CKM Status & Prospects

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Physics In Collision, June 29, 2001

- **CKM Basics**
- **Experimental Status – *b* emphasis**
  - CPV, B_d & B_s mixing, $b \rightarrow cl\nu$, $b \rightarrow ul\nu$
  - Novel approach to V_{cb}
- **Global fitting**
- **CKM, QCD, & CLEO-c**
- **Prospects**

Cabibbo-Kobayashi-Maskawa Quark Mixing

- **Lagrangian (weak charged current) :**

$$L_W = -\frac{g}{\sqrt{2}} \bar{u}_{Li} \gamma^{\mu} V_{ij} \bar{d}_{Lj} W_{\mu}^{+} + h.c.$$

- V_{CKM}: 3×3, UNITARY ($V^{\dagger}V = I$)
- Each V_{ij} has a real part + imag phase

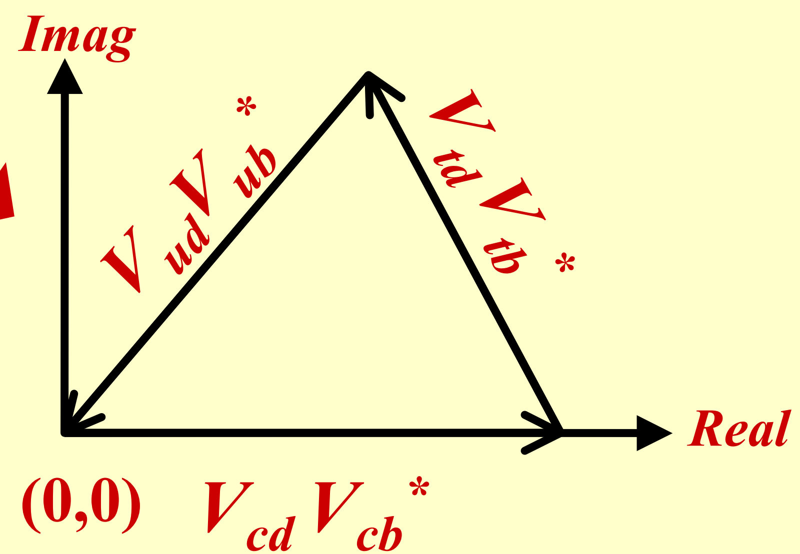
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$\not{CP} \Leftrightarrow$ 3 gen's &
$\geq$1 imag phase $\neq 0$

The Unitarity Triangle(s) (UT)

- The sum for each 0 in I is a triangle in the real-complex plane
- Phase convention: $(V_{cd}V_{cb}^{*})$ is real

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



$$V_{ud}V_{us}^{*} + V_{cd}V_{cs}^{*} + V_{td}V_{ts}^{*} = 0$$

$$V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0$$

...

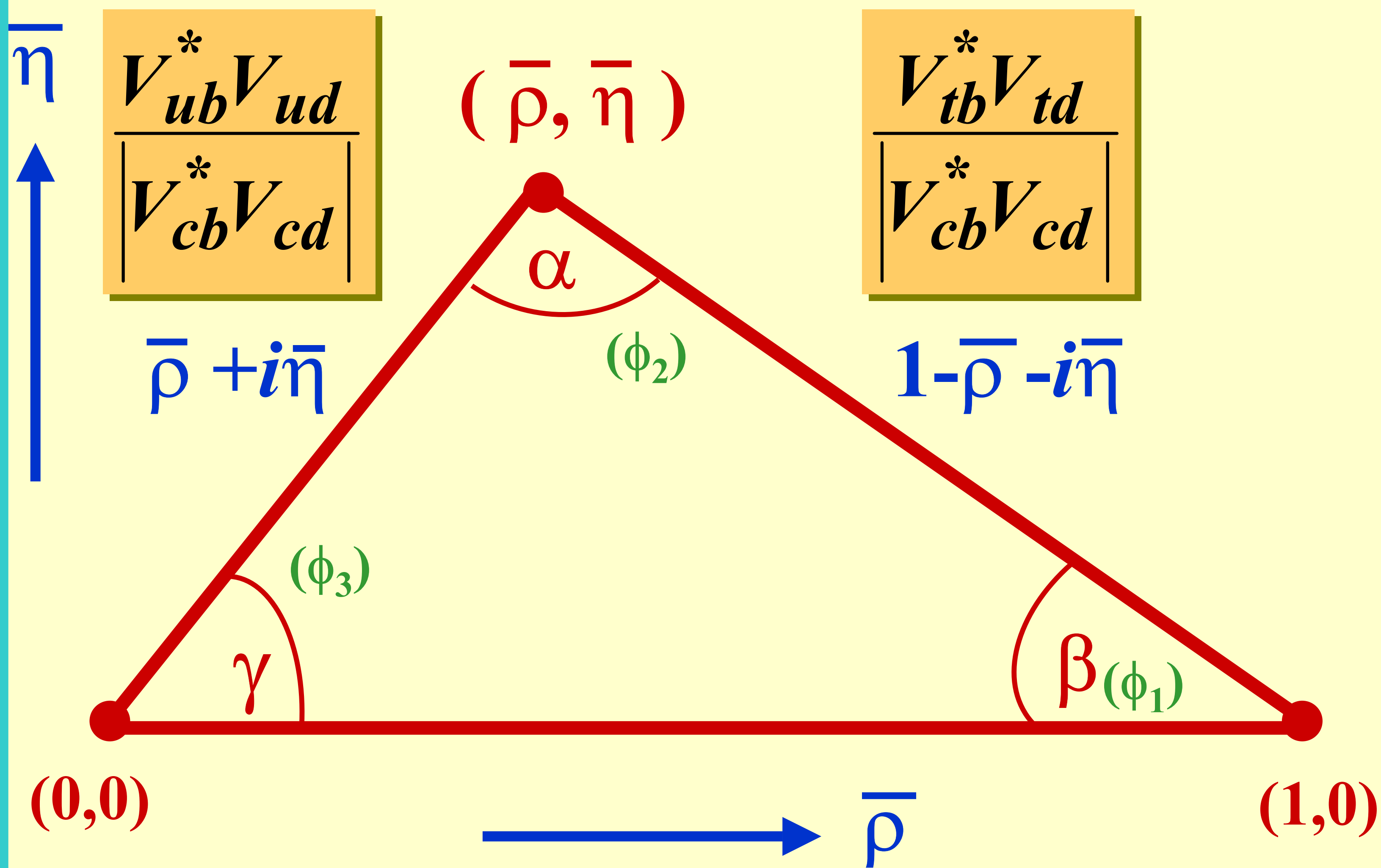
CKM parameterizations

- **Wolfenstein (original). Expand in λ^2, with $\lambda = \sin\theta_C = 0.22$.**
- **To $O(\lambda^4) \sim 10^{-3}$:**
- **Buras: slight changes attain $O(\lambda^6) \sim 10^{-4}$**
- **$\lambda, A, \bar{\rho}, \bar{\eta}$**
- **J= triangle area $\propto$ CPV**

$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda-iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2-iA\lambda^4\eta & 1 \end{pmatrix}$$

$$\bar{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right), \quad \bar{\eta} = \eta\left(1-\frac{\lambda^2}{2}\right)$$

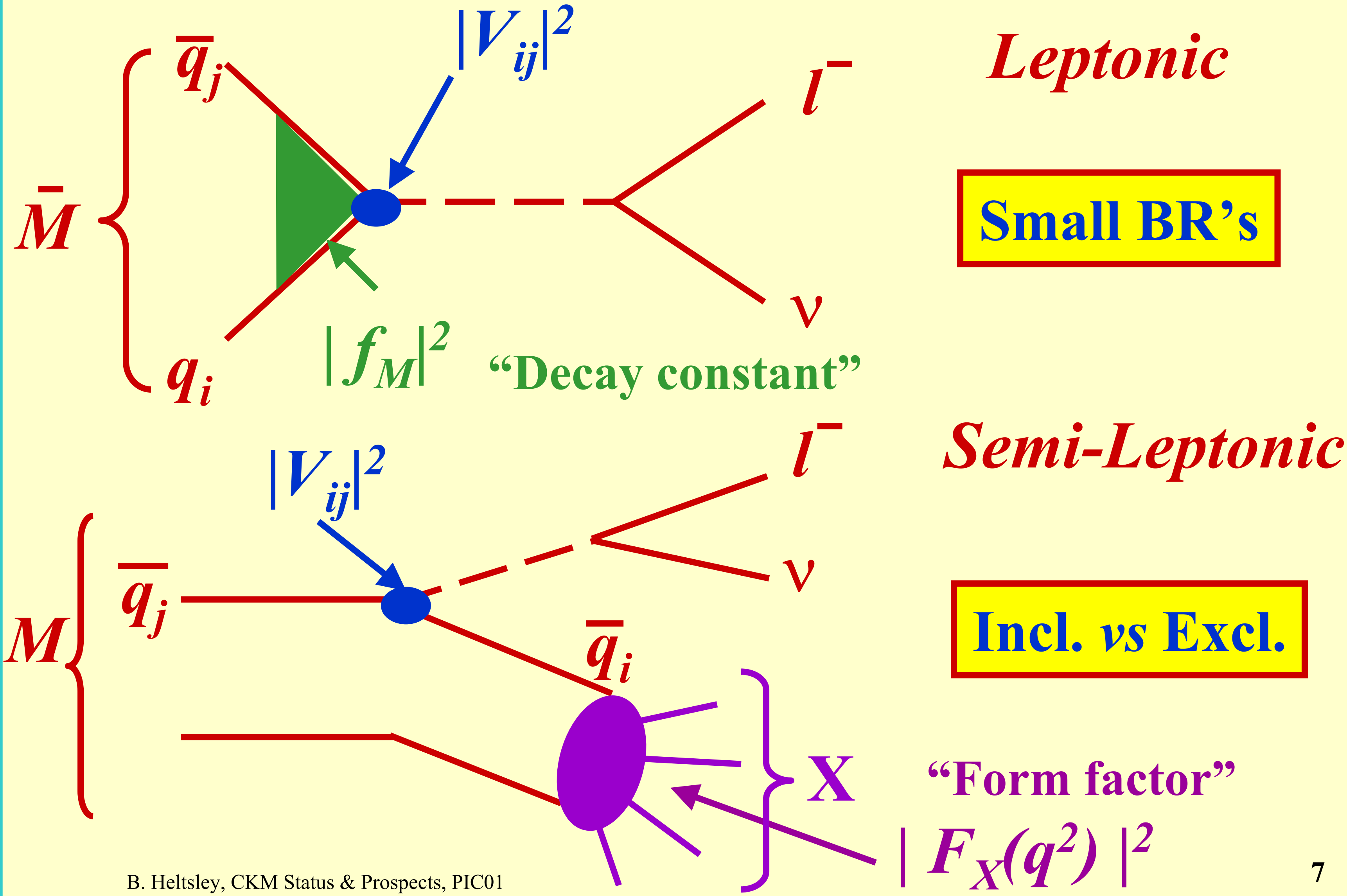
SM Unitarity Triangle



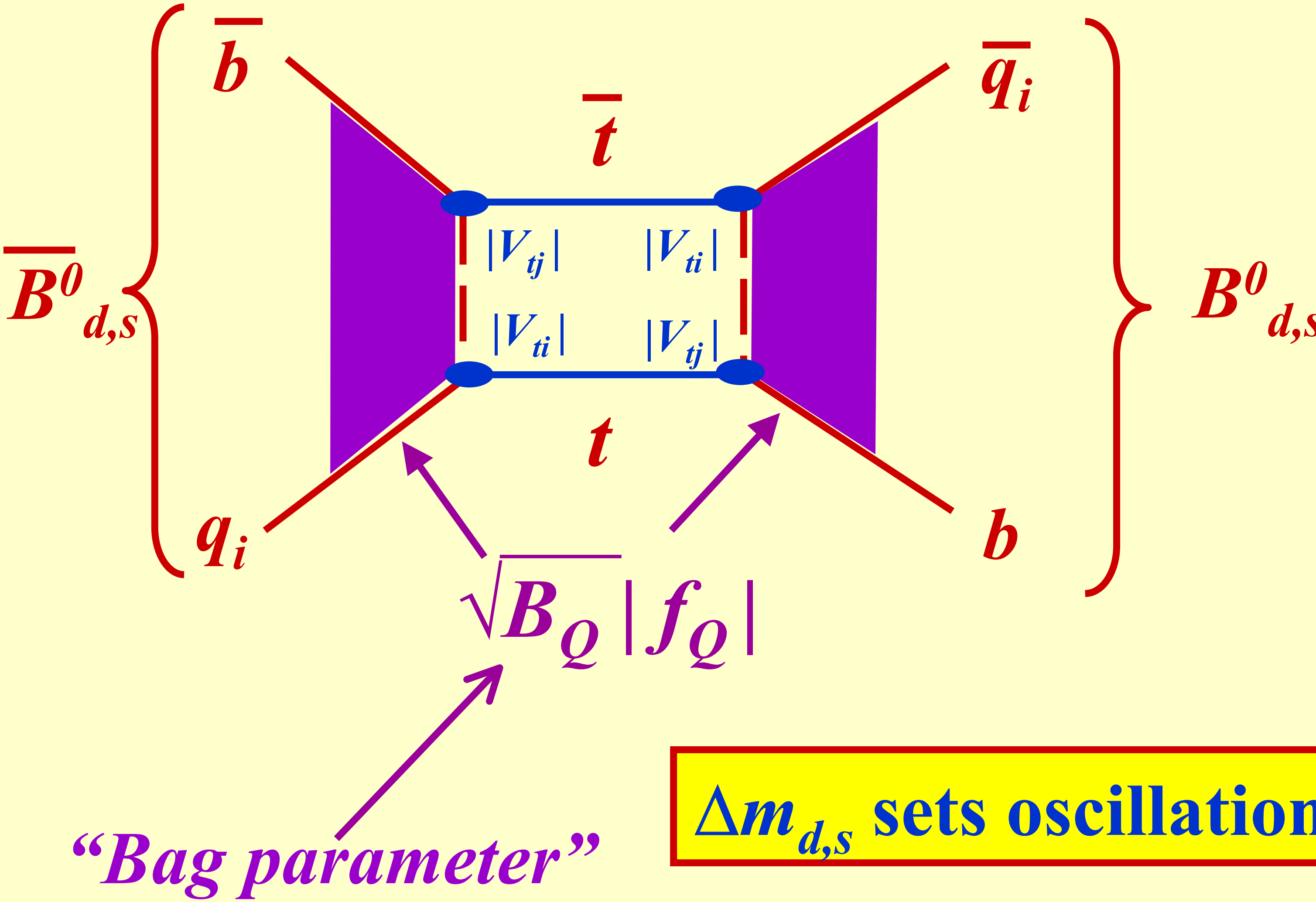
Just 4 parameters?!

- Just four parameters: λ, A, $\bar{\rho}$, $\bar{\eta}$
- Measure them as fundamental constants of nature – "metrology"
  - Now, semi-leptonic decays & mixing provide best access
- With a rich diversity of quark decays, can overconstrain them – "global fit" to data
- Inconsistencies seen at any level means **New Physics** outside SM
- BUT, hadrons, not *q*'s, are detected

CKM⇔QCD in (Semi)Leptonic Decay



CKM ⇔ QCD in B_d, B_s Mixing



$\Delta m_{d,s}$ sets oscillation rate

~ | V_{ij} | (accuracy) [*=assumes Unitarity]

ud: β-decay 0.1% 0.9739 ± 0.0009	*us*: $K\to\pi e\nu$ 1.1% 0.2200±0.0025	*ub*: $b\to ul\nu$ & 17% $B\to\pi(\rho)l\nu$ 0.0035± 0.0006
cd: $\nu d\to lc\to llX$ 6% 0.224 ± 0.014	*cs*: $D\to Ke\nu$, 6% $W\to X_c X$ 0.97 ± 0.06	*cb*: $b\to cl\nu$, 7% $B\to Dl\nu$ 0.041 ± 0.003
td: B_d mixing 19% $D_s\to\mu\nu$ 0.0083 ± 0.0016	*ts*: B_s mixing 25%* 0.04 ± 0.01 *	*tb*: $t\to bl\nu$ 15%* 0.99 ± 0.15 *

Experiment ⇔ Theory

CP-violating parameter from K decay:

$$\varepsilon_K = C_\varepsilon B_K \lambda^6 \ \bar{\eta}\ [C_1 A^2 \lambda^4 (1-\bar{\rho}) + C_2 + C_3] \Rightarrow \textit{hyperbola}$$

(b→u lν) /(b →c lν)

$$|V_{ub} / V_{cb}|^2 = \lambda^2 (\rho^2 + \eta^2) \Rightarrow \textit{circle} \ @ \ (0,0)$$

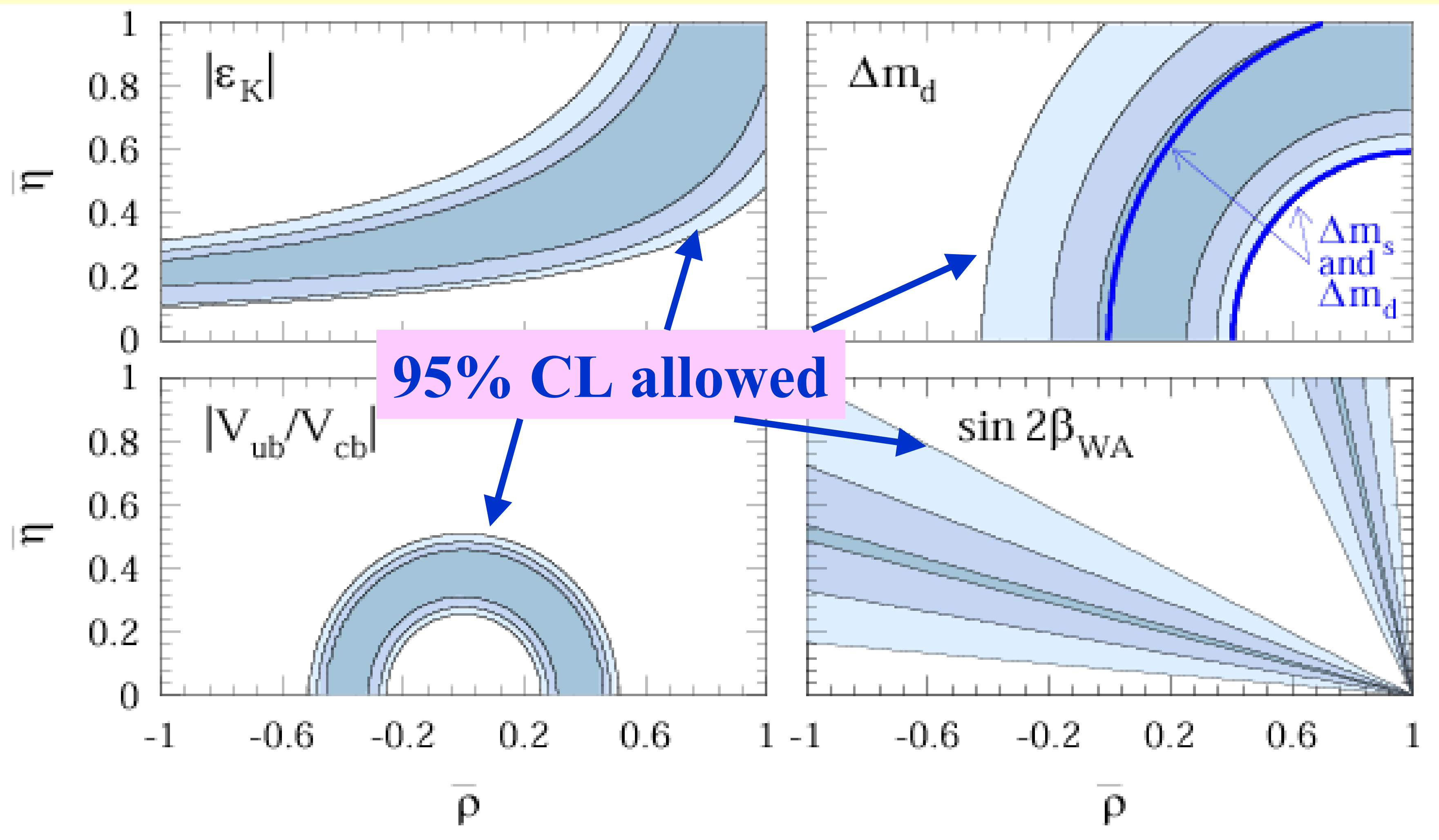
B_d-mixing frequency = mass difference

$$\Delta m_d = C_d B_d f_{B_d}^2 A^2 \lambda^6 [(1-\bar{\rho})^2 + \bar{\eta}^2] \Rightarrow \textit{circle}@(1,0)$$

B_s-mixing frequency: $\Delta m_s \propto B_s f_{B_s}^2 A^2 \lambda^4$

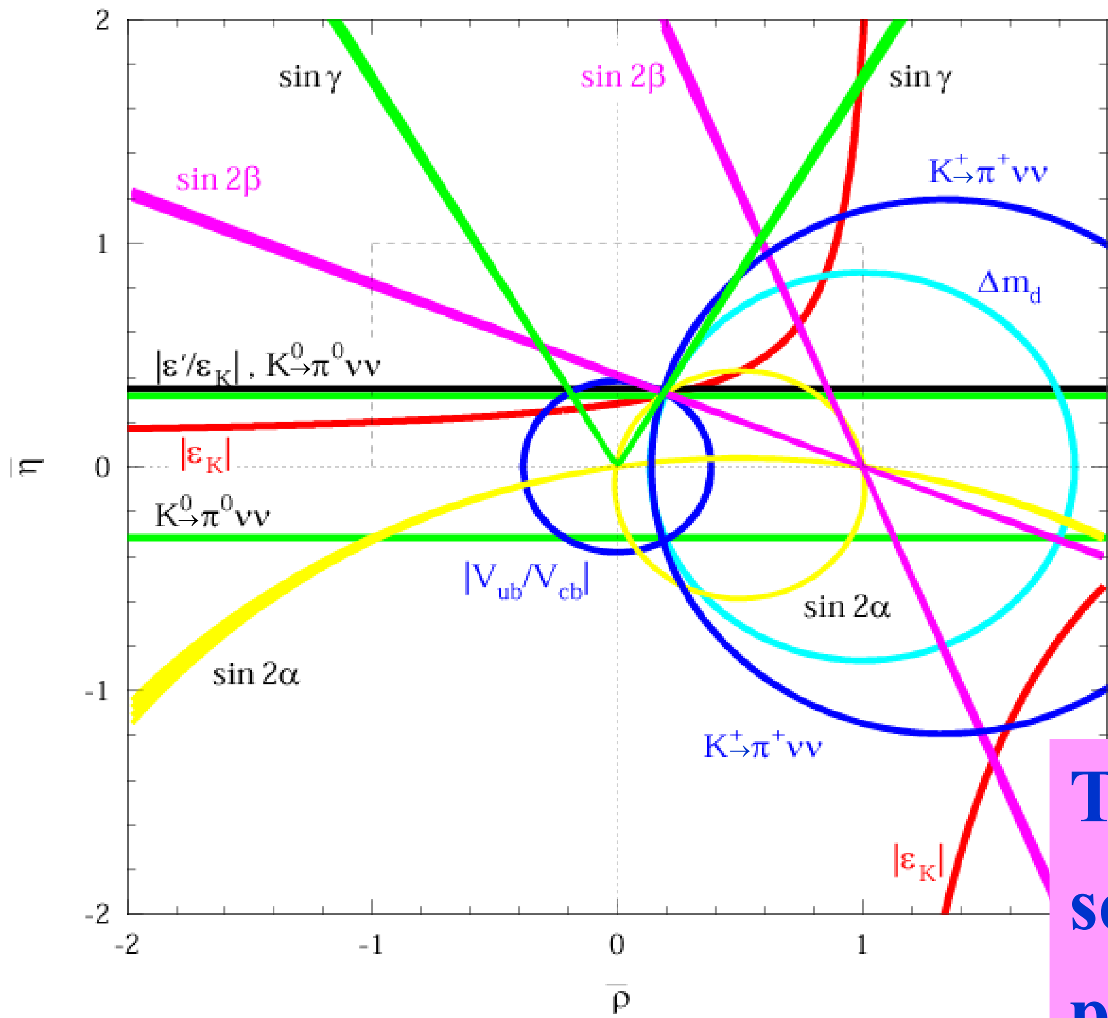
$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_d}{m_s} \frac{\lambda^2}{\xi^2} [(1-\bar{\rho})^2 + \bar{\eta}^2)] \Rightarrow \textit{circle} \ @ \ (1,0), \ \xi = \frac{f_{B_s}\sqrt{B_s}}{f_{B_d}\sqrt{B_d}}$$

UT Constraints



From A. Hocker, et al. hep-ph/0104062

More UT Constraints



From A. Hocker, et al. hep-ph/0104062

α, β, γ **constrained from 2-body hadronic *B*-decays (rare):**

B→ππ, Kπ, ρπ, DK , J/ΨK

Help from (rare) *K*→πνν after 2005

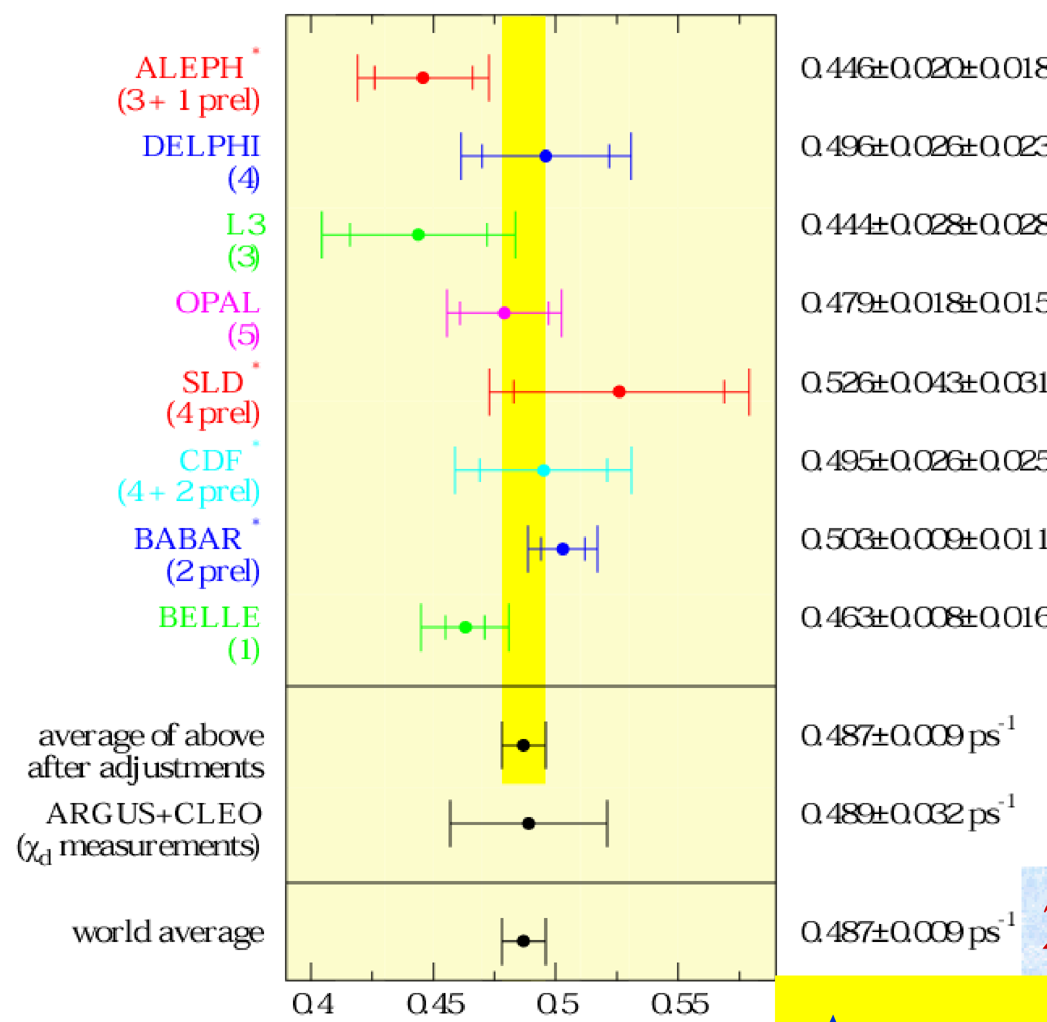
Today mixing & semi-leptonic decays provide best precision

sin 2β

- 0.34 ± 0.21 BaBar
- 0.58 ± 0.34 Belle
- 0.79 ± 0.43 CDF
- 0.84 ± 0.93 ALEPH
- 3.2 ± 2.0 OPAL

- **World Average: 0.48 ± 0.16**

B_d Mixing: Δm_d



LEP Working Group Δm_d (ps^{-1})

Measured in two ways:

- χ method: *t*-integrated B^0B^0 vs $B^0\overline{B^0}$; e.g. dileptons

- direct, *t*-dependent observation of $B^0 \Leftrightarrow \overline{B^0}$ oscillations by flavor tagging as a fcn of decay lengths

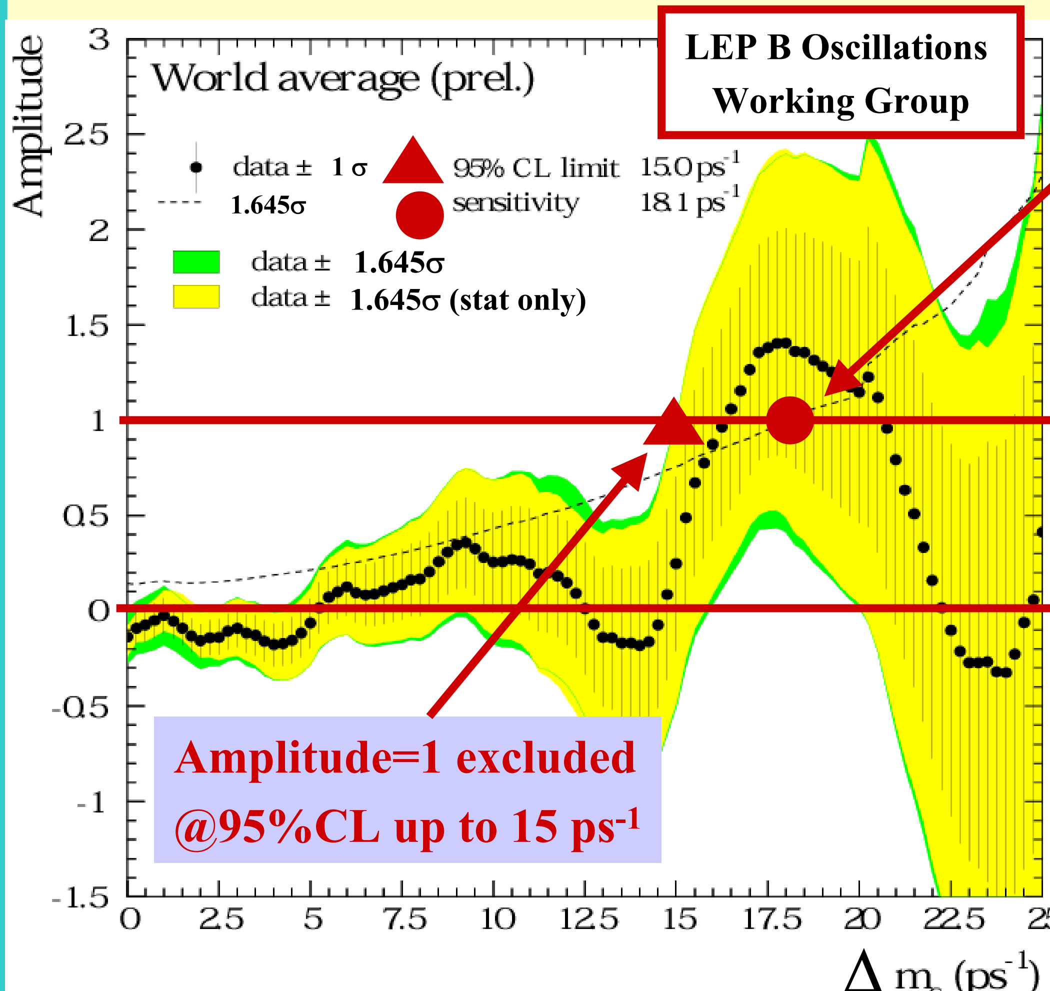
2% error

$\Delta m_d \cong 1/\tau_B$

B_s Mixing

- B_s too heavy to be produced @ Υ(4S)
  - LEP, SLC, Tevatron
- Near maximal mixing observed
  - $\Delta m_s >> 1/\tau$ unlike B_d
  - Oscillations not yet definitively seen due to large frequency; hard to measure
  - Only get lower limit on Δm_s, even when combining all expmts

Δm_s World Average



Oscillation frequency

<u>Sensitivity</u> to exclude Amplitude=0 @95%CL at 18.1 ps^{-1}

Yes oscillation

No oscillation

$\Delta m_s > 15\ ps^{-1}$

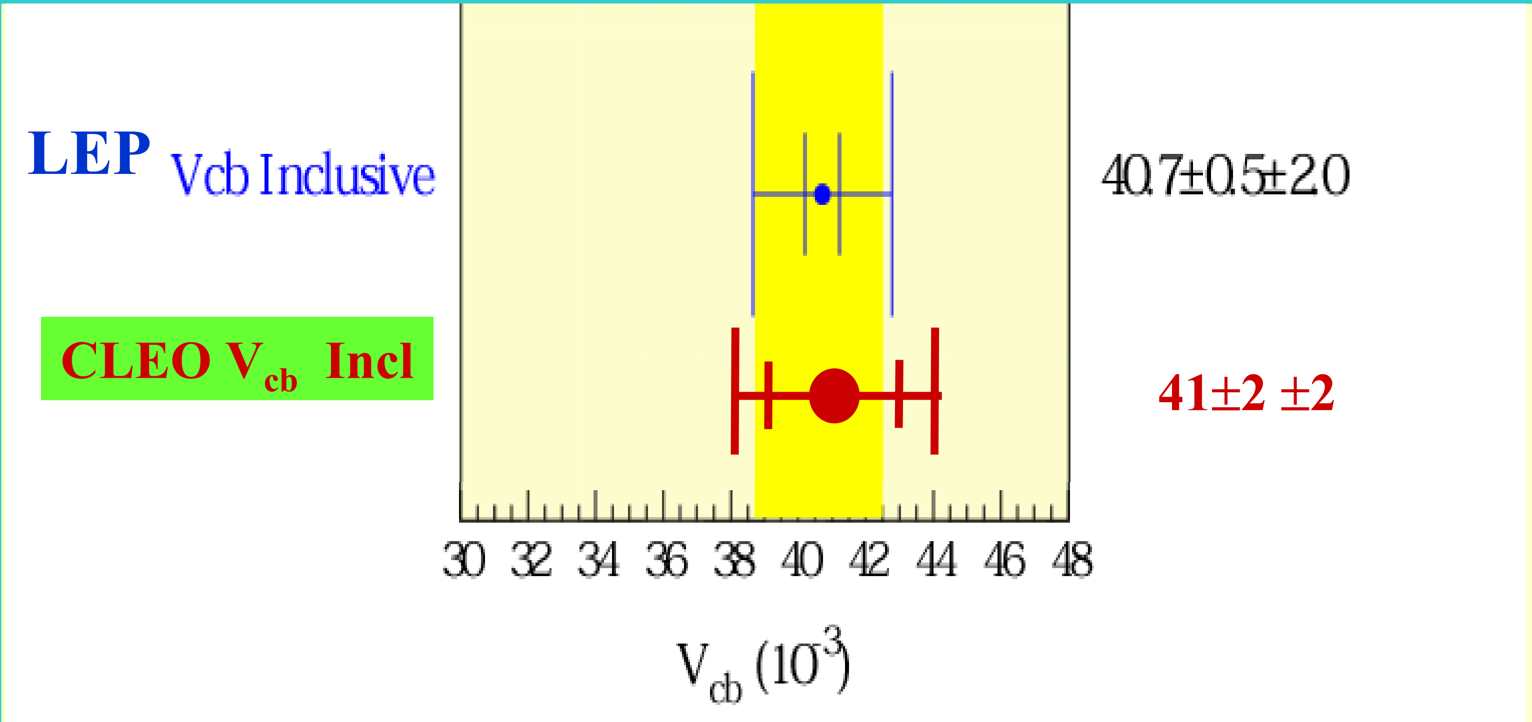
Inclusive $b \to c l \nu$

- $|V_{cb}|^2 = h(\mu, m_b) \times \Gamma(b \to c l \nu)$

  $= h(\mu, m_b) \times BR(b \to c l \nu)/\tau_b$

- $h(\mu, m_b)$ from Heavy Quark Expansion
  - Perturbative & non-perturbative pieces
  - Quark-hadron duality assumption: integrated over enough charm bound states & enough phase space, the inclusive hadronic result will match quark-level
  - No consensus on uncertainty in assumption

Inclusive $b \to c l \nu$



5%? common theoretical error

Exclusive V_{cb} : $B \to D^* l \nu$

- **Experiments measure**

Form Factor

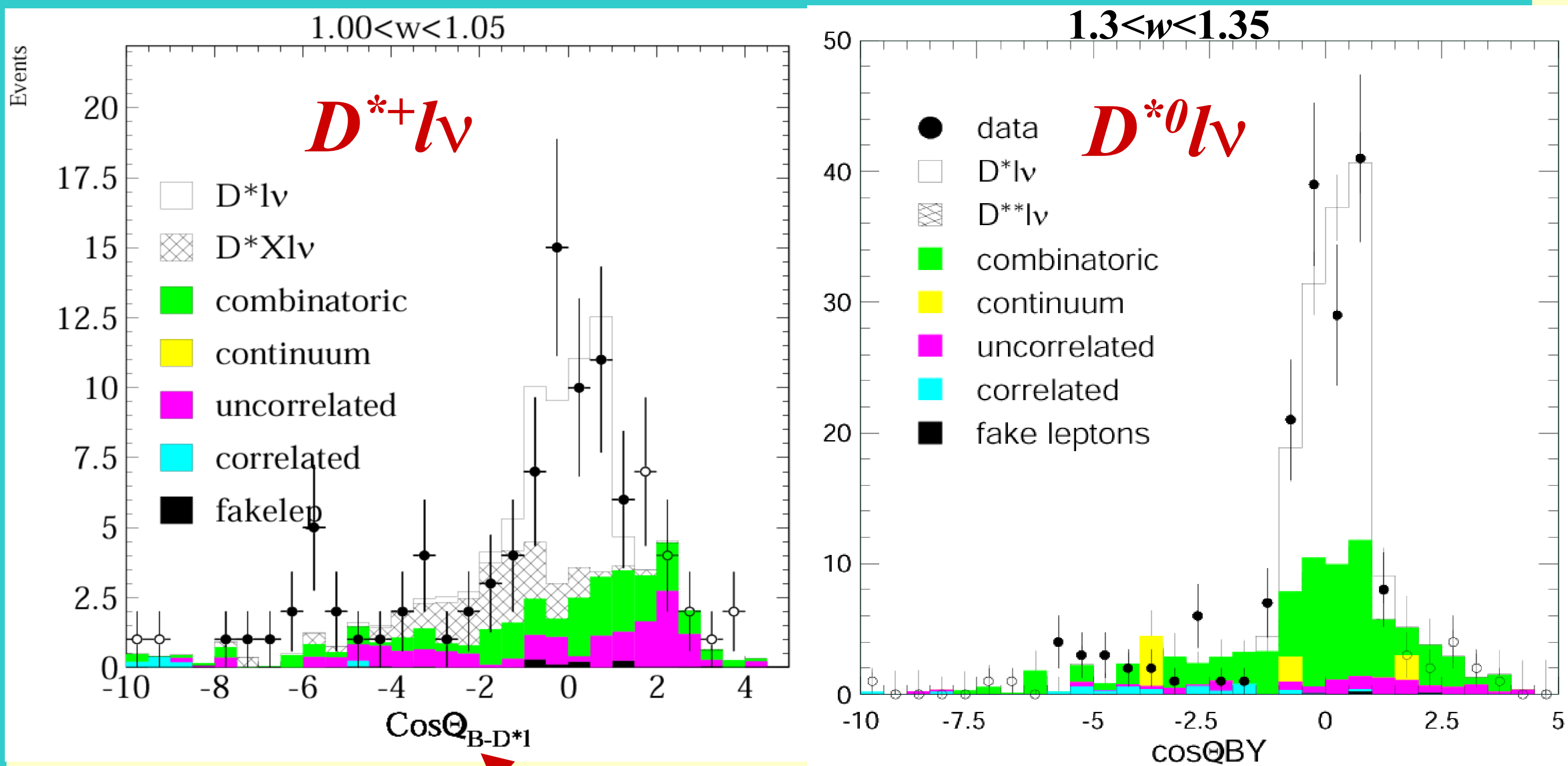
$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3} \; g(w) \; F_{D^*}^2(w) \, |V_{cb}|^2$$

$w=(m_B^2 + m_{D^*}^2 - q^2)/(2m_B m_D^*)$ = D boost in B rest-frame*

$1<w<1.5$; $g(w)$ is a known function with $g(1)=0$

- **HQET:** *$F(1) \to 1$ for $m_b \to \infty$; $(1/m_b)^n$ corr'ns*
  - $F_{D^*}(1)$ = 0.88 – 0.95: HQET, LQCD
  - Nearly linear in *w*: measure curvature: parameter "ρ^2"
  - Extrapolate data to *w*=1 (where phase space $\to$0)
  - Experimental results usually quoted as $F_{D^*}(1)|V_{cb}|$

w fits: $B \to D^* l \nu$ examples



Kinematic variable distinguishing $D^* l\nu$ $D^* X l\nu$

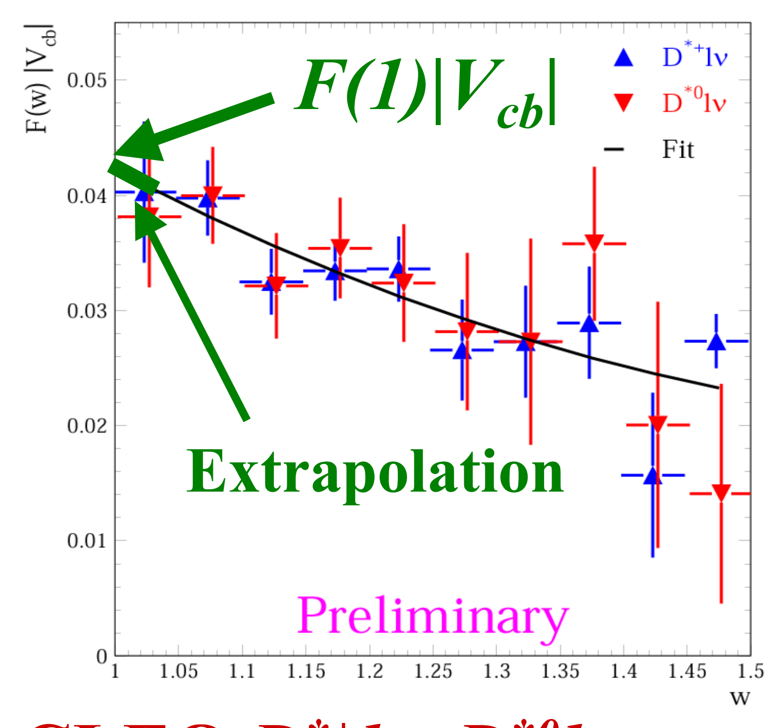
$|V_{cb}|$ from $B\to D^* l\nu$

- w msd: σ_w(CLEO)= 0.03; σ_w(LEP) ≥0.07
- Fit each w-bin for ($B\to D^* l\nu + D^* X l\nu$+bgds)
- CLEO limit: ε(slow π)
- LEP limit: $D^* X l\nu$ level
  - Model of Leibovich, *et al.* PRD 57, 308 (1997)
  - CLEO measures it, sees less

CLEO 2001

$F(1)|V_{cb}|=(42.2 \pm 1.3 \pm 1.8)\times 10^{-3}$

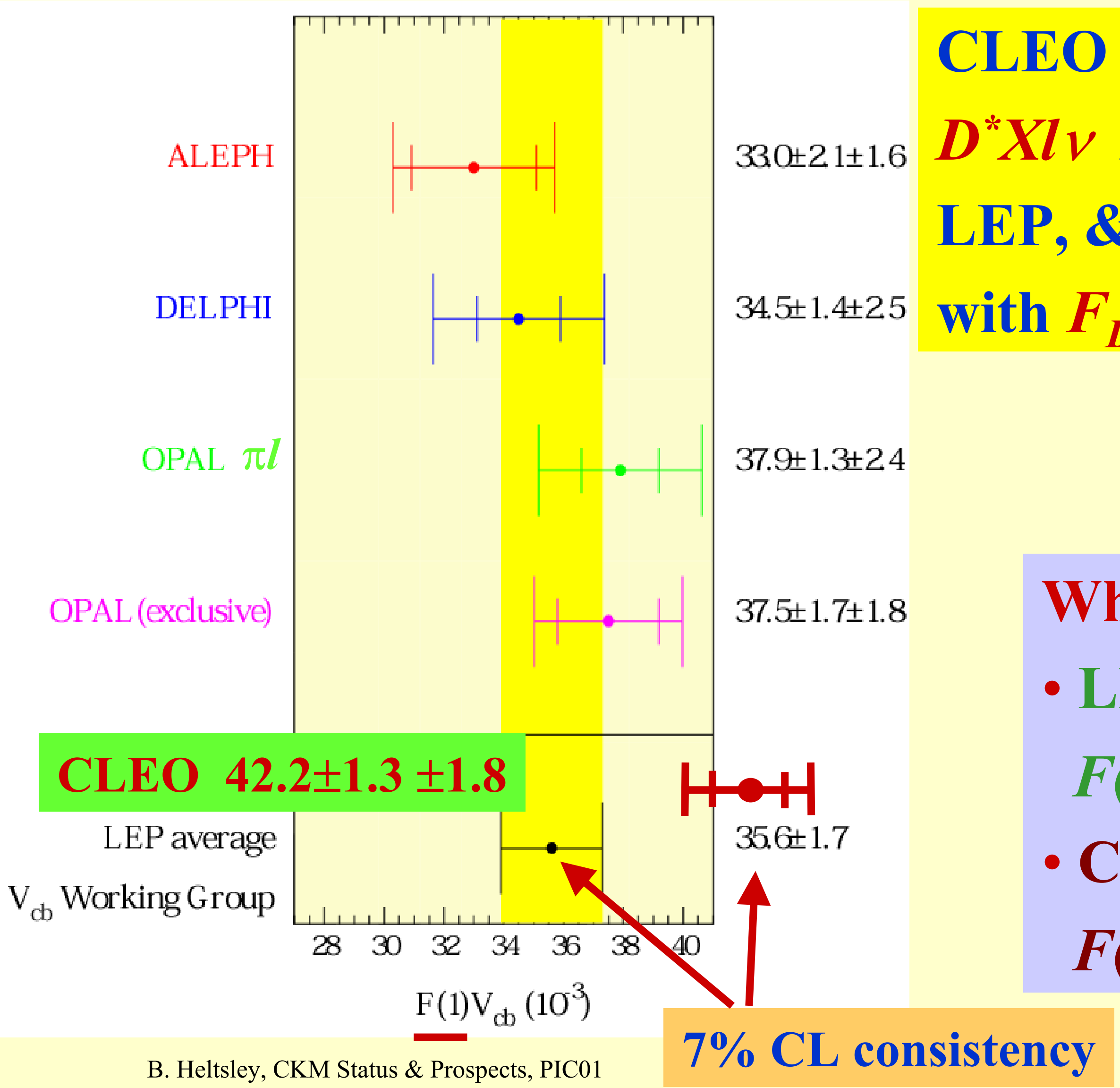
$\rho^2=1.61\pm0.09$



CLEO $D^{*+}l\nu$, $D^{*0}l\nu$

5% total error on $F(1)|V_{cb}|$

V_{cb} Exclusive Averages



CLEO fits both a smaller $D^*Xl\nu$ AND a larger ρ^2 than LEP, & both are correlated with $F_{D*}(1)|V_{cb}|$

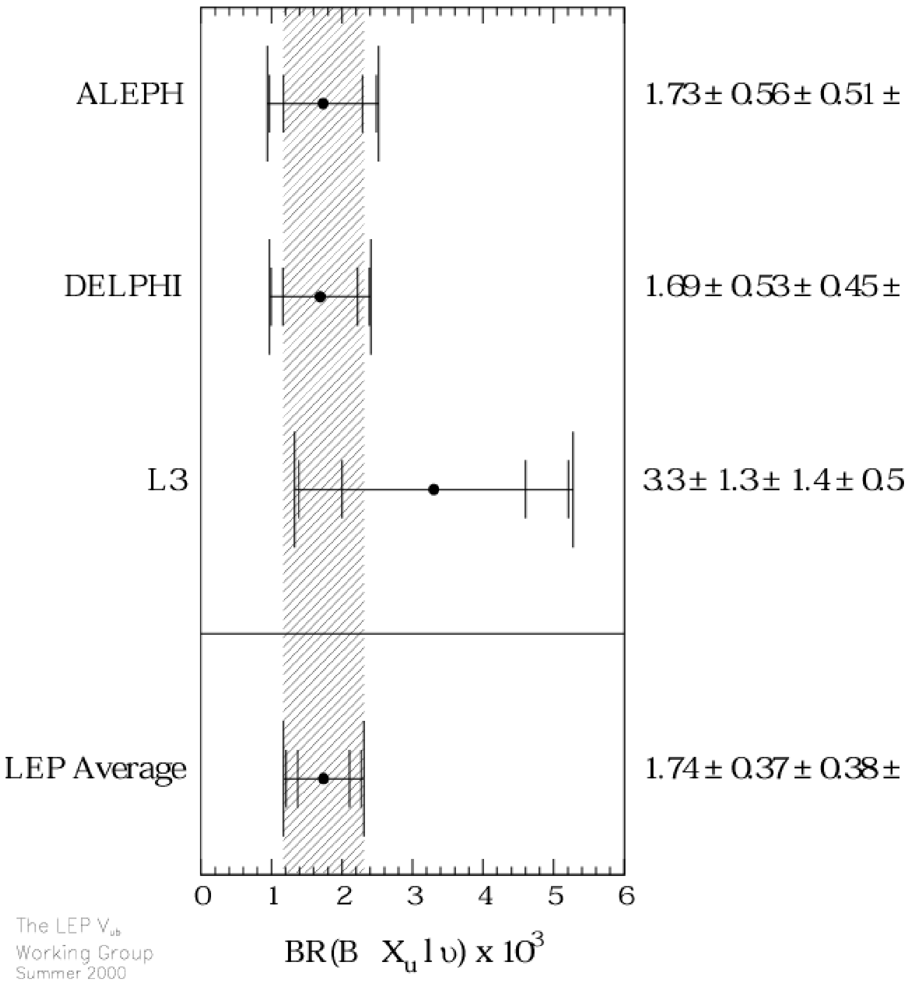
When taking out $F(1)$,

- **LEP WG uses $F(1)=0.88\pm0.05$**
- **CLEO uses $F(1)=0.913\pm0.042$**

$b \to ul\nu$

- Similar to $b \to cl\nu$ BUT $BR(b \to ul\nu) \sim 2\times10^{-3}$!
- Experimentally: few evts, swamped w/ $b \to cl\nu$
- LEP expmts use inclusive analysis
  - LEP $|V_{ub}|$ avg has 10% statistical error
  - HQE uncertainty (5%) + duality/modeling unc. (12%)
  - Systematics from identifying & separating $b \to u$, $b \to c$
  - Systematics from non-$b \to u$, non-$b \to c$ suppression
- CLEO uses "ν-recon." for $B \to \pi l\nu$, $\rho l\nu$
  - Statistical error of 4%
  - Form-factor model uncertainty of 17%

$|V_{ub}|$ Summary



0.2

0.2

0.2

$|V_{ub}|$

LEP: $(4.13 \pm 0.45 \pm 0.52)\times 10^{-3}$

Stat + Detector **Theory**

CLEO: $(3.25 \pm 0.30 \pm 0.55)\times 10^{-3}$

Global fits: Simmering tempest

Conservative Frequentists

- A. Hocker, et al., hep-ph/0104062 (BaBar)
- S. Stone, hep-ph/0012162 (Beauty 2000)
- A. Falk, hep-ph/9908520, Aug. 1999 (LepPho 1999)
- J. Rosner, hep-ph/0011184, Aug. 1999 (Beauty 2000)

Optimistic Bayesians:

- A. Stocchi, hep-ph/0010222 (ICHEP 2000), NIM A462 (2001) 318 (Beauty 2000).
- F. Parodi (CPV 2000)
- M. Ciuchini, et al., hep-ph/0012308 (Moriond 2001)

Issue: How to treat theoretical QCD predictions (TP's) & associated uncertainties in a global CKM fit?

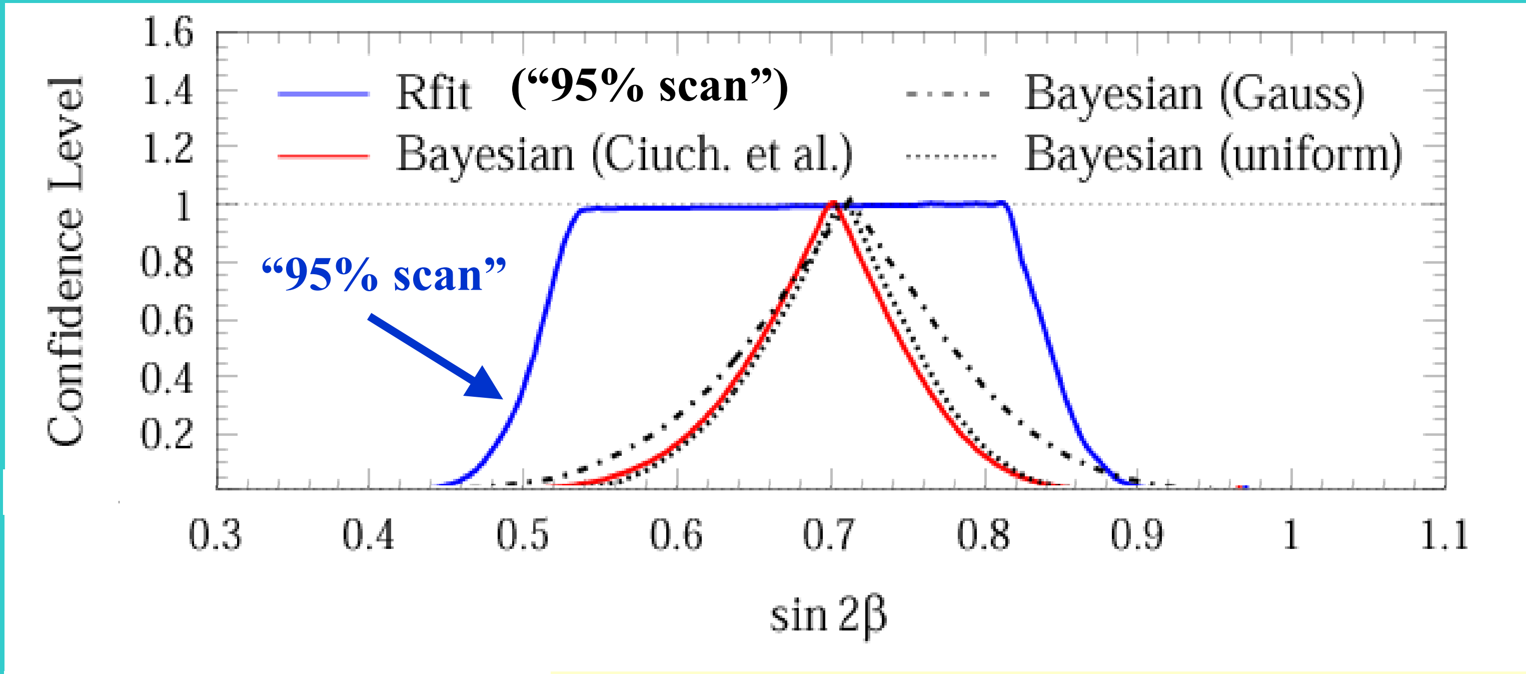
Central Q's in Tempest

- What are central values of TP's from HQET, LQCD, NLO ?
  - Do we exclude "disagreeable" or "outdated" predictions?
  - How to combine several incompatible results?
- What are the uncertainties on the TP's?
  - How well can they be estimated?
  - Do "internal" tests give adequate estimates?
  - How does one quantify errors from assumptions; e.g. quark-hadron duality in HQET?
- Can some or all theoretical errors be treated w/Bayesian analysis along with the data, with a preferred central value as a result?

Standard vs 95% CL Scanning

- **Standard method** advocates similar treatment of uncertainties for data and TP's with Gaussian (or even flat) PDF's (Bayesian)
  - LQCD is mature enough to trust results
  - Know the sign & rough magnitude of corrections
  - Can assign reasonable σ's: don't throw away information!
- **95% CL Method** advocates cautious approach to TP's by restricting them to a "95% CL interval", with no preferred central value $\Rightarrow V_{ij}$: contours or intervals with no preferred ctrs (Frequentist)
  - Even combining flat PDF's is treacherous!
  - In multi-dimensional problems Bayesian treatment unfairly predicts a narrowing of possible results, not a broadening

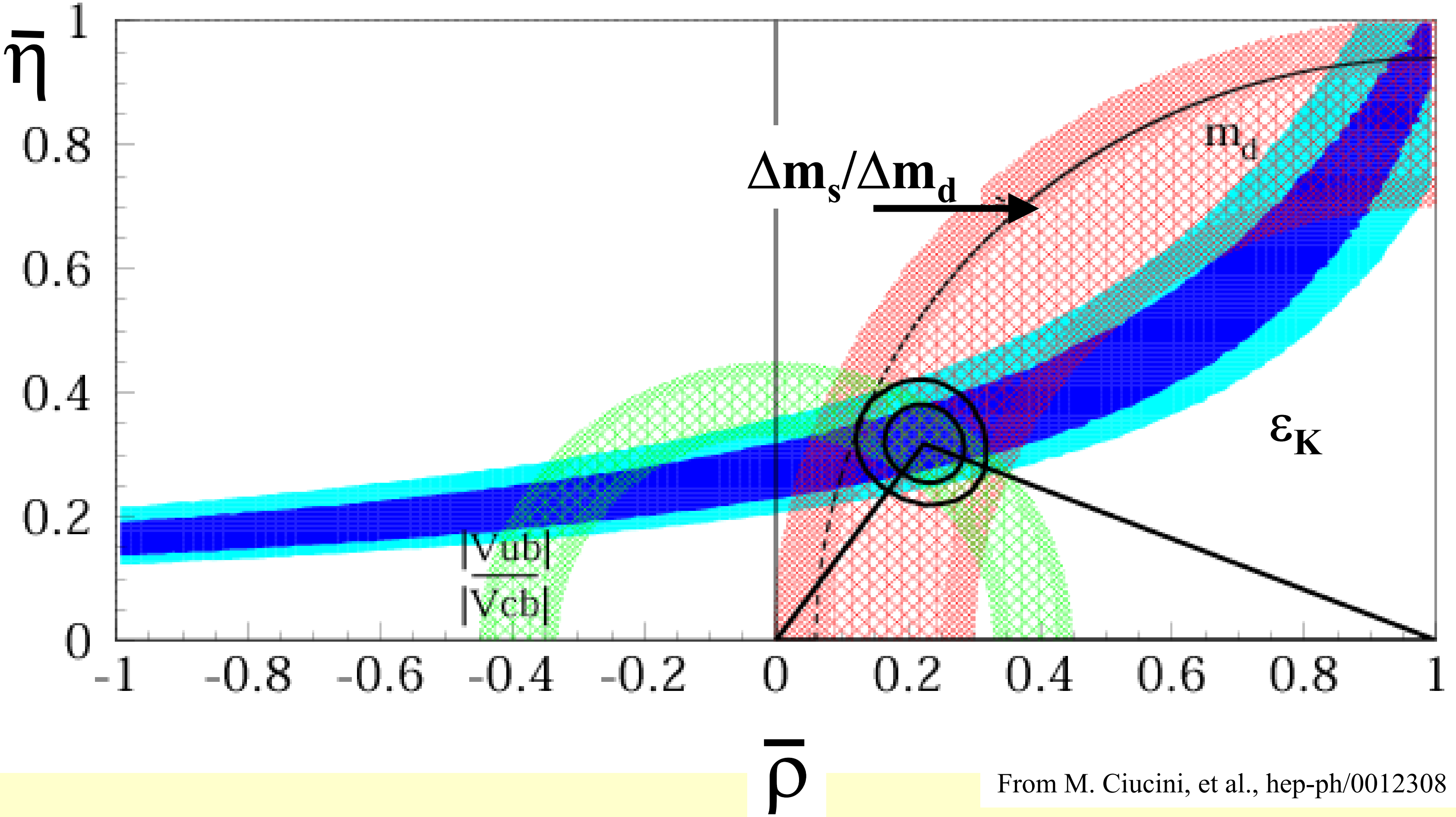
sin2β CL's in different methods



From A. Hocker, et al. hep-ph/0104062

Direct sin2β msmts not included

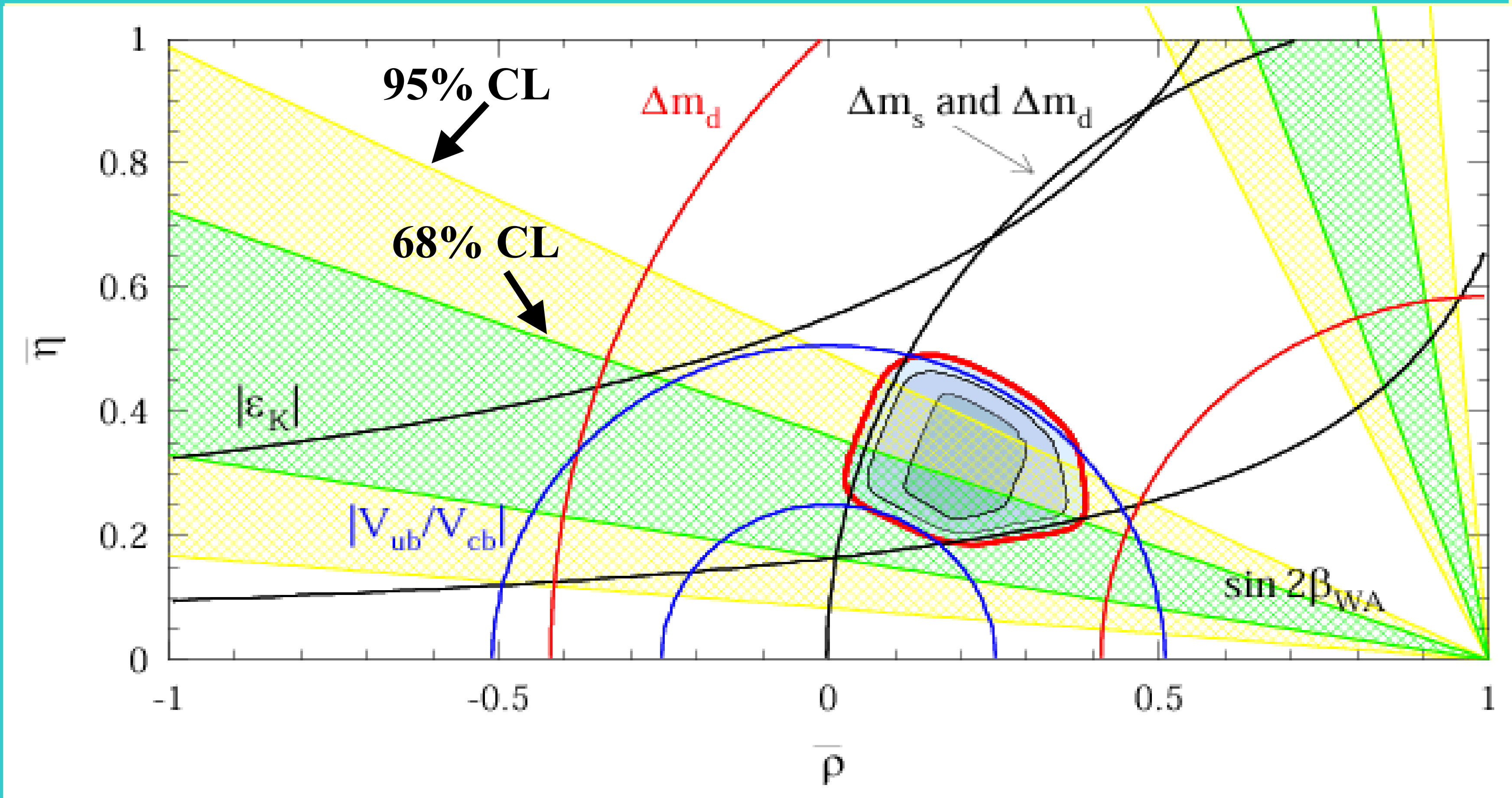
Standard Method Global Fit



From M. Ciucini, et al., hep-ph/0012308

No sin2β constraint

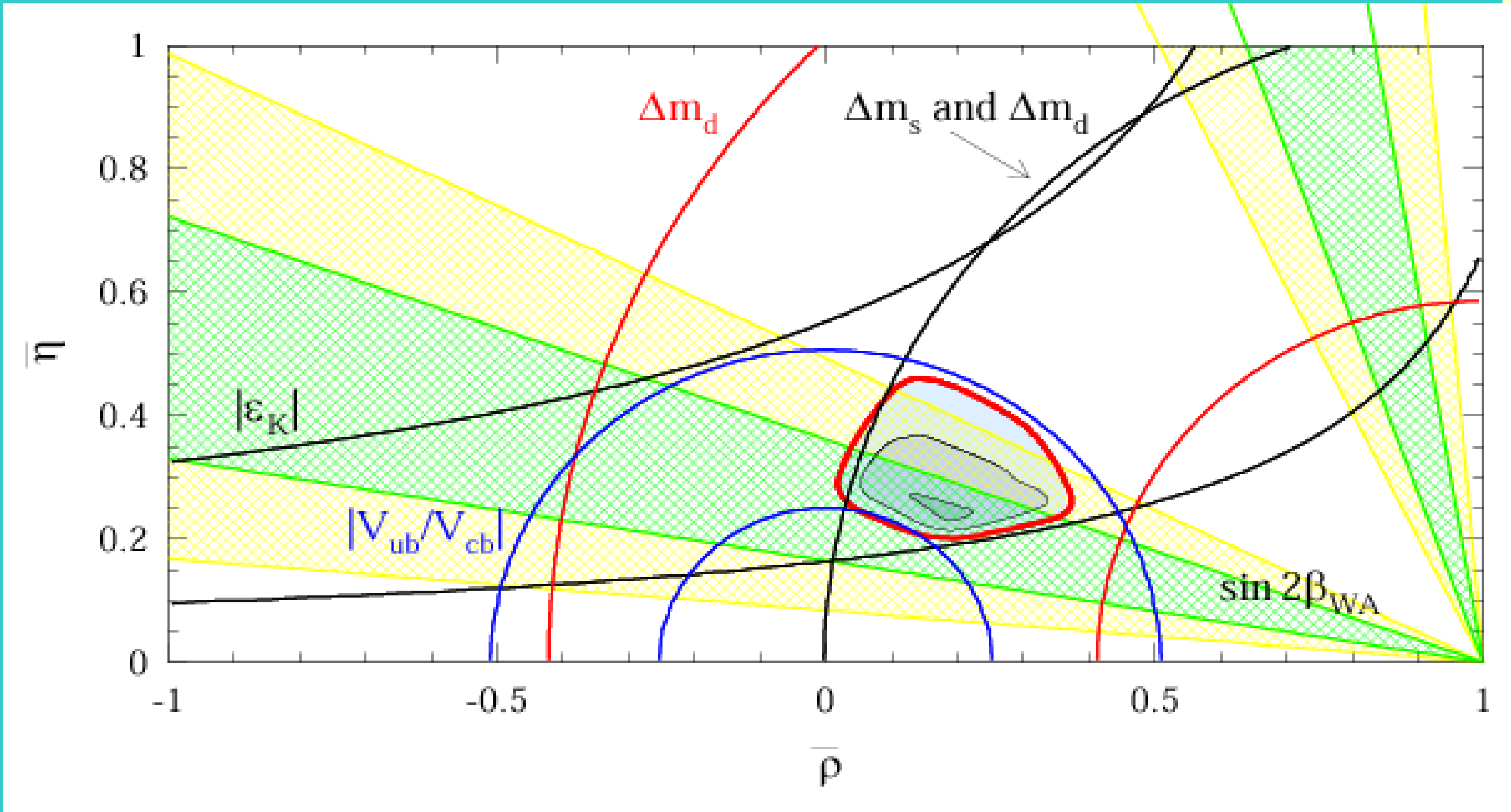
“95% Scanning” Global Fit



From A. Hocker, et al. hep-ph/0104062

No sin2β constraint

"95% CL" w/sin2β Constraint



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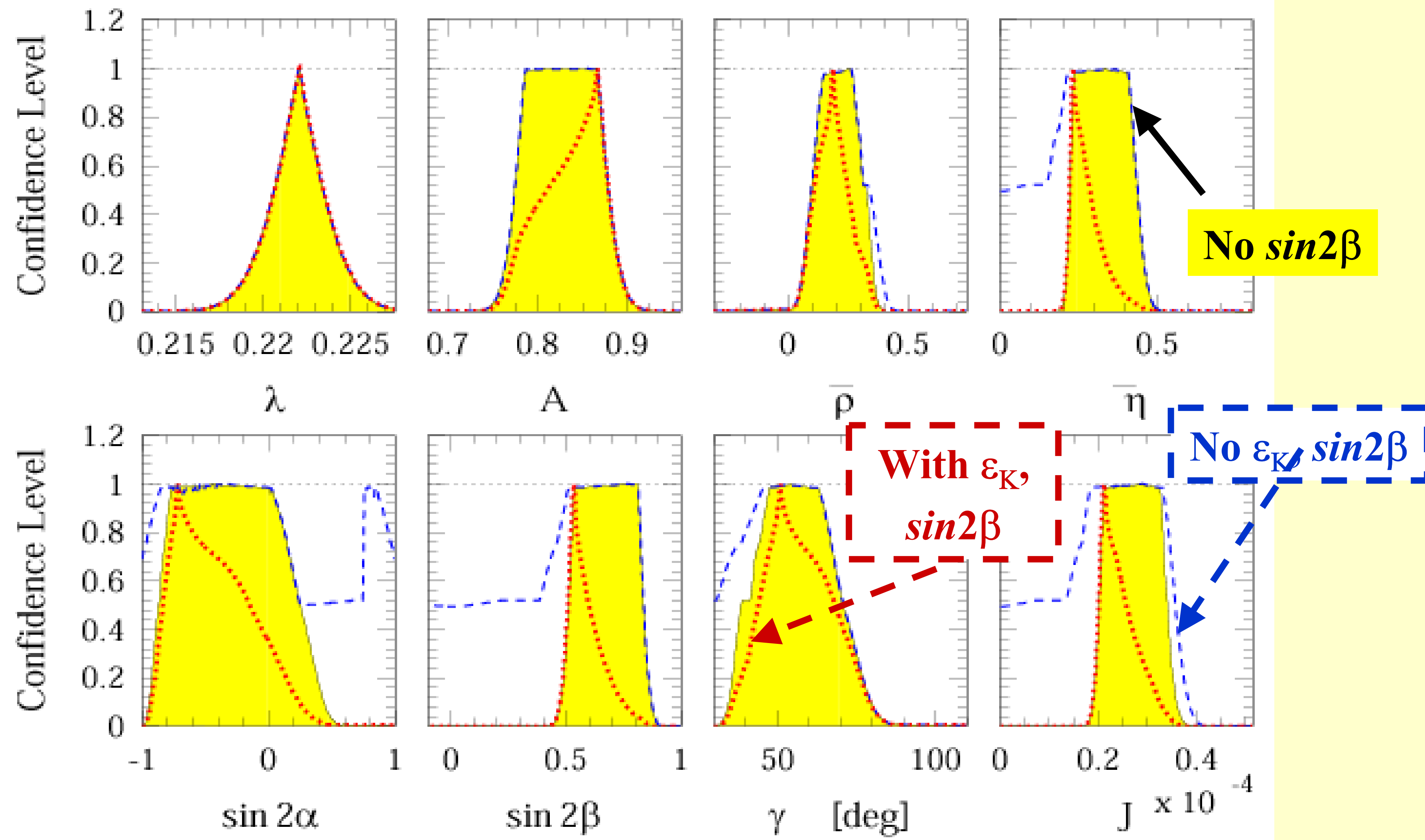
CL's in "95% Scan" Global Fit



From A. Hocker, et al. hep-ph/0104062

Y2K Global Fit 95%CL Limits

	"95% Scanning"	vs	"Standard"
ρ:	0.04 – 0.38	vs	-0.06 – 0.31
Span:	0.34	vs	0.37
η:	0.21 – 0.49	vs	0.26 – 0.42
Span:	0.28	vs	0.16
sin(2β):	0.47 – 0.89	vs	0.56 – 0.82
Span:	0.42	vs	0.26

Here uses flat PDF's

From A. Hocker, et al. hep-ph/0104062

From M. Ciucini, et al., hep-ph/0012308

No sin2β constraint

Each quoted with its own choice for QCD params

Global Fitting Conclusions

- **No consensus on QCD uncertainties**
  - Not likely to converge without data to pin it down
- **No consensus on Bayesian/Frequentist**
  - Merits & difficulties on both sides
- **Different methods will give much different answers as soon as the data are more precise (i.e. in a few weeks)**
  - Different answers may have very different implications on whether the SM is found lacking
- **Expect continuing spirited discussion**

New V_{cb} from "Moments"

- **HQET OPE: expand in $(1/m_B)^n$**

$$|V_{cb}|^2 = \Gamma(b\to cl\nu) \times h(\bar{\Lambda}, \lambda_1) \;:\; \sim O(m_B^{-3})$$

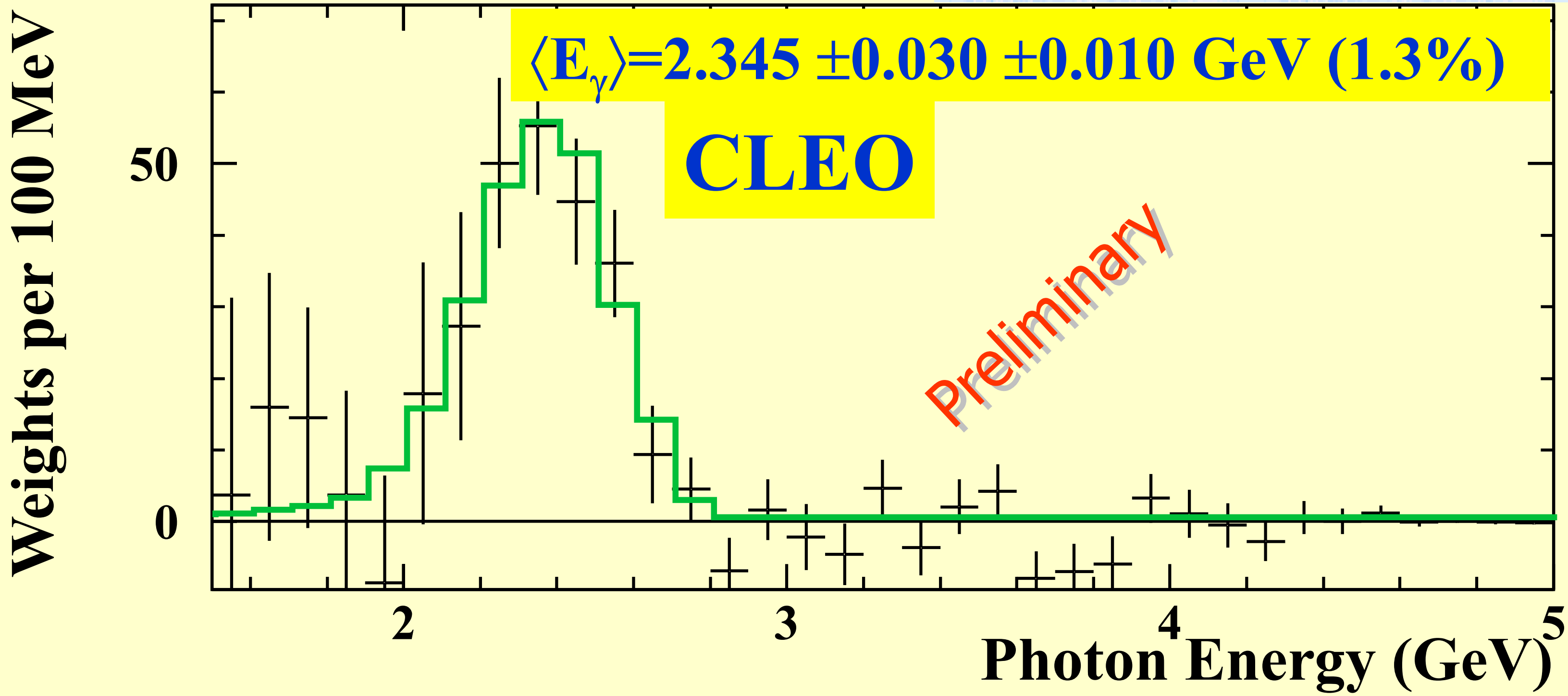
  - $\bar{\Lambda}$ = Mass of light d.o.f.
  - λ_1 = rms momentum of b quark.

A.Falk, M. Luke, & M. Savage, PRD53 (2491) 1996.
M. Gremm & A. Kapustin, PRD55 (6934) 1997.
M. Voloshin, PRD51 (4934) 1995.

- **$\bar{\Lambda}$, λ_1 determined from**
  - Lattice QCD Kronfeld & Simone, hep-ph/0006345.
  - Measured hadronic spectral moments in $b\to cl\nu$
  - Measured photon energy spectrum moments in $b\to s\gamma$
- **New, preliminary CLEO use of technique**

CLEO $b \to s\gamma$ spectral moments

- **Measure photon spectrum in lab-frame.**
- **Convert to *B* rest frame. MC accounts for smearing**
  - **Best match m_b= 4719±115 MeV/c^2; p_F = 378±150 MeV**
- **Extract moments ($E_\gamma > 2.0$ GeV)** $\left\langle \left(E_\gamma - \langle E_\gamma \rangle\right)^2 \right\rangle = 0.021 \pm 0.006 \pm 0.002\ \text{GeV}^2$

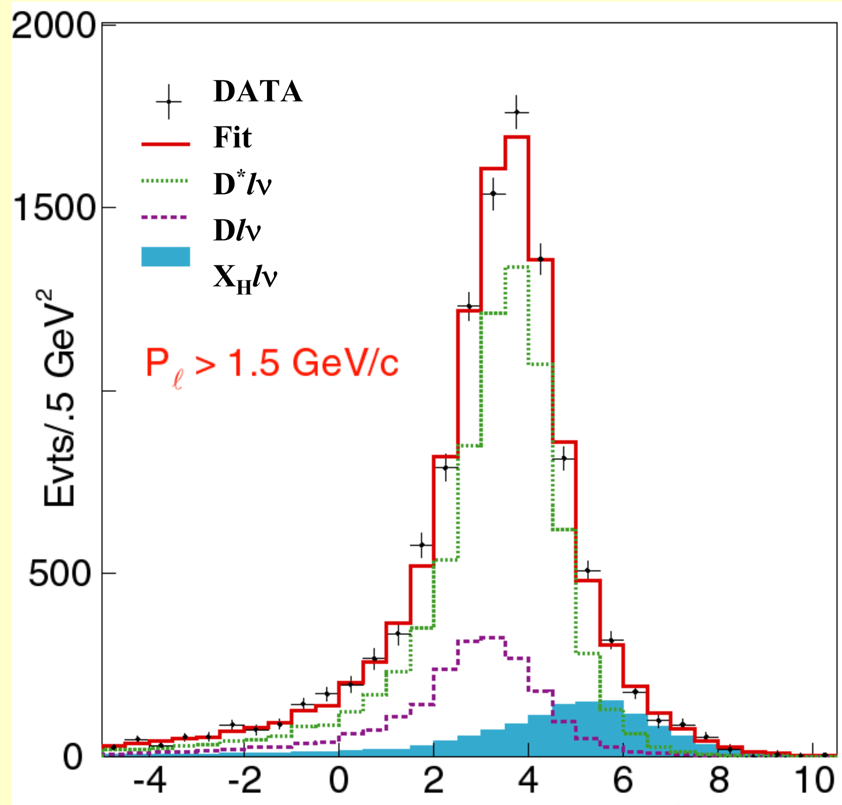


$B \to X_c l\nu$ Hadronic Mass Moments

- Lepton (p>1.5 GeV)
- ν-reconstruction: p_ν
- Calculate recoil mass
- Fit spectrum w/ $B \to Dl\nu$, $B \to D^* l\nu$, $B \to X_H l\nu$ (various models for X_H)
- $\langle M_X^2 - \overline{M}_D^2 \rangle$, $\overline{M}_D$ is spin-averaged D, D* mass

$\langle M_X^2 - \overline{M}_D^2 \rangle = 0.287 \pm 0.065$ GeV^2

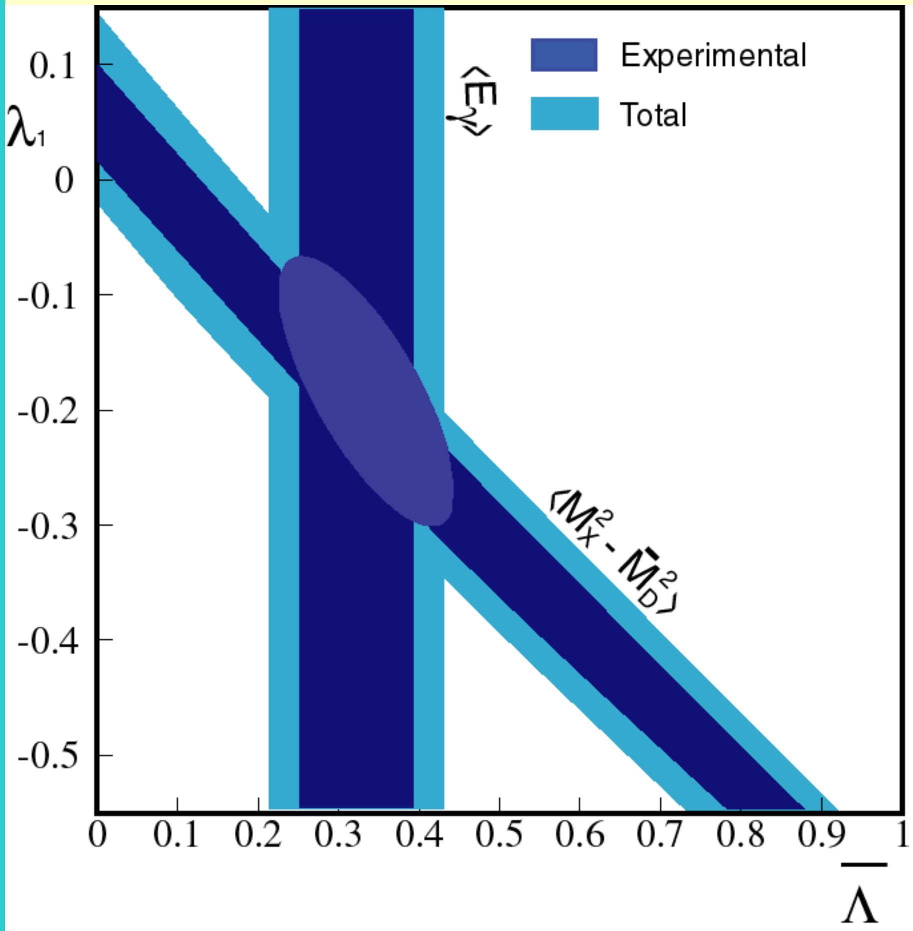
- 2nd moment: 0.63 ± 0.17 GeV^4



$\langle M_X^2 - \overline{M}_D^2 \rangle$

Second moments give consistent results, but still theoretically shaky.

$\bar{\Lambda}$, λ_1 from $b \to s\gamma$, $B \to X_c l \nu$ moments



Preliminary

$$\bar{\Lambda} = 0.35 \pm 0.07 \pm 0.10 \text{ GeV}$$

$$\lambda_1 = -0.216 \pm 0.068 \pm 0.077 \text{ GeV}^2$$

moments

$1/M_B^3$

CLEO V_{cb} from $b \to c l \nu$, $b \to s\gamma$

- **Using**
  - $B(B \to X_c\, l\, \nu) = (10.39 \pm 0.46)\%$ (CLEO, PRL76 (1570) 1996)
  - $\tau_{\pm} = (1.548 \pm 0.032)$ psec (PDG)
  - $\tau_0 = (1.653 \pm 0.028)$ psec (PDG)
  - $f_{+-}/f_{00} = 1.04 \pm 0.08$ (CLEO, hep-ex/0006002)
- $\Gamma(b \to c l \nu) = (\ 0.427 \pm 0.020\ ) \times 10^{-10}$ MeV
- $|V_{cb}| = (40.5\ \pm\ 0.9\ \pm\ 0.9\ \pm\ 0.8)\ \times 10^{-3}$

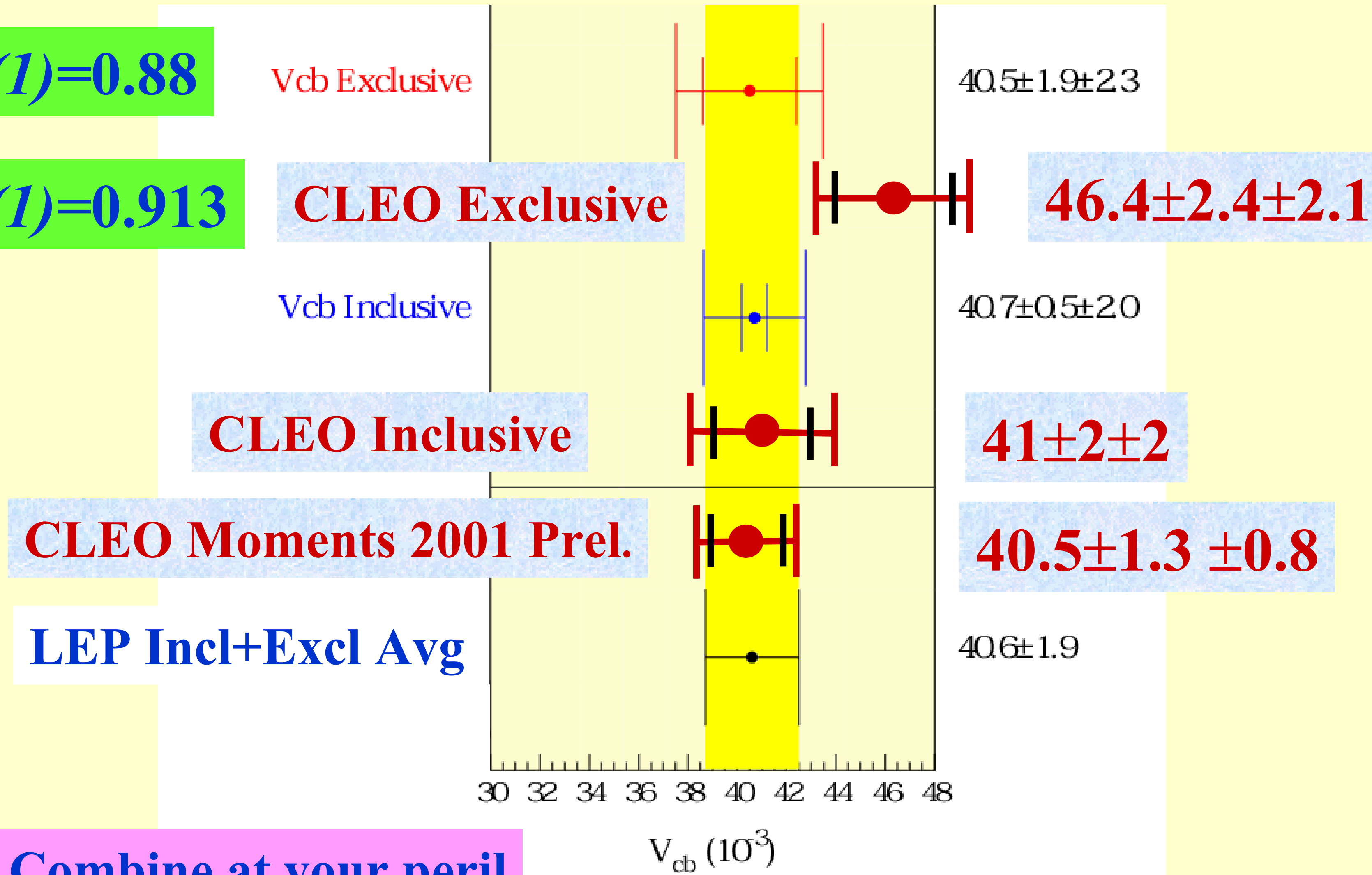
Γ_{exp} $(\Lambda, \lambda_1)_{exp}$ $1/M_B^3$

3.7% total error

$|V_{cb}|$ Summary

***F(1)*=0.88**

***F(1)*=0.913**



Combine at your peril

What's next?

- B-factories in 5 years: ~0.5 ab^{-1}

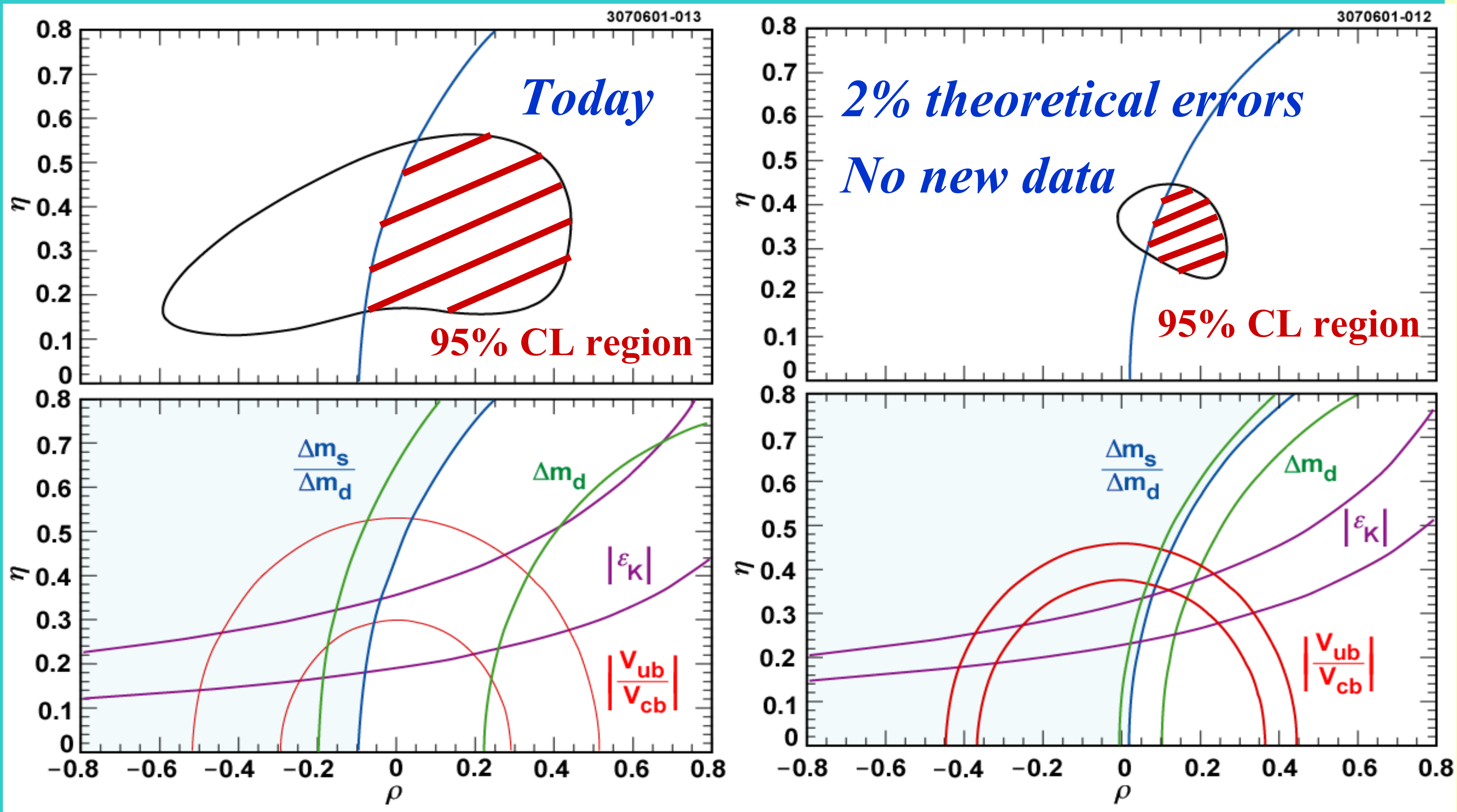
  $\Rightarrow$ ~1/10 statistical σ's

  - *D* BR's become limiting to *B*-decay precision
  - Charm physics could become less precise than *b*-physics: need better V_{cd} & V_{cs}

- Theoretical uncertainties dominate even now

  - But Lattice QCD & models promise big improvements

Just imagine …



The Role of CLEO-c

- Modify CESR for E_{cm}=3-11 GeV: L=2-4×10^{32}
- High precision charm data
  - Measure *D* BR's for input to *B*-decay studies
  - Establish successful precision testing ground of QCD for *D*'s to give credibility to those for *B*'s
- High precision quarkonia spectroscopy & decay data at ψ & ϒ resonances
  - Provide much needed experimental basis for non-perturbative QCD tests. Glueballs/Hybrids?
- Searches for non-SM phenomena in *D*-mixing, CPV in *D* decay, & rare decays

A CLEO-c Program

2002

- $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ ~1-2 fb^{-1} each
  - Spectroscopy, Matrix elements, Γ_{ee}:(>10×world)

2003

- $\psi(3770)$ -- 3 fb^{-1}, 30M events
  - 6M *tagged* D decays (310 × Mark III)

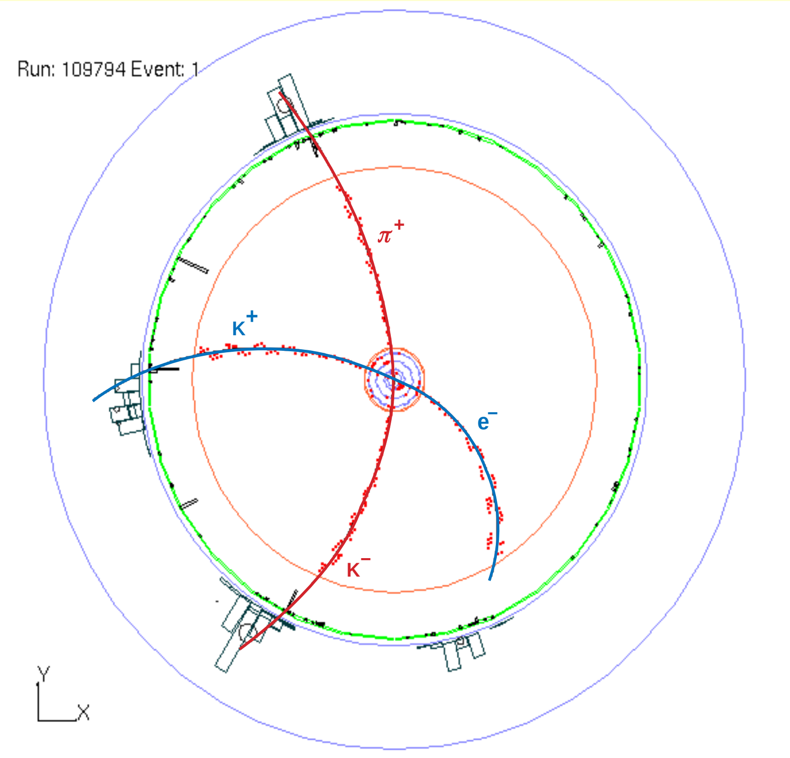
2004

- $\psi(4100)$ -- 3 fb^{-1}, 1.5M $D_s\overline{D}_s$
  - 0.3M *tagged* D_s decays (480×Mark III, 130×BESII)

2005

- $\psi(3100)$ -- 1 fb^{-1}, 10^9 J/ ψ decays
  - (170 × Mark III, 20 times BES II)

Tagging at Threshold

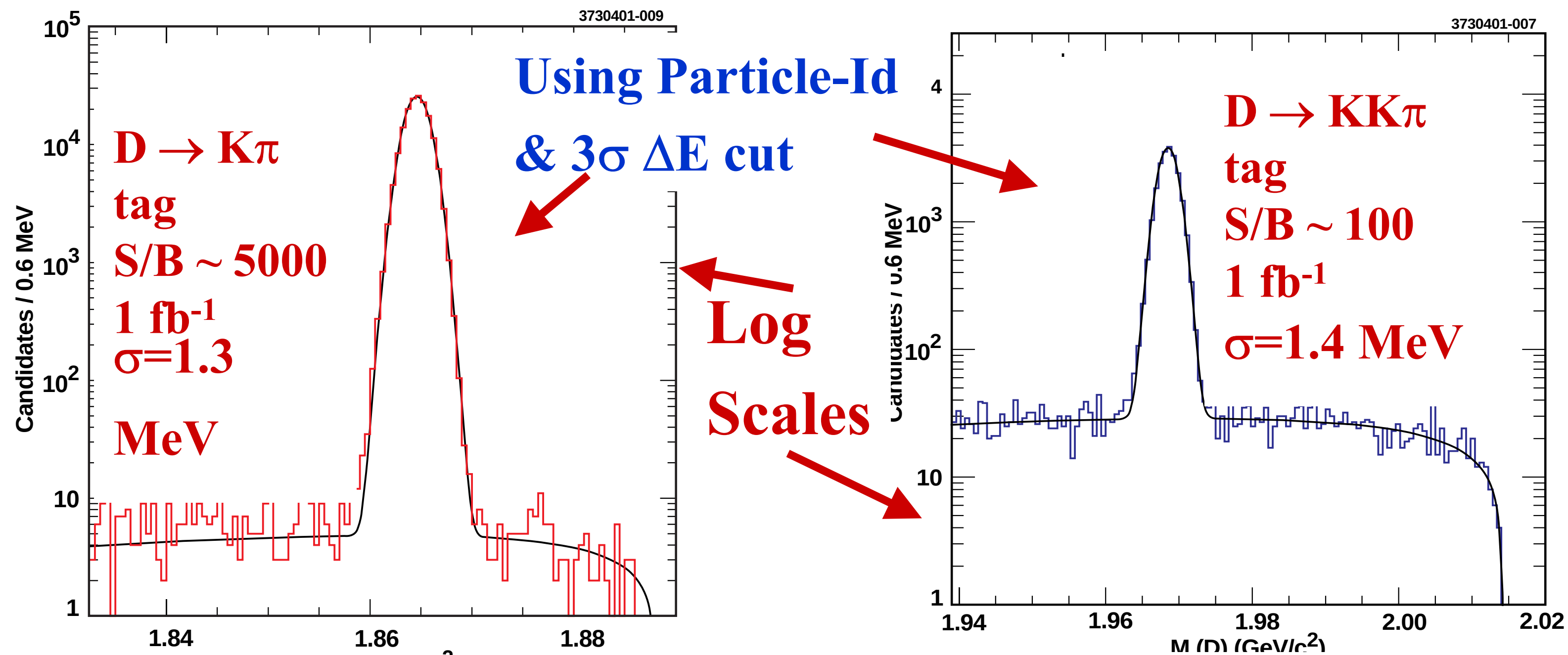


$D^0 \rightarrow K^- \pi^+$ $\qquad$ $\bar{D}^0 \rightarrow K^+ e^- \nu$

CLEO-c MC

- **Large σ**
- **Low multiplicity**
- **Pure $D\bar{D}$ init. State**
- **High recon. eff's ~ 20%**
- **6×10^6 D tags**
- **0.3×10^6 D_s tags**
- **Almost no bgd**
- **Clean ν-reconst.**
- **Coherent init state**

Tagged Branching Ratios

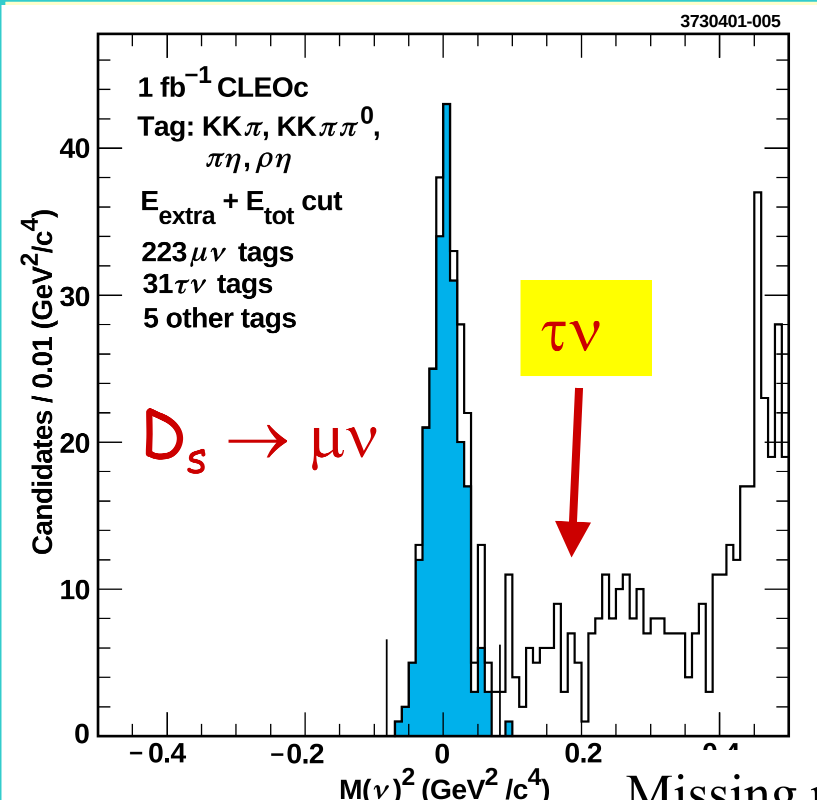


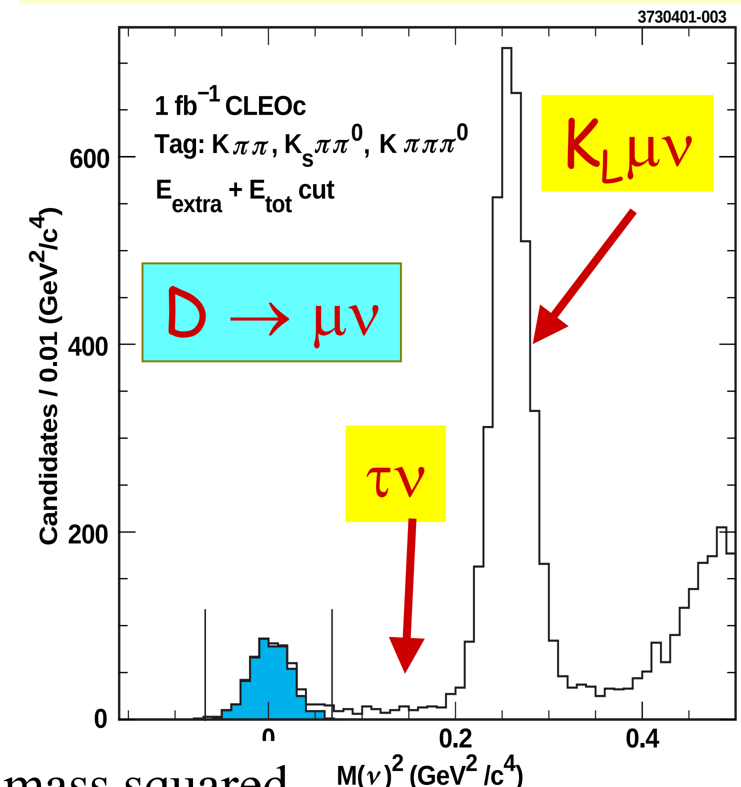
Beam-energy constrained mass

Set absolute BR's for $B \to$ "D"

Decay Mode	PDG2000 (δB/B %)	CLEOc (δB/B %)
$D^0 \to K\pi$	2.4	0.5
$D^+ \to K\pi\pi$	7.2	1.5
$D_s \to \phi\pi$	25	1.9

Leptonic Decays



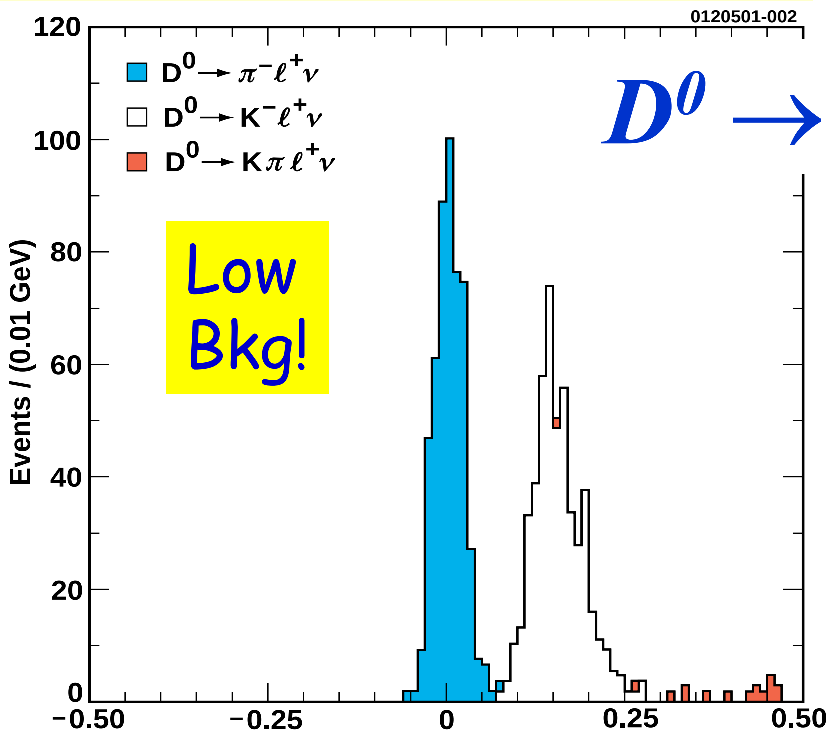


Missing mass squared

$$\frac{\delta f_{D_s}}{f_{D_s}} \approx 2.1\%$$ (Now: ±35%)

$$\frac{\delta f_D}{f_D} \approx 2.6\%$$ (Now: ±100%)

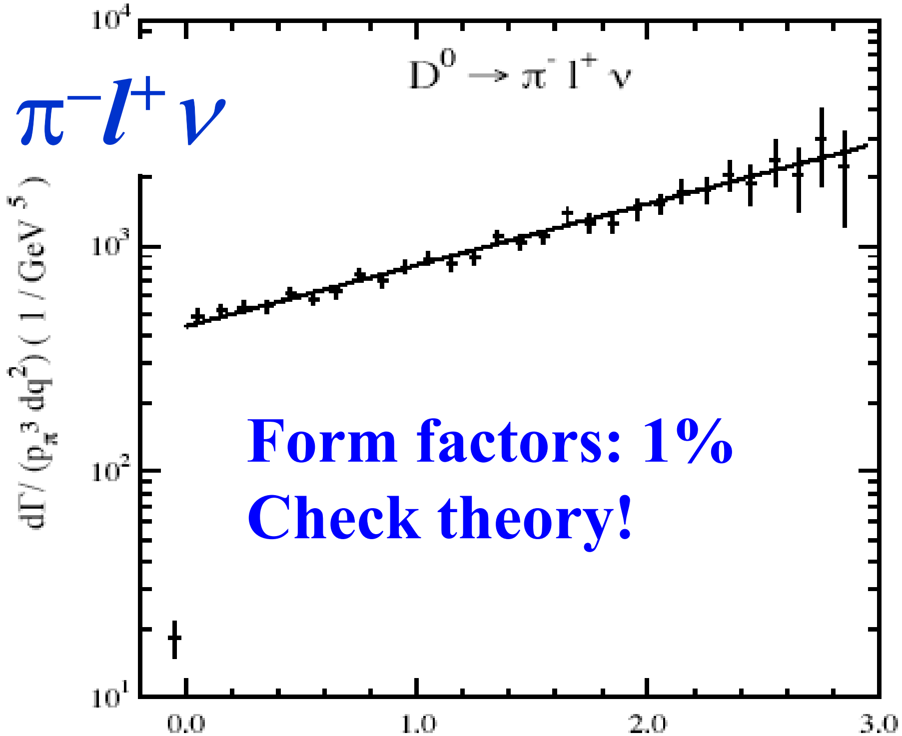
Semi-leptonic Decays



Low Bkg!

$U = E_{miss} - P_{miss}$

$D^0 \to \pi^- l^+ \nu$



Form factors: 1%
Check theory!

q^2 (GeV^2)

Semi-leptonic (cont'd)

Decay Mode	PDG2000 (δB/B %)	CLEOc (δB/B %)
$D^0 \to Kl\nu$	5	1.6
$D^0 \to \pi l\nu$	16	1.7
$D^+ \to \pi l\nu$	48	1.8
$D_s \to \phi l\nu$	25	2.8

Plus vector modes...

Systematics limited

V_{cd}, V_{cs} to ~1.5%, ratio to <1%

Cancelling systematics

Other Experiments

- **BES/BEPC**
  - CESR-c higher luminosity than BEPC I or BEPC II
  - BEPC II/BES III upgrade completion: after 2005
  - Physics priorities in τ-charm region dictate E_{cm}
- ***B*-factories**
  - Charm production not clean like at $D\bar{D}$ threshold
  - Charm measurements will quickly become systematics limited
  - D, D_s branching ratio errors 2-10 times smaller with CLEO-c than *B*-factories
  - Very different systematics (a good thing)

CKM Conclusions

- ***B*-factory appetizers to be followed by full course meal: just wait a few weeks**
  - **Major improvements in *B*-decay msmts. Surprises?**
  - **Treatment of theoretical uncertainties & global fitting techniques are active & important subjects of discussion**
- **HQ models, LQCD will confront %-level *c* & *b* data in a few years: need accurate f_X, $F_X(w)$, B_X**
  - **CLEO-c to provide precision *c*, ψ, ϒ data**
    - **Better precision in *D* BR's necessary for $B \to DX$**
    - **Improve V_{cd} & V_{cs} to the 1% level**
- **%-level metrology of V_{CKM} & very high sensitivity to new physics attainable in ~5 yrs**
- **Whither the SM? It should be fun finding out.**