CKM Matrix and CP Violation in Standard Model

Measurement of sin2β. Constraints on CKM

Lecture 17

DIPARTIMENTO DI FISICA

SAPIENZA
UNIVERSITÀ DI ROMA

Shahram Rahatlou

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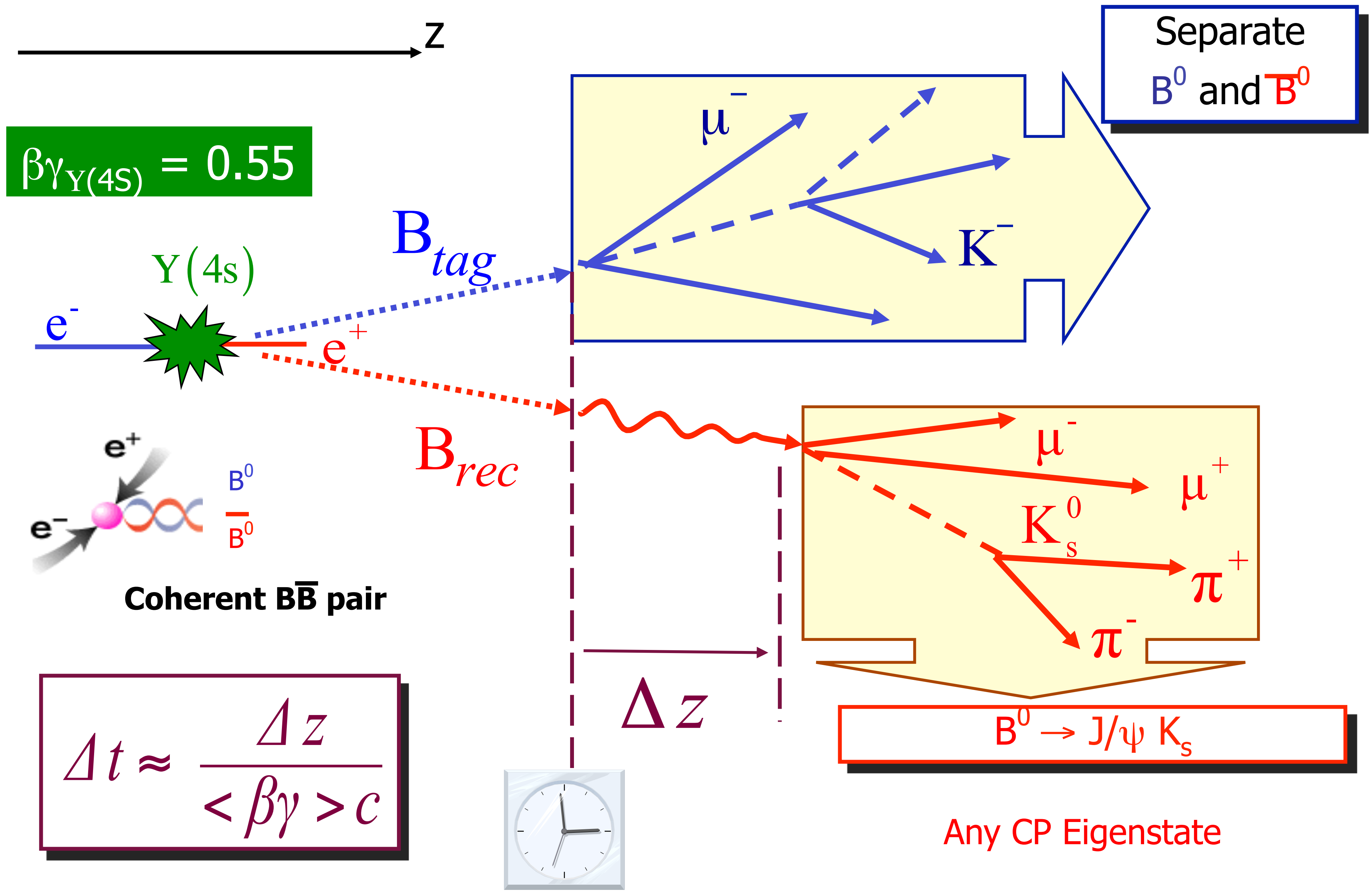
http://www.roma1.infn.it/people/rahatlou/particelle/

CP Violation in Interference between Mixing and Decay



Time-Evolution of B Decays to CP Eigenstates

- Probability of $|B^0\rangle|B^0\rangle \rightarrow |f_{CP}\rangle|f_{tag}\rangle$ depends on
  - Difference Δt between decay time of the two B mesons
  - Decay amplitudes
    $$A_{f_{CP}} = \langle f_{CP} \,|\, H \,|\, B^0, t\rangle$$
    $$\bar{A}_{f_{CP}} = \langle f_{CP} \,|\, H \,|\, \bar{B}^0, t\rangle$$
  - Oscillation parameter
    $$\frac{q}{p} = -\frac{|M_{12}|}{M_{12}} = e^{-i2\beta}$$
  - Flavor of tagging neutral B meson: B^0 or B0
- Convenient parameter to describe time evolution
  - Takes into account combined effect of oscillation and decay
    $$\lambda = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} = \eta_{f_{CP}} \frac{q}{p}\frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$

Time-Dependent Decay Rates to CP Eigenstates

$$
\begin{aligned}
f_{B_{\rm tag}=B^0}(t_{\rm tag}, t_{f_{CP}}) \;\propto\; & e^{-\Gamma(t_{f_{CP}}-t_{\rm tag})}\Big\{1+\frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2}\cos[\Delta m_d(t_{f_{CP}}-t_{\rm tag})] \\
& - \frac{2\mathcal{I}m\lambda_{f_{CP}}}{1+|\lambda_{f_{CP}}|^2}\sin[\Delta m_d(t_{f_{CP}}-t_{\rm tag})]\Big\}
\end{aligned}
$$

$$
\begin{aligned}
f_{B_{\rm tag}=\overline{B}^0}(t_{\rm tag}, t_{f_{CP}}) \;\propto\; & e^{-\Gamma(t_{f_{CP}}-t_{\rm tag})}\Big\{1-\frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2}\cos[\Delta m_d(t_{f_{CP}}-t_{\rm tag})] \\
& + \frac{2\mathcal{I}m\lambda_{f_{CP}}}{1+|\lambda_{f_{CP}}|^2}\sin[\Delta m_d(t_{f_{CP}}-t_{\rm tag})]\Big\}
\end{aligned}
$$

$$
\lambda = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = \eta_{f_{CP}}\frac{q}{p}\frac{\overline{A}_{\overline{f}_{CP}}}{A_{f_{CP}}}
$$

- Expression and complexity of λ depends on specific final states
  - Decay amplitudes A and A can be more or less complicated depending on number of amplitudes contributing to total amplitude

Time-Dependent CP Asymmetry in Interference

$$a_{f_{CP}}(\Delta t) = \frac{f_{B_{\rm tag}=B^0} - f_{B_{\rm tag}=\overline{B}^0}}{f_{B_{\rm tag}=B^0} + f_{B_{\rm tag}=\overline{B}^0}} = \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2}\cos\Delta m_d \Delta t$$

$$-\frac{2\mathcal{I}m\lambda_{f_{CP}}}{1+|\lambda_{f_{CP}}|^2}\sin\Delta m_d \Delta t$$

- CP Violation occurs if $|\lambda| = \left|\frac{q}{p}\right|\left|\frac{\overline{A}}{A}\right| \neq 1$

$\left|\frac{q}{p}\right| = 1$ No CP Violation in Mixing

$\left|\frac{\overline{A}}{A}\right| = 1$ No Direct CP Violation

- But even with $|\lambda|=1$ it is sufficient to have $\mathrm{Im}\lambda \neq 0$

In Standard Model we expect $|\lambda| \cong 1$ in most of B decays

Simple Case with $|\lambda_{CP}|=1$

$$\Phi_M = \beta$$

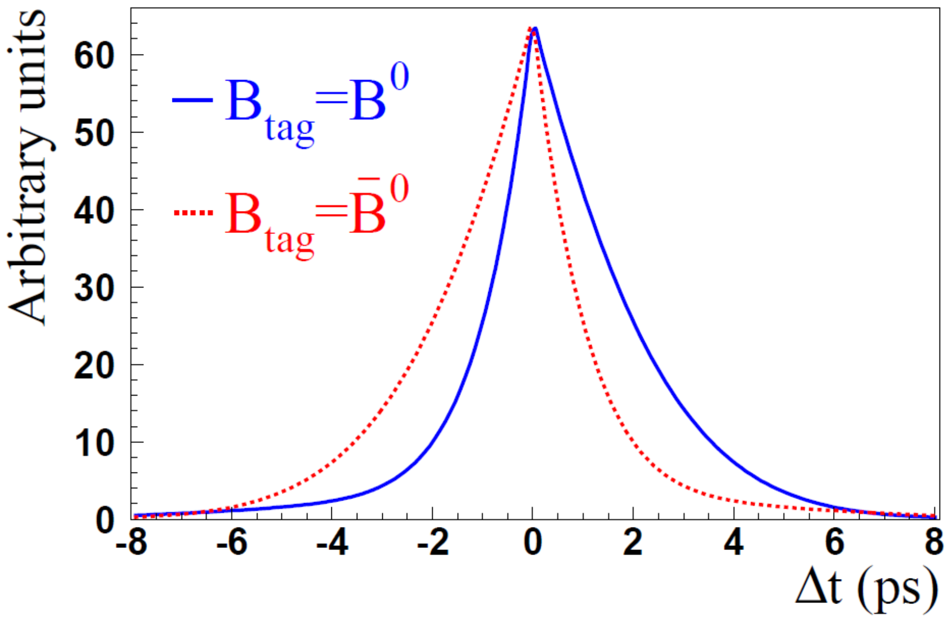
$$\begin{aligned} A_f &= A e^{i(\Phi_W+\delta)} \\ \bar{A}_f &= \eta_{f_{CP}} A e^{i(-\Phi_W+\delta)} \end{aligned}$$

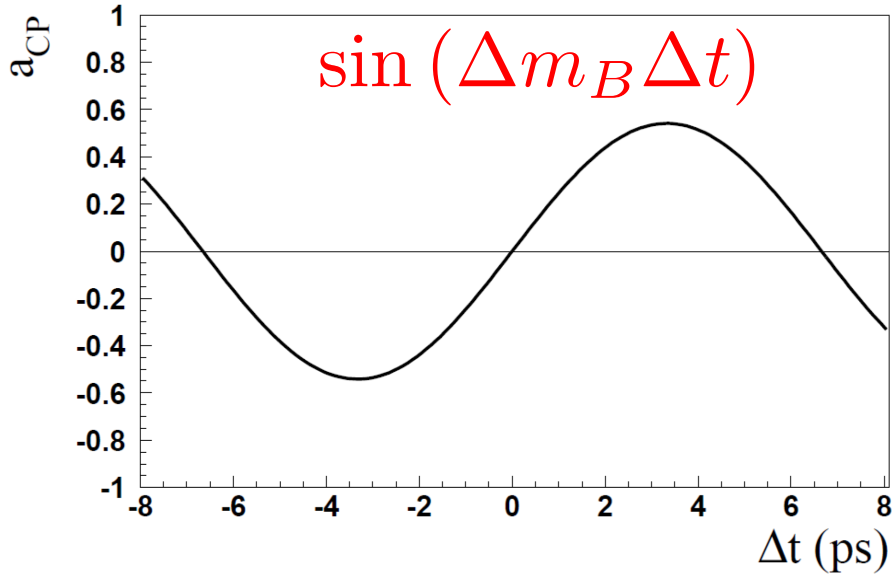
$$\lambda_{f_{CP}} = \eta_{f_{CP}} e^{-2i(\Phi_W-\Phi_M)}$$

$$a_{f_{CP}}(\Delta t) = -\mathcal{I}m\lambda_{f_{CP}} \sin \Delta m_d \Delta t = \eta_{f_{CP}} \sin 2\Phi \sin \Delta m_d \Delta t$$

- Very simple expression for CP violating asymmetry
- Amplitude of asymmetry defined by phase difference between mixing parameter q/p and ratio of decay amplitudes
- Complex phase Φ_M depends on specific final state
  - Can probe different angles of Unitarity triangle through different B decays

Why do We Need Time Dependence?



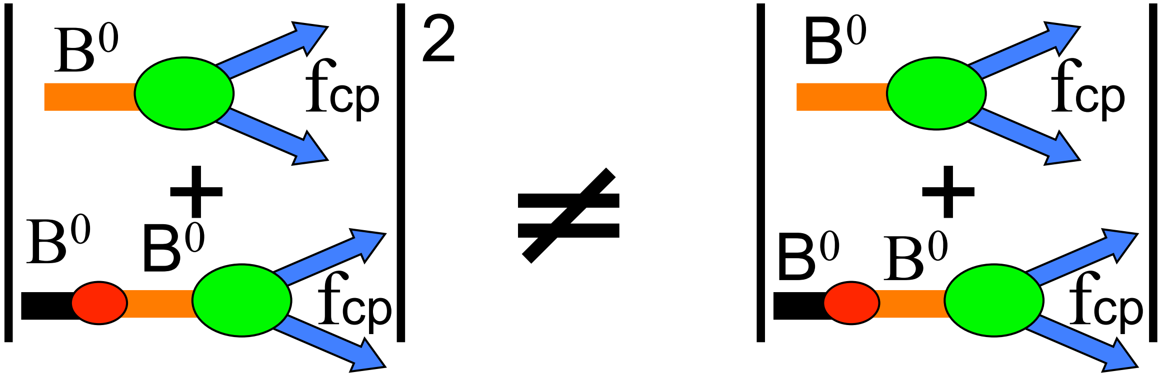


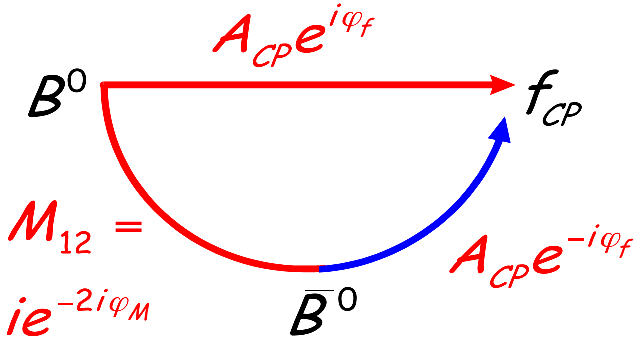
$$\int_{-\infty} a_{f_{CP}} \, d\Delta t = 0$$

At $\Upsilon(4S)$: integrated asymmetry is zero
→ must do a time-dependent analysis !

This is impossible to do in a conventional symmetric energy collider producing $\Upsilon(4S) \rightarrow BB$!!

CPV In Interference Between Mixing and Decay





Neutral B Decays into CP final state f_{CP} accesible by both B^0 & $\bar{B}^0$decays

This is CPV when $\left|\frac{q}{p}\right| = 1$ and $\left|\frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}\right| = 1$ and the CP parameter of interest is $\lambda_{f_{CP}} \equiv \eta_{f_{CP}} \frac{q}{p} \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$

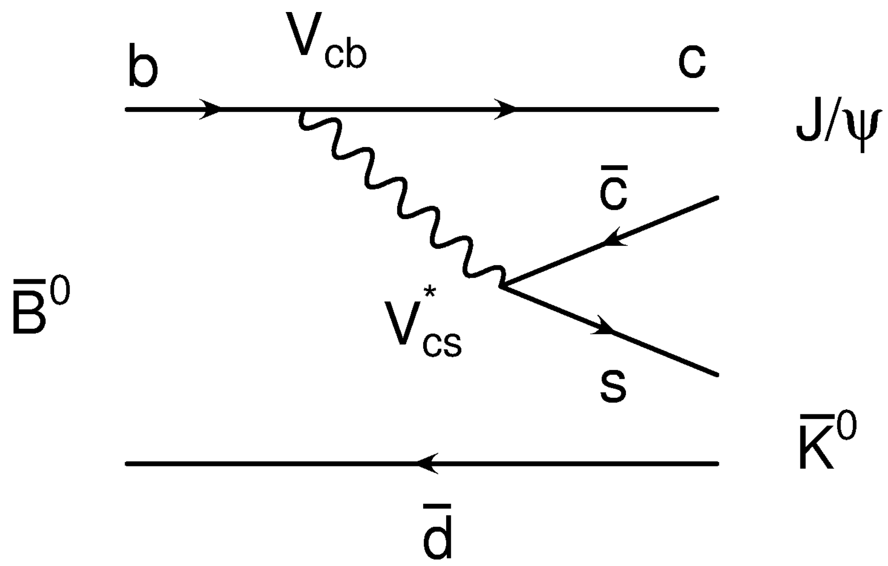
CPV Asymmetry is defined as :

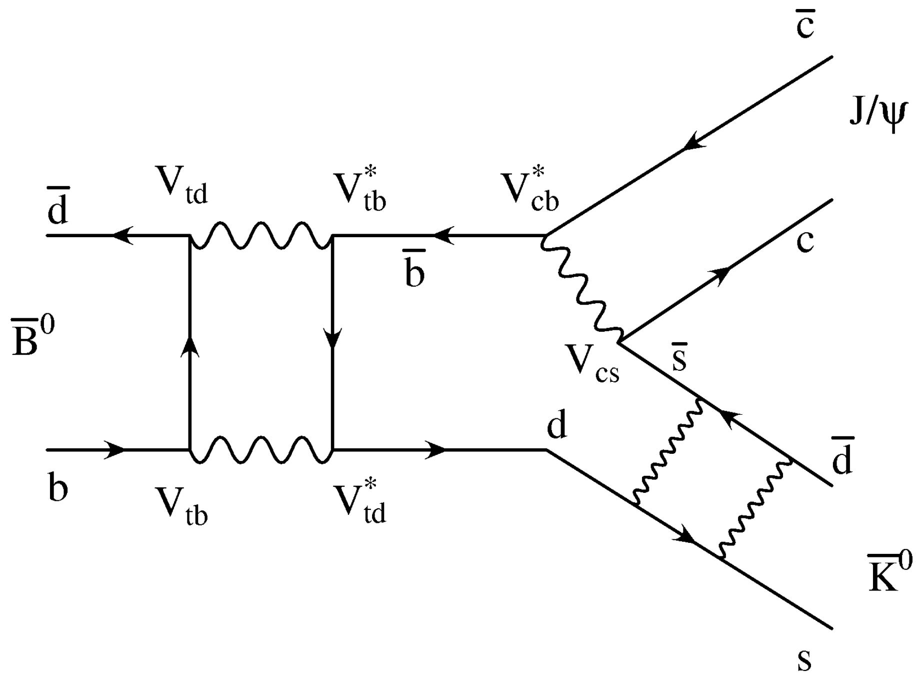
$$a_{f_{CP}} = \frac{\Gamma\left(\bar{B}^0_{phys}(t) \to f_{CP}\right) - \Gamma\left(B^0_{phys}(t) \to f_{CP}\right)}{\Gamma\left(\bar{B}^0_{phys}(t) \to f_{CP}\right) + \Gamma\left(B^0_{phys}(t) \to f_{CP}\right)} = \frac{2Im\lambda_{f_{CP}}}{1+\left|\lambda_{f_{CP}}\right|^2}\sin\left(\Delta m_B t\right) - \frac{\left(1-\left|\lambda_{f_{CP}}\right|^2\right)}{1+\left|\lambda_{f_{CP}}\right|^2}\cos\left(\Delta m_B t\right)$$

When B decay is dominated by a single diagram, $\left|\lambda_{f_{CP}}\right| = 1 \Rightarrow a_{f_{CP}} = Im\lambda_{f_{CP}} \sin\left(\Delta m_B t\right)$

CP asymm. can be very large and can be cleanly related to CKM angles

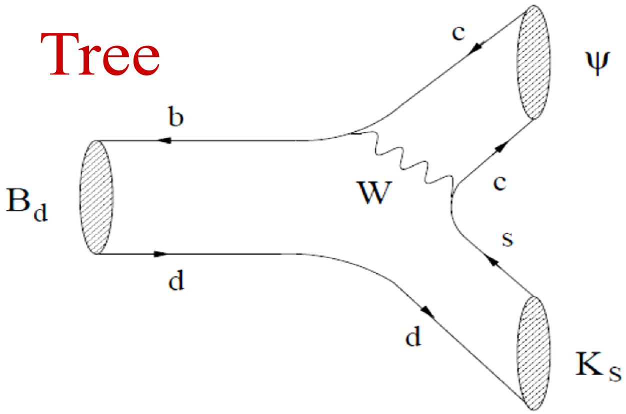
Golden Decay Mode $B^0 \rightarrow J/\psi K^0$



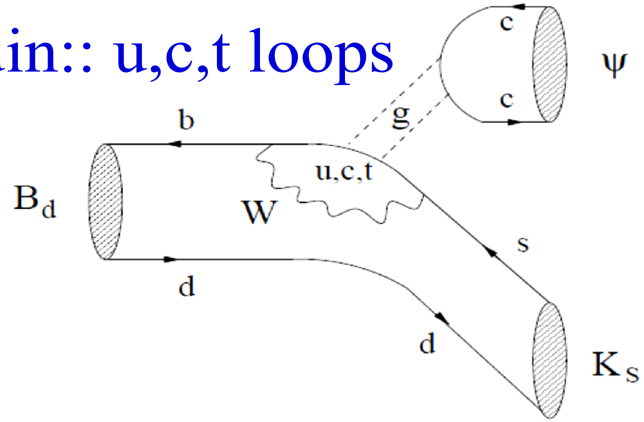


Golden Decay Mode J/ψ K^0

Tree



Penguin:: u,c,t loops



$$\bar{A}_T = V_{cb} V_{cs}^* T_{c\bar{c}s}$$

$$\bar{A}_P = V_{tb} V_{ts}^* P_t + V_{cb} V_{cs}^* P_c + V_{ub} V_{us}^* P_u$$

Use Unitarity relation $V_{tb}V_{ts}^* + V_{cb}V_{cs}^* + V_{ub}V_{us}^*$ to rearrange terms

$$\bar{A} = \bar{A}_T + \bar{A}_P = V_{cb}V_{cs}^*(T_{c\bar{c}s} + P_c - P_t) + V_{ub}V_{us}^*(P_u - P_t)$$

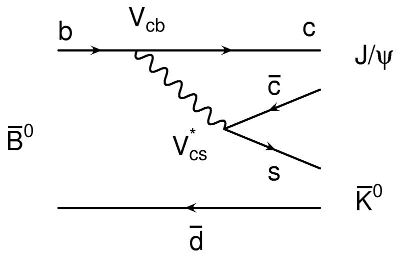
$$= (V_{cb}V_{cs}^*)\,T + \cancel{(V_{ub}V_{us}^*)}\,P$$

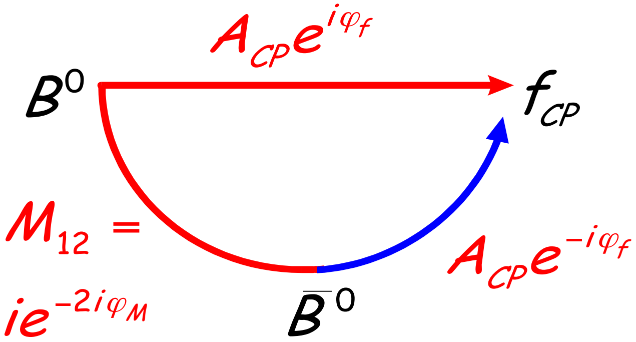
$$\text{Since } \left|\frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*}\right| ; \frac{1}{50} \Rightarrow (V_{cb}V_{cs}^*)\,T \text{ is the dominant amplitude}$$

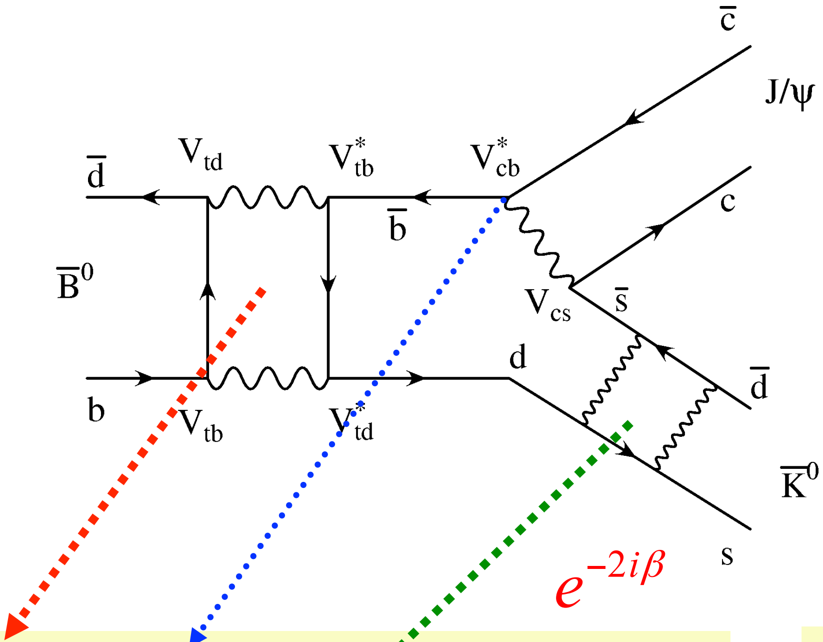
$$\text{expect} \left|\frac{\bar{A}}{A}\right| -1 = 10^{-2}$$

Hence "Platinum" mode !

CPV In Interference Between Mixing and Decay: $B^0 \to J/\psi K^0$







$$\lambda_{\psi K_S} = \frac{q_B}{p_B}\frac{\bar{A}_{\psi K_S}}{A_{\psi K_S}} = -\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\,\frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}\,\frac{V_{cs}V^*_{cd}}{V^*_{cs}V_{cd}} = -\frac{V^*_{tb}V_{td}\,V_{cb}V^*_{cd}}{V_{tb}V^*_{td}\,V^*_{cb}V_{cd}}$$

$$\Rightarrow \mathrm{Im}(\lambda_{\psi K_S}) = \sin(2\beta)$$

$$\Rightarrow \left|\lambda_{\psi K_S}\right| = 1$$

$$\lambda_{\psi K_L} = -\lambda_{\psi K_S}$$

$$\Gamma\left(B^0 \to J/\psi K_{S,L}\right) \propto e^{-t/\tau}\left[1 - \eta_{CP}\sin 2\beta \sin(\Delta m t)\right]$$

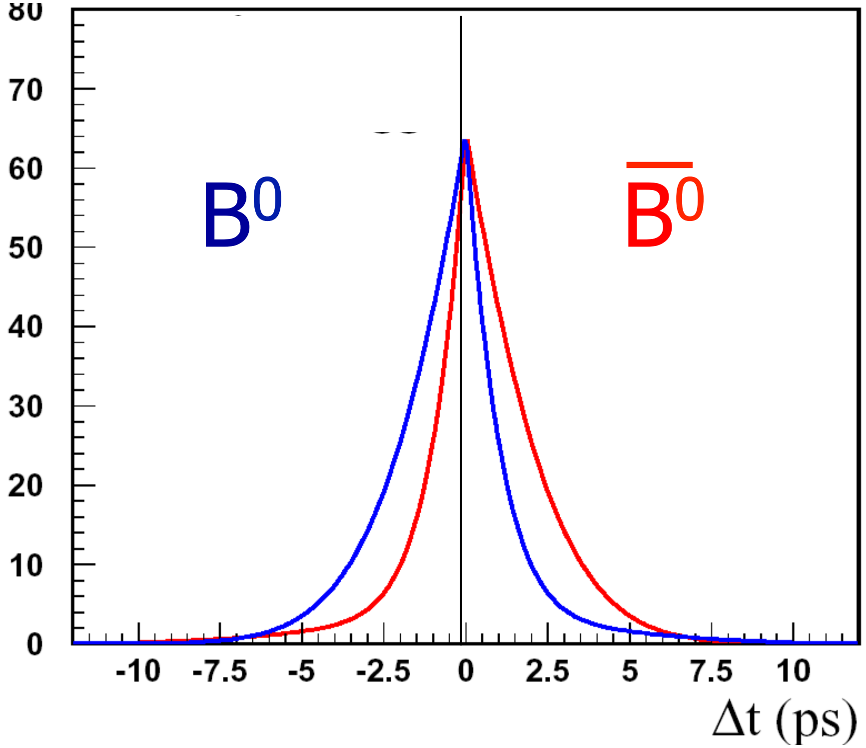
$$\Gamma\left(\bar{B}^0 \to J/\psi K_{S,L}\right) \propto e^{-t/\tau}\left[1 + \eta_{CP}\sin 2\beta \sin(\Delta m t)\right]$$

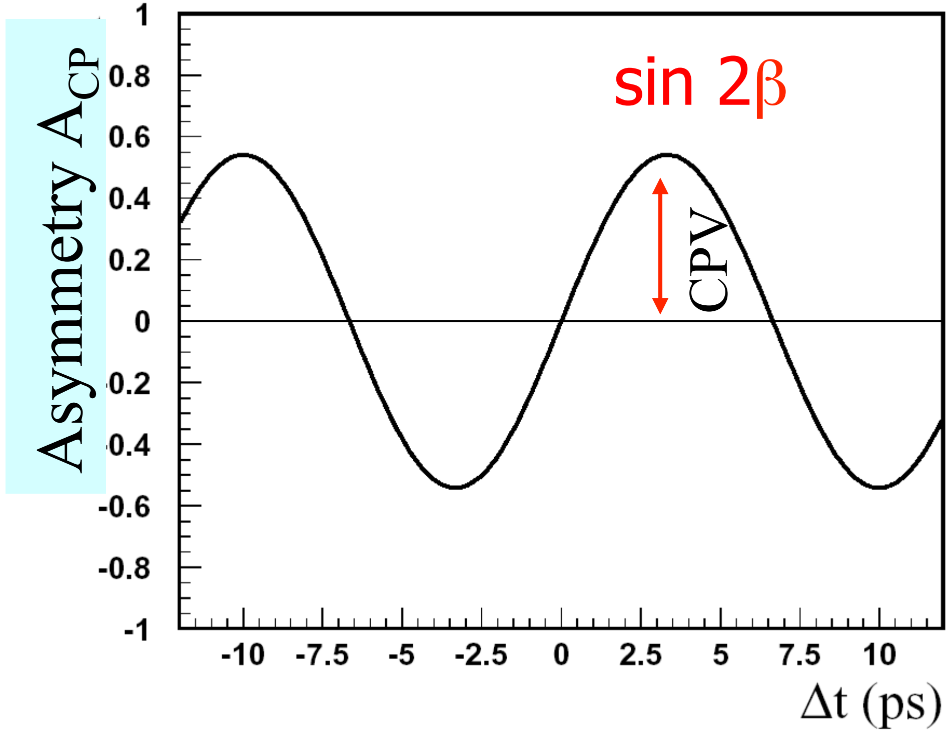
η_{CP} = -1 (+1) for J/ψ $K^0_{S(L)}$

Same is true for a variety of B →(cc) s final states

Time-Dependent CP Asymmetry with a Perfect Detector

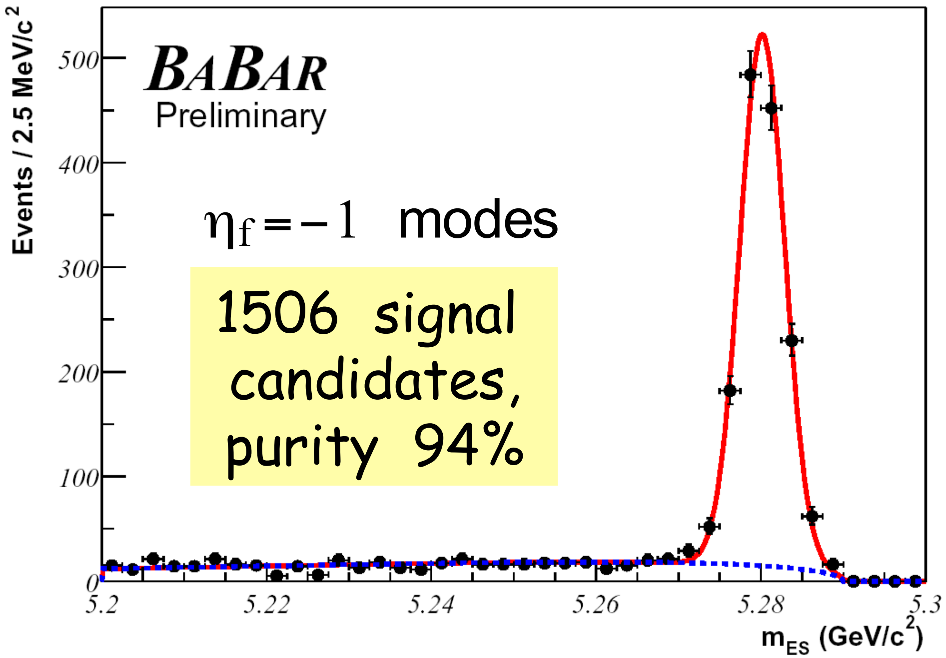
- Perfect measurement of time interval t=Δt
- Perfect tagging of B^0 and $\bar{B}^0$ meson flavors
- For a B decay mode such as $B^0 \rightarrow \psi K_s$ with $|\lambda_f|=1$





$$A_{CP}(\Delta t) = \sin 2\beta \sin(\Delta m \Delta t)$$

Charmonium+K^0 CP Sample for BABAR ('02)



$\eta_f = -1$ modes

$B^0_{CP} \to J/\psi K^0_S\{\to \pi^+\pi^-\}$

$B^0_{CP} \to J/\psi K^0_S\{\to \pi^0\pi^0\}$

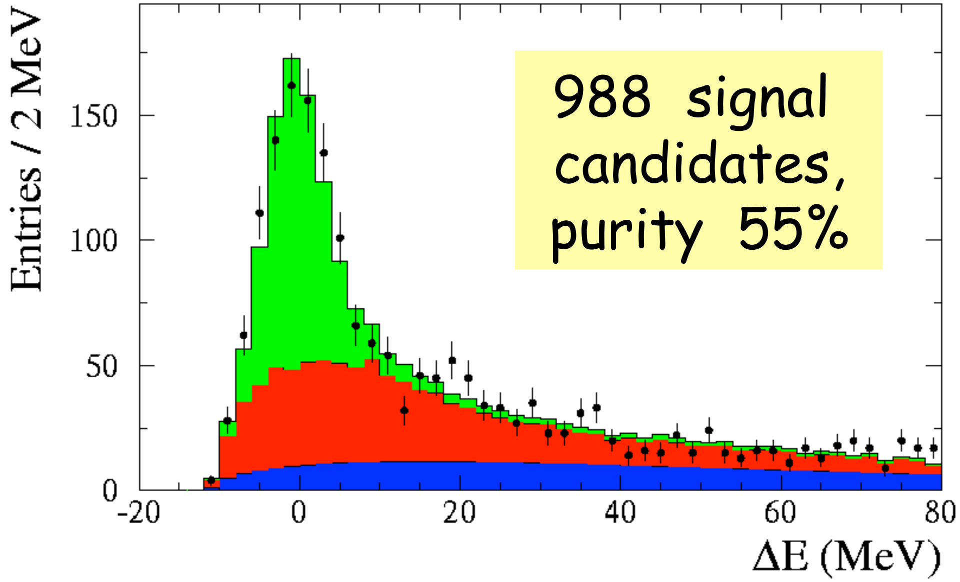
$B^0_{CP} \to \psi(2S)\{\to l^+l^-$ or $J/\psi\pi^+\pi^-\}K^0_S$

$B^0_{CP} \to \chi_{c1}\{\to J/\psi\gamma\}K^0_S$

$B^0_{CP} \to \eta_c\{\to KK\pi\}K^0_S$

$\eta_f = +1$ mode

$B^0_{CP} \to J/\psi K^0_L$



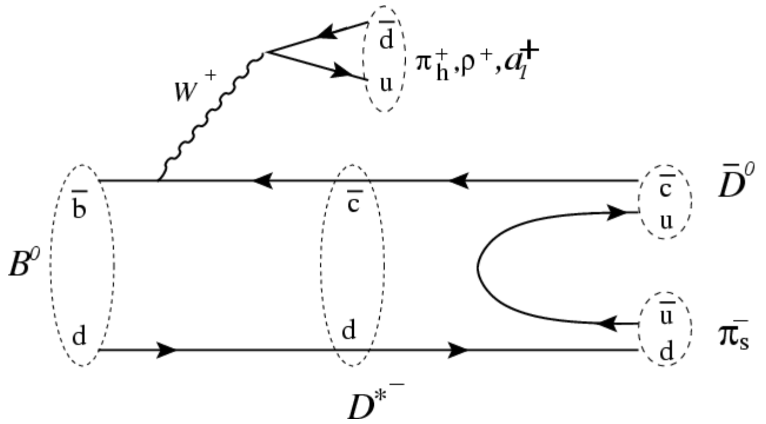
BABAR

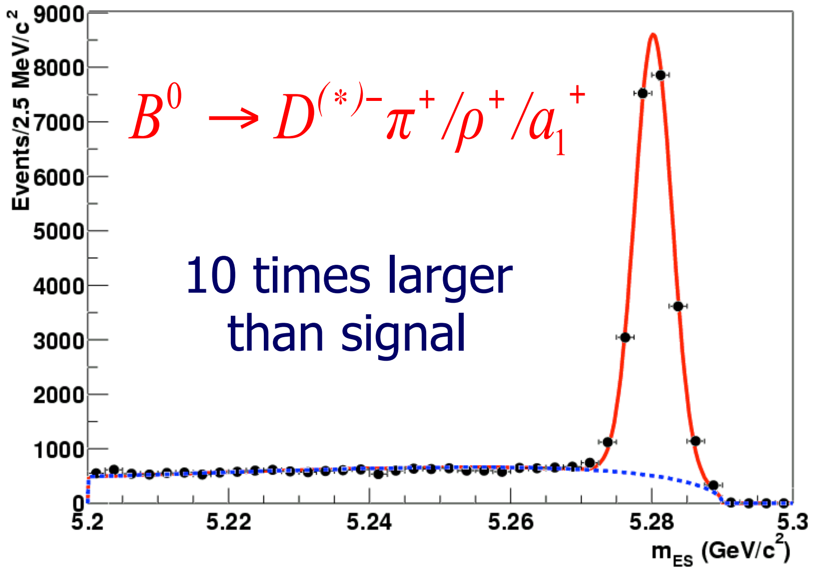
81.3 fb^{-1}

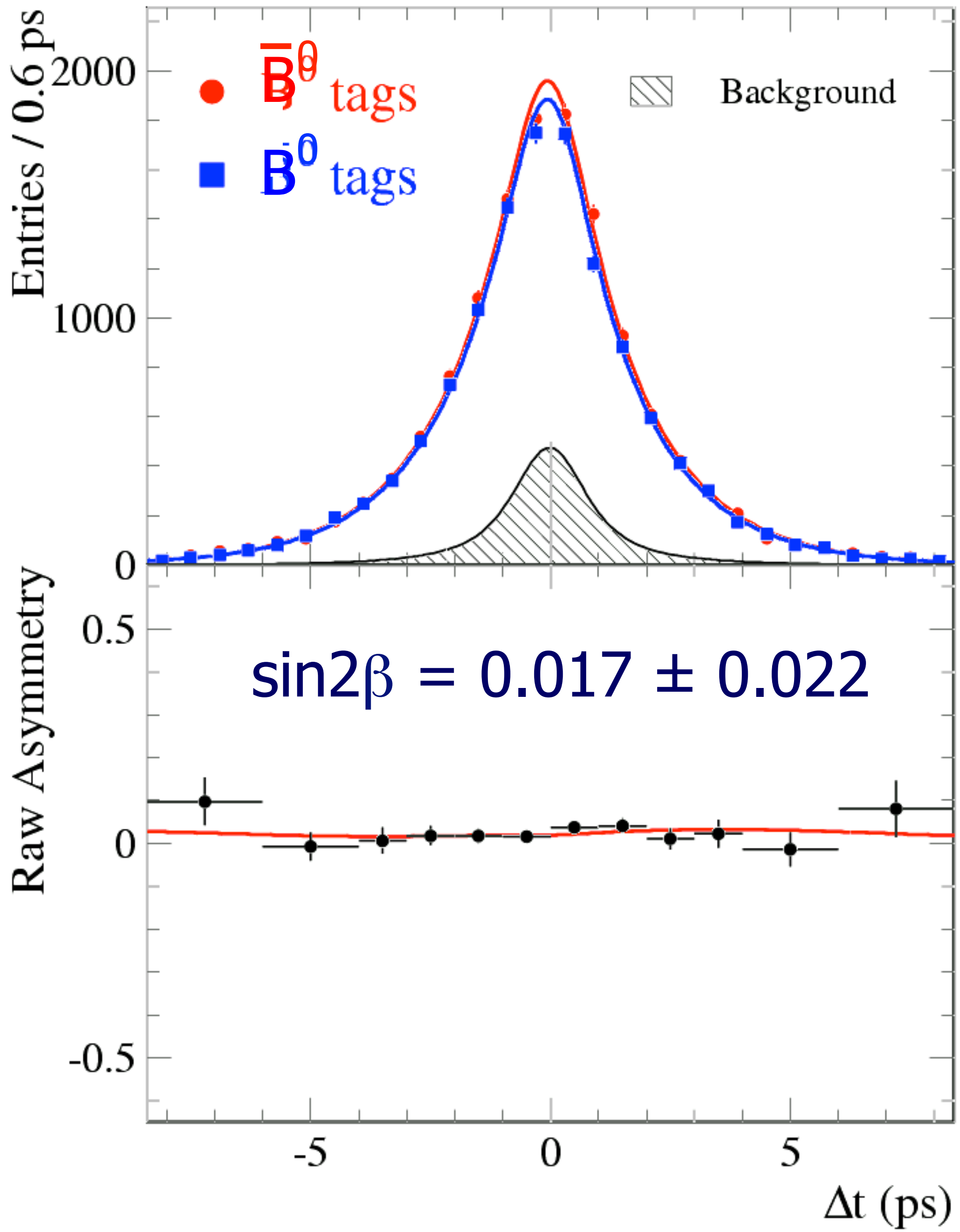
(after tagging & vertexing)

Calibration with Flavor eigenstates

Control Sample with no expected CP asymmetry



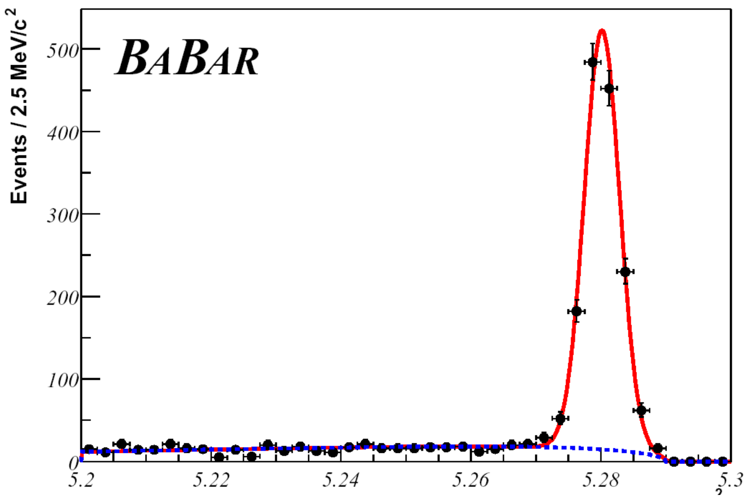


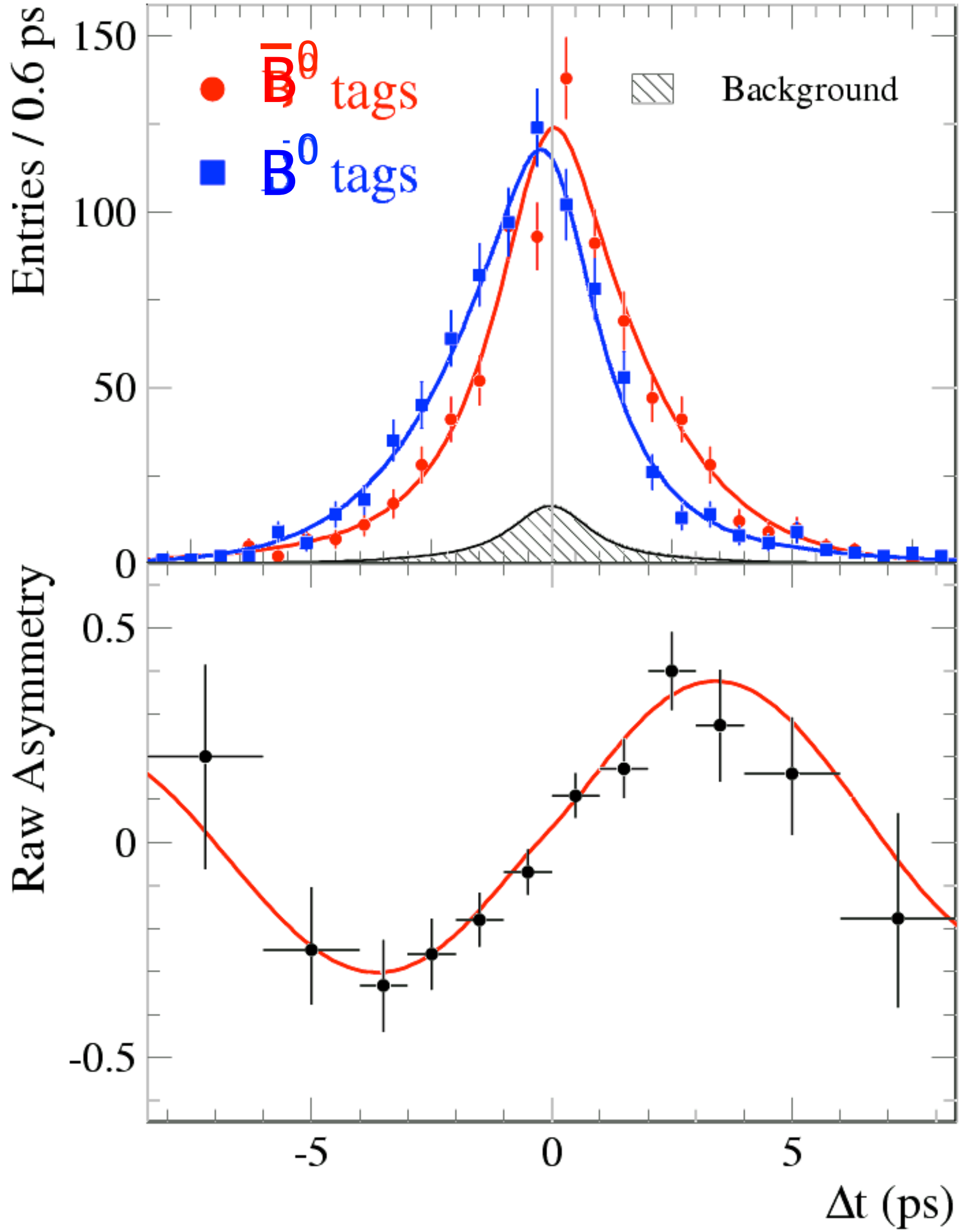


Observation of CP Violation (BaBar 2001)

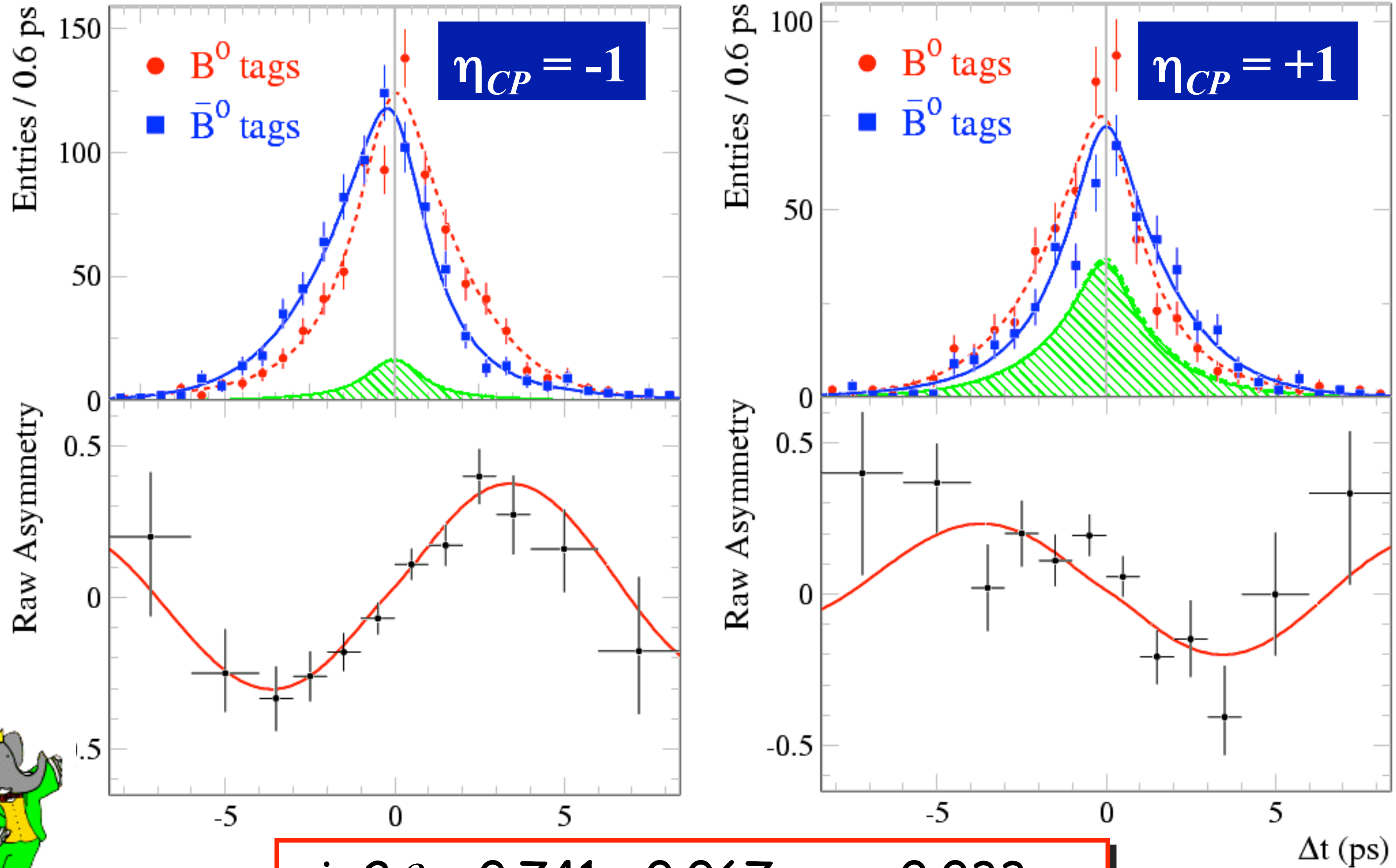
$\sin 2\beta = 0.755 \pm 0.074$

$B^0 \rightarrow J/\psi\ K_S$
$B^0 \rightarrow \psi(2S)\ K_S$
$B^0 \rightarrow \chi_c\ K_S$
$B^0 \rightarrow \eta_c\ K_S$



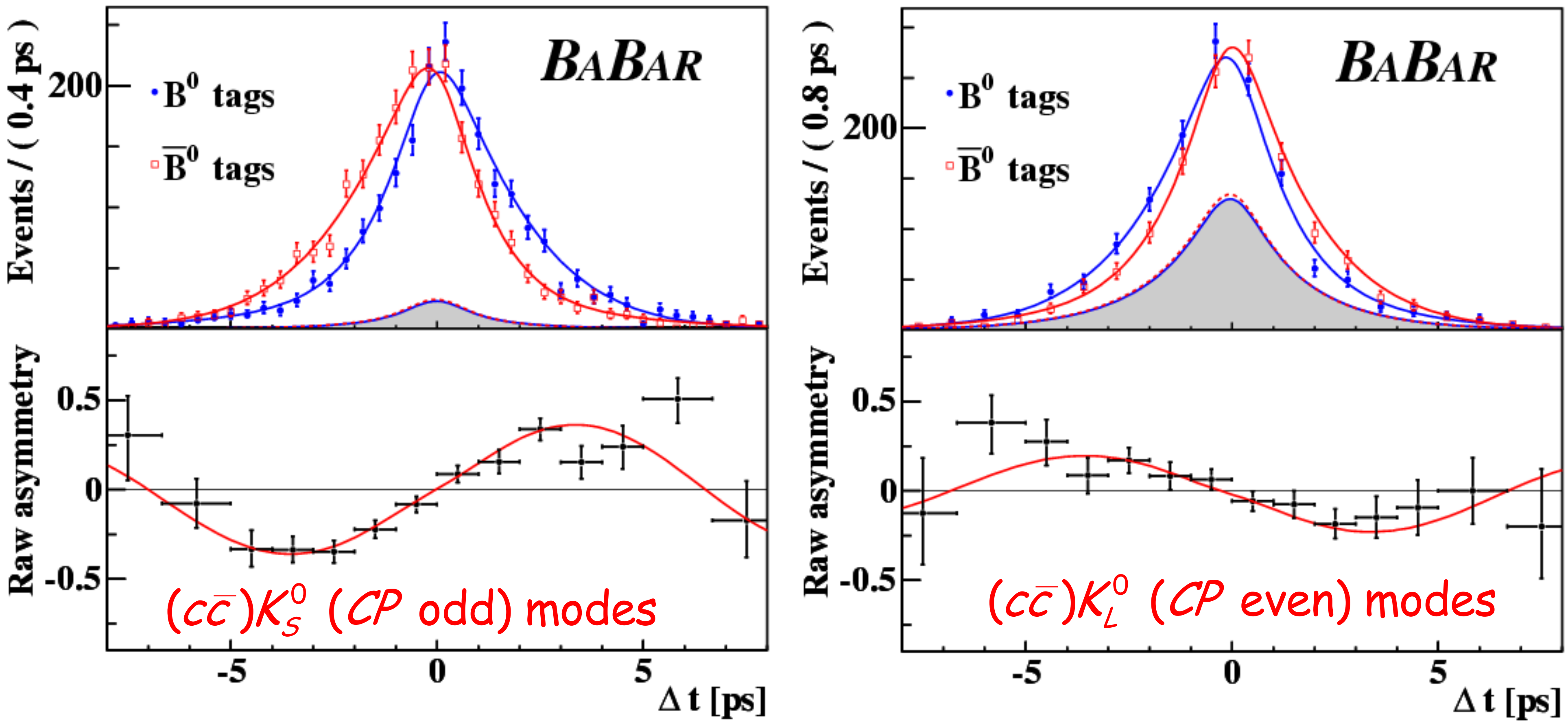


BABAR Result for sin2β (July 2002)



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

Updated (ICHEP04) sin2β results from Charmonium Modes



$205 fb^{-1}$ on peak or $227M$ $B\bar{B}$ pairs
7730 CP events (tagged signal)

$$\sin 2\beta = +0.722 \pm 0.040 \pm 0.023$$

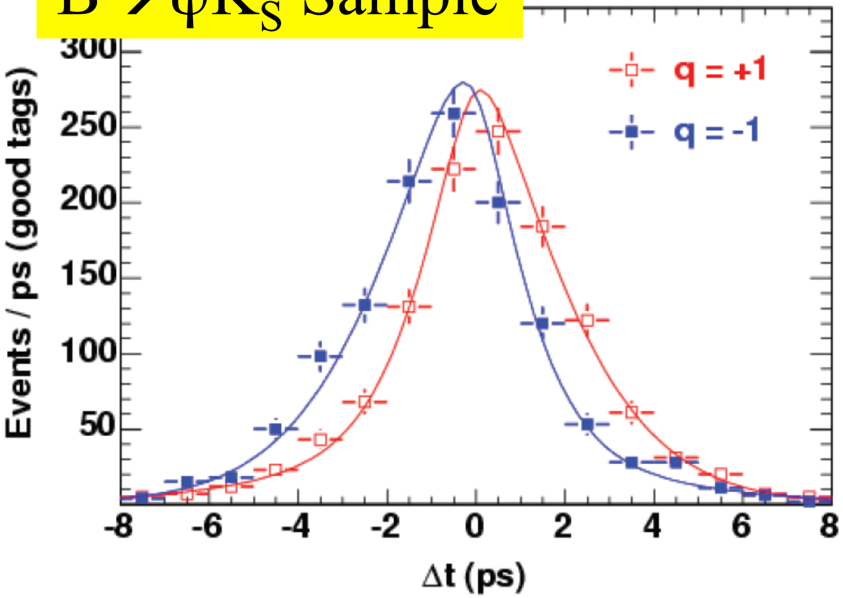
$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2} = 0.051 \pm 0.033 \pm 0.014$$

Limit on direct CPV

$c\bar{c}\ K_S$
+
$c\bar{c}\ K_L$

Belle Results on sin2β from Charmonium Modes

B→ψK_S Sample

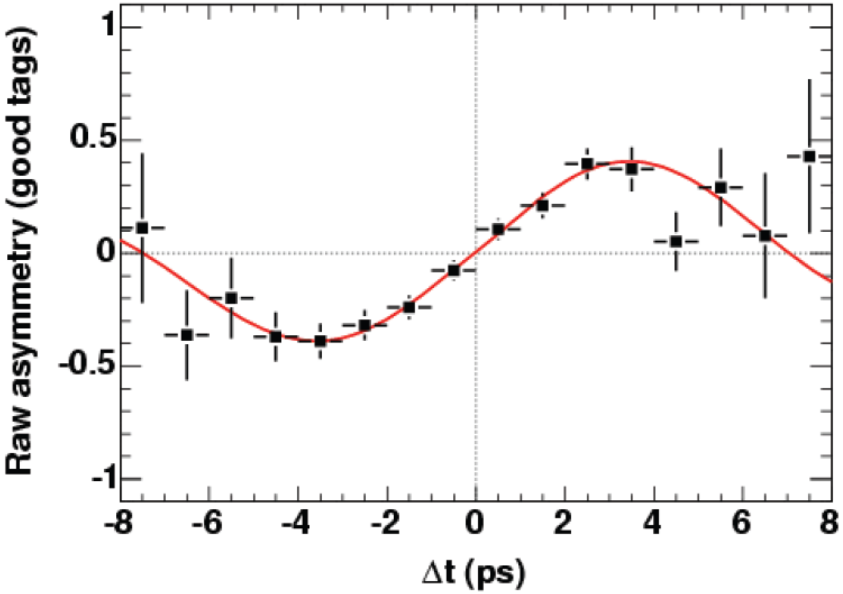


Belle 2005

386M $B\bar{B}$ pairs

$$\sin 2\beta = 0.652 \pm 0.039 \pm 0.020$$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2} = -0.010 \pm 0.026 \pm 0.036$$

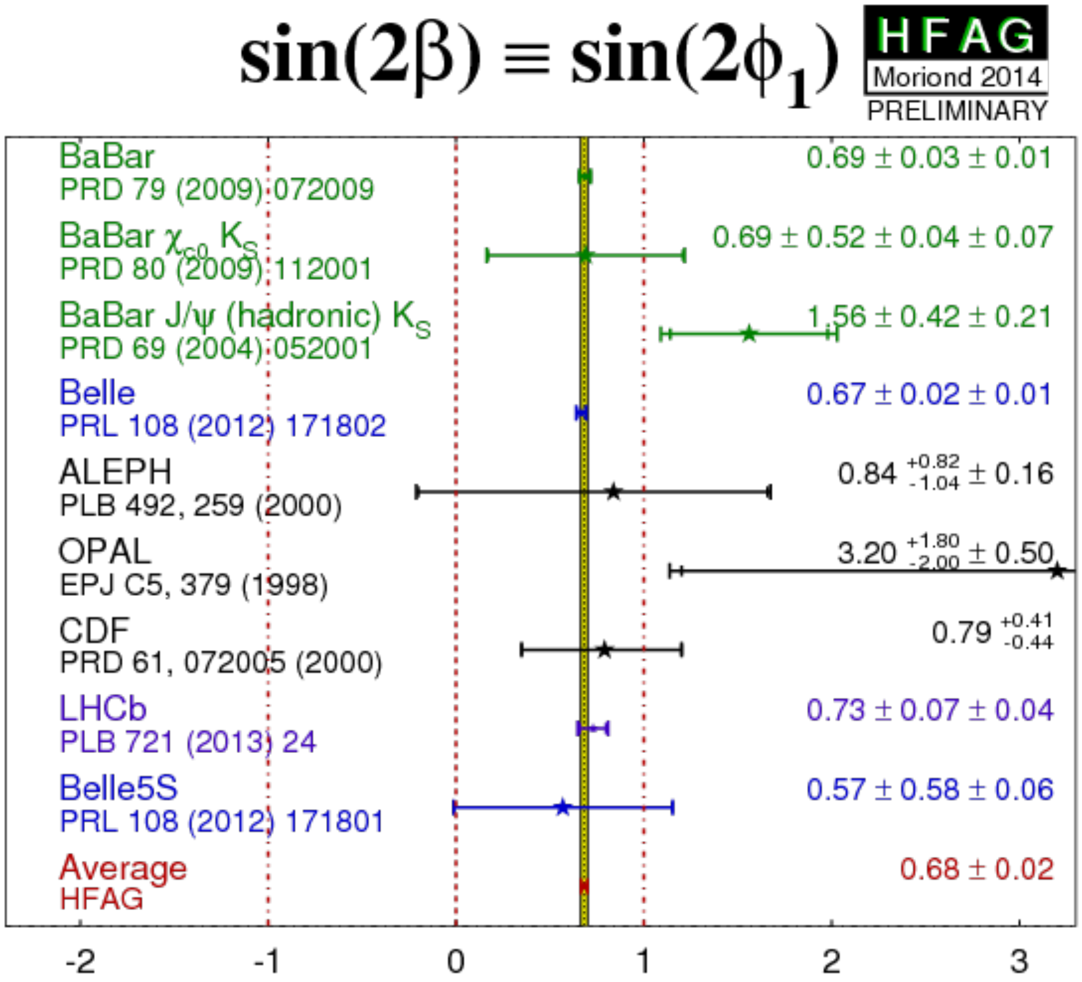


New Belle value lower than in '03

$$\sin 2\beta = +0.728 \pm 0.056 \pm 0.023$$

but still consistent with BaBar' 04

CP Violation in B Decays Firmly Established



Lessons From sin2β Measurement With $B^0 \to J/\psi K^0$

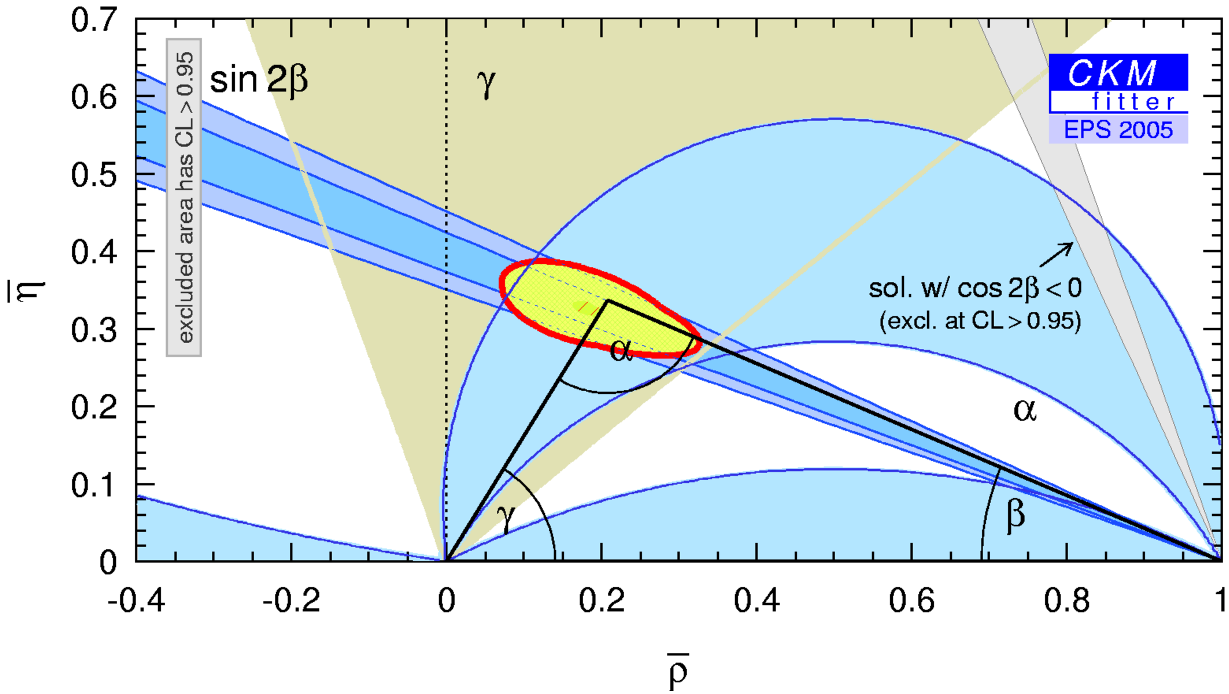
- In 2001, large CP Violation in B system was observed in this mode by BaBar and Belle.
  - First instance of CPV outside the Kaon system.

- First instance of a CPV effect which was **O(1)** in contrast with the Kaon system
  - Confirms the 1972 conjecture of Kobayashi & Maskawa.
  - Excludes models with approximate CP symmetry (small CPV).

- In 2007 sin2β became a precision measurement (5%) and agrees well with the constraints in the ρ-η plane from measurements of the CKM magnitudes (will be discussed in tomorrow's lecture)
- Appears unlikely to find another **O(1)** source of CPV
  - enterprise now moves towards looking for **corrections** rather than alternatives to SM/CKM picture

- Focus now shifts to measurements of time-dependent asymmetries in rare B decays
  - dominated by Penguin diagrams in the SM and where New Physics could contribute to the asymmetries

Constraints on Unitarity Triangle from Measurements of CKM Elements and CKM Angles



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

$$\mathbf{V}_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \quad \begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

Determination of CKM Elements from Measurements

Measurement → Constraints on theoretical parameters

x_{exp}

Theoretical predictions

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

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

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

Quarks confined in hadrons!

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

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

Often Assumed to be Gaussian

« A part of theory error might come from Guesstimates »

Frequentist → Uniform likelihoods: “allowed *ranges*”

Bayesian → a-priori PDF

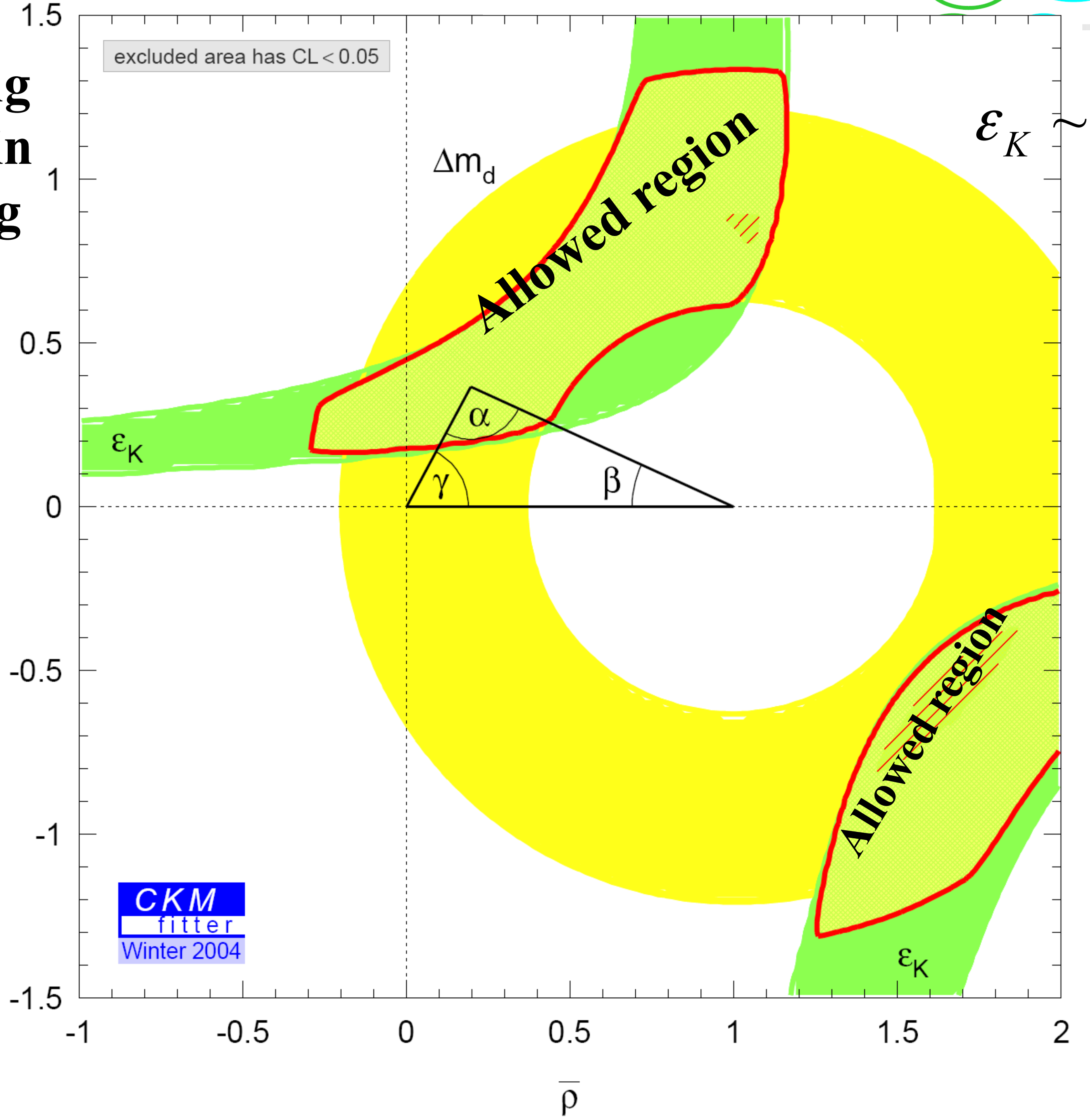
CKM Fitter
http://ckmfitter.in2p3.fr

UTfit
http://www.utfit.org

$$\Delta m_d \propto f_{B_d}^2 B_{B_d} |V_{tb}|^2 |V_{td}|^2 \propto f_{B_d}^2 B_{B_d} |V_{cb}|^2 \lambda^2 \boxed{((1-\bar\rho)^2 + \bar\eta^2)}$$

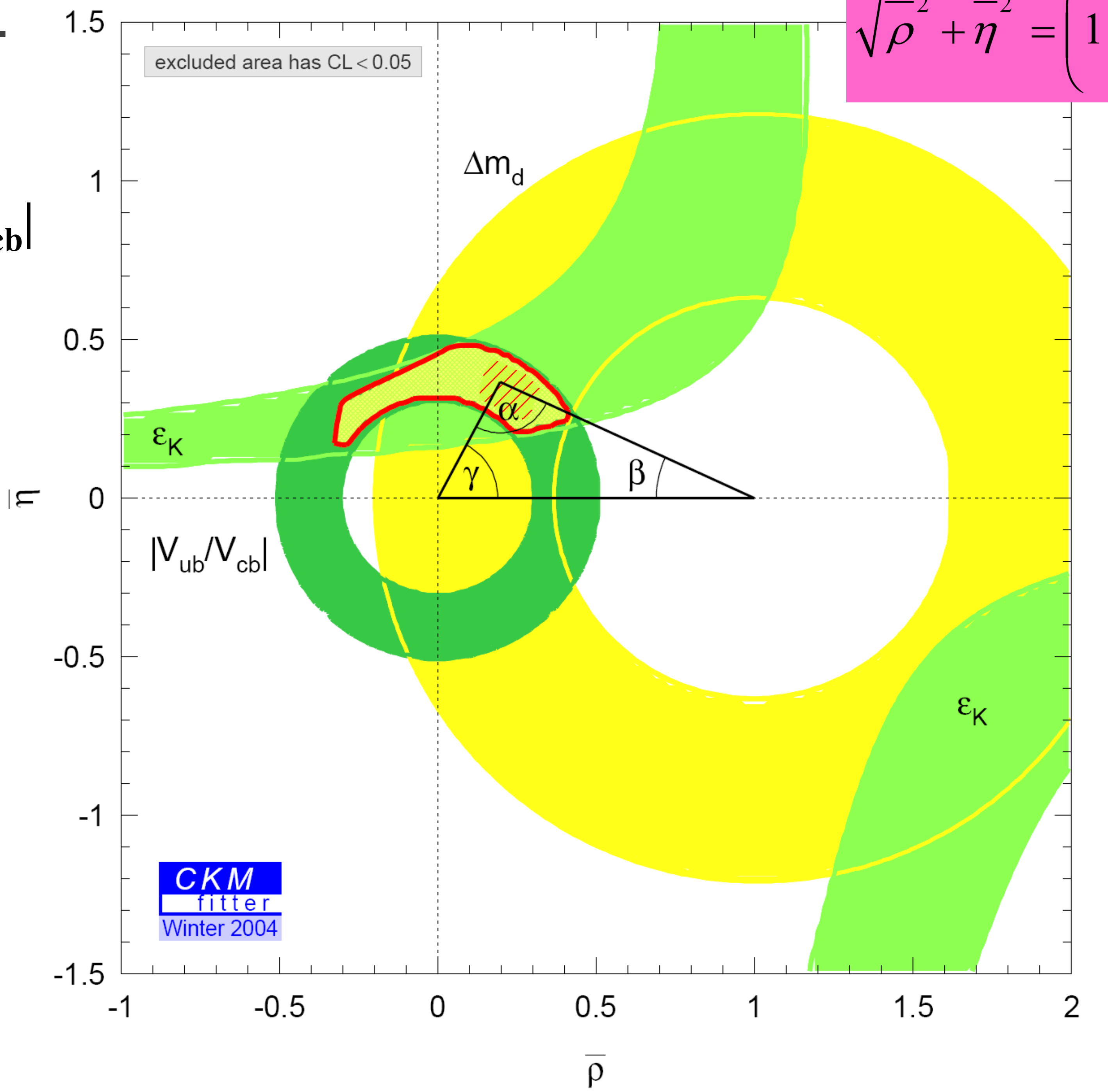
B_d mixing + CPV in K mixing (ε_K)

$$\varepsilon_K \sim \bar\eta(1-\bar\rho)$$



$$\sqrt{\bar{\rho}^2+\bar{\eta}^2}=\left(1-\frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

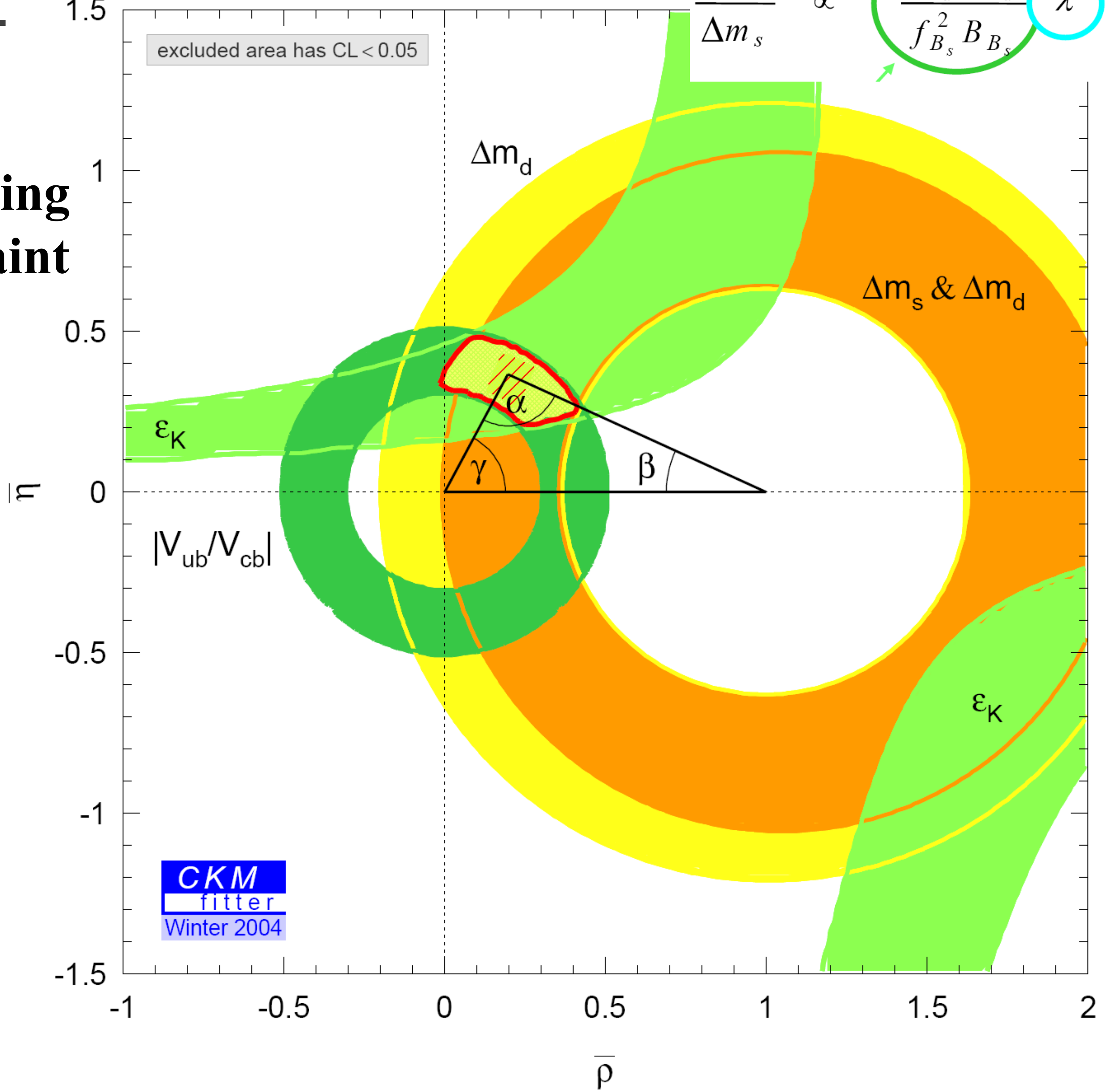
Add $|V_{ub}/V_{cb}|$



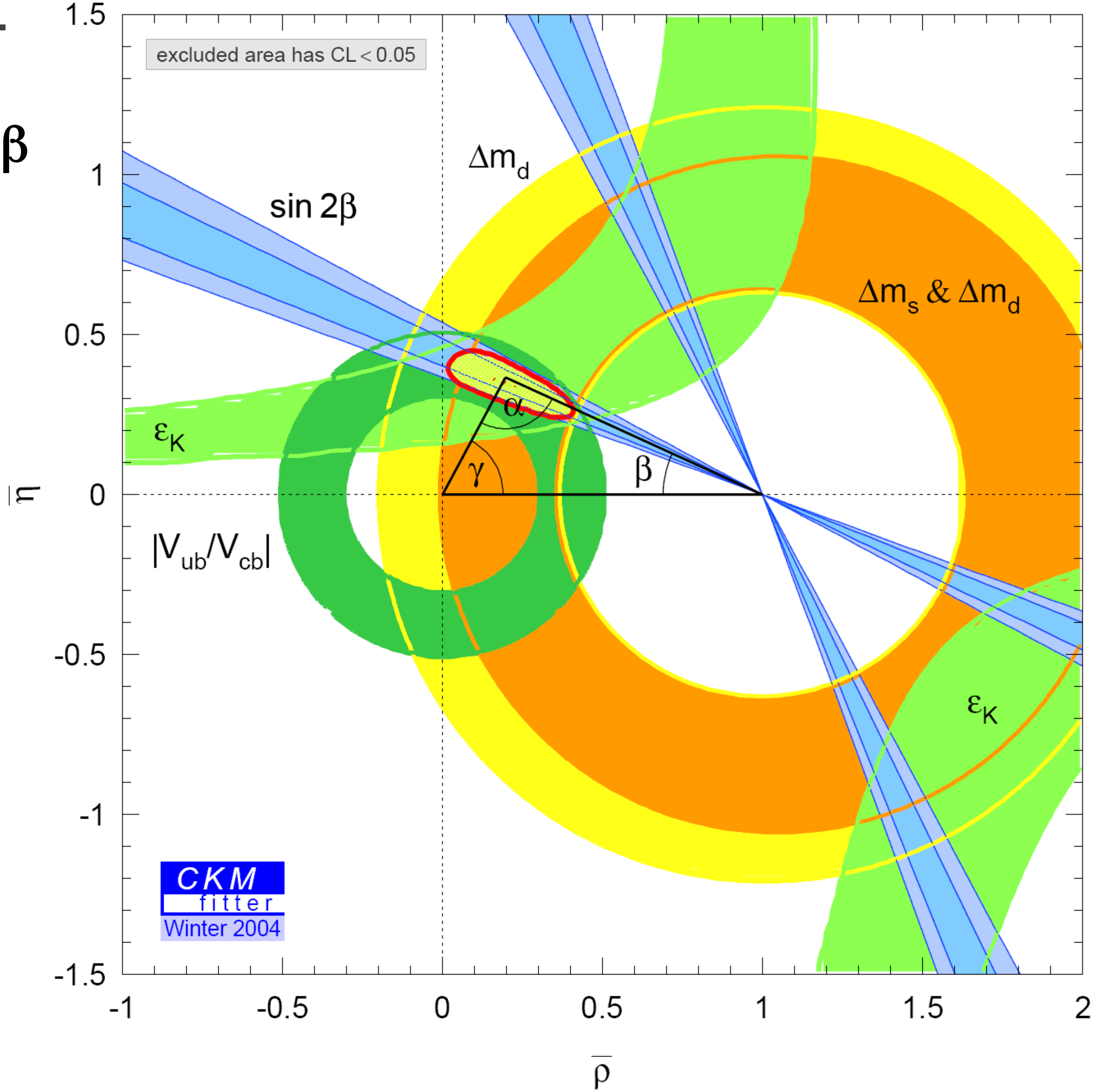
+

B_S Mixing constraint

$$\frac{\Delta m_d}{\Delta m_s} \propto \frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}} \lambda^2 \boxed{((1-\bar{\rho})^2 + \bar{\eta}^2)}$$

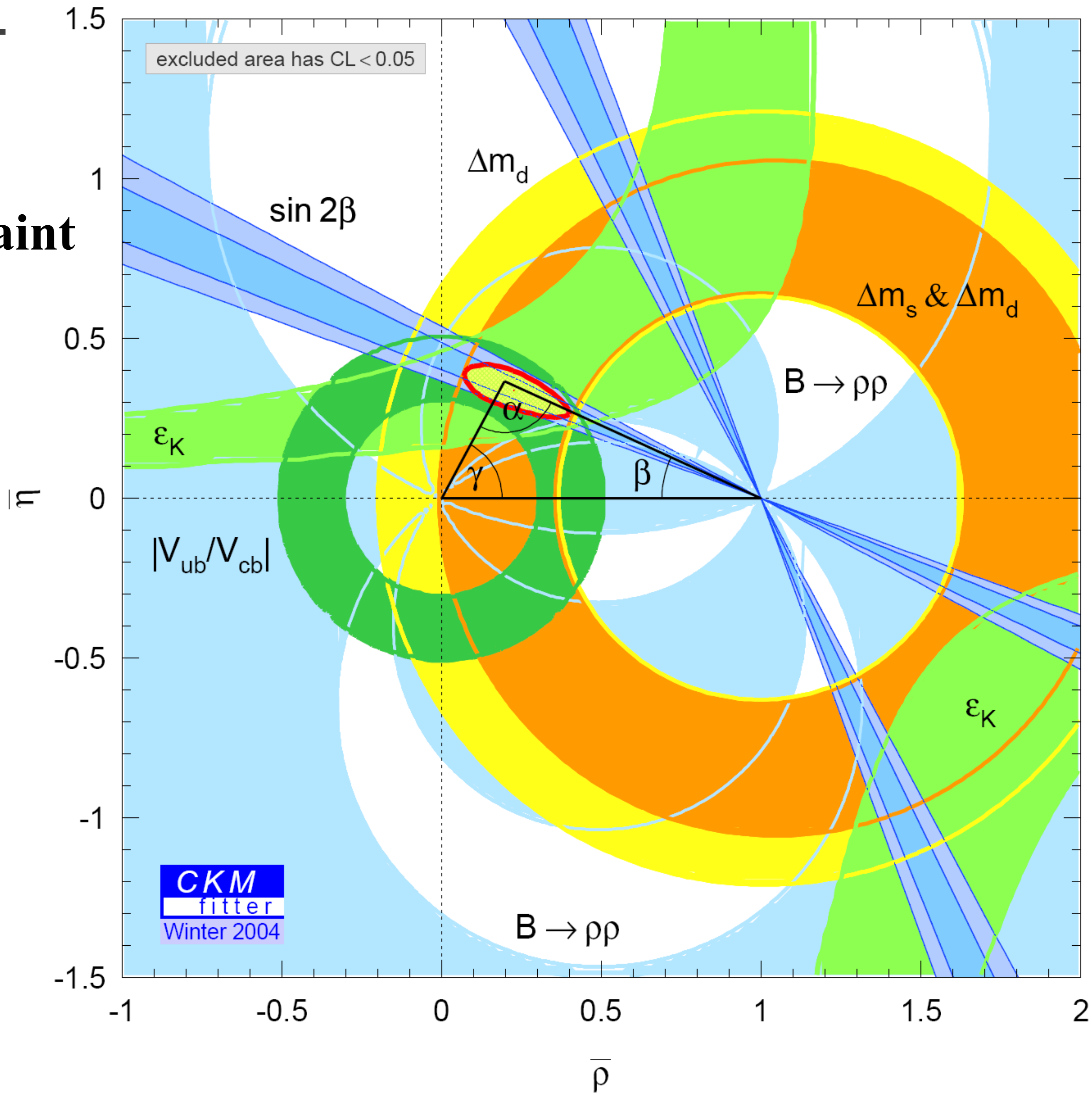


+ Sin2β



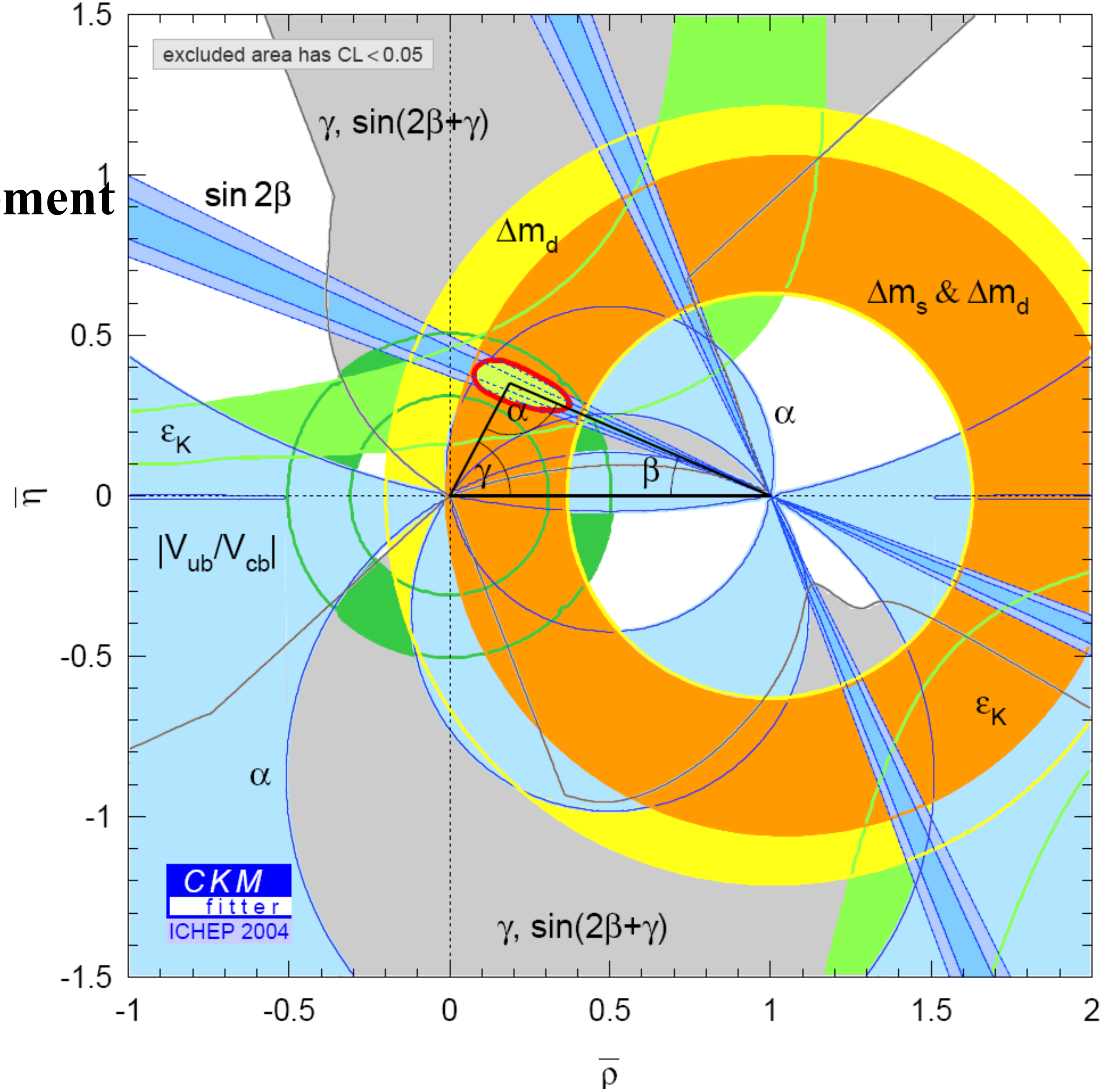
excluded area has CL < 0.05
Δm_d
sin 2β
Δm_s & Δm_d
ε_K
$|V_{ub}/V_{cb}|$
α
β
γ
ε_K
CKM fitter
Winter 2004
1.5
1
0.5
0
-0.5
-1
-1.5
-1
-0.5
0
0.5
1
1.5
2
$\bar{\eta}$
$\bar{\rho}$

+ α constraint

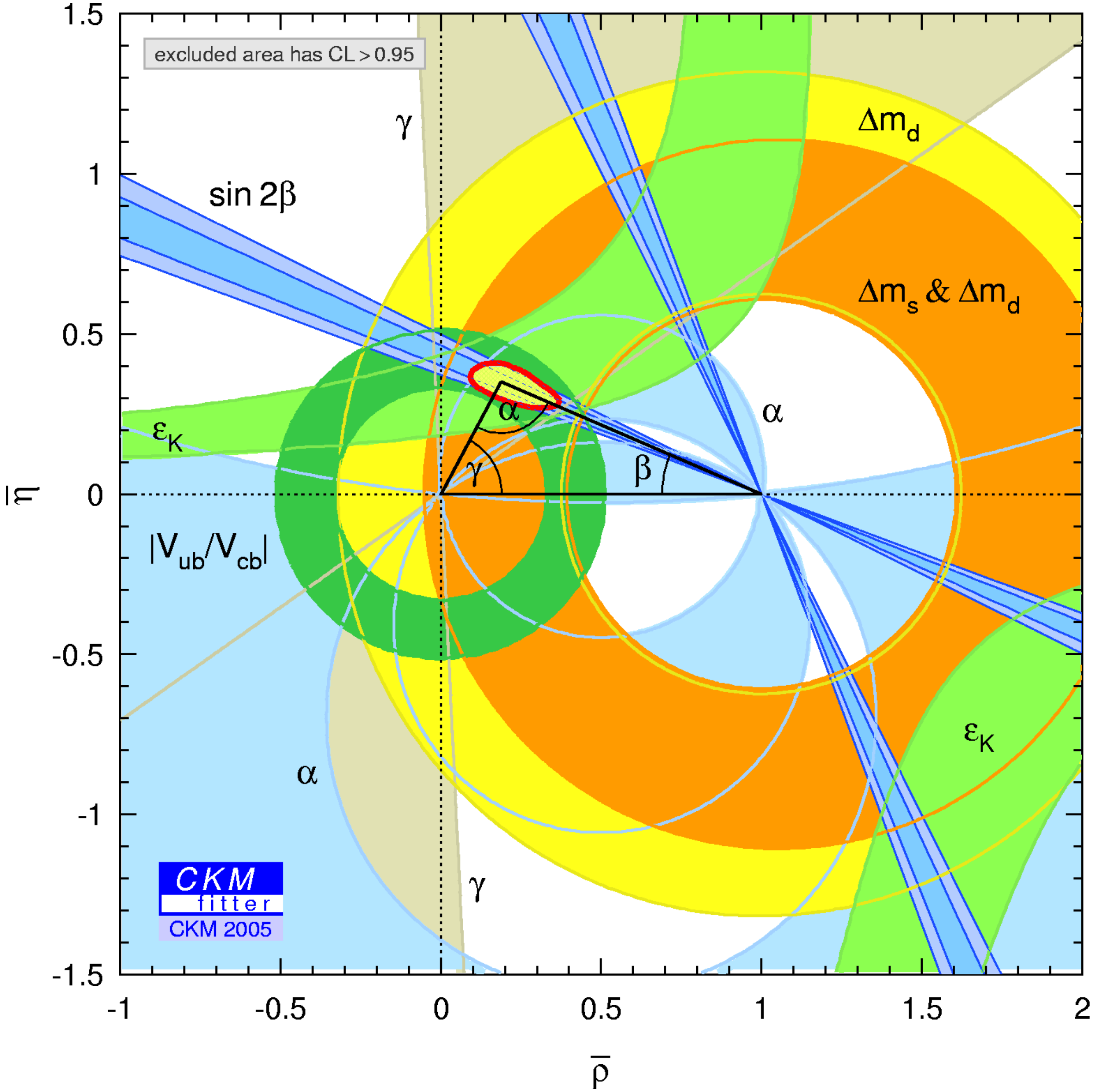


All measurements consistent, apex of (ρ,η) well defined

+ γ measurement

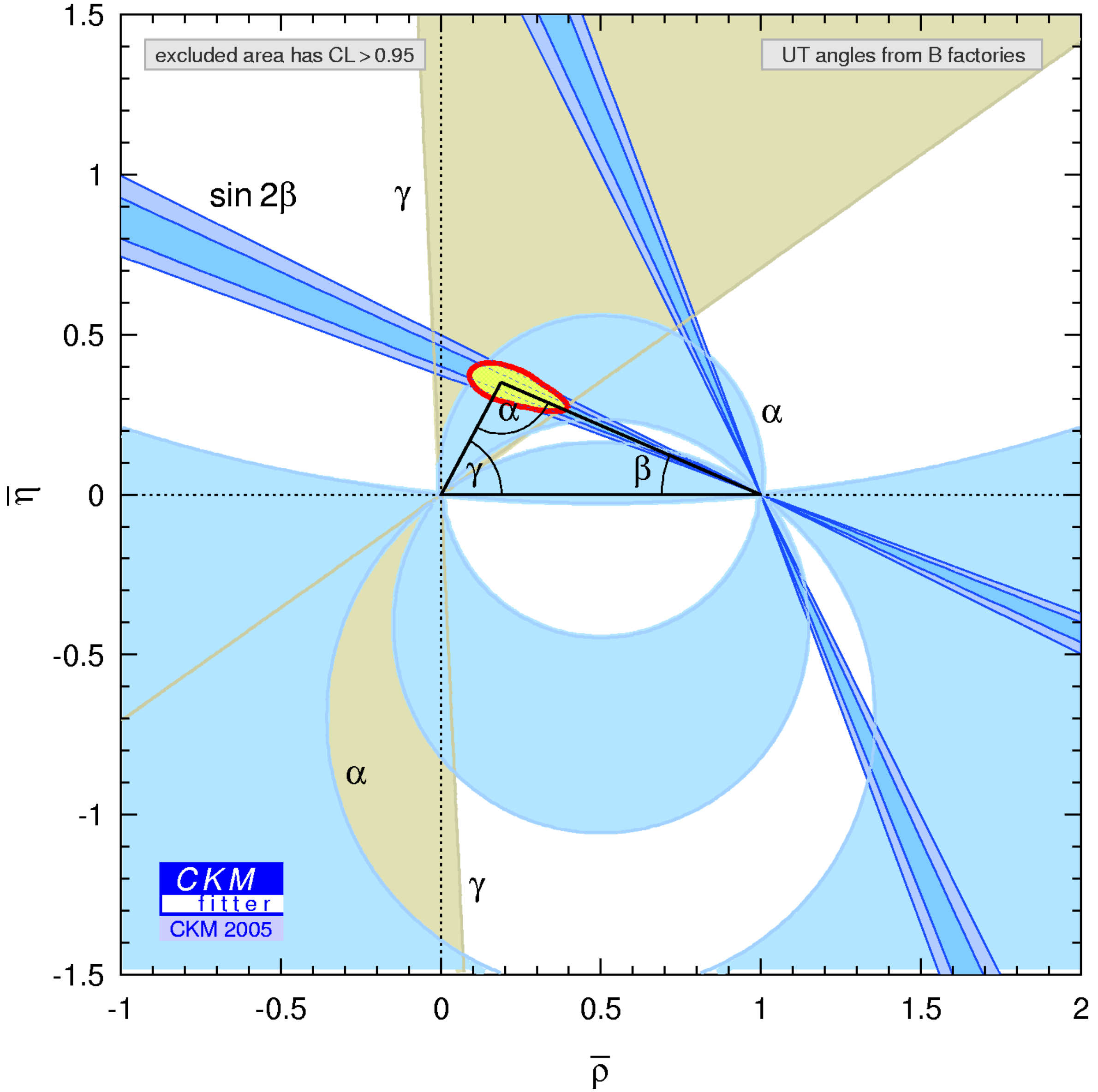


Unitarity Triangle after All Constraints



Includes constraints from all CKM-related measurements

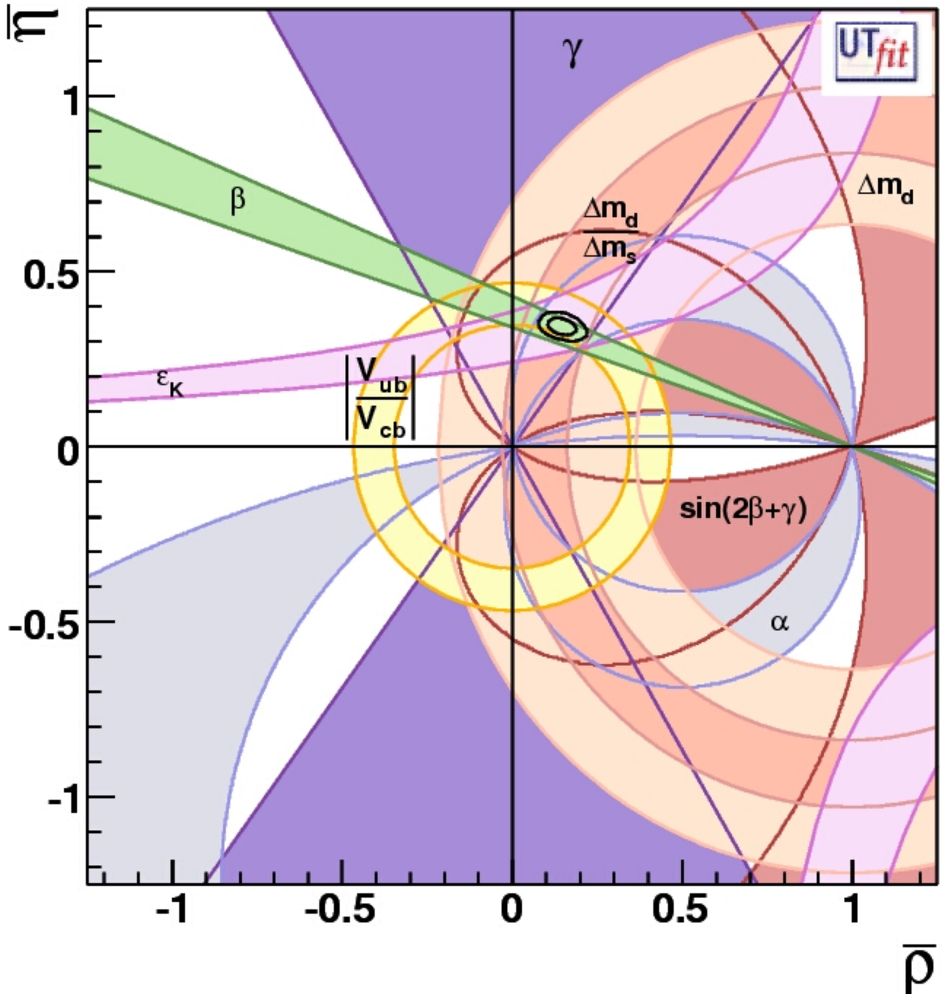
Impact of Angle Measurements on CKM Fit



Measurements of angles dominate the constraint on the UT apex!

Status of UT in 2007

All constraints



Only angles from B and ε_K from Kaons