BABAR Results on CP Violation in B Decays

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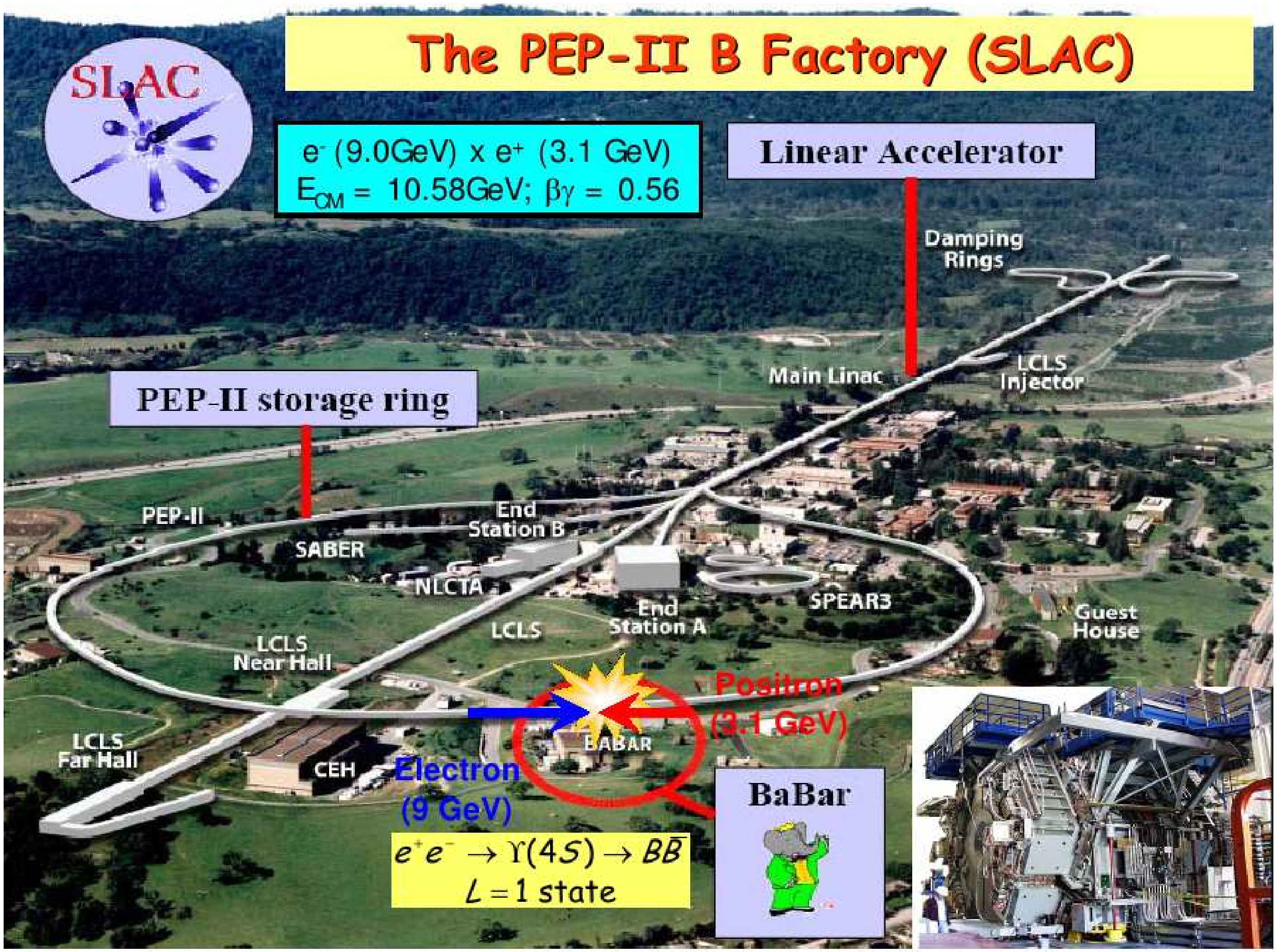
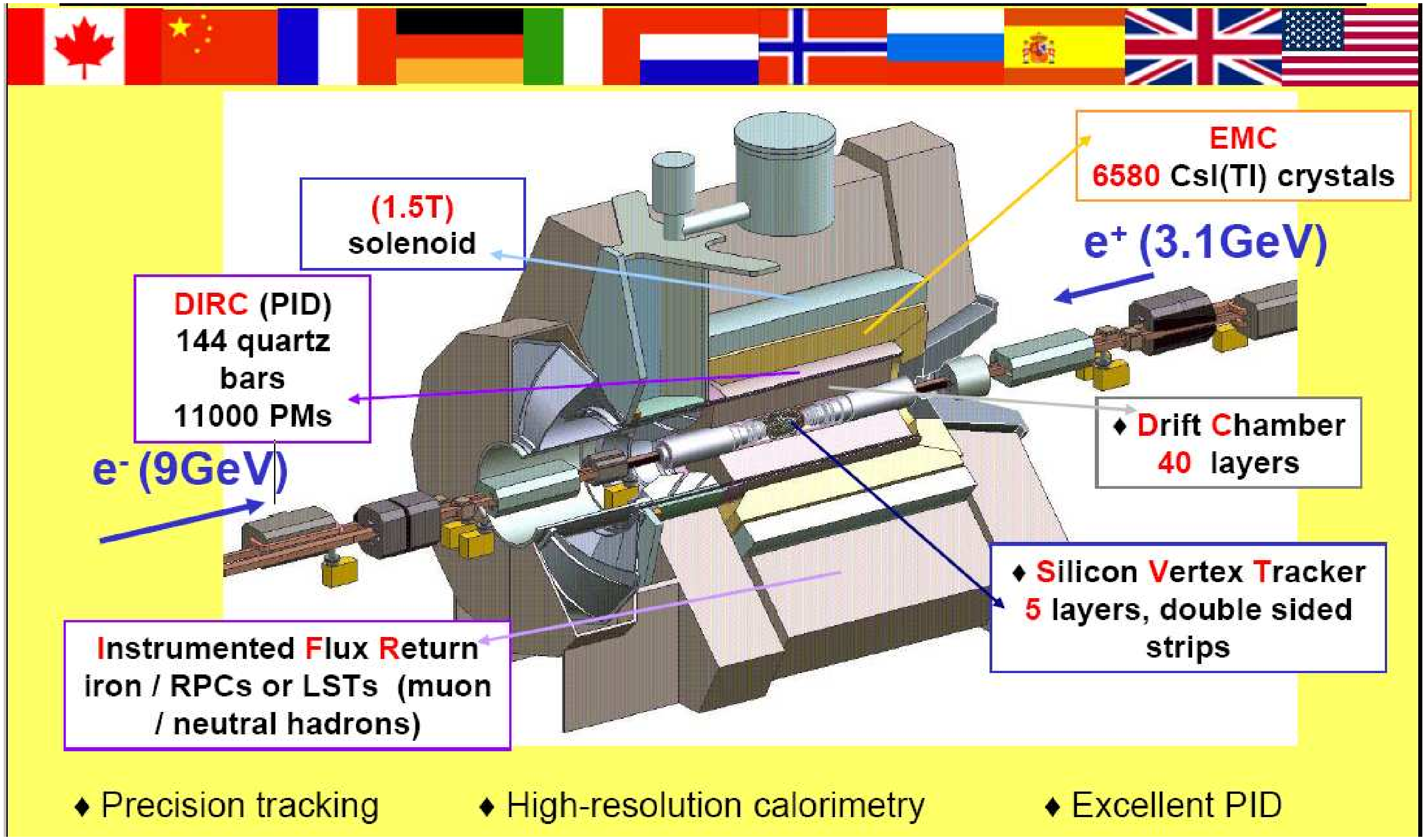
B Meson Factories

- BABAR at SLAC National Accelerator Laboratory, California, USA



- Another B-factory machine is at KEKB (Tsukuba) in Japan

BaBar Detector

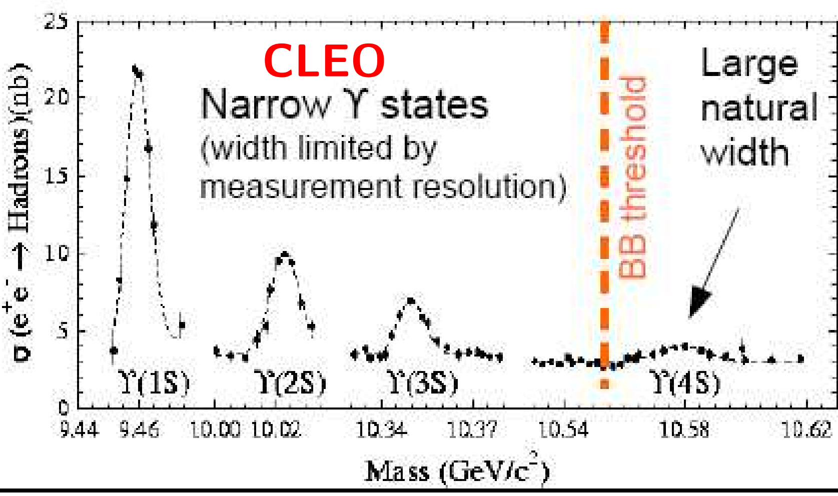


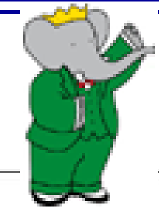
- Collides (9 GeV) $e^- \bowtie e^+$ (3.1 GeV) $\hookrightarrow \Upsilon(4S)$ with $E_{CM} = 10.58$ GeV
- Peak luminosity : $\sim 1.21 \times 10^{34}\ cm^{-2}s^{-1}$, $B^0\overline{B}^0$ production $\sim$ 12 Hz
- Boost $\beta\gamma = 0.56$ allows to measure B decay times

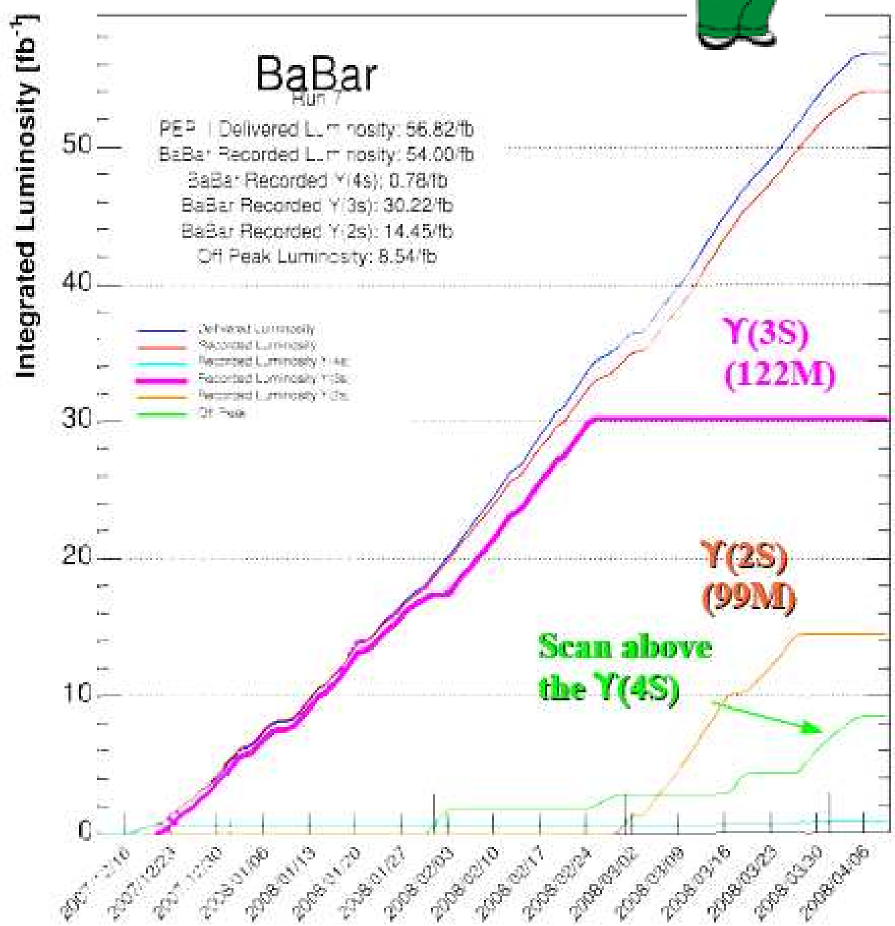
BABAR Data: $\Upsilon(nS)$

Final BABAR Data

- BaBar data sets:
  - 122×10^6 $\Upsilon(3S)$ decays
  - 99×10^6 $\Upsilon(2S)$ decays
  - "offpeak" samples of $1.4 fb^{-1}$ and $2.4 fb^{-1}$ collected ~30 MeV below the $\Upsilon(2S)$ and $\Upsilon(3S)$
  - $79 fb^{-1}$ "continuum background" samples of $\Upsilon(4S)$ with similar detector conditions







- Trigger requirements modified for narrow Υ data taking

CKM Matrix

☐ In SM, quark can change flavor by weak interactions:

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

Cabibbo-Kobayashi-Maskawa (CKM) matrix

[Weak eigenstates] = $[V_{CKM}]$ [quark mass eigenstates]

The CKM matrix contains complex numbers

- Wolfenstein's CKM matrix form:

$$V_{CKM} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

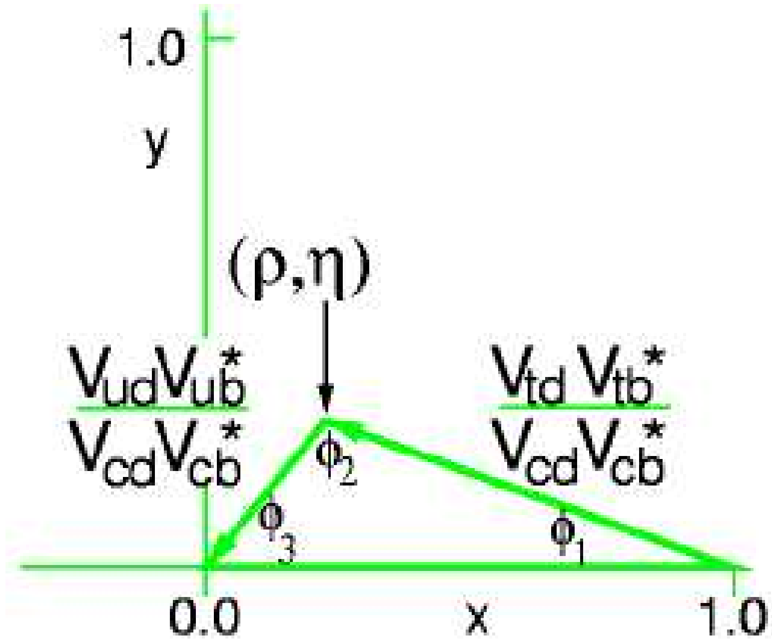
- $\lambda \sim 0.22$ (expansion parameter)
- A, ρ, and η can be measured in B decays

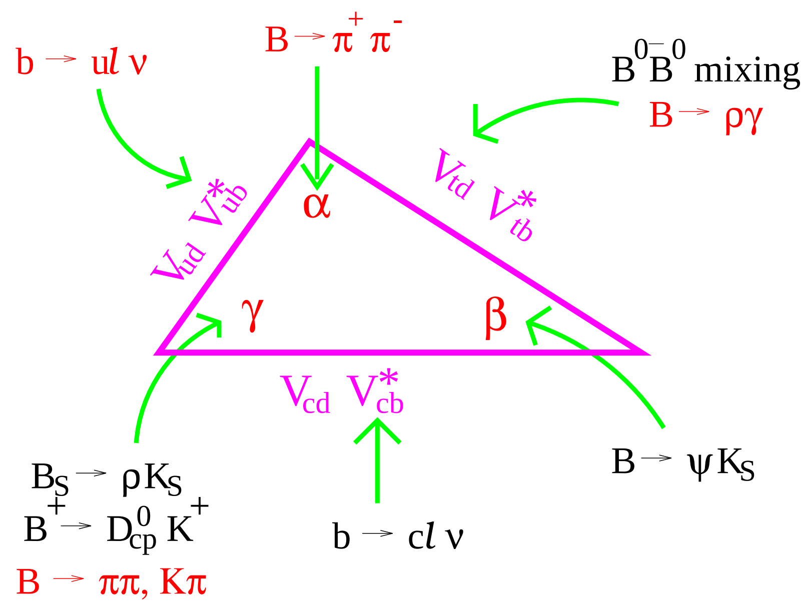
Unitarity Triangle (UT)

☐ By applying the Unitarity condition (scalar product of any two rows or columns):

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

☐ CKM matrix can be presented in the complex plane → Unitarity Triangle (UT)

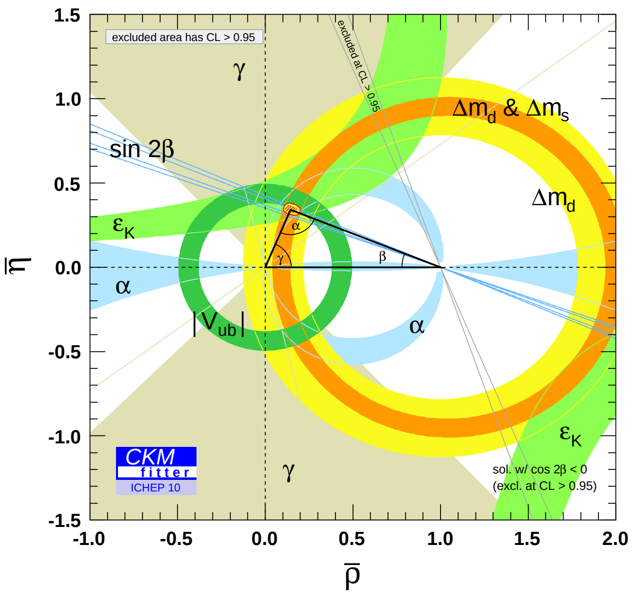


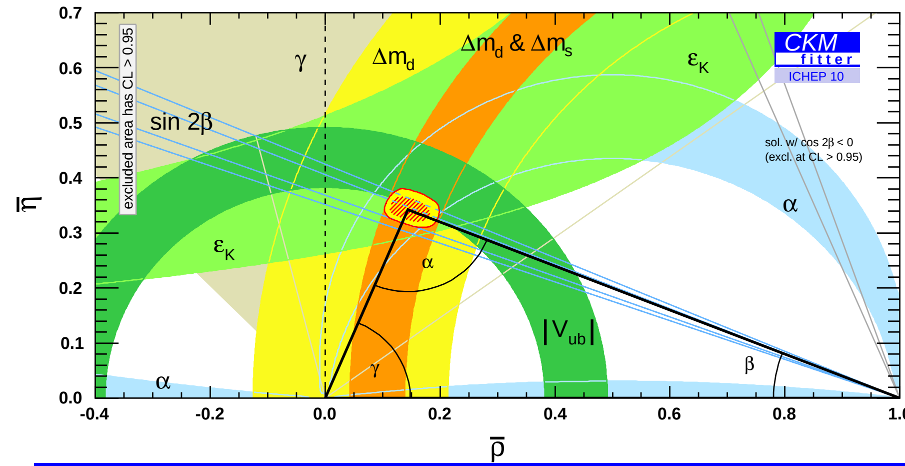


- It is very important to measure the CKM angles and its sides!
- We need to measure them precisely in order to search for New Physics

→ Deviation from the Standard Model will signal New Physics!

Status of UT Triangle





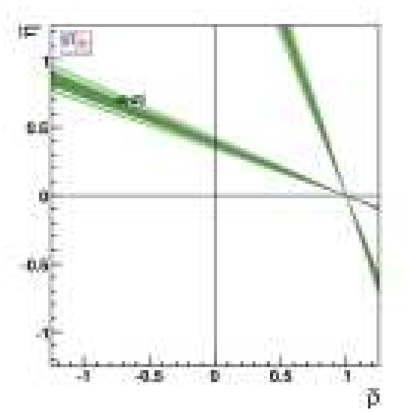
Constraints in the $\bar{\rho} - \bar{\eta}$ plane

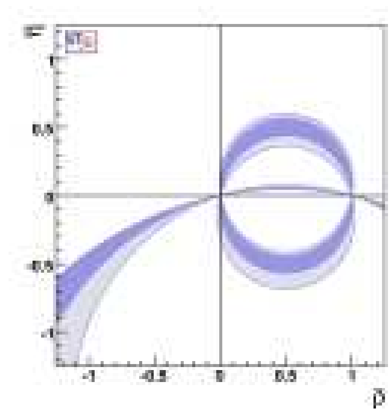
Zoomed constraints in the $\bar{\rho} - \bar{\eta}$ plane

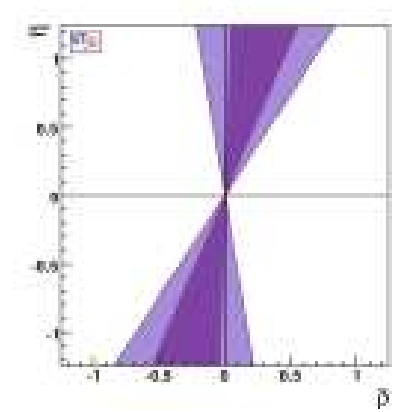
Precision $\beta \approx 1^o$

Precision $\alpha \approx 4^o$

Precision $\gamma \approx 14^o$

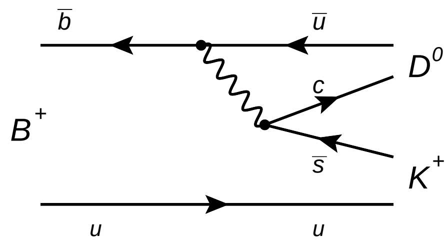


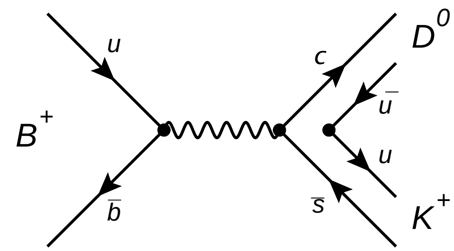




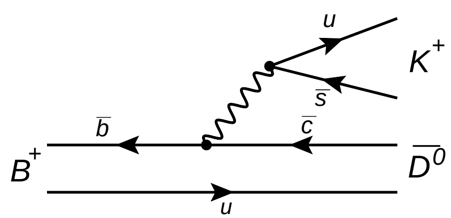
Measuring Angle γ

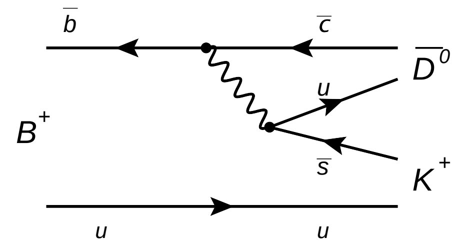
- Interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ tree amplitudes





$b \to c\bar{u}s$ **transition:** $B^+ \to D^0 K^+$





$b \to u\bar{c}s$ **transition:** $B^+ \to \bar{D}^0 K^+$

- **GLW:** Cabibbo-suppressed $D \to$ CP-eigenstates $(K^+K^-, \pi^+\pi^-)$

  Gronau, London, Wyler: PLB 253, 1991 & PLB 265, 1991

- **ADS:** $D \to$ Cabibbo-favored and doubly-Cabibbo-suppressed $(K^\pm\pi^\mp)$

  Atwood, Dunietz, Soni: PRL 78, 3257, 1997

- **GGSZ:** Cabibbo-favored $D \to$ self-conjugate $(K_s^0\pi^+\pi^-, K_s^0K^+K^-)$

  Giri, Grossman, Soffer, Zupan: PRD 68 054018, 2003 $\to$ time limited

GLW on $B^{\pm} \rightarrow DK^{\pm}$ PLB 253, 1991 & PLB 265, 1991

- In GLW method the D^0 mesons are reconstructed:
  - $CP+: D^0 \rightarrow K^+K^-, \pi^+\pi^-$
  - $CP-: D^0 \rightarrow K_s^0\pi^0, K_s^0\omega, K_s^0\phi$

  $\rightarrow D_{CP\pm} =$ CP eigenstates of D system

- Two direct CP-violating partial decay rate asymmetries:

$$A_{CP\pm} \equiv \frac{\Gamma(B^- \rightarrow D_{CP\pm}K^-) - \Gamma(B^+ \rightarrow D_{CP\pm}K^+)}{\Gamma(B^- \rightarrow D_{CP\pm}K^-) + \Gamma(B^+ \rightarrow D_{CP\pm}K^+)}$$

$\rightarrow \Gamma =$ partial decay width

- Two ratios of charged averaged partial rates:

$$R_{CP\pm} \equiv 2\frac{\Gamma(B^- \rightarrow D_{CP\pm}K^-) + \Gamma(B^+ \rightarrow D_{CP\pm}K^+)}{\Gamma(B^- \rightarrow D^0K^-) + \Gamma(B^+ \rightarrow \bar{D}^0K^+)}$$

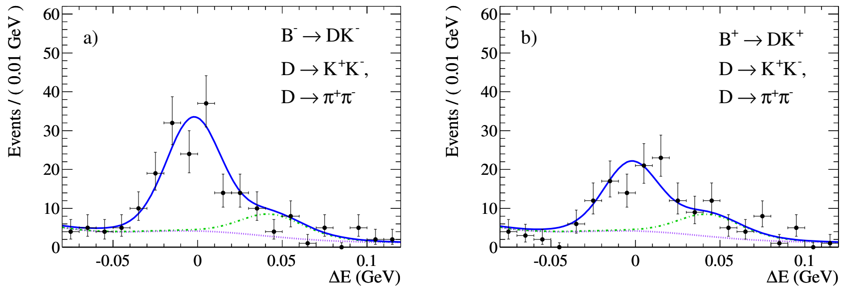
- Then γ can be extracted from the other two unknowns variables δ_B and r_B:

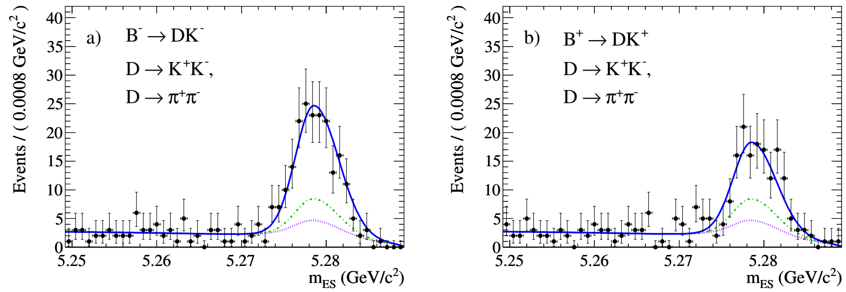
$$R_{CP\pm} = 1 + r_B^2 \pm 2r_B cos\delta_B cos\gamma \qquad A_{CP\pm} = \frac{\pm 2r_B sin\delta_B sin\gamma}{1 + r_B^2 \pm 2r_B cos\delta_B cos\gamma}$$

- δ_B = the difference of their strong phases
- r_B = the magnitude of the ratio of the amplitudes for each decay

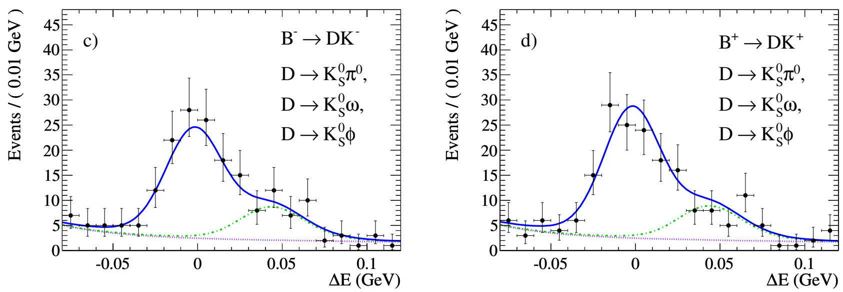
$$r_B \equiv \frac{|A(B^- \rightarrow \bar{D}^0K^-)|}{|A(B^- \rightarrow D^0K^-)|}$$

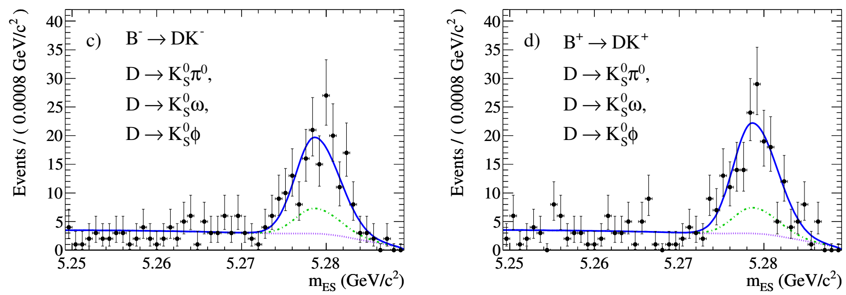
- ML fit to $\Delta E, m_{ES}$, and Fisher (event shape variable)





$CP+$: ΔE $CP+$: m_{ES}





$CP-$: ΔE $CP-$: m_{ES}

- GLW: Cabibbo-suppressed $D \to$ CP-eigenstates $(K^+K^-, \pi^+\pi^-)$

  Gronau, London, Wyler: PLB 253, 1991 & PLB 265, 1991

- Blue line: full PDF, Green: $B \to D\pi$, Purple: remaining backgrounds

- $B \to DK$ contribution: the region between blue and green

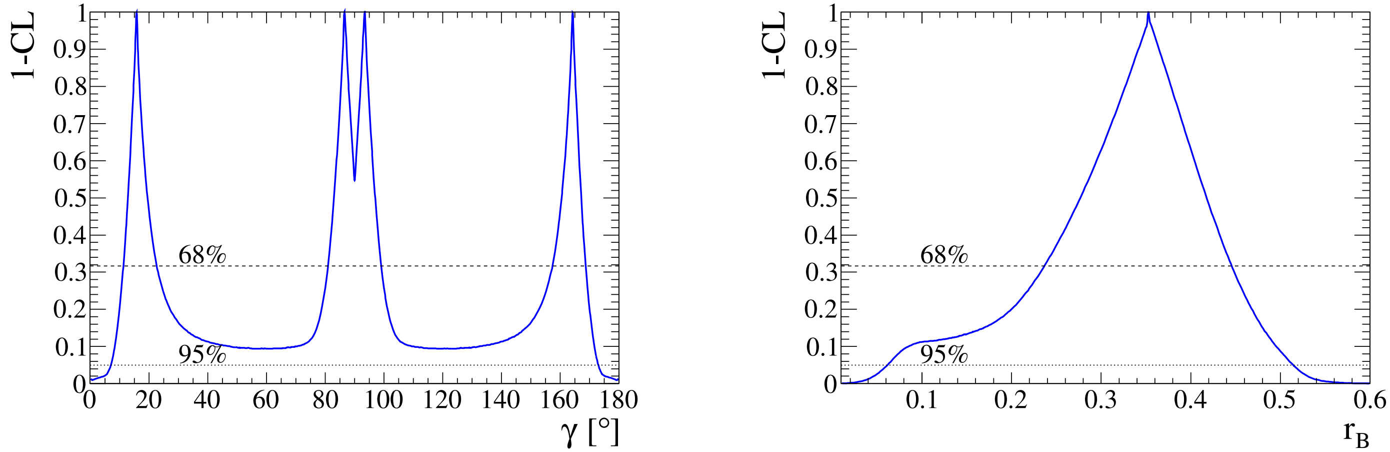
GLW BABAR Continue... PRD 82 072004, 2010

- Using BABAR Data: 425 fb^{-1} (467 M $B\overline{B}$)

$$A_{CP+} = 0.25 \pm 0.06 \pm 0.02 \qquad A_{CP-} = -0.09 \pm 0.07 \pm 0.02$$

$$R_{CP+} = 1.18 \pm 0.09 \pm 0.05 \qquad R_{CP-} = 1.07 \pm 0.08 \pm 0.04$$

- Direct CP-Violation on $B^{\pm} \rightarrow DK^{\pm}$: $A_{CP}+$ at 3.6σ from zero



- At 68% CL: angle γ mod 180^o belongs to one of the three intervals:

  $(11.3, 22.7^o)$, $(80.8^o, 99.2^o)$, $(157^o, 168.7^o)$

- At 68% CL: $0.24 < r_B < 0.45$

ADS on $B^{\pm} \to DK^{\pm}$ Theory: PRL 78, 3257, 1997

□ In ADS method (D. Atwood, I Dunietz, A Soni)

- $B^+ \to \bar{D}^0 K^+ \to \bar{D}^0 \to K^- \pi^+$ [doubly-Cabbibo-suppressed]

(interferes with $\Leftrightarrow$)

- $B^+ \to D^0 K^+ \to D^0 \to K^- \pi^+$ [Cabbibo-favored]

$\Longrightarrow$ Opposite-sign (OS) because two kaons have opposite charges

□ Define same-sign (SS) events:

- $B^+ \to \bar{D}^0 K^+ \to \bar{D}^0 \to K^+ \pi^-$ [Cabbibo-favored]

□ BABAR published 2 results where D^0 are reconstructed:

- $D^0 \to K^+ \pi^-$; Data: 467×10^6 $B\overline{B}$ $\to$ PRD 82 072006, 2010
- $D^0 \to K^+ \pi^- \pi^0$; Data: 474×10^6 $B\overline{B}$ $\to$ PRD 84 012002, 2011

ADS on $B^{\pm} \to DK^{\pm}$ Continue...

- Extract new set of variables:
  - $R^{+} = \frac{\Gamma(B^{+}\to[K^{-}\pi^{+}]K^{+})}{\Gamma(B^{+}\to[K^{+}\pi^{-}]K^{+})} \equiv \frac{opposite\ sign\ yield}{same\ sign\ yield}$ from B^{+}
  - $R^{-} = \frac{\Gamma(B^{-}\to[K^{+}\pi^{-}]K^{-})}{\Gamma(B^{-}\to[K^{-}\pi^{+}]K^{-})} \equiv \frac{opposite\ sign\ yield}{same\ sign\ yield}$ from B^{-}
- Neglecting D-mixing effects the ratios R^{+} and R^{-} can be written as

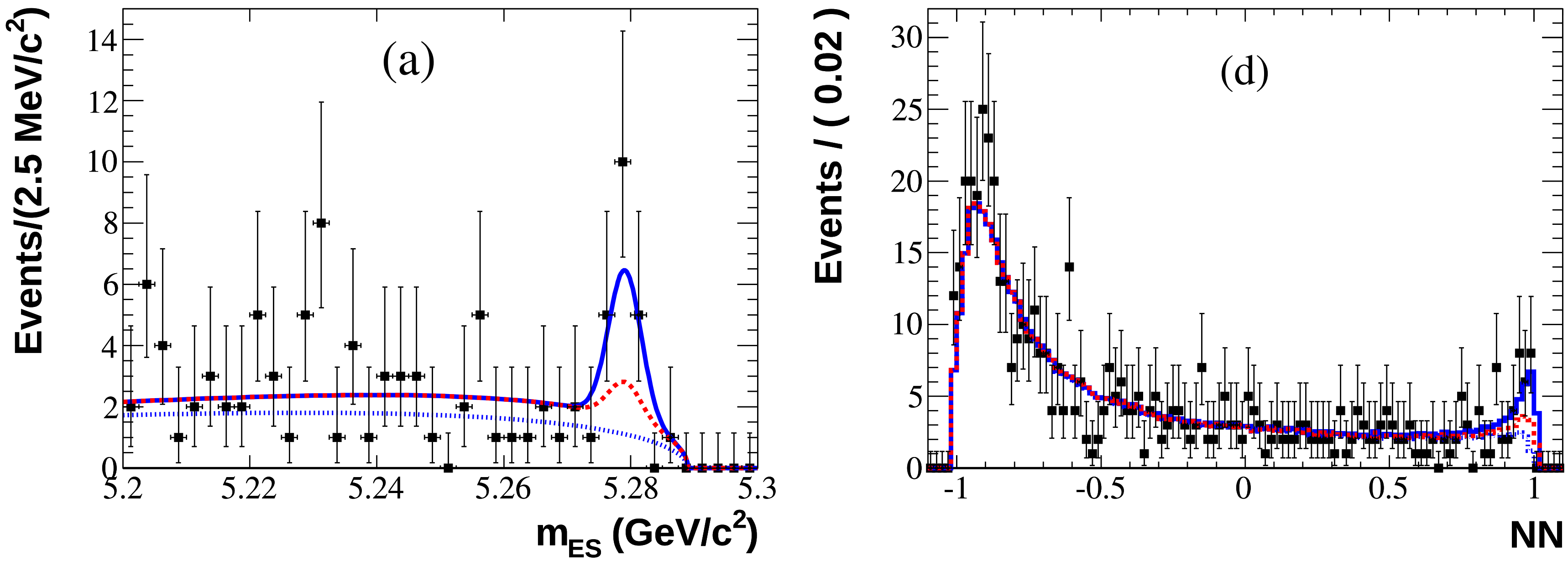
$$R^{+} = r_B^2 + r_D^2 + 2r_B r_D k_D\ cos(\gamma + \delta_B + \delta_D)$$

$$R^{-} = r_B^2 + r_D^2 + 2r_B r_D k_D\ cos(\gamma - \delta_B + \delta_D)$$

- where
  - $r_B \equiv \frac{|A(B^{+}\to D^{0}K^{+})|}{|A(B^{+}\to \bar{D}^{0}K^{+}))|} = 0.106 \pm 0.016$ $\quad r_D^2 = \frac{\Gamma(D^{0}\to K^{+}\pi-)}{\Gamma(D^{0}\to K^{-}\pi^{+})} = (2.2 \pm 0.1) \times 10^{-3}$
  - δ_B and $\delta_D = (47^{+14}_{-17})^{o}$ are CP conserving strong phase
  - γ is CP violating weak phase
  - k_D is the coherence factor between 0 to 1: $k_D = 0.84 \pm 0.07$
  - k_D and δ_D were measured from CLEOc

ADS Results on $D^0 \to K^+\pi^-$ PRD 82 072006, 2010

- Simultaneous fit to m_{ES} and NN (event shape and tagging variables)



m_{ES}: opposite-sign $B^+ \to D^0 K^+$

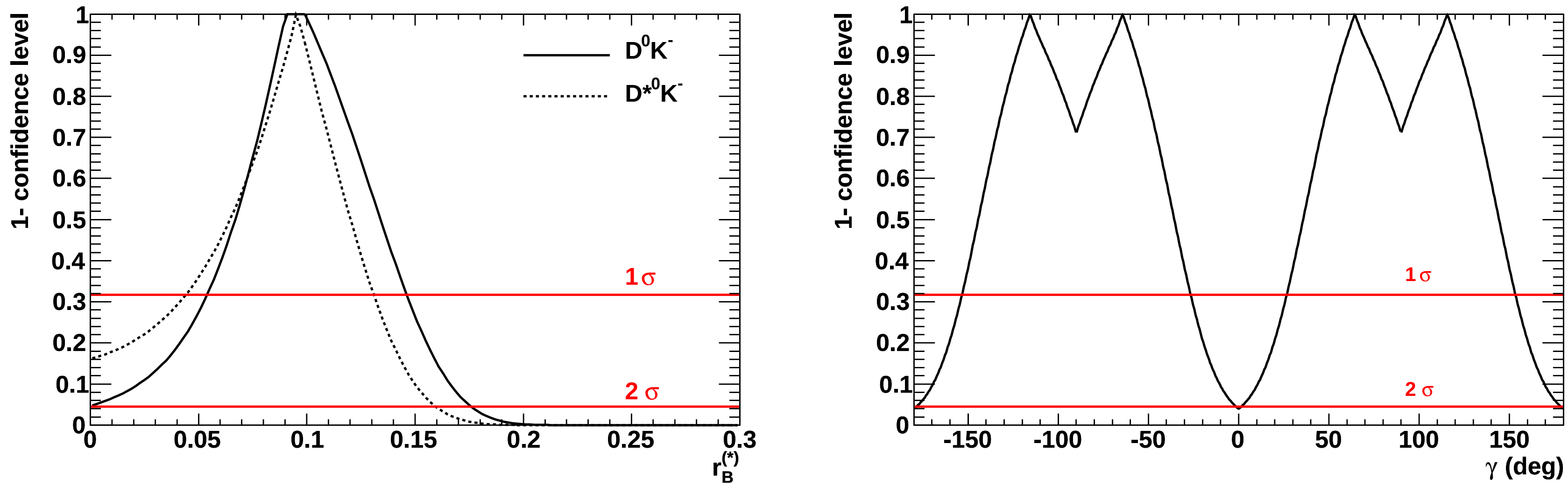
NN: opposite-sign $B^+ \to D^0 K^+$

- Solid-blue: Full PDF, Red: sum of all bkgs, Dotted-blue: $q\bar{q}$ background
- ADS $B^\pm \to DK^\pm$ results:

$$R^+ = (2.2 \pm 0.9 \pm 0.3) \times 10^{-2} \qquad R^- = (0.2 \pm 0.6 \pm 0.2) \times 10^{-2}$$

ADS BABAR Results Continue...

- This measurement allowed us to extract variables: r_B and γ



Constraints on $r_B^{(*)}$: $B^- \to D^{(*)}K^-$

C.L. curve as a function of γ

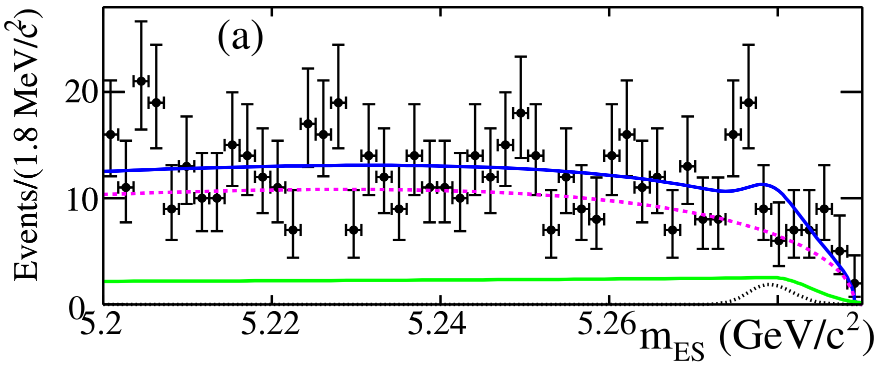
- For γ result: combining $B \to DK$ and D^*K

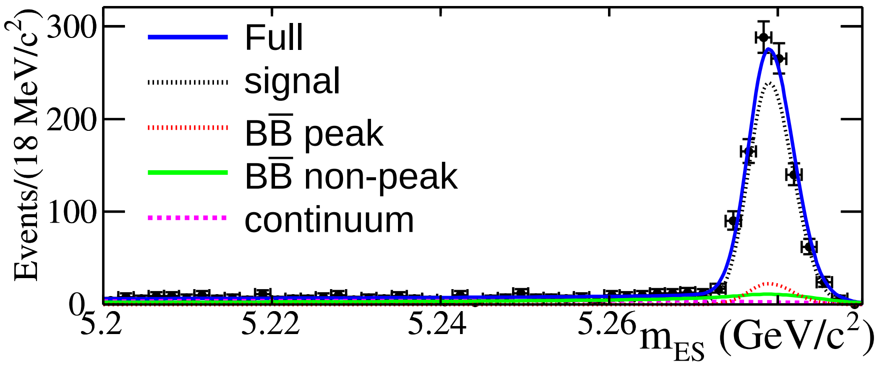
- The variables $r_B^{(*)}$ can be extracted:

$$r_B = (9.5^{+5.1}_{-4.1})\% \qquad r_B^* = (9.6^{+3.5}_{-5.1})\%$$

ADS Results on $D^0 \to K^+\pi^-\pi^0$ PRD 84 012002, 2011 (NEW)

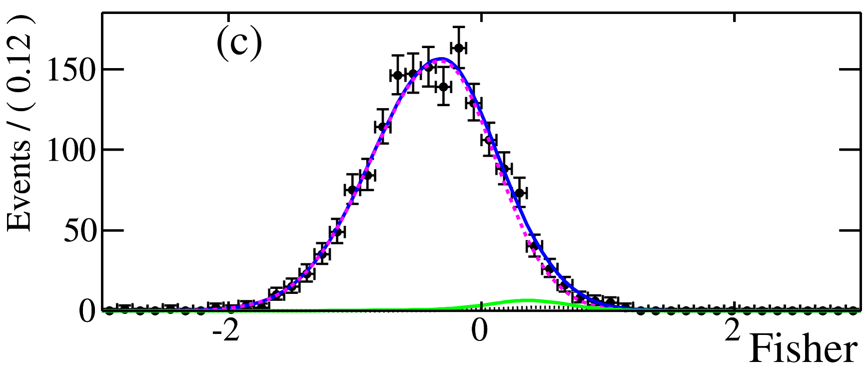
☐ **Simultaneous fit to m_{ES} and Fisher: OS ≈ 20 events; SS ≈ 2000 events**

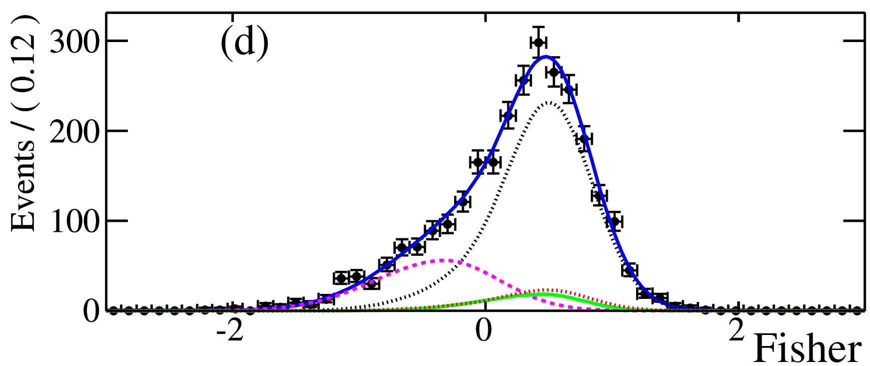




m_{ES}: opposite-sign with F $>$ 0.5

m_{ES}: same-sign with F $>$ 0.5



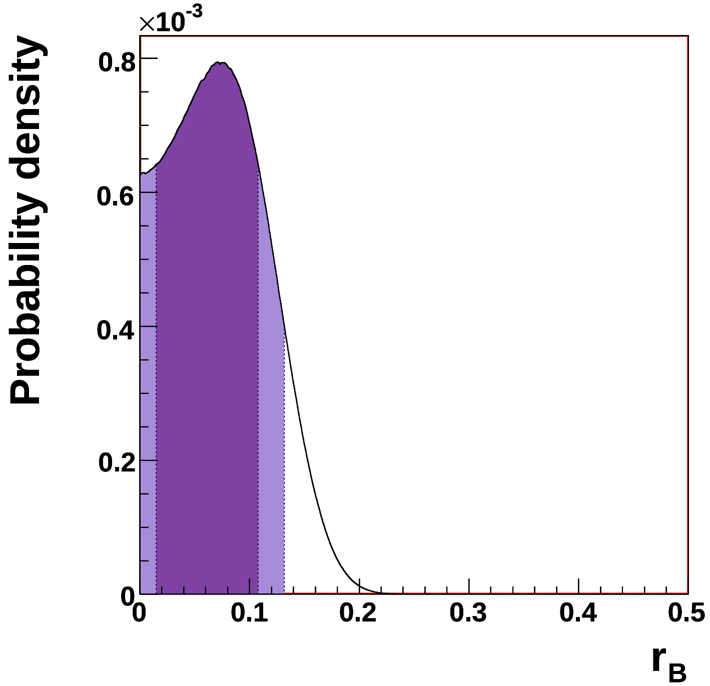


Fisher: OS $m_{ES} > 2.27$ GeV$/c^2$

Fisher: SS $m_{ES} > 2.27$ GeV$/c^2$

ADS Results on $D^0 \to K^+\pi^-\pi^0$ PRD 84 012002, 2011 (NEW)

- ADS results on r_B:



Bayesian probability density function for r_B

Dark: $0.01 < r_B < 0.11$ at 68% probability

Light: $r_B < 0.13$ at 90% probability

$\rightarrow$ Subject to small r_B, this measurement has less precision for γ result

- New results on R^+ and R^- (statistical limited):

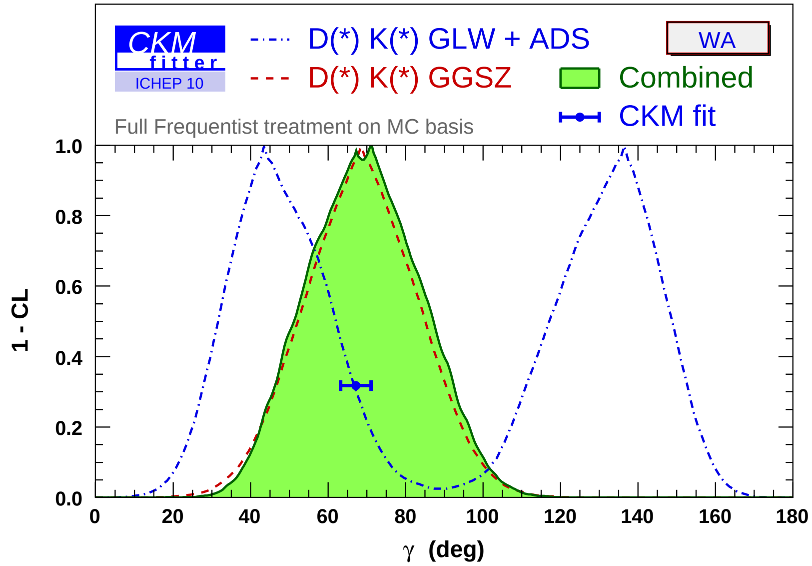
$$R^+ = (5^{+12+1}_{-10-4}) \times 10^{-3} \qquad R^- = (12^{+12+2}_{-10-4}) \times 10^{-3}$$

- At 90% probability limit:

$$R^+ < 23 \times 10^{-3} \qquad R^- < 29 \times 10^{-3}$$

Summary

- BABAR results provide increased constraints on CP Violation in B



$$\gamma = (71^{+21}_{-25})^o$$

CKMfitter Group, ICHEP 2010

◇ New results from BABAR on ADS

$D^0 \rightarrow K^+\pi^-\pi^0$, PRD 84 012002, 2011

◇ BABAR results on ADS

$D^0 \rightarrow K^+\pi^-$, PRD 82 072006, 2010

◇ BABAR results on GLW Model PRD 82 072004, 2010

- BABAR also contributes significantly on R^+, R^-, and r_B