Recent semileptonic results from Belle II

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(On behalf of the Belle II Collaboration)

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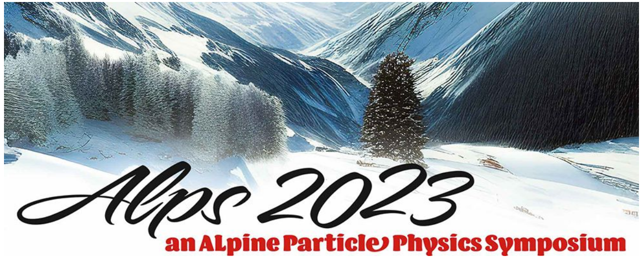
ALpine Particle physics Symposium 2023

27 March, 2023

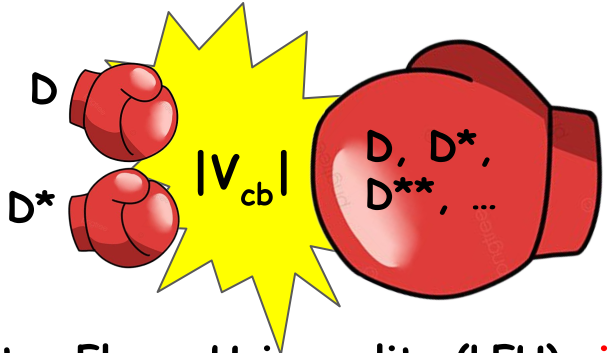


Belle II

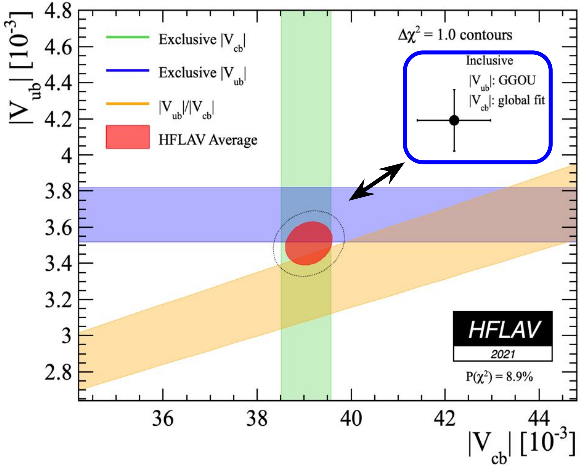
UNIVERSITÄT BONN

Two anomalies in semileptonic B decays

1. Tension between exclusive and inclusive determinations

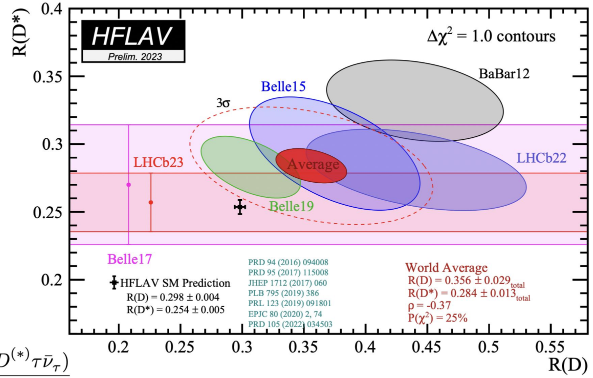


Observed in both $|V_{cb}|$ and $|V_{ub}|$.



2. Possible Lepton Flavor Universality (LFU) violation

τ-ℓ:

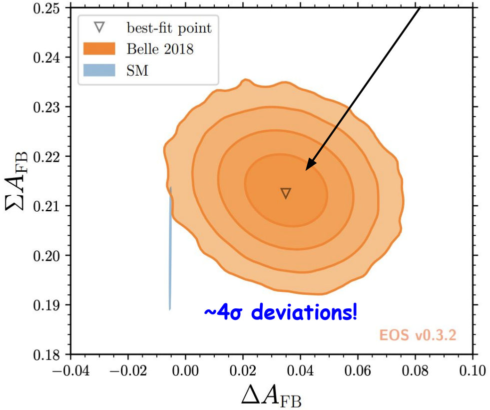


$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu}_\ell)}$$ with $\ell = e, \mu$

e-μ:

Interpretation of Belle untagged B→D*ℓν measurement

Eur.Phys.J.C 81 (2021) 11, 984



$$A_{\mathbf{FB}} = \frac{\int_0^1 \frac{d\Gamma}{d\cos\theta_\ell} d\cos\theta_\ell - \int_{-1}^0 \frac{d\Gamma}{d\cos\theta_\ell} d\cos\theta_\ell}{\int_0^1 \frac{d\Gamma}{d\cos\theta_\ell} d\cos\theta_\ell + \int_{-1}^0 \frac{d\Gamma}{d\cos\theta_\ell} d\cos\theta_\ell}$$

$\Sigma A_{FB} = (A_{FB}^{\mu} + A_{FB}^{e})/2$

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

CKM matrix

CKM matrix

SM: unitary 3×3 matrix

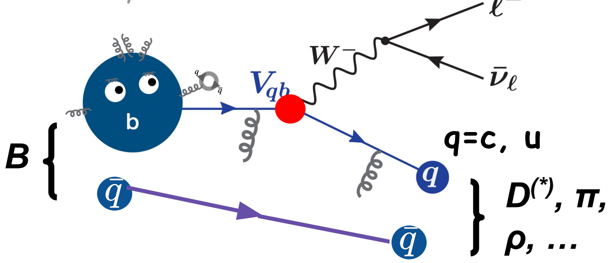
$$
\begin{array}{c} u \\ c \\ t \end{array}
\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}
$$

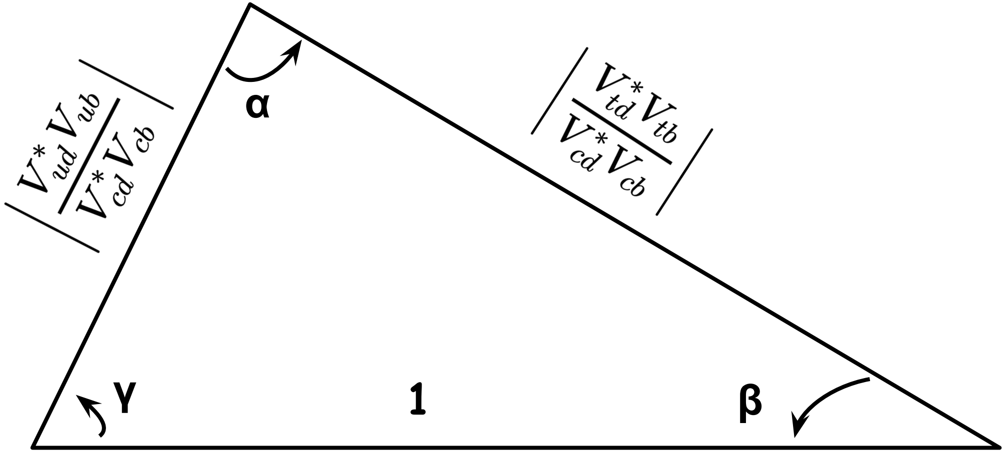
d s b

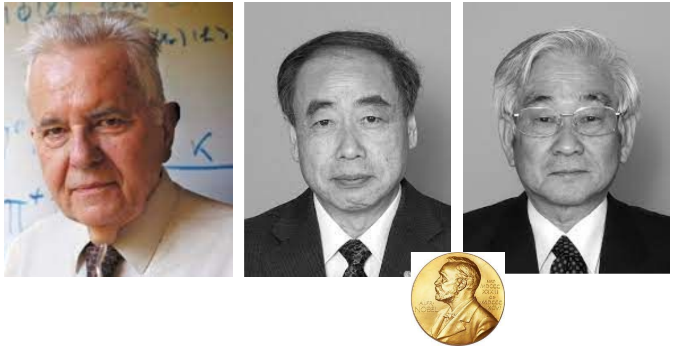
Unitarity $CC^{\dagger} = 1$

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 1$$

Plotted by F. Bernlochner







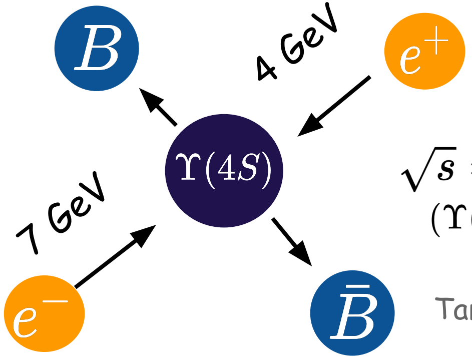
Nobel prize 2008

Belle II experiment

> 1100 active members
124 institutes
27 countries

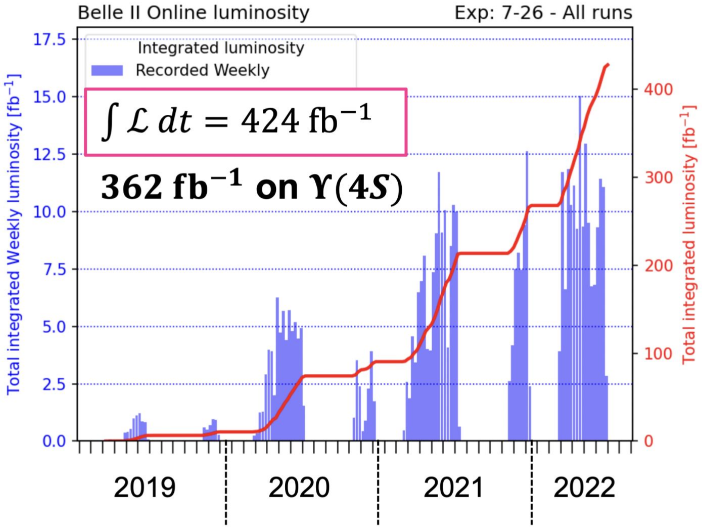
KEK
Tsukuba, Japan

B-factory



$$\sqrt{s} = 10.58\,\text{GeV}$$
($\Upsilon(4S)$ resonance)

Target int. luminosity: ~50 ab^{-1}
(To be precision frontier)



- Max instantaneous luminosity
  $\mathcal{L} = 4.7\times10^{34}\ cm^{-2}s^{-1}$ (world record)
- LS1 starts from summer 2022 to fully install the pixel detector
- Operation will be resumed around the early 2024

$|V_{cb}|$ measurement

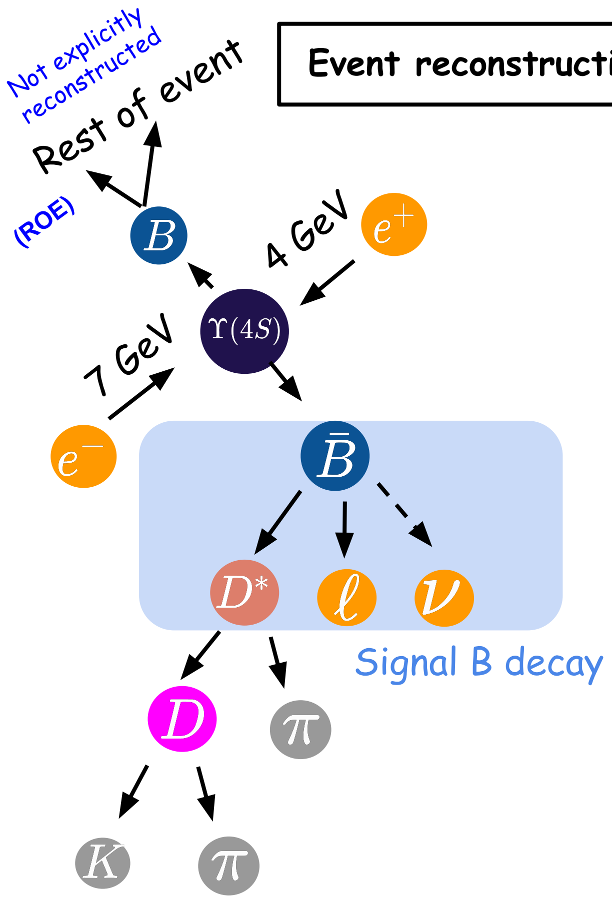
@ Belle II

Only analyze the channels with light leptons

Untagged $\bar{B}^0 \rightarrow D^{*+}\ell^- \bar{\nu}$ decay

New

Event reconstruction



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

Measurement of fully differential rate is quite challenging

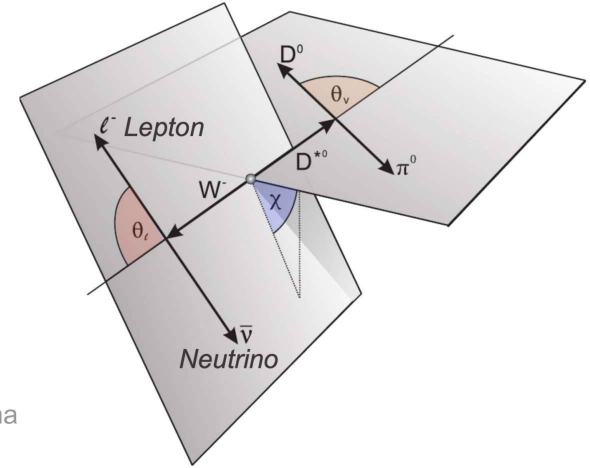
Measure partial decay rates in bins of kinematic variables (four 1D spectra)

$$\Delta\Gamma_i = \int_{w_{\min}}^{w_{\max}} \frac{d\Gamma}{dw}dw\,, \quad \int_{\cos\theta_{\ell\,\min}}^{\cos\theta_{\ell\,\max}} \frac{d\Gamma}{d\cos\theta_\ell}d\cos\theta_\ell\,, \quad \int_{\cos\theta_{V\,\min}}^{\cos\theta_{V\,\max}} \frac{d\Gamma}{d\cos\theta_V}d\cos\theta_V\,, \quad \int_{\chi_{\min}}^{\chi_{\max}} \frac{d\Gamma}{d\chi}d\chi$$

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

Kinematic variables

$$w = \frac{p_B \cdot p_{D^*}}{m_B m_{D^*}} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$



Plotted by K. Kojima

Untagged $\bar{B}^0 \rightarrow D^{*+}\ell^- \bar{\nu}$ decay

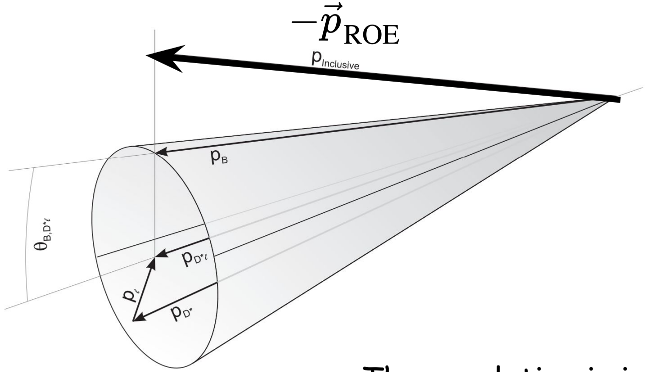
Reconstruction of kinematic variables

- What do we know about B?

$$E_B^{CM} = E_{Beam}^{CM}/2 \qquad |\vec{p}_B^{\,CM}| = \sqrt{(E_{Beam}^{CM}/2)^2 - m_{B^0}^2}$$ (magnitude of B momentum)

θ_{BY}: the angle between B and D*ℓ system (denoted by Y) determined by $\cos\theta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - m_Y^2}{2p_B^* p_Y^*}$ where all energy and momenta are in the CM frame.

- How we guess its **direction**?



➢ Pick up the direction on the cone closest to $-\vec{p}_{\mathrm{ROE}}$

➢ Consider also the B^0 angular distribution with respect to the beam axis

Novel approach

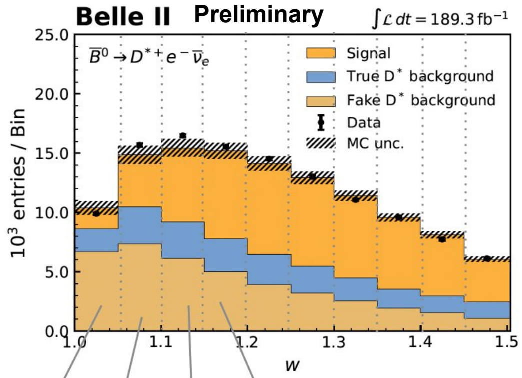
Weighted average of kinematic variables determined using 10 equal-spacing directions on the cone, where the weight is

$$\alpha = (1 - \hat{p}_{\mathrm{ROE}} \cdot \hat{p}_B)\sin^2\theta_B$$

7% - 12%

The resolution is improved compared to the previous BaBar & Belle measurements.

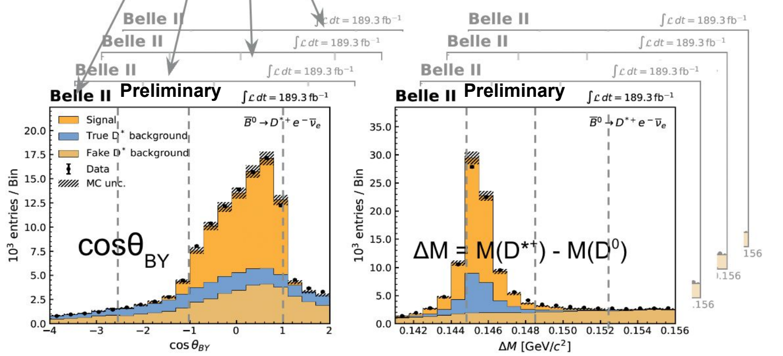
Untagged $\overline{B}^0 \to D^{*+}\ell^-\nu$ decay



Background subtraction

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

(Y:D*ℓ system)

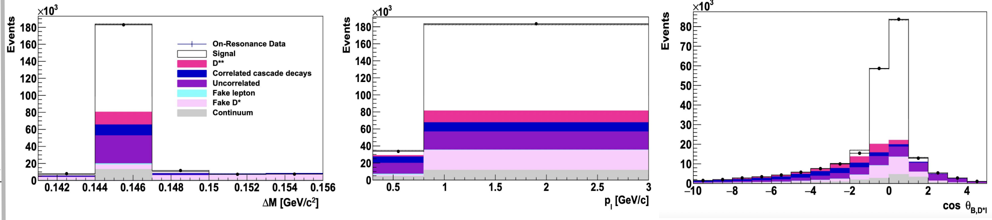


Signal yield in each bin is determined by a 2D binned template fit of $\cos\theta_{BY}$ and ΔM distributions.

(the fits are performed bin-by-bin independently)

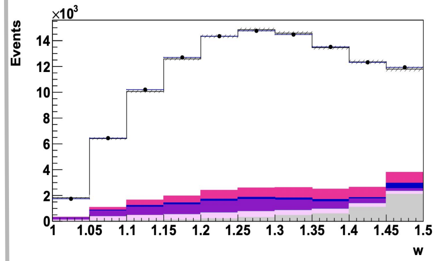
Phys.Rev.D 100 (2019) 5, 052007
Phys.Rev.D 103 (2021) 7, 079901 (erratum)

Different from Belle measurement



Determine total background yields

Constrain background components



Direct fit to four 1D experimental spectra simultaneously.

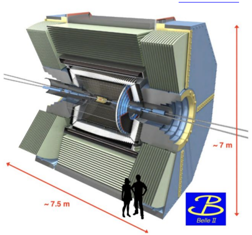
(I.e. differential rates on the projections of w, $\cos\theta_\ell$, $\cos\theta_V$, and χ, respectively)

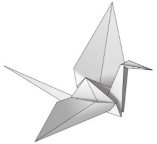
(each bin yield is not determined independently)

Untagged $\bar{B}^0 \to D^{*+}\ell^-\nu$ decay

- Fitted yields are corrected with SVD unfolding method

  (Singular Value Decomposition)





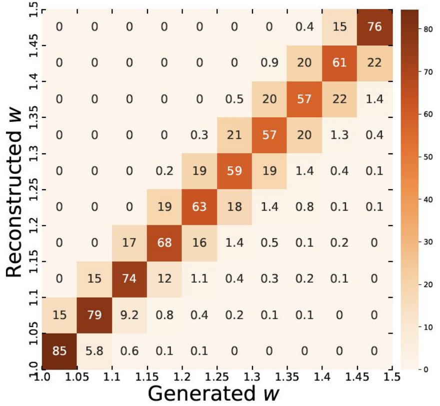
***X*: true distribution** ***M*: detector response** ***Y*: measured distribution**

Plotted by L. Cao

Unfolding

Migration matrix

$$\mathcal{M}_{ij} = \mathcal{P}(\text{measured value in bin } i |\ \text{true value in bin } j)$$



- Partial decay rates are determined from the unfolded yields

reco. eff & acc. input of PDG2022

$$\Delta\Gamma_i = \frac{y_i^{\text{unfolded}}}{\epsilon_i N_{B^0}\mathcal{B}(D^{*+}\to D^0\pi^+)\mathcal{B}(D^0\to K^-\pi^+)\tau_{B^0}}$$

Untagged $\overline{B}^0 \to D^{*+}\ell^-\nu$ decay

- $|V_{cb}|$ value is determined from measured partial rates $\Delta\Gamma$

Minimizing χ^2

Written in terms of |Vcb| and FF parameters

Experimental observation — Experimental covariance — Theoretical prediction

$$\chi^2 = \sum_{i,j}^{34} \left(\frac{\Delta\Gamma_i^{obs}}{\Gamma^{obs}} - \frac{\Delta\Gamma_i^{pre}}{\Gamma^{pre}} \right) C_{ij}^{-1} \left(\frac{\Delta\Gamma_j^{obs}}{\Gamma^{obs}} - \frac{\Delta\Gamma_j^{pre}}{\Gamma^{pre}} \right)$$

$$+ \frac{(\Gamma^{obs} - \Gamma^{pre})^2}{\sigma_\Gamma^2}$$

Phys.Rev.D 56 (1997) 6895-6911

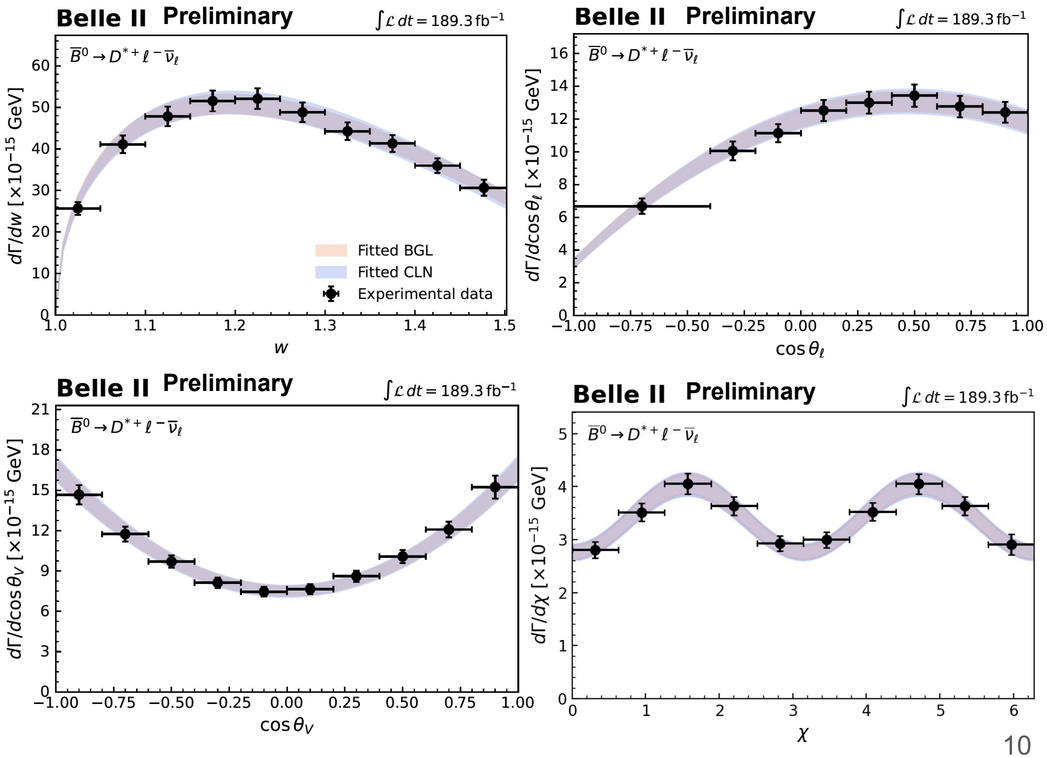
Boyd-Grinstein-Lebed parameterization

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

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

Caprini-Lellouch-Neubert parameterization

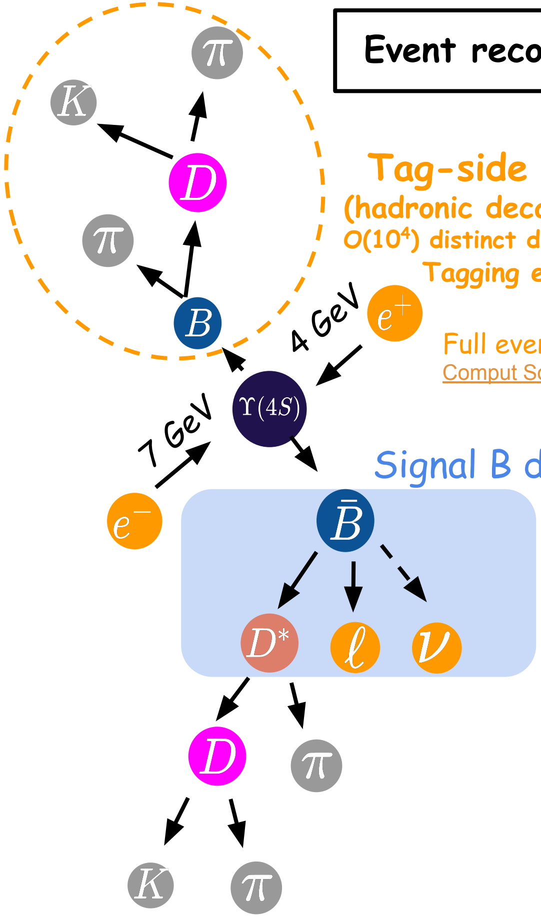
Nucl.Phys.B 530 (1998) 153-181



Tagged $\bar{B}^0 \to D^{*+}\ell^- \nu$ decay

arXiv: 2301.04716

Event reconstruction



Tag-side B

(hadronic decays)

$O(10^4)$ distinct decay chains

Tagging efficiency <1%

(But significantly higher than previous conventional methods)

Full event interpretation

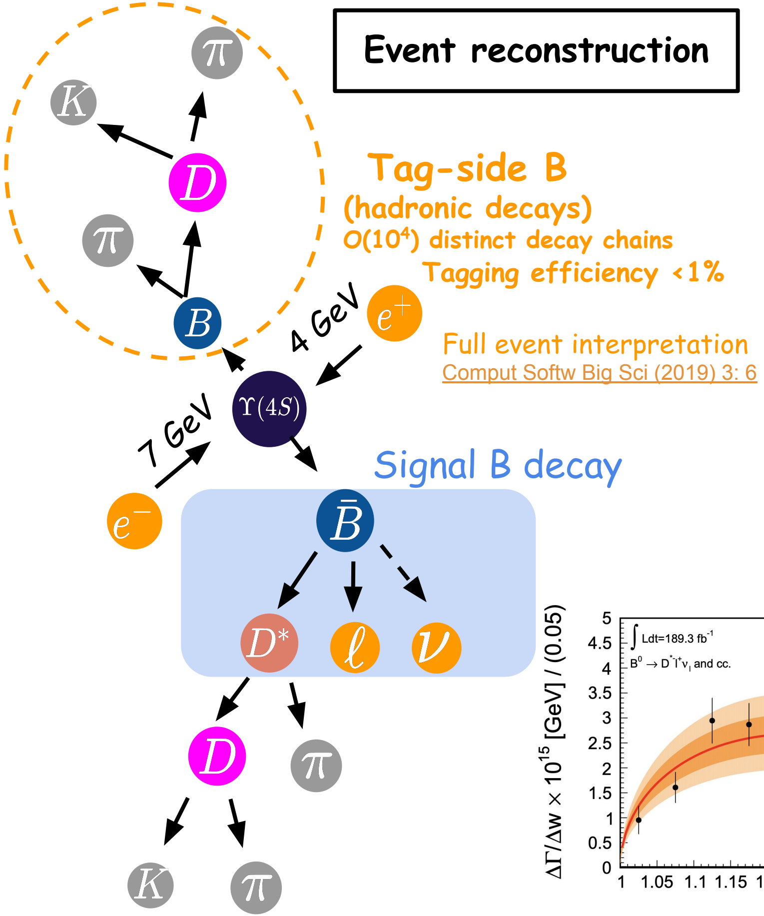
Comput Softw Big Sci (2019) 3: 6

Signal B decay

Kinematics can be inferred from the tag-side

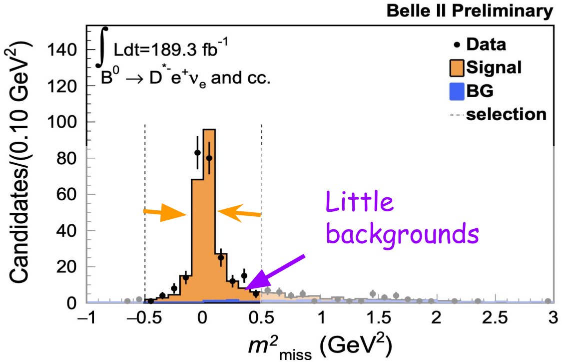
Tagged $\bar{B}^0 \to D^{*+}\ell^- \nu$ decay

arXiv: 2301.04716



- Background events are subtracted using simulated samples directly

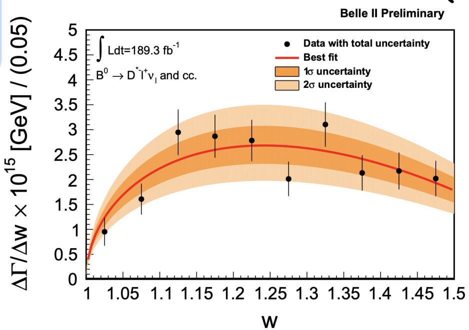
$$m^2_{\text{miss}} = (P_{\text{beam}} - P_{B_{\text{tag}}} - P_{D^*} - P_\ell)^2$$



High purity, but low efficiency

$$\frac{d\Gamma}{dw} \propto |V_{cb}|^2 \times |FF(w)|^2$$

- |Vcb| value is determined in Caprini-Lellouch-Neubert (CLN) parameterization from measured ΔΓ/Δw



$$\mathcal{B} = (5.27 \pm 0.22_{\text{stat}} \pm 0.38_{\text{syst}})\%$$

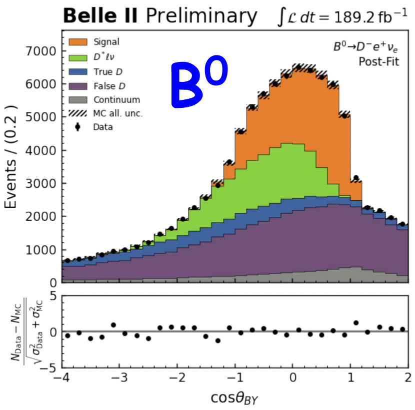
$$|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$$

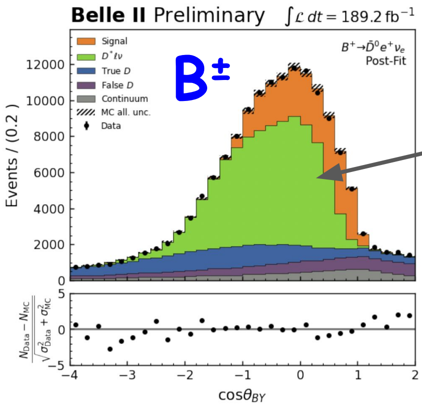
$\eta_{EW} F(1)|V_{cb}| = (34.6 \pm 1.8_{\text{stat}} \pm 1.7_{\text{syst}}) \times 10^{-3}$

Untagged B → Dℓν decay

arXiv: 2210.13143

- $\frac{d\Gamma}{dw} \propto |V_{cb}|^2 \times |FF(w)|^2$
- Signal yields are extracted in 10 bins of w by fitting $\cos\theta_{BY}$ (Y:Dℓ system) distribution



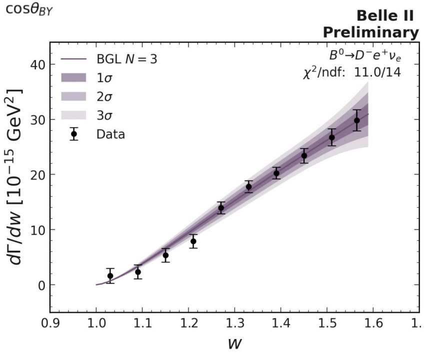


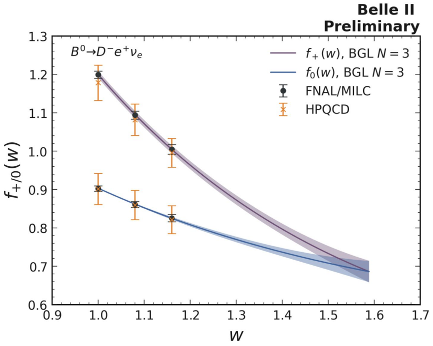
Large background contamination

B → D*ℓν decay is the dominant background source

- The $\eta_{EW}|V_{cb}|$ is determined from the measured *w* spectrum and LQCD predictions (FNAL/MILC + HPQCD)

$$|V_{cb}| = (38.3 \pm 1.1) \times 10^{-3}$$





q^2 moments of inclusive $B \to X_c \ell \nu$ Decays

arXiv: 2205.06372

- q^2 measurement: $q^2 = (p^*_{B_{\rm sig}} - p^*_X)^2$ with $p^*_{B_{\rm sig}} = (\sqrt{s}/2, -\mathbf{p}^*_{B_{\rm tag}})$

B_{tag} is reconstructed using fully hadronic decays.

- q^2 moment of order n:

event-wise signal probability

Linear correction reconstructed $q^2 \to$ generated q^2

$$\langle q^{2n} \rangle = \frac{\sum_i^{\rm event} w_i(q^2)\, q^{2n}_{{\rm calib},i}}{\sum_i^{\rm event} w_i(q^2)} \times \mathcal{C}_{\rm calib} \times \mathcal{C}_{\rm gen}$$

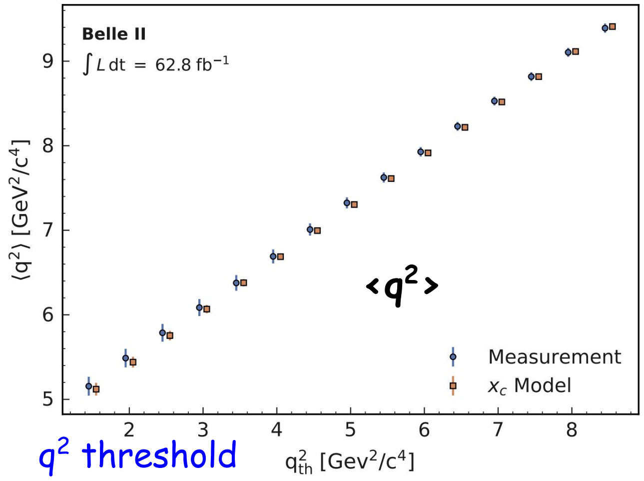
Efficiency and acceptance correction

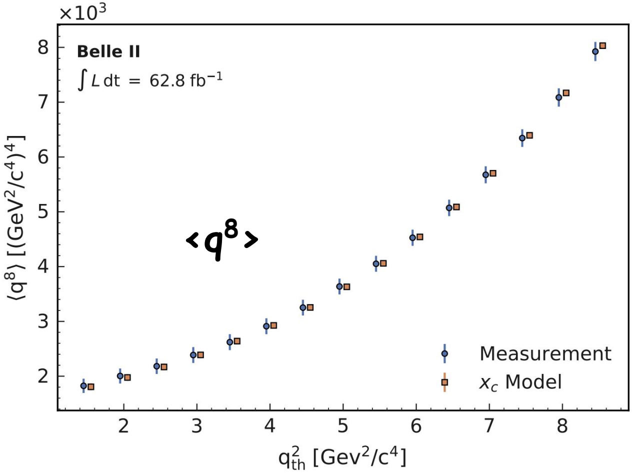
residual bias correction

q^2 moments of inclusive $B \to X_c \ell \nu$ Decays

arXiv: 2205.06372

- First to fourth moments (n=1~4) measured at a progression of cuts on q^2





A follow-up determination of $|V_{cb}|$ using Belle & Belle II $\langle q^{2n} \rangle$ measurements obtains

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

Not determined by the Belle (II) collaboration

JHEP 10 (2022) 068

$|V_{ub}|$ measurement

@ Belle II

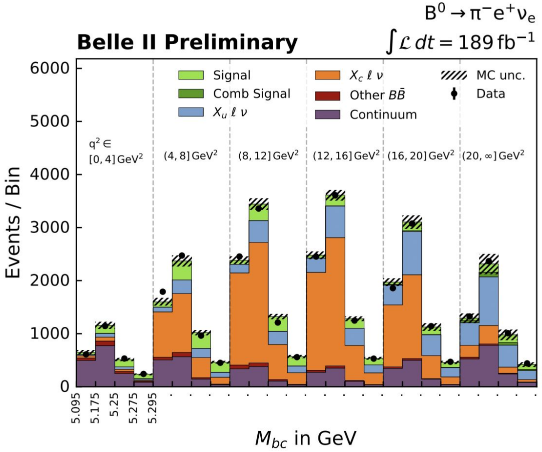
Only one exclusive decay channel

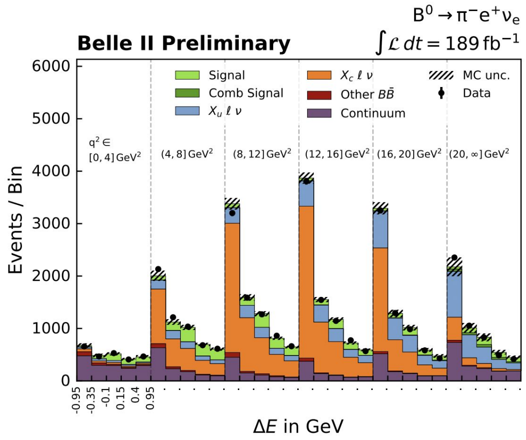
The inclusive is on-going

Untagged $B^0 \to \pi^+ \ell^- \nu$ decay

arXiv: 2210.04224

- $\frac{d\Gamma}{dq^2} \propto |V_{ub}|^2 \times |F(q^2)|^2$
- Signal yields are extracted in 6 bins of q^2 by 2D fits of M_{bc} and ΔE distributions





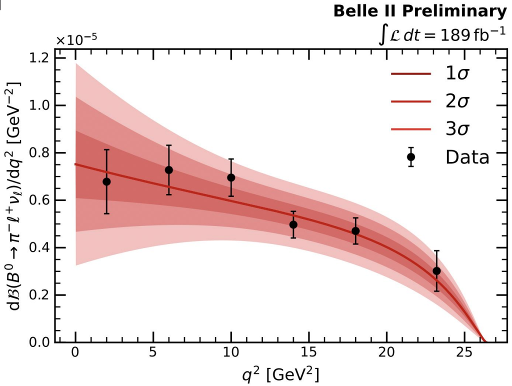
$$M_{bc} = \sqrt{E_{\mathrm{beam}}^{*2} - |\vec{p}_B^{\,*}|^2} = \sqrt{\left(\frac{\sqrt{s}}{2}\right)^2 - |\vec{p}_B^{\,*}|^2}$$

$$\Delta E = E_B^* - E_{\mathrm{beam}}^* = E_B^* - \frac{\sqrt{s}}{2}$$

- The $|V_{ub}|$ is determined from the measured $\Delta\mathcal{B}$ spectrum and LQCD predictions (FNAL/MILC)

$$\mathcal{B} = (1.426 \pm 0.056_{stat} \pm 0.125_{syst}) \times 10^{-4}$$

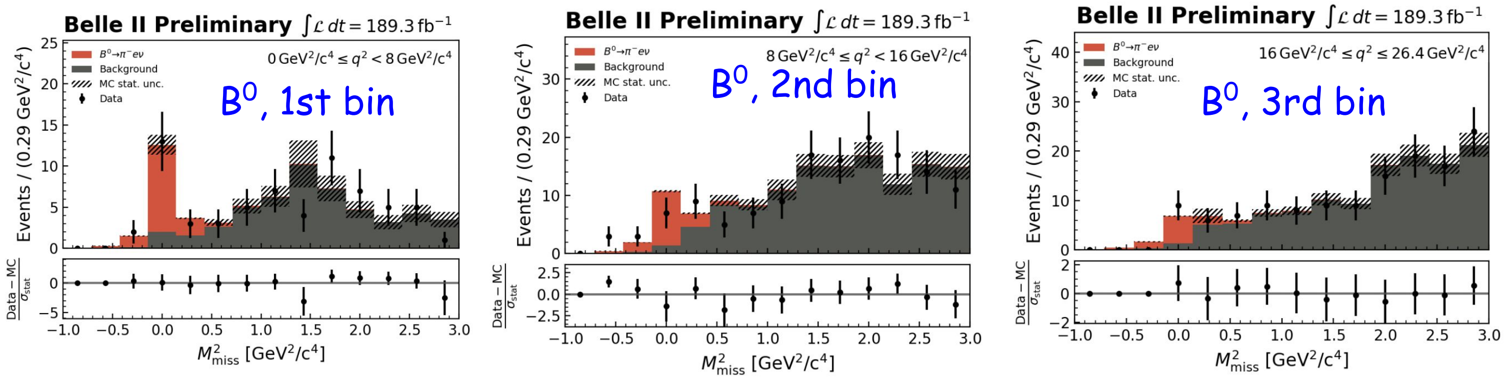
$$|V_{ub}| = (3.55 \pm 0.12_{stat} \pm 0.13_{syst} \pm 0.17_{theo}) \times 10^{-3}$$



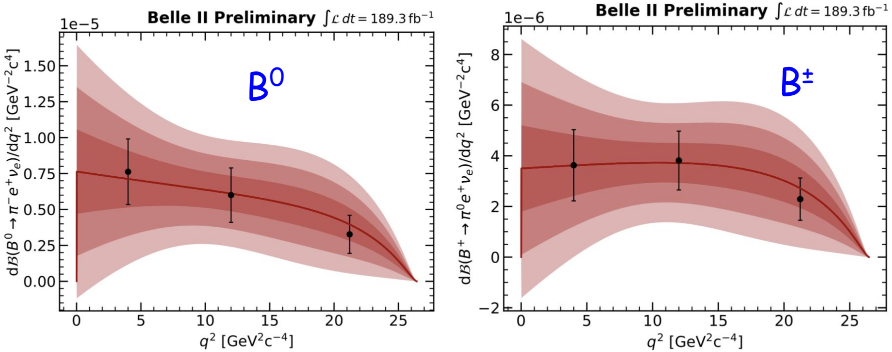
Tagged B → πeν decay

arXiv: 2206.08102

- Signal yields are extracted in 3 bins of q^2 by fitting of $M_{miss}{}^2$ distributions



- The $|V_{ub}|$ is determined from the measured $\Delta\mathcal{B}$ spectrum.



$\mathcal{B}(B^0 \to \pi^- e^+ \nu) = (1.43 \pm 0.27_{stat} \pm 0.07_{syst}) \times 10^{-4}$

$\mathcal{B}(B^+ \to \pi^0 e^+ \nu) = (8.33 \pm 1.67_{stat} \pm 0.55_{syst}) \times 10^{-5}$

$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$

LFU tests with untagged $B^0 \rightarrow D^{*+} \ell^- \nu$

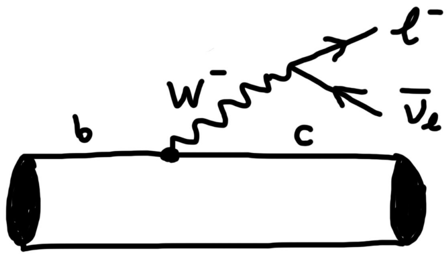
@ Belle II

Other LFU tests will be discussed in

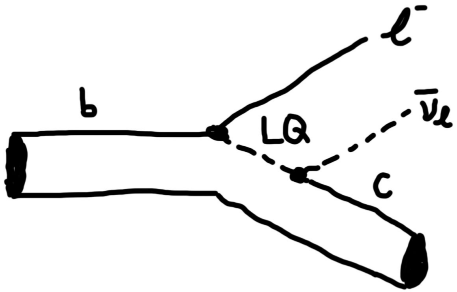
Stefano Moneta's talk this afternoon

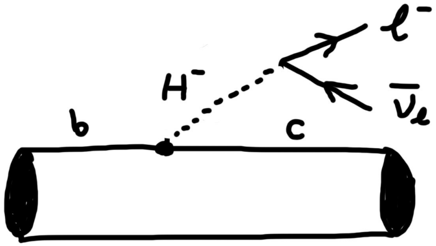
Lepton flavor universality test

To be



or to be





...

that is the question.

— Chaoyi Lyu

Helmet

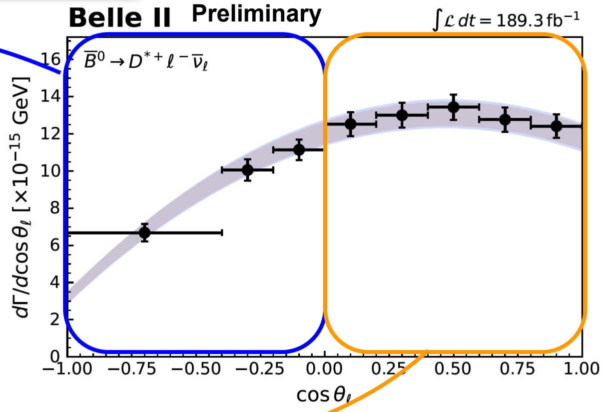
LFU tests with untagged $B^0 \to D^{*+}\ell^-\nu$ decay

- Ratio of branching fractions between e and μ

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

- 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:

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

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

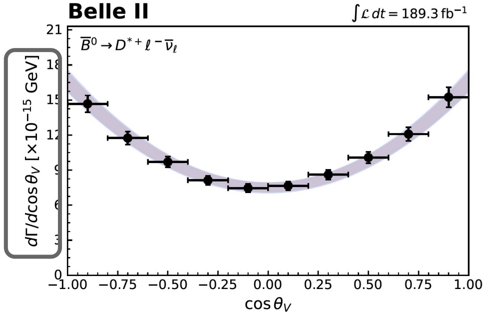
SM: $(-5.33 \pm 0.24)\times10^{-3}$ Eur.Phys.J.C 81 (2021) 11, 984

- 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 F_L and $\cos\theta_V$



Obtained results:

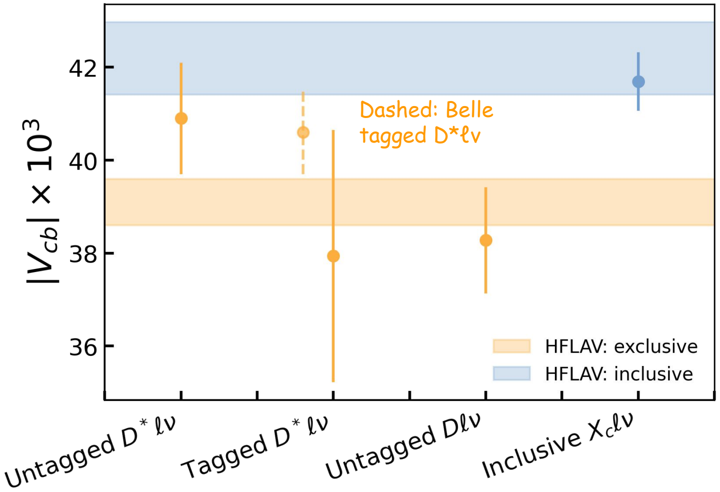
$$F_L^{e} = 0.521 \pm 0.005 \pm 0.007\,,$$
$$F_L^{\mu} = 0.534 \pm 0.005 \pm 0.006\,,$$
$$\Delta F_L = 0.013 \pm 0.007 \pm 0.007\,,$$

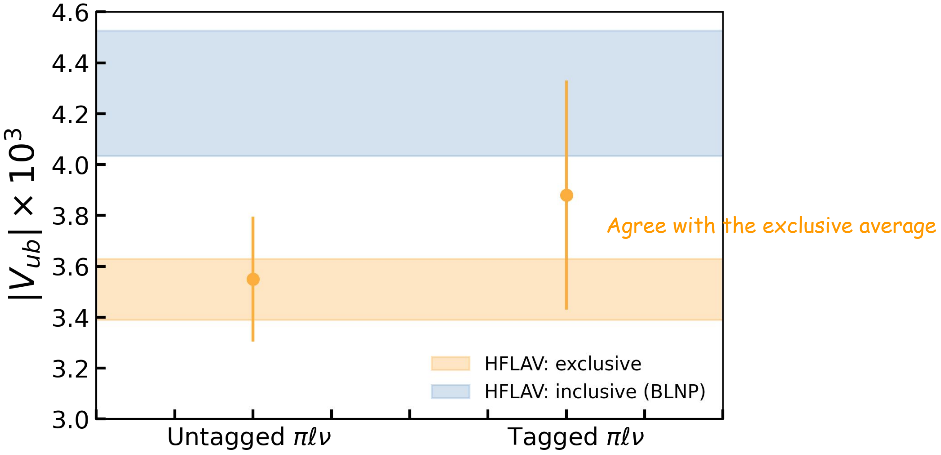
$\Delta F_L = F_L^{\mu} - F_L^{e}$

SM: $(-5.43 \pm 0.36)\times10^{-4}$ Eur.Phys.J.C 81 (2021) 11, 984

Summary

- Tension between exclusive and inclusive determinations relieves with untagged D*ℓν measurement





- No significant lepton flavor universality violation has been observed

More slides

Systematic table for untagged $B \to D^*\ell\nu$

Relative uncertainties (in %)

	$\tilde{a}_0$	$\tilde{b}_0$	$\tilde{b}_1$	$\tilde{c}_1$
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

Impact of LQCD at w > 1

LQCD constraints on $h_{A1}(w)$ at w = [1.03, 1.10, 1.17]

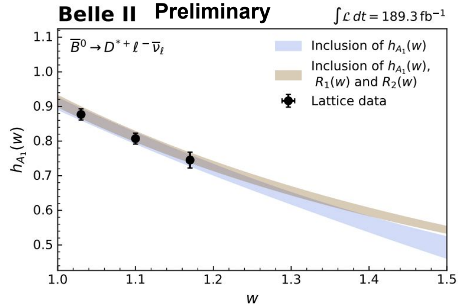
LQCD input: Eur.Phys.J.C 82 (2022) 12, 1141

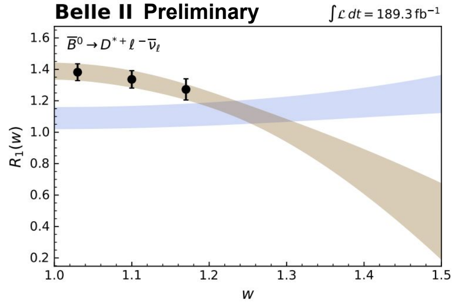
	Values	Correlations					
$\lvert V_{cb}\rvert \times 10^3$	40.4 ± 1.2	1	−0.31	−0.57	−0.1	0.02	−0.26
$a_0 \times 10^3$	22.0 ± 1.4	−0.31	1	0.27	0.1	−0.18	0.31
$b_0 \times 10^3$	13.2 ± 0.2	−0.57	0.27	1	−0.18	0.13	−0.12
$b_1 \times 10^3$	9.0 ± 14.5	−0.1	0.1	−0.18	1	−0.88	0.52
b_2	-0.5 ± 0.4	0.02	−0.18	0.13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

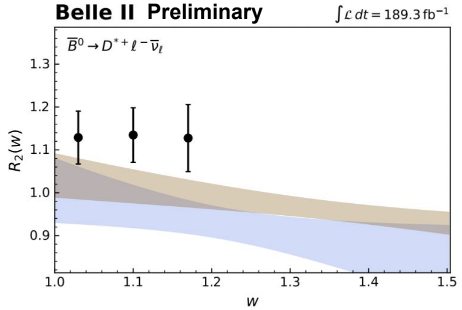
LQCD constraints on $h_{A1}(w)$, $R_1(w)$, and $R_2(w)$ at w = [1.03, 1.10, 1.17]

LQCD input: Eur.Phys.J.C 82 (2022) 12, 1141

	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





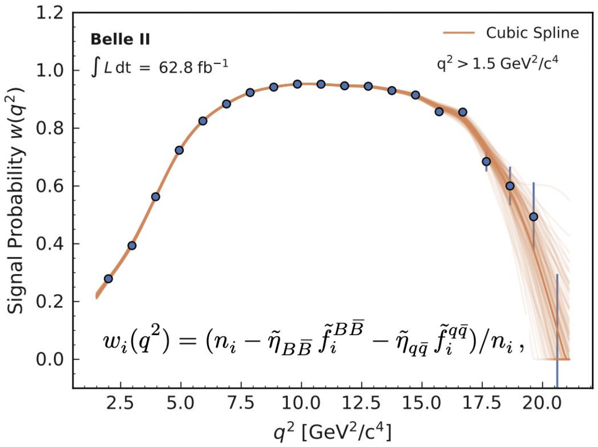


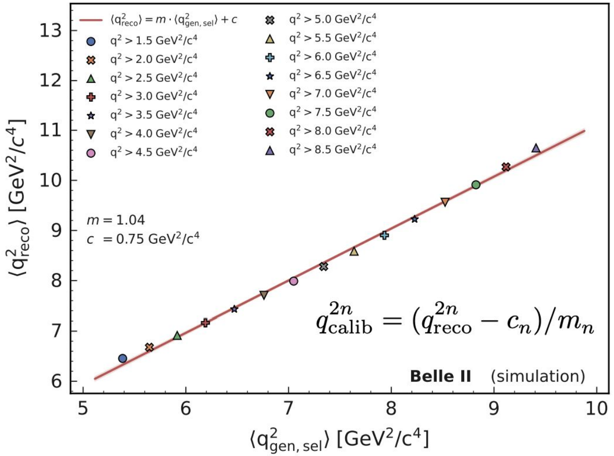
Systematic table for untagged B → Dℓv

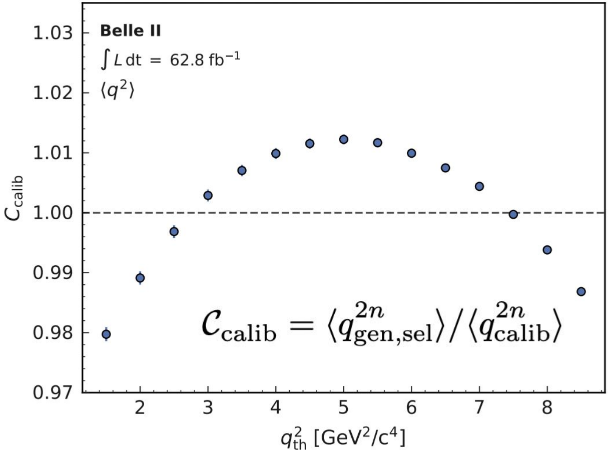
	$B^+ \to \bar{D}^0 e^+ \nu_e$	$B^+ \to \bar{D}^0 \mu^+ \nu_\mu$	$B^0 \to D^- e^+ \nu_e$	$B^0 \to D^- \mu^+ \nu_\mu$
$\mathcal{B}(B \to D\ell\nu)[\%]$	$2.21 \pm 0.03 \pm 0.08$	$2.22 \pm 0.03 \pm 0.10$	$1.99 \pm 0.04 \pm 0.08$	$2.03 \pm 0.04 \pm 0.09$
	Contributions to the systematic uncertainty [%]			
N_{BB} and f_{+-}/f_{00}	1.9	1.9	1.9	1.9
Tracking efficiency	0.9	0.9	1.2	1.2
$\mathcal{B}(D \to K\pi(\pi))$	0.8	0.8	1.7	1.7
LeptonID	1.2	3.1	0.9	1.9
HadronID	0.6	0.6	0.1	0.1
$B \to D\ell\nu$ FF	0.1	0.1	0.1	0.1
$B \to D^*\ell\nu$ FF	0.1	0.2	0.0	0.0
$\mathcal{B}(B \to X_c\ell\nu)$	1.9	1.9	0.4	0.3
Continuum normalization	0.2	0.2	0.1	0.1
Fake D PDFs	1.4	1.5	3.0	2.8
Total	3.5	4.6	4.2	4.4

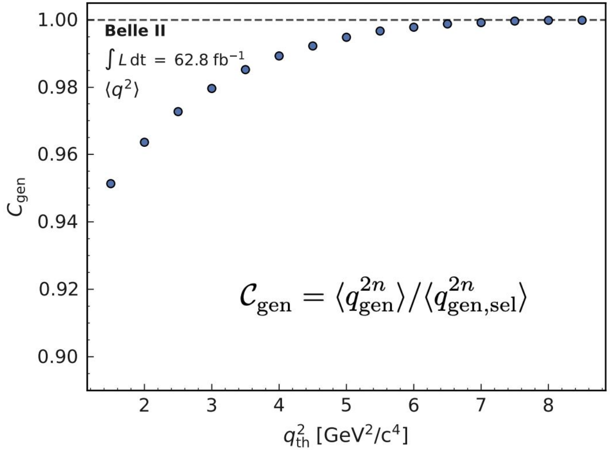
TABLE II. Branching ratio results for the decays $B^+ \to \bar{D}^0 e^+ \nu_e$, $B^+ \to \bar{D}^0 \mu^+ \nu_\mu$, $B^0 \to D^- e^+ \nu_e$, and $B^0 \to D^- \mu^+ \nu_\mu$. The first uncertainty is statistical, and the second is systematic. The lower half of the table shows the various contributions to the systematic uncertainty, which are explained in more detail in Sect. 4.3

q^2 moments of inclusive $B \to X_c \ell \nu$ Decays







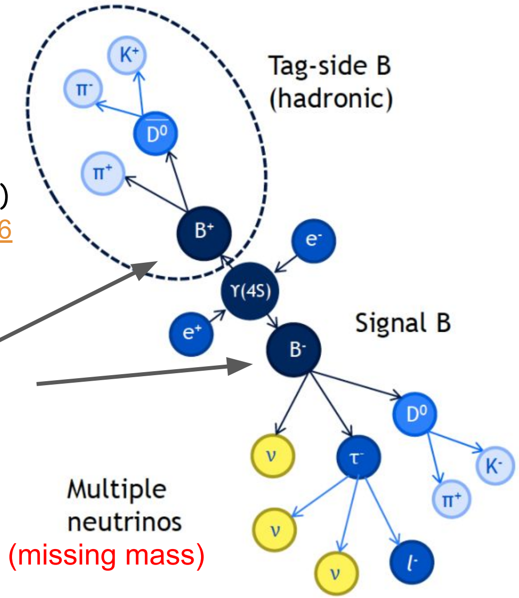


Tagged VS untagged

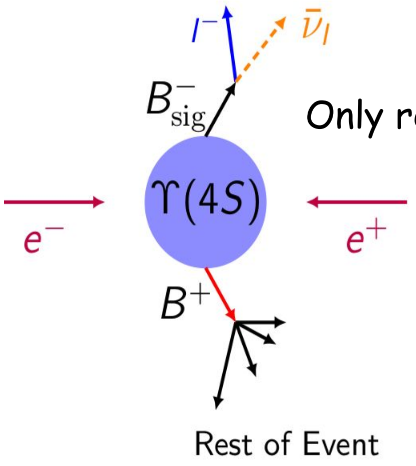
Tagged VS Untagged

Full Event Interpretation (FEI)
Comput Softw Big Sci (2019) 3: 6

Reconstruct both signal and tag-side B.



Only reconstruct signal B.



Low ←	Efficiency	→ High
High ←	Purity	→ Low

Outline

Two anomalies

Results from Belle II

Tension between inclusive and exclusive measurements → $|V_{cb}|$ measurements at Belle II
- $B^0 \to D^{*+}\ell^- \nu$ decay
- $B \to D\ell\nu$ decay
- q^2 moments of $B \to X_c\ell\nu$ decay

Tension between inclusive and exclusive measurements → $|V_{ub}|$ measurements at Belle II
- $B \to \pi\ell\nu$ decay

Possible Lepton Flavor Universality (LFU) violation → Some tests with $B^0 \to D^{*+}\ell^- \nu$ decay