THE V_{cb} PUZZLE

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PRECISION FLAVOUR PHYSICS

Tests of the ***flavour structure*** of the SM: 3 generations of up and down quarks with different masses, mixing with each other via charged current.

The unitary 3x3 Cabibbo-Kobayashi-Maskawa (CKM) parametrises the mixing and leads to CP violation in the SM.

$$\hat{V}_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad \hat{V}^\dagger_{\rm CKM}\hat{V}_{\rm CKM} = 1$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$ first row

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$$ second row etc.

New Physics could manifest itself as violation of unitarity, or shift Flavour Changing Neutral Current (loop induced in the SM) like $b \to s\gamma$, B and K mixing, etc

The importance of $|V_{cb}|$

An important CKM unitarity test is the Unitarity Triangle (UT) formed by

$$1+\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}+\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}=0$$

V_{cb} plays an important role in UT

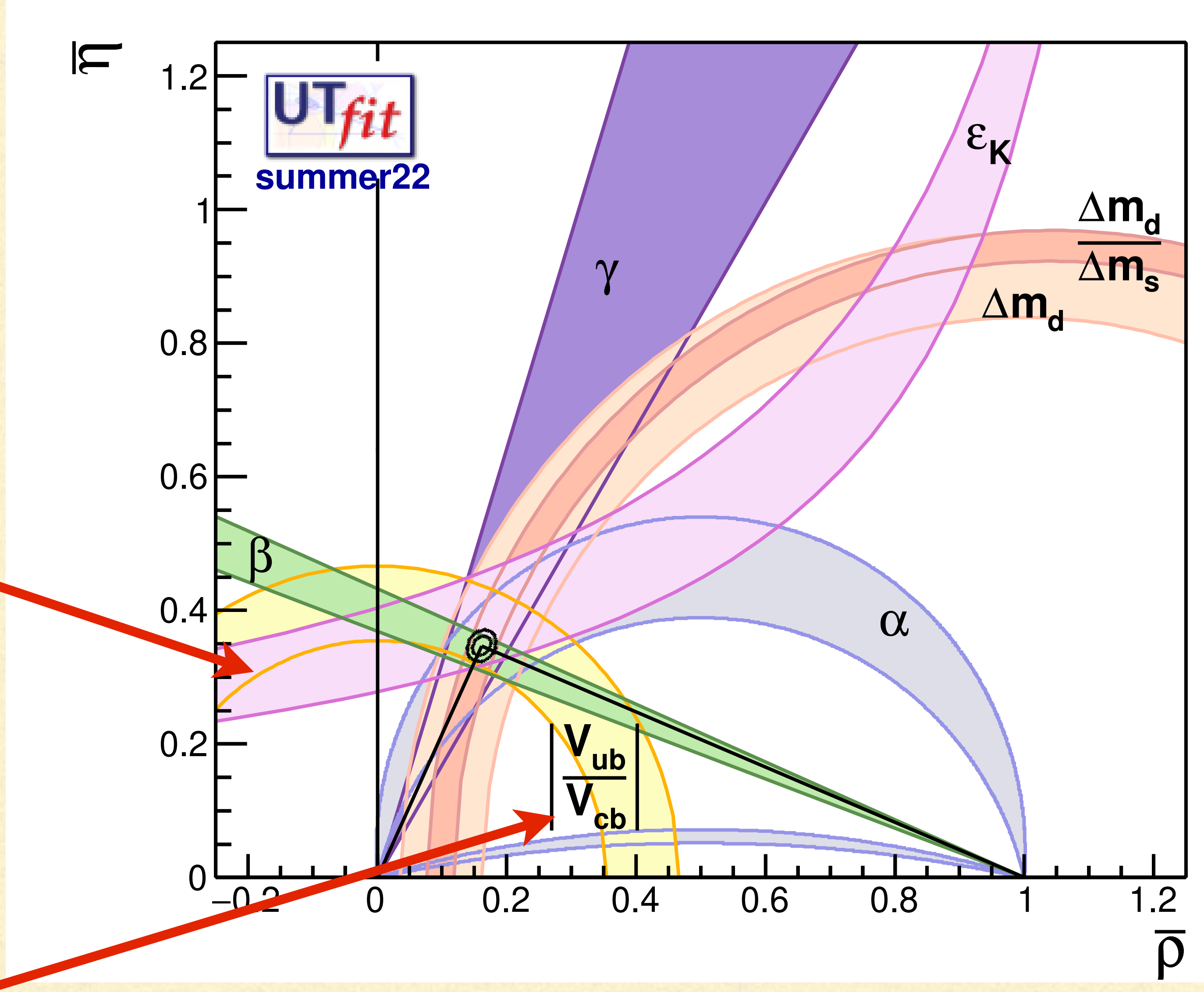
$$\varepsilon_K \approx x|V_{cb}|^4 + ...$$

and in the prediction of FCNC:

$$\propto |V_{tb}V_{ts}|^2 \simeq |V_{cb}|^2\left[1+O(\lambda^2)\right]$$

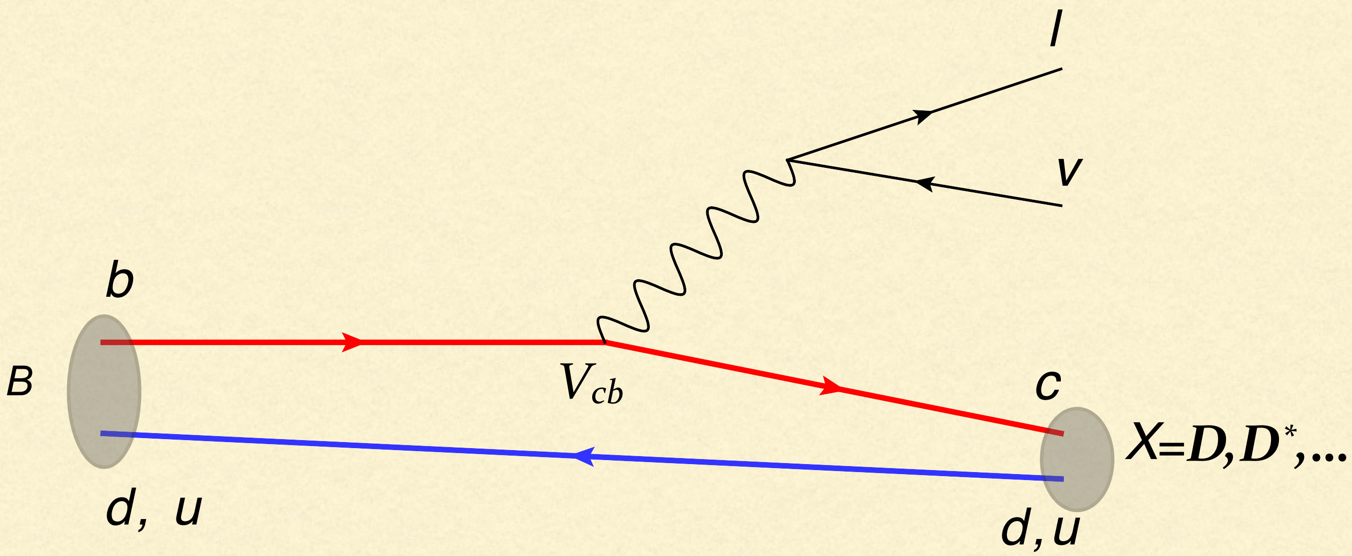
where *it often dominates the theoretical uncertainty.*

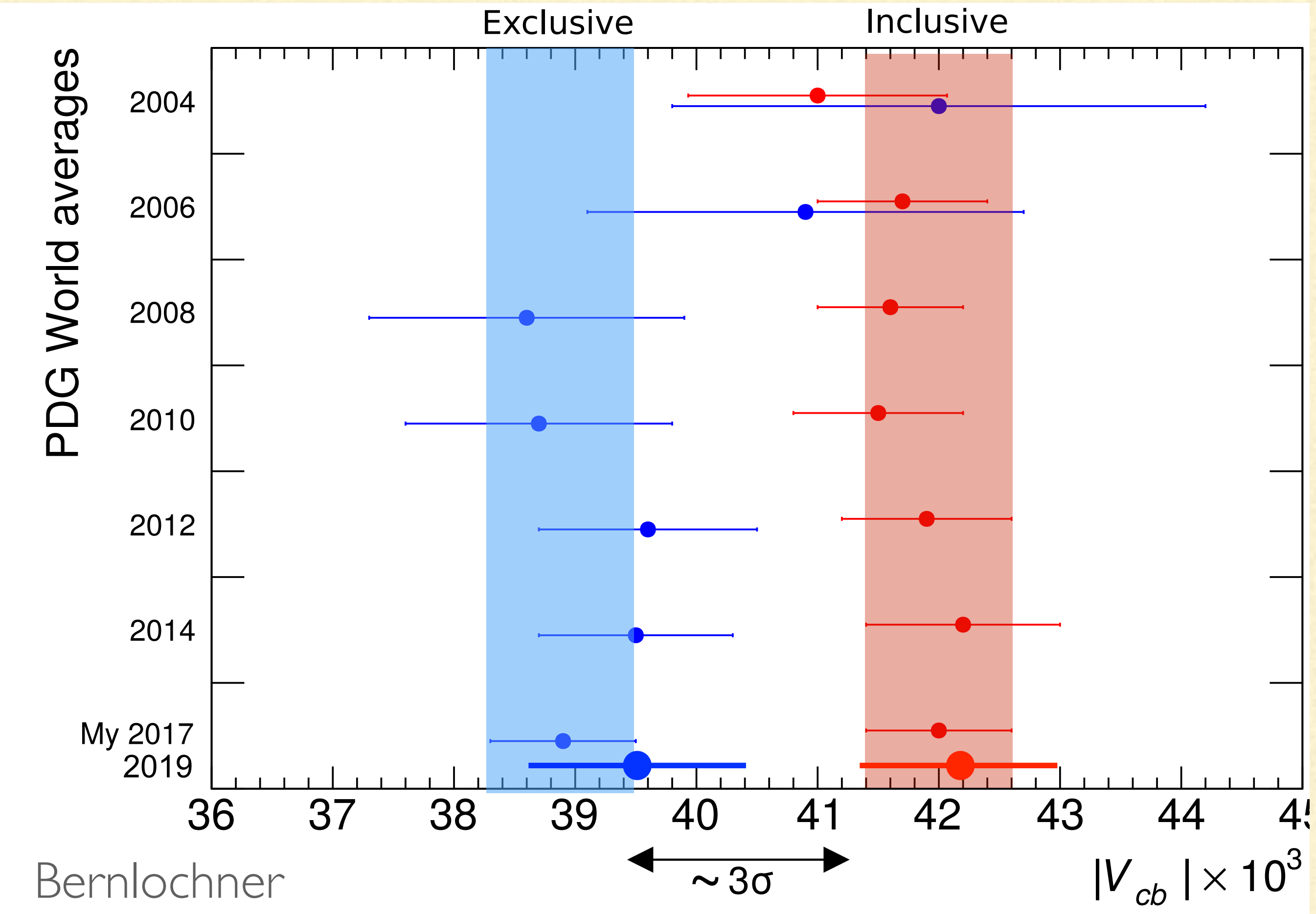
V_{ub}/V_{cb} constrains directly the UT



Our ability to determine precisely V_{cb} is crucial for indirect NP searches

A LONG-STANDING TENSION

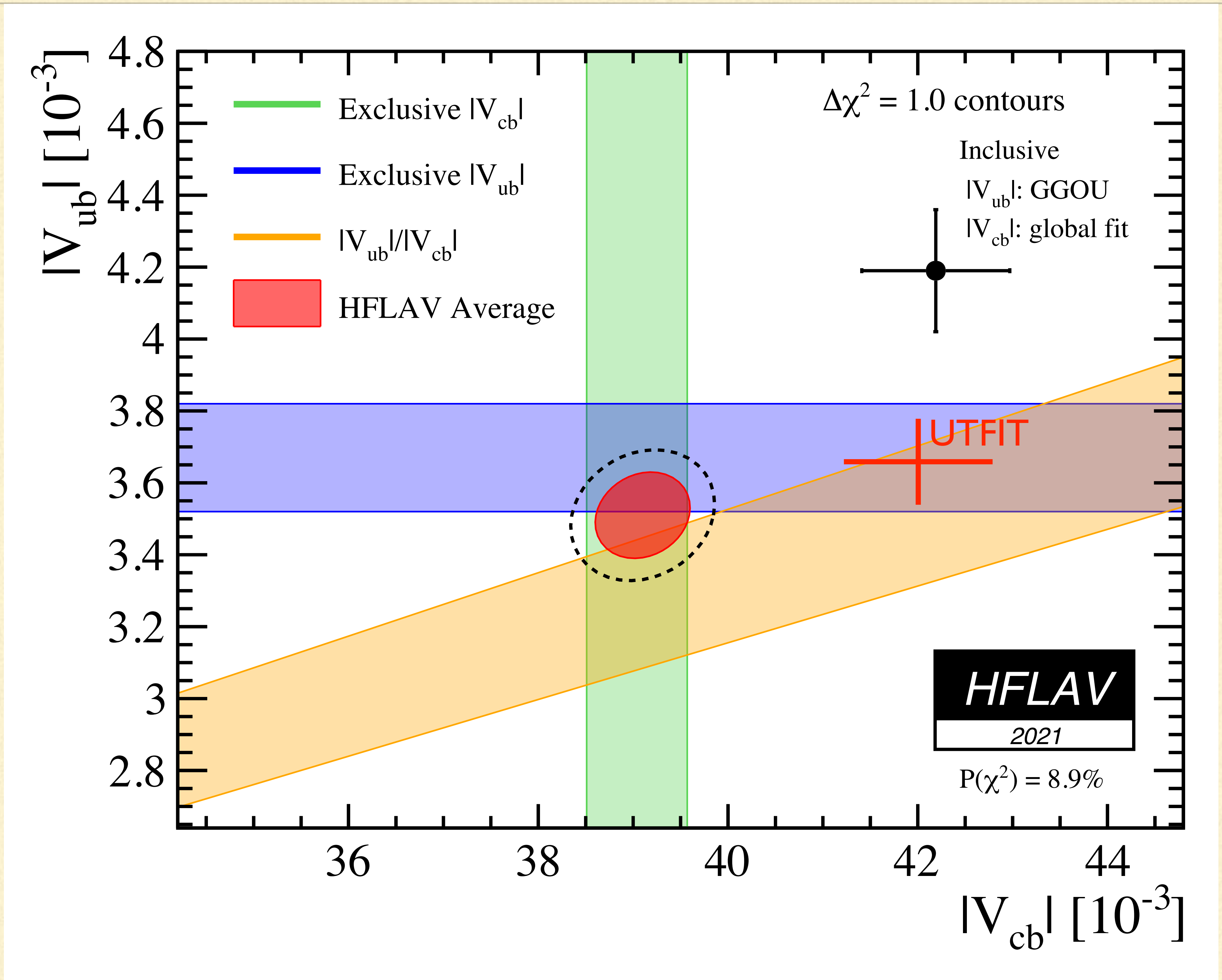




Semileptonic B decays measure the magnitude of the CKM matrix elements V_{cb} and V_{ub}

Their determinations from inclusive and exclusive decays differ since many years. Intense experimental and theoretical activity.

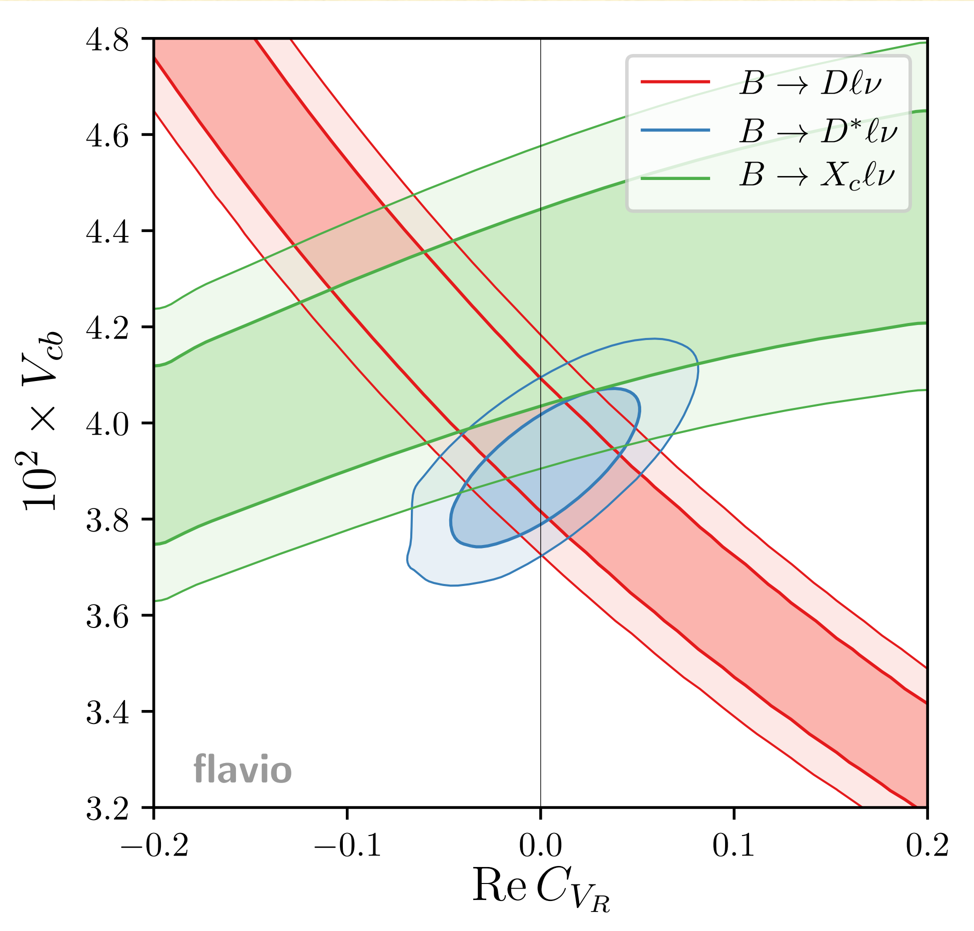
latest exp results suggest V_{ub} discrepancy may be fading away

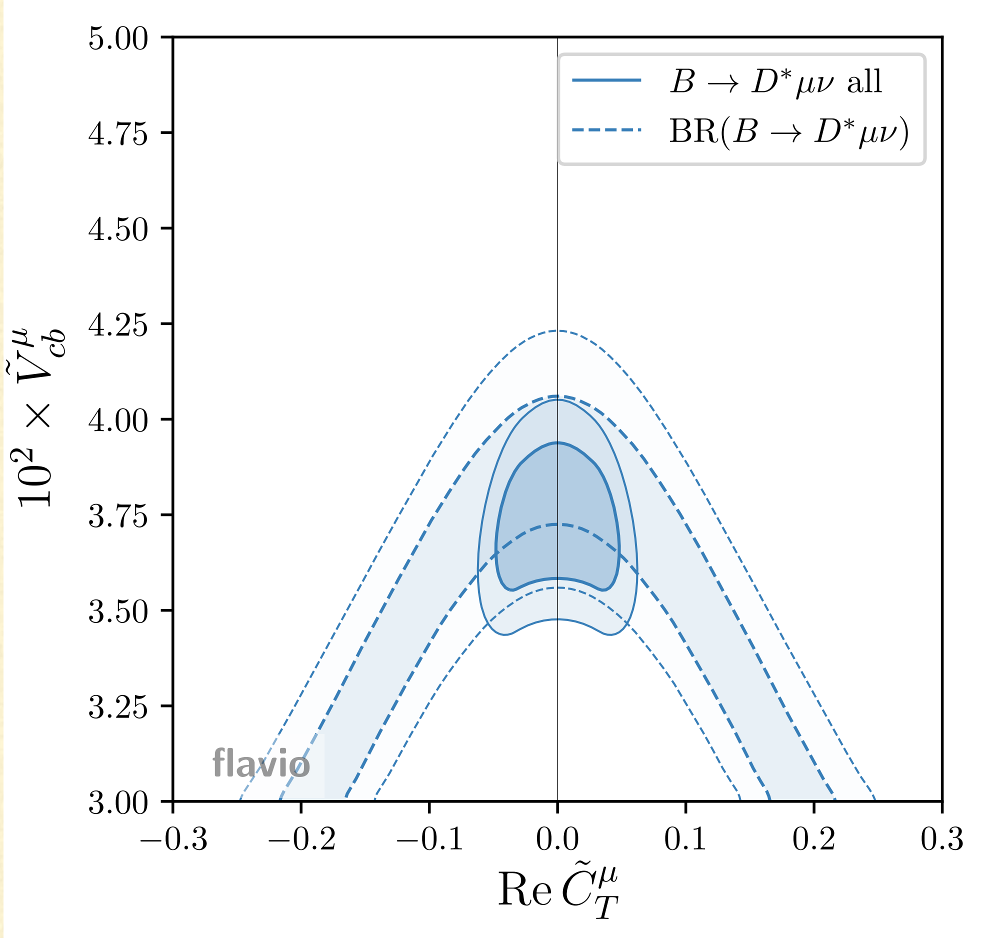


Recently: new calculations of FFs by several lattice collaborations and with light-cone sum rules, new perturbative calculations, all facing the challenges of precision measurements… and several new measurements as well!

NEW PHYSICS?

Jung & Straub, 1801.01112



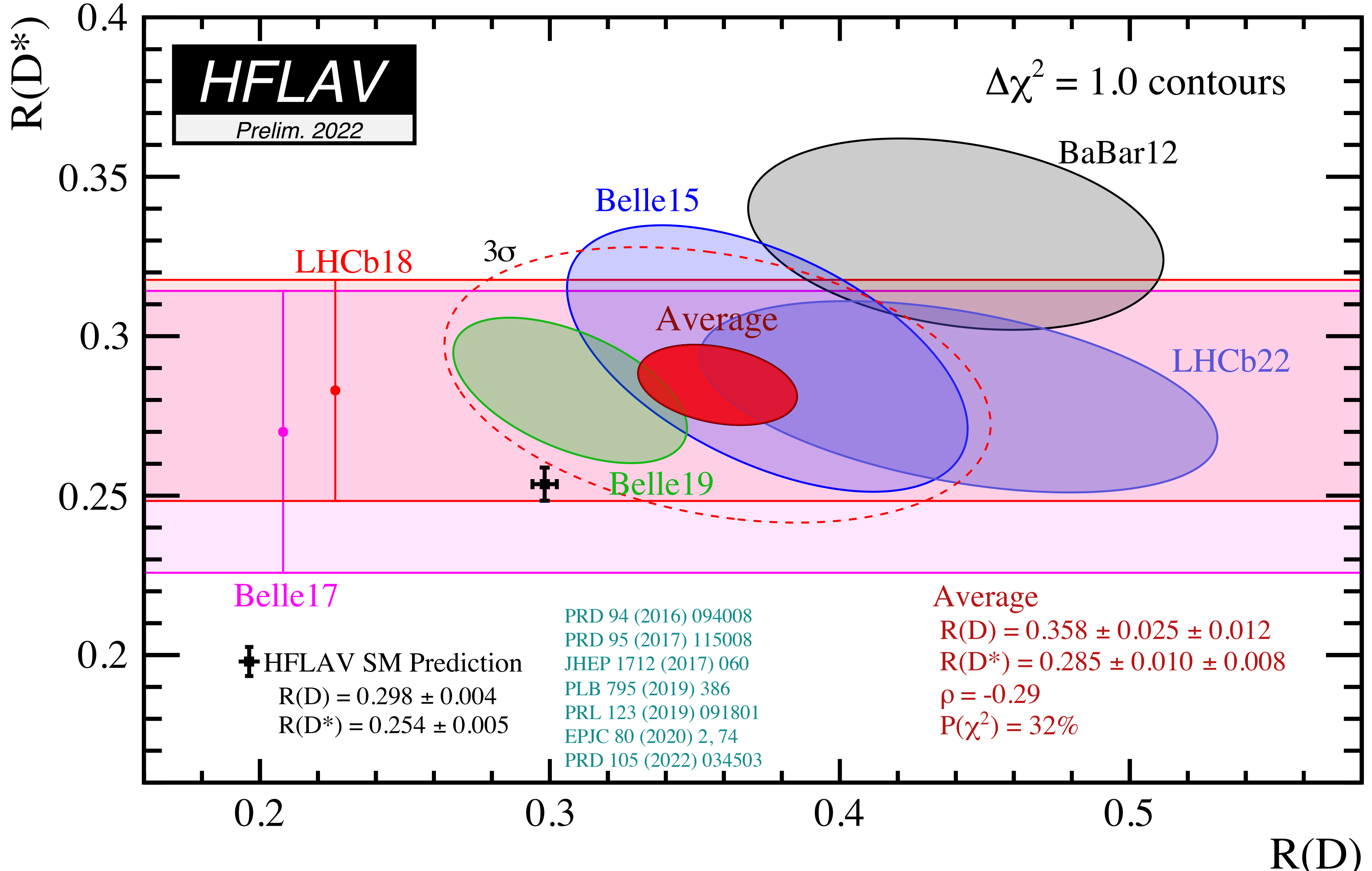


Differential distributions constrain NP strongly, SMEFT interpretation incompatible with LEP data: Crivellin, Pokorski, Jung, Straub…

VIOLATION of LFU with TAUS

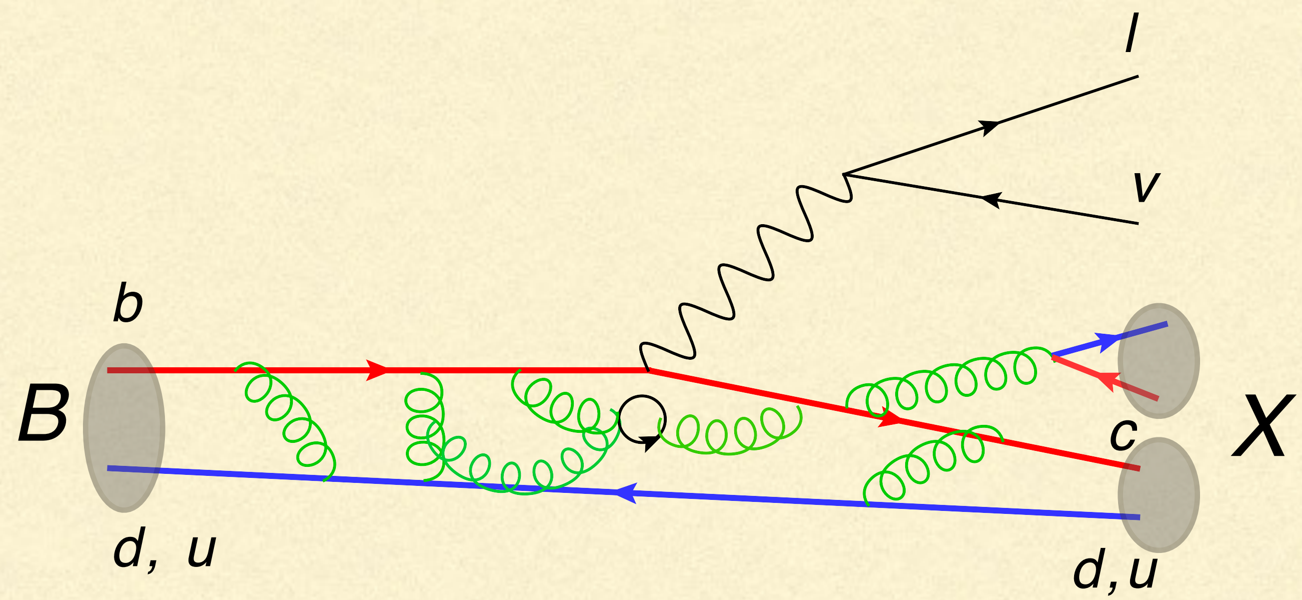
$$R\left(D^{(*)}\right) = \frac{\mathcal{B}\left(B \to D^{(*)}\tau\nu_\tau\right)}{\mathcal{B}\left(B \to D^{(*)}\ell\nu_\ell\right)}$$

SM predictions based on same theory as V_{cb} extraction



3.2σ from SM

INCLUSIVE DECAYS: BASICS



- ***Simple idea:*** inclusive decays do not depend on final state, long distance dynamics of the B meson factorizes. An OPE allows us to express it in terms of B meson matrix elements of local operators.

- The Wilson coefficients are perturbative, matrix elements of local ops parameterize non-pert physics: ***double series in*** $\alpha_s, \Lambda/m_b$

- Lowest order: decay of a free *b*, linear Λ/m_b absent. Depends on $m_{b,c}$, two parameters at $O(\Lambda^2/m_b^2)$, 2 more at $O(\Lambda^3/m_b^3)$ ... Many higher order effects have been computed.

INCLUSIVE SEMILEPTONIC B DECAYS

Inclusive observables are double series in Λ_{QCD}/m_b and α_s

$$M_i = M_i^{(0)} + \frac{\alpha_s}{\pi} M_i^{(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 M_i^{(2)} + \left(M_i^{(\pi,0)} + \frac{\alpha_s}{\pi} M_i^{(\pi,1)}\right) \frac{\mu_\pi^2}{m_b^2}$$
$$+ \left(M_i^{(G,0)} + \frac{\alpha_s}{\pi} M_i^{(G,1)}\right) \frac{\mu_G^2}{m_b^2} + M_i^{(D,0)} \frac{\rho_D^3}{m_b^3} + M_i^{(LS,0)} \frac{\rho_{LS}^3}{m_b^3} + \ldots$$

Global shape parameters (first moments of the distributions, with various lower cuts on E_l) tell us about m_b, m_c and the B structure, total rate about $|V_{cb}|$

OPE parameters describe universal properties of the B meson and of the quarks: they are useful in many applications (rare decays, V_{ub},...)

Reliability of the method depends on our control of higher order effects. Quark-hadron duality violation would manifest itself as inconsistency in the fit.

Kinetic scheme provides short distance definition of m_b and OPE parameters with hard cutoff $\mu_{kin} \sim 1\text{GeV}$. Fit includes all corrections $O(\alpha_s^2, \alpha_s/m_b^2, 1/m_b^3)$, m_c constraint from sum rules/lattice, and recent $O(\alpha_s^3)$ contribution to width.

3LOOP CALCULATIONS

Fael, Schoenwald, Steinhauser, 2011.11655, 2011.13654, 2205.03410

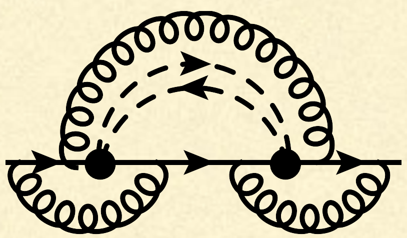
3loop and 2loop charm mass effects in relation between kinetic and $\overline{\mathrm{MS}}$ b mass

$$m_b^{kin}(1\mathrm{GeV}) = \left[4163 + 259_{\alpha_s} + 78_{\alpha_s^2} + 26_{\alpha_s^3}\right]\mathrm{MeV} = (4526 \pm 15)\,\mathrm{MeV}$$

Using FLAG $\overline{m}_b(\overline{m}_b) = 4.198(12)\mathrm{GeV}$ one gets $m_b^{kin}(1\mathrm{GeV}) = 4.565(19)\,\mathrm{GeV}$

3loop correction to ***total semileptonic width and moments without cuts***
(asymptotic expansion around $m_c = m_b$)

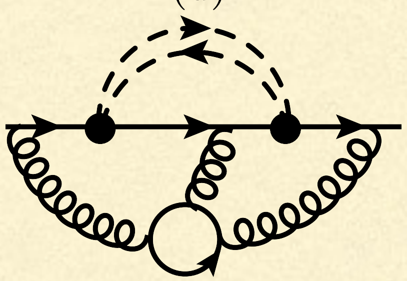
$$\Gamma_{sl} = \Gamma_0 f(\rho)\left[0.9255 - 0.1162_{\alpha_s} - 0.0350_{\alpha_s^2} - 0.0097_{\alpha_s^3}\right]$$



(d)

in the kin scheme with $\mu = 1\mathrm{GeV}$ and $\overline{m}_c(3\mathrm{GeV}) = 0.987\,\mathrm{GeV}$, $\mu_{\alpha_s} = m_b^{kin}$

$$\Gamma_{sl} = \Gamma_0 f(\rho)\left[0.9255 - 0.1140_{\alpha_s} - 0.0011_{\alpha_s^2} + 0.0103_{\alpha_s^3}\right]$$



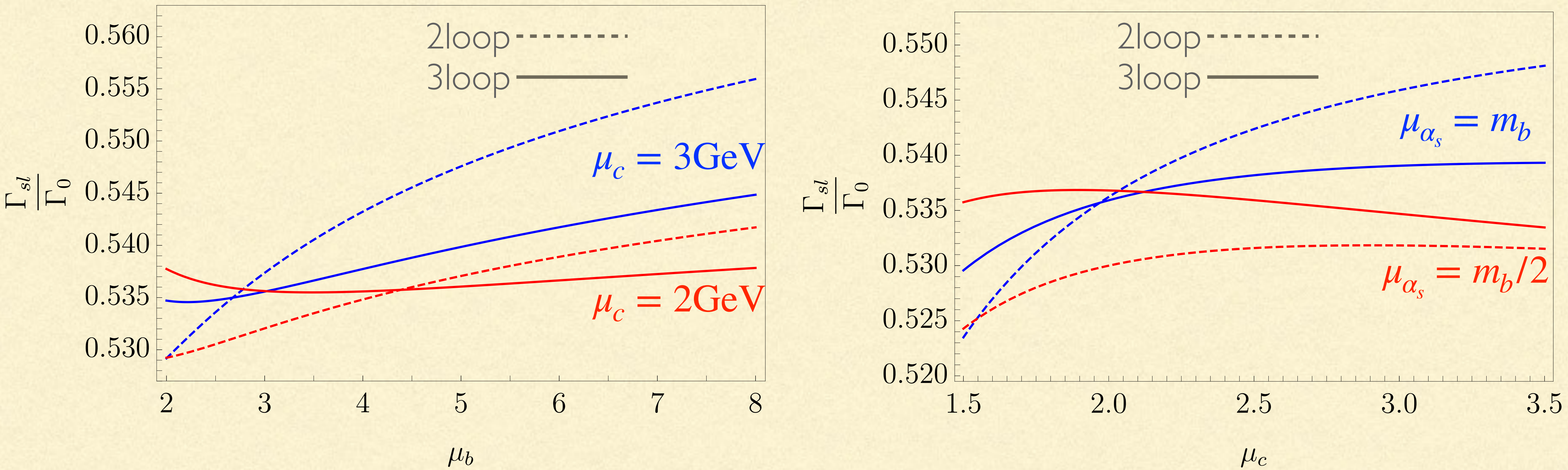
(f)

in the kin scheme with $\mu = 1\mathrm{GeV}$ and $\overline{m}_c(2\mathrm{GeV}) = 1.091\,\mathrm{GeV}$, $\mu_{\alpha_s} = m_b^{kin}/2$

3loop correction to Γ_{sl} around 1%, pushes $|V_{cb}|$ slightly up or down (~0.5%)

RESIDUAL UNCERTAINTY on Γ_{sl}

Bordone, Capdevila, PG, 2107.00604



Similar reduction in μ_{kin} dependence. Purely perturbative uncertainty $\pm 0.7\,\%$ (max spread), central values at $\mu_c = 2\text{GeV}, \mu_{\alpha_s} = m_b/2$.

$O(\alpha_s/m_b^2, \alpha_s/m_b^3)$ effects in the width are known. Additional uncertainty from higher power corrections, soft charm effects of $O(\alpha_s/m_b^3 m_c)$, duality violation.

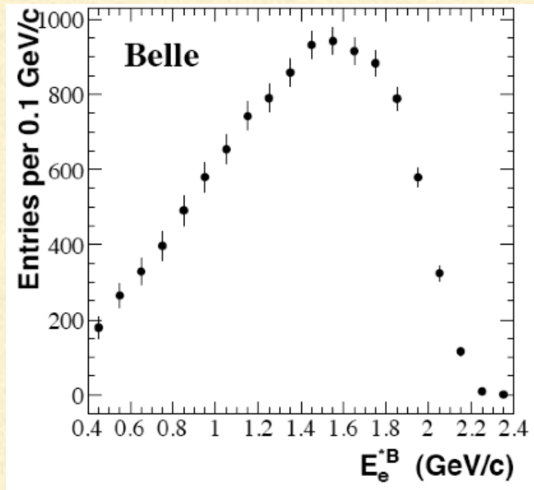
Conservatively: 1.2% overall theory uncertainty in Γ_{sl} (a ~50% reduction)

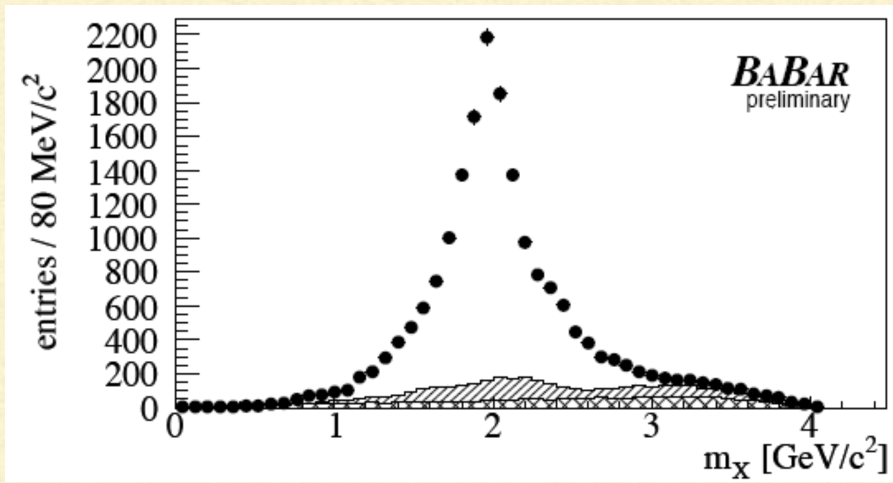
Interplay with fit to semileptonic moments, known only to $O(\alpha_s^2, \alpha_s\Lambda^2/m_b^2)$

INCLUSIVE SEMILEPTONIC FITS

Bordone, Capdevila, PG, 2107.00604

Electron energy and invariant hadronic mass spectra





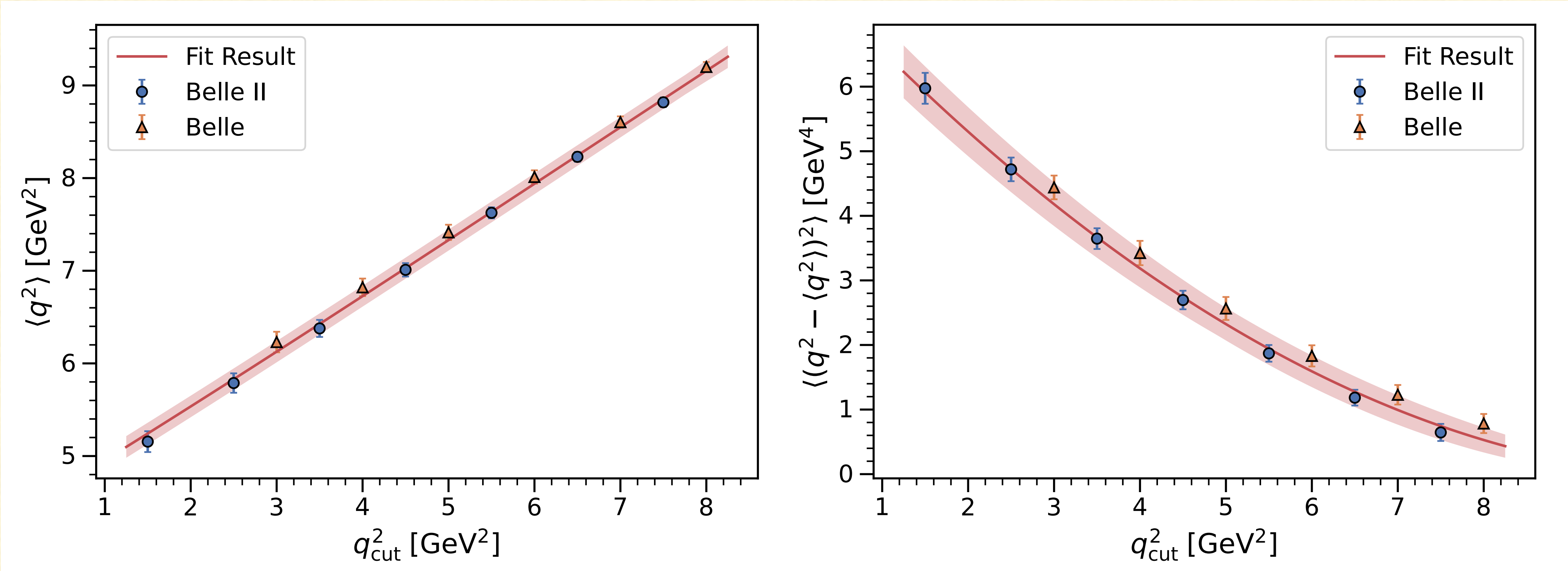
m_b^{kin}	$\overline{m}_c(2\text{GeV})$	μ_π^2	ρ_D^3	$\mu_G^2(m_b)$	ρ_{LS}^3	$\text{BR}_{c\ell\nu}$	$10^3\lvert V_{cb}\rvert$
4.573	1.092	0.477	0.185	0.306	-0.130	10.66	42.16
0.012	0.008	0.056	0.031	0.050	0.092	0.15	0.51

Higher power corrections see a proliferation of parameters but Wilson coefficients are known at LO. We use the Lowest Lying State Saturation Approximation (Mannel,Turczyk,Uraltsev 1009.4622) as loose constraint or priors (60% gaussian uncertainty, dimensional estimate for vanishing matrix elements) in a fit including higher powers.

$$|V_{cb}| = 42.00(53) \times 10^{-3}$$

Update of 1606.06174
similar results in 1S scheme Bauer et al.

q^2 MOMENTS



2205.10274

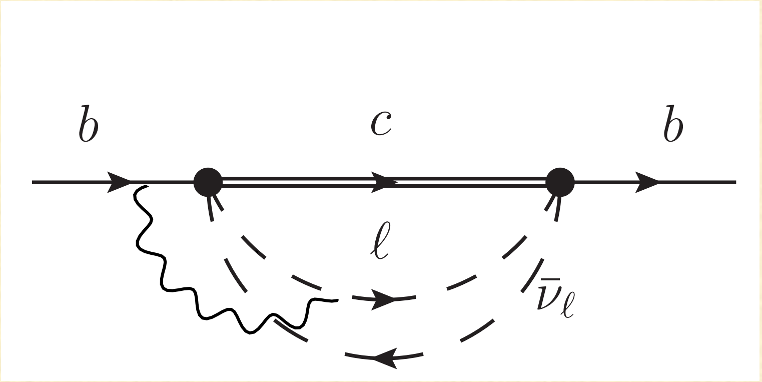
New measurements of the q^2 moments by Belle (2109.01685) and Belle II (2205.06372) not yet included in our fit (work in progress).

Reparametrisation invariance implies that q^2 moments and total width depend on a smaller set of HQE parameters (Fael, Mannel, Vos), 8 at $O(1/m_b^4)$, but *using only the q^2 moments*: ***$|V_{cb}|$= 41.99(65) 10^{-3}*** using the same BR input we employ (Bernlochner et al. 2205.10274)

It would be useful to measure also the FB asymmetry as proposed by Turzcyk

QED CORRECTIONS

D.Bigi, Bordone, Haisch, PG

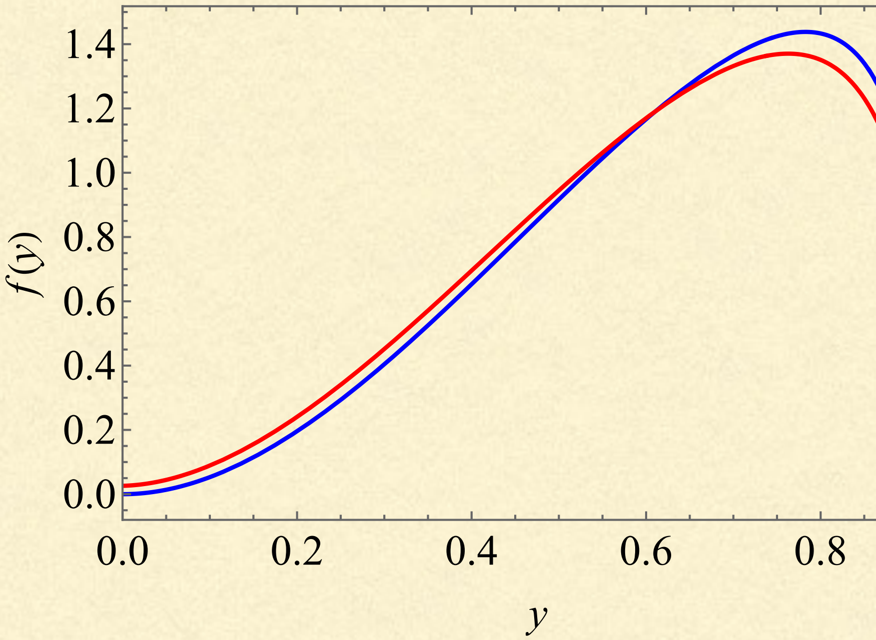


In the presence of photons, ***OPE valid only for total width*** and moments that do not resolve lepton properties (E_ℓ, q^2). Expect mass singularities and $O(\alpha\Lambda/m_b)$ corrections.

Leading logs $\alpha \ln m_e/m_b$ can be easily computed for simple observables using structure function approach, for ex the lepton energy spectrum

$$\left(\frac{d\Gamma}{dy}\right)^{(1)} = \frac{\alpha}{2\pi} \ln \frac{m_b^2}{m_\ell^2} \int_y^1 \frac{dx}{x} P_{\ell\ell}^{(0)}\left(\frac{y}{x}\right) \left(\frac{d\Gamma}{dx}\right)^{(0)}$$

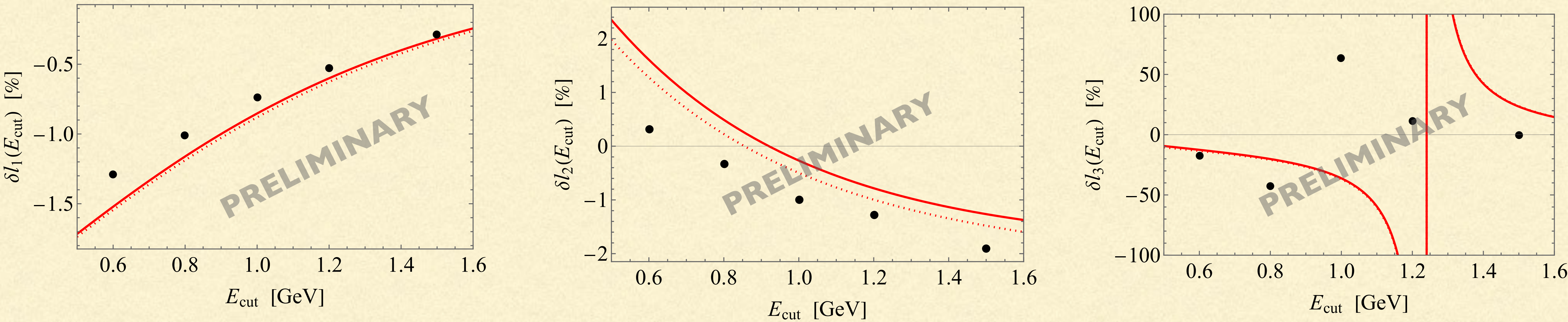
$$P_{\ell\ell}^{(0)}(z) = \left[\frac{1+z^2}{1-z}\right]_+$$



Electron energy spectrum

LEPTONIC MOMENTS

D.Bigi, Bordone, Haisch, PG



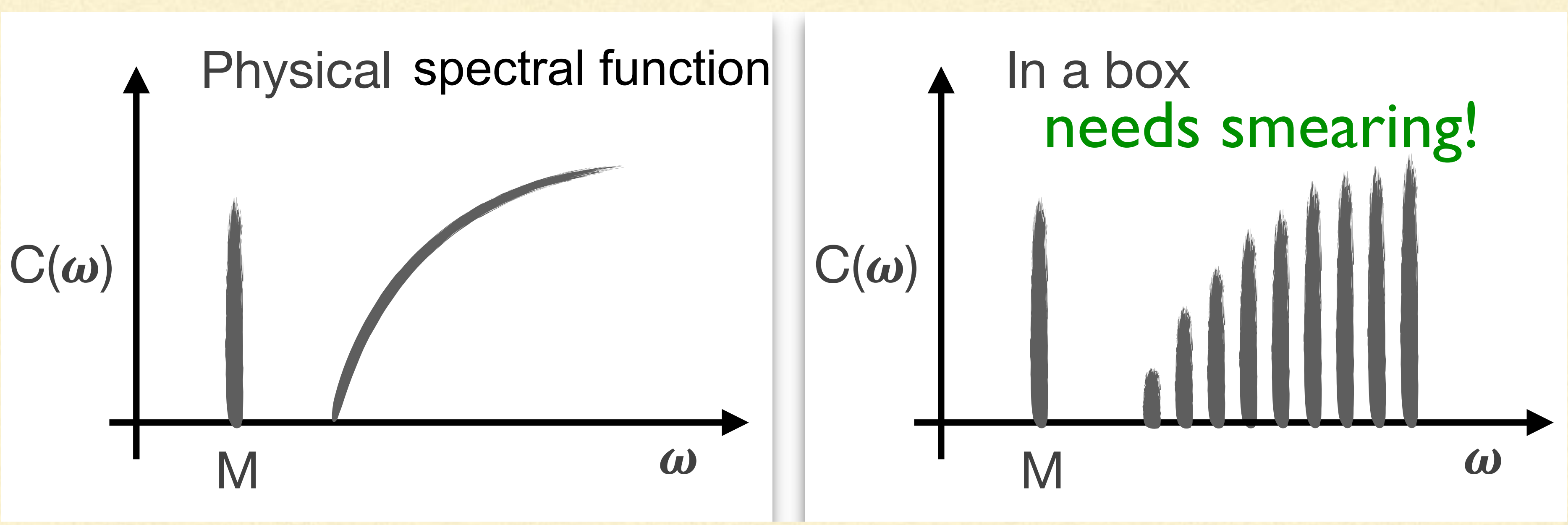
Typically exp measurements are completely inclusive, $B \to X_c \ell \nu(\gamma)$, but QED radiation is ***subtracted*** by experiments using ***Photos*** (soft-collinear photon radiation to MC final states).

BaBar hep-ex/0403030 provides both uncorrected and corrected lepton moments, allowing for comparison with our inclusive LL calculation. Shifts are 0.2-0.7σ_{exp} but NLO logs and effects on power corrections can be included.
Complete $O(\alpha)$ calculation checks subleading terms and other moments.

INCLUSIVE DECAYS ON THE LATTICE

Inclusive processes impractical to treat directly on the lattice. Vacuum current correlators computed in euclidean space-time are related to $e^+e^- \to$ hadrons or τ decay via analyticity. In our case the correlators have to be computed in the *B* meson, but analytic continuation more complicated: two cuts, decay occurs only on a portion of the physical cut.

While the lattice calculation of the spectral density of hadronic correlators is an ***ill-posed problem***, the spectral density is accessible after smearing
Hansen, Meyer, Robaina, Hansen, Lupo, Tantalo, Bailas, Hashimoto, Ishikawa



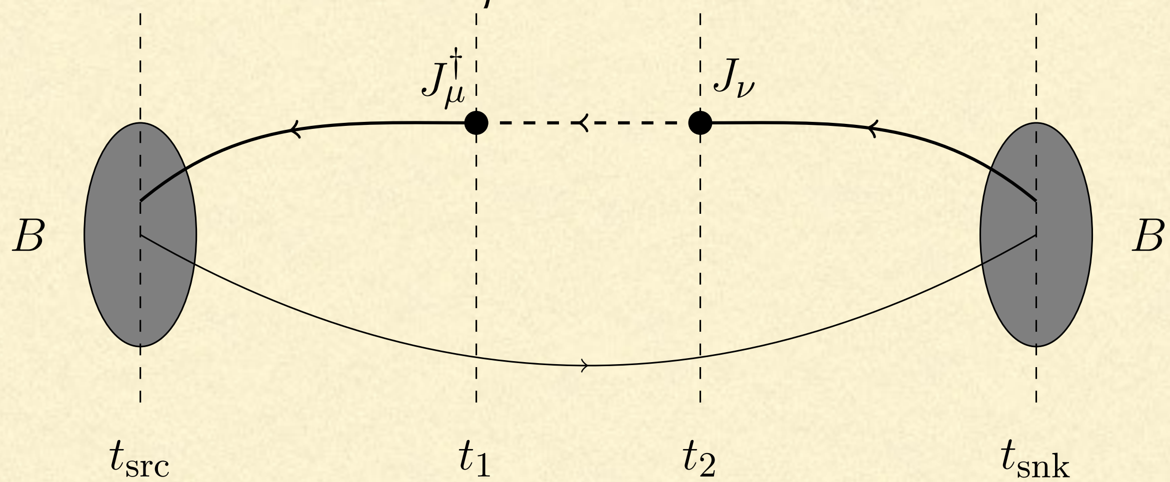
W. Jay @Snowmass workshop

A NEW APPROACH

Hashimoto, PG 2005.13730

4-point functions on the lattice are related to the hadronic tensor in euclidean

$$\sim \langle B | J_\mu^\dagger(\mathbf{x}, t) J_\nu(\mathbf{0}, 0) | B \rangle$$

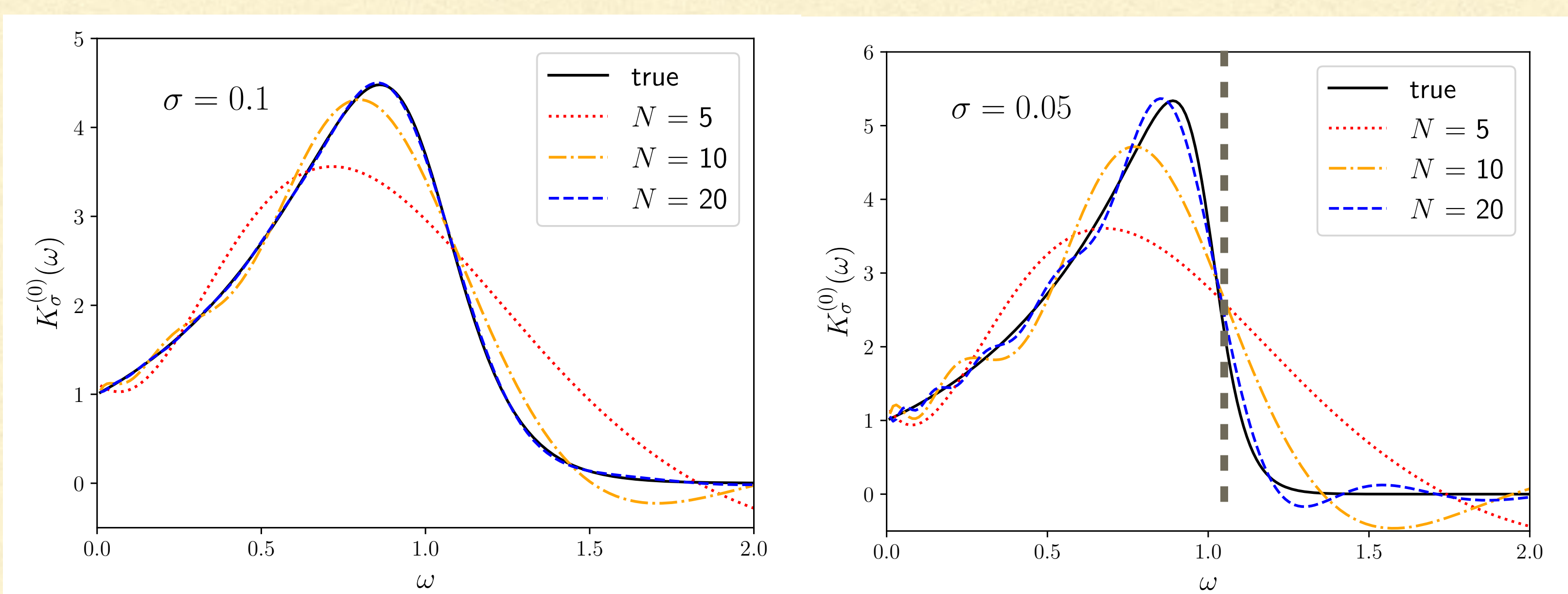


$$d\Gamma \sim L^{\mu\nu} W_{\mu\nu}$$

$$\int d^3x \frac{e^{i\mathbf{q}\cdot\mathbf{x}}}{2M_B} \langle B | J_\mu^\dagger(\mathbf{x}, t) J_\nu(\mathbf{0}, 0) | B \rangle \sim \int_0^\infty d\omega W_{\mu\nu} e^{-t\omega}$$

smearing kernel $f(\omega) = \sum_n a_n e^{-na\omega}$

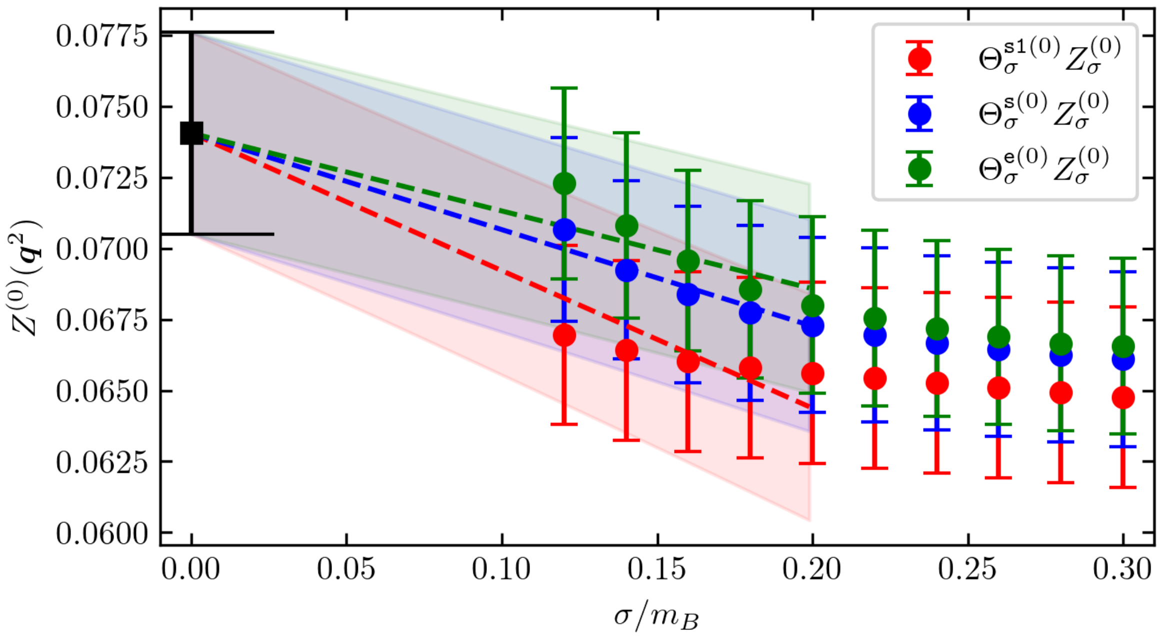
The necessary smearing is provided by phase space integration over the hadronic energy, which is cut by a θ with a sharp hedge: sigmoid $1/(1+e^{x/\sigma})$ can be used to replace kinematic $\theta(x)$ for $\sigma \to 0$. Larger number of polynomials needed for small σ

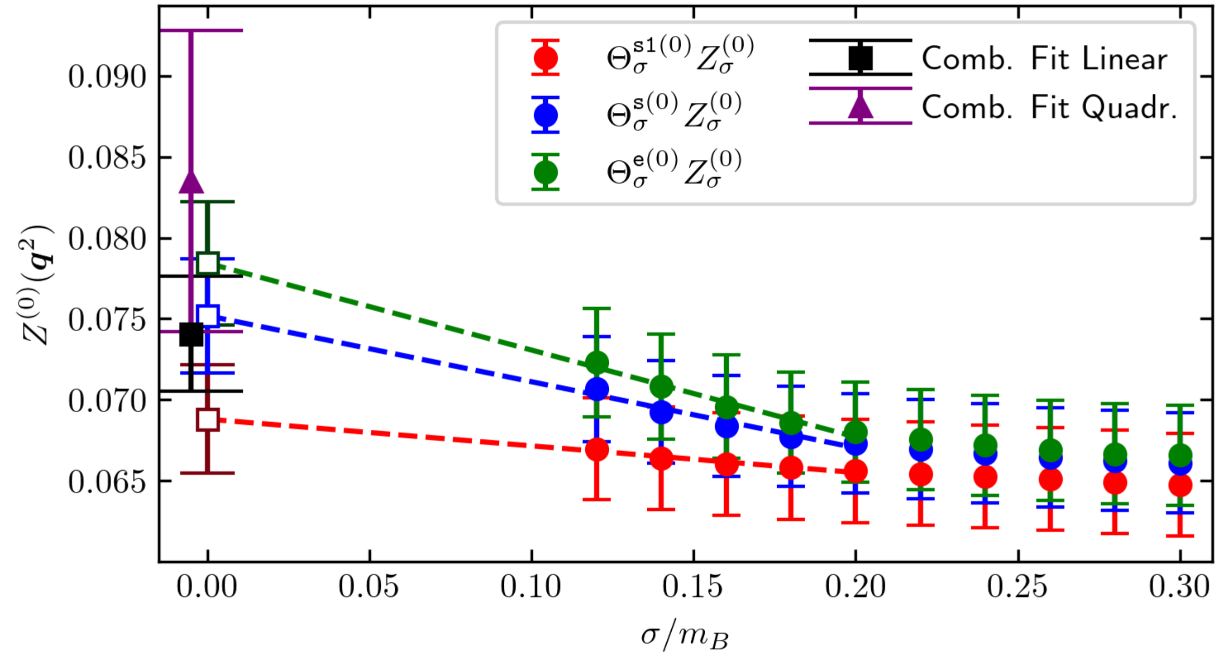


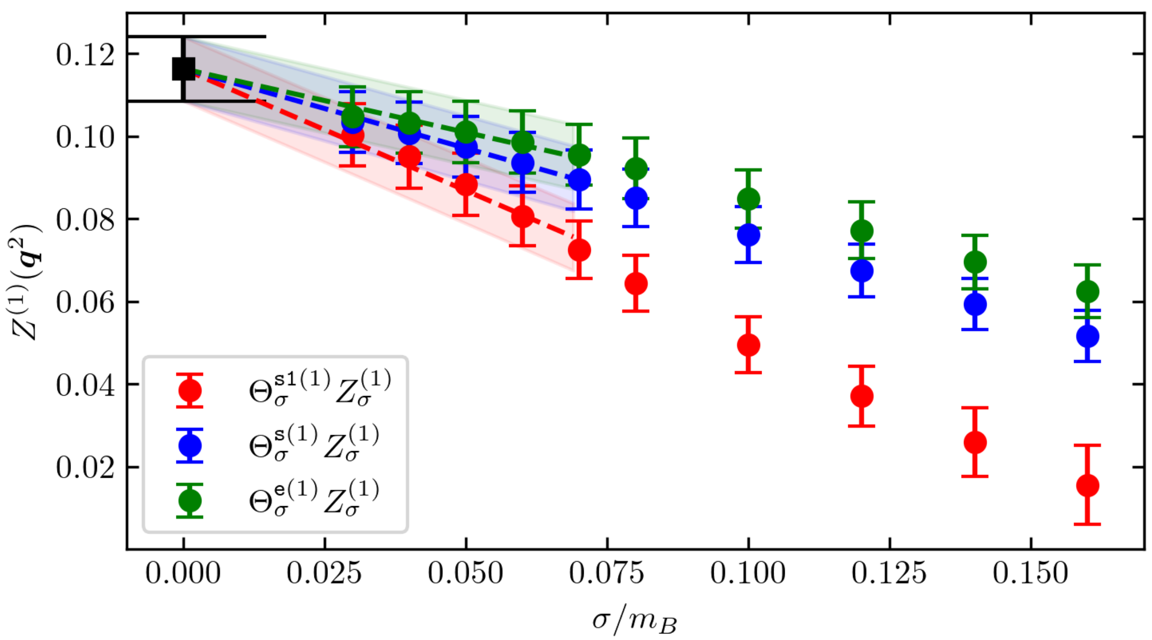
Two methods based on Chebyshev polynomials and Backus-Gilbert. Important:

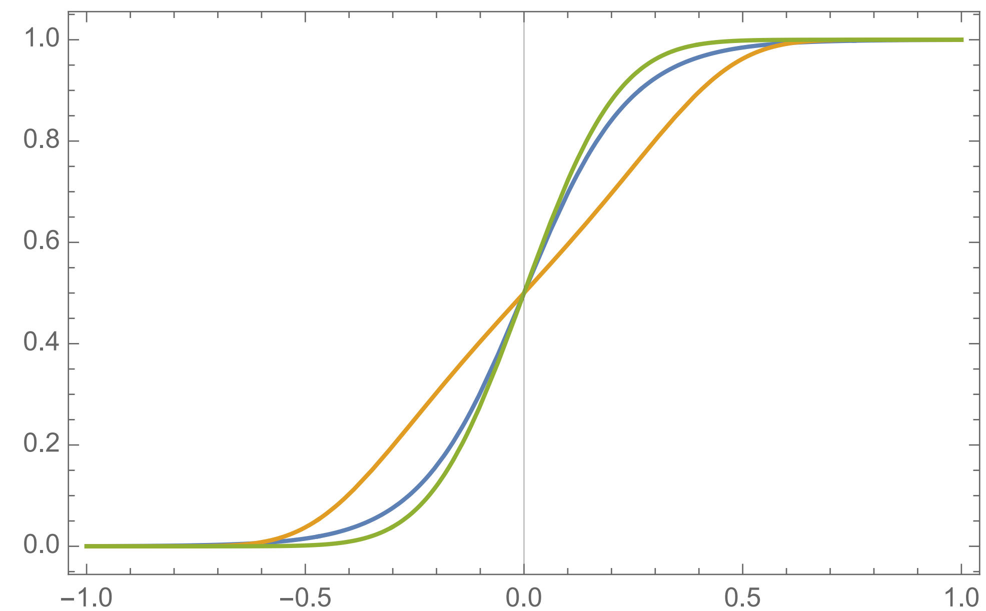
$$\lim_{\sigma\to 0} \lim_{V\to\infty} \bar{X}_\sigma$$

in detail





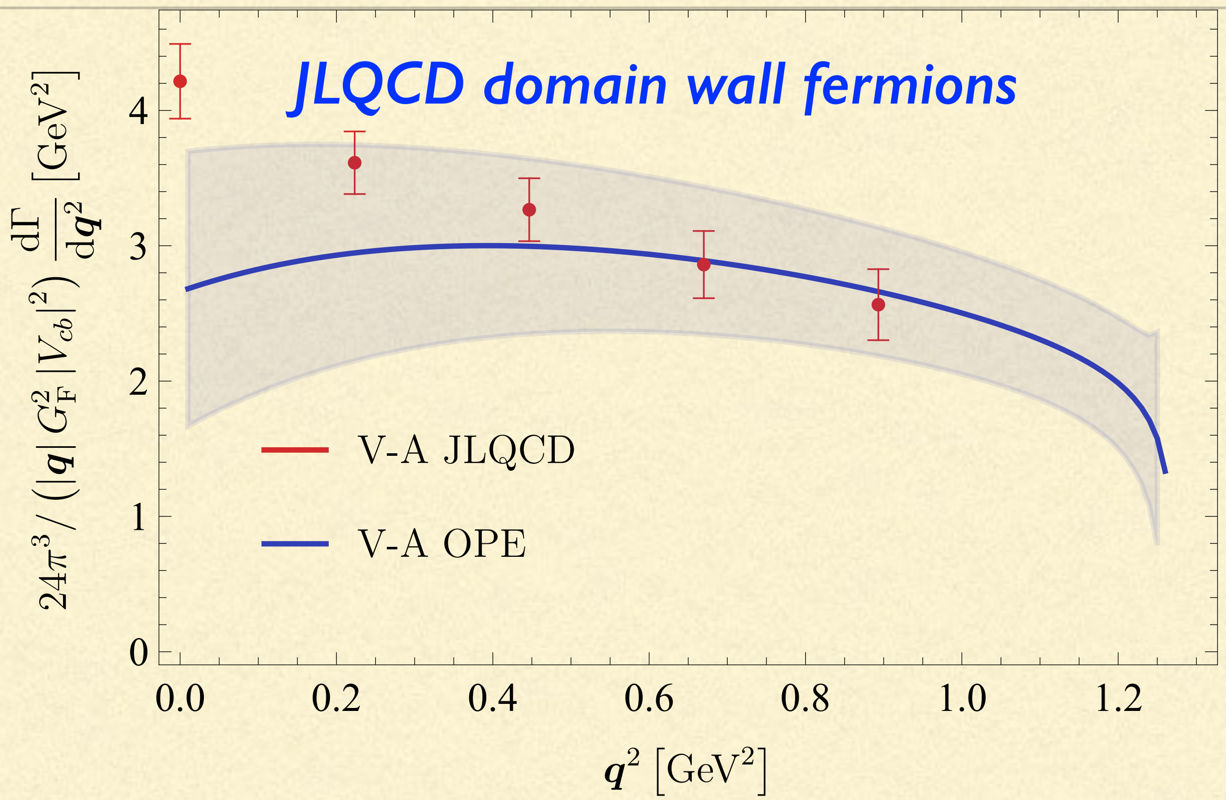


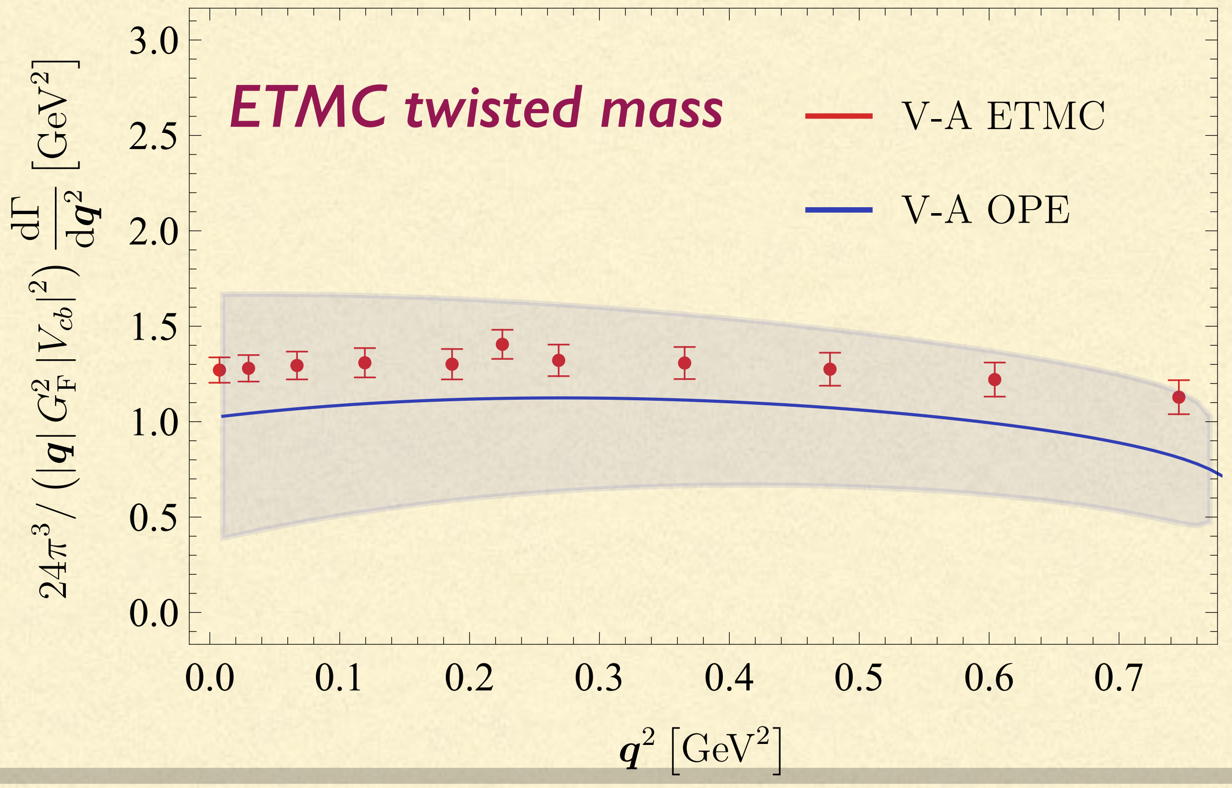


ETMC at $|\mathbf{q}| = 0.5\text{GeV}$

Using different approx to the kernel
improves the $\sigma \to 0$ extrapolation
Interplay with continuum and infinite volume limits

LATTICE VS OPE





m_b^{kin} (JLQCD)	2.70 ± 0.04
$\overline{m}_c(2\text{ GeV})$ (JLQCD)	1.10 ± 0.02
m_b^{kin} (ETMC)	2.39 ± 0.08
$\overline{m}_c(2\text{ GeV})$ (ETMC)	1.19 ± 0.04
μ_π^2	0.57 ± 0.15
ρ_D^3	0.22 ± 0.06
$\mu_G^2(m_b)$	0.37 ± 0.10
ρ_{LS}^3	-0.13 ± 0.10
$\alpha_s^{(4)}(2\text{ GeV})$	0.301 ± 0.006

OPE inputs from fits to exp data (physical m_b), HQE of meson masses on lattice

1704.06105, J.Phys.Conf.Ser. 1137 (2019) 1, 012005

We include $O(1/m_b^3)$ and $O(\alpha_s)$ terms

Hard scale $\sqrt{m_c^2 + \mathbf{q}^2} \sim 1 - 1.5\,\text{GeV}$

We do not expect OPE to work at high $|\mathbf{q}|$

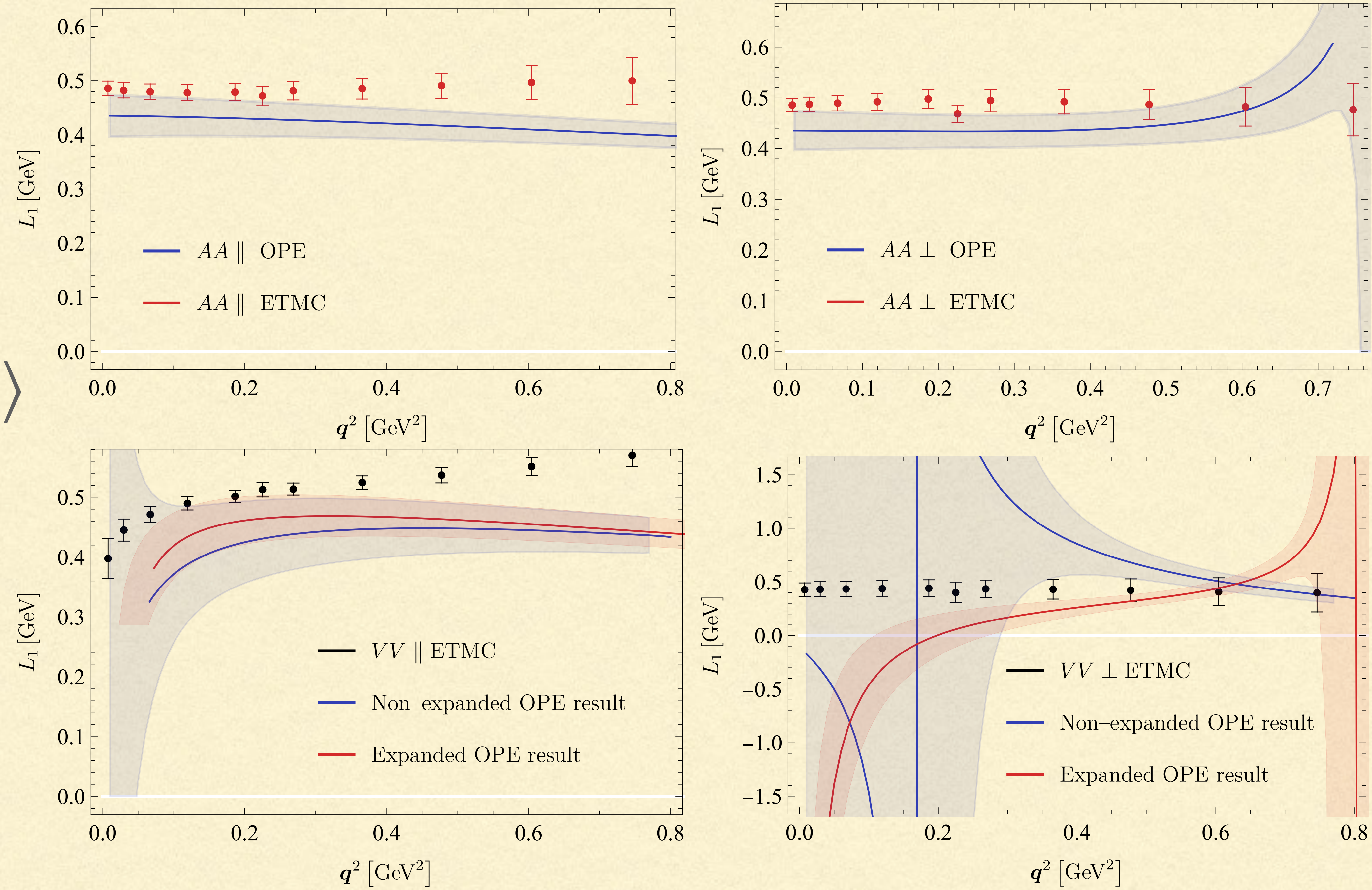
Twisted boundary conditions allow for any value of $\vec{q}^2$

Smaller statistical uncertainties

MOMENTS

PG, Hashimoto, Maechler, Panero, Sanfilippo, Simula, Smecca, Tantalo, 2203.11762

$$L_1 = \langle E_\ell(\mathbf{q}^2) \rangle$$



smaller errors, cleaner comparison with OPE, individual channels AA, VV, parallel and perpendicular polarization, could help extracting its parameters

First results at the physical *b* mass

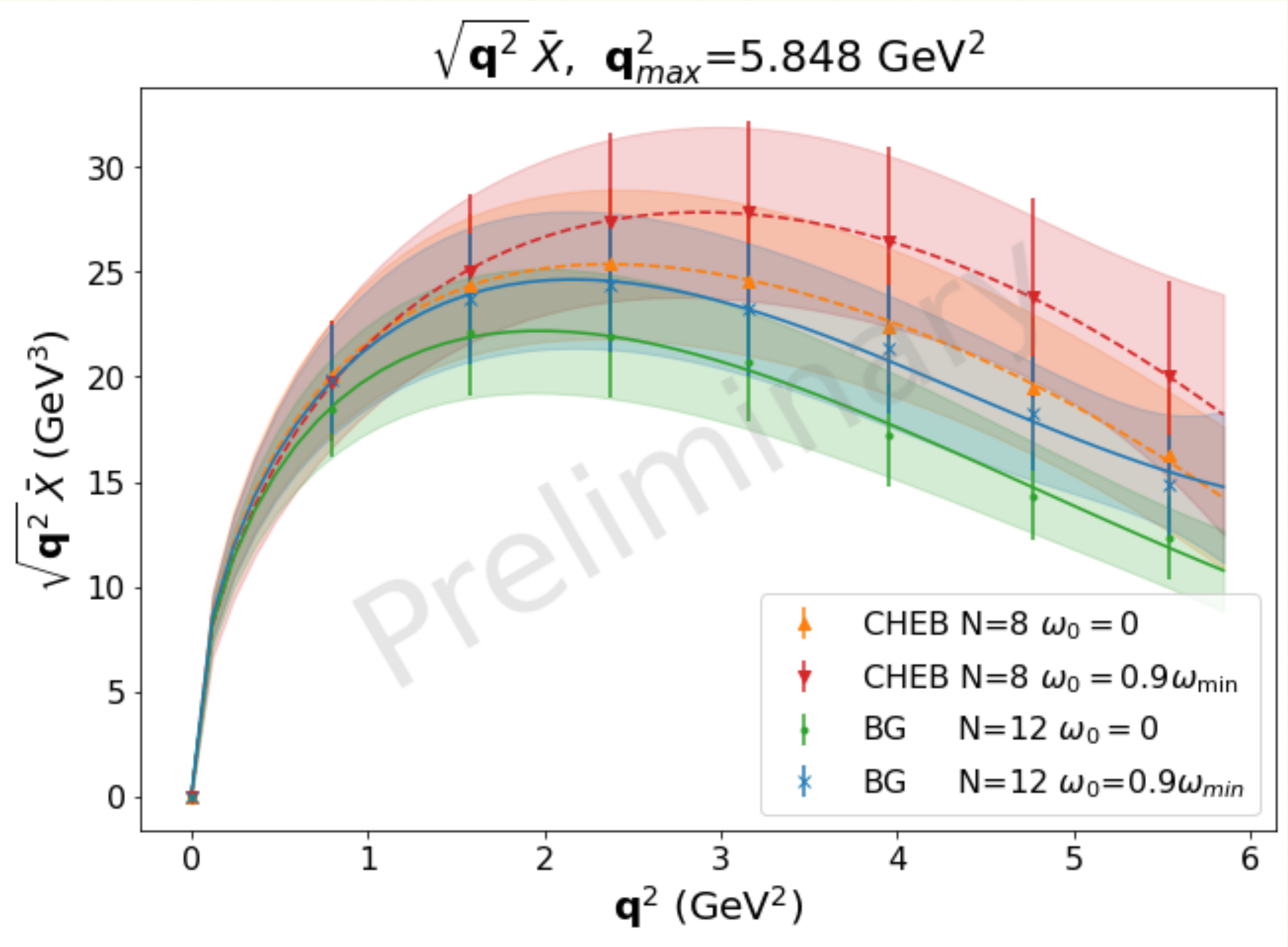
Relativistic heavy quark effective action for b

B_s decays

domain wall fermions

improved Backus-Gilbert

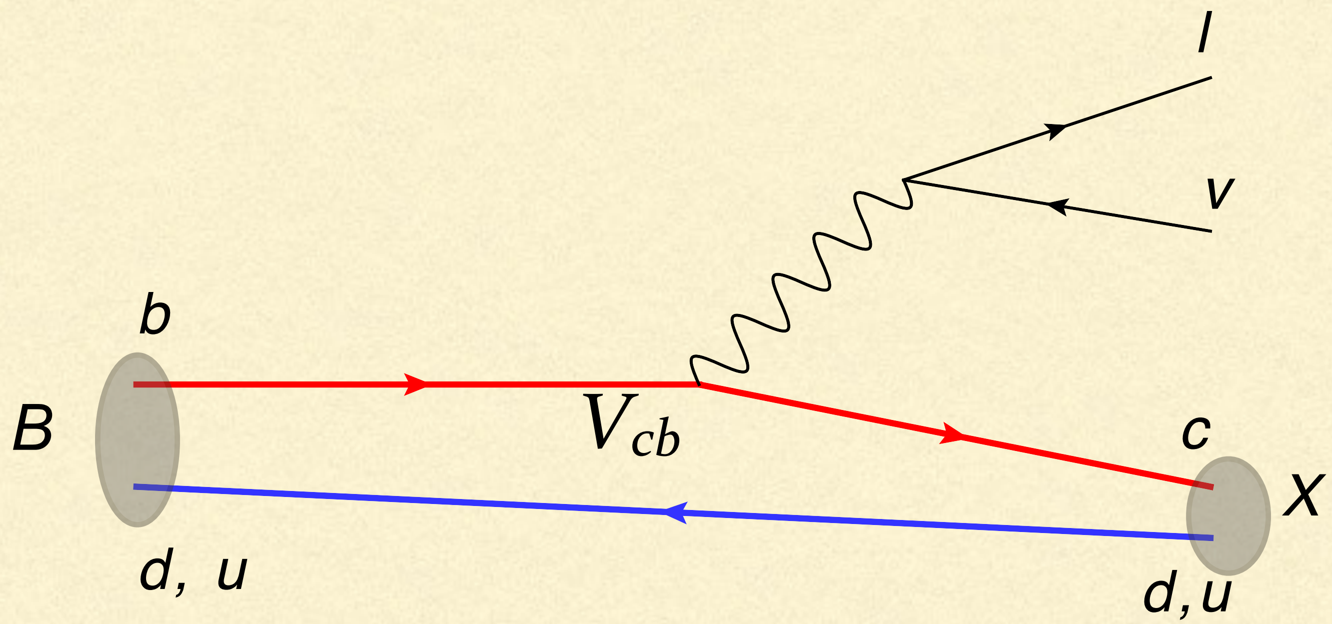
~10% determination of total width
possibly compare with partial width at low $\boldsymbol{q}^2$



Barone, Hashimoto, Juttner, Kaneko, Kellermann, 2211.15623

Ongoing work on ***semileptonic D_s decays*** by two collaborations

EXCLUSIVE DECAYS



$= D, D^*, \ldots$

There are 1(2) and 3(4) FFs for D and D* for light (heavy) leptons, for instance

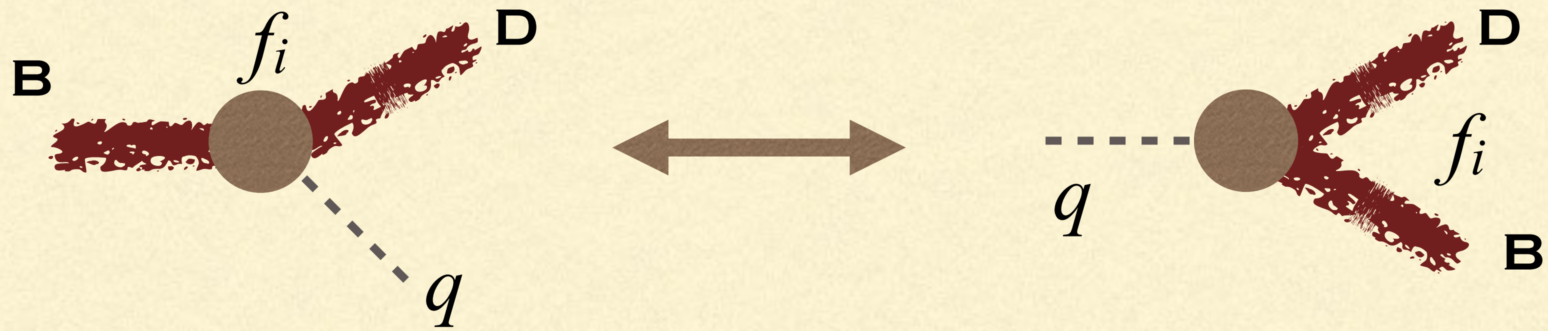
$$\langle D(k)|\,\bar{c}\gamma^\mu b\,|\bar{B}(p)\rangle = \left[(p+k)^\mu - \frac{M_B^2 - M_D^2}{q^2} q^\mu\right] f_+^{B\to D}(q^2) + \frac{M_B^2 - M_D^2}{q^2} q^\mu f_0^{B\to D}(q^2)$$

Information on FFs from LQCD (at high q^2), LCSR (at low q^2), HQE, exp, extrapolation, unitarity constraints, …

A ***model independent parametrization*** is necessary

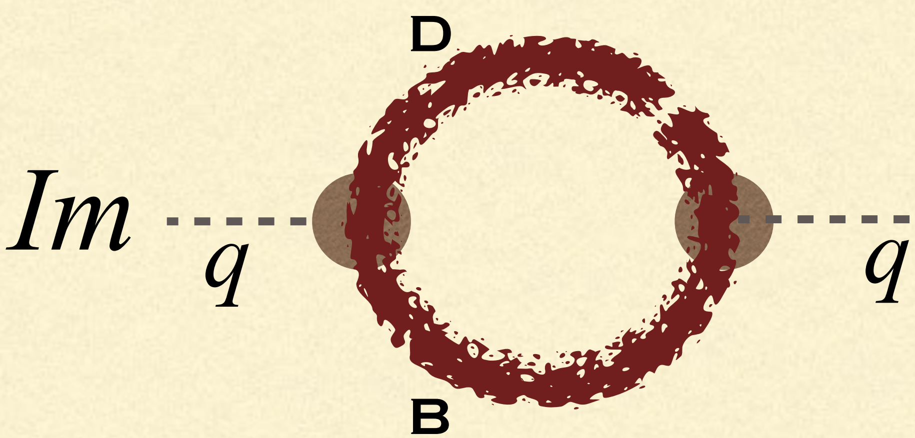
MODEL INDEPENDENT FF PARAMETRIZATION

crossing + analitycity



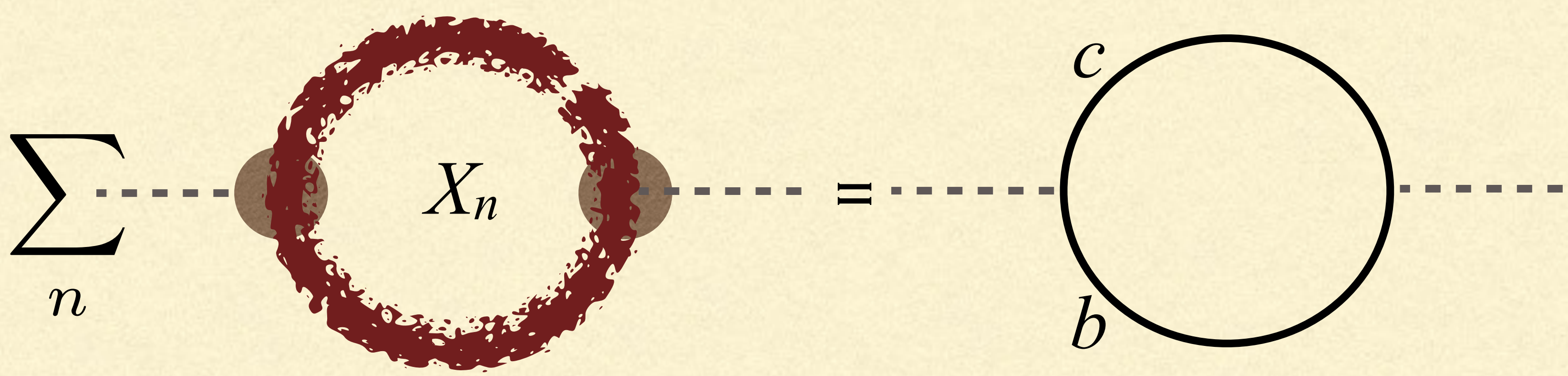
physical semileptonic region
$m_\ell^2 \le q^2 \le (m_B - m_D)^2$

2-point correlator cuts
$q^2 \ge (m_B + m_D)^2$



$\propto |f_i(q^2)|^2 < \sum_n \text{cuts}(X_n)$

poles at $q^2 = m^2_{Bc}$ etc



+ *pert corr* + *condensates*

using quark-hadron duality (OPE) + dispersion relations

PARAMETRIZATIONS

- ***Boyd-Grinstein-Lebed*** (***BGL*** 1995) based on crossing & analyticity, unitarity constraints

  based on OPE $$F(q^2) = \bar{F}(q^2) \sum_{k=0}^{\infty} a_k\, z(q^2)^n \qquad \text{with} \qquad \sum_k a_k^2 \leq 1,$$

  $0 < z < \sim 0.06$ in the physical region. Series must be truncated in a controlled way.

- HQET for $B^{(*)} \to D^{(*)}$ form factors:

$$F_i(w) = \xi(w) \left[1 + c_\alpha^i \frac{\alpha_s}{\pi} + c_b^i \frac{\overline{\Lambda}}{2m_b} + c_c^i \frac{\overline{\Lambda}}{2m_c} + \ldots \right]$$

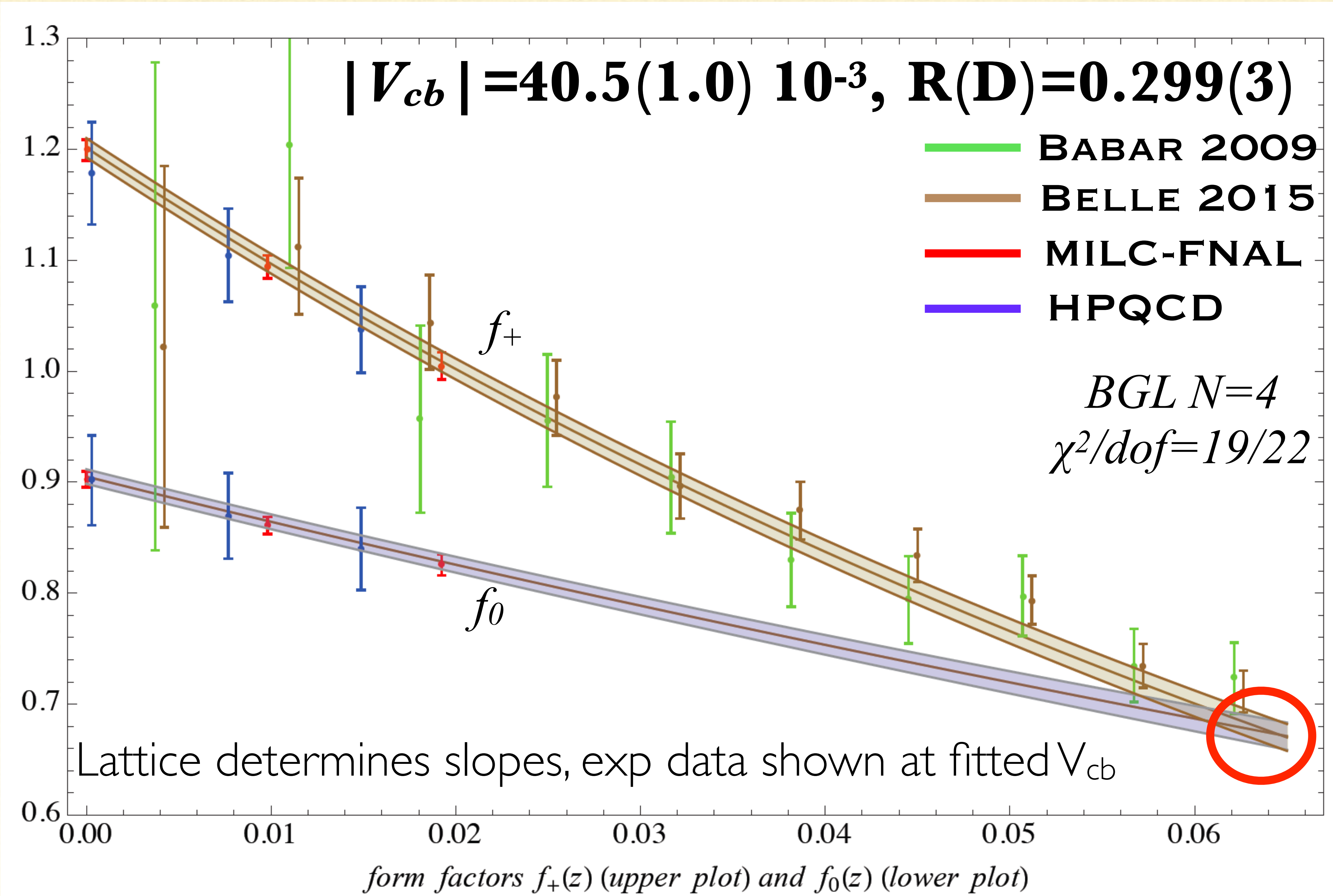
- $c^i_{b,c}$ can be computed using subleading IW functions from QCD sumrules Neubert, Ligeti, Nir 1992-93, Bernlochner et al 1703.05330

- *Ratios free of Isgur-Wise function: can use to get **strong unitarity bounds** but $1/m_c^2$ corrections can be significant as shown by lattice calculations*

- ***Caprini-Lellouch-Neubert*** (***CLN*** 1998) parametrization is simpler with fewer parameters, but relies on NLO HQET. All exp analyses before 2017 were based on CLN, did not include uncertainty.

LATTICE + EXP BGL FIT for $B \to Dl\nu$

Bigi, PG 1606.08030



R(D)=0.299(3)

1.9σ from exp

FLAG has very similar results

CLN cannot fit both ff

kinematic constraint at $q^2=0$

D'AGOSTINI BIAS

Standard χ^2 fits sometimes lead to paradoxical results

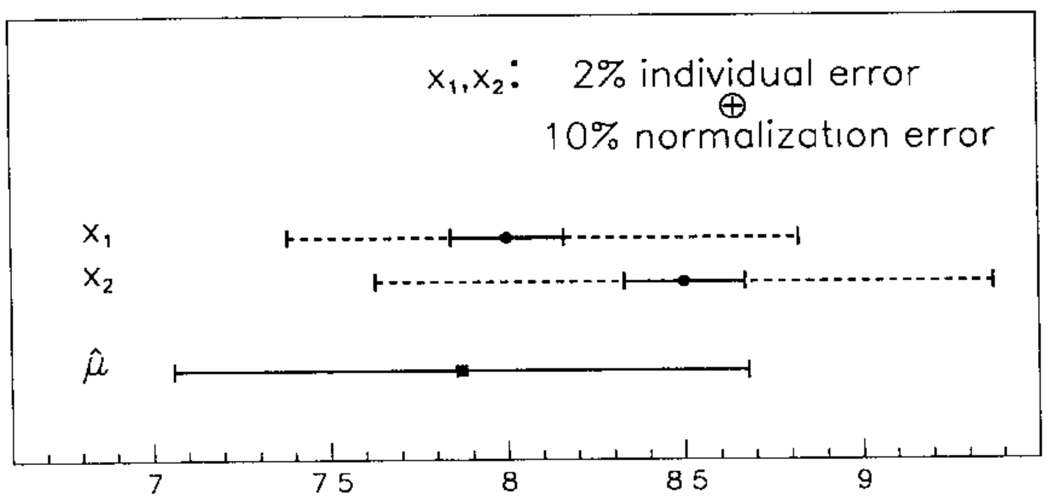


Fig. 1. Best estimate of the true value from two correlated data points, using in the χ^2 the empirical covariance matrix of the meaurements. The error bars show individual and total errors.

$$\hat{k} = \frac{x_1\sigma_2^2 + x_2\sigma_1^2}{\sigma_1^2 + \sigma_2^2 + (x_1 - x_2)^2\sigma_f^2},$$

Many exp systematics are highly correlated. Bias is stronger with more bins

On the use of the covariance matrix to fit correlated data

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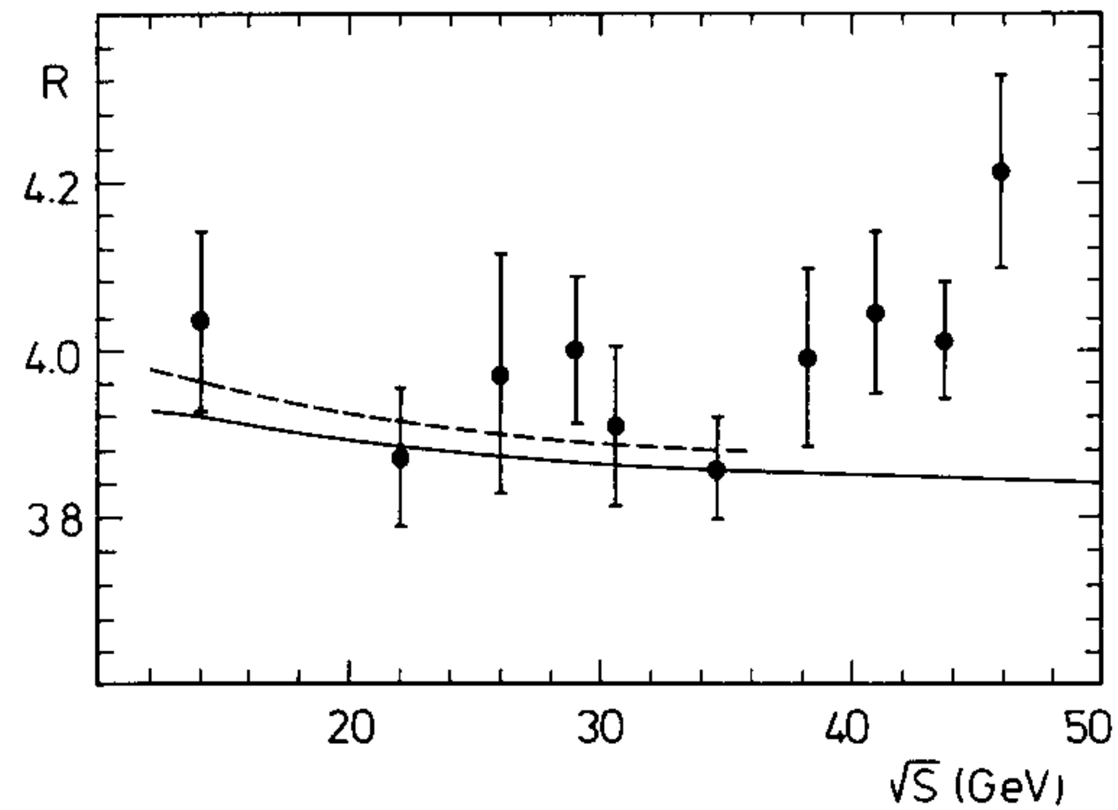
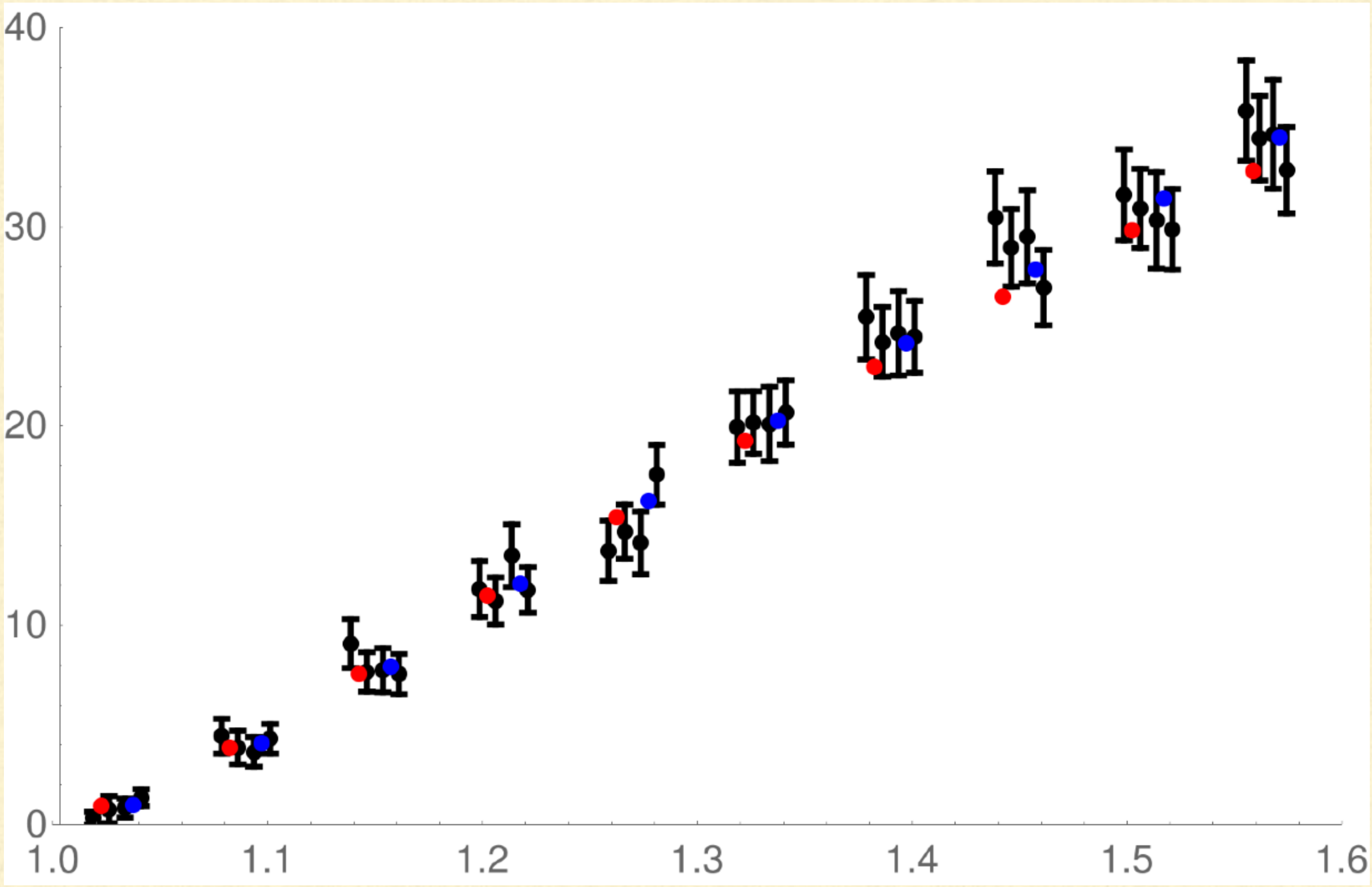


Fig. 2. R measurements from PETRA and PEP experiments with the best fits of QED + QCD to all the data (full line) and only below 36 GeV (dashed line). All data points are correlated (see text).

w DISTRIBUTION for $B \to D\ell\nu$

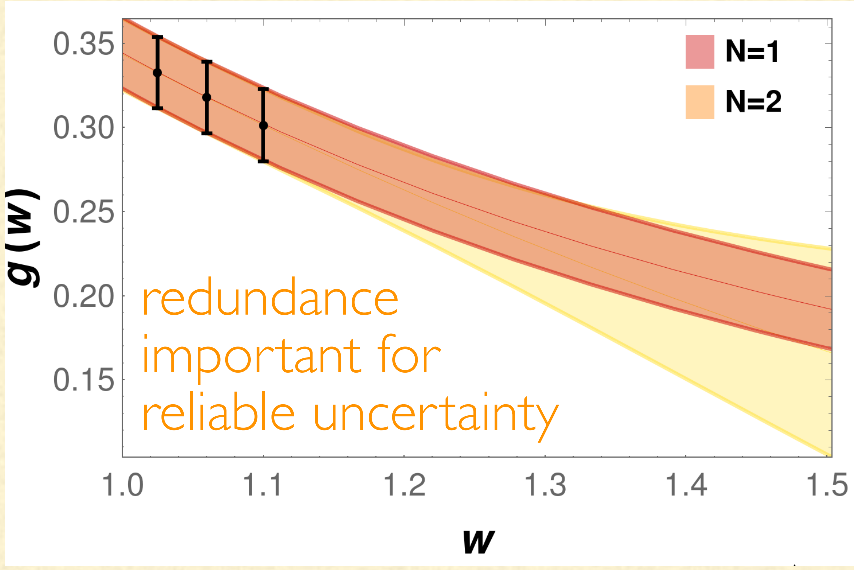


Belle 2015 consider 4 channels ($B^{0,+}, e, \mu$) for each bin.
Average (red points) usually lower than all central values. Bias?
Blue points are average of normalised bins.

Standard fit to Belle15+FNAL+HPQCD: $|V_{cb}| = 40.9(1.2)\, 10^{-3}$
Fit to normalised bins Belle15+FNAL+HPQCD: $|V_{cb}| = 41.9(1.2)\, 10^{-3}$ Jung, PG

TRUNCATION AND UNCERTAINTY

Fits with BGL parametrisation: ***model independence vs overfitting.*** Where do we truncate the series? How can we include unitarity constraints? These questions are related.



Different options with various pro/cons:

1. Frequentist fits with strong χ^2 ***penalty*** outside unitarity; increase BGL order till χ^2_{min} is stable. Uncertainties from $\Delta\chi^2_{min} = 1$ do not have probabilistic interpretation. Bigi, PG, 1606.08030, Jung,Schacht,PG 1905.08209
2. Frequentist fit with ***Nested Hypothesis Test*** to determine optimal truncation order: go to order $N+1$ if $\Delta\chi^2 = \chi^2_{min,N} - \chi^2_{min,N+1} \geq 1$ Check unitarity a posteriori Bernlochner et al, 1902.09553
3. ***Bayesian inference*** using unitarity constraints as prior with BGL Flynn, Jüttner,Tsang 2303.11285 or in the ***Dispersive Matrix approach***, Martinelli, Simula, Vittorio et al. 2105.02497

$|V_{cb}|$ from $B \to D^* l\nu$

More complicated: 4 FFs, angular spectra, D^* unstable. ***Present status unclear.***

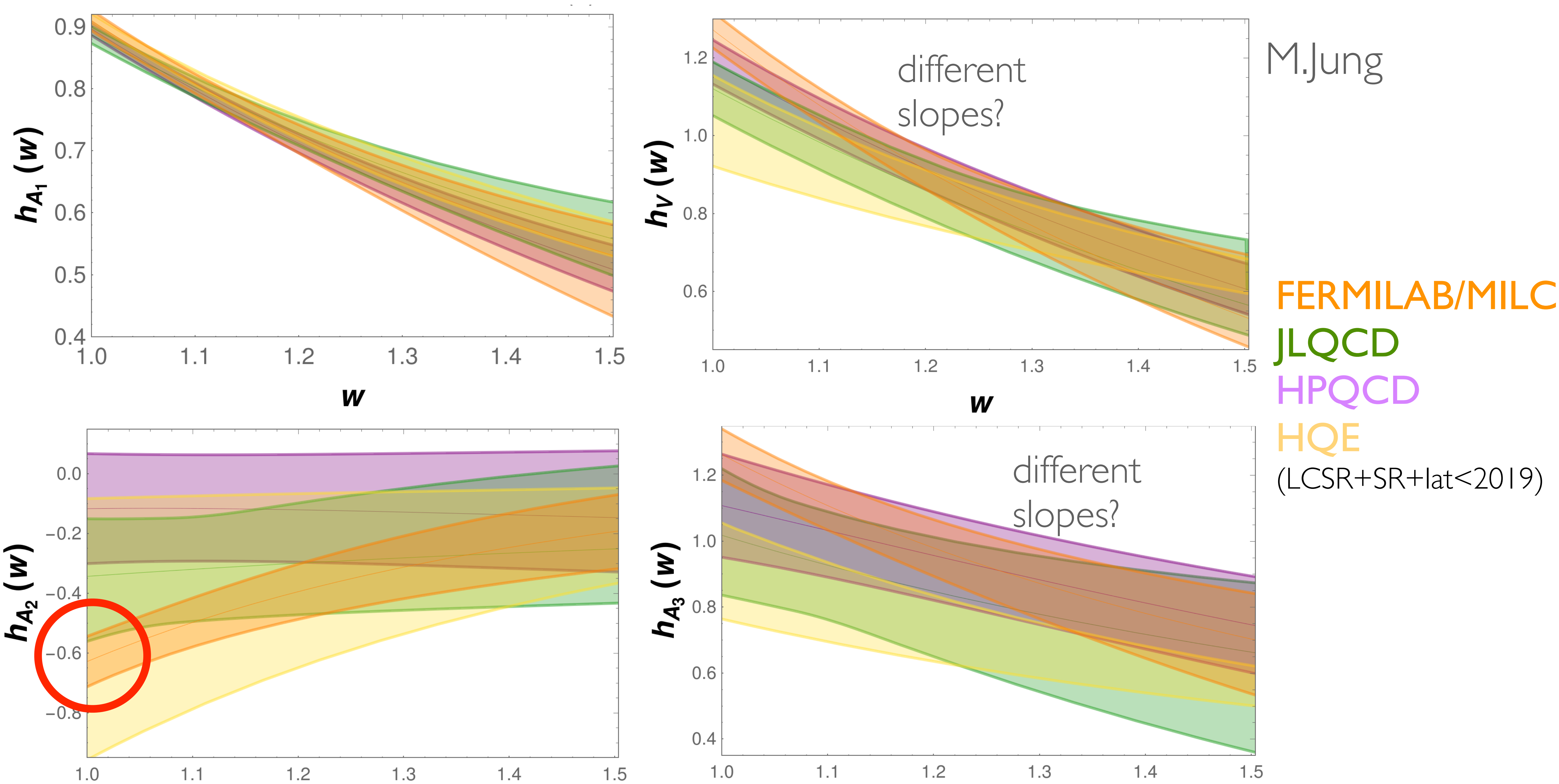
1. ***Parametrisations matter and the related uncertainties require careful consideration.*** Belle 2017 dataset analysed with BGL or CLN leads to 6-8% difference in $|V_{cb}|$. Bigi, PG, Schacht, Grinstein, Kobach
   Discard old exp results obtained with CLN and provide data in a parametrisation independent way.

2. Despite recent progress, ***lattice calculations*** are indecisive. Tension between ***Fermilab/MILC*** 2021 and HPQCD 2023 results at non-zero recoil and **Belle** untagged 2018 data, while ***JLQCD*** preliminary results give a consistent picture.

3. ***Problems*** in Belle 2018 analysis (D'Agostini bias, μ/e 4σ tension in the FB asymmetry) PG, Jung, Schacht & Bobeth, Bordone, van Dyk, Gubernari, Jung
   other experimental analyses make conflicting claims but data not yet available for independent fits

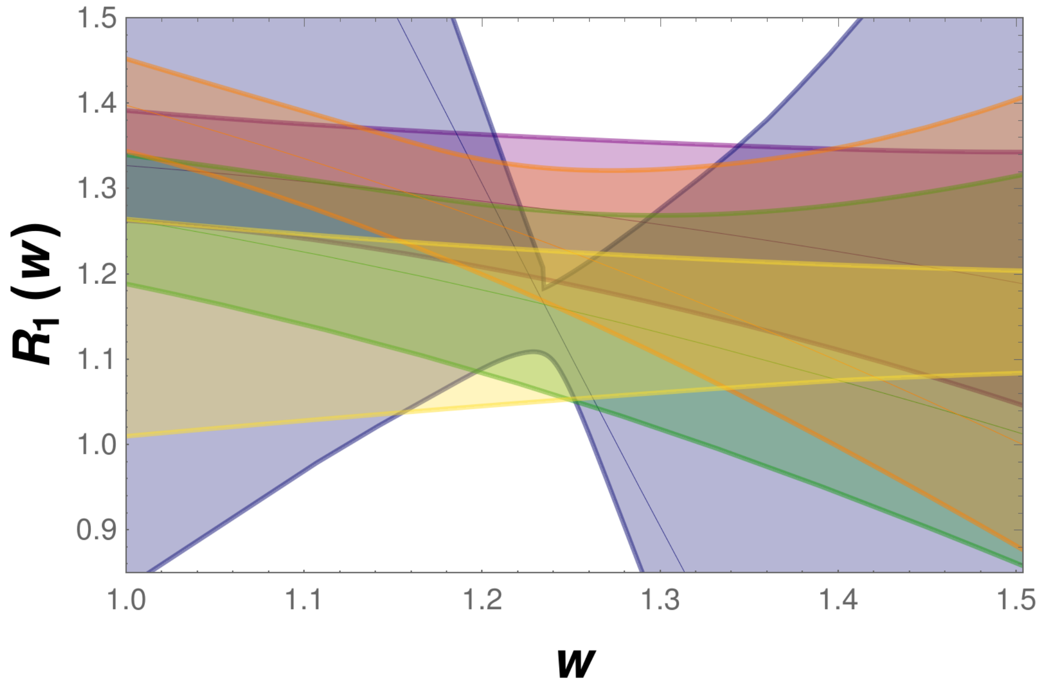
LATTICE FORM FACTORS AT NONZERO RECOIL

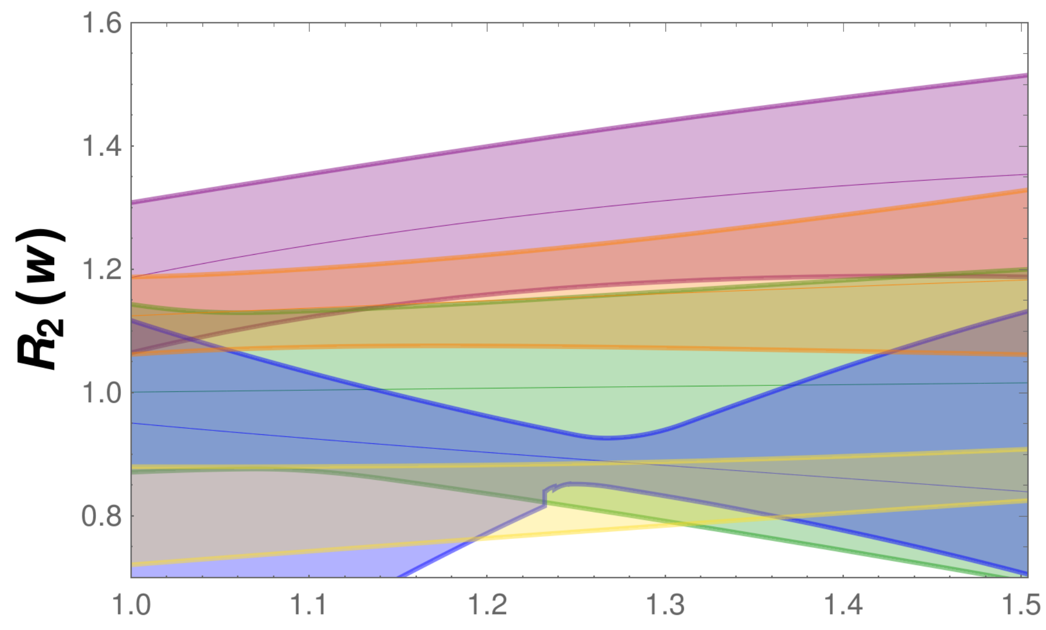
2105.14019, 2112.13775, 2304.03137



BGL fits with weak unitarity. General good agreement, but a few exceptions

RATIOS OF FORM FACTORS





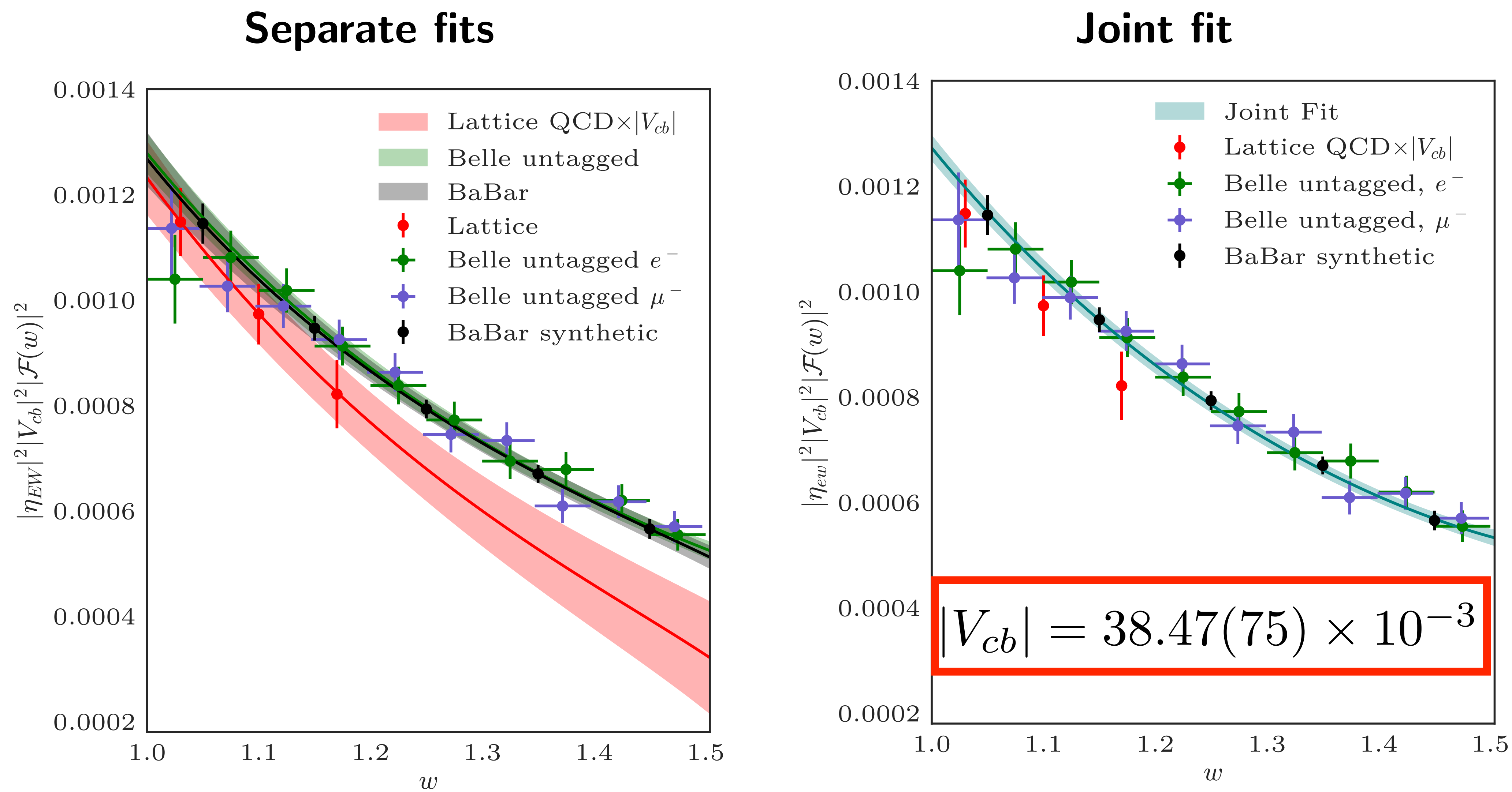
M.Jung

FERMILAB/MILC
JLQCD
HPQCD
HQE (LCSR+SR+lat<2019)
EXP (Belle 2018)

Form factor ratios more sensitive to differences. Stark disagreement between FERMILAB & HPQCD and HQE & EXP in R_2

FERMILAB/MILC CALCULATION

2105.14019



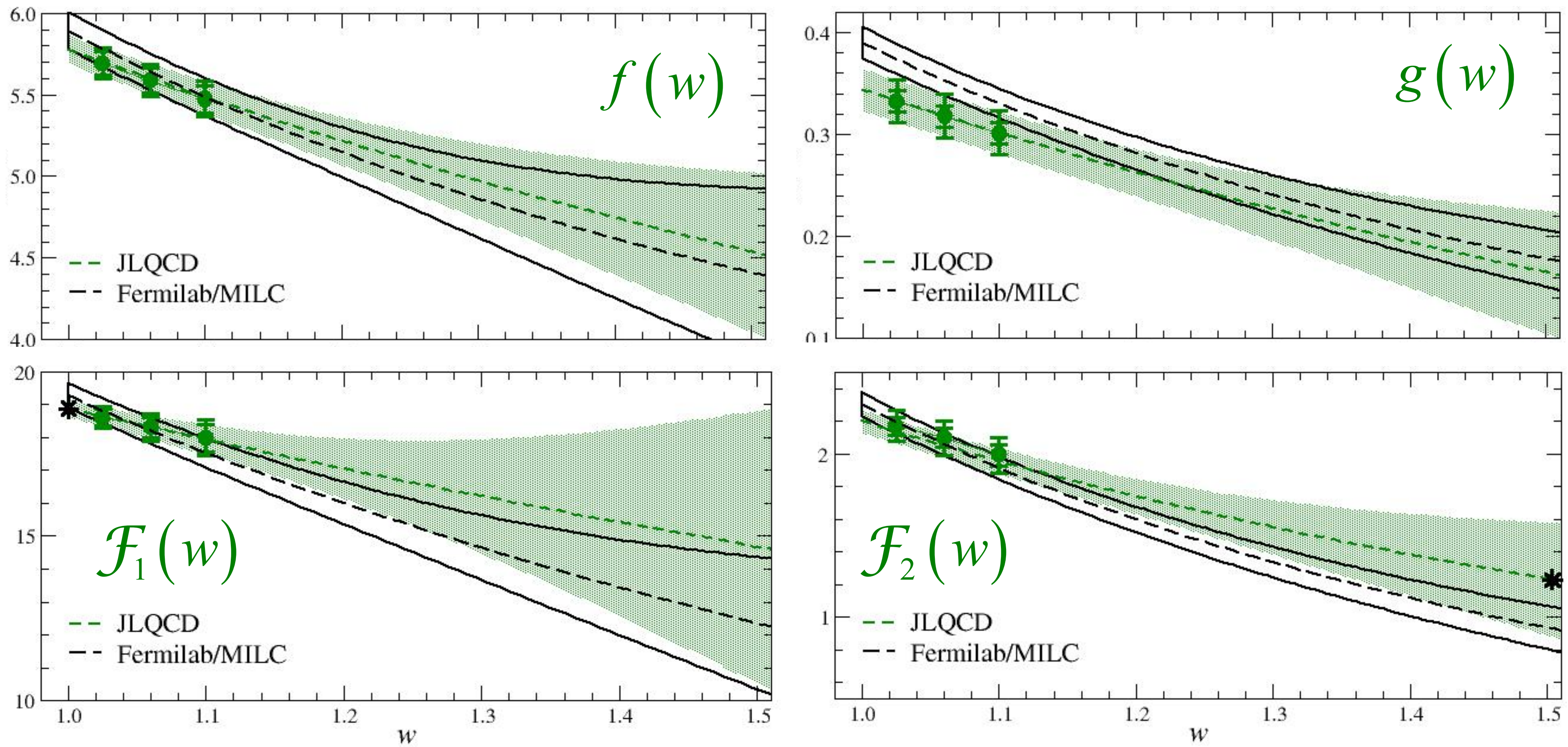
Fit	Lattice	Exp	Lat + Belle	Lat + BaBar	Lat + Exp
p-Value	0.88	0.037	0.015	0.088	0.002

First lattice calculation beyond zero recoil for this mode

Our analysis of same exp+lattice data(Jung, PG):
$|V_{cb}|=39.4(9)\ 10^{-3}$ ($\chi^2_{min} = 50$) *using only total rate* $|V_{cb}|=42.2^{+2.8}_{-1.7}\ 10^{-3}$

JLQCD PRELIMINARY RESULTS

JLQCD vs Fermilab/MILC



- reasonably consistent

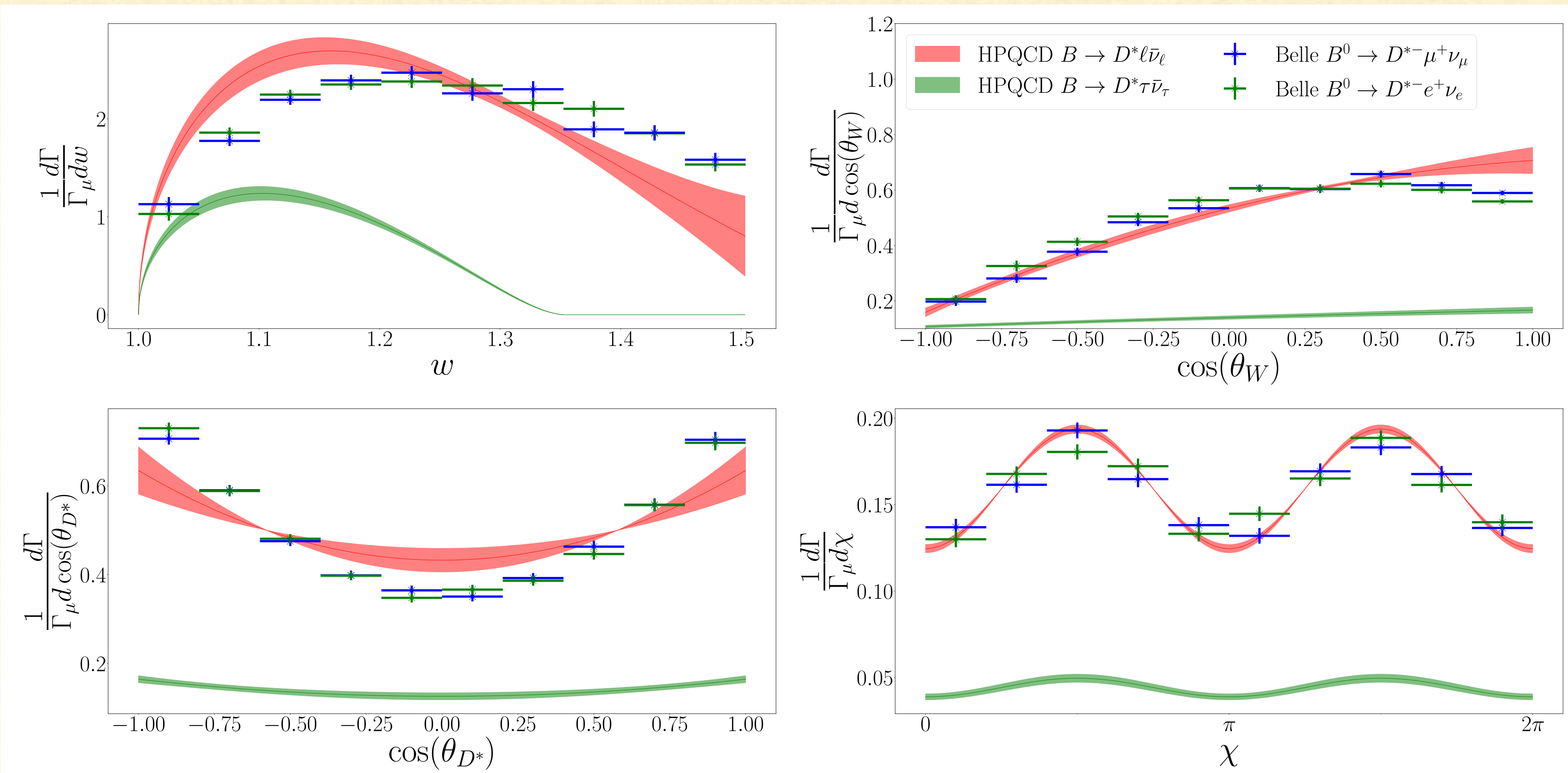
  ⇔ g @ w ~ 1

T. Kaneko @ Barolo workshop 4/2022
Kaneko et al 2112.13775

Our analysis of same exp (Belle18)+ JLQCD data (Jung, PG):
$|V_{cb}|=40.7(9)\ 10^{-3}$ (χ^2_{min} = 33) *using only total rate* $|V_{cb}|=40.8^{+1.8}_{-2.3}\ 10^{-3}$

NEW HPQCD FFS CALCULATION

2304.03137



Tension with Belle 2018 data similar to FNAL

Belle18+HPQCD

BGL exp	χ^2	$\|V_{cb}\|$
0001	78	41.0(8)
0101	68	41.2(8)
0111	57	40.8(8)
1111	57	40.8(8)
1121	54	40.6(8)
1222	52	40.6(8)
2222	50	40.4(8)
2232	50	40.4(8)
3333	50	40.4(8)

Extrapolation in m_h, data cover the whole w region

Our analysis of same exp (Belle18)+ HPQCD data (Jung, PG):
$|V_{cb}|=40.4(8)\ 10^{-3}$ *using only total rate* $|V_{cb}|=44.4 \pm 1.6\ 10^{-3}$

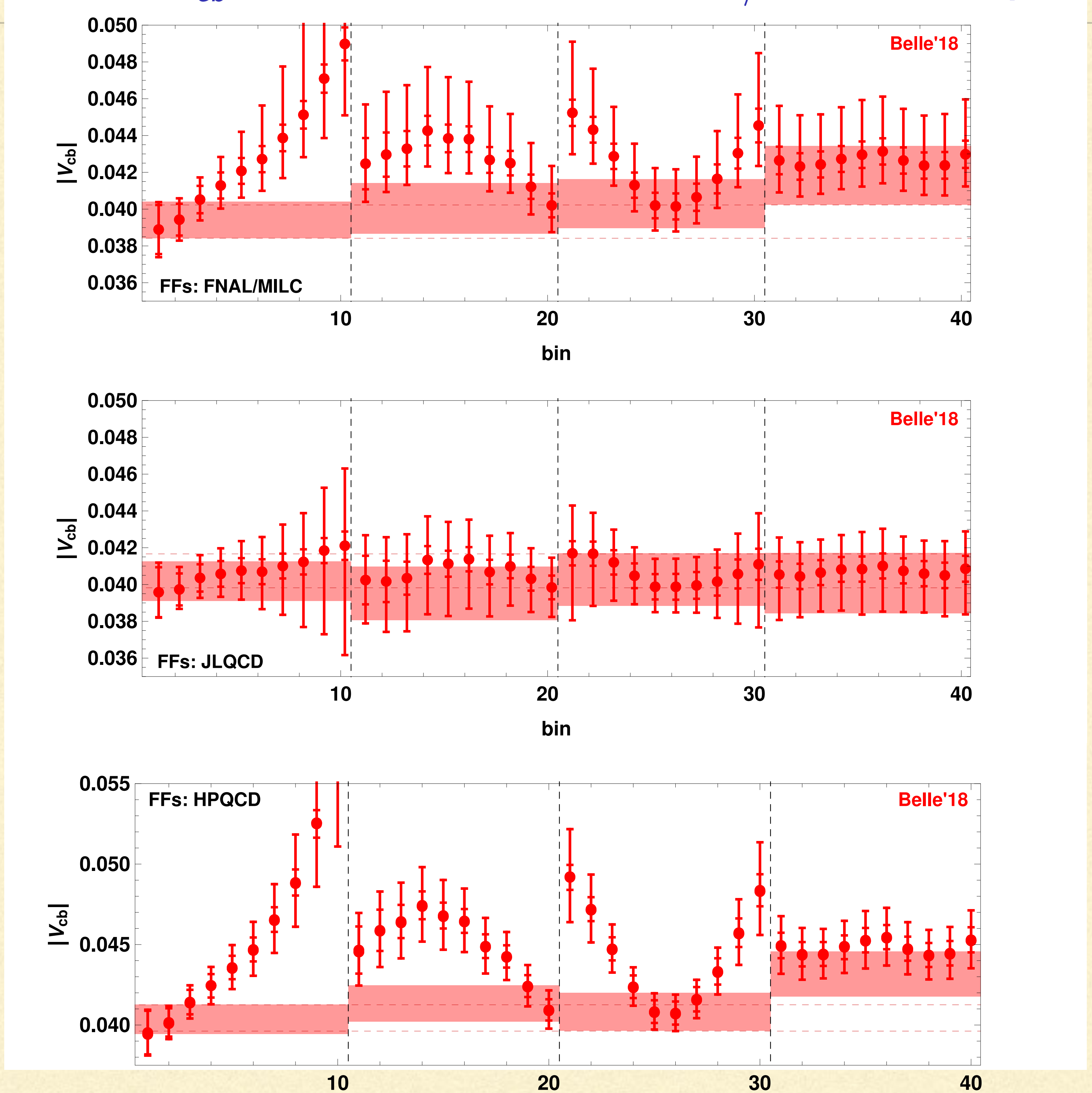
HPQCD and FNAL are not well compatible: adding 16 FNAL points increases χ^2 *by 35*

Binned V_{cb} from Belle'18 data: FNAL/MILC vs JLQCD

FNAL/MILC

JLQCD

HPQCD



Extracting V_{cb} from each bin, FFs only determined by lattice QCD

M. Jung

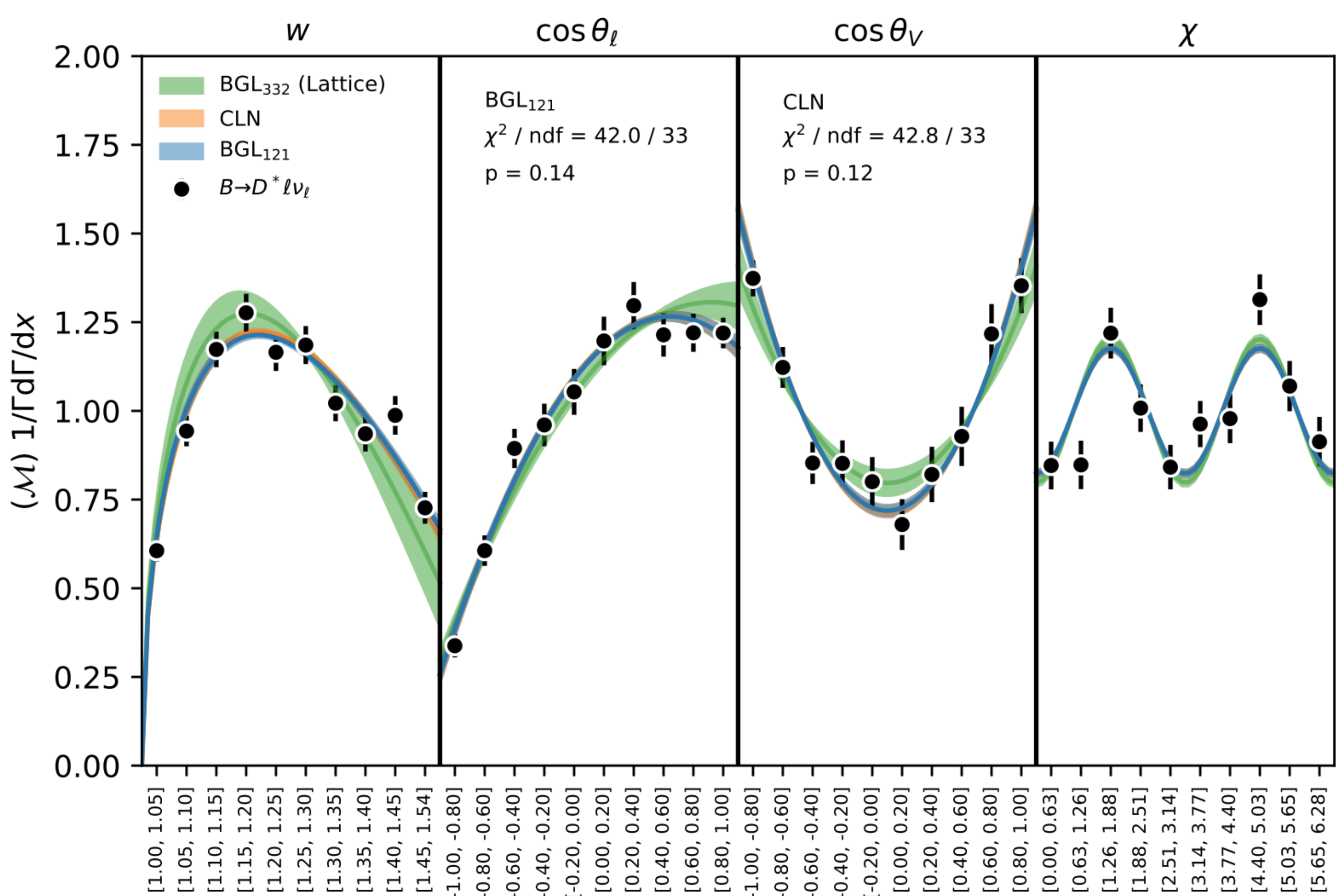
Global BGL fit to Belle18+FNAL+JLQCD+HPQCD data:

$|V_{cb}|=40.3(7)\ 10^{-3}$ ($\chi^2_{min} = 91.2$) *using only total rate* $|V_{cb}|=42.4(1.0)\ 10^{-3}$

Measurement of Differential Distributions of $B \to D^* \ell \nu_\ell$ and Determination of $|V_{cb}|$

New

[Prelimi



Measured Shapes + External Branching Ratio Input

BGL(121)	Value	Correlation				
$a_0 \times 10^3$	24.93 ± 1.41	1.00	0.25	−0.21	0.26	−0.30
$b_0 \times 10^3$	13.11 ± 0.18	0.25	1.00	−0.01	−0.01	−0.62
$b_1 \times 10^3$	-11.93 ± 12.72	−0.21	−0.01	1.00	0.25	−0.48
$c_1 \times 10^3$	-0.87 ± 0.97	0.26	−0.01	0.25	1.00	−0.49
$\lvert V_{cb} \rvert \times 10^3$	40.77 ± 0.92	−0.30	−0.62	−0.48	−0.49	1.00

CLN	Value	Correlation			
ρ^2	1.25 ± 0.09	1.00	0.56	−0.89	0.38
$R_1(1)$	1.32 ± 0.08	0.56	1.00	−0.63	−0.03
$R_2(1)$	0.85 ± 0.07	−0.89	−0.63	1.00	−0.15
$\lvert V_{cb} \rvert \times 10^3$	40.30 ± 0.86	0.38	−0.03	−0.15	1.00

Based on the lattice input at zero-recoil:

$$h_{A_1}(1) = 0.906 \pm 0.013$$

2301.07529

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

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

Belle II

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

Preliminary

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

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

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

BGL fit result

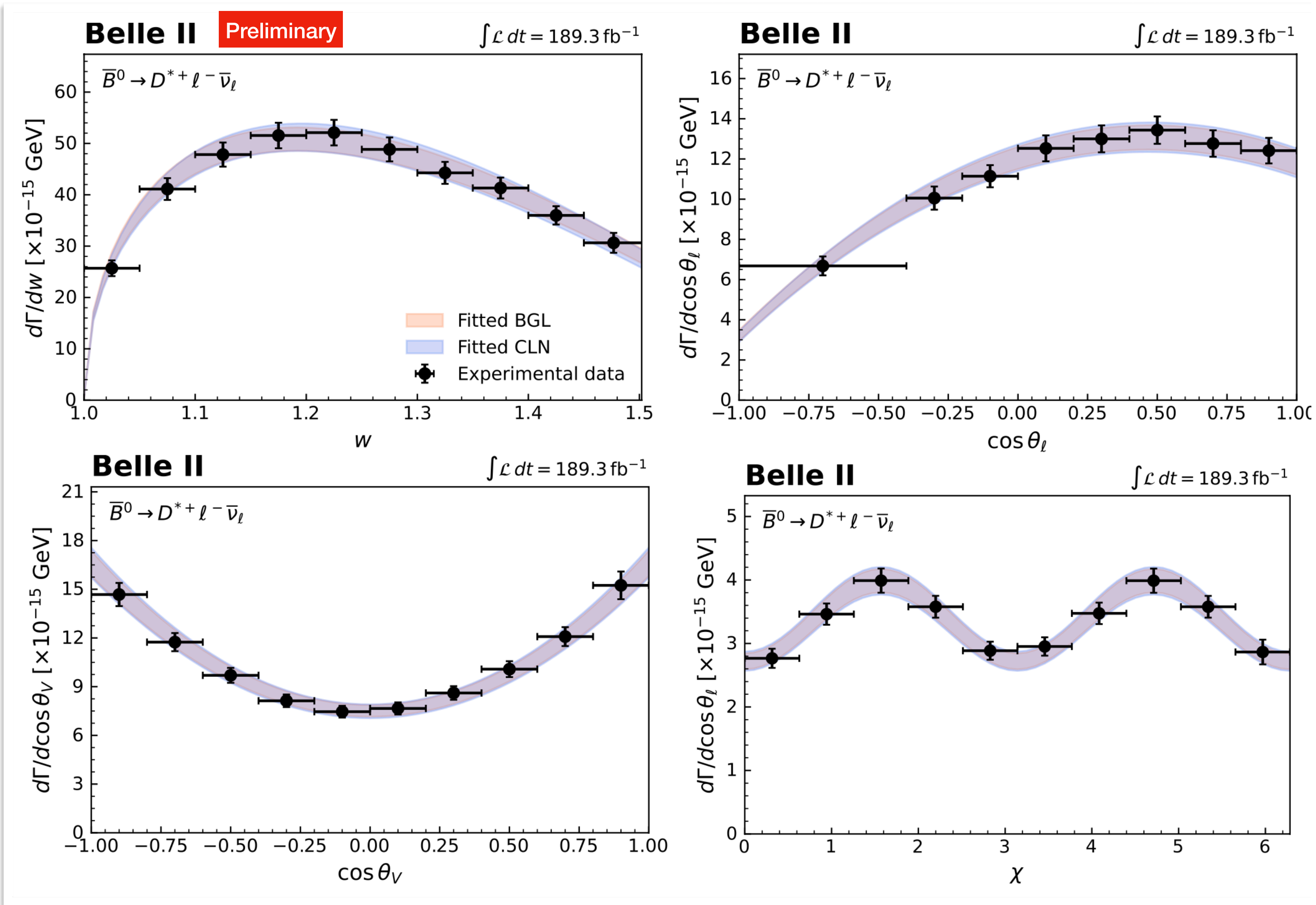
BGL truncation order determined by Nested Hypothesis Test [Phys. Rev. D100, 013005]

	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
$N_{B\overline{B}}$	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



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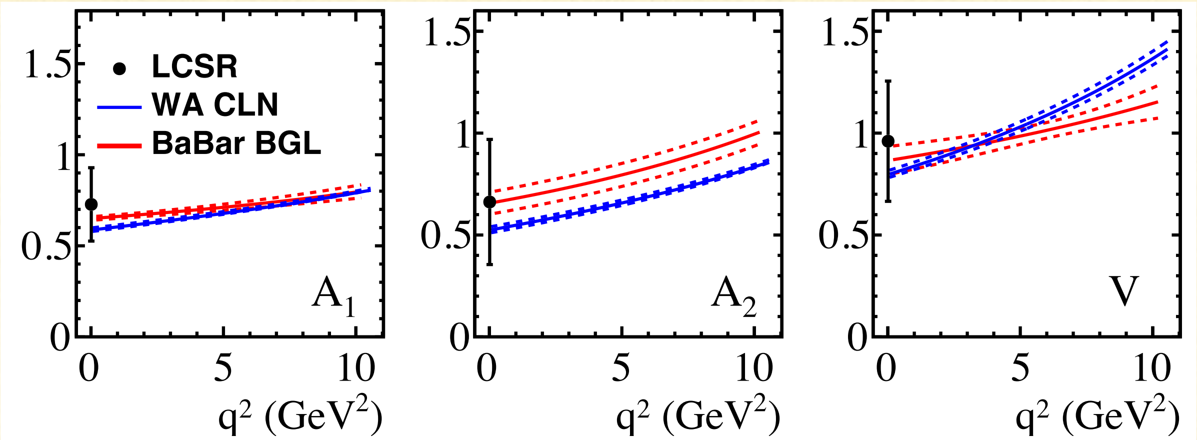
C. Schwanda, Moriond '23

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

RESULTS BY BABAR AND LHCb

1903.10002, 2001.03225

Reanalysis of tagged B^0 and B^+ data, unbinned 4 dimensional fit with simplified BGL and CLN
About 6000 events
No data provided yet



No clear BGL$^{(111)}$/CLN difference but disagreement with HFLAV CLN ffs

V_{cb}=0.0384(9)

Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ decays

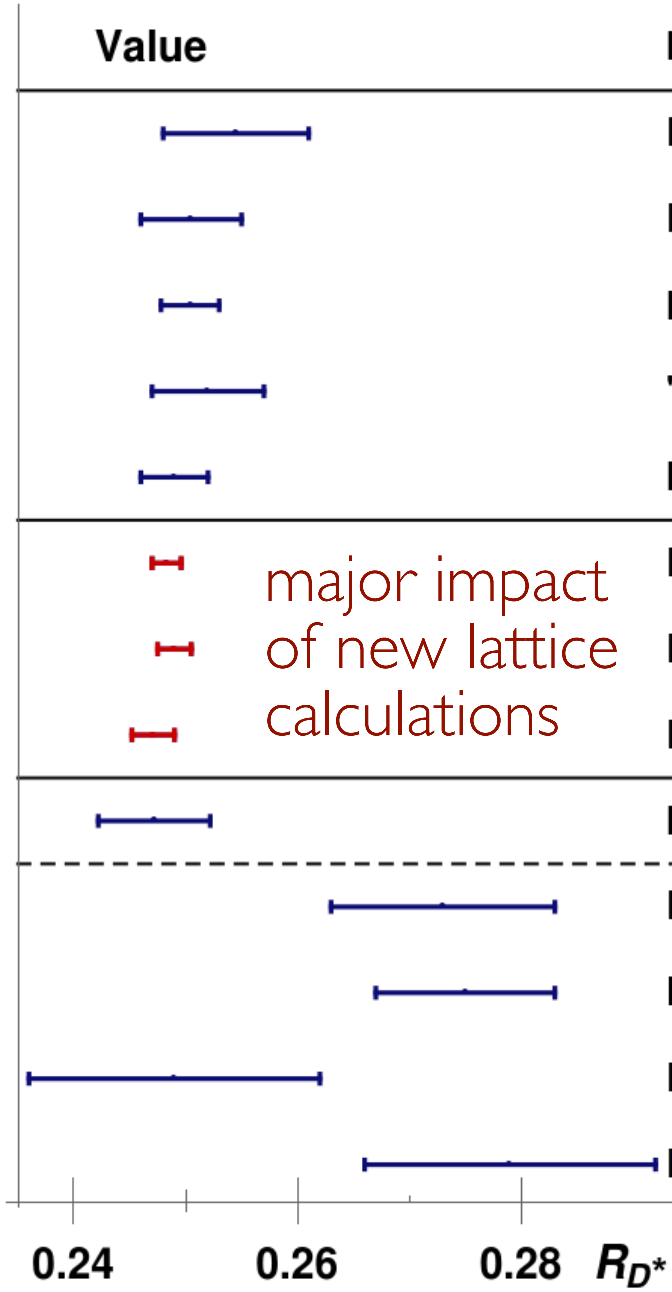
$$\mathcal{R} \equiv \frac{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^- \mu^+ \nu_\mu)},$$

$$\mathcal{R}^* \equiv \frac{\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu_\mu)}$$

V_{cb}=0.0414(16) CLN
V_{cb}=0.0423(17) BGL$^{(222)}$

Fit to exp data and lattice FFs based on HFLAV BRs, employs BGL$^{(222)}$

Overview over predictions for $R(D^*)$



Method	Input Theo	Input Exp	Reference
BGL	Lattice, HQET	Belle'17'18	Gambino et al.'19
BGL	Lattice, HQET	Belle'18	Jaiswal et al.'20
HQET@1/m_c^2,α_s	Lattice, LCSR, QCDSR	Belle'17'18	Bordone et al.'20
"Average"			HFLAV'21
$\mathrm{HQET_{RC}}$@1/m^2,$\alpha_s^{(2)}$	Belle'17'18	Lattice	Bernlochner et al.'22
BGL	Lattice	Belle'18, Babar'19	Vaquero et al.'21v2
BGL	Lattice	Belle'18	JLQCD prel. (MJ)
BGL	Lattice	Belle'18	Davies, Harrison'23
HQET@1/m_c^2,α_s	Lattice, LCSR, QCDSR	---	Bordone et al.'20
BGL	Lattice	---	Vaquero et al.'21v2
DM	Lattice	---	Martinelli et al. FNAL/MILC
BGL	Lattice	---	JLQCD prel. (MJ)
BGL	Lattice	---	Davies, Harrison'23

M.Jung

Predictions based only on Fermilab & HPQCD lead to larger R(D*), in better agreement with exp, mostly because of the suppression at high w of the denominator. ***I see no reason not to use experimental data for a SM test***, especially in presence of tensions in lattice data.

SUMMARY

- ***Despite many new theoretical and exp results, the V_{cb} puzzle persists, but there are reasons for optimism. Great and lasting progress has been achieved.***
- ***Inclusive*** $b \to c$ **:** new 3loop calculations show pert effects under control, 1.2% accuracy on $|V_{cb}|$, work on QED effects, q^2 moments
- First calculations of ***inclusive semileptonic meson decays on the lattice***. Exploratory calculations for $m_b \sim 2.5\mathrm{GeV}$ in good agreement with OPE, others ongoing. Promising to complement/validate the OPE, still a long way to go.
- ***Exclusive*** $b \to c$: uncertainties have been underestimated in the past; three lattice groups have computed the $B \to D^*$ FFs at non-zero recoil and new exp analyses are under way. The ***situation is still unclear***. FNAL & HPQCD in tension with exp spectra, JLQCD gives a more consistent picture with reduced tension with inclusive $\sim 1.2\sigma$. New Belle and Belle II analyses may confirm the trend.