Semileptonic B decays at Belle II

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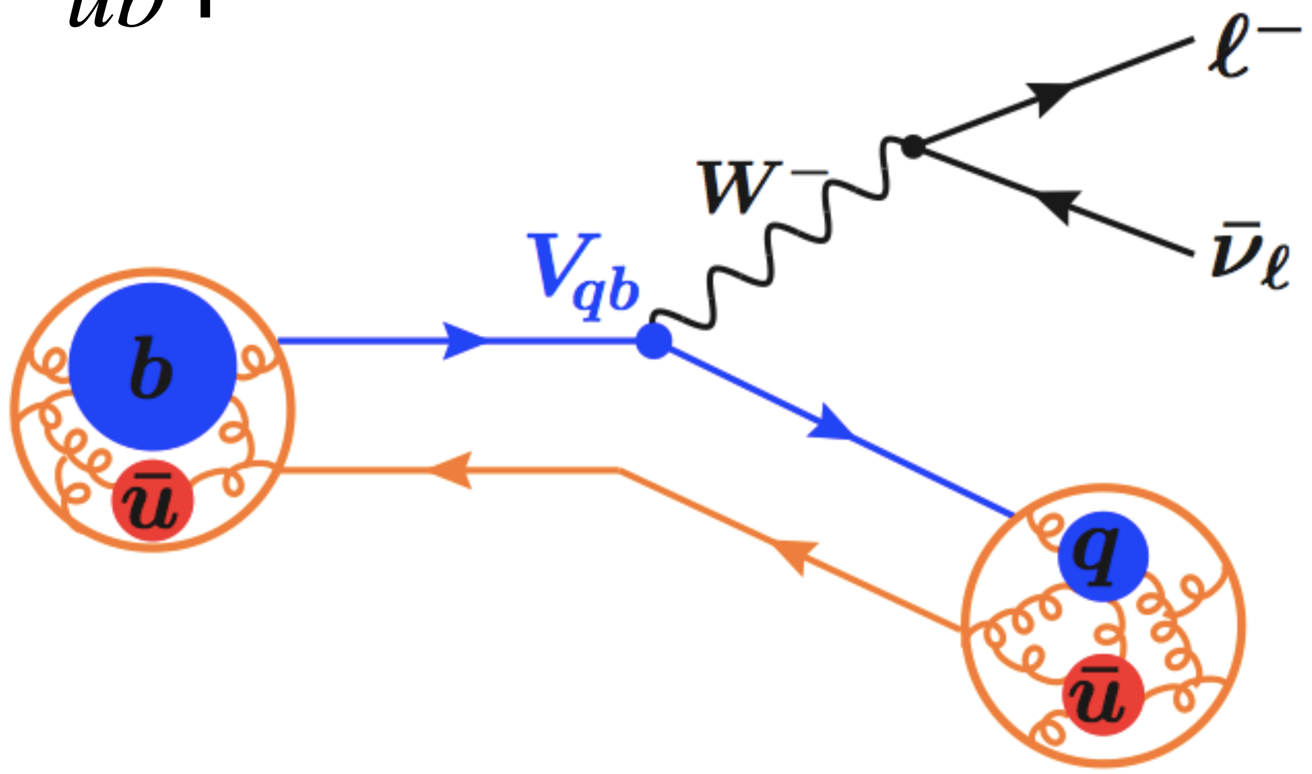
Representing the collaboration

Rencontres de Moriond — Electroweak Interactions & Unified Theories, March 20, 2023

Semileptonic B decays

Determination of the CKM elements $|V_{cb}|$ and $|V_{ub}|$

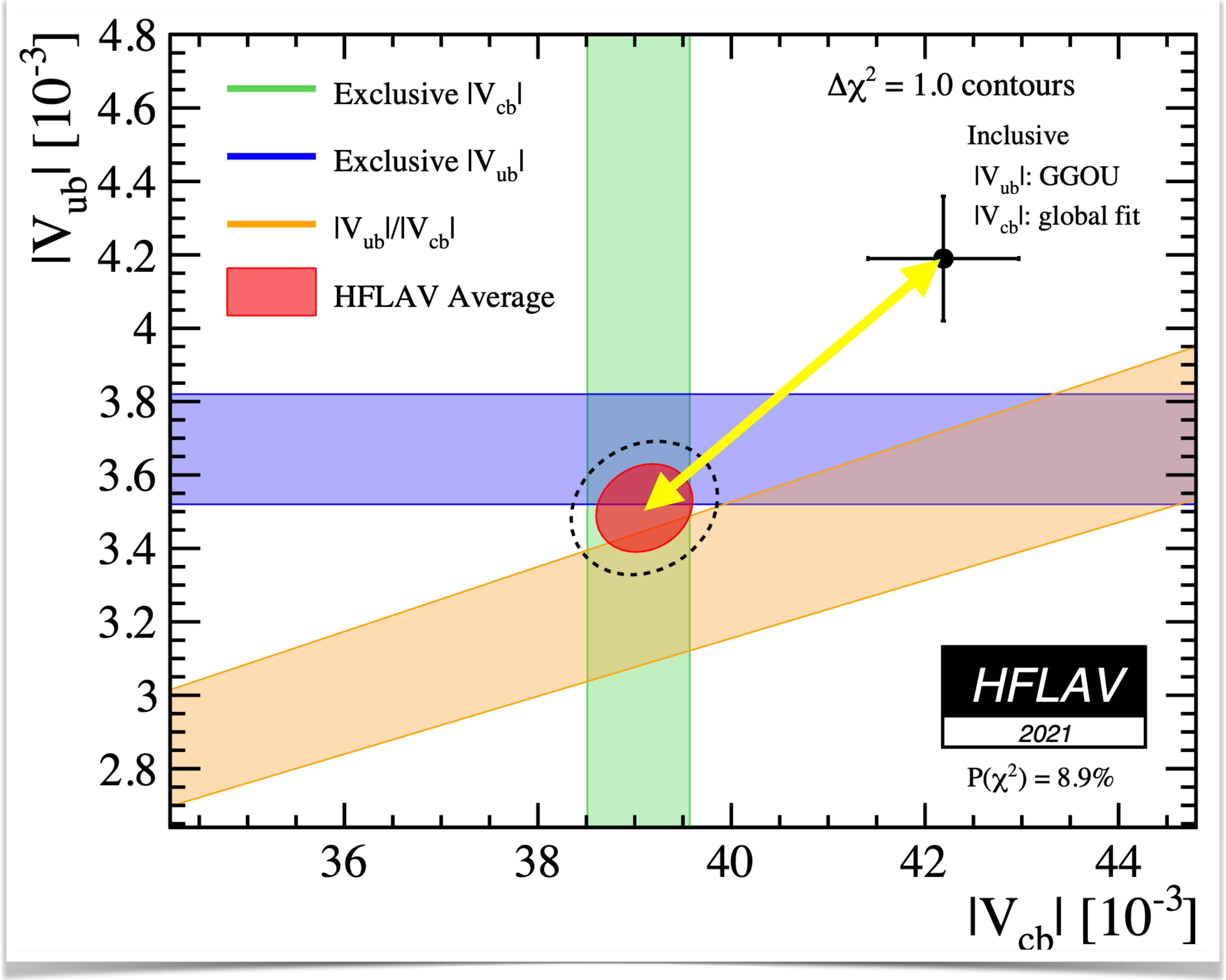
- SL B decays are studied to determine the CKM elements $|V_{cb}|$ and $|V_{ub}|$
    - $|V_{xb}|$ are limiting the global constraining power of UT fits
    - Important inputs in predictions of SM rates for ultrarare decays such as $B_s \to \mu\nu$ and $K \to \pi\nu\nu$
- The determinations can be
    - *Exclusive* — from a single final state
    - *Inclusive* — sensitive to all SL final states



$$d\Gamma \propto G_F^2 |V_{qb}|^2 \left| L_\mu \langle X | \bar{q}\gamma_\mu P_L b | B \rangle \right|^2$$

	Experiment	Theory
Exclusive $\|V_{cb}\|$	B → Dlν, D*lν (low backgrounds)	Lattice QCD, light cone sum rules
Inclusive $\|V_{cb}\|$	B → Xlν (higher background)	Operator product expansion

Experimental status $|V_{cb}|$ and $|V_{ub}|$



- Determinations of both $|V_{cb}|$ and $|V_{ub}|$ exhibit a discrepancy at the level of ~3σ between exclusive and inclusive
- The current experimental focus is on understanding the origin of this discrepancy, as this inconsistency limits the power of precision flavour physics

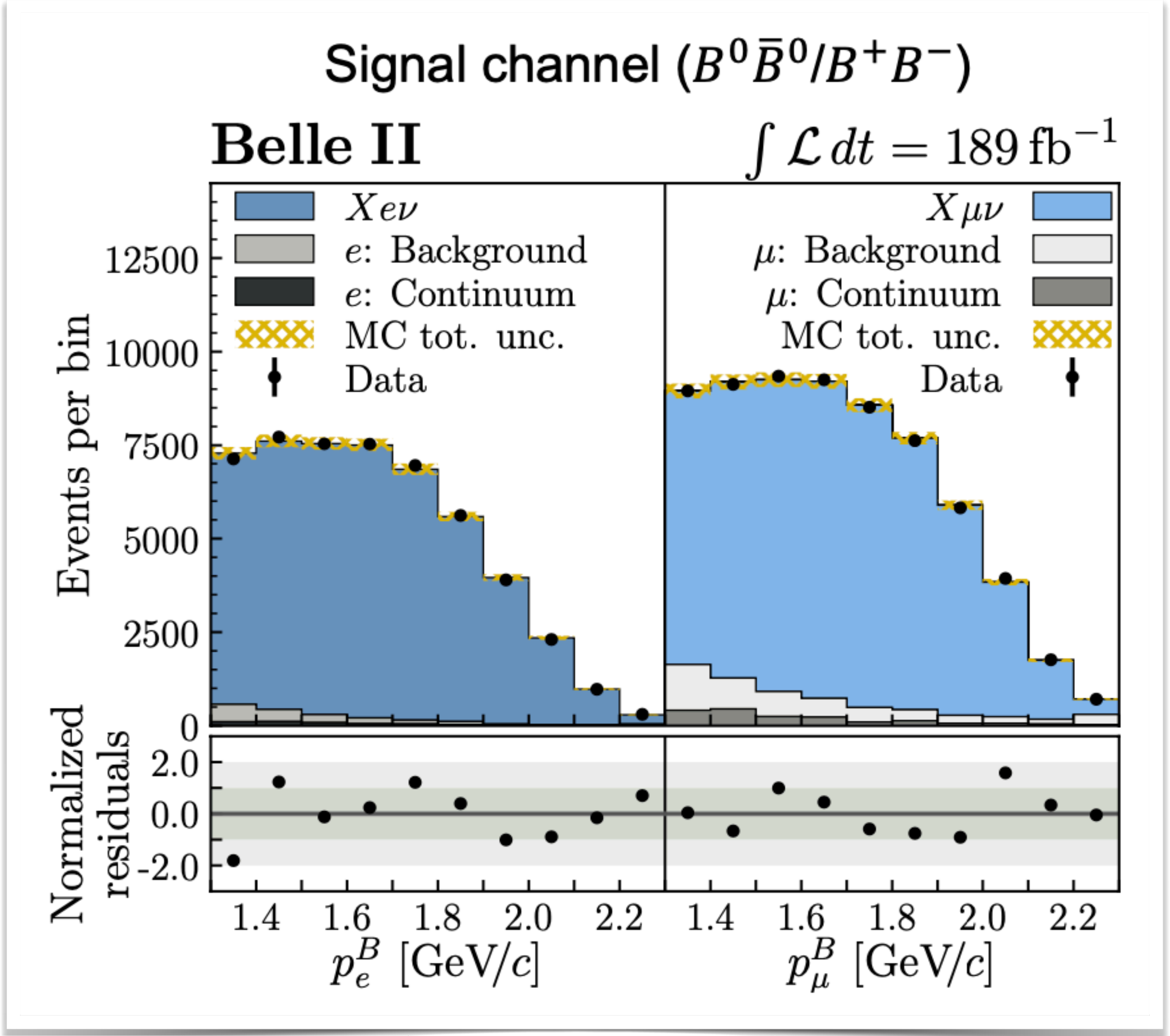
Semileptonic B decays

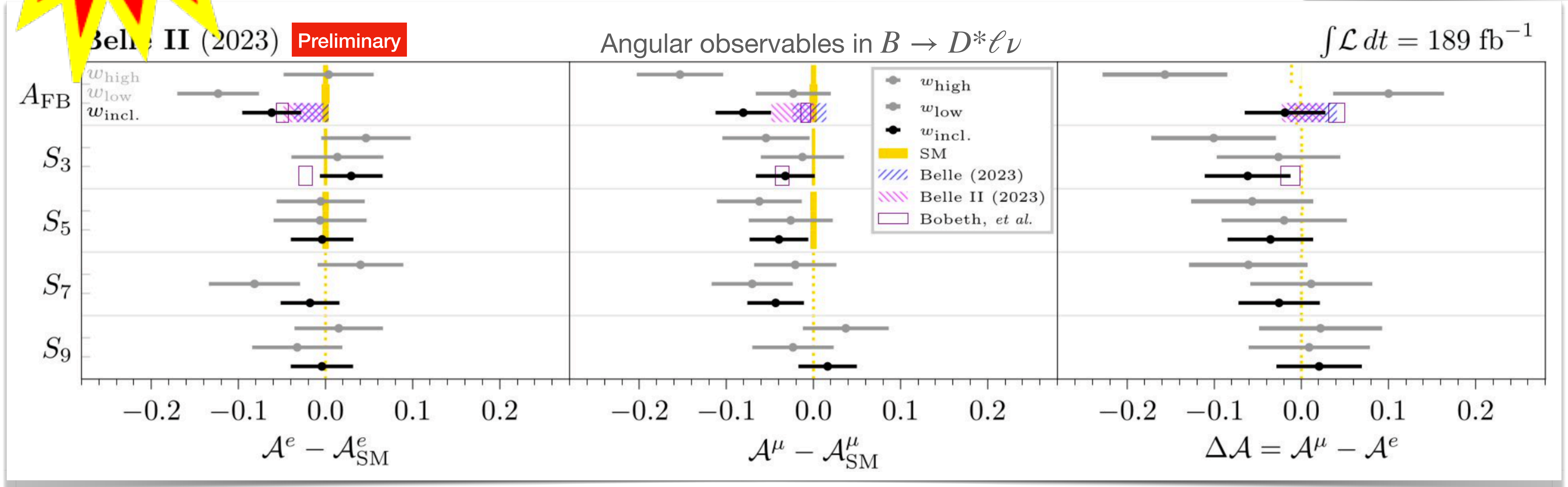
New physics sensitivity

Preliminary

$$R(X_{e/\mu}) = \frac{\mathcal{B}(\bar{B} \to X e^- \bar{\nu}_e)}{\mathcal{B}(\bar{B} \to X \mu^- \bar{\nu}_\mu)} = 1.033 \pm 0.010\ (\text{stat}) \pm 0.019\ (\text{syst})$$

[arXiv:2301.08266]

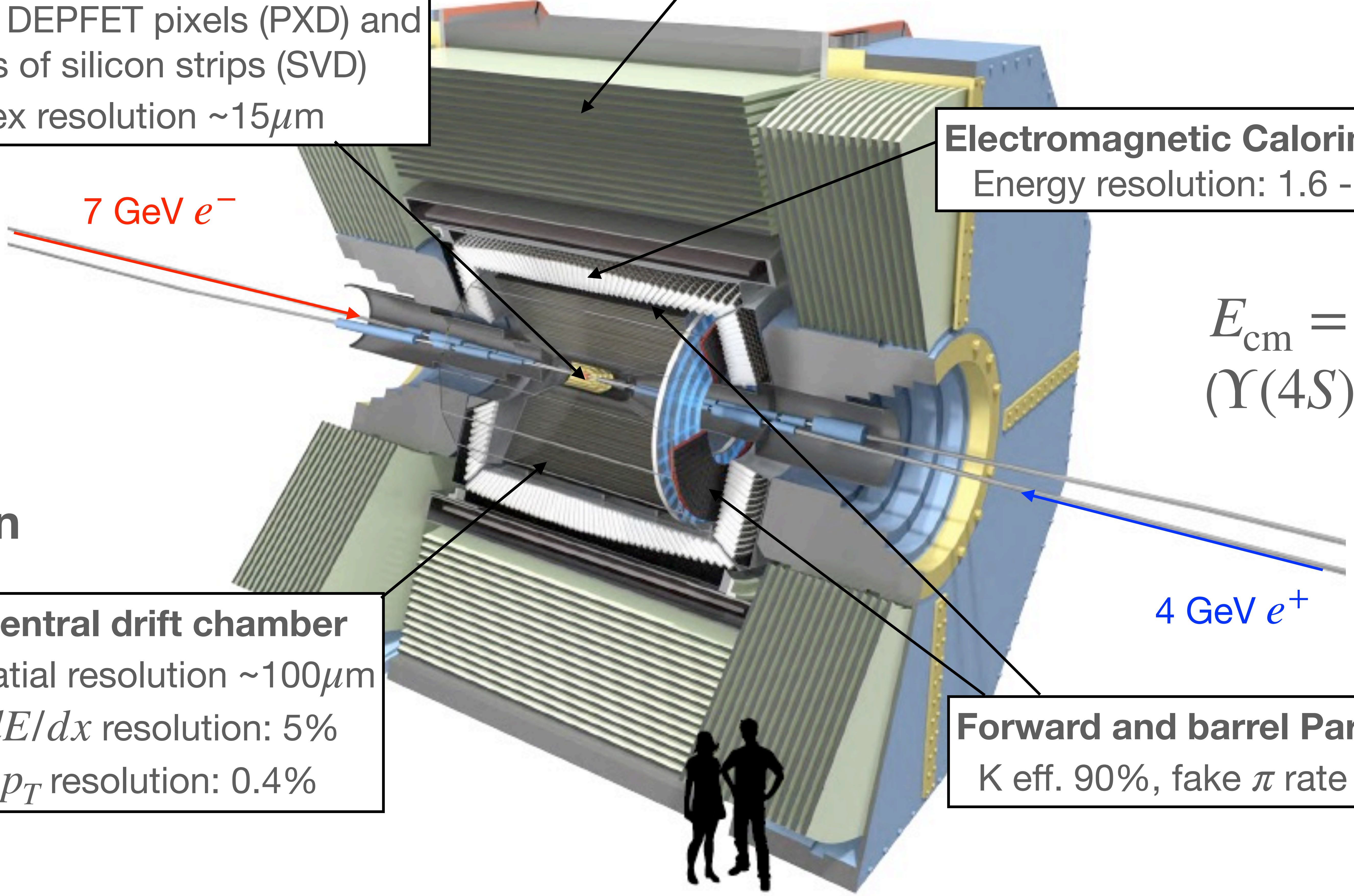




→ talk by Kazuki Kojima in the YSF later this afternoon

The Belle II detector

KEK
Tsukuba, Japan



KLM
Instrumented flux return

Vertex detector
2 layers of DEPFET pixels (PXD) and
4 layers of silicon strips (SVD)
Vertex resolution ~15μm

Electromagnetic Calorimeter
Energy resolution: 1.6 - 4%

$E_{cm} = 10.58$ GeV
($\Upsilon(4S)$ resonance)

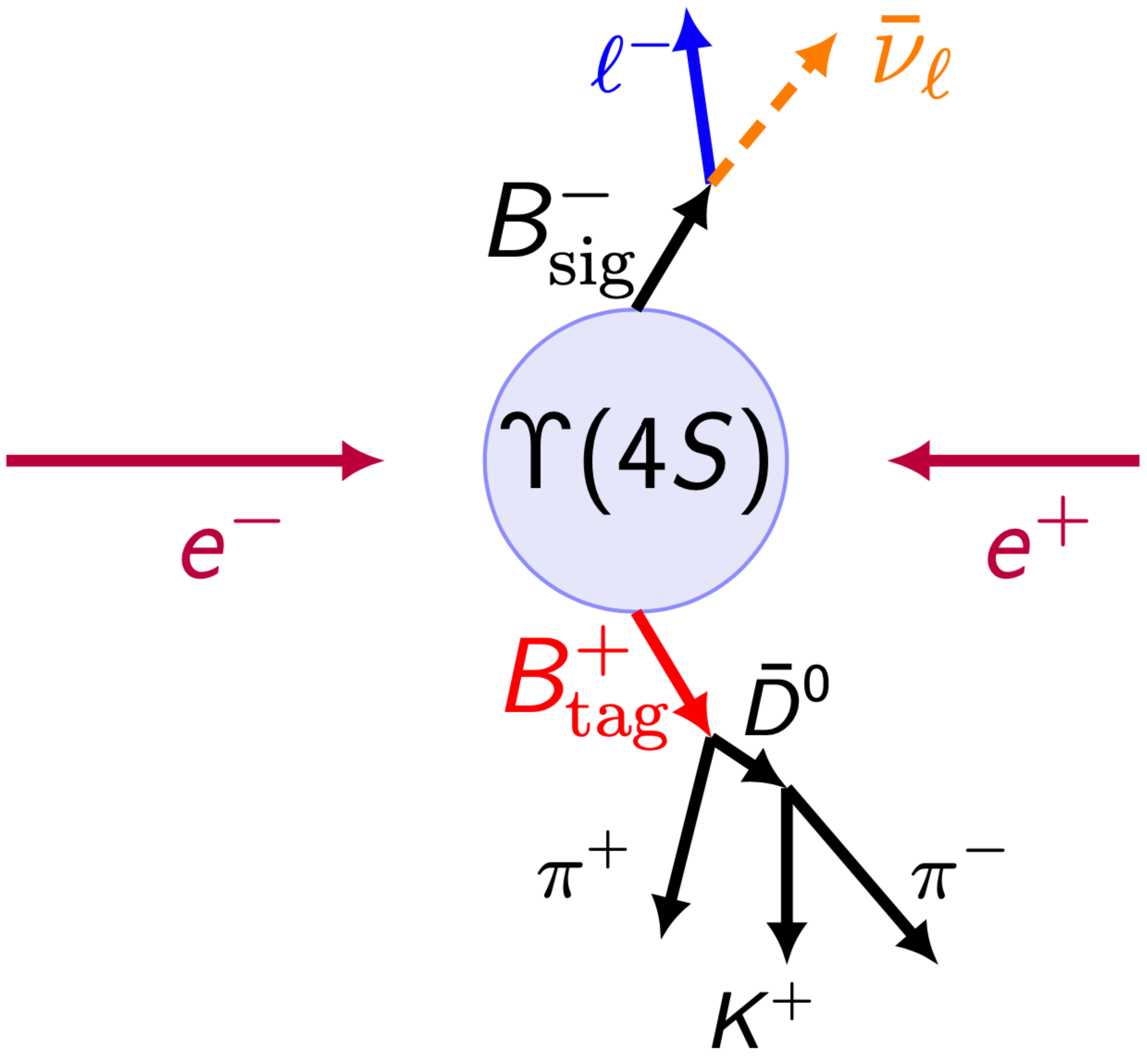
Central drift chamber
Spatial resolution ~100μm
dE/dx resolution: 5%
p_T resolution: 0.4%

Forward and barrel Part. Id.
K eff. 90%, fake π rate 5%

Untagged vs. Tagged

Untagged:
only B_{sig} is reconstructed

high signal yield (+)
high backgrounds (-)
poor neutrino reconstruction (-)



Tagged:
B_{sig} and B_{tag} are reconstructed
to take advantage of $\Upsilon(4S)$ kinematics

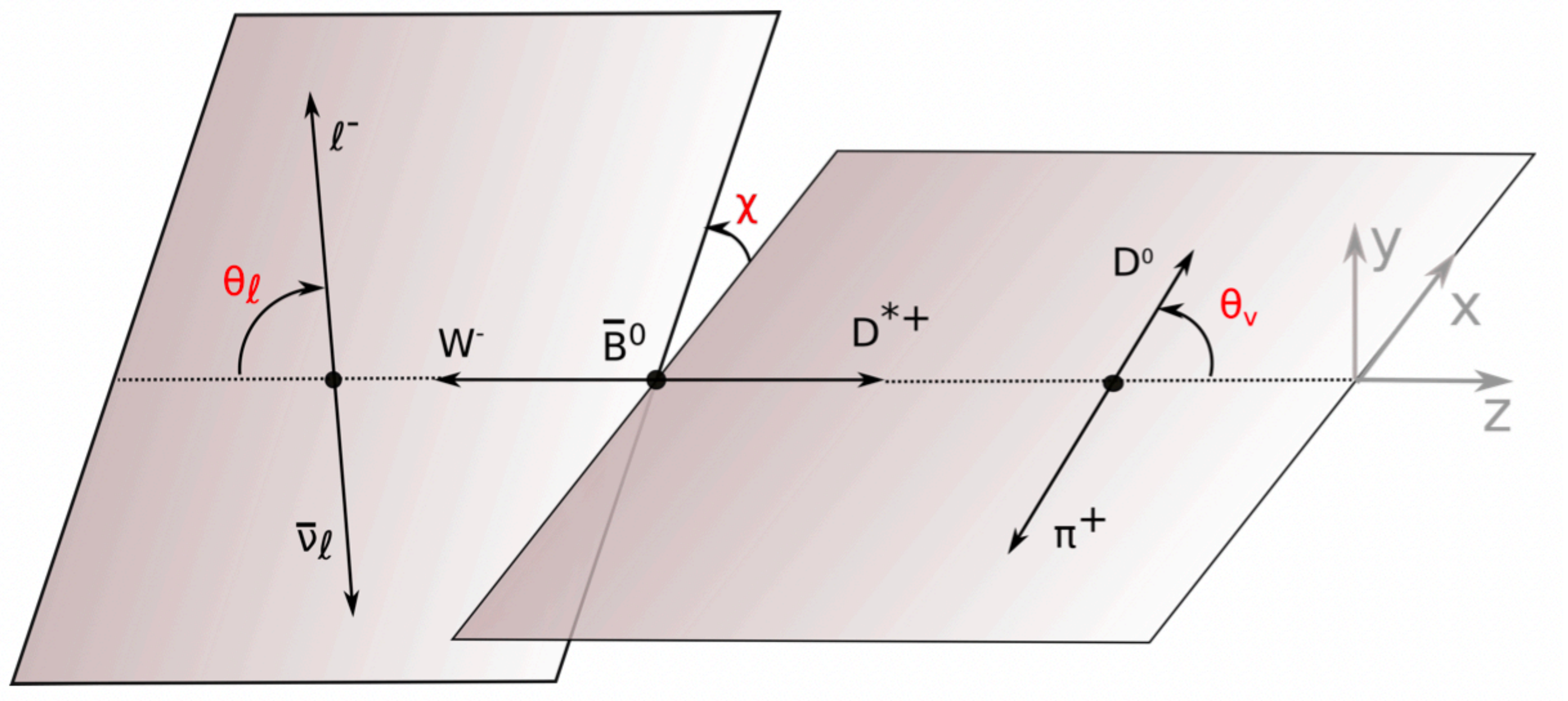
signal yield $O(10^3)$ lower (-)
low backgrounds (+)
good neutrino reconstruction (+)
tag calibration (-)

New !

$B^0 \to D^{*-}\ell^+\nu$ untagged (189/fb)

preliminary [to be submitted to Phys. Rev. D]

Parameterisation of $B \to D^* \ell \nu$



- Three form-factors as function of $w = v_B \cdot v_{D^*}$ parameterise the non-perturbative physics

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

- Form factor parameterisations
  - Boyd, Grinstein, Lebed (BGL) [Phys. Rev. D56, 6895 (1997)]:

$$g(z) = \frac{1}{P_g(z)\phi_g(z)} \sum_{n=0}^{n_a-1} a_n z^n,$$
$$f(z) = \frac{1}{P_f(z)\phi_f(z)} \sum_{n=0}^{n_b-1} b_n z^n, \qquad z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}$$
$$\mathcal{F}_1(z) = \frac{1}{P_{\mathcal{F}_1}(z)\phi_{\mathcal{F}_1}(z)} \sum_{n=0}^{n_c-1} c_n z^n,$$

  - Caprini, Lellouch, Neubert (CLN) [Nucl. Phys. B530, 153 (1998)]:

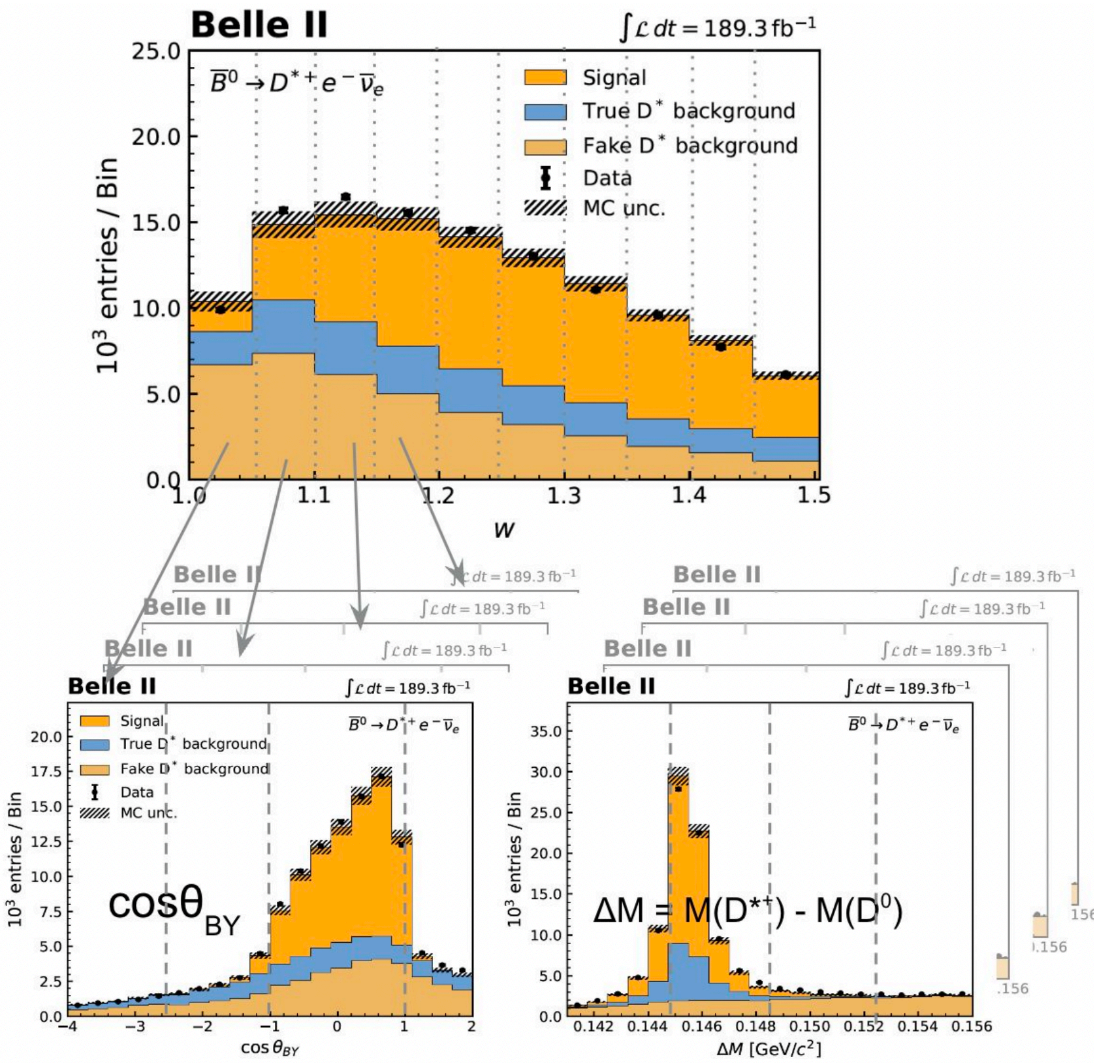
$$h_{A_1}(z) = h_{A_1}(w=1)\left(1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right)$$
$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$
$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$

Measurement

- $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ is reconstructed and combined with an appropriately charged lepton (e or μ)
- The neutrino direction is reconstructed inclusively using the known angle $\cos\theta_{BY}$ between the B and the $Y = D^* + \ell$ direction

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

- The yield in 10 (8) bins of w, $\cos\theta_\ell$, $\cos\theta_V$ and χ is extracted by fitting $\cos\theta_{BY}$ and $\Delta M = M(K\pi\pi) - M(K\pi)$
- Bin-to-bin migration is corrected with SVD unfolding [arXiv:hep-ph/9509307]
- Main challenges: accurate background model, slow pion tracking and statistical correlations between bins



BGL fit result

BGL truncation order determined by Nested Hypothesis Test [Phys. Rev. D100, 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	

Preliminary

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	1.5	18.4	22.0
Tracking of K, π, ℓ	0.5	0.5	0.6	0.5
$N_{B\bar{B}}$	0.8	0.8	1.1	0.8
$f_{+-}/f00$	1.3	1.3	1.7	1.3
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.4	0.4	0.5	0.4
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.4	0.4	0.5	0.4
B^0 lifetime	0.1	0.1	0.2	0.1
Total	6.1	2.5	78.3	64.1

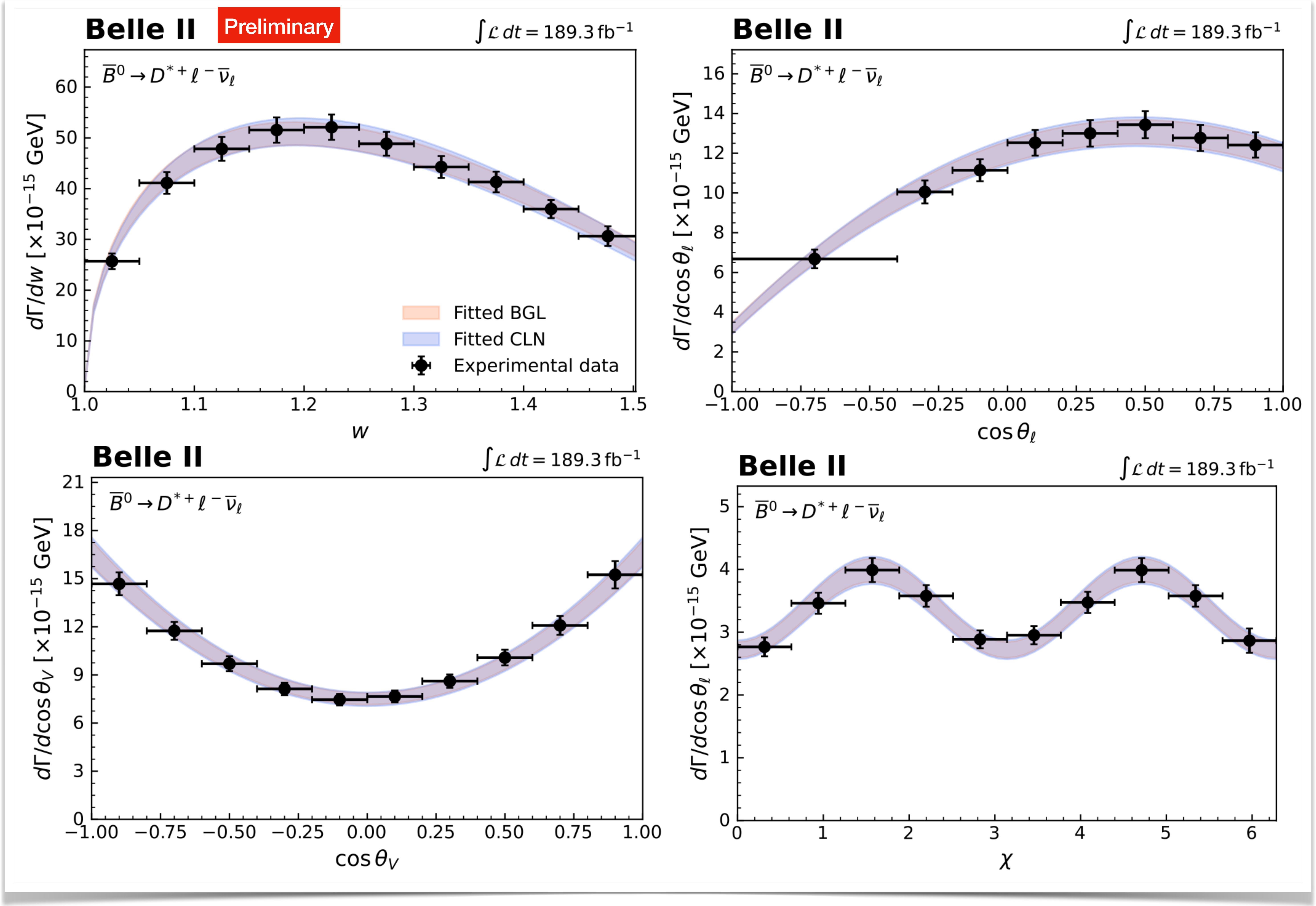
LQCD used only for normalisation at zero recoil ($w = 1$)

Preliminary

$$|V_{cb}|\eta_{\mathrm{EW}}\mathcal{F}(1) = \frac{1}{\sqrt{m_B m_{D^*}}}\left(\frac{|\tilde{b}_0|}{P_f(0)\phi_f(0)}\right)$$

$\mathcal{F}(1) = 0.906 \pm 0.013$

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



Adding LQCD at $w > 1$

LQCD constraints on $h_{A_1}(w)$ at $w = 1.03, 1.10, 1.17$

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

Preliminary

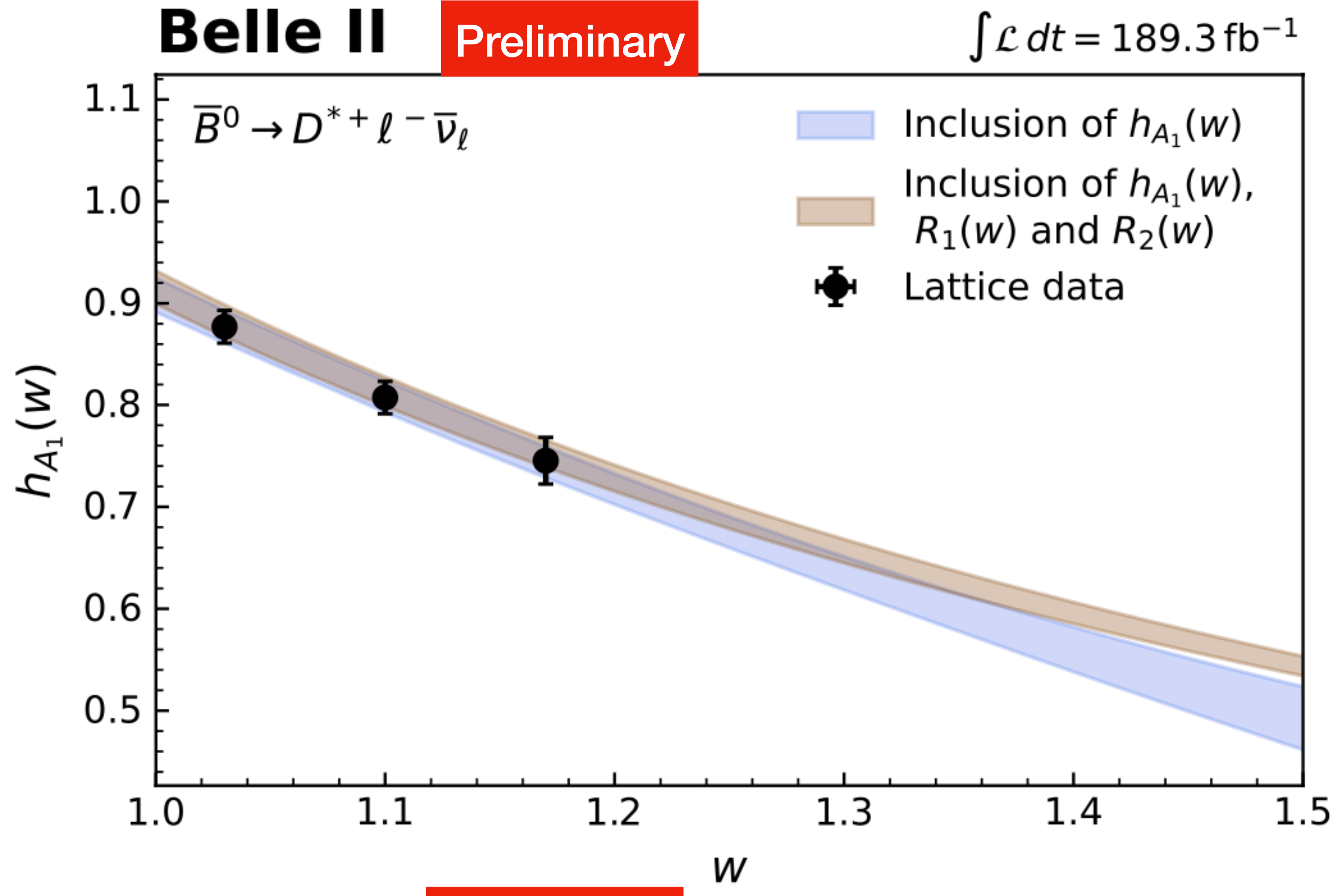
	Values	Correlations					
$\lvert V_{cb}\rvert \times 10^3$	40.4 ± 1.2	1	−0.31	−0.57	−0.1	0.02	−0.26
$a_0 \times 10^3$	22.0 ± 1.4	−0.31	1	0.27	0.1	−0.18	0.31
$b_0 \times 10^3$	13.2 ± 0.2	−0.57	0.27	1	−0.18	0.13	−0.12
$b_1 \times 10^3$	9.0 ± 14.5	−0.1	0.1	−0.18	1	−0.88	0.52
b_2	-0.5 ± 0.4	0.02	−0.18	0.13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

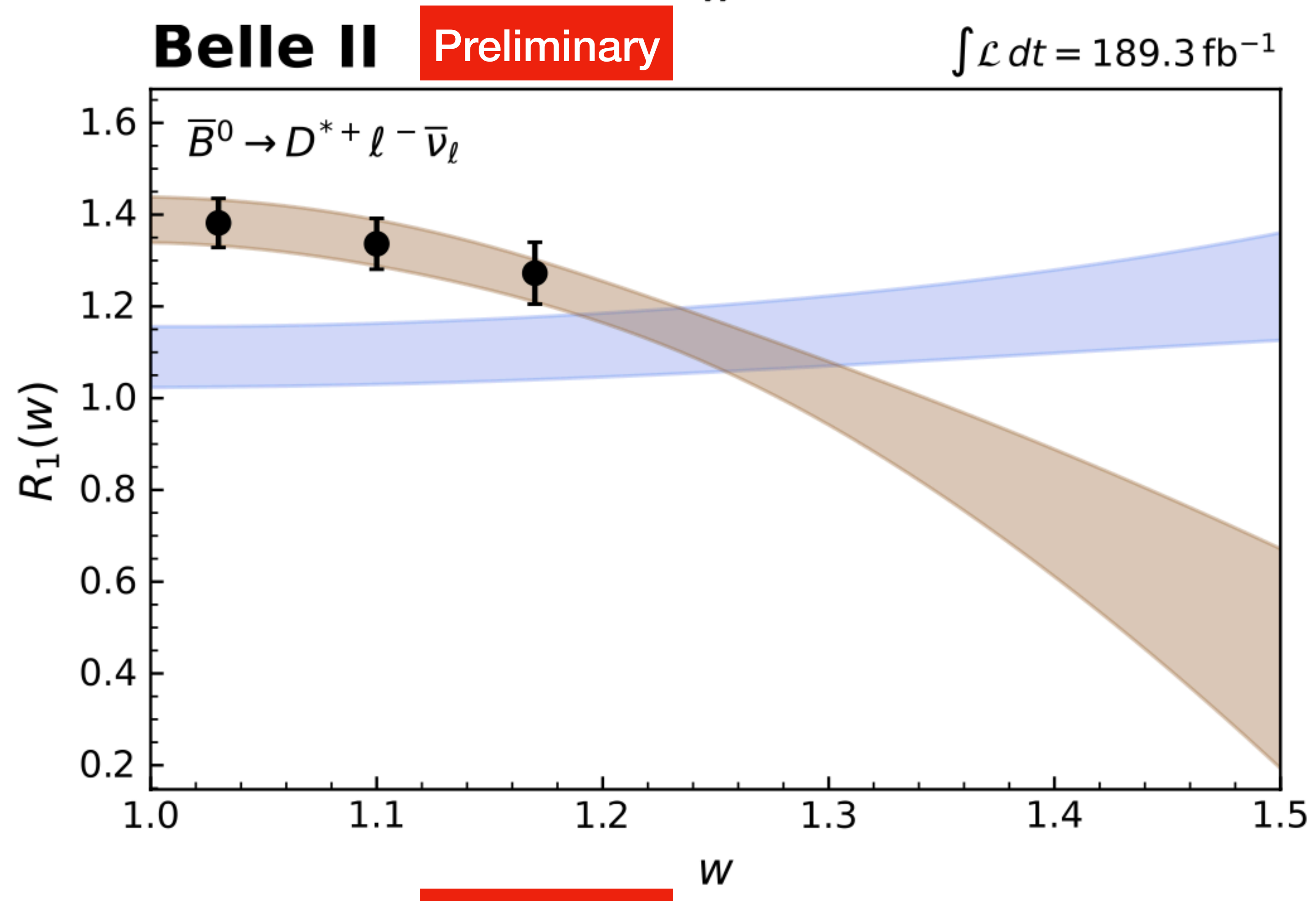
LQCD constraints on $h_{A_1}(w)$, $R_1(w)$ and $R_2(w)$ at $w = 1.03, 1.10, 1.17$

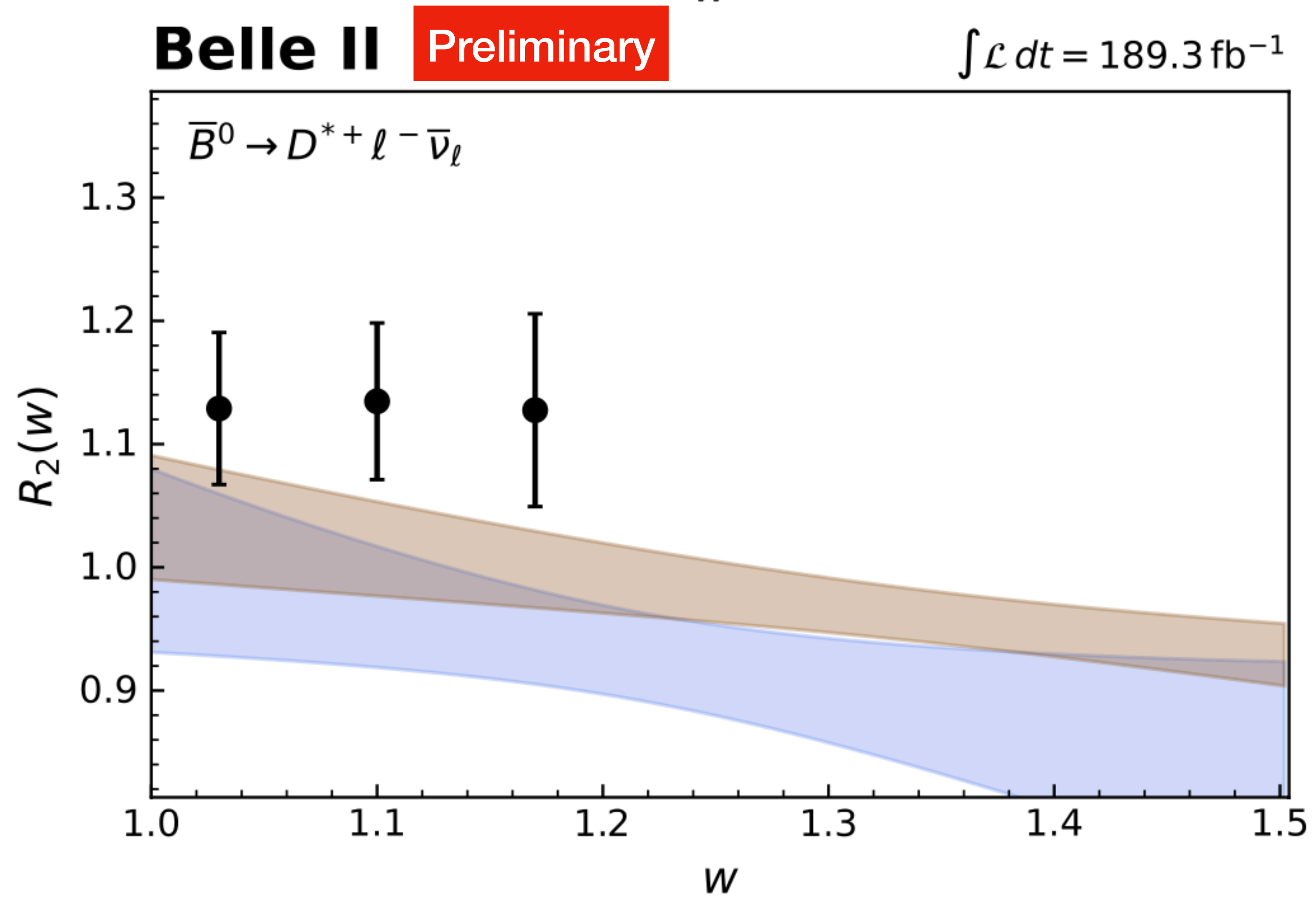
[Eur. Phys. J. C 82, 1141 (2022)]

Preliminary

	Values	Correlations						
$\lvert V_{cb}\rvert \times 10^3$	40.0 ± 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







Summary of the measurement

- Branching fraction

Preliminary

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

- Value of $|V_{cb}|$

Preliminary

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

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

- Lepton flavour universality tests

Preliminary

$$R_{e/\mu} = 1.001 \pm 0.009_{stat} \pm 0.021_{syst}$$

$$\Delta AFB = (-4 \pm 16_{stat} \pm 18_{syst}) \times 10^{-3}$$

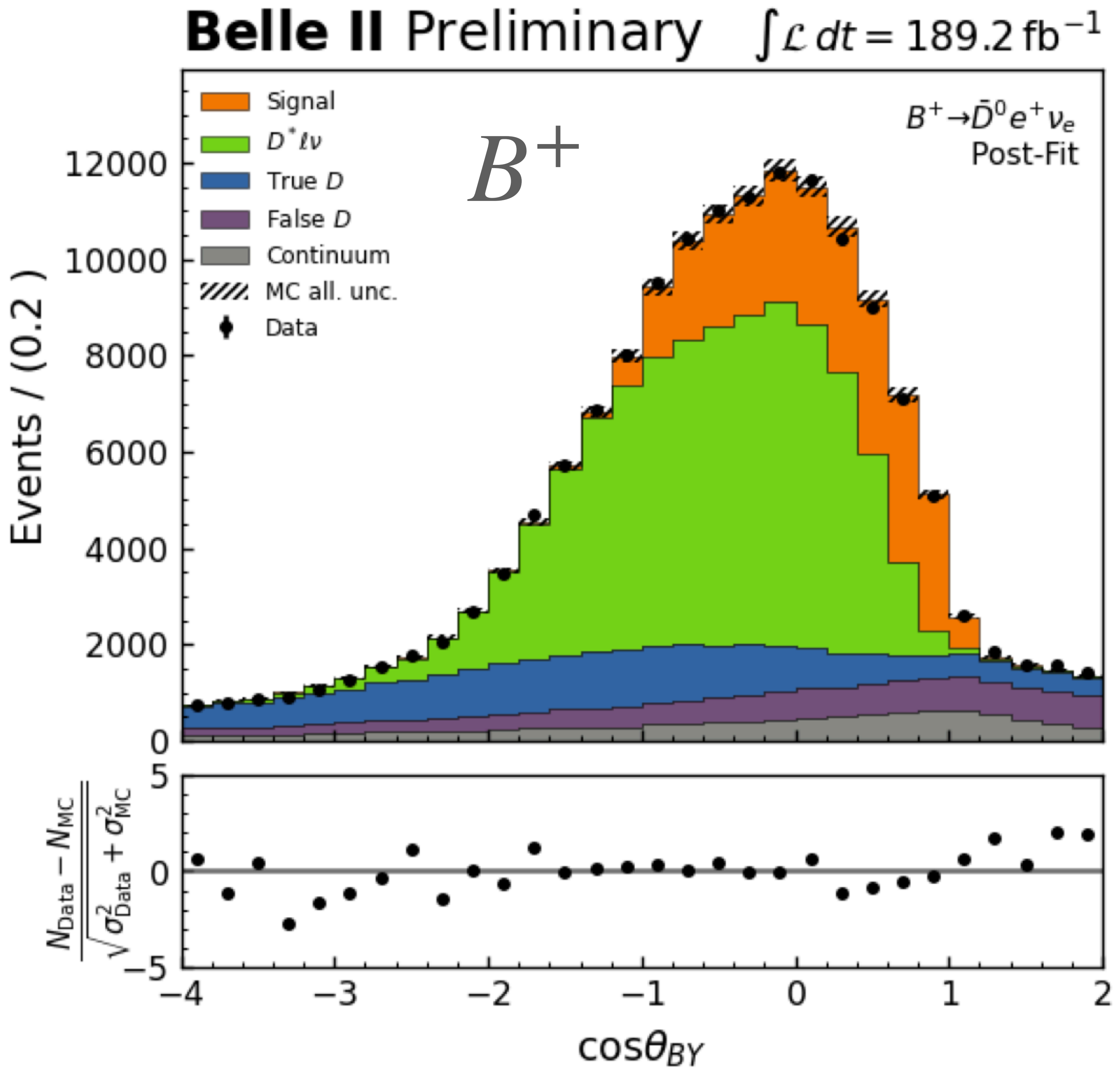
$$\Delta FL = 0.013 \pm 0.007_{stat} \pm 0.007_{syst}$$

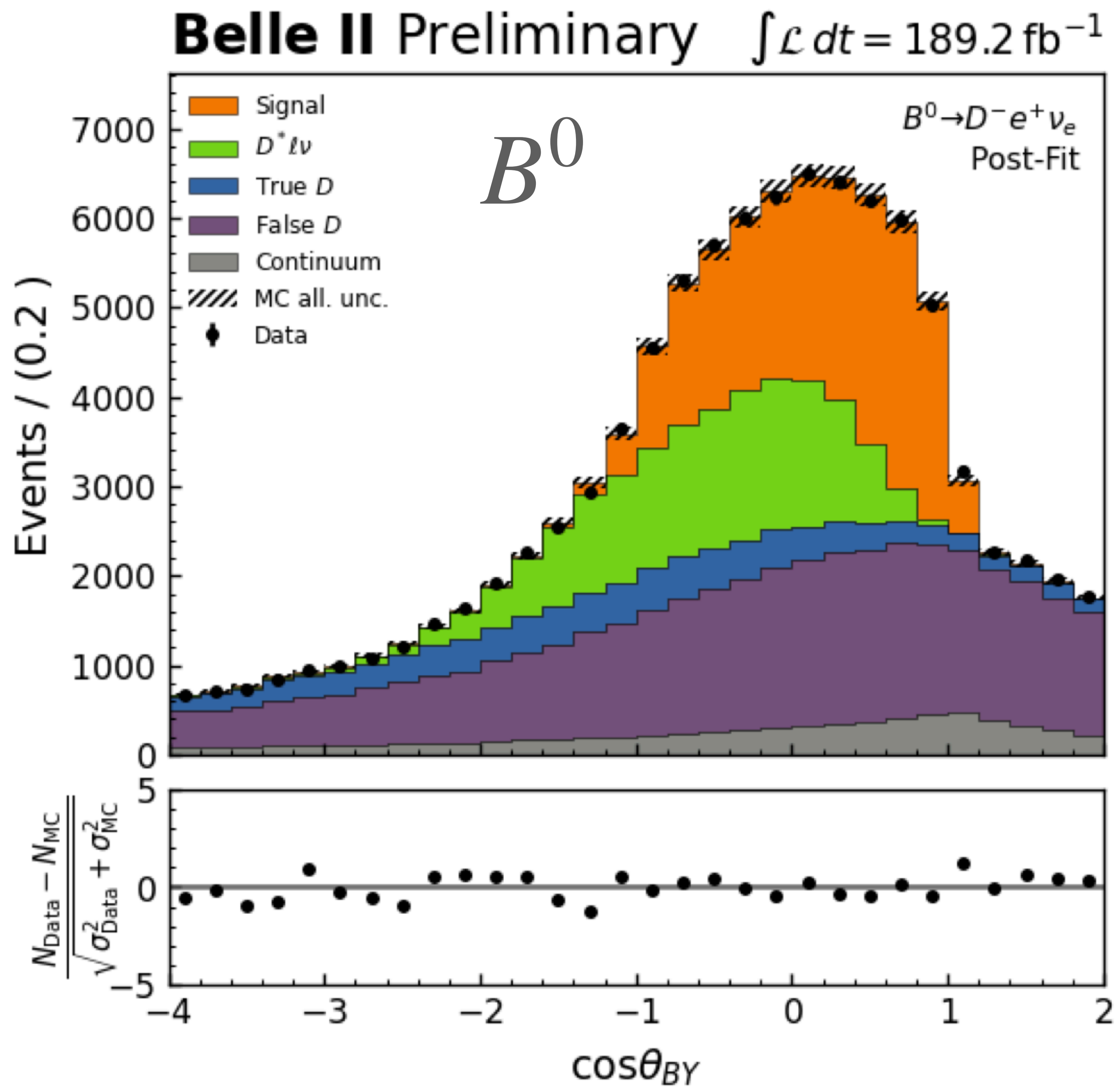
$B \to D\ell^+\nu$ untagged (189/fb)

preliminary [arXiv:2210.13143]

Measurement

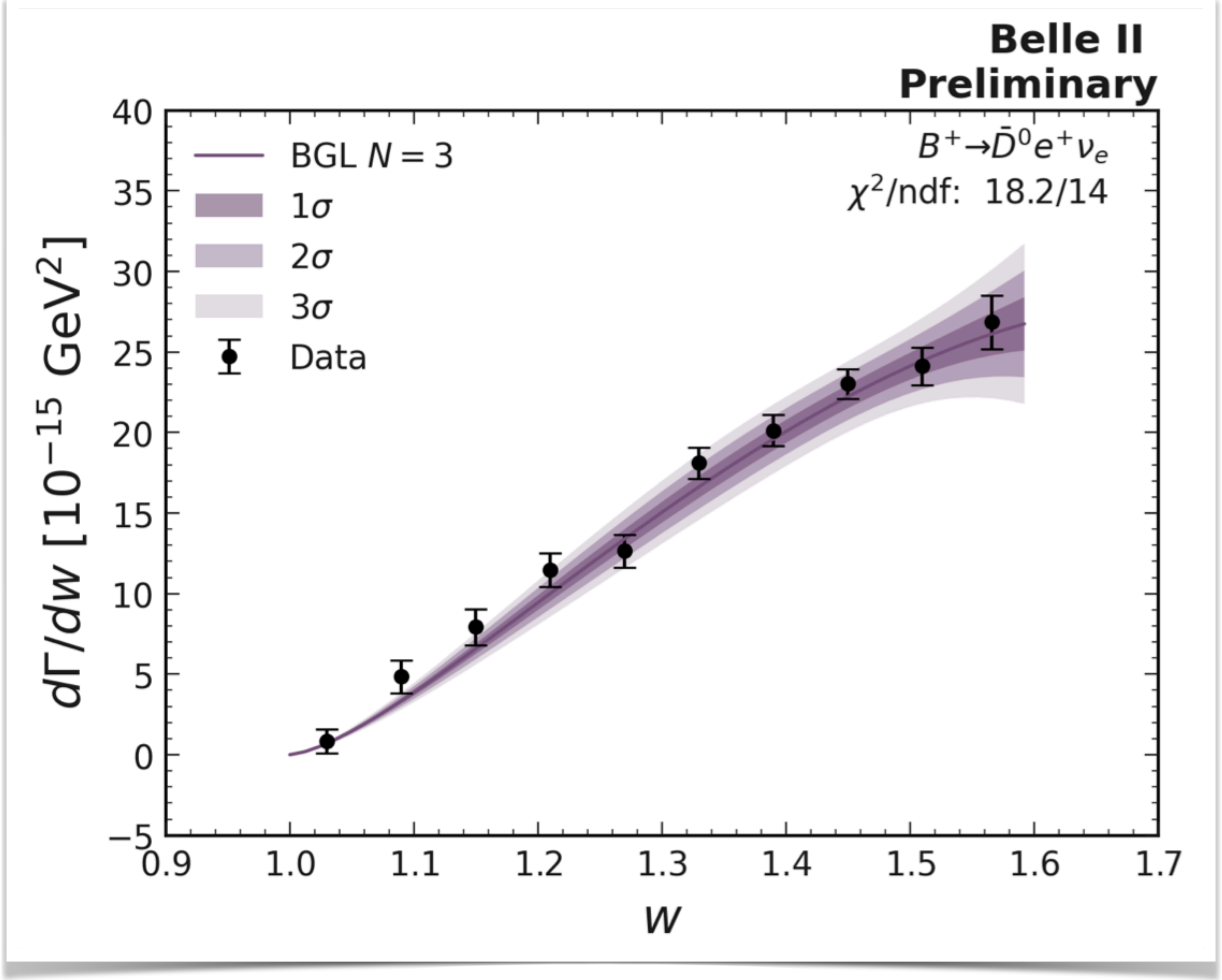
- $D\ell\nu$ kinematics are described by w only and the decay form factor contains a single function $f_+(w)$
- $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$ are reconstructed and combined with an appropriately charged lepton (e or μ)
- Yields are extracted in 10 bins of w by fitting the $\cos\theta_{BY}$ distributions
- Main challenges: background model, in particular $B \to D^*\ell\nu$ downfeed (significant despite active D^* veto)

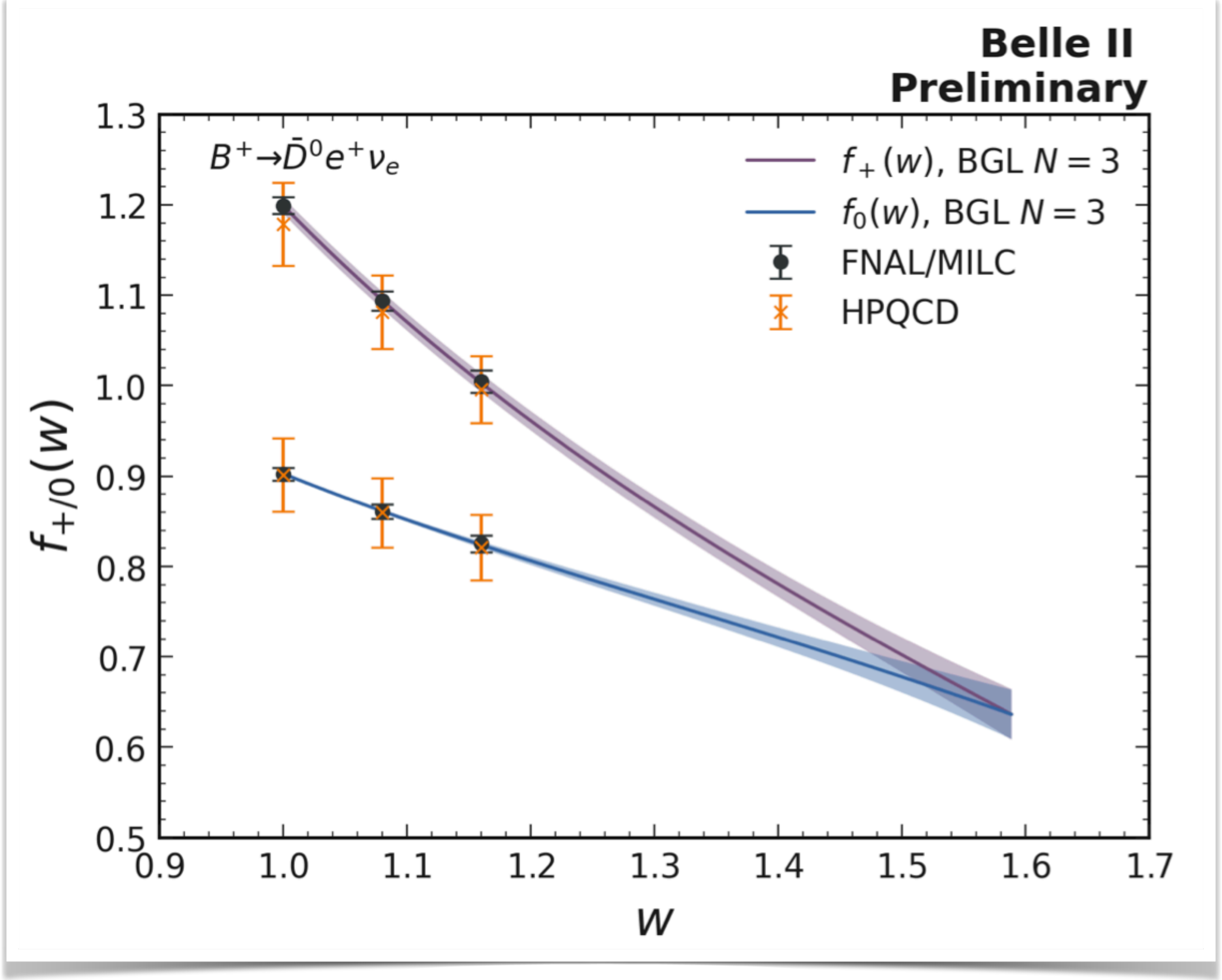




BGL fit

- Together with LQCD data by FNAL/MILC [Phys. Rev. D92, 034506] and HPQCD [Phys. Rev. D92, 054510]





$$|V_{cb}|_{\mathrm{BGL}} = (38.28 \pm 1.16) \times 10^{-3}$$

Average over B^0 and B^+, and e and μ

Preliminary

$B^0 \to \pi^- \ell^+ \nu$ untagged (189/fb)

preliminary [arXiv:2210.04224]

$B \to \pi \ell \nu$

The golden mode for $|V_{ub}|$ exclusive

- Differential rate in terms of $q^2 = (p_\ell + p_\nu)^2$

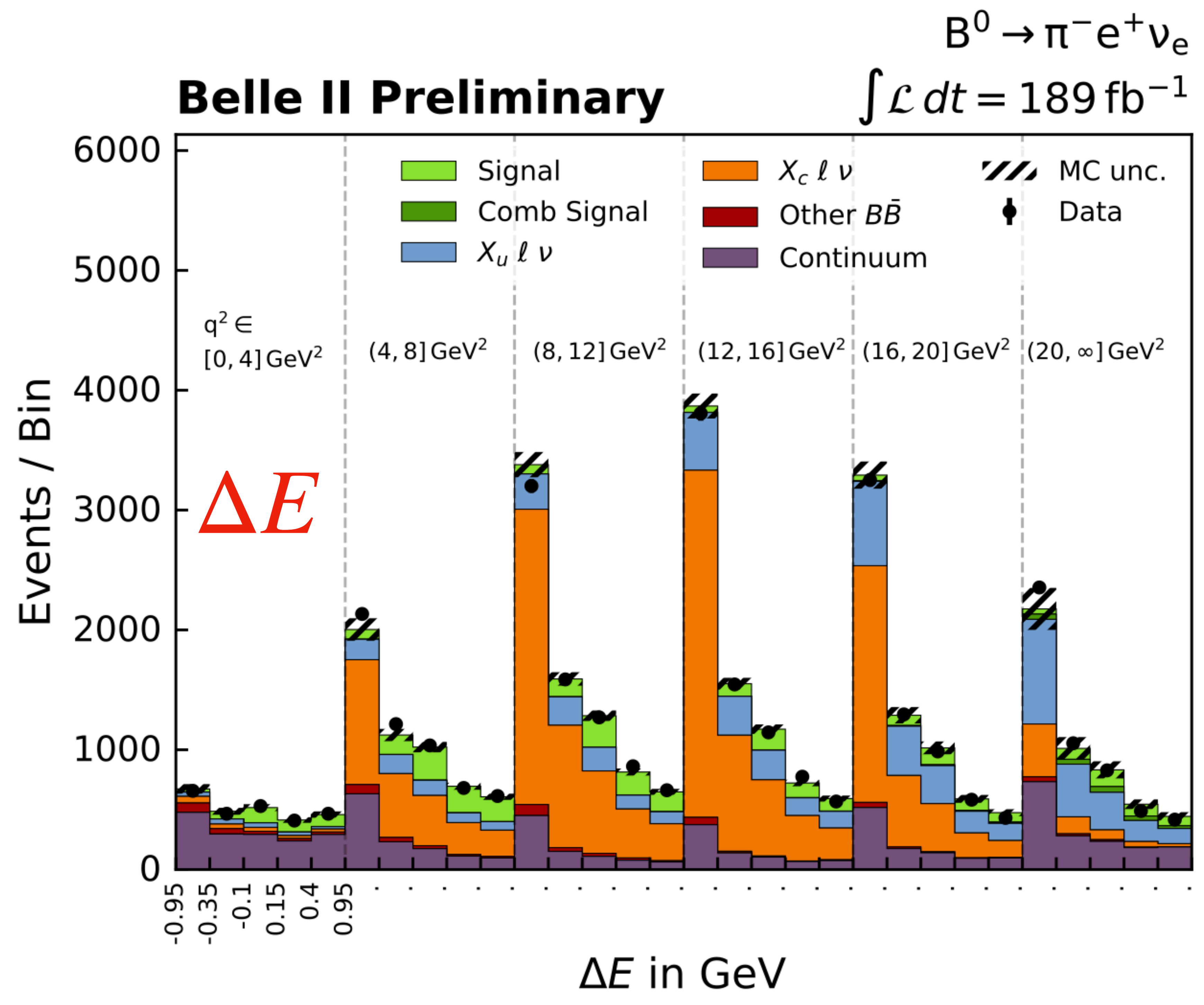
$$\frac{d\Gamma(B^0 \to \pi^- \ell^+ \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 |p_\pi|^3 |f_+(q^2)|^2$$

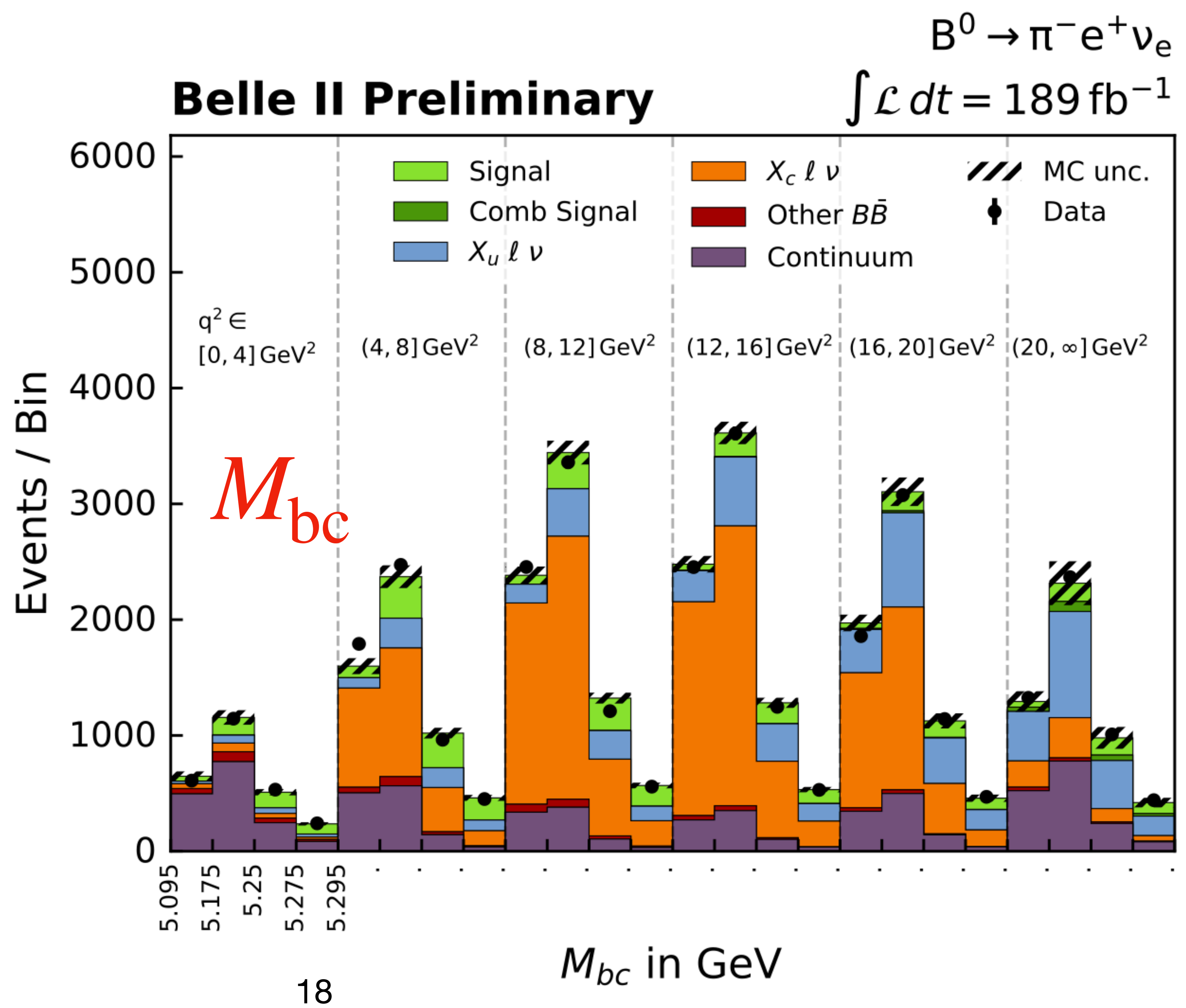
- BCL extraction of $|V_{ub}|$ [Phys.Rev.D79, 013008; Erratum-ibid. D82, 099902]
  - Measure the differential rate in bins of q^2
  - Theory calculates $f_+(q^2)$ at values of q^2
  - Combined fit to the BCL expansion to determine $|V_{ub}|$ and b_k (z is a map of q^2)

$$f_+(q^2) = \frac{1}{1 - q^2/m_{B*}^2} \sum_{k=0}^{K-1} b_k \left[z^k - (-1)^{k-K} \frac{k}{K} z^K \right]$$

Measurement

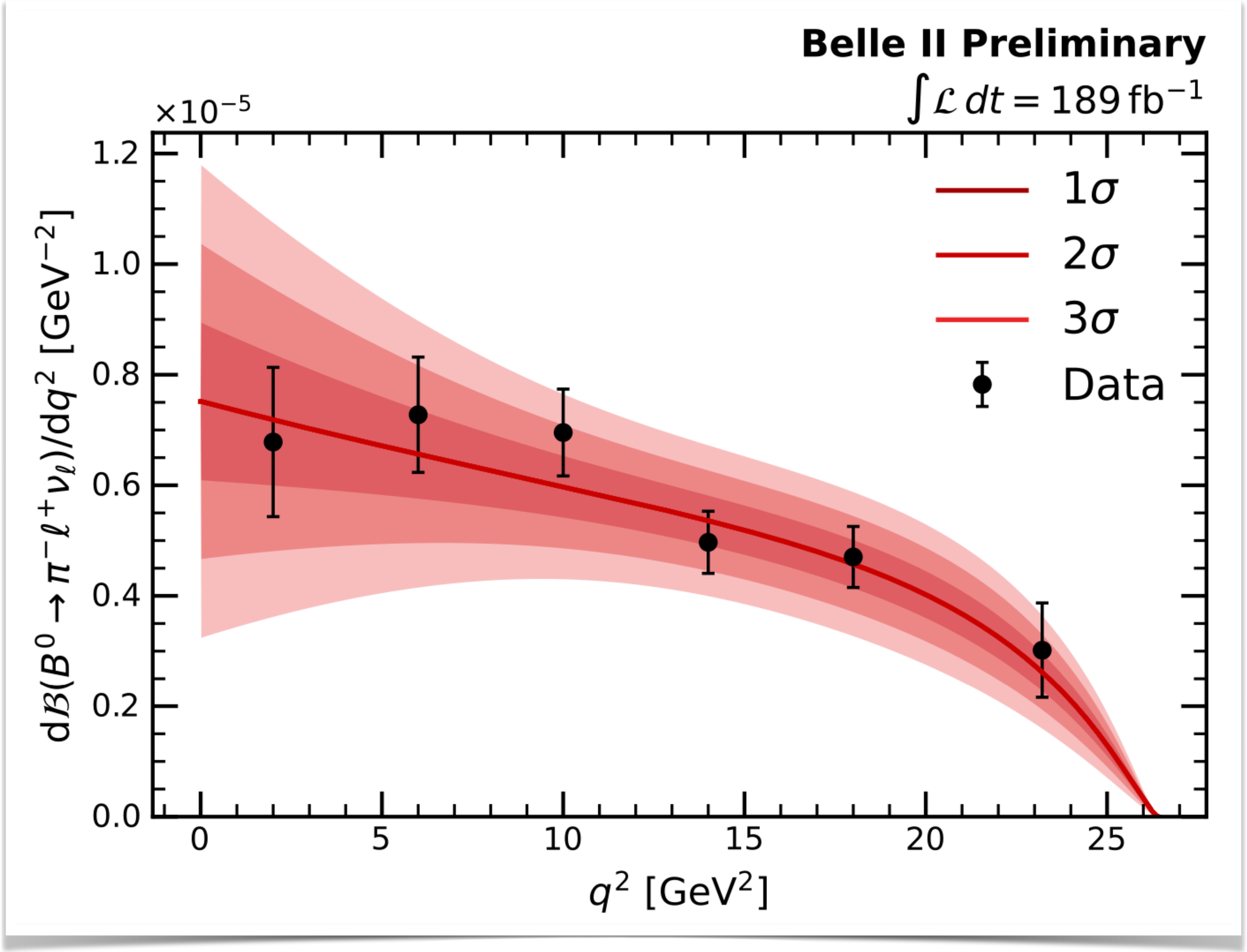
- Charged π mesons are combined with e or μ, the neutrino direction is reconstructed inclusively
- The yield in 6 bins of q^2 is determined from a fit to $M_{bc} = \sqrt{E_{\text{beam}}^{*2} - |\vec{p}_B^{\,*}|^2}$ vs. $\Delta E = E_B^* - E_{\text{beam}}^*$
- Bin-by-bin unfolding to correct migration





BCL fit result

- LQCD input from FNAL/MILC [Phys. Rev. D92, 014024]



$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.426 \pm 0.056(\mathrm{stat}) \pm 0.125(\mathrm{syst})) \times 10^{-4}$$

$$|V_{ub}|_{B^0 \to \pi^- \ell^+ \nu_\ell} = (3.55 \pm 0.12(\mathrm{stat}) \pm 0.13(\mathrm{syst}) \pm 0.17(\mathrm{theo})) \times 10^{-3}$$

Preliminary

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

Summary and conclusion

- Semileptonic B meson decays allow to determine the Cabibbo-Kobayashi-Maskawa matrix elements $|V_{cb}|$ and $|V_{ub}|$
  - Belle II is in a unique position for these measurements due to its low multiplicity events and the $\Upsilon(4S)$ kinematics
  - These determinations can be *exclusive* or *inclusive*
- There is a long-standing discrepancy between inclusive and exclusive determinations that limits our understanding of these fundamental parameters
- Belle II is aiming at resolving the situation by
  - Repeating the analyses on independent data sets with improved experimental tools
  - Addressing potential issues in previous analyses
    (form factor dependence, slow pion dependence, use of LQCD input, …)

Summary and conclusion (2)

WA values [HFLAV 2021]

$$|V_{cb}|_{excl} = (39.10 \pm 0.50) \times 10^{-3}$$

$$|V_{ub}|_{excl} = (4.19 \pm 0.17) \times 10^{-3}$$

- Recent Belle II results on exclusive decays

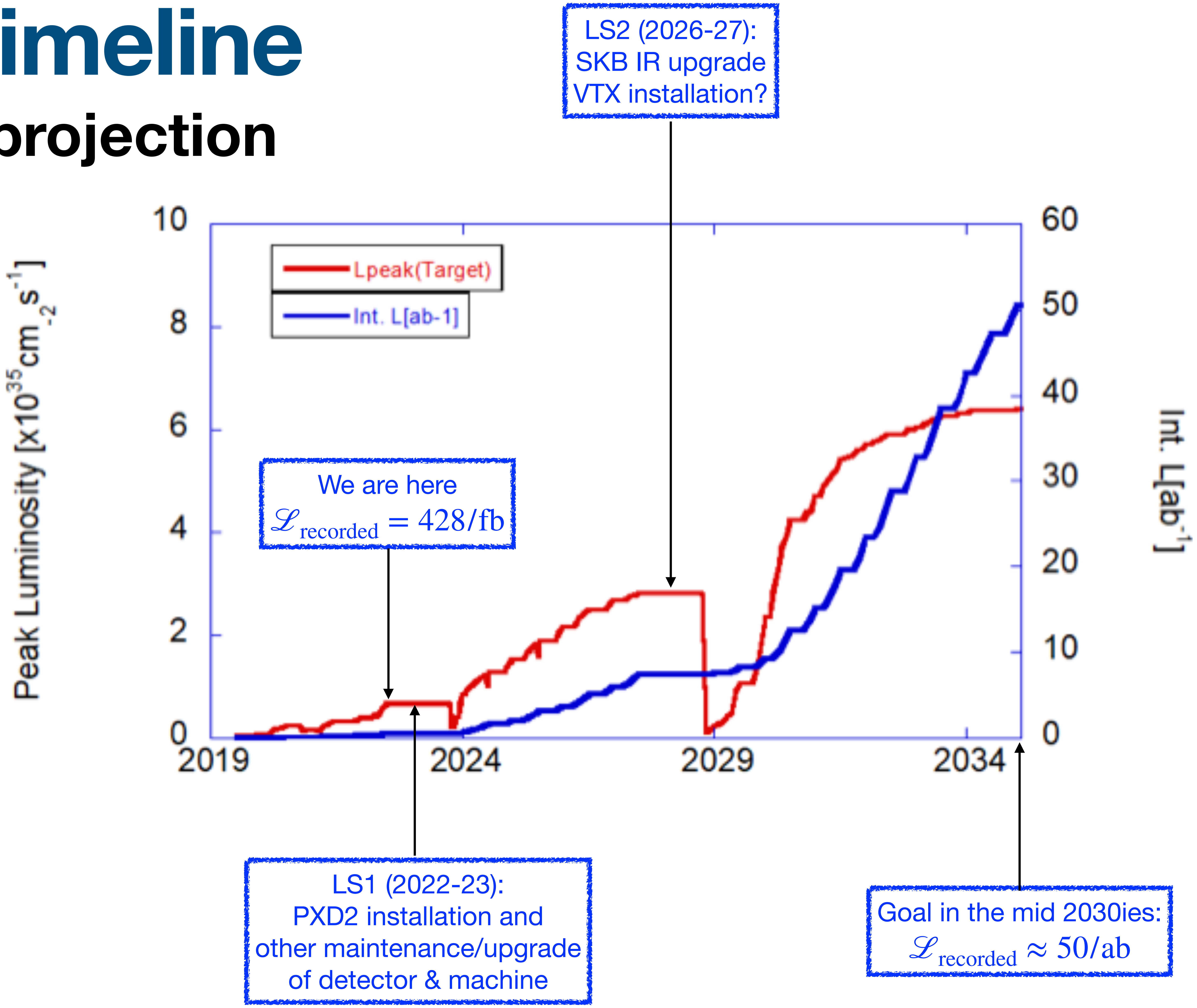
	$\|V_{cb}\| \times 10^3$	Reference
Belle II $B^0 \to D^{*-}\ell^+\nu$ untagged	40.9 ± 1.2 (BGL) Preliminary	To be submitted to PRD
Belle II $B^0 \to D^{*-}\ell^+\nu$ tagged	37.9 ± 2.7 (CLN) Preliminary	[arXiv:2301.04716]
Belle II $B \to D\ell\nu$ untagged	38.28 ± 1.16 (BGL) Preliminary	[arXiv:2210.13143]

	$\|V_{ub}\| \times 10^3$	Reference
Belle II $B \to \pi e\nu$ tagged	3.88 ± 0.45 Preliminary	[arXiv:2206.08102]
Belle II $B \to \pi\ell\nu$ untagged	3.55 ± 0.25 Preliminary	[arXiv:2210.04224]

Backup

Belle II timeline

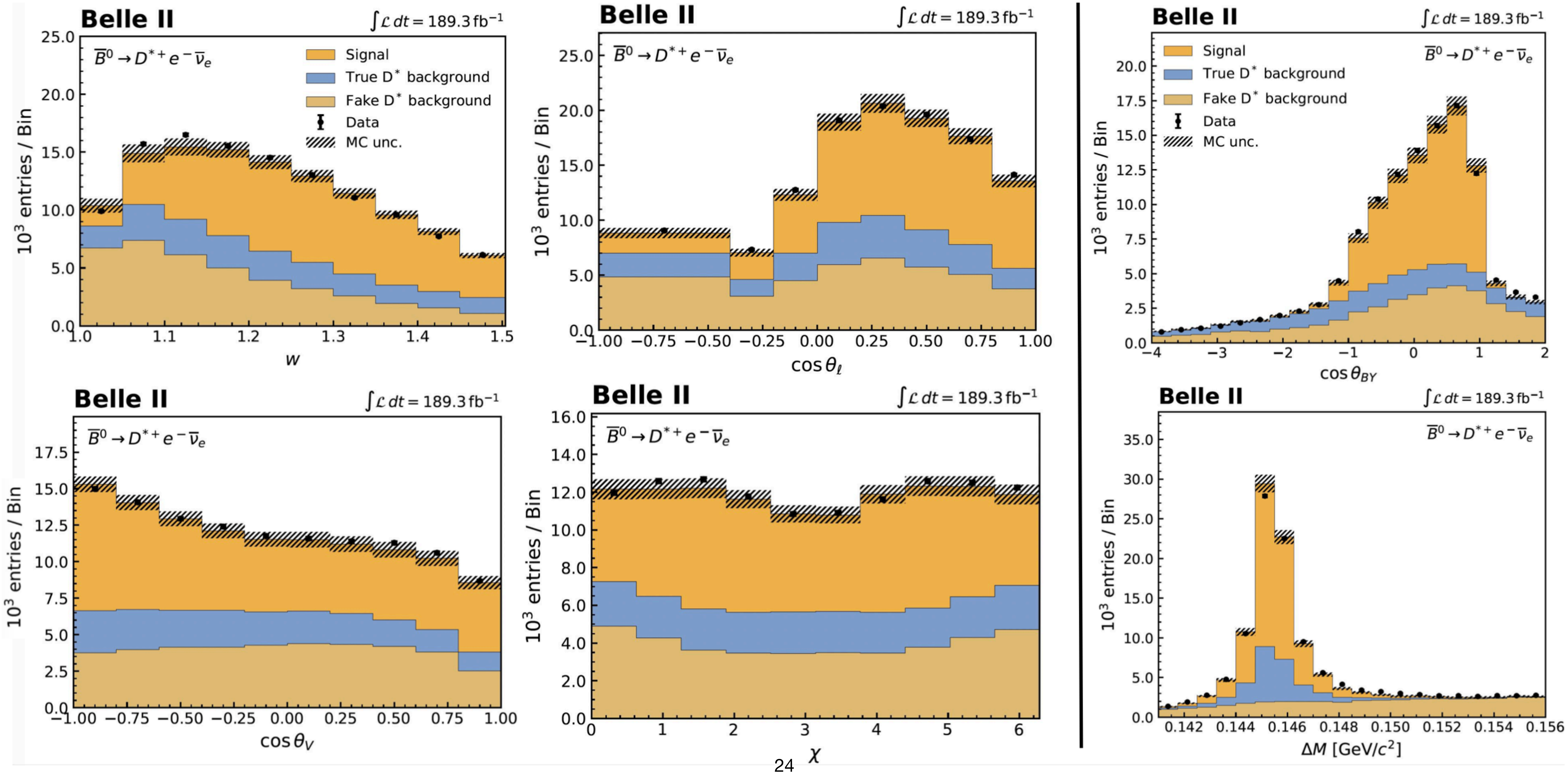
Luminosity projection



$B^0 \to D^{*-}\ell^+\nu$ untagged (189/fb)

Data & MC comparison (e channel)

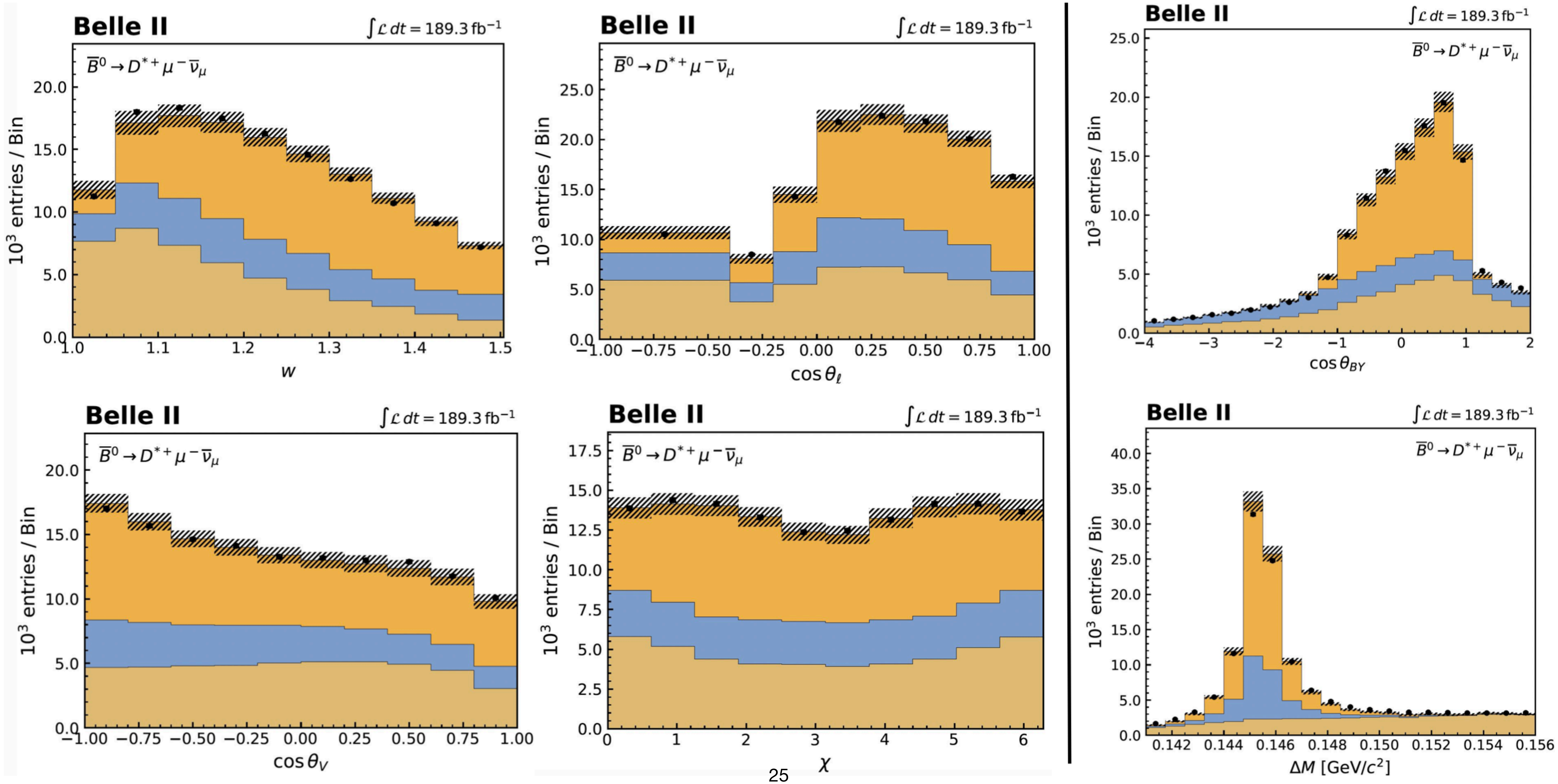
Preliminary



$B^0 \to D^{*-}\ell^+\nu$ untagged (189/fb)

Data & MC comparison (μ channel)

Preliminary



$B^0 \to D^{*-}\ell^+\nu$ untagged (189/fb)

CLN fit

Preliminary

Fitted values w/o LQCD predictions

	Values	Correlations				χ^2/ndf
ρ^2	1.25 ± 0.06	1.00	0.37	-0.81	0.32	39/31
$R_1(1)$	1.15 ± 0.07	0.37	1.00	-0.52	-0.08	
$R_2(1)$	0.88 ± 0.04	-0.81	-0.52	1.00	-0.10	
$\lvert V_{cb}\rvert \times 10^3$	40.4 ± 1.2	0.32	-0.08	-0.10	1.00	

Relative uncertainties (in %)

	ρ^2	$R_1(1)$	$R_2(1)$	$\lvert V_{cb}\rvert$
Statistical	2.8	3.7	2.9	0.6
Finite MC samples	2.5	3.3	2.4	0.6
Signal modelling	2.7	3.2	2.1	0.4
Background subtraction	1.5	1.3	1.4	0.3
Lepton ID efficiency	0.2	1.5	0.3	0.3
Slow pion efficiency	1.1	0.6	0.8	1.5
Tracking of K, π, ℓ	-	-	-	0.5
$N_{B\bar{B}}$	-	-	-	0.8
$f_{+-}/f00$	-	-	-	1.3
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	-	-	-	0.4
$\mathcal{B}(D^0 \to K^-\pi^+)$	-	-	-	0.4
B^0 lifetime	-	-	-	0.1
Total	5.0	6.2	4.7	2.5

Fully correlated between $\Delta\Gamma$, therefore only affects normalization, doesn't contribute to shape (applies to Tracking of K, π, ℓ through B^0 lifetime)

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

Preliminary

Preliminary

Fitted values with LQCD predictions

	Constraints on $h_{A_1}(w)$	Constraints on $h_{A_1}(w)$, $R_1(w)$, $R_2(w)$
$h_{A_1}(1)$	0.91 ± 0.02	0.94 ± 0.02
ρ^2	1.24 ± 0.05	1.22 ± 0.05
$R_1(1)$	1.15 ± 0.07	1.27 ± 0.04
$R_2(1)$	0.88 ± 0.04	0.90 ± 0.03
$\lvert V_{cb}\rvert \times 10^3$	40.5 ± 1.2	39.1 ± 1.1
χ^2/ndf	39/33	67/39
p-value	0.22	0.003

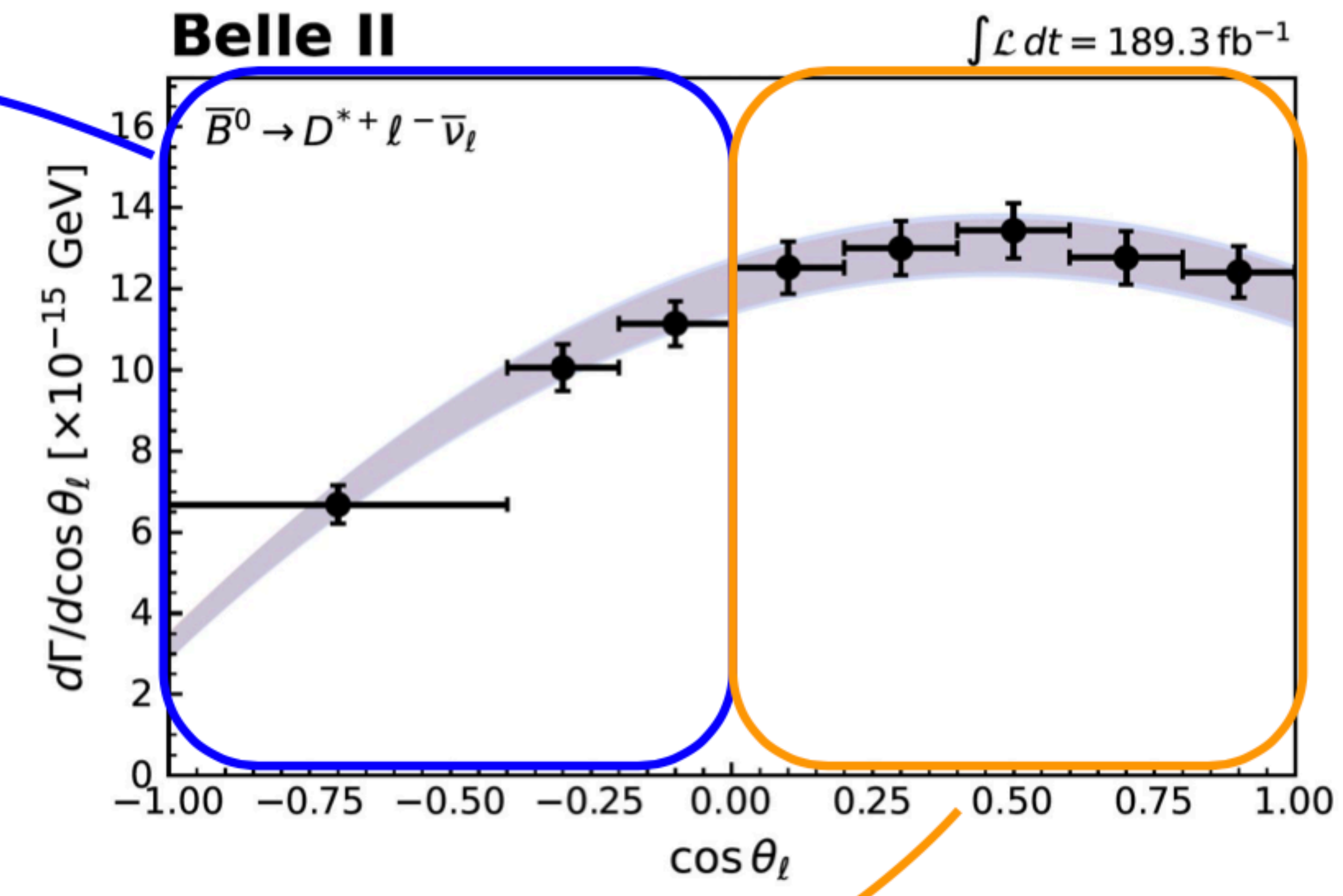
$B^0 \to D^{*-}\ell^+\nu$ untagged (189/fb)

Lepton flavour universality tests

Preliminary $R_{e/\mu} = \mathcal{B}(B \to D^*e\nu)/\mathcal{B}(B \to D^*\mu\nu) = 1.001 \pm 0.009_{stat} \pm 0.021_{syst}$

- Angular asymmetry

$$\mathcal{A}_{\rm FB} = \frac{\int_0^1 {\rm d}\cos\theta_\ell {\rm d}\Gamma/{\rm d}\cos\theta_\ell - \int_{-1}^0 {\rm d}\cos\theta_\ell {\rm d}\Gamma/{\rm d}\cos\theta_\ell}{\int_0^1 {\rm d}\cos\theta_\ell {\rm d}\Gamma/{\rm d}\cos\theta_\ell + \int_{-1}^0 {\rm d}\cos\theta_\ell {\rm d}\Gamma/{\rm d}\cos\theta_\ell}$$



Obtained results:

Preliminary

$$\mathcal{A}_{\rm FB}^e = 0.219 \pm 0.011 \pm 0.020\,,$$
$$\mathcal{A}_{\rm FB}^\mu = 0.215 \pm 0.011 \pm 0.022\,,$$
$$\Delta\mathcal{A}_{\rm FB} = (-4 \pm 16 \pm 18) \times 10^{-3}\,.$$

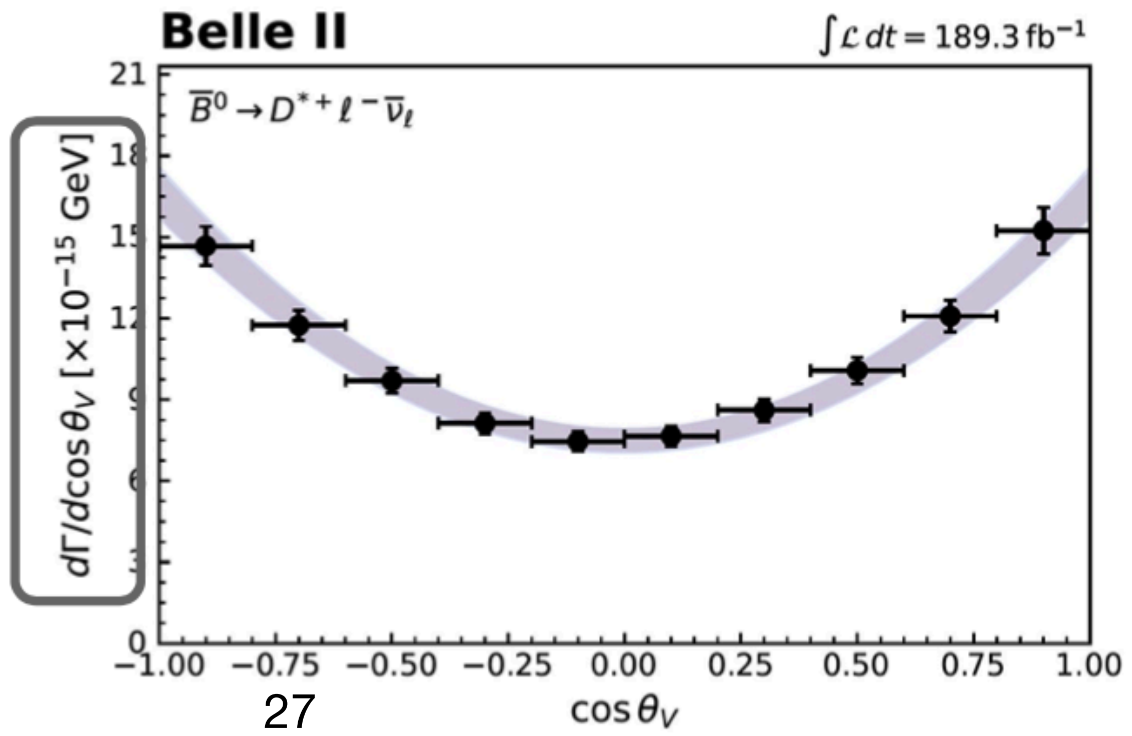
$$\Delta\mathcal{A}_{\rm FB} = \mathcal{A}_{\rm FB}^\mu - \mathcal{A}_{\rm FB}^e$$

- longitudinal D* polarization fraction F_L

$$\frac{1}{\Gamma}\frac{{\rm d}\Gamma}{{\rm d}\cos\theta_V} = \frac{3}{2}\left(F_L\cos^2\theta_V + \frac{1-F_L}{2}\sin^2\theta_V\right)$$

Normalized partial decay rate on $\cos\theta_V$ projection

A function of FL and $\cos\theta_V$



Obtained results:

$$F_L^e = 0.521 \pm 0.005 \pm 0.007\,,$$
$$F_L^\mu = 0.534 \pm 0.005 \pm 0.006\,,$$
$$\Delta F_L = 0.013 \pm 0.007 \pm 0.007\,,$$

Preliminary

$$\Delta F_L = F_L^\mu - F_L^e$$