CKM Unitarity Triangle:

Update on Angles from *BaBar*

Particle Physics Seminar
Physics Department, Brookhaven National Laboratory

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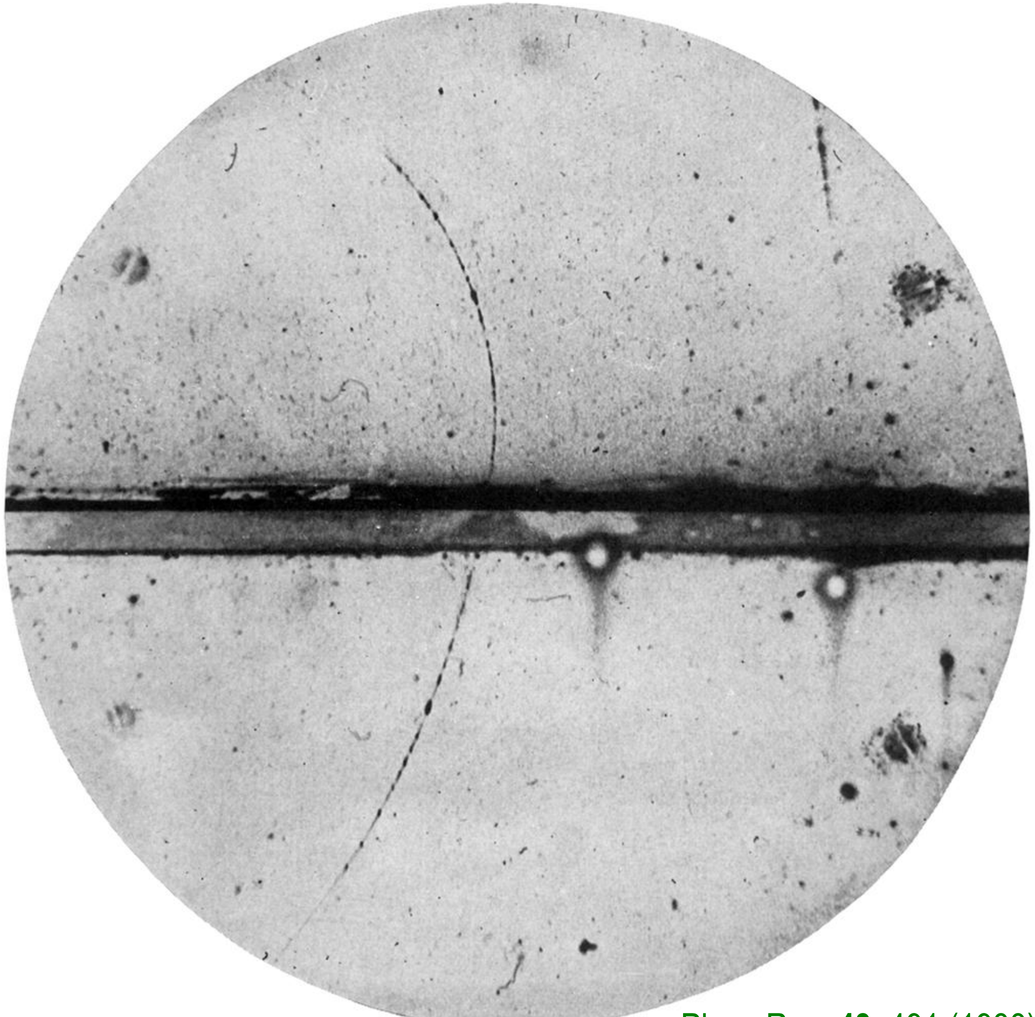
Discovery of antimatter

Each particle, except the truly neutral ones, has an antiparticle

1928: Dirac predicts antimatter to explain a seemingly unphysical solution to his equations of relativistic quantum mechanics



Phys. Rev. **43**, 491 (1933)

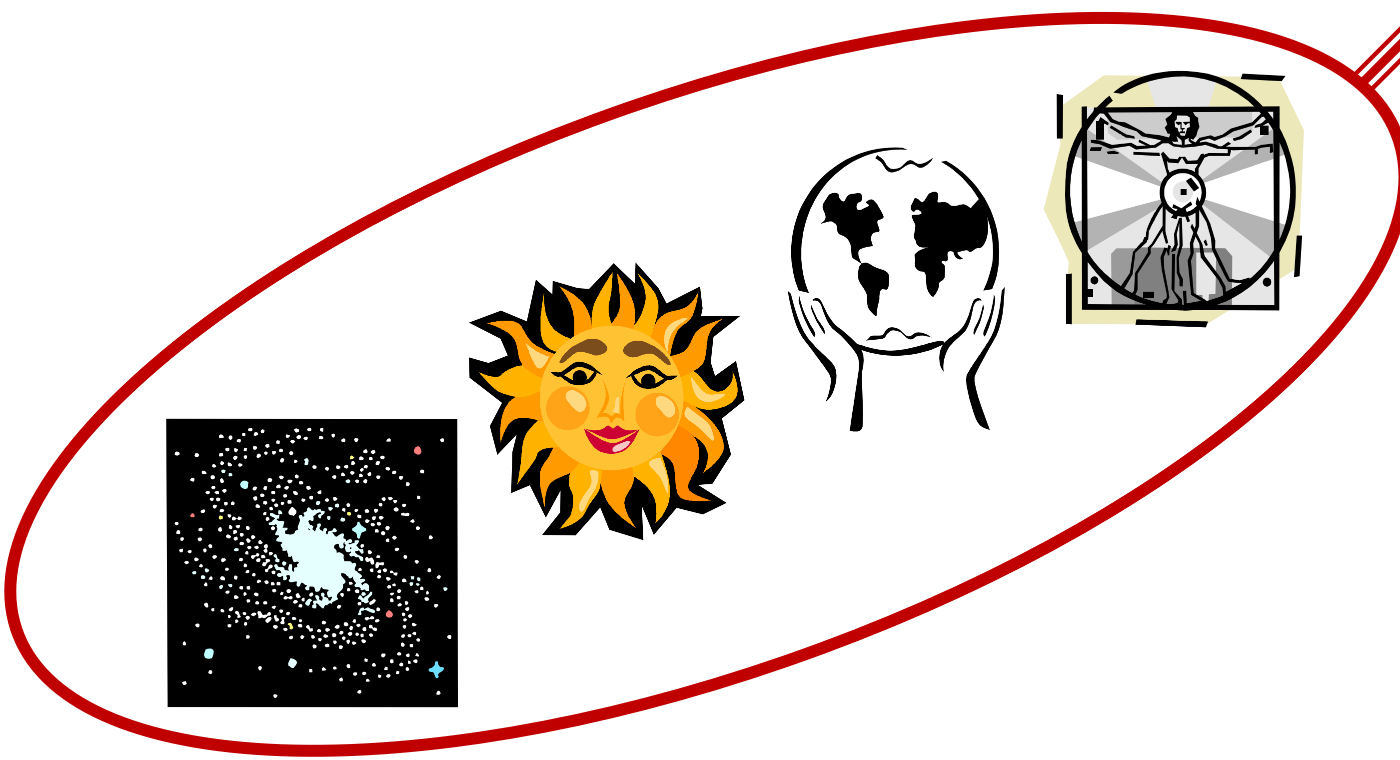
FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

1932: Anderson discovers positrons in cosmic rays passing through a Wilson chamber in 1.5 T magnetic field, shares 1936 Nobel Prize

Matter-Antimatter Asymmetry of the Universe

Very early Universe <u>must</u> have had equal amounts of matter and antimatter. Where did all the antimatter go?

Baryonic asymmetry of the Universe: $\dfrac{N_{\mathrm{B}}-N_{\bar{\mathrm{B}}}}{N_\gamma} \simeq \dfrac{N_{\mathrm{B}}}{N_\gamma} \simeq 5\times 10^{-10}$



Symmetries in Nature

Symmetries have played a central role in the development of physics:

Translation in space ↔ conservation of linear momentum

Rotation in space ↔ conservation of angular momentum

Translation in time ↔ conservation of energy

Redefinition of relative phase ↔ conservation of electrical charge

Parity: a discrete symmetry

Spatial parity $\boldsymbol{P}$:

$$\vec{r} \to -\vec{r}, \quad \vec{s} \to +\vec{s}, \quad \vec{L} \to +\vec{L}$$

$$P\,|a(E,\vec{p},\lambda)\rangle = \eta_P\,|a(E,-\vec{p},-\lambda)\rangle \qquad (\lambda \equiv \vec{s}\cdot\vec{p})$$

$$P = P^{-1} = P^{\dagger}, \quad \eta_P = \pm 1$$

$$P(Y_{\ell m}(\vartheta,\varphi)) = Y_{\ell m}(\pi-\vartheta,\pi+\varphi) = (-1)^{\ell}\,Y_{\ell m}(\vartheta,\varphi)$$

$$P(\text{fermion}) = -P(\text{antifermion}); \quad \boldsymbol{P(q\bar{q}') = (-1)^{L+1}}$$

Charge conjugation $\boldsymbol{C}$:

$$C\,|a(E,\vec{p},\lambda)\rangle = \eta_C\,|\bar{a}(E,\vec{p},\lambda)\rangle$$

$$C = C^{-1} = C^{\dagger}, \quad \eta_C = \pm 1$$

$$-1 = (-1)^{S+1}\cdot(-1)^{L}\cdot C(q\bar{q}) \;\Rightarrow\; \boldsymbol{C(q\bar{q}) = (-1)^{L+S}}$$

Fermi statistics

Spin wavefunction

Orbital wavefunction

Time reversal $\boldsymbol{T}$:

$$T\,|a(E,\vec{p},\lambda)\rangle = \eta_C\,\langle a(E,-\vec{p},\lambda)| \;; \qquad \eta_P = \pm 1$$

CPT theorem

Lagrangian of any quantum field theory

that obeys the laws of relativity and causality, conforms to the quantum mechanical interpretation of the positive, conserved probability, and is local,

is invariant under the combined *CPT* transformation.

Consequence: masses and total decay widths of a particle and its antiparticle must be equal to all orders of interactions.

Note: *equality of all* ***partial*** *decay widths requires, in addition to CPT, invariance of the Lagrangian under* ***CP****.*

Discovery of CP violation

Christensen, Cronin, Fitch, Turlay @ AGS (Brookhaven), 1964

$$\begin{cases} K^0 = d\,\bar{s} \\ \overline{K^0} = s\,\bar{d} \end{cases} ; \quad \begin{cases} CP\left|K^0\right\rangle = e^{+2i\vartheta}\left|\overline{K^0}\right\rangle \\ CP\left|\overline{K^0}\right\rangle = e^{-2i\vartheta}\left|K^0\right\rangle \end{cases}$$

(ϑ is a matter of convention)

$$\left\{ \begin{array}{l} K_1^0 = \left|K_{CP=+1}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + e^{+2i\vartheta}\left|\overline{K^0}\right\rangle\right) \rightarrow \pi^+\pi^-,\ \pi^0\pi^0 \\ K_2^0 = \left|K_{CP=-1}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - e^{+2i\vartheta}\left|\overline{K^0}\right\rangle\right) \rightarrow \pi^+\pi^-\pi^0,\ \pi^0\pi^0\pi^0 \end{array} \right\}$$

$$\begin{cases} m_{K^0} = 497.648 \pm 0.022\ \text{MeV} \\ m_{K_L^0} - m_{K_S^0} = (3.483 \pm 0.006)\times 10^{-6}\ \text{eV} \end{cases} ; \quad \begin{cases} \tau_{K_S^0} = (0.8953 \pm 0.0005)\times 10^{-10}\ \text{sec} \\ \tau_{K_L^0} = (5.116 \pm 0.020)\times 10^{-8}\ \text{sec} \end{cases}$$

$$\begin{cases} \mathrm{Br}(K_S^0 \rightarrow \pi^+\pi^-) = 69.20 \pm 0.05\,\% \\ \mathrm{Br}(K_S^0 \rightarrow \pi^0\pi^0) = 30.69 \pm 0.05\,\% \\ \mathrm{Br}(K_S^0 \rightarrow \pi^+\pi^-\pi^0) = 3.5^{+1.1}_{-0.9}\times 10^{-7} \\ \mathrm{Br}(K_S^0 \rightarrow 3\pi^0) < 1.2\times 10^{-7} \end{cases} ; \quad \begin{cases} \mathrm{Br}(K_L^0 \rightarrow 3\pi^0) = 19.51 \pm 0.12\,\% \\ \mathrm{Br}(K_L^0 \rightarrow \pi^+\pi^-\pi^0) = 12.54 \pm 0.05\,\% \\ \mathrm{Br}(K_L^0 \rightarrow \pi^+\pi^-) = (1.966 \pm 0.010)\times 10^{-3} \\ \mathrm{Br}(K_L^0 \rightarrow \pi^0\pi^0) = (8.64 \pm 0.06)\times 10^{-4} \end{cases}$$

PDG 2007 data

↑ *CP* violating decays ↑

Through the *CPT* Theorem, *CP* violation implies the existence of *T* violation

Sakharov's three conditions

The three conditions necessary to produce the baryonic asymmetry of the Universe:

(photo circa 1943)

А. Д. Сахаров, *Письма в ЖЭТФ*, **5**, № 1, 32-35, 1 января 1967
A. D. Sakharov, *Soviet Journal of Experimental and Theoretical Physics, Letters to the Editor,* **5**, No. 1, 24-27, 1st January 1967

1. Baryon number violation (proton decay)

2. *C* and *CP* violation

By far the strongest argument for existence of sources of *CP* violation in nature is the very fact that we are here today!

3. Departure from thermal equilibrium

The Quark Mixing Matrix

The only Standard-Model source of CP violation in the quark sector

The Cabibbo-Kobayashi-Maskawa matrix relates the electroweak (q') and the mass (q) quark eigenstates:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) + iO(\lambda^6)$$

$$V^\dagger V = 1 \Rightarrow V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

the "unitarity triangle"

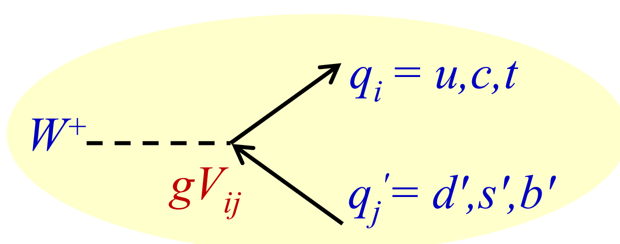
$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

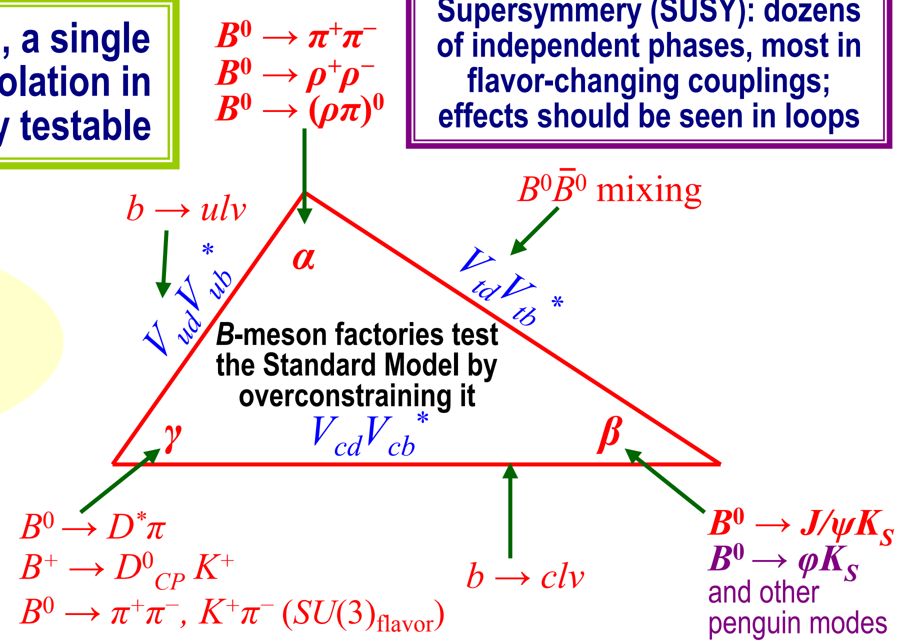
$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

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

In the Kobayashi-Maskawa model, a single phase is responsible for all *CP* violation in meson decays, making it uniquely testable

Supersymmetry (SUSY): dozens of independent phases, most in flavor-changing couplings; effects should be seen in loops





CKM mechanism alone is far too small to account for the baryon asymmetry of the universe: Gavela et.al, Nucl. Phys. ***B 430****, 382 (1994)*

Time evolution of the B^0 meson

The time-dependent rate for $\overline{B}^0$ (f_+) or B^0 (f_-) decays to a final state f (neglecting the lifetime difference between the mass eigenstates B_{Heavy} and B_{Light}):

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}[1 \mp C_f \cos(\Delta m \Delta t) \mp S_f \sin(\Delta m \Delta t)]$$

where

S and C is what we measure

$$|B_{L/H}> = p|B^0> \pm q|\overline{B^0}>, \quad \lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}, \quad S_f = \frac{-2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}, \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

from mixing, $\approx e^{-2i\beta}$

a_f is the time-evolution asymmetry:

$$a_f(\Delta t) = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)}$$

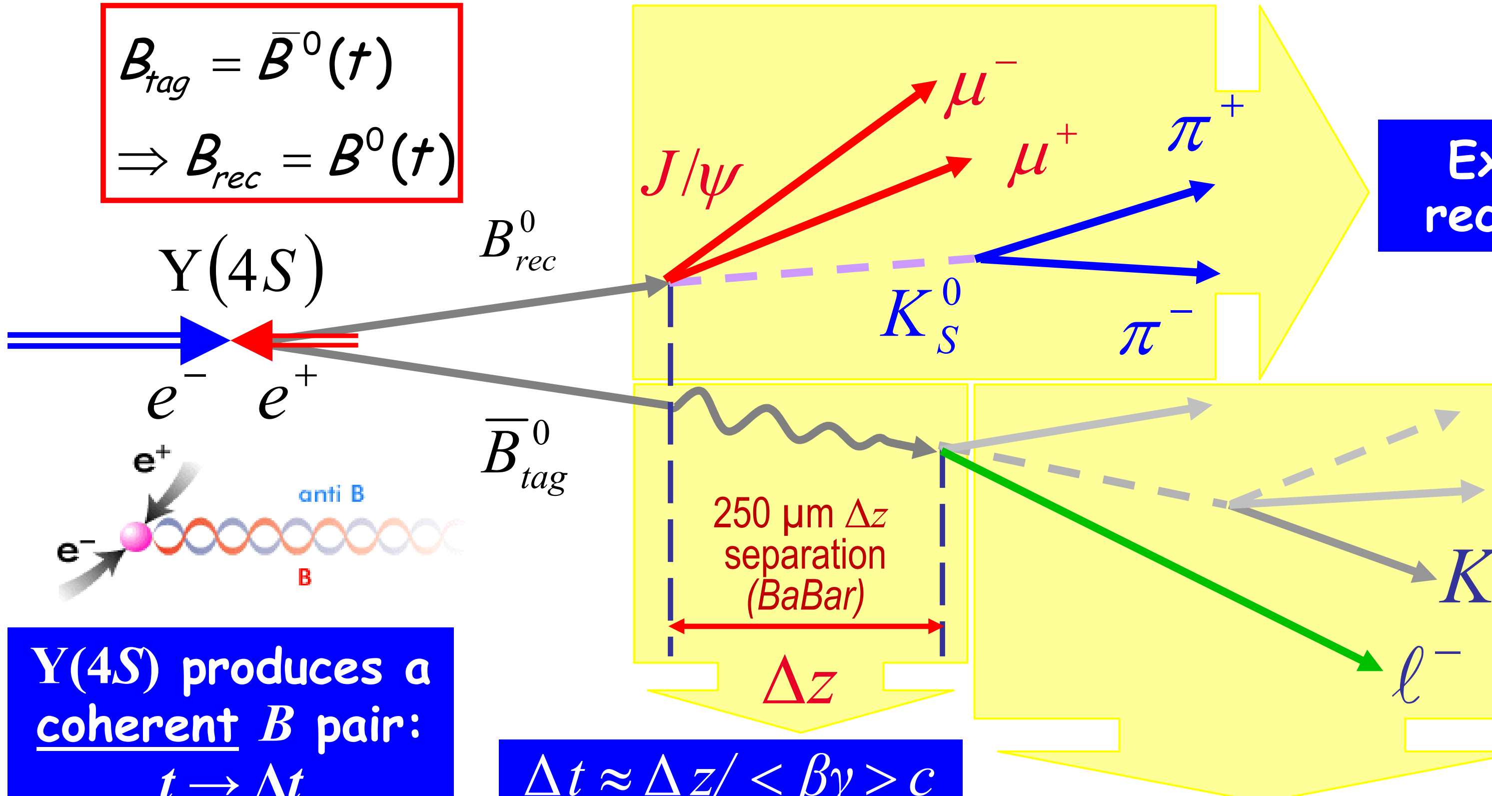
If f is a CP eigenstate, f_{CP}, we have CP violation if $\lambda_f \neq \pm 1$:

- $|q/p| \neq 1$ (CP violation in mixing, very small) ← ***B. Aubert et al. (BaBar Collaboration) Phys. Rev. Lett. 96, 251802 (2006)***
- $|\overline{A}_{\bar{f}}/A_f| \neq 1$ (direct CP violation, small in $b \to c\bar{c}s$)
- **$\mathrm{Im}(\lambda_f) \neq 0$ (interference between mixing and decay)**

Time-dependent *CP* analysis at a *B*-meson factory

$B_{tag} = \bar{B}^0(t)$

$\Rightarrow B_{rec} = B^0(t)$



Exclusive B^0 reconstruction

Effective B^0 flavor tagging efficiency Q=31.2%

Tagging by kaon charge from $b \to c \to s$ most common

Lepton tag is the most pure (94%)

6 non-overlapping Neural Nets (or no tag)

$\Upsilon(4S)$ produces a coherent B pair: $t \to \Delta t$

$\Delta t \approx \Delta z / <\beta\gamma> c$

B^0 flavor tagging

Time-integrated asymmetry is zero

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

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

PEP-II performance

Υ(4*S*) operation concluded on December 21, 2007
Υ(3*S*): 30 fb^{-1} (done)
Υ(2*S*): 20 fb^{-1} (in progress)

Υ(4*S*) CM energy: 10.580 GeV

Beam energies:
- electrons: 9.0 GeV
- positrons: 3.1 GeV

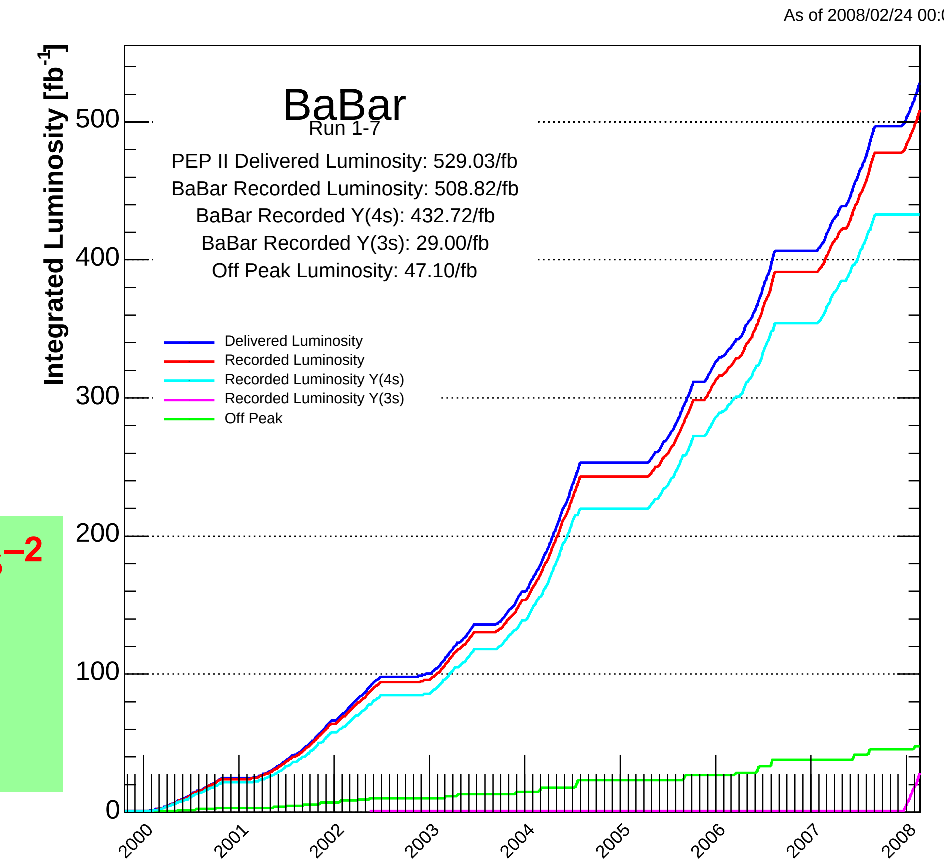
Beam currents:
- electrons: 2.05 A
- positrons: 3.03 A

Number of bunches: 1722

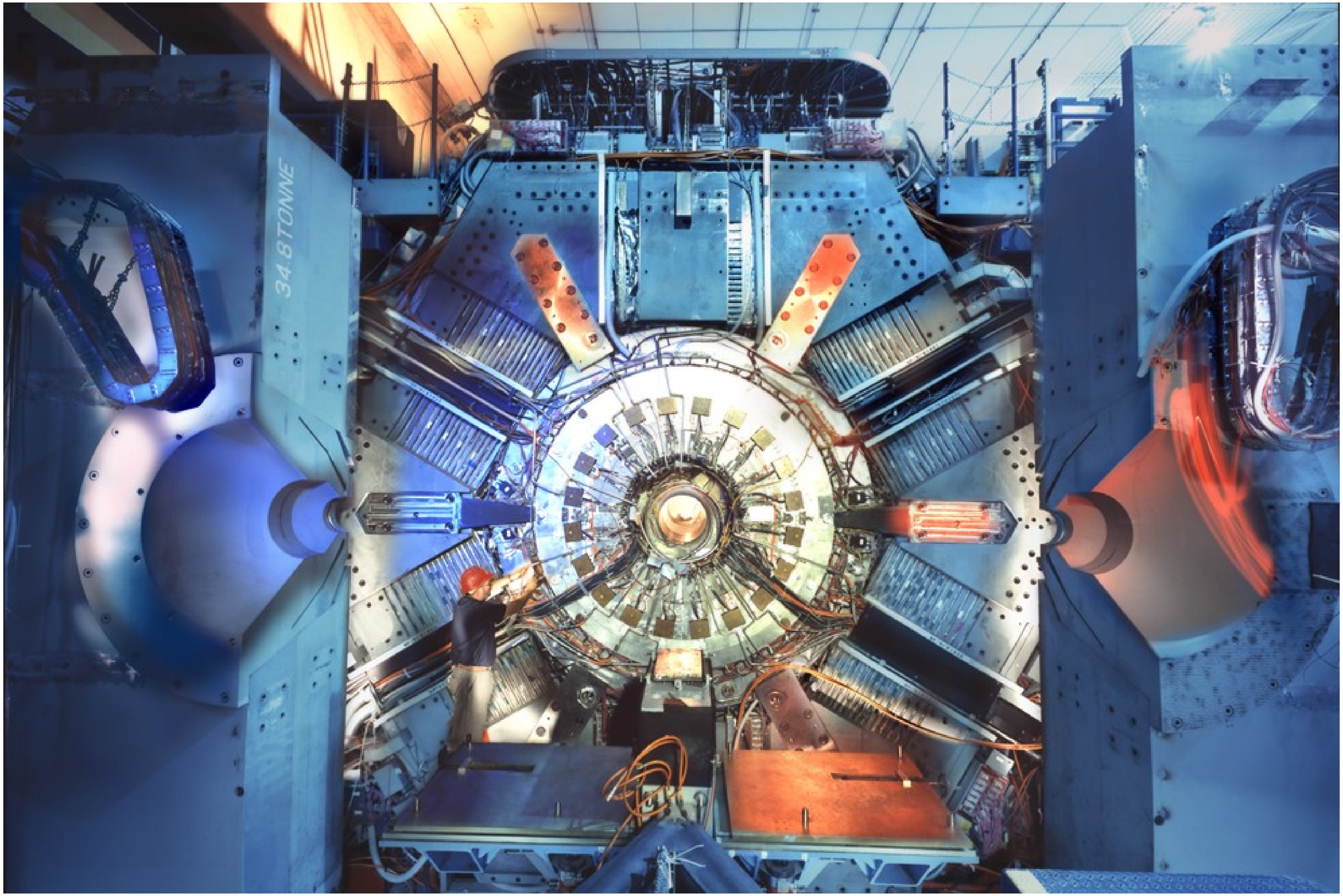
Beam size at IP: 125 μm x 4 μm

Peak luminosity: 12.1 x 10^{33} cm^{-1}s^{-2}
(design: 3 x 10^{33} cm^{-1}s^{-2})

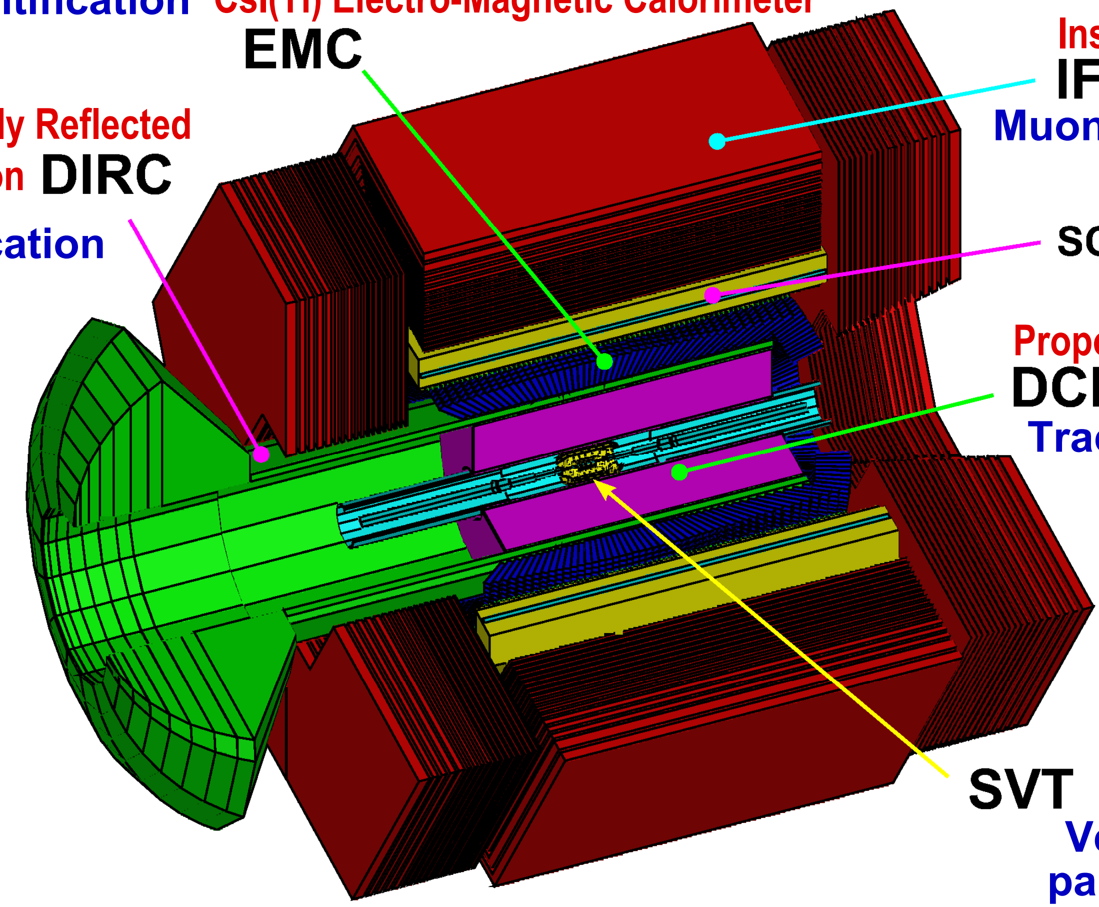
Best 24 hours: 911 pb^{-1} delivered
(design: 135 pb^{-1}/day)



The *BaBar* detector



The BaBar detector

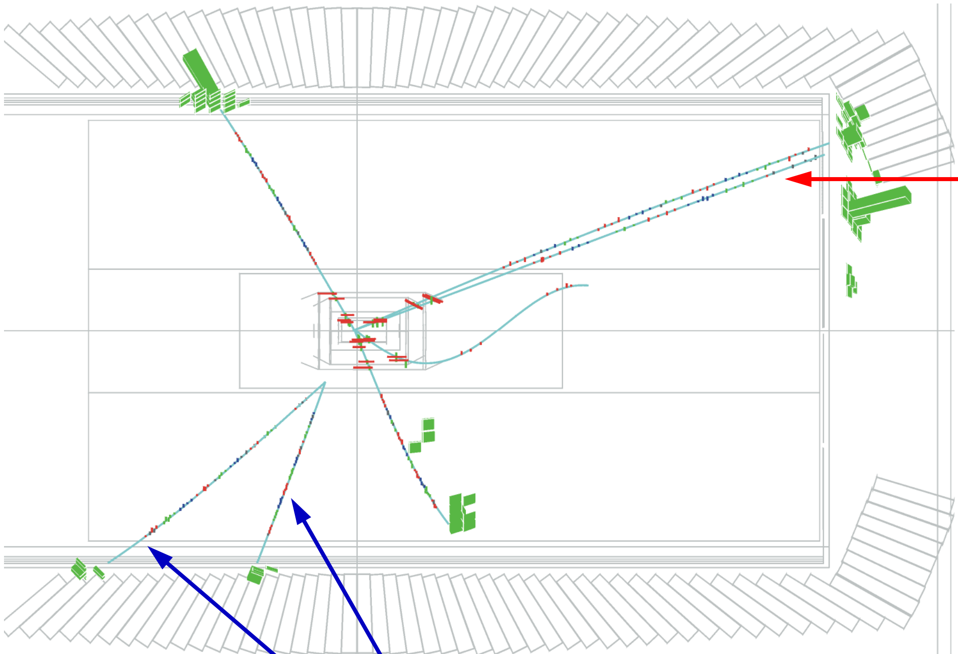


Note that electron ID and muon ID are largely orthogonal to pion/kaon/proton separation with DIRC+DCH+SVT

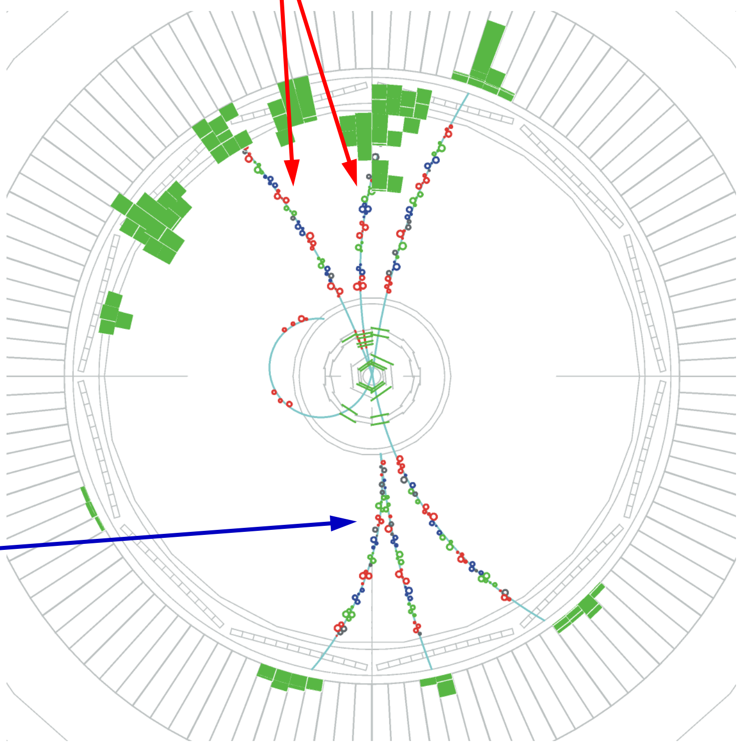
Example of a *B*-decay event in *BaBar*

$B^0 \to \varphi K_S$

only the hits that correspond to reconstructed tracks and neutral candidates are shown (noise hits are removed)



$\varphi \to K^+K^-$



$K_S \to \pi^+\pi^-$

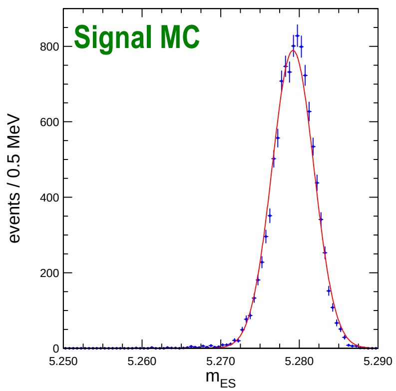
Run 29368, event hexID 249a4b/d610dd73 (June 27, 2002)
*From the dataset used in Phys.Rev.D **69**:011102, 2004*

Common discriminating variables: kinematics

A pair of weakly correlated variables that reflect energy and momentum conservation: peaking for fully reconstructed B decays, smooth for combinatorial background

$$m_{\mathrm{ES}} \equiv \sqrt{E^2_{\mathrm{CM\ beam}} - p^2_{\mathrm{CM}\ B}} = m_B$$

$$\Delta E \equiv E_{\mathrm{CM}\ B} - E_{\mathrm{CM\ beam}} = 0$$

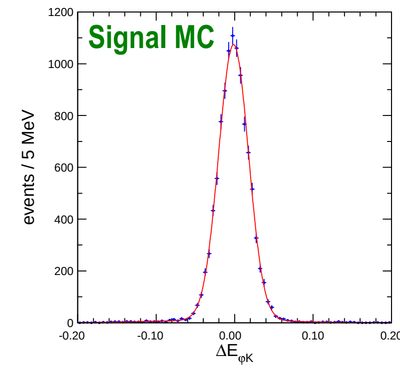


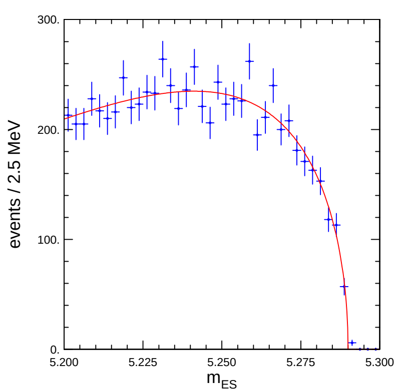
resolution ~2.6 MeV/c^2

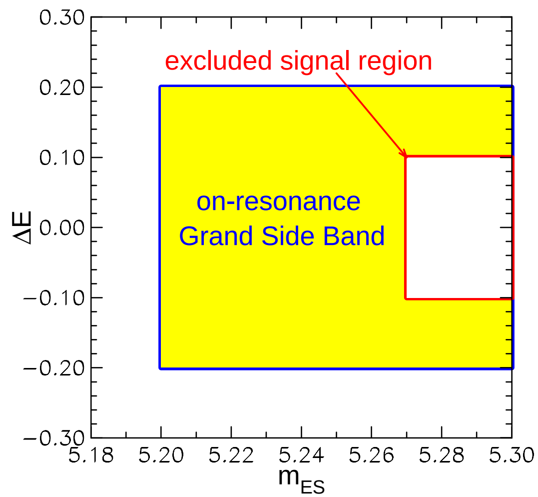
determined by the beam energy spread

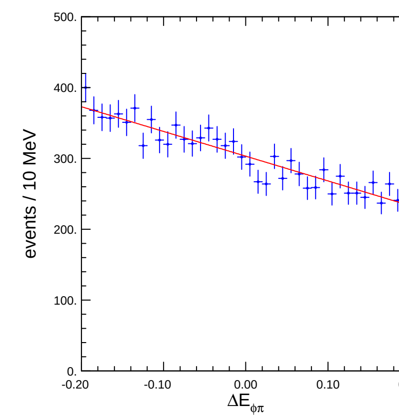
resolution ~15–80 MeV

depending on the number of tracks and presence of neutrals in the final state





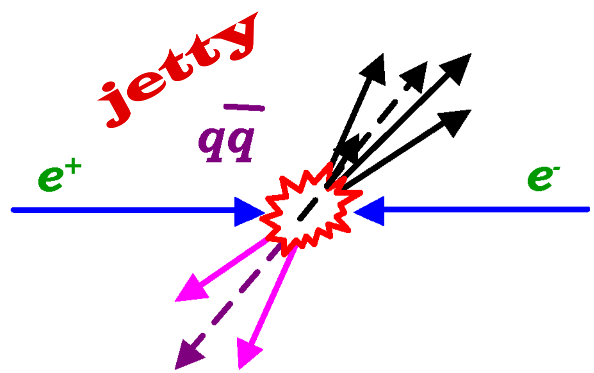


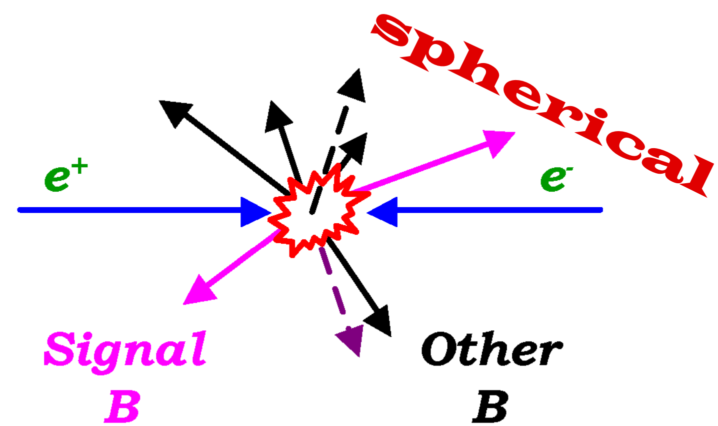


continuum background in the Grand Side Band

Common discriminating variables: event shape

- The principal source of background to rare B decays: random track/neutral combinations from quark-pair $(udsc)$ production in the continuum:
  - total $udsc$ cross section ~3.4 nb, compared to ~1.1 nb for $\Upsilon(4S)$
  - $udsc$ events have jet-like topology, while *B* decays are nearly spherical in CM
  - several topological variables are employed to suppress this background
- Backgrounds from $\tau^+\tau^-$ production and two-photon physics are usually negligible
- Backgrounds from other B decays tend to be small



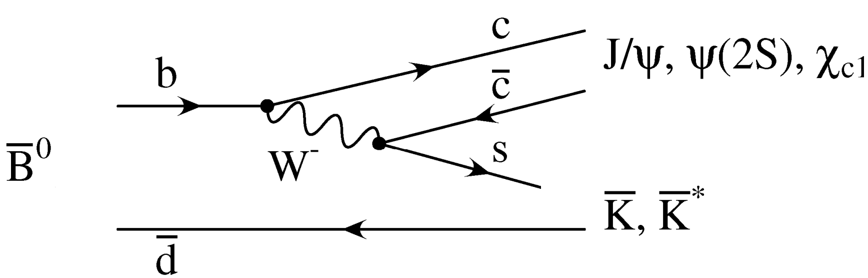


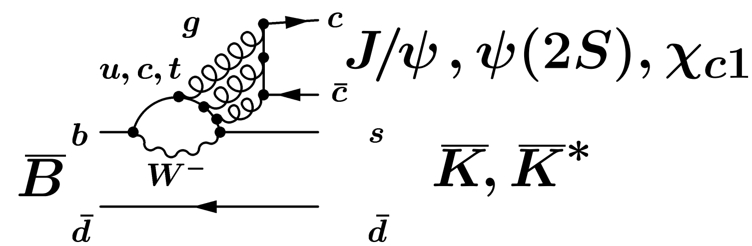
Analyses are <u>blind</u> until the methodology has been finalized and frozen

$\sin 2\beta$ in "golden" $b \to c\bar{c}s$ modes:

The highest-precision test of the KM mechanism of *CP* violation in meson decays

Golden-mode branching fractions are $O(10^{-3})$





"Golden" modes: color-suppressed tree dominates; the *t*-quark penguin has the same weak phase as the tree (none). In Standard Model, therefore,

$$S_{\text{golden}} = \eta_{CP} \times \sin 2\beta, \quad C_{\text{golden}} = 0 \quad (\eta_{CP} = \pm 1)$$

Theoretical uncertainties:

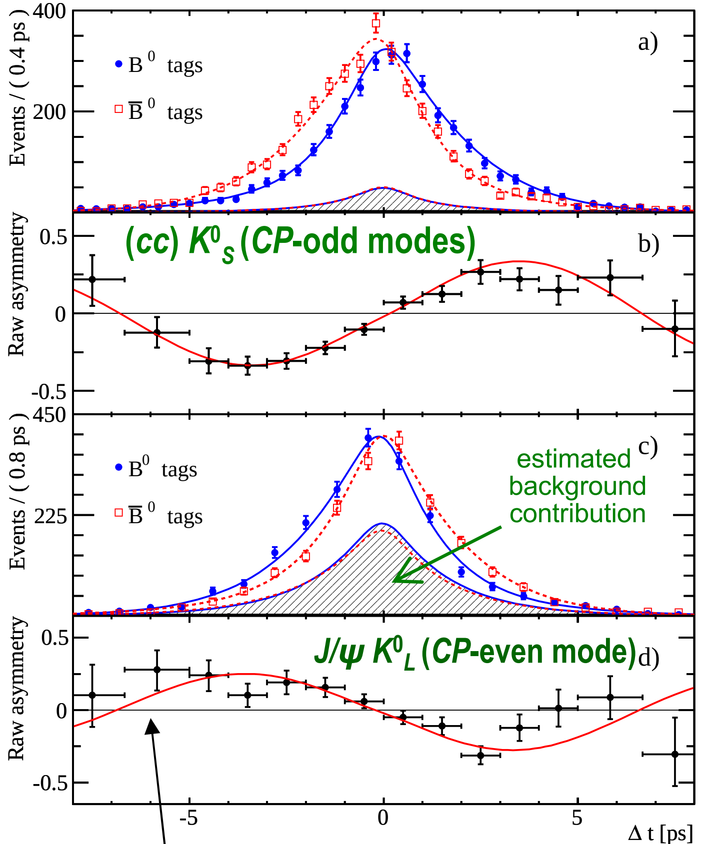
- *an example* of a model-independent, data-driven calculation: assuming $SU(3)_{\text{flavor}}$ invariance, use $B^0 \to J/\psi\pi^0$ data to constrain penguin pollution in $J/\psi K^0$ $\Rightarrow$ $\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin 2\beta = 0.000 \pm 0.012$

M. Ciuchini, M. Pierini, L. Silvestrini, Phys. Rev. Lett. **95**, 221804 (2005)

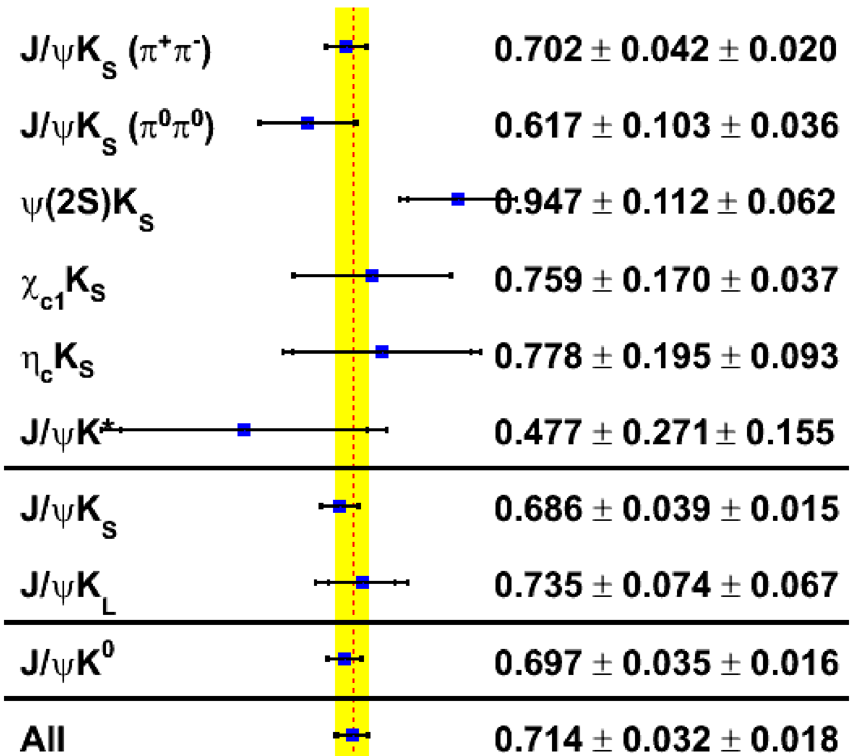
- theoretical estimates of the biases due to u- and c-quark penguins, etc.:
  - $\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin 2\beta \sim O(10^{-3})$ — H. Li, S. Mishima, JHEP 0703:009 (2007) [hep-ph/0610120]
  - $\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin 2\beta \sim O(10^{-4})$ — H. Boos et al., Phys. Rev. **D 73**, 036006 (2006)

Latest on $\sin 2\beta$ in "golden" modes

CP Violation in B mesons first observed here, in 2001



raw asymmetry $\dfrac{N(\overline{B}^0) - N(B^0)}{N(\overline{B}^0) + N(B^0)}$ as function of Δt



***CP* violation in Standard Model is <u>not</u> small, it is *O*(1).**
Smallness of *CPV* in kaon decays is due to flavor suppression.

***CP*-violating phases in New Physics can also be *O*(1).**

BaBar with 384x10⁶ BB pairs: PRL **99**, 171803 (2007)

$\sin 2\beta = 0.714 \pm 0.032$ (stat) ± 0.018 (syst)

Belle with 535x10⁶ BB pairs: PRL **98**, 031802 (2007)

$\sin 2\beta = 0.642 \pm 0.031$ (stat) ± 0.017 (syst)

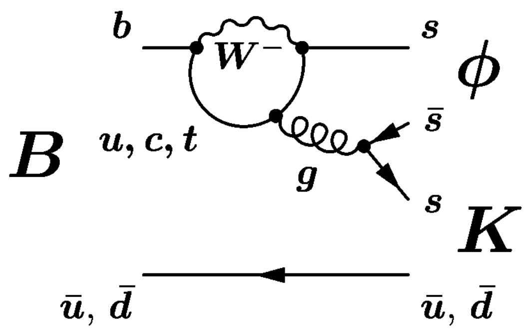
Decays dominated by gluonic penguins:

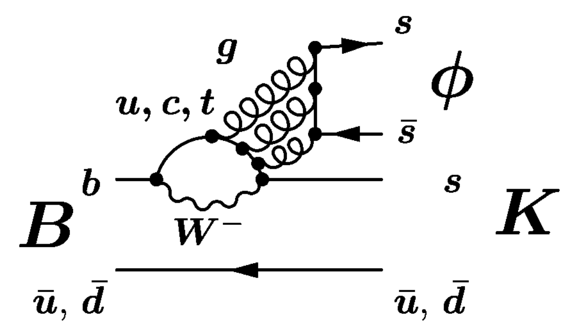
$B^0 \to \eta' K^0, \varphi K^0, K^+K^-K_S, K_S\pi^0, K_SK_SK_S, \omega K_S, f_0K_S$, etc.

For example, consider

$B^0 \to \varphi K^0$ or $K_SK_SK_S$

$$b \to s\bar{s}s$$

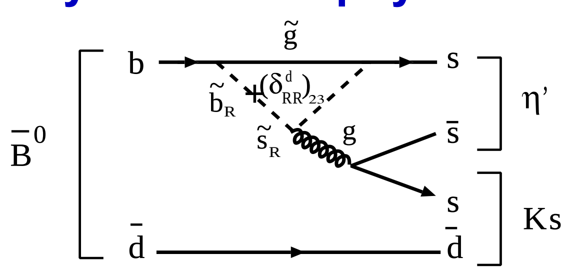




- **Tree-level SM contributions are absent**
- All other SM contributions are strongly suppressed
- SM penguins dominated by top-quark loops

  ⇒ in SM, direct *CP* violation is small, ~1%

  ⇒ and time-dependent *CP* violation is the same as in the "golden" charmonium-K^0 modes
- **Great sensitivity to non-SM physics in the loops!**



It is not easy for New Physics to hide in penguin-dominated decays unless its flavor and/or mass structure is very special

Decays dominated by gluonic penguins:

Indirect limits on squark mixing

B-meson factories

LHC

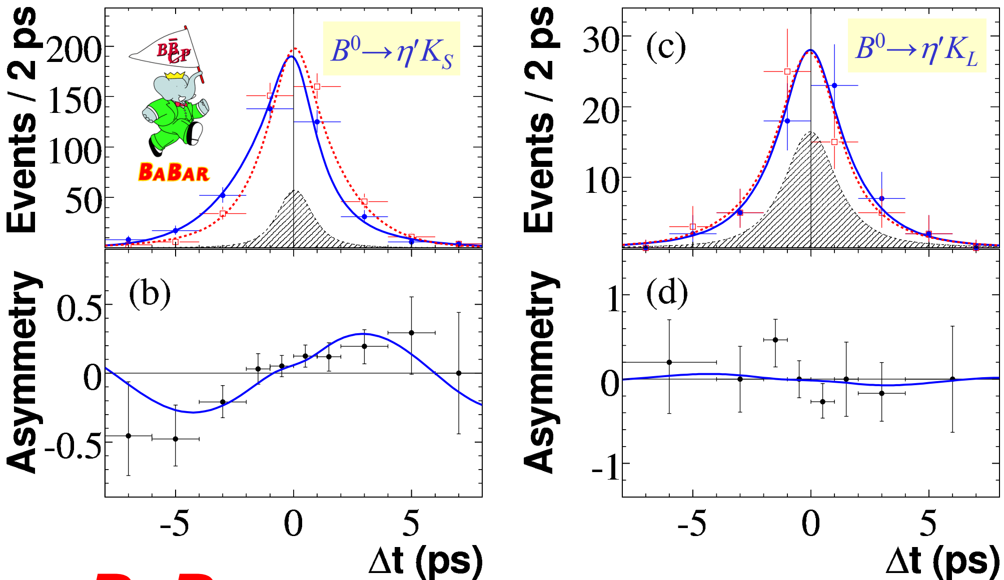
$$\begin{pmatrix} m^2_{\tilde{d}_L} & m_d(A_d-\mu\tan\beta) & (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{LR} & (\Delta^d_{13})_{LL} & (\Delta^d_{13})_{LR} \\ & m^2_{\tilde{d}_R} & (\Delta^d_{12})_{RL} & (\Delta^d_{12})_{RR} & (\Delta^d_{13})_{RL} & (\Delta^d_{13})_{RR} \\ & & m^2_{\tilde{s}_L} & m_s(A_s-\mu\tan\beta) & (\Delta^d_{23})_{LL} & (\Delta^d_{23})_{LR} \\ & & & m^2_{\tilde{s}_R} & (\Delta^d_{23})_{RL} & (\Delta^d_{23})_{RR} \\ & & & & m^2_{\tilde{b}_L} & m_b(A_b-\mu\tan\beta) \\ & & & & & m^2_{\tilde{b}_R} \end{pmatrix}$$

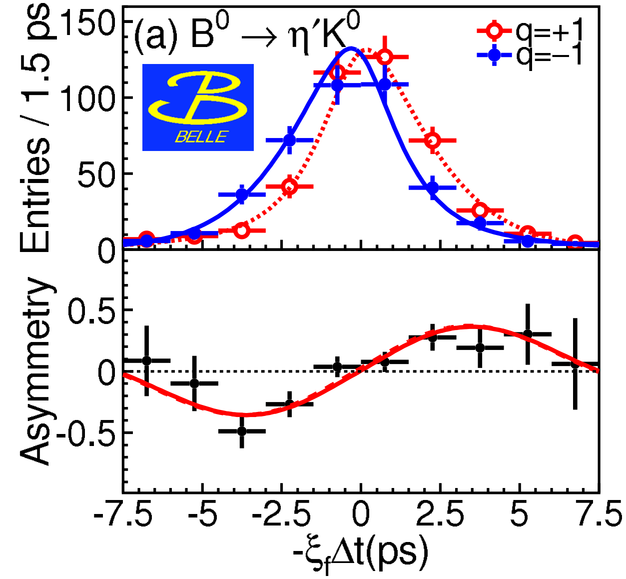
Complementarity with the LHC is part of the physics case for a "Super *B* Factory"

New Physics near the electroweak scale (i.e., accessible at the LHC) that has a generic flavor-violation structure is ruled out by K^0–$\bar{K}^0$, B^0–$\bar{B}^0$, B^0_s–$\bar{B}^0_s$ mixing and $b\to s\gamma$, $b\to sg$ measurements ("*the New Physics flavor problem*"). Flavor-blind New Physics is unnatural because Standard Model contains flavor violation in the Yukawa couplings. For supersymmetry, a solution is Minimal Flavor Violation, possibly with SM-like loop suppression

The highest-statistics penguin-dominated mode: $B^0 \to \eta' K_S$

Back-to-back:
BaBar: Phys.Rev.Lett. **98** (2007) 031801
Belle: Phys.Rev.Lett. **98** (2007) 031802





BaBar

$$S_{\eta' K^0} = +0.58 \pm 0.10 \pm 0.03 \quad (5.5\sigma)$$

$$C_{\eta' K^0} = -0.16 \pm 0.07 \pm 0.03$$

Belle

$$S_{\eta' K^0} = +0.64 \pm 0.10 \pm 0.04 \quad (5.6\sigma)$$

$$C_{\eta' K^0} = +0.01 \pm 0.07 \pm 0.05$$

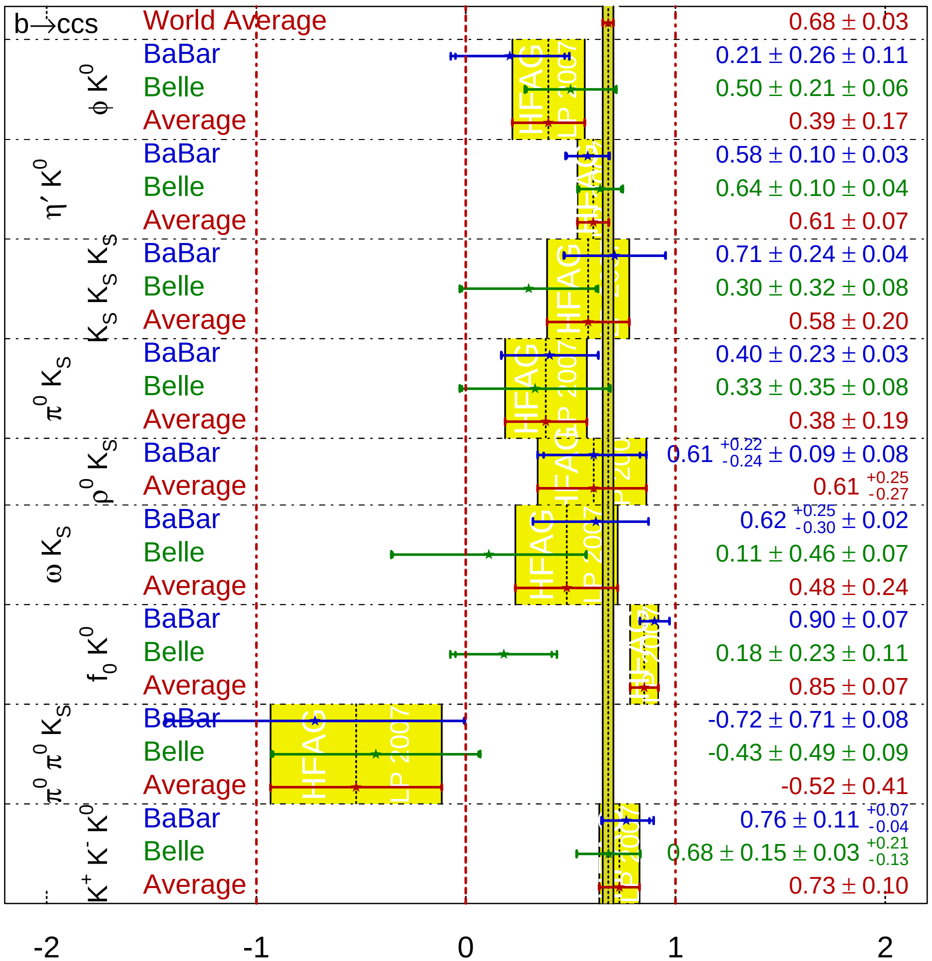
Measurements of S in $B^0 \to \eta' K^0$ by *BaBar* and then Belle are the **second** observations of *CP* violation in *B* mesons (Fall 2006)

The world-average sin2β in penguin modes is 2.2σ less than in the "golden" modes

In 2004, the difference was 3.7σ…

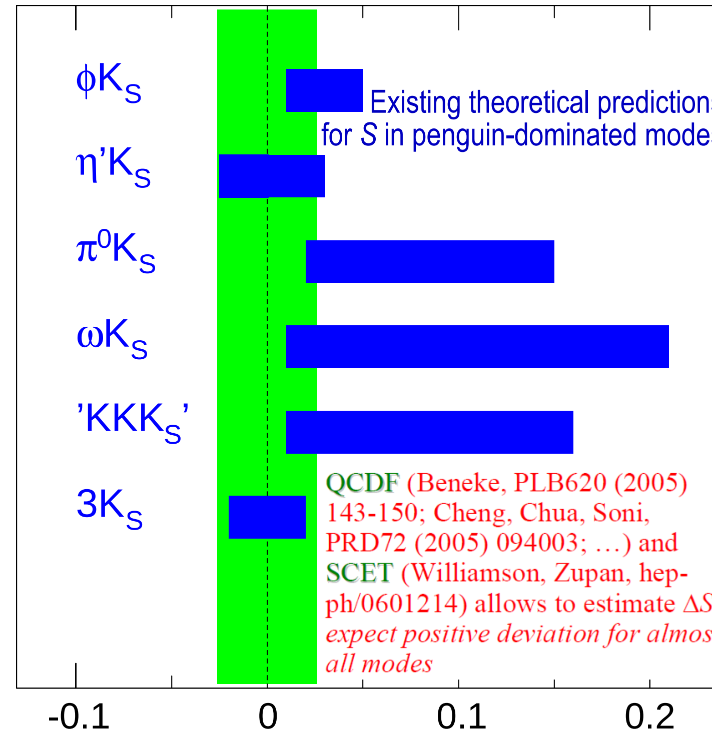
$$\sin(2\beta^{\rm eff}) \equiv \sin(2\phi_1^{\rm eff})$$

HFAG LP 2007 PRELIMINARY



This is a very naive average

$$\langle \sin 2\beta_{\rm golden} \rangle = 0.680 \pm 0.025$$

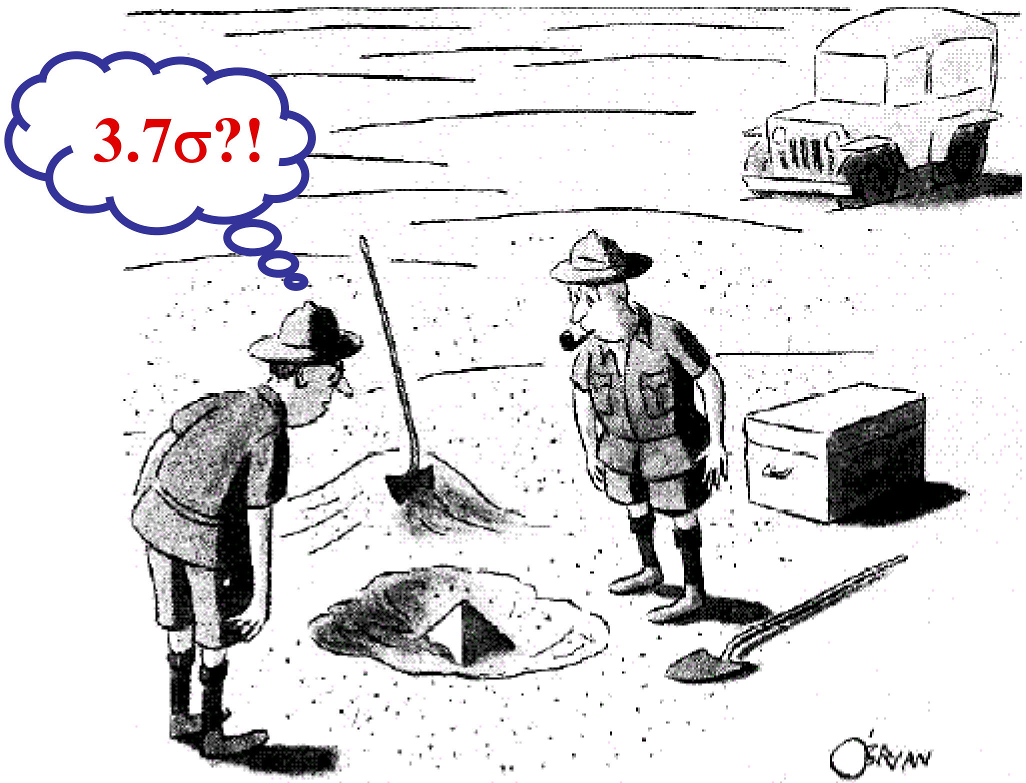


$\Delta\sin 2\beta$ (penguin−tree)

$$\langle \sin 2\beta_{\rm peng} \rangle_{\rm naive} = 0.56 \pm 0.05\ (\chi^2 = 19/16\ {\rm dof})$$

http://www.slac.stanford.edu/xorg/hfag/triangle/summer2007/index.shtml

What do we make of this discrepancy?



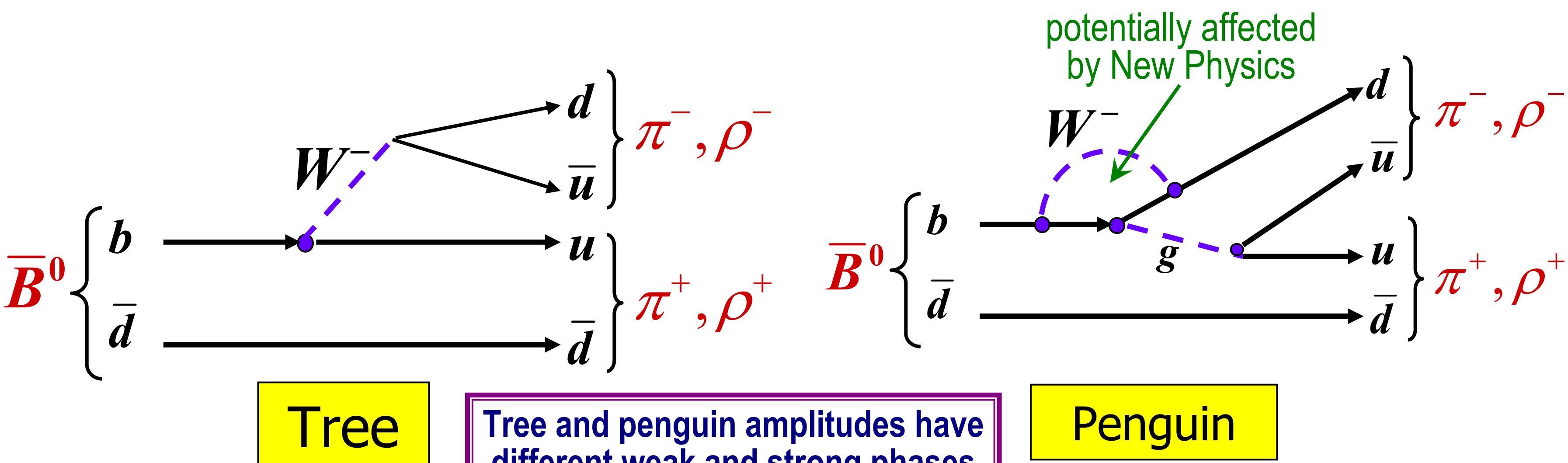
"This could be the greatest discovery of the century. Depending, of course, on how far down it goes…"

Measuring α

$\mathcal{A}_{CP}(t)$ in $b \to u\bar{u}d$ decay to a *CP* eigenstate *at the tree level* :

Measure $180° - \beta - \gamma = \alpha \equiv \arg\left[\dfrac{-V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$ (in SM)

Penguins: $\mathcal{A}_{CP}(t) \Rightarrow \sin(2\alpha_{\text{eff}})$; $\alpha_{\text{eff}} = \alpha - \Delta\alpha$; direct $\mathcal{A}_{CP} \neq 0$



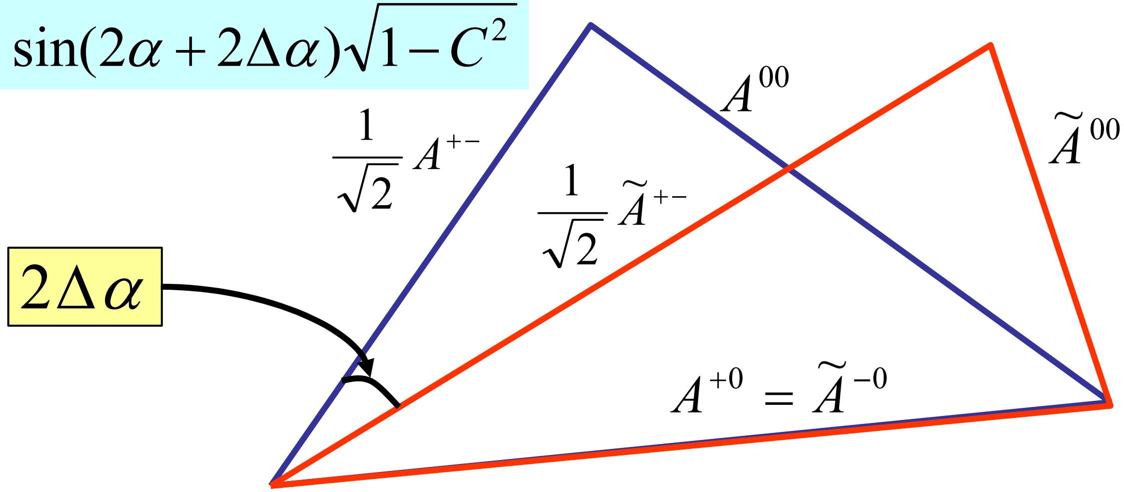
Tree and penguin amplitudes have different weak and strong phases

SU(2) isospin analysis in $B \to \pi\pi, \rho\rho$

Determines relative phase between B^0 mixing and the tree, independent of the EW model

M. Gronau, D. London, Phys. Rev. Lett. ***65****, 3381 (1990)*

$$S = \sin(2\alpha + 2\Delta\alpha)\sqrt{1 - C^2}$$



$$\begin{aligned}
A^{+-} &= A(B^0 \to \pi^+\pi^-) \\
\tilde{A}^{+-} &= A(\overline{B}^0 \to \pi^+\pi^-) \\
A^{00} &= A(B^0 \to \pi^0\pi^0) \\
\tilde{A}^{00} &= A(\overline{B}^0 \to \pi^0\pi^0) \\
A^{+0} &= A(B^+ \to \pi^+\pi^0) \\
\tilde{A}^{-0} &= A(B^- \to \pi^-\pi^0)
\end{aligned}$$

In $B \to \rho\rho$, there are 3 such relations (one for each polarization)

6 unknowns, 6 observables in $\pi\pi$ (there is no vertex to measure $S_{\pi^0\pi^0}$)

5 observables in $\rho\rho$ (or 7, when both $C_{\rho^0\rho^0}$ and $S_{\rho^0\rho^0}$ are measured)

4-fold ambiguity in $2\Delta\alpha$: either triangle can flip up or down

$$A_{hh} = e^{+i\gamma}T + e^{-i\beta}P$$

$$\tilde{A}_{hh} = e^{-i\gamma}T + e^{+i\beta}P$$

Neglecting EW penguins, ±0 is a pure tree mode, and so the two triangles share a common side:

$$A(B^+ \to h^+h^0) = \tilde{A}(B^- \to h^-h^0)$$

$$A^{+0} = \frac{1}{\sqrt{2}} A^{+-} + A^{00}$$

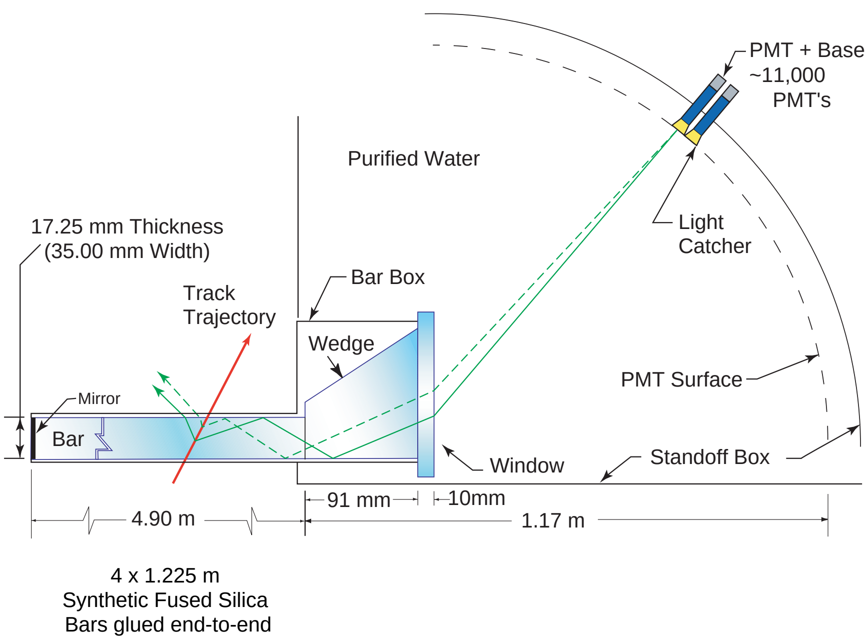
$$\tilde{A}^{-0} = \frac{1}{\sqrt{2}} \tilde{A}^{+-} + \tilde{A}^{00}$$

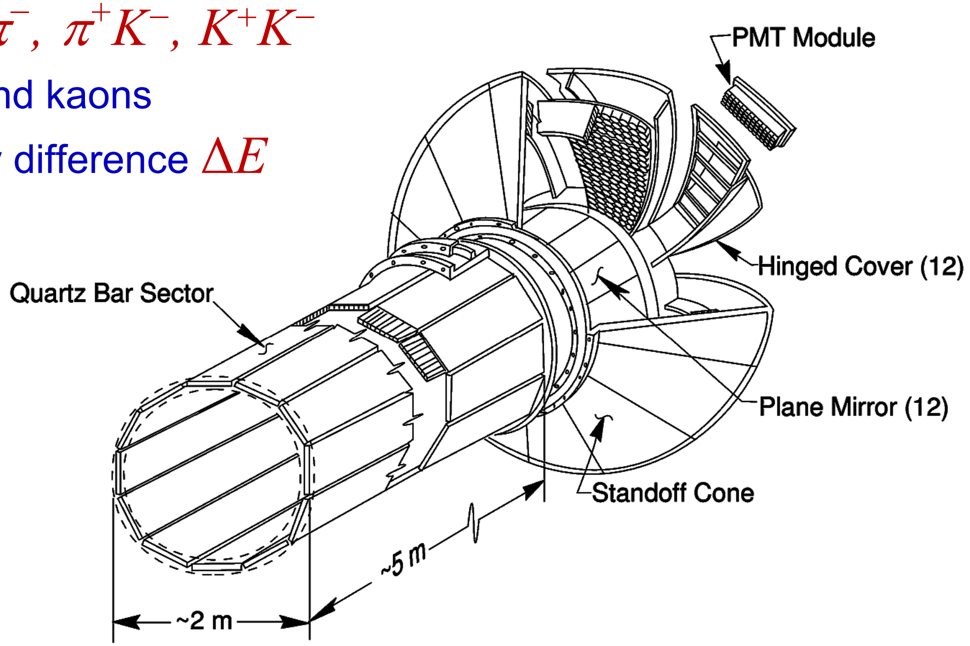
Knowledge of A^{00} is the primary limiting factor in the isospin analysis

Simultaneous ML fit to $B^0 \to \pi^+\pi^-, K^+\pi^-, \pi^+K^-, K^+K^-$

Using DIRC Cherenkov angle to identify pions and kaons

Additional $\pi\pi/K\pi/KK$ separation from energy difference ΔE





DIRC: 144 quartz bars

0.84 x 4π coverage; 91% eff. with n_γ>5

13σ π/K separation at 1.5 GeV/c, 2.5σ at 4.5 GeV/c

Calibration sample: $B^- \to \pi^- D^0$, $D^0 \to \pi^+ K^-$

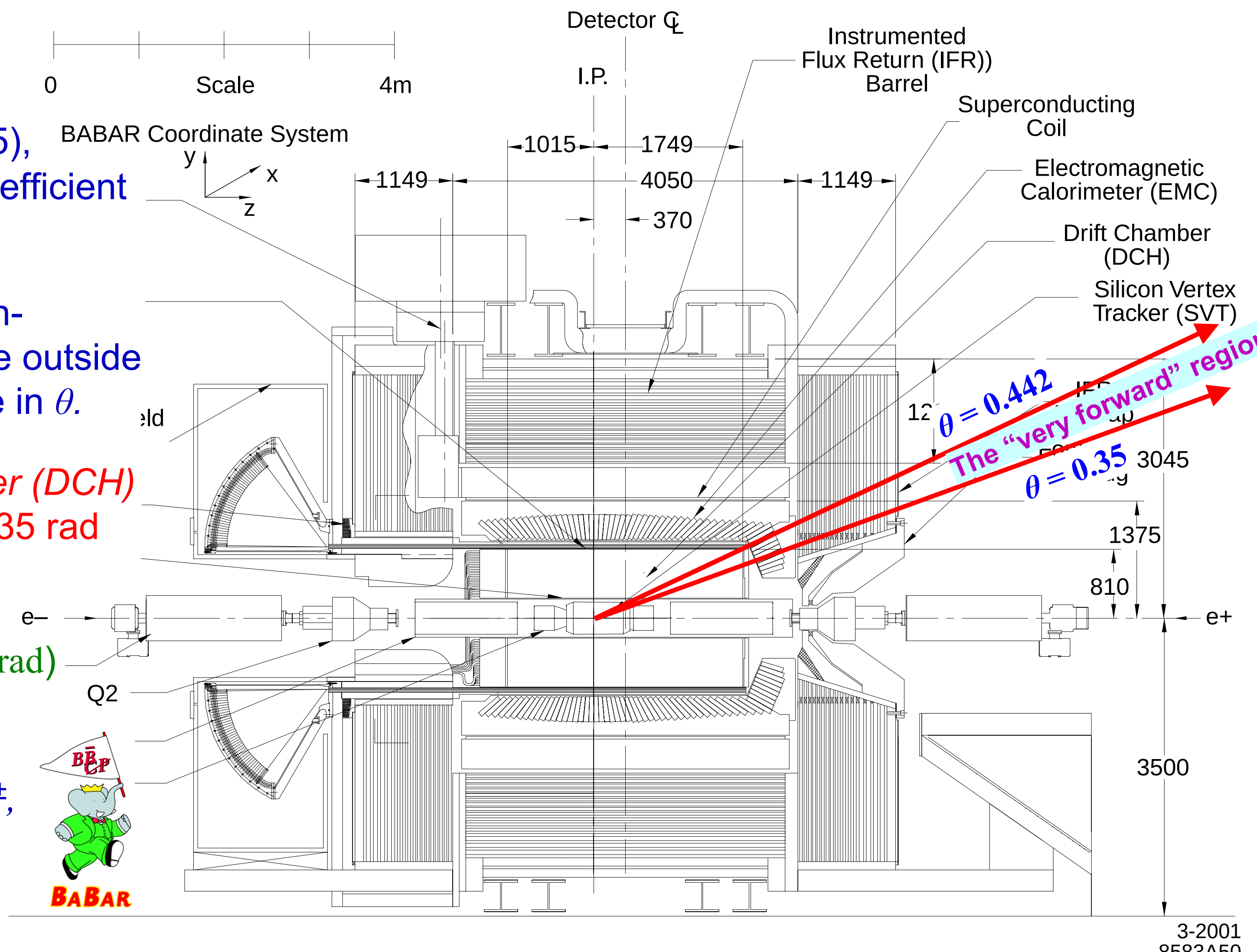
In the <u>barrel</u> (θ>0.445), the DIRC is ~9.3% inefficient (φ cracks, etc.)

Another ~12% of high-momentum tracks are outside the DIRC acceptance in θ.

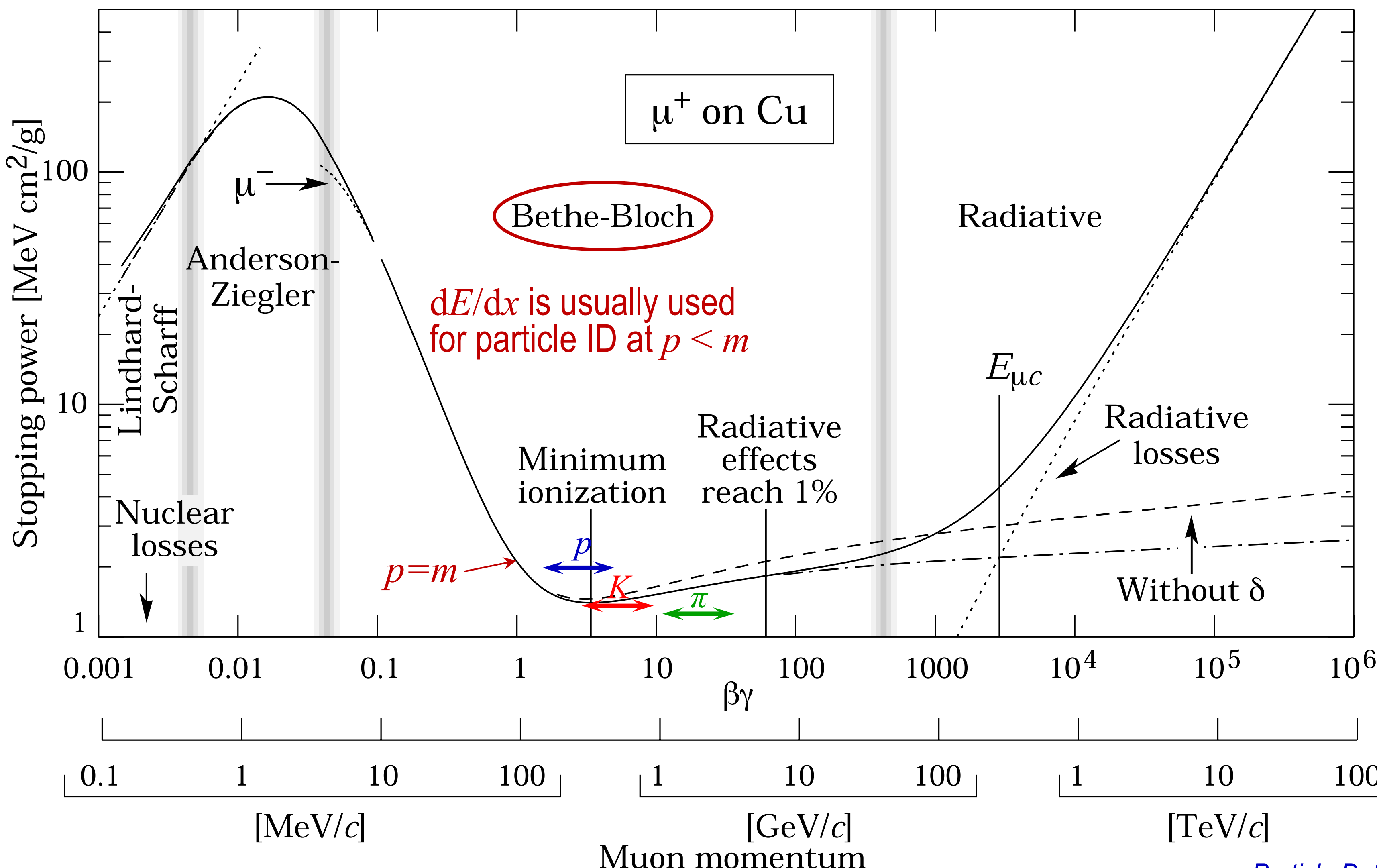
We use Drift Chamber (DCH) tracks down to θ = 0.35 rad

($J/\psi \to \mu^+\mu^-$ in sin2β analysis: down to 0.30 rad)

→16% event-yield increase for $B \to Xh^\pm$, 35% for $B^0 \to h^+ h^-$



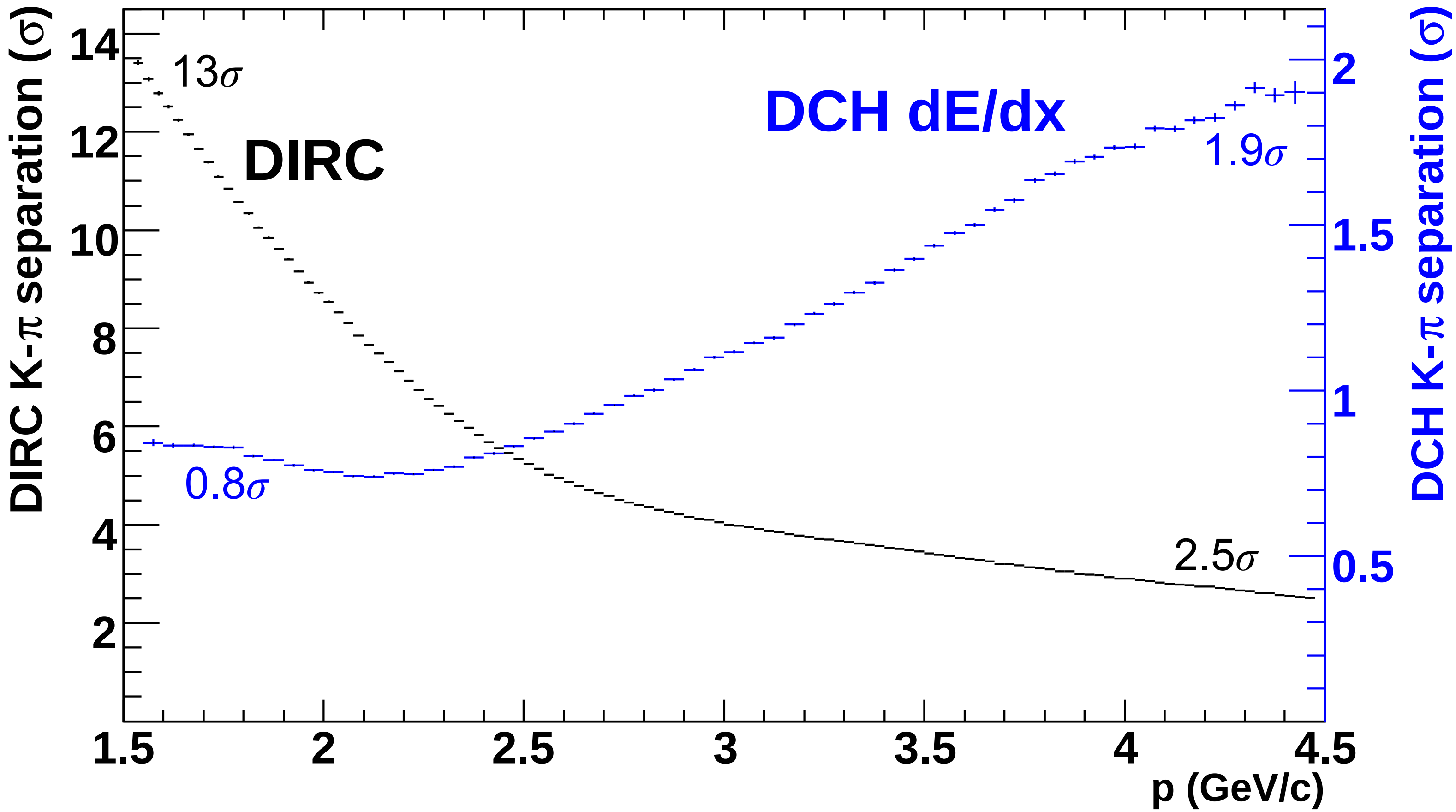
Ionization energy loss for $B \to Xh^{\pm}$ momenta



Particle Data Group

DCH dE/dx K-π separation in $B \to Xh^{\pm}$

complementary to DIRC



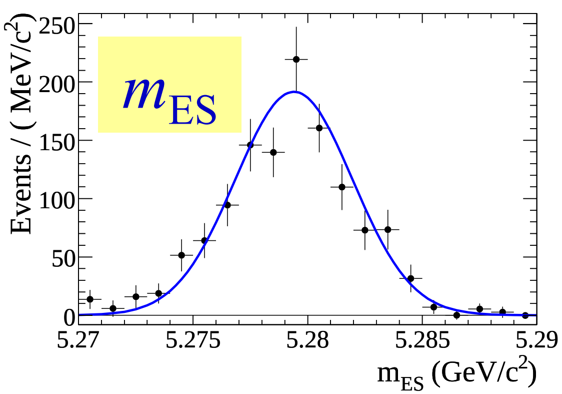
(for tracks that have good DIRC information, we use both DIRC and dE/dx)

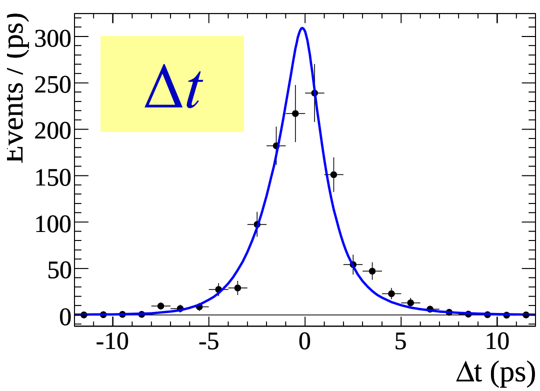
Our new result: $B^0 \to \pi^+\pi^-$

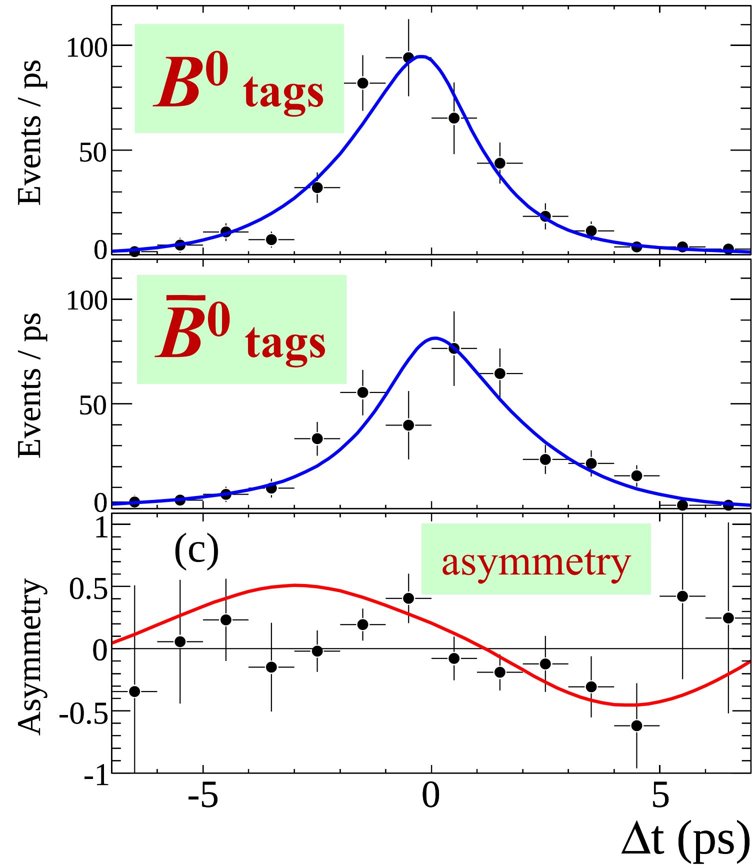
$$N_{\pi^+\pi^-} = 1139 \pm 49$$

52% overall increase
in signal reconstruction efficiency:

35% from DCH $\mathrm{d}E/\mathrm{d}x$,
13% mainly from reoptimizing the event-shape $|\cos\theta_{\mathrm{spher}}|$ cut







$_s\mathcal{P}lot$: Builds a histogram of x excluding it from the Maximum-Likelihood fit, assigning a weight to each event, keeping all signal events, getting rid of all background events, and keeping track of the statistical errors in each x bin

M. Pivk and F. R. Le Diberder,
"sPlot: a statistical tool to unfold data distributions,"
Nucl. Instrum. Meth. A ***555****, 356 (2005)*
[arXiv:physics/0402083]

Observation of CP Violation in $B^0 \to K^+\pi^-$ and $B^0 \to \pi^+\pi^-$

BaBar has made a 5.4 σ observation of CP violation in $B^0 \to \pi^+\pi^-$

$$S_{\pi\pi} = -0.60 \pm 0.11 \pm 0.03\ (5.1\sigma)$$

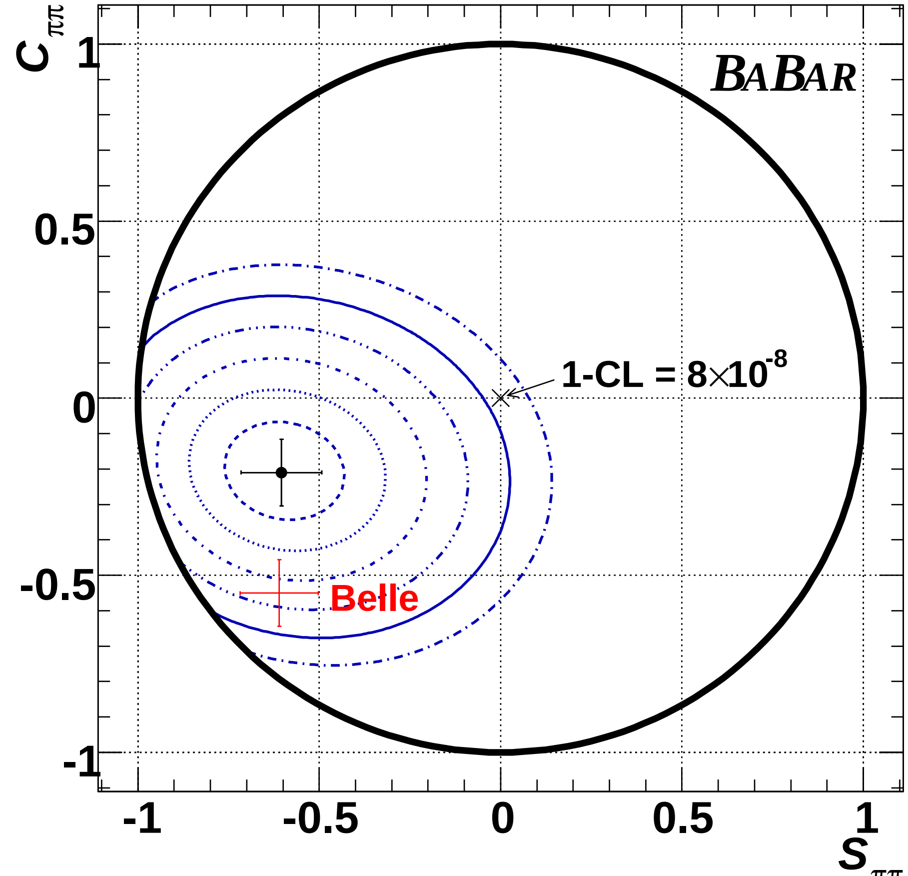
$$C_{\pi\pi} = -0.21 \pm 0.09 \pm 0.02\ (2.3\sigma)$$

BaBar: 383 million $B\bar{B}$ pairs, 1139 ± 49 $\pi^+\pi^-$
Belle: 535 million $B\bar{B}$ pairs, 1464 ± 65 $\pi^+\pi^-$

Belle PRL 98, 211801 (2007)

$$S_{\pi\pi} = -0.61 \pm 0.10 \pm 0.04\ (5.3\sigma)$$

$$C_{\pi\pi} = -0.55 \pm 0.08 \pm 0.05\ (5.5\sigma)$$



also: $\mathcal{A}_{K^+\pi^-} = -0.107 \pm 0.018\ ^{+0.007}_{-0.004}\ (5.5\sigma)$

The $B \to \pi^\pm \pi^0$, $\pi^0 \pi^0$ analysis

Simultaneous fit to $B^0 \to \pi^+\pi^0, K^+\pi^0$ (using DIRC Cherenkov angle to separate pions and kaons)
$B^0 \to \pi^0\pi^0$: branching fraction and time-integrated direct *CP* asymmetry

new: in addition to $\pi^0 \to \gamma\gamma$, *we use merged* π^0 *and* $\gamma \to e^+e^-$ *conversions*

$\Rightarrow$ *10% efficiency increase per* π^0 (4% from merged π^0, 6% from γ conversions)

At a Super *B-meson* factory, $\gamma \to e^+e^-$ conversions would make $S_{\pi^0\pi^0}$ determination possible!

merged π^0 :

the two photons are too close to one another in the calorimeter to be reconstructed individually; can be recovered using

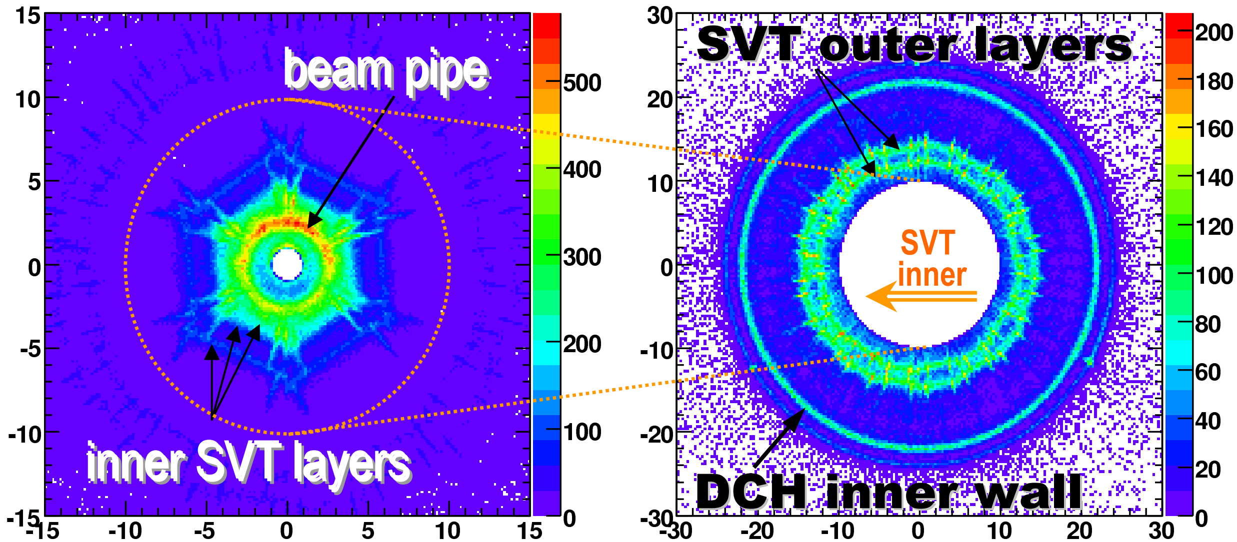
$$M^2_{\pi^0} \approx E^2_{\pi^0}(S_{\pi^0} - S_\gamma),$$

where *S* is the second EMC moment of the merged $\pi^0 \to \gamma\gamma$

The control sample: $\tau \to \rho\nu$

$\gamma \to e^+e^-$ conversions:

result from interactions with detector elements



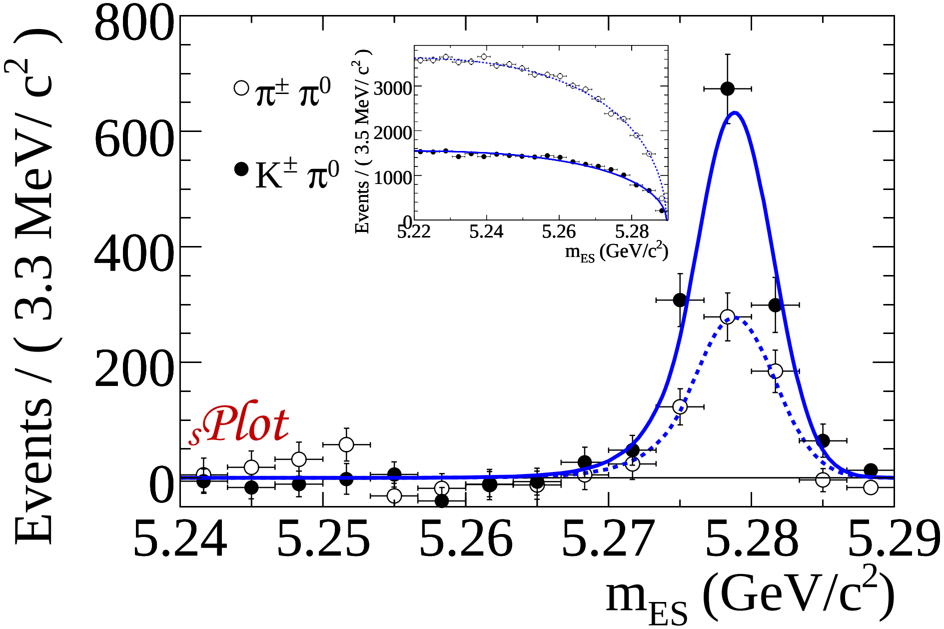
New BaBar results: $B \to \pi^{\pm}\pi^{0}, \pi^{0}\pi^{0}$

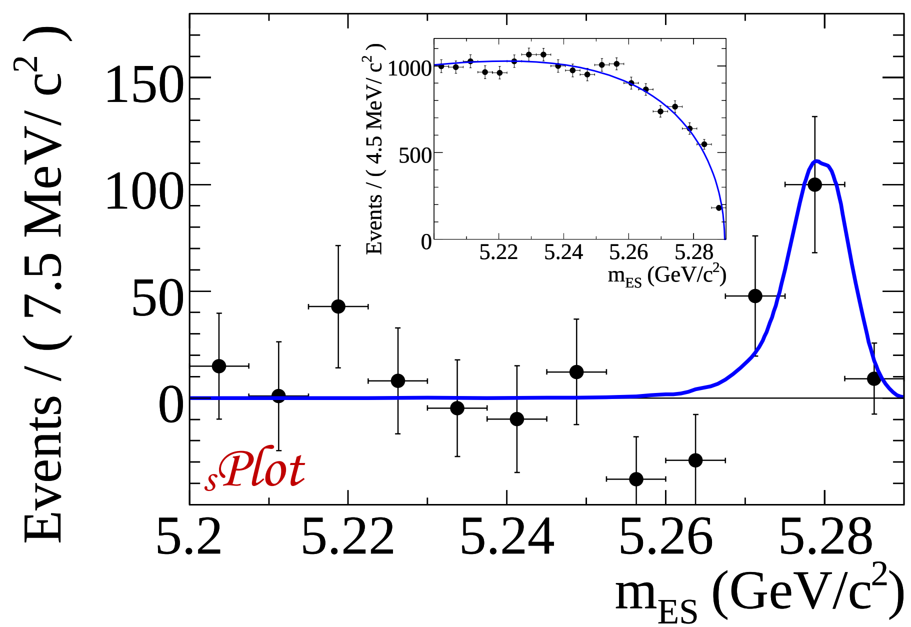
383×10^{6} $B\bar{B}$ pairs

PRD 76, 091102 (2007)

$N_{\pi^{\pm}\pi^{0}} = 627 \pm 58$

$N_{\pi^{0}\pi^{0}} = 154 \pm 27$





$\mathcal{B}r_{\pi^{\pm}\pi^{0}} = (5.02 \pm 0.46 \pm 0.29) \times 10^{-6}$

$\mathcal{B}r_{\pi^{0}\pi^{0}} = (1.47 \pm 0.25 \pm 0.12) \times 10^{-6}$

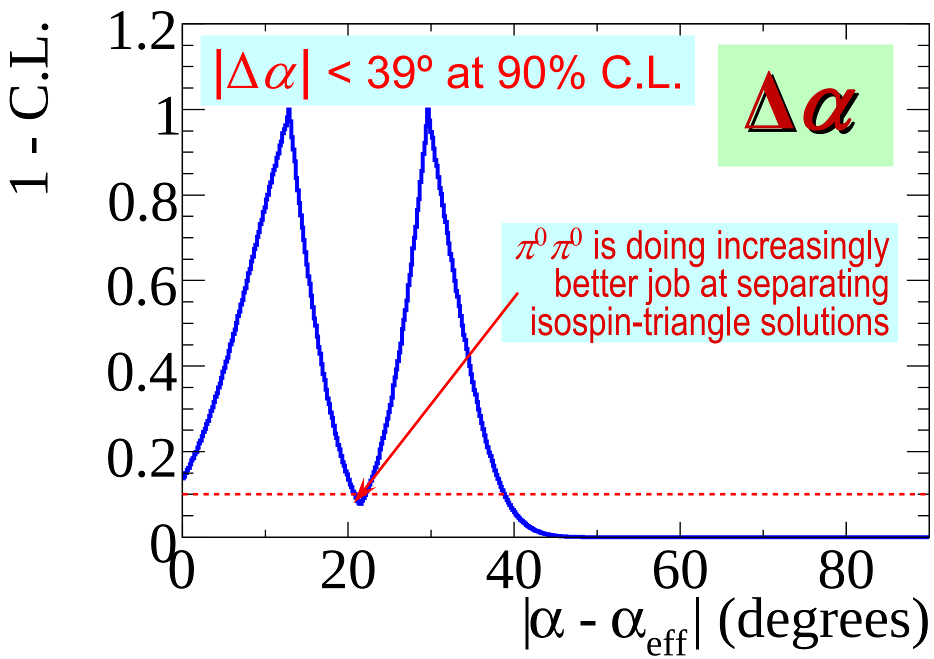
$\mathcal{A}_{\pi^{\pm}\pi^{0}} = 0.03 \pm 0.08 \pm 0.01$

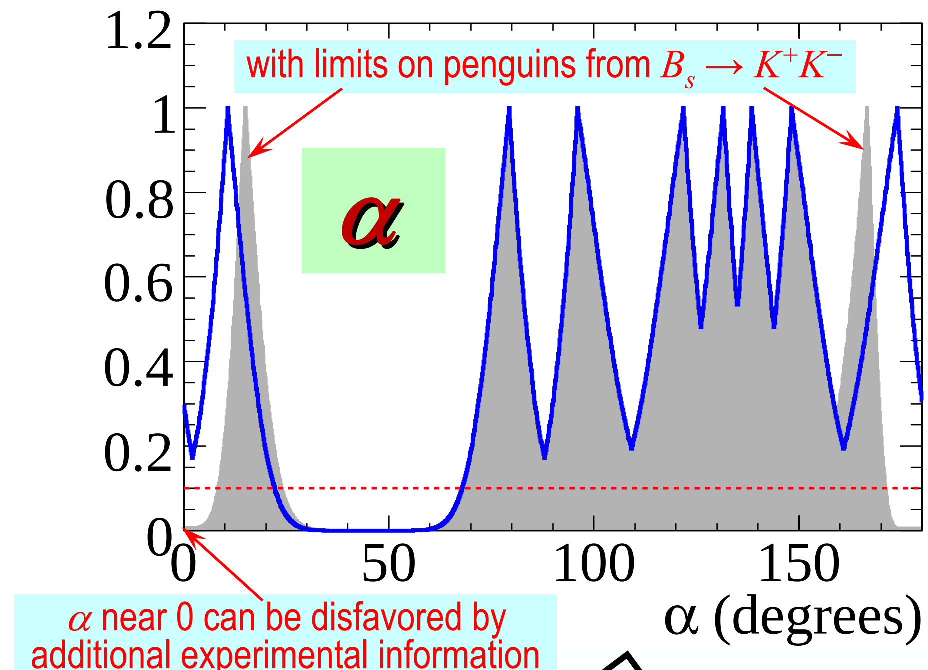
$C_{\pi^{0}\pi^{0}} = -0.49 \pm 0.35 \pm 0.05$

An interpretation of our new $B \to \pi\pi$ results

383×10^6 $B\bar{B}$ pairs

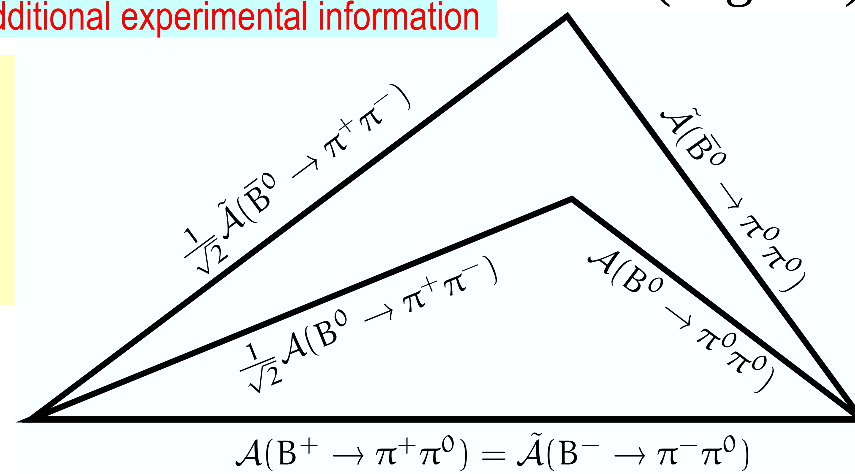
PRD 76, 091102 (2007)





This is a <u>frequentist</u> interpretation: we use only the $B \to \pi\pi$ isospin-triangle relations in arriving at these constraints on $\Delta\alpha = \alpha - \alpha_{\mathrm{eff}}$ and on α itself

Here is one of the possible solutions to the Gronau-London isospin triangle in $B \to \pi\pi$ according to the central values of the Summer 2006 BaBar results:



$B \to \rho\rho$ angular analysis

$B \to \rho\rho$ is a vector-vector state; angular analysis is required to determine *CP* content:

$$\text{Longitudinal}: \; A_0 = -\frac{1}{\sqrt{3}}S + \sqrt{\frac{2}{3}}D$$

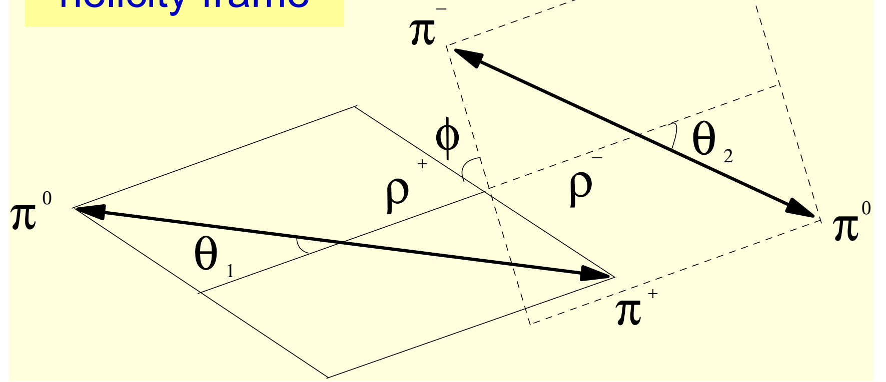
pure *CP* = +1

$$\text{Transverse} \; A_{+1} = \frac{1}{\sqrt{3}}S + \frac{1}{\sqrt{6}}D + \frac{1}{\sqrt{2}}P$$

$$\text{Transverse} \; A_{-1} = \frac{1}{\sqrt{3}}S + \frac{1}{\sqrt{6}}D - \frac{1}{\sqrt{2}}P$$

transverse is not a *CP* eigenstate

“helicity frame”



Fortunately, the fraction f_L of the helicity-zero state in $B \to \rho\rho$ decays is very close to 1:

$$f_L(B^0 \to \rho^+\rho^-)_{\mathrm{WA}} = 0.978^{+0.025}_{-0.022}$$

$$f_L(B^\pm \to \rho^\pm\rho^0)_{\mathrm{WA}} = 0.912^{+0.044}_{-0.045}$$

*Heavy Flavor Averaging Group, **Lepton-Photon 2007** update: http://www.slac.stanford.edu/xorg/hfag/rare/leppho07/polar/index.html*

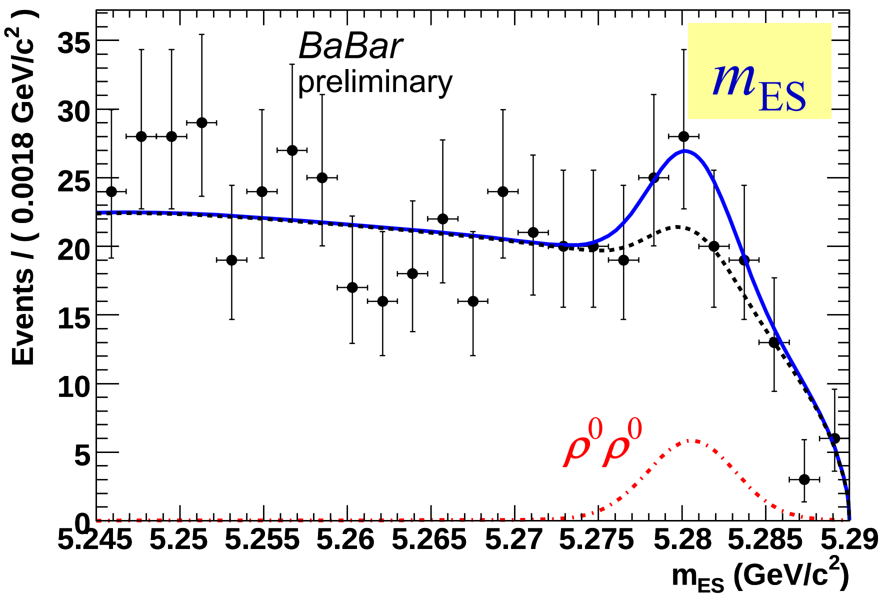
New *BaBar* result:

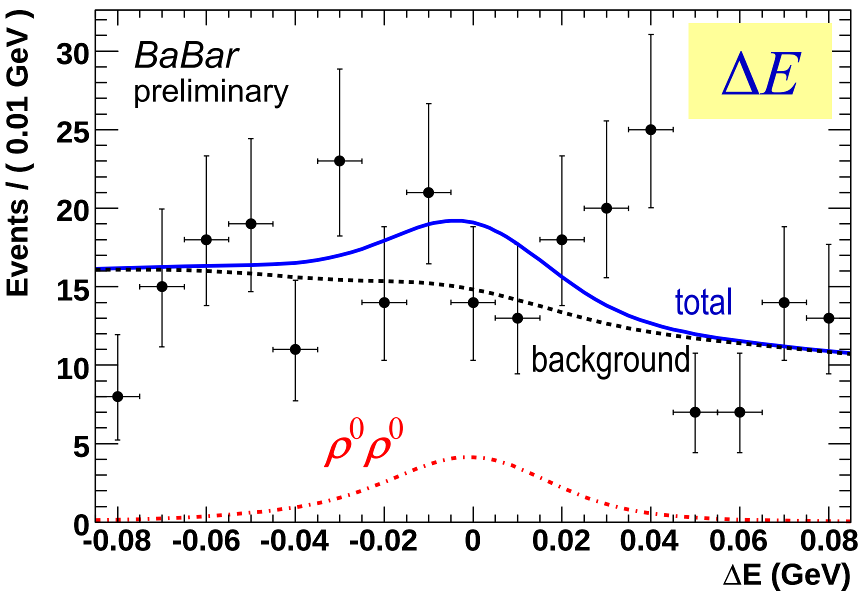
3.6σ evidence for $B^0 \to \rho^0\rho^0$

427×10^6 $B\bar{B}$ pairs
BaBar-CONF-07/012

$$N_{\rho^0\rho^0} = 85 \pm 28 \pm 17$$

A time-dependent analysis was successfully performed, despite the limited statistics



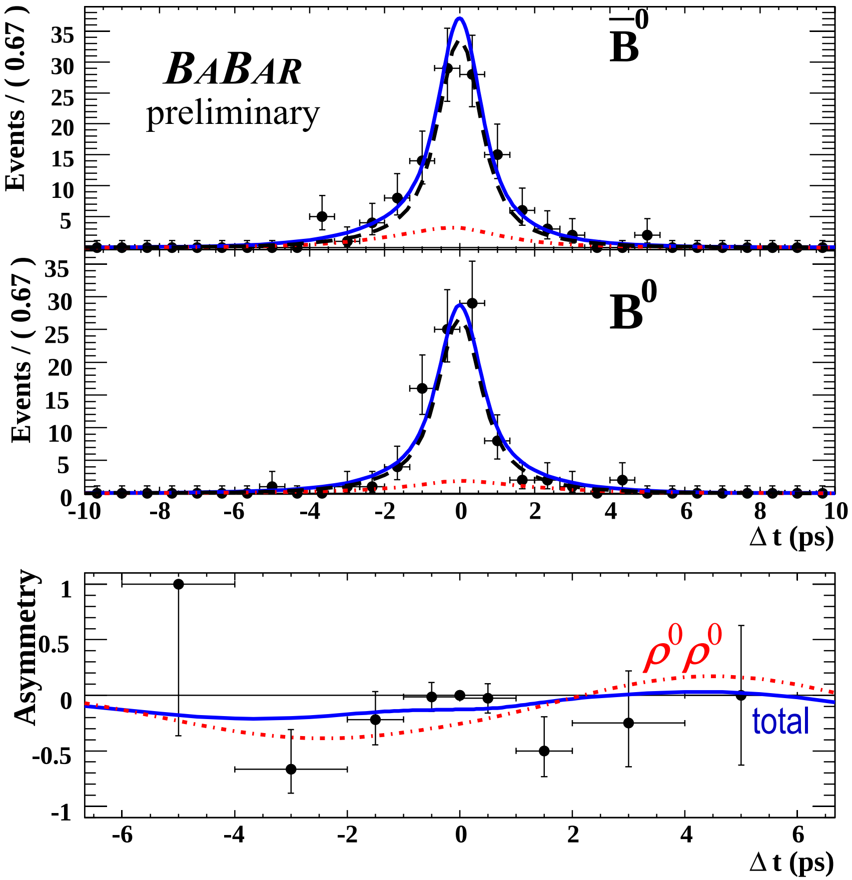


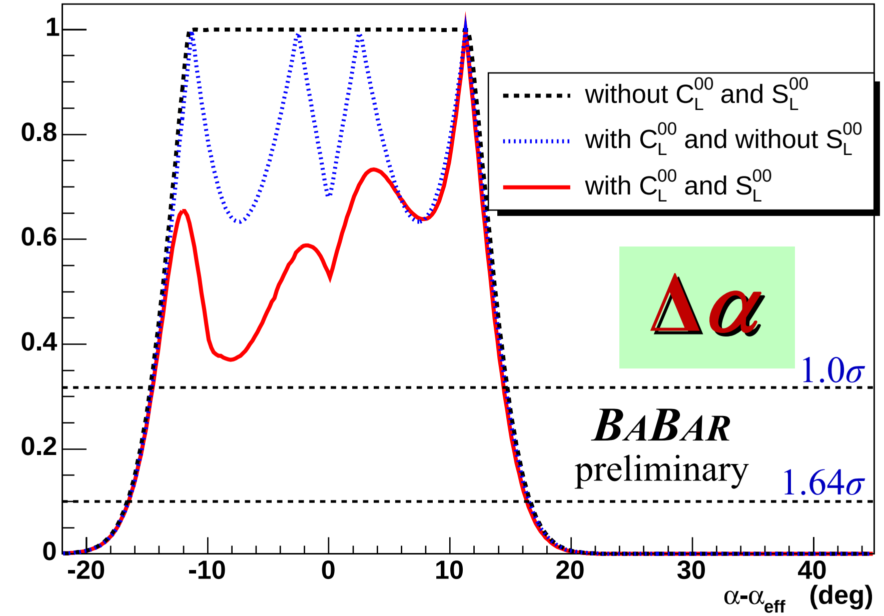
$$\mathcal{B}r_{\rho^0\rho^0} = (0.84\pm0.29\pm0.17)\times10^{-6}$$

$$f_L(B^0 \to \rho^0\rho^0) = 0.70\pm0.14\pm0.05$$

An interpretation of the new $B \to \rho\rho$ results

427x10^6 $B\bar{B}$ pairs
BaBar-CONF-07/012





$S_{Long}^{00} = 0.5 \pm 0.9 \pm 0.2$

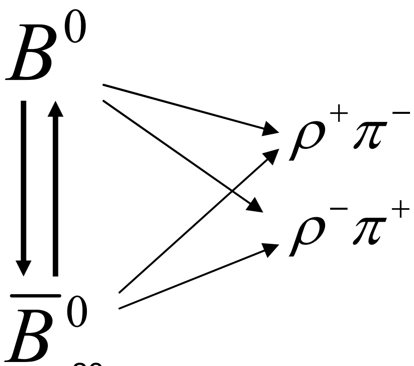
$C_{Long}^{00} = 0.4 \pm 0.9 \pm 0.2$

$|\Delta\alpha| < 14.5^o$ at 68% C.L.

$|\Delta\alpha| < 16.5^o$ at 90% C.L.

This is a frequentist interpretation: we use only the $B \to \rho\rho$ branching fractions, polarization fractions and isospin-triangle relations in arriving at these constraints on $\Delta\alpha = \alpha - \alpha_{eff}$

$B^0 \to (\rho\pi)^0$: Dalitz-plot analysis

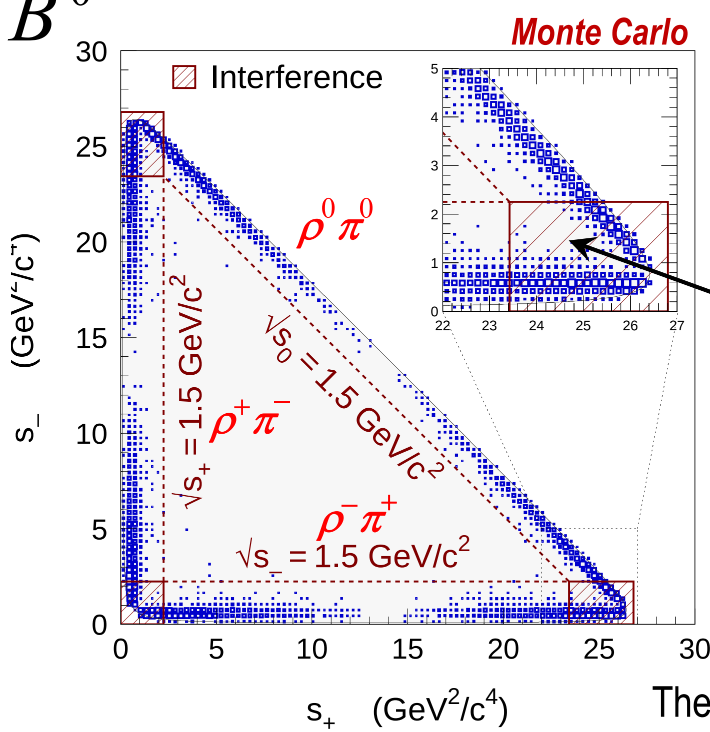


$\rho\pi$ is not a CP eigenstate

An isospin-pentagon analysis method exists but is not fruitful

$\Rightarrow$ Time-dependent Dalitz-plot analysis assuming isospin symmetry, measuring 26 coefficients of the bilinear form factors

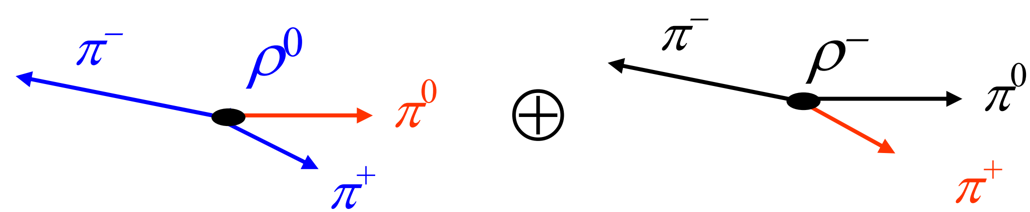
*A. Snyder and H. Quinn, Phys. Rev. **D**, 48, 2139 (1993)*



$$A(B^0 \to \pi^+\pi^-\pi^0) = f_+ A(\rho^+\pi^-) + f_- A(\rho^-\pi^+) + f_0 A(\rho^0\pi^0)$$

$$\widetilde{A}(\overline{B}^0 \to \pi^+\pi^-\pi^0) = f_+ \widetilde{A}(\rho^+\pi^-) + f_- \widetilde{A}(\rho^-\pi^+) + f_0 \widetilde{A}(\rho^0\pi^0)$$

Interference in the corners of the Dalitz plot provides information on **strong phases** between resonances

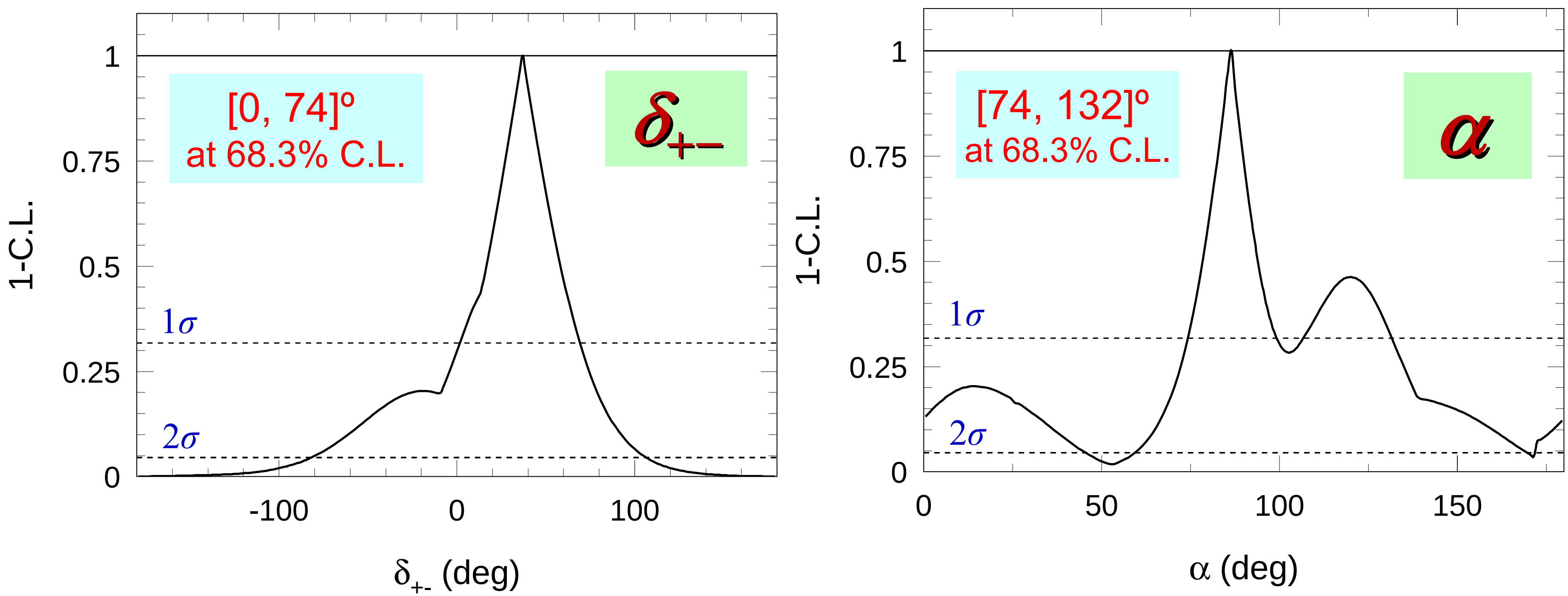


The $\rho(1450)$ and $\rho(1700)$ resonances are also included in this analysis

An interpretation of the new $B^0 \to (\rho\pi)^0$ results

375x10[6] BB pairs
PRD **76**, 012004 (2007)

$\delta_{+-} = \arg(A^{+*}A^{-})$: the relative phase between the amplitudes of $B^0 \to \rho^-\pi^+$ and $B^0 \to \rho^+\pi^-$



The constraint on α from $B^0 \to (\rho\pi)^0$ is relatively weak – but free from ambiguities!

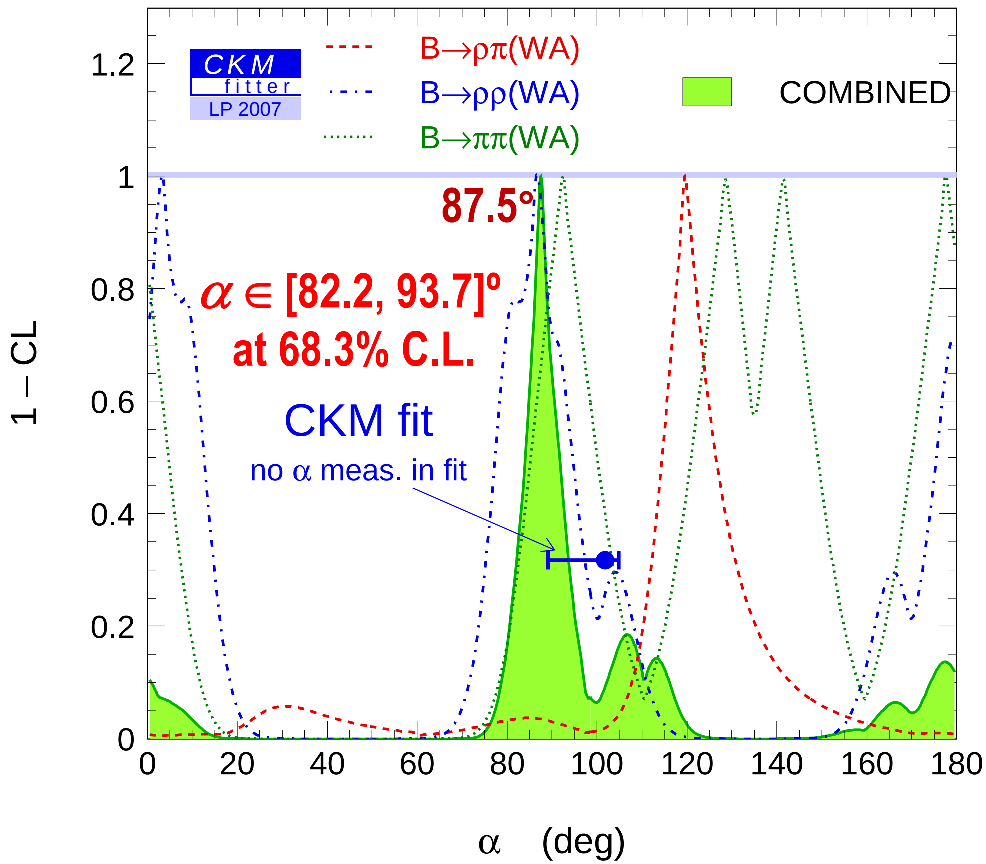
Global fits for the value of α

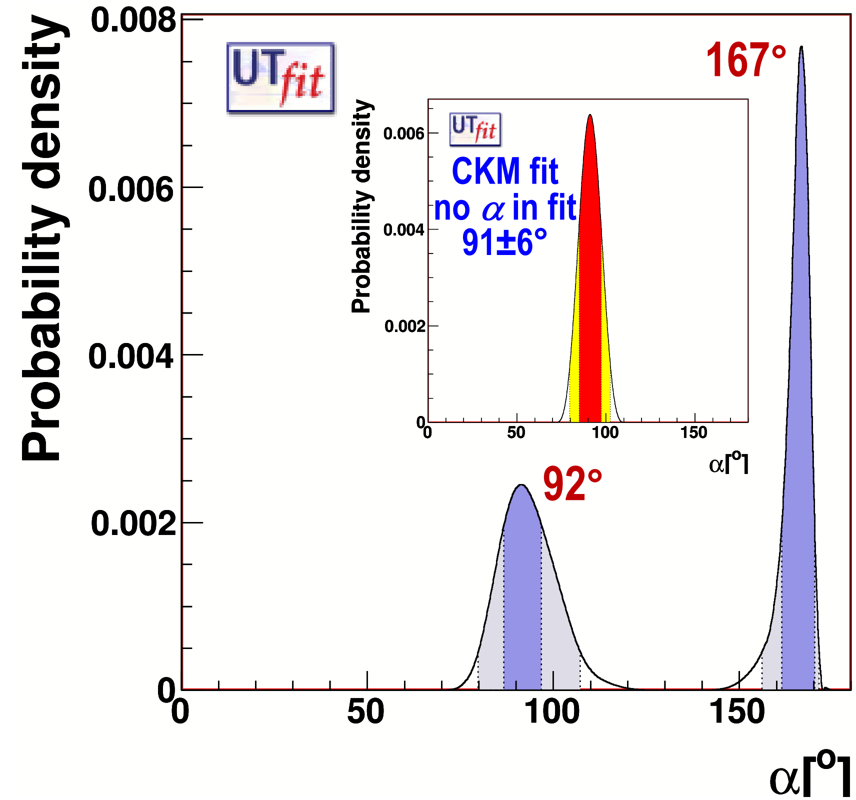
The <u>second-highest-precision</u> test of the KM mechanism of *CP* violation in meson decays

Two interpretations currently exist that convert the $B \to \pi\pi, \rho\pi, \rho\rho$ measurements to constraints on α:

A frequentist interpretation

A Bayesian interpretation, with model-dependent choices of priors





CKMfitter Group (J. Charles et al.), Eur. Phys. J. C**41**, 1-131 (2005) [hep-ph/0406184], updated results and plots available at http://ckmfitter.in2p3.fr

M. Ciuchini, G. D'Agostini, E. Franco, V. Lubicz, G. Martinelli, F. Parodi, P. Roudeau, A. Stocchi, JHEP **0107** (2001) 013 [hep-ph/0012308], updated results and plots available at http://www.utfit.org

γ : the hardest to measure directly

Several techniques are combined, but the constraint is still rather weak

Time-dependent: $\sin(2\beta+\gamma)$ from $\boldsymbol{b}\rightarrow\boldsymbol{c}$, $b\rightarrow u$ interference + B^0 mixing

- $B^0 \longrightarrow D^{\mp}\pi^{\pm}, D^{*\mp}\pi^{\pm}, D^{\mp}\rho^{\pm}$: limited sensitivity due to smallness of $r = |A(b\rightarrow u)/A(b\rightarrow c)|$
- $B^0 \longrightarrow D^{\mp}K^0\pi^{\pm}$ Dalitz plot (mostly through $B^0 \longrightarrow \overset{(-)}{D}{}^{**0}K^0_S$ and $B^0 \longrightarrow D^-K^{*+}$)

Not time-dependent: γ from $\boldsymbol{b}\rightarrow\boldsymbol{c}$, $b\rightarrow u$ interference

- $B^+ \longrightarrow D^0{}_{CP}K^+$ (GLW = Gronau, London, Wyler): the first idea on the market
- $B^+ \longrightarrow \overset{(-)}{D}{}^0K^+$, $D^0 \longrightarrow K^+\pi^-$ (ADS = Atwood, Dunietz, Soni): limited sensitivity

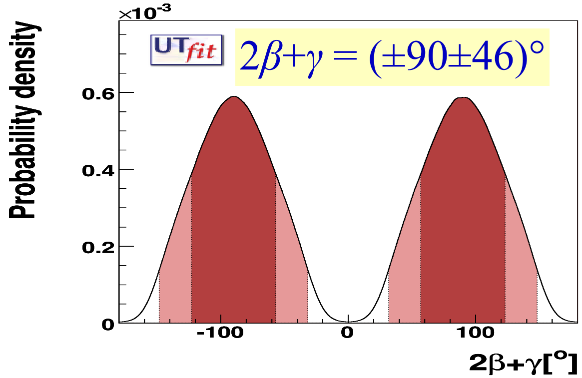
  "wrong sign" D^0 decay – doubly Cabibbo-suppressed
- $B^0 \longrightarrow \overset{(-)}{D}{}^0K^{*0}$ Dalitz plot (also "ADS")
- $B^+ \longrightarrow \overset{(-)}{D}{}^{(*)0}K^+$, $D^0 \longrightarrow K^0_S\pi^+\pi^-$ Dalitz plot (GGSZ = Giri, Grossman, Soffer, Zupan)

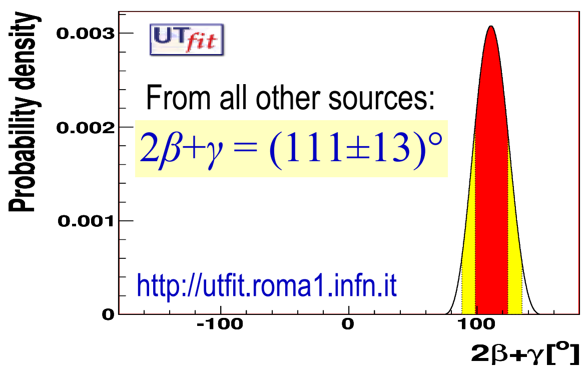
Indirect: *(model-dependent and beyond the scope of this talk)*

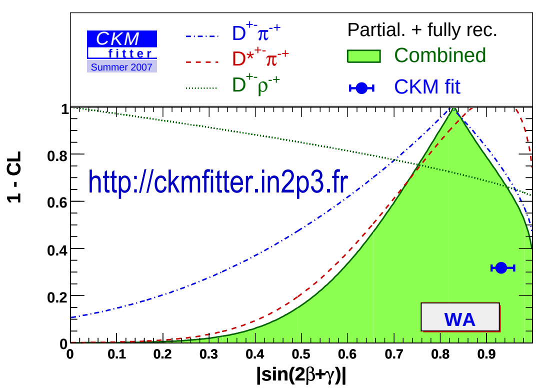
- *SU(3) analysis of amplitudes in* $B \longrightarrow K\pi, \pi\pi$ (e.g., Gronau and Rosner, arXiv:0704.3459v3 [hep-ph])

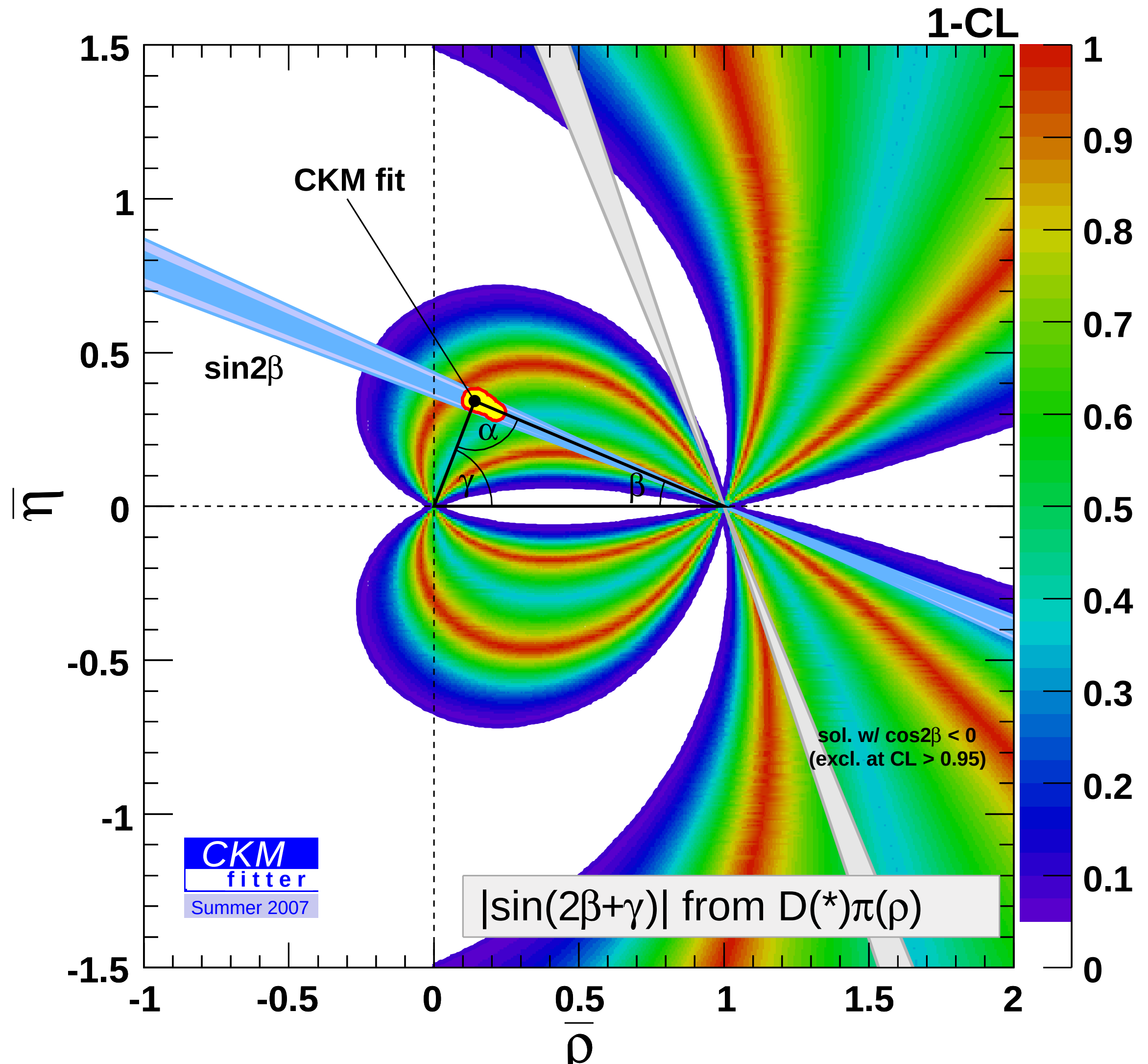
$\sin(2\beta+\gamma)$ status as of Summer 2007

Interpretations of $B^0 \to D^{\mp}\pi^{\pm}$, $D^{*\mp}\pi^{\pm}$, $D^{\mp}\rho^{\pm}$ by UTfit and CKMfitter









BaBar + Belle

$\sin(2\beta+\gamma)$ in $B^0 \to D^{\mp}K^0\pi^{\pm}$ Dalitz plot

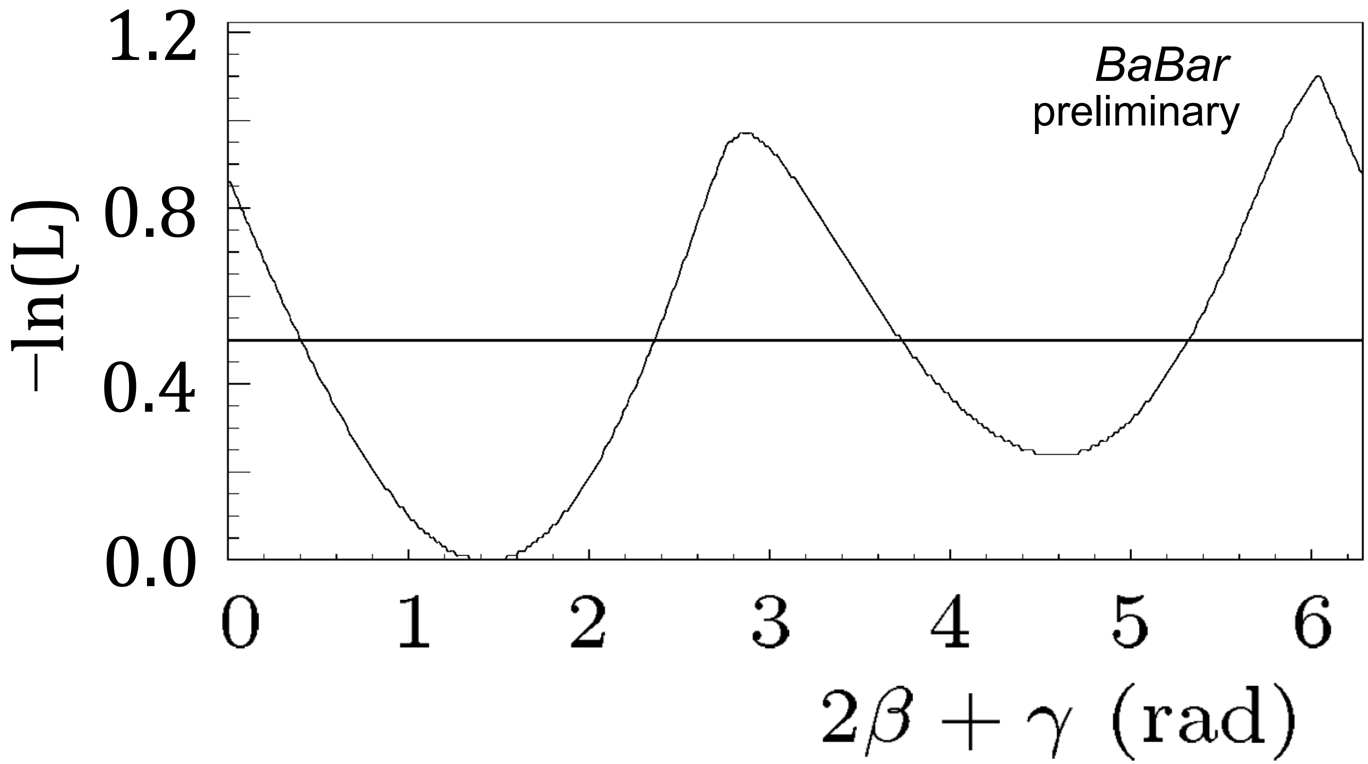
arXiv:0712.3469, accepted to Phys. Rev. D

$N_{BB} = 347\text{M}$

Assumes $r = |A(b\to u)/A(b\to c)| = 0.3\pm0.1$

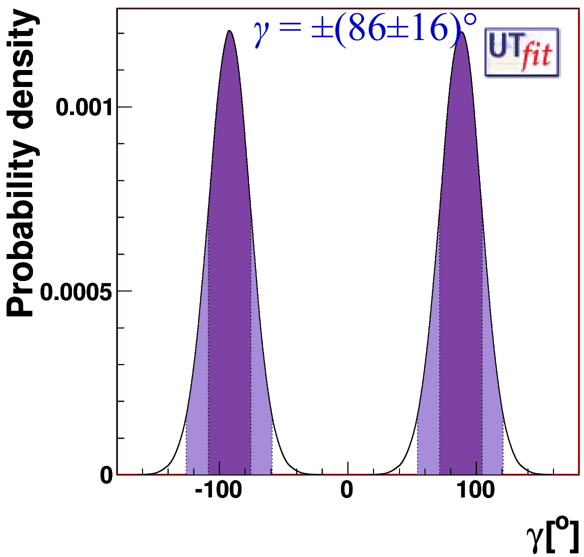
$N_{\text{sig}} = 558 \pm 34$

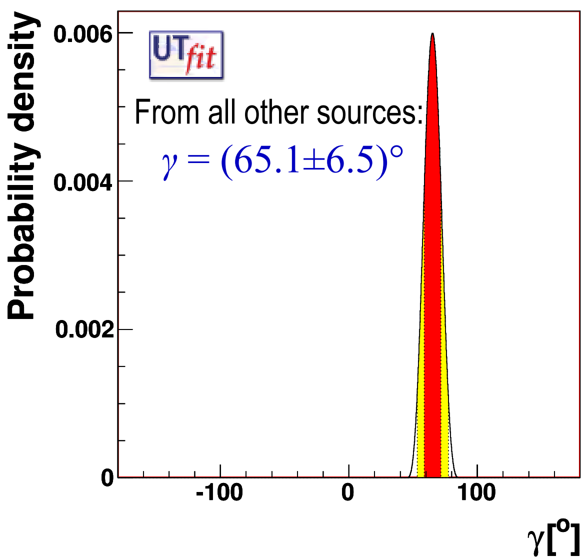
$\mathbf{2\beta+\gamma = (83\pm53\pm20)° \text{ or } (263\pm53\pm20)°}$

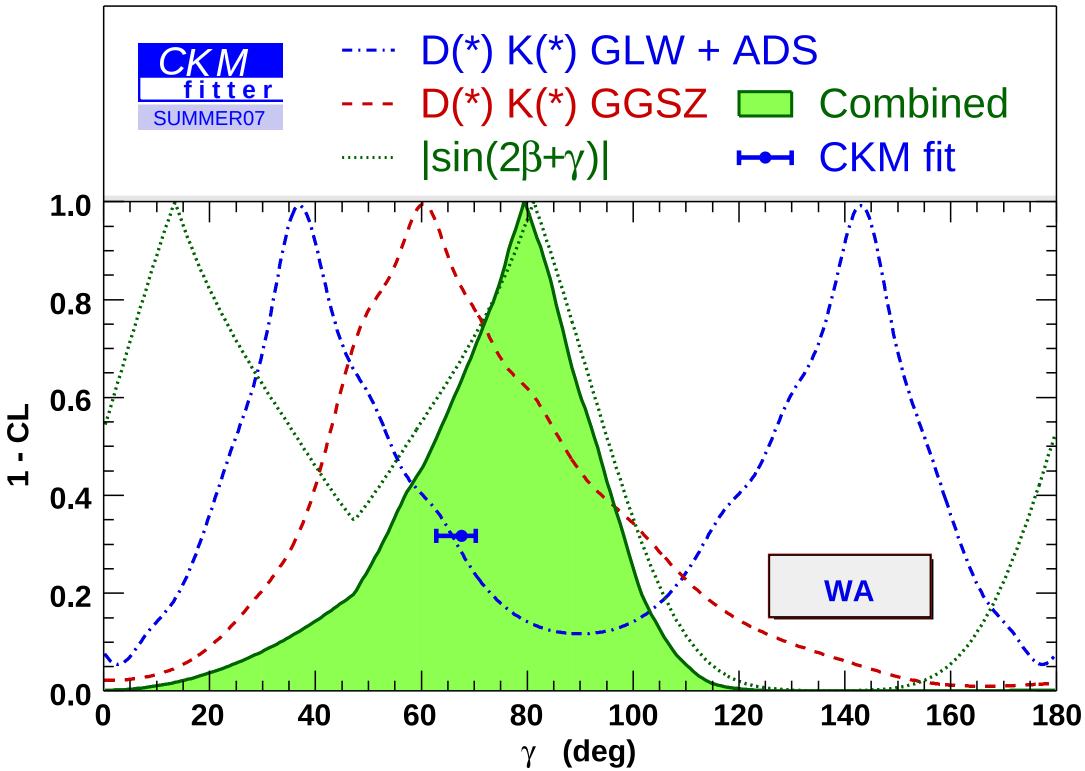


γ status as of Summer 2007

Interpretations by UTfit and CKMfitter







CKMfitter: $\gamma = (80^{+18}_{-26})^\circ$

BaBar + Belle

γ in $B^0 \to \overset{(-)}{D}{}^0 K^{*0}$ GGSZ Dalitz plot

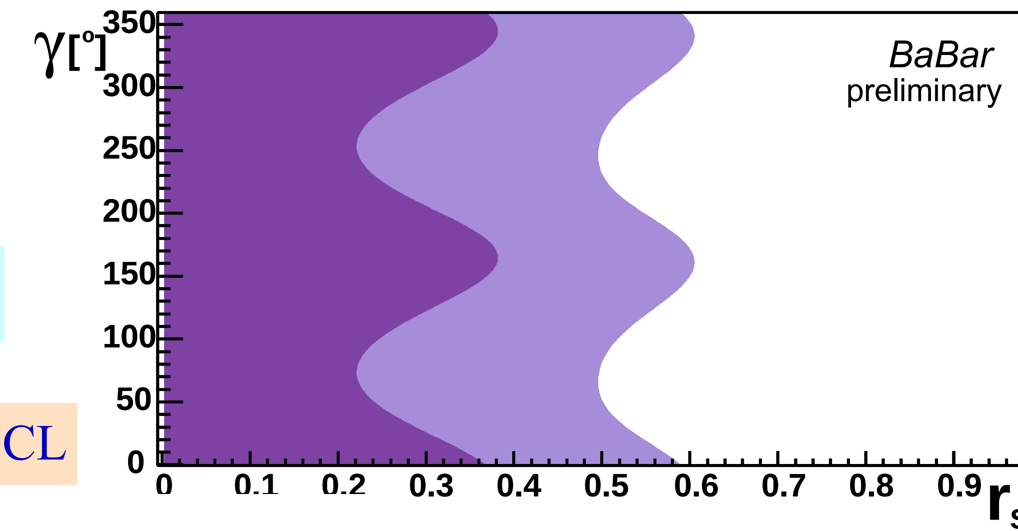
BaBar-PUB-07/072, to be submitted to Phys. Rev. D

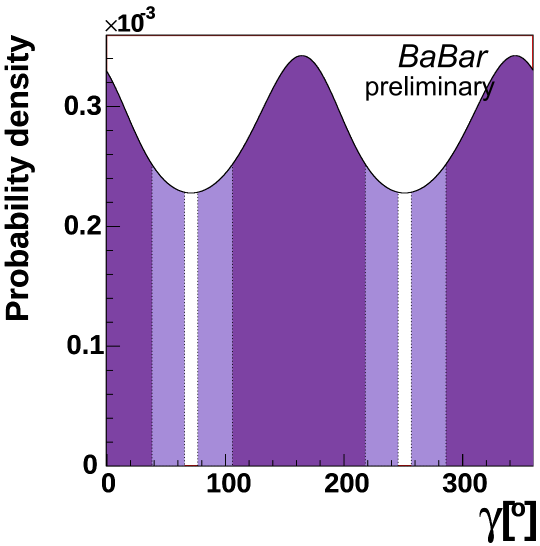
$N_{BB} = 371\text{M}$

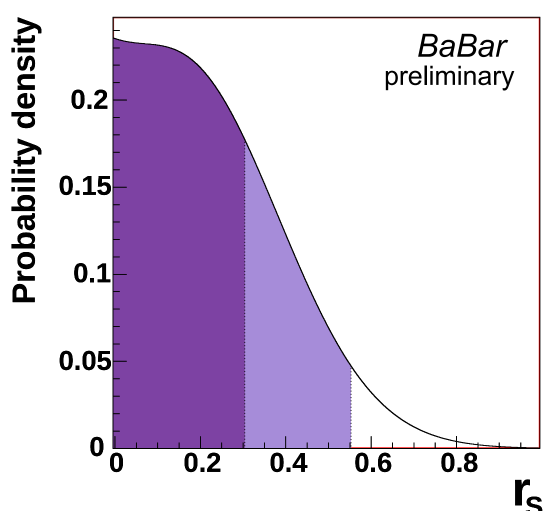
$N_{sig} = 39 \pm 9$

$\gamma = (162 \pm 56)° \text{ or } (342 \pm 56)°$

$r_s = |A(b \to u)/A(b \to c)| < 0.55$ @ 95% CL



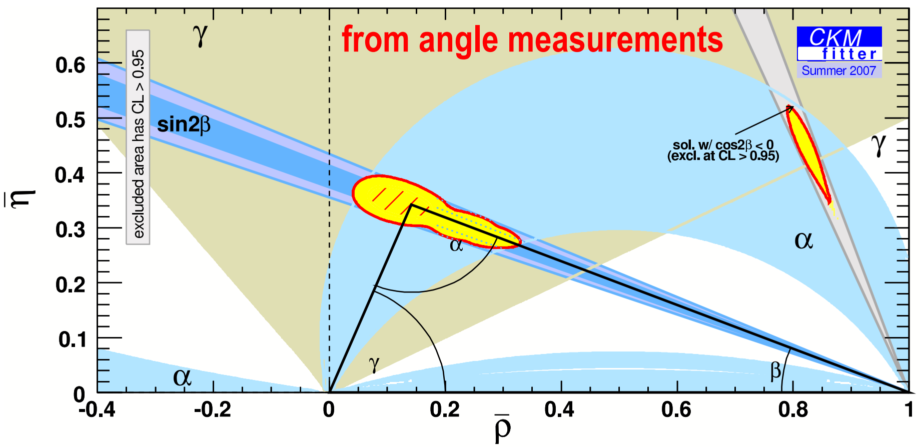


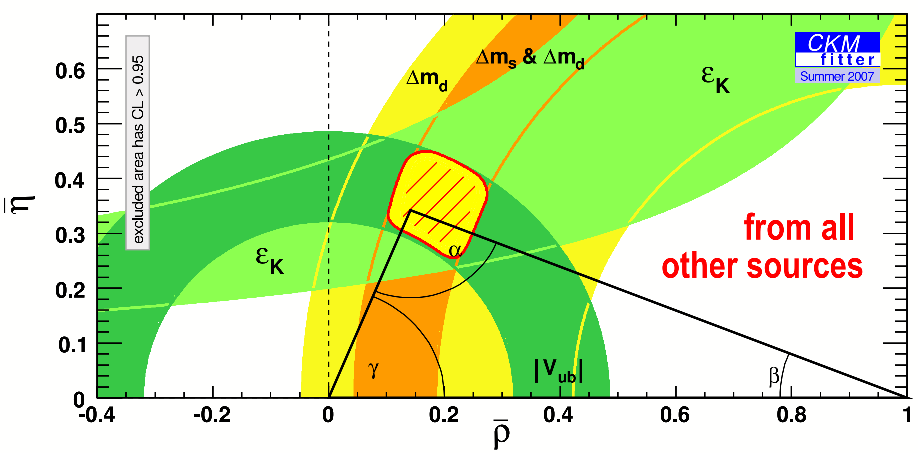


Current knowledge of the Unitarity Triangle

Important: nearly all measurements are still statistics-limited

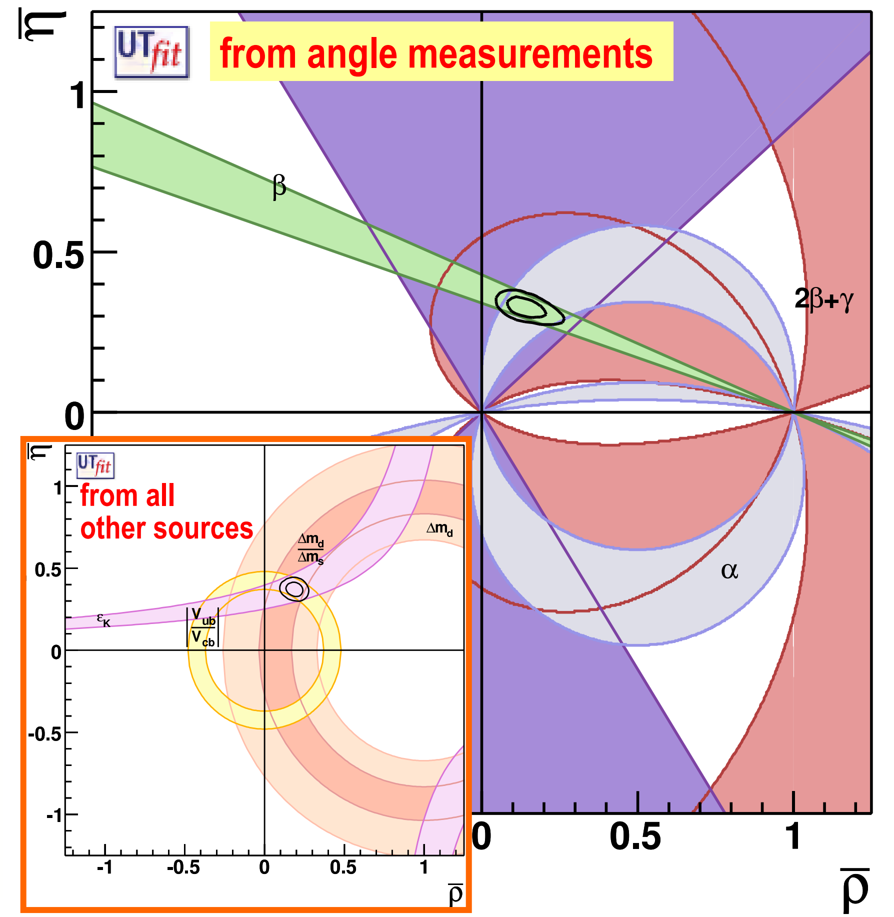
A frequentist interpretation





CKMfitter Group (J. Charles et al.), Eur. Phys. J. C**41**, 1-131 (2005), [hep-ph/0406184], updated results and plots available at http://ckmfitter.in2p3.fr

A Bayesian interpretation, with model-dependent choices of priors



M. Ciuchini, G. D'Agostini, E. Franco, V. Lubicz, G. Martinelli, F. Parodi, P. Roudeau, A. Stocchi, JHEP **0107** (2001) 013 [hep-ph/0012308], updated results and plots available at http://utfit.roma1.infn.it

Summary and outlook

The Kobayashi-Maskawa phase has been demonstrated to be the dominant source of *CP* violation in meson decays.

Constraints on the CKM Unitarity Triangle from angle measurements are statistics-limited, comparable with constraints from all other sources – and mutually consistent.

The absence of statistically significant inconsistencies contains a wealth of information about the flavor structure New Physics that can be expected at the TeV scale. In particular, it pushes up the scale of new *CP*-violating physics in many NP models.