THE UNITARITY TRIANGLE ANALYSIS AND ITS THEORETICAL INPUT PARAMETERS

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OUTLINE

1. Flavour physics and its motivations
2. Lattice QCD and the UTA input parameters
3. UTA: results and perspectives

Orsay,

April 14-16 2004

IN2P3 — Institut National de Physique Nucléaire et de Physique des Particules

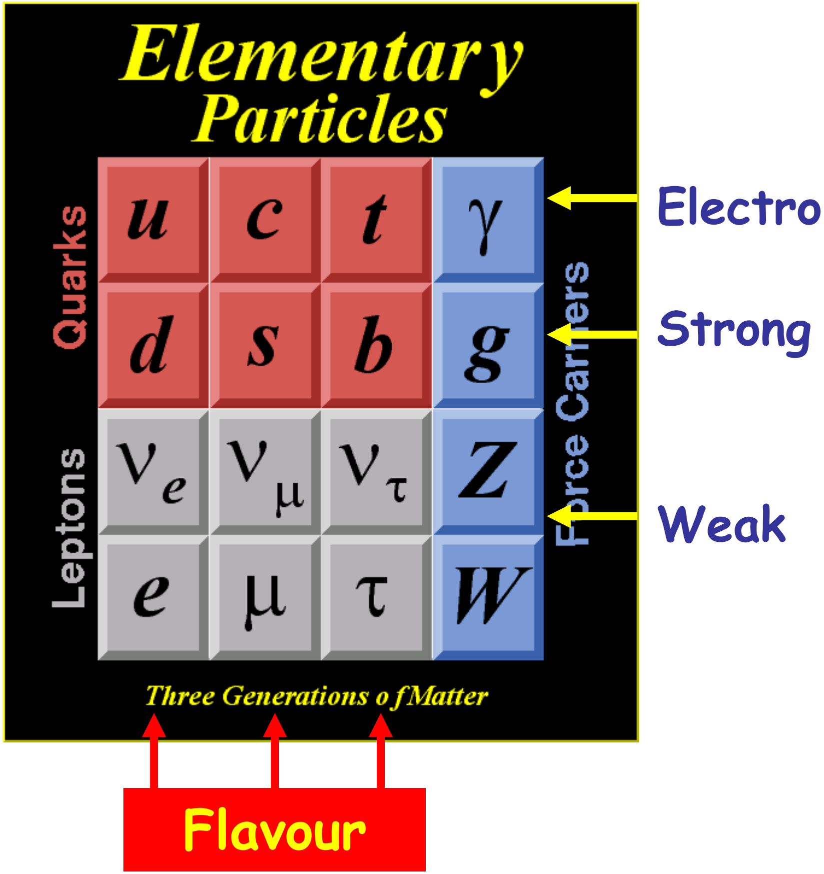
CNRS — CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

Université Paris-Sud

1

FLAVOUR PHYSICS AND ITS MOTIVATIONS

STANDARD MODEL AND FLAVOUR PHYSICS



$SU(2)_L \times U(1)_Y \times SU(3)$

Symmetry breaking: Higgs (?)

FLAVOUR PHYSICS

- Why 3 families?
- Why the hierarchy of masses?
- Is the CKM mechanism and its explanation of CP violation correct?

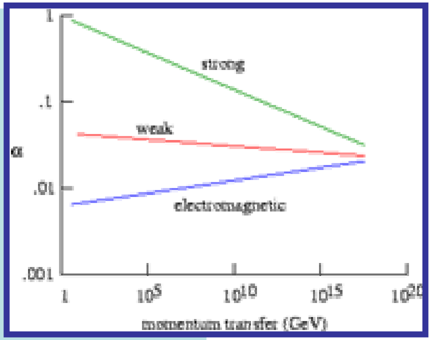
Only weak interactions can change flavour [CKM]

THE STANDARD MODEL: A LOW ENERGY EFFECTIVE THEORY

CONCEPTUAL PROBLEMS The most obvious:

- Gravity: $M_{Planck} = (\hbar c/G_N)^{1/2} \approx 10^{19}$ GeV

PHENOMENOLOGICAL INDICATIONS:



- Unification of couplings ($M_{GUT} \approx 10^{15}$-10^{16} GeV)
- Dark matter ($\Omega_M \approx 0.35$)
- Neutrino masses
- Matter/Anti-matter asymmetry (not enough ~~CP~~ in the SM)

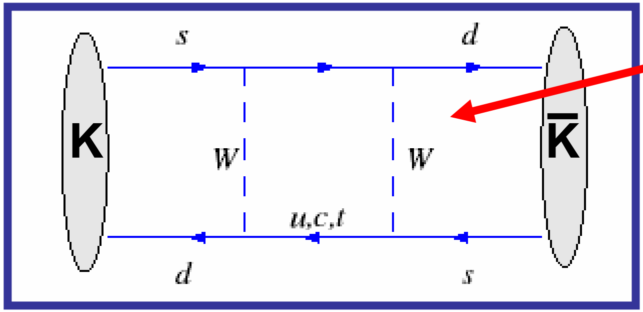
THE "NATURAL" CUT-OFF:

$$\delta m_H^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 \Lambda^2 \approx (0.3\ \Lambda)^2$$

$\longrightarrow$ $\Lambda = O(1\ \text{TeV})$

NEW PHYSICS MUST BE VERY "SPECIAL"

NEW PHYSICS EFFECTS IN FLAVOUR PHYSICS



QUANTUM EFFECTS

THE FLAVOUR PROBLEM:

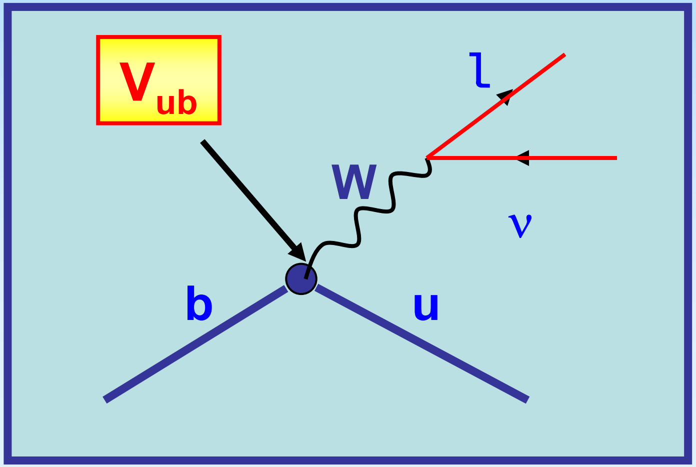
$\Lambda_{K^0-\bar{K}^0} \approx O(100\ \text{TeV})$

PRECISION ERA OF FLAVOUR PHYSICS

ε_K =	$(2.271 \pm 0.017) \times 10^{-3}$	0.7%
Δm_d =	$(0.503 \pm 0.006)\ \text{ps}^{-1}$	1%
$\sin(2\beta)$ =	0.734 ± 0.054	7%

We need to control the theoretical input parameters at a comparable level of accuracy !!

THE CKM MATRIX



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

3 FAMILIES:

3 angles and 1 phase

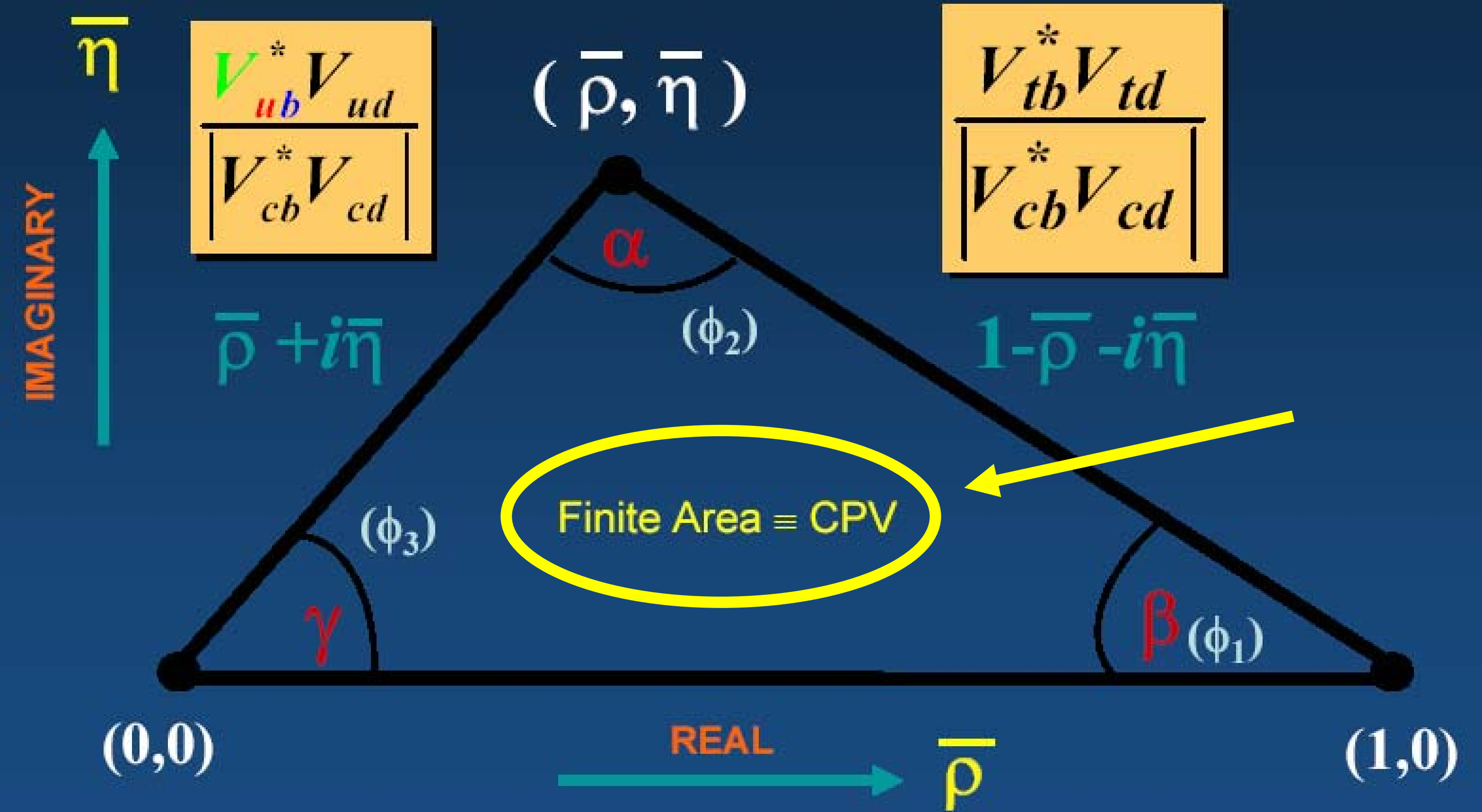
Only 1 parameter for CP VIOLATION

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

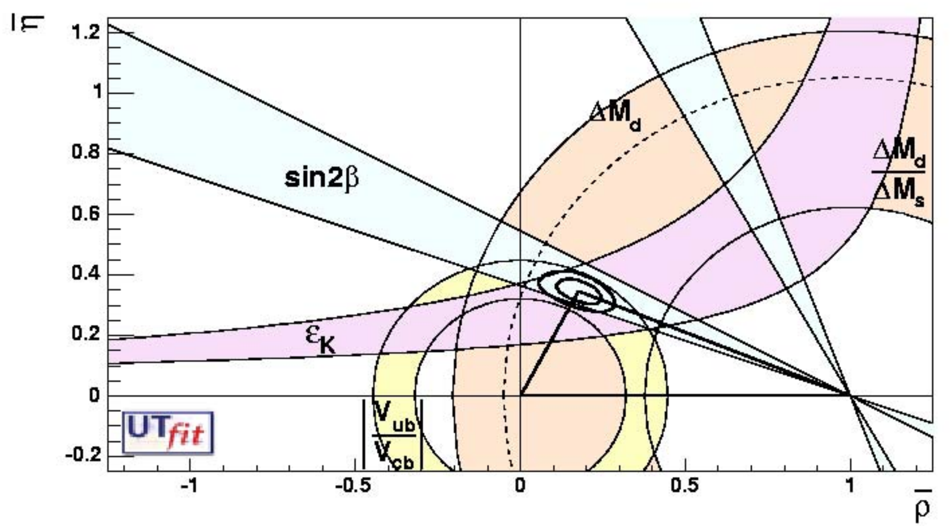
(Lincoln Wolfenstein)

THE UNITARITY TRIANGLE

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



THE UNITARITY TRIANGLE ANALYSIS



5 CONSTRAINTS
2 PARAMETERS

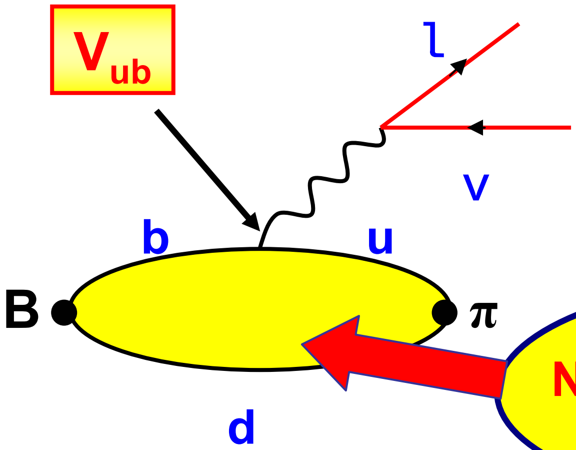
Hadronic Matrix Elements from LATTICE QCD

$(b \to u)/(b \to c)$	$\bar{\rho}^2 + \bar{\eta}^2$	$\bar{\Lambda}$, λ_1, f_+, ...
ε_K	$\bar{\eta}[(1-\bar{\rho}) + P]$	B_K
Δm_d	$(1-\bar{\rho})^2 + \bar{\eta}^2$	$f^2_{B_d} B_{B_d}$
$\Delta m_d / \Delta m_s$	$(1-\bar{\rho})^2 + \bar{\eta}^2$	ξ
$A(J/\psi K_S)$	$\sin 2\beta(\bar{\rho}, \bar{\eta})$	—

②

LATTICE QCD AND THE UTA INPUT PARAMETERS

V_{ub} FROM B-MESON SEMILEPTONIC DECAYS

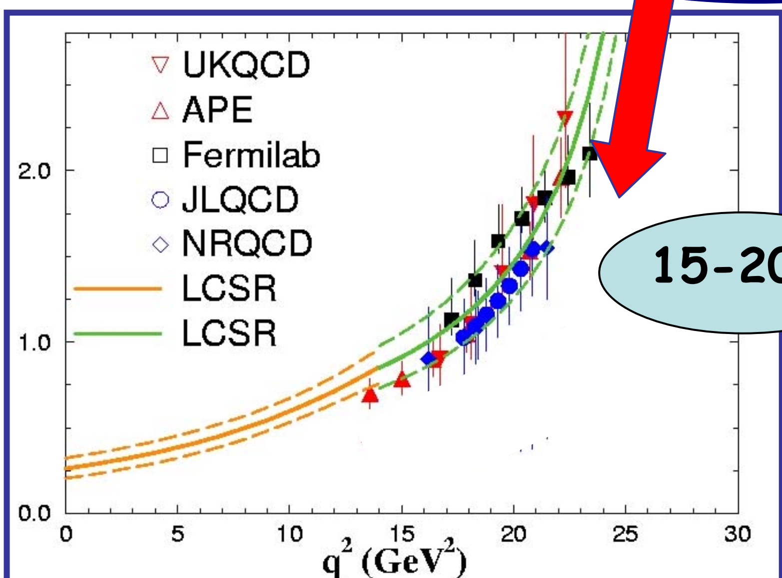


$$\Gamma(B \to \pi l \nu) = \frac{G_F^2 |V_{ub}|^2}{192\,\pi^3} \int dq^2\, \lambda(q^2)^{3/2}\, |f_+(q^2)|^2$$

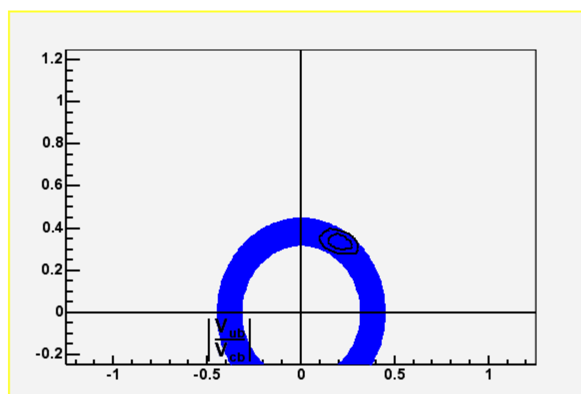
NON-PERTURBATIVE PHYSICS

EXPERIMENTS:

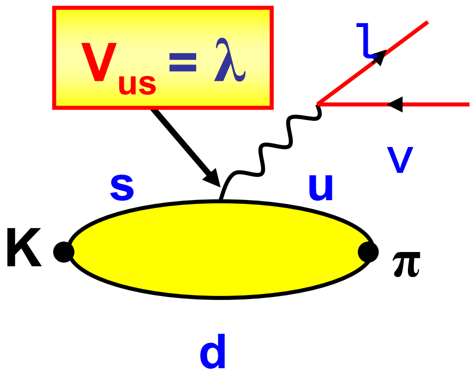
CLEO, BaBar, Belle, …

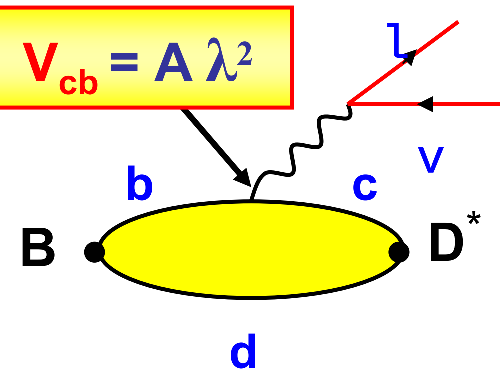


15-20%



PRECISION FLAVOUR PHYSICS ON THE LATTICE



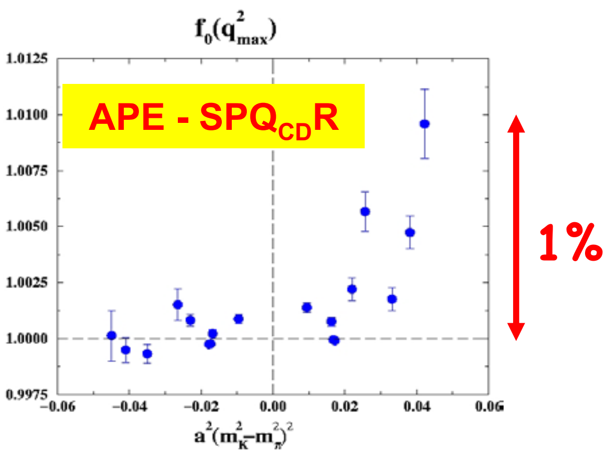


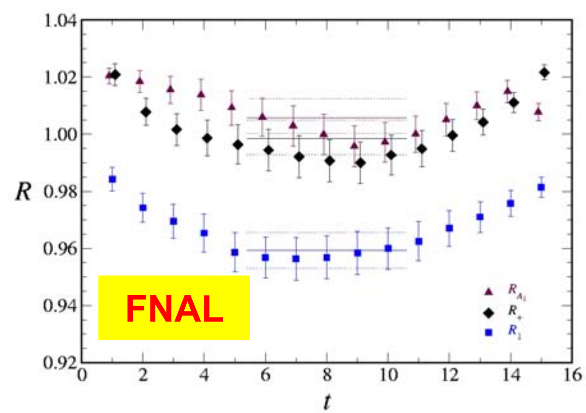
$f_+(0) = 1 - O(m_s - m_u)^2$

Ademollo-Gatto theorem

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

Luke theorem





$f_+(0) = 0.960 \pm 0.005 \pm 0.007$

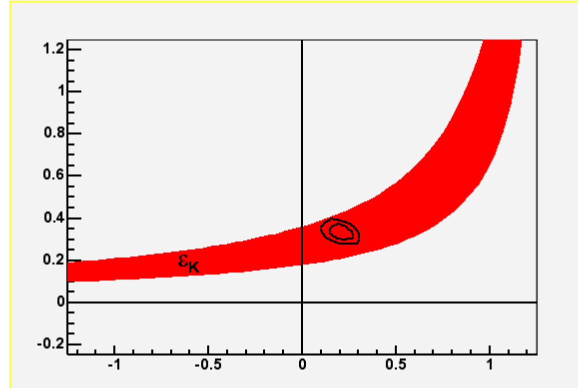
$F_{B\to D^*}(1) = 0.913\,^{+0.024}_{-0.017}\,^{+0.017}_{-0.030}$

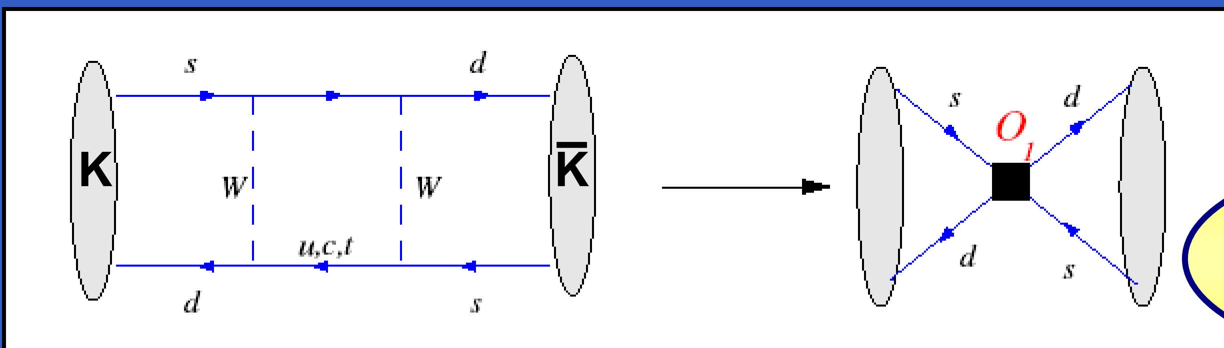
$K-\bar{K}$ Mixing: ε_K and B_K

CP=−1 CP=+1

$$K_L \sim (K^0 - \bar{K}^0) + \varepsilon_K (K^0 + \bar{K}^0)$$

CP Violation



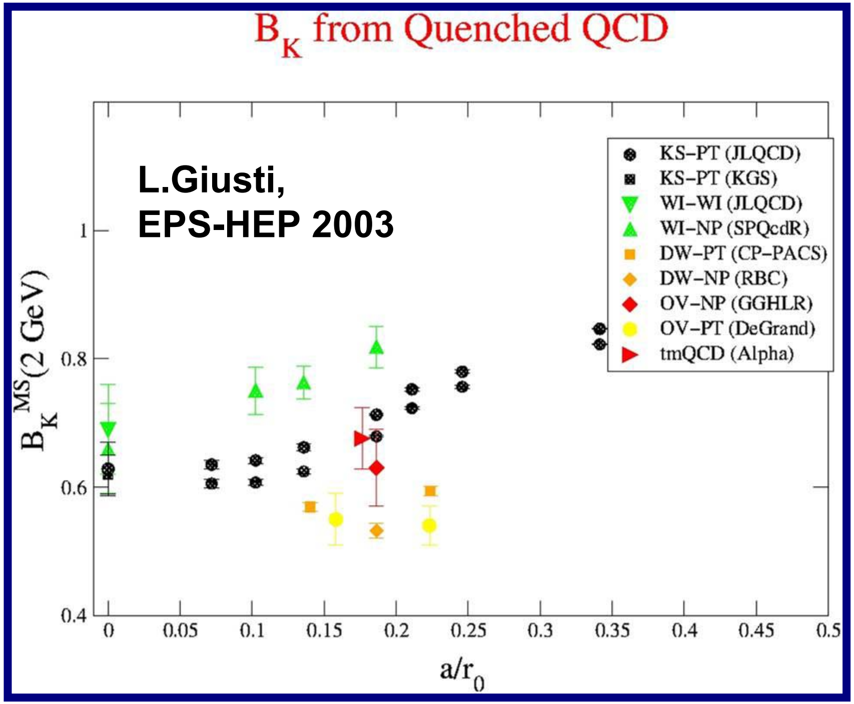


NON-PERTURBATIVE PHYSICS

$$\varepsilon_K \sim \langle \bar{K}^0 | \mathcal{H}_{\rm eff}^{\Delta S=2} | K^0 \rangle$$

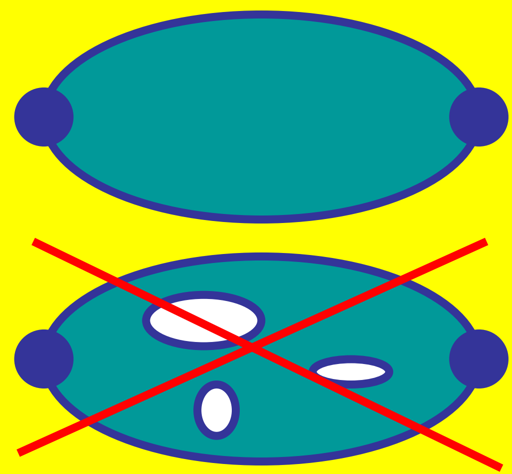
$$\langle \bar{K}^0 | Q(\mu) | K^0 \rangle = \frac{8}{3} f_K^2 m_K^2 B_K(\mu)$$

Lattice Results for B_K



- ✓ High level of accuracy
- ✓ Discretization effects not negligible
- ✓ Estimate of quenching error from ChPT ≤ 15% (Sharpe)

Quench. Appr.



$$\hat{B}_K = 0.87 \pm 0.06 \pm 0.13$$

[D. Becirevic, Plenary talk @ LATT03]

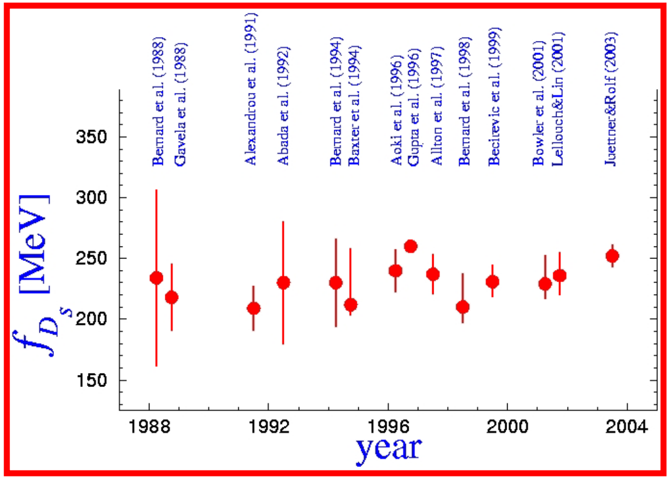
LATTICE PREDICTION (!) $\hat{B}_K = 0.90 \pm 0.20$ **[Gavela et al., 1987]**

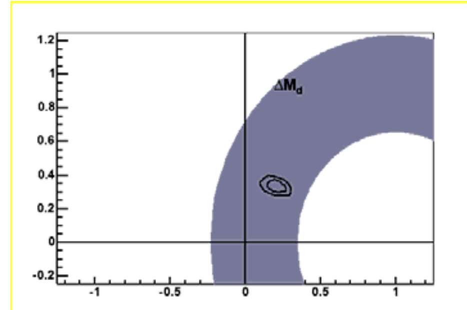
$B_{B_{d/s}} - \bar{B}_{B_{d/s}}$ Mixing: $f_{B_{d/s}}$ and $B_{B_{d/s}}$

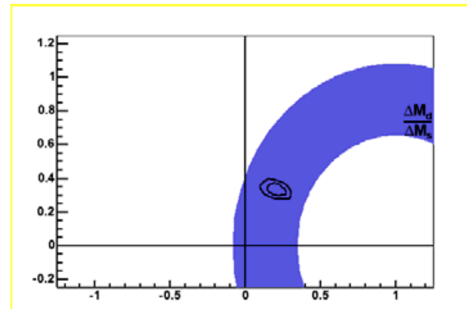
THE D_s-MESON DECAY CONSTANT

A long history of lattice calculations…

QUENCHED







$f_{Ds}^{Nf=2} / f_{Ds}^{Nf=0} = 1.08 \pm 0.05$ (CP-PACS,MILC)

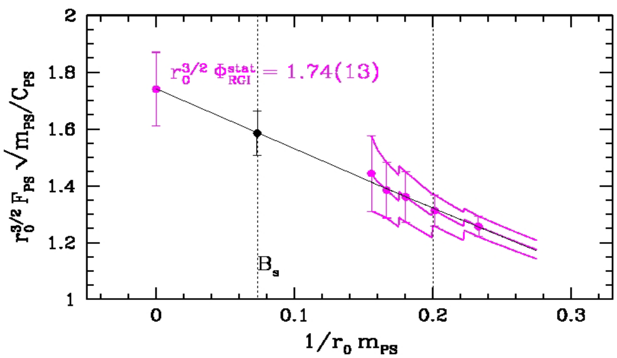
$f_{Ds} = 265 \pm 14 \pm 13$ MeV — LQCD Average [D.Becirevic]

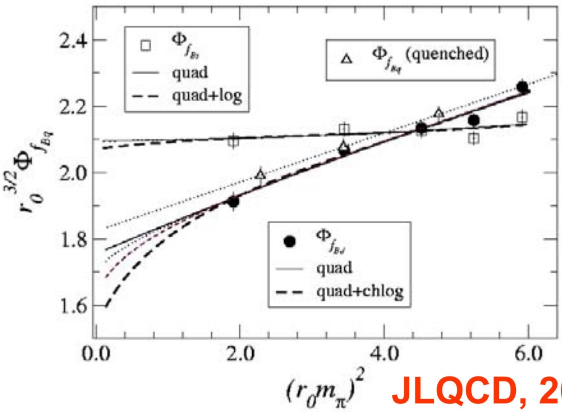
$f_{Ds} = 285 \pm 19 \pm 40$ MeV — EXP. PDG 2002

New results expected from CLEO-c

From f_{Ds} to f_{Bd}

J.Heitger, EPS-HEP 2003





JLQCD, 2003

$m_Q \ll 1/a$

- Extrapolations from $m_Q \sim m_c$ to m_b
- Effective theories: HQET, NRQCD, “FNAL”, …
- Combine the two approaches
- Finite size approach , **APE-Tov**

$m_\pi \gg 1/L$

- Extrapolations from m_q to $m_{u,d}$ using ChPT as a guidance:

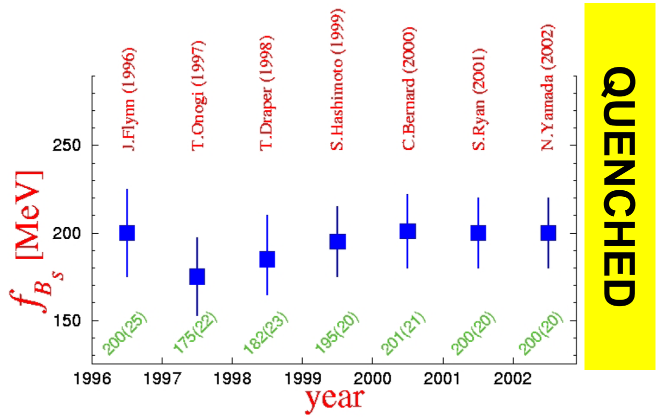
$$\frac{f_{B_s}\sqrt{m_{B_s}}}{f_{B_d}\sqrt{m_{B_d}}} = 1 + \frac{1+3\hat{g}^2}{4(4\pi f)^2}\,\chi logs + C$$

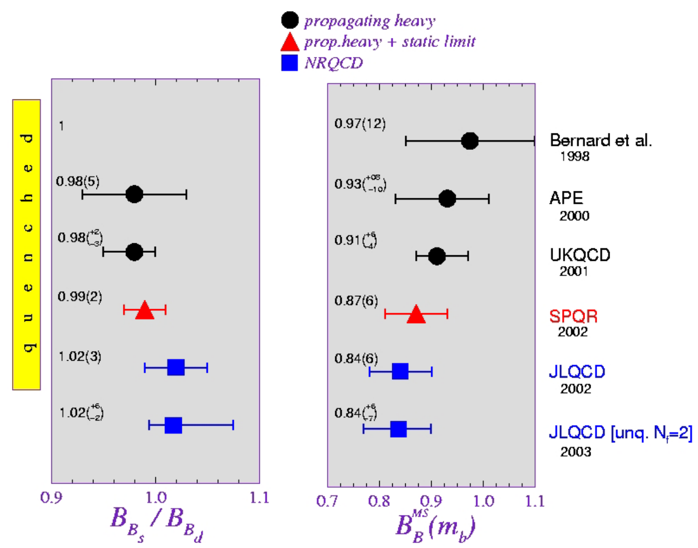
Orsay

Use $\dfrac{f_{B_s}/f_{B_d}}{f_K/f_\pi}$, **Becirevic et al.**

$B_{B_{d/s}} - \bar{B}_{B_{d/s}}$ Mixing: $f_{B_{d/s}}$ and $B_{B_{d/s}}$

f_{Bs}: the "world average" evolution





$f_{Bs}^{Nf=2}/f_{Bs}^{Nf=0} = 1.12 \pm 0.05$ (CP-PACS,MILC)

In other quantities (f_{Bs}/f_{Bd}, B_{Bd}, B_{Bs}/B_{Bd}) quenching effects are smaller

LATTICE AVERAGES

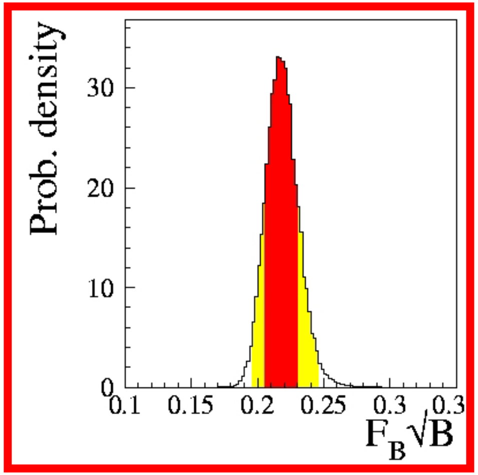
$f_{Bs}\sqrt{B_{Bs}} = 276 \pm 38$ MeV, $\xi = 1.24 \pm 0.04 \pm 0.06$

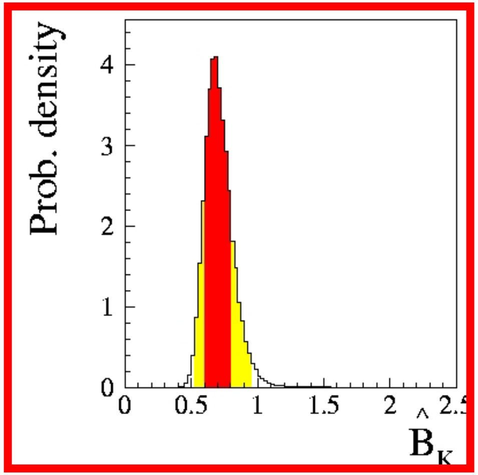
[1st Workshop on the CKM Unitarity Triangle, 2002]

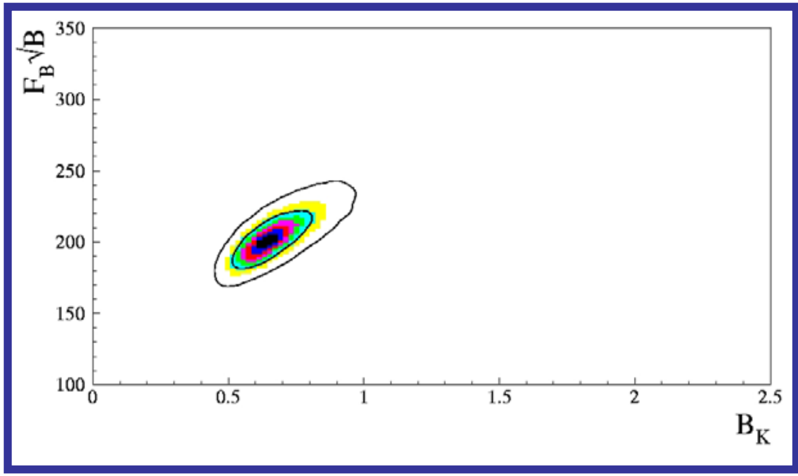
$f_{Bs}\sqrt{B_{Bs}} = 254 \pm 24$ MeV, $\xi = 1.21 \pm 0.05 \pm 0.01$

[D. Becirevic, 2nd Workshop on the CKM Unitarity Triangle, 2003]

Lattice QCD vs UT FITS







	LATTICE QCD	UT FIT
$f_B\sqrt{B_B}$	$223 \pm 33 \pm 12$ MeV	217 ± 12 MeV
B_K	$0.86 \pm 0.06 \pm 0.14$	0.71 ± 0.11

3

THE UNITARITY TRIANGLE ANALISYS: RESULTS AND PERSPECTIVES

The Collaboration

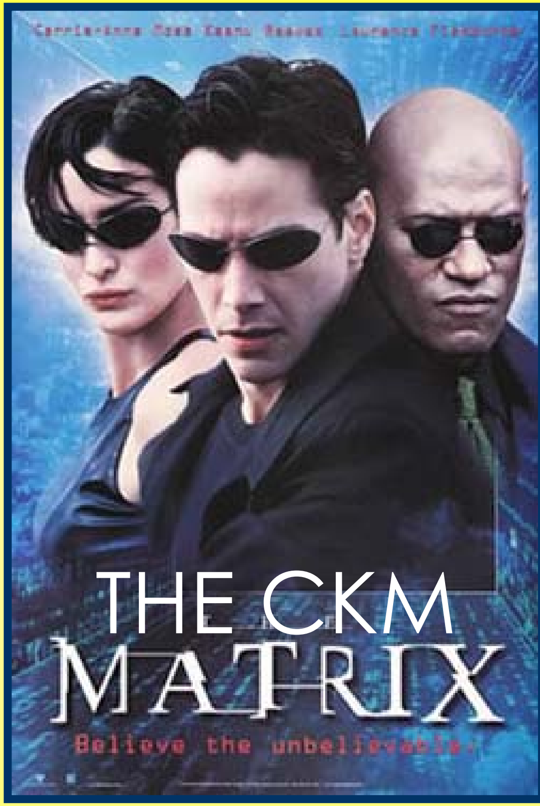
M.Bona, M.Ciuchini, E.Franco,

V.L., G.Martinelli, F.Parodi,

M.Pierini, P.Roudeau, C.Schiavi,

L.Silvestrini, A.Stocchi

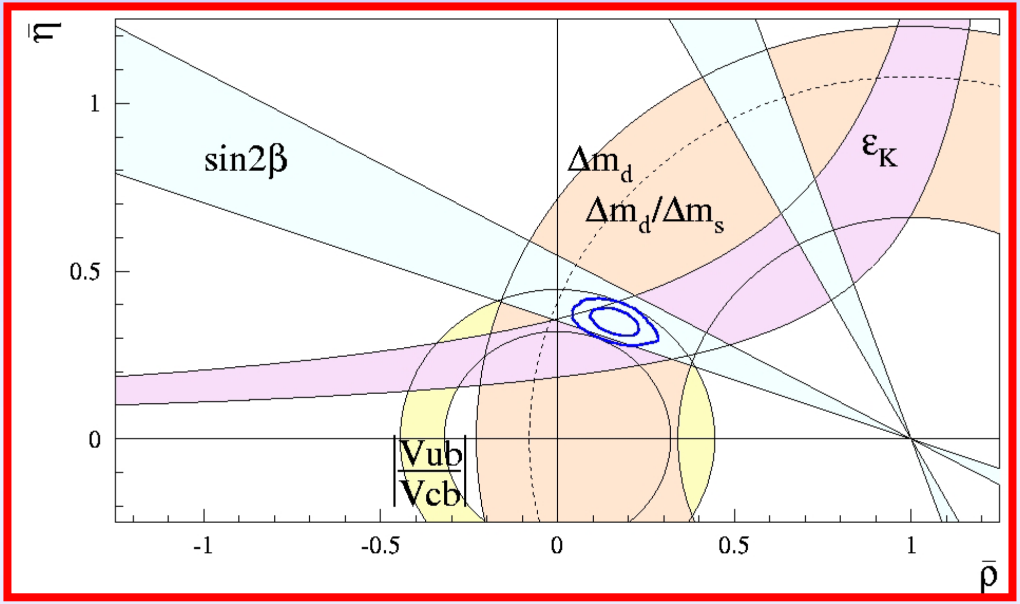
Roma, Genova, Torino, Orsay



The WEB site

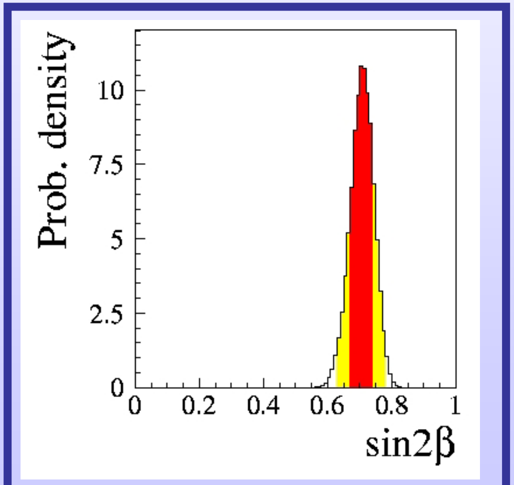
www.utfit.org

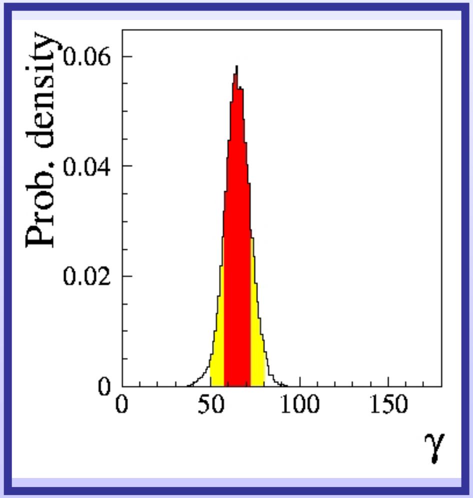
FIT RESULTS



$\bar{\rho}$ = 0.178 ± 0.046

$\bar{\eta}$ = 0.341 ± 0.028





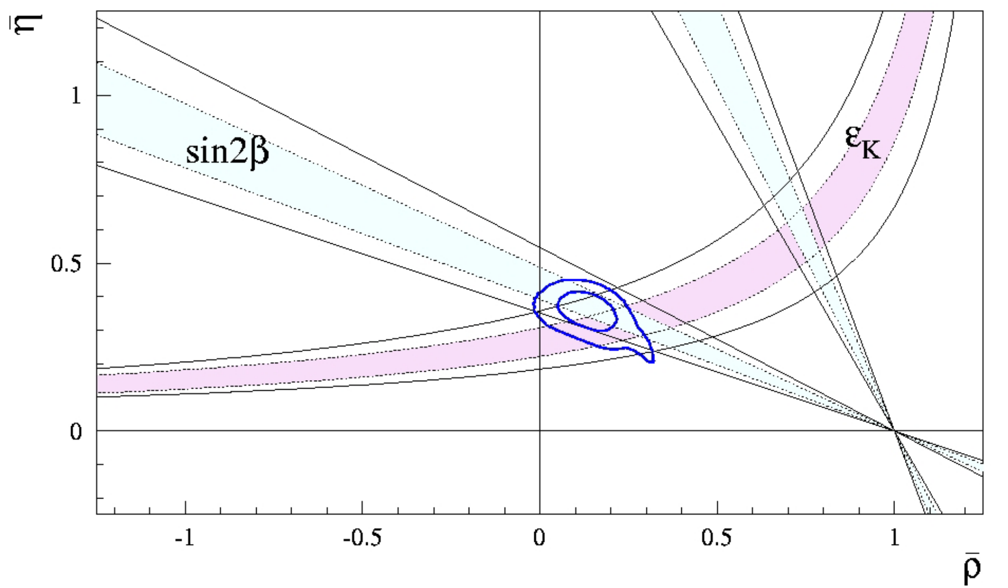
Sin2α = – 0.19 ± 0.25

Sin2β = 0.710 ± 0.037

γ = (61.5 ± 7.0)°

INDIRECT EVIDENCE OF CP VIOLATION

3 FAMILIES ⟶ - Only 1 phase - Angles from Sides



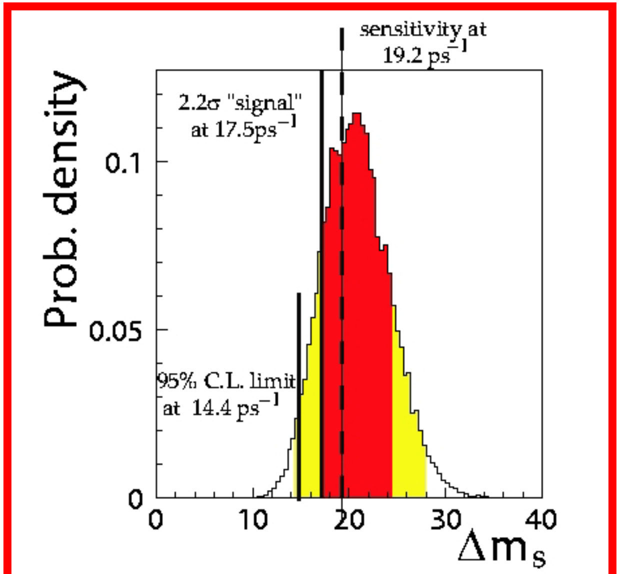
$\sin 2\beta_{UTA}$ = 0.685 ± 0.052

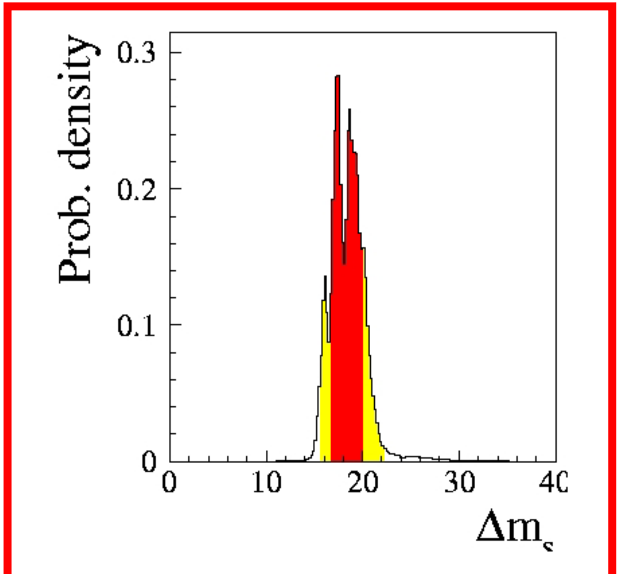
$\sin 2\beta_{J/\psi\ Ks}$ = 0.734 ± 0.054

Prediction (Ciuchini et al., 2000): $\sin 2\beta_{UTA}$ = 0.698 ± 0.066

Prediction for Δm_s

Δm_s NOT USED	WITH ALL CONSTRAINTS



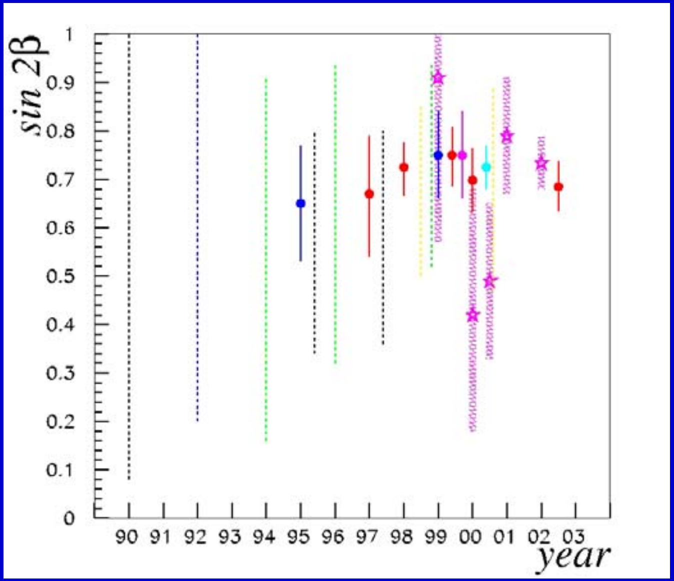


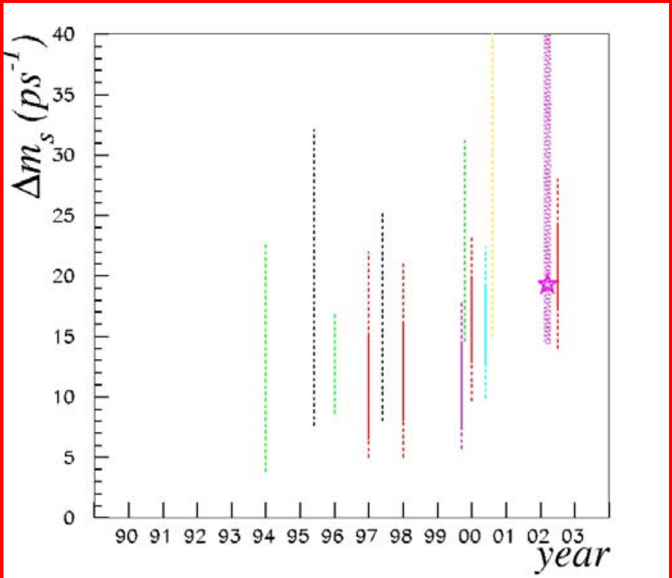
$\Delta m_s = (20.6 \pm 3.5)\ ps^{-1}$

$\Delta m_s = (18.3 \pm 1.7)\ ps^{-1}$

A measurement is expected from Tevatron !

$\mathbf{Sin2\beta}$ AND $\mathbf{\Delta m_s}$:
HISTORY OF PREDICTIONS



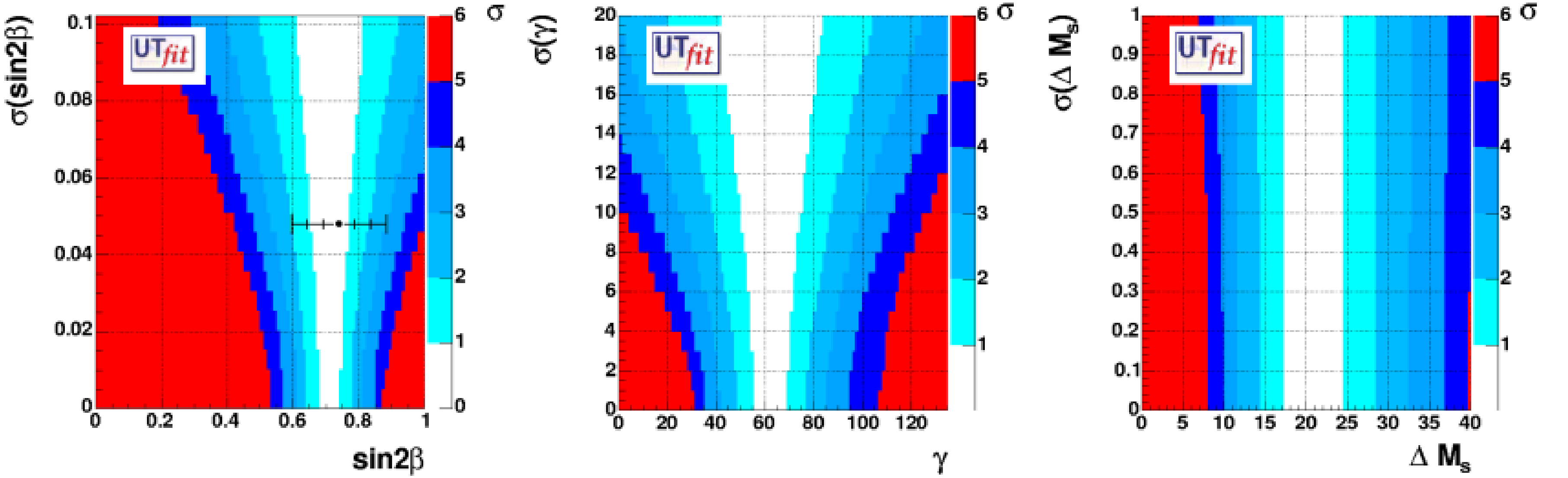


★ Experiments

Other colors: Theory

THE "COMPATIBILITY" PLOTS

"To which extent improved determinations of the experimental constraints will be able to detect New Physics?"



Compatibility between direct and indirect determinations as a function of the measured value and its experimental uncertainty

IMPACT OF IMPROVED DETERMINATIONS

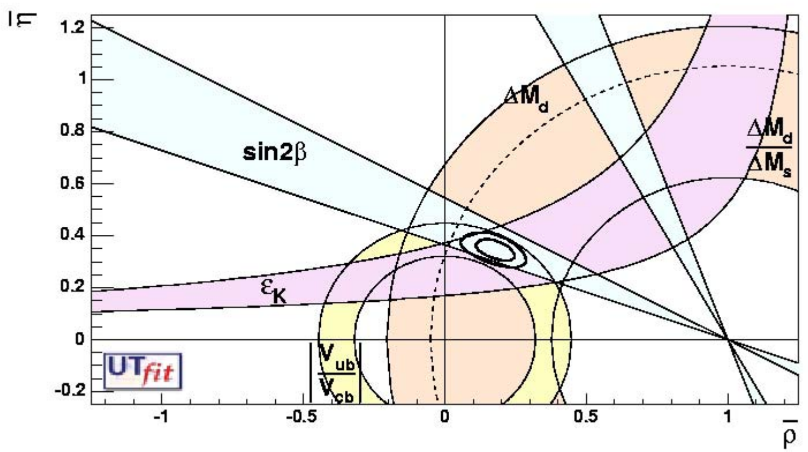
$B_K = 0.86 \pm 0.06 \pm$ ~~0.14~~

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

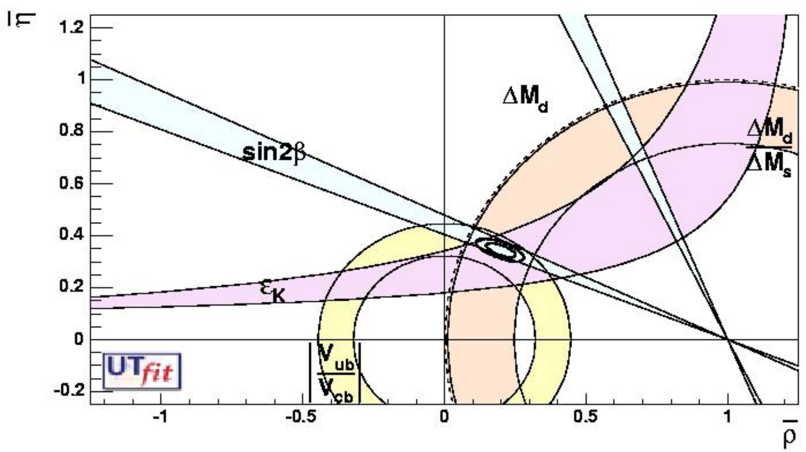
$f_{Bs}\sqrt{B_{Bs}} = 276 \pm 38$ MeV (38 → 14)

$\sin 2\beta = 0.734 \pm 0.054$ (54 → 21)

TODAY

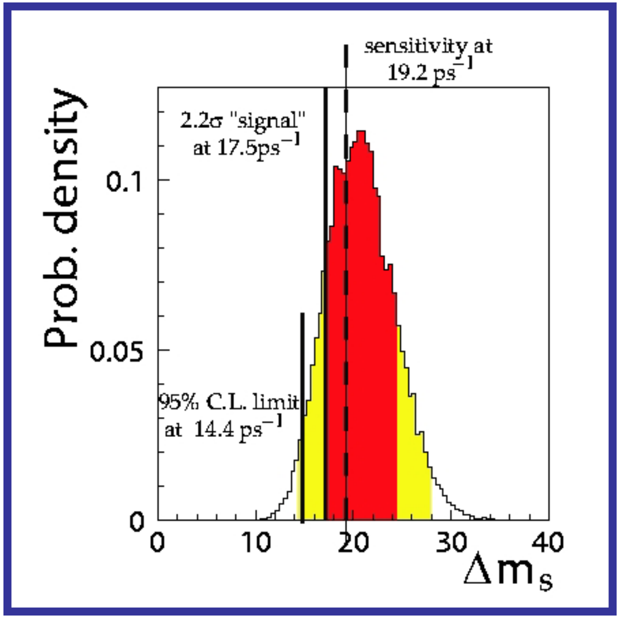


NEXT YEARS



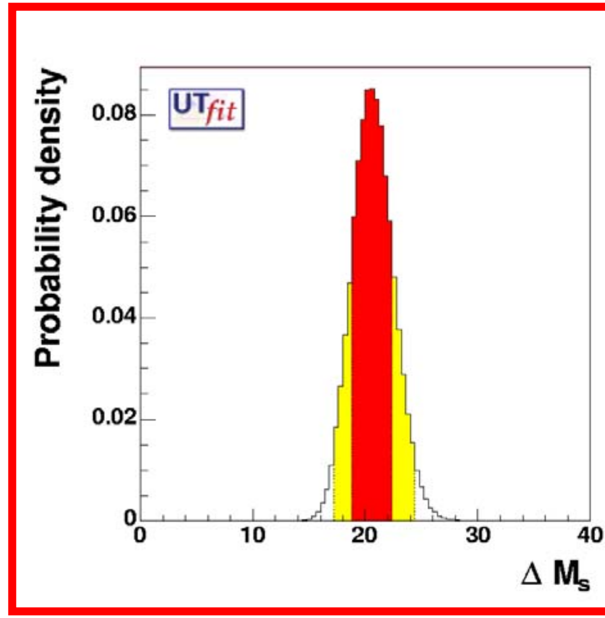
$\Delta\rho$ = 26% → 15% $\Delta\eta$ = 7.1% → 4.6%

TODAY

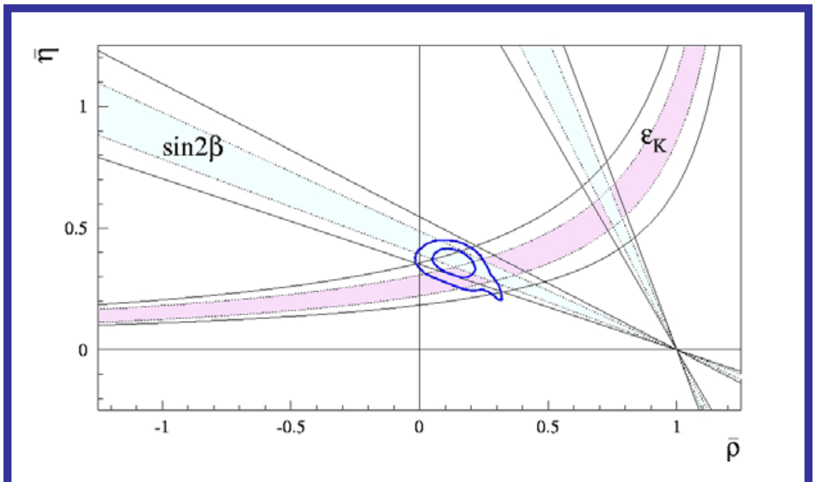


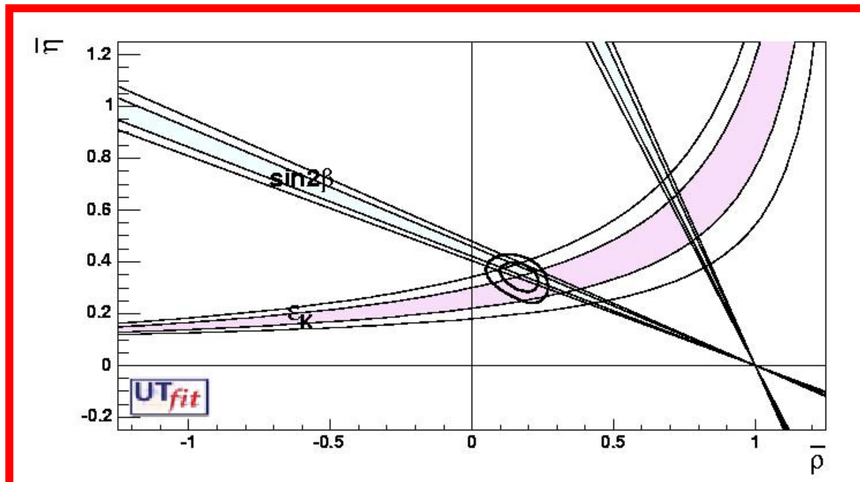
$\Delta m_s = (20.6 \pm 3.5)\ ps^{-1}$

NEXT YEARS



$\Delta m_s = (20.6 \pm 1.8)\ ps^{-1}$





SEARCH FOR NEW PHYSICS

"Given the present theoretical and experimental constraints, to which extent the UTA can still be affected by New Physics contributions?"

An interesting case:

New Physics in B_d–$\overline{B}_d$ mixing

The New Physics mixing amplitudes can be parameterized in a simple general form:

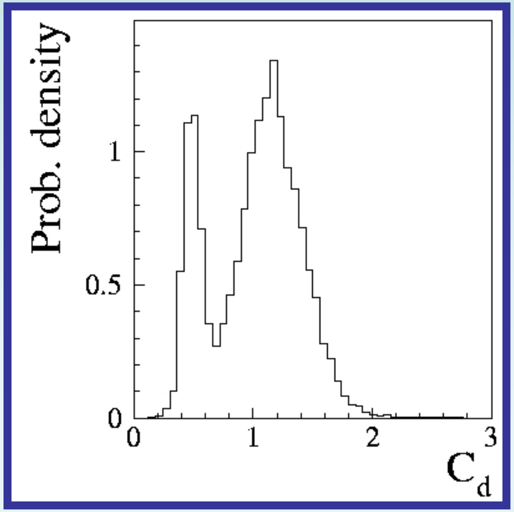
$$M_d = C_d\, e^{2i\varphi_d} (M_d)^{SM}$$

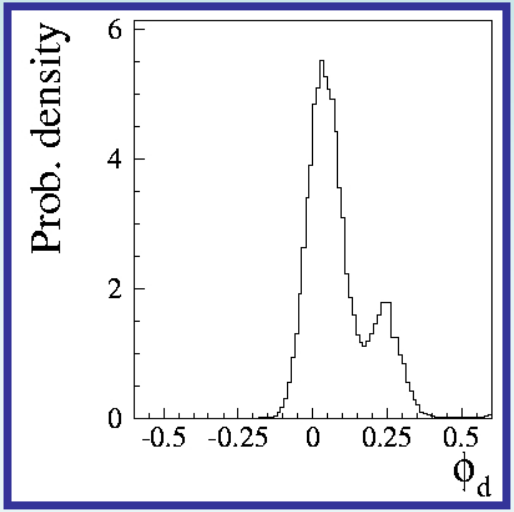
$$\Delta m_d = C_d\, (\Delta m_d)^{SM}$$

$$A(J/\psi\, K_S) \sim \sin 2(\beta + \varphi_d)$$

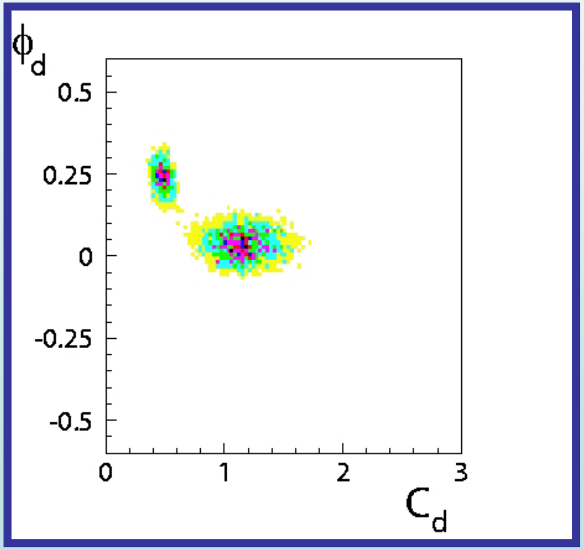
TWO SOLUTIONS:

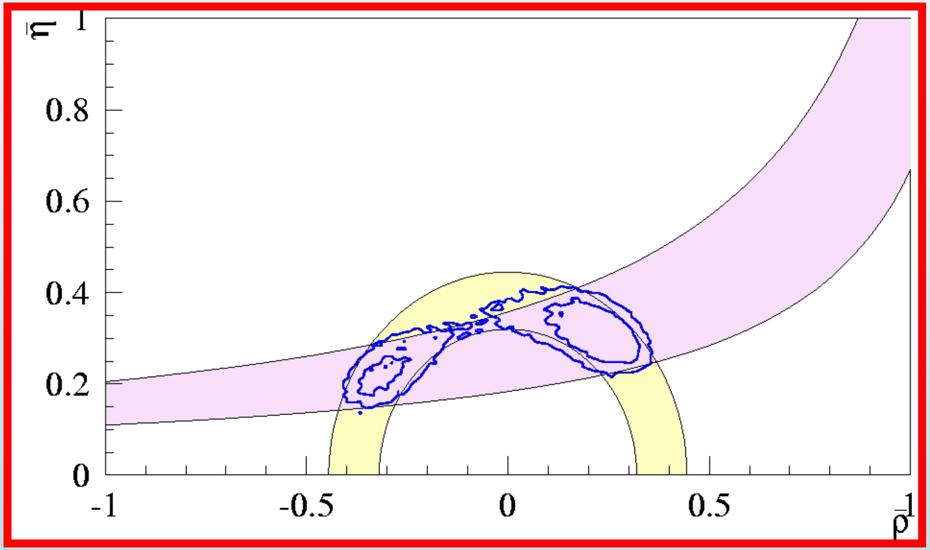
Standard Model solution:
$C_d = 1 \quad \varphi_d = 0$



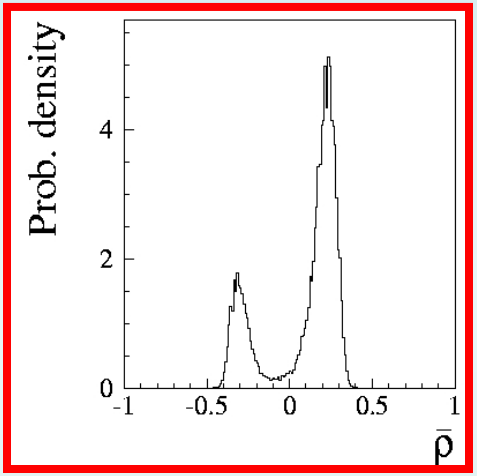


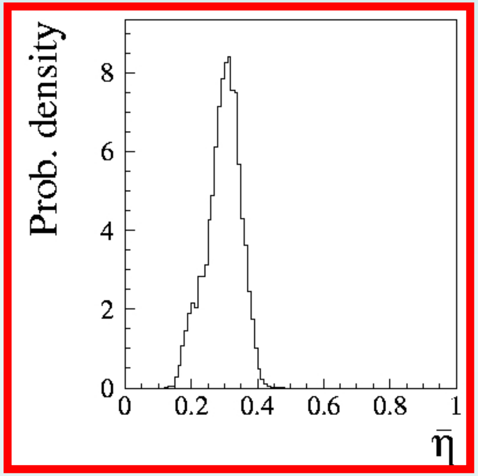
φ_d can be only determined up to a trivial twofold ambiguity:
$\beta+\varphi_d \rightarrow \pi-\beta-\varphi_d$

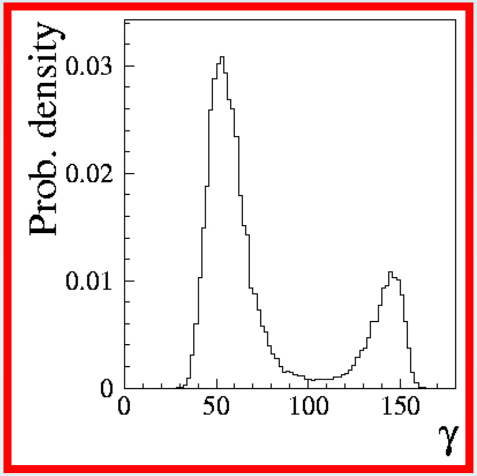




HOW CAN WE DISCRIMINATE BETWEEN THE TWO SOLUTIONS?





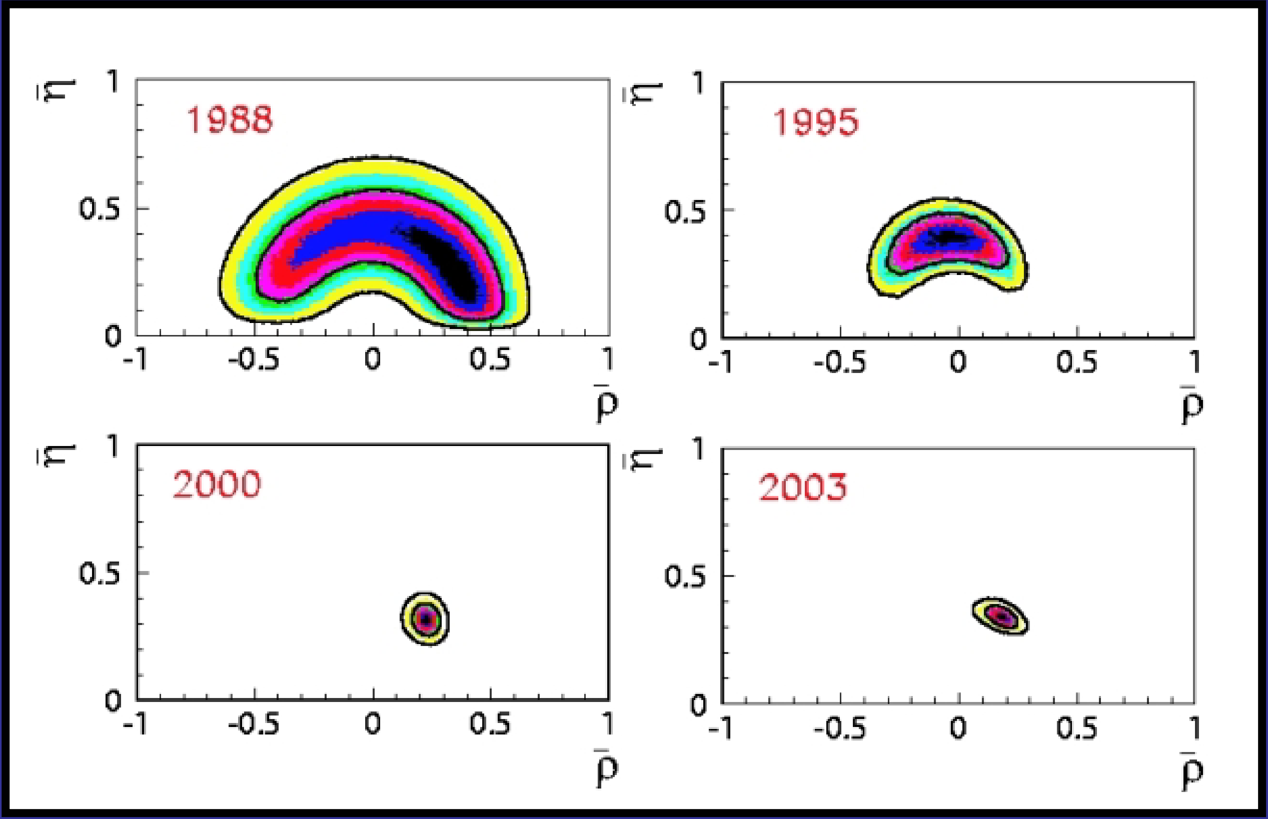


~~Δm_s~~, ~~η [$K_L \rightarrow \pi \nu \bar{\nu}$]~~, γ [$B \rightarrow DK$], $|V_{td}|$ [$B \rightarrow \rho\gamma$], ...

Coming back to the Standard Model:

15 YEARS OF ($\bar{\rho}$-$\bar{\eta}$) DETERMINATIONS

(The "commercial" plot)



CONCLUSIONS

- LATTICE QCD CALCULATIONS HAD A CRUCIAL IMPACT ON TESTING AND CONSTRAINING THE FLAVOUR SECTOR OF THE STANDARD MODEL

- IN THE PRECISION ERA OF FLAVOUR PHYSICS, LATTICE SYSTEMATIC UNCERTAINTIES MUST (AND CAN) BE FURTHER REDUCED

- IMPORTANT, BUT MORE DIFFICULT PROBLEMS (NON LEPTONIC DECAYS, RARE DECAYS, ...) ARE ALSO BEING ADDRESSED

FOR ALL THAT, WE NEED

T-FLOPS COMPUTERS!!