CKM ELEMENTS FROM SEMILEPTONIC B DECAYS

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THE CKM MATRIX

Weak and mass eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \hat{V}_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

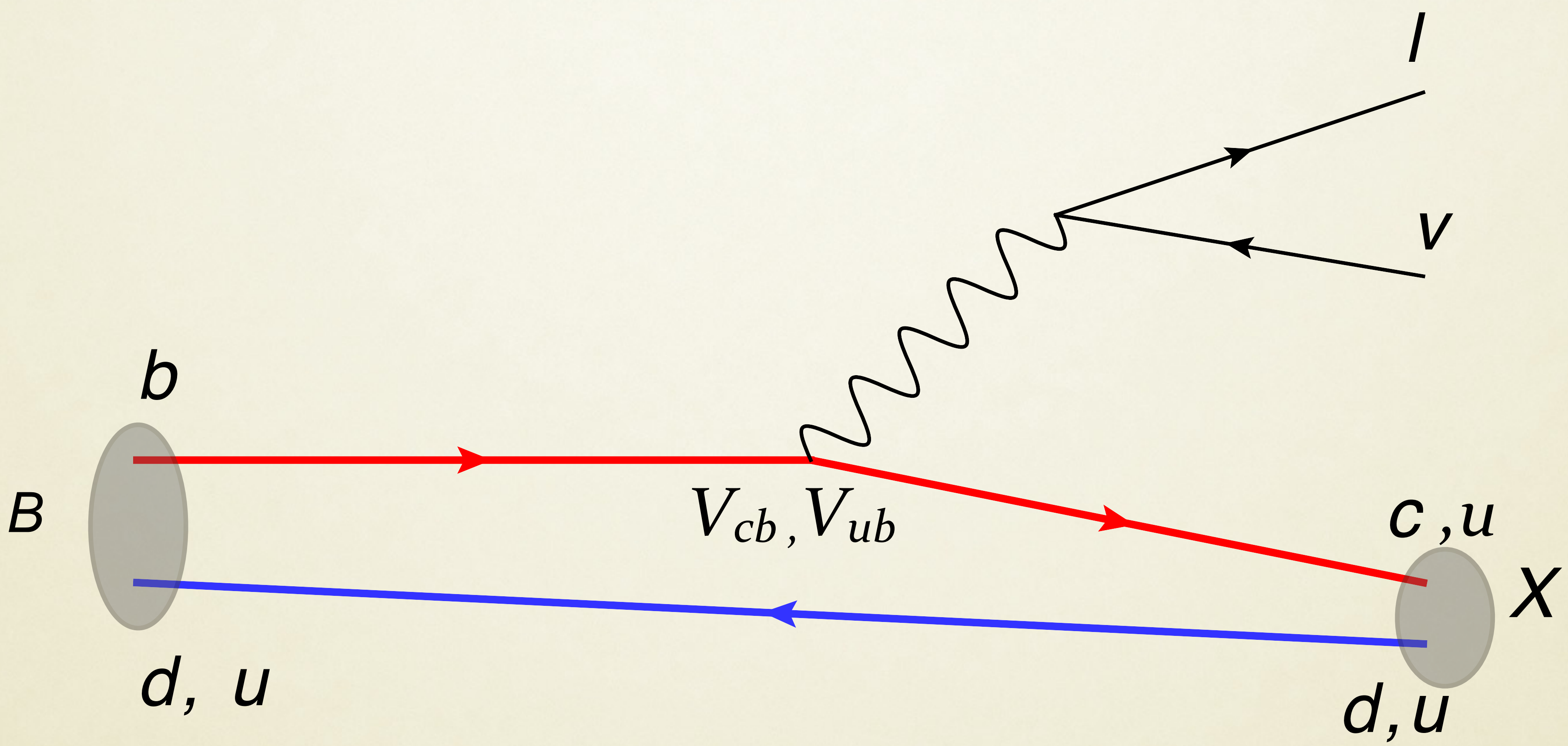
Charged currents (W exchange) mix generations
Masses and mixing arise from Yukawa matter-Higgs couplings

$$\hat{V} = \begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{pmatrix}$$

CKM matrix has strong hierarchy

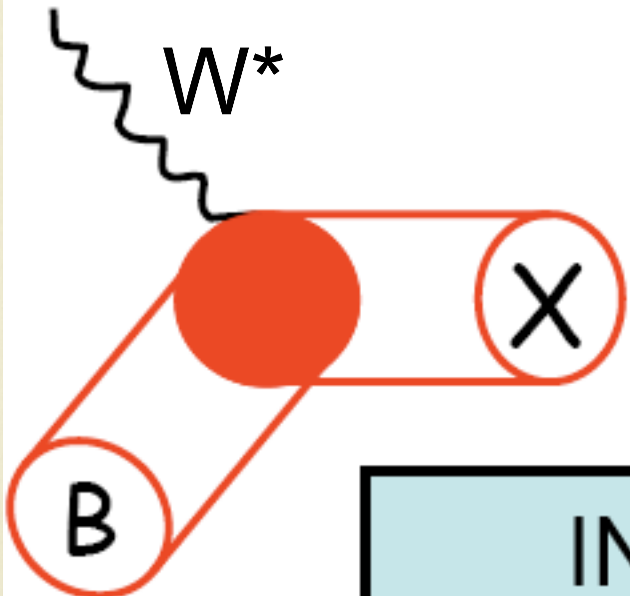
V is a unitary matrix with only 4 physical parameters (3 angles and 1 phase)

Semileptonic b decays



allow for the determination of V_{cb} and V_{ub}. Exclusive analyses look at specific final states such as X=D,D*,π,ρ

Inclusive vs exclusive *B* decays



Simplicity: ew current probes B dynamics

INCLUSIVE	EXCLUSIVE
OPE: non-pert physics described by B matrix elemnts of local operators can be extracted by exp suppressed by $1/m_b^2$	Form factors: in general computed by non pert methods (lattice, sum rules,...) symmetry can provide normalization

As we aim at high precision, things are not at all simple...

Why precision CKM studies?

- The SM accomodates flavour & CP violation, but ***we have no theory of flavour***: what is the origin of the observed masses and mixing?
- We still expect New Physics not far from the EW scale. Generic NP implies additional flavour and CP violation. Is there anything beyond the CKM? Even without NP at LHC flavour physics may probe scales up to 10^3 TeV
- But the CKM mechanism is very successful in general: NP must preserve agreement with data, NP signals will be small
- To uncover small signals of physics beyond CKM, we need precision tests, in many ways a challenge for our QCD understanding

Importance of $|V_{xb}|$

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

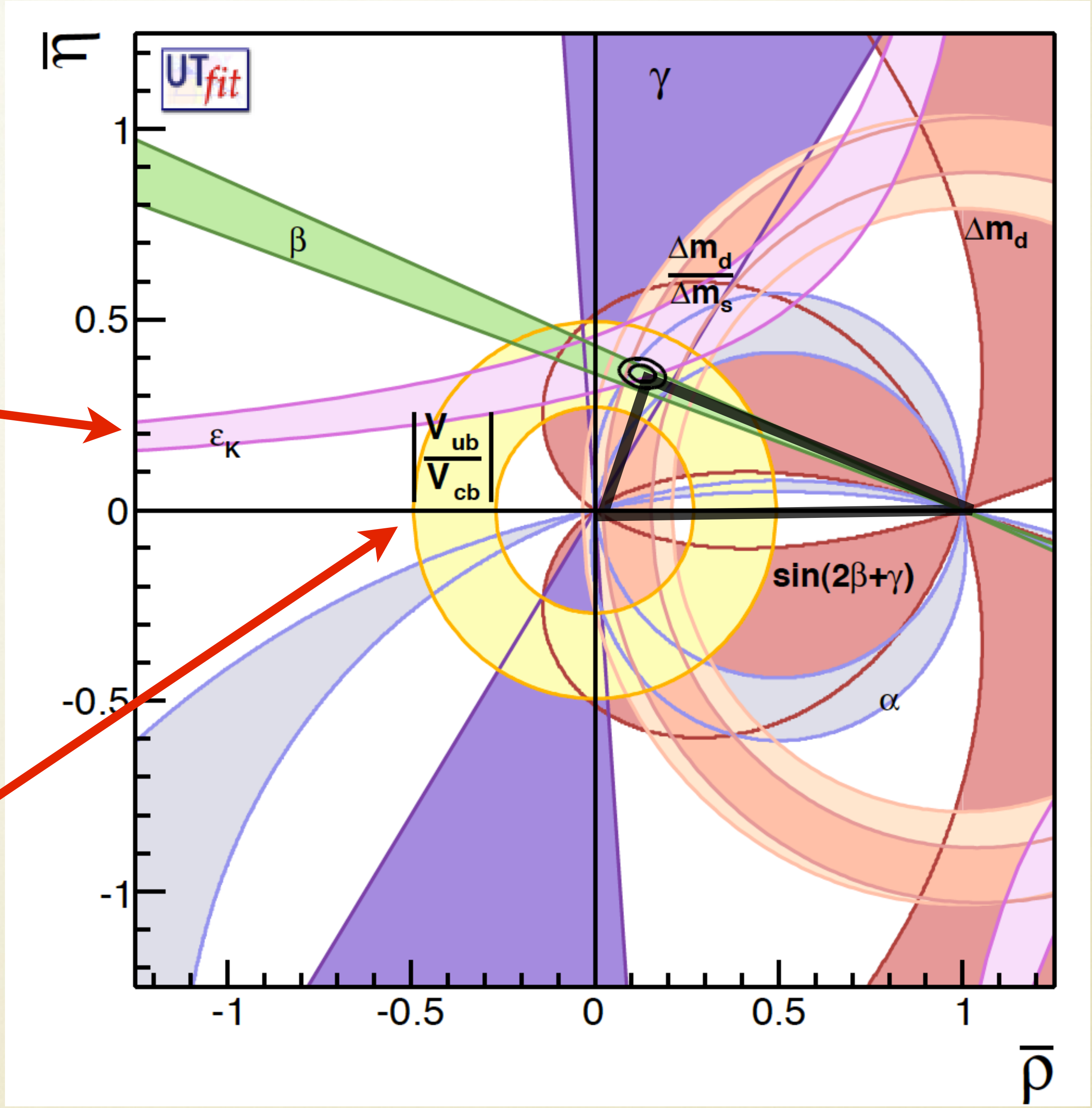
V_{cb} plays an important role in UT

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

and in the prediction of FCNC:

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

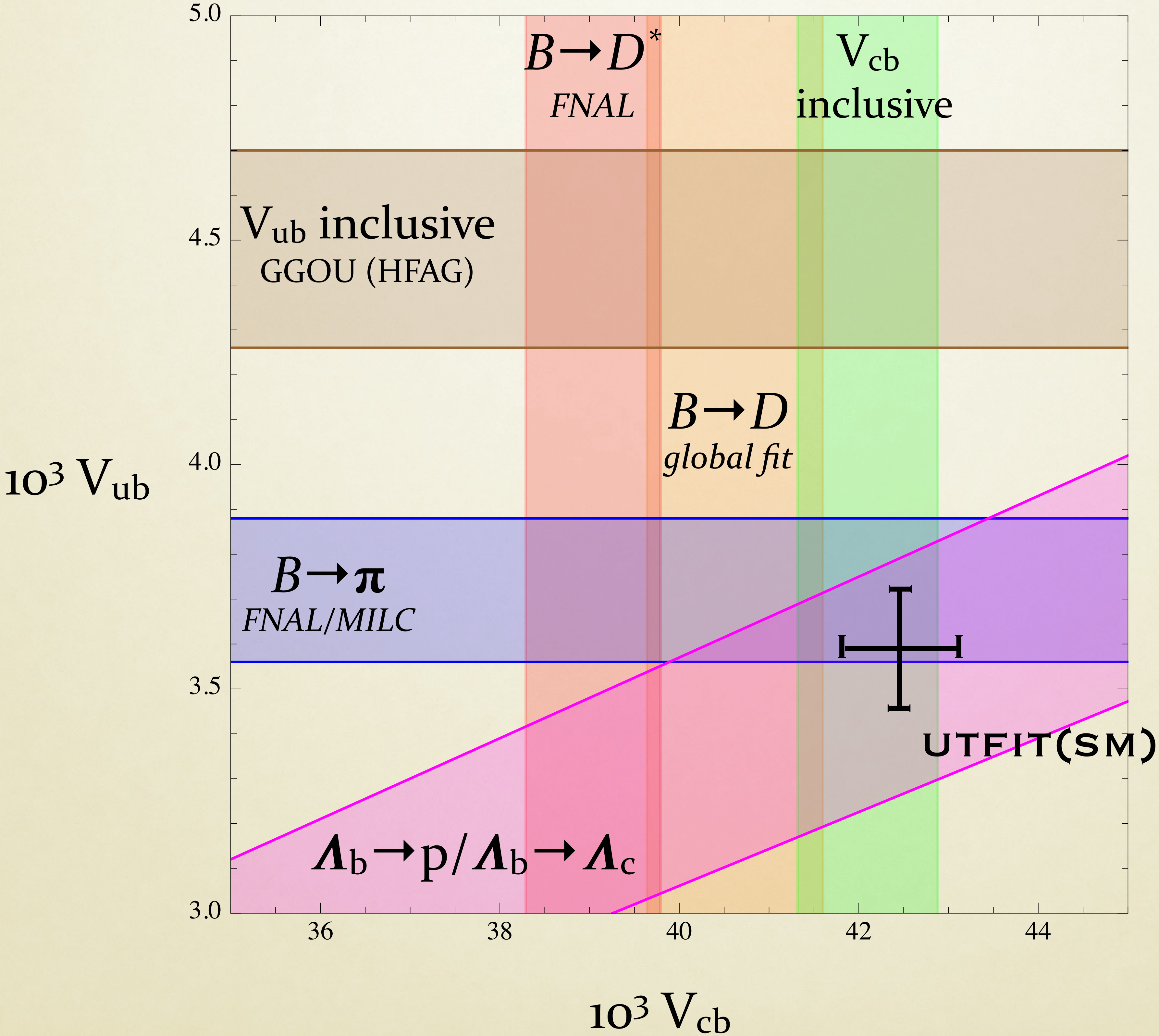
where it often dominates the theoretical uncertainty.
V_{ub}/V_{cb} constrains directly the UT



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

V_{cb} and V_{ub} status

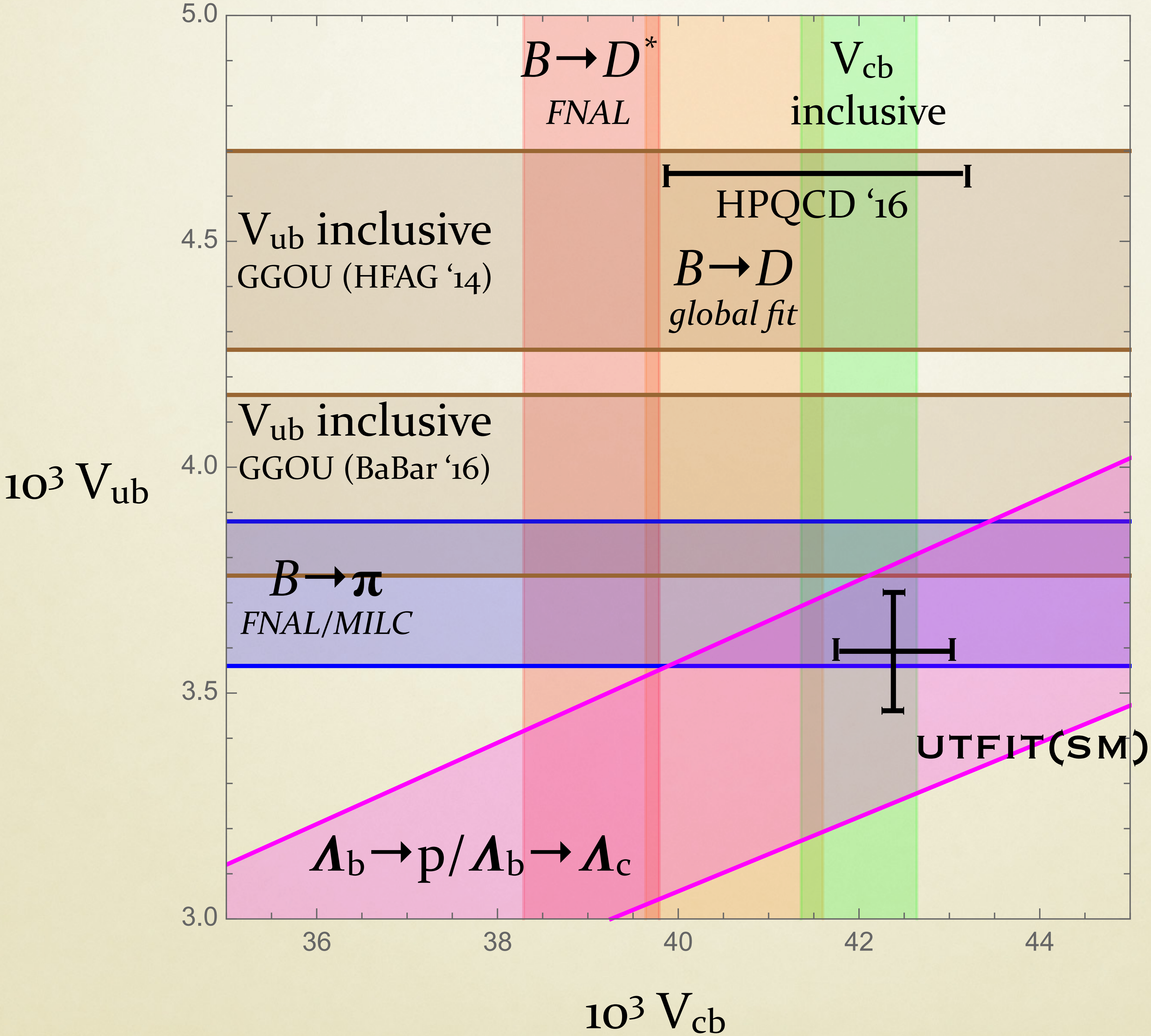
1σ ranges



reasonable consistency among exclusive channels

not all results at the same level

V_{cb} and V_{ub} updated status



CKM 2016:
NEW V_{ub} incl
by Babar
in agreement
with exclusive
but needs checks

NEW HPQCD
$B \to D^*$ result
V_{cb}=41.5(1.7) 10^{-3}

NEW Belle $B \to D^*$
result yesterday
with FNAL
V_{cb}=37.4(1.3) 10^{-3}

UNLIKELY PLACE FOR NEW PHYSICS?

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

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,Mannel,...

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

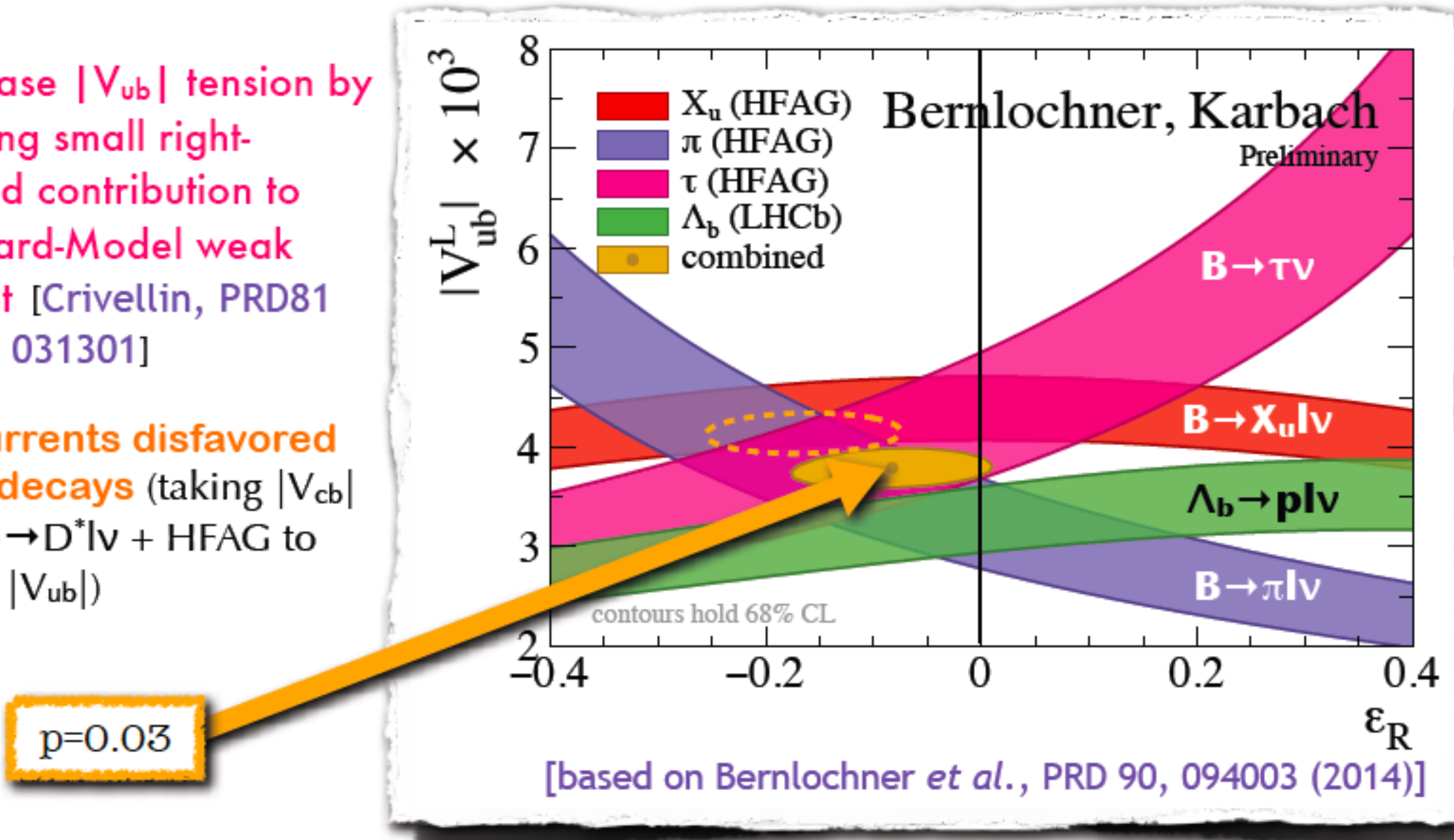
Most general SU(2) invariant dim 6 NP (without RH light neutrino) can explain results, but it is incompatible with $Z\to b\bar{b}$ data

Crivellin, Pokorski 1407.1320

(though this may not apply to the tensor operator Colangelo, De Fazio)

RH currents don't help V_{ub} either

- 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

Also here SU(2)xU(1) invariant NP cannot explain discrepancies 1407.1320

SEMITAUONIC ANOMALY

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

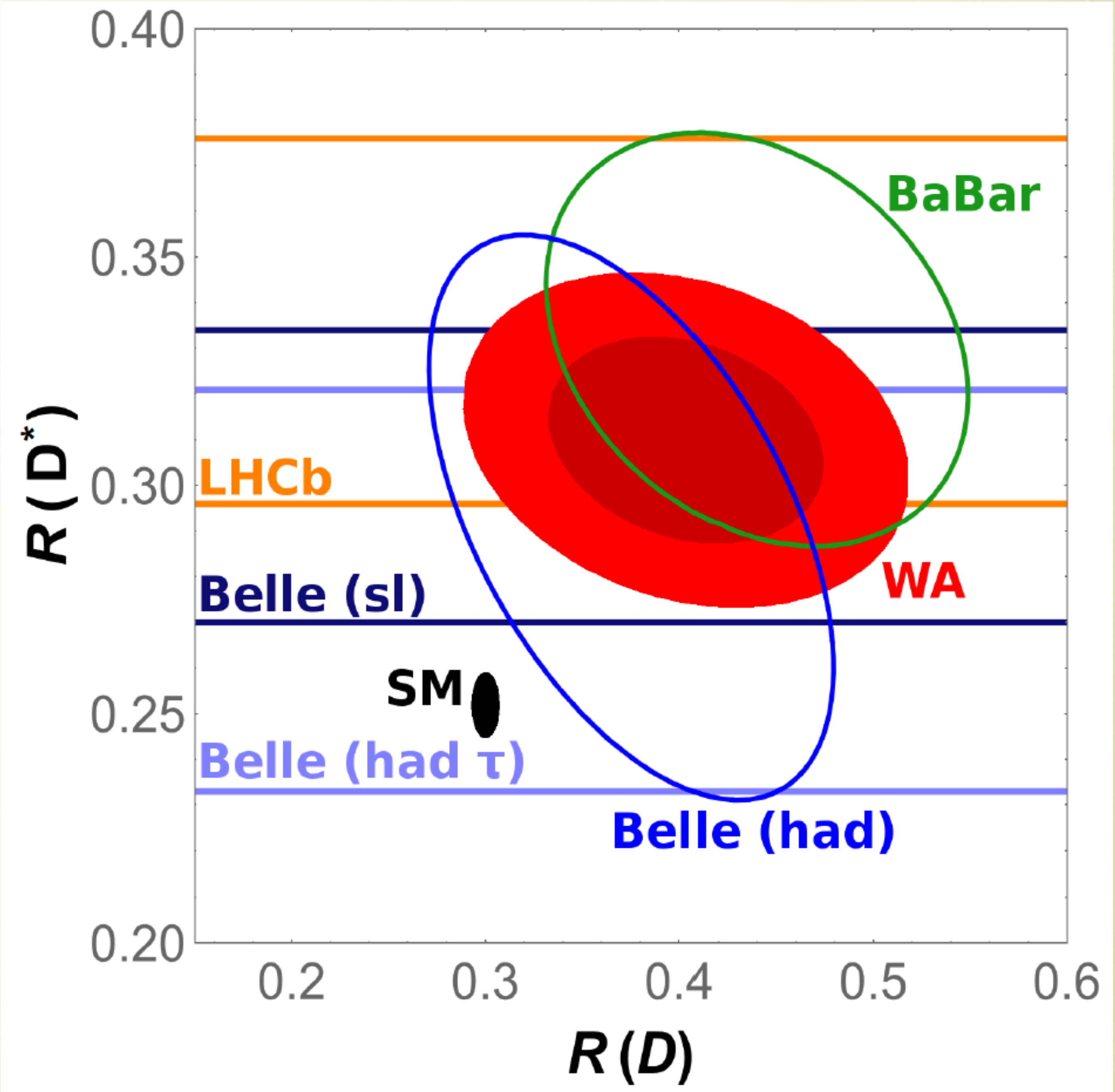
Combined discrepancy with SM 4.0σ

about 30% effect on tree-level process!

Lepton flavour universality violation: new scalars, leptoquarks, W'… possible connection with lepton flavour violation in $b \to sll$

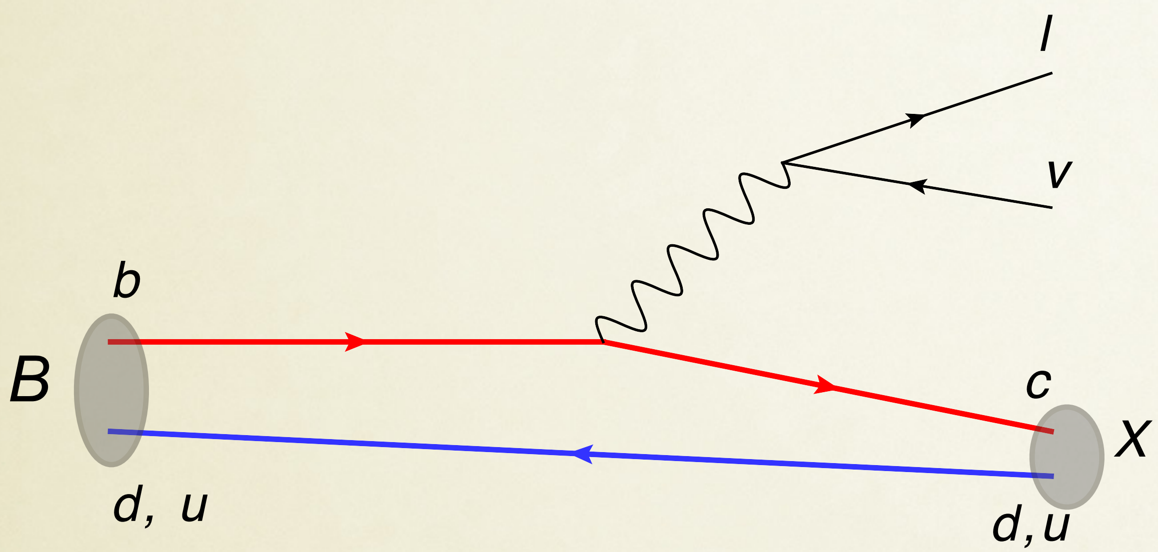
Inconsistent with LEP inclusive measurement

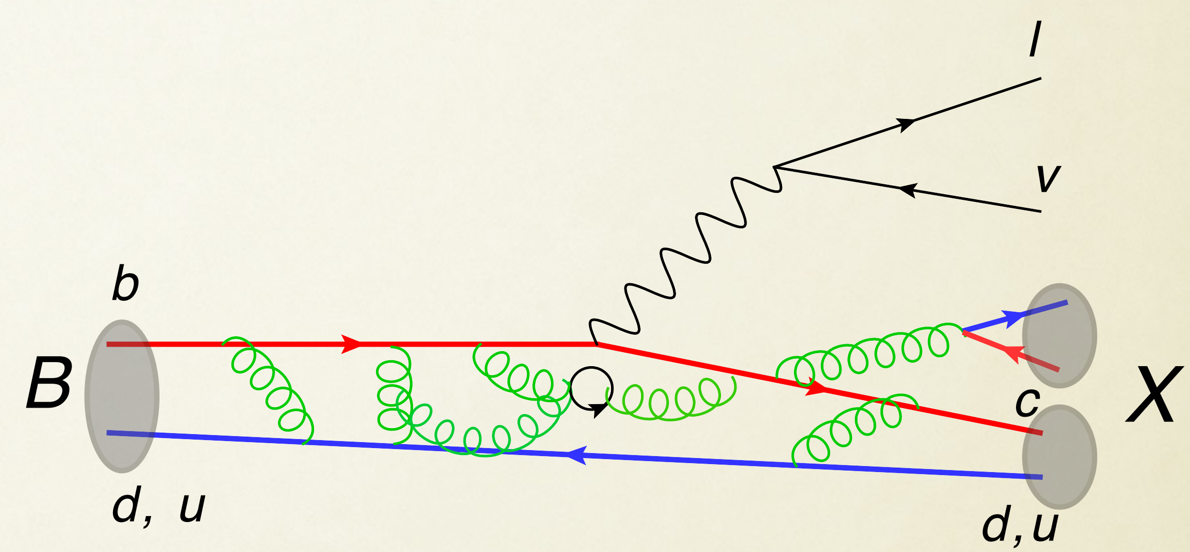
SM predictions?



Celis et al., 1612.07757

Inclusive decays: basics





- ***Simple idea:*** inclusive decays do not depend on final state, long distance dynamics of the B meson factorizes. An OPE allows 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

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

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

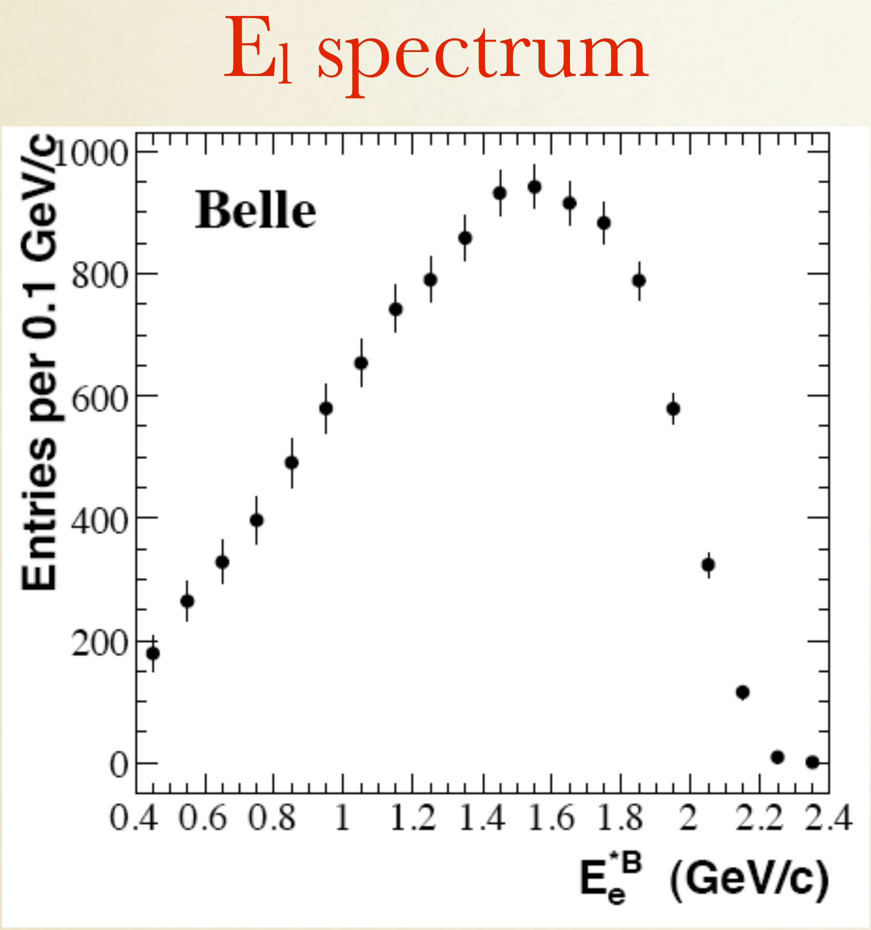
OPE valid for inclusive enough measurements, away from perturbative singularities ➠ semileptonic width, moments

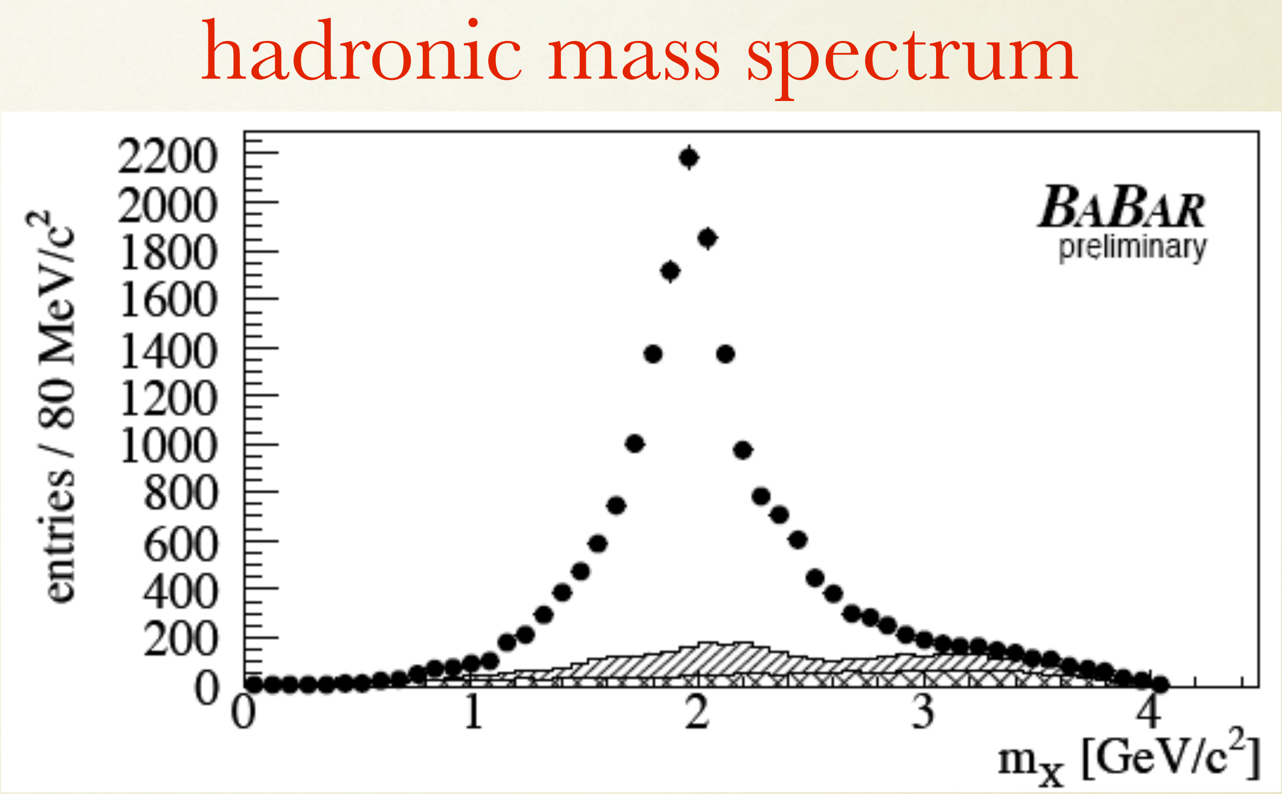
Current fits includes 6 non-pert parameters

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

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

Extraction of the OPE parameters





*Global **shape** parameters (first moments of the distributions) tell us about m_b, m_c and the B structure, total **rate** about $|V_{cb}|$*

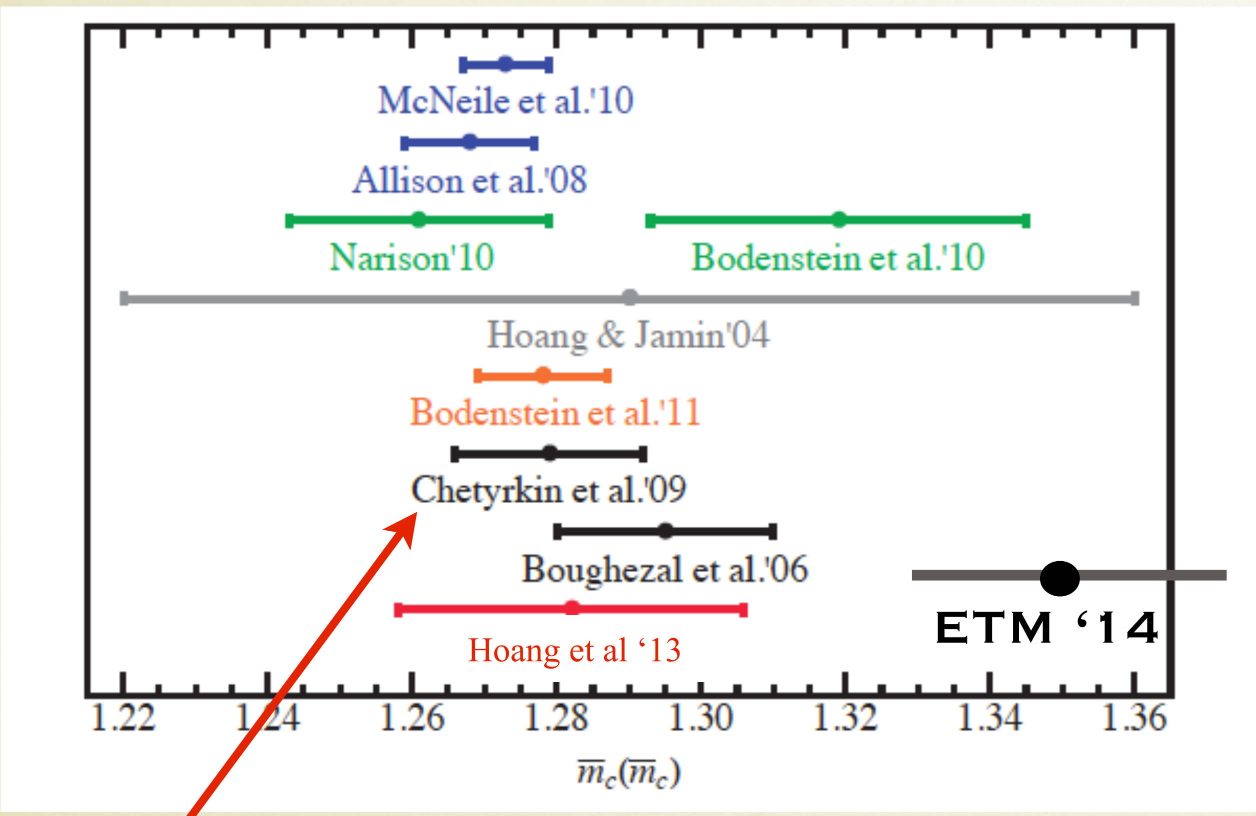
OPE parameters describe universal properties of the B meson and of the quarks → useful in many applications (rare decays, V_{ub},...)

THE CURRENT SEMILEPTONIC FIT

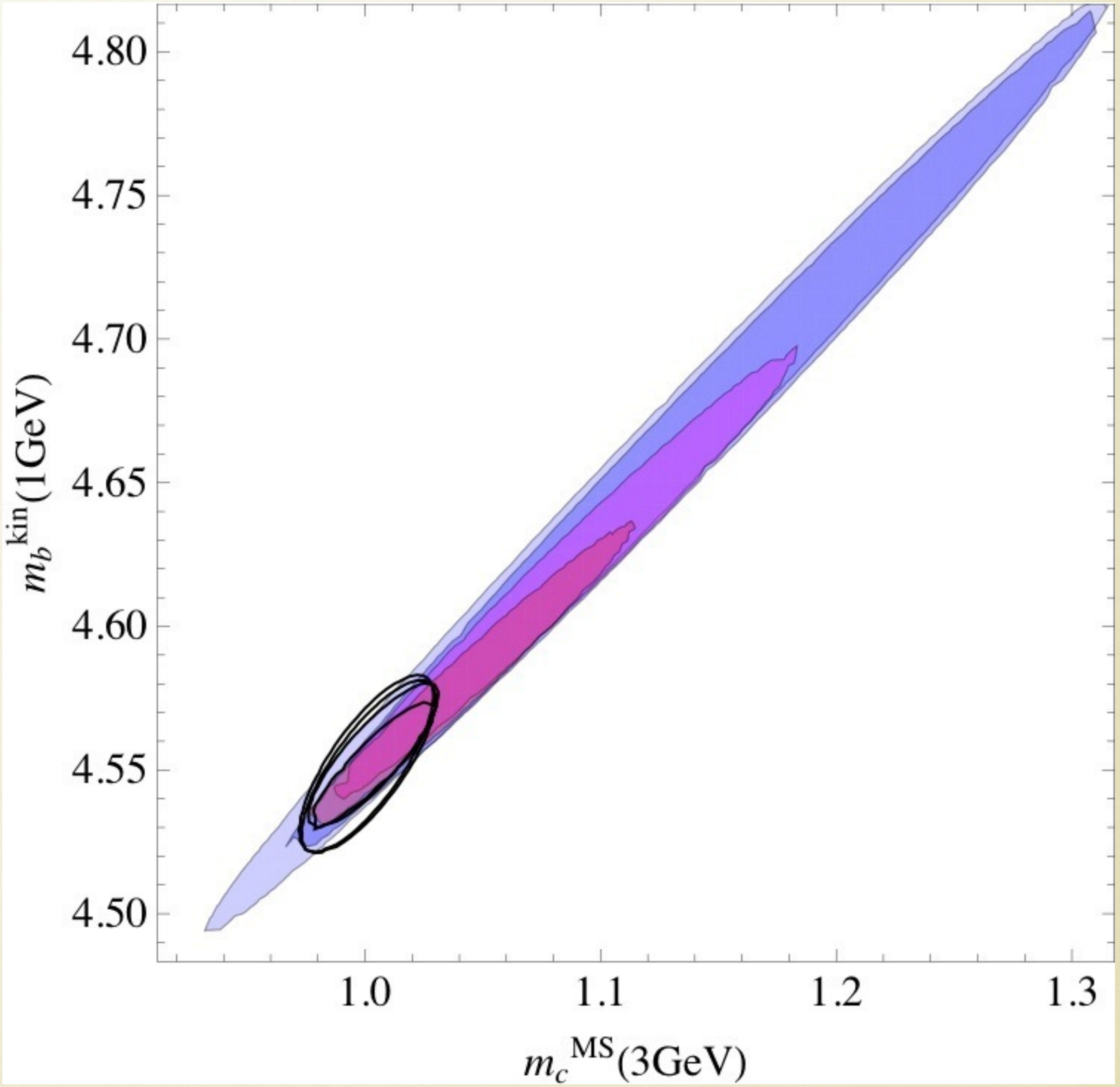
- kinetic scheme calculation based on 1107.3100; hep-ph/0401063
- includes all $O(\alpha_s^2)$ Melnikov,Biswas,Czarnecki,Pak,PG and $O(\alpha_s/m_b^2)$ corrections Becher, Boos, Lunghi, Alberti, Ewerth, Nandi, PG, Mannel,Pivovarov, Rosenthal
- Reliability of the method depends on our ability to control higher order effects. **Quark-hadron duality violation** would manifest as inconsistency in the fit.
- reassessment of theoretical errors, realistic theoretical correlations following Schwanda, PG, 1307.4551
- **external constraints**: precise heavy quark mass determinations, mild constraints on μ^2_G from hyperfine splitting and ϱ^3_{LS} from sum rules

Older fits: Buchmuller & Flaecher (2005), Bauer et al (2004) (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 last decade.

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

FIT RESULTS

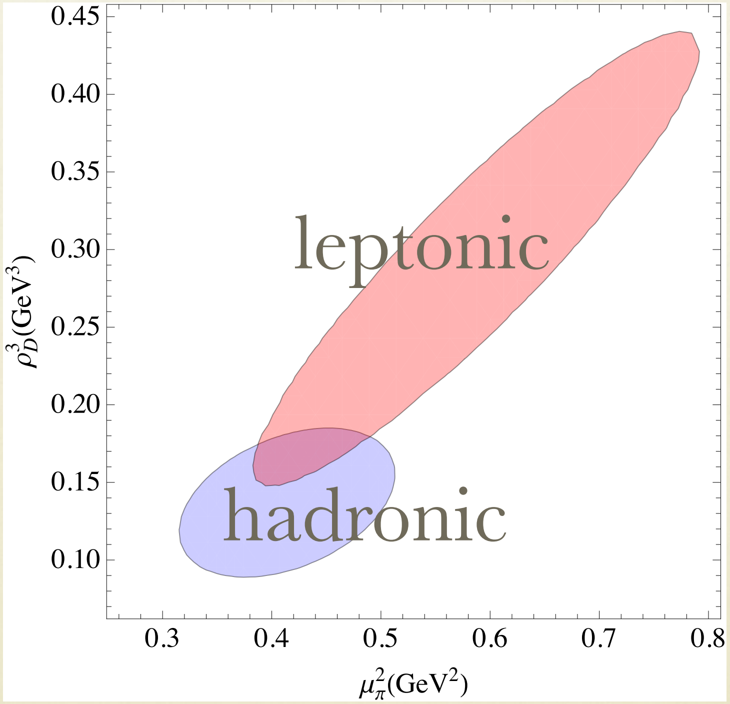
m_b^{kin}	$\overline{m}_c(3\,\mathrm{GeV})$	μ_π^2	ρ_D^3	μ_G^2	ρ_{LS}^3	$\mathrm{BR}_{c\ell\nu}$	$10^3\lvert V_{cb}\rvert$
4.553	0.987	0.465	0.170	0.332	-0.150	10.65	42.21
0.020	0.013	0.068	0.038	0.062	0.096	0.16	0.78

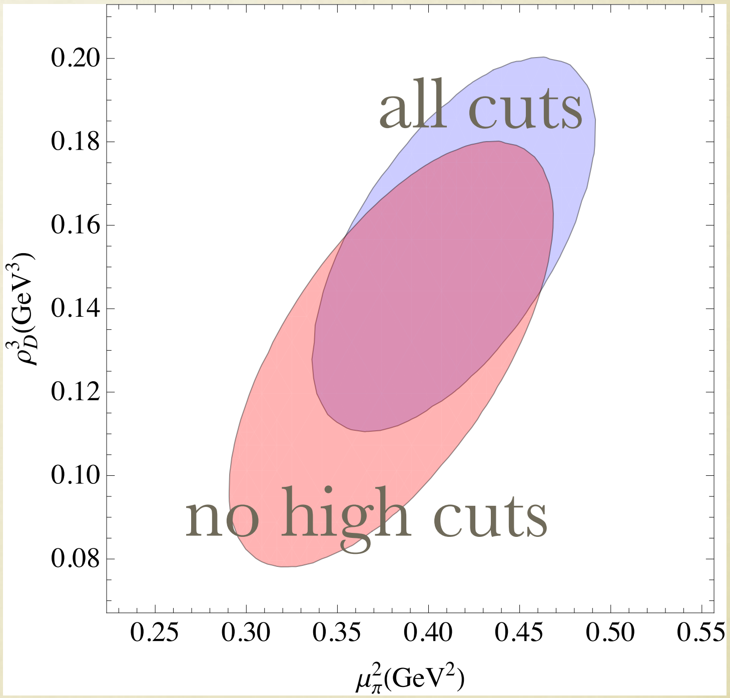
Alberti et al, 1411.6560

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

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

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

Mannel,Turczyk,Uraltsev **1009.4622**

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

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

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 (Mannel, Uraltsev, PG, 2012) In LLSA ***good convergence*** of the HQE.

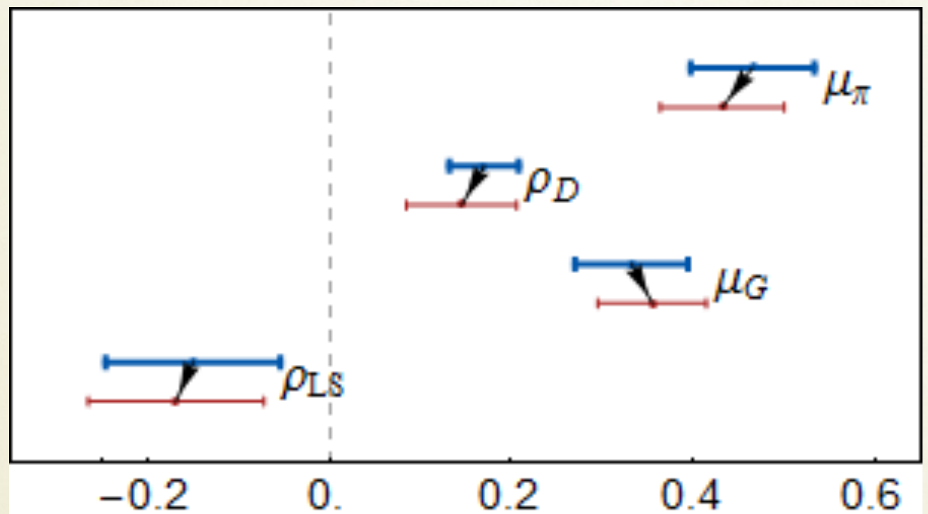
We used LLSA as loose constraint (60% gaussian uncertainty, dimensional estimate for vanishing matrix elements) in the fit including higher powers

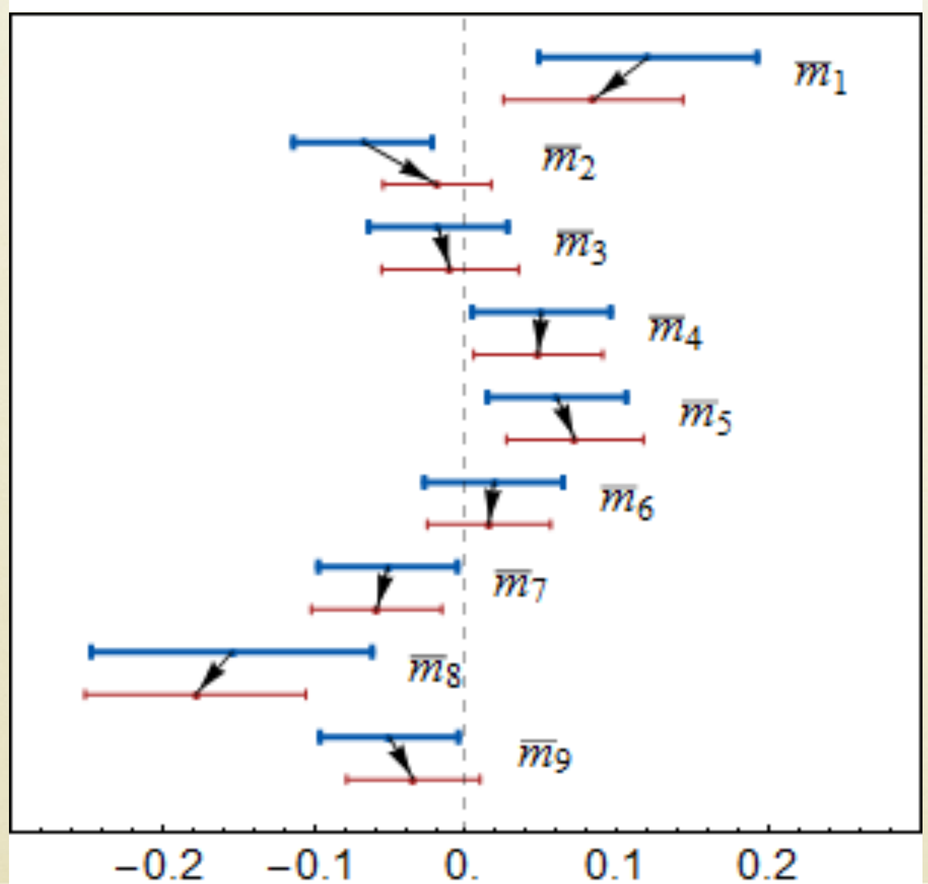
SENSITIVITY TO HIGHER POWER CORRECTIONS

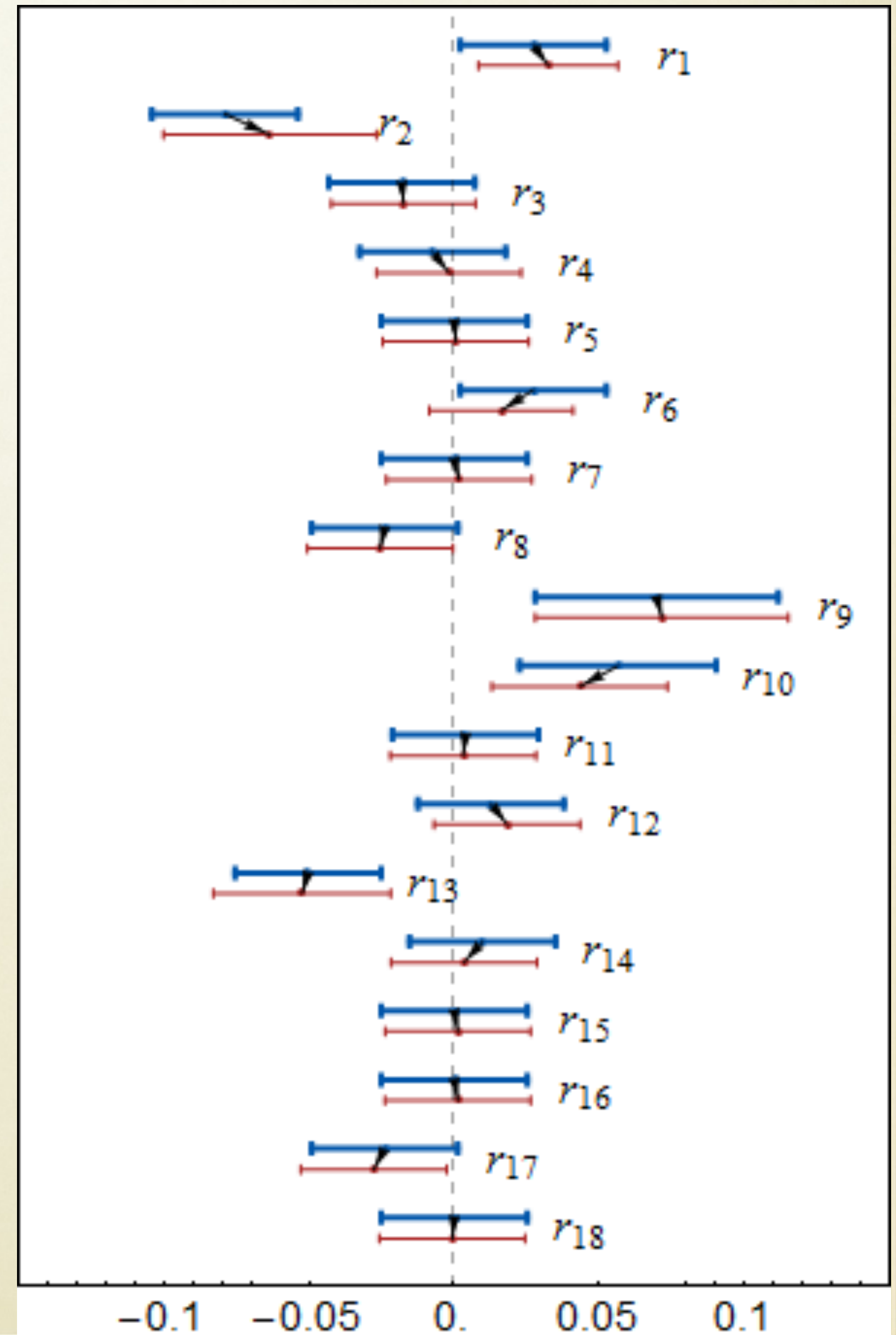
PG,Healey,Turczyk 1606.06174

$$|V_{cb}| = 42.11(74) \times 10^{-3}$$ (0.25% reduction)

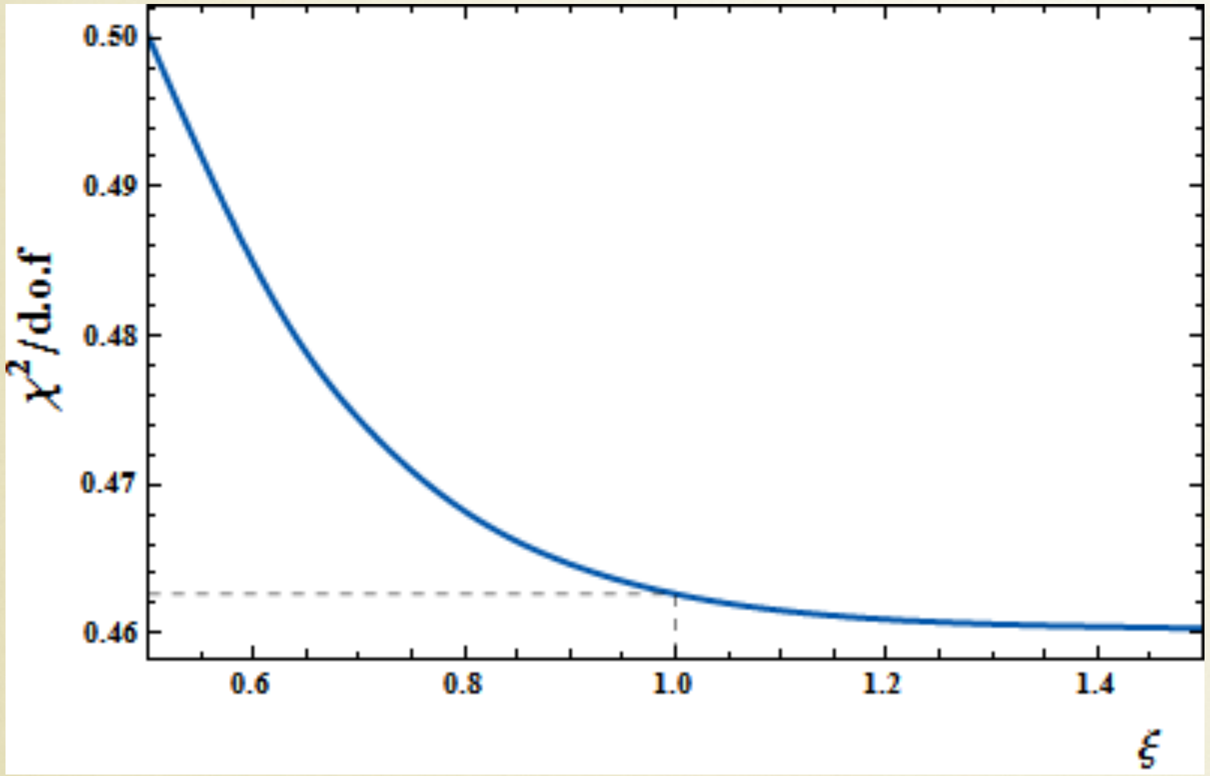
if one uses $m_c(2GeV)$ and includes PDG average for m_b **1.5% uncertainty** $|V_{cb}| = 42.00(64) \times 10^{-3}$

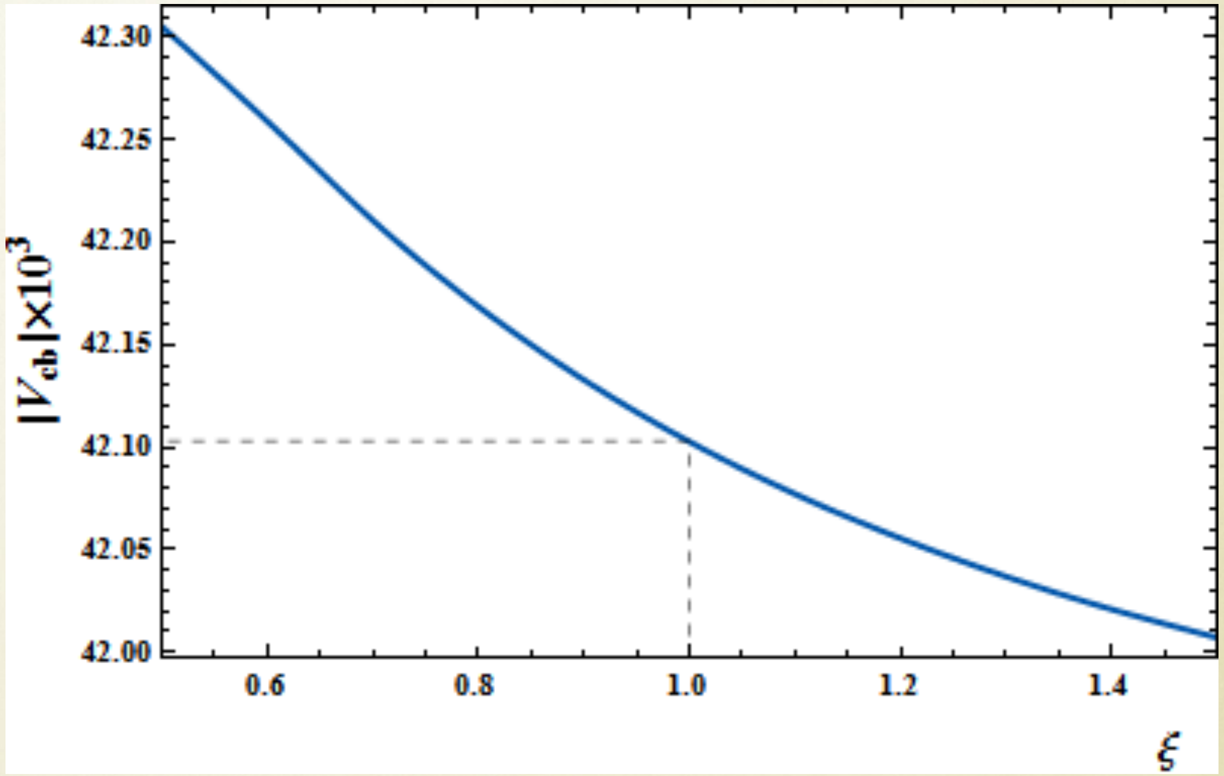






dependence on LLSA uncertainty





if we rescale all LLSA uncertainties by a factor ξ
the results change very little

Prospects of inclusive V_{cb}

- Theoretical uncertainties already dominant
- $O(\alpha_s/m_b^3)$ calculation under way
- $O(1/m_Q^{4,5})$ effects need further investigation but small effect on V_{cb}
- NNNLO corrections to total width feasible, needed for 1% uncertainty?
- Electroweak (QED) corrections
- New observables in view of Belle-II: FB asymmetry proposed by S.Turczyk could be measured already by Babar and Belle now
- **Lattice QCD information on local matrix elements is the next frontier, e.g.**

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

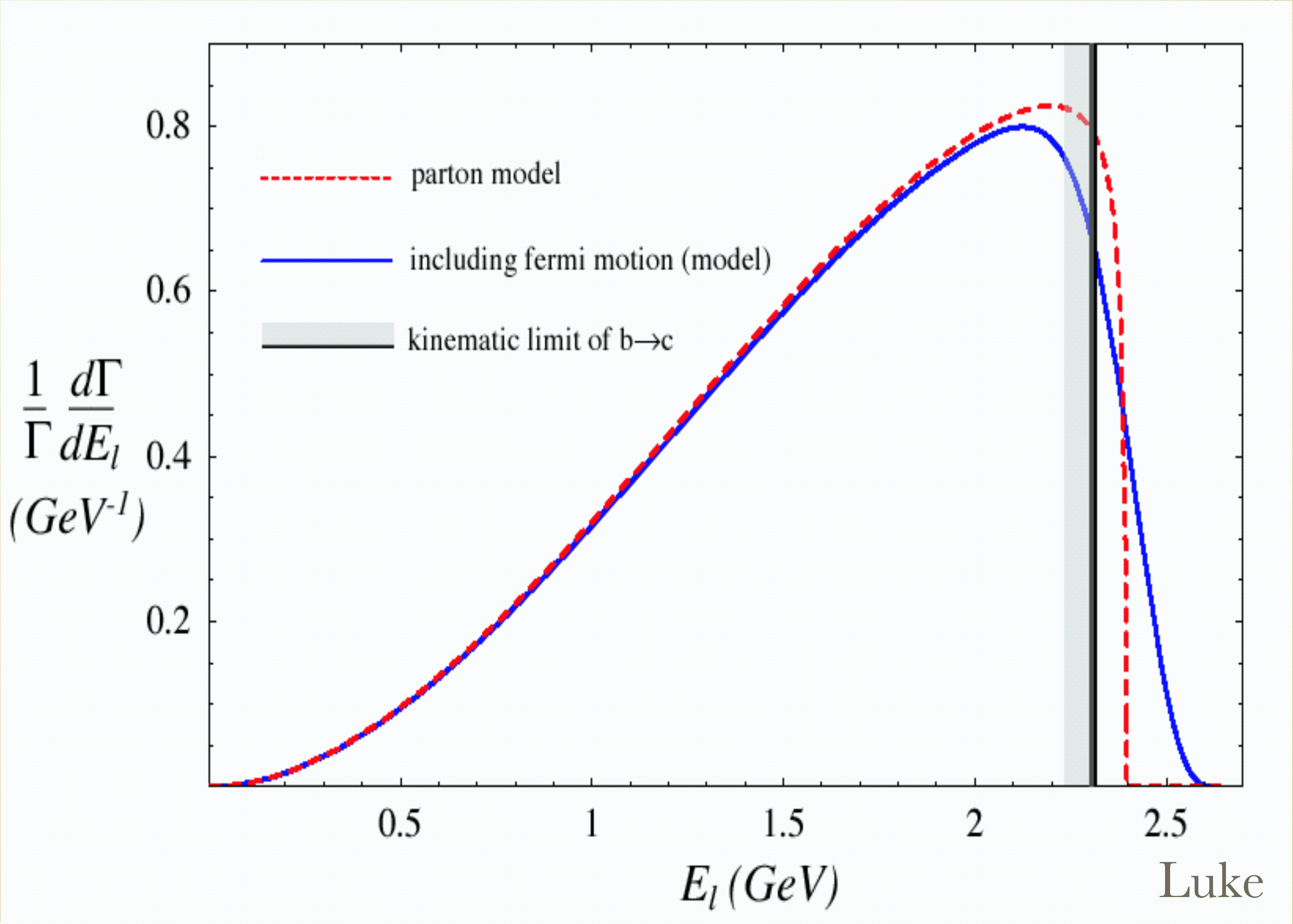
CUTS IN $B \to X_u l v$

Experiments often use kinematic cuts to avoid the b→clv background:

$$m_X < M_D \qquad E_\ell > (M_B^2 - M_D^2)/2M_B \qquad q^2 > (M_B - M_D)^2 \ldots$$

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



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

OPE constraints
e.g. at $q^2=0$

$$\int_{-\infty}^{\bar{\Lambda}} k^2 F(k)\, dk = \frac{\mu_\pi^2}{3} + O(\frac{\Lambda^3}{m_b}) \text{ etc.}$$

Predictions *based* on resummed pQCD Dress Gluon Exponentiation, ADFR	OPE constraints + parameterization without/with resummation GGOU, BLNP

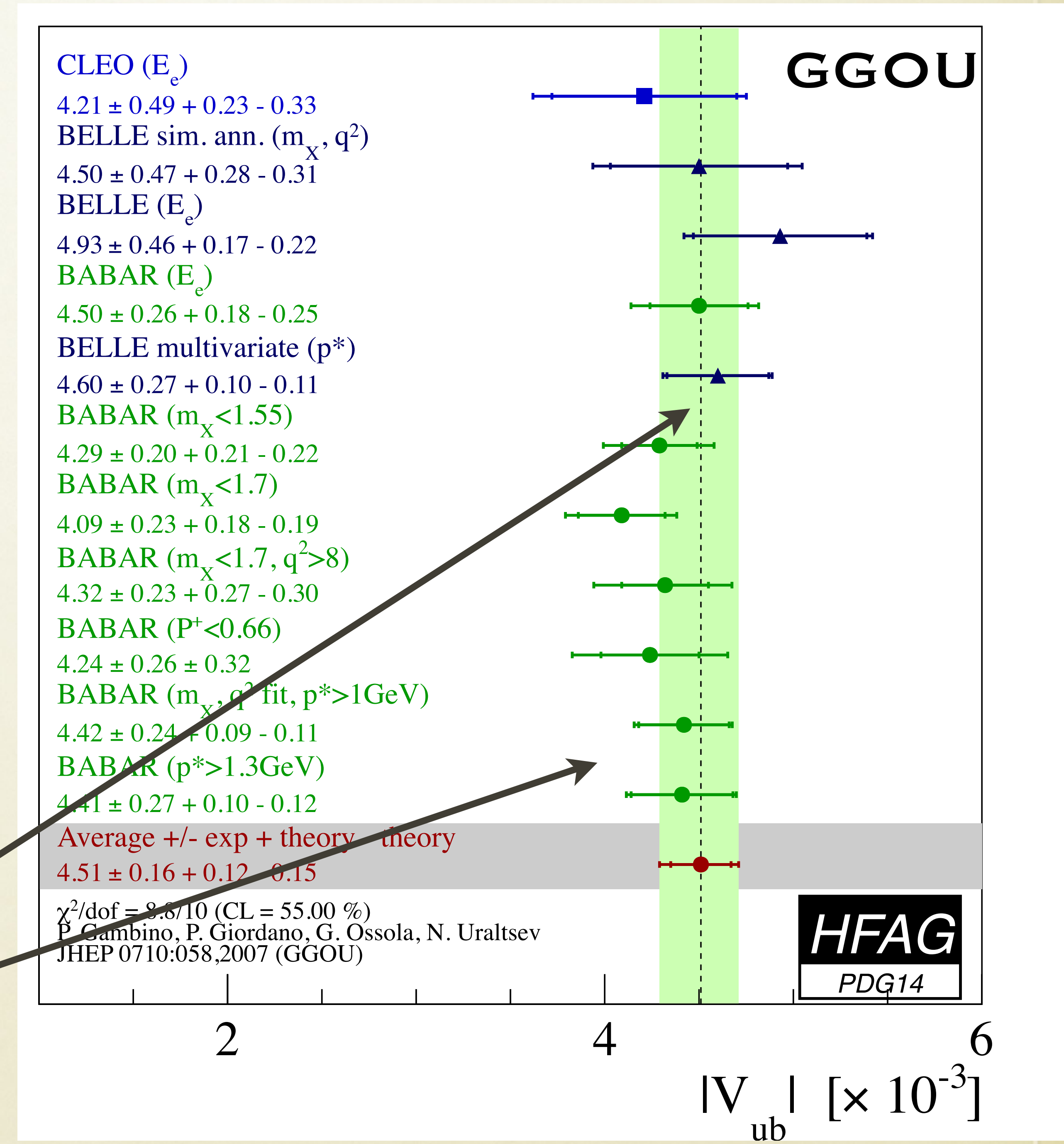
Fit semileptonic (and radiative) data
SIMBA, NNVub

$|V_{ub}|$ DETERMINATIONS

Inclusive: 5% total error

HFAG 2014	Average IV
DGE	4.52(16)(16)
BLNP	4.45(16)(22)
GGOU	4.51(16)(15)

UT fit (without direct V_{ub}):
V_{ub}=3.66(12) 10^{-3}



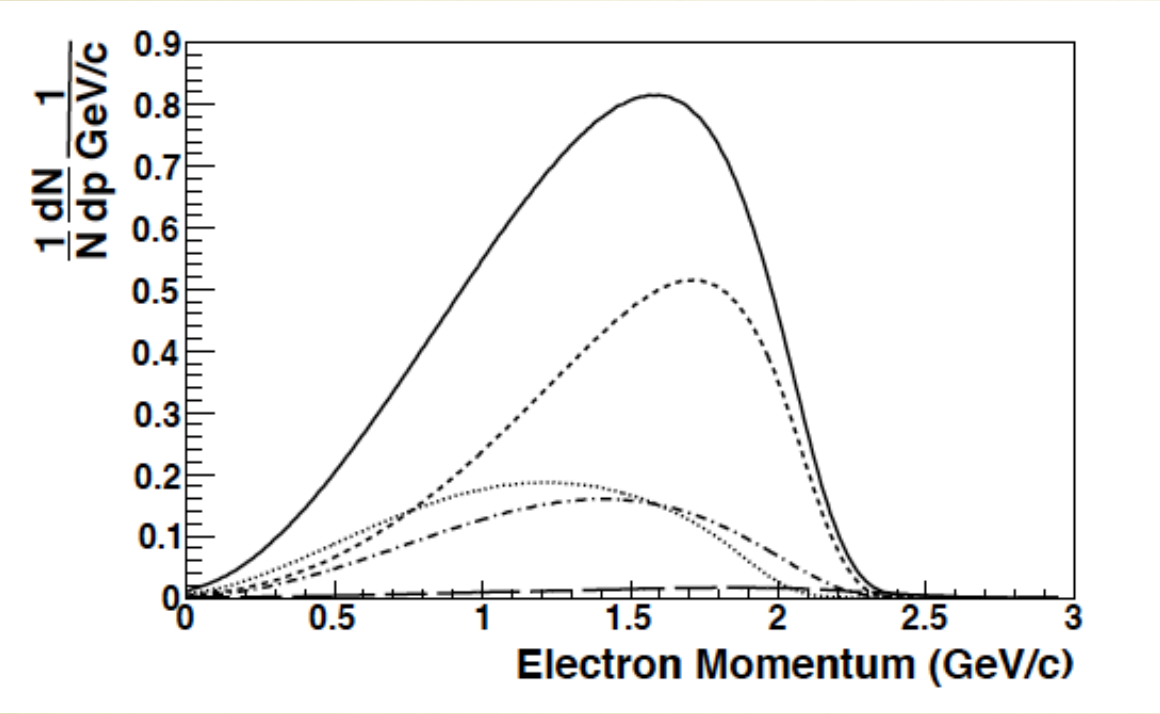
Recent experimental results
are theoretically cleanest (2%)
but based on background modelling.
Signal simulation also relies on theoretical models…

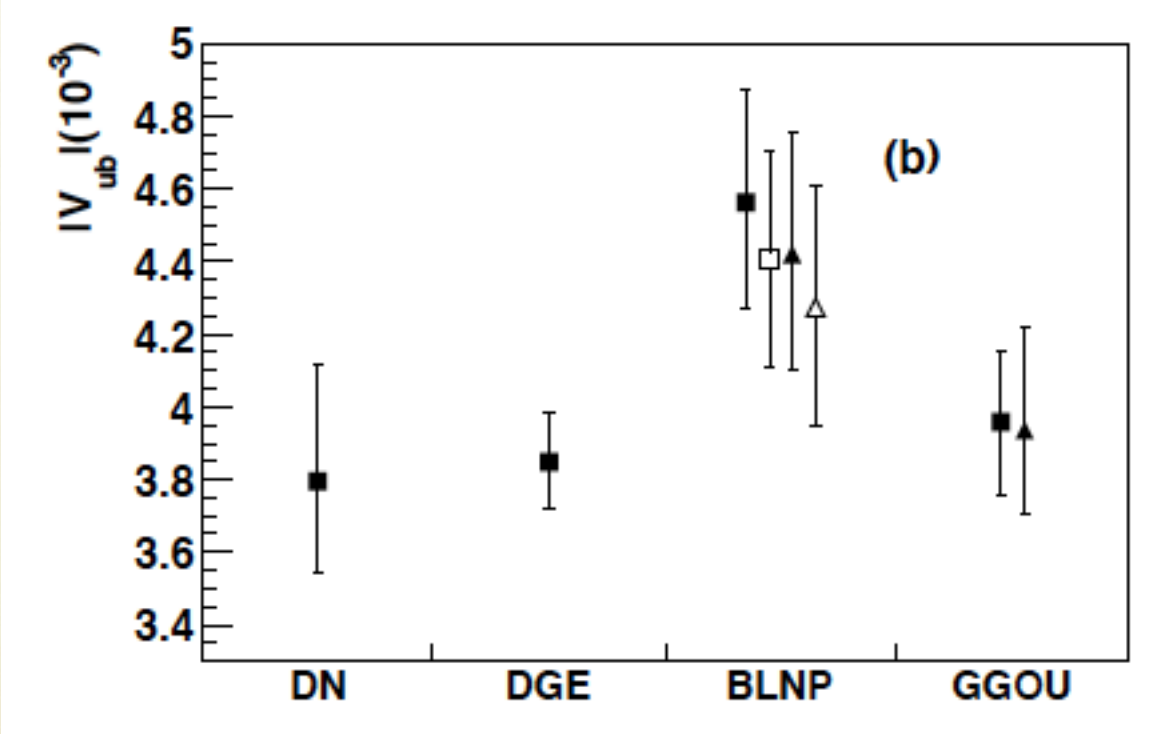
NEW Babar endpoint analysis

1611.05624

High sensitivity of the BR on the shape of the signal in the endpoint region. <u>Single most precise measurement to date, not yet in HFAG</u>

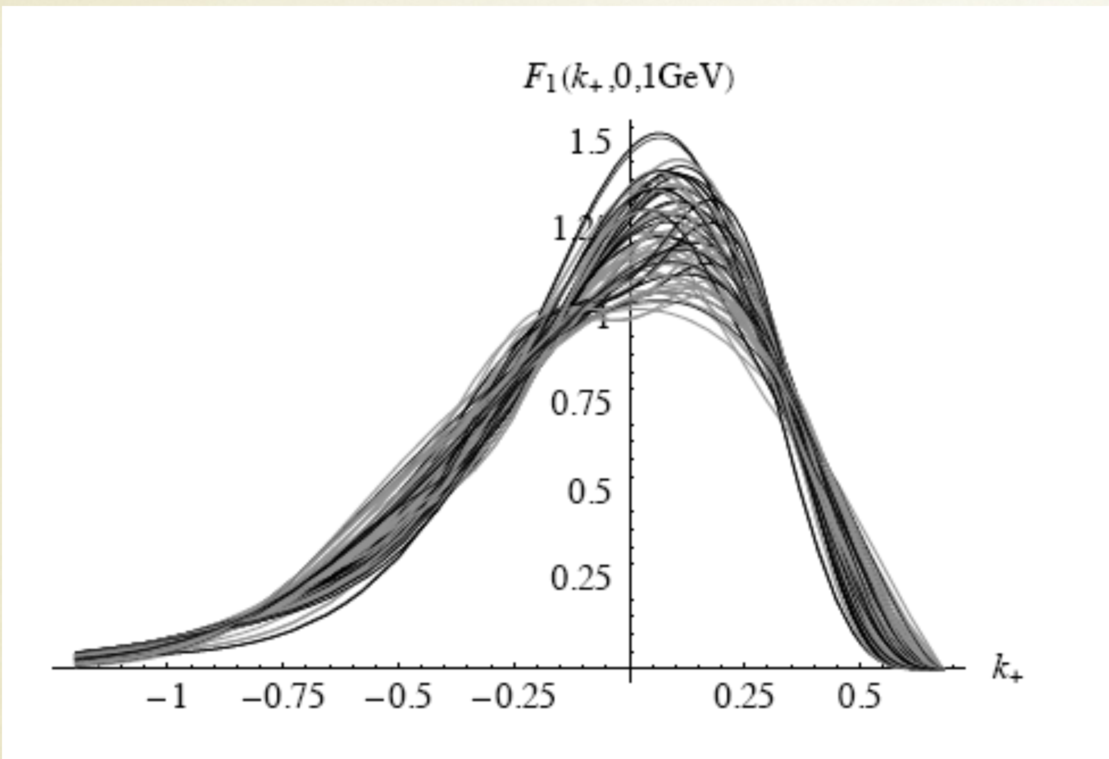
$$\text{GGOU: } |V_{ub}| = (3.96 \pm 0.10_{exp} \pm 0.17_{th}) \times 10^{-3}$$

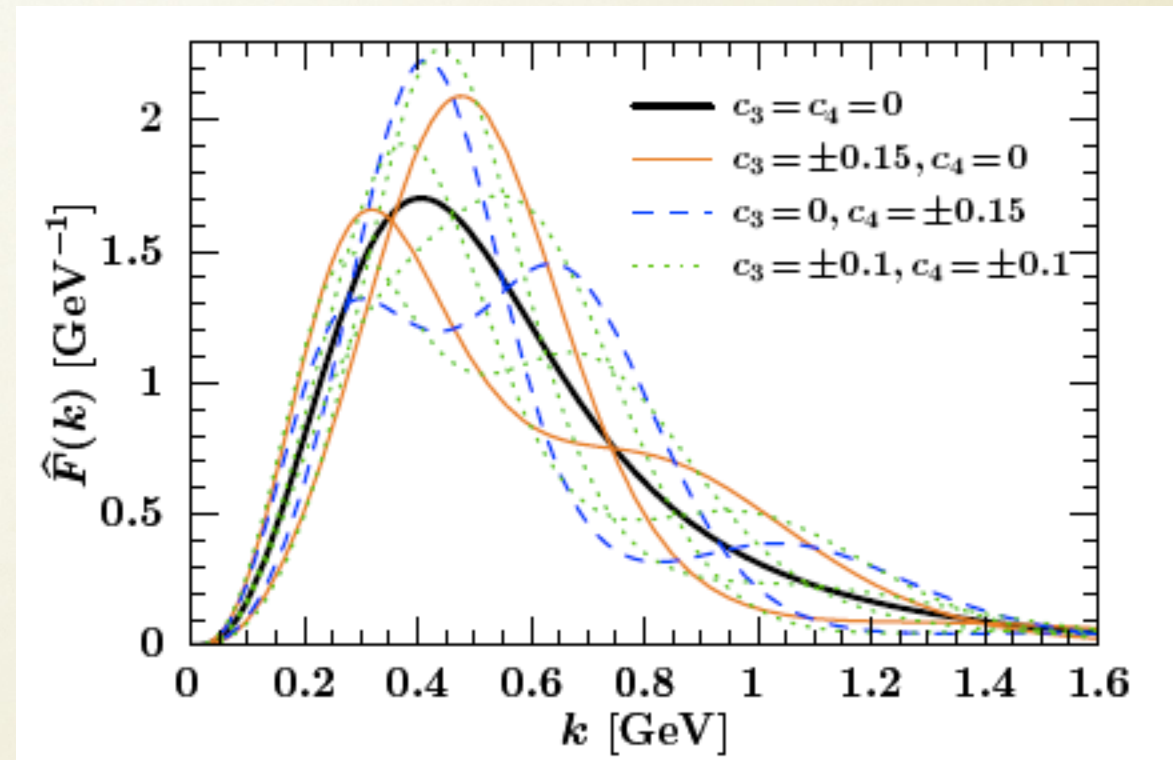




What happens if same is done in other BaBar analyses? What's going on with BLNP?
NB Belle multivariate analysis uses GGOU+DN for the inclusive part

Functional forms





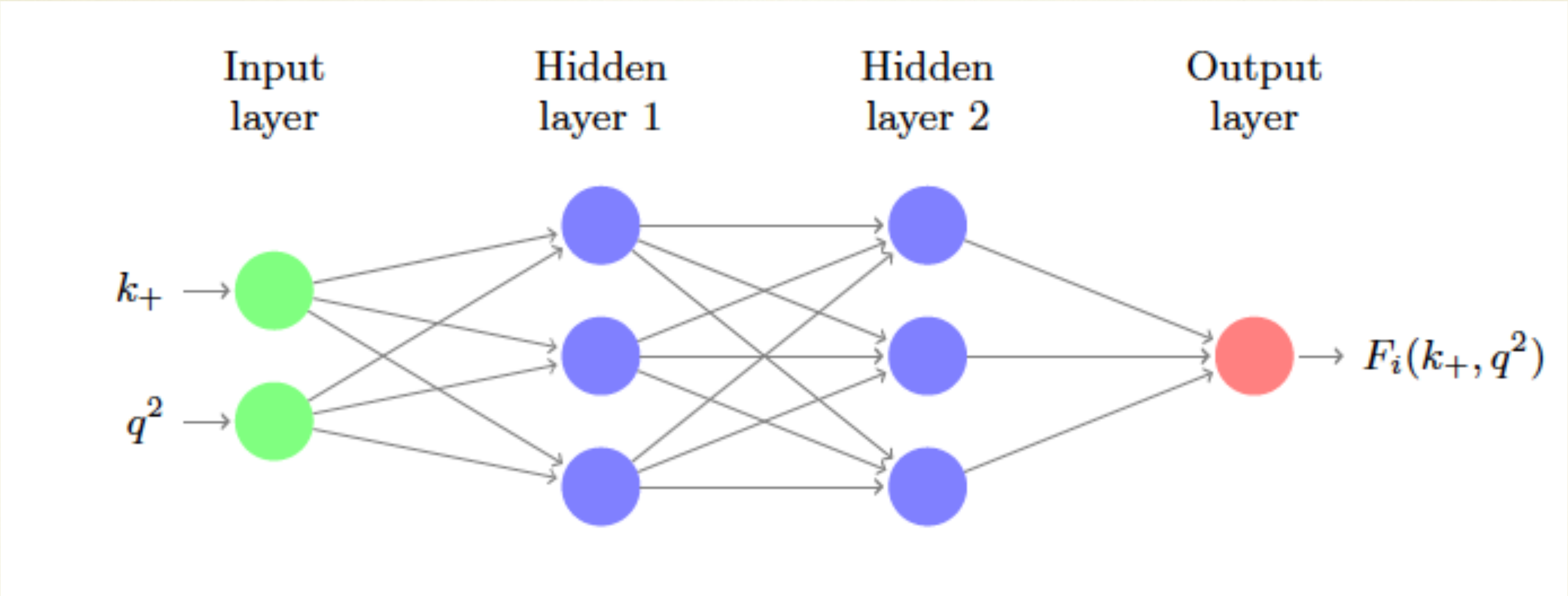
About 100 forms considered in GGOU, large variety, double max discarded. Small uncertainty (1-2%) on V_{ub}

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

Only 2 parameters FF, is that good enough?

The NNVub Project

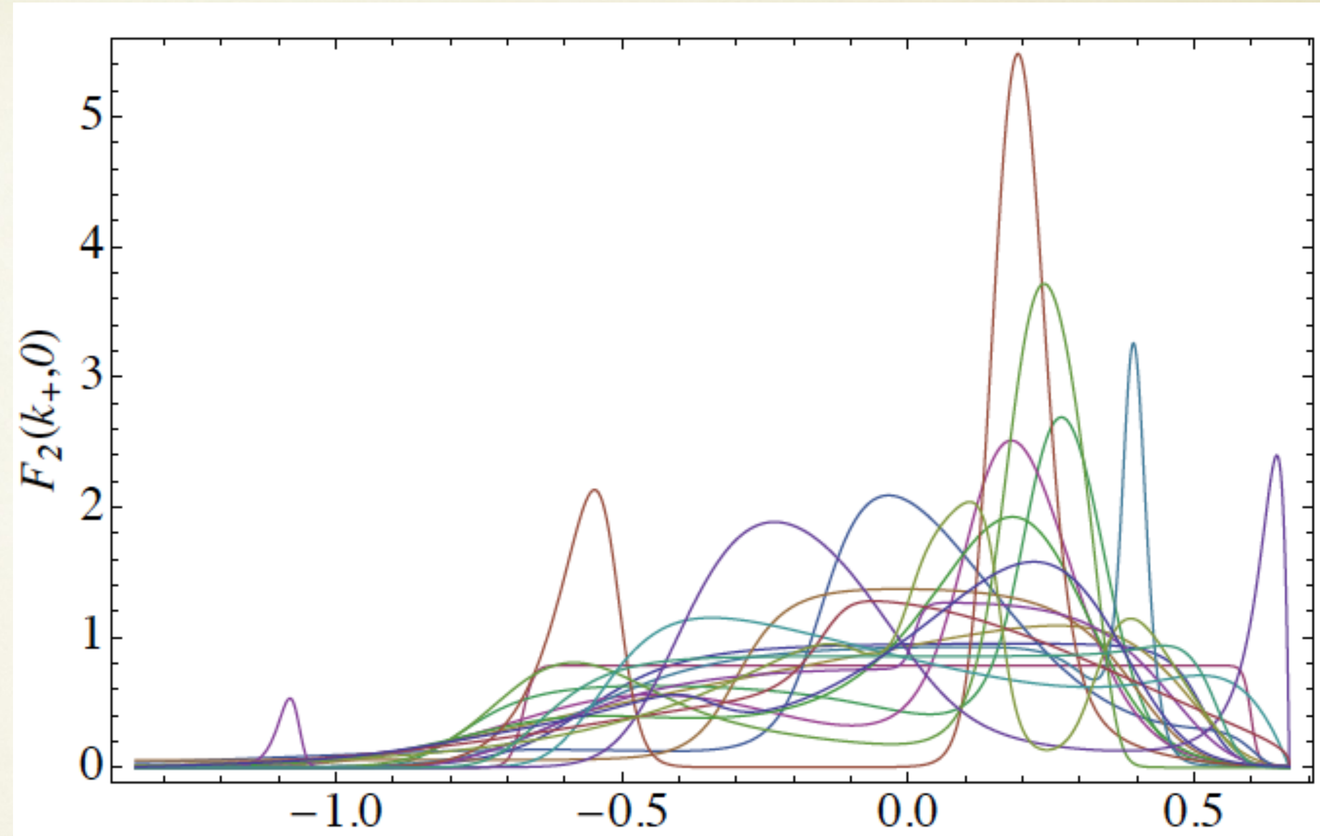
K.Healey, C. Mondino, PG, 1604.07598



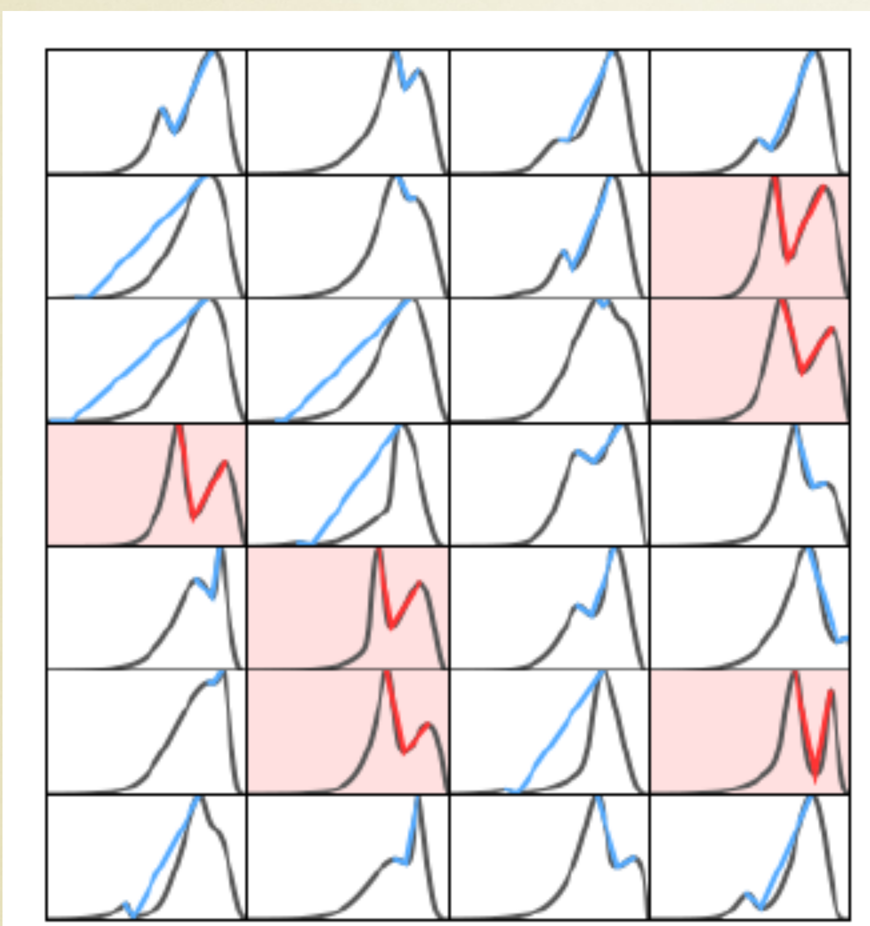
- Use **Artificial Neural Networks** to parameterize shape functions without bias and extract V_{ub} from theoretical constraints and data, together with HQE parameters in a model independent way (without assumptions on functional form). Similar to NNPDF. Applies to $b \to u l \nu$, $b \to s \gamma$, $b \to s l^+ l^-$

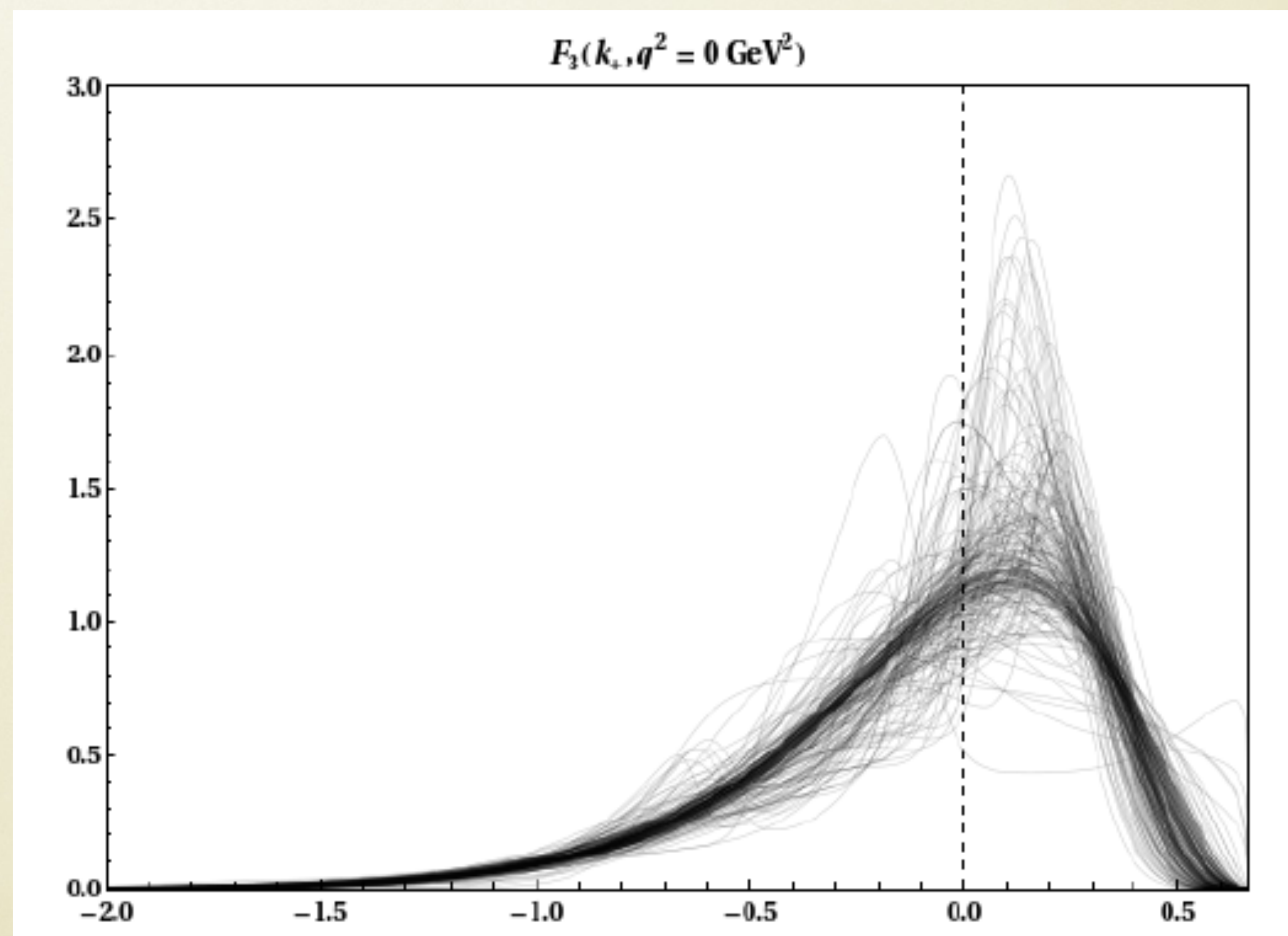
- Belle-II will be able to measure some kinematic distributions, thus constraining directly the shape functions. NNVub will provide a flexible tool to analyse data.

Selection of NN replicas trained on the first three moments only. They are not sufficient. We know photon spectrum in bsgamma: single peak dominance, not too steep

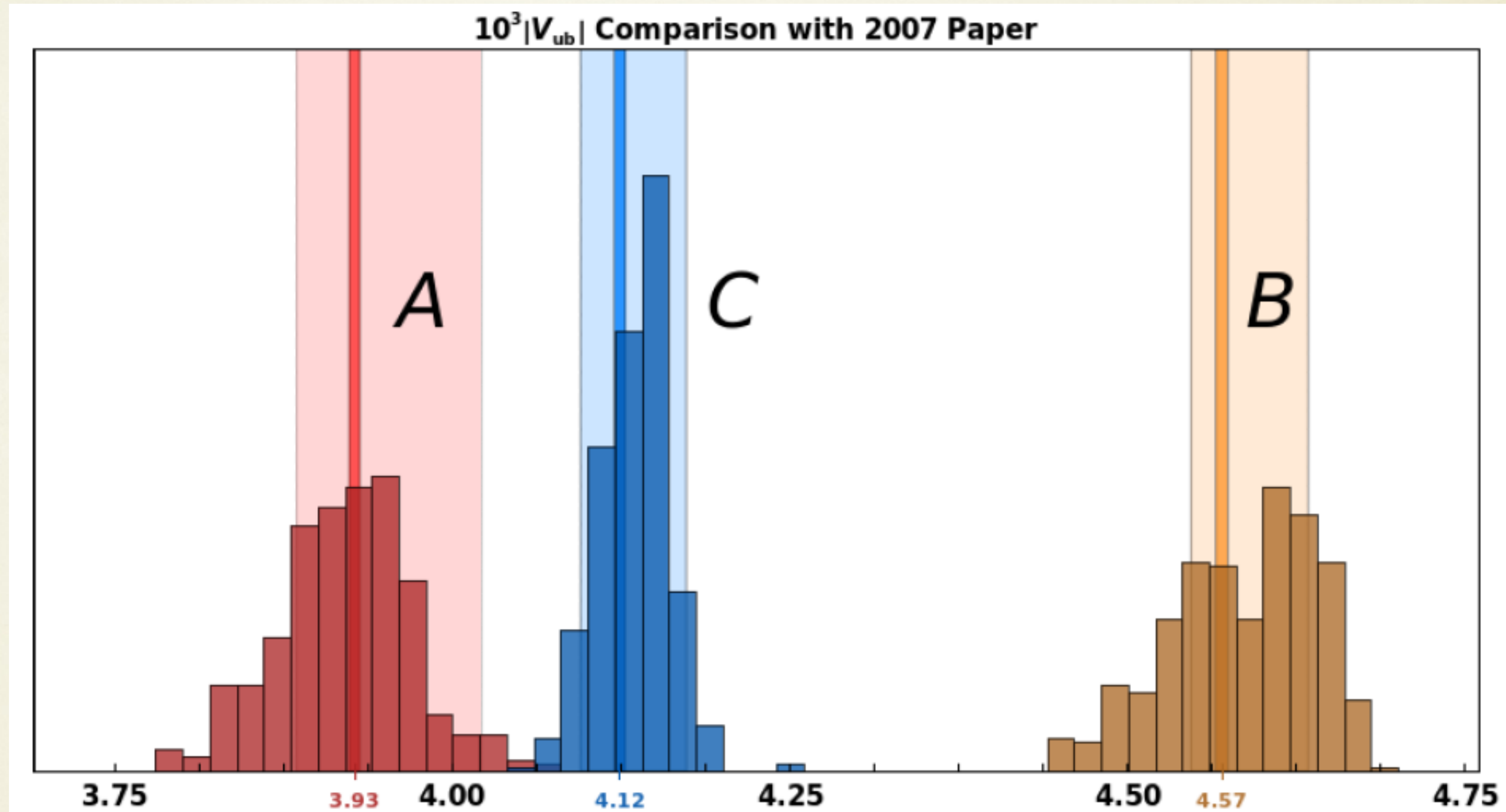


Beware: sampling can be biased by implementation!





Comparison with 2007 paper, same inputs



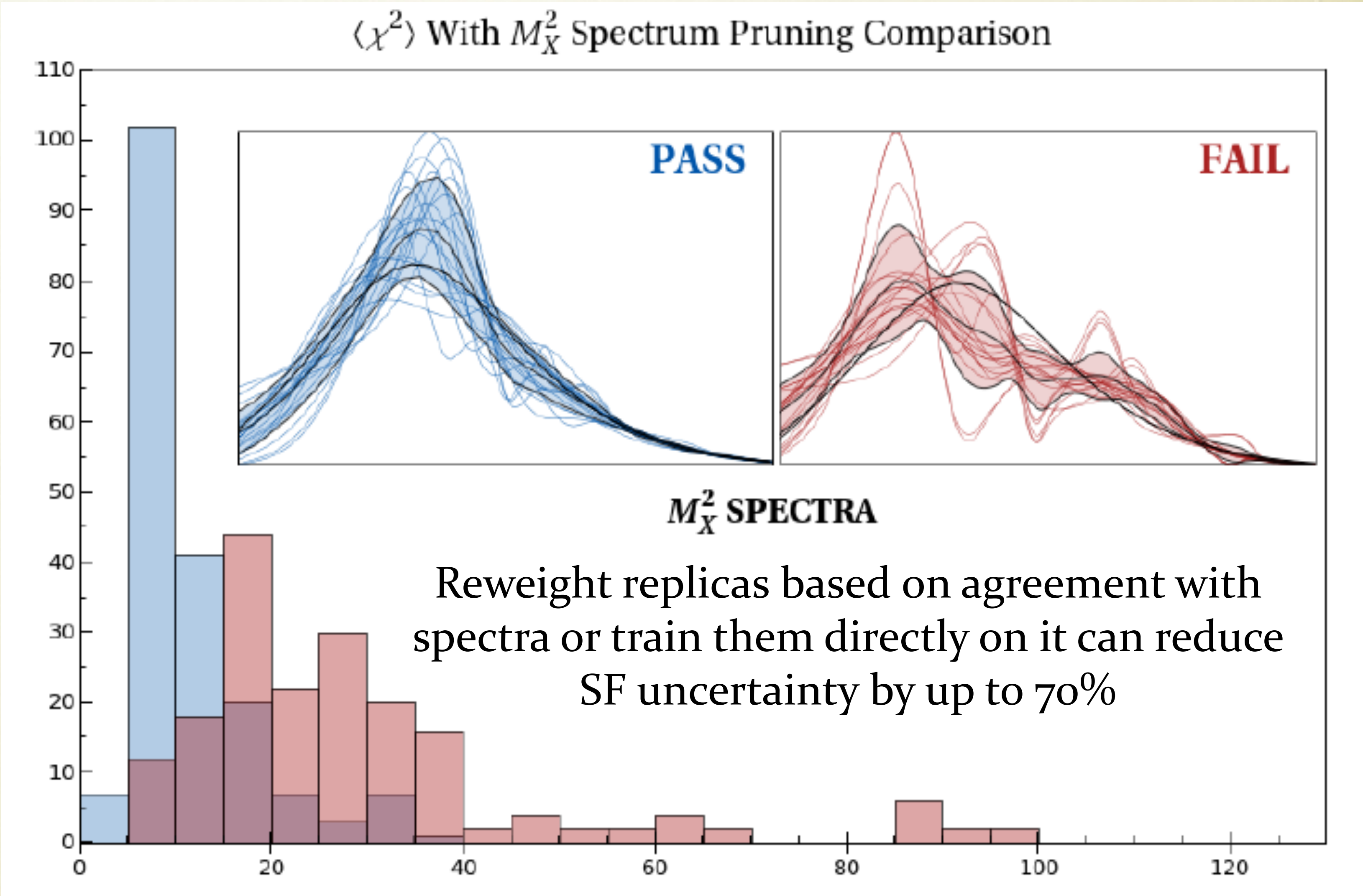
NNVub GGOU(2007)

Experimental cuts (in GeV or GeV^2)	$\lvert V_{ub}\rvert \times 10^3$	$\lvert V_{ub}\rvert \times 10^3$[15]
$M_X < 1.55, E_\ell > 1.0$ Babar [44]	$4.30(20)(^{26}_{27})$	$4.29(20)(^{21}_{22})$
$M_X < 1.7, E_\ell > 1.0$ Babar [44]	$4.05(23)(^{19}_{20})$	$4.09(23)(^{18}_{19})$
$M_X \leq 1.7, q^2 > 8, E_\ell > 1.0$ Babar[44]	$4.23(23)(^{26}_{28})$	$4.32(23)(^{27}_{30})$
$E_\ell > 2.0$ Babar [41]	$4.47(26)(^{22}_{27})$	$4.50(26)(^{18}_{25})$
$E_\ell > 1.0$ Belle [45]	$4.58(27)(^{10}_{11})$	$4.60(27)(^{10}_{11})$

Inputs for constraints from sl fit by Alberti et al, 2014 with full uncertainties and correlations

Prospects @ Belle-II

- Learning from kinematic distributions, e.g. M_X spectrum
- OPE parameters checked/ improved in $b \to u l \nu$ (moments): global NN+OPE fit
- alternative approach SIMBA
  Tackmann, Ligeti, Stewart
- check signal dependence at endpoint
- full phase space implementation of α_s^2 and α_s/m_b^2 corrections
- model/exclude high q^2 tail



At Belle-II we can expect to bring inclusive V_{ub} at almost the same level as V_{cb}

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

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

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

Thanks to measurement of slopes and shape parameters, exp error only ~1.3% extrapolation to zero recoil with CLN parameterization

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

$F(1) = 0.906(13) \Rightarrow \boxed{|V_{cb}| = 39.25(49)_{\rm exp}(53)_{\rm lat}(19)_{\rm QED}\ 10^{-3}}$

Bailey et al 1403.0635 (FNAL/MILC)

1.9% error (adding in quadrature)

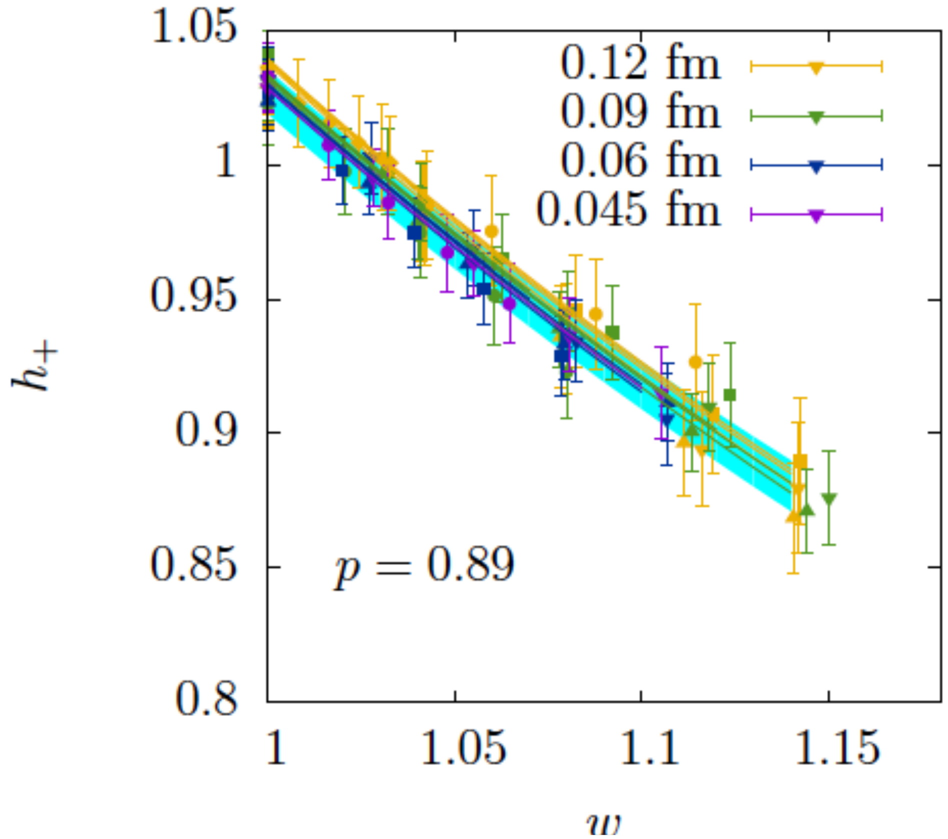
~2.9σ or ~8% from inclusive determination

NEW HPQCD F(1)=0.862(35) preliminary, CKM 2016

NB Heavy Quark Sum Rules estimate F(1)=0.86(2) PG, Mannel, Uraltsev 2012

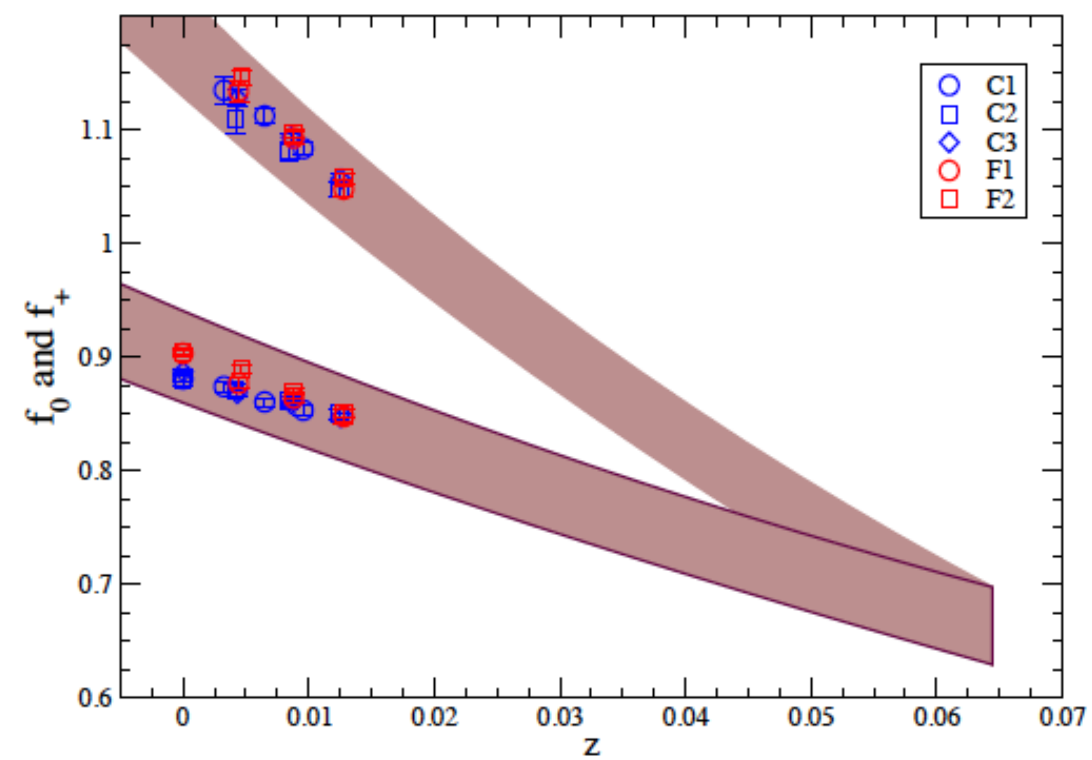
$B \to D$ form factors f_+, f_0 from lattice

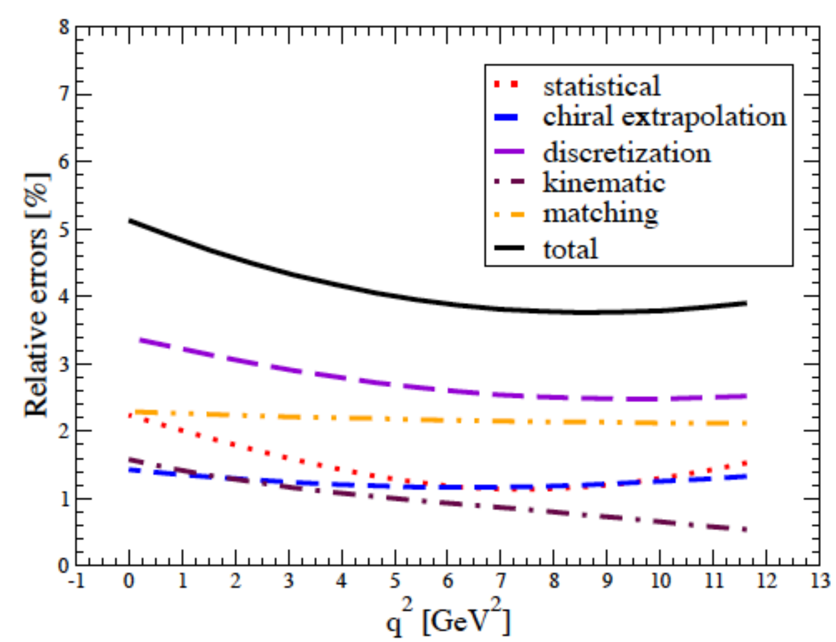
FNAL/MILC 1503.07237



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

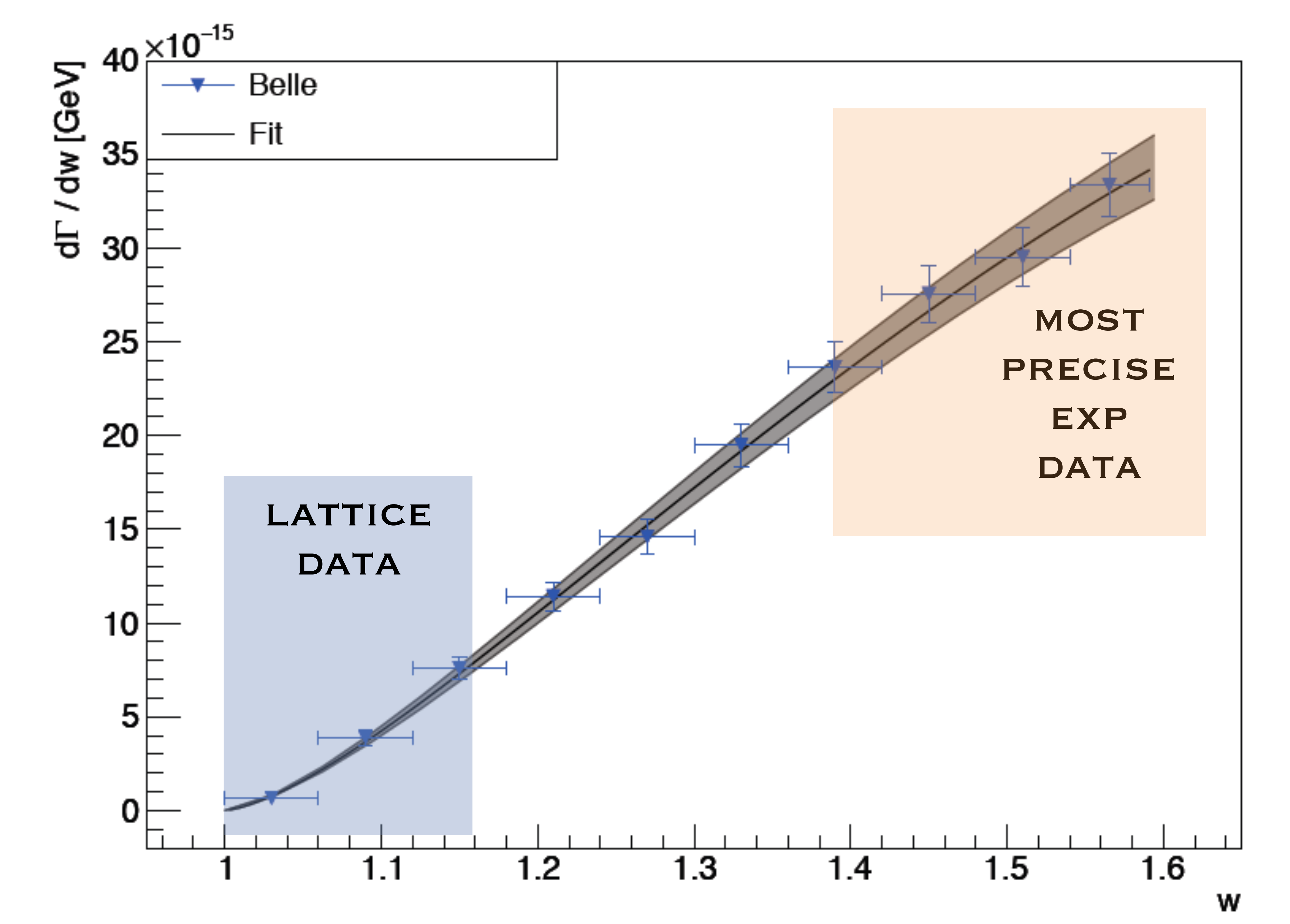
HPQCD 1505.03925





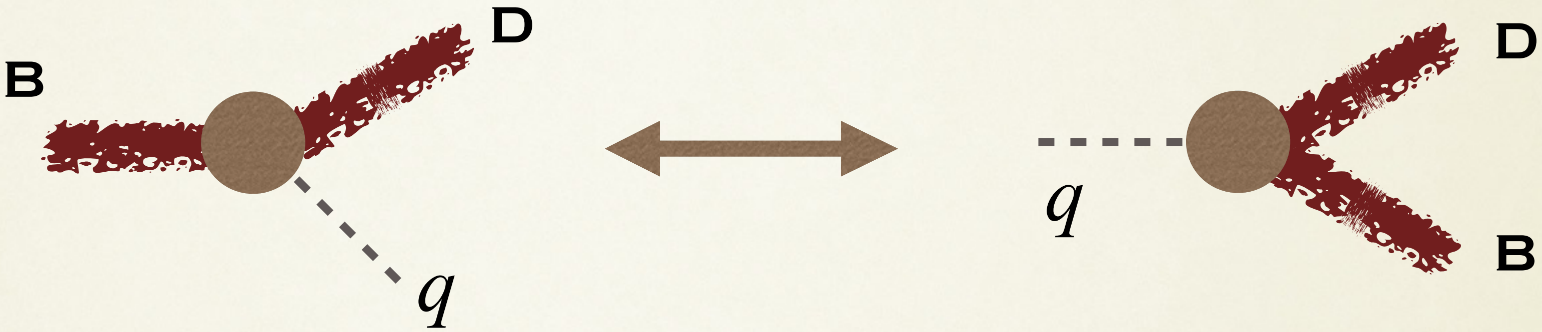
NEW BELLE SPECTRUM 1510.03657

provided in a parametrization independent way



UNITARITY CONSTRAINTS

CROSSING + ANALITYCITY



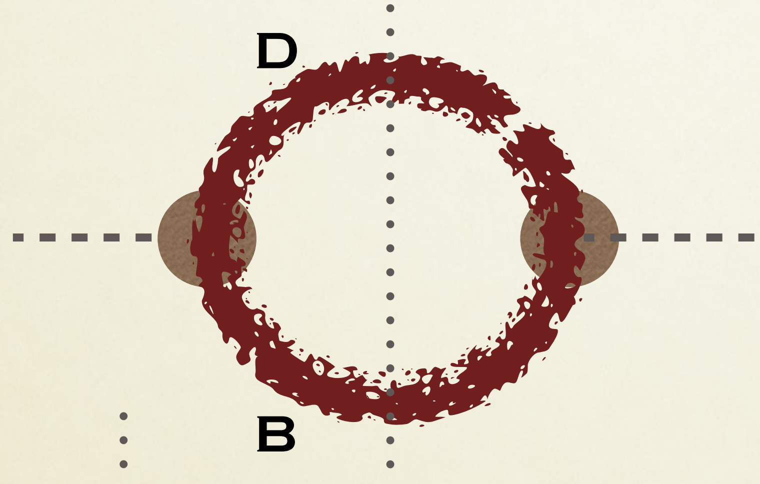
PHYSICAL SEMILEPTONIC REGION

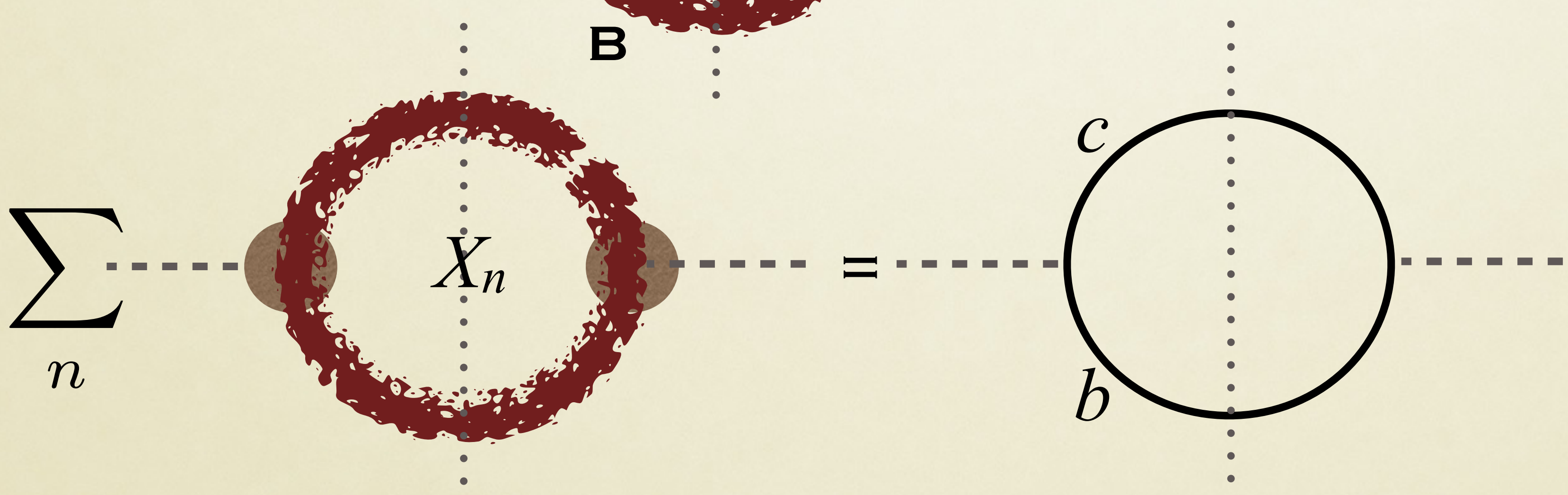
$m_\ell^2 \le q^2 \le (m_B - m_D)^2$

CUT FOR

$q^2 \ge (m_B + m_D)^2$

POLES AT $q^2 = m^2_{Bc}$ ETC

$0 <$  $\propto |f_{+,0}|^2$



+ PERT CORR

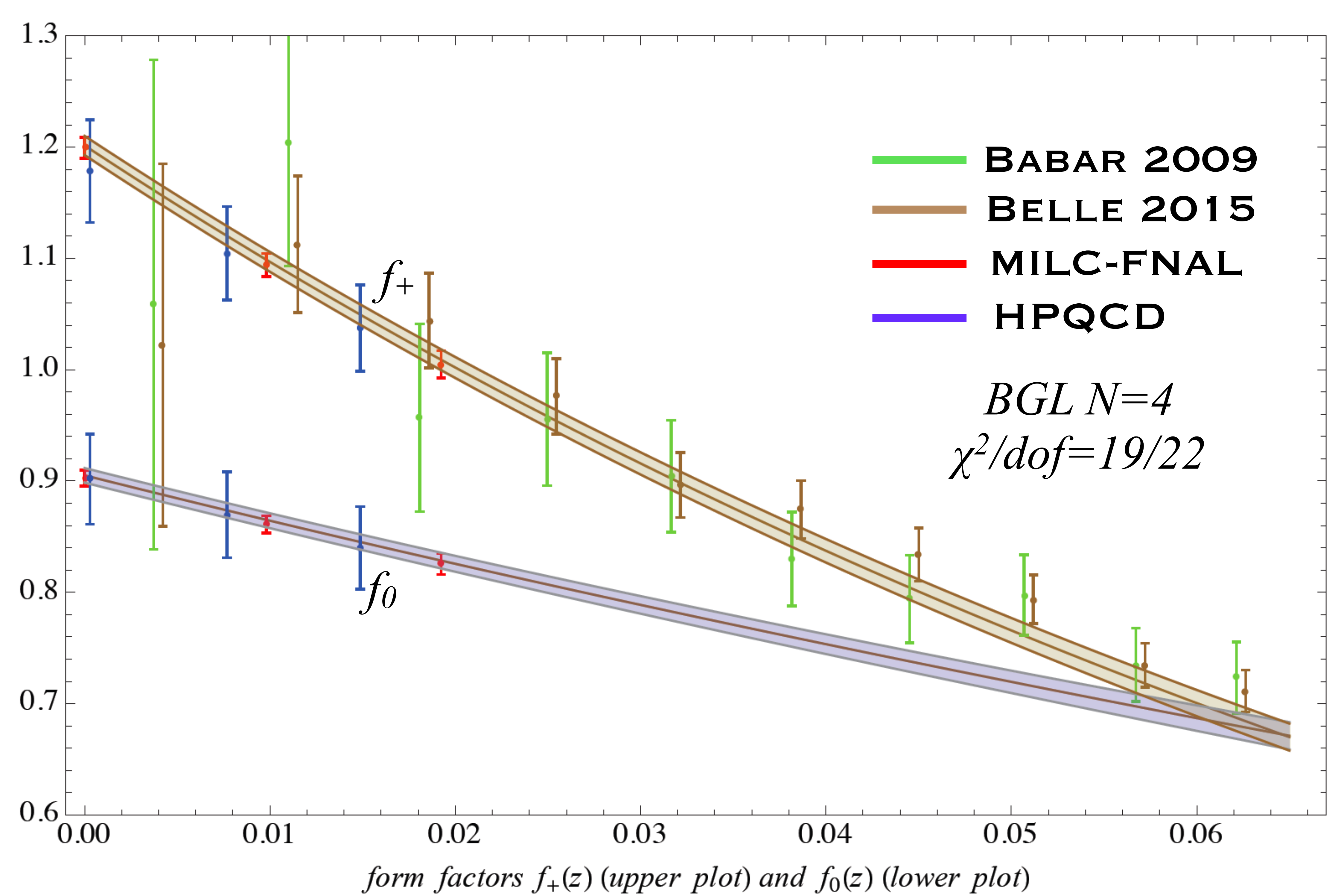
USING QUARK-HADRON DUALITY. DISPERSION RELATIONS→ GLOBAL QHD

The BGL, BCL, CLN parametrizations include in various ways these constraints

Stronger constraints use HQET relations to estimate some of the other channels

Global fit to $B \to Dl\nu$

D.Bigi, PG
arXiv:1606.08030



Global fit to $B \to Dlv$

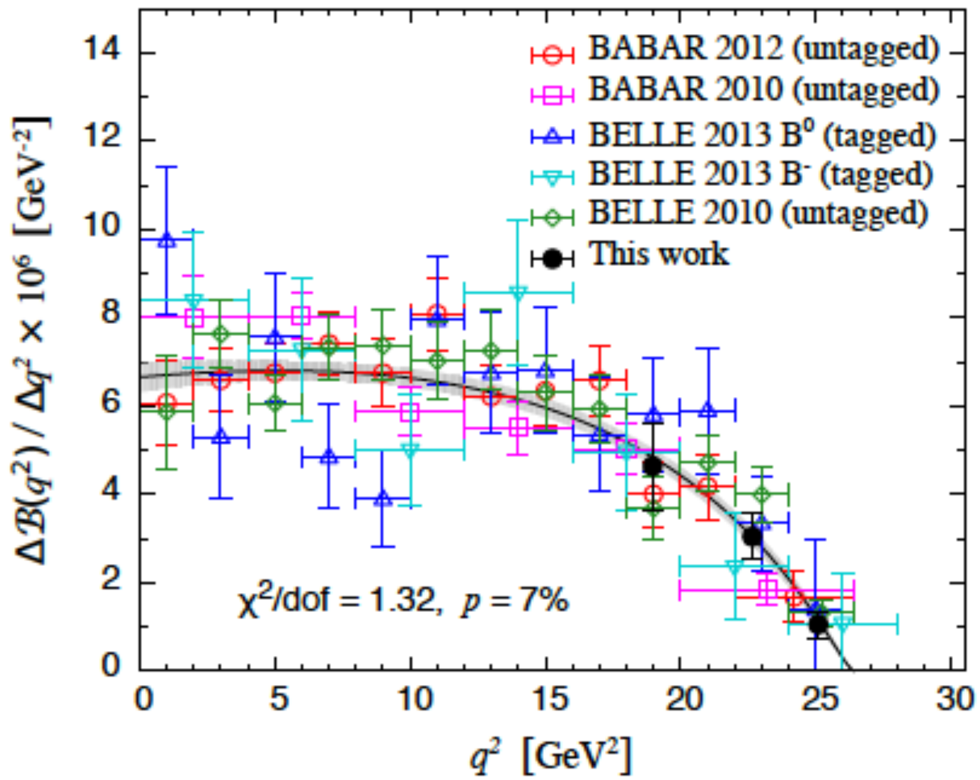
- $|V_{cb}|$***=40.49(0.97) 10***$^{-3}$ compatible with both inclusive and $B \to D^*$, same for BGL, BCL parametrizations
- Constrained fit with **strong unitarity bounds** (weak bounds lead to similar results with slightly larger errors)
- CLN relies too heavily on HQET: it has intrinsic uncertainties that can no longer be neglected
- fit assumes no correlation between FNAL and HPQCD, 3% syst error on Babar data, correct treatment of last bin, no finite size bin effect.
- Non-zero recoil lattice results are crucial: only zero recoil leads to $|V_{cb}|$=39.6(2.0) 10^{-3} (BGL)
- Possible improvements from more precise data (Belle-II, reanalysis of Babar data) and lattice calculations
- ***R(D)=0.299(3)*** 2σ from HFAG average

Prospects for exclusive V_{cb}

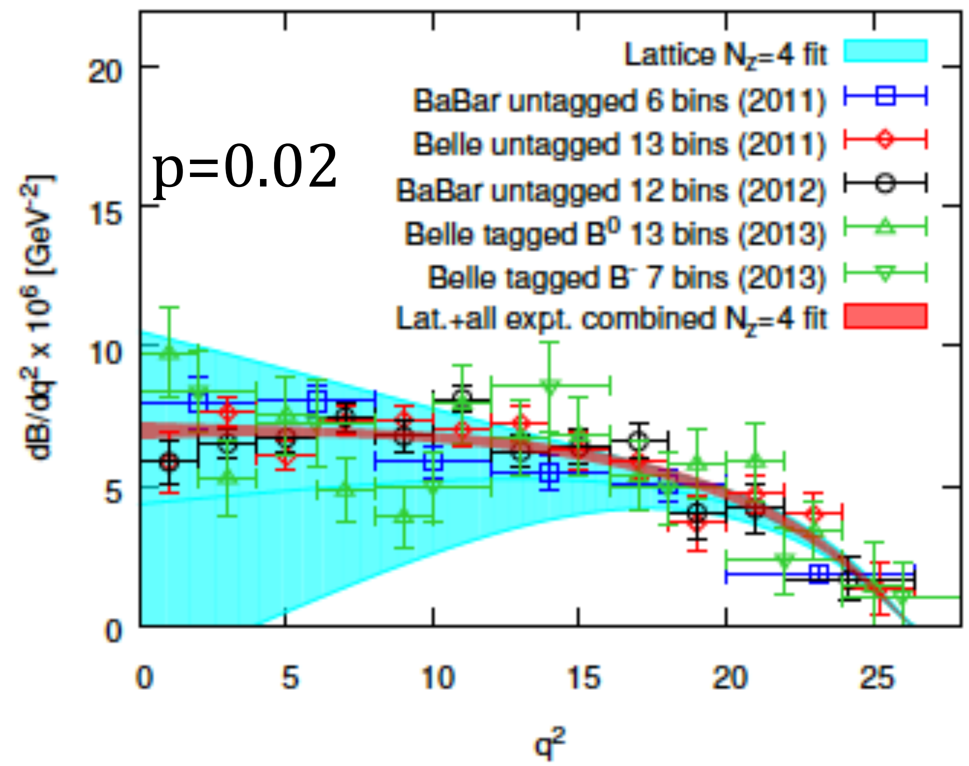
- Need for more lattice calculations and extension of **B→D* ff** to non-zero recoil. Matching at $1/m_Q^3$ for lattice discretization effects under study by FNAL/MILC. Simulations at physical pion mass and $m_b\, a \lesssim 1$?
- *All B→D* analyses based on CLN: **errors somewhat underestimated**. However the spectrum is measured precisely and extrapolation to zero-recoil are a small effect. **New Belle 1702.01521 permits alternative approach!***
- **Heavy quark sum rules** favor smaller F(1)=0.86(2) leading to agreement with inclusive. Difficult to improve, how good are the BPS arguments used?
- **QED/EW corrections**: SD log 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 decay rate?
- **New channels** (Bc, Bs, Λ_b) at Belle-II and LHCb, can also be combined for unitarity bounds, better understanding of D^{**}

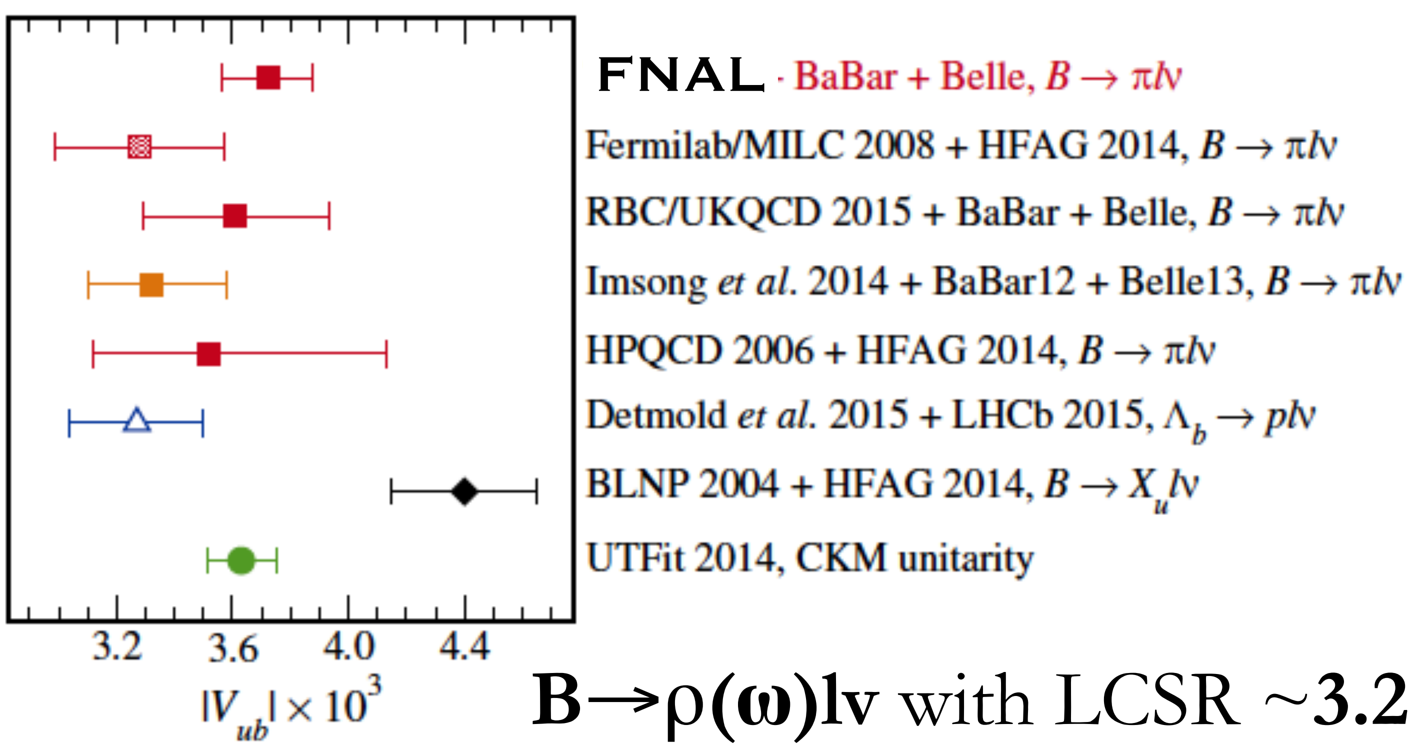
Recent lattice $B \to \pi$ results

RBC/UKQCD 1501.05373



FNAL/MILC 1503.07839





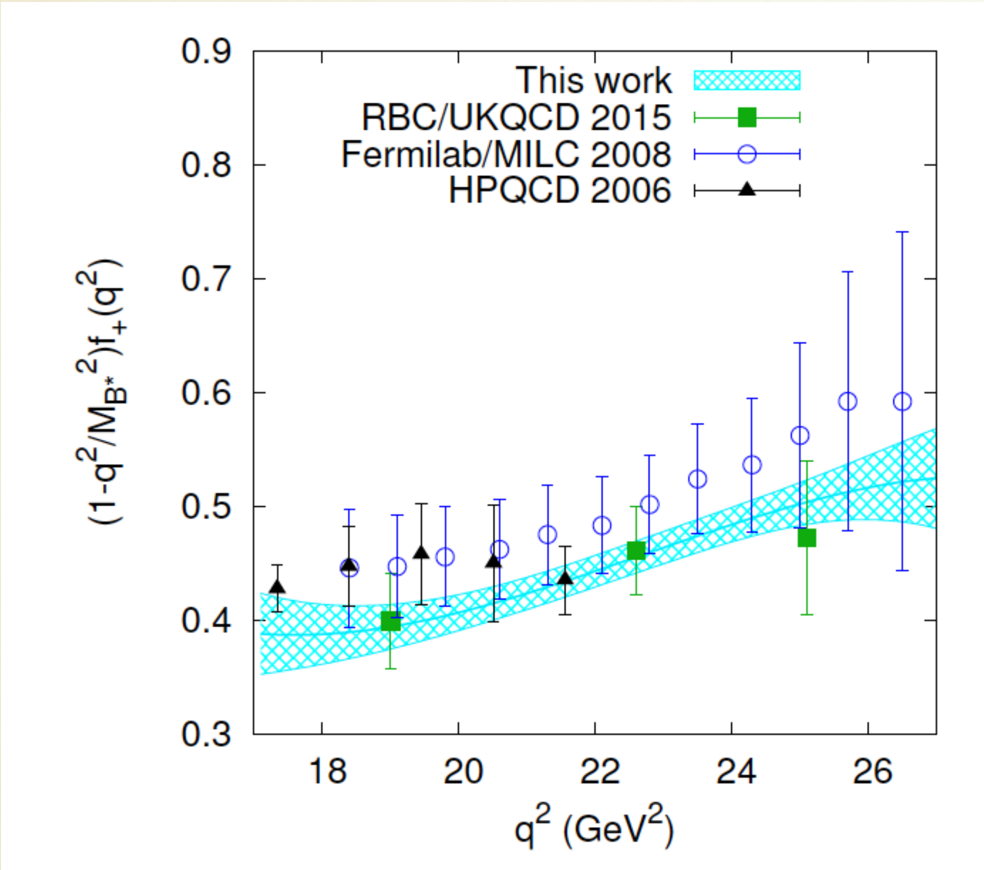
FNAL/MILC 3.72(16) 10^{-3}
only 4.3% error
2.2σ from inclusive
RBC/UKQCD 3.61(32) 10^{-3}
1.9σ from inclusive
LCSR 3.32(26) 10^{-3}
2.9σ from inclusive

$B \to \rho(\omega)l\nu$ with LCSR ~**3.2(4) 10^{-3}** Bharucha,Straub,Zwicky 2015

LHCb studied **$\Lambda_b \to pl\nu / \Lambda_b \to \Lambda_c pl\nu$** depends on V_{cb} employed but low

Recent lattice results

1503.07839



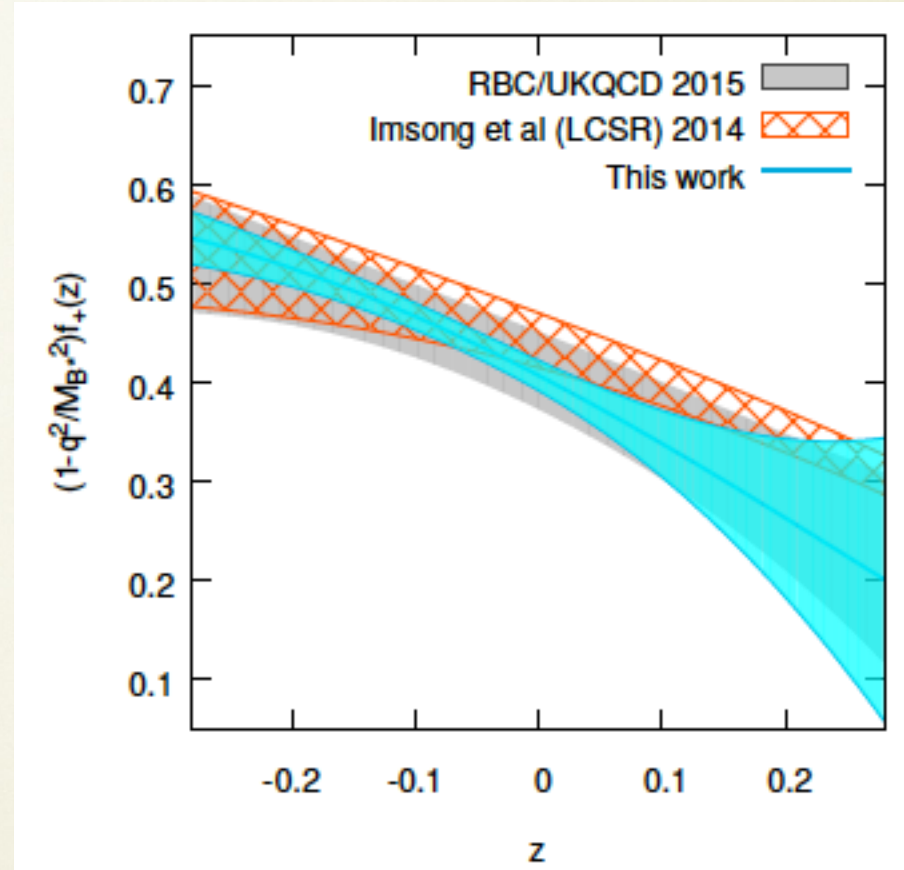


Table XVI. Results of the combined lattice+experiment fits with $N_z = 4$;.

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)

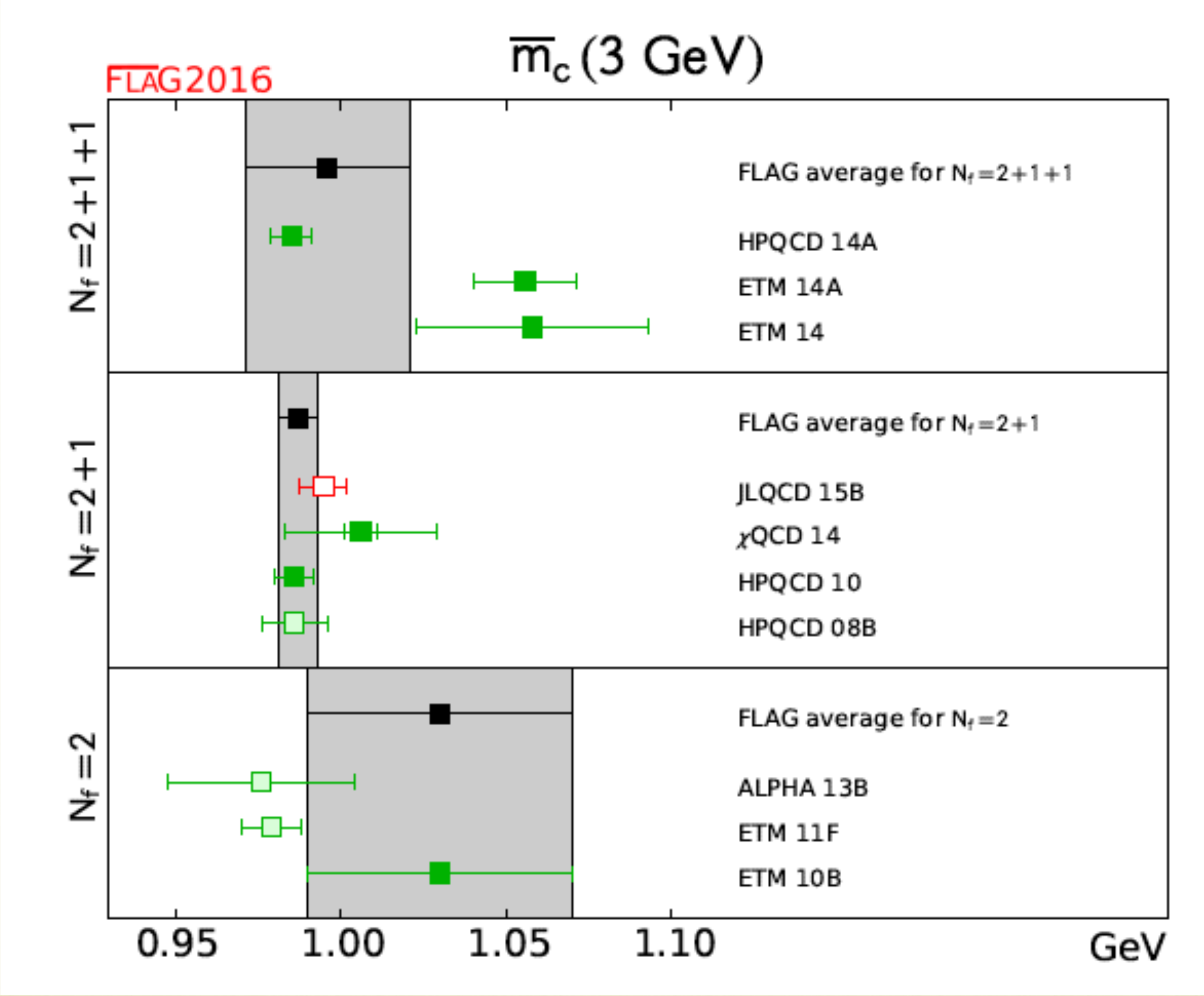
Prospects: further improvements in LQCD, much more data @ BelleII, $B_s \to Kl\nu$ and other channels @Belle-II and LHCb, $B \to \pi\pi l\nu$ vs $B \to \rho l\nu$??

Summary

- Improvements of OPE approach to s.l. decays continue. **No sign of inconsistency in this approach so far**, **competitive m_b-m_c determination.**
- Exclusive/incl. tension in V_{cb} remains (2.9σ, 8%) only in the D^* channel. The **D channel is becoming competitive and is compatible with both**. The remaining tension calls for new lattice analyses and new data
- Exclusive/incl tension in V_{ub} might be receding because of new FNAL/MILC and HPQCD results and of preliminary Babar results. Significant progress will come with Belle-II (using NNVub/SIMBA frameworks) and further LHCb data.
- New physics explanations look quite constrained for both V_{ub} and V_{cb}..
- **After 40 years of *b* physics, things may not be simple (we are becoming sensitive to nasty details) but are still exciting: this seems to bode well for the future!**

BACK-UP SLIDES

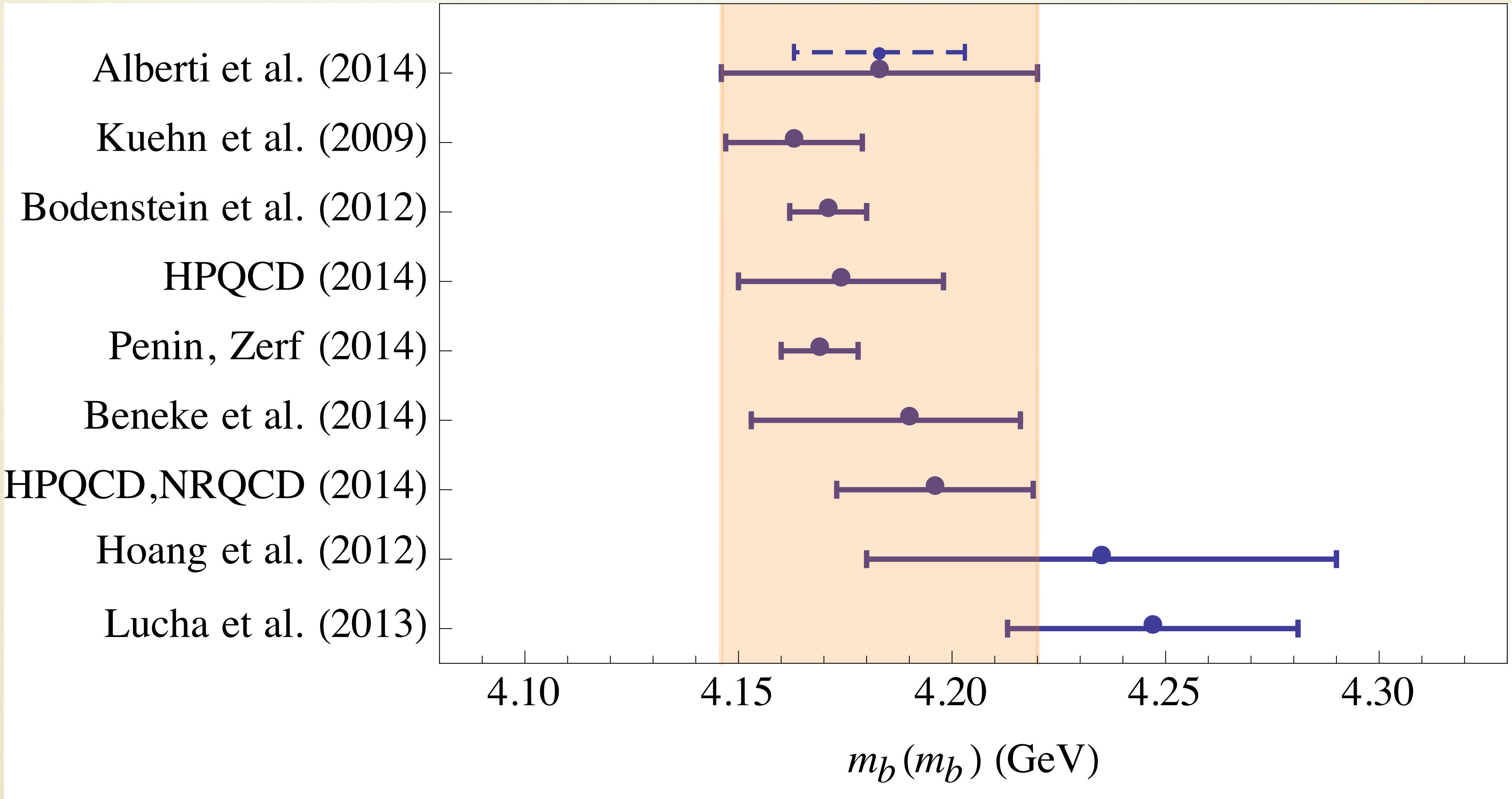
CHARM MASS DEPENDENCE



FIT PERFORMED WITH ETM CHARM MASS: $m_c(3GeV)=1.056(16)GeV$

V_{cb} only slightly smaller

CHECK: BOTTOM MASS

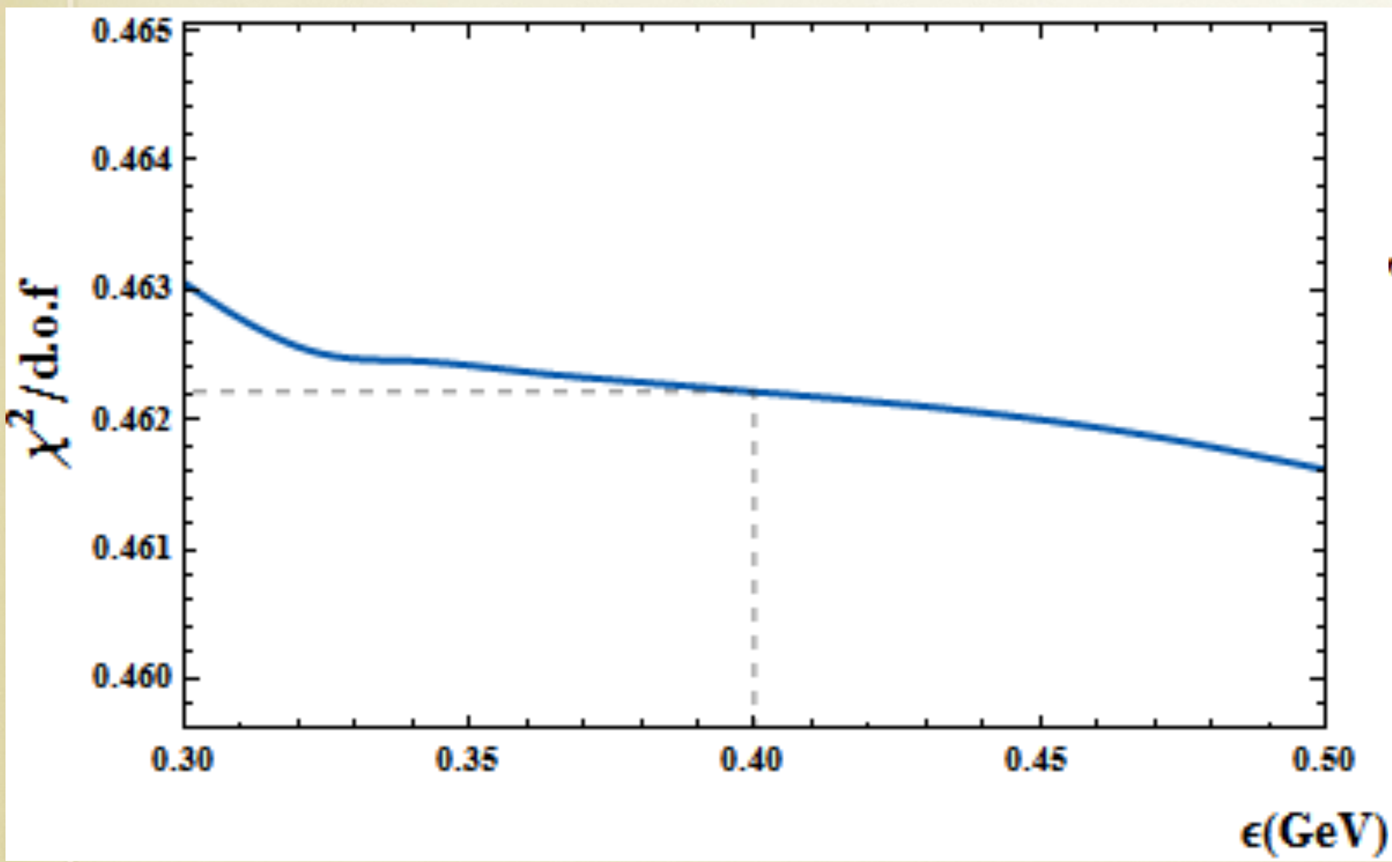


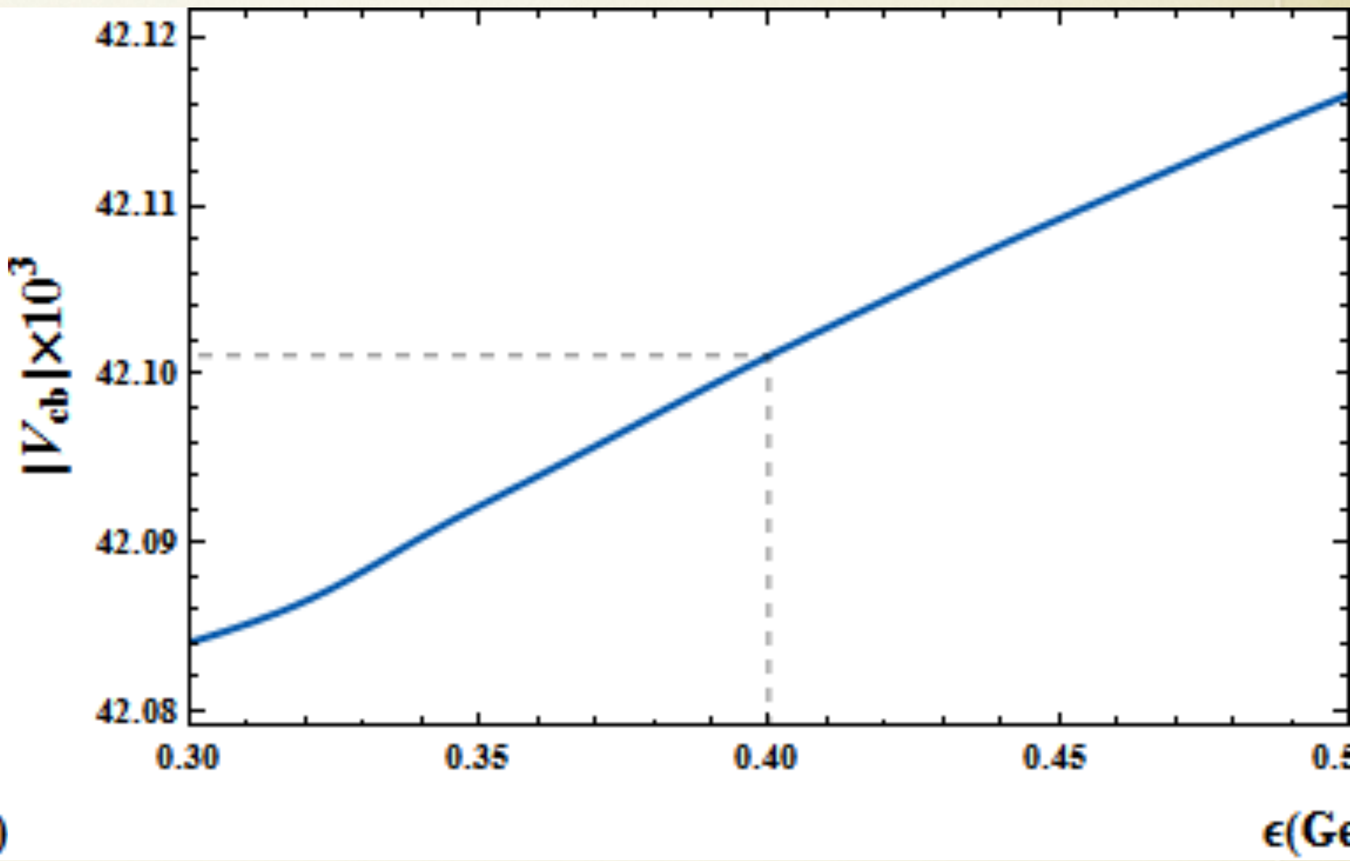
The fit gives $\boldsymbol{m_b^{kin}}$**(1GeV)=4.553(20)GeV**

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

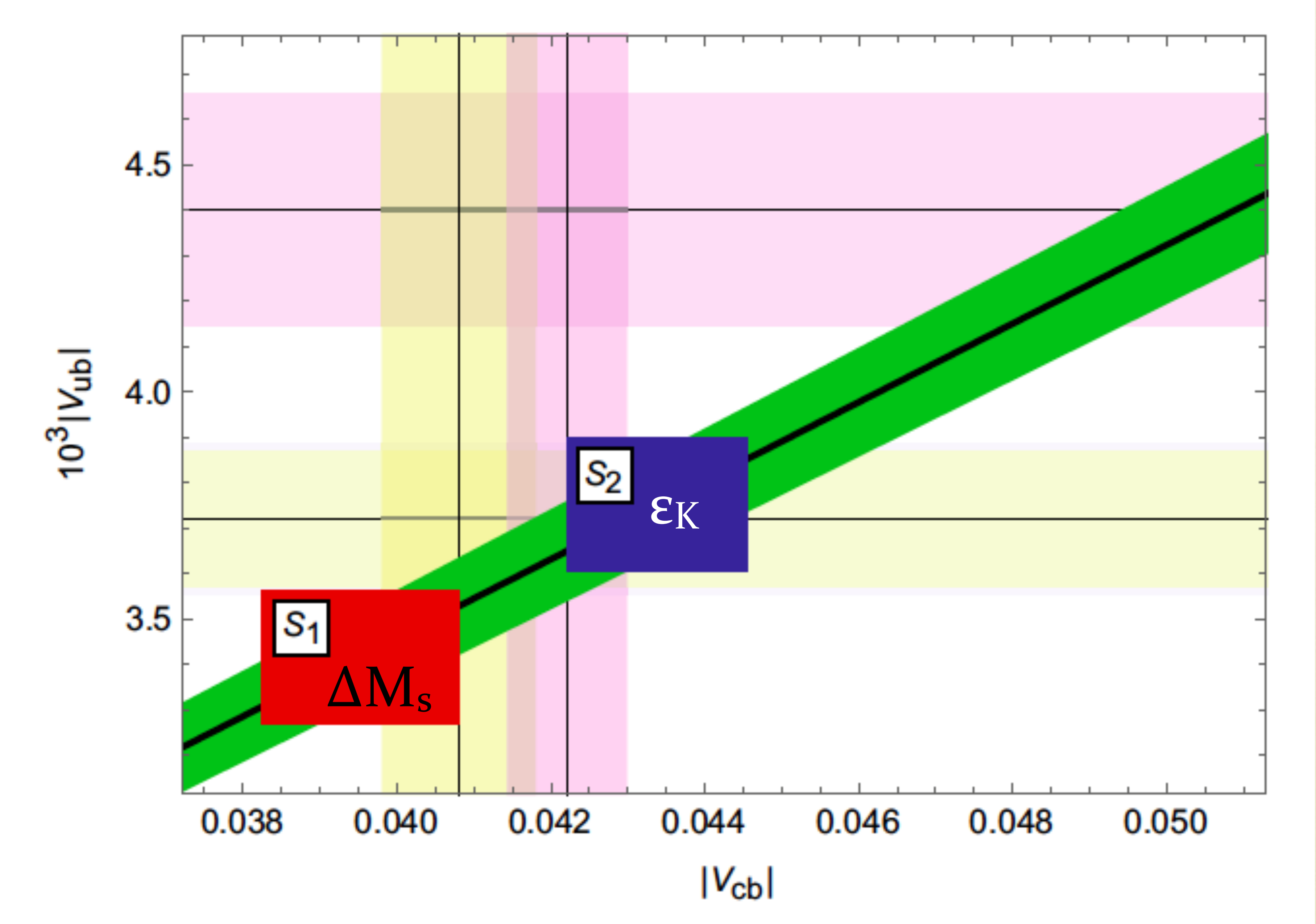
$\boldsymbol{\overline{m}_b(\overline{m}_b)}$**=4.183(37)GeV**

EXCITATION ENERGY DEPENDENCE





UUT analysis in CMFV models



$$\left|\frac{V_{ub}}{V_{cb}}\right|_{CMFV} = 0.864 \pm 0.0025$$

Blanke, Buras 1602.04020

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

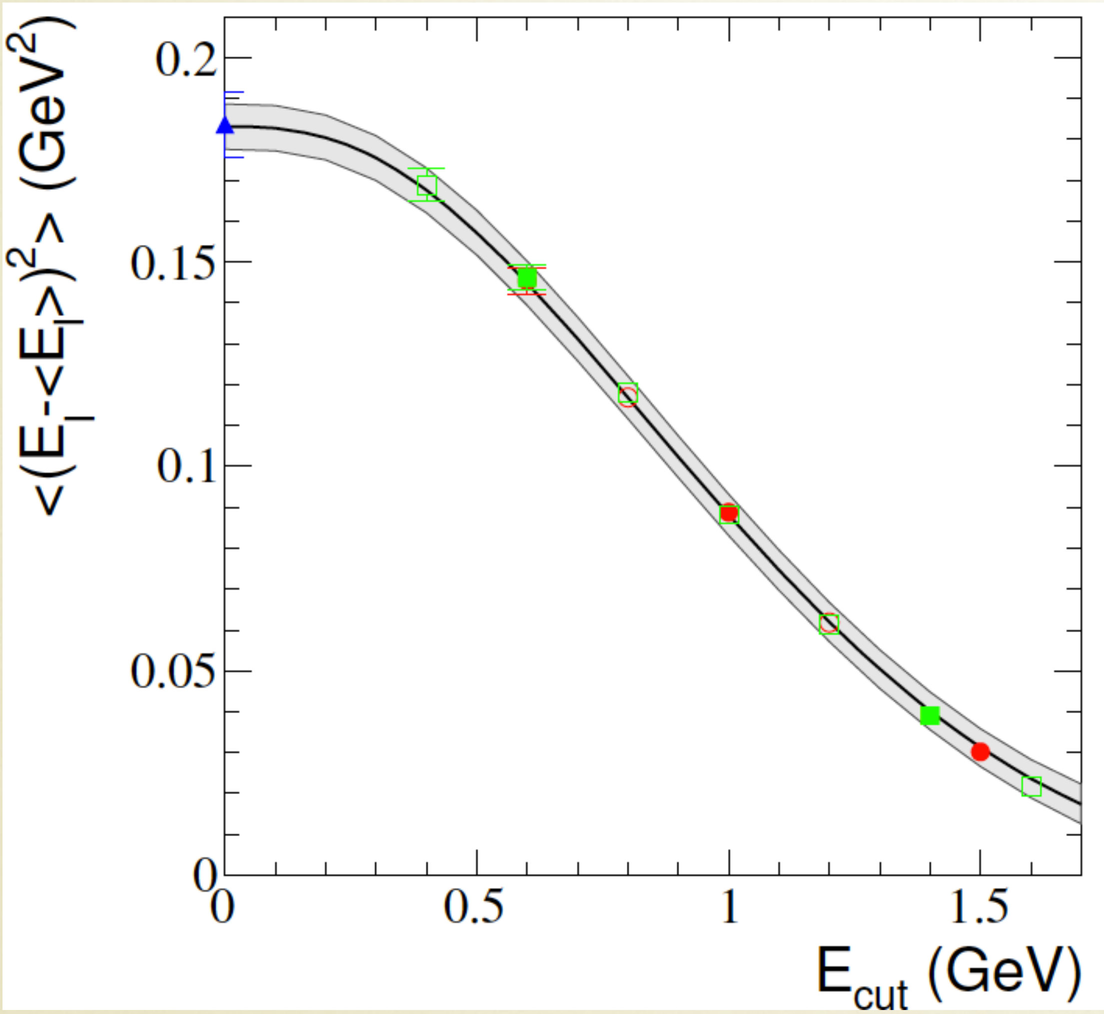
- Disclaimer: the list is not meant to be inclusive. I am focusing on the publicized results.

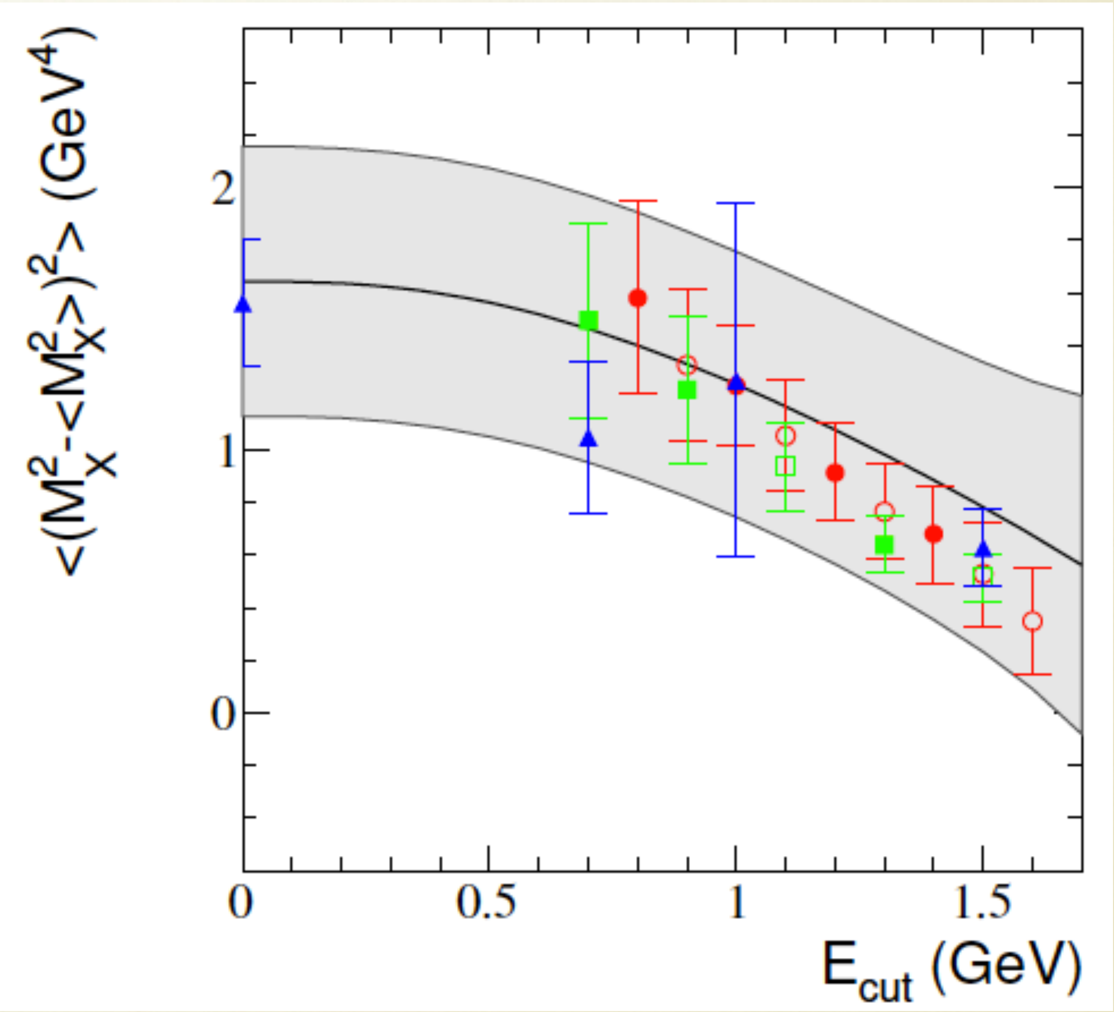
Lattice Group	Fermilab/MILC	HPQCD	RBC/UKQCD	Alpha	Detmold et al.
Process	$B \to \pi \ell \nu$ $(B_s \to K \ell \nu)$	$B_s \to K \ell \nu$ $(B \to \pi \ell \nu)$	$B \to \pi \ell \nu$ $B_s \to K \ell \nu$	$(B_s \to K \ell \nu)$	$\Lambda_b \to p \ell \nu$
Gauge ensembles	MILC asqtad	MILC asqtad	Domain-Wall	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.	$\boxed{\text{arXiv:1503.07839}}$ arXiv:1312.3197	$\boxed{\text{arXiv:1406.2279}}$ f_0 1601.04277	$\boxed{\text{arXiv:1501.05373v2}}$	arXiv:1411.3916 1601.04277	arXiv:1306.0446 $\boxed{\text{arXiv:1503.01421v2}}$ arXiv:1504.01568

Du, MITP workshop 2015

- (): work in progress

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.

FORM FACTORS

$$\boxed{\langle D(p')|V^\mu|\overline{B}(p)\rangle = f_+(q^2)(p+p')^\mu + f_-(q^2)(p-p')^\mu} \qquad q^2 = (p-p')^2$$

$$\frac{d\Gamma}{dq^2}(B \to Dl\nu_l) = \frac{\eta_{ew}^2 G_F^2 |V_{cb}|^2 m_B \lambda^{1/2}}{192\pi^3}\left(1-\frac{m_l^2}{q^2}\right)^2 \left[c_+^l\, f_+(q^2)^2 + c_0^l\, f_0(q^2)^2\right]$$

$$r = m_D/m_B,\ \lambda = (q^2 - m_B^2 - m_D^2)^2 - 4m_B^2 m_D^2$$

$$\eta_{ew} = 1 + \alpha/\pi \ln M_Z/m_b \approx 1.0066$$

$$c_+^l = \frac{\lambda}{m_B^4}\left(1+\frac{m_l^2}{2q^2}\right), \qquad c_0^l = (1-r^2)^2 \frac{3m_l^2}{2q^2}$$

$$\boxed{f_0(q^2) = f_+(q^2) + \frac{q^2}{m_B^2 - m_D^2} f_-(q^2)} \qquad \boxed{f_+(0) = f_0(0)}$$

UNITARITY CONSTRAINTS

$$\left(-g^{\mu\nu}+\frac{q^\mu q^\nu}{q^2}\right)\Pi^T(q^2)+\frac{q^\mu q^\nu}{q^2}\Pi^L(q^2)\equiv i\int d^4x\, e^{iqx}\langle 0|T\,J^\mu(x)\,J^{\dagger\nu}(0)|0\rangle$$

$$\chi^L(q^2)=\frac{\partial\Pi^L}{\partial q^2},\qquad \chi^T(q^2)=\frac{1}{2}\frac{\partial^2\Pi^T}{\partial(q^2)^2}$$

SATISFY UNSUBTRACTED DISP REL, PERT CALCULATION FOR $q^2=0$ Boyd, Grinstein, Lebed 1995

$$\chi^T(0)=[5.883+0.552_{\alpha_s}+0.050_{\alpha_s^2}]\;10^{-4}\,\mathrm{GeV}^{-2}=6.486(48)\;10^{-4}\,\mathrm{GeV}^{-2}$$
$$\chi^L(0)=[5.456+0.782_{\alpha_s}-0.034_{\alpha_s^2}]\;10^{-3}=6.204(81)\;10^{-3}$$

USING UP-TO-DATE QUARK MASSES AND 3LOOP CALCULATION Grigo et al 2012

$$\tilde{\chi}^T(0)=\chi^T(0)-\sum_{n=1,2}\frac{f_n^2(B_c^*)}{M_n^4(B_c^*)}$$

BOUND STATE CONTRIBUTIONS

Type	Mass (GeV)	Decay constants (GeV)
1^-	6.329(3)	0.422(13)
1^-	6.920(20)	0.300(30)
1^-	7.020	
1^-	7.280	
0^+	6.716	
0^+	7.121	

UNITARITY CONSTRAINTS

$$z = \frac{\sqrt{1+w}-\sqrt{2}}{\sqrt{1+w}+\sqrt{2}} \qquad w = \frac{m_B^2+m_D^2-q^2}{2m_Bm_D} \qquad 0 < z < 0.0646$$

$$f_{+,0}(z) = \frac{\sqrt{\tilde{\chi}^{T,L}}}{P_{+,0}(z)\phi_{+,0}(z)} \sum_{n=0}^{\infty} a_n^{+,0} z^n \qquad \text{(BGL)}$$

BLASCHKE FACTORS REMOVE POLES

PHASE SPACE FACTORS

$$\boxed{\sum_{n=0}^{\infty}(a_n^{+,0})^2 < 1}$$

WEAK UNITARITY CONSTRAINTS

BGL PARAMETERIZATION: TRUNCATE EXPANSION AT $n=N$

PROBLEMS AT THRESHOLD AND WITH LARGE q^2 SCALING

BCL PARAMETERIZATION BOURELLY CAPRINI LELLOUCH 2008

$$f_+(z) = \frac{1}{1-q^2/M_+^2}\sum_{n=0}^{N} a_n^+\left[z^n - (-1)^{n-N-1}\frac{n}{N+1}z^{N+1}\right] \qquad \text{(BCL)}$$

STRONG UNITARITY CONSTRAINTS

If one knows something about the other channels the constraints become tighter
In the heavy quark limit all $B^{(*)}\to D^{(*)}$ form factors either vanish or are prop to the Isgur-Wise function

$$\sum_{i=1}^{H}\sum_{n=0}^{\infty} b_{in}^2 \le 1 \qquad \sum_n b_{in} z^n = c_i(z) f_+(z)$$

CAPRINI
LELLOUCH
NEUBERT
CLN
1998

$$f_+(z) \simeq f_+(0)\left[1 - 8\rho_1^2 z + (51\rho_1^2 - 10)z^2 - (252\rho_1^2 - 84)z^3)\right]$$

$$\frac{f_0(z)}{f_+(z)} \simeq \left(\frac{2\sqrt{r}}{1+r}\right)^2 \frac{1+w}{2} 1.0036\left[1 - 0.0068 w_1 + 0.0017 w_1^2 - 0.0013 w_1^3\right]$$

$$w_1 = w - 1$$

CLN exploit NLO HQET relations between form factors to reduce to only 2 parameters…
but $1/m^2$ corrections can be sizable For ex at zero recoil

$$\frac{F_{D^*}(z=0)}{f_+(z=0)} = 0.948 \neq 0.860(14)$$

NLO HQET LATTICE (FNAL)

$$\frac{f_+(0)}{f_0(0)} = 0.775 \neq 0.753(3)$$

NLO HQET LATTICE (FNAL)

3%

CLN parameterization has intrinsic uncertainties that can no longer be neglected.
We use HQET expressions only in derivation of unitarity bounds and have checked that results are unaffected

RESULTS

exp data	lattice data	N,par	$10^3 \times \lvert V_{cb} \rvert$	χ^2/dof	$R(D)$
all	all	2,BGL	40.62(98)	22.1/26	0.302(3)
all	all	3,BGL	40.47(97)	18.2/24	0.299(3)
all	all	4,BGL	**40.49(97)**	19.0/22	**0.299(3)**
Belle	all	3,BGL	40.92(1.12)	11.6/14	0.300(3)
BaBar	all	3,BGL	40.11(1.55)	12.6/14	0.301(4)
all	FNAL	3,BGL	40.17(1.05)	10.4/18	0.293(4)
all	HPQCD	3,BGL	$40.51^{+1.82}_{-1.71}$	10.1/18	0.299(7)
all	all	CLN	40.85(95)	77.1/29	0.305(3)
all	f_+ only	CLN	40.33(99)	20.0/23	0.305(3)
all	all	2,BCL	40.49(98)	18.2/26	0.299(3)
all	all	3,BCL	40.48(96)	18.2/24	0.299(3)
all	all	4,BCL	40.48(97)	17.9/22	0.299(3)

WEAK vs STRONG BOUNDS

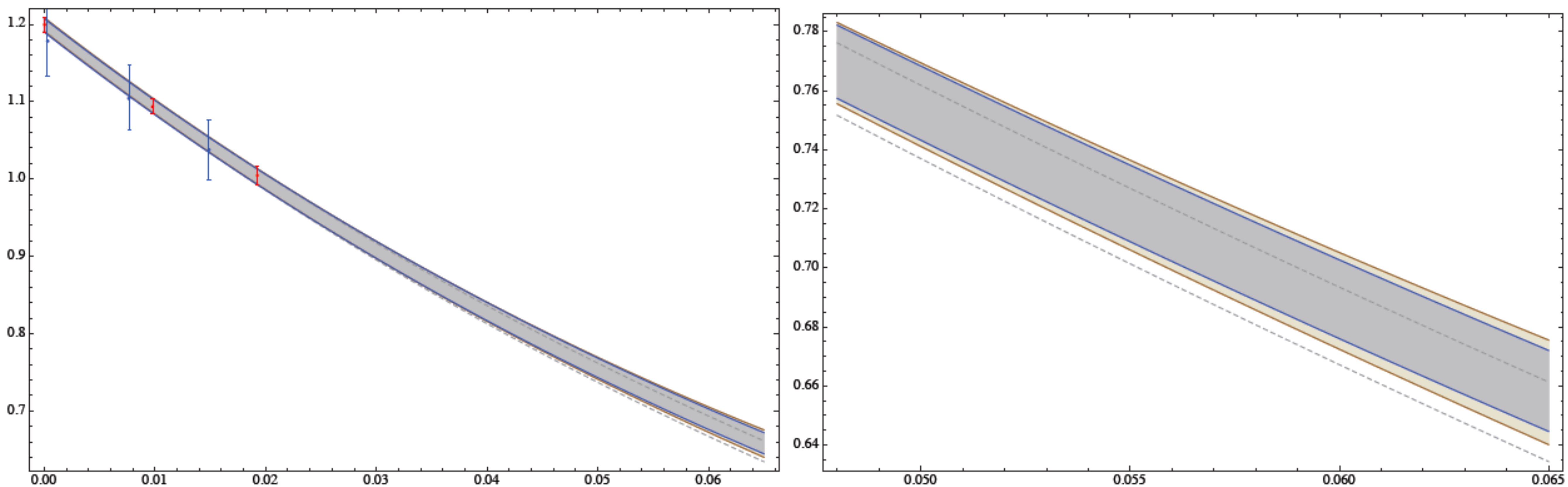
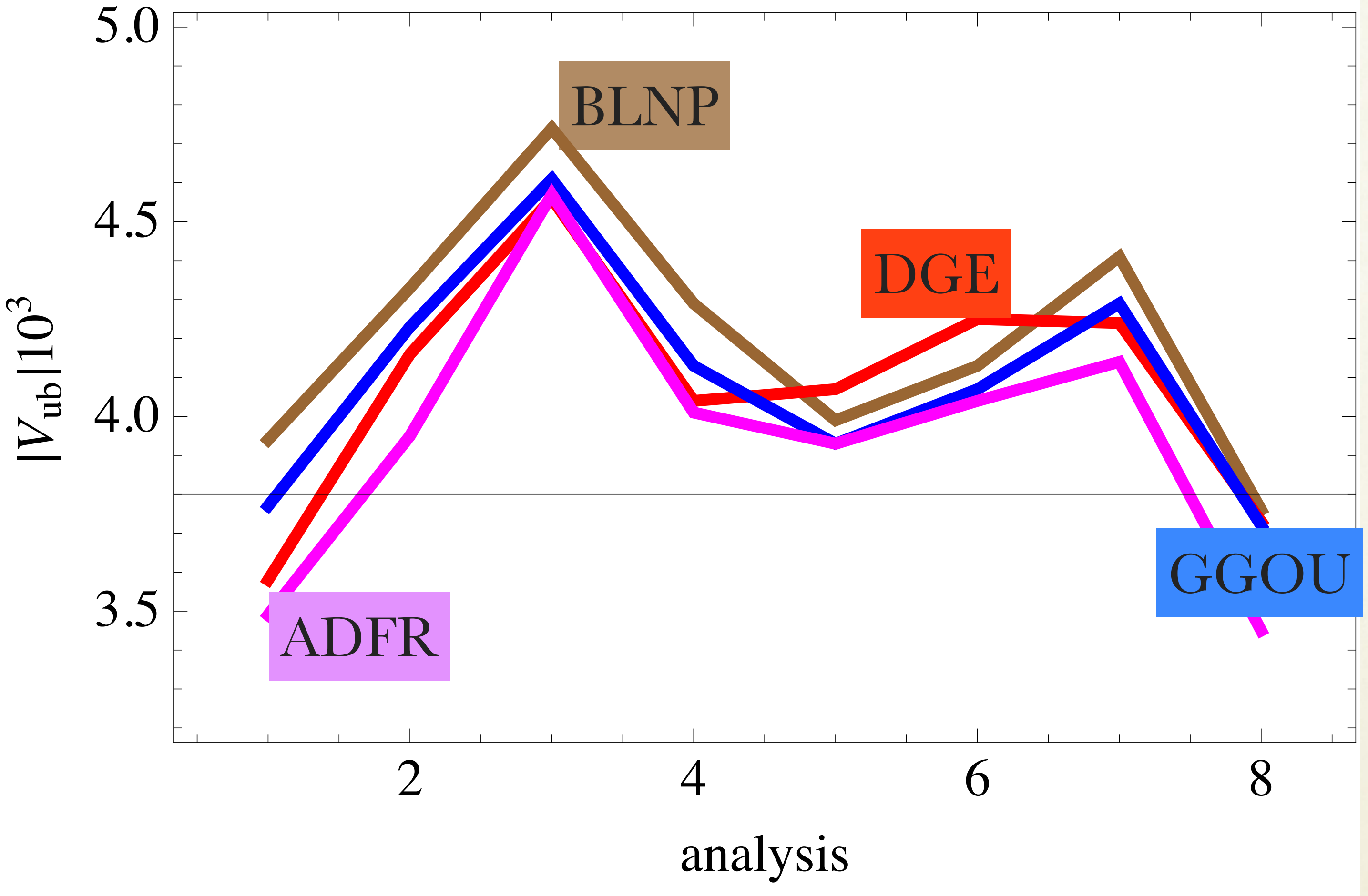


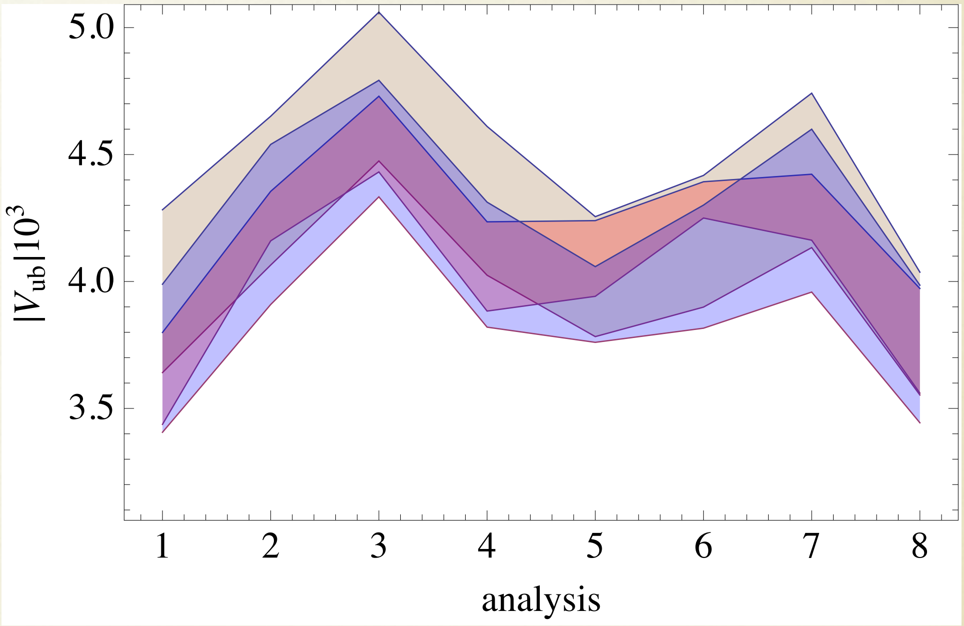
Figure 2: Form factor $f_+(z)$ in the $N = 4$ BGL fit to lattice data for $f_{+,0}(z)$ with weak (brown band) and strong (gray band) unitarity constraints. The $N = 2$ band (independent of unitarity constraints) is shown in dashed lines for comparison. FNAL/MILC synthetic data are shown in red, HPQCD in blue. On the right, enlarged detail of the tail.

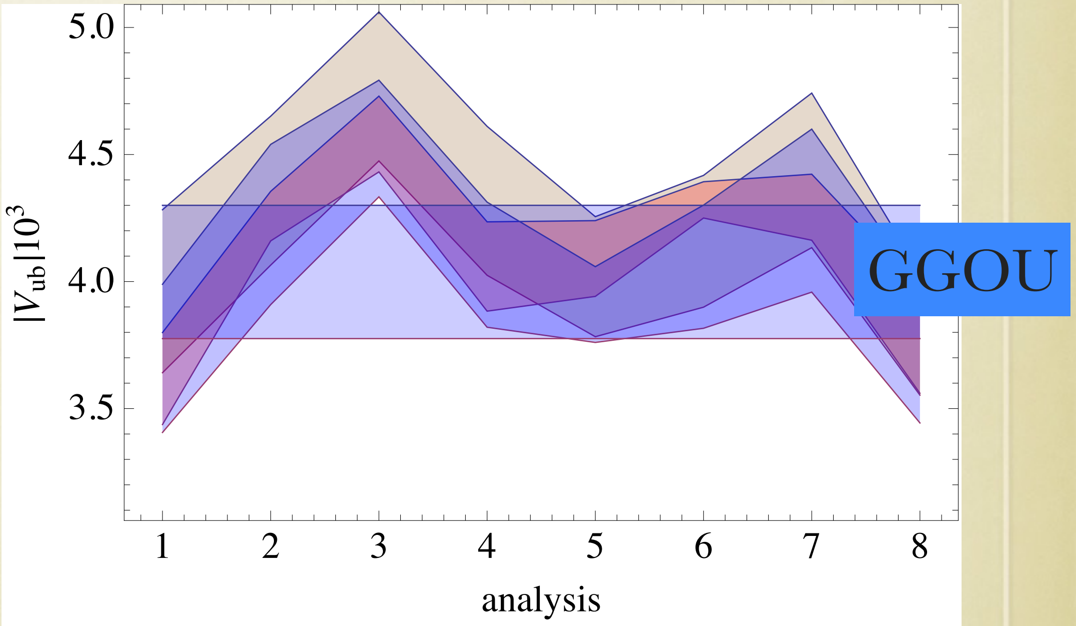
A global comparison

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

EFT view of b→cτν

Data can be best described by (a combination of) following operators

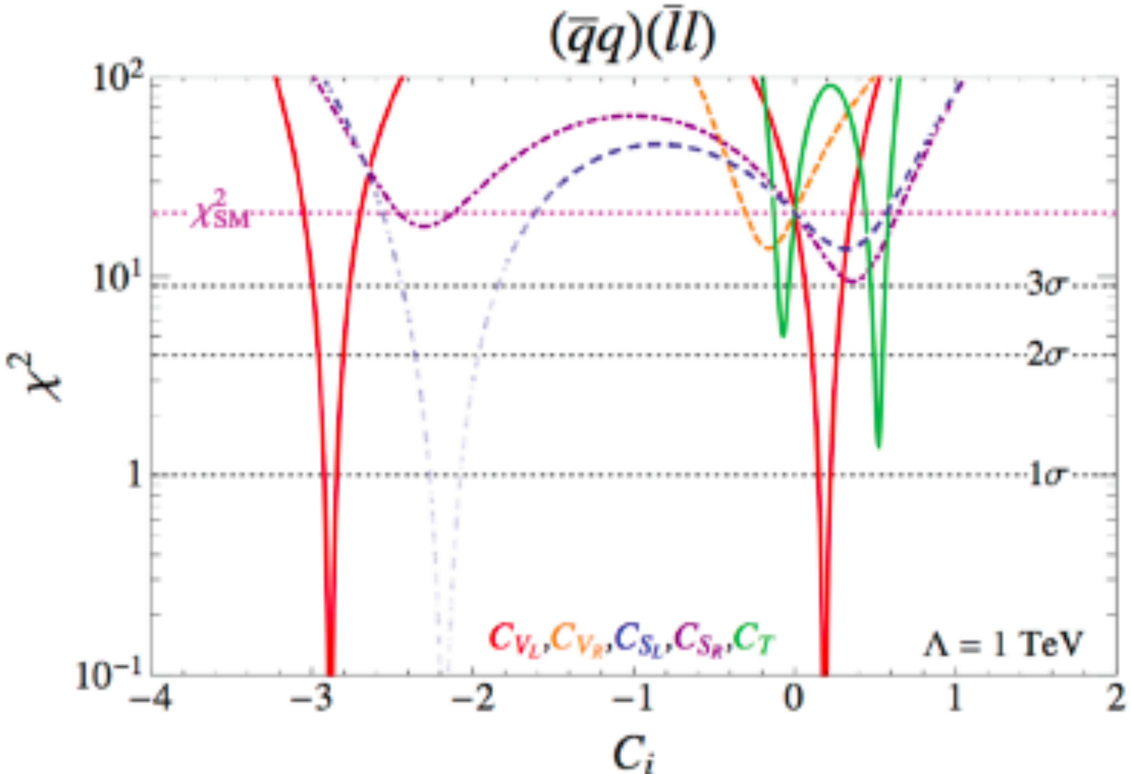
$$\mathcal{L} = -\frac{4G_F V_{cb}}{\sqrt{2}}\Big[(1+g_V)(\bar{\tau}_L\gamma^\mu\nu_L)(\bar{c}_L\gamma_\mu b_L)$$

$$+ g_S(\bar{\tau}_R\nu_L)(\bar{c}_R b_L) + g_T(\bar{\tau}_R\sigma^{\mu\nu}\nu_L)(\bar{c}_R\sigma_{\mu\nu}b_L)\Big]$$

[Becirevic, NK, Tayduganov,1206.4977]

	Operator
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L\nu)$
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_L\nu)$
$\mathcal{O}_{S_R}$	$(\bar{c}P_R b)(\bar{\tau}P_L\nu)$
$\mathcal{O}_{S_L}$	$(\bar{c}P_L b)(\bar{\tau}P_L\nu)$
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\tau}\sigma_{\mu\nu}P_L\nu)$
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)(\bar{c}\gamma^\mu P_L\nu)$
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)(\bar{c}\gamma^\mu P_L\nu)$
$\mathcal{O}'_{S_R}$	$(\bar{\tau}P_R b)(\bar{c}P_L\nu)$
$\mathcal{O}'_{S_L}$	$(\bar{\tau}P_L b)(\bar{c}P_L\nu)$
$\mathcal{O}'_T$	$(\bar{\tau}\sigma^{\mu\nu}P_L b)(\bar{c}\sigma_{\mu\nu}P_L\nu)$
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)(\bar{b}^c\gamma^\mu P_L\nu)$
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)(\bar{b}^c\gamma^\mu P_L\nu)$
$\mathcal{O}''_{S_R}$	$(\bar{\tau}P_R c^c)(\bar{b}^c P_L\nu)$
$\mathcal{O}''_{S_L}$	$(\bar{\tau}P_L c^c)(\bar{b}^c P_L\nu)$
$\mathcal{O}''_T$	$(\bar{\tau}\sigma^{\mu\nu}P_L c^c)(\bar{b}^c\sigma_{\mu\nu}P_L\nu)$

[Freytsis, Ligeti, Ruderman, 1506.08896]



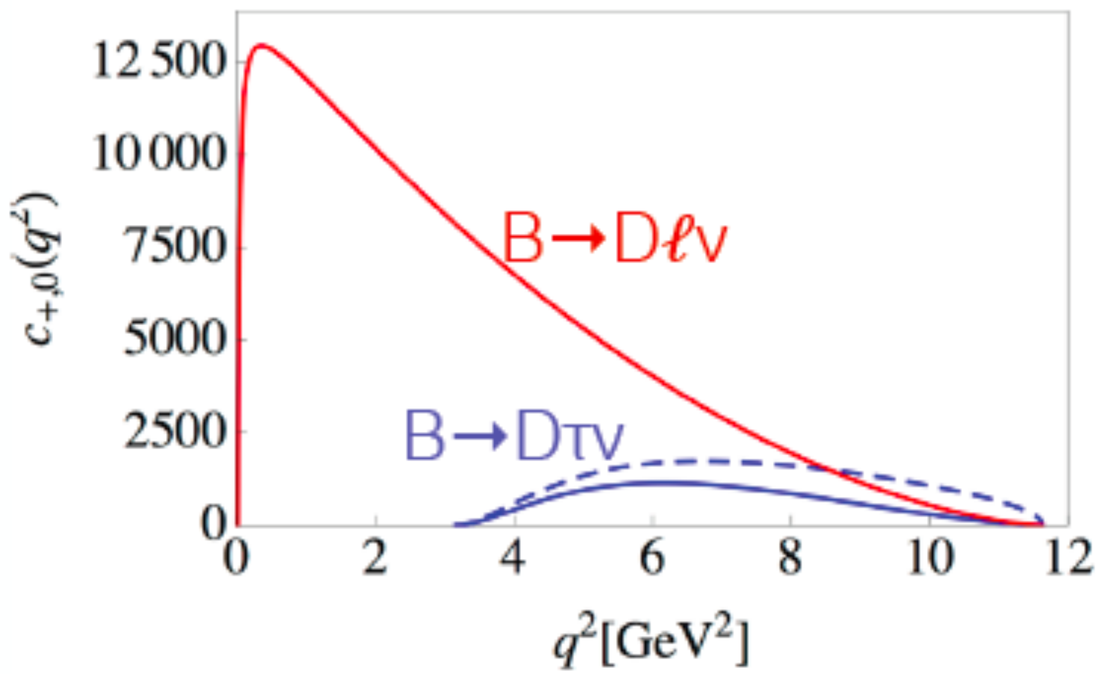
KOSNIK LCHP-2016

Models for b→cτν

Only tree-level NP can compete with tree-level SM!

Charged scalars: extra Higgs(es)

- Non-minimal flavour structure (e.g. type III)
- Scalar form factor F_0 enhanced in B→Dτν, absent in B→Dℓν



[Crivellin, Greub, Kokulu,1206.2634]
[Celis, Jung, Li, Pich,1210.8443]
...

[Ko, Omura, Yu, 1212.4607]
[Crivellin, Heeck, Stoffer,1507.07567]

Coloured bosons - LQs

- Fierzed basis of operators: →scalar/vector/tensor

[Sakaki, Tanaka, Tayduganov, Watanabe,1309.0301]
[Bauer, Neubert, 1511.01900]
[Li, Yang, Zhang, 1605.09308]
...

LQ models for b→cτν

Vector U3 (3,3)2/3

A weak triplet state couples at tree-level only to LH fermions

$$\mathcal{L}_{U_3} = g_{ij}\bar{Q}_i\gamma^\mu\,\tau^A U^A_{3\mu}\,L_j$$

[Fajfer, NK, 1511.01900]
[Barbieri, Isidori, Pattori, Senia, 1512.01560]

non-LQ triplets:
[Greljo et al,1506.01705]
[Boucenna et al,1604.03088]

$$\mathcal{L}_{U_3} = U^{(2/3)}_{3\mu}\left[(\mathcal{V}g\mathcal{U})_{ij}\,\bar{u}_i\gamma^\mu P_L\nu_j - g_{ij}\,\bar{d}_i\gamma^\mu P_L\ell_j\right]$$

LH currents for Puzzle b->sll!

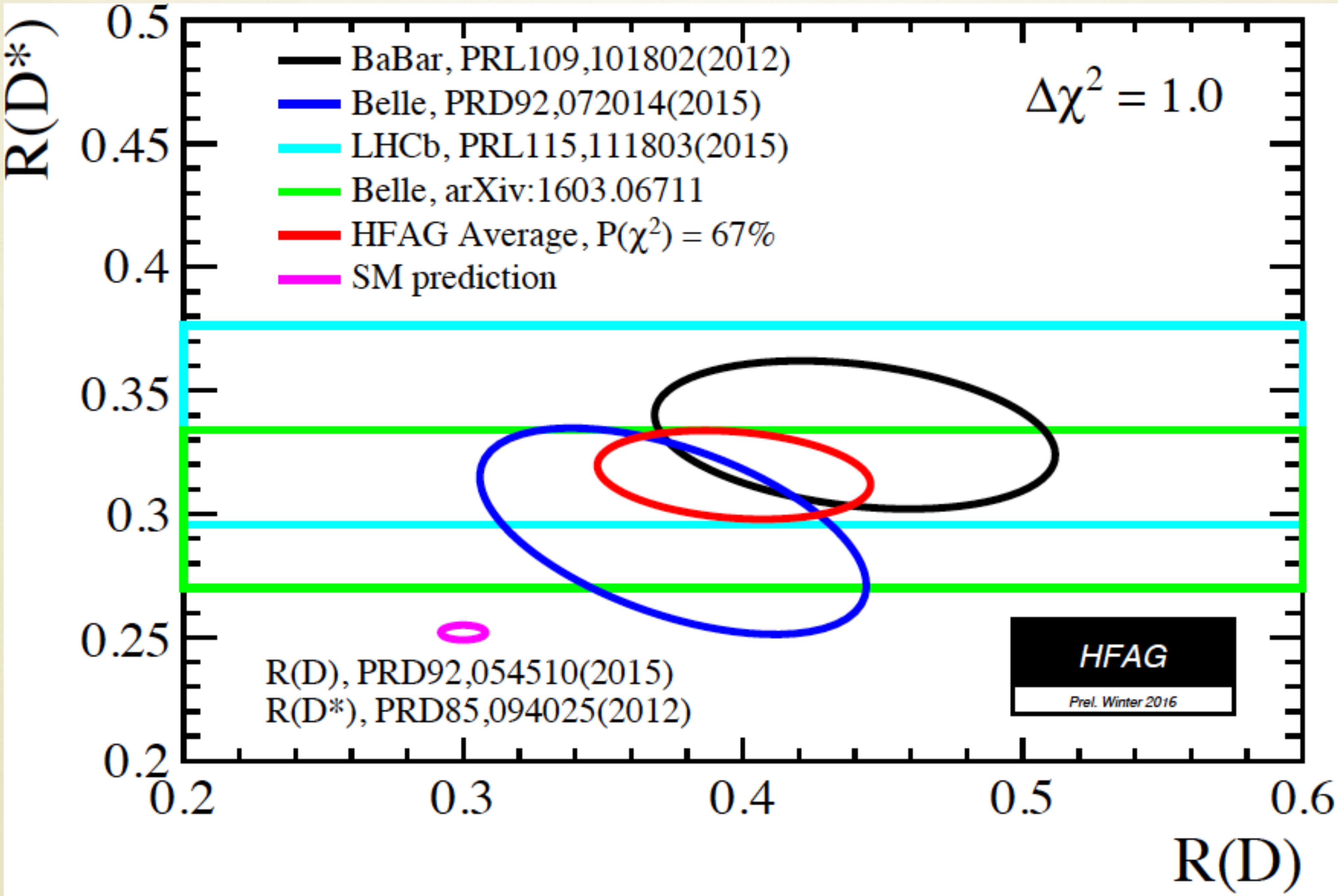
$$+\,U^{(5/3)}_{3\mu}\,(\sqrt{2}\mathcal{V}g)_{ij}\,\bar{u}_i\gamma^\mu P_L\ell_j$$

charm and top

$$+\,U^{(-1/3)}_{3\mu}\,(\sqrt{2}g\mathcal{U})_{ij}\,\bar{d}_i\gamma^\mu P_L\nu_j + \text{h.c.}.$$

B→Kνν

$$\mathcal{L}_{\rm SL} = -\left[\frac{4G_F}{\sqrt{2}}\mathcal{V}_{cb}\mathcal{U}_{\tau i} + \frac{g^*_{b\tau}(\mathcal{V}g\mathcal{U})_{ci}}{M_U^2}\right](\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L\nu_i)$$



R(D*)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, arXiv:1603.06711
HFAG Average, P(χ²) = 67%
SM prediction
Δχ² = 1.0
R(D), PRD92,054510(2015)
R(D*), PRD85,094025(2012)
HFAG
Prel. Winter 2016
0.2
0.3
0.4
0.5
0.6
R(D)