Status of the CKM matrix

Paolo Gambino
INFN Torino

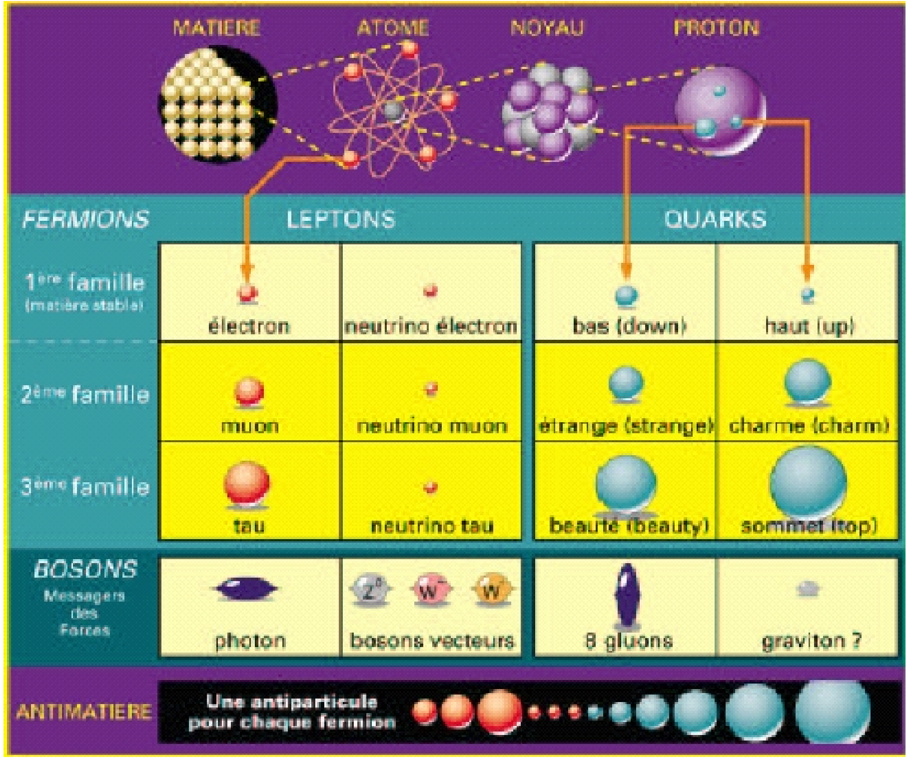
Matter comes in 3 generations

SM=SU(3)xSU(2)$_L$xU(1) gauge theory describes electroweak and strong interactions

3 generations of matter spin ½ fields (quarks and leptons)

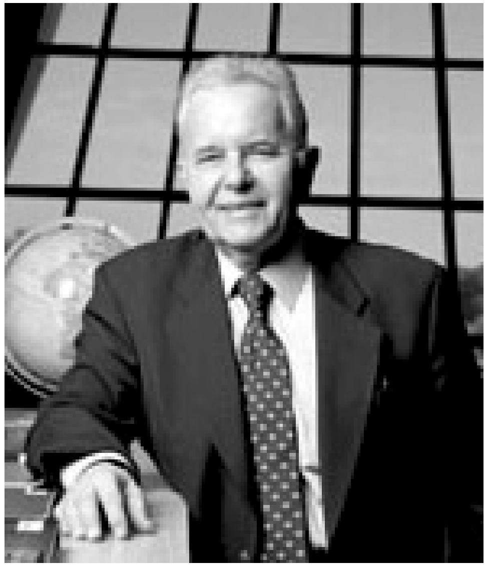
mechanism of mass generation is still unknown (Higgs?)

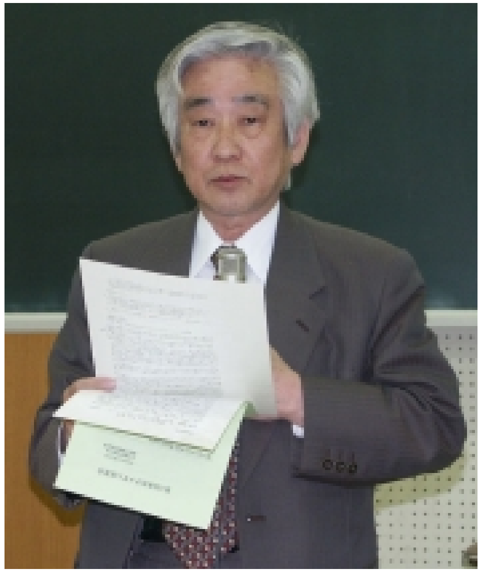
Variety of masses and mixing (Yukawa sector) is a mystery



Quark flavor mixing and CP violation are described in the SM by the CKM mechanism

The CKM paradigm





Cabibbo 1963 Kobayashi & Maskawa 1973

The CKM matrix

describes Flavor Violation (mixing between generations of quarks) in the SM

$$L_W = -\frac{g}{2\sqrt{2}} V_{ij} \bar{u}_i \gamma^\mu W_\mu^+ (1-\gamma^5) d_j + \text{ h.c.}$$

Wolfenstein parameterization

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9740 \pm 0.0010 & 0.2196 \pm 0.0023 & 0.0040^{+0.0006}_{-0.0007} \\ 0.224 \pm 0.016 & 0.91 \pm 0.16 & 0.0402 \pm 0.0019 \\ < 0.010 & \simeq 0.0400 & 0.99 \pm 0.29 \end{pmatrix}$$

3 angles and 1 phase with strong hierarchy:
$\lambda \sim 0.22$ sine of Cabibbo angle, $A,\rho,\eta = O(1)$

The CKM phase is the only source of CP violation in the SM

The CKM matrix

describes Flavor Violation in the SM

$$L_W = -\frac{g}{2\sqrt{2}} V_{ij} \bar{u}_i \gamma^\mu W^+_\mu (1-\gamma^5) d_j + \text{ h.c.}$$

Wolfenstein parameterization

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

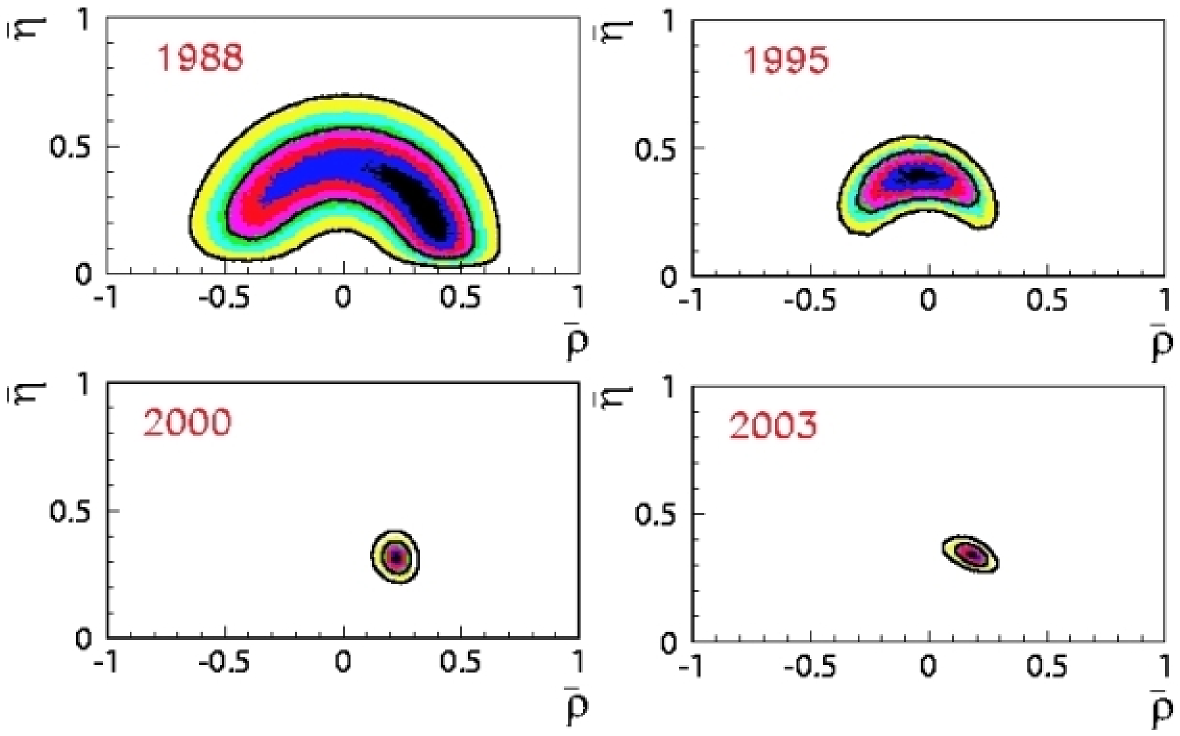
3 angles and 1 phase with strong hierarchy:

$\lambda \sim 0.22$ sine of Cabibbo angle, $A, \rho, \eta = O(1)$

At present accuracy, Wolfenstein par must be improved $\bar{\rho}, \bar{\eta}$

2 approaches: measure individual elements and test unitarity (PDG)
OR use unitarity and test as many observables as possible

On the way to precision physics



Why precision CKM studies?

We are able to describe the observed flavor violation very well
But we have no theory of flavor.
The SM does not address flavor, but rather accomodates it
Similarly, **CP violation** is (accidentally) accounted for in the CKM

Most models of new physics include new CP and Flavor violation
but measurements are surprisingly close to SM prediction
scale $\Lambda_{NP} \gg$ TeV ➔ ➔ the flavor & CP problems

Need **precision** studies to uncover new dynamics
and/or degrees of freedom, testing the CKM paradigm.

Strong interactions make CKM studies hard. Learning slowly
but steadily at crossroad of many different fields.
Theory errors dominate almost everywhere.

The Cabibbo angle

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & V_{ub} \\ -\lambda & 1-\frac{1}{2}\lambda^2 & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Historically, *universality of charged currents ←→ CKM unitarity*

Comparison between V_{ud},V_{us} determinations of tests unitarity of the first line of V_{CKM}

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$|V_{ub}|^2$ → $O(10^{-5})$

λ could also be measured from 2nd line, V_{cd} (DIS) at 10%, W decays at LEP constrains $\Sigma_{ij}|V_{ij}|^2$ at 1.3% ⇔ V_{cs} at 1.3%

λ from V_{ud}

Superallowed Fermi transitions ($0^+ \to 0^+$ β decay)

extremely precise, 9 expts, δV_{ud}~0.0005 dominated by RC and nuclear structure

$$\langle p_f; 0^+ | \bar{u}\gamma_\mu d | p_i; 0^+ \rangle = \sqrt{2}(p_i + p_f)_\mu$$

+ isospin violation

Superallowed magic

Nucleus	$\lvert V_{ud}\rvert$
^{10}C	0.97388(76)
^{14}O	0.97445(41)
^{26}Al	0.97416(35)
^{34}Cl	0.97431(40)
^{38}K	0.97424(43)
^{42}Sc	0.97351(38)
^{46}V	0.97372(43)
^{50}Mn	0.97396(44)
^{54}Co	0.97409(43)

Towner & Hardy

$0^+ \to 0^+$ Nuclear Decays Vector Current
$0^- \to 0^-$ $\pi^+ \to \pi^0 e^+ \nu$ CVC → No Hadronic Unc.

But Axial Current Enters At Loop Level

$$A^{\mu\nu}(Q) = \int d^4x\, e^{iQ\cdot x} \langle p | T(J_\gamma^\mu(x) A_W^\nu(0)) | n \rangle$$

Operator Prod. Exp $\xrightarrow[\text{large } Q^2]{}$ $\frac{1}{Q^2}$

Recently we tried to improve matching

1) S.D. Expansion + QCD $Q_{SD}^2 \le Q^2 \le \infty$ $Q_{SD} = 1.5\,\text{GeV}$
2) Interpolator $Q_{LD}^2 \le Q^2 \le Q_{SD}^2$
3) Born Appox. $0 \le Q^2 \le Q_{LD}^2$

Match Methods At $Q_{SD} = 1.5\,\text{GeV}$ & $Q_{LD} = ?$

Same QCD corr. as in Bjorken sum rule T[VV]

perturbative behaviour down to ~1 GeV (exp.)

$$\lvert V_{ud}\rvert = 0.9740(1)(3)(4)$$

largest uncertainty due to e.m. rad. corrections

$\lvert V_{ud}\rvert = 0.9739\,(2)(2)_{\text{theory}}$ $\underbrace{}_{(3)}$

Marciano Sirlin 2005

λ from V_{ud}

Superallowed Fermi transitions ($0^+ \to 0^+$ β decay)
extremely precise, 9 expts, δV_{ud}~0.0005 dominated by RC and nuclear structure

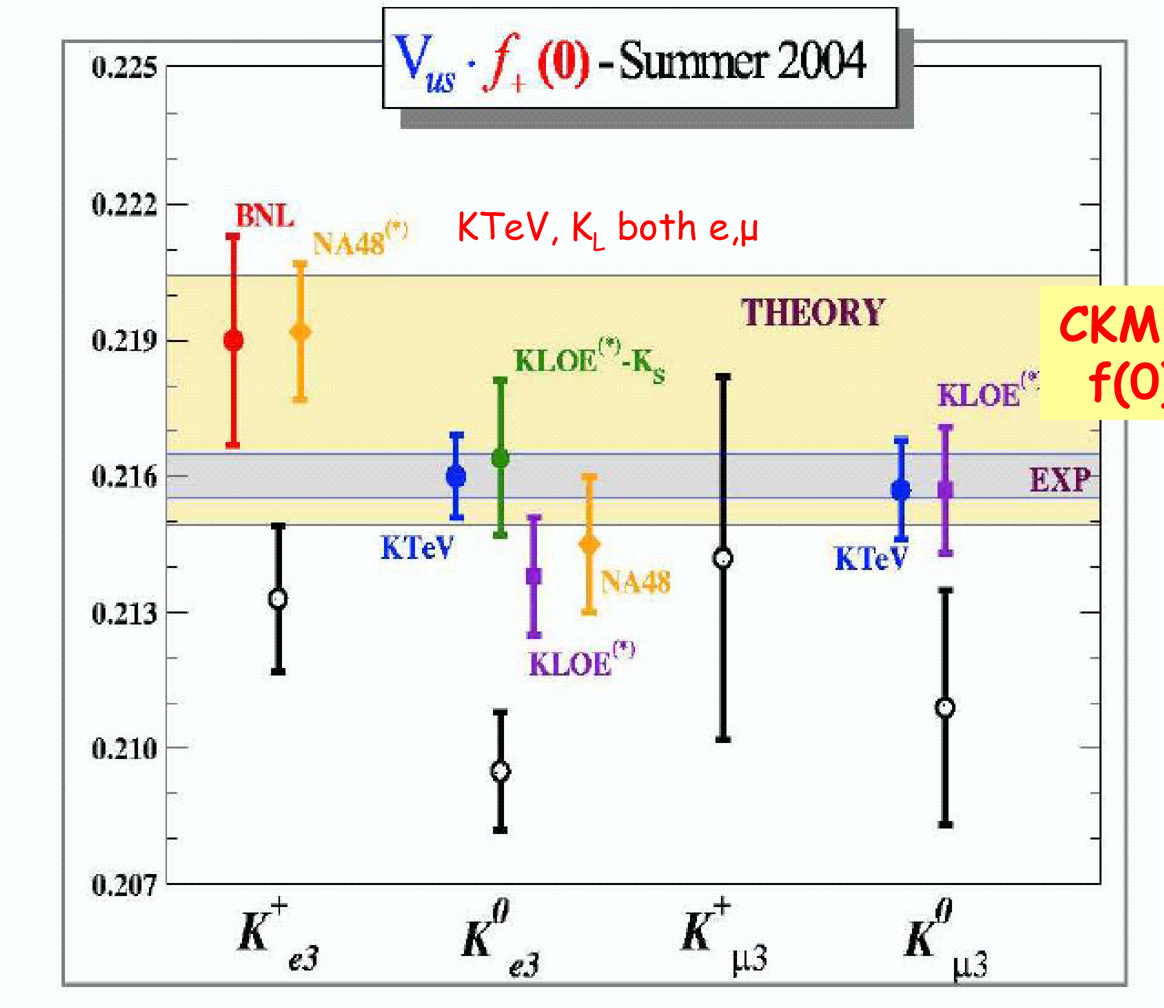
$$\langle p_f; 0^+ | \bar{u} \gamma_\mu d | p_i; 0^+ \rangle = \sqrt{2} (p_i + p_f)_\mu$$ + isospin violation

neutron β decay not pure vector, needs g_A/g_V but no nuclear structure. δV_{ud}~0.0015, will be improved at PERKEO, Heidelberg
New measurement of *n* lifetime (many σ away) serious problem!

π^+ decay to $\pi^0 e \nu$ th cleanest, promising in long term but BR~10^{-8} PIBETA at PSI already at δV_{ud}~0.003

PDG : V_{ud}=0.9738±0.0005
Marciano-Sirlin: 0.9739±0.0003 (NEW)
λ = 0.2274±0.0021 → 0.2269±0.0013

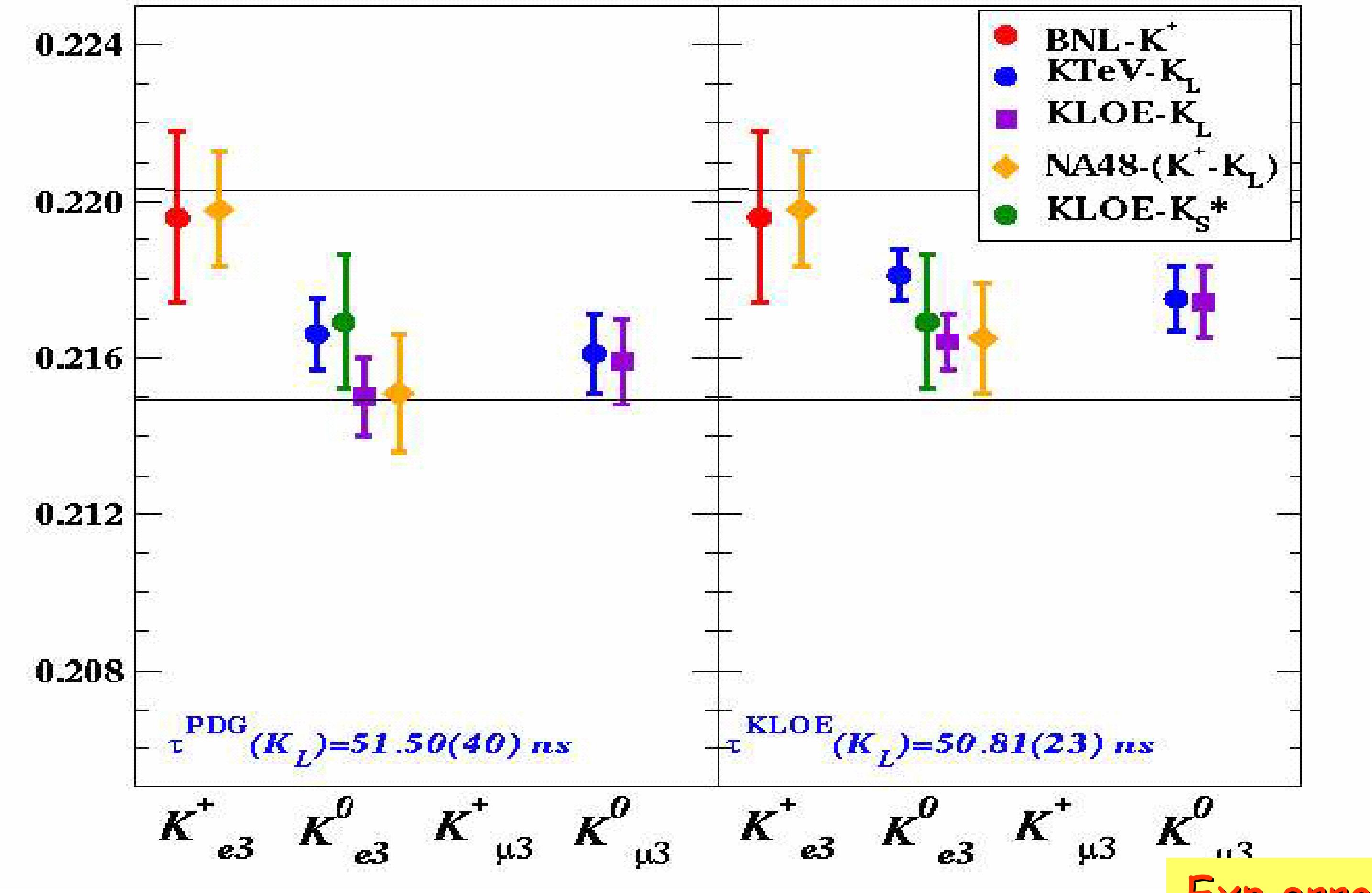
λ from V_{us} (K_{l3})



CKM unitarity + f(0) estimates

Discarding old results and using Leutwyler & Roos: $|V_{us}|_{Kl3}$= 0.2262 ±0.0023

@ CKM WS (march 2005)



Exp error below 0.5%

$$\Gamma(K_{\ell 3}) = \frac{G_\mu^2}{192\pi^3} M_K^5 |V_{us}|^2 C_K^2 |f_+(0)|^2 I(f_+, f_-)$$ +R.C.+...

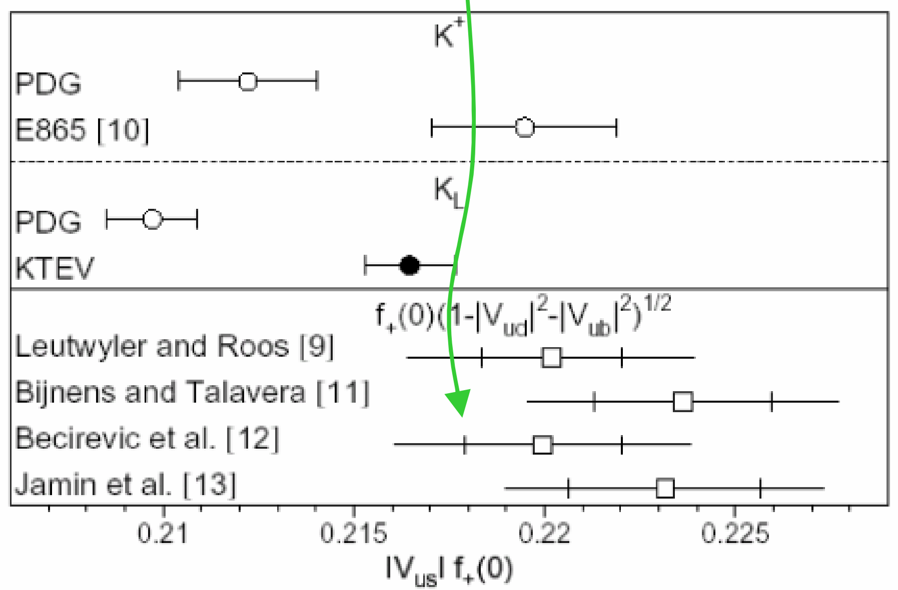
AG theorem: easily calculable

?

$$f_+(0) = 1 + f_2 + f_4 + \ldots$$ in the chiral expansion

$$f_n = \mathcal{O}[M^n_{K,\pi}/(4\pi f_\pi)^n]$$

New lattice result: Becirevic et at 1% (confirmed by MILC & JLQCD, unquenched)



Next frontier: LQCD & measure slopes for $K_{\mu 3}$(Dalitz plot) to constrain χPT

Space for theory improvement ➔ 0.5%?

New ideas

τ decay (V_{us}) Jamin et al.

m_s from sum rules or LQCD as input, may become competitive with B-factory results. At present δV_{us}~0.0034, low values

Hyperon decays (V_{us})

Cabibbo et al. have revisited the subject focussing on vector form fact.
δV_{us}~0.0027 (exp) but O(1%) or more SU(3) breaking effects NOT included, lattice calculations under way

λ using f_π/f_K from lattice Marciano (2004):

$$\frac{\Gamma(K \to \mu\bar{\nu}_\mu(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}_\mu(\gamma))} = \frac{|V_{us}|^2 f_K^2 m_K \left(1 - \frac{m_\mu^2}{m_K^2}\right)^2}{|V_{ud}|^2 f_\pi^2 m_\pi \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2} \underbrace{0.9930(35)}_{\text{R.C.}}$$

Use LQCD for f_π/f_K. Present MILC result 1.204(4)(14)
Staggered fermions, partially unquenched. From there we get

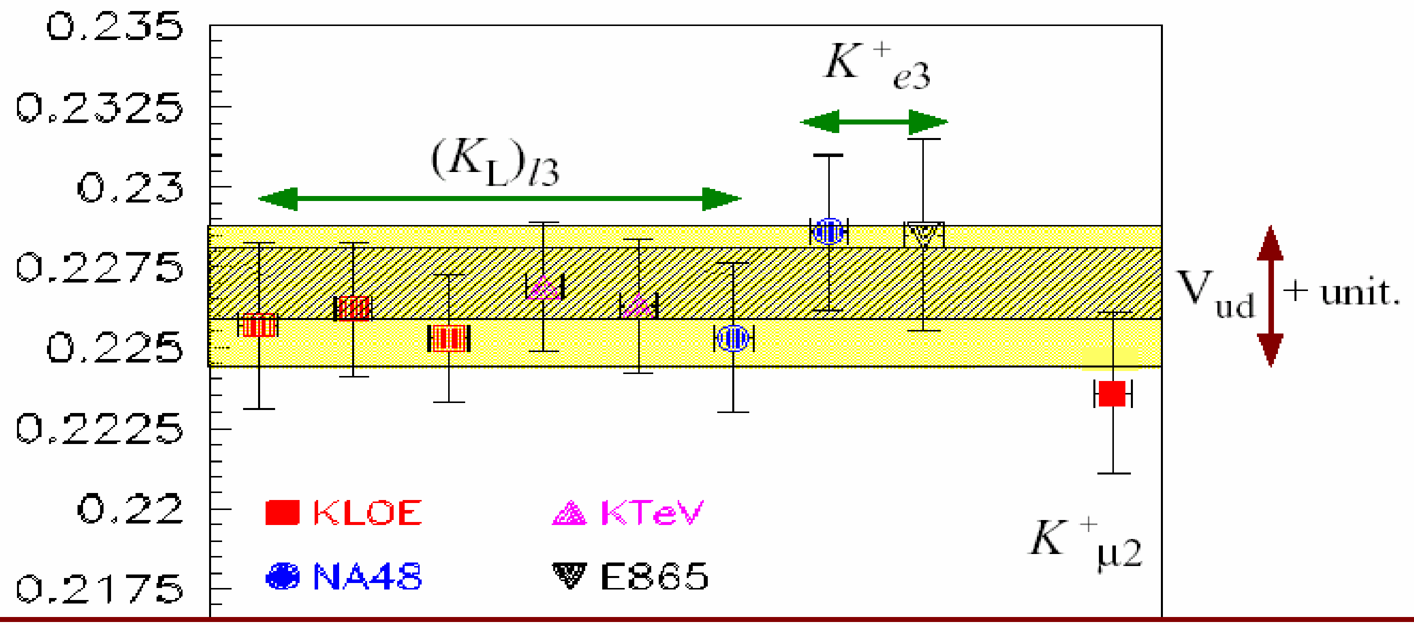
λ= 0.2234 ± 0.0003(exp) ± 0.0004(rc) ± 0.0021(lattice)

Compatible with other determinations. MILC error debated.

Good potential for improvement

Gino's conclusions at CKM WS

Summary of V_{us} from from K decays :



Preliminary numbers [not to be used yet]:

$$V_{us} = 0.2262\,(12) \cdot [0.961 / f_+(0)] \Rightarrow 0.2262\,(23)$$

$$V_{us} = 0.2234\,(05) \cdot [1.204\, f_\pi / f_K] \Rightarrow 0.2234\,(23)$$

$$V_{us}^{unit} = 0.2269\,(13)$$

Summary Cabibbo angle

- Lots going on in theory and exp
- First row unitarity problem resolved
- many competing methods
- good prospect of improvement

Determination of A

$$V_{CKM}=\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}+O(\lambda^4)$$

A can be determined using $|V_{cb}|$ or $|V_{ts}|$

Two roads to $|V_{cb}|$

EXCLUSIVE **INCLUSIVE**

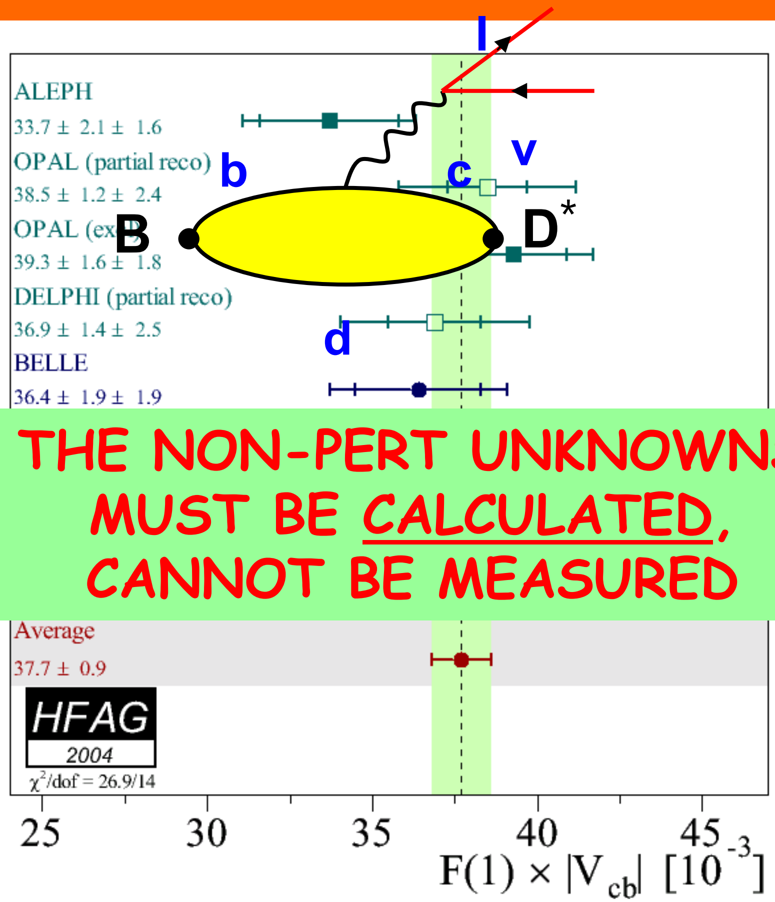
$|V_{cb}|$ from $B \to D^* l \nu$

At zero recoil, where rate vanishes.
Despite extrapolation, exp error ~ 2%
Main problem is form factor F(1)

The non-pert quantities relevant for excl decays cannot be experimentally determined Must be calculated but HQET helps.

$$F_{B\to D^*}(1) = \eta_A \,[1 - O(1/m_b, 1/m_c)^2]$$

Lattice QCD: $F(1) = 0.91^{+0.03}_{-0.04}$
Sum rules give consistent results
Needs unquenching (under way)



THE NON-PERT UNKNOWNS MUST BE CALCULATED, CANNOT BE MEASURED

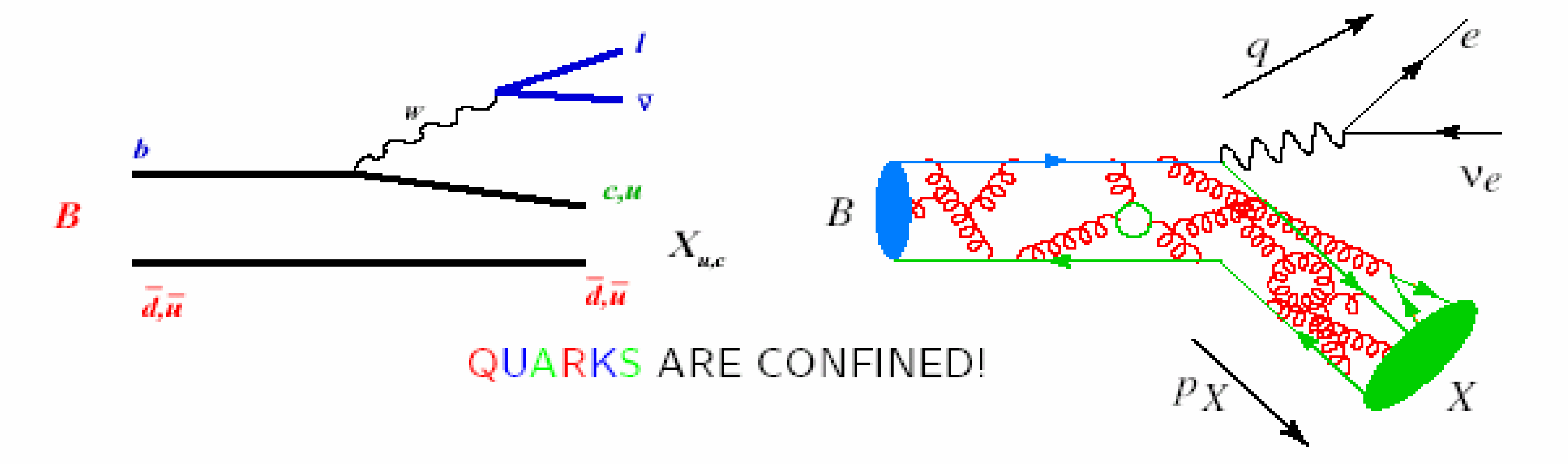
$\delta V_{cb}/V_{cb} \sim 5\%$ and agrees with inclusive det, despite contradictory exps

$B \to D l \nu$ gives consistent but less precise results

The advantage of being inclusive

$\Lambda_{QCD} \ll m_b$: inclusive decays admit systematic expansion in Λ_{QCD}/m_b
Non-pert corrections are generally small and can be controlled

Hadronization probability =1 because we sum over all states
Approximately insensitive to details of meson structure as $\Lambda_{QCD} \ll m_b$
(as long as one is far from perturbative singularities)



$$\frac{d^2\Gamma}{dE_l\, dq^2\, dq_0}$$ can be expressed as double series in α_s and Λ_{QCD}/m_b (OPE) with parton model as leading term **No $1/m_b$ correction!**

A double expansion

$$\frac{d^2\Gamma}{dE_l dq^2 dq_0}$$ can be expressed in terms of *structure functions* related to Im of

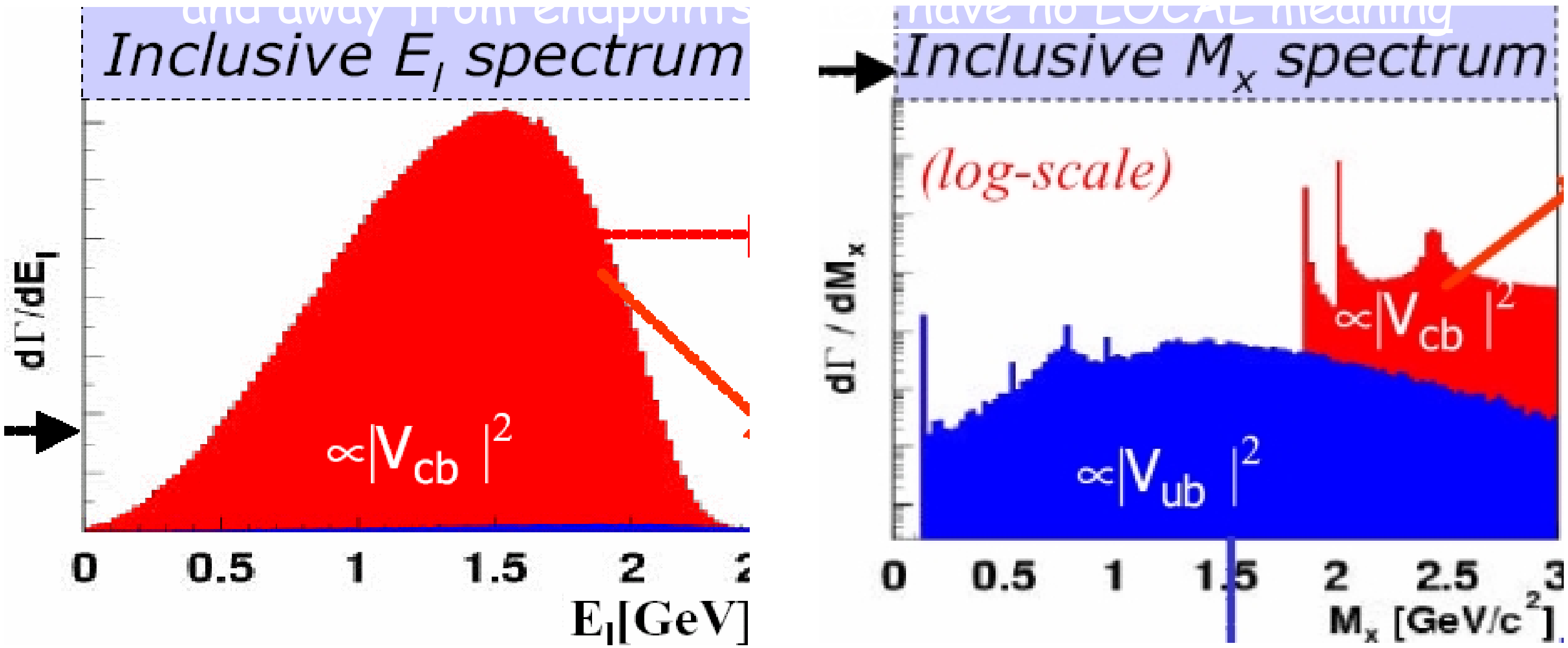
$$h_{\mu\nu}(q^2,q_0) = \frac{1}{2M_B}\langle B|\int \mathrm{d}^4x\, \mathrm{e}^{-iqx}\, iT\left\{J_\mu(x), J_\nu^\dagger(0)\right\}|B\rangle$$

OPE (HQE): $T\, J(x)\, J(0) \approx c_1 \bar{b}b + c_2 \bar{b}\, \vec{D}^2 b + c_3 \bar{b}\sigma \cdot G b + \ldots$

- The leading term is parton model, c_i are series in α_s
- New operators have non-vanishing expection values in B and are suppressed by powers of the energy released, <u>$E_r \sim m_b - m_c$</u>
- **No $1/m_b$ correction!**

OPE predictions can be compared to exp only after SMEARING and away from endpoints: <u>they have no LOCAL meaning</u>

Leptonic and hadronic spectra



Total **rate** gives CKM elmnts; global **shape** parameters tells us about B structure

State of the art

m_b, m_c

μ_G^2, μ_π^2 λ_1, λ_2

he... must be ca...

O(1/m_b^2): mean kin.energy of b in B

$$\mu_\pi^2(\mu) = \frac{1}{2M_B} \langle B | \bar{b}(i\vec{D})^2 b | B \rangle_\mu$$

State of the art

m_b, m_c μ_G^2, μ_π^2 λ_1, λ_2 ρ_D^3, ρ_{LS}^3 ρ_1, ρ_2

Gremm,Kapustin...

O($1/m_b^2$): mean kin.energy of b in B

$$\mu_\pi^2(\mu) = \frac{1}{2M_B} \langle B | \bar{b} (i\vec{D})^2 b | B \rangle_\mu$$

State of the art

m_b, m_c μ_G^2, μ_π^2 λ_1, λ_2 ρ_D^3, ρ_{LS}^3 ρ_1, ρ_2

Gremm,Kapustin...

$$\Gamma_{cl\nu} = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 A_{ew} z_0(r) \left(1 + a_1(r) \frac{\mu_\pi^2}{m_b^2} + a_2(r) \frac{\mu_G^2}{m_b^2} + a_3(r) \frac{\rho_D^3}{m_b^3} + a_4(r) \frac{\rho_{LS}^3}{m_b^3} \right)$$

Recent implementation for moments of lept and hadronic spectra including a cut on the lepton energy

Bauer et al.,Uraltsev & PG

Perturbative Corrections: full $O(\alpha_s)$ and $O(\beta_0\ \alpha_s^2)$ available
For hadronic moments thanks to **NEW** calculations

Trott
Aquila,PG,Ridolfi,Uraltsev

Implementing the OPE: masses & schemes

m_q(pole) is ill-defined, cannot be determined better than ~100MeV, and induces large uncontrolled higher orders

$|V_{cb}| \sim k_0$ [1-0.66 (m_b-4.6) +0.39 (m_c-1.15)+ +0.01 (μ_π^2 -0.4) +0.05 (μ_G^2-0.35)+0.09 (ρ_D^3-0.2)...]

- Need short distance masses: e.g. $m_b^{kin}(\mu)$ and m_b^{1S} and HQ parmts
- Exploit correlations (most moments depend on ~ m_b-0.7 m_c like width)
- Avoid unnecessary parameters, avoid 1/m_c expansion
- Define carefully $\mu_\pi^2=-\lambda_1+\ldots$ $\mu_G^2= 3\lambda_2+\ldots$

Traditionally m_Q reexpressed using

$$M_{B,D} = m_Q + \bar{\Lambda} + \frac{\mu_\pi^2 - \mu_G^2}{2m_Q} + \frac{\rho_D^3 + \rho_{LS}^3 - \rho_{nl}^3}{4m_Q^2} + \mathcal{O}\left(\frac{1}{m_Q^3}\right)$$

1/m_c expansion

Non linear ops: T_{1-4}

Using moments to extract HQE parameters

We do know something on HQE par.
need to check consistency.

- M_{B*}-M_B fix μ_G^2= 0.35±0.03
- Sum rules: $\mu_G^2 < \mu_\pi^2$, $\rho_D^3 > -\rho^3_{LS}$...

Central moments can be VERY sensitive to HQE parameters

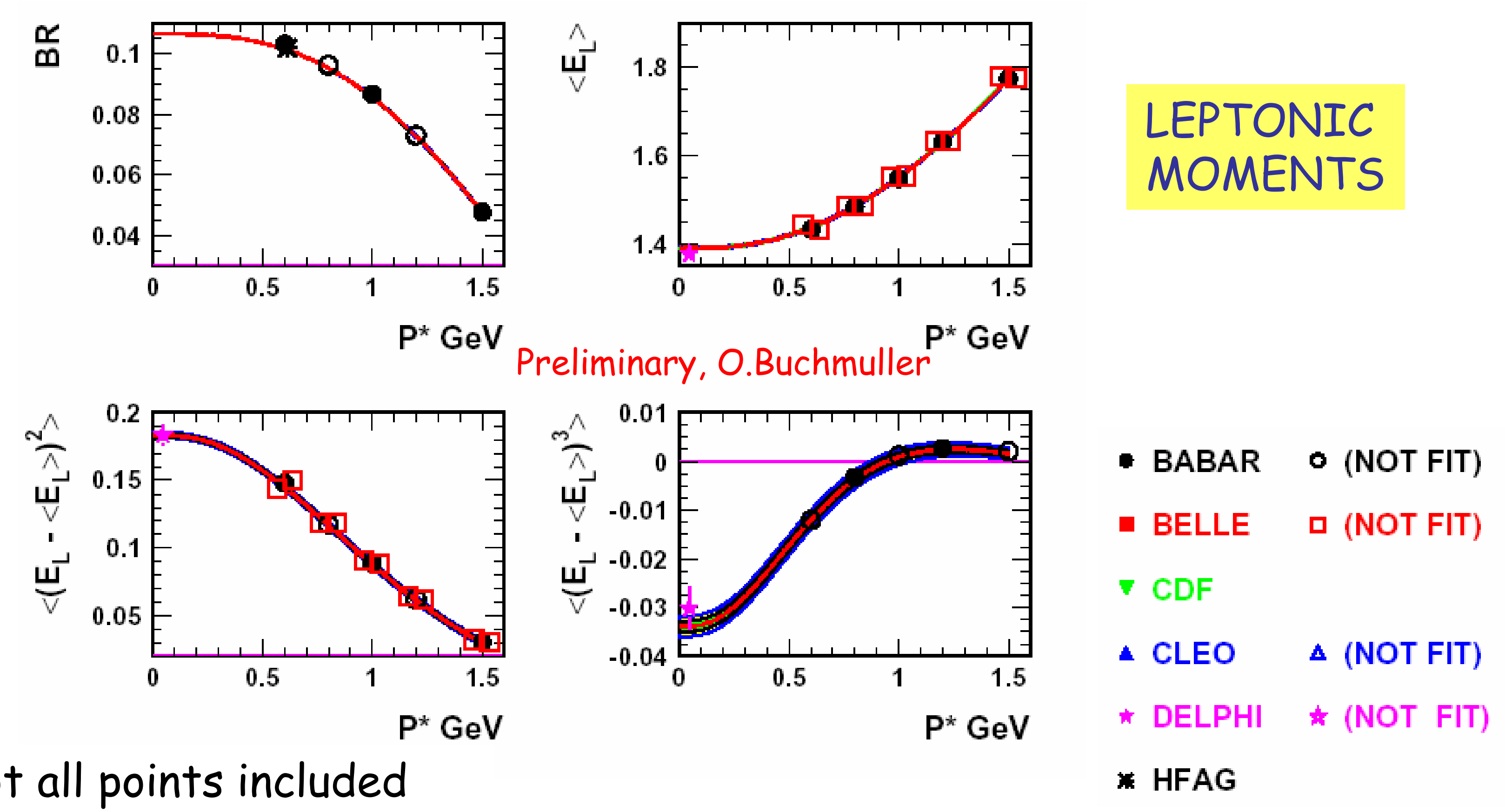
$$\left\langle \left(M_X^2 - \langle M_X^2 \rangle\right)^2 \right\rangle \approx \left[1.3 + 0.4(m_b - 4.6) - (m_c - 1.2) + 5(\mu_\pi^2 - 0.4) - 6(\rho_D^3 - 0.1) + \ldots\right] GeV^4$$

Variance of mass distribution

BUT: OPE accuracy deteriorates for higher moments (getting sensitive to local effects)

Provided cut is not too severe (~1.3GeV) the cut moments give additional info

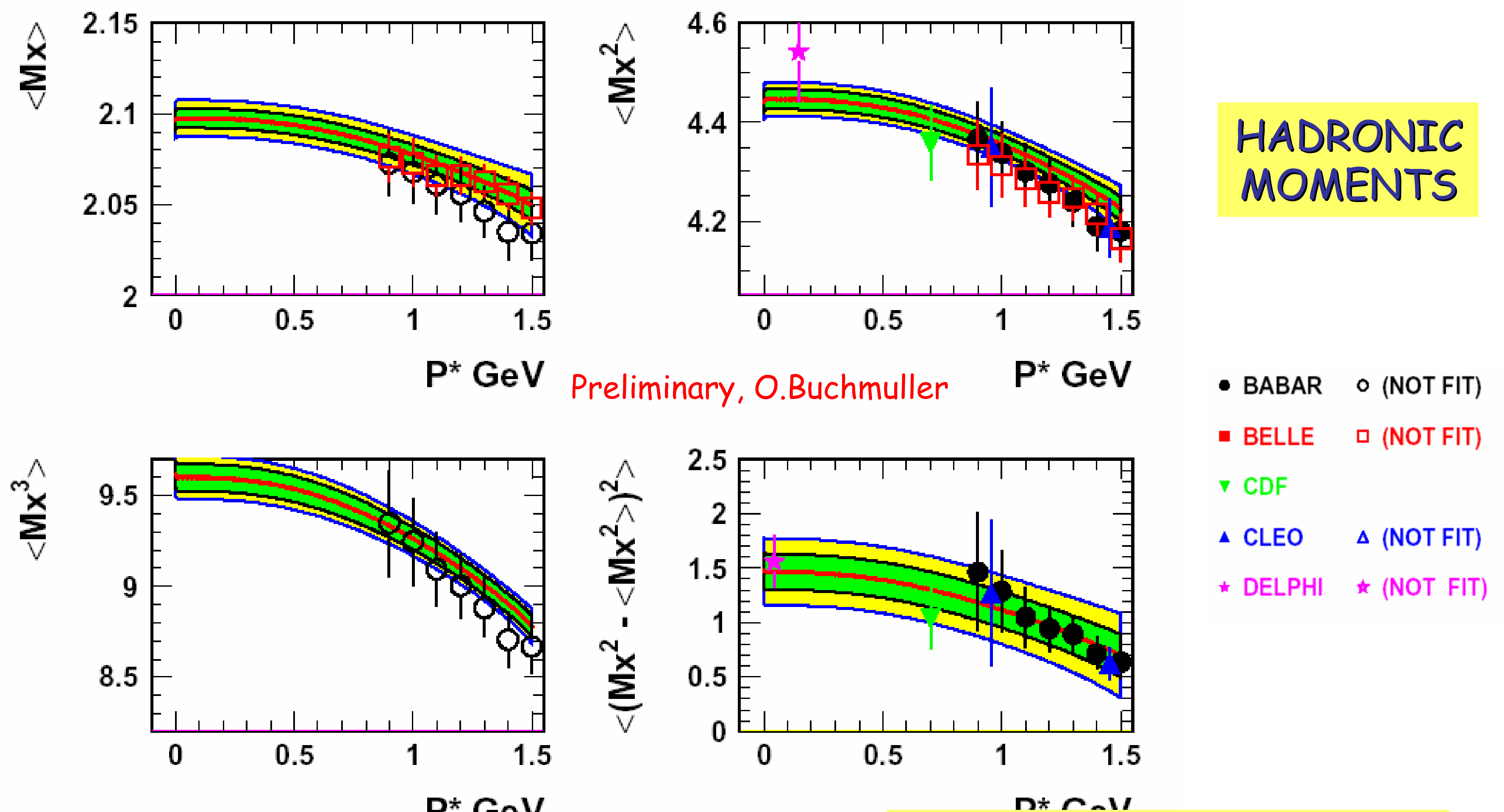
Global fit to $|V_{cb}|$, BR_{sl}, HQE parmts



Not all points included
No external constraint

Pioneer work by CLEO & Delphi employed less precise/complete data, some external constraints, and CLEO a different scheme

Global fit to $|V_{cb}|$, BR_{sl}, HQE parmts



Preliminary, O.Buchmuller

HADRONIC MOMENTS

Very similar results in a different approach/scheme, Bauer et al

Excellent agreement within exp and TH errors

H.Flaecher, CKM 2005

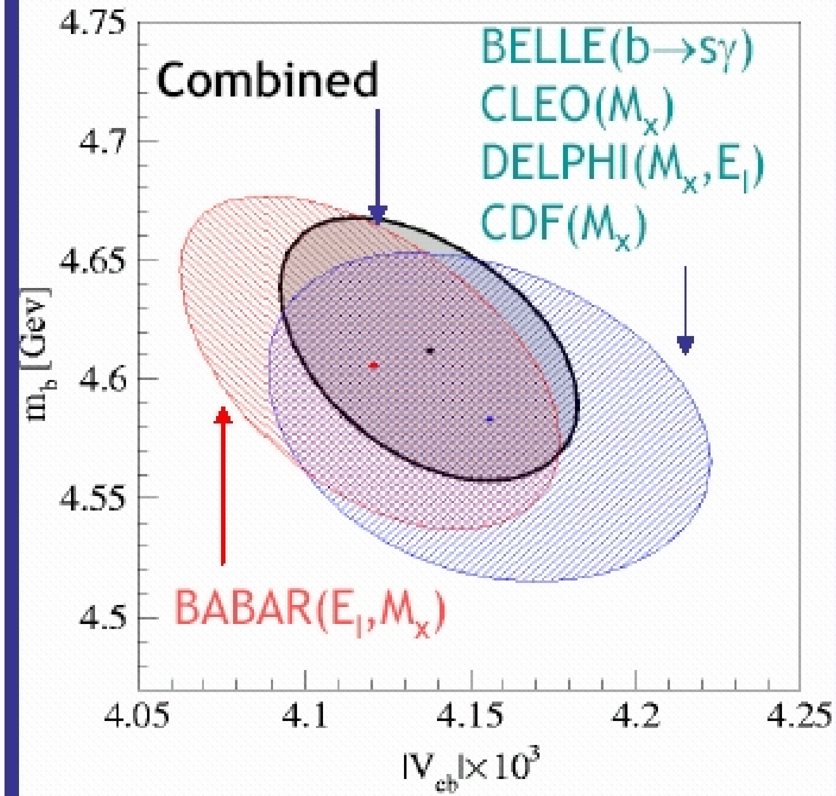
Combined fit in kinetic scheme

Benson, Bigi, Gambino, Mannel, Uraltsev

$\lvert V_{cb}\rvert$ =	41.38	+/-	0.45	10^{-3}
m_b =	4.61	+/-	0.06	GeV
m_c =	1.17	+/-	0.08	GeV
μ_π^2 =	0.40	+/-	0.04	GeV^2
μ_G =	0.29	+/-	0.05	GeV^2
ρ_D =	0.16	+/-	0.06	GeV^3
ρ_{LS} =	-0.18	+/-	0.09	GeV^3
$BR(B\to Xl\nu)$ =	10.64	+/-	0.14	%

- Stat., syst. and theo. (HQE, α_s) errors included.
- Error from uncertainty in Γ_{SL} (intrinsic charm) not included!
- $\lvert V_{cb}\rvert$ error of ≈ 1%

→ Substantial improvement from combination!

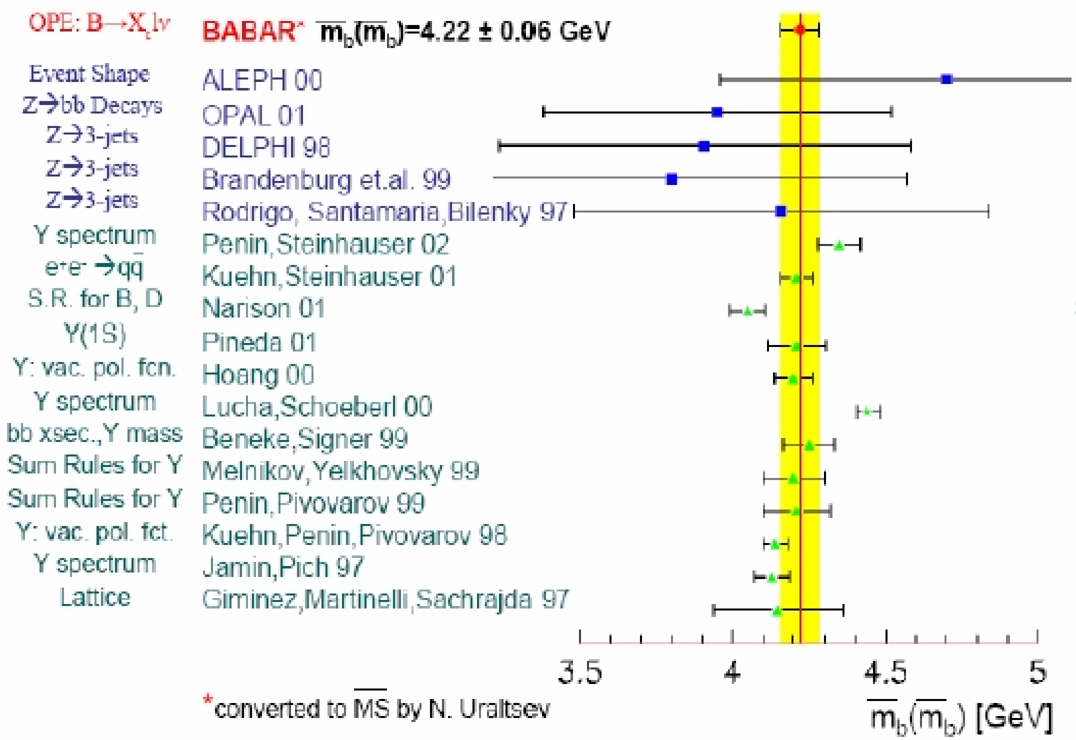


Consistent description of all moments by HQE

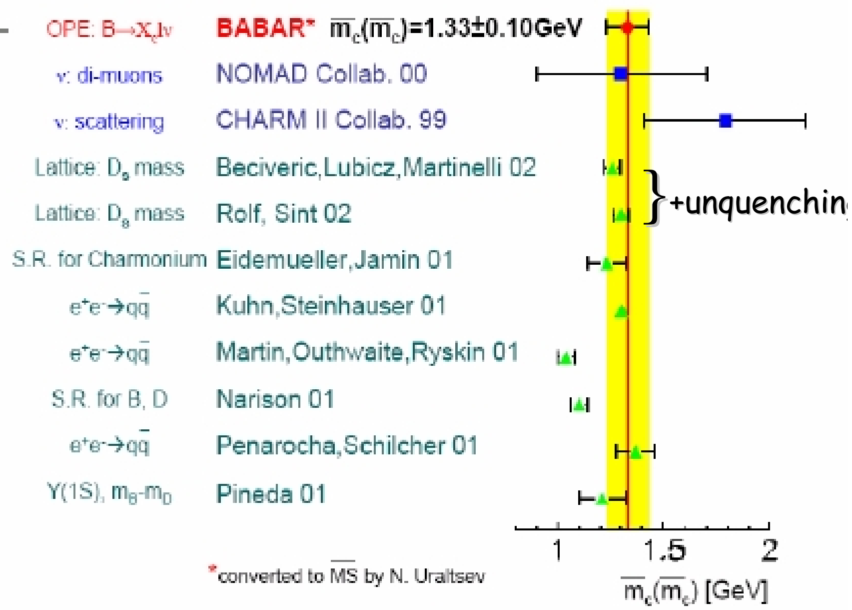
Could also be done in alternative schemes

Comparison with other Determinations

Measurements and Predictions of the b-Quark Mass ($\overline{MS}$ scheme)
PDG2003



Measurements and Predictions of the c-Quark Mass ($\overline{MS}$ scheme)
PDG2003



$\overline{m}_b(\overline{m}_b) = 4.22 \pm 0.06$ GeV

$\overline{m}_c(\overline{m}_c) = 1.33 \pm 0.10$ GeV

Conversion from kinetic mass scheme
to $\overline{MS}$ scheme with hep-ph/9708372, hep-ph/0302262
See also report from CKM WS hep-ph/0304132

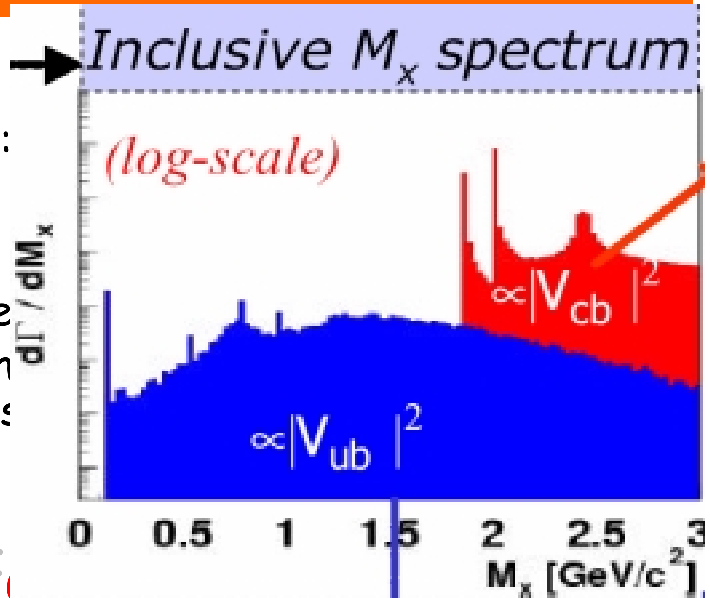
Theoretical uncertainties are crucial for the fits

- ✓ Missing higher power corrections
- ✓ Intrinsic charm
- ✓ Missing perturbative effects in the Wilson coefficients: $O(\alpha_s^2)$, $O(\alpha_s/m_b^2)$ etc
- ✓ Duality violations

How can we estimate all this?

Different recipes, results for $|V_{cb}|$ unchanged

Testing parton-hadron duality



- ✓ **What is it?** For all practical purposes:
  No OPE, no duality
- ✓ **Do we expect violations?** Ye
  because OPE must be continued analytically. th
  described by the OPE, like hadronic thresholds
  decays
- ✓ **Can we constrain them eff**
  in a self-consistent way: just check the OPE predictions.
  E.g. leptonic vs hadronic moments. Models may also give hints of how it works
- ✓ **Caveats?** HQE depends on many parameters and we know only a few terms of the double expansion in α_s and Λ/m_b.

It is not just V_{cb} ...

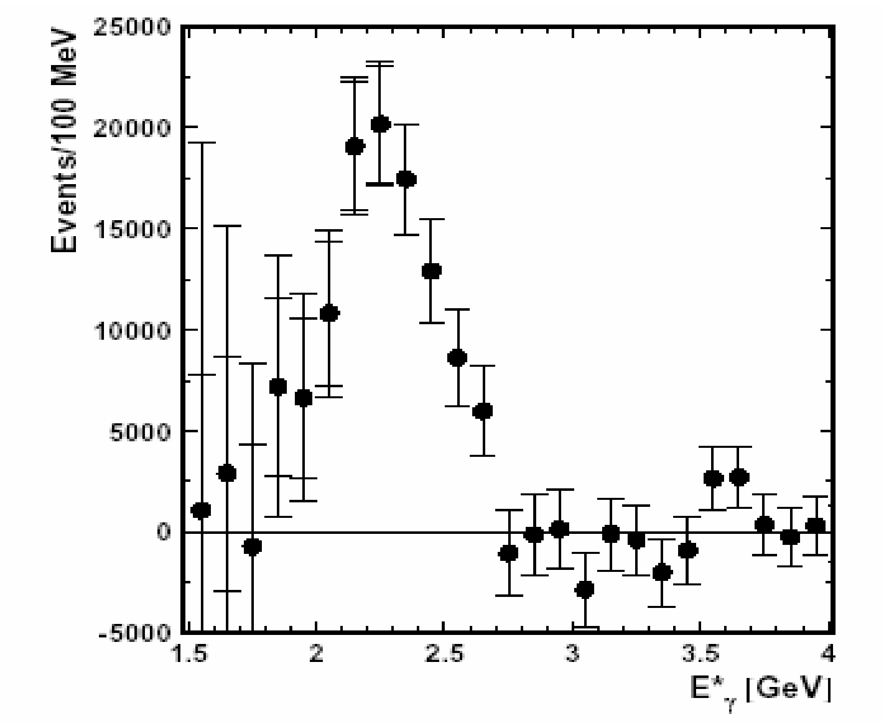
HQE parameters describe *universal* properties of the B meson and of the quarks

- c and b masses can be determined with competitive accuracy (likely better than 70 and 50 MeV)
- m_b-m_c is already measured to better than 30 MeV: a benchmark for lattice QCD etc?
- most **V_{ub} incl. determinations** are sensitive to a shape function, whose moments are related to μ_π^2 etc, **moments in $B\to X_u l\nu$** to constrain WA and to validate MC (Ossola, Uraltsev,PG)
- Bounds on ρ, the slope of IW function ($B\to D^*$ form factor)
-

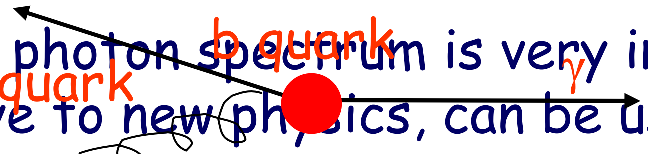
Need precision measurements to probe limits of HQE & test our th. framework

Universality: spectrum of $B \to X_s\gamma$

Motion of b quark inside B and gluon radiation smear the spike at $m_b/2$



Belle NEW: lower cut at 1.8GeV



The photon spectrum is very insensitive to new physics, can be used to study the B meson structure

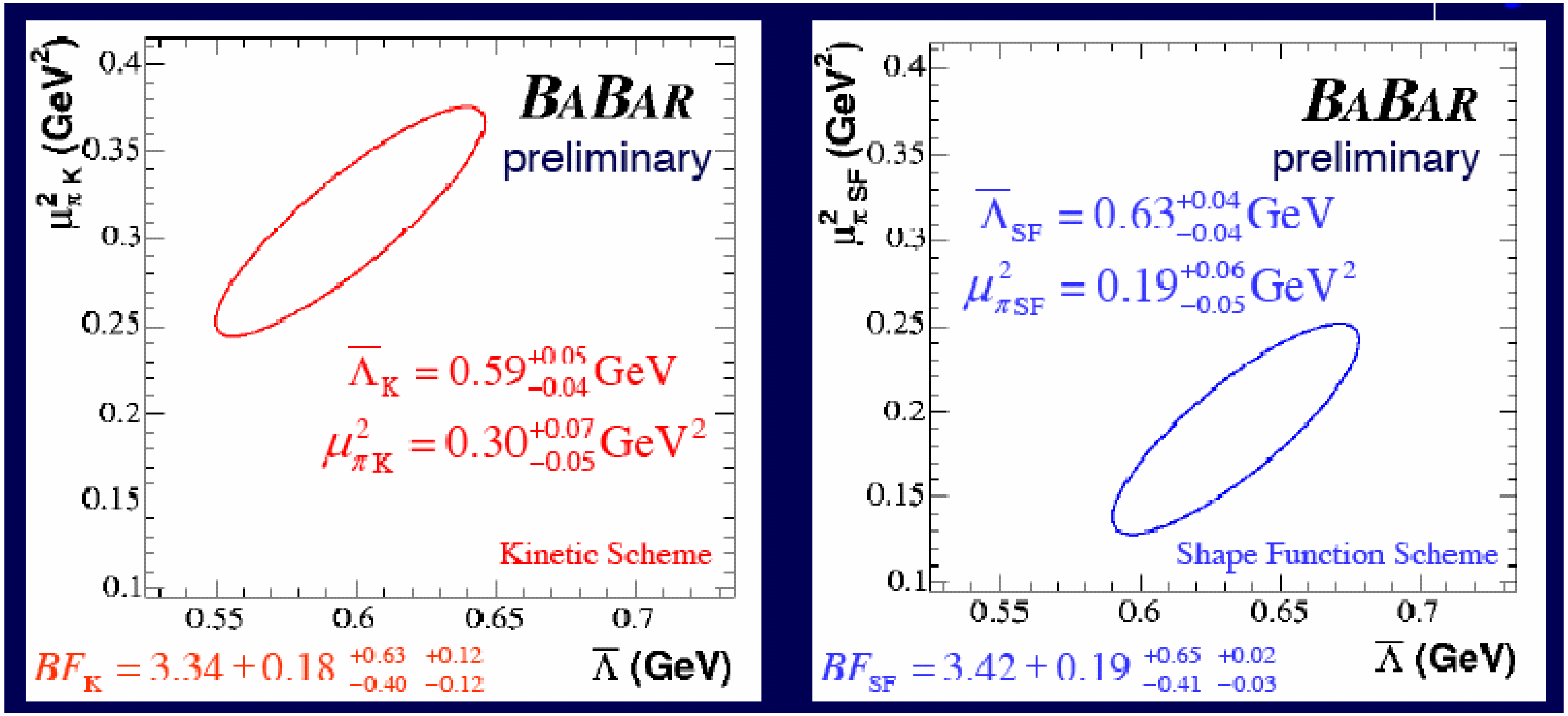
$\langle E_\gamma \rangle = m_b/2 + \ldots$ $\quad var\langle E_\gamma \rangle = \mu_\pi^2/12 + \ldots$

Importance of extending to $E_\gamma^{min} \sim 1.8$ GeV or less for the determination of both the BR AND the HQE parameters Bigi Uraltsev

Info from radiative spectrum compatible with semileptonic moments ➔ ➔

BaBar: Fit to new $b \to s$ gamma spectrum

Erkcan Ozcan



Benson-Bigi-Uraltsev

Neubert

CKM 2005, Mar. 15-18, 2005 12

The unitarity triangle

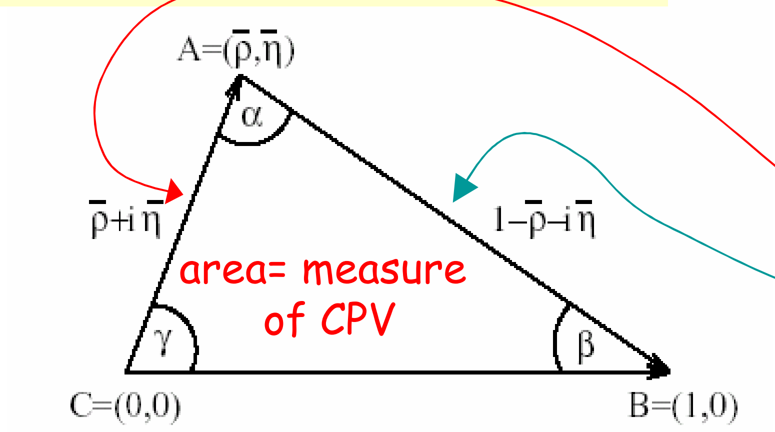
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

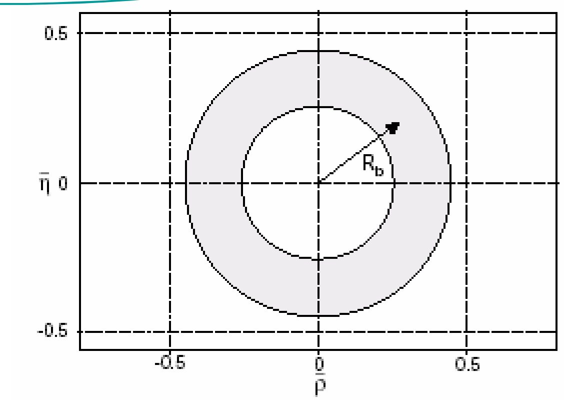
$$V_{ij} V_{jk}^{*} = \delta_{ik}$$

Unitarity determines several triangles in complex plane

$$V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0 \qquad O(\lambda^3)$$

$$1 + \frac{V_{ud} V_{ub}^{*}}{V_{cd} V_{cb}^{*}} + \frac{V_{td} V_{tb}^{*}}{V_{cd} V_{cb}^{*}} = 0$$





V_{td} cannot be accessed directly: we resort to loop transitions FCNC sensitive to new physics

$|V_{ub}|$ (not so much) inclusive

$|V_{ub}|$ from total BR($b\to ul\nu$) almost exactly like incl $|V_{cb}|$ but we need kinematic cuts to avoid the ~100x larger $b\to cl\nu$ background:

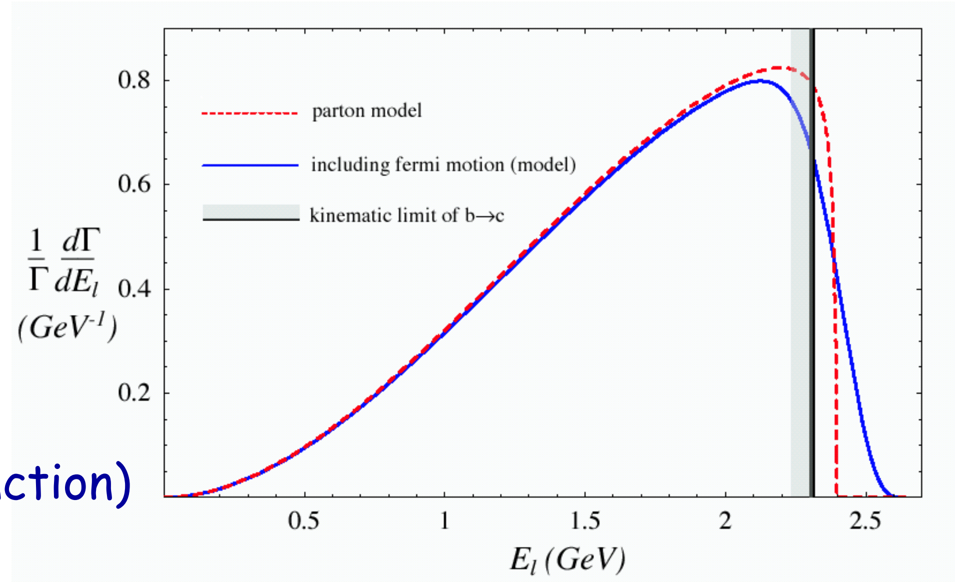
$m_X < M_D$ $\quad E_l > (M_B^2-M_D^2)/2M_B$ $\quad q^2 > (M_B-M_D)^2$

or combined (m_X,q^2) cuts

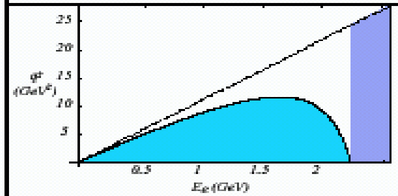
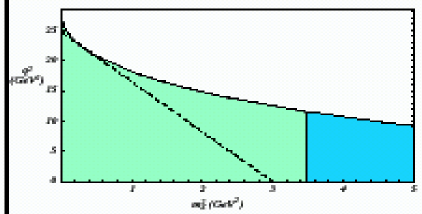
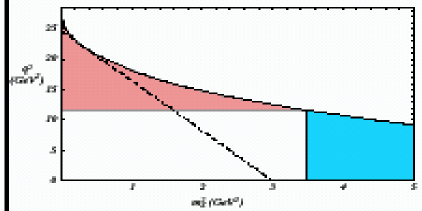
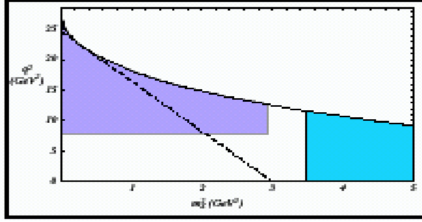
The cuts destroy convergence of the OPE, supposed to work only away from pert singularities

Rate becomes sensitive to "local" b-quark wave function properties (like Fermi motion

➔ at leading in $1/m_b$ SHAPE function)



Each strategy has pros and cons

cut	% of rate	good	bad
 $E_\ell > \frac{m_B^2 - m_D^2}{2m_B}$	~10%	don't need neutrino	- depends on $f(k^+)$ (and subleading corrections) - WA corrections may be substantial - reduced phase space - duality issues?
 $s_H < m_D^2$	~80%	lots of rate	depends on $f(k^+)$ (and subleading corrections)
 $q^2 > (m_B - m_D)^2$	~20%	insensitive to $f(k^+)$	- very sensitive to m_b - WA corrections may be substantial - effective expansion parameter is $1/m_c$
 "Optimized cut"	~45%	- insensitive to $f(k^+)$ lots of rate - can move cuts away from kinematic limits and still get small uncertainties	- sensitive to m_b (need +/- 30 MeV for 5% error)

Luke, CKM workshop 2003

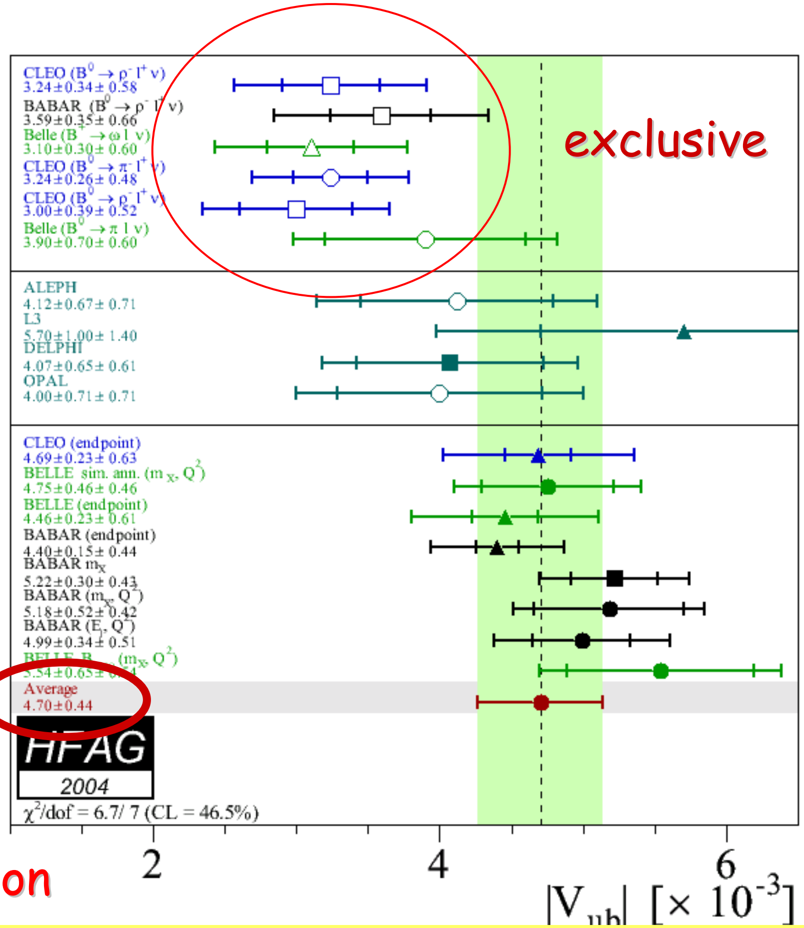
V_{ub} incl. and exclusive

Intense theoretical activity:

- ✓subleading shape functions
- ✓optimization of cuts (P_+,P_- etc)
- ✓weak annihilation contribs.
- ✓Resum. pert. effects
- ✓relation to $b \to s\gamma$ spectrum
- ✓SCET insight

A lot can be learned from exp (on WA, better constraints on s.f., subleading effects from cut dependence, $b \to s\gamma$...)

REQUIRES MANY COMPLEMENTARY MEASUREMENTS (affected by different uncert.)



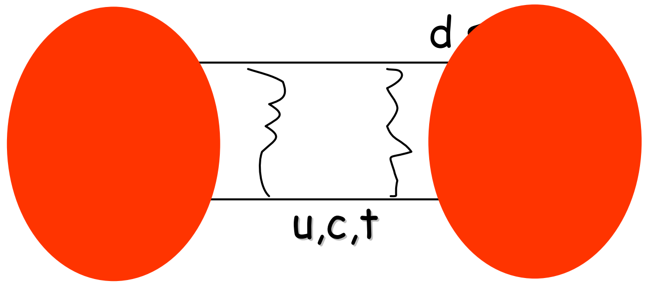
Exclusive modes: NO HQET ff normalization

LCSR and LQCD complement each other, but ~20% error. Waiting for unquenching

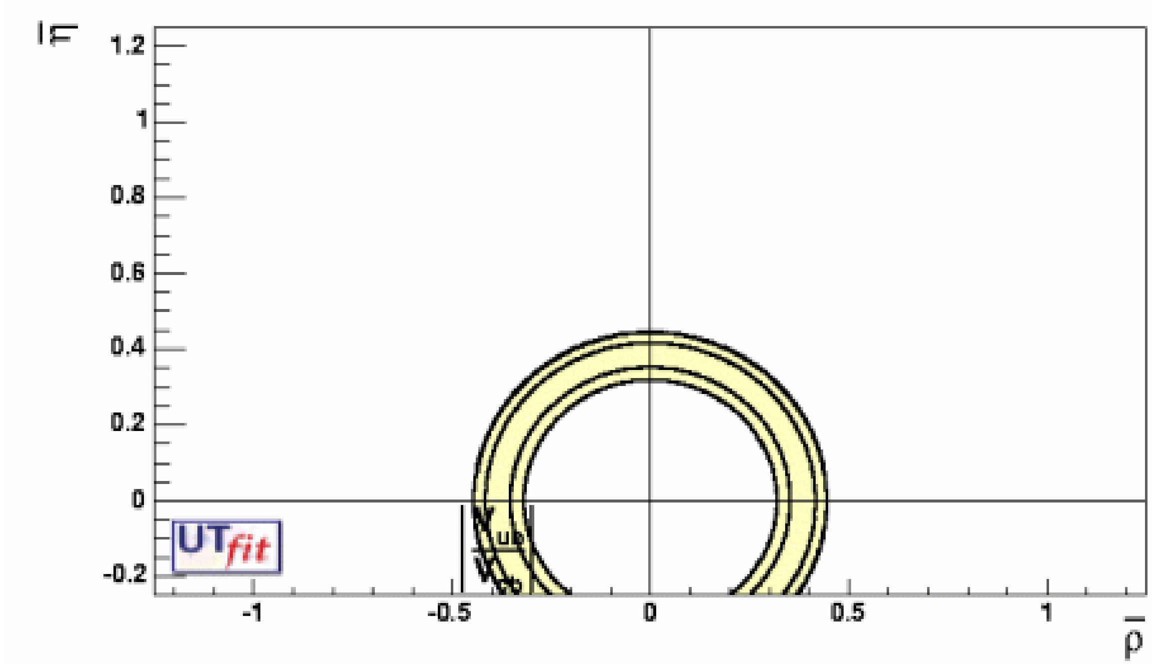
WE ARE ALREADY AT 10%
New BRECO analyses; new results soon...

Other constraints on the UT

Looking for V_{td} (and V_{ts}) through loop processes



ε_K, ΔM_d,ΔM_s: at the mercy of lattice QCD



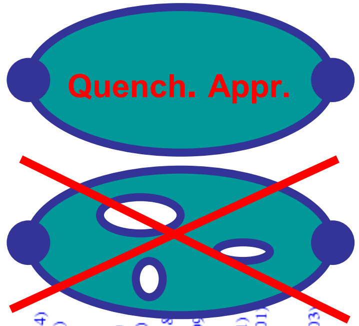
$$\langle \overline{K}^0 | Q(\Delta S = 2) | K^0 \rangle \equiv \frac{8}{3} B_K(\mu) F_K^2 M_K^2 \qquad \Delta M_q = \frac{G_F^2}{6\pi^2} \eta_B M_{B_q} (\hat{B}_{B_q} F_{B_q}^2) M_W^2 S_0(x_t) |V_{tq}|^2$$

To use ε_K and $\Delta m_{Bd,s}$ to extract CKM parameters, we need 3 quantities from lattice: $\boldsymbol{B_K}$, $\boldsymbol{B_{Bd} F^2_{Bd}}$ and

$$\xi = \frac{F_{B_s}\sqrt{\hat{B}_{B_s}}}{F_{B_d}\sqrt{\hat{B}_{B_d}}}$$

Typical errors for quenched results: 10-17%, less for ξ

Progress in LQCD



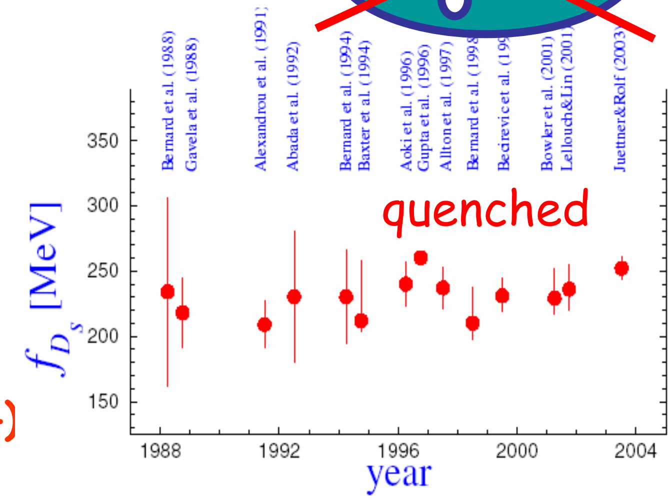
Despite folklore, **there has been progress**

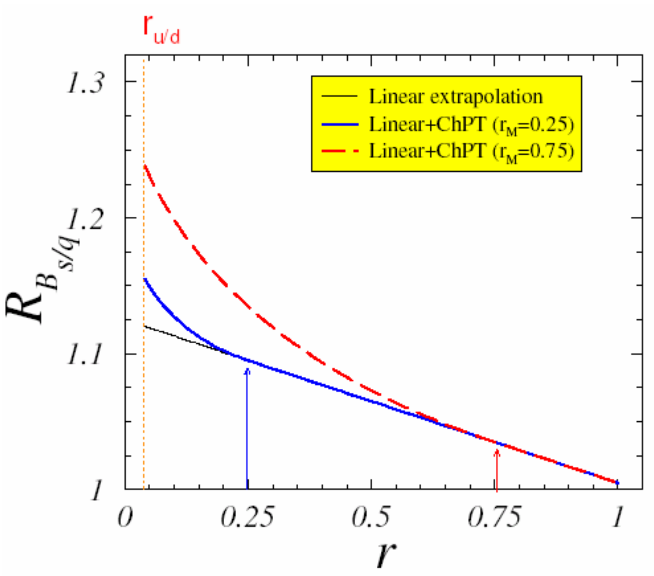
B physics simulations are *multiscale:* present lattices can resolve neither b (too heavy) nor light q (too light)

3 main sources of systematics:

- Discretization (different complementary approach)
- Chiral extrapolation (needs lighter quarks)
- Quenching (getting there: many new unquenched results)

NEW B_K=0.79(4)(9) instead of 0.86(6)(14)





Example of difficulties: ξ parameter

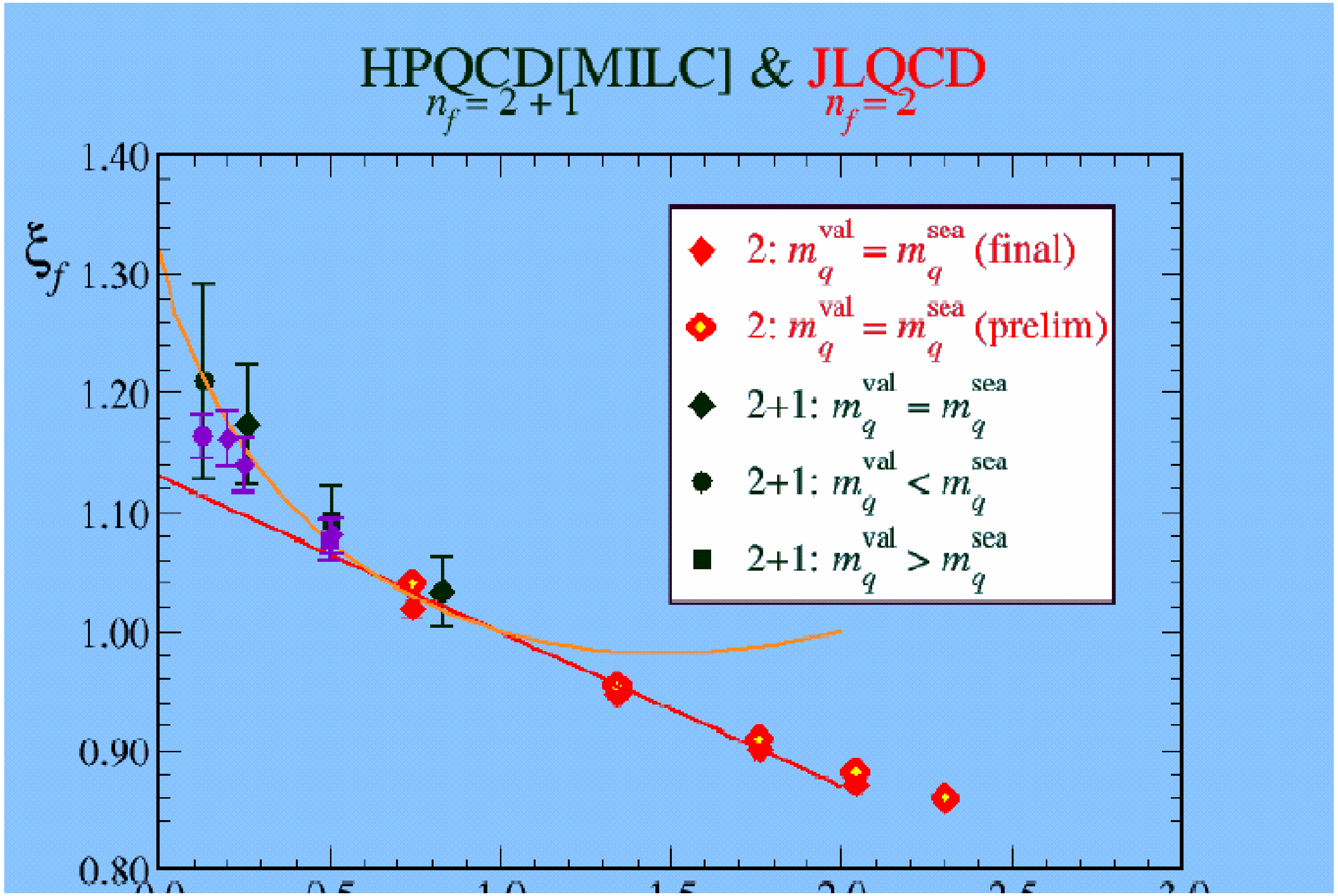
Chiral extrapolation done using ChPT
but at NLO large logs appear (+10-20%)

can we trust ChPT in regime of simulations?

(chiral logs are not observed in that range)
Waiting for lower m_q, a 10% effect maybe safe

ξ=1.18(4)($^{+12}_{-0}$) Lellouch ξ=1.21(5)(1) Becirevic

New unquenched simulations

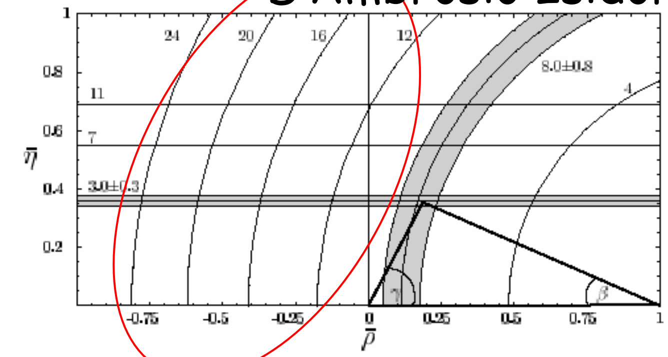


some evidence for chiral logs (Kronfeld, ckm2005)

Two alternative routes to $|V_{td}|$

- A good measurement of **BR($K^+ \to \pi^+ \nu\nu$),** $O(10^{-10})$, will provide an excellent clean determination of $|V_{td}|$.
- BR($K_L \to \pi^0 \nu\nu$)~3×10^{-11}, determines η
- Both very useful, but theory must be improved,exp is still far and prospects at NA48, CKM,JHF,KOPIO unclear

D'Ambrosio Isidori



$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (14.7^{+13.0}_{-8.9}) \cdot 10^{-11}$$

$$Br(K_L \to \pi^0 \nu\bar{\nu}) < 5.9 \times 10^{-7},$$

$B \to \rho\gamma / B \to K^*\gamma$ can give a determination of V_{td}/V_{ts}

New Belle result (first observation of $b \to d$) :

BR($B \to (\rho,\omega)\ \gamma$)=$(1.8 \pm 0.6 \pm 0.1) \times 10^{-6}$ R($B \to \rho\gamma / B \to K^*\gamma$)=$(4.2 \pm 1.3)\%$

Ali et al. extract from this $0.16 < |V_{td}/V_{ts}| < 0.29$ at 1σ, in agreement with fits, but less precise. Form factors from LC sum-rules. Exploratory calculations on the lattice confirm LCSR: their improvement is essential

NEW: the UT from radiative decays

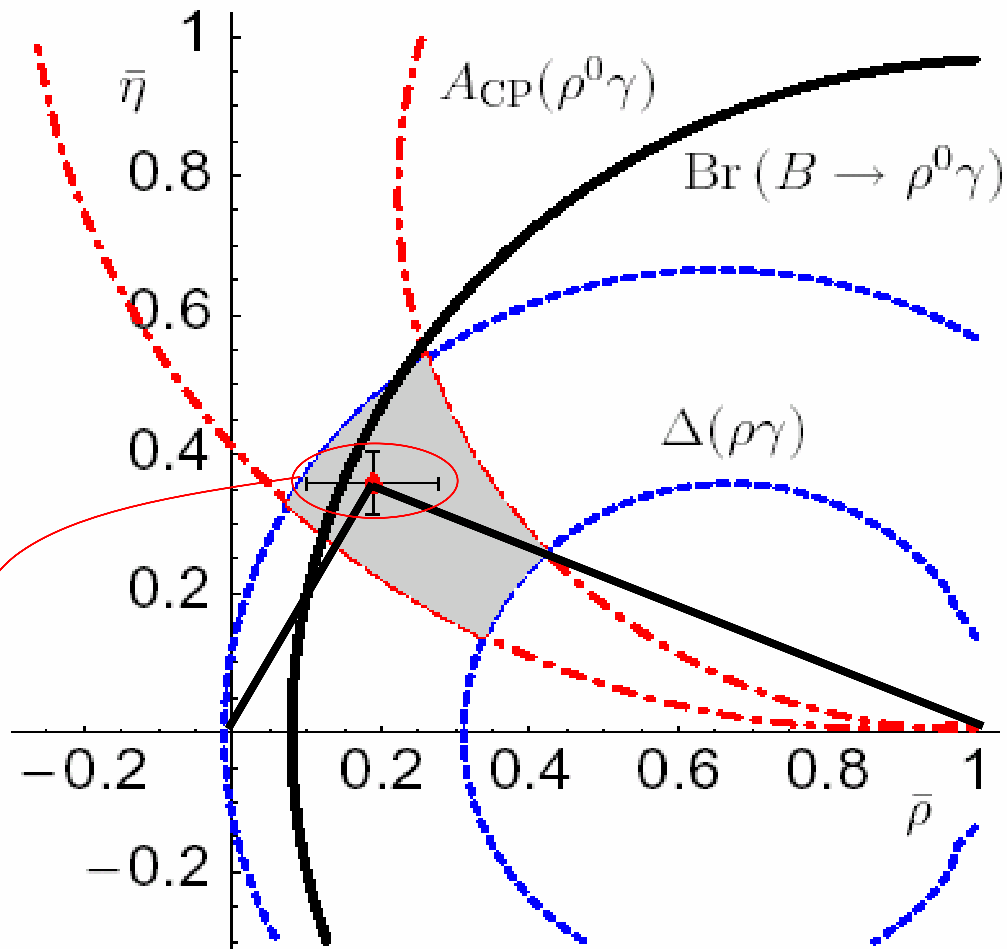
Beneke et al. (dec 2004) use QCD factorization in various exclusive radiative decays (BR, CP and isospin asymmetries) to constrain UT

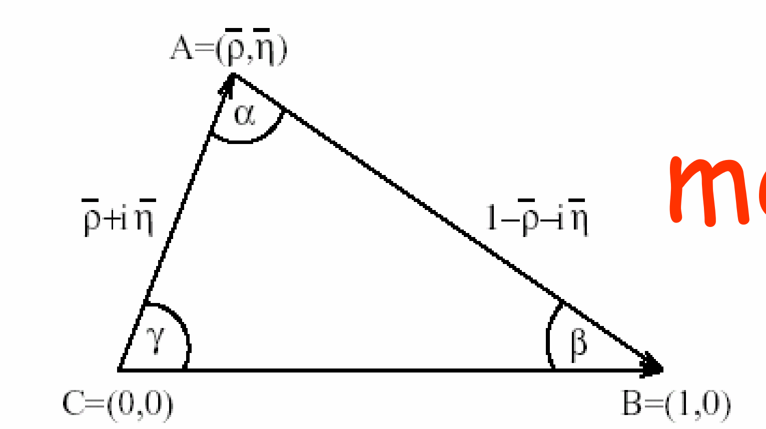
Bound on $BR(B\to\rho^0\gamma)/ BR(B\to K^*\gamma)$ gives $|V_{td}/ V_{ts}| < 0.21$, cutting into the area selected by present standard fits...

VERY PROMISING

But beware of theor. errors!

Standard UT fit

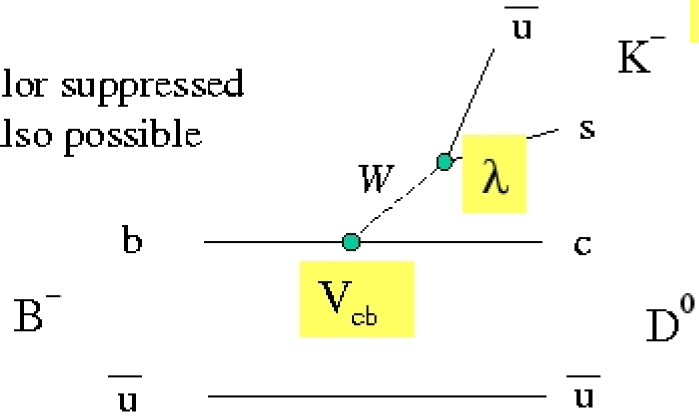


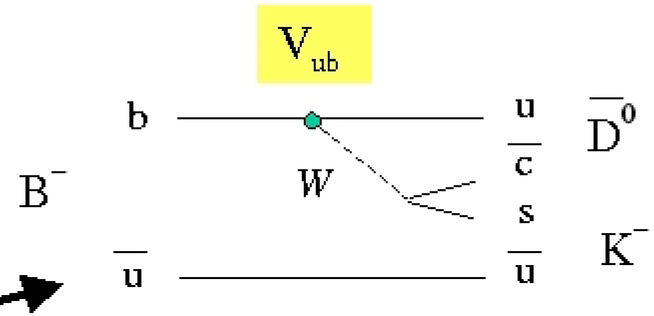


measurement of γ

PURE TREE LEVEL

Color suppressed also possible

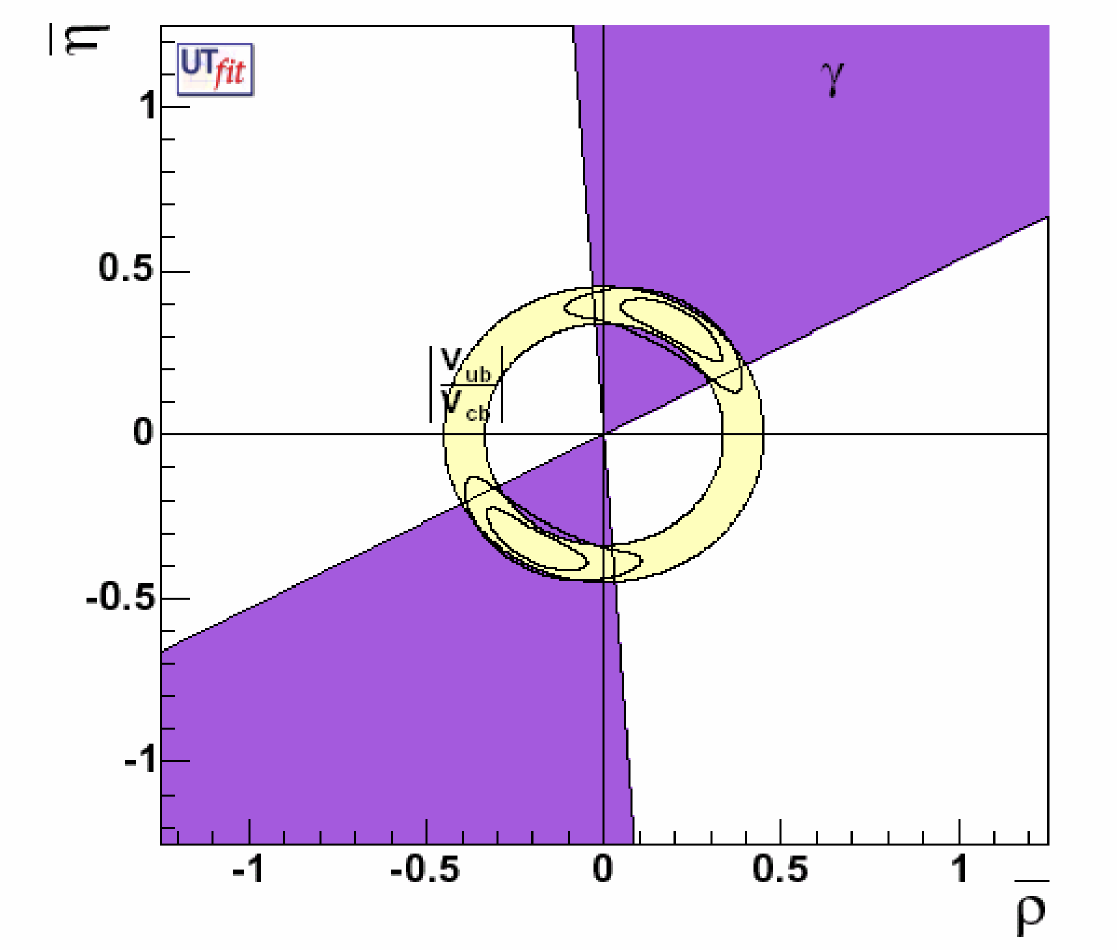




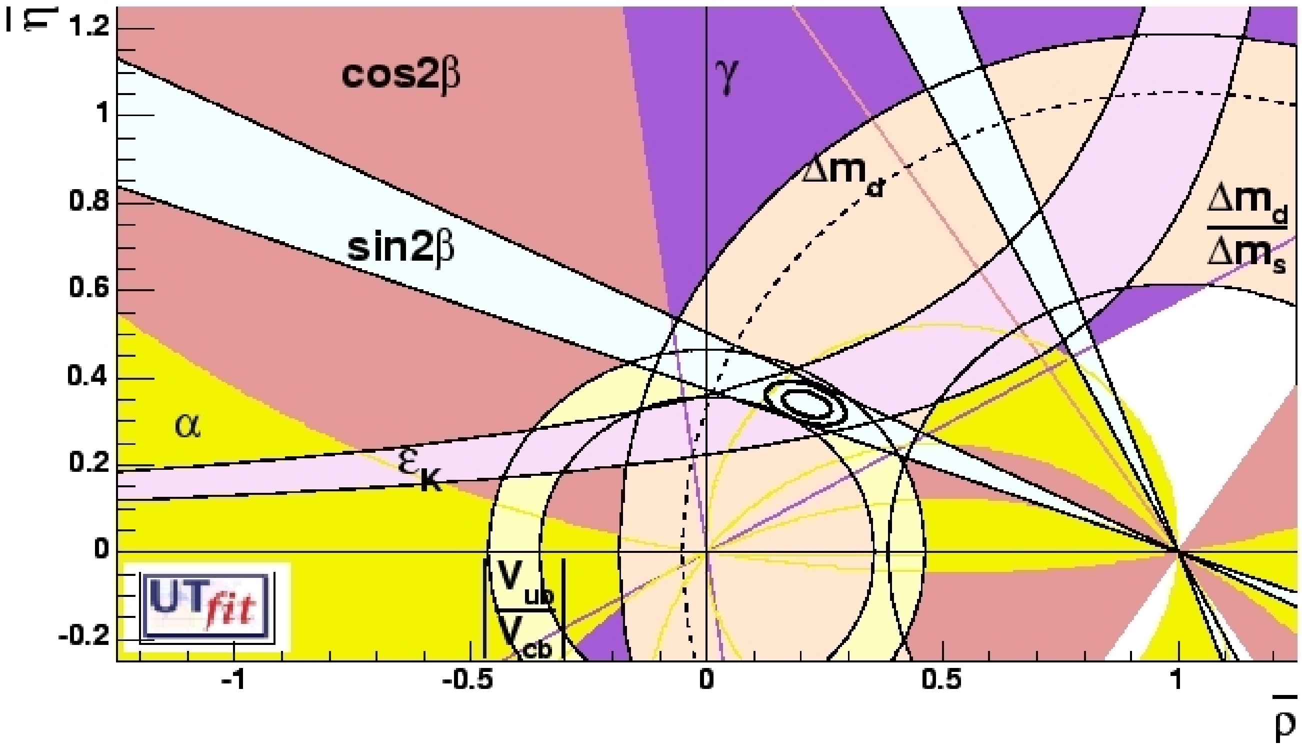
$$A_-(B^- \to f) = v_1 A_1 e^{i\alpha_1} + v_2 A_2 e^{i\alpha_2} \quad , \quad A_+(B^+ \to \overline{f}) = v_1^* A_1 e^{i\alpha_1} + v_2^* A_2 e^{i\alpha_2}$$

Various strategies:
the most effective is Dalitz plot analysis of D->3 body final states

Strictly tree level



Global fit results

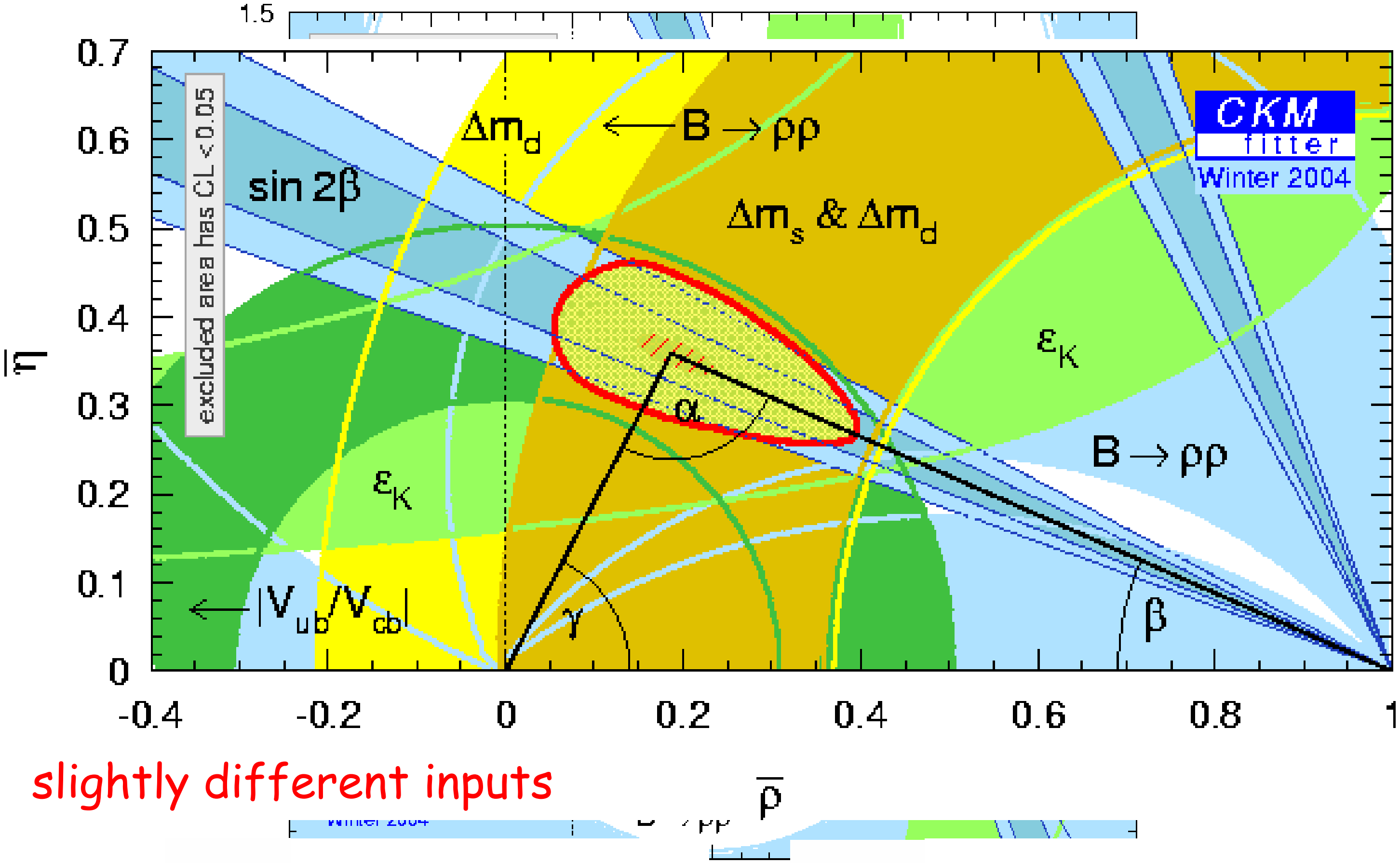


$\bar{\rho} = 0.210 \pm 0.035$

$\bar{\eta} = 0.339 \pm 0.021$

http://www.utfit.org

Global fit results (II)



slightly different inputs

$\bar{\rho}$ = 0.207±0.040 $\bar{\eta}$ =0.339±0.024

http://ckmfitter.in2p3.fr

Fitting methods: a matter of taste

Differ in treatment of theory error. Two main groups:

Bayesian (UTfit)

Non gaussian errors (th & exp) are assigned a flat pdf, to be convoluted with gaussian pdfs

Pro: conceptually clean, easy for Δm_s.

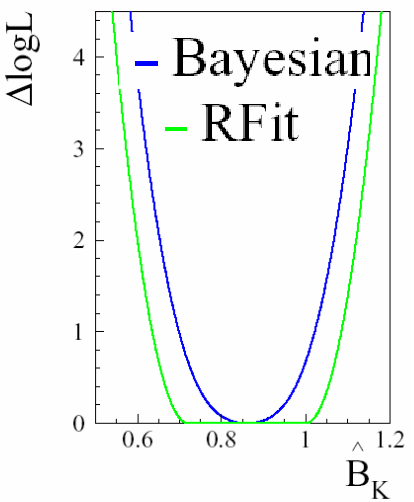
Con: does not provide a χ^2 test

Rfit (CKMfitter)

Non gaussian parameters have flat likelihood, not pdf

Pro: more conservative (beware of theorists guessing errors!)

Con: CL is *at least* x%



Parameters	68% range	95% range
$\hat{B}_K$ *R*fit (Bayes) [ratio R/B]	0.68-1.06 (0.76-0.98) [1.70]	0.62-1.12 (0.67-1.06) [1.25]

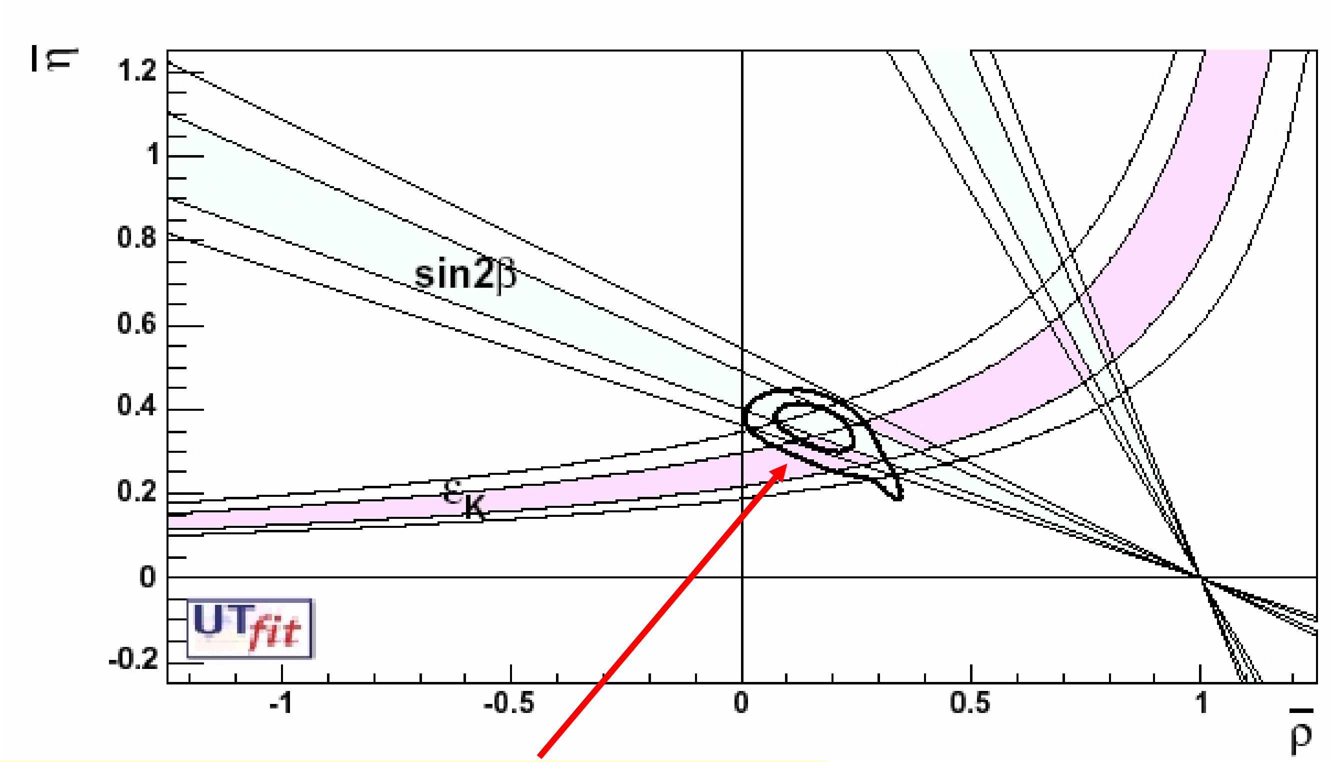
Difference important especially when theory (non-gaussian) error dominates. The 99% CL ranges of global fit are quite similar with SAME INPUTS.

see CKM Yellow book

Ratio *R*fit/Bayesian Method			
Parameter	5% CL	1% CL	0.1% CL
[illegible]	[illegible]	[illegible]	[illegible]
γ°	1.46	1.31	1.09

DO NOT TAKE 1σ RANGES TOO SERIOUSLY

CP violation in the B and K sectors

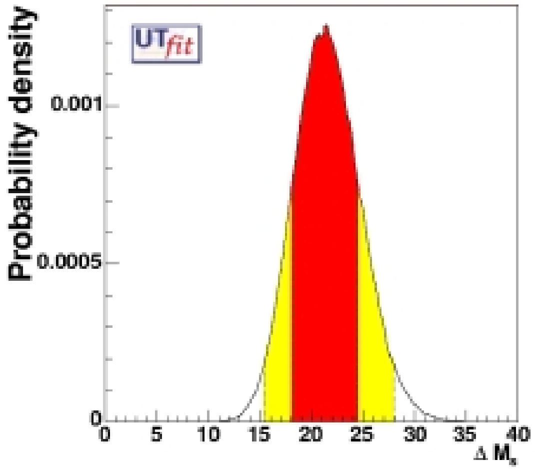


Using only the sides of the UT (CP conserving)

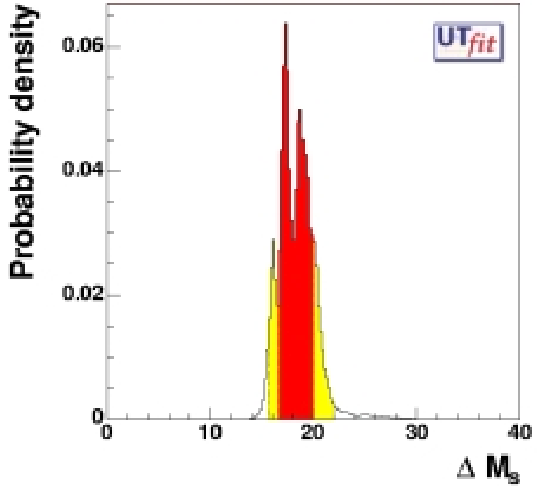
$\text{Sin2}\beta_{UT}$ = 0.725 ± 0.043
(without direct meas.)

$\text{Sin2}\beta_{J/\psi\ Ks}$ = 0.726 ± 0.037

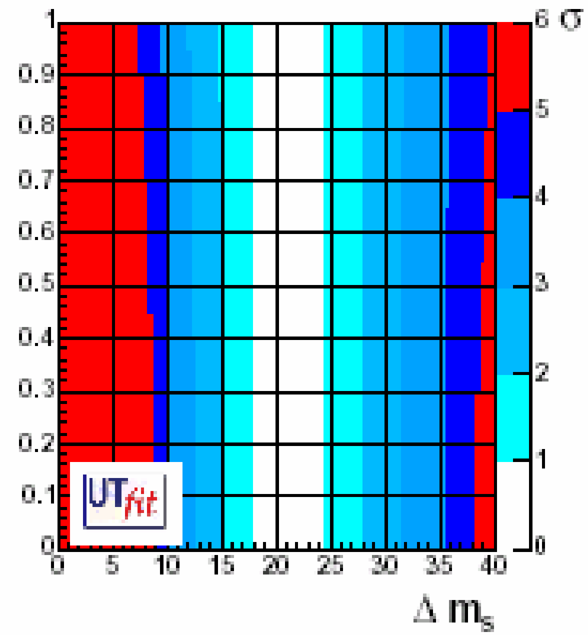
Prediction of Δm_s



$\Delta m_s = 21.2 \pm 3.2\ ps^{-1}$
(Δm_s not used)



$\Delta m_s = 18.9 \pm 1.7\ ps^{-1}$
(with all constraints)



$\Delta m_s >$ 30 ➔ new physics at 3σ

DIRECT MEASUREMENT:
$\Delta m_s > 14.5$ @ 95 % C.L.

In the absence of new physics Tevatron should measure it soon

Prediction of γ and α

$$\gamma = (58.1 \pm 5.0)^\circ$$

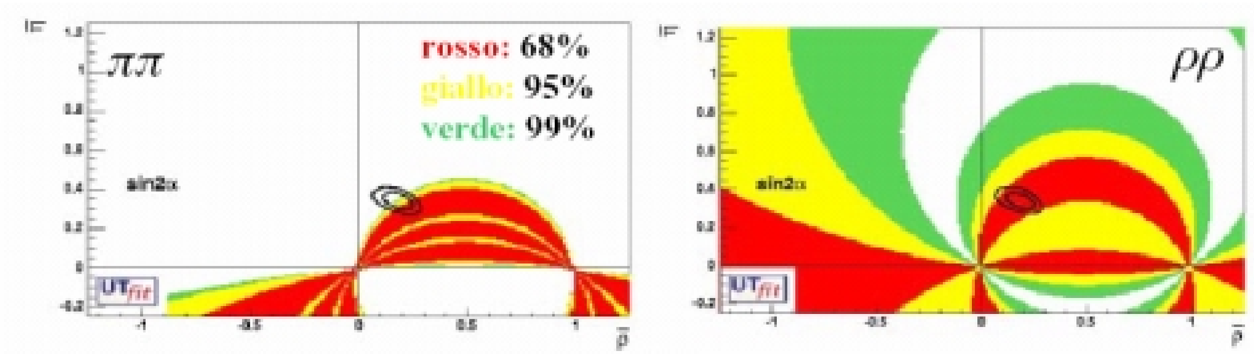
At 95%CL [48.6-68.6]

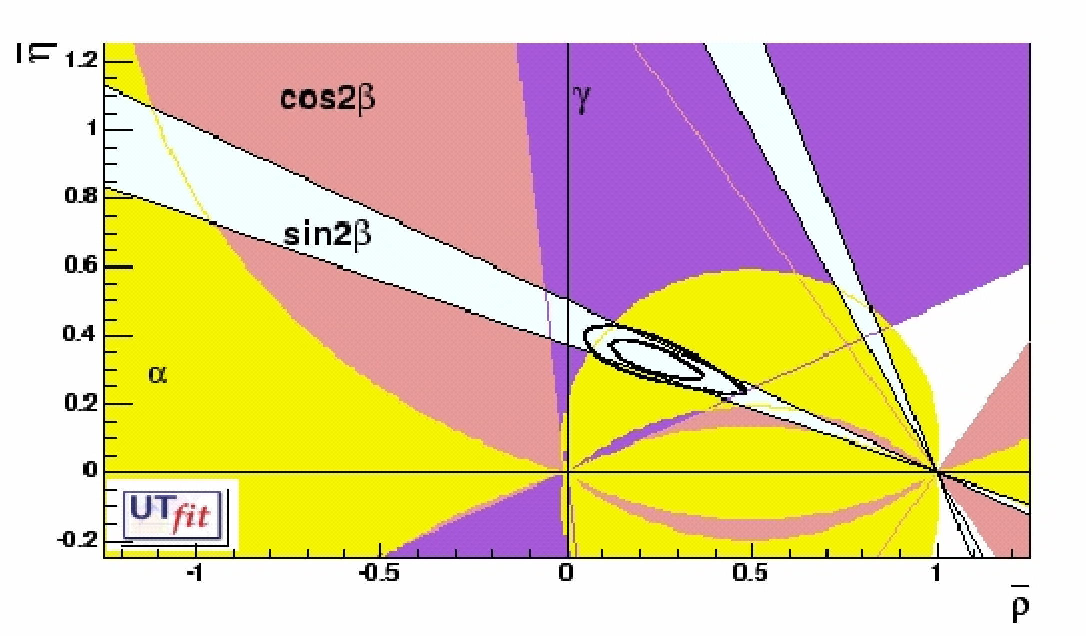
$$\sin 2\alpha = -0.29 \pm 0.17$$

$$\gamma = (57.5 \pm^{8.7}_{6.8})^\circ$$

$$\sin 2\alpha = -0.29 \pm^{0.46}_{0.56}$$

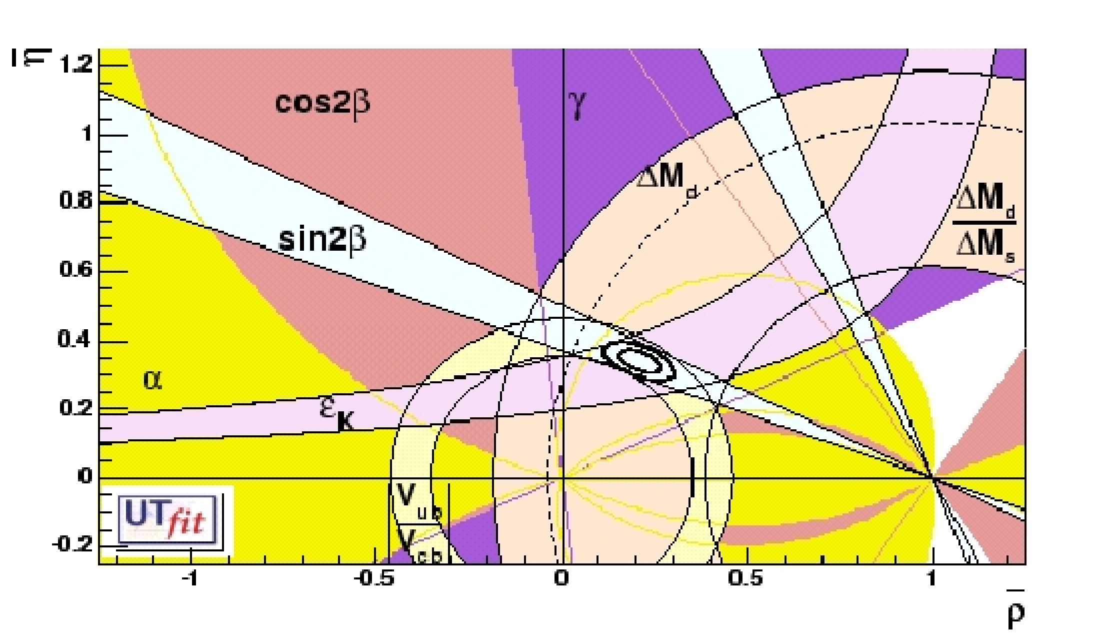
direct determinations sin2α





ONLY ANGLES

ALL (reliable) DATA
angle measurements
start being noticed



The near (unquenched) future?

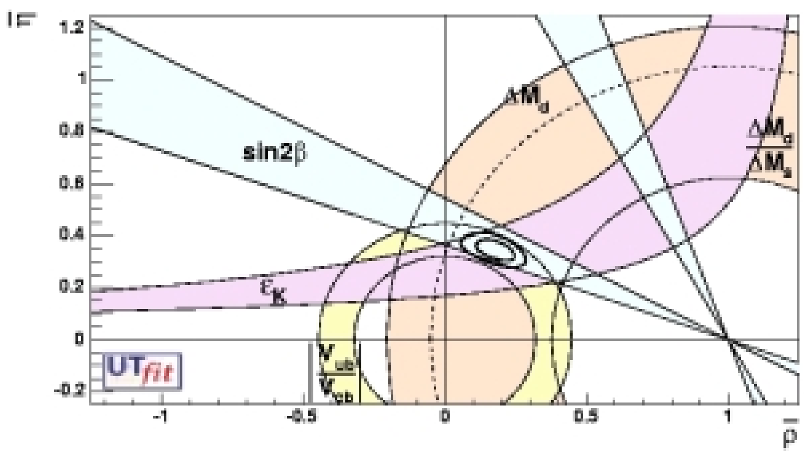
$B_K = 0.79 \pm 0.06 \pm$ ~~0.09~~

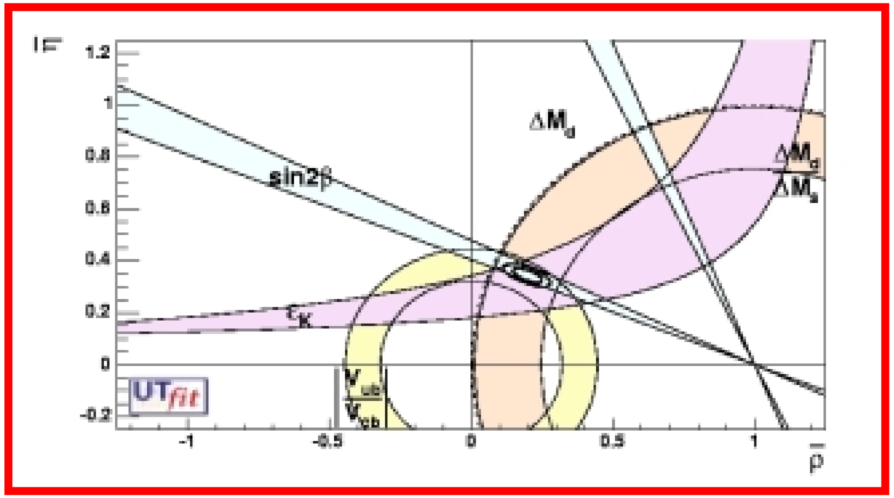
$f_{Bs}\sqrt{B_{Bs}} = 276 \pm 38$ MeV → 14

$\xi = 1.24 \pm 0.04 \pm$ ~~0.06~~

$\sin 2\beta = 0.734 \pm 0.054$ → 21

A direct measmnt of Δm_s and improvement on V_{ub} will also have a significant effect





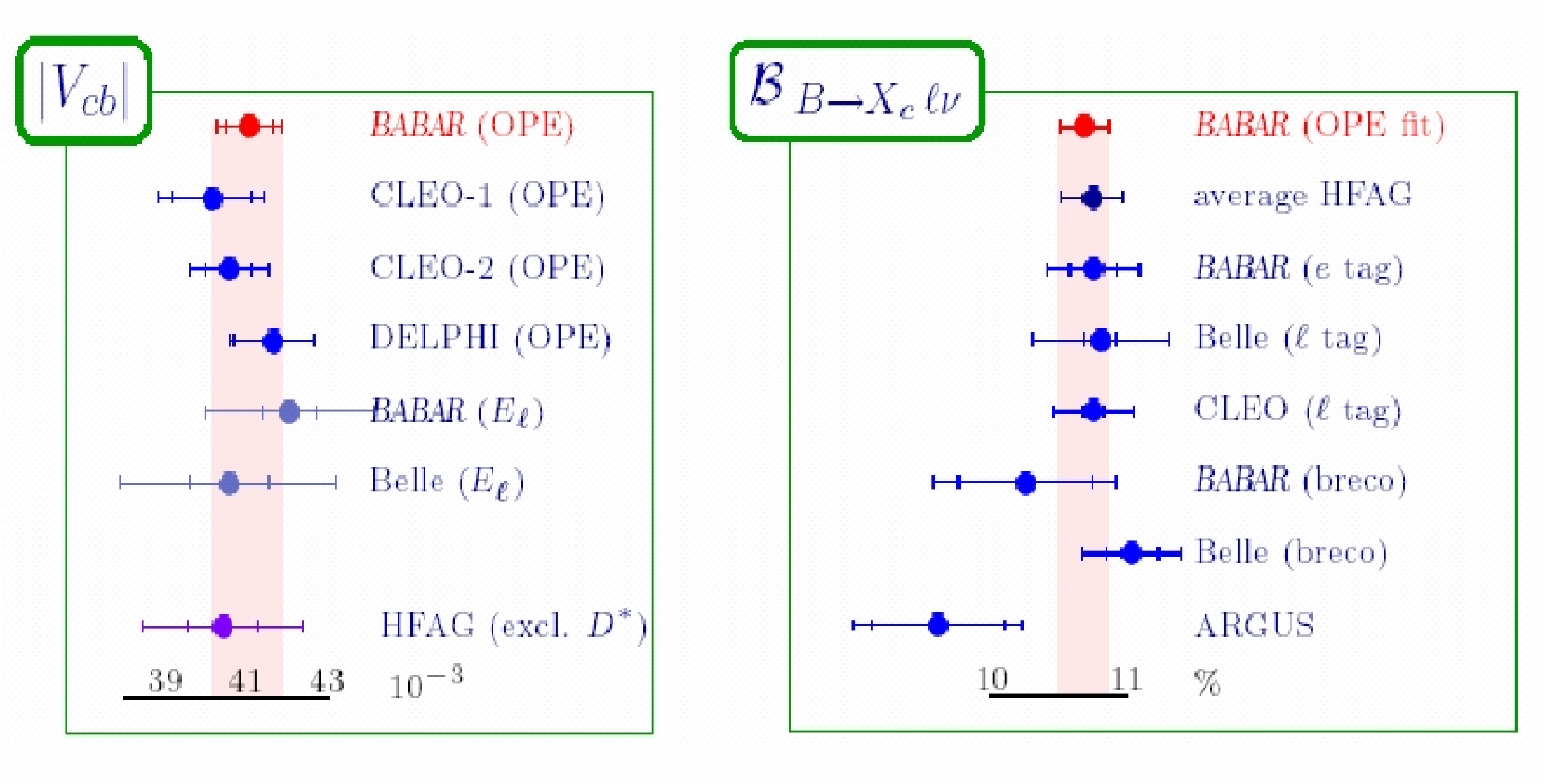
$\Delta\rho$ = 24% → 15% $\Delta\eta$ = 7% → 4.6%

Summary

- CKM describes well a host of data. Present errors are dominantly theoretical: LQCD best hope, but theory control can be improved by exploiting new data at B-Factories,Cleo-c,Tevatron..
- First row universality problem resolved by new K_{l3} data
- $|V_{cb}|$ inclusive/momnts analyses: duality verified at % level, V_{cb} at 1.5%, better determination of non-pert B parameters
- Progress in LQCD is slow but sure: learning to unquench etc
- **Excellent agreement so far with direct angle measurmnt**
  (pending scrutiny of $B \to \Phi K_S$)

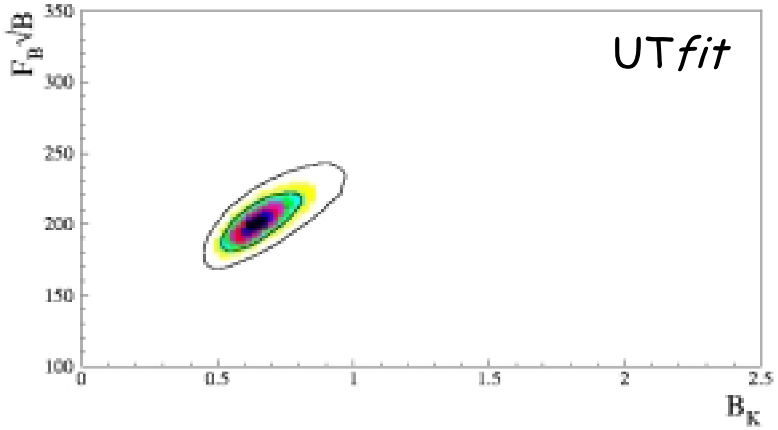
...nevertheless, still room for new physics
(we have tested only a few FCNC)

A dramatic step forward...



A real advance: non-pert parameters are everywhere in B physics

Fitting non-pert parameters



	LATTICE QCD	UT FIT
$f_B\sqrt{B_B}$	$223 \pm 33 \pm 12$ MeV	257 ± 15 MeV
B_K	$0.86 \pm 0.06 \pm 0.14$	0.68 ± 0.10

Fit Results

$$|V_{cb}| = (41.4 \pm 0.4_{\exp} \pm 0.4_{\rm HQE} \pm 0.2_{\alpha_s} \pm 0.6_{\Gamma_{\rm SL}}) \times 10^{-3}$$

$$Br(B \to X_c e \nu) = (10.61 \pm 0.16_{\exp} \pm 0.06_{\rm HQE})\%$$

kinetic mass scheme

$$m_b(1\,GeV) = (4.61 \pm 0.05_{\exp} \pm 0.04_{\rm HQE} \pm 0.02_{\alpha_s})\,GeV$$

$$m_c(1\,GeV) = (1.18 \pm 0.07_{\exp} \pm 0.06_{\rm HQE} \pm 0.02_{\alpha_s})\,GeV$$

$$\mu_\pi^2 = (0.45 \pm 0.04_{\exp} \pm 0.04_{\rm HQE} \pm 0.01_{\alpha_s})\,GeV^2$$

$$\mu_G^2 = (0.27 \pm 0.06_{\exp} \pm 0.03_{\rm HQE} \pm 0.02_{\alpha_s})\,GeV^2$$

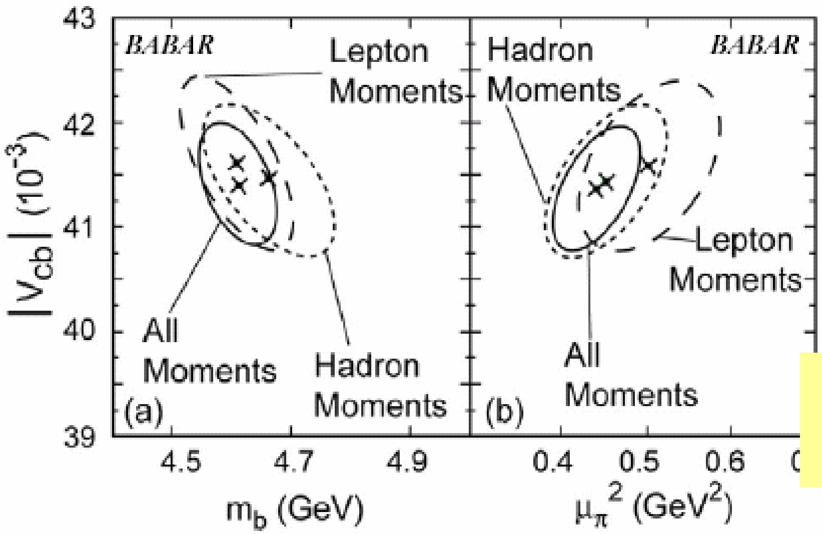
$$\rho_D^3 = (0.20 \pm 0.02_{\exp} \pm 0.02_{\rm HQE} \pm 0.00_{\alpha_s})\,GeV^3$$

$$\rho_{LS}^3 = (-0.09 \pm 0.04_{\exp} \pm 0.07_{\rm HQE} \pm 0.01_{\alpha_s})\,GeV^3$$

Kinetic scheme:
Small pert corrections
Minimal set of parmts
No $1/m_c$ expansion
Uraltsev & PG

Strong correlation between m_b and m_c:

$m_b(1\ \text{GeV}) - m_c(1\ \text{GeV}) = (3.44 \pm 0.03_{\exp} \pm 0.02_{\rm HQE} \pm 0.01_{\alpha_s})$ GeV



2D projections of the fit result:

$\Delta\chi^2 = 1$ ellipses

No sign of deterioration for higher cuts