CKM Quark Flavor Mixing

Recent *CP* Violation Results from the *B* Factories and their Implications on the CKM Paradigm

Taming(*) the Penguin to Determine α

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LAL - Orsay

DESY Seminar

November 19, 2002

(*)J. Charles'99

Reference for updated plots: http://ckmfitter.in2p3.fr

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:

Determination of weak phases

Search for new physics and direct CPV

CP Violation in the Standard Model

- Local SU(2) invariance of $\mathcal{L}_{SM}$ with doublets (ν_{iL}, l_{iL}), (u_{iL}, d_{iL}), i=1..3 gives rise to charged weak currents

- Mass terms: $m_f\left(\bar{f}_L f_R + \bar{f}_R f_L\right)$ require scalar doublet (ϕ_1, ϕ_2)
- Spontaneous symmetry breaking leads to 3 x 3 quark mass matrices

$$M_{u(d)} = \frac{v\ g_{u(d)}}{\sqrt{2}}$$

- Unitary rotation from mass to flavour eigenstates via

$$U_{u(d,e)} M_{u(d,e)} U^{+}_{u(d,e)} = \text{diag}\left(m_{u(d,e)}, m_{c(s,\mu)}, m_{t(b,\tau)}\right)$$

- Modifies $\mathcal{L}_{SM}$ for charged weak currents: $V_{CKM} = U_u U_d^{+}$ $(V_{CKM} V_{CKM}^{+} = \text{Id})$

CKM Matrix

Kobayashi, Maskawa
1973

The Cabibbo-Kobayashi-Maskawa Matrix

Mass eigenstates ≠ Flavor eigenstates ➜ Quark mixing

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

➜ modified couplings for charged weak currents:

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

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

$J \approx A^2\lambda^6\eta$ ➜ $\eta = 0 \Rightarrow$ no CPV in SM

The Unitarity Triangle

B sector:

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

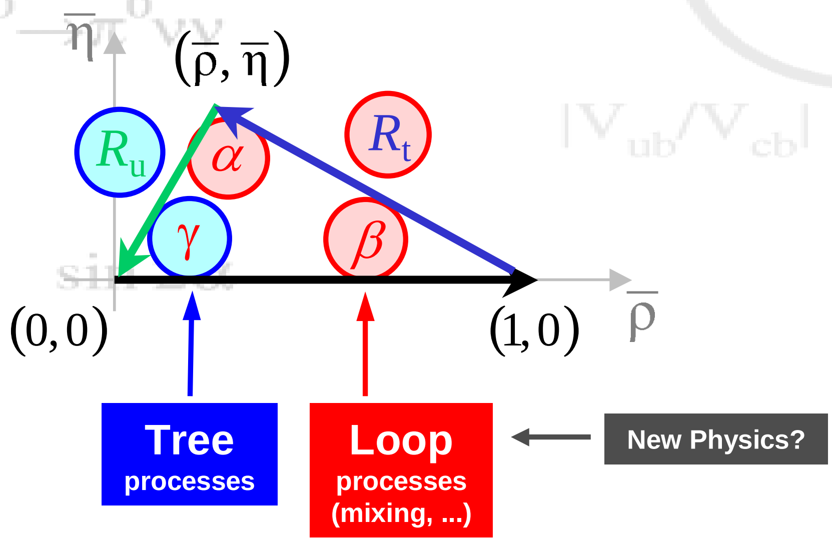
$$\propto A\lambda^{3} \quad \propto -A\lambda^{3} \quad \propto A\lambda^{3}$$

K sector:

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

$$\propto \lambda \quad \propto -\lambda \quad \propto -A^{2}\lambda^{5}$$

Expect large *CP*-violating effects in *B*-System



$$R_t = \frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}} \approx -\sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2}\, e^{-i\beta}$$

$$R_u = \frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}} \approx -\sqrt{\bar{\rho}^2 + \bar{\eta}^2}\, e^{i\gamma}$$

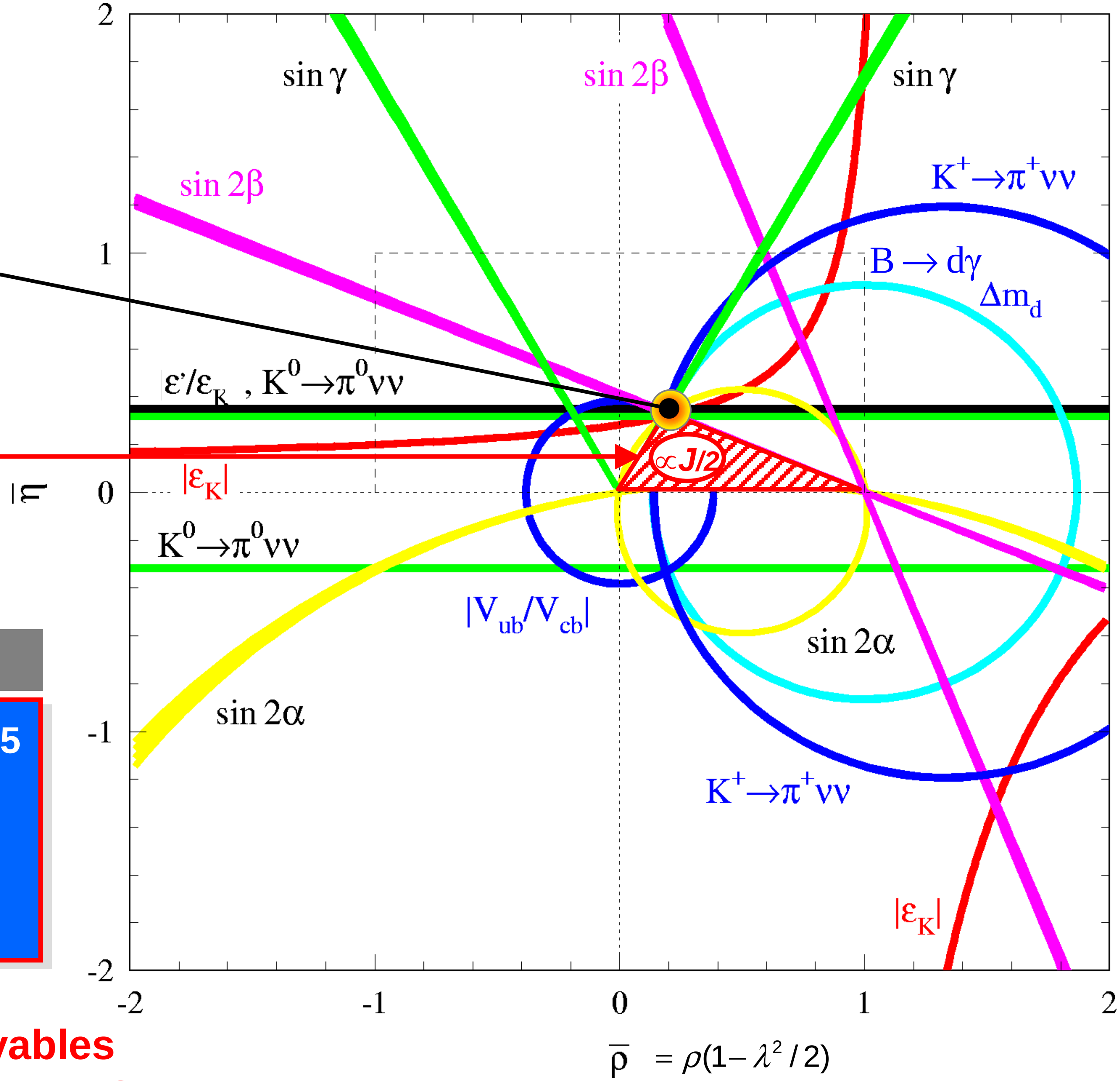
$$\gamma = \arg V_{ub}^{*}\;, \quad \alpha = \pi - \gamma - \beta$$

Many Ways Lead to the Unitarity Triangle

Point of Knowledge:

SM or new phases (fields)?

What is the value of J in our world?



Wolfenstein-Parameters:

$\lambda = |V_{us}| \cong 0.2200 \pm 0.0025$

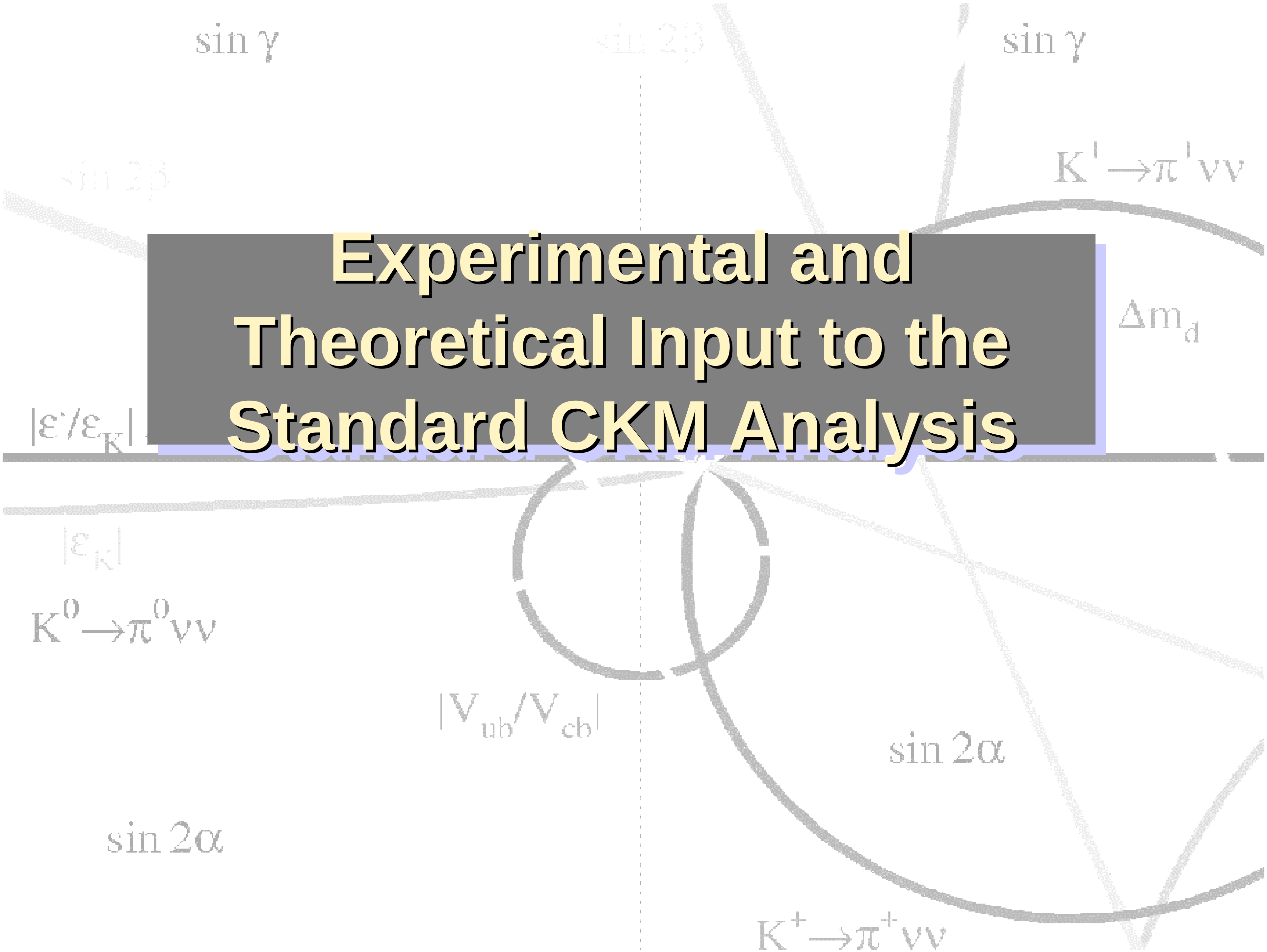
$A = |V_{cb}| / \lambda^2 \cong 0.83 \pm 0.05$

(ρ,η) not well known

"ρ,η"-plane

Can we describe all observables with one unique set of λ, A, ρ, η ?

Experimental and Theoretical Input to the Standard CKM Analysis

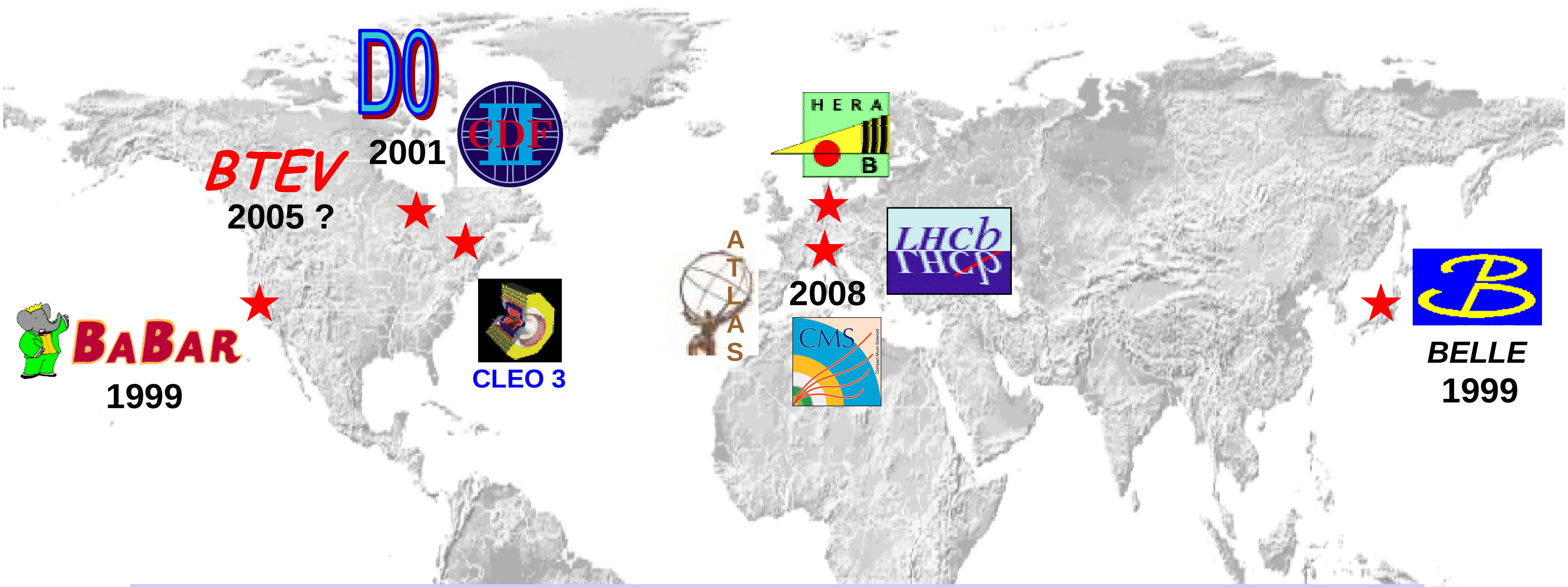


The CKM Matrix: Impact of non-*B* Physics

Observables	CKM Parameters(*)	Experimental Sources	Theoretical Uncertainties	Quality
$\lvert V_{ud}\rvert$ $\lvert V_{us}\rvert$	λ	nuclear β decay $K^{+(0)} \rightarrow \pi^{+(0)} e\nu$	small	* * *
ε_K	$\eta \propto (1-\rho)^{-1}$	$K^0 \rightarrow \pi^+\pi^-, \pi^0\pi^0$	B_K, η_{cc}	*
$\varepsilon'/\varepsilon_K$	η	$K^0 \rightarrow \pi^+\pi^-, \pi^0\pi^0$	B_6, B_8	?
$\mathrm{Im}^2[V^*_{ts} V_{td} \ldots]$	$\propto (\lambda^2 A)^4 \eta^2$	$K^0_L \rightarrow \pi^0\nu\bar{\nu}$	small (but: $(\lambda^2 A)^4$)	* * (*)
$\lvert V_{td}\rvert$	$(1-\rho)^2 + \eta^2$	$K^+ \rightarrow \pi^+\nu\bar{\nu}$	charm loop (and: $(\lambda^2 A)^4$)	* (*)

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

NA48



A Worldwide Effort -
Testing the Standard Model:

The Quest for CP Violation in the *B* System

The CKM Matrix: Impact of *B* Physics

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

3 km

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

SLAC

Stanford Linear Accelerator Center

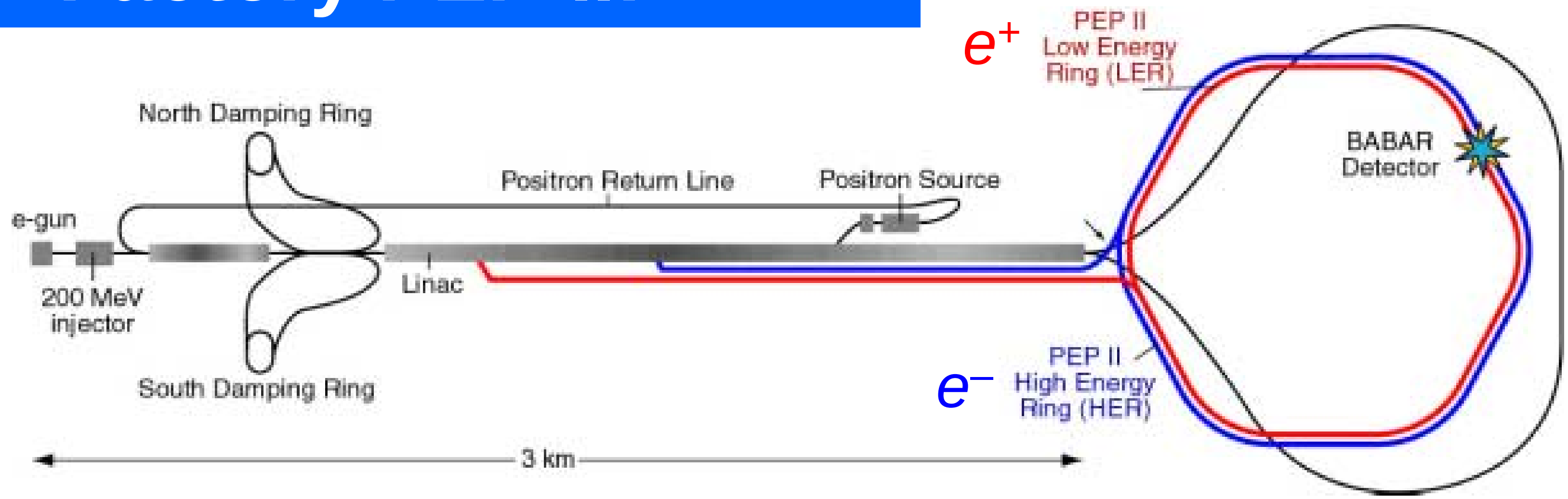
Linac

Fixed Target Experiments

BABAR

SLD (& MARK II)

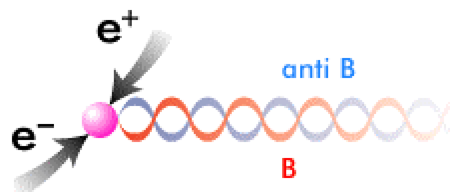
The Asymmetric *B*-Meson Factory PEP-II:



9 GeV e^- on 3.1 GeV e^+ :

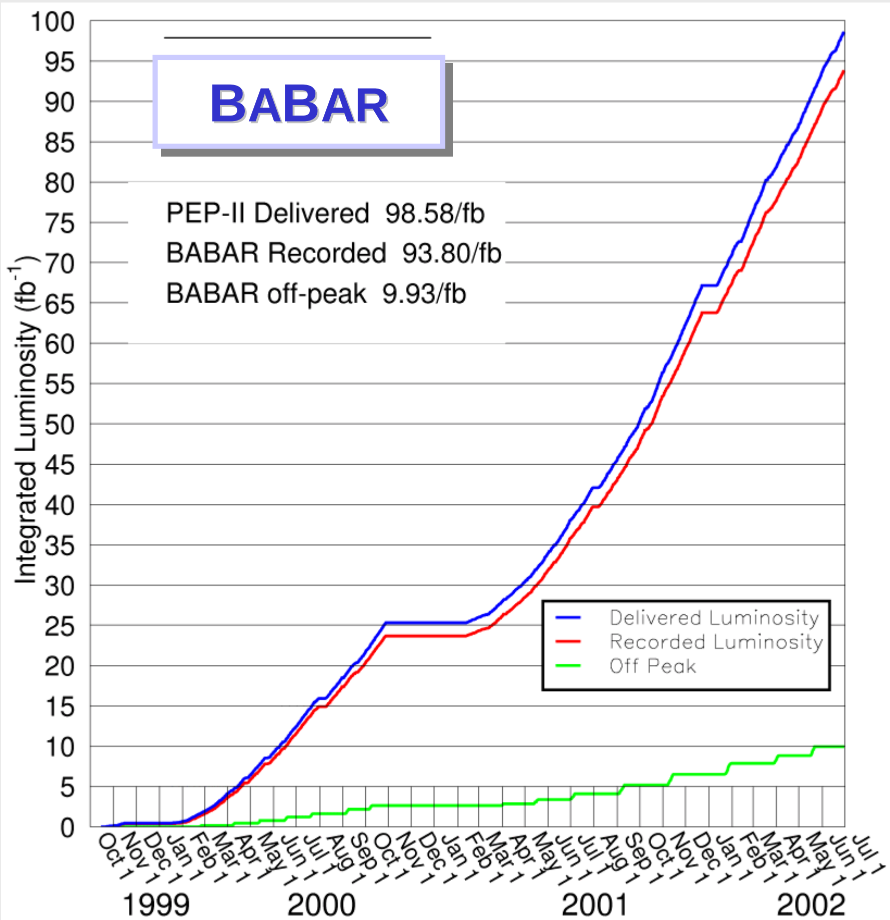
$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$

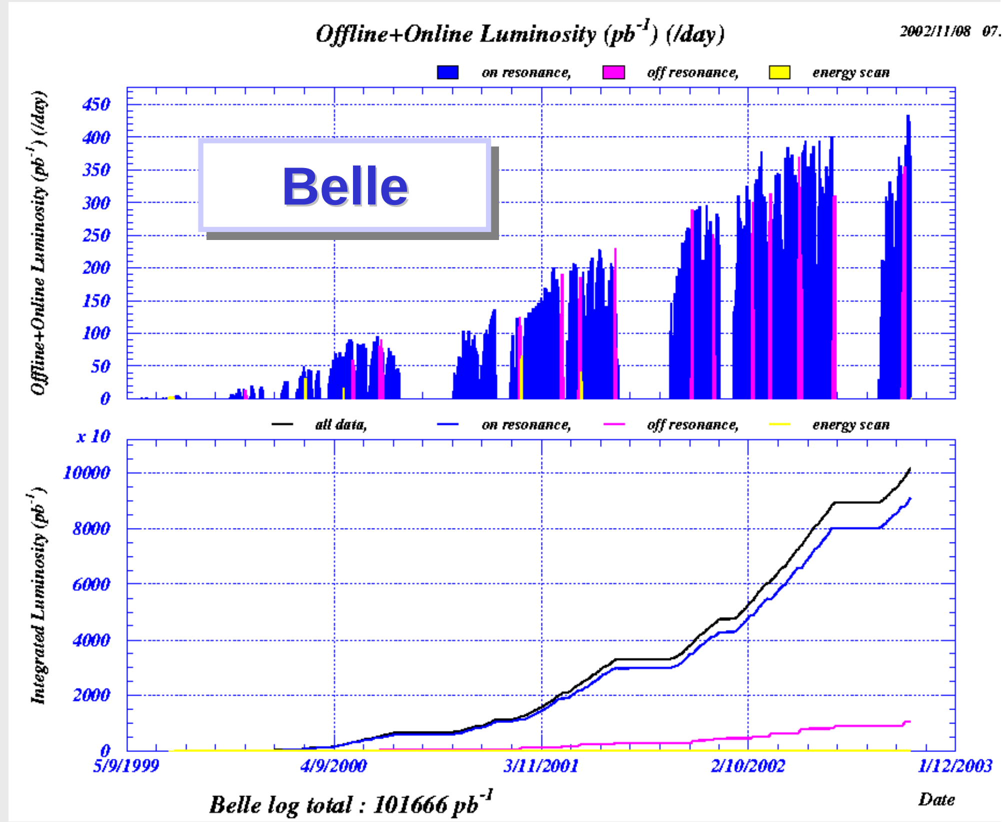
- coherent neutral *B* pair production and decay (p-wave)



- boost of $\Upsilon(4S)$ in lab frame : $\beta\gamma = 0.56$

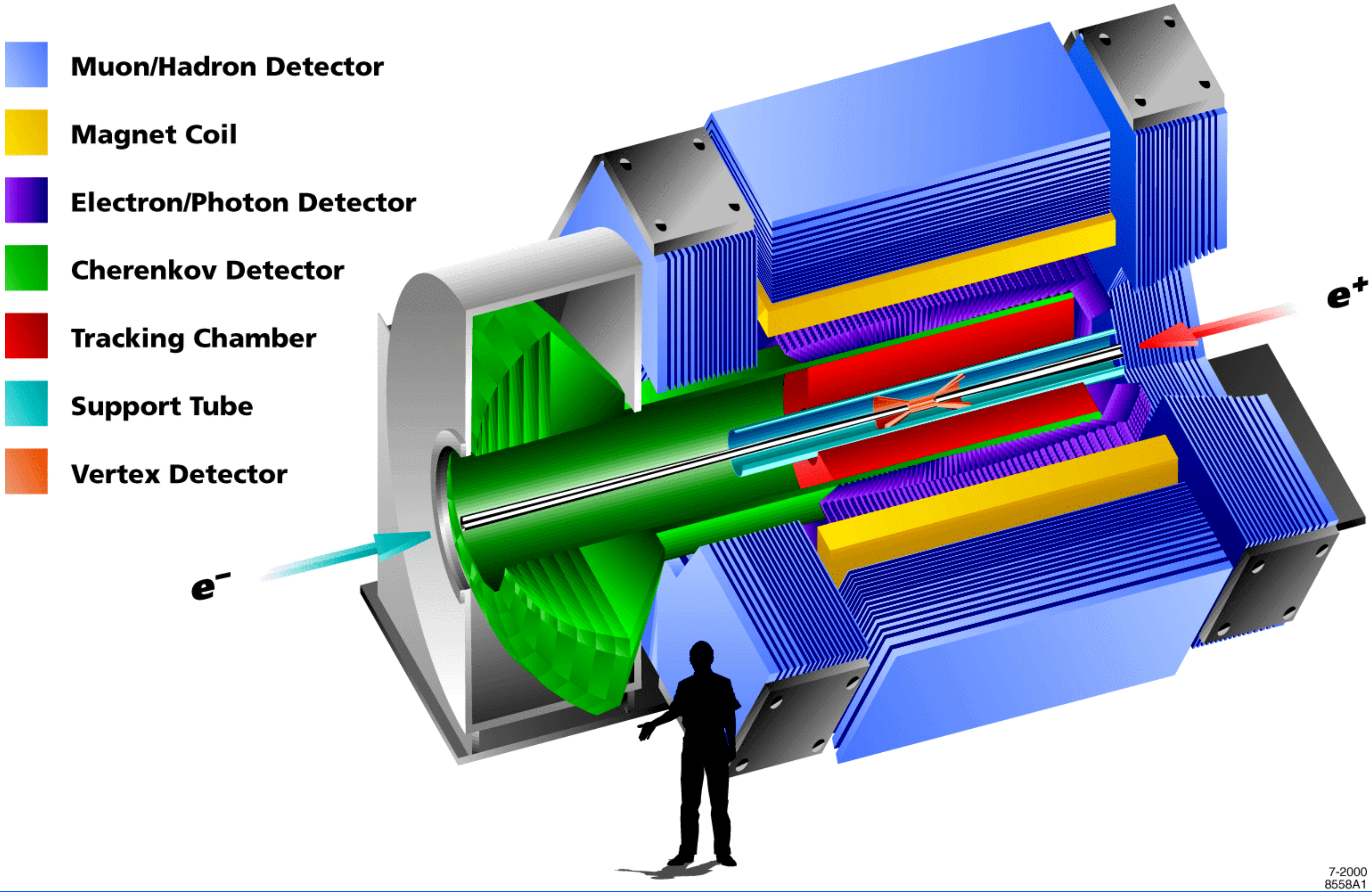
BABAR and Belle: Integrated Luminosity





Belle just passed 100 fb^{-1} ~ 113 million $B\bar{B}$ pairs

BABAR Detector



SVT	97% efficiency, 70 -180 μm Δz resolution
Tracking	$\sigma(p_T)/p_T = 0.13\%\ p_T \oplus 0.45\%$
DIRC	K-π separation > 3.4σ for p < 3.5 GeV/c
EMC	$\sigma_E/E = 1.3\%\ E^{-1/4} \oplus 2.1\%$

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

Schrödinger equation governs time evolution of B^0-$\bar{B}^0$ System:

$$i\frac{d}{dt}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \left(M - \tfrac{i}{2}\Gamma\right)\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

with mass eigenstates:

$$\left|B_L\right\rangle \propto p\left|B^0\right\rangle + q\left|\bar{B}^0\right\rangle$$

$$\left|B_H\right\rangle \propto p\left|B^0\right\rangle - q\left|\bar{B}^0\right\rangle$$

Defining:

$$\Delta m_B \equiv M_H - M_L \simeq 2\,|M_{12}|$$

$$\Delta\Gamma_B \equiv \Gamma_H - \Gamma_L = 2\mathrm{Re}\left(M_{12}\Gamma_{12}^*\right)/\,|M_{12}|$$

One obtains for the time-dependent asymmetry:

$$A_{\text{mixing}}(\Delta t) = \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})} = \cos\left(\Delta m_B \Delta t\right)$$

where::

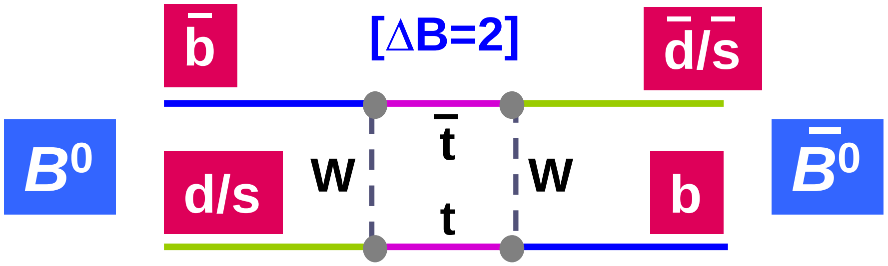
unmixed: $e^+e^- \rightarrow B^0(\Delta t)\bar{B}^0(\Delta t)$

mixed: $e^+e^- \rightarrow B^0(\Delta t)B^0(\Delta t)$

and: $A_{\text{mixing}}(\Delta t = 0) = 1$

$B^0\bar{B}^0$ Mixing (Theory)

Effective FCNC Processes
(*CP* conserving):



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

Perturbative QCD

CKM Matrix Elements

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

mit : $q = s, d$

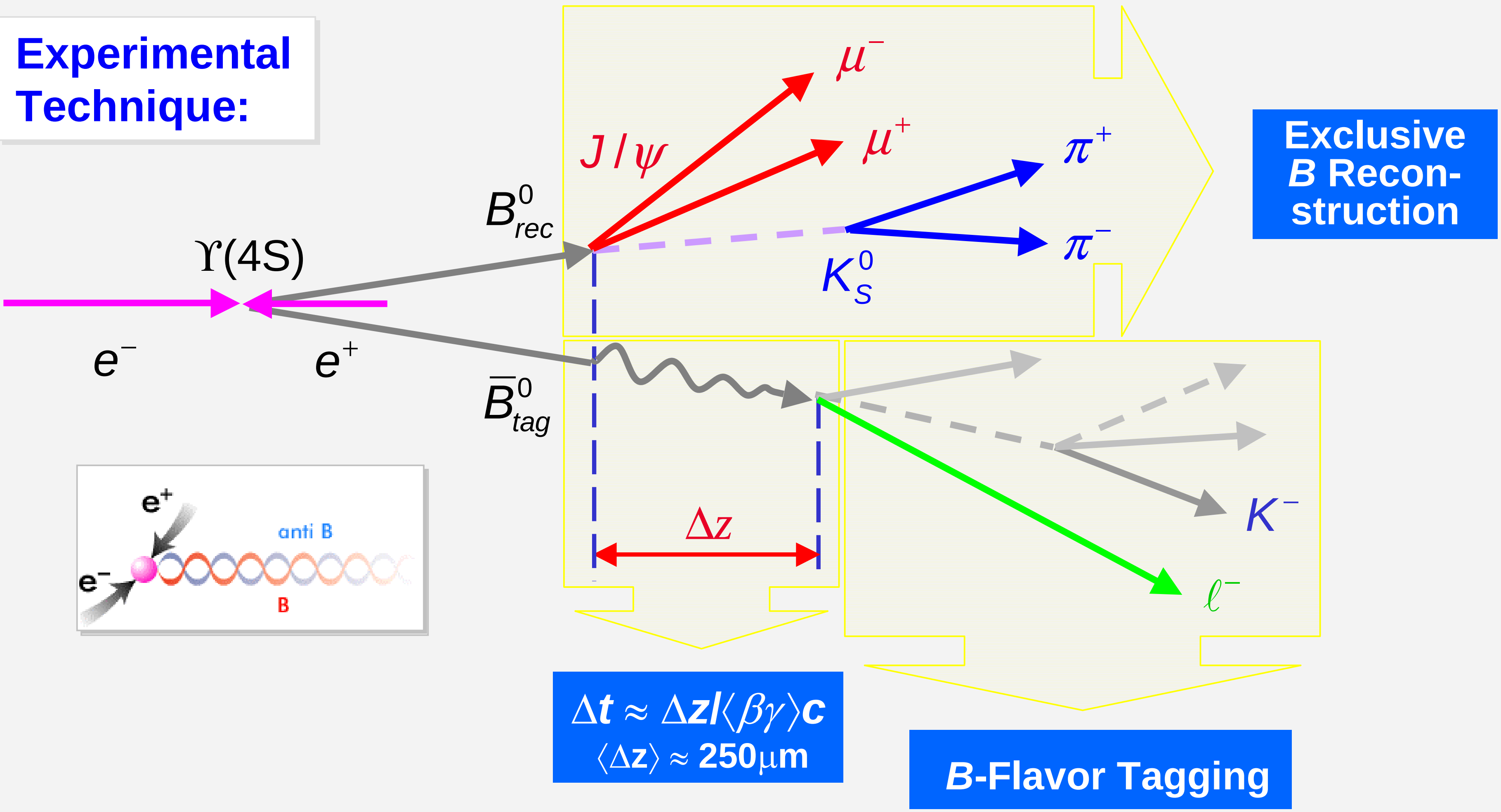
Lattice QCD (eff. 4 fermion operator)

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

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

$B^0\overline{B}^0$ Mixing (Experiment)

Experimental Technique:



$B^0_{rec} = B^0_{flav}$ (flavor eigenstates) → lifetime, mixing analyses

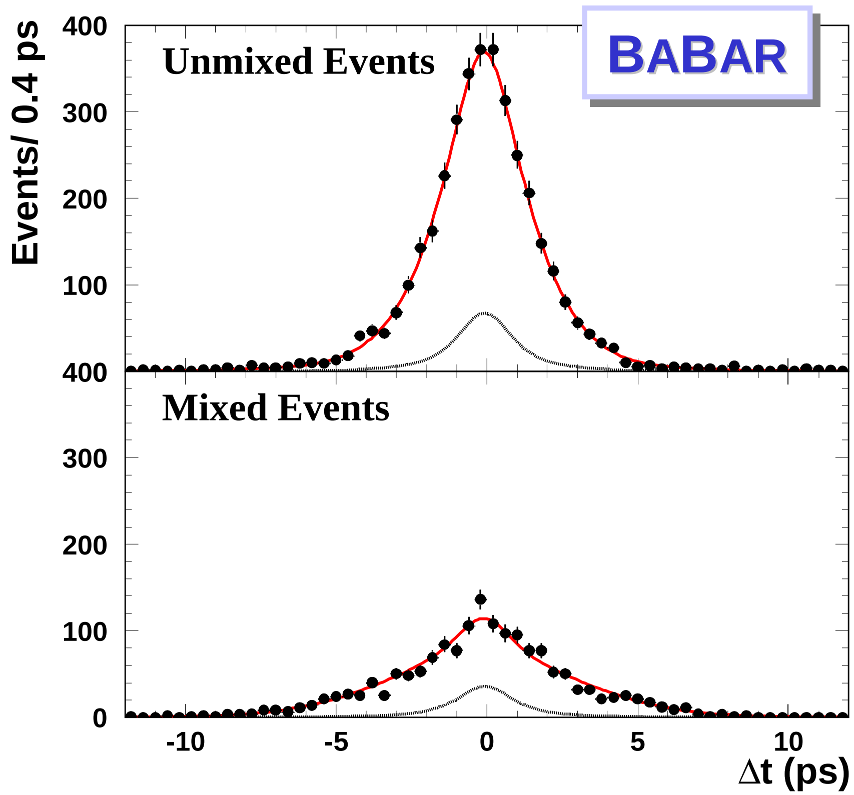
$B^0_{rec} = B^0_{CP}$ (*CP* eigenstates) → *CP* analysis

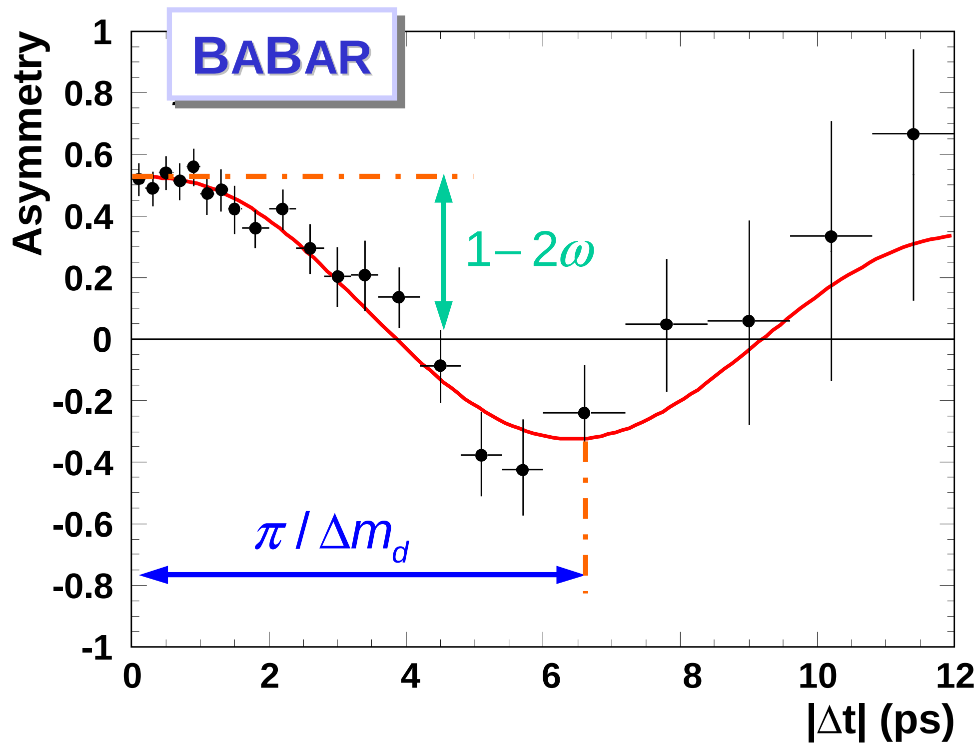
$B^0\bar{B}^0$ Mixing using Flavour Eigenstates

$$A_{mixing}(\Delta t') = \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})} = (1-2\omega)\cos(\Delta m_{B_d}\Delta t) \otimes \text{Res}(\Delta t, \Delta t')$$

Mistag probability

Detector Resolution





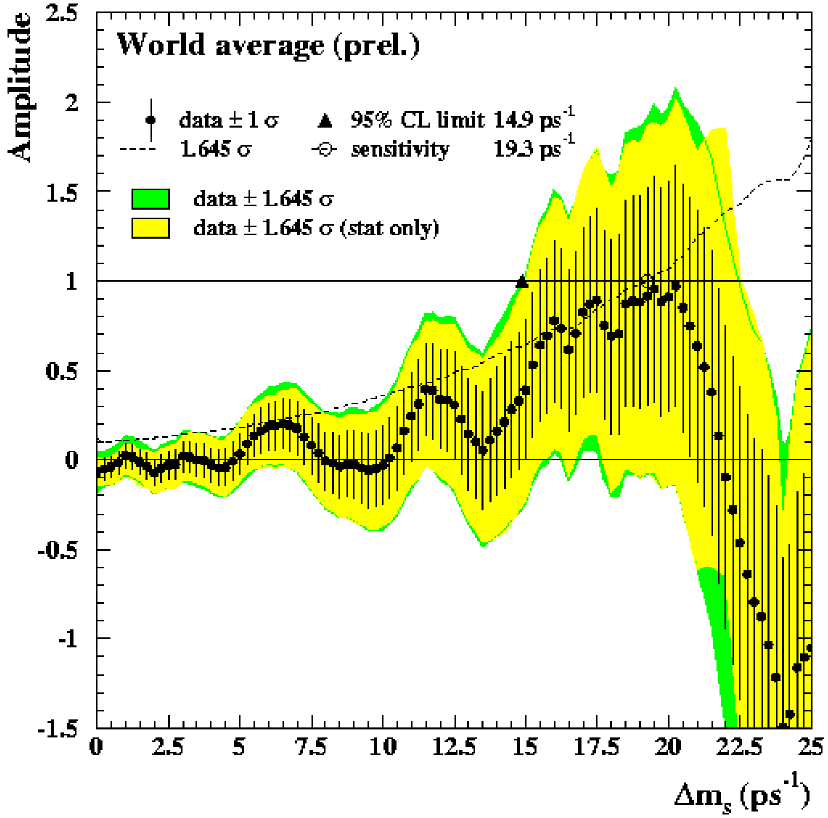
$$\Delta m_{B_d} = (0.516 \pm 0.016_{(stat)} \pm 0.010_{(syst)})\text{ps}^{-1}$$

BABAR PRD 66 (2002) 032003

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

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

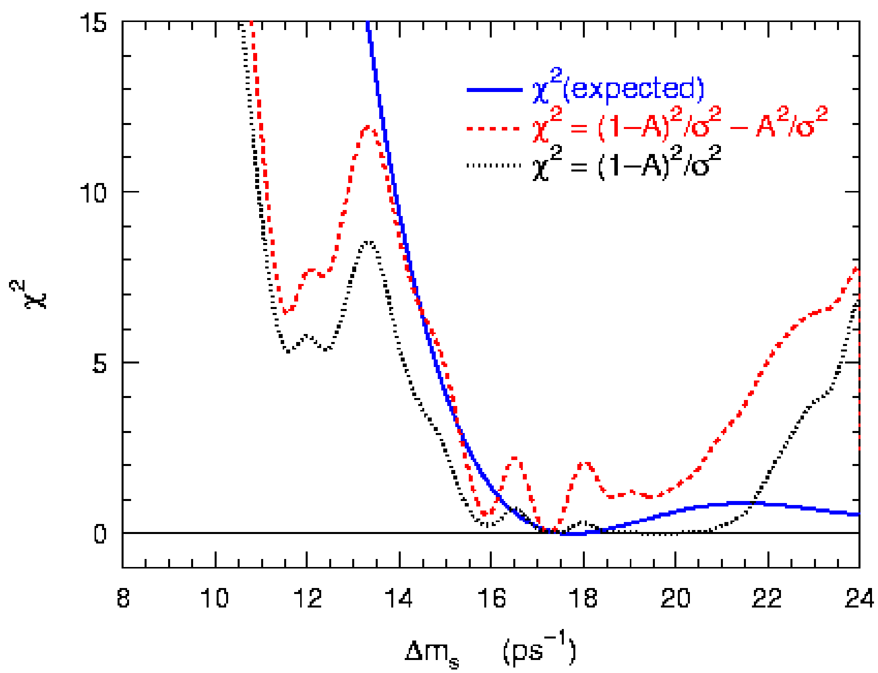
Amplitude spectrum: LEP/SLD/CDF



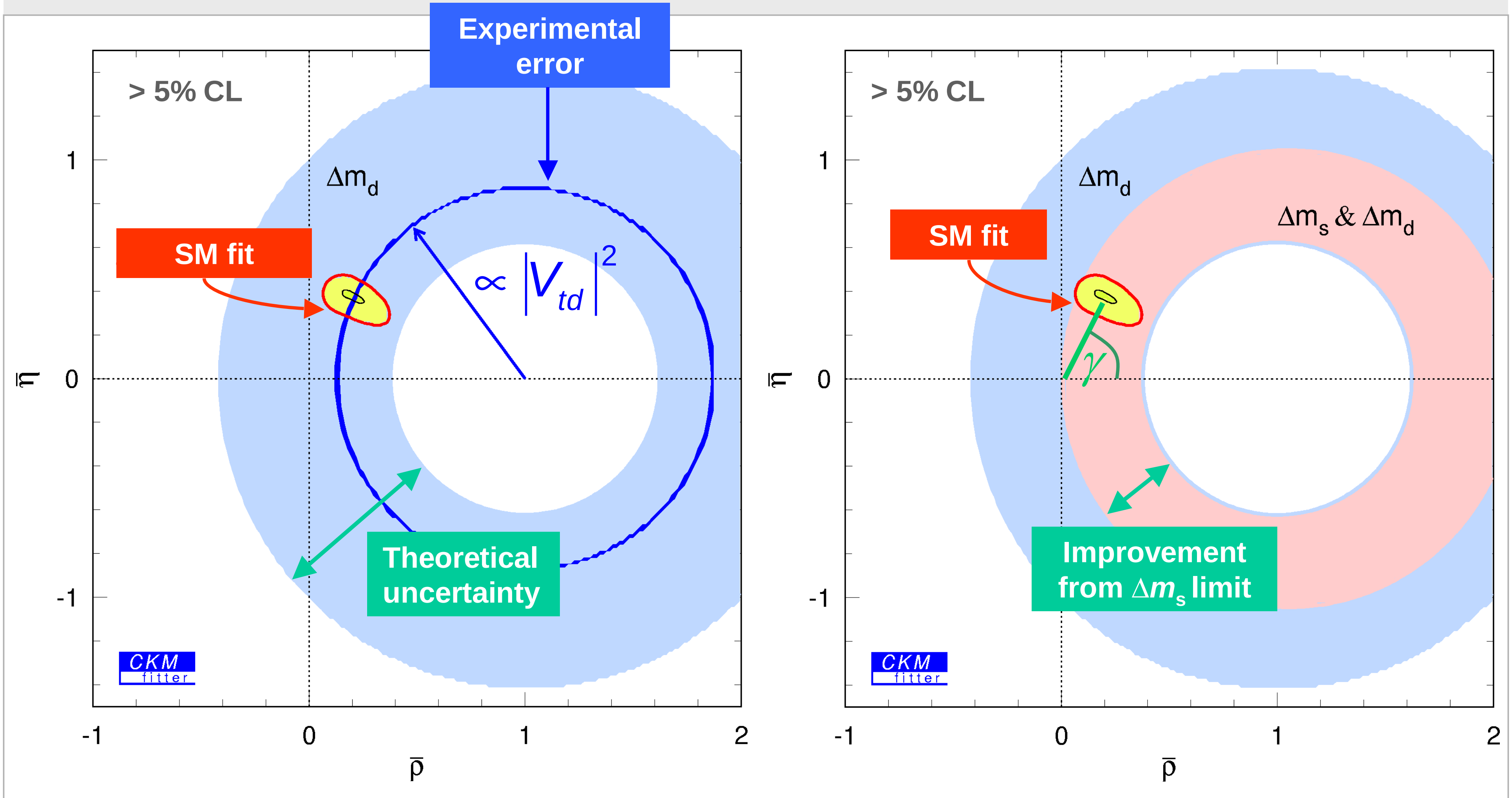
Preferred value is 17.2 ps^{-1}, but only limit exploitable in CKM fit

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



Constraints from Δm_d and Δm_s



Waiting for a Δm_s measurment at Tevatron...

Time-dependent *CP* Asymmetry

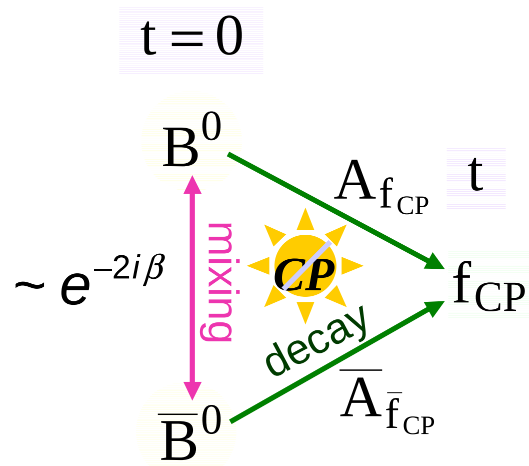
_CP_ violation arises from interference between decays with and without mixing:

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

amplitude ratio

CP eigenvalue

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



$$\lambda_{f_{CP}} \neq \pm \text{Prob}(\bar{B}^0(t) \to f_{CP}) \neq \text{Prob}(B^0(t) \to f_{CP})$$

Time-dependent _CP_ Observables:

$$A_{f_{CP}}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

$$= -\eta_{f_{CP}} \left(S_{f_{CP}} \sin(\Delta m_d t) - C_{f_{CP}} \cos(\Delta m_d t) \right)$$

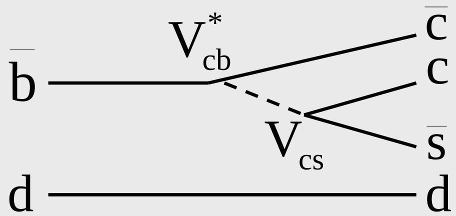
with: = sin(2β) and = 0 for $b \to c\bar{c}s,\ s\bar{s}s$

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

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

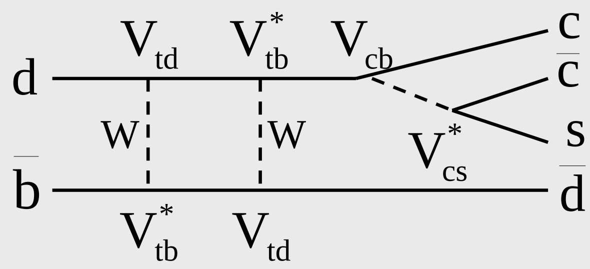
The Golden Channel: $B^0, \bar{B}^0 \rightarrow J/\psi K_{S,L}$

Tree Diagram



$V_{cb} V_{cs}^* \propto A \cdot \lambda^2$

⊕

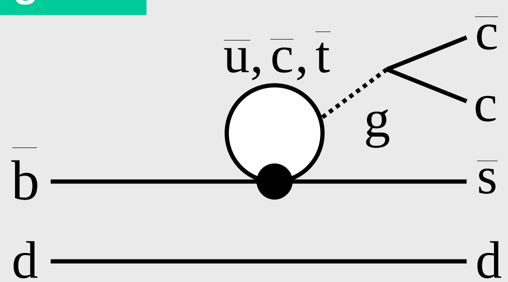


top-quark dominates

$$\frac{q}{p}\frac{\bar{A}}{A} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}$$

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

Penguin



$V_{cb} V_{cs}^*$ real

$V_{tb} V_{ts}^*$ real

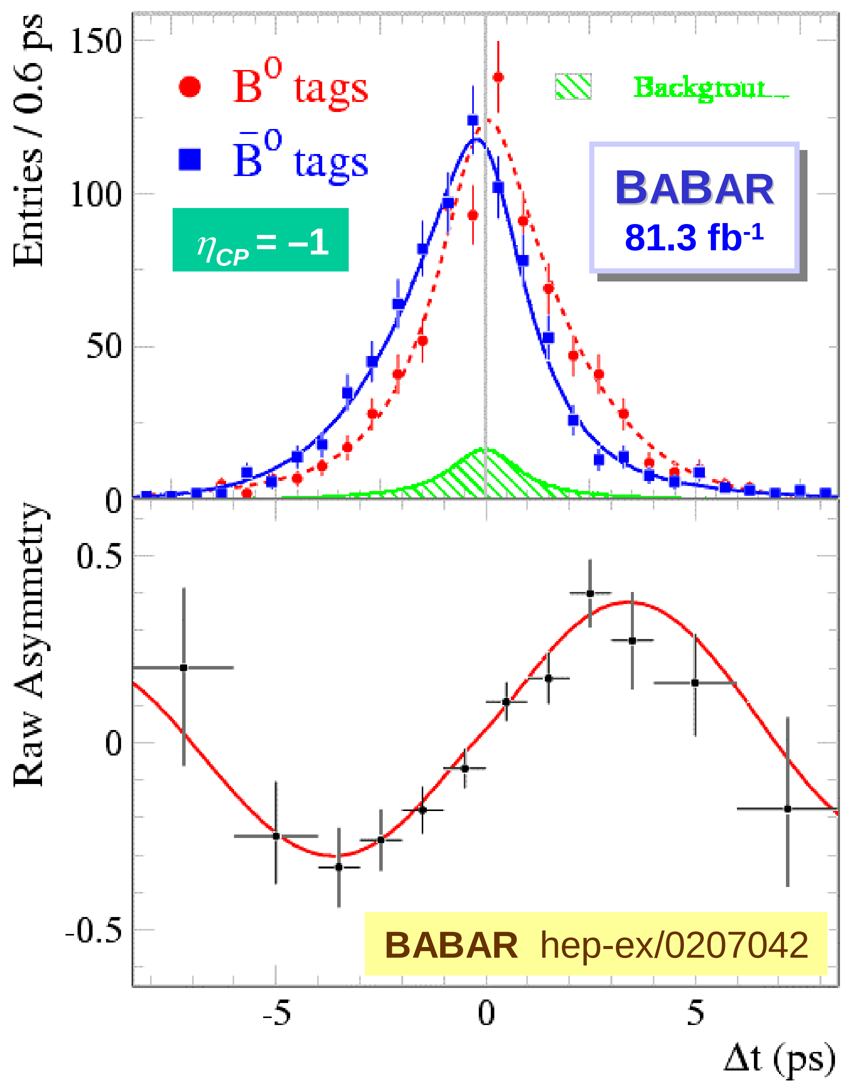
$V_{ub} V_{us}^* \rightarrow \gamma (\propto A \cdot \lambda^4)$

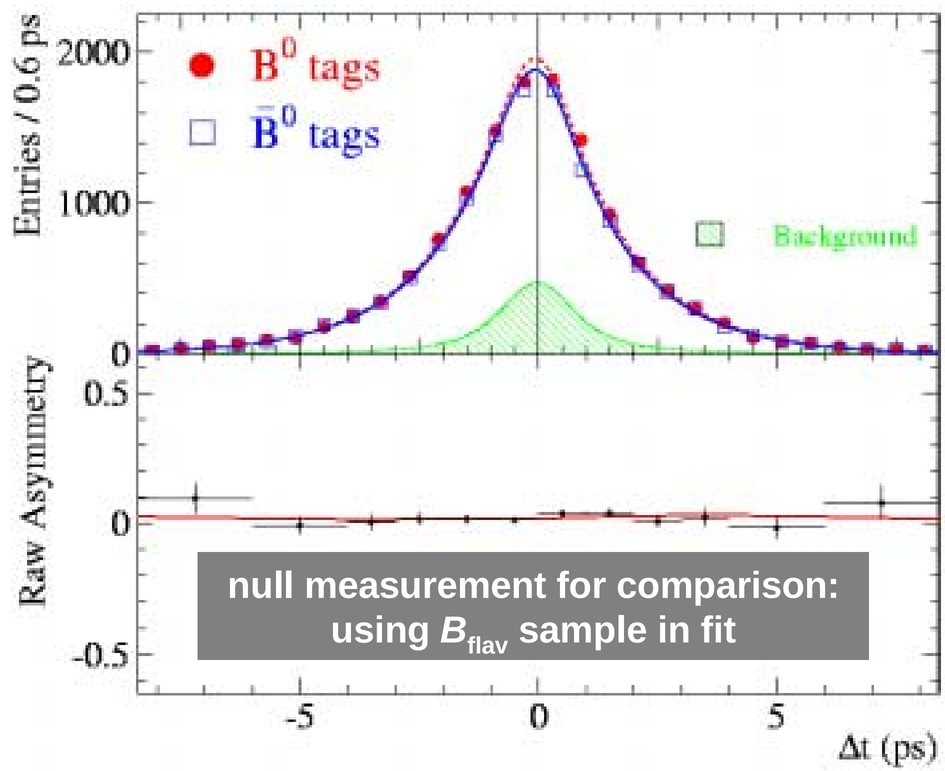
Single weak phase:

- clean extraction of CP phase
- no direct CPV: $\left| \lambda_{J/\psi K^0_{S,L}} \right| = 1$

$$A_{J/\psi K^0_{S,L}}(t) = -\eta_{J/\psi K^0_{S,L}} \cdot \sin(2\beta) \cdot \sin(\Delta m_{B_d} t)$$

Time-dependent *CP* Asymmetries



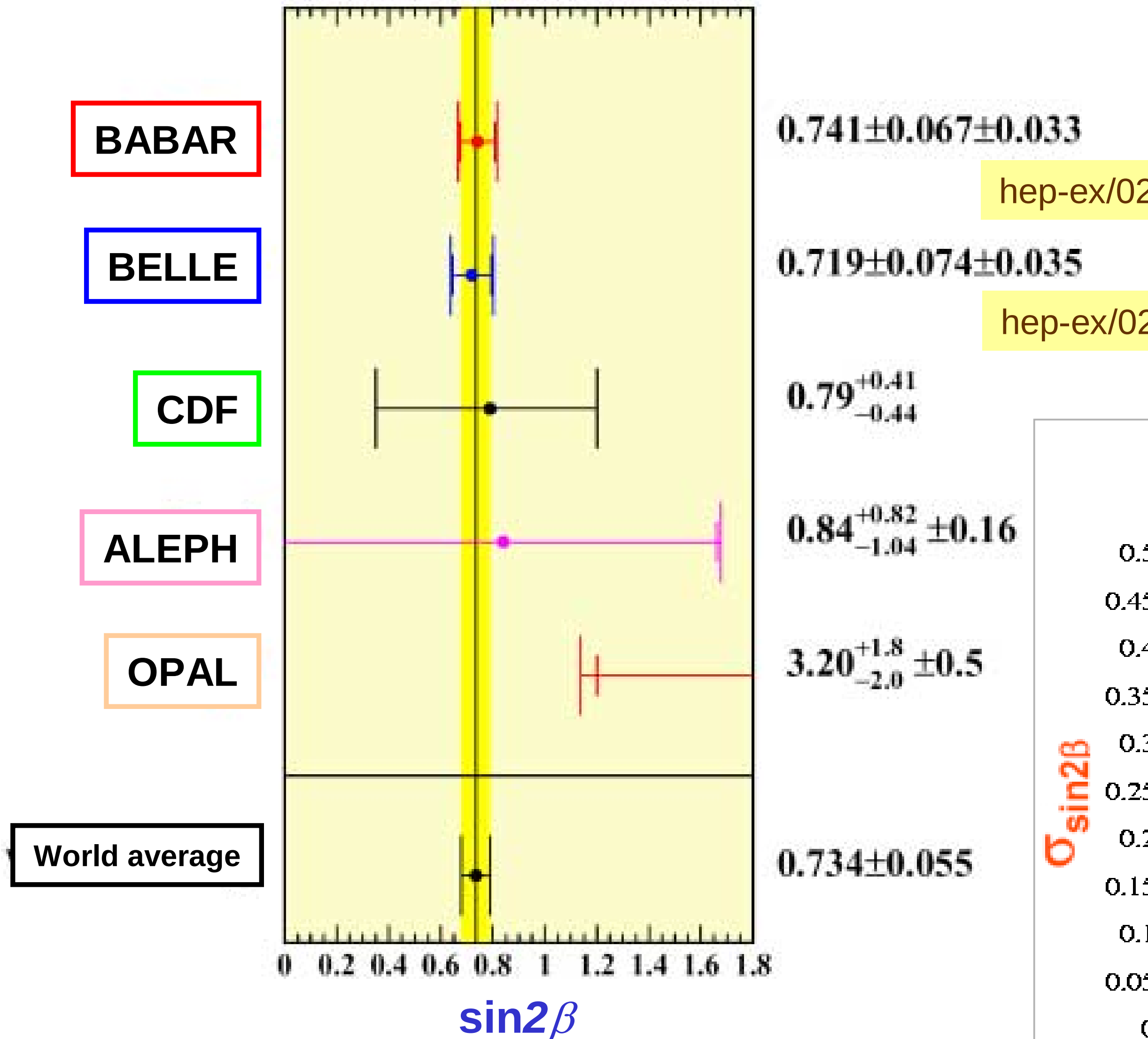


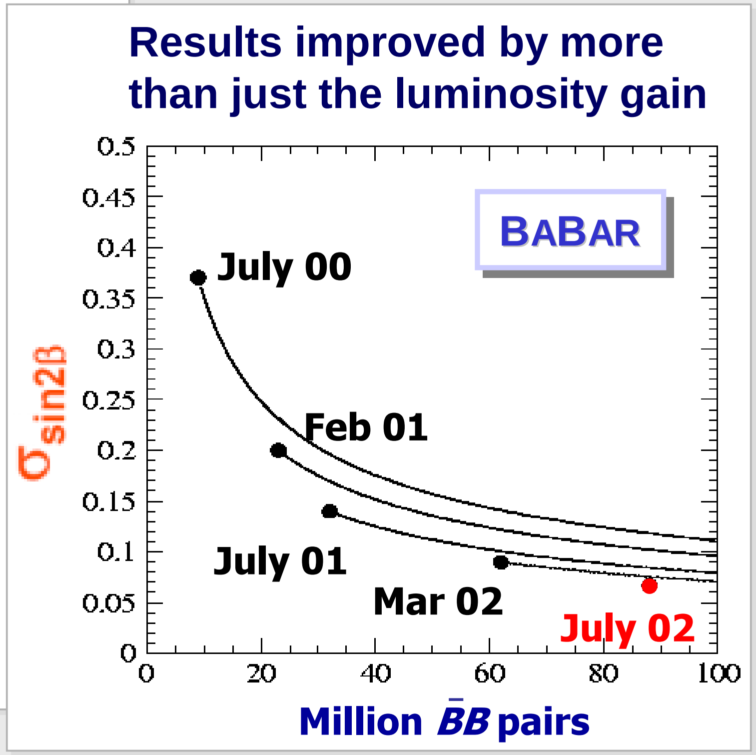
CP Violation established in the *B* system !

$$\sin 2\beta = 0.741 \pm 0.067_{(stat)} \pm 0.033_{(syst)}$$

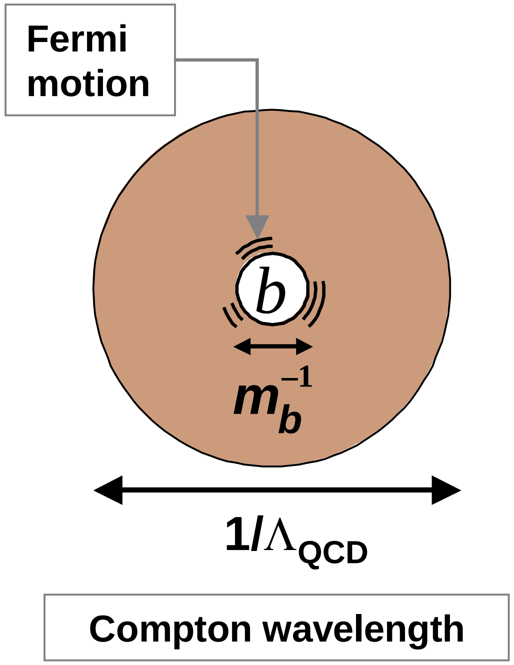
more on time-dependent CP asymmetries later...

World Average:





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



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 heavy quark

See the very pedagogical talk given by M. Luke at FPCP'02:
http://www.hep.upenn.edu/FPCP/talks/1801/180101Luke.pdf

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

The theoretical tools are *Heavy Quark Effective Theory* (HQET) and the Operator Product Expansion (OPE), respectively.

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

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

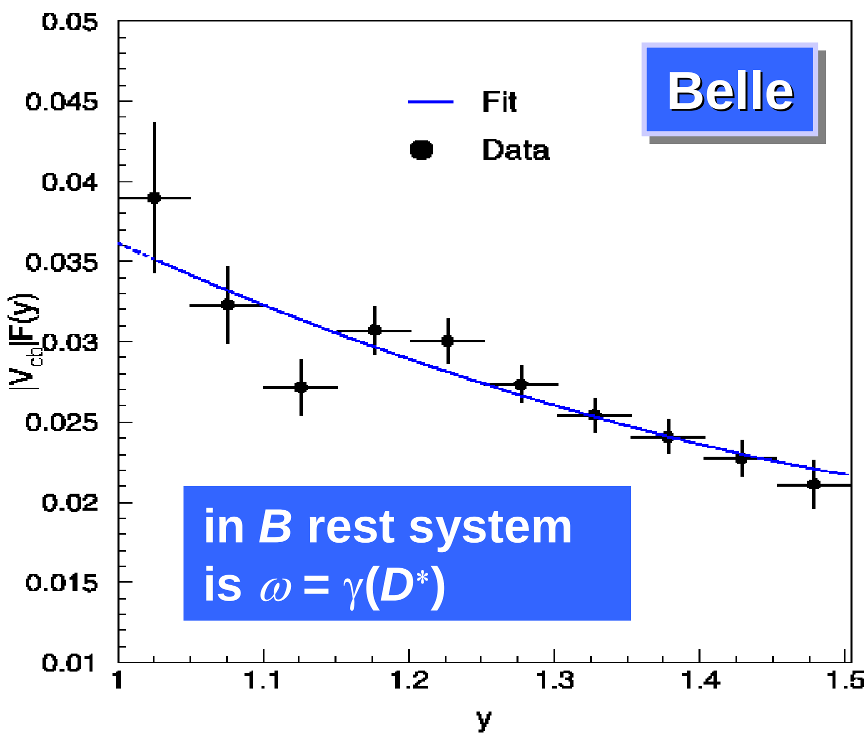
- Measurement of $B \to D^* \ell \bar{\nu}$ rate as fct. of $B \to \ell \bar{\nu}$ momentum transition ω
- Determination of $|V_{cb}|$ from extrapolation to $\omega \to 1$ (theory is most restrictive)

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

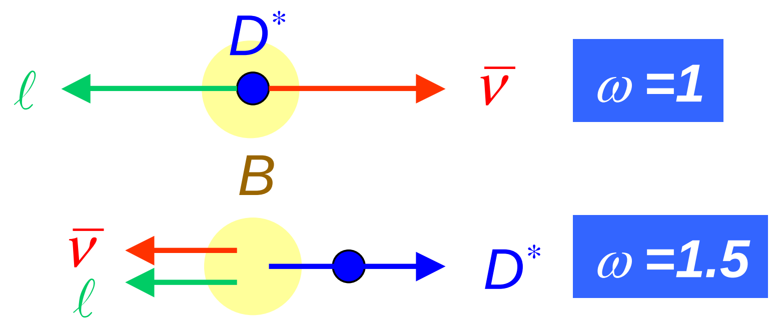
HQ Symmetry:

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

Bigi; Uraltsev; Neubert; ...
Lattice QCD: Hashimoto *et al.* [hep-ph/0110253]



in B rest system is $\omega = \gamma(D^*)$



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

Belle, PLB 526, 247 (2002)

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

- OPE shows that for $\Lambda_{QCD} \ll m_b$, inclusive B decay rates are equal to b quark decay rates. Corrections are suppressed by Λ_{QCD} / m_b and $\alpha_s(m_b)$.

Bigi, Shifman, Uraltsev; Hoang, Ligeti, Manohar, ...

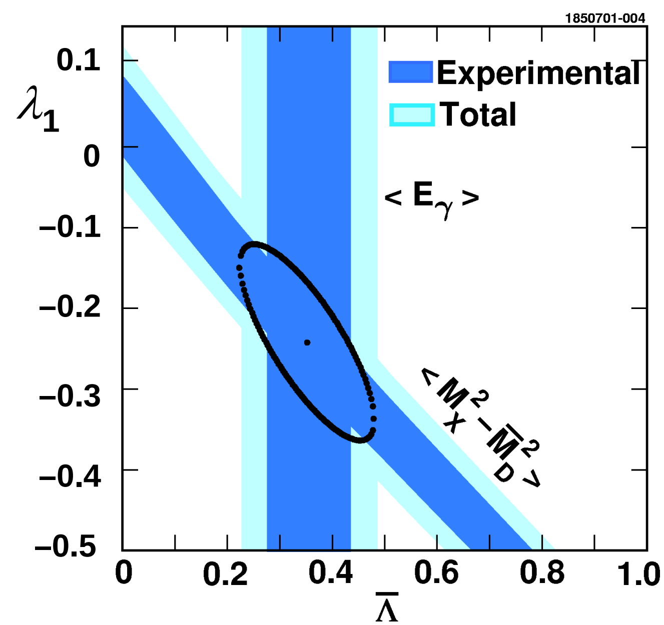
$$|V_{cb}| \simeq 0.0411 \sqrt{\frac{BR(B \to X_c \ell \bar{\nu})}{0.105} \frac{1.6\ \text{ps}}{\tau_B}} \left(1 \pm 0.015_{\text{pQCD}} \pm 0.010_{m_b} \pm 0.012_{1/m_b^3}\right)$$

A promising approach for a theoretically improved analysis is the combined fit of the HQET parameters Λ und λ_1 (CLEO) to $B \to X_u \ell \bar{\nu}$ mass and lepton moments or to $b \to s\gamma$. Allows to directly probe Quark-Hadron Duality ➜ successful in τ decays

➜ $|V_{cb}| \cong (40.9 \pm 0.9) \times 10^{-3}$

Bauer et al., hep-ex/0210027 [BABAR, CLEO, DELPHI data]

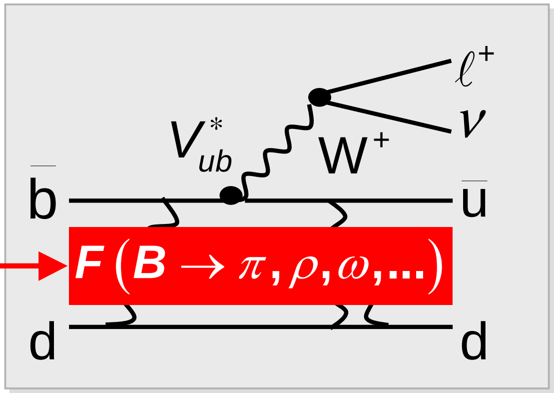
BABAR, hep-ex/0207084



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

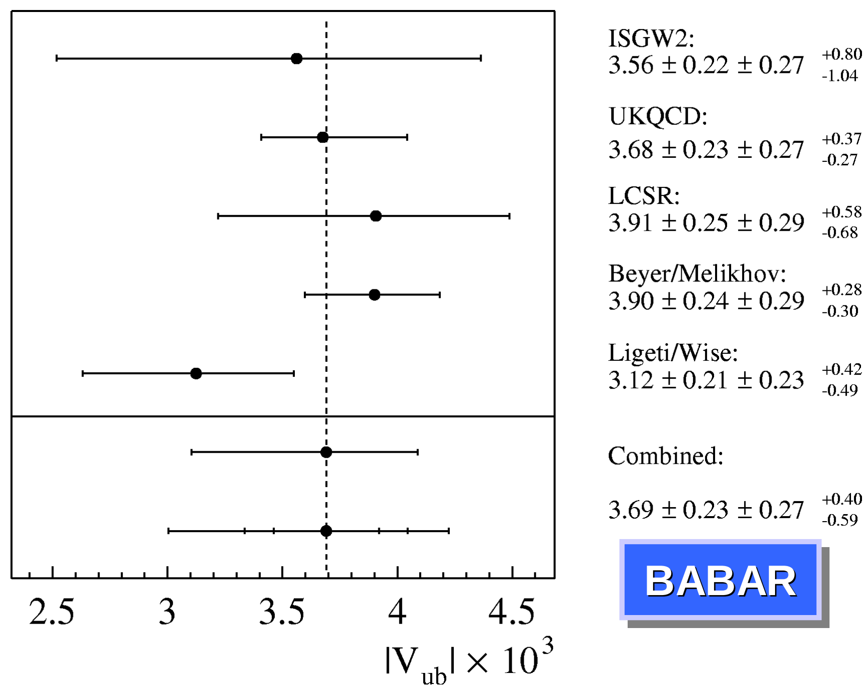
- Pure tree decay.
- Decay rate is proportional to CKM element $|V_{ub}|^2$

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



Problem:
form factor is model dependent !

Would need unquenched lattice calculation to become model-independent...

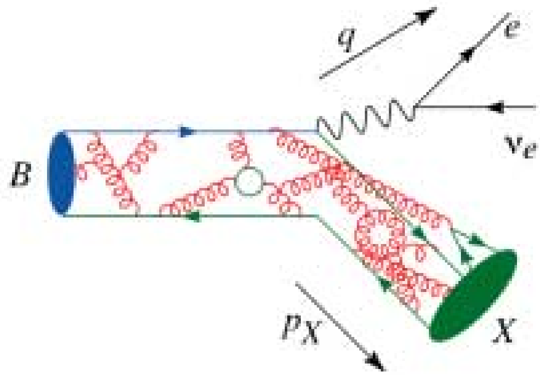


$$|V_{ub}| = \left(3.25 \pm 0.14\,^{+0.21}_{-0.29} \pm 0.55\right) \times 10^{-3} \text{ (CLEO)}$$

$$|V_{ub}| = \left(3.69 \pm 0.23 \pm 0.27\,^{+0.40}_{-0.59}\right) \times 10^{-3} \text{ (BABAR)}$$

CLEO, Phys.Rev.D61:052001,2000;
BABAR hep-ex/0207080

$|V_{ub}|$ from inclusive Decays



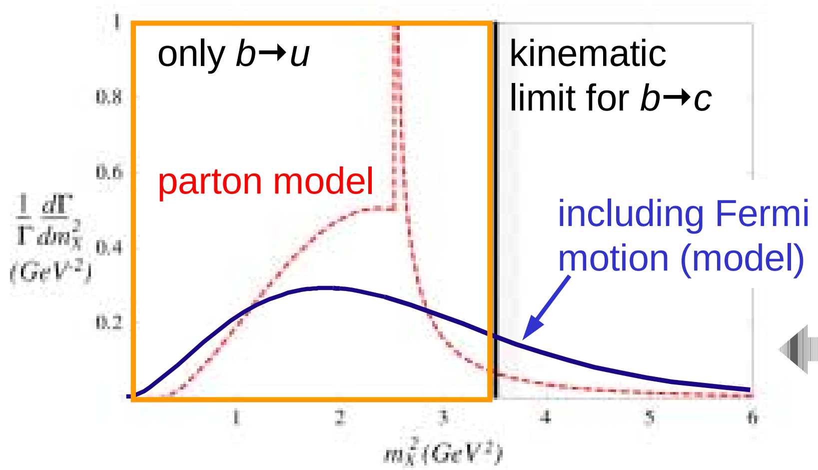
$$\simeq \frac{d\Gamma}{d(\mathrm{PS})} \sim \underbrace{\text{parton model}}_{\text{free quark decay}} + \underbrace{\sum_n C_n \left(\frac{\Lambda_{QCD}}{m_b}\right)^n}_{\text{nonperturbative corrections}}$$

Good: relation between $\sum_{X_u} \Gamma(B \to X_u \ell \bar{\nu})$ & $|V_{ub}|$ known to ~5%

Bad: cannot be measured fully inclusively, since $\frac{\Gamma(B \to X_c \ell \bar{\nu})}{\Gamma(B \to X_u \ell \bar{\nu})} \sim 100$

→ need to impose stringent cuts to eliminate charm background …

"… and here the troubles begin" (M. Luke, FPCP'02)

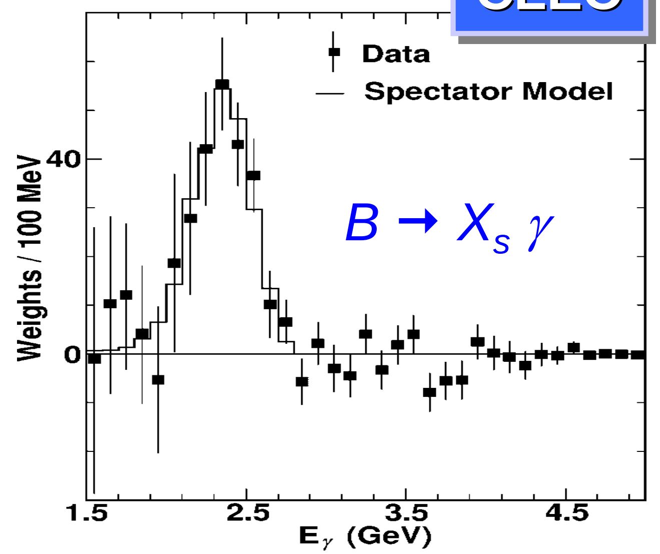


hadronic invariant mass spectrum for *b→u decay*

$|V_{ub}|$ 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 $B \to X_s \gamma$

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

(stat) (fu) (1/m_b) (HQE)

Validity of quark-hadron duality?

CLEO, hep-ex/0202019

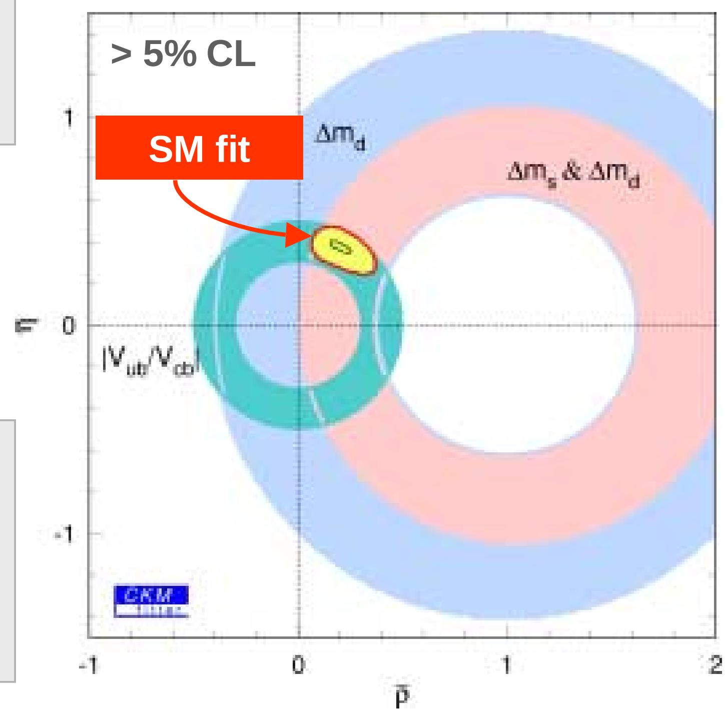
- Measurement of the whole spectrum (→ Theorie under control) $B \to X_u l \nu$ (Neural Net for Signal)

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

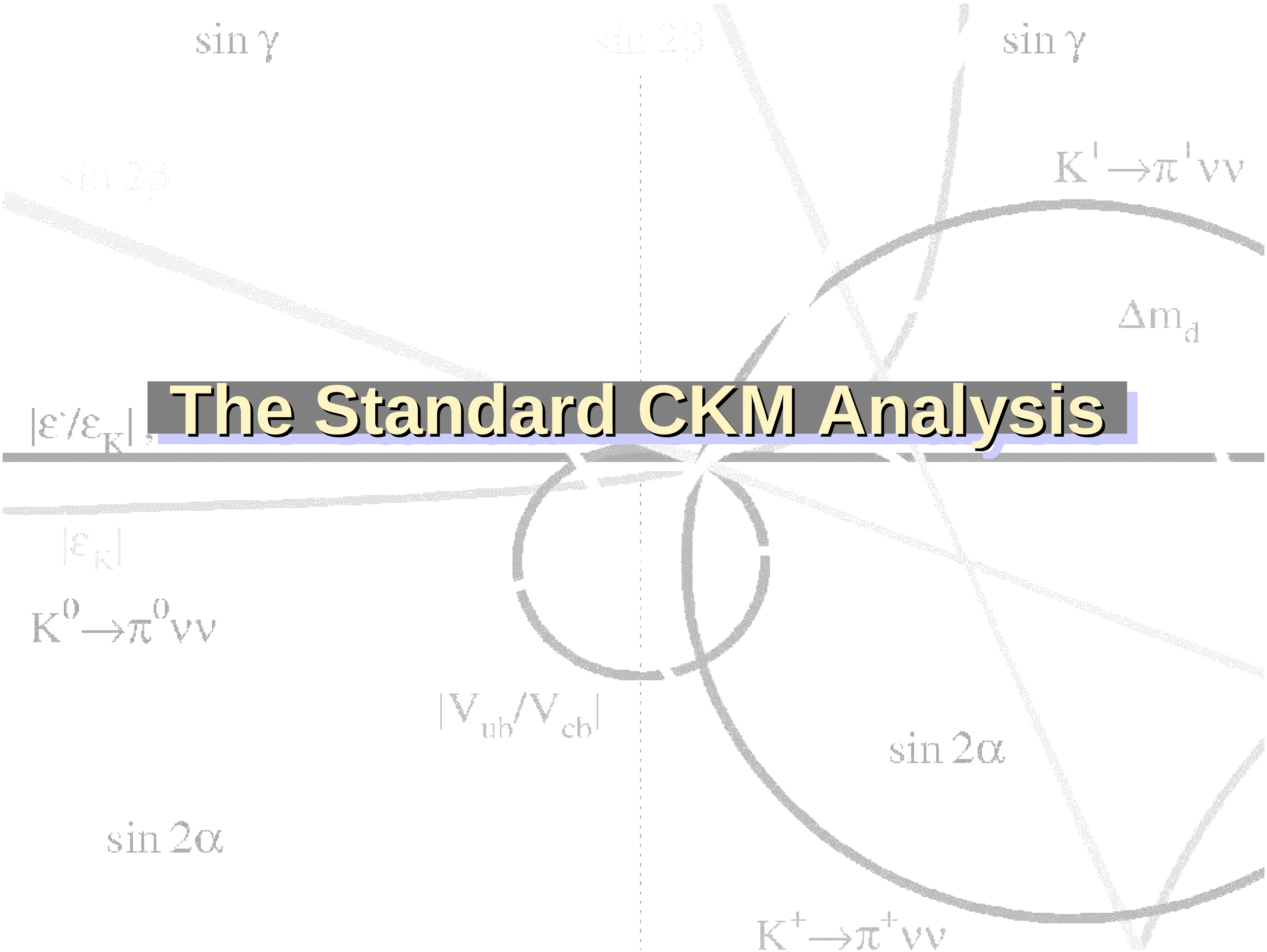
(exp) ($b \to c$) ($b \to u$) τ_b (HQE)

Knowledge of $b \to c$ background; inclusive measurement ?

LEP $|V_{ub}|$ Working group



The Standard CKM Analysis



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: “allowed *ranges*”**

Bayesian → **Probabilities**

Three Step CKM Analysis Using *R*fit

CKM fitter

fit package

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 $\{\mu\}$
  $\chi^2_{\min;\mu}(a) = \min_{\mu}\{\chi^2(a, \mu)\}$
- $\Delta\chi^2(a) = \chi^2_{\min;\mu}(a) - \chi^2_{\min;y_{mod}}$

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

Test New Physics

- If CL(SM) good

Obtain limits on New Physics parameters

- If CL(SM) bad

Hint for New Physics ?!

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

Standard Inputs

status: ICHEP'02

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)*
$\|V_{ub}\|$	$(4.09 \pm 0.61 \pm 0.42) \times 10^{-3}$	*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)*
$\sin 2\beta$	0.734 ± 0.055	*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*

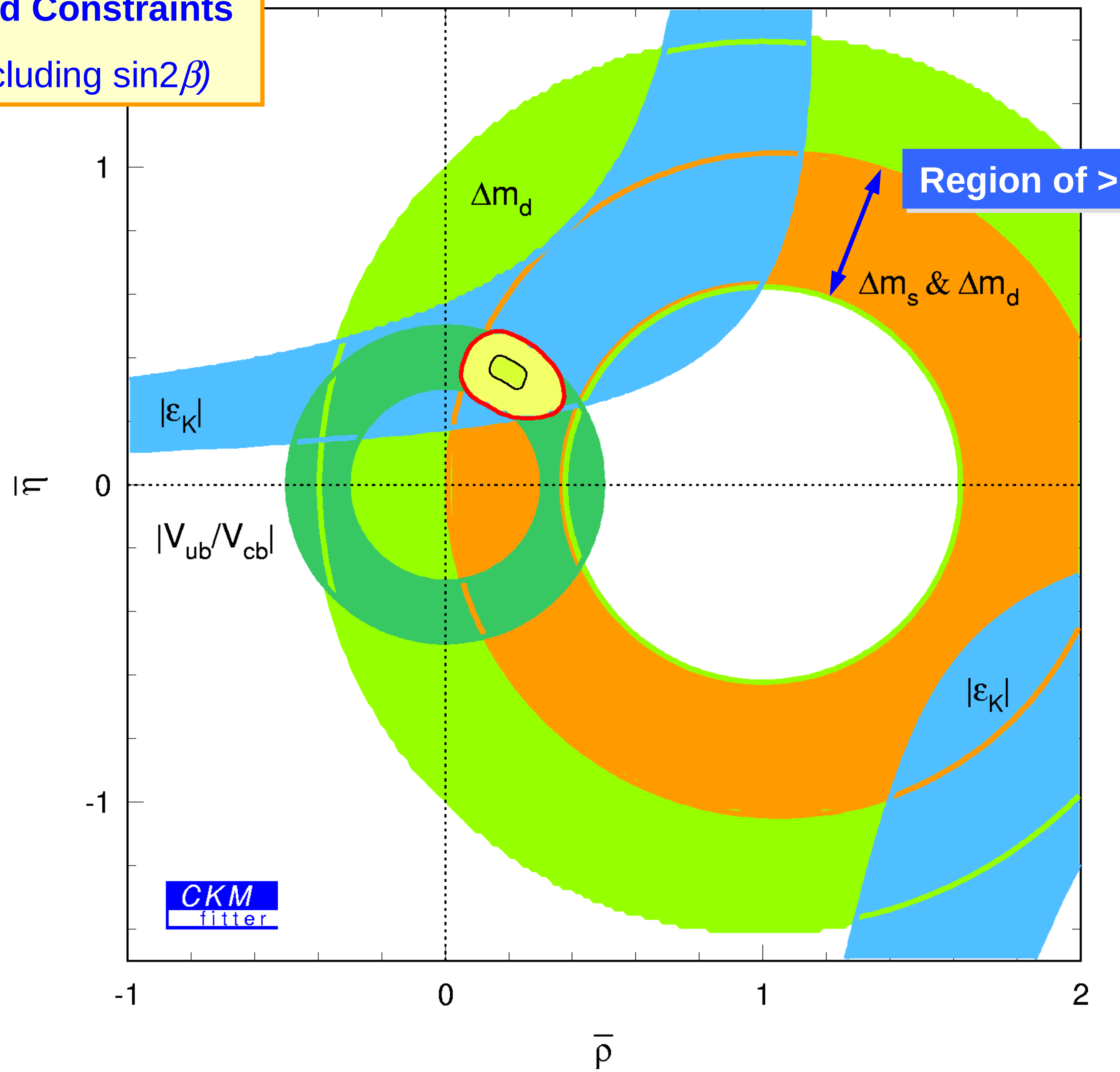
+ other parameters with less relevant errors…

Metrology (I)

status: ICHEP'02

Standard Constraints

(not including sin2β)

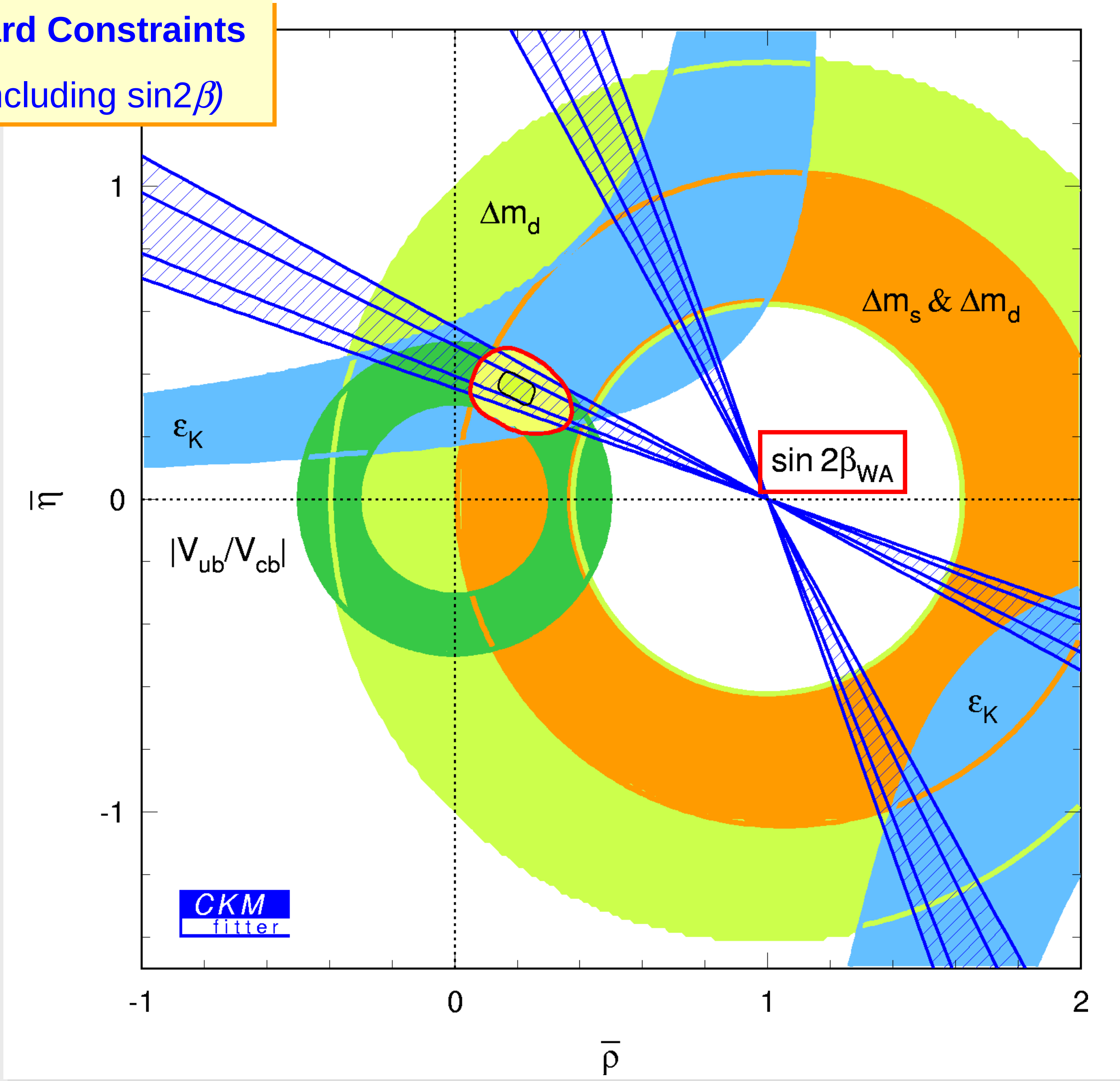


Metrology (I)

status: ICHEP'02

Standard Constraints

(not including sin2β)



A TRIUMPH FOR THE STANDARD MODEL AND THE KM PARADIGM !

KM mechanism most probably the dominant source of CPV at EW scale

Still true???

Metrology (I)

status: ICHEP'02

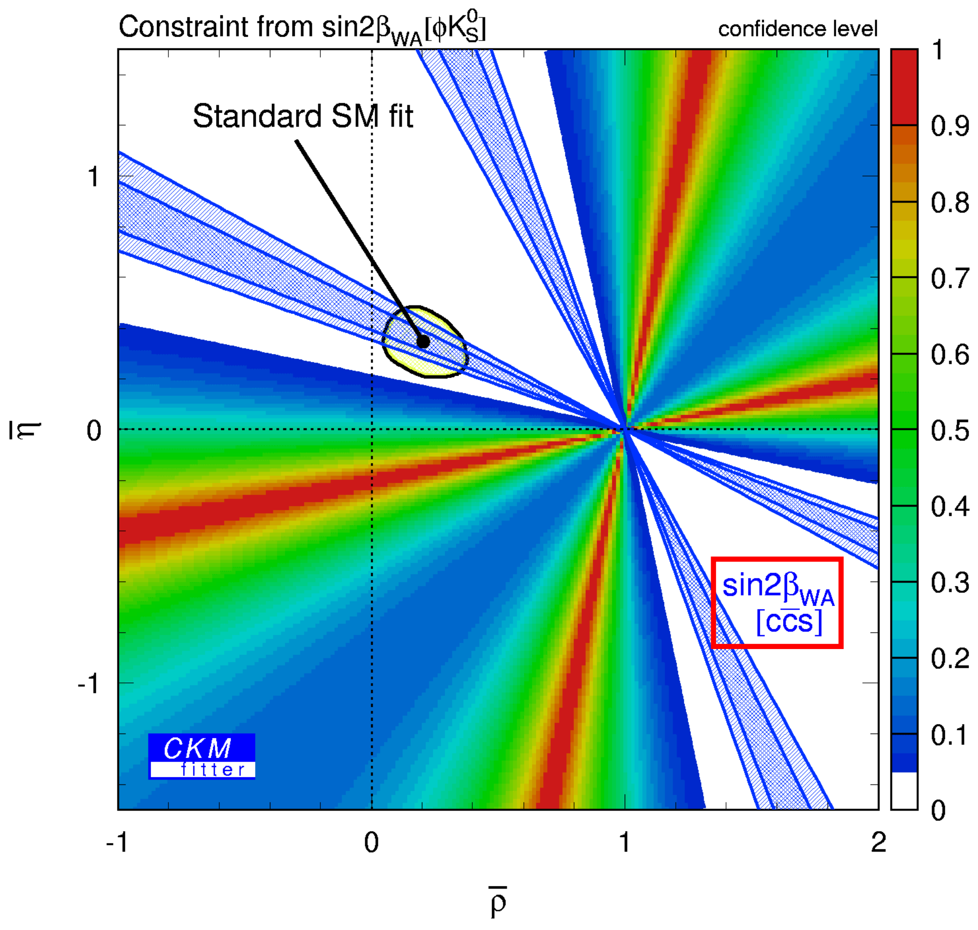
New *CP* Results from complementary modes:

BABAR, hep-ex/020707

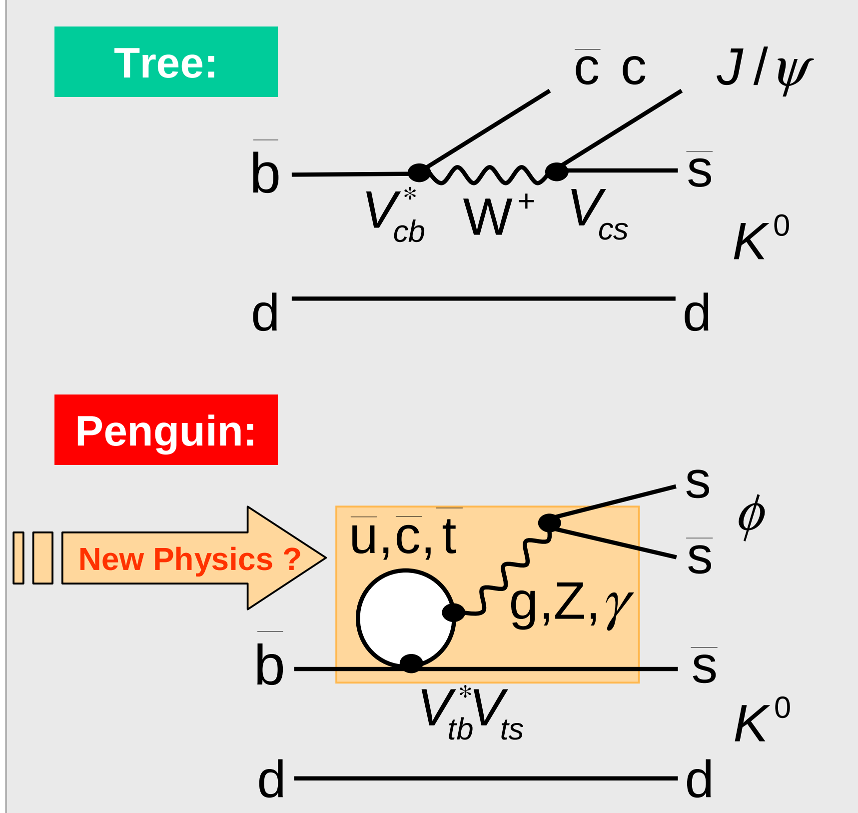
$$"\sin 2\beta" = \begin{cases} [\phi K_s^0] & -0.19^{+0.52}_{-0.50} \pm 0.09_{syst} \\ [\phi K_s^0] & -0.73 \pm 0.64 \pm 0.18_{syst} \\ [\eta' K_s^0] & +0.76 \pm 0.64^{+0.05}_{-0.06 syst} \end{cases}$$

The first two lines (BABAR and Belle ϕK_s^0) combine to: $= -0.39 \pm 0.40$

Belle, hep-ex/0207098



Both decays dominated by single weak phase

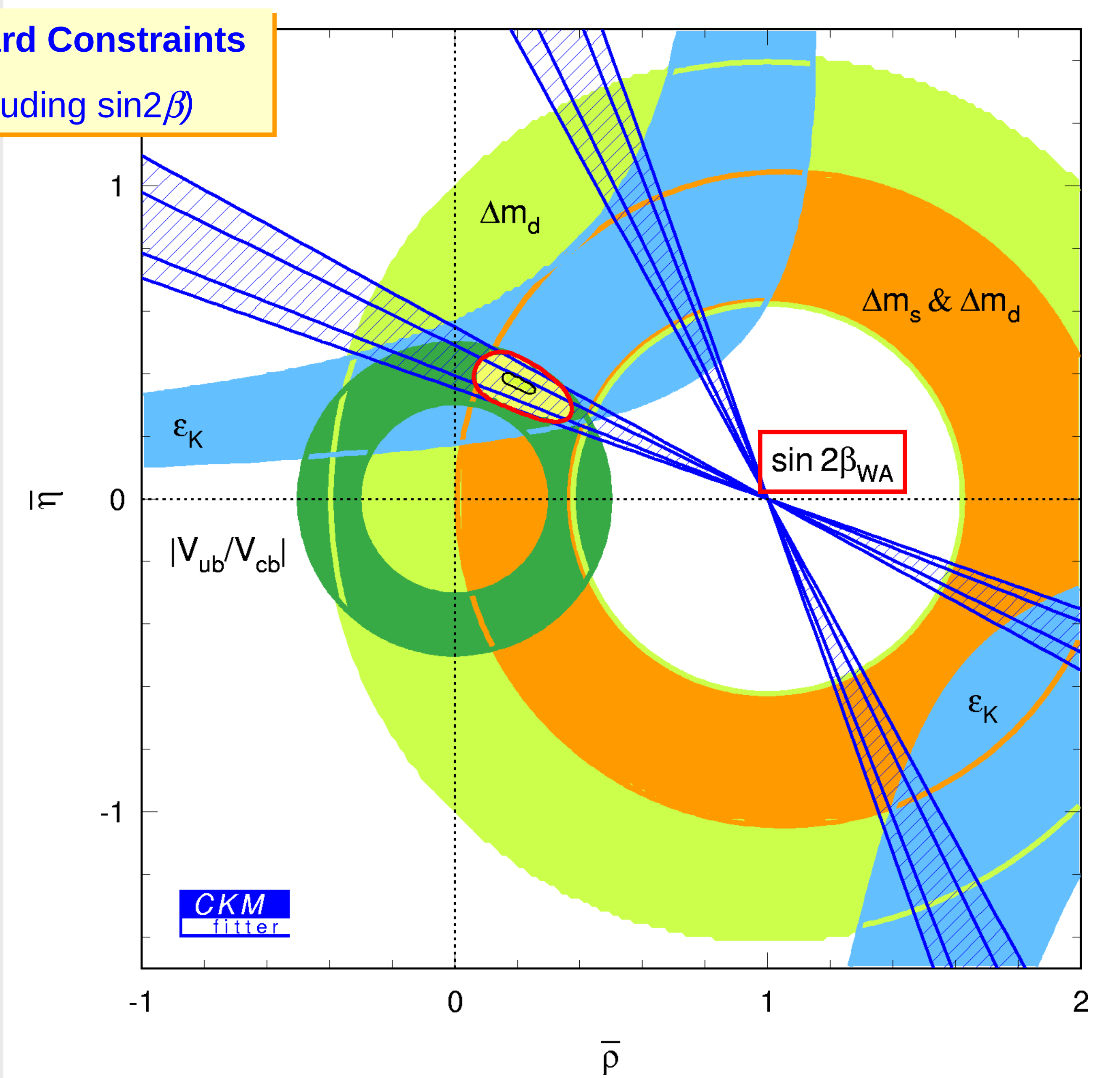


Metrology (I)

status: ICHEP'02

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 ?**

...

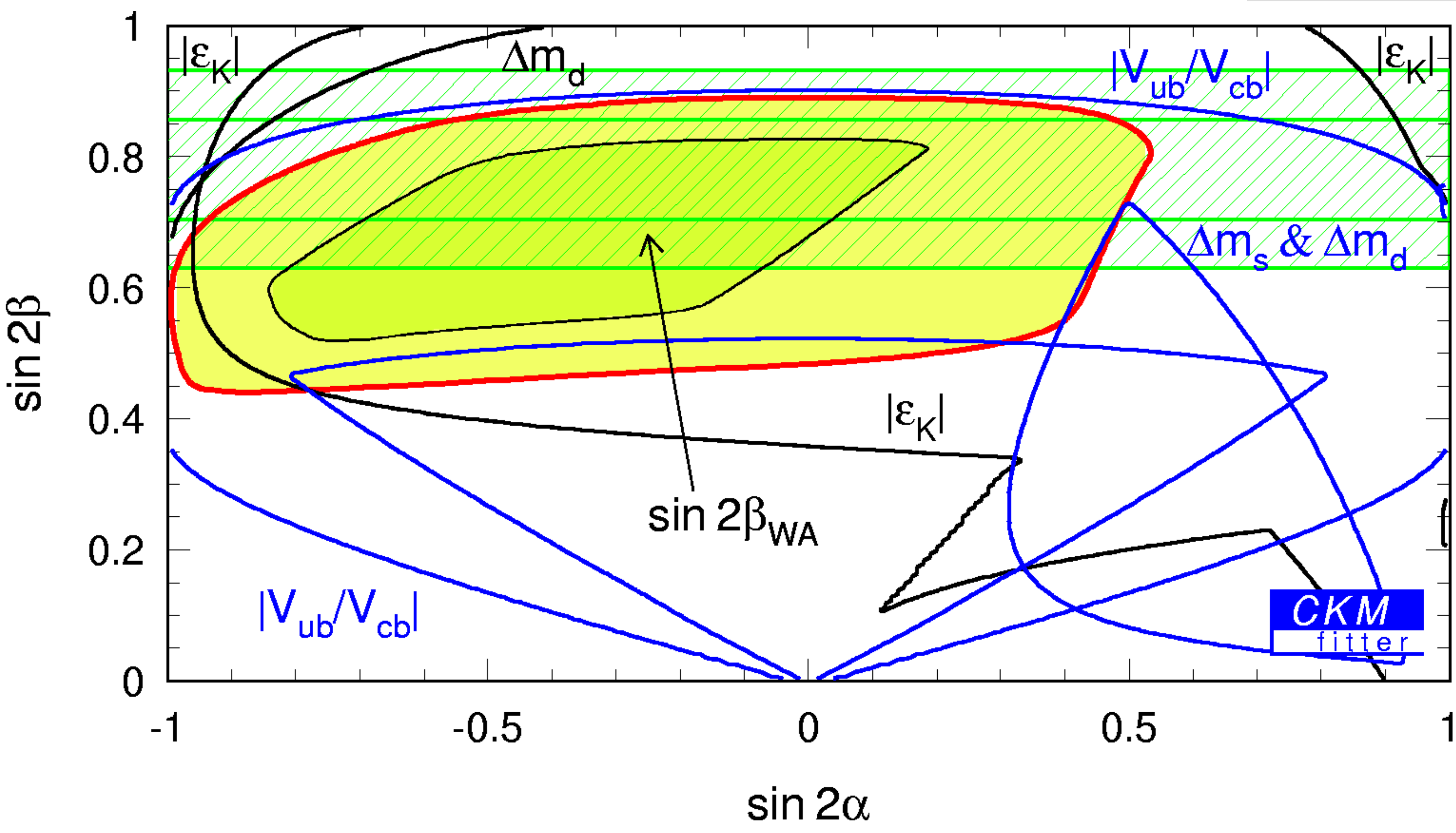
Metrology (II): the sin(2α) - sin(2β) Plane

status: FPCP'02

Standard Constraints

(not including sin2β)

Be aware of ambiguities !

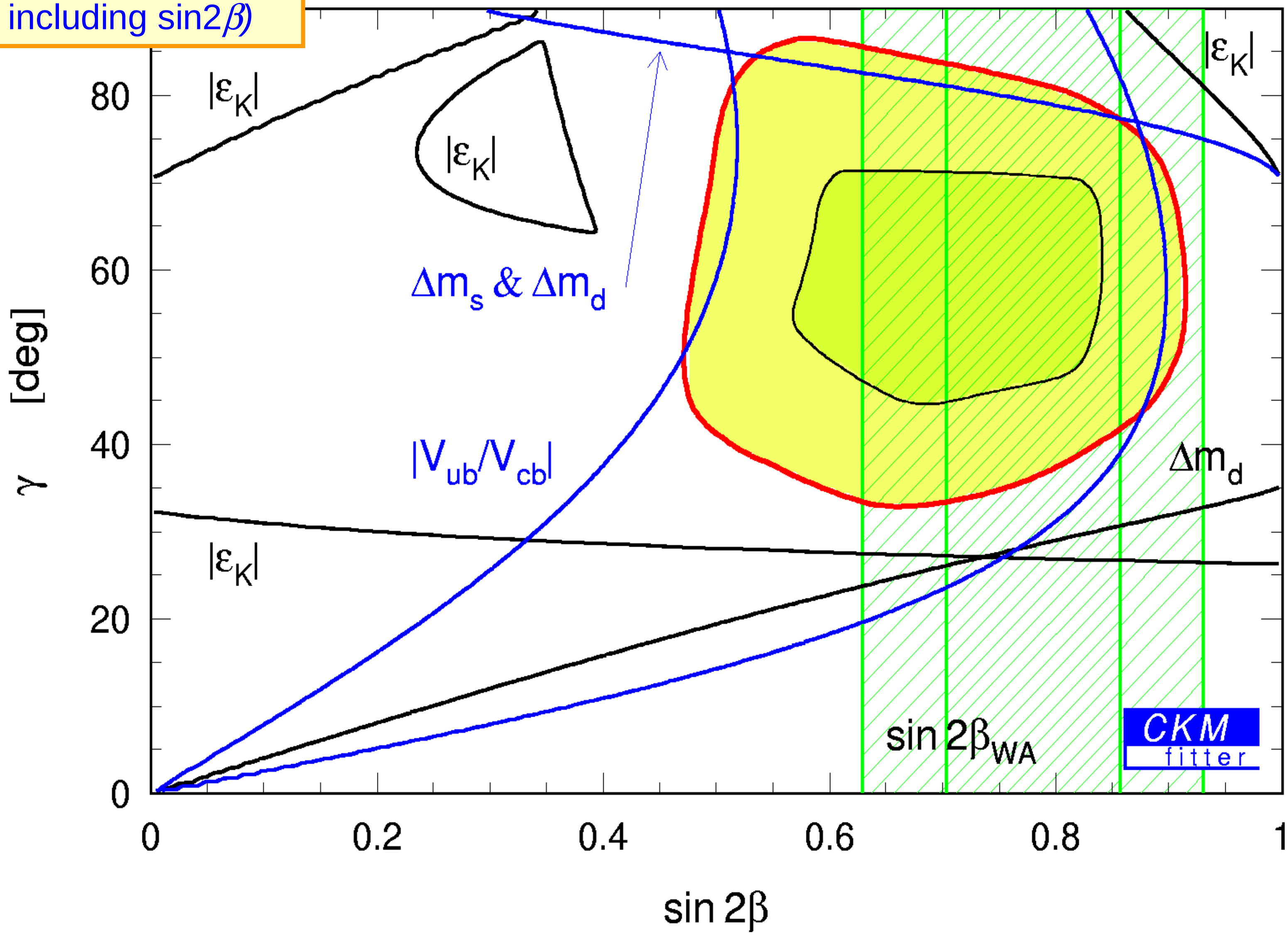


Metrology (II): the sin(2β) - γ Plane

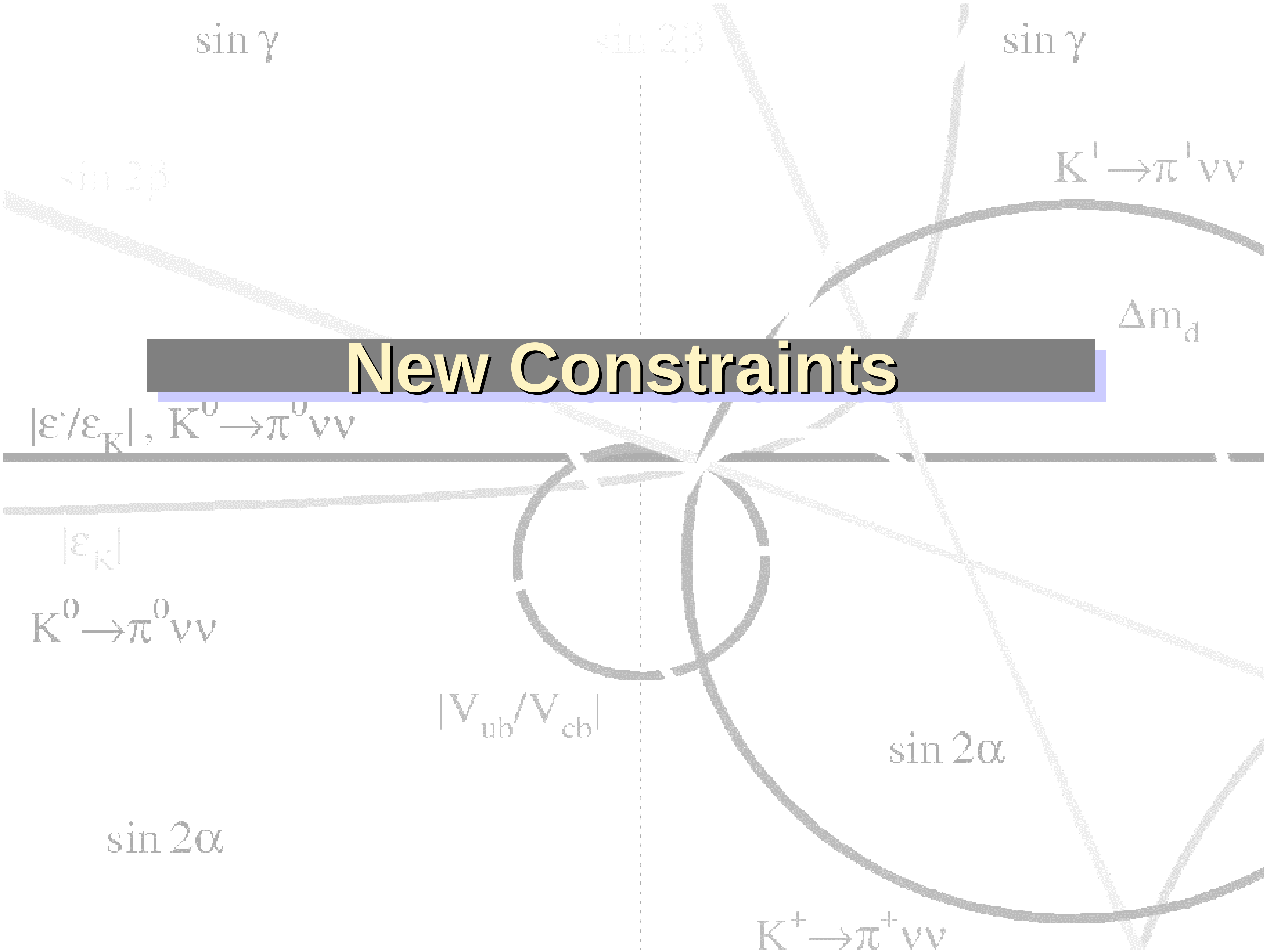
status: FPCP'02

Standard Constraints

(not including sin2β)



New Constraints

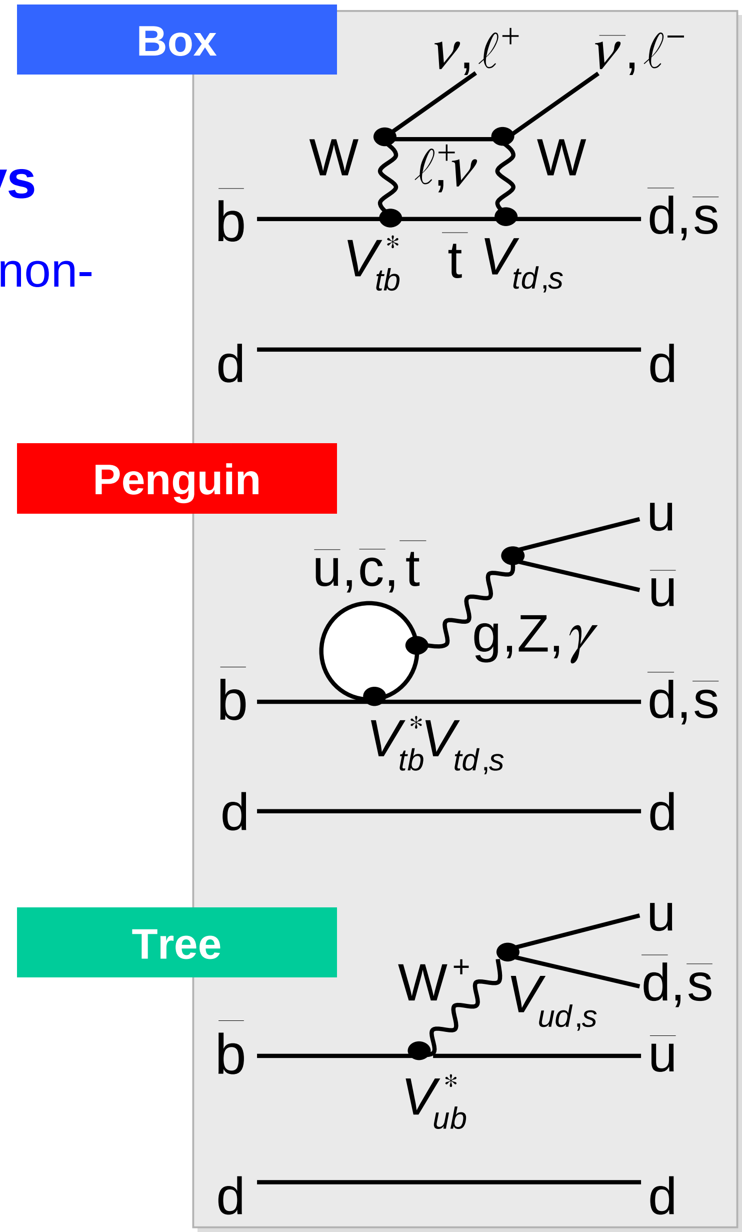


Rare Charmless *B* Decays

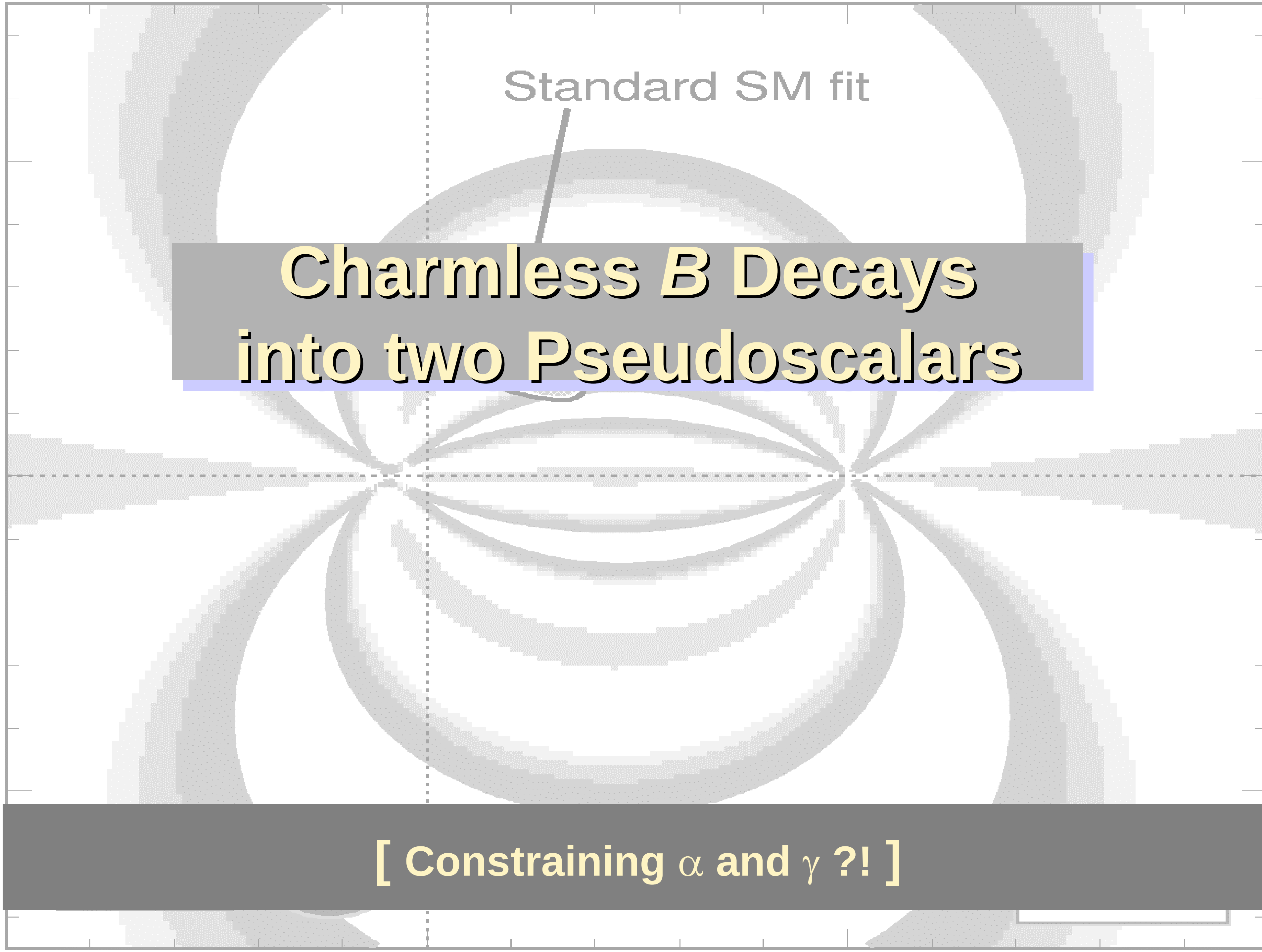
We distinguish two Categories:

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



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:

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

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!

Theoretical analysis deals with:

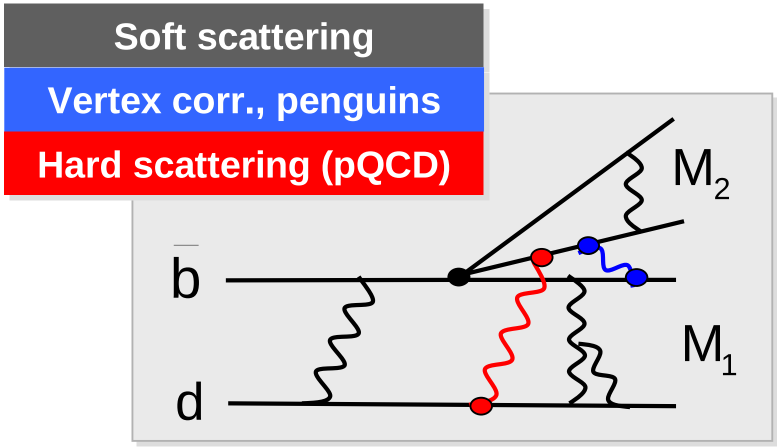
- SU(3) breaking
- Rescattering (FSI)
- EW penguins

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 $m_b \to \infty$.

But, m_b finite → corrections: $O(\Lambda_{QCD}/m_b)$



Branching Fs. and A_{CP} for $B \to \pi\pi / K\pi$

status: ICHEP'02

Mode	*BABAR* $(\times 10^{-6})$	Belle	CLEO	World average
$B^0 \to \pi^+\pi^-$	$4.7 \pm 0.6 \pm 0.2$	$5.4 \pm 1.2 \pm 0.5$	$4.3^{+1.6}_{-1.4} \pm 0.5$	4.78 ± 0.54
$B^+ \to \pi^+\pi^0$	$5.5^{+1.0}_{-0.9} \pm 0.6$	$7.4^{+2.3}_{-2.2} \pm 0.9$	$5.6^{+2.1}_{-2.0} \pm 1.5$	5.83 ± 0.96
$B^0 \to \pi^0\pi^0$	< 3.6 $(1.6^{+0.7}_{-0.6}{}^{+0.6}_{-0.3})$	< 6.4 $(3.2 \pm 1.5 \pm 0.7)$	< 5.7 $(2.2^{+1.7}_{-1.3} \pm 0.7)$	$(2.01^{+0.70}_{-0.67})$
$B^0 \to K^+\pi^-$	$17.9 \pm 0.9 \pm 0.7$	$22.5 \pm 1.9 \pm 1.8$	$17.2^{+2.5}_{-2.4} \pm 1.2$	18.46 ± 0.98
$B^+ \to K^+\pi^0$	$12.8^{+1.2}_{-1.1} \pm 1.0$	$13.0^{+2.5}_{-2.4} \pm 1.3$	$11.6^{+3.0}_{-2.7}{}^{+1.4}_{-1.3}$	12.68 ± 1.23
$B^+ \to K^0\pi^+$	$17.5^{+1.8}_{-1.7} \pm 1.3$	$19.4^{+3.1}_{-3.0} \pm 1.6$	$18.2^{+4.6}_{-4.0} \pm 1.6$	$18.09^{+1.73}_{-1.69}$
$B^0 \to K^0\pi^0$	$10.4 \pm 1.5 \pm 0.8$	$8.0^{+3.3}_{-3.1} \pm 1.6$	$14.6^{+5.9}_{-5.1}{}^{+2.4}_{-3.3}$	10.34 ± 1.48
$B^0 \to K^+K^-$	< 0.6	< 0.9	< 1.9	
$B^+ \to K^+\bar{K}^0$	< 1.3	< 2.0	< 5.1	
$B^0 \to K^0\bar{K}^0$	< 0.6	< 4.1	$-$	
$A_{CP}(\pi^+\pi^0)$	$-0.03^{+0.18}_{-0.17} \pm 0.02$	$+0.30 \pm 0.30^{+0.06}_{-0.04}$	-	$+0.06 \pm 0.16$
$A_{CP}(K^+\pi^-)$	$-0.102 \pm 0.050 \pm 0.016$	$-0.06 \pm 0.09^{+0.01}_{-0.02}$	-0.04 ± 0.16	-0.088 ± 0.044
$A_{CP}(K^+\pi^0)$	$-0.09 \pm 0.09 \pm 0.01$	$0.02 \pm 0.09 \pm 0.01$	-0.29 ± 0.23	□ 0.05 ± 0.07
$A_{CP}(K^0\pi^+)$	$-0.17 \pm 0.10 \pm 0.02$	$+0.46 \pm 0.15 \pm 0.02$	$+0.18 \pm 0.24$	$+0.04 \pm 0.08$
$A_{CP}(K^0\pi^0)$	$0.03 \pm 0.36 \pm 0.09$	-	-	$0.03 \pm 0.36 \pm 0.09$

Agreement among experiments. Most rare decay channels discovered

Bounds on γ

status: ICHEP'02

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

Fleischer, Mannel PRD D57 (1998) 2752

FM bound: $$R = \frac{\tau(B^+)}{\tau(B^0)} \cdot \frac{BR(K^\pm \pi^\mp)}{BR(K^0 \pi^\pm)} = 1.09\,^{+0.13}_{-0.11}$$ **< 1 ?** ➜ no constraint

Buras, Fleischer EPJ C11 (1998) 93

BF bound: $$R_n = \frac{1}{2} \frac{BR(K^\pm \pi^\mp)}{BR(K^0 \pi^0)} = 0.89\,^{+0.16}_{-0.12}$$ $\neq$ **1 ?** ➜ no constraint

Neubert, Rosner PL B441 (1998) 403

NR bound: $$R_c = 2 \frac{BR(K^\pm \pi^0)}{BR(K^0 \pi^\pm)} = 1.40\,^{+0.20}_{-0.18}$$ $\neq$ **1 ?** ➜ some constraint

Neubert-Rosner Bound

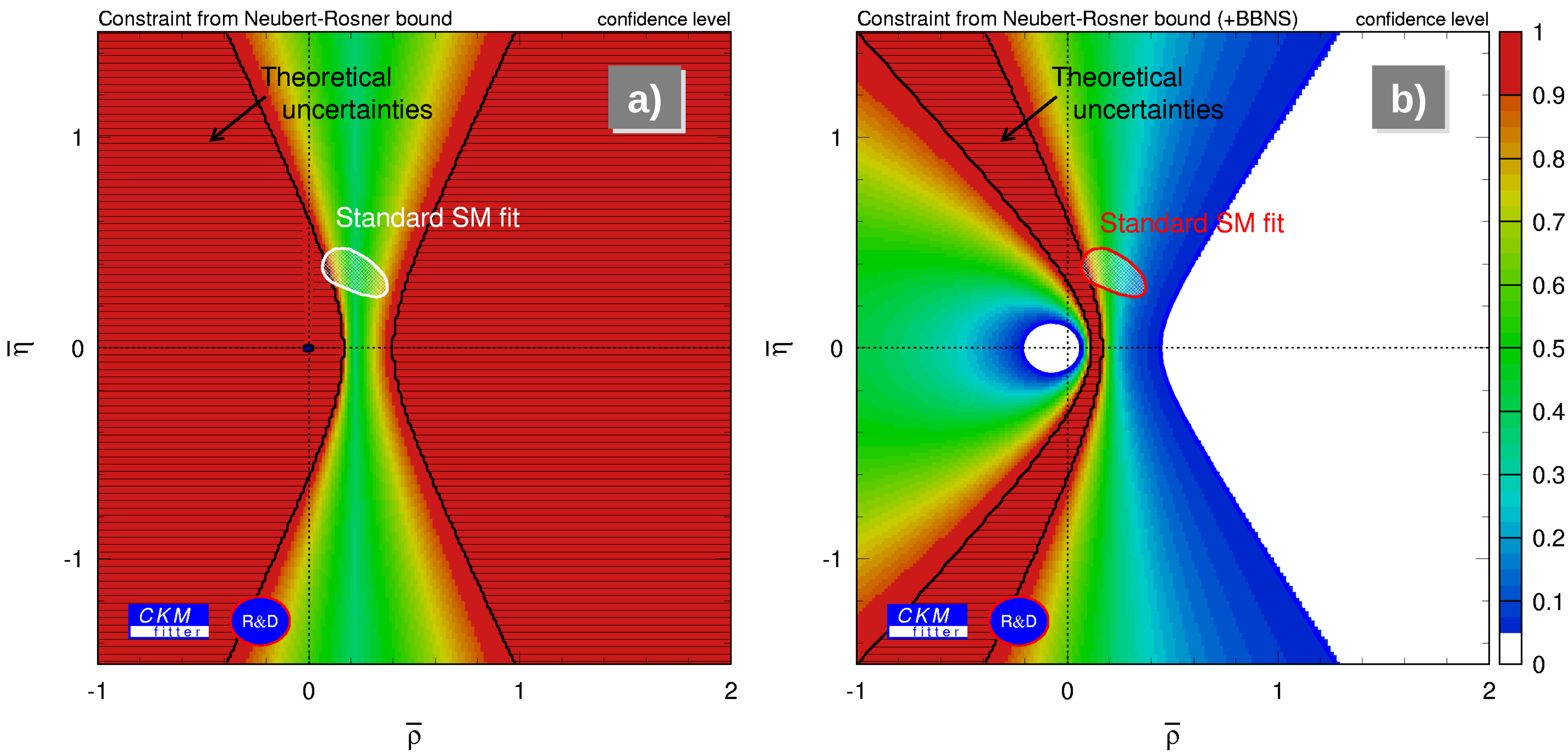
status: FPCP'02

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

Tree: $\pi^\pm \pi^0$

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

b) QCD FA: small relative strong phases



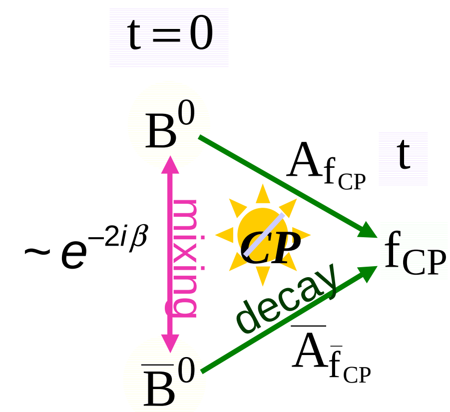
CP Violation in $B^0 \to \pi^+\pi^-$ Decays

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

ratio of amplitudes

CP eigenvalue

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

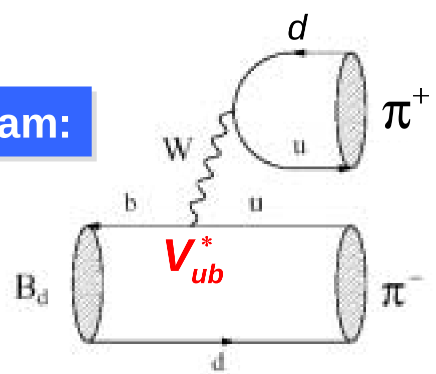


$$A_{f_{CP}}(t) \propto S_{f_{CP}} \sin(\Delta m_d t) - C_{f_{CP}} \cos(\Delta m_d t)$$

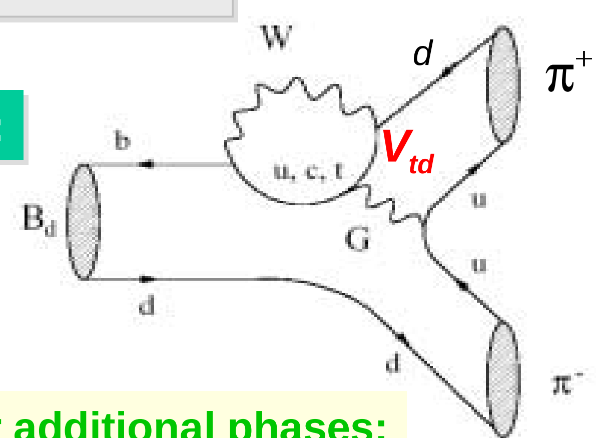
$$C_{f_{CP}} = \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2}$$

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

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*
Im $(\lambda) \neq \sin(2\alpha) \Rightarrow$ need to relate asymmetry to α

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

Bounds/Predictions on $|\alpha - \alpha_{eff}|$

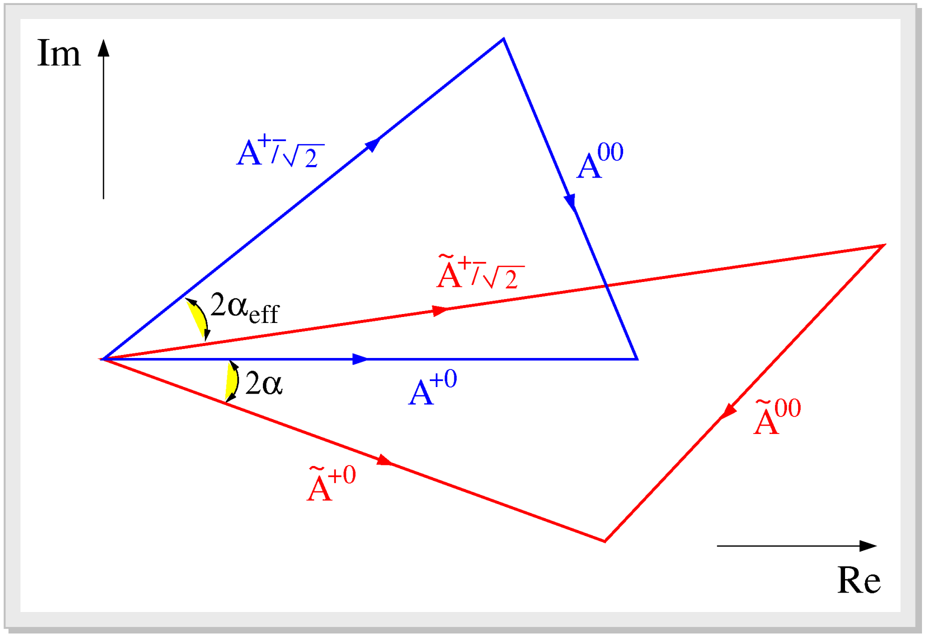
$$S_{\pi\pi} = \frac{2\mathrm{Im}\,\lambda_{\pi\pi}}{1+|\lambda_{\pi\pi}|^2}\ ,\quad C_{\pi\pi} = \frac{1-|\lambda_{\pi\pi}|^2}{1+|\lambda_{\pi\pi}|^2}$$

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

to be "tamed"... (Charles)

Different Strategies:

- **Determination of *P*/*T* by virtue of flavour symmetries** (mild theoretical assumptions, eg, P_{EW}=0)
  - **SU(2):**
    Gronau-London Isospin Analysis
    Grossmann-Quinn bound (also Charles, Gonau *et al.*)
  - **SU(3):**
    Fleischer-Buras, Charles
    ($P_{\pi\pi} \sim P_{K\pi}$)



- **Using theoretical predictions for P/T**
  - **"naive" Factorization ($|P/T|^2$ ~ BR($B^+ \to \pi^+ K^0$) / BR($B^+ \to \pi^+ \pi^0$))**
  - **|*P*/*T*| and phase from QCD Factorization (Beneke *et al.*) and pQCD (Lee *et al.*)**

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

status: ICHEP'02

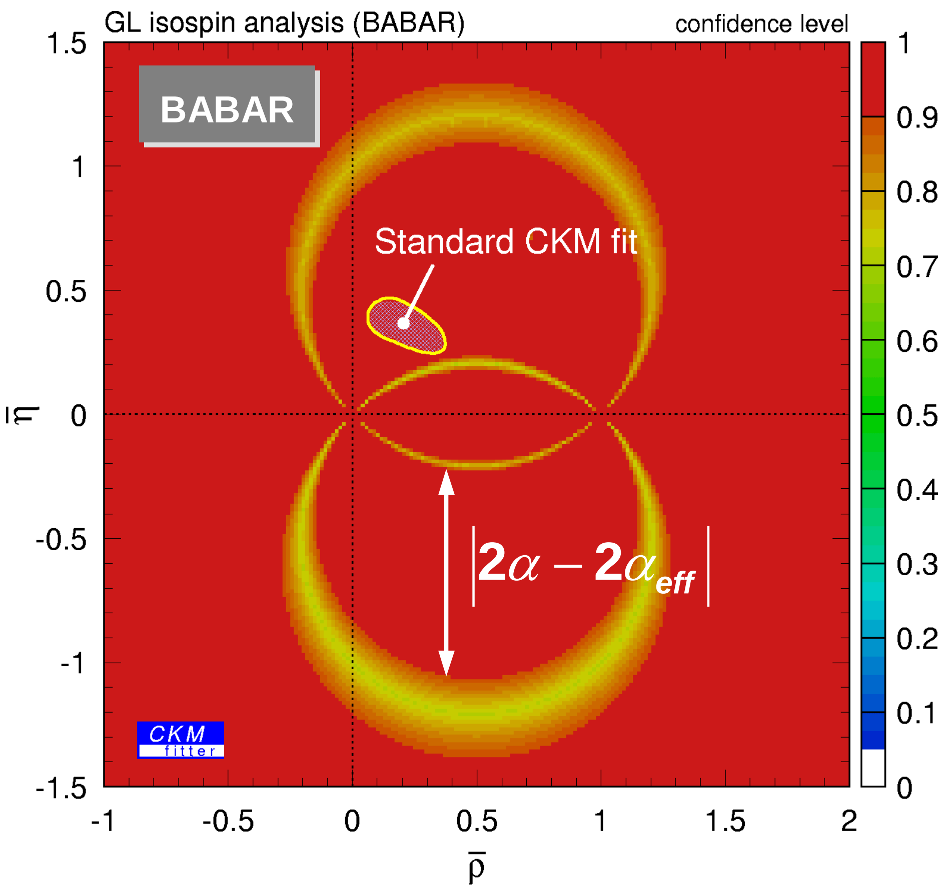
Using the BRs : $\pi^+\pi^-$, $\pi^\pm\pi^0$, $\pi^0\pi^0$ (limit)

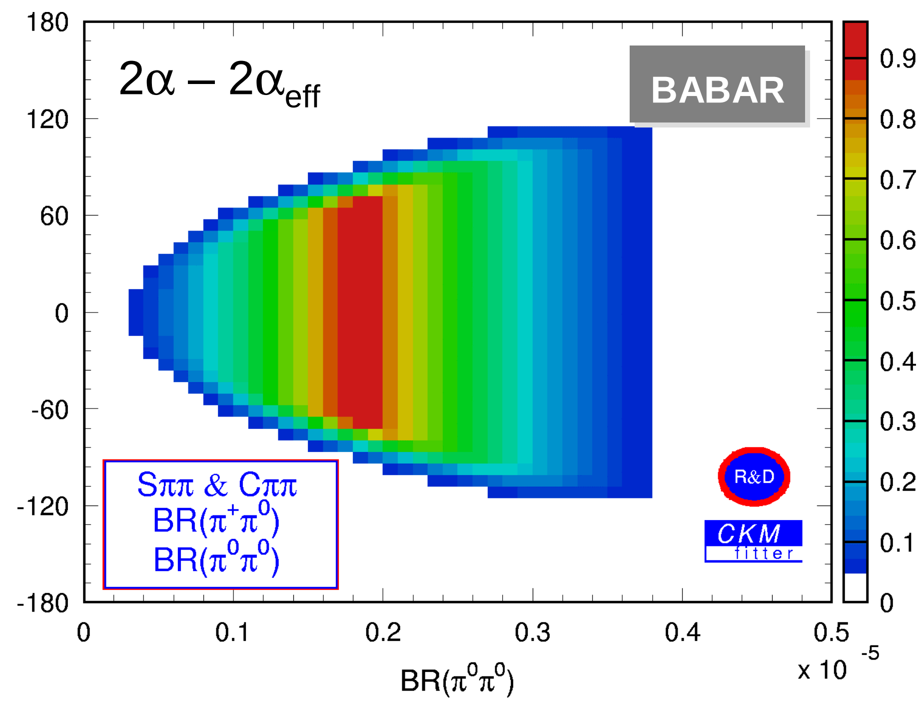
and the CP asymmetries : $A_{CP}(\pi^\pm\pi^0)$, $S_{\pi\pi}$, $C_{\pi\pi}$

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

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

BABAR	
$S_{\pi\pi}$	$+0.02 \pm 0.34$
$C_{\pi\pi}$	-0.30 ± 0.25

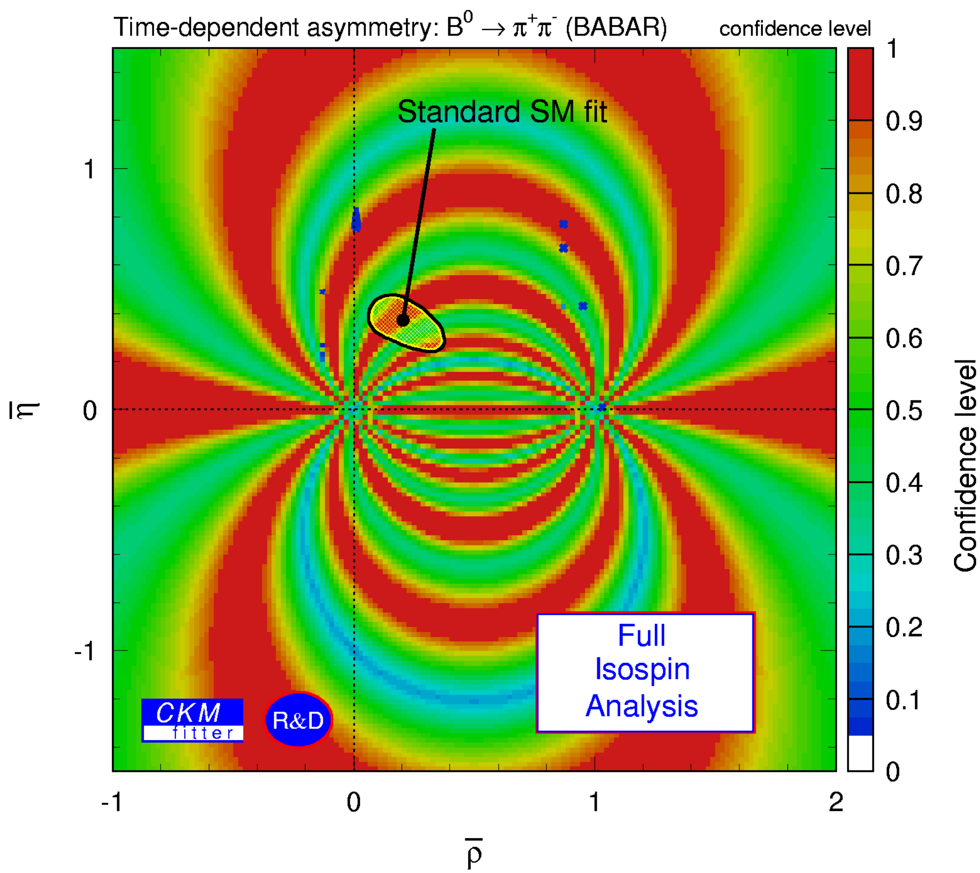




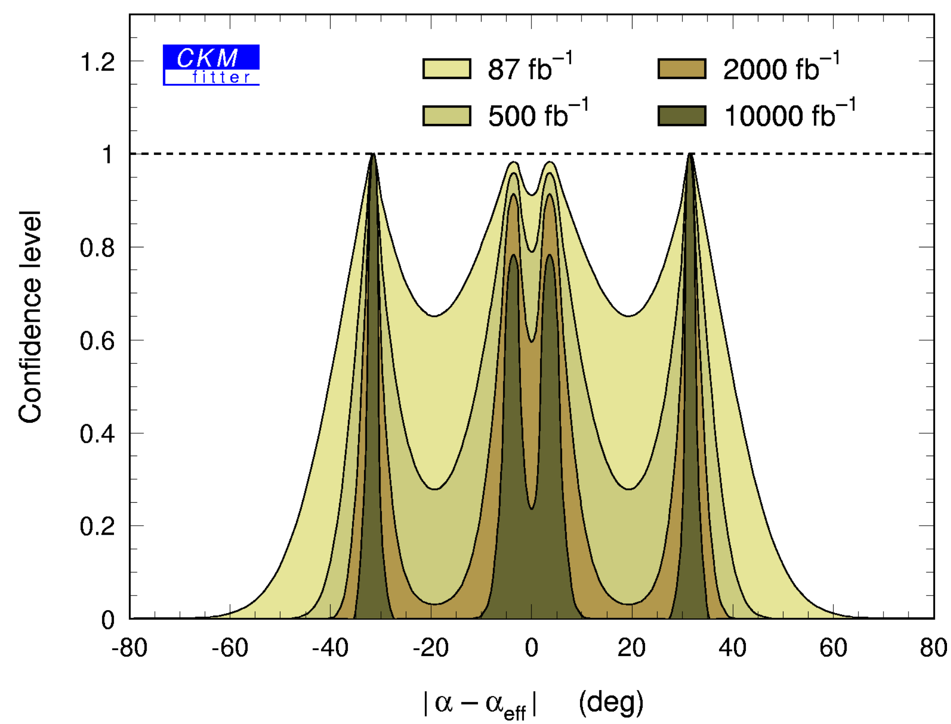
$|\alpha - \alpha_{eff}| \leq 51^o$

How about More Statistics?

Isospin analysis for present central values, but 500 fb^{-1}



and even more...

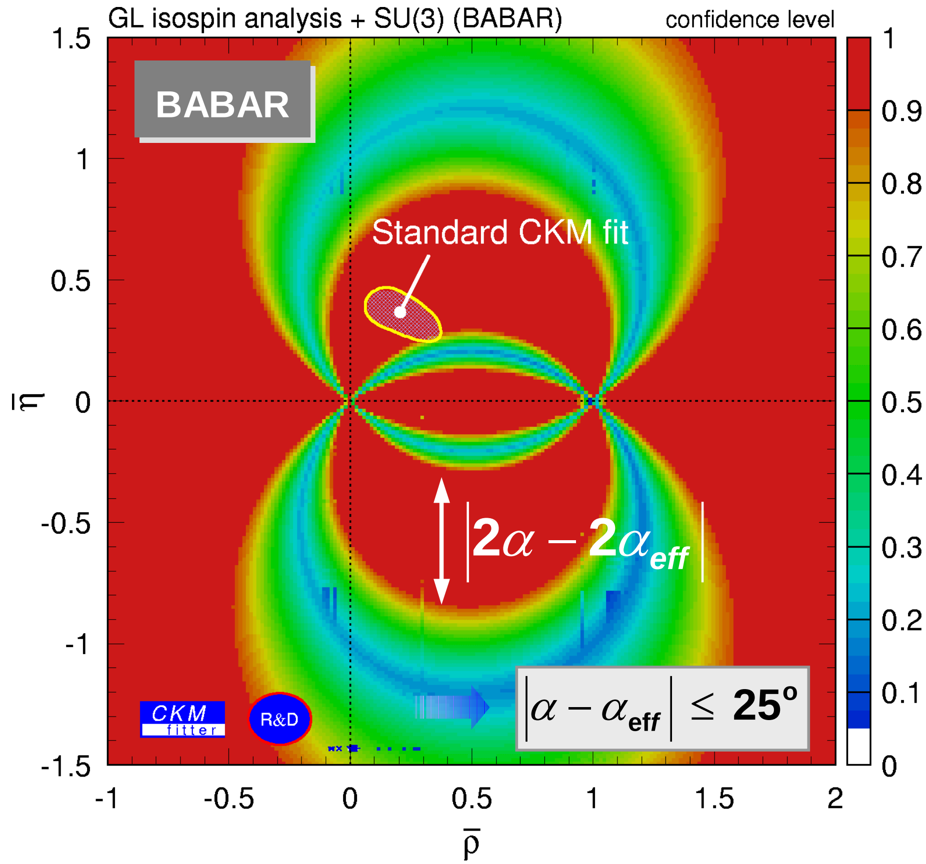


If central value of BR($\pi^0\pi^0$) stays large, isospin analysis cannot be performed by first generation B factories

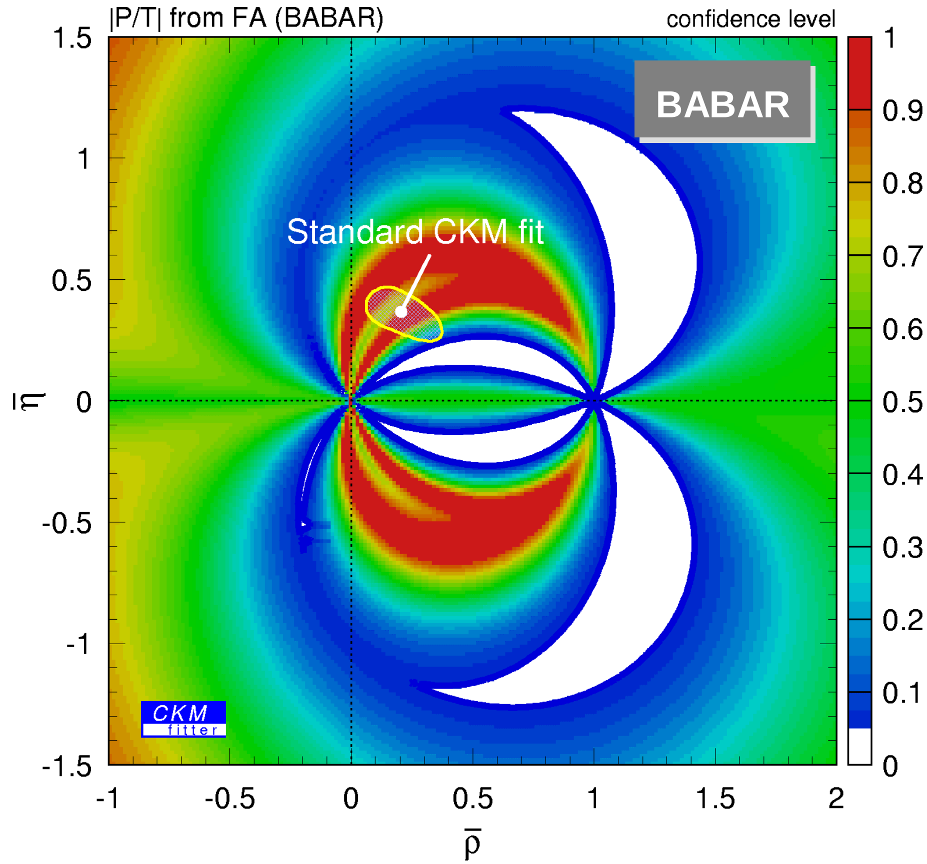
$\sin(2\alpha_{eff})$ & SU(3) or "naive" FA

Need to make more assumptions ... achieve better constraints

Input: SU(2) + BR($K^+\pi^-$)



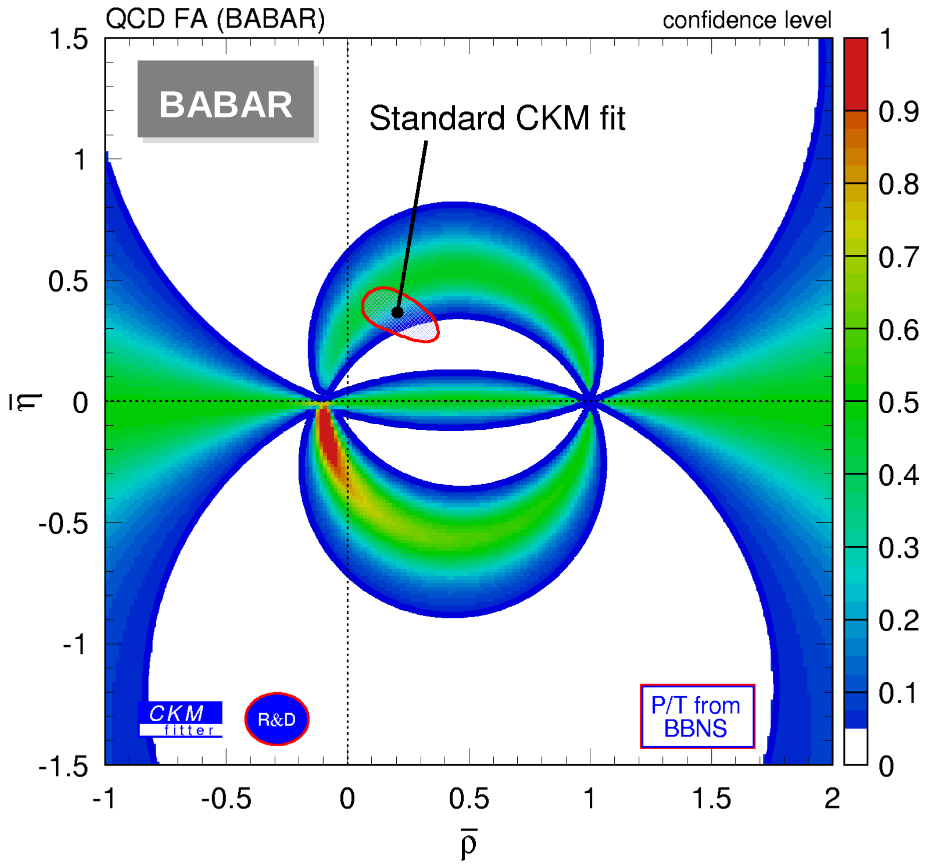
Input: |P| from BR($K^0\pi^+$)



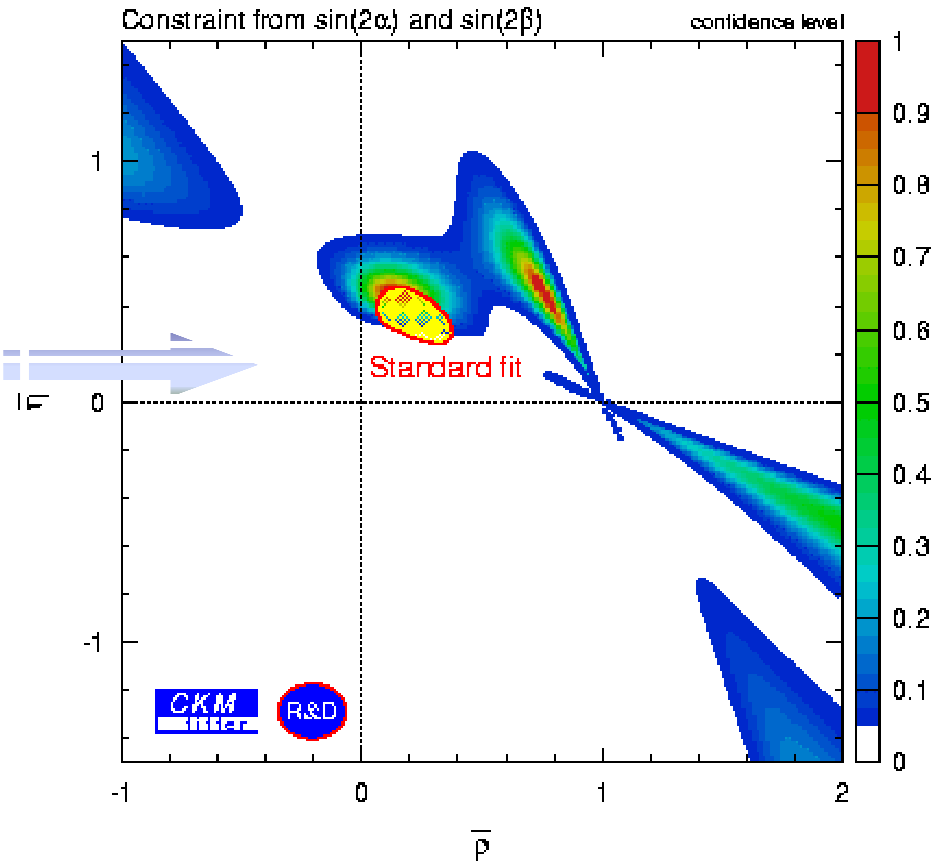
sin($2\alpha_{eff}$) & QCD FA

|P/T| and arg(P/T) predicted by QCD FA (BBNS'01)

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



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



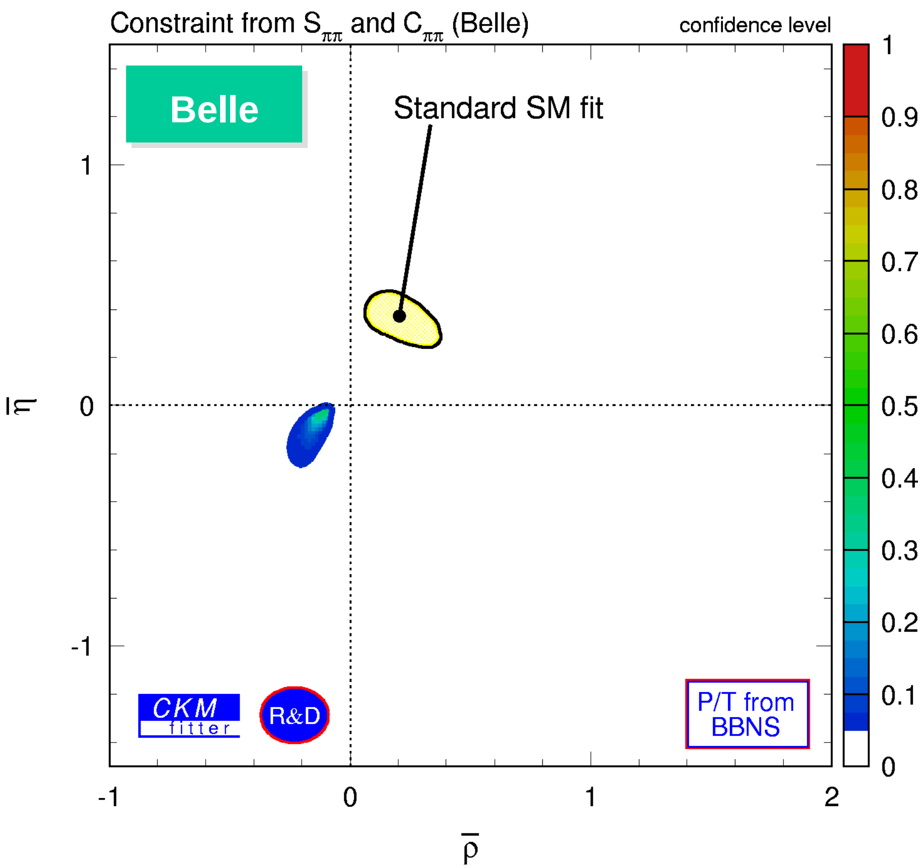
$\sin(2\alpha_{eff})$ & QCD FA

Belle:
(Moriond'02)

$S_{\pi\pi}$	$-1.21^{+0.41}_{-0.30}$
$C_{\pi\pi}$	$-0.94^{+0.32}_{-0.27}$

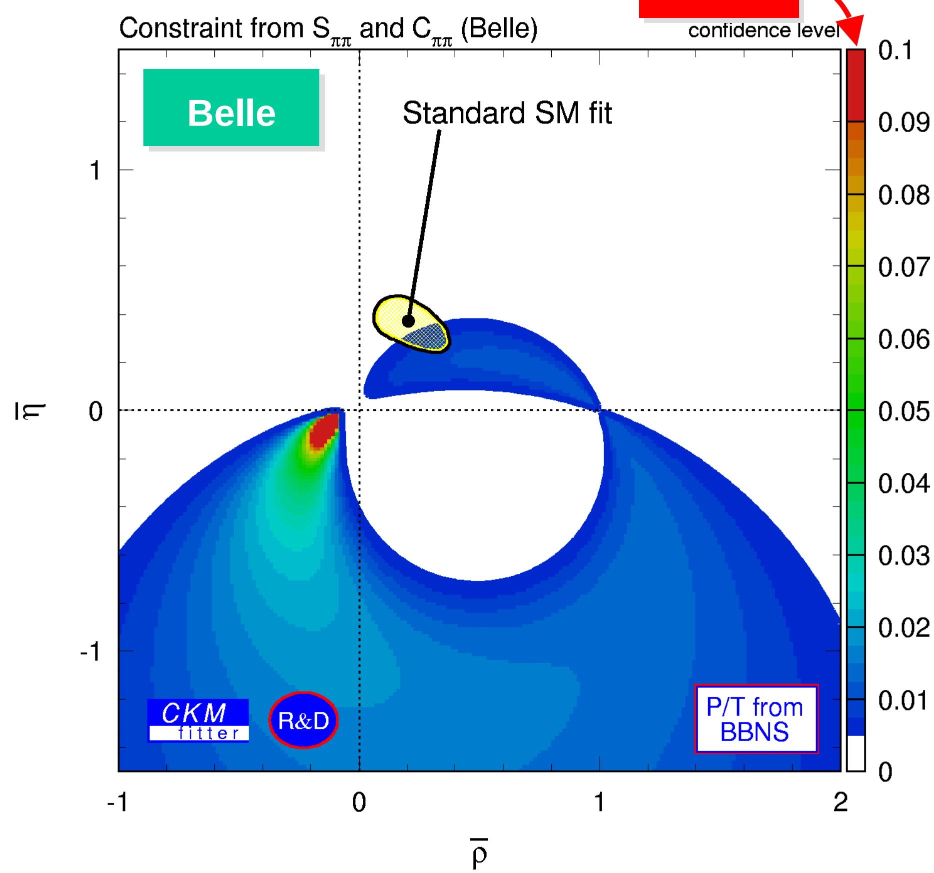
no update since Moriond'02

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

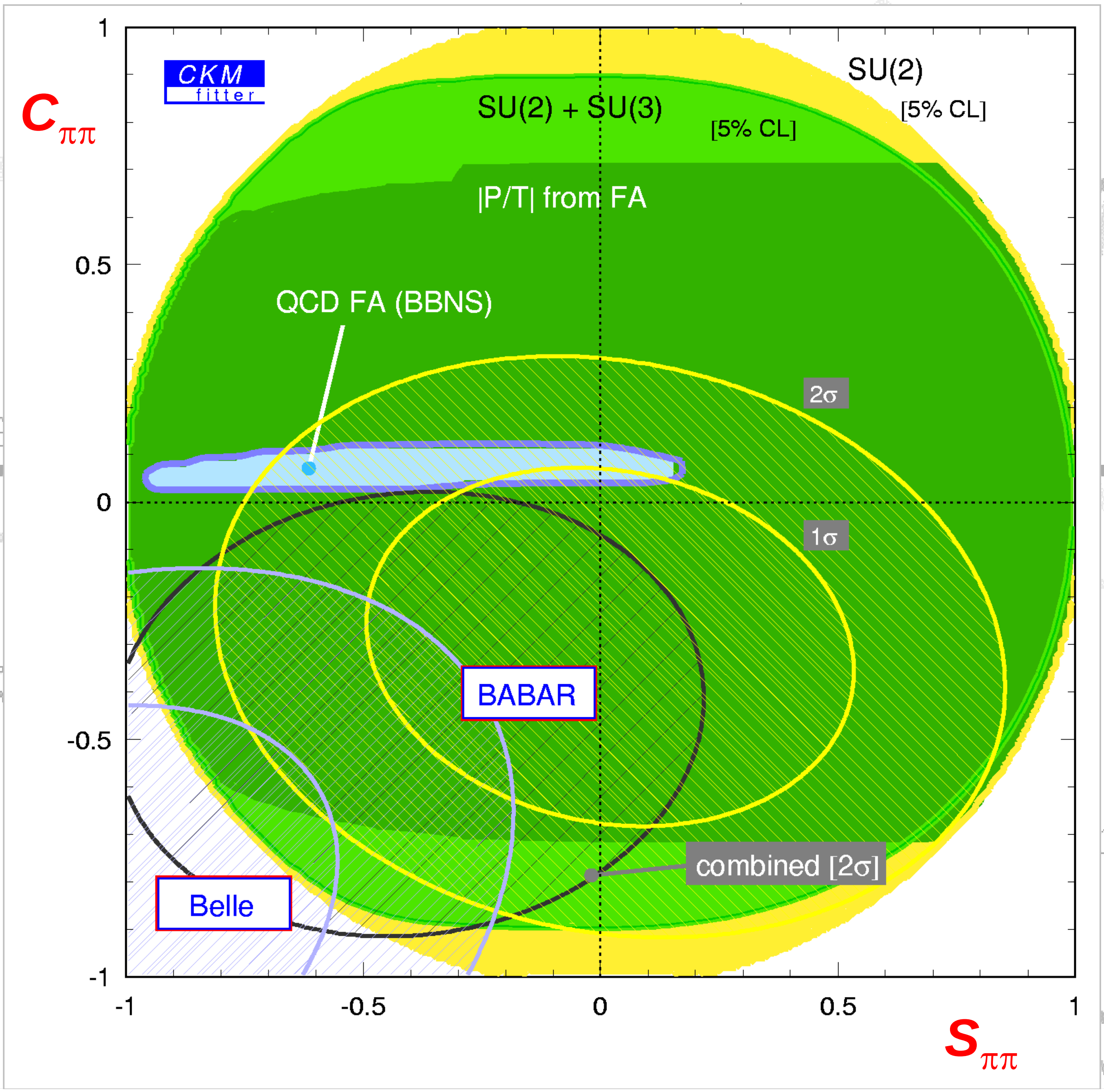


Input: $S_{\pi\pi}$ & $C_{\pi\pi}$

Zoom



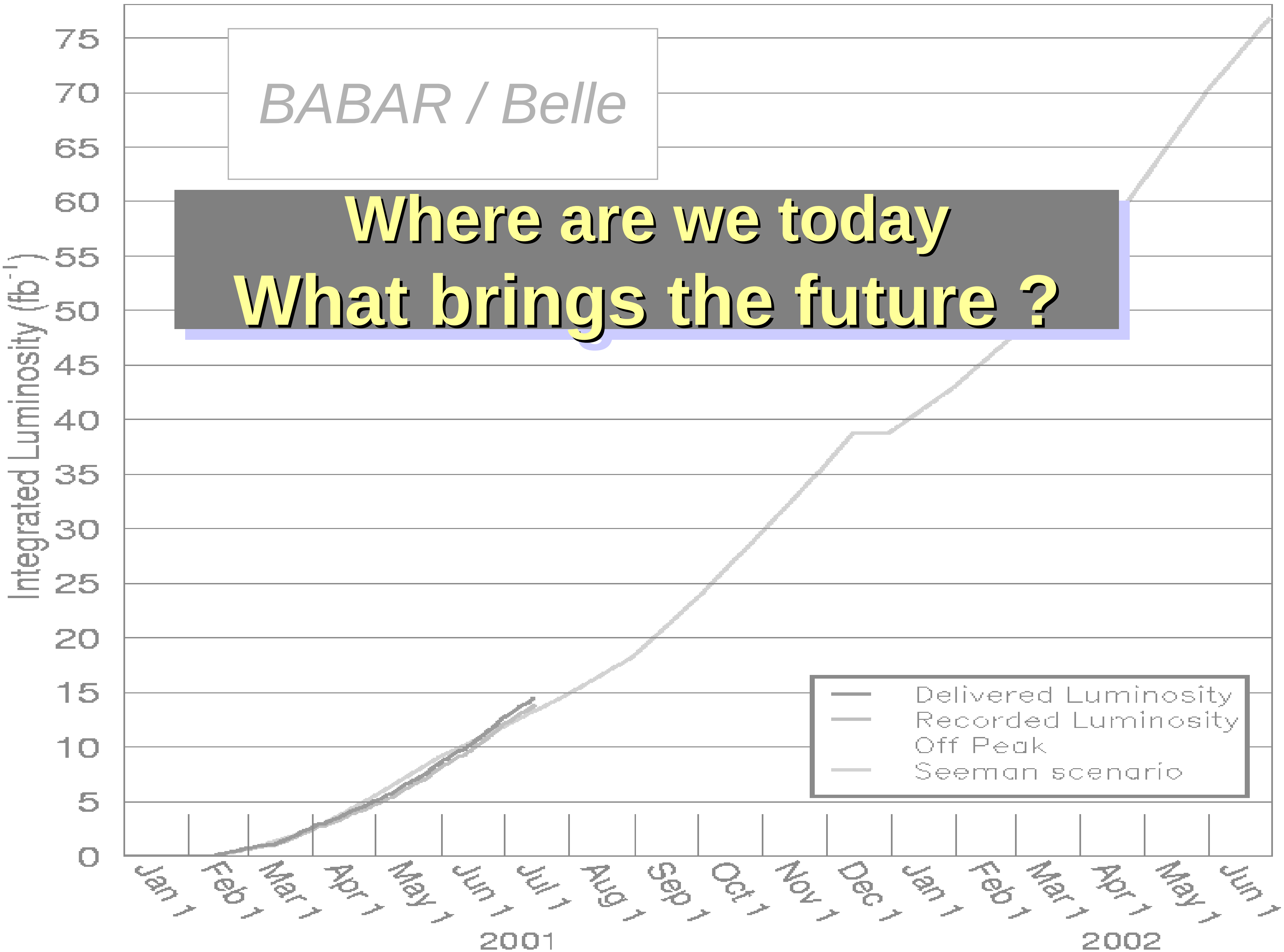
Predicting the Experimental Observables



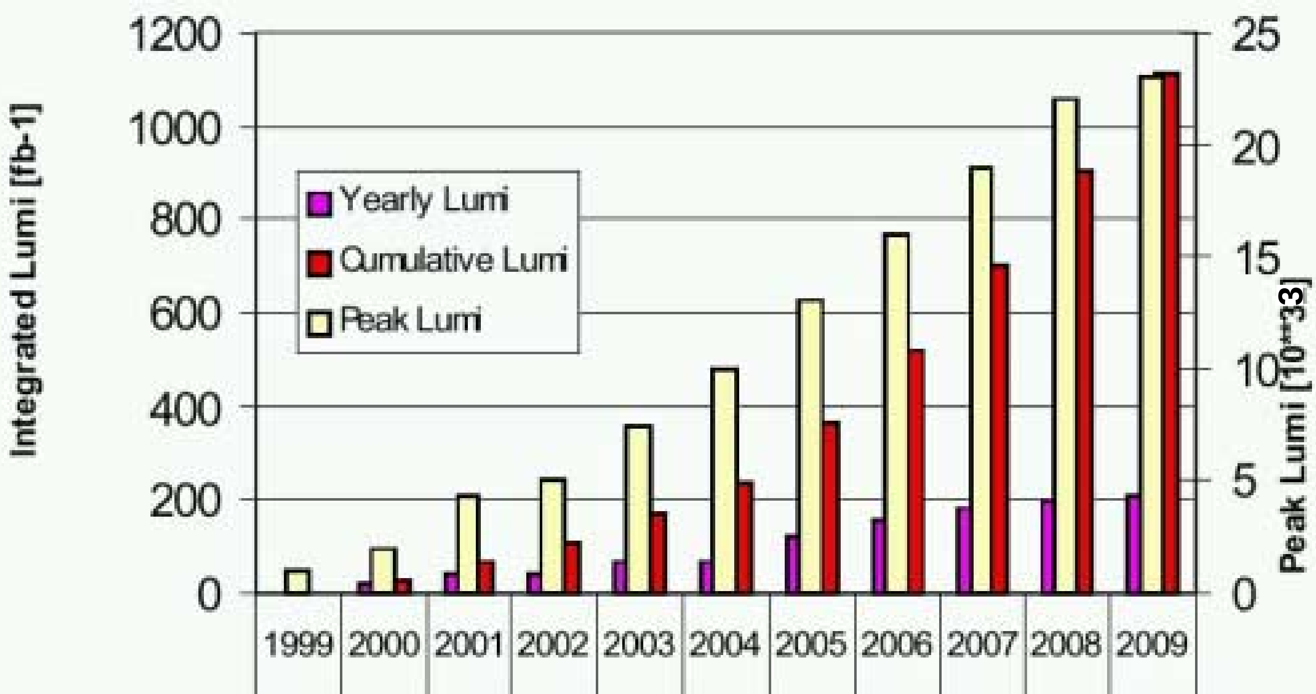
Using ρ, η from standard CKM fit

Only predictive approach: QCD FA...it works...yet !

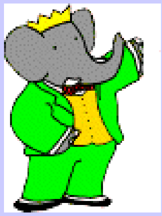
Where are we today
What brings the future ?



PEP-II Luminosity Projections



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Yearly Lumi	3	23	41	39	64.6	68.2	124	156	185	199	212
Cumulative Lumi	3	26	67	106	171	239	363	519	704	903	1115
Peak Lumi	1	2	4.4	5	7.5	10	13	16	19	22	23



Similar scenario expected for Belle

Conclusions

- Global CKM fit (CKMfitter) gives consistent picture of Standard Model
- $\sin(2\beta)$ now most accurate constraint
  - ⇒ future consistencies: BABAR ⇔ Belle ?
    $J/\psi K_S \Leftrightarrow \phi K_S$

Summer '06: $\sigma(\sin 2\beta_{WA}) \sim 0.025$ for 1000 fb^{-1}

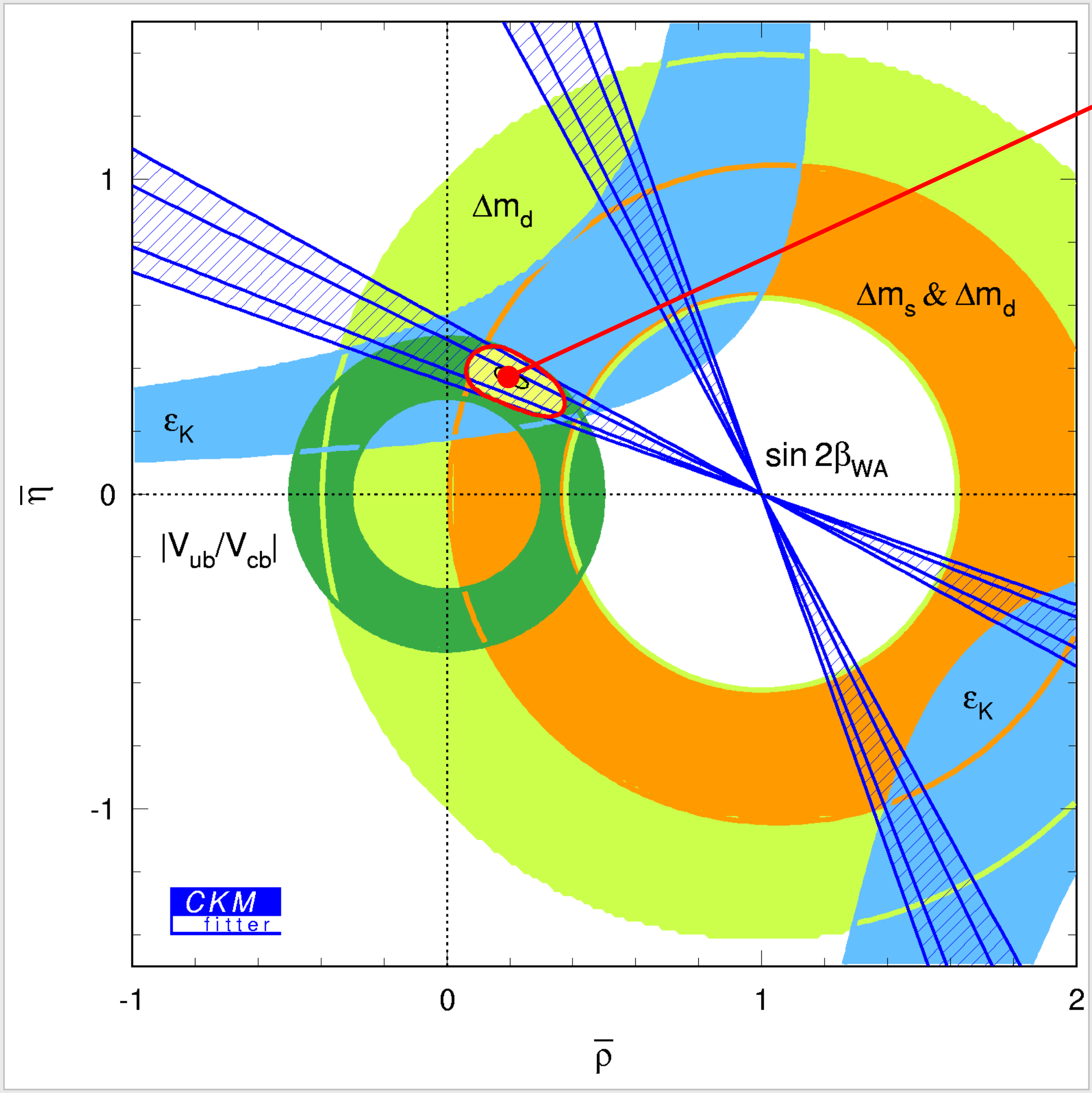
- Δm_s : constraint on UT angle γ from LEP/SLD/CDF limit
  expect measurement from TEVATRON soon: sensitive to new physics!
- Rare *K* decays enter the game, but more statistics needed
  also: *keep an eye on improving* $|V_{cb}|$!

Need more constraints on CKM phase:

- Charmless *B* decays and *CP* violation: best fits (in BBNS) around $\gamma \approx 80^{\circ}$
  - Conventional isospin analysis potentially unfruitful to extract $\sin(2\alpha)$
  - Significant theoretical input needed
  - Requires detailed study of relevant theoretical uncertainties
- The race for γ : high statistics needed for $B \to DK(\pi)$ – low theoretical input

Many more results to come from the *B*-factories

The Model Standard remains unscathed



We know the center already quite well… but there is not enough redundancy

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

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