CKM Quark Flavor Mixing

Implications of the Most Recent Results on CP Violation and Rare Decay Searches in the *B* and *K* Meson Systems

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Reference for recent plots: http://www.slac.stanford.edu/~laplace/ckmfitter.html

Determining the CP-Violating CKM Phase

α ϕ_2

β ϕ_1

γ ϕ_3

CP Violation (CPV) in *B* and *K* Systems:

CPV in interference of decays with and without mixing

CPV in mixing

CPV in interference between decay amplitudes

Neutral B_d and B_s Mixing

Precise Determination of the Matrix Elements $|V_{ub}|$ and $|V_{cb}|$

Detection of Rare Decays:

Search for new physics and direct CPV

Determination of weak phases

The CKM Matrix

Mass eigenstates ≠ Flavor eigenstates → Quark mixing

***B* and *K* mesons decay weakly**

→ modified couplings for charged weak currents:

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

V_{CKM} unitary and complex

4 real parameters (3 angles and 1 phase)

Kobayashi, Maskawa 1973

Wolfenstein Parameterization (expansion in λ ~ 0.2):

$$V_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

CPV phase

"Explicit" CPV in SM, if:

$$J = \mathrm{Im}\left(V_{ij} V_{k\ell} V_{i\ell}^* V_{kj}^*\right) \neq 0$$

(phase invariant!)

Jarlskog 1985

$$J \approx A^2 \lambda^6 \eta \quad \Rightarrow \quad \eta = 0 \Rightarrow \text{ no CPV in SM}$$

Many Ways Lead to the Unitarity Triangle

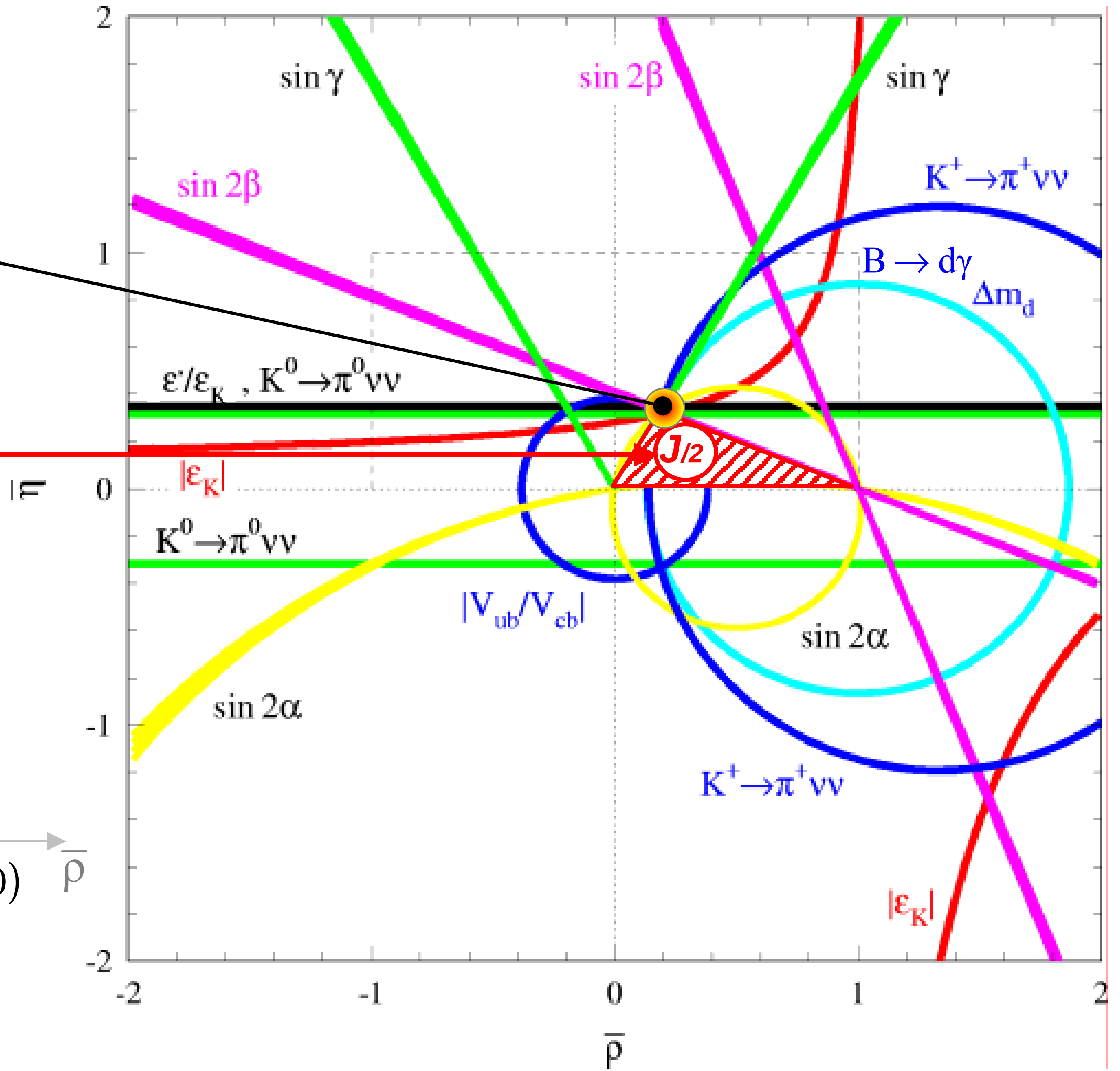
Point of Knowledge:

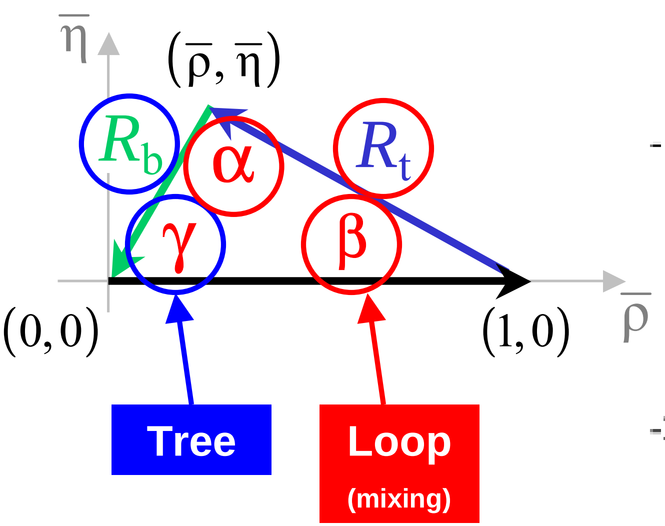
SM or new phases (fields)?

What is the value of

J

in our world?

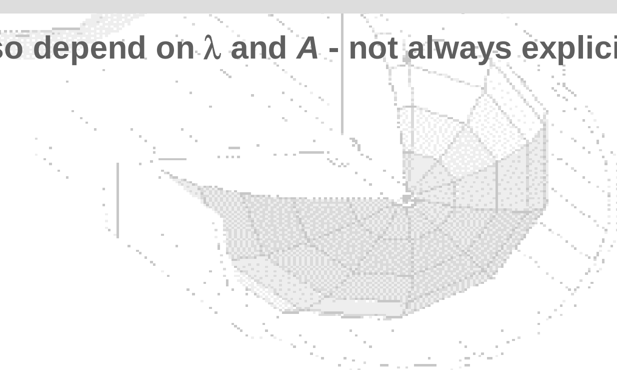




The CKM Matrix: Impact of non-*B* Physics

Observables	CKM Parameters(*)	Experimental Sources	Theoretical Uncertainties	Quality
$\|V_{ud}\|$ $\|V_{us}\|$	λ	nuclear β decay $K^{+(0)} \to \pi^{+(0)} e\nu$	small	* * *
ε_K	$\eta \propto (1-\rho)^{-1}$	$K^0 \to \pi^+\pi^-,\ \pi^0\pi^0$	$B_K,\ \eta_{cc}$	*
$\varepsilon'/\varepsilon_K$	η	$K^0 \to \pi^+\pi^-,\ \pi^0\pi^0$	$B_{6(\text{QCD-peng})},\ B_{8(\text{EW-peng})}$	?
$\mathrm{Im}^2[V^*_{ts} V_{td} \ldots]$	$\propto (\lambda^2 A)^4 \eta^2$	$K^0_L \to \pi^0 \nu\bar{\nu}$	small (but: $(\lambda^2 A)^4$)	* * (*)
$\|V_{td}\|$	$(1-\rho)^2 + \eta^2$	$K^+ \to \pi^+ \nu\bar{\nu}$	charm loop (and: $(\lambda^2 A)^4$)	* (*)

(*) Observables may also depend on λ and *A* - not always explicitly noted



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The CKM Matrix: Present Impact of *B* Physics

Observables	CKM Parameters(*)	Experimental Sources	Theoretical Uncertainties	Quality
Δm_d ($\lvert V_{td} \rvert$)	$(1-\rho)^2 + \eta^2$	$B_d \bar{B}_d \to f^+ f^- + X$, X_{RECO}	$f_{B_d}\sqrt{B_d}$	*
Δm_s ($\lvert V_{ts} \rvert$)	A	$B_s \to f^+ + X$	$\xi = f_{B_s}\sqrt{B_s}/f_{B_d}\sqrt{B_d}$	* *
$\sin 2\beta$	ρ, η	$B_d \to c\bar{c}\, s\bar{d}$	small	* * *
$\sin 2\alpha$	ρ, η	$B_d \to \pi^+(\rho^+)\, \pi^-$	Strong phases, penguins	?
γ	ρ, η	$B^+ \to D^0 K^+$	small	* *
		$b \to u$, Direct CPV	Strong phases, penguins	?
$\lvert V_{cb} \rvert$	A	$b \to c l \nu$ (excl. / incl.)	$F_{D^*}(1)$ / OPE	* *
$\lvert V_{ub} \rvert$	$\rho^2 + \eta^2$	$b \to u l \nu$ (excl. / incl.)	Model / OPE	*
$\lvert V_{td} \rvert$	$(1-\rho)^2 + \eta^2$	$B_d \to \rho\, \gamma$	Model (QCD FA)	?
$\lvert V_{ts} \rvert$	A (NP)	$B_d \to X_s$ ($K^{(*)}$) γ, $K^{(*)}\, l^+ l^-$ (FCNC)	Model	?
$\lvert V_{ub} \rvert$, f_{Bd}	$\rho^2 + \eta^2$	$B^+ \to \tau^+ \nu$	f_{Bd}	* *

(*) Observables may also depend on λ and A - not always explicitly noted

Extracting the CKM Parameters

Measurement → Constraints on theoretical parameters

x_{exp}

Theoretical predictions

$y_{theo} = (A, \lambda, \rho, \eta, m_t, \ldots)$

$x_{theo}(y_{model} = y_{theo}, y_{QCD})$

$y_{QCD} = (B_K, f_B, B_{Bd}, \ldots)$

$$\text{“}\chi^2\text{”} = -2 \ln L(y_{model})$$

$$L(y_{model}) = L_{exp}[x_{exp} - x_{theo}(y_{model})] \times L_{theo}(y_{QCD})$$

Assumed to be **Gaussian**

« Guesstimates »

Frequentist: *Rfit*

Uniform likelihoods: *Ranges*

Bayesian

Probabilities

Three Step CKM Analysis

CKM fitter
fit package

Probing the SM

Test: “Goodness-of-fit”

- Evaluate global minimum
  $\chi^2_{\mathrm{min};y_{\mathrm{mod}}}(y_{\mathrm{mod\text{-}opt}})$
- Fake perfect agreement:
  $x_{\mathrm{exp\text{-}opt}} = x_{\mathrm{theo}}(y_{\mathrm{mod\text{-}opt}})$
  generate x_{exp} using $\mathcal{L}_{\mathrm{exp}}$
- Perform many toy fits:
  $\chi^2_{\mathrm{min\text{-}toy}}(y_{\mathrm{mod\text{-}opt}}) \rightarrow F(\chi^2_{\mathrm{min\text{-}toy}})$

$$\mathrm{CL(SM)} \leq \int_{\chi^2 \geq \chi^2_{\mathrm{min};y_{\mathrm{mod}}}}^{\infty} F\left(\chi^2\right) d\chi^2$$

Metrology

- Define:
  $y_{\mathrm{mod}} = \{a;\ \mu\}$
  $= \{\rho,\ \eta,\ A, \lambda, y_{\mathrm{QCD}}, \ldots\}$
- Set Confidence Levels in $\{a\}$ space, irrespective of the μ values
- Fit with respect to $\{\mu\}$
  $\chi^2_{\mathrm{min};\,\mu}(a) = \min_{\mu}\{\chi^2(a,\ \mu)\}$
- $\Delta\chi^2(a) = \chi^2_{\mathrm{min};\,\mu}(a) - \chi^2_{\mathrm{min};y_{\mathrm{mod}}}$

$$\mathrm{CL}(a) = \mathrm{Prob}(\Delta\chi^2(a),\ N_{\mathrm{dof}})$$

Test New Physics

- If CL(SM) good

Obtain limits on New Physics parameters

- If CL(SM) bad

Hint for New Physics ?!

AH, H. Lacker, S. Laplace, F. Le Diberder
EPJ C21 (2001) 225, [hep-ph/0104062]

Inputs Before FPCP'02 (status: Moriond 2002)

Tree process ➔ no New Physics

$\|V_{ud}\|$	0.97394 ± 0.00089	*neutron & nuclear β decay*
$\|V_{us}\|$	0.2200 ± 0.0025	*$K \to \pi l \nu$*
$\|V_{cd}\|$	0.224 ± 0.014	*dimuon production: νN (DIS)*
$\|V_{cs}\|$	0.969 ± 0.058	*$W \to XcX$ (OPAL)*
$\|V_{ub}\|$	$(4.08 \pm 0.61 \pm 0.47) \times 10^{-3}$	*LEP inclusive*
$\|V_{ub}\|$	$(4.08 \pm 0.56 \pm 0.40) \times 10^{-3}$	*CLEO inclusive & moments $b \to s\gamma$*
$\|V_{ub}\|$	$(3.25 \pm 0.29 \pm 0.55) \times 10^{-3}$	*CLEO exclusive*
		$\to$ product of likelihoods for $\langle\|V_{ub}\|\rangle$
$\|V_{cb}\|$	$(40.4 \pm 1.3 \pm 0.9) \times 10^{-3}$	*Excl./Incl.+CLEO Moment Analysis*
ε_K	$(2.271 \pm 0.017) \times 10^{-3}$	*PDG 2000*
Δm_d	(0.496 ± 0.007) ps^{-1}	*BABAR,Belle,CDF,LEP,SLD (2002)*
Δm_s	Amplitude Spectrum'02	*LEP, SLD, CDF (2002)*
$\sin 2\beta$	0.78 ± 0.08	*WA, Updates Moriond'02 BABAR and Belle included*

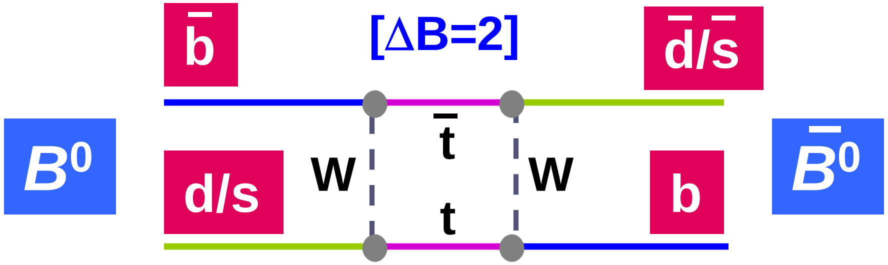
Standard CKM fit in hand of lattice QCD

$m_t(\overline{MS})$	(166 ± 5) GeV/c^2	*CDF, D0, PDG 2000*
$f_{Bd}\sqrt{B_d}$	$(230 \pm 28 \pm 28)$ MeV	*Lattice 2000*
ξ	$1.16 \pm 0.03 \pm 0.05$	*Lattice 2000*
B_K	$0.87 \pm 0.06 \pm 0.13$	*Lattice 2000*

+ other parameters with less relevant errors…

$B^0\bar{B}^0$ Mixing

Effective FCNC Processes (CP conserving):



whose oscillation frequencies $\Delta m_{d/s}$ are computed by:

Perturbative QCD

CKM Matrix Elements

$$\Delta m_q = \frac{G_F^2}{6\pi^2} m_{B_q} m_W^2 \, \eta_B S(x_t) \, f_{B_q}^2 B_q \left| V_{tq} V_{tb}^* \right|^2 \approx 0.5 \text{ ps}^{-1}$$

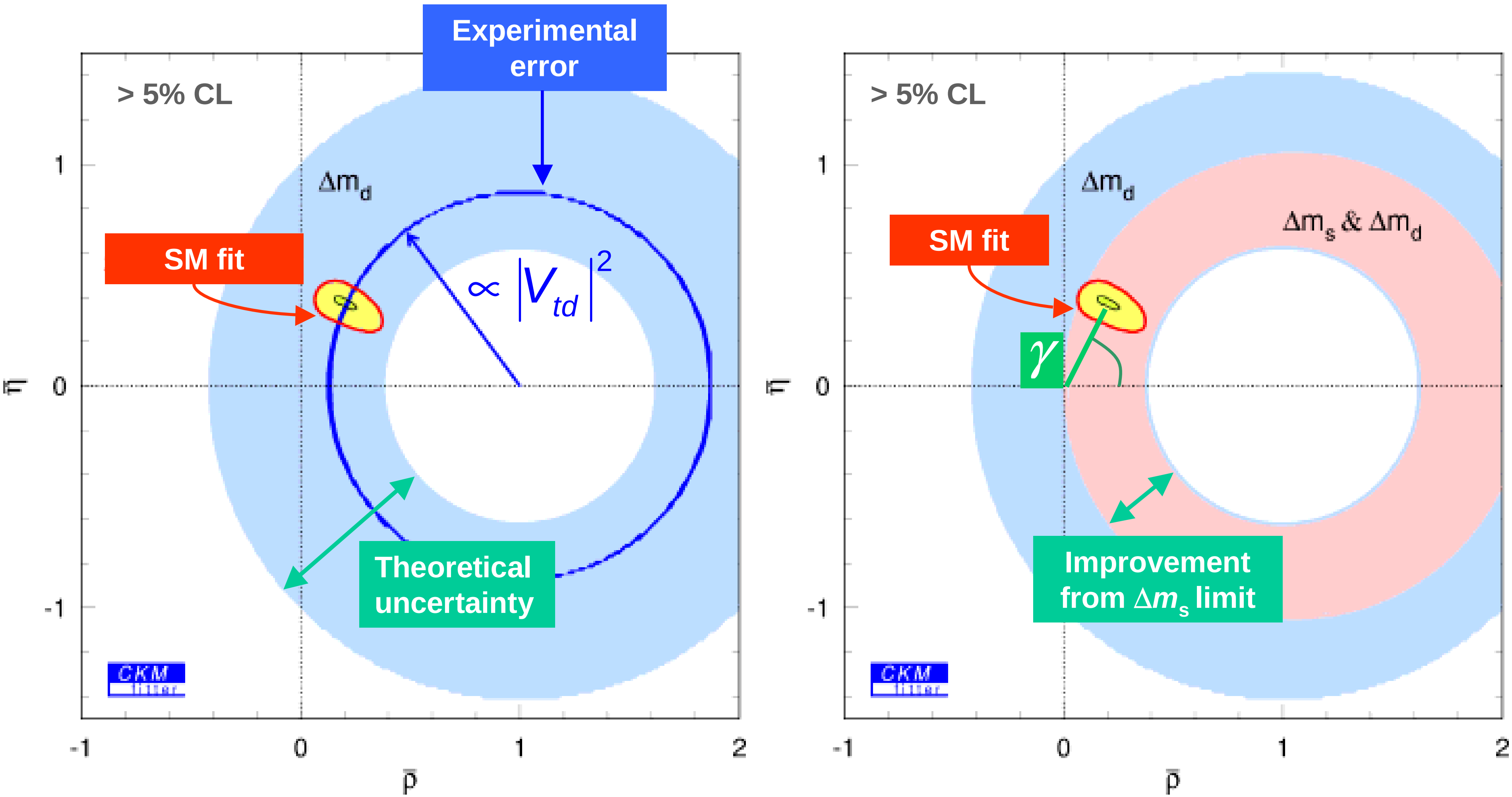
mit: $q = s, d$

Lattice QCD (eff. 4 fermion operator)

Important theoretical uncertainties: $\sigma_{\text{rel}}\left(f_{B_{d/s}}^2 B_{d/s}\right) \sim 36\%$

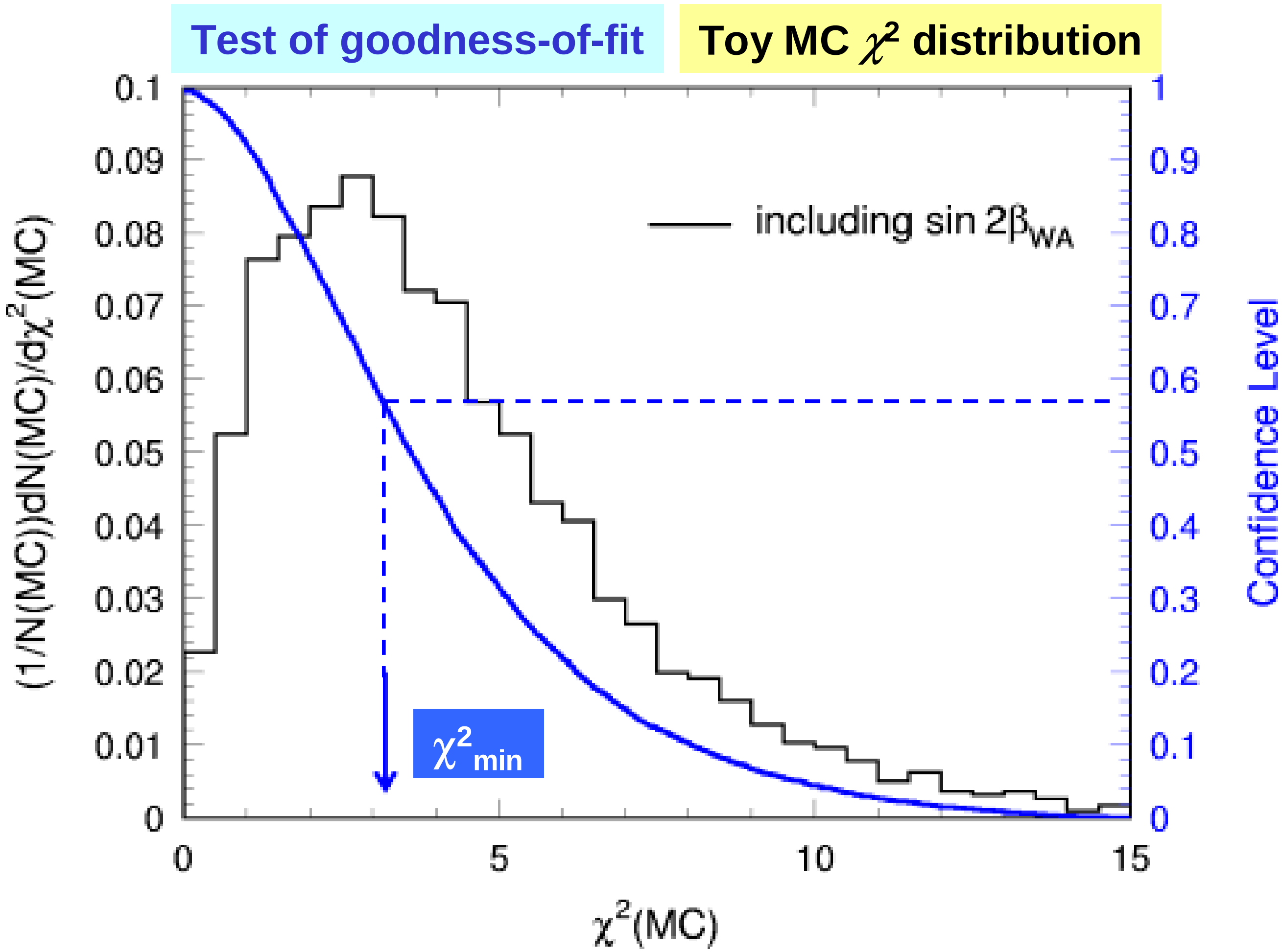
Improved error from Δm_s measurement: $\sigma_{\text{rel}}\left(\xi^2 = f_{B_s}^2 B_s / f_{B_d}^2 B_d\right) \sim 10\%$

Using Δm_s



Waiting for a Δm_s measurment at Tevatron...

Probing the Standard Model

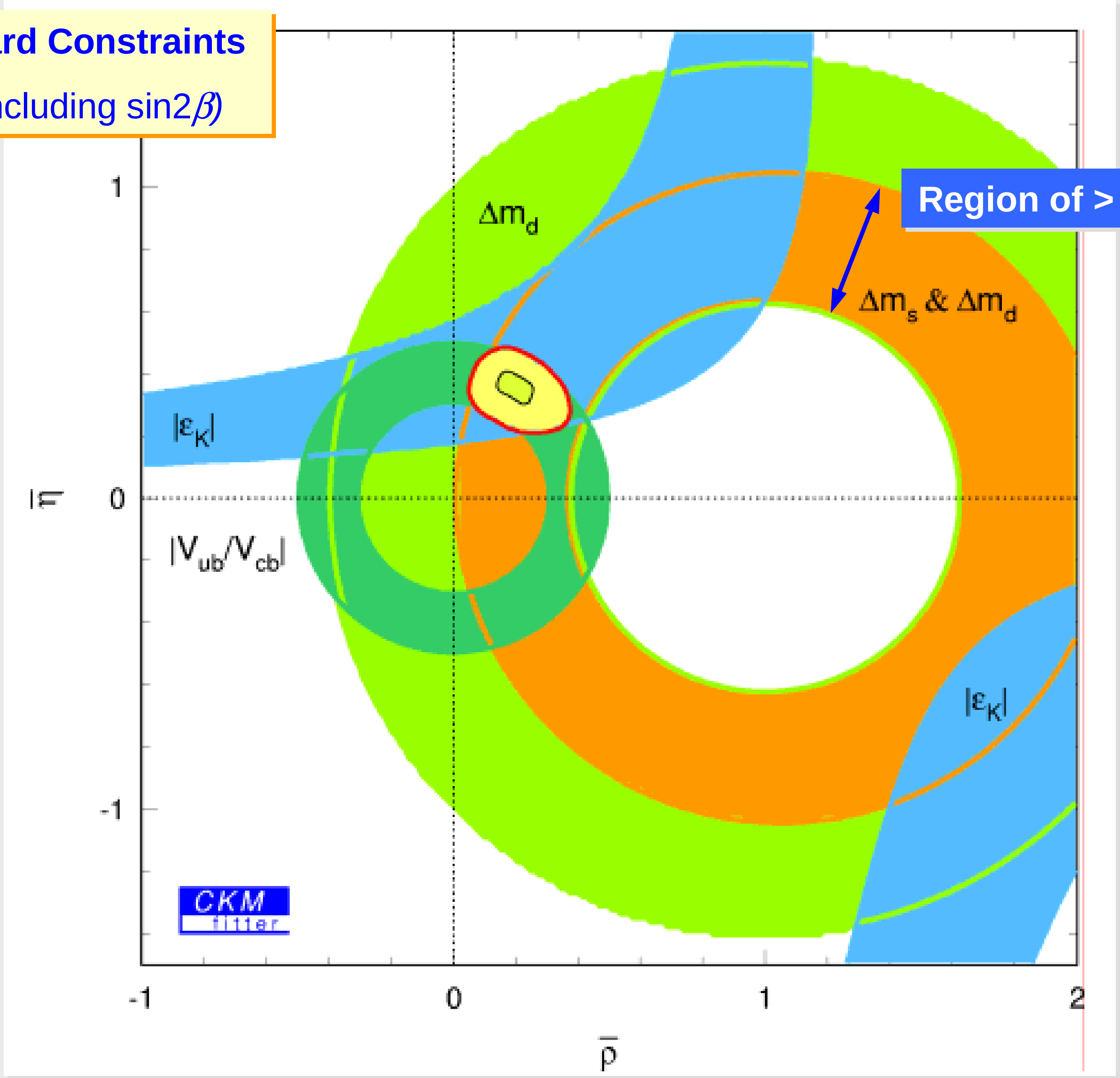


Confidence Level of Standard Model: CL(SM) = 57%

Metrology (I)

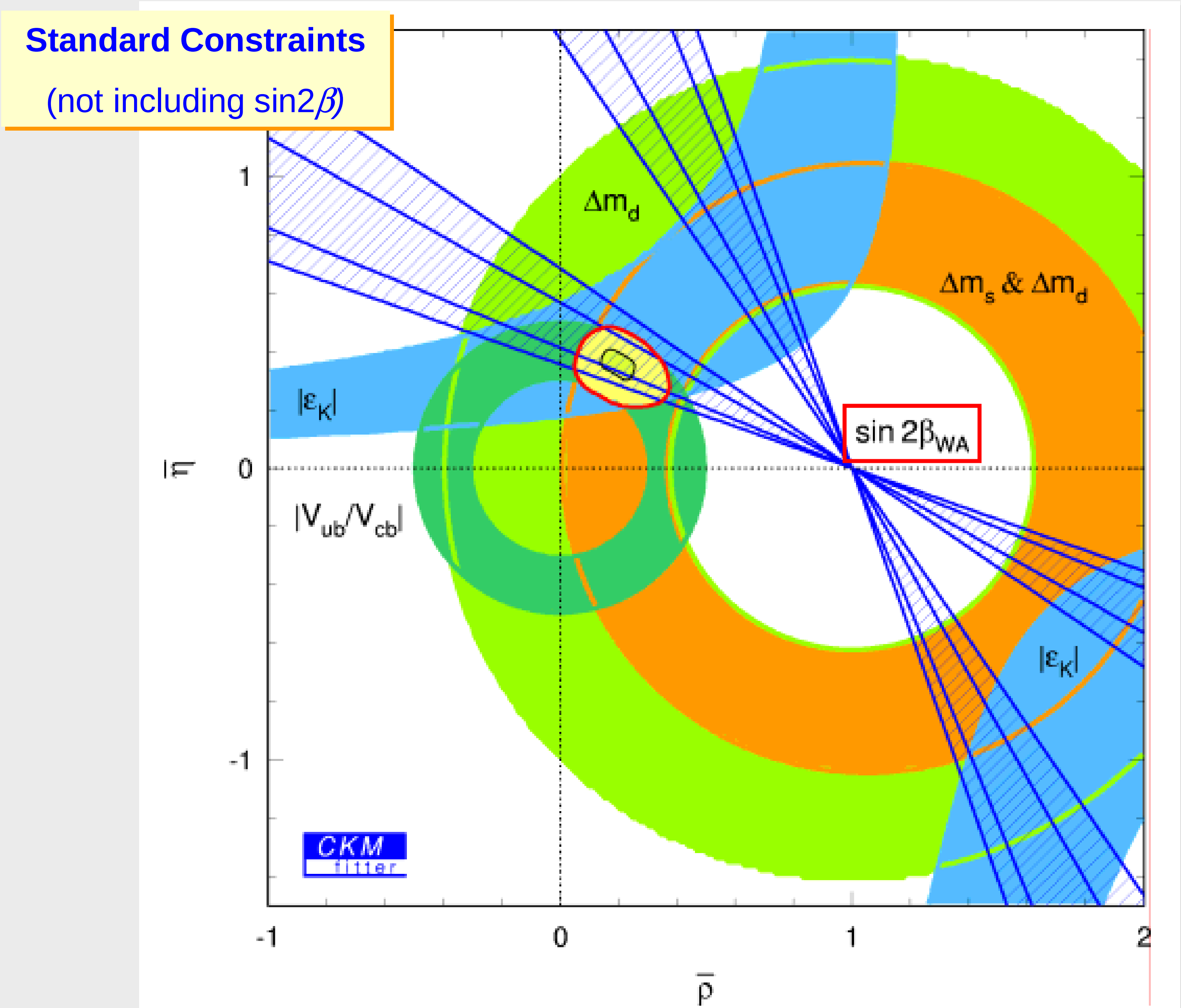
Standard Constraints

(not including sin2β)



Region of > 5% CL

Metrology (I)



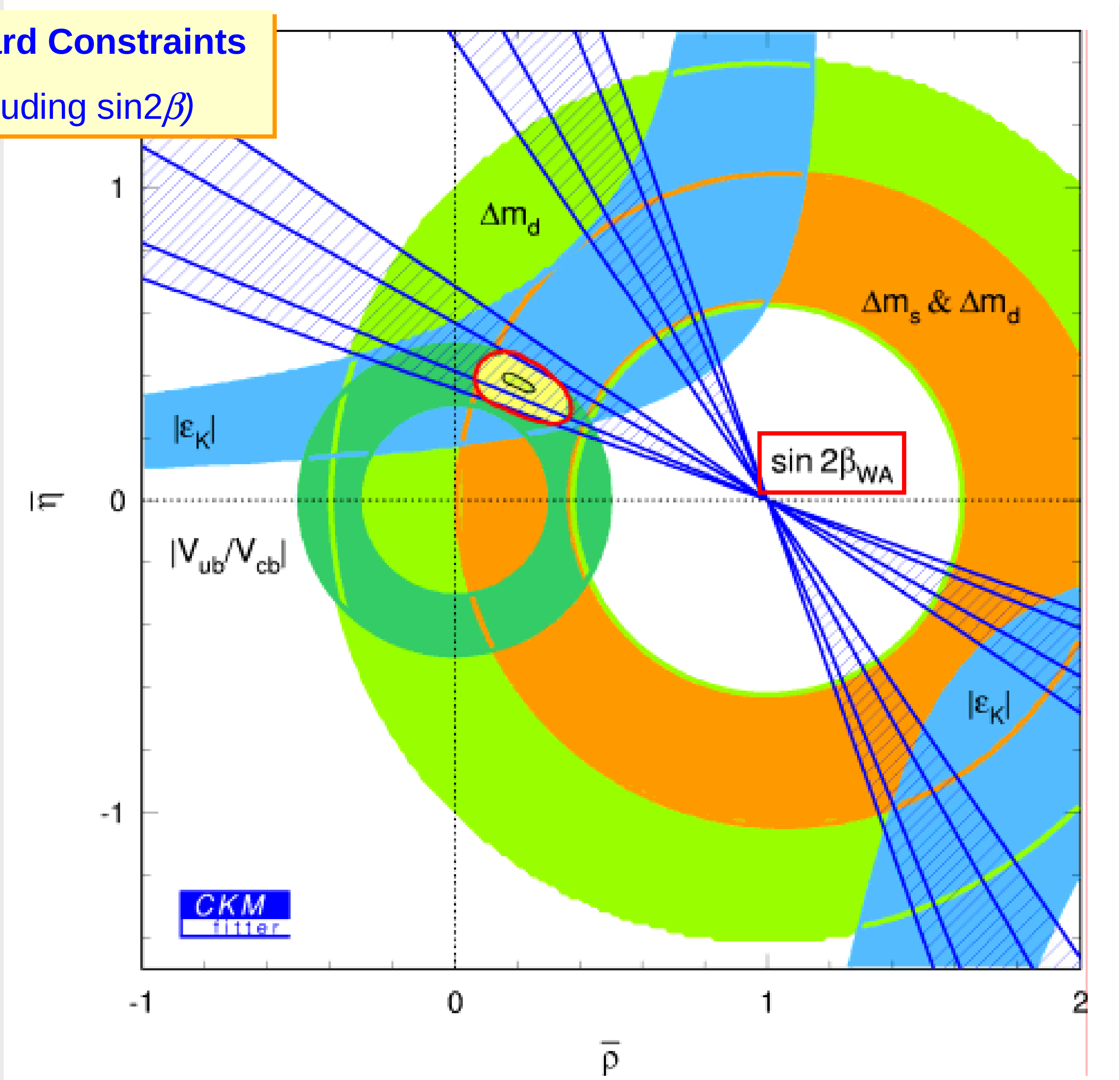
A TRIUMPH FOR THE STANDARD MODEL AND THE KM PARADIGM !

KM mechanism most probably dominant source of CPV at EW scale

Metrology (I)

Standard Constraints

(including sin2β)



sin2β already provides one of the most precise and robust constraints

- **How to improve these constraints?**
- **How to measure the missing angles ?**

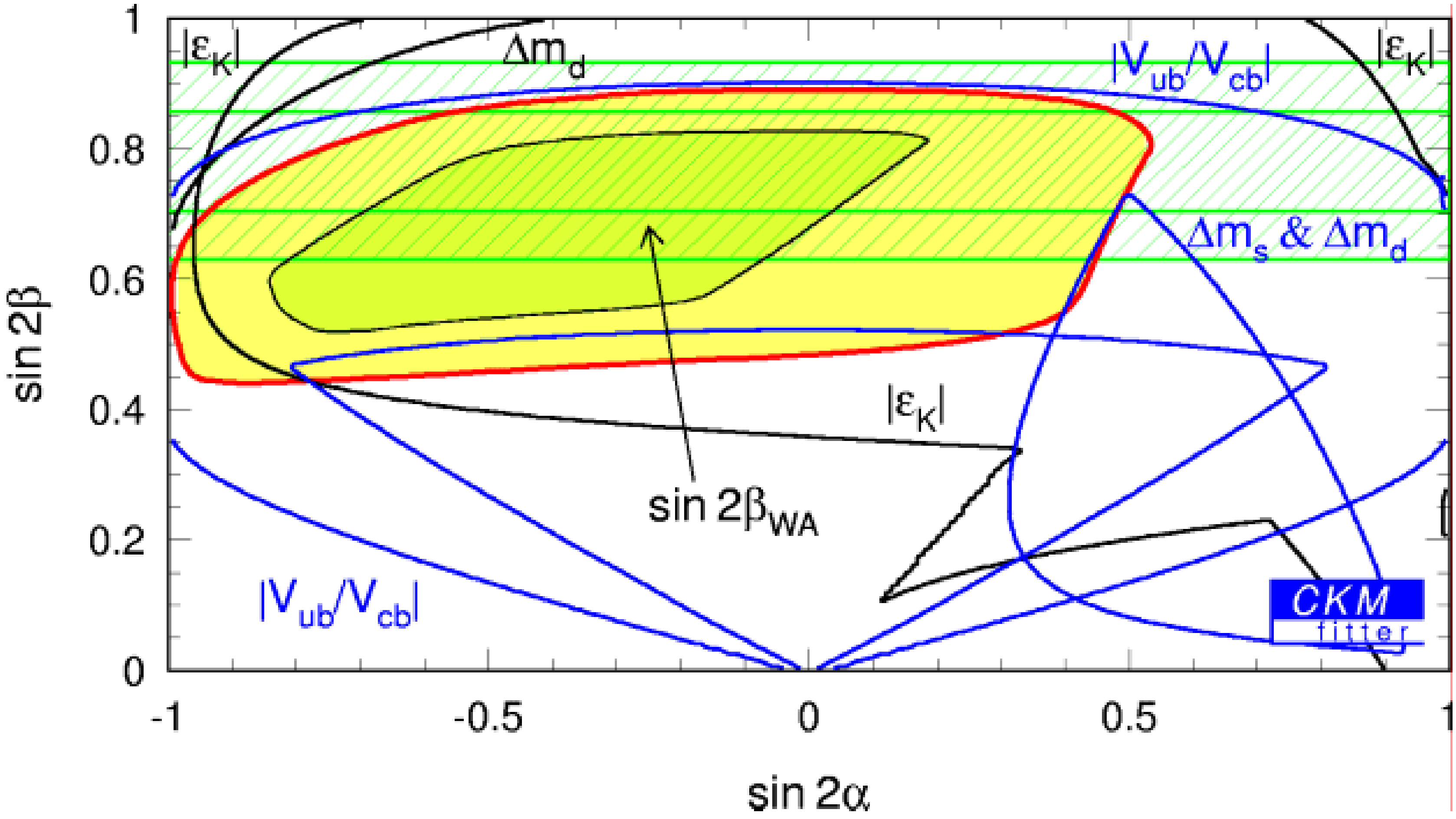
...

Metrology (II): the sin(2α) - sin(2β) Plane

Standard Constraints

(not including sin2β)

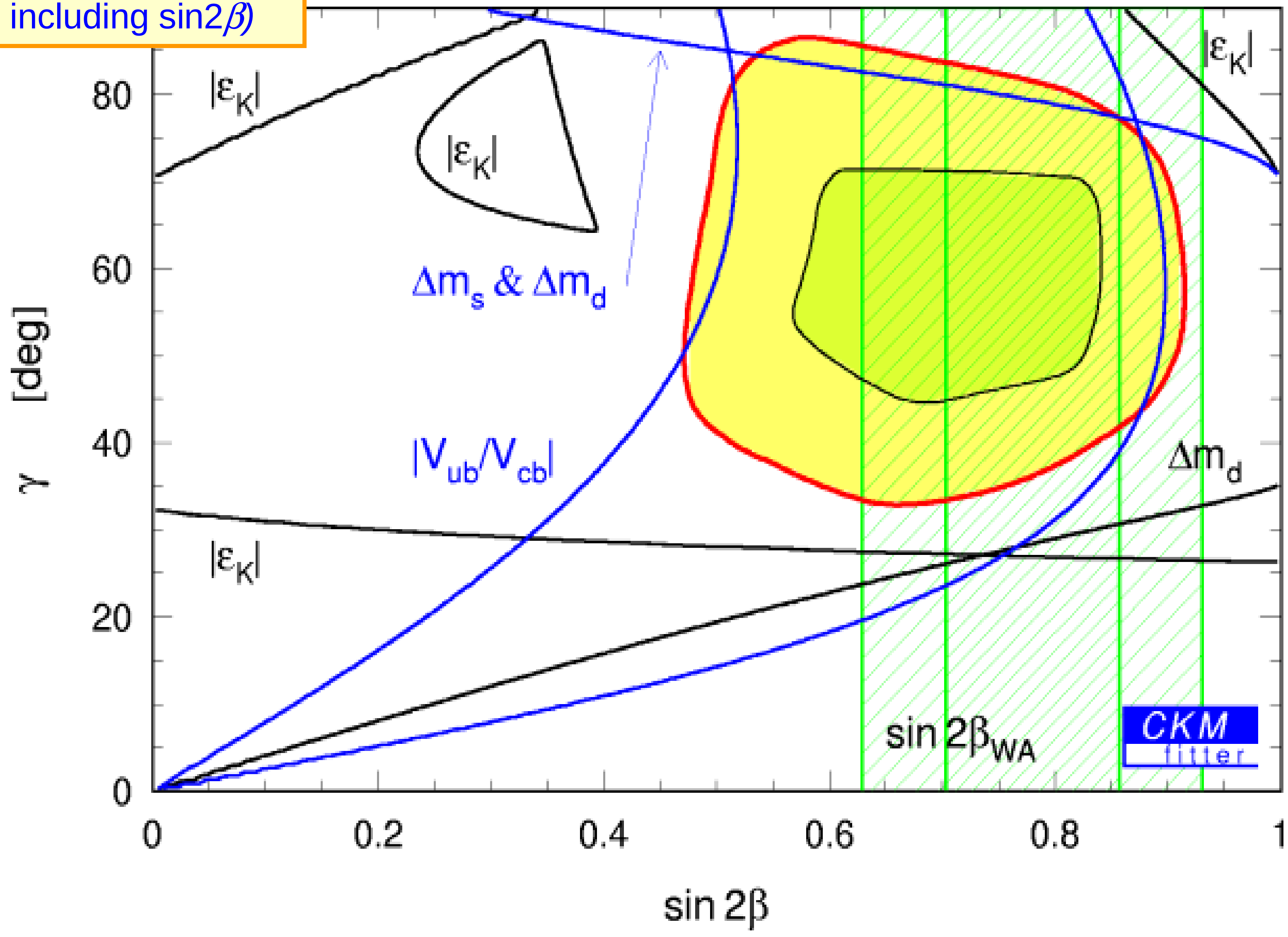
Be aware of ambiguities !



Metrology (II): the sin(2β) - γ Plane

Standard Constraints

(not including sin2β)



Metrology (III): Selected Numerical Results

CKM and UT Parameters

Parameter	95% CL region
λ	0.2221 ± 0.0041
A	0.76 - 0.90
ρ	0.08 - 0.35
η	0.28 - 0.45
J	$(2.2 - 3.5) \times 10^{-5}$
$\sin(2\alpha)$	– 0.81 - 0.43
$\sin(2\beta)$	0.64 - 0.84
α	77° - 117°
β	19.9° - 28.6°
γ	40° - 78°

Rare Branching Fractions

Observable	95% CL region
$BR(K_L \to \pi^0 \nu\nu)$	$(1.6 - 4.2) \times 10^{-11}$
$BR(K^+ \to \pi^+ \nu\nu)$	$(5.1 - 8.4) \times 10^{-11}$
$BR(B^+ \to \tau^+ \nu)$	$(7.2 - 22.1) \times 10^{-5}$
$BR(B^+ \to \mu^+ \nu)$	$(2.9 - 8.7) \times 10^{-7}$

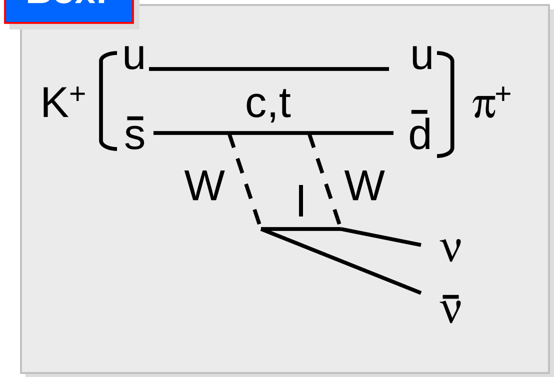
Theory Parameters(*)

Observable	95% CL region
m_t	(104 - 380) GeV/c^2
$f_{Bd}\sqrt{B_d}$	(199 - 282) MeV
B_K	0.59 - 1.55

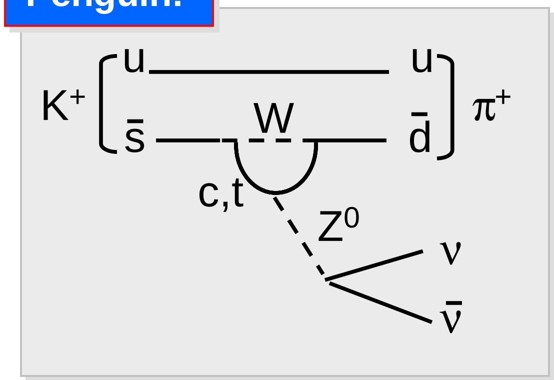
(*) Without using a priori information

Constraint from Rare Kaon Decays: $K^+ \to \pi^+ \nu\bar{\nu}$

Box:



Penguin:



Buchalla, Buras, Nucl.Phys. B548 (1999) 309

$$BR\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \propto \frac{BR\left(K^+ \to \pi^0 e^+ \nu\right)}{|V_{us}|^2} \sum_{l=e,\mu,\tau} \left| V_{cs}{}^* V_{cd} X^l_{NL} + V_{ts}{}^* V_{td} X(x_t) \right|^2$$

top contribution — *charm contribution*

$$BR\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \propto \lambda^8 A^4 X^2(x_t) \frac{1}{\sigma}\left[\left(\sigma\bar{\eta}\right)^2 + \left(\rho_0 - \bar{\rho}\right)^2\right]$$

ellipse

Main theoretical uncertainty comes from charm contribution

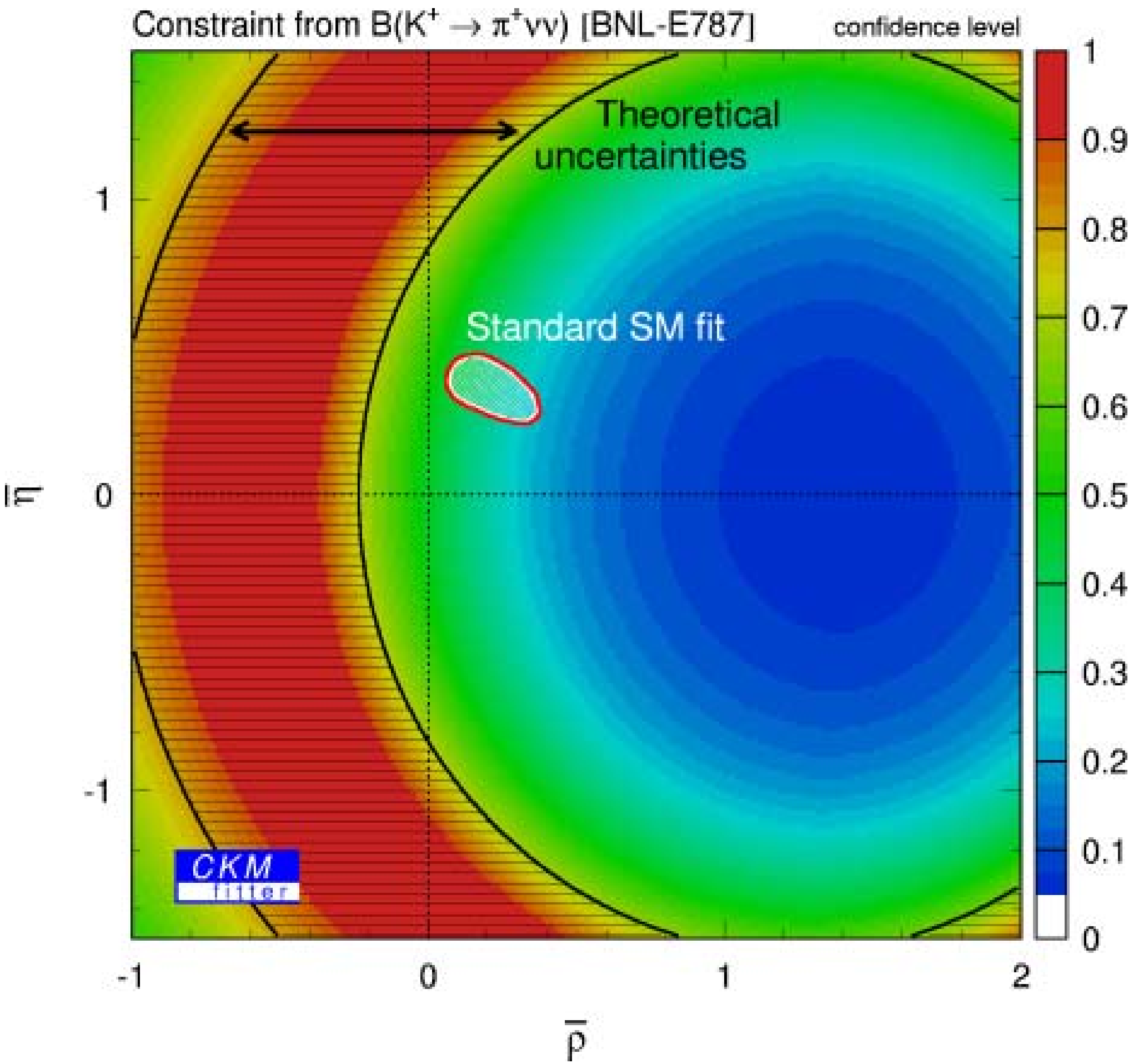
Experiment:

Two events observed at BNL (E787), yielding:

$$\boldsymbol{B\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(1.57\,^{+1.75}_{-0.82}\right) \times 10^{-10}}$$

E787 (BNL-68713)
hep-ex/0111091

Constraint from Rare Kaon Decays: $K^+ \to \pi^+ \nu\nu$



At present dominated by experimental errors.

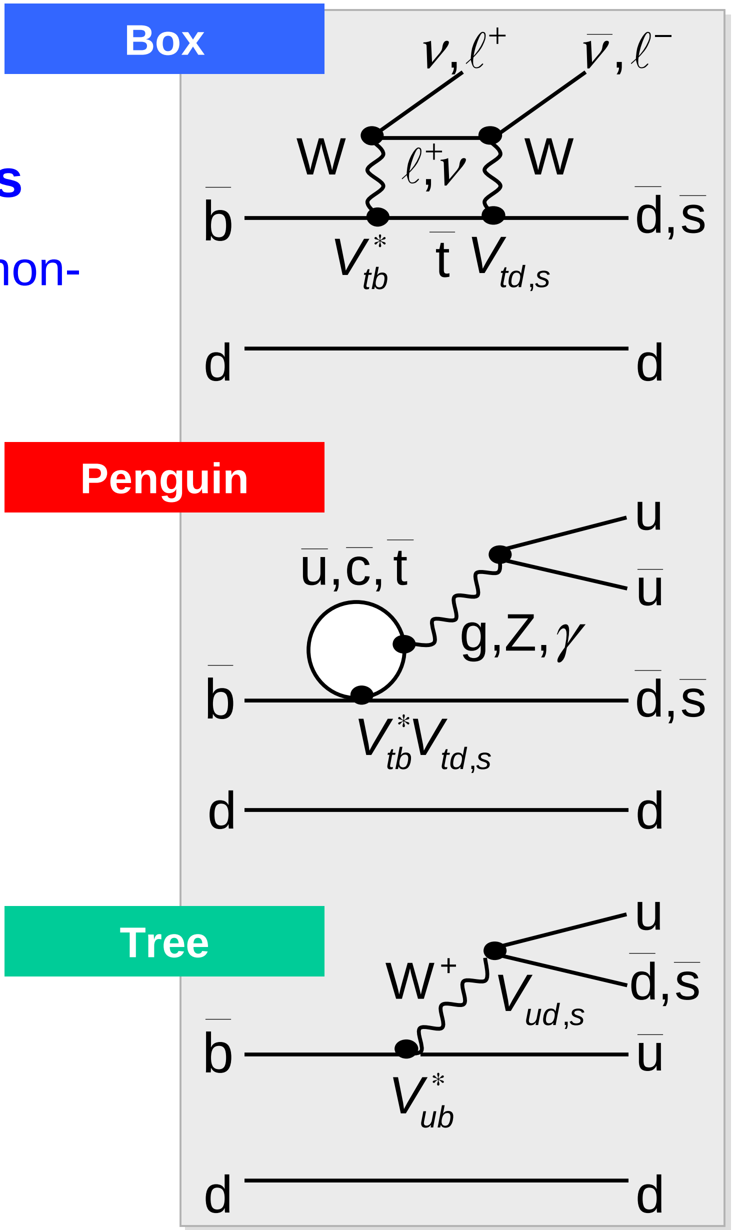
<u>However:</u>
uncertainties on $|V_{cb}|^4=\lambda^8 A^4$ will become important for constraints in the ρ-η plane

Rare Charmless B Decays

We distinguish two Categories:

- **Semileptonic (FCNC) and radiative decays**
  - $(G_F)^2\alpha$ increased compared to loop-induced non-radiative decays $\propto (G_F\,\alpha)^2$
  - Sensitive sondes for new physics (SUSY, right-handed couplings, ...)
  - Determination of $|V_{td}|$ and $|V_{ts}|$
  - Determination of HQET parameters
  - Search for direct CP asymmetry

- **Hadronic $b \rightarrow u(d)$ decays**
  - Measurement of CPV
  - Determination of UT angles α and γ
  - Test der *B* decay dynamics (Factorization)



Radiative *B* Decays

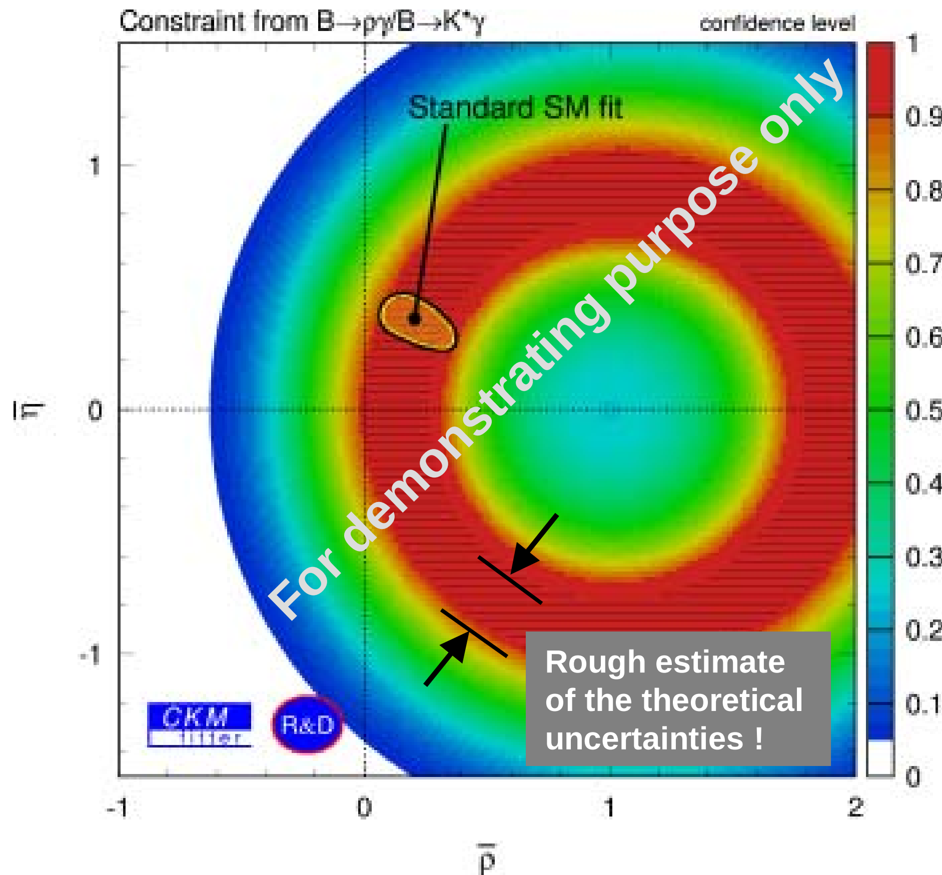
The ratio of the rates $B \to \rho\gamma$ to $B \to K^*\gamma$ can be predicted more cleanly than the individual rates: determines $|V_{td}|$

$$\frac{\mathrm{BR}(B \to \rho\gamma)}{\mathrm{BR}(B \to K^*\gamma)} \propto \left|\frac{V_{td}}{V_{ts}}\right|^2 \zeta^2 \left(1 + \Delta R_{\mathrm{NP}}\right)$$

Ali, Parkhomenko, EPJ C23 (2002) 89
see also :
Bosch, Buchalla, NP B621 (2002) 459

$$\zeta = 0.76 \pm 0.06\ ,\quad \Delta R_{\mathrm{NP}} < 0.15$$

Source	$B^0 \to \rho^0\gamma$ (BR×10⁻⁶)	$B^+ \to \rho^+\gamma$ (BR×10⁻⁶)
Ali, Parkhomenko	0.5 ± 0.2	0.9 ± 0.4
Bosch, Buchalla	0.8 ± 0.3	1.5 ± 0.5
BABAR	< 1.5	< 2.8
Belle	< 1.0	< 1.1
CLEO	< 1.7	< 1.3



Charmless *B* Decays into two Pseudoscalars

[Constraining α and γ?!]

$B \to K\pi$ and the Determination of γ

Interfering contributions of tree and penguin amplitudes:

$$A_{K\pi} \propto P + \lambda^2 e^{i\gamma} T$$

➡ Potential for significant direct CPV

CP averaged BRs and measurements of direct CPV determine the angle γ

Fleischer, Mannel (98)
Gronau, Rosner, London (94, 98)
Neubert, Rosner (98)
Buras, Fleischer (98)
Beneke, Buchalla, Neubert, Sachrajda (01)
Keum, Li, Sanda (01)
Ciuchini et al. (01)
...list by far not exhaustive!

➔ see contributions at this conference

Theoretical analysis deals with:

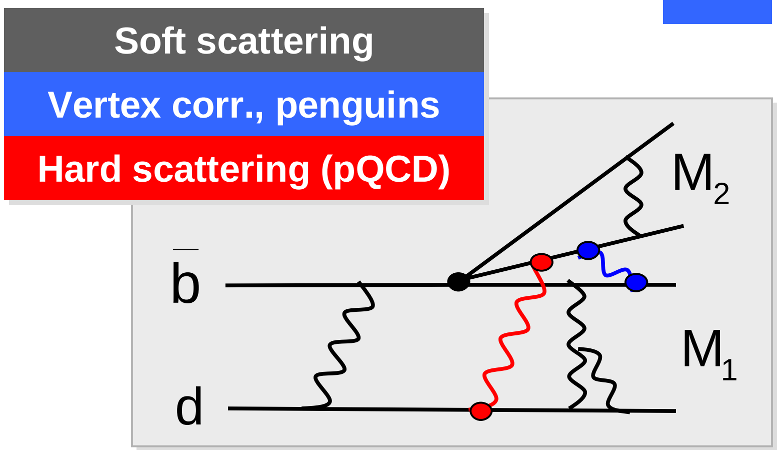
- SU(3) breaking
- Rescattering (FSI)
- EW penguins

The tool is: QCD Factorization...

... based on *Color Transparancy*

- Large energy release
- soft gluons do not interact with small qq-bar color dipole of emitted mesons
- non-fact. contributions are calculable in pQCD perfect for $m_b \to \infty$.

Higher order corrections: (Λ_{QCD}/m_b)



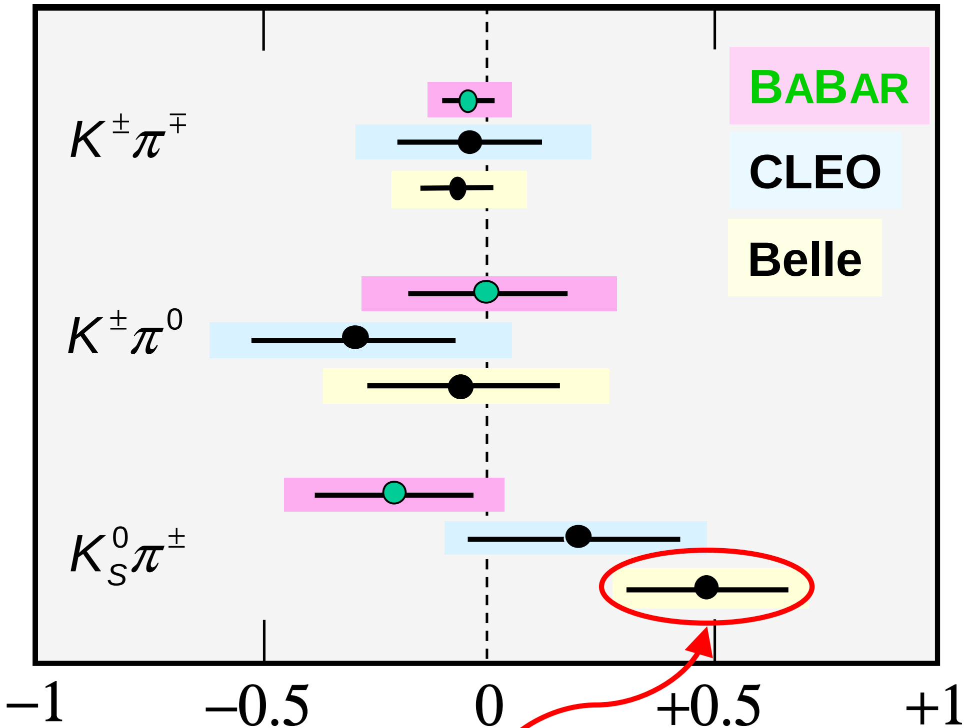
Branching Fractions for $B \to \pi\pi / K\pi$

Updated Belle (La Thuile'02)
Updated BABAR (Moriond EW'02)

BR ($\times 10^6$)	CLEO 9 fb^{-1}	BABAR up to 56 fb^{-1}	Belle 32 fb^{-1}	World average
$B^0 \to \pi^+\pi^-$	$4.3^{+1.6}_{-1.4} \pm 0.5$	$5.4 \pm 0.7 \pm 0.4$	$5.1 \pm 1.1 \pm 0.4$	**5.17 ± 0.62**
$B^0 \to K^+\pi^-$	$17.2^{+2.5}_{-2.4} \pm 1.2$	$17.8 \pm 1.1 \pm 0.8$	$21.8 \pm 1.8 \pm 1.5$	**18.6 ± 1.1**
$B^0 \to K^+K^-$	< 1.9 (90%)	< 1.1 (90%)	< 0.5 (90%)	
$B^+ \to \pi^+\pi^0$	$5.6^{+2.6}_{-2.3} \pm 1.7$	$5.1 \pm 2.0 \pm 0.8$	$7.0 \pm 2.2 \pm 0.8$	**5.9 ± 1.4**
$B^+ \to K^+\pi^0$	$11.6^{+3.0\,+1.4}_{-2.7\,-1.3}$	$10.8 \pm 2.1 \pm 1.0$	$12.5 \pm 2.4 \pm 1.2$	**11.5 ± 1.5**
$B^+ \to K^0\pi^+$	$18.2^{+4.6}_{-4.0} \pm 1.6$	$18.2 \pm 3.3 \pm 2.0$	$18.8 \pm 3.0 \pm 1.5$	**$18.5^{+2.3}_{-2.2}$**
$B^0 \to K^0\pi^0$	$14.6^{+5.9\,+2.4}_{-5.1\,-3.3}$	$8.2 \pm 3.1 \pm 1.2$	$7.7 \pm 3.2 \pm 1.6$	**8.9 ± 2.3**
$B^0 \to \pi^0\pi^0$	< 5.7 (90%)	< 3.4 (90%)	< 5.6 (90%)	

Agreement among experiments. Most rare decay channels discovered

Direct CP Asymmetries in $K\pi$ Modes



Are annihilation contributions important?

Agreement among experiments.
No significant deviation from zero.

BABAR: **BABAR** Moriond'02

$A_{CP}(K^+\pi^-) = -0.05 \pm 0.06 \pm 0.01$
$A_{CP}(K^+\pi^0) = +0.00 \pm 0.18 \pm 0.04$
$A_{CP}(K^0\pi^+) = -0.21 \pm 0.18 \pm 0.03$

Belle: **BELLE** La Thuile'02

$A_{CP}(K^+\pi^-) = -0.06 \pm 0.08 \pm 0.08$
$A_{CP}(K^+\pi^0) = -0.04 \pm 0.19 \pm 0.03$
$A_{CP}(K^0\pi^+) = +0.46 \pm 0.15 \pm 0.02$

CLEO: **CLEO** PRL 85 (2000) 525

$A_{CP}(K^+\pi^-) = -0.04 \pm 0.16$
$A_{CP}(K^+\pi^0) = -0.29 \pm 0.23$
$A_{CP}(K^0\pi^+) = +0.18 \pm 0.24$

World averages:

$A_{CP}(K^+\pi^-) = -0.05 \pm 0.05$
$A_{CP}(K^+\pi^0) = -0.09 \pm 0.12$
$A_{CP}(K^0\pi^+) = +0.18 \pm 0.10$

Bounds on γ

Ratios of CP averaged branching fractions can lead to bounds on γ:

Fleischer, Mannel PRD D57 (1998) 2752

FM bound:

$$R = \frac{\tau(B^+)}{\tau(B^0)} \cdot \frac{BR(K^\pm \pi^\mp)}{BR(K^0 \pi^\pm)} = 1.07\,^{+0.15}_{-0.12}$$

< 1 ? ➔ no constraint

Buras, Fleischer EPJ C11 (1998) 93

BF bound:

$$R_n = \frac{1}{2}\frac{BR(K^\pm \pi^\mp)}{BR(K^0 \pi^0)} = 1.04\,^{+0.37}_{-0.22}$$

$\neq 1$? ➔ no constraint

Neubert, Rosner PL B441 (1998) 403

NR bound:

$$R_*^{-1} = 2\frac{BR(K^\pm \pi^0)}{BR(K^0 \pi^\pm)} = 1.24\,^{+0.24}_{-0.21}$$

$\neq 1$? ➔ no constraint

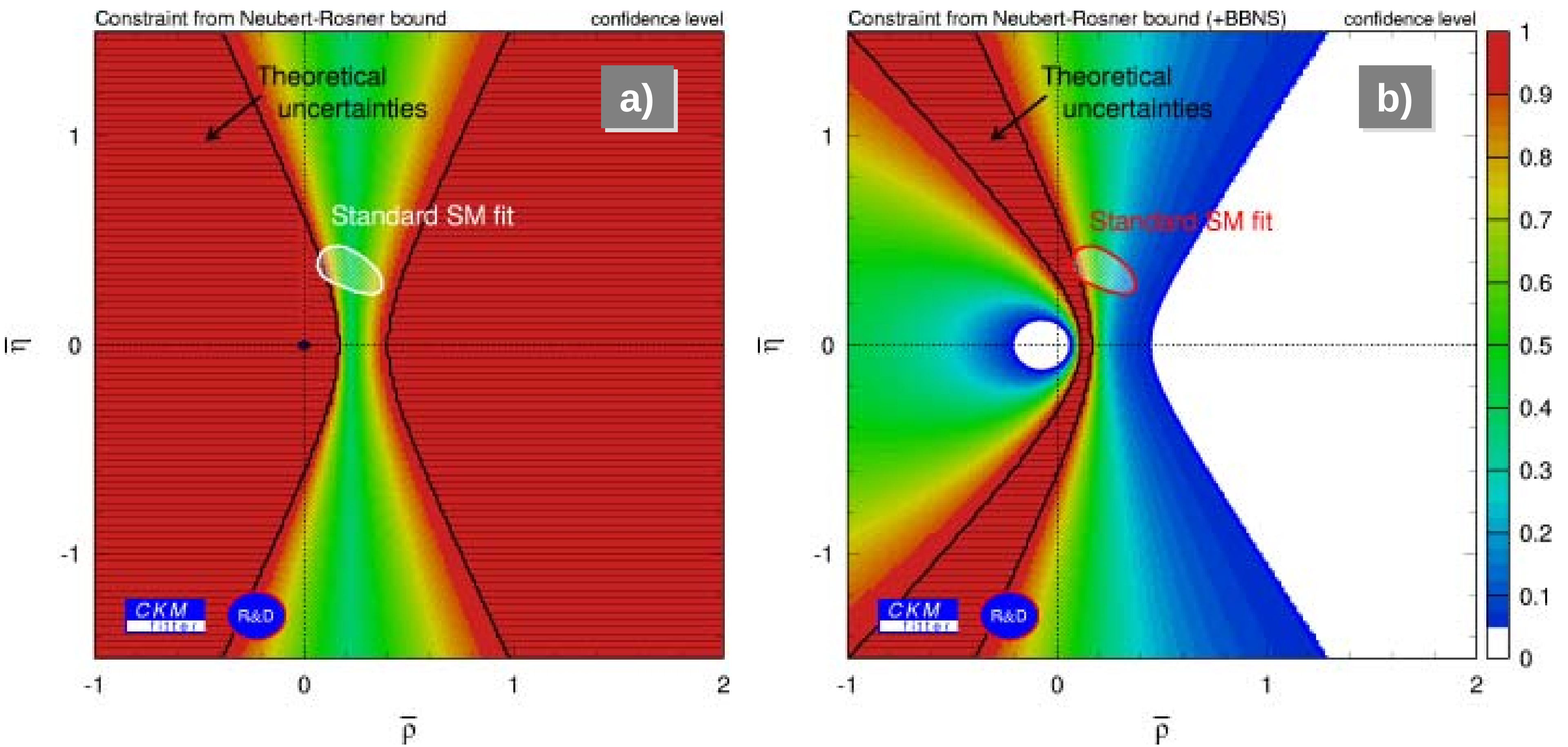
➔ See also recent *Bayesian* analysis: **Bargiotti et al.** hep-ph/0204029

Neubert-Rosner Bound

a) $T/P \rightarrow \bar{\varepsilon}_{3/2} = R_{th} \cdot \tan\theta_c \frac{f_K}{f_\pi} \sqrt{\frac{2 \cdot BR(\pi^\pm \pi^0)}{BR(K^0 \pi^\pm)}} = R_{th}(\text{SU(3),BBNS}) \cdot (0.221 \pm 0.028)$

Tree: $\pi^\pm \pi^0$ — Penguin: $K^0 \pi^\pm$

b) QCD FA: small relative strong phases



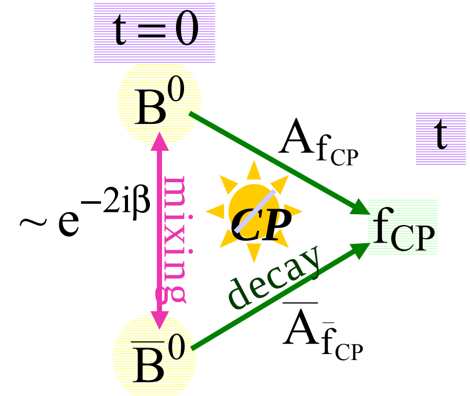
CP Violation in $B^0 \to \pi^+\pi^-$ Decays

$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$

ratio of amplitudes

CP eigenvalue

$\approx e^{-2i\beta}$

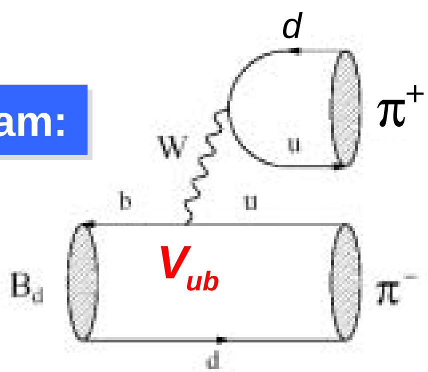


$$A_{f_{CP}}(t) \propto C_{f_{CP}} \cos(\Delta m_d t) + S_{f_{CP}} \sin(\Delta m_d t)$$

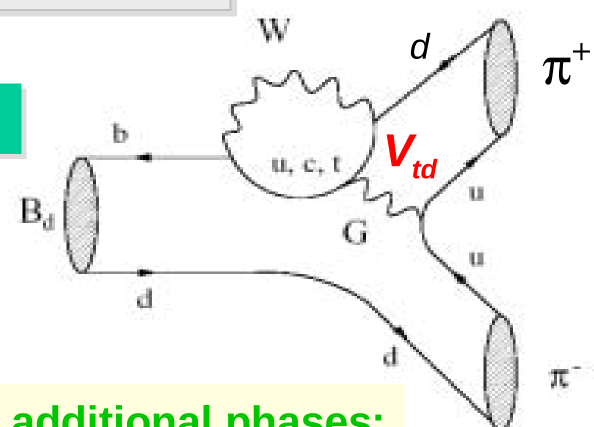
$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$

$$S_{f_{CP}} = \frac{2\,\mathrm{Im}\,\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}$$

Tree diagram:



Penguin diagram:



For a single weak phase (tree):

$$\lambda = \frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_f} = \eta_f e^{-2i(\beta+\gamma)} = \eta_f e^{2i\alpha}$$

$C_{\pi\pi} = 0$, $S_{\pi\pi} = \sin(2\alpha)$

For additional phases:

$|\lambda| \neq 1 \Rightarrow$ must fit for direct *CP*
$\mathrm{Im}\,(\lambda) \neq \sin(2\alpha) \Rightarrow$ need to relate asymmetry to α

$C_{\pi\pi} \neq 0$, $S_{\pi\pi} = \sin(2\alpha_{\mathrm{eff}})$

$\sin(2\alpha_{eff})$ & Gronau-London Isopin Analysis

Using the BRs : $\pi^+\pi^-$, $\pi^\pm\pi^0$, $\pi^0\pi^0$ (limit)

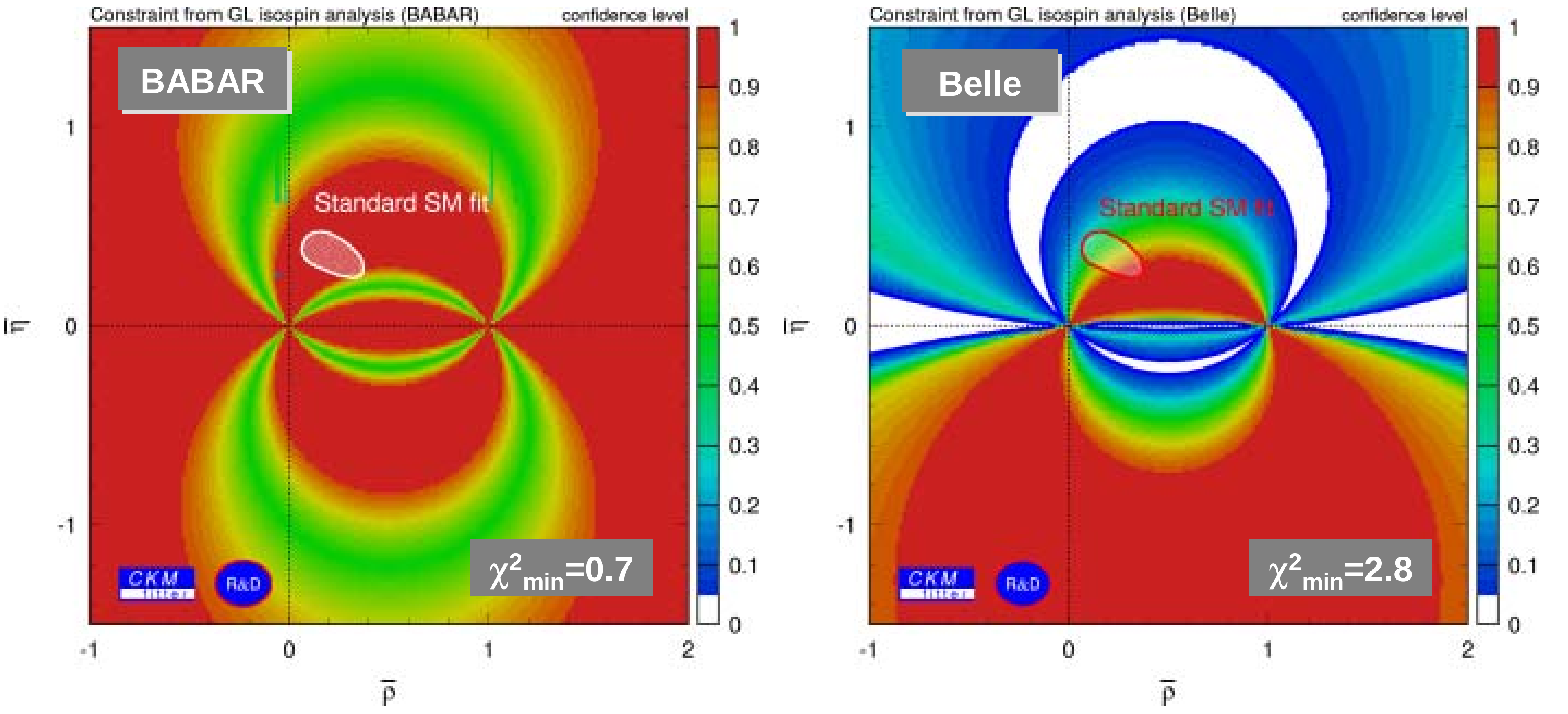
and the CP asymmetries : $A_{CP}(\pi^\pm\pi^0)$, $S_{\pi\pi}$, $C_{\pi\pi}$

and the amplitude relations: $A^{+-}/\sqrt{2} + A^{00} = A^{+0}$,

$(A \leftrightarrow \bar{A})$ and $|A^{+0}| = |\bar{A}^{+0}|$

	BABAR	Belle
$S_{\pi\pi}$	-0.01 ± 0.38	$-1.21^{+0.41}_{-0.30}$
$C_{\pi\pi}$	-0.02 ± 0.30	$-0.94^{+0.32}_{-0.27}$

sign convention changed!



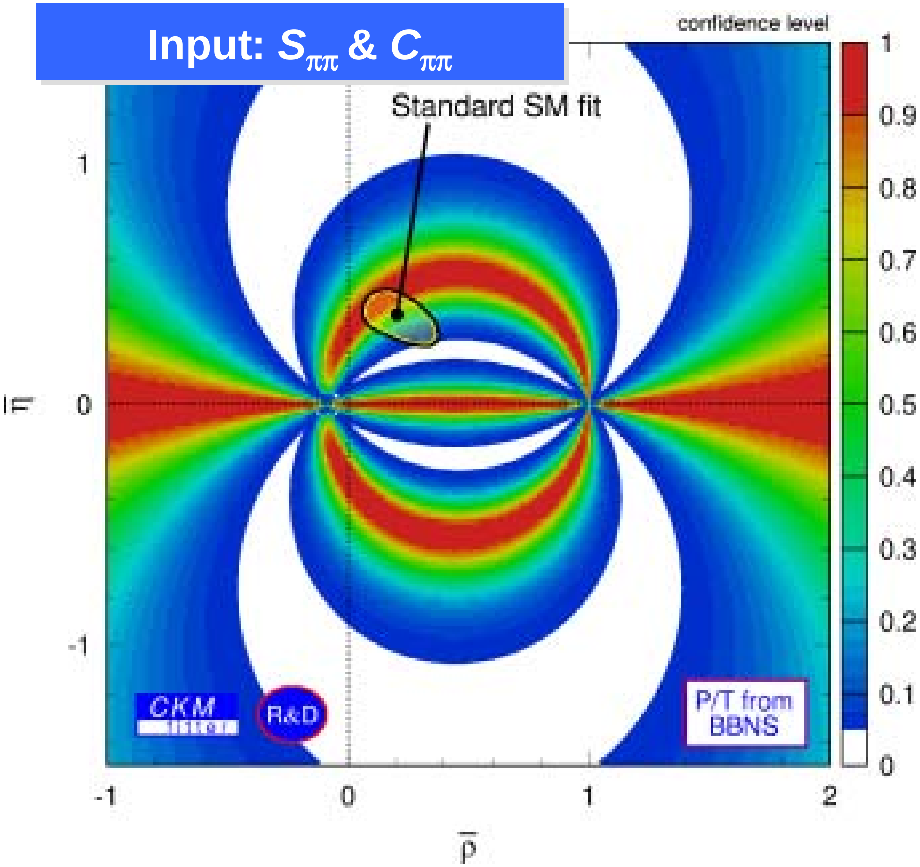
BABAR: sin(2α_{eff}) & Theory (QCD FA)

$$S_{\pi\pi} = \frac{2\,\mathrm{Im}\,\lambda_{\pi\pi}}{1+|\lambda_{\pi\pi}|^2}\ ,\quad C_{\pi\pi} = \frac{1-|\lambda_{\pi\pi}|^2}{1+|\lambda_{\pi\pi}|^2}$$

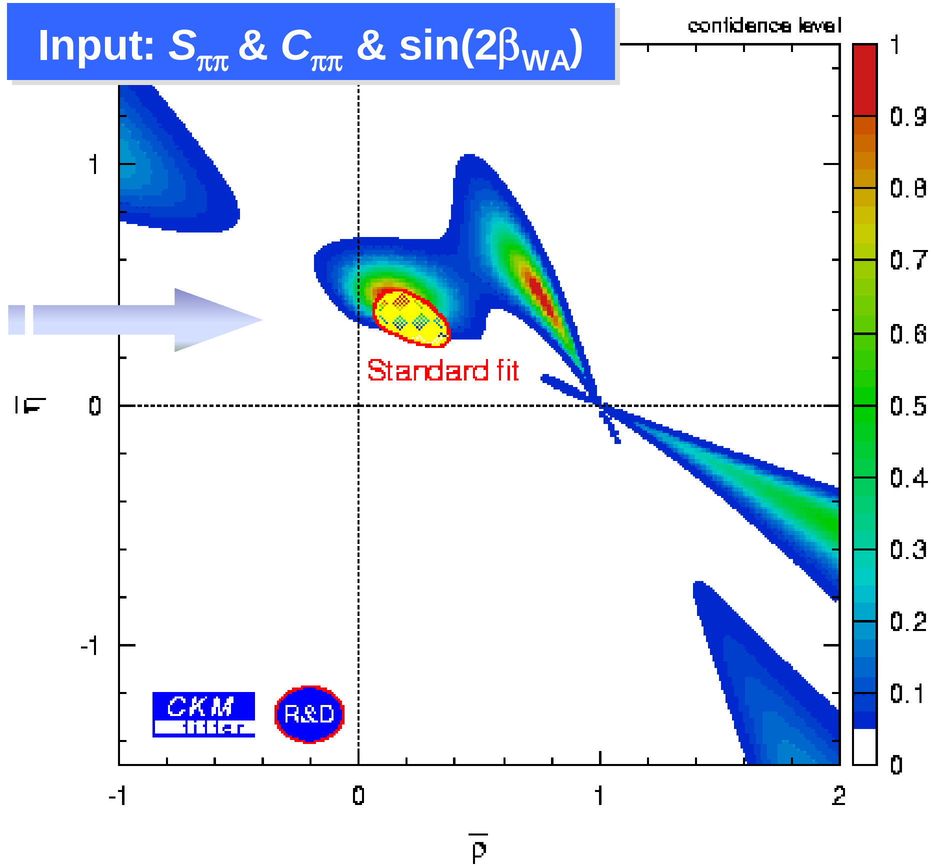
$$\lambda_{\pi\pi} = e^{-2i\beta}\,\frac{e^{-i\gamma} + P_{\pi\pi}/T_{\pi\pi}}{e^{+i\gamma} + P_{\pi\pi}/T_{\pi\pi}}$$

& QCD FA (BBNS)

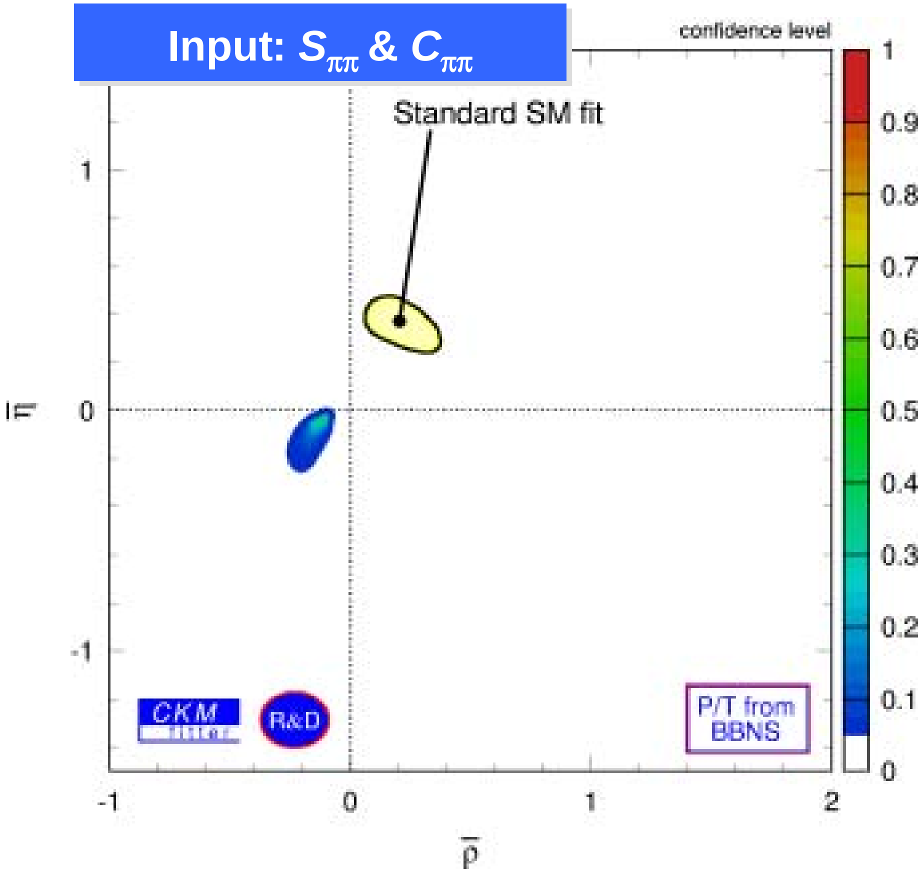
Input: $S_{\pi\pi}$ & $C_{\pi\pi}$

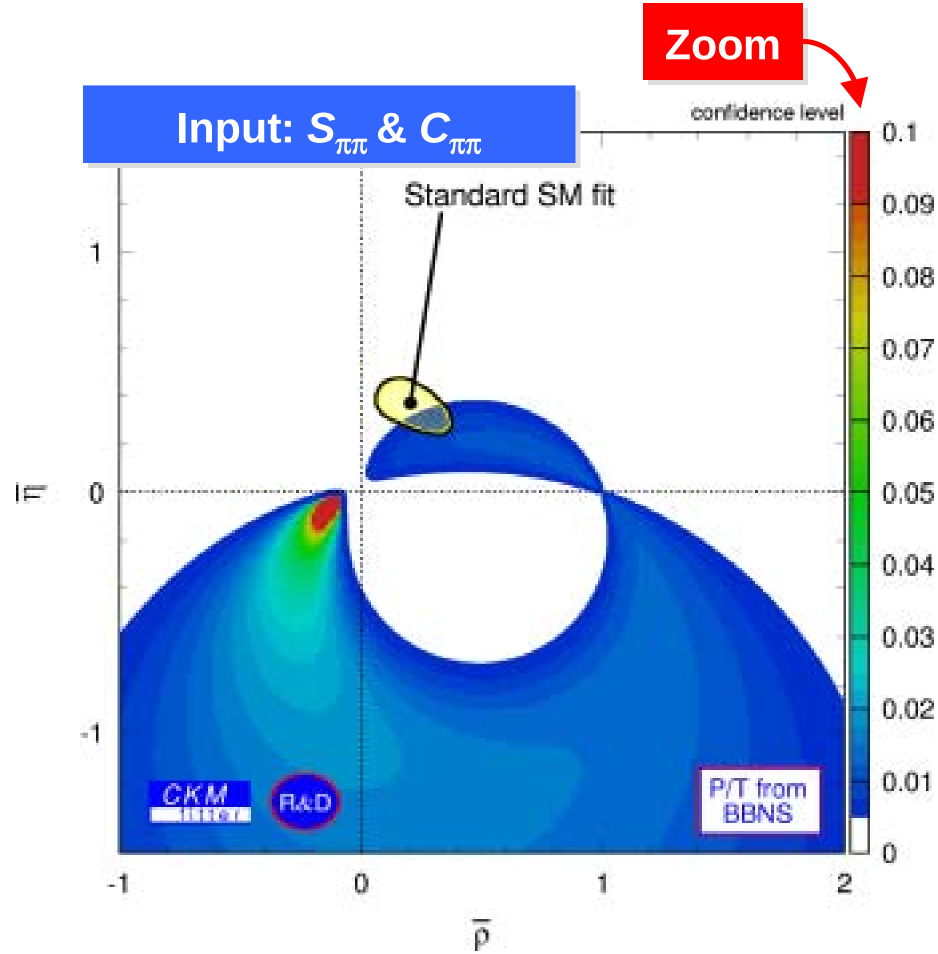


Input: $S_{\pi\pi}$ & $C_{\pi\pi}$ & sin(2β_{WA})



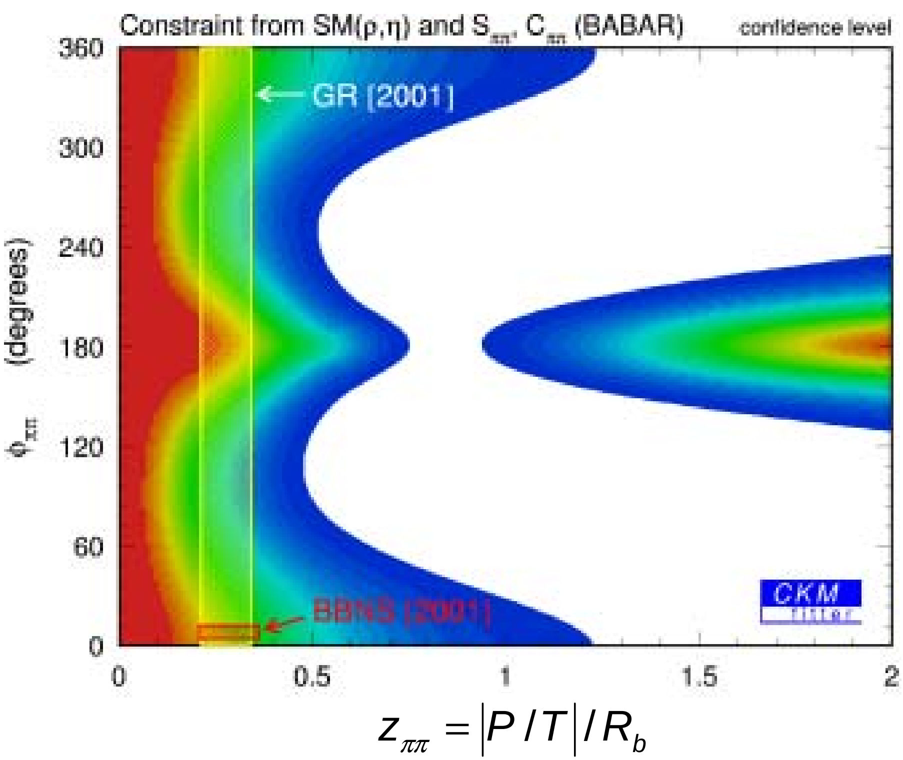
Belle: sin($2\alpha_{eff}$) & Theory (QCD FA)

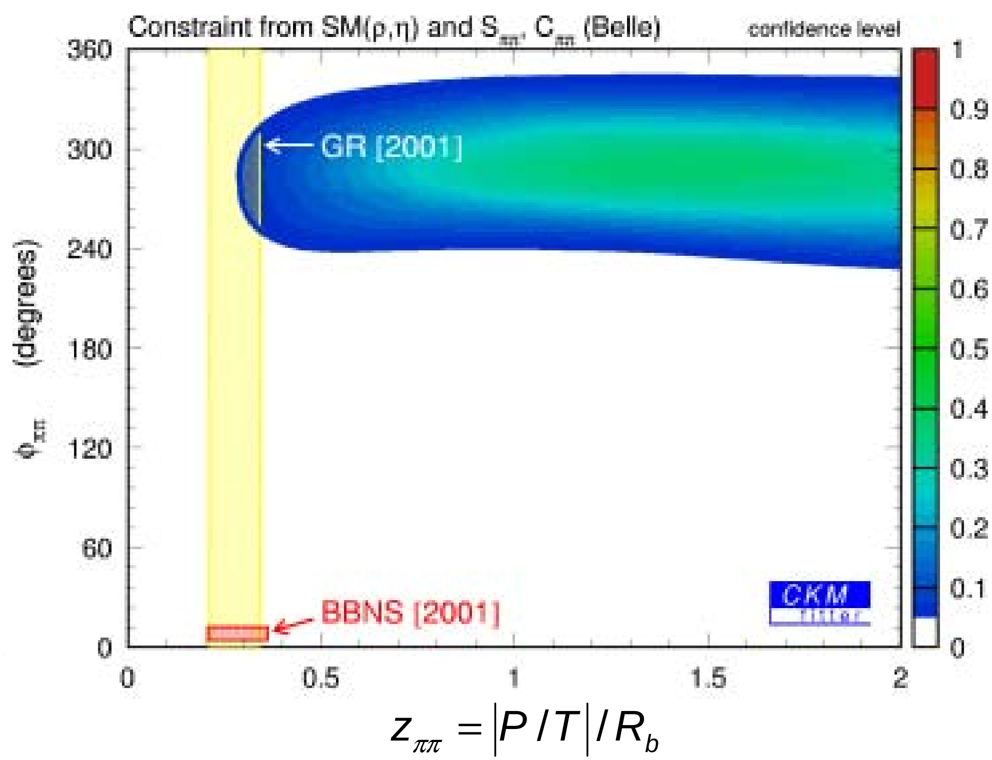




The Reverse: sin(2α_{eff} , 2β) & SM fit → THEORY

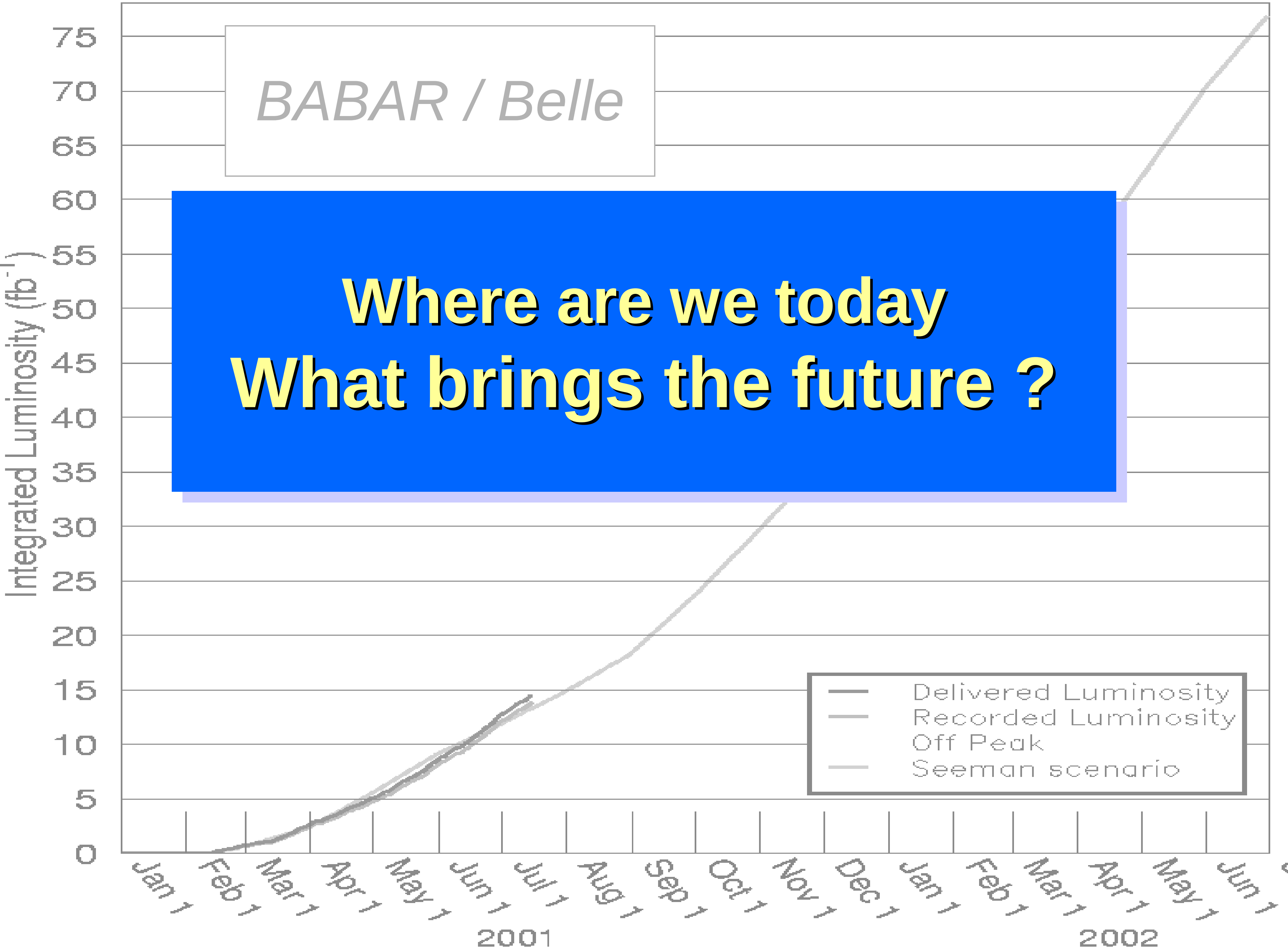
- **The theory provides tree und penguin contributions and their relative phases**
- **The global fit determines the agreement between experiment and theory, using all measured BRs and CP asymmetries (also time-dependent)**
- **Determine also the free parameters of the theory (*i.e.*, the CKM elements)**



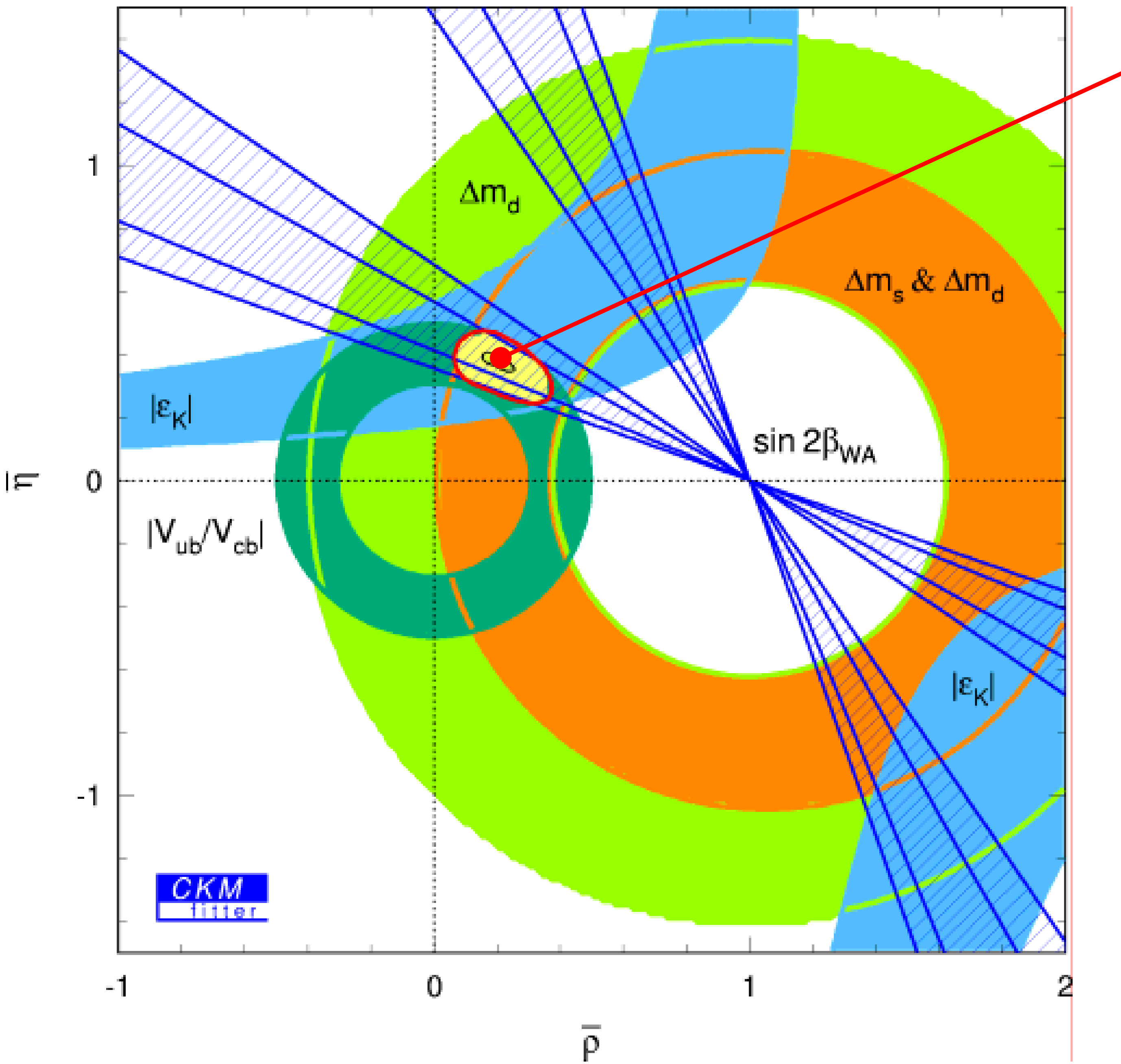


GR: Gronau, Rosner, Phys.Rev.D65:013004,2002
BBNS: Beneke et al., Nucl.Phys.B606:245-321,2001

Where are we today
What brings the future ?



The Standard Model holds the castle:

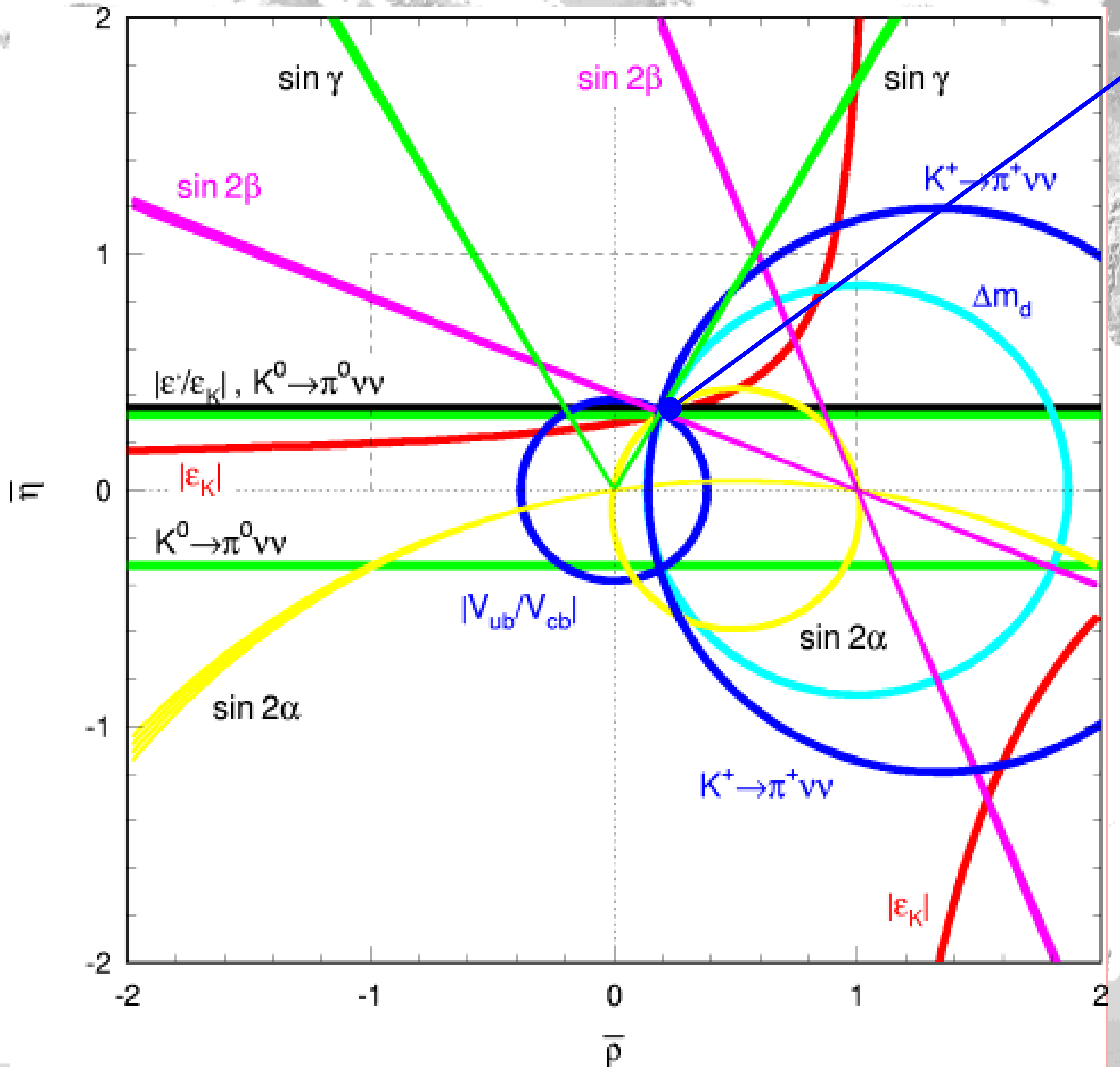


We know the center already quite well… but it is too large!

A better understanding of long distance QCD opens the shrine to a full exploitation of the huge data samples currently produced at KEKB and PEPII.

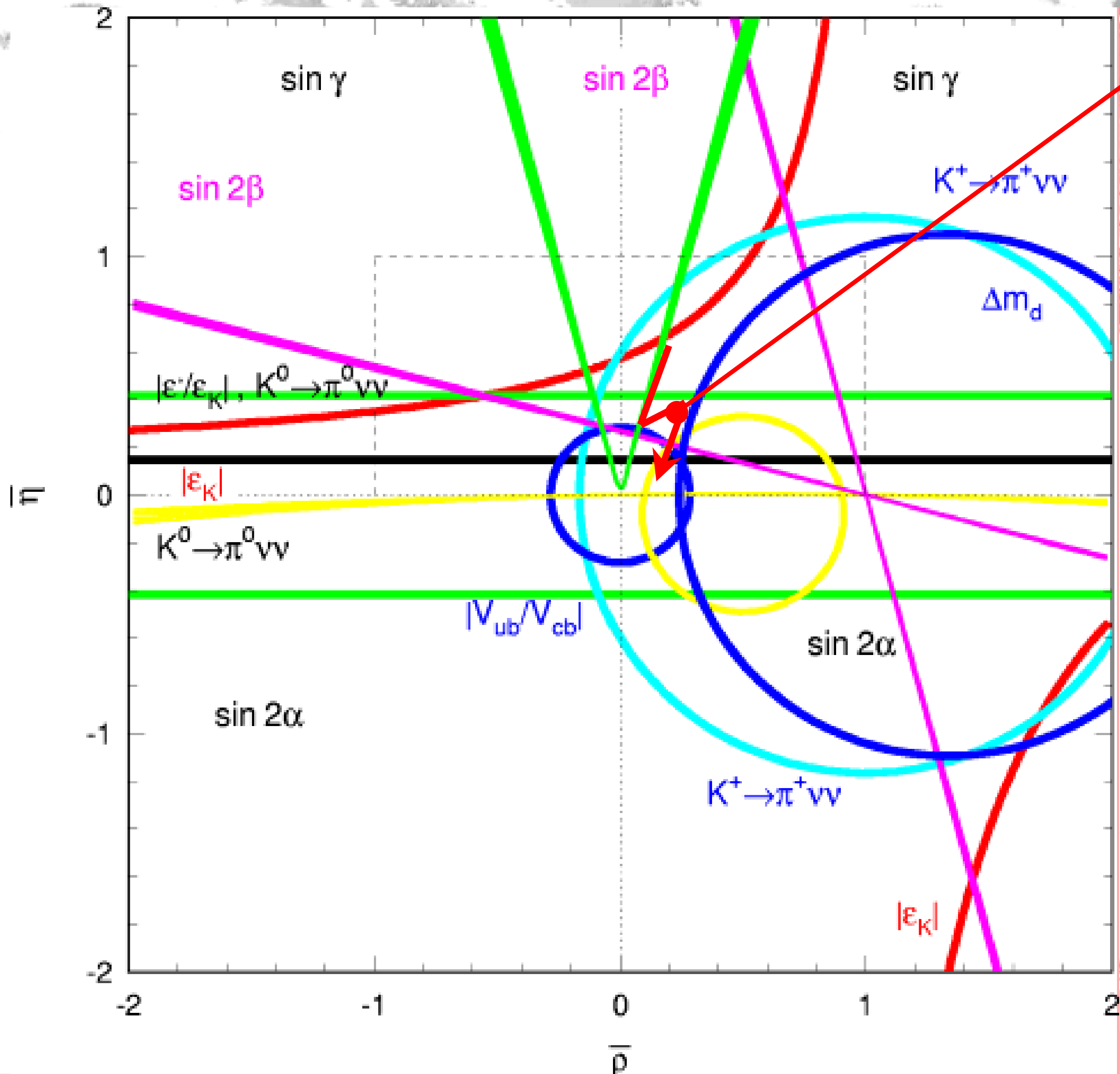
...and the incredible data quantities that will be produced at the Tevatron & LHC

And in the far future ?



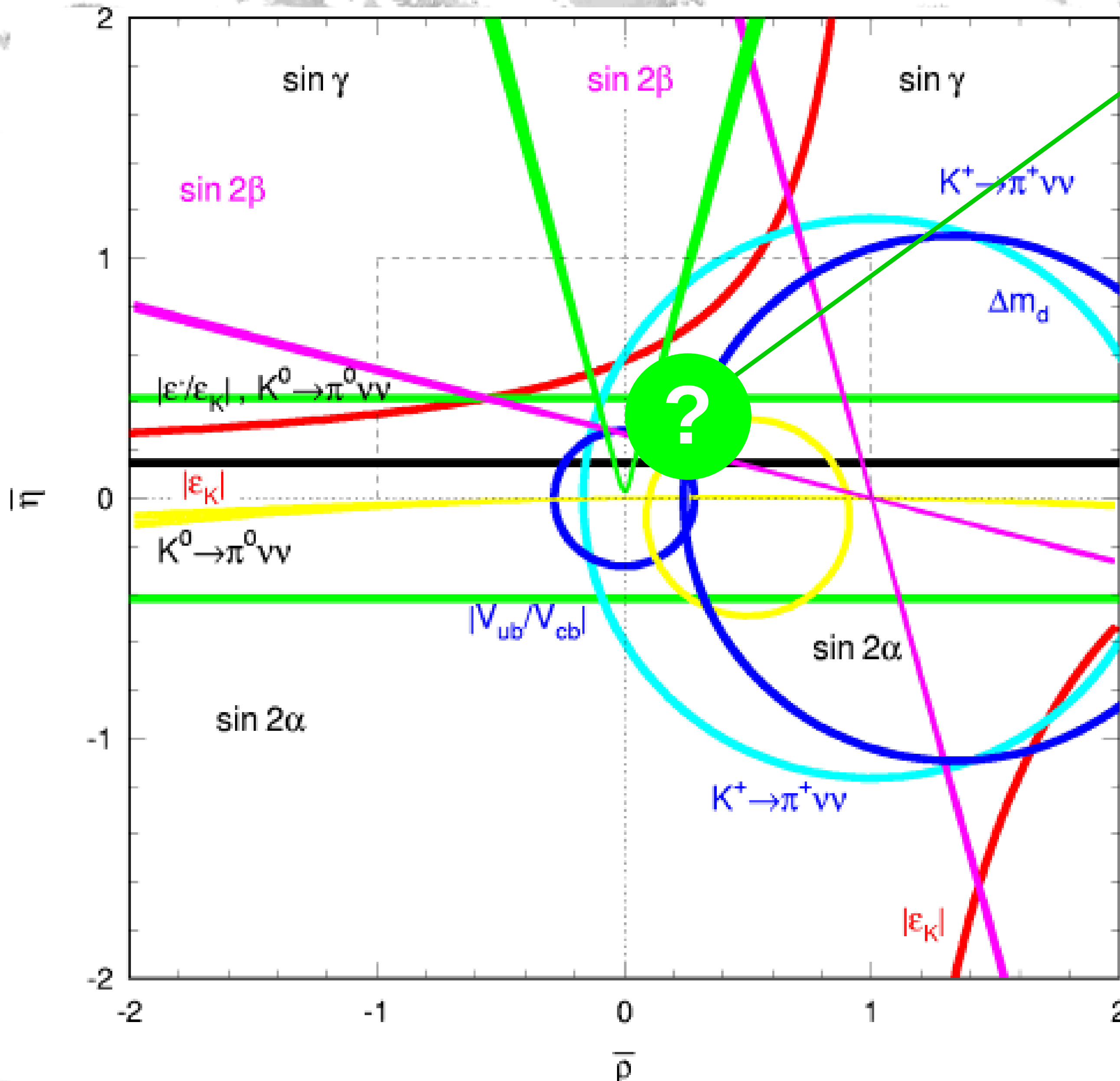
In 2010 we will need a zoom, to see the overlap region...

And in the far future ?



Will there still be an overlap region ?

And in the far future ?



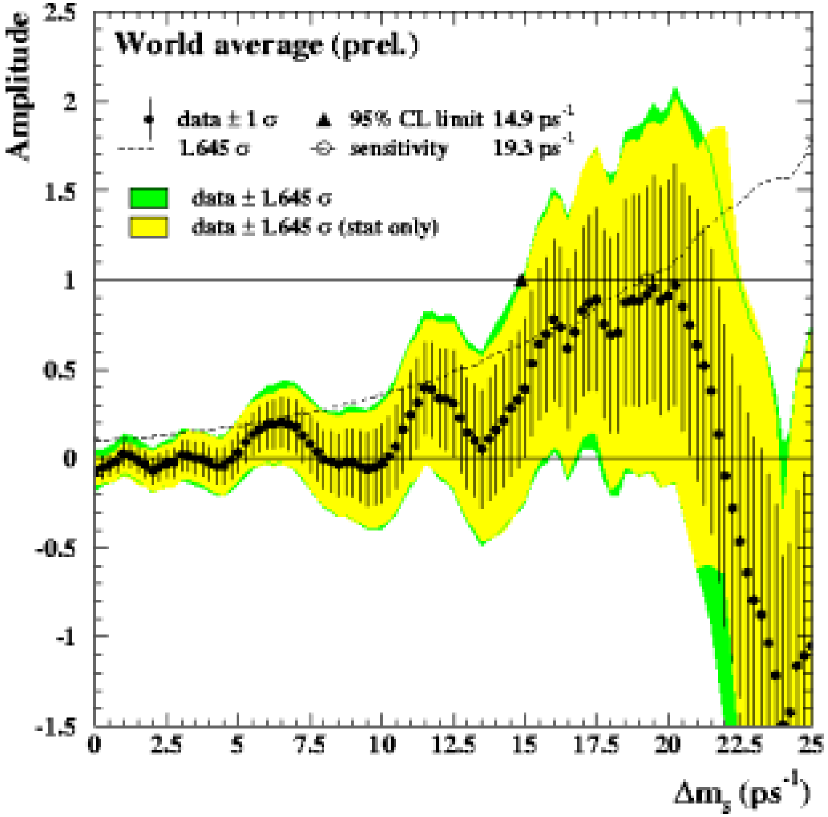
... maybe we can establish new physics before the LHC finds it ???

Backup Material

Using Δm_s

Δm_s not yet measured. How to use the available experimental inform.?

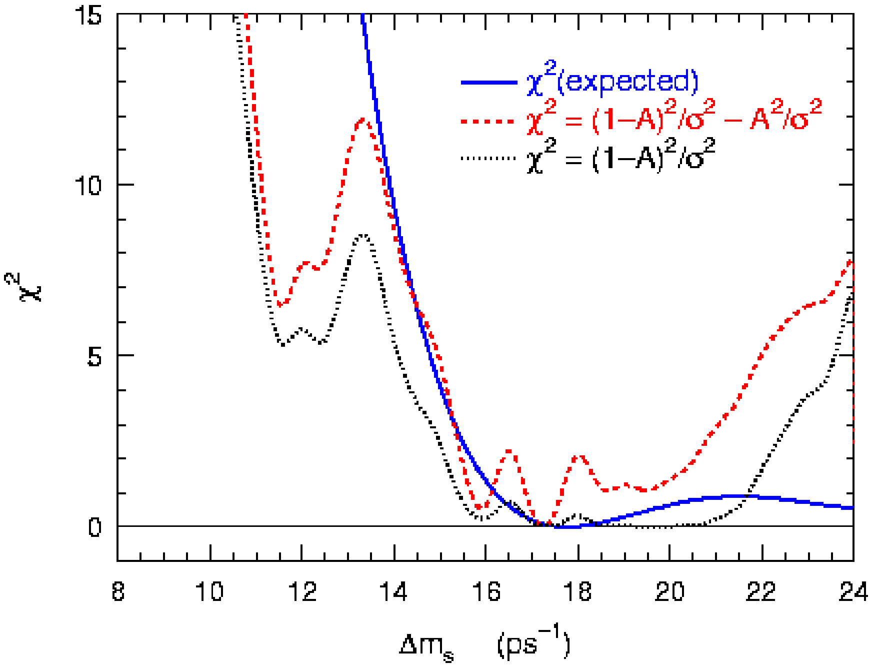
Amplitude spectrum: LEP/SLD/CDF



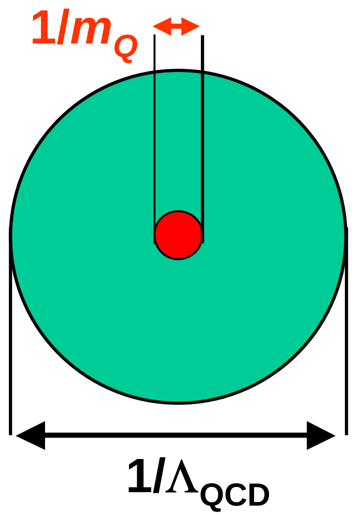
Preferred value: 17.2 ps^{-1}

Following a presentation of F. Le Diberder at the CERN CKM workshop (Feb. 02)

- compute the expected PDF for the current prefered value
- compute the CL
- infer an equivalent χ^2



Determination of the Matrix Elements $|V_{cb}|$ and $|V_{ub}|$



Compton wavelength

Symmetry of heavy quarks [=SU($2n_Q$)]:

in the limit $m_Q \to \infty$ of a *Qq* system, the heavy quark represents a static color source with fixed 4-momentum.

The light degrees of freedom become insensitive to spin and flavor of the quark.

For both, $|V_{cb}|$ and $|V_{ub}|$, exist exclusive and inclusive semileptonic approaches.

The theoretical tools is *Heavy Quark Effective Theory* (HQET) and the Operator Product Expansion (OPE)

- **$|V_{ub}|$ ($\to \rho^2+\eta^2$) is important for the SM prediction of sin(2β)**
- **$|V_{cb}|$ ($\to A$) is crucial for the interpretation of kaon decays (ε_K, BR($K\to\pi\nu\nu$), …)**

Exclusive Semileptonic $B \to D^* l \nu$ Decays

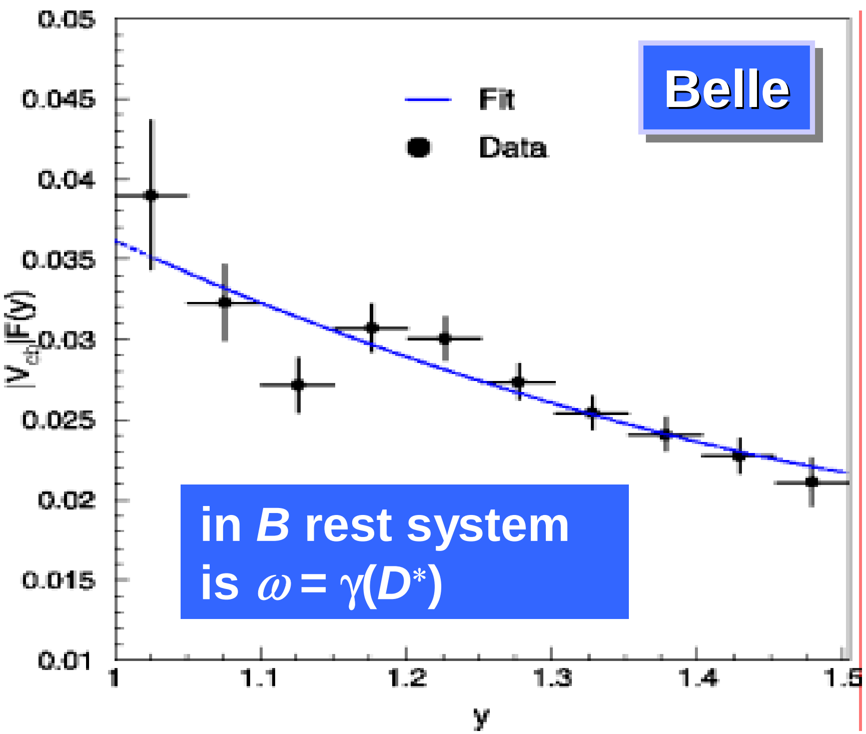
- Measurement of $B \to D^* \ell \bar{\nu}$ rate as fct. of $B \to \ell \bar{\nu}$ momentum transition ω
- Determination of $|V_{cb}|$ from extrapolation to $\omega \to 1$ (theory is most restrictive)

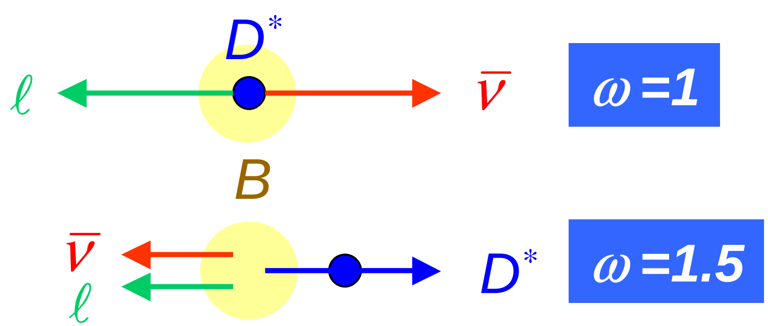
$$\frac{d\Gamma(B \to D^* \ell \bar{\nu})}{d\omega} \propto F_*^2(\omega) |V_{cb}|^2$$

HQ Symmetry:

$$F_*(1) \approx 0.9 \quad (\pm 5\%)$$

Bigi, Uraltsev; Neubert; ...; Lattice QCD





$$F_*(1)|V_{cb}| = 10^{-3} \times \begin{cases} 35.6 \pm 1.7 \quad \text{(LEP)} \\ 42.2 \pm 2.2 \quad \text{(CLEO)} \\ 36.2 \pm 2.3 \quad \text{(Belle)} \end{cases}$$

Belle, PLB 526, 247 (2002)

Inclusive Semileptonic $B \to X_c l \nu$ Decays

- OPE: expansion of decay rate in $\Lambda_{\text{QCD}} / m_b$ und $\alpha_s(m_b)$
- Model-independent results for sufficiently inclusive observables:

Bigi, Shifman, Uraltsev; Hoang, Ligeti, Manohar

$$|V_{cb}| \approx 0.0419 \sqrt{\frac{\text{BR}(B \to X_c \ell \bar{\nu})}{0.105} \frac{1.55\text{ ps}}{\tau_B}} \left(1 \pm 0.015_{\text{pQCD}} \pm 0.010_{m_b} \pm 0.012_{1/m_b^3}\right)$$

Experimental strategy

- Identify $\Upsilon(4S) \to B^0 \bar{B}^0$ by tagging one of the Bs:
  - Full reconstruction of the high energetic lepton
- Select leptons from the semileptonic decay of the other B

$$B^0\bar{B}^0 \text{ tag}: \begin{cases} B^{0/+} \to X_{\bar{c},\bar{u}} e^+ \nu_e \\ B^{0/+} \to X_{\bar{c},\bar{u}} Y, \; X_{\bar{c}} \to X' e^- \bar{\nu}_e \end{cases}$$

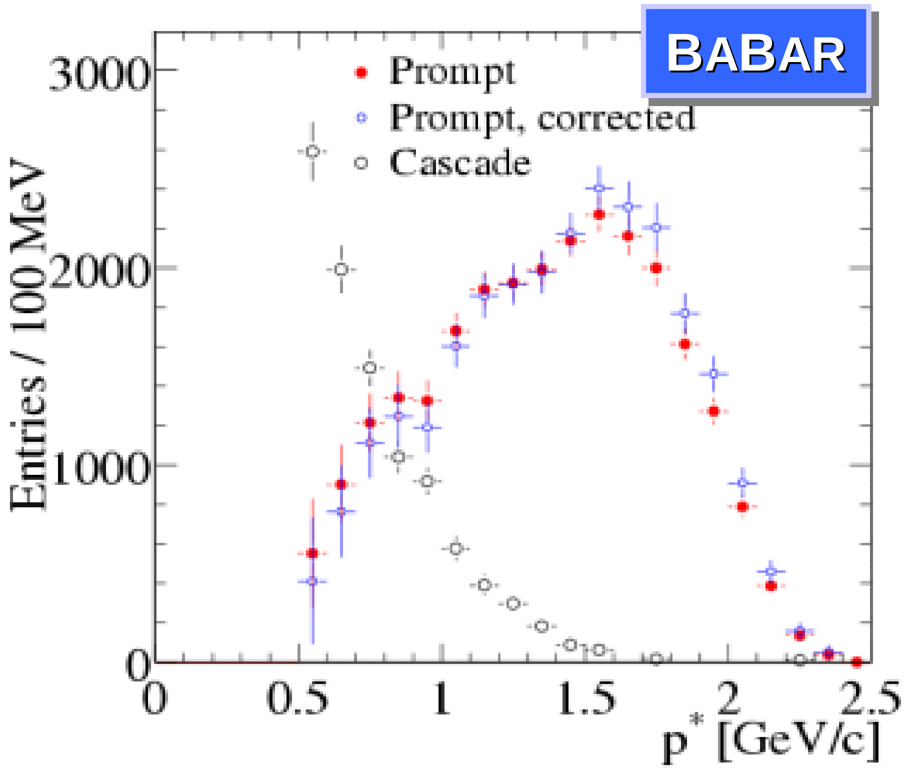
Fast e^+: „right-sign“

Cascade e^-: „wrong-sign“

- $\text{BR}(B \to X \ell \nu_\ell) \propto N_{\text{fast}} / N_{\text{tag}}$

BR($B \to X\, l(e)\nu$):

BABAR:	**(10.82 ± 0.21 ± 0.38) %**
Belle:	**(10.86 ± 0.14 ± 0.47) %**
CLEO:	**(10.49 ± 0.17 ± 0.43) %**
LEP:	**(10.65 ± 0.23) %**
ARGUS :	**(9.7 ± 0.5 ± 0.4)%**



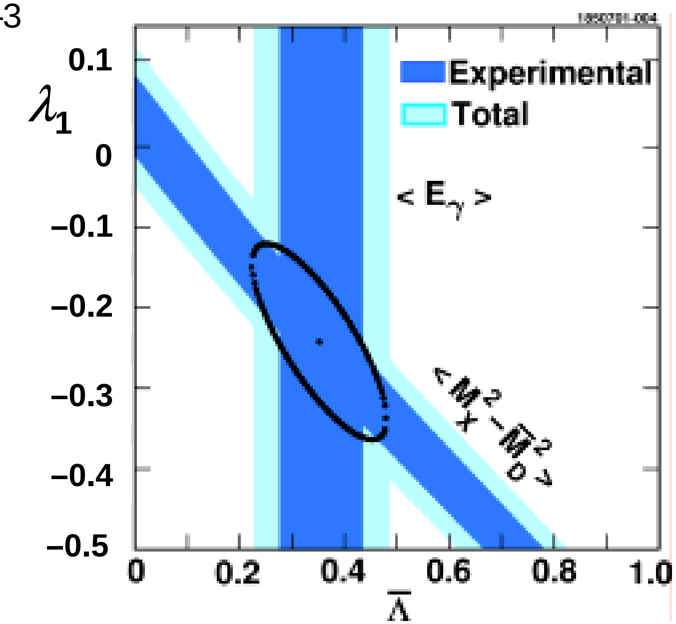
BABAR preliminär:

z.B.: $|V_{cb}|(\text{BABAR}) \cong (40.8 \pm 1.7 \pm 1.5)\times 10^{-3}$

A promising approach for a theoretically improved analysis is the combined fit of the HQET parameters Λ und λ_1 (CLEO) by means of $b \to s\gamma$. Allows to test Quark-Hadron Duality. (See also spectral moments analysis of hadronic Tau decays).

$|V_{cb}|(\text{CLEO}) \cong (40.4 \pm 1.3)\times 10^{-3}$

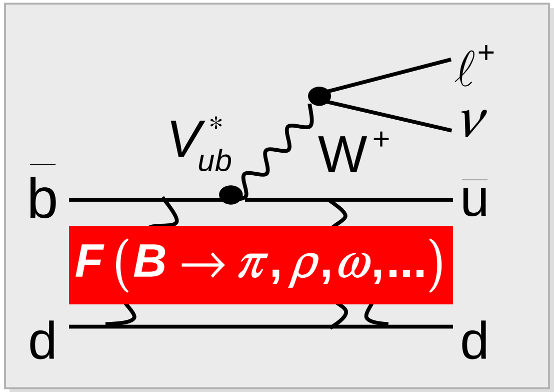
CLEO, Phys. Rev. Lett. 87, 251808 (2001)



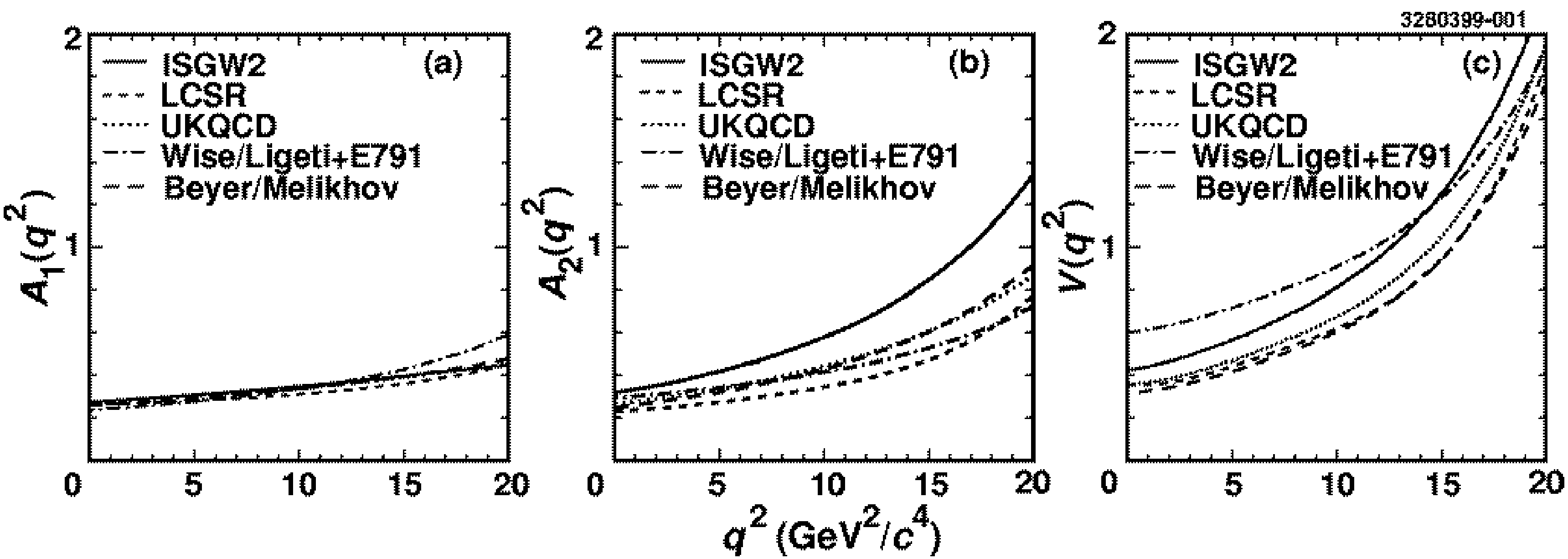
$|V_{ub}|$ from exclusive Decays (I)

Pure tree decay. The decay rate is proportional to the CKM element $|V_{ub}|^2$

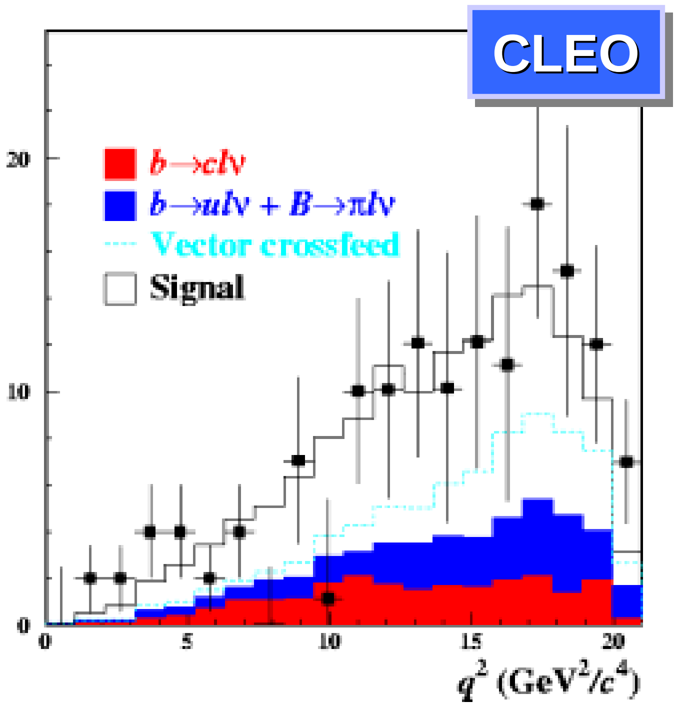
$$\mathrm{BR}\left(B^0 \to h^- \ell^+ \nu\right) \propto \left|V_{ub}\right|^2 F_B^2(q^2)$$

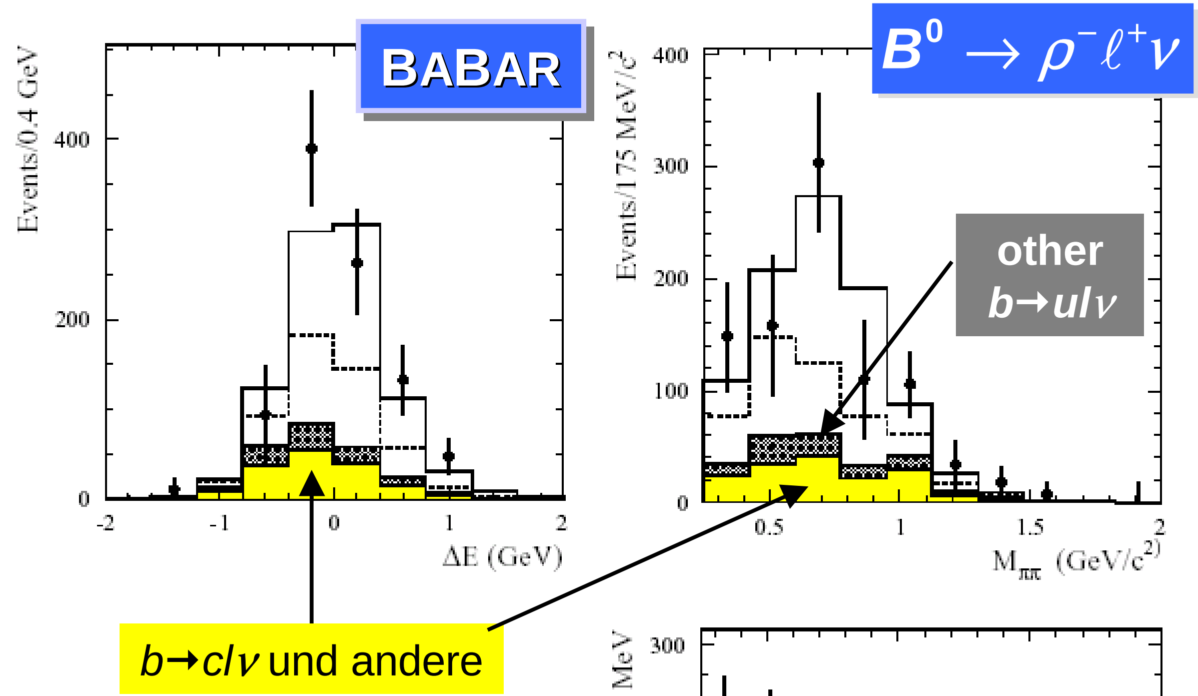


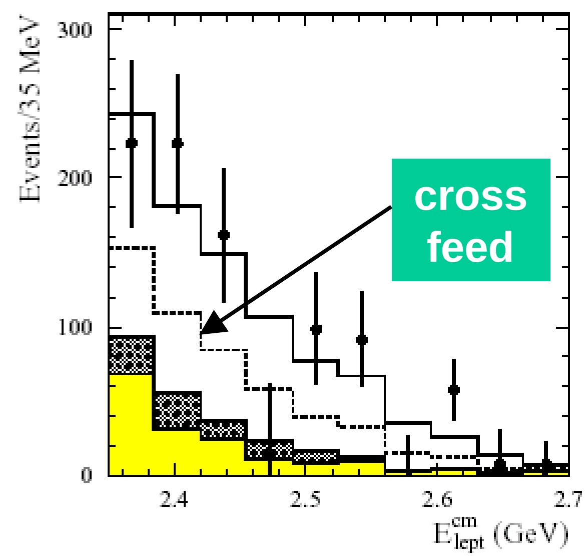
Problem: form factor is model dependent



$|V_{ub}|$ from exclusive Decays (II)







$$\text{CLEO}: \quad |V_{ub}| = \left(3.25 \pm 0.14\ {}^{+0.21}_{-0.29} \pm 0.55\right) \times 10^{-3}$$

$$\text{BABAR}: \quad |V_{ub}| = \left(3.57 \pm 0.36\ {}^{+0.33}_{-0.38} \pm 0.60\right) \times 10^{-3}$$

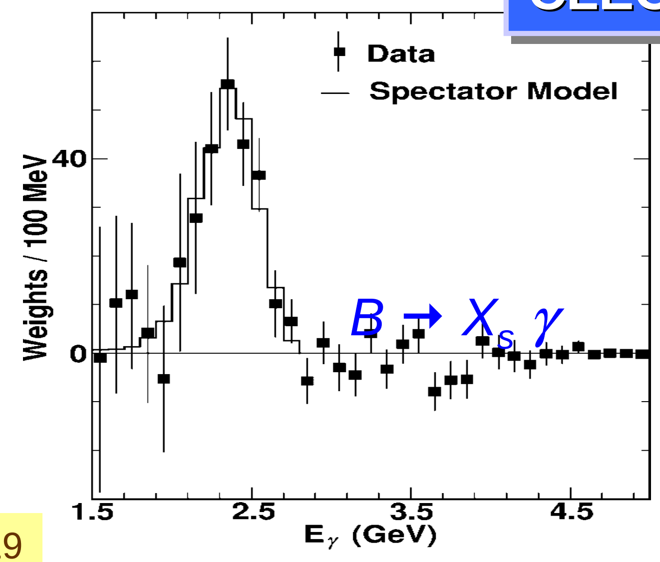
stat sys mod

CLEO, Phys.Rev.D61:052001,2000
BABAR preliminary (Moriond'02)

$|V_{ub}|$ from inclusive Decays

CLEO

Suppression of the dominant charm background by cutting on the $B \to X_u l \nu$ lepton momentum beyond the kinematic limit of $B \to X_c l \nu$



Problem: strong model dependence of $|V_{ub}|$

➡ Reduction of model dependence by using HQE and the “shape function“ measured in $B \to X_s \gamma$

CLEO, hep-ex/0202019

$$|V_{ub}| = (4.08 \pm 0.34 \pm 0.44 \pm 0.16 \pm 0.24) \times 10^{-3}$$

stat fu $1/m_b$ HQE

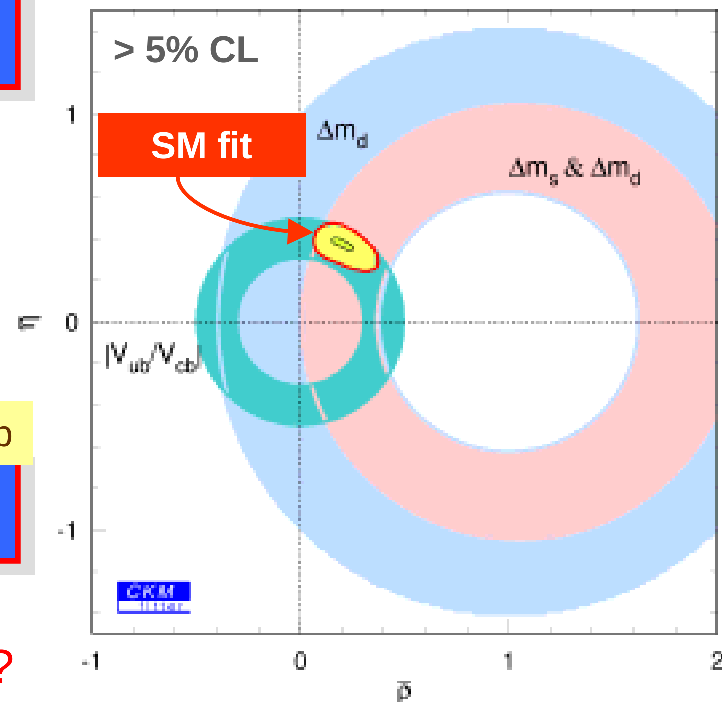
Possible “violation“ of quark-hadron duality?

➡ Measurement of the whole spectrum (➡ Theorie under control) $B \to X_u l \nu$ (Neural Net for Signal)

LEP B Working group

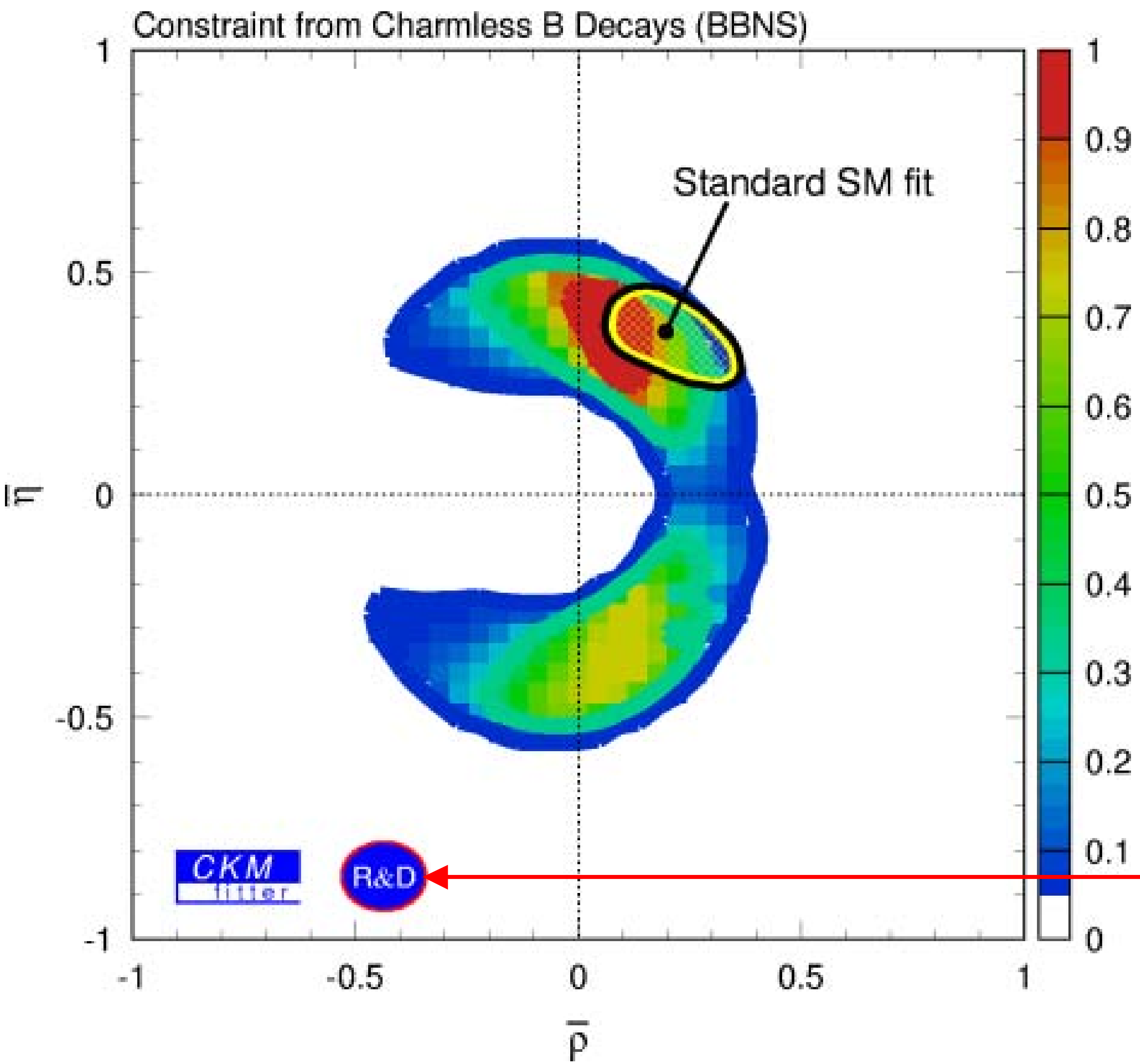
$$|V_{ub}| = \left(4.09 \,{}^{+0.36}_{-0.39}\,{}^{+0.42}_{-0.47}\,{}^{+0.24}_{-0.26} \pm 0.01 \pm 0.17\right) \times 10^{-3}$$

exp $b \to c$ $b \to u$ τ_b HQE



Knowledge of $b \to c$ background, incl. measurement ?

BR($B \to \pi\pi$ /$K\pi$) & A_{CP} & Theory (QCD FA)



Beneke, Buchalla, Neubert, Sachrajda (BBNS)
Nucl.Phys.B606:245-321,2001

Theoretical uncertainties:

- m_s, m_c, λ_B, $R_{\pi K}$
- Renorm. scale μ
- Gegenbauer moms: $a_1(K)$, $a_2(K)$, $a_2(\pi)$
- $F(B \to \pi)$, f_B
- X_H, X_A

This means:
error estimation not settled yet **!!!**

Frequentist Approach: R*fit*

CKM fitter — the package

Three main analysis steps:

AH, H. Lacker, S. Laplace, F. Le Diberder
EPJ C21 (2001) 225, [hep-ph/0104062]

Probing the SM

Test: "Goodness-of-fit"

- **Evaluate global minimum**
  $\chi^2_{\min;y_{mod}}(y_{mod\text{-}opt})$
- **Fake perfect agreement:**
  $x_{exp\text{-}opt} = x_{theo}(y_{mod\text{-}opt})$
  generate x_{exp} using $\mathcal{L}_{exp}$
- **Perform many toy fits:**
  $\chi^2_{min\text{-}toy}(y_{mod\text{-}opt}) \rightarrow F(\chi^2_{min\text{-}toy})$

↓

$$CL(SM) \leq \int_{\chi^2 \geq \chi^2_{min;y_{mod}}}^{\infty} F(\chi^2)\, d\chi^2$$

Metrology

- **Define:**
  $y_{mod} = \{a;\ \mu\}$
  $= \{\rho,\ \eta,\ A, \lambda, y_{QCD}, \ldots\}$
- **Set Confidence Levels in $\{a\}$ space, irrespective of the μ values**
- **Fit with respect to $\{\mu\}$**
  $\chi^2_{min;\,\mu}(a) = \min_{\mu}\{\chi^2(a,\ \mu)\}$
- $\Delta\chi^2(a) = \chi^2_{min;\,\mu}(a) - \chi^2_{min;y_{mod}}$

↓

$$CL(a) = Prob(\Delta\chi^2(a),\ N_{dof})$$

Test New Physics

- **If CL(SM) good**

↓

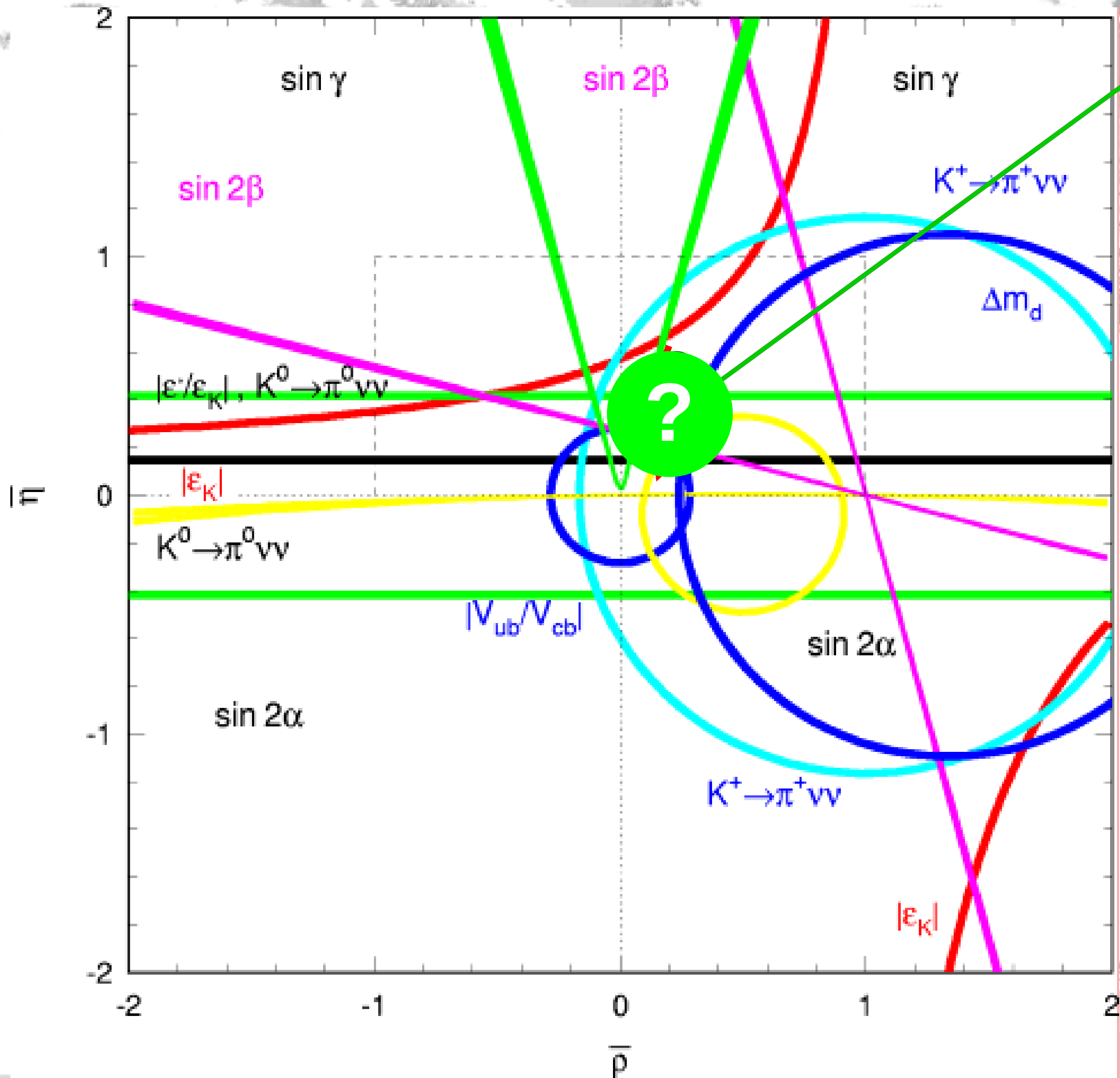
Obtain limits on New Physics parameters

- **If CL(SM) bad**

↓

Hint for New Physics ?!

And in the far future ?



... maybe we can establish new physics before the LHC finds it ???