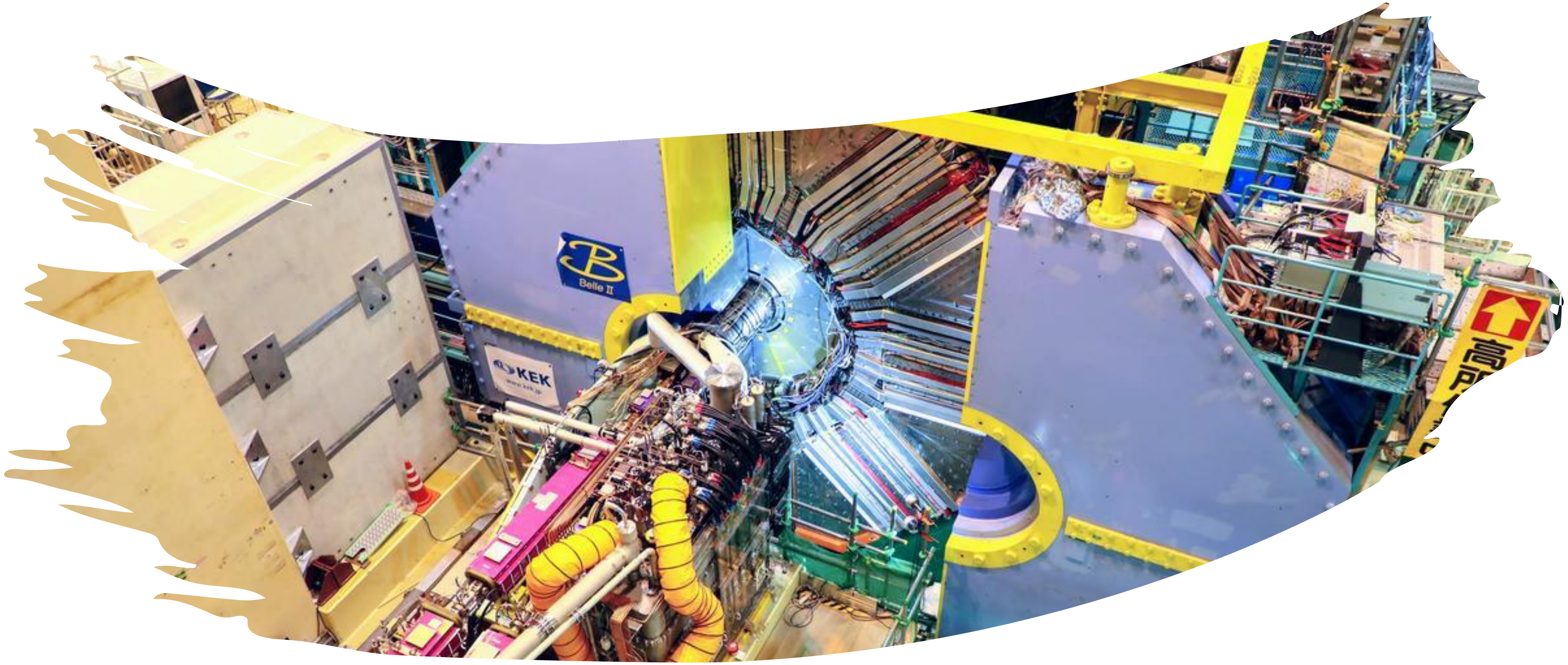


Status and prospects for semileptonic analyses at Belle and Belle II

Markus Prim on behalf of the Belle II Collaboration
markus.prim@uni-bonn.de

BELLE

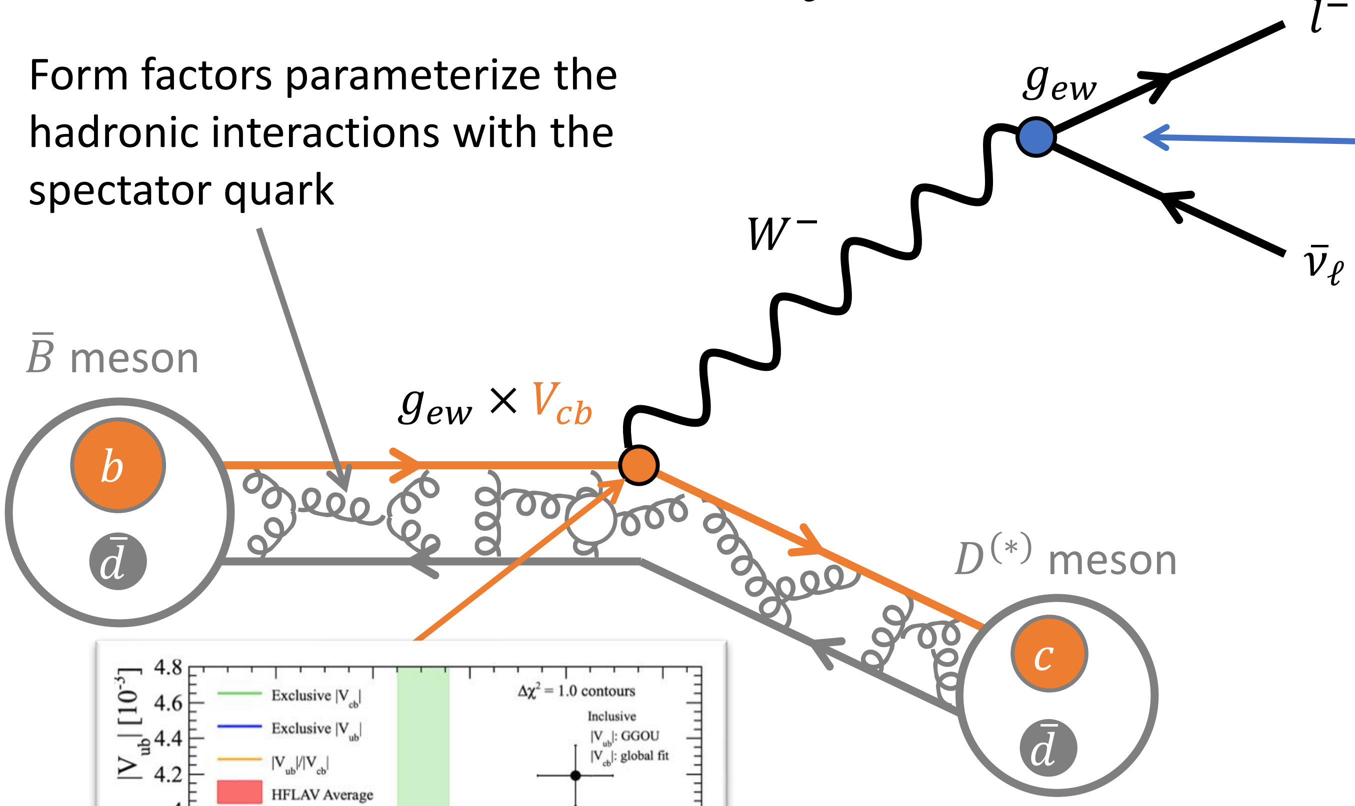
UNIVERSITÄT BONN

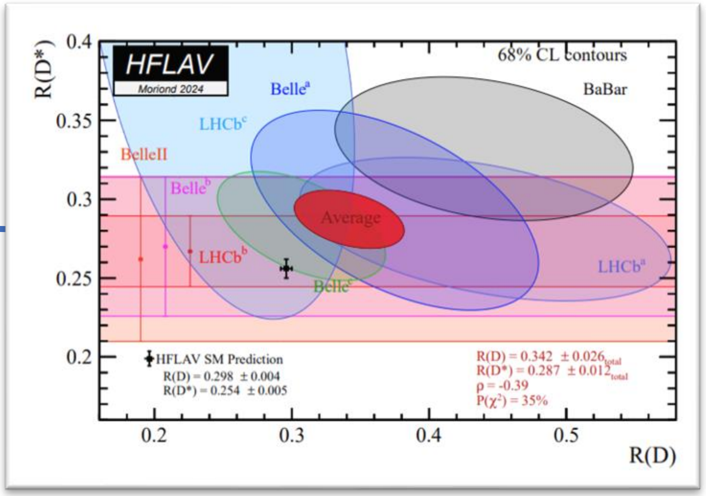
Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

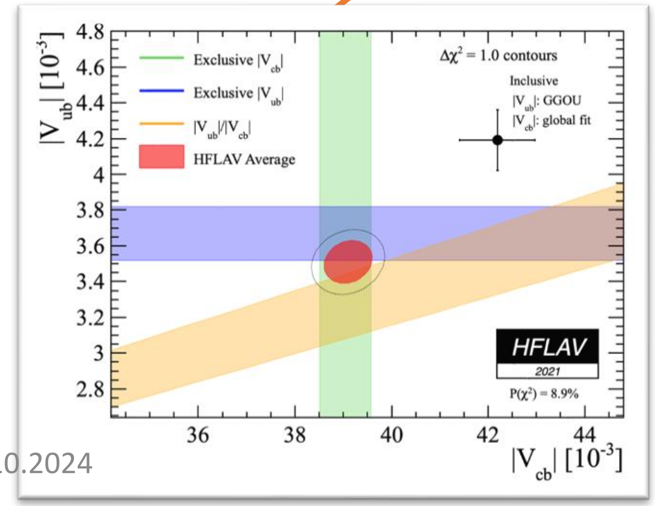
The $\bar{B} \to D^{(*)} \ell \bar{\nu}_\ell$ decay

$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)} \tau \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)} \ell \bar{\nu}_\ell)}$

Form factors parameterize the hadronic interactions with the spectator quark





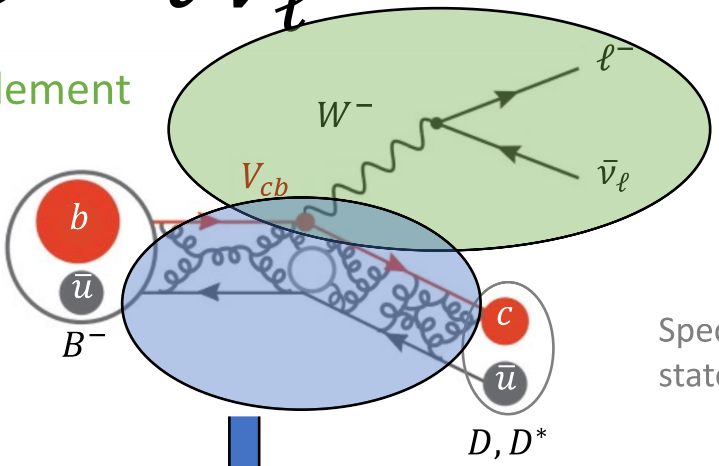


Good understanding of the form factors is crucial for precise predictions and determinations of observables

$R(D^{(*)})$, A_{FB}, $P_\tau(D^{(*)})$, $F_{L,\tau}(D^{(*)})$, $|V_{cb}|$

$\bar{B} \to D^{(*)} \ell \bar{\nu}_\ell$

Leptonic Matrix Element



$$\Gamma(\bar{B} \to D\ell\bar{\nu}_\ell) \propto |V_{cb}|^2 \mathcal{G}(1) \qquad \mathcal{G}(1) = h_+(1)$$

$$\Gamma(\bar{B} \to D^*\ell\bar{\nu}_\ell) \propto |V_{cb}|^2 \mathcal{F}(1) \qquad \mathcal{F}(1) = h_{A_1}(1)$$

Specific final state meson

Hadronic Matrix Elements can not be calculated from first principles

→ Can be parameterized with form factors $h_X = h_X(w)$ and **extracted from data**

→ Theory must provide (at least) inputs on their normalization

$$\frac{\langle D(p')|\bar{c}\gamma^\mu b|B(p)\rangle}{\sqrt{m_B m_D}} = h_+(v+v')^\mu + h_-(v-v')^\mu$$

$$\frac{\langle D^*(p')|\bar{c}\gamma^\mu b|B(p)\rangle}{\sqrt{m_B m_{D^*}}} = h_V \epsilon^{\mu\nu\alpha\beta}\epsilon^*_\nu v'_\alpha v_\beta$$

$$\frac{\langle D^*(p')|\bar{c}\gamma^\mu\gamma^5 b|B(p)\rangle}{\sqrt{m_B m_{D^*}}} = h_{A_1}(w+1)\epsilon^{*\mu} - h_{A_2}(\epsilon^*\cdot v)v^\mu - h_{A_3}(\epsilon^*\cdot v)v'^\mu$$

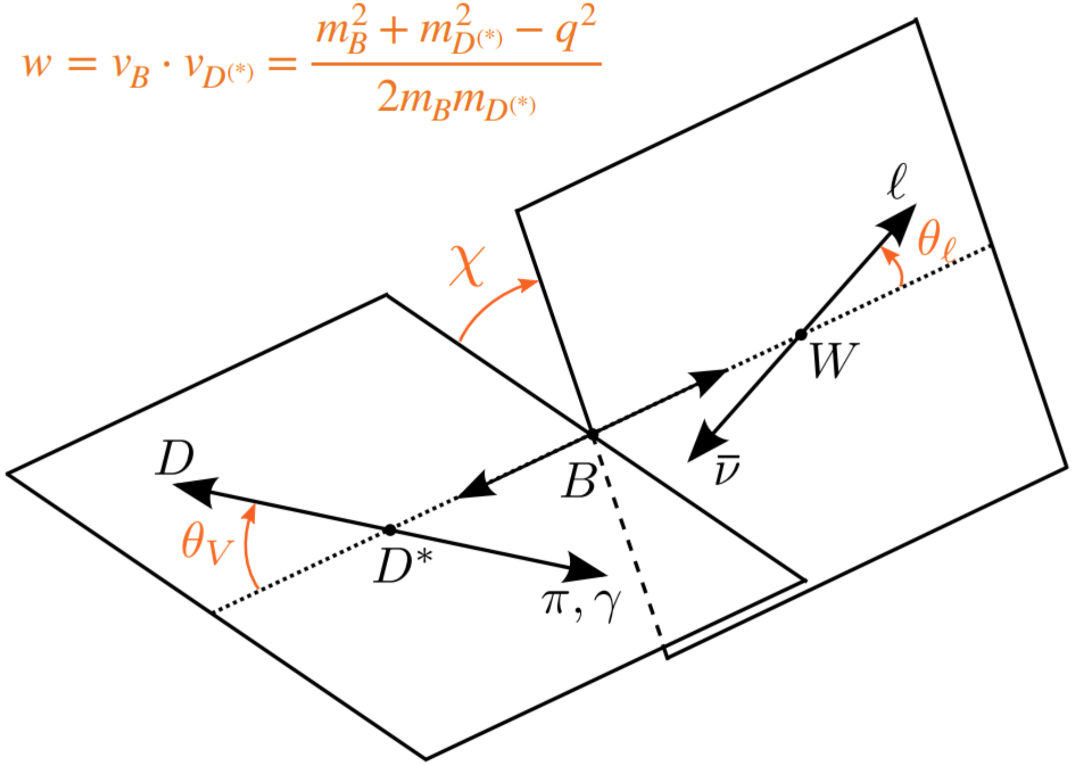
Heavy Quark Symmetry Basis

Exclusive $\bar{B} \to D^* \ell \bar{\nu}_\ell$

Hadronic Tagged

Exclusive $\bar{B} \to D^* \ell \bar{\nu}_\ell$

$$w = v_B \cdot v_{D^{(*)}} = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$$



- Form factors are a function of w only
- Angles provide information on, e.g.
  - Forward-backward asymmetry
  - Longitudinal polarization fraction
  - “S” observables sensitive to new physics

$$\frac{\mathrm{d}\Gamma(B \to D^* \ell \nu_\ell)}{\mathrm{d}w \mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_\mathrm{V} \mathrm{d}\chi} = \frac{6 m_\mathrm{B} m_{\mathrm{D}^*}^2}{8(4\pi)^4} \sqrt{w^2 - 1}(1 - 2wr + r^2) G_\mathrm{F}^2 \eta_\mathrm{EW}^2 |V_\mathrm{cb}|^2$$
$$\times \Big((1-\cos\theta_\ell)^2 \sin^2\theta_\mathrm{V} H_+^2 + (1+\cos\theta_\ell)^2 \sin^2\theta_\mathrm{V} H_-^2$$
$$+ 4\sin^2\theta_\ell \cos^2\theta_\mathrm{V} H_0^2 - 2\sin^2\theta_\ell \sin^2\theta_\mathrm{V} \cos 2\chi H_+ H_-$$
$$- 4\sin\theta_\ell(1-\cos\theta_\ell)\sin\theta_\mathrm{V}\cos\theta_\mathrm{V}\cos\chi H_+ H_0$$
$$+ 4\sin\theta_\ell(1+\cos\theta_\ell)\sin\theta_\mathrm{V}\cos\theta_\mathrm{V}\cos\chi H_- H_0 \Big) ,$$

- Measuring the 4D rate is not feasible
- **So, what do we do?**

Measurement Strategy

- Measure the marginal distributions of the 4D differential decay rate
- Measure the angular coefficients $J(w)$ in bins of w

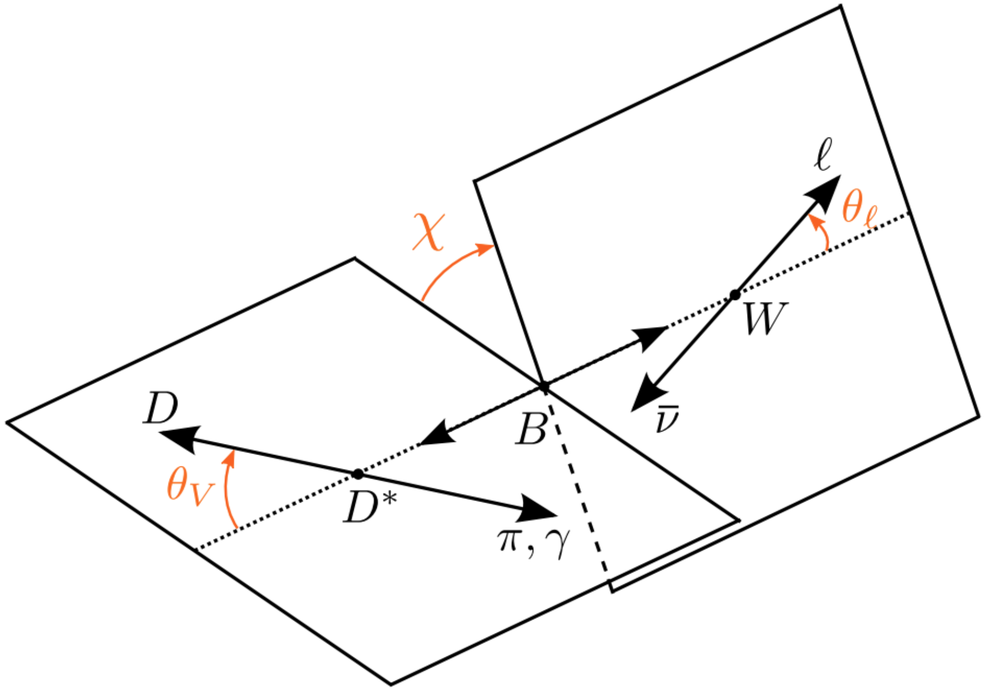
Belle, Prim, et al
arXiv:2301.07529
(Published in PRD)

Belle, Prim, et al
arXiv:2310.20286
(Accepted by PRL)

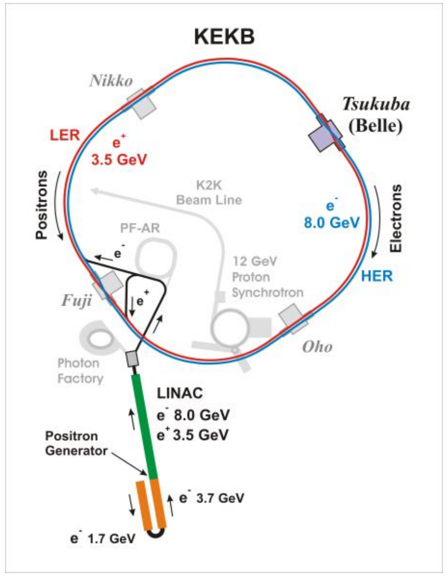
Conceptually both analyses are very similar:

- Signal extraction via a model independent variable M_{miss}^2
- Correction for migration and acceptance

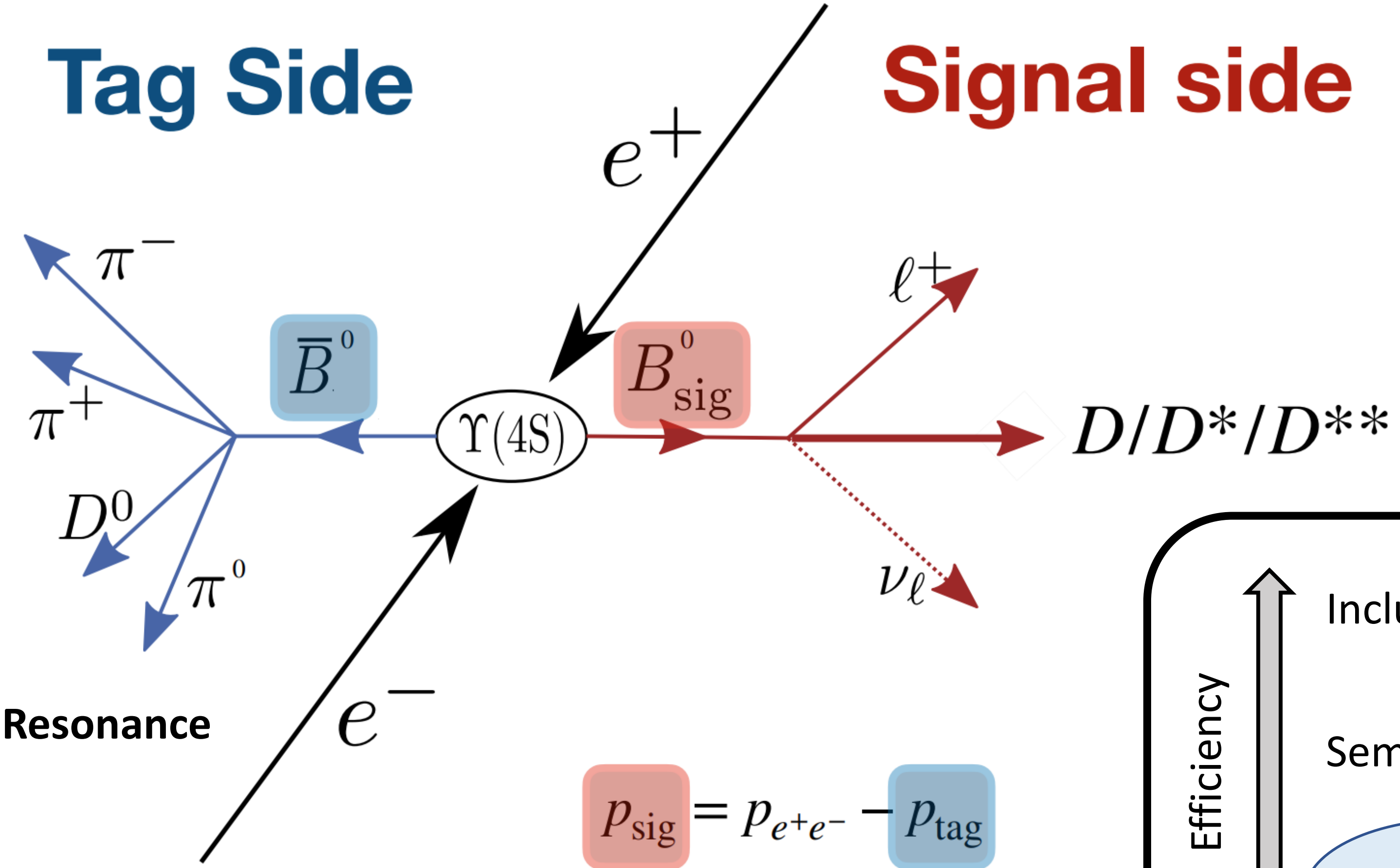
$$w = v_B \cdot v_{D^{(*)}} = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$$



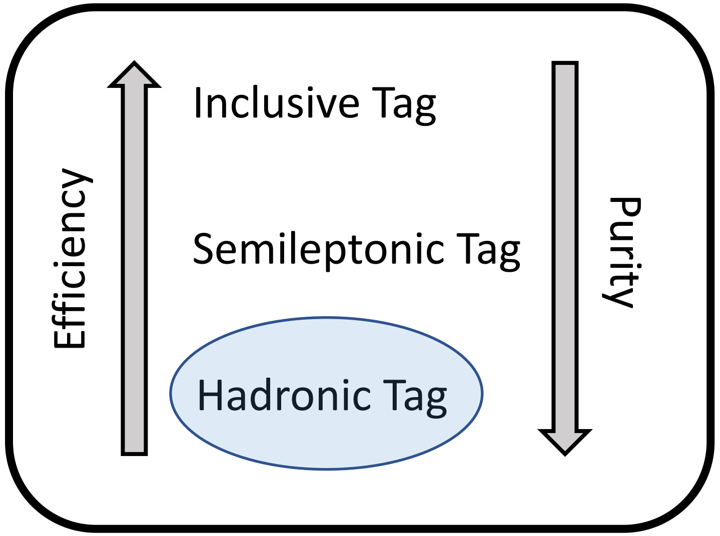
Measurement Strategy at Belle



$\mathcal{L} = 711\ \mathrm{fb}^{-1}$ @ $\Upsilon(4S)$ **Resonance**



$$p_{\mathrm{sig}} = p_{e^+e^-} - p_{\mathrm{tag}}$$

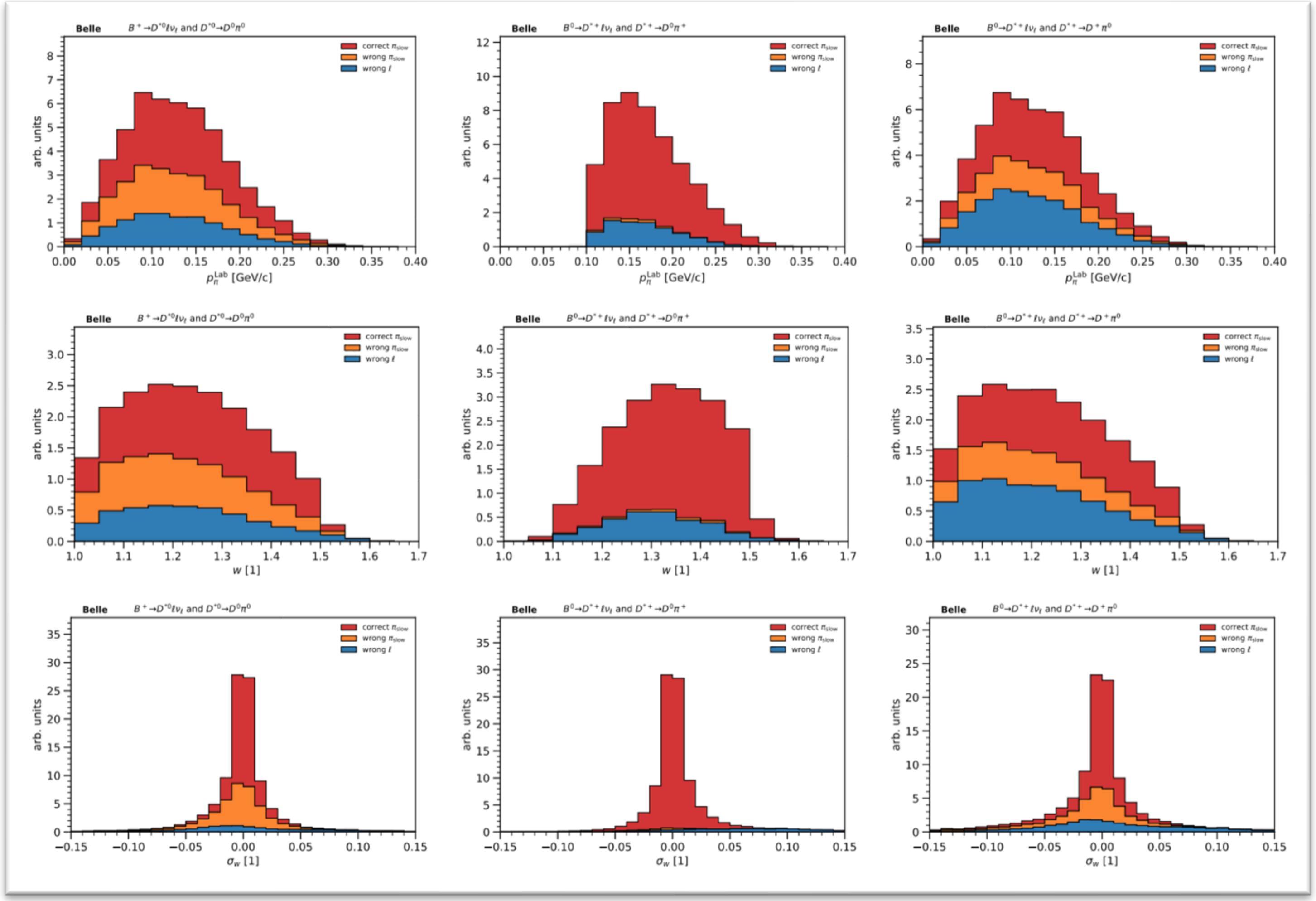


$\bar{B} \to D^{*}\ell\bar{\nu}_{\ell}$ Channels

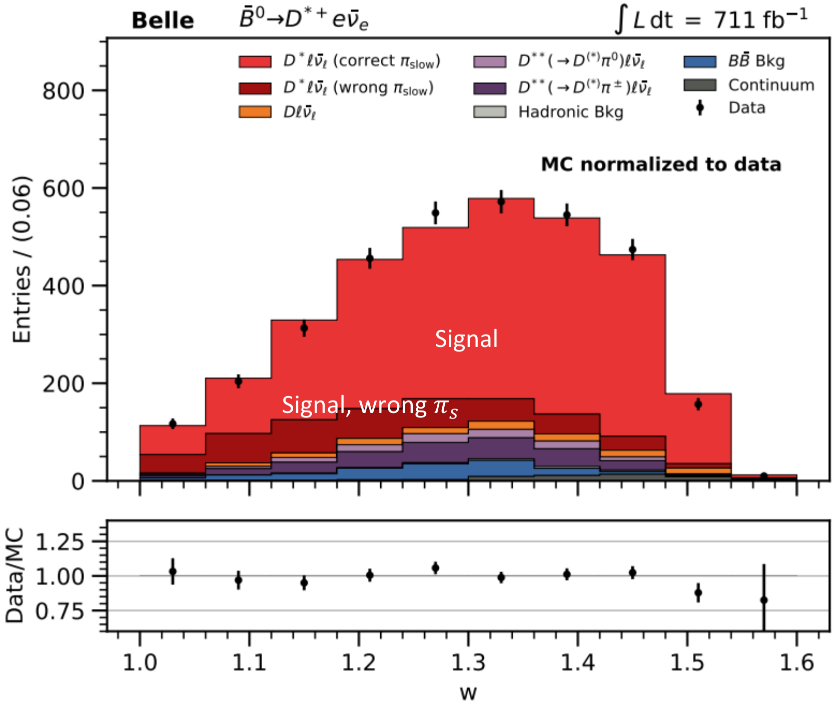
$\bar{B}^0 \to D^{*+}(\to D^0\pi_s^+, D^+\pi_s^0)\ell\bar{\nu}_\ell$

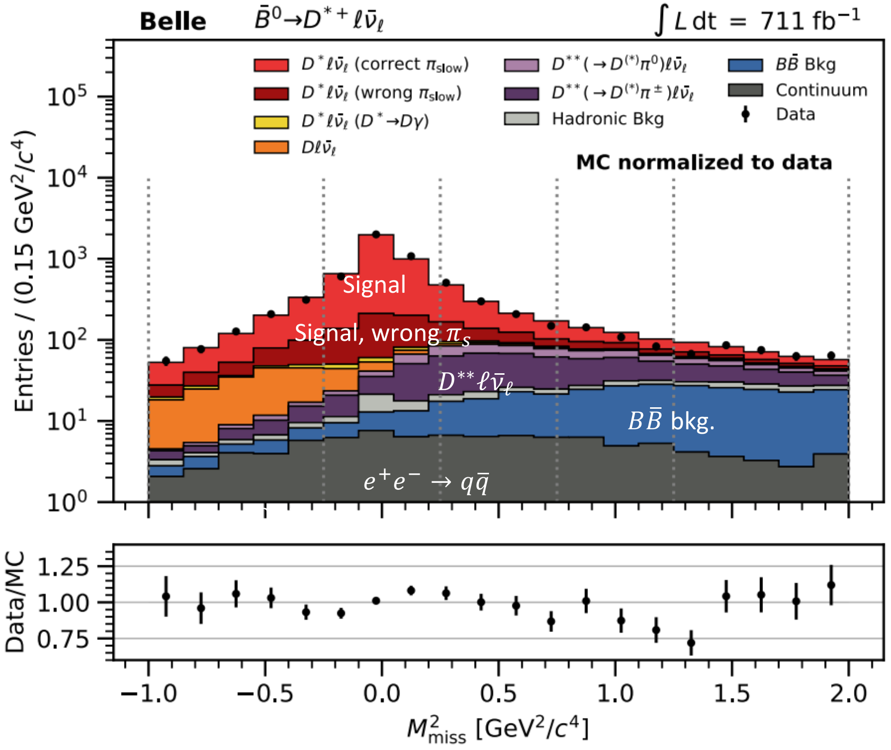
$B^- \to D^{*0}(\to D^0\pi_s^0)\ell\bar{\nu}_\ell$

First time we consider neutral slow pions
→ larger kinematic coverage
→ but more mis-identified pions and
worse resolution



Background Subtraction $\bar{B} \rightarrow D^{*}\ell\bar{\nu}_{\ell}$



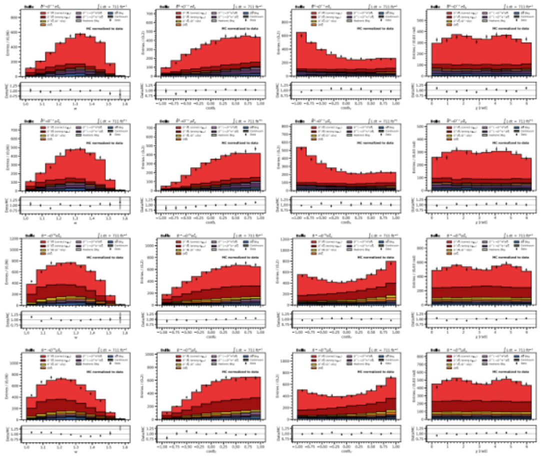


Background subtraction in independent variable to reduce model dependency.

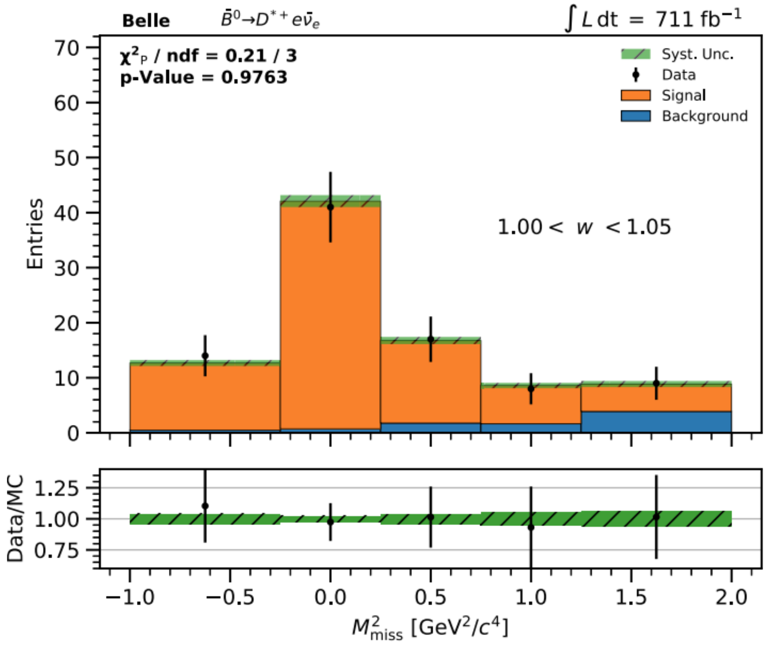
Extraction Method: Missing Mass Squared

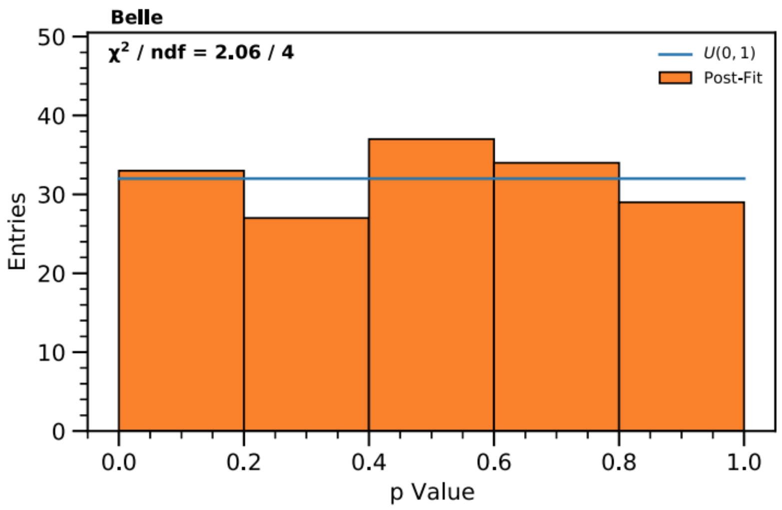
$$0 = m_\nu^2 = \mathrm{M}^2_{\mathrm{miss}} = (p_{e^+e^-} - \mathrm{p_B} - \mathrm{p_{D^*}} - \mathrm{p}_\ell)^2$$

Background Subtraction $\bar{B} \to D^*\ell\bar{\nu}_\ell$



Repeat in 4 channels, 4 variables, 10 bins each
→ 160 fits $\mathrm{M}^2_{\mathrm{miss}}$



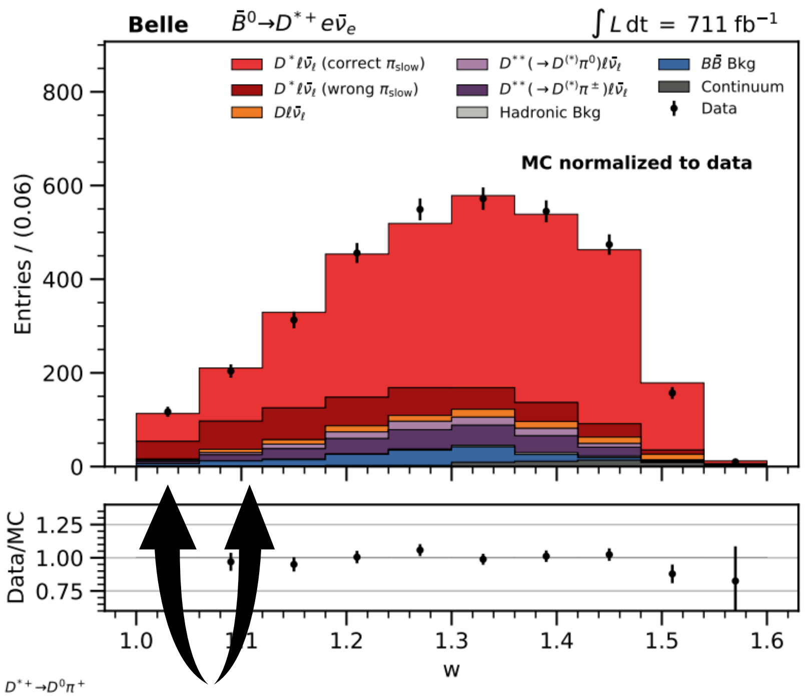


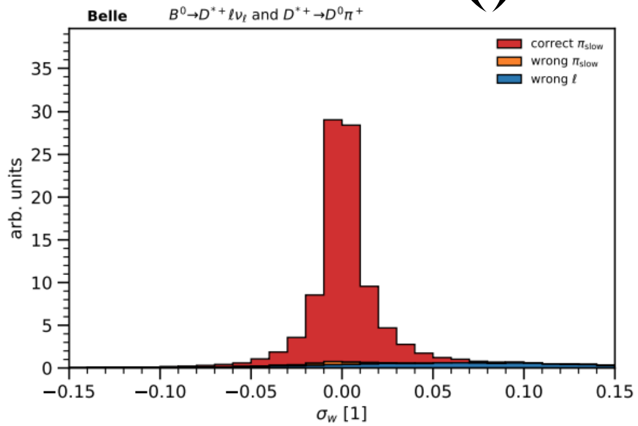
The p-value distribution for the 160 fits

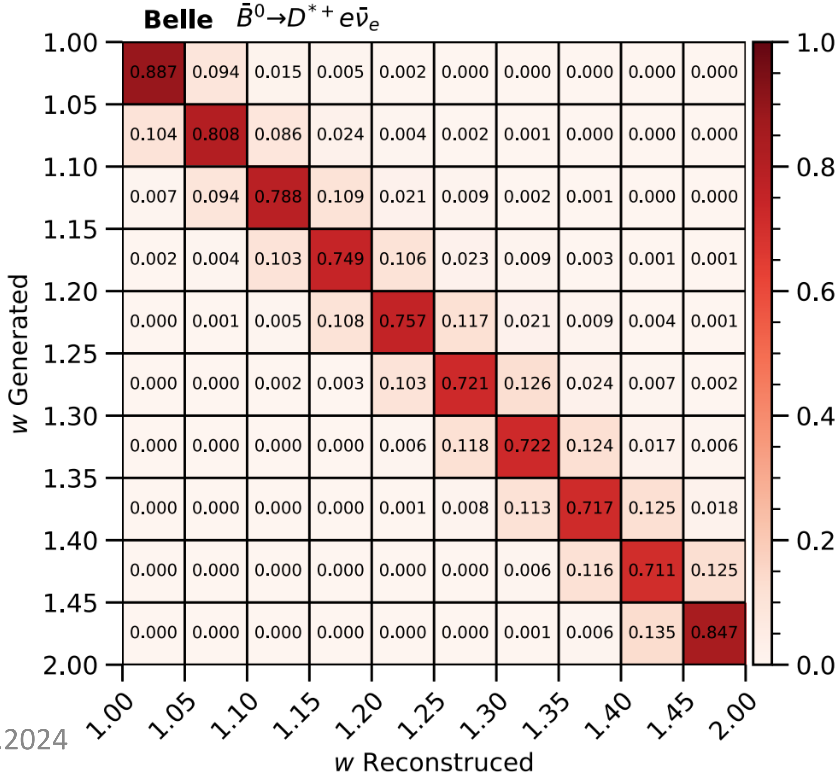
Unfolding & Acceptance

- We measure the e.g., w distribution smeared by the detector resolution, and impacted by acceptance effects
- We are interested in the true underlying distribution

→ Correct for migration effects and efficiencies







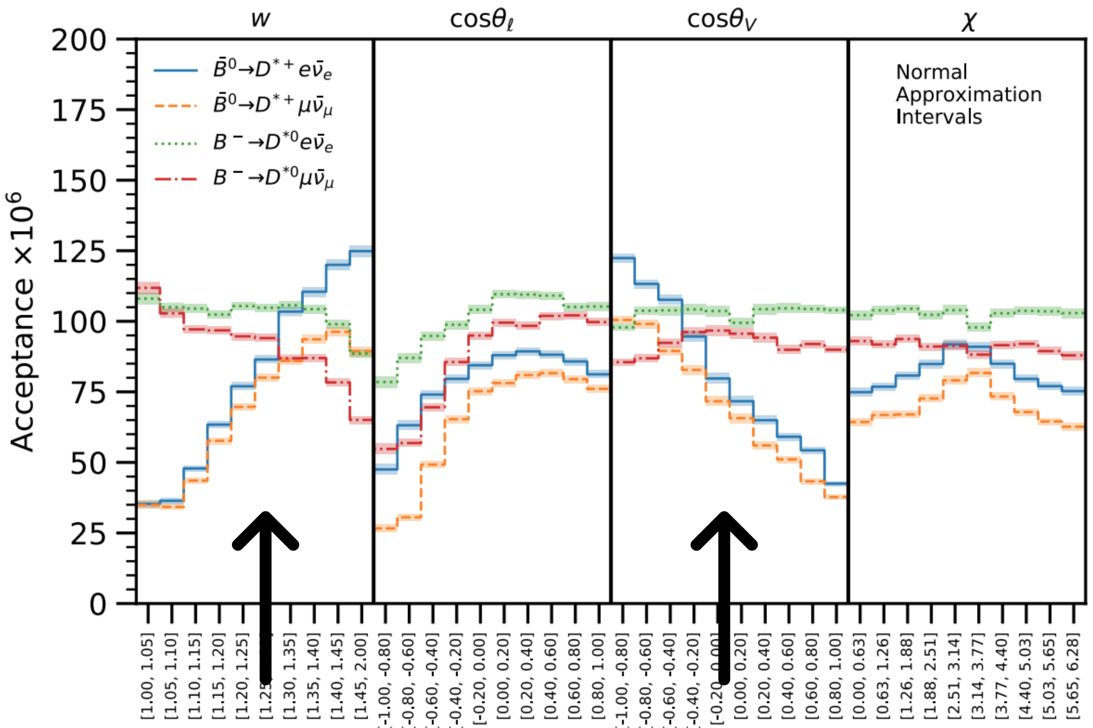
Resolution effect encoded in the migration matrix, extracted from simulation. Simulation assumptions are accounted for in the systematics budget.

Unfolding & Acceptance

- We measure the e.g., w distribution smeared by the detector resolution, and impacted by acceptance effects
- We are interested in the true underlying distribution

→ Correct for migration effects and efficiencies

Acceptance extracted from simulation. Simulation assumptions are accounted for in the systematics budget

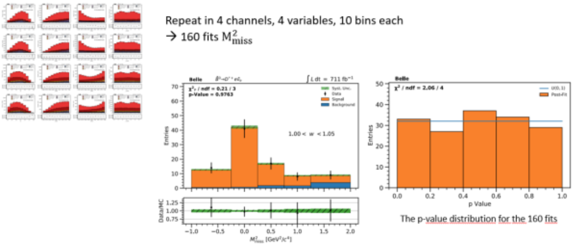


Difference in the differential efficiency is caused by the slow pion efficiency: charged vs neutral

Systematics

We can check the slow pion & lepton identification efficiency by testing the compatibility of different decay modes

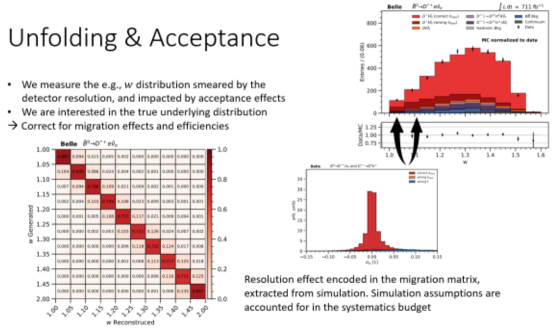
Background Subtraction $B \to D^* \ell \bar{\nu}_\ell$



M^2_{miss} almost model-independent
→ No significant systematic effects here

Systematic effects enter in the unfolding procedure:
Vary the MC simulation according to the size of the systematic effects, and repeat unfolding and acceptance correction (simultaneously)

Unfolding & Acceptance



Unfolding & Acceptance

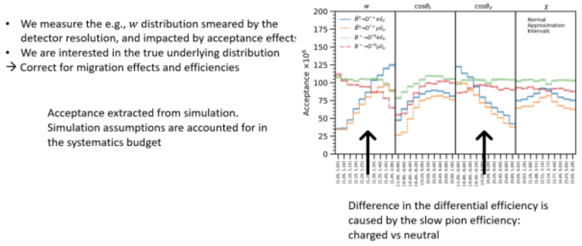
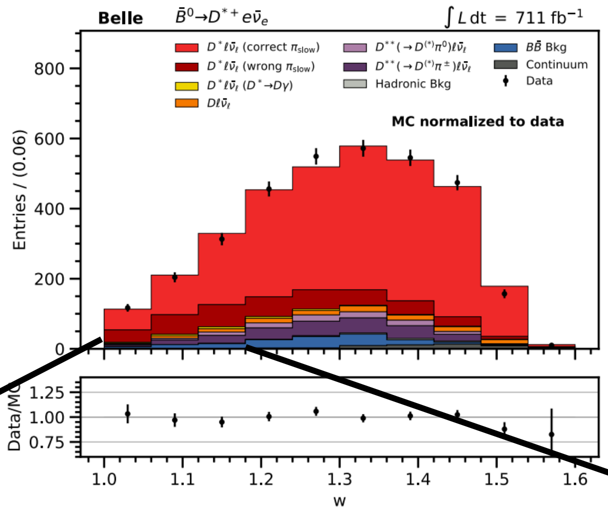


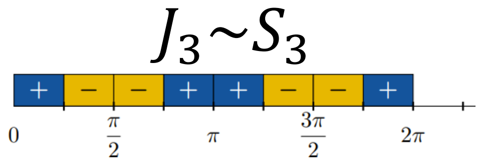
TABLE XII. Uncertainties in % for the $\bar{B}^0 \to D^* e \bar{\nu}_e$ channel.

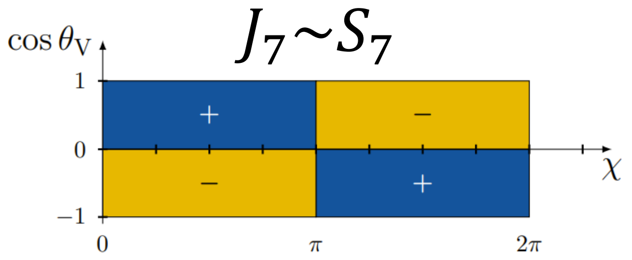
Projection	Bin	Total	M^2_{miss} fit	Unfolding and acceptance								
				$FF(B \to D^* \ell \bar{\nu}_\ell)$	$\mathcal{B}(D \to X)$	MC statistics	$\epsilon(\pi_{slow})$	$\epsilon(LID)$	$\epsilon(\pi^0)$	$\epsilon(Tracking)$	$\epsilon(K^0_S)$	FEI shape
w	[1.00, 1.05)	17.50	16.65	1.48	1.04	4.91	0.85	0.32	0.19	0.09	0.02	0.81
	[1.05, 1.10)	16.27	15.76	0.63	1.01	3.78	0.64	0.20	0.14	0.07	0.01	0.46
	[1.10, 1.15)	13.38	13.08	0.46	0.40	2.74	0.20	0.15	0.10	0.04	0.01	0.21
	[1.15, 1.20)	10.54	10.09	0.52	0.16	2.98	0.12	0.09	0.02	0.00	0.02	0.31
	[1.20, 1.25)	10.01	9.69	0.52	0.17	2.43	0.17	0.04	0.01	0.00	0.00	0.29
	[1.25, 1.30)	9.42	9.11	0.59	0.23	2.29	0.17	0.05	0.05	0.03	0.01	0.18
	[1.30, 1.35)	9.87	9.50	0.41	0.40	2.57	0.24	0.10	0.08	0.02	0.01	0.41
	[1.35, 1.40)	10.33	10.05	0.23	0.45	2.28	0.25	0.18	0.08	0.03	0.01	0.41
	[1.40, 1.45)	9.62	9.33	0.61	0.40	2.19	0.29	0.21	0.10	0.03	0.01	0.06
	[1.45, 1.50)	10.86	10.58	1.43	0.60	1.86	0.34	0.25	0.09	0.04	0.02	0.01
$\cos\theta_\ell$	[−1.00, −0.80)	24.22	23.61	2.19	0.23	4.79	0.17	0.89	0.04	0.01	0.01	0.73
	[−0.80, −0.60)	15.05	14.63	0.58	0.15	3.37	0.09	0.81	0.05	0.01	0.00	0.27
	[−0.60, −0.40)	16.92	16.39	0.40	0.11	4.06	0.09	0.80	0.02	0.00	0.01	0.48
	[−0.40, −0.20)	12.97	12.64	0.30	0.09	2.84	0.06	0.47	0.03	0.00	0.00	0.07
	[−0.20, 0.00)	12.97	12.60	0.35	0.12	2.85	0.10	0.16	0.01	0.01	0.01	0.97
	[0.00, 0.20)	17.44	16.88	0.46	0.12	4.15	0.08	0.33	0.00	0.02	0.01	1.19
	[0.20, 0.40)	10.94	10.64	0.41	0.13	2.46	0.03	0.32	0.05	0.01	0.00	0.38
	[0.40, 0.60)	11.57	11.24	0.32	0.06	2.71	0.07	0.37	0.01	0.01	0.01	0.31
	[0.60, 0.80)	10.51	10.11	0.39	0.10	2.80	0.04	0.34	0.05	0.00	0.01	0.25
	[0.80, 1.00)	8.00	7.64	1.02	0.06	2.11	0.06	0.34	0.01	0.00	0.00	0.01
$\cos\theta_V$	[−1.00, −0.80)	6.66	6.44	0.41	0.50	1.54	0.33	0.12	0.09	0.04	0.00	0.02
	[−0.80, −0.60)	8.24	7.88	0.74	0.39	2.22	0.28	0.06	0.05	0.04	0.00	0.24
	[−0.60, −0.40)	11.30	10.97	0.69	0.48	2.56	0.27	0.04	0.07	0.03	0.00	0.08
	[−0.40, −0.20)	12.97	12.54	0.47	0.31	3.26	0.24	0.02	0.04	0.03	0.01	0.01
	[−0.20, 0.00)	14.95	14.43	1.16	0.26	3.72	0.16	0.17	0.08	0.02	0.01	0.25
	[0.00, 0.20)	21.68	21.01	1.14	0.17	5.20	0.20	0.08	0.06	0.02	0.01	0.21
	[0.20, 0.40)	17.48	16.95	0.52	0.30	4.21	0.16	0.14	0.05	0.00	0.02	0.35
	[0.40, 0.60)	17.02	16.44	0.79	0.16	4.32	0.23	0.02	0.02	0.02	0.01	0.28
	[0.60, 0.80)	26.78	26.30	0.41	0.56	5.00	0.43	0.08	0.10	0.05	0.01	0.35
	[0.80, 1.00)	13.60	13.19	0.33	0.92	3.08	0.58	0.12	0.20	0.06	0.01	0.02
χ	[0.00, 0.63)	15.48	15.11	0.34	0.23	3.36	0.10	0.09	0.02	0.00	0.01	0.17
	[0.63, 1.26)	15.11	14.67	0.27	0.23	3.61	0.08	0.01	0.00	0.01	0.01	0.43
	[1.26, 1.88)	12.66	12.34	0.41	0.15	2.79	0.05	0.04	0.01	0.01	0.01	0.24
	[1.88, 2.51)	10.54	10.21	0.18	0.09	2.54	0.06	0.01	0.02	0.00	0.01	0.58
	[2.51, 3.14)	16.15	15.70	0.55	0.20	3.69	0.06	0.05	0.07	0.01	0.01	0.58
	[3.14, 3.77)	11.41	11.02	0.58	0.16	2.89	0.06	0.09	0.01	0.03	0.01	0.20
	[3.77, 4.40)	11.74	11.40	0.17	0.05	2.83	0.10	0.01	0.01	0.00	0.00	0.01
	[4.40, 5.03)	11.70	11.32	0.35	0.10	2.95	0.07	0.01	0.03	0.00	0.00	0.31
	[5.03, 5.65)	12.11	11.83	0.29	0.10	2.57	0.06	0.04	0.00	0.01	0.00	0.04
	[5.65, 6.28)	14.07	13.63	0.31	0.08	3.44	0.10	0.05	0.00	0.02	0.00	0.21

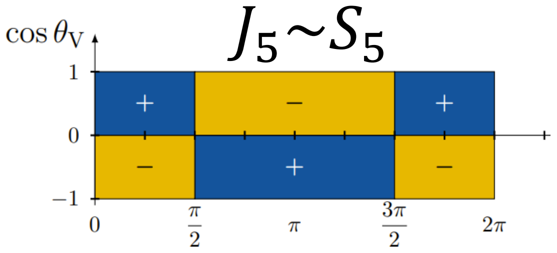
MC statistics dominant systematic effect

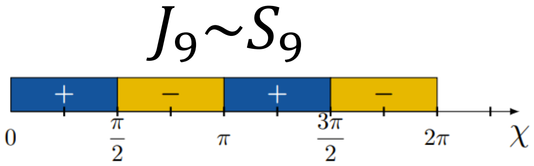
Angular Coefficients of $\bar{B} \rightarrow D^{*}\ell\bar{\nu}_{\ell}$





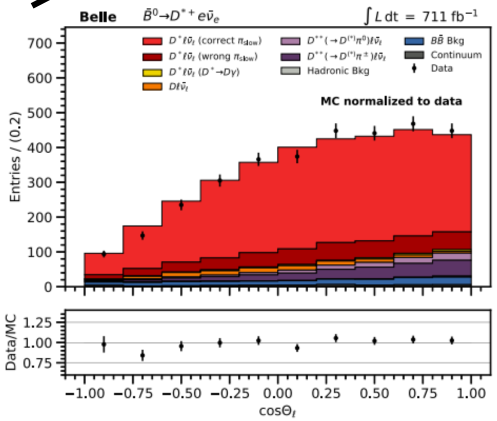


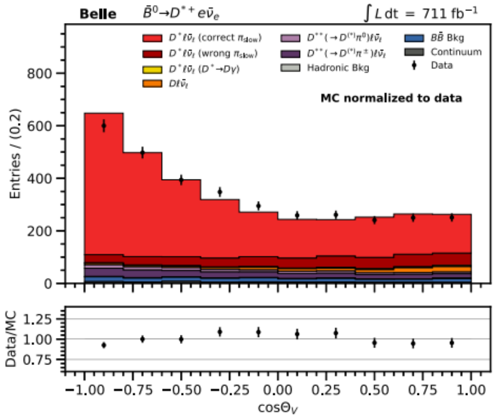


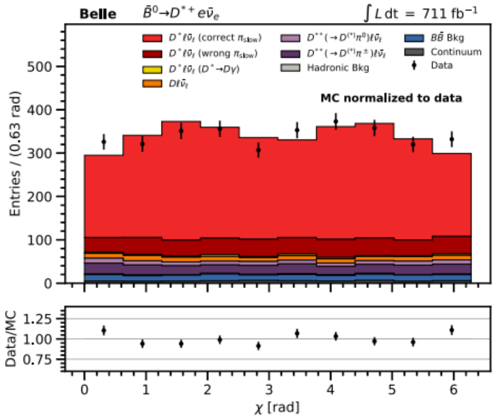


Measure angular information in bins of w instead of “full” marginal distributions

$$\mathcal{A}_x(w) = \frac{N_x^+(w) - N_x^-(w)}{N_x^+(w) + N_x^-(w)}.$$

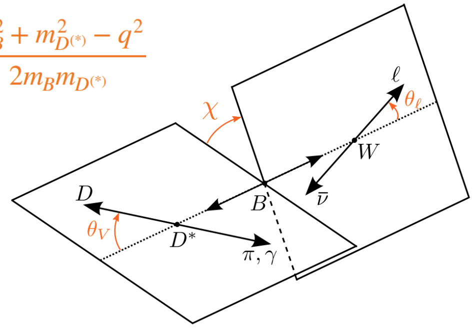






Angular Coefficients of $\bar{B} \to D^* \ell \bar{\nu}_\ell$

$$w = v_B \cdot v_{D^{(*)}} = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$$



Instead of binning in $w, \cos\theta_\ell, \cos\theta_V, \chi$, we now bin the data to determine the angular coefficients in bins of w and:

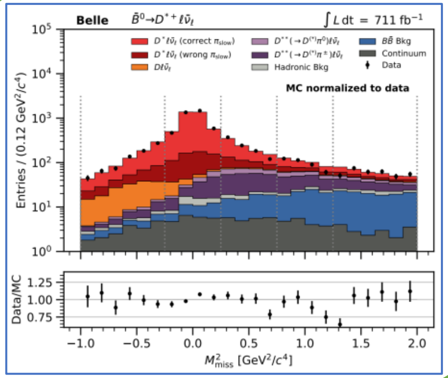
Phys.Rev.D 90 (2014) 9, 094003

$$\bar{J}_i = \frac{1}{N_i} \sum_{j=1}^{8} \sum_{k,l=1}^{4} \eta_{i,j}^{\chi} \eta_{i,k}^{\theta_\ell} \eta_{i,l}^{\theta_V} \left[\chi^{(j)} \otimes \chi^{(k)} \otimes \chi^{(l)} \right]$$

$J_i = J_i(w)$

Normalization — Weights — Unfolded Yields

J_i	η_i^{χ}	$\eta_i^{\theta_\ell}$	$\eta_i^{\theta_V}$	normalization N_i
J_{1s}	$\{+\}$	$\{+,a,a,+\}$	$\{-,c,c,-\}$	$2\pi(1)2$
J_{1c}	$\{+\}$	$\{+,a,a,+\}$	$\{+,d,d,+\}$	$2\pi(1)(2/5)$
J_{2s}	$\{+\}$	$\{-,b,b,-\}$	$\{-,c,c,-\}$	$2\pi(-2/3)2$
J_{2c}	$\{+\}$	$\{-,b,b,-\}$	$\{+,d,d,+\}$	$2\pi(-2/3)(2/5)$
J_3	$\{+,-,-,+,+,-,-,+\}$	$\{+\}$	$\{+\}$	$4(4/3)^2$
J_4	$\{+,+,-,-,-,-,+,+\}$	$\{+,+,-,-\}$	$\{+,+,-,-\}$	$4(4/3)^2$
J_5	$\{+,+,-,-,-,-,+,+\}$	$\{+\}$	$\{+,+,-,-\}$	$4(\pi/2)(4/3)$
J_{6s}	$\{+\}$	$\{+,+,-,-\}$	$\{-,c,c,-\}$	$2\pi(1)2$
J_{6c}	$\{+\}$	$\{+,+,-,-\}$	$\{+,d,d,+\}$	$2\pi(1)(2/5)$
J_7	$\{+,+,+,+,-,-,-,-\}$	$\{+\}$	$\{+,+,-,-\}$	$4(\pi/2)(4/3)$
J_8	$\{+,+,+,+,-,-,-,-\}$	$\{+,+,-,-\}$	$\{+,+,-,-\}$	$4(4/3)^2$
J_9	$\{+,+,-,-,+,+,-,-\}$	$\{+\}$	$\{+\}$	$4(4/3)^2$

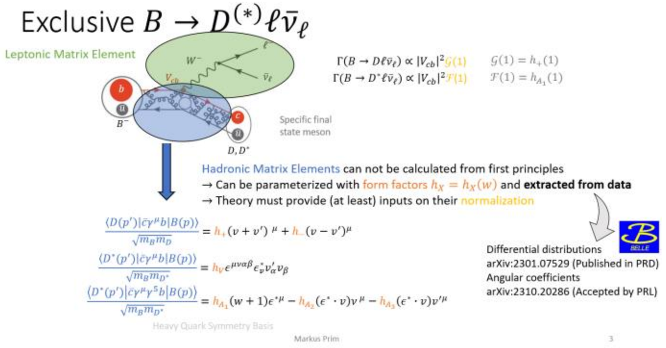


Conceptually same signal extraction, unfolding and acceptance correction strategy as before!

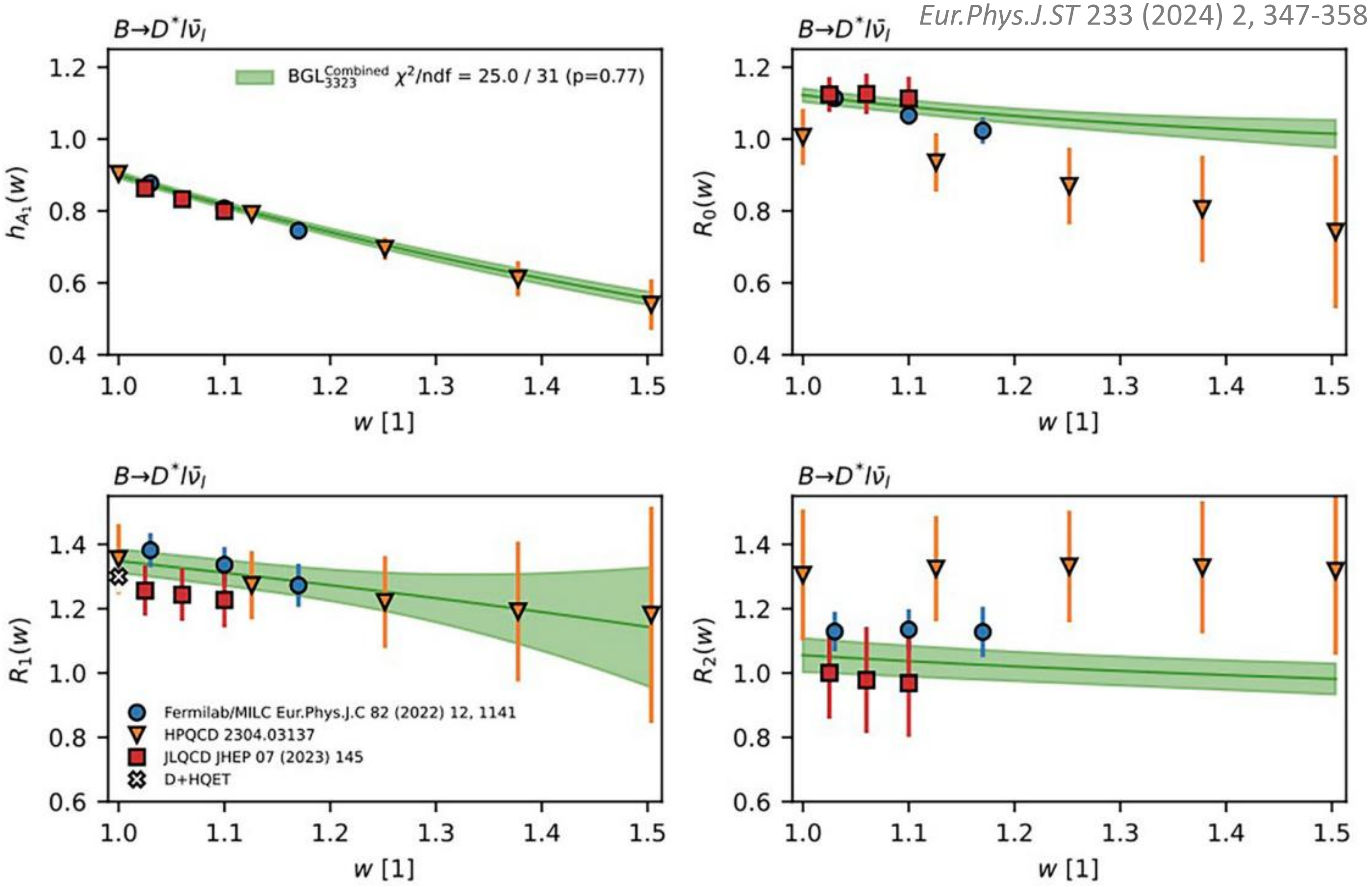
Instead of measuring the signal yield in bins of the marginal distributions:
Measure signal yield in the bins of 36 angles x 4 bins of w x 4 decay modes → 576 fits in M^2_{miss}

Lattice Compatibility

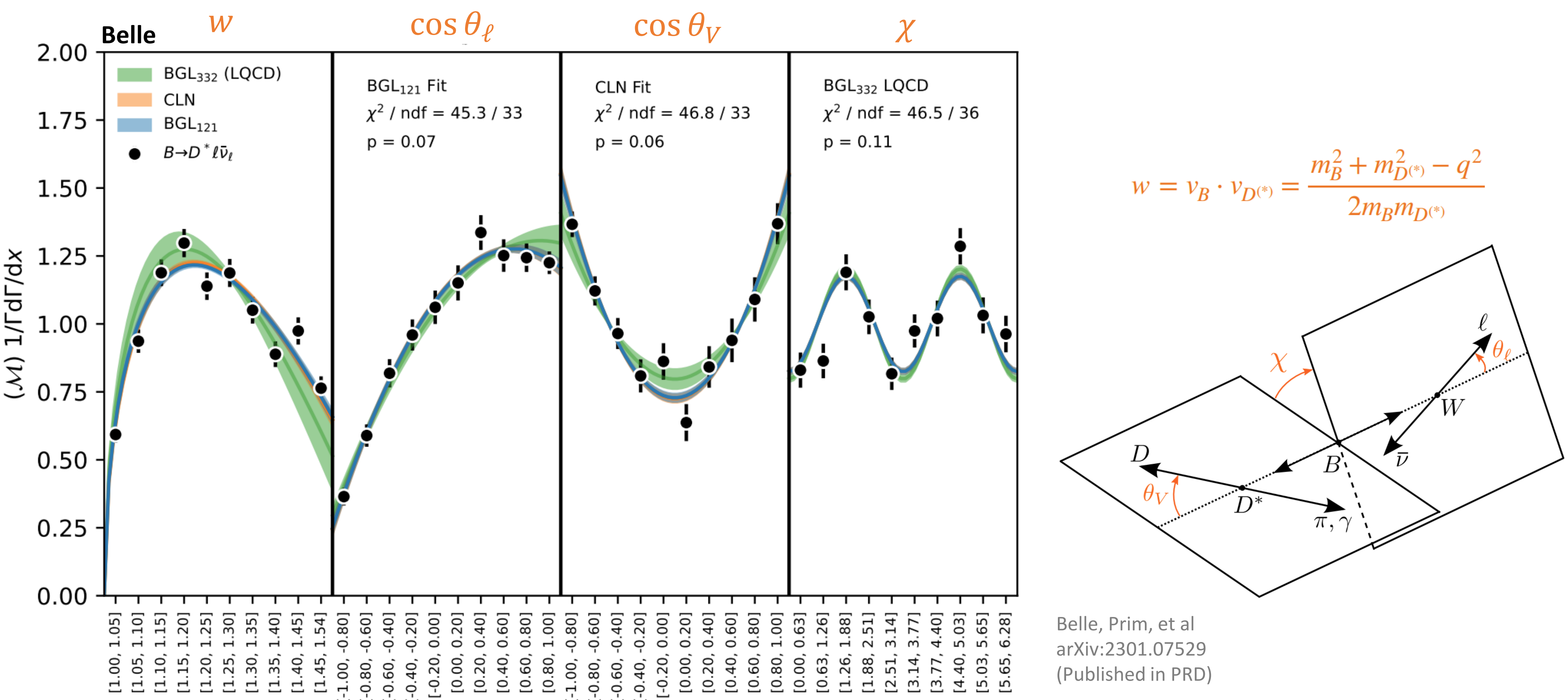
As mentioned in the beginning:
We need inputs from LQCD to extract $|V_{cb}|$



Eur.Phys.J.ST 233 (2024) 2, 347-358



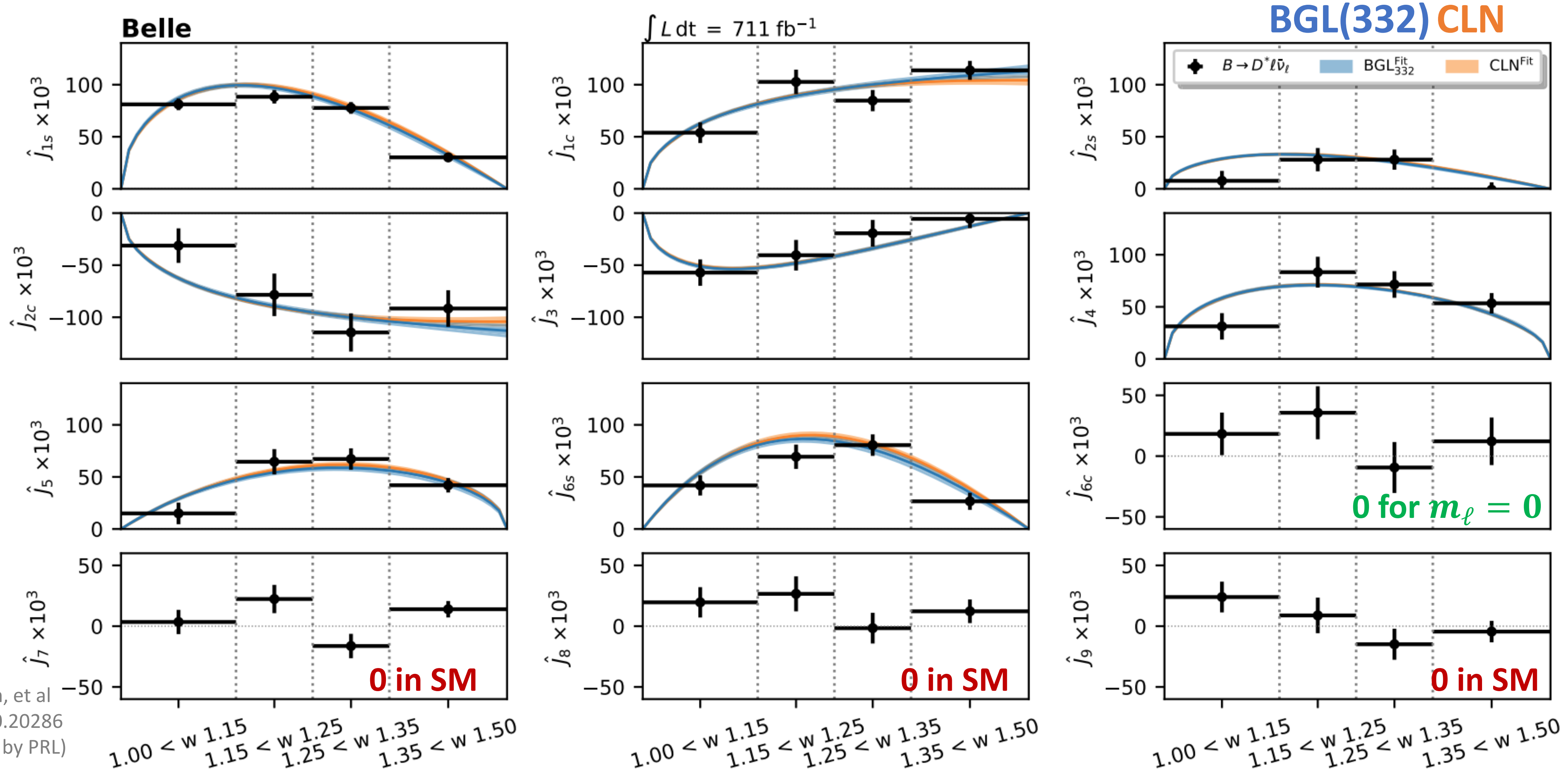
Differential Distributions of $\bar{B} \to D^* \ell \bar{\nu}_\ell$



$$w = v_B \cdot v_{D^{(*)}} = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$$

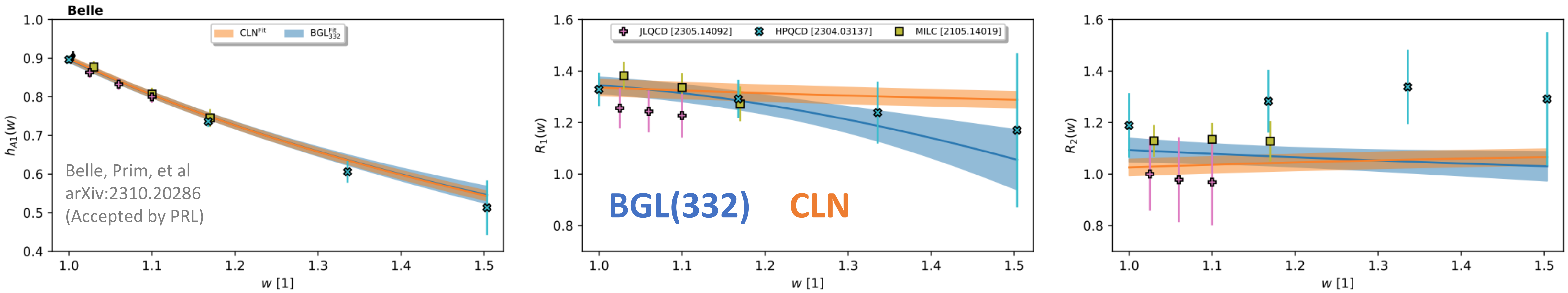
Belle, Prim, et al
arXiv:2301.07529
(Published in PRD)

Angular Coefficients of $\bar{B} \to D^* \ell \bar{\nu}_\ell$



Belle, Prim, et al
arXiv:2310.20286
(Accepted by PRL)

Form Factors of $\bar{B} \to D^* \ell \bar{\nu}_\ell$



Based on the angular coefficients

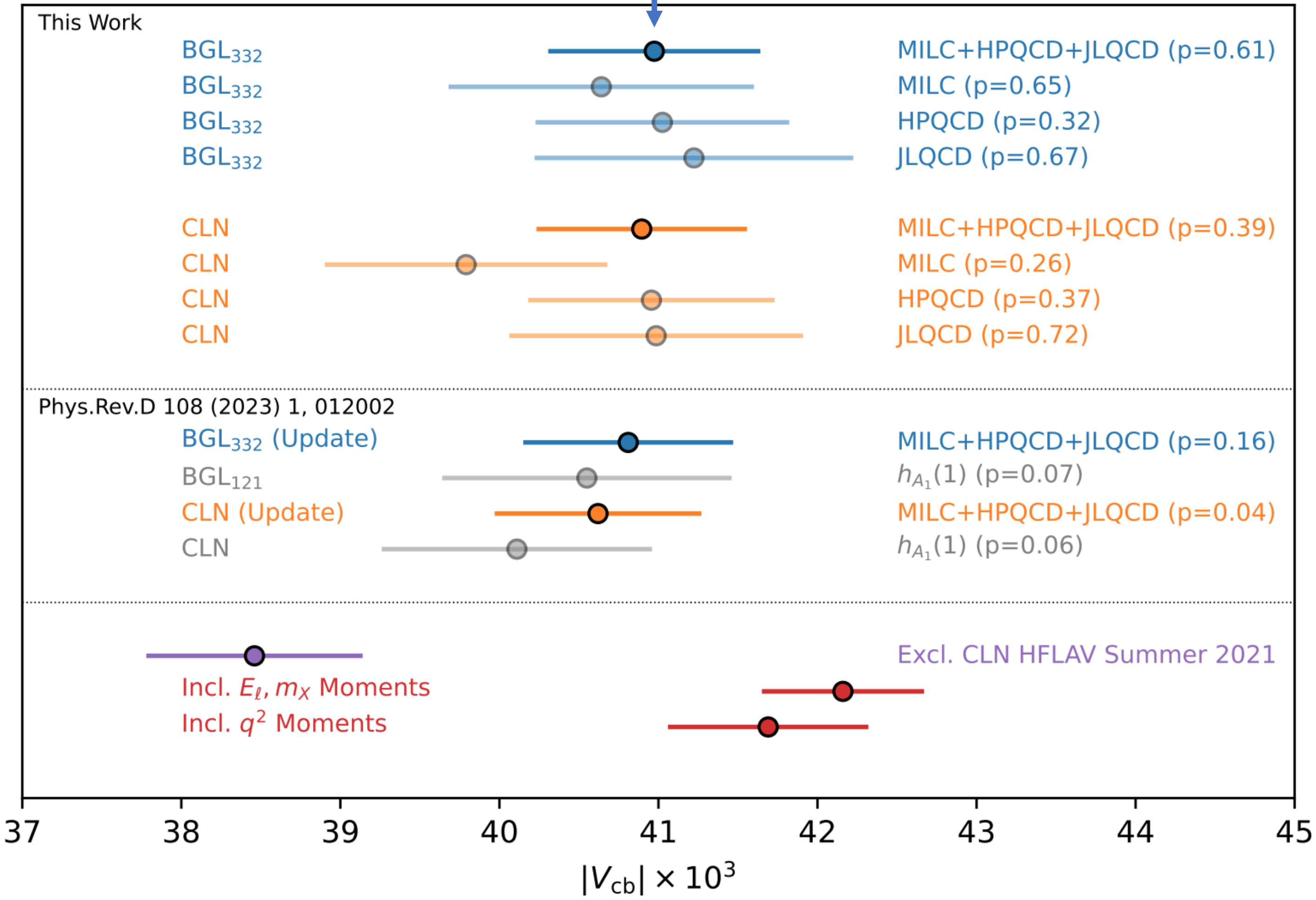
Overview on $|V_{cb}|$

$$|V_{\rm cb}| = (40.7 \pm 0.3 \pm 0.4 \pm 0.5) \times 10^{-3} \qquad (\text{BGL}_{332})$$

exp. shape $\mathcal{B}$ LQCD

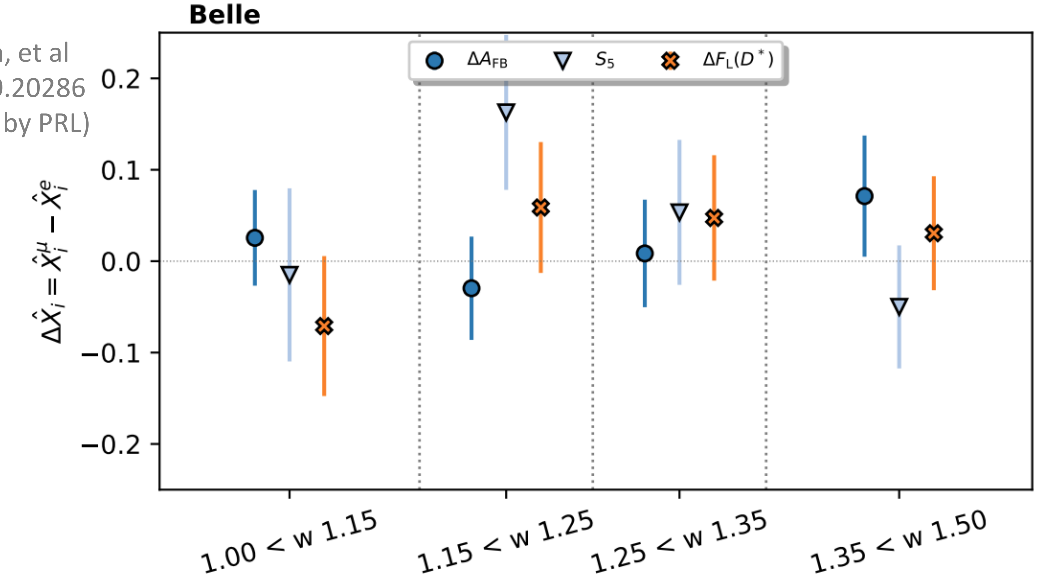
Here we use the current world average
$\mathcal{B}(\bar{B} \to D^* \ell \bar{\nu}_\ell)$
$= (4.97 \pm 0.12)\%$

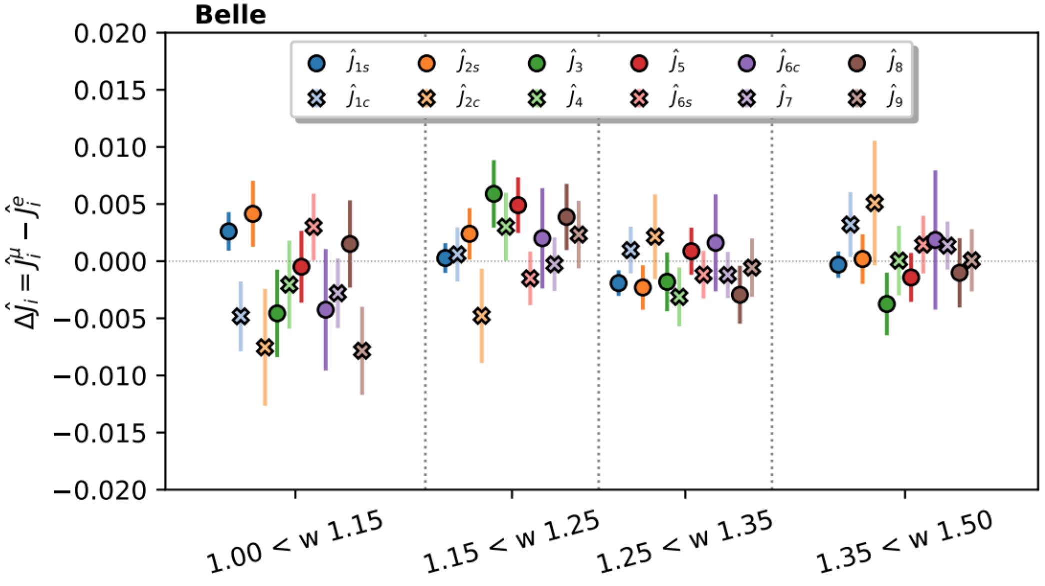
(both measurements only measure shapes!)



LFU Observables of $\bar{B} \to D^* \ell \bar{\nu}_\ell$

Belle, Prim, et al
arXiv:2310.20286
(Accepted by PRL)





Belle, Prim, et al
arXiv:2301.07529
(Published in PRD)

$$\Delta A_{FB} = A_{FB}^{\mu} - A_{FB}^{e} = 0.022 \pm 0.027$$

$$\Delta F_L = F_L^{\mu} - F_L^{e} = 0.034 \pm 0.024$$

Measured over full w range

Exclusive $\bar{B} \to D^* \ell \bar{\nu}_\ell$

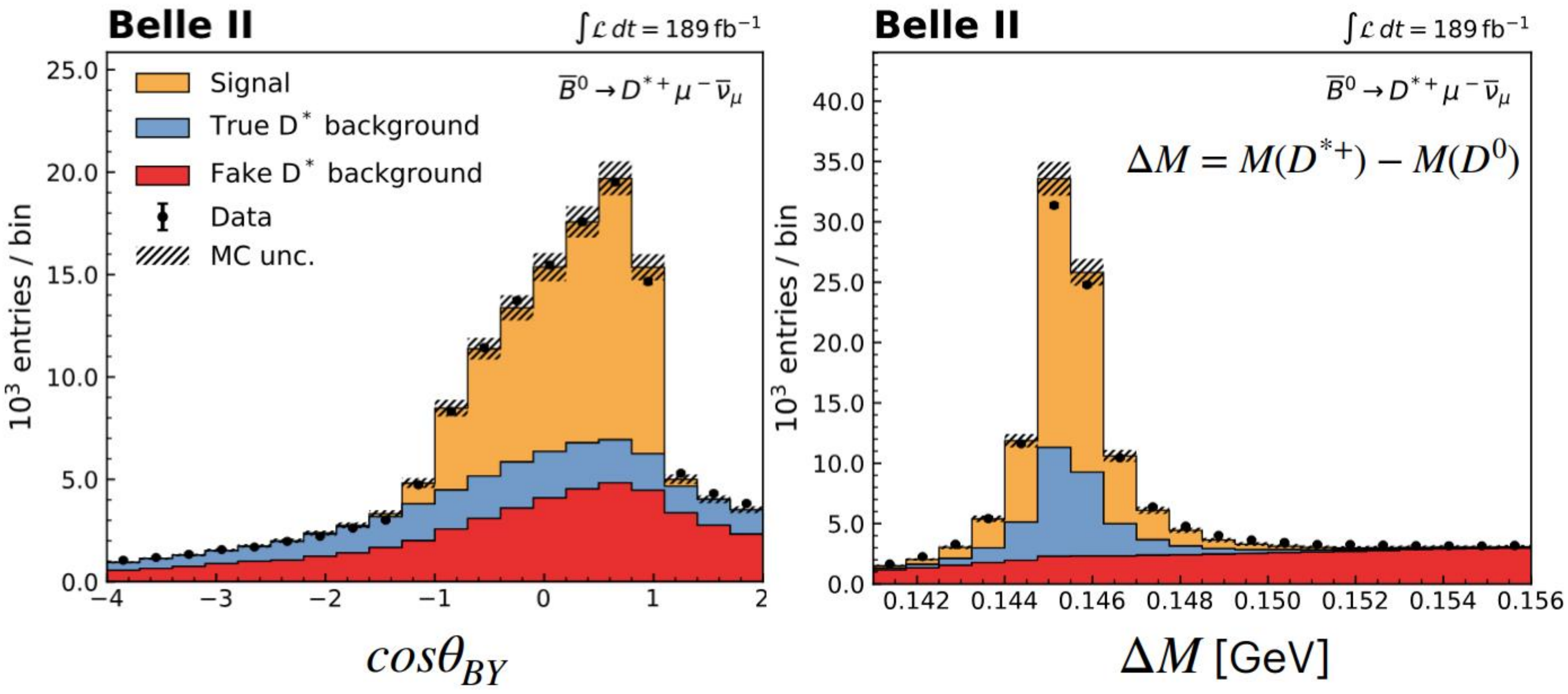
Untagged

Untagged $\bar{B} \to D^* \ell \bar{\nu}_\ell$ Strategy

Belle II
arXiv:2310.01170
PhysRevD.108.092013

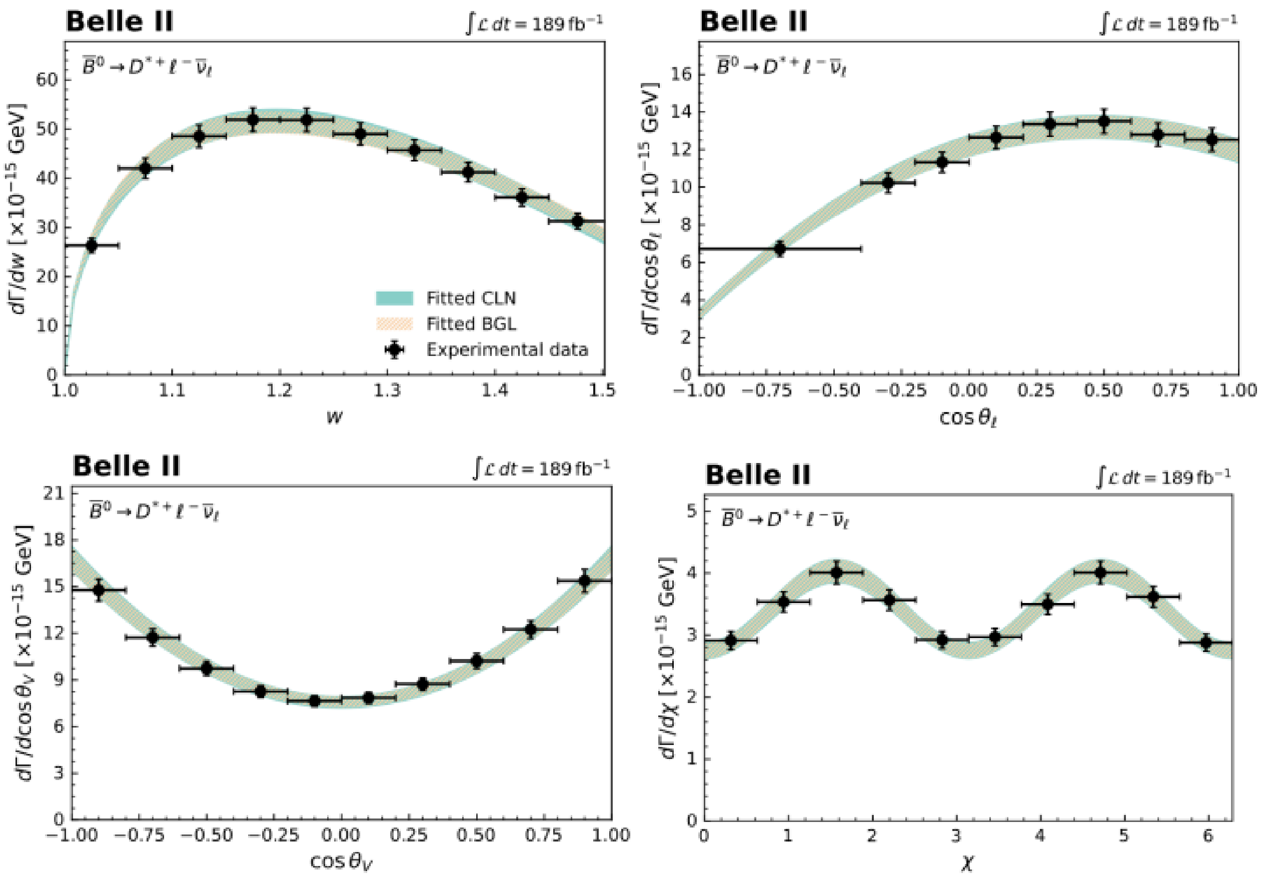
- $\cos\Theta_{BY}$ to discriminate signal from background
- ΔM to constrain the fake D^* background component

$$cos\theta_{BY} = \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|p_B^*||p_Y^*|}$$



Untagged $\bar{B} \to D^* \ell \bar{\nu}_\ell$ Result

Belle II
arXiv:2310.01170
PhysRevD.108.092013



Untagged $\bar{B} \to D^*\ell\bar{\nu}_\ell$ Result

Belle II
arXiv:2310.01170
PhysRevD.108.092013

ToDo: Update Slide or merge with previous

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

Compatible with the current WA: $(4.97 \pm 0.12)\,\%$

$$|V_{cb}|_{BGL} = (40.57 \pm 0.31(stat) \pm 0.95(syst) \pm 0.58(th)) \cdot 10^{-3}$$

Compatible with the exclusive (inclusive) WA: 1.5σ (1.3σ)

$$|V_{cb}|_{CLN} = (40.13 \pm 0.27(stat) \pm 0.93(syst) \pm 0.58(th)) \cdot 10^{-3}$$

Compatible with the exclusive (inclusive) WA: 1.1σ (1.6σ)

Use FNAL/MILC lattice QCD data at zero recoil ($w = 1$) for normalisation. BGL truncated using nested hypothesis test: BGL(1,2,2).

LFU test by comparing separated results for electrons and muons:

$$R_{e/\mu} = 0.998 \pm 0.009(stat) \pm 0.020(syst)$$

$$\Delta A_{FB} = (-17 \pm 16(stat) \pm 16(syst)) \cdot 10^{-3}$$

$$\Delta F_L = (0.006 \pm 0.007(stat) \pm 0.005(syst)) \cdot 10^{-3}$$

No deviations observed from the SM.

Dominant systematic sources:

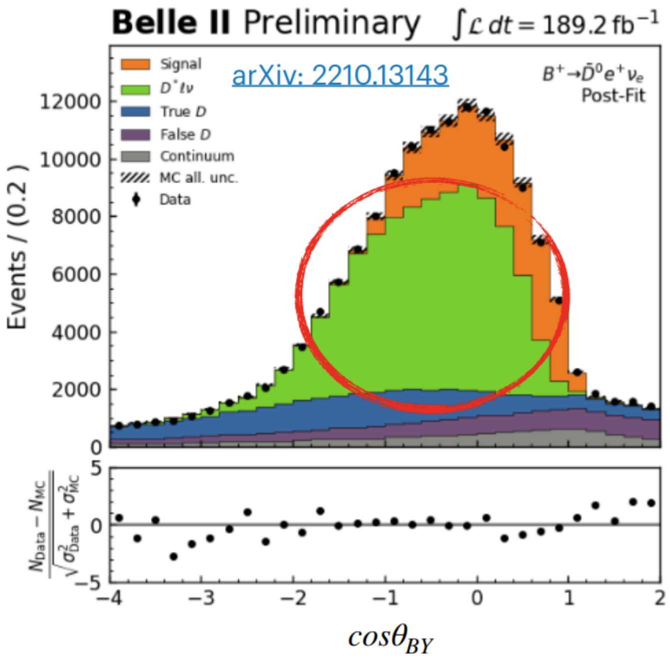
1) slow-pion reconstruction efficiency $\to$ 1.5% on $|V_{cb}|$

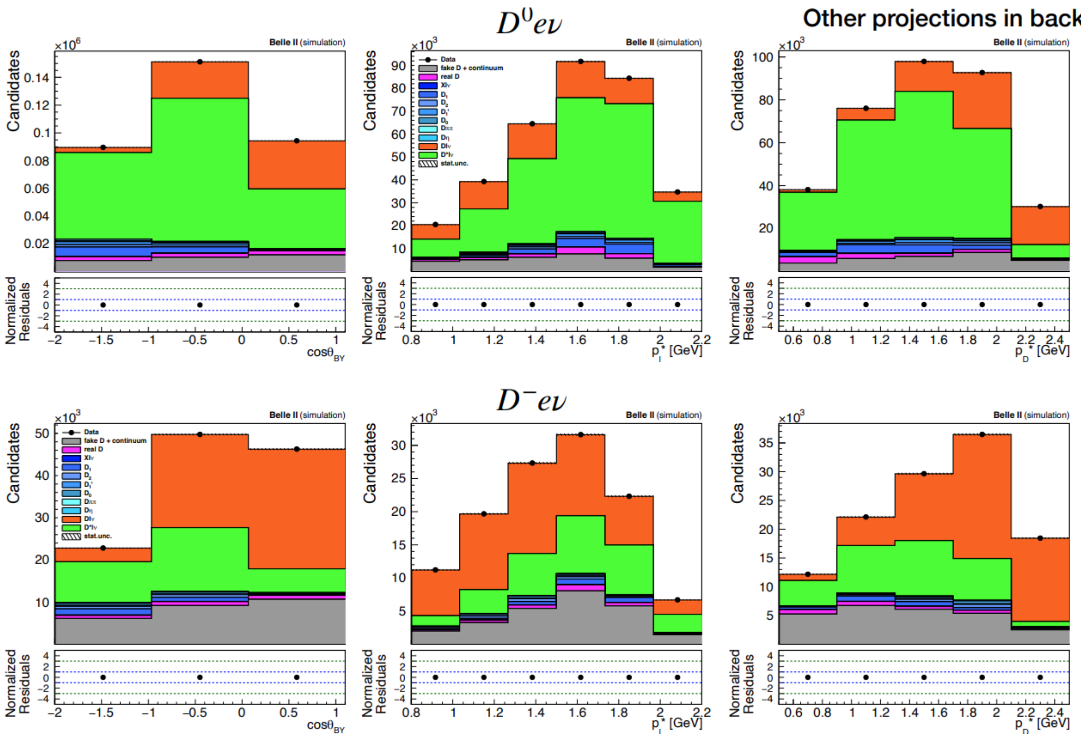
2) $f_{+0} = \dfrac{\mathcal{B}(\Upsilon(4S) \to B^+B^-)}{\mathcal{B}(\Upsilon(4S) \to B^0\bar{B}^0)} \to$ 1.3% on $|V_{cb}|$

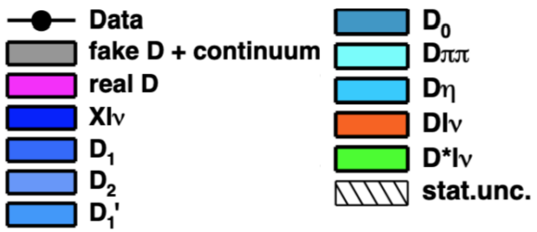
Untagged Combined $\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell$ Strategy

Ongoing analysis – Today: Sensitivity Study

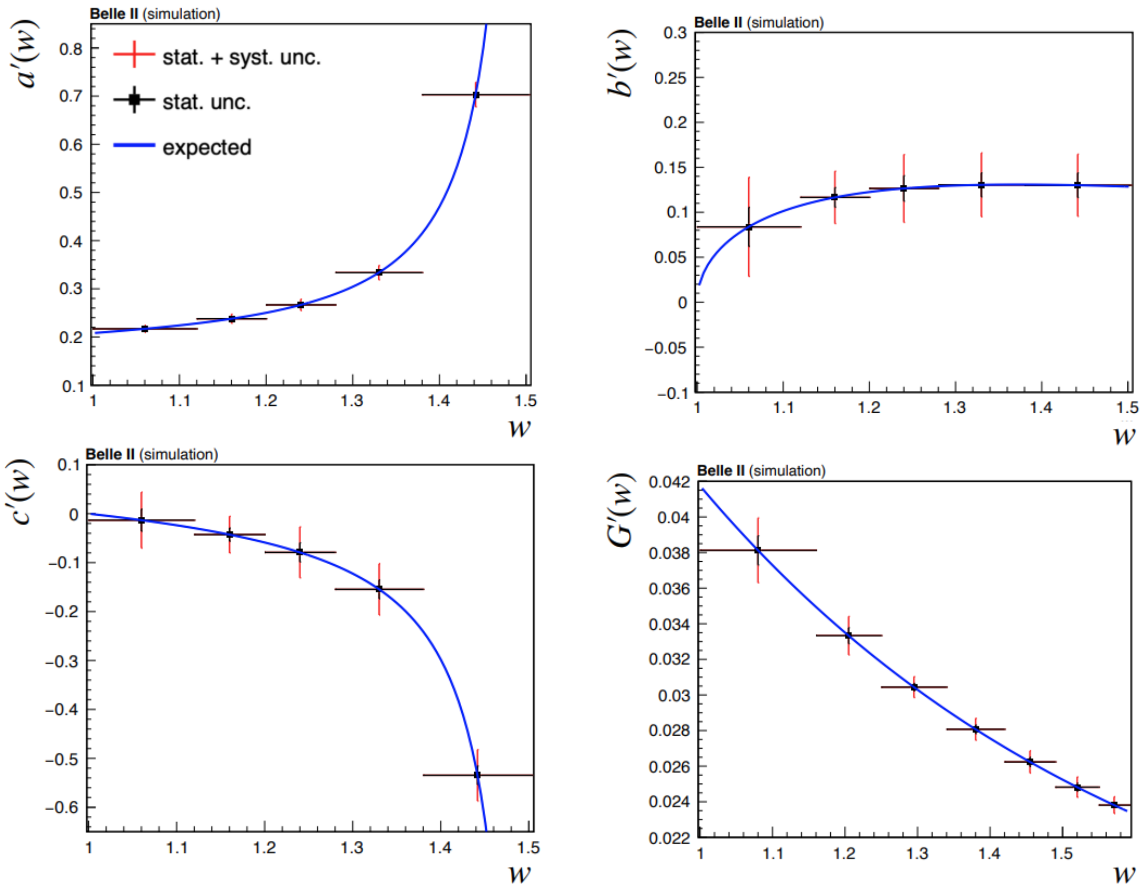
- Combined analyses allows to utilize $B \to D^*\ell\bar{\nu}_\ell$ downfeed also as signal
- Avoids one of the dominant systematics from the slow pion efficiency
- Directly fit helicity coefficients via forward folding to kinematic observables







Untagged Combined $\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell$



$$\frac{d^2\Gamma}{dw\,d\cos\theta_\ell} \propto \Gamma_0(w)\,|V_{cb}|^2 \Big\{ \underbrace{H_+^2(w) + H_-^2(w) + 2H_0^2(w)}_{a(w)} + 2\underbrace{[H_-^2(w) - H_+^2(w)]}_{b(w)}\cos\theta_\ell + \underbrace{[H_+^2(w) + H_-^2(w) - 2H_0^2(w)]}_{c(w)}\cos^2\theta_\ell \Big\}$$

$a'(w), b'(w), c'(w)$, measured in 5 bins of w

$$\frac{d\Gamma}{dw} \propto \Gamma_0(w)\,|V_{cb}|^2\,|G(w)|^2$$

$G'(w)$, measured in 7 bins of w

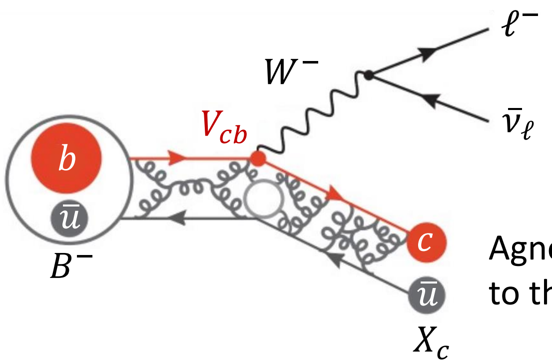
	Relative uncertainties [%] on $\mathcal{B}(B \to D\ell\nu)$	Relative uncertainties [%] on $\mathcal{B}(B \to D^*\ell\nu)$	Relative uncertainties [%] on f_{+-}/f_{00}
NBB	1.5	1.5	< 0.1
BR(D decays)	1.0	0.7	1.9
Lifetime ratio	0.2	0.2	0.4
track efficiency	0.8	0.8	0.2
BR(D** + gap)	1.3	1.2	1.1
Backgrounds modelling	0.6	0.3	1.0
MC stat	0.1	0.1	0.1
Coulomb factor (th. unc.)	1.0	1.1	2.3
TOTAL SYST	2.0 (syst) + 1.0 (th.)	1.9 (syst) + 1.1 (th.)	2.0 (syst) + 2.3 (th.)
Stat	0.3	0.2	0.3

Competitive with world's best measurements

Inclusive $\bar{B} \to X_c \ell \bar{\nu}_\ell$

Hadronic Tagged

Inclusive $B \to X_c \ell \bar{\nu}_\ell$



Agnostic with respect to the hadronic system

The theoretical framework is Operator Product Expansion (OPE) and Heavy Quark Expansion (HQE)

$$d\Gamma = d\Gamma_0 + d\Gamma_{\mu_\pi} \frac{\mu_\pi^2}{m_b^2} + d\Gamma_{\mu_G} \frac{\mu_G^2}{m_b^2} + d\Gamma_{\rho_D} \frac{\rho_D^3}{m_b^3} + d\Gamma_{\rho_{LS}} \frac{\rho_{LS}^3}{m_b^3} + \mathcal{O}(1/m_b^4)$$

$d\Gamma$ are calculated perturbatively

Available at $\mathcal{O}(\alpha_s^3)$
Fael, Schönwald, Steinhauser
Phys. Rev. D 104, 016003 (2021)

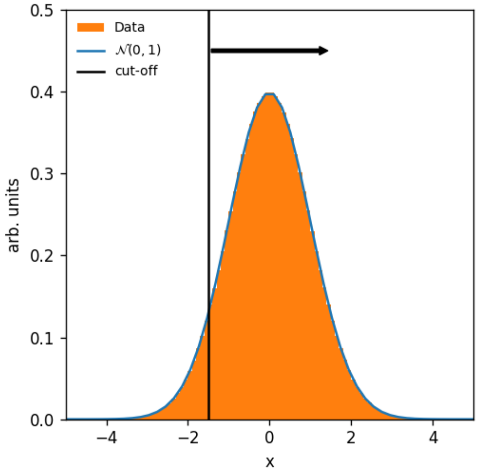
$\mu_\pi, \mu_G, \rho_D, \rho_{LS}$ encapsulate non-perturbative dynamics

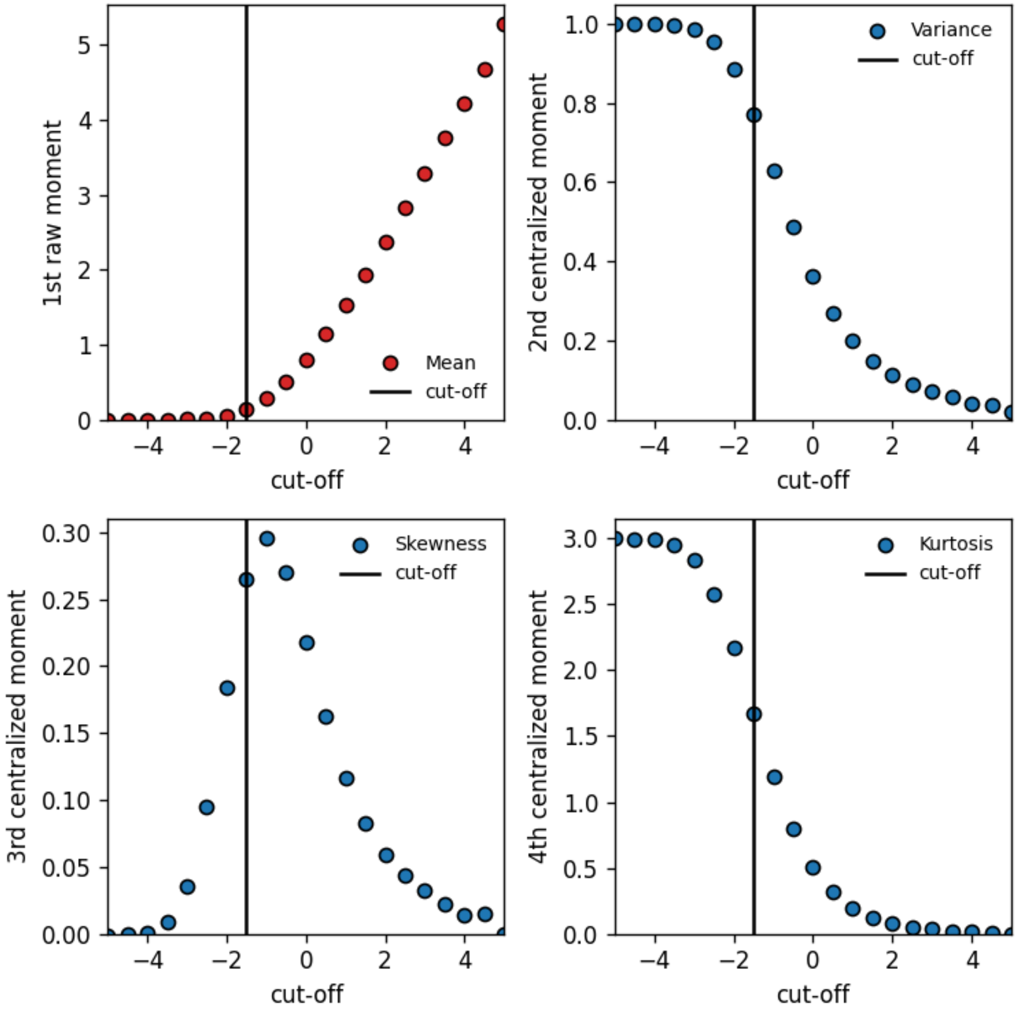
HQE parameters must be extracted from data

requires the spectral moments of $B \to X_c \ell \nu$

Challenge: Proliferation of HQE parameters at higher order

Spectral Moments of a Distribution





- The moments are measured with cut-offs in the distribution
- Data points are highly-correlated

$$\mu_n = \int_{-\infty}^{-\infty} (x - c)^n f(x) dx$$

Raw moment: $c = 0$
Central moment: $c = \text{Mean}$

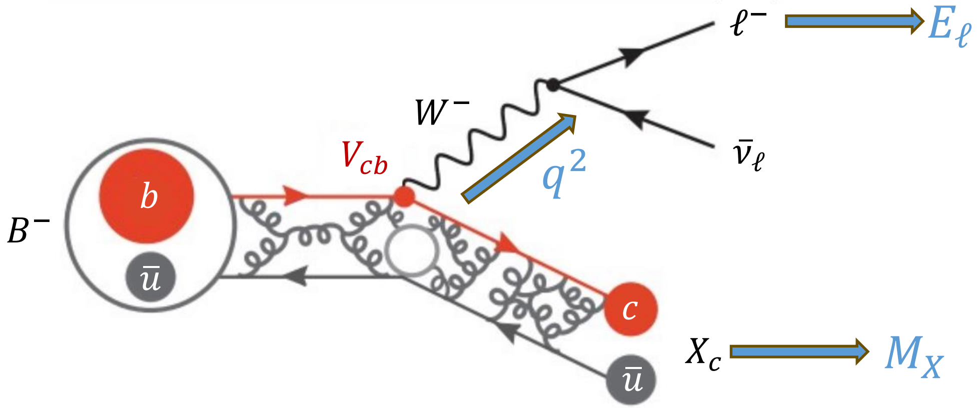
First raw moment: Mean
Measures the location

Second central moment: Variance
Measures the spread

Third central moment: Skewness
Measures asymmetry

Fourth central moment: Kurtosis
Measures "tailedness"

Inclusive $B \to X_c \ell \bar{\nu}_\ell$ - Existing Measurements



$\langle E_\ell \rangle$ and $\langle M_X \rangle$

- DELPHI
  Eur.Phys.J.C45:35-59,2006
- CLEO
  Phys.Rev.D70:032002,2004
  Phys.Rev.D70:032003,2004
- CDF
  Phys.Rev.D71:051103,2005
- Babar
  Phys.Rev.D69:111104,2004
  Phys.Rev.D81:032003,2010
- Belle
  Phys.Rev.D75:032005,2007
  Phys.Rev.D75:032001,2007

11 years

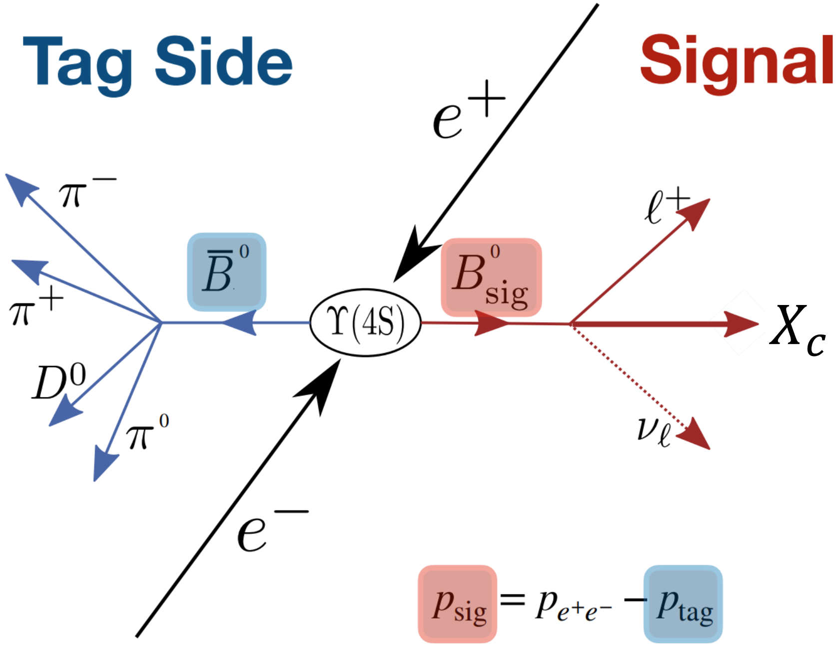
$\langle q^2 \rangle$

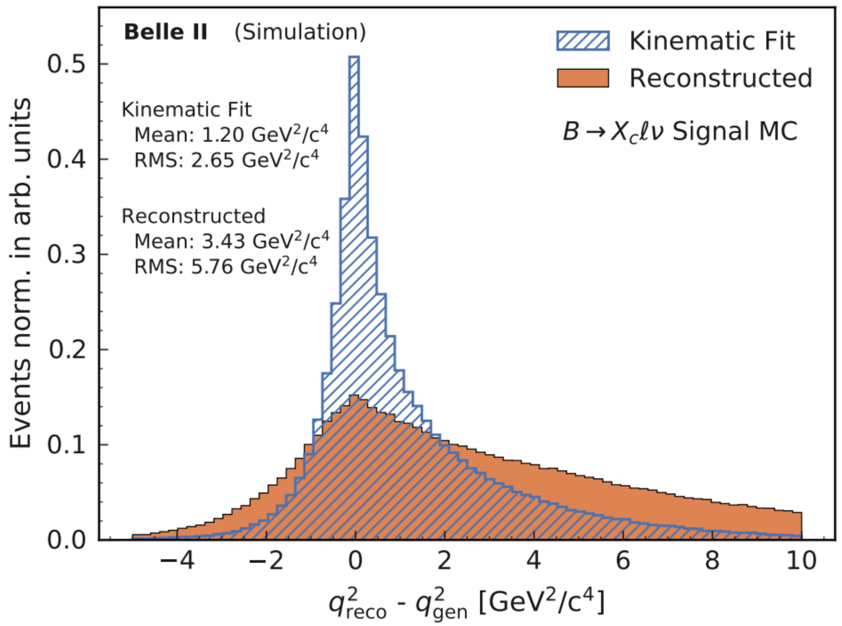
- Belle
  Phys.Rev.D 104 (2021) 11, 112011
- Belle II
  Phys.Rev.D 107 (2023) 7, 072002

Both analyses are conceptually identical

$\langle q^2 \rangle$ Moments – Measurement Strategy

Key-techniques: Hadronic tagging and kinematic fitting exploit the known initial state kinematics





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

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

Kinematic constraints:

$$\hat{p}_X^2 > 0,\ \hat{p}_{B_{tag}}^2 = m_B^2$$

$$(\hat{p}_\ell + \hat{p}_X + \hat{p}_\nu)^2 = m_B^2$$

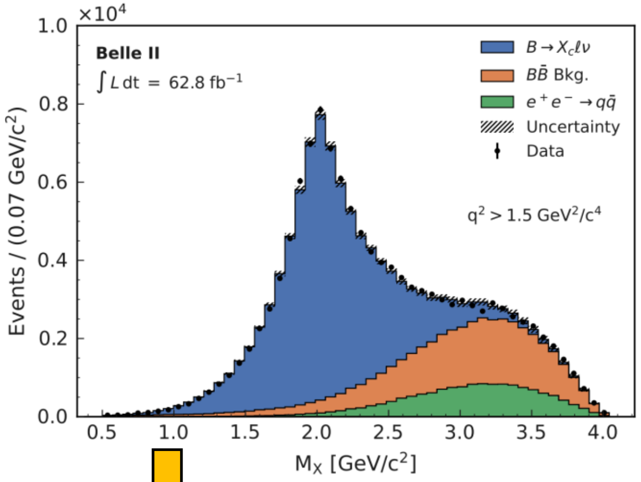
$$\left(\hat{p}_{e^+e^-} - \hat{p}_{B_{tag}} - \hat{p}_\ell - \hat{p}_X - \hat{p}_\nu\right) = 0$$

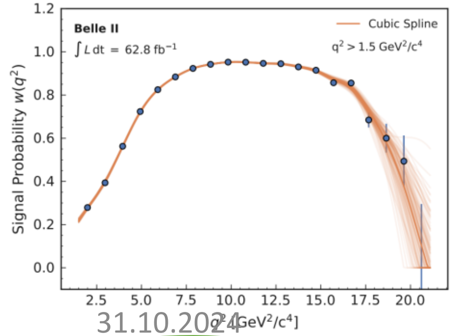
$\langle q^2 \rangle$ Moments – Background Subtraction

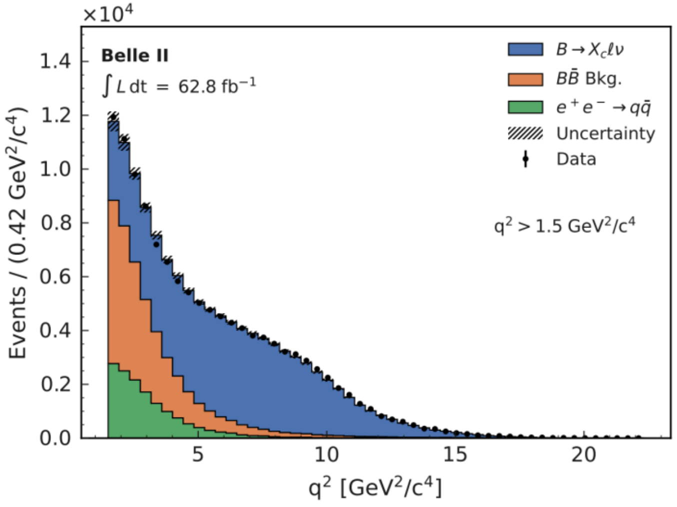
Event-wise master formula

$$\langle q^{2n} \rangle = \frac{\Sigma_{i=0}^{N_{data}} w(q_i^2) \times q_{calib,i}^{2n}}{\Sigma_{j=0}^{N_{data}} w(q_j^2)} \times \mathcal{C}_{calib} \times \mathcal{C}_{gen}$$

Determine background normalization in q^2 through fits to M_X







Calculate event-wise signal probability

- Linear calibration function
  $q_{calib}^{2n} = (q_{reco}^{2n} - c_n)/m_n$
- Bias from assumed linearity
  $\mathcal{C}_{calib} = \langle q_{gen,sel}^{2n} \rangle / \langle q_{calib}^{2n} \rangle$
- Reconstruction effects & final state radiation
  $\mathcal{C}_{gen} = \langle q_{gen}^{2n} \rangle / \langle q_{gen,sel}^{2n} \rangle$

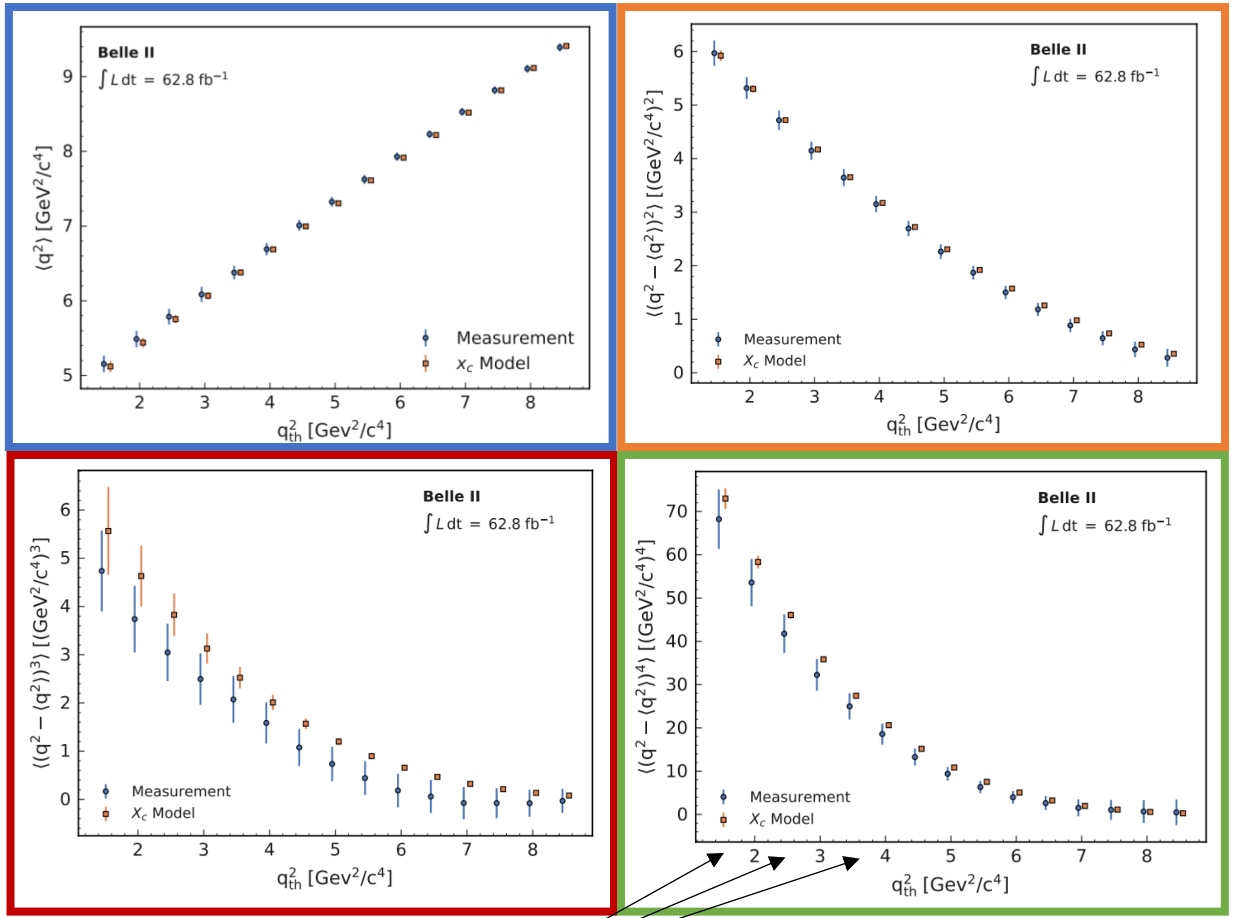
$\langle q^2 \rangle$ Moments – Result

$$\mu_n = \int_{-\infty}^{-\infty} (x-c)^n f(x) dx$$

Raw moment: $c = 0$

Central moment: $c = \text{Mean}$

$\langle q^2 \rangle$ Moments



cut-offs

First raw moment: Mean

Measures the location

Second central moment: Variance

Measures the spread

Third central moment: Skewness

Measures asymmetry

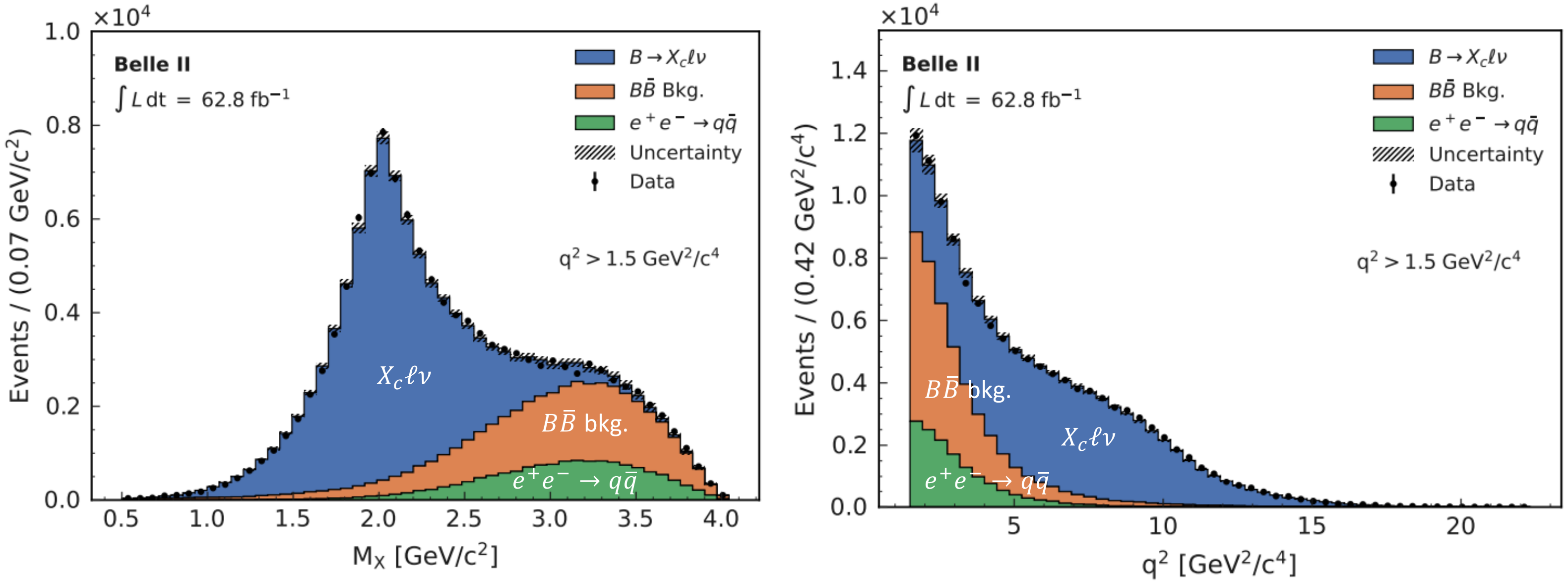
Fourth central moment: Kurtosis

Measures "tailedness"

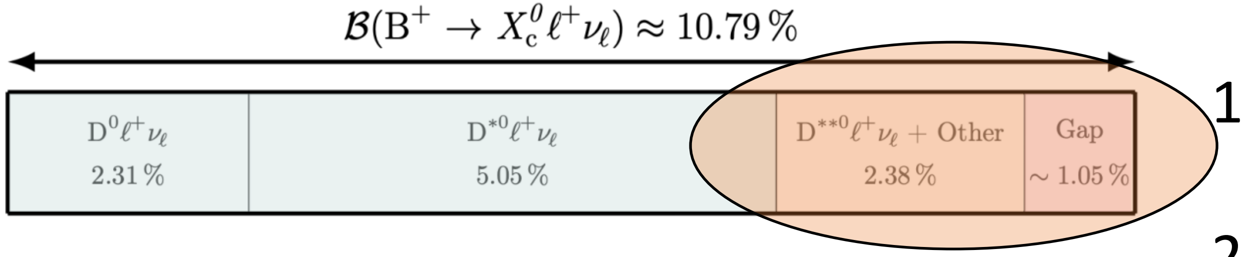
Systematics

- Background yields and shape
- Composition of the X_c system
- Simulated detector resolution

$\langle q^2 \rangle$ Moments – Systematics

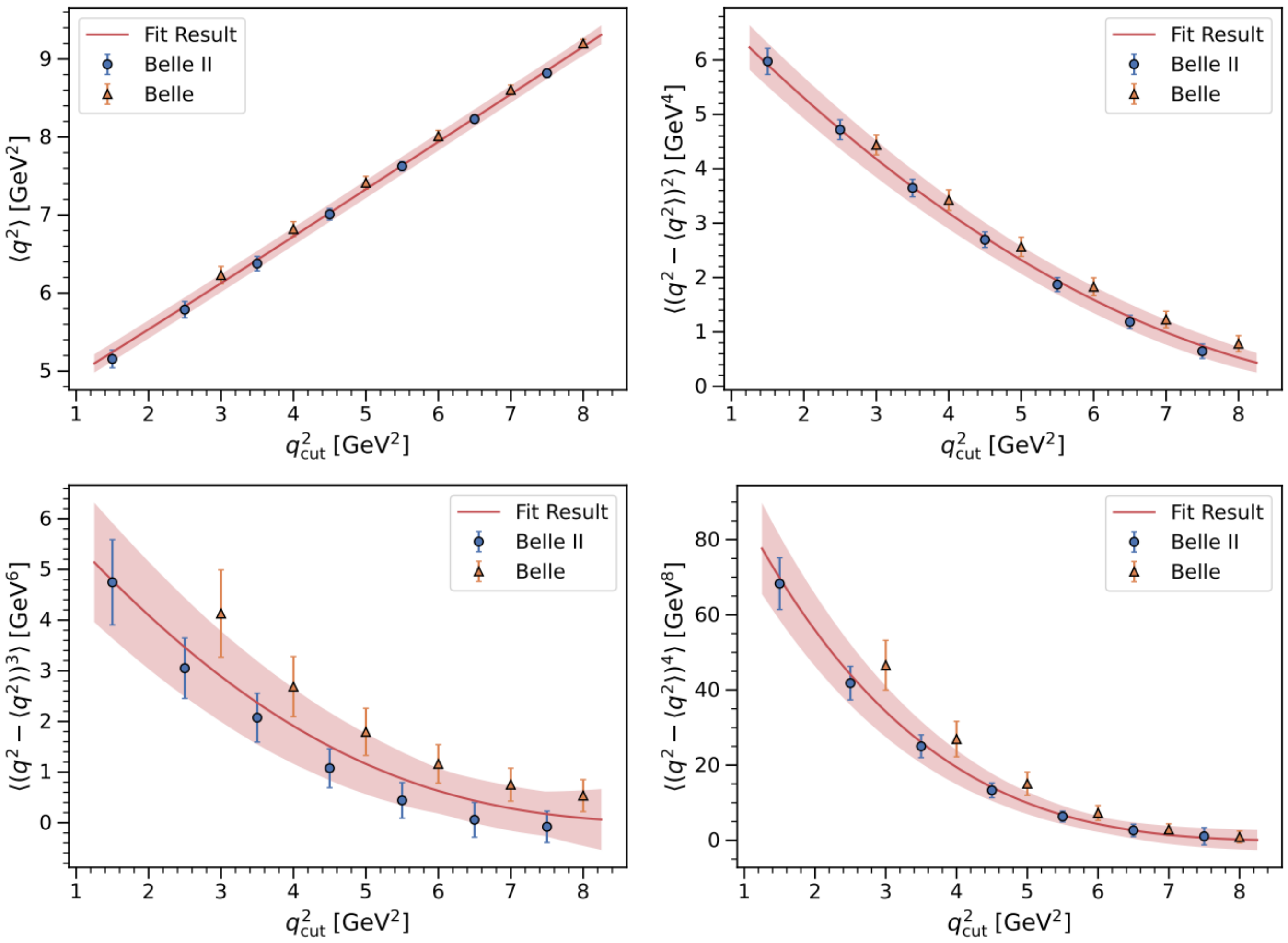


Sizeable uncertainty from the $B \to X_c \ell \bar{\nu}_\ell$ modelling



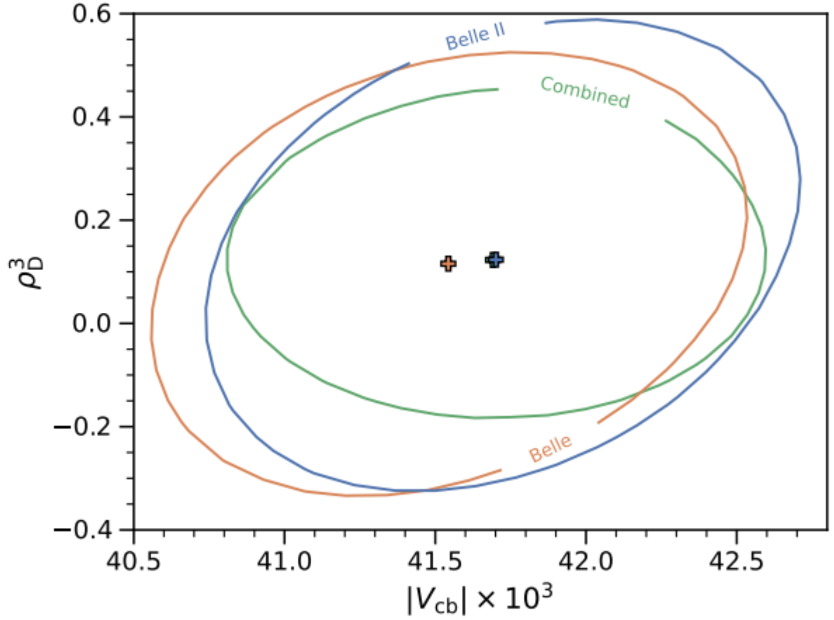
1. Better understanding of $B \to D^{**} \ell \bar{\nu}_\ell$
   → Differential measurements
2. Better understanding of D^{**} states
   → Spectroscopy

Combined fit to Belle & Belle II $\langle q^2 \rangle$



$$|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}$$

Bernlochner, Fael, Olschwesky, Persson, van Tonder, Vos, Welsch JHEP 10 (2022) 068

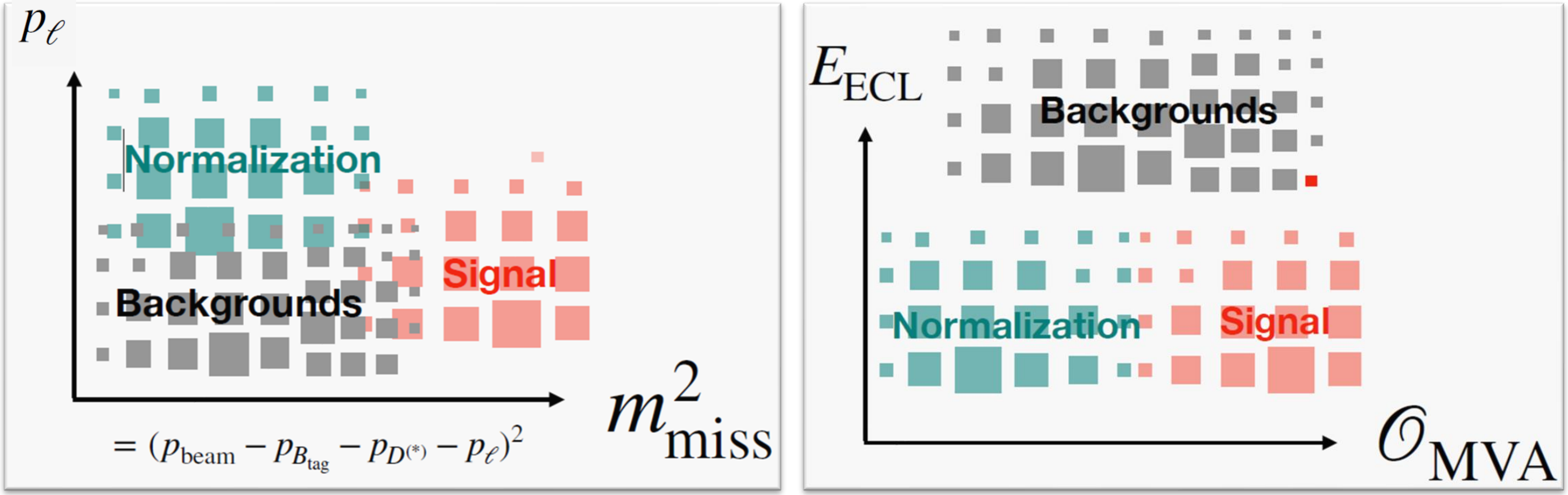


$R\left(D^{(*)}\right)$

Hadronic and Semileptonic Tagged

Generic Strategy at B-Factories

- **3-class classification problem:** signal, normalization, background
- Normalization chosen to cancel systematics (same topology and/or final state)



Nice illustration by F. Bernlochner

Leverage **fully known kinematics** and that **each reconstructed particle is assigned** to a decay

Belle Legacy Results

Had. Tag
$\tau \to \ell$

Belle, Phys.Rev.D 92, 072014 (2015)

$$R(D) = 0.375 \pm 0.064 \pm 0.026$$
$$R(D^*) = 0.293 \pm 0.038 \pm 0.015$$

SL Tag
$\tau \to \ell$

Belle, Phys. Rev. Lett. 124, 161803 (2020)

$$R(D) = 0.307 \pm 0.037 \pm 0.016$$
$$R(D^*) = 0.283 \pm 0.018 \pm 0.014$$

Had. Tag
$\tau \to \ell$

BaBar, Phys.Rev.D 88, 072012 (2013)

$$R(D) = 0.440 \pm 0.058 \pm 0.042$$
$$R(D^*) = 0.332 \pm 0.024 \pm 0.018$$

Had. Tag
$\tau \to \pi, \rho$

Belle, Phys. Rev. D 97, 012004 (2018)

$$P_\tau(D^*) = -0.38 \pm 0.51 \pm^{0.21}_{0.16}$$
$$R(D^*) = 0.270 \pm 0.035 \pm^{0.028}_{0.025}$$

And the Start of a New Era

Had. Tag
$\tau \to \ell$

Belle, Phys.Rev.D 92, 072014 (2015)

$$R(D) = 0.375 \pm 0.064 \pm 0.026$$
$$R(D^*) = 0.293 \pm 0.038 \pm 0.015$$

Had. Tag
$\tau \to \ell$

BaBar, Phys.Rev.D 88, 072012 (2013)

$$R(D) = 0.440 \pm 0.058 \pm 0.042$$
$$R(D^*) = 0.332 \pm 0.024 \pm 0.018$$

SL Tag
$\tau \to \ell$

Belle, Phys. Rev. Lett. 124, 161803 (2020)

$$R(D) = 0.307 \pm 0.037 \pm 0.016$$
$$R(D^*) = 0.283 \pm 0.018 \pm 0.014$$

Had. Tag
$\tau \to \pi, \rho$

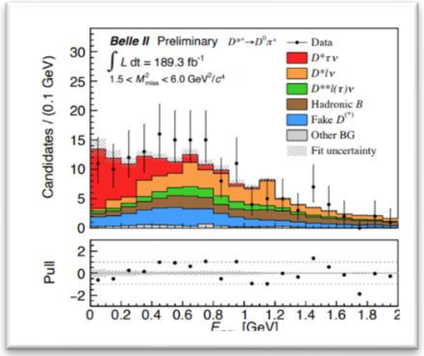
Belle, Phys. Rev. D 97, 012004 (2018)

$$P_\tau(D^*) = -0.38 \pm 0.51 \pm^{0.21}_{0.16}$$
$$R(D^*) = 0.270 \pm 0.035 \pm^{0.028}_{0.025}$$

Had. Tag
$\tau \to \ell$

Belle II, arXiv:2401.02840

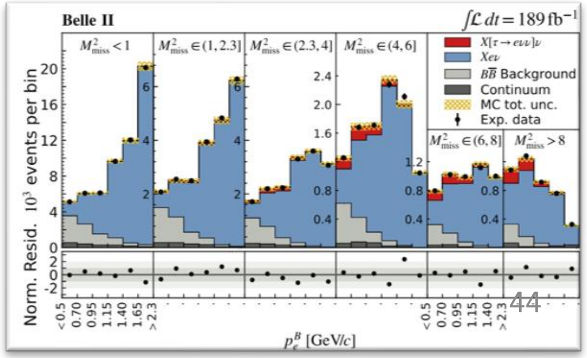
$$R(D^*) = 0.262 \pm^{0.041}_{0.039} \pm^{0.035}_{0.032}$$



Had. Tag
$\tau \to \ell$

Belle II, arXiv:2311.07248

$$R(X) = 0.228 \pm 0.016 \pm 0.036$$



Challenges: Form Factors

Result	Experiment	τ decay	Tag	Systematic uncertainty [%] MC stats	$D^{(*)}l\nu$	$D^{**}l\nu$	Other bkg.	Other sources	Total uncert. [%] Syst.	Stat.	Total
$\mathcal{R}(D)$	*BABAR* [a]	$\ell\nu\nu$	Had.	5.7	2.5	5.8	3.9	0.9	**9.6**	**13.1**	**16.2**
	Belle[b]	$\ell\nu\nu$	Semil.	4.4	0.7	0.8	1.7	3.4	**5.2**	**12.1**	**13.1**
	Belle[c]	$\ell\nu\nu$	Had.	4.4	3.3	4.4	0.7	0.5	**7.1**	**17.1**	**18.5**
$\mathcal{R}(D^*)$	*BABAR* [a]	$\ell\nu\nu$	Had.	2.8	1.0	3.7	2.3	0.9	**5.6**	**7.1**	**9.0**
	Belle[b]	$\ell\nu\nu$	Semil.	2.3	0.3	1.4	0.5	4.7	**4.9**	**6.4**	**8.1**
	Belle[c]	$\ell\nu\nu$	Had.	3.6	1.3	3.4	0.7	0.5	**5.2**	**13.0**	**14.0**
	Belle[d]	$\pi\nu$, $\rho\nu$	Had.	3.5	2.3	2.4	8.1	2.9	**9.9**	**13.0**	**16.3**
	LHCb[e]	$\pi\pi\pi(\pi^0)\nu$	—	4.9	4.0	2.7	5.4	4.8	**10.2**	**6.5**	**12.0**
	LHCb[f]	$\mu\nu\nu$	—	6.3	2.2	2.1	5.1	2.0	**8.9**	**8.0**	**12.0**

[a] (Lees *et al.*, 2012, 2013)
[b] (Caria *et al.*, 2020) [c] (Huschle *et al.*, 2015) [d] (Hirose *et al.*, 2018) [e] (Aaij *et al.*, 2015c) [f] (Aaij *et al.*, 2018b)

F. Bernlochner, M. Franco Sevilla, D. Robinson, G. Wormser
arXiv:2101.08326, Review of Modern Physics

Source	Uncertainty
PDF shapes	$^{+9.1\%}_{-8.3\%}$
Simulation sample size	$^{+7.5\%}_{-7.5\%}$
$\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell$ branching fractions	$^{+4.8\%}_{-3.5\%}$
Fixed backgrounds	$^{+2.7\%}_{-2.3\%}$
Hadronic B decay branching fractions	$^{+2.1\%}_{-2.1\%}$
Reconstruction efficiency	$^{+2.0\%}_{-2.0\%}$
Kernel density estimation	$^{+2.0\%}_{-0.8\%}$
Form factors	$^{+0.5\%}_{-0.1\%}$
Peaking background in ΔM_{D^*}	$^{+0.4\%}_{-0.4\%}$
$\tau^- \to \ell^-\nu_\tau\bar{\nu}_\ell$ branching fractions	$^{+0.2\%}_{-0.2\%}$
$R(D^*)$ fit method	$^{+0.1\%}_{-0.1\%}$
Total systematic uncertainty	$^{+13.5\%}_{-12.3\%}$

Belle II $R(D^*)$
arXiv:2401.02840

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

Belle II $R(X)$
arXiv:2311.07248

LHCb $R(D^+)$ LHCb-PAPER-2024-007

Source	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$
Form factors	0.023	0.035
$B \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$\overline{B}^{+/0} \to D^+X_cX$ fraction	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.086

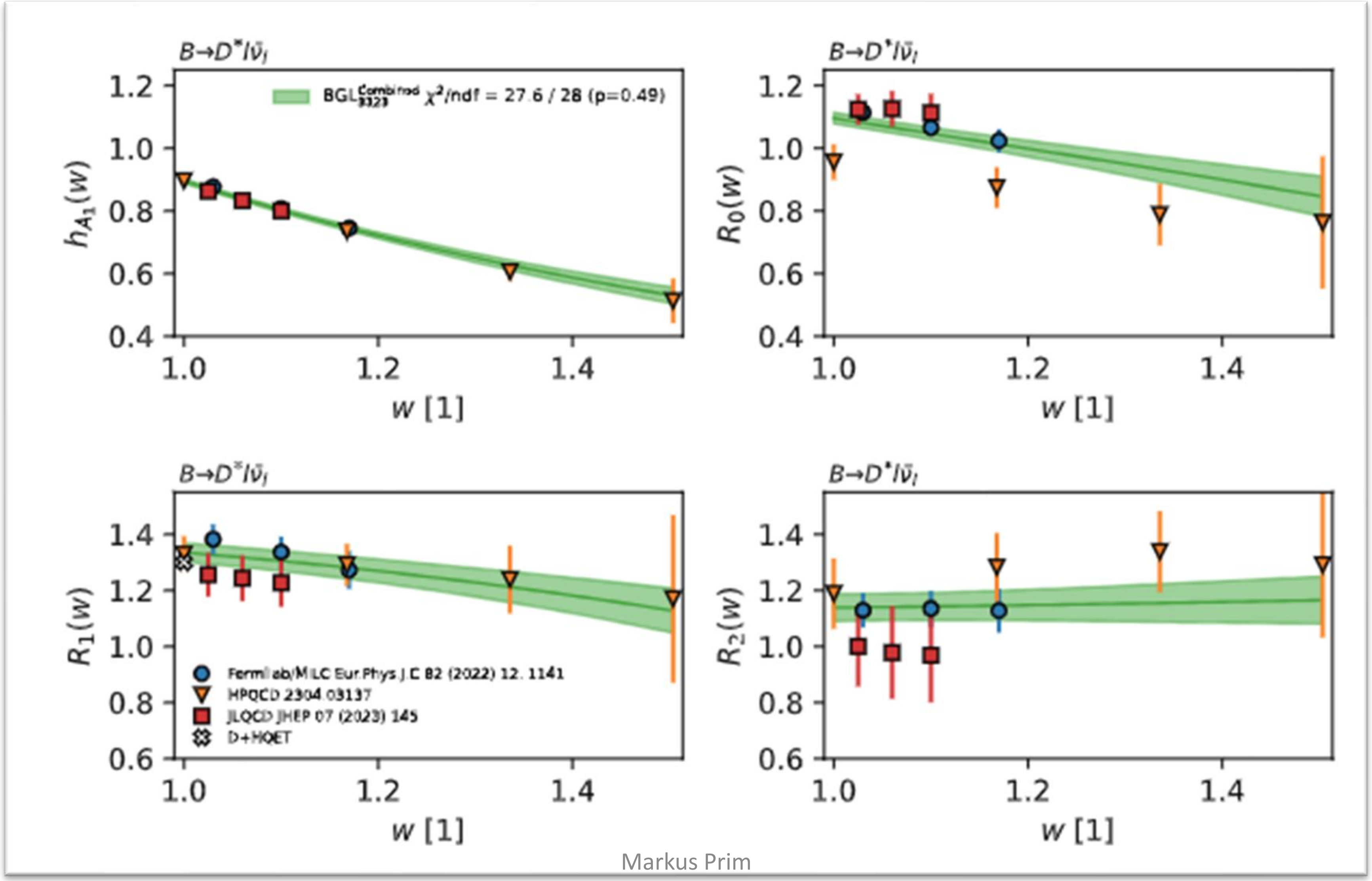
$B \to D^{(*)}\ell\overline{\nu}_\ell$ **form factors** impact the efficiency determination

- Lots of progress from lattice community: nonzero-recoil $B \to D^*$ form factors

  Fermilab/MILC arXiv:2105.14019
  HPQCD arXiv:2304.03137
  JLQCD arXiv:2306.05657

- Lots of progress from the experimental community: new Belle & Belle II measurements of $B \to D^{(*)}\ell\bar{\nu}_\ell$
  - differential distributions — Belle arXiv:2301.07529, PRD; Belle II arXiv:2310.01170, PRD
  - angular coefficients — Belle arXiv:2310.20286

Challenges: Form Factors



Challenges: Feeddown from $\bar{B} \to D^{**} \ell \bar{\nu}_\ell$

Result	Experiment	τ decay	Tag	Systematic uncertainty [%] MC stats	$D^{(*)} l\nu$	$D^{**} l\nu$	Other bkg.	Other sources	Total uncert. [%] Syst.	Stat.	Total
$\mathcal{R}(D)$	*BABAR* [a]	$\ell\nu\nu$	Had.	5.7	2.5	5.8	3.9	0.9	**9.6**	**13.1**	**16.2**
	Belle[b]	$\ell\nu\nu$	Semil.	4.4	0.7	0.8	1.7	3.4	**5.2**	**12.1**	**13.1**
	Belle[c]	$\ell\nu\nu$	Had.	4.4	3.3	4.4	0.7	0.5	**7.1**	**17.1**	**18.5**
$\mathcal{R}(D^*)$	*BABAR* [a]	$\ell\nu\nu$	Had.	2.8	1.0	3.7	2.3	0.9	**5.6**	**7.1**	**9.0**
	Belle[b]	$\ell\nu\nu$	Semil.	2.3	0.3	1.4	0.5	4.7	**4.9**	**6.4**	**8.1**
	Belle[c]	$\ell\nu\nu$	Had.	3.6	1.3	3.4	0.7	0.5	**5.2**	**13.0**	**14.0**
	Belle[d]	$\pi\nu$, $\rho\nu$	Had.	3.5	2.3	2.4	8.1	2.9	**9.9**	**13.0**	**16.3**
	LHCb[e]	$\pi\pi\pi(\pi^0)\nu$	—	4.9	4.0	2.7	5.4	4.8	**10.2**	**6.5**	**12.0**
	LHCb[f]	$\mu\nu\nu$	—	6.3	2.2	2.1	5.1	2.0	**8.9**	**8.0**	**12.0**

[a] (Lees *et al.*, 2012, 2013)
[b] (Caria *et al.*, 2020) [c] (Huschle *et al.*, 2015) [d] (Hirose *et al.*, 2018) [e] (Aaij *et al.*, 2015c) [f] (Aaij *et al.*, 2018b)

F. Bernlochner, M. Franco Sevilla, D. Robinson, G. Wormser
arXiv:2101.08326, Review of Modern Physics

Source	Uncertainty
PDF shapes	$^{+9.1\%}_{-8.3\%}$
Simulation sample size	$^{+7.5\%}_{-7.5\%}$
$\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell$ branching fractions	$^{+4.8\%}_{-3.5\%}$
Fixed backgrounds	$^{+2.7\%}_{-2.3\%}$
Hadronic B decay branching fractions	$^{+2.1\%}_{-2.1\%}$
Reconstruction efficiency	$^{+2.0\%}_{-2.0\%}$
Kernel density estimation	$^{+2.0\%}_{-0.8\%}$
Form factors	$^{+0.5\%}_{-0.1\%}$
Peaking background in ΔM_{D^*}	$^{+0.4\%}_{-0.4\%}$
$\tau^- \to \ell^-\nu_\tau\bar{\nu}_\ell$ branching fractions	$^{+0.2\%}_{-0.2\%}$
$R(D^*)$ fit method	$^{+0.1\%}_{-0.1\%}$
Total systematic uncertainty	$^{+13.5\%}_{-12.3\%}$

Belle II $R(D^*)$
arXiv:2401.02840

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

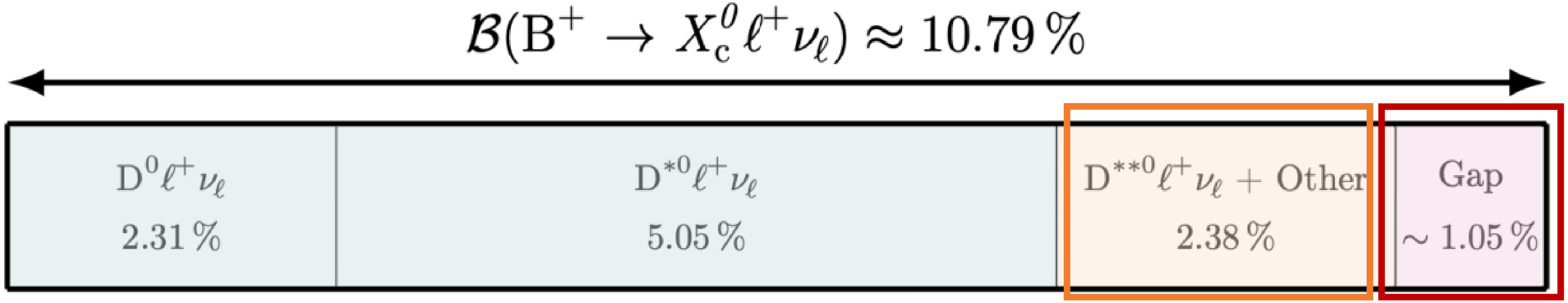
Belle II $R(X)$
arXiv:2311.07248

Sizeable systematic impact from **$B \to D^{**}\ell\bar{\nu}_\ell$ decays**

LHCb $R(D^+)$ LHCb-PAPER-2024-007

Source	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$
Form factors	0.023	0.035
$B \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$\overline{B}^{+/0} \to D^+X_cX$ fraction	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.086

Challenges: Feeddown from $\bar{B} \to D^{**}\ell\bar{\nu}_\ell$



Discrepancies in the measurements of $B \to D^{**}\ell\bar{\nu}_\ell$

- Tension in the available measurements
- Tension with theory prediction: $^1/_2 \leftrightarrow {}^3/_2$ puzzle
- The nature of the D^{**} states is unclear

inclusive ≠ sum of exclusive

- These poorly understood components lead to a sizeable systematic effect in the experimental measurements
- Common for Belle II & LHCb

Challenges: Feeddown from $\bar{B} \to D^{**}\ell\bar{\nu}_\ell$

- Is the $D_0^*(2300)$ a resonance from the quark model, or a more complex structure described by $\boldsymbol{U\chi PT}$?
- Form factors for semileptonic $\bar{B} \to D^{**}\ell\bar{\nu}_\ell$ decays assume the narrow width approximation for the broad D^{**}

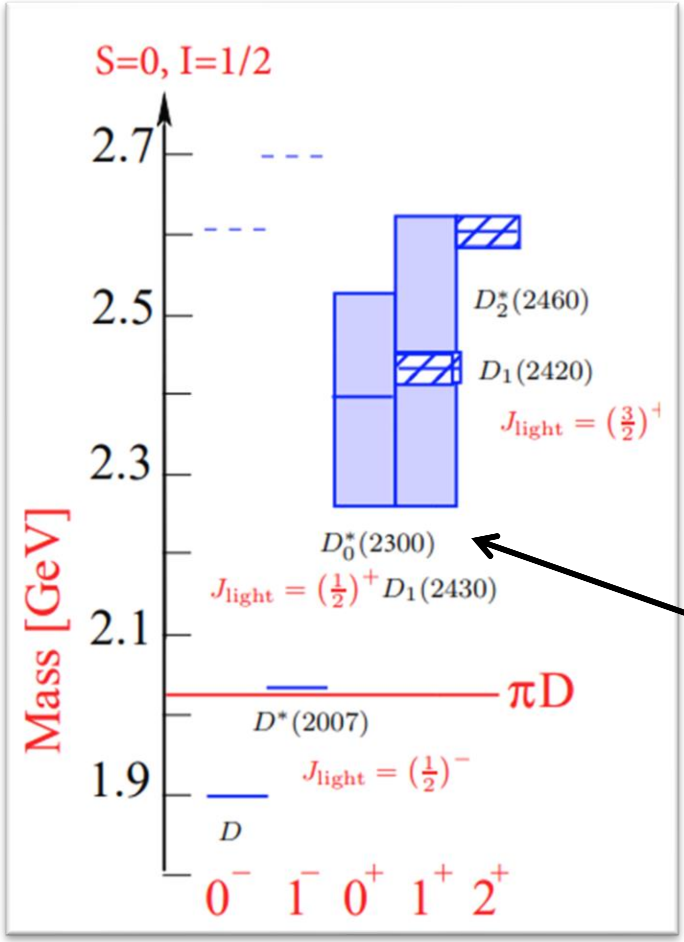
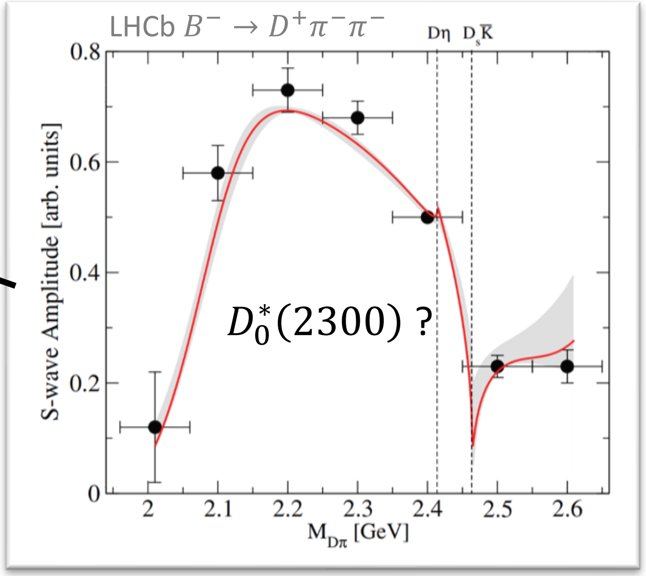
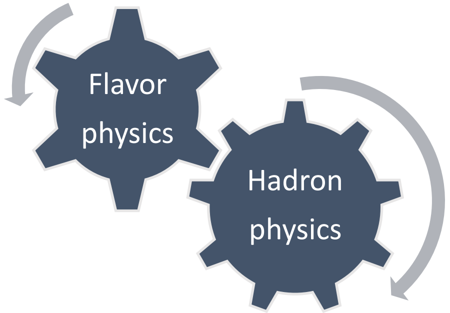


Illustration by C. Hanhart

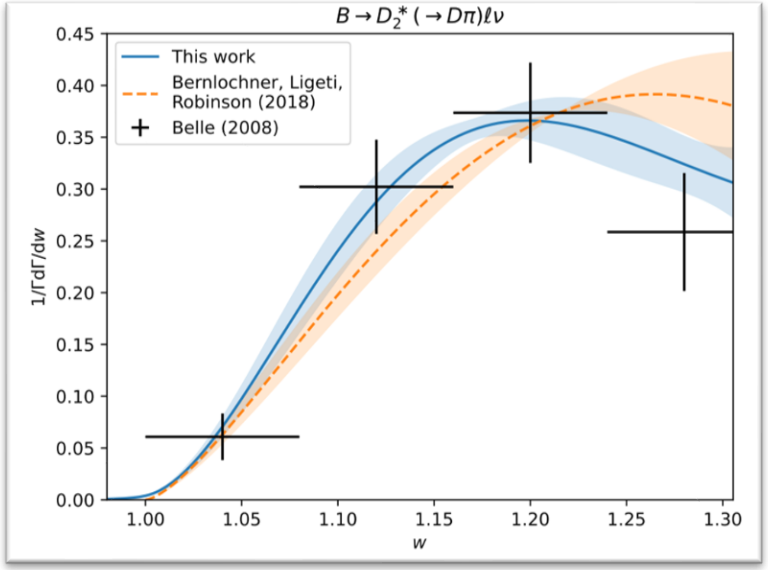




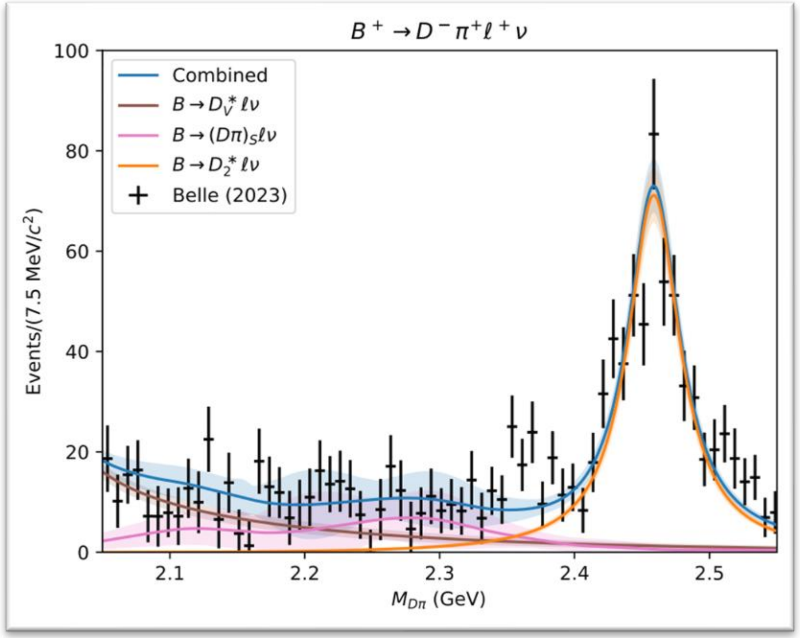
Inputs from hadron physics (theory and experiment) will drive us forward

Challenges: Feeddown from $\bar{B} \to D^{**}\ell\bar{\nu}_\ell$

- Is the $D_0^*(2300)$ a resonance from the quark model, or a more complex structure described by $\boldsymbol{U\chi PT}$?
- Form factors for semileptonic $\bar{B} \to D^{**}\ell\bar{\nu}_\ell$ decays assume the narrow width approximation for the broad D^{**}

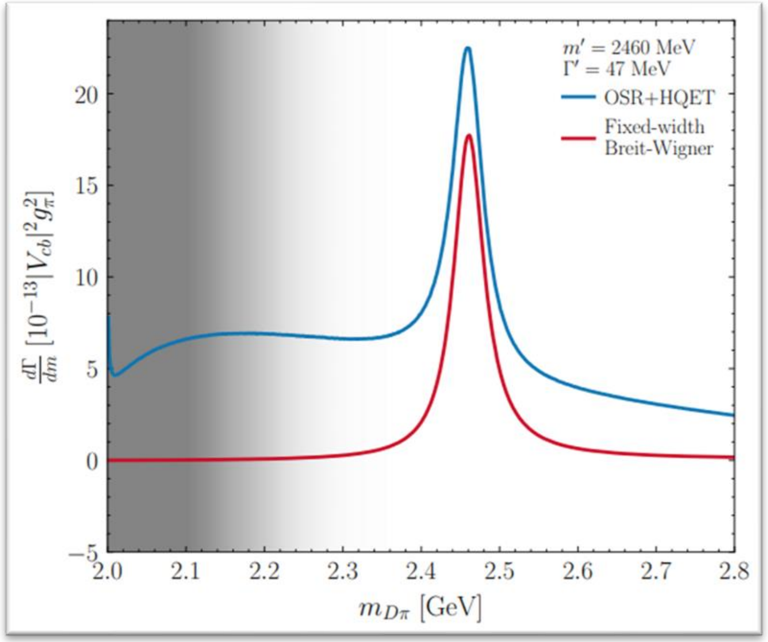


- Modelling of $\bar{B} \to D^{**}\ell\bar{\nu}_\ell$ decays in simulation depends on proper knowledge of form factors
- Background estimation challenging
- Active progress from our theory colleagues



BGL generalization

E. J. Gustafson, F. Herren, R. S. Van de Water, R. van Tonder, M. L. Wagman
arXiv:2311.00864



On-shell recursion + HQET

C. A. Manzari, D. J. Robinson
arXiv:2402.12460

Challenges: Simulation Sample Size

Result	Experiment	τ decay	Tag	Systematic uncertainty [%] MC stats	$D^{(*)}l\nu$	$D^{**}l\nu$	Other bkg.	Other sources	Total uncert. [%] Syst.	Stat.	Total
$\mathcal{R}(D)$	*BABAR* [a]	$\ell\nu\nu$	Had.	5.7	2.5	5.8	3.9	0.9	**9.6**	**13.1**	**16.2**
	Belle[b]	$\ell\nu\nu$	Semil.	4.4	0.7	0.8	1.7	3.4	**5.2**	**12.1**	**13.1**
	Belle[c]	$\ell\nu\nu$	Had.	4.4	3.3	4.4	0.7	0.5	**7.1**	**17.1**	**18.5**
$\mathcal{R}(D^*)$	*BABAR* [a]	$\ell\nu\nu$	Had.	2.8	1.0	3.7	2.3	0.9	**5.6**	**7.1**	**9.0**
	Belle[b]	$\ell\nu\nu$	Semil.	2.3	0.3	1.4	0.5	4.7	**4.9**	**6.4**	**8.1**
	Belle[c]	$\ell\nu\nu$	Had.	3.6	1.3	3.4	0.7	0.5	**5.2**	**13.0**	**14.0**
	Belle[d]	$\pi\nu$, $\rho\nu$	Had.	3.5	2.3	2.4	8.1	2.9	**9.9**	**13.0**	**16.3**
	LHCb[e]	$\pi\pi\pi(\pi^0)\nu$	—	4.9	4.0	2.7	5.4	4.8	**10.2**	**6.5**	**12.0**
	LHCb[f]	$\mu\nu\nu$	—	6.3	2.2	2.1	5.1	2.0	**8.9**	**8.0**	**12.0**

[a] (Lees *et al.*, 2012, 2013)
[b] (Caria *et al.*, 2020) [c] (Huschle *et al.*, 2015) [d] (Hirose *et al.*, 2018) [e] (Aaij *et al.*, 2015c) [f] (Aaij *et al.*, 2018b)

F. Bernlochner, M. Franco Sevilla, D. Robinson, G. Wormser
arXiv:2101.08326, Review of Modern Physics

Source	Uncertainty
PDF shapes	$^{+9.1\%}_{-8.3\%}$
Simulation sample size	$^{+7.5\%}_{-7.5\%}$
$\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell$ branching fractions	$^{+4.8\%}_{-3.5\%}$
Fixed backgrounds	$^{+2.7\%}_{-2.3\%}$
Hadronic B decay branching fractions	$^{+2.1\%}_{-2.1\%}$
Reconstruction efficiency	$^{+2.0\%}_{-2.0\%}$
Kernel density estimation	$^{+2.0\%}_{-0.8\%}$
Form factors	$^{+0.5\%}_{-0.1\%}$
Peaking background in ΔM_{D^*}	$^{+0.4\%}_{-0.4\%}$
$\tau^- \to \ell^-\nu_\tau\bar{\nu}_\ell$ branching fractions	$^{+0.2\%}_{-0.2\%}$
$R(D^*)$ fit method	$^{+0.1\%}_{-0.1\%}$
Total systematic uncertainty	$^{+13.5\%}_{-12.3\%}$

Belle II $R(D^*)$
arXiv:2401.02840

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

Belle II $R(X)$
arXiv:2311.07248

MC statistics is often the leading systematic uncertainty, needed for:

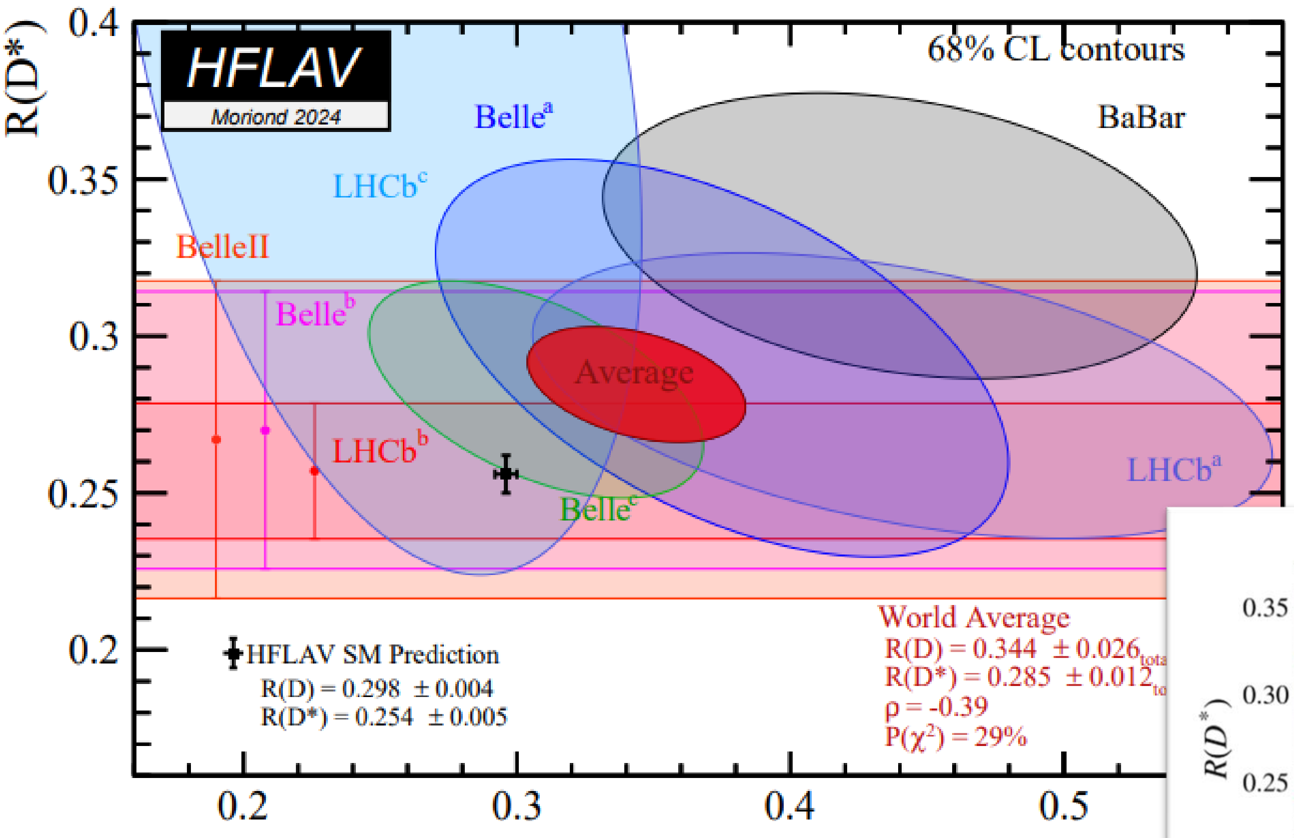
- Fit templates
- Efficiency determination
- Training of MVA classifiers

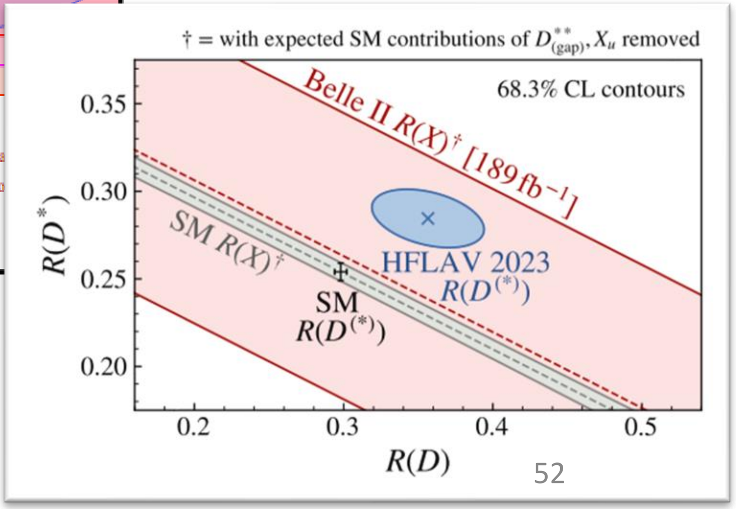
"trivial but costly" to improve

LHCb $R(D^+)$ LHCb-PAPER-2024-007

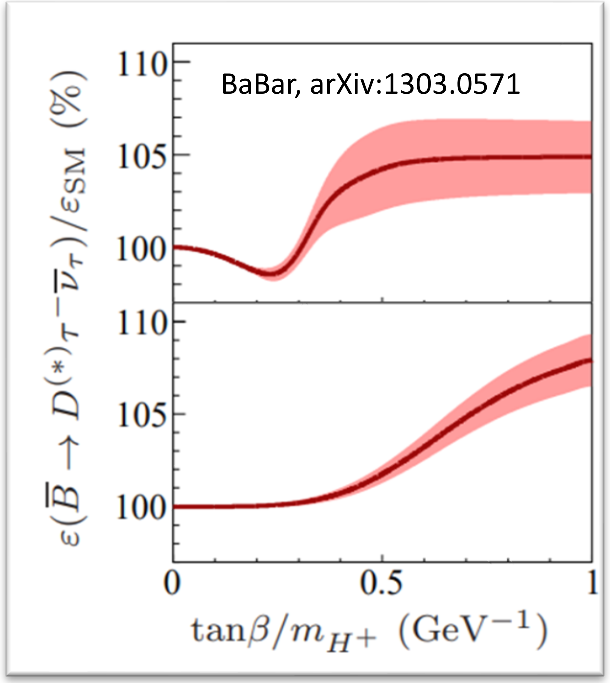
Source	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$
Form factors	0.023	0.035
$\overline{B} \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$\overline{B}^{+/0} \to D^+X_cX$ fraction	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.086

Status Quo & Quo Vadis

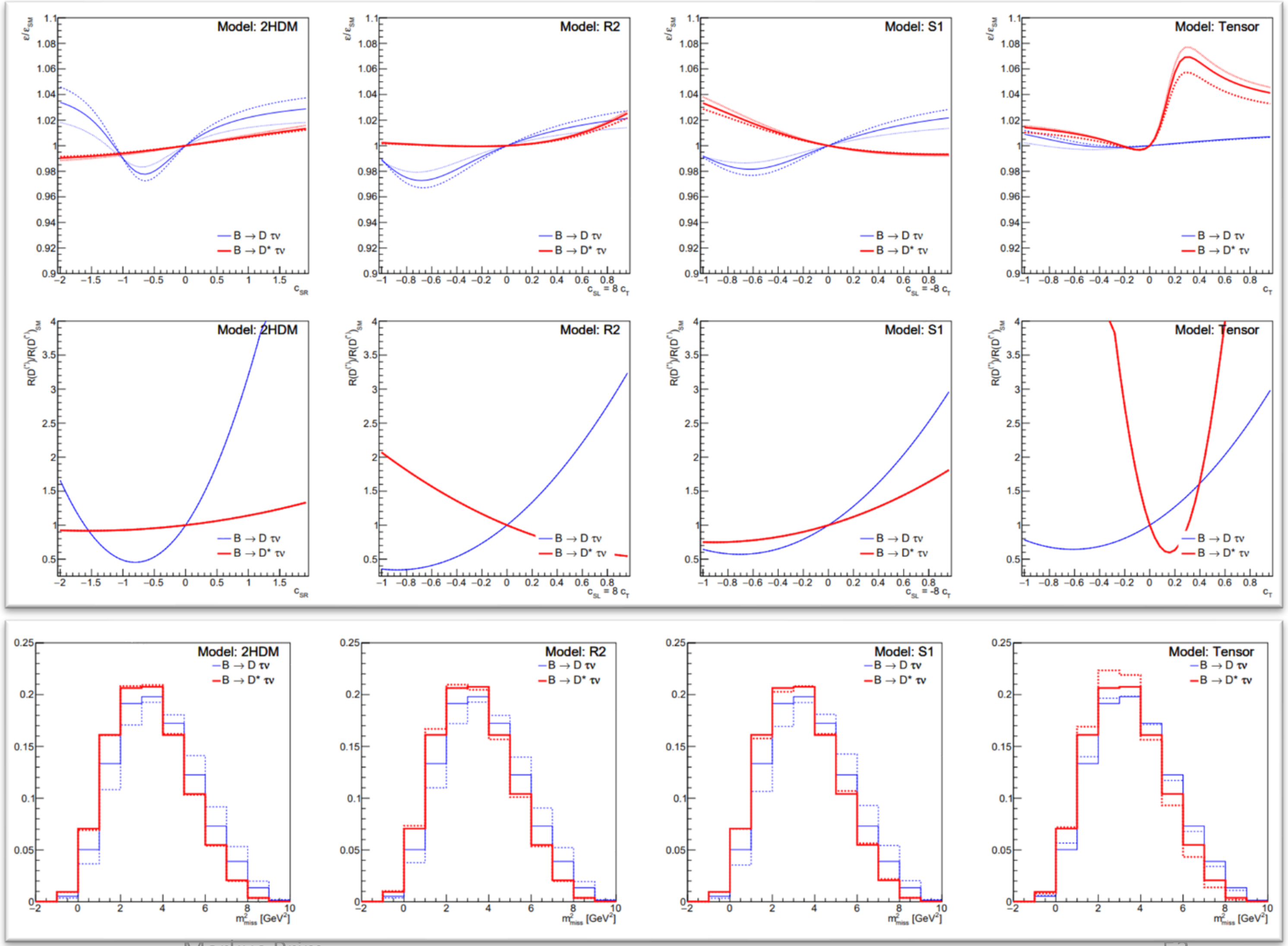




Searching for New Physics



New physics contribution **alter signal and background decay distributions** → Impact on the acceptance and fitting templates



arXiv:2101.08326

Searching for New Physics

Challenge: We need MC for each NP working point

- Our standard generator EvtGen does not incorporate NP effects
- **Very** costly to re-produce MC at various NP working points

Luckily for us, this problem has been solved!

HAMMER
Helicity Amplitude Module
for Matrix Element Reweighting

It also allows us to perform **truly global** fits for $b \to c\tau\bar{\nu}_\tau$ transitions that **avoid biases and remove SM priors**

Belle II $R(D^*)$

Belle II $\mathrm{R}(X)$

Belle $\mathrm{P}_\tau(D^*)$

LHCb $R(D^{(*)})$

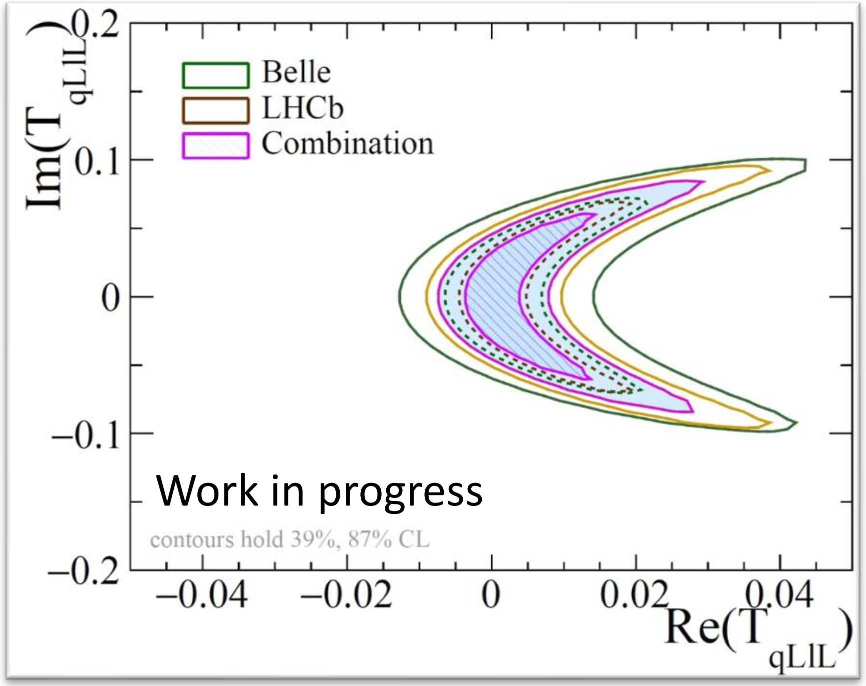
$$\Pi_i \mathcal{L}_i(C, \theta)$$

Full experimental Likelihood

Correlation of common systematic uncertainties

Searching for New Physics

Proof of concept based on LHCb simulation and a Belle toy



J. Albrecht, F. Bernlochner, M. Colonna, B. Mitreska, M. Prim, I. Tsaklidis
Work in progress

It also allows us to perform **truly global** fits for $b \to c\tau\bar{\nu}_\tau$ transitions that **avoid biases and remove SM priors**