SEMILEPTONIC B DECAYS

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Miapp, Munich 3 november 2016

Importance of $|V_{xb}|$

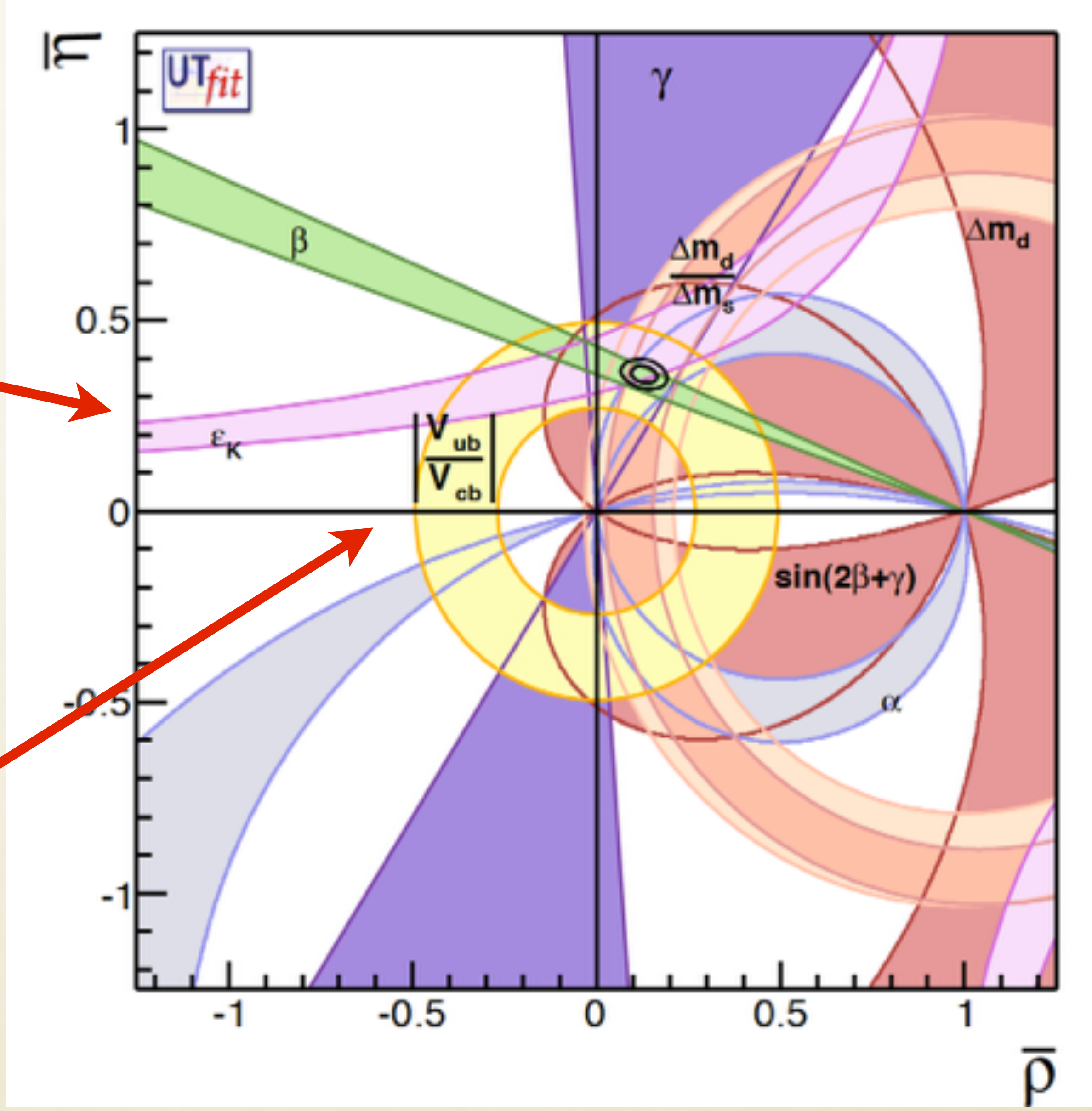
V_{cb} plays an important role in the determination of UT

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

and in the prediction of FCNC:

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

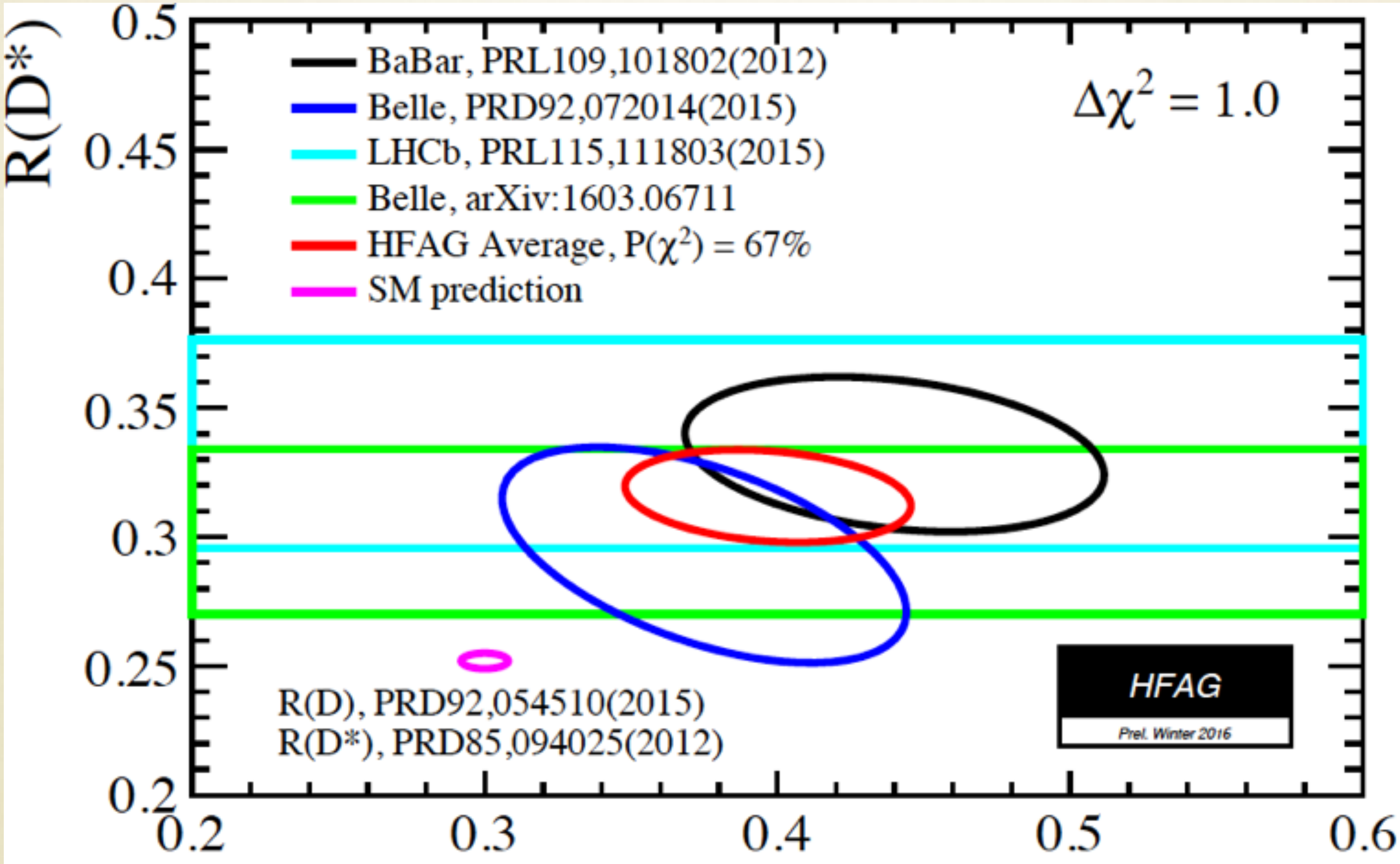
where it often dominates the theoretical uncertainty.
V_{ub}/V_{cb} constrains directly the UT



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

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

Inclusive semileptonic B decays

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

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

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

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

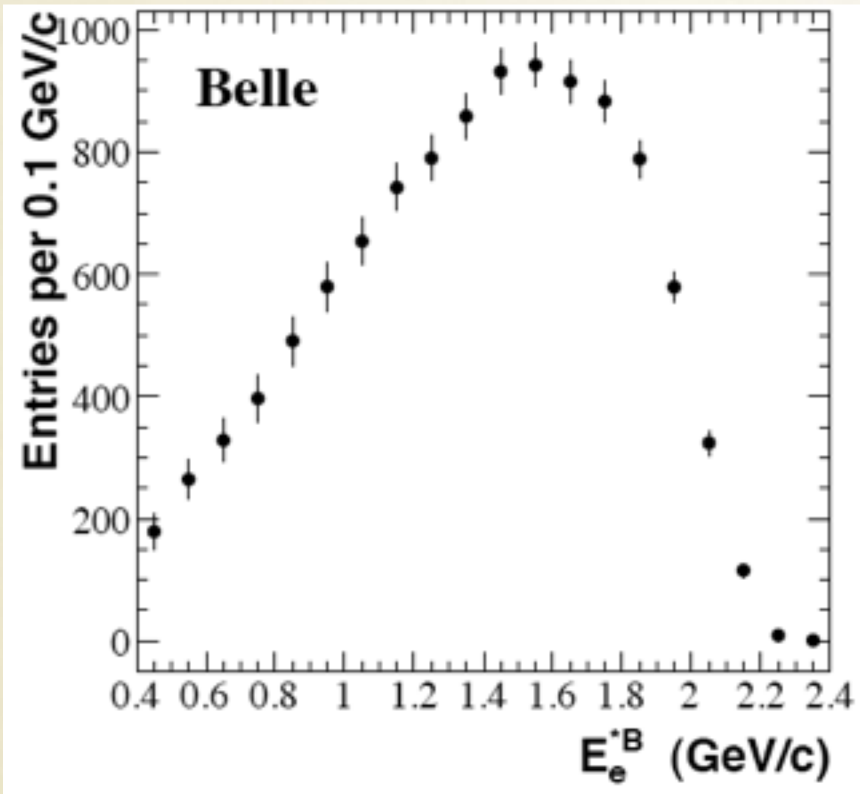
Current fits includes 6 non-pert parameters

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

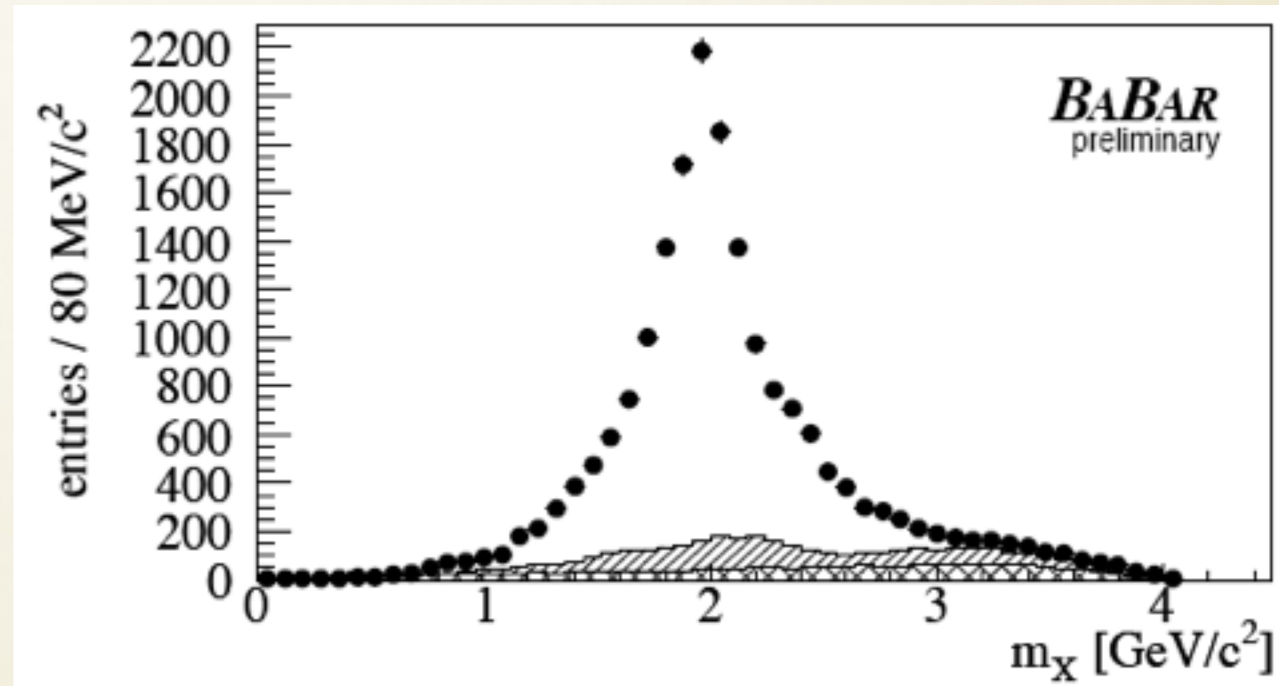
and all known corrections up to $O(\Lambda^3/m_b^3)$

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},...)

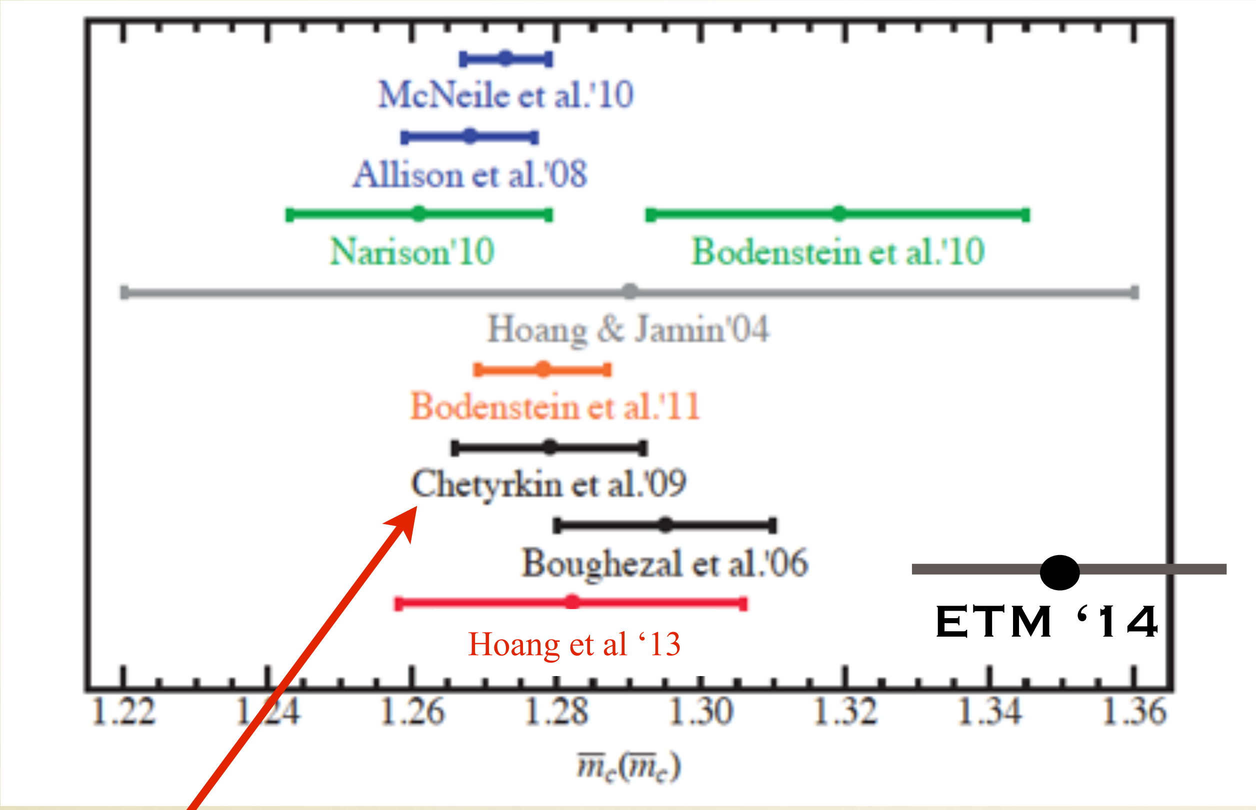
THE SEMILEPTONIC FIT

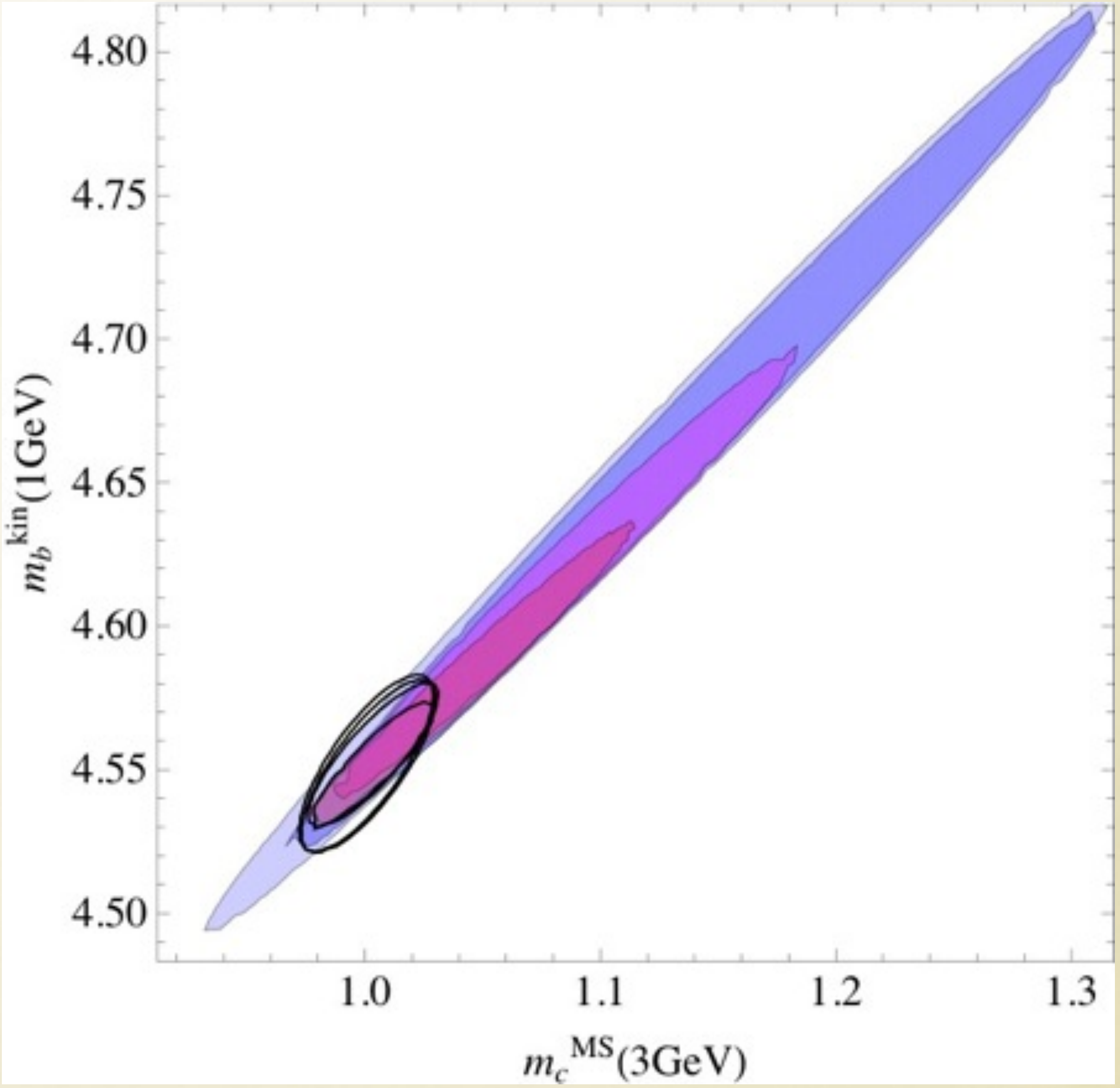
Alberti, Healey, Nandi, PG 1411.6560

- 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 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

Previous global 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

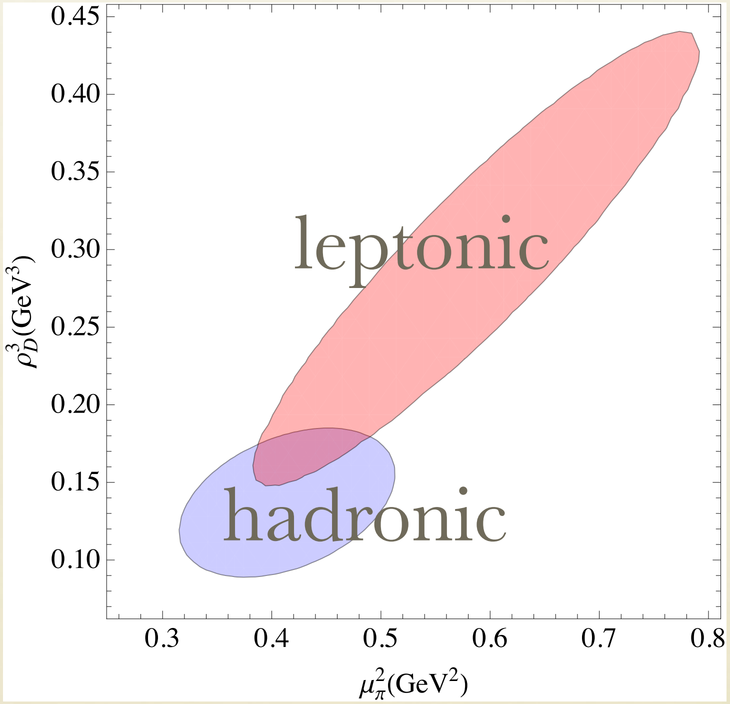
m_b^{kin}	$\overline{m}_c(3\,\text{GeV})$	μ_π^2	ρ_D^3	μ_G^2	ρ_{LS}^3	$\text{BR}_{c\ell\nu}$	$10^3\lvert V_{cb}\rvert$
4.553	0.987	0.465	0.170	0.332	-0.150	10.65	42.21
0.020	0.013	0.068	0.038	0.062	0.096	0.16	0.78

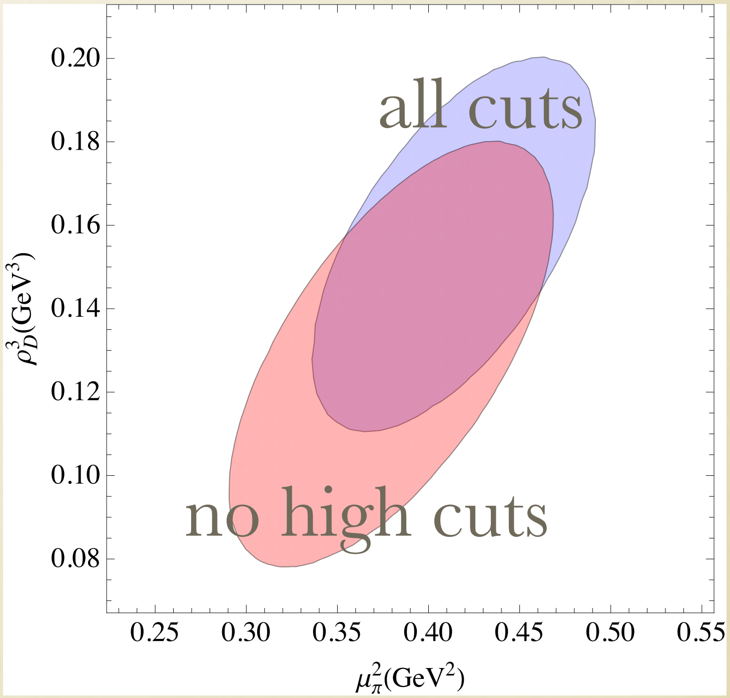
Alberti et al, 1411.6560

Without mass constraints

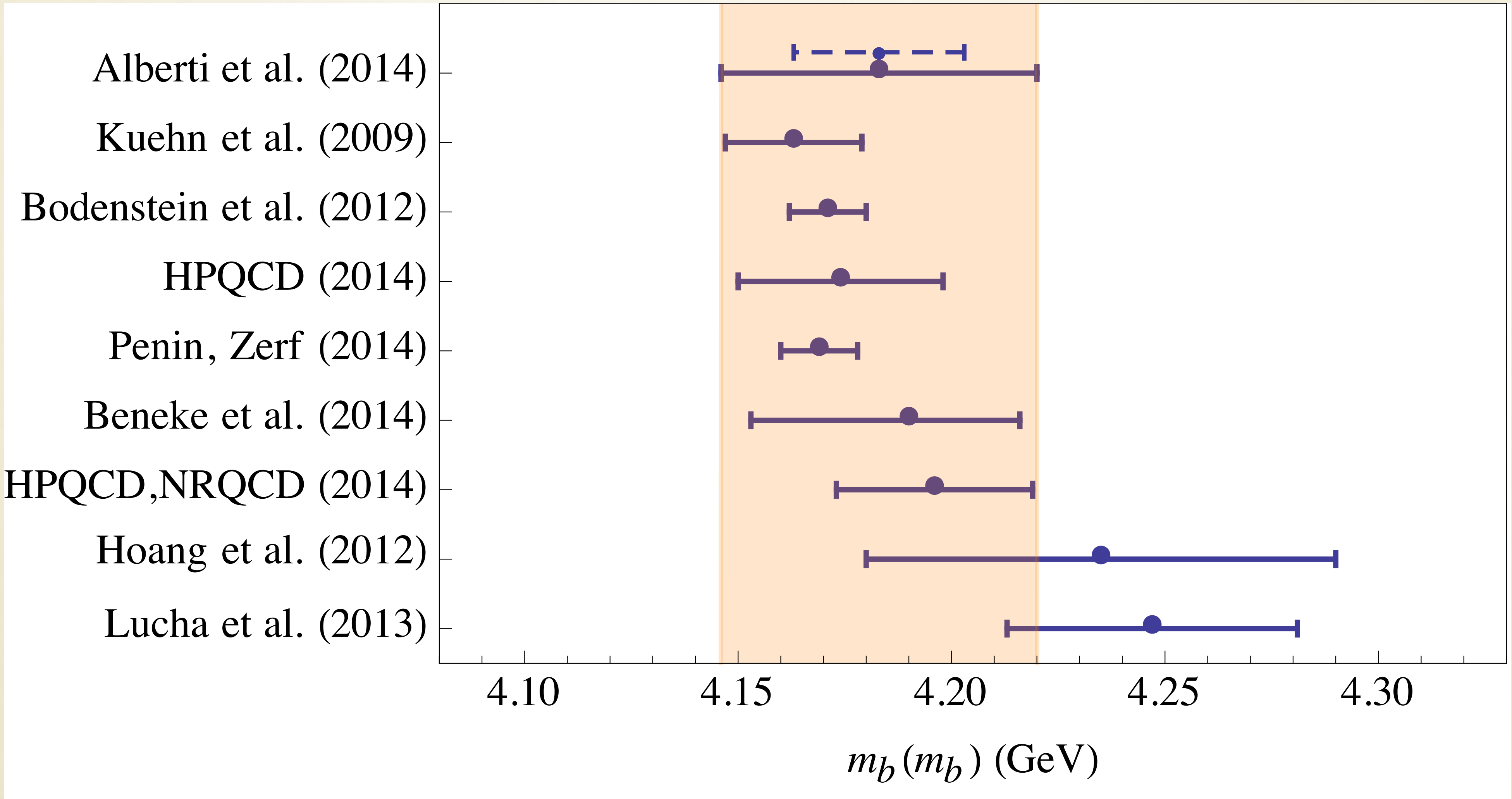
$$m_b^{kin}(1\text{GeV}) - 0.85\,\overline{m}_c(3\text{GeV}) = 3.714 \pm 0.018\,\text{GeV}$$

- 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

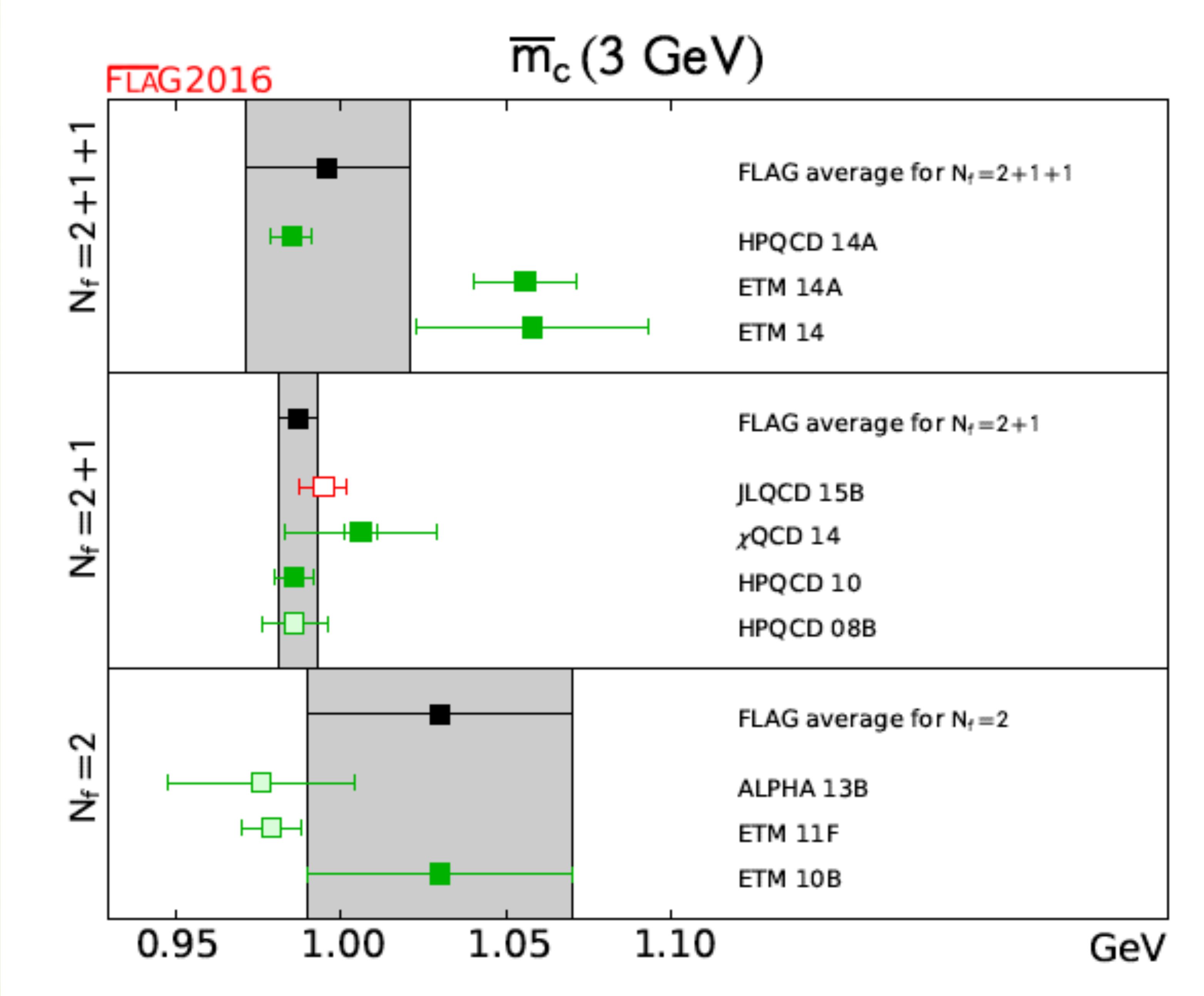


The fit gives $\boldsymbol{m_b^{kin}(1\mathrm{GeV})=4.553(20)\mathrm{GeV}}$

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

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

CHARM MASS DEPENDENCE



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

V_{cb} only slightly smaller

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

- **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

Higher power corrections

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

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

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

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

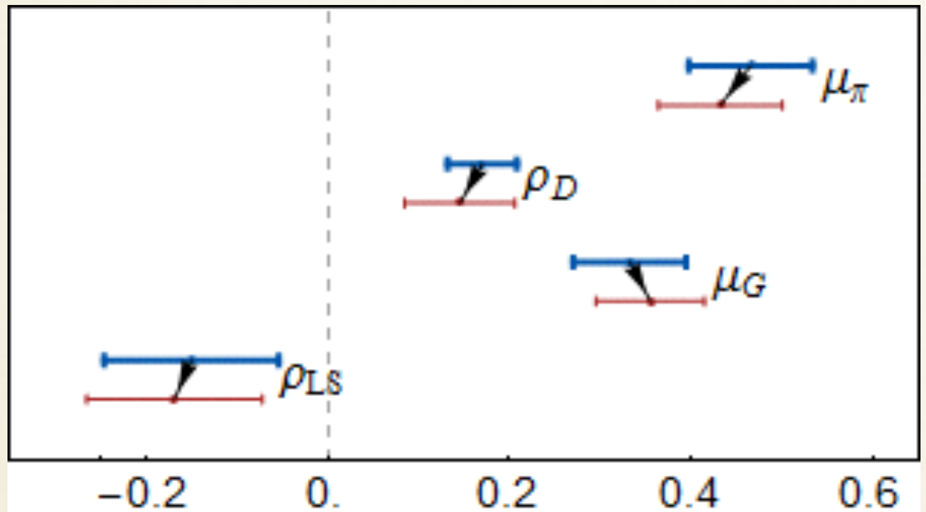
PG,Healey,Turczyk 1606.06174

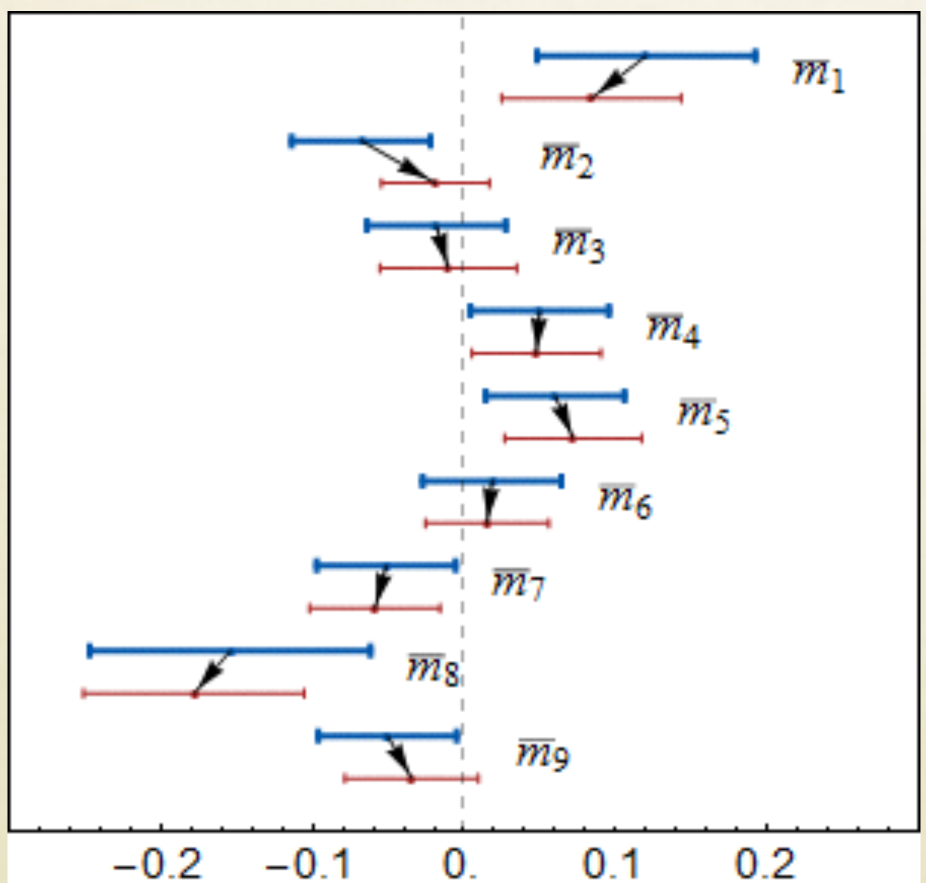
$$|V_{cb}| = 42.11(74) \times 10^{-3}$$ (0.25% reduction)

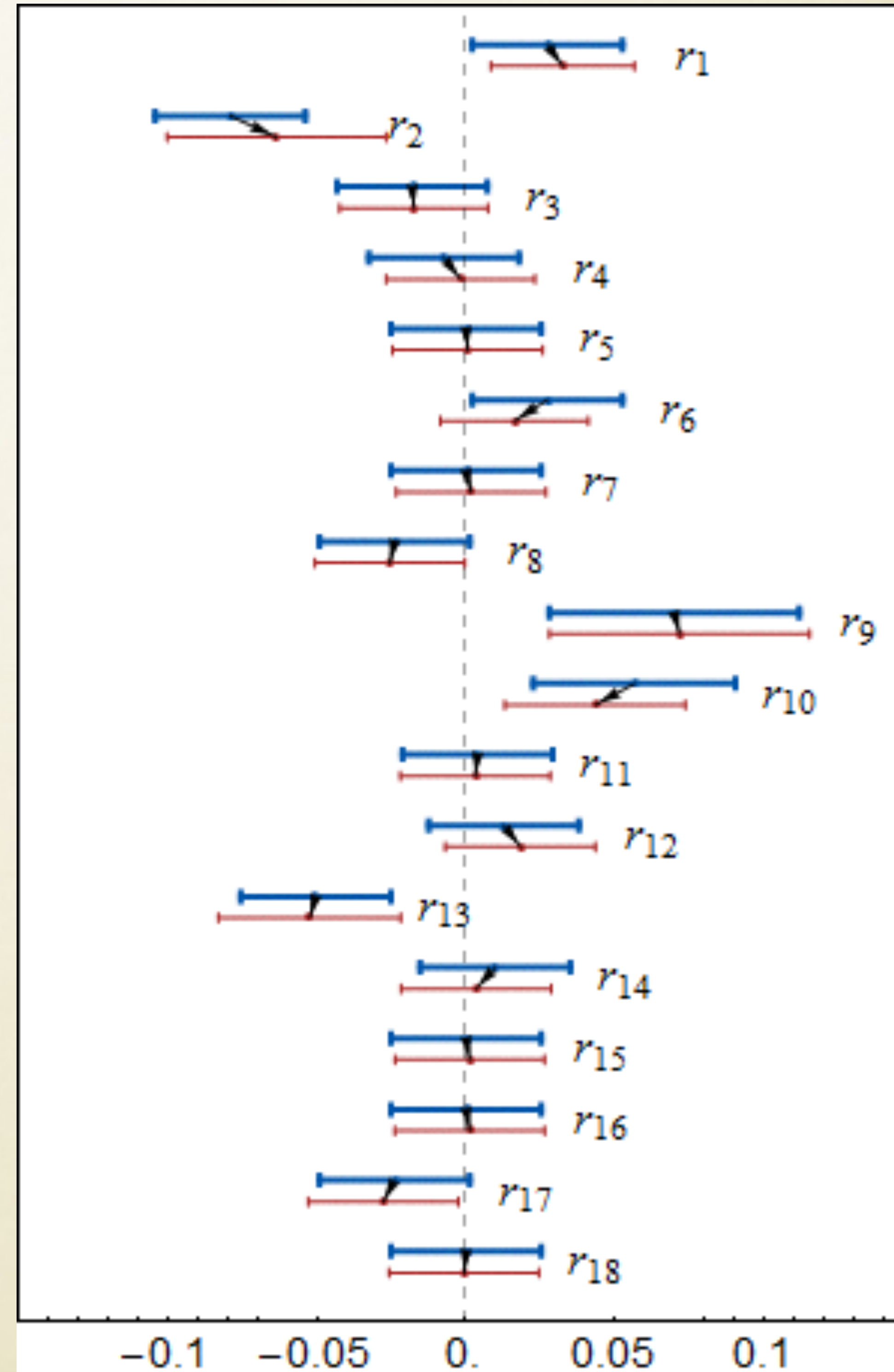
$$|V_{cb}| = 42.00(64) \times 10^{-3}$$

if one uses $m_c(2GeV)$ and includes PDG average for m_b

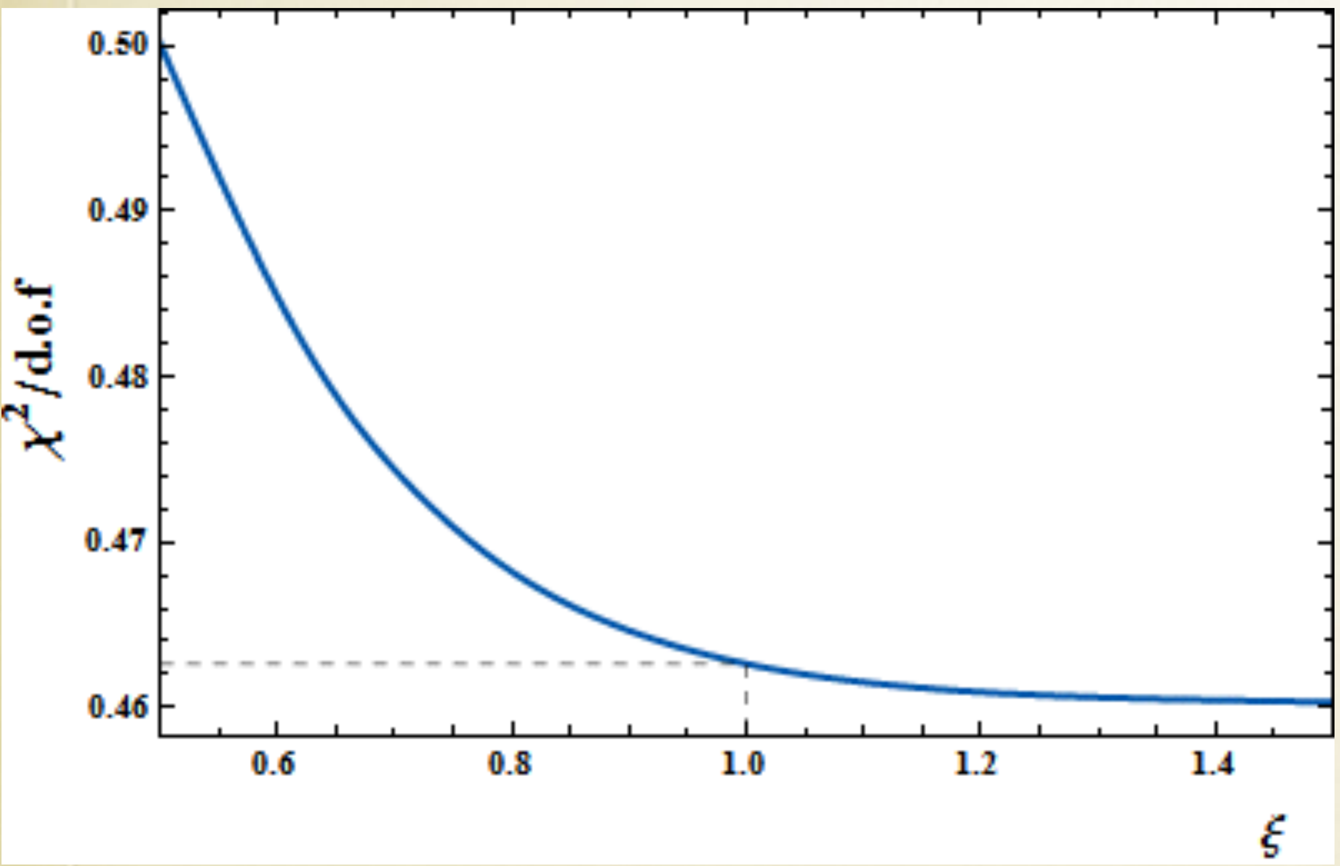
1.5% uncertainty

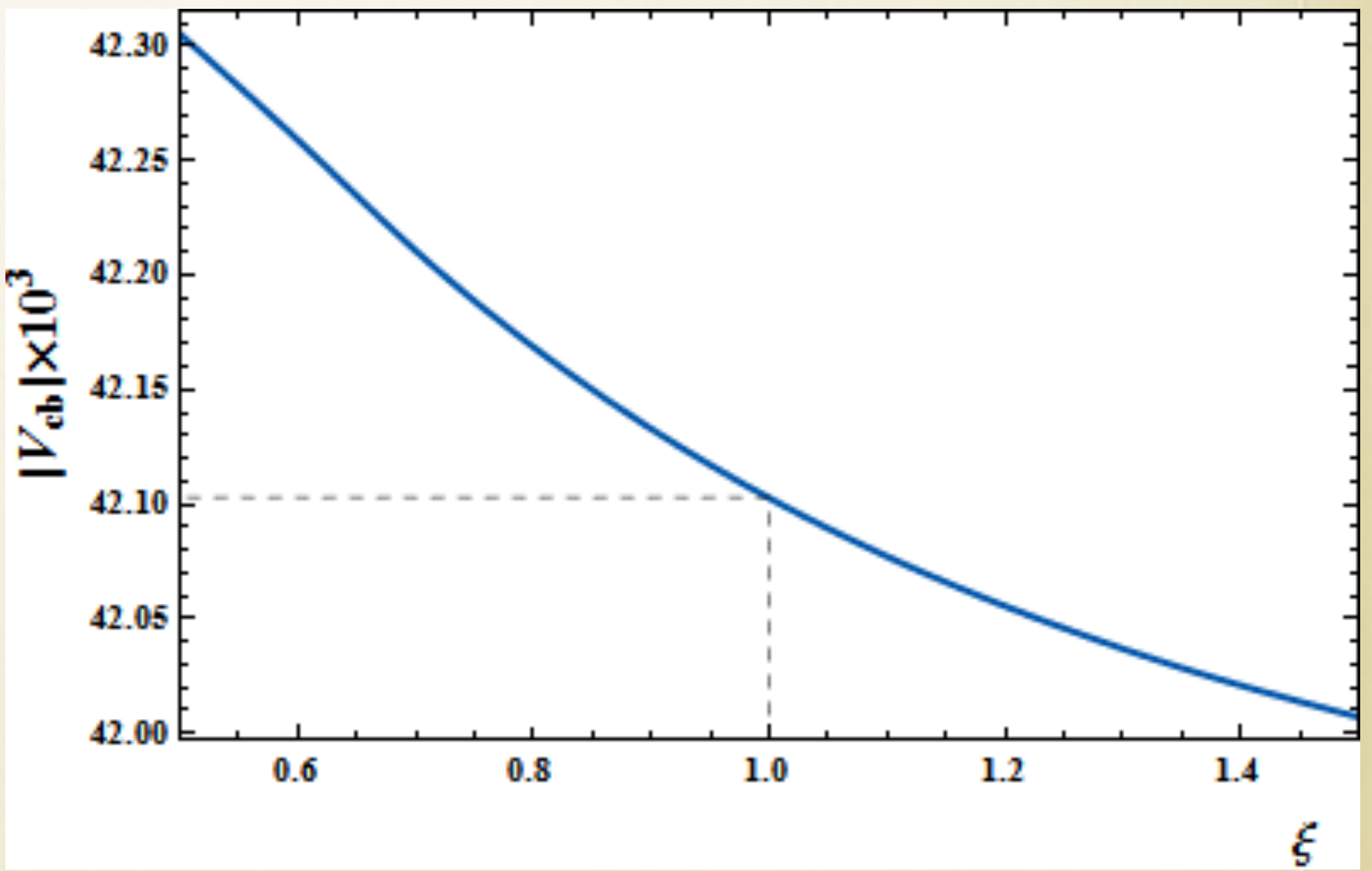






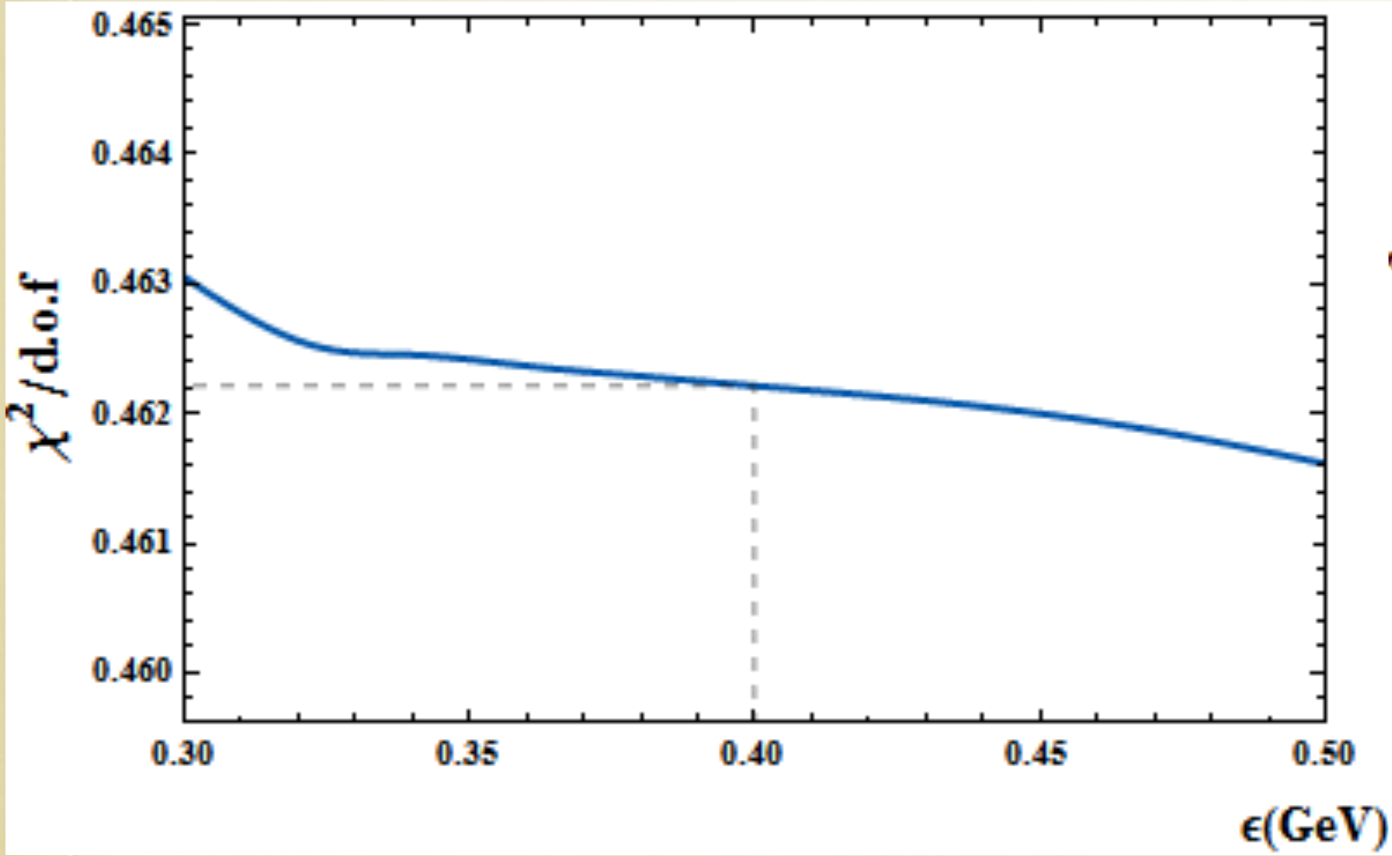
DEPENDENCE ON LLSA UNCERTAINTY

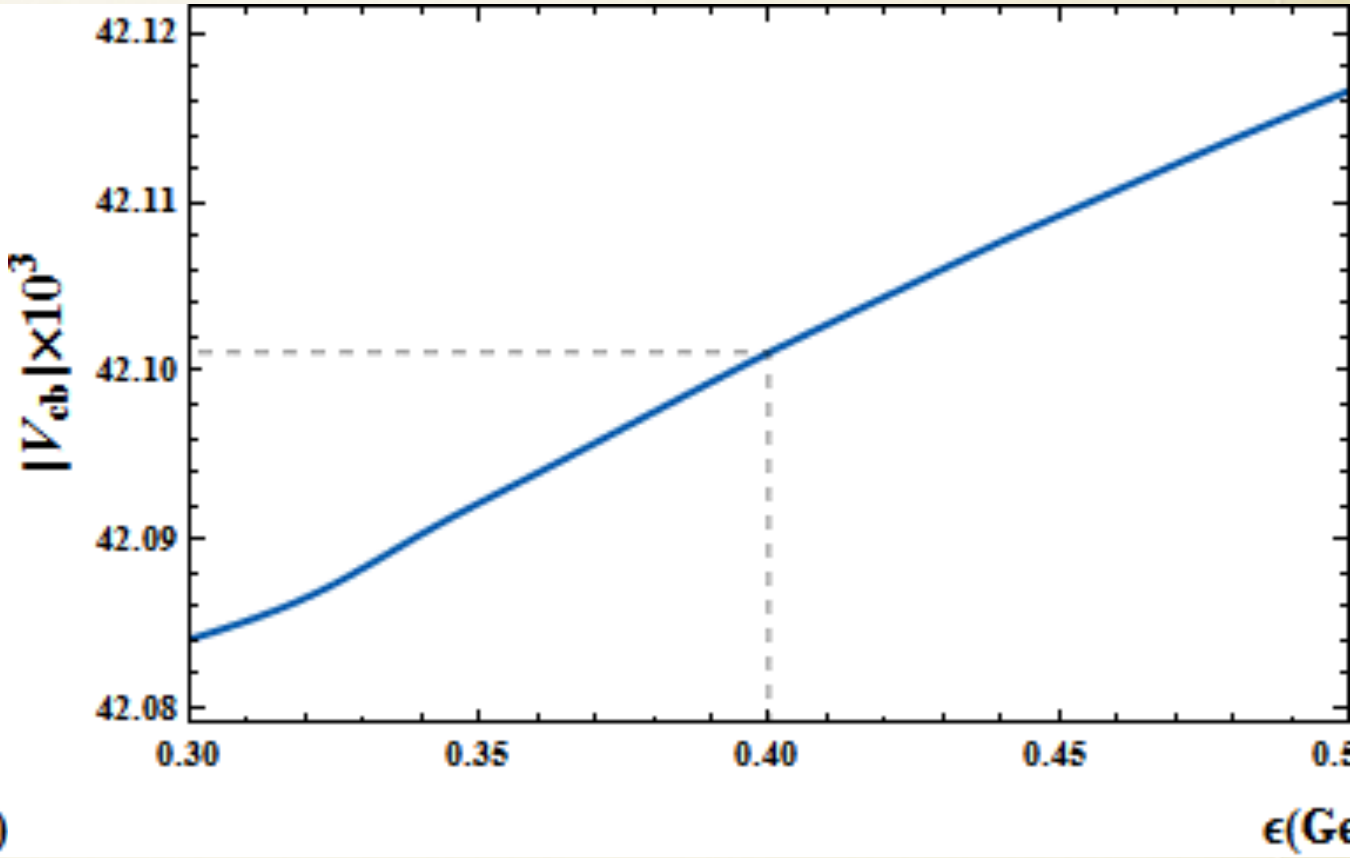




WE RESCALE ALL LLSA UNCERTAINTIES BY A FACTOR ξ

EXCITATION ENERGY DEPENDENCE





Prospects

- 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.**

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

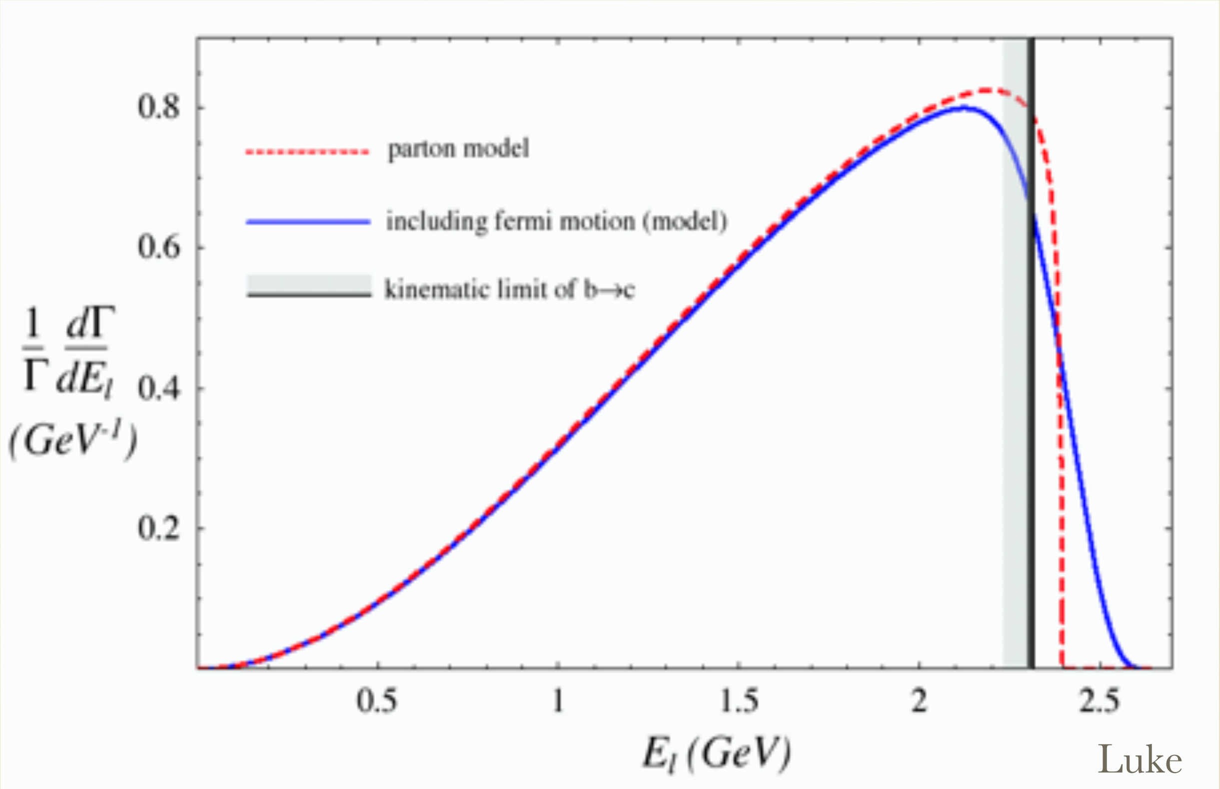
CUTS IN $B \to X_u l \nu$

Experiments often use kinematic cuts to avoid the $b \to c l \nu$ background:

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

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 DGE, ADFR	OPE constraints + parameterization without/with resummation GGOU, BLNP

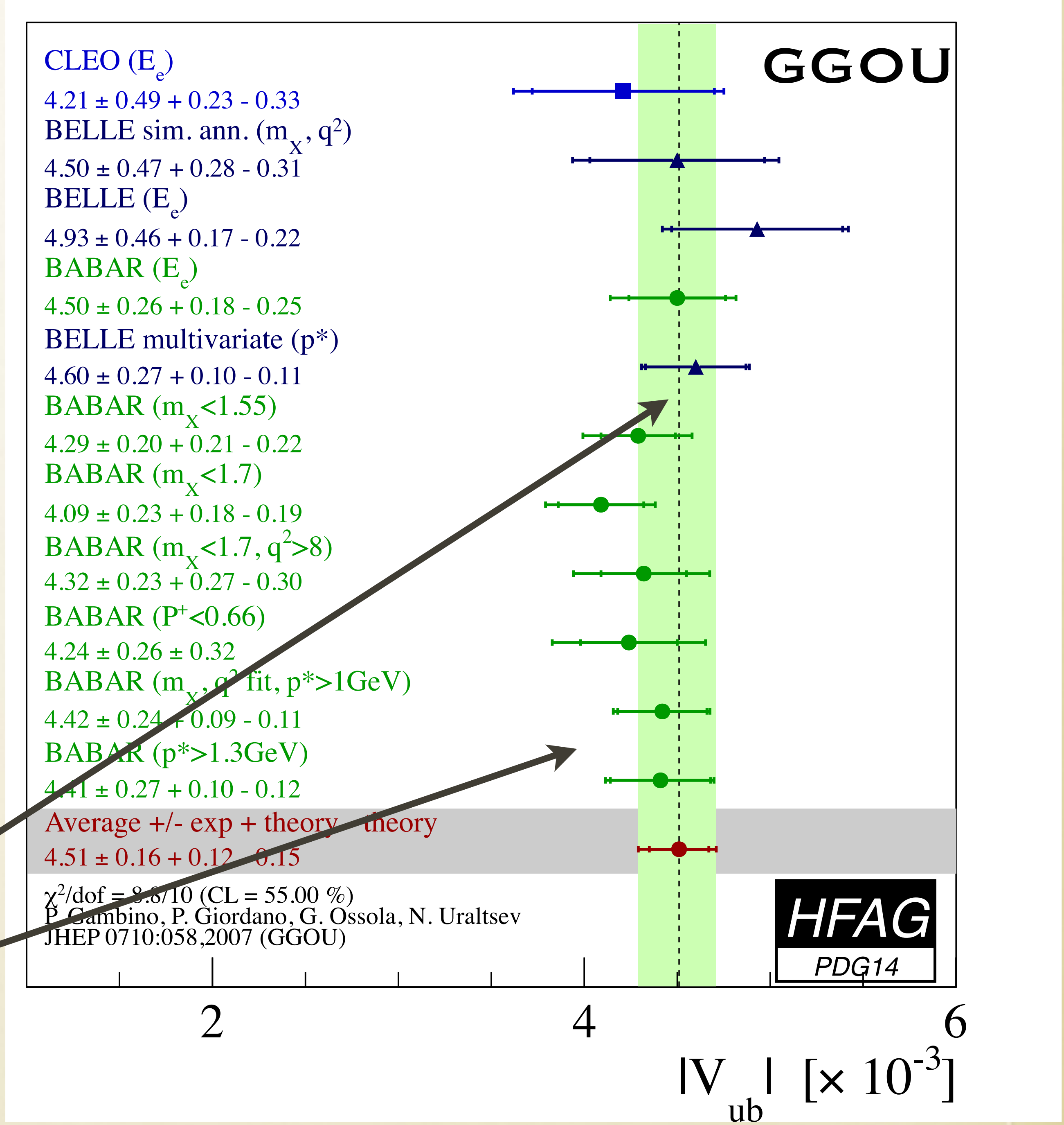
Fit semileptonic (and radiative) data
SIMBA, NNVub

$|V_{ub}|$ DETERMINATIONS

Inclusive: 5% total error

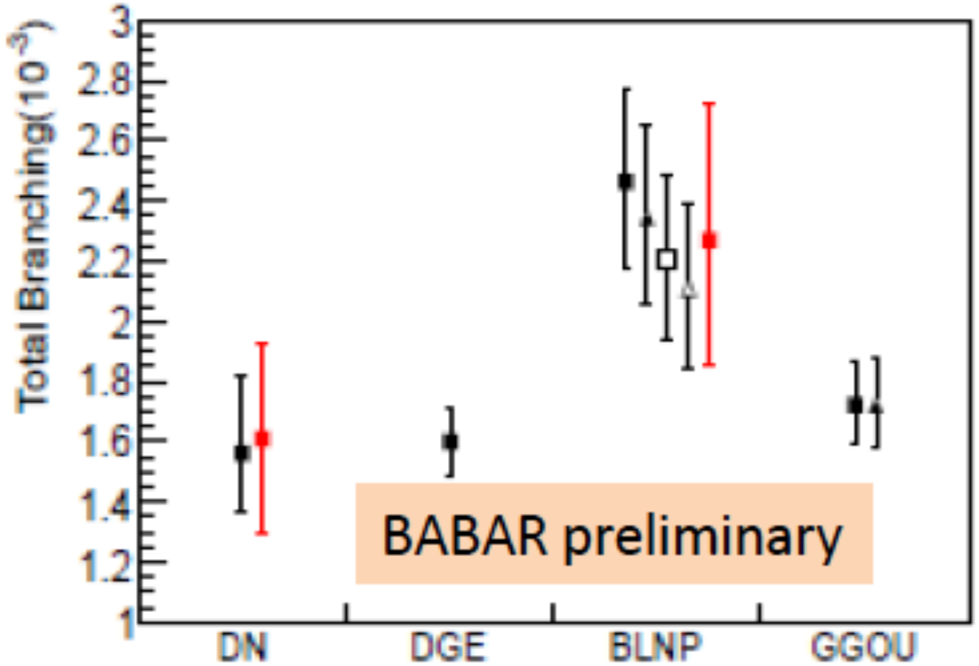
HFAG 2014	Average |V
DGE	4.52(16)(16)
BLNP	4.45(16)(22)
GGOU	4.51(16)(15)

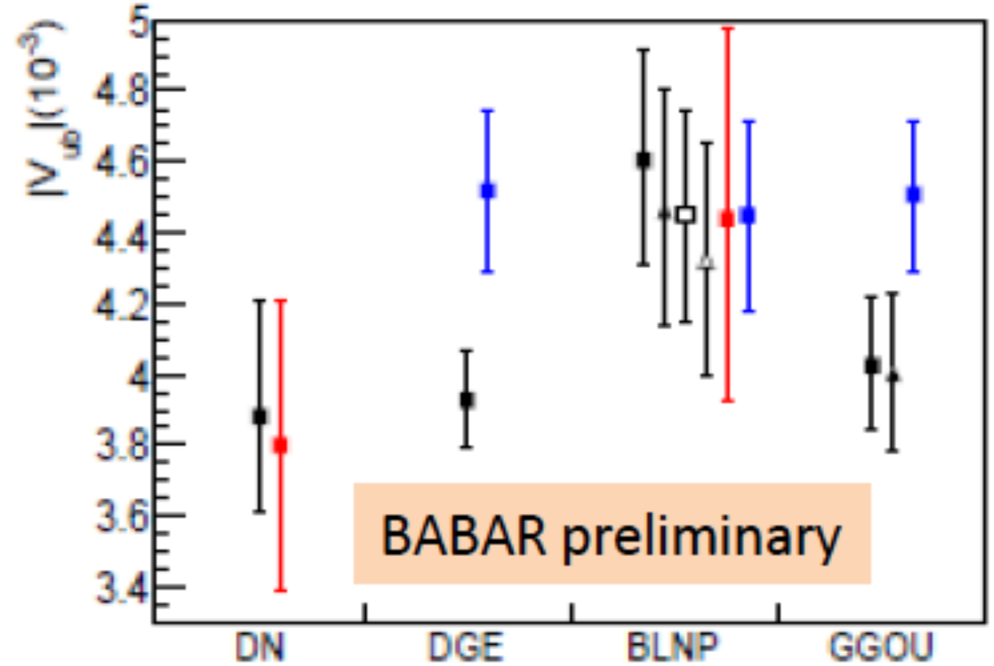
UT fit (without direct V_{ub}):
V_{ub}=3.66(12) 10^{-3}



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

NEW preliminary Babar endpoint analysis
High sensitivity of the BR on the shape of the signal
in the endpoint region. GGOU: $|V_{ub}| = 4.03^{+0.20}_{-0.22} \times 10^{-3}$



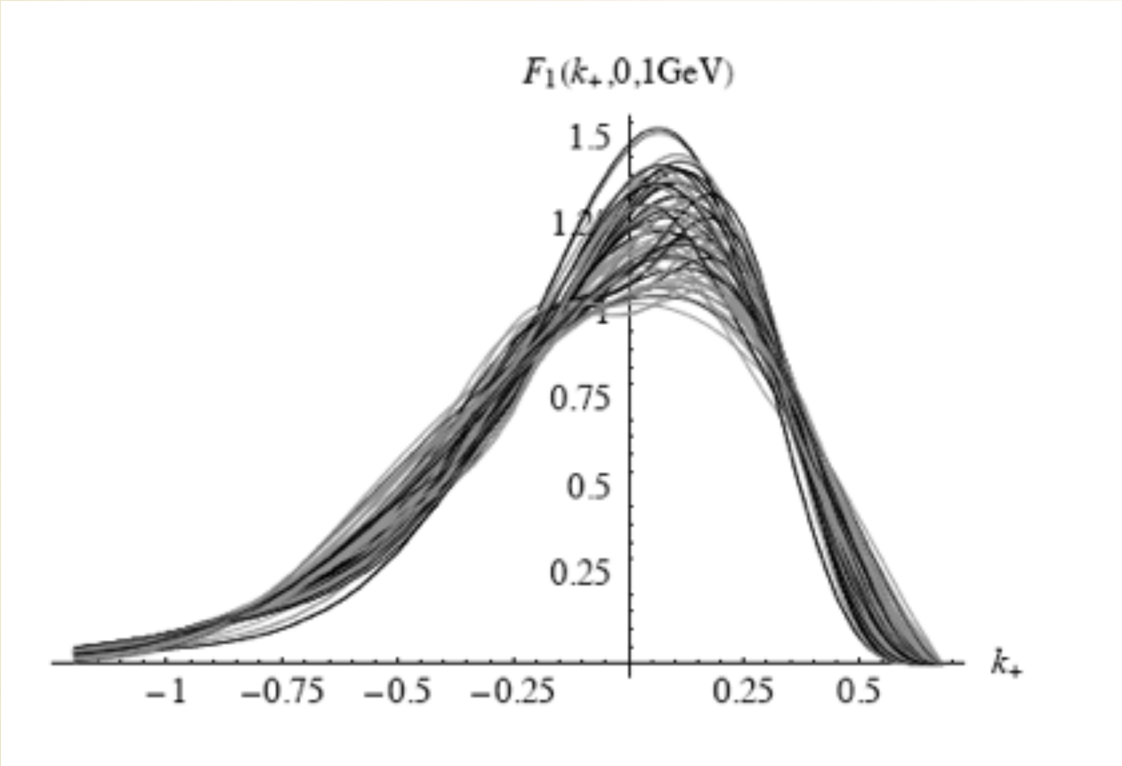


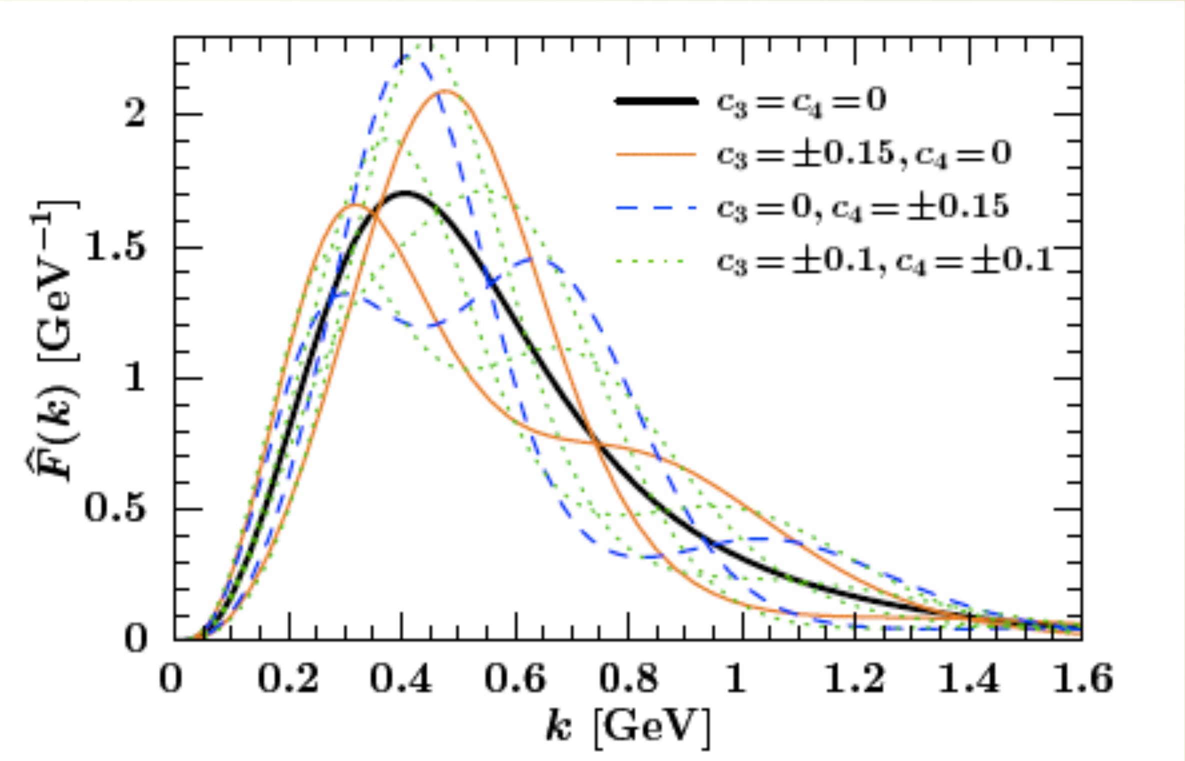
solid squares and triangles – X_c with mc constraint fit and X_c+$X_s\gamma$ fit of SF parameters (BLNP and GGOU)
solid and open - translation "kinetic" to "shape-function" with μ = 2.0GeV and μ = 1.5GeV (BLNP), respectively
results based on 0.8-2.6GeV/c momentum range
HFAG 2014 average based on tagged and untagged measurements
Consistent with and more precise than our previous result:
BaBar, Phys.Rev. D73(2006)012006 (p_e > 2 GeV/c)

Y.SKOVPEN, EPS-PH 2015

NB Belle multivariate analysis uses GGOU+DN for the inclusive part

Functional forms





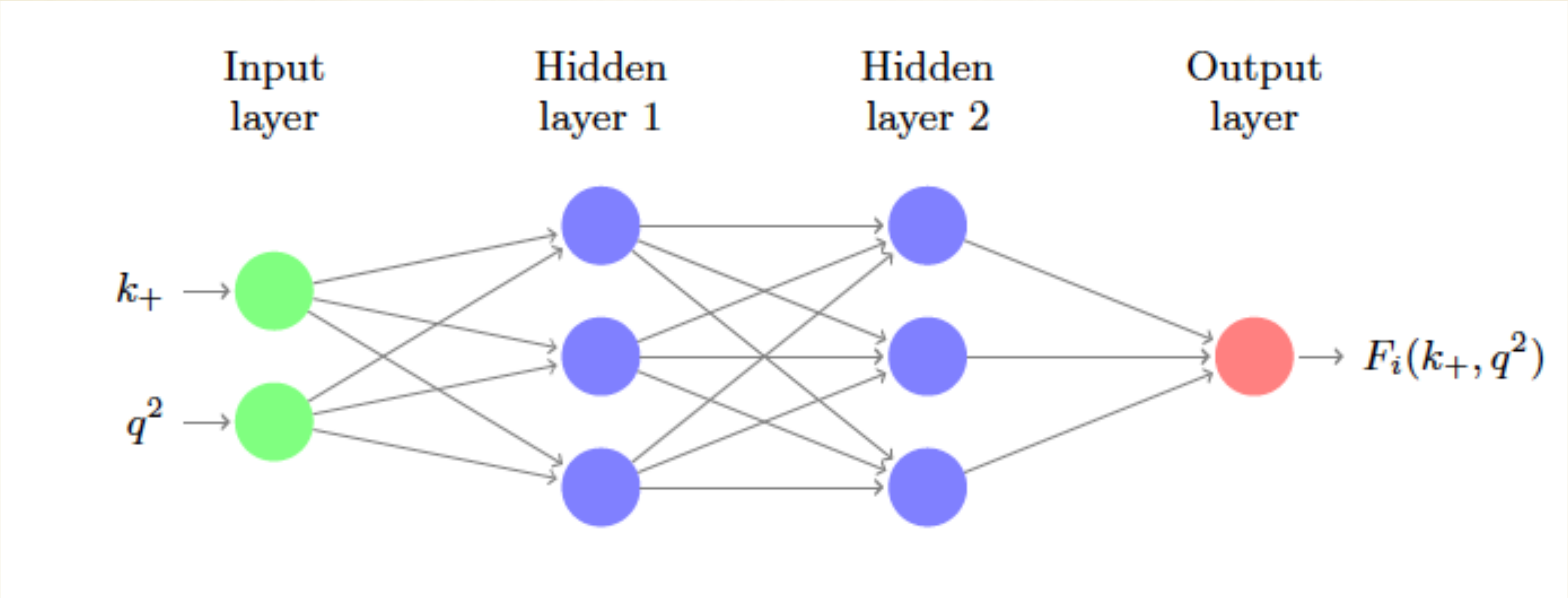
About 100 forms considered in GGOU, large variety, double max discarded. Small uncertainty (1-2%) on V_{ub}

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

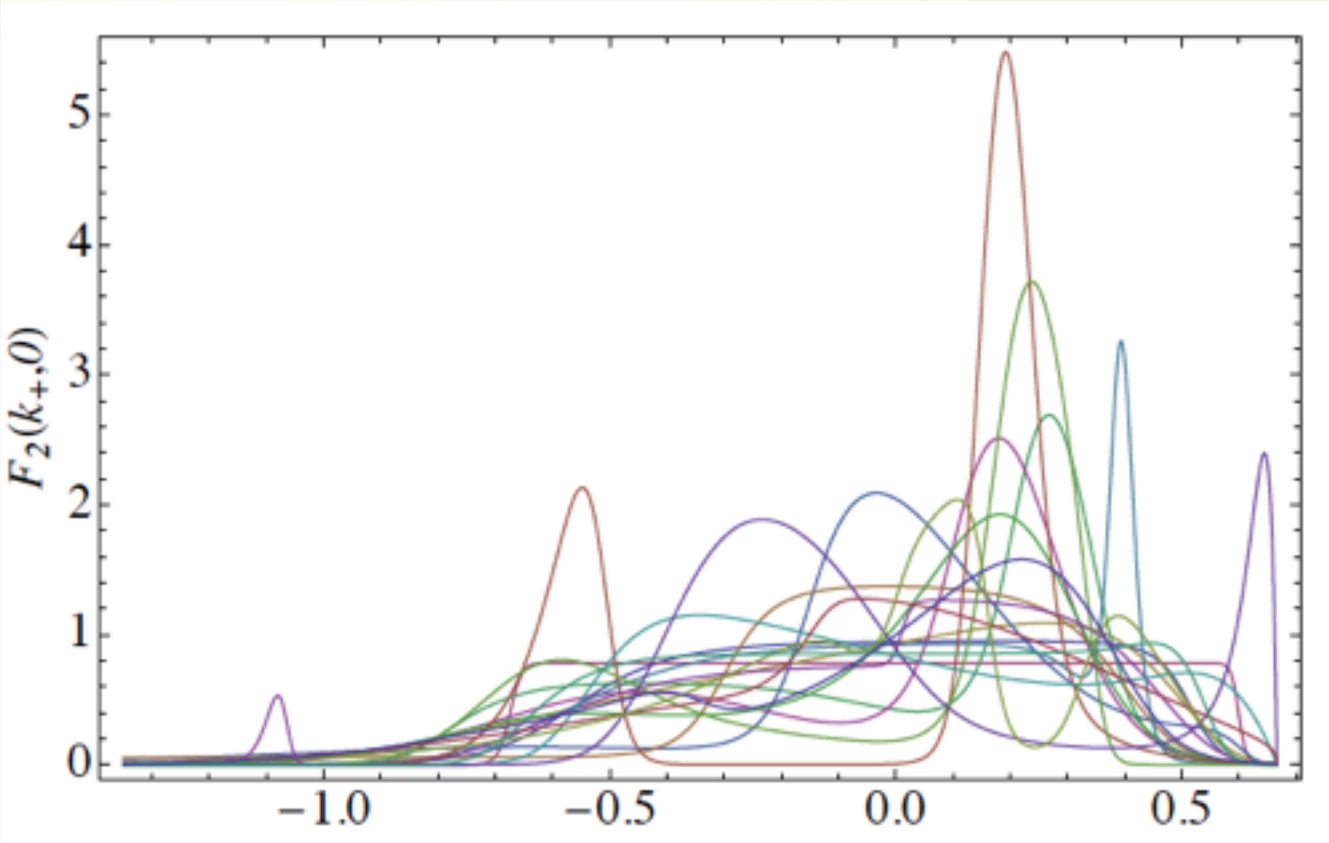
K.Healey, C. Mondino, PG, 1604.07598



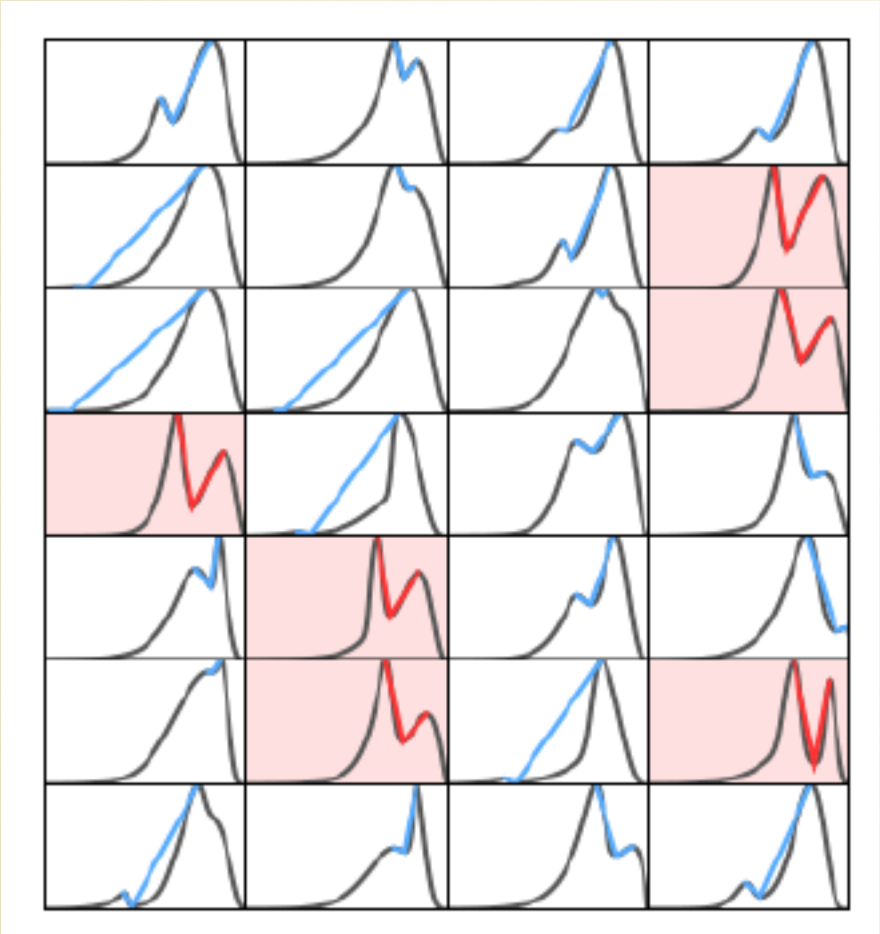
- Use **Artificial Neural Networks** to parameterize shape functions without bias and extract V_{ub} from theoretical constraints and data, together with HQE parameters in a model independent way (without assumptions on functional form). Similar to NNPDF. Applies to $b \to u l \nu$, $b \to s \gamma$,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

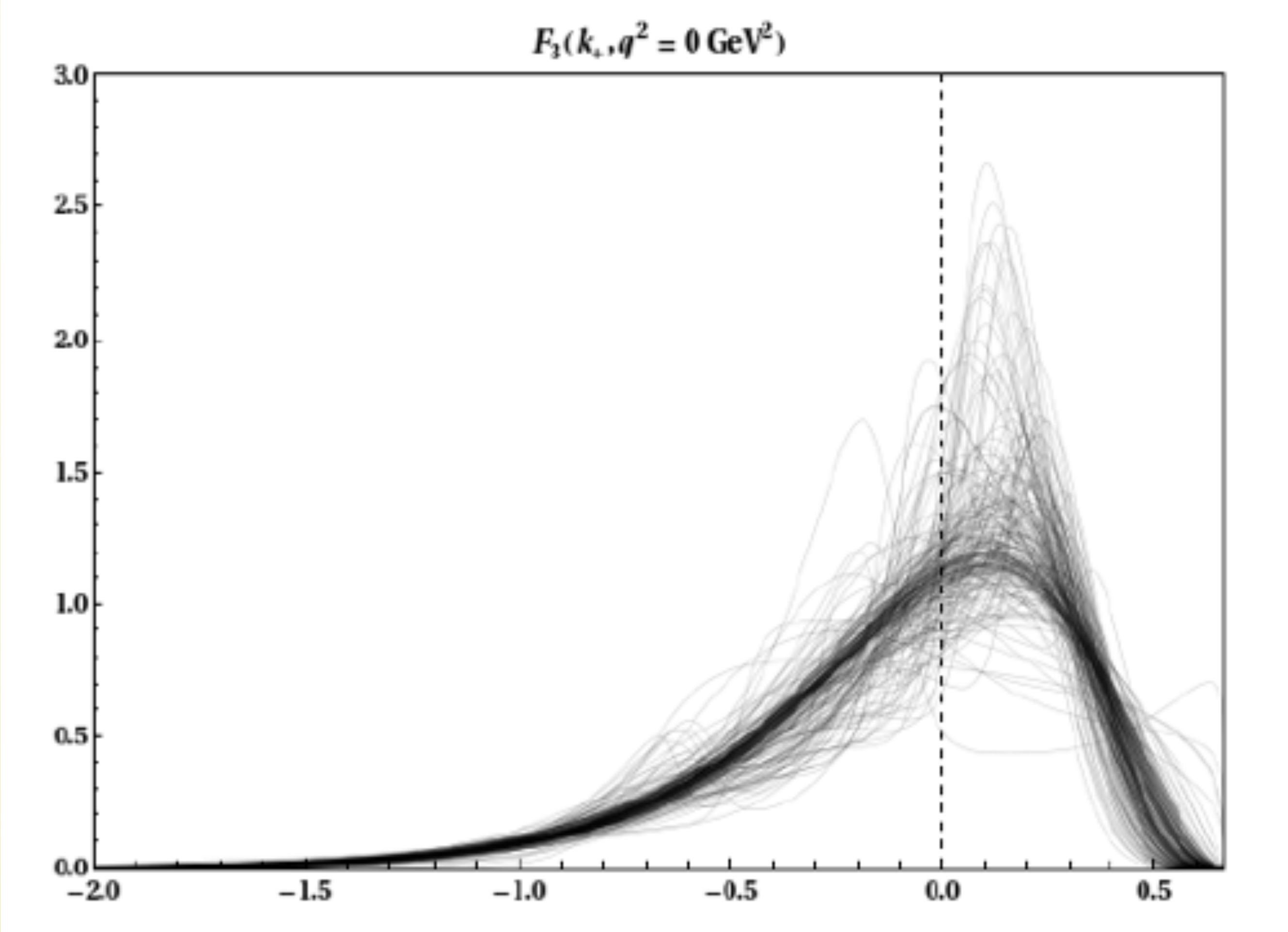
- Belle-II will be able to measure some kinematic distributions, thus constraining directly the shape functions. NNVub will provide a flexible tool to analyse data.

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

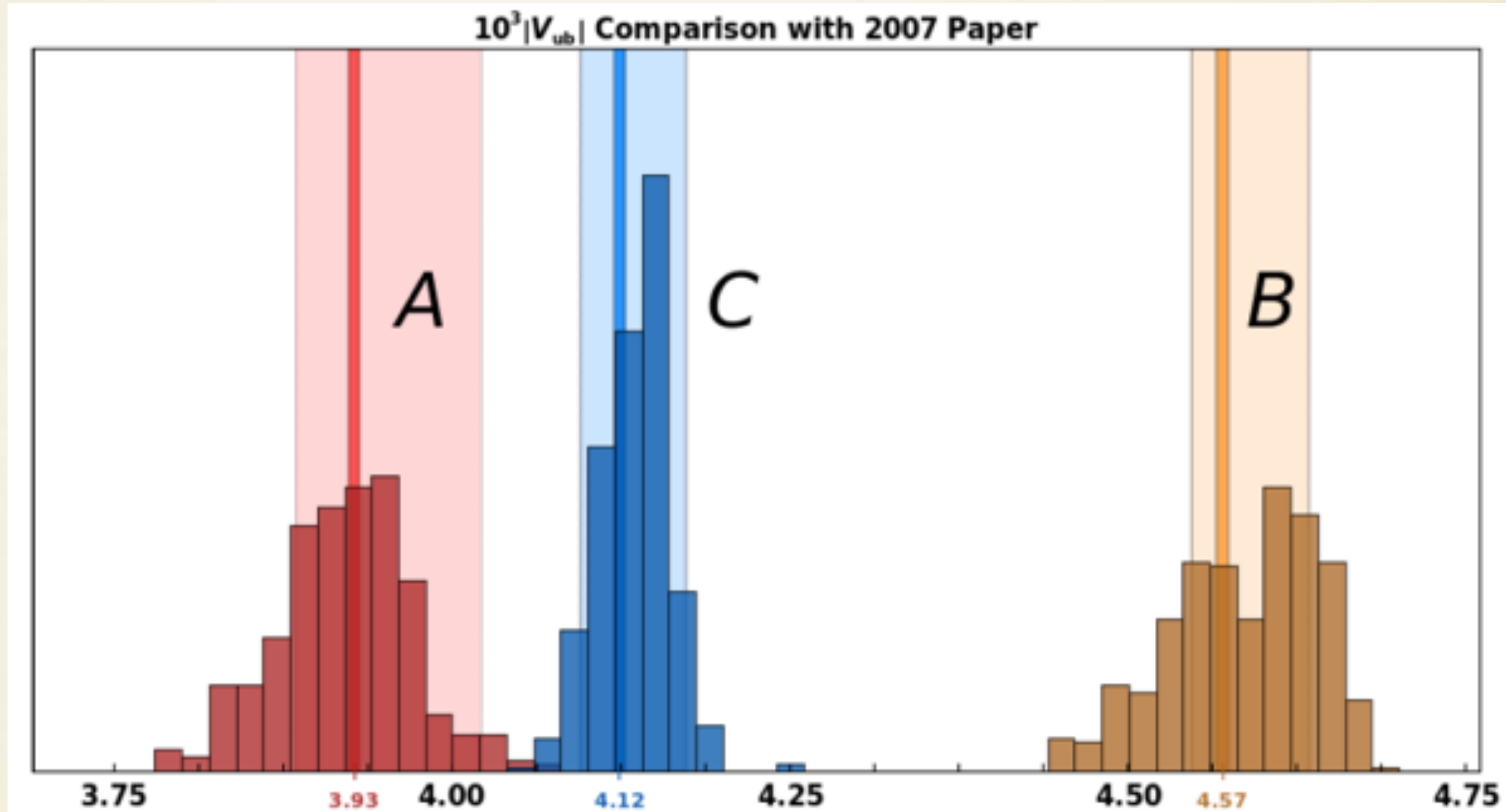


Beware: sampling can be biased by implementation!





Comparison with 2007 paper, same inputs

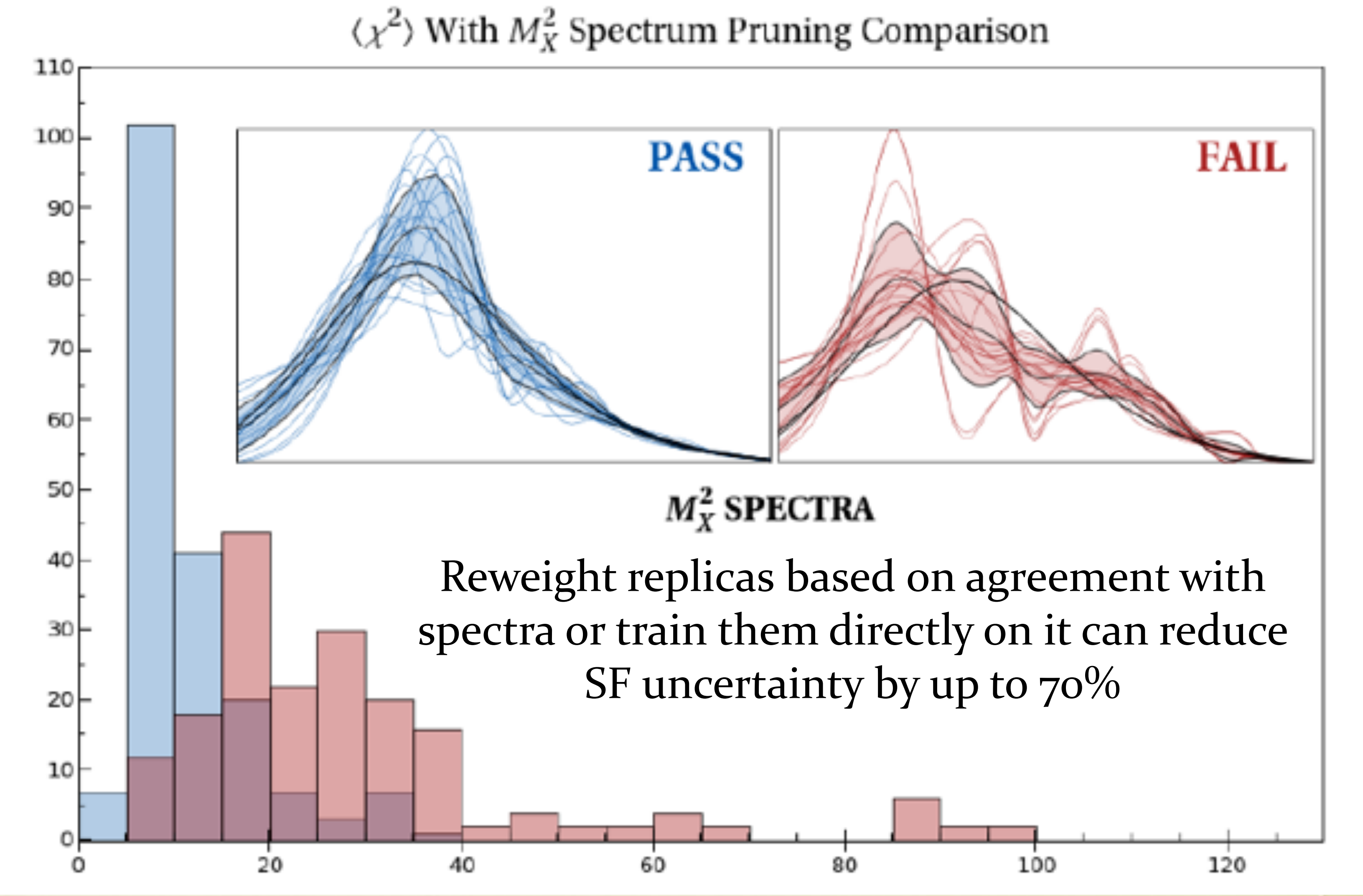


	NNVub	GGOU(2007)
Experimental cuts (in GeV or GeV^2)	$\|V_{ub}\| \times 10^3$	$\|V_{ub}\| \times 10^3$[15]
$M_X < 1.55, E_\ell > 1.0$ Babar [44]	$4.30(20)(^{26}_{27})$	$4.29(20)(^{21}_{22})$
$M_X < 1.7, E_\ell > 1.0$ Babar [44]	$4.05(23)(^{19}_{20})$	$4.09(23)(^{18}_{19})$
$M_X \leq 1.7, q^2 > 8, E_\ell > 1.0$ 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

- Learning @ Belle-II from kinematic distributions, e.g. M_X spectrum
- OPE parameters checked/ improved in $b \to ul\nu$ (moments): global NN+OPE fit
- alternative approach SIMBA
  Tackmann, Ligeti, Stewart
- include all relevant information with correlations
- 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

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

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:

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

Bailey et al 1403.0635 (FNAL/MILC)

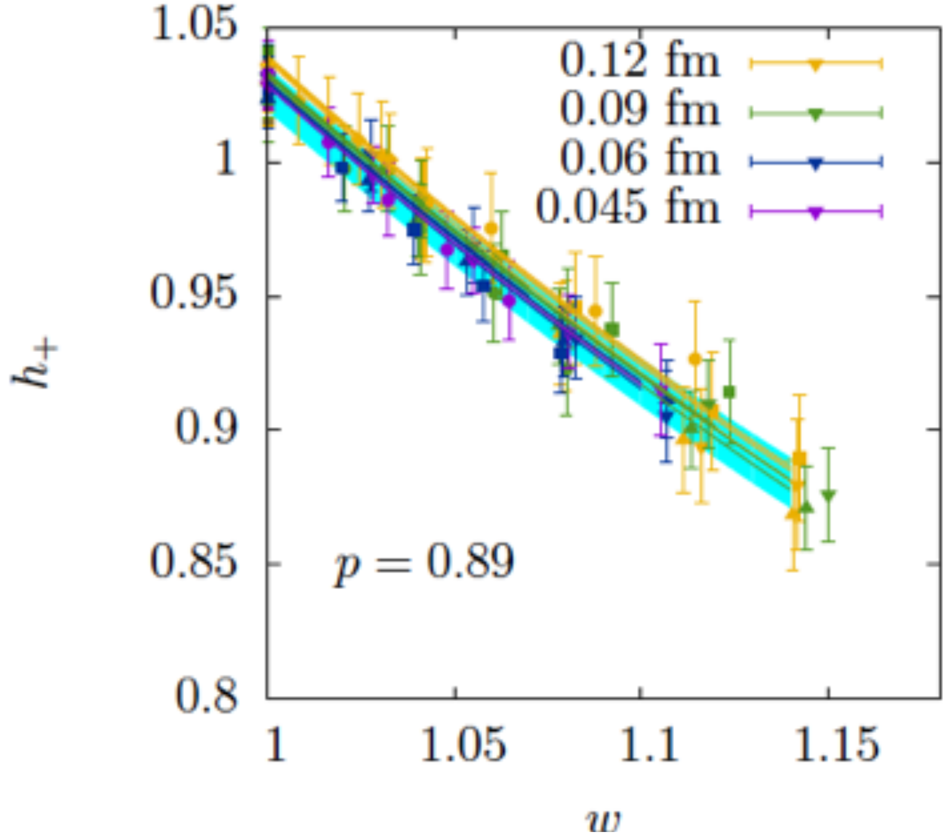
1.9% error (adding in quadrature)

~2.9σ or ~8% from inclusive determination

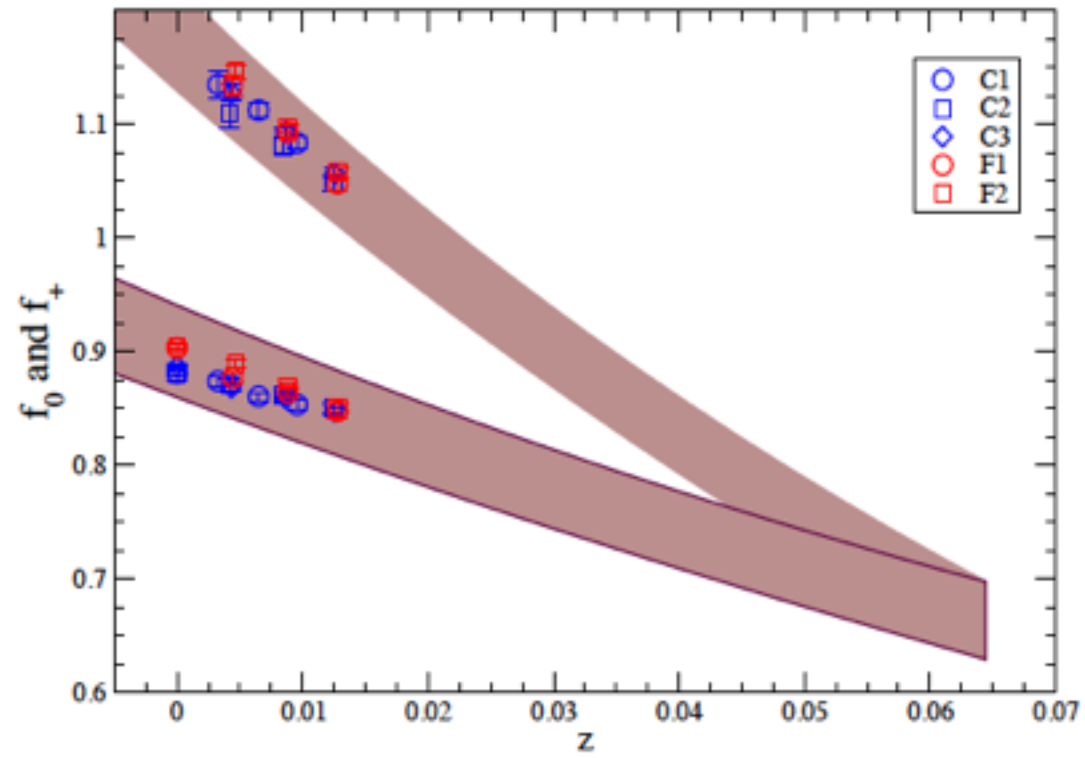
NB Heavy Quark Sum Rules estimate F(1)=0.86(2)   PG, Mannel, Uraltsev 2012

New results for $B \to Dl\nu$ FFs

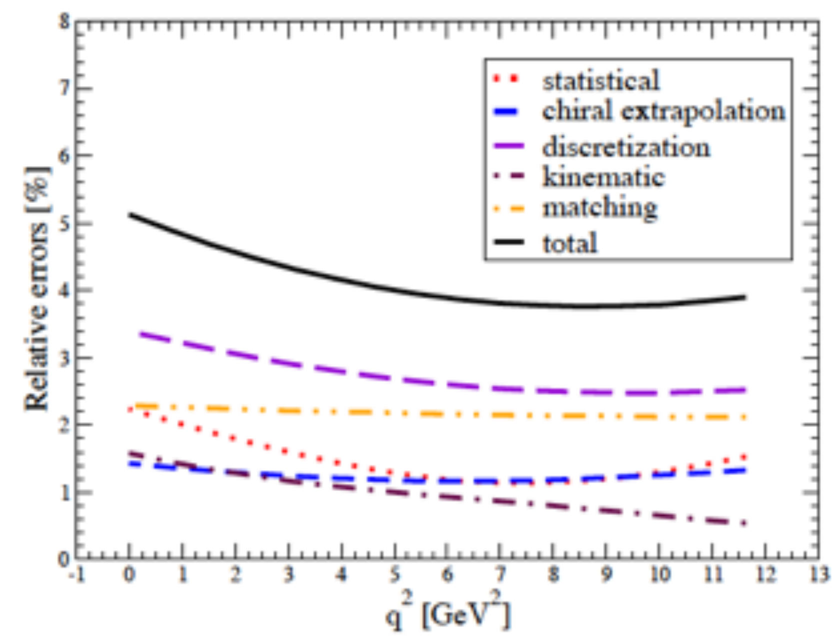
FNAL/MILC 1503.07237



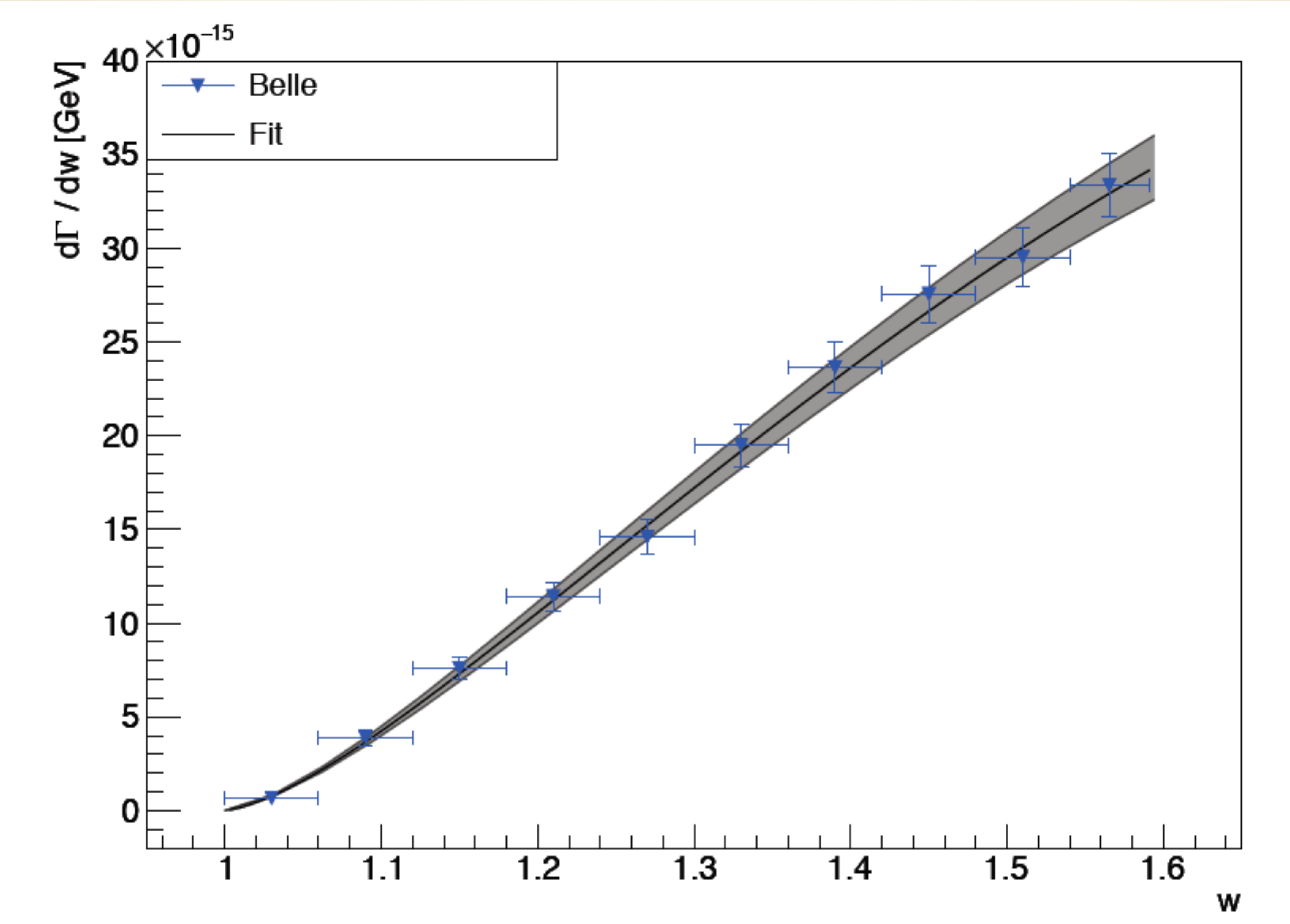
HPQCD 1505.03925



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



NEW BELLE SPECTRUM 1510.03657



FORM FACTORS

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

$$q^2 = (p-p')^2$$

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

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

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

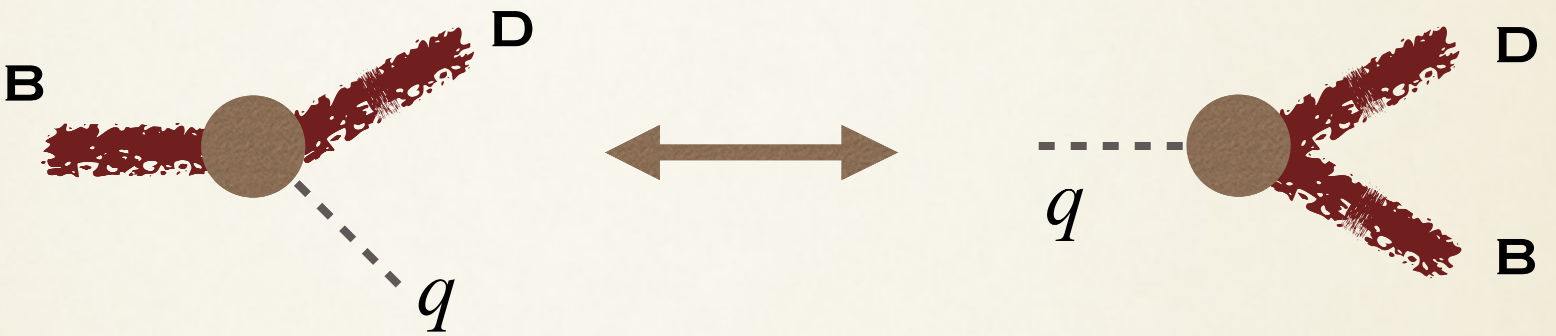
$$c_+^l = \frac{\lambda}{m_B^4}\left(1+\frac{m_l^2}{2q^2}\right), \qquad c_0^l = (1-r^2)^2\frac{3m_l^2}{2q^2}$$

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

$$f_+(0) = f_0(0)$$

UNITARITY CONSTRAINTS

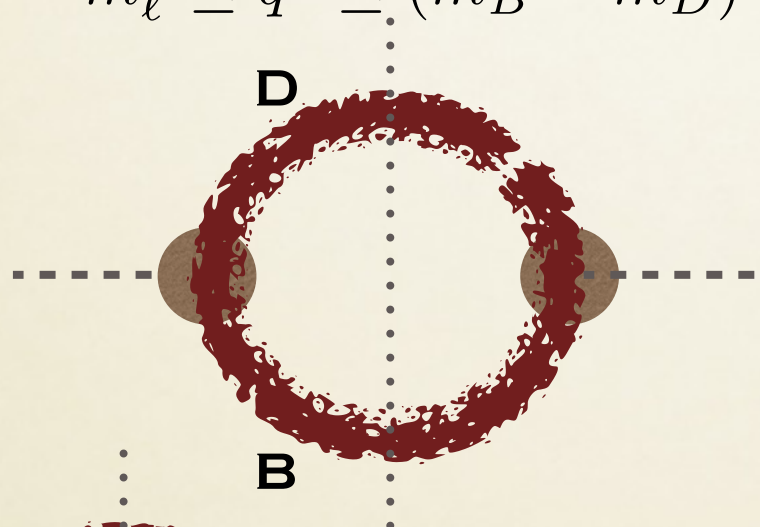
CROSSING + ANALITYCITY



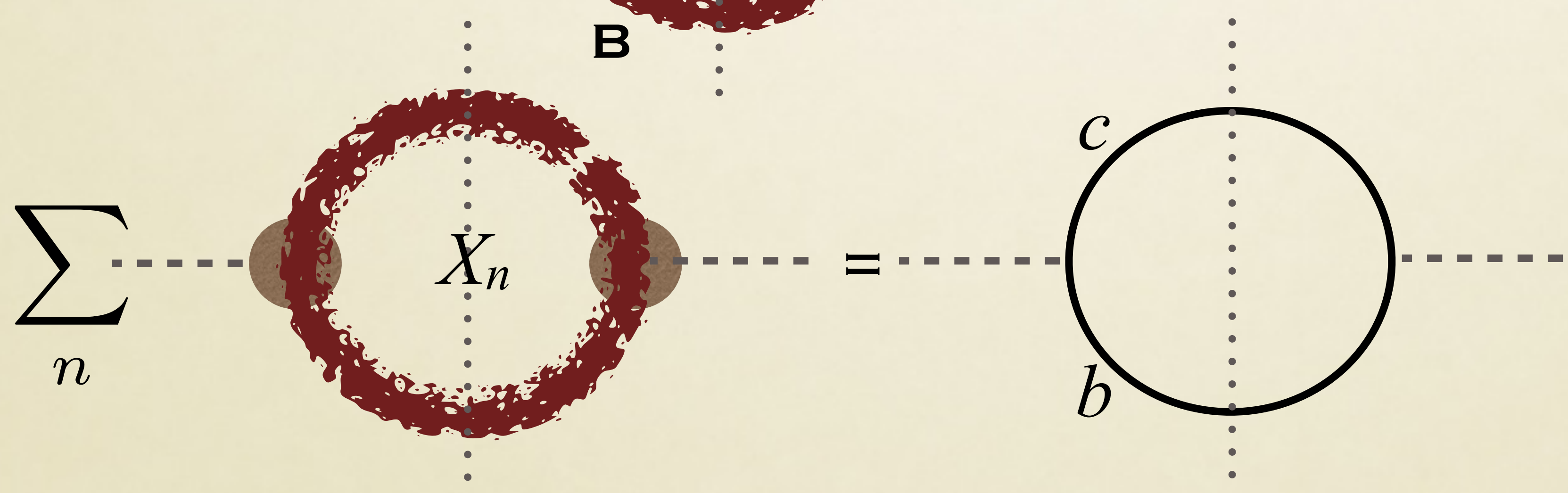
PHYSICAL SEMILEPTONIC REGION
$m_\ell^2 \le q^2 \le (m_B - m_D)^2$

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

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

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

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

BLASCHKE FACTORS REMOVE POLES

PHASE SPACE FACTORS

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

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

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

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

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

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 $1/\mathrm{m}^2$ corrections can be sizable For ex at zero recoil

$$\frac{F_{D^*}(z=0)}{f_+(z=0)} = 0.948 \neq 0.860(14) \qquad \frac{f_+(0)}{f_0(0)} = 0.775 \neq 0.753(3)$$

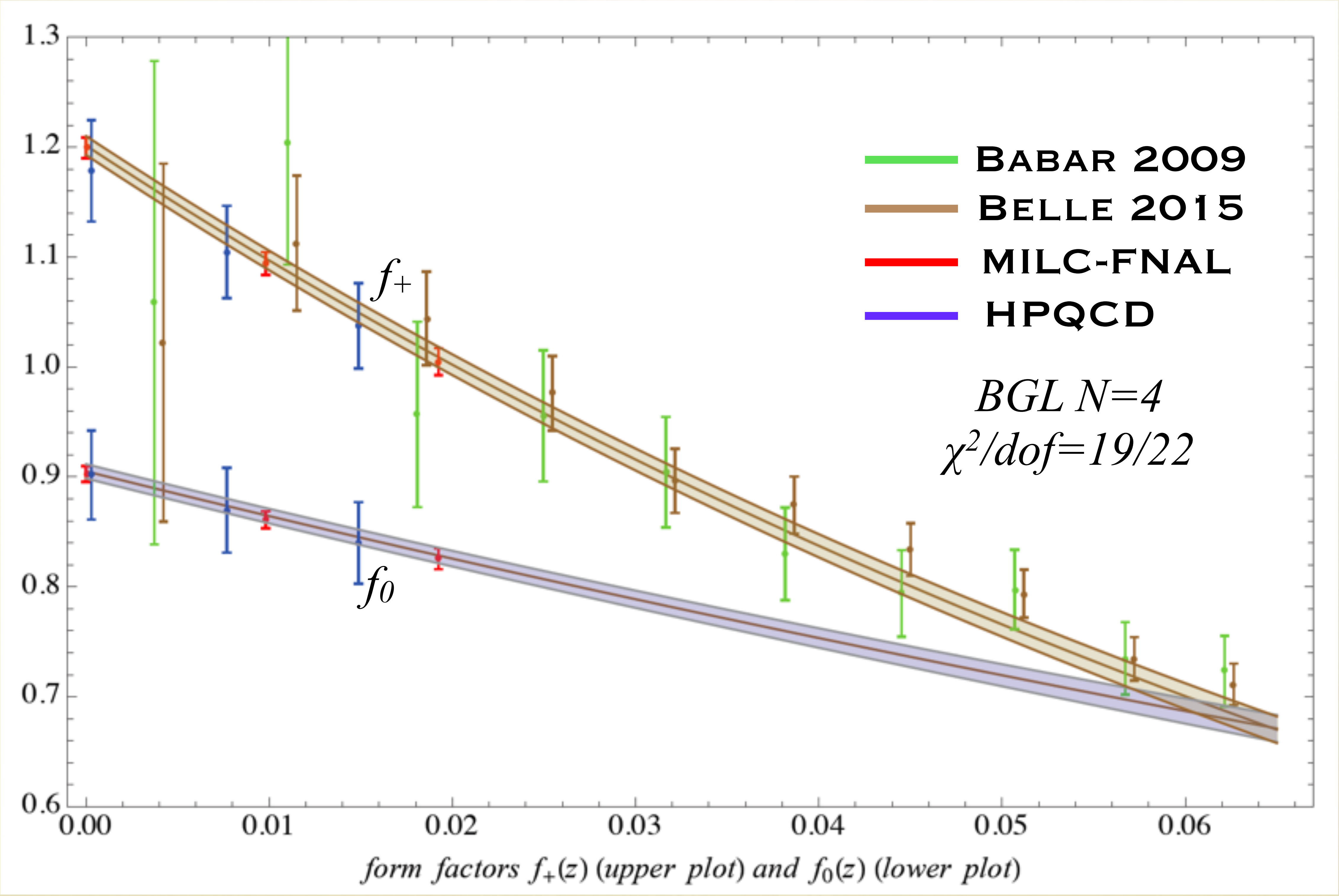
NLO HQET LATTICE (FNAL) NLO HQET LATTICE (FNAL)

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

Global fit to $B \to Dl\nu$

D.Bigi, PG
arXiv:1606.08030



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)

Global fit to $B \to Dl\nu$

- $|V_{cb}|$=40.49(0.97) 10^{-3} (BGL,N=4) compatible with both inclusive and $B \to D^*$
- $R(D)$=0.299(3) 2σ from HFAG average
- **Constrained fit with strong unitarity bounds**
- weak bounds leads to very similar results with slightly larger errors
- BGL and BCL parameterizations give almost identical results
- 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)
- Belle only fit has higher V_{cb}
- Possible improvements from more precise data (Belle-II, reanalysis of Babar data) and lattice calculations

WEAK vs STRONG BOUNDS

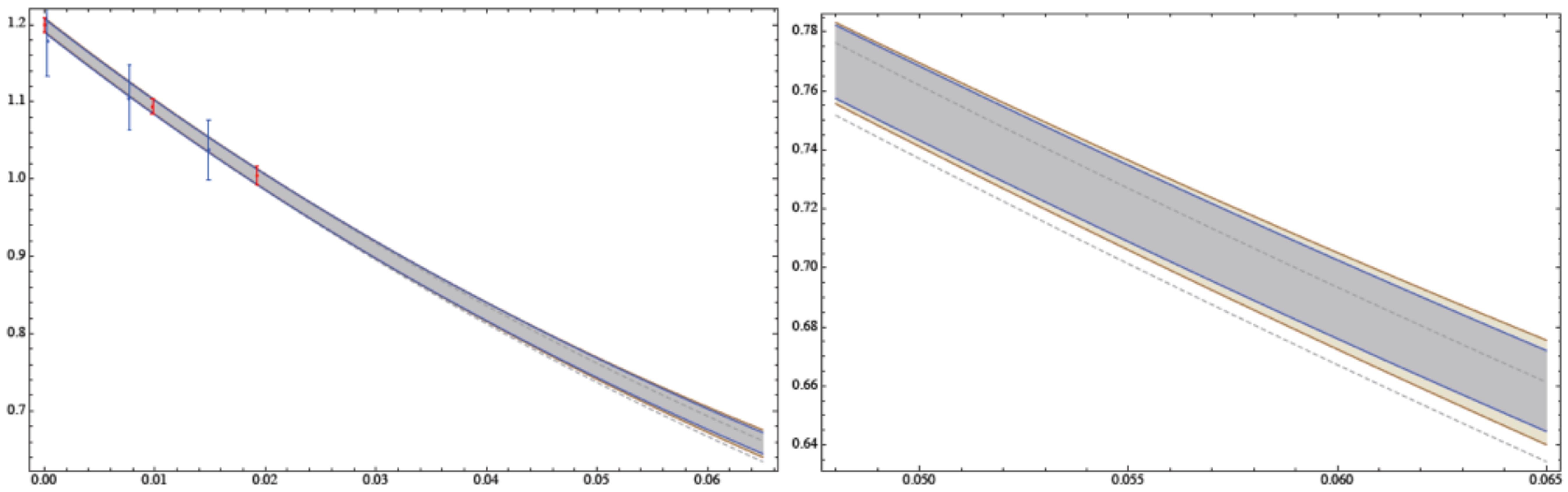
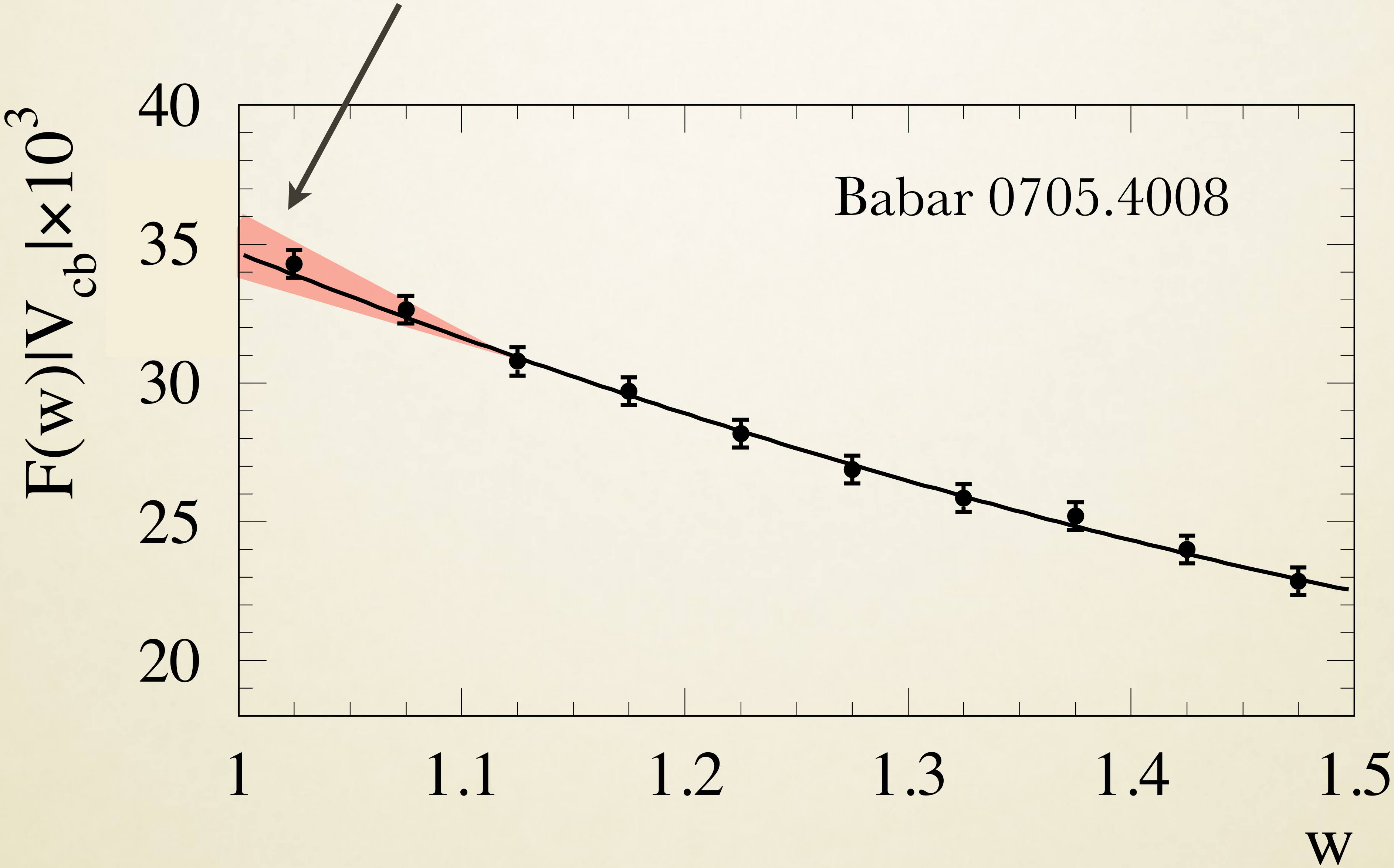


Figure 2: Form factor $f_+(z)$ in the $N = 4$ BGL fit to lattice data for $f_{+,0}(z)$ with weak (brown band) and strong (gray band) unitarity constraints. The $N = 2$ band (independent of unitarity constraints) is shown in dashed lines for comparison. FNAL/MILC synthetic data are shown in red, HPQCD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

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



$B\to D^*$ analyses based on CLN: errors underestimated.
However the spectrum is measured precisely and extrapolation to zero-recoil is a small effect. New Belle analysis under way…

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 $m_b\, a \lesssim 1$?

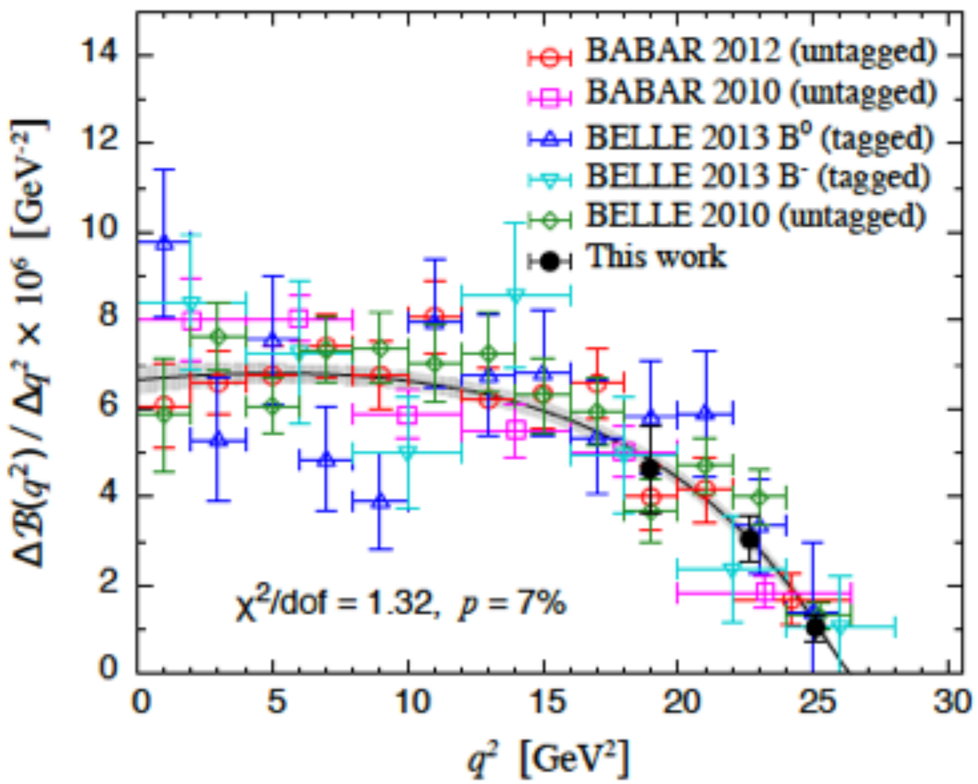
- **Heavy quark sum rules** (with BPS arguments) favor smaller F(1)=0.86(2) leading to agreement with inclusive. Difficult to improve, how good is the BPS limit?

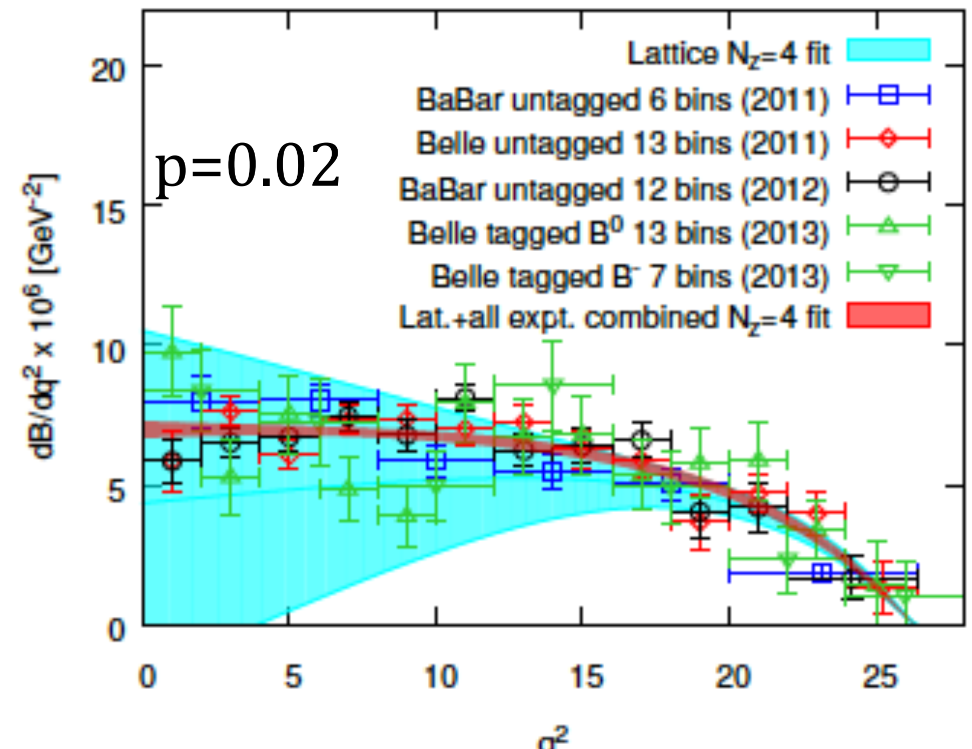
- **QED/EW corrections**: SD log OK, SD remainder tiny if G_μ employed, soft/collinear radiation subtracted out by Photos, intermediate photons (IR finite) are structure dependent: lattice calculations? exp cuts? relevance of Coulomb enhancement for B^0 decay rate?

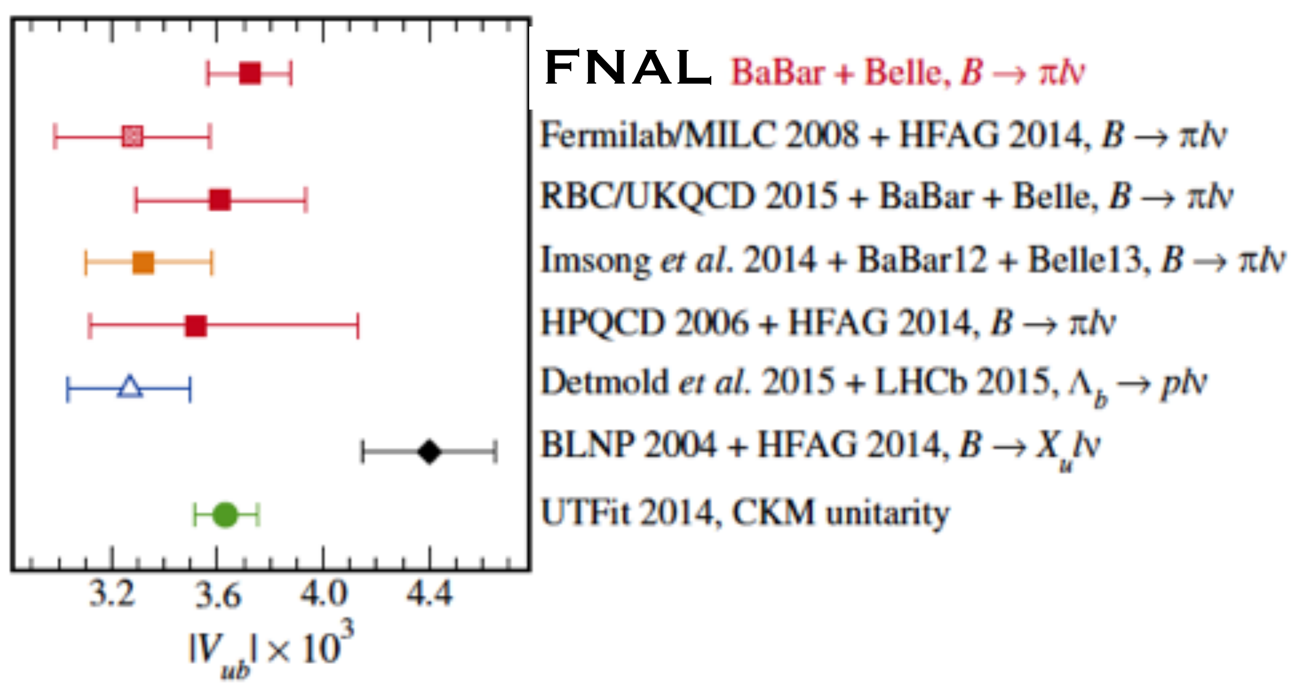
- **New channels** (Bc, Bs, Λ_b) at Belle-II and LHCb, can also be combined for unitarity bounds, better understanding of D**

Recent lattice $B\to\pi$

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







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

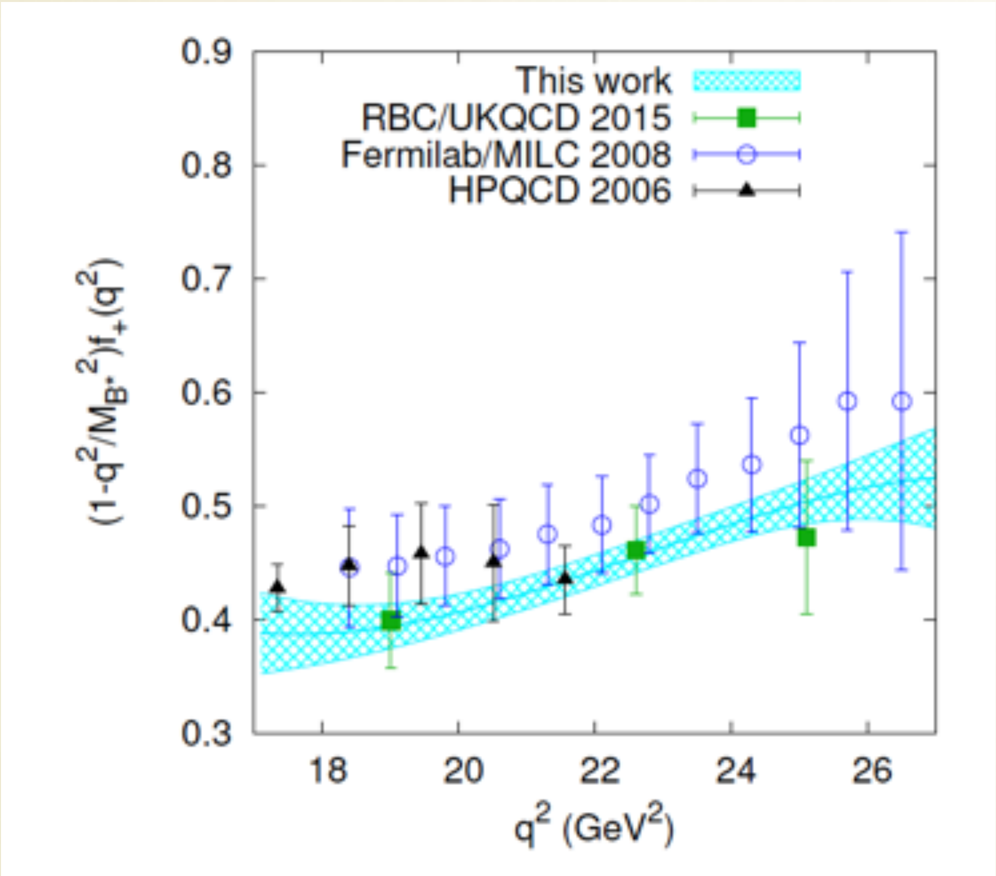
RBC/UKQCD 3.61(32) 10^{-3}
1.9σ from inclusive

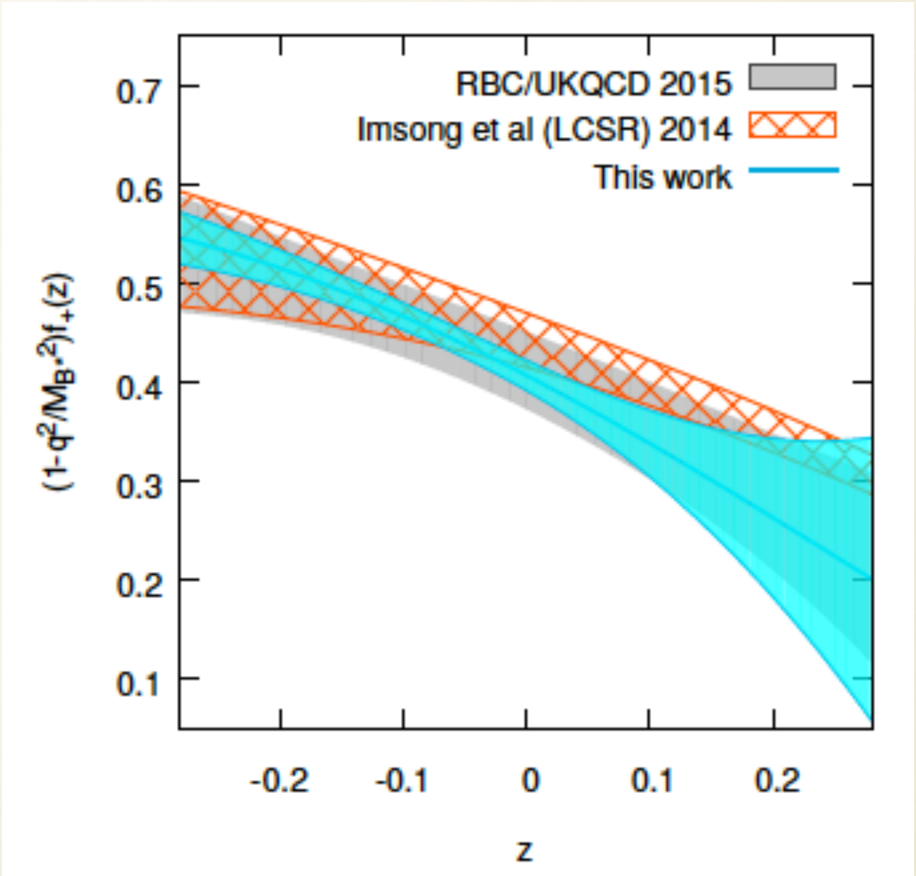
LCSR 3.32(26) 10^{-3}
2.9σ from inclusive

LHCb depends
on V_{cb} employed but low

Recent lattice results

1503.07839





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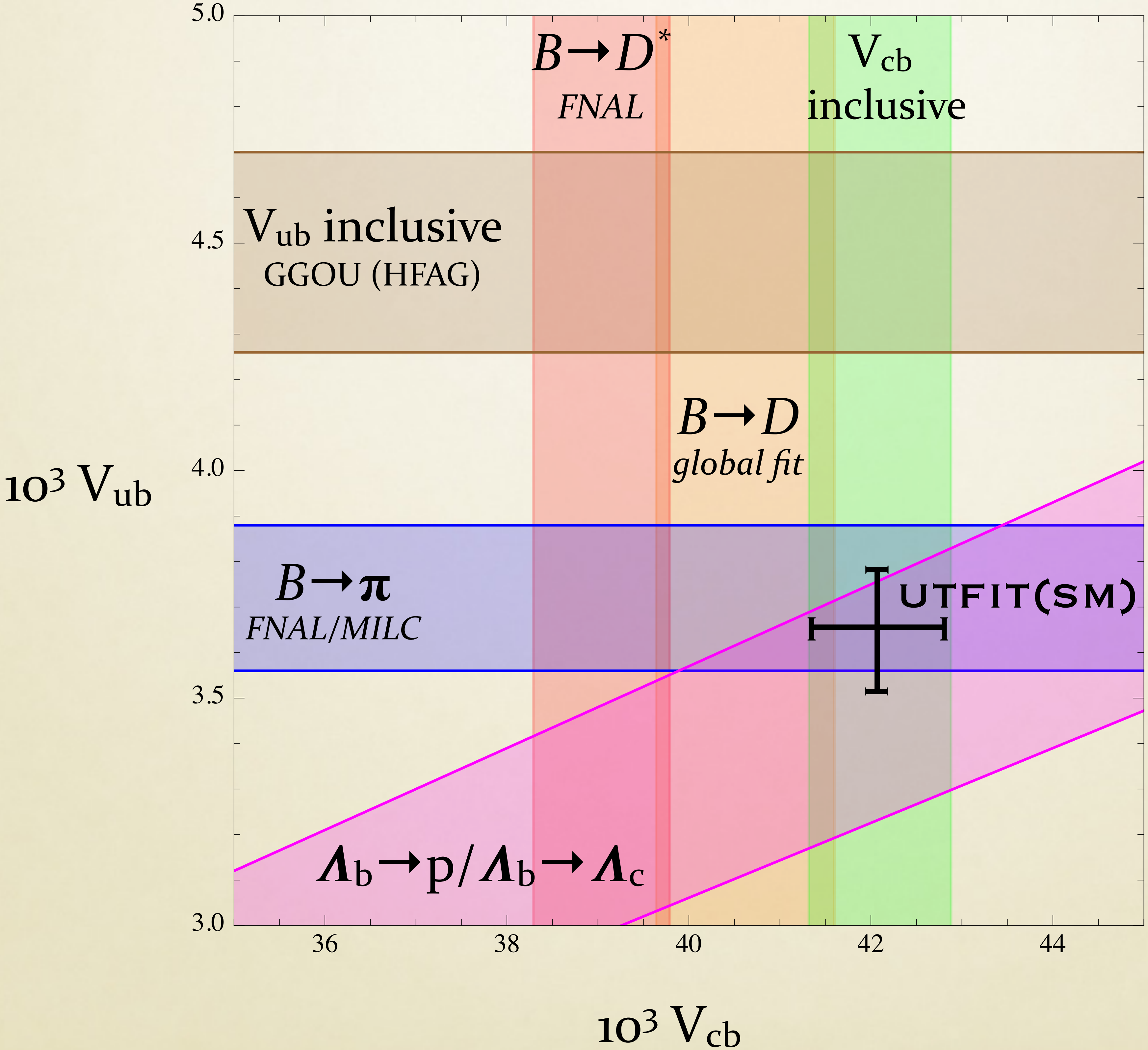
all	all	4,BCL	40.48(97)	17.9/22	0.299(3)

Prospects: further improvements in LQCD, much more data @ BelleII, $B_s \rightarrow K l \nu$ and other channels @Belle-II and LHCb

VISUAL SUMMARY



reasonable consistency among exclusive channels

not all results at the same level

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%, 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,Mannel,...

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

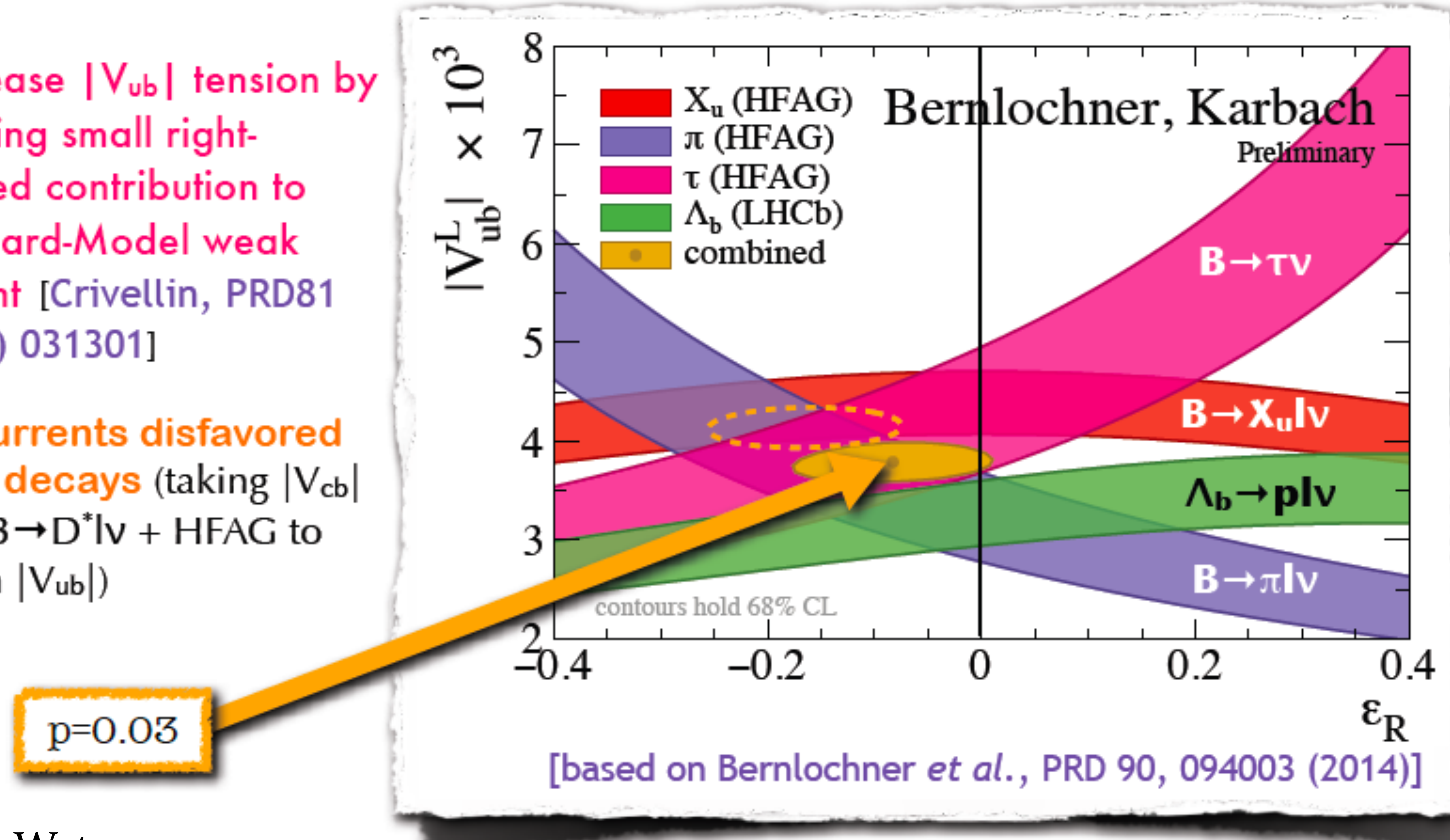
Most general SU(2) invariant dim 6 NP (without RH light neutrino) can explain results, but it is incompatible with $Z\to b\bar{b}$ data

Crivellin, Pokorski 1407.1320

(though this may need update after new $B\to Dl\nu$ result…)

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

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 (ongoing Belle analysis, Belle-II)
- New fit allows for precise SM determination R(D)=0.299(3)
- Exclusive/incl tension in V_{ub} seems receding because of new FNAL/MILC and HPQCD results and of preliminary Babar results. Significant progress will come with Belle-II and further LHCb data ($B\to\tau\nu$ etc).
- NNVub framework permits implementation of Belle-II experimental data and OPE constraints, reducing the SFs uncertainty. Comparison with data will validate inclusive approach to V_{ub} in a much more stringent way.
- New physics explanations quite constrained for both V_{ub} and V_{cb}..