Recent developments in semileptonic B decays

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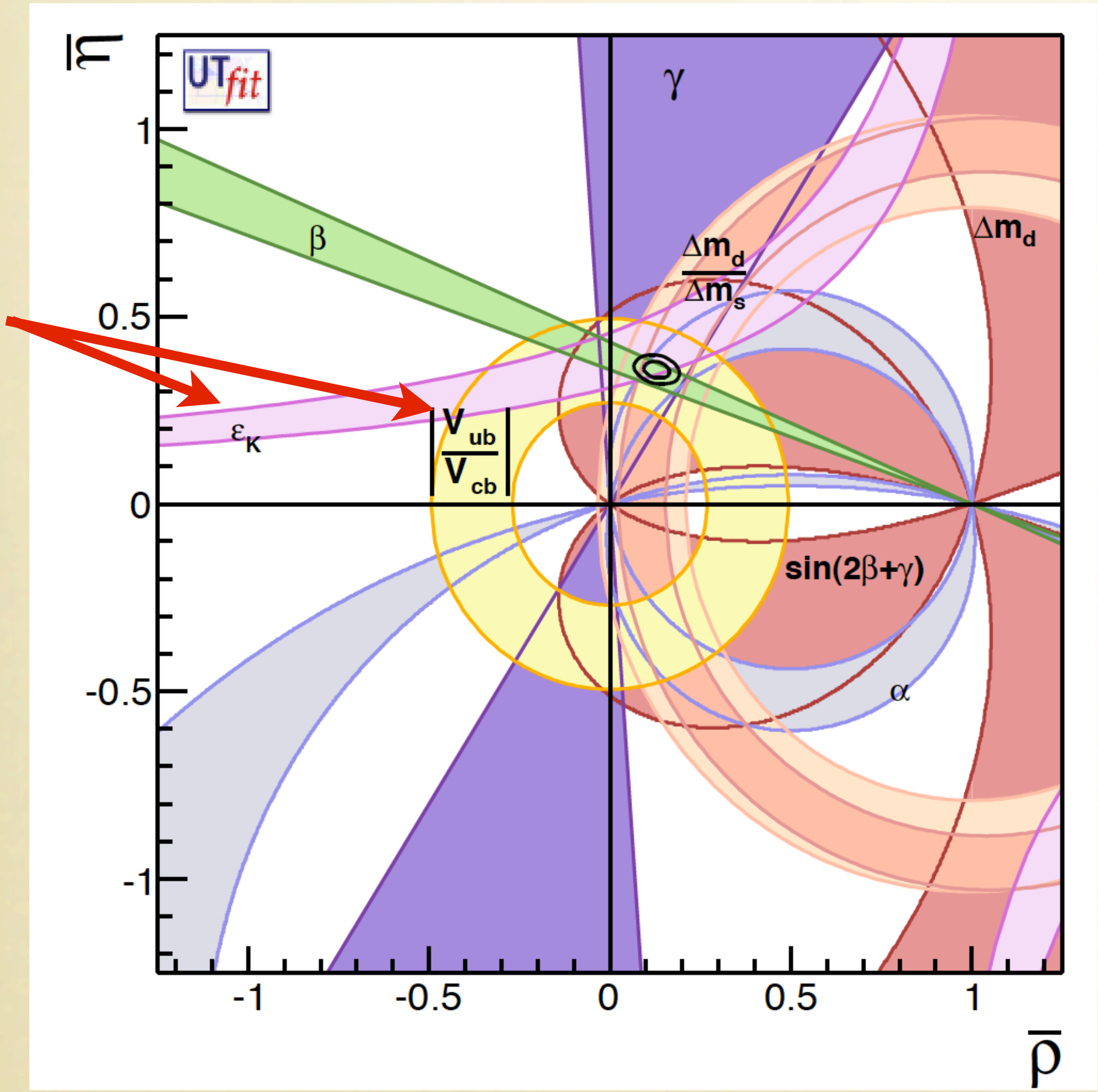
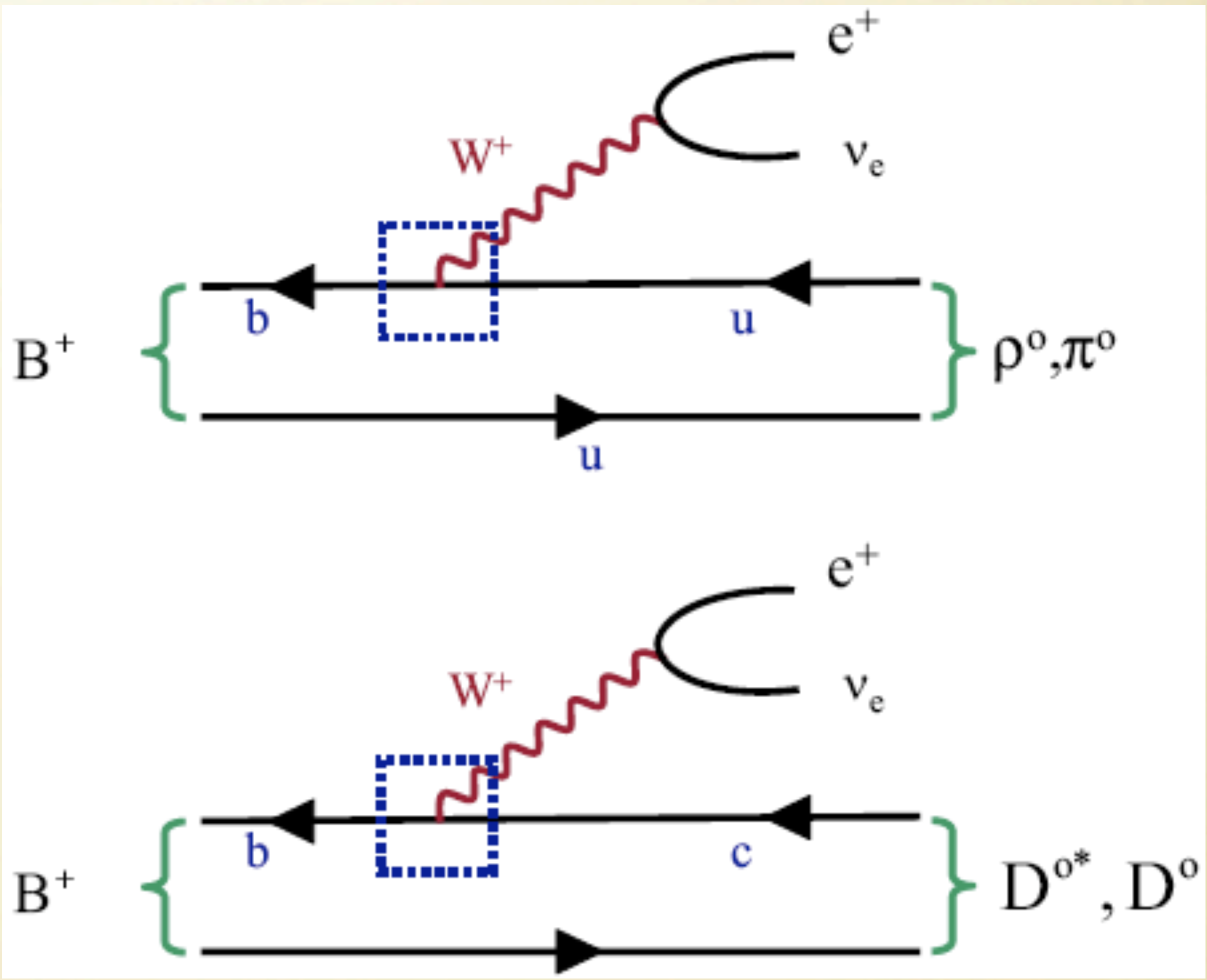
Portoroz, 15/4/2013

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





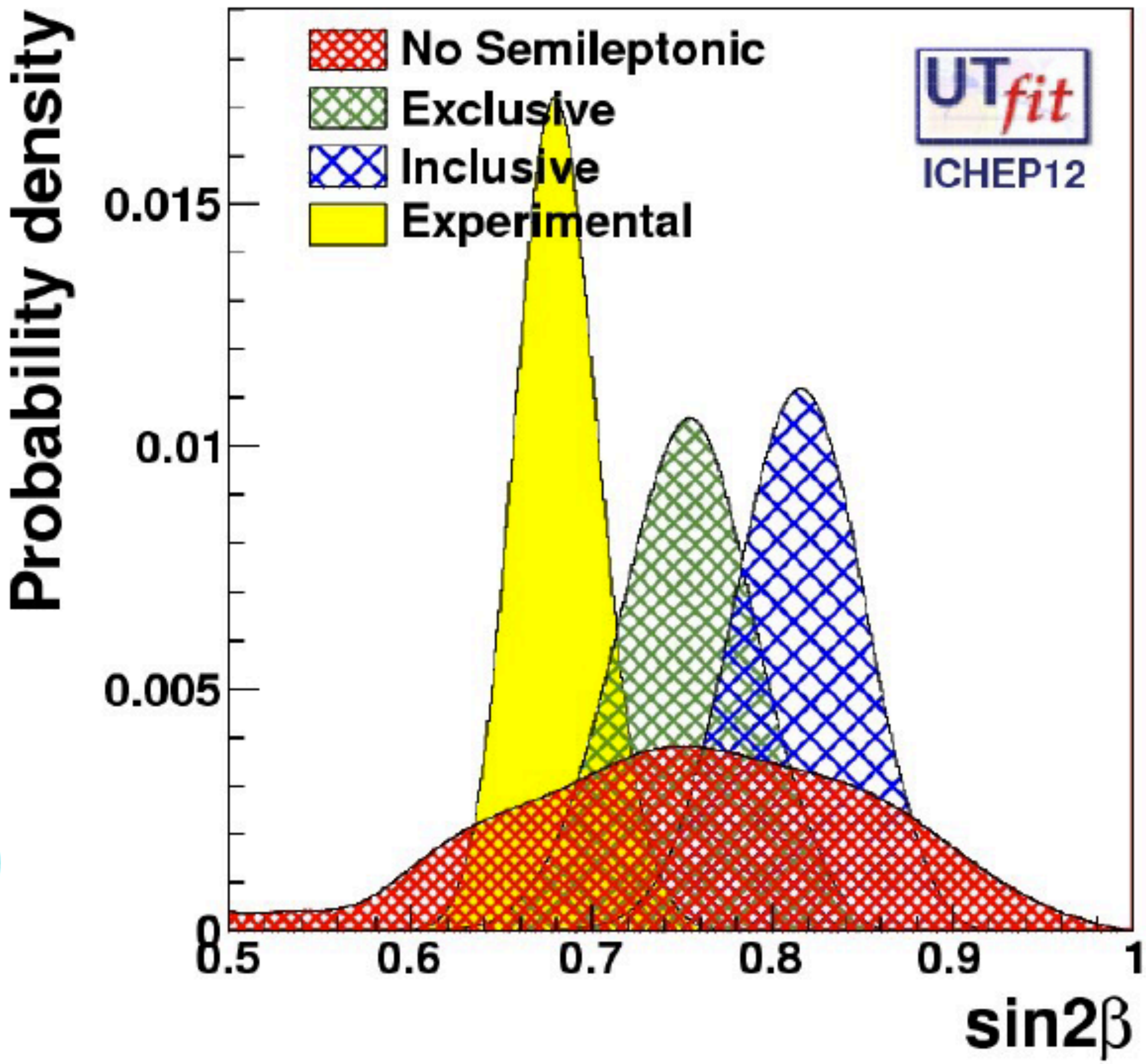
Since several years, exclusive decays prefer smaller $|V_{ub}|$ and $|V_{cb}|$

inclusives vs exclusives

only exclusive values

$\sin 2\beta_{UTfit}$ = 0.751 ± 0.039

~1.8σ



only inclusive values

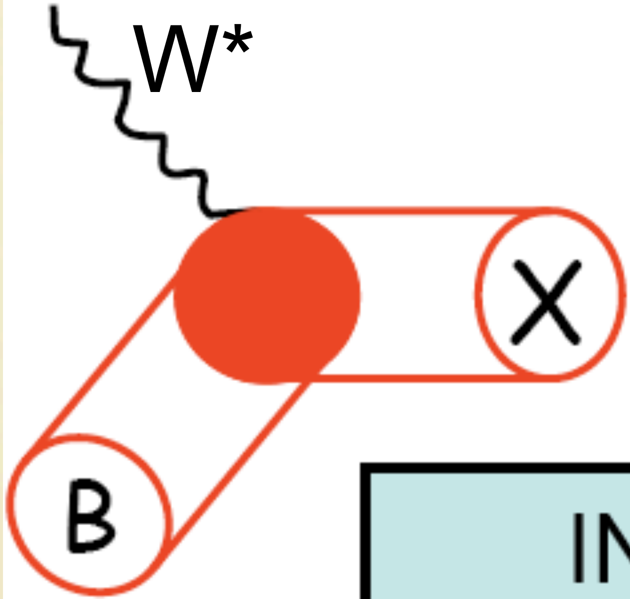
$\sin 2\beta_{UTfit}$ = 0.813 ± 0.036

~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

The total width in the OPE

$$\Gamma[B \to X_c l\bar{\nu}] = \Gamma_0 \; g(r)\Big[1 + \frac{\alpha_s}{\pi} c_1(r) + \frac{\alpha_s^2}{\pi^2} c_2(r) - \frac{\mu_\pi^2}{2m_b^2} + c_G(r)\frac{\mu_G^2}{m_b^2}$$

$$+ c_D(r)\frac{\rho_D^3}{m_b^3} + c_{LS}(r)\frac{\rho_{LS}^3}{m_b^3} + O\Big(\alpha_s \frac{\mu_{\pi,G}^2}{m_b^2}\Big) + O\Big(\frac{1}{m_b^4}\Big)\Big]$$

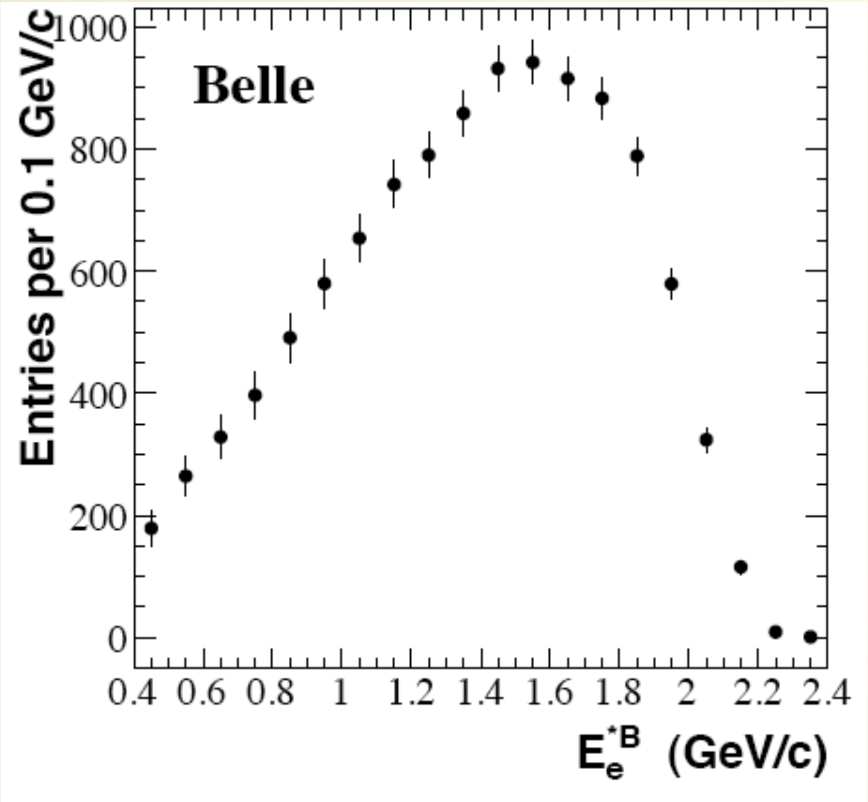
$$r = \frac{m_c^2}{m_b^2} \qquad \Gamma_0 = \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3}$$

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

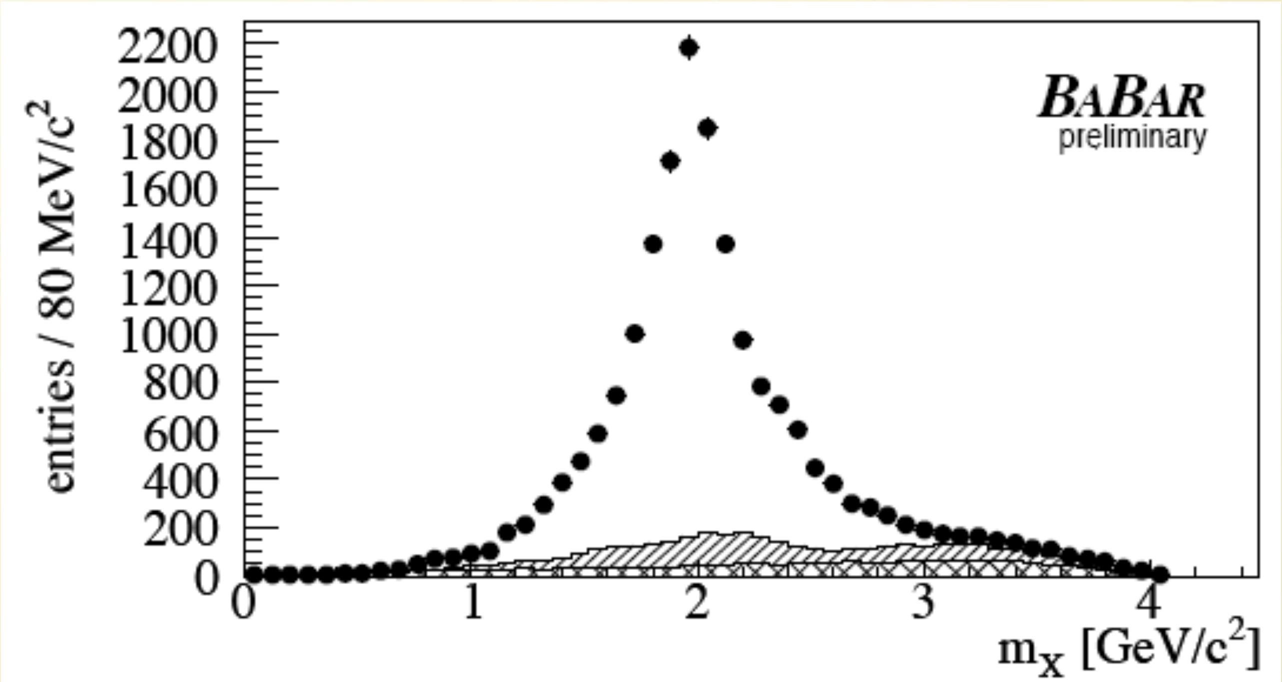
Present implementations include all terms through $O(\alpha_s^2, 1/m_b^3)$: $m_{b,c}, \mu^2_{\pi,G}, \rho^3_{D,LS}$ 6 parameters

Fitting OPE parameters to the moments

E_l spectrum



m_X spectrum



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

OPE parameters describe universal properties of the B meson and of the quarks → useful in many applications

FITS AND MASS CONSTRAINTS

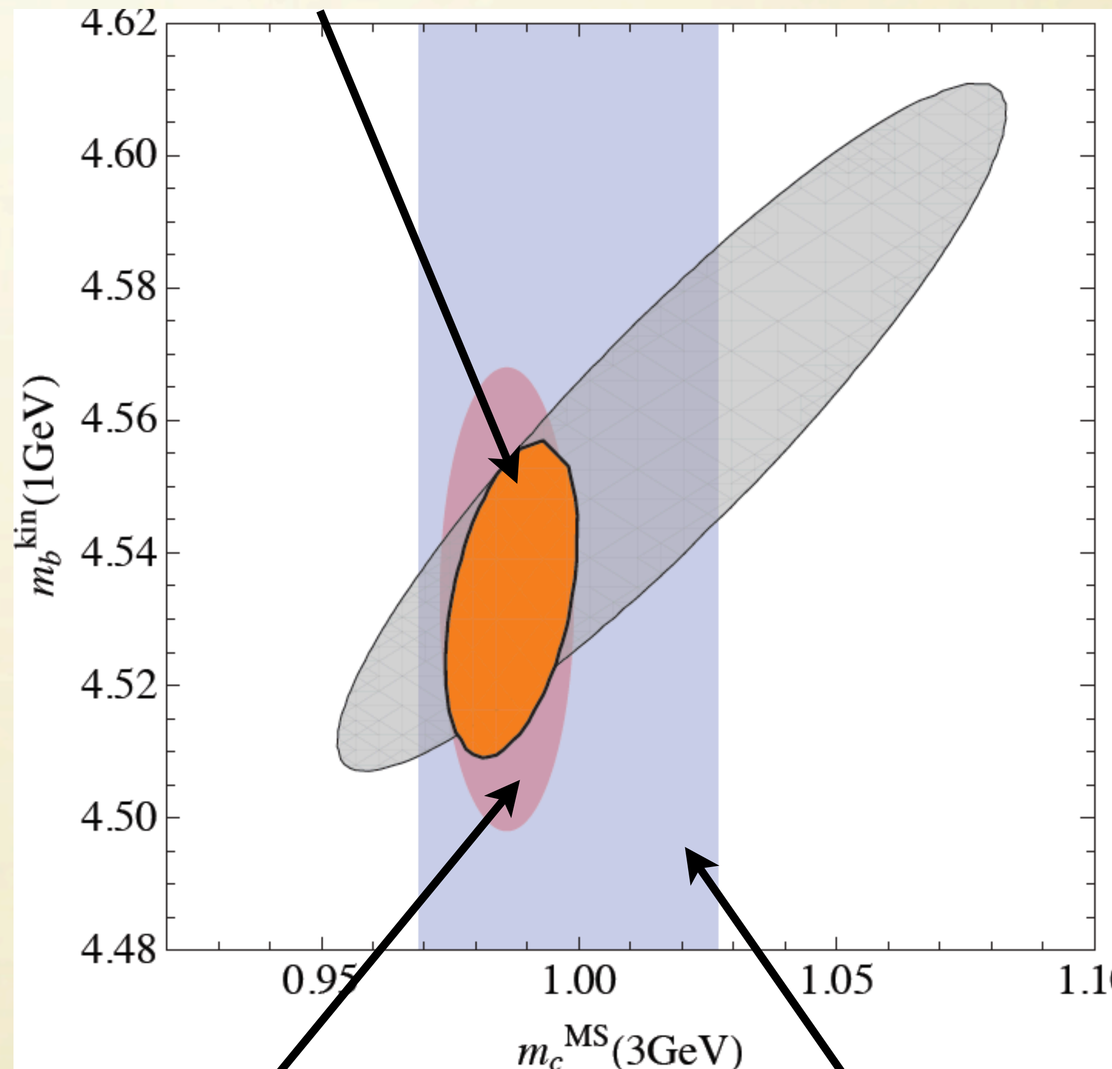
Inputs	$\lvert V_{cb}\rvert\ 10^3$	m_b^{kin}	χ^2/ndf
$b\to c$ & $b\to s\gamma$	41.94(43)(58)	4.574(32)	29.7/59
$b\to c$ & m_c	41.88(44)(58)	4.560(23)	33.3/48

Schwanda,PG 2012, using m_c from Hoang et al

Similar results in 1S scheme (Bauer et al)

Recent sum rules studies of $\sigma(e^+e^- \to \text{hadrons})$ and lattice calculations give very precise NNNLO determinations of m_c (and m_b). They are consistent with our NNLO fit and can be used to improve precision

SL fit with only m_c constraint (Kuhn)

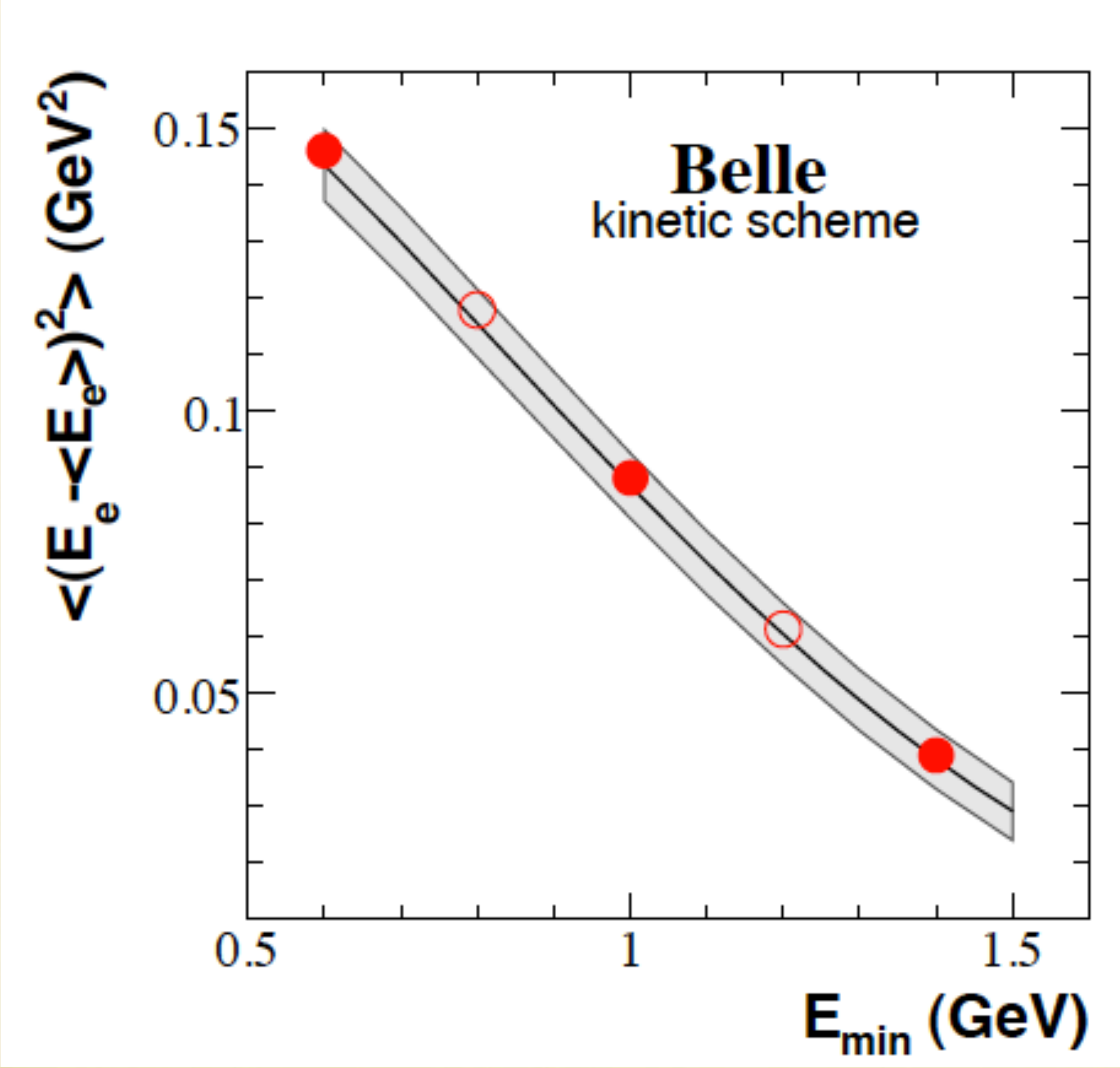


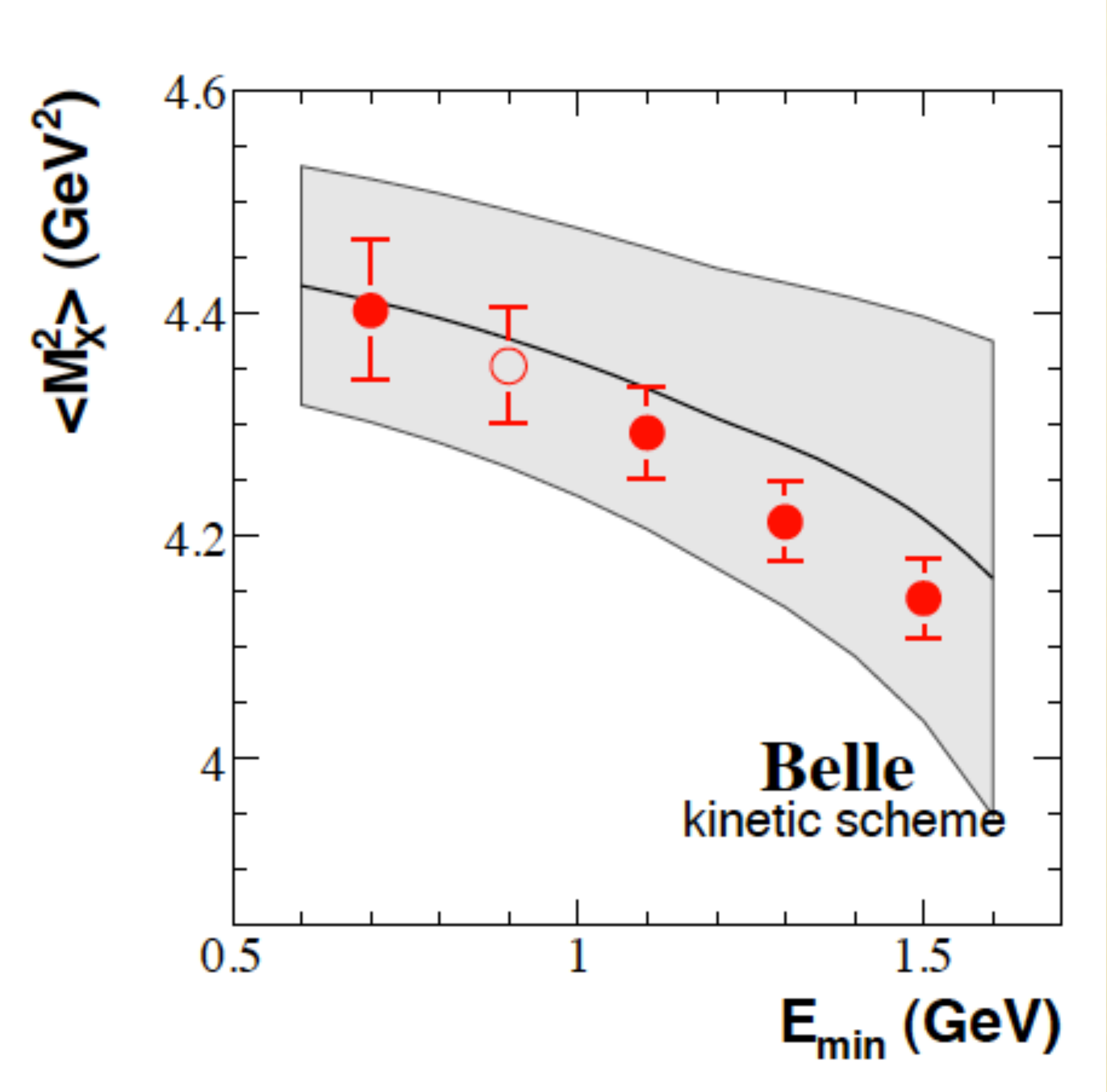
Kuhn et al 2009

Hoang et al 2011

$m_c(3\mathrm{GeV})=0.986(13)\mathrm{GeV}$
$m_b(m_b)=4.163(16)\mathrm{GeV}$

Theoretical errors dominate





HIGHER ORDER EFFECTS

- The reliability of the inclusive method depends on our ability to control higher order effect and quark-hadron duality violations.

- **Purely perturbative corrections** complete $O(\alpha_s^2)$ known.
  Melnikov, Czarnecki, Pak, PG

- **Power corrections** included up to $O(1/m_b^3)$, $O(1/m_b^{4,5})$ 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

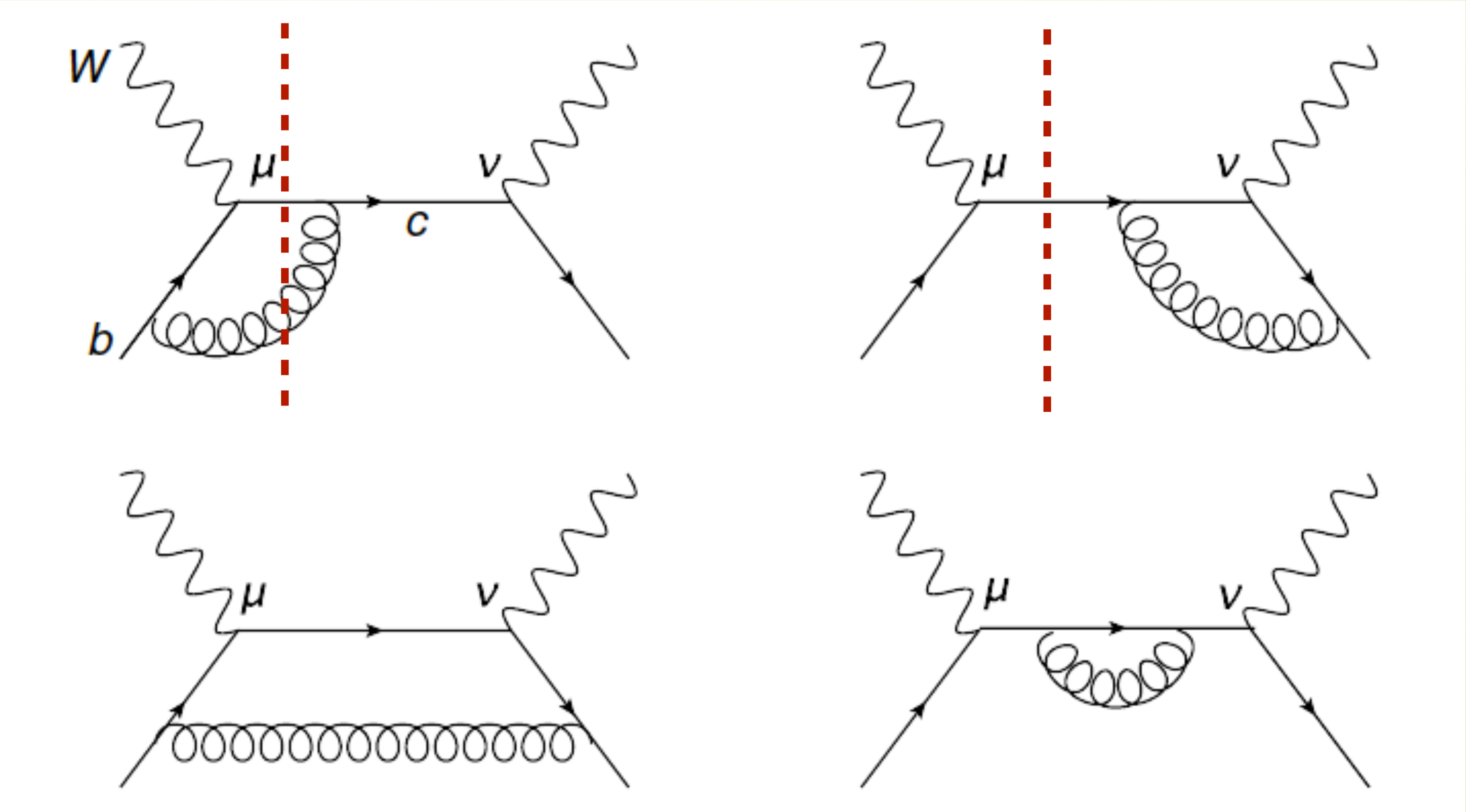
Boos,Becher,Lunghi 2007
Alberti,Ewerth,Nandi,PG 2012

They can be 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* 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)



RESULT FOR W$_1$

$$
\begin{aligned}
W_1^{(\pi,1)} \;=\;& 2E_0\, B_{(1,\pi)} + \frac{8}{3}(1-E_0 I_{1,0})(1-E_0)\left(E_0\left[\frac{1}{\hat{u}^2}\right]_+ - 2\left[\frac{1}{\hat{u}}\right]_+\right) + R_1^{(\pi)}\,\theta(\hat{u}) \\
&+\frac{8E_0}{3}\left[\frac{1-E_0}{2}S_1 - \lambda_0(1-E_0 I_{1,0}) - \frac{E_0^2}{\rho} + (3E_0^2-\rho)I_{1,0} - 2E_0(1+I_{1,0}) + 3\right]\delta'(\hat{u}) \\
&+\frac{8}{3}\left[S_2 - E_0 S_1 + E_0(1-E_0 I_{1,0})\left(\frac{\lambda_0}{2} - \frac{(1-E_0)^2}{\lambda_0} + E_0\right) + \left(E_0^2 - \frac{3}{4}E_0 - \frac{\rho}{4}\right) I_{1,0}\right. \\
&\left.+\frac{\frac{3}{4}E_0^3 - \frac{\rho}{4}(E_0^2 + 2E_0 - 2\rho(1-E_0))}{\rho^2}\right]\delta(\hat{u}), \qquad (4.2)
\end{aligned}
$$

$$
B_{(i,\pi)} = \frac{\lambda_0}{3}\left\{\left[S_i + 3(1-E_0 I_{1,0})\right]\delta''(\hat{u}) - 4\,(1-E_0 I_{1,0})\left[\frac{1}{\hat{u}^3}\right]_+\right\}
$$

$$
\begin{aligned}
R_1^{(\pi)} \;=\;& \frac{8}{3}E_0\left(\frac{(1-E_0)(E_0-2\hat{u})}{\hat{u}^2} - \frac{E_0\lambda_0}{\hat{u}^3}\right)I_{1,0} - \frac{\frac{4}{3}\hat{u}^2 + 2(1-5E)\hat{u} + \frac{28}{3}(E^2-E)}{\lambda}\left(I_1 - \frac{1}{E}\right) \\
&+\frac{8}{3}\left(\frac{7}{8}E - \frac{3}{8} - \frac{\hat{u}}{4} + \frac{E-z}{\hat{u}} + \frac{E^2\lambda}{\hat{u}^3} + \frac{E(E-E^2-\lambda)}{\hat{u}^2}\right)I_1 + \frac{16E^2(E-z)}{3\hat{u}^2 z} \\
&-\frac{\hat{u}^2\,(4E^2 - Ez - 2z^2)}{6Ez^3} + \frac{-8E^3 - 3E^2 z + 5Ez(z+1) + (5-2z)z^2}{3z^3} \qquad (4.7) \\
&+\frac{4E(2E^2 - 5Ez + 4z^2)}{3\hat{u}\,z^2} + \frac{\hat{u}\,(24E^4 - 12E^3 z + 4E^2(z-3)z + E\,(z^2 - 6z^3) + 3z^3)}{6Ez^4},
\end{aligned}
$$

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) Laiho et al 2010

$|V_{cb}|=39.6(0.7)(0.6)\times10^{-3}$

2.1% error (adding in quadrature)

~2σ or ~5% from inclusive determination

B→Dlν has larger errors $|V_{cb}|=39.1(1.4)(1.3)\times10^{-3}$

ZERO RECOIL SUM RULE

Heavy quark sum rules put bounds on the zero recoil form factor F(1) for $B \to D^*$

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 $\mathcal{F}(1) < 0.935$

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

within a ~25% uncertainty

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

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 $\quad I_{inel}(\varepsilon_M \sim 0.75\text{GeV}) \gtrsim 0.14 \pm 0.03$

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

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

in perfect agreement with inclusive V_{cb} which would lead to 0.85±0.03

"RADIAL" CONTRIBUTIONS TO TOTAL WIDTH

- Non-local guys determined by transitions to + parity light d.o.f.: $\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+$
- Large I_{inel} implies strong transitions to "radial" excitations (radial & D-wave states)
- Assuming a single multiplet of "radials" for each j_q hyperfine splitting constrains the strength of B→"radials"
- At leading order in the heavy quark expansion and neglecting v dependence of the form factors one typically gets

$$\frac{\Gamma_{rad}}{\Gamma_{sl}} \approx 6 \div 7\%$$

Mannel,Uraltsev, PG

suggesting "radials" contribute significantly to the broad resonances, a possible solution of 1/2>3/2 puzzle

see also Bernlochner, Ligeti,Turczyk

$|V_{ub}|$ 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	$4.39(15)_{ex}{}^{+12}{}_{-14}$

2.7-3σ from B→πlν (MILC-FNAL)
2σ from B→πlν (LCSR, Siegen)
2.5-3σ from UTFit 2011

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→πlν data poorly consistent!

UT fit (without direct V_{ub}):
V_{ub}=3.62(14) 10^{-3}

The discrepancy here is around 30% !!

V_{ub} IN THE GGOU APPROACH

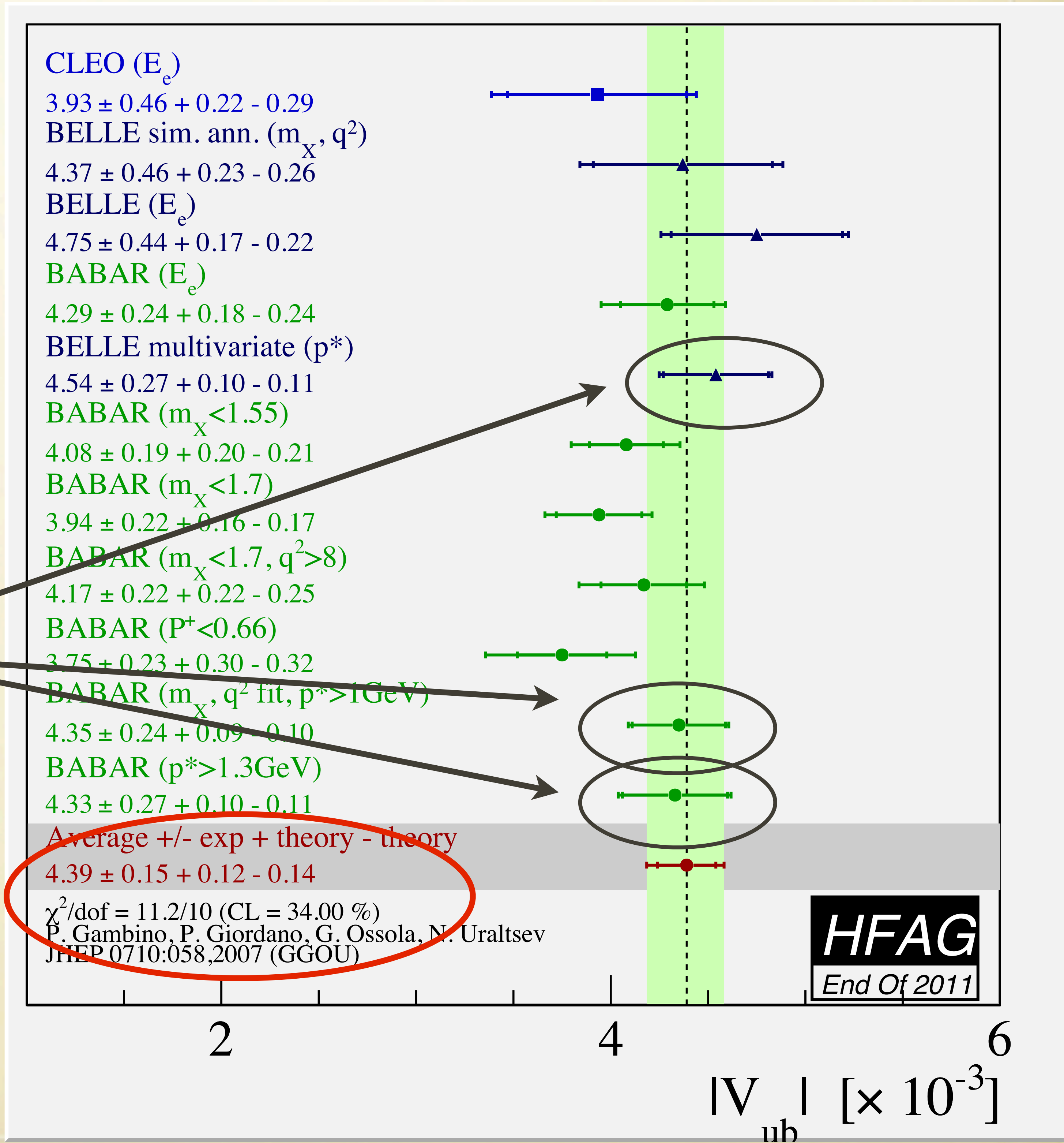
PG,Giordano,Ossola,Uraltsev

Good consistency & small th error.

4.7% total error

strong dependence on m_b

recent experimental results are theoretically cleanest but signal simulation relies on theoretical models



PERTURBATIVE EFFECTS

- O(α_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(α_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(α_s^2) calculation

Brucherseifer,Caola,Melnikov, arXiv:1302.0444

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

SUMMARY

- Theoretical efforts to develop the OPE approach to semileptonic decays goes on. More results soon. No sign of inconsistency in this approach.
- HQSR determination of zero recoil $B \to D^*$ form factor agrees with inclusive determination.
- 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 $b \to u l \nu$ decays. Measurement of spectra will enable direct constraints on shape function(s), see e.g. SIMBA.

Nikolai Uraltsev

a first class physicist, an enthusiastic colleague, a good friend has died on Feb 13.

BACK-UP SLIDES

HEAVY QUARK MASSES

Table 17.1.5. Recent results for the charm-quark mass. An asterisk indicates that we have obtained this number fr
of m_c quoted as the main result of the paper using four-loop accuracy (together with $\alpha_s(M_Z) = 0.1184$ (Nakamur

m_c(3 GeV) (GeV)	$m_c(m_c)$ (GeV)	Method	Reference
0.986 ± 0.013	1.275 ± 0.013*	LESR	Kühn, Steinhauser, and Sturm (2007)
0.96 ± 0.04*	1.25 ± 0.04	NRSR	Signer (2009)
0.986 ± 0.006	1.275 ± 0.006*	LQCD	McNeile, Davies, Follana, Hornbostel, and Lepage (2010)
0.998 ± 0.029	1.277 ± 0.026	LESR	Dehnadi, Hoang, Mateu, and Zebarjad (2011)
0.987 ± 0.009	1.278 ± 0.009	FESR	Bodenstein, Bordes, Dominguez, Penarrocha, and Schilche
0.972 ± 0.006*	1.262 ± 0.006	FESR	Narison (2012)

Table 17.1.6. Recent results for the bottom-quark mass.

$m_b(m_b)$	Method	Reference
4.19 ± 0.06	NRSR	Pineda and Signer (2006)
4.163 ± 0.016	LESR	Chetyrkin et al. (2009)
4.164 ± 0.023	LQCD	McNeile, Davies, Follana, Hornbostel, and Lepage (2010)
4.167 ± 0.013	LESR	Narison (2012)

OPE: power corrections

$$\Delta_{1/m^2} = \frac{\mu_G^2}{3m_c^2} + \frac{\mu_\pi^2 - \mu_G^2}{4}\left(\frac{1}{m_c^2} + \frac{2}{3m_c m_b} + \frac{1}{m_b^2}\right),$$
$$\Delta_{1/m^3} = \frac{\rho_D^3 - \frac{1}{3}\rho_{LS}^3}{4m_c^3} + \frac{1}{12m_b}\left(\frac{1}{m_c^2} + \frac{1}{m_c m_b} + \frac{3}{m_b^2}\right)(\rho_D^3 + \rho_{LS}^3)$$

matrix elements from moments fits & sum rule constraints

$1/m^4$ and $1/m^5$ also known, matrix elements have been estimated by ground state saturation — Mannel, Turczyk, Uraltsev

$$\Delta_A \simeq 0.090 + 0.029 - 0.023 - 0.013 + \ldots$$

heavy quark expansion converges reasonably well

Including all errors for ε_M=0.75GeV

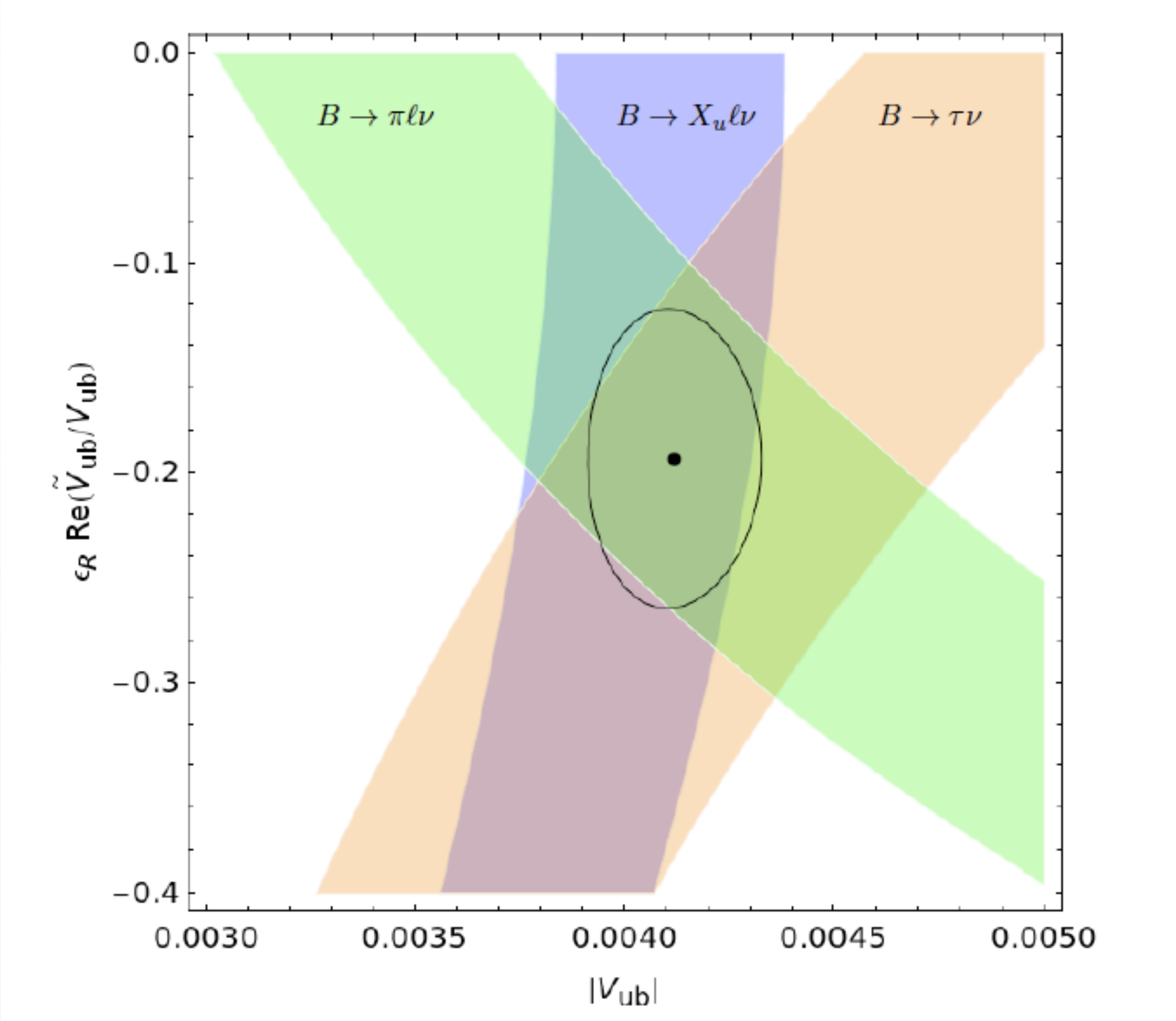
$$\mathcal{F}(1) < 0.935$$

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 sin2β (ψK_S) stronger...



Buras, Gemmler, Isidori 1007.1993

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:

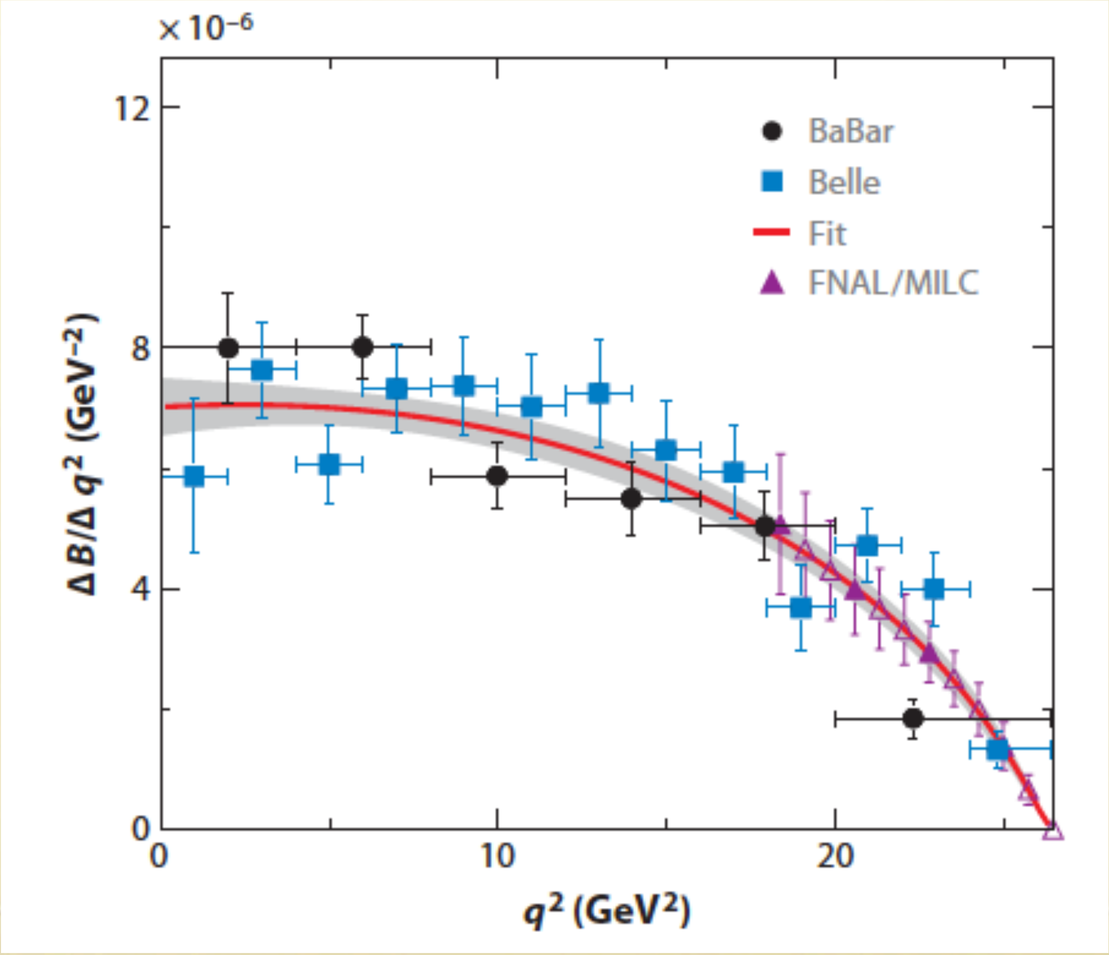
MILC collaboration

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

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

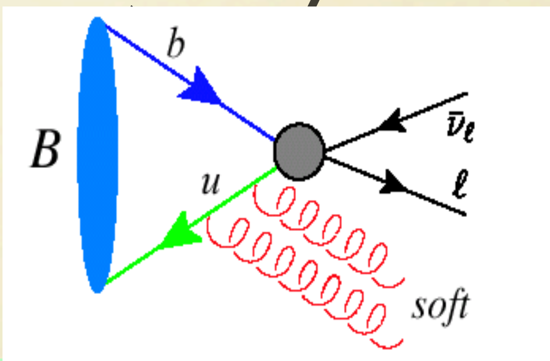
Experimental data are not well consistent

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

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

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

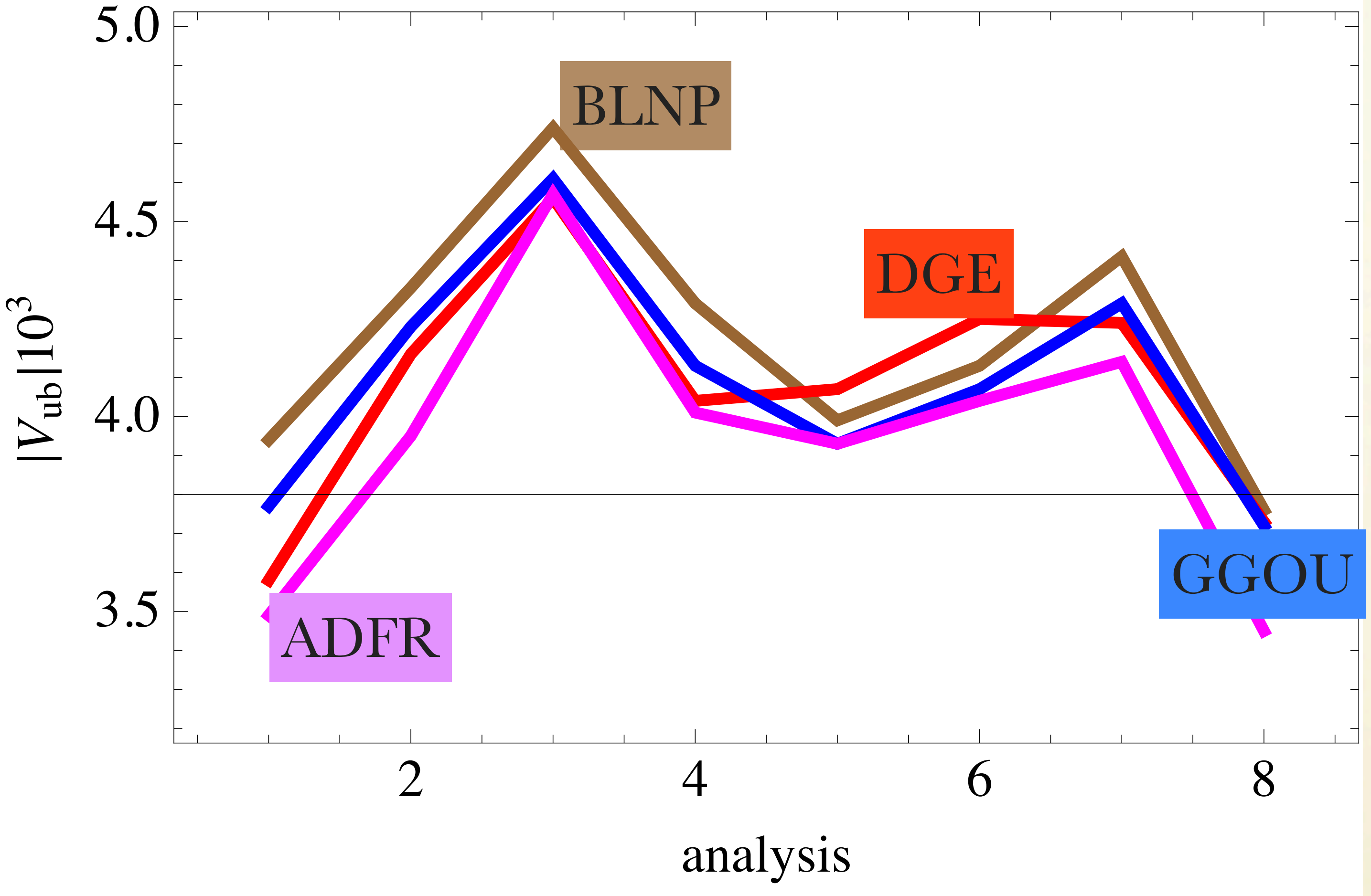
Using the results of the fit, V_{ub} could be extracted if we had the total width...



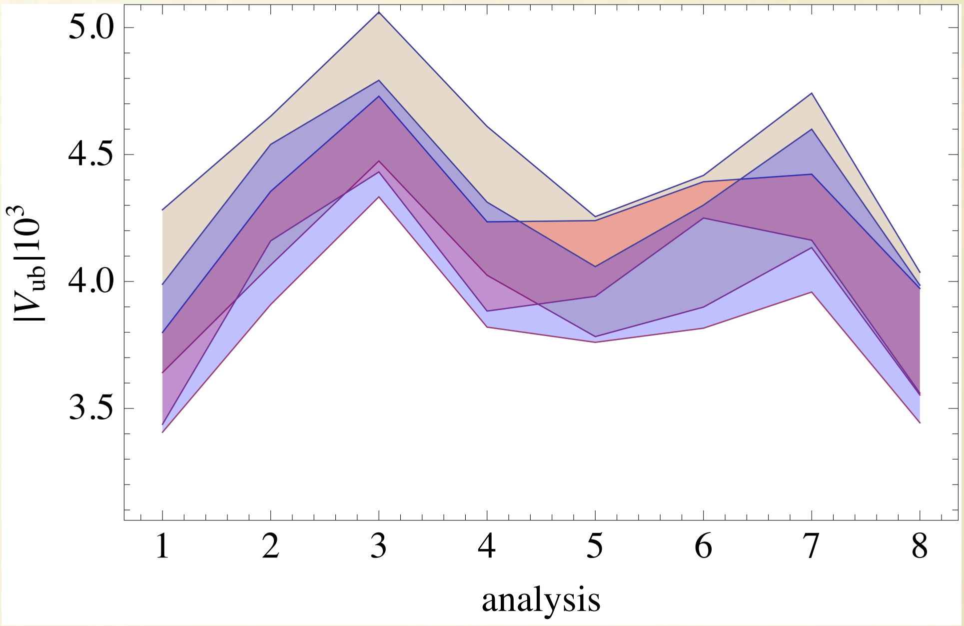
Weak Annihilation, severely constrained from D decays,
see Kamenik, PG, arXiv:1004.0114

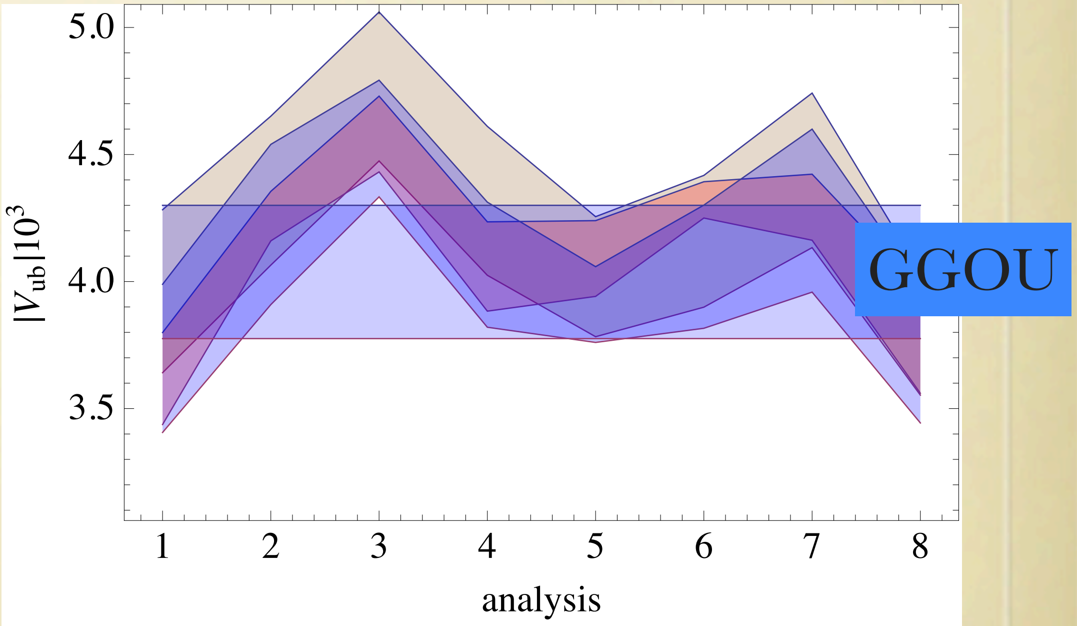
A GLOBAL COMPARISON

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

OPE: Perturbative effects

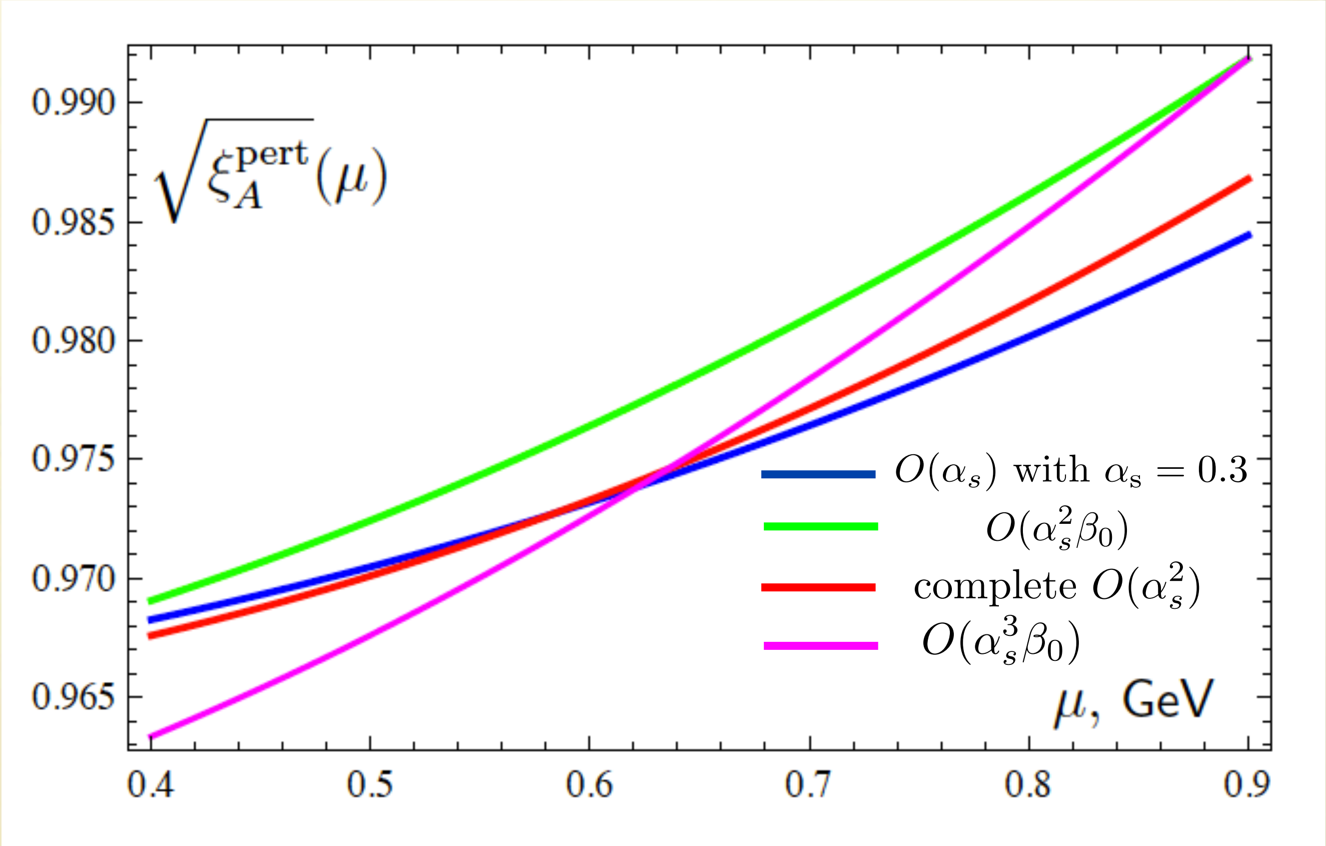
$$I_0(\varepsilon_M) \;=\; \xi_A^{\rm pert}(\varepsilon_M,\mu) + \sum_k C_k(\varepsilon_M,\mu)\,\frac{\frac{1}{2M_B}\langle B|O_k|B\rangle_\mu}{m_Q^{d_k-3}}$$

the cutoff μ separates pert and non-pert physics

Power corrections start with $1/m_c^2$ $\quad \Lambda_{QCD} \ll \varepsilon_M,\, \mu \ll 2m_c$

We choose $\varepsilon_M = \mu = 0.75\text{GeV}$ and include 1, 2 loop and higher BLM corrections with no expansion in μ/m_c

$$\sqrt{\xi_A^{\rm pert}(0.75\text{GeV})} = 0.98 \pm 0.01$$

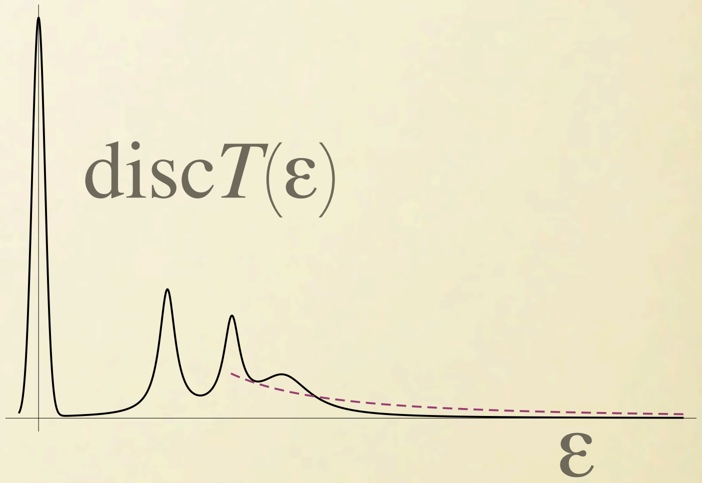


ZERO RECOIL SUM RULE

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

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

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



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

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

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

Unitarity bound