SEMILEPTONIC B DECAYS, QUARK MASSES, AND CKM

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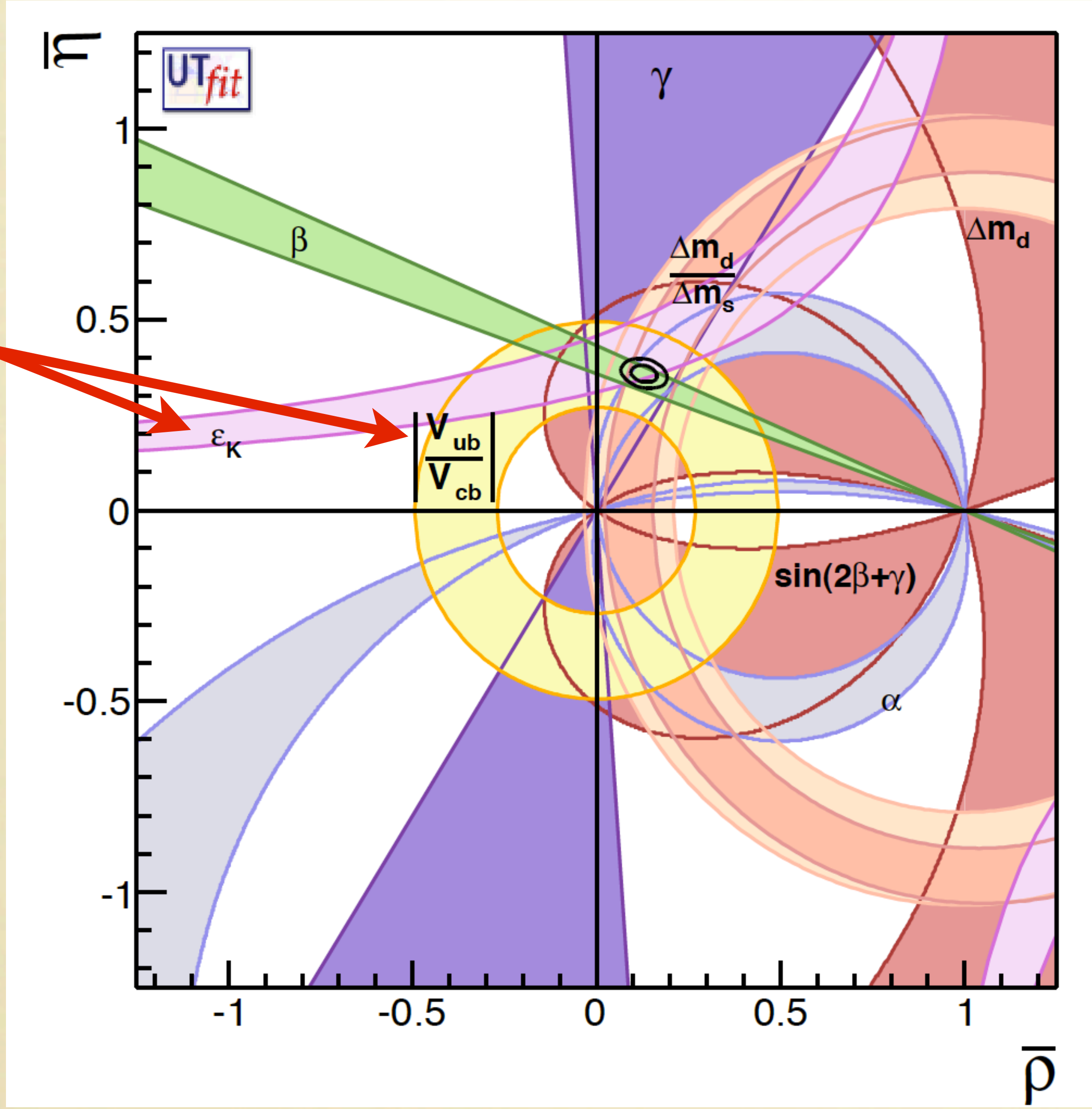
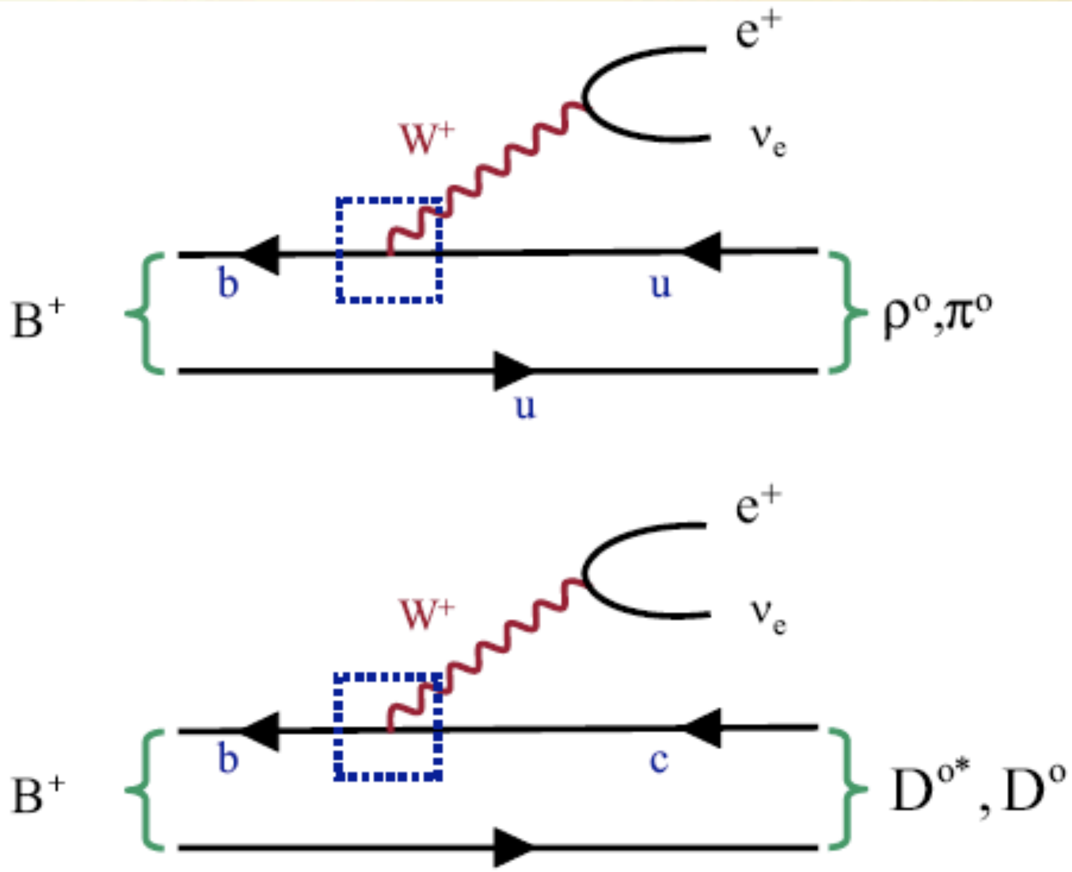
MATTER TO THE DEEPEST, USTRON, 4/9/2013

S.L. DECAYS DETERMINE $|V_{ub}|$ AND $|V_{cb}|$



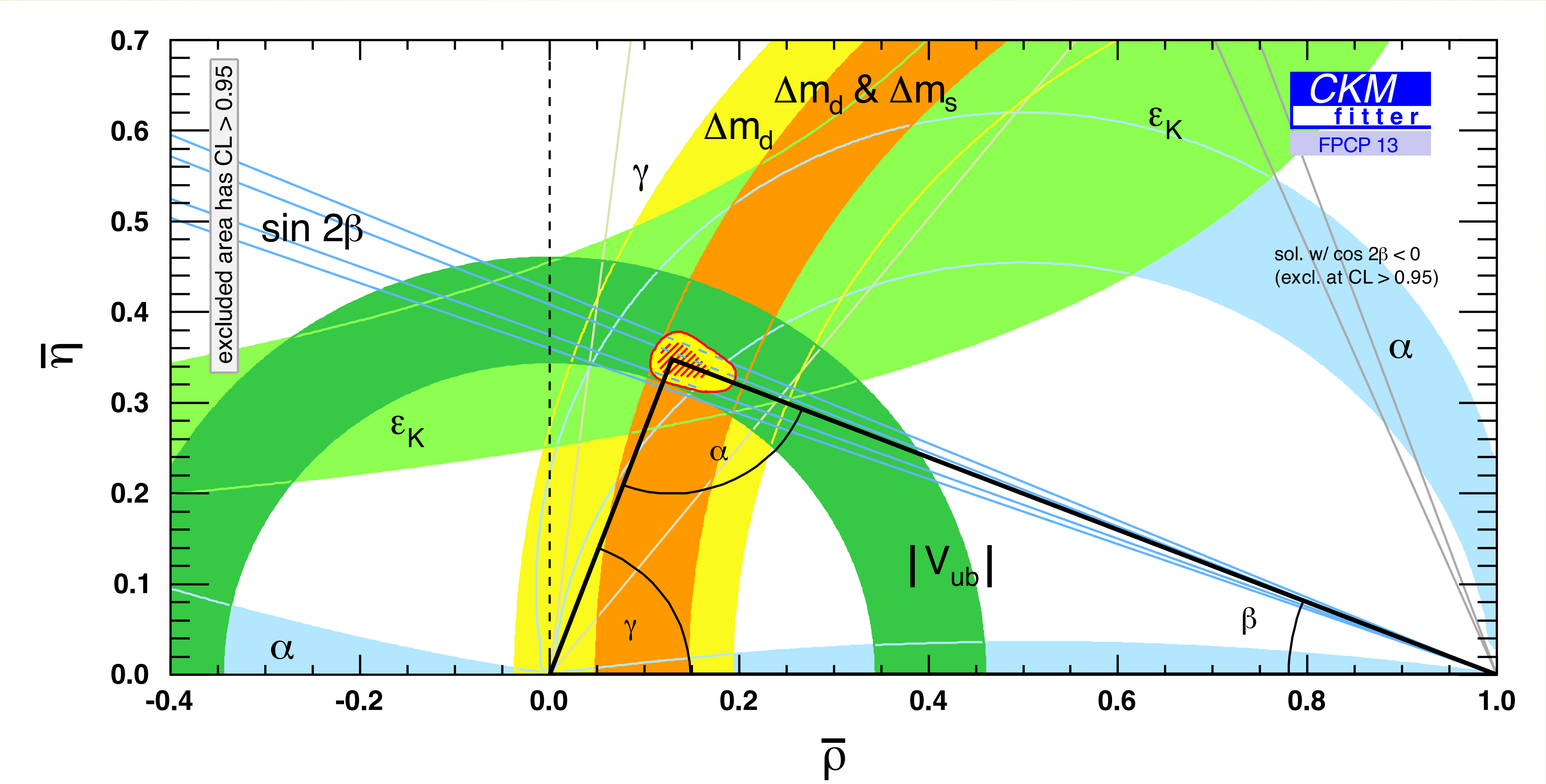


$B \to \tau\nu$ is not yet competitive

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

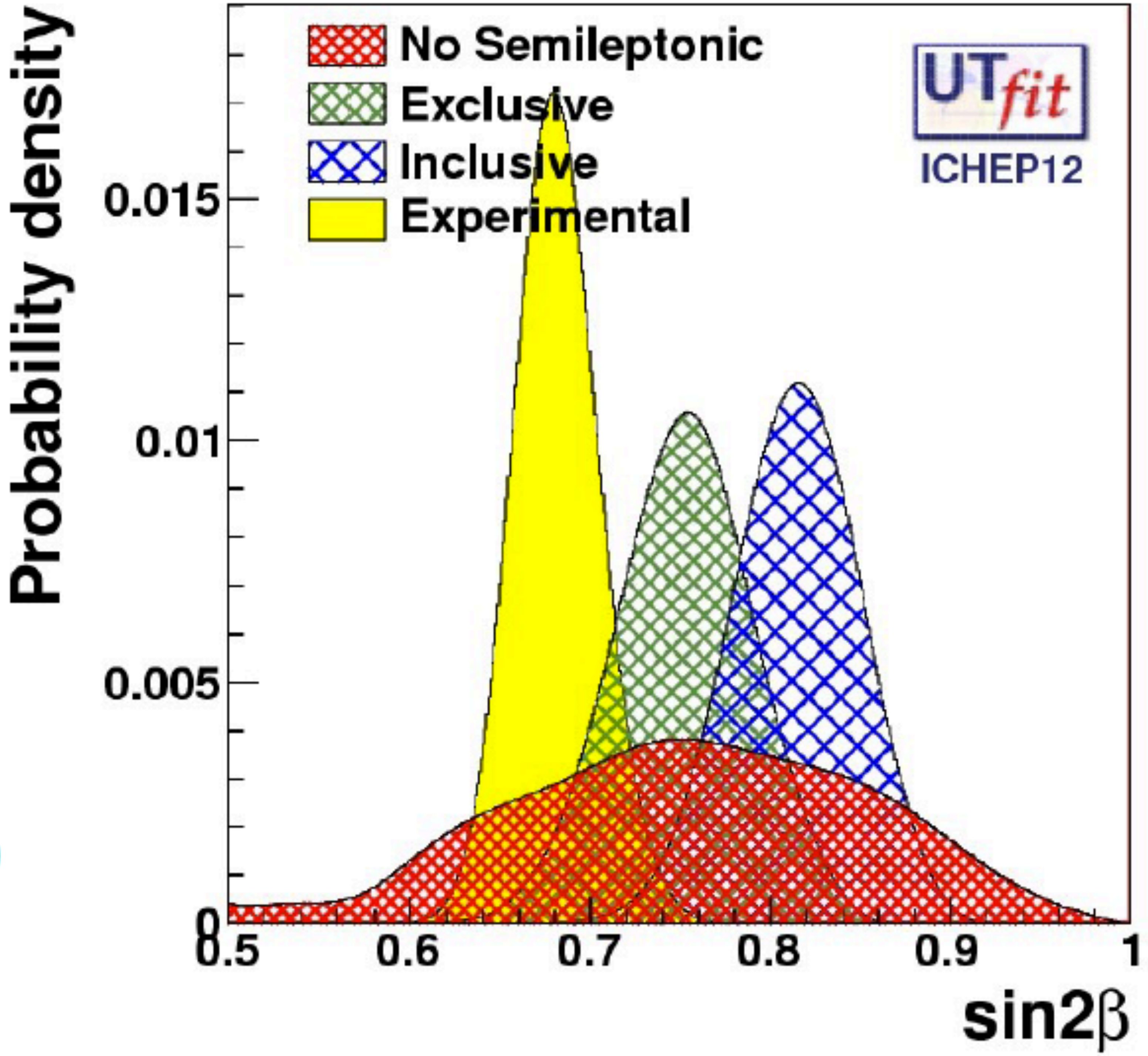
THE UNITARITY TRIANGLE

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



sin2β is measured directly in CP asymmetries in B→J/Ψ K_S

inclusives vs exclusives



only exclusive values

$\sin 2\beta_{UTfit}$ = 0.751 ± 0.039

~1.8σ

only inclusive values

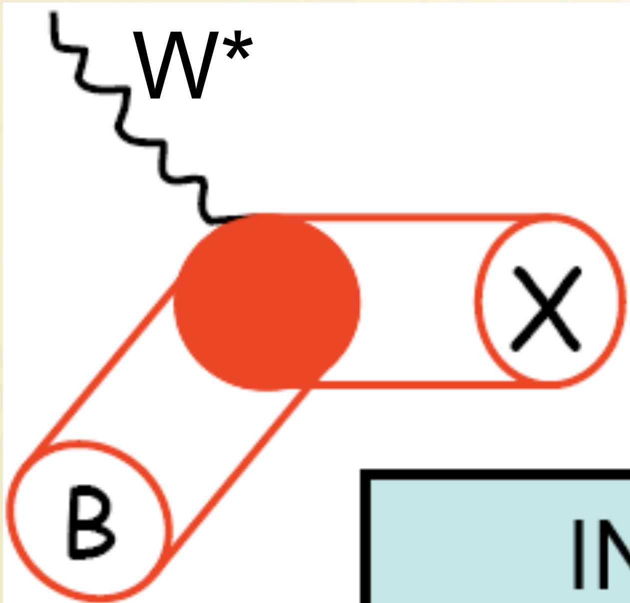
$\sin 2\beta_{UTfit}$ = 0.813 ± 0.036

~3.2σ

$\sin 2\beta_{UTfit}$ = 0.76 ± 0.10 → *no semileptonic*

~0.9σ

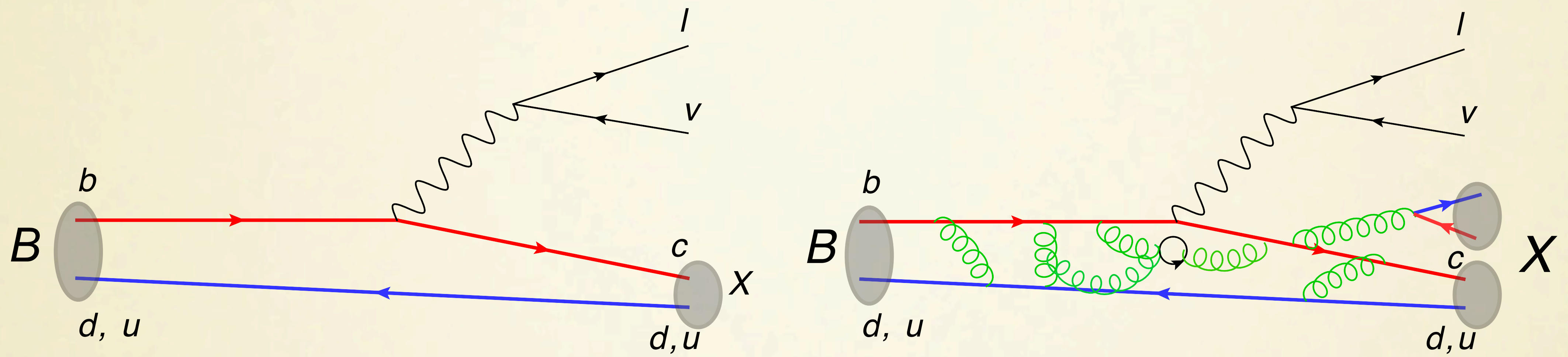
Inclusive vs exclusive B decays



Simplicity: ew (or em) currents probe the 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

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 $O(1/m_b^3)$...

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

THE TOTAL WIDTH IN THE OPE

$$\Gamma[B \to X_c l \bar{\nu}] = \Gamma_0 \; g(r) \Big[1 + \frac{\alpha_s}{\pi} c_1(r) + \frac{\alpha_s^2}{\pi^2} c_2(r) - \frac{\mu_\pi^2}{2m_b^2} + c_G(r) \frac{\mu_G^2}{m_b^2}$$
$$+ c_D(r) \frac{\rho_D^3}{m_b^3} + c_{LS}(r) \frac{\rho_{LS}^3}{m_b^3} + O\Big(\alpha_s \frac{\mu_{\pi,G}^2}{m_b^2}\Big) + O\Big(\frac{1}{m_b^4}\Big) \Big]$$

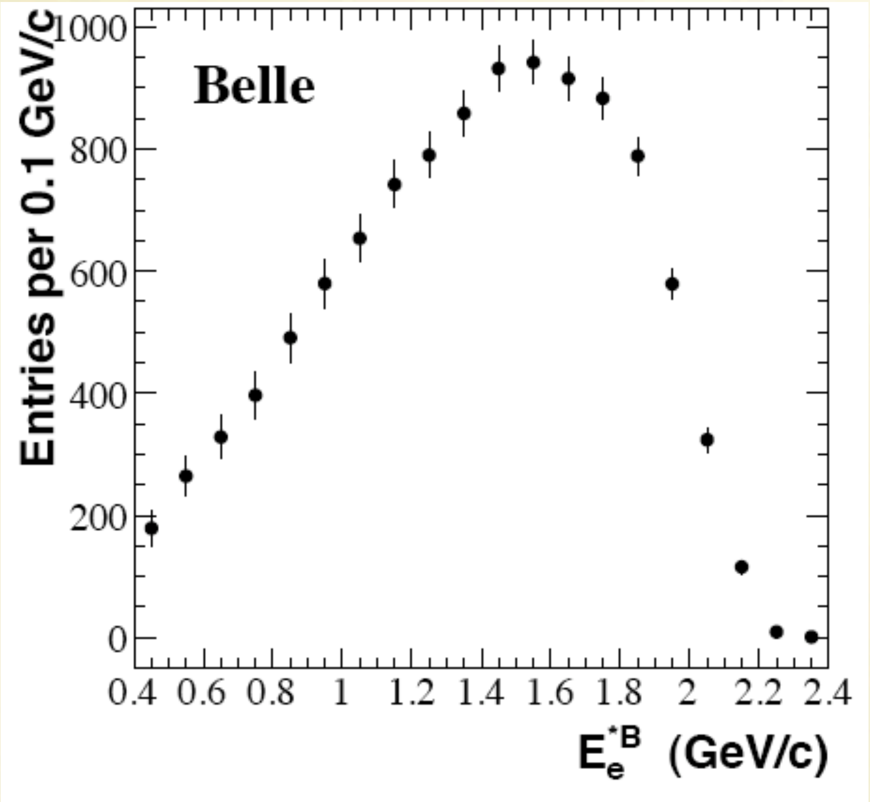
$$\Gamma_0 = \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3} \qquad r = \frac{m_c^2}{m_b^2}$$

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

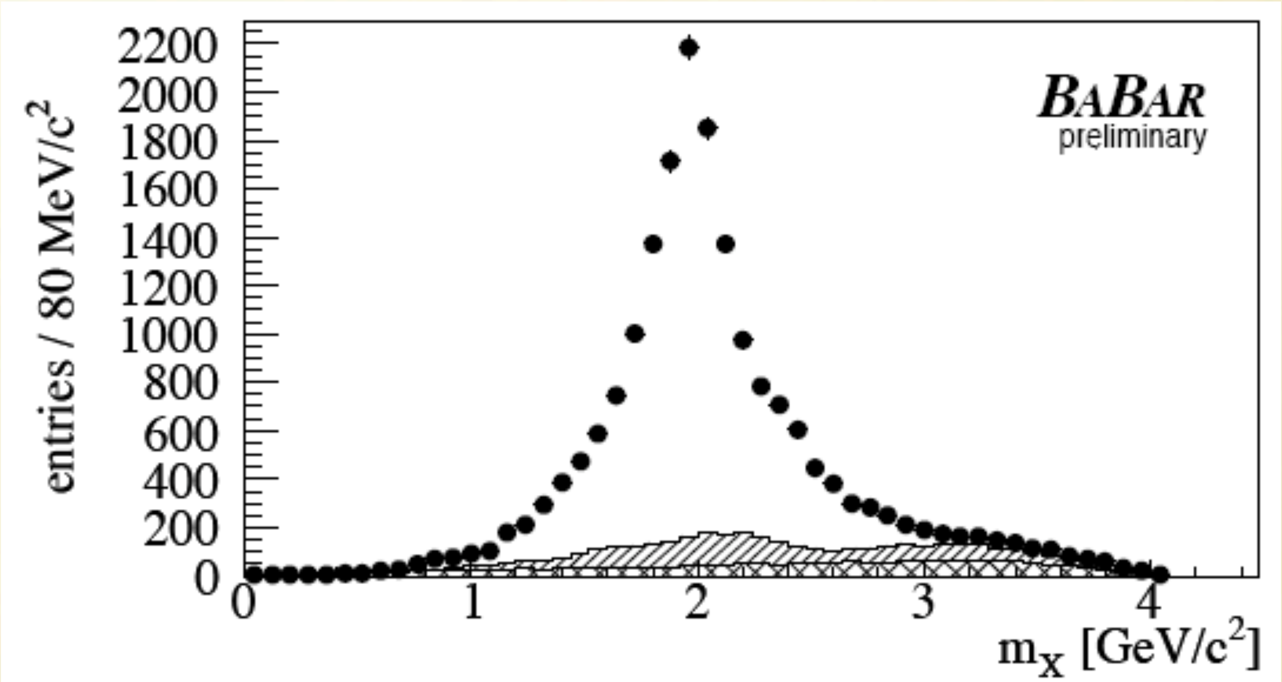
Present implementations include all terms through $O(\alpha_s^2, 1/m_b^3)$: $m_{b,c}, \mu^2_{\pi,G}, \rho^3_{D,LS}$ 6 parameters

EXTRACTION OF THE OPE PARAMETERS

E_l spectrum



m_x spectrum



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

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

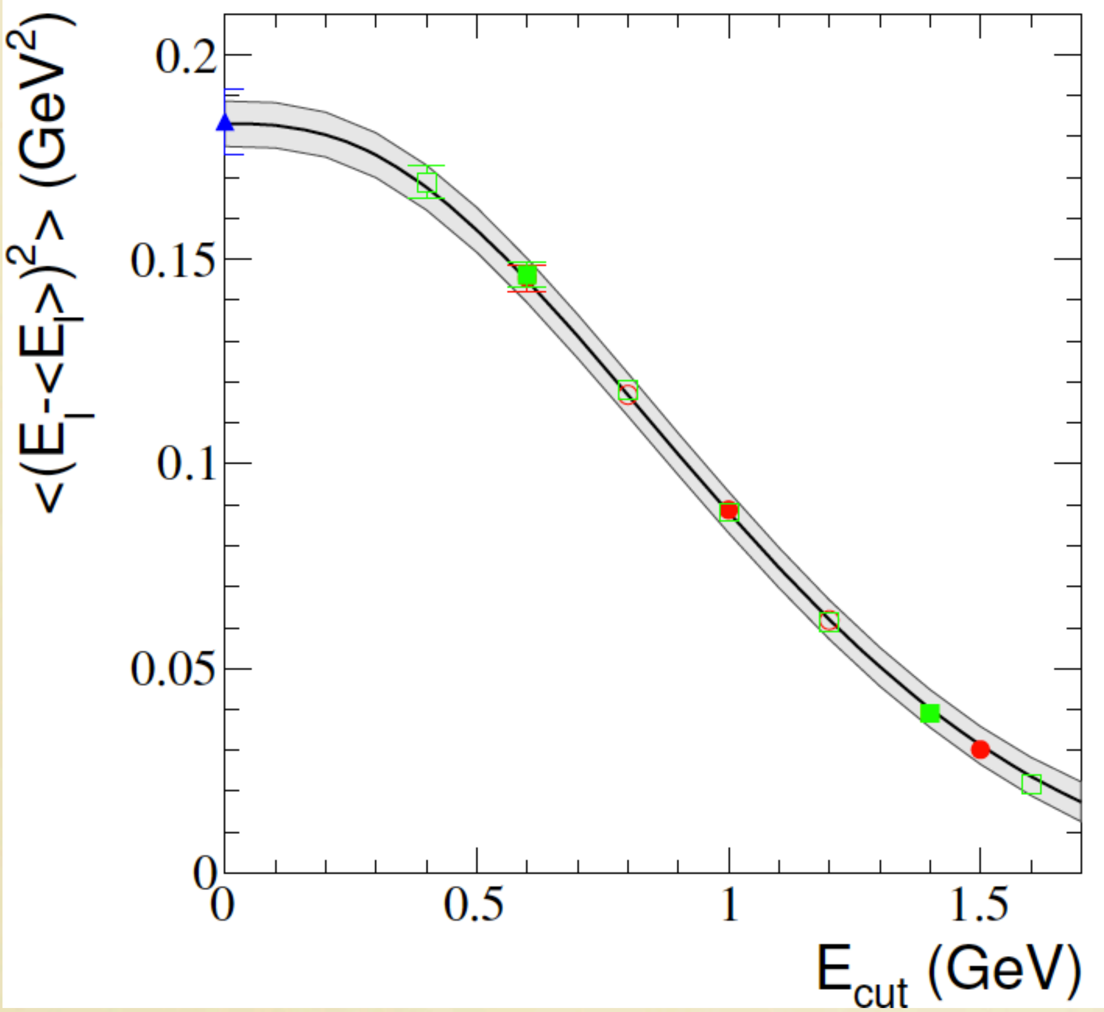
New semileptonic fits

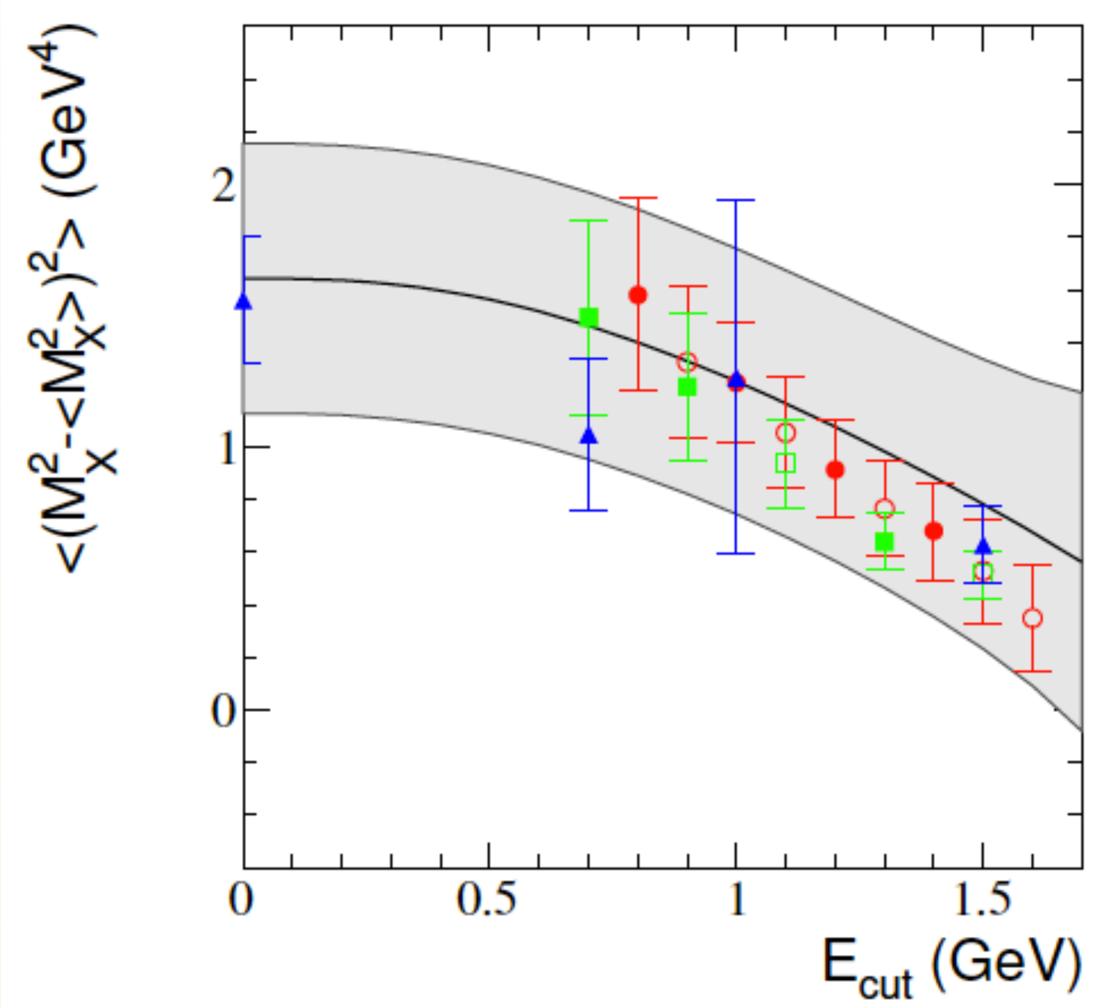
Schwanda, PG, 1307.4551

- first fits to include all $O(\alpha_s^2)$ corrections and
  Czarnecki, Pak, Melnikov, Biswas 2008-10
- reassessment of theoretical errors, study of their correlations
- new external constraints: precise heavy quark mass determinations
- kinetic scheme calculation based on
  PG, 1107.3100; Uraltsev & PG,hep-ph/0401063

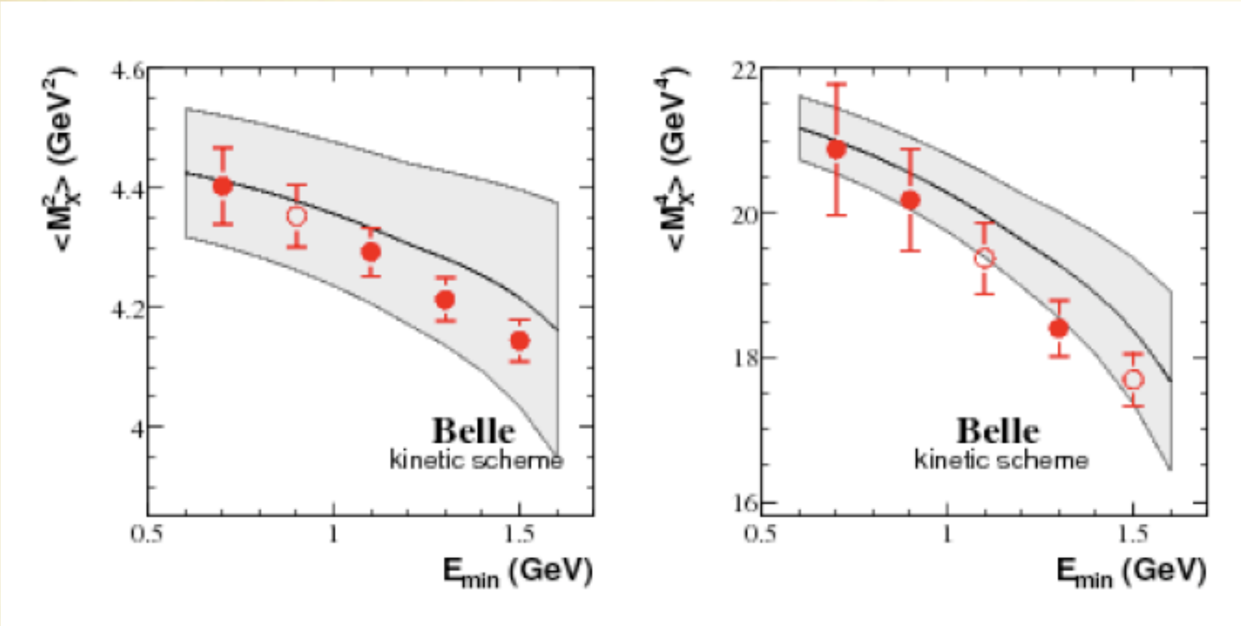
Previous fits: Buchmuller, Flaecher hep-ph/0507253,
Bauer et al, hep-ph/0408002 (1S scheme)

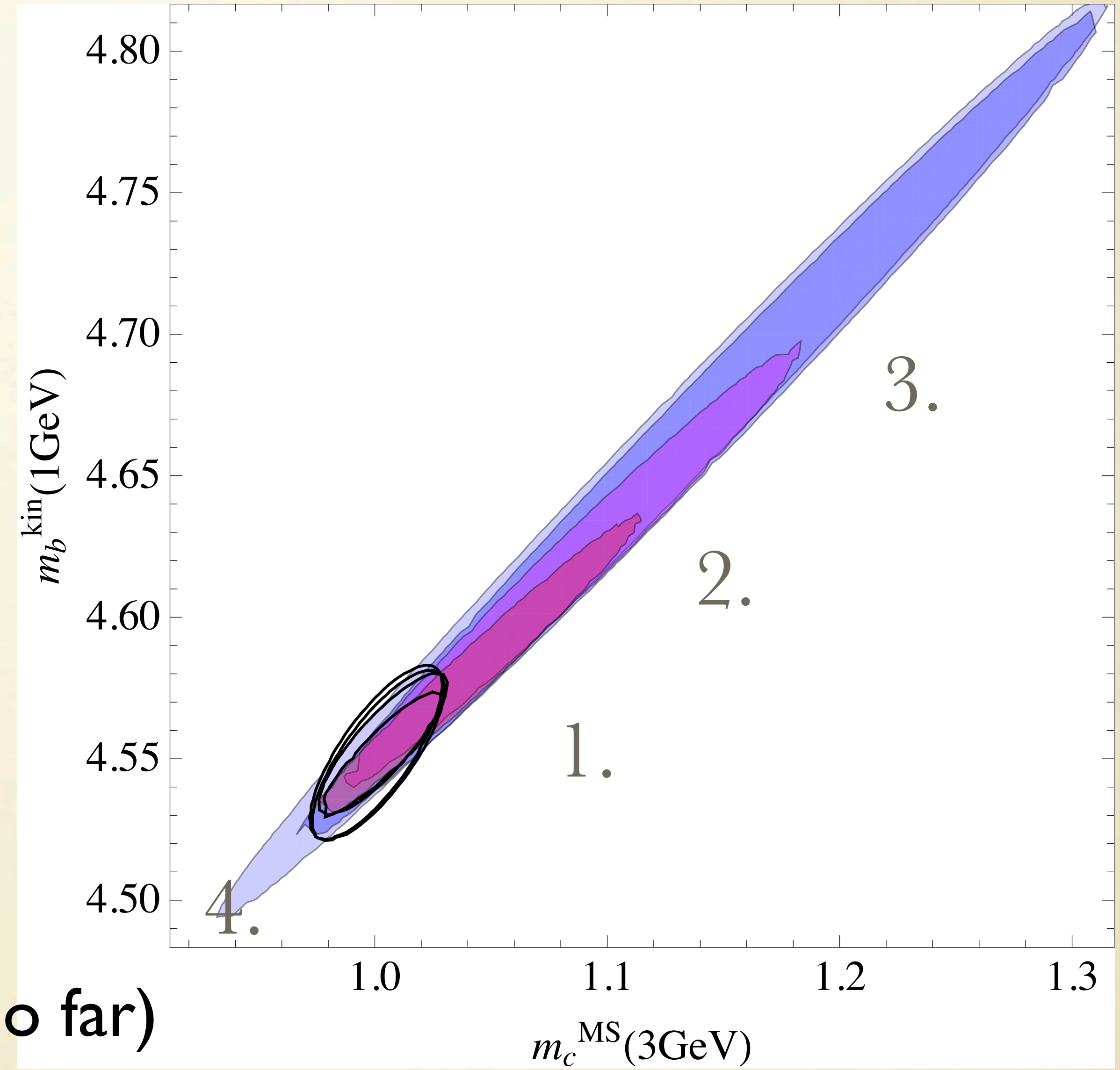
Theoretical errors dominate





Theoretical correlations



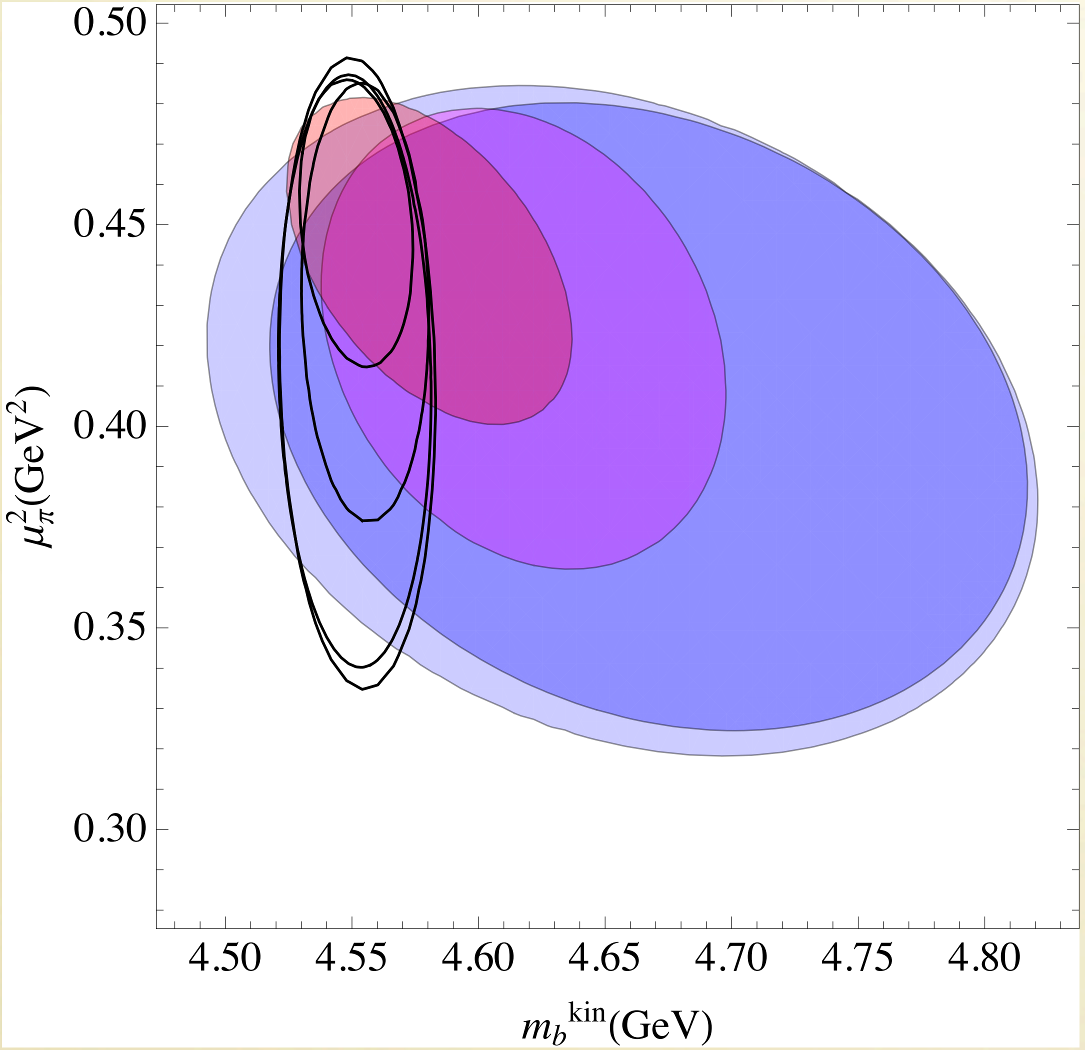


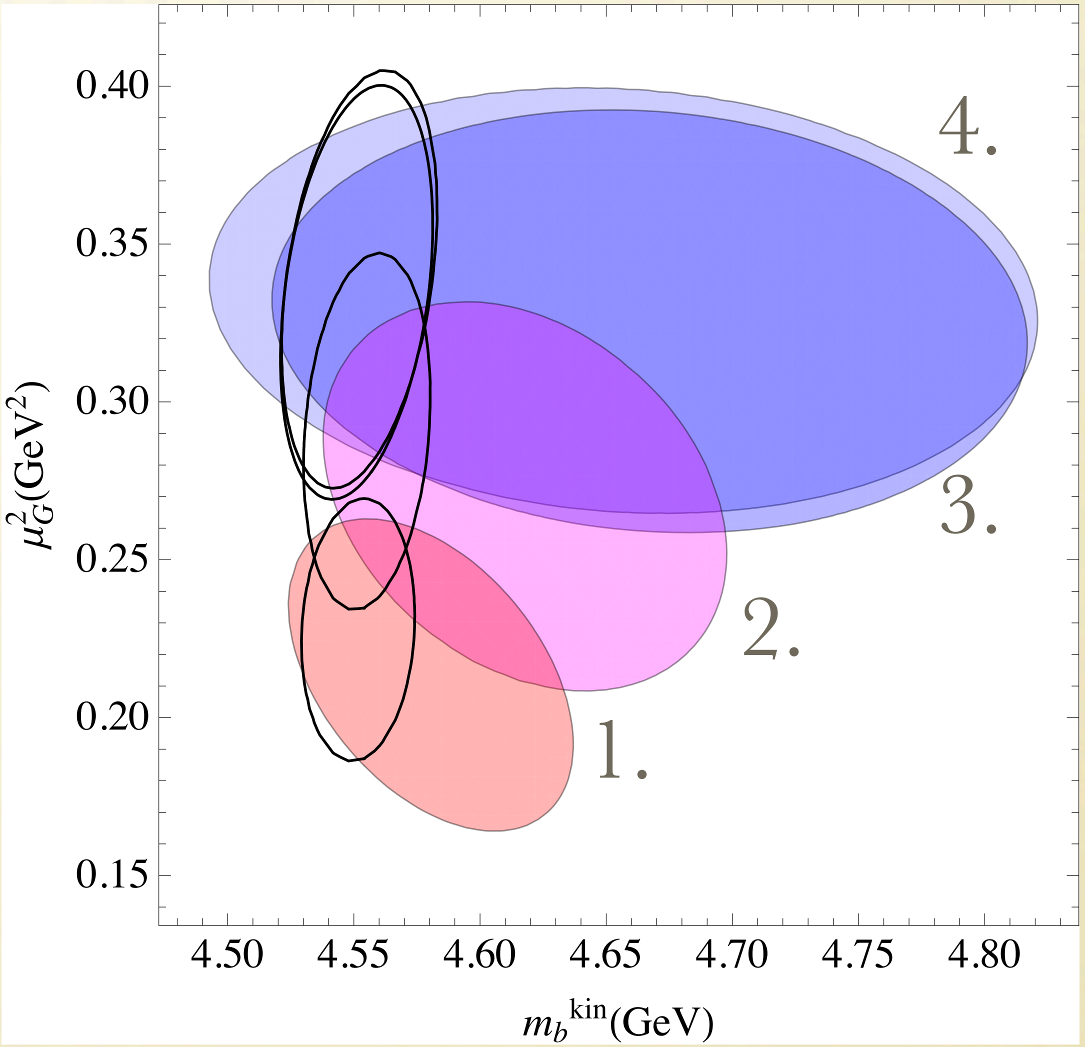
Correlations between theory errors of moments with different cuts difficult to estimate

1. 100% correlations (unrealistic but used so far)
2. corr. computed from low-order expressions
3. constant factor 0<ξ<1 for 100MeV step
4. same as 3. but larger for larger cuts

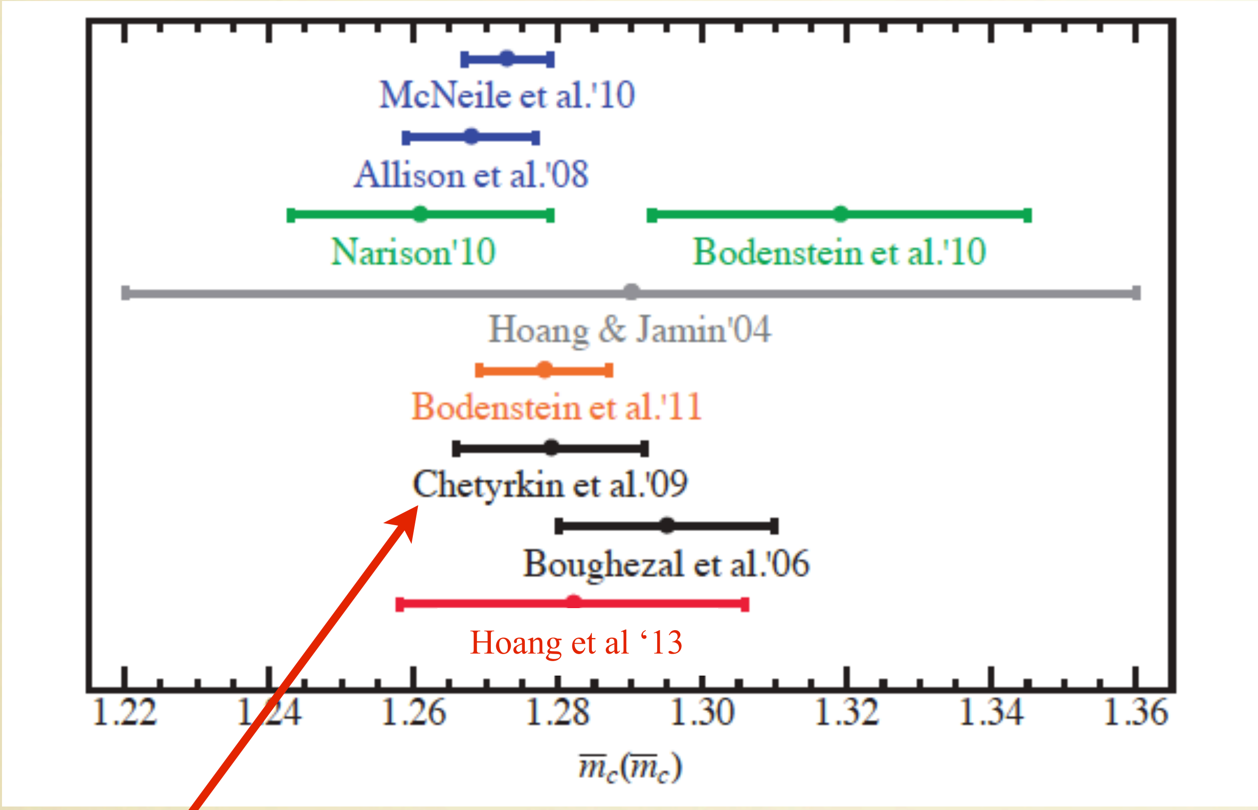
always assume different central moments uncorrelated

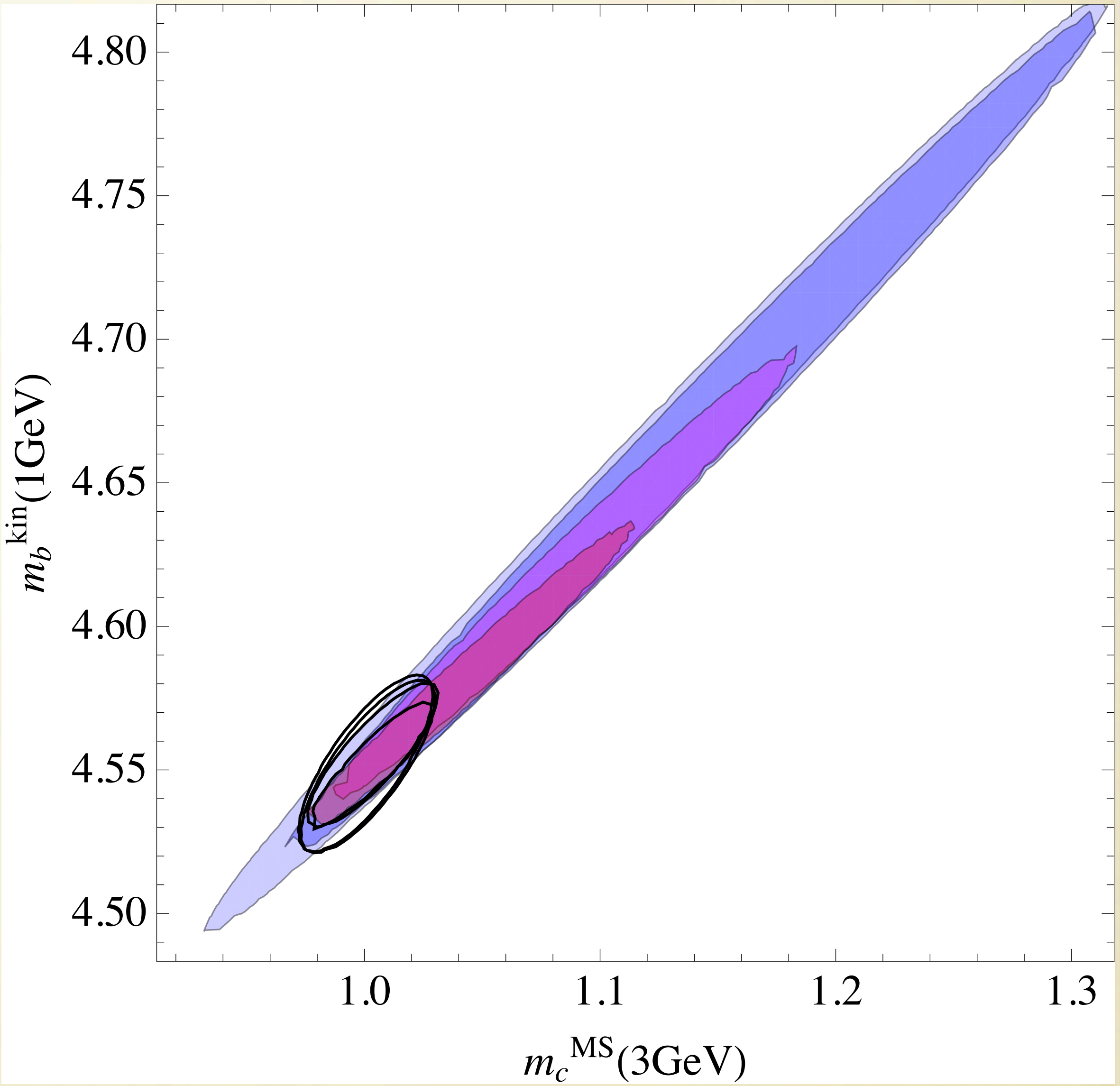
Theoretical correlations





CHARM MASS DETERMINATIONS





our default choice

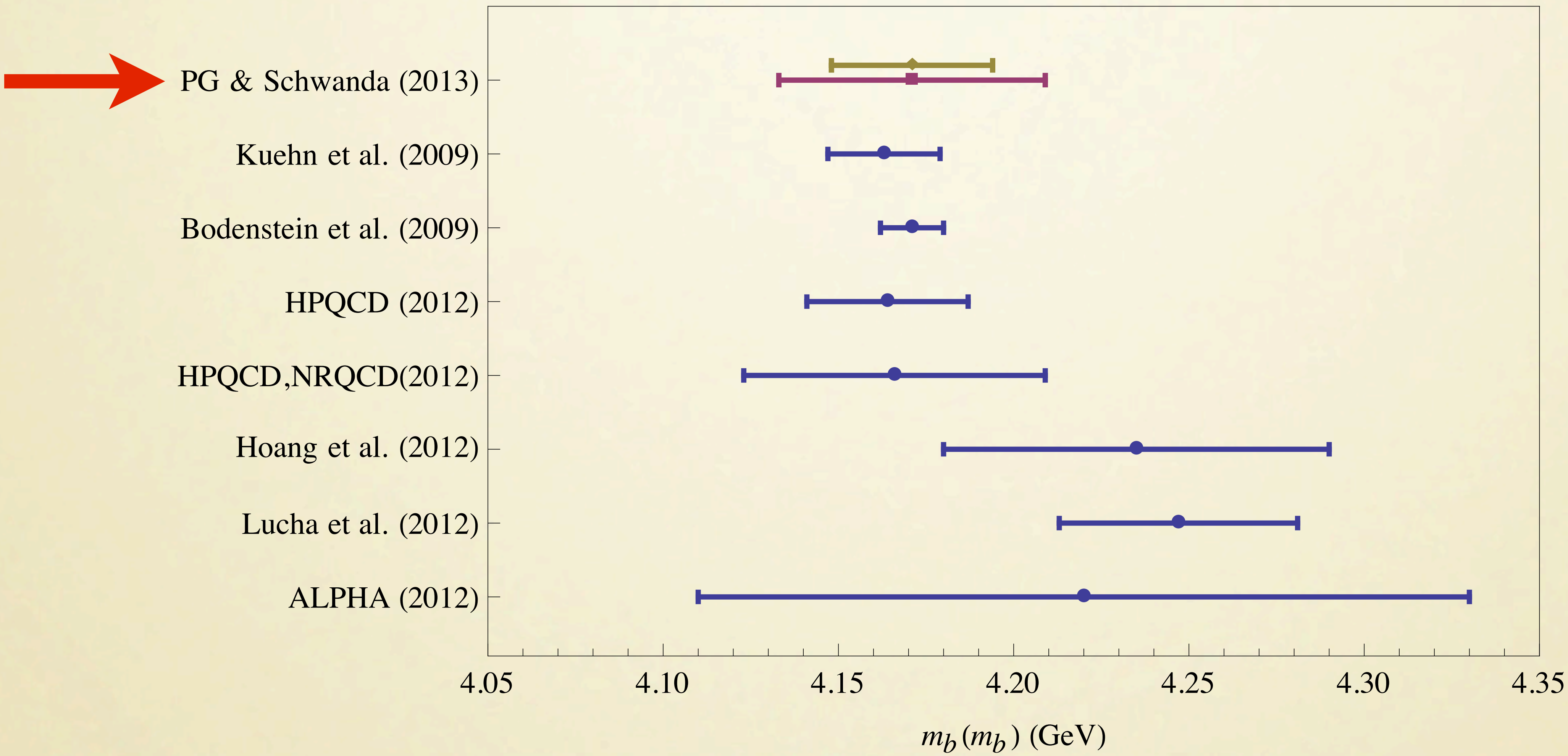
sum rules studies of $\sigma(e^+e^- \rightarrow$ hadrons)

almost all at NNNLO

Remarkable improvement in recent years.

m_c can be used as precise input to fix m_b

Results: bottom mass



The fits give $\boldsymbol{m_b^{kin}(1\mathrm{GeV})=4.541(23)\mathrm{GeV}}$, independent of th corr.

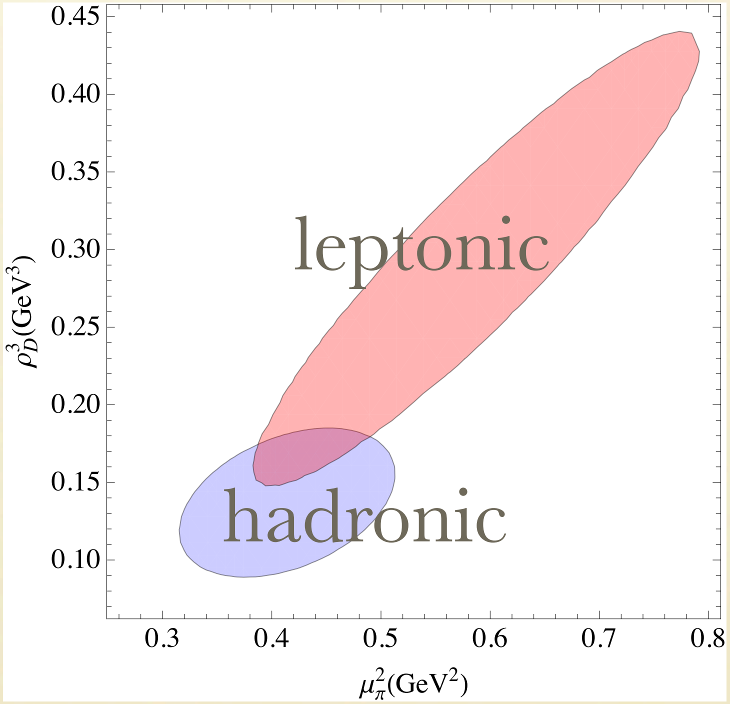
scheme translation error $m_b^{kin}(1\mathrm{GeV})=m_b(m_b)+0.37(3)\mathrm{GeV}$

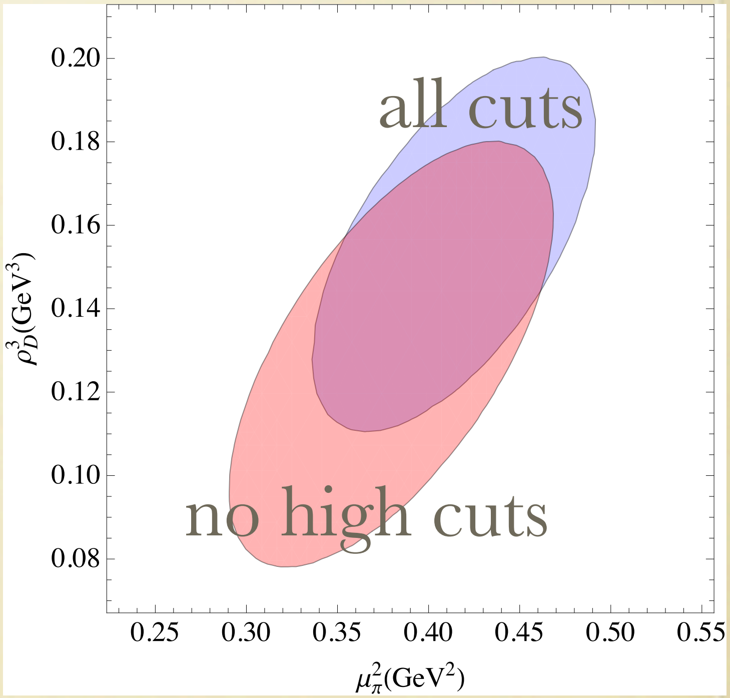
FIT RESULTS

th. corr. scenario	m_b^{kin}	$m_c^{(3\mathrm{GeV})}$	μ_π^2	ρ_D^3	μ_G^2	ρ_{LS}^3	$\mathrm{BR}_{c\ell\nu}(\%)$	$10^3\,\lvert V_{cb}\rvert$
4.	4.541	0.987	0.414	0.154	0.340	-0.147	10.65	42.42
uncertainty	0.023	0.013	0.078	0.045	0.066	0.098	0.16	0.86

Without mass constraints $m_b^{kin}(1\,\mathrm{GeV}) - 0.85\,\overline{m}_c(3\,\mathrm{GeV}) = 3.701 \pm 0.019\,\mathrm{GeV}$

- results depend little on assumption for correlations and choice of inputs, 2% determination of V_{cb}
- 20-30% determination of the OPE parameters





HIGHER ORDER EFFECTS

- Reliability of the method depends on our ability to control higher order effect and quark-hadron duality violations.
- **Purely perturbative corrections** complete $O(\alpha_s^2)$ included, small residual error
  Melnikov, Czarnecki, Pak, PG
- **Power corrections** $O(1/m_Q^{4,5})$ known but involve many new parameters, numerical relevance under study. In vacuum saturation approx small effect on V_{cb}
  Mannel,Turczyk,Uraltsev
- **Mixed** *perturbative corrections to power suppressed coefficients* at $O(\alpha_s/m_b^2)$ almost finished, already known for $b \to s\gamma$
  Becher, Boos, Lunghi, Alberti, Ewerth, Nandi, PG

$O(\alpha_s/m_b^2)$ EFFECTS

Boos,Becher,Lunghi 2007
Alberti,Ewerth,Nandi,PG 2012

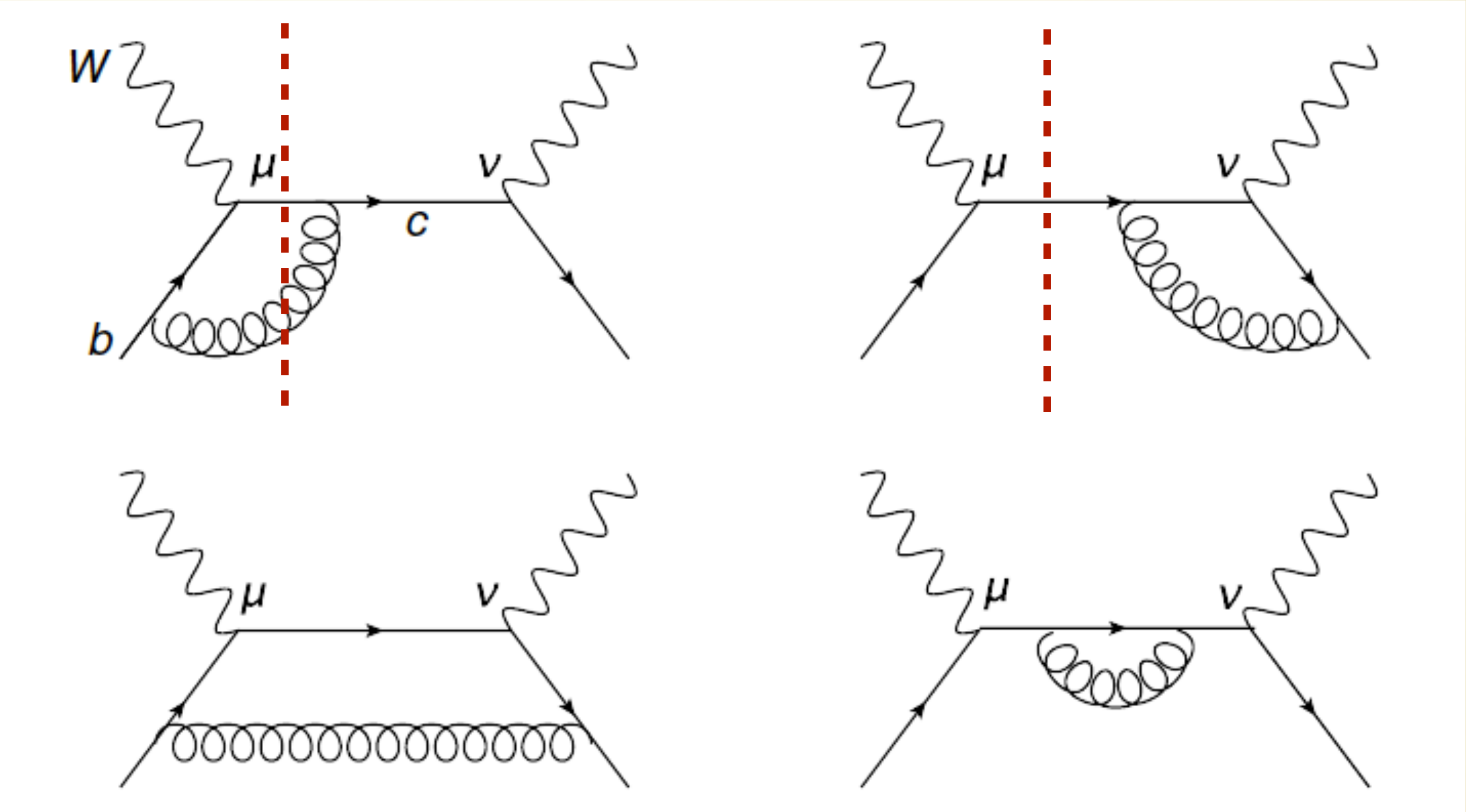
They can be in part computed using reparameterization invariance which relates different orders in the HQET

$$W_i = W_i^{(0)} + \frac{\mu_\pi^2}{2m_b^2} W_i^{(\pi,0)} + \frac{\mu_G^2}{2m_b^2} W_i^{(G,0)} + \frac{C_F \alpha_s}{\pi} \left[W_i^{(1)} + \frac{\mu_\pi^2}{2m_b^2} W_i^{(\pi,1)} + \frac{\mu_G^2}{2m_b^2} W_i^{(G,1)} \right]$$

For *i=3* RPI at all orders $$W_3^{(\pi,n)} = \frac{5}{3}\hat{q}_0 \frac{dW_3^{(n)}}{d\hat{q}_0} - \frac{\hat{q}^2 - \hat{q}_0^2}{3} \frac{d^2 W_3^{(n)}}{d\hat{q}_0^2}$$ Manohar 2010

good testing ground for the calculation.
Proliferation of power divergences, up to $1/u^3$, and complex kinematics (q^2, q_0, m_c, m_b)

$W_i^{(G,1)}$ are now ready!
new results soon



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

At zero recoil, where rate vanishes, the ff is

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

Recent progress in measurement of slopes and shape parameters, exp error only ~2%

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

F(1) =0.902(17) ➠ $\boxed{|V_{cb}|=39.05(0.7)(0.6)10^{-3}}$

Laiho et al 2010

2.1% error (adding in quadrature)

~2.7σ or ~8% from inclusive determination

B→Dlν has larger errors: new $|V_{cb}|=40.2(2.0)\times10^{-3}$

at non-zero recoil! Qiu et al, Lattice 2013

ZERO RECOIL SUM RULE

Heavy quark sum rules put bounds on the zero recoil form factor F(1) for B→ D* Shifman, Vainshtein, Uraltsev 1996

$$\mathcal{F}(1) = \sqrt{I_0(\varepsilon_M) - I_{inel}(\varepsilon_M)} \qquad \mathcal{F}(1) \leq \sqrt{I_0(\varepsilon_M)}$$

Unitarity bound $\boxed{\mathcal{F}(1) < 0.935}$

- Starting point OPE for axial vector current at zero recoil: expansion of I_0 in $1/m_c$ and $1/m_b$ and α_s
- Recent calculation incorporates higher order effects and estimates inelastic contributions Mannel, Uraltsev, PG 2012
- Estimate of inelastic (non-resonant) contribution is hard

The inelastic contribution

$$I_1(\varepsilon_M) = -\frac{1}{2\pi i}\oint_{|\varepsilon|=\varepsilon_M} T(\varepsilon)\,\varepsilon\, d\varepsilon \qquad I_{inel}(\varepsilon_M) = \frac{I_1(\varepsilon_M)}{\bar{\varepsilon}}$$

$\bar{\varepsilon}$ represents the average excitation energy mainly controlled by the lowest radial $(1/2^+)$ and D-wave $(3/2^+)$ excitations, therefore about 700MeV

OPE:

$$I_1 = \frac{-(\rho^3_{\pi G}+\rho^3_A)}{3m_c^2} + \frac{-2\rho^3_{\pi\pi}-\rho^3_{\pi G}}{3m_c m_b} + \frac{\rho^3_{\pi\pi}+\rho^3_{\pi G}+\rho^3_S+\rho^3_A}{4}\left(\frac{1}{m_c^2}+\frac{2}{3m_c m_b}+\frac{1}{m_b^2}\right) + \mathcal{O}\left(\frac{1}{m_Q^3}\right)$$

in terms of little known non-local correlators of the form

$$\frac{i}{2M_B}\int d^4x \langle B|T\{O_i(x), O_j(x)\}|B\rangle, \qquad O \sim \bar{b}\,\pi_k \pi_l\, b$$

$$\rho^3_{\pi\pi} + \rho^3_{\pi G} + \rho^3_S + \rho^3_A \geq 0$$

each of them is integral of spectral function with specific spin structure e.g.

$$\rho^3_{\pi\pi} = \int_{\omega>0} d\omega\, \frac{\rho_P^{(\frac{1}{2}^+)}}{\omega}$$

ESTIMATING THE NON-LOCAL GUYS

Hyperfine splitting

$$\Delta M_Q^2 = M_{Q^*}^2 - M_Q^2 = \frac{4}{3} c_G(m_Q)\mu_G^2 + \frac{2}{3}\frac{\rho_{\pi G}^3 + \rho_A^3 - \rho_{LS}^3 + 2\bar{\Lambda}\mu_G^2}{m_Q} + O\left(\frac{1}{m_Q^2}\right)$$

Experimentally $\Delta M_B^2 \simeq \Delta M_D^2$ $\boxed{\rho_{\pi G}^3 + \rho_A^3 \approx -0.45\mathrm{GeV}^3}$

within a ~25% uncertainty

From $\overline{M}_B$-$\overline{M}_D$ and moments fits $\boxed{\rho_{\pi G}^3 + \rho_A^3 \lesssim -0.33\mathrm{GeV}^3}$

with somewhat larger uncertainty

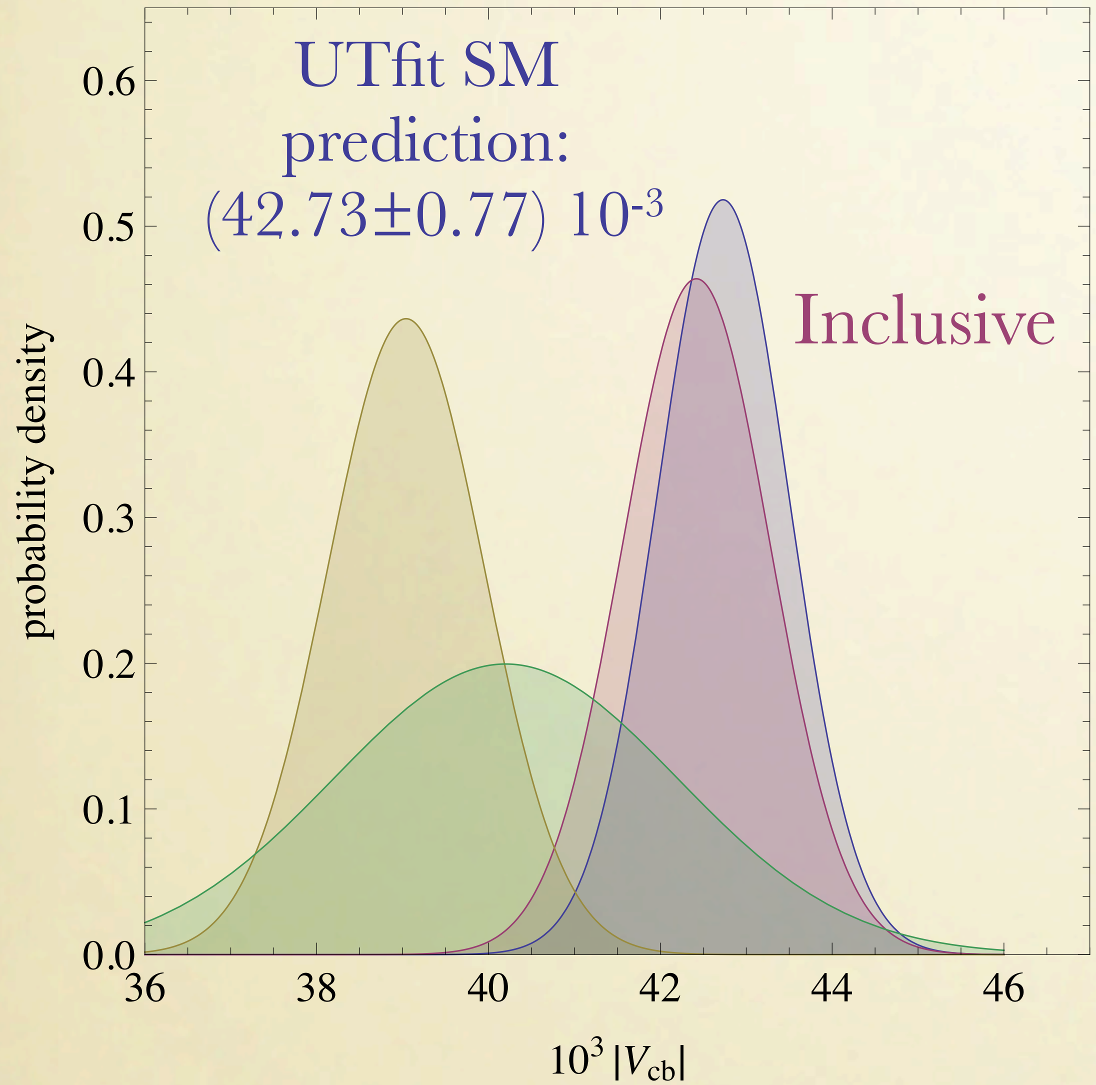
These are strong indications that non-local guys are larger than expected.
Based on a BPS expansion we get a minimum $I_{inel}(\varepsilon_M \sim 0.75\mathrm{GeV}) \gtrsim 0.14 \pm 0.03$

using the lowest value of I_{inel} and interpreting the total uncertainty as gaussian

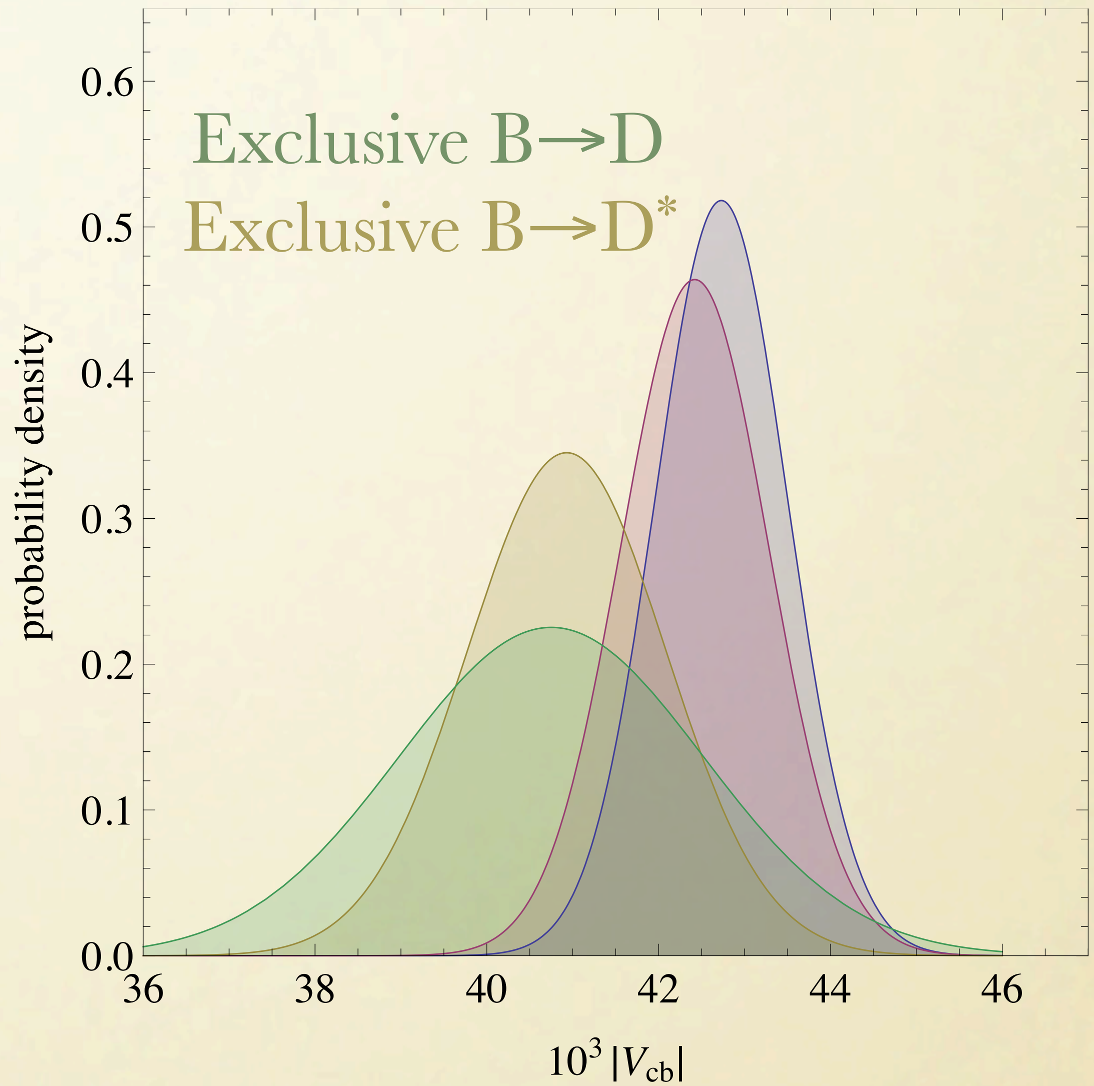
$$\boxed{\mathcal{F}(1) = 0.86 \pm 0.02}$$

which leads to $V_{cb}=40.9(1.1)10^{-3}$ in good agreement with inclusive V_{cb}

V_{cb} summary



Latest lattice results for exclusives



HQSR,HQE for exclusives

$|V_{ub}|$ DETERMINATIONS

Inclusive: 5-6% total error

HFAG 2012	Average $\|V_{ub}\| \times 10^3$
DGE	$4.45(15)_{ex}{}^{+15}{}_{-16}$
BLNP	$4.40(15)_{ex}{}^{+19}{}_{-21}$
GGOU	$4.39(15)_{ex}{}^{+12}{}_{-14}$

Exclusive: 10-15% total error

$$|V_{ub}| = (3.25 \pm 0.31) \times 10^{-3}$$

MILC

$$|V_{ub}| = \left(3.50^{+0.38}_{-0.33}\Big|_{th.} \pm 0.11\Big|_{exp.}\right) \times 10^{-3}$$

LCSR, Khodjamirian et al, see also Bharucha

$B \to \pi l \nu$ data poorly consistent!

2.7-3σ from $B \to \pi l \nu$ (MILC-FNAL)
2σ from $B \to \pi l \nu$ (LCSR, Siegen)
2.5-3σ from UTFit 2011

UT fit (without direct V_{ub}):
$V_{ub} = 3.64(13)\ 10^{-3}$

The discrepancy here is around 25% !!

V_{ub} IN THE GGOU APPROACH

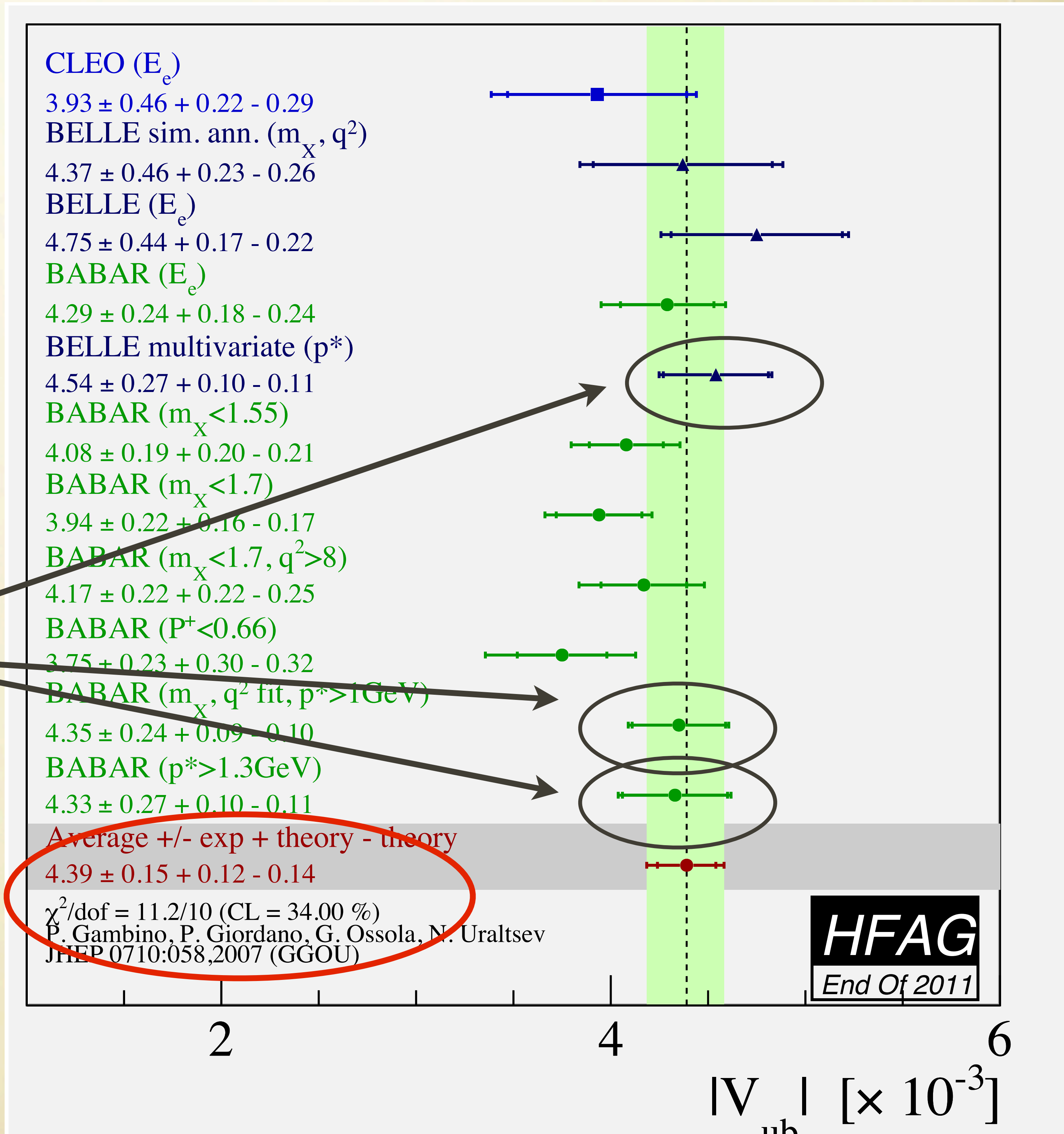
PG,Giordano,Ossola,Uraltsev

Good consistency & small th error.

4.7% total error

strong dependence on m_b

recent experimental results are theoretically cleanest (2%) but signal simulation relies on theoretical models

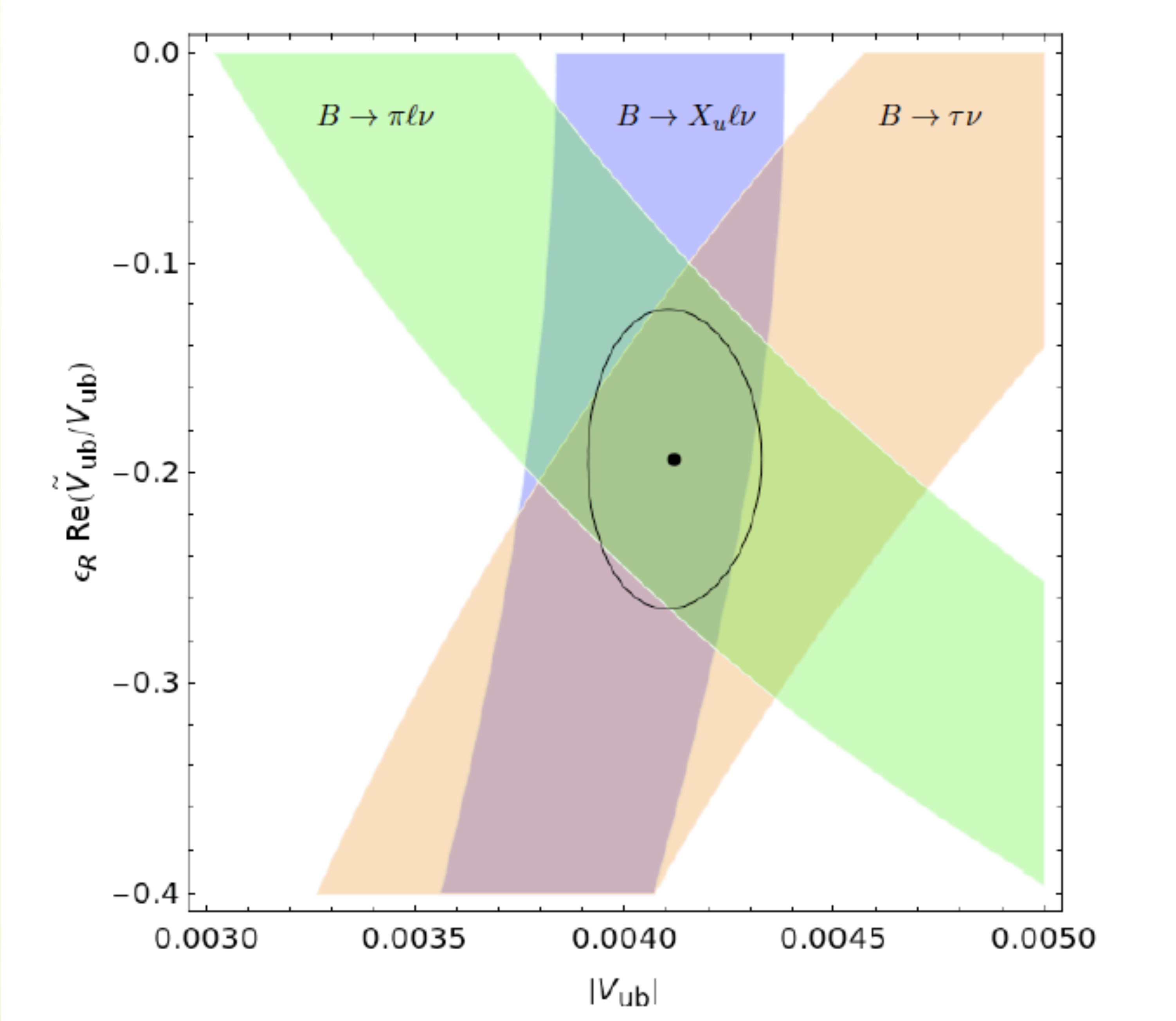


NEW PHYSICS?

LR models can explain a difference between inclusive and exclusive V_{ub} determinations (Chen,Nam)

Also in MSSM (Crivellin)

BUT the RH currents affect predominantly the exclusive V_{ub}, making the conflict between V_{ub} and $\sin 2\beta$ (ψK_S) stronger...



Buras, Gemmler, Isidori 1007.1993

SUMMARY

- Theoretical efforts to improve the OPE approach to semileptonic decays continue, more results soon. No sign of inconsistency in this approach so far.
- New fit results: interesting m_b determination based on precise m_c
- HQSR calculation of zero recoil $B \rightarrow D^*$ form factor agrees with inclusive determination of V_{cb}, unlike FNAL lattice one
- Exclusive/incl. tension in V_{ub} remains misterious (2-3σ). It could be explained by right-handed current... Belle-II will increase significantly the statistics for $b \rightarrow ul\nu$ decays. Measurement of spectra will enable direct constraints on shape function(s).

BACK-UP SLIDES

Perturbative effects

- $O(\alpha_s)$ implemented by all groups De Fazio,Neubert
- Running coupling $O(\alpha_s^2\beta_0)$ (PG,Gardi,Ridolfi) in GGOU, DGE lead to -5% & +2%, resp. in $|V_{ub}|$
- Complete $O(\alpha_s^2)$ in the SF region Asatrian,Greub,Pecjak-Bonciani,Ferroglia-Beneke,Huber, Li - G. Bell 2008
- In BLNP leads to up 8% increase in V_{ub} related to resummation, not yet included by HFAG. It is an **artefact** of this approach.

- $P_+ < 0.66$ GeV:

	$\Gamma_u^{(0)}$	μ_h	μ_i
NLO	60.37	${}^{+3.52}_{-3.37}$	${}^{+3.81}_{-6.67}$
NNLO	52.92	${}^{+1.46}_{-1.72}$	${}^{+0.09}_{-2.79}$

Greub,Neubert,Pecjak arXiv:0909.1609

- $P_+ < 0.66$ GeV:

Fixed-Order	$\Gamma_u^{(0)}$	μ
NLO	49.11	${}^{+5.43}_{-9.41}$
NNLO	49.53	${}^{+0.13}_{-4.01}$

NEW: full phase space $O(\alpha_s^2)$ calculation

Brucherseifer,Caola,Melnikov, arXiv:1302.0444

Confirms non-BLM/BLM approx 20% over relevant phase space

EXCLUSIVE V_{ub} FROM $B \to \pi l \nu$

Here there is no preferred point in phase space. Lattice and light-cone sum rules estimate form factor.

Recent lattice based:

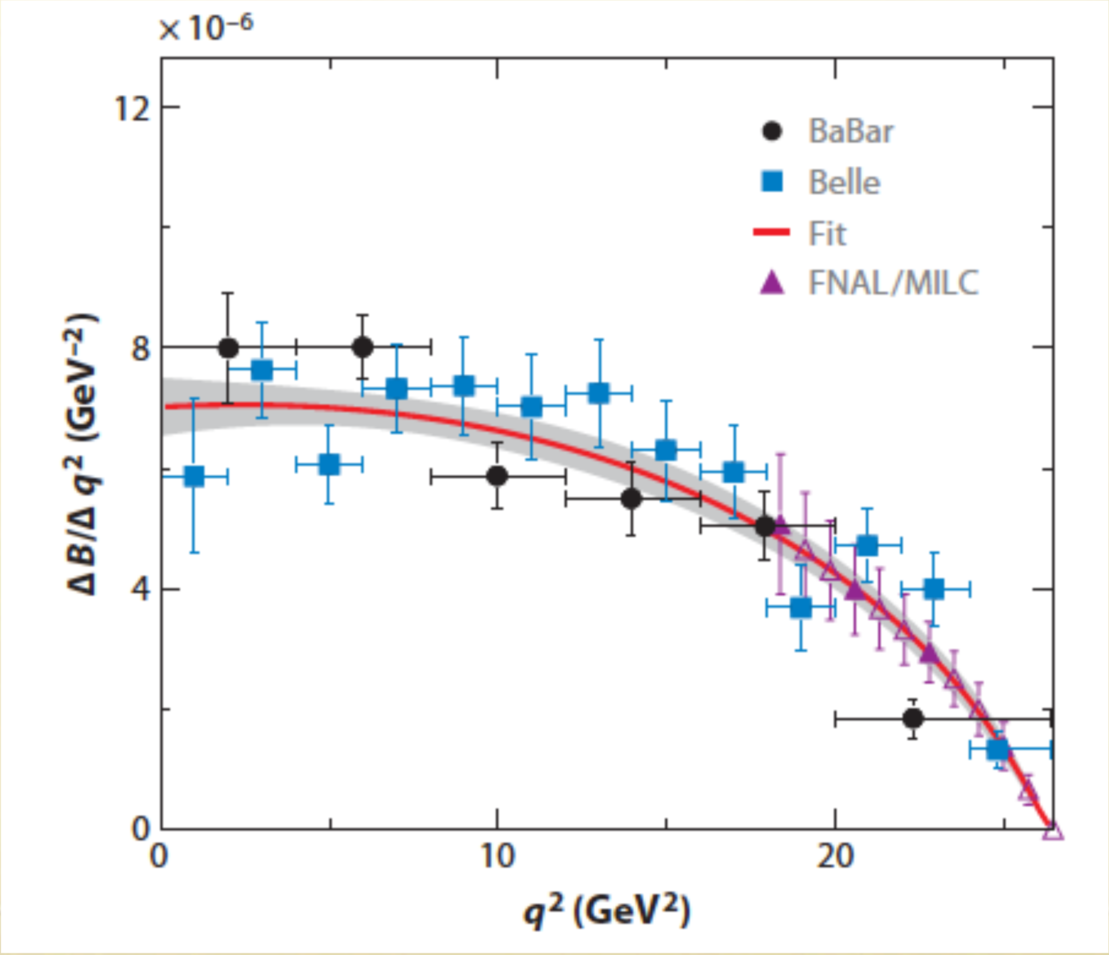
MILC collaboration

$$|V_{ub}| = (3.25 \pm 0.31) \times 10^{-3}$$

Recent sum-rules based:

Khodjamirian, Mannel,Offen,Wang 2011
see also Bharucha

$$|V_{ub}| = \left(3.50^{+0.38}_{-0.33}\Big|_{th.} \pm 0.11\Big|_{exp.} \right) \times 10^{-3}$$



Precision is improved by fitting lattice/LCSR together with data

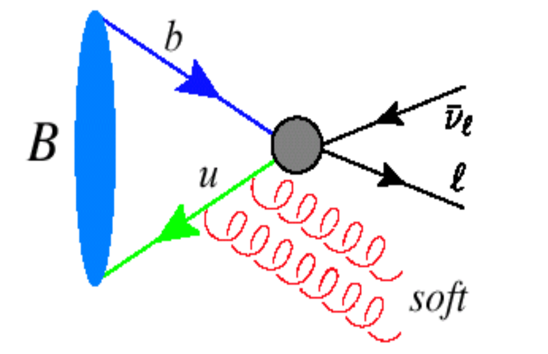
Experimental data are not well consistent

The total $B \to X_u \ell \nu$ width

$$\Gamma[\bar{B} \to X_u e \bar{\nu}] = \frac{G_F^2 m_b^5}{192\pi^3} |V_{ub}|^2 \Bigg[1 + \frac{\alpha_s}{\pi} p_u^{(1)}(\mu) + \frac{\alpha_s^2}{\pi^2} p_u^{(2)}(r,\mu) - \frac{\mu_\pi^2}{2m_b^2} - \frac{3\mu_G^2}{2m_b^2} + \left(\frac{77}{6} + 8 \ln \frac{\mu_{\rm WA}^2}{m_b^2} \right) \frac{\rho_D^3}{m_b^3} + \frac{3\rho_{LS}^3}{2m_b^3} + \frac{32\pi^2}{m_b^3} B_{\rm WA}(\mu_{\rm WA}) \Bigg]$$

$$+ \; O(\alpha_s \frac{\mu_{\pi,G}^2}{m_b^2}) \;\; + O(\frac{1}{m_b^4})$$

Using the results of the fit, V_{ub} could be extracted if we had the total width...



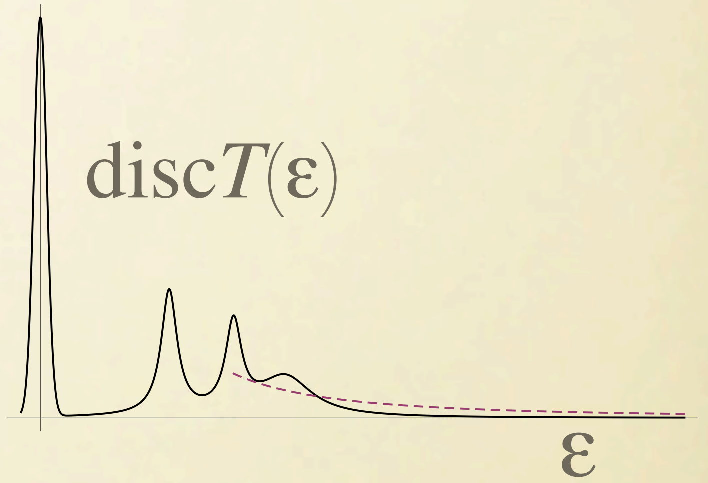
Weak Annihilation, severely constrained from D decays, see Kamenik, PG, arXiv:1004.0114

ZERO RECOIL SUM RULE

$$T(\varepsilon) = \frac{i}{6M_B} \int d^4x e^{-ix_0(M_B - M_{D^*} - \varepsilon)} \langle B | T J_A^k(x) J_{Ak}(0) | B \rangle$$

$$\varepsilon = M_X - M_{D^*}$$

$$\boxed{I_0(\varepsilon_M) = -\frac{1}{2\pi i} \oint_{|\varepsilon| = \varepsilon_M} T(\varepsilon)\, d\varepsilon = \mathcal{F}^2(1) + I_{inel}(\varepsilon_M)}$$



Inelastic non-resonant piece $I_{inel}(\varepsilon_M) = \frac{1}{2\pi i} \int_{0+}^{\varepsilon_M} \mathrm{disc}\, T(\varepsilon) d\varepsilon$

$$\mathcal{F}(1) = \sqrt{I_0(\varepsilon_M) - I_{inel}(\varepsilon_M)}$$

$$\boxed{\mathcal{F}(1) \leq \sqrt{I_0(\varepsilon_M)}}$$

Unitarity bound