Semileptonic b→c decays: puzzles and opportunities

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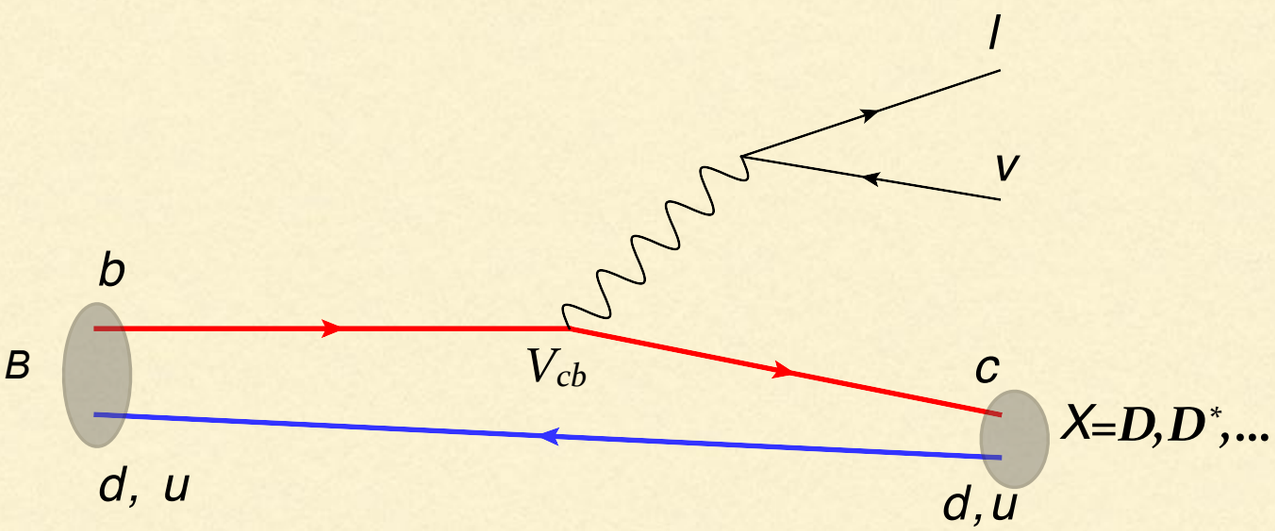
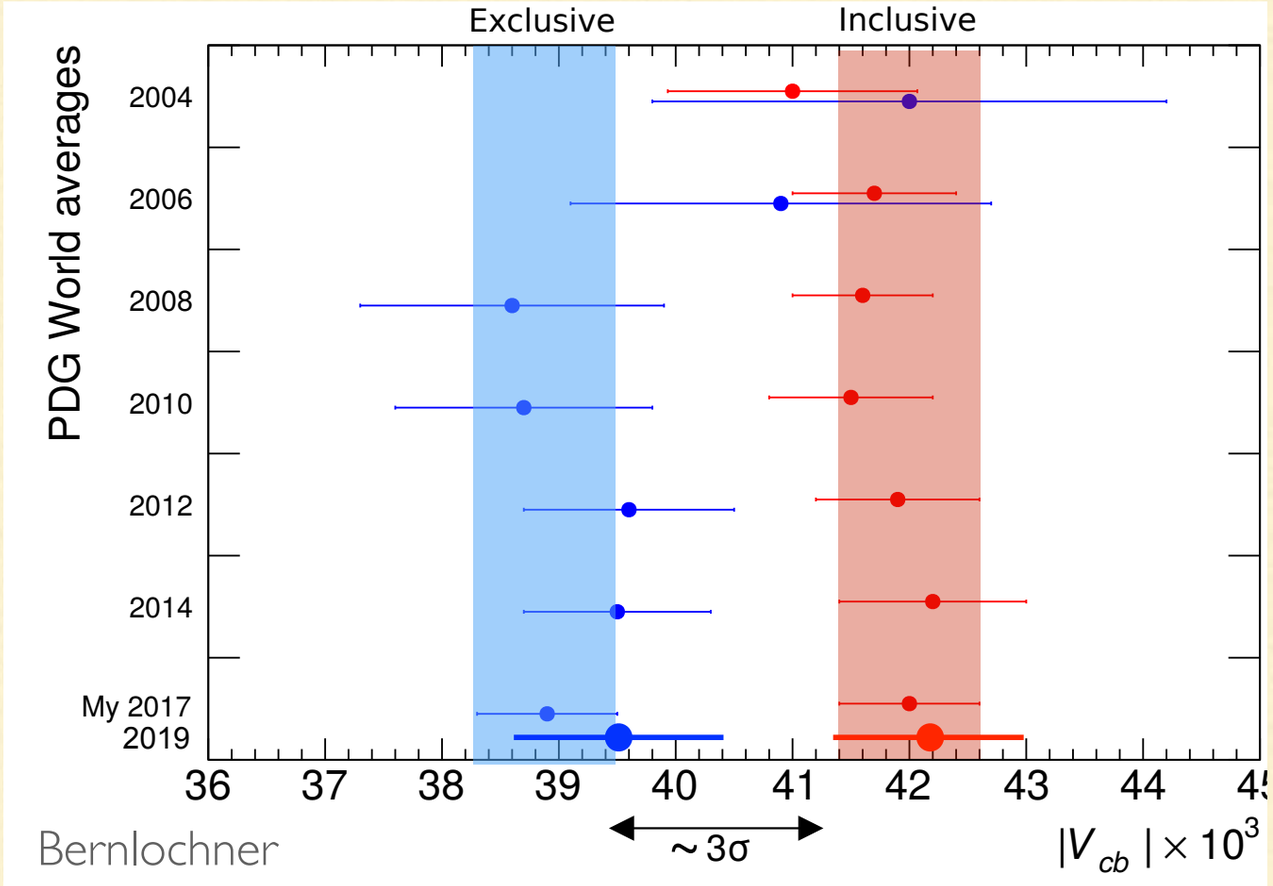
University of Vienna, 18 May 2021

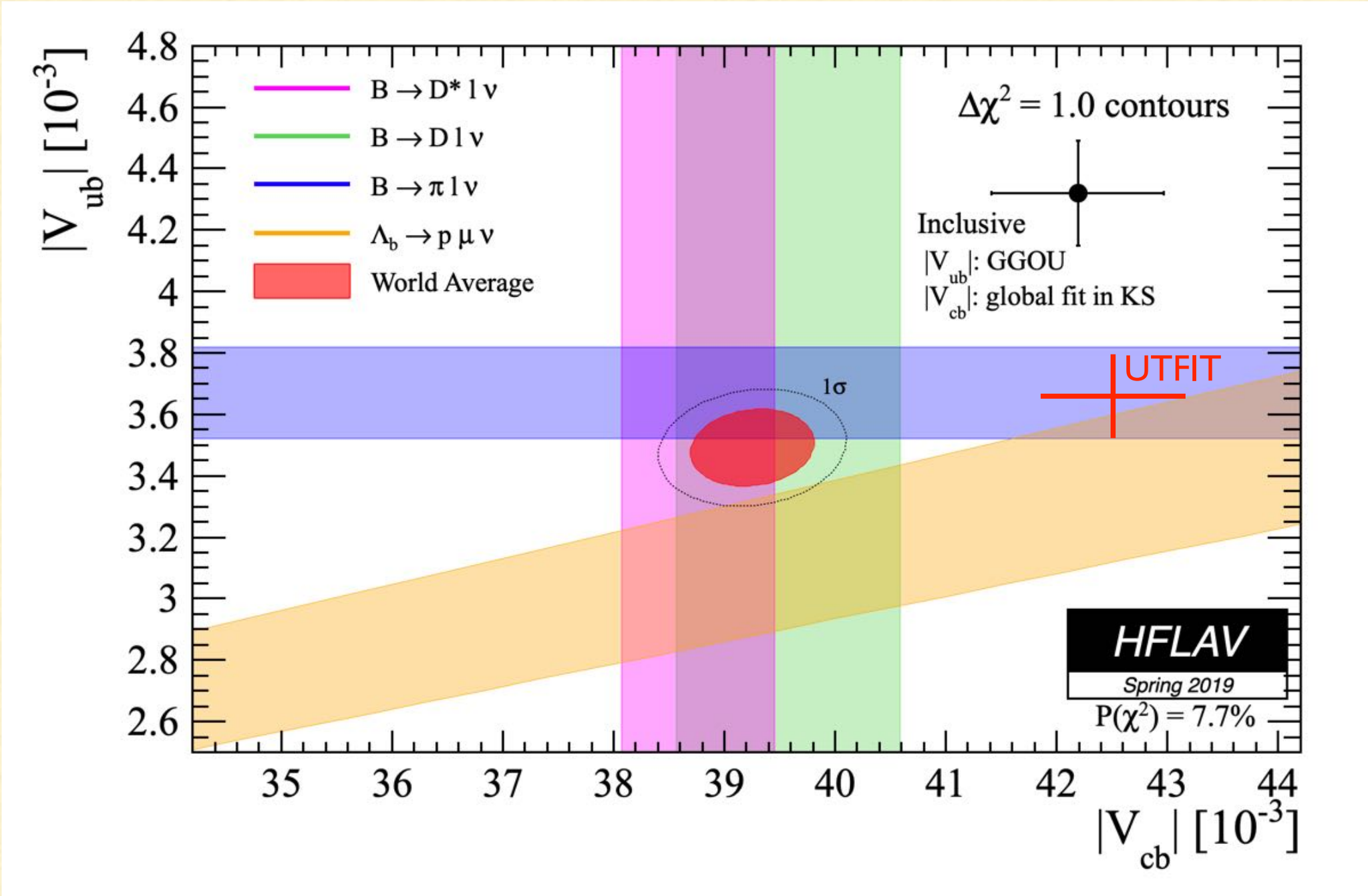
A LONG-STANDING TENSION





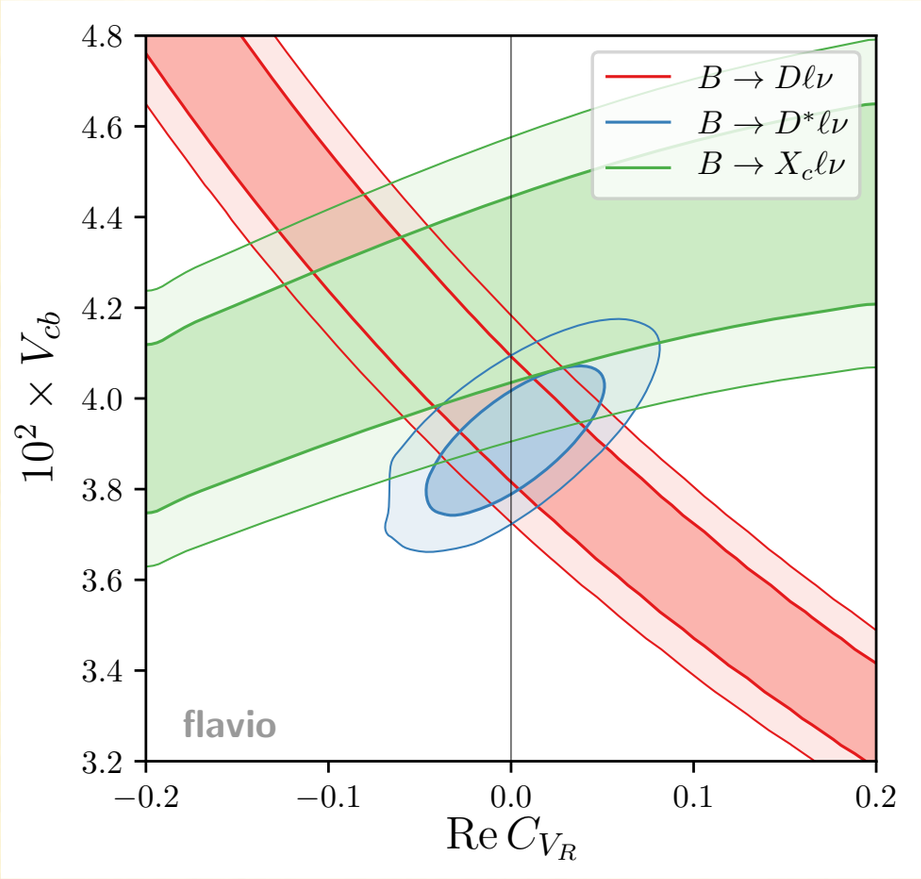
Semileptonic B decays measure the magnitude of the CKM matrix elements V_{cb} and V_{ub}

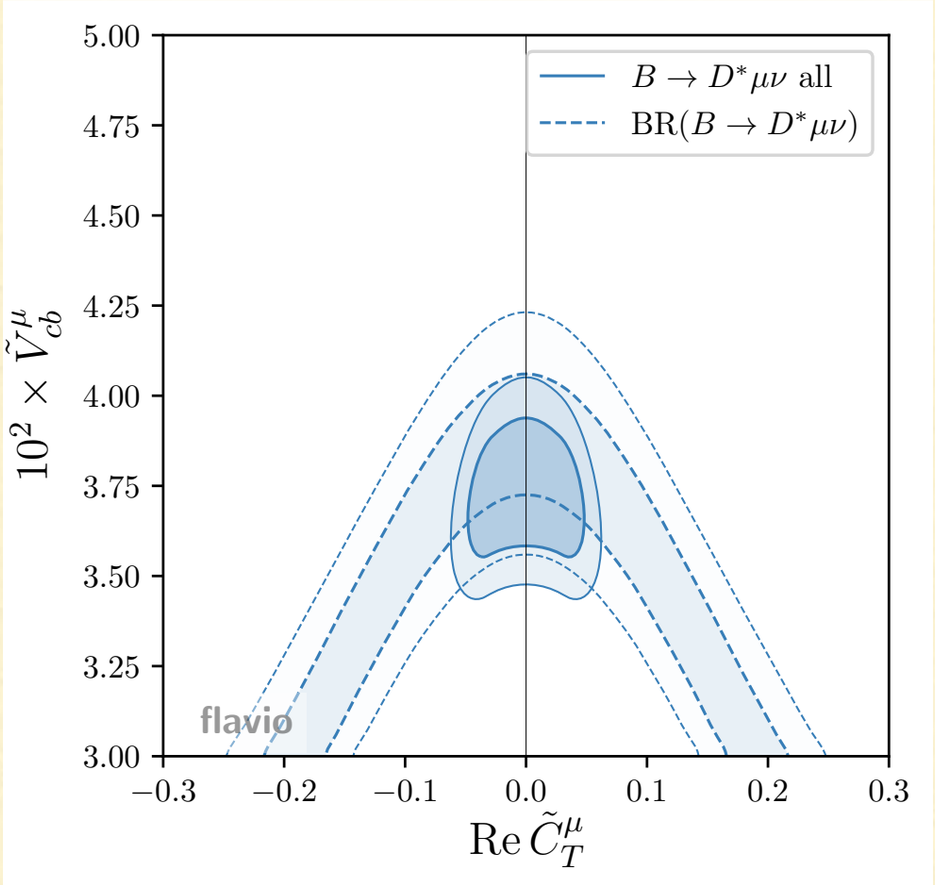
Their determinations from inclusive and exclusive decays differ since many years.



Last few years: new analyses of B-factories data, new calculations of FFs by several lattice collaborations and with light-cone sum rules, rising to the challenges of a precision measurement

NEW PHYSICS?





Differential distributions constrain NP strongly, SMEFT interpretation incompatible with LEP data (Crivellin, Pokorski etc.)

Jung & Straub 1801.01112

The importance of $|V_{cb}|$

The most important CKM unitarity test is the Unitarity Triangle (UT)

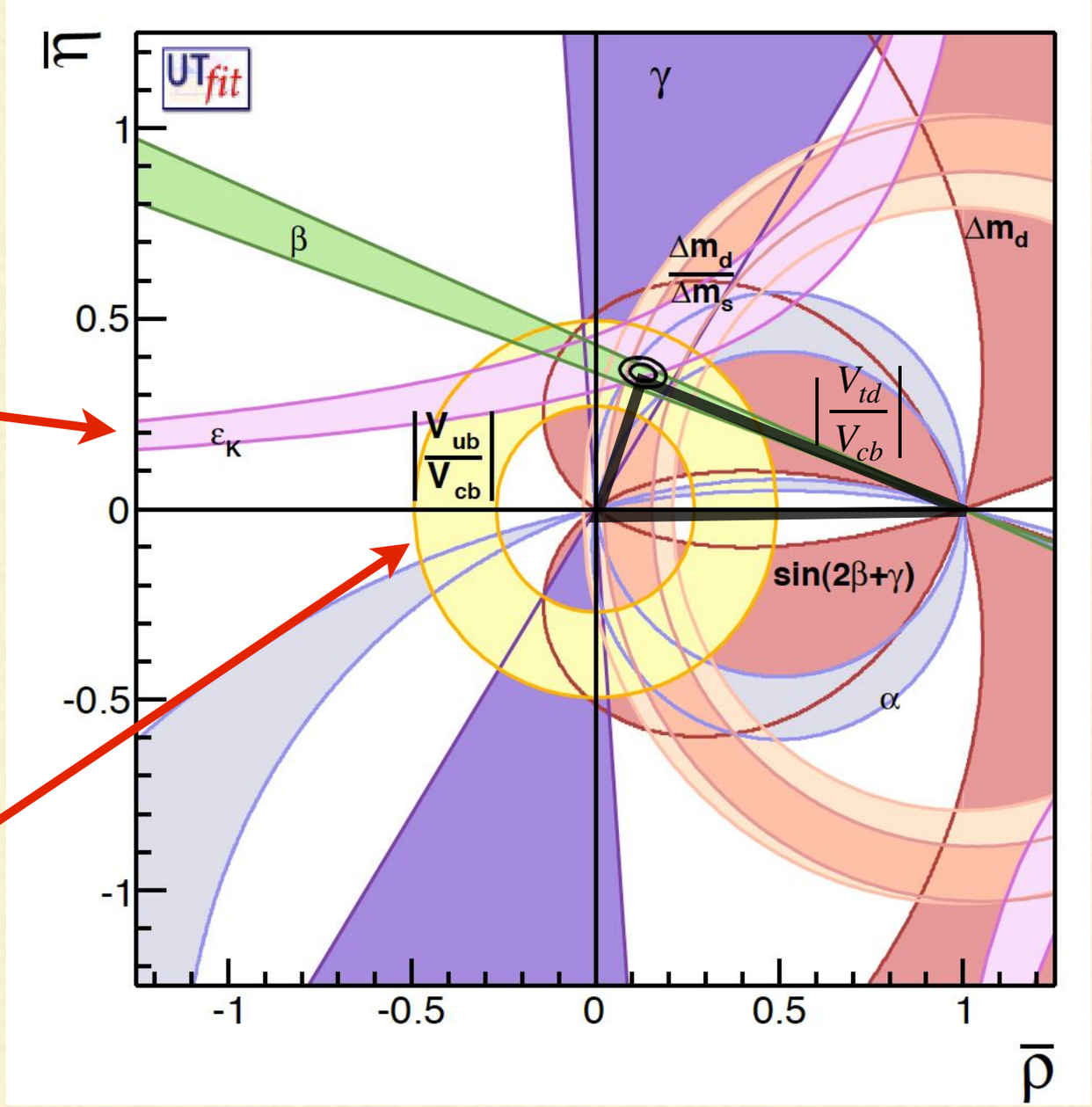
V_{cb} plays an important role in UT

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

and in the prediction of FCNC:

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

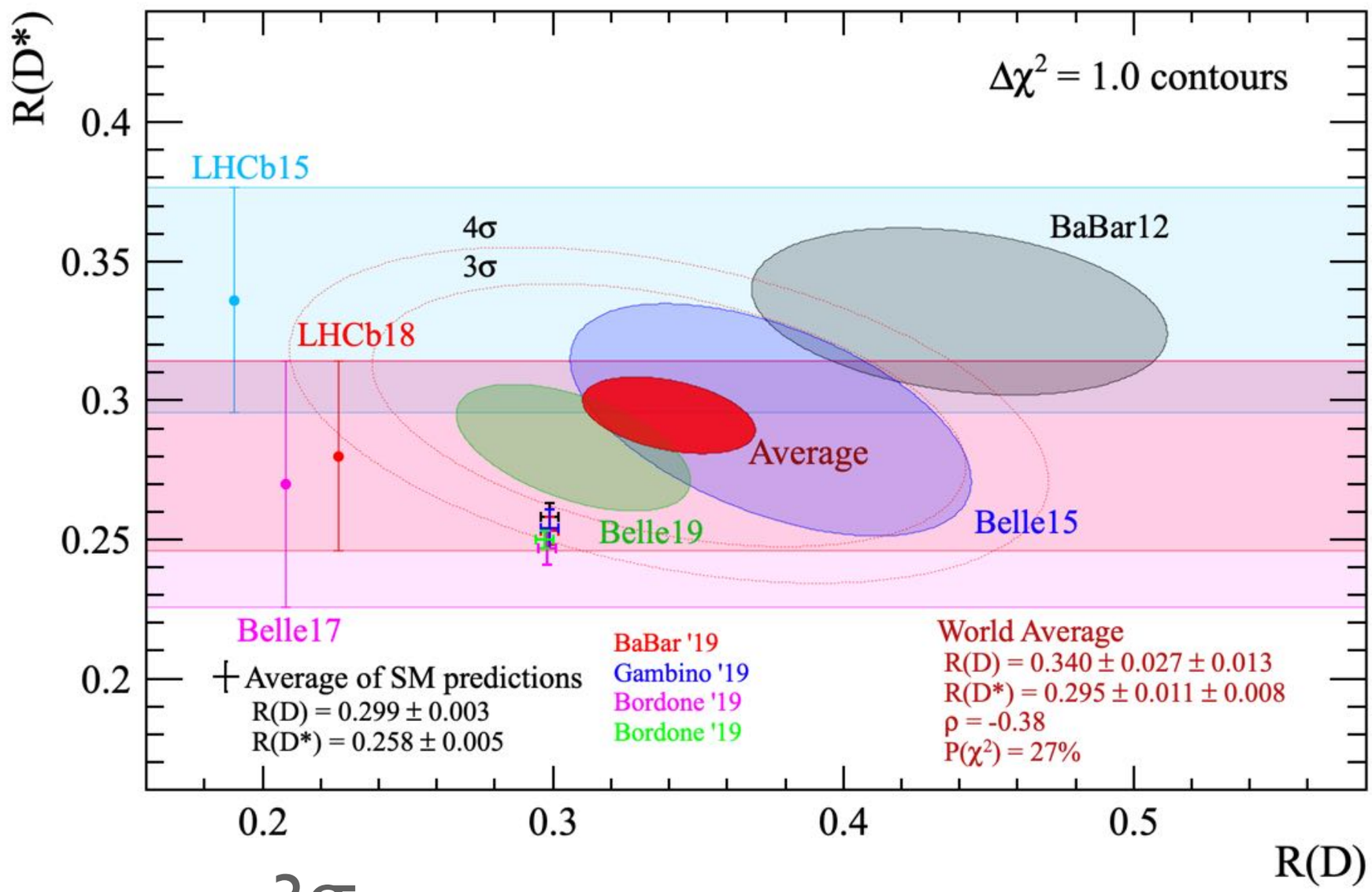
where it often dominates the theoretical uncertainty.
V_{ub}/V_{cb} constrains directly the UT



Our inability to determine precisely V_{cb} hampers significantly NP searches

VIOLATION OF LFU WITH TAUS

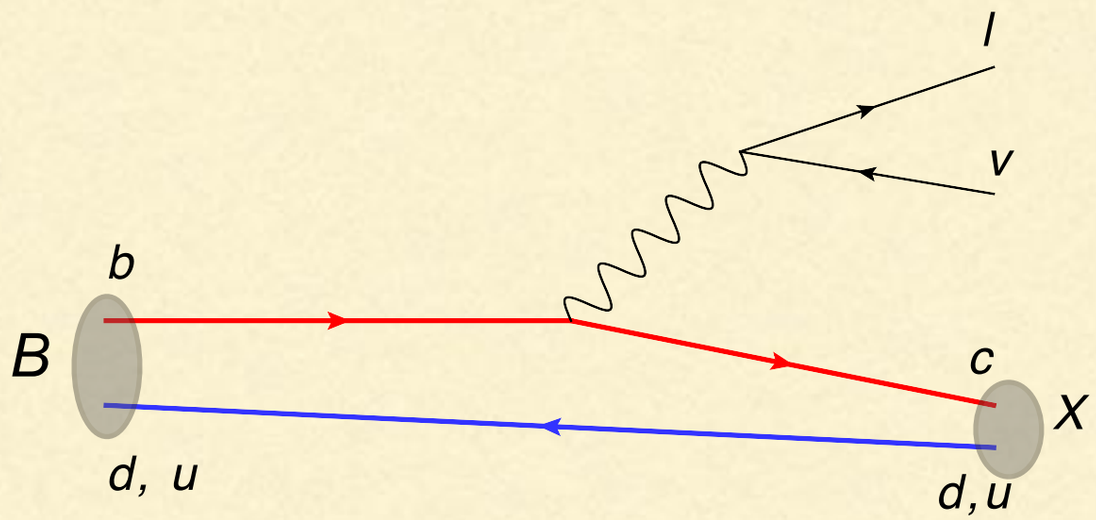
$$R\left(D^{(*)}\right) = \frac{\mathcal{B}\left(B \to D^{(*)}\tau\nu_\tau\right)}{\mathcal{B}\left(B \to D^{(*)}\ell\nu_\ell\right)}$$

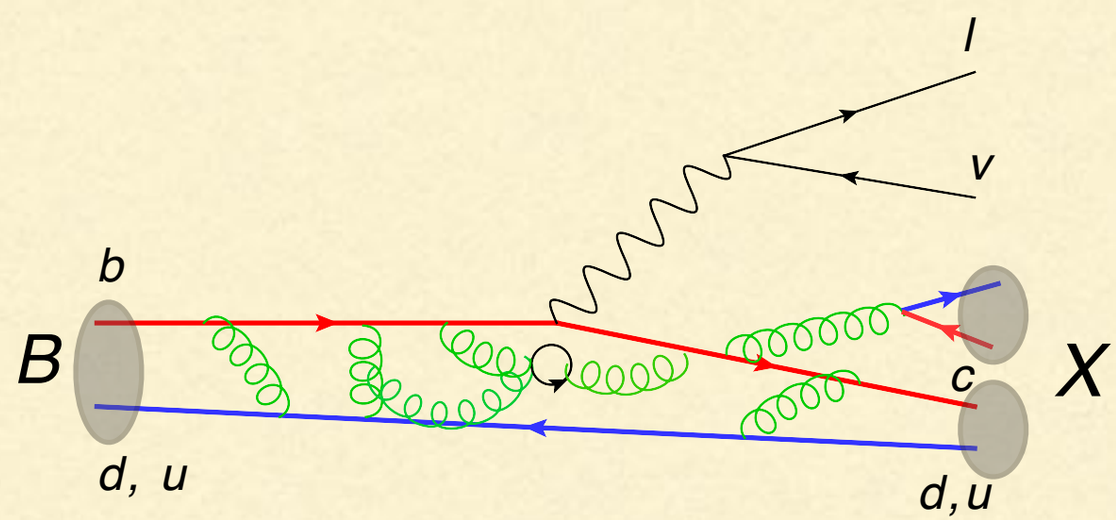


~3σ

M. Rotondo, Beauty 2019

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 α_s, Λ/m_b***

- Lowest order: decay of a free *b*, linear Λ/m_b absent. Depends on $m_{b,c}$, 2 parameters at $O(1/m_b^2)$, 2 more at $O(1/m_b^3)$...

INCLUSIVE SEMILEPTONIC B DECAYS

Inclusive observables are double series in Λ/m_b and α_s

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

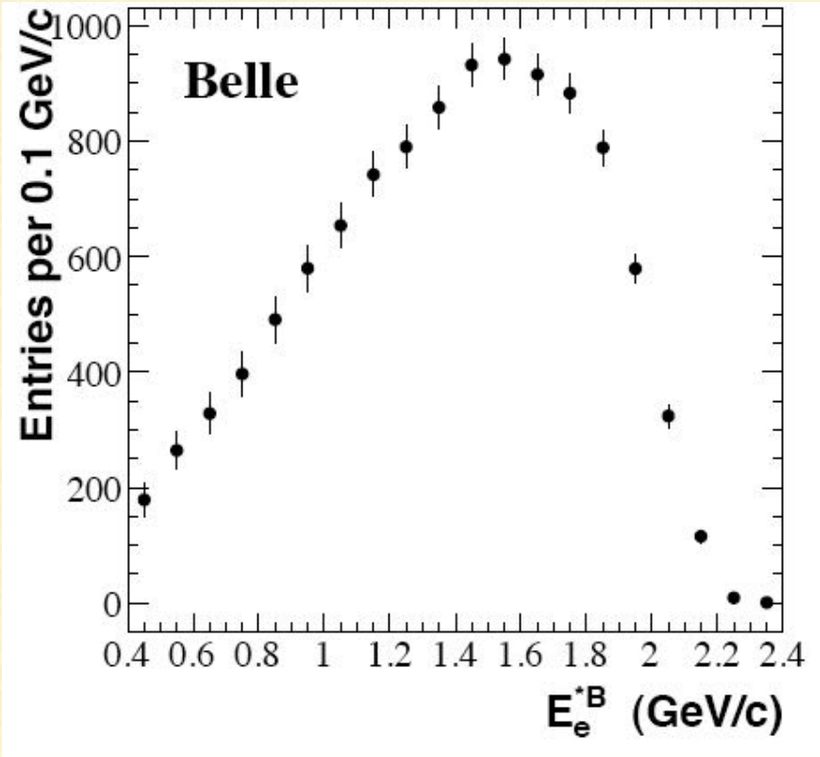
$$\mu_\pi^2(\mu) = \frac{1}{2M_B} \langle B | \bar{b}_v (i\overrightarrow{D})^2 b_v | B \rangle_\mu \qquad \mu_G^2(\mu) = \frac{1}{2M_B} \langle B | \bar{b}_v \frac{i}{2} \sigma_{\mu\nu} G^{\mu\nu} b_v | B \rangle_\mu$$

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

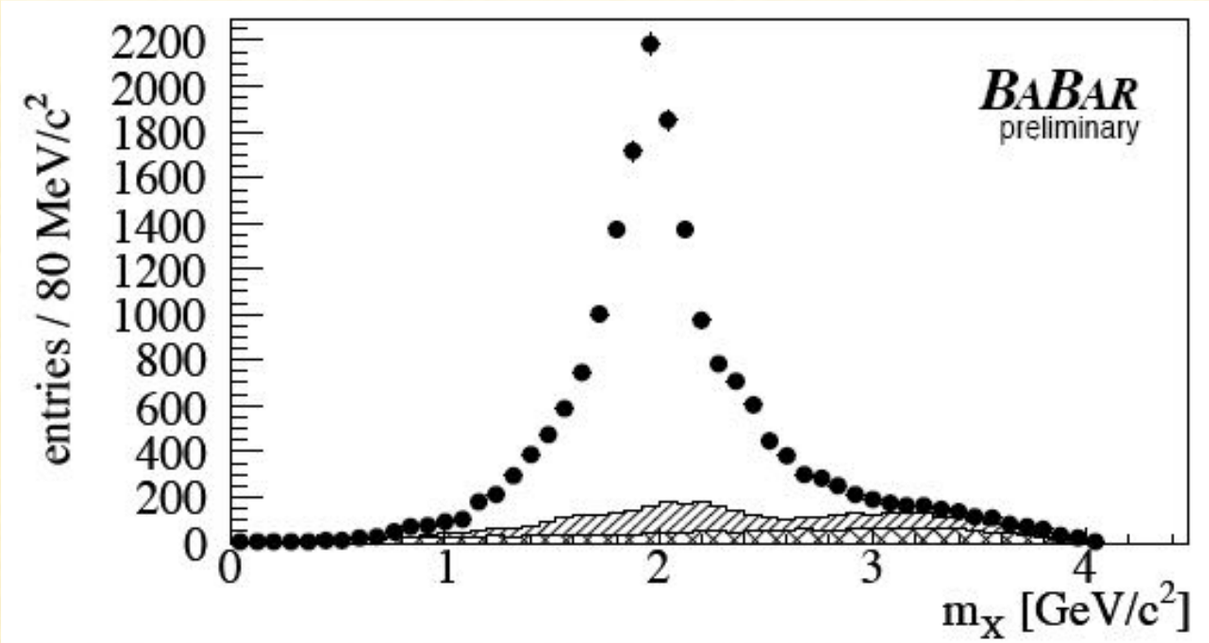
Current HFLAV **kinetic scheme** fit includes all corrections $O(\alpha_s^2, \alpha_s/m_b^2, 1/m_b^3)$, m_c and other constraints from sum rules/lattice

EXTRACTION OF THE OPE PARAMETERS

E_l spectrum



hadronic mass spectrum

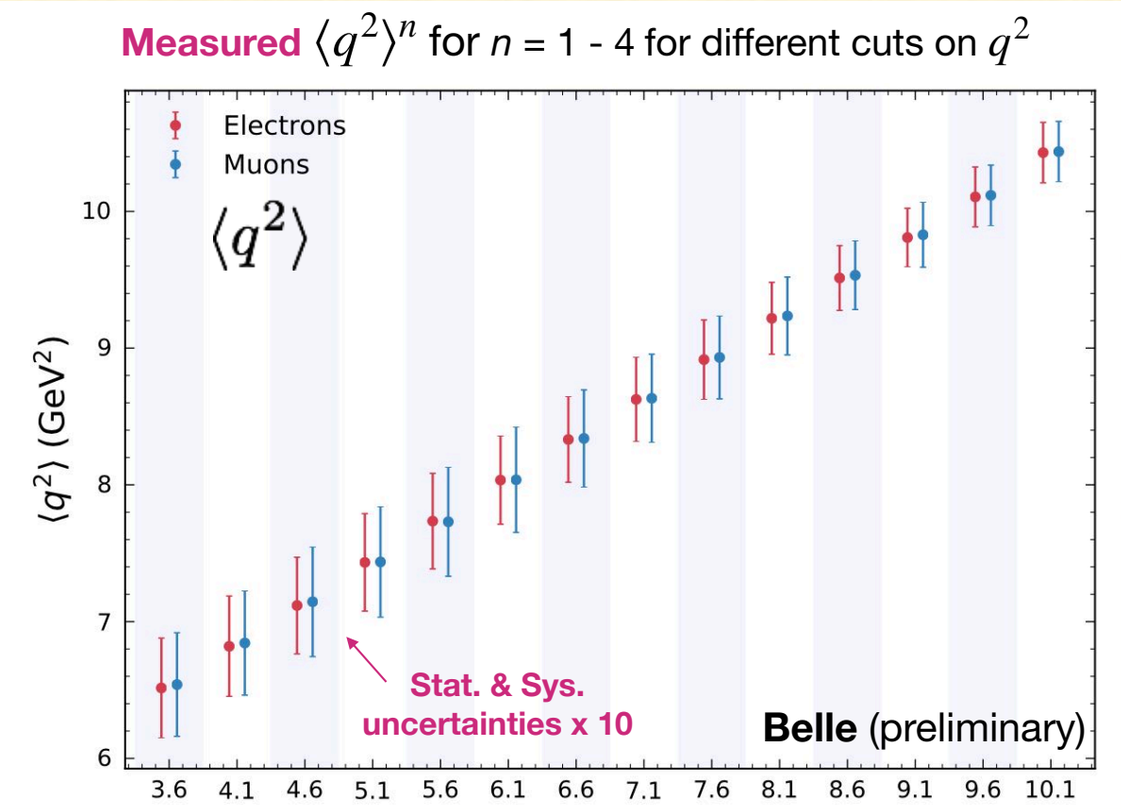


Global shape parameters (first moments of the distributions for various lower cut on E_l) tell us about m_b, m_c and the B structure, total rate about $|V_{cb}|$

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

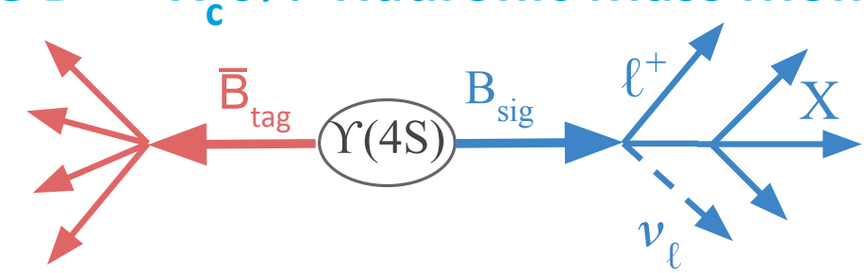
New from Belle and Belle II

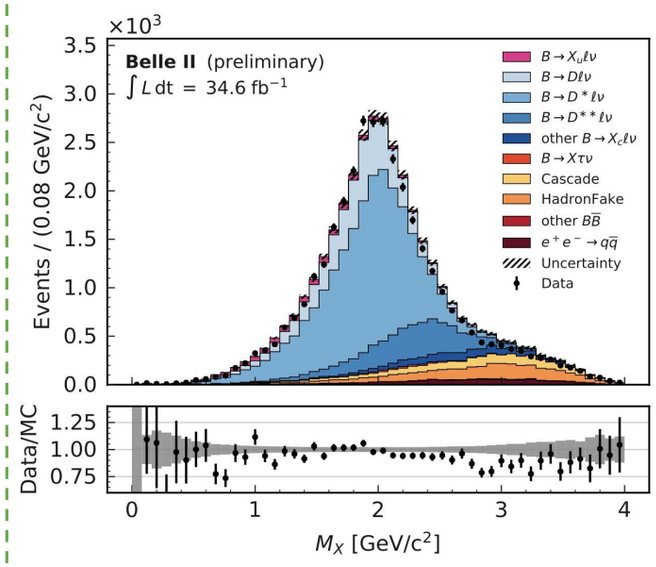
big potential for improvement @ Belle II

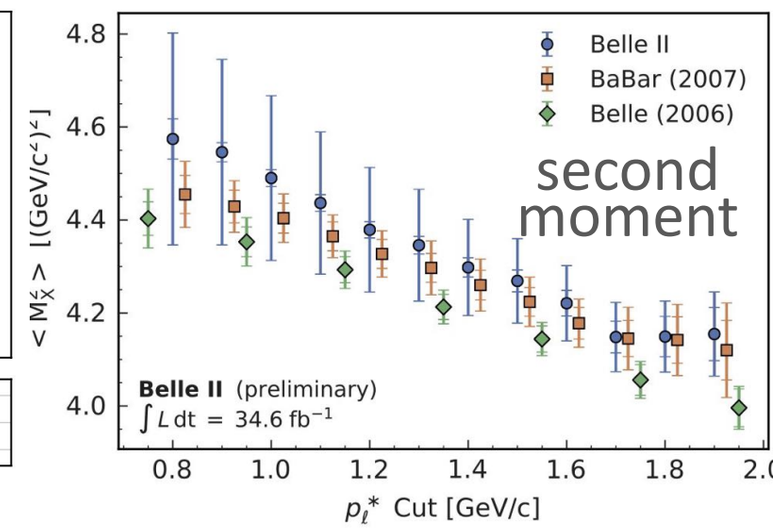


arXiv:2009.04493

Inclusive $B \to X_c \ell \nu$: Hadronic Mass Moments







$$\langle M_X^n \rangle = \frac{\sum_i w_i(M_X) M_{X,\mathrm{calib}\,i}^{\,n}}{\sum_i w_i(M_X)} \times \mathcal{C}_{\mathrm{calib}} \times \mathcal{C}_{\mathrm{true}}.$$

...Related upcoming analysis: measurement of q^2 moments

- alternative method based on arXiv:1812.07472
- includes corrections up to $1/m_b^4$
- see Belle YSF talk by Raynette van Tonder

⇒ brand new inclusive V_{cb} measurement…. coming soon!

FIT RESULTS

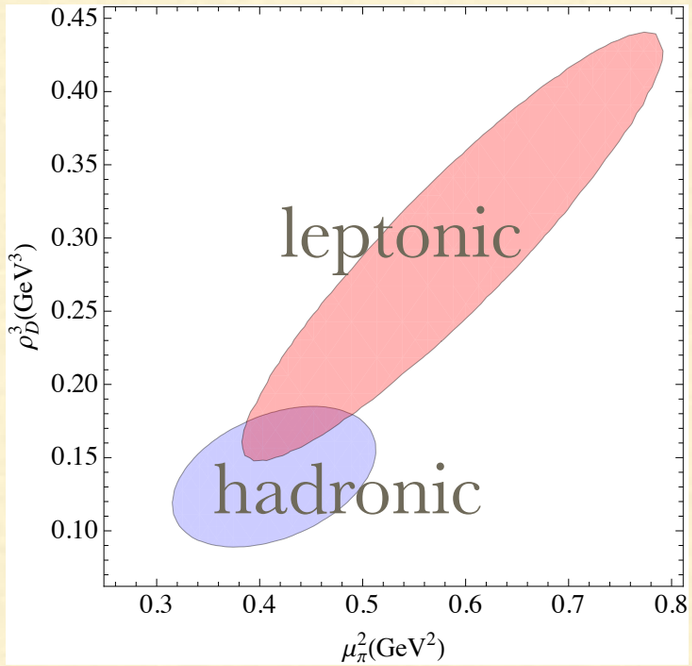
m_b^{kin}	$\overline{m}_c(3\,\mathrm{GeV})$	μ_π^2	ρ_D^3	μ_G^2	ρ_{LS}^3	$\mathrm{BR}_{c\ell\nu}$	$10^3\lvert V_{cb}\rvert$
4.553	0.987	0.465	0.170	0.332	-0.150	10.65	42.21
0.020	0.013	0.068	0.038	0.062	0.096	0.16	0.78

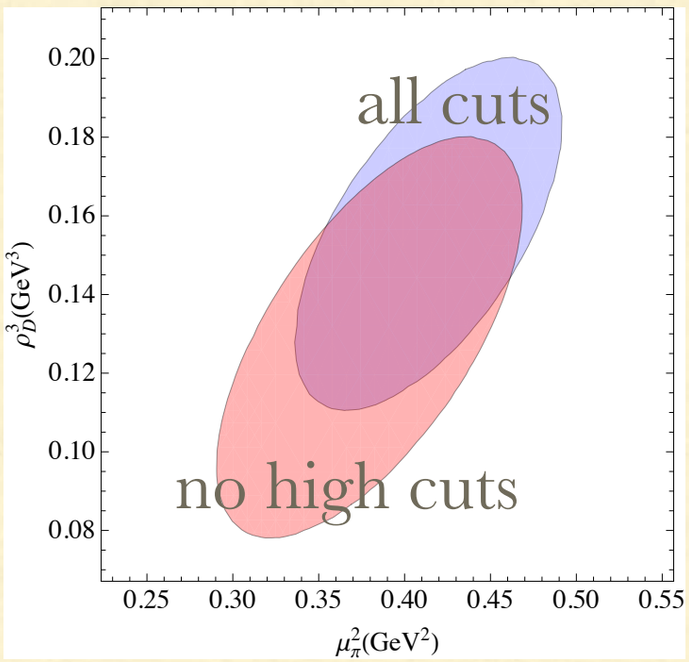
this is HFLAV fit

Alberti, Healey, Nandi, PG, 1411.6560

Without mass constraints $m_b^{kin}(1\mathrm{GeV}) - 0.85\,\overline{m}_c(3\mathrm{GeV}) = 3.714 \pm 0.018\,\mathrm{GeV}$

- results depend little on assumption for correlations and choice of inputs, 1.8% determination of V_{cb}
- 20-30% determination of the OPE parameters
- b mass determination in agreement with recent lattice and sum rules results





HIGHER POWER CORRECTIONS

Proliferation of non-pert parameters starting $1/m^4$: 9 at dim 7, 18 at dim 8

In principle relevant: HQE contains $O(1/m_b^n 1/m_c^k)$

Mannel,Turczyk,Uraltsev 1009.4622

Lowest Lying State Saturation Approx (LLSA) truncating

$$\langle B|O_1 O_2|B\rangle = \sum_n \langle B|O_1|n\rangle\langle n|O_2|B\rangle$$

see also Heinonen,Mannel 1407.4384

and relating higher dimensional to lower dimensional matrix elements, e.g.

$$\rho_D^3 = \epsilon\,\mu_\pi^2 \qquad \rho_{LS}^3 = -\epsilon\,\mu_G^2 \qquad \epsilon \sim 0.4\mathrm{GeV}$$

excitation energy to P-wave states. LLSA might set the scale of effect, but large corrections to LLSA have been found in some cases 1206.2296

We use LLSA as loose constraint or priors (60% gaussian uncertainty, dimensional estimate for vanishing matrix elements) in a fit including higher powers. The rest of the fit is unchanged, with slightly smaller theoretical errors

$$|V_{cb}| = 42.00(64) \times 10^{-3}$$

Healy,Turzcyk,PG 1606.06174

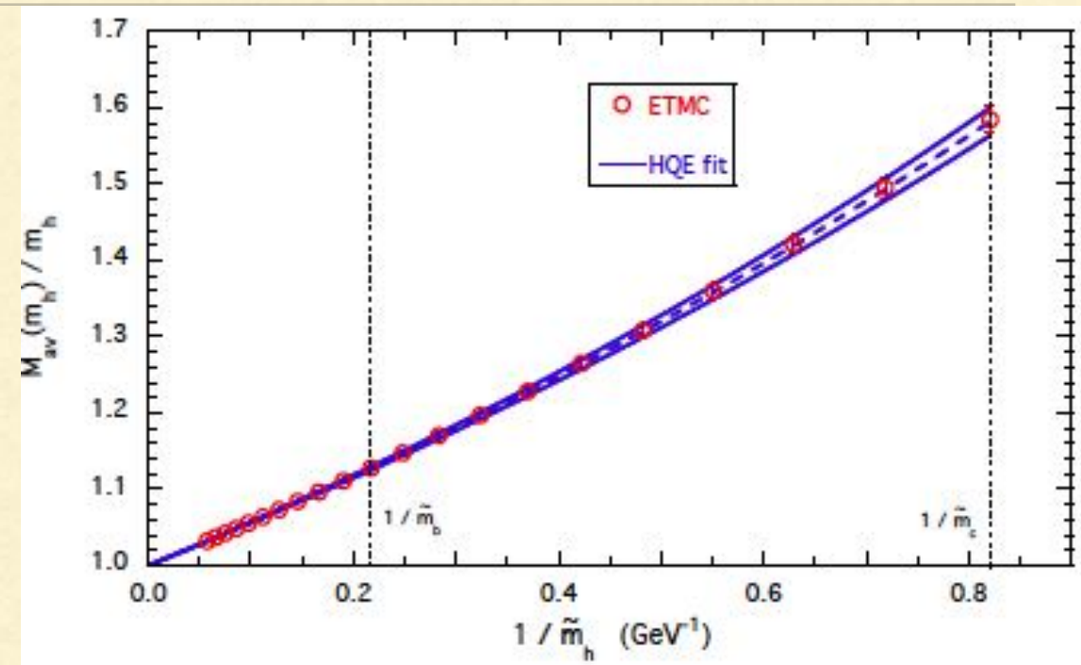
PROSPECTS for INCLUSIVE V_{cb}

- Theoretical uncertainties generally larger than experimental ones
- $O(\alpha_s/m_b^3)$ calculation completed for width (Mannel, Pivovarov) in progress for the moments (S. Nandi, PG)
- 3loop relation between MSbar and kin scheme recently completed in 2005.06487. It can be used to improve the precision of the m_b input
- ***$O(\alpha_s^3)$ corrections to total width*** just completed by Fael, Schoenwald, Steinhauser 2011.13654: towards 1% uncertainty
- Electroweak (QED) corrections require checks, in progress
- ***New observables*** in view of Belle-II: ***FB asymmetry*** proposed by S.Turczyk could be measured already by Babar and Belle now, ***q^2 moments*** (Fael, Mannel, Vos: preliminary V_{cb}=41.7(1.2) 10^{-3}, useful check of higher powers
- **Lattice QCD** is the next frontier

MESON MASSES FROM ETMC

Melis, Simula, PG 1704.06105

$$M_{H_Q} = m_Q + \bar{\Lambda} + \frac{\mu_\pi^2 - a_H \mu_G^2}{2m_Q} + \ldots$$



- on the lattice one can compute ***mesons masses for arbitrary quark masses***

  see also Kronfeld & Simone hep-ph/0006345, 1802.04248
- We used both pseudoscalar and vector mesons
- Direct 2+1+1 simulation, a=0.62-0.89 fm, m_π=210-450 MeV, heavy masses from m_c to $3m_c$, ETM ratio method with extrapolation to static point.
- Kinetic scheme with cutoff at 1GeV, good sensitivity up to $1/m^3$ corrections
- Results consistent with s.l. fits, improvements under way, also following new 3loop calculation of pole-kinetic mass relation

INCLUSIVE DECAYS ON THE LATTICE

- Inclusive processes nearly impossible to treat directly on the lattice
- However, vacuum current correlators can be computed in euclidean space-time and related to $e^+e^- \to$ hadrons or τ decay via analyticity
- In our case the correlators have to be computed in the B meson
  Hashimoto 1703.01881
- Analytic continuation more complicated: two cuts, decay occurs only on a portion of the physical cut.
- While the calculation of the spectral density of hadronic correlators is an ill-posed problem, it is accessible after smearing, as provided by phase-space integration Hansen, Meyer, Robaina, Lupo, Tantalo, Bailas, Hashimoto, Ishikawa

A NEW APPROACH

Hashimoto, PG 2005.13730

$$\frac{d\Gamma}{dq^2 dq^0 dE_\ell} = \frac{G_F^2 |V_{cb}|^2}{8\pi^3} L_{\mu\nu} W^{\mu\nu}$$ triple diff distribution B_s decays

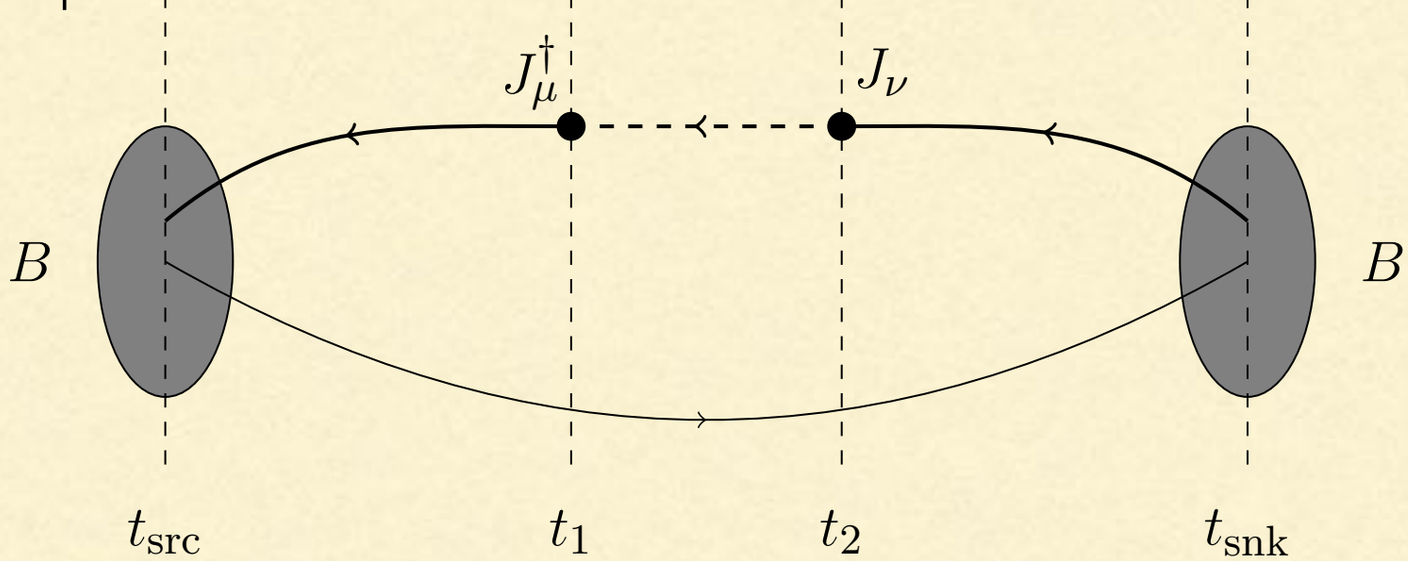
$$W^{\mu\nu} \sim \sum_{X_c} \frac{1}{2E_{B_s}} \langle \bar{B}_s(\boldsymbol{p}) | J^{\mu\dagger} | X_c(\boldsymbol{r}) \rangle \langle X_c(\boldsymbol{r}) | J^\nu | \bar{B}_s(\boldsymbol{p}) \rangle \sim Im\, i \int d^4x e^{-iq.x} \langle B_s | T J^{\mu\dagger}(x) J^\nu(0) | B_s \rangle$$

after integration over E_l

$$\Gamma = \frac{G_F^2 |V_{cb}|^2}{24\pi^3} \int_0^{\mathbf{q^2_{max}}} d\mathbf{q^2} \sqrt{\mathbf{q^2}}\, \bar{X} \qquad \bar{X} \equiv \int_{\sqrt{m_D^2 + \mathbf{q^2}}}^{m_{B_s} - \sqrt{\mathbf{q^2}}} X\, d\omega = \int K(\omega, \mathbf{q})_{\mu\nu} \mathbf{W}^{\mu\nu} \mathbf{d}\omega$$

where $\boldsymbol{\omega}$ hadr. energy, $X^{(l)}$ linear combinations of $W^{\mu\nu}$.

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



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

Quantum Mechanics in a Box

$$C(t) = \langle 0|\pi(t)\pi(0)|0\rangle$$

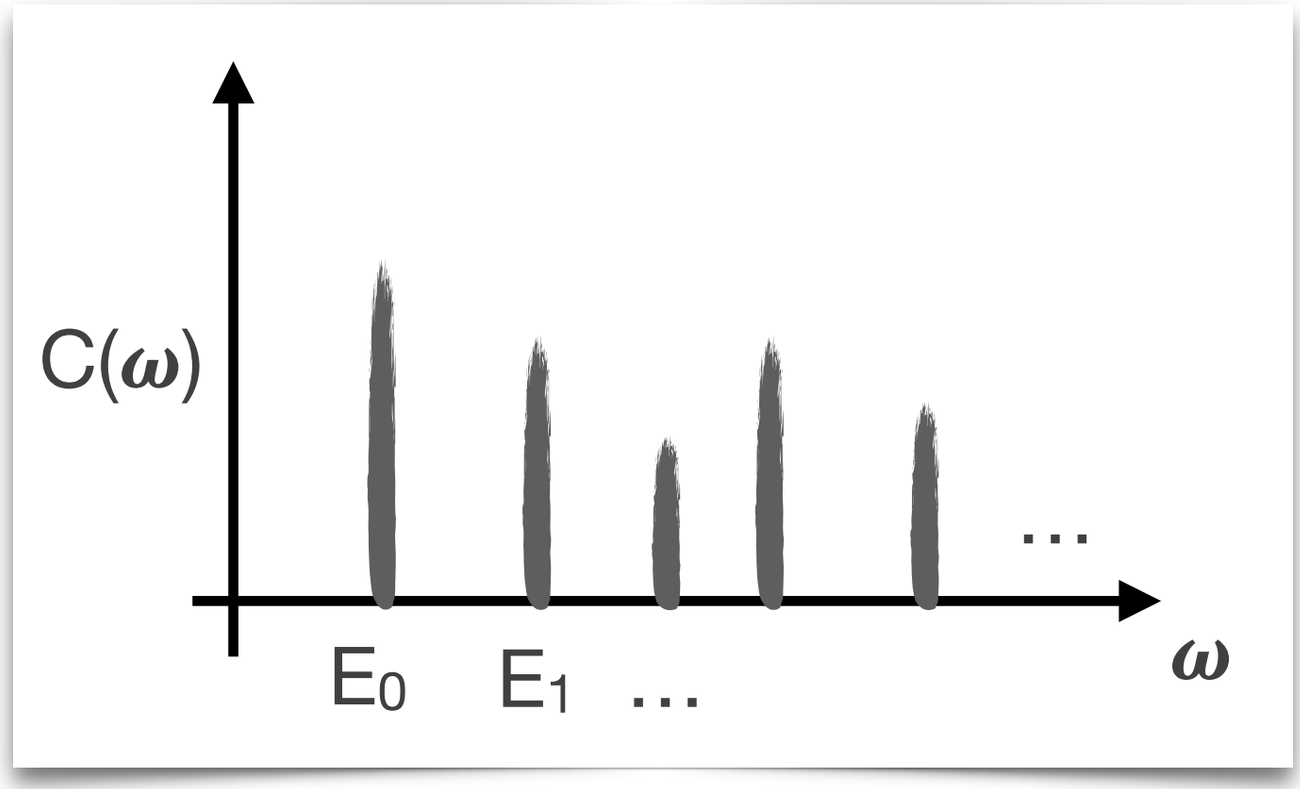
$$C(t) = \sum_n |Z_n|^2 e^{-E_n t}$$

Laplace transform

$$C(\omega) = \sum_n |Z_n|^2 \delta(\omega - E_n)$$

$$= \langle 0|\, \mathcal{O}\, \delta(\hat{H} - \omega)\, \mathcal{O}\, |0\rangle$$

$$= \langle \psi|\, \delta(\hat{H} - \omega)\, |\psi\rangle$$



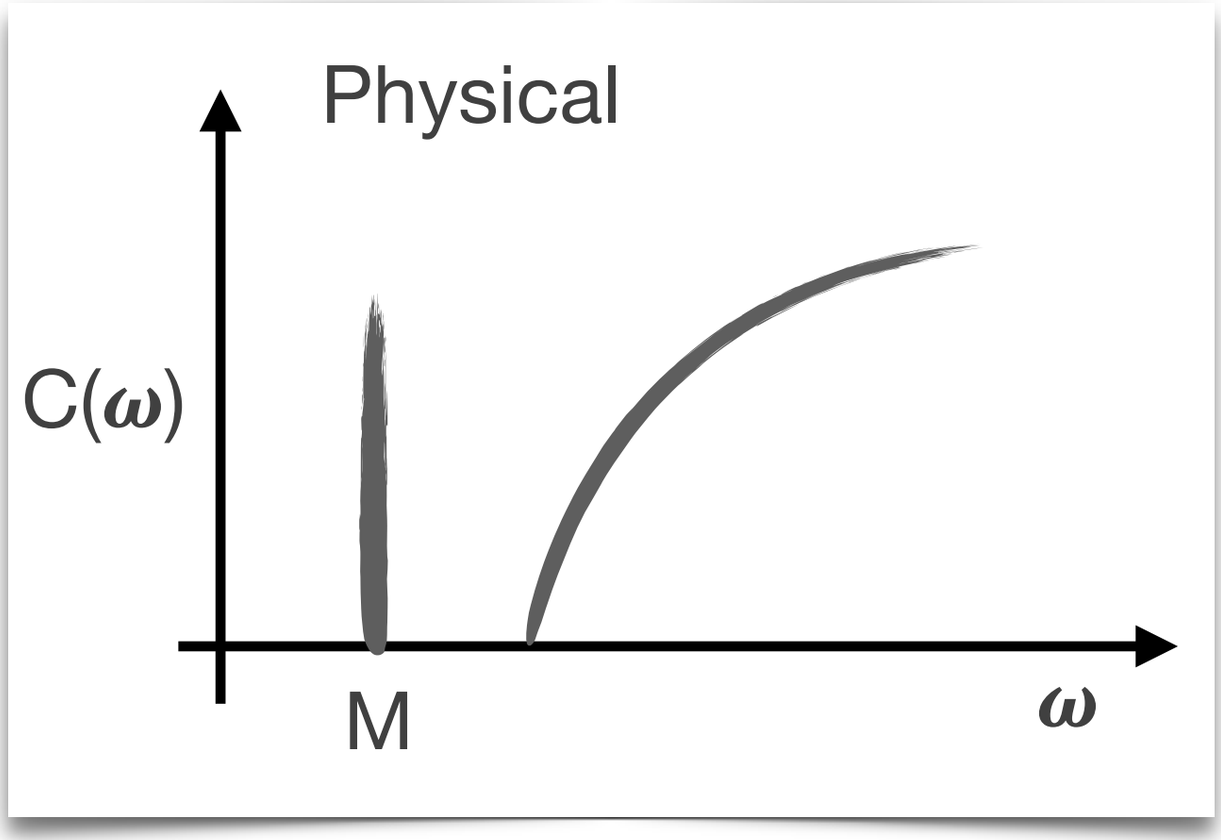
Or for inclusive B-decays:

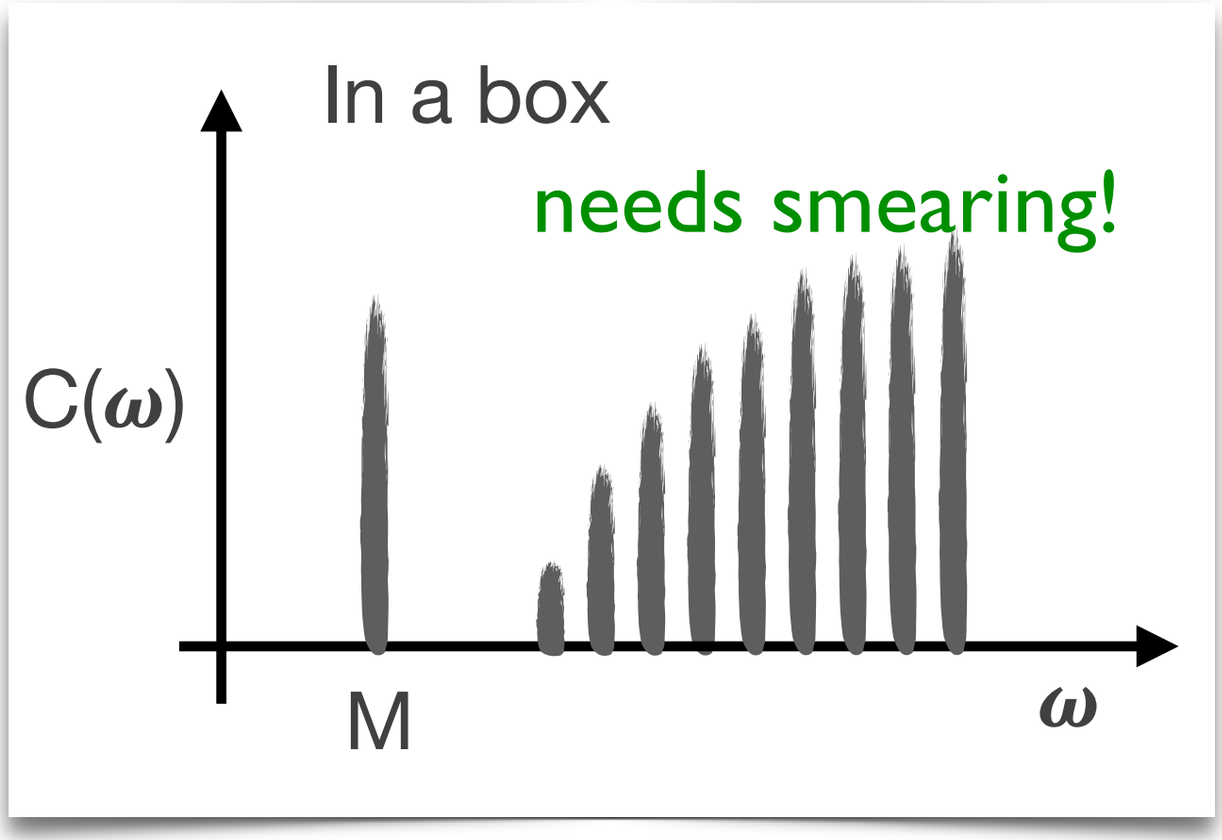
$$|\psi\rangle = J\mathcal{O}\,|0\rangle$$

W. Jay @Snowmass workshop

Quantum Mechanics in a Box

- What about hadronic tensor W($\boldsymbol{\omega}$, **q**)?
- Elastic channel: $\propto \delta(\omega - M)$
- Inelastic thesholds: $\propto \Theta(\omega - E_{\mathrm{thresh}}) \times (\mathrm{phase\ space})$





W. Jay @Snowmass workshop

A NEW APPROACH

Hashimoto, PG 2005.13730

$$\sum_{\boldsymbol{x}} e^{i\boldsymbol{q}\cdot\boldsymbol{x}} \frac{1}{2m_{B_s}} \langle B_s(\mathbf{0})|J_\mu^\dagger(\boldsymbol{x},t)J_\nu(\mathbf{0},0)|B_s(\mathbf{0})\rangle \sim \langle B_s(\mathbf{0})|\tilde{J}_\mu^\dagger(-\boldsymbol{q})e^{-\hat{H}t}\tilde{J}_\nu(\boldsymbol{q})|B(\mathbf{0})\rangle$$

$\tilde{J}$ FT of J

integral over ω becomes

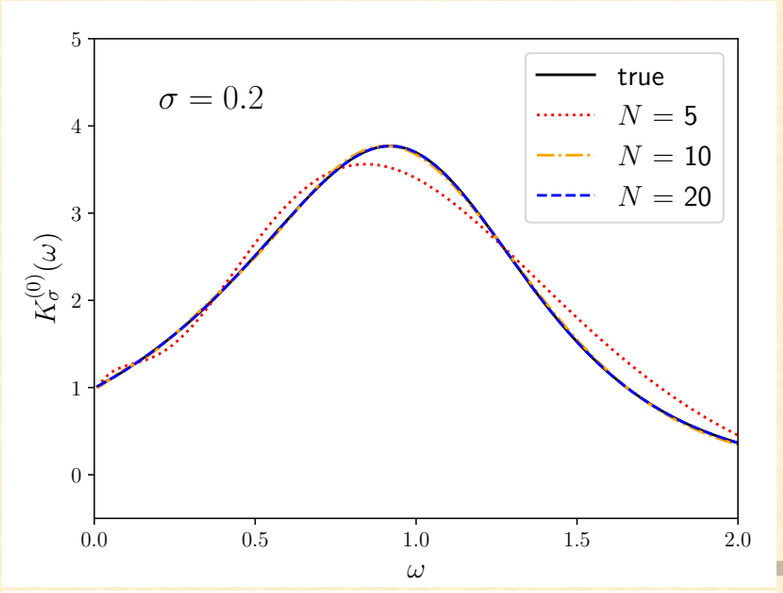
$$\int_0^\infty d\omega\, K(\omega,\boldsymbol{q})\langle B_s(\mathbf{0})|\tilde{J}_\mu^\dagger(-\boldsymbol{q})\delta(\hat{H}-\omega)\tilde{J}_\nu(\boldsymbol{q})|B_s(\mathbf{0})\rangle$$

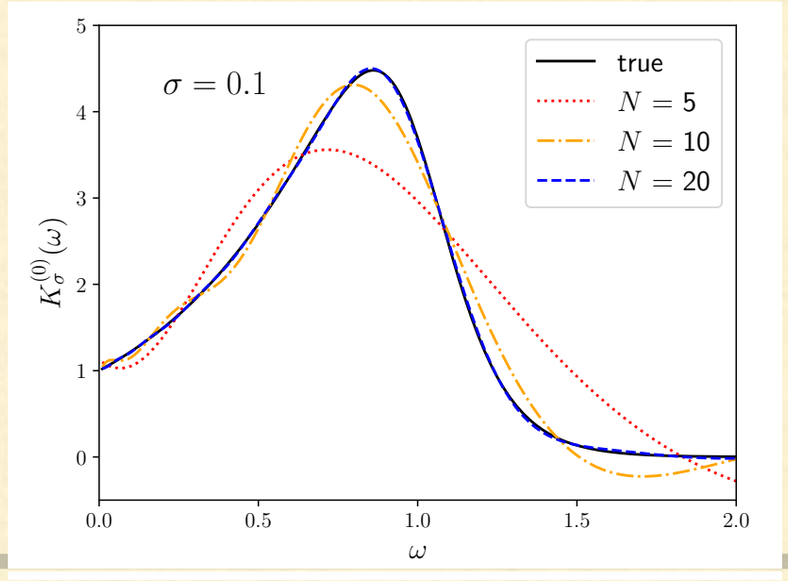
$$= \langle B_s(\mathbf{0})|\tilde{J}_\mu^\dagger(-\boldsymbol{q})K(\hat{H},\boldsymbol{q})\tilde{J}_\nu(\boldsymbol{q})|B_s(\mathbf{0})\rangle$$

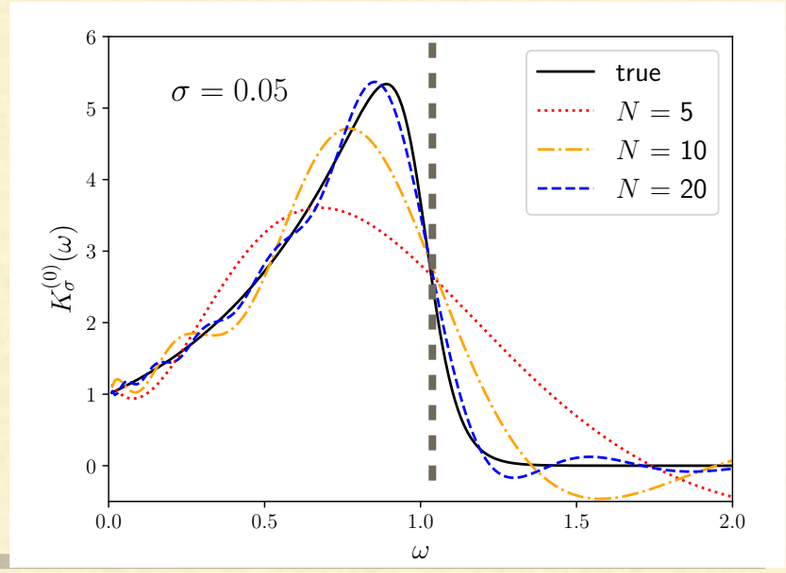
K approximated by polynomials $\quad K(\hat{H},\boldsymbol{q}) = k_0(\boldsymbol{q}) + k_1(\boldsymbol{q})e^{-\hat{H}} + \cdots + k_N(\boldsymbol{q})e^{-N\hat{H}}$

K has a sharp hedge: sigmoid $1/(1+e^{x/\sigma})$ used to replace kinematic $\theta(x)$ for $\sigma \to 0$

Larger number N of Chebyshev polynomials needed for small σ

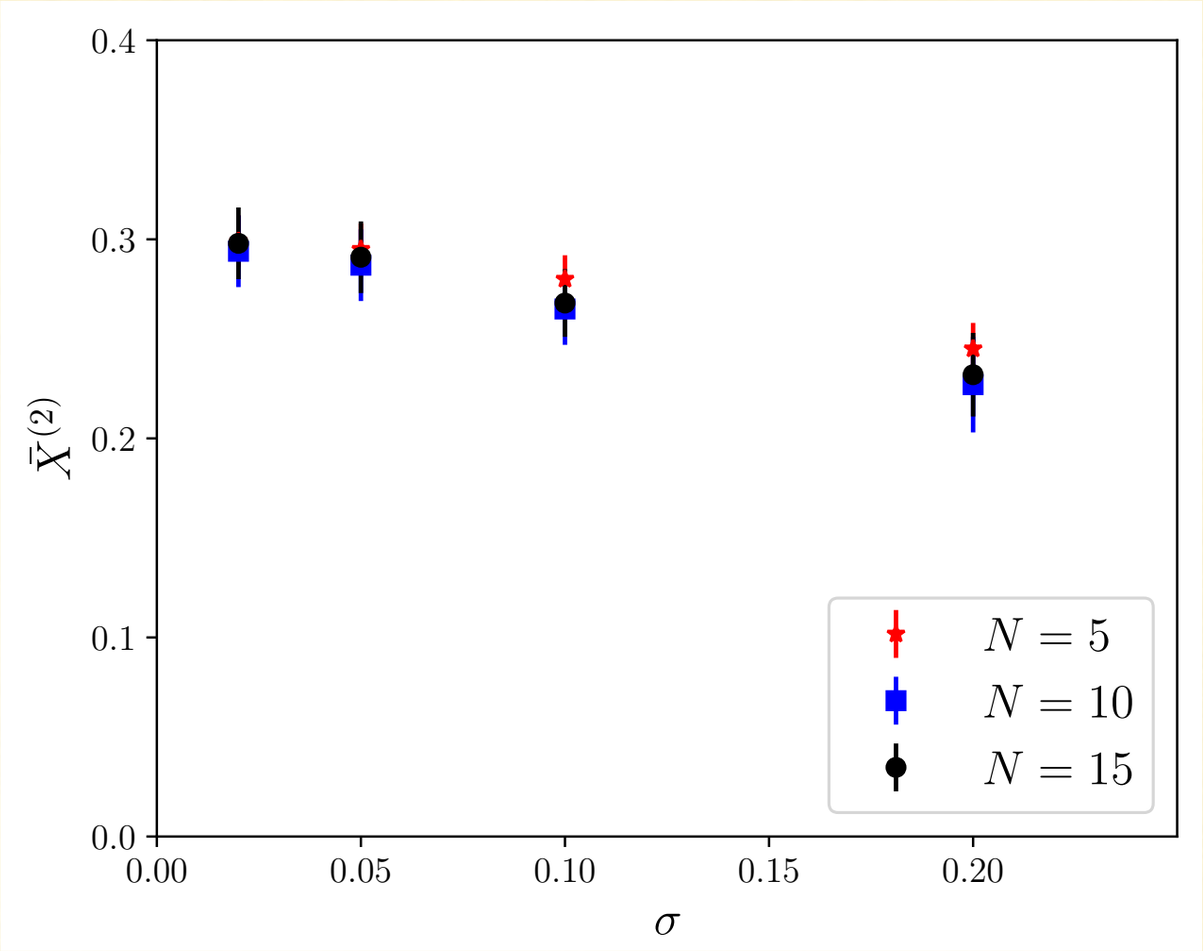






A PILOT NUMERICAL STUDY

Hashimoto, PG 2005.13730



Smeared spectral functions can be computed on the lattice in JLQCD setup, see 1704.08993

2+1 flavours of Moebius domain wall fermions with $1/a$=3.610(9)GeV on 48^3x96

M_{Bs}=3.45 GeV, i.e. $m_b^{kin}(1GeV) \approx 2.70$GeV

physical charm mass $m_c^{MS}(3GeV) = 1.00$GeV

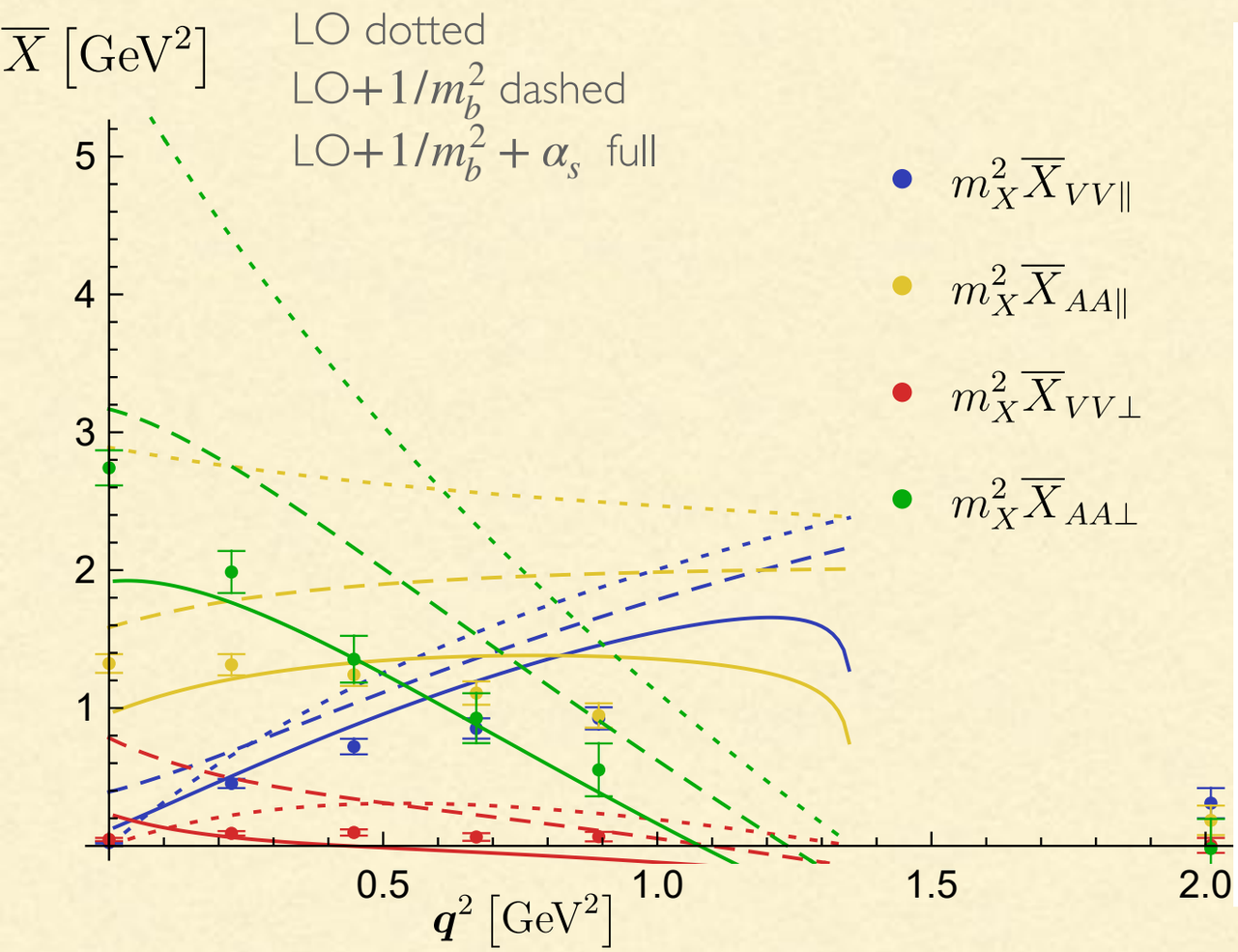
m_b-m_c~1.7GeV only, $\mathbf{q}^{max} \sim 1.16$GeV

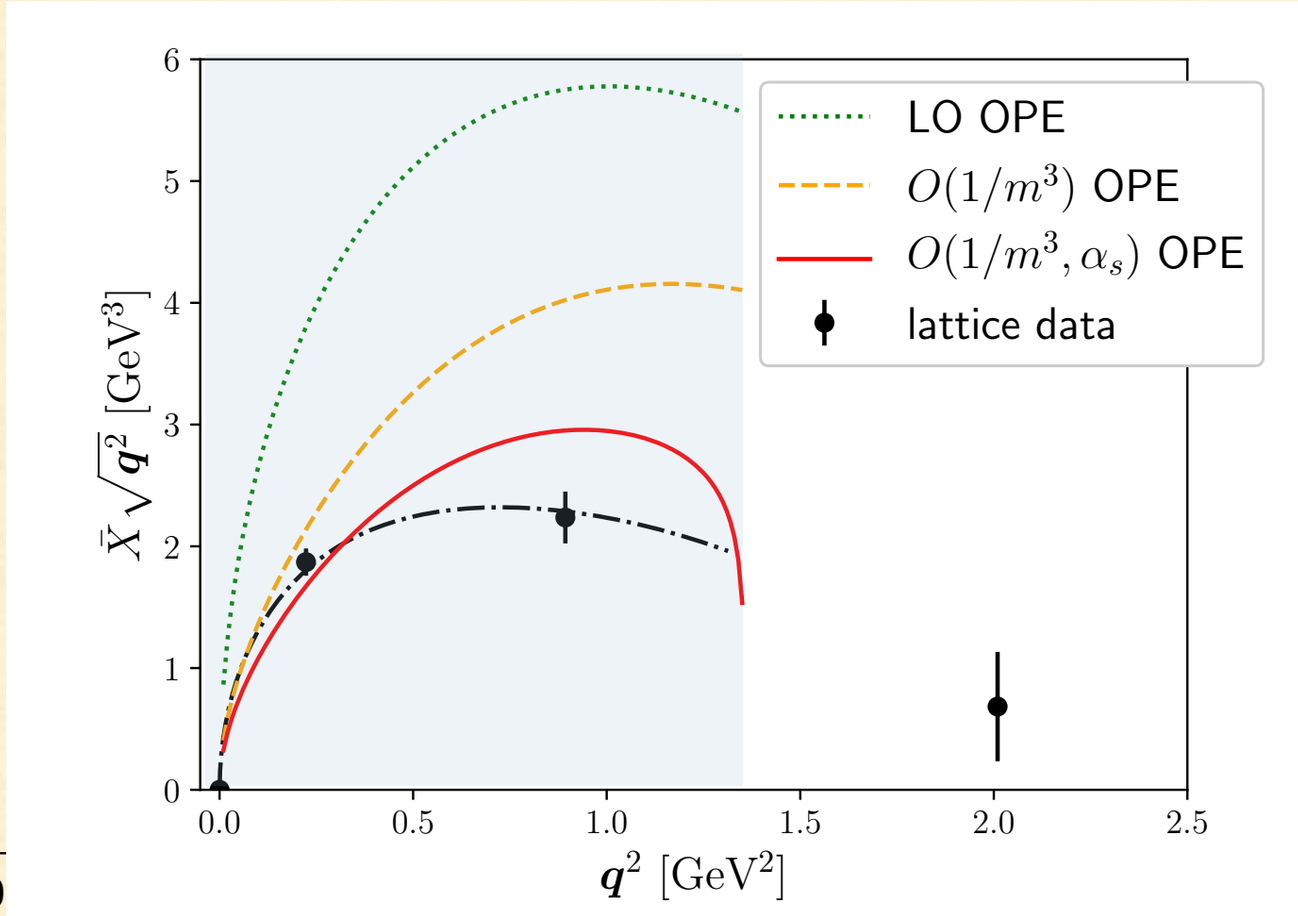
NB $m_b^{lat} = 2.44 m_c^{lat}$: we don't know it precisely…

Extrapolation to $\sigma \to 0$ possible, but error due to finite N must be estimated

COMPARISON WITH OPE

OPE matrix elements from fits, sizeable power and pert corrections!





$\Gamma/|V_{cb}|^2 = 4.5(6)\ 10^{-13}\,\mathrm{GeV}$ Lattice

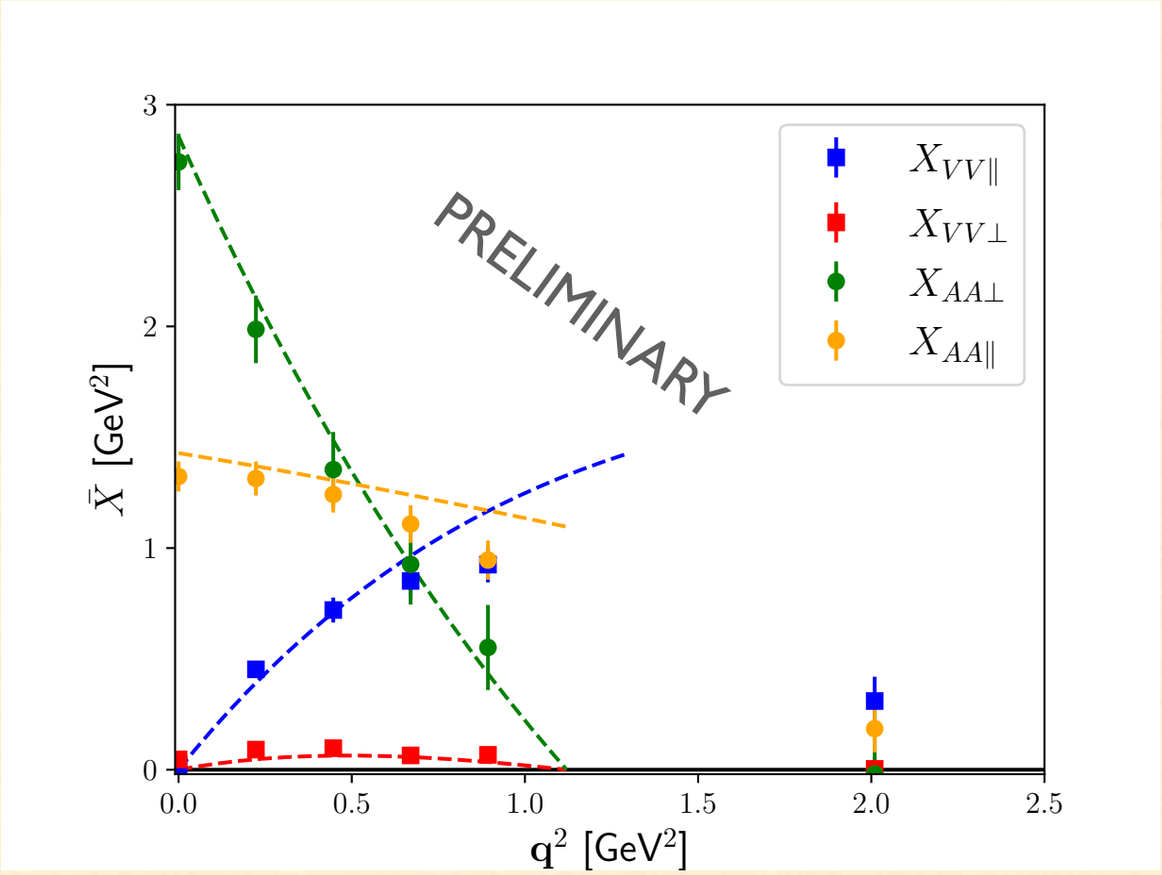
$\Gamma/|V_{cb}|^2 = 5.4(8)\ 10^{-13}\,\mathrm{GeV}$ OPE including $O(\alpha_s^2, 1/m_b^3)$

OPE uncertainty: "*b*" mass error (dominant), higher orders, matrix elements

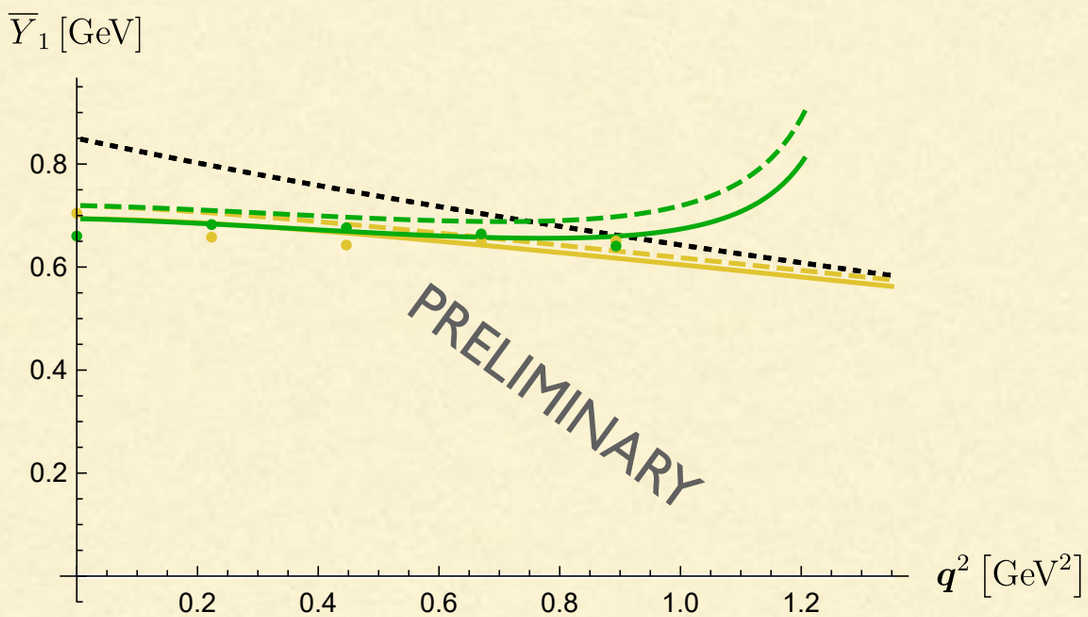
SINGLE CHANNEL SATURATION

Comparison of data with JLQCD B→D$^{(*)}$ form factors. D$^{(**)}$ and continuum strongly suppressed.

This is due to approx heavy quark symmetry and is stronger for unphysically light m_b

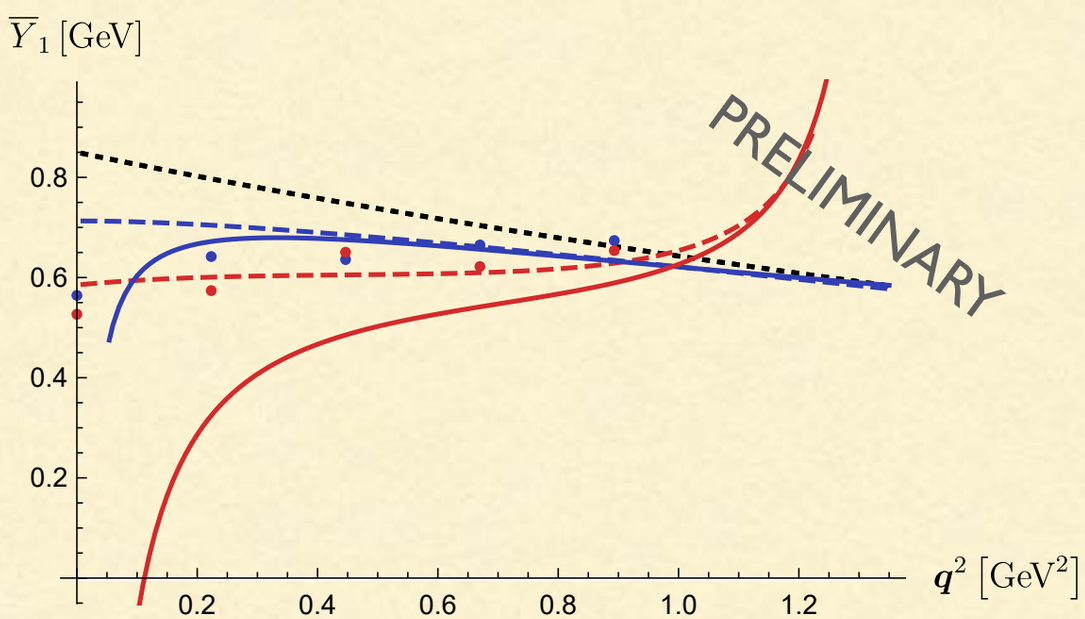


LEPTONIC MOMENTS



$\langle E_\ell \rangle$ for fixed $\mathbf{q^2}$

- LO OPE
- $\overline{Y}_1^{AA,\parallel}$ at $\mathcal{O}\left(1/m_b^2, \alpha_s^0\right)$ and $\mathcal{O}\left(1/m_b^3, \alpha_s\right)$
- $\overline{Y}_1^{AA,\perp}$ at $\mathcal{O}\left(1/m_b^2, \alpha_s^0\right)$ and $\mathcal{O}\left(1/m_b^3, \alpha_s\right)$



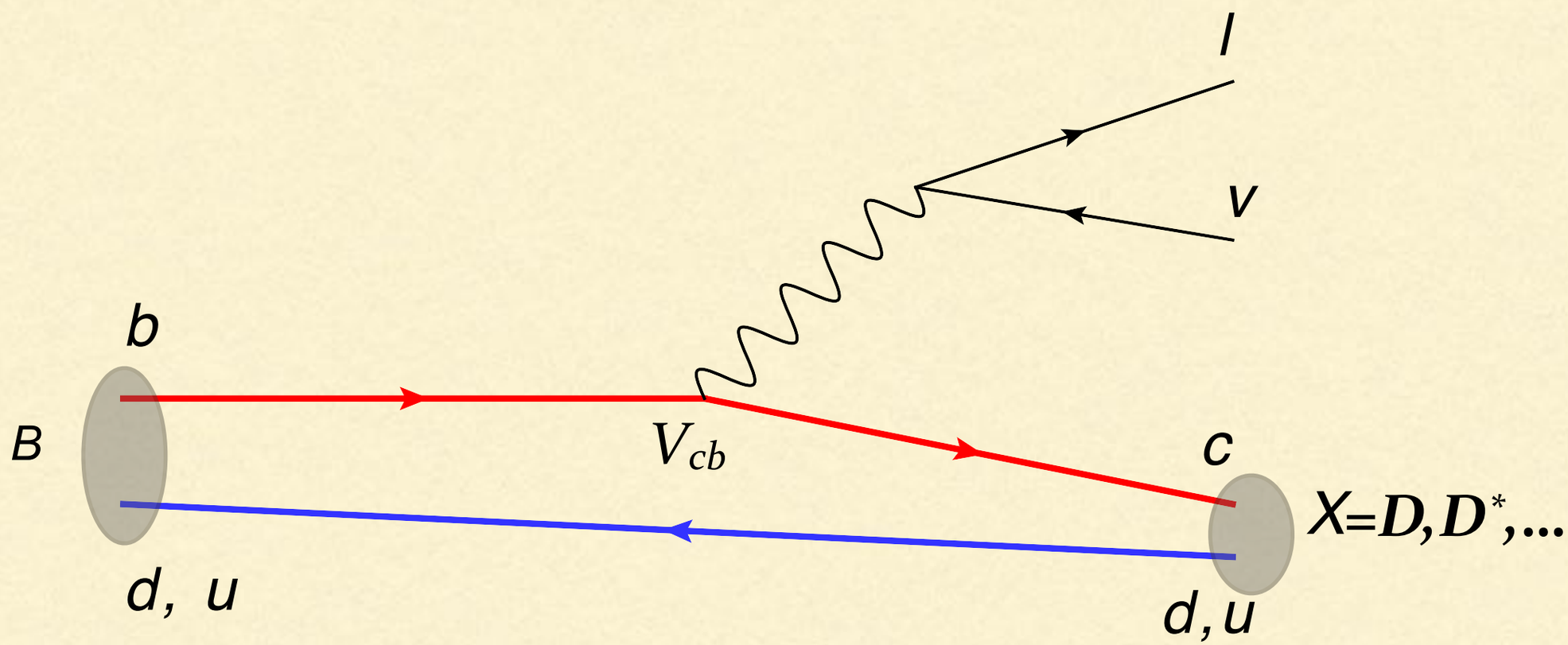
- LO OPE
- $\overline{Y}_1^{VV,\parallel}$ at $\mathcal{O}\left(1/m_b^2, \alpha_s^0\right)$ and $\mathcal{O}\left(1/m_b^3, \alpha_s\right)$
- $\overline{Y}_1^{VV,\perp}$ at $\mathcal{O}\left(1/m_b^2, \alpha_s^0\right)$ and $\mathcal{O}\left(1/m_b^3, \alpha_s\right)$

Hashimoto, Kaneko, Maechler, PG in progress

WHAT NEXT?

- Leptonic, hadronic energy moments, SV sum rules with existing data
- D inclusive semileptonic decays vs Cleo-c data for widths and lepton spectra (validation of the method, study of lattice systematics such as finite volume effects and disconnected diagrams, …)
- Towards the physical *b* mass (ratio method, step scaling, …): large recoil momentum $\mathbf{q}$ problematic
- Smooth cuts on experimental and OPE side?
- $B \to X_u \ell \nu, B \to X_s \ell^+ \ell^-$: kinematic cuts can *in principle* be implemented
- Extension of the method to low energy l-N inelastic scattering
  Hashimoto et al., 2010.01253 [hep-lat]

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…

FORM FACTOR PARAMETRIZATION

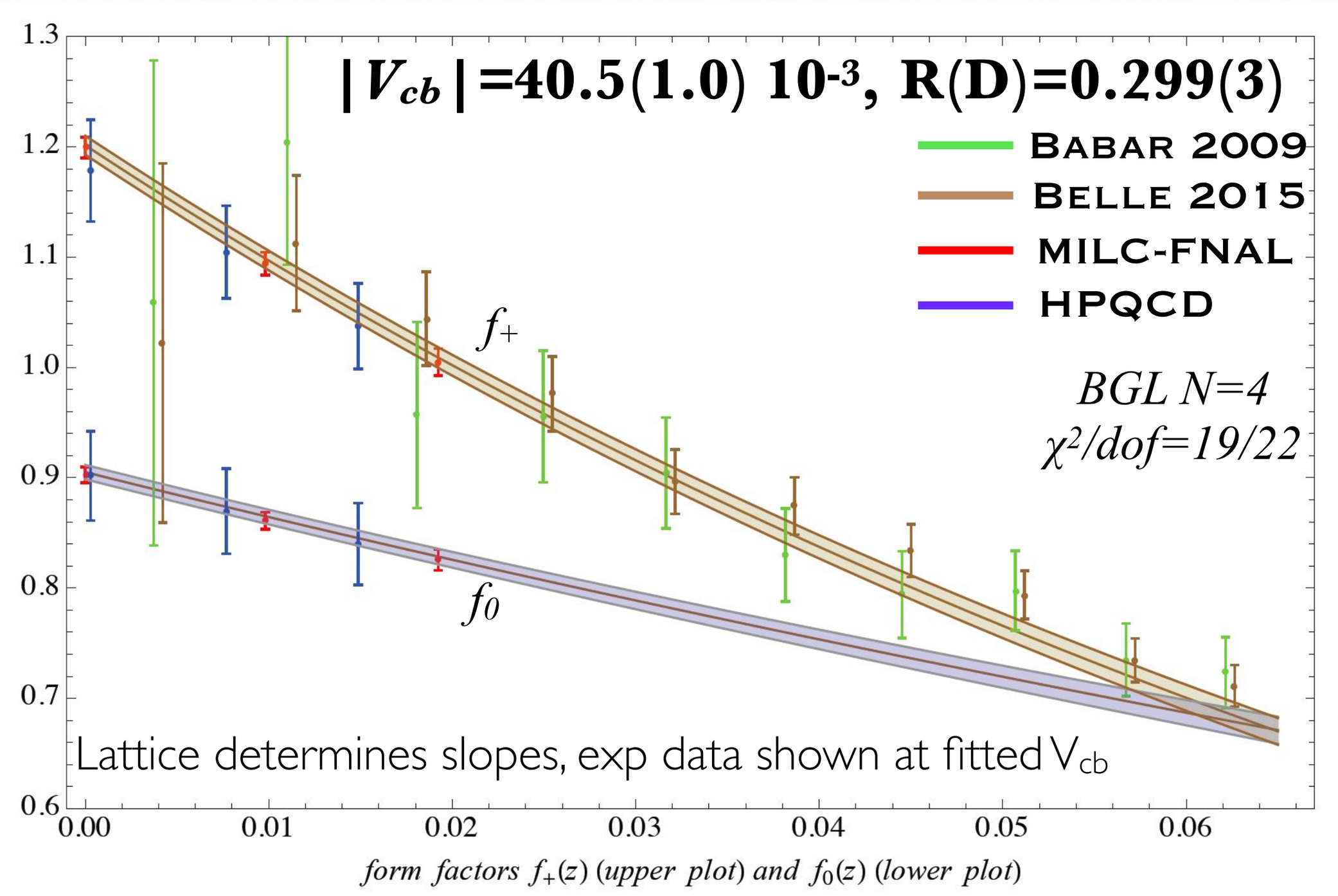
- A model independent parametrization is necessary
- BGL (Boyd, Grinstein, Lebed 1995-7) is based on crossing & analyticity, power series in $z(q^2)$ with coefficients a_i that satisfy unitarity bounds $\Sigma_i\, a_i^2 \leq 1$
- HQET for $B^{(*)} \rightarrow D^{(*)}$ form factors:

$$F_i(w) = \xi(w)\left[1 + c^i_{\alpha_s}\frac{\alpha_s}{\pi} + c^i_b\,\epsilon_b + c^i_c\,\epsilon_c + \ldots\right] \qquad \epsilon_{b,c} = \overline{\Lambda}/2m_{b,c}$$

- $c_{b,c}$ can be computed using subleading Isgur-Wise functions from QCD sumrules Neubert, Ligeti, Nir 1992-93, Bernlochner et al 1703.05330
- Ratios are free of IW function: can be used 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 simple and has few parameters, but relies on NLO HQET. All exp analyses before 2017 were based on CLN.

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

Bigi, PG 1606.08030



R(D) 1.3σ from exp

FLAG has very similar results

CLN cannot fit both ff missing higher orders!

$|V_{cb}|$ from $B \to D^* l\nu$ according to HFLAV (2019)

LQCD provides only light lepton FF at zero recoil, w=1, where rate vanishes.
Experimental results must therefore be **extrapolated to zero-recoil**

Exp error only ~1.1% $\mathcal{F}(1)\eta_{ew}|V_{cb}| = 35.27(38) \times 10^{-3}$

Beware: HFLAV extrapolate with CLN (w/o error)

Two unquenched lattice calculations

$\mathcal{F}(1) = 0.906(13)$

Bailey et al 1403.0635 (FNAL/MILC)

$\mathcal{F}(1) = 0.895(26)$

Harrison et al 1711.11013 (HPQCD)

Using their average 0.904(12): $|V_{cb}| = 38.8(7)\ 10^{-3}$

~ 3.4σ or ~ 8% from inclusive determination

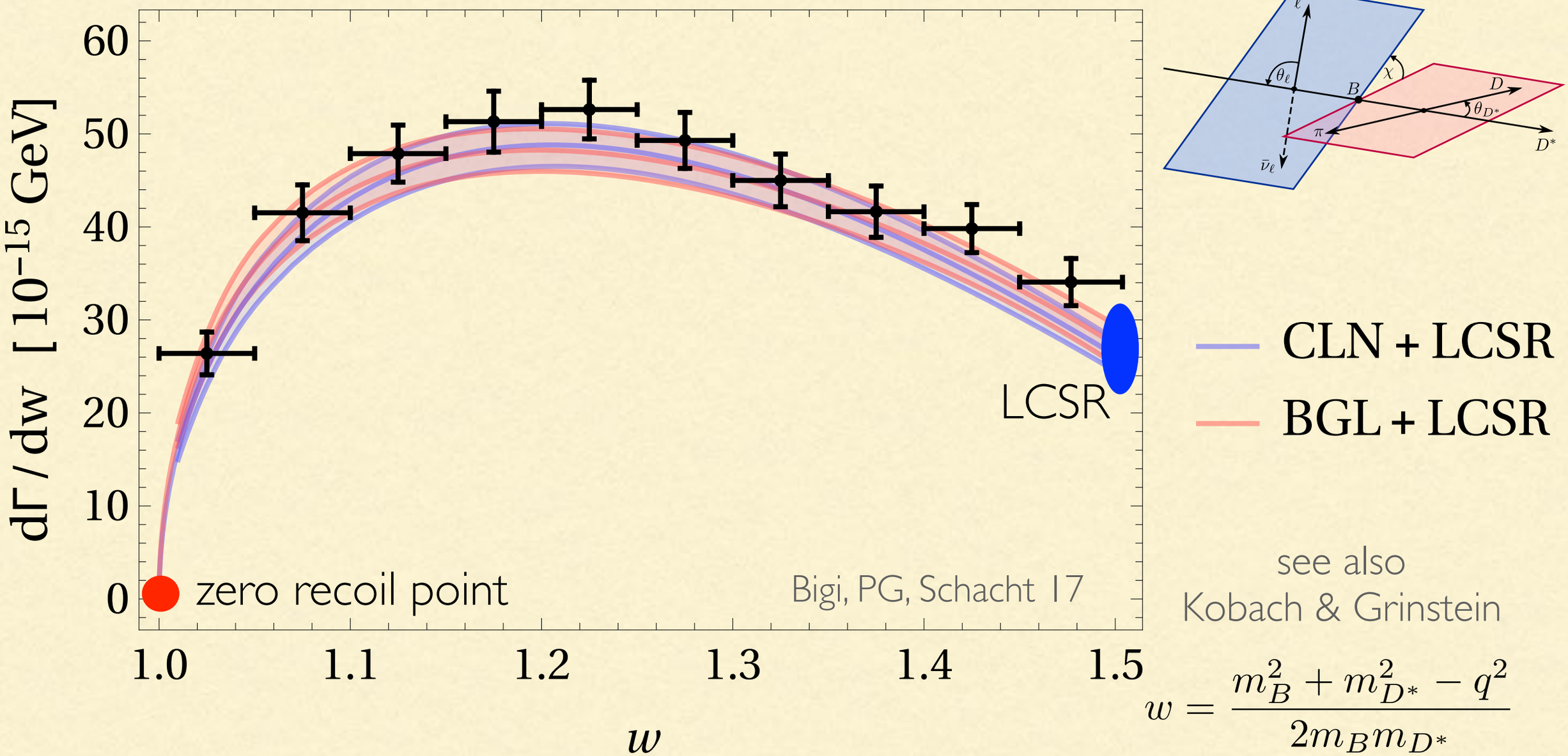
Heavy quark sum rules F(1)< 0.925 and estimate of inelastic contribution F(1)≈0.86

Mannel, Uraltsev, PG, 2012

2017 tagged Belle analysis (still preliminary!)

1702.01521

w and angular deconvoluted distributions (independent of parameterization).
All previous analyses are CLN based and do NOT provide diff distributions.

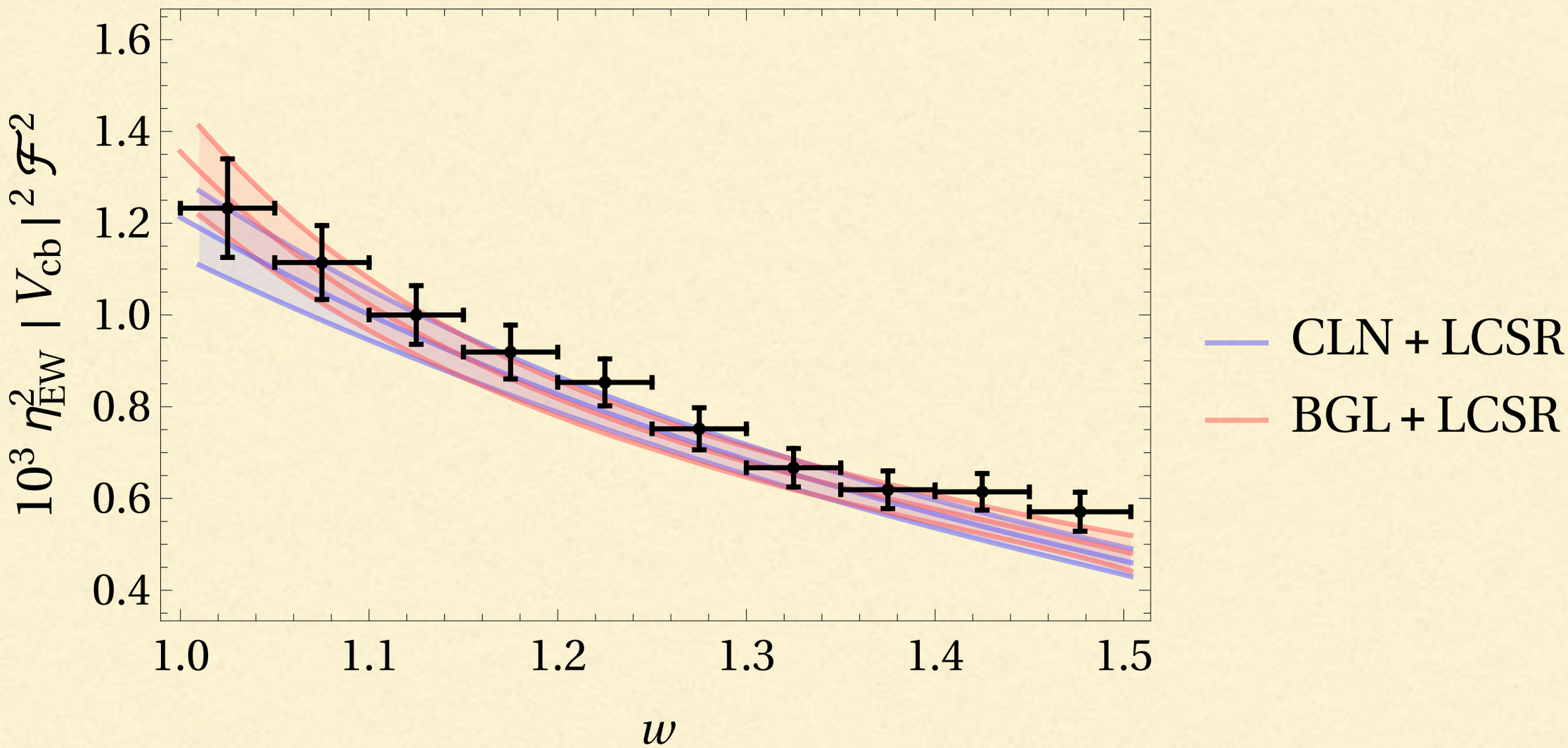


see also
Kobach & Grinstein

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

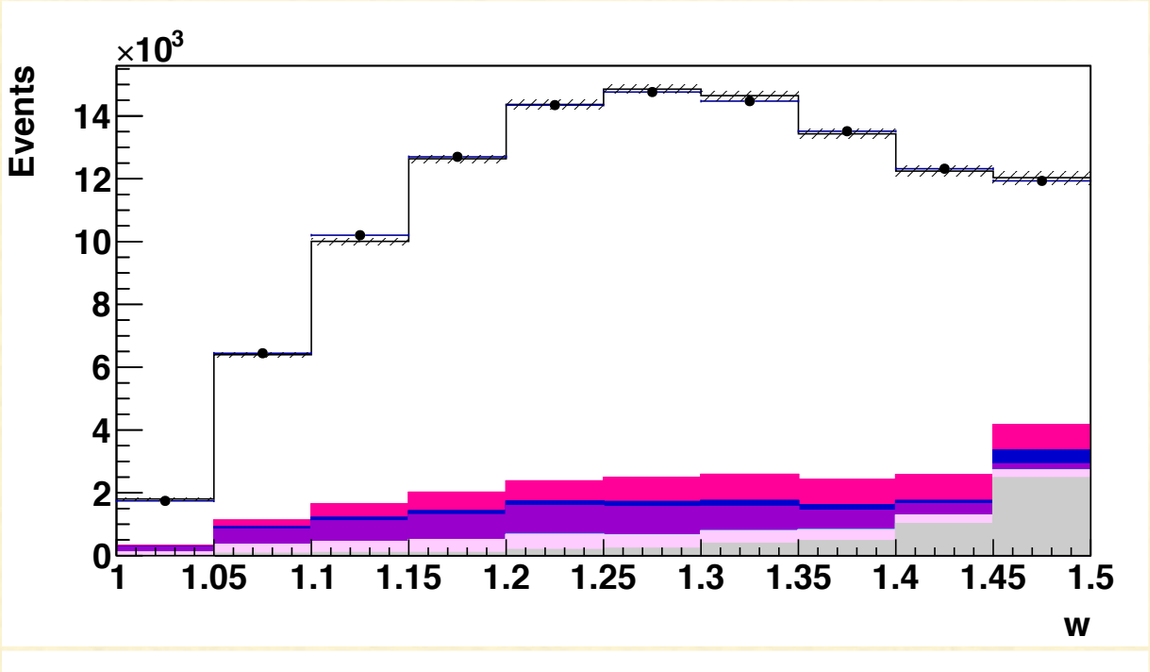
Bands show two parametrizations both fitting data well, with 6% different V_{cb}

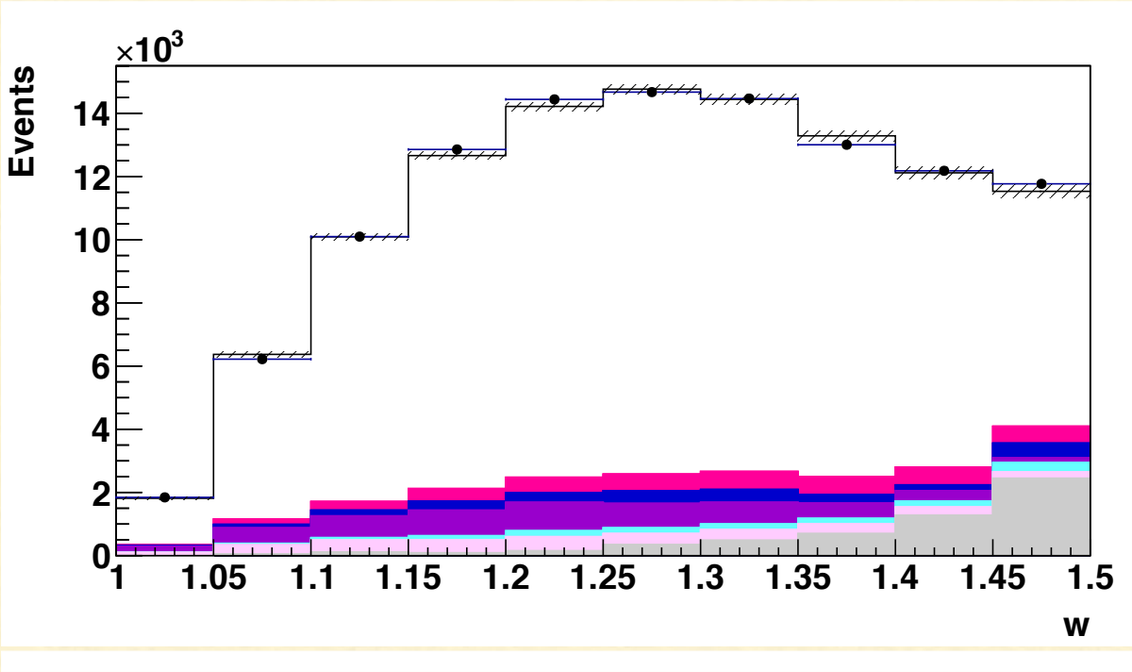
EXTRAPOLATING TO ZERO RECOIL



+30 additional angular bins

2018 UNTAGGED BELLE ANALYSIS 1809.03290v3

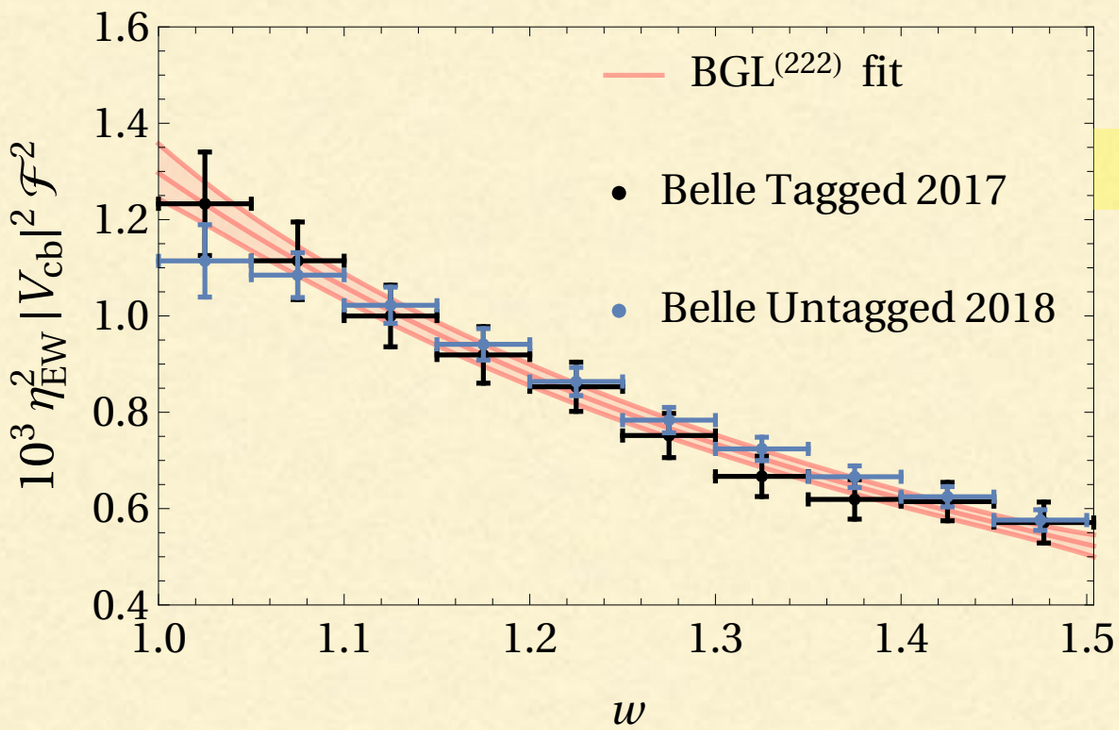




- Full Belle dataset, most precise study to date; provides data in a way that can be reanalysed with different assumptions. Central values obtained without systematics.
- CLN and BGL(102) analysis lead to very similar results, suggesting low **$|V_{cb}|$=38.4(0.9) 10^{-3}** .
- We used BGL(222) to fit the data, taking into account *D'Agostini effect* and got **$|V_{cb}|$=39.1(+1.5-1.3) 10^{-3}** 1905.08209

A GLOBAL FIT TO 2017 & 2018 DATA

Jung, Schacht, PG 1905.08209



$\mathrm{BGL}^{(222)}$	Data + lattice (weak)	Data + lattice (strong)
χ^2/dof	80.1/72	80.1/72
$\lvert V_{cb}\rvert 10^3$	$39.6\left(^{+1.1}_{-1.0}\right)$	$39.6\left(^{+1.1}_{-1.0}\right)$
a_0^f	0.01221(16)	0.01221(16)
a_1^f	$0.006\left(^{+32}_{-45}\right)$	$0.006\left(^{+20}_{-32}\right)$
a_2^f	$-0.2\left(^{+12}_{-8}\right)$	$-0.2\left(^{+7}_{-3}\right)$
$a_1^{\mathcal{F}_1}$	$0.0042\left(^{+22}_{-22}\right)$	$0.0042\left(^{+19}_{-22}\right)$
$a_2^{\mathcal{F}_1}$	$-0.069\left(^{+41}_{-37}\right)$	$-0.068\left(^{+41}_{-30}\right)$
a_0^g	$0.024\left(^{+21}_{-9}\right)$	$0.024\left(^{+12}_{-4}\right)$
a_1^g	$0.05\left(^{+39}_{-72}\right)$	$0.05\left(^{+21}_{-41}\right)$
a_2^g	$1.0\left(^{+0}_{-20}\right)$	$0.9\left(^{+0}_{-18}\right)$

- No parametrization dependence (CLN and BGL give ~same central value)
- About 1σ higher than HFLAV, larger uncertainty on firmer ground, p-value ~24% ***1.9σ from inclusive, consistent with B to Dlv***
- We truncate the BGL series when additional terms do not change the fit (no overfitting!). Fit stable. Strong constraints irrelevant.

COMPARISON WITH HQET+QCDSR

1905.08209

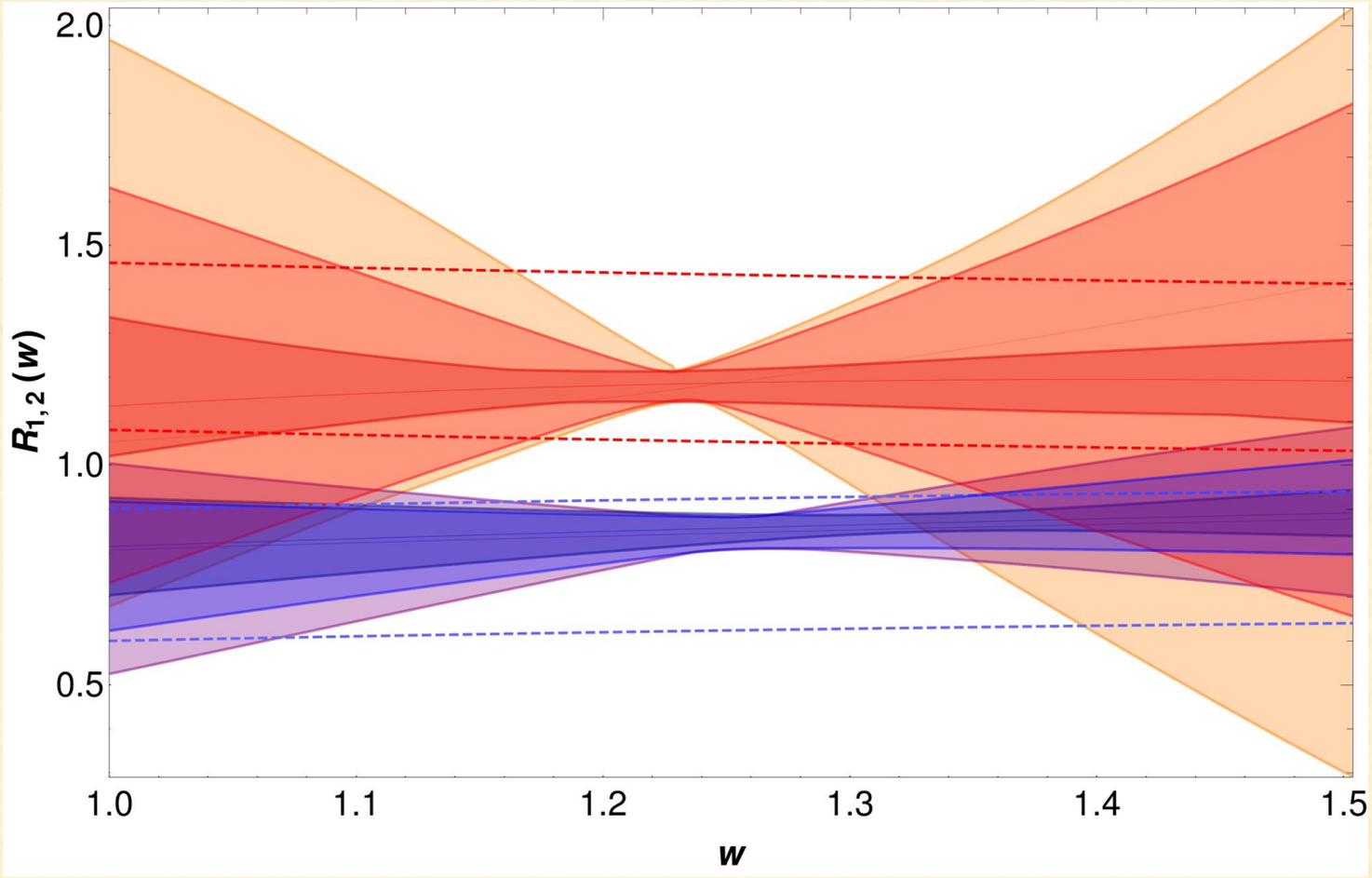
$$R_1(w) = \frac{V_4(w)}{A_1(w)} = 1 + O(\alpha_s, 1/m)$$

$$R_2(w) = \frac{w-r}{w-1}\left(1 - \frac{1-r}{w-r}\frac{A_5(w)}{A_1(w)}\right)$$

Comparison of $R_{1,2}$ from BGL fit to 2017+2018 data vs NLO HQET+QCDSR predictions (with parametric + 15% th uncertainty)

Very good agreement in both cases.

Narrower bands correspond to adding strong unitarity and LCSRs

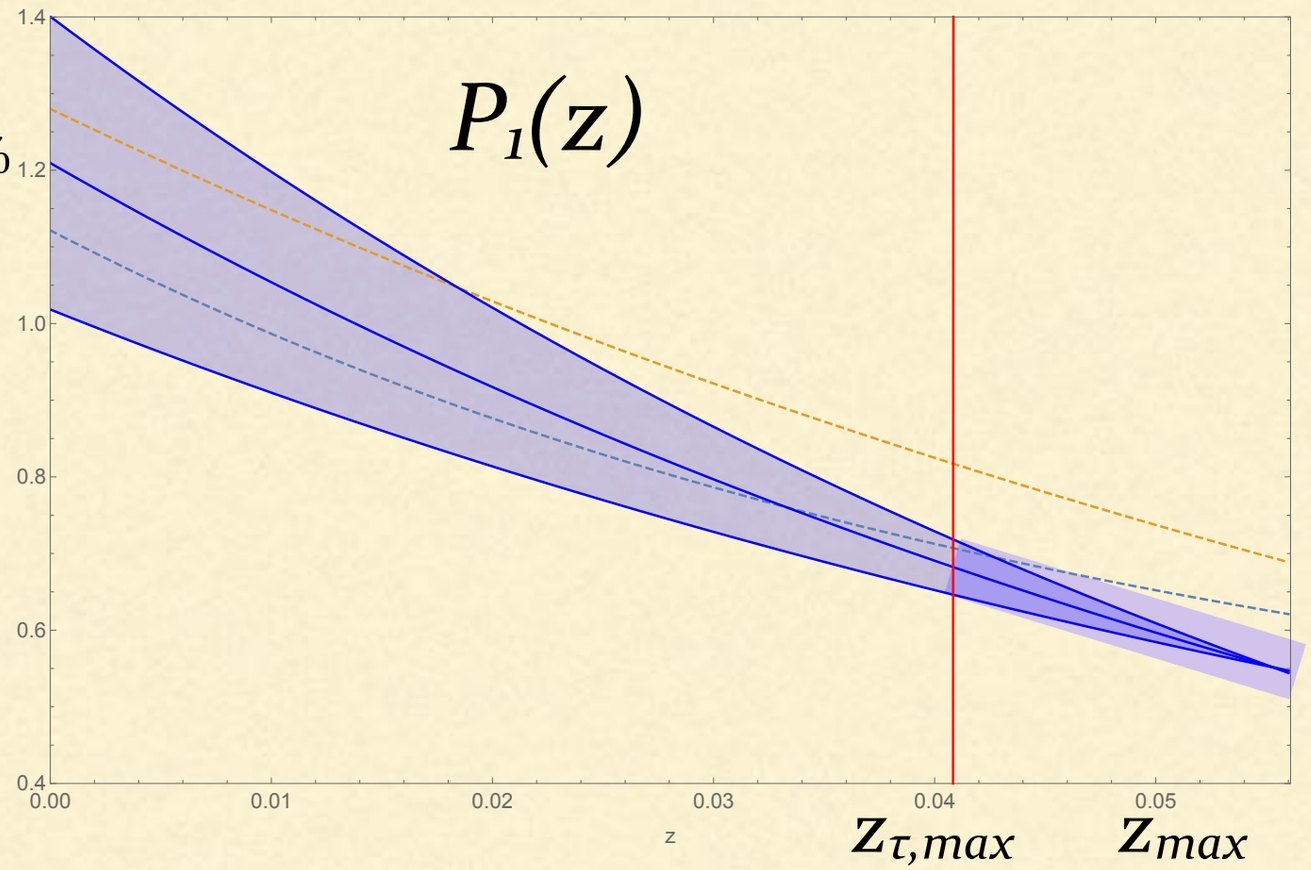


SEMITAUONIC DECAYS

1905.08209

Decays with tau require pseudoscalar FF unconstrained from fit, no lattice calculation yet. We use kinematic constraint at $q^2=0$ and HQET with conservative uncertainty.

NLO HQET+QCDSR ±15%



normalized to V_1
normalized to A_1
$A_5(w_{max})$

Endpoint constraint

$$P_1(w_{max}) = A_5(w_{max})$$

$$R(D^*) = 0.254^{+0.007}_{-0.006}\,,$$ 2.8σ from exp

$$P_\tau = -0.476^{+0.037}_{-0.034}\,,$$ 1.4σ from exp

$$F_L^{D^*} = 0.476^{+0.015}_{-0.014}\,,$$

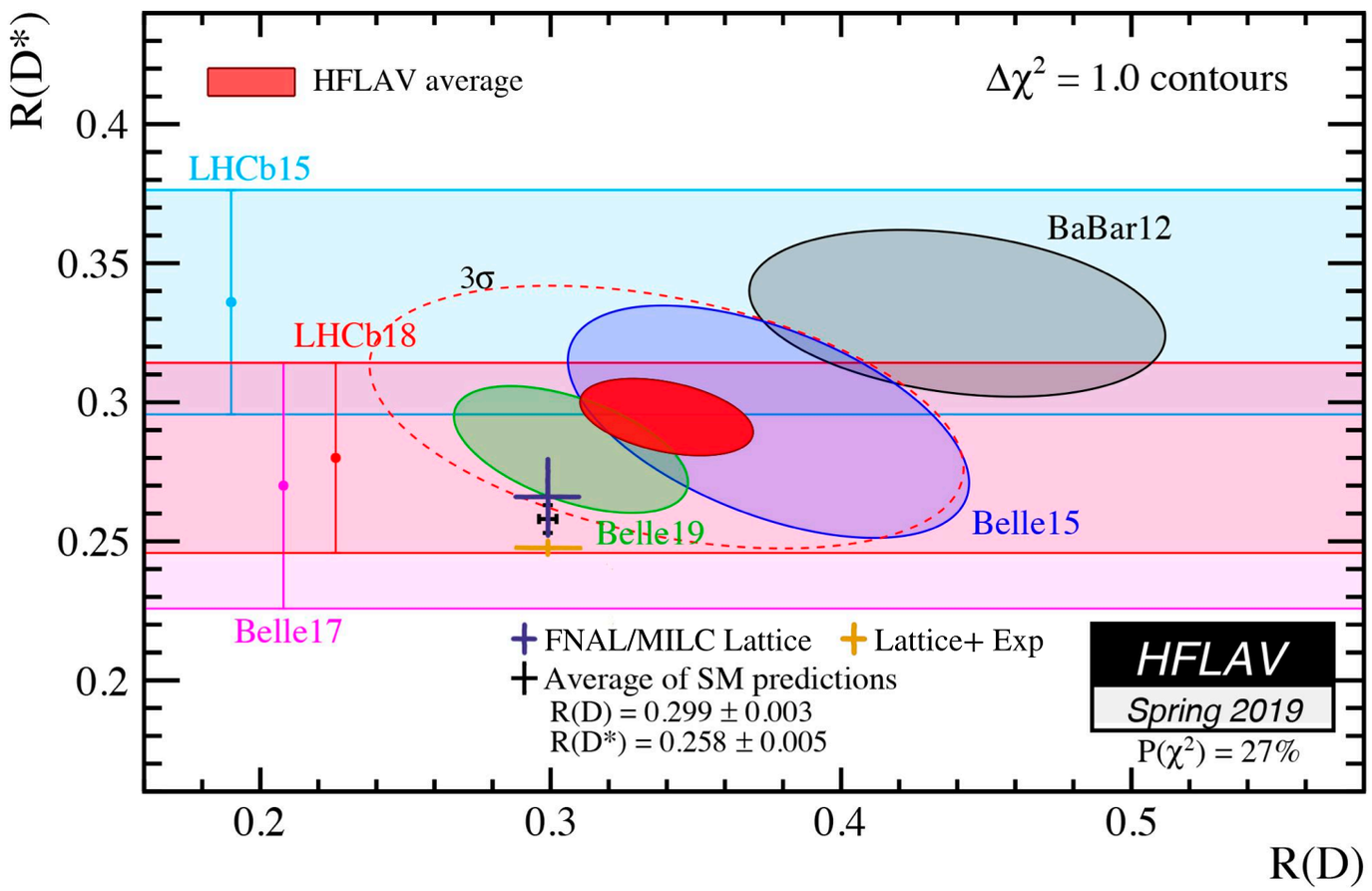
Ref.	$R(D^*)$	Exp. deviation
[32]	0.257(3)	3.3σ
[13,36]	$0.254\,\binom{7}{6}$	3.2σ
[34]	0.257(5)	3.1σ
[37]	0.250(3)	3.7σ

NEW PRELIMINARY LATTICE RESULT

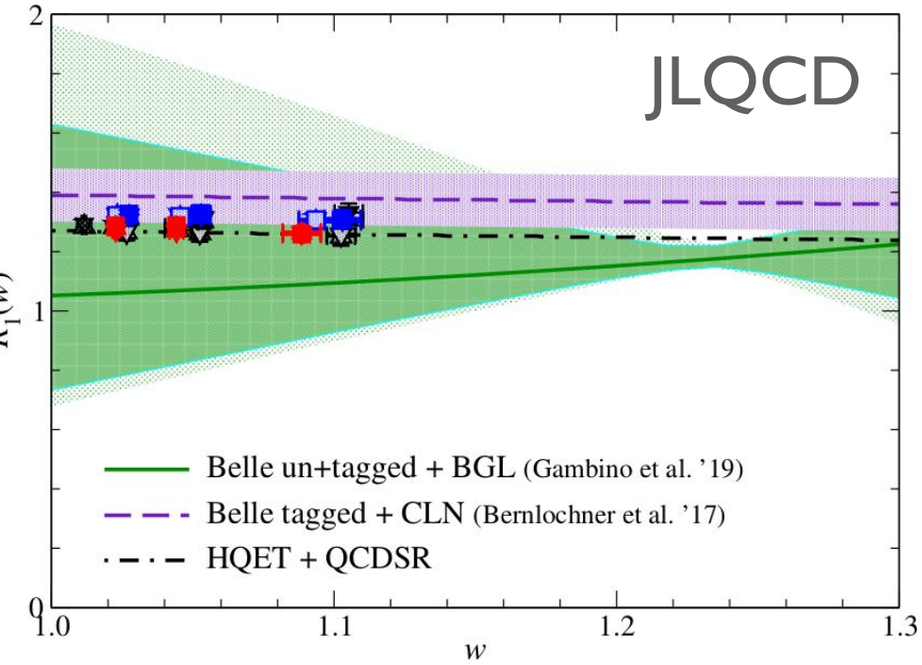
$R(D^*)$ results in context

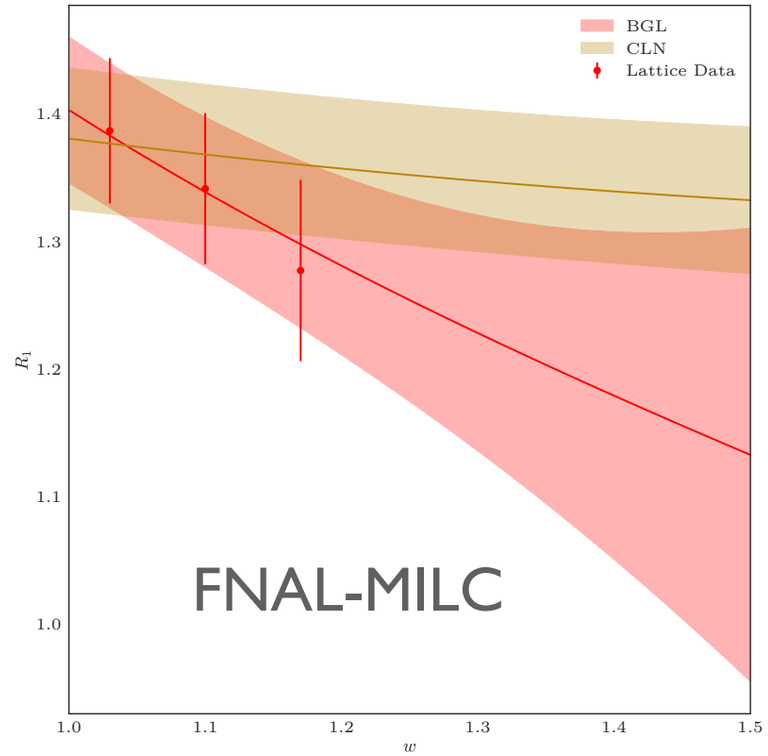
No constraint $w_{\mathbf{Max}}$**:** $R(D^*)_{\mathbf{Lat}} = 0.266(14)$ $R(D^*)_{\mathbf{Lat+Exp}} = 0.2484(13)$
W/ constraint $w_{\mathbf{Max}}$**:** $R(D^*)_{\mathbf{Lat}} = 0.274(10)$ $R(D^*)_{\mathbf{Lat+Exp}} = 0.2492(12)$

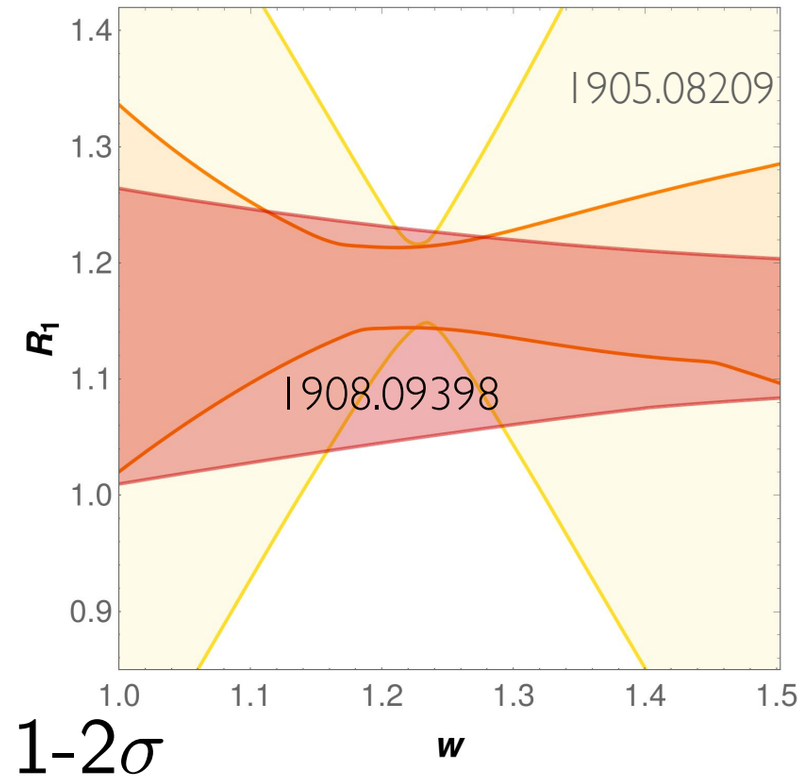
Phys.Rev.D 100 (2019), 052007; Phys.Rev.D 103 (2021), 079901; Phys.Rev.Lett. 123 (2019), 091801



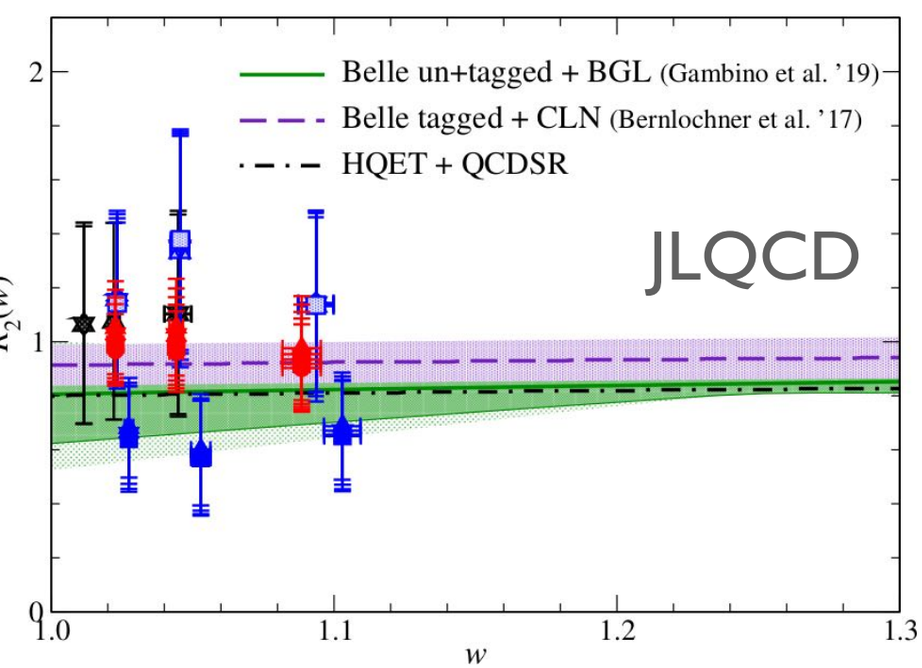
Preliminary lattice calculations (M.Jung)

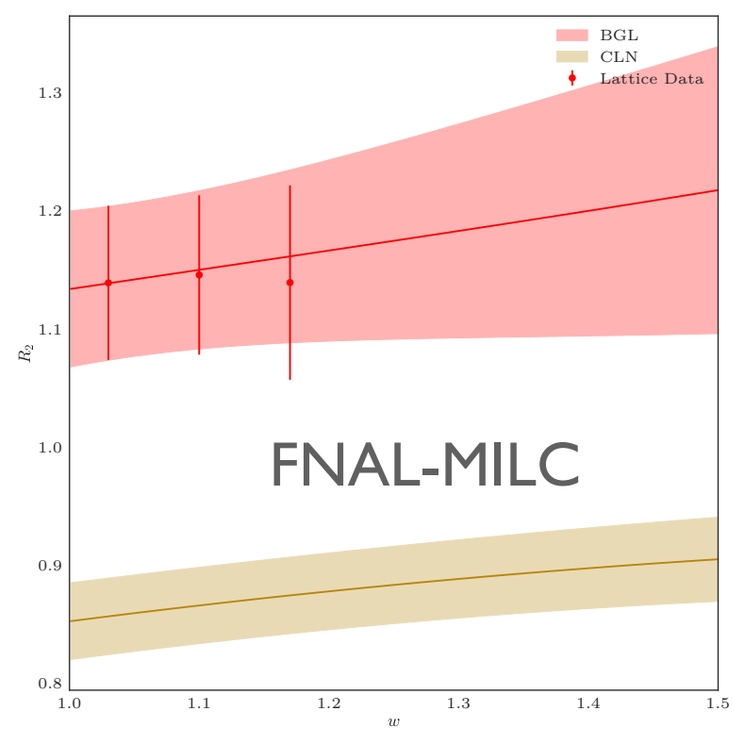


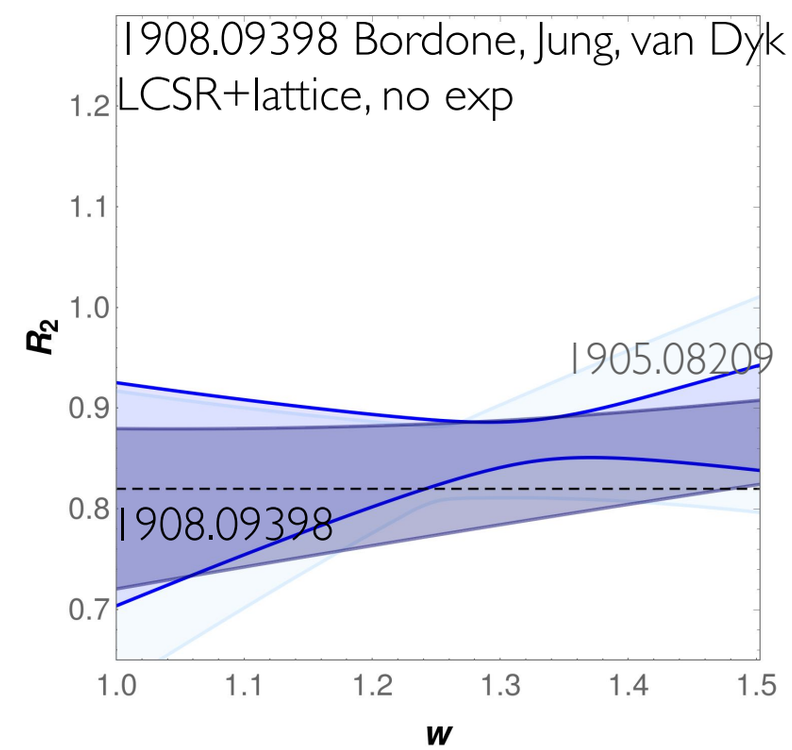




$R_1(w)$: FNAL slope surprising, compatible at 1-2σ







R_2(I): Discrepancy FNAL (1.12 ± 0.06) vs. (HQE fit, experiment)!

HQE@$1/m_c^2$: $0.78^{+0.10}_{-0.06}$, BGL: 0.81 ± 0.11, HFLAV: 0.852 ± 0.018

Flavour universality in $B \to D^*(e,\mu)\nu$ (M.Jung)

[Bobeth/Bordone/Gubernari/MJ/vDyk'21]

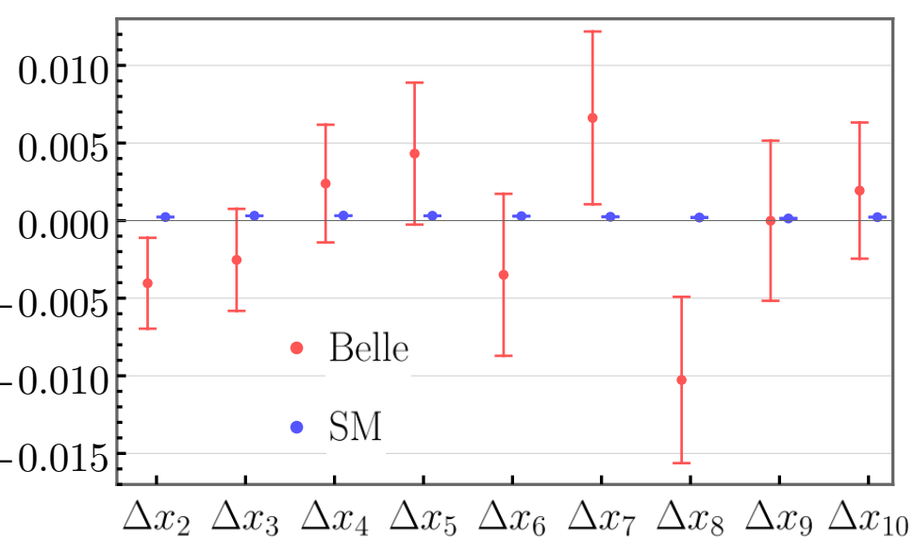
So far: Belle'18 data used in SM fits, flavour-averaged

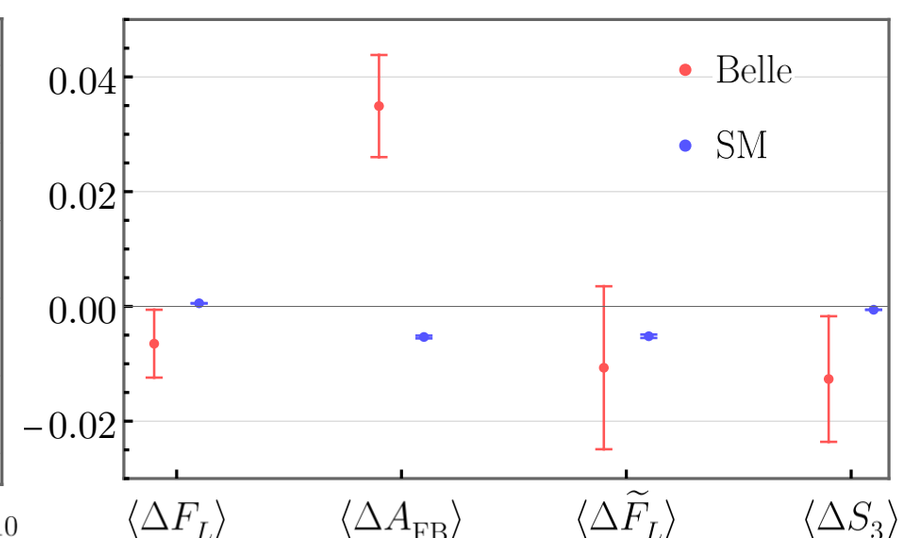
However: Bins 40×40 covariances given separately for $\ell = e, \mu$

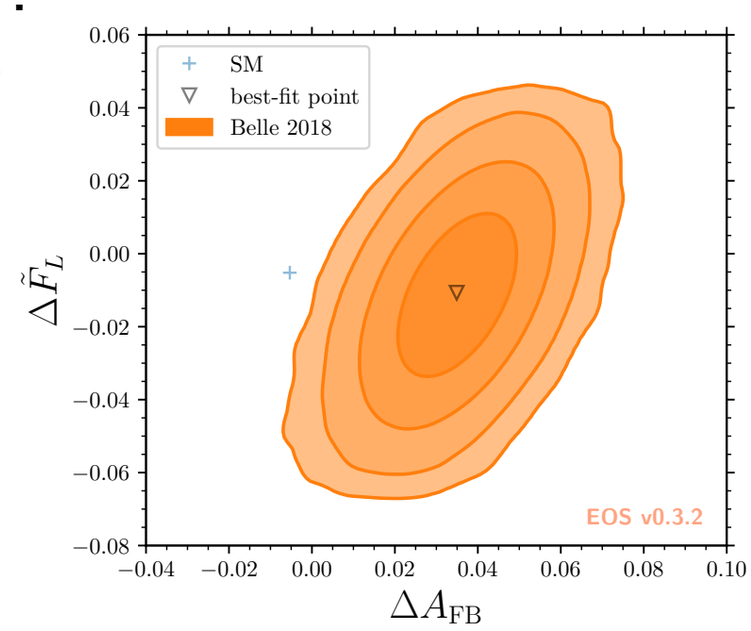
- Belle'18: $R_{e/\mu}(D^*) = 1.01 \pm 0.01 \pm 0.03$
- What can we learn about flavour-non-universality? $\to$ 2 issues:
  1. $e - \mu$ correlations not given $\to$ constructable from Belle'18
  2. 3 bins linearly dependent, but covariances not singular

Two-step analysis:

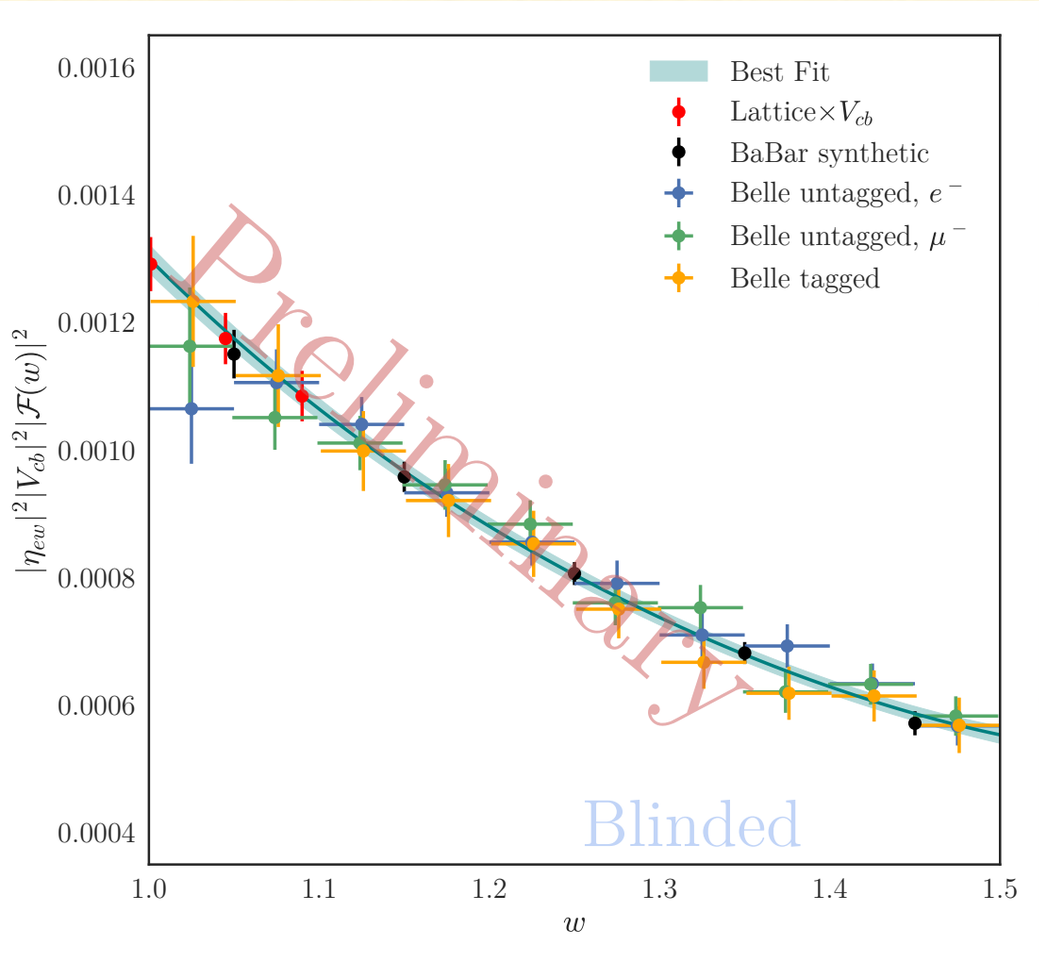
1. Extract 2×4 angular observables for 2×30 angular bins
   - Model-independent description including NP!
2. Compare with SM predictions, using FFs@$1/m_c^2$ [Bordone+'19]
   - $\sim 4\sigma$ discrepancy in $\Delta A_{\rm FB} = A_{\rm FB}^{\mu} - A_{\rm FB}^{e}$







THE IMPORTANCE OF THE SLOPE



Blinding affects only marginally the slope of the ff F, which is key to V_{cb}.

Plot suggests well determined slope, $dF/dw|_{w=1}$.

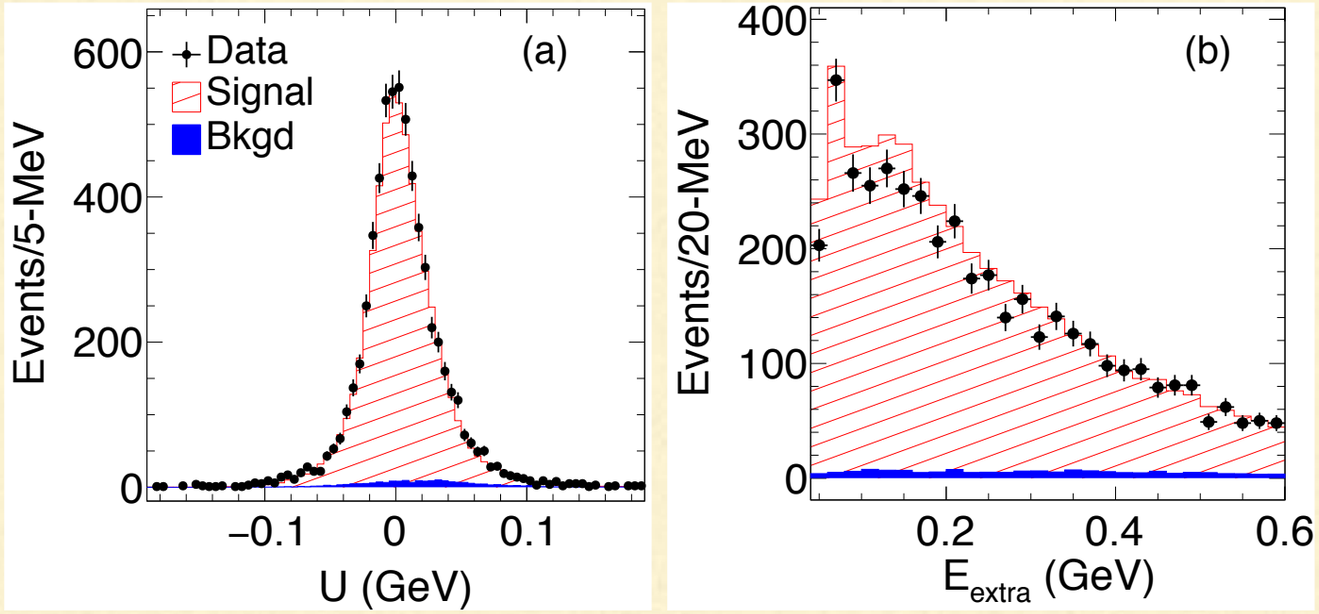
If it were -1.40(7) the fit could still accomodate a high V_{cb}

Here we use **new improved LCSR** results by Gubernari, Kokulu, van Dyk, 1811.00983 that improve upon 0809.0222

Constraints	$10^3\ V_{cb}$	χ^2
slope	40.8(0.8)	84.5/73
slope+LCSR	40.8(0.8)	88.0/76

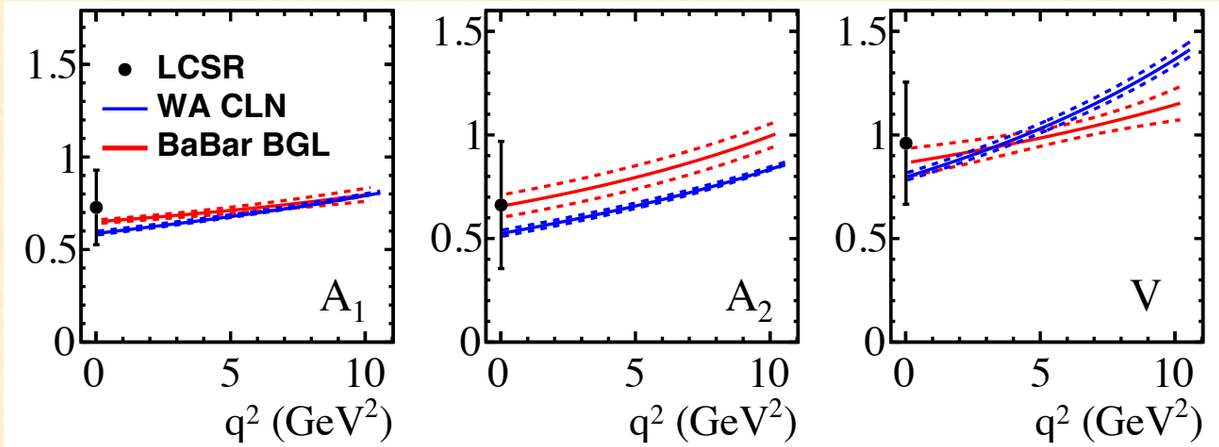
BABAR REANALYSIS 1903.10002

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(III)/CLN difference

V_{cb}=0.0384(9)



BGL form factors compared with CLN HFLAV

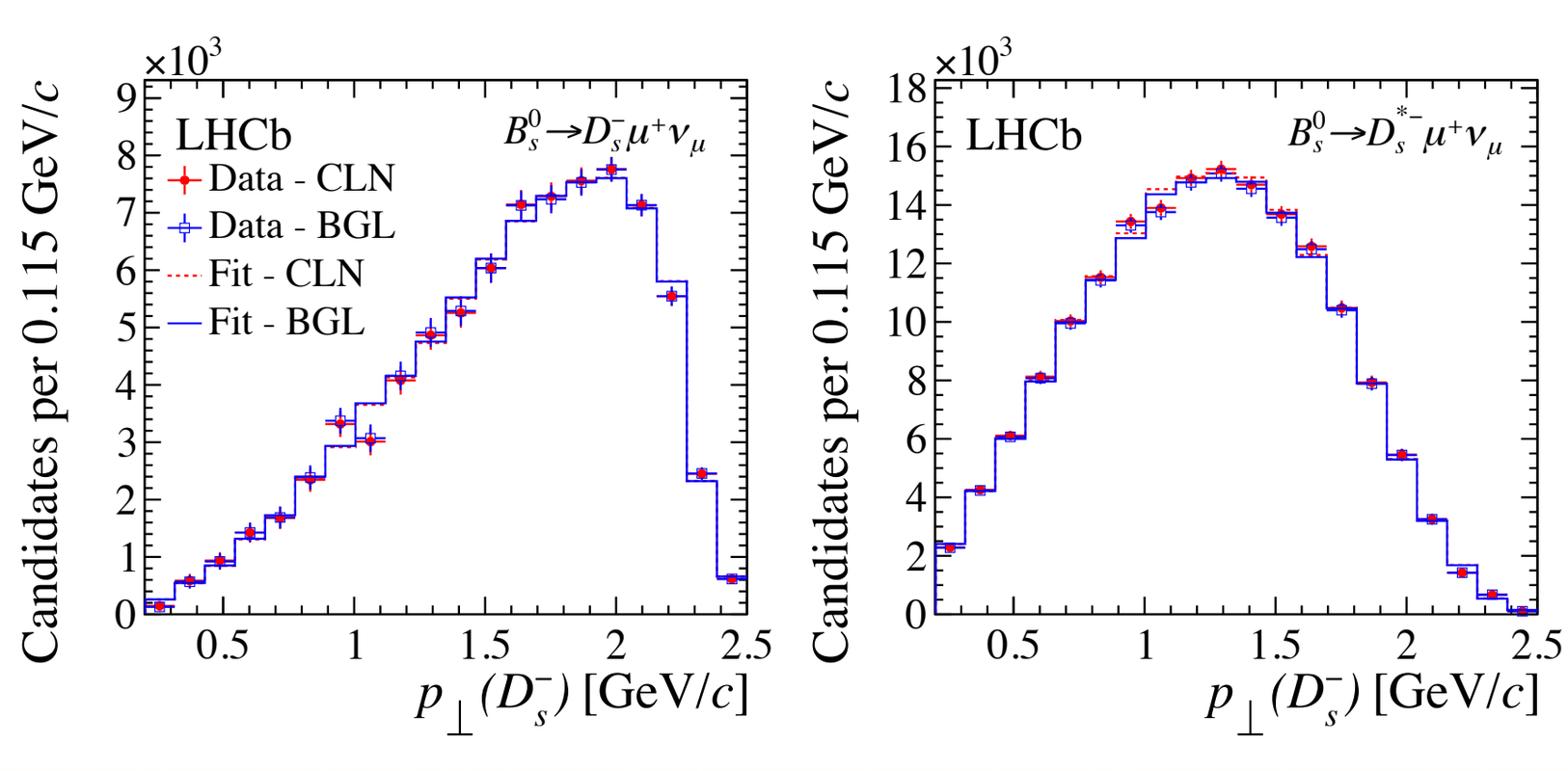
V_{cb} FROM B_s DECAYS

2001.03225

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

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

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



$$|V_{cb}|_{\rm CLN} = (41.4 \pm 0.6\,({\rm stat}) \pm 0.9\,({\rm syst}) \pm 1.2\,({\rm ext})) \times 10^{-3}\,,$$
$$|V_{cb}|_{\rm BGL} = (42.3 \pm 0.8\,({\rm stat}) \pm 0.9\,({\rm syst}) \pm 1.2\,({\rm ext})) \times 10^{-3}\,,$$

Fit to exp data and lattice FFs based on HFLAV BRs, employs BGL_{222}

CONCLUSIONS

- The ***inclusive determination*** appears in a good shape and can be improved by 3loop calculations and studies on the lattice (virtual lab).
- Experimental situation for $B \to D^*$ confused, but ***revisiting the exclusive b→c decays was useful***: uncertainties were underestimated and results possibly biased, several new experimental analyses appeared (Babar, LHCb) or are under way. The *practical CLN* must be abandoned and data reported model-independently.
- Several lattice coll. are computing all necessary FFs, but ***progress is slow*** and FNAL preliminary result problematic.
- Belle-II should improve both incl and excl measurements.
- ***The semitauonic anomaly*** persists and the SM predictions are robust.
- Inclusive/Exclusive tension remains, a bit weaker. Hopefully, it will disappear. Eventually, ***LQCD will decide the fate of the V_{cb} puzzle***.