The CKM Paradigm

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

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

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http://www.slac.stanford.edu/~laplace/ckmfitter.html

ElectroWeak Interactions and Unified Theories

Moriond, 2002

Outline

CKM Fits: Motivation and Method

Recent B and K Decay
Measurements and their Implications

Testing QCD Factorization:
Charmless B Decays to 2 Pseudoscalars

Constraining New Physics:
Semi-Leptonic Asymmetry

The CKM Matrix

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

- Couplings of flavour changing charged currents to the quarks are proportional to the CKM matrix elements
- Unitary matrix described by 4 independent real parameters

Wolfenstein parametrization (expansion in λ ~ 0.22):

$$V_{CKM} \approx \begin{pmatrix} 1 - l^2/2 & l & A l^3 (r - ih) \\ -l & 1 - l^2/2 & A l^2 \\ A l^3 (1 - r - ih) & -A l^2 & 1 \end{pmatrix}$$

CPV phase

$h \neq 0 \Rightarrow$ CPV in SM

The Unitarity Triangles

B sector:

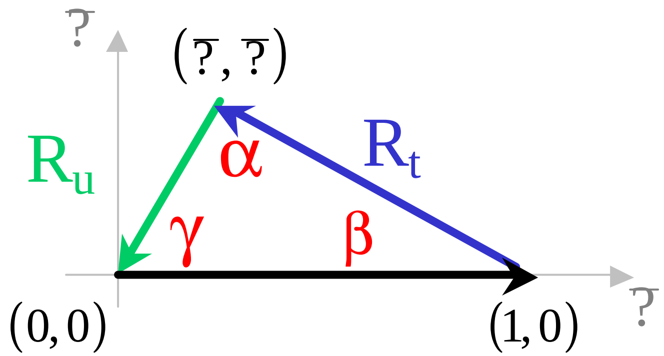
$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}+\frac{V_{cd}V_{cb}^*}{V_{cd}V_{cb}^*}+\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}=0$$

$$\frac{A\ l^3}{A\ l^3}+1+\frac{A\ l^3}{A\ l^3}=0$$

K sector:

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

$$\frac{l}{l}+1+\frac{A^2 l^5}{l}=0$$



$$R_u=\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\approx-\sqrt{\bar{r}^2+\bar{h}^2}\,e^{ig}$$

$$R_t=\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\approx-\sqrt{(1-\bar{r})^2+\bar{h}^2}\,e^{-ib}$$

$\gamma = \arg(-V_{ub}^*)$ $\beta = \arg(-V_{td}^*)$

Constraining The Unitarity Triangle

Wolfenstein parameters:

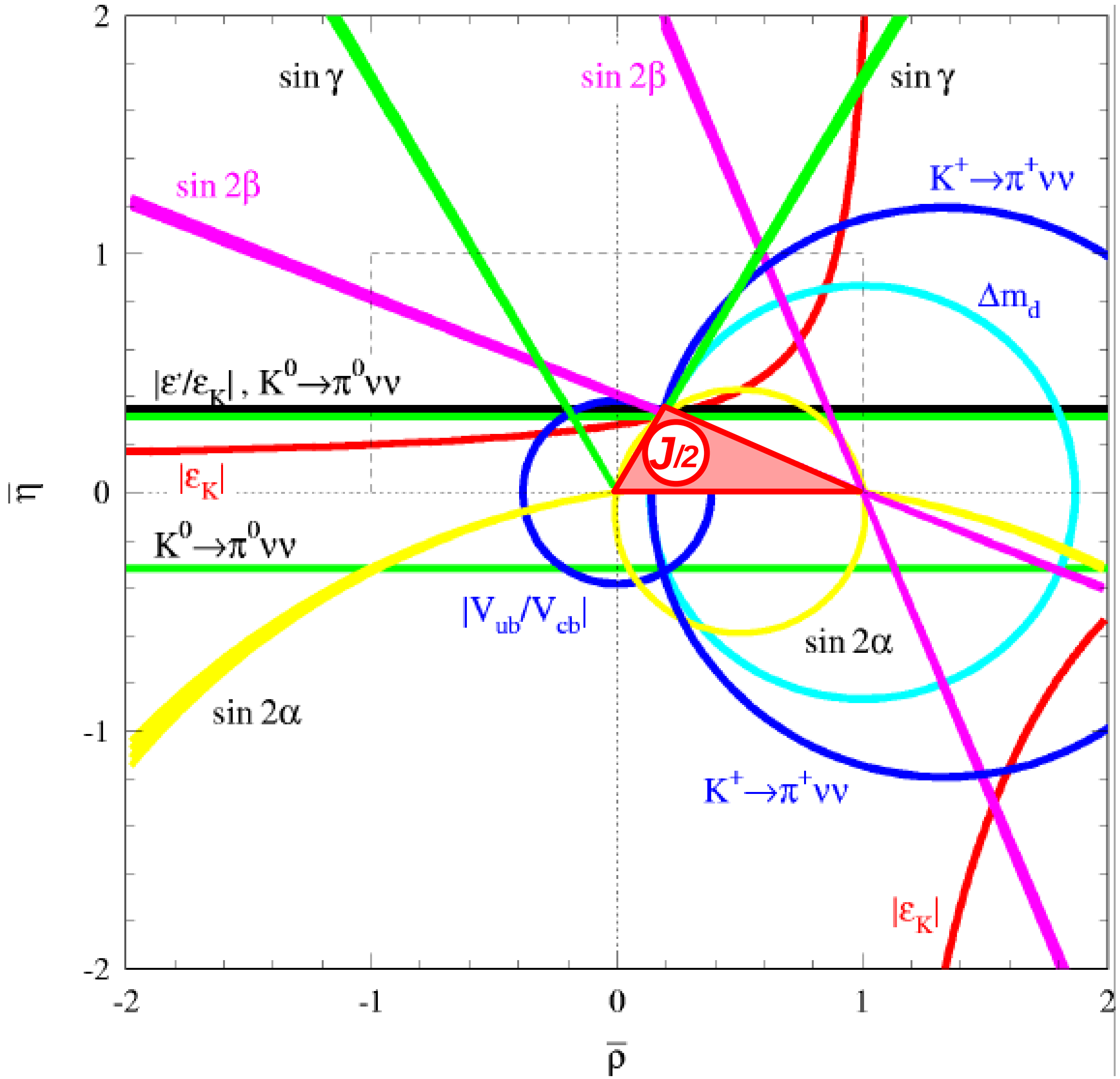
l, A, $\bar{r}$ and $\bar{h}$

Known at the 1% level:
λ= $|V_{us}|$ = 0.2200 $\pm$ 0.0025

Known at the 5% level:
A = $|V_{cb}|$ / l^2 = 0.83 $\pm$ 0.06

(r,h) less known

$\Rightarrow$ " Constrain the (r,h) plane "



Extracting CKM Parameters

Measurement → **Constraints on theoretical parameters**

x_{exp}

Theoretical predictions

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

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

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

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

$$\mathcal{L}(y_{model}) = \mathcal{L}_{exp}[x_{exp} - x_{theo}(y_{model})] \cdot \mathcal{L}_{theo}(y_{QCD})$$

« Guesstimates »

Frequentist

Bayesian

“Uniform likelihoods: ranges”

Frequentist Approach: Rfit

CKM fitter

Three main analysis steps:

EPJ C21 (2001) 225, [hep-ph/0104062]

Probing the SM

- 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 fits:
  $\chi^2_{min\text{-}toy}(y_{mod\text{-}opt}) \rightarrow F(\chi^2_{min\text{-}toy})$

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

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: stop working and buy ticket to Stockholm

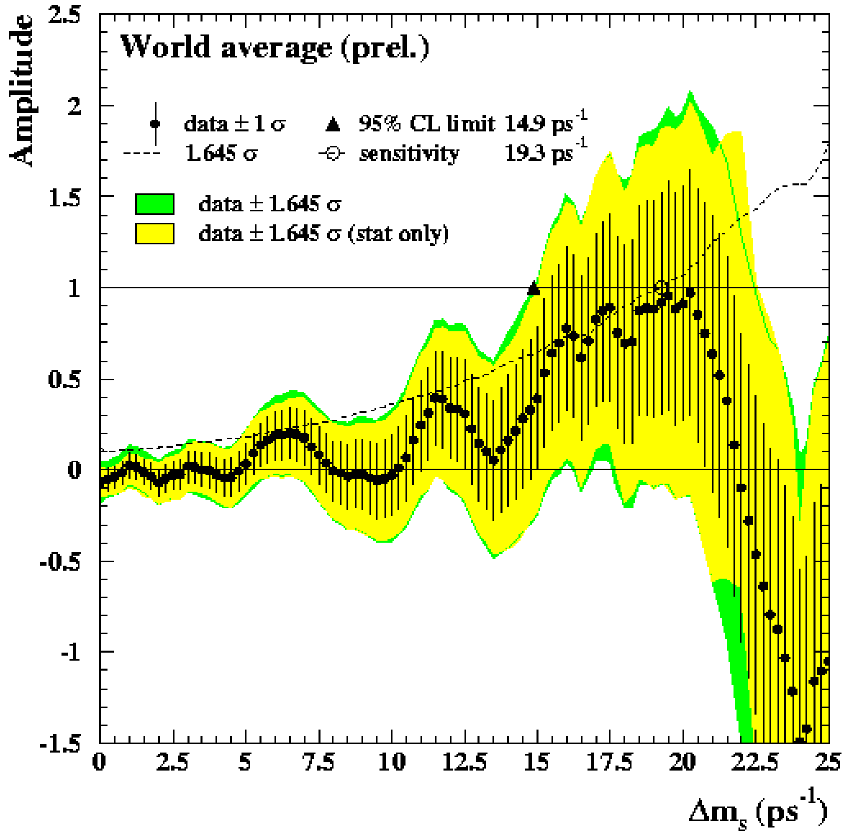
Standard Inputs: Moriond 02

$\|V_{ud}\|$	0.97394 ± 0.00089	*neutron + nuclear b decay*
$\|V_{us}\|$	0.2200 ± 0.0025	*K ® plu*
$\|V_{cd}\|$	0.224 ± 0.014	*dimuon production: uN (DIS)*
$\|V_{cs}\|$	0.969 ± 0.058	*W ® XcX (OPAL)*
$\|V_{ub}\|$	(4.08 ±0.61 ±0.47)10-3	*LEP inclusive*
$\|V_{ub}\|$	(4.08 ± 0.56±0.40)10-3	*CLEO inclusive*
$\|V_{ub}\|$	(3.25 ±0.29 ±0.55)10-3	*CLEO exclusive*
		® *product of likelihoods for* $\|V_{ub}\|$
$\|V_{cb}\|$	(40.4 ±1.3 ±0.9)10-3	*Excl./Incl.+CLEO Moment Analysis*
$\|e_K\|$	(2.271 ±0.017)10-3	*PDG 2000*
Dm_d	(0.496 ±0.007) ps-1	*BABAR,Belle,CDF,LEP,SLD (2002)*
Dm_s	Amplitude	*CDF,LEP,SLD (2002)*
sin2b	0.780 ±0.077	*WA, Updates Moriond 02 BABAR and Belle included*
$m_t(\overline{MS})$	(166 ±5) GeV	*CDF,D0, PDG 2000*
f_{Bd}ÖB_d	(0.230 ±0.028 ±0.028)GeV	*Lattice 2000*
x	1.16 ±0.03 ±0.05	*Lattice 2000*
h_{cc}	0.87 ±0.06 ±0.13	*Lattice 2000*

+ other parameters with less relevant errors…

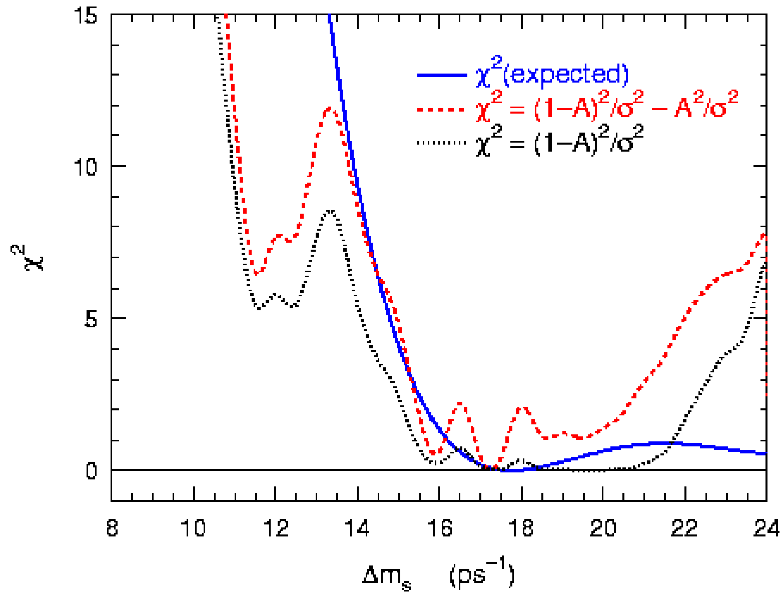
Refined Treatment of Dm_s

No measurement of Dm_S : how do we use the available experimental information ?



Following F. Le Diberder's treatment presented at the CERN CKM workshop in Feb. 02

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

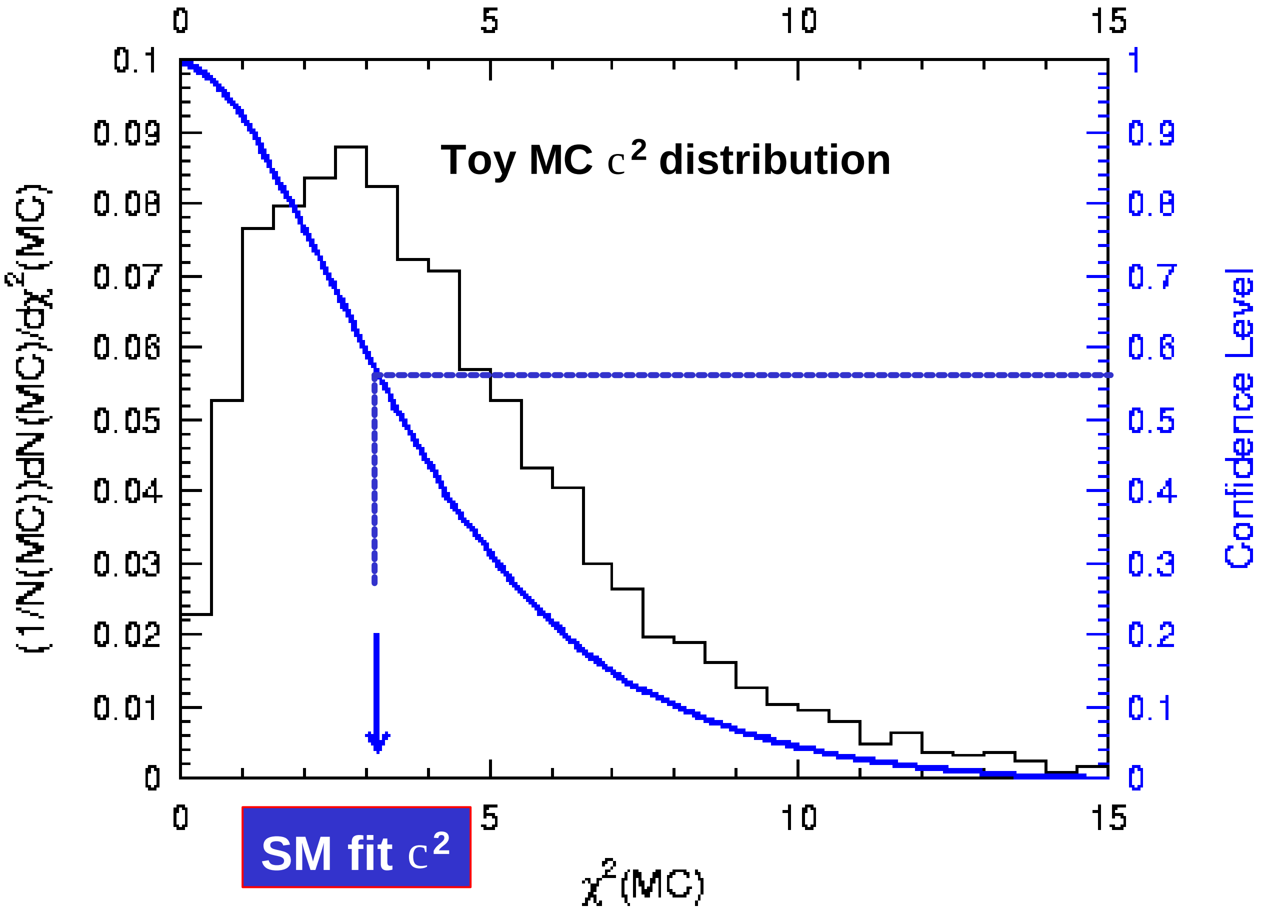


Prefered value = 17.2 ps^{-1}

See CKM workshop web page
Paper in preparation

(I) Probing the SM

Test of goodness of fit

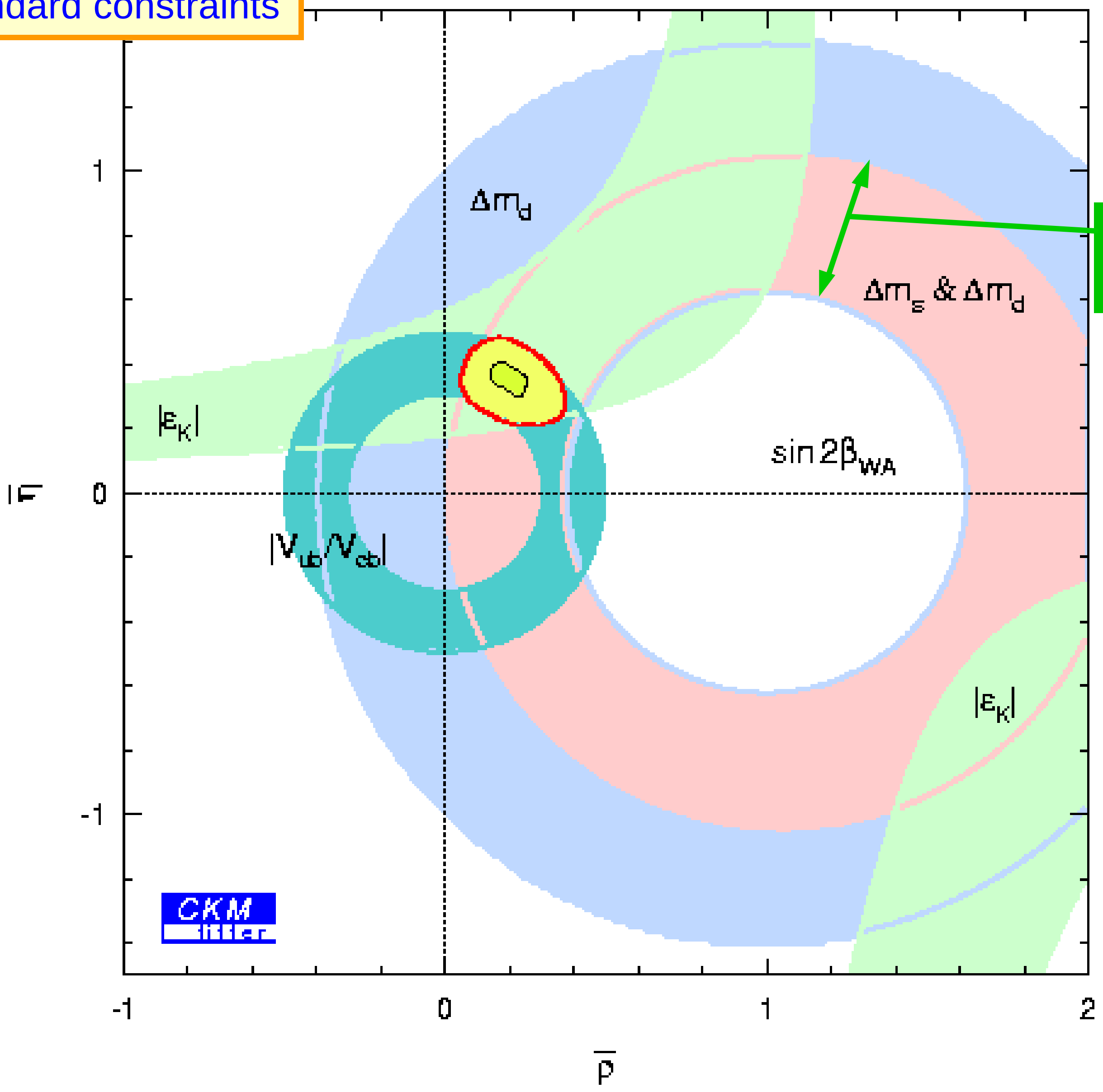


Confidence Level of Standard Model: CL(SM) = 57%

(II) Metrology

The standard constraints

Does not include sin2β

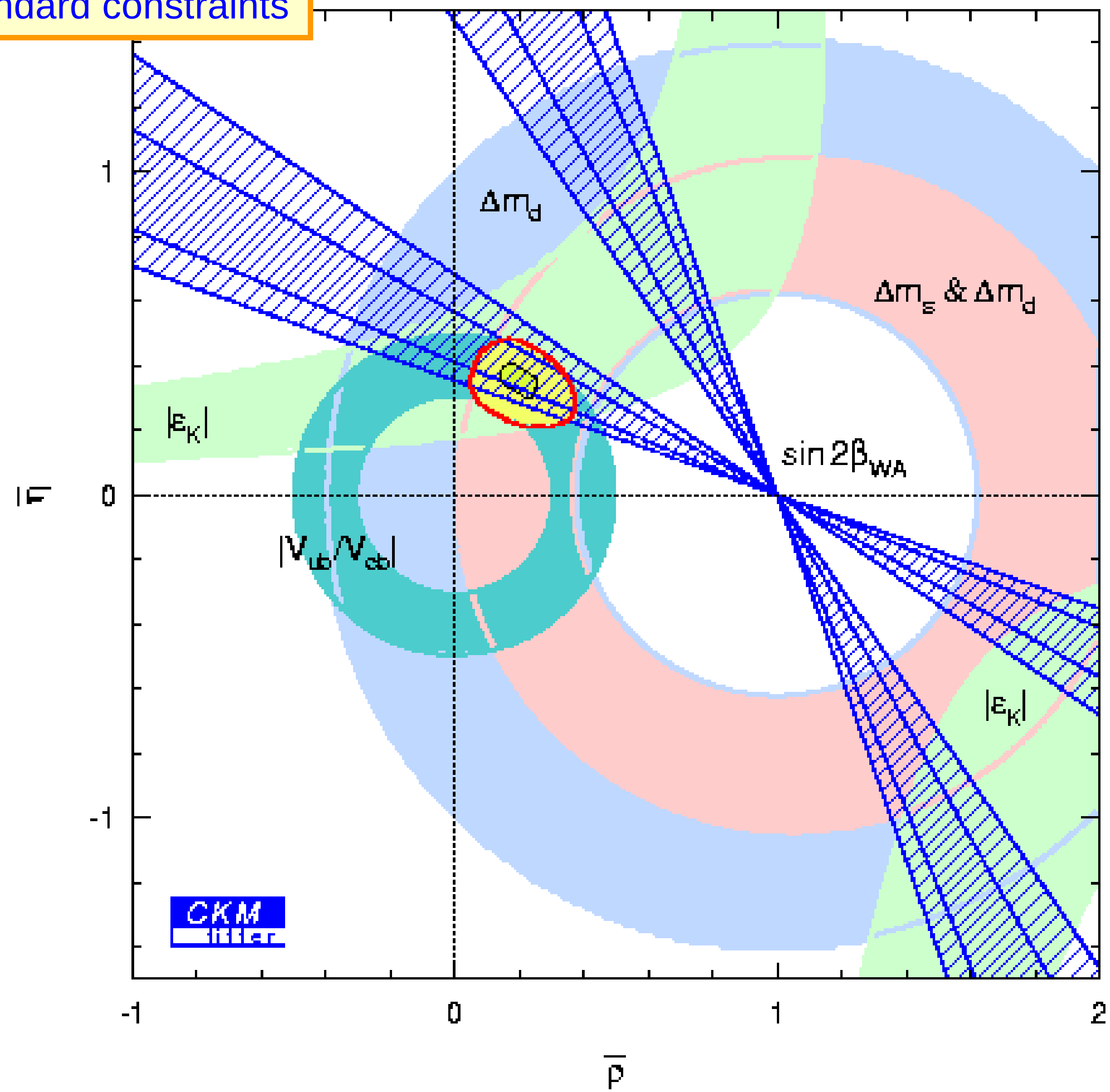


Region containing points > 5% CL

(II) Metrology

The standard constraints

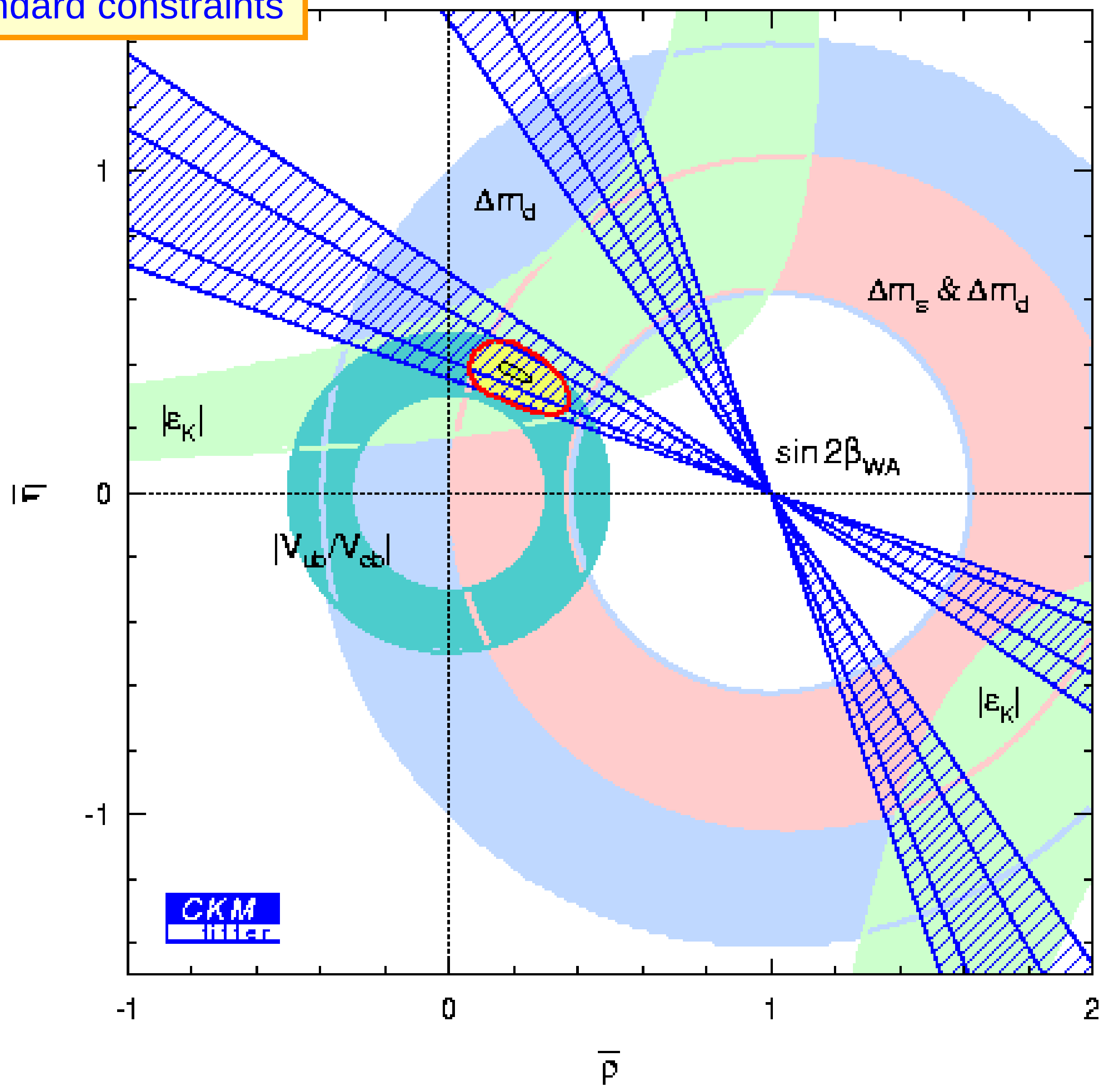
Does not include sin2β



(II) Metrology

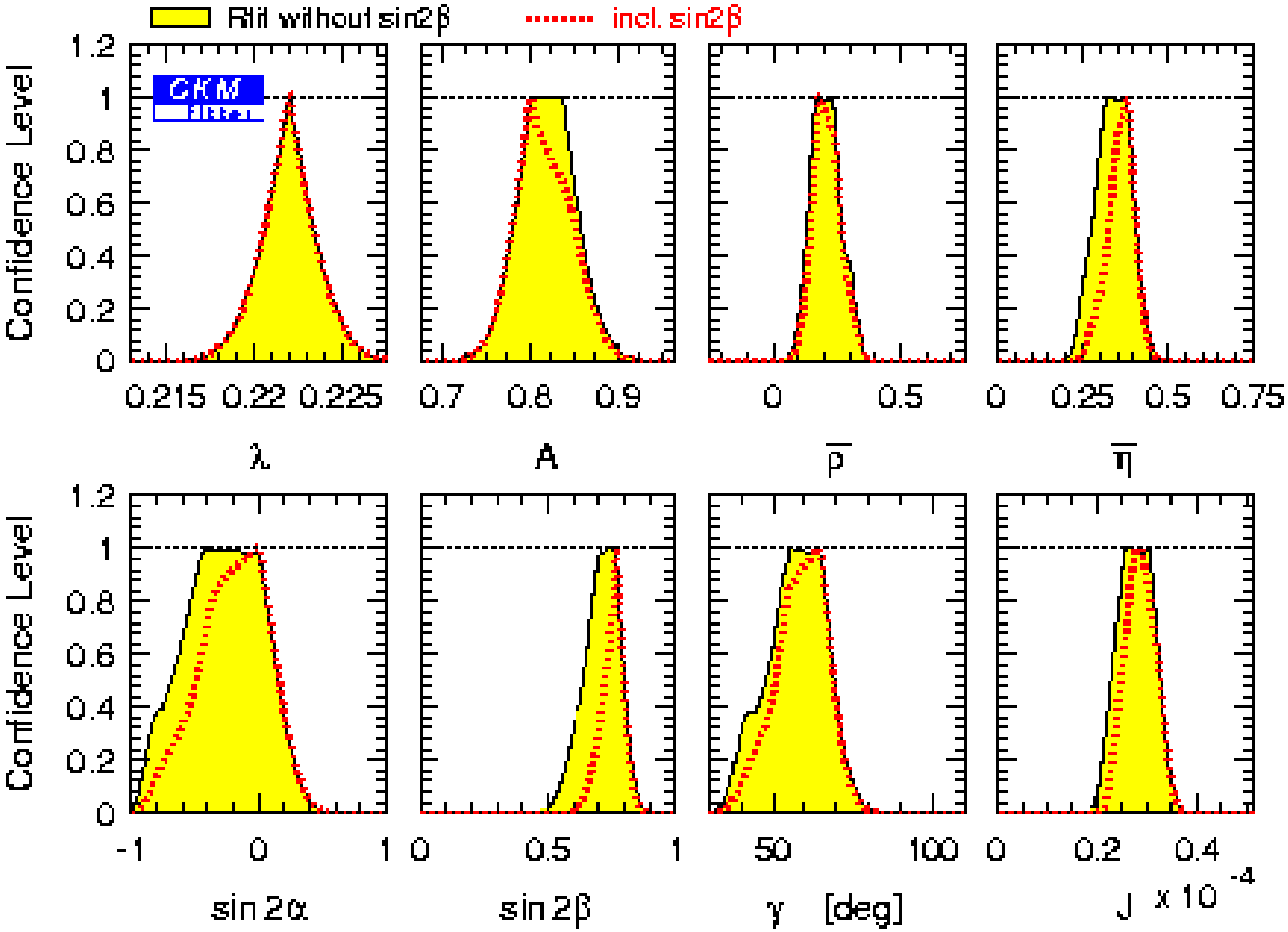
The standard constraints

Fit including sin2β



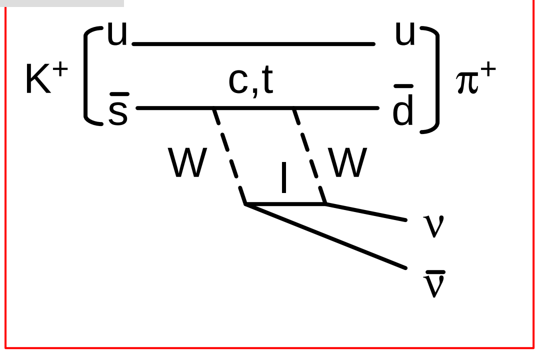
Fit Outputs

One-dimensional constraints:



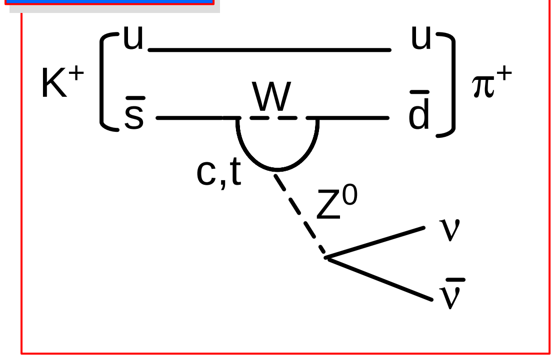
Constraint from Rare Kaon Decays: K^+ ® $p^+n\bar{n}$

Box:



$$BR\left(K^+\to p^+n\bar{n}\right)\propto\frac{BR\left(K^+\to p^0e^+n\right)}{|V_{us}|^2}\sum_{l=e,m,t}|V_{cs}^*V_{cd}X_{NL}^l+V_{ts}^*V_{td}X(x_t)|^2$$

Penguin:



top contribution *charm contribution*

$$BR\left(K^+\to p^+n\bar{n}\right)\propto l^8A^4X^2(x_t)\frac{1}{s}\left[\left(s\bar{h}\right)^2+\left(r_0-\bar{r}\right)^2\right]$$

ellipse

Main theoretical uncertainty comes from charm contribution

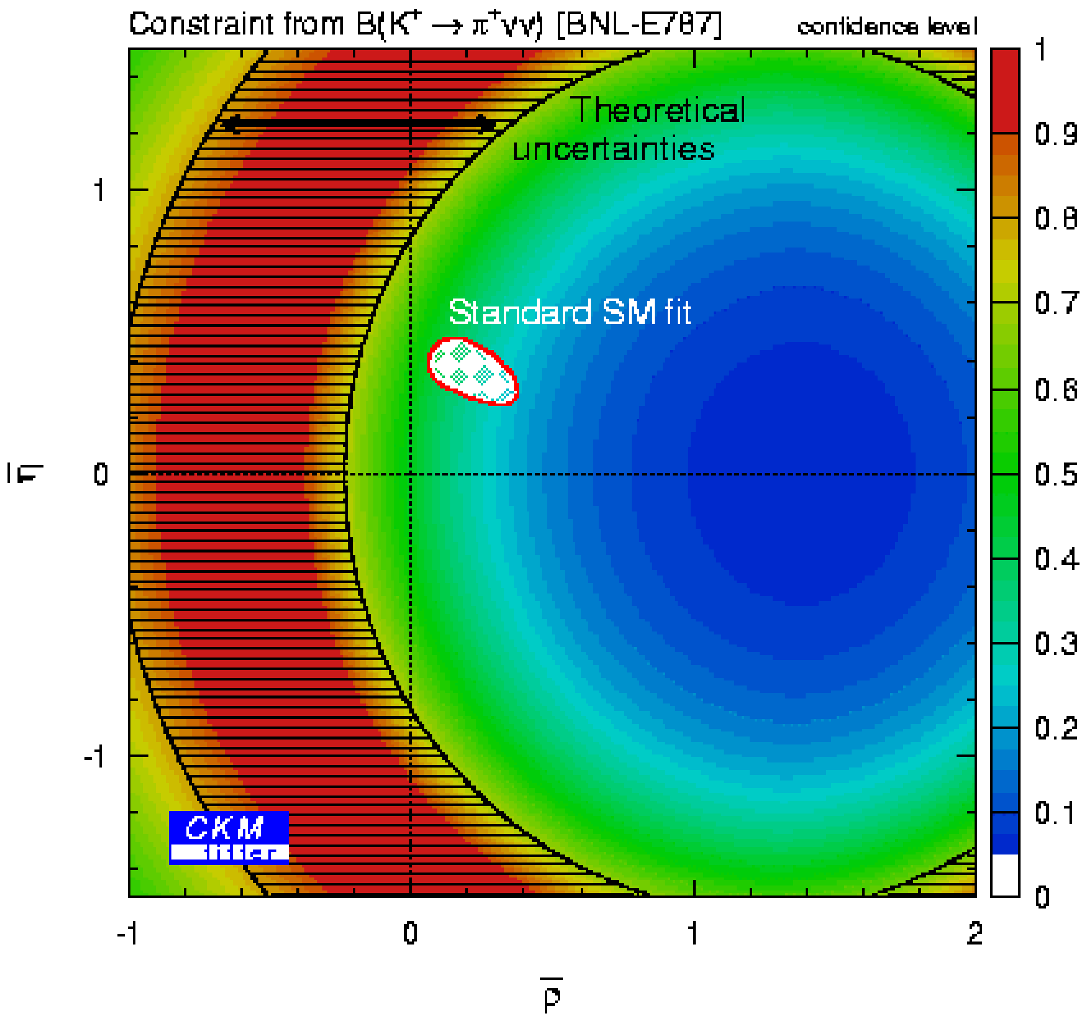
Experiment:

Two events observed at BNL (E787), yielding:

$$B(K^+\to\pi^+\nu\nu) = (1.57\,^{+1.75}_{-0.82})\times10^{-10}$$

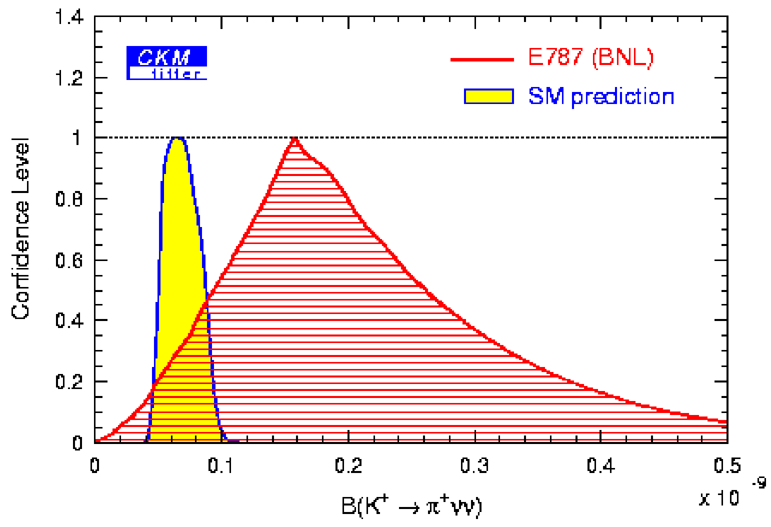
E787 (BNL-68713)
hep-ex/0111091

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



At present dominated by experimental errors.

<u>However:</u>
theoretical uncertainties will become important for constraints in the ρ-η plane



Testing New Approaches: Charmless 2-body B decays

BBNS: QCD FACTORISATION APPROACH:
M. Beneke, G. Buchalla, M. Neubert and C.T. Sachrajda
"QCD Factorization in B -> pK, pp Decays and Extraction of Wolfenstein Parameters", **Nucl.Phys.B606 (2001) 245**

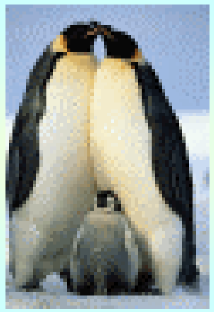
Endpoint Singularities ?

W Annihilation ?

Sudakov ?

PERTURBATIVE QCD APPROACH
Y. -Y. Keum, H-n. Li and A.I. Sanda
"Penguin enhancement and B->pK decays in perturbative QCD", **hep-ph/0004173**

M. Ciuchini, E. Franco, G. Martinelli, M. Pierini and L. Silvestrini, "Charming Penguins strike back", **Phys.Lett. B515 (2001) 33**; "Two body B Decays, Factorization and λ_{QCD} / m_B corrections", **hep-ph/0110022**



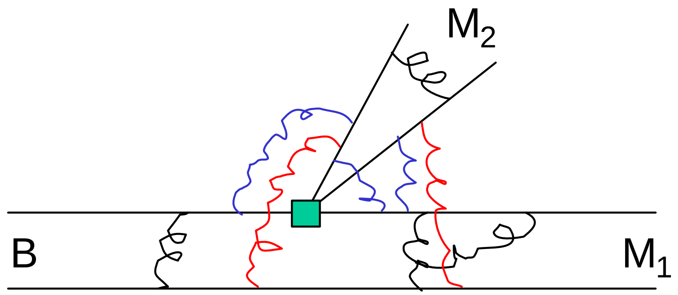
…and many more papers !

HERE: FITS TO BBNS R&D

the QCD Factorization Approach

Color transparency:

- energy release large
- qq pair in emitted meson is collinear
- soft gluons do not interact with small color dipole
- non-factorizable contributions calculable in pQCD



Non-perturbative physics:
formation of M_2 and B ® M_1
Vertex corrections and penguins
Hard spectator interactions

For physical m_b, understanding (Λ_{QCD}/m_b) corrections is important

BBNS Approach

- Tree, strong and EW penguin Wilson coefficients **calculated**
- **Strong phases** predicted **small** ® direct CP asymmetries small
- Annihilation diagrams not rigorously calculated but estimated $\rightarrow X_A$
- Soft physics contribution in the spectator interaction is parametrized $\rightarrow X_H$

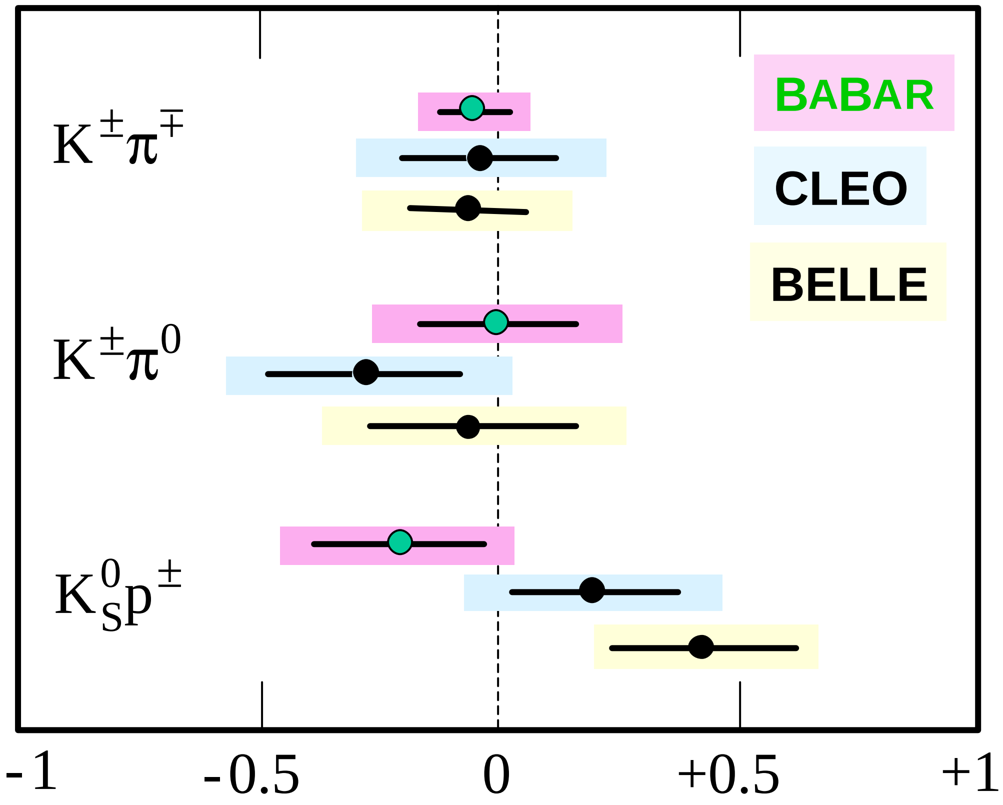
B ® pp / Kp Branching Fractions

Updated Belle (CERN CKM workshop, Feb 02)
Updated BABAR (Moriond EW 02)

BF ($\times 10^6$)	CLEO 9.1 fb^{-1}	BABAR 55.6 fb^{-1}	BELLE 31.7 fb^{-1}	World Average
$B^0 \to p^+p^-$	$4.3^{+1.6}_{-1.4} \pm 0.5$	$5.4 \pm 0.7 \pm 0.4$	$5.1 \pm 1.1 \pm 0.4$	5.17 ± 0.62
$B^0 \to K^+p^-$	$17.2^{+2.5}_{-1.4} \pm 1.2$	$17.8 \pm 1.1 \pm 0.5$	$21.8 \pm 1.8 \pm 1.5$	18.5 ± 1.0
$B^0 \to K^+K^-$	<1.9 (90%)	< 2.5 (90%)	<2.7 (90%)	
$B^+ \to p^+p^0$	$5.6^{+2.6}_{-2.3} \pm 1.7$	$5.1 \pm 2.0 \pm 0.8$	$7.0 \pm 2.2 \pm 0.8$	5.9 ± 1.4
$B^+ \to K^+p^0$	$11.6^{+3.0}_{-2.7}{}^{+1.4}_{-1.3}$	$10.8 \pm 2.1 \pm 1.0$	$12.5 \pm 2.4 \pm 1.2$	$11.6^{+1.6}_{-1.5}$
$B^+ \to K^0p^+$	$18.2^{+4.6}_{-4.0} \pm 1.6$	$18.2 \pm 3.3 \pm 2.0$	$18.8 \pm 3.0 \pm 1.5$	$18.5^{+2.3}_{-2.2}$
$B^0 \to K^0p^0$	$14.6^{+5.9}_{-5.1}{}^{+2.4}_{-3.3}$	$8.2 \pm 3.1 \pm 1.2$	$7.7 \pm 3.2 \pm 1.6$	9.0 ± 2.2

Compatibility among experiments. Most rare modes discovered!

Direct CP Asymmetries in Kp modes



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 CERN CKM Workshop

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

CLEO CLEO PRL 85 (2000) 525

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

Compatibility among experiments

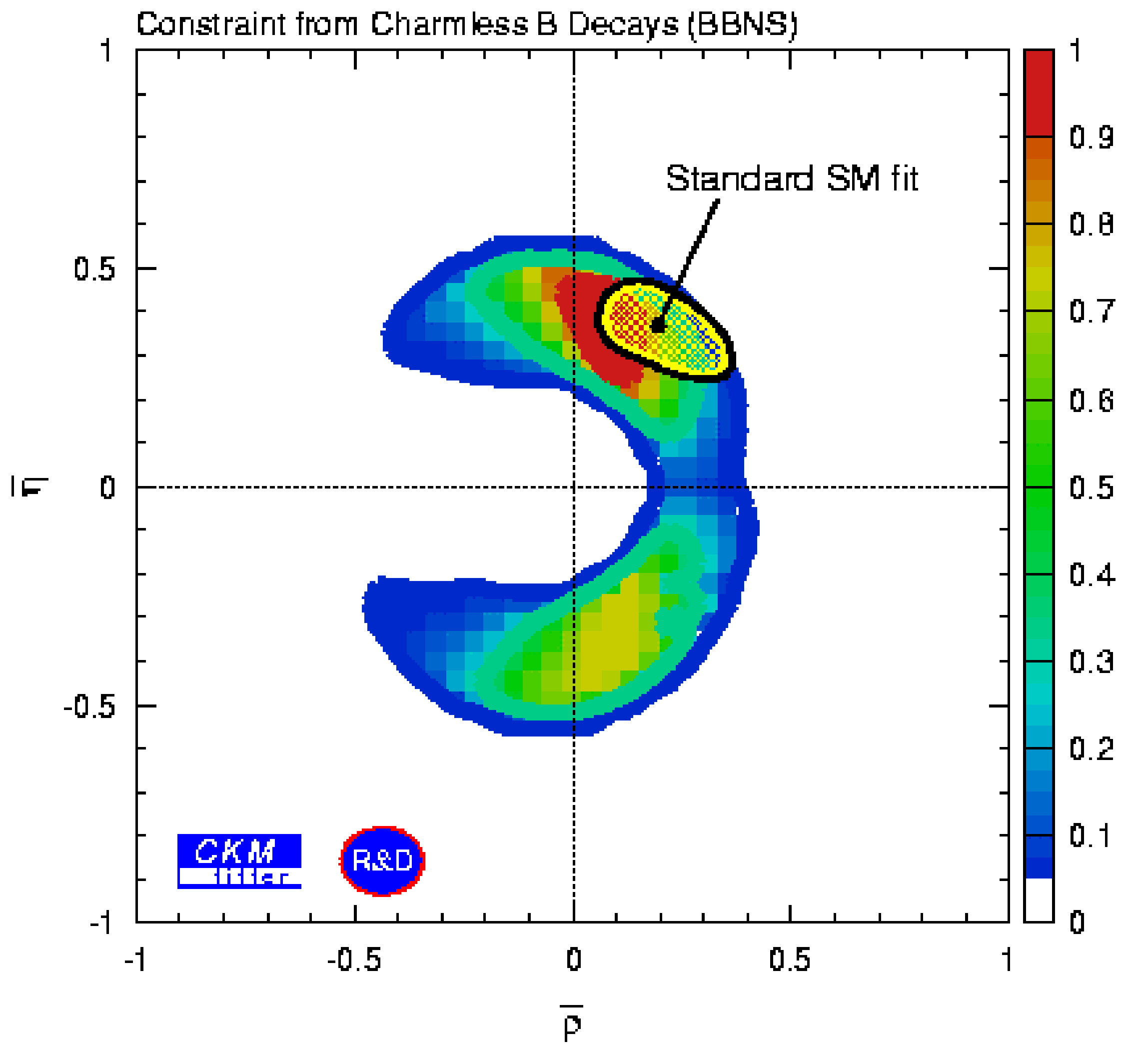
No significant deviation from zero

World Averages

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

Branching Ratios and A_{CP} Fits in BBNS

Compared to standard CKM fit



Theoretical uncertainties:

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

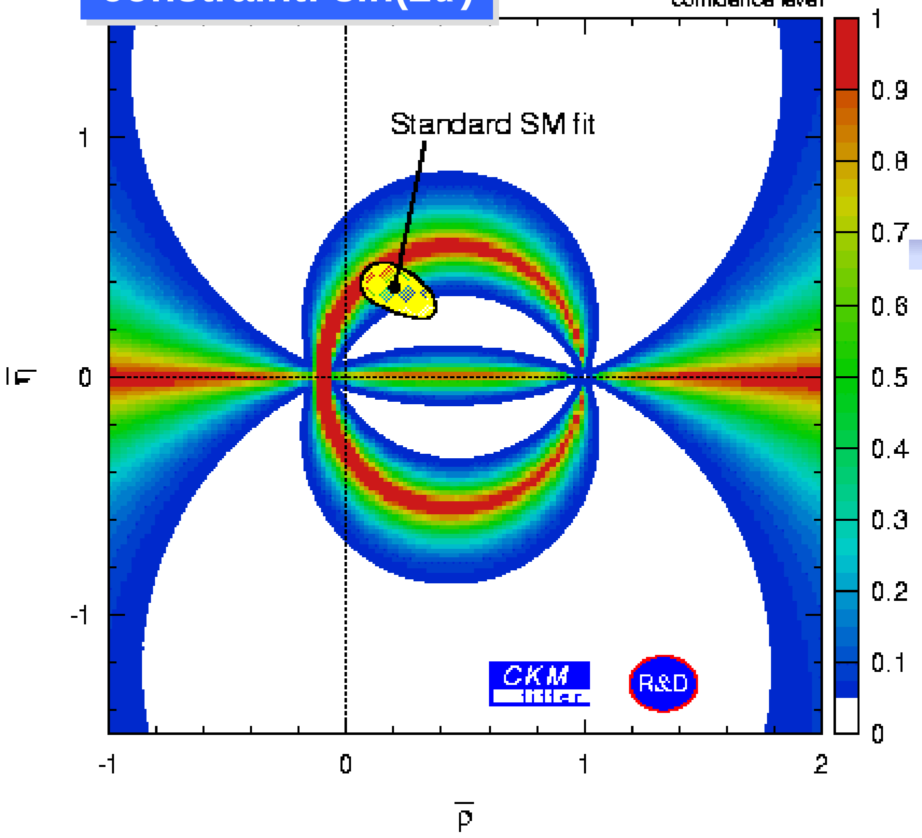
sin2α Constraint assuming BBNS

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

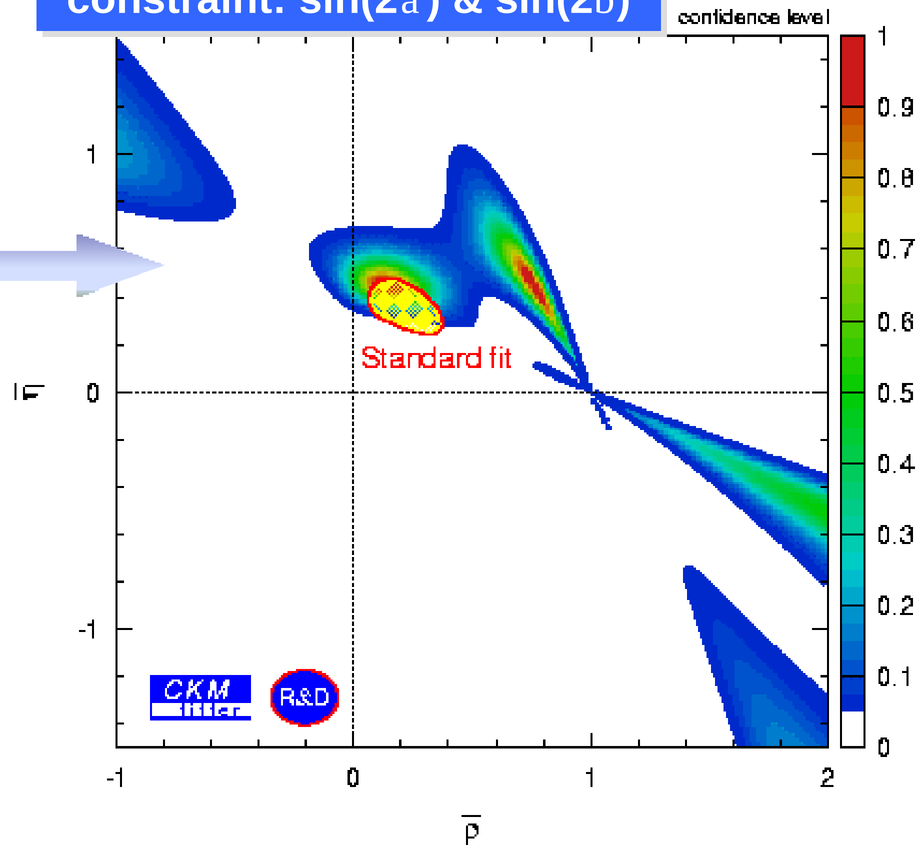
$$\lambda_{\pi\pi} = e^{-2i\beta}\,\frac{e^{-i\gamma} + P_{\pi\pi}/T_{\pi\pi}}{e^{+i\gamma} + P_{\pi\pi}/T_{\pi\pi}}$$

Use BABAR result:
$S_{\pi\pi}$ = -0.01 ± 0.37 ± 0.07
& BBNS

constraint: sin(2α)



constraint: sin(2α) & sin(2β)



(III) Testing New Physics: The Semi-leptonic Asymmetry

$$A_{SL} = \frac{\Gamma\left[\overline{B}^0_{phys}(t) \to l^+ X\right] - \Gamma\left[B^0_{phys}(t) \to l^- X\right]}{\Gamma\left[\overline{B}^0_{phys}(t) \to l^+ X\right] + \Gamma\left[B^0_{phys}(t) \to l^- X\right]} = \mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)$$

SL, Z. Ligeti, Y. Nir, G. Perez
hep-ph/0202010

	SM	NP
$\lvert\Gamma_{12}/M_{12}\rvert$	$O(m_b^2/m_W^2)$	
$\arg(\Gamma_{12}/M_{12})$	$O(m_c^2/m_b^2)$	$O(1)$
A_{SL}	10^{-3}	10^{-2}

	Measurements
OPAL	$(0.4 \pm 5.7) \times 10^{-2}$
CLEO	$(1.4 \pm 4.2) \times 10^{-2}$
ALEPH	$(-1.2 \pm 2.8) \times 10^{-2}$
BABAR	$(0.48 \pm 1.85) \times 10^{-2}$
WA	$(0.2 \pm 1.4) \times 10^{-2}$

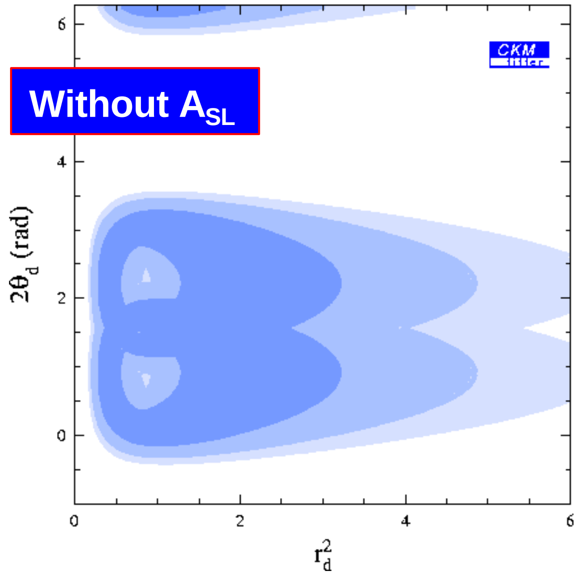
SM $-1.4 < A_{SL}(10^{-3}) < -0.5$ (>10% CL)

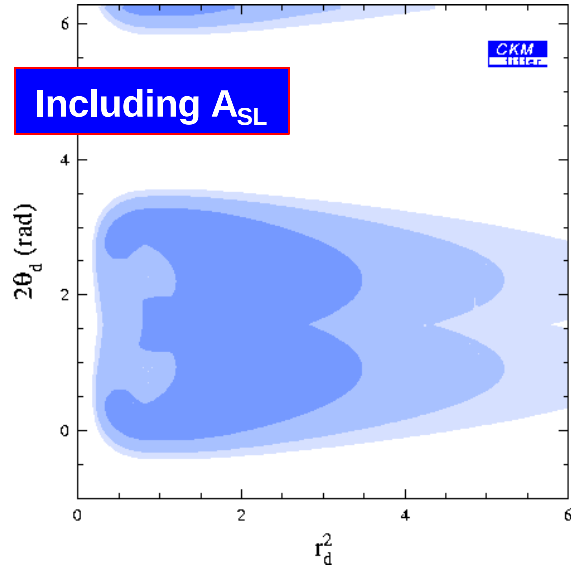
ASL not expected to constrain ρ,η but to exhibit / constrain New Physics
The present WA already constrains some models…

The Semi-leptonic Asymmetry

General NP in mixing amplitude

$$M_{12} = r_d^2 \, e^{2iJ_d} \, M_{12}^{SM}$$



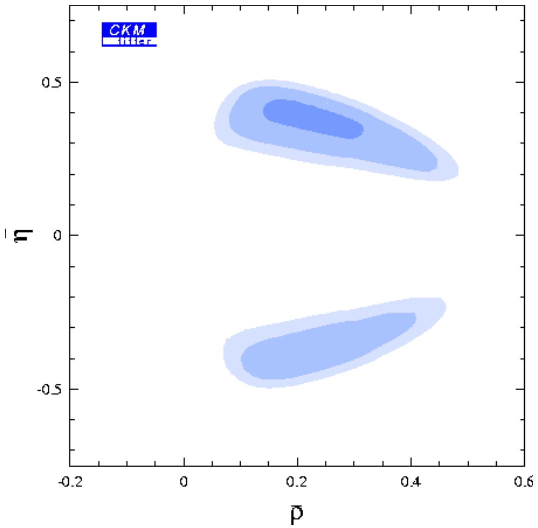


Minimal Flavour Violation model

$$r_d^2 = \frac{|F_{tt}|}{S_0(x_t)} \quad \text{and} \quad 2J = 0(p)$$

A_{SL} not significantly enhanced

- $\eta<0$ allowed



Conclusion

Measurement can discriminate between various NP models

Summary

CKM Fits:

- Global CKM fit → consistent picture of Standard Model
- sin2β: perfect agreement with SM expectations
  the most precise constraint in the (ρ,η) plane
- New measurements on the market: rare K decays, …

Test of new approaches in QCD:

- BBNS is implemented in CKMFitter and gives interesting results
- Other approaches intended to be implemented

Test New Physics:

- Recent measurements (*e.g.* A_{SL}) already provide meaningful constrains on general New Physics models