Workshop summary 'Challenges in semileptonic B decays'

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Challenges in Semileptonic B decays

- Mainz 20-24 Apr 2015
  - P. Gambino, A. Kronfeld, M. Rotondo, C. Schwanda, S. Turczyk
  - 33 Participants
- Mainz 9-13 Apr 2018
  - P. Gambino, A. Kronfeld, M. Rotondo, C. Schwanda
  - 35 Participants
  - Challenges in Semileptonic B Decays arXiv:2006.07297
- Barolo 19-23 Apr 2022
  - P. Gambino, A. Kronfeld, M. Rotondo, C. Schwanda, M.Jung, T. Mannel
  - 39 Participants
- Vienna 23-27 Sept 2024
  - F.Bernlochner, A.Kronfeld, M.Rotondo, C.Schwanda, M.Jung, T.Mannel
  - 48 Participants

Challenges in Semileptonic B decays

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Gather together experimentalists, lattice and continuum theorists: develop a medium-term strategy of analyses and calculations aimed at solving the puzzling discrepancies between inclusive and exclusive determinations, for both |Vub| and |Vcb|

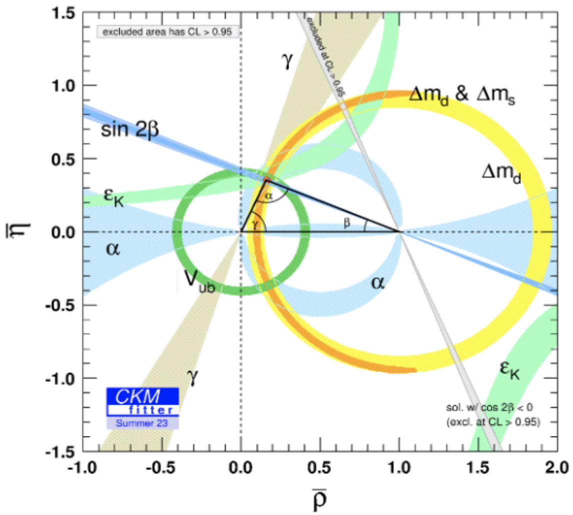
Understand the discrepancy between SM prediction and measurements of "semitauonic" decays

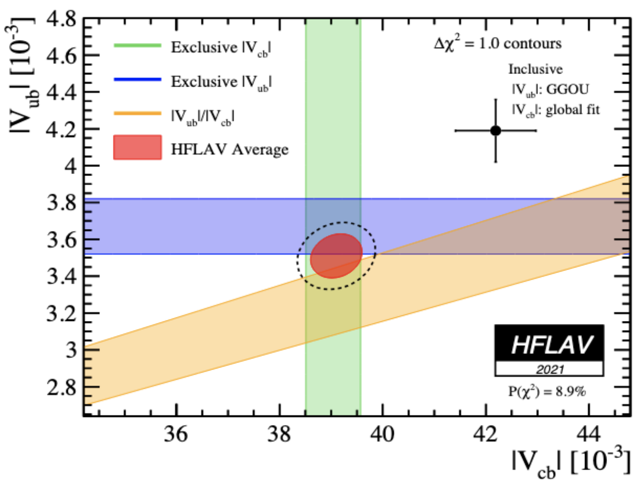
prospects of semileptonic decays at LHCb, on the implications of the first Belle-II data

Why is V_{cb} so important?

S. Schacht

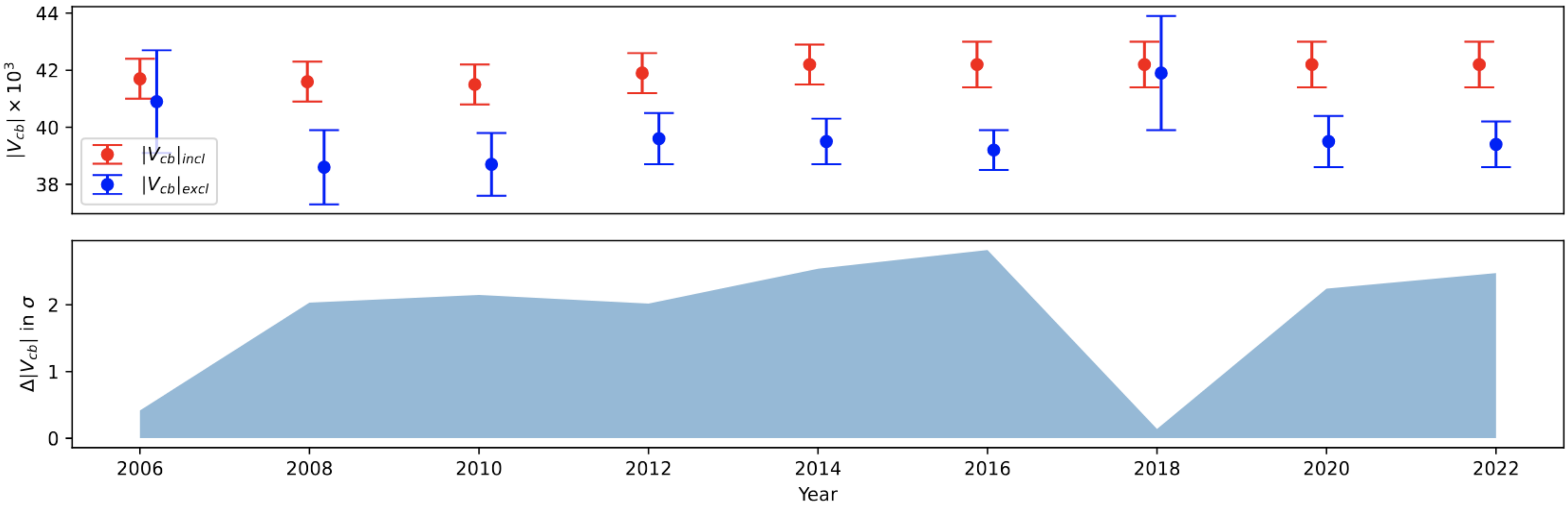
- Fundamental parameter of the Standard Model.
- Important role in Unitarity Triangle.
- Important for prediction of $\varepsilon_K \propto x\,|V_{cb}|^4 + \ldots$.
- Important for predictions of FCNCs.
- Ratio $|V_{ub}/V_{cb}|$ directly constrains one side of the Unitarity Triangle.





Exclusive b → c

A. Vaquero



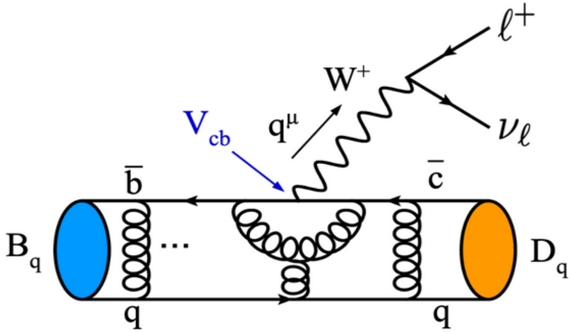
- Current values (PDG 2024):

$$|V_{cb}|_{\rm excl} \times 10^{-3} = 39.8(6)$$

→ Dominated by B → D*

$$|V_{cb}|_{\rm incl} \times 10^{-3} = 42.2(5)$$

Exclusive b → c: B → D*lν



$$w = \frac{M_B^2 + M_{D^*}^2 - q^2}{2M_B M_{D^*}} \qquad q_\mu = (p_B - p_{D^*})_\mu$$

$$\underbrace{\frac{d\Gamma}{dw}\left(B_{(s)} \to D_{(s)}^{(*)}\ell\bar{\nu}_\ell\right)}_{\text{Experiment}} = \underbrace{K_{B_{(s)}\to D_{(s)}^{(*)}}(w, m_\ell)}_{\text{Known factors}} \underbrace{|\mathcal{F}(w)|^2}_{\text{Theory}} \times |V_{cb}|^2$$

$$\langle D^*(\varepsilon, p')|\bar{c}\gamma^\mu b|\bar{B}(p)\rangle = ig\epsilon^{\mu\nu\alpha\beta}\varepsilon^*_\nu p_\alpha p'_\beta,$$
$$\langle D^*(\varepsilon, p')|\bar{c}\gamma^\mu\gamma^5 b|\bar{B}(p)\rangle = f\varepsilon^{*\mu} + (\varepsilon^* \cdot p)[a_+(p+p')^\mu + a_-(p-p')^\mu],$$

CLN used only for cross checks

BGL parameterization

$$g(z) = \frac{1}{P_g(z)\phi_g(z)}\sum_{n=0}^{N} a_n z^n, \qquad f(z) = \frac{1}{P_f(z)\phi_f(z)}\sum_{n=0}^{N} b_n z^n, \qquad \mathcal{F}_1(z) = \frac{1}{P_{\mathcal{F}_1}(z)\phi_{\mathcal{F}_1}(z)}\sum_{n=0}^{N} c_n z^n,$$

Combination of f and a_+

$$\sum_{j=0}^{\infty} a_j^2 \lesssim 1$$
$$\sum_{j=0}^{\infty} (b_j^2 + c_j^2) \lesssim 1$$
$$\sum_{j=0}^{\infty} d_j^2 \lesssim 1$$

Conformal variable z:

$$z = \frac{\sqrt{w+1} - \sqrt{2a}}{\sqrt{w+1} + \sqrt{2a}}$$

QCD encoded in coefficients:

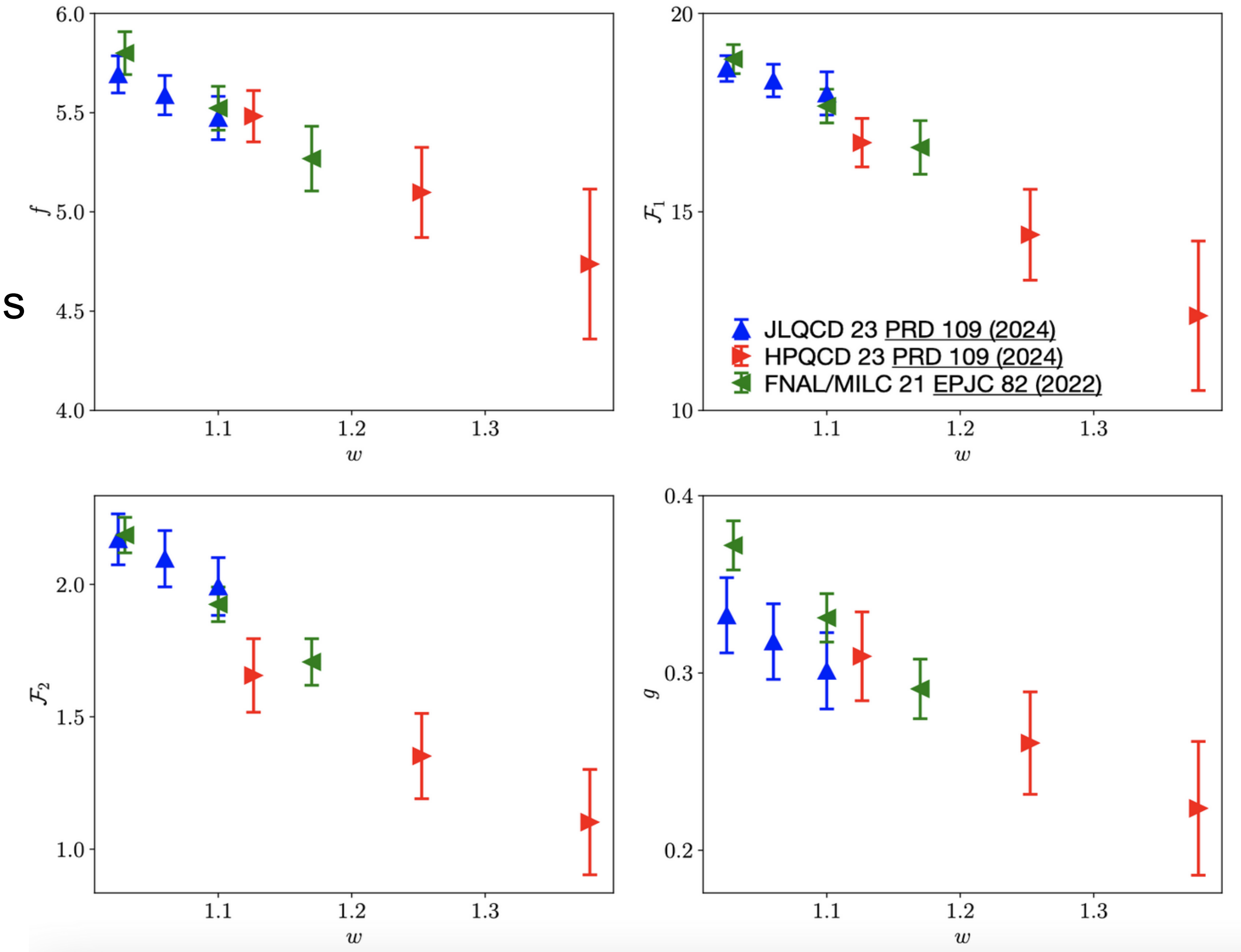
$$\{a_n, b_n, c_n\}$$

$c_0 =$ **constants** $\times\, b_0$

Exclusive b → c: LQCD B → D*lv

Lattice Data

- first time that lattice data covers kinematical range
- three different and independent collaborations



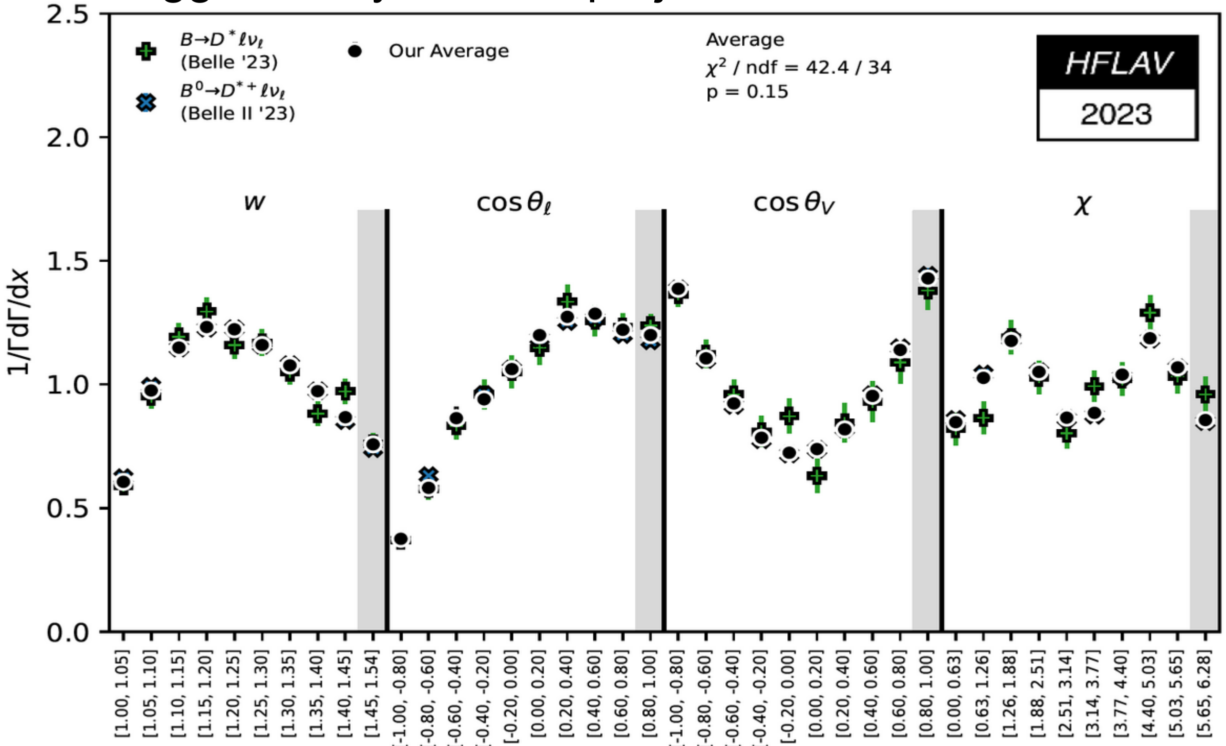
JLQCD 23 PRD 109 (2024)

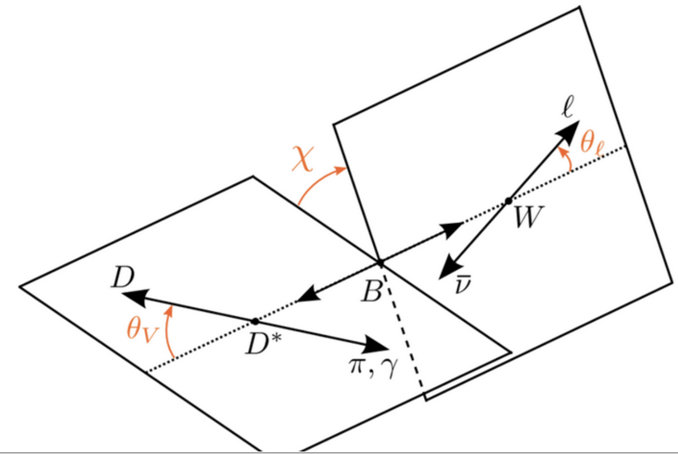
HPQCD 23 PRD 109 (2024)

FNAL/MILC EPJC 82 (2022)

Tagged analyses, 1-D projections

M. Primm





$$
\frac{\mathrm{d}\Gamma(B \to D^* \ell \nu_\ell)}{\mathrm{d}w\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_V\,\mathrm{d}\chi} = \frac{6 m_B m_{D^*}^2}{8(4\pi)^4}\sqrt{w^2-1}(1-2wr+r^2)G_F^2\eta_{EW}^2|V_{cb}|^2
$$

$$
\times\Big((1-\cos\theta_\ell)^2\sin^2\theta_V H_+^2 + (1+\cos\theta_\ell)^2\sin^2\theta_V H_-^2
$$

$$
+ 4\sin^2\theta_\ell\cos^2\theta_V H_0^2 - 2\sin^2\theta_\ell\sin^2\theta_V\cos 2\chi H_+ H_-
$$

$$
- 4\sin\theta_\ell(1-\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi H_+ H_0
$$

$$
+ 4\sin\theta_\ell(1+\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi H_- H_0\Big),
$$

B Tagged analysis:

- Belle Phys.Rev.D 108 (2023) 1, 012002
- Belle II Phys.Rev.D 108 (2023) 9, 9

B untagged analyses:

- Belle Phys. Rev. D 100 (2019) 052007
- Belle II Phys.Rev.D 108 (2023) 092013

Informations available in HepData

Exclusive b → c: B → D(*)lv

How to best analyse this new quality of data as part of a precision test of the SM?

- Where should we truncate the series?
- How shall we include the unitarity constraints?
- Which statistical method is “best” to fit data?

Truncation order dilemma:
The choice of where to truncate the BGL expansion can impact the extracted value:
- Truncate too soon: Model dependence in extracted result for |Vcb|?
- Truncate too late: Unnecessarily increase variance on |Vcb|?

Exclusive b → c: B → D(*)lν

S. Schacht

"Standard" (frequentist)

- χ^2 fit with hard unitarity constraints as side condition.
- Increase BGL order until χ^2 stable. [Gambino Jung Schacht 1905.08209]

Feldman Cousins (frequentist)

- Well-defined CL including hard unitarity constraints, using toy Monte Carlo data. [Gambino Jung Schacht 24xx.soon]

Nested Hypothesis Test to determine truncation order. (frequentist)

- Go to order $N+1$ if $\Delta\chi^2 = \chi^2_N - \chi^2_{N+1} \geq 1$. Check unitarity a posteriori. [Bernlochner Ligeti Robinson 1902.09553]
- Alternative: Akaike Information Criterion. [Persson Bernlochner Ligeti Prim Robinson 2024]

Bayesian inference

- BGL unitarity constraints as prior [Flynn Jüttner Tsang 2303.11285, Bordone Jüttner 2406.10074]
- Dispersive Matrix approach [Di Carlo, Martinelli, Naviglio, Sanfilippo, Simula, Vittorio 2105.02497]

Next slide
F. Bernlochner

Next next slide
A. Juttner

Exclusive b → c: B → D(*)lν

Different approaches on the market

F. Bernlochner

	Evaluation Metric	Selection Rule	Search Algorithm
Bernlocher et al. (2019)	χ^2	Choose nested model if $\Delta\chi^2 > 1$	Forward stepwise selection
Gambino, Jung, Schacht	χ^2 + unitarity penalty	Higher complexity until stable	Forward selection
Current paper	AIC	Lowest metric (w/ and w/o UT)	Exhaustive search

Akaike Information Criterion
AIC = 2*k – 2 log(L)

Toys studies to show effectiveness of AIC in choosing BGL order: unbiased |Vcb| with correct coverage properties

Beyond single Model selection Global AIC

An approach that weighs multiple models based on their AIC scores, rather than selecting a single best model:

$$w_i = \exp(-\frac{1}{2}\Delta_i)/\sum_j \exp(-\frac{1}{2}\Delta_j) \qquad \Delta_i = \mathrm{AIC}_i - \mathrm{AIC}_{\min} \qquad |V_{cb}| = \sum_i w_i |V_{cb}|_i$$

Exclusive b → c: B → D(*)lν

A. Juttner

Bayesian form-factor fit

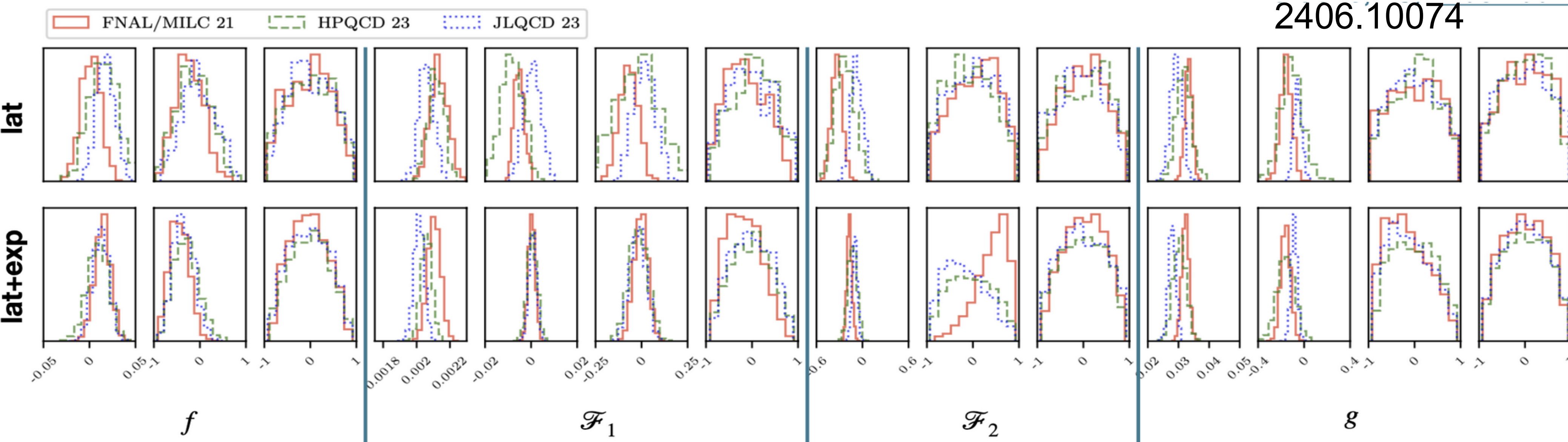
Flynn, AJ, Tsang, JHEP 12 (2023) 175

Compute BGL parameters as expectation values $\langle g(\mathbf{a})\rangle = \mathcal{N}\int d\mathbf{a}\, g(\mathbf{a})\,\pi(\mathbf{a}\,|\,\mathbf{f}, C_{\mathbf{f}})\,\pi_{\mathbf{a}}$

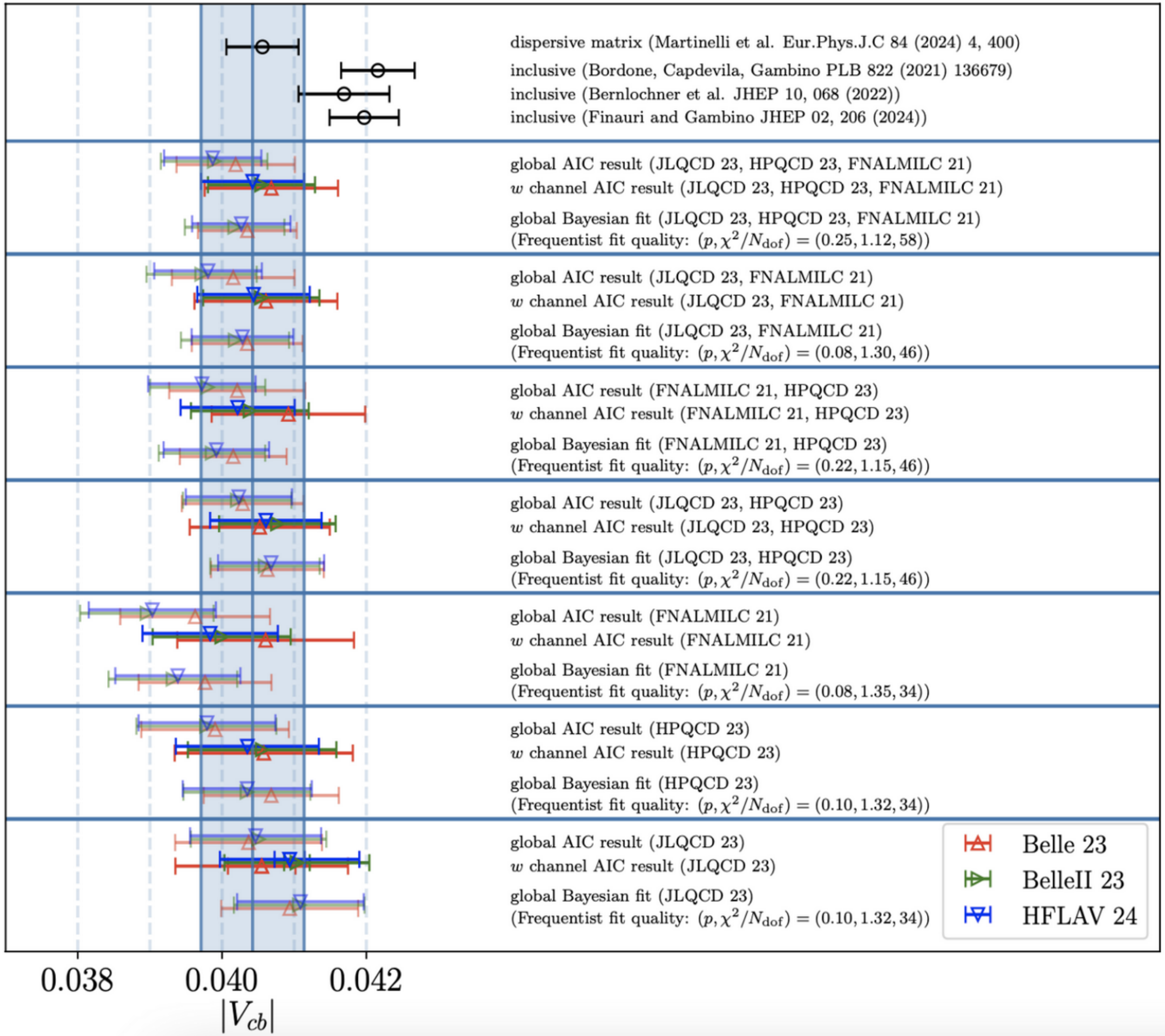
where *probability for parameters given model and data (assume input Gaussian)*

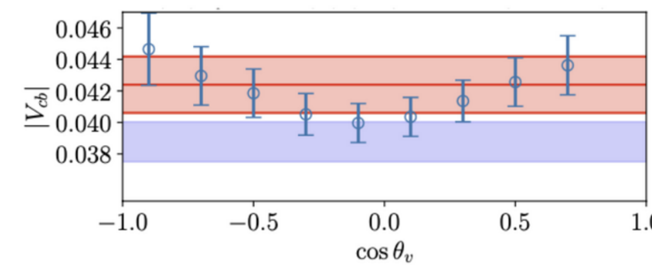
$$\pi(\mathbf{a}\,|\,\mathbf{f}, C_{\mathbf{f}}) \propto \exp\left(-\frac{1}{2}\chi^2(\mathbf{a},\mathbf{f})\right) \quad \text{where} \quad \chi^2(\mathbf{a},\mathbf{f}) = [\mathbf{f} - Z\mathbf{a}]^T C_{\mathbf{f}}^{-1}[\mathbf{f} - Z\mathbf{a}]$$

Bordone, Juttner, 2406.10074



Exclusive b → c: B → D(*)lν





blue:
- Frequentist fit $(p, \chi^2/N_{\rm dof}, N_{\rm dof}) = (0.00, 2.82, 8)$
- d'Agostini Bias? [d'Agostini, Nucl.Instrum.Meth.A 346 (1994)]

red:
- Akaike-Information-Criterion analysis [H. Akaike IEEE TAC (19,6,1974)] average over all possible fits with at least two data points and then weighted average:

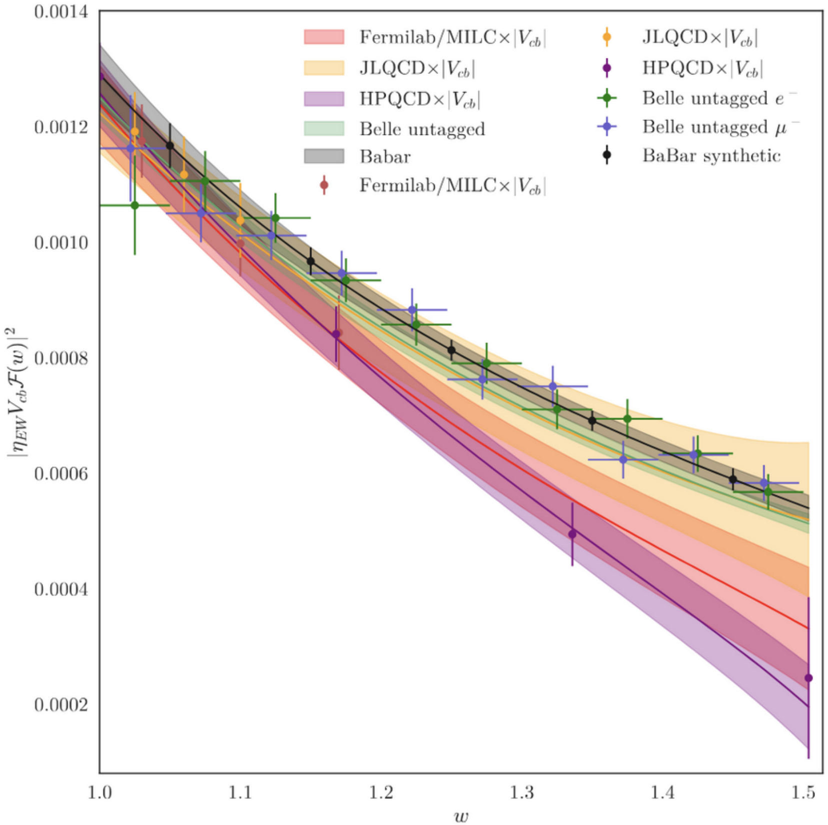
$$w_{\{\alpha,i\}} = \mathcal{N}^{-1} \exp\left(-\frac{1}{2}(\chi^2_{\{\alpha,i\}} - 2N_{\mathrm{dof},\{\alpha,i\}})\right) \qquad \mathcal{N} = \sum_{\mathrm{set}\in\{\alpha,i\}} w_{\mathrm{set}}$$

$$|V_{cb}| = \langle |V_{cb}| \rangle \equiv \sum_{\mathrm{set}\in\{\alpha,i\}} w_{\mathrm{set}} |V_{cb}|_{\mathrm{set}}$$

- result more *sensible* and bias apparently reduced

- **We find no noteworthy tensions between the results from both strategies**
- **This analysis confirms a slight tension with insclusive analyses**

Exclusive b → c: combined fit Data + LQCD

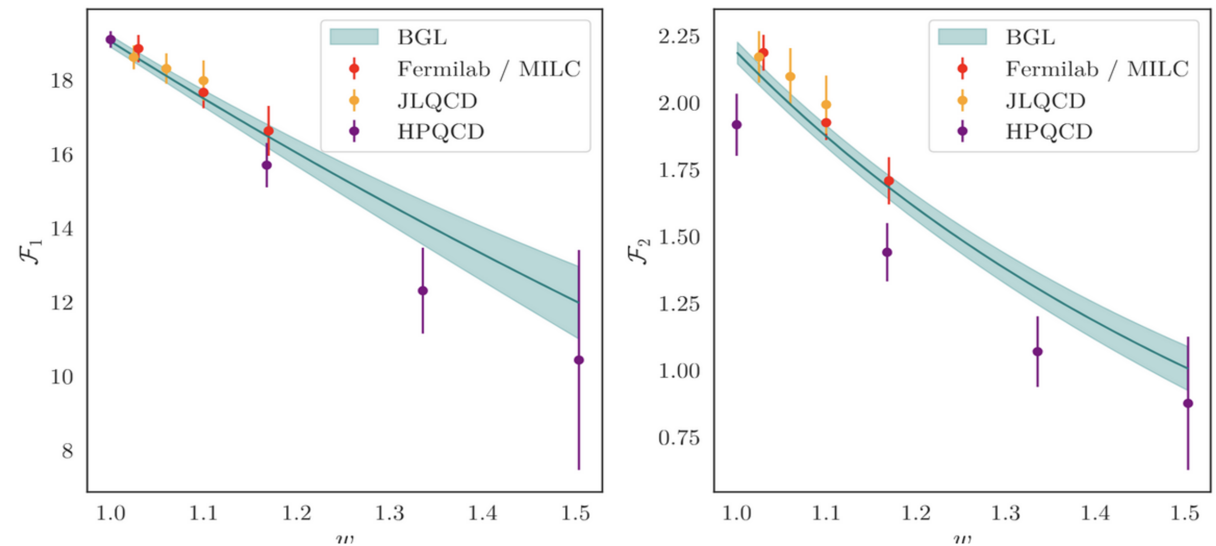


$$|V_{cb}|^{\rm FM} = 38.40(78) \times 10^{-3}$$

$$|V_{cb}|^{\rm JLQCD} = 39.19(90) \times 10^{-3}$$

$$|V_{cb}|^{\rm HPQCD} = 39.31(74) \times 10^{-3}$$

Combined fit of only Lattice results



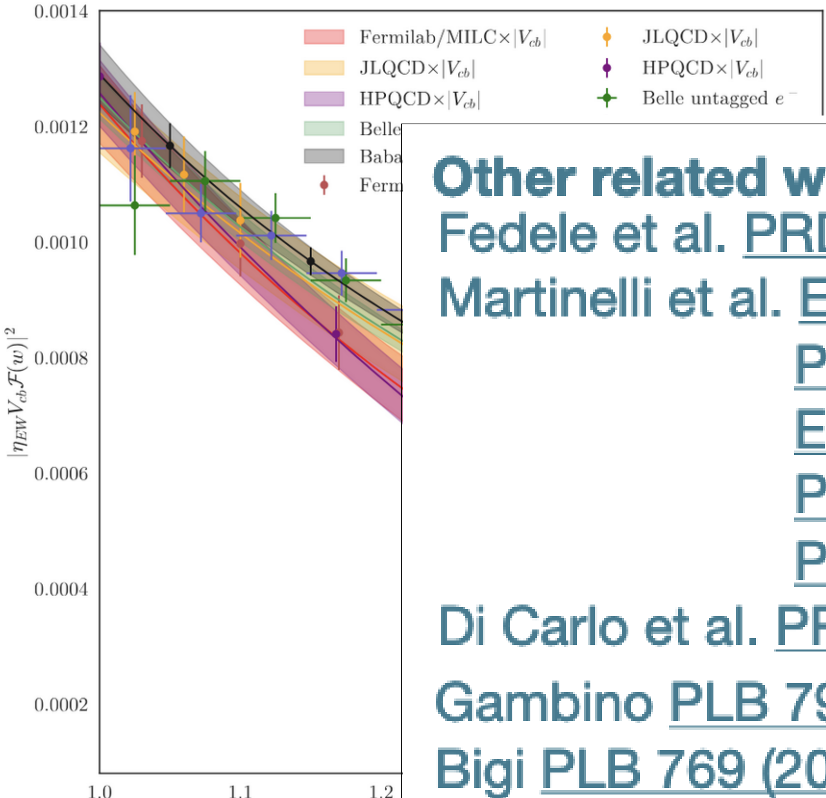
- BGL fit 2222

	w Constraint		w/o Constraint	
	p	$R_2(1)$	p	$R_2(1)$
MILC	0.51	1.20(12)	0.43	1.27(13)
JLQCD	0.52	0.98(19)	0.25	0.97(19)
HPQCD	0.77	1.39(16)	0.65	1.39(16)
MILC+JLQCD	0.40	1.118(97)	0.36	1.16(11)
MILC+HPQCD	0.44	1.262(93)	0.37	1.262(93)
JLQCD+HPQCD	0.73	1.18(12)	0.67	1.18(12)
All	0.56	1.193(83)	0.50	1.193(83)

- p-value of Belle untagged + BaBar BGL fit 223 is ≈ 0.04

Exclusive b → c: combined fit Data + LQCD

A. Vaquero



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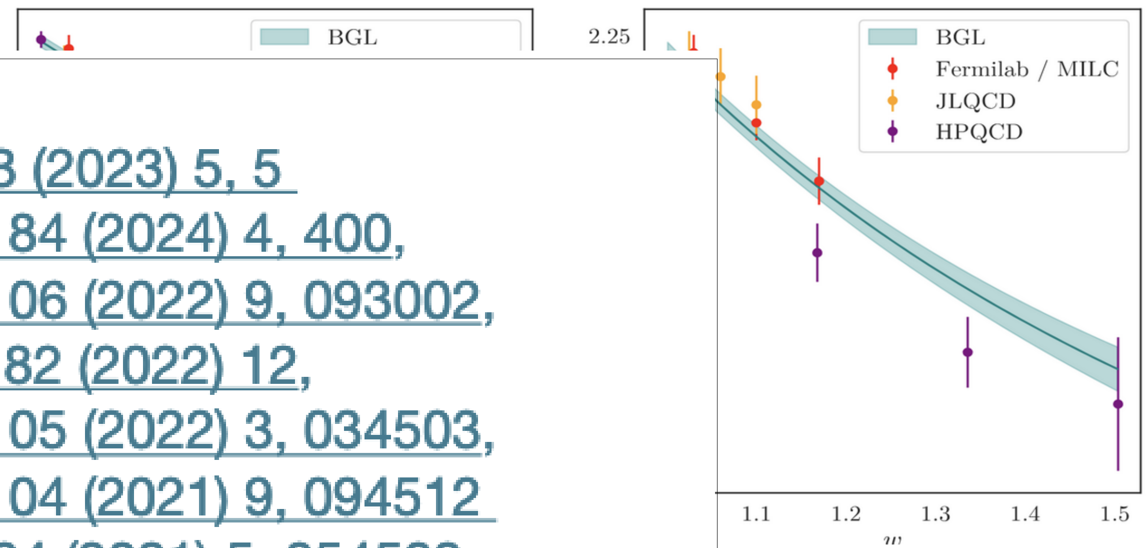
Combined fit of only Lattice results



			w/o Constraint	
			p	$R_2(1)$
		2)	0.43	1.27(13)
		9)	0.25	0.97(19)
		5)	0.65	1.39(16)
MILC+JLQCD	0.40	1.118(97)	0.36	1.16(11)
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All	0.56	1.193(83)	0.50	1.193(83)

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Other related work:

Fedele et al. PRD 108 (2023) 5, 5

Martinelli et al. EPJC 84 (2024) 4, 400,
PRD 106 (2022) 9, 093002,
EPJC 82 (2022) 12,
PRD 105 (2022) 3, 034503,
PRD 104 (2021) 9, 094512

Di Carlo et al. PRD 104 (2021) 5, 054502

Gambino PLB 795 (2019) 386-390

Bigi PLB 769 (2017) 441-445, JHEP 11 (2017) 061

Bernlochner et al. PRD 100 (2019) 1, 013005

Exclusive b → c: B → Dlv, B → D*lv

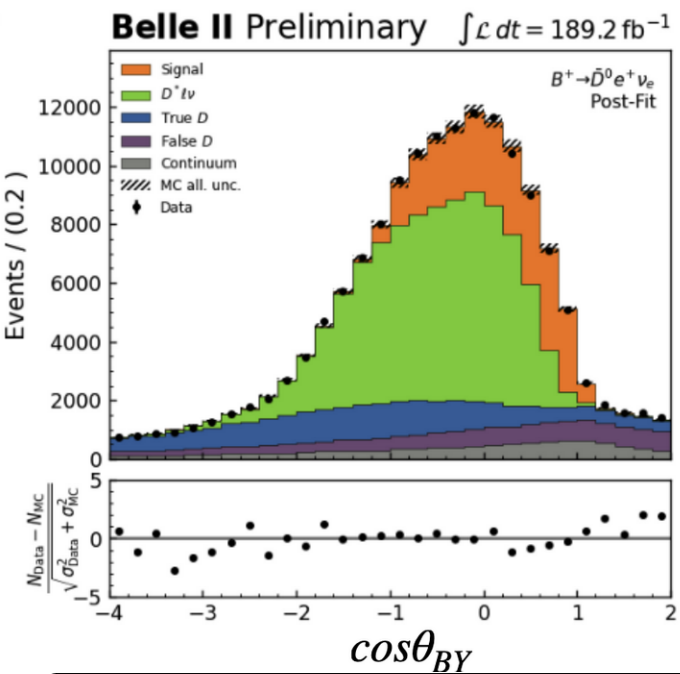
$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ with hadronic tagging at BABAR

[PRL123,091801(2019) + PRD110,032018(2024)]

Different approach: unbinned analyses

B. Dey

$B^0 \to D^-(K\pi\pi)\, l^+ \nu$ and $B^+ \to D^0(K\pi)\, l^+ \nu$: untagged



Exploit isospin symmetry: reduced systematics

Extract signal yields from fit to $\cos\theta_{BY}$ (10 bins in w)

Update to 362/fb ongoing

	$\lvert V_{cb,BGL}\rvert$ [%]	$\lvert V_{cb,BCL}\rvert$ [%]
Stat. Error	0.7	0.6
MC Stat. Error	0.4	0.3
N_{bb}	0.8	0.8
f_{00}/f_{+-}	< 0.1	< 0.1
$\mathcal{B}(D \to K\pi(\pi))$	0.4	0.4
Selection	0.2	0.2
$\mathcal{B}(B \to X_c \ell\nu)$	0.2	0.1
LeptonID	0.1	0.1
KaonID	0.4	0.4
Tracking efficiency	0.5	0.5
$B \to D\ell\nu_\ell$ form factor	0.8	0.4
$B \to D^*\ell\nu_\ell$ form factor	0.1	0.1
$\cos\theta_{BY}$ background modelling	0.2	0.2
w background modelling	0.5	0.4
$\tau_{B^0/\pm}$	0.1	0.1
Total systematic	1.5	1.4
Theory PRD 79, 013008, PRD 93, 119906	1.3	1.2
Total	2.1	1.9

Can we analyse $B \to D^*\ell\nu$ and $B \to D\ell\nu$ together?

[inspired by a BaBar analysis from 2008 (**PRD 79, 012002**)]

Ongoing analysis: no soft pion and independent from f_{00}

M. Mantovano

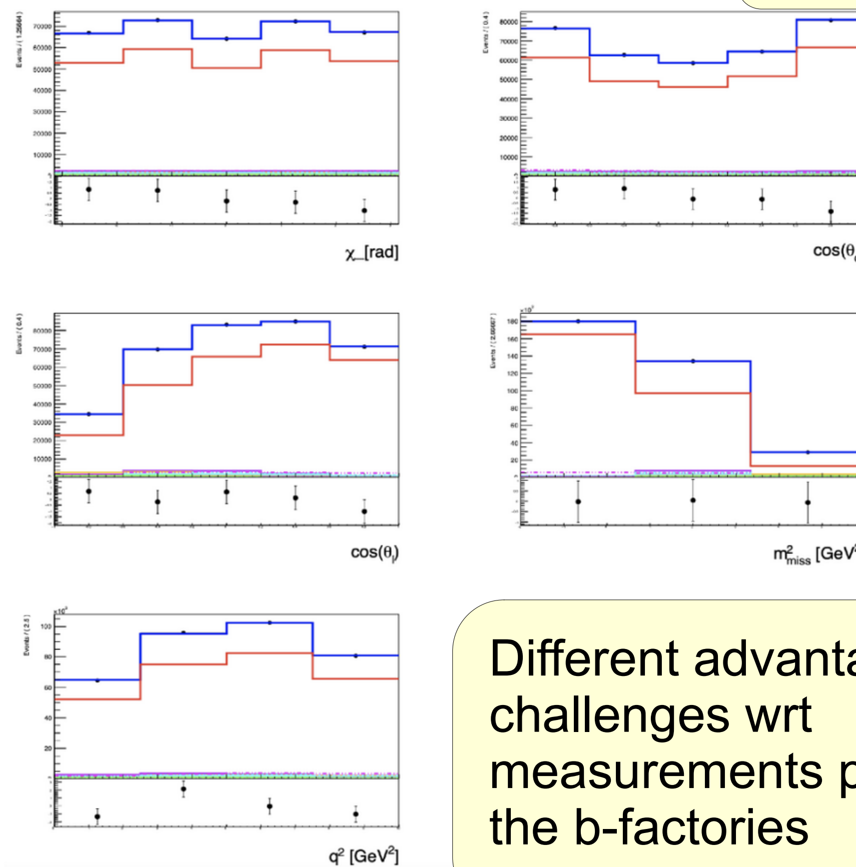
arXiv: 2210.13143

Exploiting angular observables: $B^0 \to D^* \mu \nu$

18 L. Grillo

Enough statistics for a 5D fit !

- **Extract directly Wilson Coefficients and FF parameters** from fit to data
- **Shape analysis** - no attempt to measure $|V_{cb}|$
- SM fits: CLN (Nuclear Physics B 530 (1998) 153-181) , BGL (Phys.Rev. D56 (1997) 6895-6911) and BLPR parametrisation for hadronic FF
- NP fits: **BLPR** parametrisation (F. Bernlochner et. al. Phys. Rev. D 95, 115008 (2017))
- High statistics $B^0 \to D^* \mu \nu$ sample(s), could fit for hadronic FF parameters and NP WC at the same time, if correlations allow
- First sensitivity estimates B. Mitreska CERN-THESIS-2022-105



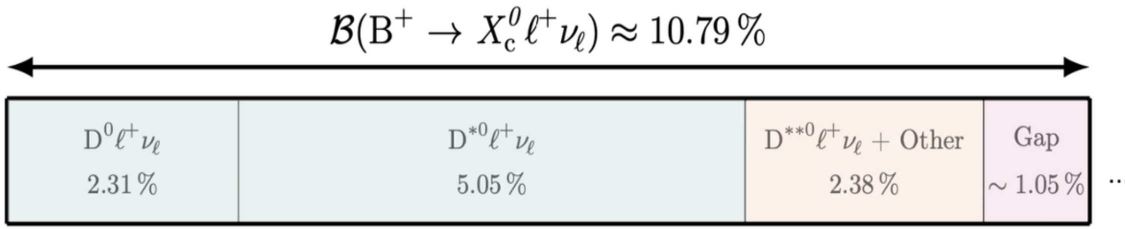
Pseudo-experiments

Different advantages and challenges wrt measurements performed at the b-factories

Exclusive b → c: B → D**

Some blocks are still missing…

A **leading systematic** for many analyses (not just semileptonic):



Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to D\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to D^*\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to X_c \ell \nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$

→ Fairly well known.

→ Broad states based on 3 measurements. (BaBar, Belle, DELPHI)

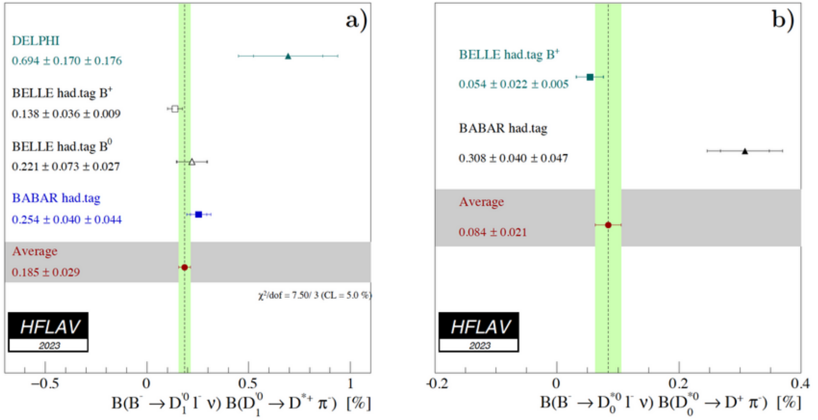
→ Some hints from BaBar & recent Belle result.

→ Fill the gap with current "best guess".

$B \to D^{**} \ell \nu$

- D_0^* and friends are not what we think they are. We need more spectra (not BFs) to disentangle different resonances.
- The D^* tail should be correctly handled in MC!

Broad resonances

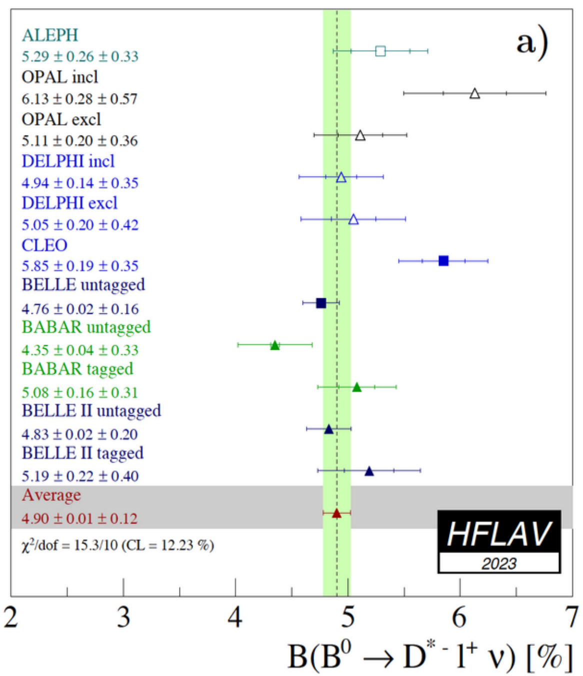


Exclusive b → c: discussion points

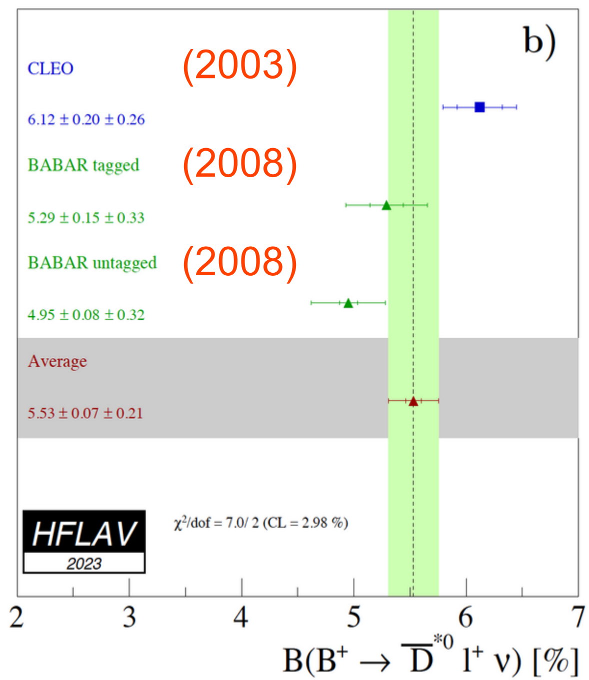
- Are there alternative approaches to HPQCD to cover full w range?
- Not only LQCD, LCSR + HQE approaches (N. Gubernari)
- Paramount to provide data in a form that can be reused: provide more informations? Final tuples, code…

- Crucial to study B → D** semileptonic decays
  - New measurements required: BFs + q^2 shapes
- Combine with analyses of fully hadronic b → c decays

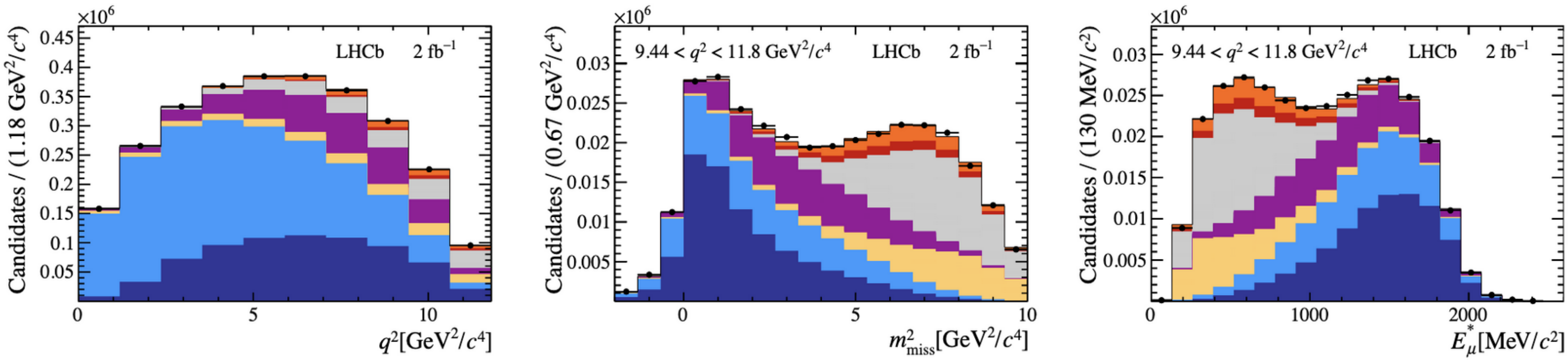
$B^0 \to D^{*+} l\nu$



$B^+ \to D^{*0} l\nu$



- Re-measure BFs
- How should experiments (and LQCD groups) deal with old measurements (predictions) ?



- Very nice additional sample reconstructed with neutral! $D^{*+} \to D^+\pi^0$

- Important caveat: measurements assume SM shape+uncertainties for $\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$
  - Fine for a SM null test
  - If there is non lefthanded vector new physics, measurements of $\mathcal{R}(D^{(*)})$no longer valid
- Much more to come!

Exclusive b → c: R(D⁺)-R(D*⁺)

- **Background from b → c $\bar{c}$ q decays (double-charm)**
  - Need additional measurements: absolute BF of specific modes (also inclusive BF)
    - For the LHCb ongoing analysis in B2OC: please, extract also branching fractions!
- R(D)-R(D*) with LHCb hadronic tau: need external inputs: B → D*3pi

- **Commons systematics**
  - B → D** / FF: different treatment between different meas./exp.
  - Assumptions are implied on correlations in combining measurements

SysVar

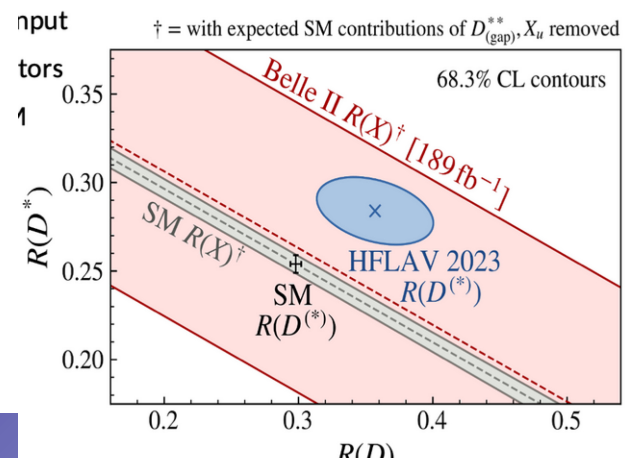
A New Tool for Enhancing Consistency in the Treatment of Systematic Uncert.

- properly combine Belle II measurements

I. Tsakidis

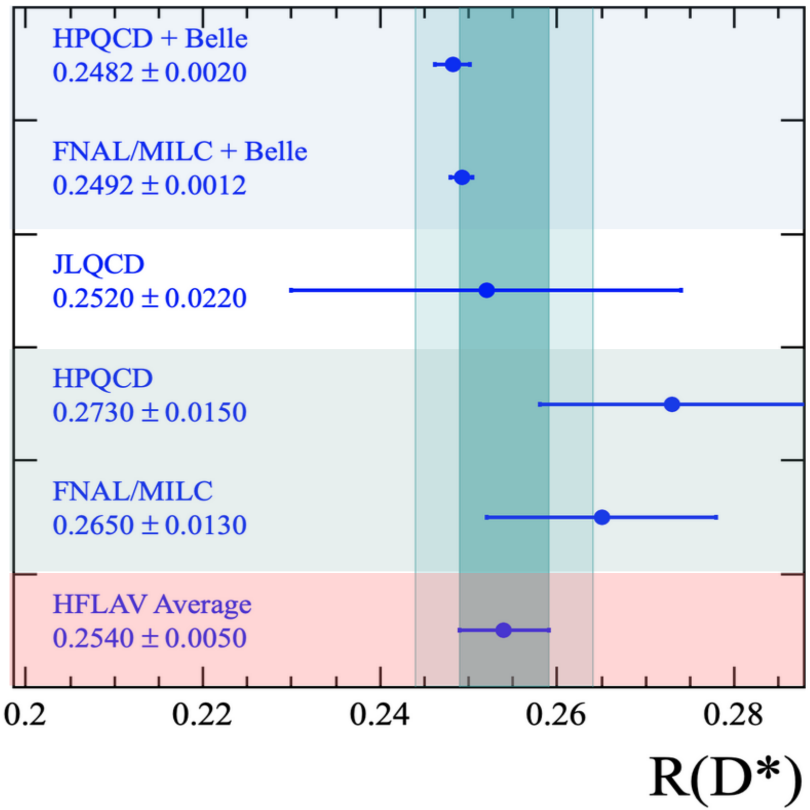
Other observables

- Angular observables, tau polarization: try to go differential as much as possible
- Inclusive $R(X_c)$

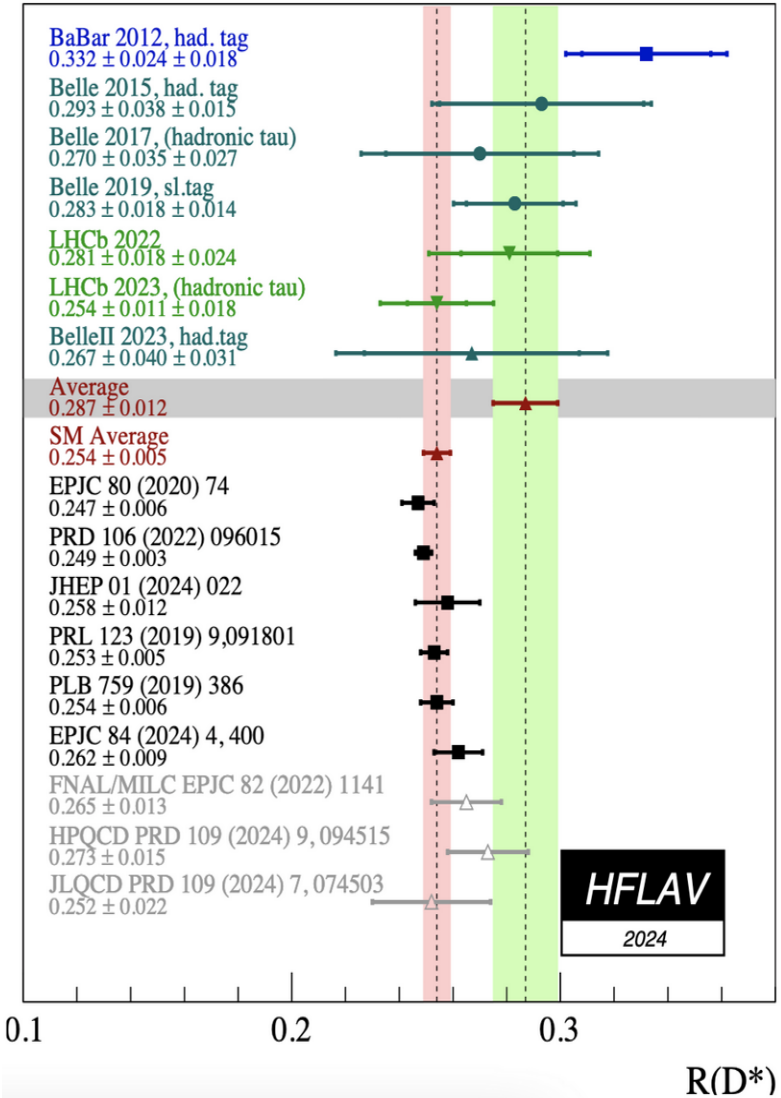


Exclusive b → c: SM predictions of R(D)

Most of the SM predictions use fit of theory inputs (mostly LQCD) and experimental data of B→D/D* ℓ ν with light leptons

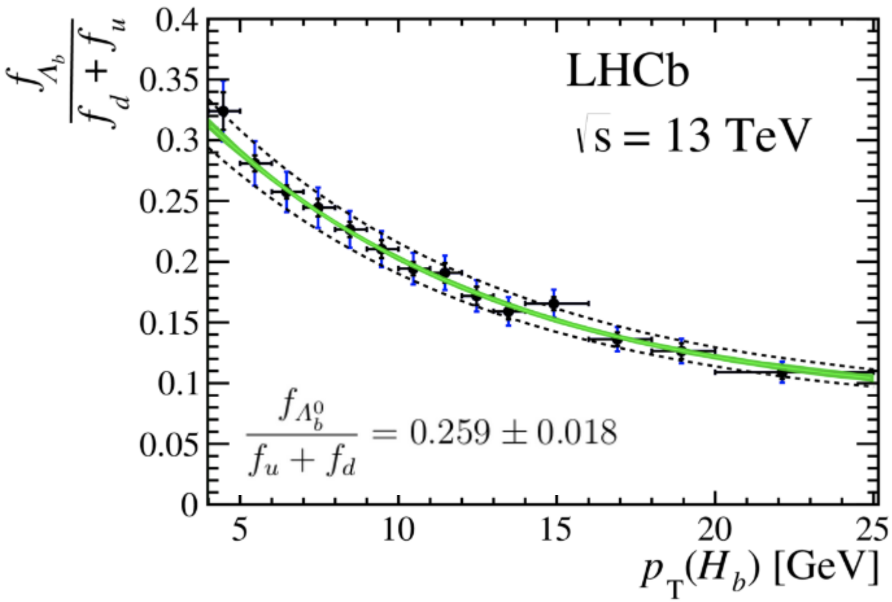


Impact of including B→ D*ℓν data from Belle
[PRD 100, 052007 (2019)]



Exclusive b → c: b-baryons

A. Lupato



- Broad SL physics program at LHCb: measurement of CKM matrix elements, angular analysis, Wilson coefficients, LFU tests…
- Successful Run1 and Run2: 3+6 fb-1, still many analysis ongoing

b-baryons should be investigated more

- Additional LQCD would be desirable!
- But HQET is very predictive for Λ_b (***ud*** pair in spin-0 configuration)
- Additional baryons?
  - Ω_b(bss) → Ω_c(css) μ ν
  - …

FLAG2021

Process	Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization	heavy-quark treatment
$\Lambda_b \to \Lambda_c^*(2625)\,\ell^-\bar{\nu}_\ell$	Meinel 21	[147]	2+1	A	○	○	■	○	✓
$\Lambda_b \to \Lambda_c^*(2595)\,\ell^-\bar{\nu}_\ell$	Meinel 21	[147]	2+1	A	○	○	■	○	✓
$\Lambda_b \to \Lambda^*(1520)\,\ell^+\ell^-$	Meinel 20	[157]	2+1	A	○	○	■	○	✓
$\Lambda_b \to \Lambda\,\ell^+\ell^-$	Detmold 16	[152]	2+1	A	○	○	■	○	✓
$\Lambda_b \to p\,\ell^-\bar{\nu}_\ell$	Detmold 15	[145]	2+1	A	○	○	■	○	✓
$\Lambda_b \to \Lambda_c\,\ell^-\bar{\nu}_\ell$	Detmold 15, Datta 17	[145, 146]	2+1	A	○	○	■	○	✓

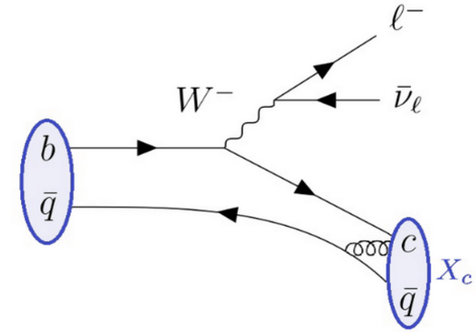
Inclusive b → c

G.Finauri

The inclusive semi-leptonic decay rate in the SM

$$\Gamma(\bar{B} \to X_c \ell^- \bar{\nu}_\ell) = |V_{cb}|^2 G_F^2 \frac{m_b^5}{16\pi^3} f(m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3, \dots)$$

is computed through a power expansion in $\Lambda_{\text{QCD}}/m_b \sim 0.1$



Heavy Quark Expansion (HQE)

$$f(m_b, m_c, \dots) = f^{\text{LP}} + f^{\text{NLP},\pi} \frac{\mu_\pi^2}{m_b^2} + f^{\text{NLP},G} \frac{\mu_G^2}{m_b^2} + f^{\text{NNLP},D} \frac{\rho_D^3}{m_b^3} + f^{\text{NNLP},LS} \frac{\rho_{LS}^3}{m_b^3} + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^4}{m_b^4}\right)$$

$$\langle O^n \rangle_{\text{cut}} = \frac{\int_{\text{cut}} dO\, O^n \frac{d\Gamma}{dO}}{\int_{\text{cut}} dO \frac{d\Gamma}{dO}}$$

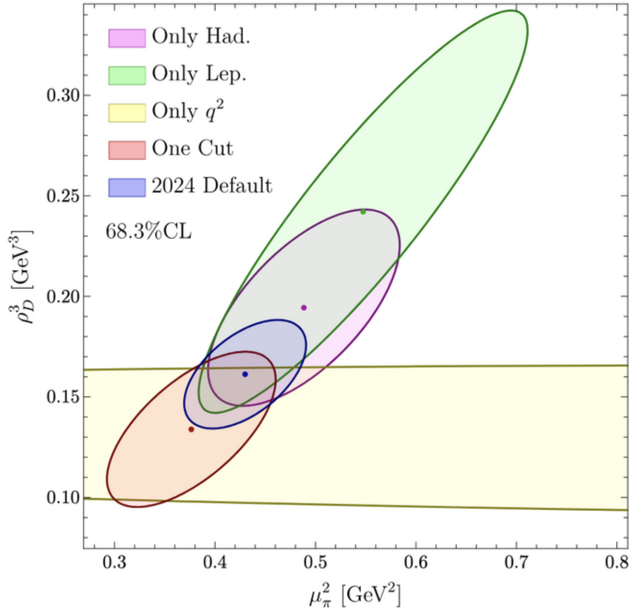
Theory State of the Art in $\bar{B} \to X_c \ell \bar{\nu}$

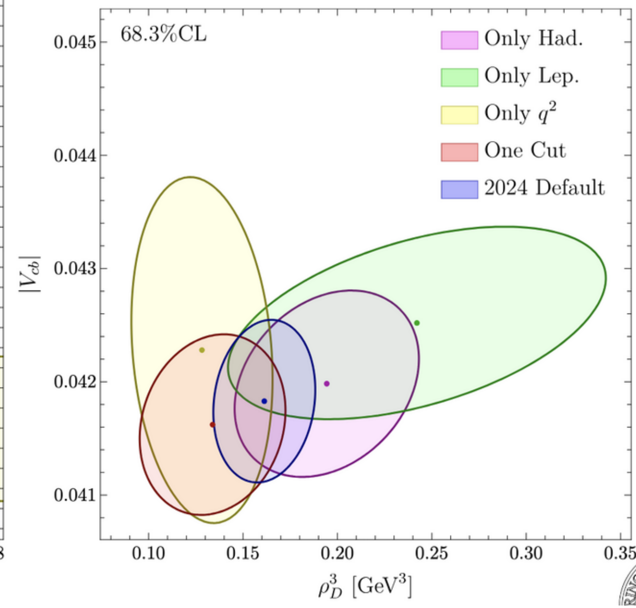
	dE_ℓ	dm_X^2	dq^2	Γ
1	α_s^2 [Melnikov 2008]	α_s^2 [Pak, Czarnecki 2008]	α_s^2 [Fael, Herren 2024]	α_s^3 [Fael, Schönwald, Steinhauser 2020]
$1/m_b^2$	α_s	α_s [Alberti, Ewerth, Gambino, Nandi 2012, 2013]	α_s	α_s
$1/m_b^3$	1 [Gremm, Kapustin 1997]	1	α_s [Mannel, Moreno Pivovarov 2021]	α_s [Mannel, Pivovarov 2019]
$1/m_b^{4,5}$ $1/(m_b^3 m_c^2)$	1 [Mannel, Turczyk, Uraltsev 2010]	1	1 [Mannel, Milutin, Vos 2023]	1 [Mannel, Turczyk, Uraltsev 2010]

Experimental inputs from:

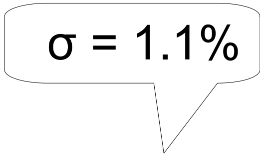
- Delphi, CDF, BaBar, Belle
  - E_{lep}, M_X, ΔBF
- Belle, Belle II
  - q^2

Inclusive b → c

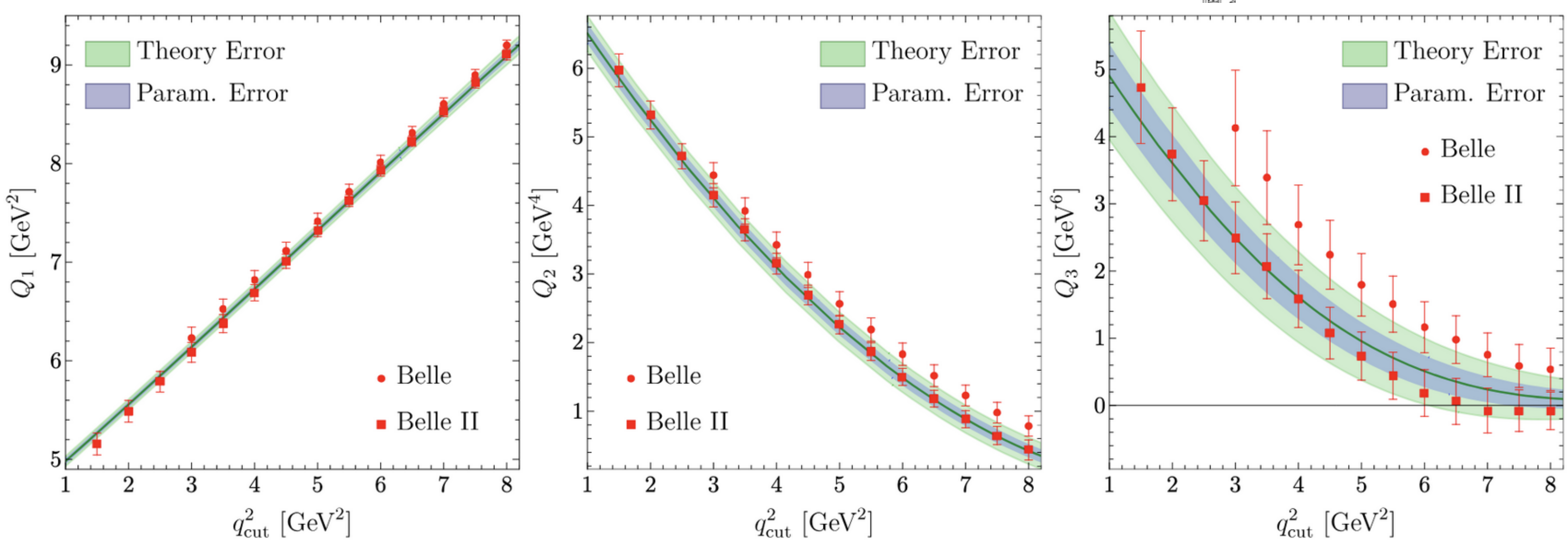




G.Finauri



m_b^{kin}	$\overline{m}_c(2\,\text{GeV})$	μ_π^2	$\mu_G^2(m_b)$	$\rho_D^3(m_b)$	ρ_{LS}^3	$BR_{c\ell\nu}$	$10^3\lvert V_{cb}\rvert$
4.573	1.090	0.454	0.288	0.176	−0.113	10.63	41.97
0.012	0.010	0.043	0.049	0.019	0.090	0.15	0.48
1	0.380	-0.219	0.557	-0.013	-0.172	-0.063	-0.428
	1	0.005	-0.235	-0.051	0.083	0.030	0.071
		1	-0.083	0.537	0.241	0.140	0.335
			1	-0.247	0.010	0.007	-0.253
				1	-0.023	0.023	0.140
					1	-0.011	0.060
						1	0.696
							1



Systematic shift between Belle and Belle II data ~ 2σ

Inclusion of NLO and NNLO terms have big impact on HQE parameters

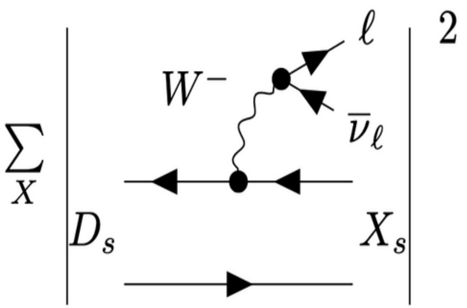
Inclusive on LQCD

R. Kellermann

Inclusive semileptonic decays from Lattice QCD

Lattice QCD might be able to provide input of non-perturbative parameters

On-going analysis of inclusive semileptonic decay rate $D_s \to X_s \ell \nu_\ell$



$$\frac{d\Gamma}{dq^2 dq_0^2 dE_l} = \frac{G_F^2 |V_{cs}|^2}{8\pi^2} L_{\mu\nu} W^{\mu\nu}$$

$L_{\mu\nu}$: Leptonic tensor (analytically known)

$W^{\mu\nu}$: Hadronic tensor (nonperturbative QCD)

Challenges on the lattice

- Require external states
  - ➢ Long time separations
- Large number of states
  - ➢ Identify all of them?
- Extraction of $W_{\mu\nu}$ from correlator ill-posed problem (**inverse problem**)

Future:

- Consider various observables: q^2 moments, El,...?
- Extend to B_s → LHCb prospects

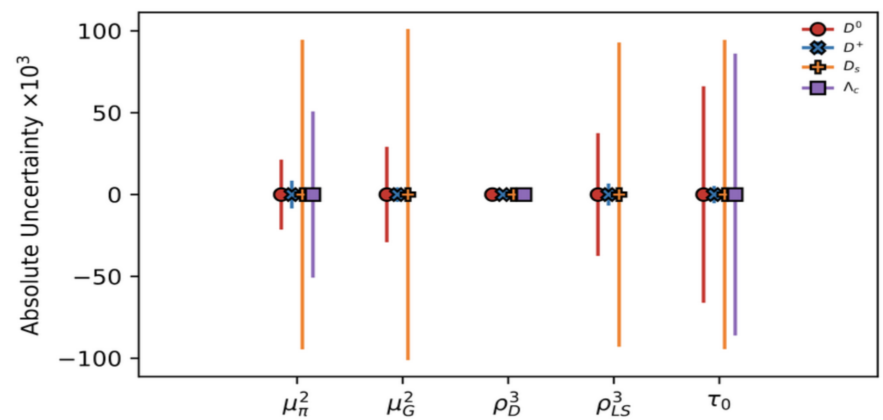
Prospects for inclusive semileptonic charm decays
based on arXiv:2408.10063

A. Gilman

The (not as) Heavy Quark Expansion

- Heavy-Quark Expansion (HQE) expands in $\frac{\Lambda_{QCD}}{m_q}$
- Since $m_c < m_b$. converges more slowly for charm than but more sensitive to hadronic matrix elements

Estimated sensitivity to HQE parameters
Based on fast simulation of currently available data



Very strong prospects for first determinations of charm HQE parameters with current data and first HQE analysis of inclusive heavy baryon decays.

BESIII datasets

	D^0	D^+	D_s^+	Λ_c^+
E_{cm} GeV	3.773	3.773	4.130–4.230	4.600-4.699
Int. Lumi. [fb^{-1}]	21	21	7.1	4.5
Estimated DT Yields	200000	700000	30000	4300

Strong prospects for competitive inclusive determinations of |Vcs|, maybe also for |Vcd|

Inclusive b → u

L.Cao

BELLE

Full data: 711fb^{-1}

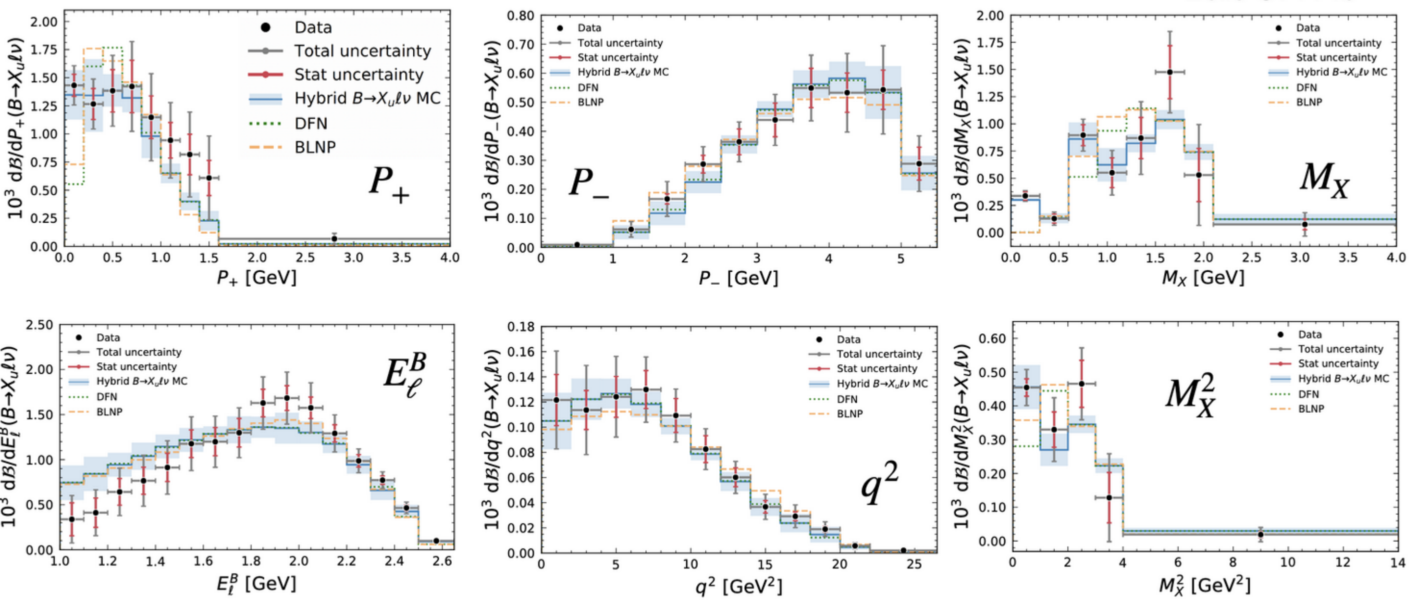
- $\Delta\mathcal{B}(B \to X_u \ell \nu)$ and |V$_{ub}$| [PRD 104 , 012008 (2021)]
- $d\mathcal{B}/dx, x = M_X, M_X^2, q^2, P^{\pm}, E_l^B$ [PRL 127, 261801 (2021)]
- Simultaneous determination of excl. & incl. |V$_{ub}$| [PRL 131, 211801 (2023)]

Belle II

Run1 data: 364fb^{-1}, **ongoing**

- $\Delta\mathcal{B}(B \to X_u \ell \nu)$ and |V$_{ub}$|
- $d\mathcal{B}/dx, x = x_{\text{Belle}} + \cos\theta_\ell$
- Weak annihilation in $B \to X_u \ell \nu$

Belle @711 fb^{-1}



Unfolded/eff. corrected 1-d projections

Improvements on inclusive signal modeling are urgently needed!

Inclusive b → u: theory developments

Expected updates for BLNP and GGOU

GGOU, Gambino2007

B. Capdevila

⇒ We have developed a robust numerical approach to extract the $b \to uW^*$ form factors at NLO and NNLO, overcoming the challenges posed by missing analytic structures

BLNP, Bosch2004 and Lange2005

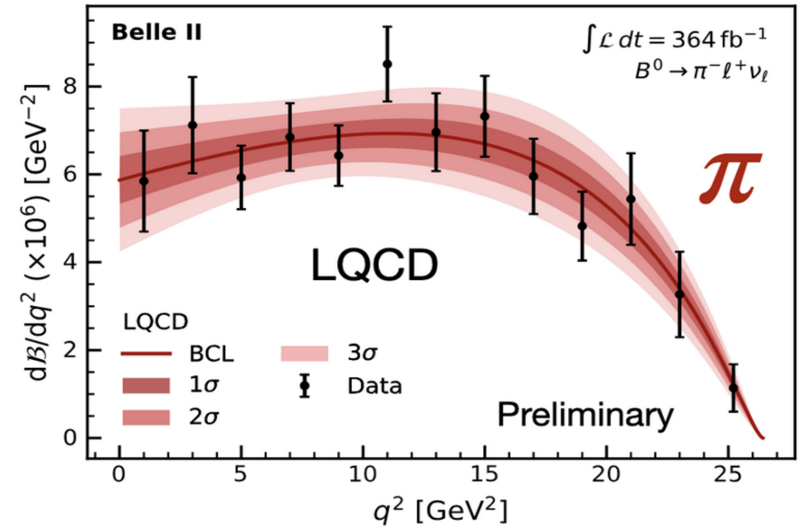
B. O. Lange

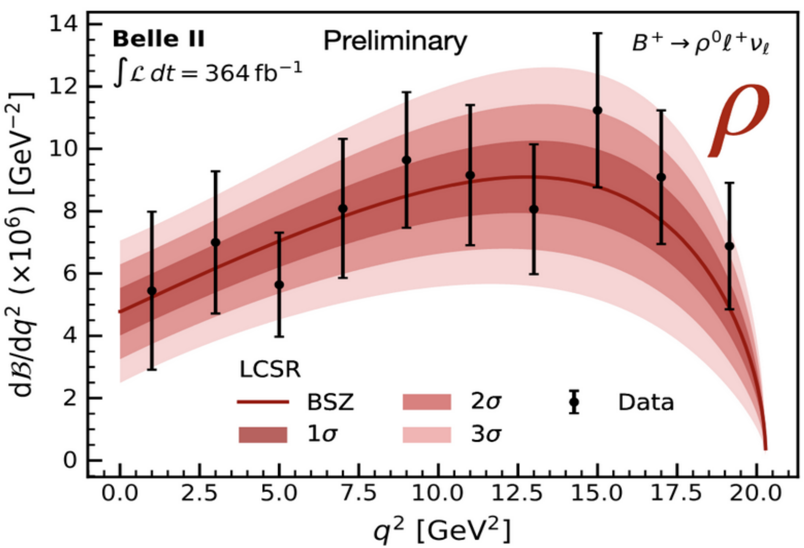
BLNP mandatory maintenance

- reduced perturbative uncertainty at NNLO.
- reduced SF uncertainty by including ρ_D^3
- updating power corrections

Exclusive b → u @Belle II

F. Bernlochner





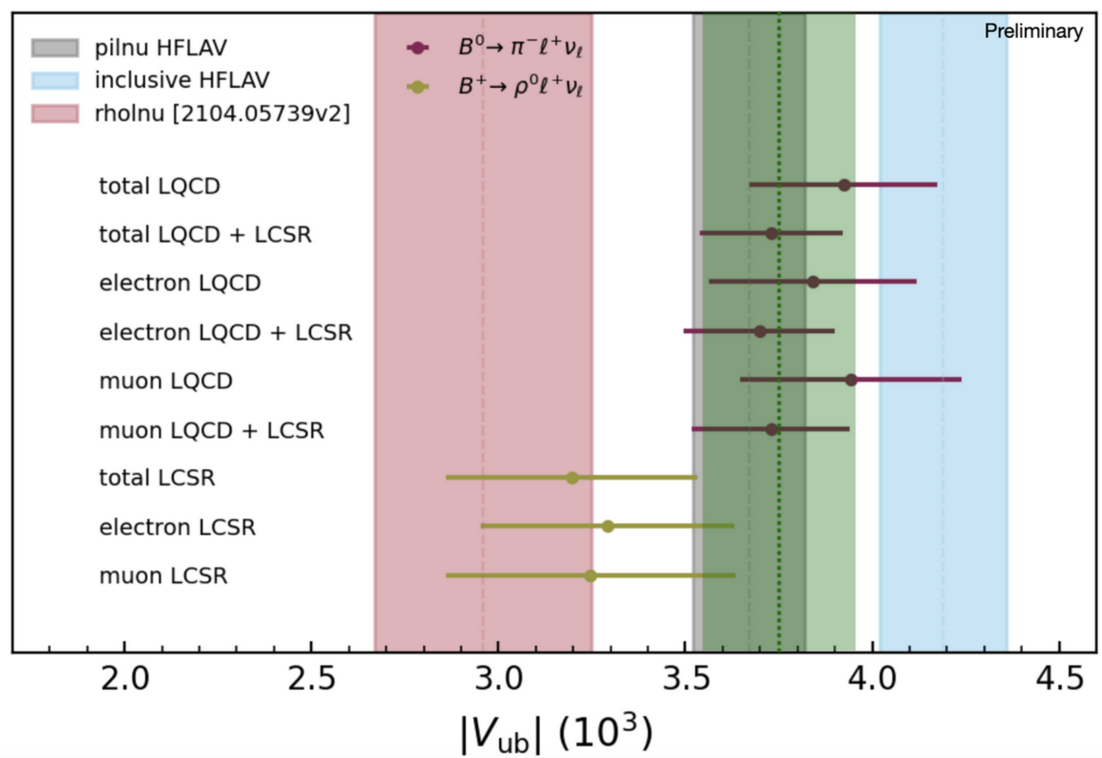
Determine $|V_{ub}|$ by minimising χ^2:

$$\chi^2 = \sum_{i,j}^{N} (\Delta B_i - \Delta\Gamma_i \tau) C_{ij}^{-1} (\Delta B_j - \Delta\Gamma_j \tau) + \chi^2_{\text{Theory}}$$

- Experimental observation
- Experimental covariance
- Theoretical prediction

	$B^0 \to \pi^+ l^- \bar{\nu}_l$	$B^- \to \rho^0 l^- \bar{\nu}_l$
Form factor param.	Bourrely-Caprini-Lellouch (BCL) Phys. Rev. D 82, 099902	Bharucha-Straub-Zwicky (BSZ) J. High Energ. Phys. **2016**, 98
Theory input	LQCD Eur. Phys. J. C 82 (2022) 869 LQCD + LCSR J. High Energ. Phys. **2021**, 36	LCSR J. High Energ. Phys. **2016**, 98

Updated HFLAV 2024 (**LQCD only**, including latest JLQCD)



Exclusive b → u @LHCb

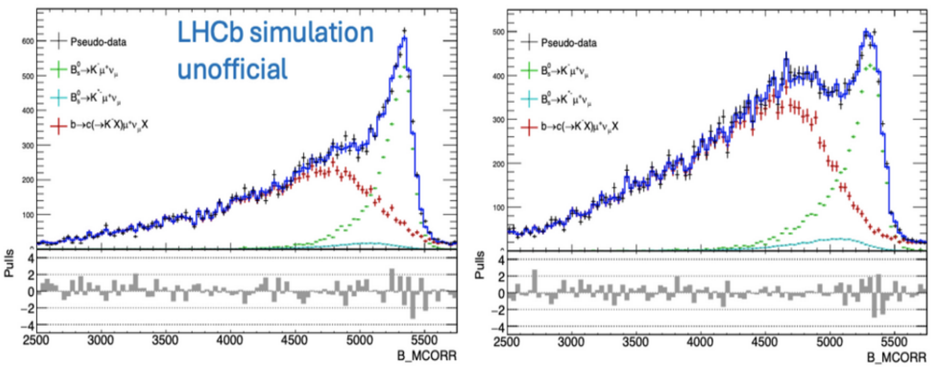
M. Calvi

$B^0_s \to K^- \mu^+ \nu_\mu$

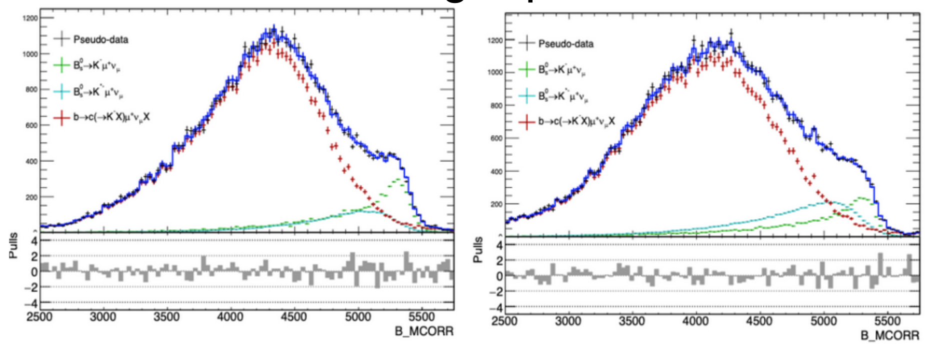
Chosen normalisation mode is $B^- \to J/\psi(\mu^+\mu^-)K^-$

- Very clean and large sample
    - small additional statistical uncertainty
- Same number of tracks and similar topology to signal when one muon is neglected.
    - reduced systematic uncertainty on efficiencies ratio

Low q^2



High q^2



$B^+ \to \rho^0 \mu^+ \nu_\mu$

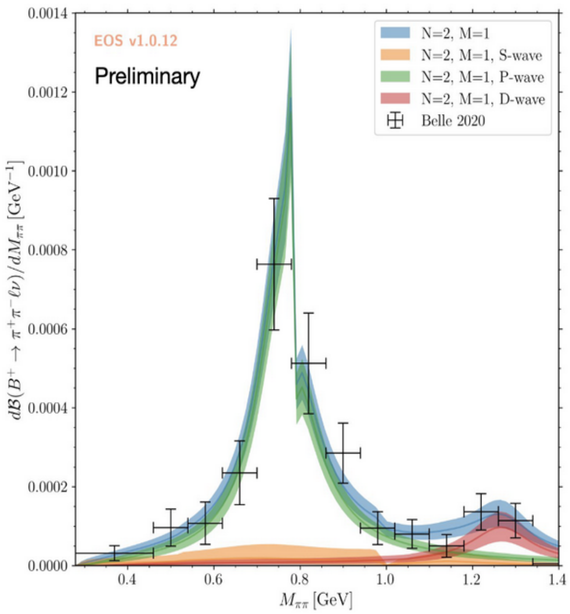
- Goal: measure the differential branching fraction in bins of q^2 and extract the FF
- Normalization mode chosen as $B^+ \to \overline{D}^0 \mu^+ \nu_\mu$, $\overline{D}^0 \to \pi^+\pi^-$

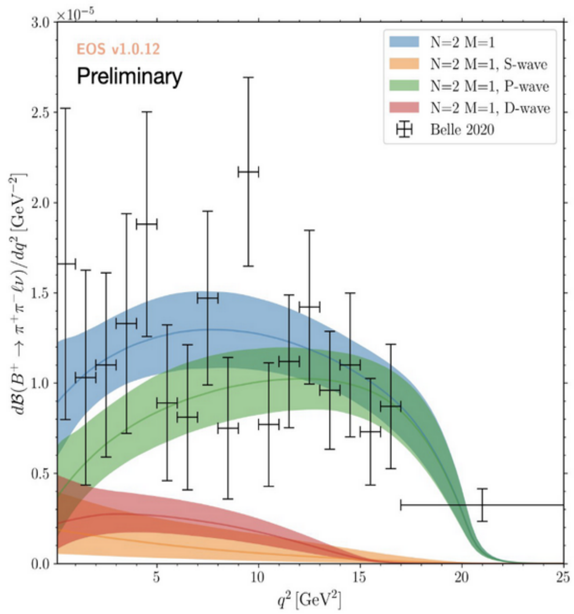
  $\mathcal{B}(B^+ \to \overline{D}^0(\pi^+\pi^-)\mu^+\nu_\mu = (3.34 \pm 0.14)\ 10^{-5}$ with a 4.2% relative uncertainty

    - Same set of final state tracks to reduce systematic uncertainty in efficiency ratio

R. von Tonder
(paper in preparation)

A recent Belle measurement of $B^+ \to \pi^+\pi^-\ell^+\nu$ decays provides 2-D correlated spectra of q^2 & $M_{\pi^+\pi^-}$.
We fit to the 2-D spectra using the EOS package.





Discussed points:

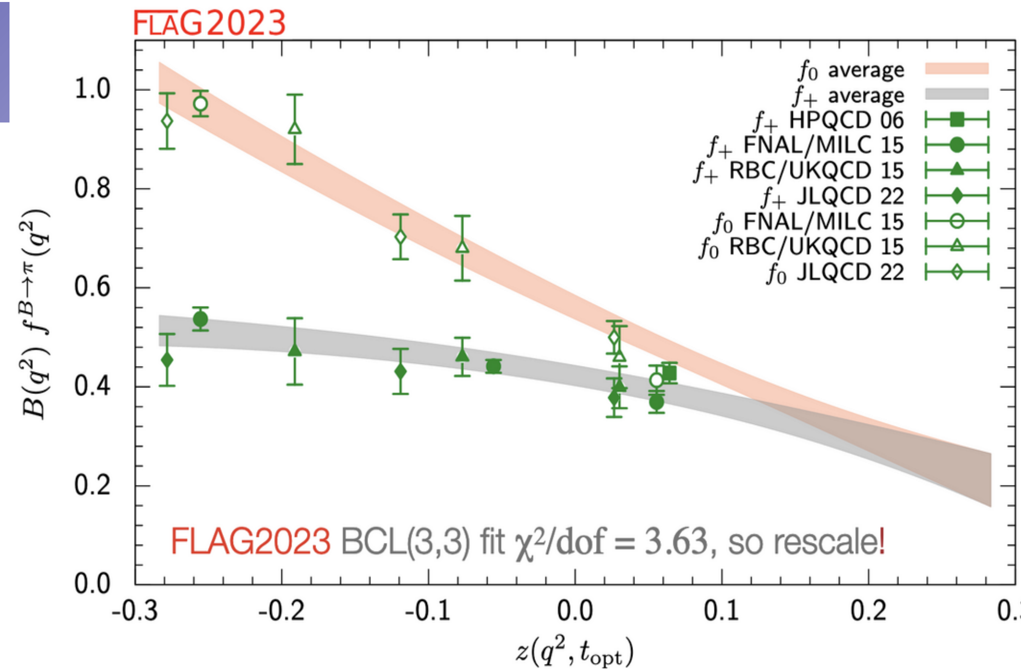
- B → ρ, ω form factors: rely on LCSR, but computed for narrow states
- Start from general B→$\pi^+\pi^-$: require additional data: Belle II + LHCb?
- $B^+ \to \pi^+ \pi^0$ l ν? simpler than $\pi^+ \pi^-$ (absence of f_0 states)

Exclusive b→u

$B \to \pi l \nu$ in FLAG2023

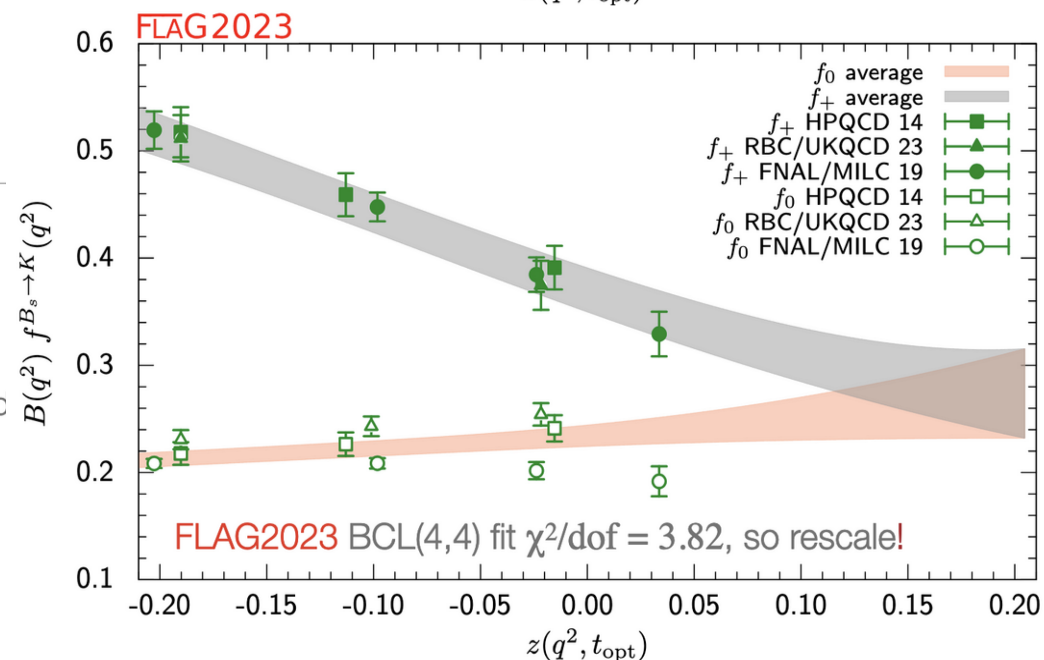
A.Kronfeld

- **HPQCD 2006** [arXiv:hep-lat/0601021]: NRQCD b quark on 2+1 asqtad sea (MILC); six ensembles at two lattice spacings; smallest $m_l = m_s/8$.
- **RBC/UKQCD 2015** [arXiv:1501.05373]: RHQ b quark on 2+1 DWF sea; five ensembles at two lattice spacings; smallest $m_l = m_s/8$.
- **Fermilab-MILC 2015** [arXiv:1503.07839]: Fermilab b quark on 2+1 asqtad sea (MILC); twelve ensembles at four lattice spacings; smallest $m_l = m_s/20$. Supersedes arXiv:0811.3640.
- **JLQCD 2022** [arXiv:2203.04938]: DWF h quark, $m_h \leq 2.44 m_c$, on 2+1 DWF sea; eleven ensembles at three lattice spacings; smallest $m_l = 7m_s/80$.



$B_s \to K l \nu$ in FLAG2023

- **HPQCD 2014** [arXiv:1406.2279]: NRQCD b quark on 2+1 asqtad sea (MILC); five ensembles at two lattice spacings; smallest $m_{l,\rm sea} = m_{s,\rm sea}/10$, $m_{l,\rm val} = m_{s,\rm val}/7$.
- **Fermilab-MILC 2019** [arXiv:1901.02561]: Fermilab b quark on 2+1 asqtac sea (MILC); six ensembles at three lattice spacings; smallest $m_l = m_s/20$.
- **RBC/UKQCD 2023** [arXiv:2303.11280]: RHQ b quark on 2+1 DWF sea; six ensembles at three lattice spacings; smallest $m_l = m_s/10$. Supersedes RBC/UKQCD 2015 [arXiv:1501.05373], says FLAG.



Exclusive b→u

$B \to \pi l \nu$ in FLAG2023

A.Kronfeld

- **HPQCD 2006** [arXiv:hep-lat/0601021]: NRQCD b quark on 2+1 asqtad sea (MILC); six ensembles at two lattice spacings; smallest $m_l = m_s/8$.
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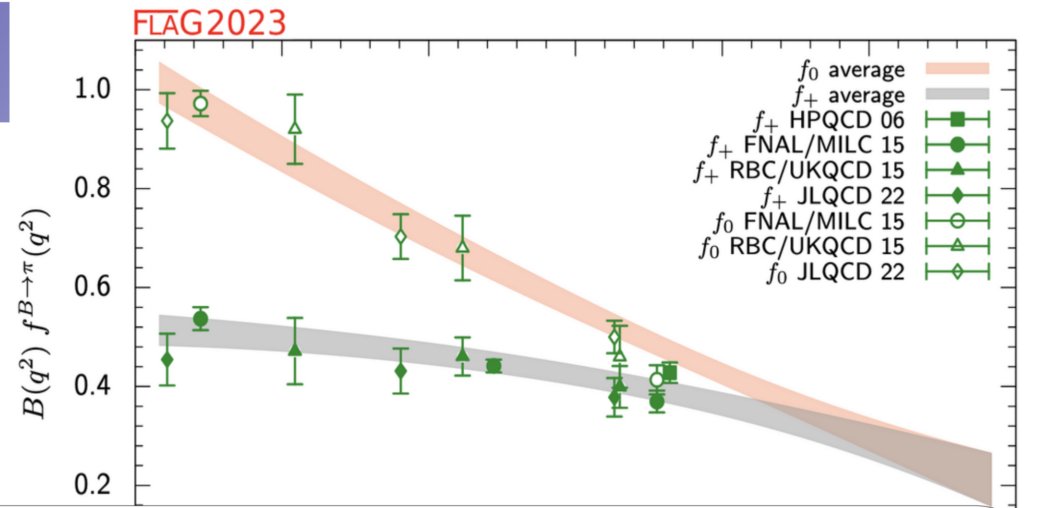
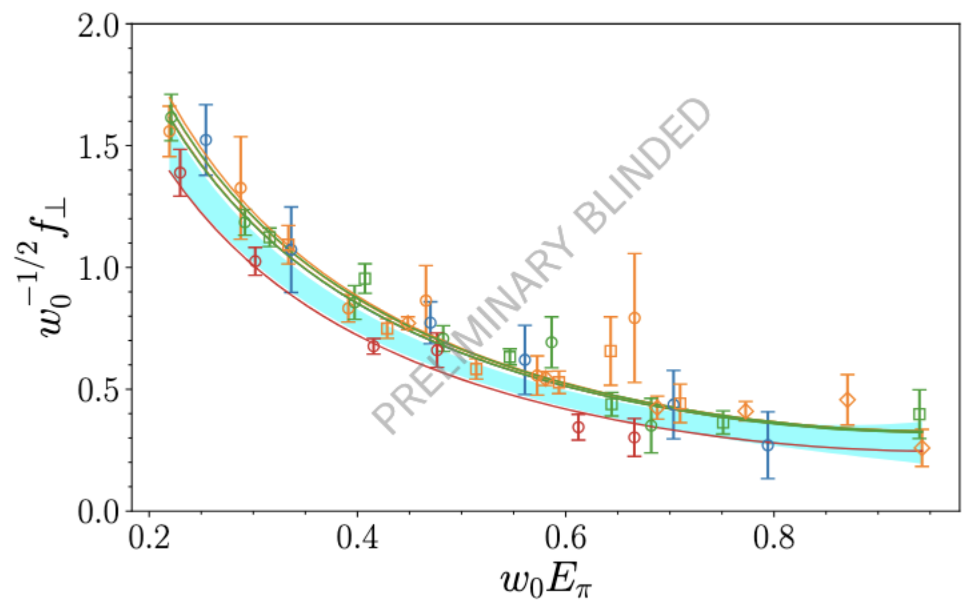
- **JLQCD 2022** [arXiv:2203.04938]: DWF h quark, … sea; eleven ensembles at three lattice spacings; s…



$B_s \to K l \nu$ in FLAG2023

- **HPQCD 2014** [arXiv:1406.2279]: NRQCD b quar… (MILC); five ensembles at two lattice spacings; s… $m_{l,\mathrm{val}} = m_{s,\mathrm{val}}/7$.
- **Fermilab-MILC 2019** [arXiv:1901.02561]: Fermil… sea (MILC); six ensembles at three lattice spacing…
- **RBC/UKQCD 2023** [arXiv:2303.11280]: RHQ b … six ensembles at three lattice spacings; smallest … RBC/UKQCD 2015 [arXiv:1501.05373], says FLA…

Fermilab-MILC on 2+1+1-Flavor Ensembles: update ongoing



Fruitful discussions in a nice venue

More than I summarized here!

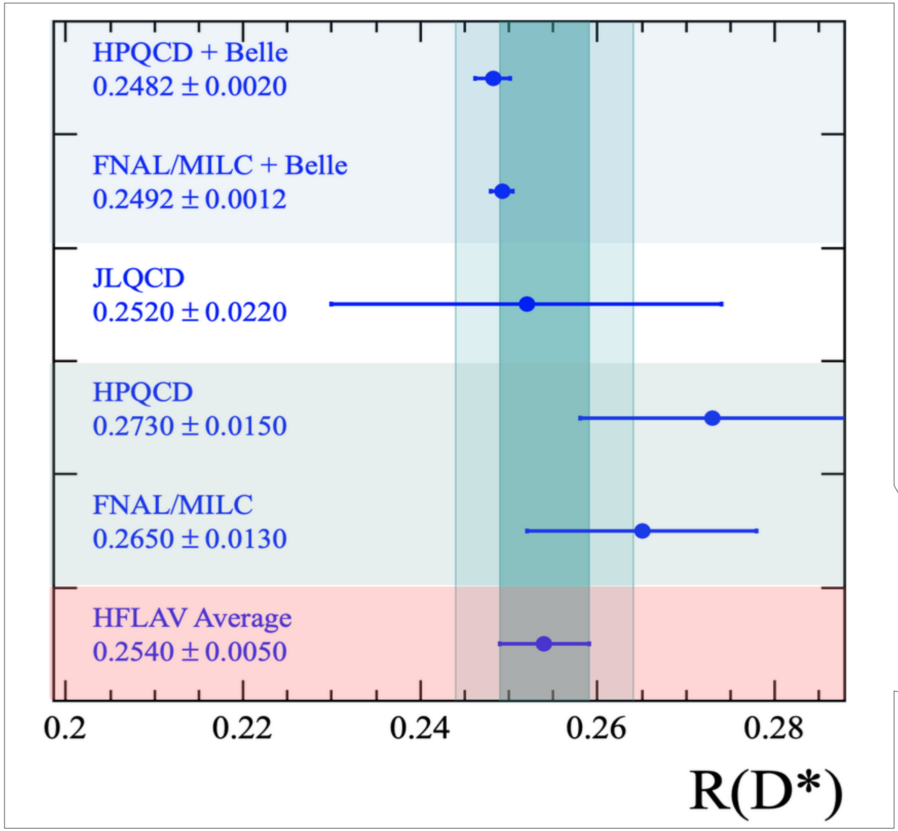
(I apologize for not mentioning the many interesting contributions)

Thanks!

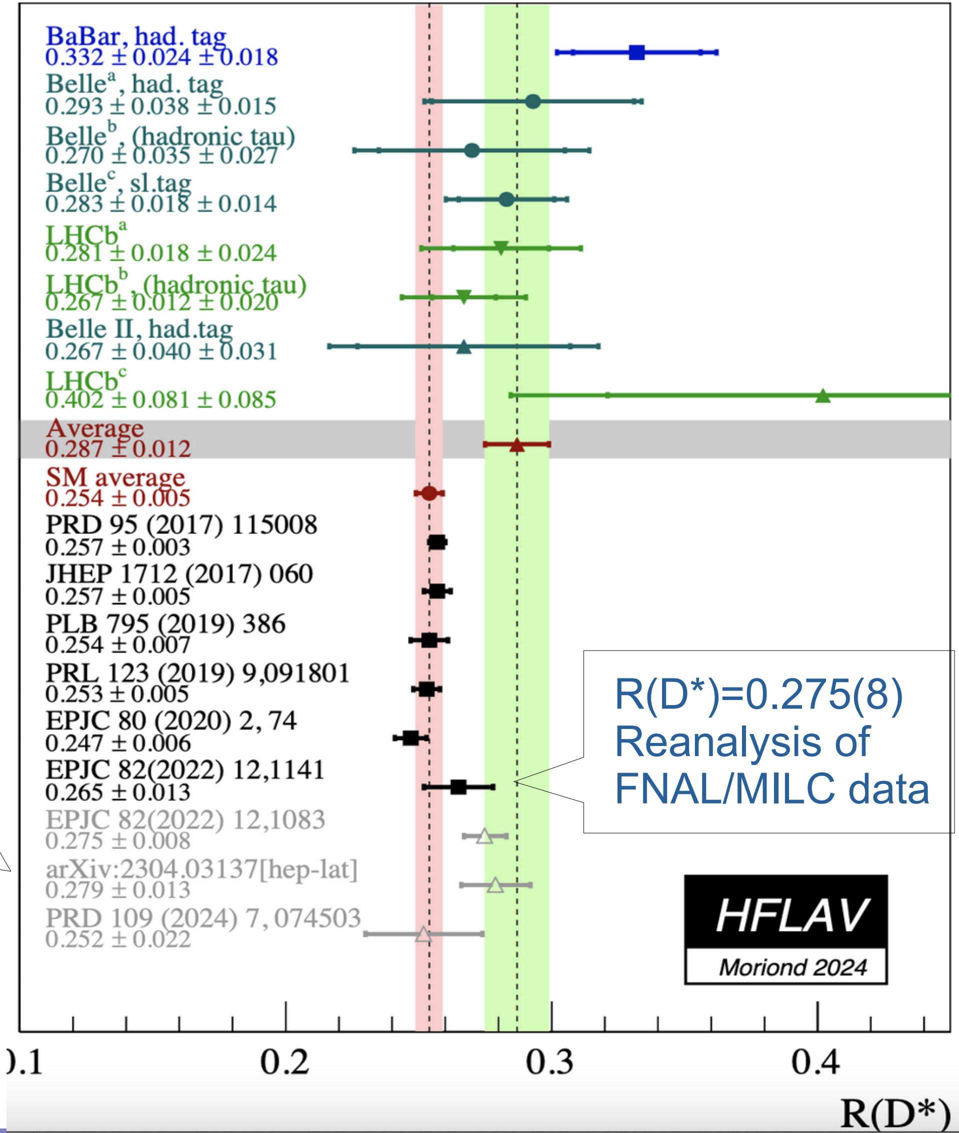
BACKUP

Status of R(D*) predictions

Most of the SM predictions use fit of theory inputs (mostly LQCD) and experimental data of B→D/D* ℓ ν with light leptons



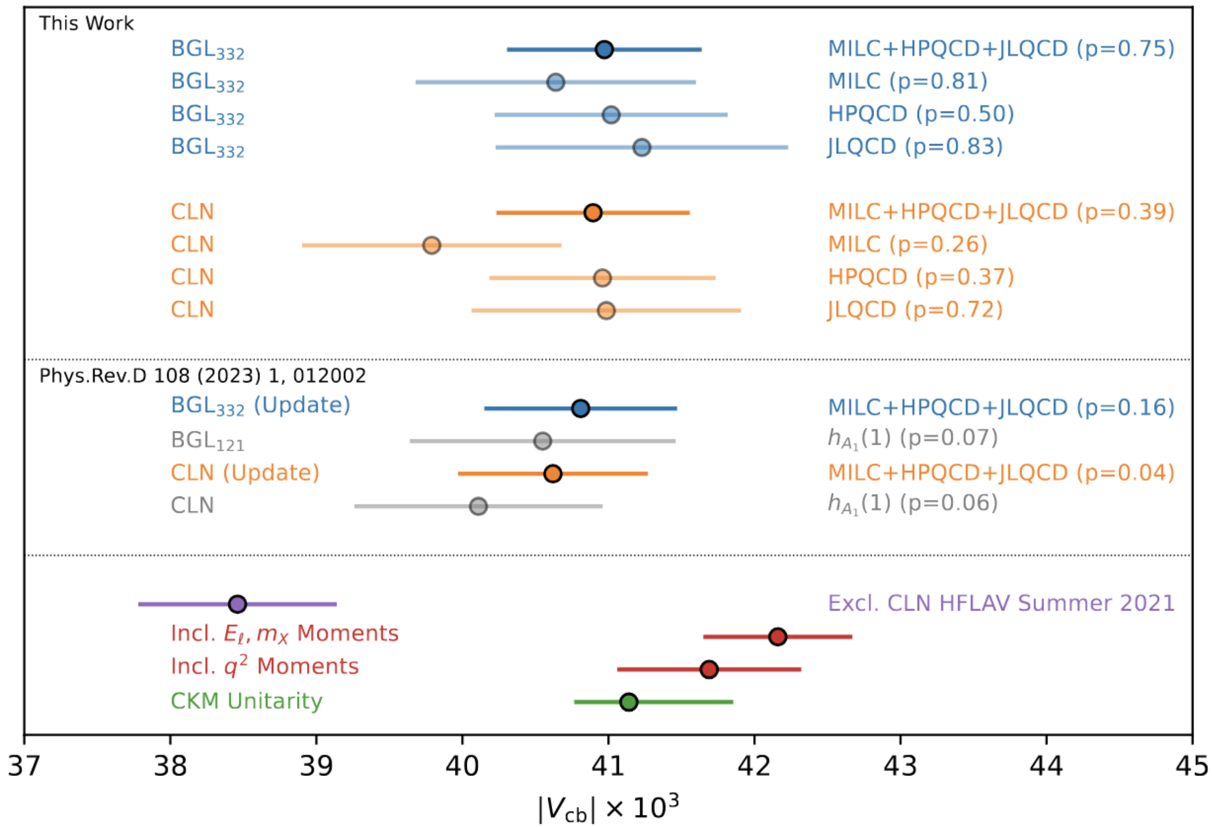
Impact of including B→ D*ℓν data from Belle [PRD 100, 052007 (2019)]



Exclusive b → c

At ∼1% precision things become complicated

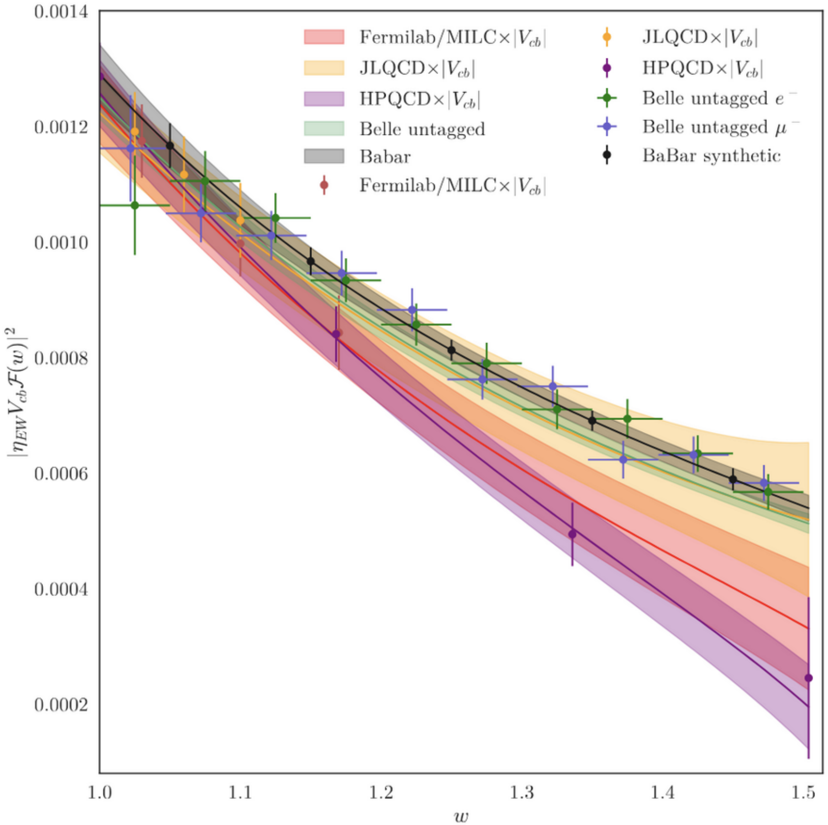
S. Schacht
M. Primm



[overview from Belle 2310.20286]

Exclusive b → c: combined fit Data + LQCD

A. Vaquero

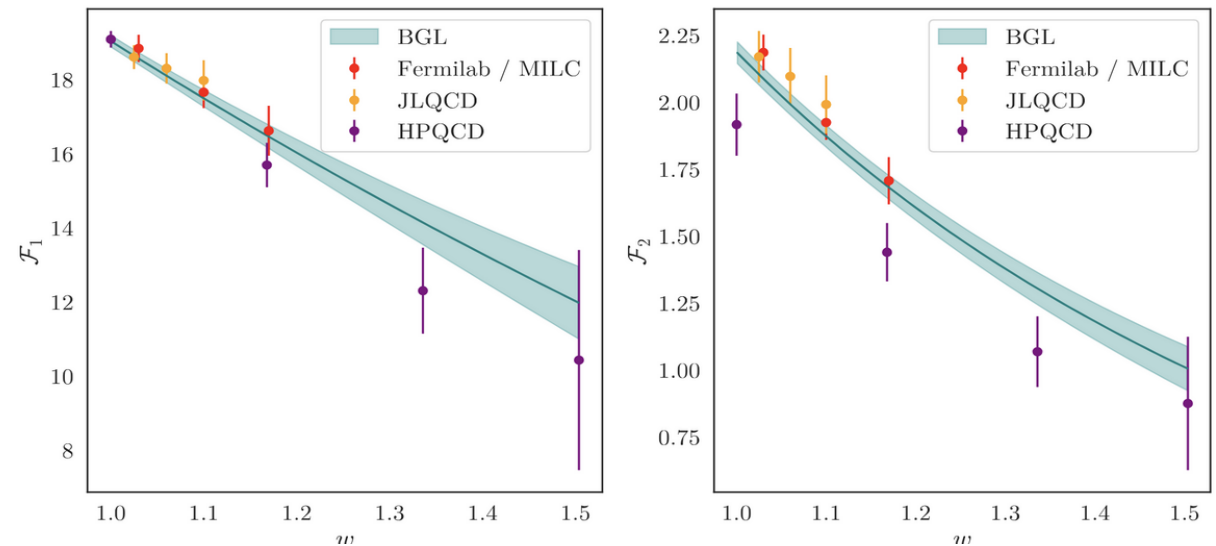


$$|V_{cb}|^{\mathrm{FM}} = 38.40(78) \times 10^{-3}$$

$$|V_{cb}|^{\mathrm{JLQCD}} = 39.19(90) \times 10^{-3}$$

$$|V_{cb}|^{\mathrm{HPQCD}} = 39.31(74) \times 10^{-3}$$

Combined fit of only Lattice results



- BGL fit 2222

	w Constraint		w/o Constraint	
	p	$R_2(1)$	p	$R_2(1)$
MILC	0.51	1.20(12)	0.43	1.27(13)
JLQCD	0.52	0.98(19)	0.25	0.97(19)
HPQCD	0.77	1.39(16)	0.65	1.39(16)
MILC+JLQCD	0.40	1.118(97)	0.36	1.16(11)
MILC+HPQCD	0.44	1.262(93)	0.37	1.262(93)
JLQCD+HPQCD	0.73	1.18(12)	0.67	1.18(12)
All	0.56	1.193(83)	0.50	1.193(83)

- p-value of Belle untagged + BaBar BGL fit 223 is ≈ 0.04

Exclusive b → c: not only LQCD

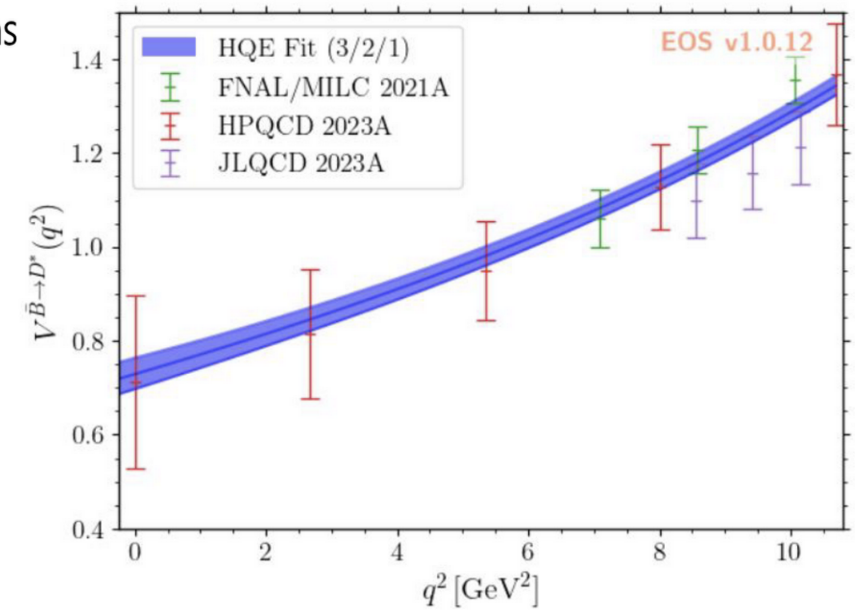
Heavy Quark Expansion (HQE)

N. Gubernari

use HQE: perform a power series expansion in Λ_{QCD}/m_c and Λ_{QCD}/m_b of FFs

$$\mathcal{F}^i_{\text{HQE}}(q^2) = \xi(q^2)\left(c^i_0 + c^i_1 \frac{\alpha_s}{\pi}\right) + c^i_2 \frac{1}{m_b} L_k(q^2) + c^i_3 \frac{1}{m_c} L_k(q^2) + c^i_4 \frac{1}{m_c^2} l_k(q^2)$$

all the $B^{(*)} \to D^{(*)}$ FFs can be expressed in terms of 10 Isgur-Wise functions (1 leading, 3 subleading, 6 subsubleading)



HQE analyses are important for the interpretation of FFs calculations and measurements

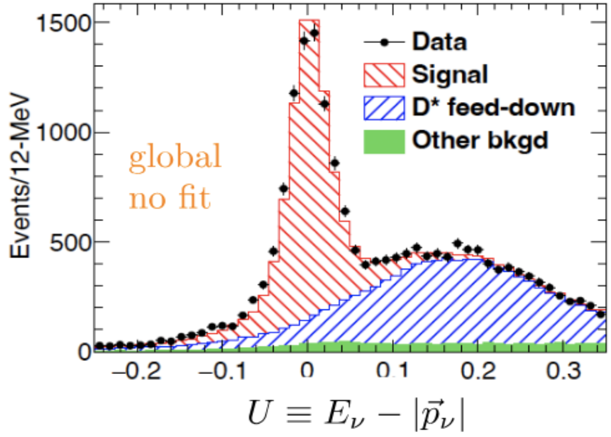
B. Dey

$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ with hadronic tagging at BaBar

[PRL123,091801(2019) + PRD110,032018(2024)]

Novel approach: unbinned analysis

$B \to D\ell^-\overline{\nu}_\ell$: ANALYSIS SETUP



- Full BaBar dataset w/ hadronic tagging. 2d problem in $\{q^2, \cos\theta_\ell\}$.

$$\frac{d\Gamma}{dq^2 d\cos\theta_\ell} = \frac{G_F^2 |V_{cb}|^2 \eta_{EW}^2}{32\pi^3} k^3 |f_+(q^2)|^2 \sin^2\theta_\ell$$

- Rate factorizes but efficiency and background correlated.

$\mathcal{B}$ measurement (had-tagged)	$N = 2$	$N = 3$
	$\lvert V_{cb}\rvert \times 10^3$	
BaBar-10, B^0	40.02 ± 1.76	39.60 ± 1.76
BaBar-10, B^+	38.67 ± 1.41	38.25 ± 1.42
Belle-16, B^0	41.66 ± 1.21	41.22 ± 1.24
Belle-16, B^+	41.27 ± 1.22	40.82 ± 1.25

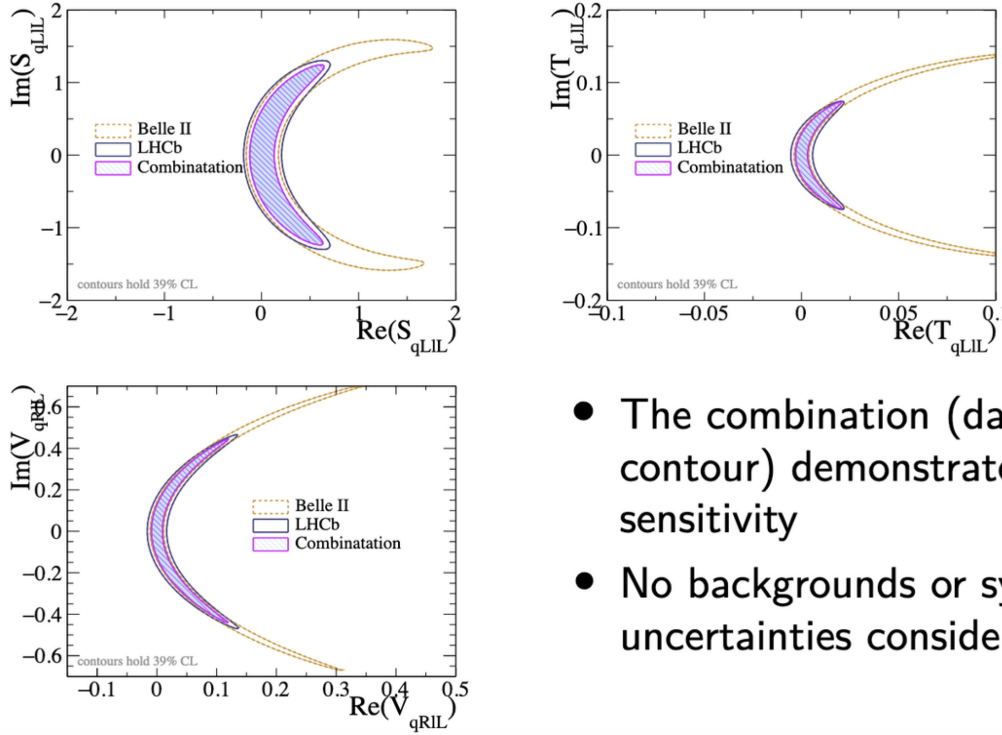
Simultaneous fit between B→D and B → D* ongoing

Release synthetic data

B. Mitreska

- New Physics with b → c ?
- Global Wilson coefficient fit with LHCb and Belle II

- LHCb input: Toy MC with $B^0 \to D^*\tau\nu$ (with $\tau \to \mu\nu\nu$)
- Belle II input: Toy MC with $B^0 \to D^*\tau\nu$ (with $\tau \to \pi/\rho\nu$)



- The combination (dashed pink contour) demonstrates improvement in sensitivity
- No backgrounds or systematic uncertainties considered in the plots

Recent review of D** feed-down recipes in

Florian U. Bernlochner, Manuel Franco Sevilla, Dean J. Robinson, and Guy Wormser, Rev. Mod. Phys. 94, 015003

- R(D**) assumptions for feed-down subtraction :
  - BABAR 0.18
  - BELLE ~0.15
  - LHCb –muonic : 0.12
  - LHCb-hadronic –Run1 : Sum is 11% of $D^*\tau\nu$ yield

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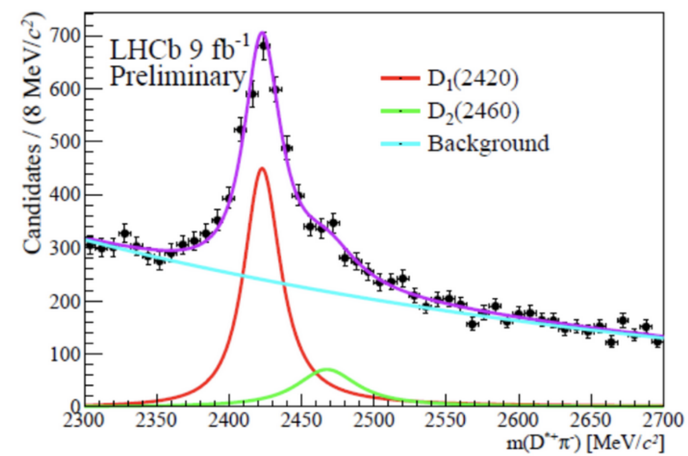

$B^- \rightarrow D^{**0}\tau^-\nu_\tau$ physics results

- Using the normalisation channel yield , one finds:

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Preliminary

$$\frac{\mathcal{B}(B^- \to (D_1(2420)^0 + D_2^*(2460)^0)\tau^-\overline{\nu}_\tau)}{\mathcal{B}(B^- \to (D_1(2420)^0 + D_2^*(2460)^0)D_s^{(*)-})} = 0.19 \pm 0.05,$$

External input:
LHCb-PAPER-2024-001

$R(D_1 + D_2^*)$ =
0.13 0.03 0.01 0.02

NEW: Inclusive decays: The Kolya package

K. Vos

Kolya package, Fael, Milutin, KKV [2409.15007]

Open source Python package:
https://gitlab.com/vcb-inclusive/kolya

- Add total rate to extract $|V_{cb}|$
- Use $\mathcal{B} = (10.48 \pm 0.13)\%$ Bernlochner, Fael, KKV

Order	$\lvert V_{cb}\rvert \cdot 10^{-3}$	Moments Unc.	Rate Unc.
O_3	41.64	0.27	0.34
O_3 no NNLO	41.95	0.32	0.35
O_4	42.03	0.34	0.35
O_4 no NNLO	42.24	0.24	0.35
O_5	42.00	0.31	0.36
O_5 no NNLO	42.06	0.35	0.34