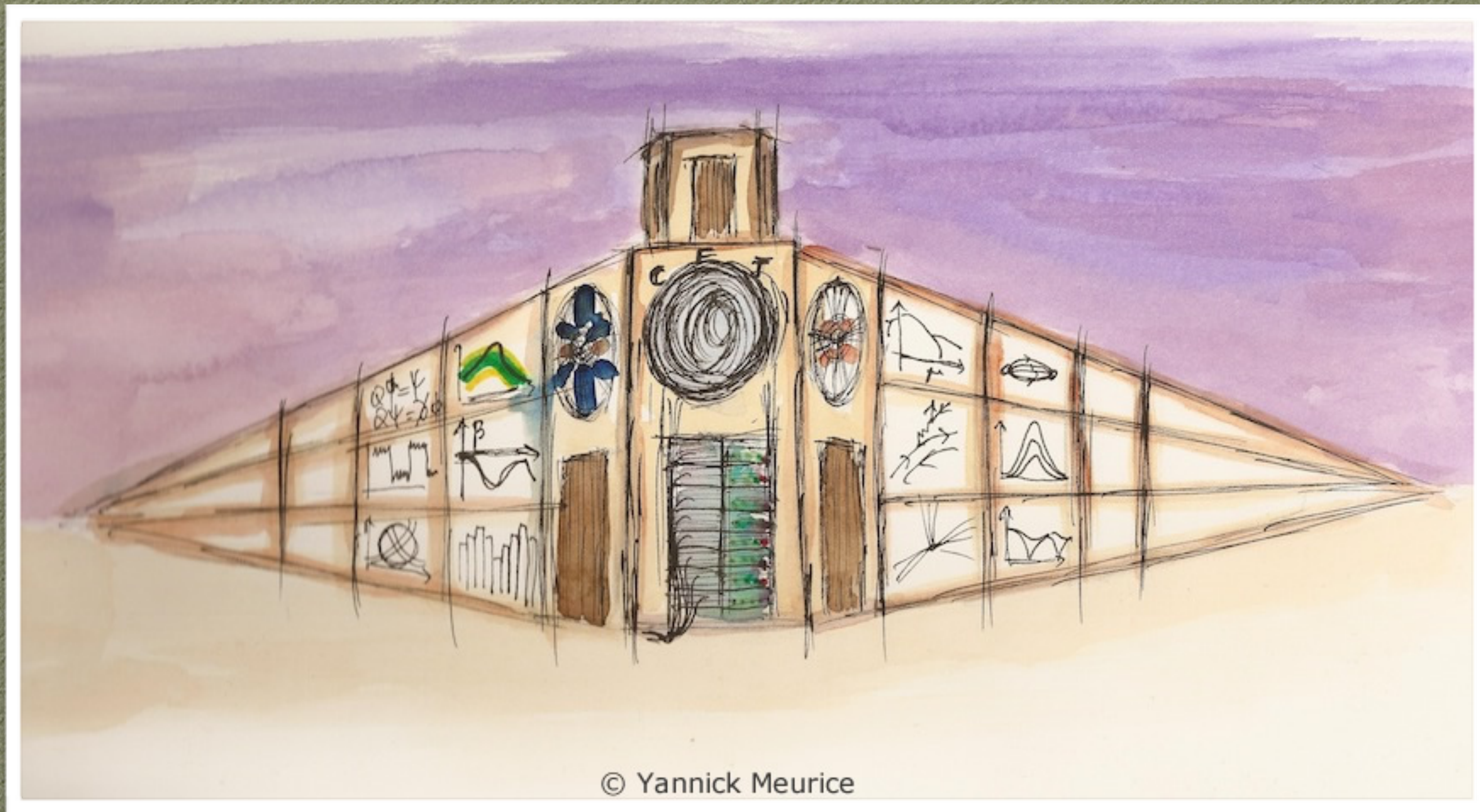


ISSUES IN SEMILEPTONIC B DECAYS

PAOLO GAMBINO
UNIVERSITÀ DI TORINO & INFN

KITP UCSB, 12 AUGUST 2015

Executive Summary of the mitp topical Workshop

Challenges in Semileptonic B decays

April 20-24, 2015, JGU Campus Mainz

Organized by

Paolo Gambino (Turin Univ.), Andreas Kronfeld (Fermilab), Marcello Rotondo (INFN Padua), Christoph Schwanda (Vienna), Sascha Turczyk (JGU Mainz)

V_{ub} & V_{cb} SAGA
EPIC ADVENTURE

IMPORTANCE OF $|V_{xb}|$

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

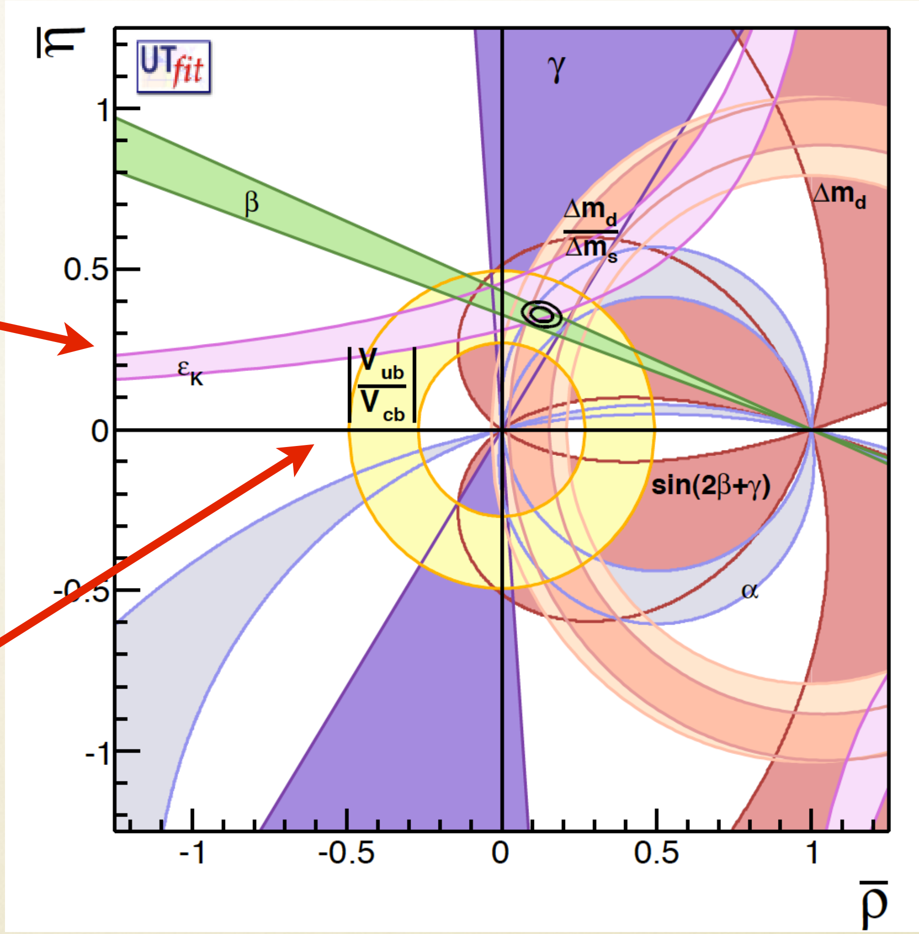
$$\varepsilon_K \approx x|V_{cb}|^4 + ...$$

and in the prediction of FCNC:

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

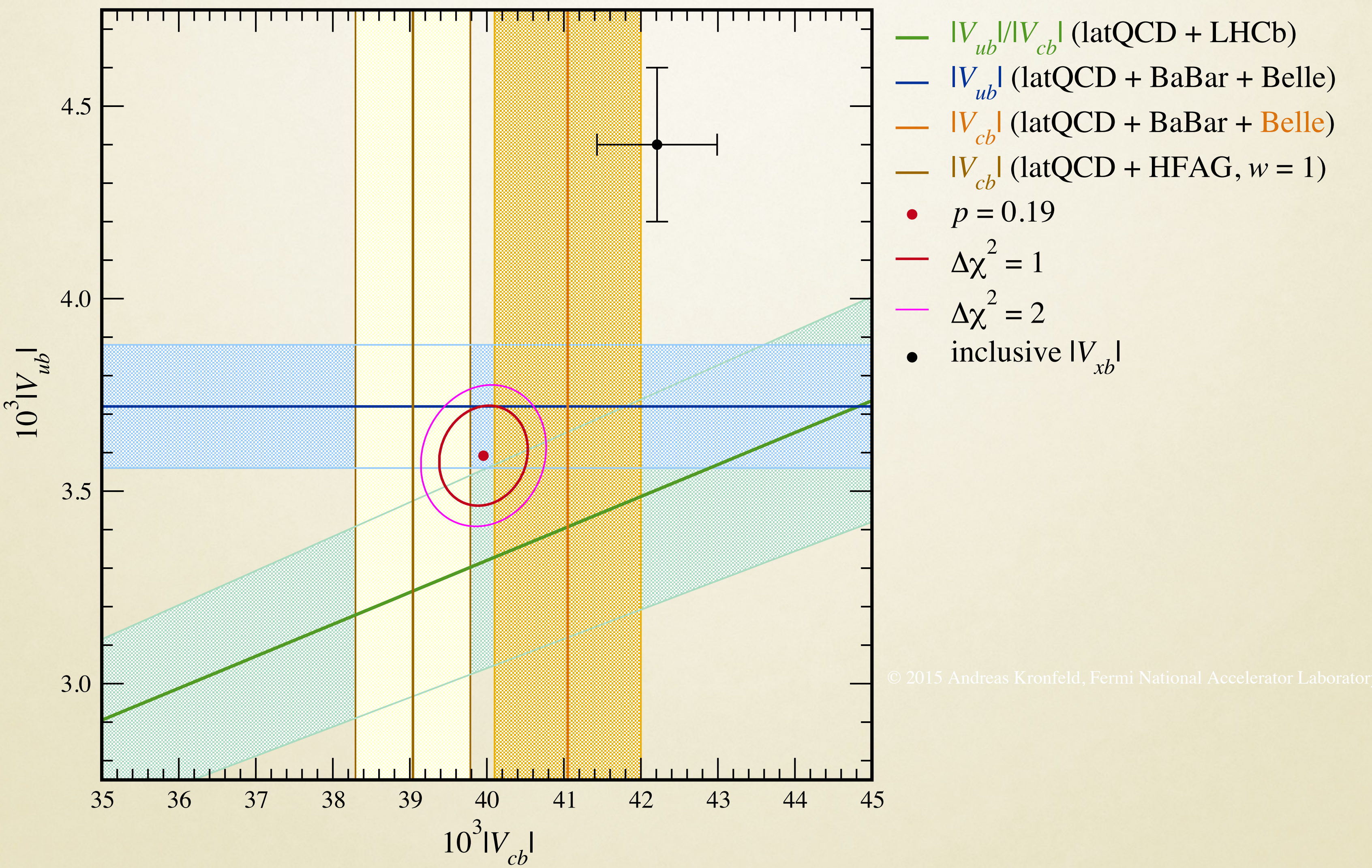
where it often dominates the theoretical uncertainty.

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

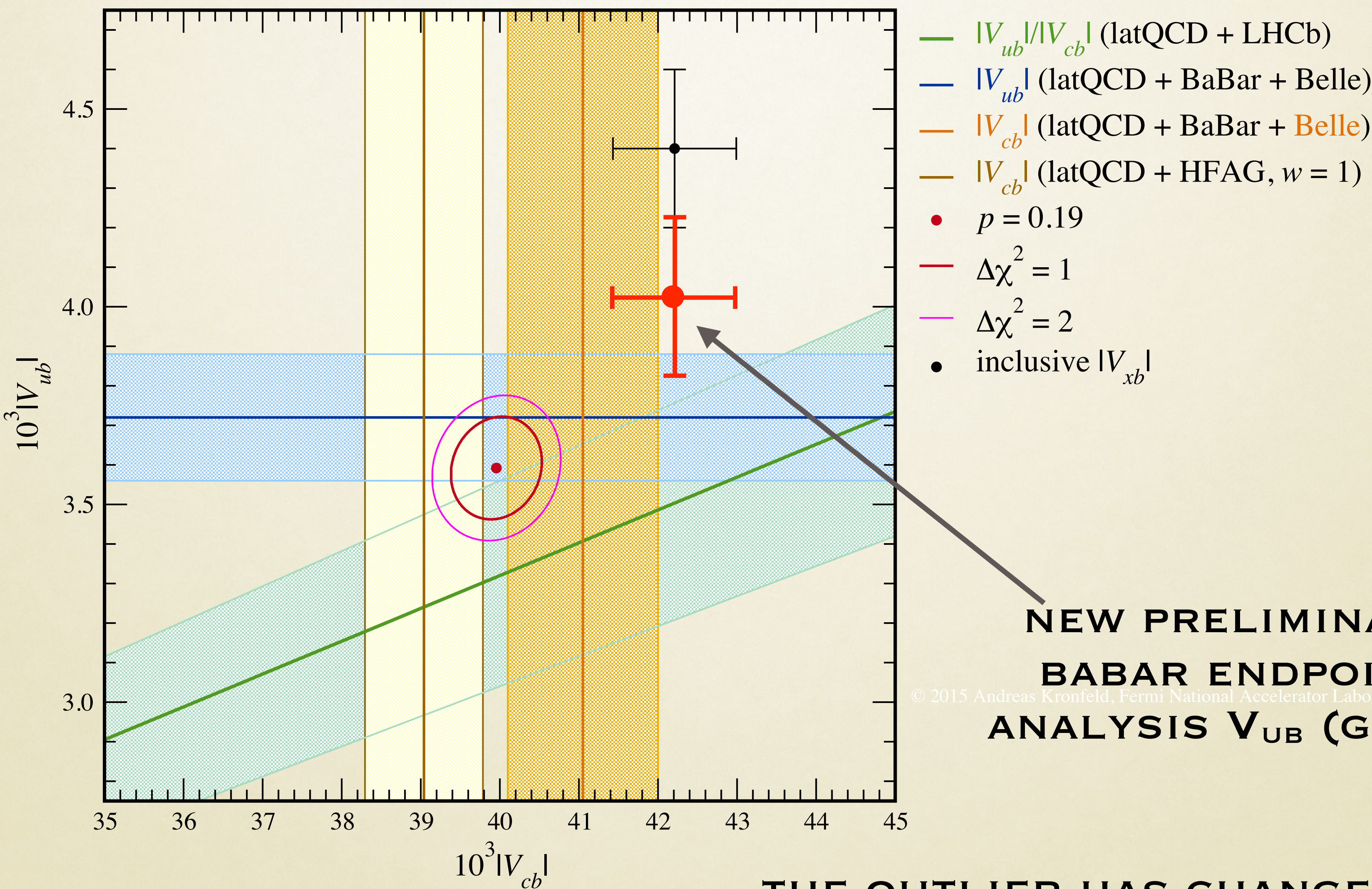


Since several years, exclusive decays prefer smaller $|V_{ub}|$ and $|V_{cb}|$

A simplistic picture?



A simplistic picture?

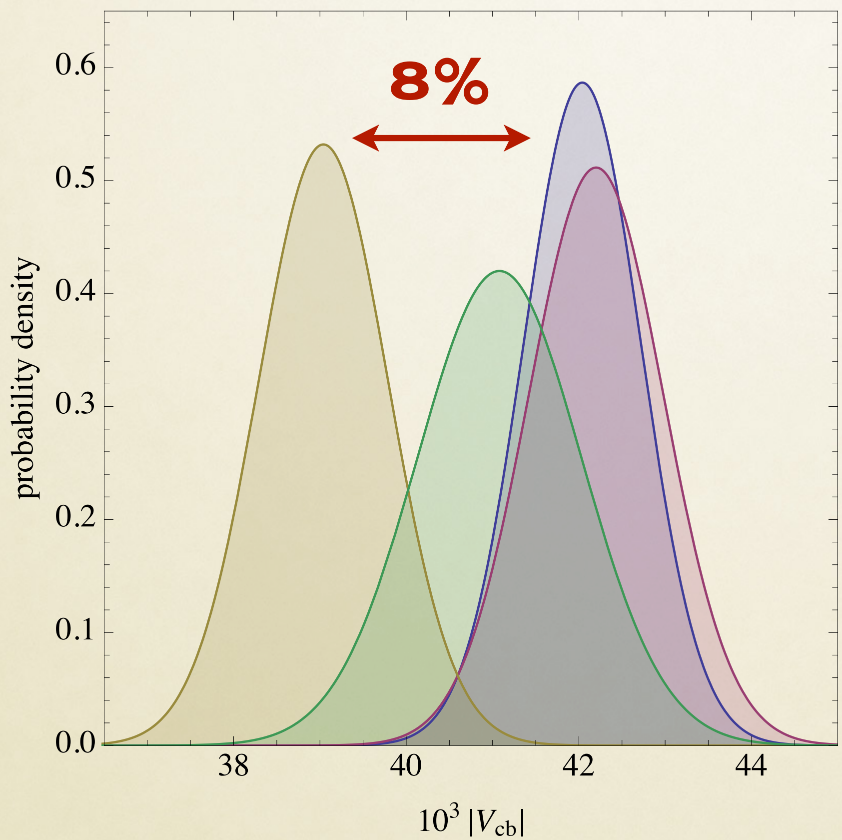


NEW PRELIMINARY BABAR ENDPOINT ANALYSIS V_{UB} (GGOU)

THE OUTLIER HAS CHANGED

V_{cb} SUMMARY

Exclusive B→D Exclusive B→D* Inclusive UTfit SM prediction: (42.04±0.68) 10^{-3}



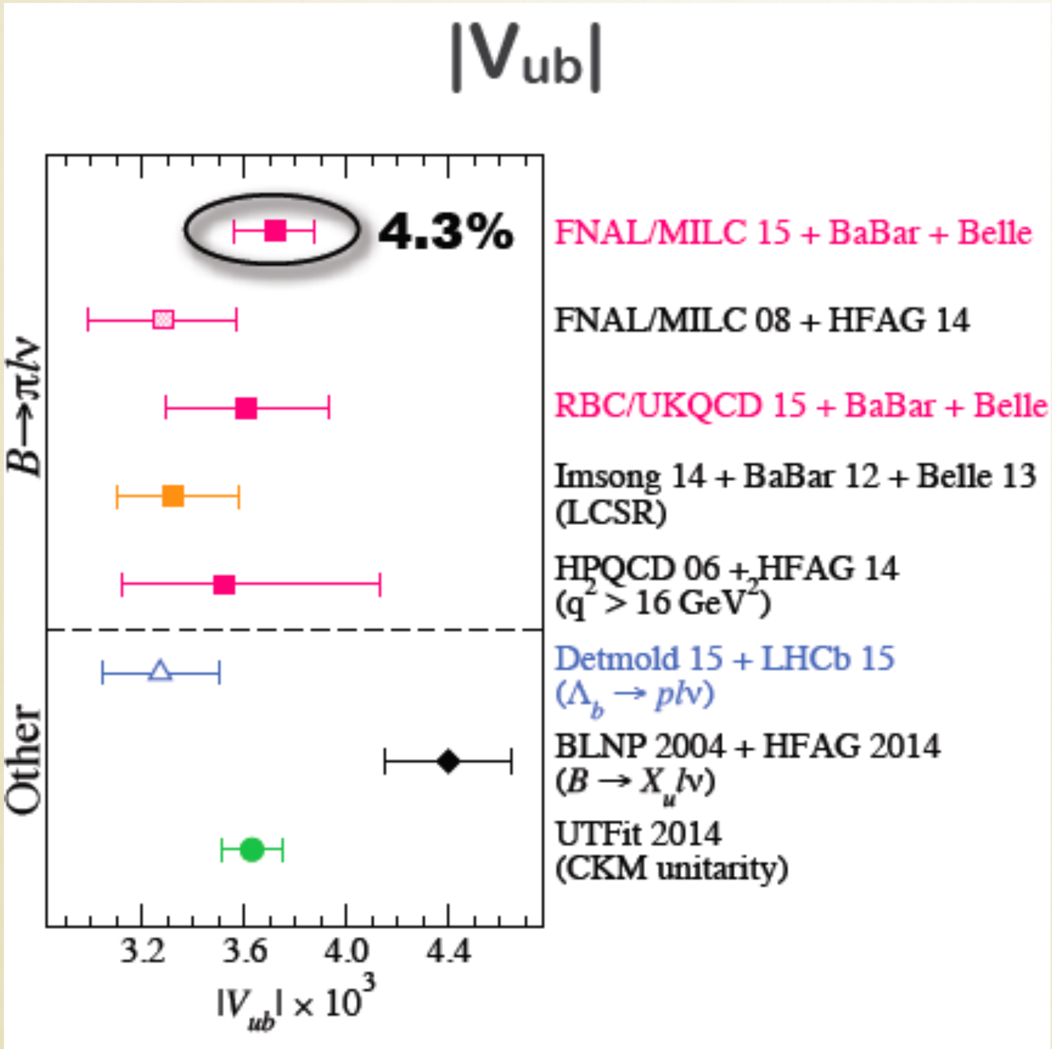
form factors from HQSR,HQE,LCSR for exclusives also available but less precise

HQSR lead to ~5% higher V_{cb} from $B \to D^*$

Mannel, Uraltsev, PG

New Belle B→D analysis + latest lattice results (FNAL/MILC+HPQCD) at non-zero recoil !

V_{ub} SUMMARY



Latest lattice results (FNAL/MILC+RBC/UKQCD) prefer higher V_{ub}

LHCb measures V_{ub}/V_{cb} but prefers lowish V_{ub}

New Babar precise endpoint analysis prefers lower V_{ub}

$4.03(16)(11)\ 10^{-3}$ (GGOU)

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,...

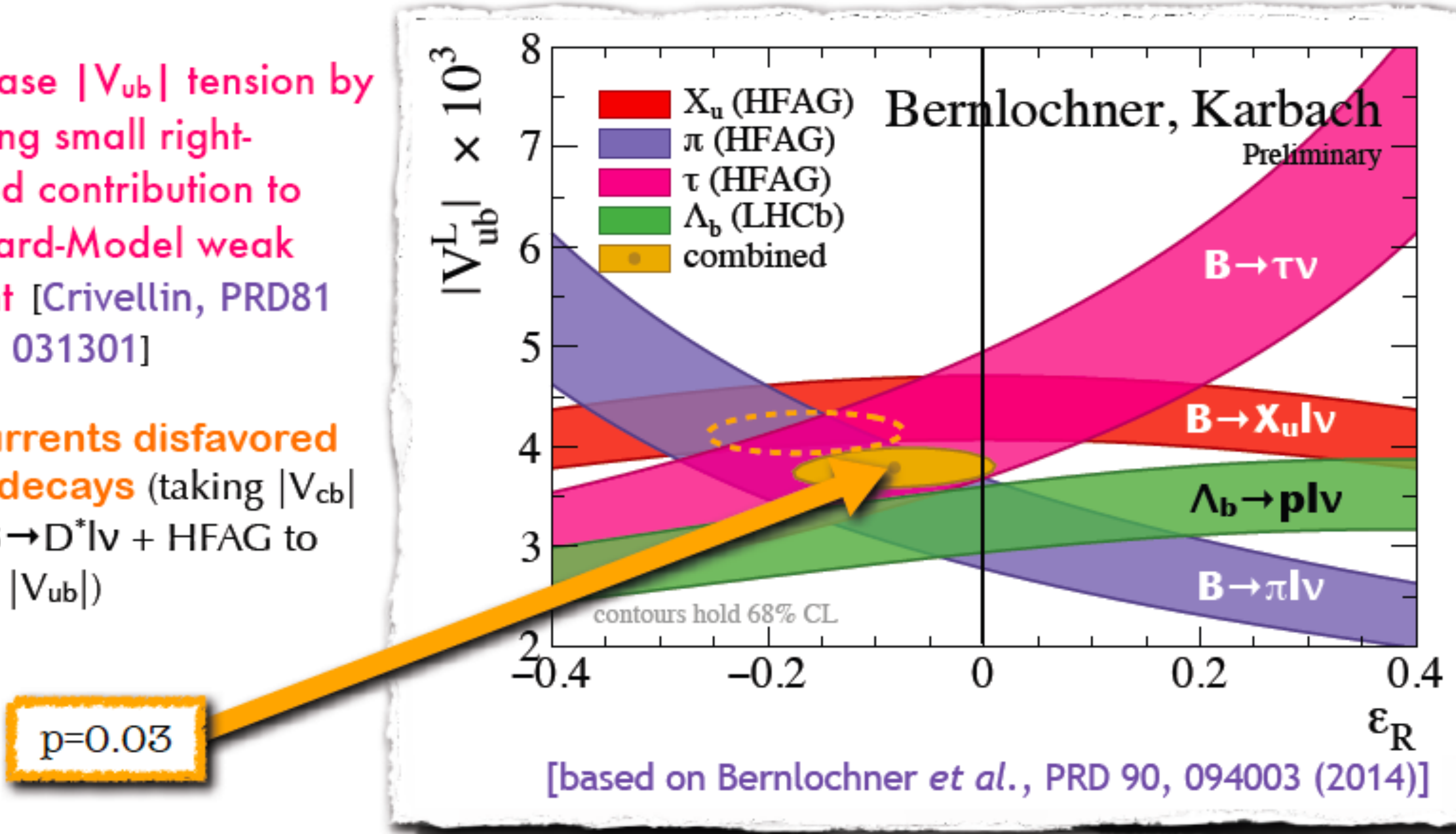
$$\delta = \epsilon_R \frac{\tilde{V}_{cb}}{V_{cb}} \approx 0.08$$

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

NEW PHYSICS?

- Can ease $|V_{ub}|$ tension by allowing small right-handed contribution to Standard-Model weak current [Crivellin, PRD81 (2010) 031301]
- RH currents disfavored by Λ_b decays (taking $|V_{cb}|$ from $B\to D^*l\nu$ + HFAG to obtain $|V_{ub}|$)



[based on Bernlochner *et al.*, PRD 90, 094003 (2014)]

R. van de Water

New HFAG average of R(D) and R(D*)

$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}$$

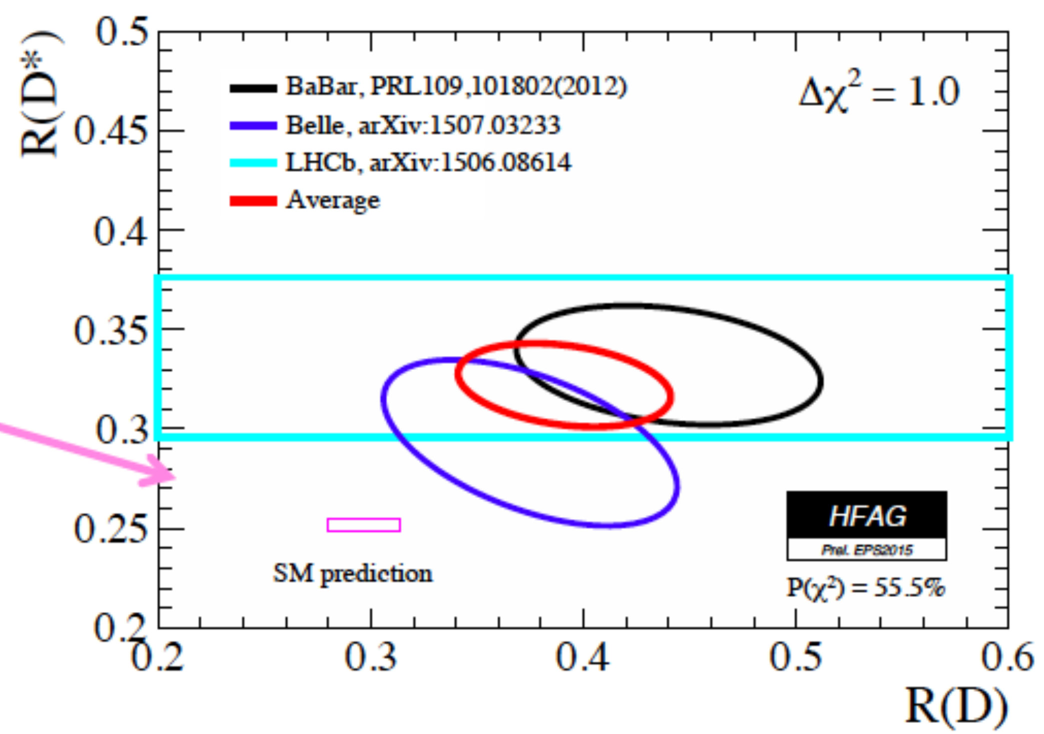
SM predictions

R(D*)=0.252 ±0.003

*PRD **85** (2012) 094025*

R(D) =0.297 ±0.017

*PRD **78** (2008) 014003*



HFAG average

R(D*)= 0.322 ± 0.018 ± 0.012

R (D) = 0.391 ± 0.041 ± 0.028

Corr (D,D*)= − 0.29

- Difference with the SM predictions at 3.9 σ level.

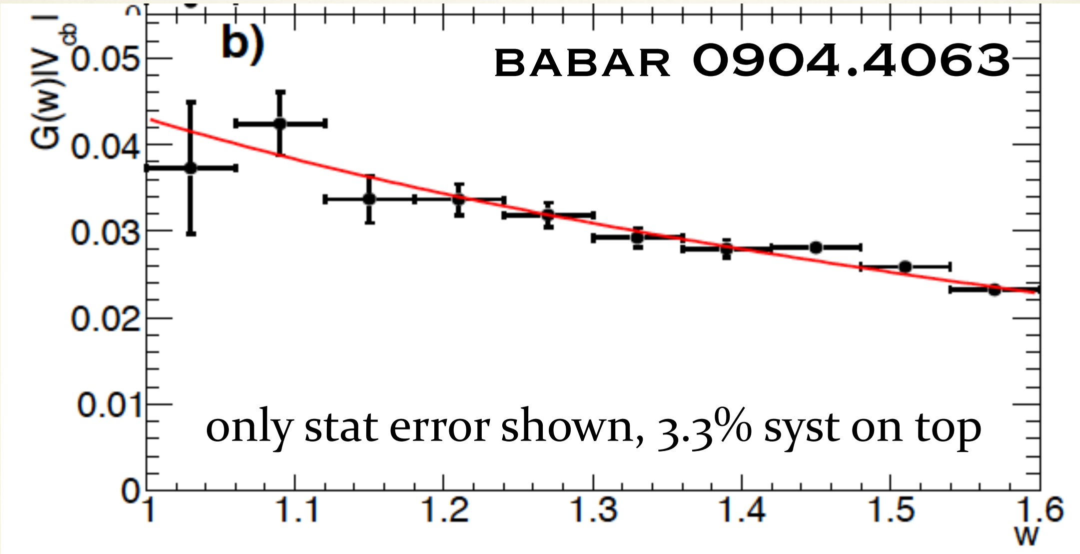
DISCUSSION

Great recent progress but still tensions, NP unlikely.

A. How can exclusive can be improved?
 a closer look at $B \to D$ may be useful

B. How can inclusive can be improved?
 (how can lattice help continuum?)

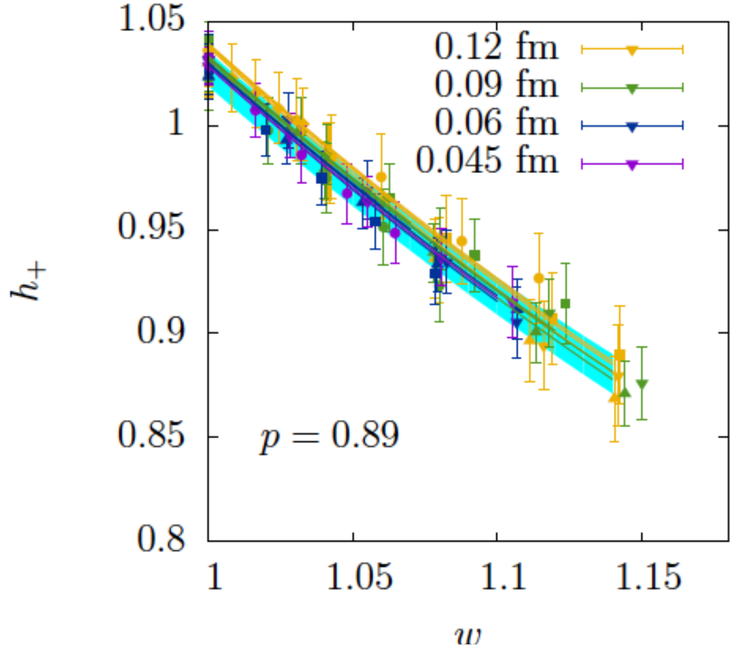
PROGRESS IN B→Dlν



- First calculation at non-zero recoil by FNAL/MILC
- First unquenched non FNAL/MILC calculation by HPQCD
- New Belle analysis with full statistics, reported in a model independent way (no CLN or else) at EPS-HEP 2015

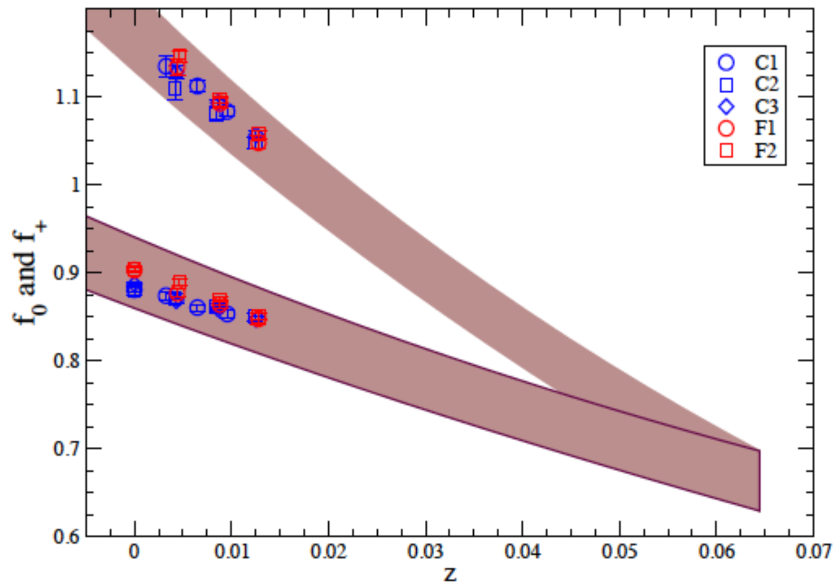
NEW RESULTS FOR $B \to Dl\nu$ F.F.

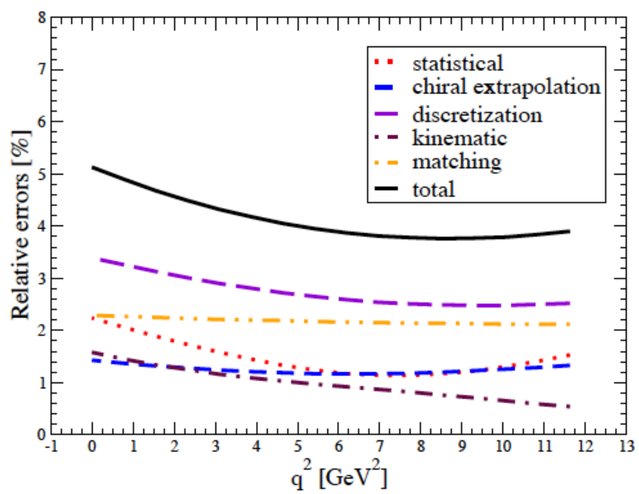
FNAL/MILC 1503.07237



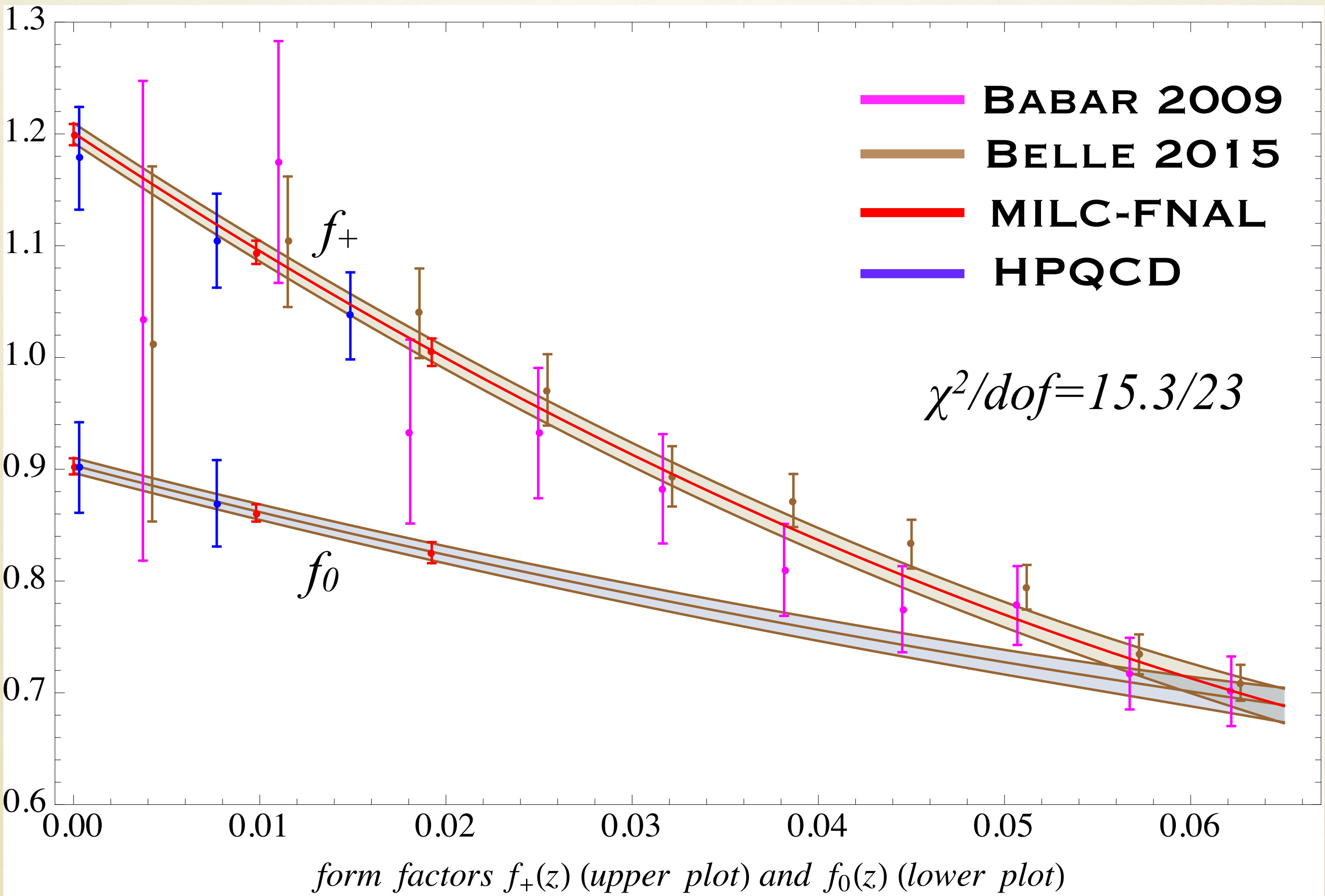
Source	$f_+(\%)$
Statistics+matching+χPT cont. extrap.	1.2
(Statistics)	(0.7)
(Matching)	(0.7)
(χPT/cont. extrap.)	(0.6)
Heavy-quark discretization	0.4
Lattice scale r_1	0.2
Total error	1.2

HPQCD 1505.03925





Global fit to B→Dlν



A Global fit to B→Dlν

- **$|V_{cb}|$=41.09(95) 10^{-3}** p-value: 0.88
- based on z-expansion with unitarity constraints (BGL, N=2)
- BGL N=3: 40.87(98) 10^{-3} p-value: 0.88
  only FNAL 40.79(1.07) (N=3) 40.87(1.04) (N=2)
- assumes no correlation between FNAL and HPQCD, 3.3% syst error on Babar data, correct treatment of last bin, no finite size bin effect
- little dependence on parameterization (CLN gives 41.03(97) 10^{-3}) if lattice data at non-zero recoil are included
- **Non-zero recoil data are <u>crucial</u>:** only zero recoil leads to $|V_{cb}|$=39.8(1.1)10^{-3} (CLN) 39.6(1.9) (BGL,N=2)...
- R(D)=0.302(9) (preliminary) 1.8σ from recent HFAG average

ISSUES IN EXCLUSIVES

- Most experimental $B \to D^{(*)}$ results tied up with CLN…
- Is there anything we don't know yet about **z-expansions**? (e.g. for Λ_b, or its relation to continuum and chiral limit)
- Need for checks and extension of **$B \to D^*$ ff** to non-zero recoil. Matching at $1/m_Q^3$ for lattice discretization effects under study by FNAL/MILC. Simulations at physical pion mass and $m_b\, a \lesssim 1$?
- **QED/EW corrections**: SD log (Sirlin factor, 0.7%) OK, SD remainder tiny if G_μ employed, soft/collinear radiation subtracted out by Photos, intermediate photons (IR finite) are structure dependent: lattice calculations? exp cuts?
- relevance of Coulomb enhancement for B^0 decays?

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

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

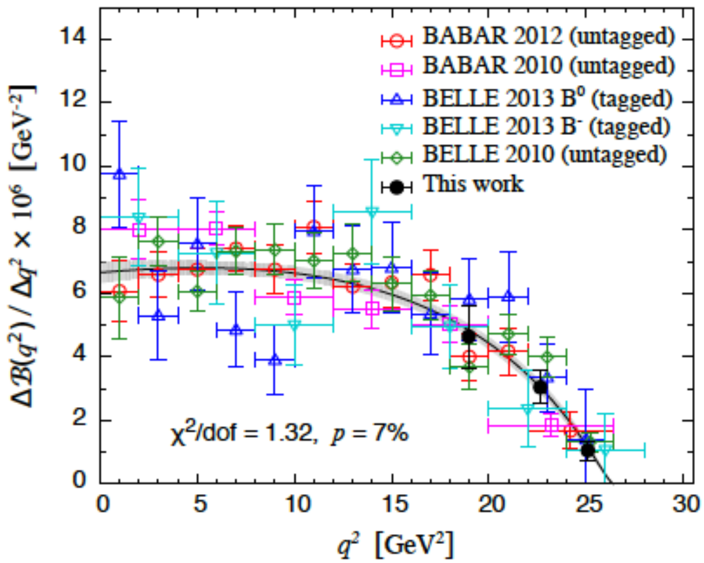
Lattice Group	Fermilab/MILC	HPQCD	RBC/UKQCD	Alpha	Detmold et al.
Process	$B \to \pi\ell\nu$	$B_s \to K\ell\nu$	$B \to \pi\ell\nu$	$(B_s \to K\ell\nu)$	$\Lambda_b \to p\ell\nu$
	$(B_s \to K\ell\nu)$	$(B \to \pi\ell\nu)$	$B_s \to K\ell\nu$		
Gauge ensembles	MILC asqtad	MILC asqtad	Domain-Wall	CLS	Domain-Wall
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:1406.2279	arXiv:1501.05373v2	arXiv:1411.3916	arXiv:1306.0446
	arXiv:1312.3197				arXiv:1503.01421v2
					arXiv:1504.01568

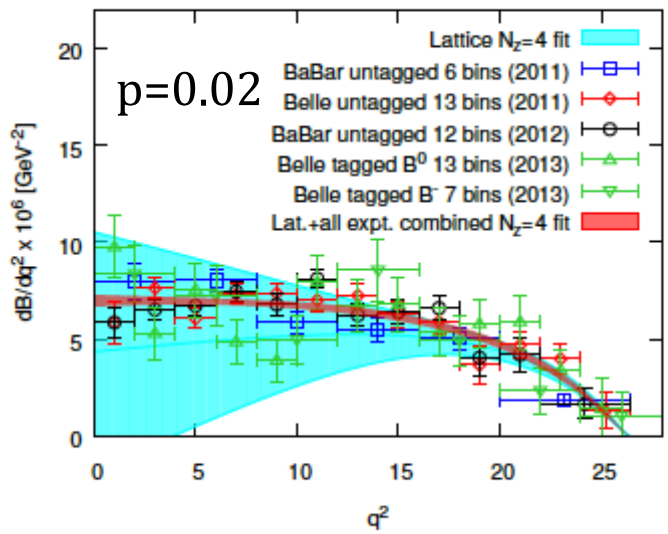
- (): work in progress

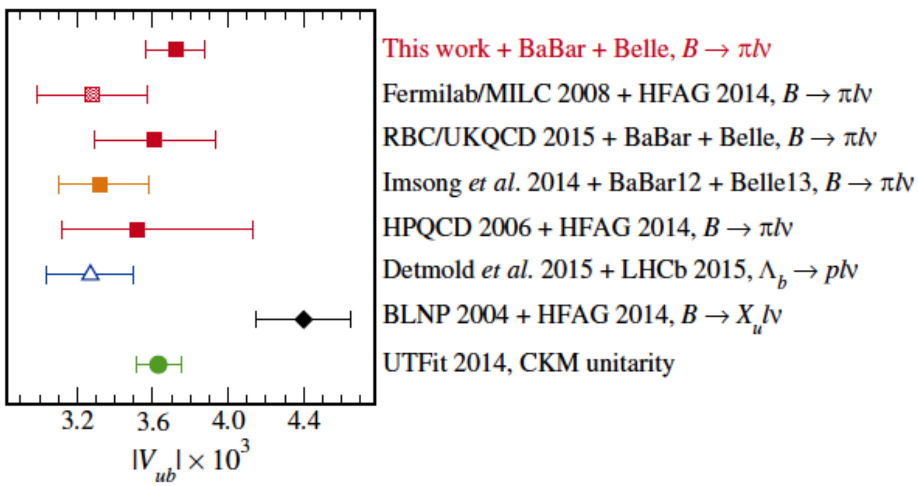
Du, MITP workshop, April 2015

New lattice results

RBC/UKQCD 1501.05373 **FNAL/MILC 1503.07839**



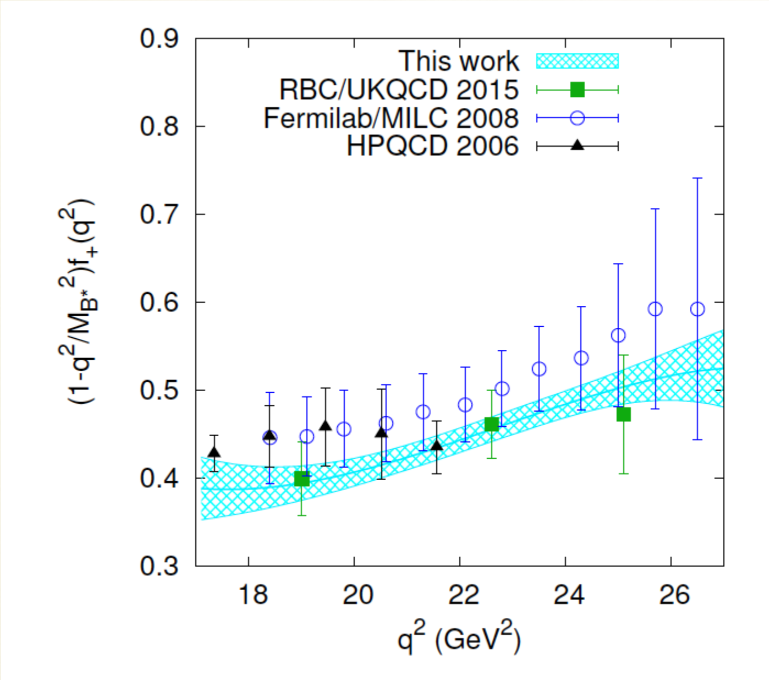




FNAL 3.72(16) 10^{-3}
only 4.3% error
2.2σ from inclusive
RBC/UKQCD 3.61(32) 10^{-3}
1.9σ from inclusive
LCSR 3.32(26) 10^{-3}
2.9σ from inclusive
LHCb depends
on V_{cb} employed

New lattice results

from 1503.07839



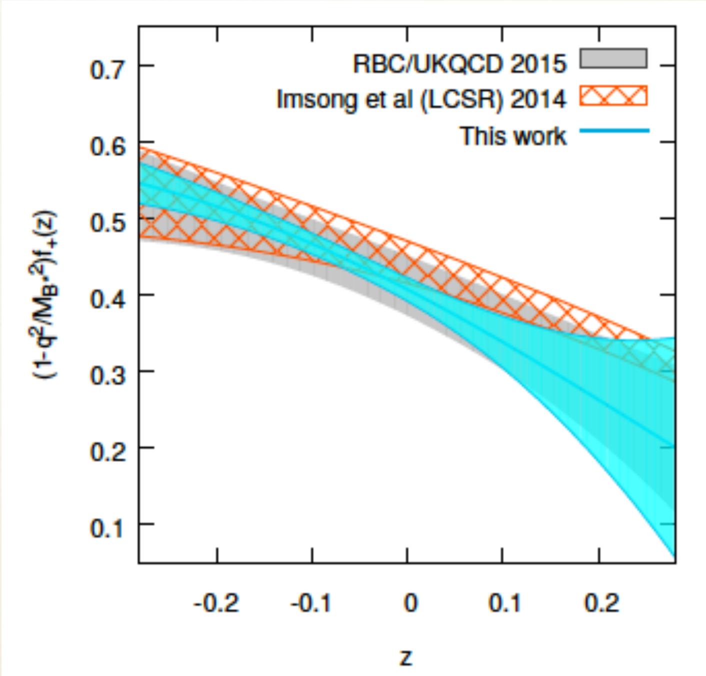


Table XVI. Results of the combined lattice+experiment fits with $N_z = 4$;.

Fit	χ^2/dof	dof	p value	b_0^+	b_1^+	b_2^+	b_3^+	$\|V_{ub}\|(\times 10^3)$
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)

Inclusive semileptonic B decays

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

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

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

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

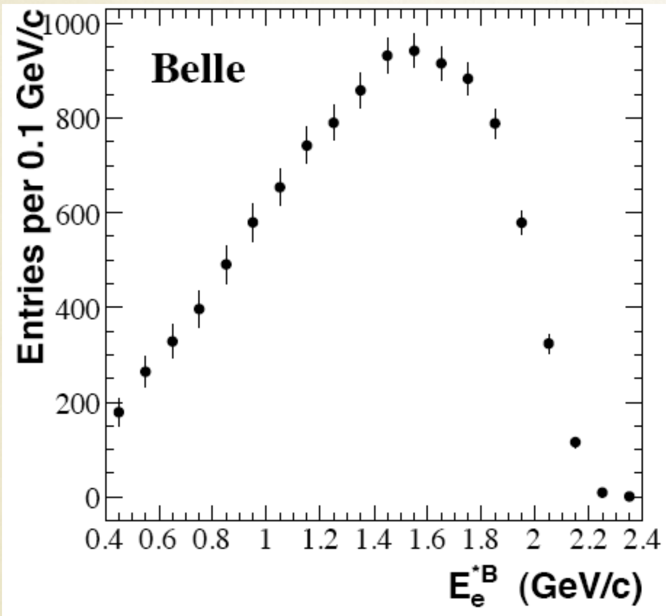
Current fits includes 6 non-pert parameters

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

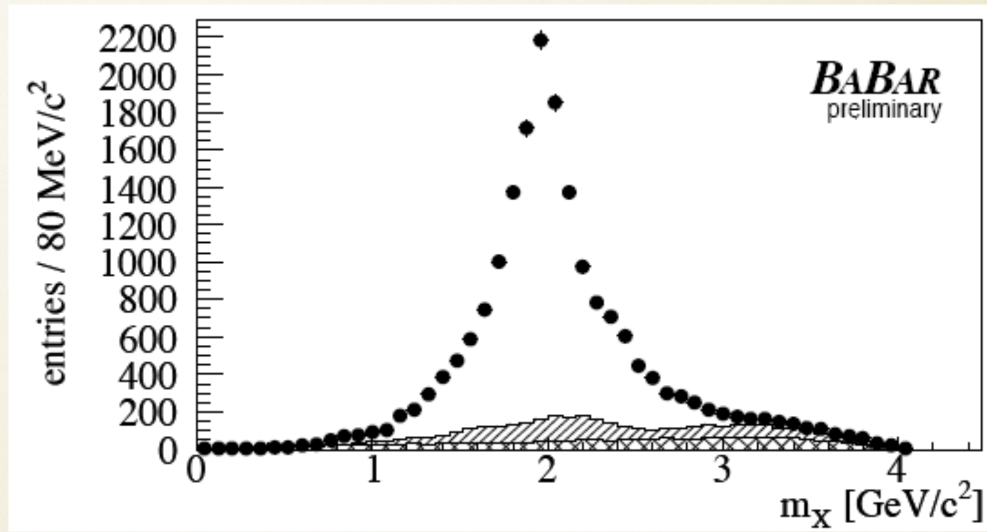
and all known corrections up to $O(\Lambda^3/m_b^3)$

Extraction of the OPE parameters

E_l spectrum



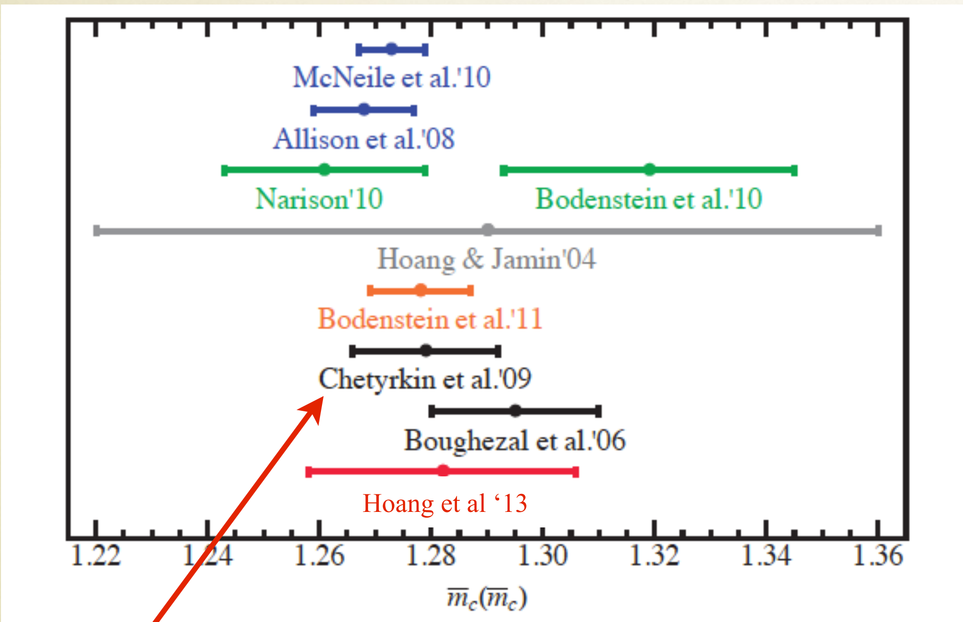
hadronic mass spectrum



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},...)

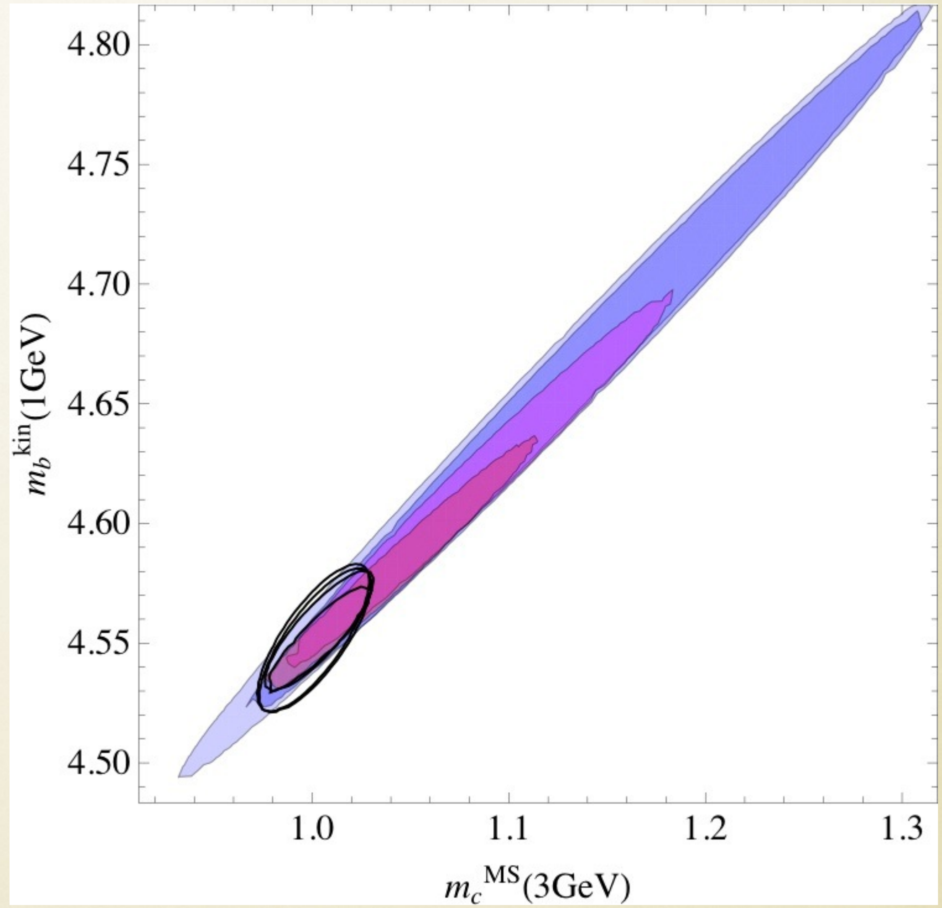
CHARM MASS DETERMINATIONS



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

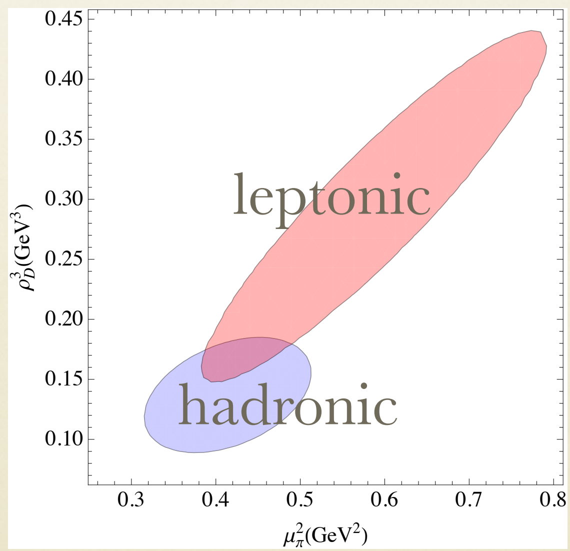
Alberti et al, 1411.6560

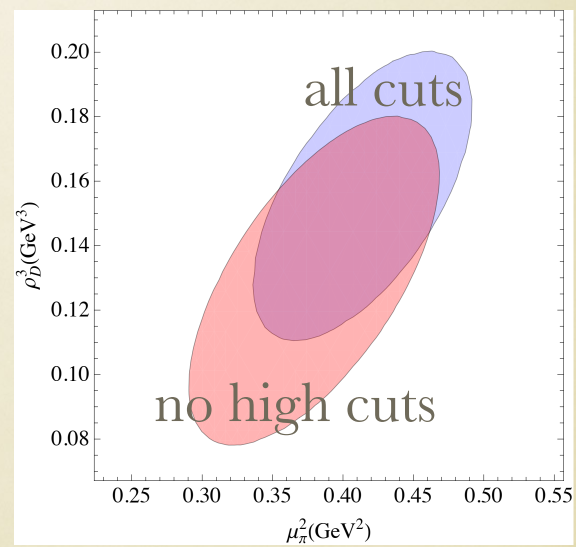
m_b^{kin}	$\overline{m}_c(3\,\text{GeV})$	μ_π^2	ρ_D^3	μ_G^2	ρ_{LS}^3	$\text{BR}_{c\ell\nu}$	$10^3\lvert V_{cb}\rvert$
4.553	0.987	0.465	0.170	0.332	-0.150	10.65	42.21
0.020	0.013	0.068	0.038	0.062	0.096	0.16	0.78

Without mass constraints

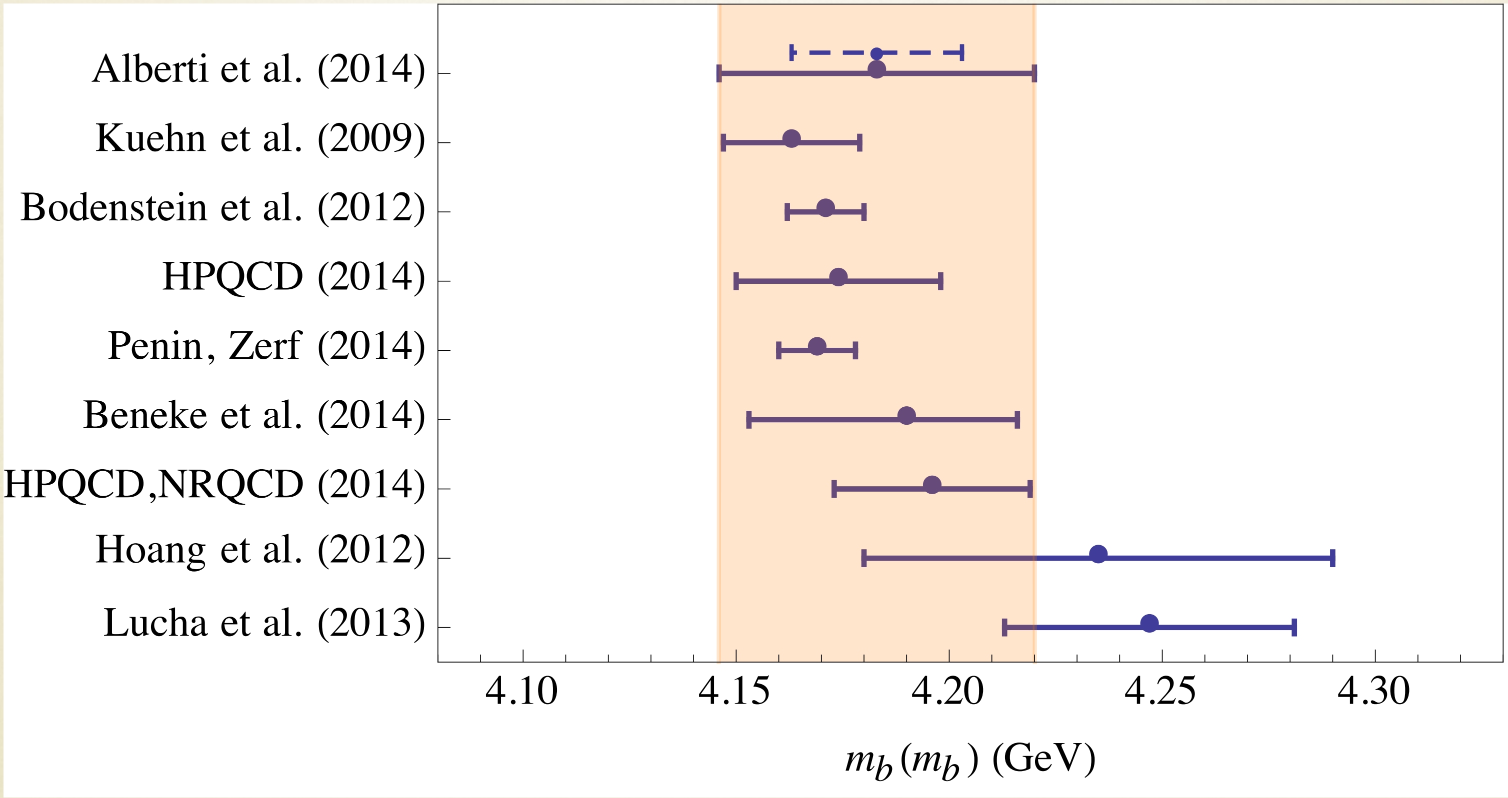
$$m_b^{kin}(1\text{GeV}) - 0.85\,\overline{m}_c(3\text{GeV}) = 3.714 \pm 0.018\,\text{GeV}$$

- 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 $\boldsymbol{m_b^{kin}(1\mathrm{GeV})=4.553(20)\mathrm{GeV}}$

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

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

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
- Electroweak corrections
- **Lattice QCD information on local matrix elements is the next frontier**

HOW CAN LATTICE HELP?

- Improve heavy quark mass determinations
- Compute M_B and M_{B^*} as function of the heavy quark mass: chromomagnetic and kinetic m.el., non local guys needed in HQSR
- HQE parameters are B meson expectation values of local heavy quark operators. Direct evaluation looks tricky…
- …but it can perhaps be sidestepped: compute current correlators in the B meson to extract matrix elements in euclidean in analogy with HPQCD studies to extract m_b and m_c

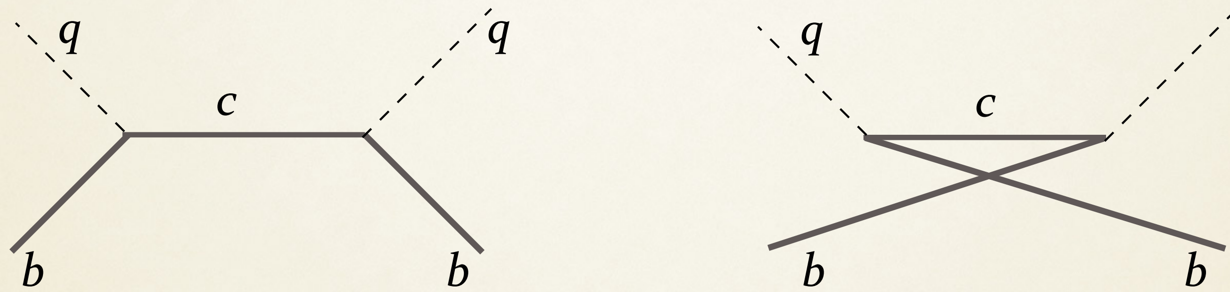
$$\frac{d^n}{d(q^2)^n}\Pi_p(q^2)\Big|_{q^2=0}, \qquad \Pi_p(q^2) = i\int d^x e^{iq\cdot x}\langle 0|TJ_5(x)J_5(0)|0\rangle$$

$$G_{2n} = a^6\sum_{t,\vec{x}}(am_{0c})^2\left(\frac{t}{a}\right)^{2n}\langle 0|j_5(\vec{x},t)j_5(0,0)|0\rangle$$

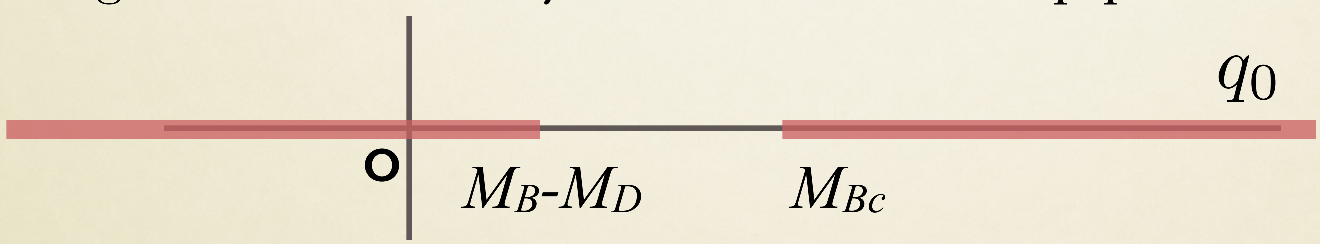
In inclusive decays we compute moments of *Im* T^i

$$T^{\mu\nu}(q) = \frac{2i}{\pi M_B}\int d^x e^{-iq\cdot x}\langle \bar{B}|T J_L^{\mu}(x) J_L^{\nu}(0)|\bar{B}\rangle$$

with contributions from *(4 point functions)*



Setting $\vec{q} = 0$ the analytic structure in the q_0 plane is



and appropriate dispersion relations/analytic continuation to connect to euclidean. Alternatively, one can compute OPE in euclidean, but it's much more work…

Pros: moments suppress lower dimensional operators, can study OPE convergence at different quark masses, can change currents…

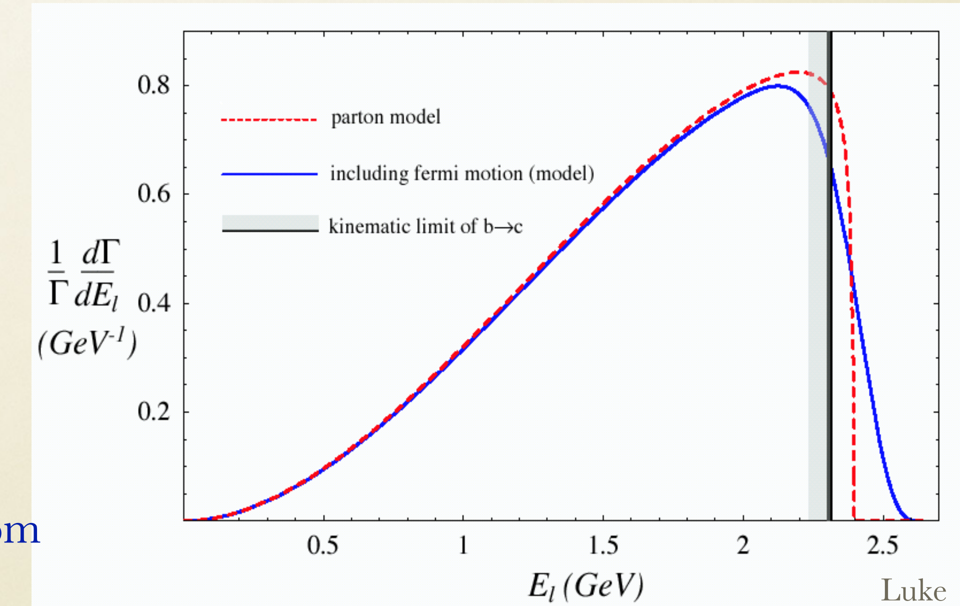
$B \to X_u l \nu$ AND CUTS

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→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



Luke

How to access the SF?

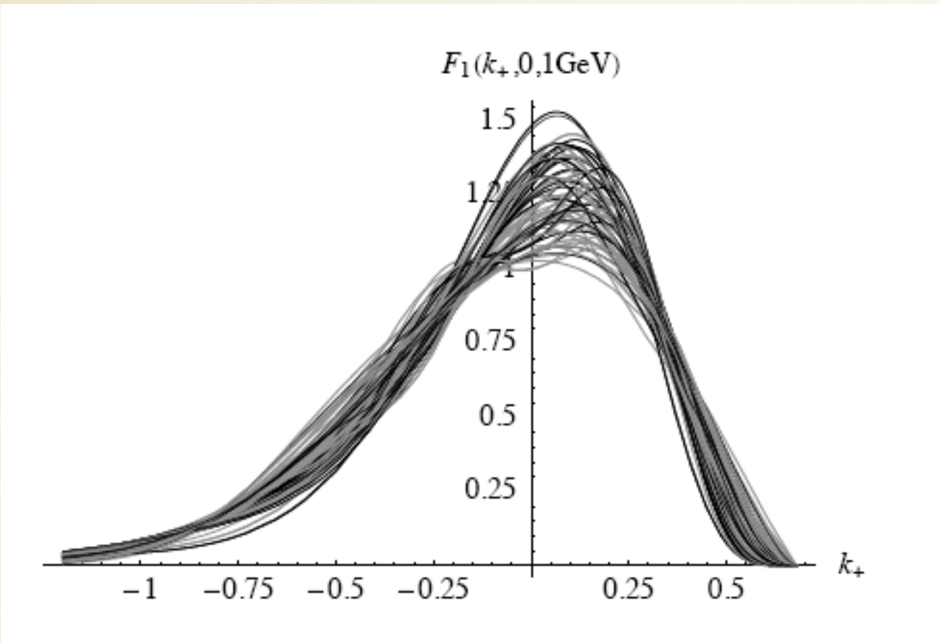
$$\frac{d^3\Gamma}{dp_+ dp_- dE_\ell} = \frac{G_F^2 |V_{ub}|^2}{192\pi^3} \int dk C(E_\ell, p_+, p_-, k) F(k) + O\left(\frac{\Lambda}{m_b}\right)$$

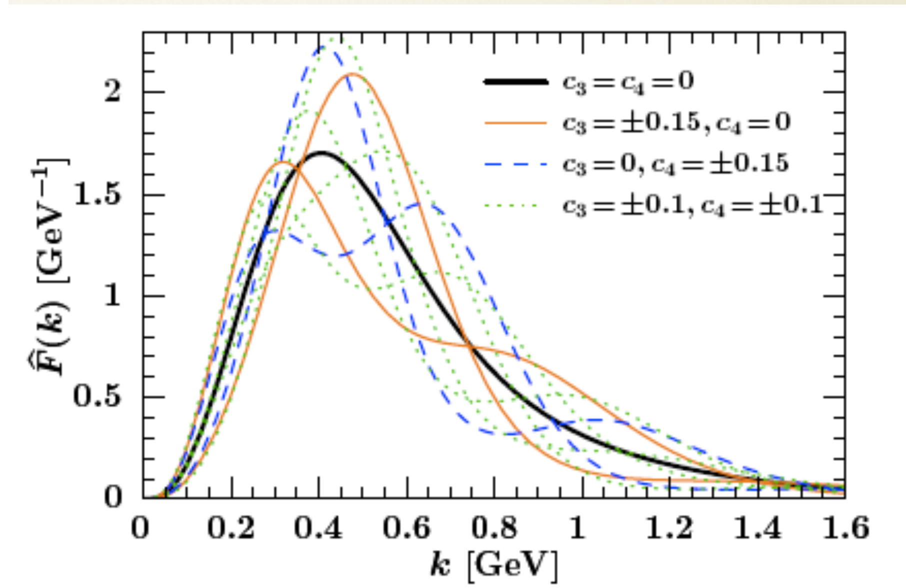
Subleading SFs

Prediction *based* on resummed pQCD DGE, ADFR	OPE constraints + parameterization without/with resummation GGOU, BLNP

Fit semileptonic (and radiative) data
SIMBA, NNVub

Functional forms



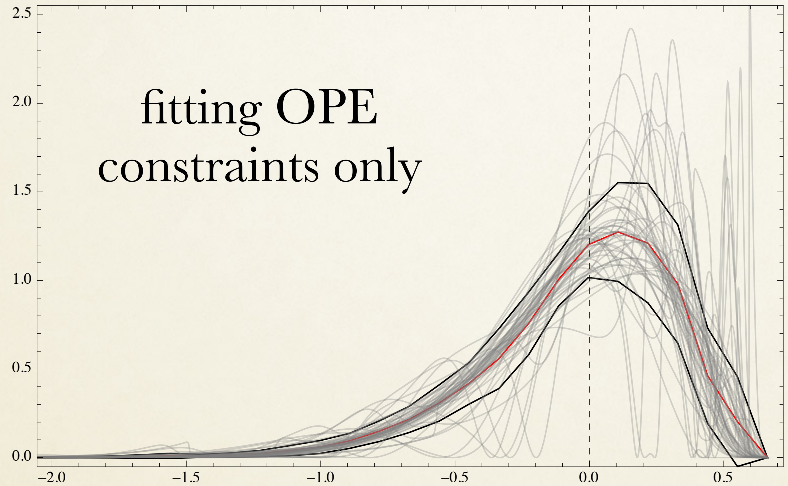


About 100 forms considered in GGOU, large variety, double max discarded. Small uncertainty (1-2%) on V_{ub}

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

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).

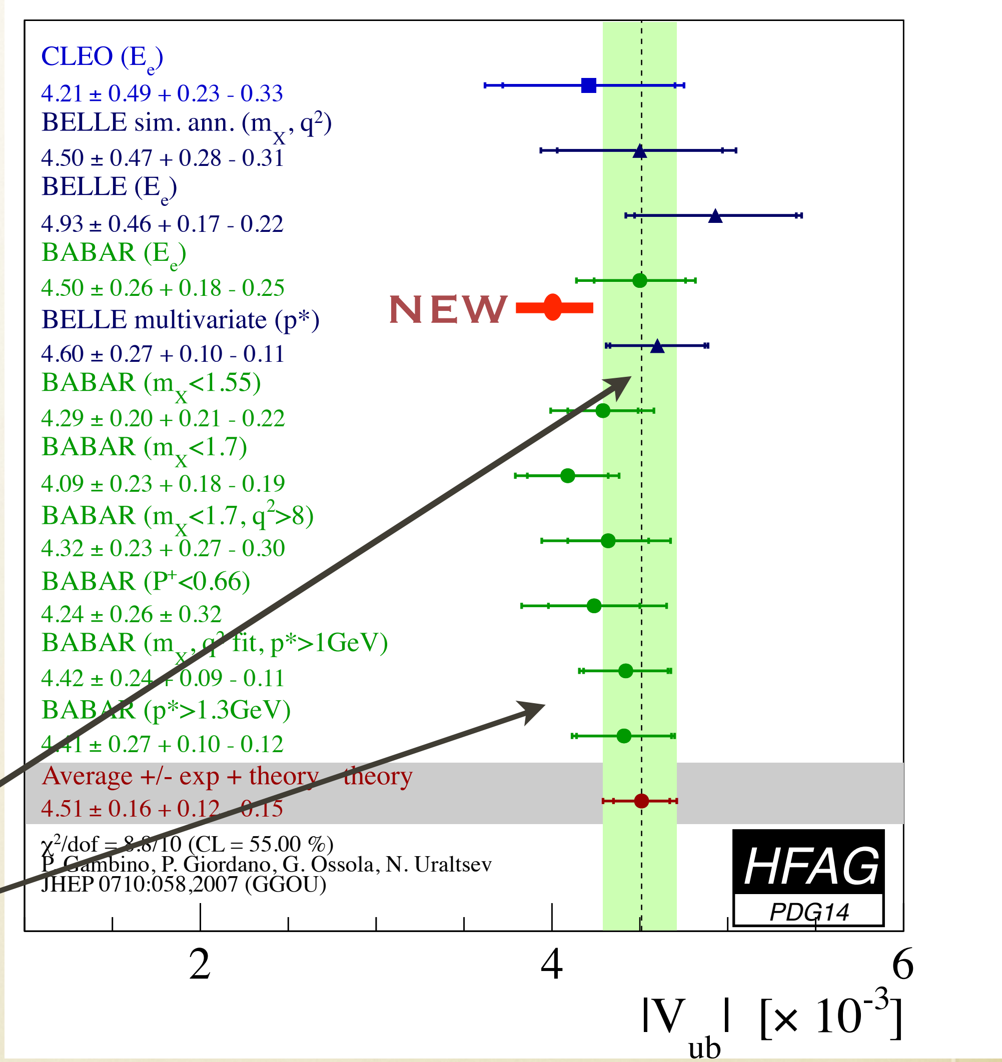
- Belle-II will be able to measure some kinematic distributions, thus constraining directly the shape function. NNVub will provide a flexible tool to analyse data.

$|V_{ub}|$ DETERMINATIONS

Inclusive: 5% total error

HFAG 2014	Average |Vub| 1000
DGE	4.52(16)(16)
BLNP	4.45(16)(22)
GGOU	4.51(16)(15)

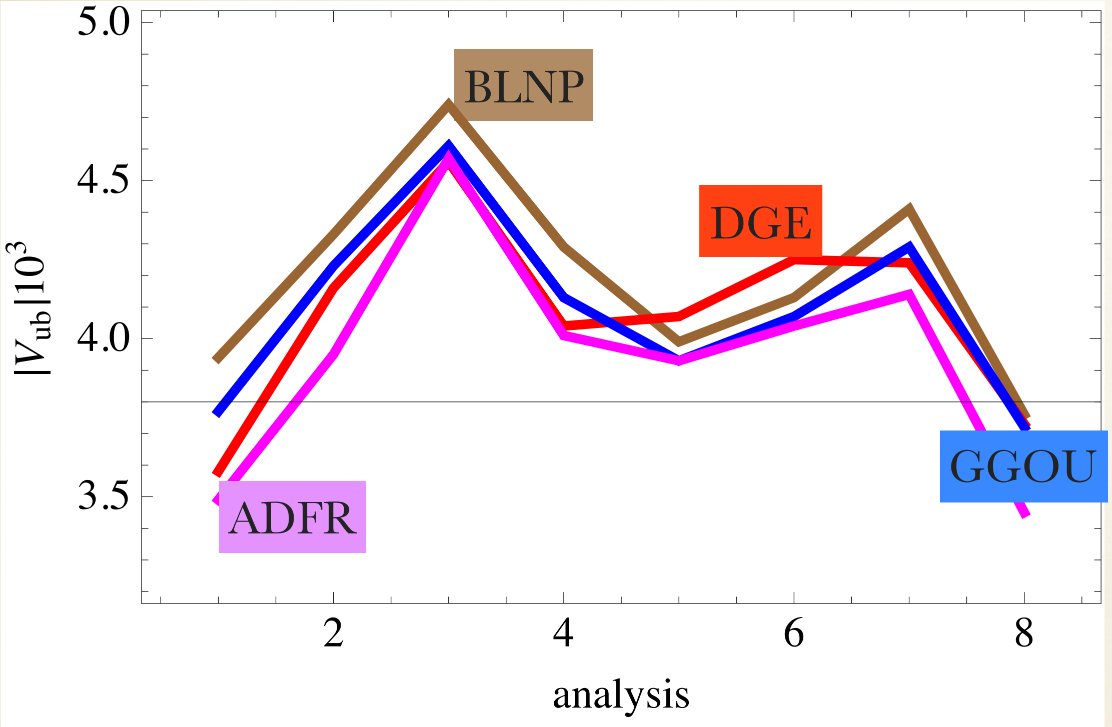
UT fit (without direct V_{ub}):
V_{ub}=3.62(12) 10^{-3}



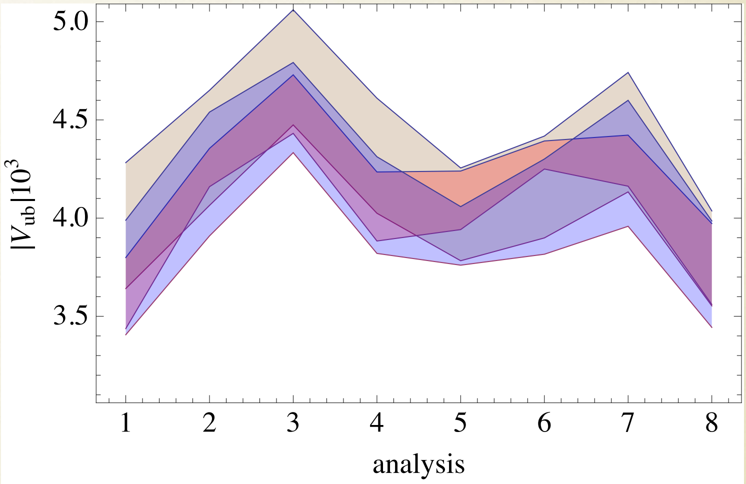
Recent experimental results are theoretically cleanest (2%) but based on background modelling.
Signal simulation also relies on theoretical models…

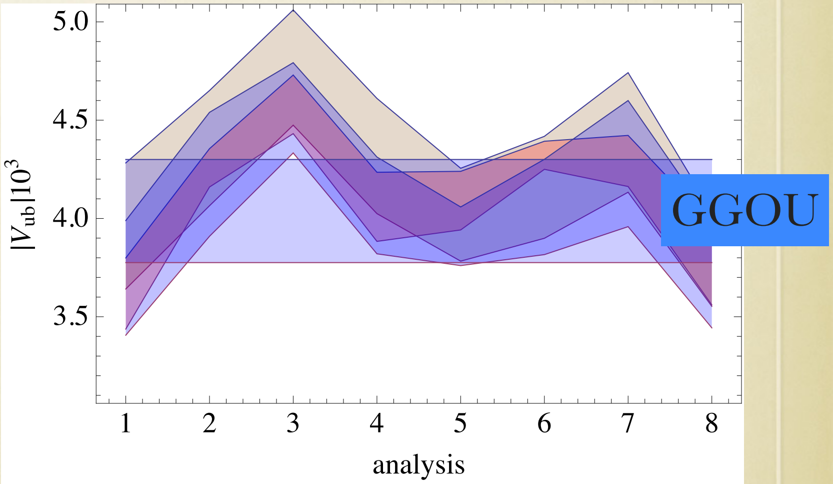
A global comparison

0907.5386, Phys Rept



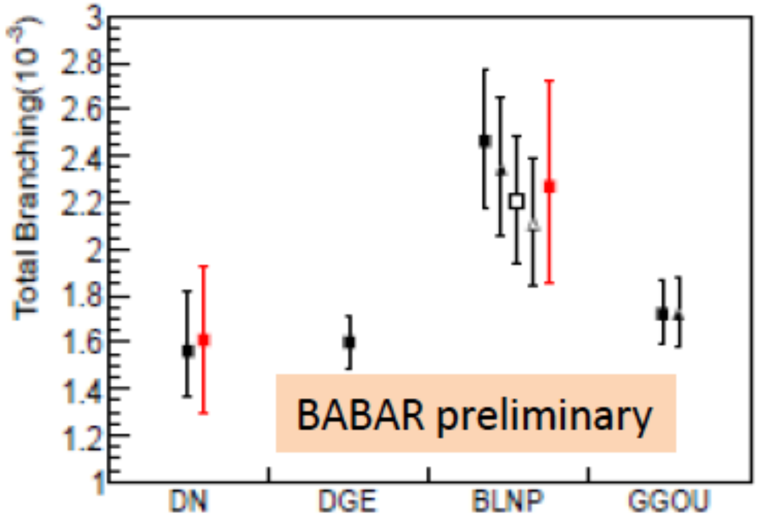
only theory errors
(without common parametric)

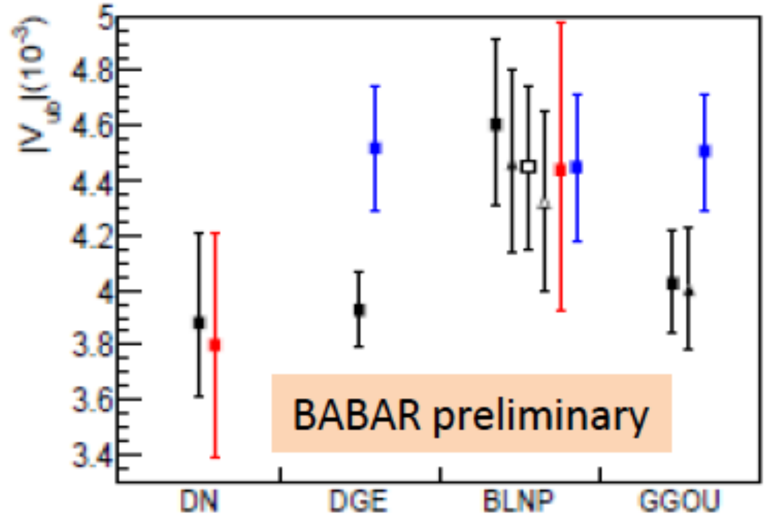




- common inputs (except ADFR)
- Overall good agreement **SPREAD WITHIN THEORY ERRORS**
- NNLO BLNP still missing: will push it up a bit
- Systematic offset of central values: normalization? to be investigated

Summary





solid squares and triangles – X_c with mc constraint fit and X_c+$X_s\gamma$ fit of SF parameters (BLNP and GGOU)

solid and open - translation “kinetic” to “shape-function” with μ = 2.0GeV and μ = 1.5GeV (BLNP), respectively

results based on 0.8-2.6GeV/c momentum range

HFAG 2014 average based on tagged and untagged measurements

Consistent with and more precise than our previous result:

BaBar, Phys.Rev. D73(2006)012006 (p_e > 2 GeV/c)

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 and of new Babar inclusive analysis (if confirmed).
- Belle-II will improve precision and allow for consistency checks of our methods, especially for inclusive V_{ub}.