



# CP Violation in $B$ Decays at BABAR



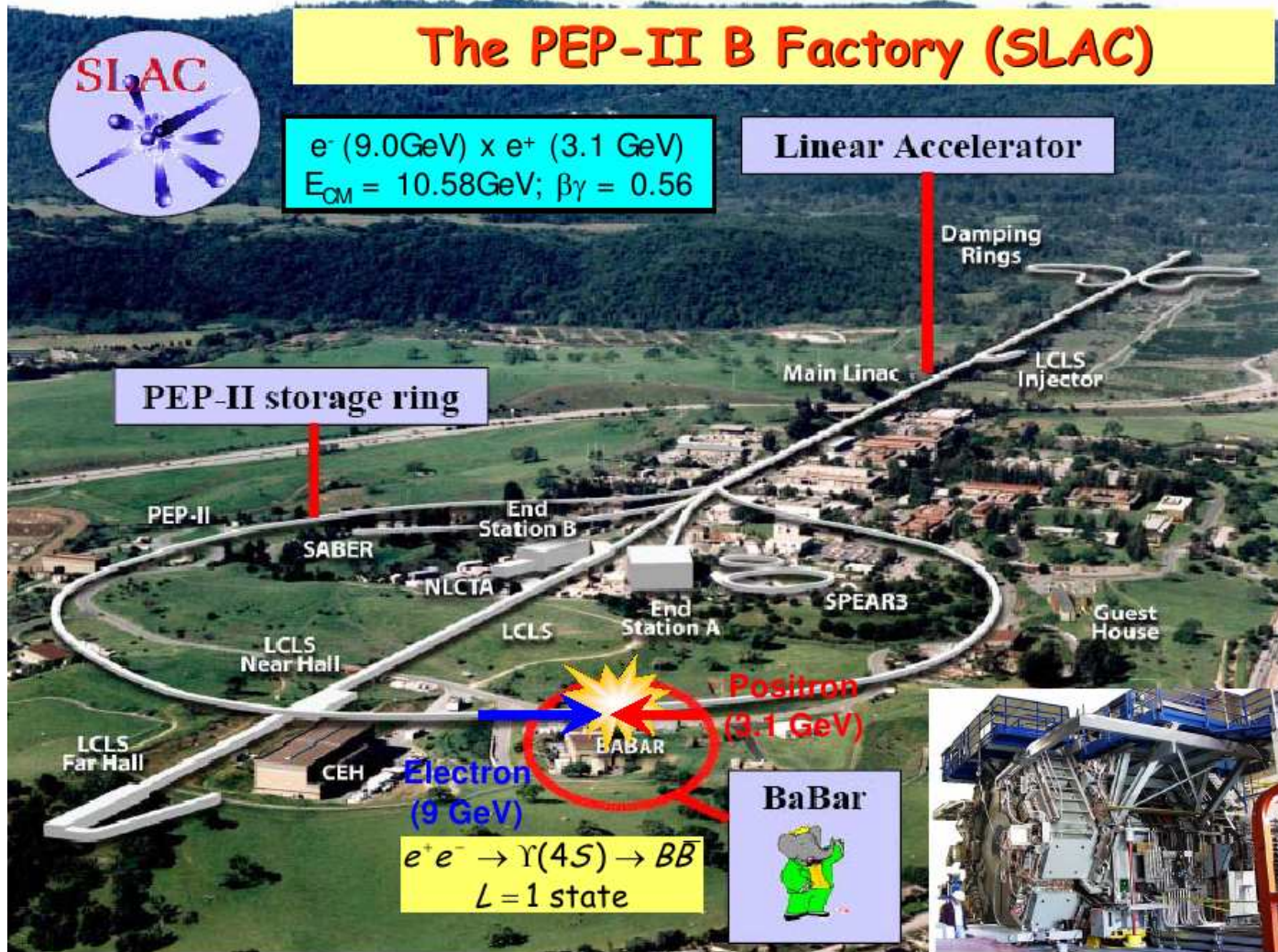
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University of South Alabama

**October 19-22, 2011**  
SESAPS-Virginia Tech, Roanoke, Virginia



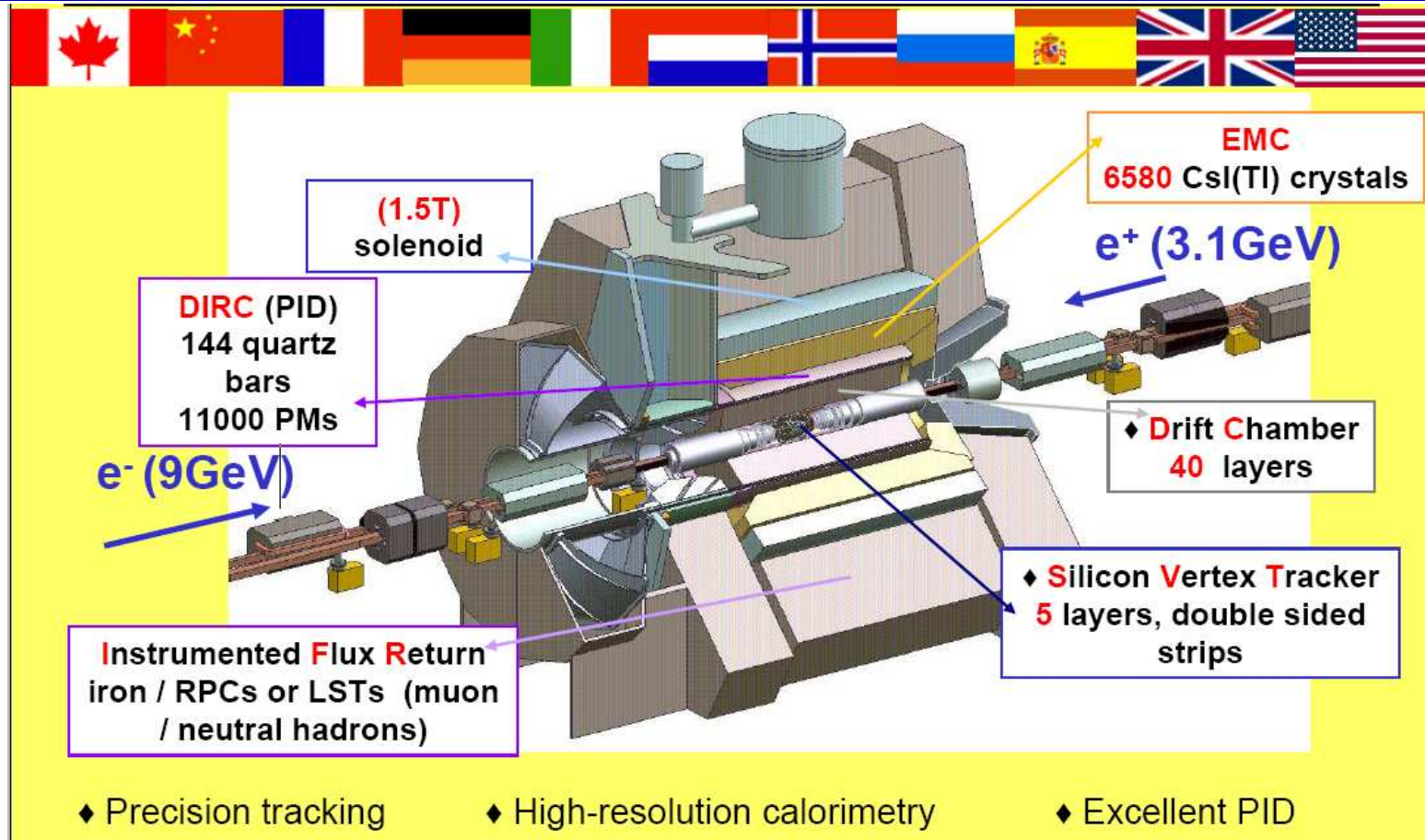
# B Meson Factories

- BABAR at SLAC National Accelerator Laboratory, California, USA



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

# BABAR Detector



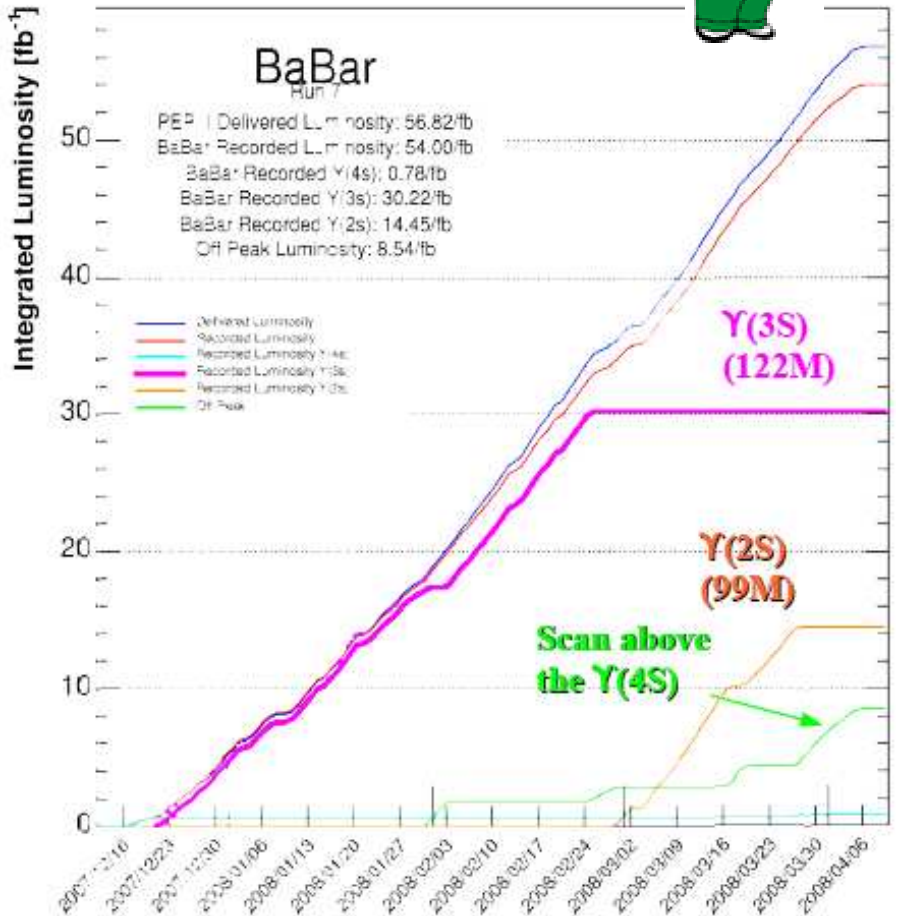
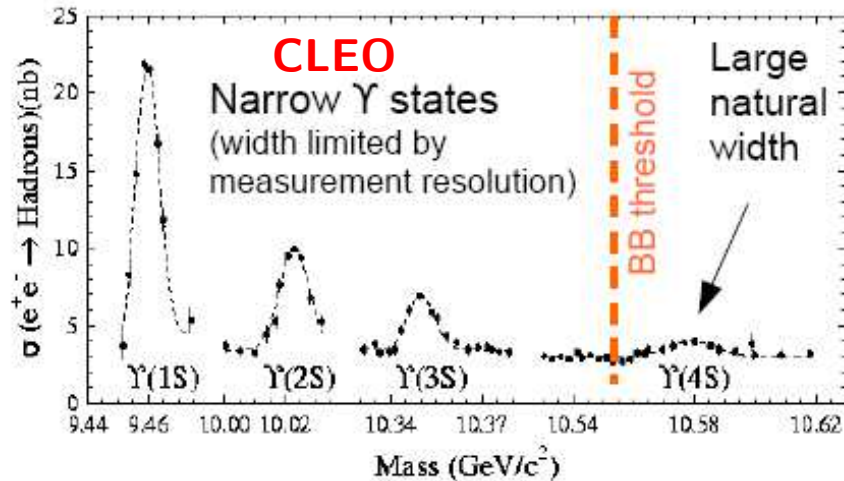
- Collides (9 GeV)  $e^- \times e^+$  (3.1 GeV)  $\hookrightarrow \Upsilon(4S)$  with  $E_{CM} = 10.58$  GeV
- Peak luminosity :  $\sim 1.21 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ,  $B^0 \bar{B}^0$  production  $\sim 12$  Hz
- Boost  $\beta\gamma = 0.56$  allows to measure  $B$  decay times

# BABAR Data: $\Upsilon(nS)$

## Final BABAR Data



- BaBar data sets:
  - 122 x 10<sup>6</sup>  $\Upsilon(3S)$  decays
  - 99 x 10<sup>6</sup>  $\Upsilon(2S)$  decays
  - “offpeak” samples of 1.4fb<sup>-1</sup> and 2.4fb<sup>-1</sup> collected ~30 MeV below the  $\Upsilon(2S)$  and  $\Upsilon(3S)$
  - 79 fb<sup>-1</sup> “continuum background” samples of  $\Upsilon(4S)$  with similar detector conditions



- Trigger requirements modified for narrow  $\Upsilon$  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

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

The CKM matrix contains complex numbers

- Wolfenstein's CKM matrix form:

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

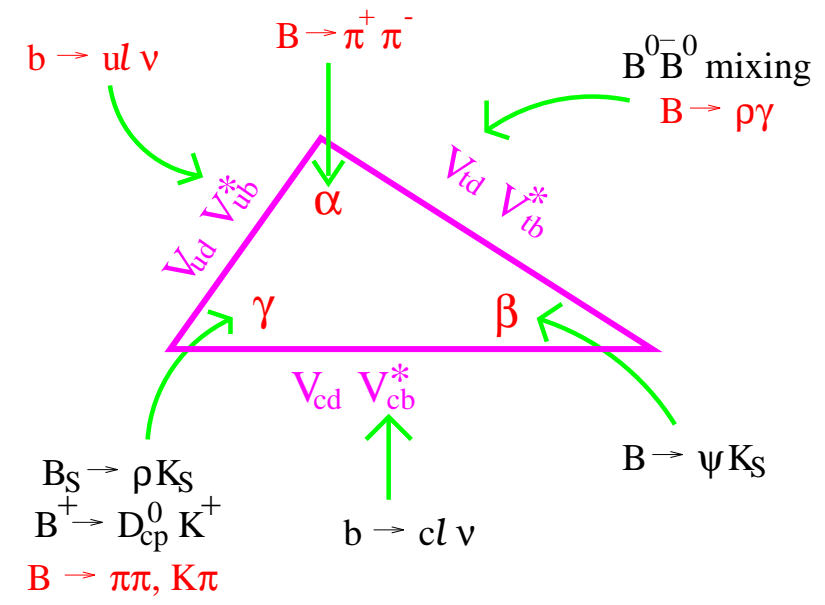
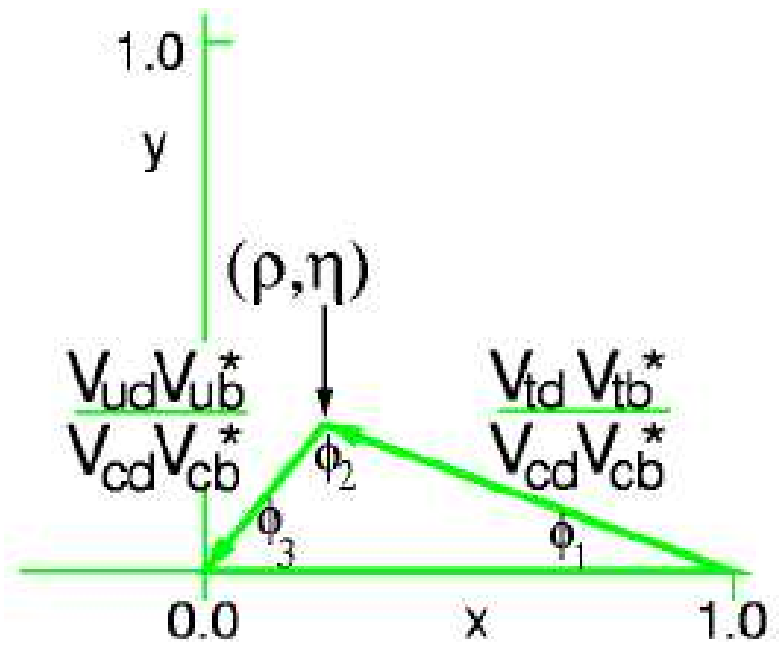
- $\lambda \sim 0.22$  (expansion parameter)
- $A$ ,  $\rho$ , and  $\eta$  can be measured in  $B$  decays

# Unitarity Triangle (UT)

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

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

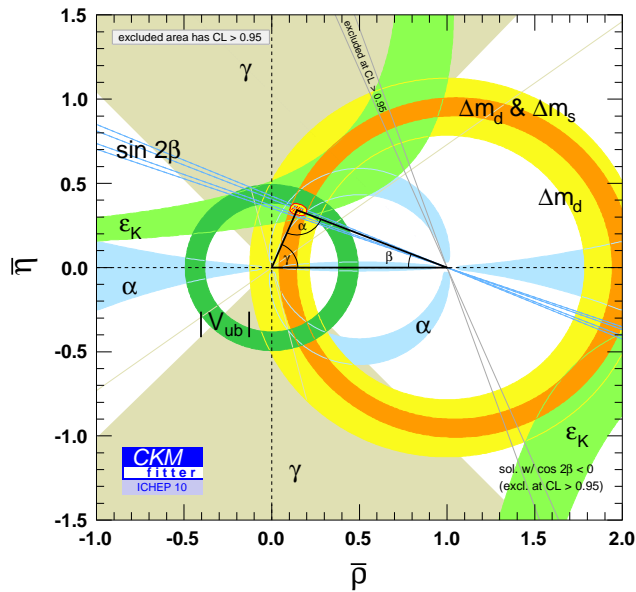
- CKM matrix can be presented in the complex plane → Unitarity Triangle (UT)



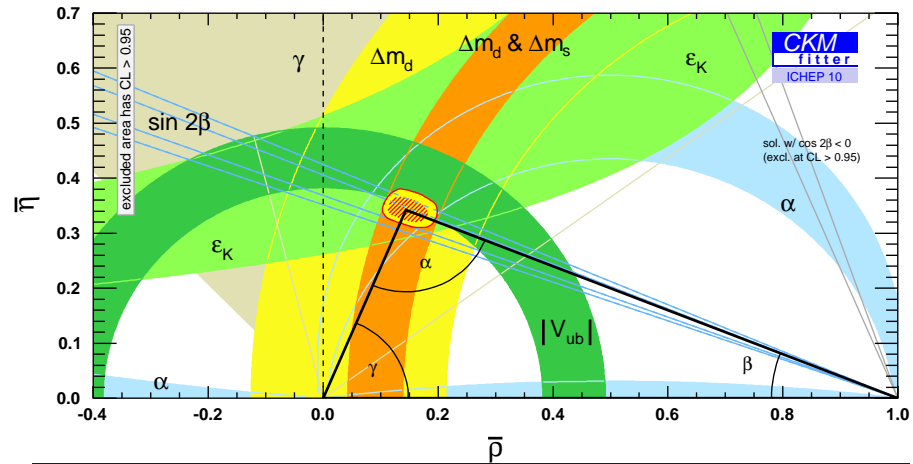
- It is very important to measure the CKM angles and its sides!
- We need to measure them precisely in order to search for New Physics

→ Deviation from the Standard Model will signal New Physics!

# Status of UT Triangle

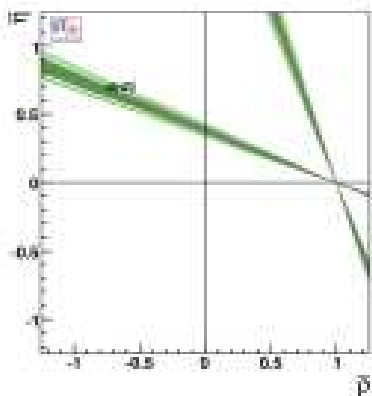


Constraints in the  $\bar{\rho} - \bar{\eta}$  plane

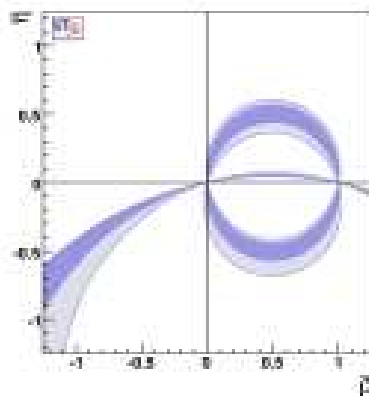


Zoomed constraints in the  $\bar{\rho} - \bar{\eta}$  plane

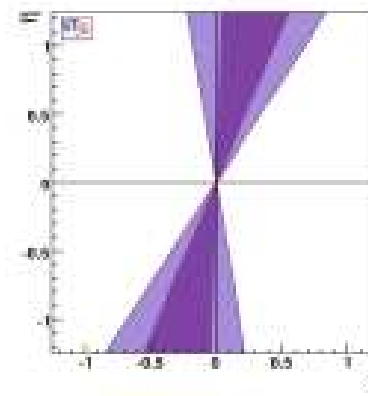
Precision  $\beta \approx 1^\circ$



Precision  $\alpha \approx 4^\circ$

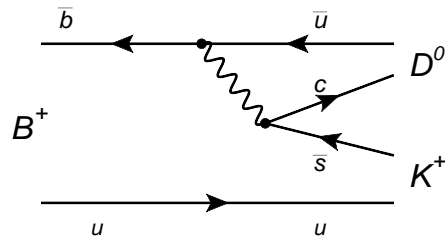


Precision  $\gamma \approx 14^\circ$

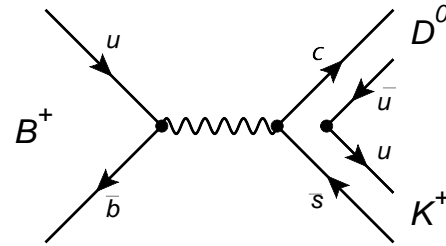


# Measuring Angle $\gamma$

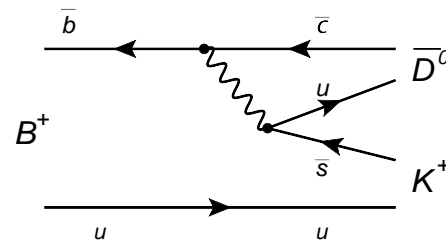
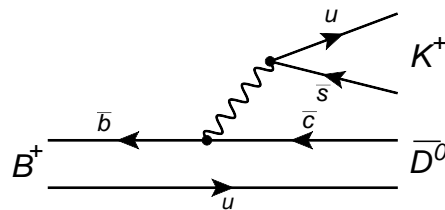
- Interference between  $b \rightarrow c\bar{u}s$  and  $b \rightarrow u\bar{c}s$  tree amplitudes



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



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



- **GLW:** Cabibbo-suppressed  $D \rightarrow$  CP-eigenstates ( $K^+ K^-, \pi^+ \pi^-$ )  
Gronau, London, Wyler: PLB 253, 1991 & PLB 265, 1991
- **ADS:**  $D \rightarrow$  Cabibbo-favored and doubly-Cabibbo-suppressed ( $K^\pm \pi^\mp$ )  
Atwood, Dunietz, Soni: PRL 78, 3257, 1997
- **GGSZ:** Cabibbo-favored  $D \rightarrow$  self-conjugate ( $K_s^0 \pi^+ \pi^-, K_s^0 K^+ K^-$ )  
Giri, Grossman, Soffer, Zupan: PRD 68 054018, 2003  $\rightarrow$  time limited



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

□ In GLW method the  $D^0$  mesons are reconstructed:

- $CP+$  :  $D^0 \rightarrow K^+K^-, \pi^+\pi^- \rightarrow D_{CP\pm} = \text{CP eigenstates of } D \text{ system}$
- $CP-$  :  $D^0 \rightarrow K_s^0\pi^0, K_s^0\omega, K_s^0\phi$

□ Two direct CP-violating partial decay rate asymmetries:

$$A_{CP\pm} \equiv \frac{\Gamma(B^- \rightarrow D_{CP\pm} K^-) - \Gamma(B^+ \rightarrow D_{CP\pm} K^+)}{\Gamma(B^- \rightarrow D_{CP\pm} K^-) + \Gamma(B^+ \rightarrow D_{CP\pm} K^+)} \rightarrow \Gamma = \text{partial decay width}$$

□ Two ratios of charged averaged partial rates:

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

□ Then  $\gamma$  can be extracted from the other two unknowns variables  $\delta_B$  and  $r_B$ :

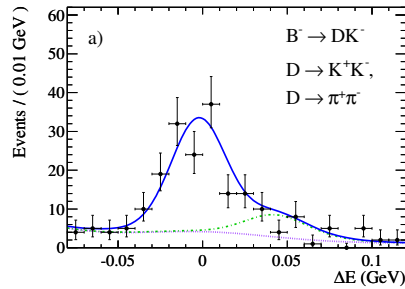
$$R_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\gamma \quad A_{CP\pm} = \frac{\pm 2r_B \sin\delta_B \sin\gamma}{1 + r_B^2 \pm 2r_B \cos\delta_B \cos\gamma}$$

□  $\delta_B$  = the difference of their strong phases

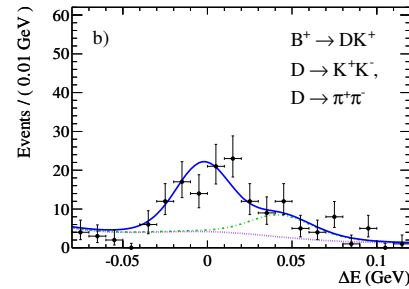
□  $r_B$  = the magnitude of the ratio of the amplitudes for each decay

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

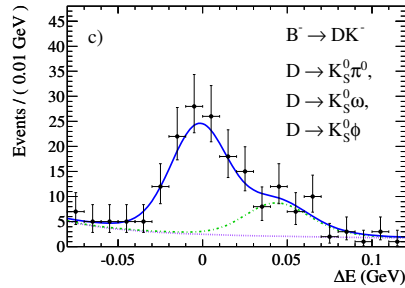
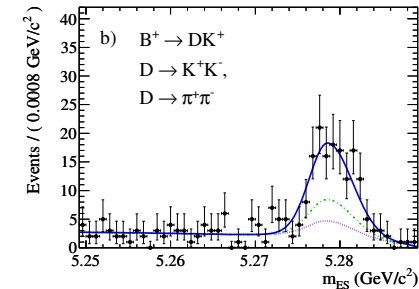
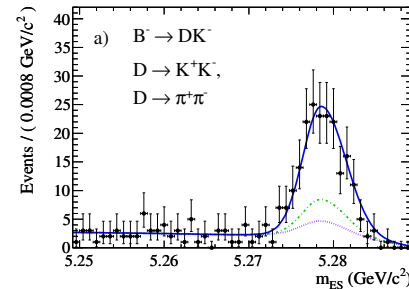
□ ML fit to  $\Delta E$ ,  $m_{ES}$ , and Fisher (event shape variable)



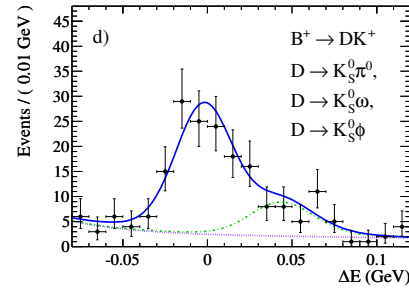
**CP+ :  $\Delta E$**



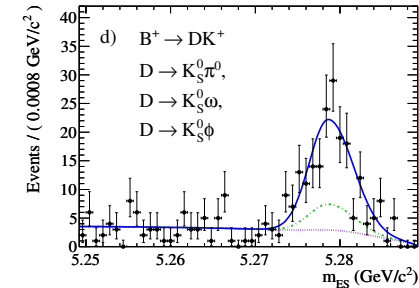
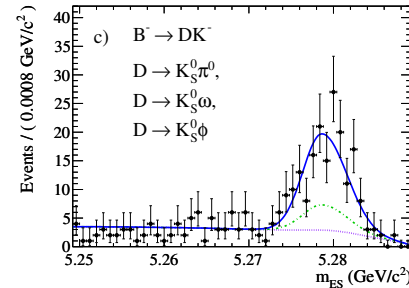
**CP+ :  $m_{ES}$**



**CP- :  $\Delta E$**



**CP- :  $m_{ES}$**



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

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

□ Blue line: full PDF, Green:  $B \rightarrow D\pi$ , Purple: remaining backgrounds

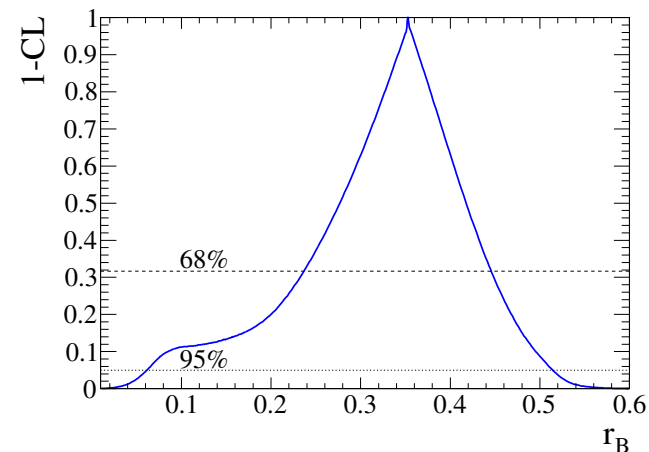
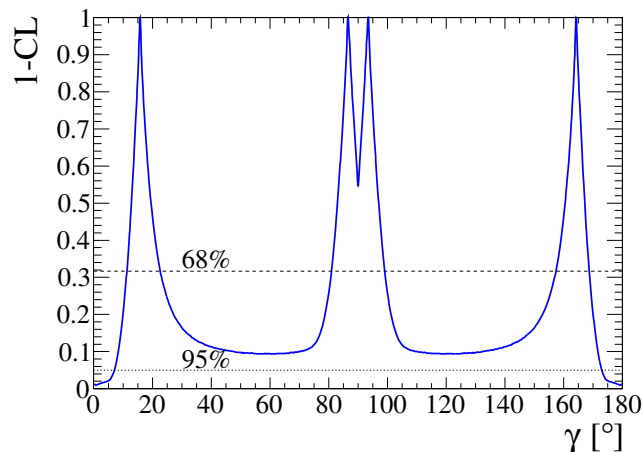
□  $B \rightarrow DK$  contribution: the region between blue and green

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

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

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

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



- At 68% CL: angle  $\gamma \text{ mod } 180^\circ$  belongs to one of the three intervals:  
 $(11.3^\circ, 22.7^\circ)$ ,  $(80.8^\circ, 99.2^\circ)$ ,  $(157^\circ, 168.7^\circ)$

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

## ADS on $B^\pm \rightarrow DK^\pm$ Theory: PRL 78, 3257, 1997

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

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

(interferes with  $\Leftrightarrow$ )

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

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

□ Define same-sign (SS) events:

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

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

- $D^0 \rightarrow K^+ \pi^-$ ; Data:  $467 \times 10^6 B\bar{B} \rightarrow$  PRD 82 072006, 2010

- $D^0 \rightarrow K^+ \pi^- \pi^0$ ; Data:  $474 \times 10^6 B\bar{B} \rightarrow$  PRD 84 012002, 2011

## ADS on $B^\pm \rightarrow DK^\pm$ Continue...

### □ Extract new set of variables:

- $R^+ = \frac{\Gamma(B^+ \rightarrow [K^- \pi^+] K^+)}{\Gamma(B^+ \rightarrow [K^+ \pi^-] K^+)} \equiv \frac{\text{opposite sign yield}}{\text{same sign yield}}$  from  $B^+$
- $R^- = \frac{\Gamma(B^- \rightarrow [K^+ \pi^-] K^-)}{\Gamma(B^- \rightarrow [K^- \pi^+] K^-)} \equiv \frac{\text{opposite sign yield}}{\text{same sign yield}}$  from  $B^-$

### □ Neglecting D-mixing effects the ratios $R^+$ and $R^-$ can be written as

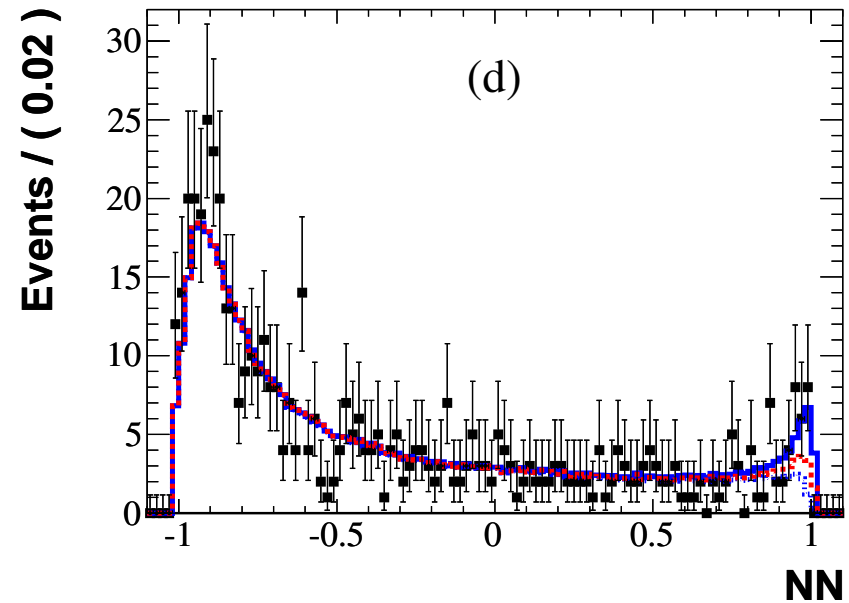
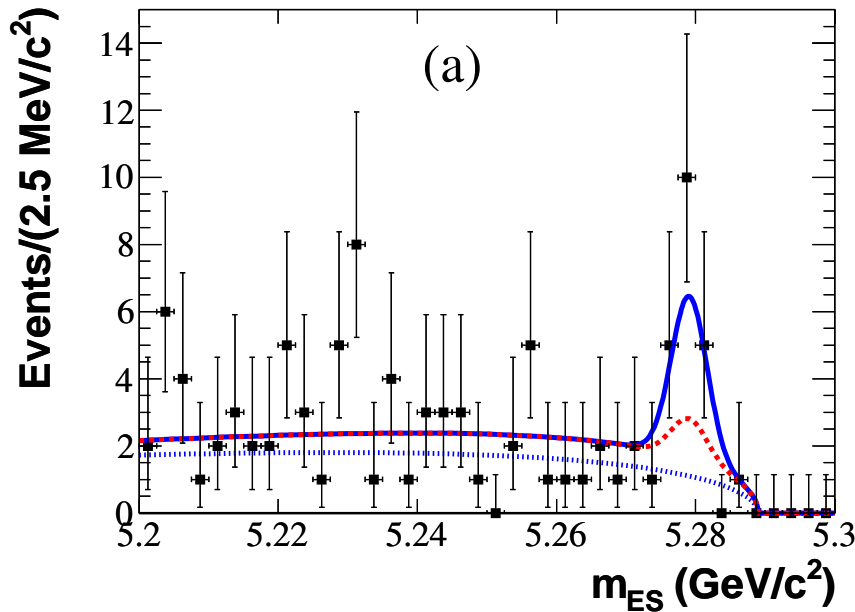
$$R^+ = r_B^2 + r_D^2 + 2r_B r_D k_D \cos(\gamma + \delta_B + \delta_D)$$

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

### □ where

- $r_B \equiv \frac{|A(B^+ \rightarrow D^0 K^+)|}{|A(B^+ \rightarrow D^0 K^+)|} = 0.106 \pm 0.016$       $r_D^2 = \frac{\Gamma(D^0 \rightarrow K^+ \pi^-)}{\Gamma(D^0 \rightarrow K^- \pi^+)} = (2.2 \pm 0.1) \times 10^{-3}$
- $\delta_B$  and  $\delta_D = (47_{-17}^{+14})^\circ$  are CP conserving strong phase
- $\gamma$  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  $\delta_D$  were measured from CLEOc

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



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

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

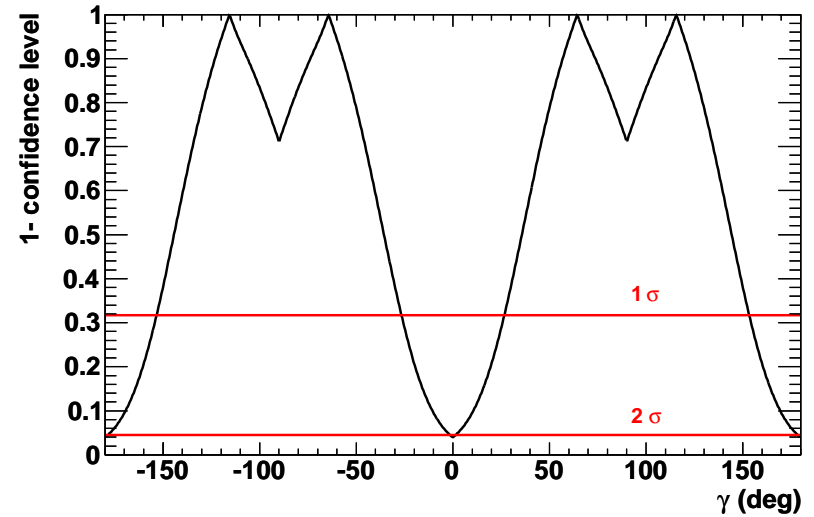
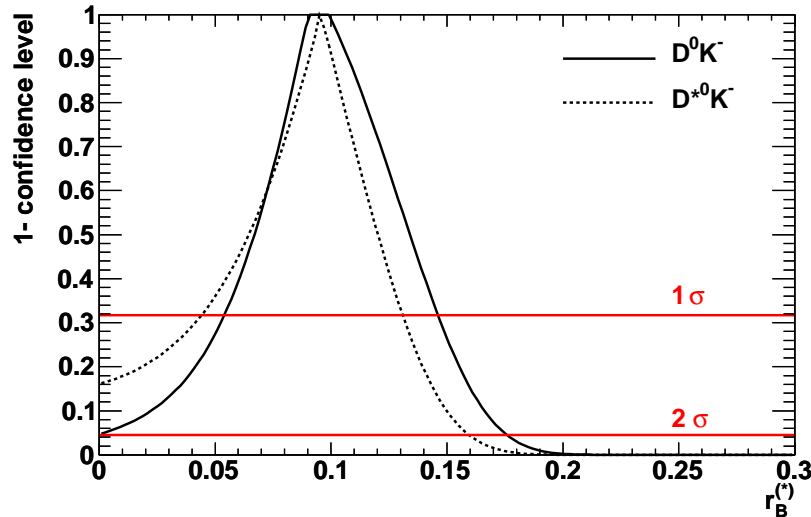
- Solid-blue: Full PDF, Red: sum of all bkg, Dotted-blue:  $q\bar{q}$  background

- ADS  $B^\pm \rightarrow DK^\pm$  results:

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

# ADS BABAR Results Continue...

- This measurement allowed us to extract variables:  $r_B$  and  $\gamma$



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

C.L. curve as a function of  $\gamma$

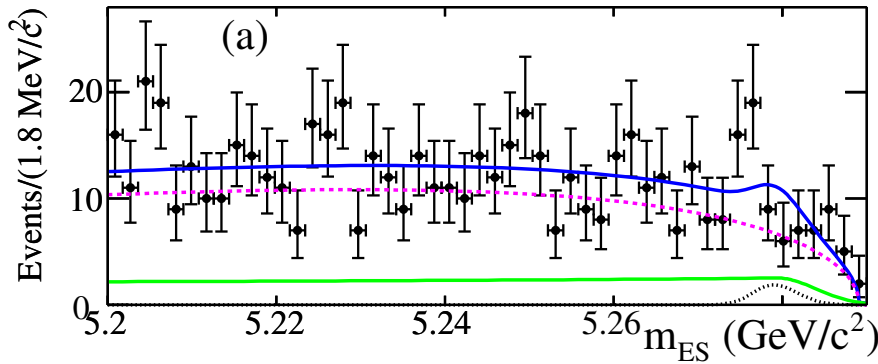
- For  $\gamma$  result: combining  $B \rightarrow DK$  and  $D^* K$

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

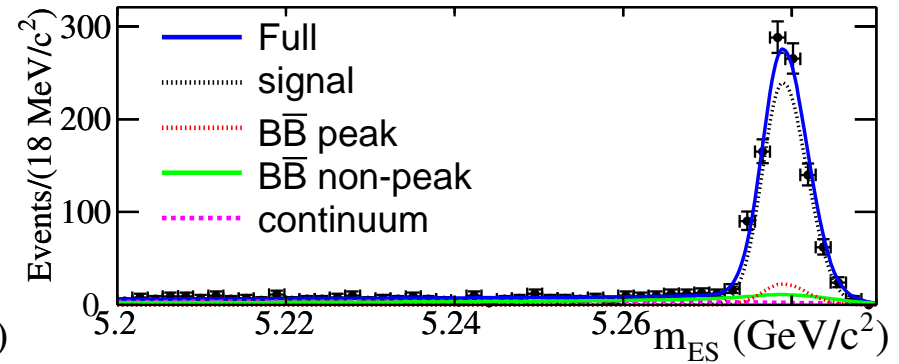
$$r_B = (9.5^{+5.1}_{-4.1})\% \quad r_B^* = (9.6^{+3.5}_{-5.1})\%$$

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

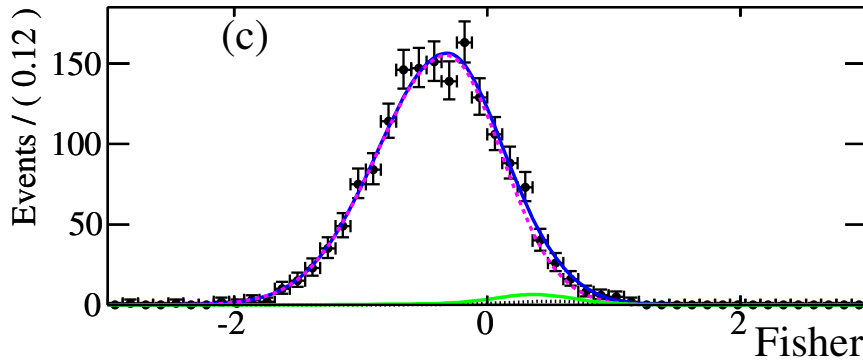
□ Simultaneous fit to  $m_{ES}$  and Fisher: OS  $\approx 20$  events; SS  $\approx 2000$  events



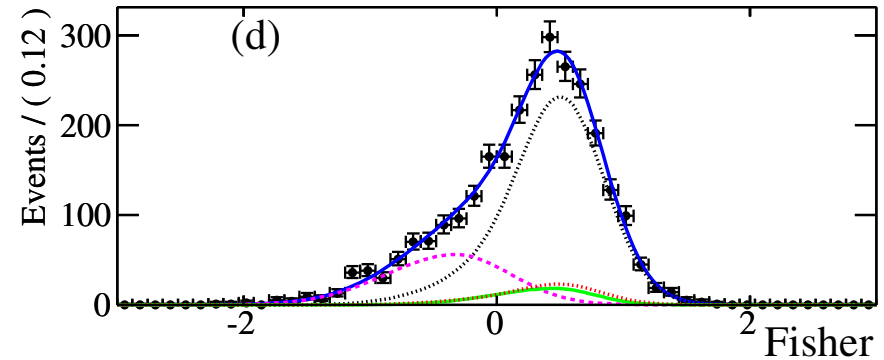
$m_{ES}$ : opposite-sign with  $F > 0.5$



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



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

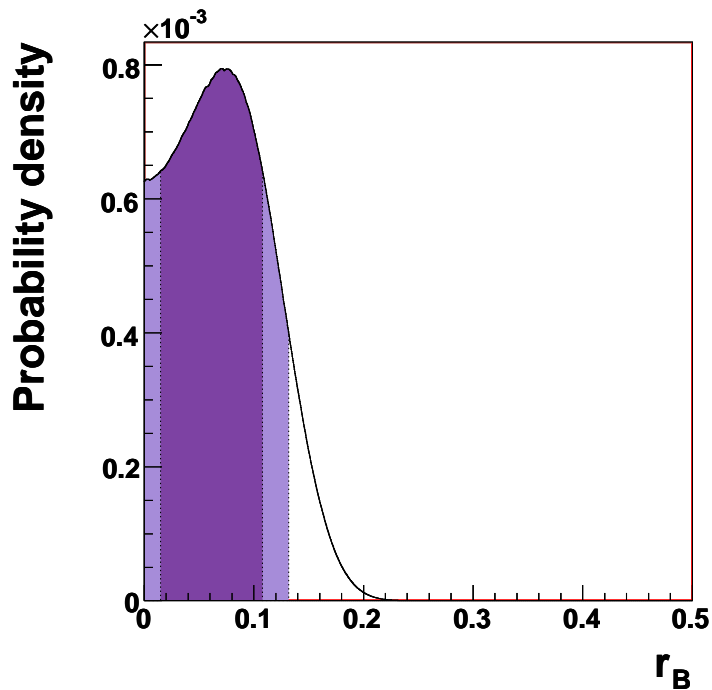


Fisher: SS  $m_{ES} > 2.27 \text{ GeV}/c^2$



# ADS Results on $D^0 \rightarrow K^+ \pi^- \pi^0$ 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

→ Subject to small  $r_B$ , this measurement

has less precision for  $\gamma$  result

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

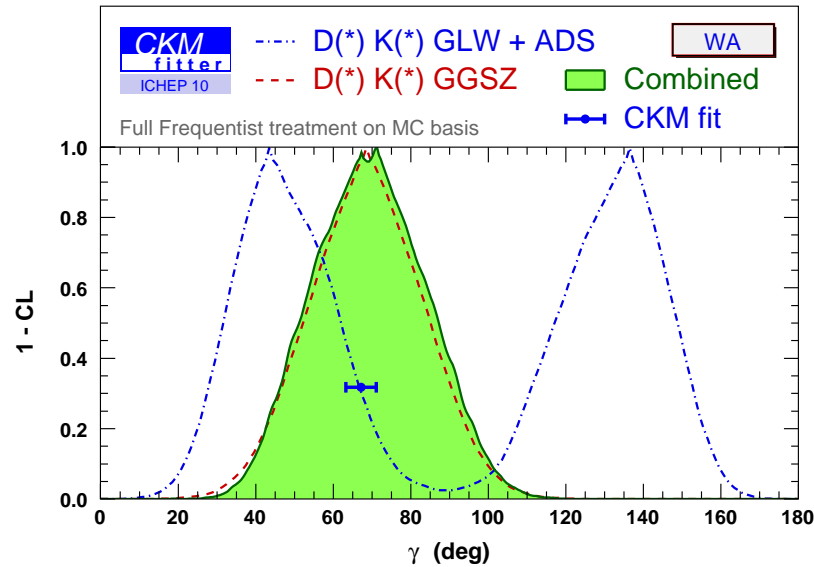
$$R^+ = (5_{-10}^{+12+1}) \times 10^{-3} \quad R^- = (12_{-10}^{+12+2}) \times 10^{-3}$$

## □ At 90% probability limit:

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

# Summary

- BABAR results provide increased constraints on CP Violation in  $B$



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

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  $r_B$