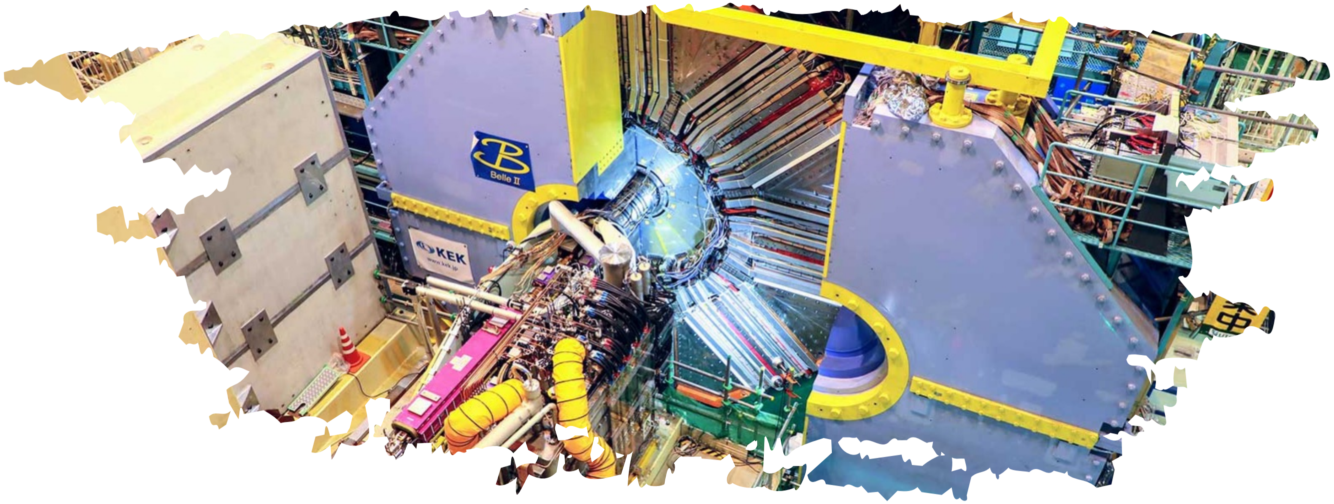

16TH INTERNATIONAL CONFERENCE ON HEAVY QUARKS AND LEPTONS: NOV. 29, 2023

LEPTON UNIVERSALITY TESTS AND SEARCHES FOR NEW PHYSICS IN CHARGED CURRENT DECAYS AT BELLE II

Henrik Junkerkalefeld* on behalf of the collaboration

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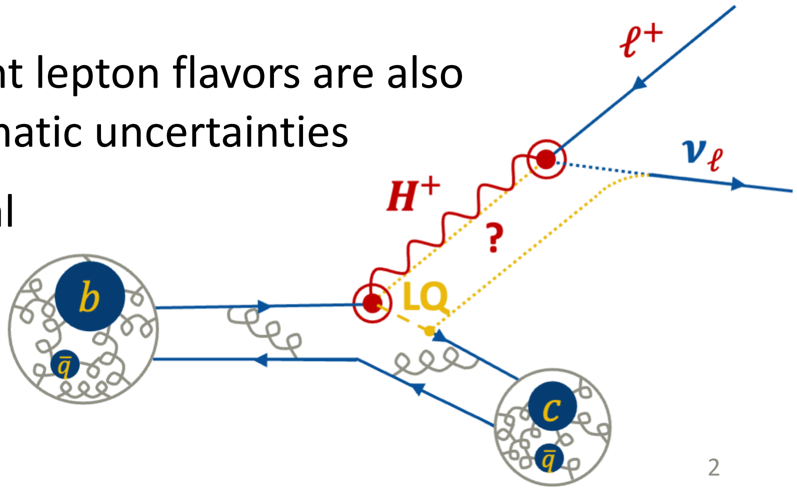
LEPTON UNIVERSALITY
MOTIVATION

- The **universality of the lepton coupling (e, μ, τ)** to the electroweak gauge bosons **can be probed**
  - Semileptonic decays are **clean**; several **uncertainties** partially **cancel** in ratios R of $b \to q\tau\nu / q\mu\nu / qe\nu$ decay rates
  - Differences in **angular asymmetries** for different lepton flavors are also **sensitive to BSM physics** and have small systematic uncertainties
  - Lepton universality (LU) is **challenged** by several current measurements. Deviations would be a **clear sign of BSM** physics.

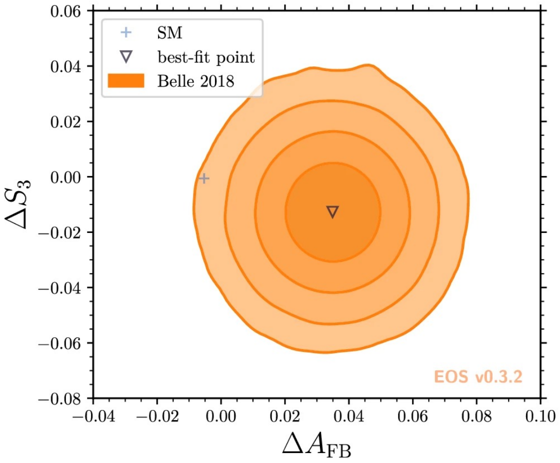


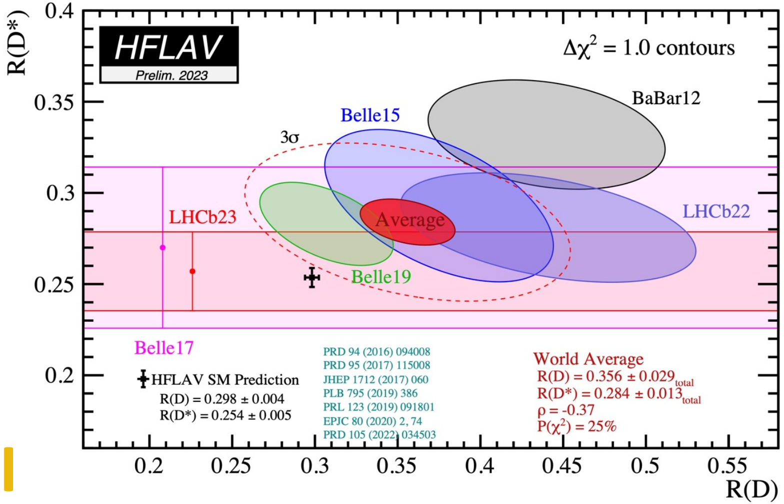
LEPTON UNIVERSALITY

e/μ universality

τ/ℓ universality

Reanalysis of Belle data, Bobeth *et al.*, EPJC 81, 984 (2021):





Belle II

- **Angular asymmetries in $B \to D^* \ell \nu$:** Phys. Rev. Lett. **131**, 181801
- **$R(D^*_{e/\mu})$ & ΔA_{FB} in $B \to D^* \ell \nu$:** arXiv:2310.01170
- **$R(X_{e/\mu})$:** Phys. Rev. Lett. **131**, 051804

- **$R(D^*_{\tau/\ell})$:** preliminary (Lepton-Photon 2023)
- **$R(X_{\tau/\ell})$:** arXiv:2311.07248

LEPTON UNIVERSALITY

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τ/ℓ universality

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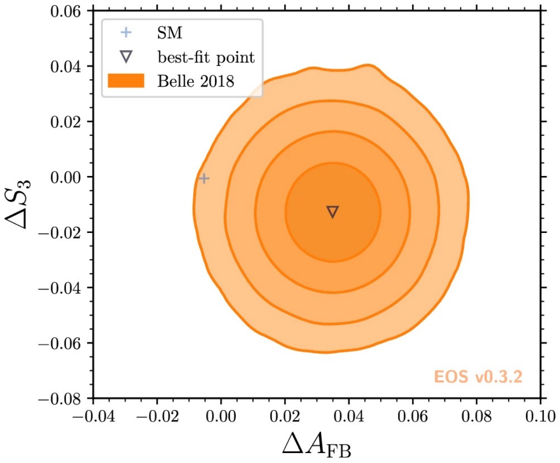
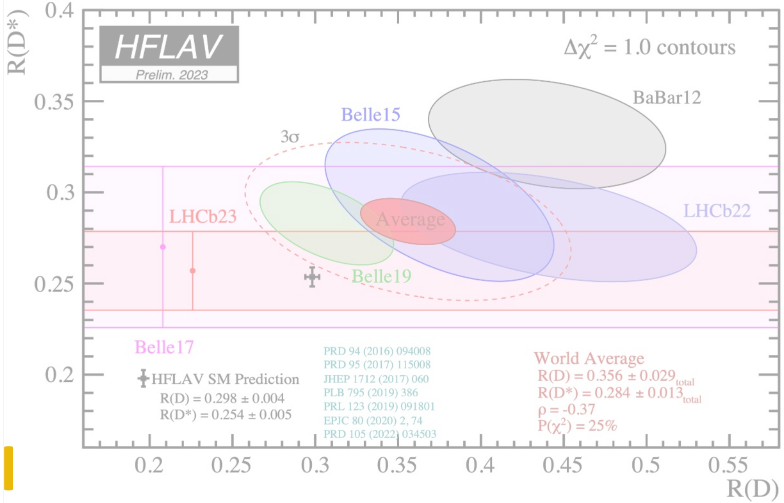


Belle II



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- $R(D^*_{\tau/\ell})$: preliminary (Lepton-Photon 2023)
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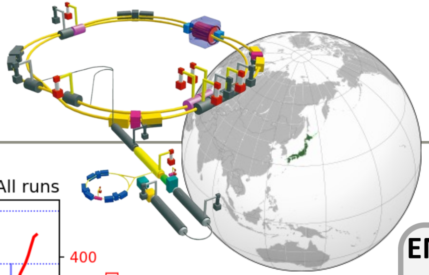
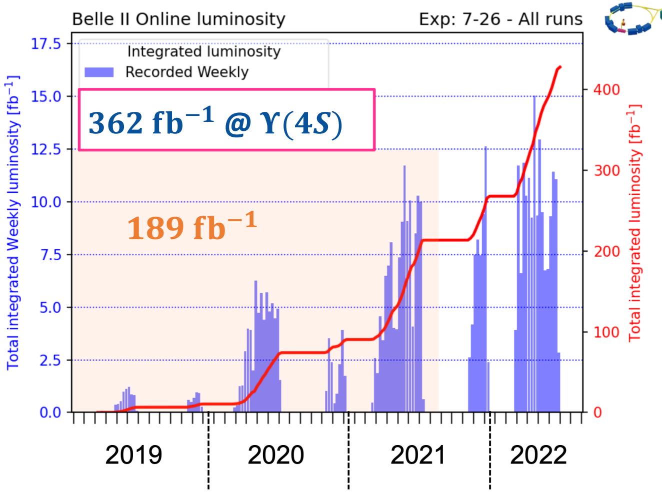
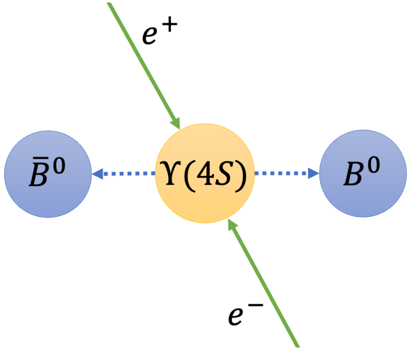
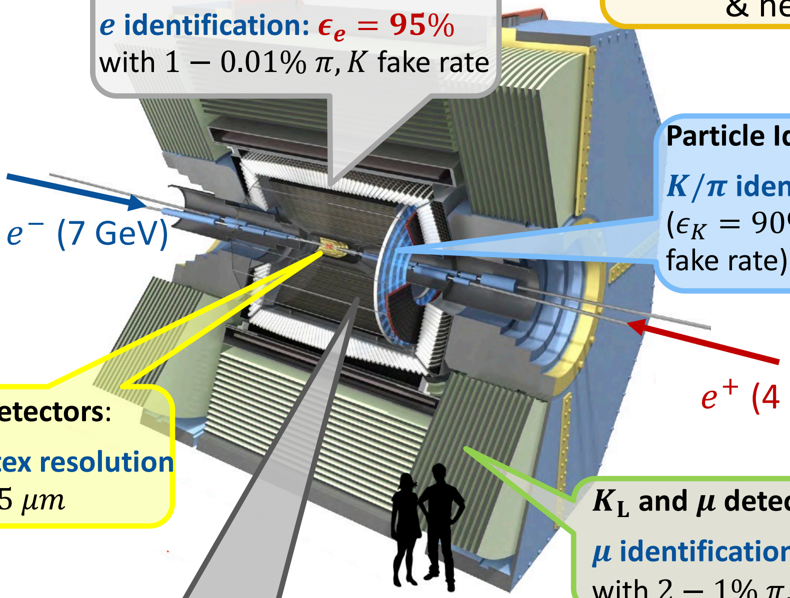
SUPERKEKB & BELLE II DETECTOR







Nearly **4π coverage** to reconstruct inclusive states & neutrinos



EM Calorimeter (ECL):

e identification: $\epsilon_e = 95\%$
with $1 - 0.01\%$ π, K fake rate

Particle Identification:

K/π identification
($\epsilon_K = 90\%$ with 1.8% π fake rate)

Vertex detectors:

- **Vertex resolution** $\approx 15\ \mu m$

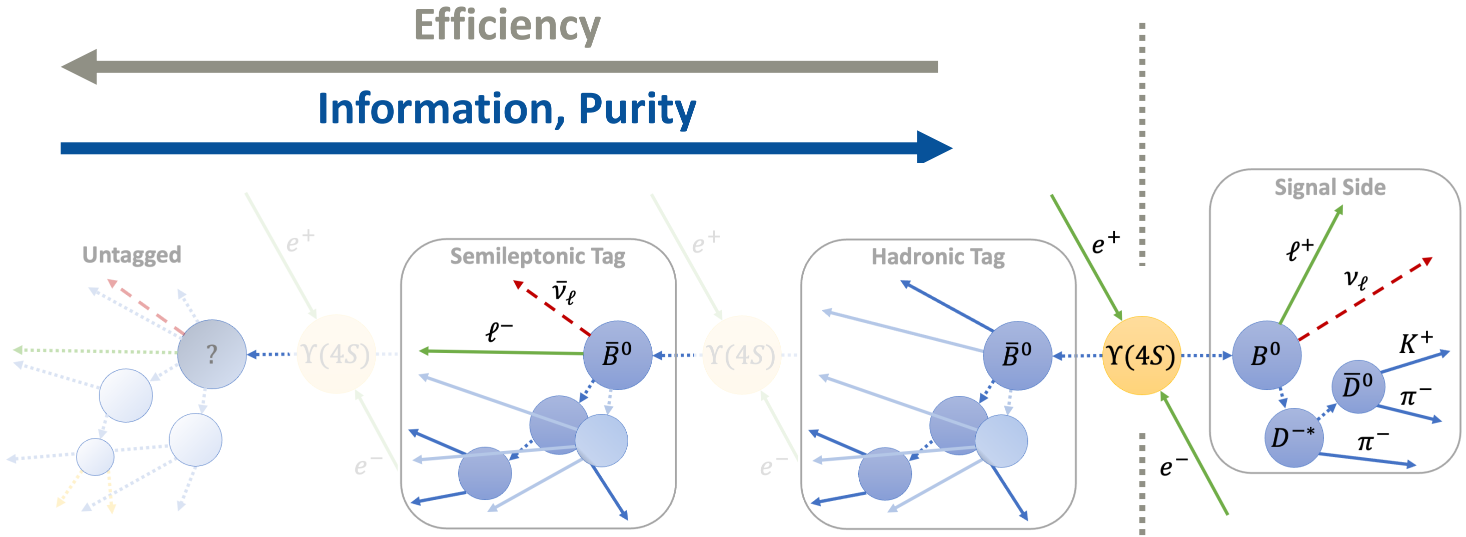
Central Drift Chamber:

- **p_T resolution** $\approx 0.4\%$

K_L and μ detector:

μ identification: $\epsilon_\mu = 90\%$
with $2 - 1\%$ π, K fake rate

B-MESON FLAVOR TAGGING

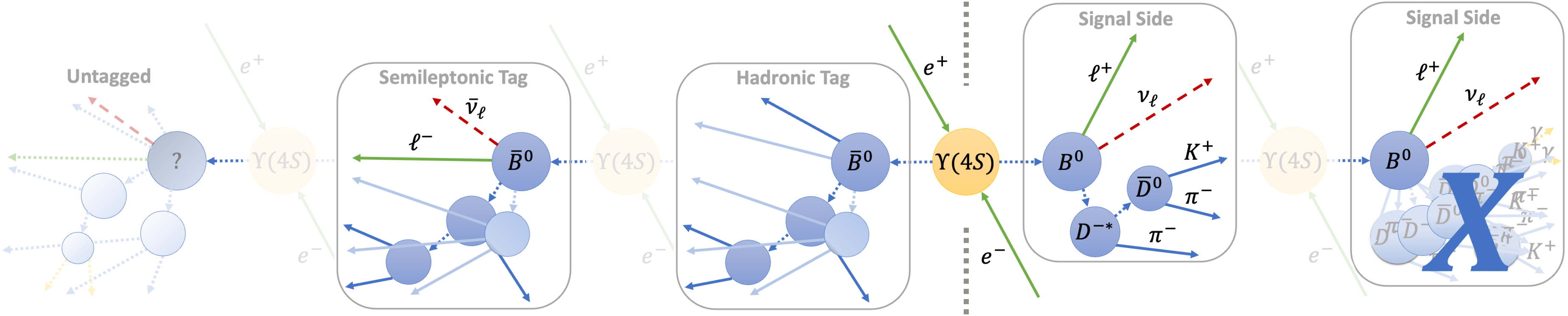


$\epsilon = \mathcal{O}(100\%)$	$\epsilon = \mathcal{O}(1\%)$	$\epsilon = \mathcal{O}(0.1\%)$
Only approximate kinematical information	Rough knowledge of B_{tag} kinematics (missing ν)	**Exact** knowledge of B_{tag} kinematics

B-MESON FLAVOR TAGGING & SIGNAL RECO.

Efficiency

Information, Purity



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

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

Exclusive:

$B \to D/D^*/\pi \ldots \ell\nu$

(a single final state)

Experimentally clean

Low efficiencies

Inclusive:

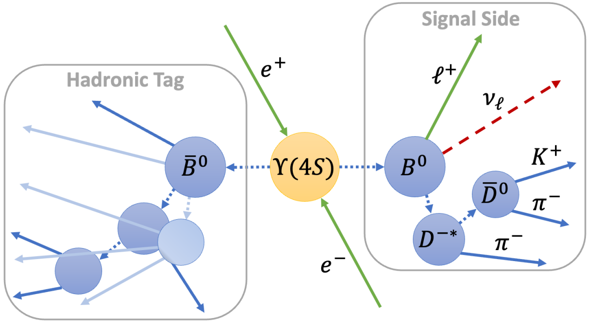
$B \to X\ell\nu$

(sensitive to all final states)

Exp. Challenging

High efficiencies

ANGULAR ASYMMETRIES IN $B \to D^* \ell\nu$



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

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

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

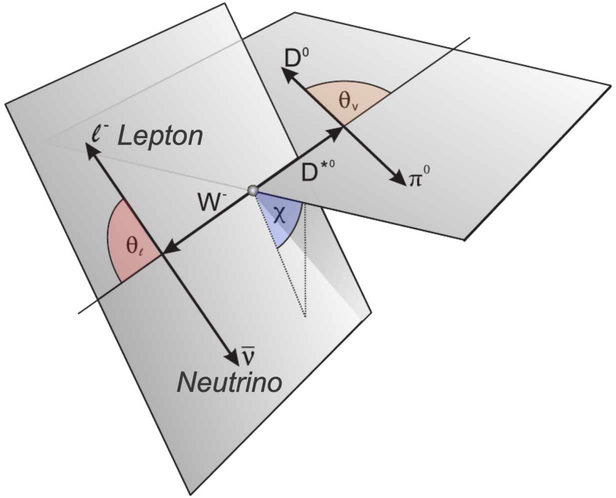
$S_3(w)$: $dx = d(\cos 2\chi)$

$S_5(w)$: ...

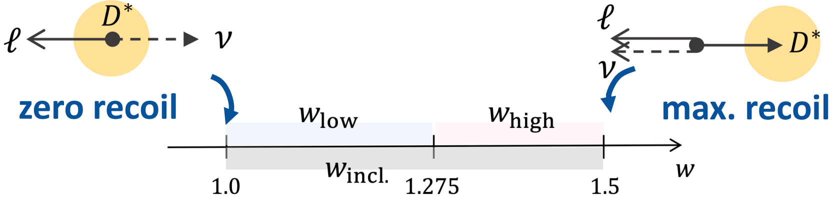
$S_7(w)$

$S_9(w)$

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

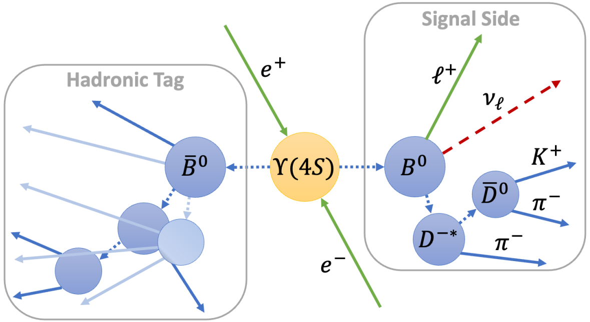


- The simultaneous determination of all asymmetries in **different w ranges** is performed

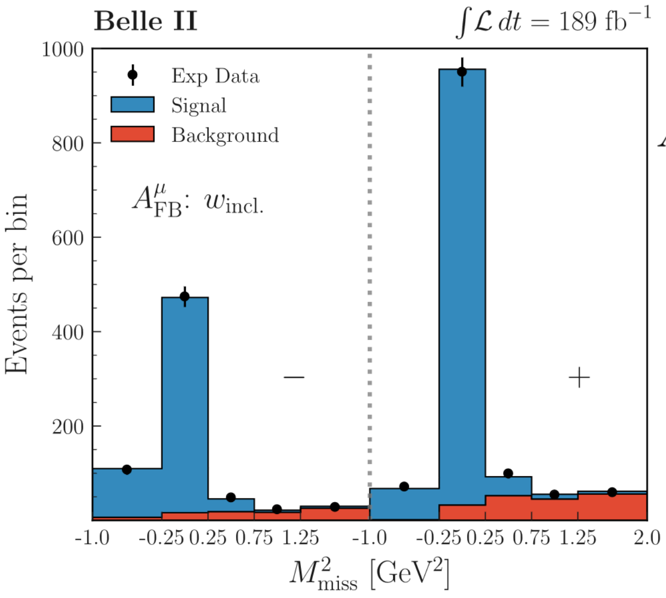


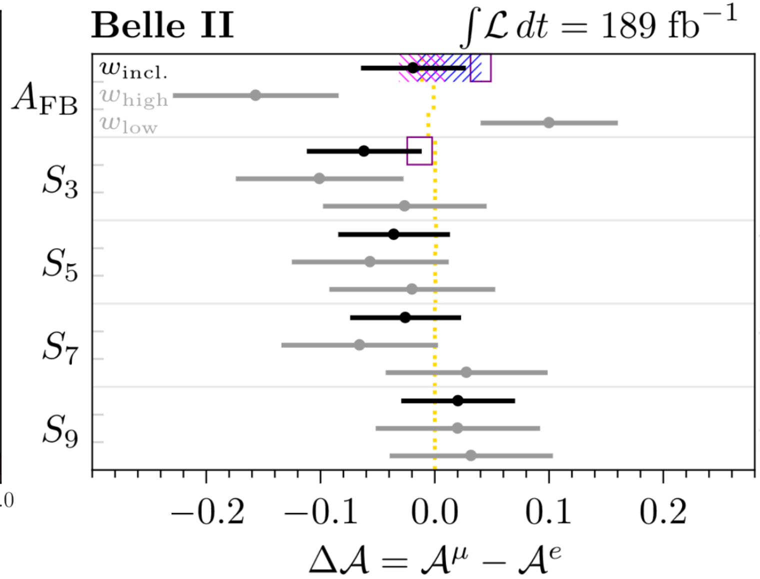
Phys. Rev. Lett. **131**, 181801 (2023)

ANGULAR ASYMMETRIES IN $B \to D^* \ell \nu$

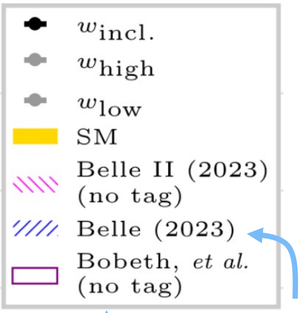


- The signal yields are extracted through a binned maximum-likelihood fit to M^2_{miss} **distributions**





Uncertainties **statistically** dominated



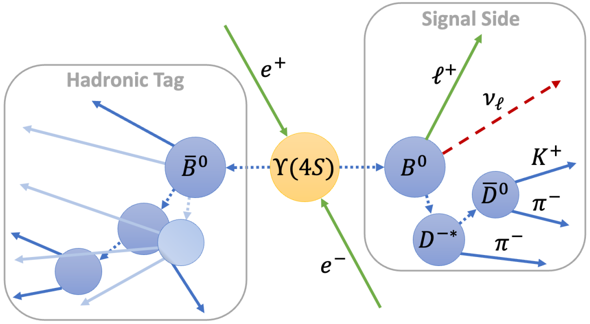
Phys. Rev. D **108**, 012002

EPJC **81**, 984 (2021)

➢ **Results in agreement with SM expectation, providing no evidence for LUV**

Phys. Rev. Lett. **131**, 181801 (2023)

ANGULAR ASYMMETRIES IN $B \to D^* \ell \nu$



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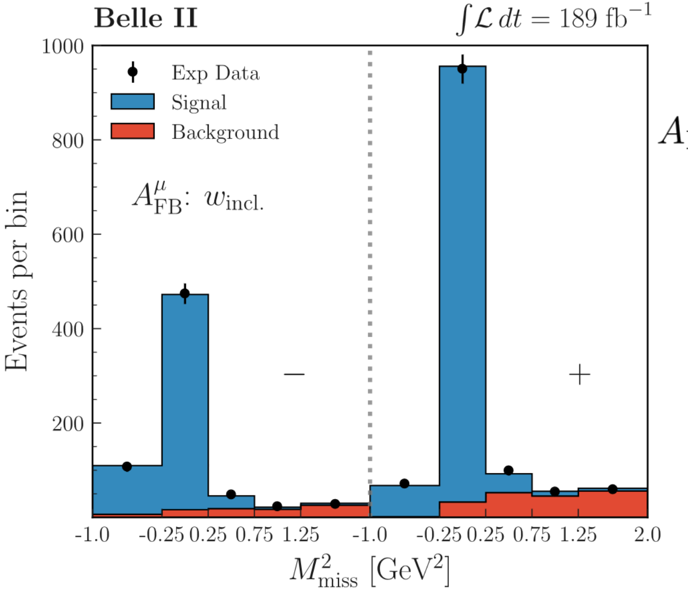

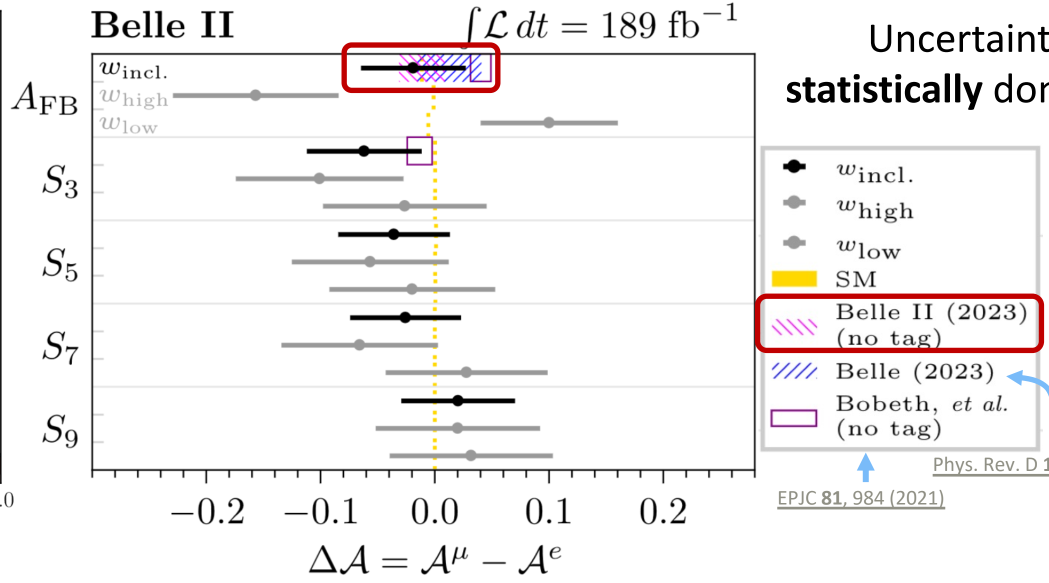

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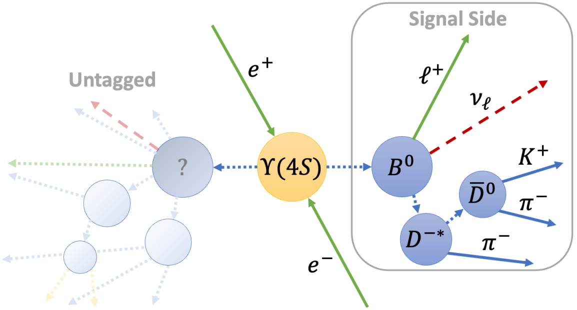
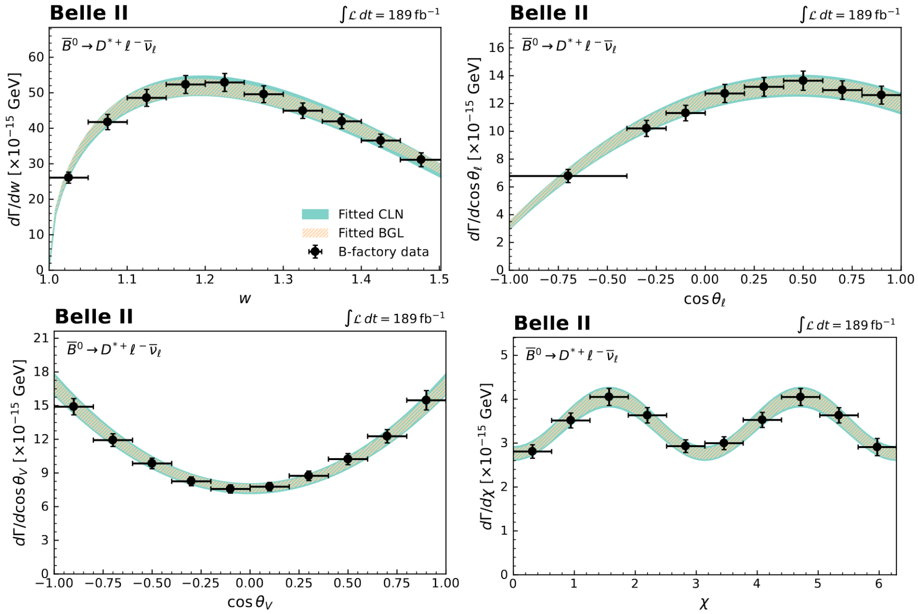
arXiv: 2310.01170 (accepted by PRD)

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



- Primary goal is the **extraction of $|V_{cb}|$ and $\mathscr{B}(B \to D^*\ell\nu)$**
- Challenging due to **lack of clean kinematic signatures** and missing knowledge of the B_{sig} direction
- The yield is extracted in 10 (8) bins of w, $\cos\theta_\ell$, $\cos\theta_V$ and χ



[arXiv: 2310.01170 (accepted by PRD)](https://arxiv.org/abs/2310.01170)

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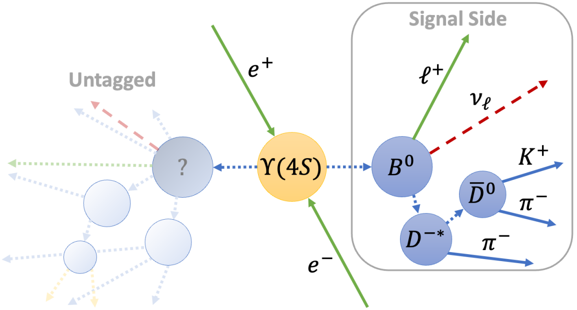

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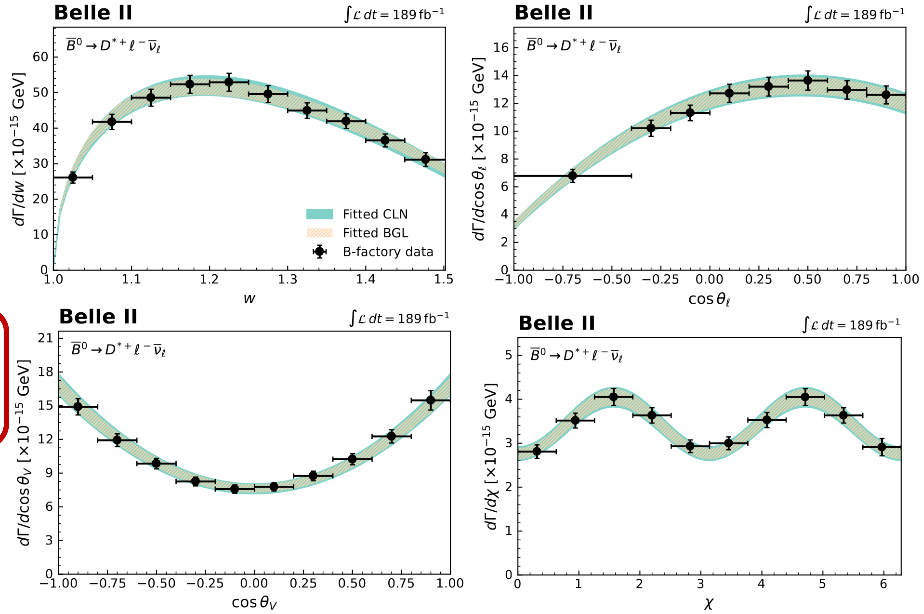
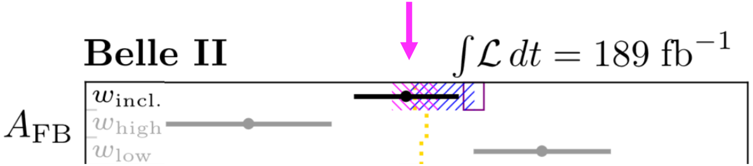


Light-lepton universality results:

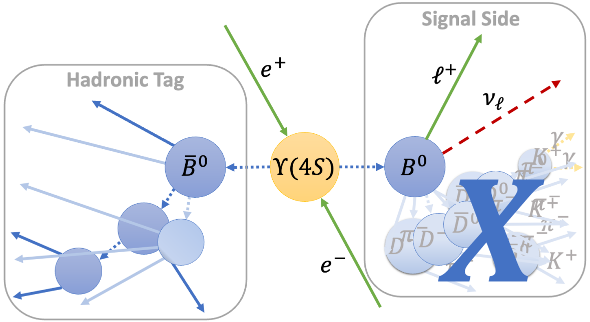
$R(D^*_{e/\mu}) = \rightarrow$ **next slide**

$\Delta A_{\rm FB} = (-17 \pm 16\,(\mathrm{stat.}) \pm 16\,(\mathrm{syst.}))\times 10^{-3}$



Phys. Rev. Lett. **131**, 051804 (2023)

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



- Directly compare semileptonic B decays to e/μ, where the large majority of uncertainties cancel

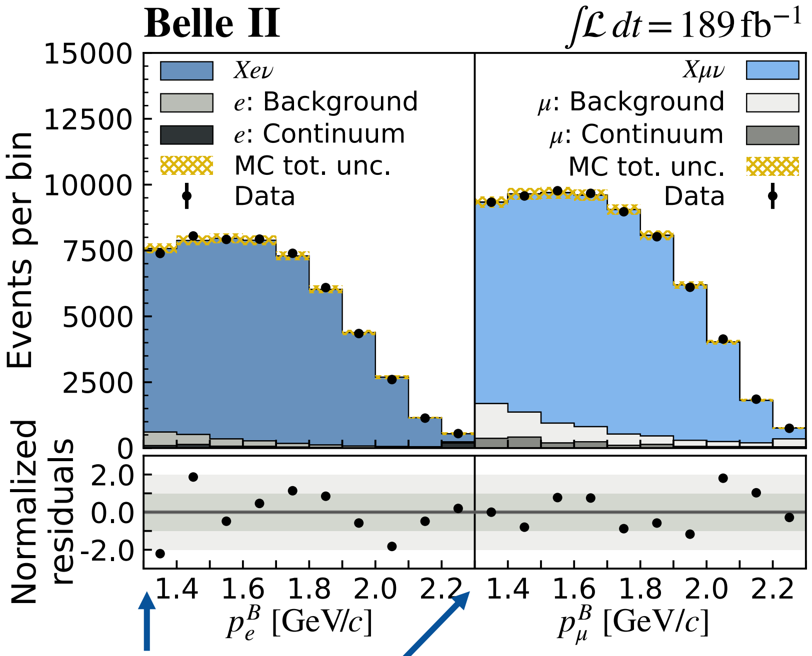
$$R(X_{e/\mu}) = 1.007 \pm 0.009^{\text{stat}} \pm 0.019^{\text{syst}}$$

- **Most precise** BF based lepton universality tests in semileptonic B-meson decays to date

$B^0 \to D^{*-}\ell^+\nu$ untagged: arXiv: 2310.01170 (accepted by PRD)

$$R(D^*_{e/\mu}) = \mathcal{B}(B\to D^*e\nu)/\mathcal{B}(B\to D^*\mu\nu)$$
$$= 0.998 \pm 0.009\,(\text{stat.}) \pm 0.020\,(\text{syst.})$$

- Syst. unc. dominated by **lepton ID**



$p_\ell^B > 1.3$ GeV!

In agreement with SM values

$R(X_{e/\mu}) = 1.006 \pm 0.001$ & $R(D^*_{e/\mu}) = 1.0026 - 1.0041$

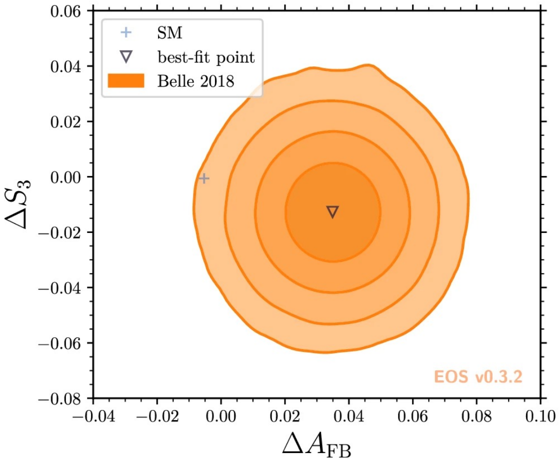
JHEP **11**, 007 (2022) EPJC **81**, 984 (2021) PRD **106**, 096015 (2022)

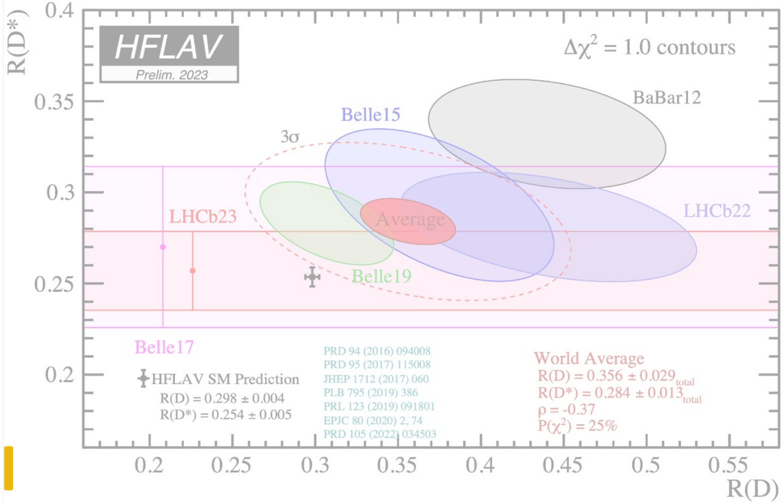
LEPTON UNIVERSALITY

e/μ universality

τ/ℓ universality

Reanalysis of Belle data, Bobeth *et al.*, EPJC 81, 984 (2021):





Belle II

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LEPTON UNIVERSALITY

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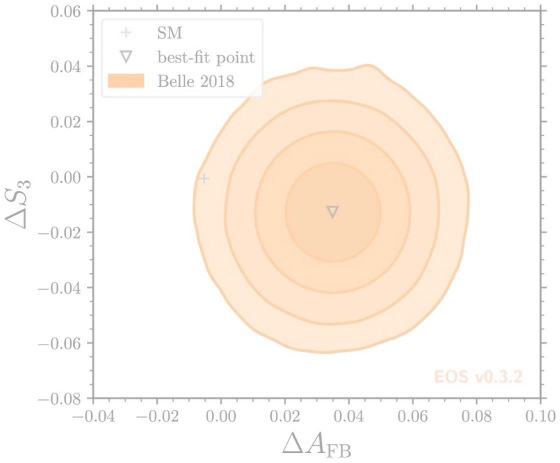

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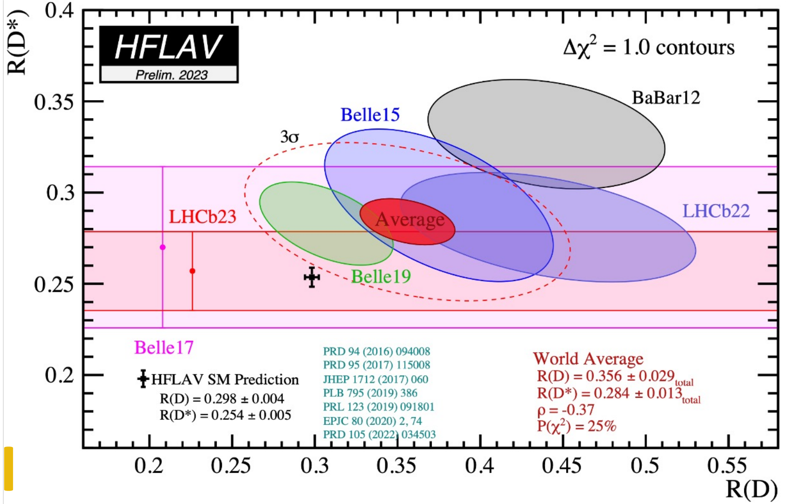
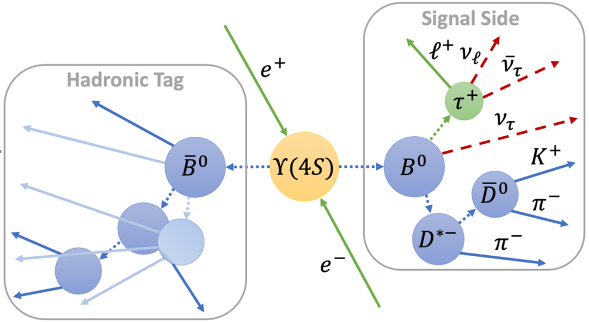
τ/ℓ universality



- $R(D^*_{\tau/\ell})$: preliminary (Lepton-Photon 2023)
- $R(X_{\tau/\ell})$: arXiv:2311.07248

HADRONICALLY TAGGED $R(D^*_{\tau/\ell})$



- Reconstruct signal $B \to D^*[\tau \to \ell\nu\nu]\nu$ and normalization $B \to D^*\ell\nu$ in the same final state particle to cancel many systematic uncertainties
- Require **no extra tracks (completeness constraint)** and **small additional EM-calorimeter energy (E_{ECL})**
- Yields determined in 2D binned likelihood fit (M^2_{miss}, E_{ECL})

D^* reconstruction:

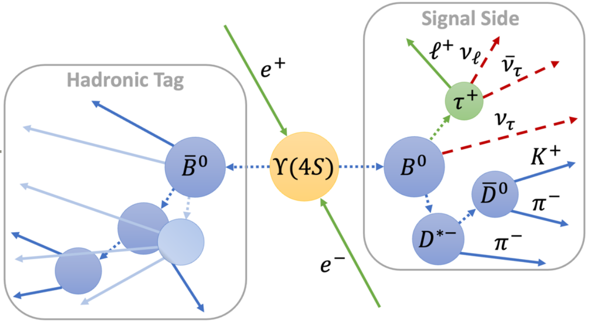
$D^{*+} \to D^0\pi^+$, $D^+\pi^0$, or $D^{*0} \to D^0\pi^0$

$D^0 \to K^-\pi^+(\pi^0), K^-\pi^+\pi^-\pi^+,$

$\mathrm{K_S^0}\pi^+\pi^-(\pi^0),\ K_S^0\pi^0, h^+h^-$

$D^+ \to K_S^0\pi^+, K^-h^+\pi^+$ where $h^+ = K^+, \pi^+$

HAD. TAGGED $R(D^*_{\tau/\ell})$: RESULT



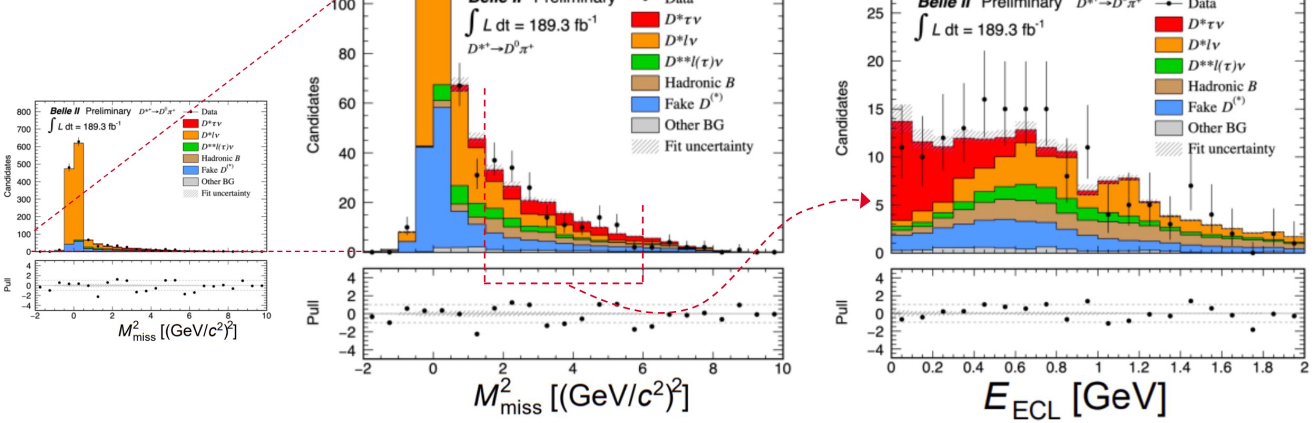
Preliminary

$$R(D^*_{\tau/\ell}) = 0.267\ ^{+0.041}_{-0.039}\ (\text{stat.})\ ^{+0.028}_{-0.033}\ (\text{syst.})$$

- Consistent with **SM $R(D^*) = 0.254 \pm 0.005$** and with **HFLAV 23, $R(D^*) = 0.284 \pm 0.013$**
- Leading syst. uncertainties are **MC statistics**, **E_{ECL} PDF shapes** and **D^{**} modeling**

- **$D^{**}\ell\nu$ modes** validated in $B \to D^*\pi^0\ell\nu$ control sample
- **Fake D^*** calibrated in $m_{D\pi} > m_{D^*}$ sideband
- **Other backgrounds** with true D^* fixed from MC

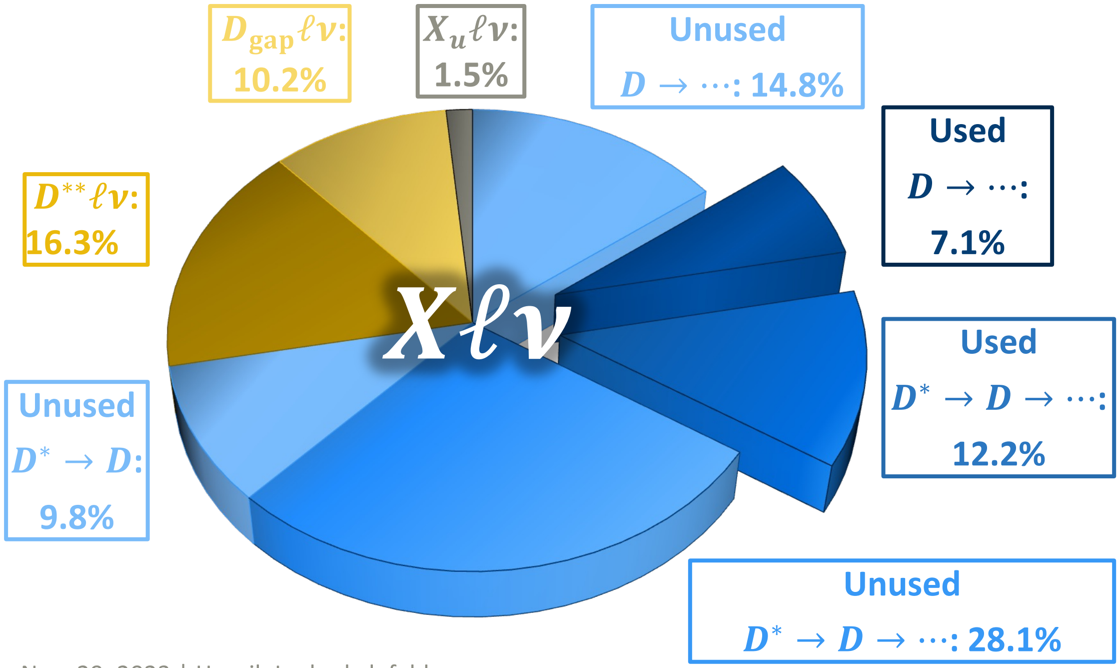
$D^{*+} \to D^0\pi^+$ mode:



arXiv:2311.07248

INCLUSIVE $R\left(X_{\tau/\ell}\right) = \dfrac{\mathcal{B}\,(B \to X\tau\nu)}{\mathcal{B}\,(B \to X\ell\nu)}$

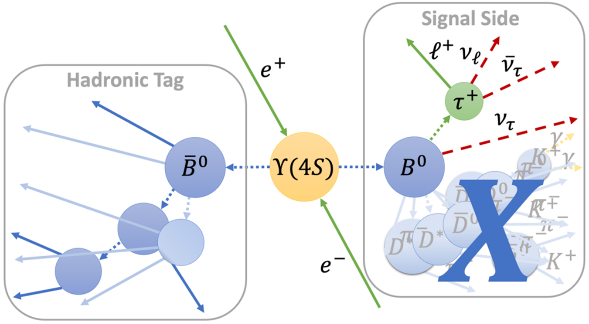
Fraction of $B \to X\ell\nu$ usually targeted in $R(D^{(*)})$ analyses:



- Due to reco. efficiencies, only $\mathcal{O}(1\%)$ **stat. overlap**
- Inclusive $\mathbf{R}\left(\mathbf{X}_{\tau/\ell}\right)$ **distinct** in its sensitivity to **statistical** and **systematic uncertainties**
- largest contribution from $B \to D^{(*)}\tau\nu$, but ≈ 17% unexplored $D^{**}_{gap}, X_u\tau\nu$
- In 1990s LEP experiments measured. $\mathcal{B}\,(b_{admix} \to X\tau\nu)$ at $Z \to b\bar{b}$, **not previously measured at $\Upsilon(4S)$**

arXiv:2311.07248

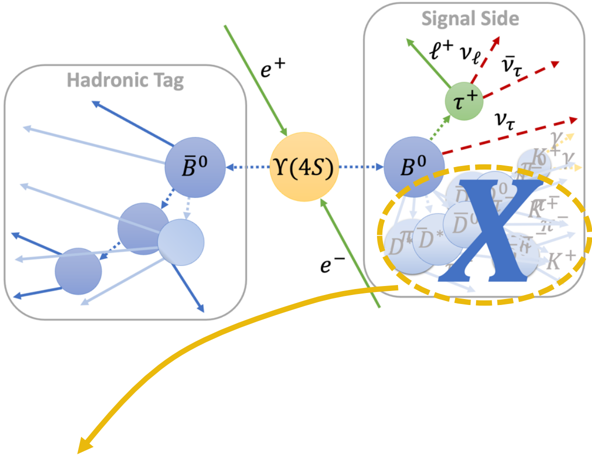
INCLUSIVE $R(X_{\tau/\ell}) = \frac{\mathcal{B}(B\to X\tau\nu)}{\mathcal{B}(B\to X\ell\nu)}$



- Select events with B_{tag} + ℓ, remaining particles attributed to hadronic system X

arXiv:2311.07248

INCLUSIVE $R(X_{\tau/\ell}) = \frac{\mathcal{B}(B\to X\tau\nu)}{\mathcal{B}(B\to X\ell\nu)}$



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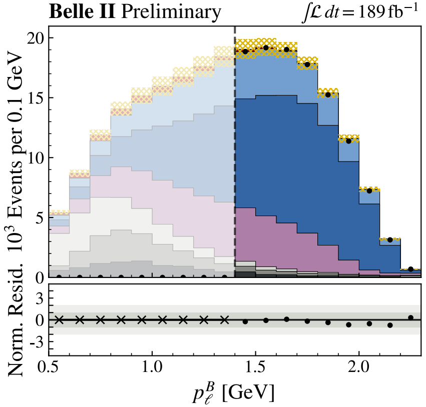
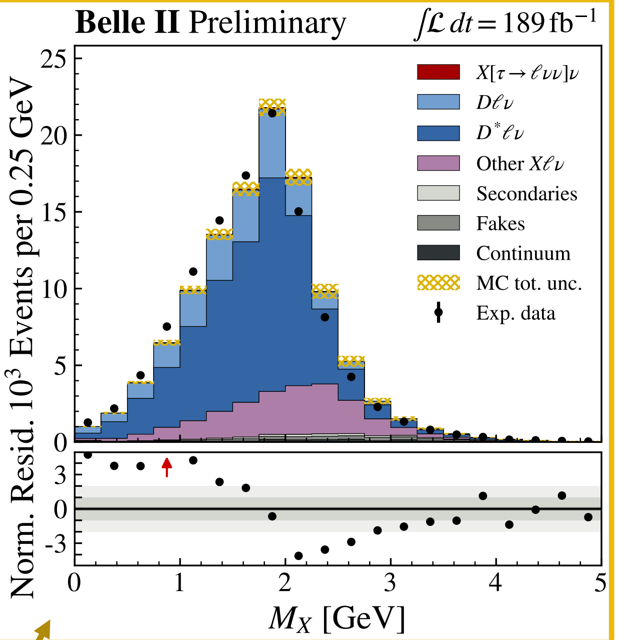
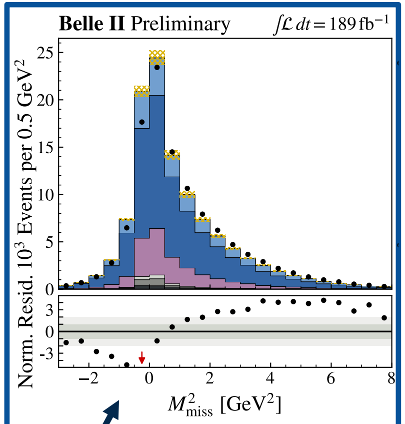
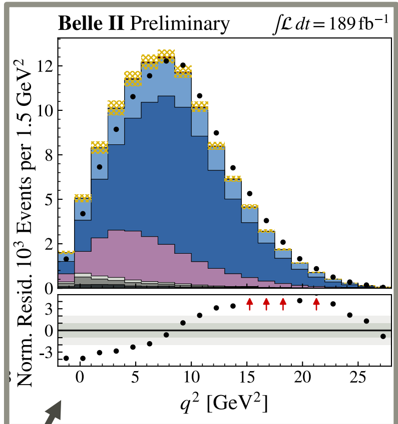








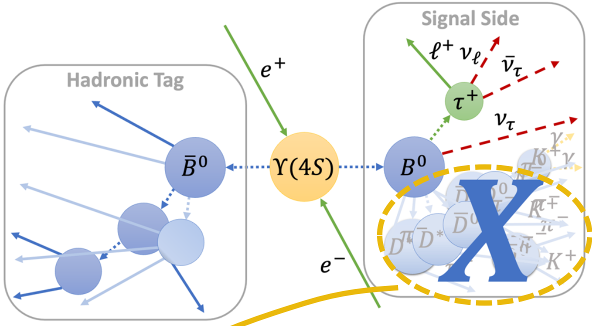
$$M_X^2 = \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}^2$$

$$M_{\text{miss}}^2 = \left[\begin{pmatrix} E_{\text{CMS}} \\ \vec{p}_{\text{CMS}} \end{pmatrix} - \begin{pmatrix} E_{\text{CMS}}/2 \\ -\vec{p}_{B_{\text{tag}}} \end{pmatrix} - \begin{pmatrix} E_\ell \\ \vec{p}_\ell \end{pmatrix} - \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}\right]^2$$

$$q^2 = \left[\begin{pmatrix} E_{\text{CMS}}/2 \\ -\vec{p}_{B_{\text{tag}}} \end{pmatrix} - \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}\right]^2$$

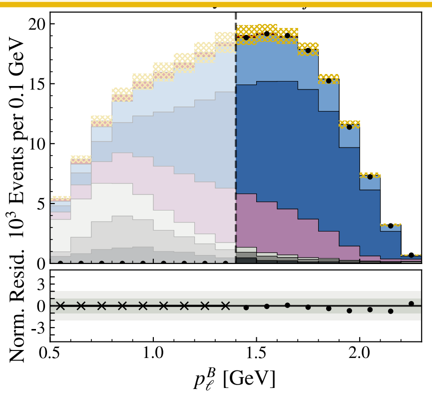
arXiv:2311.07248

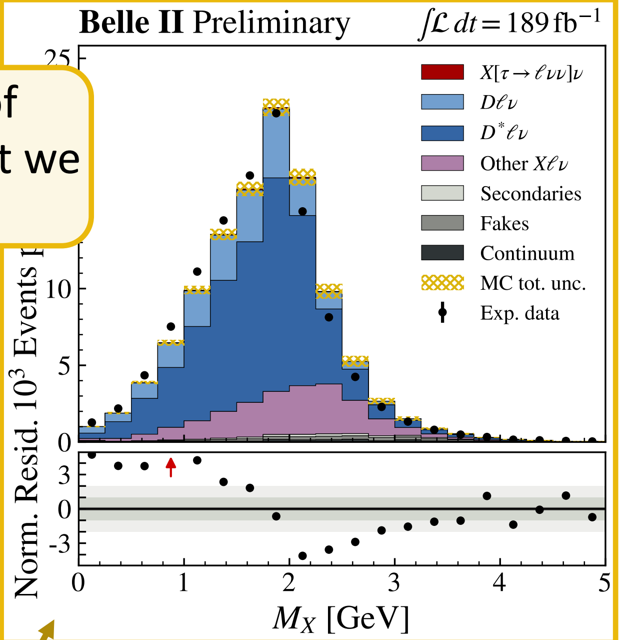
INCLUSIVE $R(X_{\tau/\ell}) = \frac{\mathcal{B}(B\to X\tau\nu)}{\mathcal{B}(B\to X\ell\nu)}$

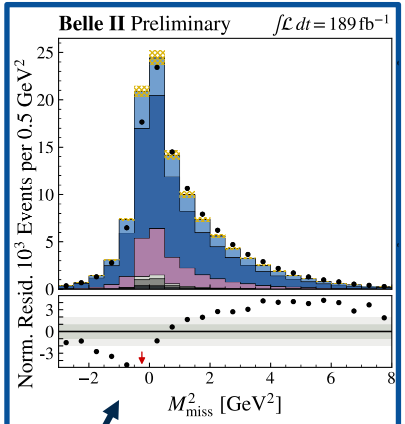


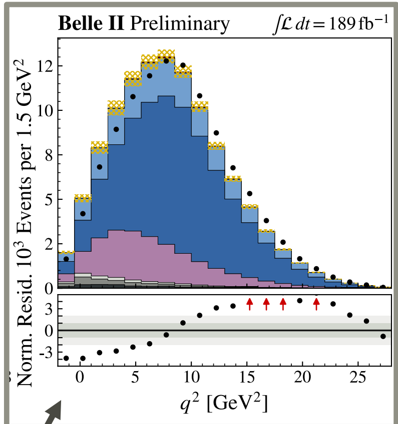
- Select events with B_{tag} + ℓ, remaining particles attributed to hadronic system X

> ➢ M_X controls the part of the reconstruction that we know the least about!









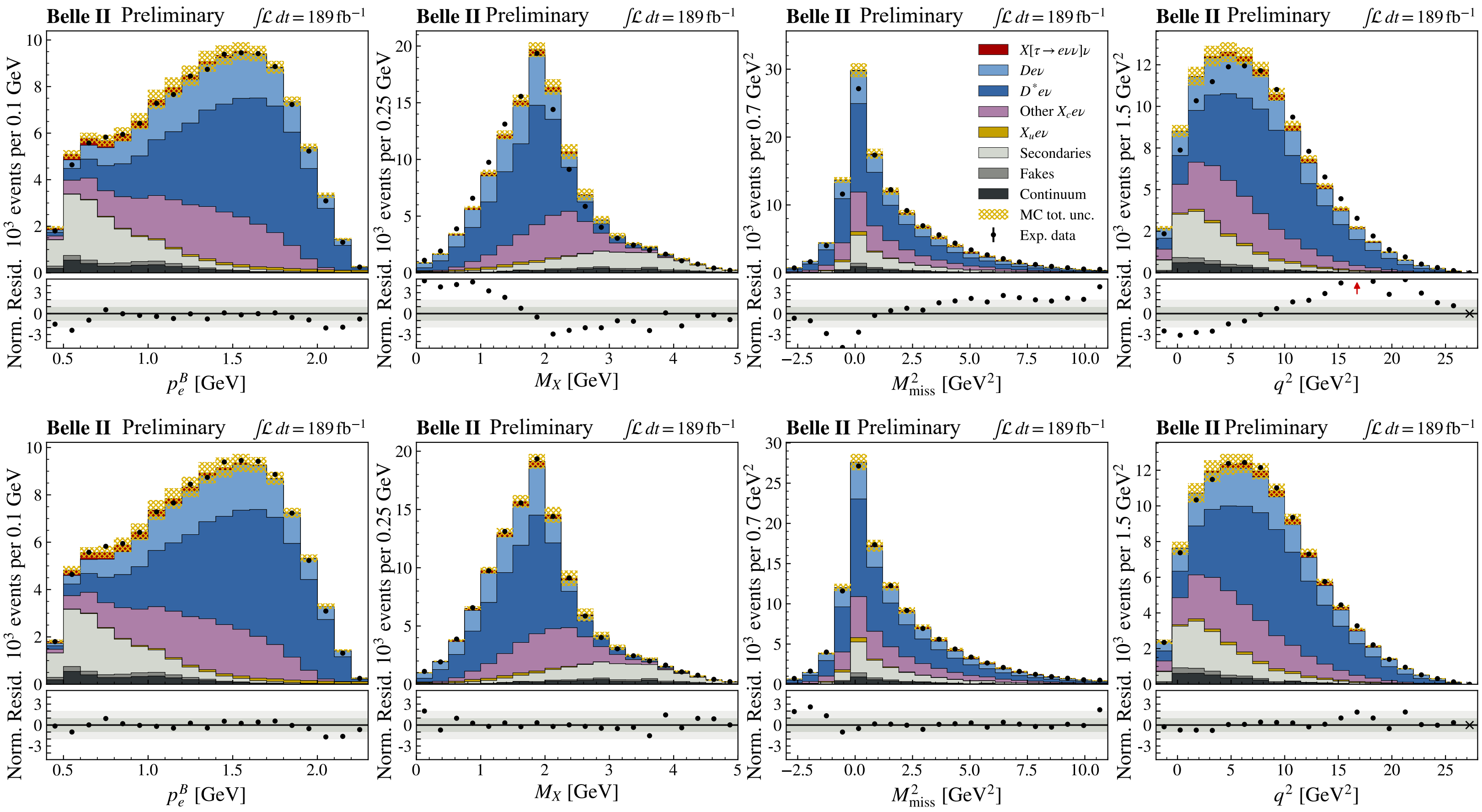
$$M_X^2 = \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}^2$$

$$M^2_{\text{miss}} = \left[\begin{pmatrix} E_{\text{CMS}} \\ \vec{p}_{\text{CMS}} \end{pmatrix} - \begin{pmatrix} E_{\text{CMS}}/2 \\ -\vec{p}_{B_{\text{tag}}} \end{pmatrix} - \begin{pmatrix} E_\ell \\ \vec{p}_\ell \end{pmatrix} - \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}\right]^2$$

$$q^2 = \left[\begin{pmatrix} E_{\text{CMS}}/2 \\ -\vec{p}_{B_{\text{tag}}} \end{pmatrix} - \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}\right]^2$$

SIMULATION REWEIGHTING: FULL PHASE SPACE (e)

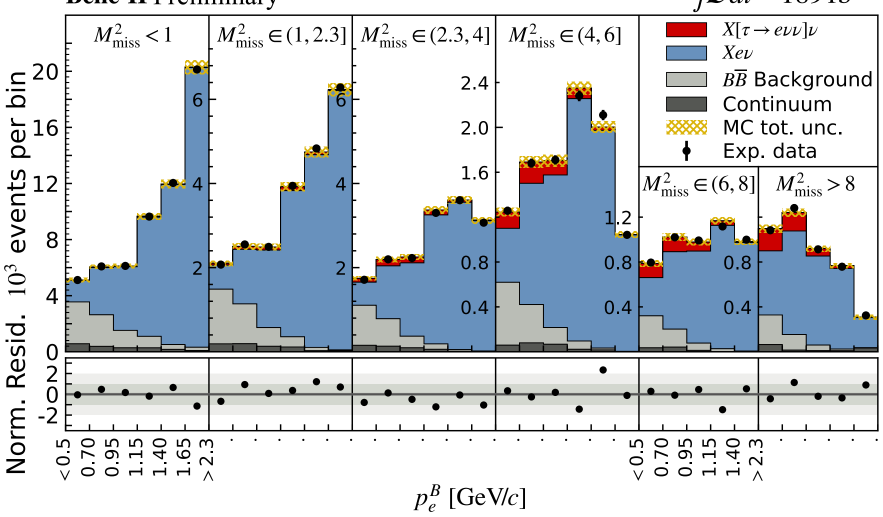
Reweight $X\ell\nu$ based on M_X, backgrounds based on (p_ℓ, M_X)



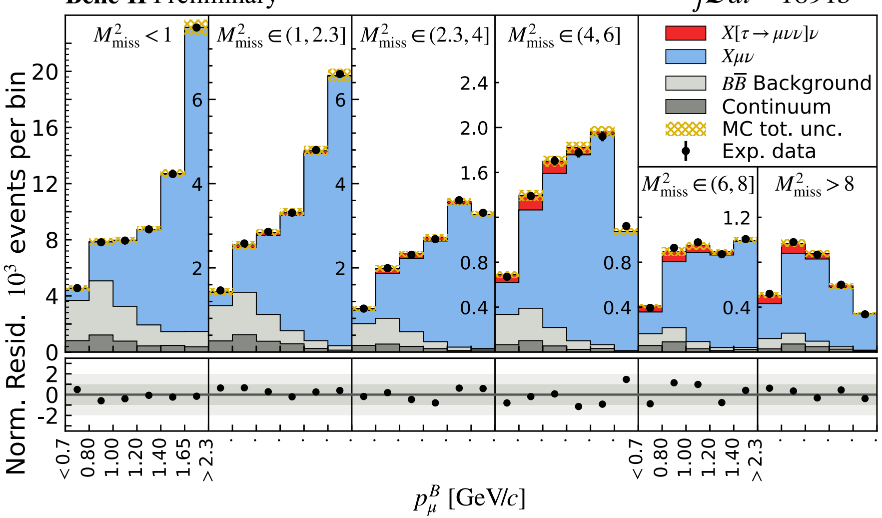
Mismodeling is fixed in **all other variables!**

$R(X_{\tau/\ell})$ SIGNAL EXTRACTION

Electron channel



Muon channel



- e and μ templates are fitted simultaneously in $p_\ell^B \times M^2_{\mathrm{miss}}$ in a binned **likelihood fit**
- $2 \cdot 4$ templates: **"Continuum" (off-resonance data, yields constrained), "$B\bar{B}$ background", $X\ell\nu$, $X\tau\nu$**

$R(X_{\tau/\ell})$ RESULTS

Preliminary

$$R(X_{\tau/e}) = 0.232 \pm 0.020\,(\text{stat.}) \pm 0.037\,(\text{syst.})$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.027\,(\text{stat.}) \pm 0.050\,(\text{syst.})$$
$$R(X_{\tau/\ell}) = 0.228 \pm 0.016\,(\text{stat.}) \pm 0.036\,(\text{syst.})$$

➢ First measurement of its kind

- In agreement with SM prediction[1−4] of 0.223 ± 0.005 and $R(D^{(*)})$ measurements
- Main systematic uncertainties from $\mathscr{B}(B \to D_{\text{gap}}\ell\nu)$, $(B \to D^*\ell\nu)$ form factors, and M_X shape corrections
- Several major systematics are statistical in nature and will decrease with more data

Preliminary

Source	Uncertainty [%] e	μ	ℓ
Experimental sample size	8.8	12.0	7.1
Simulation sample size	6.7	10.6	5.7
Tracking efficiency	2.9	3.3	3.0
Lepton identification	2.8	5.2	2.4
$X_c\ell\nu$ M_X shape	7.3	6.8	7.1
Background (p_ℓ, M_X) shape	5.8	11.5	5.7
$X\ell\nu$ branching fractions	7.0	10.0	7.7
$X\tau\nu$ branching fractions	1.0	1.0	1.0
$X_c\tau(\ell)\nu$ form factors	7.4	8.9	7.8
Total	18.1	25.6	17.3

[1]: Rahimi, Vos (2022) [2]: Freytsis, Ligeti, Ruderman (2015) [3]: Ligeti, Luke, Tackmann (2022) [4]: HFLAV, Eur. Phys. J. C **81**, (2021)

$R(X_{\tau/\ell})$ RESULTS

Preliminary

$$R(X_{\tau/e}) = 0.232 \pm 0.020\,(\text{stat.}) \pm 0.037\,(\text{syst.})$$
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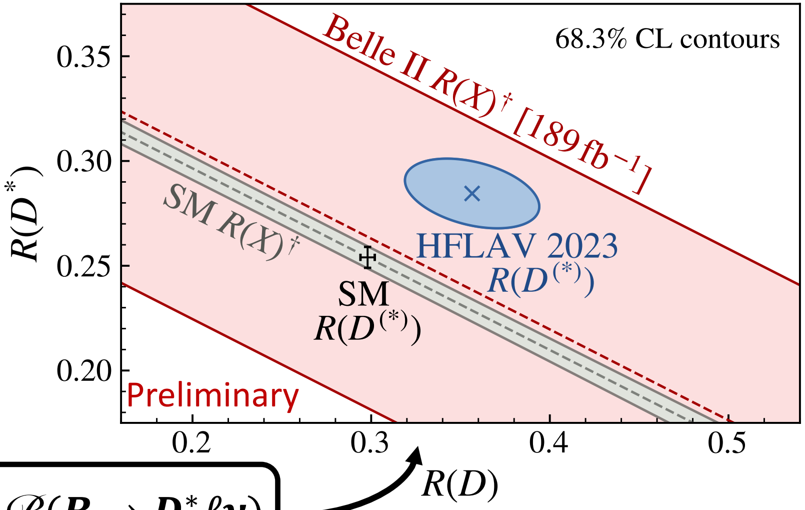
$$\mathcal{B}(B \to X\tau\nu) \cdot R(X)_{\text{SM}} - \mathcal{B}(B \to D\tau\nu) \cdot R(D)_{\text{SM}} - \mathcal{B}(B \to D^*\tau\nu) \cdot R(D^*)_{\text{SM}}$$

$$R(X)^\dagger := R(X)_{\text{exp}} - \frac{\mathcal{B}(B \to D^{**}_{(gap)}, X_u\tau\nu)_{\text{SM}}}{\mathcal{B}(B \to X\ell\nu)}$$

† = with expected SM contributions of $D^{**}_{(\text{gap})}, X_u$ removed



$$R(X)^\dagger \cdot \mathcal{B}(B \to X\ell\nu) = [x\text{ axis}] \cdot \mathcal{B}(B \to D\ell\nu) + [y\text{ axis}] \cdot \mathcal{B}(B \to D^*\ell\nu)$$

SUMMARY AND CONCLUSION

- Belle II's **exclusive $B\overline{B}$ production** enables **unique kinematic control of semileptonic B-meson decays** despite the neutrino(s)
- Already with half its current dataset, Belle II is able to provide **world-leading and unique** measurements to probe (light-)lepton universality

Summary of recent LU tests (all consistent with SM):

Preliminary

τ/ℓ:

$$R(D^*_{\tau/\ell}) = 0.267\ ^{+\ 0.041}_{-\ 0.039}\ ^{+\ 0.028}_{-\ 0.033}$$

$$R(X_{\tau/\ell}) = 0.228 \pm 0.016 \pm 0.036$$

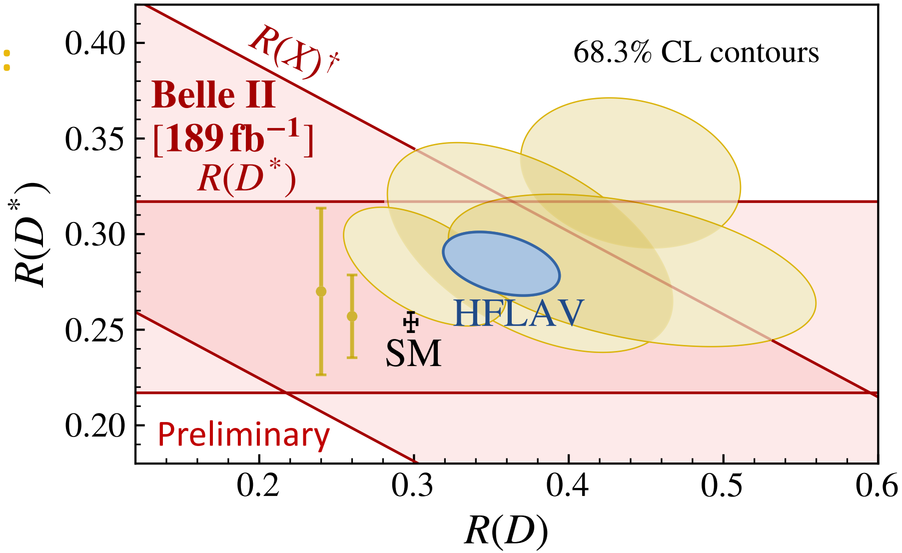
e/μ:

$$R(X_{e/\mu}) = 1.007 \pm 0.009 \pm 0.019$$

$$R(D^*_{e/\mu}) = 0.998 \pm 0.009 \pm 0.020$$

Angular asymmetries $\Delta A_x \equiv A_x^{\mu} - A_x^{e}$ measured

† = with expected SM contributions of $D^{**}_{(\text{gap})}, X_u$ removed

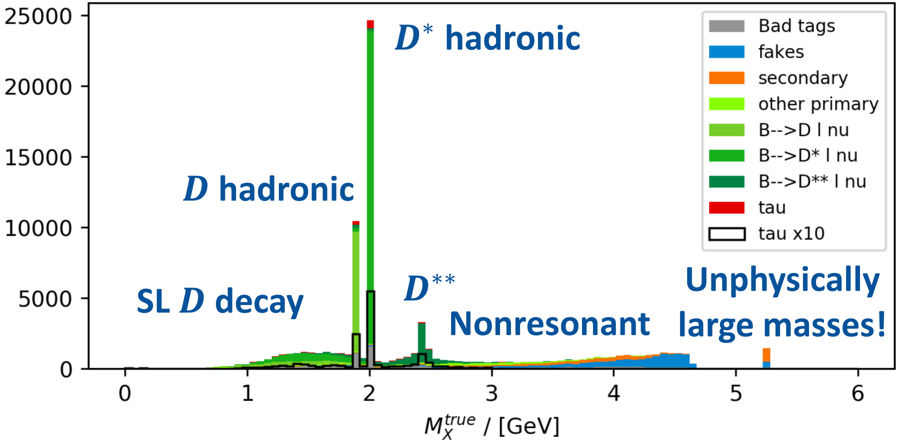


BACKUP

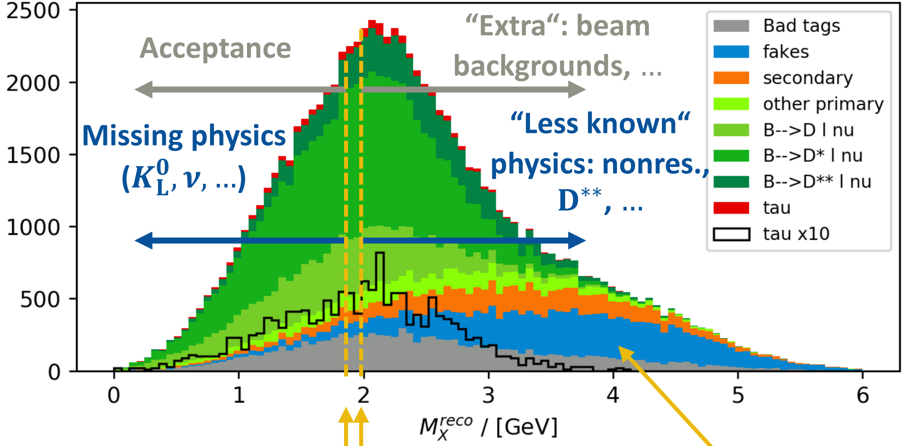
M_X RECONSTRUCTION

Ideally reconstructed M_X, if we made **no reconstruction errors in the X system** except missing neutrinos.

Dennis Benterbusch, Masterthesis, Uni Bonn (2020)



Real M_X distribution (in MC)



Minimum X_c mass (M_D, M_{D^*}); $\approx {}^2/_3$ of events

Not-$X\ell\nu$ is separable

		D^0	$D^{+/-}$
Neutrinos	e^+ anything [4]	$(6.49 \pm 0.11)\%$	$(16.07 \pm 0.30)\%$
	μ^+ anything	$(6.8 \pm 0.6)\%$	$(17.6 \pm 3.2)\%$
	K^- anything	$(54.7 \pm 2.8)\%$	$(25.7 \pm 1.4)\%$
1/2 K_L^0	$\overline{K}^0$ anything + K^0 anything	$(47 \pm 4)\%$	$(61 \pm 5)\%$
	K^+ anything	$(3.4 \pm 0.4)\%$	$(5.9 \pm 0.8)\%$

D DECAY MODELING

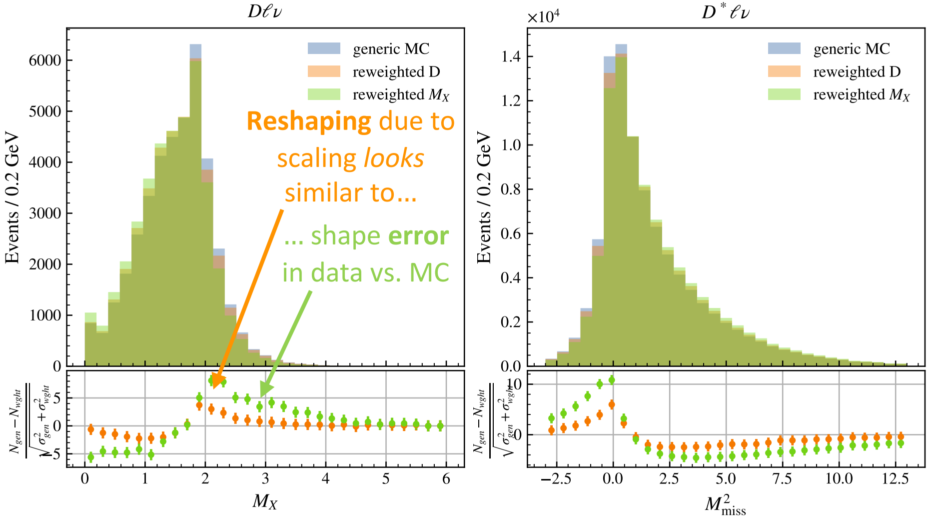
N_K uncertainty of 5-10% natural

$K_S^0 \to \pi^{0,\pm}\pi^{0,\mp}$ extends this to an **N_π** and **N_γ uncertainty**

Why not just fix the modeling instead?

- The M_X shape is sensitive to the **types of modeling** that are **not well known** (inclusive K_L^0 BF, D^{**} and nonres. BF, modeling of high multiplicity D decays)
- **Branching fractions** are a big piece of the puzzle (particularly $D \to K_L^0 X$), but cannot solve it entirely
- The **phase-space modeling** used in $\approx 40\%$ of the D decays is significant/unfixable
- The PDG inclusive and exclusive BFs cannot be reconciled

	PDG		MC	
Decay	D^0 BF / %	D^+ BF / %	D^0 BF / %	D^+ BF / %
K^-	54.7 ± 2.8	25.7 ± 1.4	56.1	30.5
K^0 / $\bar{K}^0$	47 ± 4	61 ± 5	40.0	57.5
K^+	3.4 ± 0.4	5.9 ± 0.8	3.7	7.0
$K^{*,-}$	15 ± 9	6 ± 5	12.7	4.6
$\bar{K}^{*,0}$	9 ± 4	23 ± 5	9.1	19.3
$K^{*,0}$	2.8 ± 1.3	< 6.6		



Fixing this at generator level is not feasible; instead, use M_X to reweight our MC in a data-driven way!

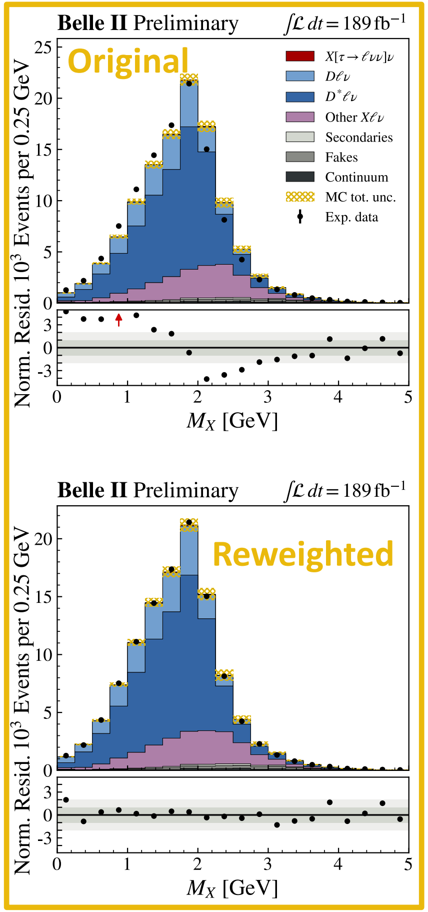
Success can be evaluated in non-trivial improvements in **several quantities** (M^2_{miss}, q^2, $N_{K^\pm}$, $N_{\pi^\pm}$, N_γ) **at the same time** while keeping other unchanged (p_ℓ^B).

SIMULATION REWEIGHTING IN CONTROL REGIONS

$X\ell\nu$:

Event weights from data/MC ratio in M_X

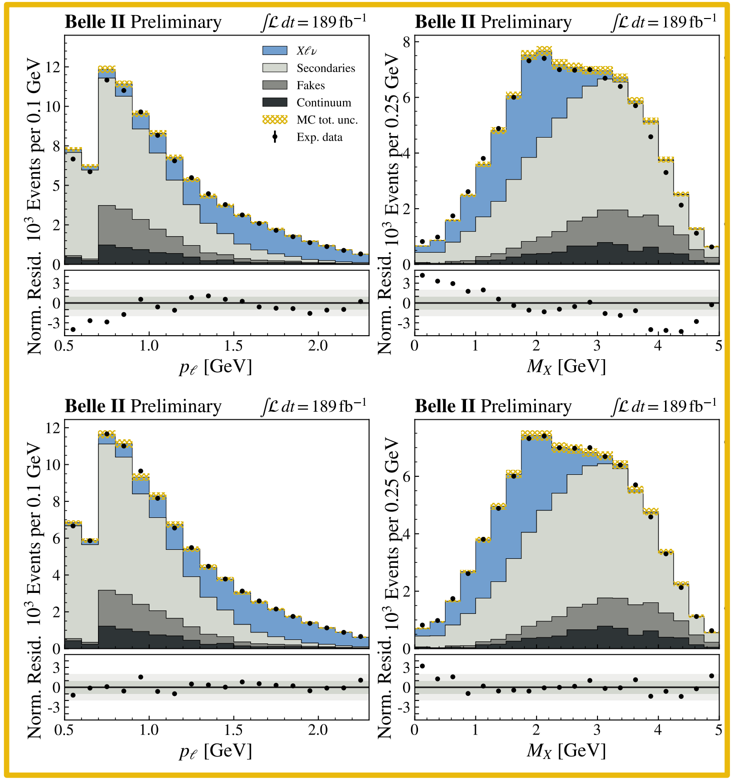
(high p_ℓ^B sideband)



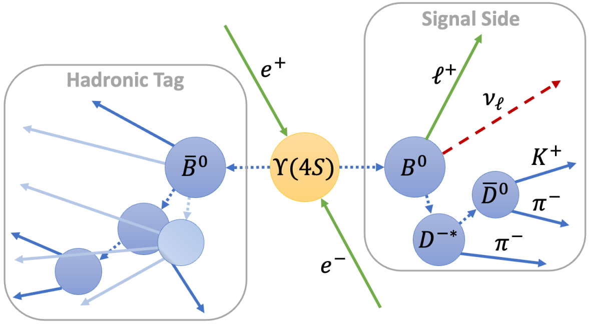
BACKGROUNDS:

Event weights from **2D $p_\ell - M_X$ grid**

(same B flavor region)



ANGULAR ASYMMETRIES IN $B \to D^* \ell \nu$



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

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

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

Highly sensitive to lepton universality violation

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

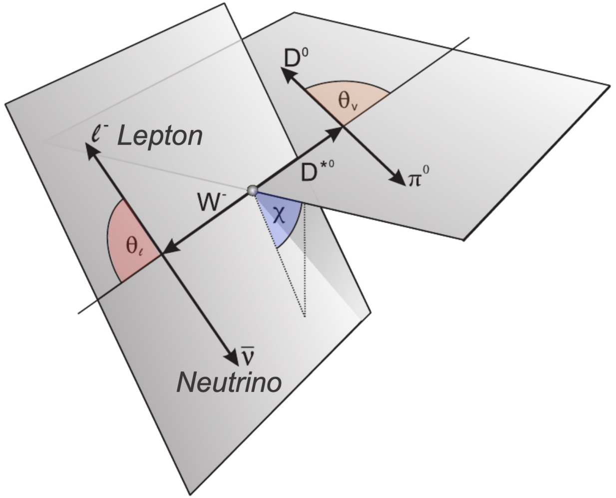
$S_3(w)$: $dx = d(\cos 2\chi)$

$S_5(w)$: $dx = d(\cos\chi \cos\theta_V)$

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

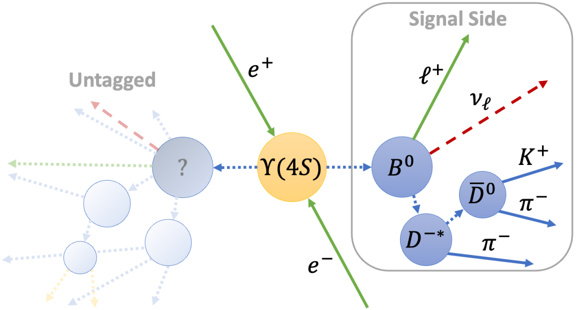
$S_7(w)$: $dx = d(\sin\chi \cos\theta_V)$

$S_9(w)$: $dx = d(\sin 2\chi)$



arXiv: 2310.01170 (accepted by PRD)

$B^0 \to D^{*-}\ell^+\nu$ UNTAGGED: B_{sig}



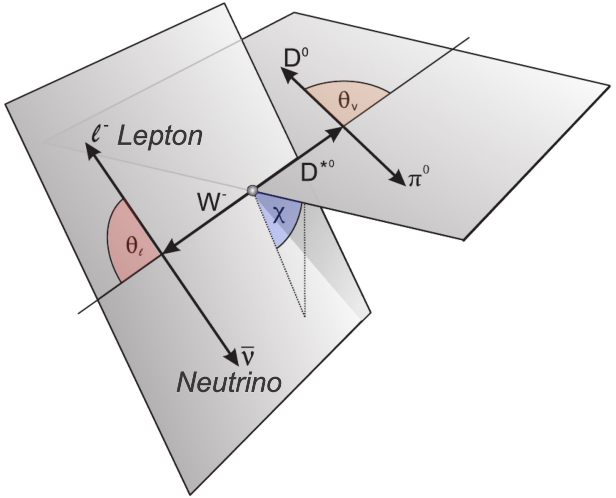
- Challenging due to lack of clean kinematic signatures and missing knowledge of the B_{sig} direction

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

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

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

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



The $\boldsymbol{B}_{\textbf{sig}}$ **direction** is estimated in a **novel approach** using

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

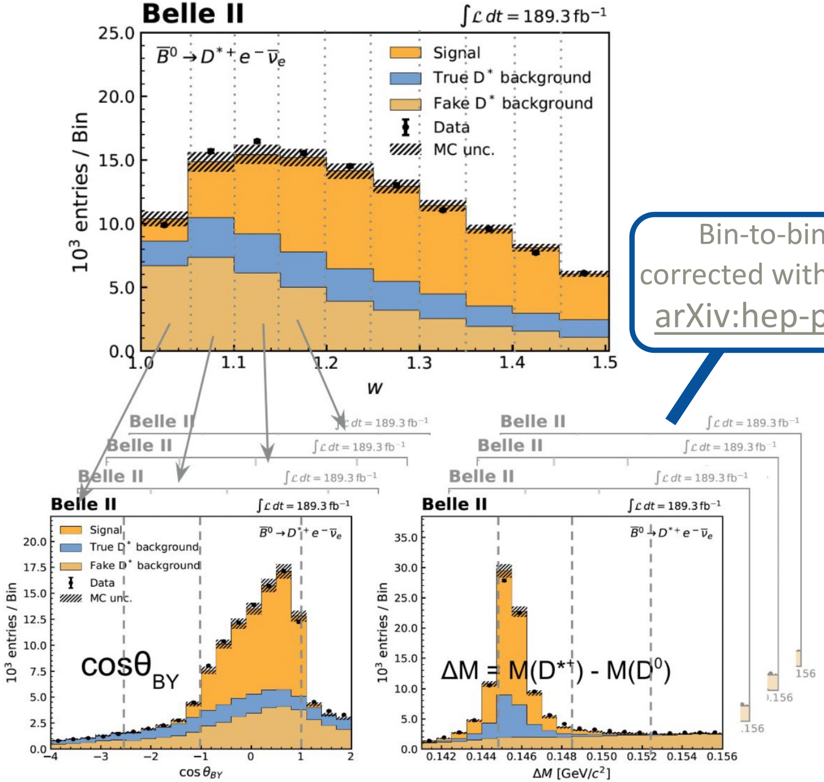
  $$\cos\theta_{BY} = \frac{2E_B^{\text{c.m.}} E_Y^{\text{c.m.}} - m_B^2 c^4 - m_Y^2 c^4}{2|\vec{p}_B^{\,\text{c.m.}}||\vec{p}_Y^{\,\text{c.m.}}|c^2}$$

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

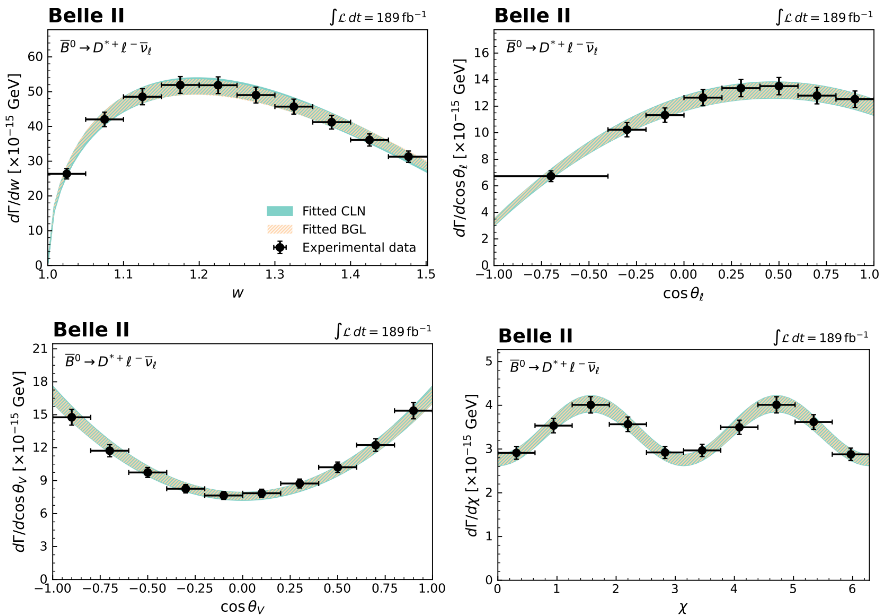
arXiv: 2310.01170 (accepted by PRD)

$B^0 \to D^{*-}\ell^+\nu$ UNTAGGED: SIGNAL EXTRACTION

- 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



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

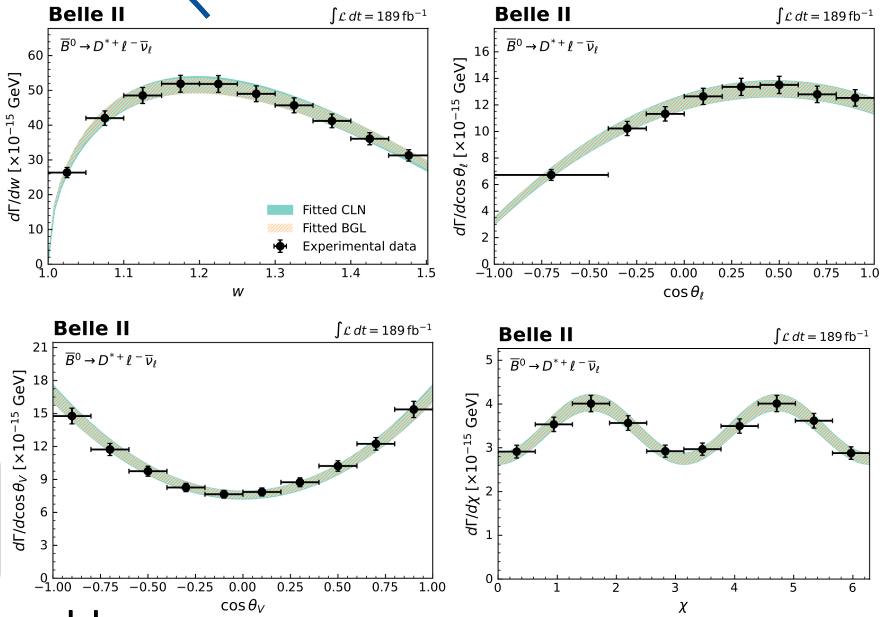
$$\mathscr{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell) = (4.922 \pm 0.023^{\text{stat}} \pm 0.220^{\text{syst}})\%$$

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

	Value	Correlation				χ^2/ndf
$\tilde{a}_0 \times 10^3$	0.88 ± 0.05	1.00	0.26	−0.28	0.19	39/31
$\tilde{b}_0 \times 10^3$	0.54 ± 0.01	0.26	1.00	−0.37	−0.43	
$\tilde{b}_1 \times 10^3$	-0.31 ± 0.30	−0.28	−0.37	1.00	0.57	
$\tilde{c}_1 \times 10^3$	-0.04 ± 0.03	0.19	−0.43	0.57	1.00	

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

$$|V_{cb}|_{\text{BGL}} = (40.57 \pm 0.31^{\text{stat}} \pm 0.95^{\text{syst}} \pm 0.58^{\text{theo}})\times 10^{-3}$$
$$|V_{cb}|_{\text{CLN}} = (40.13 \pm 0.27^{\text{stat}} \pm 0.93^{\text{syst}} \pm 0.58^{\text{theo}})\times 10^{-3}$$



- 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)

$B^0 \to D^{*-}\ell^+\nu$ UNTAGGED: EXPERIMENTAL UNCERTAINTIES

Relative uncertainty (%)

	$\tilde{a}_0$	$\tilde{b}_0$	$\tilde{b}_1$	$\tilde{c}_1$
Statistical	3.7	0.8	65.1	50.8
Background subtraction	2.1	0.4	31.3	21.8
Size of simulated samples	1.5	0.3	26.4	20.5
Lepton ID efficiency	1.6	0.3	3.4	2.8
Tracking of K, π, ℓ	0.4	0.4	0.5	0.4
Slow-pion efficiency	1.6	1.5	23.8	24.7
$N_{B\bar{B}}$	0.8	0.8	0.8	0.8
f_{+0}	1.3	1.3	1.3	1.2
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.4	0.4	0.4	0.4
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.4	0.4	0.4	0.4
B^0 lifetime	0.1	0.1	0.1	0.1
Signal modeling	2.3	0.5	52.1	35.0
Total	5.8	2.5	96.0	73.0