CP Violation at BABAR
α and γ

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Outline:

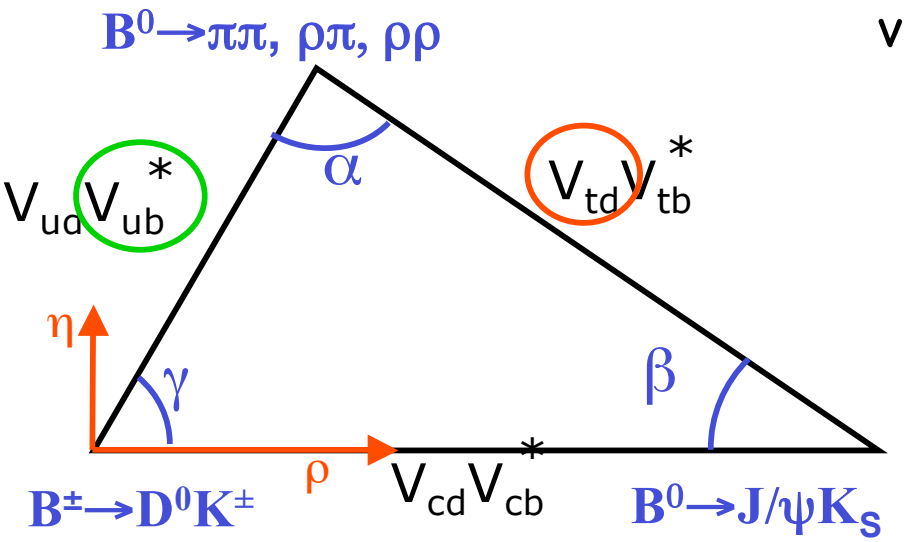
- Methodology in B factories
- Measurements of α
- Direct CP violation
- Measurements of γ

B-Factory Symposium, October 27th, 2008, SLAC

Angles of Unitarity Triangle BaBar Methodology

CP Violation and CKM Matrix

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

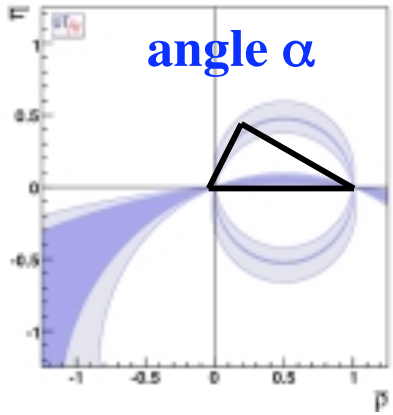


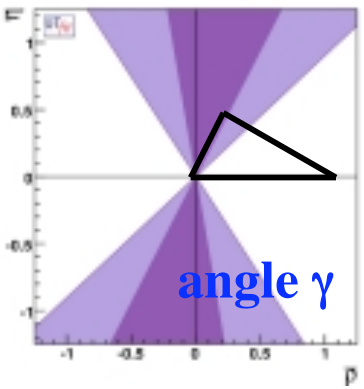
Representation with Unitary Triangle:

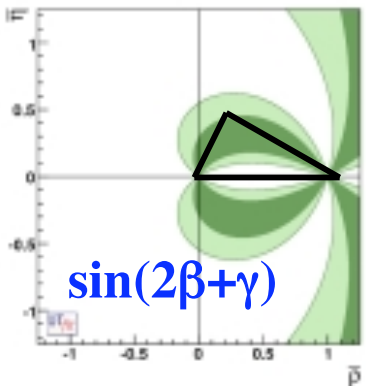
- The angles (α,β,γ) are related to CP violating asymmetries in specific B decays

$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}}\right] \qquad \gamma = \arg\left[-\frac{V_{cd}V_{cb}^{*}}{V_{ud}V_{ub}^{*}}\right]$$

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







Signal Selection

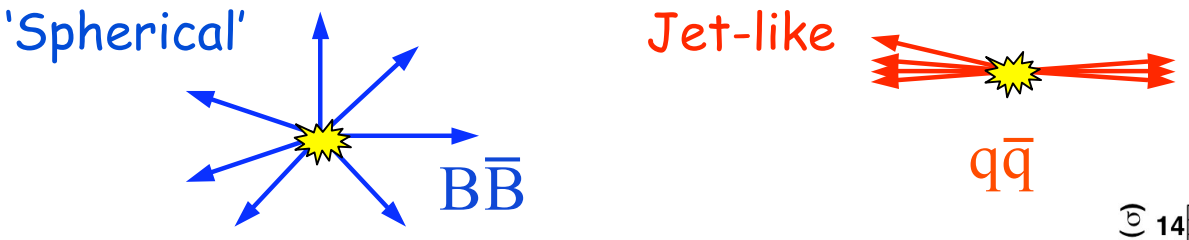
Continuum ($u\bar{u}$...$c\bar{c}$) event rejection:

- Kinematical variables:
  - The beam-energy substituted mass
    Resolutions $\sigma(m_{ES}) \approx 2.6$ MeV/c^2
  - The energy difference
    Resolutions $\sigma(\Delta E) \approx 26$ MeV

$$m_{ES} = \sqrt{E^{*2}_{\text{beam}} - p^{*2}_{B}}$$

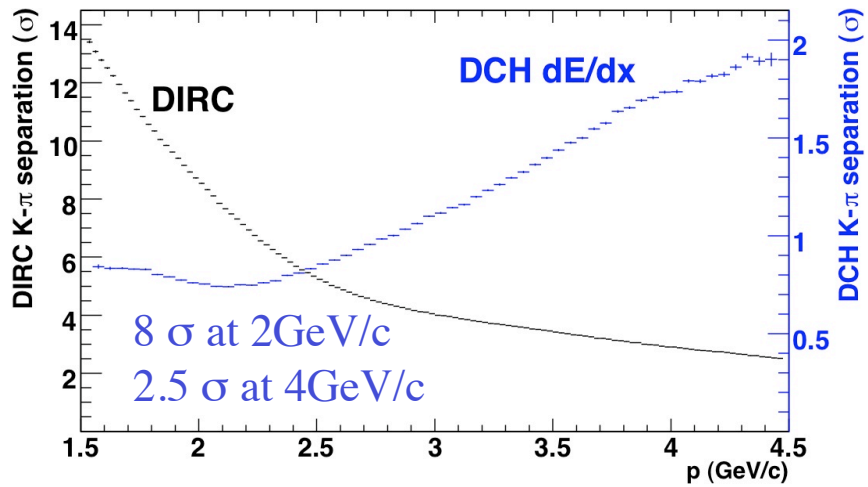
$$\Delta E = E^{*}_{B} - E^{*}_{\text{beam}}$$

- **Event-shape variables** combined in a neural network or Fisher discriminant to suppress jet-like continuum events.



Hadron ID:

- Very important for α:
  Contamination from modes like (πK, ρK, ρK^*...)
- π/K separation using a ring imaging Cerenkov detector and dE/dx in Dch

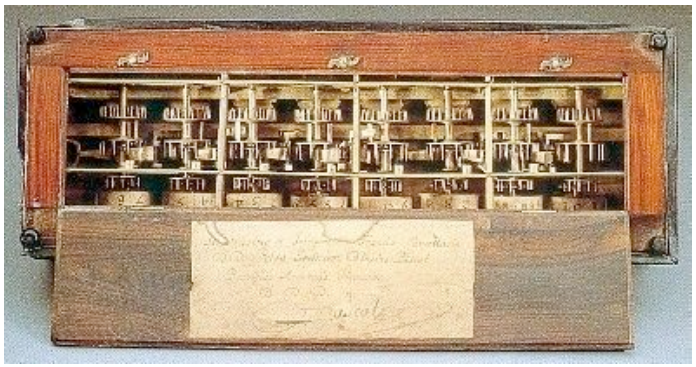


Analysis strategy

The analyses ($B^0 \to \pi\pi, \rho\rho, \rho\pi$) for α or ($B^{\pm} \to D^{0(*)}K^{\pm(*)}\ldots$) for γ share **the same philosophy and use very similar techniques**:

- **Unbinned maximum likelihood** fit combining m_{ES}, ΔE, NN/F, Δt, Dalitz variables, resonance mass or helicity ….
- Each component (signal, backgrounds…) has its own modeling ("PDF") in the likelihood
- Few hundreds of PDF per likelihood
  $\Rightarrow$ BaBar : **Pdf Factory**
- Sophisticated methodology to "observe" the signal: sPlots…

B. Pascal (1645)

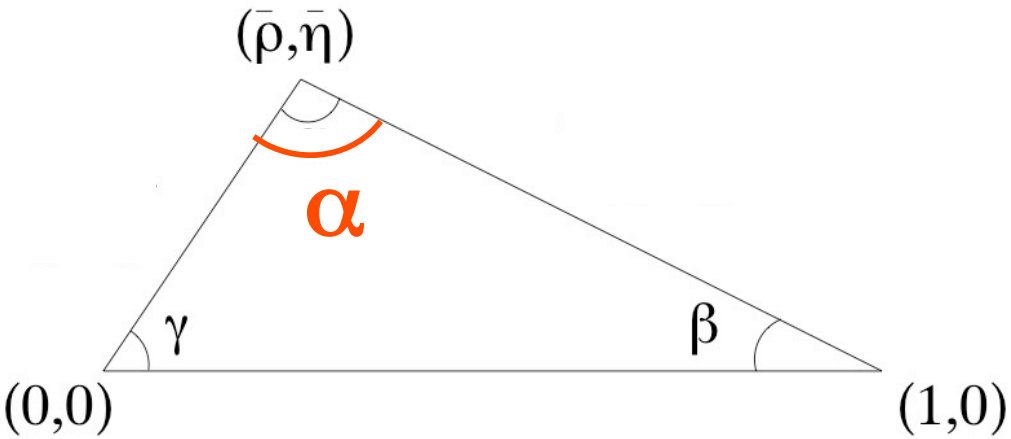


What's the gain?

α: $B^0 \to \rho^+\rho^-$	$\sigma(C)$	$\sigma(S)$
BELLE 535M $B\bar{B}$	0.21	0.30
BABAR 387M $B\bar{B}$	0.15	0.20

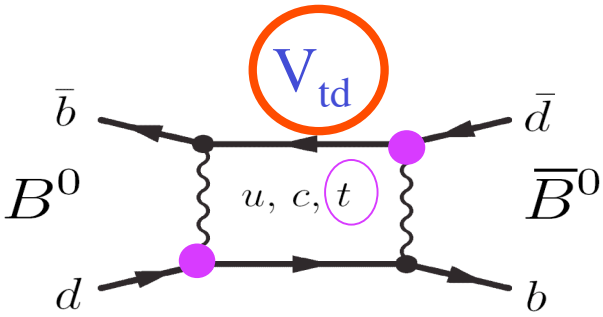
γ: $B^+ \to D^0K^+$	$\sigma(x^+)$	$\sigma(y^+)$
BELLE 657M $B\bar{B}$	0.043	0.059
BABAR 383M $B\bar{B}$	0.043	0.055

Measurements of α

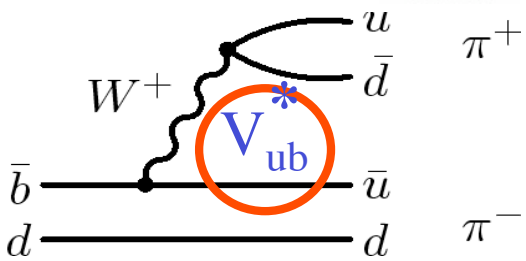


CP Violation in $B^0 \to \pi^+\pi^-/\rho\rho^-$

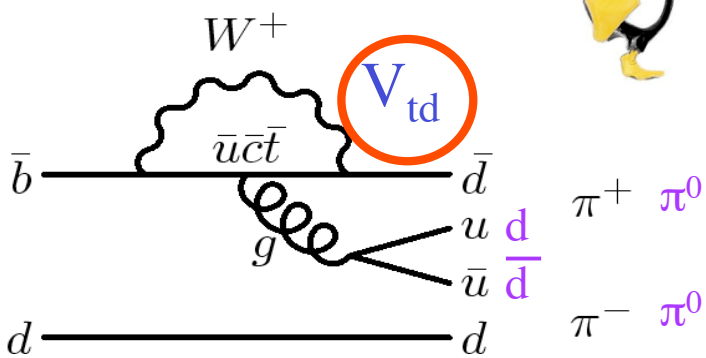
B^0-$\bar{B}^0$ mixing



Tree diagram



Penguin diagram



Time-dependent Asymmetry

$$A_{hh}(\Delta t) = S_{hh} \sin \Delta m_d \Delta t - C_{hh} \cos \Delta m_d \Delta t$$

For single weak phase

$$C_{hh} = 0 \quad S_{hh} = \sin\left(-2(\gamma + \beta)\right) = \sin(2\alpha)$$

- α may be extracted directly from S as for β.

With an additional weak phase

$$C_{hh} \neq 0 \quad S_{hh} = \sqrt{1 - C_{hh}^{\ 2}} \sin(2\alpha_{\text{eff}}) \neq \sin(2\alpha)$$

- Need additional information to estimate penguin contribution ($BF(B^0 \to h^0 h^0)$ …)
- **Use Isospin SU(2) symmetry**

SU(2) Symmetry: Isospin Triangles

Similar approaches for $B \to \rho\rho$ and $B \to \pi\pi$:

M. Gronau, D. London, PRL, 65, 3381 (1990)

- Two Isospin relations (one for (B^0, B^+), one for $(\bar{B}^0, B^-)$)

$$A(B^+ \to h^+ h^0) = 1/\sqrt{2} \cdot A(B^0 \to h^- h^+) + A(B^0 \to h^0 h^0)$$

- Neglecting EW penguins, $B^+ \to h^+ h^0$ (I=2) is pure tree diagram

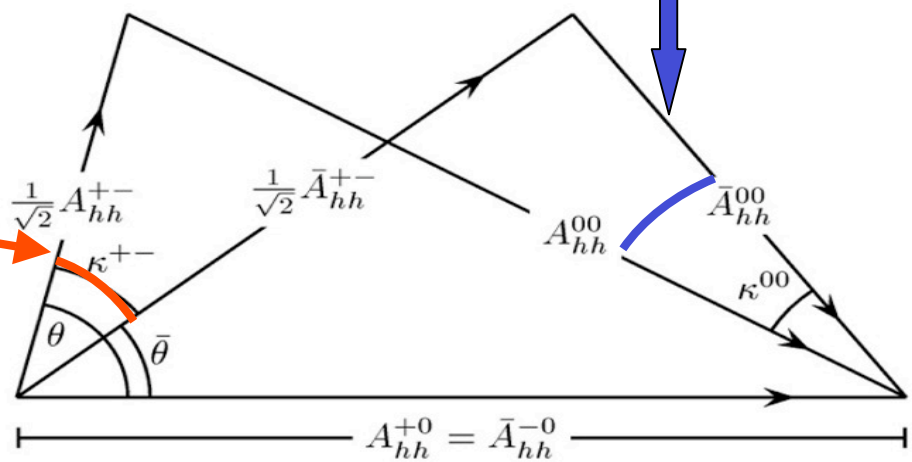
$$A(B^+ \to h^+ h^0) = \bar{A}(B^- \to h^- h^0)$$

- Representation with a triangle with a common side
- Triangle relations allow determination of penguin-induced shift in α

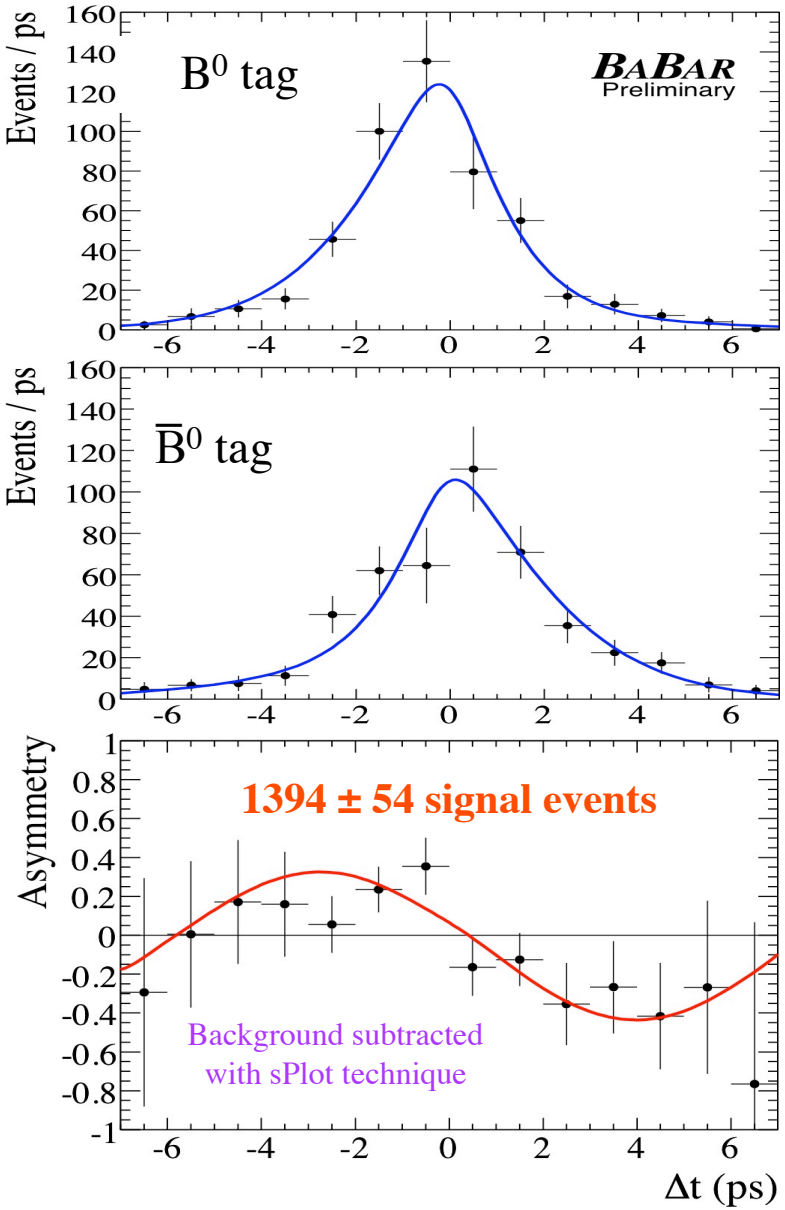
$$\kappa^{+-} = 2(\alpha_{eff} - \alpha)$$

- Four-fold ambiguities

For $B^0 \to \rho^0\rho^0$, S^{00} measurement $\Rightarrow$ constraint on this angle



Measurement of α with $B^0 \to \pi^+\pi^-$

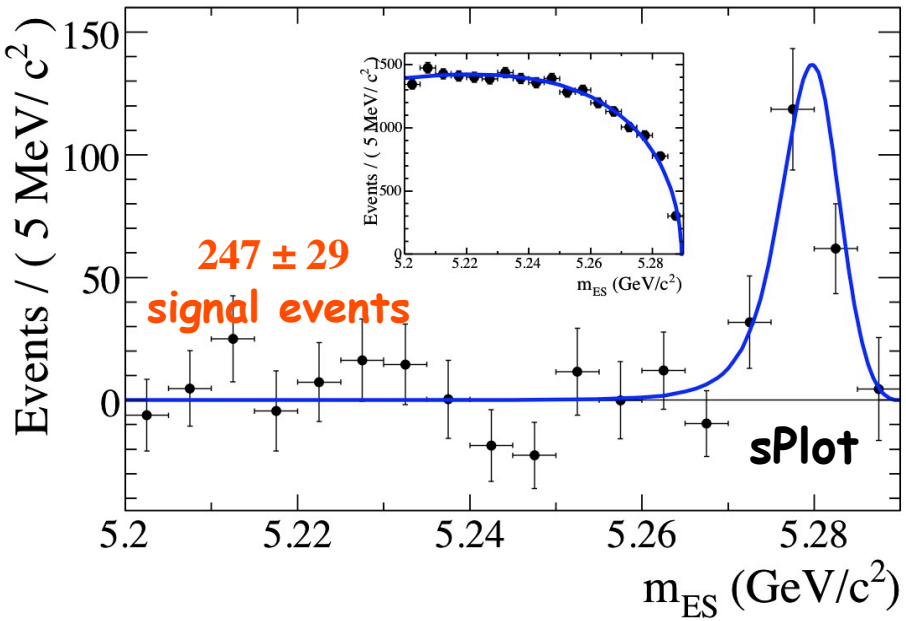


- Time dependent analysis similar to $\sin(2\beta)$ measurements
- CP Violation for both C_{+-} and S_{+-}

467M $B\bar{B}$ arXiv: 0807.4226

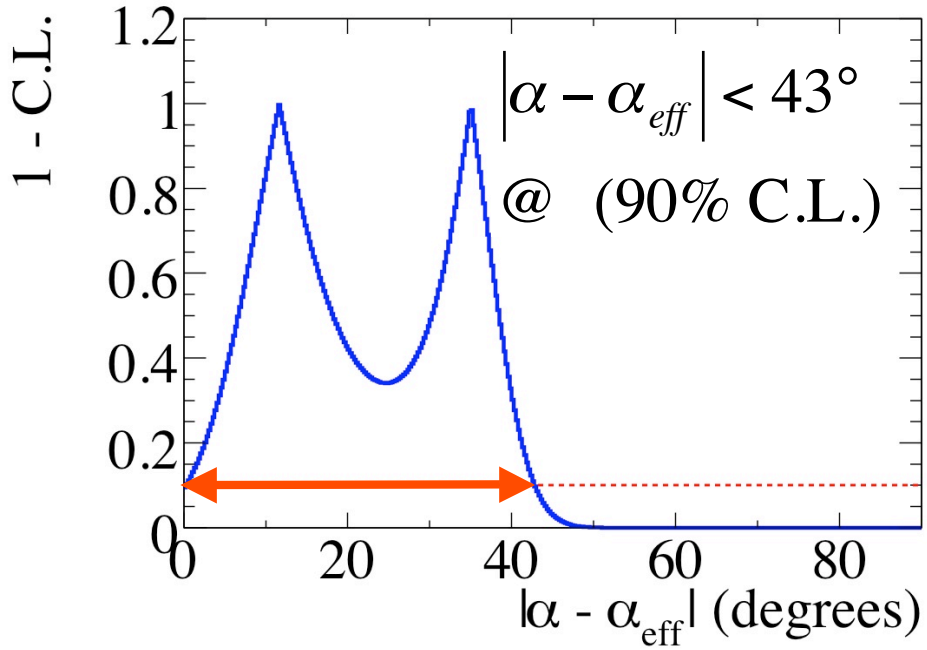
$$S_{+-} = -0.68 \pm 0.11 \pm 0.03 \quad (6.0\sigma)$$
$$C_{+-} = -0.25 \pm 0.08 \pm 0.02 \quad (3.0\sigma)$$

Measurement of α with $B^0 \to \pi\pi$



$$BF(\pi^0\pi^0) = (1.83 \pm 0.21 \pm 0.13) \times 10^{-6}$$
$$C_{00} = -0.43 \pm 0.26 \pm 0.05$$
$$BF(\pi^\pm\pi^0) = (5.02 \pm 0.46 \pm 0.29) \times 10^{-6}$$
$$BF(\pi^+\pi^-) = (5.5 \pm 0.4 \pm 0.3) \times 10^{-6}$$

467M $B\bar{B}$ arXiv: 0807.4226

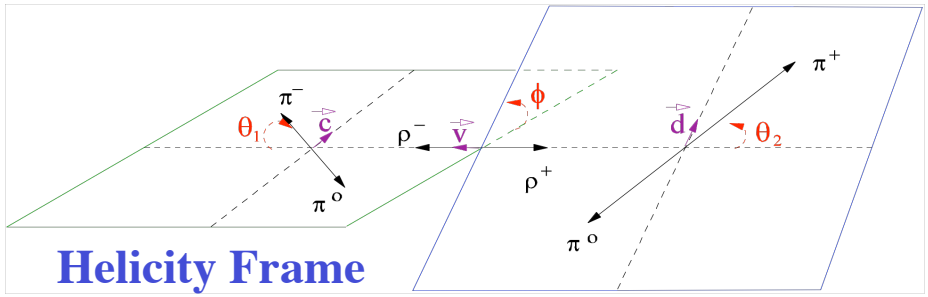


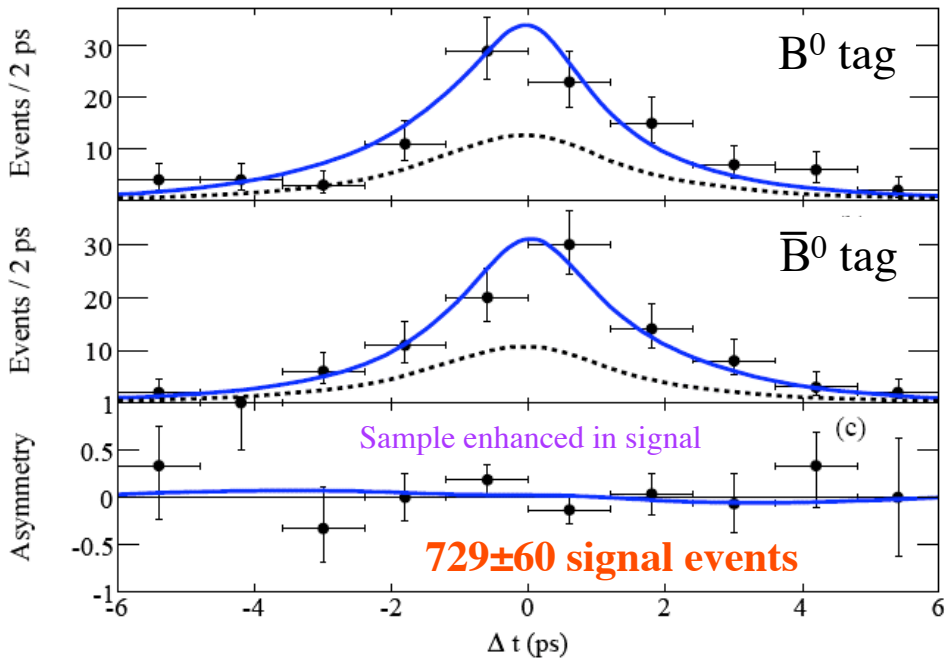
- "Large" BR for $B^0 \to \pi^0\pi^0$
- Large fraction of penguin contamination
- Isospin analysis is required

Measuring α with $B^0 \to \rho^- \rho^+$ decays

Analysis more complex:

- 2 π^0 in the final state.
- Wide ρ resonances.
- V-V decay: L=0,1,2 partial waves :
  - Longitudinal: CP-even state.
  - Transverse: Mixed CP states.
  - Analysis based on ρ polarization.





383M $B\bar{B}$ PRD 76, 052007 (2007)

$$BF(\rho^+\rho^-) = (25.5 \pm 2.1^{+3.6}_{-3.9}) \times 10^{-6}$$

$$f_L^{+-} = 0.992 \pm 0.024^{+0.026}_{-0.013}$$

$$C_L^{+-} = 0.01 \pm 0.11 \pm 0.06$$

$$S_L^{+-} = -0.17 \pm 0.20^{+0.05}_{-0.06}$$

Eventually a very efficient mode:

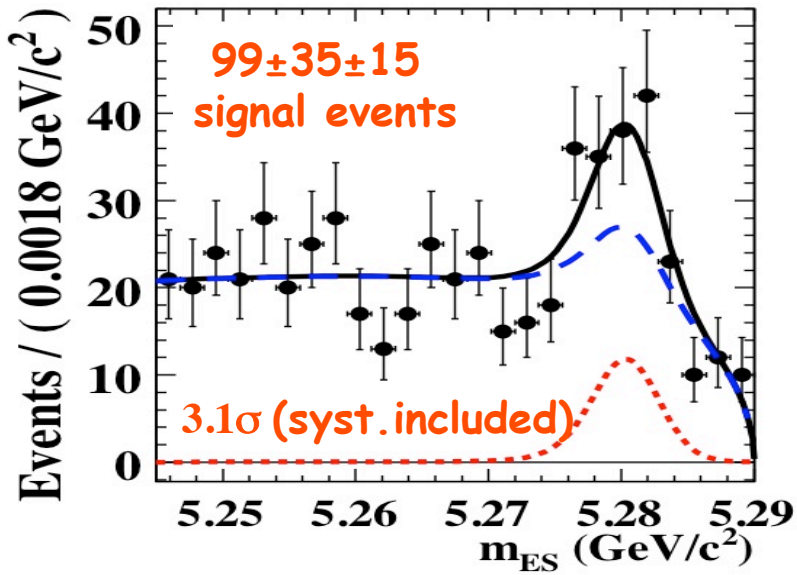
- BF~ **5 times larger** than for $B \to \pi\pi$.
- Penguin much smaller than in $\pi\pi$.
- ρ are ~100% longitudinally polarized.
- **Almost a pure CP-even state!**

α with $B^0 \to \rho^-\rho^+/\rho^0\rho^0$ and $B^+ \to \rho^+\rho^0$

CP asymmetries in $B^0 \to \rho^0\rho^0$:

- Small BF for $B^0 \to \rho^0\rho^0$
- In contrast with $\pi^0\pi^0$, decay vertex can be reconstructed ($\rho^0 \to \pi^+\pi^-$).
- Time-dependent analysis feasible.
- Measurement of C_L^{00} and S_L^{00}

$\Rightarrow$ Over-constrained isospin relations



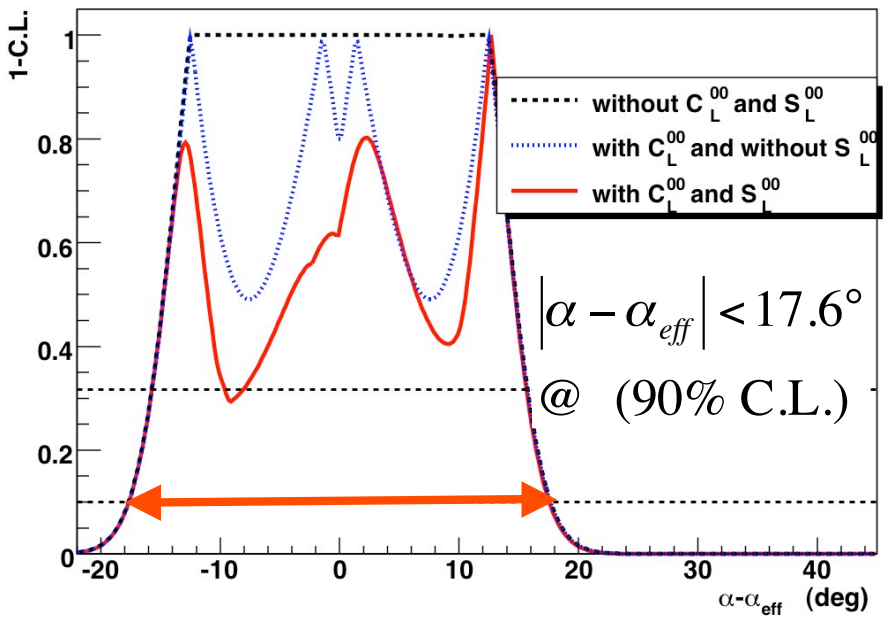
$$\mathrm{BF}(\rho^0\rho^0) = (0.92 \pm 0.32 \pm 0.14) \times 10^{-6}$$

$$f_L^{00} = 0.75^{+0.11}_{-0.14} \pm 0.05$$

$$C_L^{00} = 0.2 \pm 0.8 \pm 0.3$$

$$S_L^{00} = 0.3 \pm 0.7 \pm 0.2$$

465M $B\bar{B}$ arXiv: 0807.4977



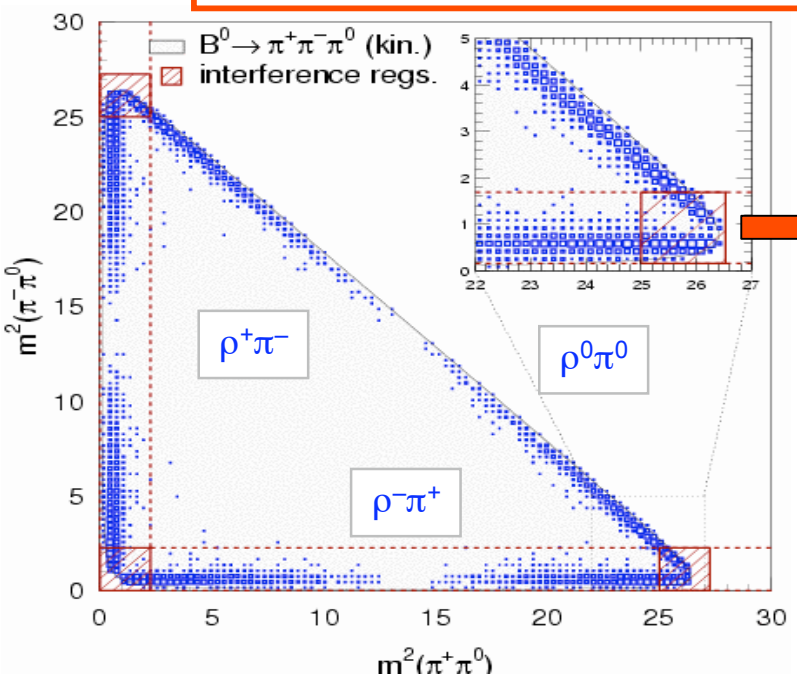
Dalitz analysis of $B^0 \to (\rho\pi)^0 \to \pi^+\pi^-\pi^0$

- Dominant decay $B^0 \to \rho^+\pi^-$ is not **a CP eigenstate**
- Two-body Isospin analysis not viable: 5 amplitudes need to be considered $B^0 \to \rho^+\pi^-/\rho^-\pi^+/\rho^0\pi^0$ and $B^+ \to \rho^+\pi^0/\rho^0\pi^+$ Isospin Triangle Þ Isospin Pentagon.

- Better approach: **Time-dependent Dalitz analysis** assuming SU(2):

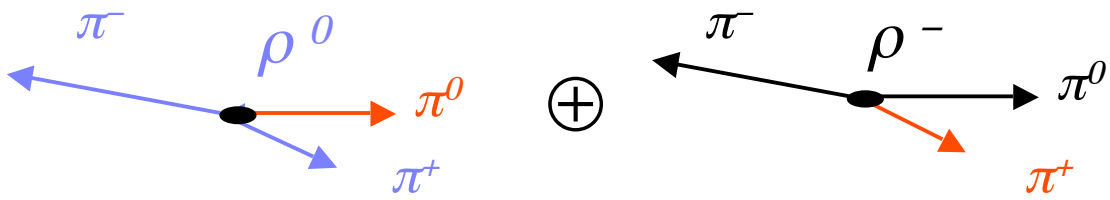
$$A(B^0 \to \pi^+\pi^-\pi^0) = f_+ A(\rho^+\pi^-) + f_- A(\rho^-\pi^+) + f_0 A(\rho^0\pi^0)$$
$$\overline{A}(\overline{B}^0 \to \pi^+\pi^-\pi^0) = f_+ \overline{A}(\rho^+\pi^-) + f_- \overline{A}(\rho^-\pi^+) + f_0 \overline{A}(\rho^0\pi^0)$$

f_k relativistic Breit-Wigner



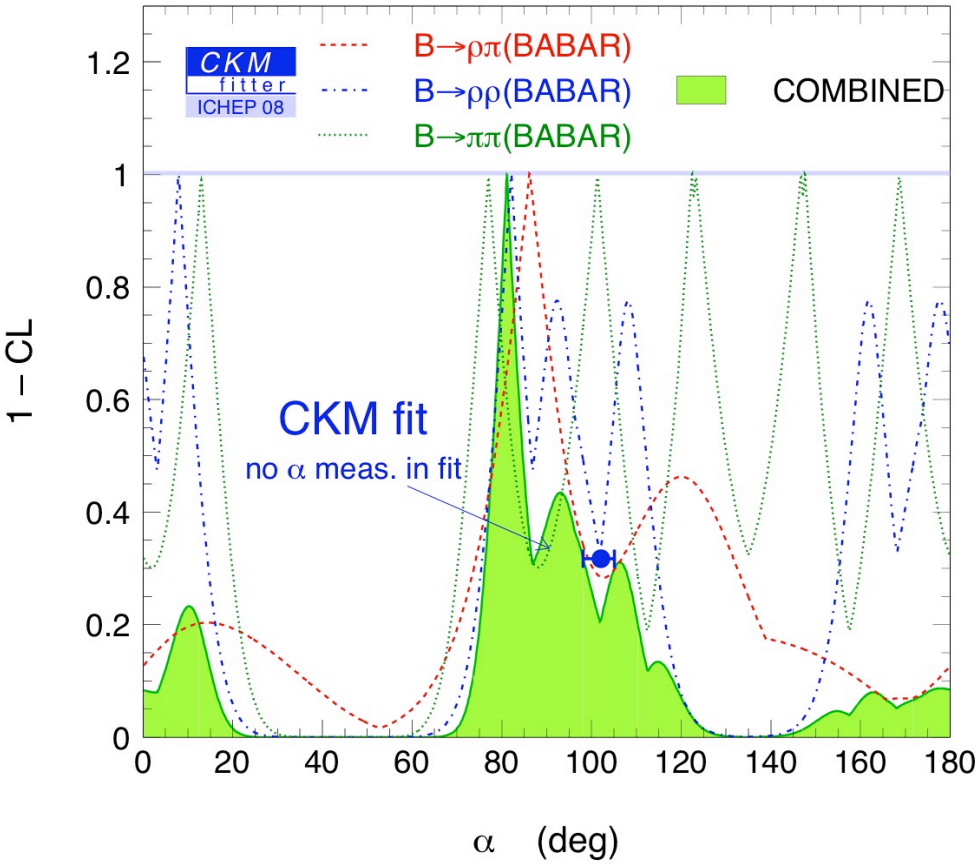
A. Snyder and H. Quinn, Phys. Rev. D, 48, 2139 (1993)

- Interference at equal masses-squared gives information on **strong phases** between resonances.



383M $B\overline{B}$ PRD 76, 012004 (2007)

Summary on α



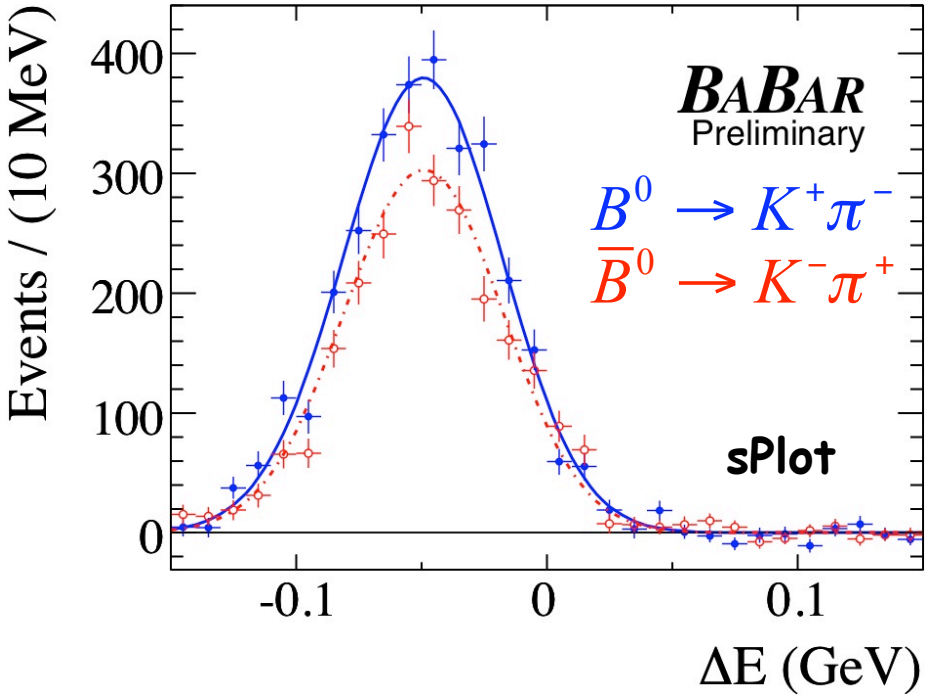
$$\alpha = 81.1^{\circ}{}^{+17.5^{\circ}}_{-\ 4.9^{\circ}}$$

- The 3 decays modes $B \to \pi\pi/\rho\pi$(Dalitz)/ $\rho\rho$ give **consistent and complementary** measurements of α.
- **Single solution** when combining the three methods!
- Eventually, better result for α than this expected in the BaBar Physics Book (1998)
- Stay tuned : new BaBar results are coming!!!

Intermezzo

Direct CP Violation

First observation of direct CP Violation



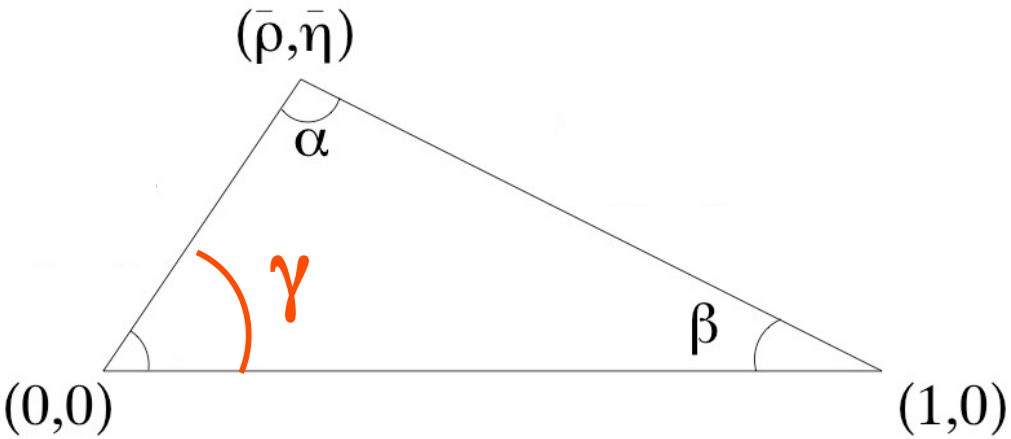
467M $B\bar{B}$ arXiv: 0807.4226

$$A_{CP} = -0.107 \pm 0.016^{+0.006}_{-0.004}$$

with 6.1σ significance

- In 2004, first observation of direct CP violation in $B^0(\bar{B}^0) \to K^+\pi^-/K^-\pi^+$ (4.2σ significance)
- Effect much larger than in K^0-$\bar{K}^0$ system and the discovery was much faster: K^0-$\bar{K}^0$ 1964 →1999
  B^0-$\bar{B}^0$ 2001 →2004
- Now, direct CP violation is observed in many other modes (for instance, $B^\pm \to D^0(\bar{D}^0)^{(*)}K^{\pm(*)}$ see next slides)

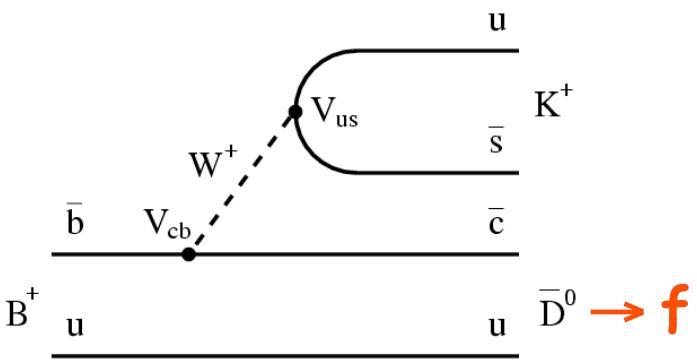
Measurements of γ

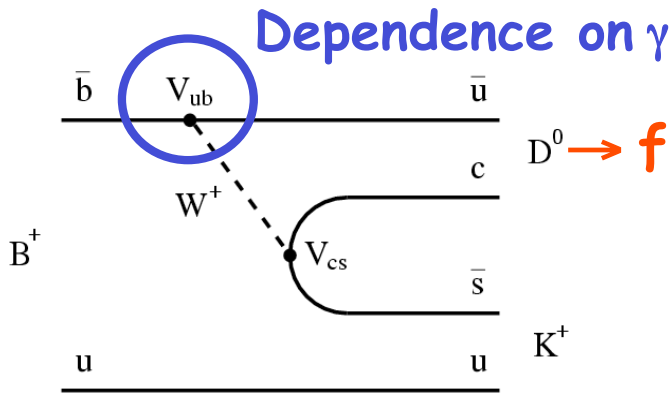


Measurement of γ

Several methods but all are based on the same principles:

- Tree decays $B^{\pm} \to D^0(\bar{D}^0)^{(*)}K^{\pm(*)}$
- **Interference** between a **Cabibbo-suppressed ($b \to c$)** tree decay and a **CKM- and color-suppressed** ($b \to u$) tree decay
- Decay of $D^0(\bar{D}^0)$ to a common final state **f**





Key parameter

$r_B \equiv A(b \to u)/A(b \to c)$

$\sim 0.1\text{-}0.3$

δ_B: strong phase

Measurement of γ

Direct CP violation with $B^{\pm} \to D^0(\bar{D}^0)^{(*)}K^{\pm(*)}$

- **GWL** *(Gronau-Wyler-London):*
  f is an eigenstate ($\pi\pi$, KK)
  $\Rightarrow$ *Small interference, sensitivity to γ, small sensitivity to r_B*
- **ADS** *(Atwood-Dunietz-Soni)*
  $\bar{D}^0 \to f$ is doubly-Cabbibo- suppressed ($K\pi$)
  $\Rightarrow$ *Larger interference, sensitivity to r_B (no observation)*
- **GGSZ** *(Giri-Grossman-Soffer-Zupan)*
  $D^0(\bar{D}^0) \to K_S\pi^+\pi^-$ (Dalitz plot)
  $\Rightarrow$ *Larger interference, sensitivity to both r_B and γ*
  $\Rightarrow$ *Best method currently*

Several complementary Techniques:

- $B^0 \to D^0(\bar{D}^0)^{(*)}K^{0(*)}$: CKM suppression only r_B~0.4; low statistics yet
- Time-dependent CP violation in $B^0 \to D^{(*)}\pi$, $D^{(*)}\rho$
  $\Rightarrow$ *Measurement of $\sin(2\beta+\gamma)$*

γ with GLW method

Final States:

➢ KK, ππ (CP=+1), $K^0\pi^0$, $K^0\omega$ (CP=-1)

4 observables:

➢ 2 CP asymmetries and 2 ratio of BF

3 unknowns :

➢ Strong phase δ_B, r_B and γ

➢ 8-fold ambiguities, small sensitivity to r_B

Ratio of BFs

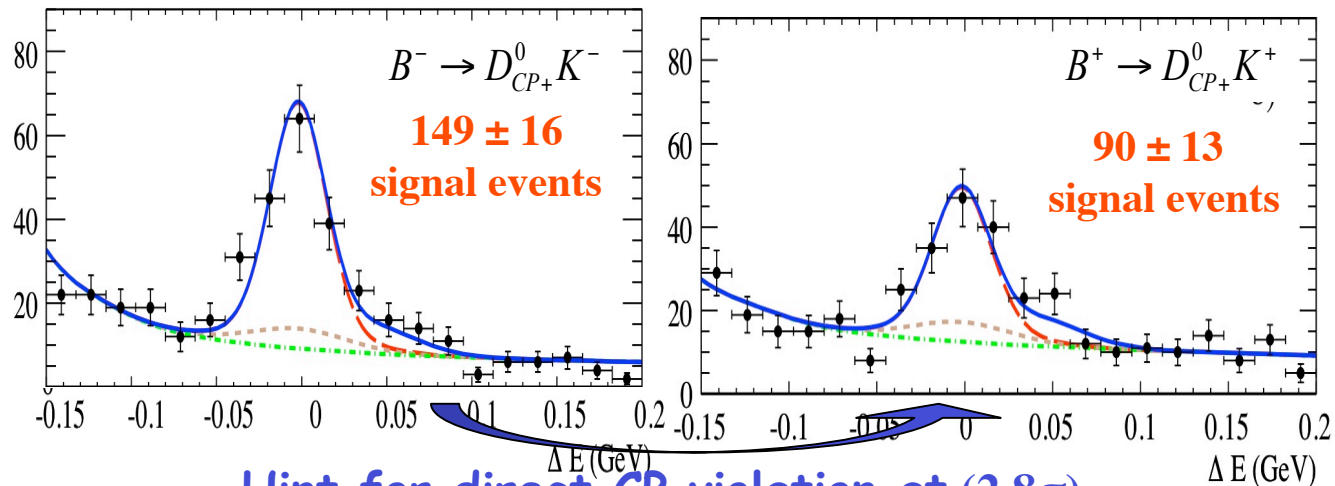
$$R_{CP\pm} = \frac{\Gamma(B^- \to D^0_{CP\pm}K^-) + \Gamma(B^+ \to D^0_{CP\pm}K^+)}{[\Gamma(B^- \to D^0K^-) + \Gamma(B^+ \to D^0K^+)]/2}$$
$$= 1 + r_B \pm 2r_B \cos\delta_B \cos\gamma$$

CP asymmetries

$$A_{CP\pm} = \frac{\Gamma(B^- \to D^0_{CP\pm}K^-) - \Gamma(B^+ \to D^0_{CP\pm}K^+)}{\Gamma(B^- \to D^0_{CP\pm}K^-) + \Gamma(B^+ \to D^0_{CP\pm}K^+)}$$
$$= \frac{\pm 2r_B \sin\delta_B \sin\gamma}{1 + r_B \pm 2r_B \cos\delta_B \cos\gamma}$$

$$R_{CP-} = 1.03 \pm 0.10 \pm 0.05$$
$$R_{CP+} = 1.06 \pm 0.10 \pm 0.05$$
$$A_{CP-} = -0.09 \pm 0.09 \pm 0.02$$
$$A_{CP+} = 0.27 \pm 0.09 \pm 0.04$$

382M $B\bar{B}$ PRD 77 111102 (2008)



Hint for direct CP violation at (2.8σ)

γ with Dalitz method

$$|A_\pm|^2 = \left| \text{[Dalitz plot for } D^0(\bar{D}^0) \text{, } D^0 \to K_S\pi^+\pi^- \text{, axes } m_+^2 \text{ vs } m_-^2 \right. + r_B\, e^{i(\delta \pm \gamma)} \left. \text{[Dalitz plot for } \bar{D}^0(D^0) \text{, } \bar{D}^0 \to K_S\pi^+\pi^- \text{, axes } m_-^2 \text{ vs } m_+^2 \right|^2$$

Control sample

Use flavor tagged D from $D^{*\pm} \to (K_S\pi^+\pi^-)\pi^\pm$

- Use interference in Dalitz plot $B^\pm \to D^0(\bar{D}^0)K^\pm$ decay
- Sensitive to r_B, strong phases δ and the CKM phase γ
- Two-fold ambiguity remains in γ extraction
- 4 quantities are measured:

$$\boxed{\begin{aligned} x_\pm &= r_B \cos(\delta \pm \gamma) \\ y_\pm &= r_B \sin(\delta \pm \gamma) \end{aligned}}$$

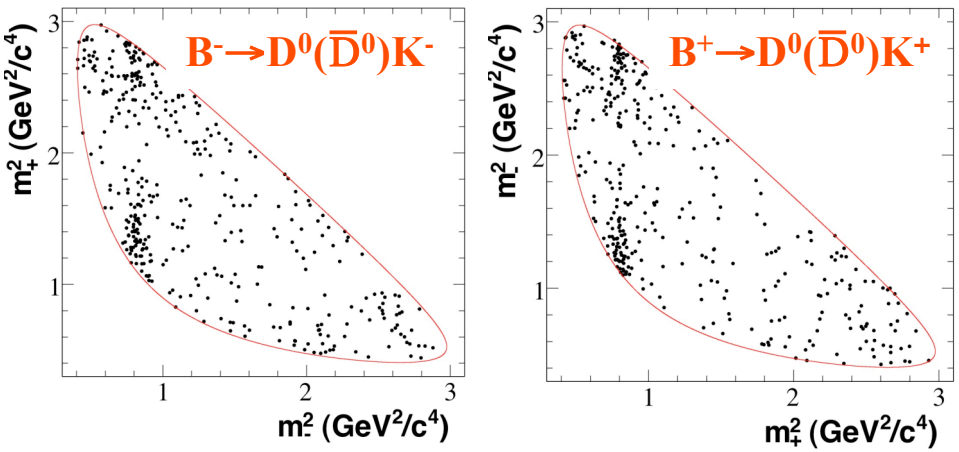
3 modes

$$\begin{cases} B^\pm \to D^0(\bar{D}^0)K^\pm \\ B^\pm \to D^0(\bar{D}^0)^{(*)}K^\pm \\ B^\pm \to D^0(\bar{D}^0)K^{\pm(*)}) \end{cases}$$

2 Dalitz decays

$$\begin{cases} D^0 \to K_S\pi^+\pi^- \\ D^0 \to K_S K^+ K^- \end{cases}$$

γ with Dalitz method

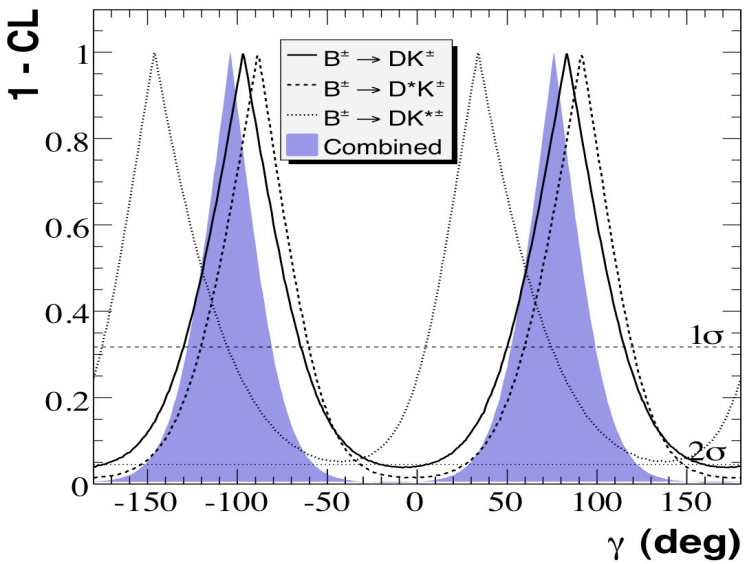


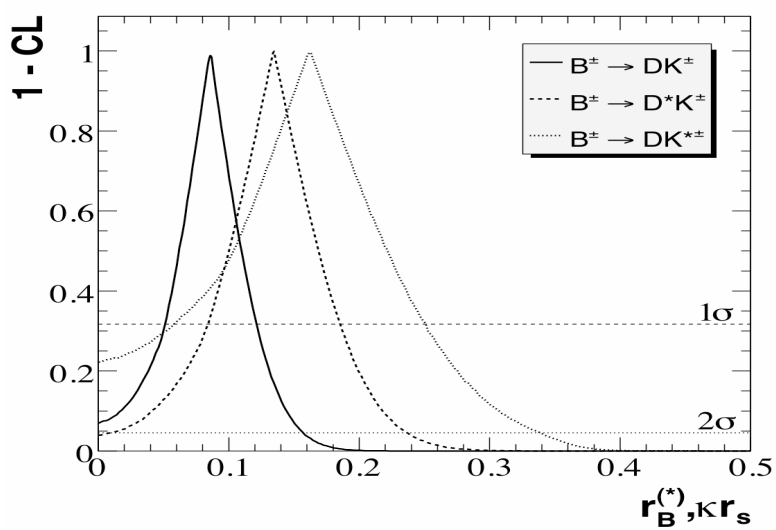
383M $B\bar{B}$ PRD 78 034023 (2008)

- With a frequentist approach, constraints are derived on $r_B^{(*)}, \kappa r_s$ and γ
- Smaller values of $r_B^{(*)}, \kappa r_s$ than BELLE
- Error on $\gamma \propto (1/r_B)$

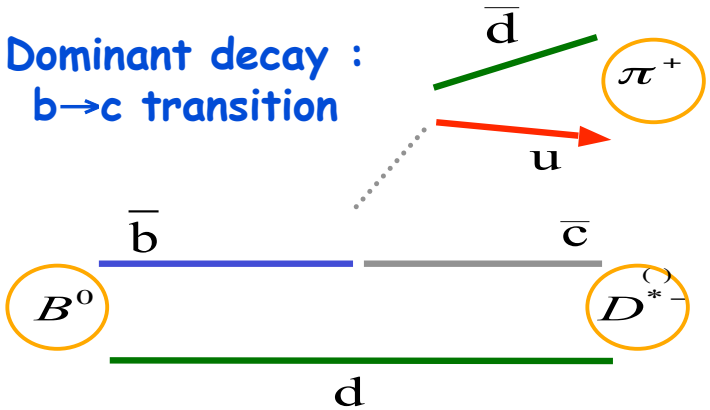
$$\gamma = 76^\circ \pm 22^\circ \pm 5^\circ \pm 5^\circ$$

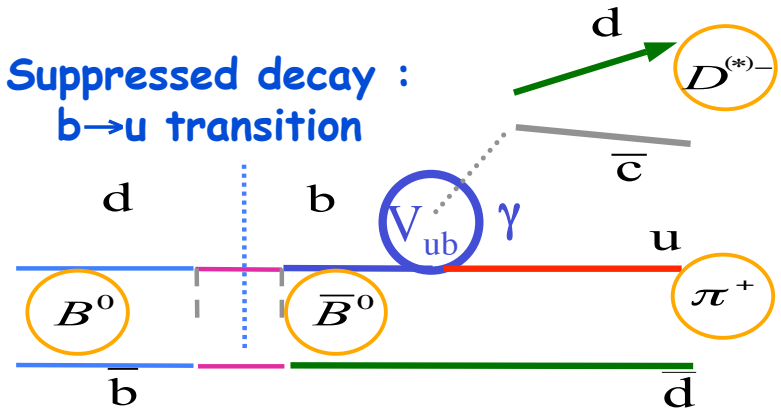
- **3σ direct CP violation**





$\sin(2\beta+\gamma)$ with $B^0 \to D^{(*)\pm}\pi^\pm/\rho^\pm$

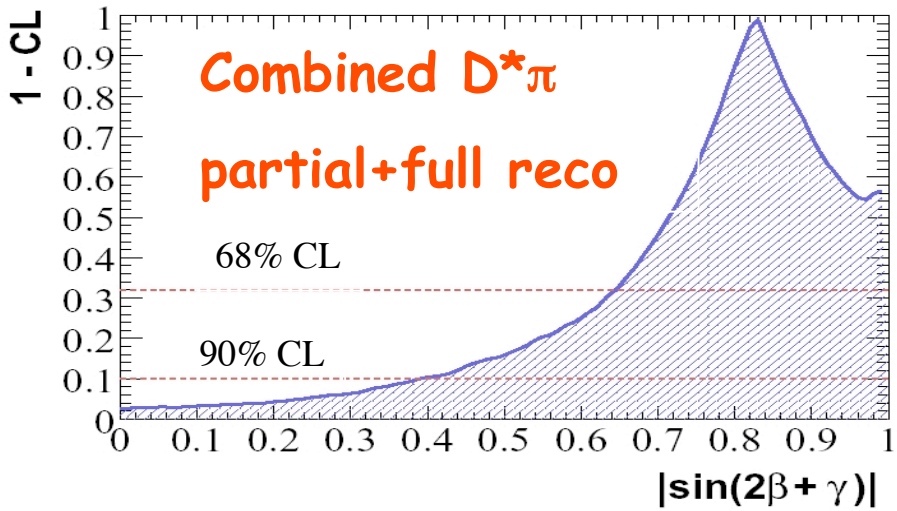




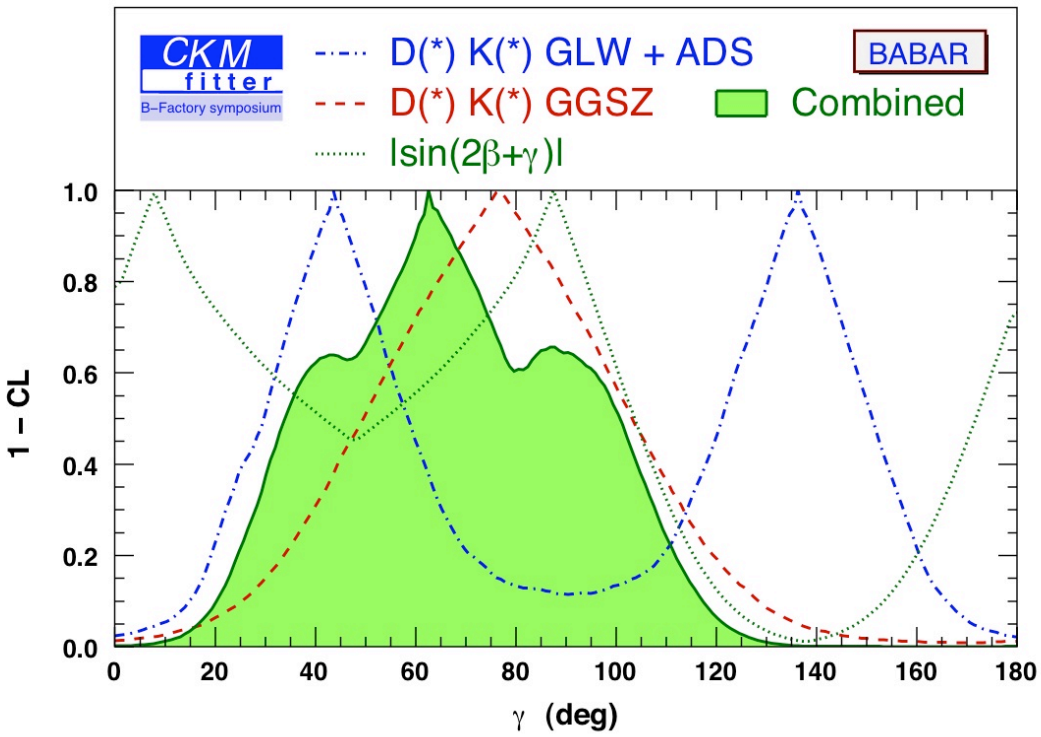
- CP violation from **interference** between 2 decays through $(B^0,\bar{B}^0)$ mixing.
- Time -dependant asymmetry to measure $\sin(2\beta+\gamma)$.
- Two complementary approaches :
  - **Full reconst.** of $D\rho$, $D\pi$ and $D^*\pi$.
  - **Partial reconst.** for $D^*\pi$ only.

$|\sin(2\beta+\gamma)|>0.64$ @68% CL

232M $B\bar{B}$ PRD71, 112003 (2005)
232M $B\bar{B}$ PRD73, 111101 (2006)



Summary on γ



$$\gamma(\text{indirect}) = \left(55.4^{\circ}{}^{+2.5^{\circ}}_{-2.2^{\circ}}\right) \cup \left(67.4^{\circ}{}^{+3.3^{\circ}}_{-5.6^{\circ}}\right)$$

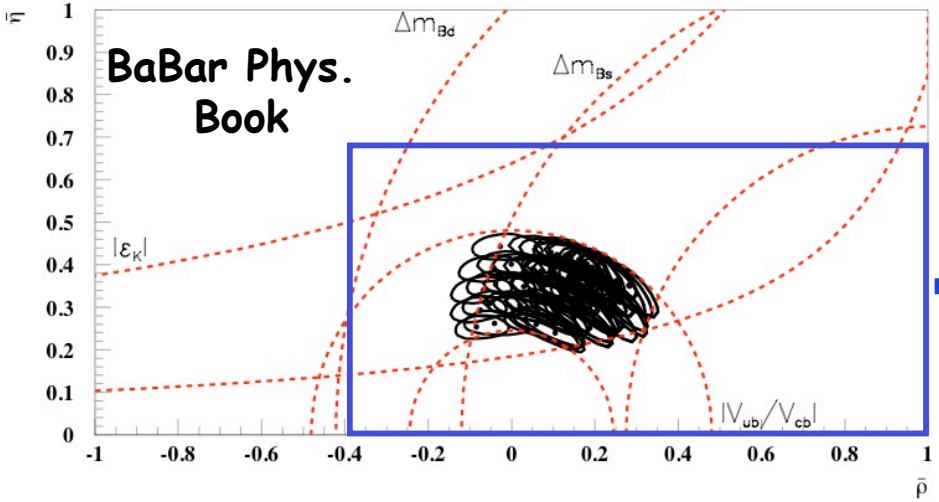
- Need to combine the various approaches (GWL, ADS, GGSZ…)
- The Dalitz method dominates the average and is consistent with CKM fits
- Internal consistency with other indirect CKM constraints
- Much better than what was predicted in the BaBar Physics Book (1998)

Summary

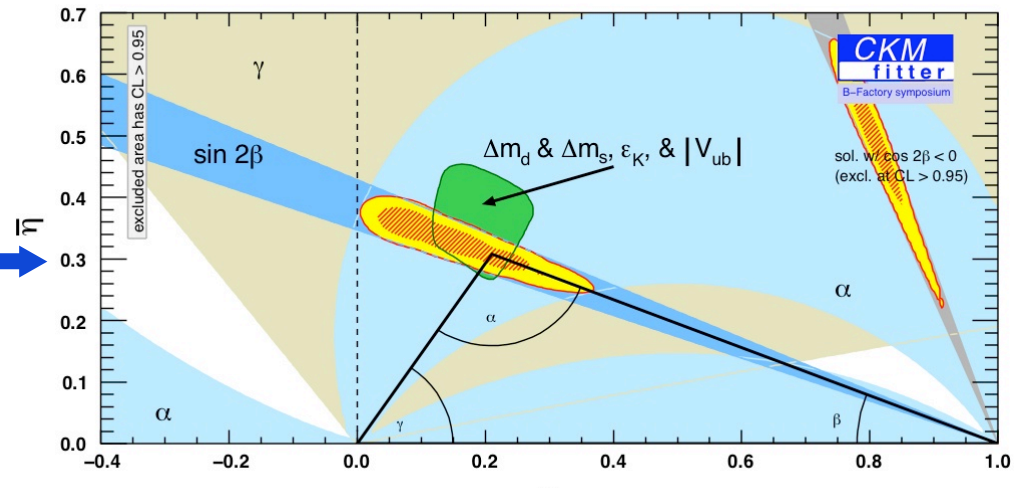
Conclusions

- Unitarity Triangle: Consistent results between the measurements of the angles (α, β and γ) and those of the UT sides (Δm_d, Δm_s, $|V_{ub}|$....).

Status in 1998



Angle constraints in 2008



- Impressive confirmation of SM in quark-flavor sector!!!
  - Errors on UT angles α,β,γ are still decreasing and are still limited by statistics!!!
  - More to come with future accelerators and projects