V_{cb} and V_{ub}
Where do we stand?

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Importance of $|V_{xb}|$

V_{cb} plays an important role in the determination of UT

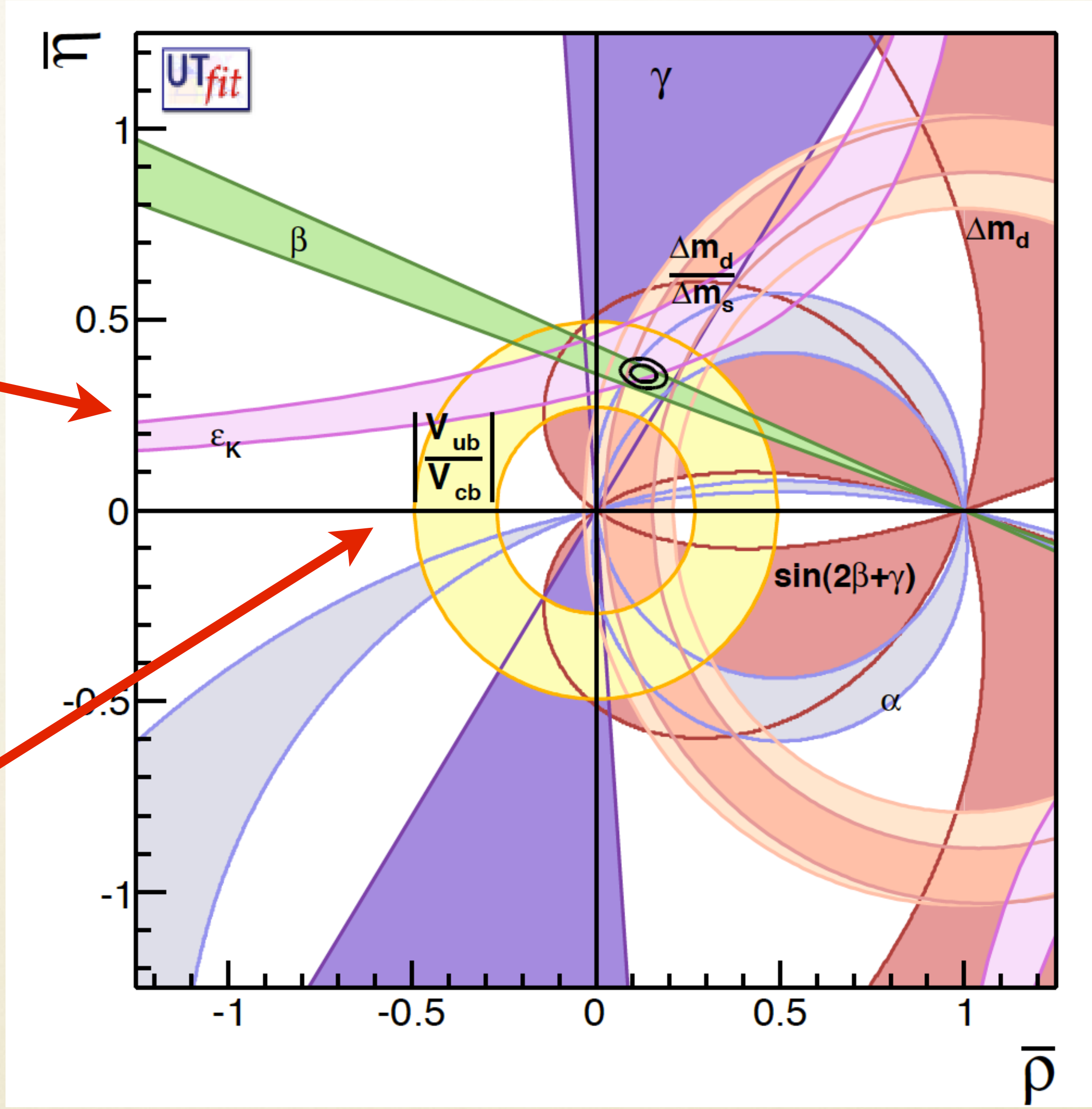
$$\varepsilon_K \approx x|V_{cb}|^4 + \ldots$$

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



Since several years, exclusive decays prefer smaller $|V_{ub}|$ and $|V_{cb}|$

Inclusive semileptonic B decays

OPE allows us to write inclusive observables as double series in $1/m_b$ and α_s

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

OPE valid for inclusive enough measurements, away from perturbative singularities ➠ semileptonic width, moments

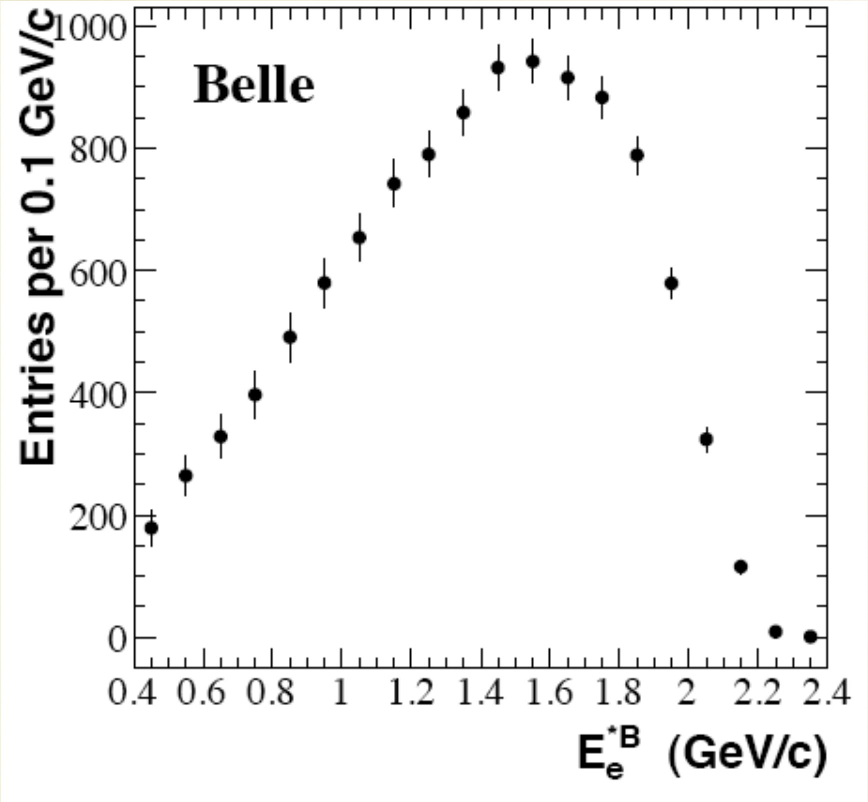
Current fits includes 6 non-pert parameters

$m_{b,c}$ $\quad$ ${\mu^2}_{\pi,G}$ $\quad$ ${\rho^3}_{D,LS}$

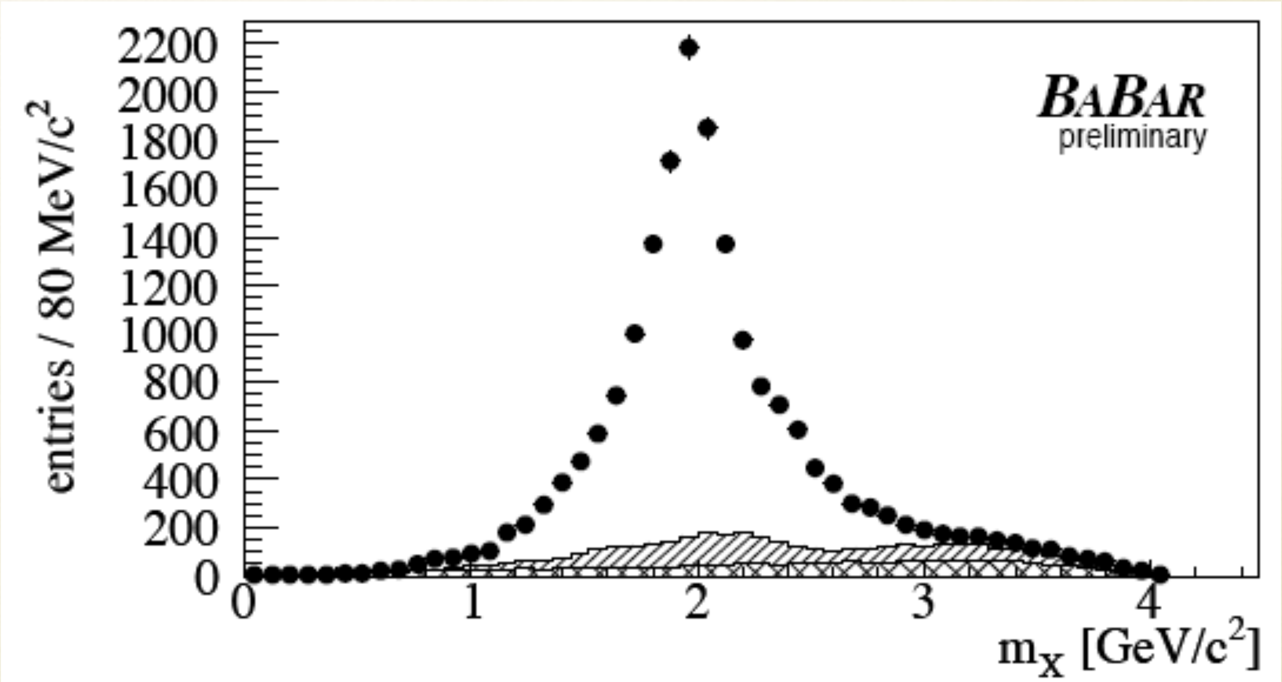
and all known corrections up to $O(\Lambda^3/m_b{}^3)$

Extraction of the OPE parameters

E_l spectrum



hadronic mass spectrum



*Global **shape** parameters (first moments of the distributions) 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},...)

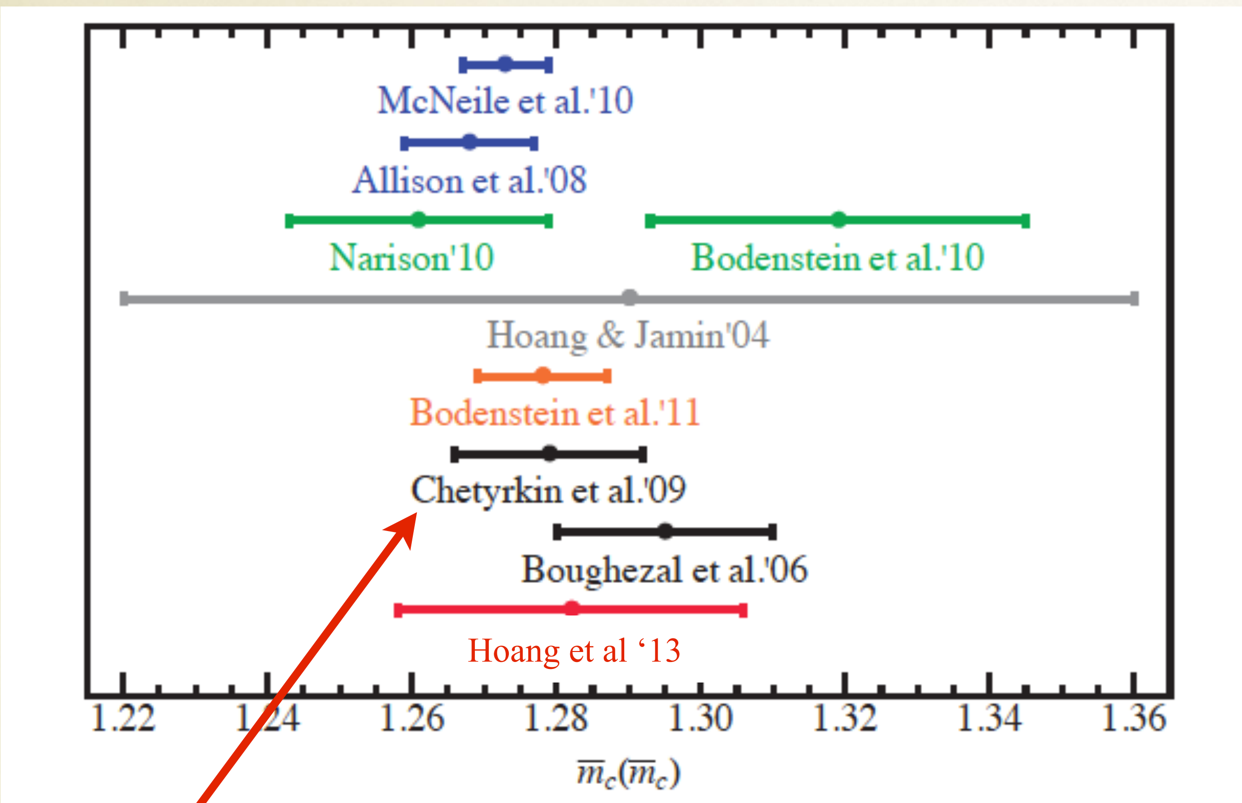
Latest semileptonic fit

Alberti, Healey, Nandi, PG 1411.6560

- **updates** the fit in Schwanda, PG, 1307.4551
- kinetic scheme calculation based on 1107.3100; hep-ph/0401063
- includes all $O(\alpha_s^2)$ and $O(\alpha_s/m_b^2)$ corrections
- reassessment of theoretical errors, realistic correlations
- **external constraints**: precise heavy quark mass determinations, plus mild constraints on μ^2_G from hyperfine splitting and ρ^3_{LS} from sum rules

Previous fits: Buchmuller, Flaecher hep-ph/0507253,
Bauer et al, hep-ph/0408002 (1S scheme)

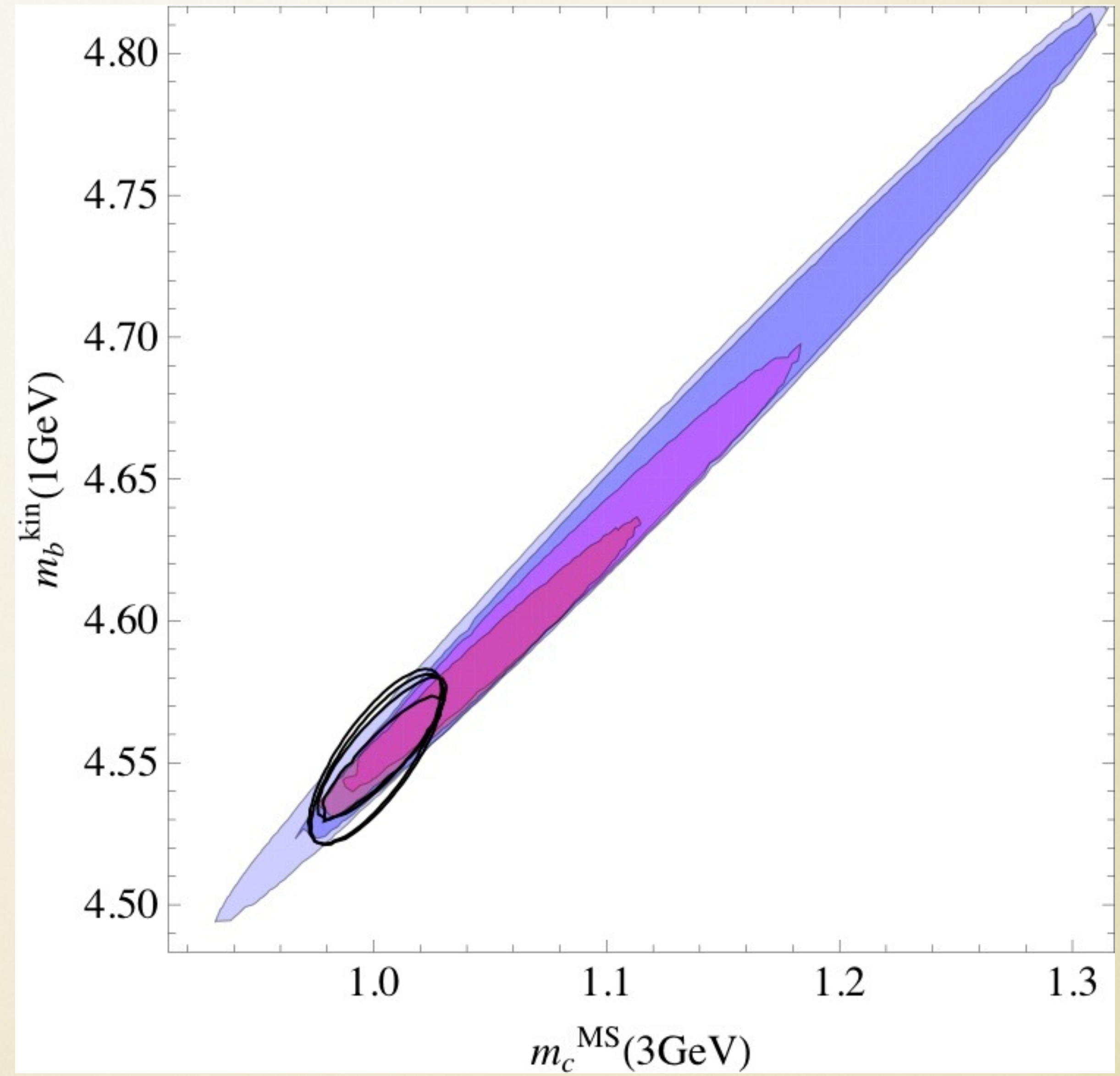
CHARM MASS DETERMINATIONS



our default choice

sum rules studies of $\sigma(e^+e^- \to \text{hadrons})$

almost all at NNNLO



Remarkable improvement in recent years.

m_c can be used as precise input to fix m_b instead of radiative moments

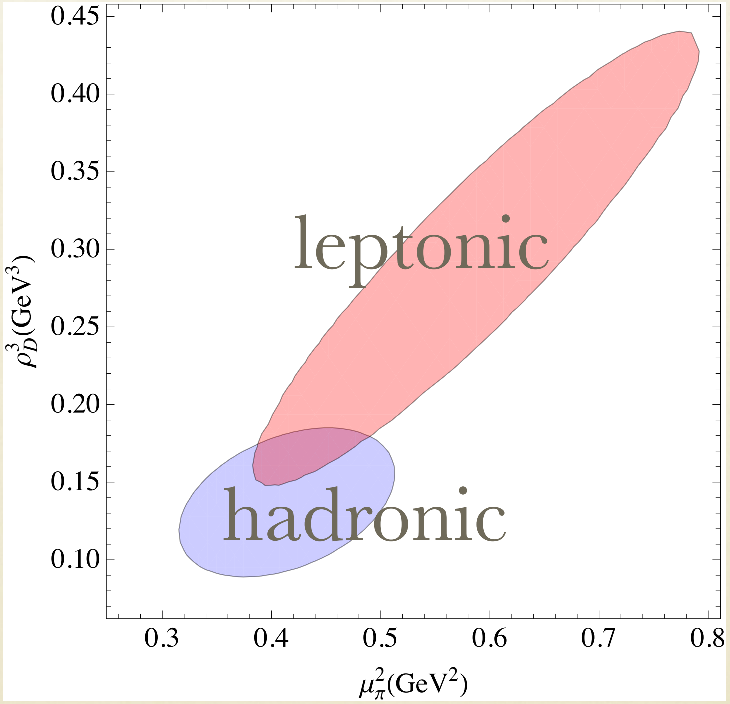
FIT RESULTS

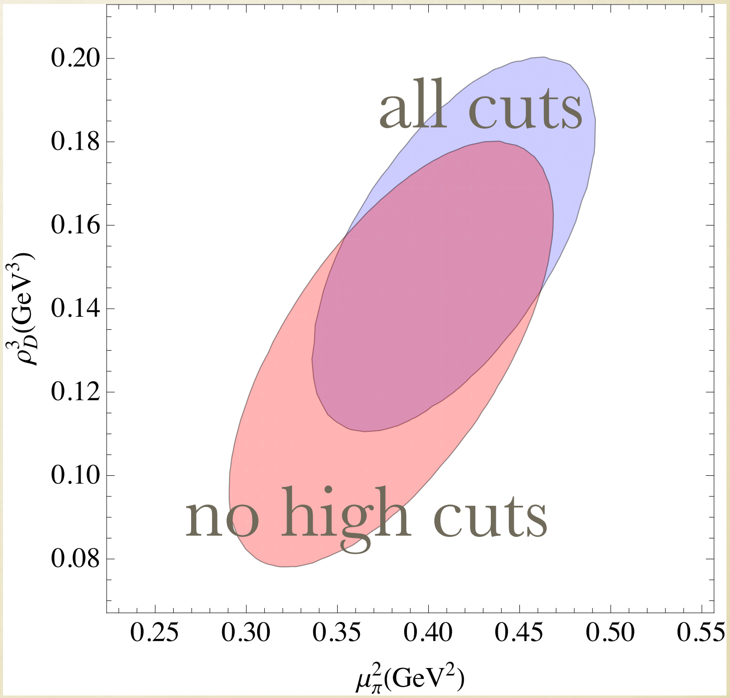
m_b^{kin}	$\overline{m}_c(3\,\mathrm{GeV})$	μ_π^2	ρ_D^3	μ_G^2	ρ_{LS}^3	$\mathrm{BR}_{c\ell\nu}$	$10^3\lvert V_{cb}\rvert$
4.553	0.987	0.465	0.170	0.332	-0.150	10.65	42.21
0.020	0.013	0.068	0.038	0.062	0.096	0.16	0.78

Without mass constraints

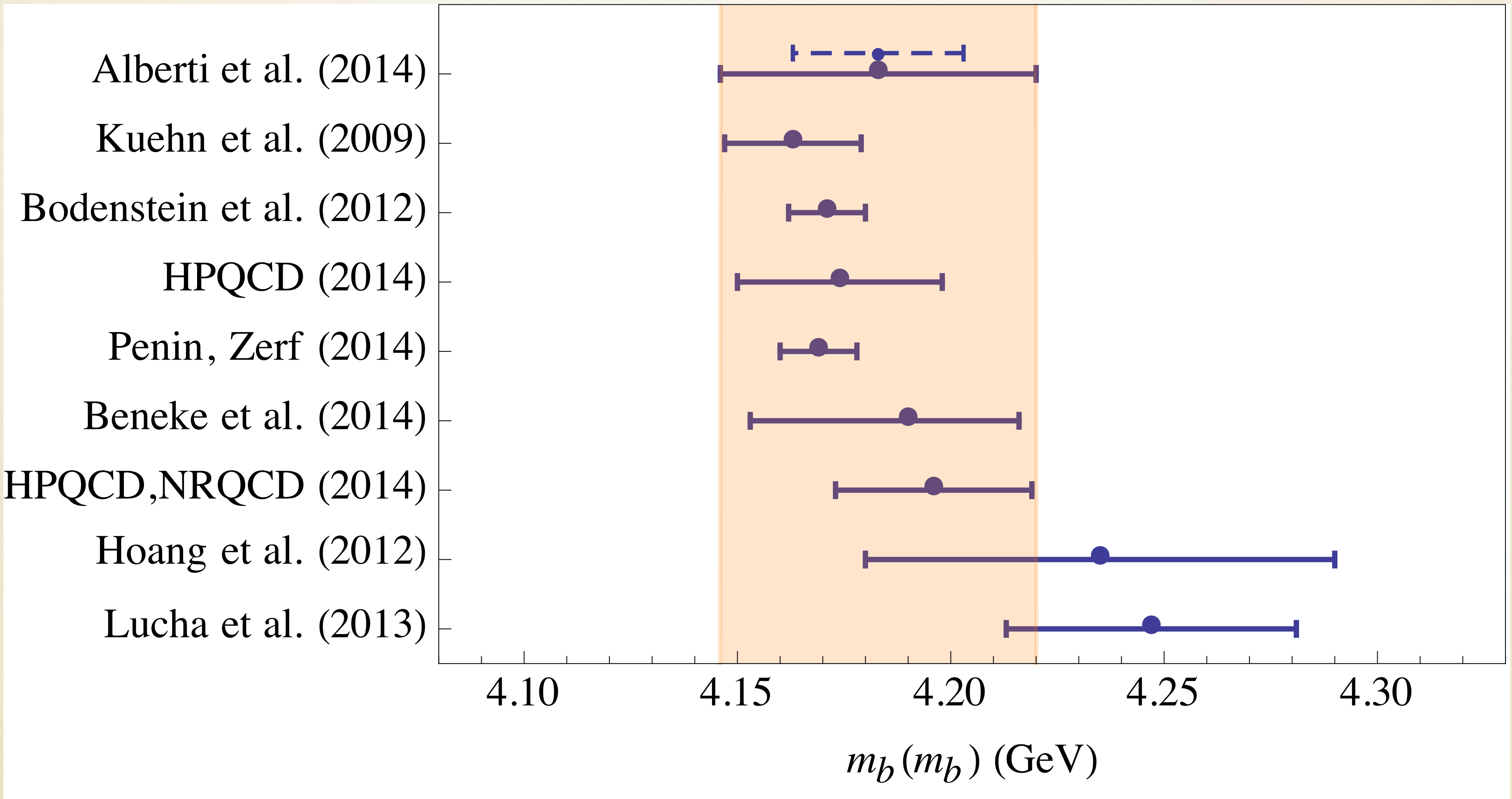
$$m_b^{kin}(1\mathrm{GeV}) - 0.85\,\overline{m}_c(3\mathrm{GeV}) = 3.714 \pm 0.018\,\mathrm{GeV}$$

- results depend little on assumption for correlations and choice of inputs, 1.8% determination of V_{cb}
- 20-30% determination of the OPE parameters





Results: bottom mass



The fit gives $\boldsymbol{m_b^{kin}}$**(1GeV)=4.553(20)GeV**

scheme translation error $m_b^{kin}(1\text{GeV})=m_b(m_b)+0.37(3)\text{GeV}$

$\boldsymbol{\overline{m}_b(\overline{m}_b)}$**=4.183(37)GeV**

HIGHER ORDER EFFECTS

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

- **Purely perturbative corrections** complete at NNLO, small residual error (kin scheme) Melnikov,Biswas,Czarnecki,Pak,PG

- **Higher power corrections** $O(1/m_Q^{4,5})$ known
  Mannel,Turczyk,Uraltsev 2010 not included in fit

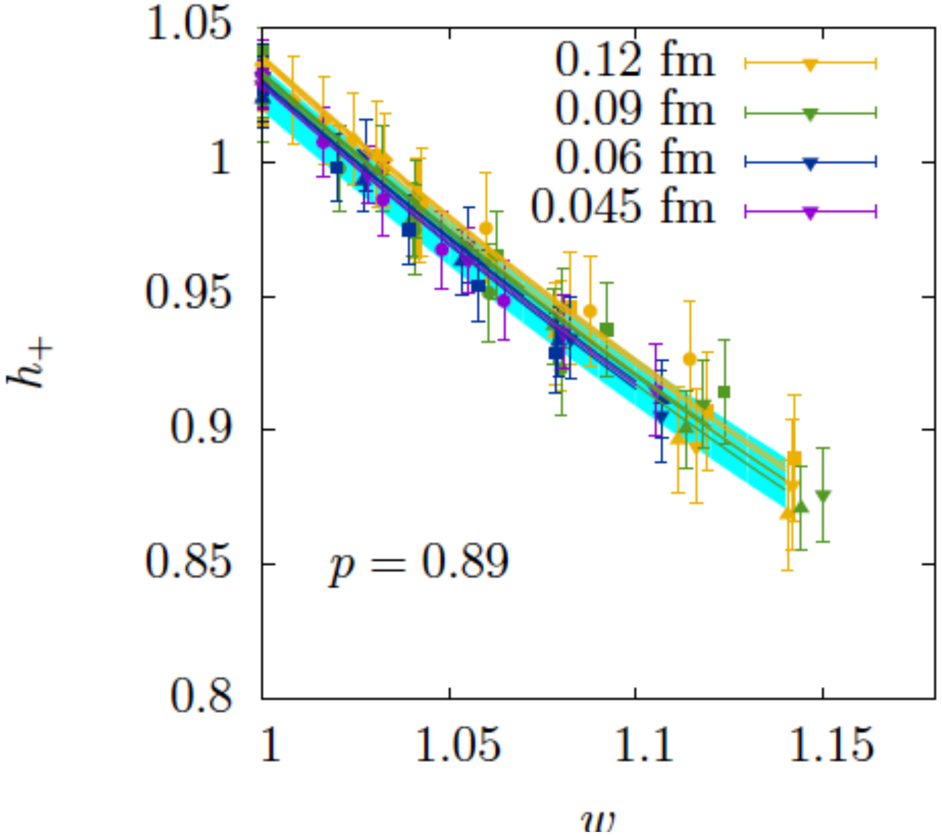
- **Mixed corrections** perturbative corrections to power suppressed coefficients completed at $O(\alpha_s/m_b^2)$
  Becher, Boos, Lunghi, Alberti, Ewerth, Nandi, PG, Mannel,Pivovarov, Rosenthal

Prospects for theory

- Theoretical uncertainties dominate already
- $O(a_s/m_b^3)$ calculation under way
- $O(1/m_Q^{4,5})$ effects need further investigation: estimates based on vacuum saturation approx suggest small impact Turczyk, PG, preliminary
- NNNLO corrections to total width feasible
- Lattice QCD information on local matrix elements is the next frontier
- Electroweak corrections

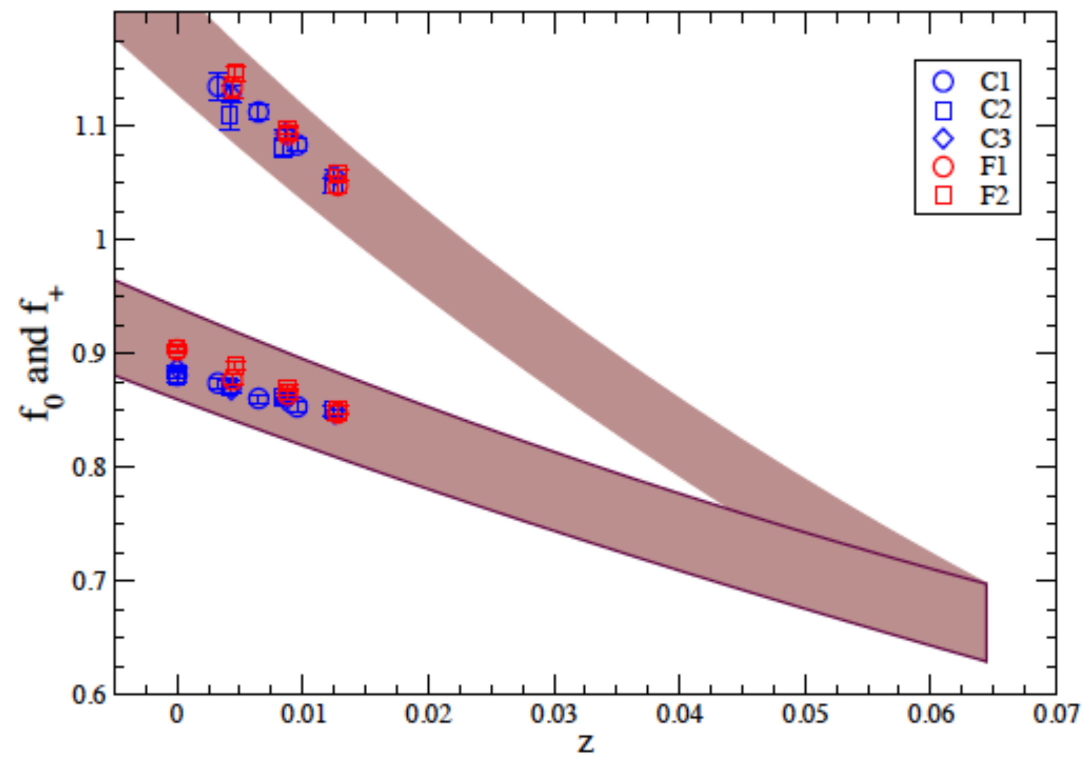
New results for $B \to D l \nu$ f.f.

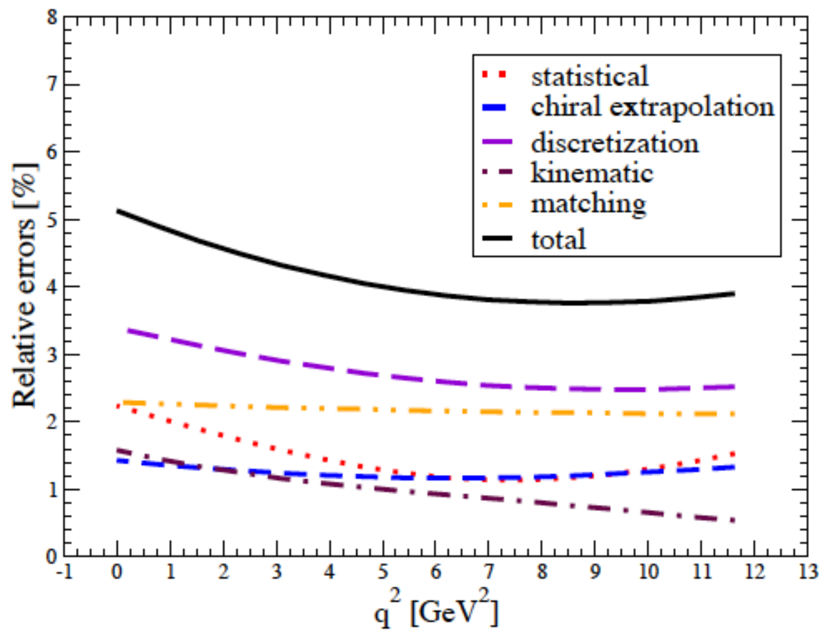
FNAL/MILC 1503.07237



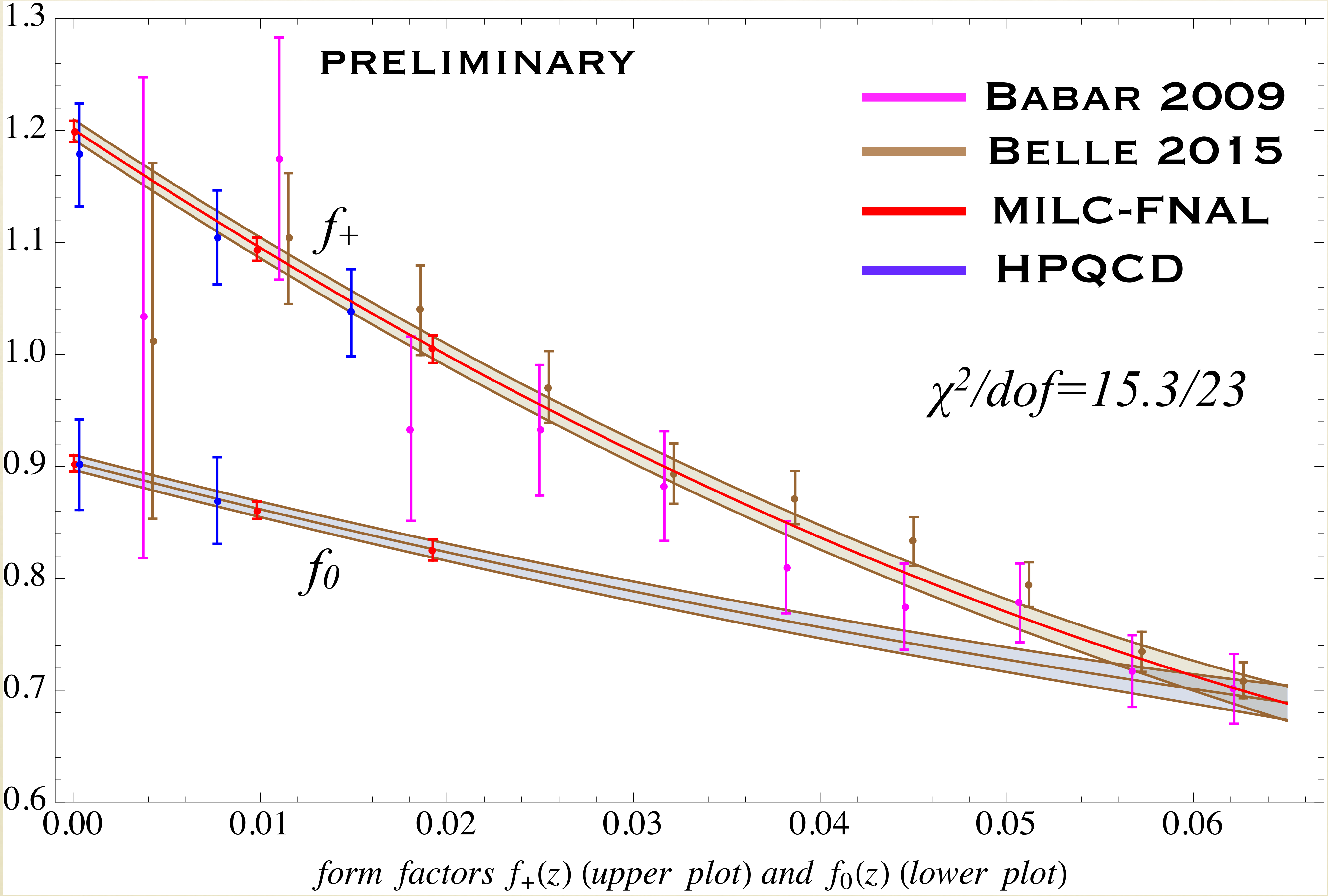
Source	$f_+(\%)$
Statistics+matching+χPT cont. extrap.	1.2
(Statistics)	(0.7)
(Matching)	(0.7)
(χPT/cont. extrap.)	(0.6)
Heavy-quark discretization	0.4
Lattice scale r_1	0.2
Total error	1.2

HPQCD 1505.03925





Global fit to B→Dlν



A Global fit to B→Dlν

- $\mathbf{|V_{cb}|=41.08(0.95)\ 10^{-3}}$ preliminary
- based on *z*-expansion with unitarity constraints (BGL)
- assumes no correlation between FNAL and HPQCD, 3% syst error on Babar data, correct treatment of last bin, no finite size bin effect
- little dependence on parameterization if lattice data at non-zero recoil are included (CLN gives $40.99(97)\ 10^{-3}$)
- Non-zero recoil data are crucial: only zero recoil leads to $|V_{cb}|=39.80(1.1)\ 10^{-3}$
- Babar prefers lower V_{cb}
- $R(D)=0.302(9)$ (preliminary) 1.8σ from HFAG average

Exclusive $B \to D^* \ell \nu$

<u>At zero recoil</u>, where rate vanishes, the ff is

$$\mathcal{F}(1) = \eta_A \left[1 + O\left(\frac{1}{m_c^2}\right) + ... \right]$$

Recent progress in measurement of slopes and shape parameters,
exp error only ~1.3%

The ff F(1) cannot be experimentally determined. Lattice QCD is the best hope to compute it. <u>Only one</u> unquenched Lattice calculation:

F(1) =0.906(13) ➠ $\boxed{|V_{cb}| = 39.04(49)_{exp}(53)_{lat}(19)_{QED}\ 10^{-3}}$

Bailey et al 1403.0635 (FNAL/MILC)

1.9% error (adding in quadrature)

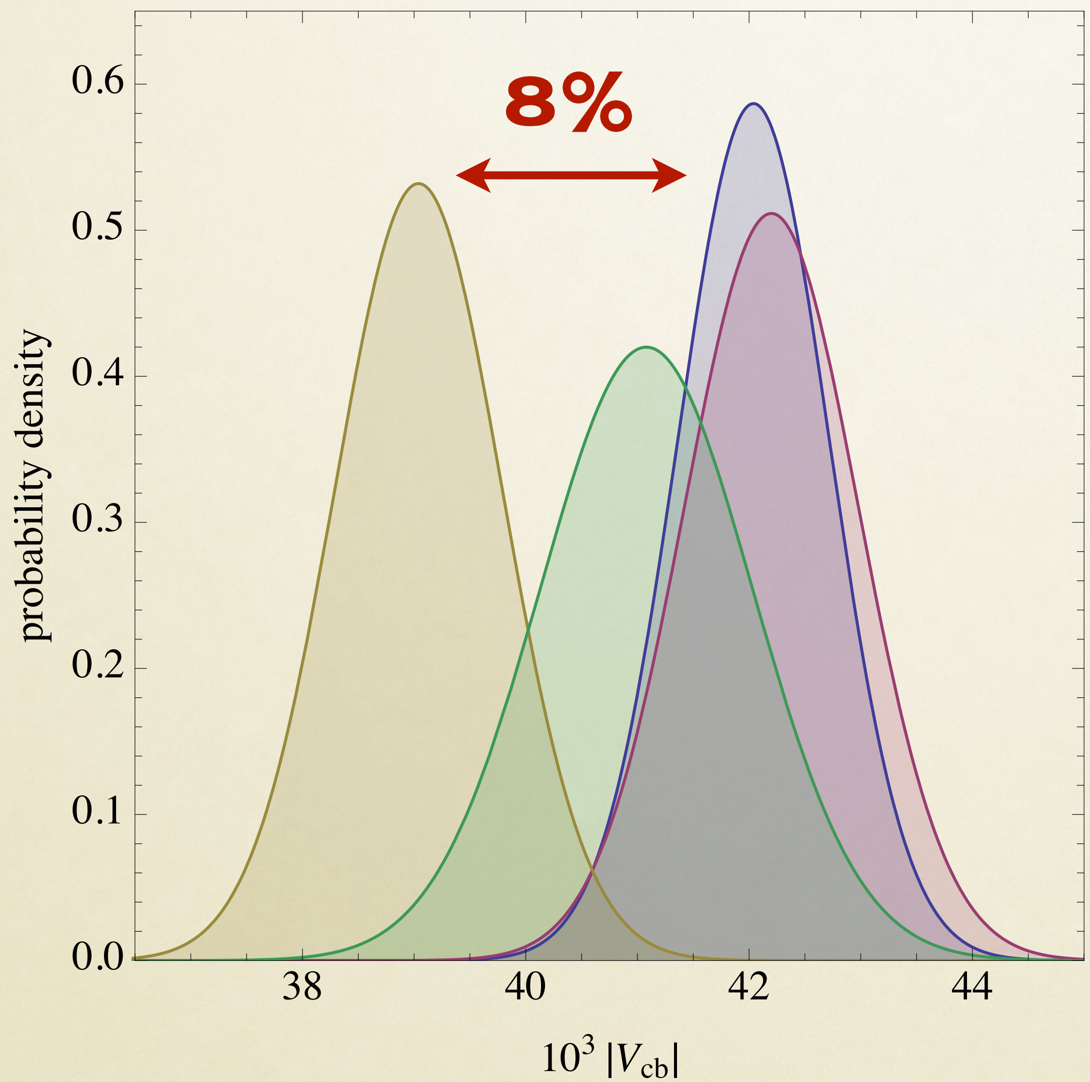
~2.9σ or ~8% from inclusive determination

COMMENTS ON D^*

- **Heavy quark sum rules** (with BPS arguments) favor smaller F(1)=0.86(2) leading to agreement with inclusive. Difficult to improve, how good is BPS limit?
- **Extrapolations to zero recoil** by experiments use CLN parameterization, based on NLO HQET, and **do not include a 1%** uncertainty. CLN has only 2 parameters, fits well exp data but makes assumptions. Lattice simulations at non zero recoil under way.
- Matching at $1/m_Q^3$ for **lattice discretization** effects under study by FNAL/MILC. Other collaborations working on $B \to D^*$ ff.
- **Indirect $|V_{cb}|$ determinations** assuming SM+unitarity CKM: UTFit 42.05(65) 10^{-3} CKMFitter $41.4^{+2.4}_{-1.4}$ 10^{-3}

V_{cb} VISUAL SUMMARY

EXCLUSIVE B→D EXCLUSIVE B→D* INCLUSIVE UTFIT SM PREDICTION: (42.04±0.68) 10^{-3}



Latest lattice results (FNAL/MILC+HPQCD)

form factors from HQSR,HQE,LCSR for exclusives also available, less precise

Mannel, Uraltsev, PG, Khodjamirian et al

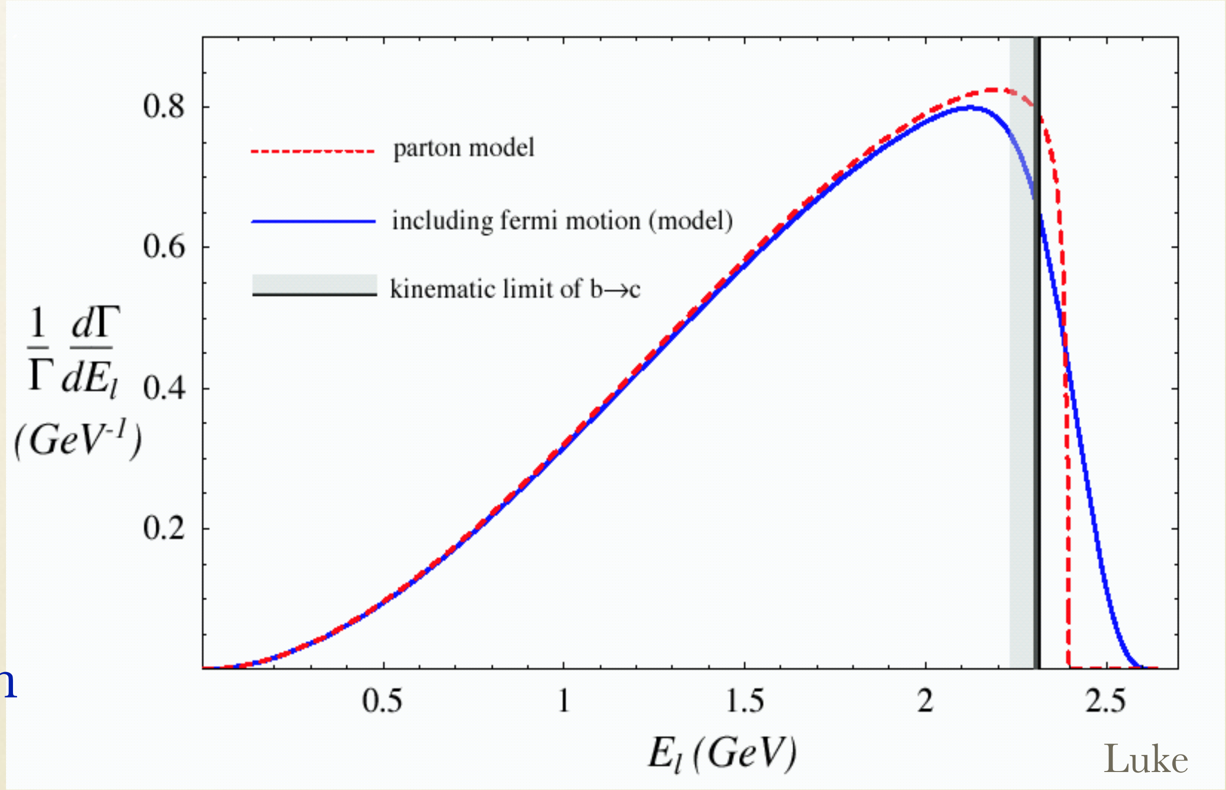
$B \to X_u l \nu$ and cuts

Experiments often use kinematic cuts to avoid the ~100x larger $b \to cl\nu$ background:

$m_X < M_D$ $\quad E_l > (M_B^2 - M_D^2)/2M_B$ $\quad q^2 > (M_B - M_D)^2$ ...

The cuts destroy convergence of the OPE that works so well in $b \to c$. OPE expected to work only away from pert singularities

Rate becomes sensitive to *local* b-quark wave function properties like Fermi motion. Dominant non-pert contributions can be resummed into a **SHAPE FUNCTION** f(k+). Equivalently the SF is seen to emerge from soft gluon resummation



How to access the SF?

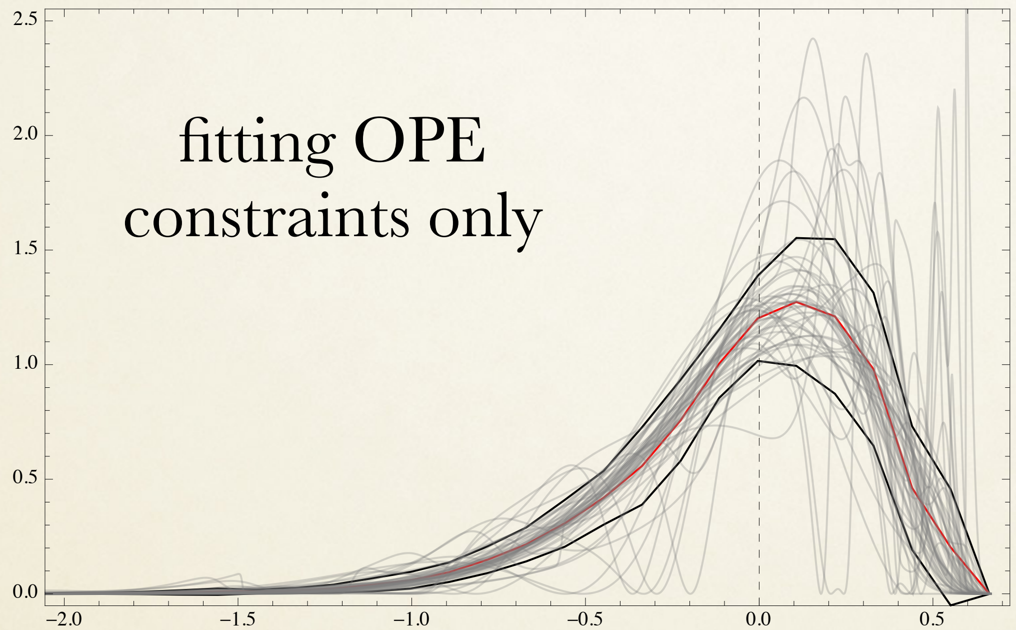
$$\frac{d^3\Gamma}{dp_+ dp_- dE_\ell} = \frac{G_F^2 |V_{ub}|^2}{192\pi^3} \int dk C(E_\ell, p_+, p_-, k) F(k) + O\left(\frac{\Lambda}{m_b}\right)$$

Subleading SFs

Prediction *based* on resummed pQCD DGE, ADFR	OPE constraints + parameterization without/with resummation GGOU, BLNP
Fit semileptonic (and radiative) data SIMBA, NNVub	

The NNVub Project

K.Healey, C. Mondino, PG, in progress



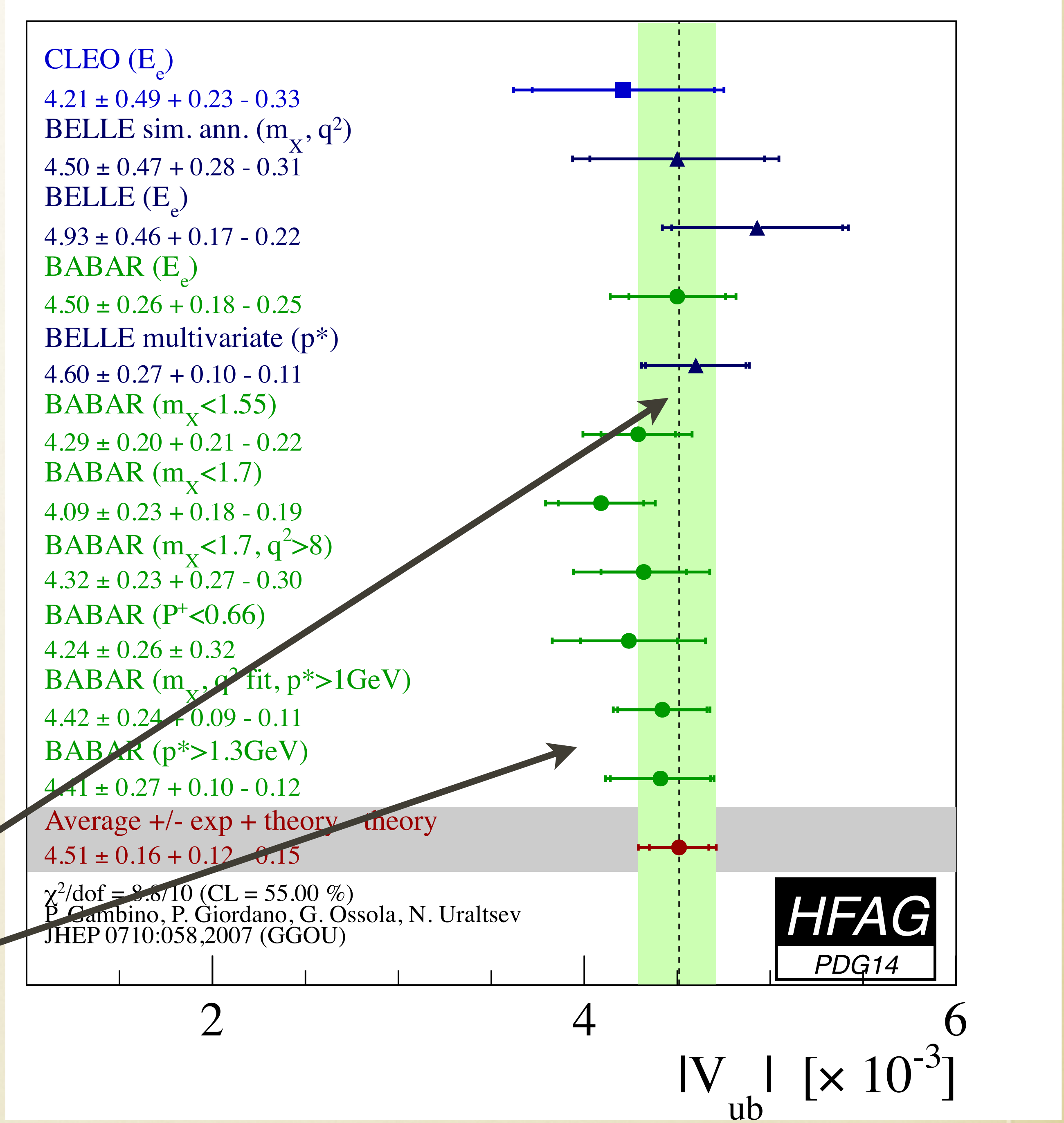
- Use **Artificial Neural Networks** to fit shape functions to theoretical constraints and data without bias, extracting V_{ub} and HQE parameters in a model independent way (without assumptions on functional form).
- Belle-II will be able to measure some kinematic distributions, thus constraining directly the shape function. NNVub will provide a flexible tool to analyse data.

$|V_{ub}|$ DETERMINATIONS

Inclusive: 5% total error

HFAG 2014	Average $|V_{ub}|$ 1000
DGE	4.52(16)(16)
BLNP	4.45(16)(22)
GGOU	4.51(16)(15)

UT fit (without direct V_{ub}):
$V_{ub}=3.62(12)\ 10^{-3}$



Recent experimental results
are theoretically cleanest (2%)
but based on background modelling.
Signal simulation also relies on theoretical models…

LQCD calculations for $|V_{ub}|$: recent progress

- Disclaimer: the list is not meant to be inclusive. I am focusing on the publicized results.

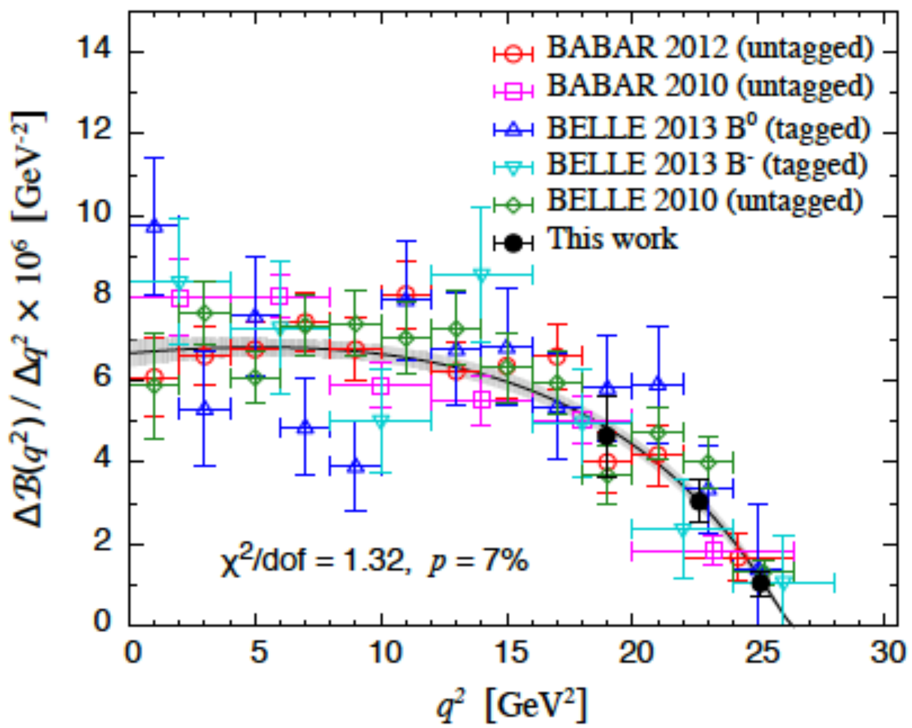
Lattice Group	Fermilab/MILC	HPQCD	RBC/UKQCD	Alpha	Detmold et al.
Process	$B \to \pi \ell \nu$ $(B_s \to K \ell \nu)$	$B_s \to K \ell \nu$ $(B \to \pi \ell \nu)$	$B \to \pi \ell \nu$ $B_s \to K \ell \nu$	$(B_s \to K \ell \nu)$	$\Lambda_b \to p \ell \nu$
Gauge ensembles	MILC asqtad	MILC asqtad	Domain-Wall	CLS	Domain-Wall
Sea flavors	2+1	2+1	2+1	2	2+1
a (fm)	0.045–0.12	0.09–12	0.086–0.11	0.049–0.076	0.086–0.11
M_π	≥ 177 MeV	≥ 354 MeV	≥ 289 MeV	≥ 310 MeV	≥ 295 MeV
l-quark action	asqtad	HISQ	Domain-Wall	Imprv. Wilson	Domain-Wall
b-quark action	Fermilab Clover	NRQCD	RHQ	Lat. HQET	RHQ
χPT	NNLO,SU(2), hard-π	HPχPT+	NLO,SU(2), hard-π		
q^2-extrapolation	functional BCL	modified z	synthetic BCL		modified-z
Ref.	arXiv:1503.07839 arXiv:1312.3197	arXiv:1406.2279	arXiv:1501.05373v2	arXiv:1411.3916	arXiv:1306.0446 arXiv:1503.01421v2 arXiv:1504.01568

- (): work in progress

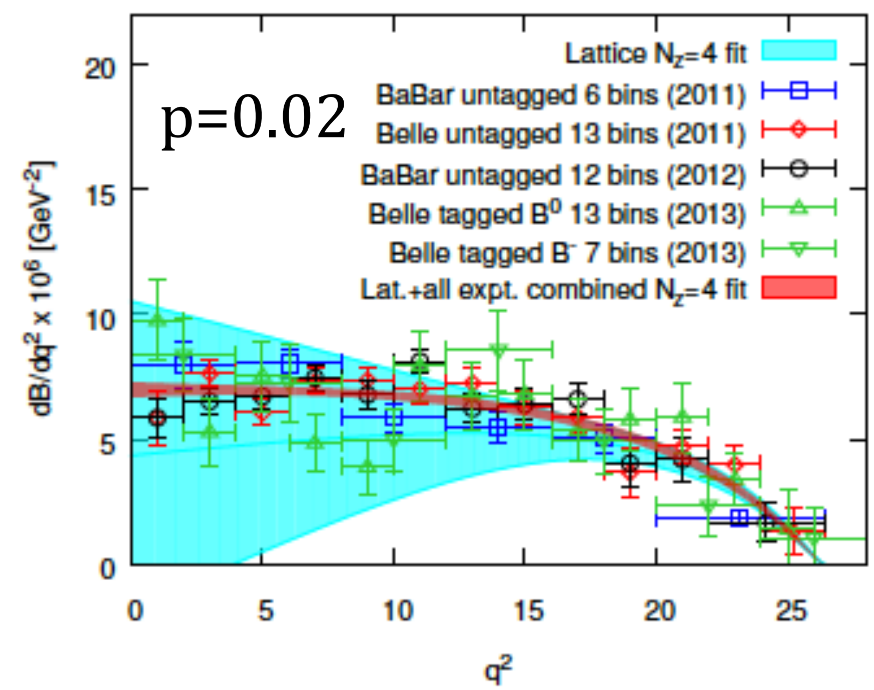
Du, MITP workshop, April 2015

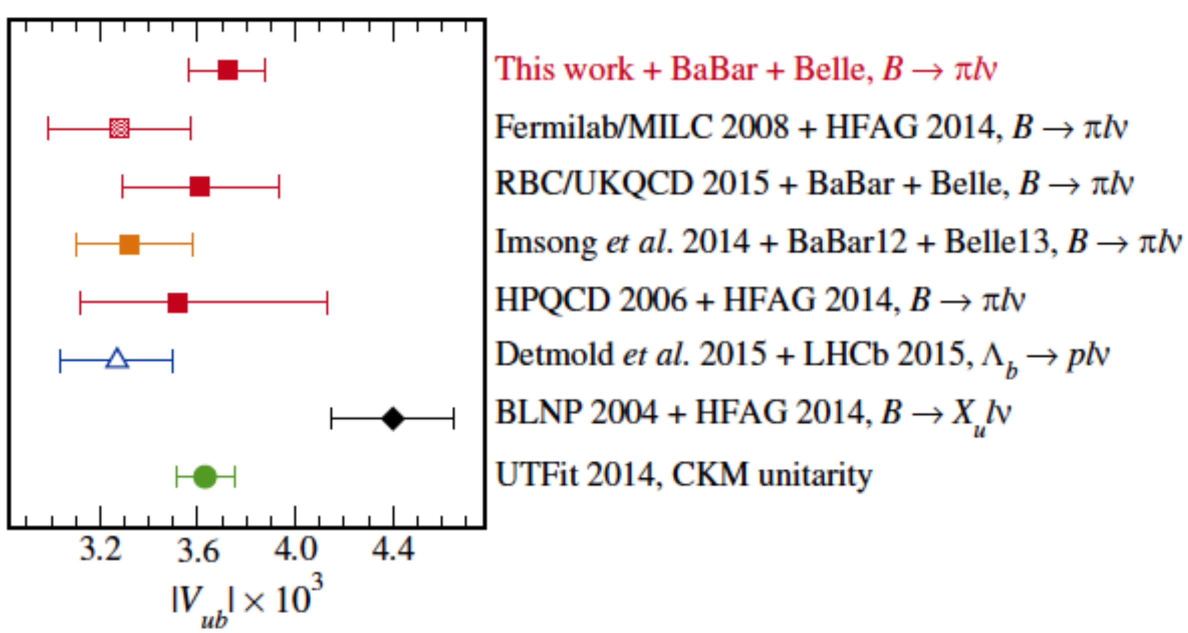
New lattice results

RBC/UKQCD 1501.05373



FNAL/MILC 1503.07839





FNAL $3.72(16)\ 10^{-3}$
only 4.3% error
2.2σ from inclusive

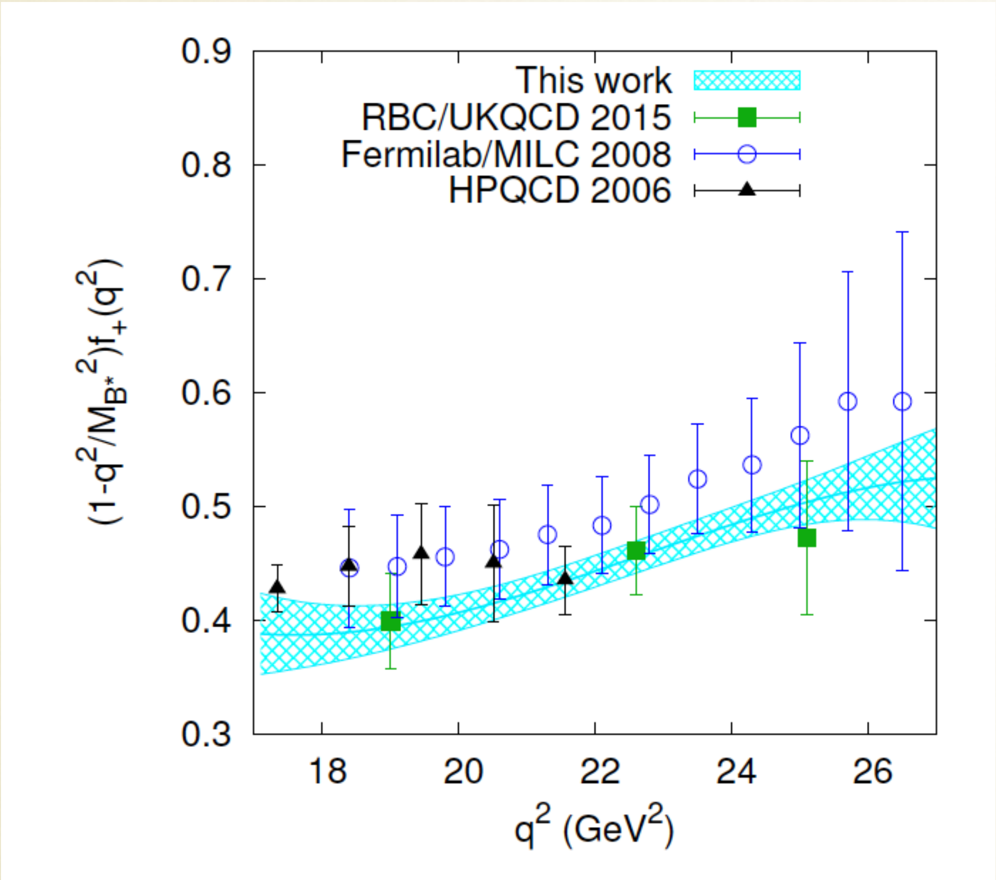
RBC/UKQCD $3.61(32)\ 10^{-3}$
1.9σ from inclusive

LCSR $3.32(26)\ 10^{-3}$
2.9σ from inclusive

LHCb depends
on V_{cb} employed

New lattice results

from 1503.07839



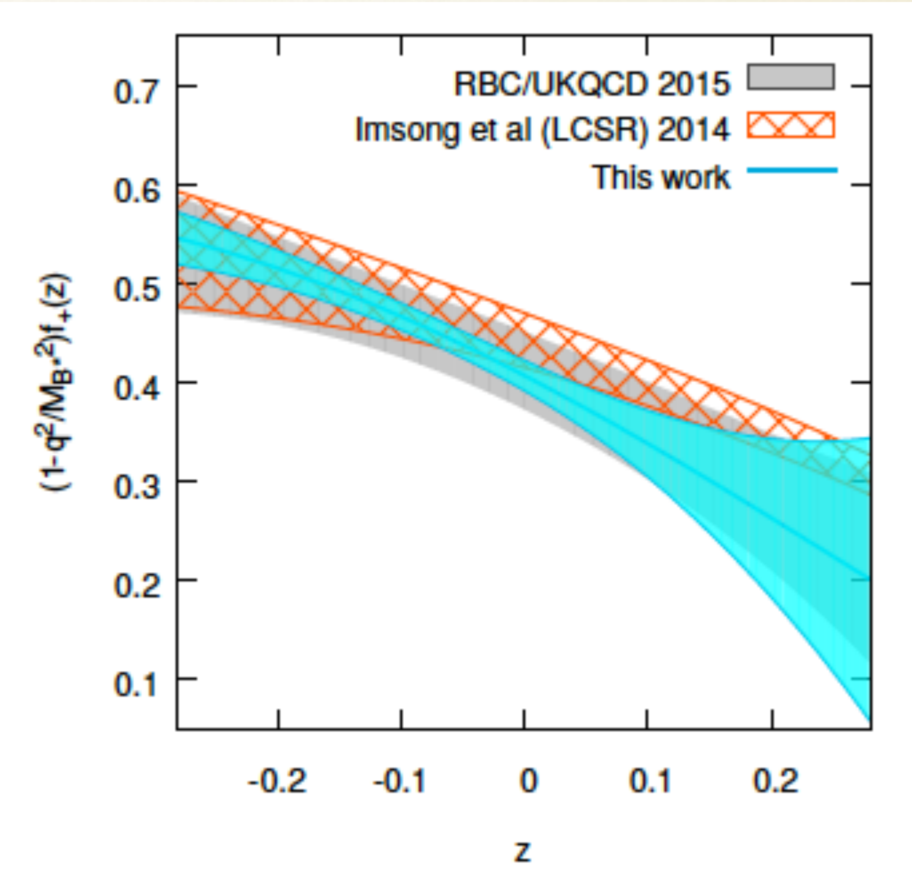


Table XVI. Results of the combined lattice+experiment fits with $N_z = 4$;.

Fit	χ^2/dof	dof	p value	b_0^+	b_1^+	b_2^+	b_3^+	$\lvert V_{ub}\rvert(\times 10^3)$
Lattice+exp.(all)	1.4	54	0.02	0.419(13)	−0.495(55)	−0.43(14)	0.22(31)	3.72(16)
Lattice+BaBar11 [7]	1.1	9	0.38	0.414(14)	−0.488(73)	−0.24(22)	1.33(44)	3.36(21)
Lattice+BaBar12 [8]	1.1	15	0.34	0.415(14)	−0.551(72)	−0.45(18)	0.27(41)	3.97(22)
Lattice+Belle11 [9]	0.9	16	0.55	0.412(13)	−0.574(65)	−0.40(16)	0.38(36)	4.03(21)
Lattice+Belle13 [10]	1.0	23	0.42	0.406(14)	−0.623(73)	−0.13(22)	0.92(45)	3.81(25)

New physics?

The difference in V_{cb} incl vs excl D^* with FNAL/MILC form factor is **quite large**: 3σ or about 8%. The perturbative corrections to inclusive V_{cb} total 5%, the power corrections about 4%.

Right Handed currents now excluded since

$$|V_{cb}|_{incl} \simeq |V_{cb}|\left(1 + \frac{1}{2}|\delta|^2\right)$$

$$|V_{cb}|_{B\to D^*} \simeq |V_{cb}|\left(1 - \delta\right)$$

$$|V_{cb}|_{B\to D} \simeq |V_{cb}|\left(1 + \delta\right)$$

Chen,Nam,Crivellin,Buras,Gemmler,Isidori,...

$$\delta = \epsilon_R \frac{\tilde{V}_{cb}}{V_{cb}} \approx 0.08$$

Most general SU(2) invariant dim 6 NP (without RH neutrino) can explain results, but it is incompatible with $Z\to b\bar{b}$ data

Crivellin, Pokorski 1407.1320

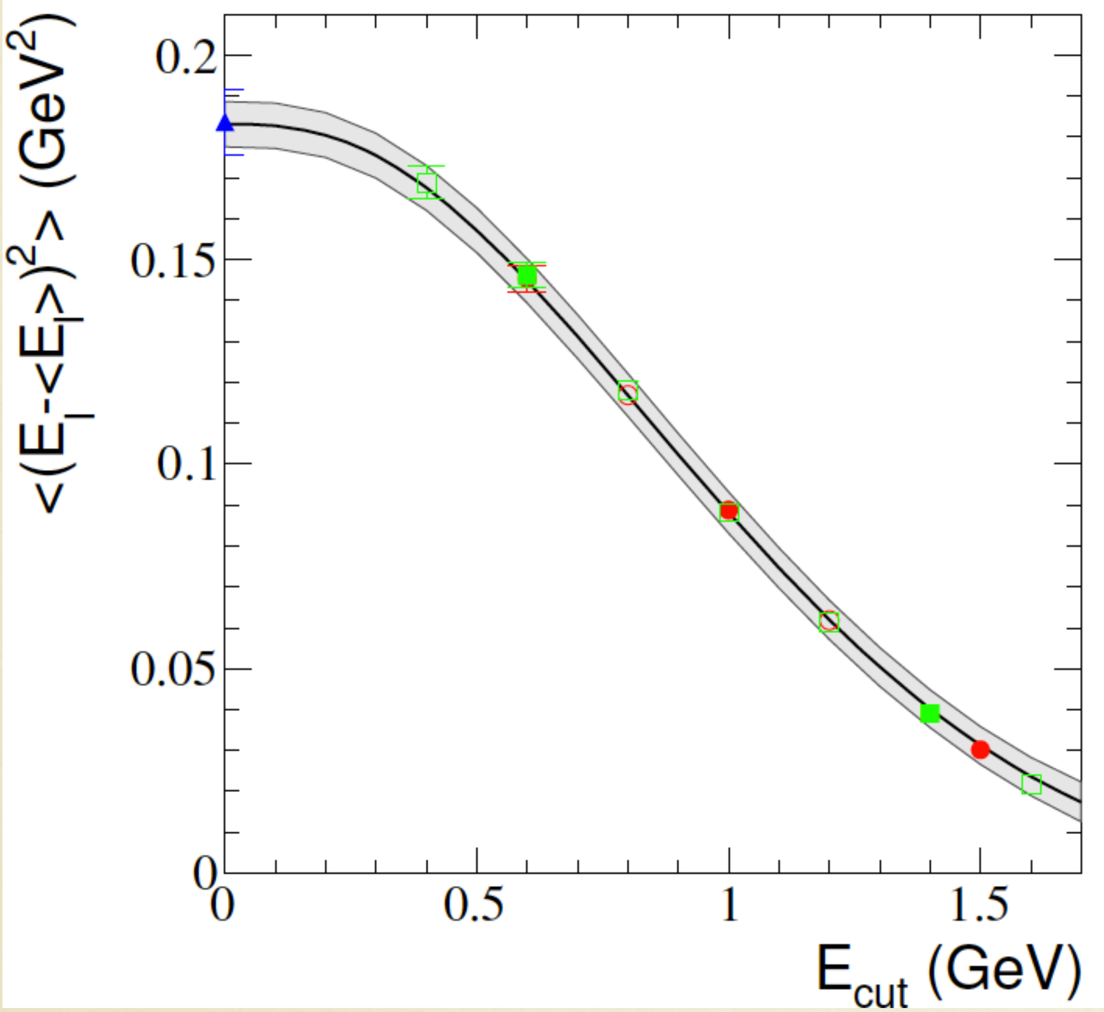
Explaining V_{ub} tension is easier

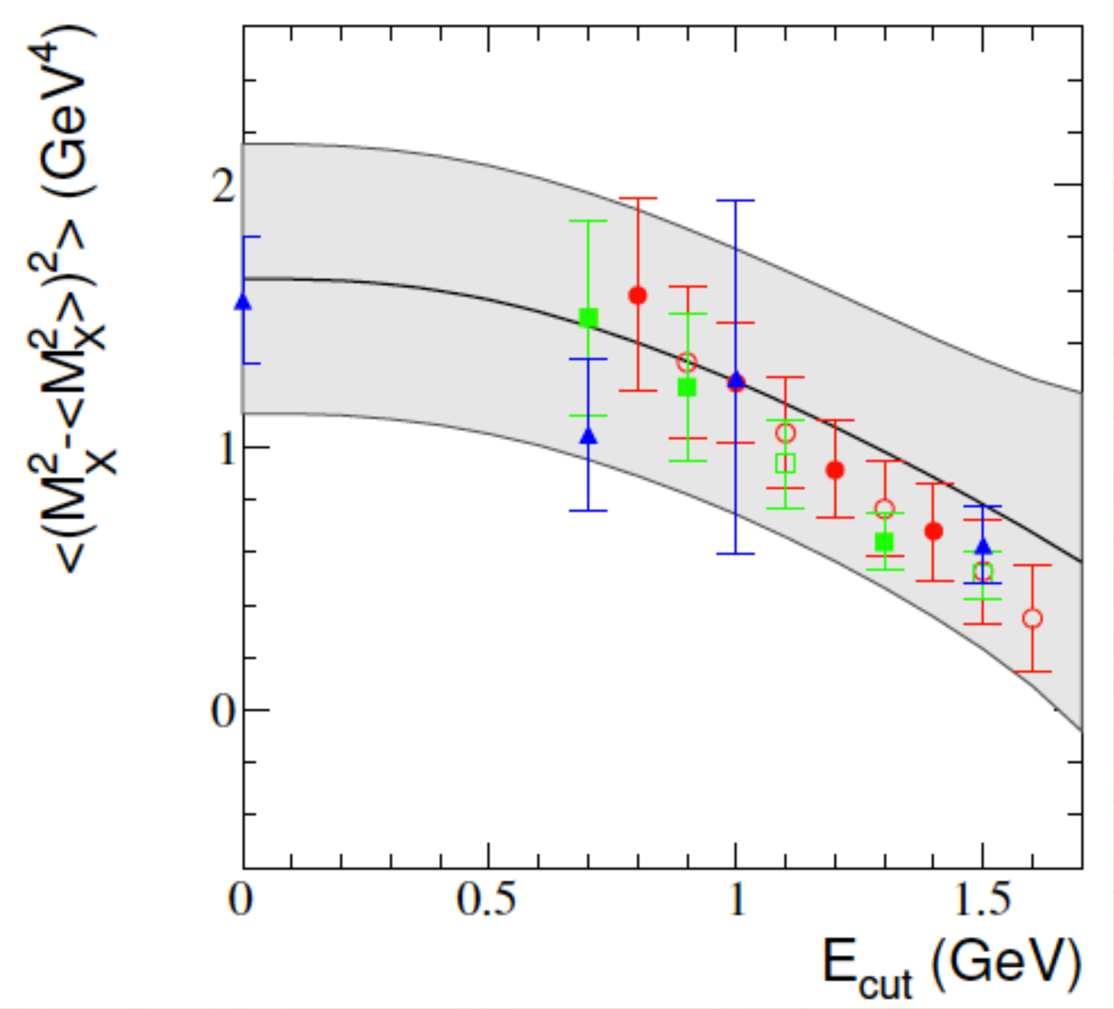
Summary

- **New twists in the V_{ub},V_{cb} saga!** Too early to draw conclusions though, we need more precise data and calculations.
- Improvements of OPE approach to semileptonic decays continue. All effects $O(\alpha_s \Lambda^2/m_b^2)$ implemented. **No sign of inconsistency in this approach so far**, **competitive m_b determination.**
- Exclusive/incl. tension in V_{cb} remains (3σ, 8%) only in the D* channel. The **D channel is becoming competitive and agrees with inclusive**. The remaining tension calls for new lattice analyses and probably for model independent reanalyses of B factories data.
- Exclusive/incl tension in V_{ub} slightly receding because of new FNAL/MILC result. New physics explanations less constrained than for V_{cb}.
- Belle-II will improve precision and allow for consistency checks of our methods, especially for inclusive V_{ub}.

BACK-UP SLIDES

Theoretical errors

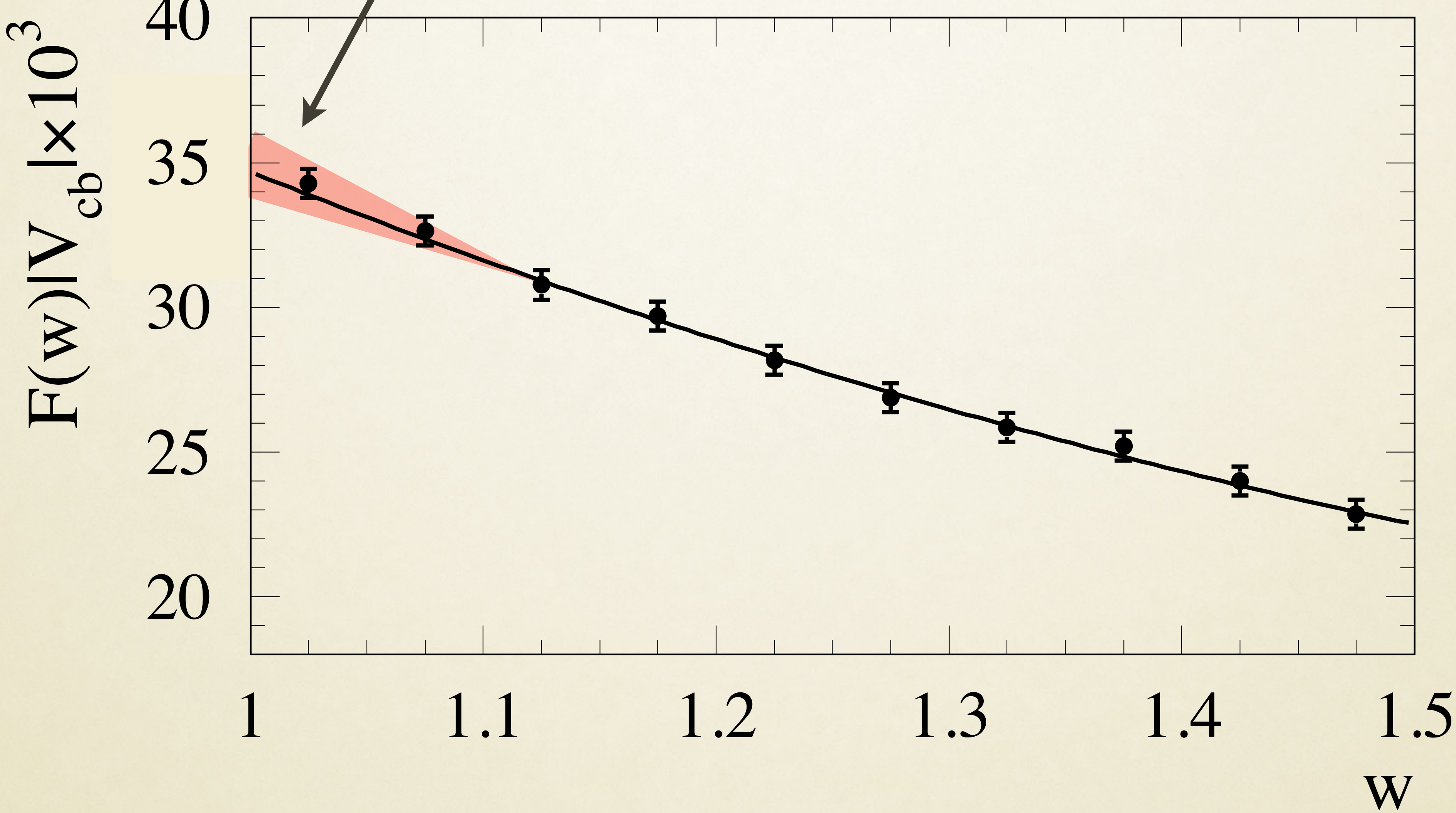




Theoretical errors are generally the **dominant** ones in the fits.
We estimate them in a **conservative** way, mimicking higher orders by varying the parameters by fixed amounts: $m_{c,b}$ 8MeV, $\alpha_s(m_b)$ 0.018, 7% in $1/m^2$ parameters, 30% in $1/m^3$ parameters

New corrections have been within theor. uncertainties so far.

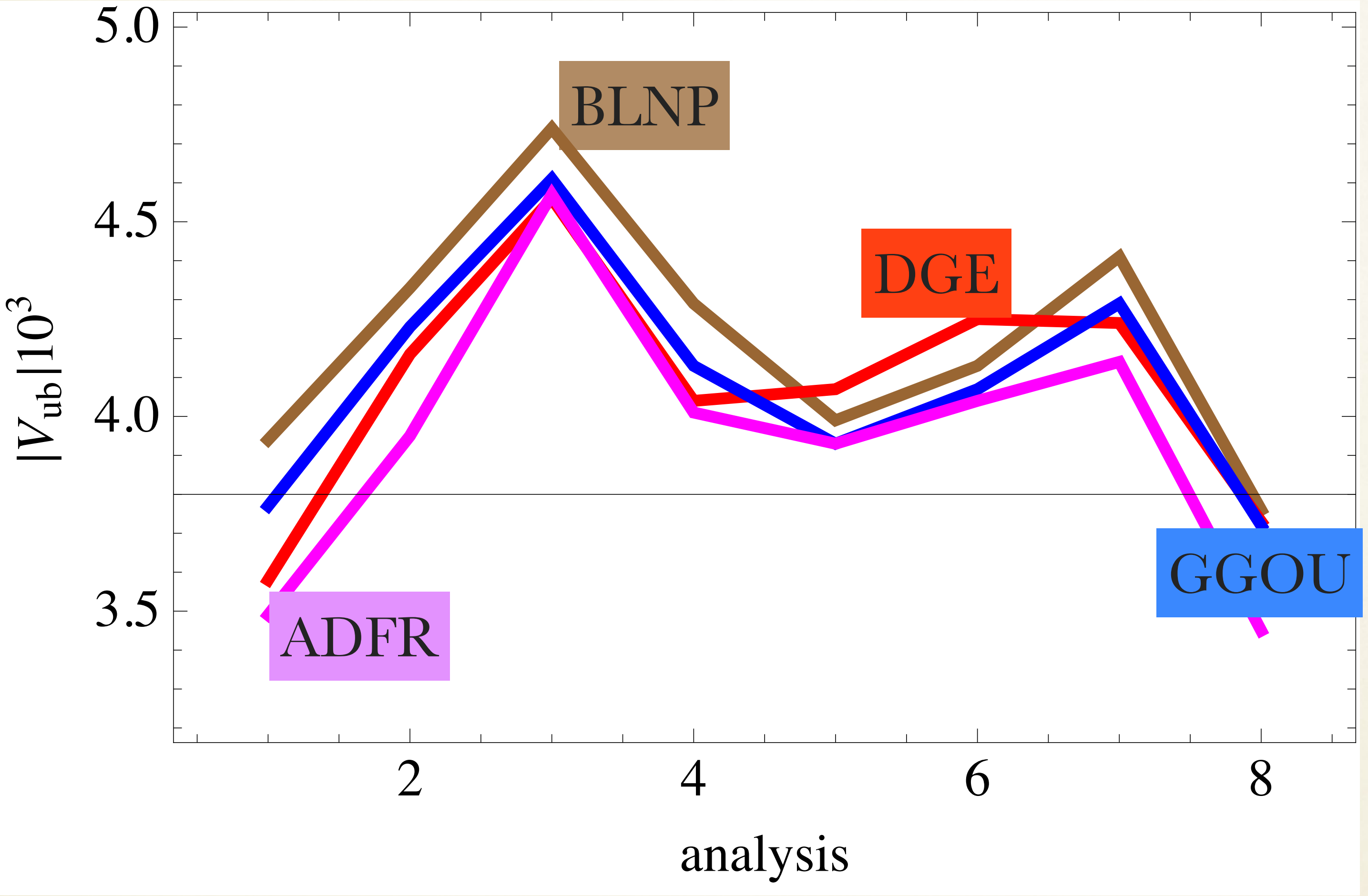
Extrapolation to zero recoil,
possible parameterization effect (qualitative picture)



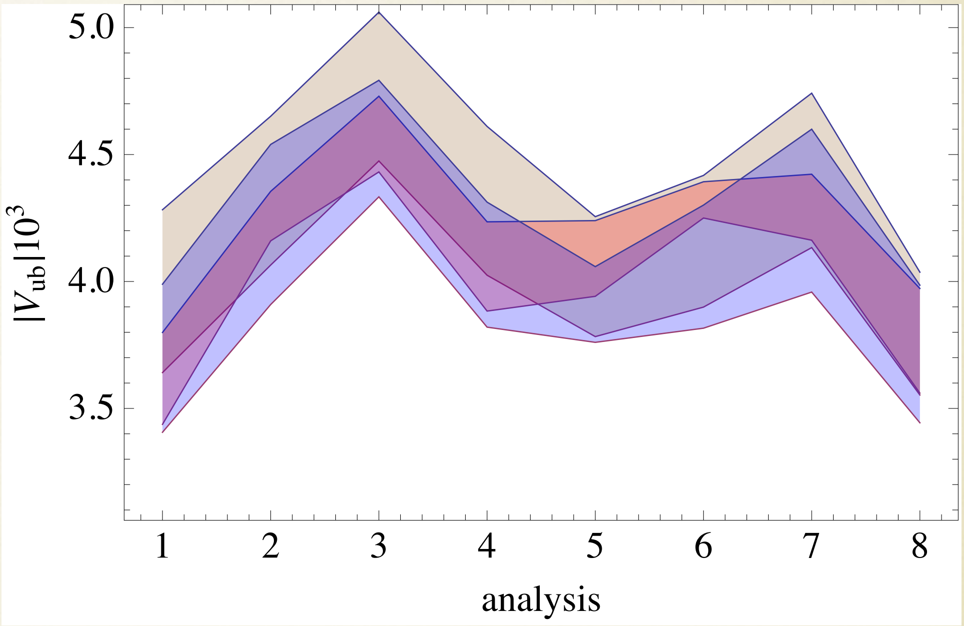
Babar form factor shape from 0705.4008

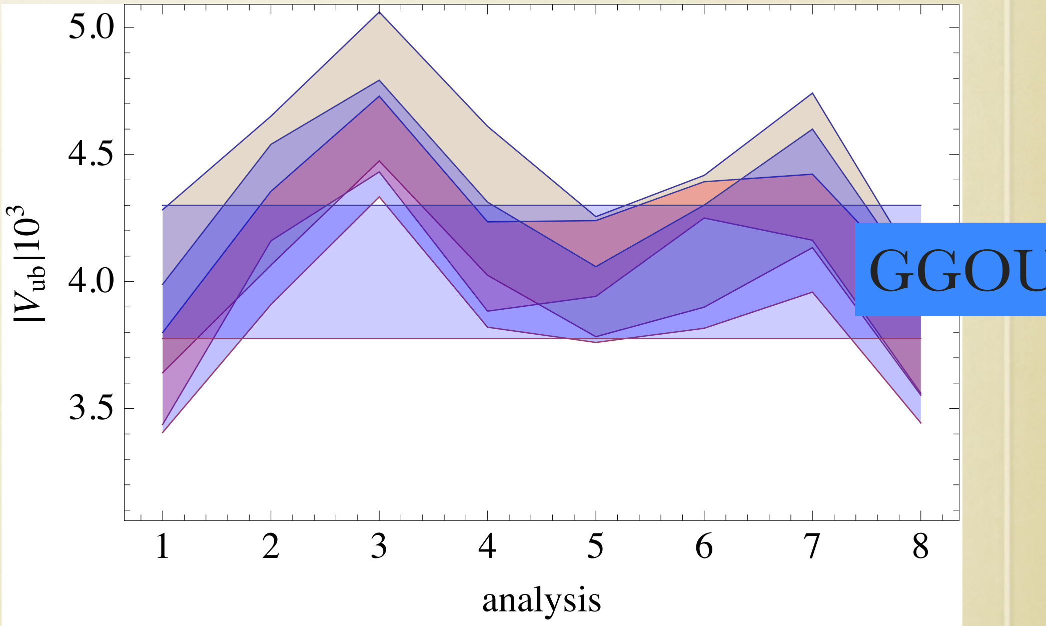
A global comparison

0907.5386, Phys Rept



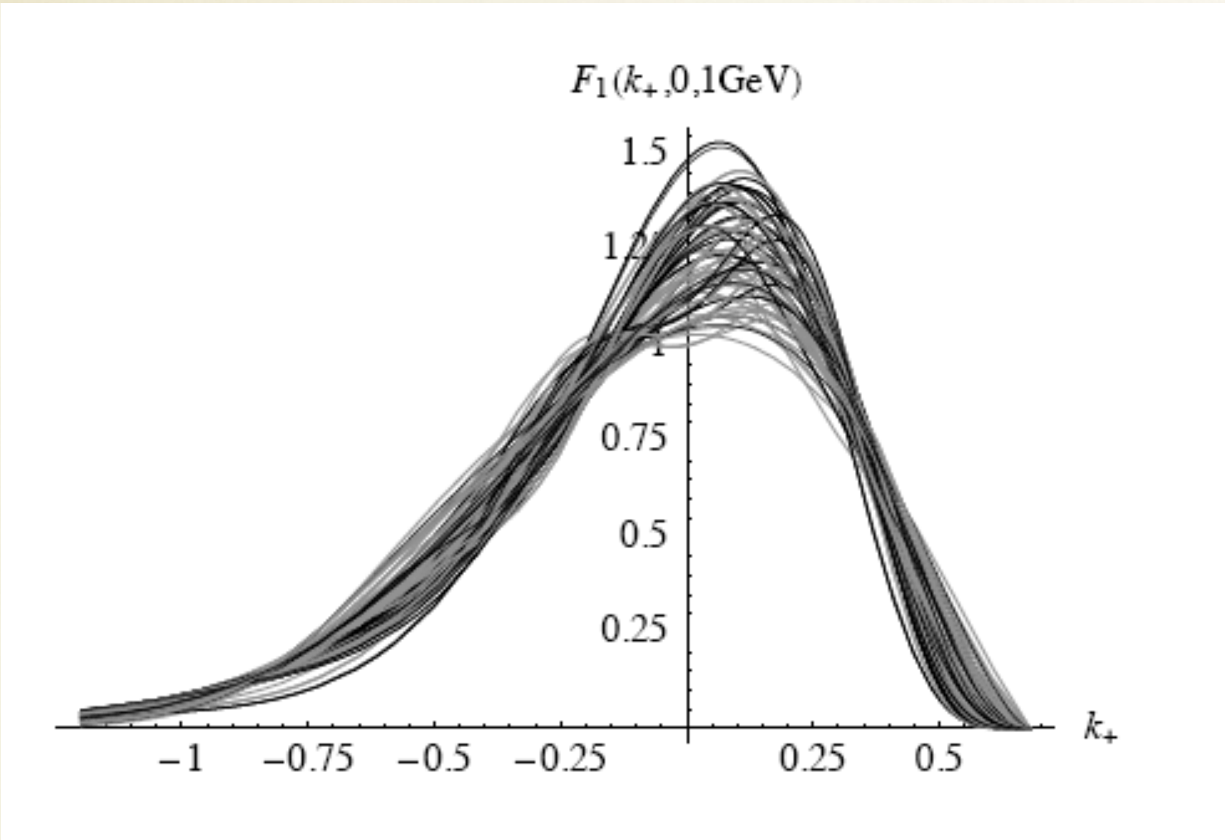
only theory errors
(without common parametric)

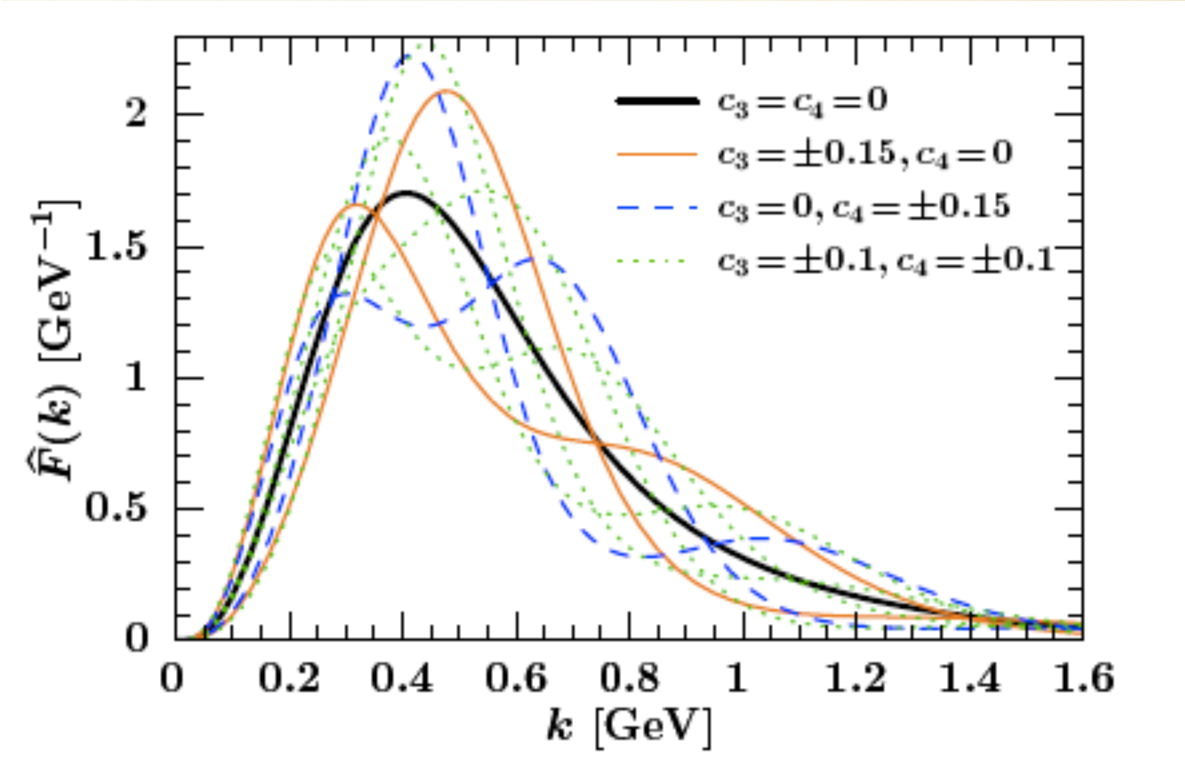




- common inputs (except ADFR)
- Overall good agreement **SPREAD WITHIN THEORY ERRORS**
- NNLO BLNP still missing: will push it up a bit
- Systematic offset of central values: normalization? to be investigated

Functional forms





About 100 forms considered in GGOU, large variety, double max discarded. Small uncertainty (1-2%) on V_{ub}

A more systematic method by Ligeti et al. arXiv:0807.1926 Plot shows 9 SFs that satisfy all the first three moments

Higher power corrections

Mannel,Turczyk,Uraltsev **1009.4622**

Proliferation of non-pert parameters and powers of $1/m_c$ starting $1/m^5$. At $1/m_b{}^4$

$$2M_B m_1 = \langle ((\vec p)^2)^2 \rangle$$
$$2M_B m_2 = g^2 \langle \vec E^2 \rangle$$
$$2M_B m_3 = g^2 \langle \vec B^2 \rangle$$
$$2M_B m_4 = g \langle \vec p \cdot \mathrm{rot}\, \vec B \rangle$$

$$2M_B m_5 = g^2 \langle \vec S \cdot (\vec E \times \vec E) \rangle$$
$$2M_B m_6 = g^2 \langle \vec S \cdot (\vec B \times \vec B) \rangle$$
$$2M_B m_7 = g \langle (\vec S \cdot \vec p)(\vec p \cdot \vec B) \rangle$$
$$2M_B m_8 = g \langle (\vec S \cdot \vec B)(\vec p)^2 \rangle$$
$$2M_B m_9 = g \langle \Delta(\vec \sigma \cdot \vec B) \rangle$$

can be estimated by **Lowest Lying State Saturation** approx by truncating

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

In LLSA ***good convergence*** of the HQE. First fit with $1/m^{4,5}$:

$$\frac{\delta V_{cb}}{V_{cb}} \simeq -0.35\%$$

Turczyk,PG preliminary

Heinonen,Mannel 1407.4384 have more systematic approach

LLSA might set the scale of effect, not yet clear *how much it depends on assumptions on expectation values.* Large corrections to LLSA have been found.

Mannel, Uraltsev, PG, 2012

Allowing 80% gaussian deviations from LLSA seem to leave V_{cb} unaffected.