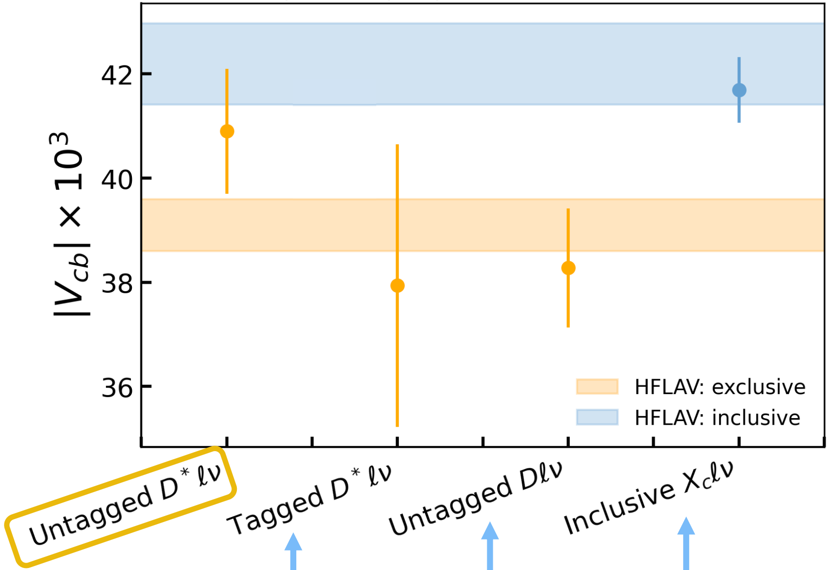
LQCD input from FNAL/MILC
Phys. Rev. D **92**, 014024

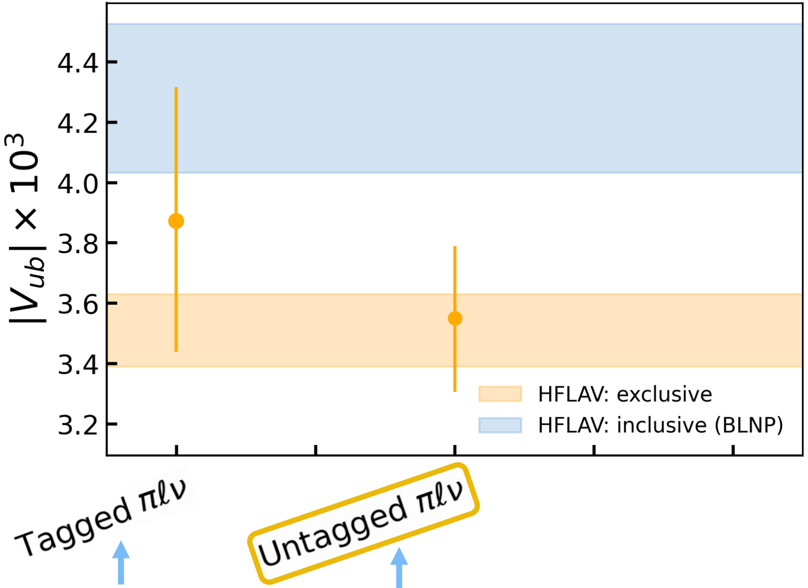
$$|V_{ub}| = \left(3.55 \pm 0.12^{\mathrm{stat}} \pm 0.13^{\mathrm{syst}} \pm 0.17^{\mathrm{theo}}\right) \times 10^{-3}$$
$$\mathcal{B}\left(B^0 \to \pi^- \ell^+ \nu\right) = \left(1.426 \pm 0.056^{\mathrm{stat}} \pm 0.125^{\mathrm{syst}}\right) \times 10^{-4}$$

- Experimental uncertainties dominated by $e^+e^- \to q\bar{q}$ and $B \to \rho \ell \nu$ modeling

BELLE II'S RECENT $|V_{cb}|$ & $|V_{ub}|$ SUMMARIZED

Plotted by Chaoyi Lyu





arXiv:2210.13143

arXiv:2206.08102

arXiv:2301.04716

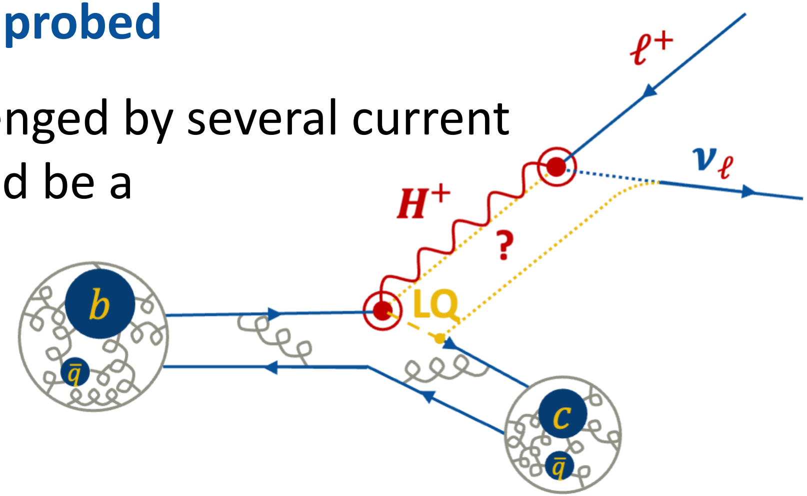
Novel $|V_{cb}|$ extraction method[1] based on measured q^2 moments by Belle[2] & Belle II[3]

arXiv:2210.04224

[1] = JHEP **10** 068 (2022), [2] = Phys. Rev. D **104**, 112011, [3] = arXiv:2205.06372

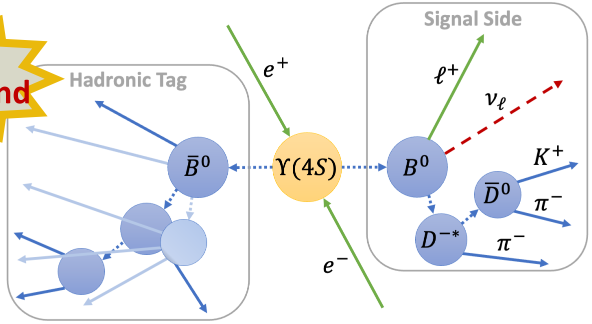
LIGHT LEPTON UNIVERSALITY

- The **universality of the lepton coupling, g_ℓ $(\ell = e, \mu, \tau)$,** to the electroweak gauge bosons **can be probed**
  - Lepton universality (LU) is challenged by several current measurements. Deviations would be a clear sign of BSM physics



LU: ANGULAR ASYMMETRIES

NEW for Moriond



- Light lepton universality tested by measuring a **complete set** of **five angular asymmetries** of e and μ, $\boldsymbol{\Delta\mathcal{A}_x = \mathcal{A}_x^e - \mathcal{A}_x^\mu}$ using $\boldsymbol{B^0 \to D^{*-}\ell^+\nu}$ decays.

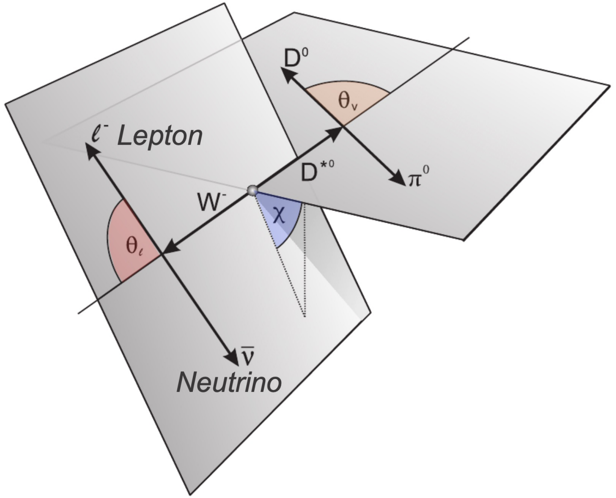
$$\mathcal{A}_x(w) = \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\underbrace{\int_0^1}_{+} - \underbrace{\int_{-1}^0}_{-}\right] dx \, \frac{d^2\Gamma}{dw\,dx}$$

$A_{\mathrm{FB}}(w)$: $dx = d(\cos\theta_\ell)$

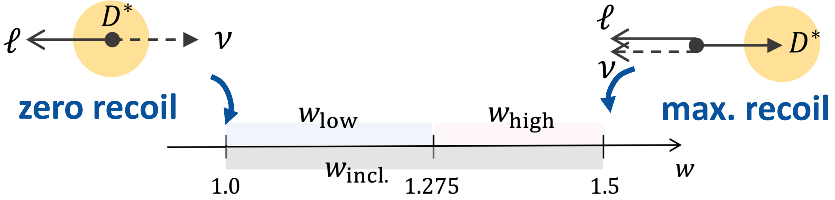
$S_3(w)$: $dx = d(\cos 2\chi)$

$\vdots$

Recoil parameter $w = \dfrac{m_B^2+m_{D^*}^2-q^2}{2m_B m_{D^*}}$

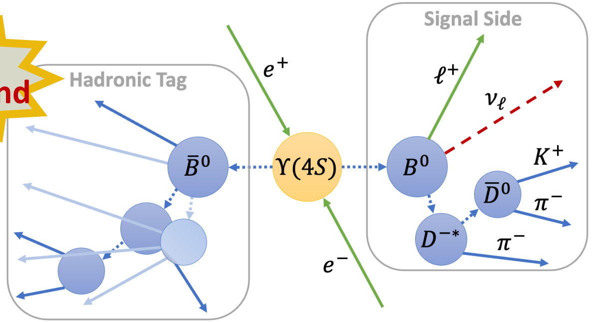


- The simultaneous determination of all asymmetries in **different w ranges** is performed

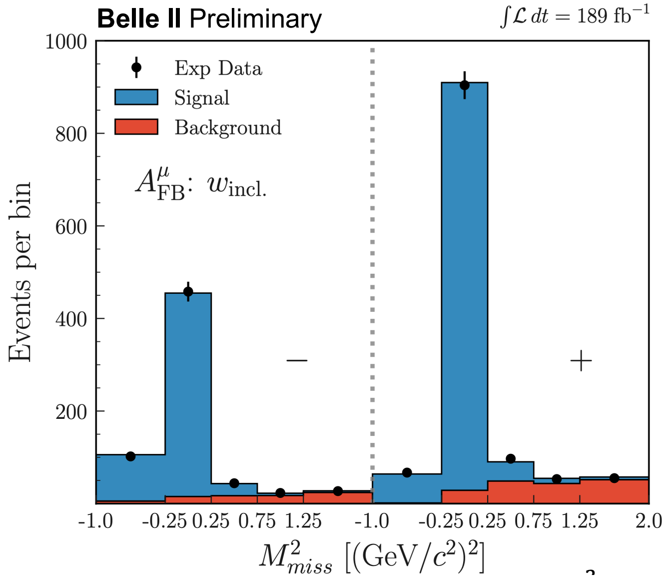


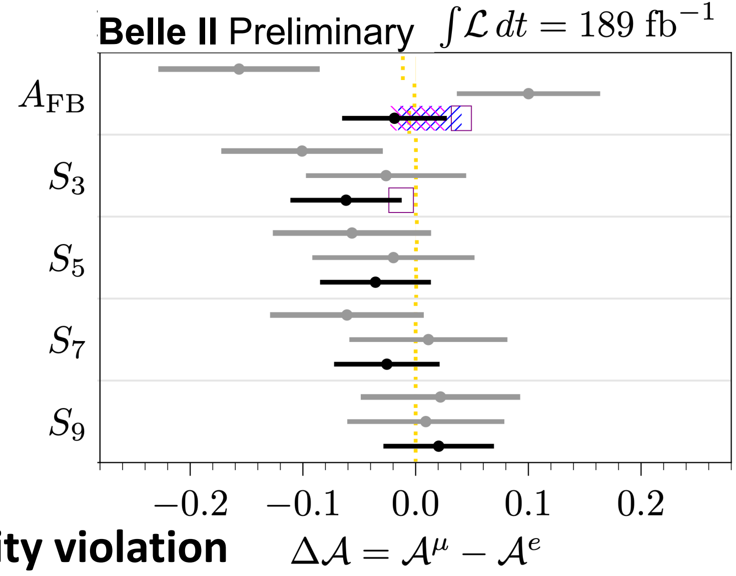
LU: ANGULAR ASYMMETRIES

NEW for Moriond

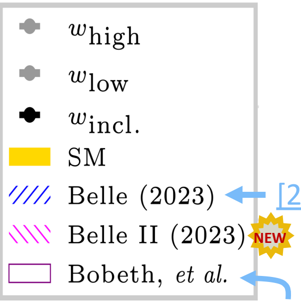


- The signal yields are extracted through a binned maximum-likelihood fit to M^2_{miss} **distributions**





Uncertainties **statistically** dominated



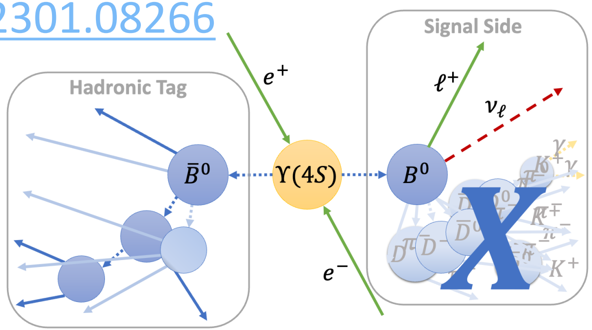
[2301.07529]

EPJC **81**, 984 (2021)

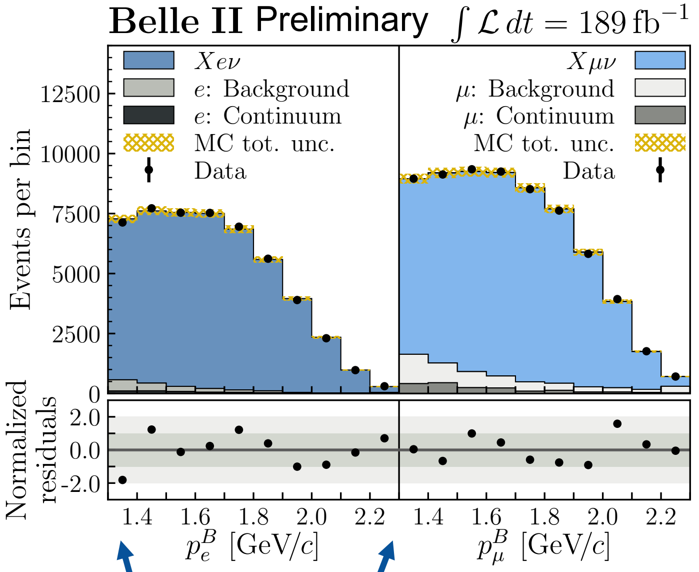
➢ **No evidence of lepton universality violation found**

LU: INCLUSIVE $R(X_{e/\mu}) = \frac{\mathcal{B}(B\to Xe\nu)}{\mathcal{B}(B\to X\mu\nu)}$

arXiv:2301.08266



- Challenging to model & control miscellaneous backgrounds
- Same flavor B pair used as background-enriched control sample, high momentum cut to suppress backgrounds
- Signal extracted in simultaneous fit on the **lepton momentum in the B_{sig} rest frame, p_ℓ^B.**



$p_\ell^B > 1.3$ **GeV!**

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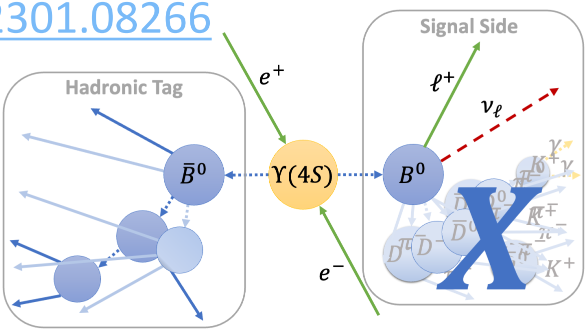

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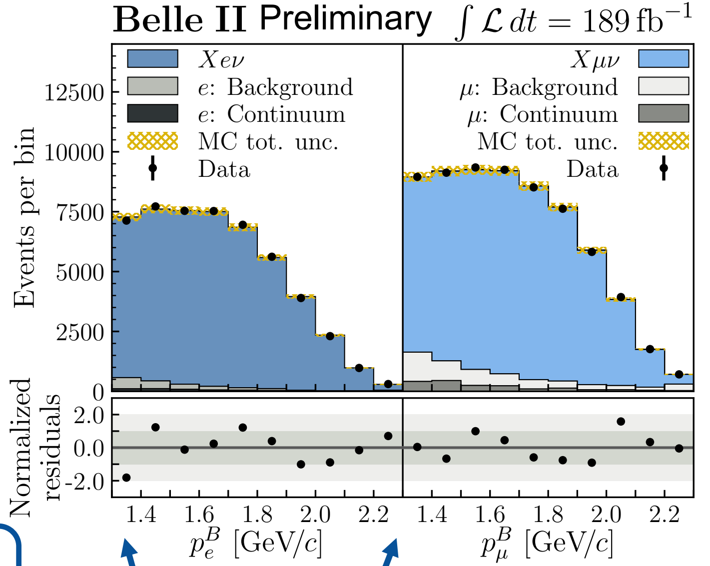
Preliminary

$$R(X_{e/\mu}) = \mathbf{1.033 \pm 0.010^{stat} \pm 0.019^{syst}}$$

- **Most precise** BF based lepton universality test in semileptonic B-meson decays to date
- **First inclusive** measurement
- Syst. unc. dominated by **lepton ID**

Consistent with SM[1] within $1.2\,\sigma$



$p_\ell^B > 1.3$ **GeV!**

[1] = JHEP 11, 007 (2022)

SUMMARY AND CONCLUSION

- Belle II's **full coverage + constrained $B\overline{B}$ production** enables **unique kinematic control of semileptonic B-meson decays** despite the neutrino(s)
- The long-standing discrepancy between **exclusive and inclusive** determinations of $|V_{cb}|$ **&** $|V_{ub}|$ limits our understanding of these fundamental parameters
- Belle II is trying to resolve the situation by
  - Probe existing analyses on **independent data sets with improved experimental tools**
  - Addressing potential issues in previous analyses like form factor dependence or slow pion tracking
- **Lepton universality** is challenged by several measurements
  - Already with half its current dataset, Belle II is able to provide **world-leading and unique** measurements to probe LU

BACKUP

FORM FACTORS AND LATTICE CONSTRAINTS

LQCD input only used for normalization at zero recoil ($w = 1$):

FNAL/MILC Phys. Rev. D **89**, 114504

BGL truncation order determined by Nested Hypothesis Test
Phys. Rev. D **100**, 013005

Preliminary	Values	Correlations				χ^2/ndf
$\tilde{a}_0 \times 10^3$	0.89 ± 0.05	1.00	0.26	−0.27	0.07	40/31
$\tilde{b}_0 \times 10^3$	0.54 ± 0.01	0.26	1.00	−0.41	−0.46	
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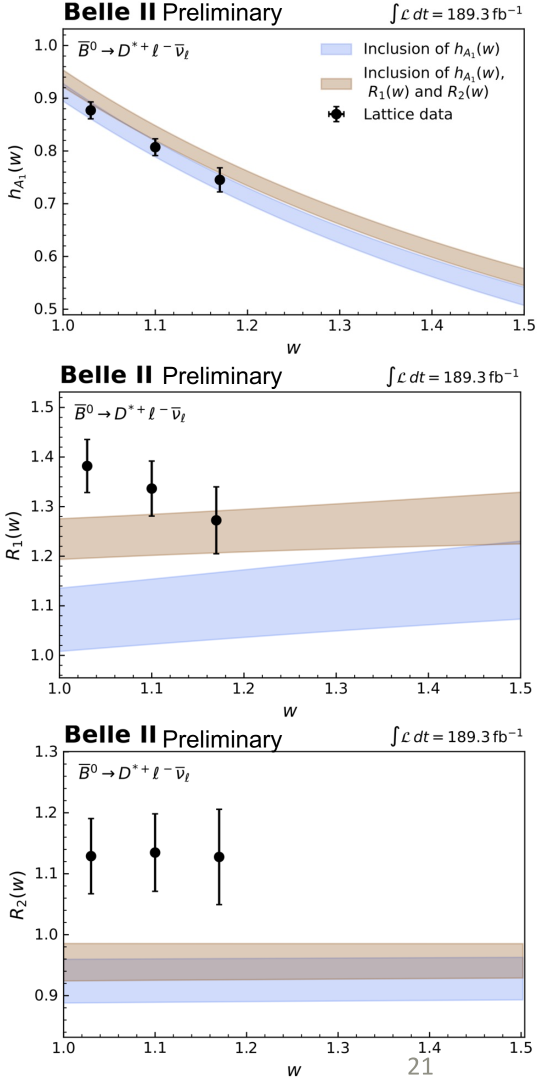
$$\boxed{|V_{cb}| = 40.9 \pm 1.2}$$



FORM FACTORS AND LATTICE CONSTRAINTS

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FNAL/MILC Phys. Rev. D **89**, 114504

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$$\boxed{|V_{cb}| = 40.9 \pm 1.2}$$

FNAL/MILC predictions of h_{A_1} at $w = 1.03, 1.10, 1.17$:

Eur. Phys. J. C **82**, 1141 (2022)

Preliminary

	Values	Correlations					
$\lvert V_{cb}\rvert \times 10^3$	$\boxed{40.4 \pm 1.2}$	1	−0.31	−0.57	−0.1	0.02	−0.26
$a_0 \times 10^3$	22.0 ± 1.4	−0.31	1	0.27	0.1	−0.18	0.31
$b_0 \times 10^3$	13.2 ± 0.2	−0.57	0.27	1	−0.18	0.13	−0.12
$b_1 \times 10^3$	9.0 ± 14.5	−0.1	0.1	−0.18	1	−0.88	0.52
b_2	-0.5 ± 0.4	0.02	−0.18	0.13	−0.88	1	−0.36
$c_1 \times 10^3$	-0.7 ± 0.8	−0.26	0.31	−0.12	0.52	−0.36	1

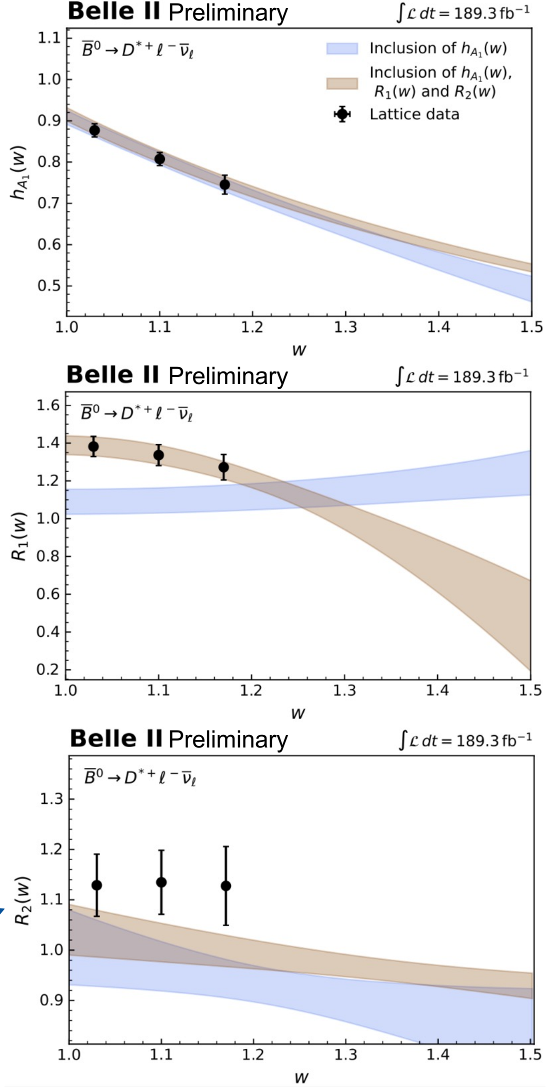
$$\boxed{|V_{cb}| = 40.4 \pm 1.2}$$

FNAL/MILC predictions of h_{A_1}, R_1, and R_2 at $w = 1.03, 1.10, 1.17$:

Preliminary

	Values	Correlations						
$\lvert V_{cb}\rvert \times 10^3$	$\boxed{40.0 \pm 1.2}$	1	−0.16	0.02	−0.09	−0.61	−0.17	0.1
$a_0 \times 10^3$	28.3 ± 1.0	−0.16	1	−0.08	−0.19	0.17	0.12	−0.03
$a_1 \times 10^3$	-31.5 ± 66.6	0.02	−0.08	1	−0.85	−0.04	−0.07	0.11
a_2	-5.8 ± 2.5	−0.09	−0.19	−0.85	1	0.1	0.1	−0.13
$b_0 \times 10^3$	13.3 ± 0.2	−0.61	0.17	−0.04	0.1	1	0.11	−0.13
$c_1 \times 10^3$	-3.2 ± 1.4	−0.17	0.12	−0.07	0.1	0.11	1	−0.9
$c_2 \times 10^3$	59.1 ± 31.1	0.1	−0.03	0.11	−0.13	−0.13	−0.9	1

$$\boxed{|V_{cb}| = 40.0 \pm 1.2}$$



$|V_{xb}|$: UNTAGGED: EXPERIMENTAL UNCERTAINTIES

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

Relative uncertainty (%) Preliminary

	$\tilde{a}_0$	$\tilde{b}_0$	$\tilde{b}_1$	$\tilde{c}_1$
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	$\boxed{1.5}$	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	$\boxed{1.3}$	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

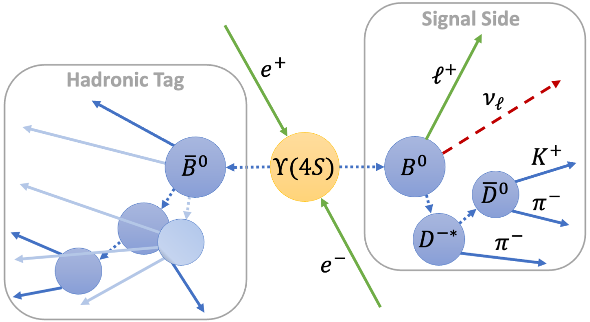
$B^0 \to \pi^-\ell^+\nu$

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

LU: ANGULAR ASYMMETRIES



- Light lepton universality tested by measuring a **complete set** of **five angular asymmetries** of e and μ, $\boldsymbol{\Delta\mathcal{A}_x = \mathcal{A}_x^e - \mathcal{A}_x^\mu}$ using $\boldsymbol{B^0 \to D^{*-}\ell^+\nu}$ decays.

$$\mathcal{A}_x(w) = \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}w}\right)^{-1}\left[\underbrace{\int_0^1}_{+} - \underbrace{\int_{-1}^0}_{-}\right]\mathrm{d}x\,\frac{\mathrm{d}^2\Gamma}{\mathrm{d}w\,\mathrm{d}x}$$

Recoil parameter $w = \dfrac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$

Highly sensitive to lepton universality violation

$A_{\mathrm{FB}}(w)$: $\mathrm{d}x = \mathrm{d}(\cos\theta_\ell)$

$S_3(w)$: $\mathrm{d}x = \mathrm{d}(\cos 2\chi)$

$S_5(w)$: $\mathrm{d}x = \mathrm{d}(\cos\chi\cos\theta_V)$

Less sensitive or insensitive to NP. Control tests of the analysis method

$S_7(w)$: $\mathrm{d}x = \mathrm{d}(\sin\chi\cos\theta_V)$

$S_9(w)$: $\mathrm{d}x = \mathrm{d}(\sin 2\chi)$