Measurements of CKM parameters at the B factories

Gabriella Sciolla (MIT)

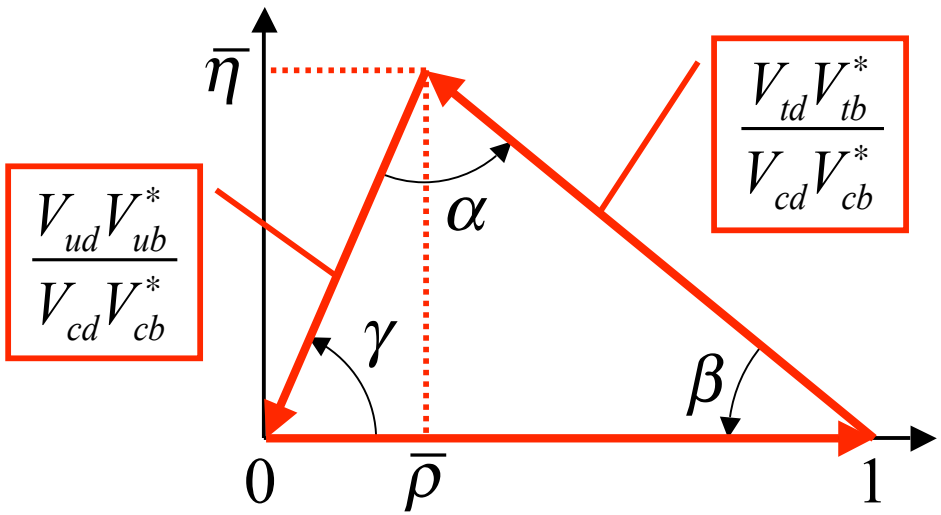
Outline:

- CP violation in the Standard Model
  - The CKM mechanism
- The beauty of the Unitarity Triangle
  - Measurements of angles
    - β, α, γ
  - Measurements of sides
    - V_{ub}, V_{cb}, V_{td}/V_{ts}
- Conclusion

La Thuile - March 4, 2009

CPV and the Unitarity Triangle

- 1964: CPV observed by Fitch and Cronin in K_L decays
- 1973: Kobayashi and Maskawa explained CP violation in SM introducing a 3x3 quark mixing matrix with an imaginary phase



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

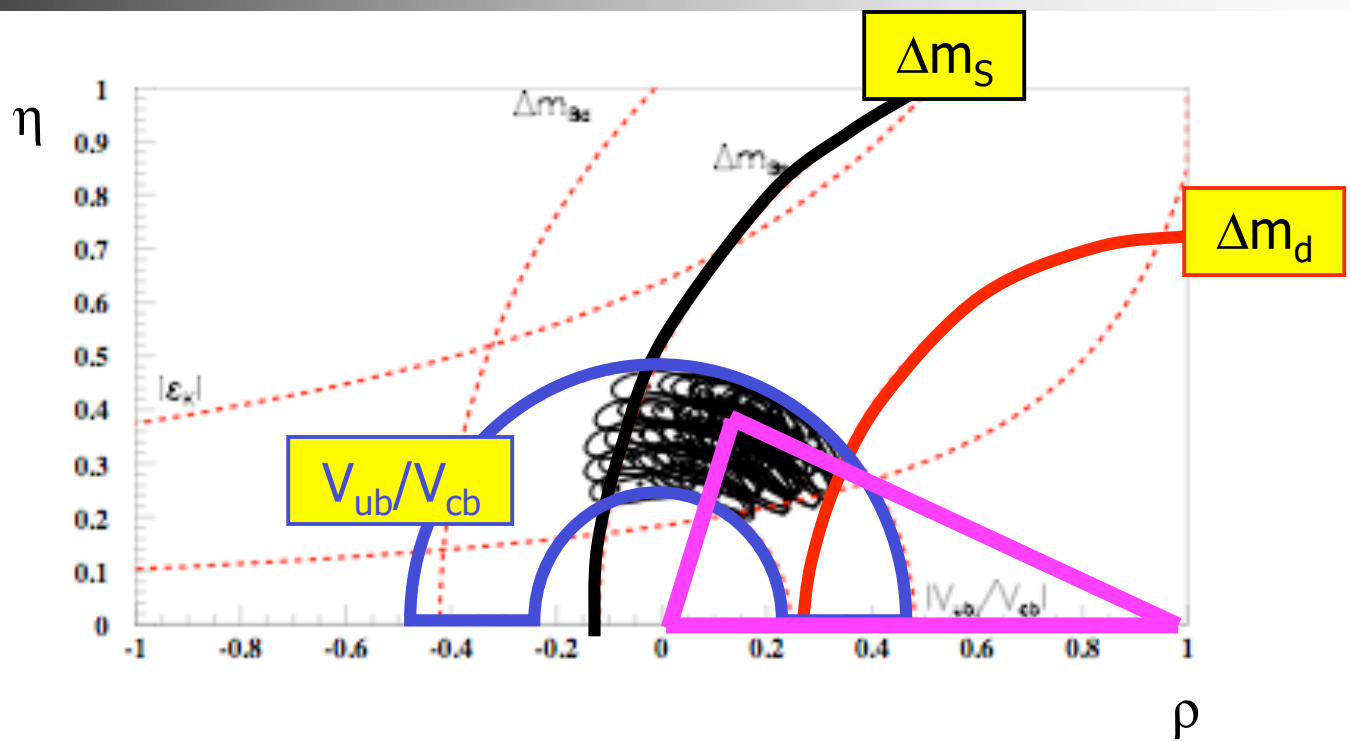
NB: UT constrained by 2 quantities

→ any additional measurement: test CKM/probe for New Physics

Two approaches:

1) Over constrain the triangle (e.g.: sides vs angles)
2) Independent measurements of the same quantity

The Unitarity Triangle in 1999



3 ways to look for New Physics:

a) Sides vs. angles

b) Angle vs. angle

c) Side vs. side

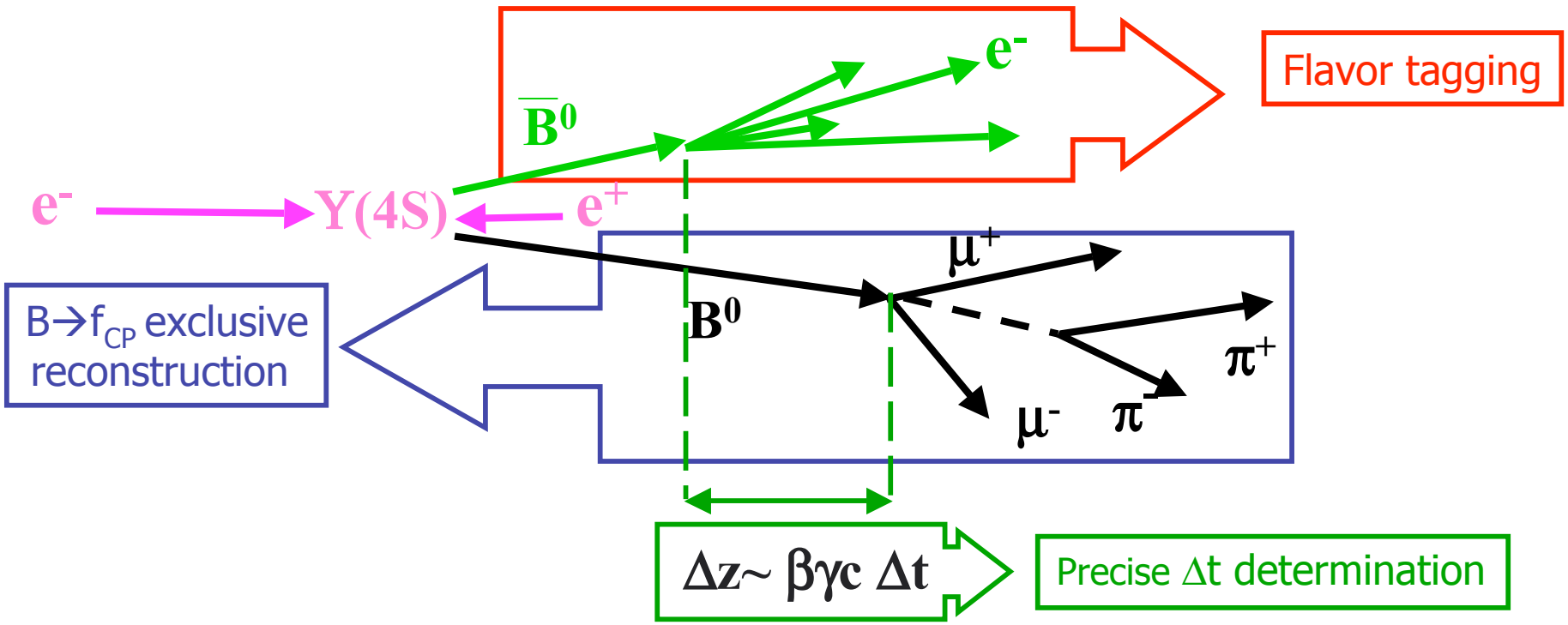
Some measurement of the sides, but no angles!

First goal of the B factories:

measure the angles of UT

Time dependent CP asymmetry:

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

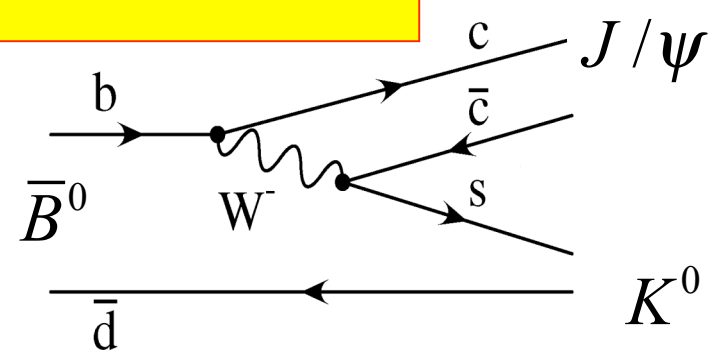


CPV in B^0 decays: sin2β

When only one diagram contributes to the decay $B \rightarrow f_{CP}$

$$A_{CP}(t) = \frac{N(\bar{B}^0(t) \rightarrow f_{CP}) - N(B^0(t) \rightarrow f_{CP})}{N(\bar{B}^0(t) \rightarrow f_{CP}) + N(B^0(t) \rightarrow f_{CP})} = \pm \ \mathrm{Im}\,\lambda \ \sin(\Delta m t)$$

For some modes, Imλ is directly and simply related to the angles of the UT



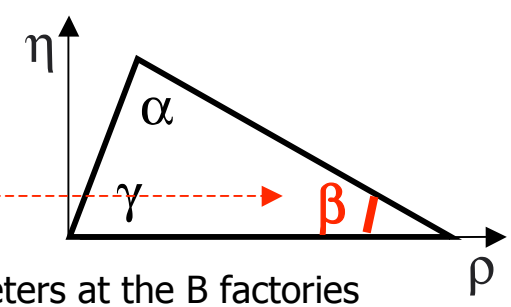
Example:

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

- Theoretically clean
- Experimentally clean
- Relatively large BF (~10^{-4})

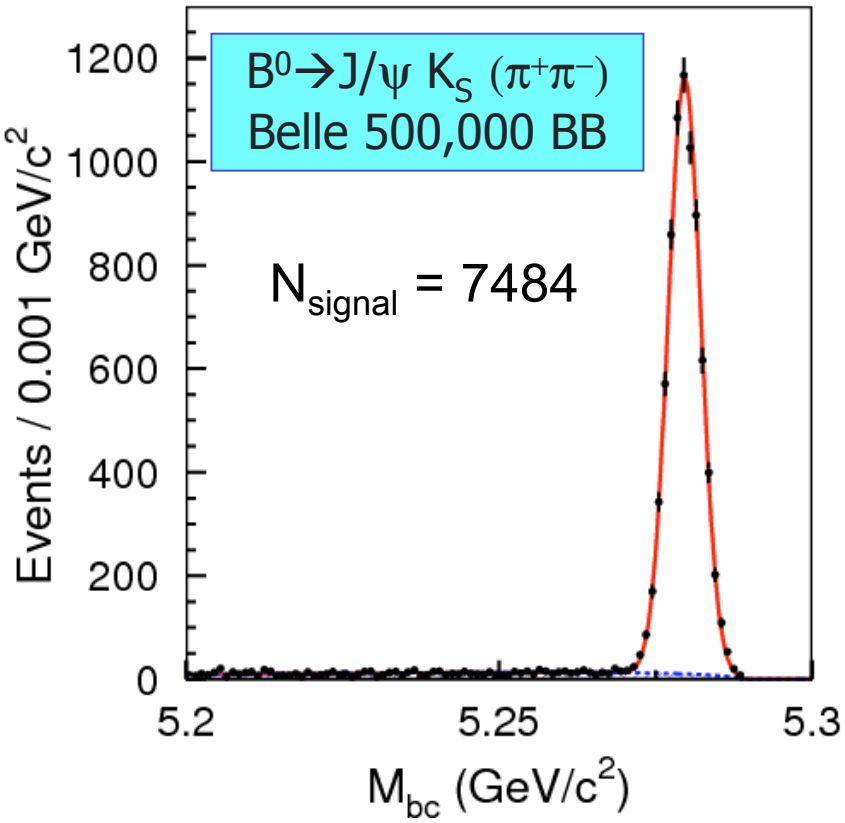
$$\lambda = \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)_{B^0_{mix}} \left(\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*}\right)_{decay} \left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right)_{K^0_{mix}} = e^{-i2\beta}$$

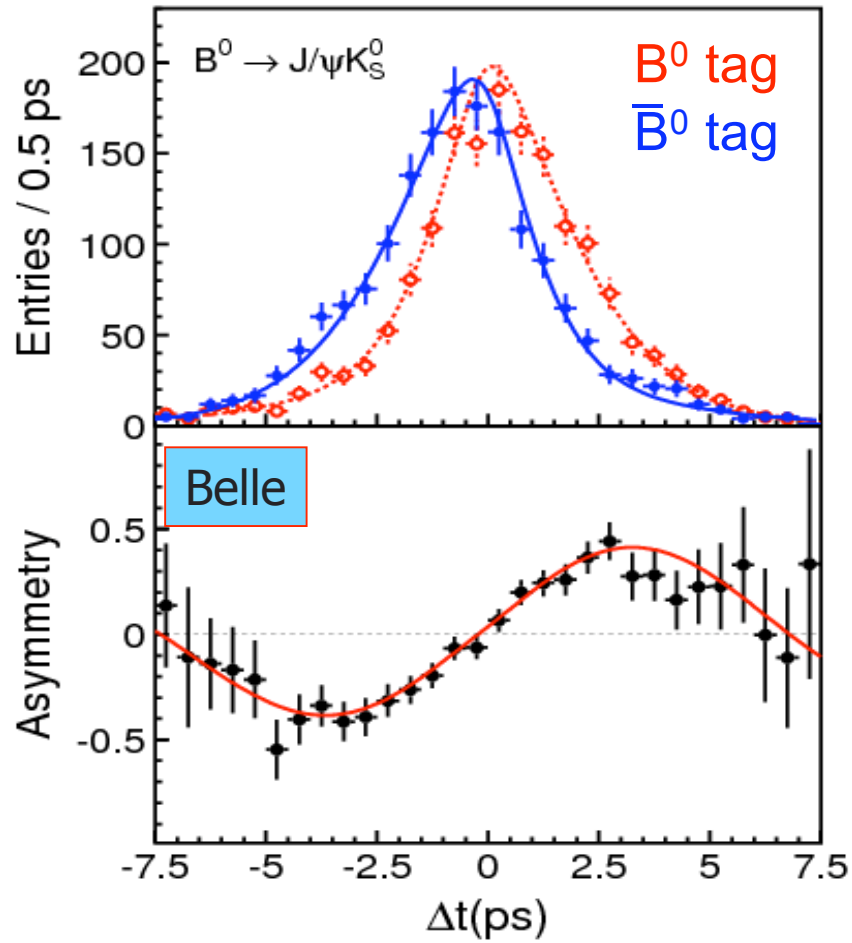
$$A_{CP}(t) = \sin 2\beta \ \sin \Delta m t$$



The golden mode for sin2β:

sin2β in $B^0 \rightarrow J/\psi\ K^0$





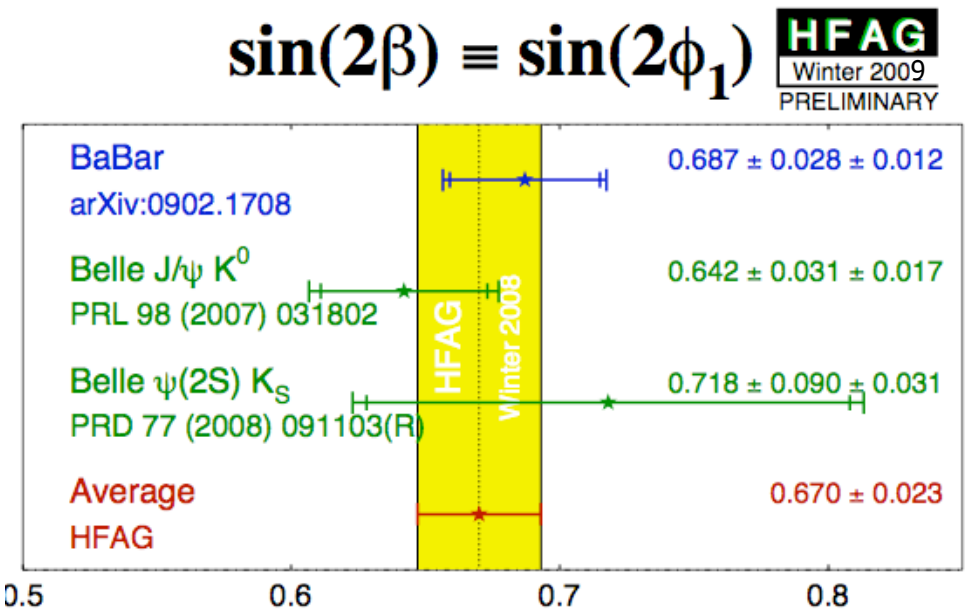
$\sin(2\beta) = 0.670 \pm 0.023$

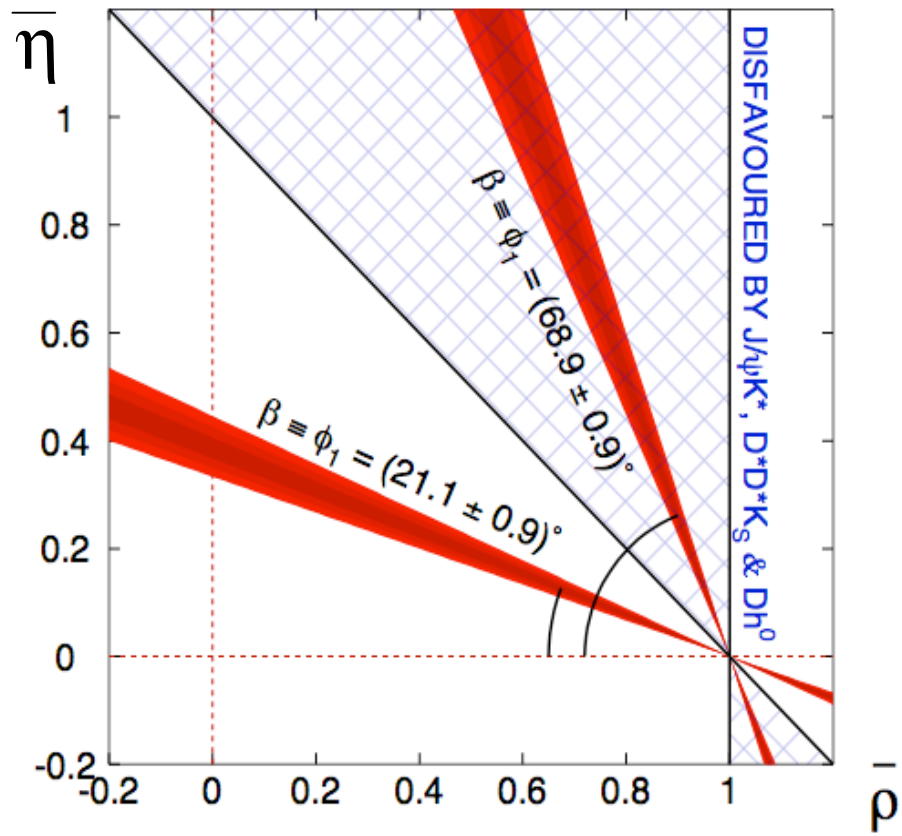
HFAG Moriond 2009

Belle PRL 98 (2007) 031802

BaBar arXiv:0902.1708

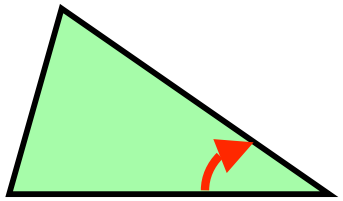
UT constraint #1: angle β

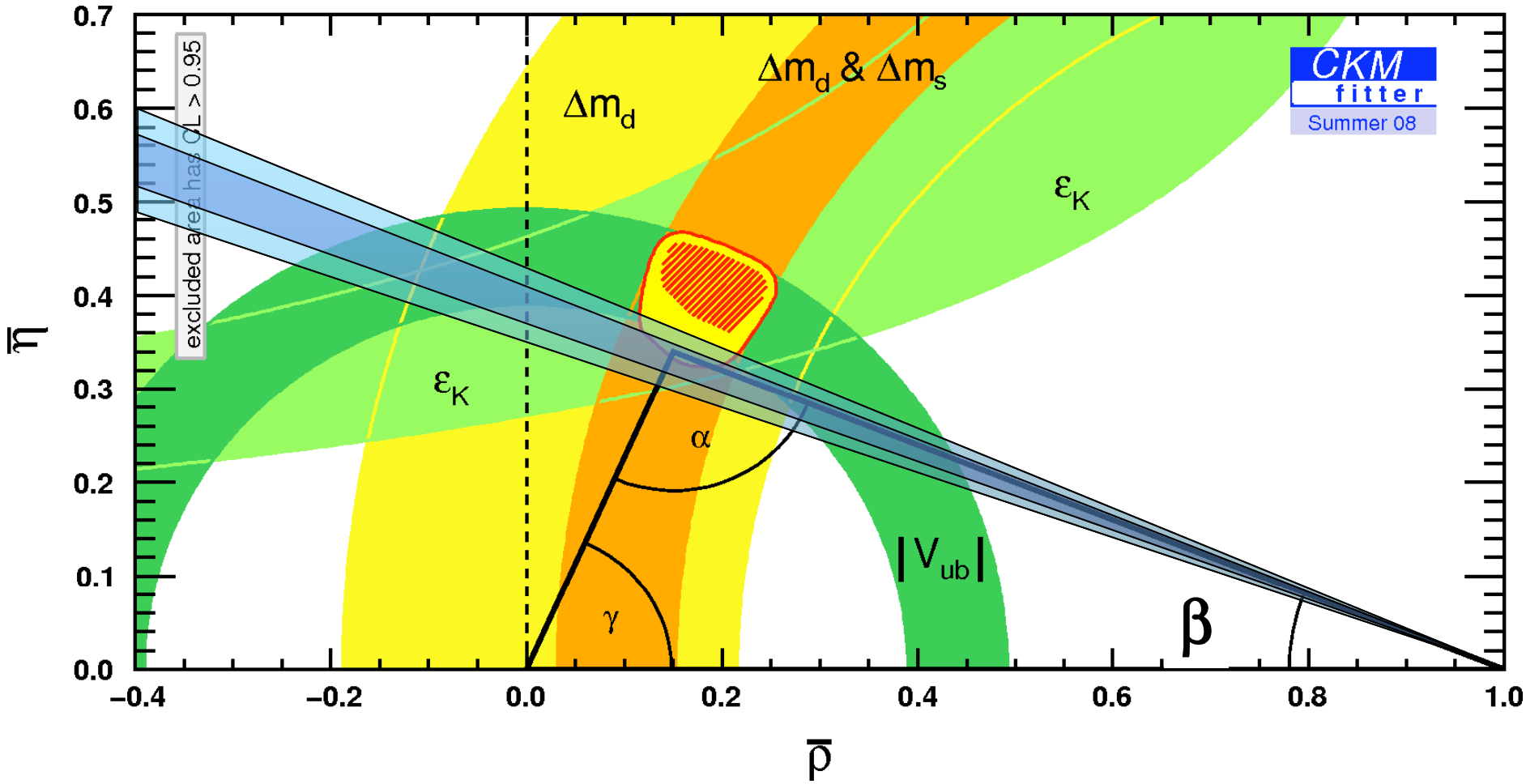




- Ambiguity resolved by Dalitz analysis of $B \to K^+K^-K_S$, $B \to J/\Psi\ K^*$…
- Most stringent constraint on the UT to date (3.5%)

First test of CKM

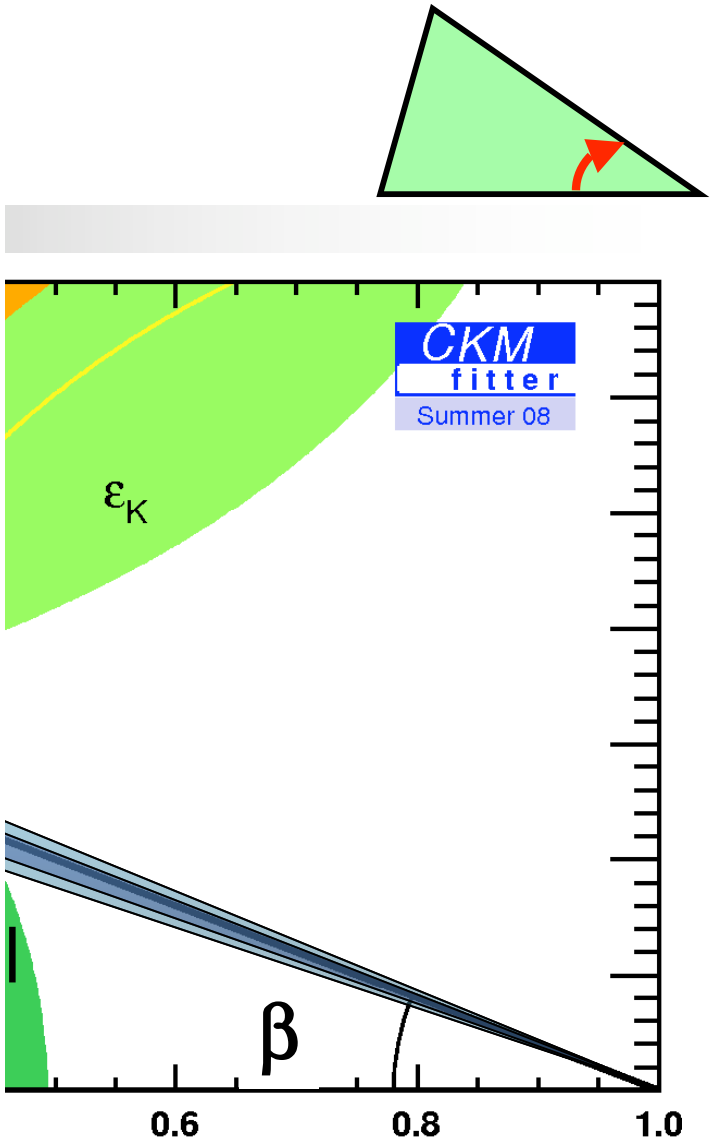




First test of CKM

2008 Nobel Prize in Physics

M. Kobayashi T. Maskawa



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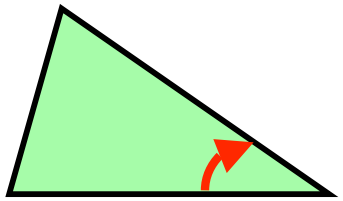
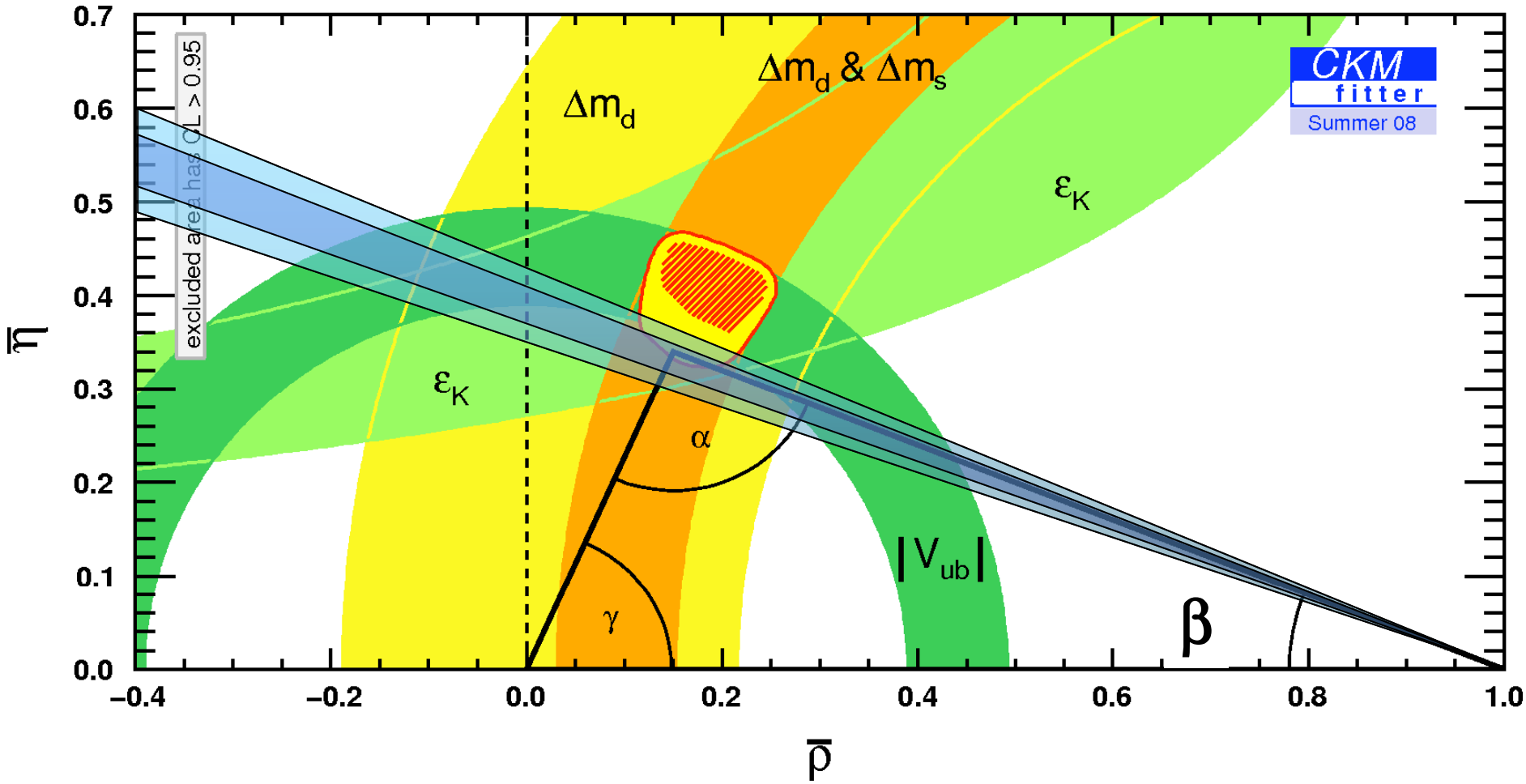
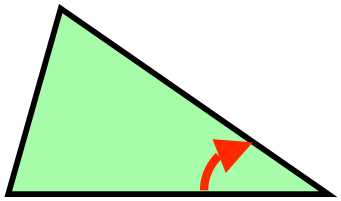




"Yesterday's sensation is <u>today's calibration</u> and tomorrow's background."
Val Telegdi

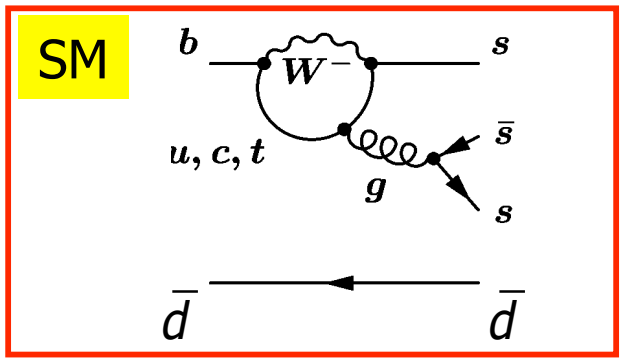
An independent measurement of β:

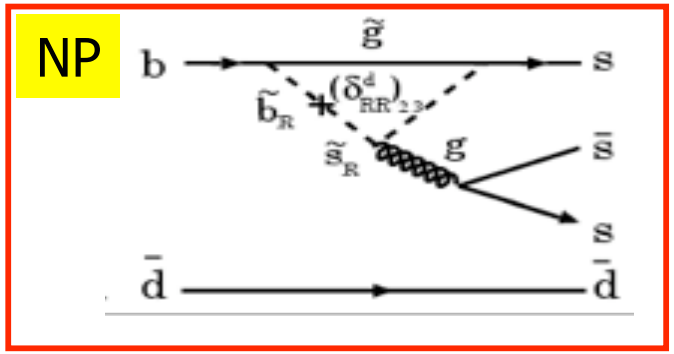
The Penguin Modes



Decays dominated by gluonic penguin diagrams

- The typical example: $B^0 \rightarrow \phi K_S$



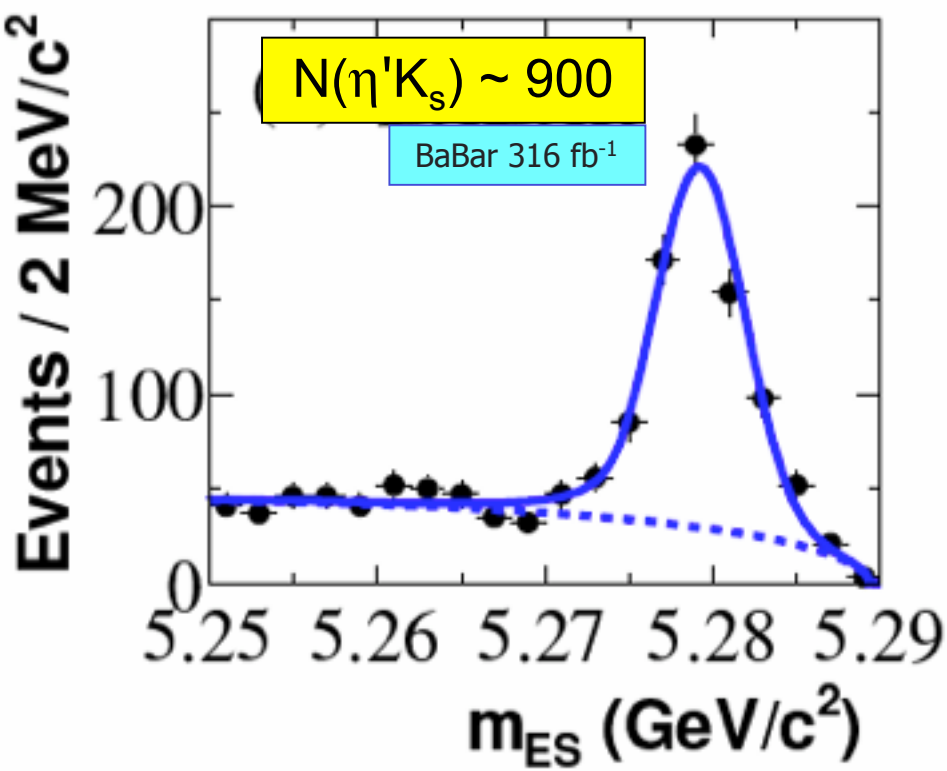


  - No tree level contributions: theoretically clean
  - SM predicts: $A_{CP}(t) = \sin 2\beta \sin(\Delta m t)$

- Impact of New Physics could be significant
  - New particles could participate in the loop → new CPV phases

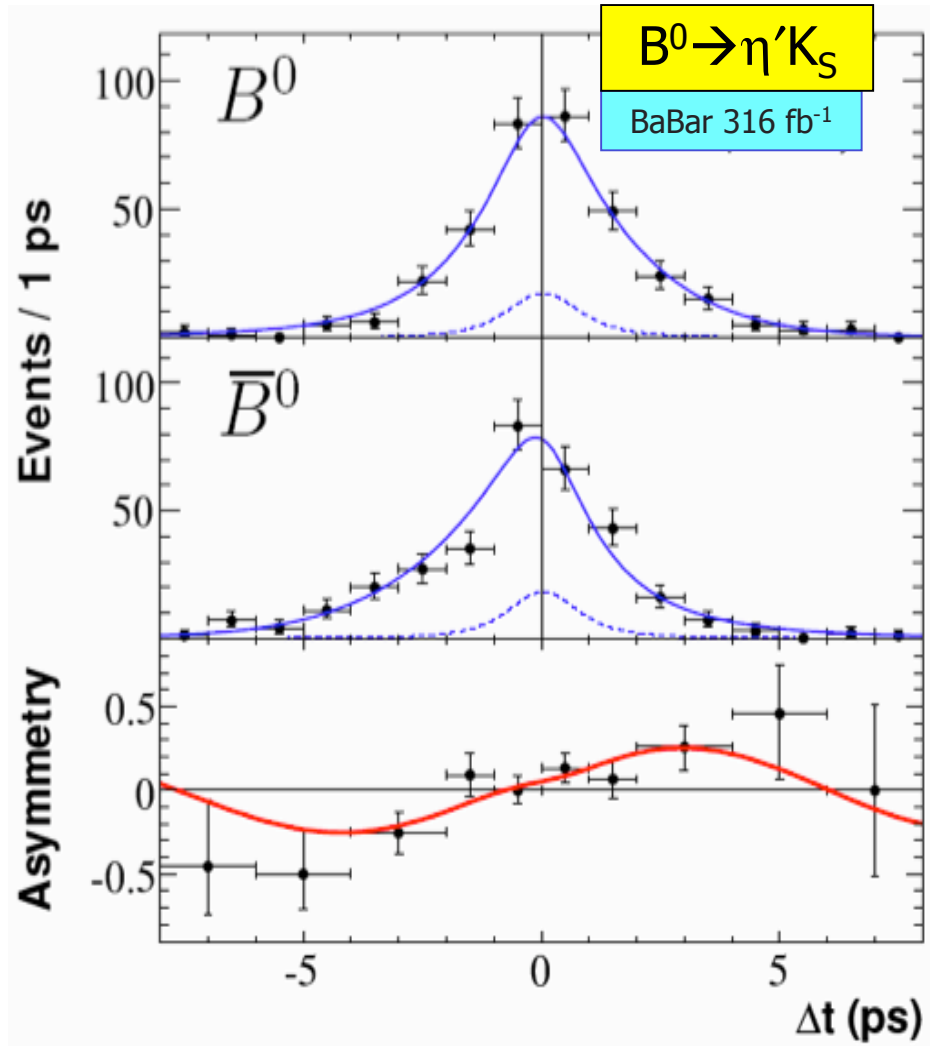
- Low branching fractions (10^{-5})
  - Measure A_{CP} in as many $b \rightarrow s q \bar{q}$ penguins as possible!
    - φK^0, $K^+ K^- K_S$, $\eta' K_S$, $K_S \pi^0$, $K_S K_S K_S$, ωK_S, $f_0(980) K_S$

The silver penguin: $B^0 \rightarrow \eta' K^0$



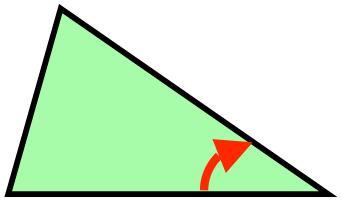
$$S_{\eta' K^0} = 0.55 \pm 0.11 \pm 0.02$$

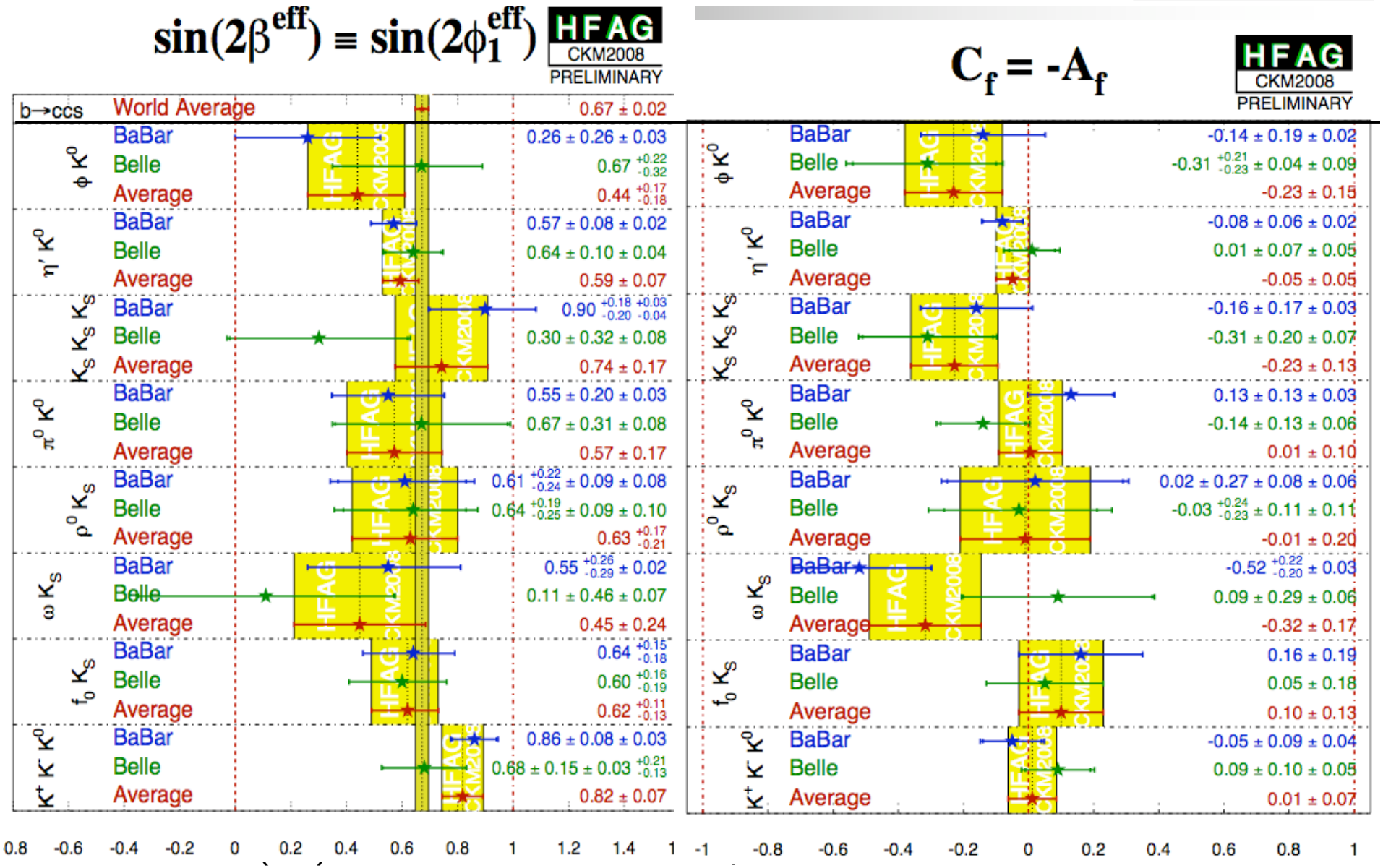
BaBar 316 fb^{-1}



NP test #2:

sin2β: penguins vs golden mode





NP test #2:

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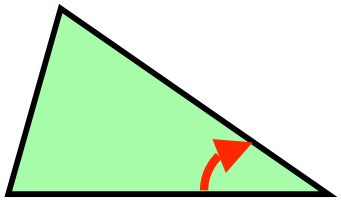
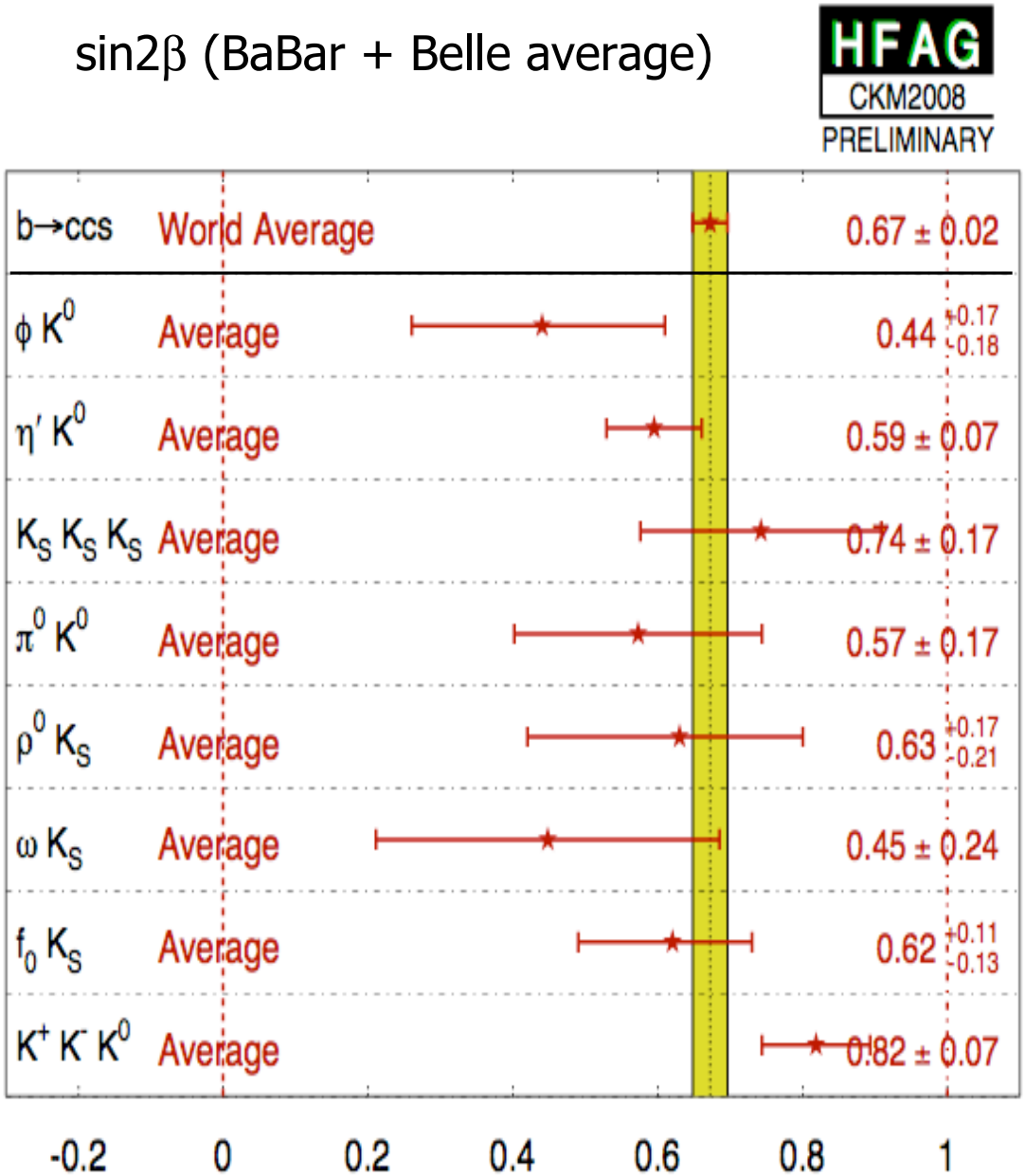


sin2β (BaBar + Belle average)



No discrepancy observed

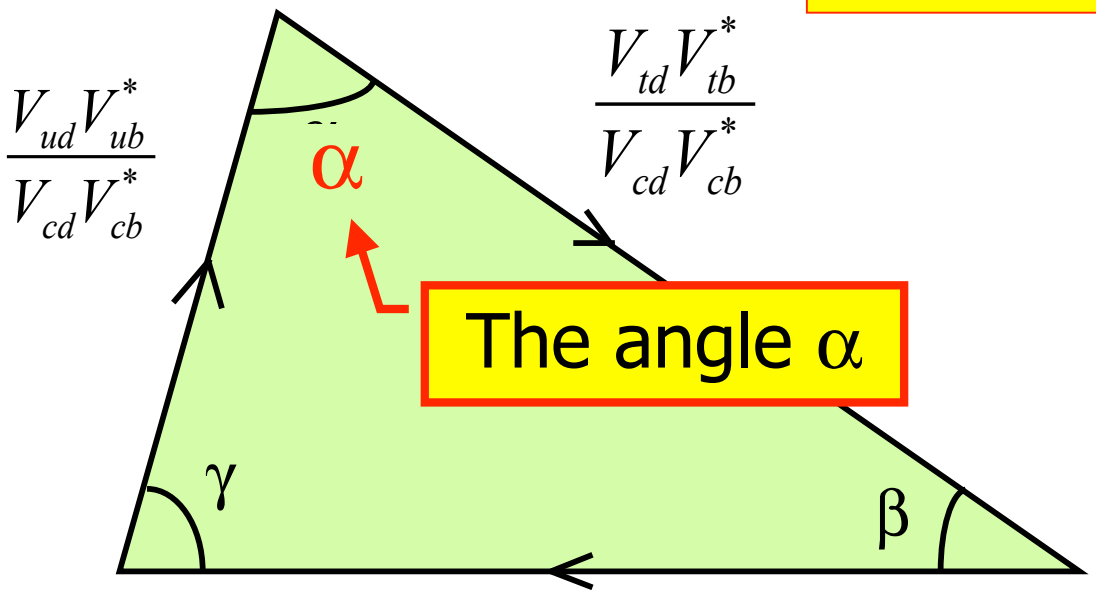
- If New Physics is there, effects are very subtle

Visible at future machines?

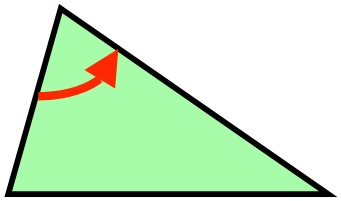
- Hadronic uncertainties for golden penguin modes are ~0.02
- SuperB or LHCb

The angle α

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



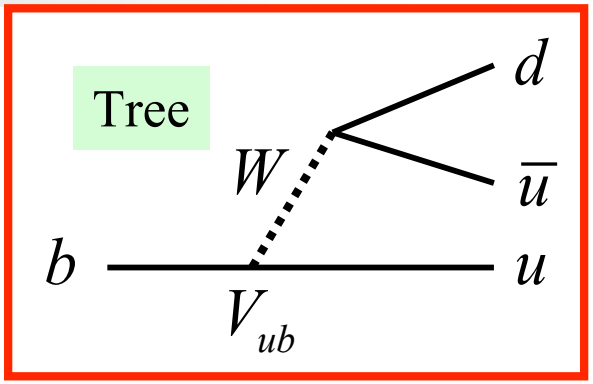
α from $B^0 \rightarrow \rho\rho/\pi\pi/\rho\pi$



- If tree diagram dominates:

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

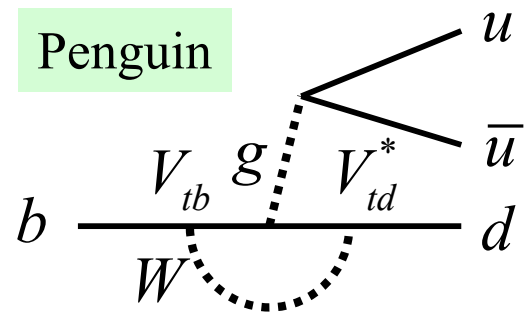
$$A_{CP}(t) = \sin 2\alpha \, \sin\Delta m t$$



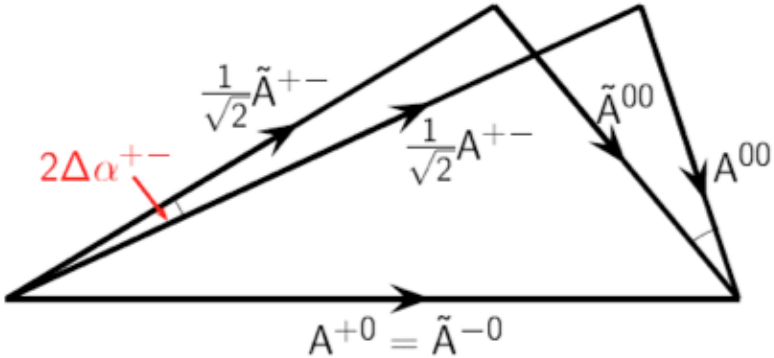
- If penguin contribution is non negligible

$$\sin 2\alpha \rightarrow \sqrt{1-C^2} \bullet \sin 2\alpha_{eff}$$

with $\alpha_{eff} = \alpha - \Delta\alpha$



- Isospin analysis measures $\Delta\alpha$
  - Gronau and London, PRL65, 3381 (1990)

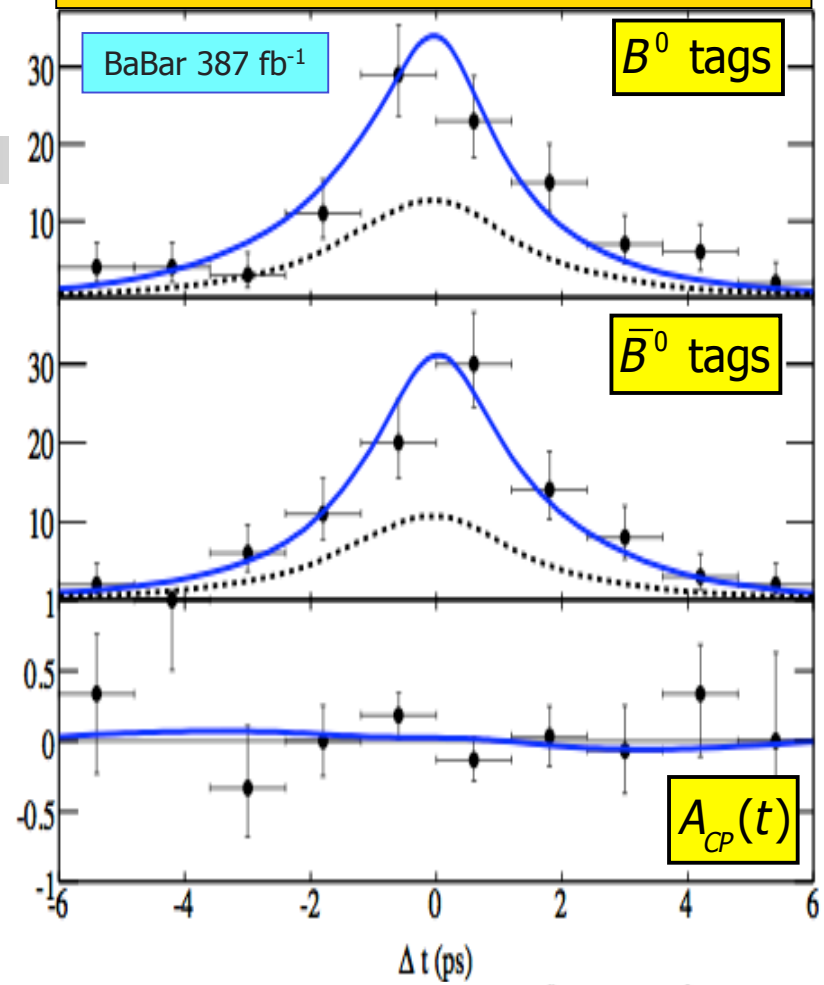


- Recent progress in B-->$\rho\rho$ decays
  - New BaBar result: arXiv:0901.3522 (hep-ex)

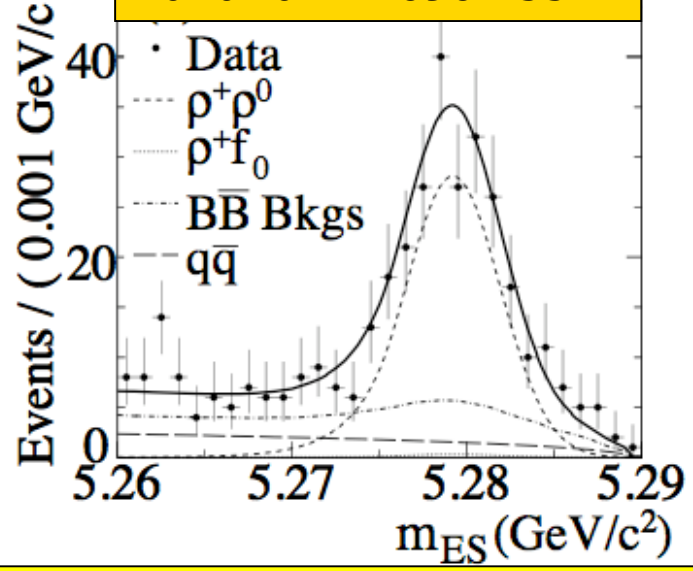
The long road to α

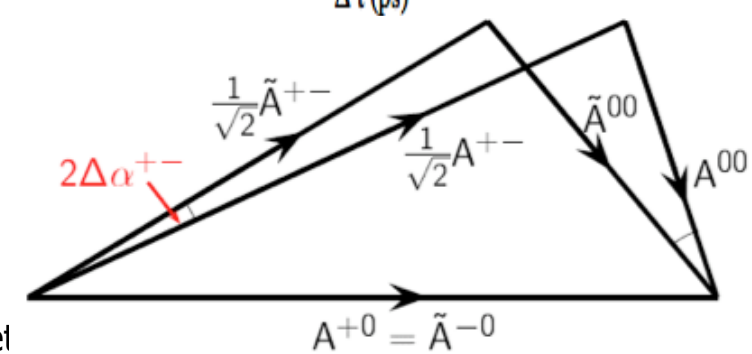
- CP violation parameters in $B^0 \to \rho^+\rho^-$
- Fraction of longitudinal polarization
  - B-->ρρ is a vector-vector final state
  - ~ 100% longitudinally polarized :-)
- All 5 BF needed to build isospin triangle
  - Neutral channel very hard to get to!

BaBar PRD 76, 052007(2007)



BaBar arXiv:0901.3522



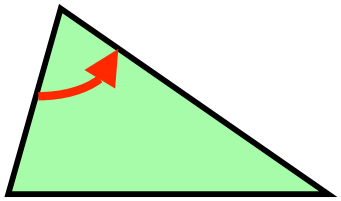


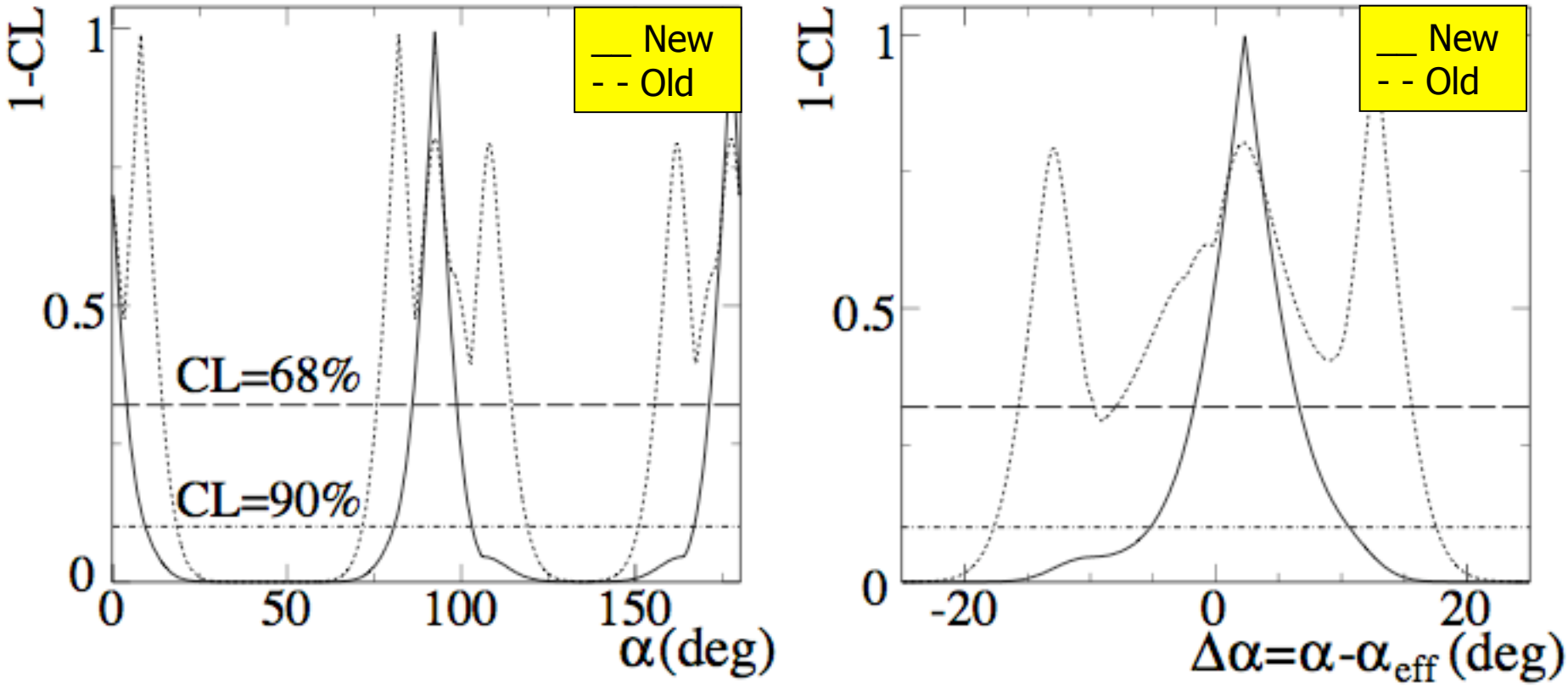
$BF(B^+ \to \rho^+\rho^0) = (23.7 \pm 1.4 \pm 1.4) \times 10^{-6}$

of CKM paramet

BaBar arXiv:0901.3522

New constraints on α from ρρ





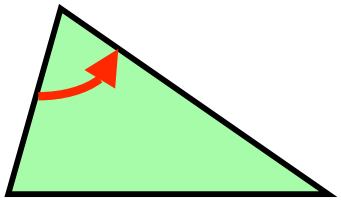
$$\alpha = \left(92^{+6.0}_{-6.5}\right)^{\circ} \quad \text{with} \quad -1.8^{\circ} < \Delta\alpha < 6.7^{\circ}$$

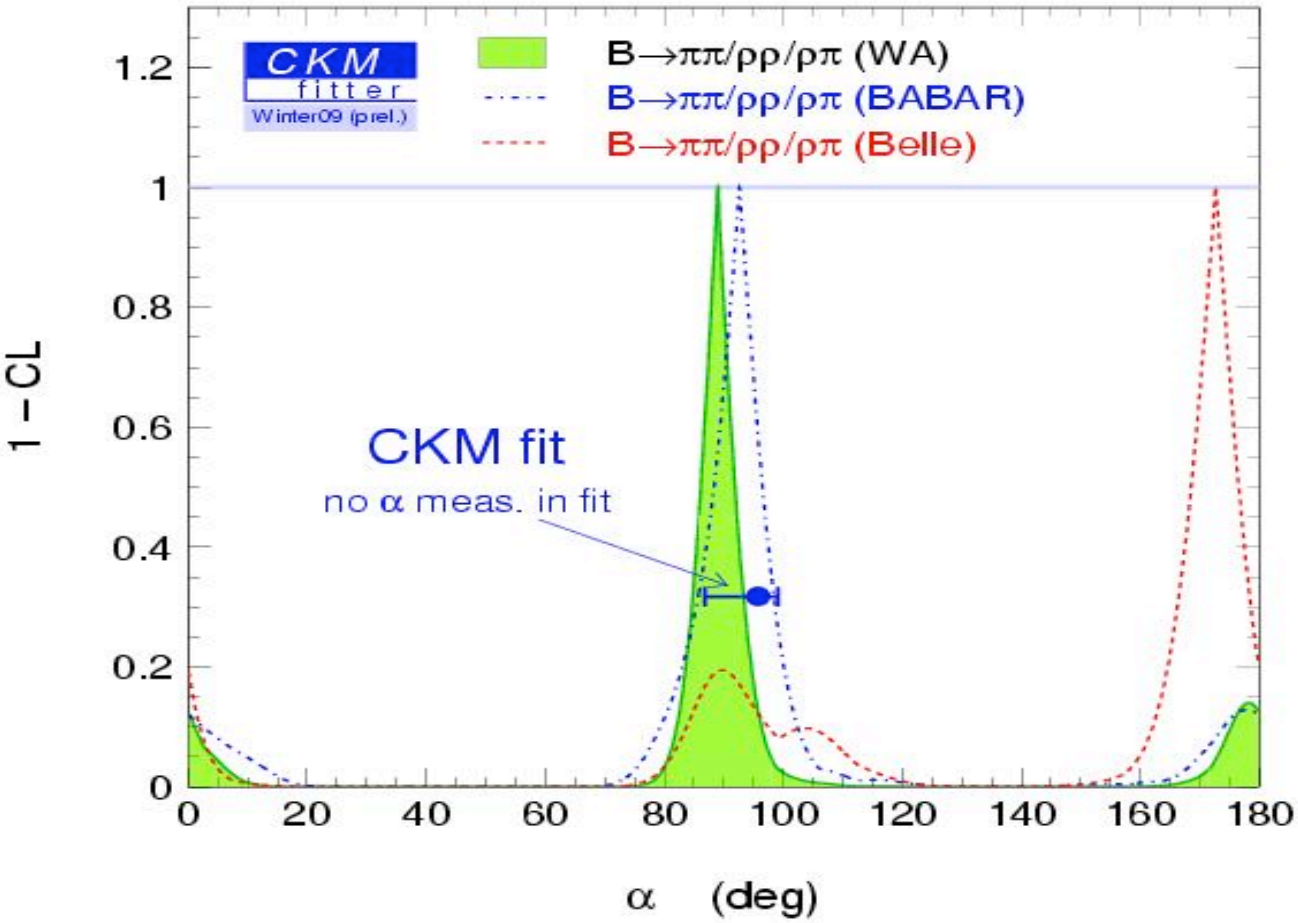
New ρ+ρ0

$$\alpha = \left(82.6^{+32.6}_{-6.3}\right)^{\circ} \quad \text{with} \quad |\Delta\alpha| < 15.7^{\circ}$$

Old ρ+ρ0

New constraints on α (WA)

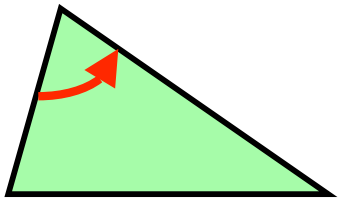


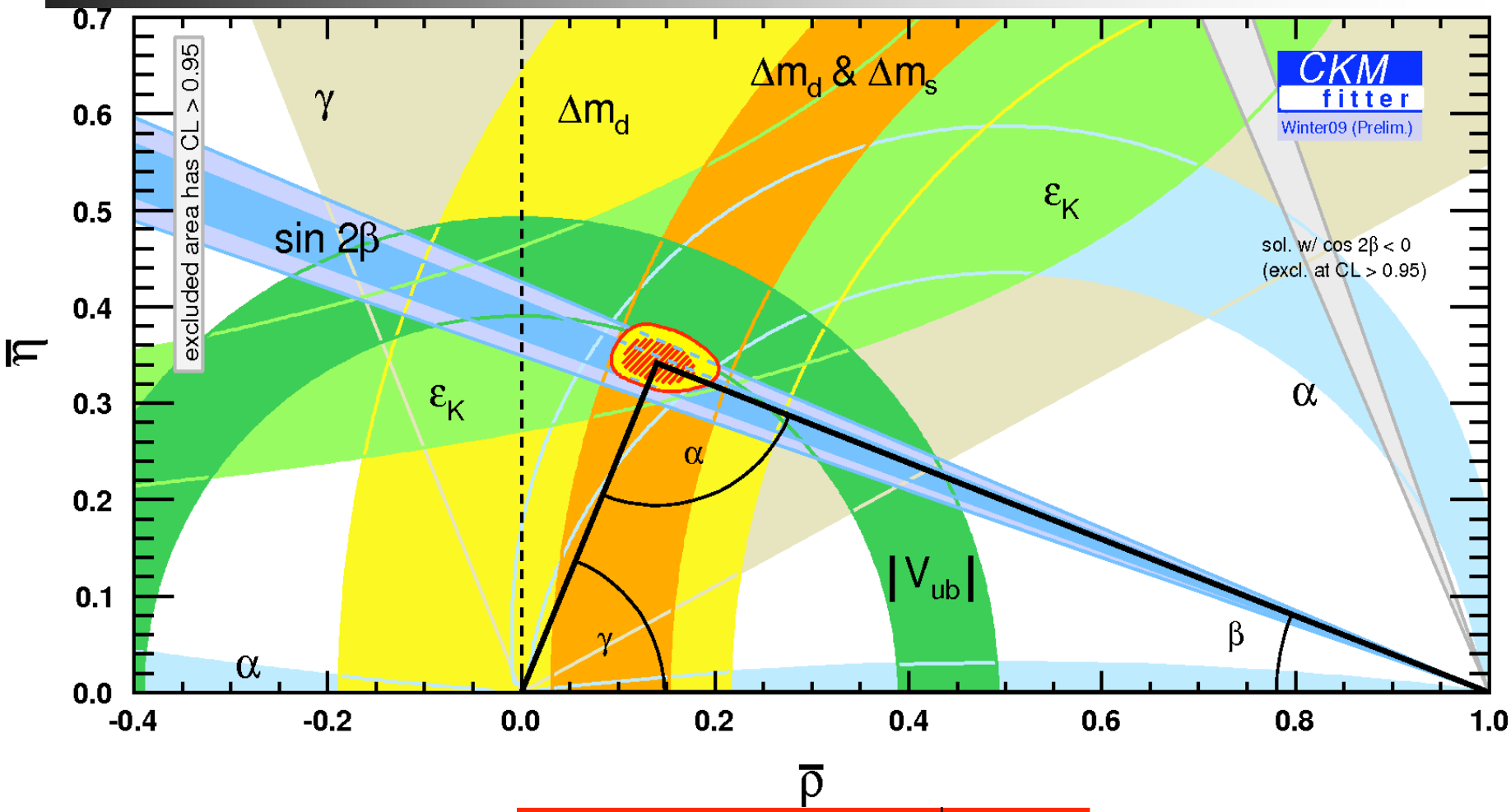


Average of BaBar and Belle

$$\alpha = \left(89.0^{+4.4}_{-4.2}\right)^{\circ}$$

New constraints on α (WA)

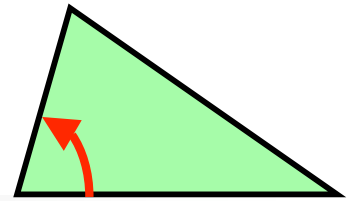




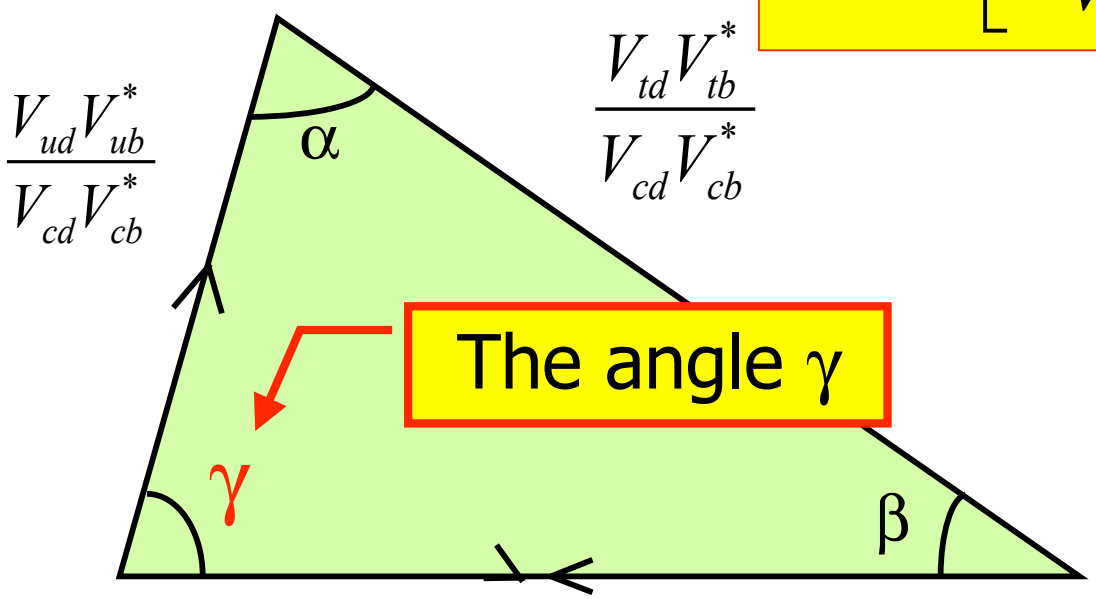
Average of BaBar and Belle

$$\alpha = \left(89.0^{+4.4}_{-4.2}\right)^{\circ}$$

The angle γ



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

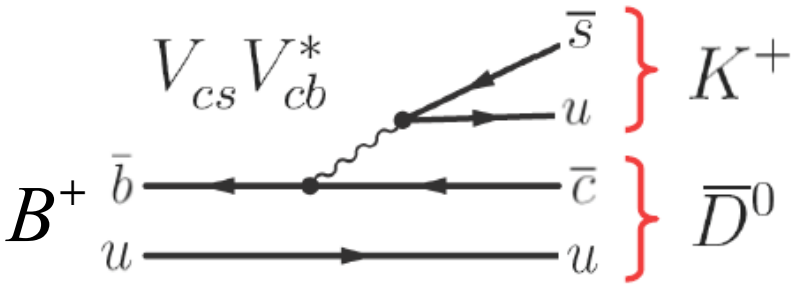


The angle γ

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

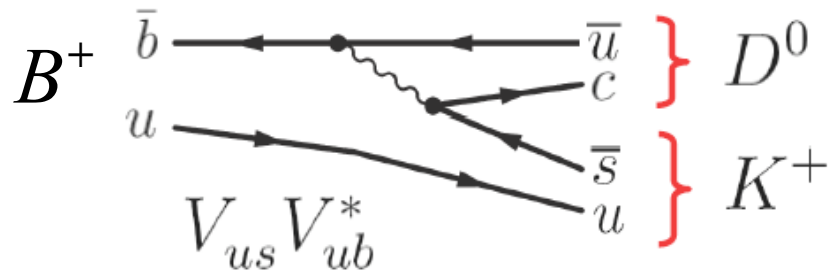
Use interference between $B^+ \to D^0K^+$ and $B^+ \to \bar{D}^0K^+$ with both D^0 and $\bar{D}^0$ decaying to the same final state f

Cabibbo allowed



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

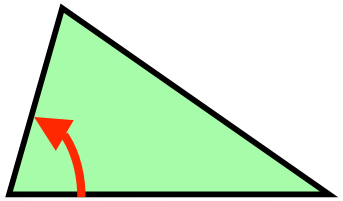
Cabibbo and color suppressed



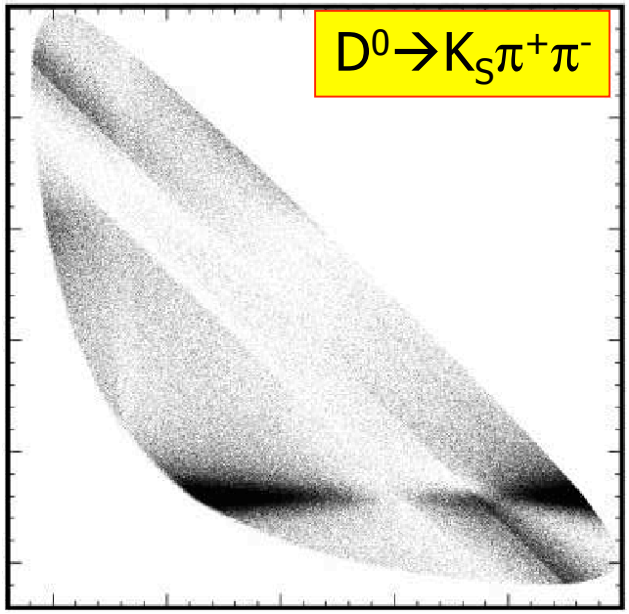
$$A(B^+ \to D^0K^+) \propto V_{ub}^*V_{cs} \propto \lambda^3\, r_B e^{i\delta_B} e^{i\gamma}$$

NB: only tree diagrams: 100% Standard Model

γ from B $\rightarrow$ DK

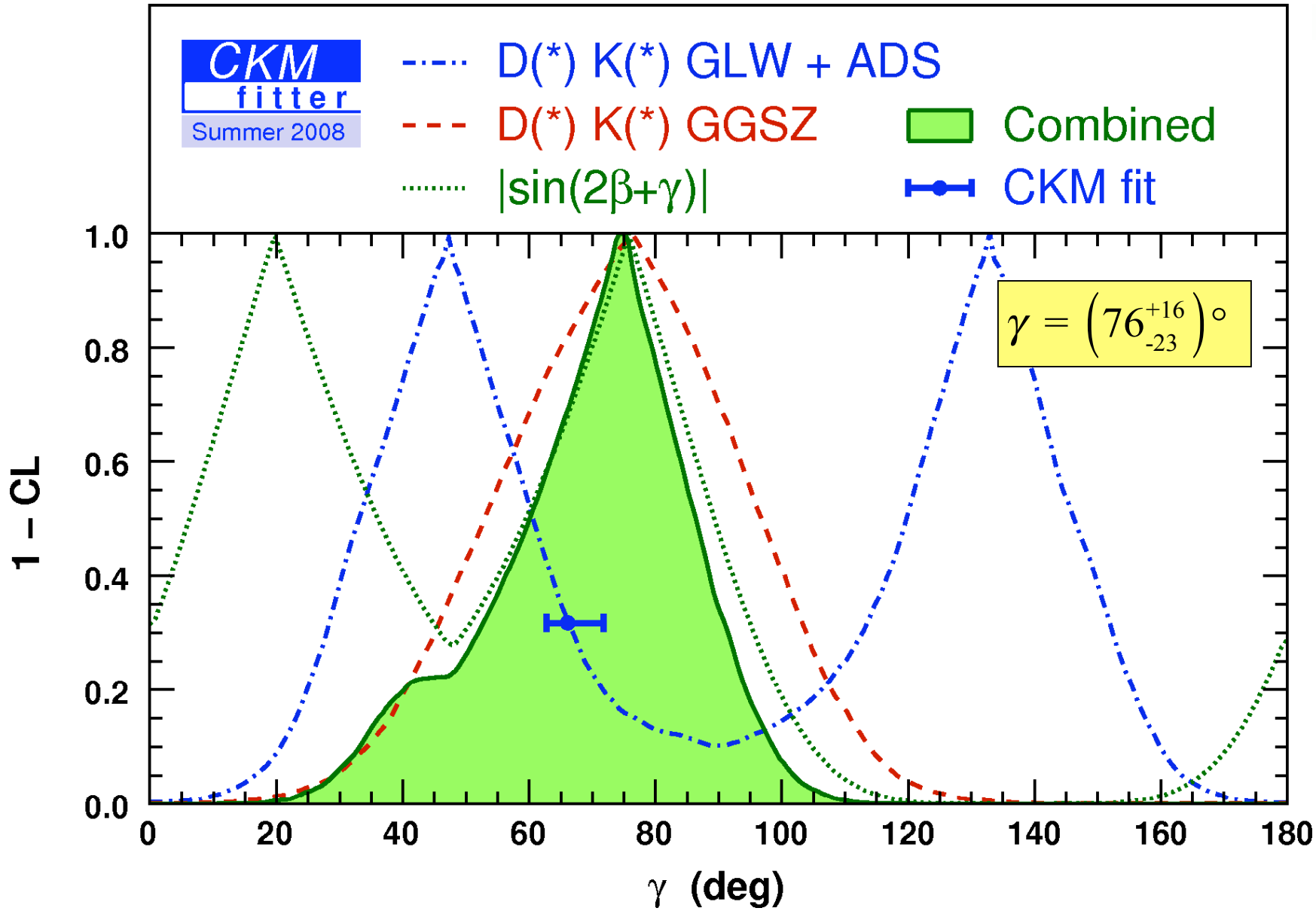


- GWL (Gronau, Wyler, London)
  - D → CP eigenstate
    - Theoretically clean
    - Small interference: needs more data
- ADS (Atwood, Dunietz, Soni)
  - $A(\bar{D} \rightarrow f)$ is doubly Cabibbo suppressed
    - Larger interference
    - Small BF: needs more data
- Dalitz method (Giri, Grossman, 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



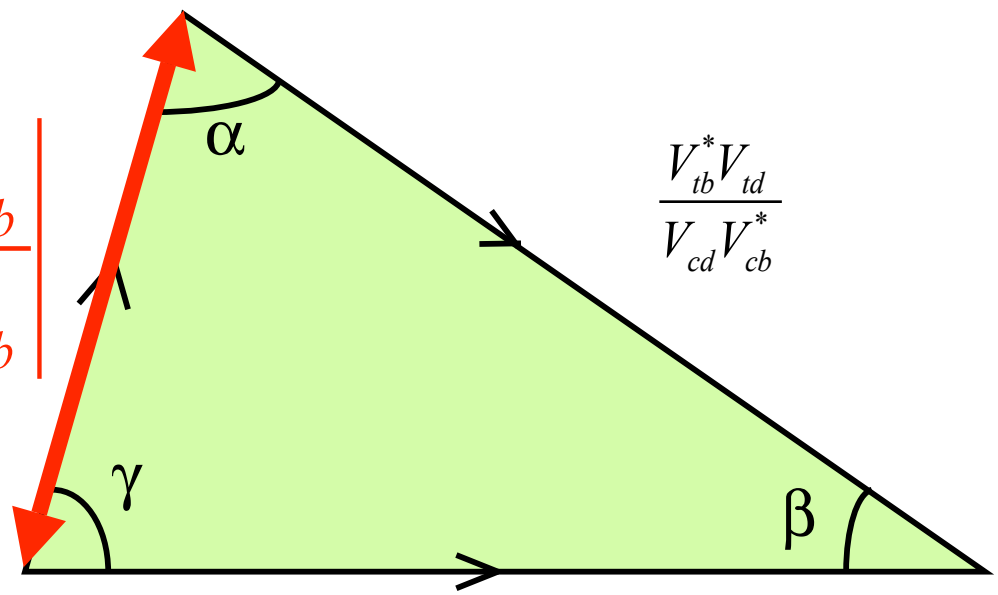
Currently most sensitive

Summary of γ measurements



The left side: R_b

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

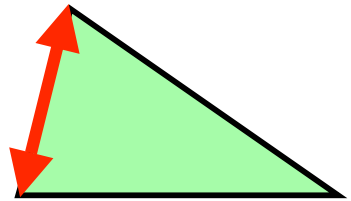


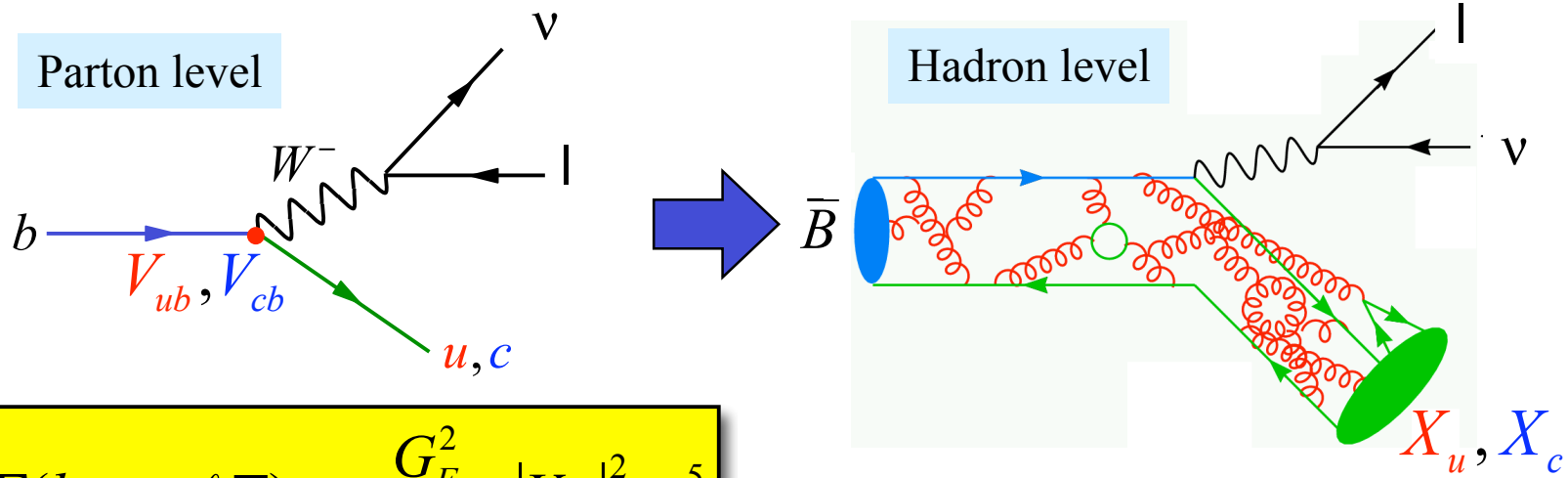
NB: β is the best measured quantity in the Unitarity Triangle

$$\boxed{\beta = (21.1 \pm 0.9)\,\text{degrees}}$$

→ precise measurement of R_b is needed for accurate tests of SM

Semileptonic B Decays

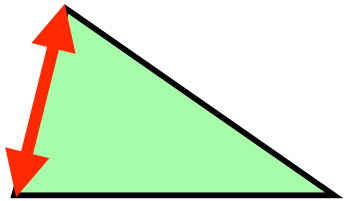


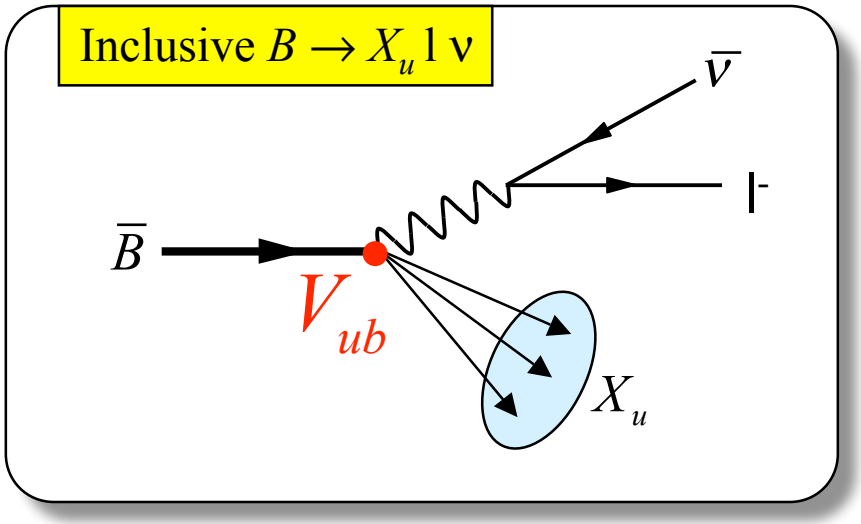


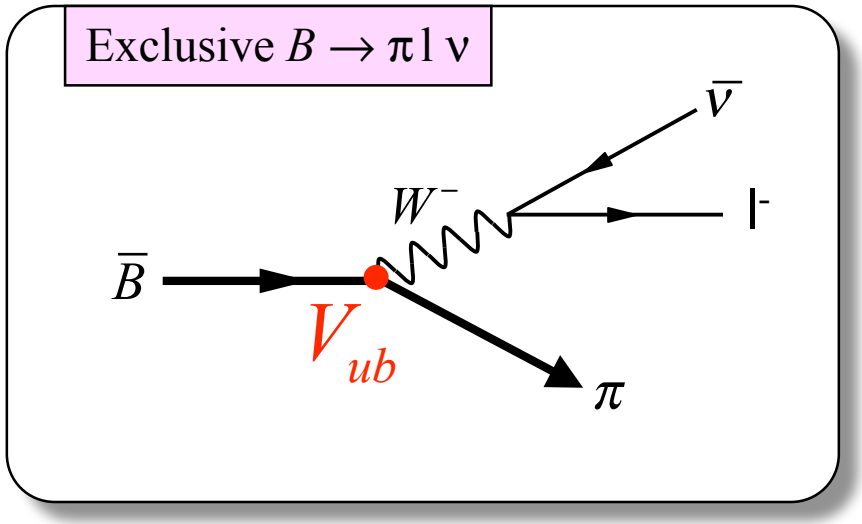
$$\Gamma(b \to u\ell\bar{\nu}) = \frac{G_F^2}{192\pi^2}|V_{ub}|^2 m_b^5$$

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

Two approaches to V_{ub}







Inclusive $B \to X_u l \nu$

- Hadronic final state is not specified
- b→c l ν background is suppressed using kinematical variables
- Partial rate is measured

  → theoretical uncertainties ~6%

Exclusive $B \to \pi l \nu$

- Better S/B but lower branching fraction (10^{-4})
- Needs form factor calculation from Lattice QCD

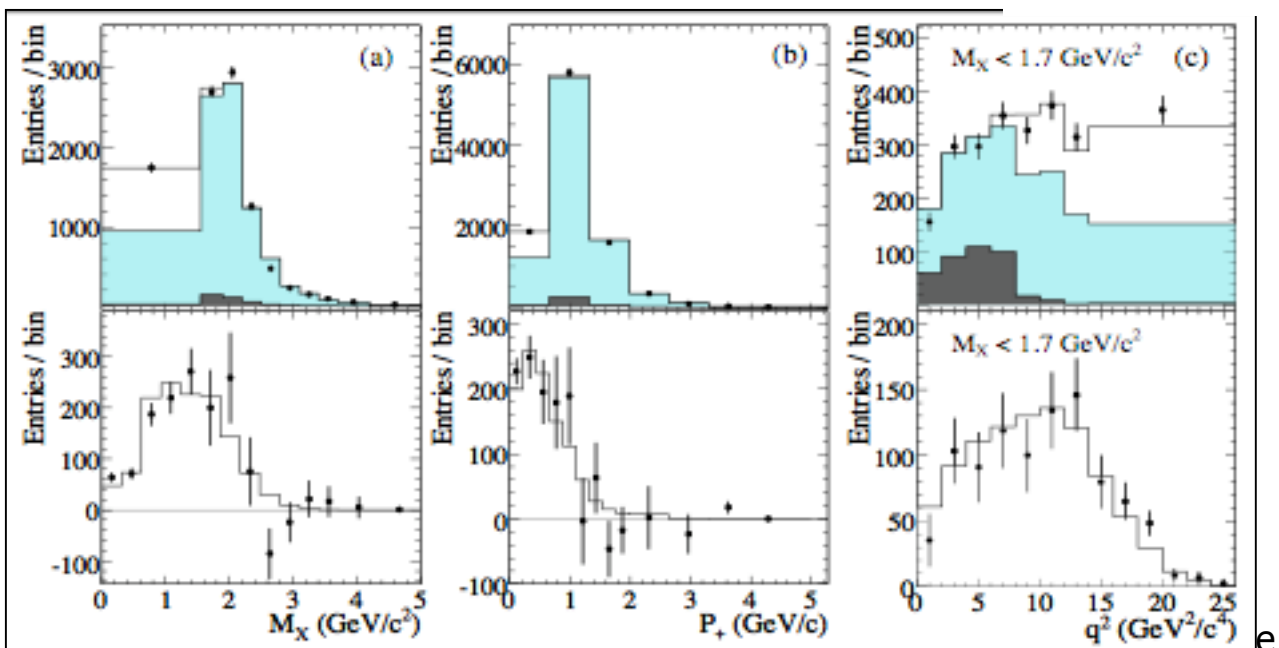
  → uncertainty of ~> 10%

Example:

BaBar's V_{ub} in tagged events

- $\Upsilon(4s) \rightarrow B_1 B_2$
  - $B_1 \rightarrow$ hadronic/SL mode, $B_2 \rightarrow u l \nu$
- Partial BF extracted fitting M_X, q^2, $P^+ = E_X - |P_X|$ distributions

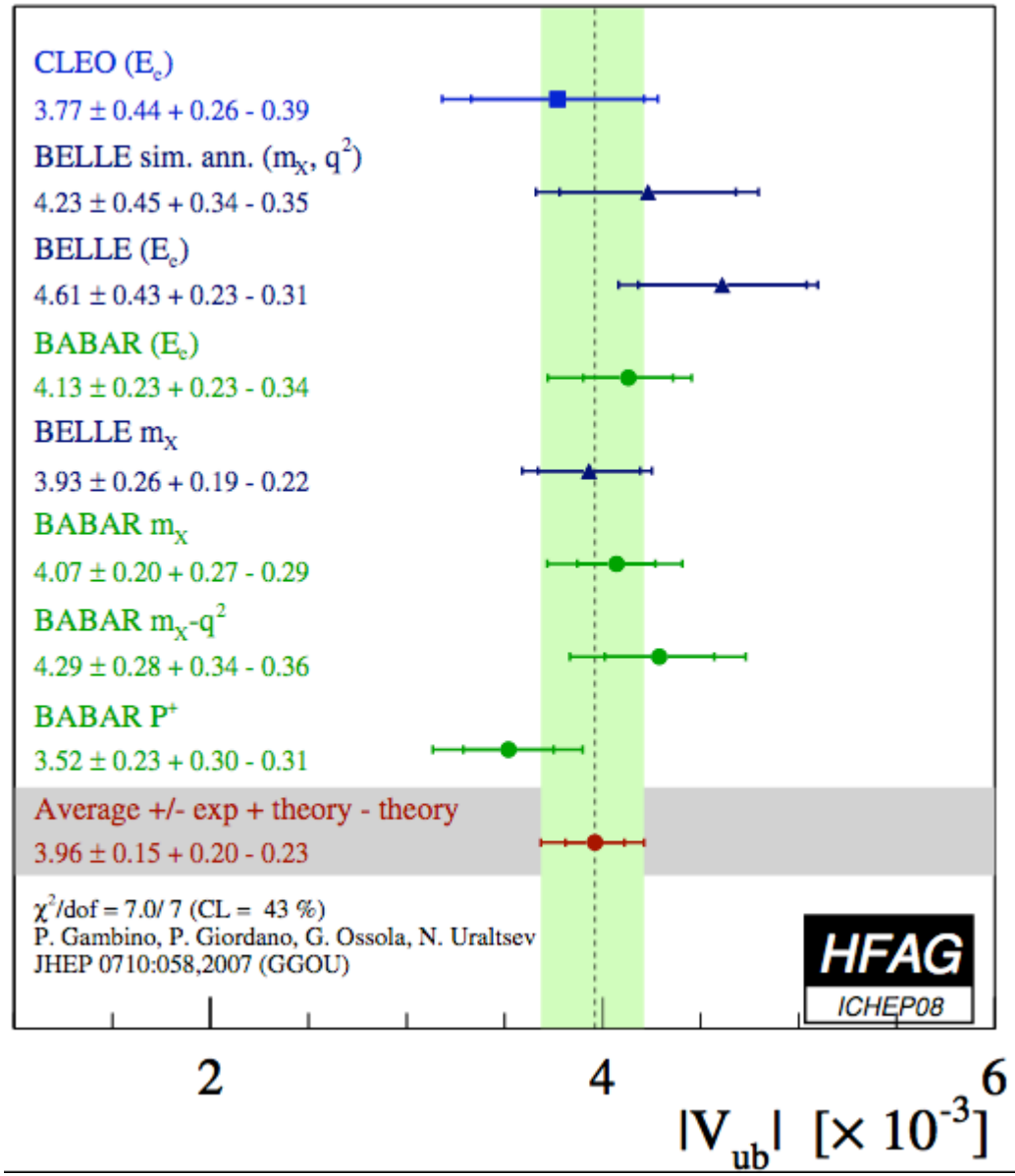
	Method	$\Delta\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})$ (10^{-3})	$\lvert V_{ub}\rvert \times (10^{-3})$
a)	M_X	$1.18 \pm 0.09 \pm 0.07 \pm 0.01$	$4.27 \pm 0.16 \pm 0.13 \pm 0.30$ [4]
			$4.56 \pm 0.17 \pm 0.14 \pm 0.32$ [5]
b)	P_+	$0.95 \pm 0.10 \pm 0.08 \pm 0.01$	$3.88 \pm 0.19 \pm 0.16 \pm 0.28$ [4]
			$3.99 \pm 0.20 \pm 0.16 \pm 0.24$ [5]
c)	M_X, q^2	$0.81 \pm 0.08 \pm 0.07 \pm 0.02$	$4.57 \pm 0.22 \pm 0.19 \pm 0.30$ [4]
			$4.64 \pm 0.23 \pm 0.19 \pm 0.25$ [5]
			$4.93 \pm 0.24 \pm 0.20 \pm 0.36$ [6]



[4] Lange, Neubert, Paz (2005)
[5] Andersen, Gardi (2006)
[6] Bauer, Ligeti, Luke (2001)

Kinematical regions:
a) $M_X < 1.55$ GeV/c^2
b) $P_+ < 0.66$ GeV/c
c) $M_x < 1.7$GeV/c^2, $q^2 > 8$GeV^2/c^4

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



Close collaboration between theorists and experimentalists led to

Precision on V_{ub}: ±6.5%

c.f.r.: precision on β: 3.5%

Conclusion

- Standard Model: precision
  - Tremendous improvement in ρ and η
    - Precision ~ 0.02-0.03
  - First quantitative test of CPV in SM
    - CKM is the dominant source of CPV

- New Physics: redundancy
  - Many different channels searched
  - No outstanding inconsistencies found
    - Limits on New Physics (Gambino)
  - B factories will soon pass the baton
    - LHCb & SuperB