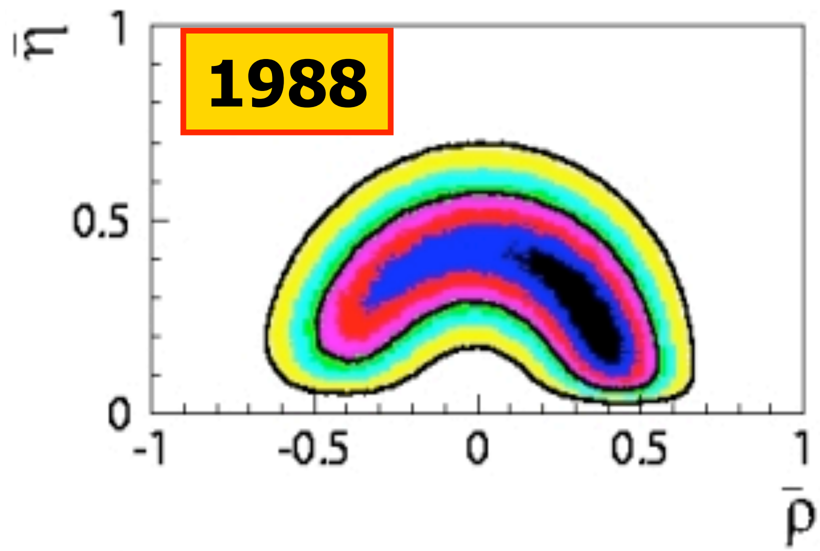
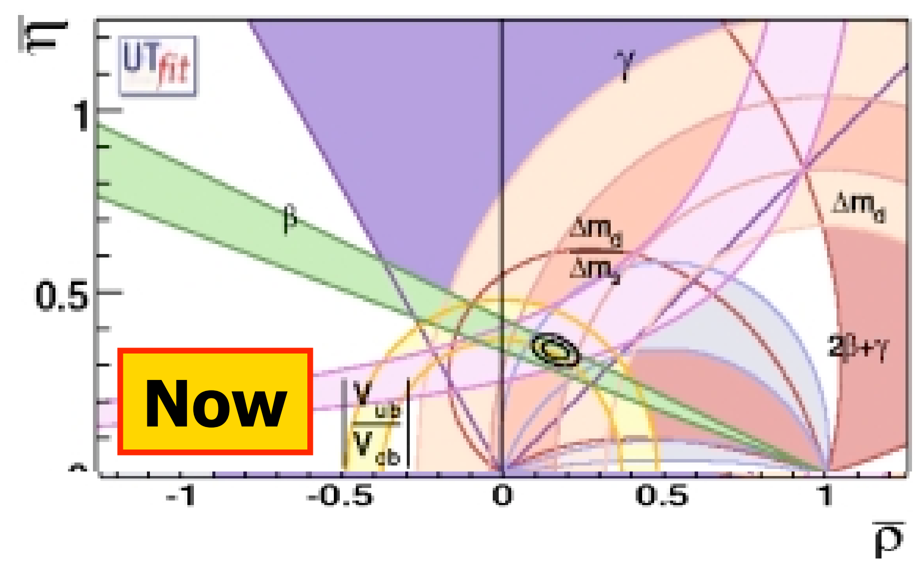
How well do we know the Unitarity Triangle? An experimental overview

Gabriella Sciolla (MIT)





Kaon 2007 - Frascati - May 21 - 25, 2007

Outline

- The beauty of the Unitarity Triangle
  - Its role in understanding CP violation in the Standard Model
  - Sensitivity to New Physics
- The players
  - B factories, Tevatron and kaon experiments
- The measurements
  - CP violation in K^0: the "ε_K band"
  - CP violation in B^0: the angles of the Triangle
  - B^0 mixing and semileptonic B decays: the sides of the Triangle

  … and more!
- What have we learned?
  - Summary and conclusion

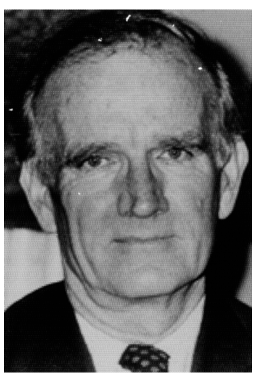
It all started with kaons…

In 1964 Cronin and Fitch discovered CP violation in the decays of K_L mesons: $K_L \rightarrow \pi^+\pi^-$

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

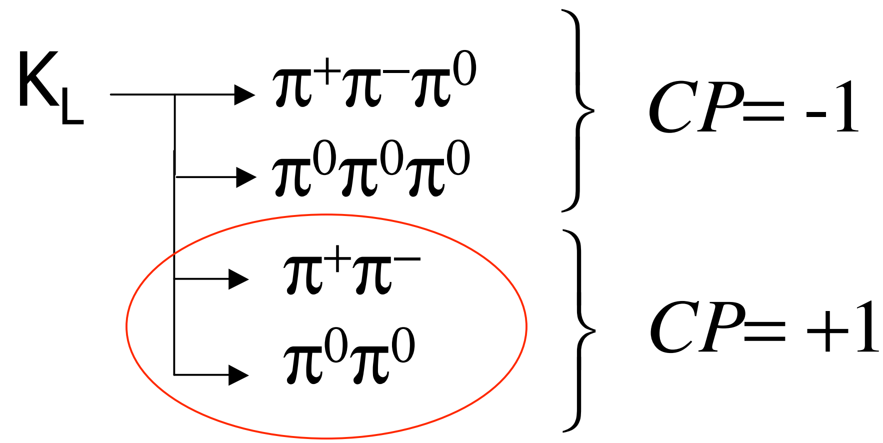
J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)



V. Fitch

J.Cronin

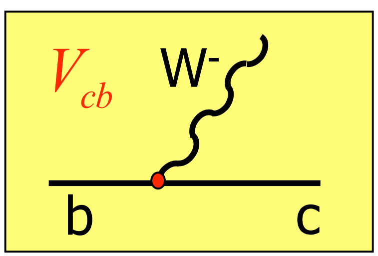
1980 NOBEL PRIZE



CP violation in the Standard Model

- Explained in Standard Model in 1973 by Kobayashi and Maskawa
- In KM mechanism, CP violation originates from a complex phase in the quark mixing matrix (CKM matrix)

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



A,λ (Cabibbo angle): very well measured
ρ,η: poorly known until recently

Going beyond CKM

The (many) strengths of CKM

- ✓ Simple explanation of CPV in SM
- ✓ It is very predictive: only one CPV phase
- ✓ It accommodates all experimental results
  - CP violation in $K \rightarrow \pi\pi$ and $K_L \rightarrow \pi l \nu$
  - CP violation in the B system

New Physics models have many sources of CP violation

- e.g.: MSSM has 43 new CP violating phases!

→ Exploit CKM prediction power: use CPV as probe for New Physics

Measure CP violation in channels theoretically well understood and look for deviations w.r.t. SM expectations

The Unitarity Triangle

Unitarity of CKM implies: $V^{\dagger}V = 1$ → 6 unitarity conditions

Of particular interest: $\mathbf{V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0}$

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

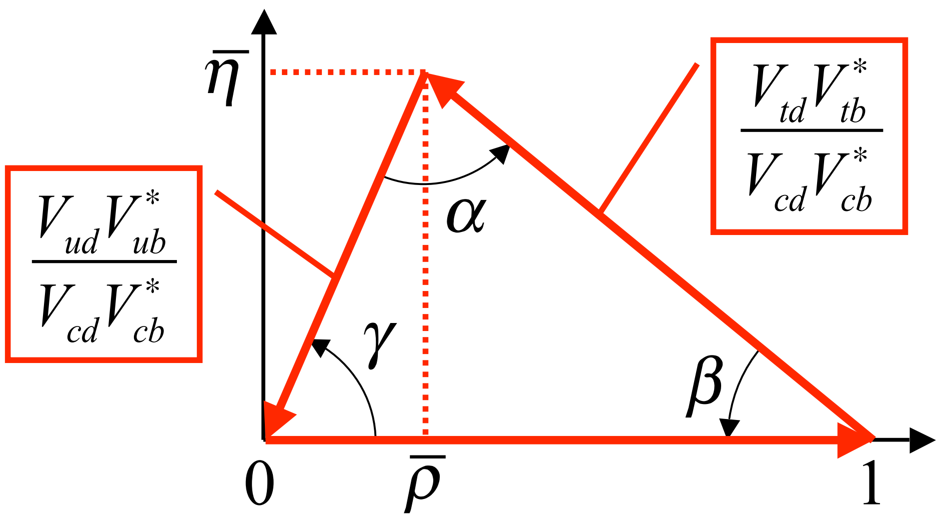
All sides are ~ O(1) → possible to measure both sides and angles!

- CP asymmetries in B meson decays measure α, β and γ
- Sides from semileptonic B decays, B mixing, rare B decays
- Complementary constraints from CP violation in K_L (ε_K)

The Unitarity Triangle

Unitarity of CKM implies: $V^\dagger V = 1$ → 6 unitarity conditions

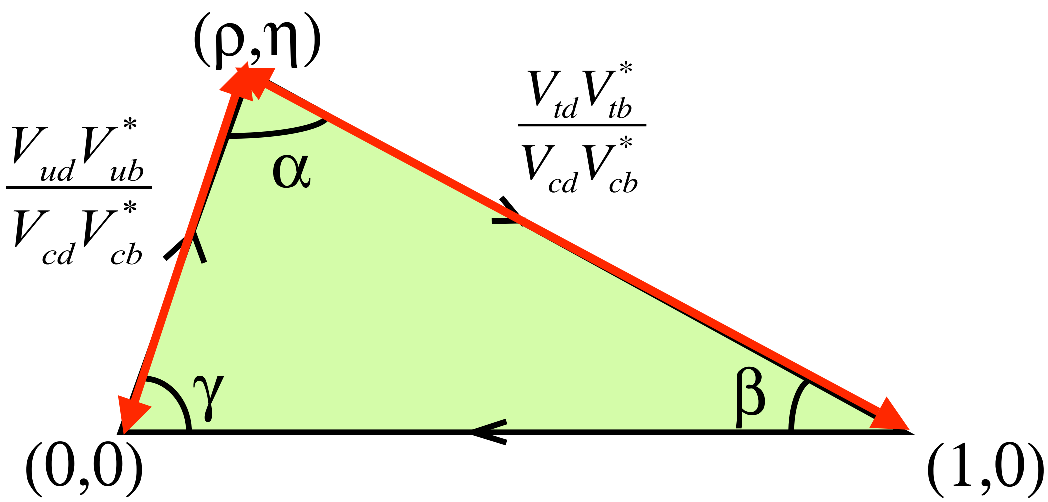
Of particular interest: $\mathbf{V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0}$



All sides are ~ O(1) → possible to measure both sides and angles!

- CP asymmetries in B meson decays measure α, β and γ
- Sides from semileptonic B decays, B mixing, rare B decays
- Complementary constraints from CP violation in K_L (ε_K)

Going beyond the Standard Model



- Two measurements fully define the apex
  - This triangle has a base normalized to 1
- All additional measurements probe Physics Beyond SM
  - All pieces of the puzzle must fit in the Standard Model
  - Inconsistencies can be explained only by New Physics

Precision and redundancy are essential!

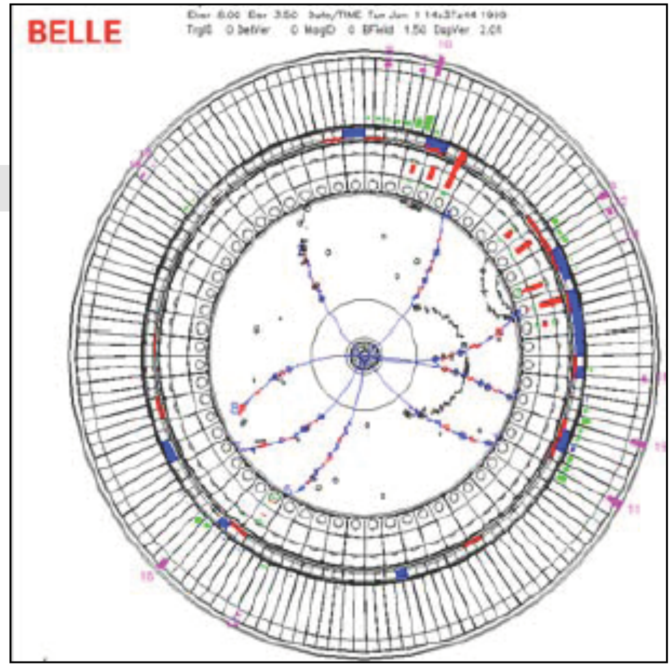
The experiments:

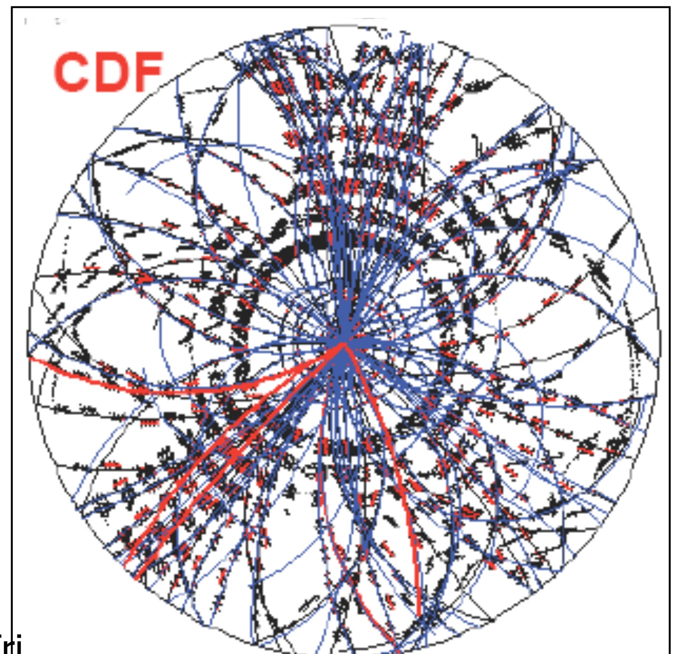
B meson experiments

- Asymmetric B factories:
  BaBar (SLAC) and Belle (KEK)
  - $e^+e^- \rightarrow \Upsilon(4s) \rightarrow B\bar{B}$
  - Very clean environment
  - Very high luminosity

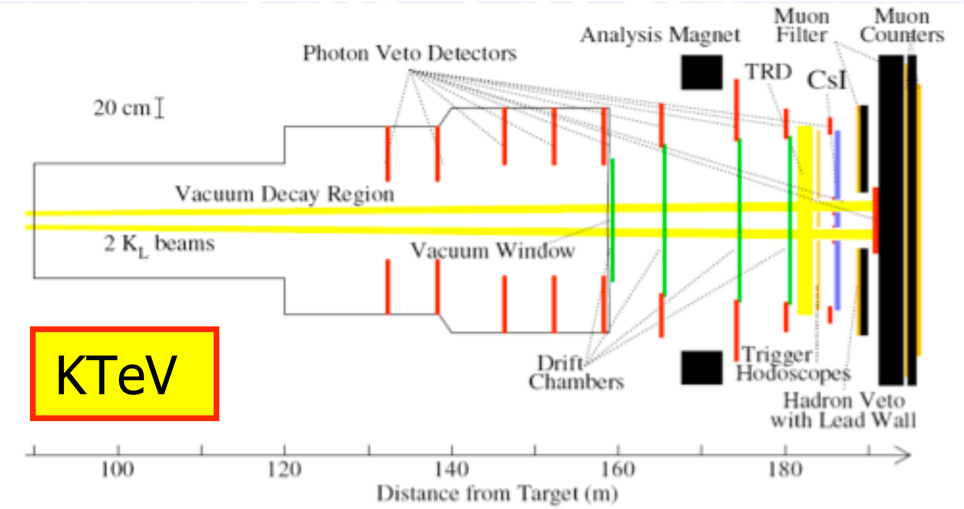
1 billion $B\bar{B}$ pairs (BaBar/Belle)

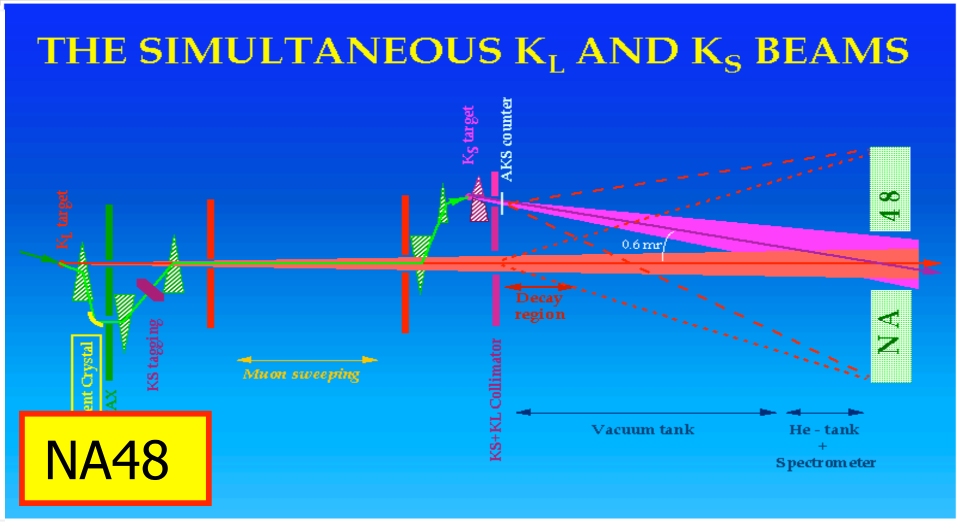
- Tevatron experiments:
  CDF and D0 at Fermilab
  - $p\bar{p}$ collisions at $\sqrt{s} \sim 2$ TeV
  - Challenges: high multiplicity and $b\bar{b}$ trigger
  - Complementarity: all b hadrons are produced
    - B_S, Λ_b, B_C, …

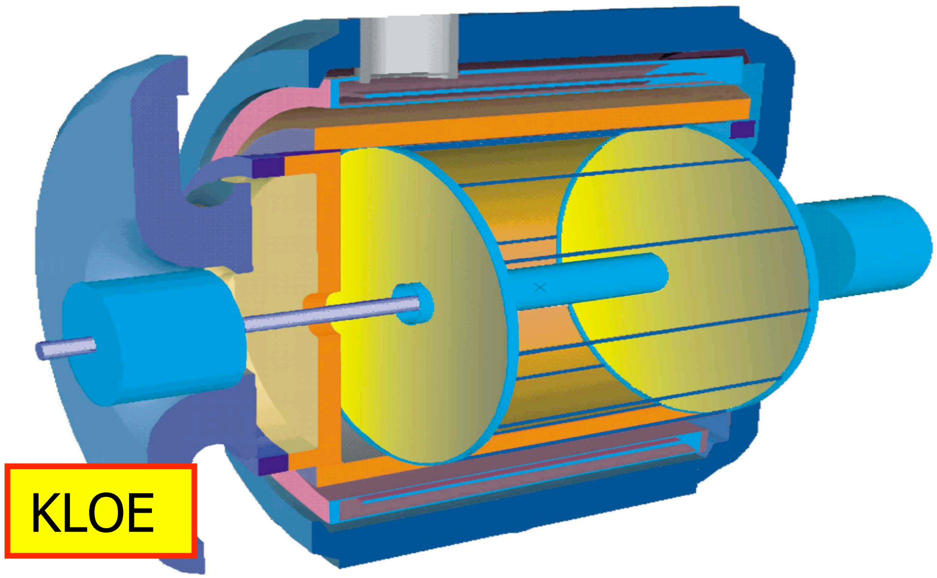


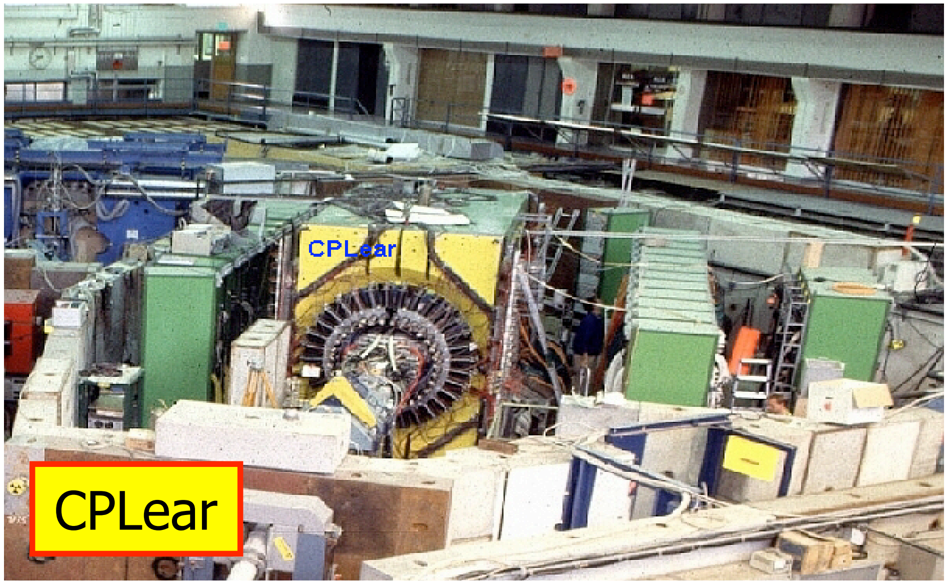


Kaon Experiments

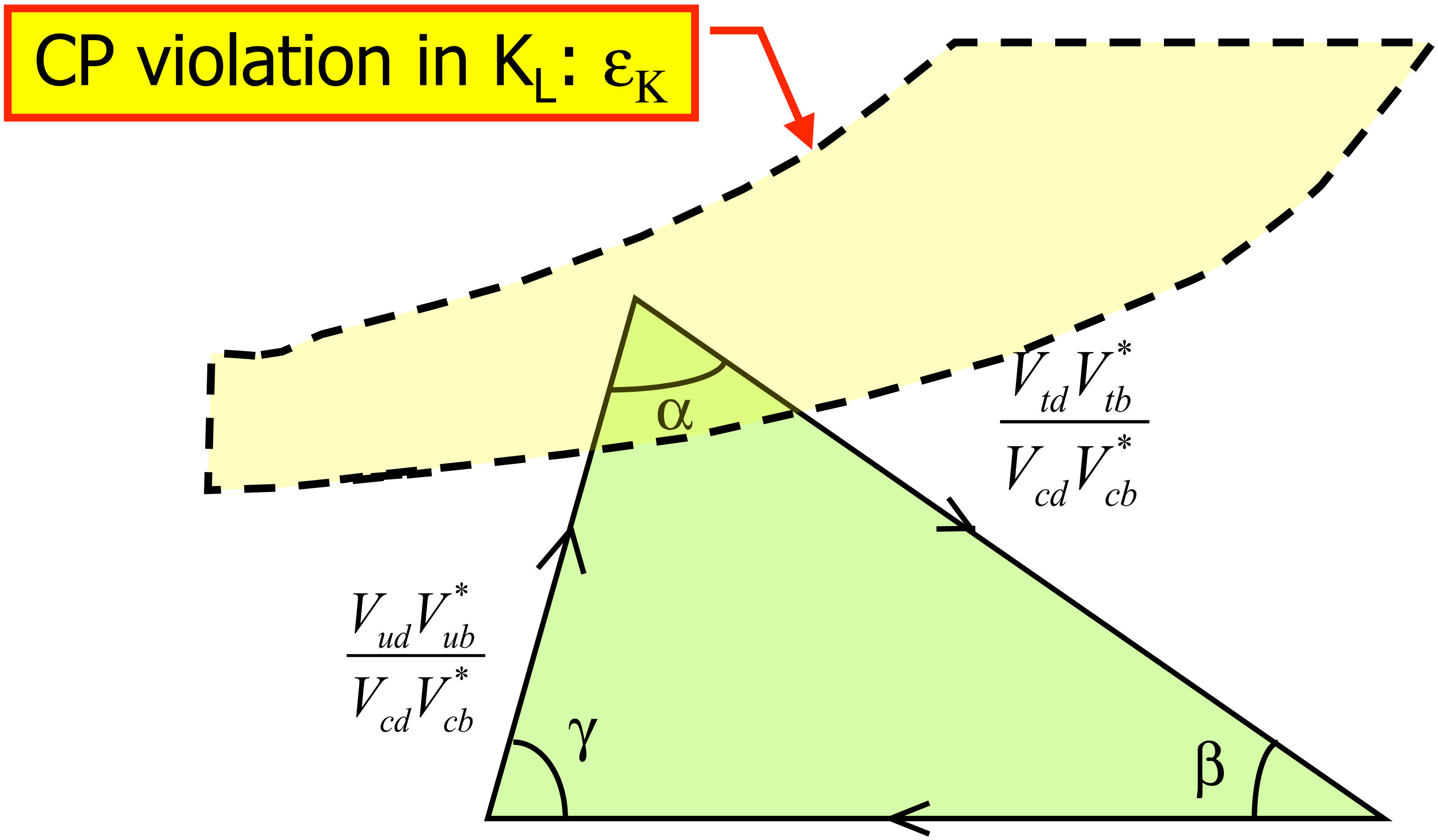








The measurements: ε_K



CP violation in K_L

- Constraints on Unitarity Triangle come from indirect CP violation (due to mixing): ε

$$|\varepsilon_K| \sim \frac{2}{3}|\eta_{+-}| + \frac{1}{3}|\eta_{00}|$$

$$\text{where} \begin{cases} \eta_{+-} = \dfrac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \sqrt{\dfrac{BF(K_L \to \pi^+\pi^-)}{\tau_L} \dfrac{\tau_S}{BF(K_S \to \pi^+\pi^-)}} \\ \eta_{00} = \dfrac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \sqrt{\dfrac{BF(K_L \to \pi^0\pi^0)}{\tau_L} \dfrac{\tau_S}{BF(K_S \to \pi^0\pi^0)}} \end{cases}$$

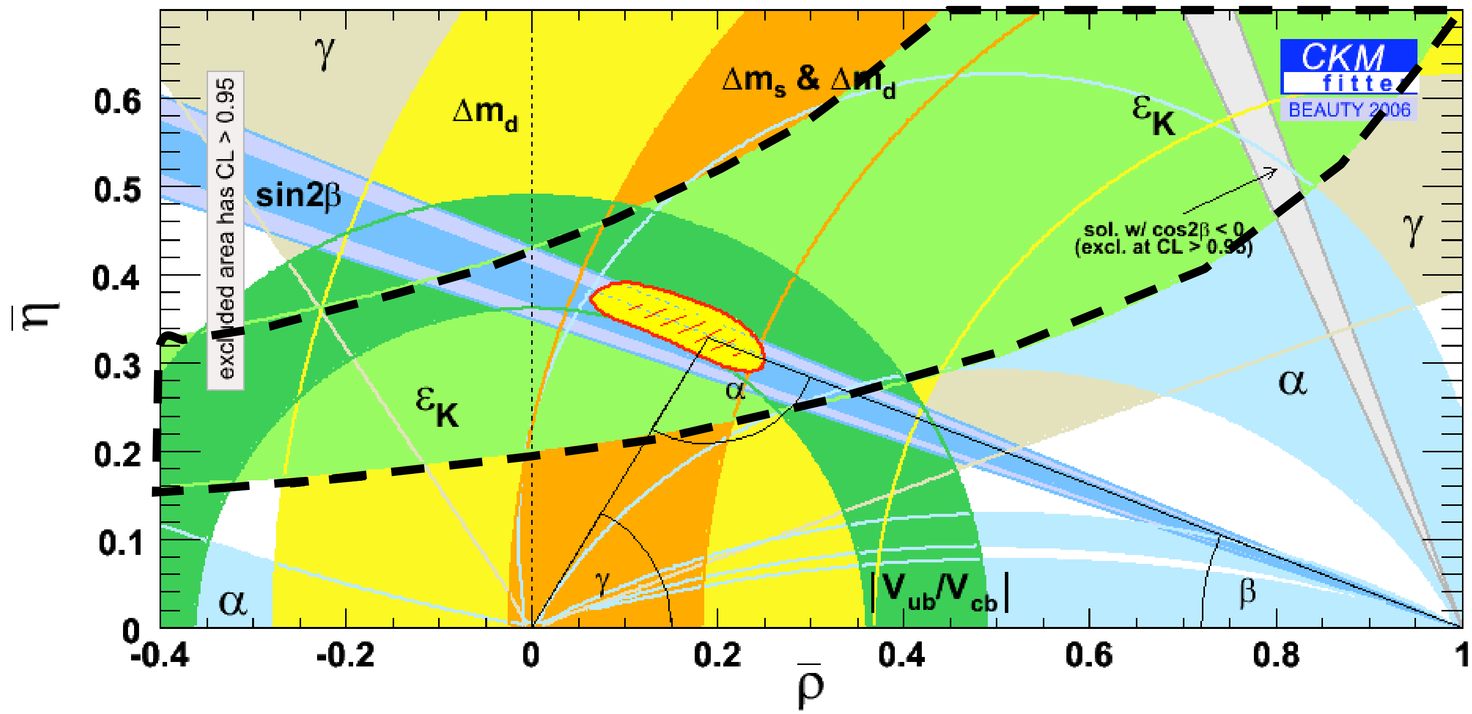
- World Average in PDG 2006:

$$|\varepsilon_K| = (2.232 \pm 0.007) \times 10^{-3}$$

Precision: 0.3%!

  - NB: ~3.7σ shift wrt PDG 2004 after including: KTeV, KLOE, NA48

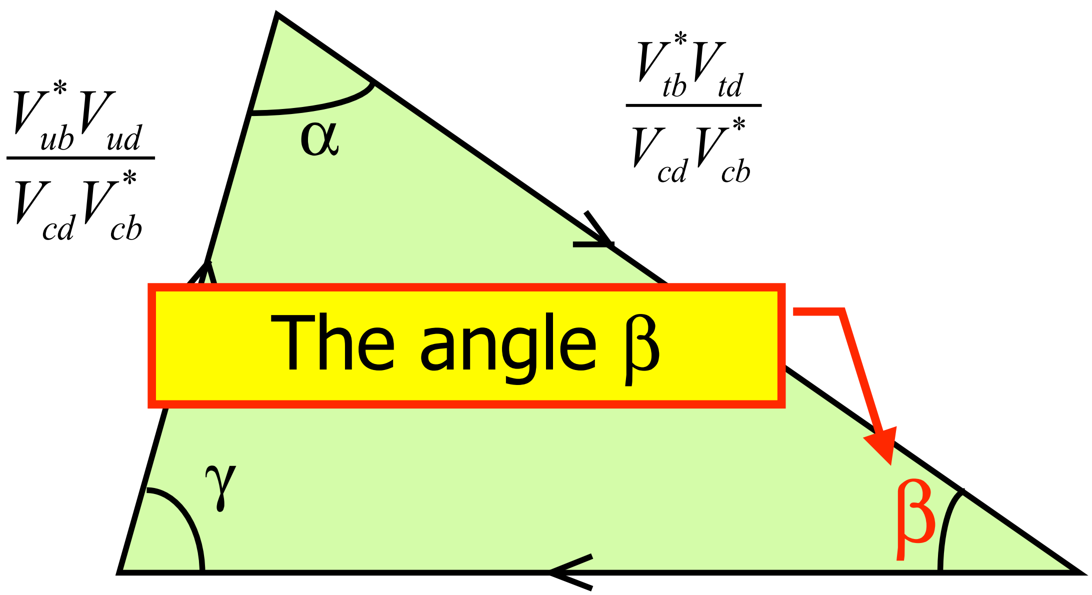
Kaons's contribution to the UT: ε_K



- Experimental error on ε_K ~ 0.3%

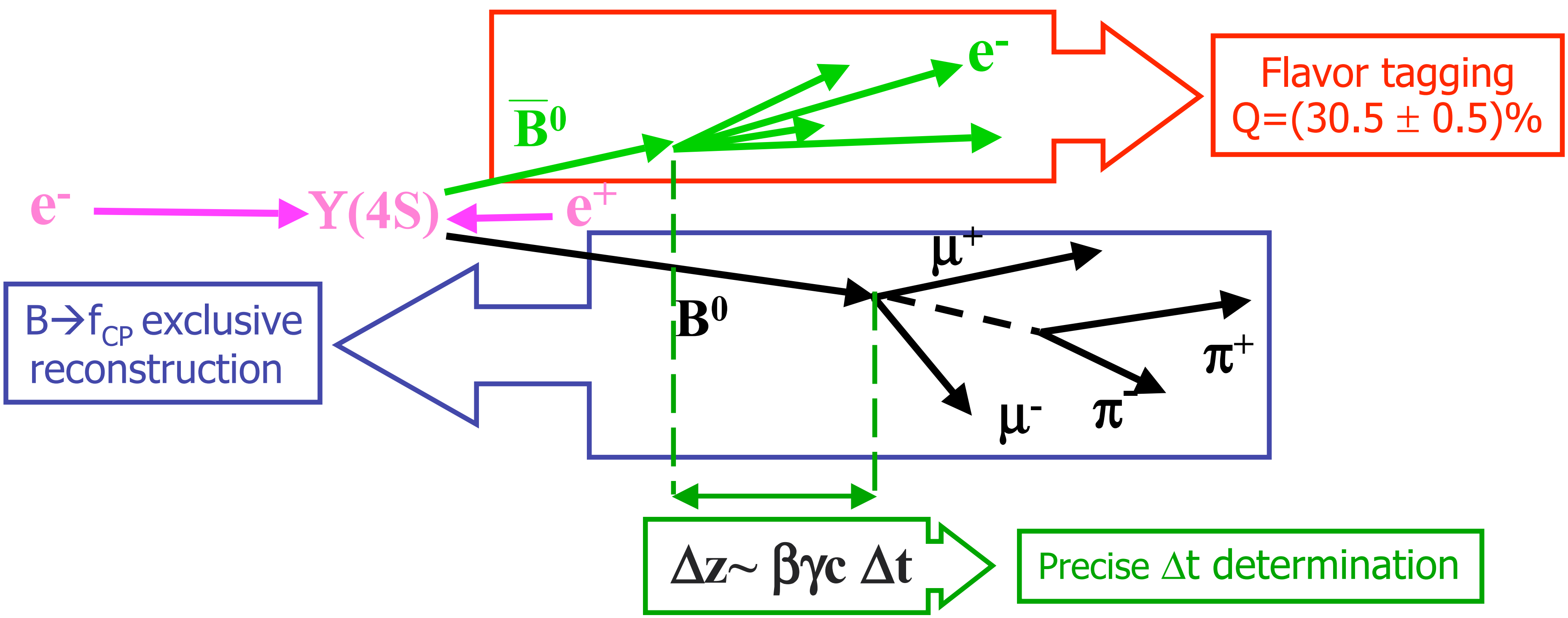
  … but large errors on constraints of (ρ,η)
  - Bag parameter from Lattice QCD B_K=0.86 ± 0.06 ± 0.14 (16% precision)
  - Kaon decay constant from leptonic decay rate f_K=(159.8 ± 1.5) MeV

The measurements: β

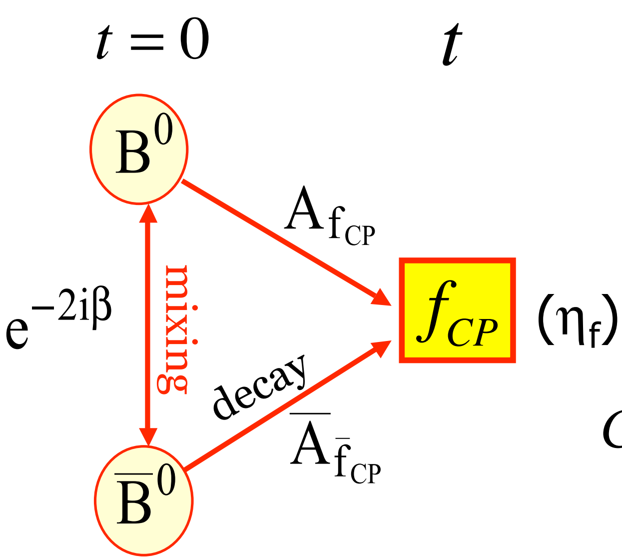


How to measure the CP asymmetry

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



CP violation at the B factories



$$A_{CP}(t) = \frac{N(\bar{B}^0(t) \to f_{CP}) - N(B^0(t) \to f_{CP})}{N(\bar{B}^0(t) \to f_{CP}) + N(B^0(t) \to f_{CP})}$$
$$= S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2} \qquad \lambda_f = \frac{q}{p} \cdot \frac{\bar{A}_f}{A_f}$$

- When only one diagram contributes to the final state, $|\lambda|=1$

$$\begin{cases} C_f = 0 \\ S_f = \mathrm{Im}\,\lambda \end{cases}$$

$$A_{CP}(t) = \pm\, \mathrm{Im}\lambda \, \sin(\Delta m t)$$

(CP violation in interference between mixing and decays in B^0)

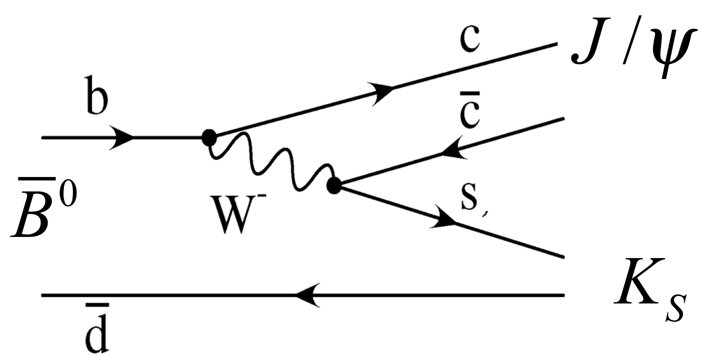
CP violation in B^0 decays: sin2β

For some modes, Imλ is directly and simply related to the angles of the Unitarity Triangle.

Example:

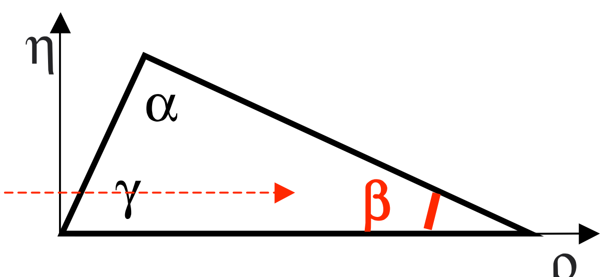
$B^0 \to J/\Psi K_S$: the "golden mode"

- Theoretically clean
- Experimentally clean
- Relatively large BF ($\sim 10^{-4}$)



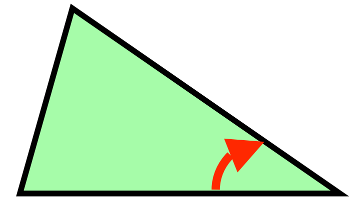
$$\lambda = \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)_{B^0_{mix}} \left(\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*}\right)_{decay} \left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right)_{K^0_{mix}} = e^{-i2\beta}$$

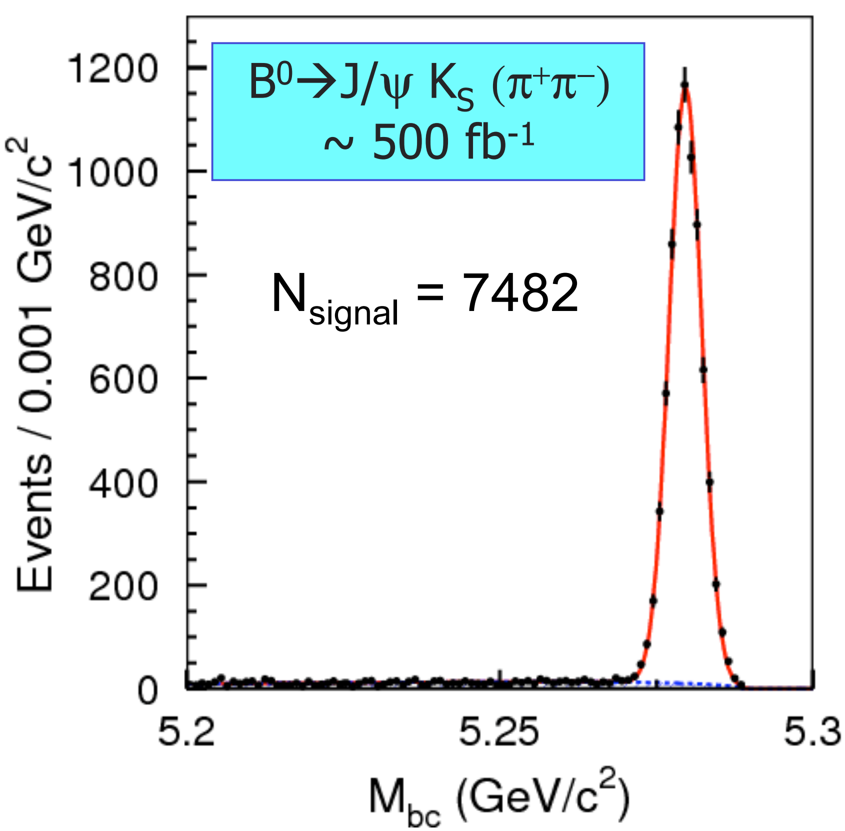
$A_{CP}(t) = \sin 2\beta \sin \Delta m t$

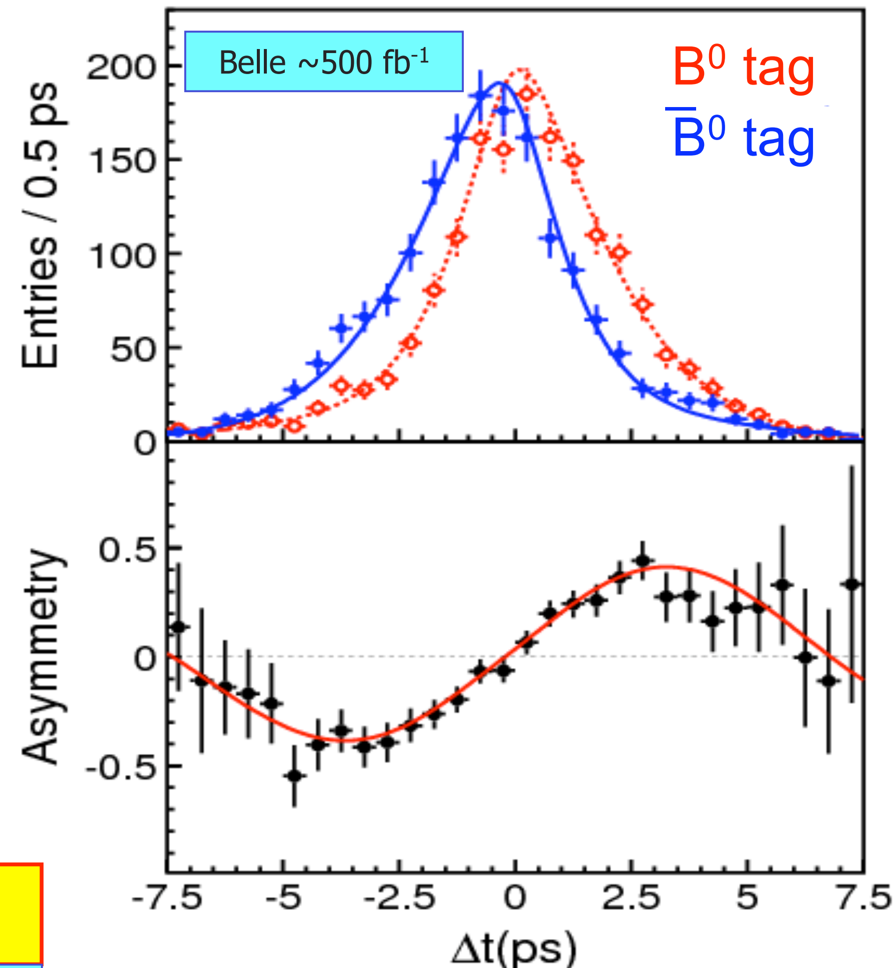


The golden mode for sin2β:

sin2β in $B^0 \to J/\psi\ K^0$



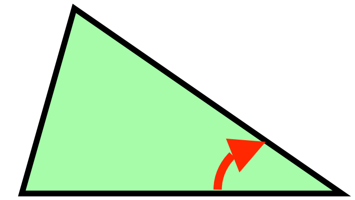


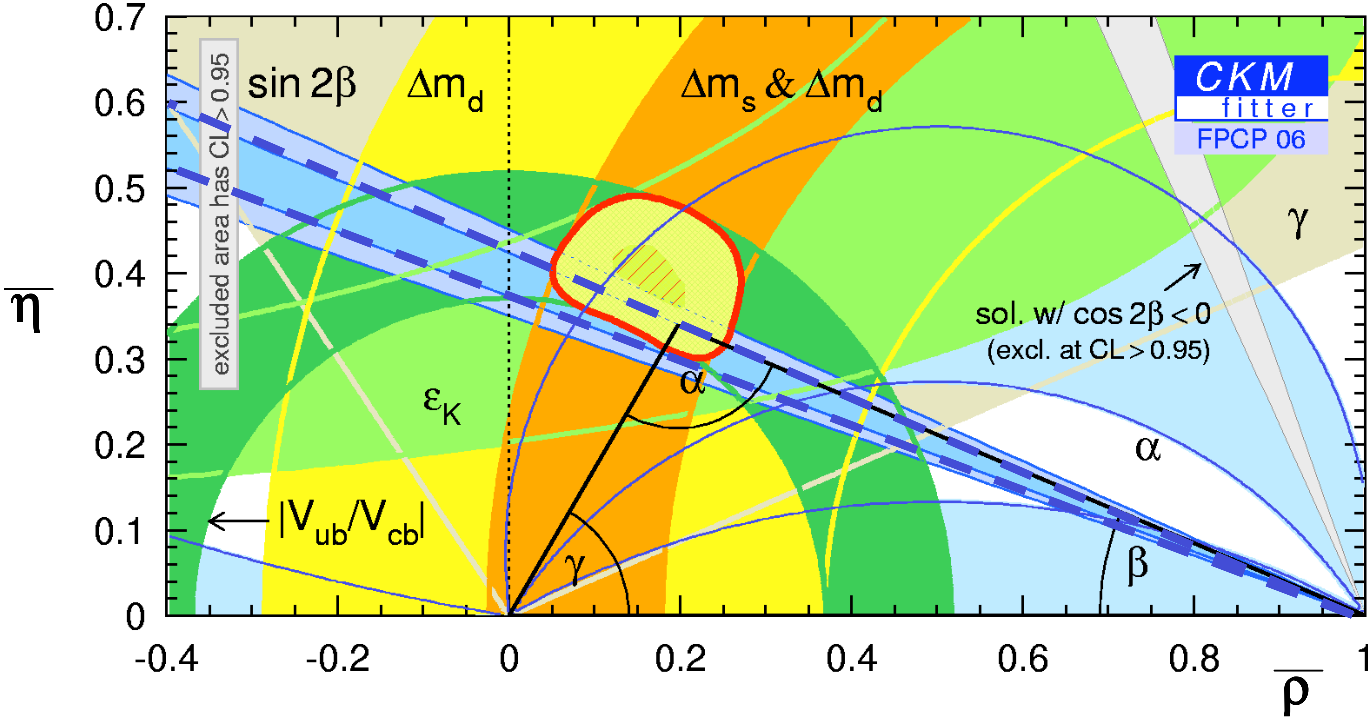


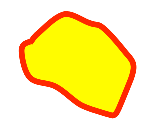
$\sin(2\beta) = 0.678 \pm 0.026$

BaBar+Belle Moriond 2007

Constraints from β on the UT





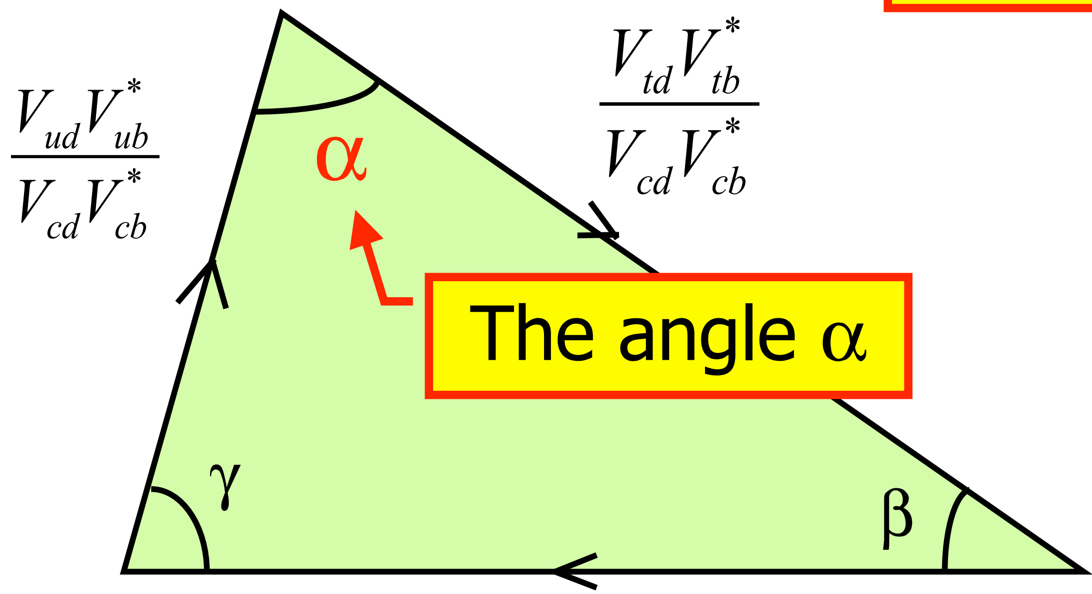


95% CL
from other
measurements

- sin2β is measured with a precision of 3.8%
  - Most stringent constraint for Unitarity Triangle
- Precision is purely dominated by statistical error
  - Will improve in the near future

The measurements: α

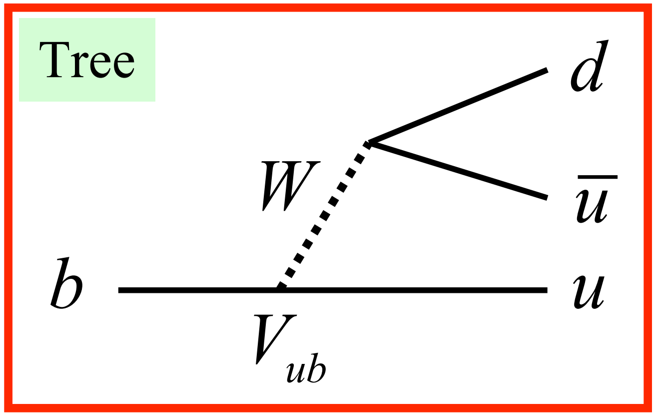
$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

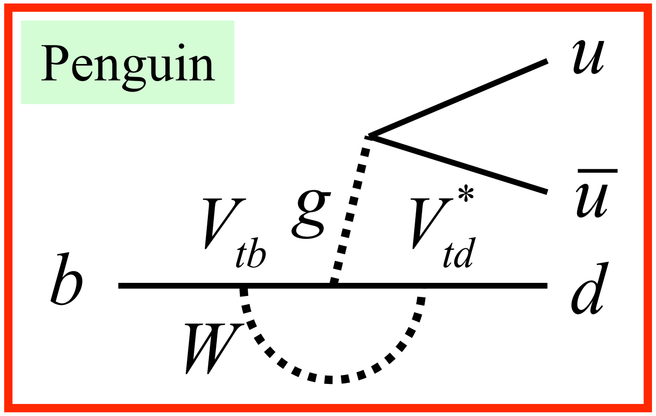


α from $B^0 \rightarrow \pi\pi, \rho\rho, \rho\pi$

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

- Not as simple as β in the golden mode: tree and penguin diagrams



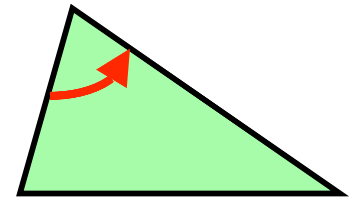


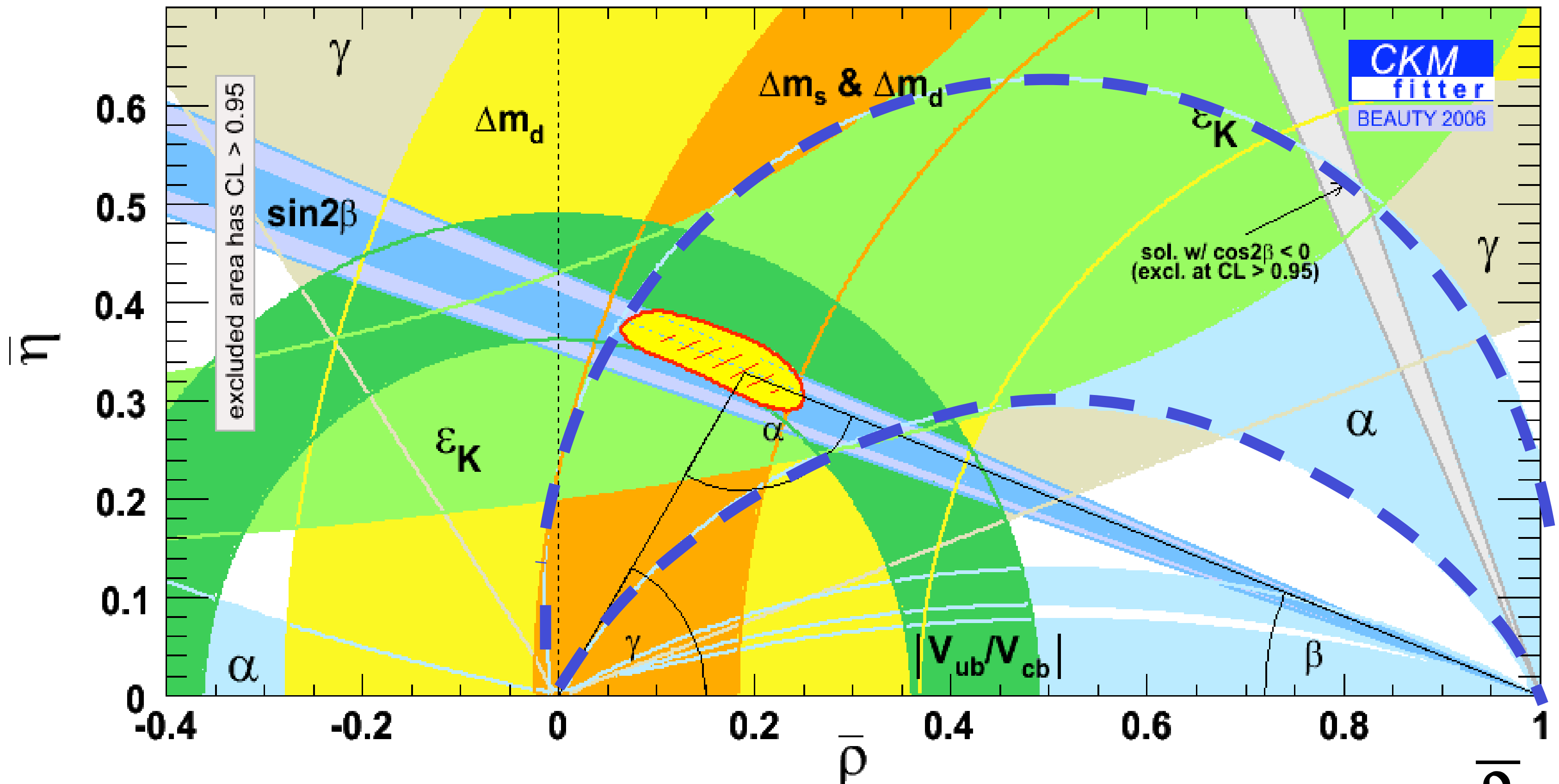
- $A_{CP}(t)$ will have two contributions:

$$A_{CP}(t) = S\sin(\Delta m t) - C\cos(\Delta m t)$$

  - S measures UT angle α
  - C measures direct CP violation

Combined constraints on α





ρ̄

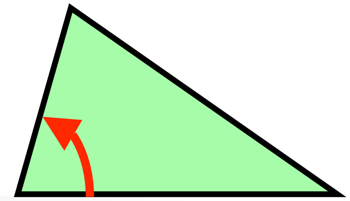
Average of BaBar and Belle

$$\alpha = \left(92.6^{+10.7}_{-9.3}\right)^\circ$$

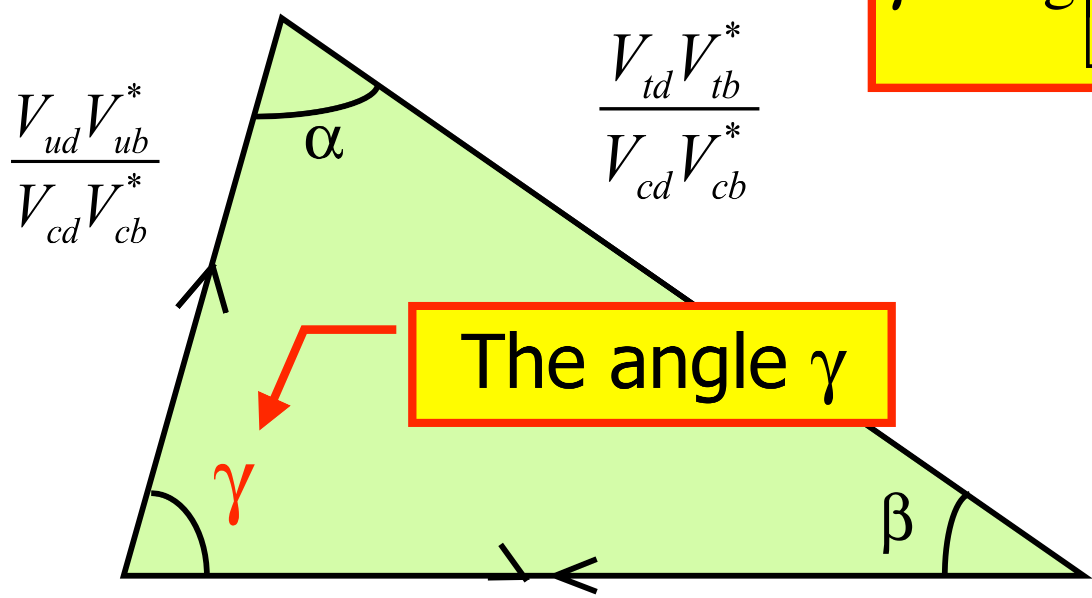
CKM fit

$$\alpha = \left(100.0^{+4.5}_{-7.3}\right)^\circ$$

The measurements: γ



$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

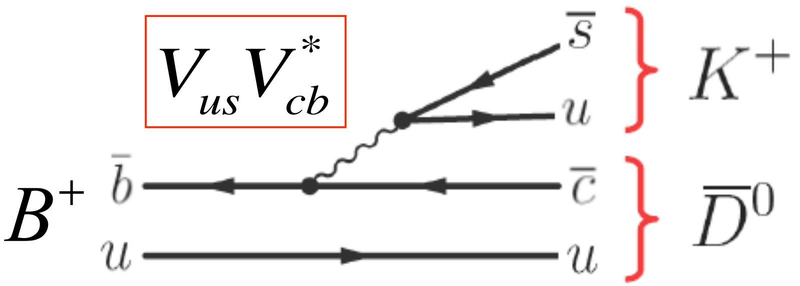


The angle γ

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right]$$

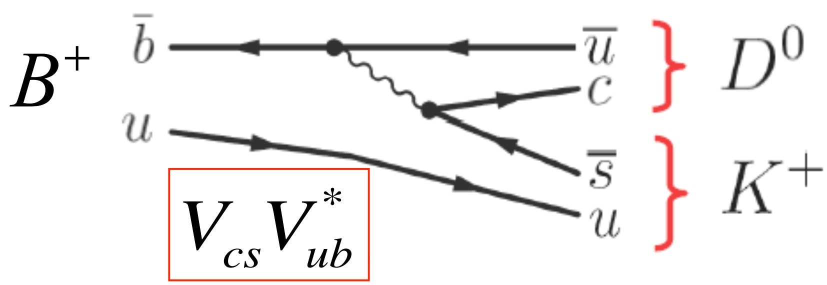
Use interference between $B^+ \to \bar{D}^0K^+$ and $B^+ \to D^0K^+$ with both D^0 and $\bar{D}^0$ decaying to the same final state f

Cabibbo allowed



$$A(B^+ \to \overline{D}^0 K^+) \propto V_{us}V_{cb}^{*} \propto \lambda^3$$

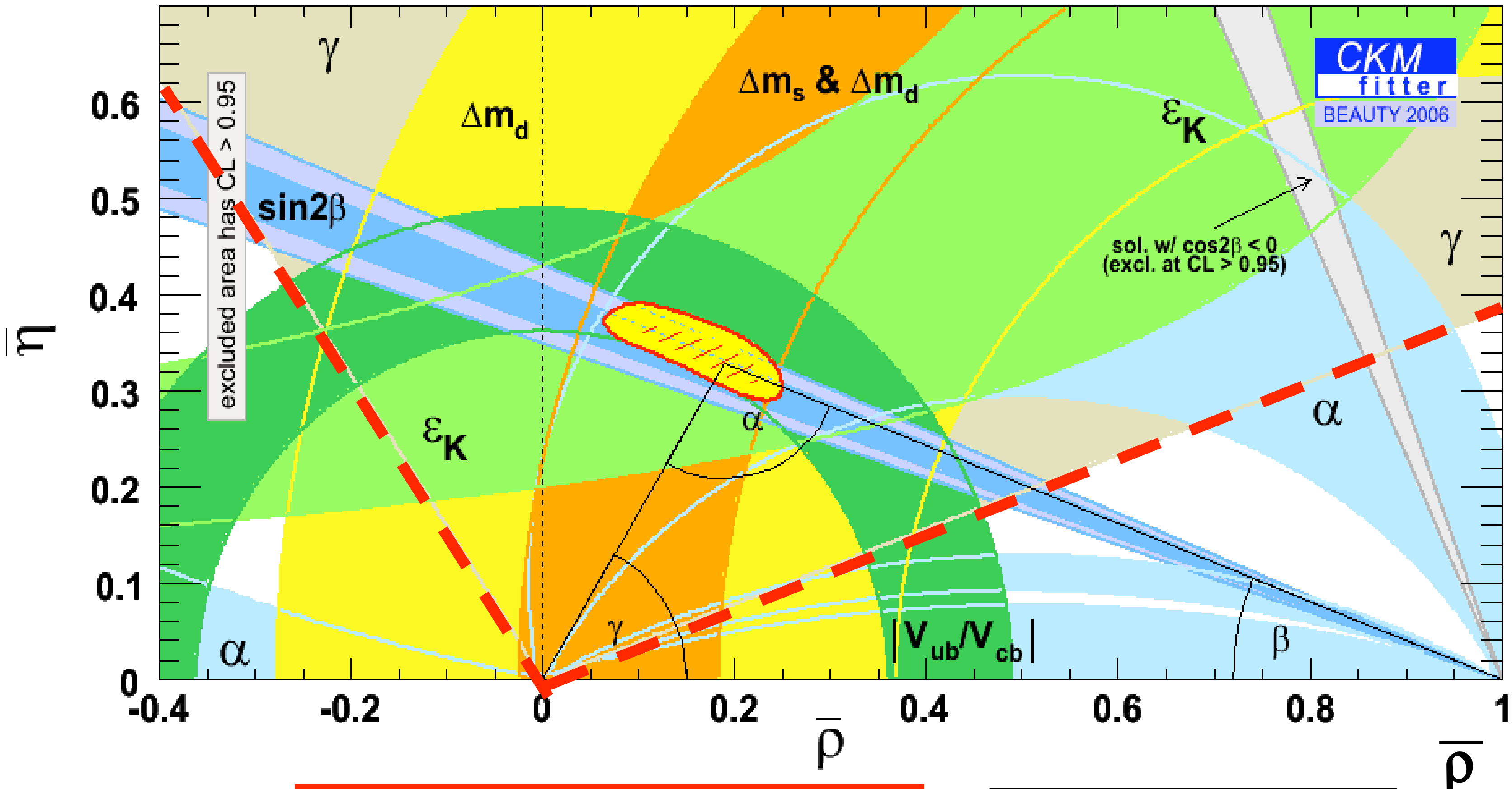
Cabibbo and color suppressed



$$A(B^+ \to D^0 K^+) \propto V_{cs}V_{ub}^{*} \propto \lambda^3 e^{i\gamma}$$

- Only tree diagrams contribute: pure Standard Model process!
- Low Branching Fractions: more statistics would help
- Best measurements from D→$K_s\pi\pi$ Dalitz analysis

Summary of γ measurements



Average of BaBar and Belle

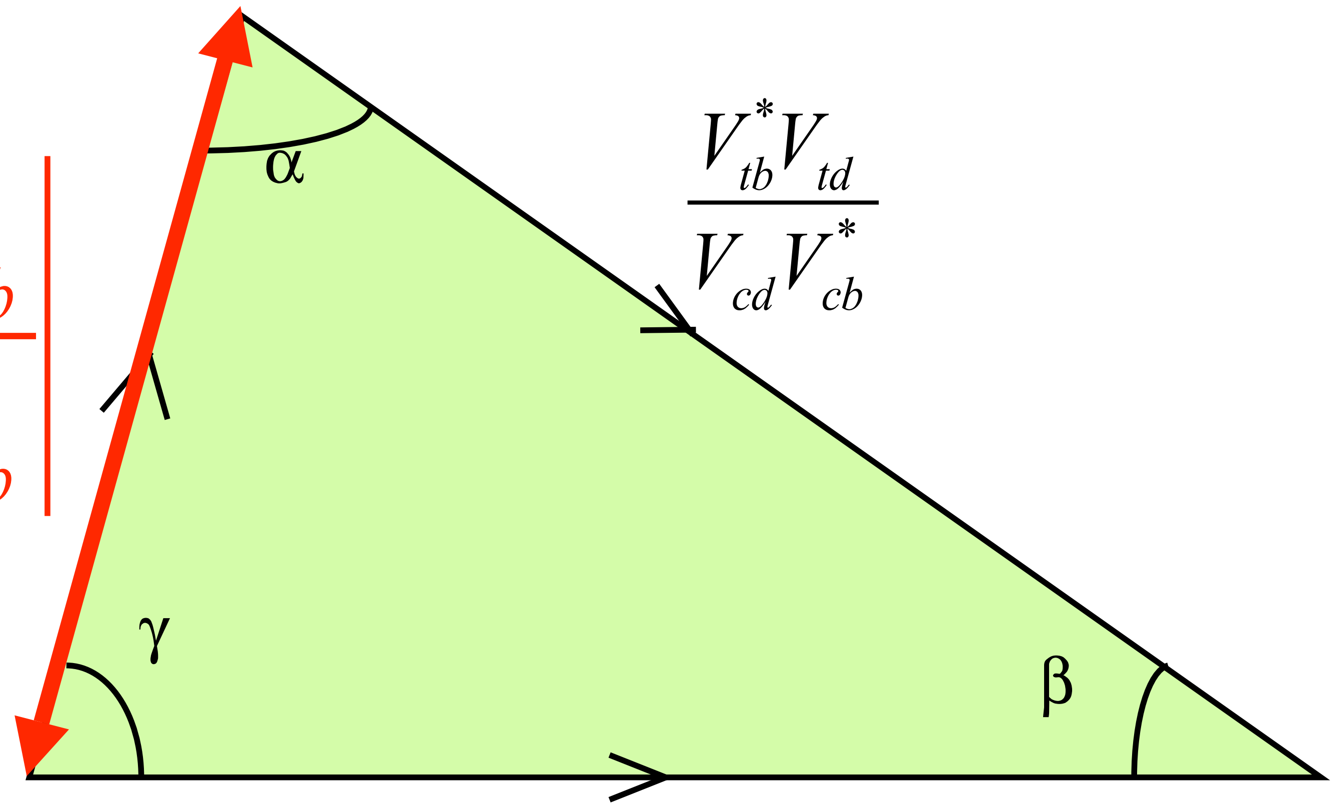
$$\gamma = \left(60^{+38}_{-24}\right)^\circ$$

CKM fit:

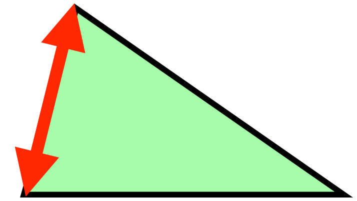
$$\gamma = \left(59.0^{+9.3}_{-3.8}\right)^\circ$$

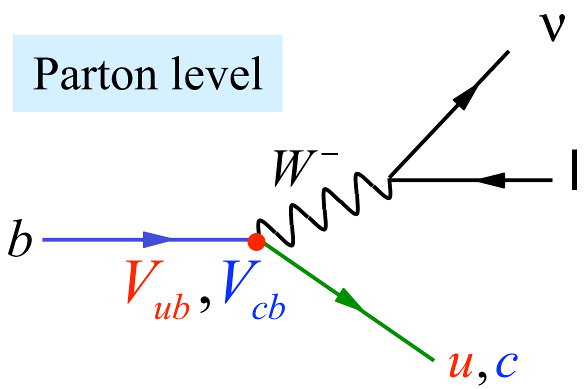
The measurements: R_b

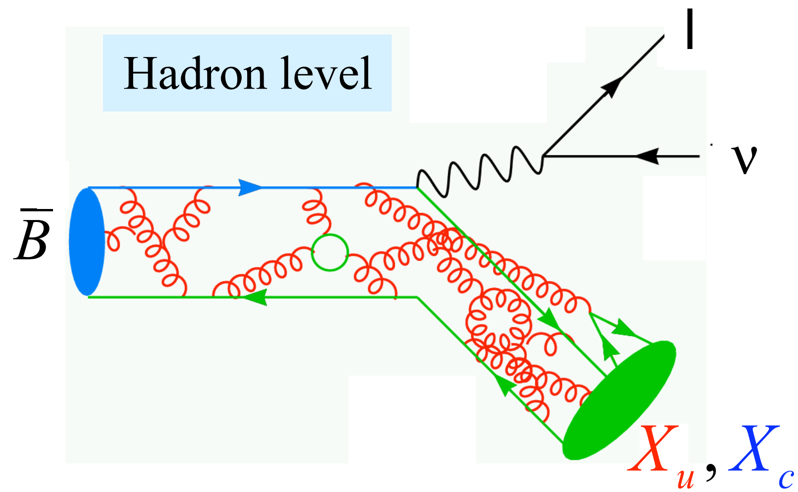
$$R_b \propto \left|\frac{V_{ub}}{V_{cb}}\right|$$



Semileptonic B Decays



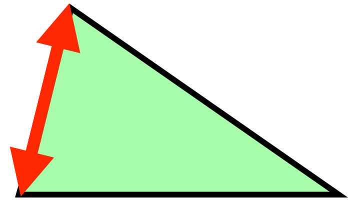


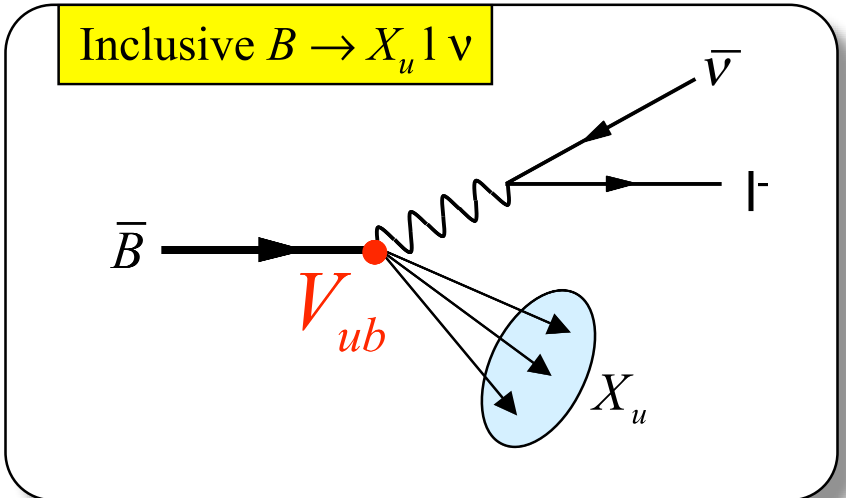


$$\Gamma(b \to u\ell\bar{\nu}) = \frac{G_F^2}{192\pi^2}|V_{ub}|^2 m_b^5$$

- Sensitive to hadronic effects
  - Theory error not negligible
- $\Gamma(b \to c)/\Gamma(b \to u) \sim 50$
  - V_{cb} precisely measured (±2%)
  - V_{ub} is the challenge

$|V_{ub}|$ from Inclusive $B \to X_u l \nu$

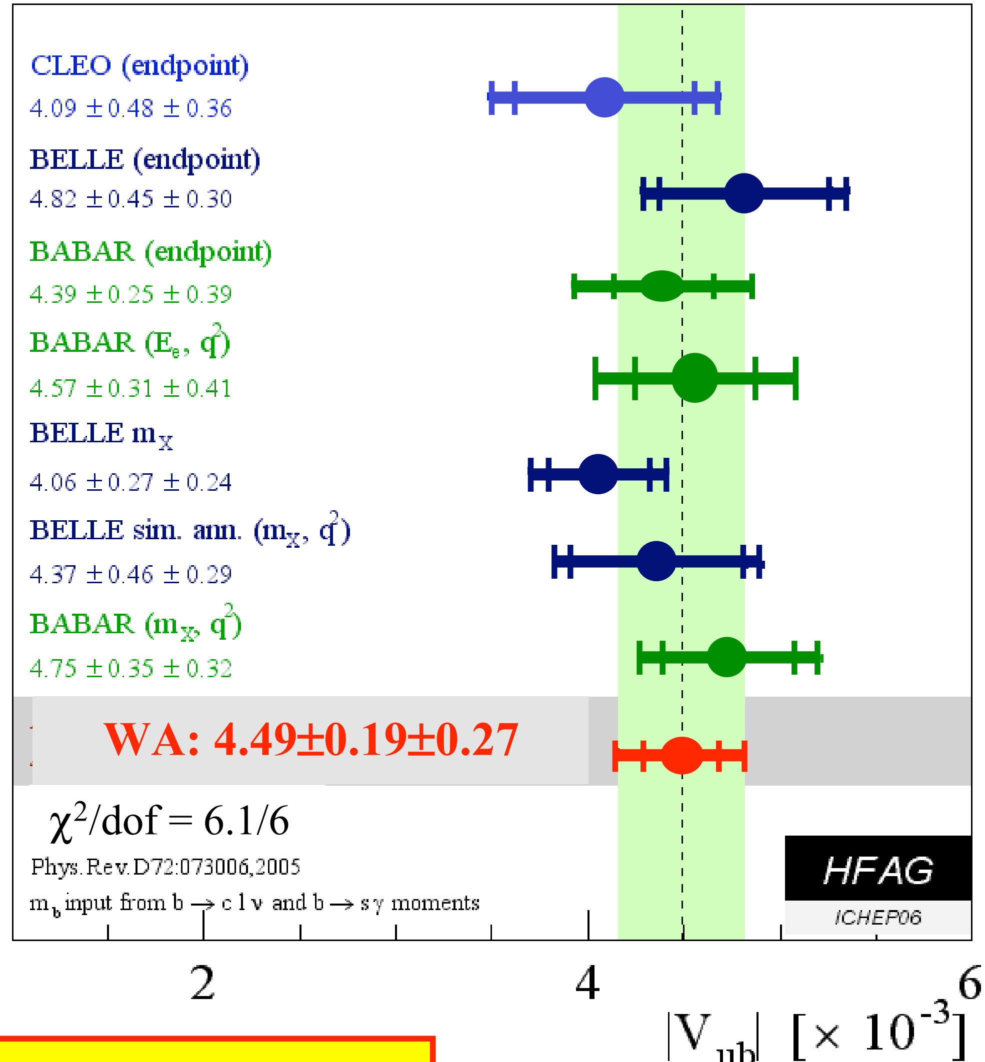




Inclusive $B \to X_u l \nu$

- Hadronic final state is not specified
- $b \to c\, l\, \nu$ background is suppressed using kinematical variables
- Partial rate is measured

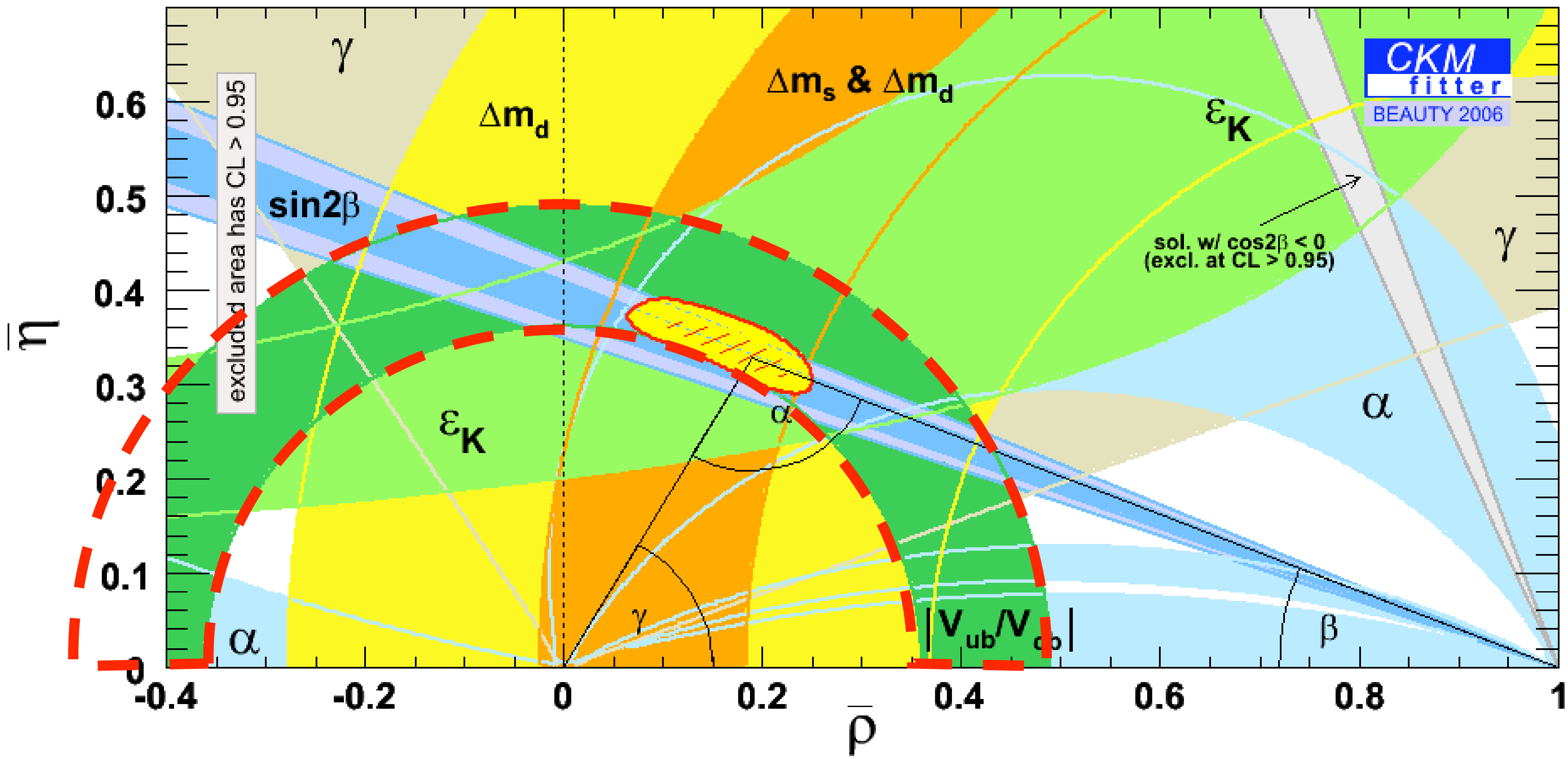
  → theoretical uncertainties ~5%



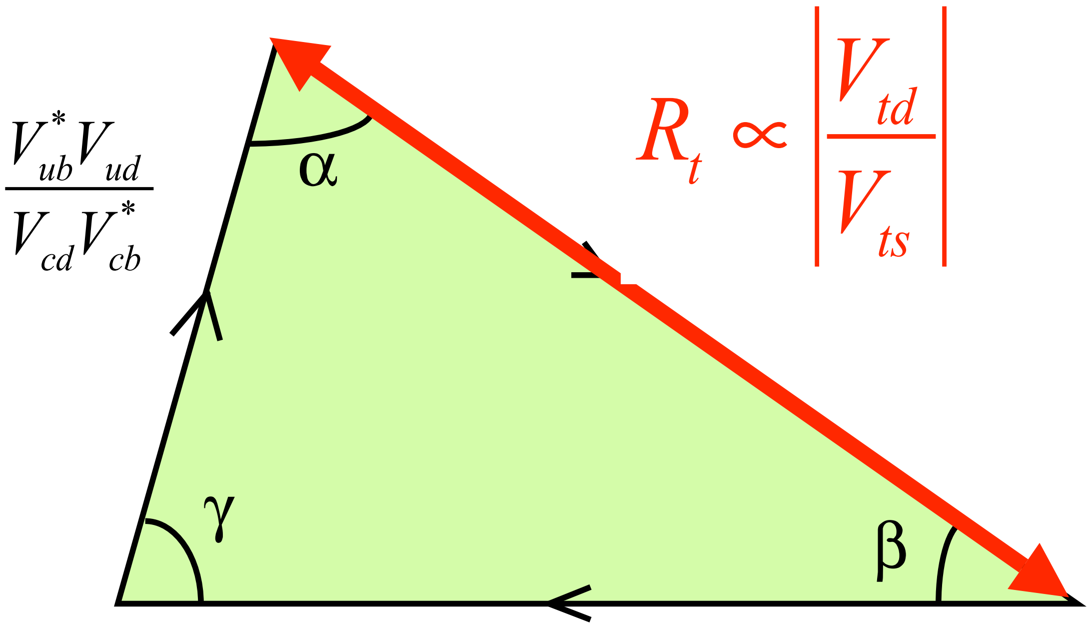
Precision on V_{ub}: ±7.3%

$|V_{ub}/V_{cb}|$ and the Unitarity Triangle

Third most precise constraint in the (ρ,η) plane

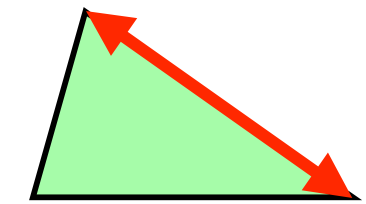


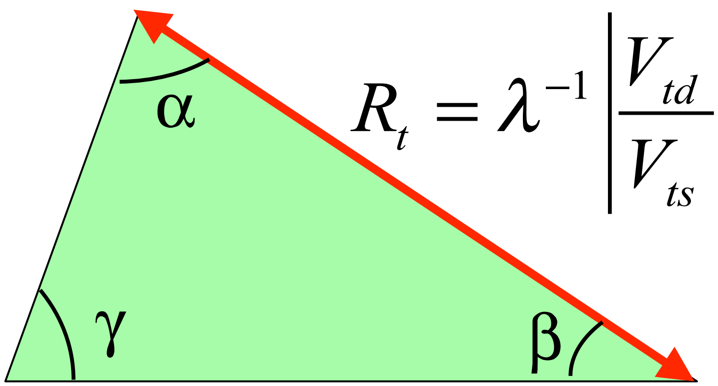
The measurement: R_t



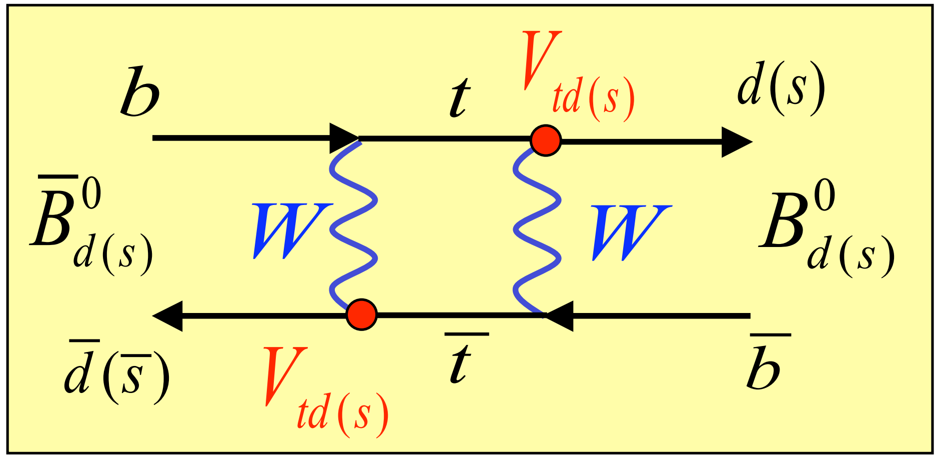
$$R_t = \left| \frac{V_{tb}^* V_{td}}{V_{cd} V_{cb}^*} \right| \approx \frac{1 \cdot |V_{td}|}{\lambda \cdot |V_{ts}|}$$

The measurement of R_t





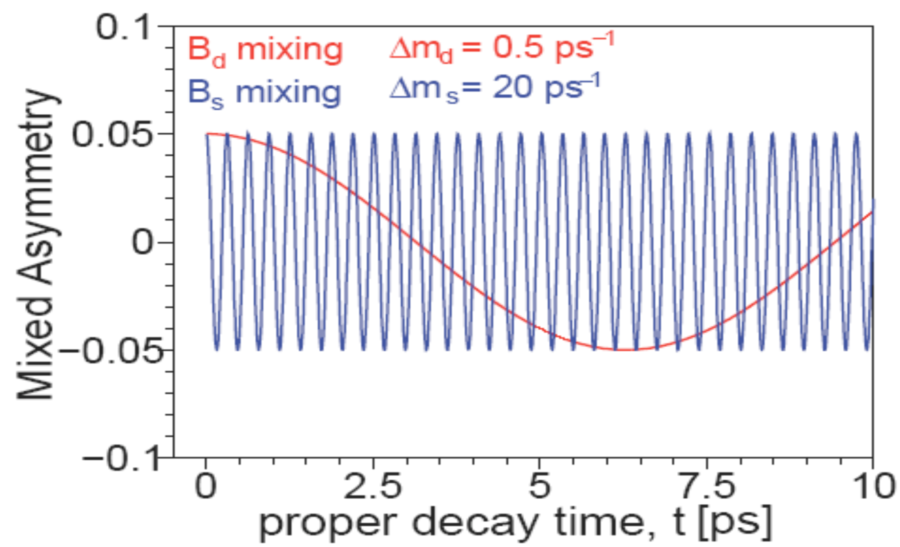
$$R_t = \lambda^{-1}\left|\frac{V_{td}}{V_{ts}}\right|$$



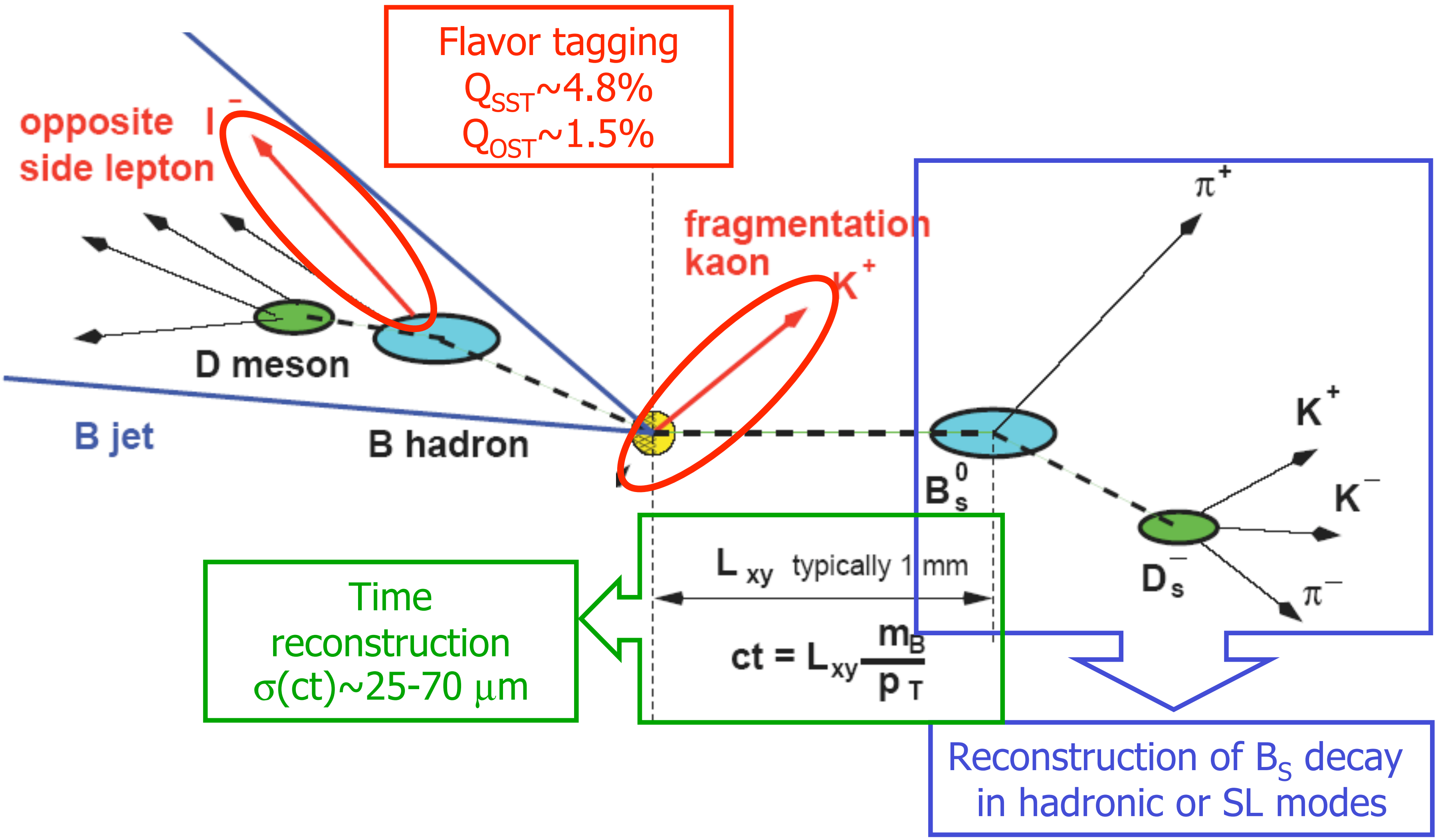
- B_s/B_d oscillations

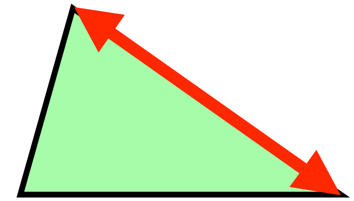
$$\frac{\Delta m_d}{\Delta m_s} \propto \left|\frac{V_{td}}{V_{ts}}\right|^2$$

  - Theory error <5% (LQCD)
  - Δm_d is precisely measured
  - But B_s mixing is very hard…

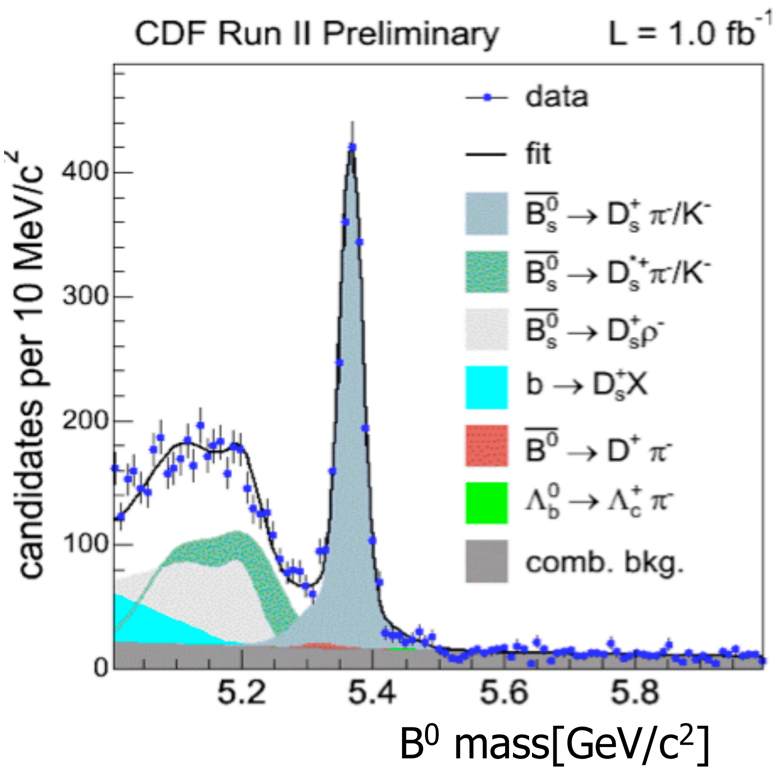


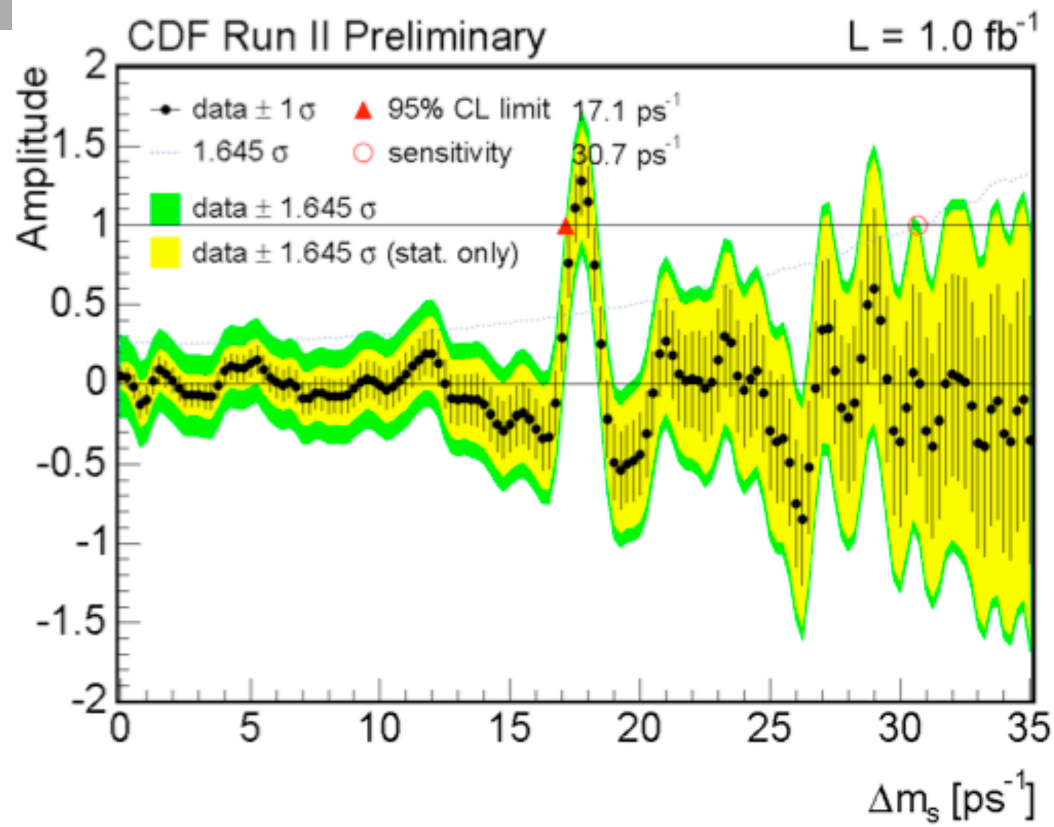
B_S mixing at the Tevatron





CDF result





$$\Delta m_S = 17.77 \pm 0.10 \pm 0.07 \text{ ps}^{-1}$$

>5σ

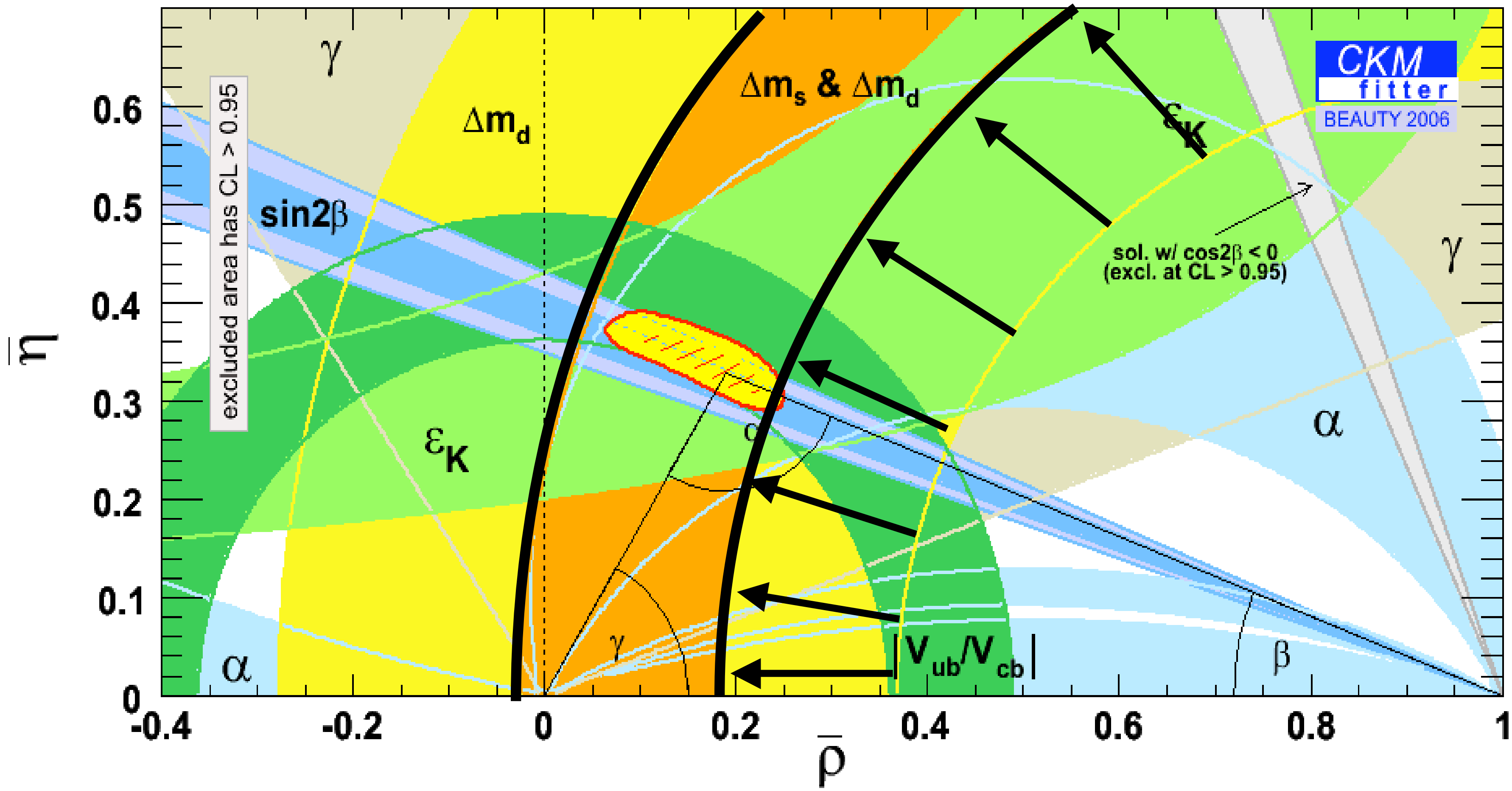
$$\Rightarrow \left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007^{+0.0080}_{-0.0070}$$

Exp. <1%

Theory ~4%

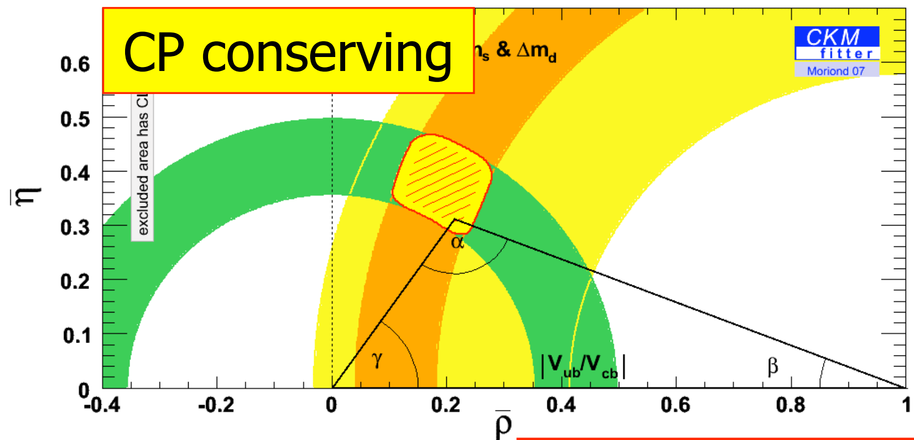
Impact of Δm_s on Unitarity Triangle

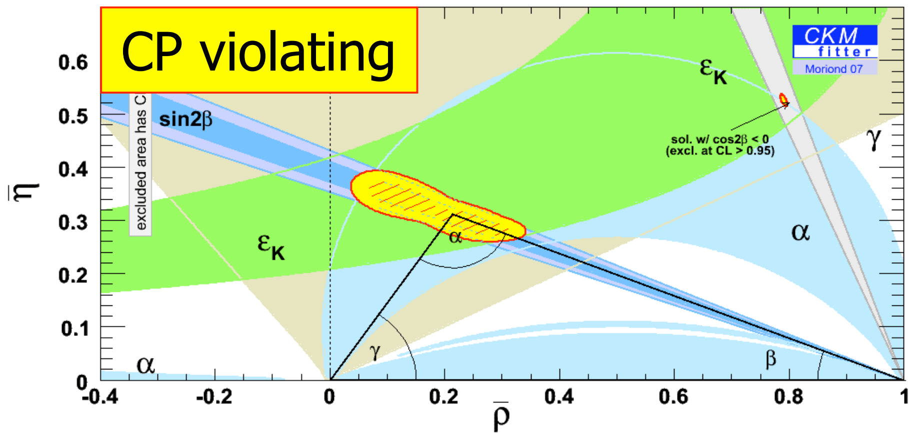
- Measurement vs limit: a factor of 2 improvement



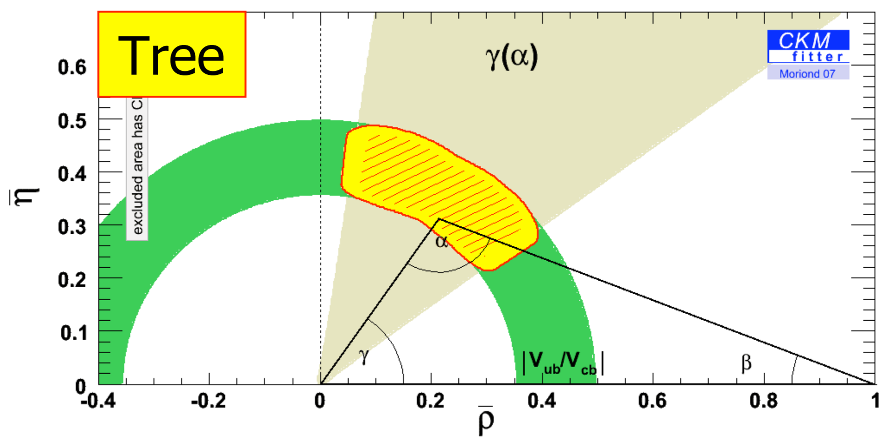
Standard Model or New Physics?

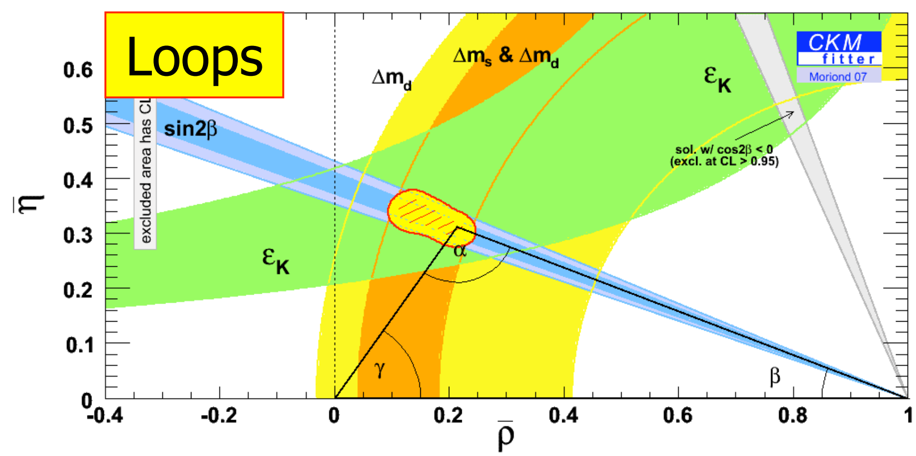
Do all pieces of the puzzle fit?





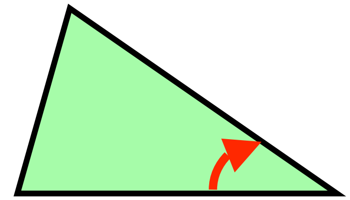
All measurements are consistent:
SM still going strong…





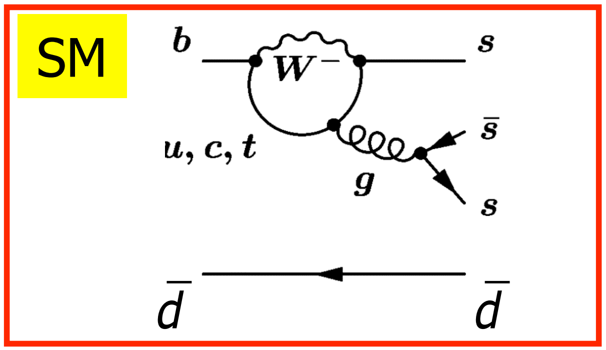
Standard Model or New Physics?

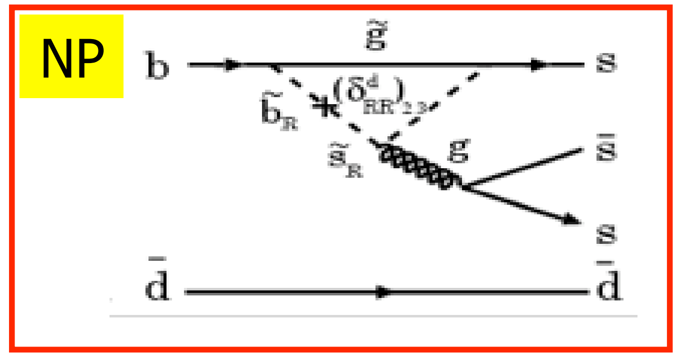
CP violation in Penguins



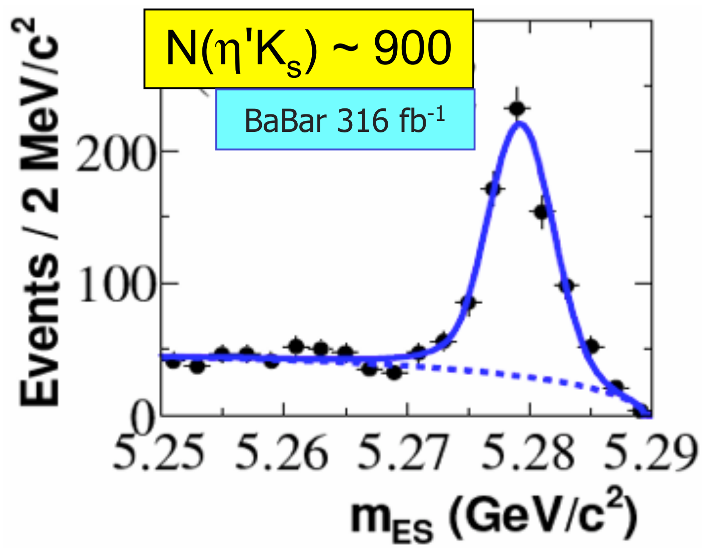
Complementary test: measure same angle in channels with different sensitivity to New Physics

- Example β from $B^0 \to J/\Psi K^0$ vs "Penguin Modes" (e.g.: $B^0 \to \phi K_S$)



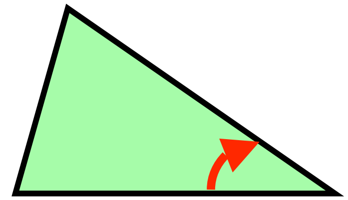


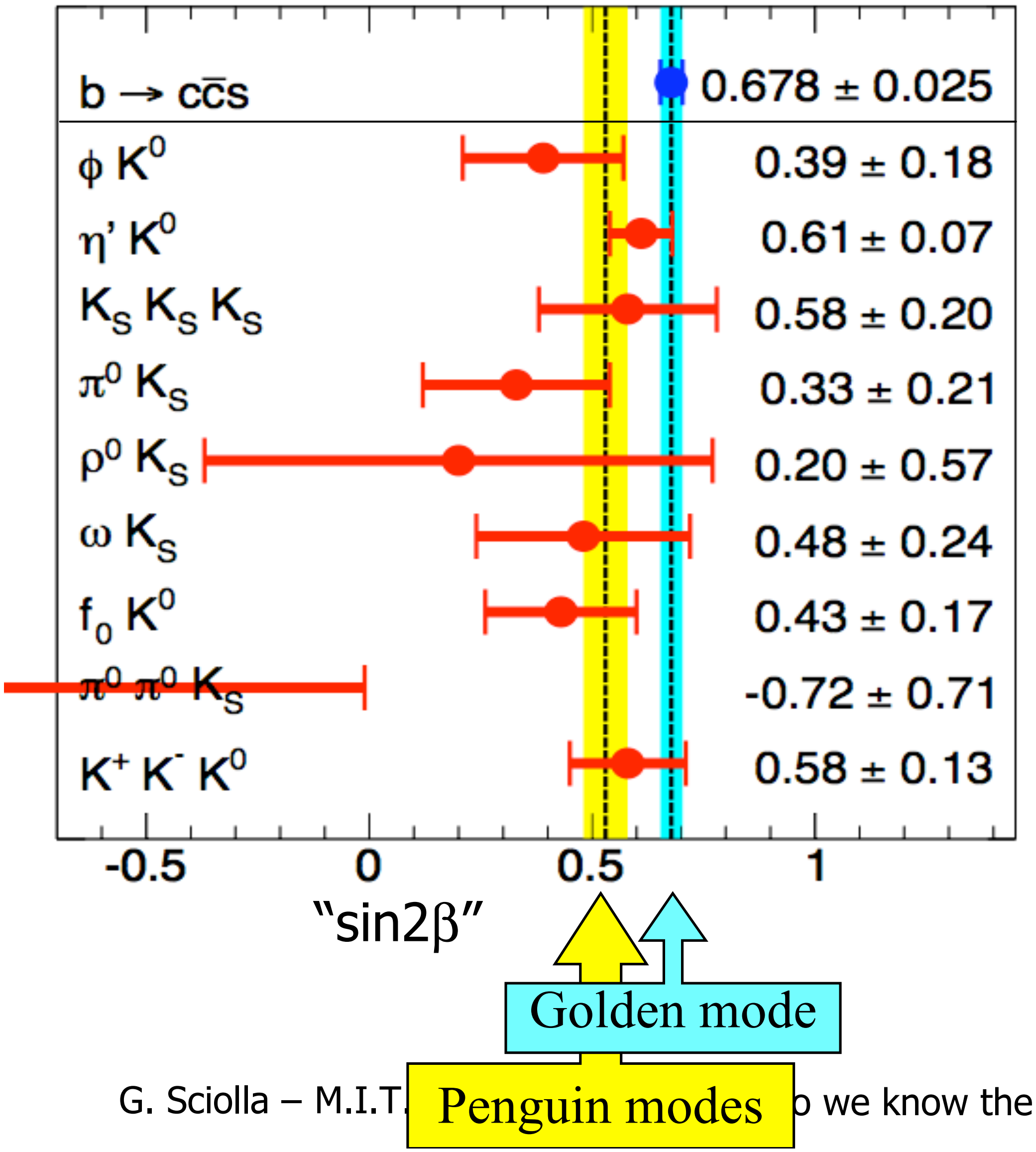
- SM predicts same $A_{CP}(t)$; small theory errors
- Impact of New Physics could be significant
  - New particles in the loop → new CPV phases
- Low branching fractions (10^{-5})
  - Many final states: φK^0, $K^+ K^- K_S$, $\eta' K_S$, $K_S K_S K_S$, etc.



Standard Model or New Physics?

β in penguins vs golden mode



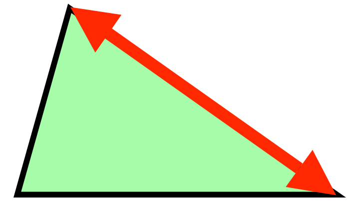


BaBar + Belle average

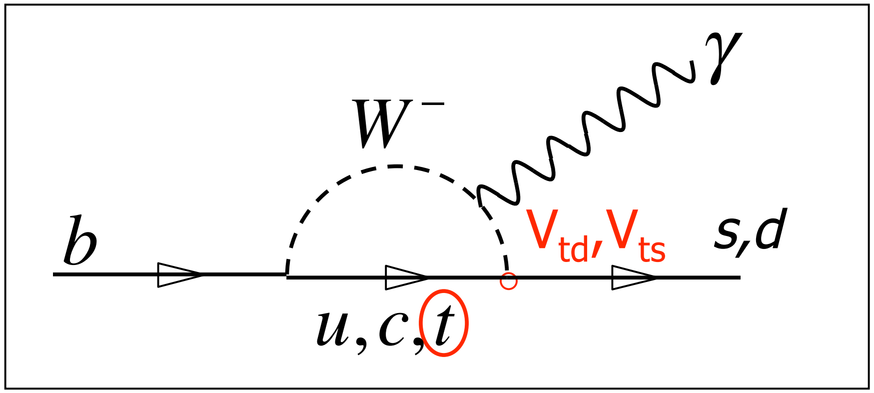
- A trend is visible
  - although each measurement is compatible with J/ΨK_S…
- Naïve average: 0.53±0.05
  - ~2.6 σ
- Statistical errors still large…
  - More statistics will help

Standard Model or New Physics?

New measurement of $|V_{td}/V_{ts}|$



- $|V_{td}/V_{ts}|$ can be measured from decays of $B\rightarrow\rho\gamma/B\rightarrow K^{*}\gamma$

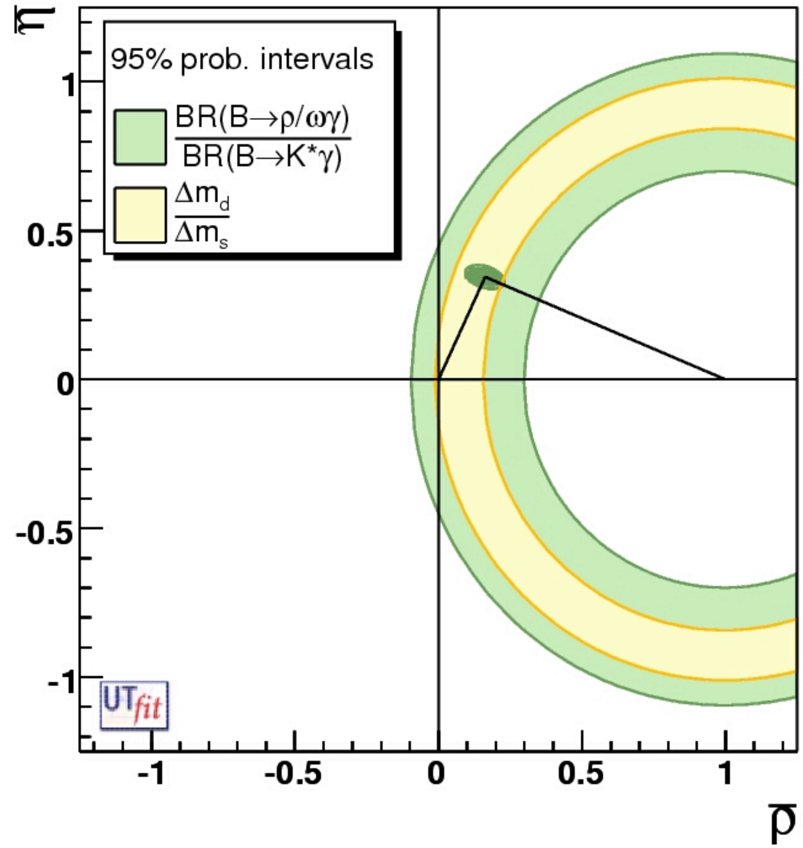


$$\frac{\mathrm{BF}(B\rightarrow\rho\gamma)}{\mathrm{BF}(B\rightarrow K^{*}\gamma)} \propto \left|\frac{V_{td}}{V_{ts}}\right|^2$$

- Recent results from B factories
  - Challenge: BF $(B\rightarrow\rho\gamma) \sim 10^{-6}$!
  - Theory error ~7.5% (LCSR)

$$\left|\frac{V_{td}}{V_{ts}}\right|_{\rho/\omega\gamma} = 0.202^{+0.017}_{-0.016}(\mathrm{exp}) \pm 0.015(\mathrm{th})$$

Average BaBar+Belle



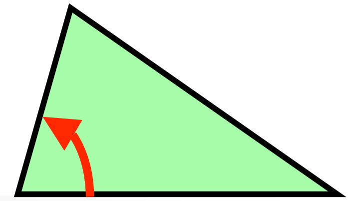
... as expected in the Standard Model...

Unitarity Triangle?

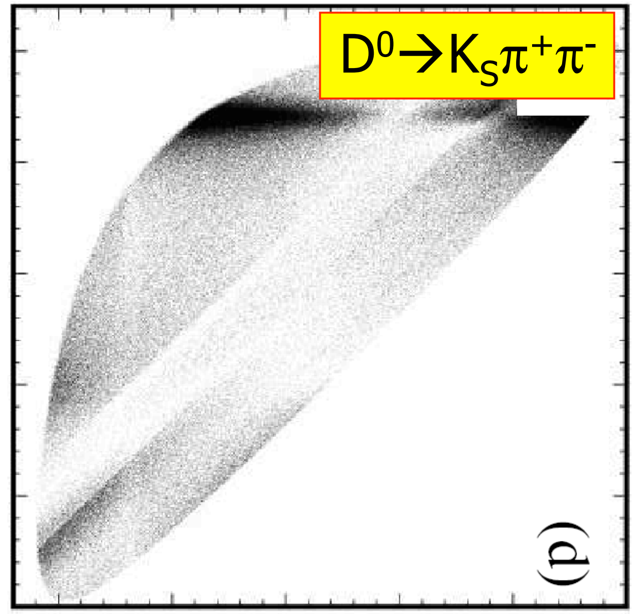
Conclusion

- Precise test of CP violation in the Standard Model
  - …thanks to many years of hard work by many experiments!
  - Tremendous improvement in our knowledge of ρ and η
    - Precision on apex ~ 0.04
- CKM is the dominant source of CP violation at low energy
  - … since all pieces of the puzzle seem to fit together
- Search for New Physics is just getting interesting
  - Expected effects of NP in loops ~10%
    - Experimental precision is just getting there…
    - First hints of NP in penguins? Statistics will tell
- Exciting times ahead…
  - B factories (~2 ab^{-1} by 2008)
  - New experiments (e.g.: LHCb, SuperB)
  - Theoretical progress will be crucial (e.g.: Lattice QCD).

γ from B $\rightarrow$ DK



- GWL (Gronau, Wyler, London)
  - D → CP eigenstate
    - Theoretically clean
    - Small interference: needs more data
- ADS (Atwood, Dunietz, Soni)
  - $A(\bar{D} \rightarrow f)$ is doubly Cabibbo suppressed
    - Larger interference
    - Needs more data
- Dalitz method (Giri, Grossman, Soffer, Zupan)
  - Exploits interference pattern in Dalitz plot in $D \rightarrow K_S\pi^+\pi^-$
    - Combines many modes → statistical advantage
    - Small systematics due to Dalitz model



Currently most sensitive

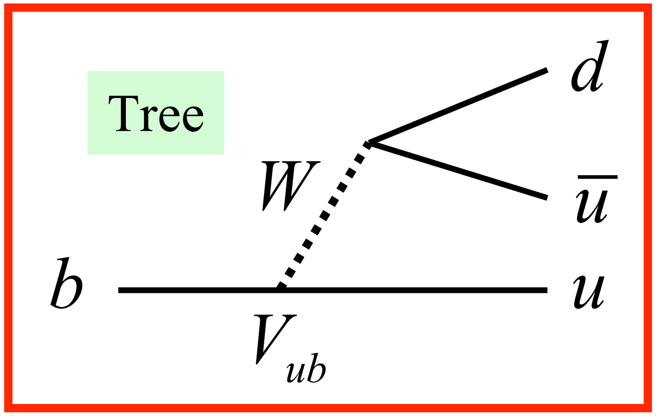
α from $B^0 \rightarrow \pi\pi, \rho\pi, \rho\rho$

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

- If tree diagram dominates

$$\lambda = (-1)\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{ud}^* V_{ub}}{V_{ud} V_{ub}^*}\right)$$

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



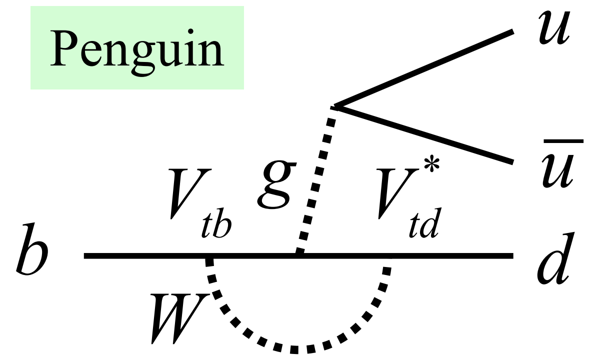
- Large penguin contributions in $\pi\pi$

$$\frac{Penguin}{Tree} \propto \sqrt{\frac{BF(B^0 \to \pi^0\pi^0)}{BF(B^0 \to \pi^+\pi^+)}} \sim 50\%$$

- …not so small even in B->$\rho\rho$…

$$\frac{Penguin}{Tree} \propto \sqrt{\frac{BF(B^0 \to \rho^0\rho^0)}{BF(B^0 \to \rho^+\rho^+)}} \sim 20\%$$

$$A_{CP}(t) = S\sin(\Delta m t) - C\cos(\Delta m t)$$



- S related to α; C related to direct CPV
  - Isospin analysis a la Gronau-London required to extract α…