Exclusive semileptonic B decays at Belle and Belle II

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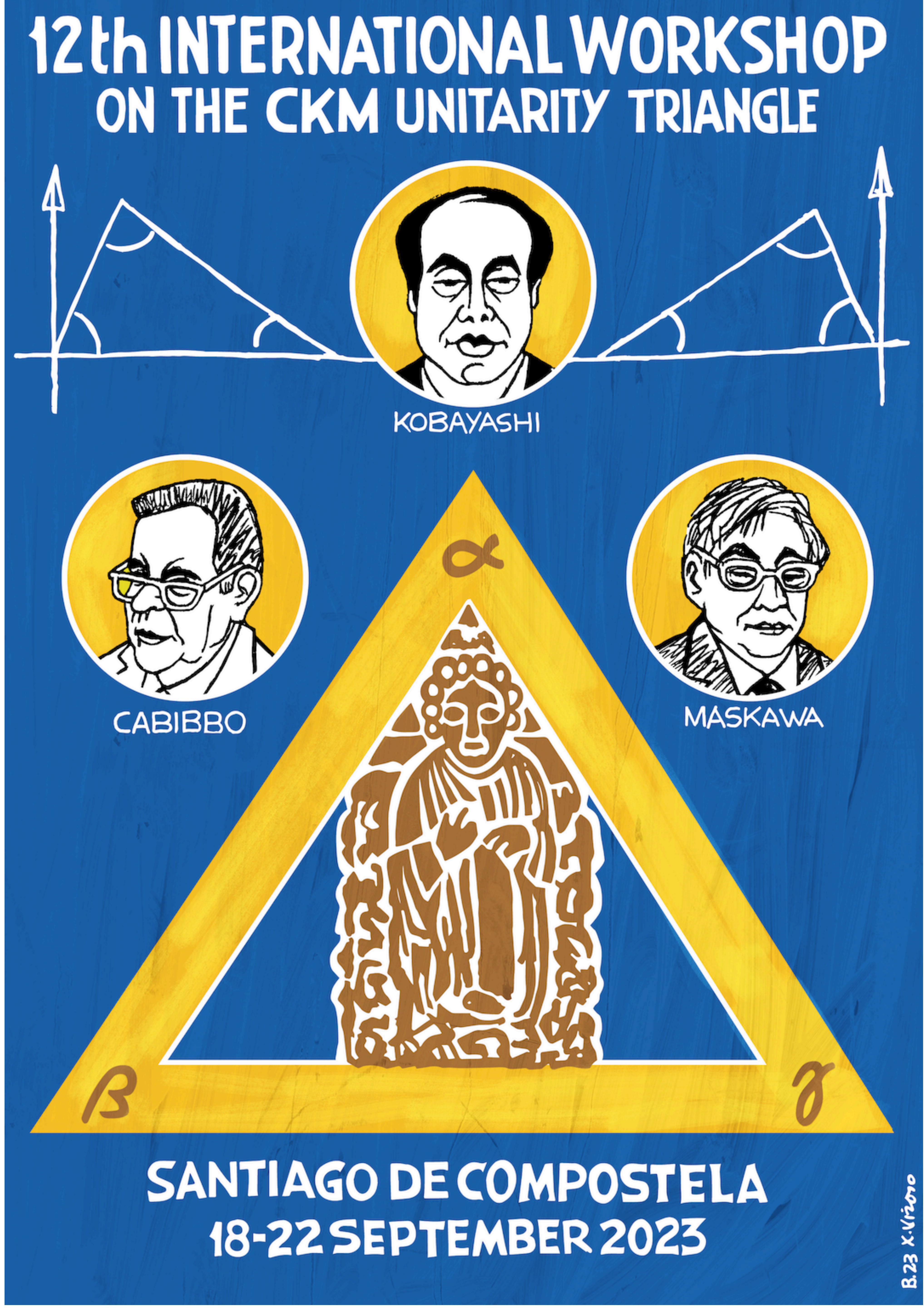
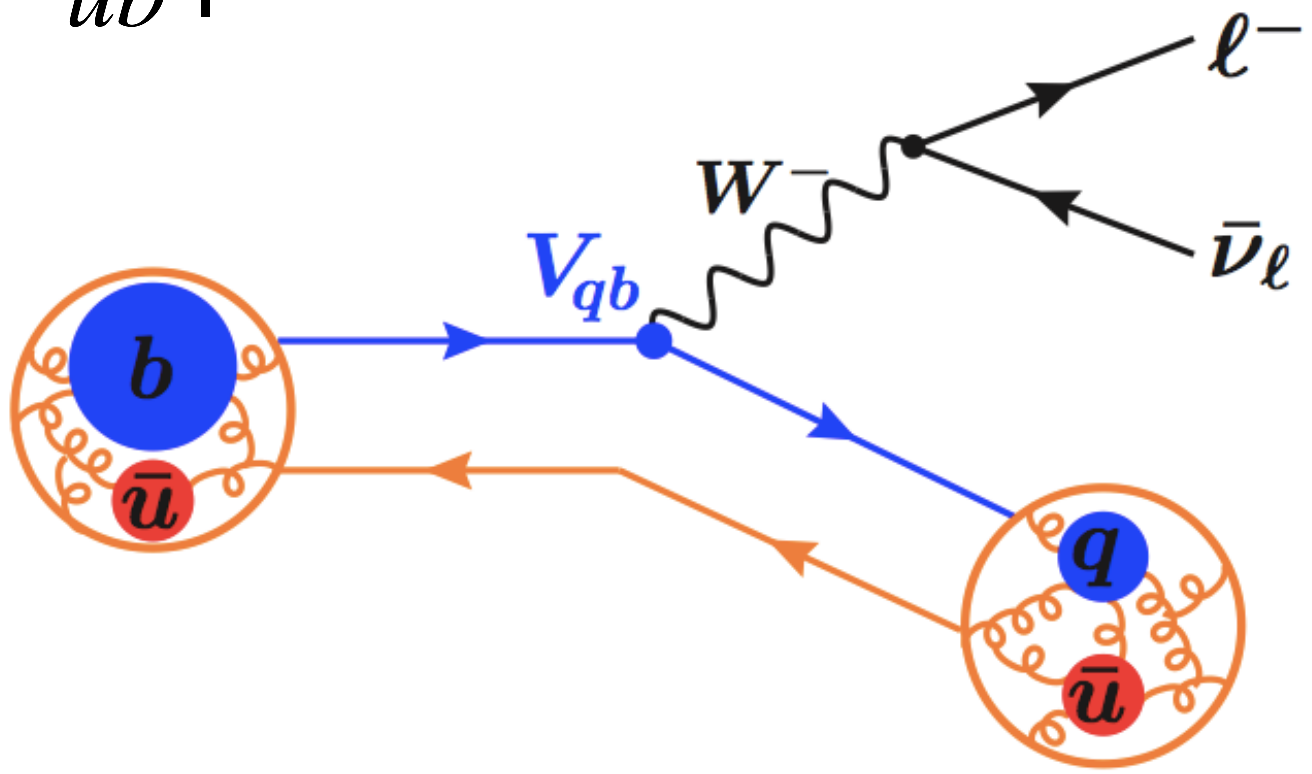
Representing the collaborations



Semileptonic B decays

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

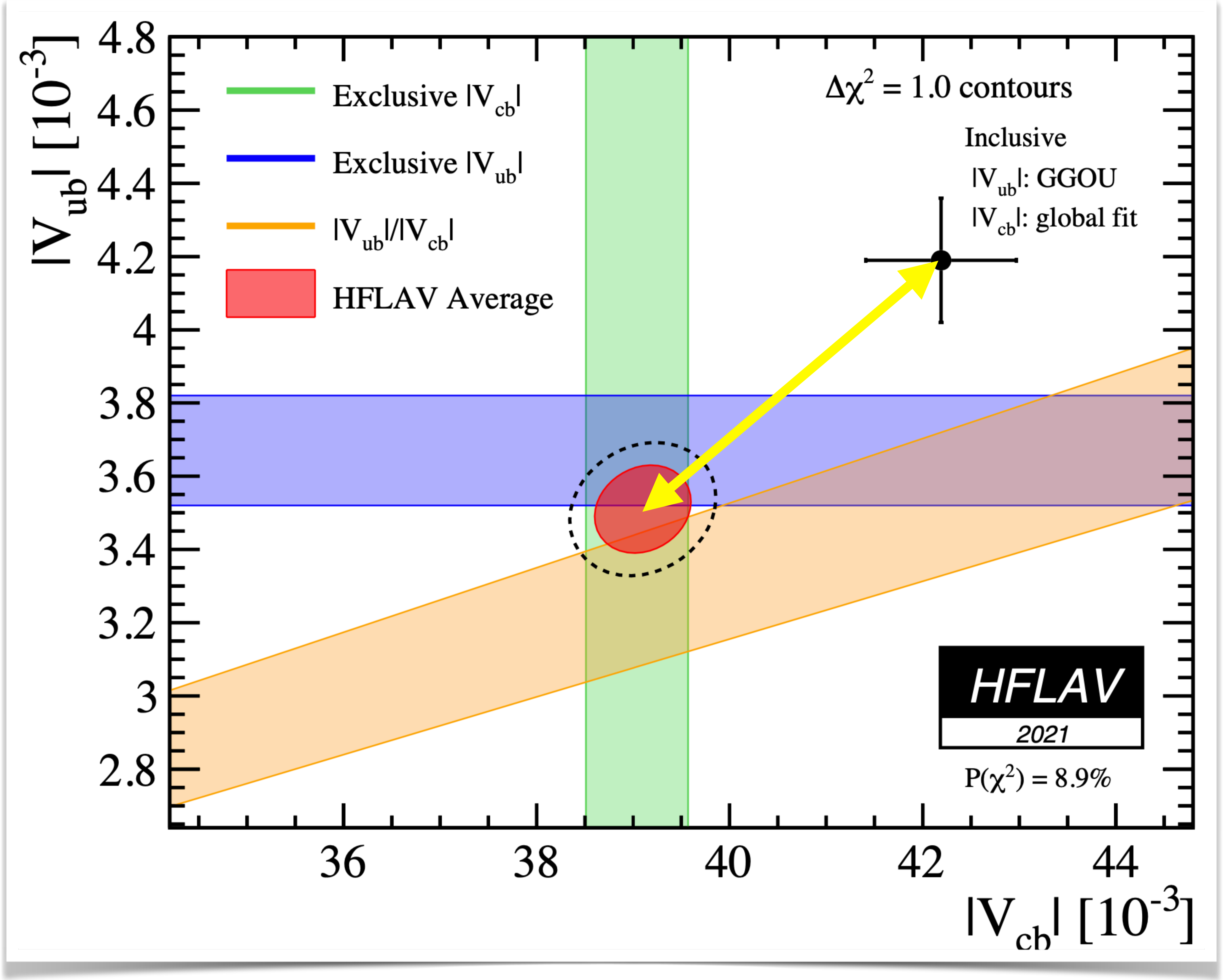


$$d\Gamma \propto G_F^2 |V_{qb}|^2 \left| L_\mu \langle X | \bar{q}\gamma_\mu P_L b | B \rangle \right|^2$$

- 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 $B_s \to \mu\mu$ and $K \to \pi\nu\nu$
- The determinations can be
  - *Exclusive* — from a single final state
  - *Inclusive* — sensitive to all SL final states
    → talk by M. Prim Tue 12:30 pm (WG1&2)

	Experiment	**Theory**
Exclusive $\|V_{cb}\|$	$B \to D l \nu$, $D^* l \nu$ (low backgrounds)	Lattice QCD, light cone sum rules
Inclusive $\|V_{cb}\|$	$B \to X l \nu$ (higher background)	Operator product expansion

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



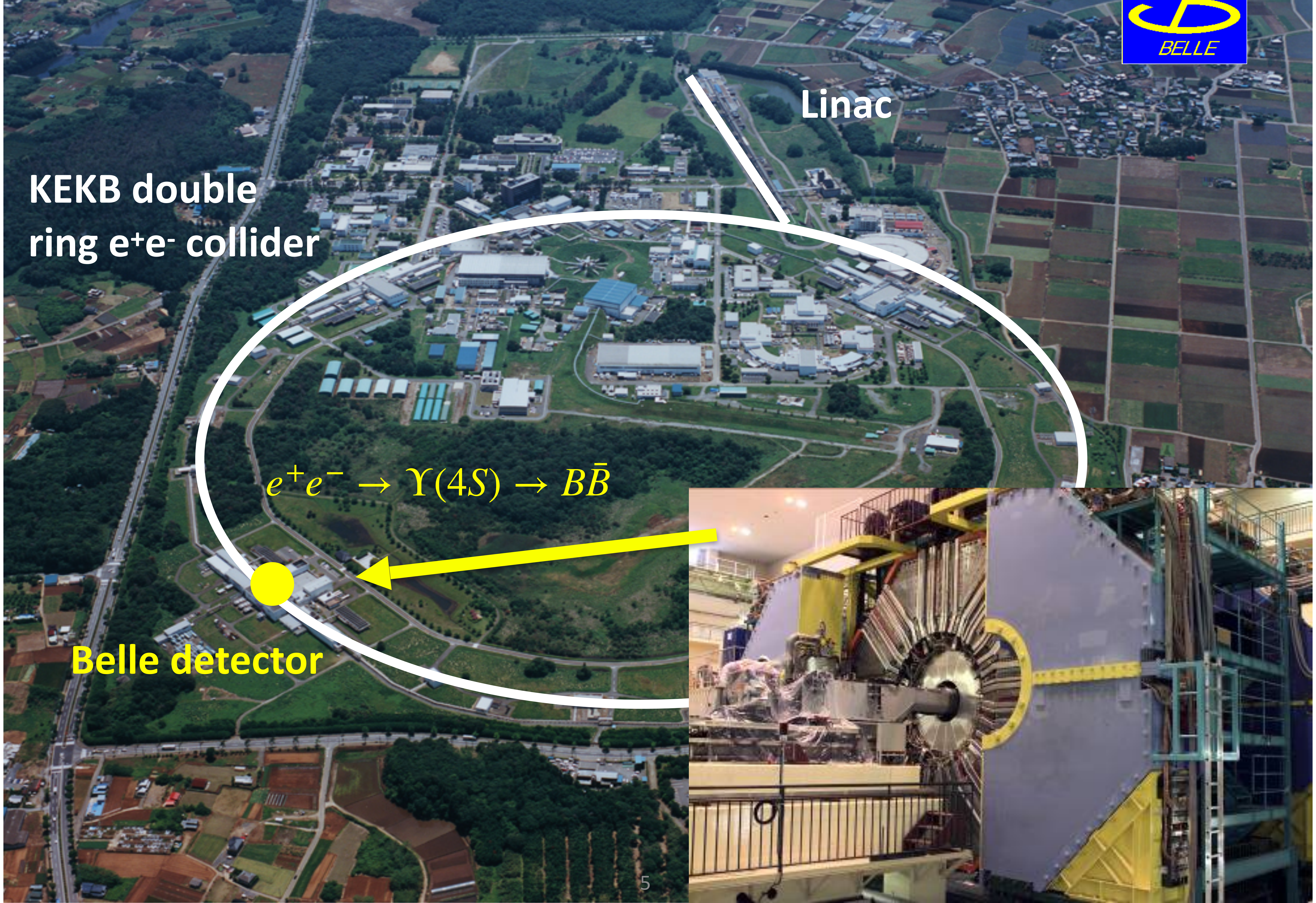
- Determinations of both $|V_{cb}|$ and $|V_{ub}|$ exhibit a discrepancy at the level of ~3σ between exclusive and inclusive
- The current experimental focus is on understanding the origin of this discrepancy, as this inconsistency limits the power of precision flavour physics

Outline

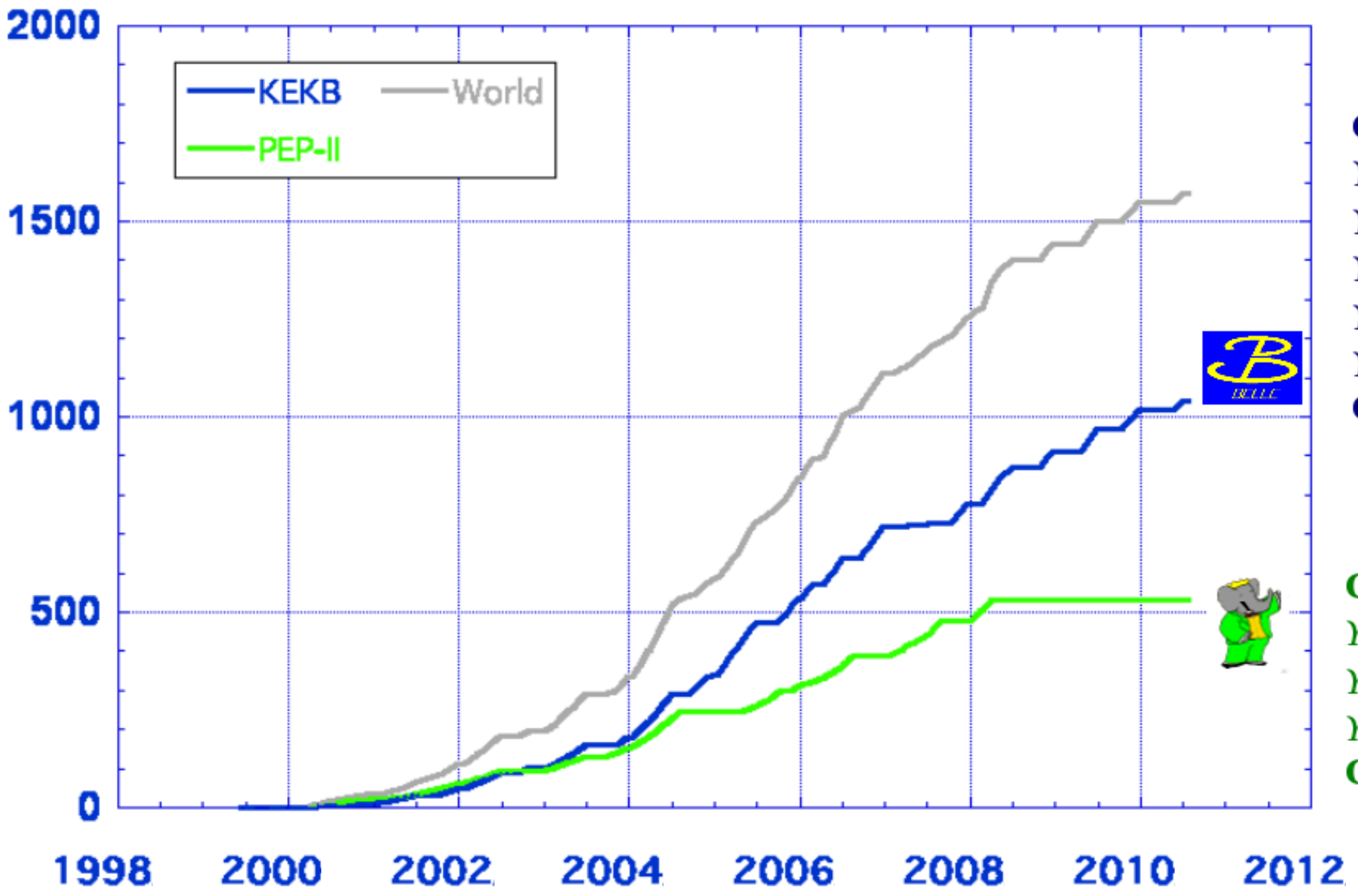
Results covered in this presentation

- **Belle II**
  - $B^0 \to D^{*-}\ell^+\nu$ and determination of $|V_{cb}|$
    [189/fb, to be submitted to Phys. Rev. D]
- **Belle**
  - $B \to D^*\ell\nu$ differential decay distributions and $|V_{cb}|$
    [711/fb, Phys.Rev.D 108 (2023) 1, 012002, arXiv:2301.07529 [hep-ex]]
  - Angular coefficients in $B \to D^*\ell\nu$ and $|V_{cb}|$
    [711/fb, EPS-HEP23 preliminary]
  - Measurement of $B \to \bar{D}^{(*)}\pi\ell^+\nu, D^{(*)}\pi^+\pi^-\ell^+\nu$
    [711/fb, Phys.Rev.D 107 (2023) 9, 092003, arXiv:2211.09833 [hep-ex]]

1999 – 2010: B factory at KEK (Japan)



Comparison of B factories (1999-2010)



$> 1\ ab^{-1}$

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 24 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

$\sim 100\ fb^{-1}$

$\sim 550\ fb^{-1}$

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

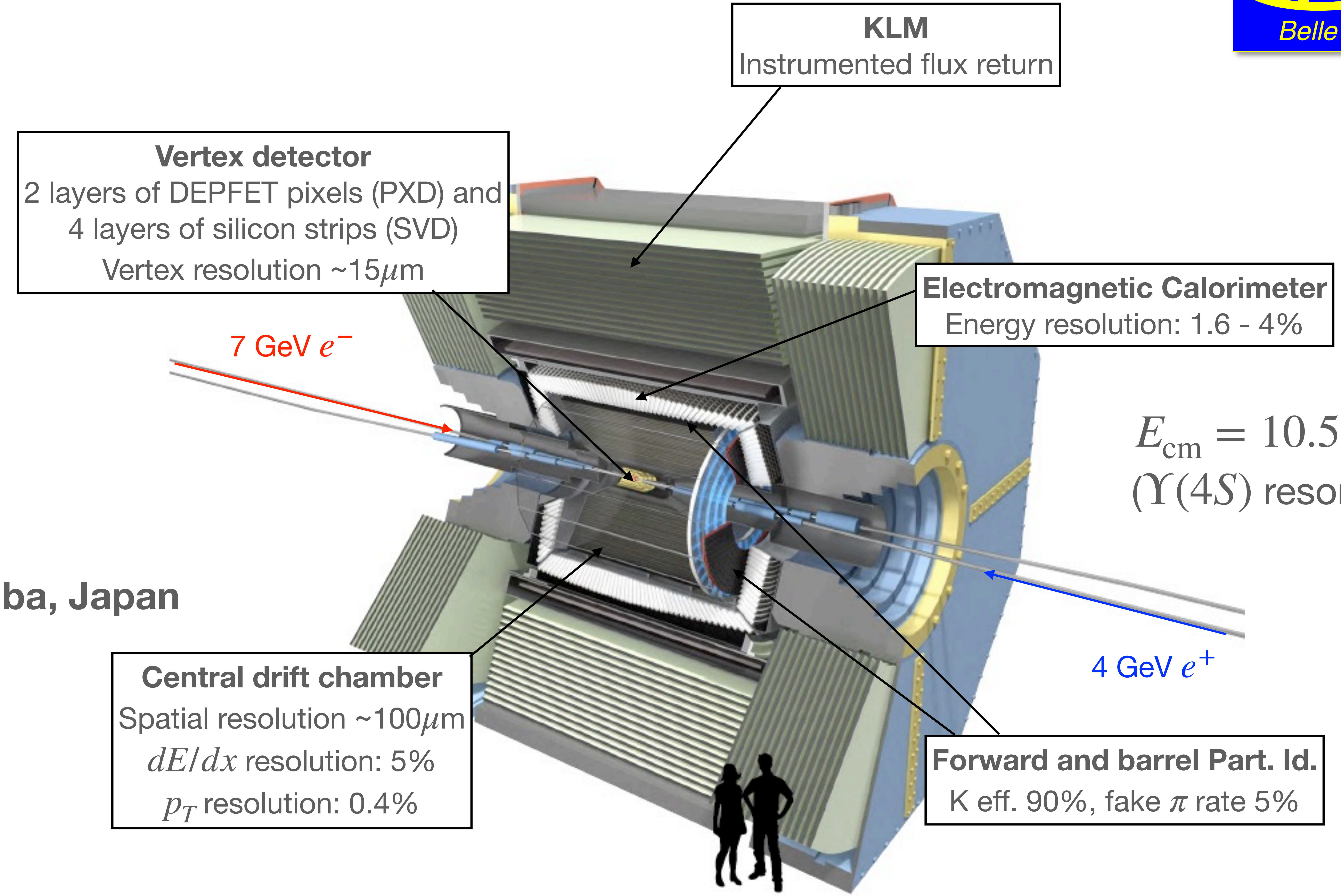
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

$\sim 54\ fb^{-1}$

The Belle II detector

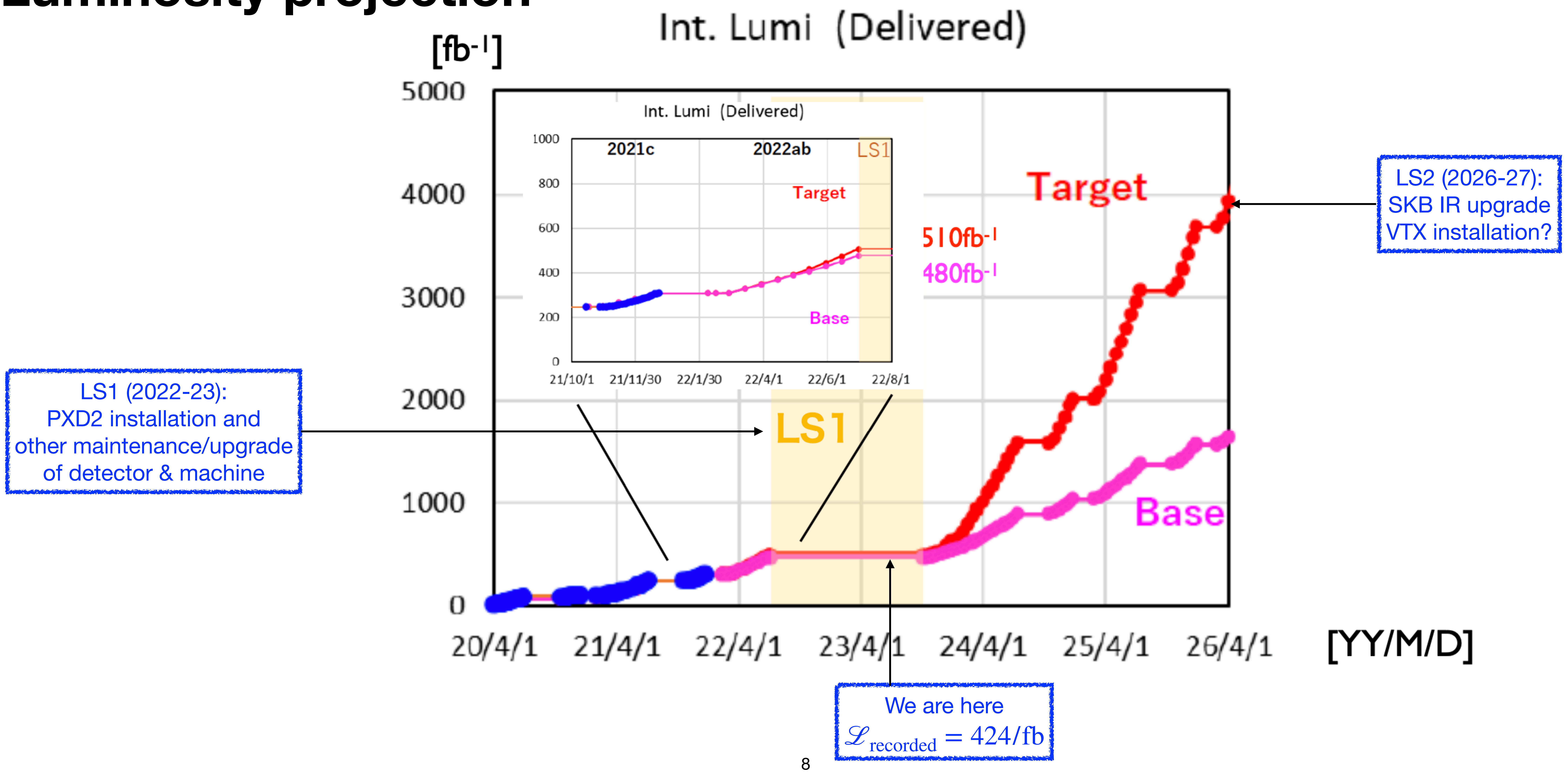
KEK
Tsukuba, Japan



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

Belle II timeline

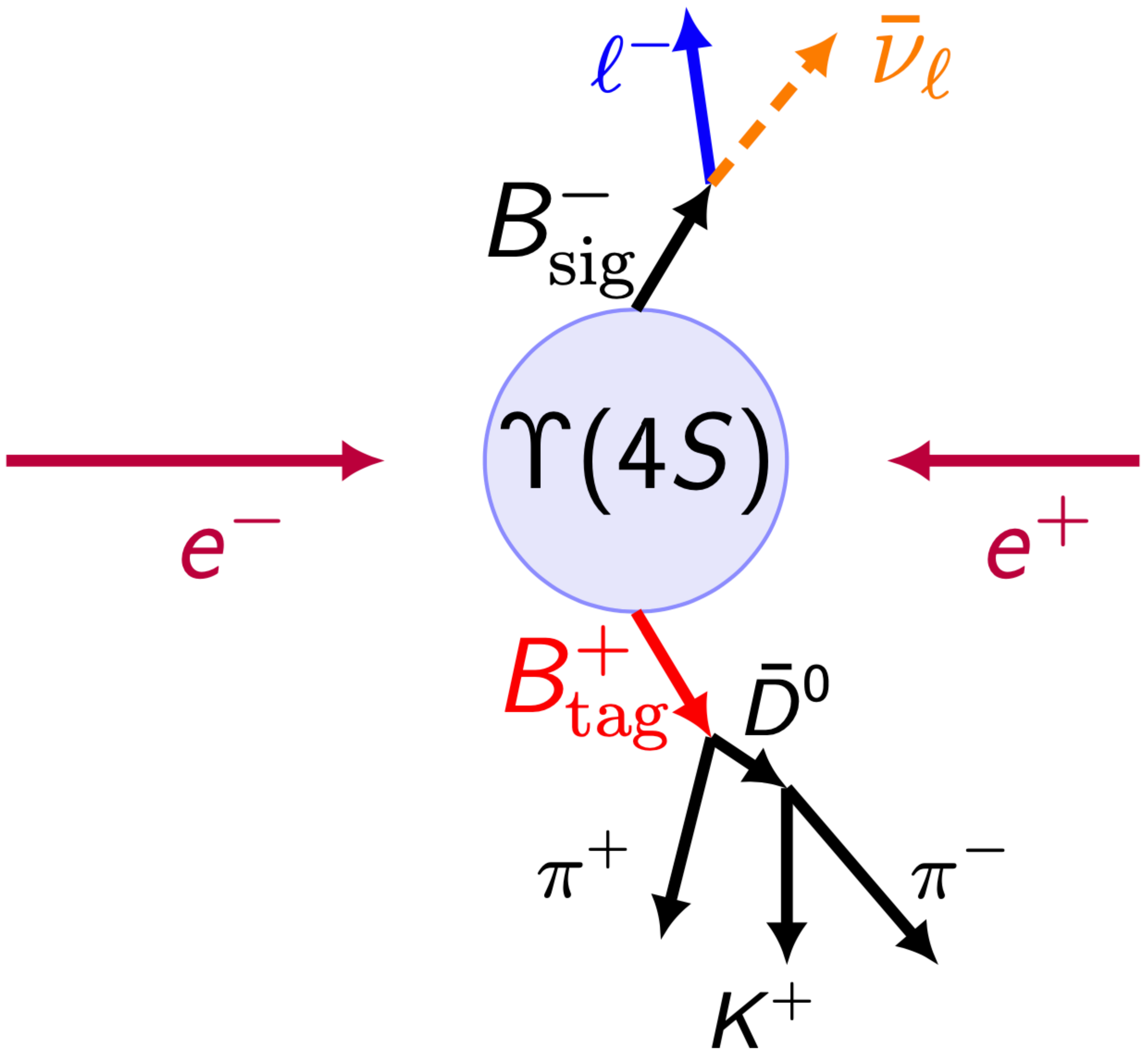
Luminosity projection



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

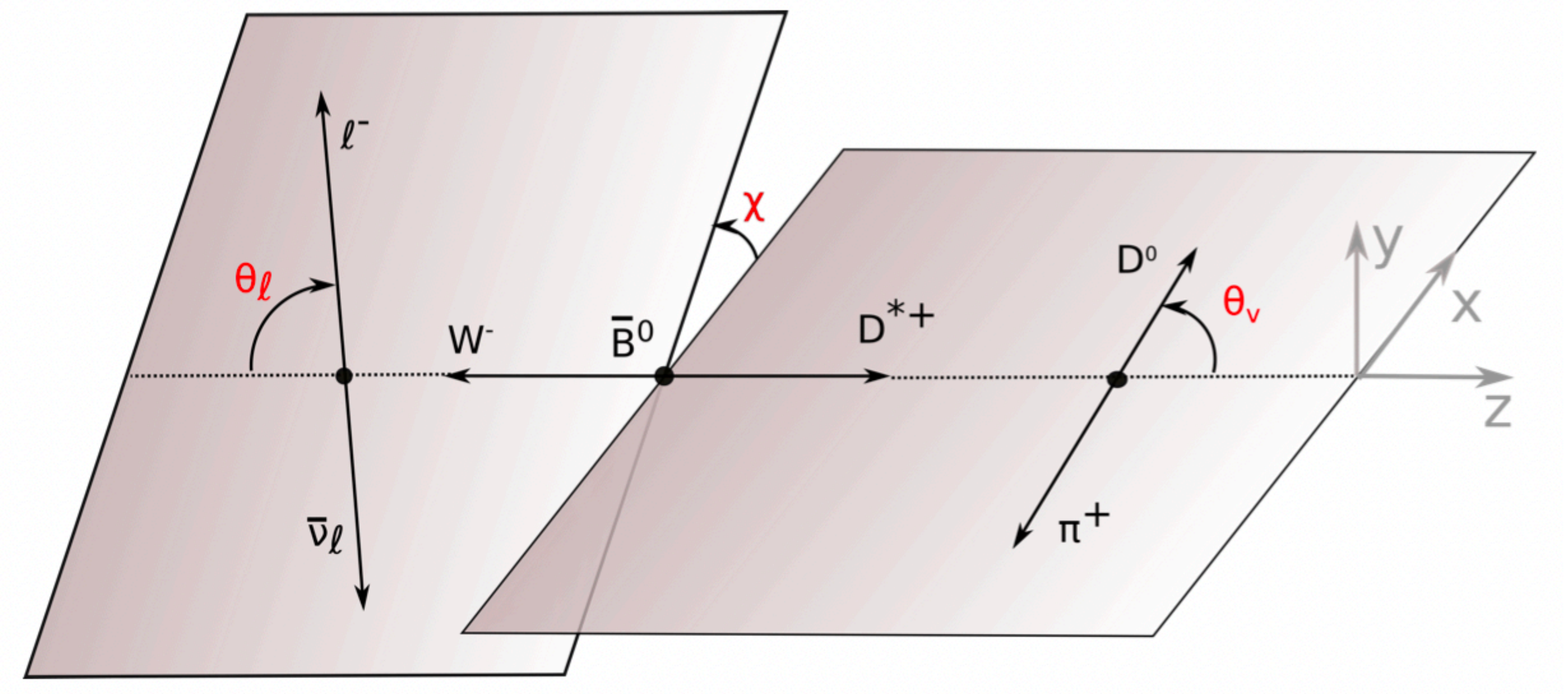
signal yield $O(10^3)$ lower (-)
low backgrounds (+)
good neutrino reconstruction (+)
tag calibration (-)

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

to be submitted to Phys. Rev. D

Updated numbers with respect to winter 2022/23 presentations

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



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

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

- 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)]:

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

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$

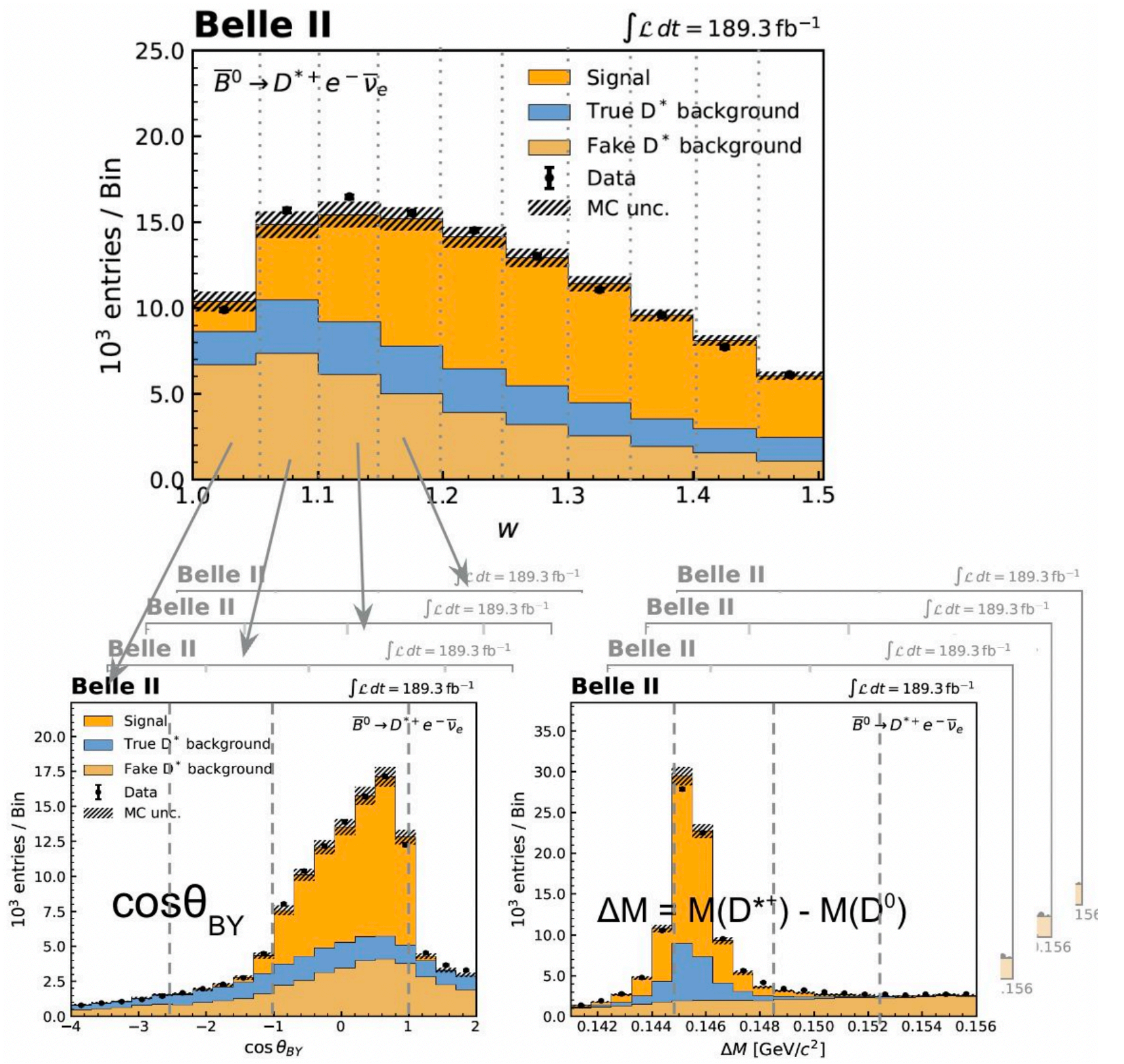
$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$

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



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

BGL fit result

Preliminary

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

LQCD data at zero recoil

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

$$|V_{cb}|_{\rm BGL} = (40.57 \pm 0.31 \pm 0.95 \pm 0.58) \times 10^{-3}$$

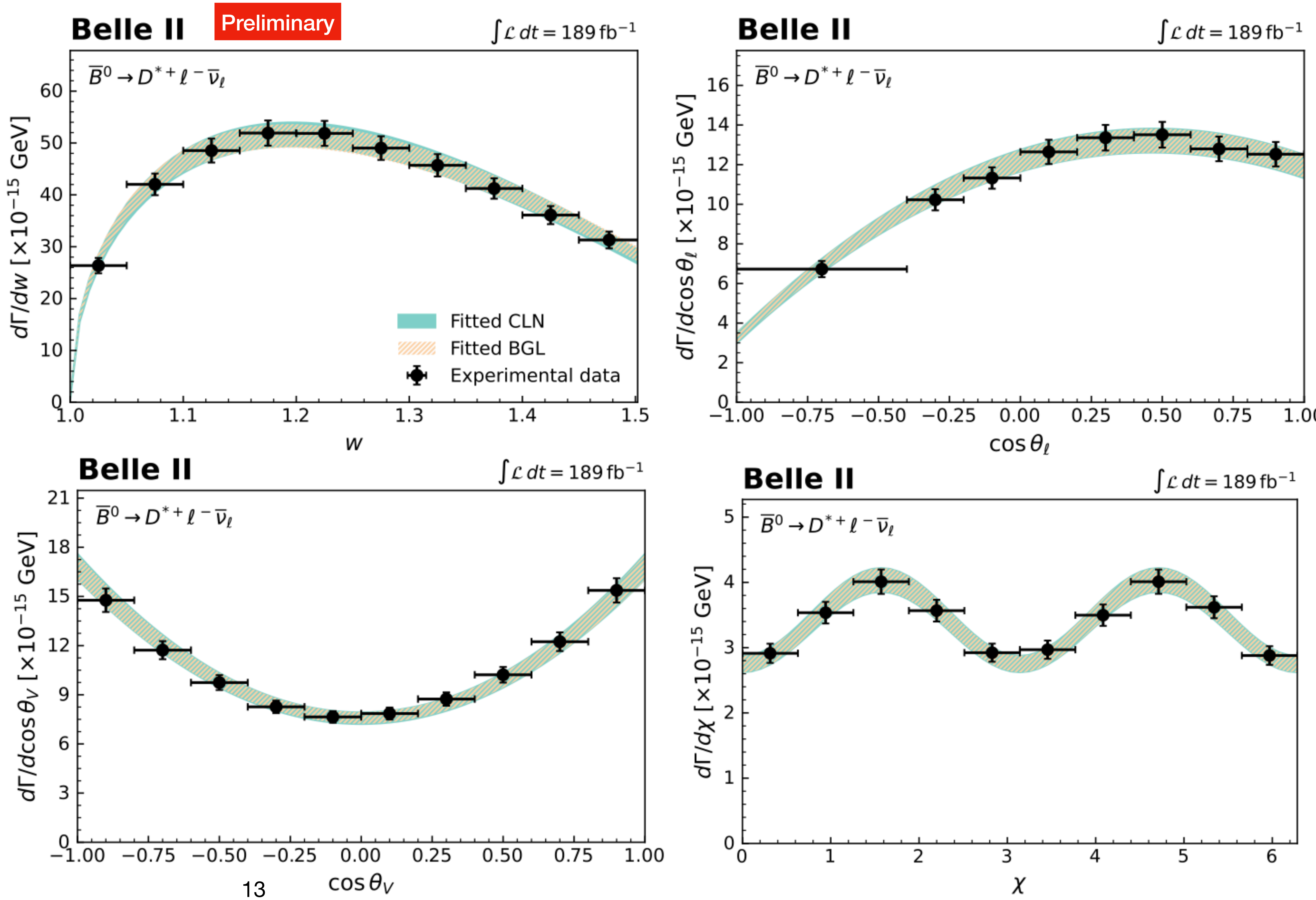
BGL truncation order determined by Nested Hypothesis Test [Phys. Rev. D100, 013005]

Preliminary

	Values	Correlations				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	

Relative uncertainty (%) Preliminary

	$\tilde{a}_0$	$\tilde{b}_0$	$\tilde{b}_1$	$\tilde{c}_1$
Statistical	3.7	0.8	65.1	50.8
Background subtraction	2.1	0.4	31.3	21.8
Finite MC 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 modelling	2.3	0.5	52.1	35.0
Total	5.8	2.5	96.0	73.0



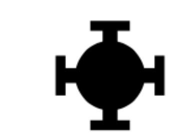
Fit with non-zero recoil LQCD

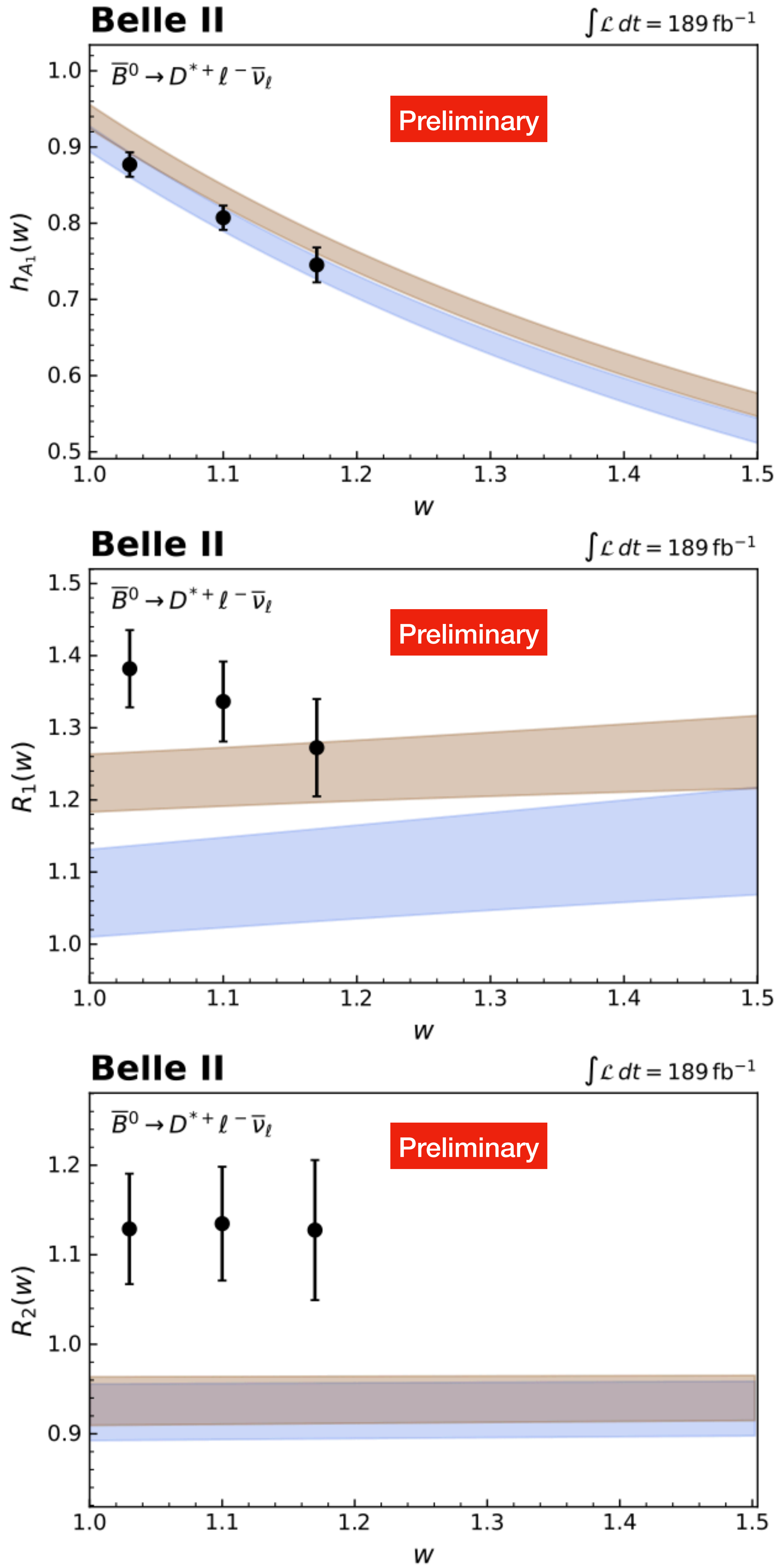
LQCD constraints at $w = 1.03, 1.10, 1.17$

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

	Constraints on $h_{A_1}(w)$	Constraints on $h_{A_1}(w)$, $R_1(w)$, $R_2(w)$
$a_0 \times 10^3$	21.7 ± 1.3	25.6 ± 0.8
$b_0 \times 10^3$	13.19 ± 0.24	13.61 ± 0.23
$b_1 \times 10^3$	-6 ± 6	2 ± 6
$c_1 \times 10^3$	-0.9 ± 0.7	0.0 ± 0.7
$\lvert V_{cb}\rvert \times 10^3$	40.3 ± 1.2	38.3 ± 1.1
χ^2/ndf	39/33	75/39
p-value	21%	0.04%

Preliminary





Summary of the measurement

- Branching fraction

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

Preliminary

- Value of $|V_{cb}|$

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

Preliminary

- Lepton flavour universality tests

$$R_{e/\mu} = 0.998 \pm 0.009 \pm 0.020$$
$$\Delta\mathcal{A}_{\text{FB}} = (-17 \pm 16 \pm 16) \times 10^{-3}$$
$$\Delta F_L = 0.006 \pm 0.007 \pm 0.005$$

Preliminary

$|V_{cb}|$ and $|V_{ub}|$ from Belle II

WA values [HFLAV 2021]

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

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

- Recent, preliminary results from exclusive decays

	$\lvert V_{cb}\rvert \times 10^3$	Reference
Belle II $B^0 \to D^{*-}\ell^+\nu$ untagged	40.57 ± 1.16 (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]

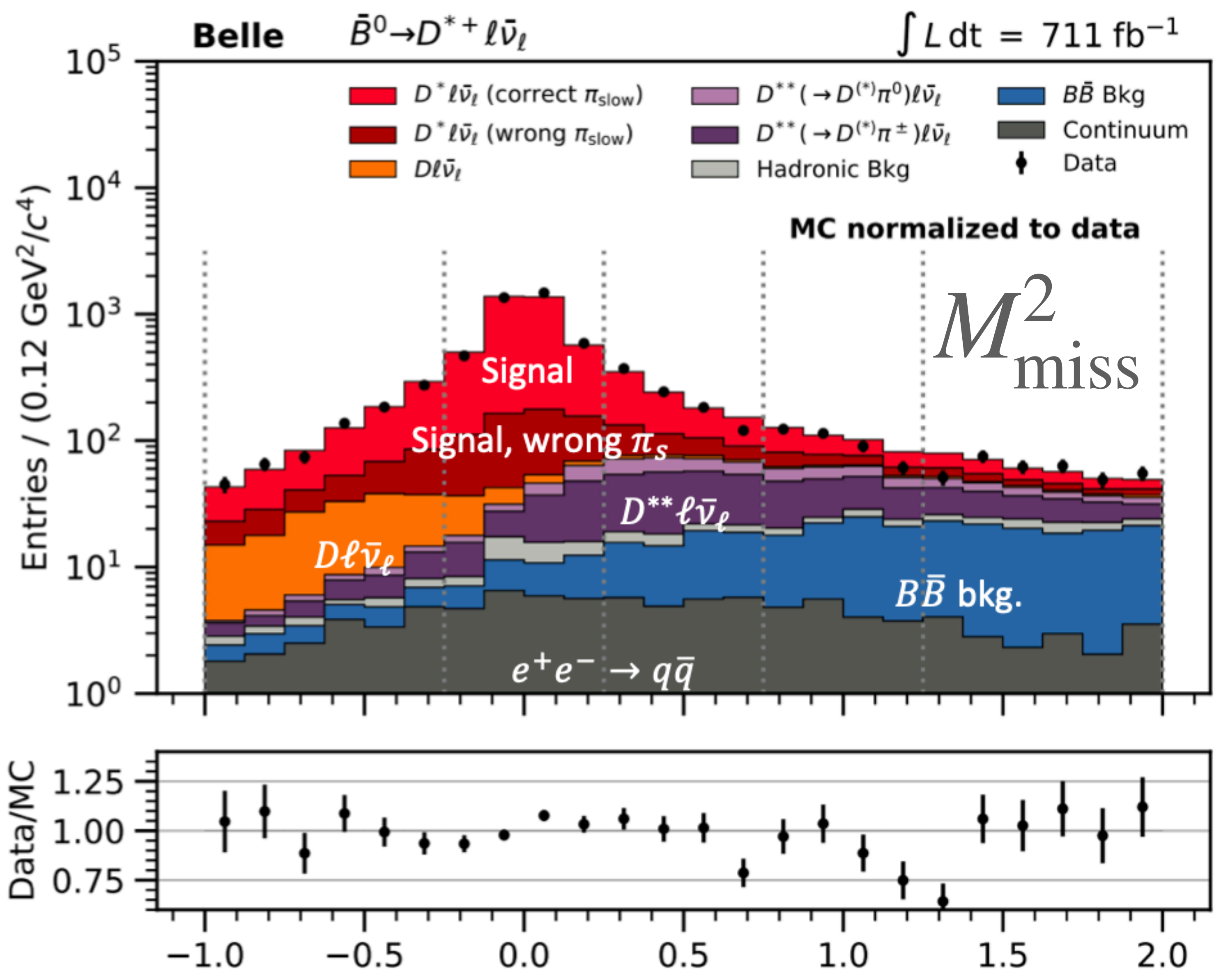
	$\lvert V_{ub}\rvert \times 10^3$	Reference
Belle II $B \to \pi e\nu$ tagged	3.88 ± 0.45 Preliminary	[arXiv:2206.08102]
Belle II $B \to \pi\ell\nu$ untagged	3.55 ± 0.25 Preliminary	[arXiv:2210.04224]

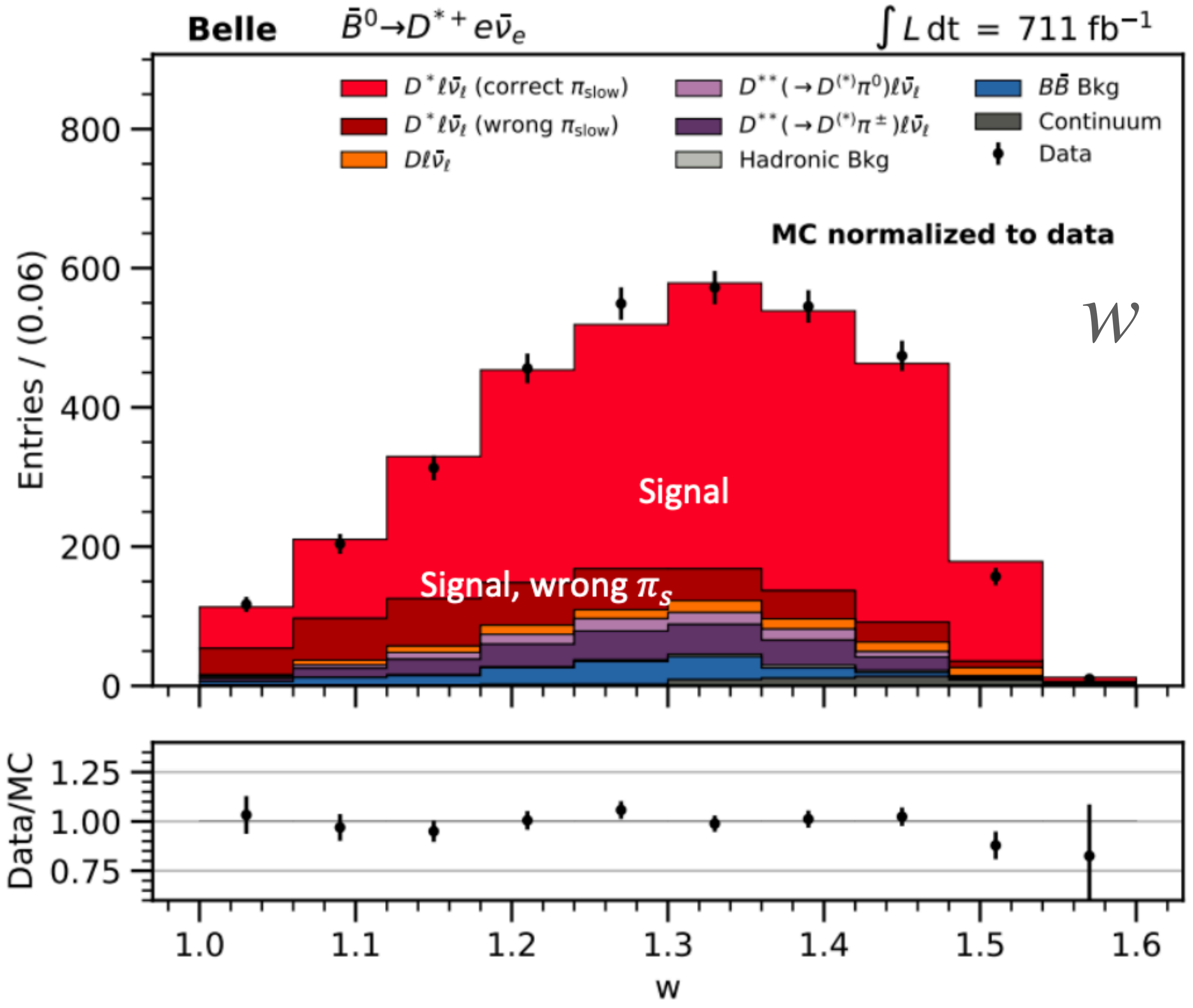
$B \to D^* \ell^+ \nu$ differential decay distributions (711/fb)

Phys.Rev.D 108 (2023) 1, 012002, arXiv:2301.07529 [hep-ex]]

Reconstruction

- One B meson is fully reconstructed in a hadronic mode (tag side)
- $D^{*+} \to D^0\pi^+, D^+\pi^0$, $D^{*0} \to D^0\pi^0$ are searched on signal side
  - D^{*0} channel has higher signal efficiency than D^{*+} near zero recoil
- And combined with an appropriately charged $\ell = e, \mu$ to identify a $B \to D^*\ell\nu$ decay



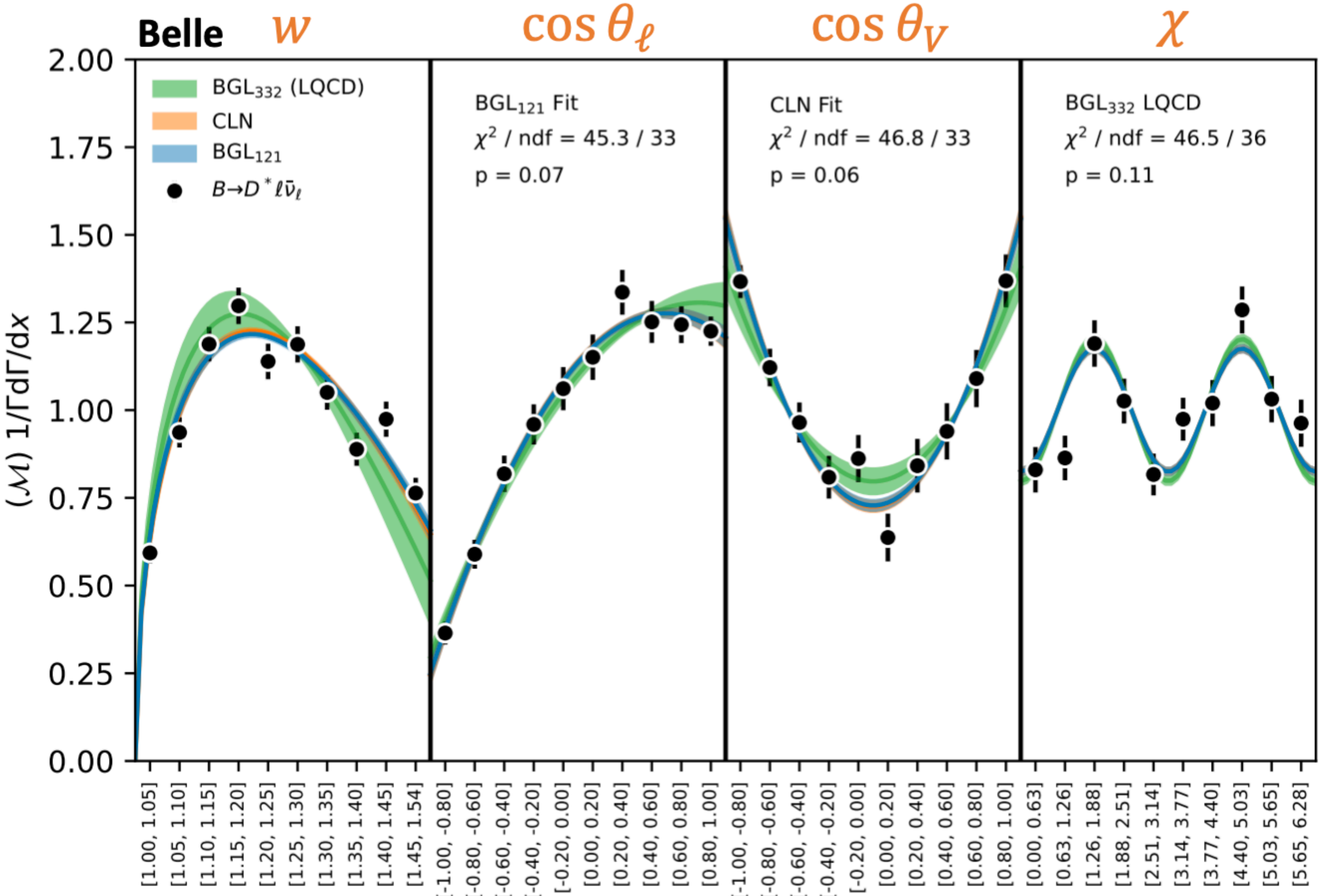


Extraction Method: Missing Mass Squared

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

Results

- Normalisation is not measured, $\mathscr{B}$ taken from HFLAV
- Fit to marginal distributions of $w, \cos\theta_\ell, \cos\theta_V, \chi$ (40 bins)



$$|V_{cb}|^{\rm BGL} = (40.6 \pm 0.9) \times 10^{-3}$$
$$|V_{cb}|^{\rm CLN} = (40.1 \pm 0.9) \times 10^{-3}$$

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

LFV observables

$$\Delta A_{FB} = A_{FB}^{\mu} - A_{FB}^{e} = 0.022 \pm 0.027$$
$$\Delta F_L = F_L^{\mu} - F_L^{e} = 0.034 \pm 0.024$$
$$R_{e\mu} = \frac{\mathcal{B}(B \to D^* e \bar{\nu}_e)}{\mathcal{B}(B \to D^* \mu \bar{\nu}_\mu)} = 0.990 \pm 0.031$$

BGL332 is the LQCD prediction
Eur.Phys.J.C 82 (2022) 12, 1141,
Eur.Phys.J.C 83 (2023) 1, 21 (erratum)
arXiv:2105.14019 [hep-lat]

Angular coefficients of $B \to D^* \ell^+ \nu$ (711/fb)

EPS-HEP 2023 preliminary

Preliminary

New !

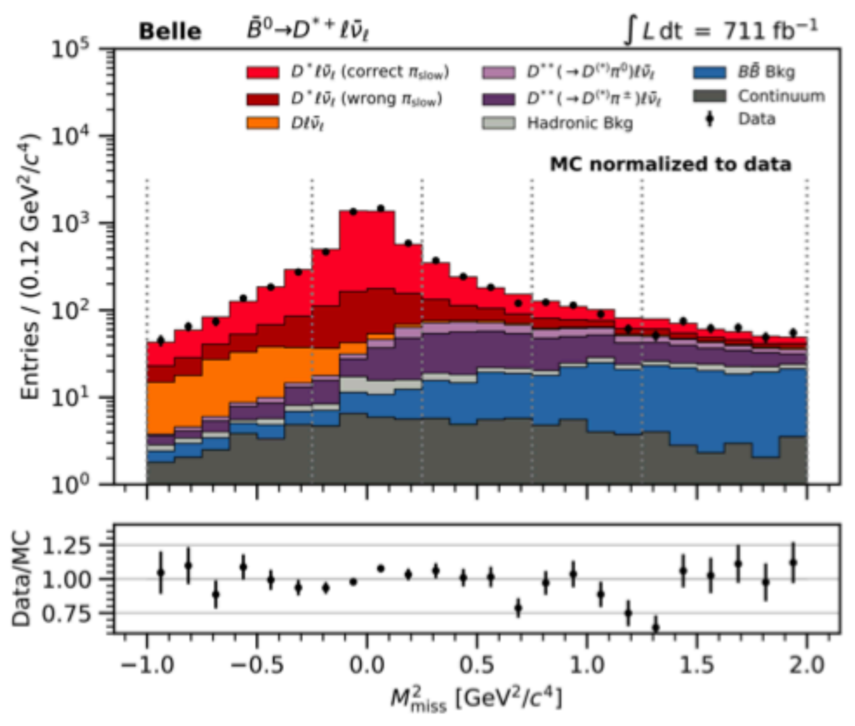
Reconstruction

- Same dataset, fit 12 angular coefficients $J_i = J_i(w)$ in 4 bins of w
- In total 144 M^2_{miss} fits per mode, 576 in total

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

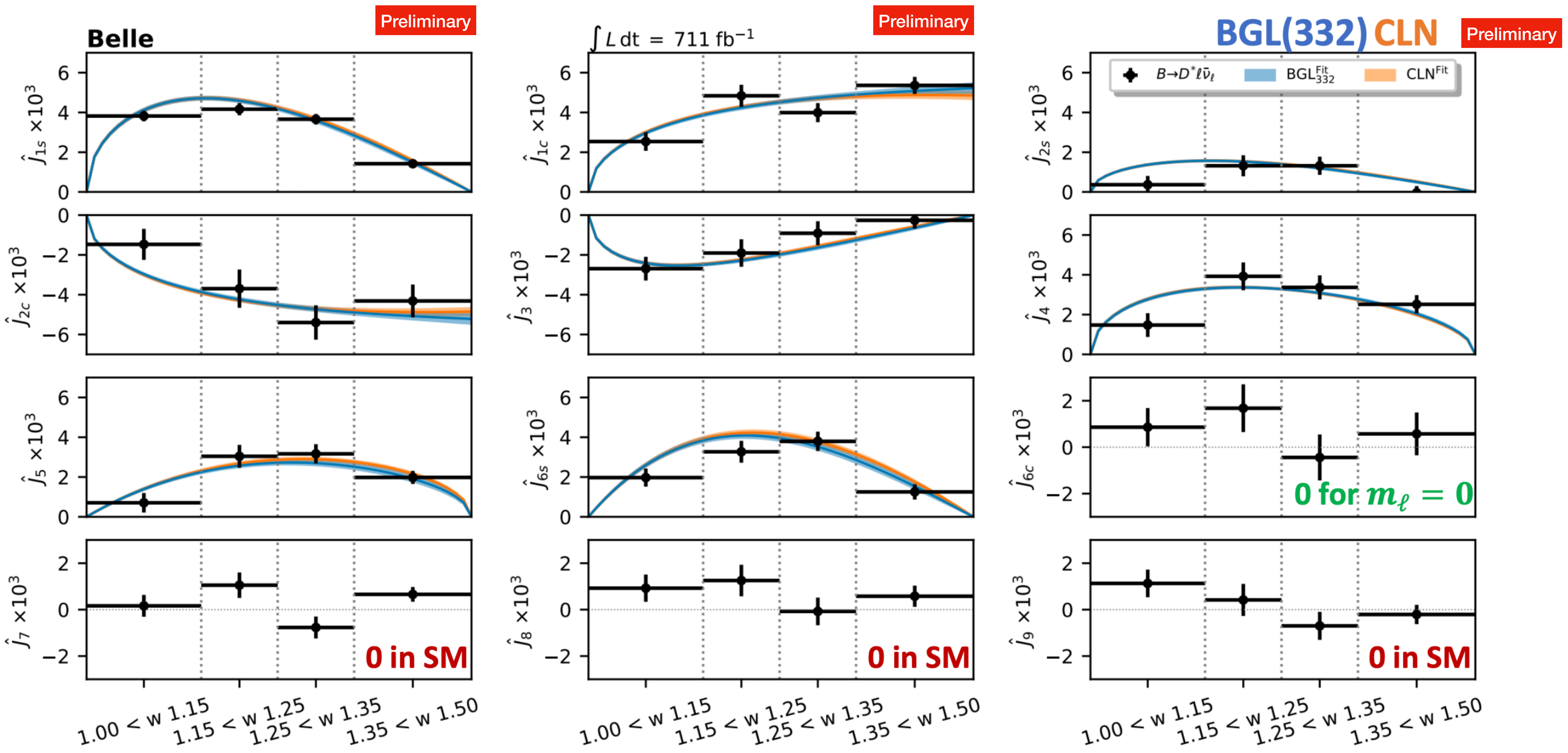
$$\bar{J}_i = \frac{1}{N_i} \sum_{j=1}^{8} \sum_{k,l=1}^{4} \eta^{\chi}_{i,j} \eta^{\theta_\ell}_{i,k} \eta^{\theta_V}_{i,l} \left| \chi^{(j)} \otimes \chi^{(k)} \otimes \chi^{(l)} \right|$$

Normalization Weights Unfolded Yields

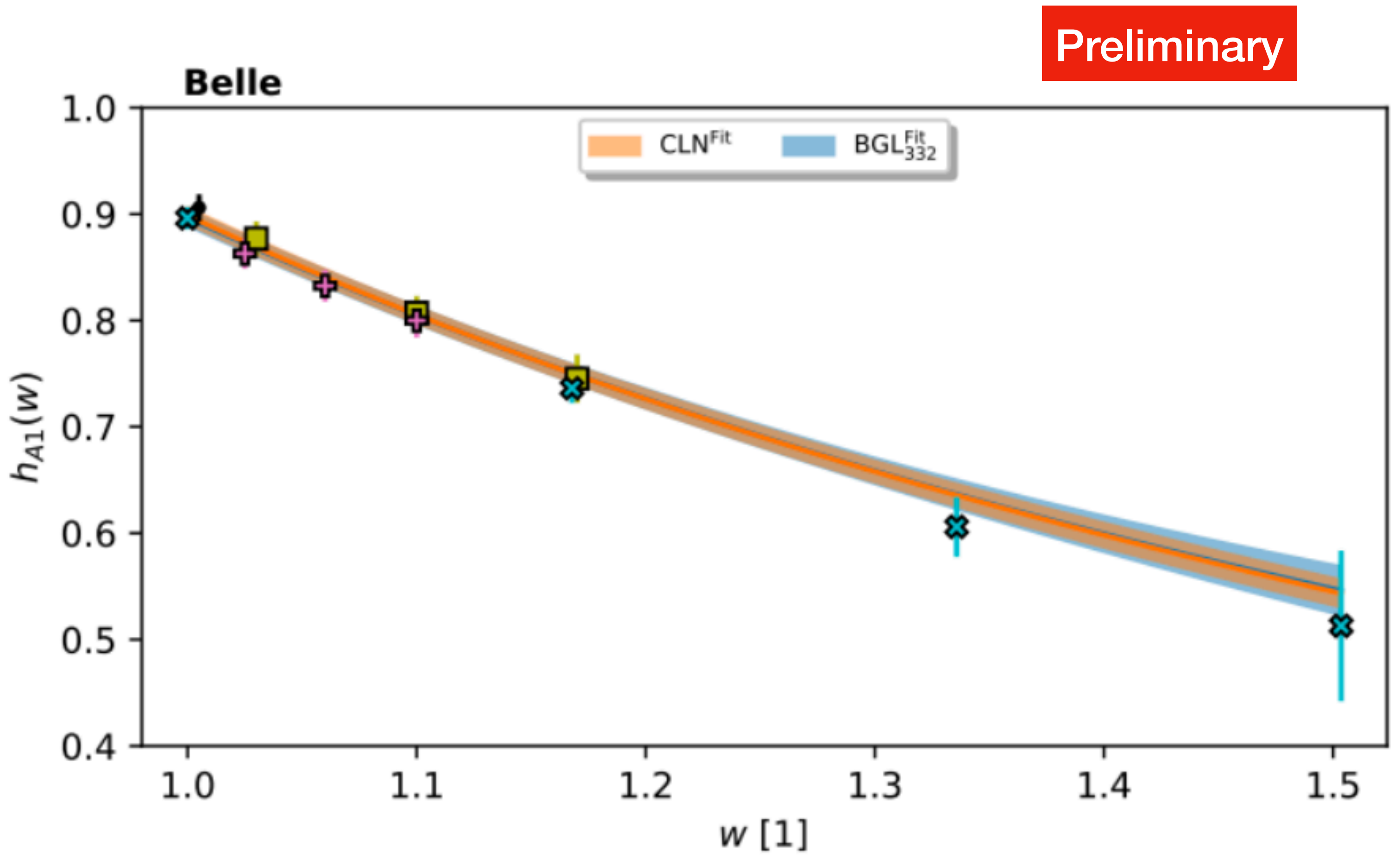


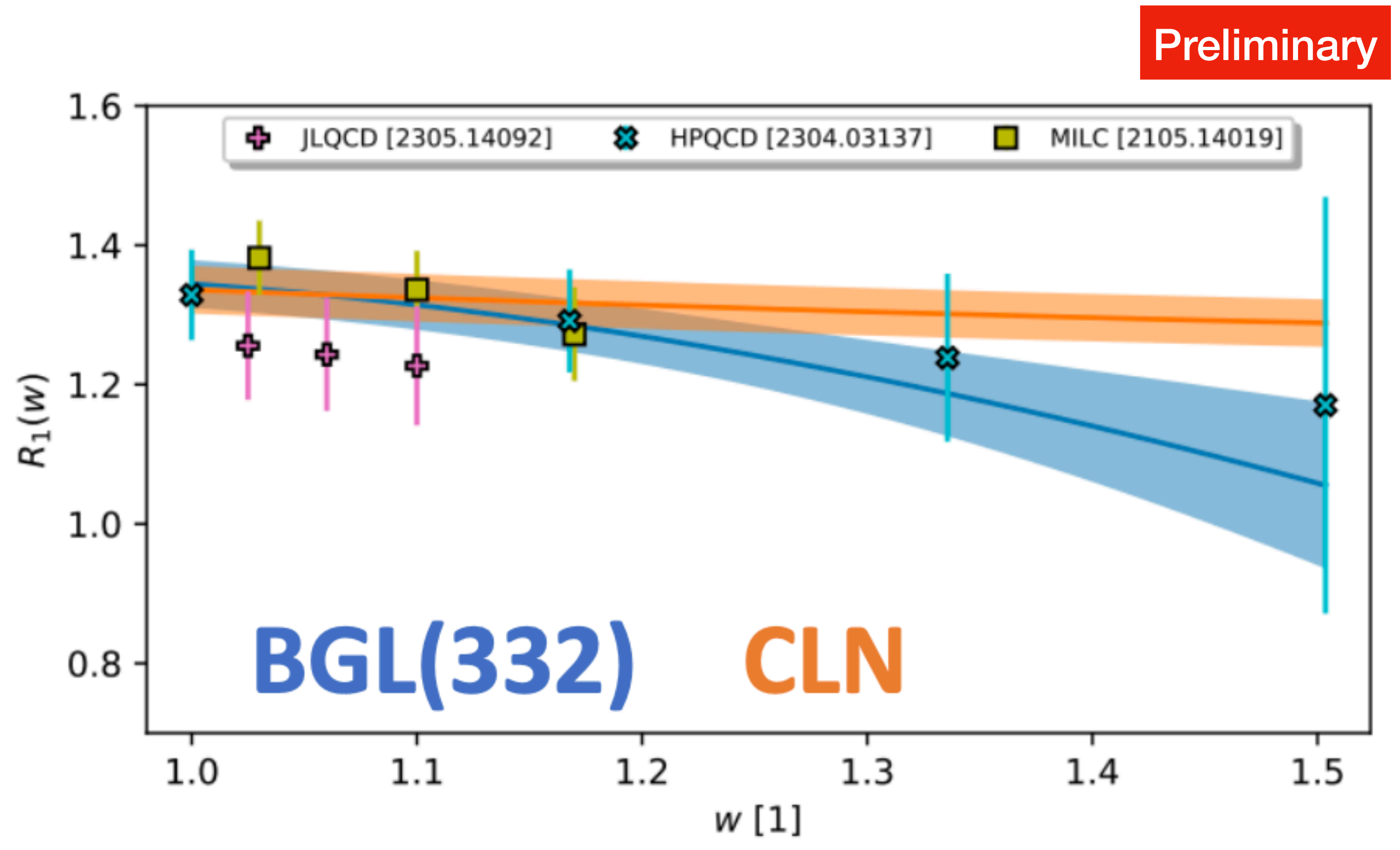
$$\frac{d\Gamma(B \to D^* \ell \nu_\ell)}{dw \, d\cos\theta_\ell \, d\cos\theta_V \, d\chi} = \frac{2 G_F^2 \eta_{EW}^2 |V_{cb}|^2 m_B^4 m_{D^*}}{2\pi^4} \times \Big(J_{1s} \sin^2\theta_V + J_{1c} \cos^2\theta_V$$
$$+ (J_{2s} \sin^2\theta_V + J_{2c} \cos^2\theta_V) \cos 2\theta_\ell + J_3 \sin^2\theta_V \sin^2\theta_\ell \cos 2\chi$$
$$+ J_4 \sin 2\theta_V \sin 2\theta_\ell \cos\chi + J_5 \sin 2\theta_V \sin\theta_\ell \cos\chi + (J_{6s} \sin^2\theta_V + J_{6c} \cos^2\theta_V) \cos\theta_\ell$$
$$+ J_7 \sin 2\theta_V \sin\theta_\ell \sin\chi + J_8 \sin 2\theta_V \sin 2\theta_\ell \sin\chi + J_9 \sin^2\theta_V \sin^2\theta_\ell \sin 2\chi \Big) .$$

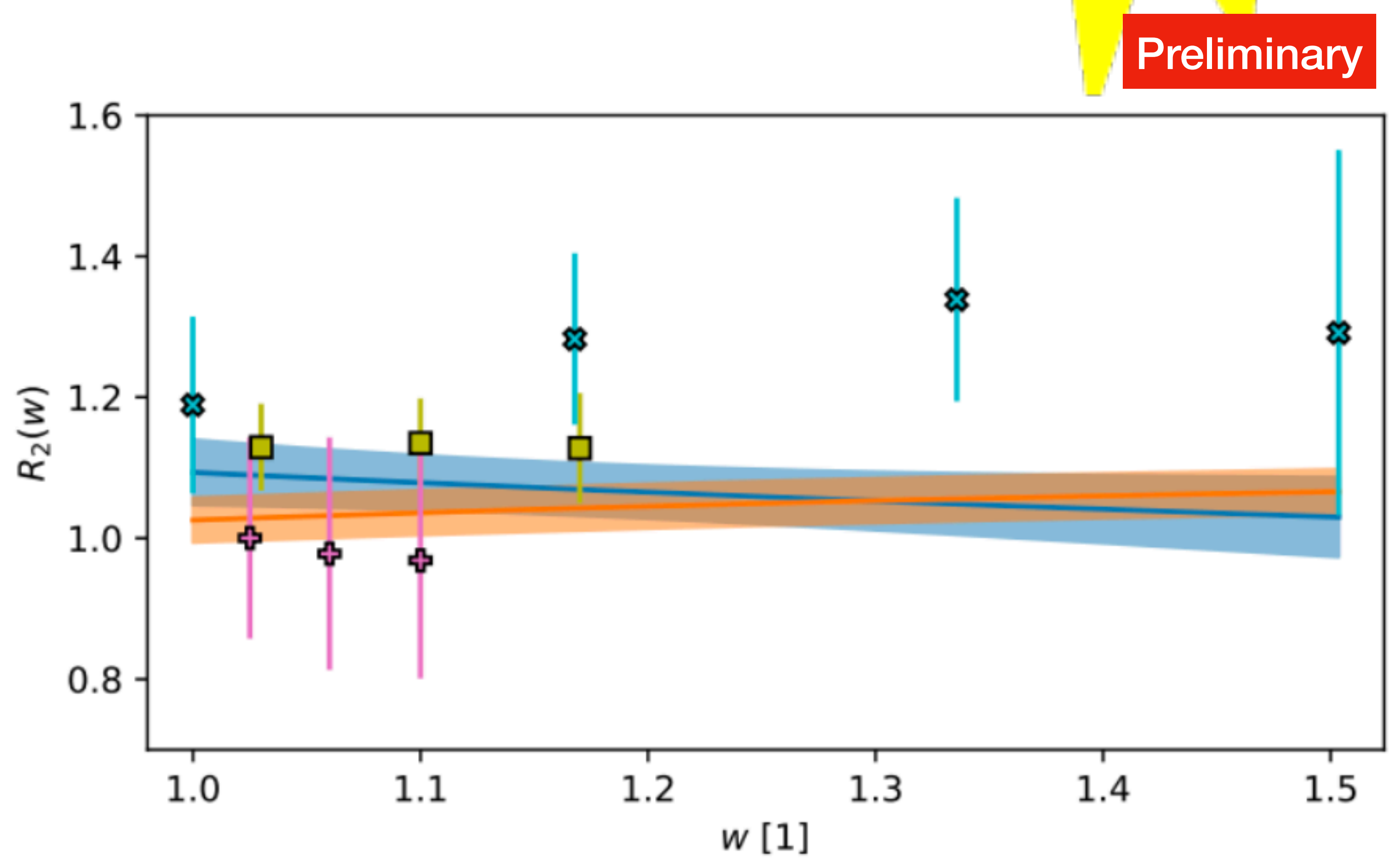
Fitted angular coefficients



Results



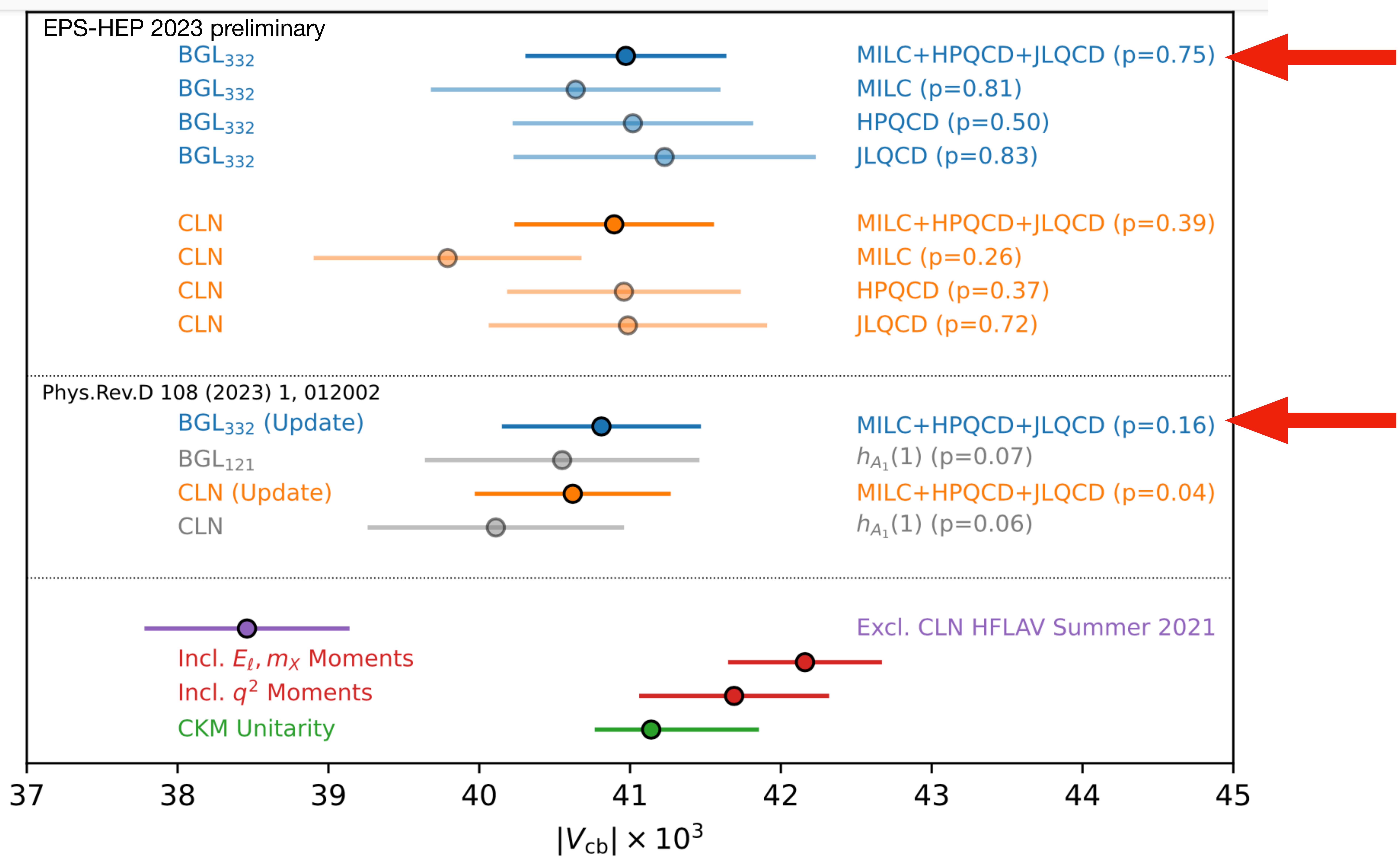




$$|V_{cb}|^{\mathrm{BGL}} = (41.0 \pm 0.7) \times 10^{-3}$$
$$|V_{cb}|^{\mathrm{CLN}} = (40.9 \pm 0.7) \times 10^{-3}$$

Preliminary

- Combined fit with non-zero recoil lattice data (FNAL/MILC, HPQCD, JLQCD)
- $p = 0.75$ for BGL_{332}
- Average $\mathcal{F}(1)$ of new LQCD results: $\mathcal{F}(1) = 0.895 \pm 0.007$



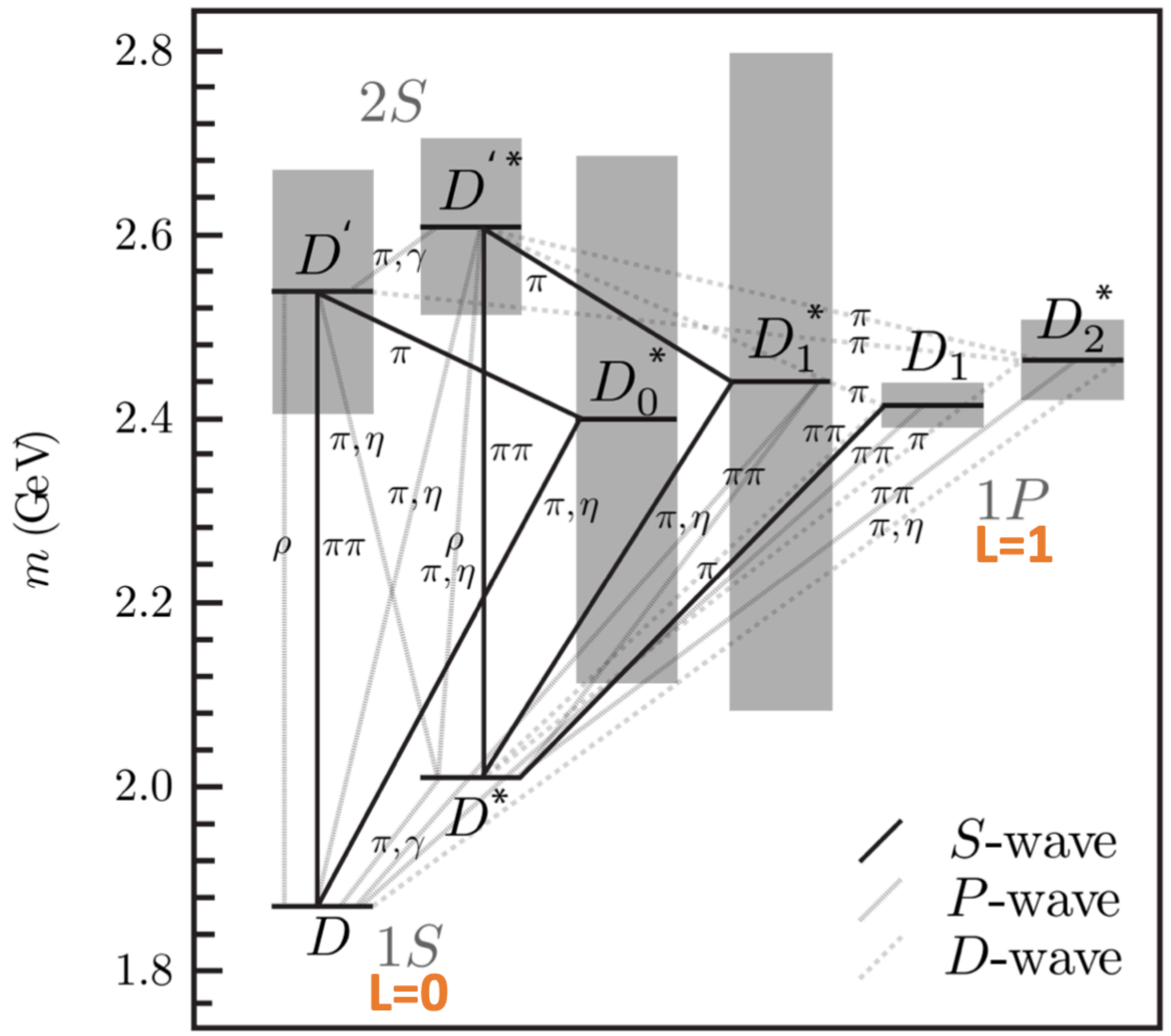
EPS-HEP 2023 preliminary
BGL_{332} MILC+HPQCD+JLQCD (p=0.75)
BGL_{332} MILC (p=0.81)
BGL_{332} HPQCD (p=0.50)
BGL_{332} JLQCD (p=0.83)
CLN MILC+HPQCD+JLQCD (p=0.39)
CLN MILC (p=0.26)
CLN HPQCD (p=0.37)
CLN JLQCD (p=0.72)
Phys.Rev.D 108 (2023) 1, 012002
BGL_{332} (Update) MILC+HPQCD+JLQCD (p=0.16)
BGL_{121} $h_{A_1}(1)$ (p=0.07)
CLN (Update) MILC+HPQCD+JLQCD (p=0.04)
CLN $h_{A_1}(1)$ (p=0.06)
Excl. CLN HFLAV Summer 2021
Incl. E_ℓ, m_X Moments
Incl. q^2 Moments
CKM Unitarity
37 38 39 40 41 42 43 44 45
$|V_{cb}| \times 10^3$

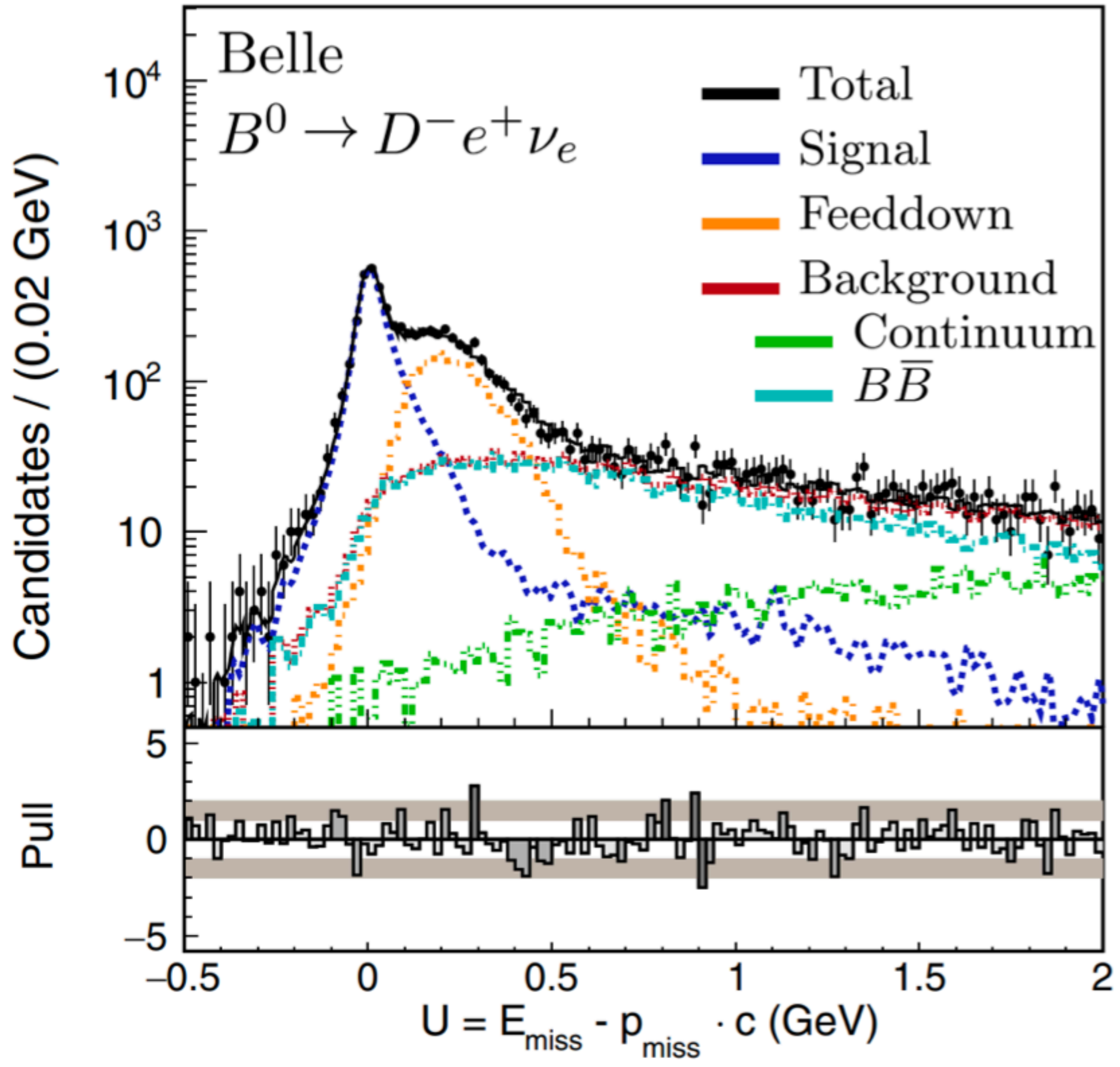
Measurement of $B \to \bar{D}^{(*)}\pi\ell^{+}\nu$ and $B \to \bar{D}^{(*)}\pi^{+}\pi^{-}\ell^{+}\nu$

Phys.Rev.D 107 (2023) 9, 092003, arXiv:2211.09833 [hep-ex]]

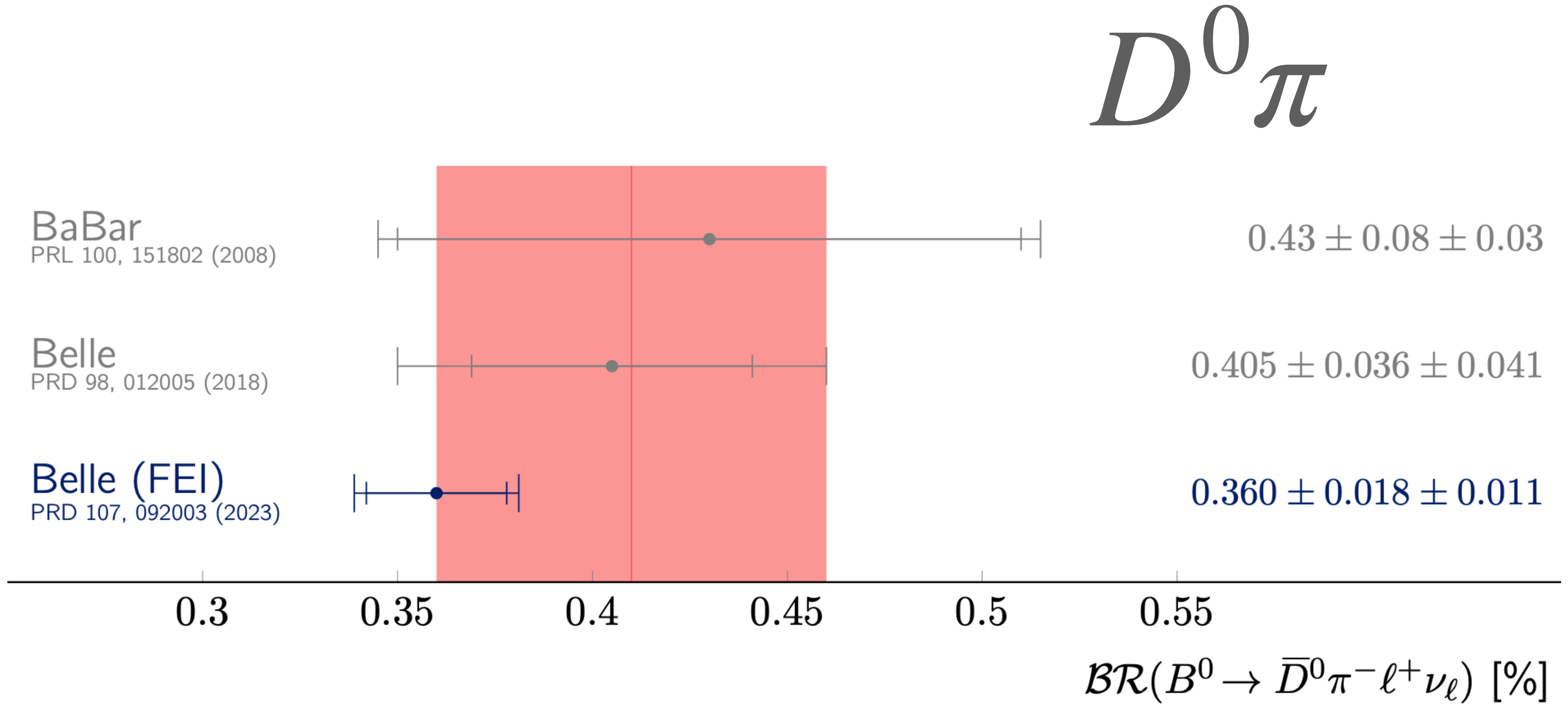
Reconstruction

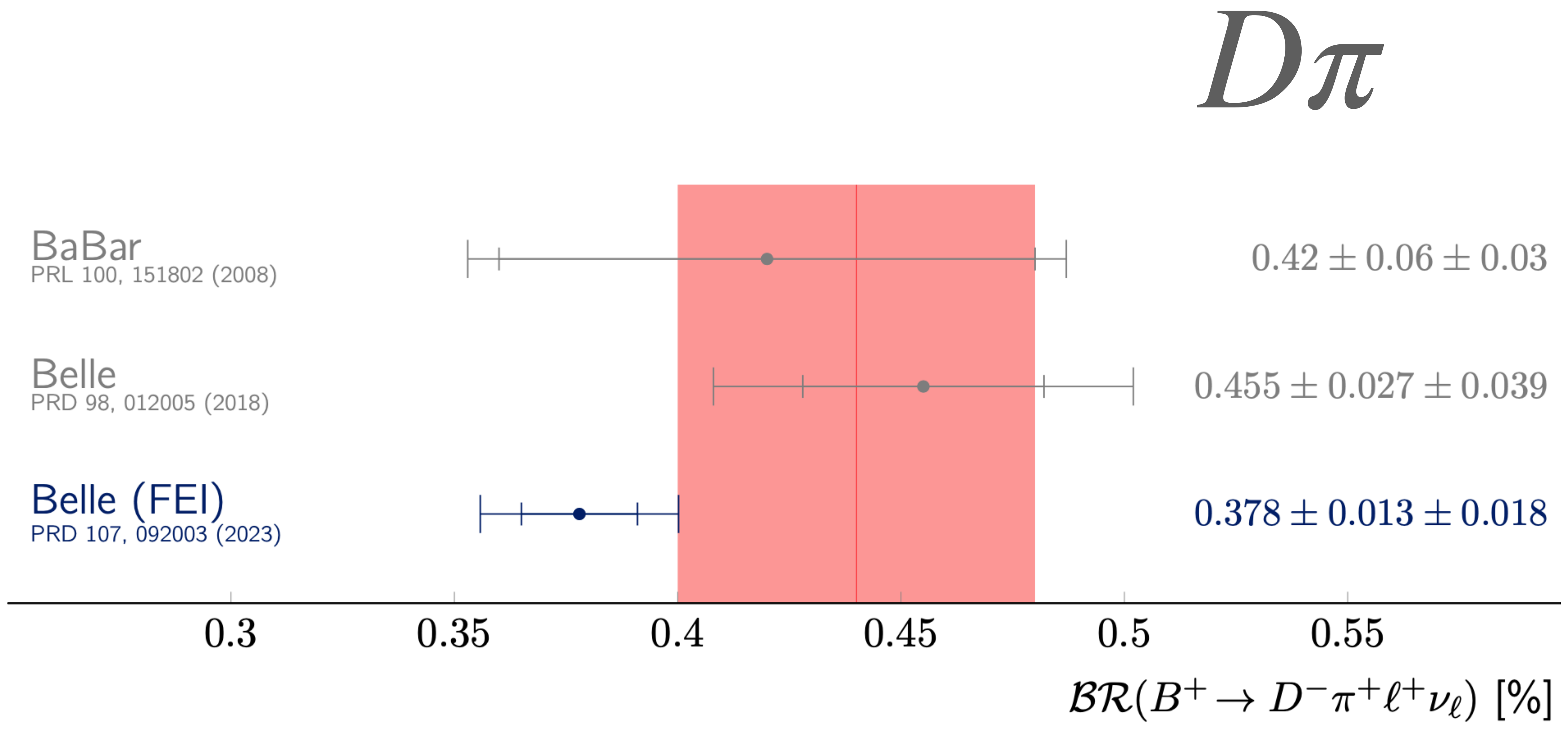
- 711/fb of hadronically tagged events
- 16 final states are searched for on the signal side:
  $\bar{D}^0\pi^-, D^-\pi^+, \bar{D}^{*0}\pi^-, D^{*-}\pi^+, D^-\pi^+\pi^-, \bar{D}^0\pi^+\pi^-, D^{*-}\pi^+\pi^-, D^{*0}\pi^+\pi^-\ell^+\nu$
  with $\ell = e, \mu$
- Normalisation modes: $B^0 \to D^{*-}\ell^+\nu$ and $B^+ \to \bar{D}^{*0}\ell^+\nu$
- Signal extracted from $U = E_{\text{miss}} - p_{\text{miss}}$

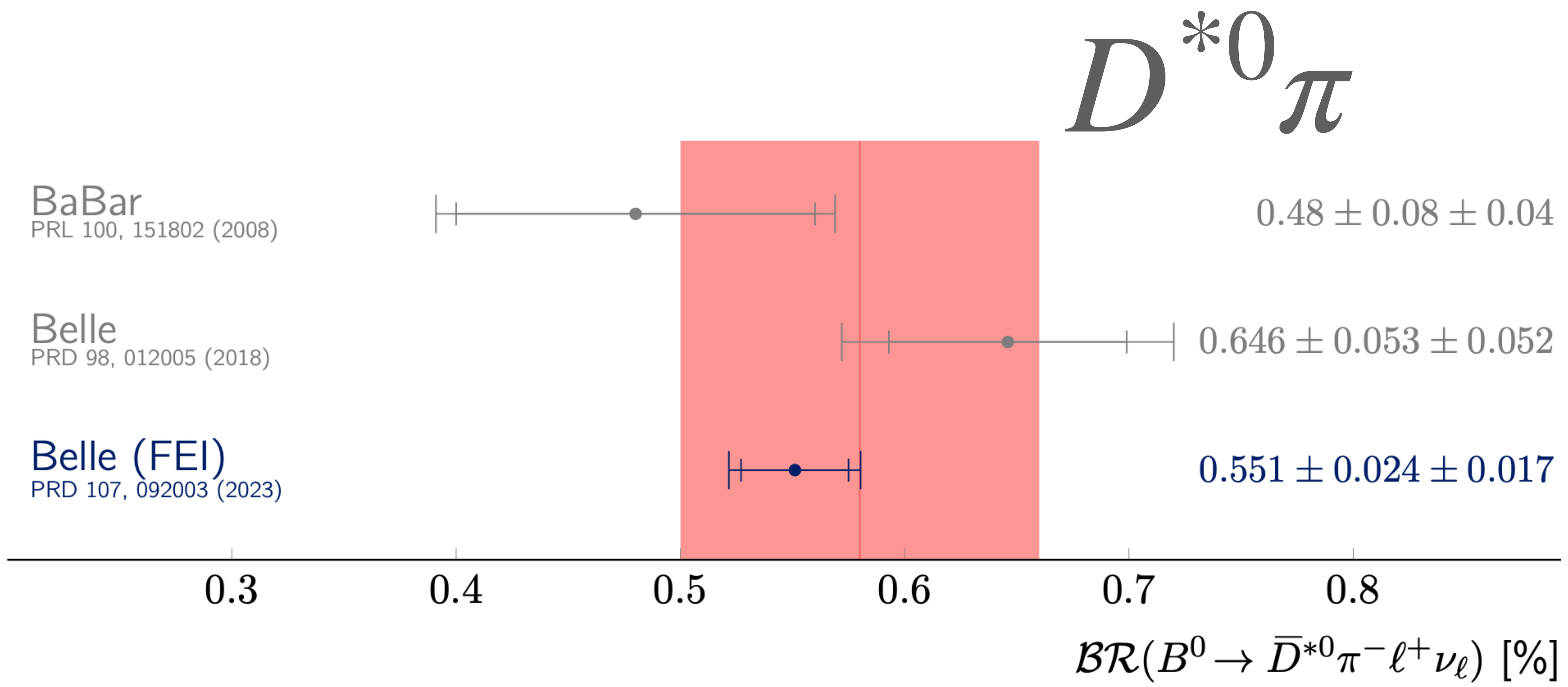


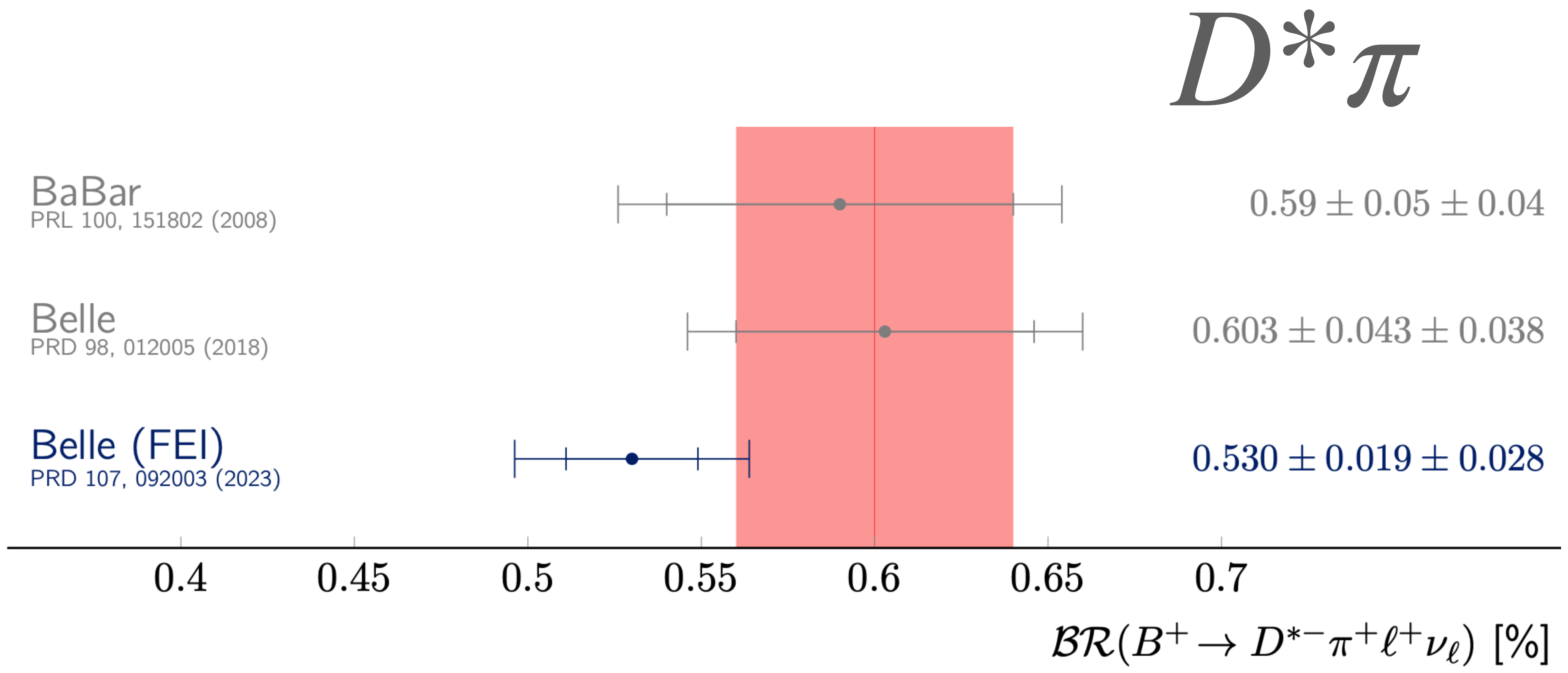


Branching fraction results (π)

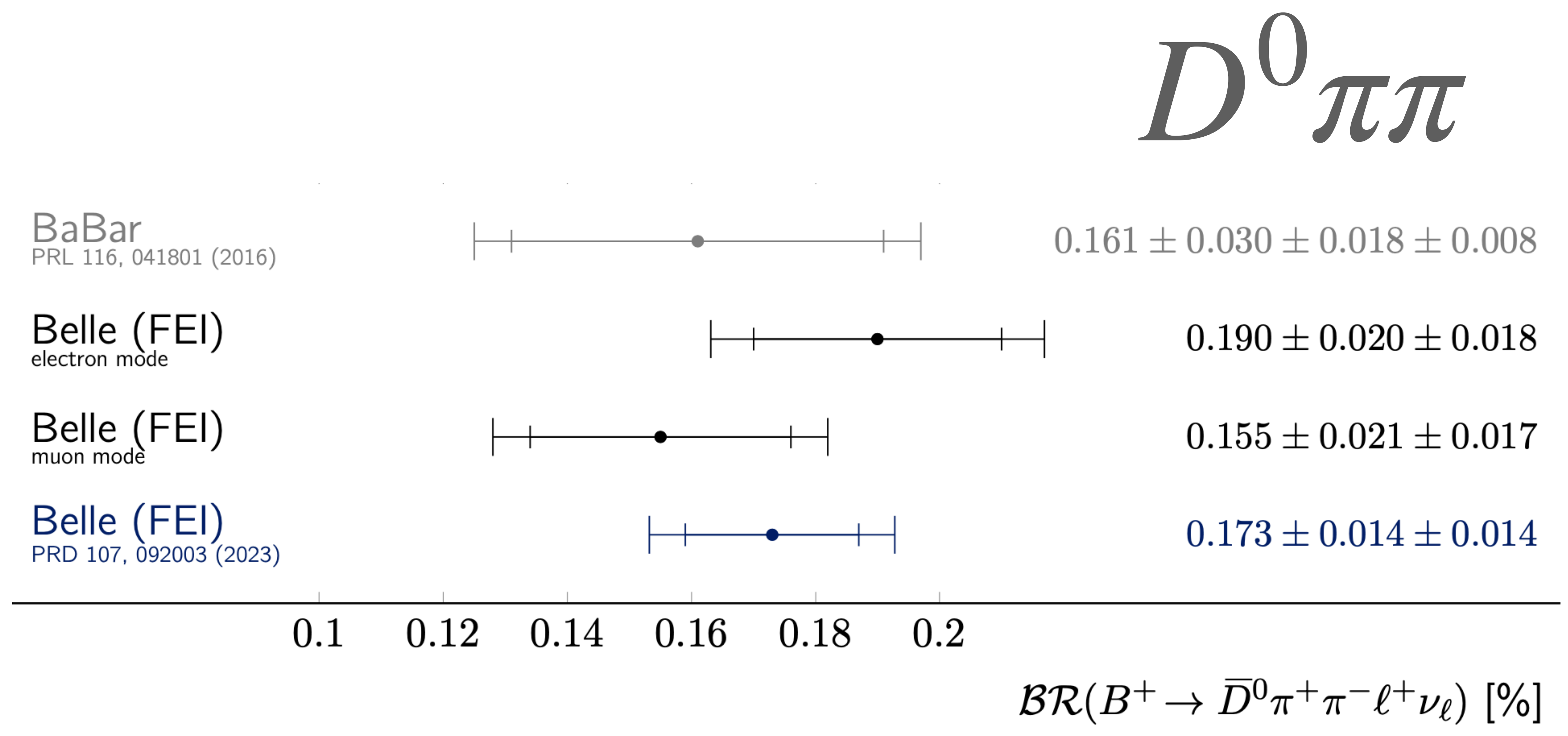


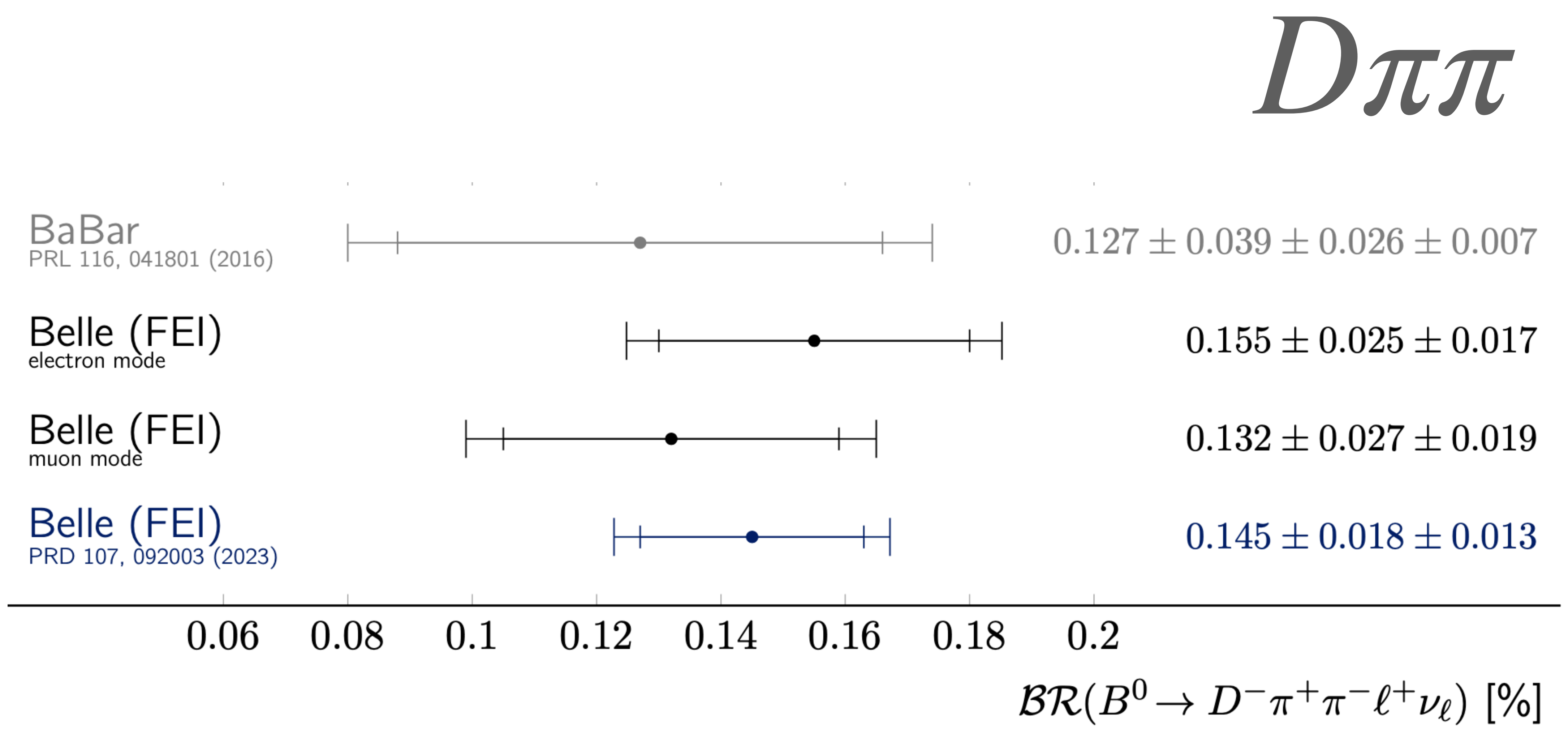


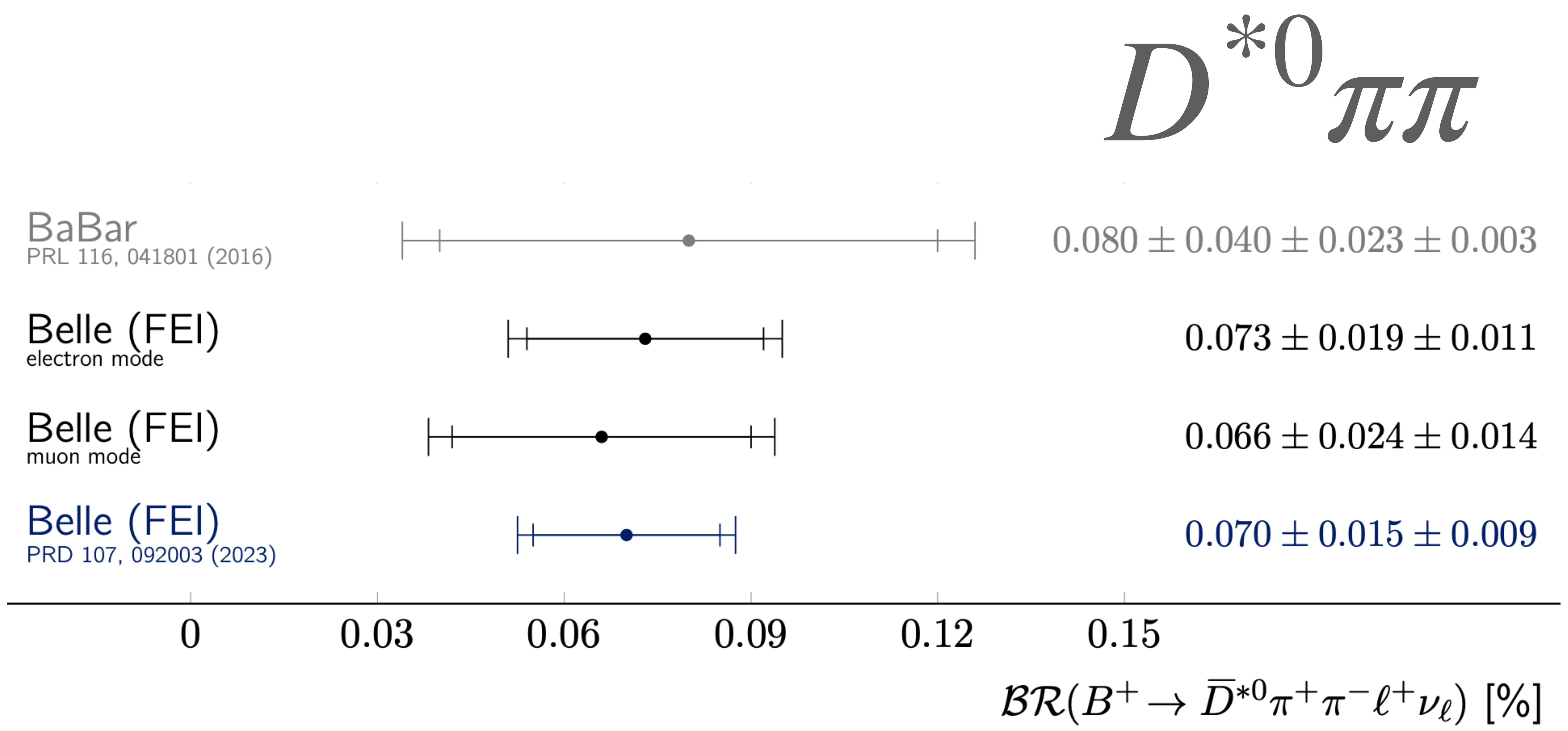


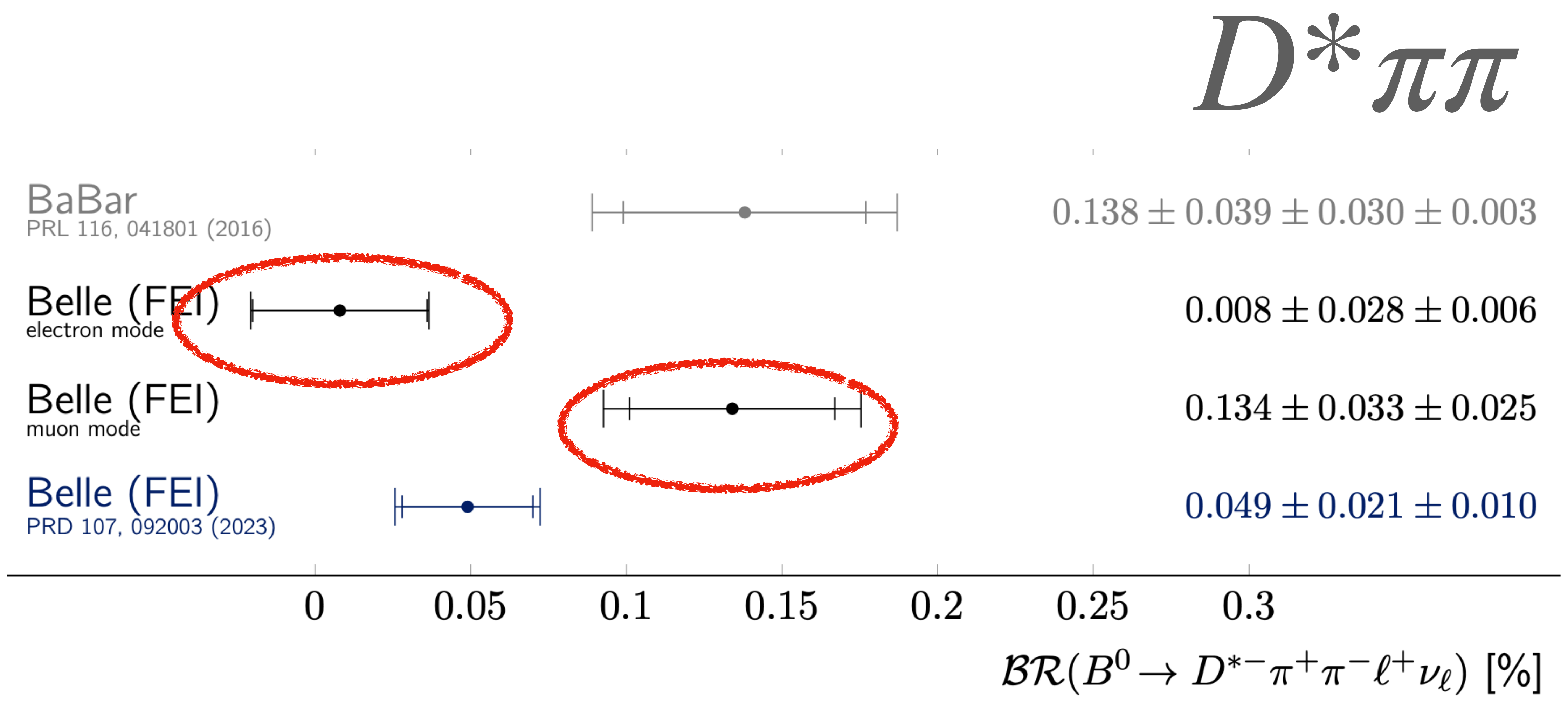


Branching fraction results ($\pi\pi$)



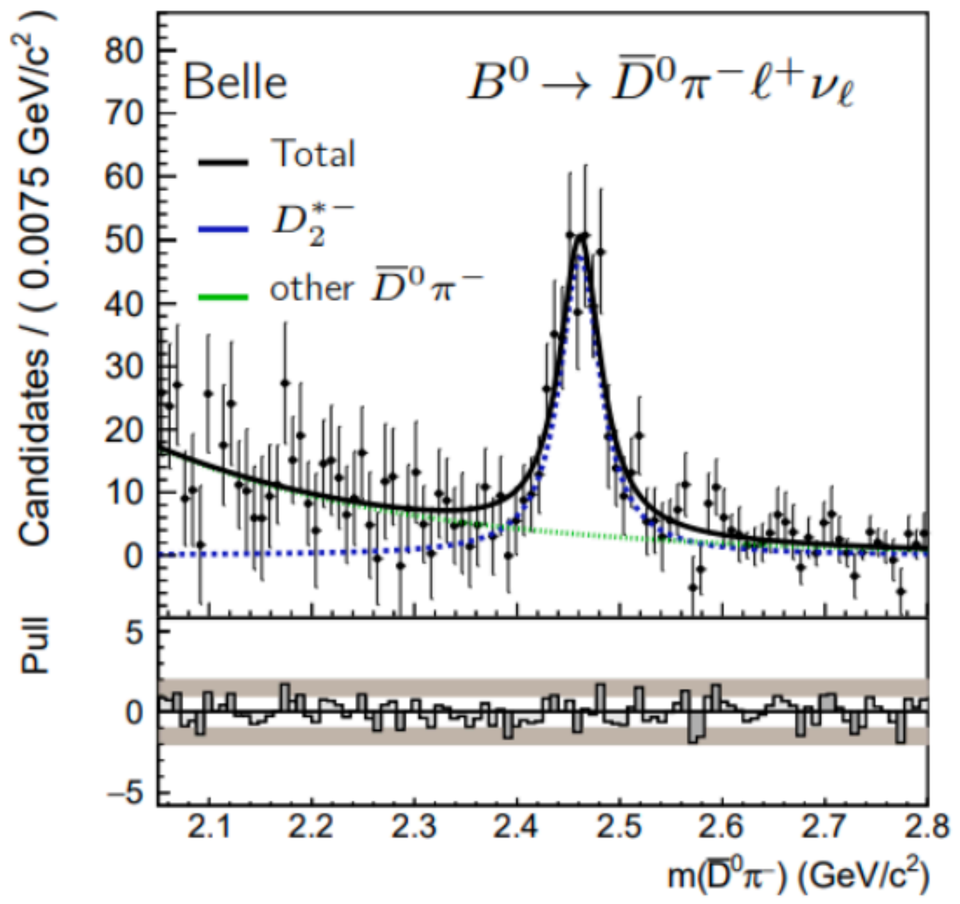


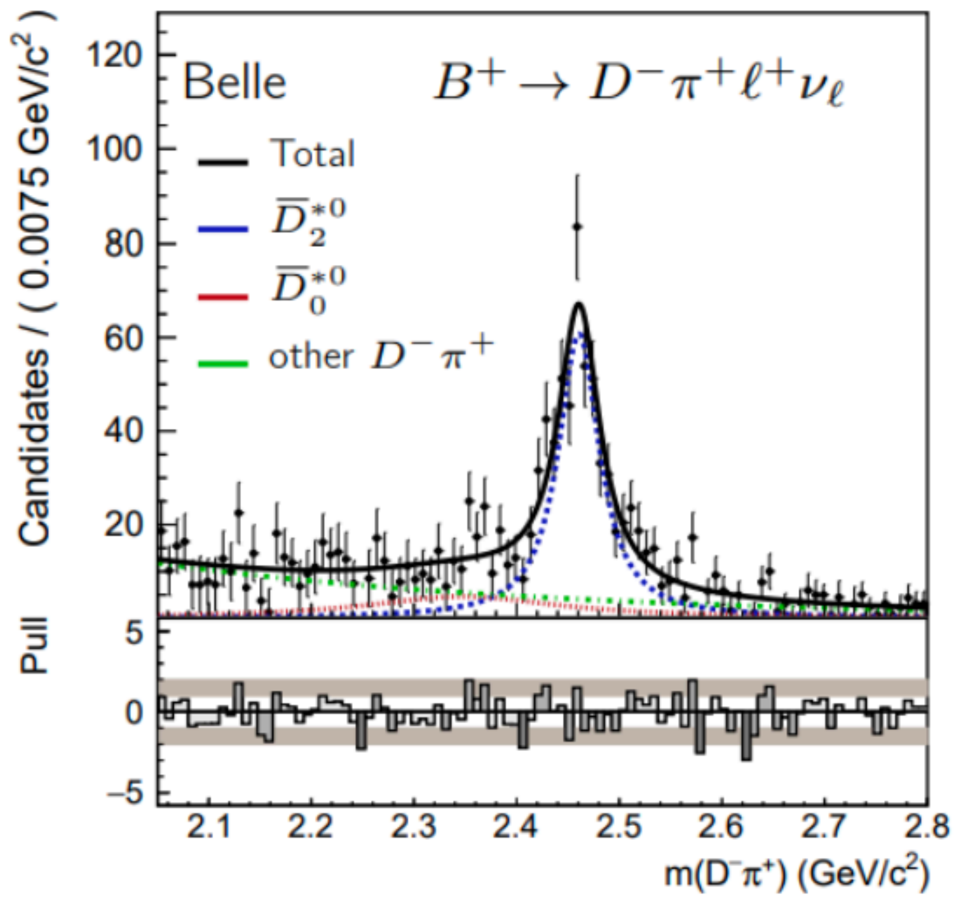




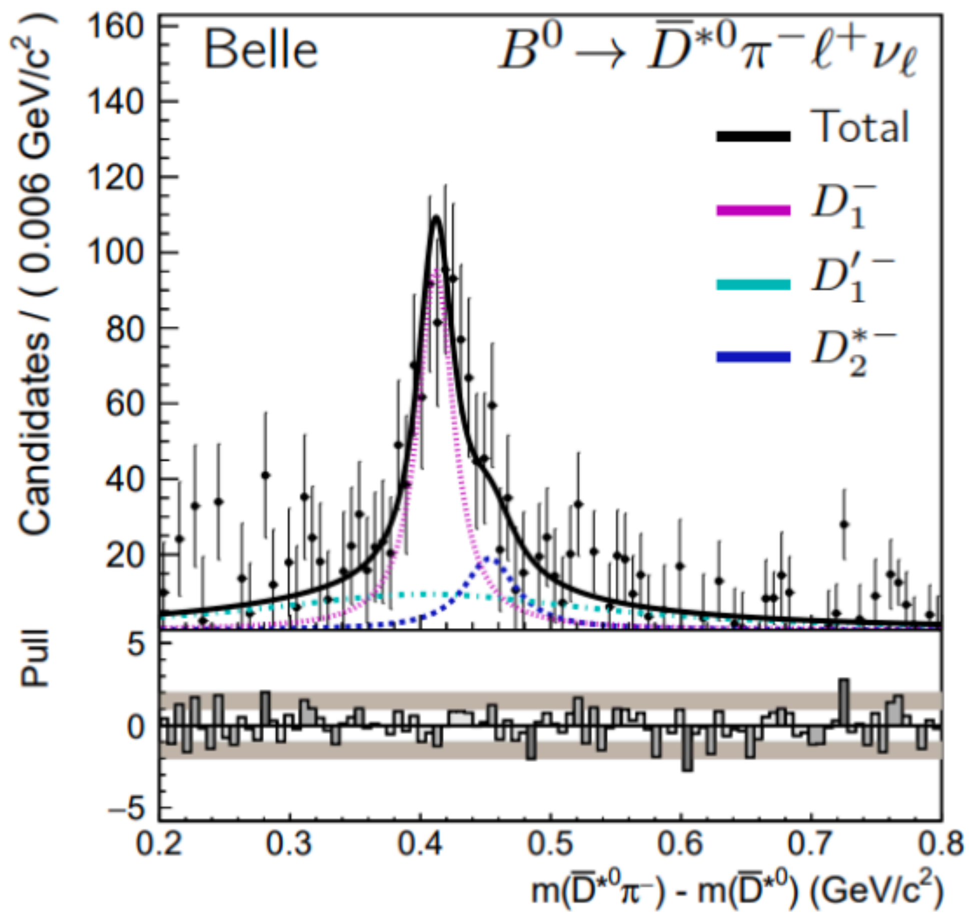
D^{**} composition

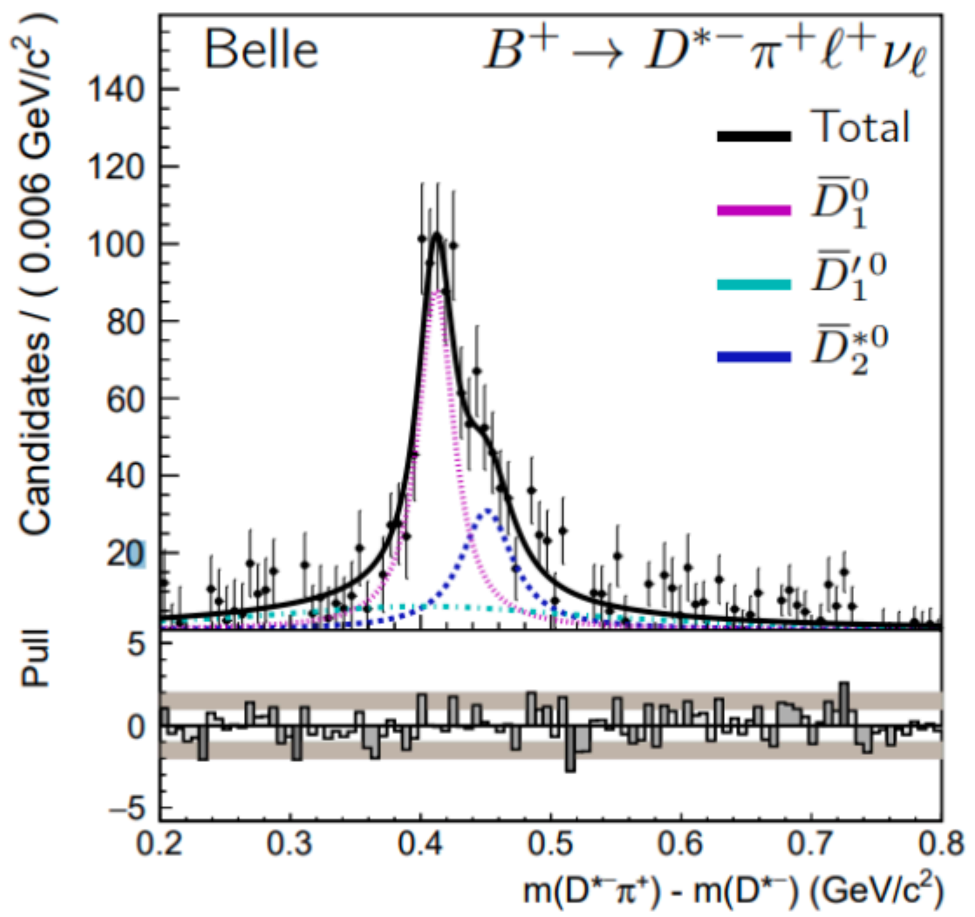
$M(D\pi)$





$M(D^*\pi)$



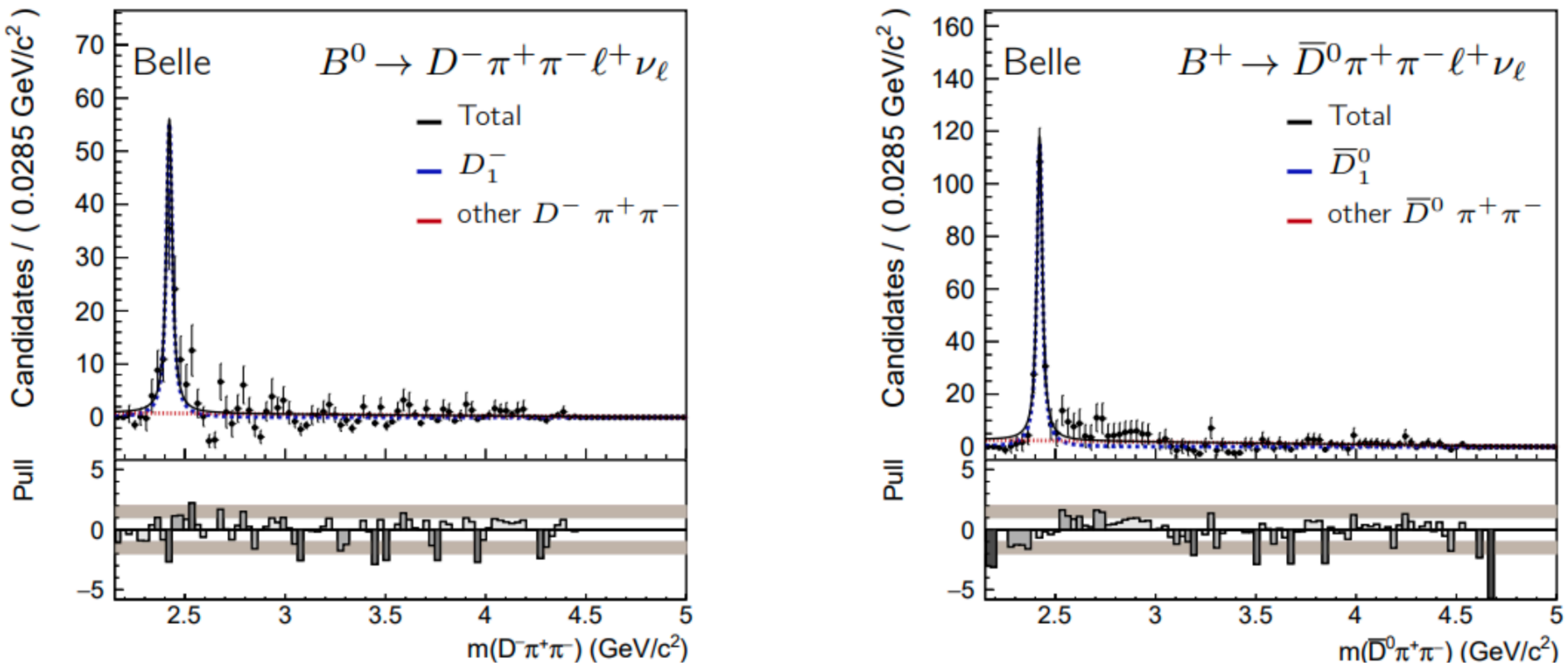


	yield	branching fraction [%]	PDG [%]
$B^0 \to D_0^{*-}\ell^+\nu_\ell$ with $D_0^{*-} \to \bar{D}^0\pi^-$	-	<0.044 at 90% CL	0.30 ± 0.12
$B^0 \to D_2^{*-}\ell^+\nu_\ell$ with $D_2^{*-} \to \bar{D}^0\pi^-$	457±45	$0.157 \pm 0.015\,(\text{stat}) \pm 0.005\,(\text{syst})$	0.121 ± 0.033
other $B^0 \to \bar{D}^0\pi^-\ell^+\nu_\ell$	547±45	-	
$B^+ \to \bar{D}_0^{*0}\ell^+\nu_\ell$ with $\bar{D}_0^{*0} \to D^-\pi^+$	180±72	$0.054 \pm 0.022\,(\text{stat}) \pm 0.005\,(\text{syst})$	0.25 ± 0.05
$B^+ \to \bar{D}_2^{*0}\ell^+\nu_\ell$ with $\bar{D}_2^{*0} \to D^-\pi^+$	590±39	$0.163 \pm 0.011\,(\text{stat}) \pm 0.008\,(\text{syst})$	0.153 ± 0.016
other $B^+ \to D^-\pi^+\ell^+\nu_\ell$	520±70	-	

	yield	branching fraction [%]	PDG [%]
$B^0 \to D_1^-\ell^+\nu_\ell$ with $D_1^- \to \bar{D}^{*0}\pi^-$	866± 142	$0.306 \pm 0.050\,(\text{stat}) \pm 0.029\,(\text{syst})$	0.280 ± 0.028
$B^0 \to D_1'^-\ell^+\nu_\ell$ with $D_1'^- \to \bar{D}^{*0}\pi^-$	523± 173	$0.206 \pm 0.068\,(\text{stat}) \pm 0.025\,(\text{syst})$	0.31 ± 0.09
$B^0 \to D_2^{*-}\ell^+\nu_\ell$ with $D_2^{*-} \to \bar{D}^{*0}\pi^-$	145± 114	$0.051 \pm 0.040\,(\text{stat}) \pm 0.010\,(\text{syst})$	0.068 ± 0.012
$B^+ \to \bar{D}_1^0\ell^+\nu_\ell$ with $\bar{D}_1^0 \to D^{*-}\pi^+$	698± 65	$0.249 \pm 0.023\,(\text{stat}) \pm 0.015\,(\text{syst})$	0.303 ± 0.020
$B^+ \to \bar{D}_1'^0\ell^+\nu_\ell$ with $\bar{D}_1'^0 \to D^{*-}\pi^+$	353± 93	$0.138 \pm 0.036\,(\text{stat}) \pm 0.009\,(\text{syst})$	0.27 ± 0.06
$B^+ \to \bar{D}_2^{*0}\ell^+\nu_\ell$ with $\bar{D}_2^{*0} \to D^{*-}\pi^+$	382± 74	$0.137 \pm 0.026\,(\text{stat}) \pm 0.009\,(\text{syst})$	0.101 ± 0.024

First observation of $B \to \bar{D}_1(\to \bar{D}\pi^+\pi^-)\ell^+\nu$

$M(D\pi^+\pi^-)$



$$\mathcal{B}(B^0 \to D_1^-\ell^+\nu_\ell) \times \mathcal{B}(D_1^- \to D^-\pi^+\pi^-) = (0.102 \pm 0.013\,(\text{stat}) \pm 0.009\,(\text{syst}))\%$$

$$\mathcal{B}(B^+ \to \bar{D}_1^0\ell^+\nu_\ell) \times \mathcal{B}(\bar{D}_1^0 \to \bar{D}^0\pi^+\pi^-) = (0.105 \pm 0.011\,(\text{stat}) \pm 0.009\,(\text{syst}))\%$$

Summary and conclusions

- Two new results for $|V_{cb}|$ from $B \to D^* \ell \nu$:
  Belle II $B^0 \to D^{*-} \ell^+ \nu$ untagged (189/fb), Belle $B \to D^* \ell \nu$ tagged (711/fb)
  - Obtain values closer to the inclusive result/expection from CKM unitary
  - No significant form factor dependence
  - Is experiment compatible with non zero recoil lattice data?
- Improved Belle measurement of $B \to D^{**} \ell \nu$ modes
  - First observation of $B \to \bar{D}_1(\to \bar{D}\pi^+\pi^-)\ell^+\nu$
- Many more Belle II analyses on exclusive semileptonic B decays are in the making — stay tuned!

Backup

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

CLN fit

Fitted values without LQCD predictions

Preliminary

	Values	Correlations				χ^2/ndf
ρ^2	1.22 ± 0.05	1.00	0.36	-0.81	0.29	39/31
$R_1(1)$	1.14 ± 0.07	0.36	1.00	-0.60	-0.10	
$R_2(1)$	0.89 ± 0.03	-0.81	-0.60	1.00	-0.08	
$\lvert V_{cb}\rvert \times 10^3$	40.1 ± 1.1	0.29	-0.10	-0.08	1.00	

Relative uncertainties (in %)

Preliminary

	ρ^2	$R_1(1)$	$R_2(1)$	$\lvert V_{cb}\rvert$
Statistical	3.0	4.1	2.8	0.7
Background subtraction	1.4	2.2	1.2	0.3
Finite MC samples	1.2	1.7	1.1	0.3
Lepton ID efficiency	0.2	1.6	0.1	0.3
Slow pion efficiency	1.0	0.9	0.8	1.5
Tracking of K, π, ℓ				0.4
$N_{B\bar{B}}$				0.8
f_{+0}				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
Signal modelling	2.6	2.6	2.0	0.5
Total	4.5	5.9	3.9	2.4

Preliminary

$$|V_{cb}|_{\mathrm{CLN}} = (40.13 \pm 0.27 \pm 0.93 \pm 0.58) \times 10^{-3}$$

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

Fitted values with LQCD constraints
at $w = 1.03, 1.10, 1.17$
[Eur. Phys. J. C 82, 1141 (2022)]

Preliminary

	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	1.22 ± 0.05	1.21 ± 0.04
$R_1(1)$	1.14 ± 0.07	1.26 ± 0.04
$R_2(1)$	0.88 ± 0.03	0.88 ± 0.03
$\lvert V_{cb}\rvert \times 10^3$	40.3 ± 1.2	38.7 ± 1.1
χ^2/ndf	39/33	70/39
p-value	23%	0.2%

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

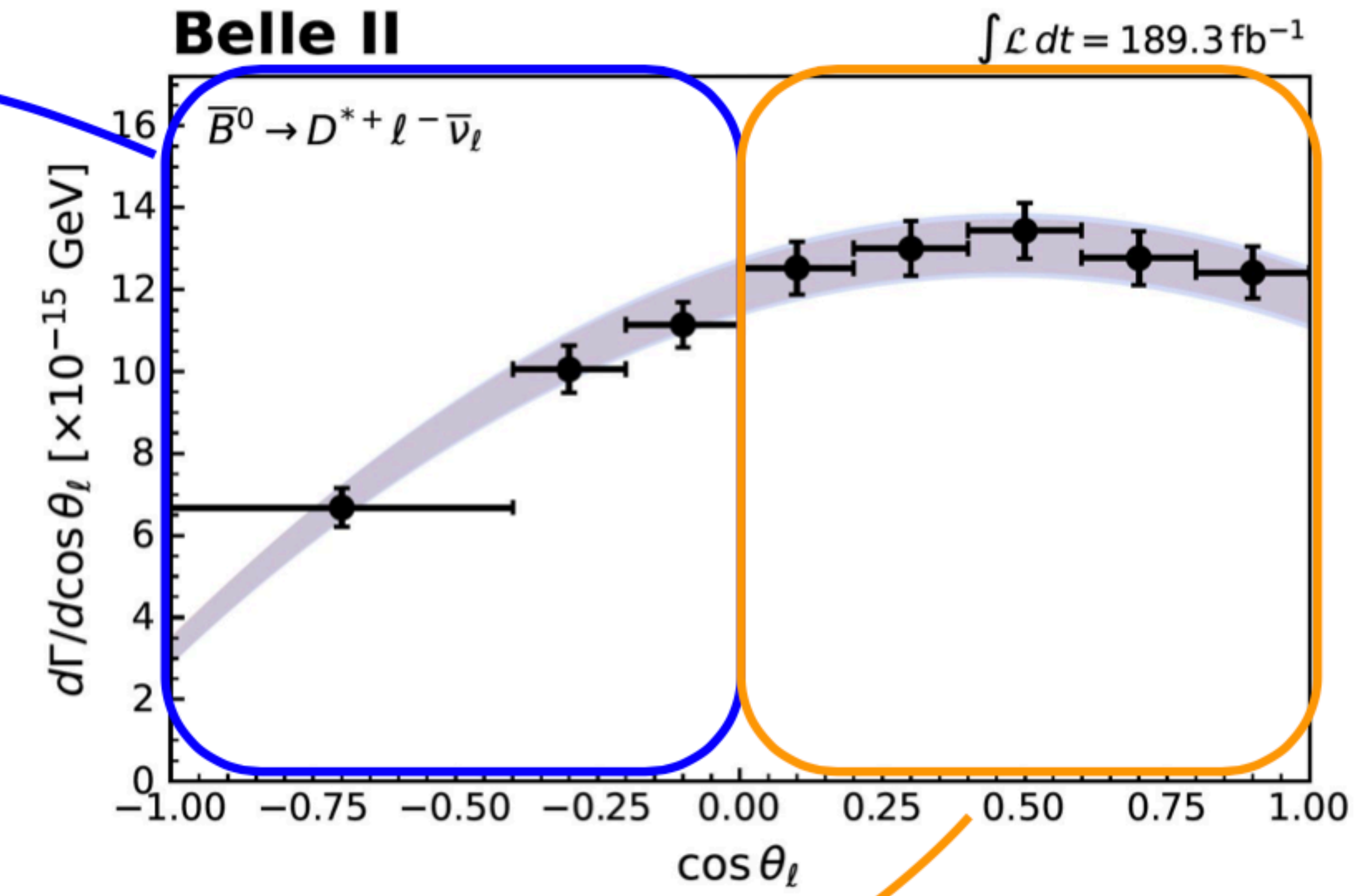
Lepton flavour universality tests

Preliminary

$$R_{e/\mu} = 0.998 \pm 0.009 \pm 0.020$$

- Angular asymmetry

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



Obtained results:

Preliminary

$$\mathcal{A}_{\mathrm{FB}}^{e} = 0.228 \pm 0.012 \pm 0.018$$
$$\mathcal{A}_{\mathrm{FB}}^{\mu} = 0.211 \pm 0.011 \pm 0.021$$
$$\Delta\mathcal{A}_{\mathrm{FB}} = (-17 \pm 16 \pm 16) \times 10^{-3}$$

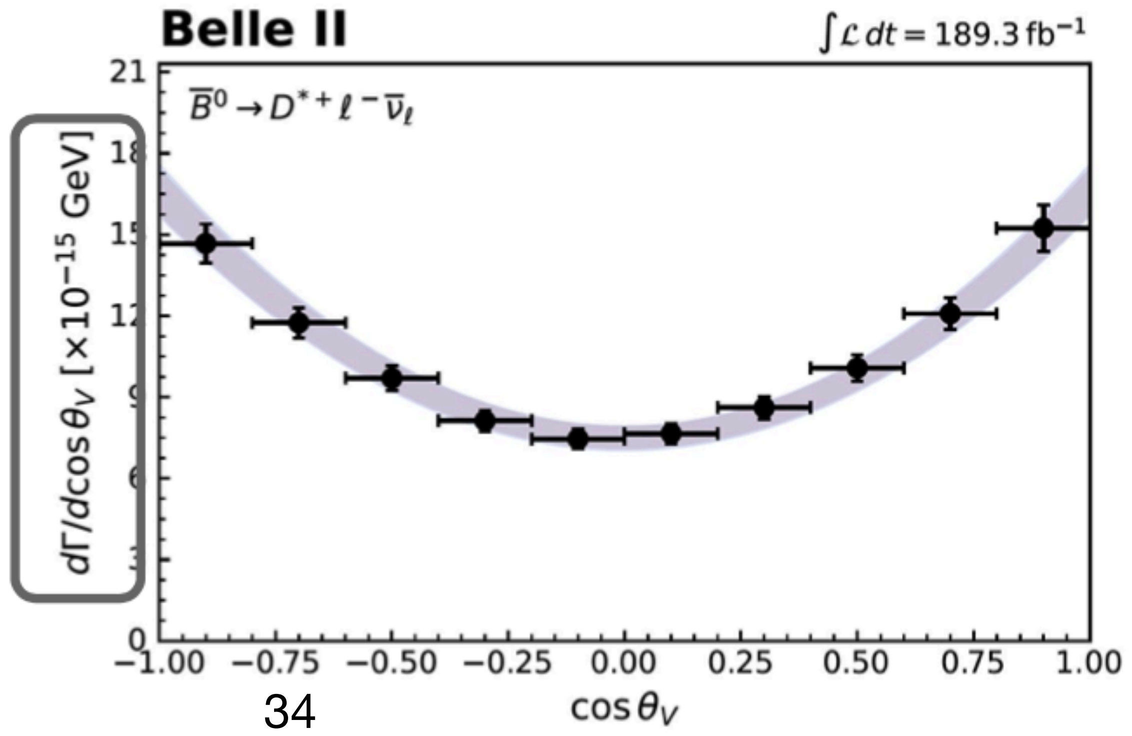
$$\Delta\mathcal{A}_{\mathrm{FB}} = \mathcal{A}_{\mathrm{FB}}^{\mu} - \mathcal{A}_{\mathrm{FB}}^{e}$$

- longitudinal D* polarization fraction F_L

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

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

A function of FL and $\cos\theta_V$



Obtained results:

$$F_L^{e} = 0.520 \pm 0.005 \pm 0.005$$
$$F_L^{\mu} = 0.527 \pm 0.005 \pm 0.005$$
$$\Delta F_L = 0.006 \pm 0.007 \pm 0.005$$

Preliminary

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

Nested hypothesis test

Phys.Rev.D 100 (2019) 1, 013005, arXiv:1902.09553 [hep-ph]

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

(n_a, n_b, n_c)	$\|V_{cb}\| \times 10^3$	$\rho_{\max}$	χ^2	Ndf	p-value
$(1,1,2)$	40.2 ± 1.1	0.43	40	32	16%
$(2,1,2)$	40.1 ± 1.1	0.97	38.6	31	16%
$(1,2,2)$	**40.6 ± 1.2**	**0.57**	**38.9**	**31**	**16%**
$(1,1,3)$	40.1 ± 1.1	0.96	39.5	31	14%
$(2,2,2)$	40.3 ± 1.3	0.99	38.6	30	13%
$(1,3,2)$	40.0 ± 1.3	0.98	38	30	15%
$(1,2,3)$	40.5 ± 1.2	0.96	38.8	30	13%

Belle $B \to D^*\ell^+\nu$ tagged

	$\|V_{cb}\|$	χ^2	dof	N	$\rho_{\max}$
BGL_{111}	40.3 ± 0.8	45.7	32	3	0.71
BGL_{112}	40.8 ± 0.8	42.6	31	4	0.97
BGL_{121}	**40.6 ± 0.9**	**45.3**	**31**	**4**	**0.62**
BGL_{122}	41.4 ± 1.0	41.5	30	5	0.97
BGL_{131}	39.9 ± 0.9	42.4	30	5	0.61
BGL_{132}	40.7 ± 1.0	39.3	29	6	0.98
BGL_{211}	39.8 ± 0.9	42.1	31	4	0.99
BGL_{212}	40.4 ± 0.9	37.5	30	5	0.99
BGL_{221}	40.9 ± 1.0	45.1	30	5	0.93
BGL_{222}	39.2 ± 1.0	36.5	29	6	0.96
BGL_{231}	40.3 ± 1.0	41.8	29	6	0.94
BGL_{232}	41.0 ± 1.0	39.0	28	7	0.97
BGL_{311}	39.8 ± 0.9	42.1	30	5	0.99
BGL_{312}	40.4 ± 0.9	37.4	29	6	0.99
BGL_{321}	38.5 ± 0.9	39.4	29	6	0.65
BGL_{322}	39.2 ± 1.0	36.4	28	7	0.96
BGL_{331}	38.3 ± 0.9	38.1	28	7	0.86
BGL_{332}	38.7 ± 1.5	36.0	27	8	0.99