# UPDATE ON THE $V_{cb}$ PUZZLE

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Beyond Flavour Anomalies IV, Barcelona, 21.4.2023

# The importance of $|V_{cb}|$

Another 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

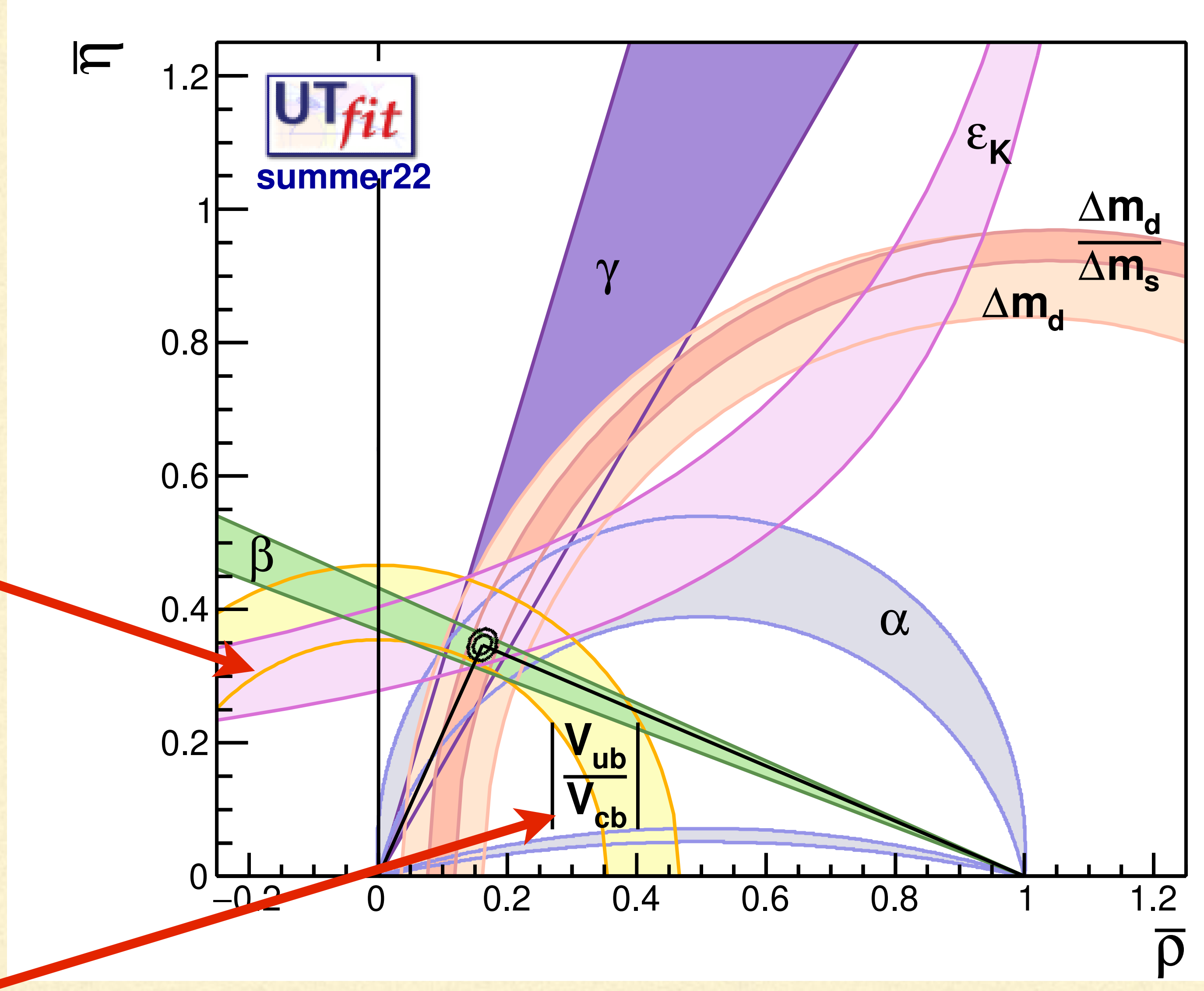
$$\varepsilon_K \approx x|V_{cb}|^4 + \ldots$$

and in the prediction of FCNC:

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

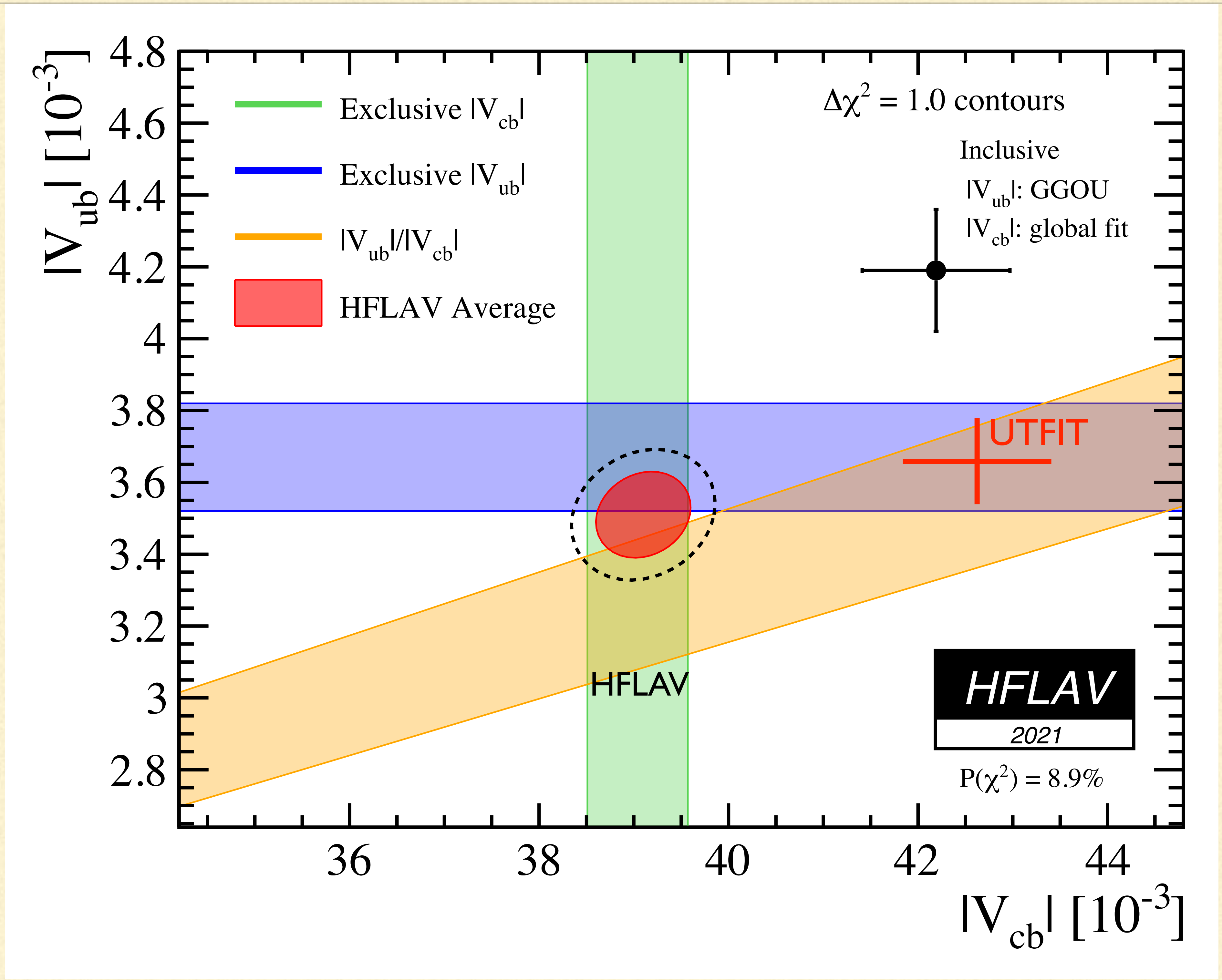
where it often dominates the theoretical uncertainty.

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



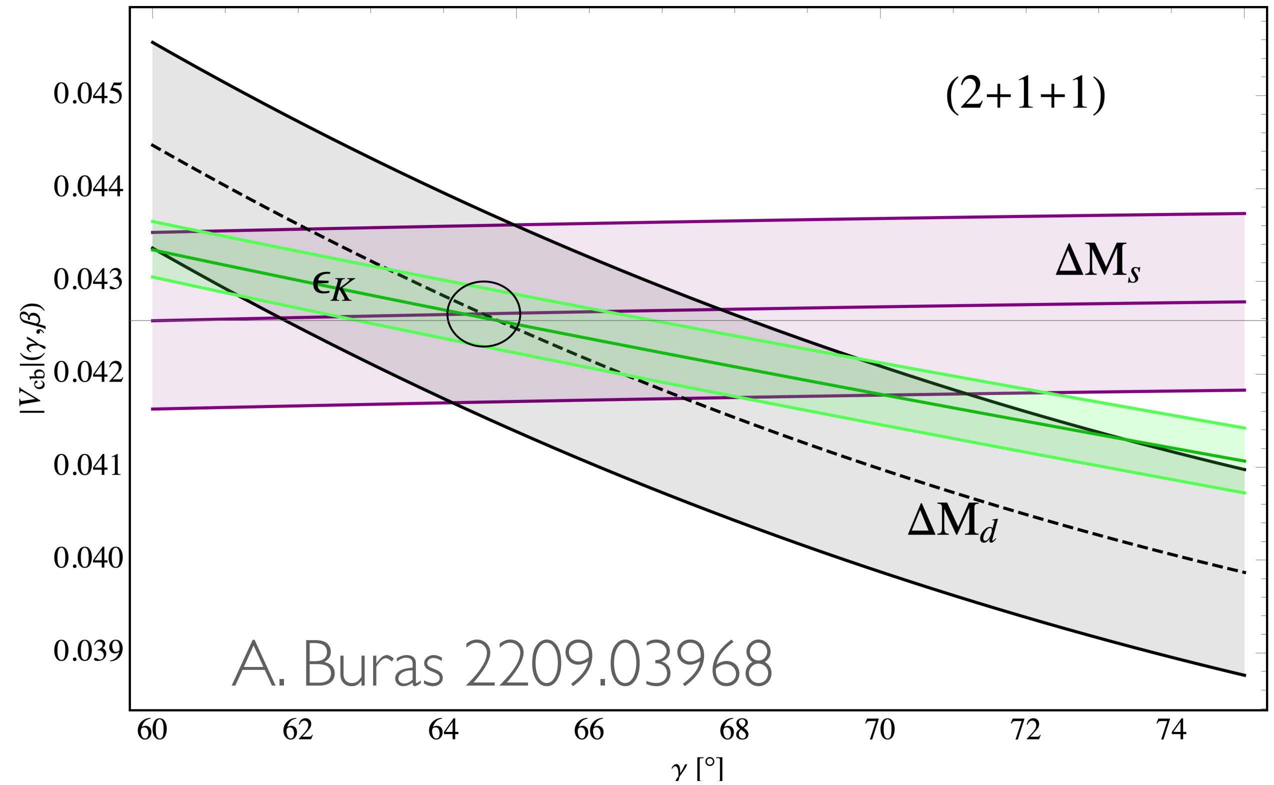

***Our ability to determine precisely $V_{cb}$ is crucial for indirect NP searches***

Since several years the inclusive and exclusive determinations of $|V_{cb}|$ diverge

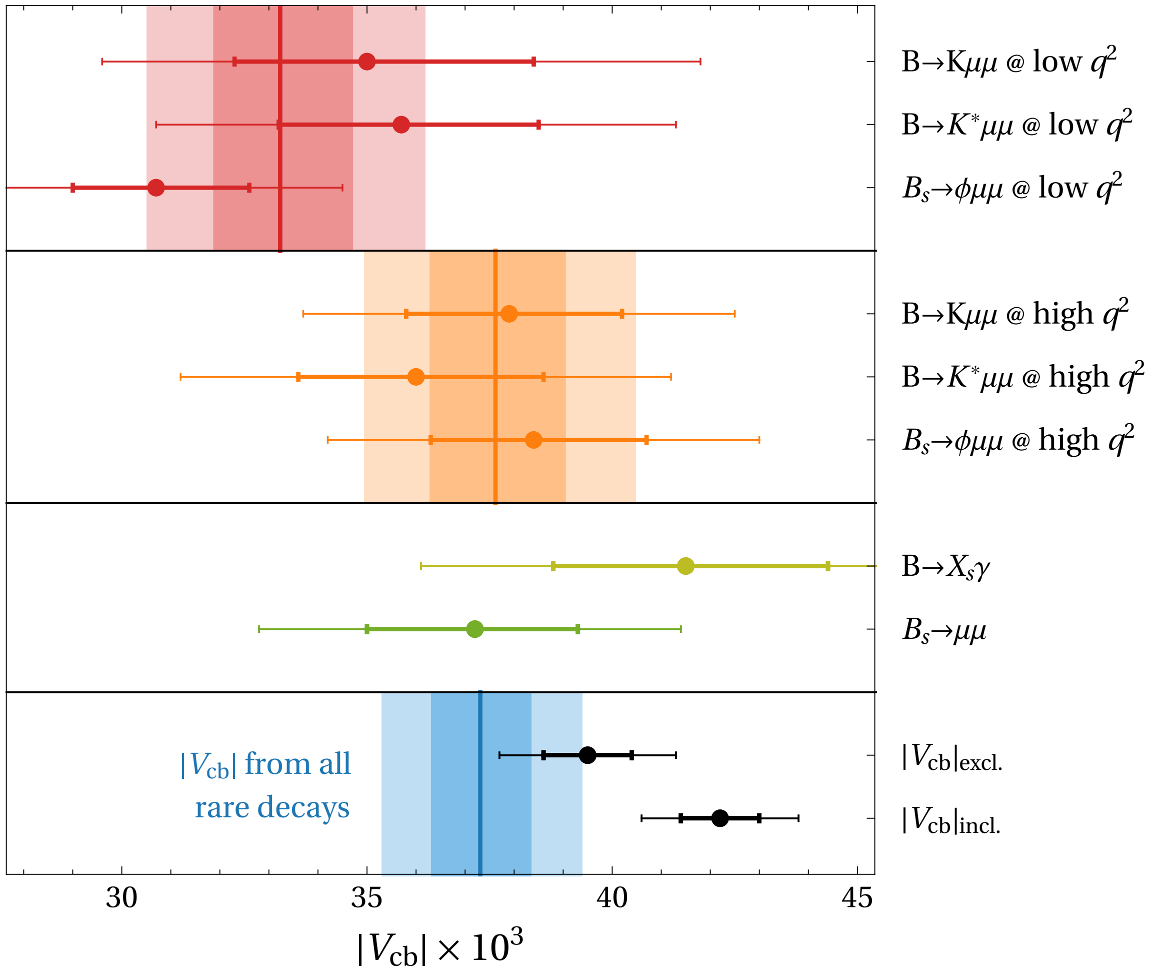



***Recently:*** new calculations of FFs by several lattice collaborations and with light-cone sum rules, new perturbative calculations, all facing the challenges of a precision measurements… and several new measurements as well!

**Indirect determinations** of $|V_{cb}|$ from loop induced $\Delta F=2$ processes ***assuming the SM***. They tend to prefer a high $|V_{cb}|$ but sensitive to lattice calculations for mixing

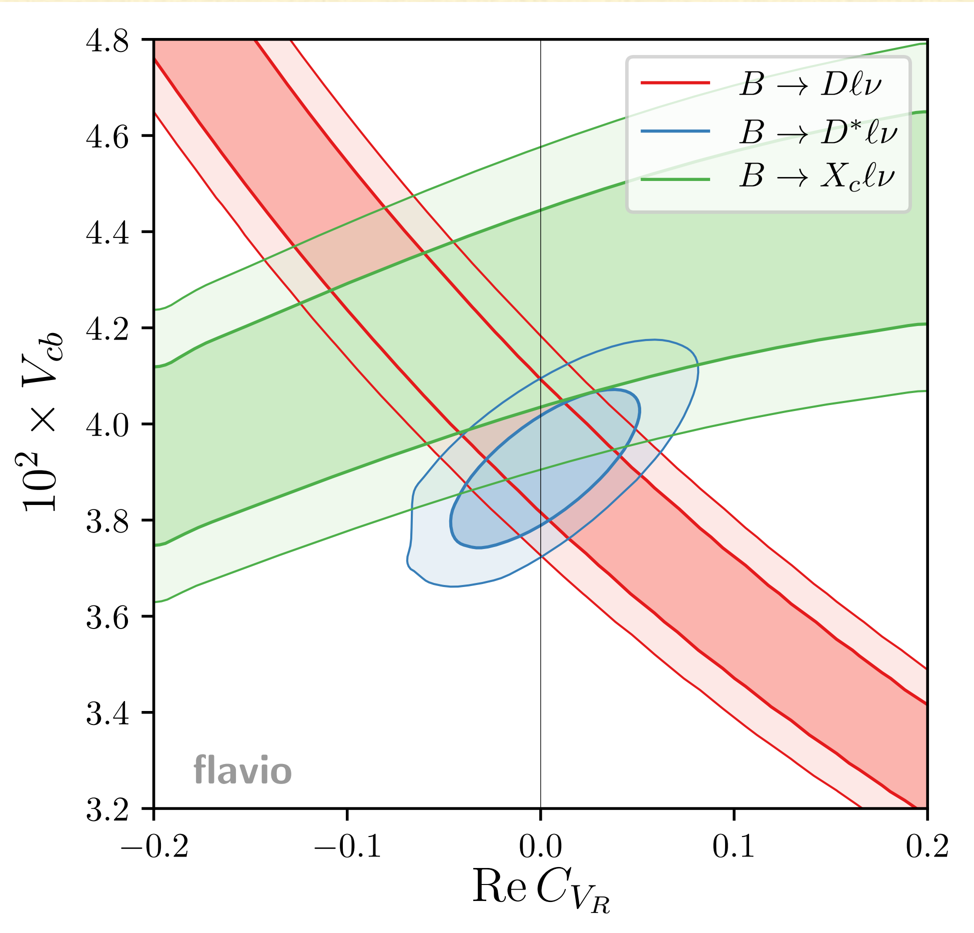


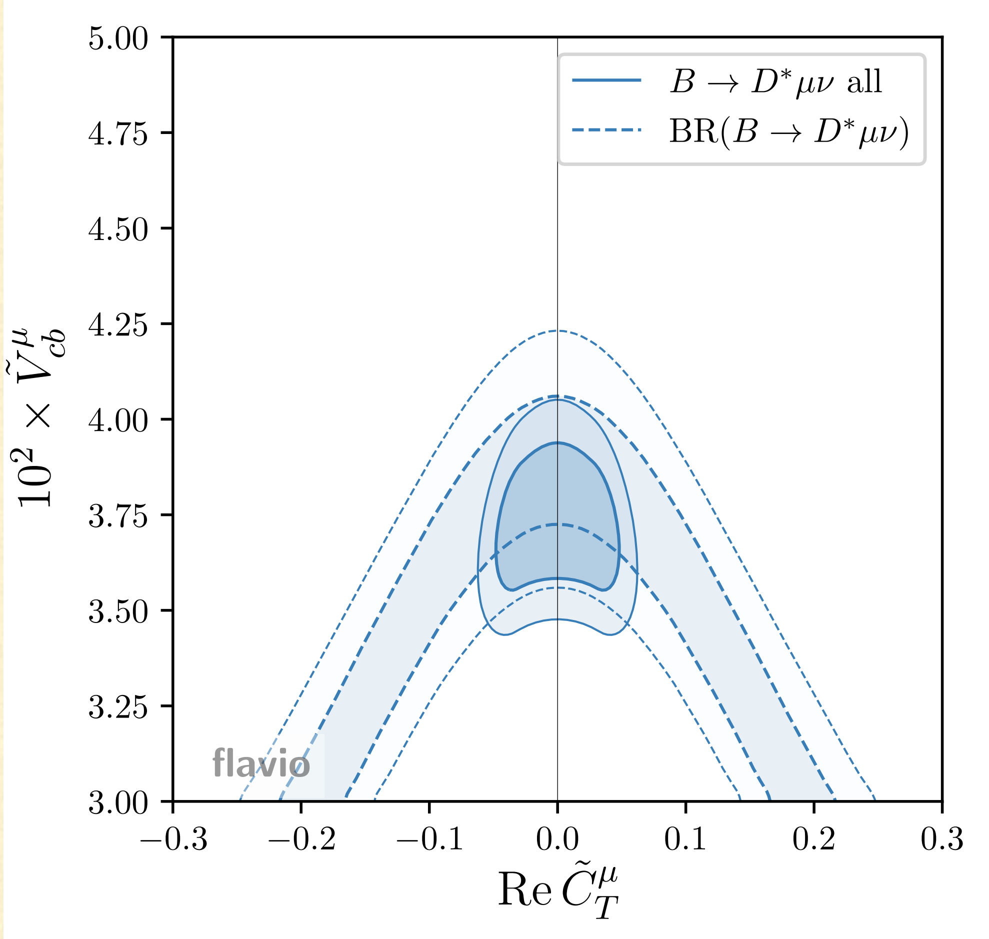

see also
W. Altmannshofer's talk
2112.03437



# NEW PHYSICS?

Jung & Straub, 1801.01112

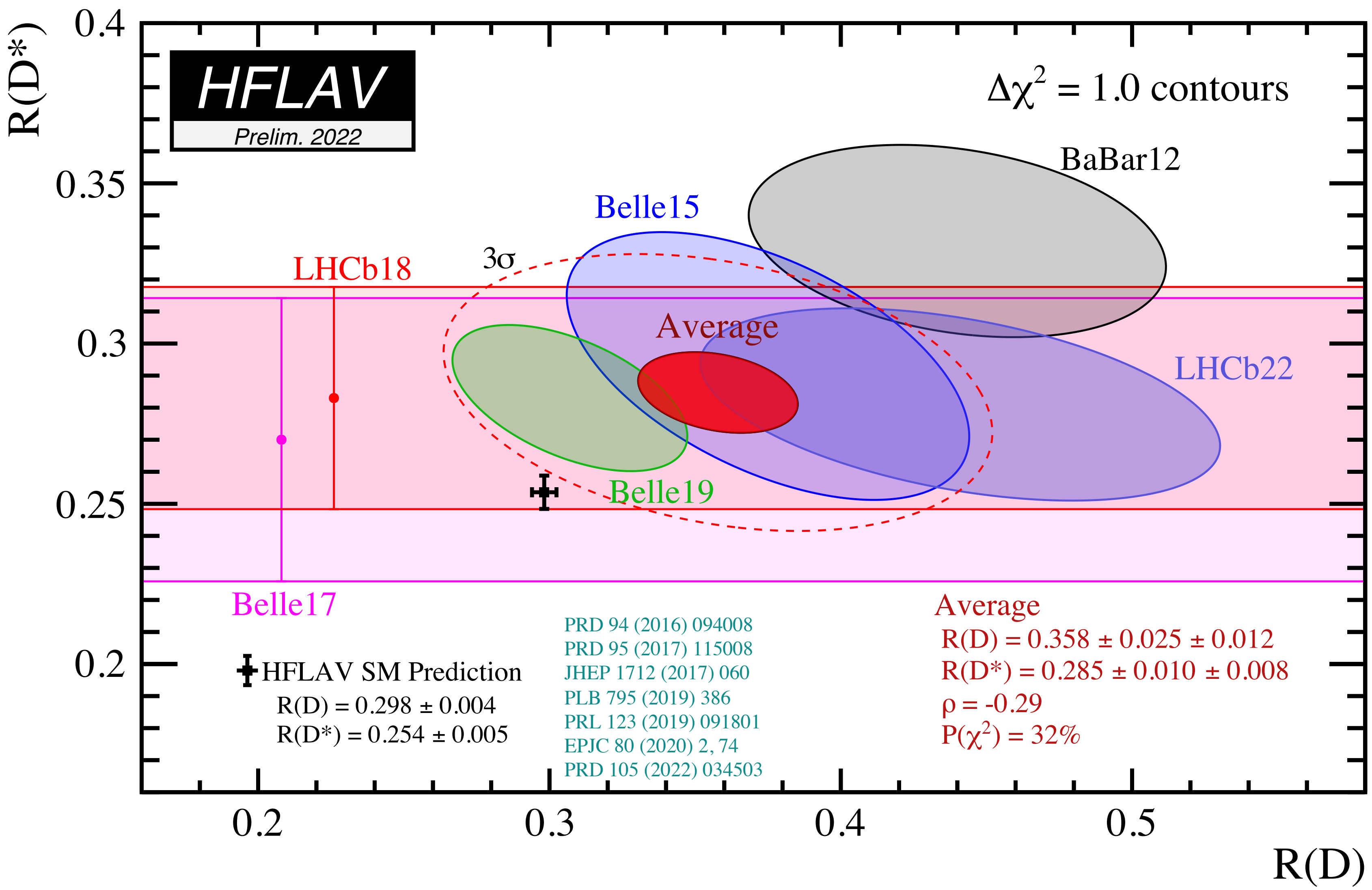



Differential distributions constrain NP strongly, SMEFT interpretation incompatible with LEP data: Crivellin, Pokorski, Jung, Straub…

# VIOLATION OF LFU with TAUS

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




$3.2\sigma$ from SM

*see Jung & Harrison talk*

# INCLUSIVE SEMILEPTONIC B DECAYS

Inclusive observables are double series in $\Lambda/m_b$ and $\alpha_s$

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

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** 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

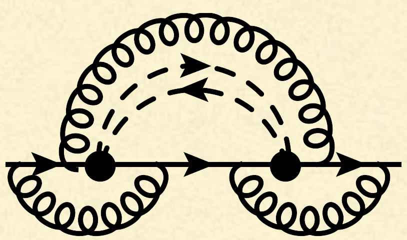
3loop and 2loop charm mass effects in relation between kinetic and $\overline{\mathrm{MS}}$ $b$ mass

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

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***

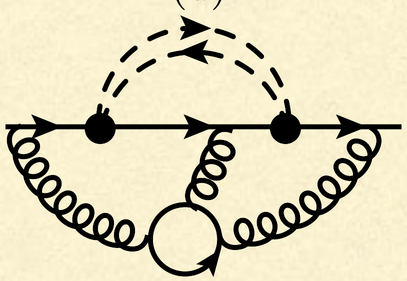
$$\Gamma_{sl} = \Gamma_0 f(\rho)\left[0.9255 - 0.1162_{\alpha_s} - 0.0350_{\alpha_s^2} - 0.0097_{\alpha_s^3}\right]$$



(d)

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

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



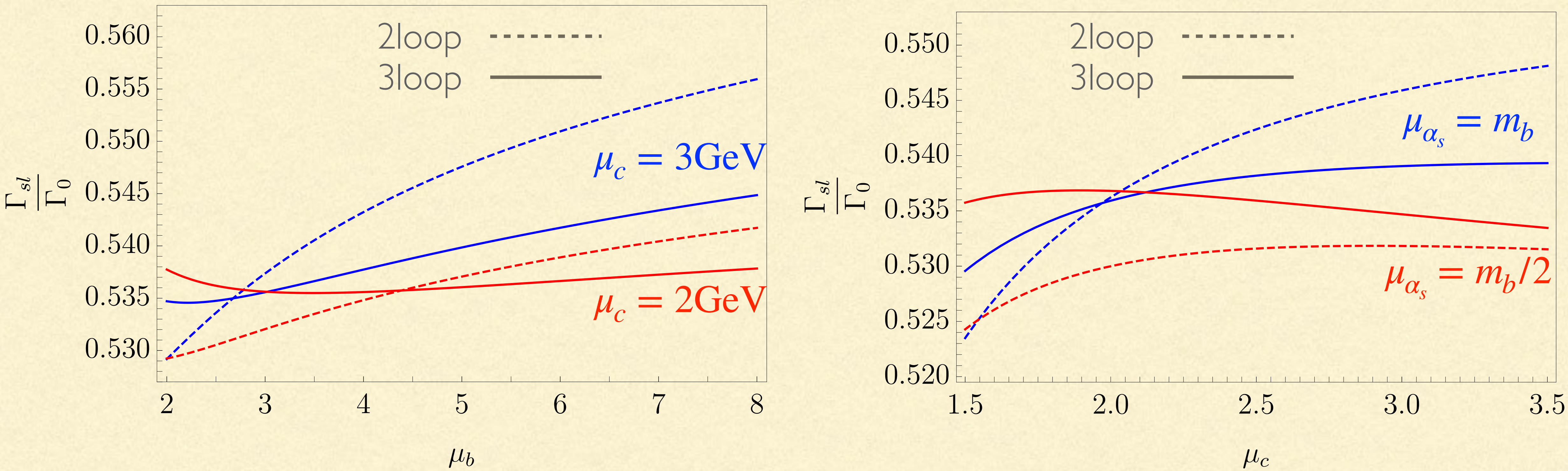
(f)

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 tends to lower $\Gamma_{sl}$ and therefore pushes $|V_{cb}|$ slightly up (~0.5%)***

# RESIDUAL UNCERTAINTY on $\Gamma_{sl}$

Bordone, Capdevila, PG, 2107.00604




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

$O(\alpha_s/m_b^2, \alpha_s/m_b^3)$ 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 $\Gamma_{sl}$ (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

| $m_b^{kin}$ | $\overline{m}_c(2\text{GeV})$ | $\mu_\pi^2$ | $\rho_D^3$ | $\mu_G^2(m_b)$ | $\rho_{LS}^3$ | $\text{BR}_{c\ell\nu}$ | $10^3\lvert V_{cb}\rvert$ |
|---|---|---|---|---|---|---|---|
| 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. 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.

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

***Update of 1606.06174***

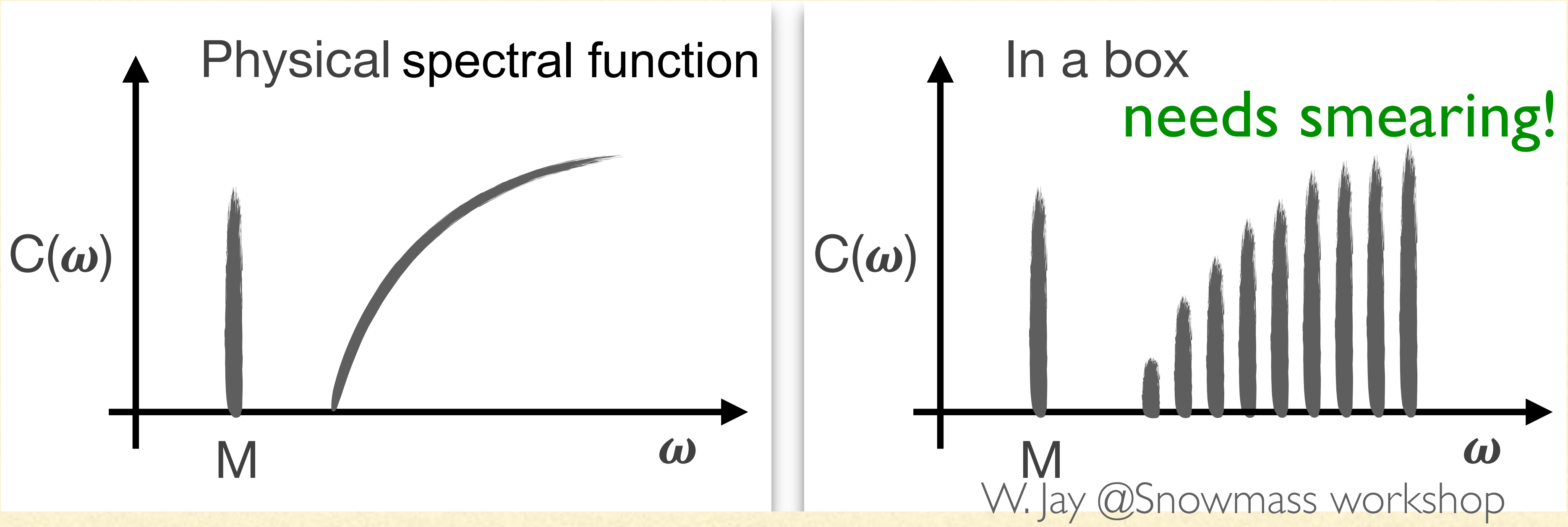
# PROSPECTS for INCLUSIVE $V_{cb}$

- Theoretical uncertainties no longer dominate, we are now close to 1% accuracy
- $O(\alpha_s \rho_D^3/m_b^3)$ calculation completed for width (Mannel, Pivovarov) in progress for the moments (S. Nandi, PG)
- Electroweak (QED) corrections require attention, a study is under way
- ***New observables***: FB asymmetry (Turczyk) could be measured already by Babar and Belle now, ***new $q^2$ moments measurements*** by Belle (2109.01685) and Belle II (2205.06372) not yet included in our fit
- ***Reparametrisation invariance*** implies that $q^2$ moments 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 inputs we employ (2205.10274)
- ***Lattice QCD calculations: HQE determination of matrix elements*** *(PG, Melis, Simula 1704.06105)* ***or direct inclusive calculation***

# 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 $\tau$ 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.

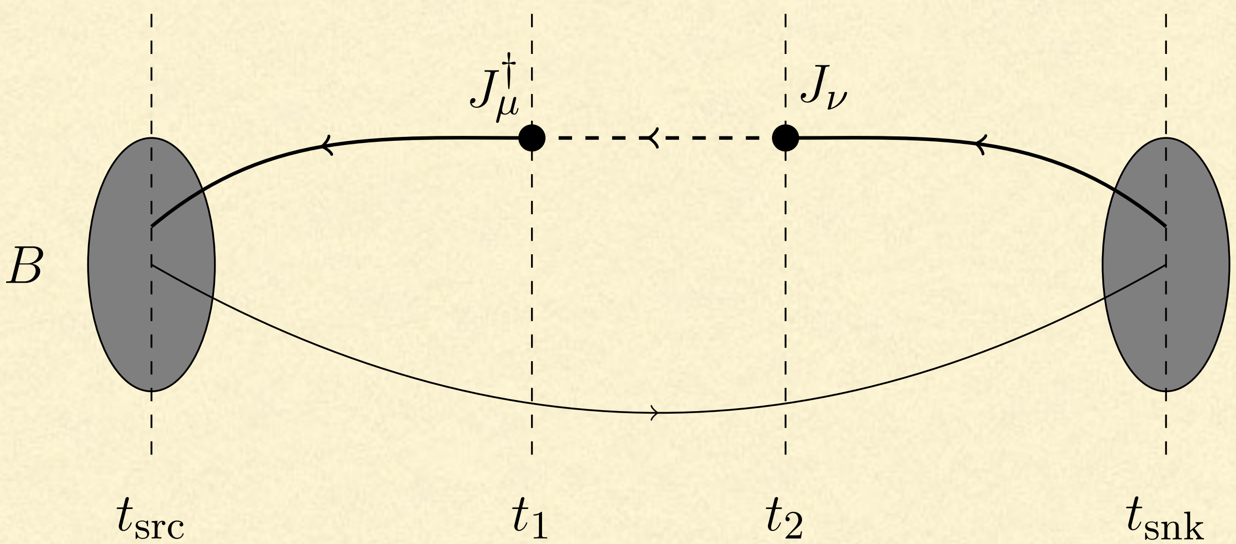
- While the lattice calculation of the spectral density of hadronic correlators is an ***ill-posed problem***, the spectral density is accessible after smearing, as provided by phase-space integration Hansen, Meyer, Robaina, Hansen, Lupo, Tantalo, Bailas, Hashimoto, Ishikawa



# A NEW APPROACH

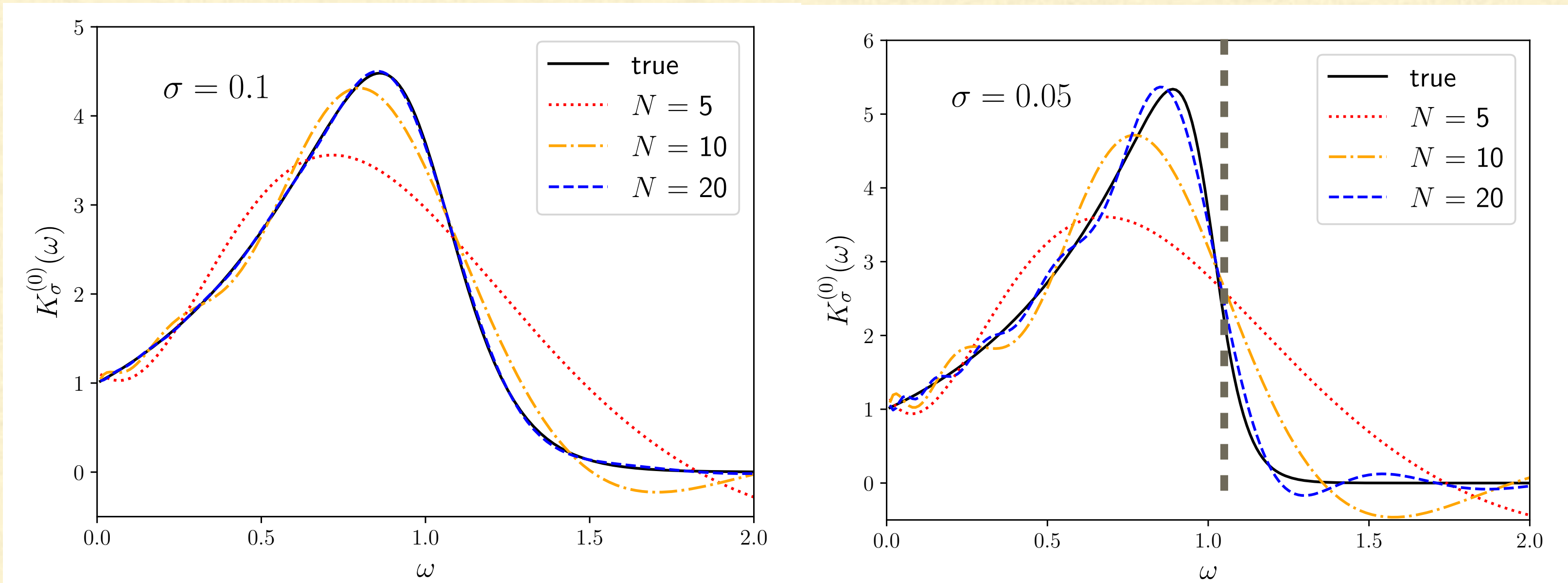
Hashimoto, PG 2005.13730

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




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

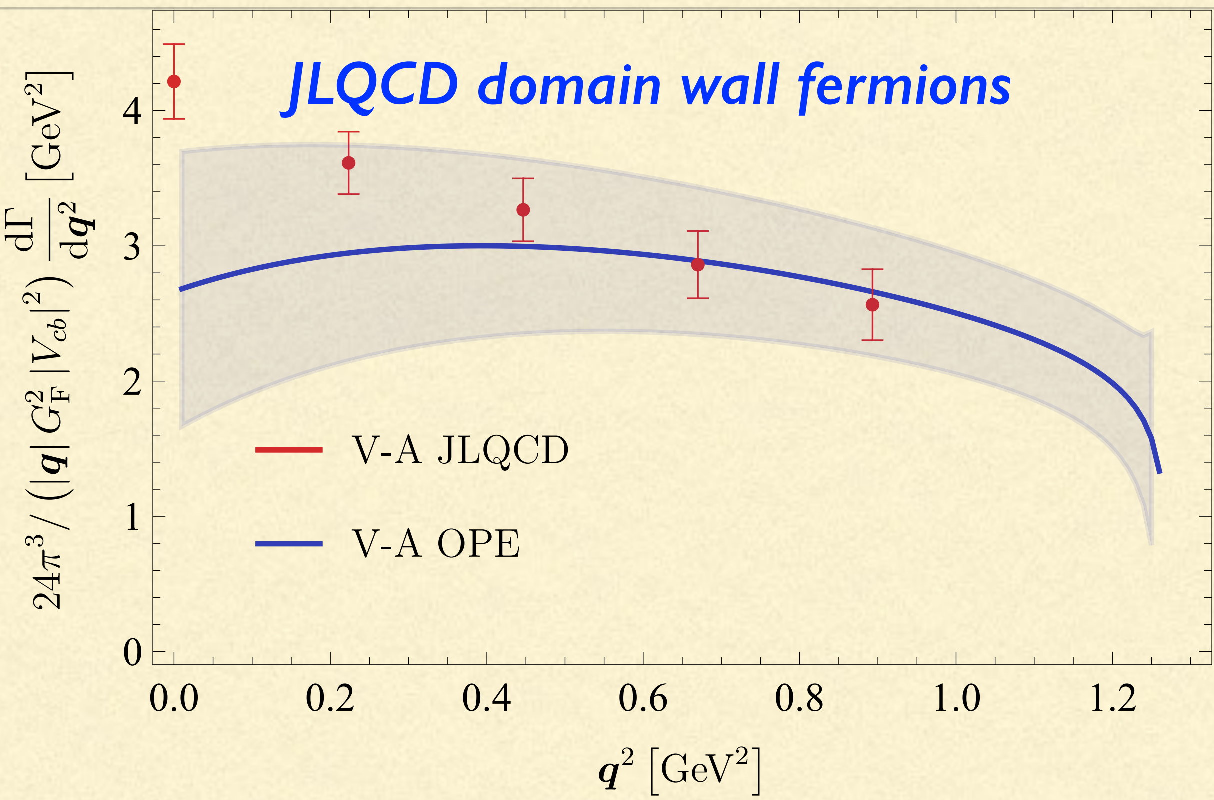
***The necessary smearing is provided by phase space integration*** over the hadronic energy, which however is cut by a $\theta$ with a sharp hedge: sigmoid $1/(1+e^{x/\sigma})$ can be used to replace kinematic $\theta(x)$ for $\sigma \to 0$. Larger number of polynomials needed for small $\sigma$

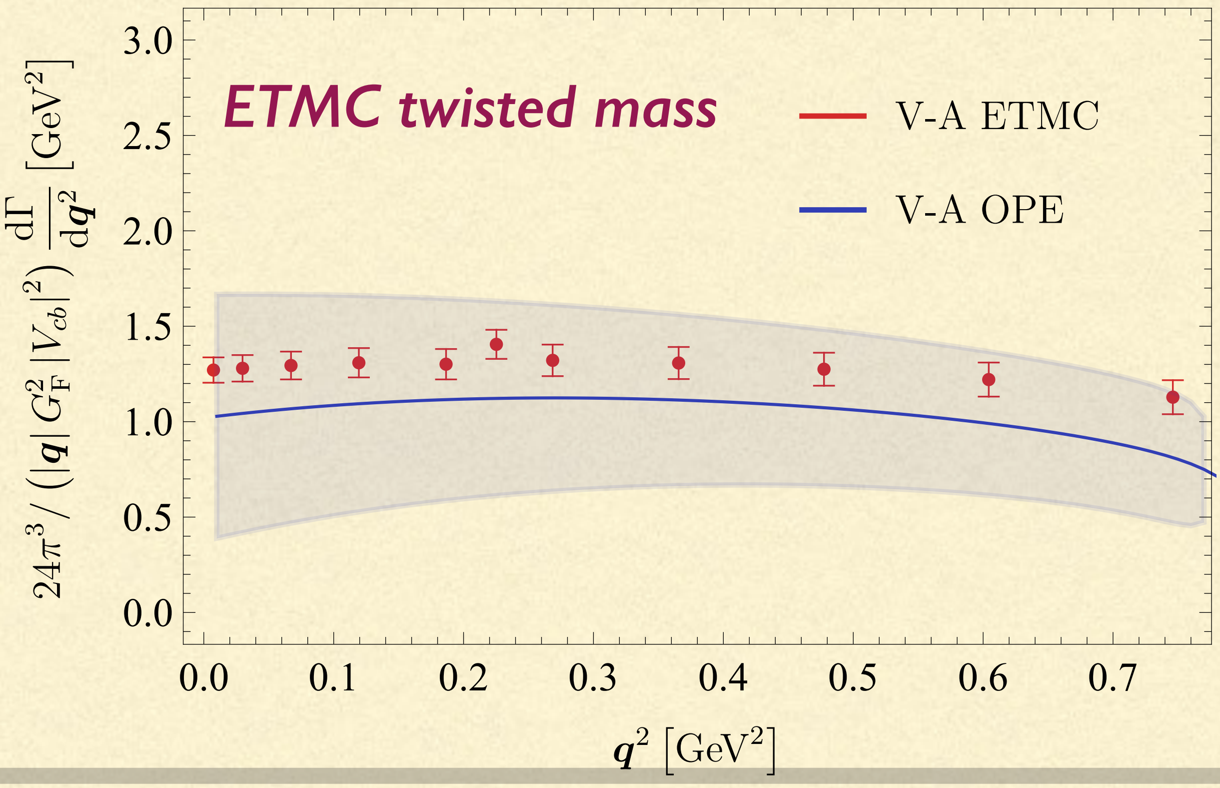



important:

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

# LATTICE VS OPE




| | |
|---|---|
| $m_b^{kin}$ (JLQCD) | $2.70 \pm 0.04$ |
| $\overline{m}_c(2\text{ GeV})$ (JLQCD) | $1.10 \pm 0.02$ |
| $m_b^{kin}$ (ETMC) | $2.39 \pm 0.08$ |
| $\overline{m}_c(2\text{ GeV})$ (ETMC) | $1.19 \pm 0.04$ |
| $\mu_\pi^2$ | $0.57 \pm 0.15$ |
| $\rho_D^3$ | $0.22 \pm 0.06$ |
| $\mu_G^2(m_b)$ | $0.37 \pm 0.10$ |
| $\rho_{LS}^3$ | $-0.13 \pm 0.10$ |
| $\alpha_s^{(4)}(2\text{ GeV})$ | $0.301 \pm 0.006$ |

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

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

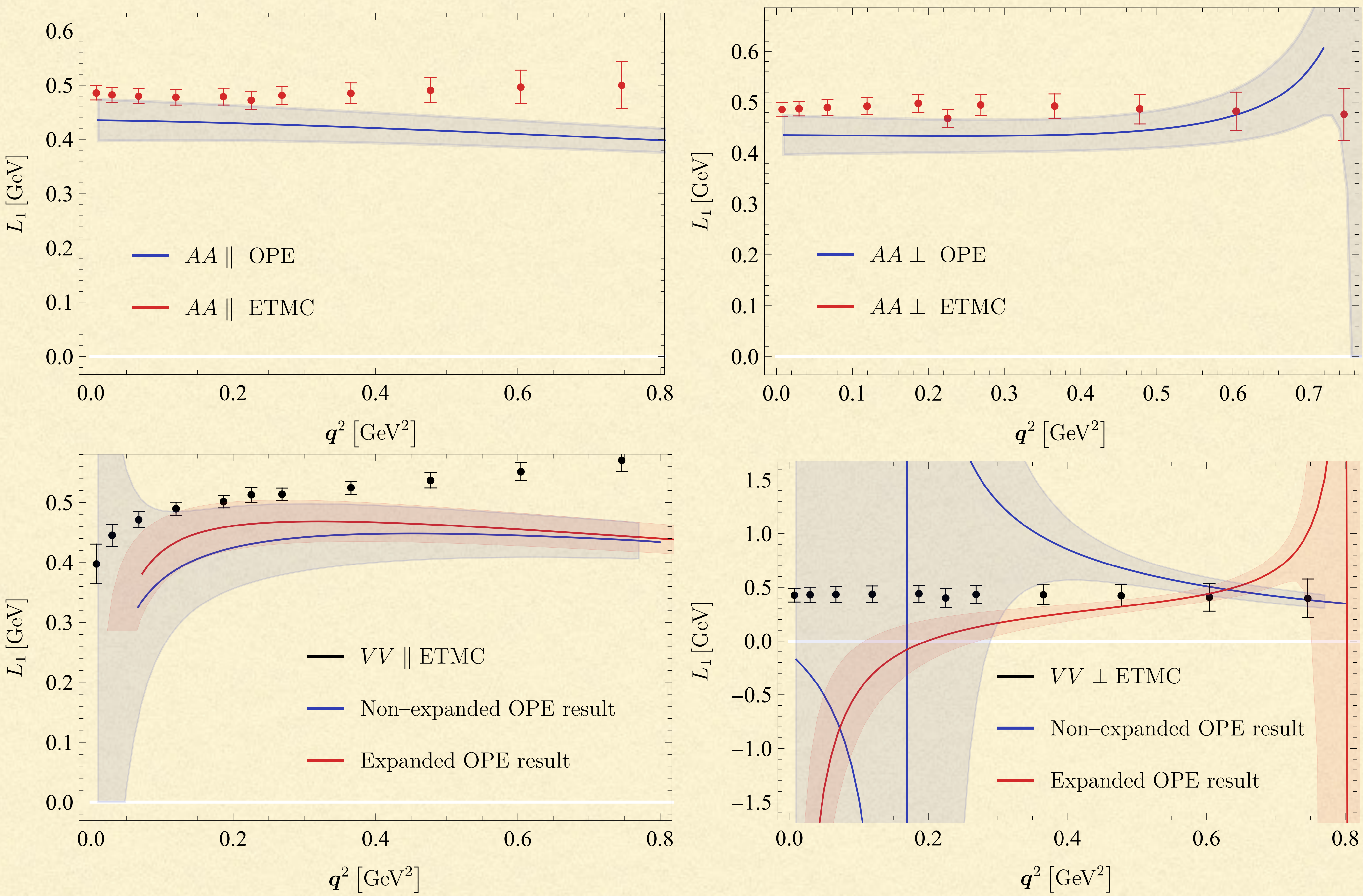
Twisted boundary conditions allow for any value of $\vec{q}^{\,2}$

Smaller statistical uncertainties

# MOMENTS

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

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



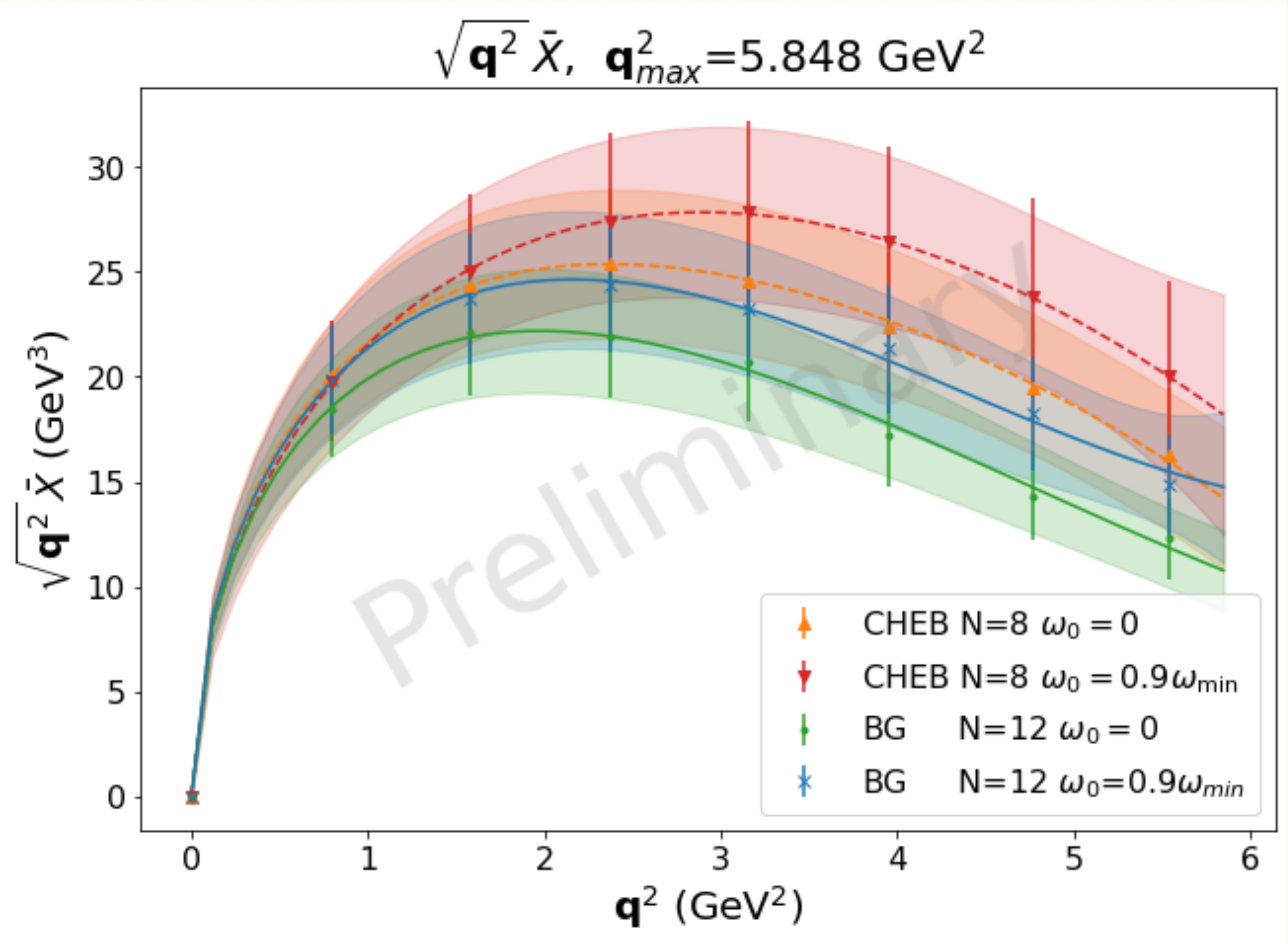

smaller errors, cleaner comparison with OPE, individual channels AA, VV, parallel and perpendicular polarization, could help extracting its parameters

# First results at the physical *b* mass

Relativistic heavy quark effective action for b $B_s$ decays

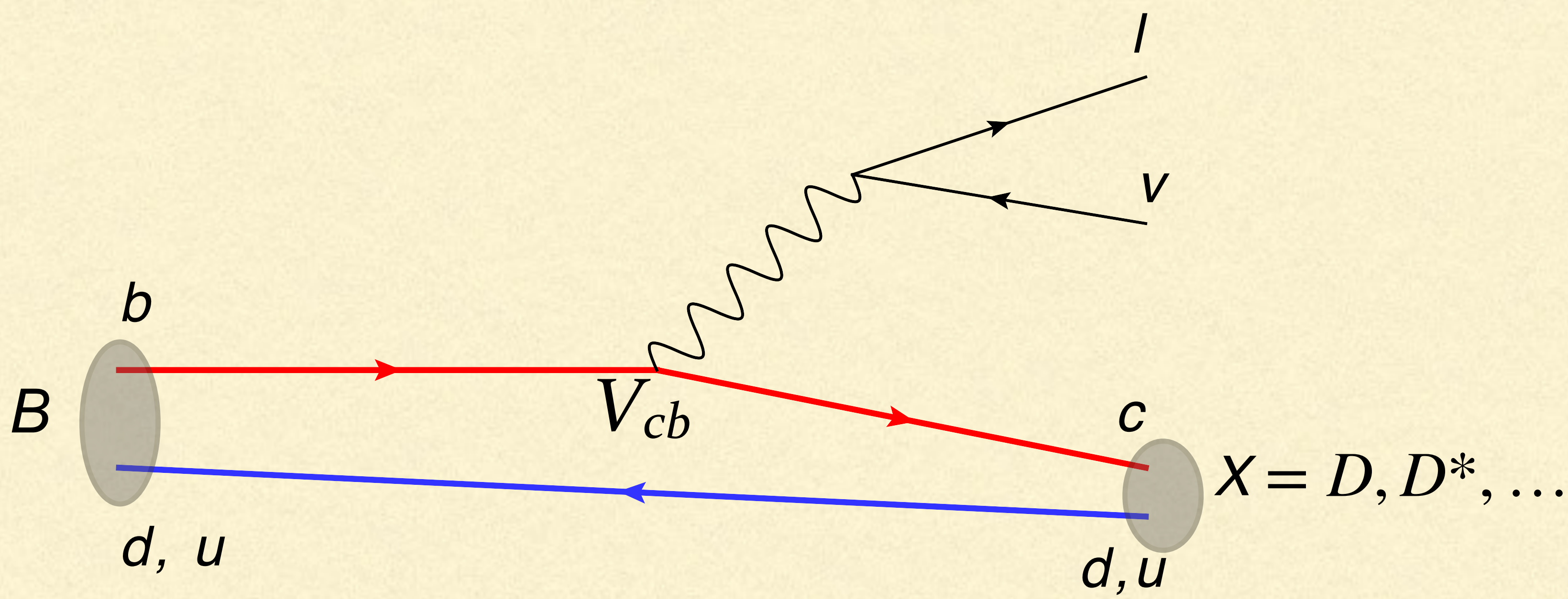
domain wall fermions

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




Barone, Hashimoto, Juttner, Kaneko, Kellermann, Lattice 2022

# EXCLUSIVE DECAYS




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

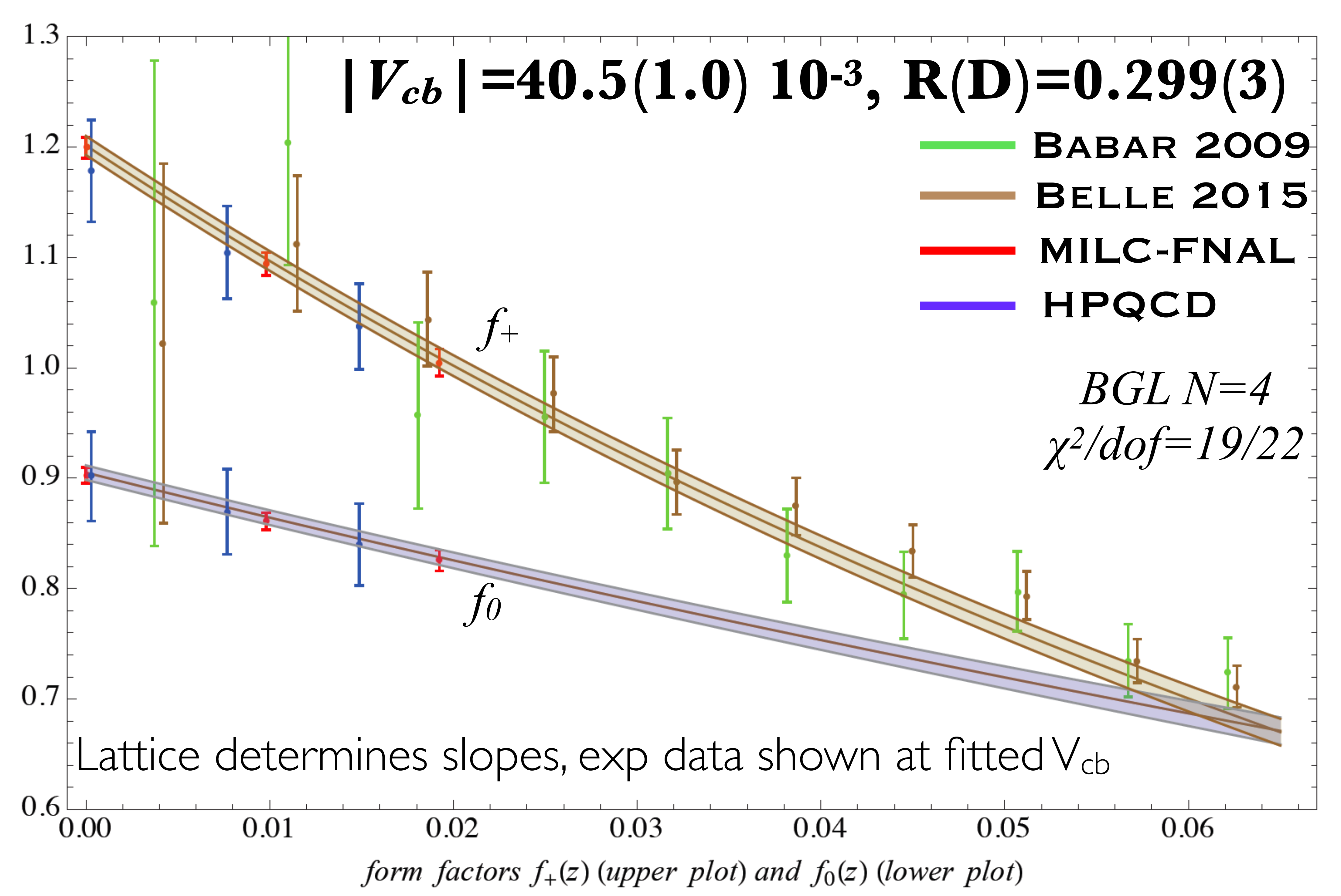
$$\langle D(k)|\, \bar{c}\gamma^\mu b\, |\bar{B}(p)\rangle = \left[(p+k)^\mu - \frac{M_B^2 - M_D^2}{q^2} q^\mu\right] f_+^{B\to D}(q^2) + \frac{M_B^2 - M_D^2}{q^2} q^\mu f_0^{B\to D}(q^2)$$

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

# LATTICE + EXP BGL FIT for $B \to D\ell\nu$

Bigi, PG 1606.08030




R(D)=0.299(3)

1.3$\sigma$ from exp

FLAG has very similar results

CLN cannot fit both ff

# D’AGOSTINI BIAS

Standard $\chi^2$ fits
sometimes lead
to paradoxical results

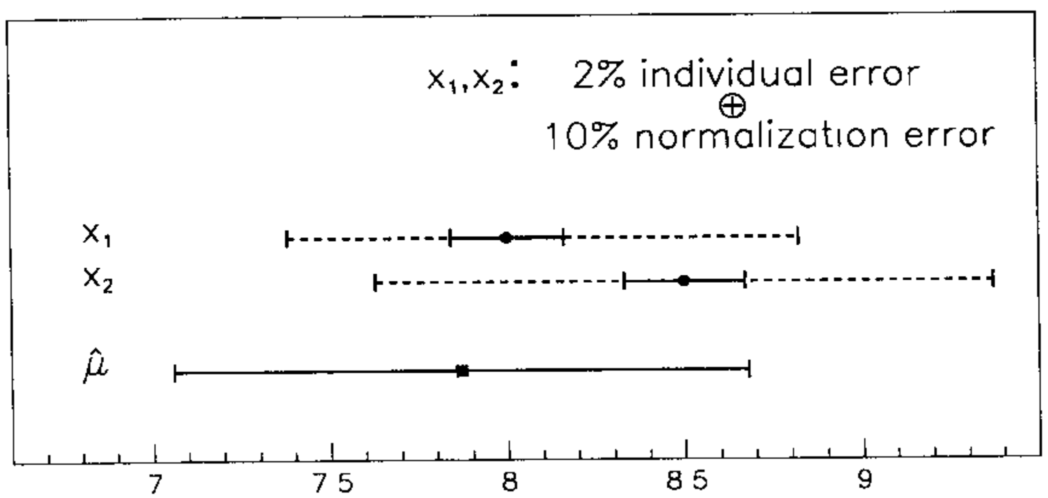



Fig. 1. Best estimate of the true value from two correlated data points, using in the $\chi^2$ the empirical covariance matrix of the meaurements. The error bars show individual and total errors.

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

Many exp systematics are highly corre-
lated. Bias is stronger with more bins

On the use of the covariance matrix to fit correlated data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(Received 10 December 1993; revised form received 18 February 1994)

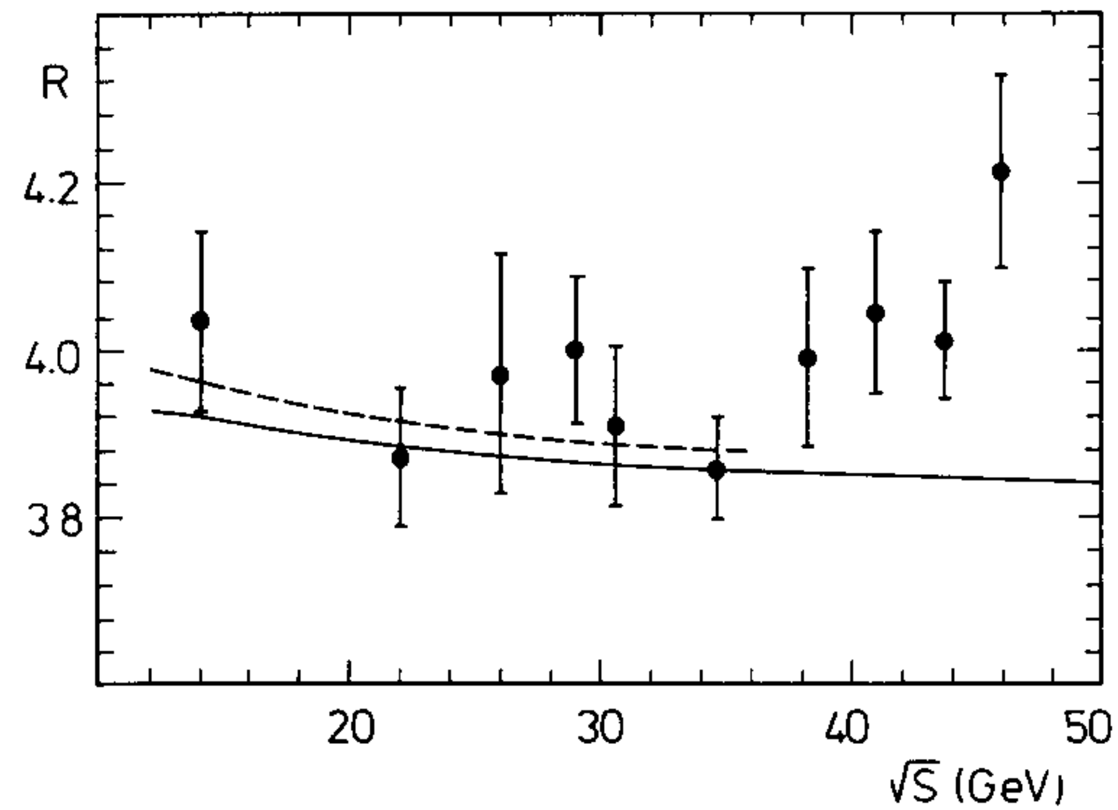
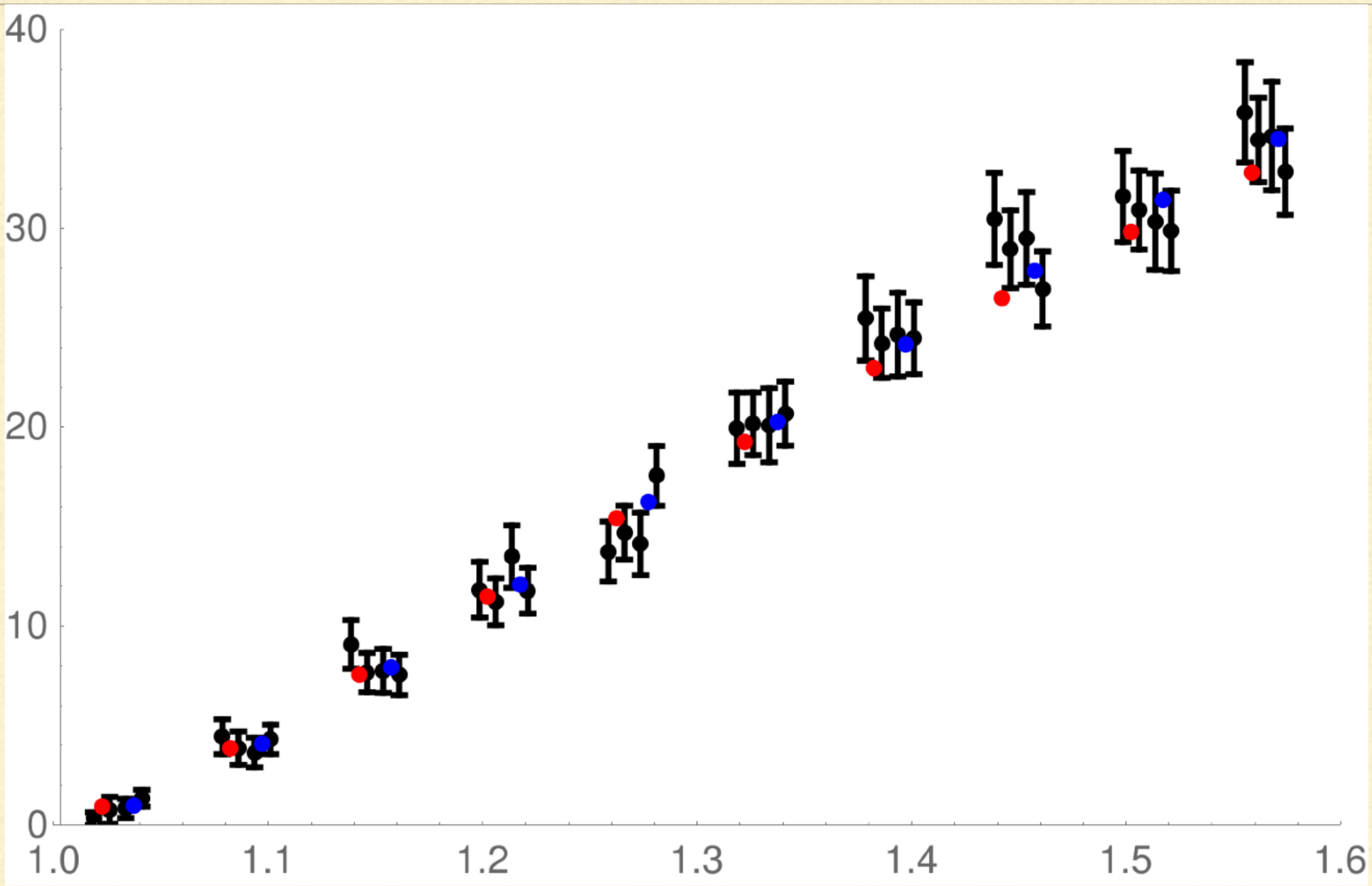




Fig. 2. R measurements from PETRA and PEP experiments with the best fits of QED + QCD to all the data (full line) and only below 36 GeV (dashed line). All data points are correlated (see text).

# $w$ 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

# $|V_{cb}|$ 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, $\mu/e$ 4σ tension in the FB asymmetry) PG, Jung, Schacht & Bobeth, Bordone, van Dyk, Gubernari, Jung
   ***new Belle tagged analysis*** leads to higher $|V_{cb}|$, ***Babar 2019*** to low $|V_{cb}|$, ***LHCb*** to high $|V_{cb}|$. ***New Belle II untagged*** analysis presented at Moriond. ***Data not yet available.***

# Nested Hypothesis Tests or Saturation Constraints



See also Jung's talk

**Z. Ligeti, D. Robinson, M. Papucci, FB**
[arXiv:1902.09553, PRD100,013005 (2019)]

Use a **nested hypothesis test (NHT)** to determine optimal truncation order

Challenge nested fits

$$\mathbf{BGL}_{n_a,n_b,n_c} \leftrightarrow \mathbf{BGL}_{n_a+1,n_b,n_c}$$
$$\mathbf{BGL}_{n_a,n_b,n_c} \leftrightarrow \mathbf{BGL}_{n_a,n_b+1,n_c}$$
$$\mathbf{BGL}_{n_a,n_b,n_c} \leftrightarrow \mathbf{BGL}_{n_a,n_b,n_c+1}$$

Test statistics & Decision boundary

$$\Delta\chi^2 = \chi^2_N - \chi^2_{N+1} \qquad \Delta\chi^2 > 1$$

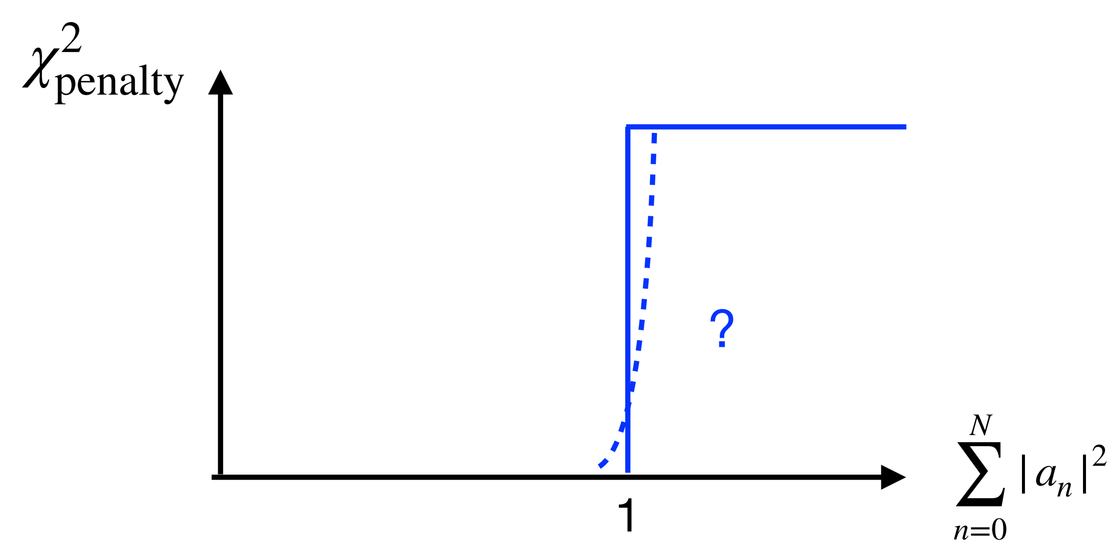
Distributed like a $\chi^2$-distribution with 1 dof
(Wilk's theorem)

**Gambino, Jung, Schacht**
[arXiv:1905.08209, PLB]

Constrain contributions from higher order coefficients using **unitarity bounds**

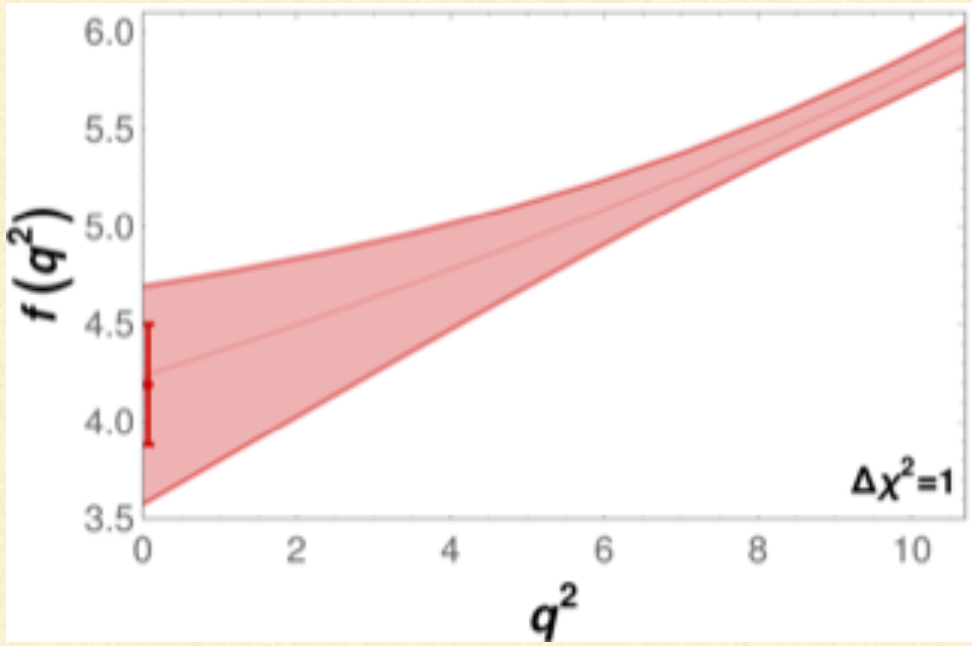
$$\sum_{n=0}^{N} |a_n|^2 \le 1 \qquad \sum_{n=0}^{N} \left( |b_n|^2 + |c_n|^2 \right) \le 1$$

e.g. $\chi^2 \to \chi^2 + \chi^2_{\text{penalty}}$



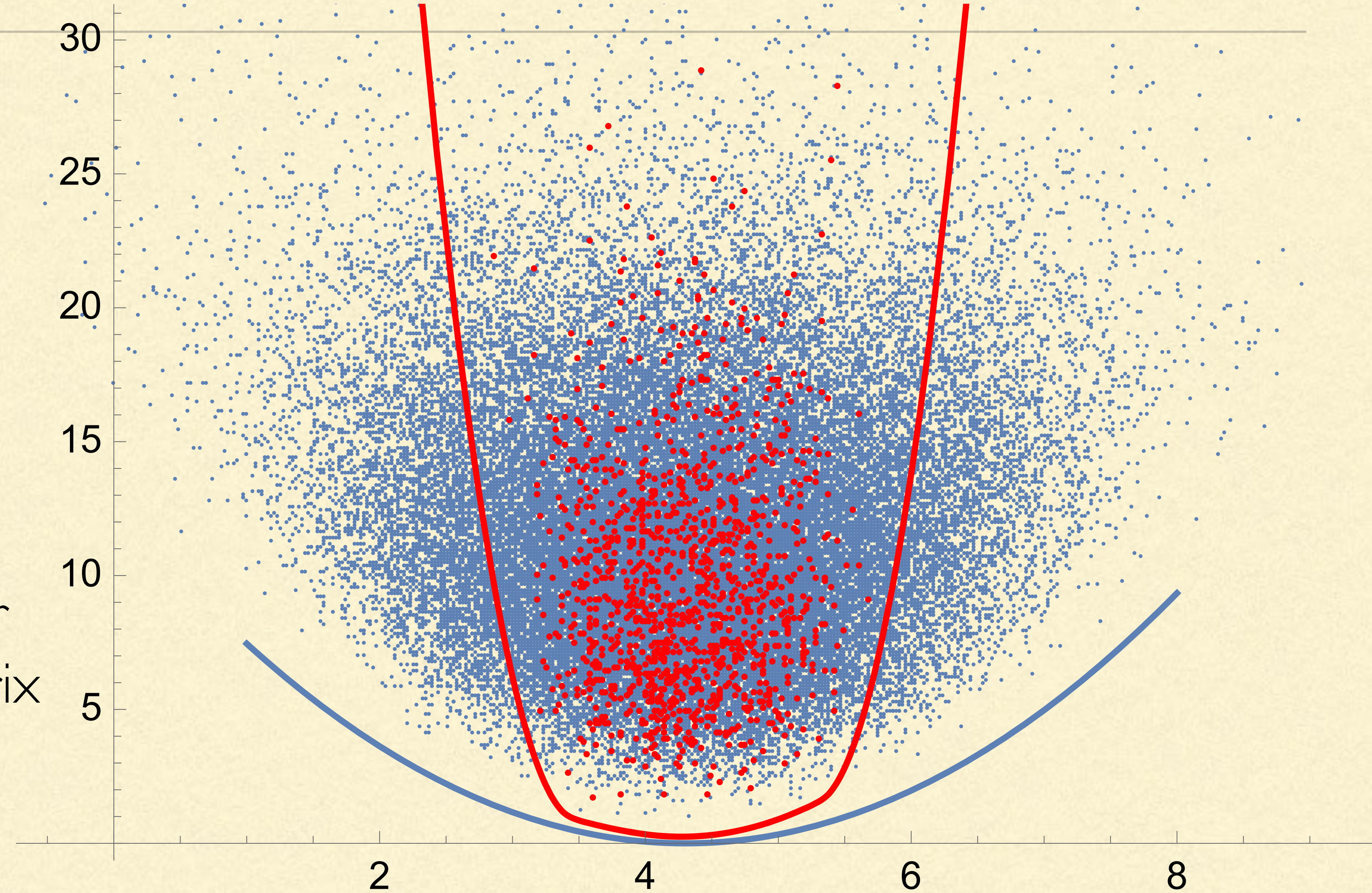

Other approaches: Dispersive Matrix Lellouch, Martinelli, Simula, Vittorio
and similar Bayesian inference method by Flynn, Juttner, Tsang 2303.11285

# UNITARITY CONSTRAINTS and UNCERTAINTY




low $q^2$ extrapolation of FNAL $f$: our method (up to $z^2$) vs Dispersive Matrix

In JLQCD case the difference between methods is much smaller

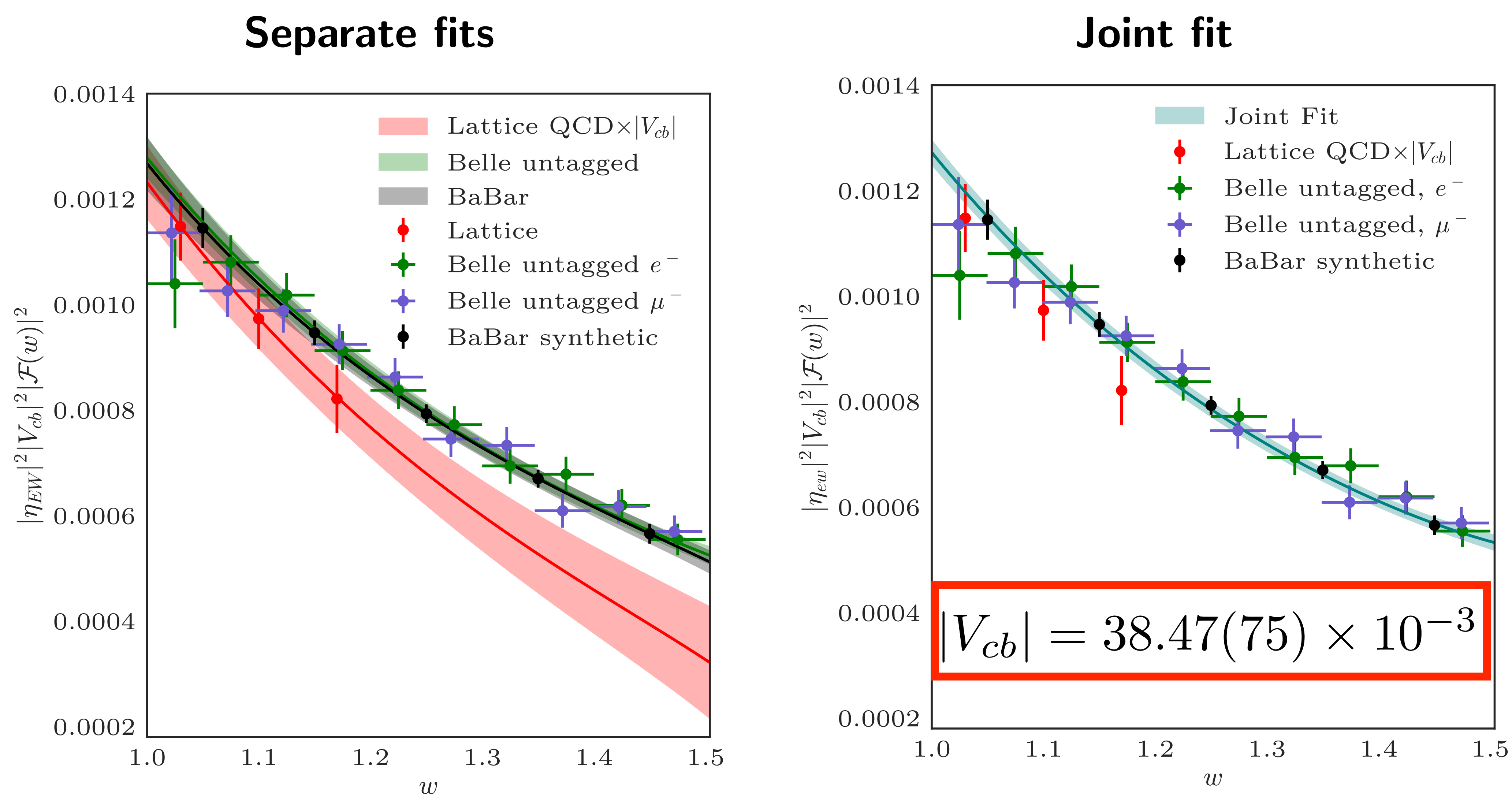



In **blue** the $\chi^2_{min}$ profile as a function of $f(q^2=0)$ without imposing unitarity. In red with minimum complying with unitarity. Our $\delta_{\pm} f(0)$ corresponds to $\Delta\chi^2_{min} = 1$ from the absolute minimum.

**Blue points** are generated according to FNAL covariance matrix. **Red points** survive unitarity filtering: their distribution is much narrower but the points at its edge correspond to ***small fluctuations*** in FNAL data. Our $\delta_{\pm} f(0)$ reflect this and are always larger than its standard deviation. The curves at the edge of our band are consistent with unitarity and represent $\sim 1\sigma$ fluctuations in FNAL data

# FERMILAB/MILC CALCULATION

2105.14019



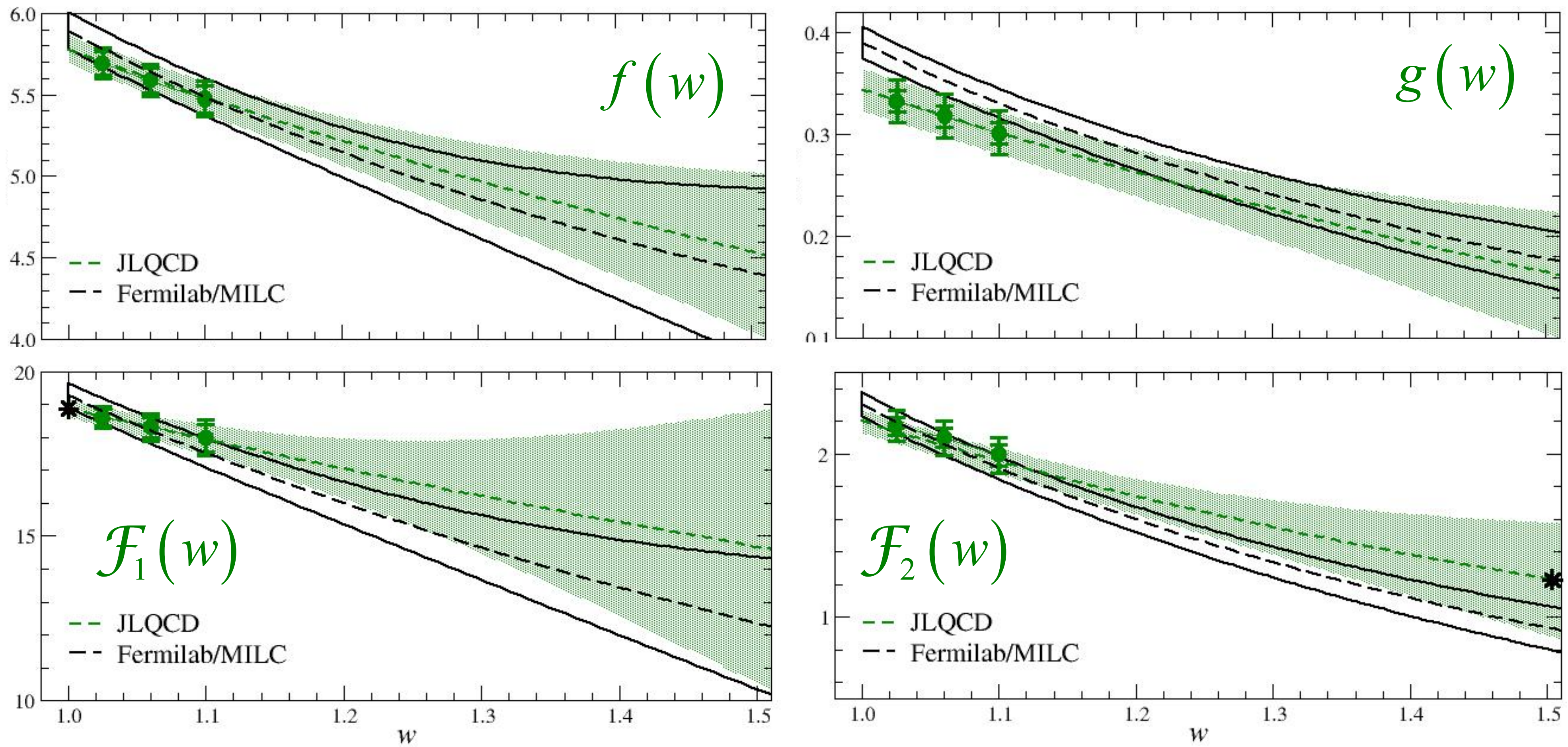

| Fit | Lattice | Exp | Lat + Belle | Lat + BaBar | Lat + Exp |
|---|---|---|---|---|---|
| $p$-Value | 0.88 | 0.037 | 0.015 | 0.088 | 0.002 |

*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



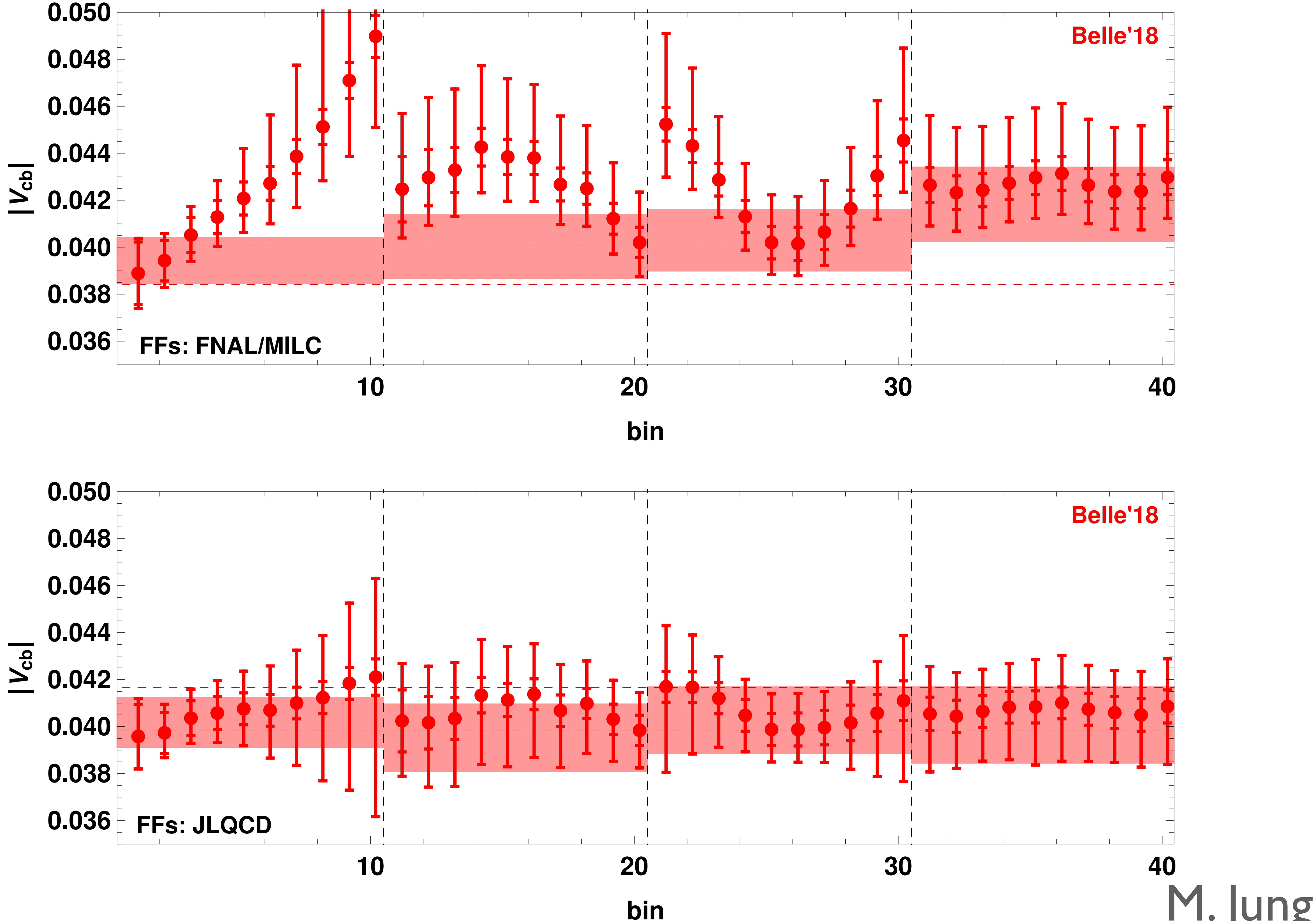

- reasonably consistent

$\Leftrightarrow$ $g$ @ $w$ ~ 1

T. Kaneko @ Barolo workshop 4/2021
Kaneko et al 2112.13775

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

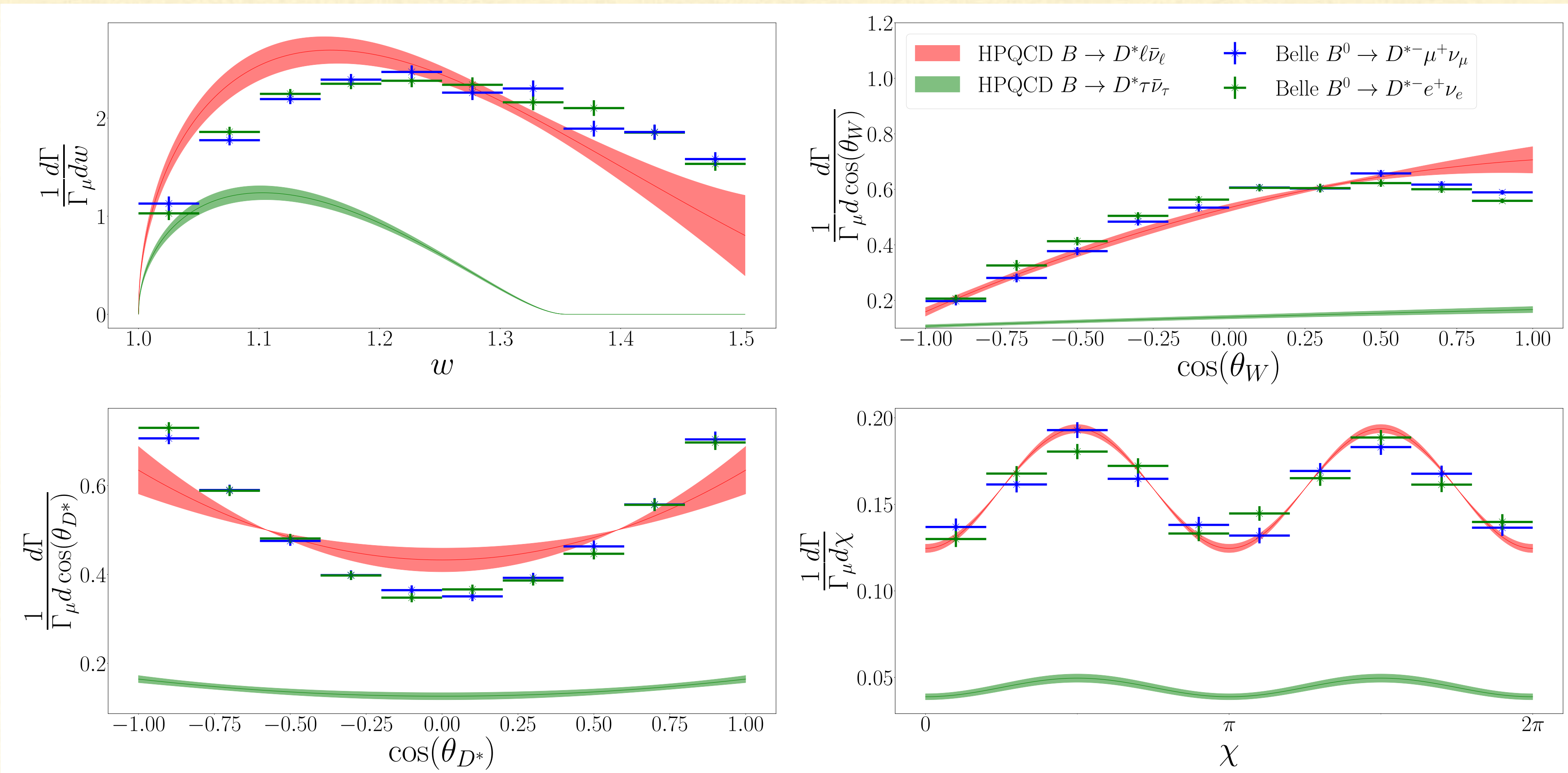
# Binned $V_{cb}$ from Belle'18 data: FNAL/MILC vs JLQCD




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

# NEW HPQCD FFS CALCULATION

2304.03137




Tension with Belle 2018 data similar to FNAL

***Belle18+HPQCD***

| BGL exp | $\chi^2$ | $\lvert V_{cb}\rvert$ |
|---|---|---|
| 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

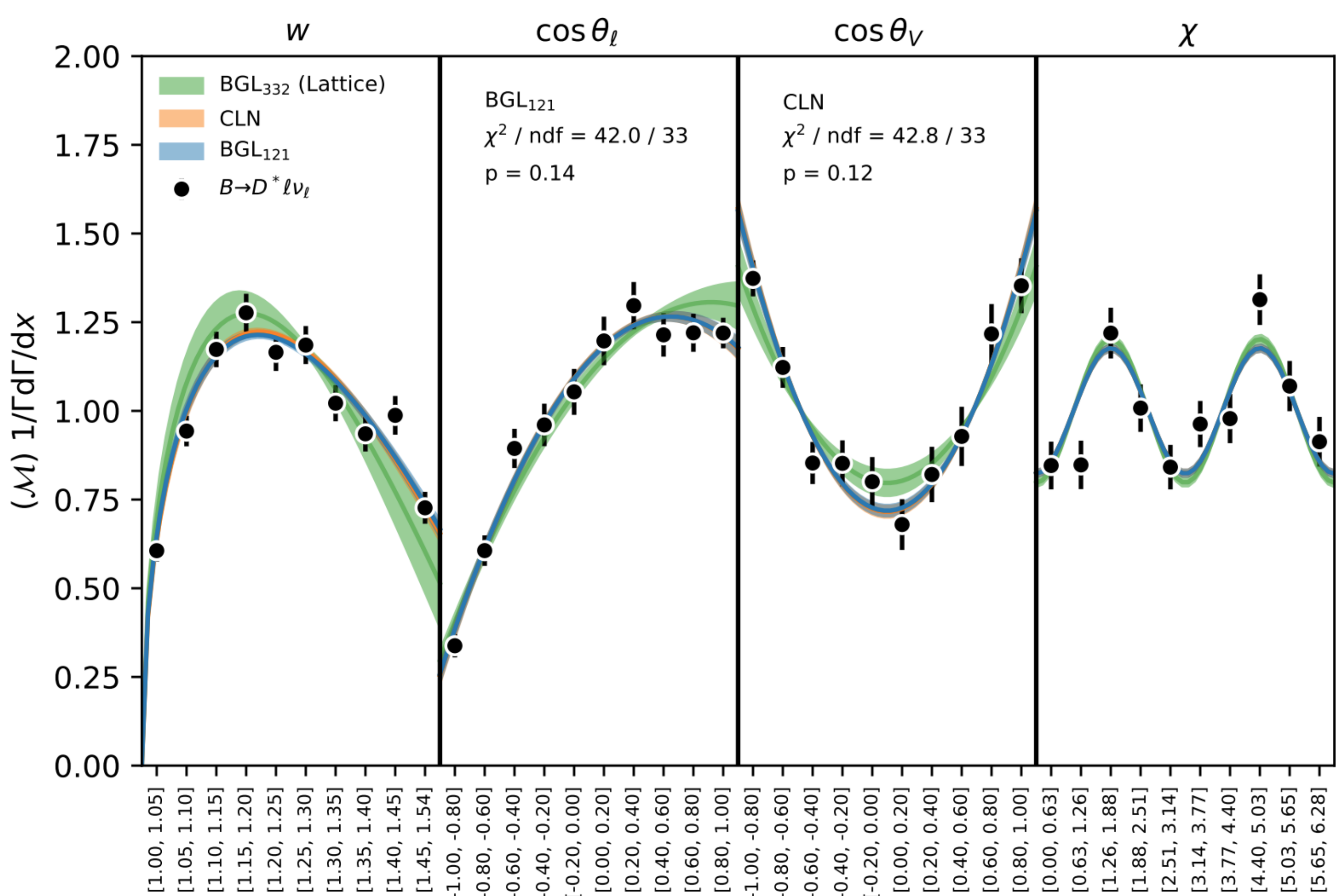
*Our analysis of same exp (Belle18)+ HPQCD data (Jung, PG):*
$|V_{cb}|=40.4(8)\ 10^{-3}$ *using only total rate* $|V_{cb}|=44.4 \pm 1.6\ 10^{-3}$

*HPQCD and FNAL are not really compatible: adding 16 FNAL points increases $\chi^2$ by 35*

# 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 | | | | |
|---|---|---|---|---|---|---|
| $a_0 \times 10^3$ | $24.93 \pm 1.41$ | $1.00$ | $0.25$ | $-0.21$ | $0.26$ | $-0.30$ |
| $b_0 \times 10^3$ | $13.11 \pm 0.18$ | $0.25$ | $1.00$ | $-0.01$ | $-0.01$ | $-0.62$ |
| $b_1 \times 10^3$ | $-11.93 \pm 12.72$ | $-0.21$ | $-0.01$ | $1.00$ | $0.25$ | $-0.48$ |
| $c_1 \times 10^3$ | $-0.87 \pm 0.97$ | $0.26$ | $-0.01$ | $0.25$ | $1.00$ | $-0.49$ |
| $\boxed{\lvert V_{cb}\rvert \times 10^3}$ | $40.77 \pm 0.92$ | $-0.30$ | $-0.62$ | $-0.48$ | $-0.49$ | $1.00$ |

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

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

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

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

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

## BGL fit result

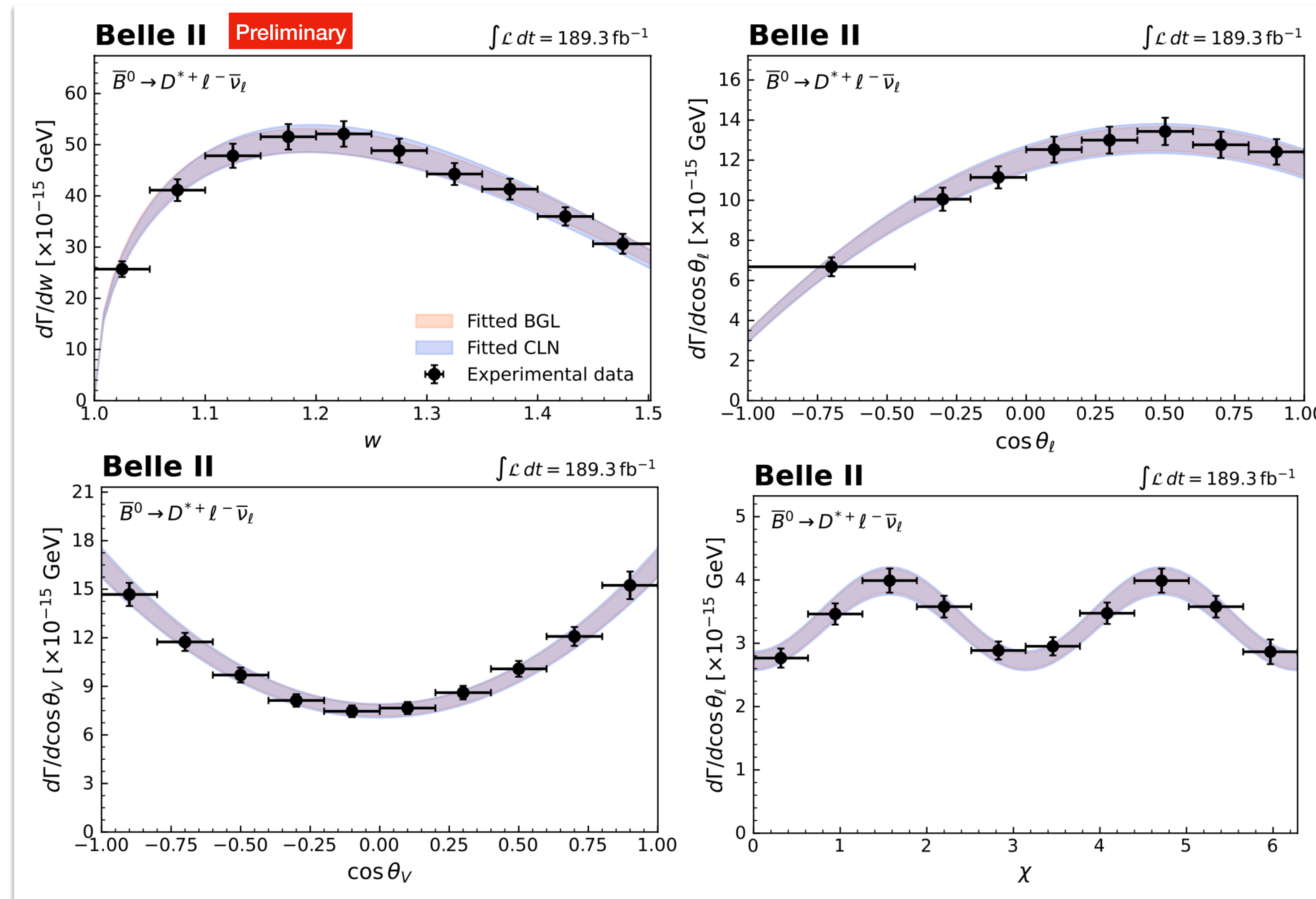
BGL truncation order determined by
Nested Hypothesis Test [Phys. Rev. D100, 013005]

| | Values | Correlations | | | | $\chi^2$/ndf |
|---|---|---|---|---|---|---|
| $\tilde{a}_0 \times 10^3$ | $0.89 \pm 0.05$ | 1.00 | 0.26 | −0.27 | 0.07 | 40/31 |
| $\tilde{b}_0 \times 10^3$ | $0.54 \pm 0.01$ | 0.26 | 1.00 | −0.41 | −0.46 | |
| $\tilde{b}_1 \times 10^3$ | $-0.44 \pm 0.34$ | −0.27 | −0.41 | 1.00 | 0.56 | |
| $\tilde{c}_1 \times 10^3$ | $-0.05 \pm 0.03$ | 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 | $\boxed{1.5}$ | 18.4 | 22.0 |
| Tracking of $K$, $\pi$, $\ell$ | 0.5 | 0.5 | 0.6 | 0.5 |
| $N_{B\overline{B}}$ | 0.8 | 0.8 | 1.1 | 0.8 |
| $f_{+-}/f00$ | 1.3 | $\boxed{1.3}$ | 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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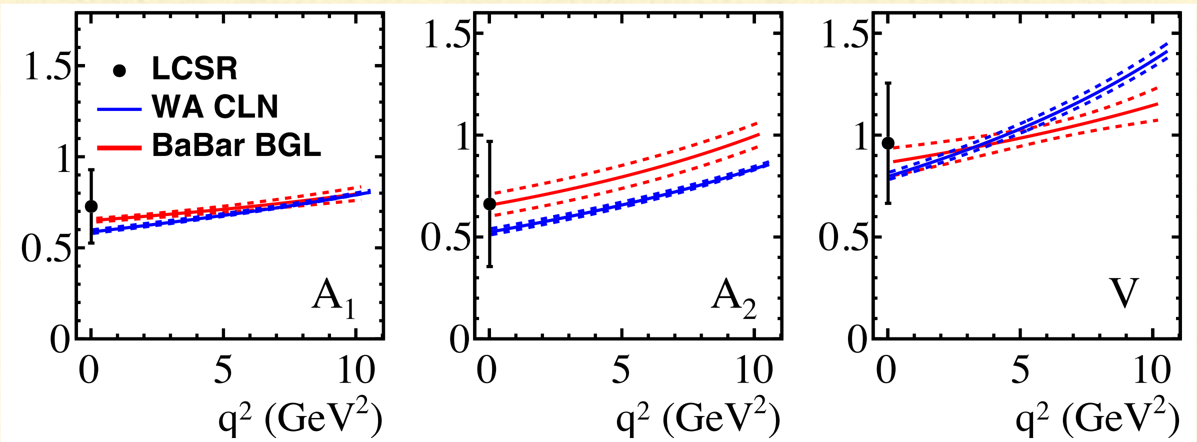
$$|V_{cb}|_{CLN} = (40.4 \pm 0.3_{stat} \pm 1.0_{syst} \pm 0.6_{theo}) \times 10^{-3}$$

C. Schwanda, Moriond '23

# 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$^{(222)}$

# SUMMARY

- ***Despite many new theoretical and exp results, the $V_{cb}$ puzzle persists. However, the level of activity gives hope.***
- ***Inclusive $b \to c$:*** new 3loop calculations show pert effects under control, 1.2% accuracy on $|V_{cb}|$
- New method to study ***inclusive semileptonic meson decays on the lattice***. Exploratory calculations for $m_b \sim 2.5\mathrm{GeV}$ in good agreement with OPE. Promising way to complement/validate the OPE, but still a long way to go
- ***Exclusive*** $b \to c$: uncertainties have been underestimated; several lattice groups are computing necessary FFs at non-zero recoil and new exp analyses are under way but the ***situation is still unclear***. FNAL & HPQCD in tension with exp spectra, JLQCD gives a more consistent picture with reduced tension with inclusive.