Lecture 2: CPV in B system

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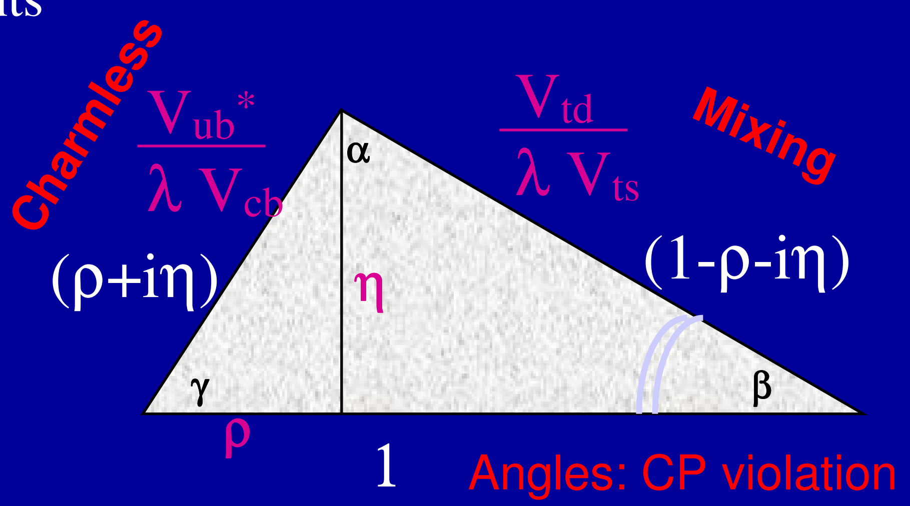
Outline

- Reminder CKM matrix
- Basic theory CP violation in B system
- β , α, γ , β_s (χ)
  - Current status of B-factory measurements
  - Estimate of Hadron Collider experimental reach
- Global picture and implications on new physics

b-decays: CKM matrix

- V_{ub}/V_{cb} is related to fraction of b-hadron decays with no charm in final state
  - Hard to measure at hadron colliders. Done at CLEO, LEP, B-factories
- V_{td}/V_{ts} is related to mixing (see later)
  - Hadron colliders are very competitive and are the only place where V_{ts} can be measured directly
- The angles of the triangle are related to CP violation
  - Hadron colliders and B-factories complement each other in these difficult measurements

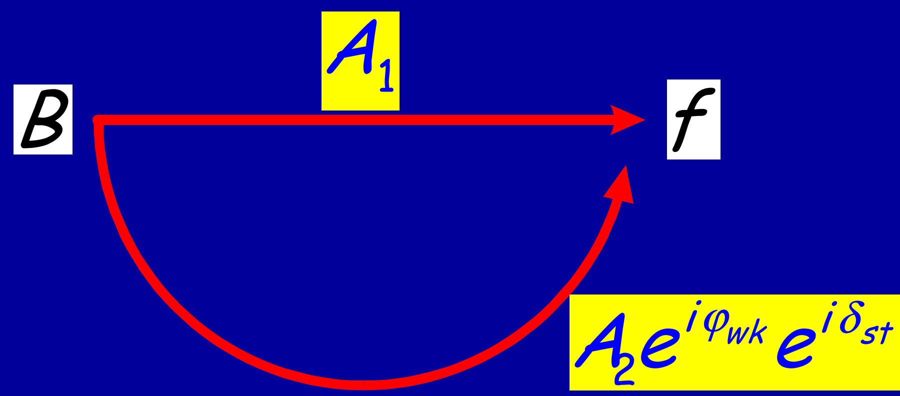


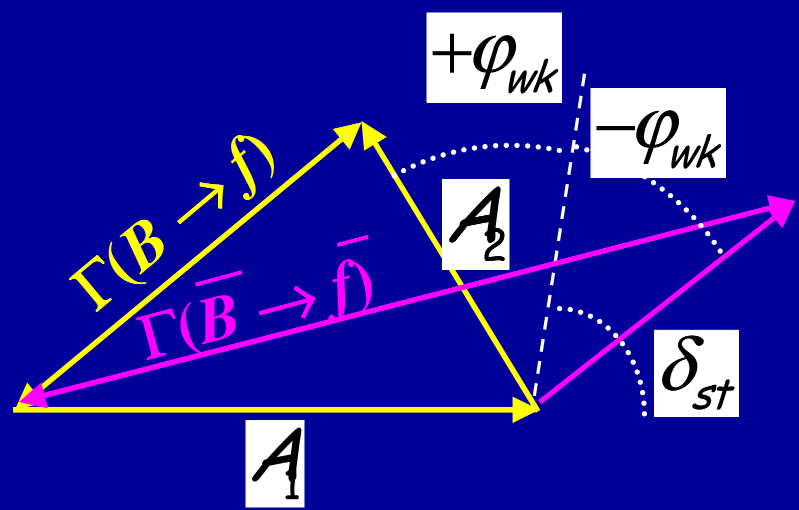
CP violation classification

- CP transformation flips sign of weak phases and leaves strong phases unchanged in amplitudes
  - CP violation in decay
    - $A(B \rightarrow f) \neq A(\bar{B} \rightarrow \bar{f})$
  - CP violation in mixing (already discussed)
    - $N(BB) \neq N(\bar{B}\bar{B})$
  - CP violation in the interference between a decay with mixing and one without mixing

CP violation in B decays

- **CPV through interference of decay amplitudes**





$$\Gamma(\bar{B} \to \bar{f}) = \left| A_1 + A_2 e^{-i\varphi_{wk}} e^{i\delta_{st}} \right|^2$$

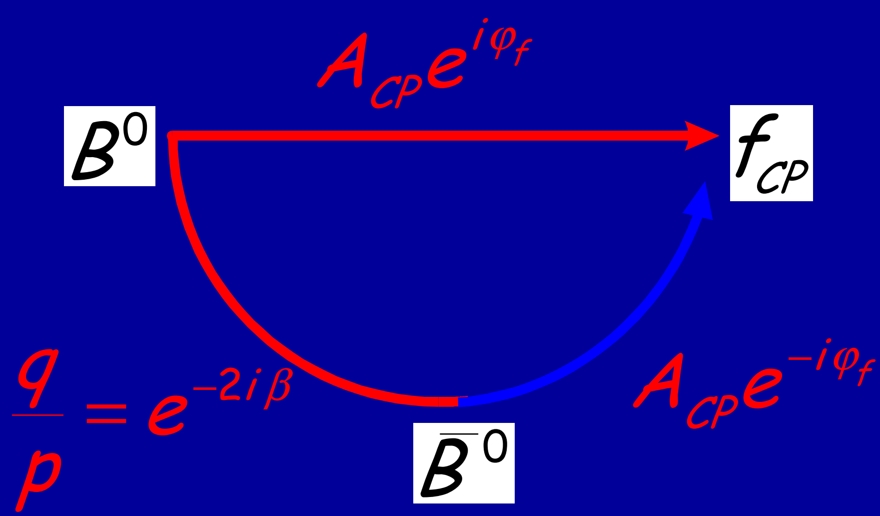
$$\Gamma(B \to f) = \left| A_1 + A_2 e^{i\varphi_{wk}} e^{i\delta_{st}} \right|^2$$

$$\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})$$
for $\varphi_{wk} \neq 0$ and $\delta_{st} \neq 0$

CP Violation in the B System

- **CPV through interference between mixing and decay amplitudes**

Directly related to CKM angles for single decay amplitude



Mixing mediated CPV (1)

- CPV from interference of unmixed and mixed decays to a common final state → |A(B→f)| ≠ |A($\overline{\text{B}}$→f)|
  - Definitions:

$$A = < f|B(0) > \quad , \quad \bar{A} = < f|\bar{B}(0) >$$
$$\lambda = \frac{\bar{A}}{A}\frac{q}{p} \approx \frac{\bar{A}}{A} e^{2i\beta_{(s)}} \quad , \quad |\lambda| \approx \frac{|\bar{A}|}{|A|}$$

  - Use again equations of time evolution of B states:

$$< f|B(t) > \; = \; e^{-imt} e^{-\frac{\Gamma t}{2}} A \left(cos\frac{\Delta mt}{2} - i\frac{\bar{A}}{A}\frac{q}{p} sin\frac{\Delta mt}{2} \right)$$

B(0) → f

$$< f|\bar{B}(t) > \; = \; e^{-imt} e^{-\frac{\Gamma t}{2}} \bar{A} \left(cos\frac{\Delta mt}{2} - i\frac{A}{\bar{A}}\frac{p}{q} sin\frac{\Delta mt}{2} \right)$$

$\overline{\text{B}}$(0) → f

$$| < f|B(t) > |^2 \; = \; \frac{e^{-\Gamma t}}{2} \left[\left(|A|^2 + |\bar{A}|^2 \right) + \left(|A|^2 - |\bar{A}|^2 \right) cos\Delta mt + 2|A|^2 \mathcal{I}m\lambda sin\Delta mt \right]$$
$$| < f|\bar{B}(t) > |^2 \; = \; \frac{e^{-\Gamma t}}{2} \left[\left(|A|^2 + |\bar{A}|^2 \right) + \left(|\bar{A}|^2 - |A|^2 \right) cos\Delta mt - 2|A|^2 \mathcal{I}m\lambda sin\Delta mt \right]$$

Mixing mediated CPV (2)

- A_{CP} = asymmetry between two processes

$$A_{CP} = \frac{|<f|B>|^2 - |<f|\bar{B}>|^2}{|<f|B>|^2 + |<f|\bar{B}>|^2} = -\frac{2\mathcal{I}m\lambda}{1+|\lambda|^2} sin\Delta mt + \frac{1-|\lambda|^2}{1+|\lambda|^2} cos\Delta mt$$

-S

C ≡ -A

- Simpler when A contains a single weak phase ϕ_D

$$A = A_0 e^{-i\varphi_D}\ ,\ \bar{A} = \eta_f A_0 e^{i\varphi_D}$$

$$\lambda = \eta_f e^{2i(\varphi_D + \beta_{(s)})}\ ,\ |\lambda| = 1$$

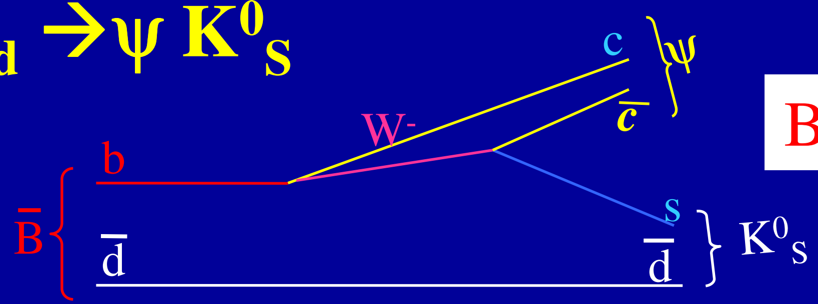
$$A_{CP} = -\eta_f sin2(\varphi_D + \beta_{(s)}) sin\Delta mt$$

Phase of V_{td} (V_{ts})

CKM angle β

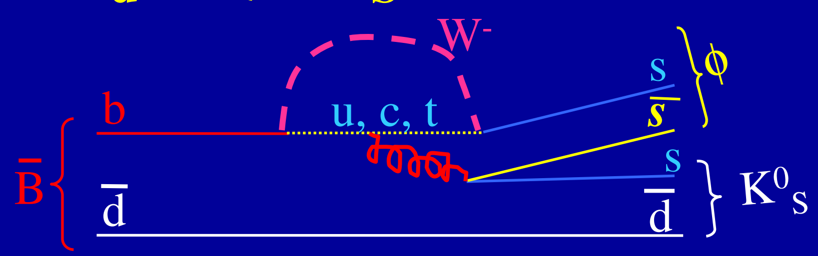
- Bd:
  - **Select CP eigenstates with no weak phases in decay**
    - $A_{CP} = \sin(2\beta)\sin(\Delta mt), |\lambda| = 1$

- **Pure tree: $B_d \rightarrow \psi K^0_S$**



BR ~ 10^{-3}

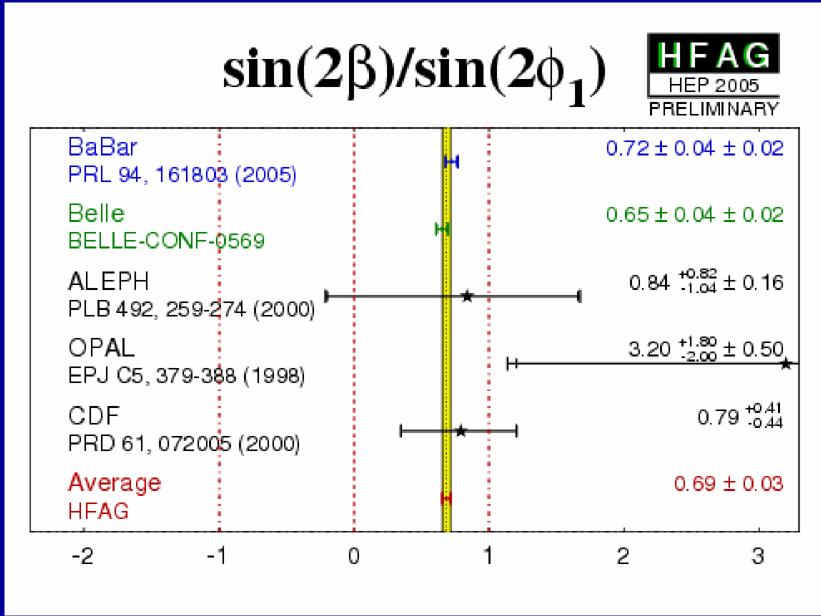
- **Pure penguin: $B_d \rightarrow \phi K^0_S$**



BR ~ 10^{-5}

CKM angle β

- Current results dominated by B-factories
- Tevatron experiments: comparable statistics but smaller tagging power



- Experimental considerations:
  - Very similar to mixing analysis
  - Very important dilution calibration
    - We measure D sin(2β)
  - Expected accuracy from time dependent fit ($x_d = \Delta m_d \tau_d$):

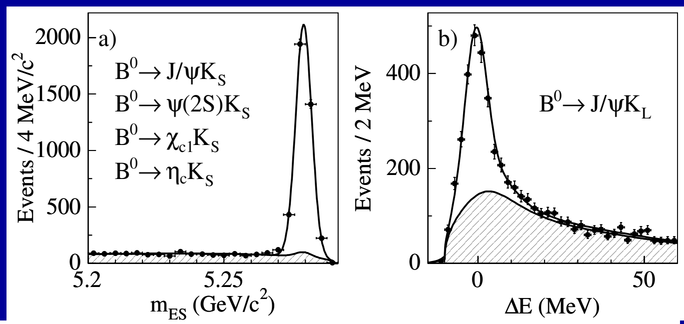
$$\sigma(sin(2\beta)) = e^{(\Delta m \sigma_t)^2}\sqrt{\frac{1+4x_d^2}{2x_d^2}}\sqrt{\frac{N_S+N_B}{N_S}}\sqrt{\frac{1}{N_S \epsilon D^2}}$$

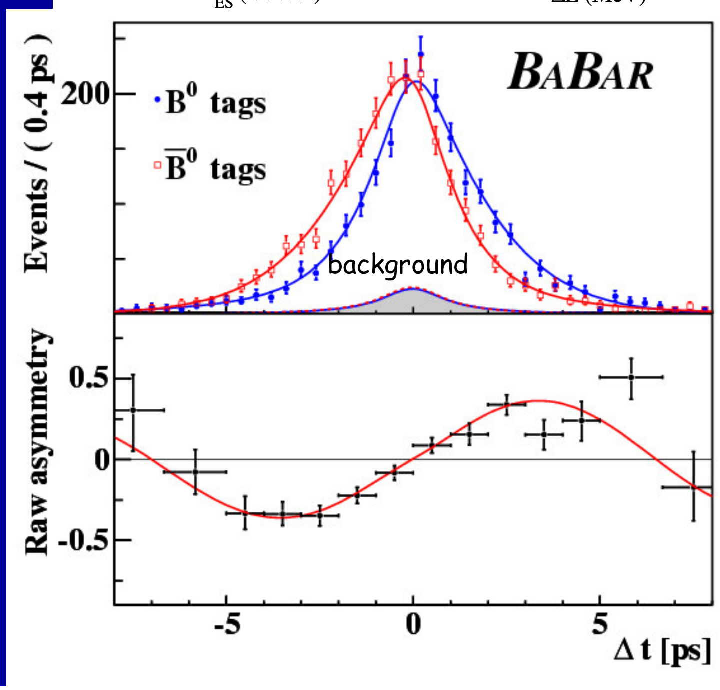
~ 1.7 ~ 1

CKM angle β

BaBar 2004: 227x10⁶ BB

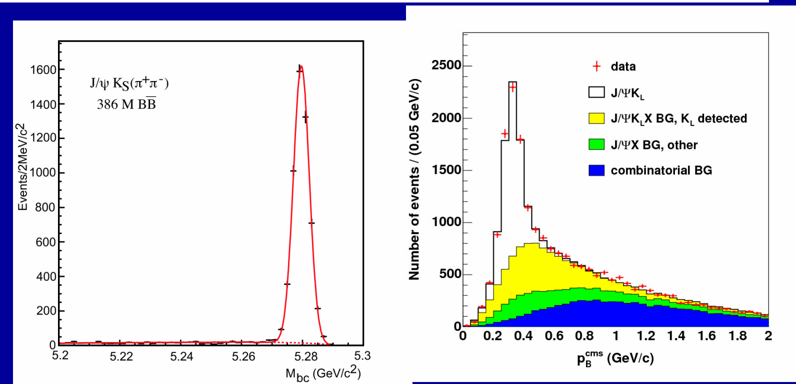
$$\sin 2\beta = 0.722 \pm 0.040 \pm 0.023$$

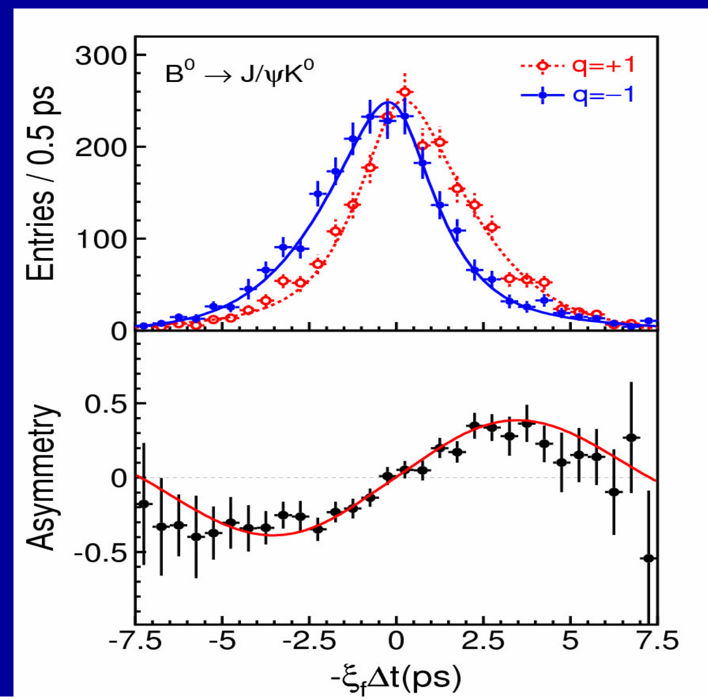


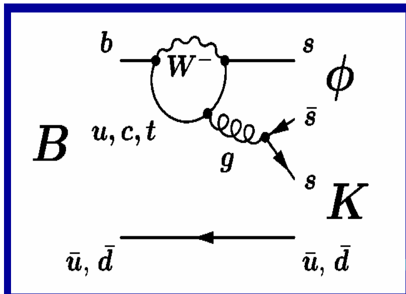


Belle 2005: 386x10⁶ BB

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

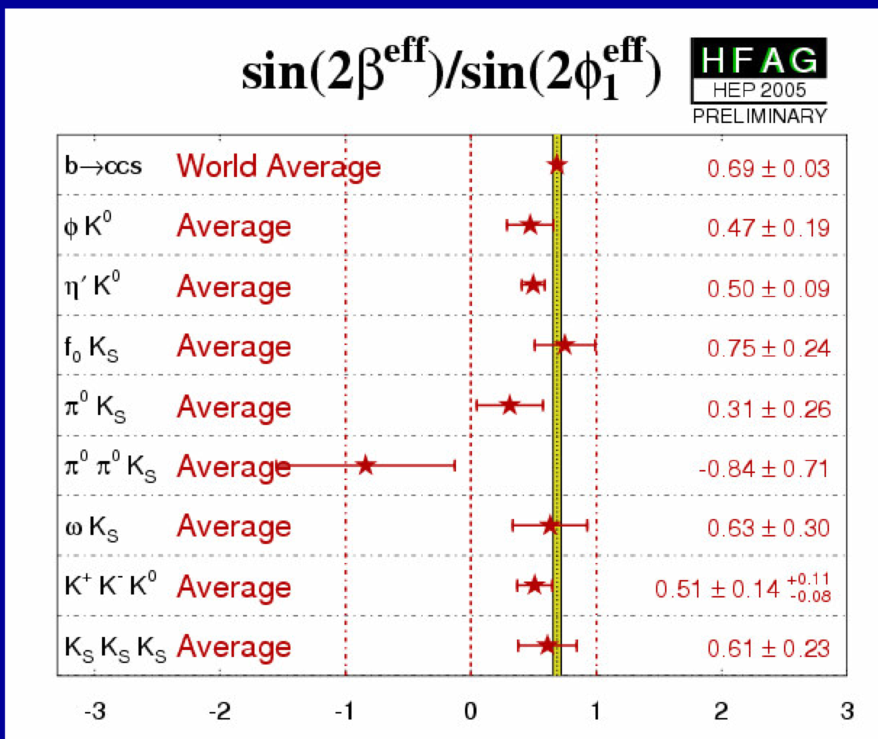




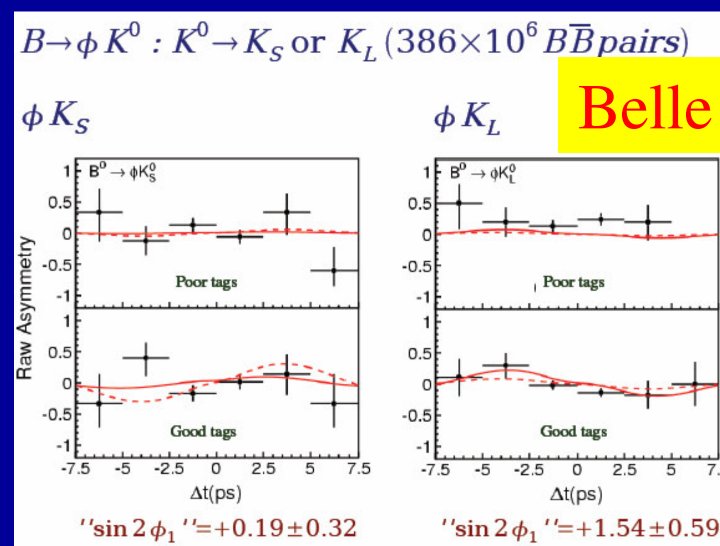


CKM angle β

- ❖ Pure penguins sensitive to new physics in loops
  - ➢ Interesting to compare pure tree with pure penguins



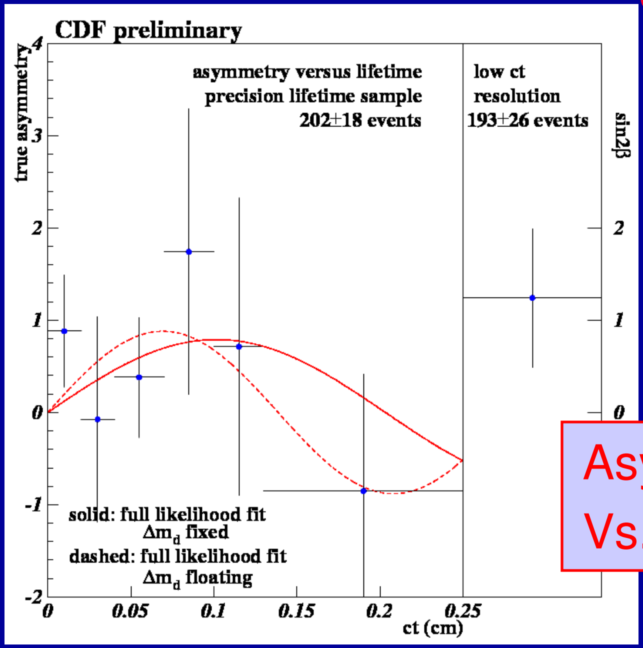
BaBar/Belle find Penguin systematically lower then Tree 2.8 σ effect … more statistics will tell



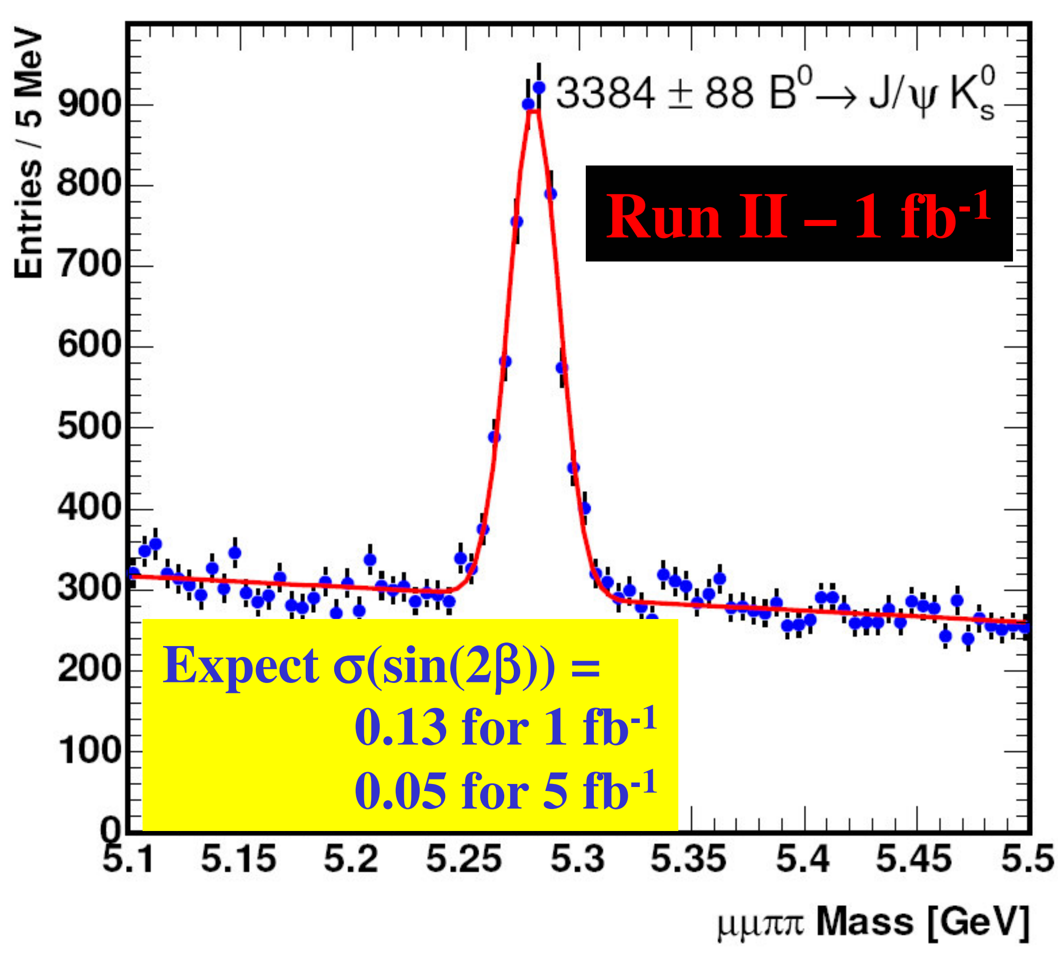
Naïve avg. 0.50± 0.06

Sin 2β at Tevatron

- CDF Run 1 result is based on:
  - ~ 400 $B^0 \rightarrow J/\psi K^0_S$
  - All available taggers:
    - Opposite side: lepton, Jet-charg
    - Same side: pion charge correlat
- Result: $\sin(2\beta) = 0.91^{+0.37}_{-0.36}$



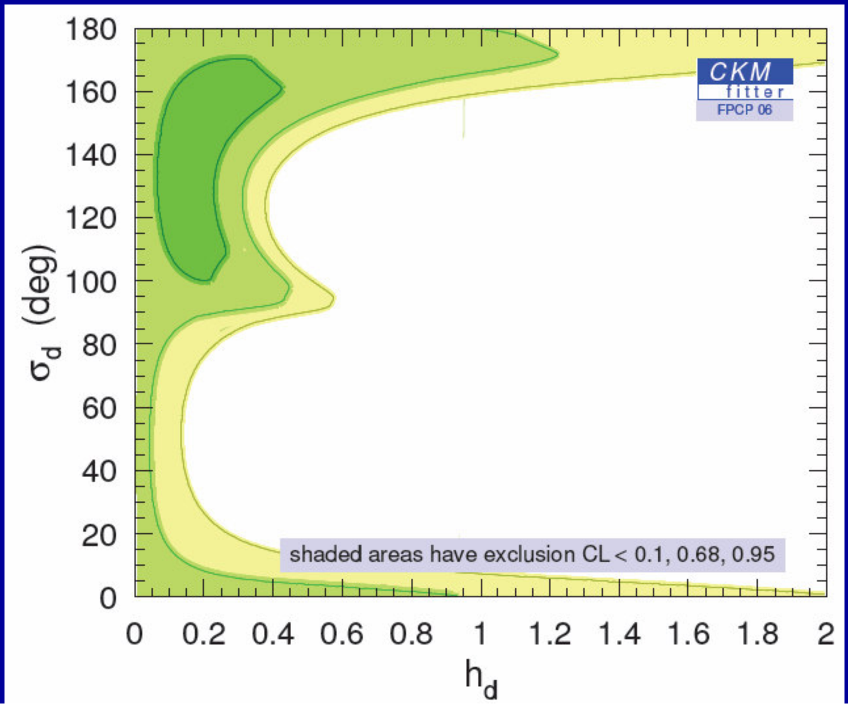
Asymmet
Vs. lifetime



Expect $\sigma(\sin(2\beta))$ =
0.13 for 1 fb^{-1}
0.05 for 5 fb^{-1}

Model independent limits on new physics

- $M_{12} = M_{12}^{SM} + M_{12}^{BSM} = M_{12}^{SM}(1+he^{i\sigma})$
  - $\Delta m = 2|M_{12}|$, $\arg(M_{12}) = \beta$
  - Combined measurement of mixing frequency and mixing phase provides strong model independent limit on new physics contributions



Excluded @ 95% CL

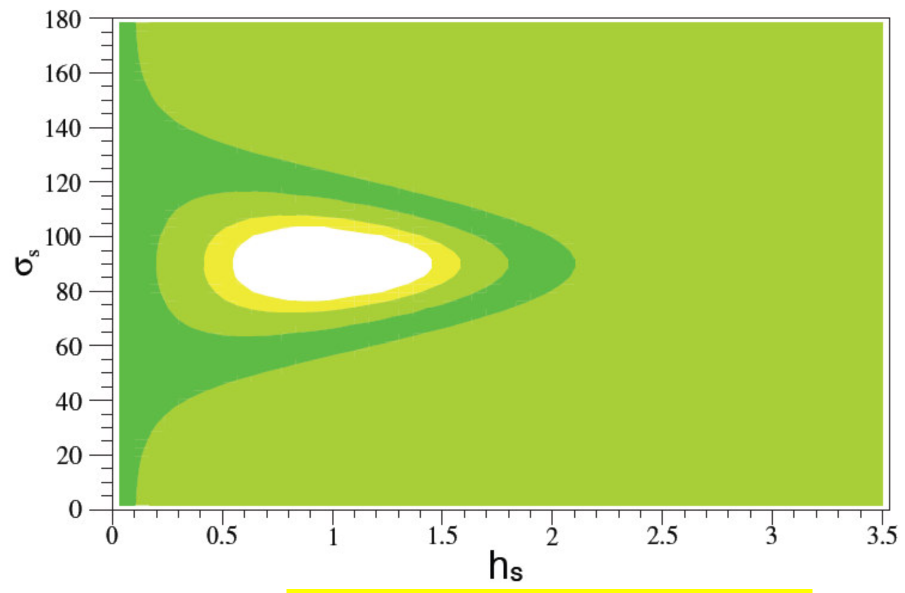
Excluded @ 68% CL

Excluded @ 10% CL

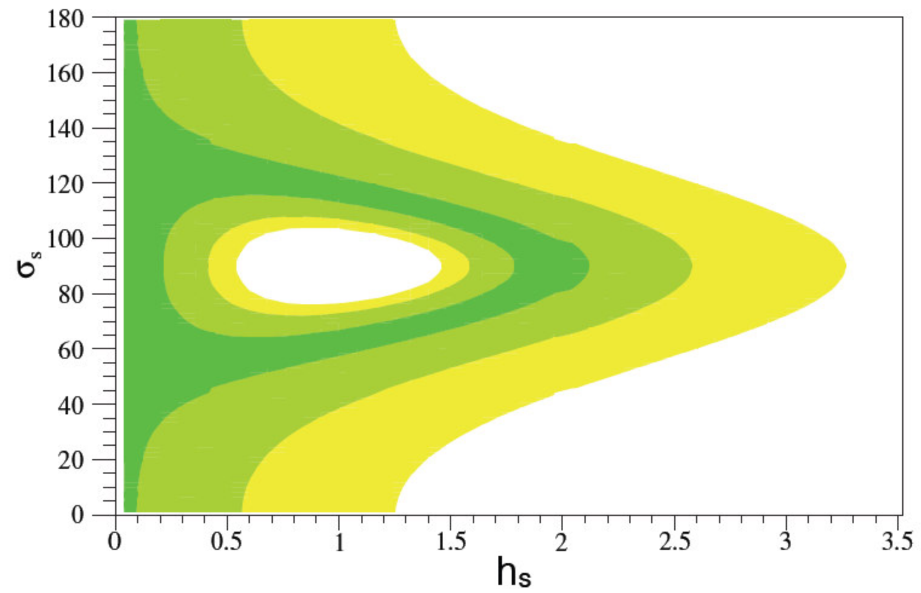
Not excluded

Limits on new physics (2)

- Status much less constrained in the case of the Bs
  - Need to measure the phase β_s …. even with a large error!
  - Feasible only at hadron colliders



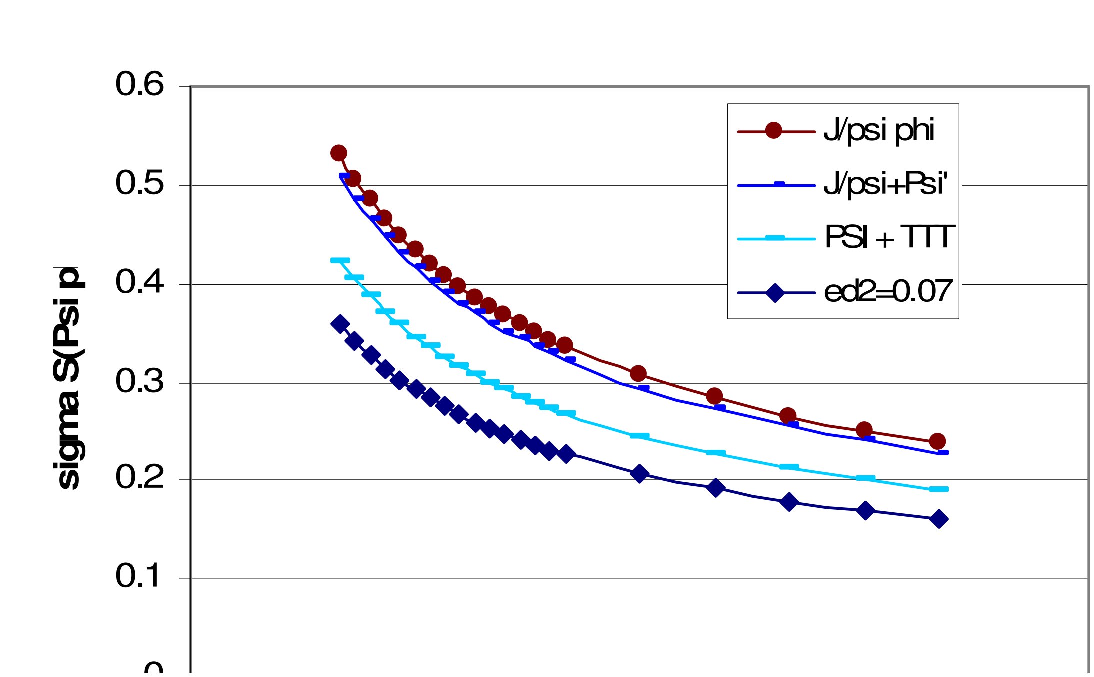
Before CDF result

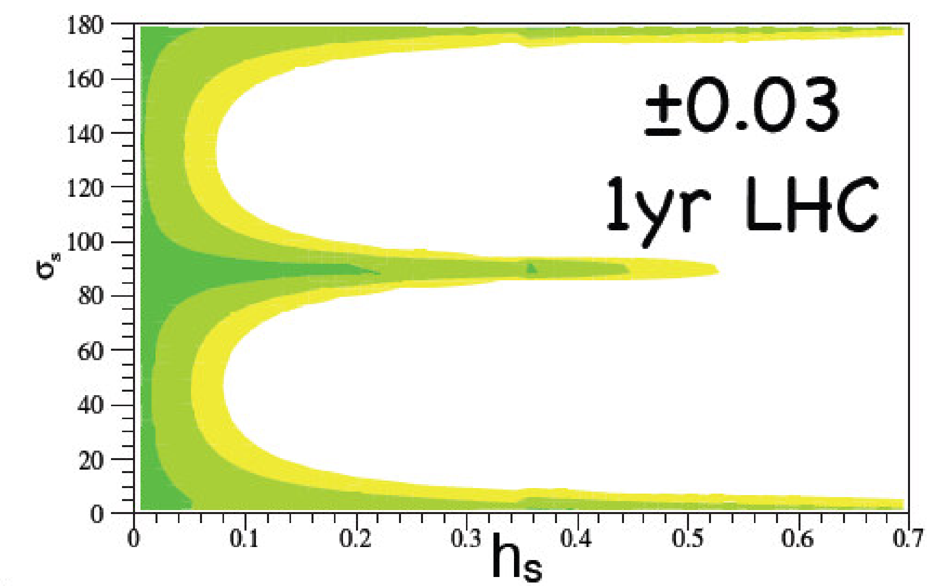


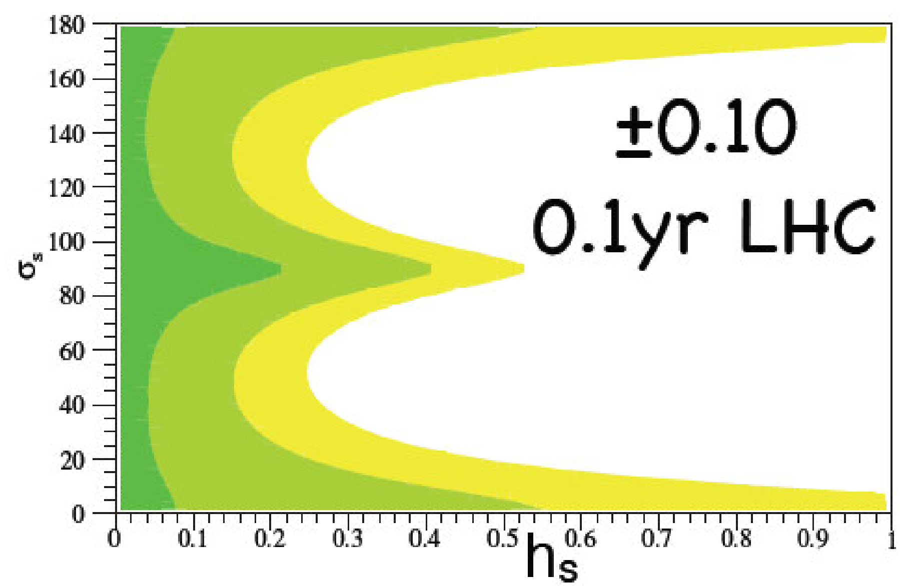
With CDF Bs mixing data

Sin $2\beta_s$ expectations

- Use CP asymmetry in $B_s \rightarrow \psi\phi$
  - 80% CP-even
    - Reduced asymmetry
      - $S_{\psi\phi} = 60\% \sin 2\beta_s$
  - Could reach **$\sigma(A) \sim 0.15$**
  - ~ early LHC-B

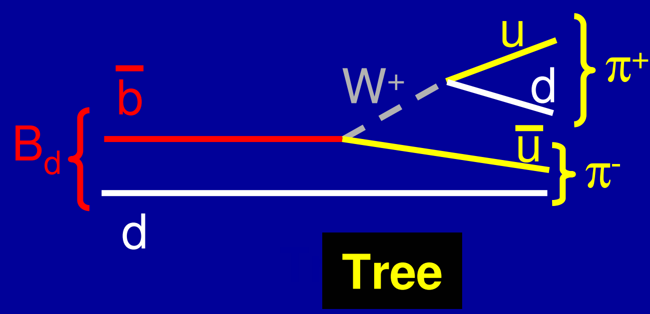




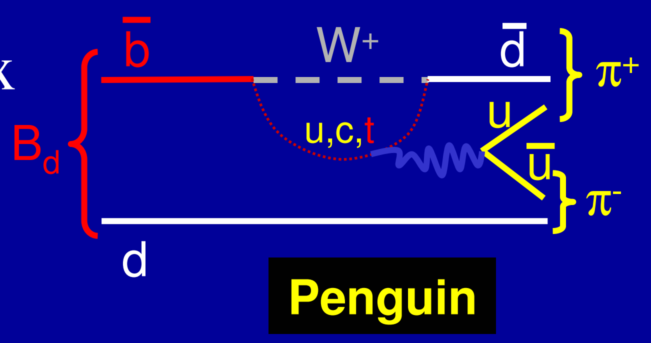


Sin 2α

- $\alpha=\pi-\beta-\gamma$ $(\sin(\alpha) = \sin(\beta+\gamma))$
  - Need decay with weak phase γ
  - $B_d \rightarrow \pi^+\pi^-$, $\rho^+\rho^-$



- … but:
  - serious penguin contamination at same order in $\lambda \rightarrow S, C \neq 0$
  - Unfolding penguins requires complex isospin analysis involving also other decay modes:
    - BR and A_{CP} of $B_d\rightarrow\pi^0\pi^0$, $B^\pm\rightarrow\pi^\pm\pi^0$
    - Done at B-factories

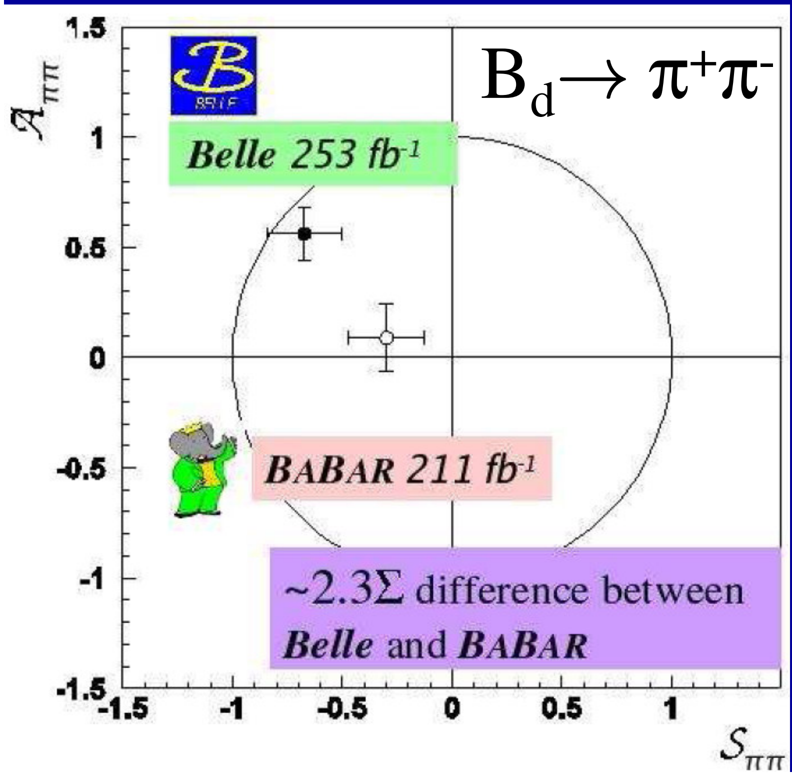


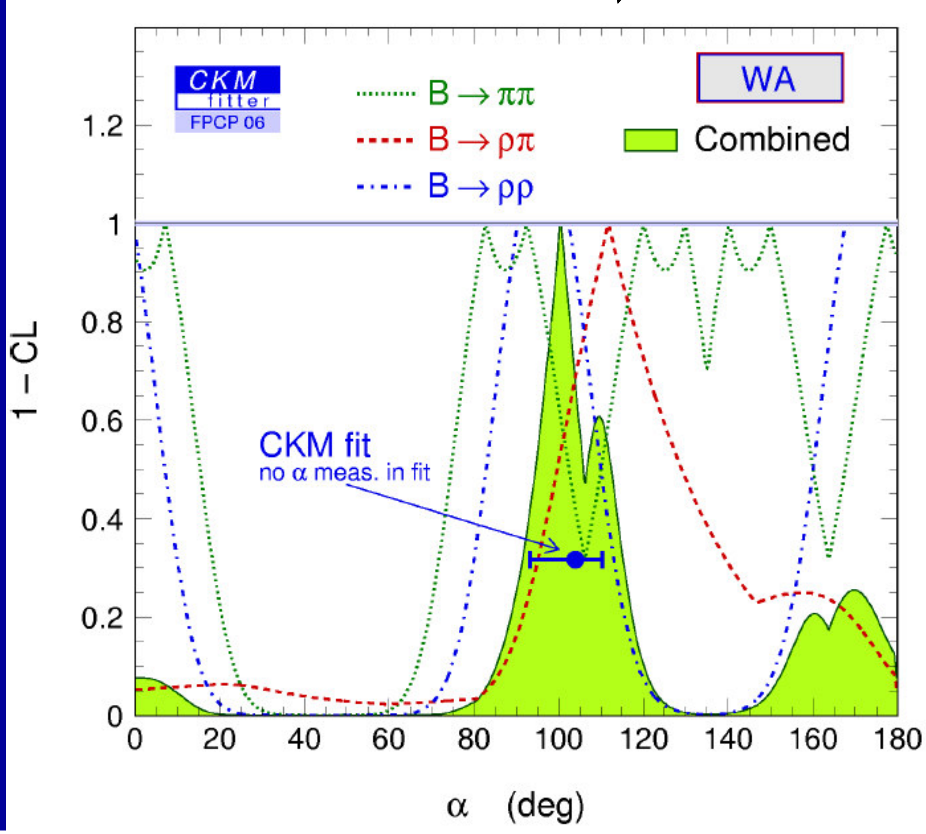
- At the Tevatron can measure both $B_d\rightarrow\pi^+\pi^-$ and $B_s\rightarrow K^+K^-$ then assume SU(3) symmetry

Sin 2α at B-factories

- $B_d \to \pi^+\pi^-$ asymmetries at 0.15 errors
  - Some discrepancy between BaBar and Belle
- $B_d \to \rho^+\rho^-$ is lucky:
  - Small penguin contribution and > 95% longitudinal polarization
- Added Dalitz analysis of $B_d \to \rho^+\pi^-$

$$\alpha = 99^\circ {}^{+12^\circ}_{-9^\circ}$$



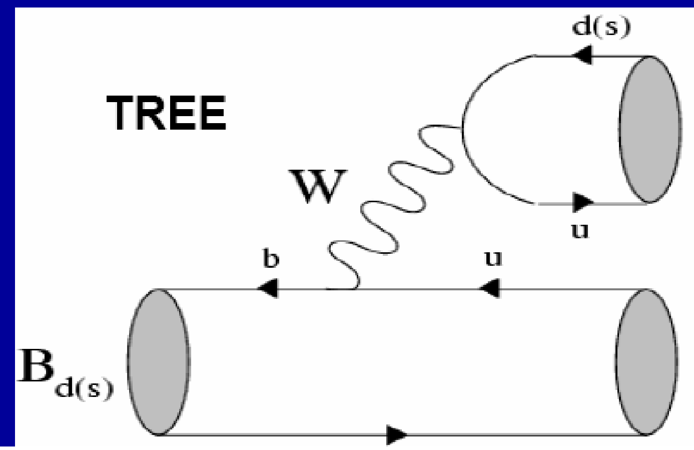


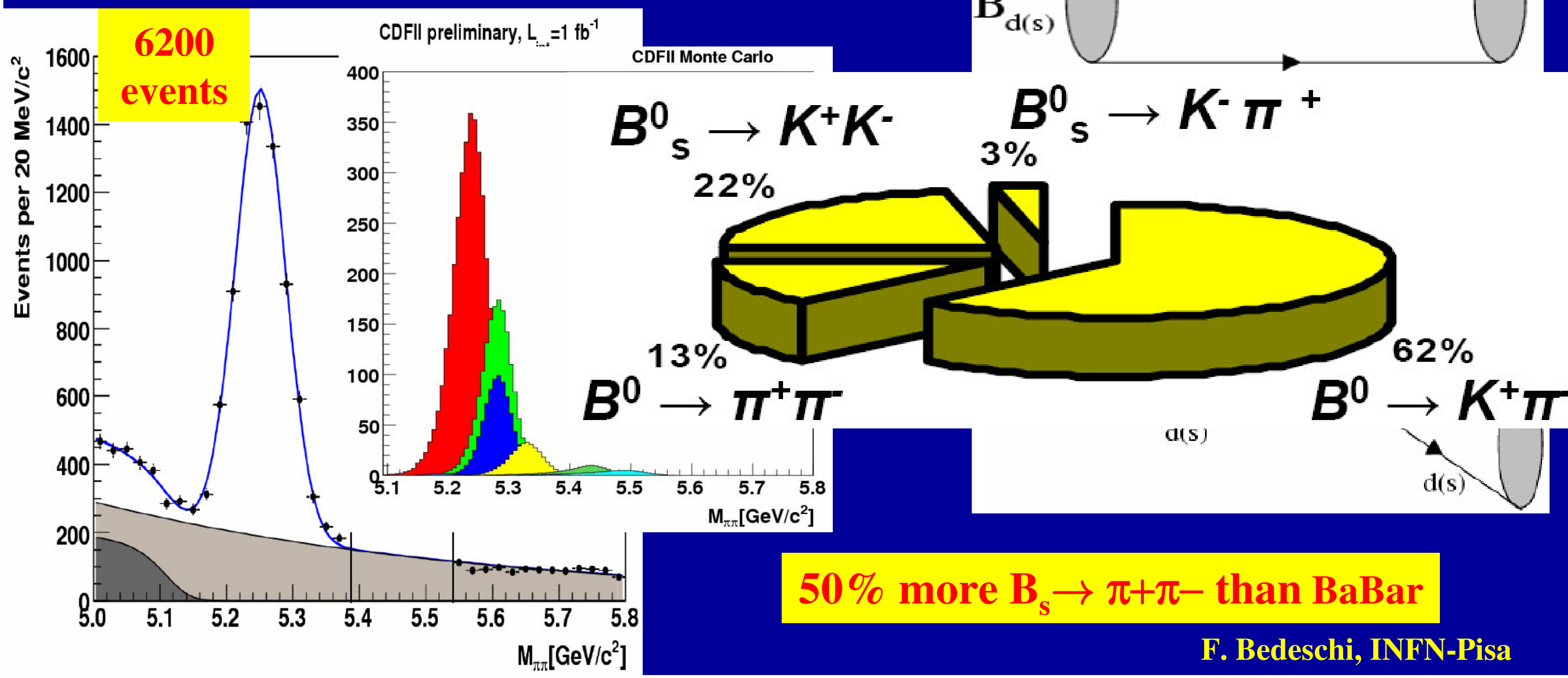
$B \rightarrow h^+h^-$ at Tevatron

- Large $B_d \rightarrow \pi^+\pi^-$ signals
  - Can measure $A_{\pi\pi}$, $S_{\pi\pi}$ with accuracy comparable to B factories
  - … isospin analysis impossible, but measurement can be combined to B-factories to add accuracy to asymmetries
- Can measure direct CP violation in $B_d \rightarrow K^+\pi^-$ decays
  - Checks B-factories
- Can measure also $B_s \rightarrow K^+K^-$ and the associate asymmetries
  - Allows determination of γ under the assumption of SU(3) symmetry

B→h⁺h⁻ at Tevatron

- Produce both B_d and $B_s \rightarrow \pi\pi$, $K\pi$, KK
- Mass peaks overlap
  - Statistical separation achieved with combination of kinematics and PID

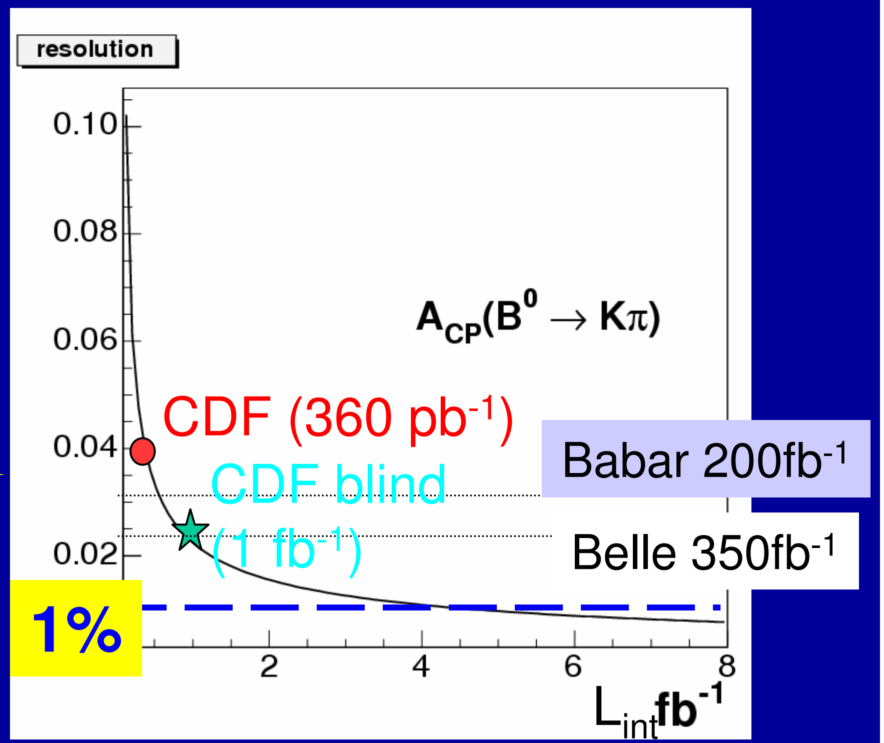




50% more $B_s \rightarrow \pi^+\pi^-$ than BaBar

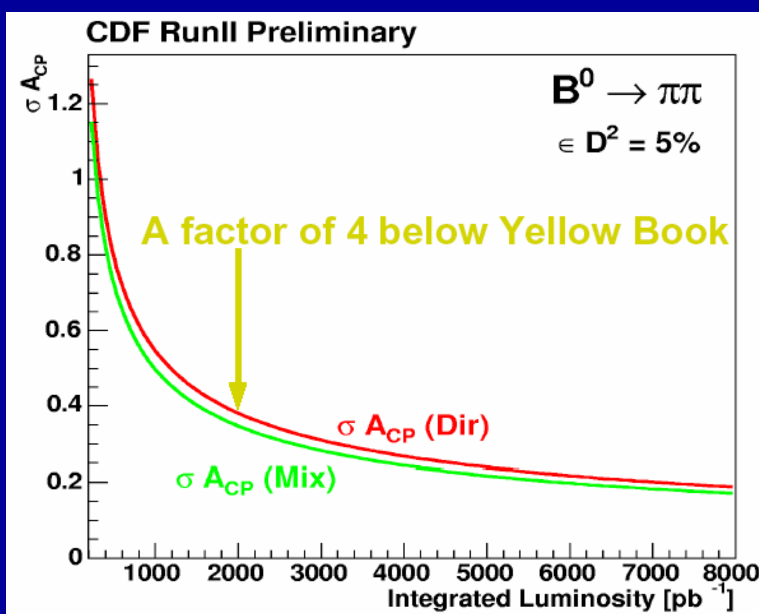
Direct CP in $B_d \rightarrow K^+\pi^-$

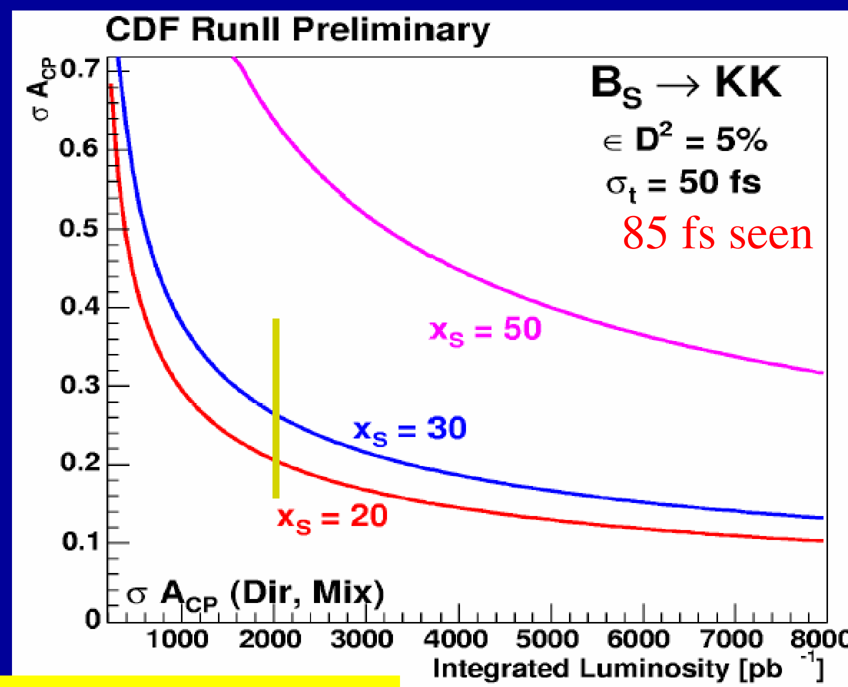
- Interference between penguin and tree diagrams
- First observed at B-factories:
  - $A_{CP}^{BaBar} = -0.133 \pm 0.030 \pm 0.009$
  - $A_{CP}^{Belle} = -0.113 \pm 0.022 \pm 0.008$
- Current Tevatron result with 360 pb^{-1}
  - $A_{CP}^{CDF} = -0.058 \pm 0.039 \pm 0.007$
    - Small systematics from calibration with huge sample of $D \rightarrow K\pi$
    - Expect resolution at B-factories level with 1 fb^{-1} already on tape



$(S_{\pi\pi}, A_{\pi\pi}), (S_{KK}, A_{KK})$ expectations

- Expected CP asymmetry resolutions in Bd → ππ and Bs → KK
  - Can reach resolution at 0.2 level → comparable to B-factories for ππ
- Will measure also Bs asymmetry with comparable resolution
  - B-factories can't do it!
  - Can use to measure γ

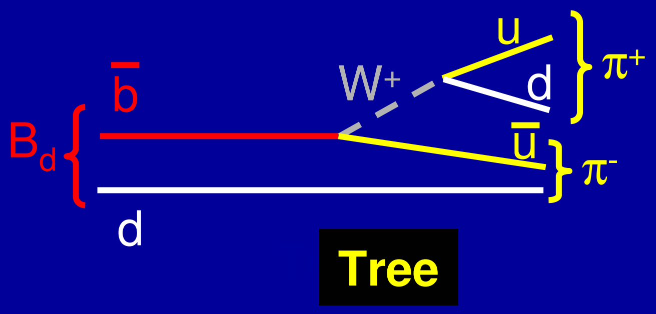


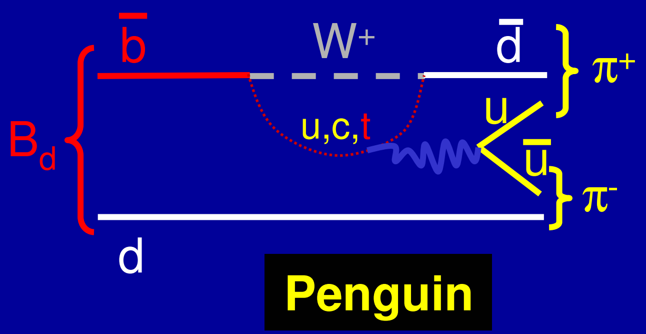


Scaling from current yields

Measuring γ with B→hh

- Interpretation of asymmetries (Fleischer, PLB459, 1999)
  - Parameterize in terms of
    - CKM phase γ, β
      - β from ψK^0_S
    - $d\, e^{i\theta}$ = hadronic Penguin/Tree
  - Assume SU(3) symmetry
    - $d\, e^{i\theta}$ same for $B_d \to \pi\pi$, $B_s \to KK$ (~ 20%)
    - $A^{dir}(\pi\pi) = -2d \sin\theta \sin\gamma + O(d^2)$
    - $A^{dir}(KK) = \frac{2\lambda^2}{d(1-\lambda^2)} \sin\theta \sin\gamma + O((\lambda^2/d)^2)$
    - $A^{mix}(KK) = \frac{2\lambda^2}{d(1-\lambda^2)} \cos\theta \sin\gamma + O((\lambda^2/d)^2)$
      - $A^{mix}(\pi\pi) = \sin 2(\beta+\gamma) + 2d \cos\theta \times (\cos\gamma \sin 2(\beta+\gamma) - \sin(2\beta+\gamma)) + O(d^2)$



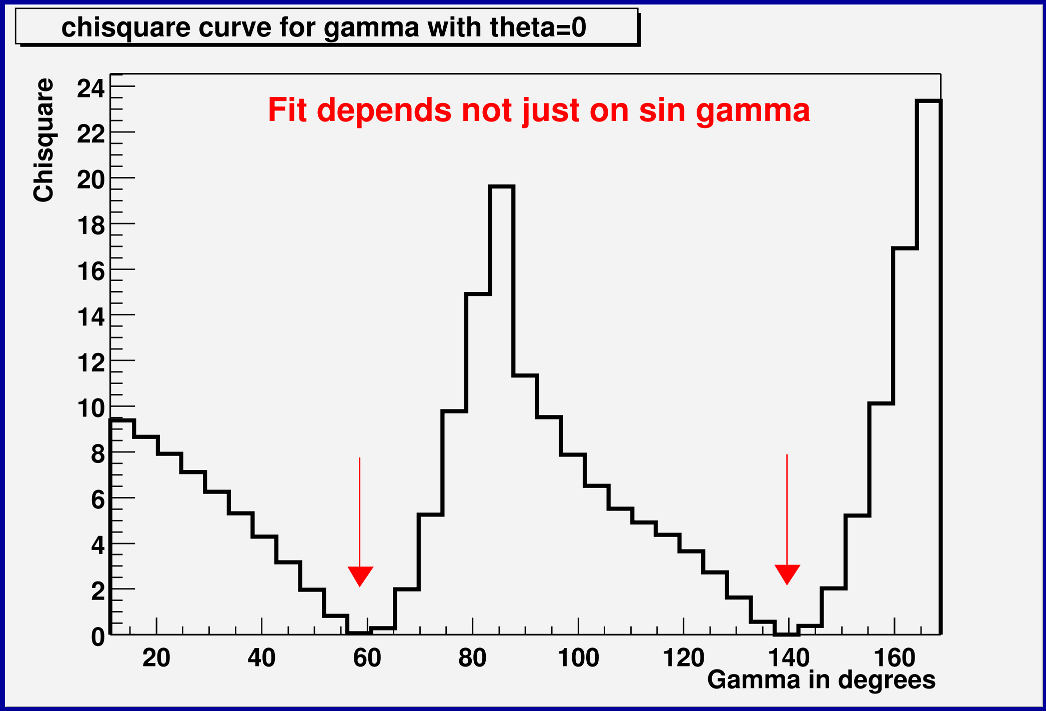


d ~ 0.3
θ ????

Measuring γ with B→hh

- Can solve for d, θ and γ
  - Worse case when sin θ ~ 0 assumed
  - Fit result when
    - $\gamma = 60°$, $\beta = 22.2°$, $\theta = 0$
    - $\sigma_\gamma \sim 10 \pm 3$ degrees

20% SU(3) breaking effects

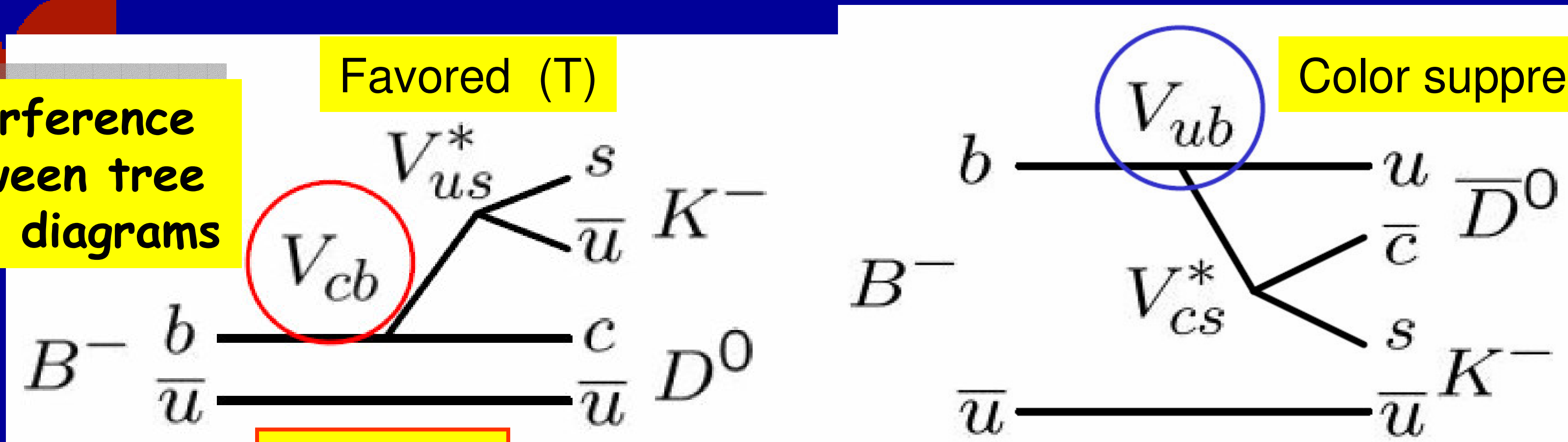


Measurements of γ

- Methods for γ determination at B-factories
  - GLW, ADS, Dalitz
- Recent development at Tevatron and perspectives

Determining γ in $B^{\pm} \to D^{(*)0} K^{(*)\pm}$

Interference Between tree level diagrams



$A_1 \equiv \lambda^3$

$A_2 \equiv \lambda^3 \sqrt{(\rho^2+\eta^2)}\, e^{-i\gamma}\, e^{i\delta}$

Interference if same D^0 and $\bar{D}^0$ final states: $A_{tot} = A_1 + A_2$

- ★ GLW method: $\mathbf{D^0}, \mathbf{\bar{D}^0} \to \mathbf{K^+K^-}, \pi^+\pi^-, \mathbf{K^0_S}\pi^0, \mathbf{K^0_s}\omega, \mathbf{K^0_s}\phi$
- ★ ADS method: $\mathbf{D^0} \to \mathbf{K^+}\pi^-$ (suppr.), $\mathbf{\bar{D}^0} \to \mathbf{K^+}\pi^-$ (fav.)
- ★ GGSZ [Dalitz] method: $\mathbf{D^0}, \mathbf{\bar{D}^0} \to \mathbf{K^0_S}\pi^+\pi^-$

Theoretically clean (no penguins)

3 parameters r_B , γ and δ

~0.36±0.04

F_{CS}~ [0.2,0.6]
(0.3 for $B^0 \to D^0\, \pi^0$)

$$\textbf{Critical parameter } \mathbf{r_B} = \left| \frac{\mathbf{A(B^- \to \bar{D}^0 K^-)}}{\mathbf{A(B^- \to D^0 K^-)}} \right| = \sqrt{\bar{\eta}^2 + \bar{\rho}^2} \times \mathbf{F_{CS}}$$

$r_B \sim$ 0.1-0.2

The GLW Method & observables

Clean but statistically limited: $Bf(B^- \to D^0K^-) \times Bf(D^0 \to cp) \sim 10^{-6}$

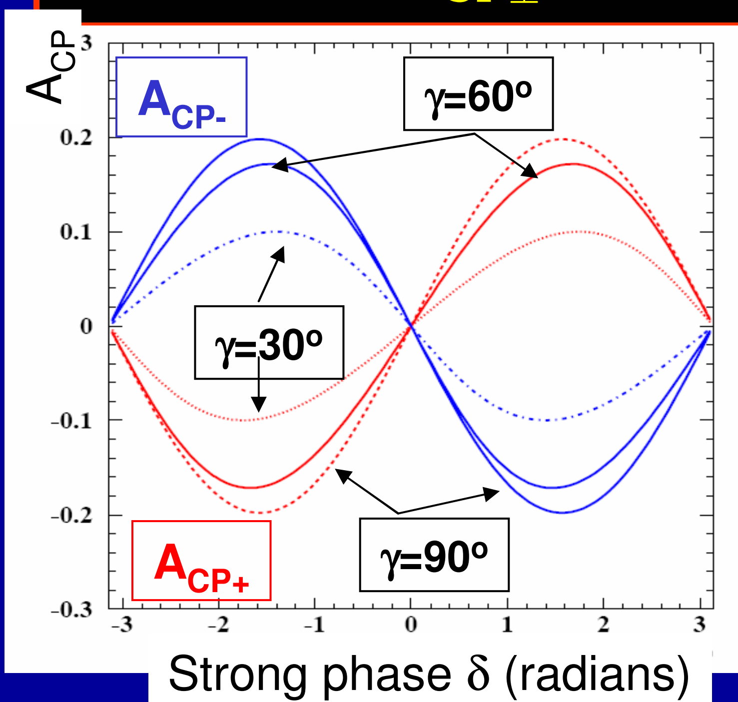
Asymmetry B-/B+ for CP=+1/-1

$$A_{CP\pm} = \frac{\mathcal{B}(B^- \to D^0_\pm K^-) - \mathcal{B}(B^+ \to D^0_\pm K^+)}{\mathcal{B}(B^- \to D^0_\pm K^-) + \mathcal{B}(B^+ \to D^0_\pm K^+)} = \frac{\pm 2 r_B \sin(\delta)\sin(\gamma)}{R_{CP\pm}}$$

Ratio of Bf for CP/non CP

$$R_{CP\pm} = \frac{\mathcal{B}(B^+ \to D^0_\pm K^+) + \mathcal{B}(B^- \to D^0_\pm K^-)}{\mathcal{B}(B^+ \to D^0 K^+) + \mathcal{B}(B^- \to D^0 K^-)} = 1 + r_B^2 \pm 2 r_B \cos(\delta)\cos(\gamma)$$

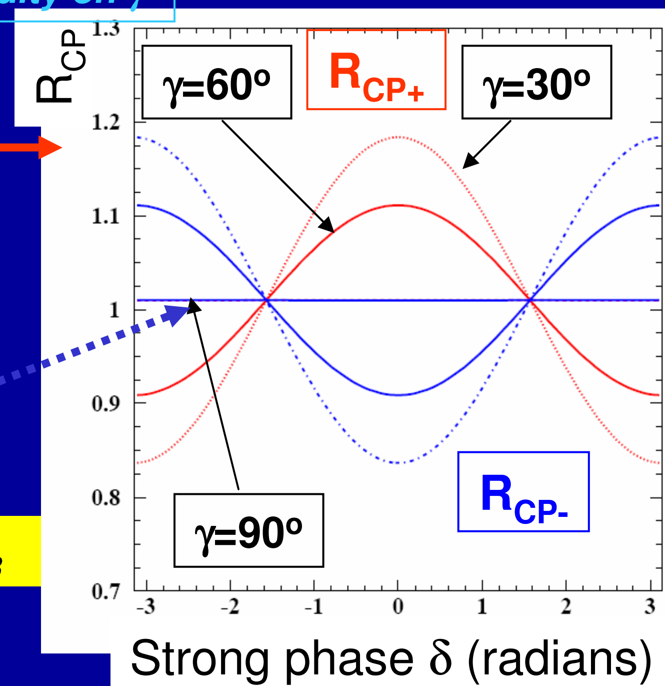
8 fold ambiguity on γ



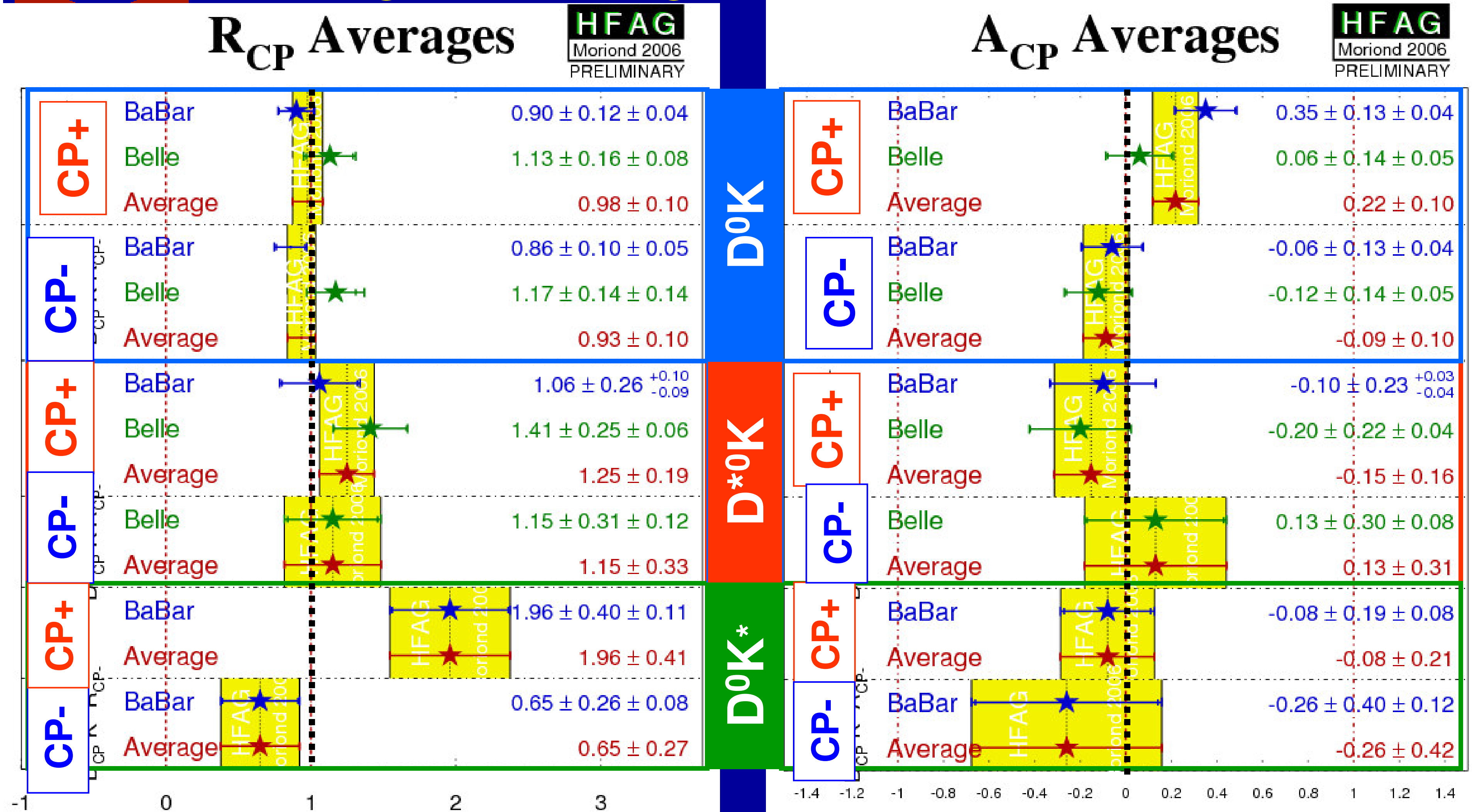
r_B=0.1

$$\frac{R_{CP+} + R_{CP-}}{2} = 1 + r_B^2$$

Weak sensitivity to r_B



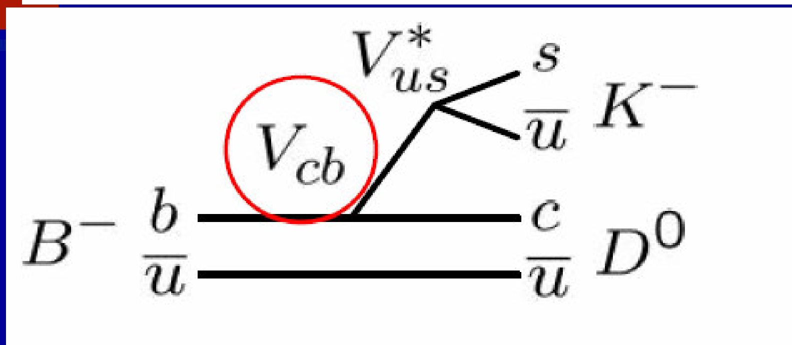
R_{CP} and A_{CP} World Averages

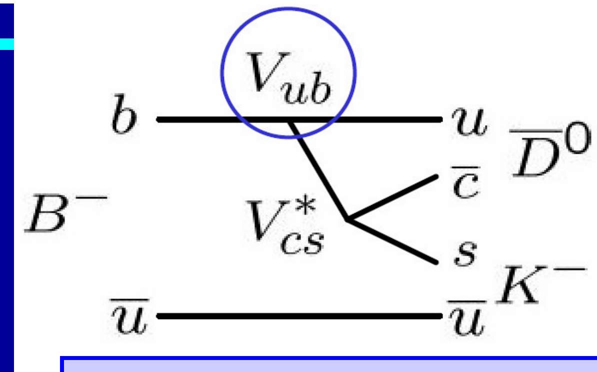


GLW measurements alone do not constraint γ/ϕ_3. Information on γ and r_B from combination with other methods.

Dalitz Analysis of $B^- \to D^{(*)0}[K_S\pi^+\pi^-]K^-$

A.Giri, Y.Grossman,A.Soffer & J.Zupan, Phys.Rev. **D68,** 054018 (2003)





$A_1 = A(B^- \to D^0 K^-) \times \mathbf{A}_D(m^2_{K_S\pi^-}, m^2_{K_S\pi^+})$

$A_2 = r_B\, e^{-i\gamma} e^{i\delta}\, |A(B^- \to D^0 K^-)| \times \mathbf{A}_D(m^2_{K_S\pi^+}, m^2_{K_S\pi^-})$

- Get r_B, γ, δ from simultaneous fit of the $K_s\pi^+\pi^-$ dalitz plot density of B^- and B^+ data

Sensitivity to γ is here!

$$d\sigma(m-,m+) \propto |A_D(m-,m+)|^2 + r_B^2\,|A_D(m+,m-)|^2$$

$$+\, 2\, r_B\, \mathrm{Re}\,[\, A_D(m-,m+)A_D^*(m+,m-)e^{i(-\gamma+\delta)}\,]$$

$B^- \to B^+ \Rightarrow$
$m- \leftrightarrow m+$ and $-\gamma \to +\gamma$

- Need precise knowledge of $A_D(m_-^2, m_+^2)$

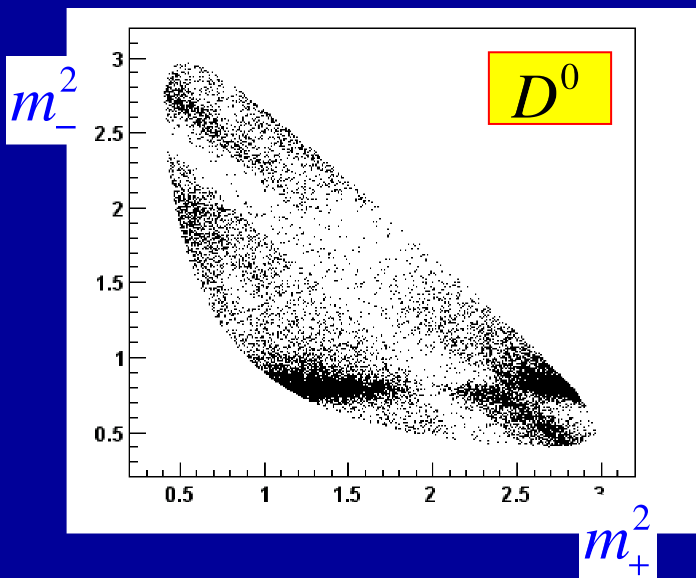
Some model uncertainty in the γ/ϕ_3 measurement

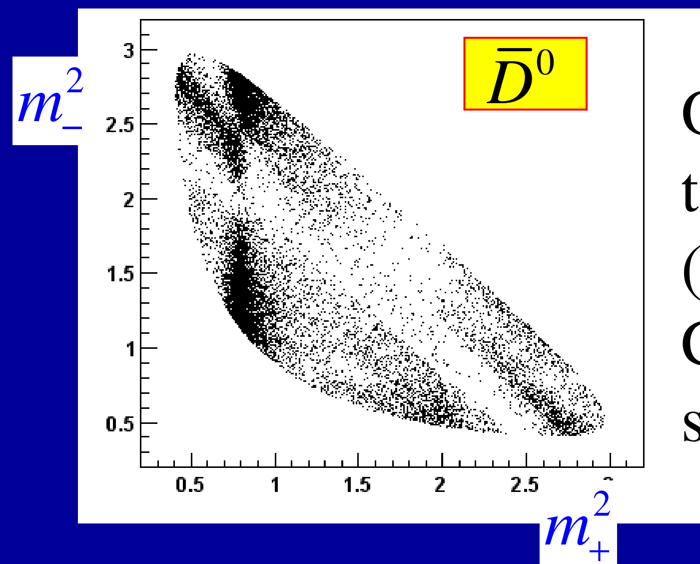
- **Calibrate with large sample of D0**

“Belle” results γ/ϕ_3: Dalitz

$\phi_3 = 53.3^{+14.8}_{-17.7}\,^\circ$

Poluektov *et al* hep-ex/0604054 (subm. PRD)





Obtain from tagged D^0 ($D^{*+} \to D^0\pi^+$) Continuum sample

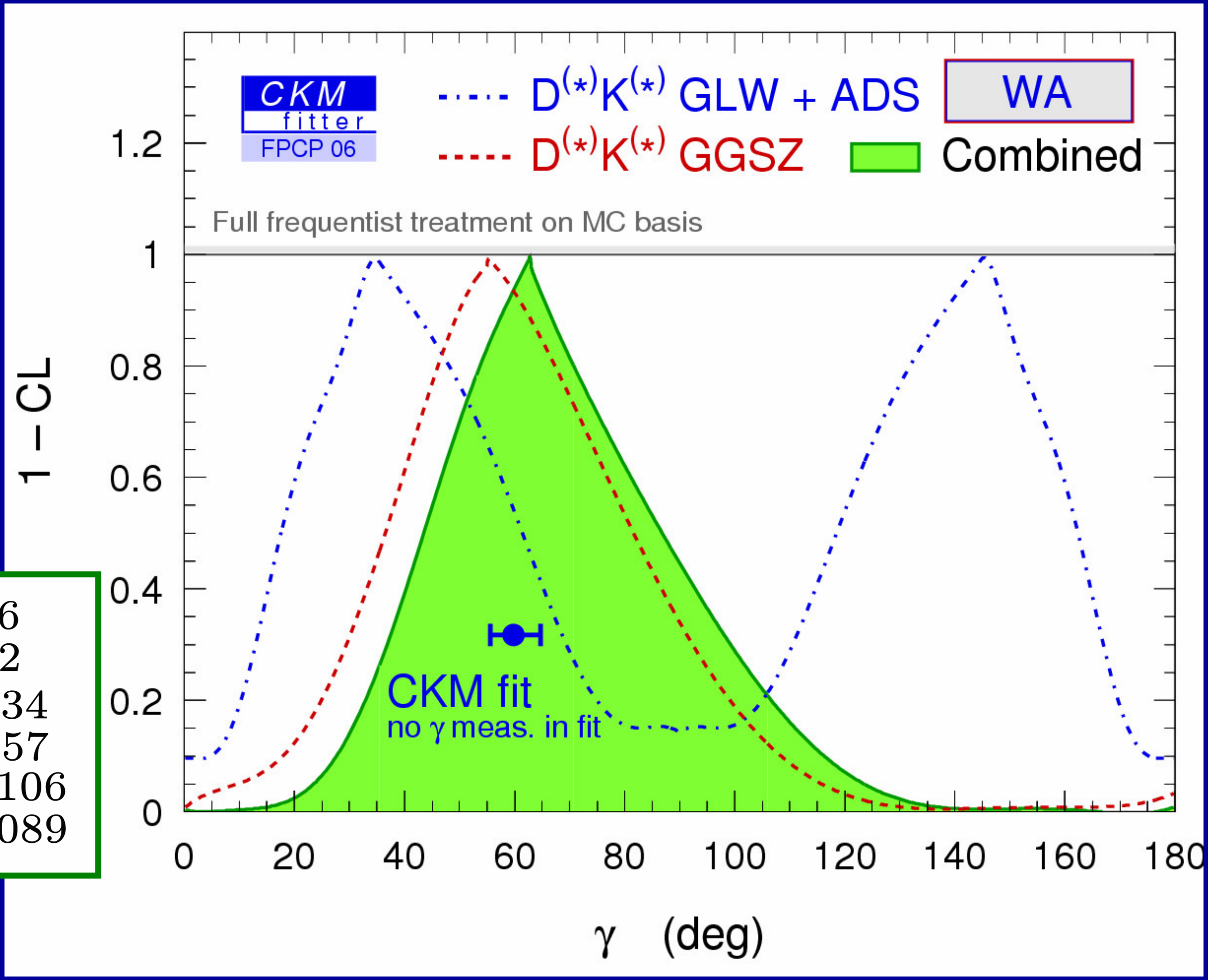
$m_+ = m(K_s\pi^+)$, $m_- = m(K_s\pi^-)$

WA: CKM-Fitter

$\gamma = 59.8^{+13.9}_{-7.9}\,^\circ$

γ summary from B-factories

- WA:
  - $\gamma = 62^{+35}_{-25}$



$$\mathbf{r}_{\mathrm{B}}(DK) = 0.106^{+0.036}_{-0.042}$$
$$\mathbf{r}^*_{\mathrm{B}}(D^*K) = 0.102^{+0.034}_{-0.057}$$
$$\mathrm{rs}_{\mathrm{B}}(DK^*) = 0.176^{+0.106}_{-0.089}$$

GLW γ prospects at Tevatron

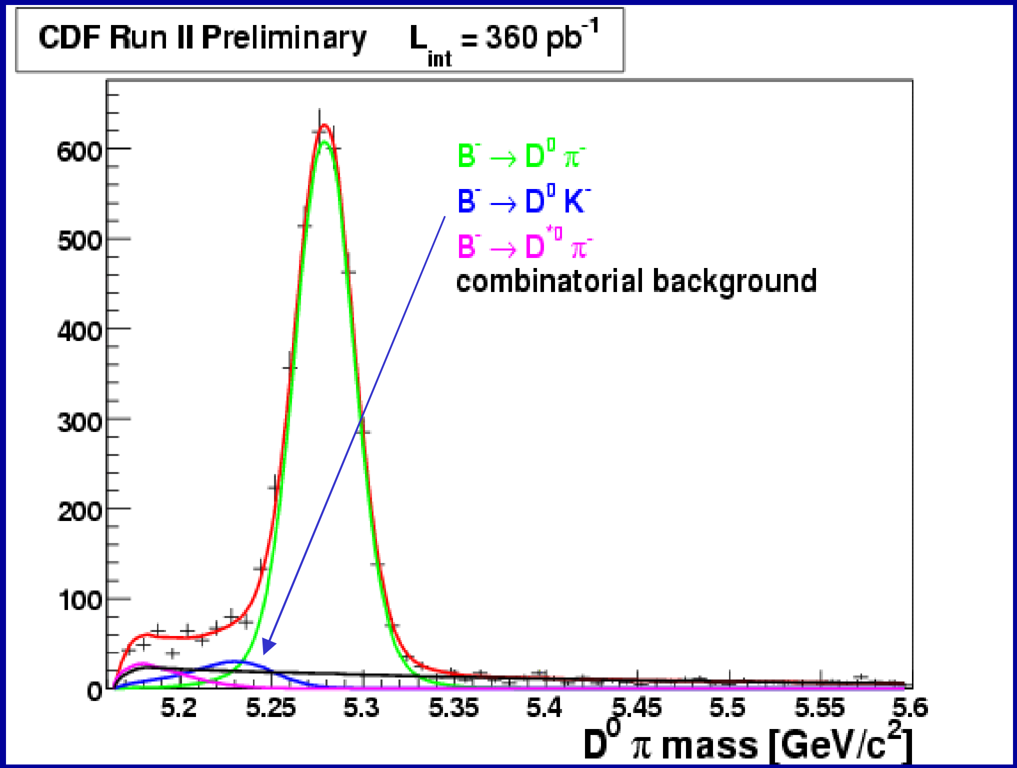
- Same γ searches possible at Tevatron
  - No tagging so statistics pays off in full
- Work in progress:
  - Show status of GLW analysis

GLW γ at Tevatron (1)

- First step achieved with 360 pb^{-1}
  - Measured

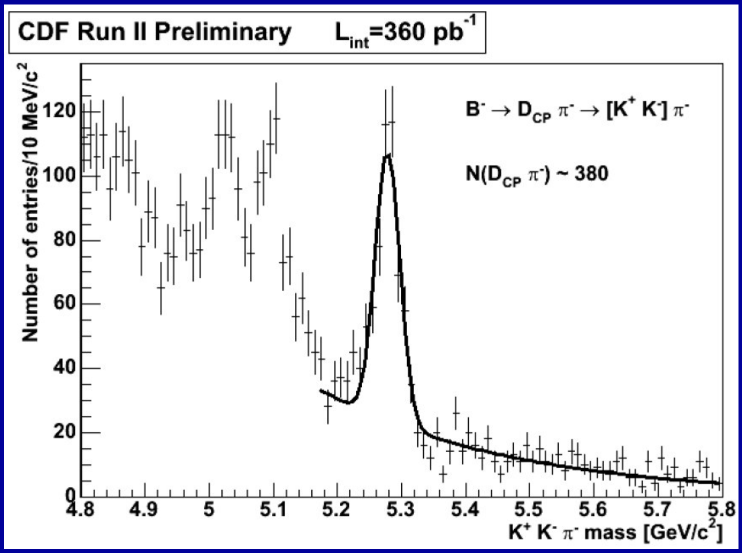
$$R = \frac{BR(B^+ \to D^0_{flav} K^+)}{BR(B^+ \to D^0_{flav} \pi^+)} = 0.065 \pm 0.007\ (stat) \pm 0.004\ (sys)$$

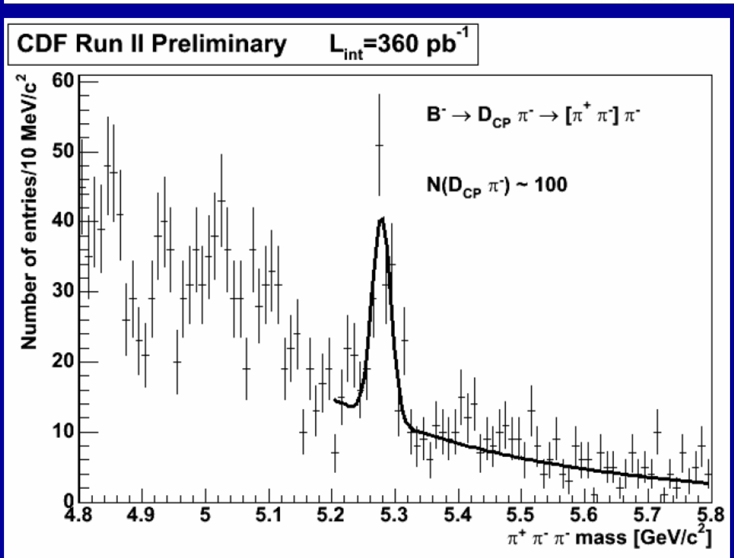
  - Use combination of PID and kinematics as in B→hh case



GLW γ at Tevatron (2)

- Next step iterate procedure on CP D meson decays
- For same D K statistics obtain same resolution as Belle
- Yield comparison:
  - Belle 500fb^{-1}: expect 36k $D^0\pi+$
  - CDF 1 fb^{-1}: 26k $D^0\pi+$
    6 fb^{-1}: 150k $D^0\pi+$
- Tevatron could provide significant improvement of measurement of γ with this method



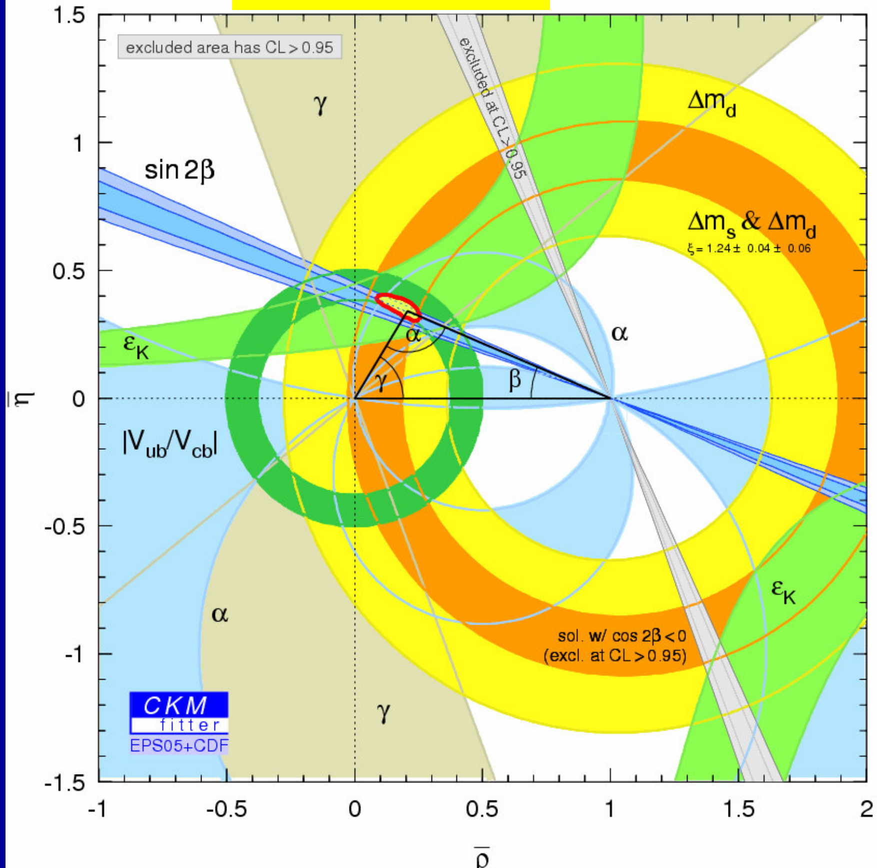


Global fits

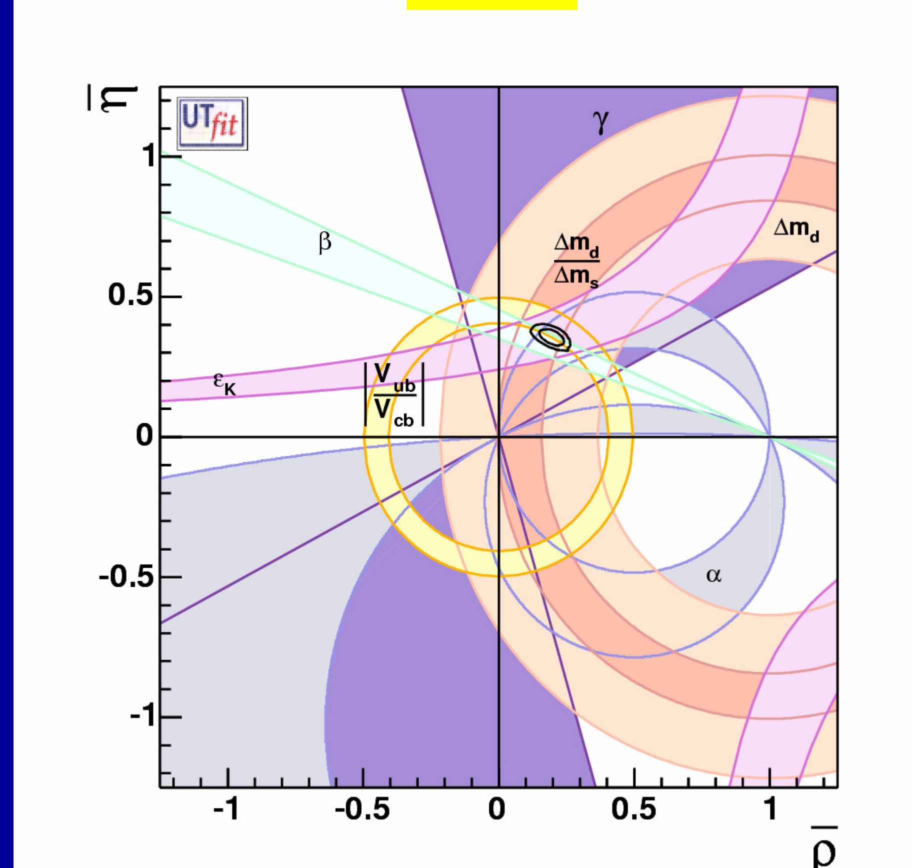
- Can test consistency of all measurements performing global fits of CKM parameters using all available measurements
  - Two major efforts on the market
    - CKM fitter
    - UT fitter

Global fit results

CKM fitter
EPS05+CDF



UT fit
2006



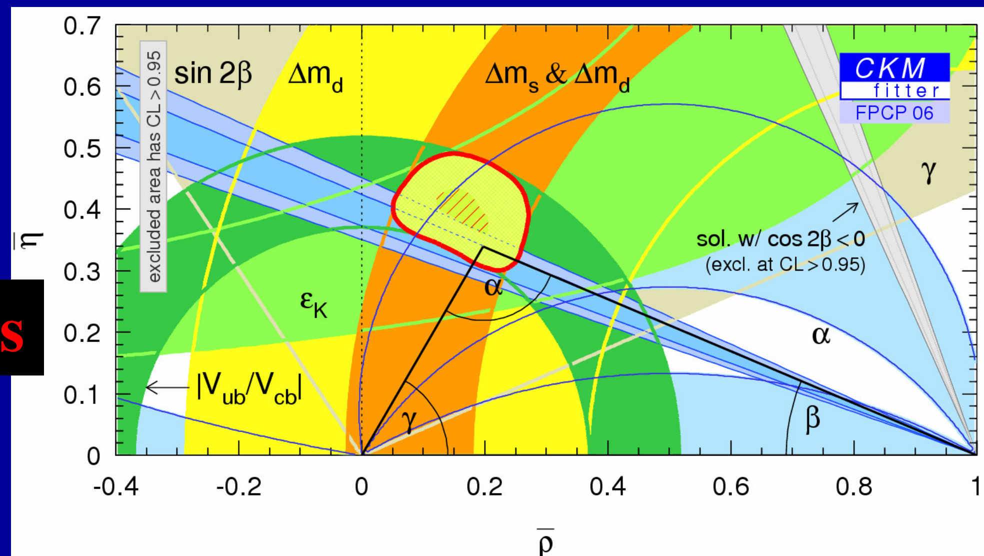
Excellent consistency with Standard Model!!!

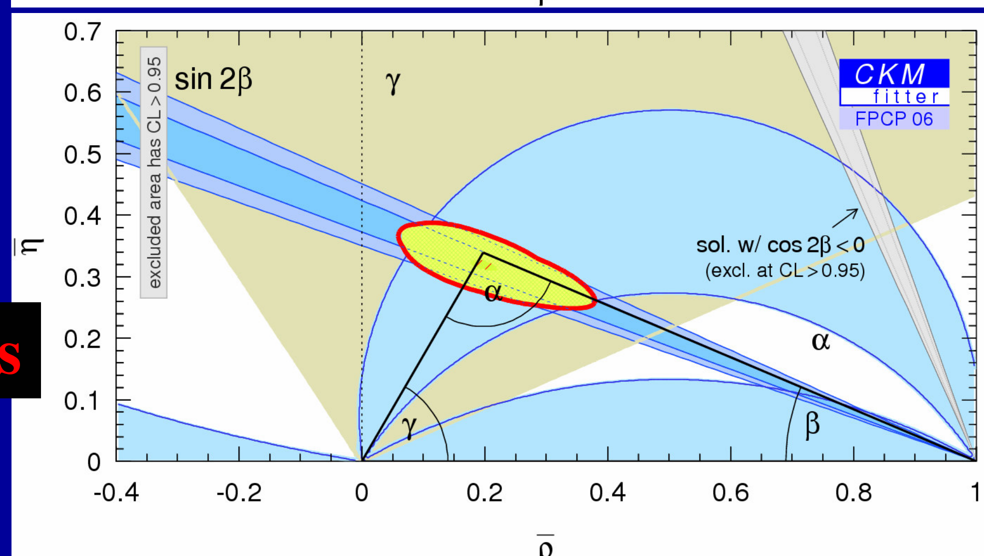
Partial measurement comparisons: angles vs. sides

- Look for hints of discrepancies

sides only:
η=0.342±0.02
ρ=0.216±0.06

Sides



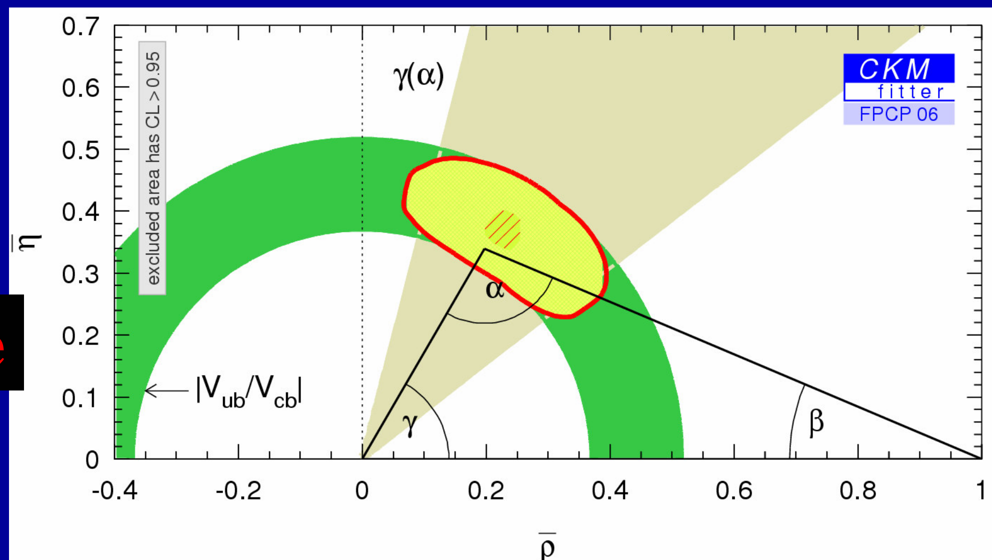


CPV angles only:
η=0.321±0.027
ρ=0.193±0.57

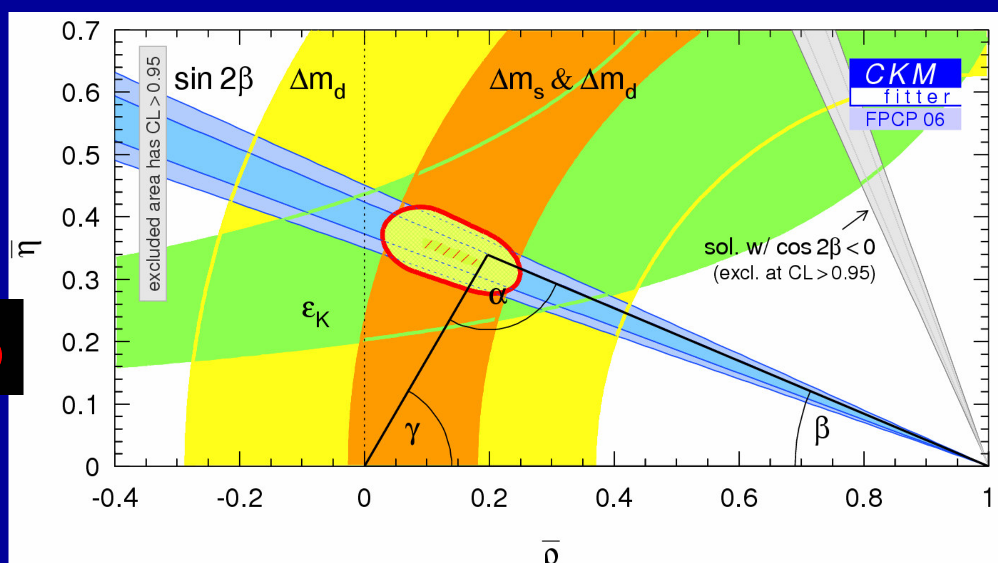
Angles

Partial measurement comparisons: loop vs. tree

Tree



Loop



Conclusions

- CKM is established as the primary source of CP violation
  - On average the SM describes well all present measurements
- New physics in b→ d transitions is highly constrained
  - b → s transitions have become major new focus
    - Tree/penguin discrepancies in sin(2β)
- Improved accuracy required to resolve this
  - Also α and γ need better resolution
- Measurements at hadron colliders can be competitive and complementary (B_s) to B-factories
  - Very interesting to see evolution with full B-factories and Tevatron statistics toward the end of the decade
- New data from LHC-B with LHC startup could continue and extend the Tevatron program
- Future new facilities like Super B factories could continue the work started by BaBar and Belle