# Measurements of $B^- \rightarrow D^{(*)0}K^{(*)-}$ Decays related to $\gamma$ at BABAR

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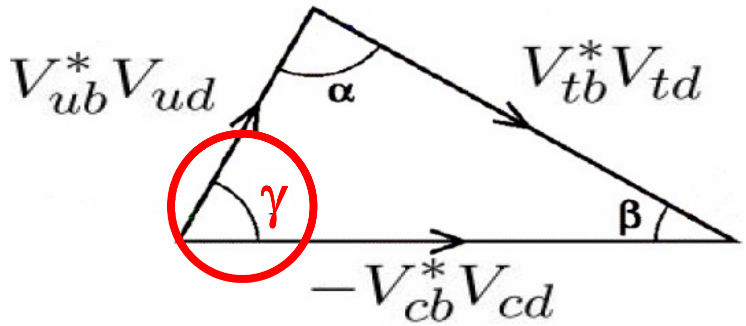
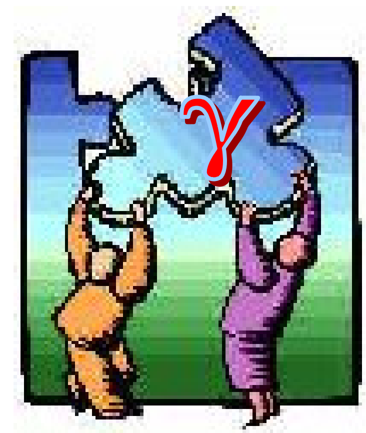
# Outline




- γ is the phase between b → u and b → c decay amplitudes
  - Can be determined by their interference

**MODES and METHODS**




- $B^- \rightarrow D^0_{CP} K^-$
- $B^- \rightarrow D^{*0}_{CP} K^-$
- $B^- \rightarrow D^0_{CP} K^{*-}$

} GLW

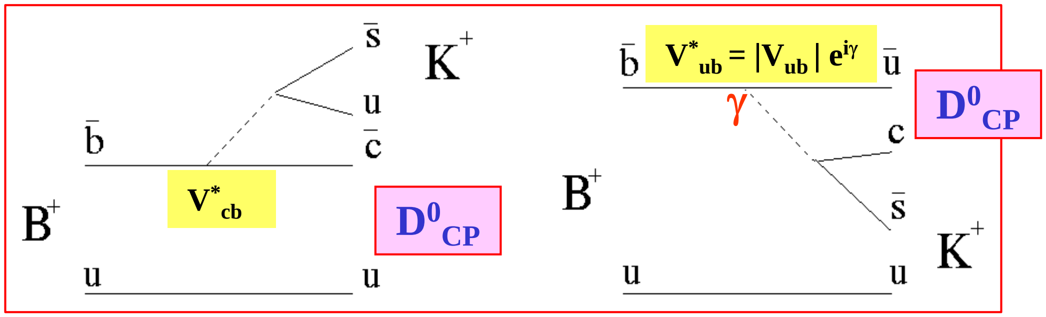
- $B^- \rightarrow D^{(*)0}[K^+\pi^-]K^-$ → ADS

  - See also talks by Shahram Rahatlou and Yan-Pan Lau
  - Updated and New results – all Preliminary unless noted

# $B^- \to D^{(*)0}K^{(*)-}$ - b → u/c Interference

Gronau-London-Wyler (Phys. Lett. B253, 483 (1991); Phys. Lett. B265 172 (1991))

$\gamma$ from interference between (b→u) and (b→c) decay amplitudes




Theoretically Clean

$$A\left(B^+ \to D^0 K^+\right) = |A| e^{i\delta_2} e^{i\gamma}$$
$$A\left(B^+ \to \bar{D}^0 K^+\right) = |\bar{A}| e^{i\delta_1}$$
$$A\left(B^- \to \bar{D}^0 K^-\right) = |A| e^{i\delta_2} e^{-i\gamma}$$
$$A\left(B^- \to D^0 K^-\right) = |\bar{A}| e^{i\delta_1}$$

$$\Gamma\left(B^+ \to \bar{D}^0 K^+\right) = \Gamma\left(B^- \to D^0 K^-\right) = |\bar{A}|^2$$
$$\Gamma\left(B^+ \to D^0 K^+\right) = \Gamma\left(B^- \to \bar{D}^0 K^-\right) = |A|^2$$

**We can sum up different CP modes as they have same phase modulo $\pi$**

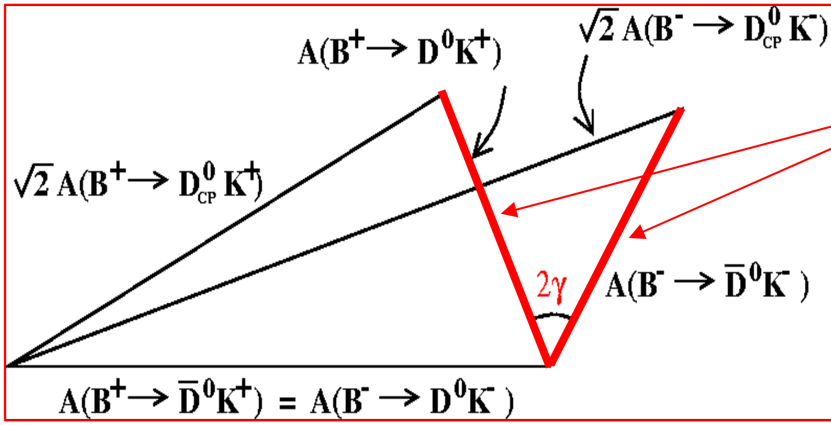
$$D_{CP-} = K_S\pi^0, K_S\omega^0, K_S\phi...$$
$$D_{CP+} = \pi^+\pi^-, K^+K^-...$$

**D⇔D*, K⇔K* in what follows, but not DK⇔D*K* (more complicated, need partial waves analysis, as strong phase may be different for each wave)**

# The GLW Method

$$D^0_{CP+} = \frac{D^0 + \bar{D}^0}{\sqrt{2}}, \qquad D^0_{CP-} = \frac{D^0 - \bar{D}^0}{\sqrt{2}}$$

$$\sqrt{2}A\left(B^\pm \to D^0_{CP+}K^\pm\right) = A\left(B^\pm \to \bar{D}^0 K^\pm\right) + A\left(B^\pm \to D^0 K^\pm\right)$$




**Color suppressed**

**$\gamma$ from direct CP Violation**

**2 equations → 2 unknowns ($\gamma$, $\delta_1$-$\delta_2$)**

$$r_b \equiv \left|\frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)}\right|$$

**$r_b$ and $r_b$* can be different!**

**NOTE:**
**disregard**
**- D mixing**
**- CPV in $D^0$ decays**

# Difficulties of the GLW method

- **Very elegant, but…:**
  - $\gamma$ ambiguity (8 fold)
  - b→u is color suppressed and b→c is color allowed
    - Small ratio of amplitudes ⇨ small interference
- **…and a major difficulty…**
  - The GLW original method requires an independent measurement of the color suppressed decay $B^- \to \bar{D}^0 K^-$.

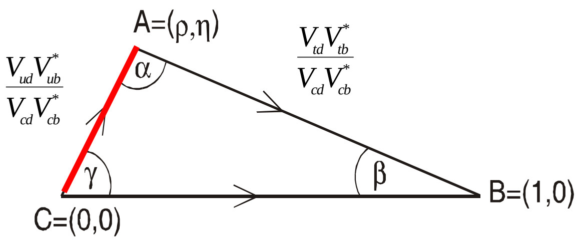
$$\frac{A(B^- \to D^0 K^-)A(D^0 \to K^+\pi^-)}{A(B^- \to \bar{D}^0 K^-)A(\bar{D}^0 \to K^+\pi^-)} \approx \left|\frac{V_{cb}}{V_{ub}}\right|\left|\frac{V_{us}^*}{V_{cs}^*}\right|\left|\frac{a_1}{a_2}\right|\sqrt{\frac{\Gamma(\bar{D}^0 \to K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+)}} \approx \left|\frac{1}{0.08}\right|\left|0.22\right|\left|\frac{1}{0.2(0.5)}\right|\sqrt{0.0036} = 0.8(0.3)$$

**What is $r_b$?**

$$r_b \equiv \left|\frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)}\right| = R_u F_{CS}$$

>0.2?

But this was all before this summer…




$R_u$ is one side of the Unitarity Triangle (~0.4)

$F_{CS}$ is an unknown color-suppression factor (~[0.2,0.5])

# Modified GLW Method

Gronau Phys.Lett. B557, 198 (2003)

$$\Gamma\left(B^{\pm} \to D^0_+ K^{\pm}\right) = \frac{1}{2}\left(\left|A\right|^2 + \left|\bar{A}\right|^2 + 2\left|A\right|\left|\bar{A}\cos\left(\Delta\delta \pm \gamma\right)\right|\right)$$

$$\Gamma\left(B^{\pm} \to D^0_- K^{\pm}\right) = \frac{1}{2}\left(\left|A\right|^2 + \left|\bar{A}\right|^2 - 2\left|A\right|\left|\bar{A}\cos\left(\Delta\delta \pm \gamma\right)\right|\right)$$

$\Delta\delta = \delta_1 - \delta_2$ = difference of strong phases between $B^+ \to D^0 K^+$ and $B^- \to D^0 K^-$

$$R_{CP\pm} \equiv 2\frac{\Gamma(B^+ \to D^0_{\pm} K^+) + \Gamma(B^- \to D^0_{\pm} K^-)}{\Gamma(B^+ \to \overline{D}^0_{flav} K^+) + \Gamma(B^- \to D^0_{flav} K^-)} = 1 + r_b^2 \pm 2 r_b \cos\Delta\delta \sin\gamma$$

$$A_{CP\pm} \equiv \frac{\Gamma(B^+ \to D^0_{\pm} K^+) - \Gamma(B^- \to D^0_{\pm} K^-)}{\Gamma(B^+ \to D^0_{\pm} K^+) + \Gamma(B^- \to D^0_{\pm} K^-)} = \mp 2 r_b \sin\Delta\delta \sin\gamma / R_{CP\pm}$$

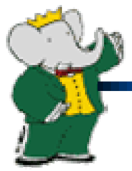
**3 equations**

↓

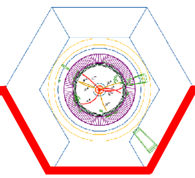
**3 unknowns ($r_b$, $\Delta\delta$, $\gamma$)**

$$R^{K/\pi}_{CP\pm/\,flav} = \frac{\Gamma(B^- \to D^0_{\pm/\,flav} K^-) + \Gamma(B^+ \to D^0_{\pm/\,flav} K^+)}{\Gamma(B^- \to D^0_{\pm/\,flav} \pi^-) + \Gamma(B^+ \to D^0_{\pm/\,flav} \pi^+)}$$

$$R_{CP\pm} \cong R^{K/\pi}_{CP\pm} / R^{K/\pi}_{flav}$$

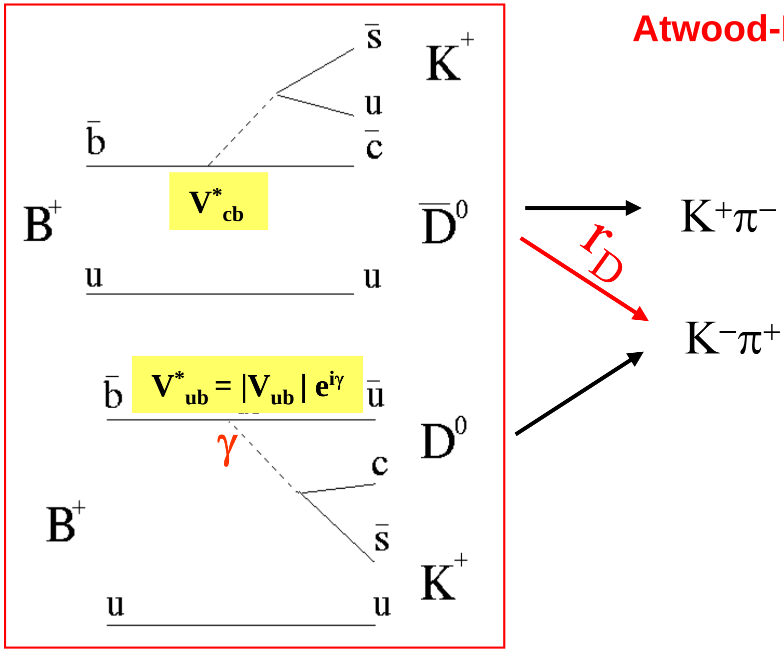






# ADS Method

Atwood-Dunietz-Soni (Phys. Rev. Lett. 78 (1997) 3257-3260)




Takes advantage of previous interference which was the main problem with GLW method…

3 unknowns ($r_b$, $\delta_D+\delta_B$, $\gamma$)

$$R_{ADS} = \frac{\Gamma([K^+\pi^-]K^-) + \Gamma([K^-\pi^+]K^+)}{\Gamma([K^-\pi^+]K^-) + \Gamma([K^+\pi^-]K^+)} = r_D^2 + r_B^2 + 2r_B r_D \cos(\delta_D + \delta_B)\cos\gamma$$

$$A_{ADS} = \frac{\Gamma([K^+\pi^-]K^-) - \Gamma([K^-\pi^+]K^+)}{\Gamma([K^+\pi^-]K^-) + \Gamma([K^-\pi^+]K^+)} = 2r_B r_D \sin(\delta_D + \delta_B)\sin\gamma / R_{ADS}$$

$$r_D = \frac{|A(D^0 \to K^+\pi^-)|}{|A(D^0 \to K^-\pi^+)|} = 0.060 \pm 0.003$$

from $D^{*+} \to D^0(\to K\pi)\pi^+$

Phys.Rev.Lett.91:171801,2003

# Analysis Techniques - I

- Reconstruct $B^- \rightarrow D^{(*)0} K^{(*)-}/\pi^-$ decays.
  - **Non-CP ($D^0_{flav}$: $K^-\pi^+$, $K^-\pi^-\pi^+\pi^+$, $K^-\pi^+\pi^0$)**
  - **CP-odd ($D^0_{CP-}$ : $K^0_s\pi^0$, $K^0_s\phi$, $K^0_s\omega$)**
  - **CP-even ($D^0_{CP+}$ : $K^+K^-$, $\pi^+\pi^-$)**

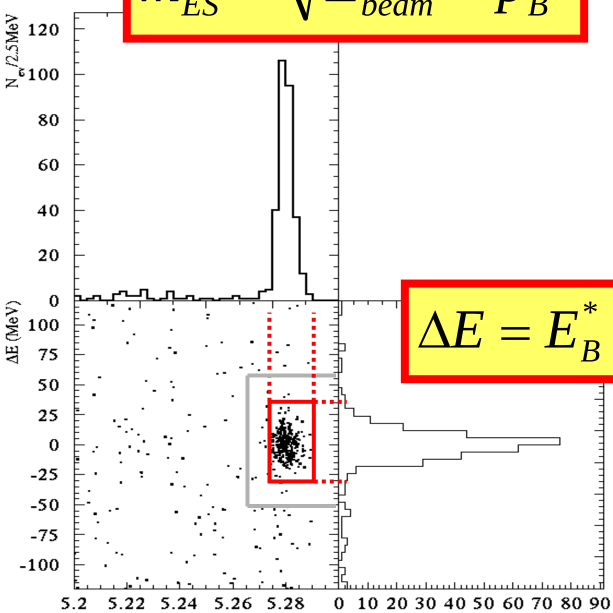
**$\Gamma(B \rightarrow DK) \sim 10^{-4}$, $\Gamma(D \rightarrow x) \sim 10^{-2}$**

**Need as many final states as possible**

**Need high efficiency**

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

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




**Reject**

$$e^+e^- \rightarrow q\bar{q}$$

events

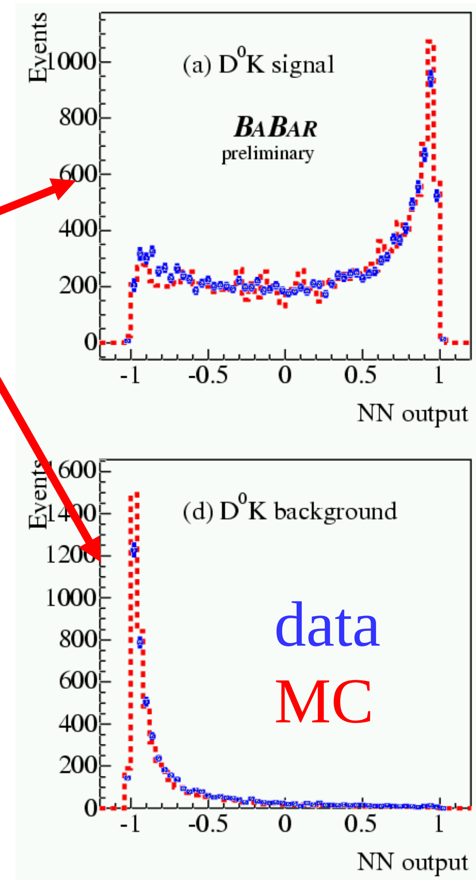
topological variables

in

Neural Network or

Fisher discriminant or

cut based selection

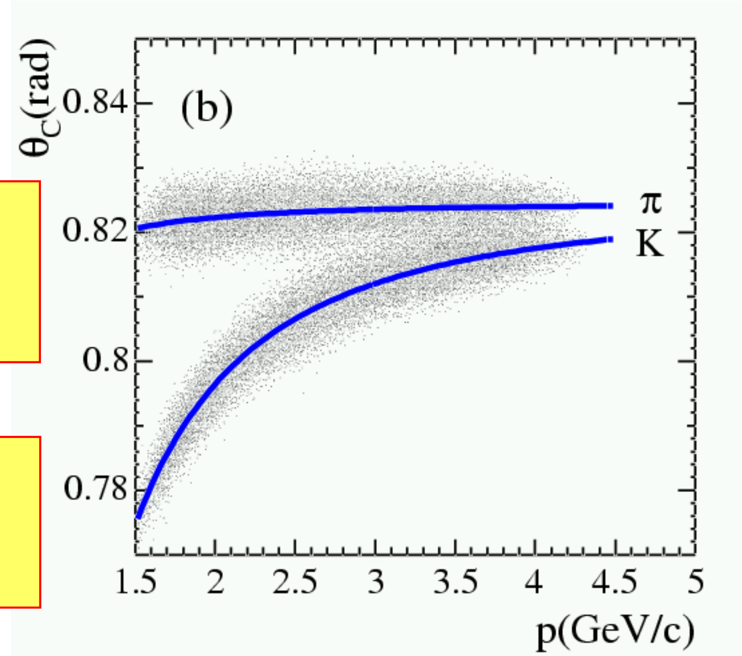


# Analysis Techniques - II

- To separate $B^- \rightarrow D^{(*)0}K^-$ from $B^- \rightarrow D^{(*)0}\pi^-$

**Cherenkov Angle is the main ingredient:**
**K/π Separation > 5 σ up to P= 2.8 GeV/c**
**K/π Separation > 3 σ up to P= 3.5 GeV/c**

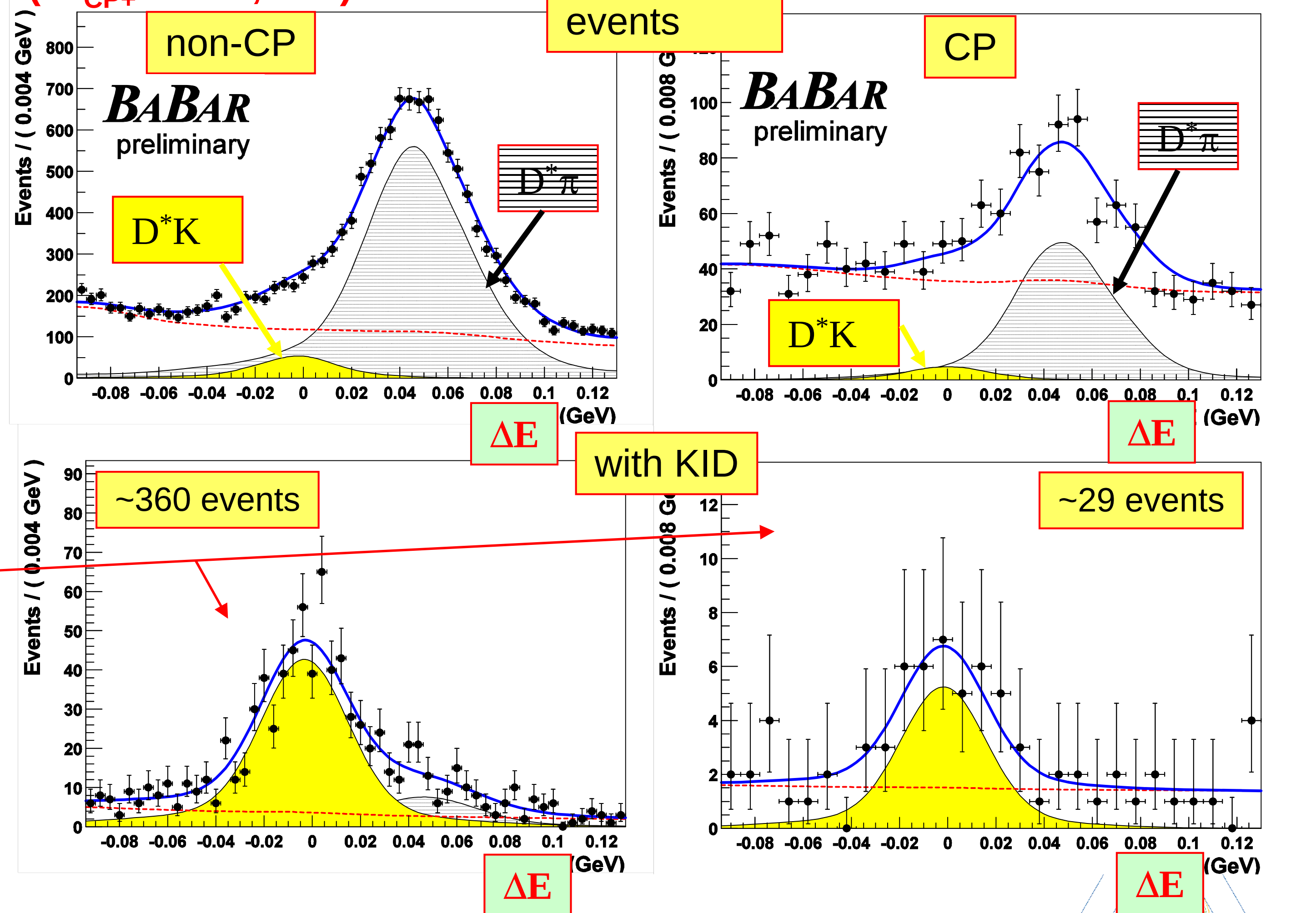
**ΔE also contributes**
**It depends on the mass hypothesis of the prompt track**




- BGs (B events and continuum) characterized using MC and data (off-resonance)
- $B \rightarrow D^{(*)0}h$ ($h=\pi$, $K^{(*)}$) yields measured with unbinned mono (or multi) dimensional ML fits exploiting the $m_{ES}$ (or $m_{ES}$, ΔE, and Cherenkov angle of the prompt track *h)*
- Best candidate in events selected using observables not inputs to the fit
- The ratios $R^{K/\pi}$ (and/or R) and $A_{CP}$ are measured
- Main systematics
  - PDFs characterizations and PID
  - Many (absolute efficiencies) cancel in ratio measurements
  - Charge detector asymmetries (all consistent with 0) are evaluated in $A_{CP}$ measurements

# $B^- \rightarrow D^{*0}_{(CP)} K^- / \pi^-$

- $D^{*0} \rightarrow D^0 \pi^0$
  - Non-CP ($D^0_{flav}$: $K^-\pi^+$, $K^-\pi^-\pi^+\pi^+$, $K^-\pi^+\pi^0$)
  - CP-even ($D^0_{CP+}$ : $K^+K^-$, $\pi^+\pi^-$)




**Applying Kaon ID algorithm before fit**
**$\varepsilon \sim 86\%$**
**$\pi \rightarrow K$ misID ~ 1.4%**
**and $m_{ES}$>5.27GeV/c²**

# $B^- \to D^{*0}_{(CP)} K^- / \pi^-$ (Results and Systematics)

3D Maximum Likelihood fit ($\Delta E, m_{ES}, \theta_c$)

Updated

$$R^{K/\pi}(\%) = 8.05 \pm 0.40^{+0.39}_{-0.32}$$

$$R^{K/\pi}_{CP+}(\%) = 8.8 \pm 2.1^{+0.7}_{-0.5}$$

New Result

$$A_{CP+} = -0.02 \pm 0.24 \pm 0.05$$

$$A_{Detector} = -0.010 \pm 0.012^{+0.002}_{-0.001}$$

Measured with non CP modes and $D^{*0}\pi$ events

Average systematics

| Systematic Source | $\Delta R^{K/\pi}/R^{K/\pi}$ (%) | $\Delta R_+^{K/\pi}/R_+^{K/\pi}$ (%) |
|---|---|---|
| $\Delta E_K$(signal) | 1.9 | 2.4 |
| $\Delta E_K$(non-B bg) | 0.4 | 1.9 |
| $\Delta E_K$(B bg) | 0.3 | 1.4 |
| $m_{ES}$(signal) | 0.4 | 0.7 |
| $m_{ES}$(non-B bg) | 0.9 | 3.5 |
| $m_{ES}$(B bg) | 1.6 | 3.4 |
| PID PDF | 2.3 | 2.1 |
| Fit procedure | 2.7 | 1.1 |
| $\varepsilon$ correction | 1.5 | 2.0 |
| | Non-CP | CP |

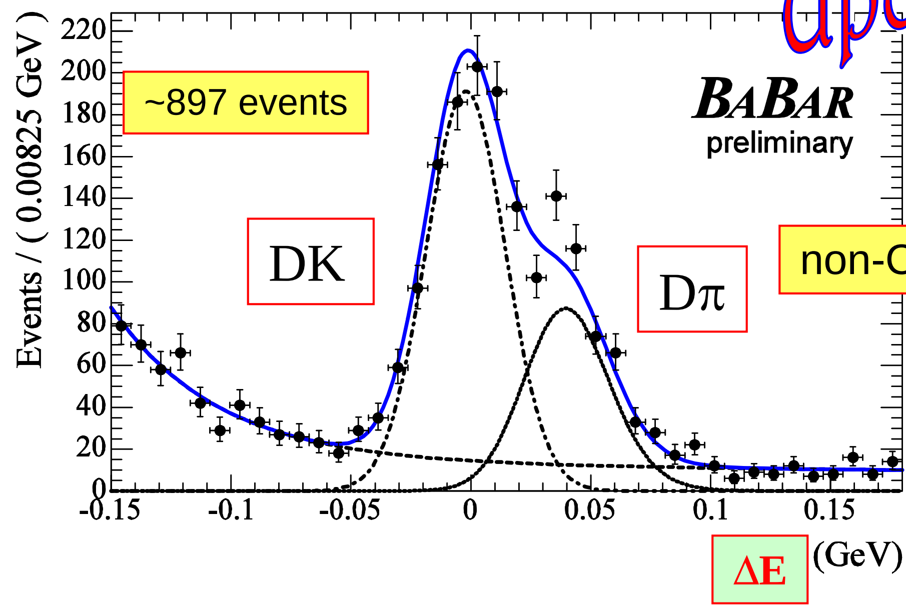
# $B^- \to D^0_{(CP)} K^- / \pi^-$

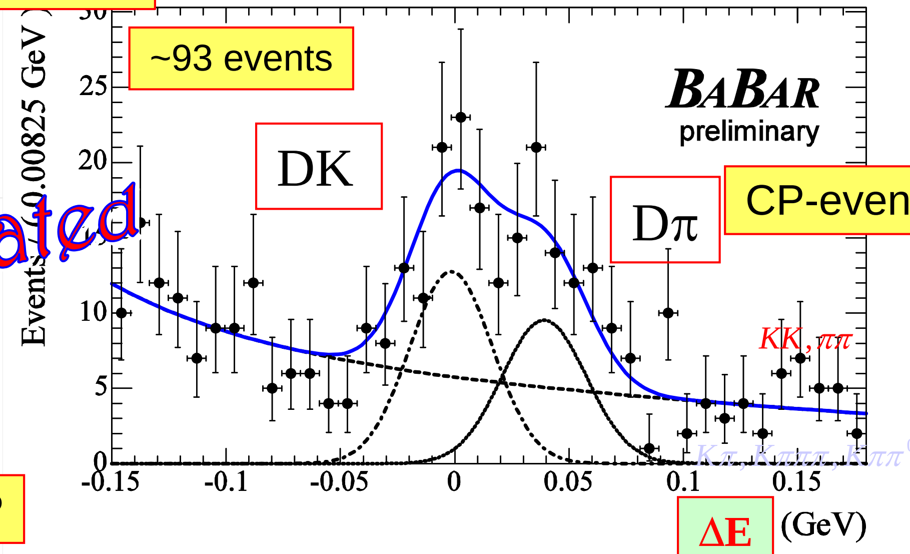
- Non-CP ($D^0_{flav}$: $K^- \pi^+$)
- CP-odd ($D^0_{CP-}$ : $K^0_s \pi^0$)
- CP-even ($D^0_{CP+}$ : $K^+K^-$, $\pi^+\pi^-$)

$216 \cdot 10^6$ $B\bar{B}$ pairs

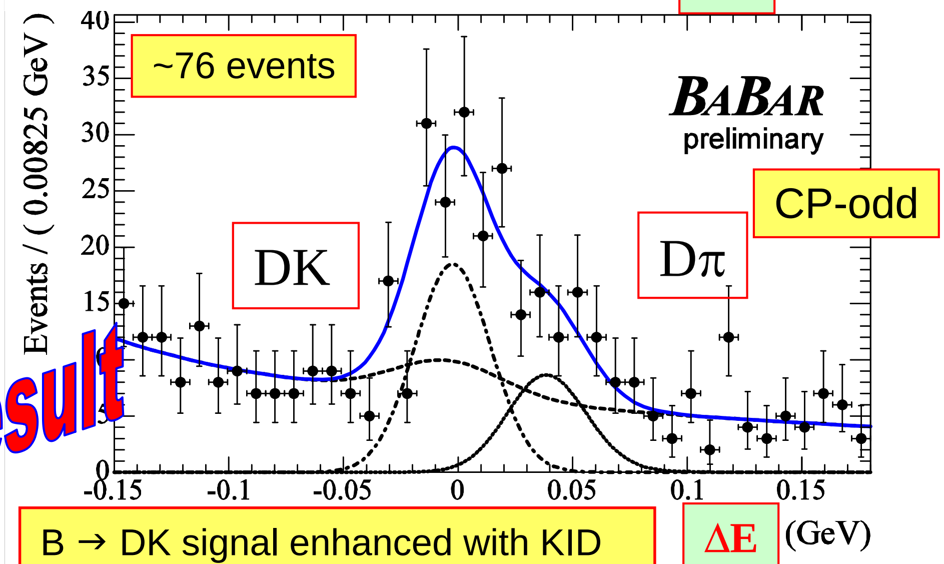
2D Maximum Likelihood fit ($\Delta E, \theta_c$)

Updated

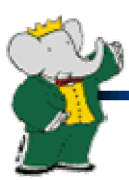



New Result



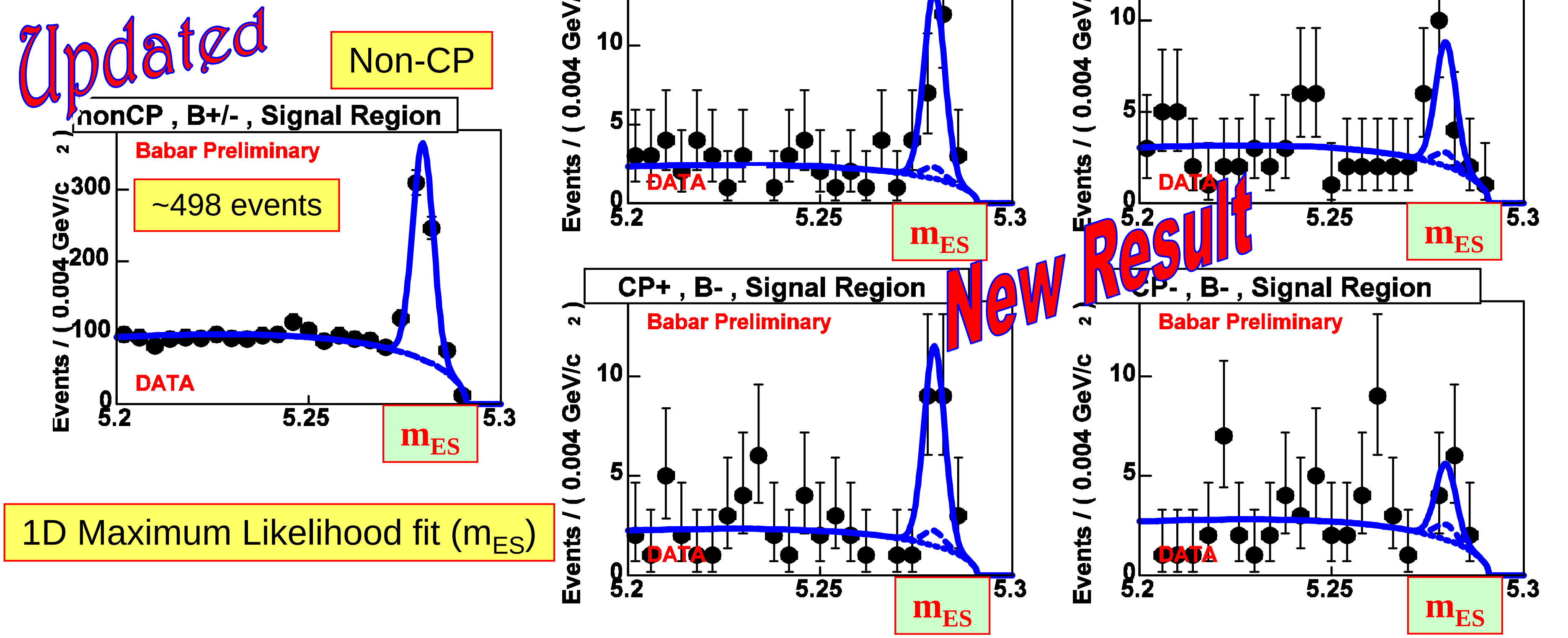

B → DK signal enhanced with KID



# $B^- \to D^0_{(CP)} K^{*-}$

- Non-CP ($D^0_{flav}$: $K^-\pi^+$, $K^-\pi^-\pi^+\pi^+$, $K^-\pi^+\pi^0$)
- CP-odd ($D^0_{CP-}$ : $K^0_s\pi^0$, $K^0_s\phi$, $K^0_s\omega$)
- CP-even ($D^0_{CP+}$ : $K^+K^-$, $\pi^+\pi^-$)
  - $K^{*-} \to K^0_s\pi^-$

$227 \cdot 10^6\ B\bar{B}\ pairs$




1D Maximum Likelihood fit ($m_{ES}$)

Uses previous measurements of $\Gamma(B^- \to D^0K^{*-})$ to derive $R_{CP\pm}$

# $B^- \to D^{(*)0}_{CP} K^{(*)-}$ - Summary of Results

**$D^0_{CP}\ K^-$** hep-ex/0408082

$$R_{CP+} = 0.87 \pm 0.14 \pm 0.06$$
$$A_{CP+} = 0.40 \pm 0.15 \pm 0.08$$
$$R_{CP-} = 0.80 \pm 0.14 \pm 0.08$$
$$A_{CP-} = 0.21 \pm 0.17 \pm 0.07$$

**$D^0_{CP}\ K^{*-}\ (K^{*-} \to K_S \pi^-)$** hep-ex/0408069

$$R_{CP+} = 1.77 \pm 0.37 \pm 0.12$$
$$A_{CP+} = -0.09 \pm 0.20 \pm 0.06$$
$$R_{CP-} = 0.76 \pm 0.29 \pm 0.06^{-0.04}_{-0.14}$$
$$A_{CP-} = -0.33 \pm 0.34 \pm 0.10 (+1.15 \pm 0.12)(A_{CP-} - A_{CP+})$$

**$D^{*0}\ (D^0_{CP} \pi^0) K^-$** hep-ex/0408060

$$R_{CP+} = 1.09 \pm 0.26^{+0.10}_{-0.08}$$
$$A_{CP+} = -0.02 \pm 0.24 \pm 0.05$$

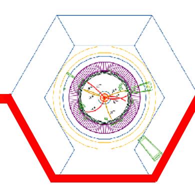
**$D^{*0}\ K^{*-}$**

$86 \cdot 10^6\ B\bar{B}\ pairs$

$$\Gamma = (8.3 \pm 1.1 \pm 1.0) \times 10^{-4}$$
$$\Gamma_L / \Gamma = 0.86 \pm 0.06 \pm 0.03$$

Phys. Rev. Lett. 92, 141801 (2004)

**More CP eigenstates final states still to be added…**
**More statistics needed to constrain $\gamma$**



# ADS

- $D^0 \to K^+\pi^-$
- $D^{*0} \to D^0 \pi^0$: $D^0 \to K^+\pi^-$
- $D^{*0} \to D^0 \gamma$: $D^0 \to K^+\pi^-$

**No Signal** →

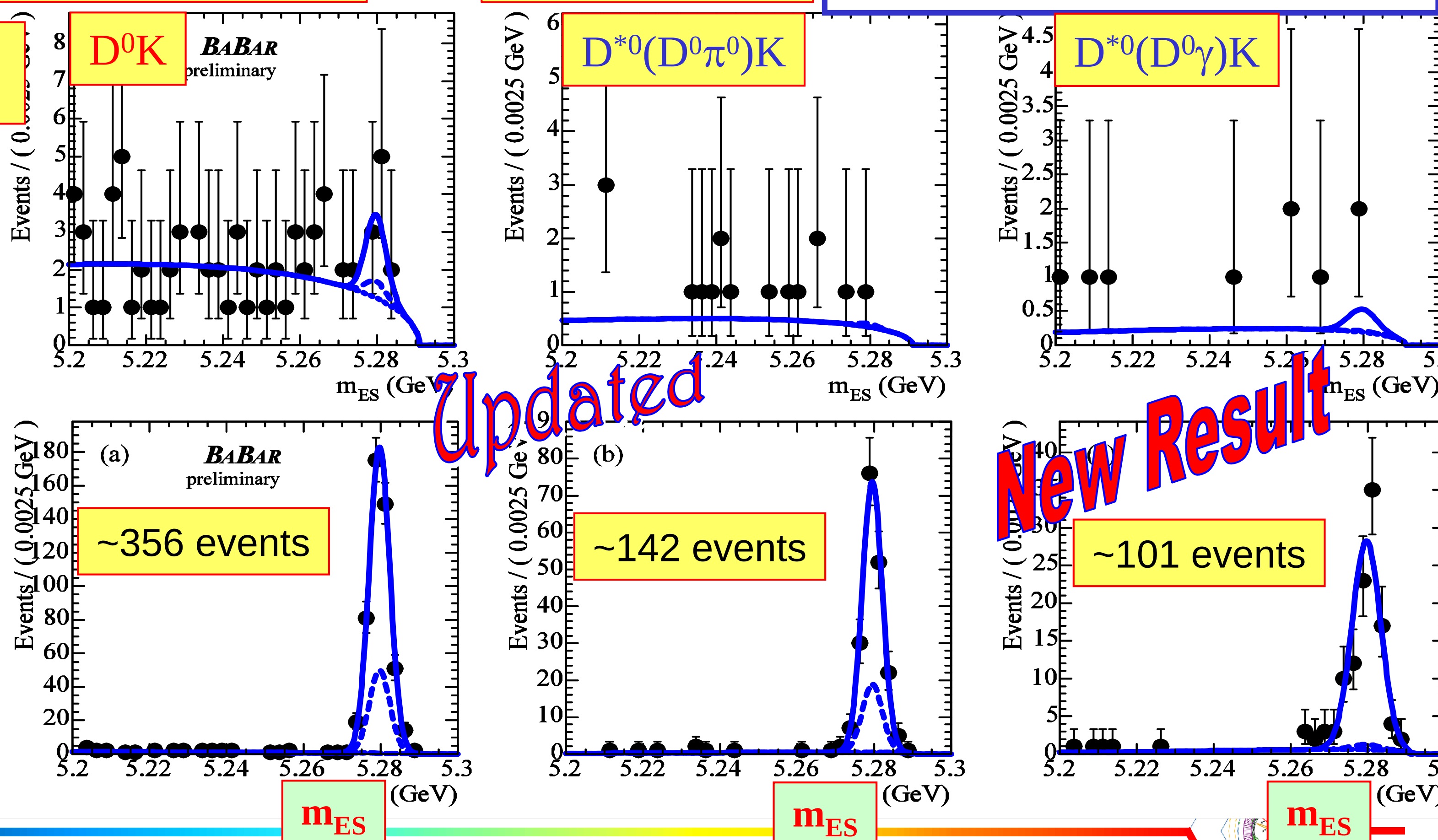
$$N([K^{\pm}\pi^{\mp}]_D K^{\mp}) = 4.7^{+4.0}_{-3.2}$$
$$N([K^{\pm}\pi^{\mp}]_{D^*(D\pi)} K^{\mp}) = -0.2^{+1.3}_{-0.8}$$
$$N([K^{\pm}\pi^{\mp}]_{D^*(D\gamma)} K^{\mp}) = 1.2^{+2.1}_{-1.4}$$

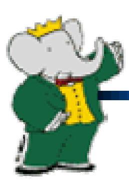
1D Maximum Likelihood fit ($m_{ES}$)

$227 \cdot 10^6$ $B\bar{B}$ *pairs*

Color or DCKM suppressed

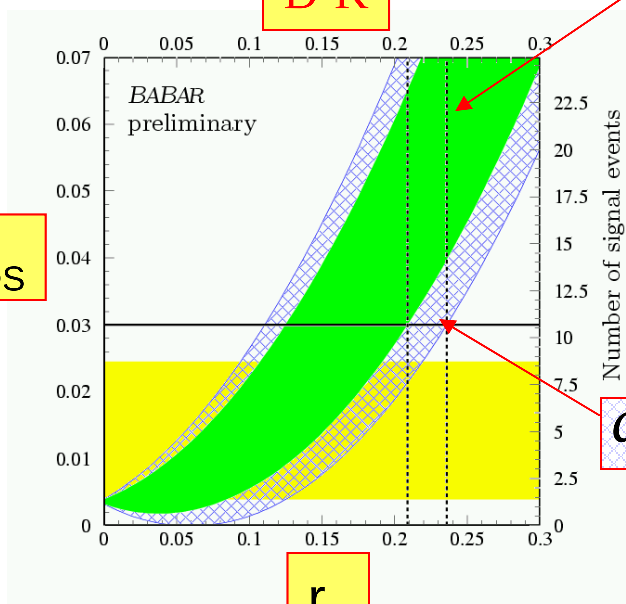
Color and CKM allowed

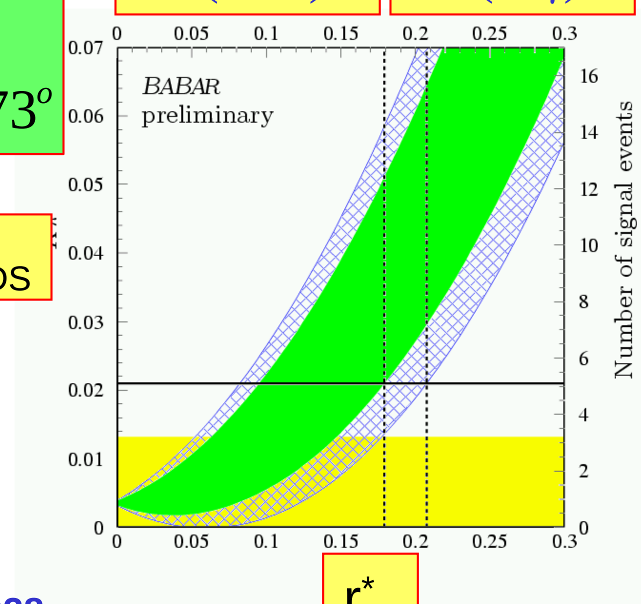


# $r_B$ from ADS Method

$A_{ADS}$ not measured → experimental limit on $\mathbf{r_B}$ ($R_{ADS} \sim \mathbf{r_B^2}$)




hep-ex/0408028

$$R_{ADS} < 0.030 \text{ (90\% CL)}$$

$$r_B < 0.23 \ (90\% \ CL)$$

$$R^*_{ADS} < 0.021 \text{ (90\% CL)}$$

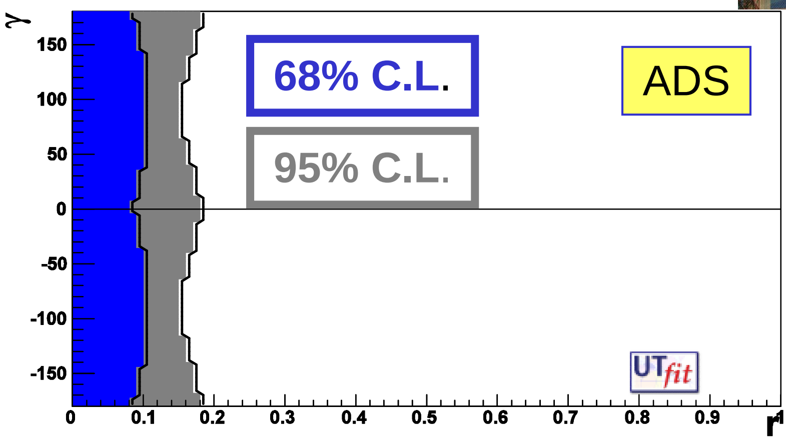
$$r^*_B < 0.21 \ (90\% \ CL)$$

Bad news for the measurement of $\gamma$...

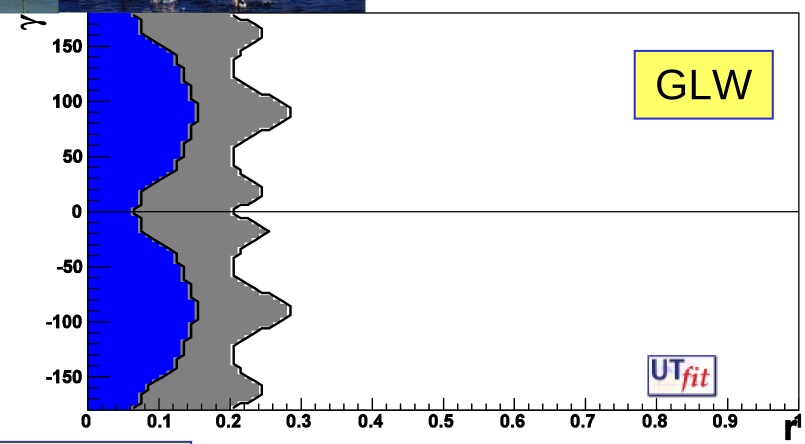
# Sooo…what about $\gamma/\phi_3$? – BABAR & Belle

- Need to combine
  - MODES
  - LUMINOSITY
  - EFFORTS

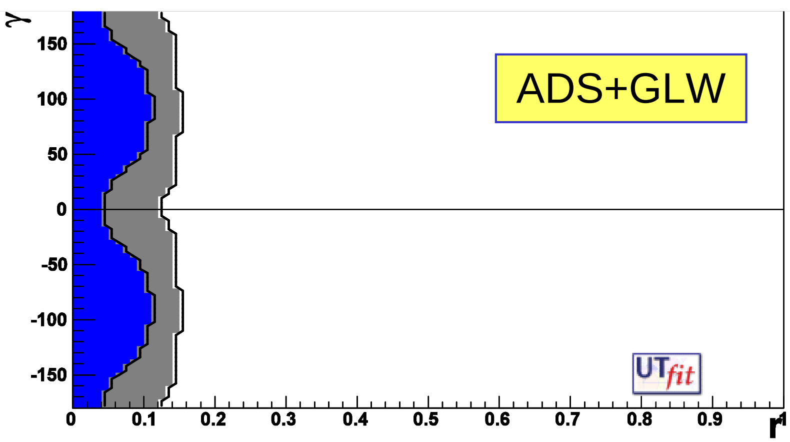

→ $\gamma/\phi_3$




$D^0K$




**BABAR+Belle**



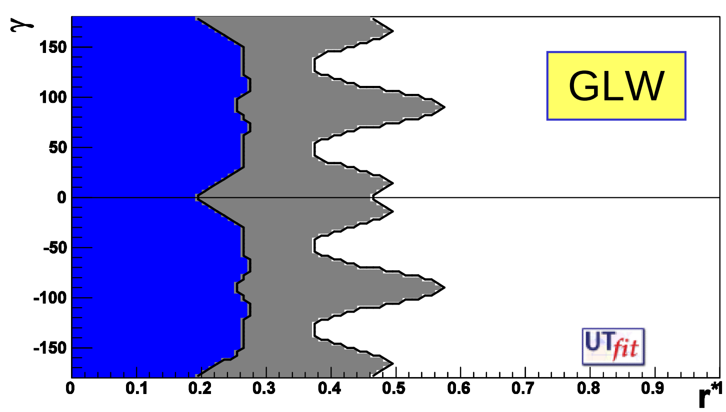

Bayesian approach by the
**UTfit group:**
**http://utfit.roma1.infn.it**

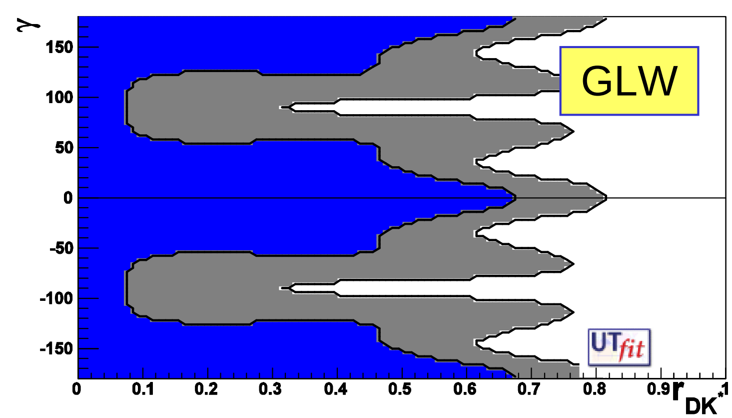
# And more modes…

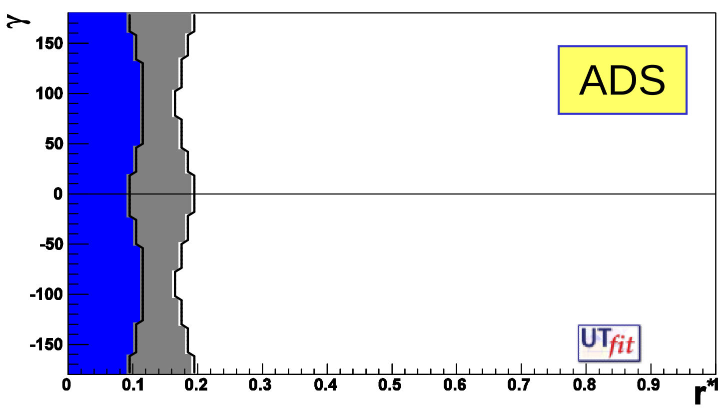
**BABAR+Belle**

$D^{*0}K$

$D^0K^*$



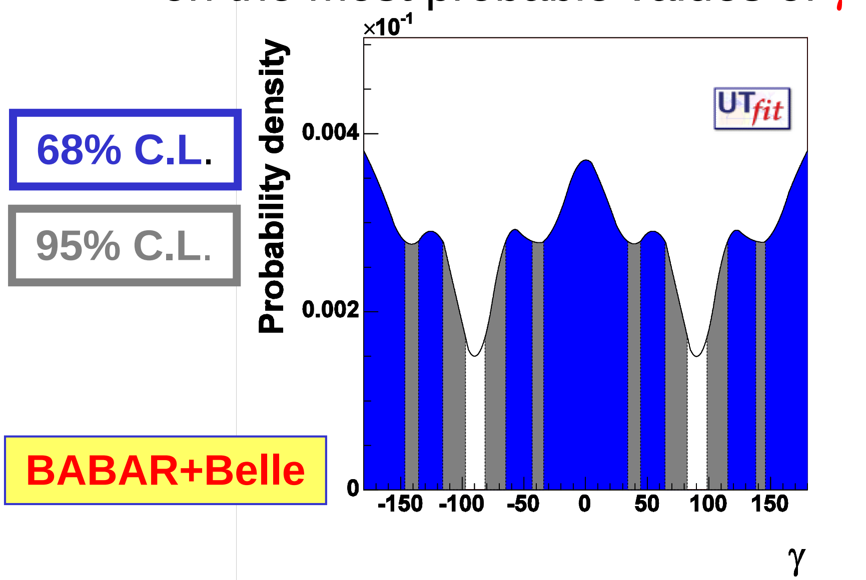

**68% C.L.**

**95% C.L.**

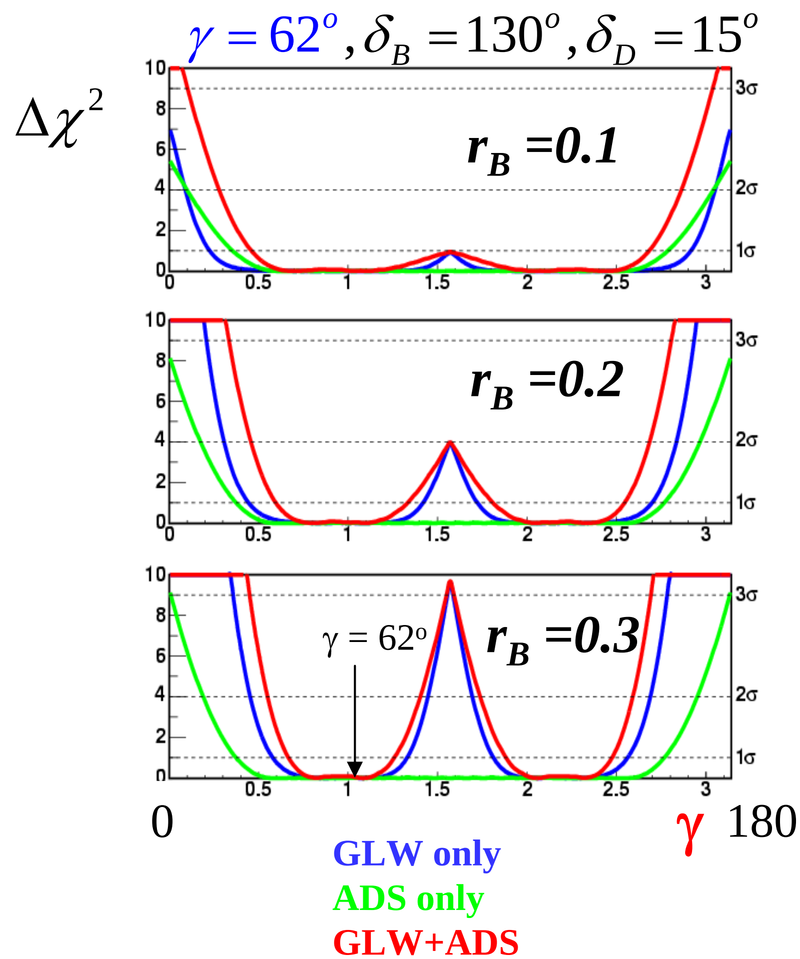
**UTfit group:**
**http://utfit.roma1.infn.it**

# Conclusions

- BABAR added or updated results with many $B^- \to D^{(*)0}K^{(*)-}$ modes
- Constraining γ with the GLW+ADS methods depends heavily on $r^{(*)}_b$
- $r_b$ appears to be very small…
- …nonetheless we can start "guessing" on the most probable values of γ




**γ sensitivity projection for 500 fb⁻¹**




- **Need to join modes/methods/forces (with Belle) to complete this difficult measurement**

# BACKUP SLIDES

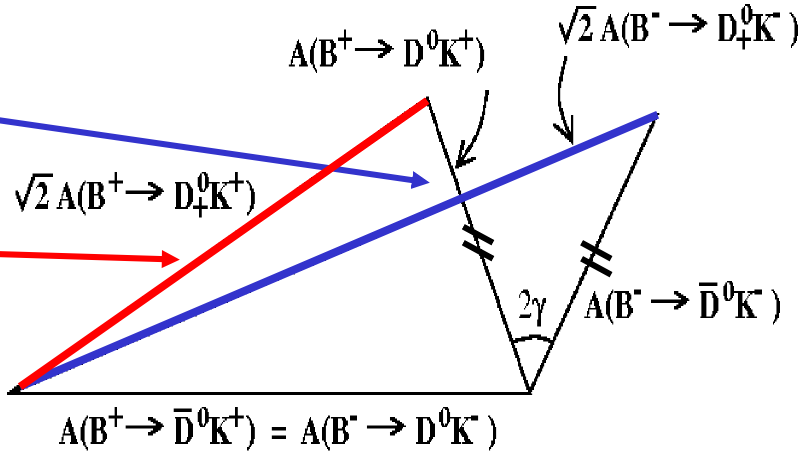
# Modified GLW Method - backup

$$n_1 \equiv \frac{\Gamma(B^- \to D_+ K^-)}{\Gamma(B^- \to D_0 K^-)} = \frac{1+r^2}{2} + r\cos(\Delta\delta - \gamma)$$

$$p_1 \equiv \frac{\Gamma(B^+ \to D_+ K^+)}{\Gamma(B^- \to D_0 K^-)} = \frac{1+r^2}{2} + r\cos(\gamma + \Delta\delta)$$

$$n_2 \equiv \frac{\Gamma(B^- \to D_- K^-)}{\Gamma(B^- \to D_0 K^-)} = \frac{1+r^2}{2} - r\cos(\Delta\delta - \gamma)$$

$$p_2 \equiv \frac{\Gamma(B^+ \to D_- K^+)}{\Gamma(B^- \to D_0 K^-)} = \frac{1+r^2}{2} - r\cos(\gamma + \Delta\delta)$$




**Note 1: only ratio of BR are required!!!!**

$$\alpha^2 = \frac{(R_+ - R_-)^2}{8(R_+ + R_- - 2)}, \beta^2 = \frac{A_{CP}^2}{2(R_+ + R_- - 2)}$$

$$\sin^2\gamma = \frac{1+\beta^2-\alpha^2}{2} \pm \sqrt{\left(\frac{1+\beta^2-\alpha^2}{2}\right)^2 - \beta^2}$$

**Note 2: 8 fold ambiguities!**

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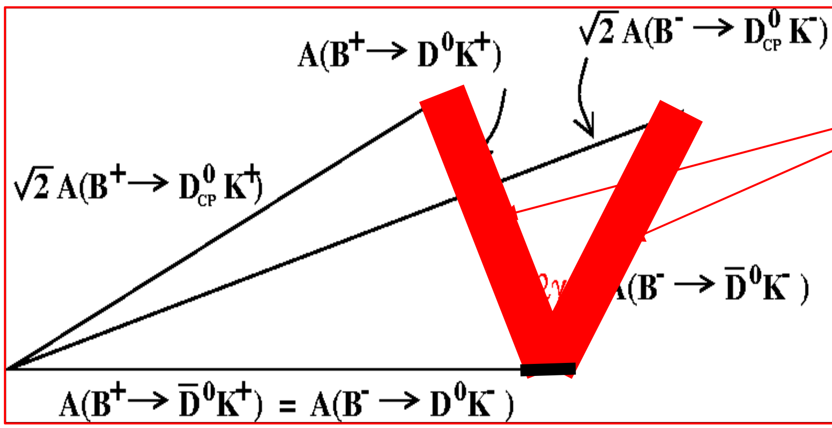


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