Determination of the Cabibbo-Kobayashi-Maskawa matrix elements $|V_{cb}|$ and $|V_{ub}|$

Christoph Schwanda (Austrian Academy of Sciences)
On behalf of the Belle and Belle II collaborations

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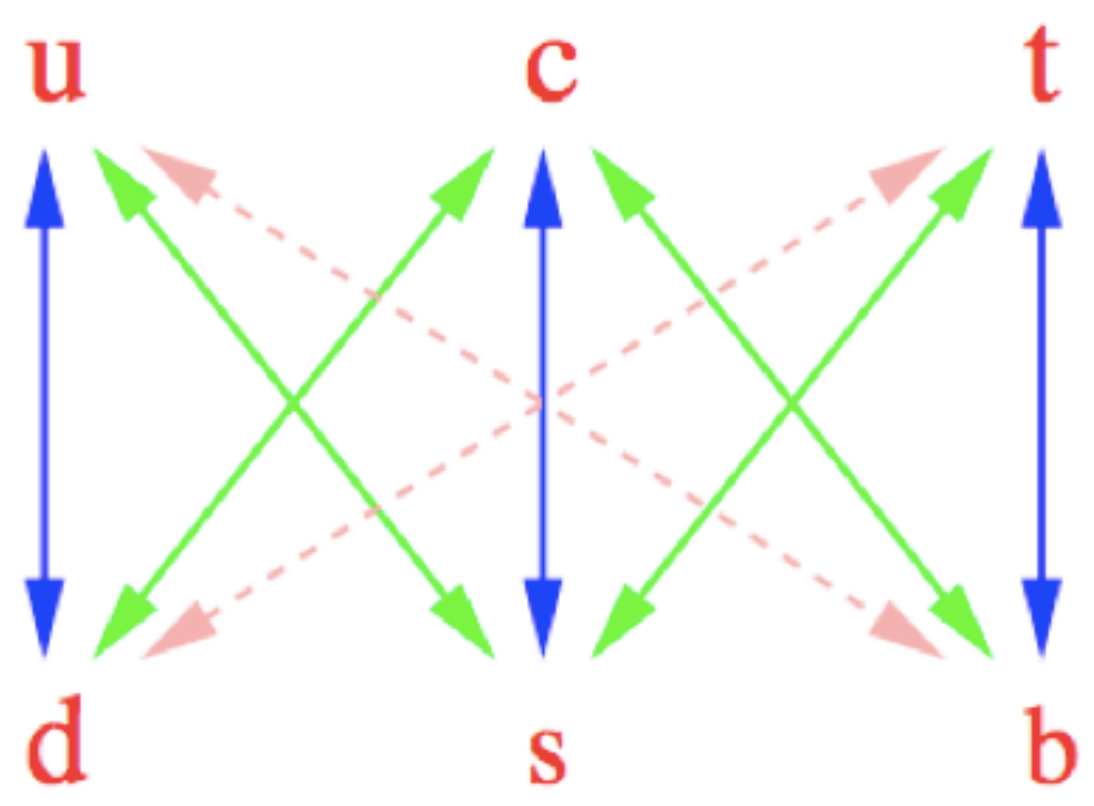
The Cabibbo-Kobayashi-Maskawa mechanism

Cabibbo-Kobayashi-Maskawa quark mixing

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathbf{V} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\mathbf{V}\,\mathbf{V}^{\dagger} = \mathbf{V}^{\dagger}\,\mathbf{V} = 1$$



- The weak interaction down-type doublet partners are a mixture of the mass (flavour) eigenstates described by the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix
- The CKM element magnitudes squared determine the rate of quark flavour transitions in charged current processes

$$-\mathcal{L}_{W^{\pm}} = \frac{g}{\sqrt{2}}\,\overline{u_{Li}}\,\gamma^{\mu}\,(V_{\mathrm{CKM}})_{ij}\,d_{Lj}\,W_{\mu}^{+} + \mathrm{h.c.}$$

CP violation

Wolfenstein parametrization of V_{CKM}

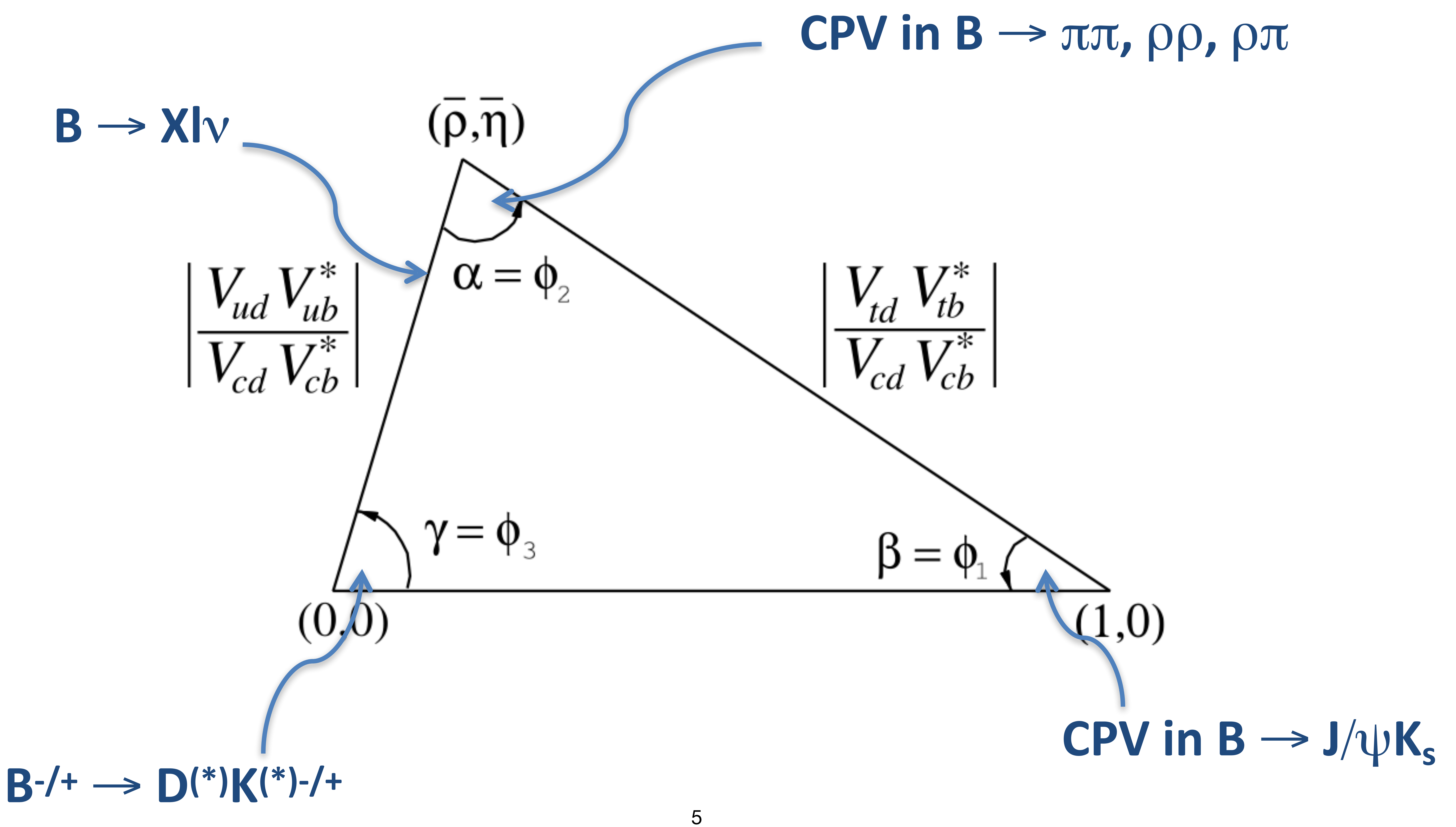
$$V_{\text{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

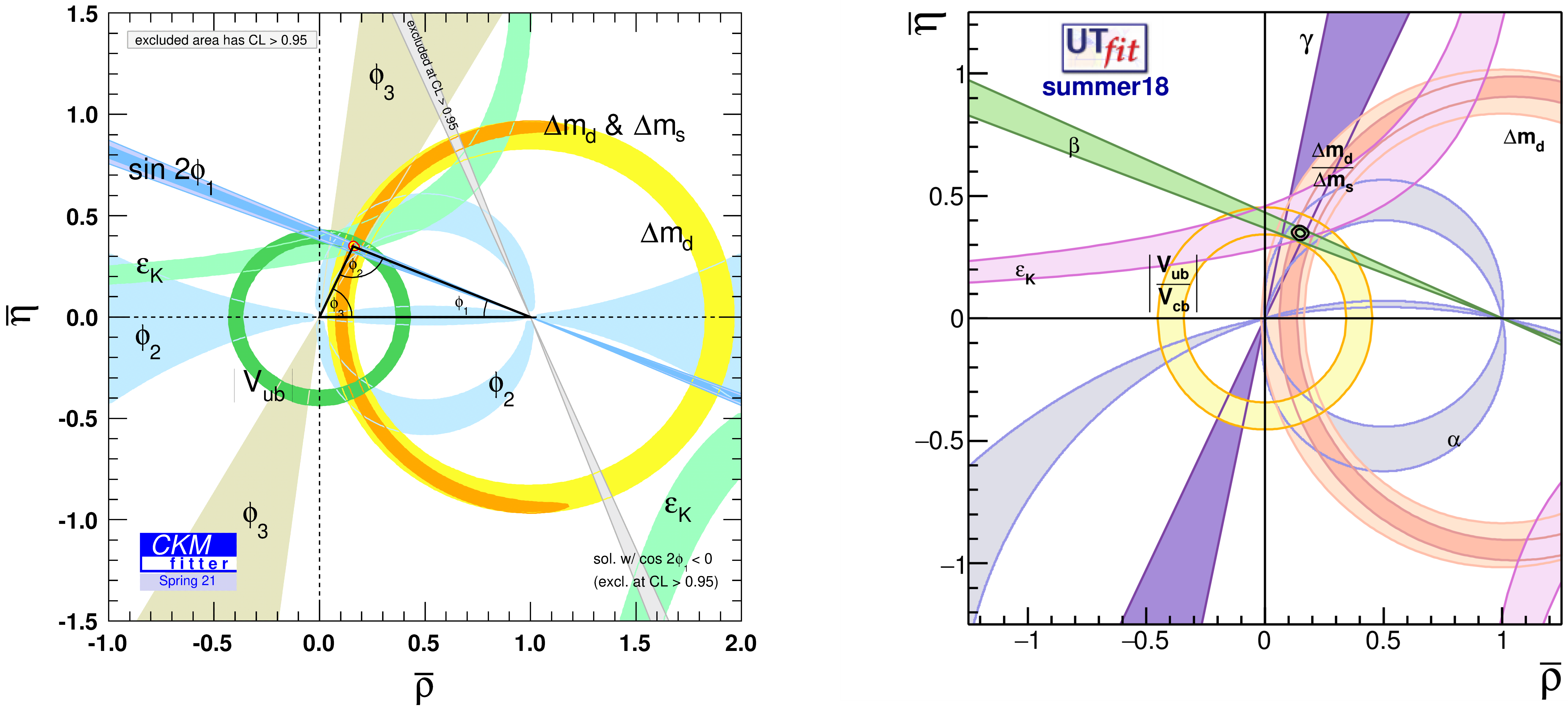
- However, V_{CKM} also contains a complex phase, responsible for all CP-violating phenomena in the quark sector of the SM, and consistent with observations in K, D and B meson decays so far
- New physics would typically disturb the SM pattern of CPV

The CKM unitarity triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

…and how to probe it with B mesons

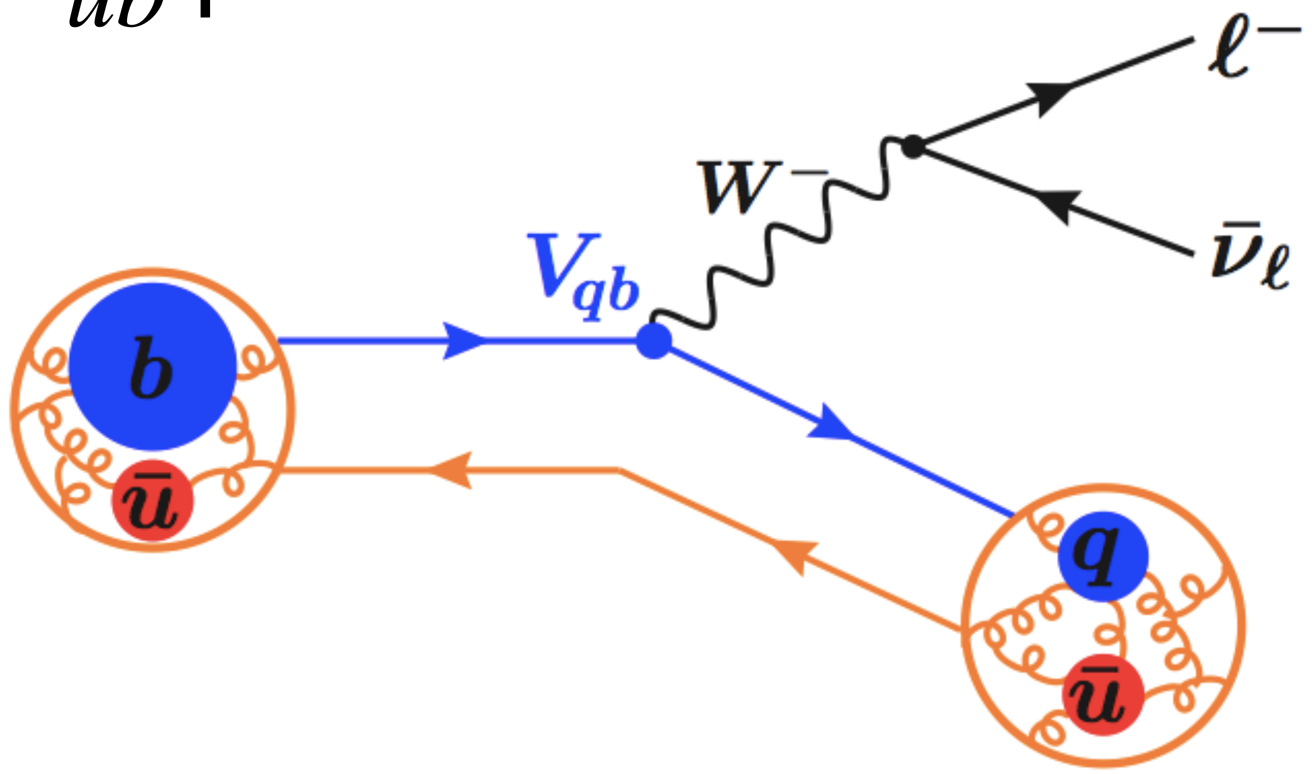



excluded area has CL > 0.95
excluded at CL > 0.95
sin 2φ1
φ3
Δmd & Δms
Δmd
εK
φ2
Vub
CKM fitter
Spring 21
sol. w/ cos 2φ1 < 0
(excl. at CL > 0.95)
η̄
ρ̄
UTfit
summer18
γ
β
Δmd/Δms
|Vub/Vcb|
α

Semileptonic B decays

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

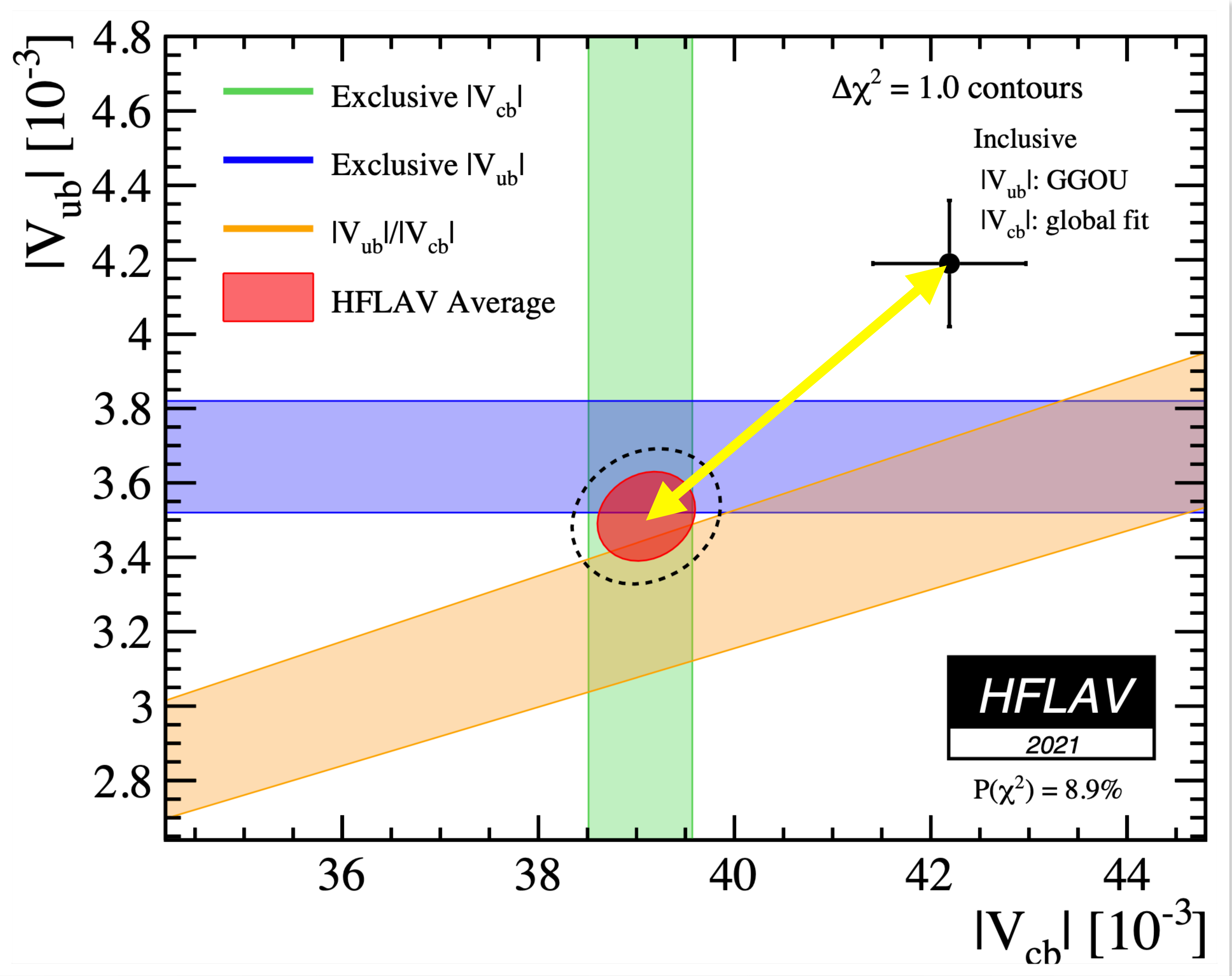
- SL B decays are studied to determine the CKM elements $|V_{cb}|$ and $|V_{ub}|$
  - $|V_{xb}|$ are limiting the global constraining power of UT fits
  - Important inputs in predictions of SM rates for ultrarare decays such as $B_s \to \mu\nu$ and $K \to \pi\nu\nu$
- The determinations can be
  - *Exclusive* — 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 $\|V_{cb}\|$	$B \to D l\nu$, $D^* l\nu$ (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 $|V_{ub}|$



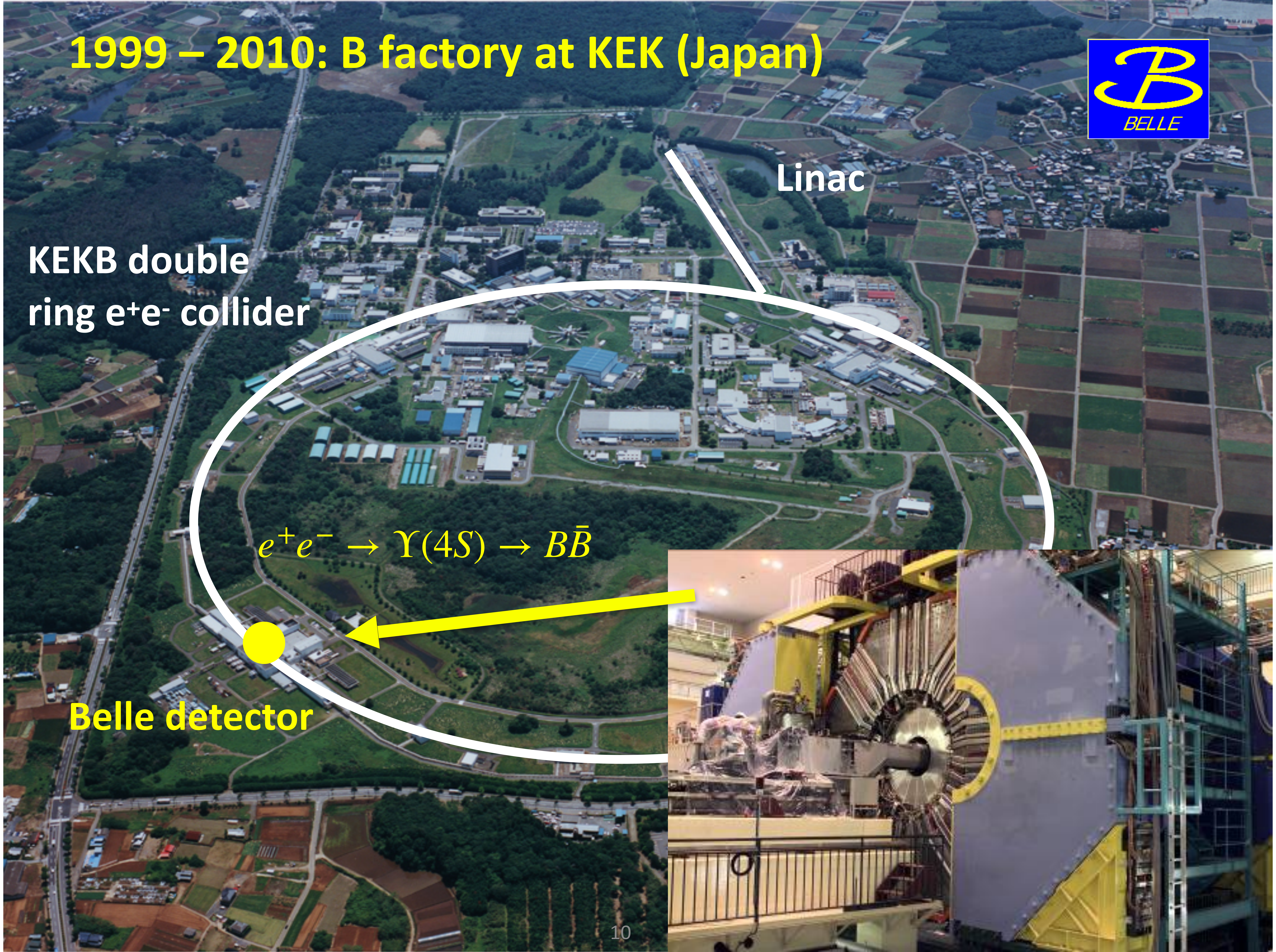
- Determinations of both $|V_{cb}|$ and $|V_{ub}|$ exhibit a discrepancy at the level of ~3σ between exclusive and inclusive
- The current experimental focus is on understanding the origin of this discrepancy, as this inconsistency limits the power of precision flavour physics

$$|V_{cb}|_{\text{excl}} = (39.10 \pm 0.50) \times 10^{-3} \quad |V_{cb}|_{\text{incl}} = (42.19 \pm 0.78) \times 10^{-3}$$
$$|V_{ub}|_{\text{excl}} = (3.51 \pm 0.12) \times 10^{-3} \quad |V_{ub}|_{\text{incl}} = (4.19 \pm 0.17) \times 10^{-3}$$

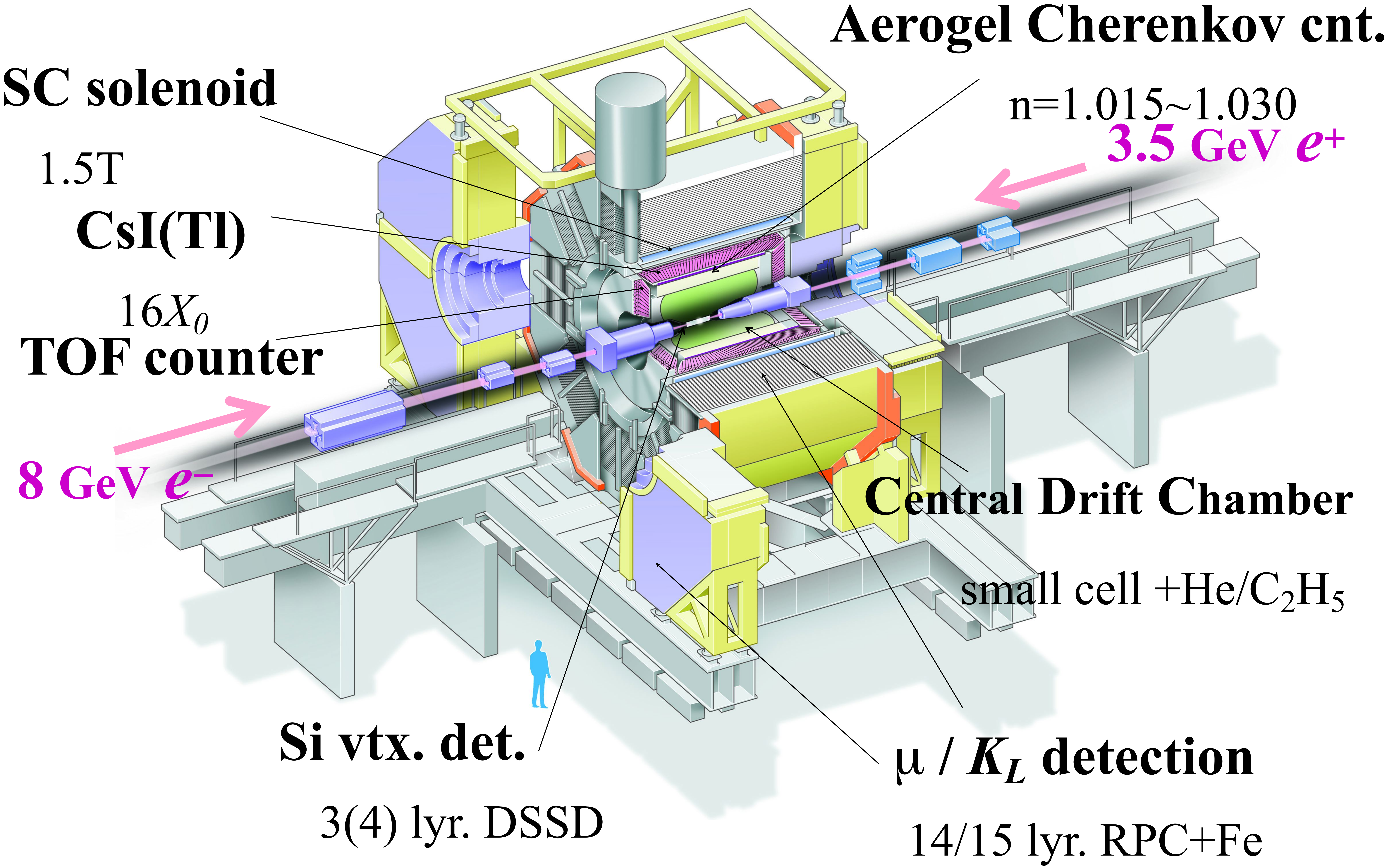
[PRD 107, 052008 (2023)]

The facilities

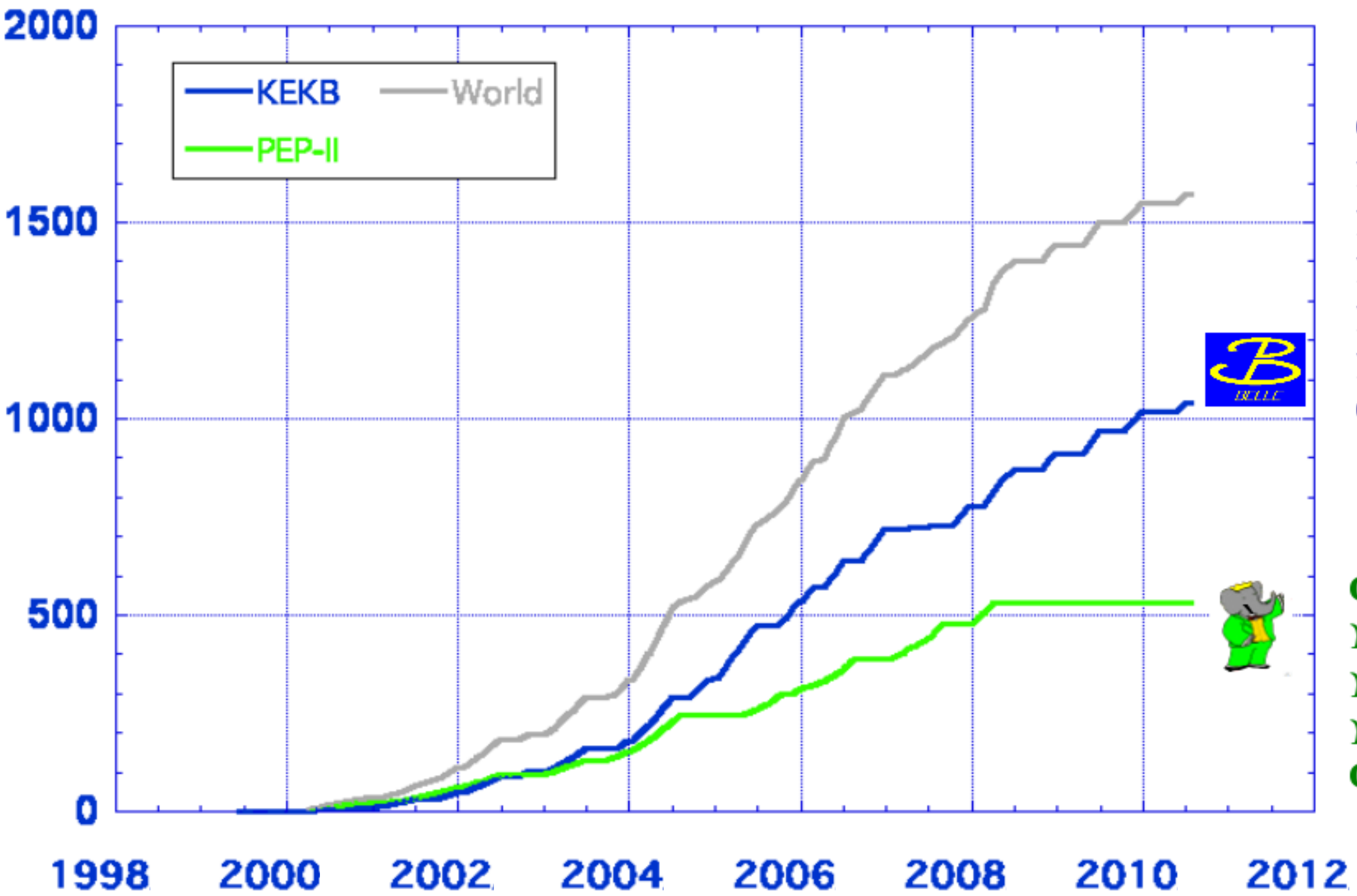
1999 – 2010: B factory at KEK (Japan)



The Belle detector



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}

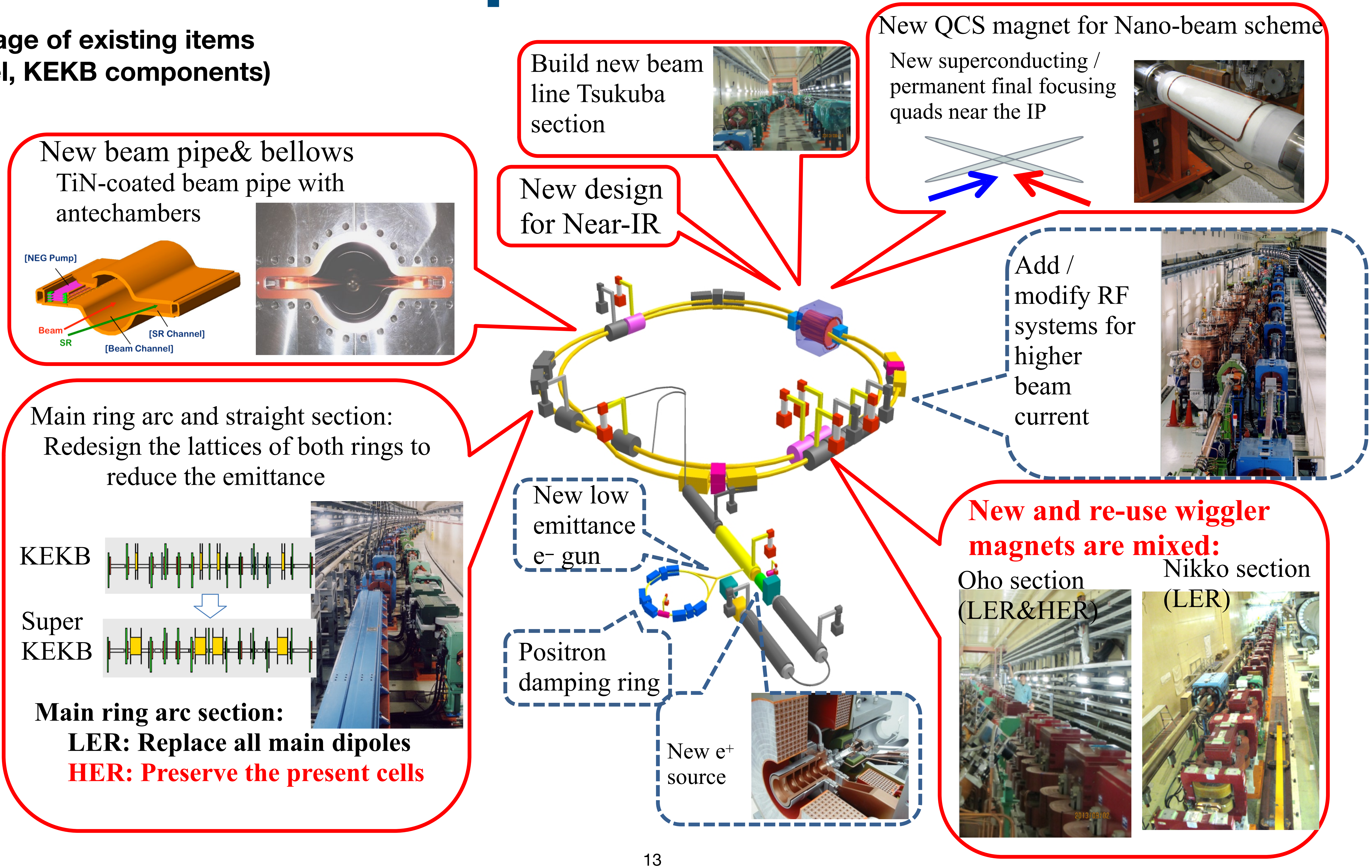
Off resonance:

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

From KEKB to SuperKEKB

$$L = 8\times10^{-35}\left[cm^{-2}s^{-1}\right] \propto \frac{I_{e\pm}\xi_{\pm y}}{\beta_y^*}.$$

Take advantage of existing items (KEKB tunnel, KEKB components)



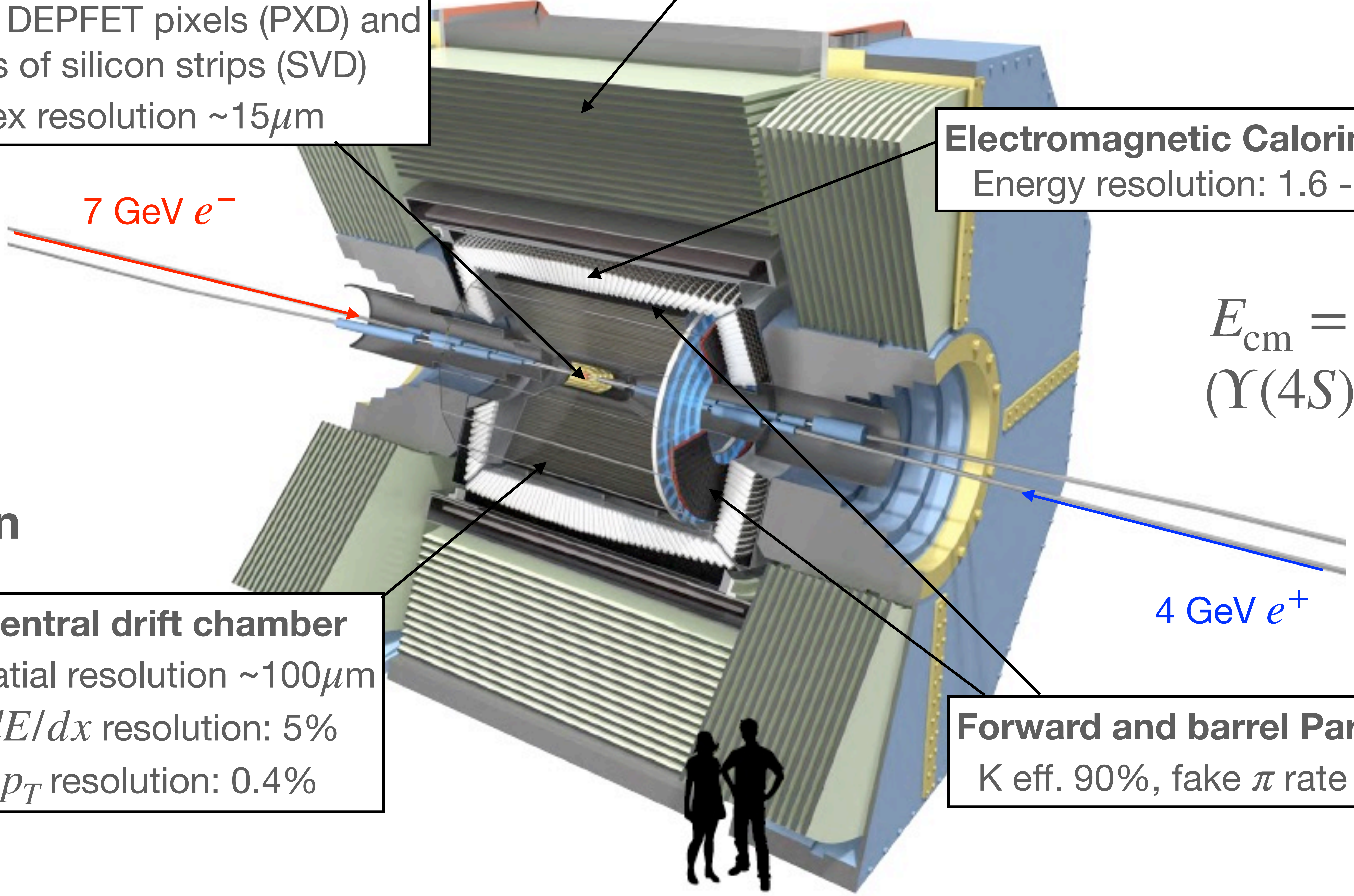
(Final parameters)

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
Half crossing angle	ϕ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	4.3-4.6	nm
Emittance ratio	κ	0.88	0.66	0.27	0.25	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.31	mm
Beam currents	I_b	1.64	1.19	3.60	2.60	A
beam-beam parameter	ξ_y	0.129	0.090	0.0886	0.0830	
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

- **Small beam size & high current** to increase luminosity
- **Large crossing angle**
- **Change beam energies** to solve the problem of LER short lifetime

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%

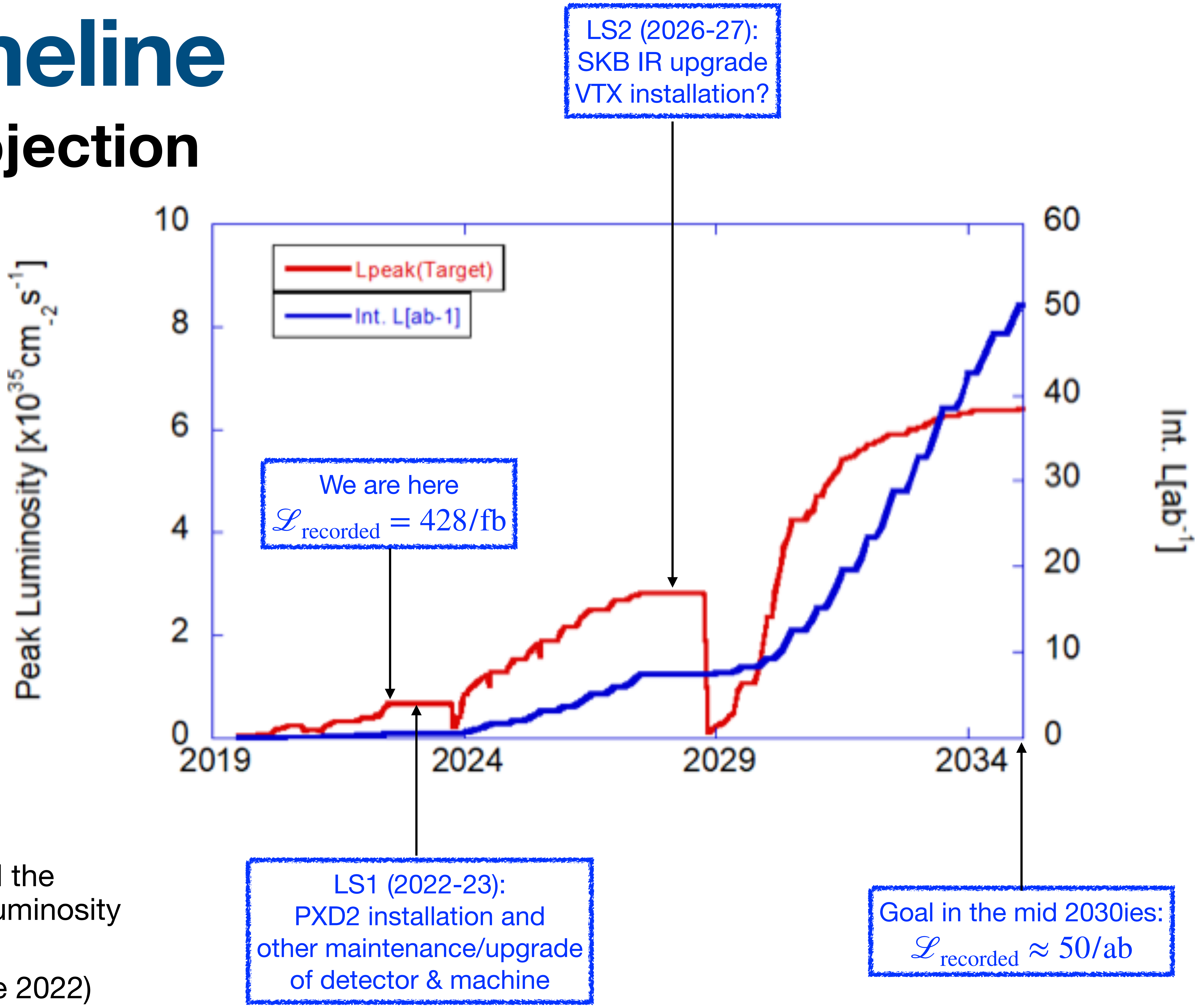
$E_{\text{cm}} = 10.58$ GeV
($\Upsilon(4S)$ resonance)

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%

Belle II timeline

Luminosity projection



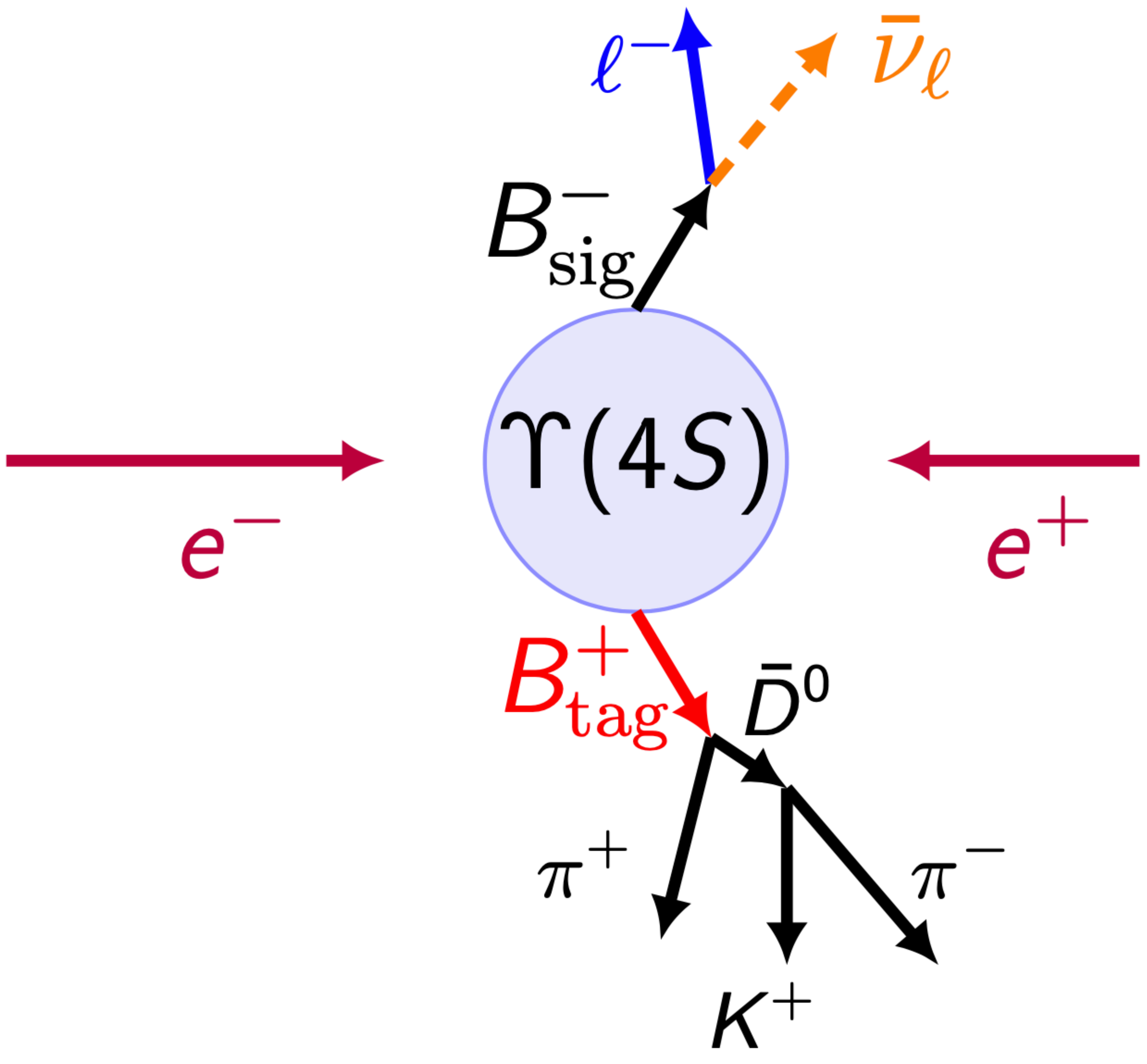
- Super-KEKB already delivered the world highest instantaneous luminosity at an e^+e^- machine (4.71×10^{34} cm^{-2}s^{-1} in June 2022)

Untagged vs. Tagged

Untagged:

only B_{sig} is reconstructed

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



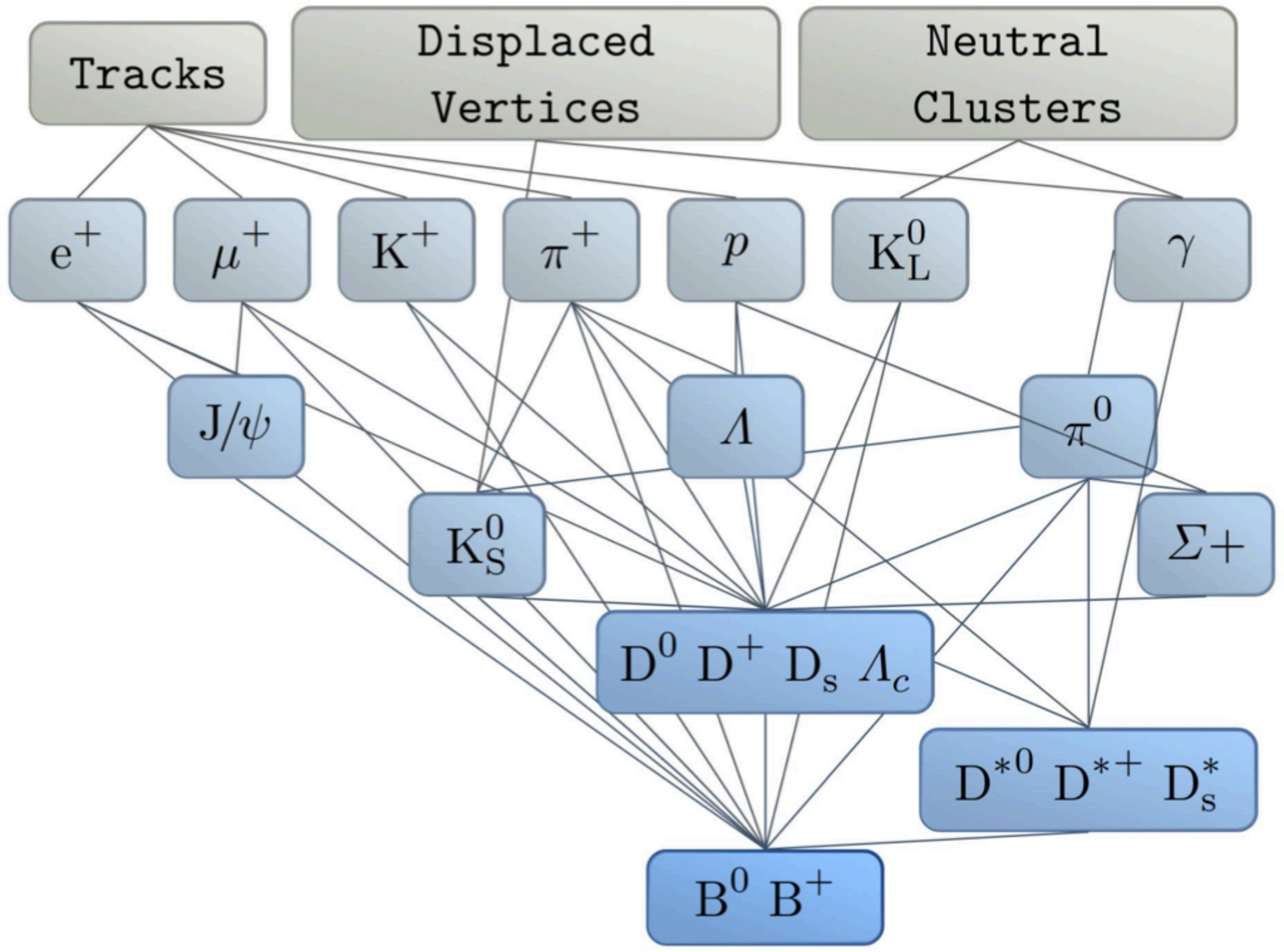
Tagged:

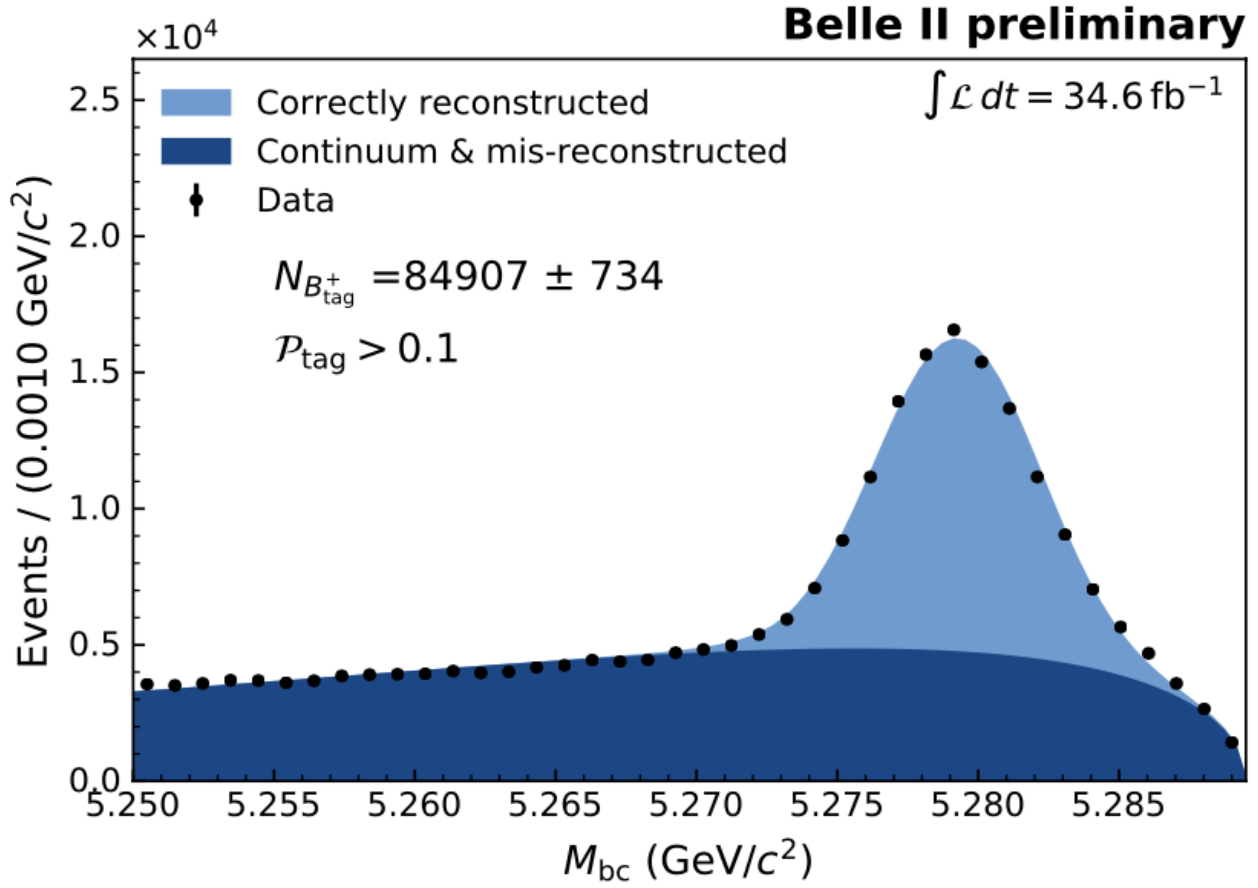
B_{sig} and B_{tag} are reconstructed

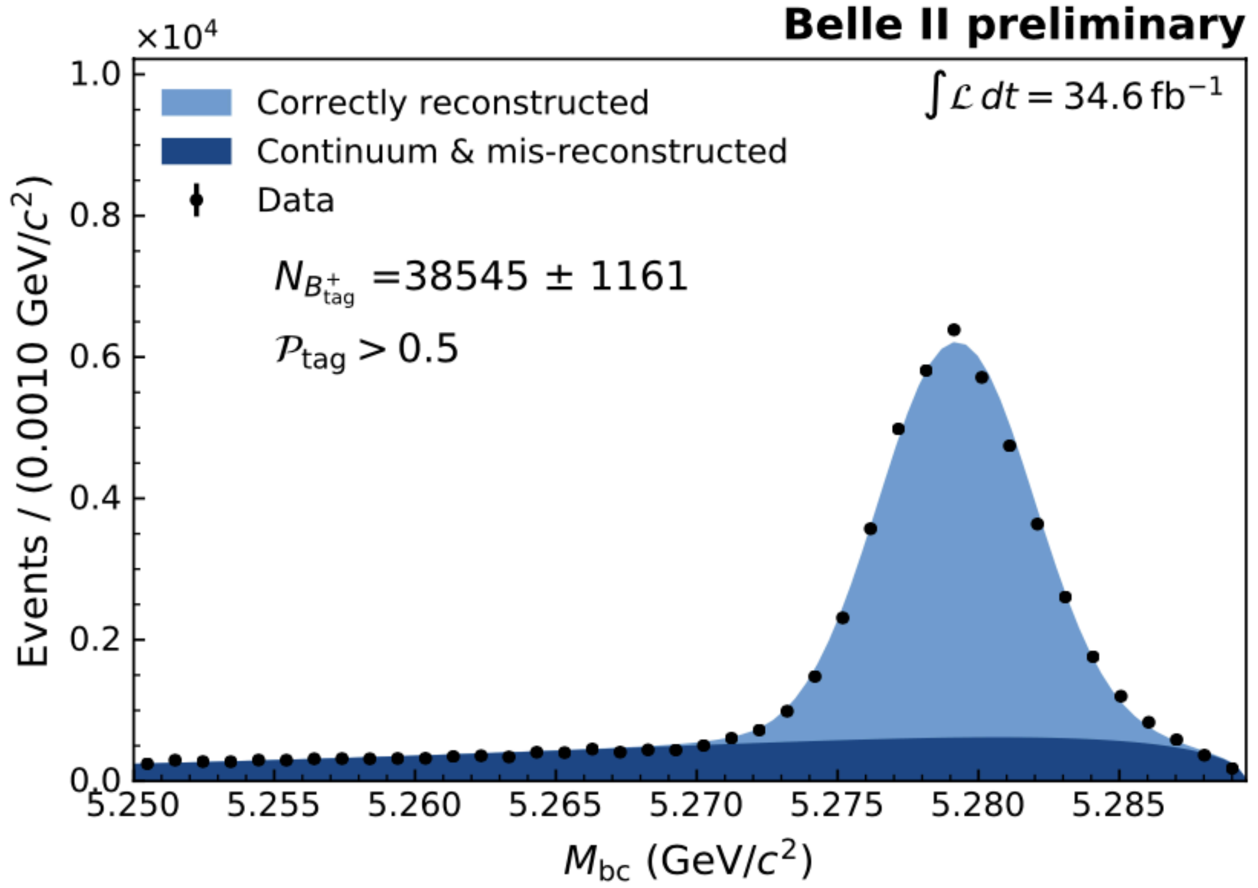
signal yield $O(10^3)$ lower (-)
low backgrounds (+)
good neutrino reconstruction (+)
tag calibration (-)

Hadronic tagging at Belle II

Comput Softw Big Sci (2019) 3: 6.







$$M_{bc} = \sqrt{E^2_{beam}/4 - (p^{\mathrm{cm}}_{B_{\mathrm{tag}}})^2} > 5.27\ \mathrm{GeV}/c^2$$

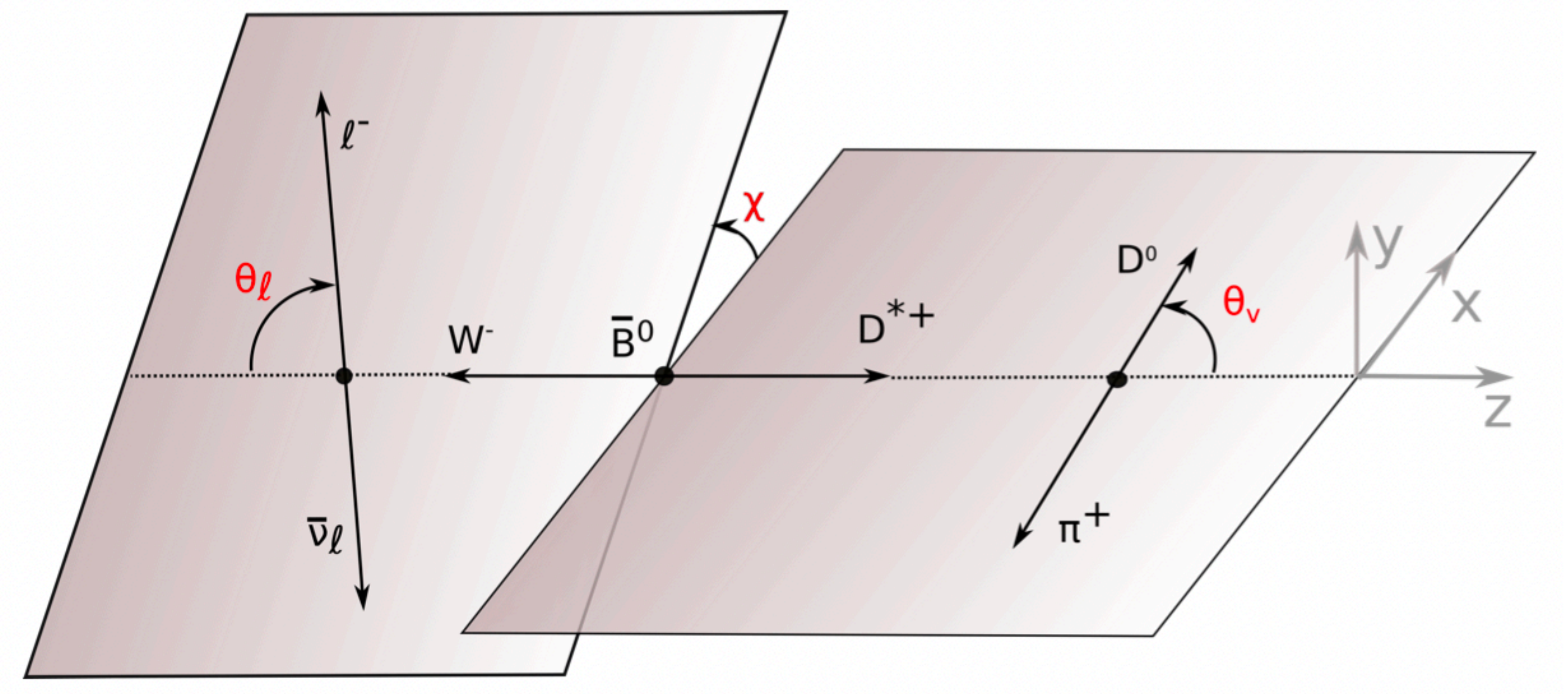
- The hadronic FEI employs over 200 boosted decision trees to reconstruct 10000 B decay chains
  - $\epsilon_{B^+} \approx 0.5\ \%$, $\epsilon_{B^0} \approx 0.3\ \%$ at low purity (about 50% increase with respect to the Belle tag)

Exclusive measurements

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

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

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

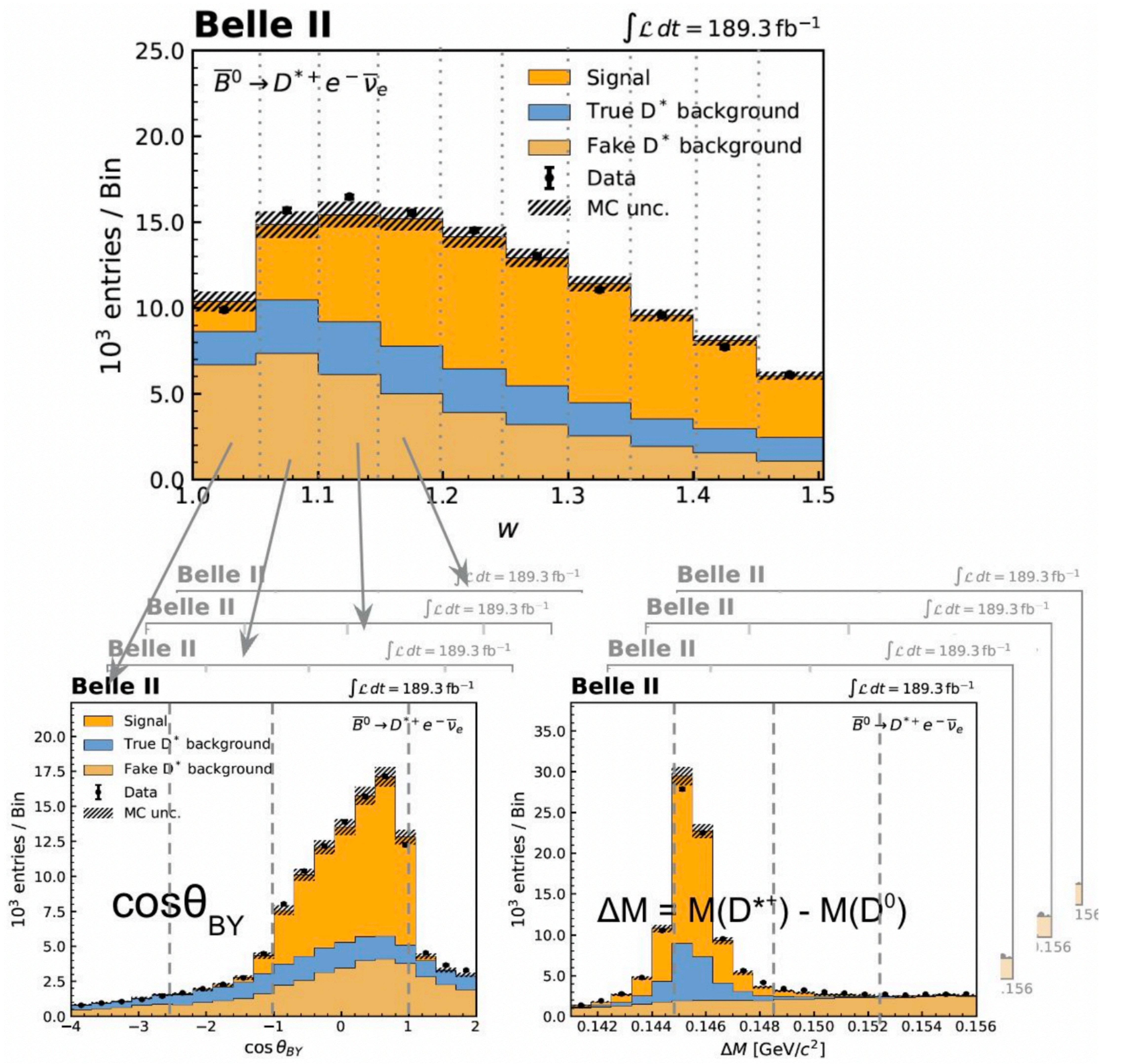
$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$

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

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

- 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

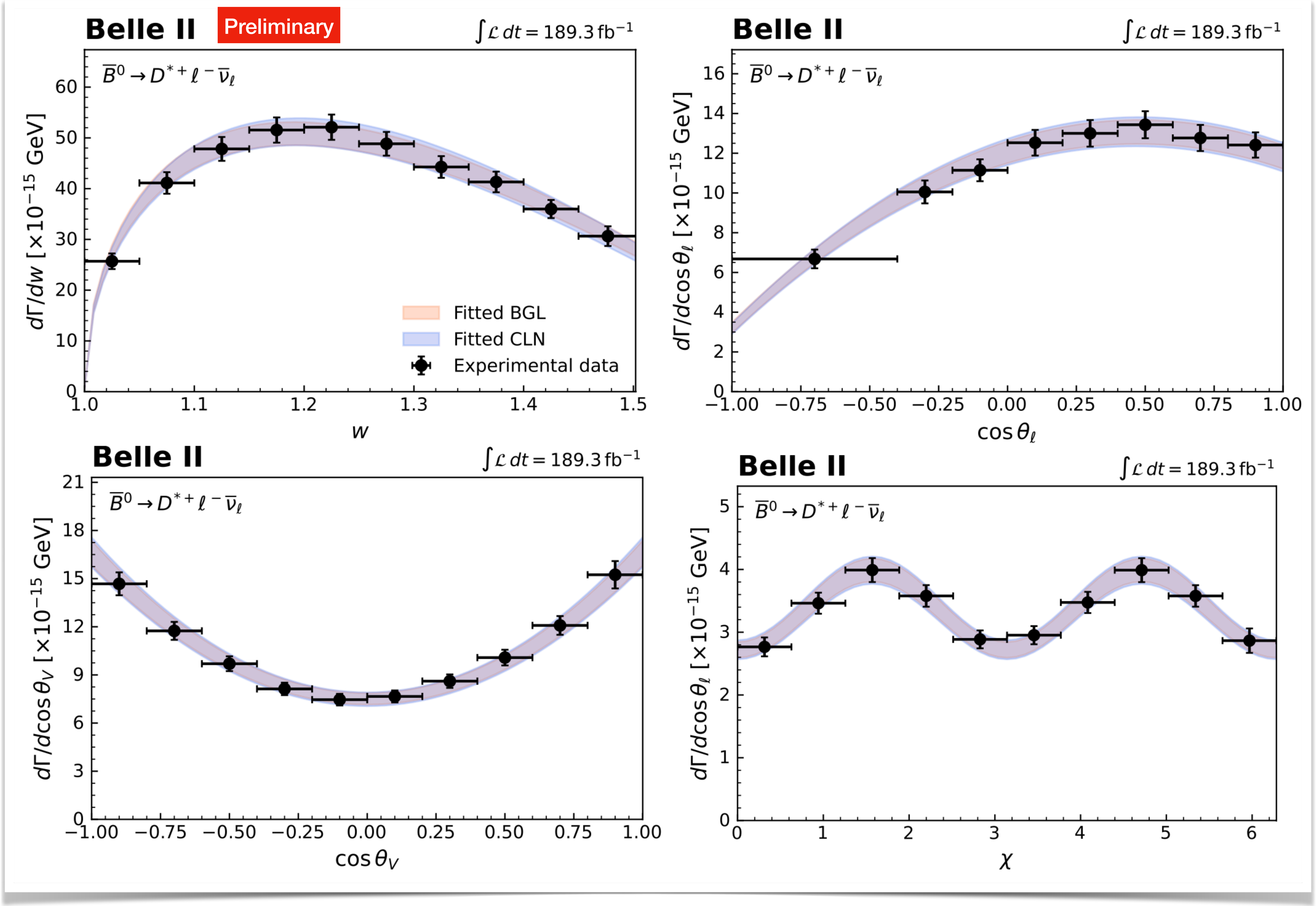
LQCD used only for normalisation at zero recoil ($w = 1$)

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

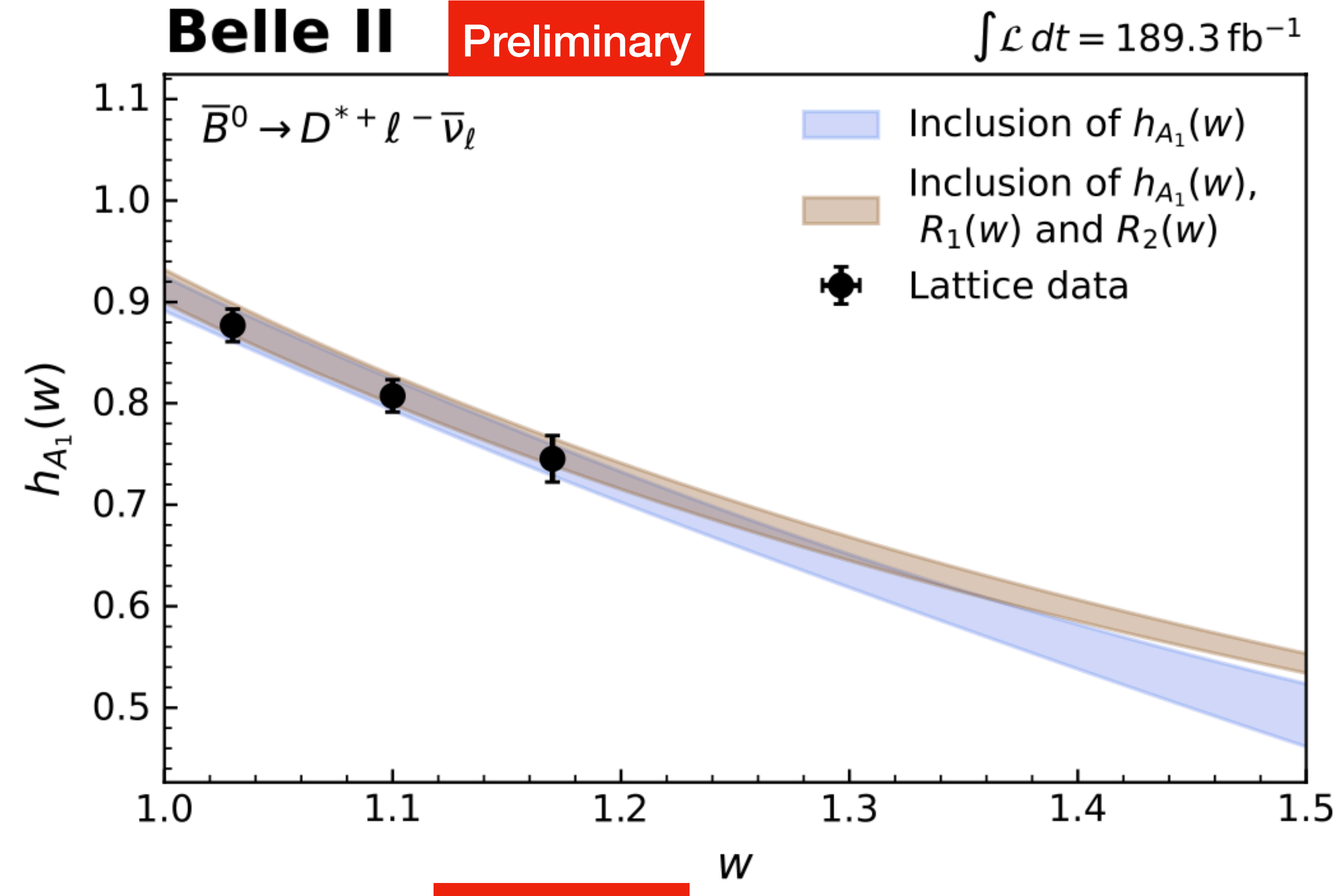
	Values	Correlations					
$\lvert V_{cb}\rvert \times 10^3$	40.4 ± 1.2	1	−0.31	−0.57	−0.1	0.02	−0.26
$a_0 \times 10^3$	22.0 ± 1.4	−0.31	1	0.27	0.1	−0.18	0.31
$b_0 \times 10^3$	13.2 ± 0.2	−0.57	0.27	1	−0.18	0.13	−0.12
$b_1 \times 10^3$	9.0 ± 14.5	−0.1	0.1	−0.18	1	−0.88	0.52
b_2	-0.5 ± 0.4	0.02	−0.18	0.13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

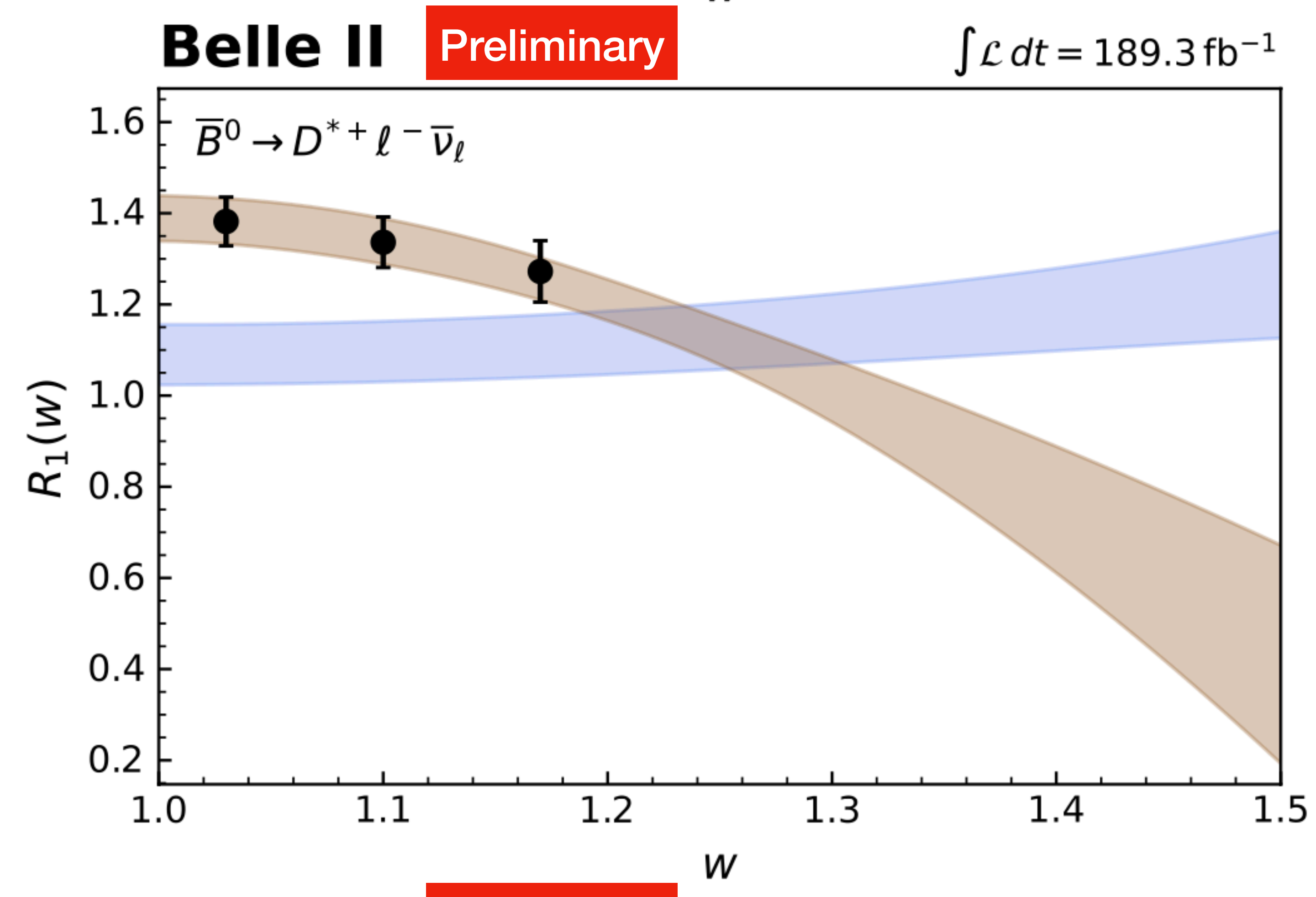
LQCD constraints on $h_{A_1}(w)$, $R_1(w)$ and $R_2(w)$ at $w = 1.03, 1.10, 1.17$

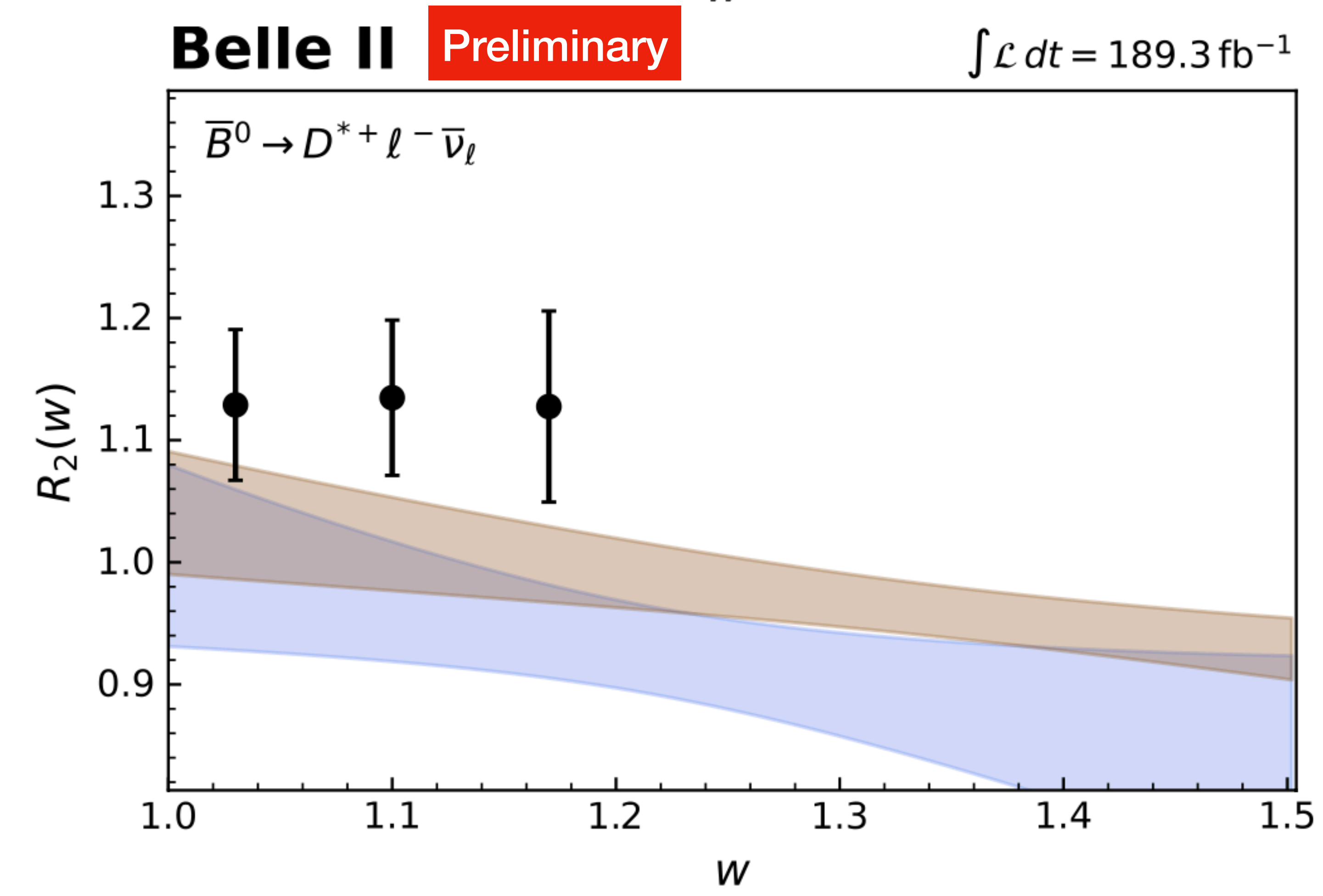
[Eur. Phys. J. C 82, 1141 (2022)]

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

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

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

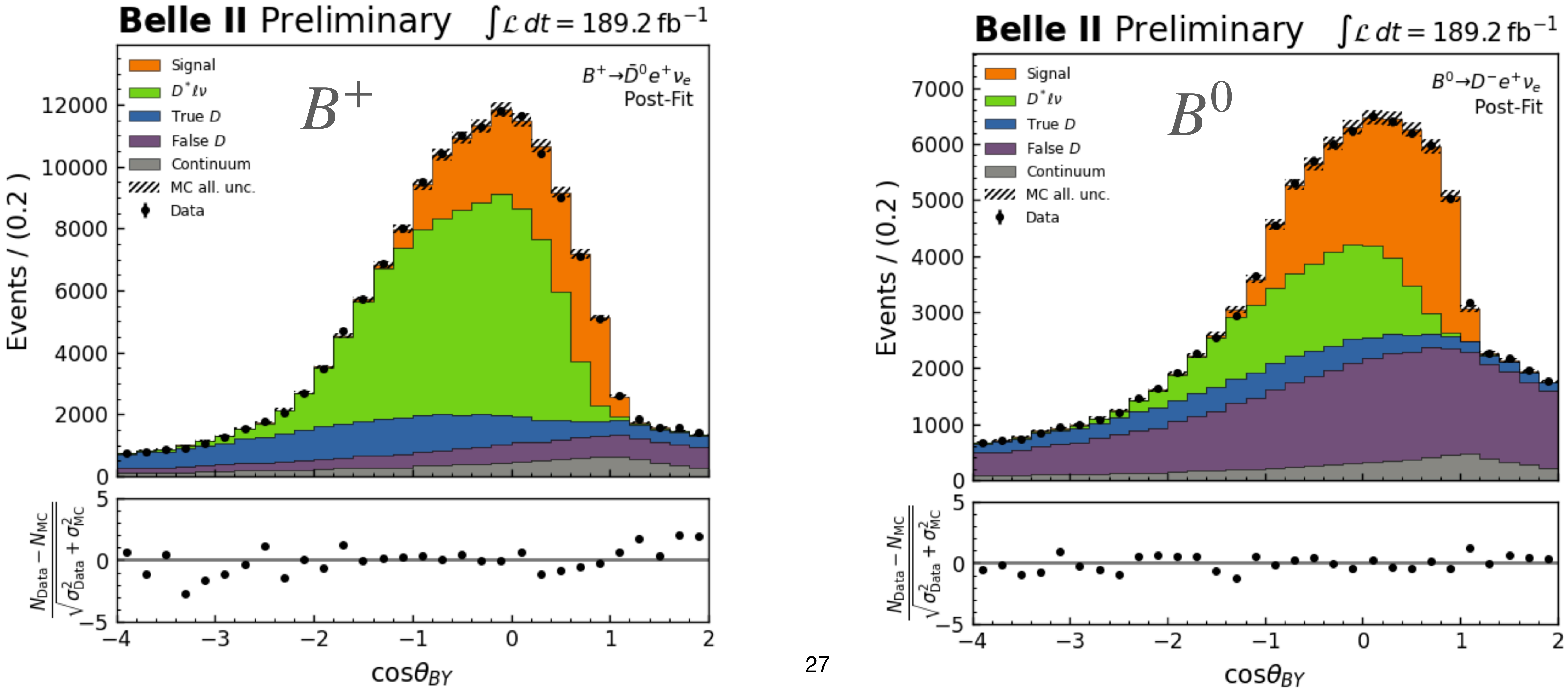
$$\Delta FL = 0.013 \pm 0.007_{stat} \pm 0.007_{syst}$$

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

preliminary [arXiv:2210.13143]

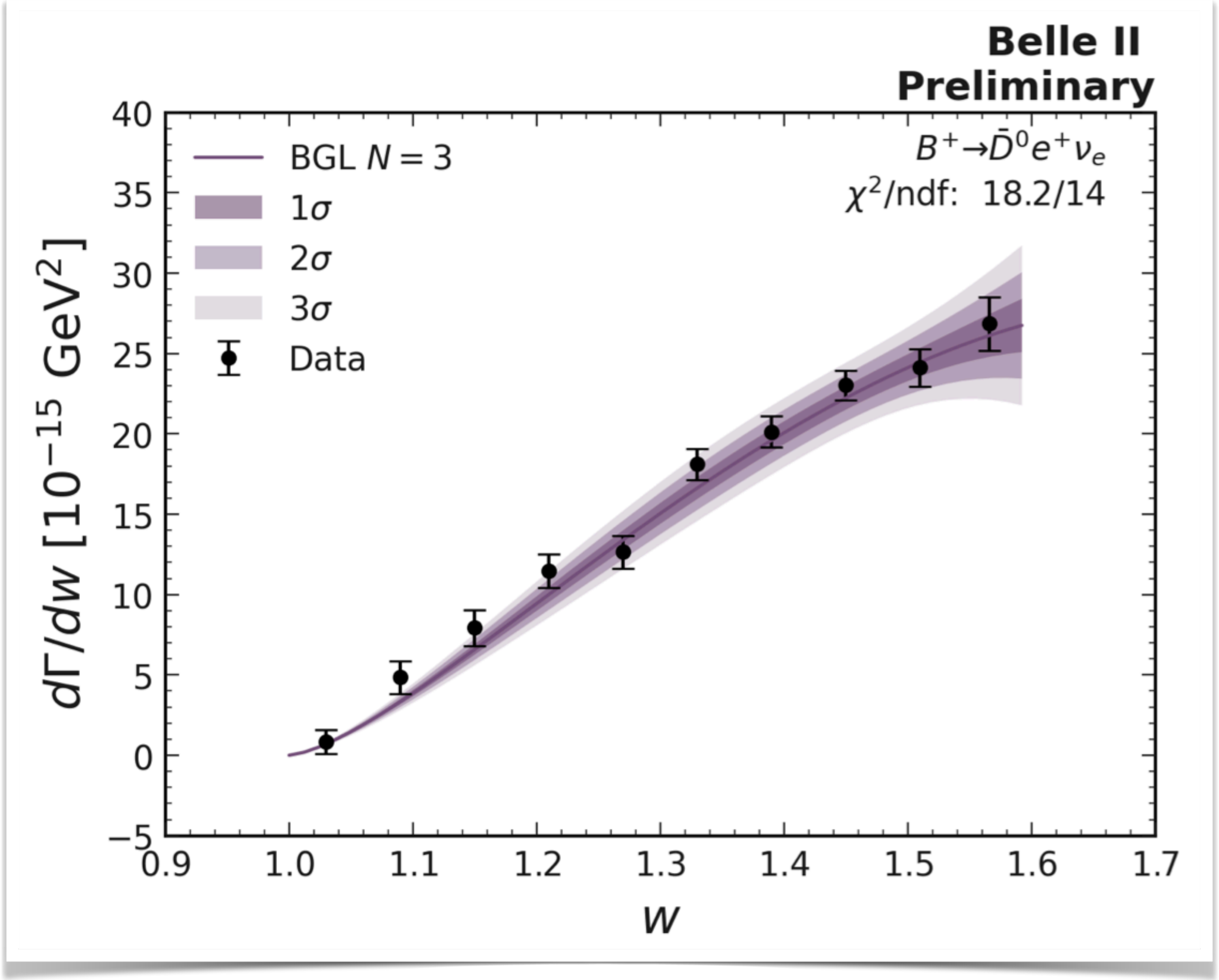
Measurement

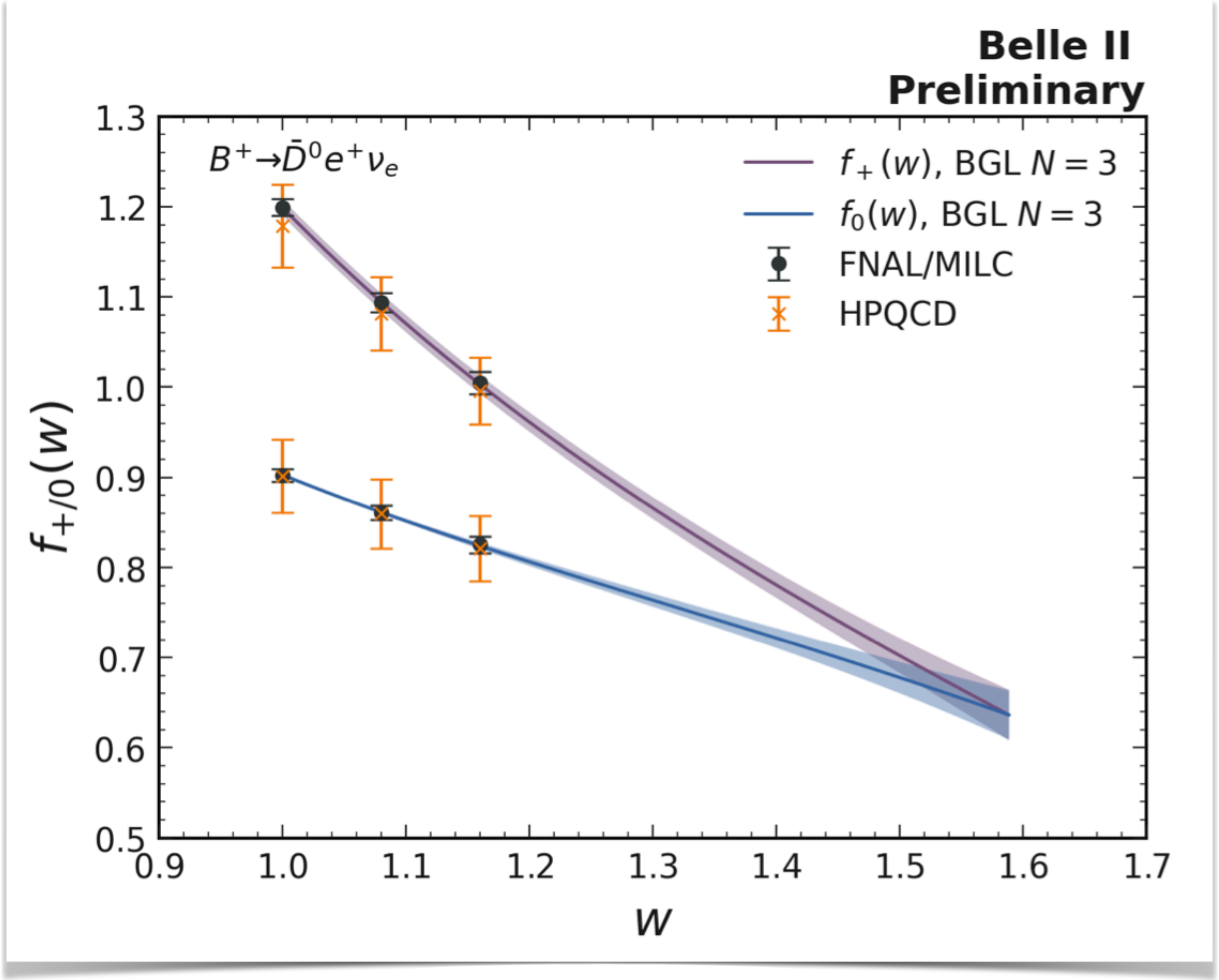
- $D\ell\nu$ kinematics are described by w only and the decay form factor contains a single function $f_+(w)$
- $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$ are reconstructed and combined with an appropriately charged lepton (e or μ)
- Yields are extracted in 10 bins of w by fitting the $\cos\theta_{BY}$ 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 $q^2 = (p_\ell + p_\nu)^2$

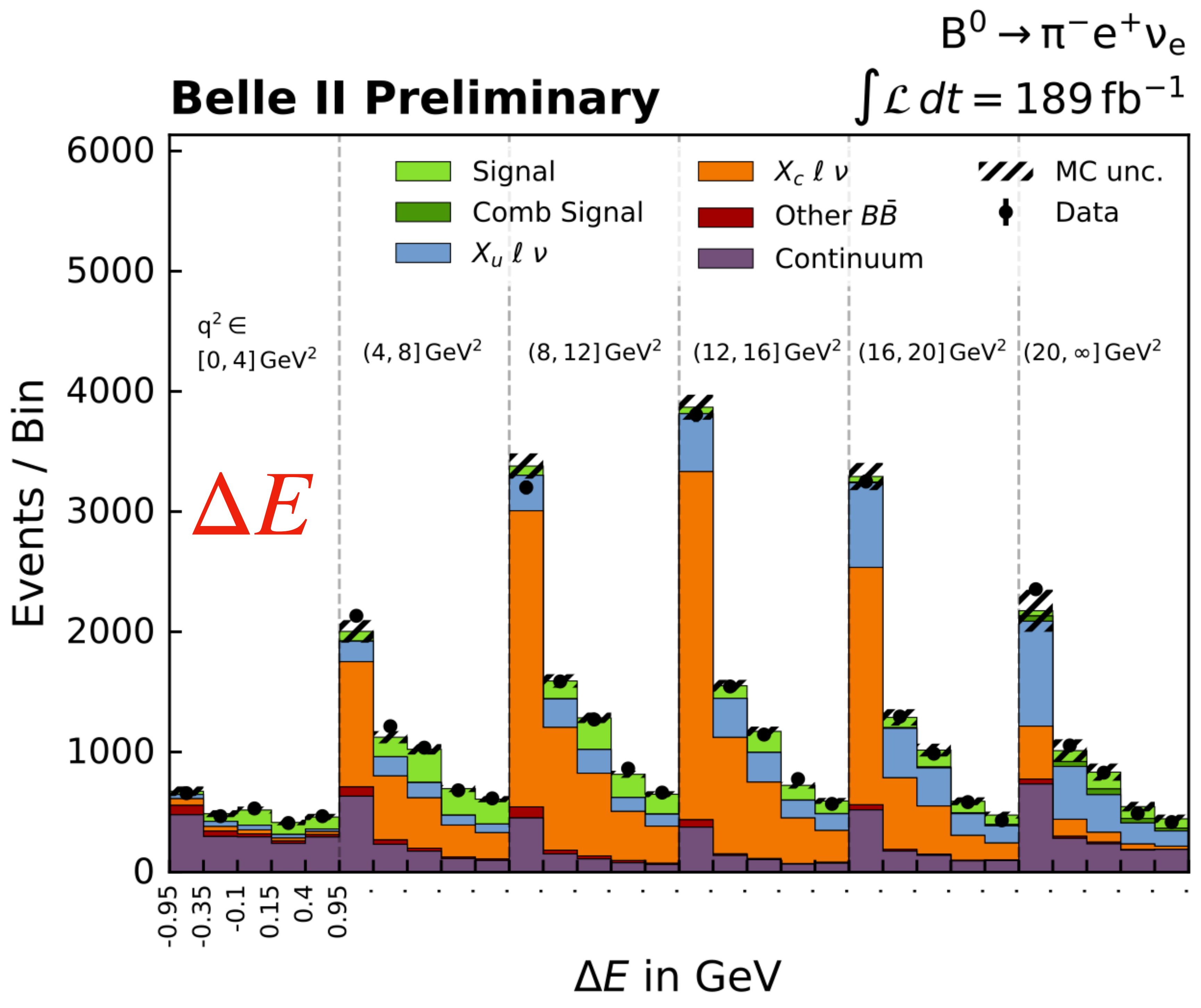
$$\frac{d\Gamma(B^0 \to \pi^- \ell^+ \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 |p_\pi|^3 |f_+(q^2)|^2$$

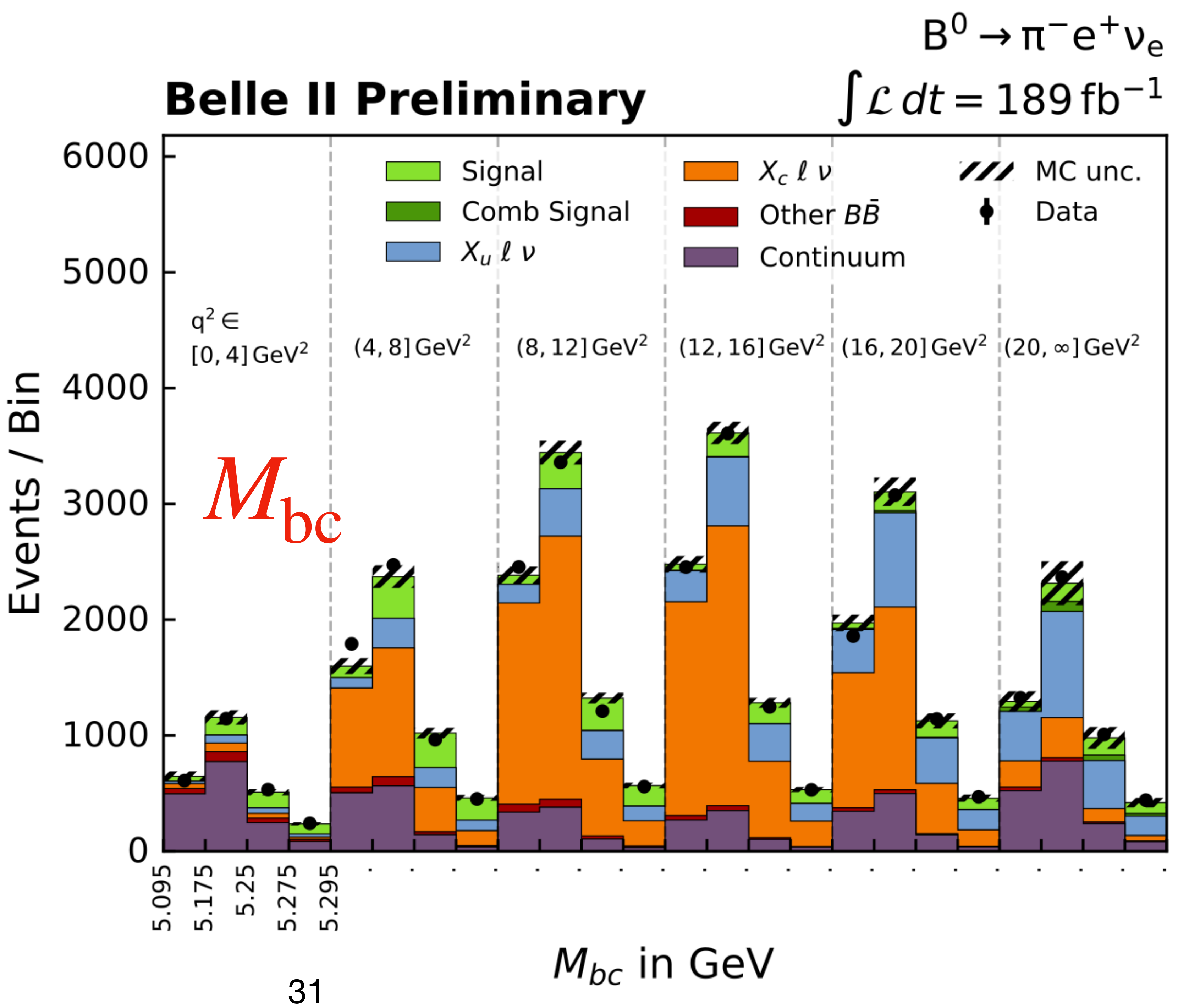
- BCL extraction of $|V_{ub}|$ [Phys.Rev.D79, 013008; Erratum-ibid. D82, 099902]
  - Measure the differential rate in bins of q^2
  - Theory calculates $f_+(q^2)$ at values of q^2
  - Combined fit to the BCL expansion to determine $|V_{ub}|$ and b_k (z is a map of q^2)

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

Measurement

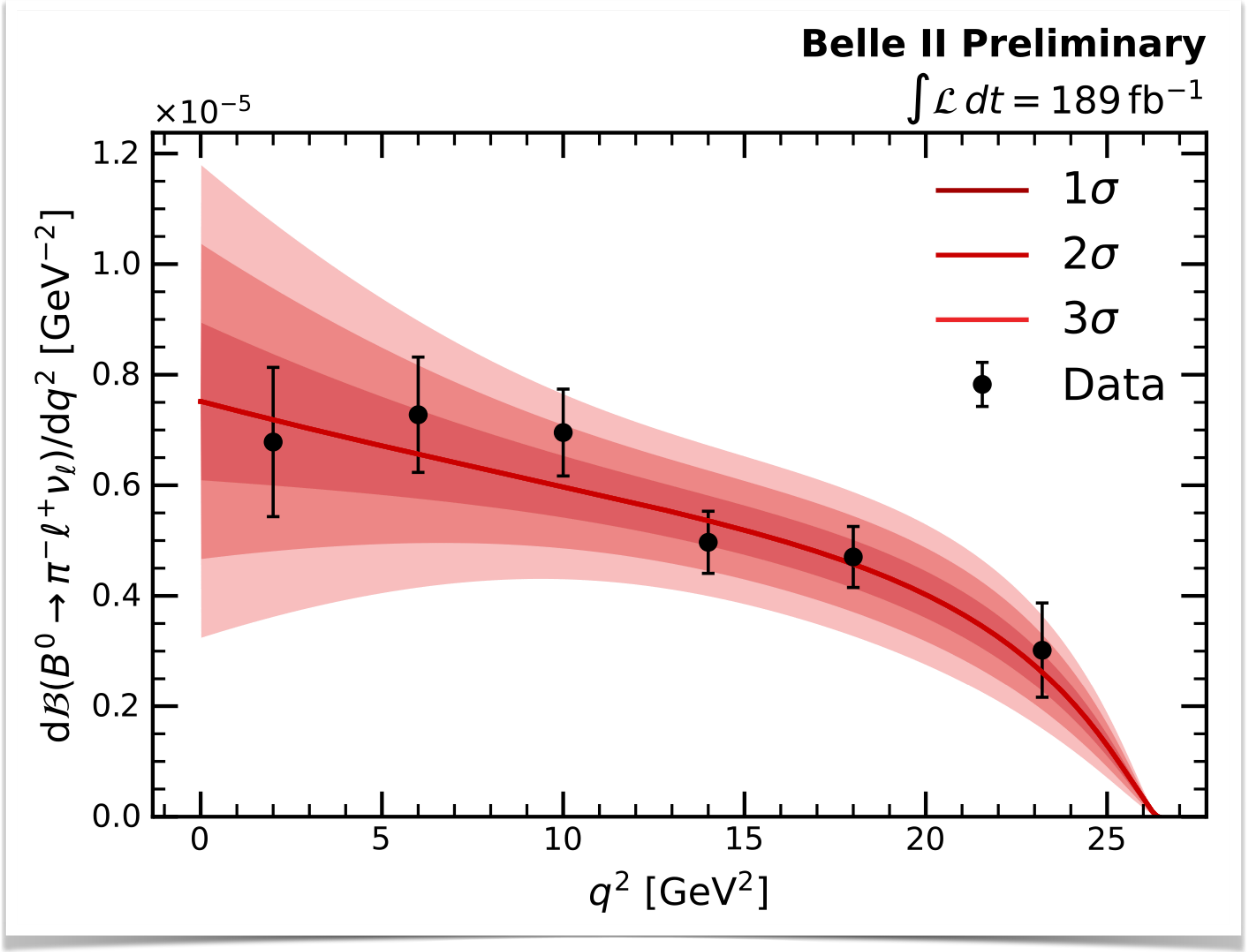
- Charged π mesons are combined with e or μ, the neutrino direction is reconstructed inclusively
- The yield in 6 bins of q^2 is determined from a fit to $M_{bc} = \sqrt{E_{\text{beam}}^{*2} - |\vec{p}_B^{\,*}|^2}$ vs.
  $\Delta E = E_B^* - E_{\text{beam}}^*$
- Bin-by-bin unfolding to correct migration





BCL fit result

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



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

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

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

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

- Recent Belle II results on exclusive decays

WA values [HFLAV 2021]

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

$|V_{ub}|_{excl} = (3.51 \pm 0.12) \times 10^{-3}$

	$|V_{cb}| \times 10^3$		**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]

Inclusive measurements

$|V_{cb}|$ from inclusive decays

$B \to Xl\nu$

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2\left(1 + \frac{c_5(\mu)\,\langle O_5\rangle(\mu)}{m_b^2} + \frac{c_6(\mu)\,\langle O_6\rangle(\mu)}{m_b^3} + \mathcal{O}\left(\frac{1}{m_b^4}\right)\right)$$

- Based on the Operator Product Expansion (OPE)
- $\langle O_i \rangle$: hadronic matrix elements (non-perturbative)
  c_i: coefficients (perturbative)
- Parton-hadron duality → the hadronic ME depend only on the initial state

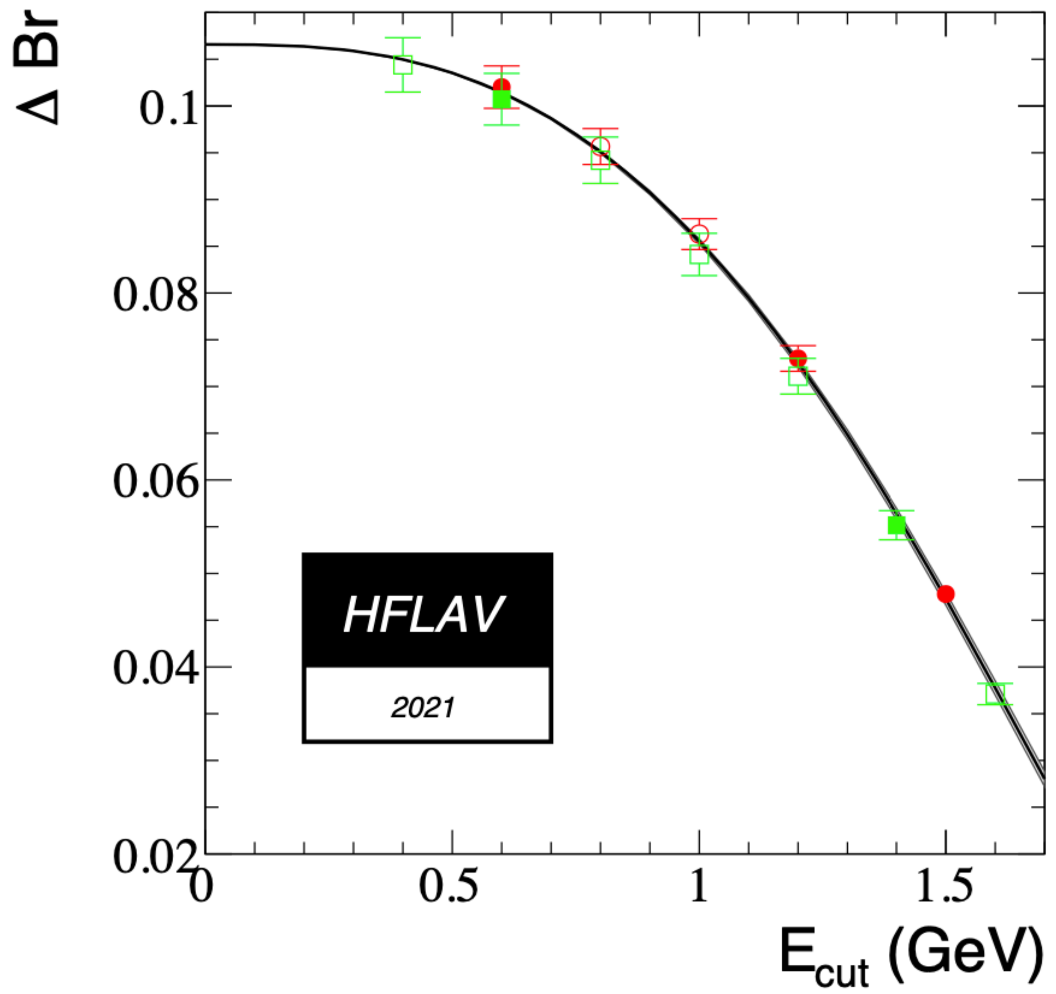
	Kinetic [JHEP 1109 (2011) 055]	1S [PRD70, 094017 (2004)]
O(1)	m_b, m_c	m_b
$O(1/m^2_b)$	μ^2_π, μ^2_G	λ_1, λ_2
$O(1/m^3_b)$	ρ^3_D, ρ^3_{LS}	ρ_1, $\tau_{1\text{-}3}$

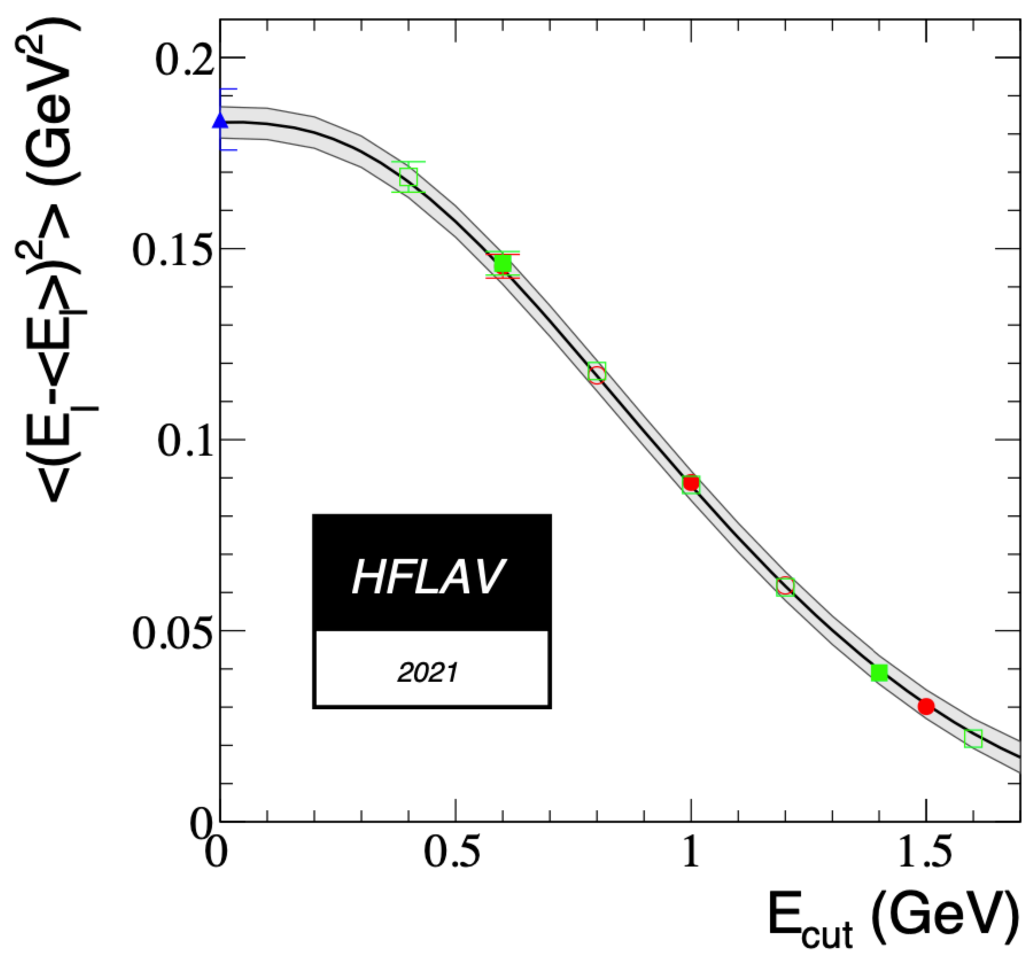
HFLAV fit (kinetic scheme)

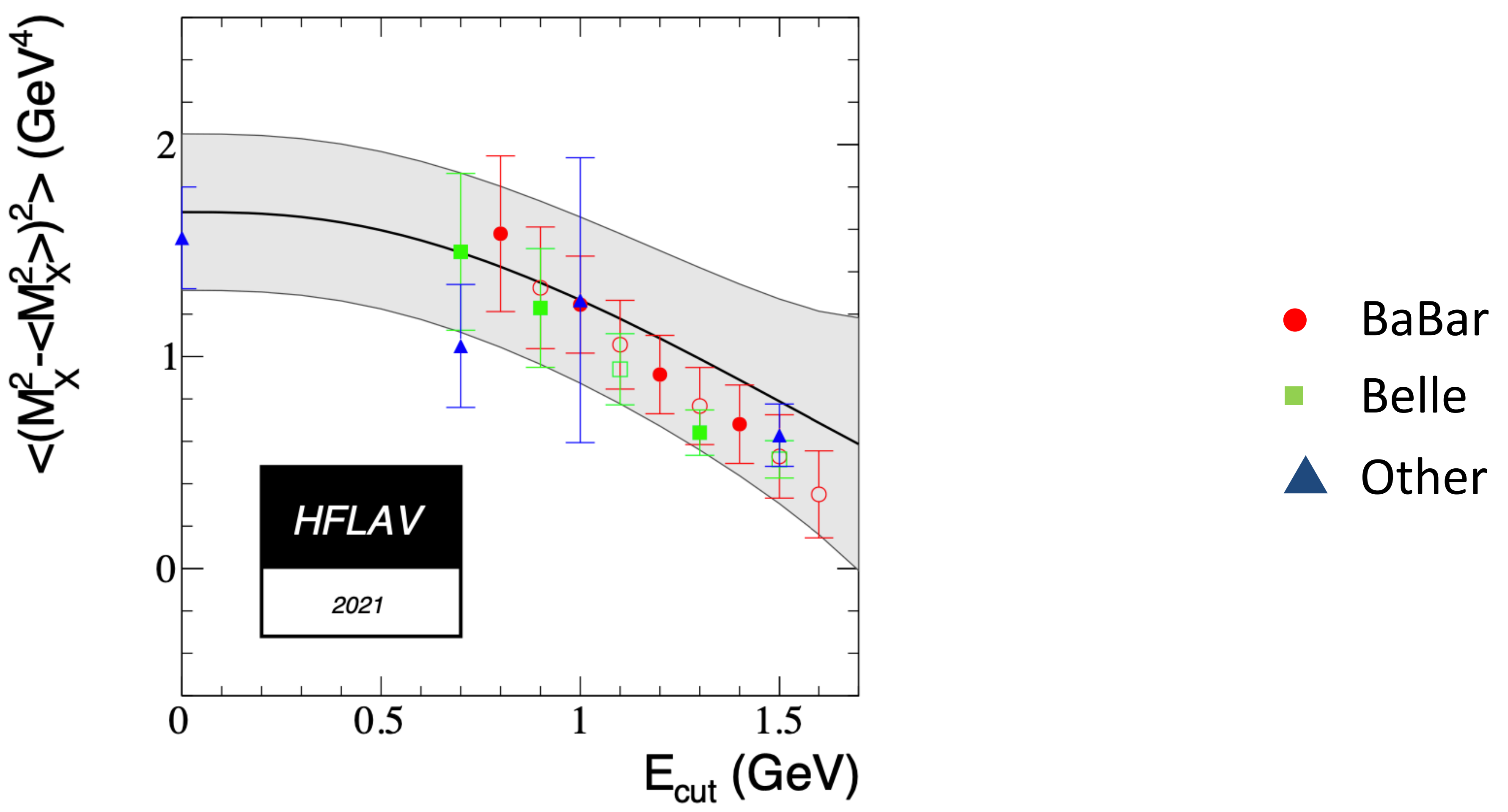
[PRD 107, 052008 (2023)]

	$\lvert V_{cb}\rvert$ [10^{-3}]	m_b^{kin} [GeV]	$m_c^{\overline{\mathrm{MS}}}$ [GeV]	μ_π^2 [GeV^2]	ρ_D^3 [GeV^3]	μ_G^2 [GeV^2]	ρ_{LS}^3 [GeV^3]
value	42.19	4.554	0.987	0.464	0.169	0.333	−0.153
error	0.78	0.018	0.015	0.076	0.043	0.053	0.096
$\lvert V_{cb}\rvert$	1.000	−0.257	−0.078	0.354	0.289	−0.080	−0.051
m_b^{kin}		1.000	0.769	−0.054	0.097	0.360	−0.087
$m_c^{\overline{\mathrm{MS}}}$			1.000	−0.021	0.027	0.059	−0.013
μ_π^2				1.000	0.732	0.012	0.020
ρ_D^3					1.000	−0.173	−0.123
μ_G^2						1.000	0.066
ρ_{LS}^3							1.000

- Global fit to Γ_{SL} and other inclusive observables
- At different lepton energy thresholds





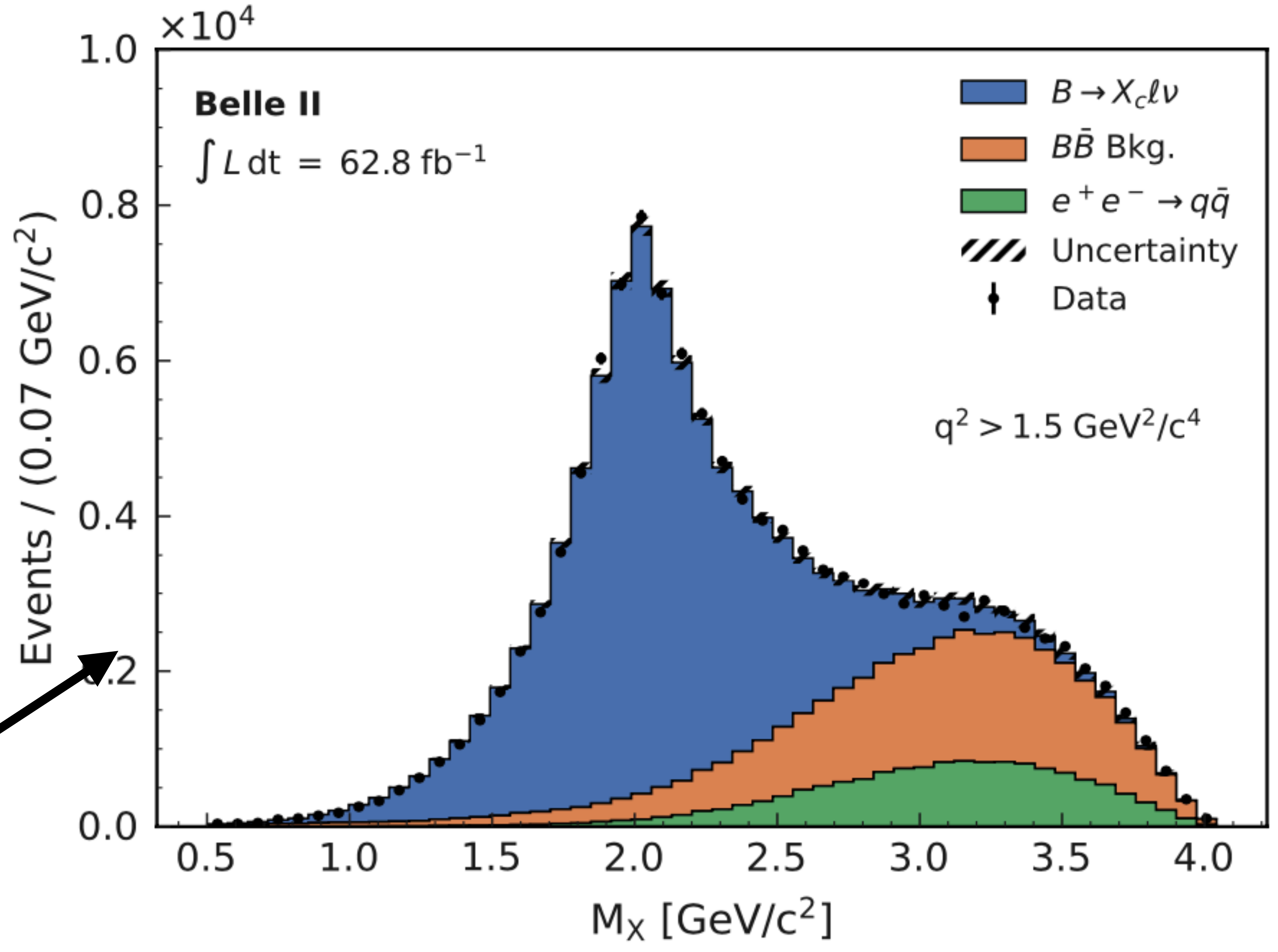


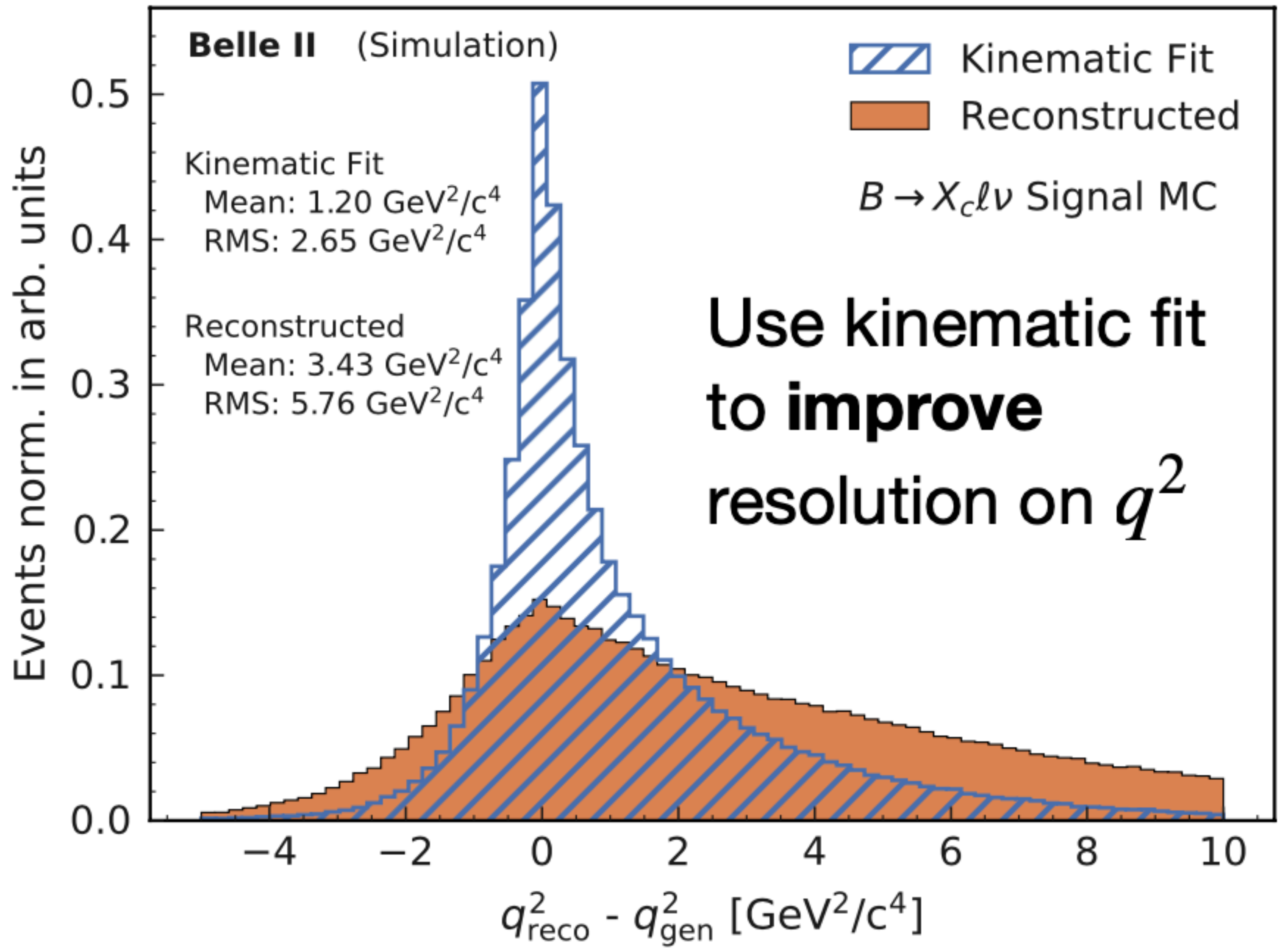
$q^2 = (p_\ell + p_\nu)^2$

q^2 moments in $B \to X_c \ell \nu$

arXiv:2205.06372, submitted to PRD

- Motivated by JHEP 02 (2019) 177 [arXiv:1812.07472]
- Semileptonic B decays are reconstructed in 62.8/fb of hadronic tagged Belle II events
- Signal weight w as a function of q^2 determined from fitting the hadronic mass M_X
- q^2 spectra are calculated as event-wise average
- Leading systematics: background, moment calibration



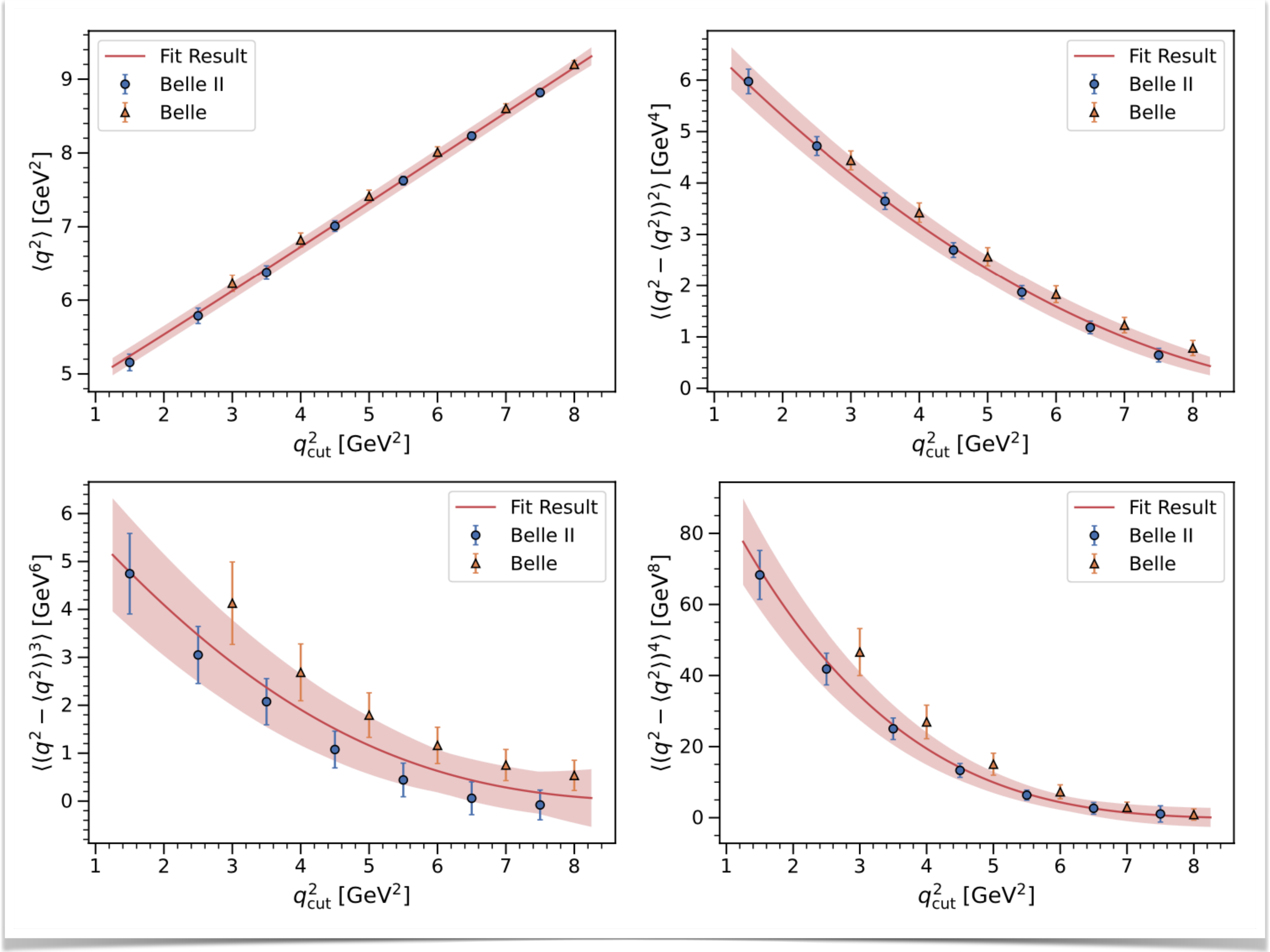


Use kinematic fit to **improve** resolution on q^2

$$\langle q^{2m} \rangle = \frac{C_{\mathrm{cal}} \cdot C_{\mathrm{acc}}}{\sum_i^{\mathrm{events}} w(q_i^2)} \times \sum_i^{\mathrm{events}} w(q_i^2) \cdot q_{\mathrm{cal}\,i}^{2m}$$

q^2 moments in $B \to X_c \ell \nu$

arXiv:2205.06372, submitted to PRD



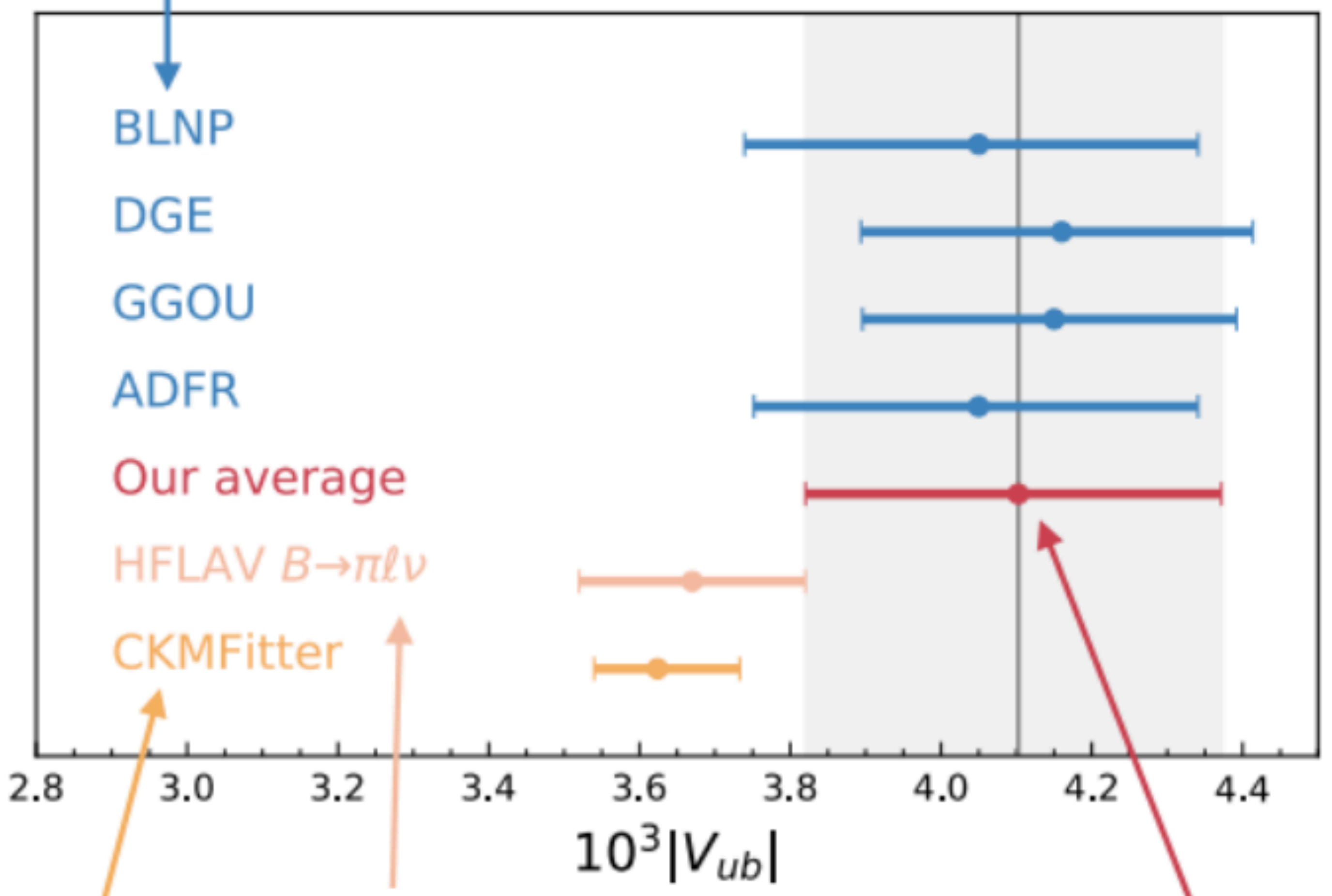
- Belle II q^2 moments compared to Belle q^2 moments PRD 104, 112011 (2021) [arXiv:2109.01685]
- And fit by Bernlochner et al. [arXiv:2205.10274]
- This fit gives $|V_{cb}| = (41.69 \pm 0.63) \cdot 10^{-3}$

$B \to X_u \ell \nu$ and $|V_{ub}|$ inclusive

PRD 104, 012008 (2021), PRL 127, 261801 (2021)

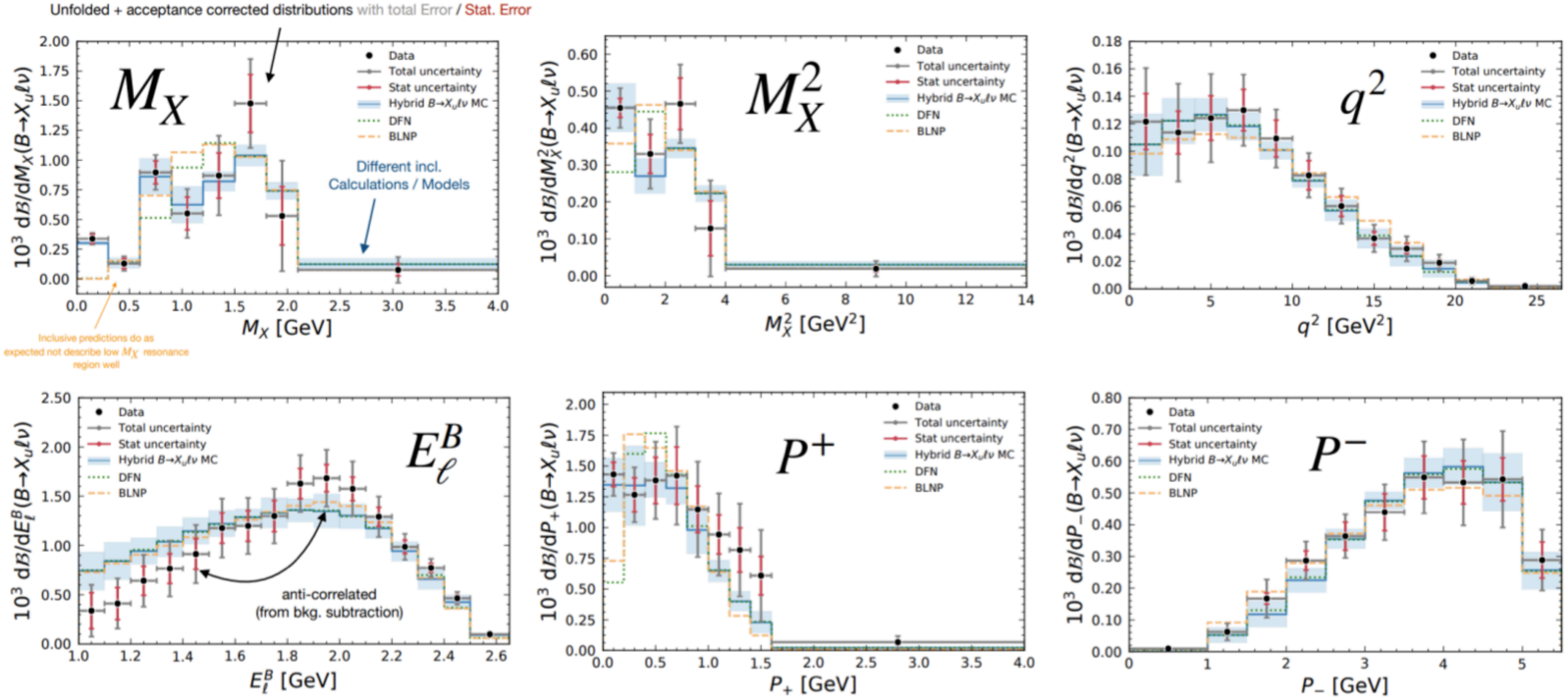
4 predictions of the partial rate

Result for most inclusive region with $E_\ell^B > 1\,\mathrm{GeV}$



Exclusive Average for $B \to \pi \ell \bar{\nu}_\ell$: $|V_{ub}| = (3.67 \pm 0.09 \pm 0.12) \times 10^{-3}$

CKM Unitarity: $|V_{ub}| = (3.62^{+0.11}_{-0.08}) \times 10^{-3}$



Arithmetic average:
$|V_{ub}| = (4.10 \pm 0.09 \pm 0.22 \pm 0.15) \times 10^{-3}$

Can be used for future shape-function independent determination of Vub

NNVub

P. Gambino, K. Healey, C. Mondino, Phys. Rev. D 94, 014031 (2016), [arXiv:1604.07598]

SIMBA - Analysis of B-Meson Inclusive Spectra

F. Bernlochner, H. Lacker, Z. Ligeti, I. Stewart, F. Tackmann, K. Tackmann Phys. Rev. Lett. 127, 102001 (2021) [arXiv:2007.04320]

Summary and conclusion

- The Cabibbo-Kobayashi-Maskawa magnitudes $|V_{cb}|$ and $|V_{ub}|$ are fundamental parameters of the Standard Model that play an important role in constraining the mechanism of quark-mixing/CP violation

- $|V_{cb}|$ and $|V_{ub}|$ are currently known to the level of <2% and <4% (respectively) but there is a discrepancy at the level of 3σ between exclusive and inclusive determinations

- The aim of ongoing measurements is to understand/identify the origin of this discrepancy

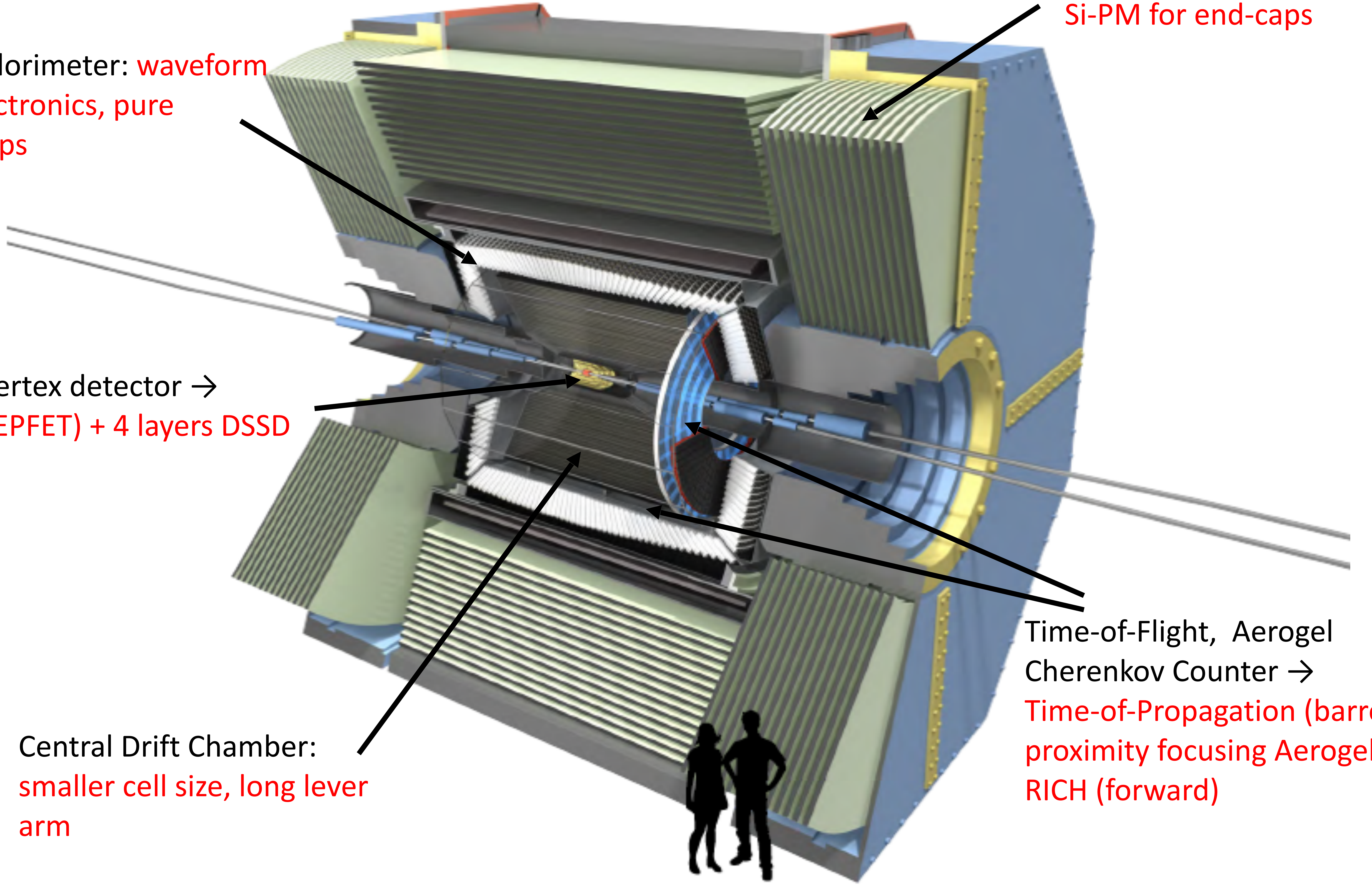
$|V_{cb}|_{\text{excl}} = (39.10 \pm 0.50) \times 10^{-3}$ $|V_{cb}|_{\text{incl}} = (42.19 \pm 0.78) \times 10^{-3}$

$|V_{ub}|_{\text{excl}} = (3.51 \pm 0.12) \times 10^{-3}$ $|V_{ub}|_{\text{incl}} = (4.19 \pm 0.17) \times 10^{-3}$

[PRD 107, 052008 (2023)]

Backup

From Belle to Belle II



RPC μ & K_L counter: scintillator + Si-PM for end-caps

CsI(Tl) EM calorimeter: waveform sampling electronics, pure CsI for endcaps

4 layers DSSD vertex detector →
2 layers PXD (DEPFET) + 4 layers DSSD

Central Drift Chamber: smaller cell size, long lever arm

Time-of-Flight, Aerogel Cherenkov Counter →
Time-of-Propagation (barrel), proximity focusing Aerogel RICH (forward)