Measurement of the angle γ of the Unitarity Triangle: Status and prospects

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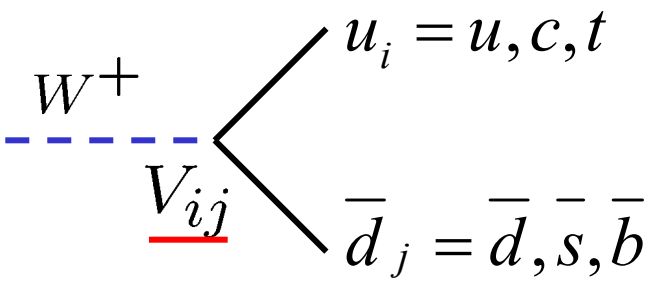
Seminar at Fermilab, May 25 2007

The weak interactions of quarks

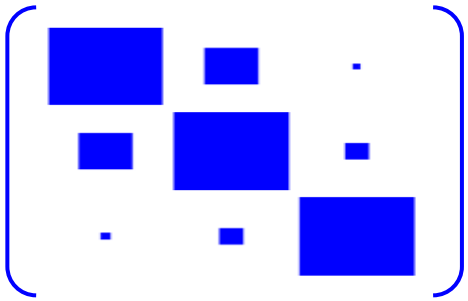
- *The electroweak coupling strength of the $W^{\pm}$ to quarks is described by the elements of the Cabibbo-Kobayashi-Maskawa matrix in the Standard Model (SM)*

$$-\mathcal{L}_{W^{\pm}} = \frac{g}{\sqrt{2}}\, \overline{u_{Li}}\, \gamma^{\mu}\, (V_{\mathrm{CKM}})_{ij}\, d_{Lj}\, W^{+}_{\mu} + \mathrm{h.c.}$$



- *3x3 unitary matrix ==> 4 parameters (after ad hoc choice of quark field phases)*

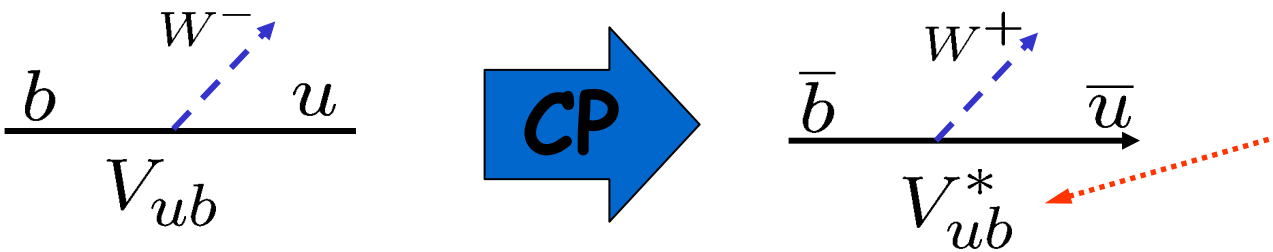
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$



relative magnitude of the elements (exp)

The Cabibbo-Kobayashi-Maskawa Matrix

- *An irremovable complex phase in V_{CKM} is the origin of CP violation in the SM*



the phase changes sign in the CP-conjugated process

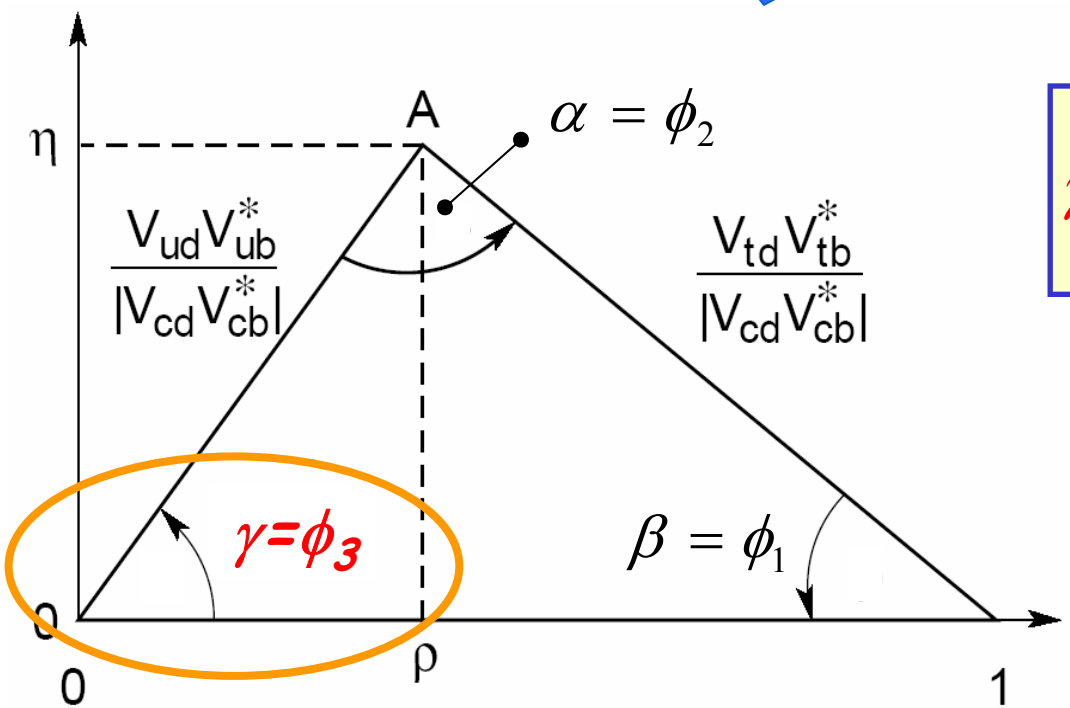
- *In the Wolfenstein parameterization:*

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

The Unitarity Triangle

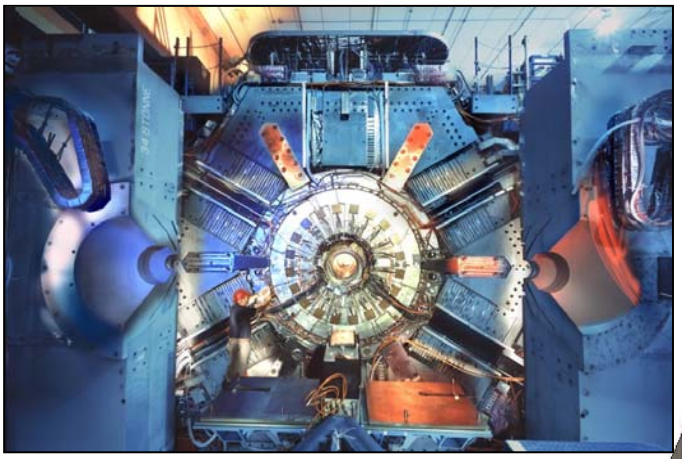
- *V is unitary: $VV^{+}=1$ ===>* $$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

in the complex plane



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

The BaBar Detector



Electromagnetic Calorimeter
6580 CsI crystals
e+ ID, π^0 and γ reco

Instrumented Flux Return
12-18 layers of RPC/LST
μ ID

e^+ [3.1 GeV]

Cherenkov Detector
144 quartz bars
K, π, p separation

Drift Chamber
40 layers
tracking + dE/dx

e^- [9 GeV]

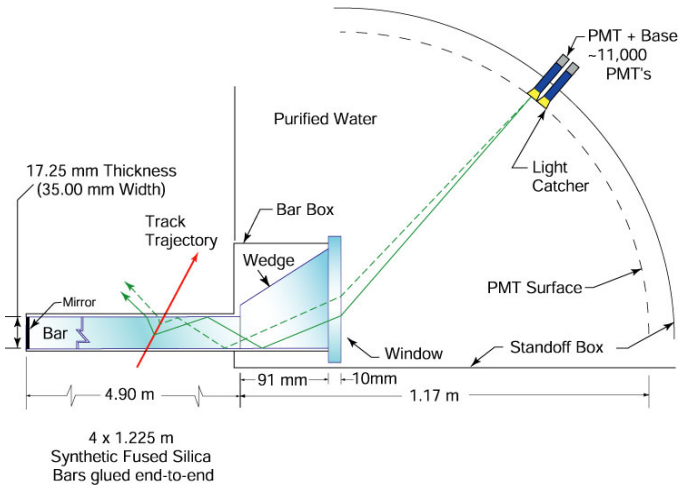
1.5T Magnet

Silicon Vertex Tracker
5 layers (double-sided Si sensors)
vertexing + tracking (+ dE/dx)

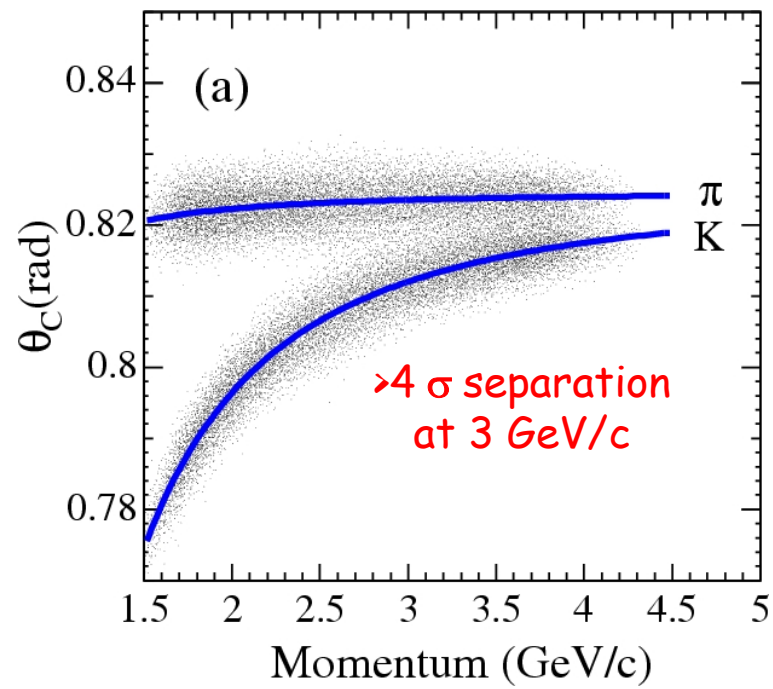
Pion/Kaon Discrimination

DIRC: Detector of Internally Reflected Cherenkov light

SIGNAL FORMATION in the DIRC



Cherenkov angle vs. momentum for pions and kaons

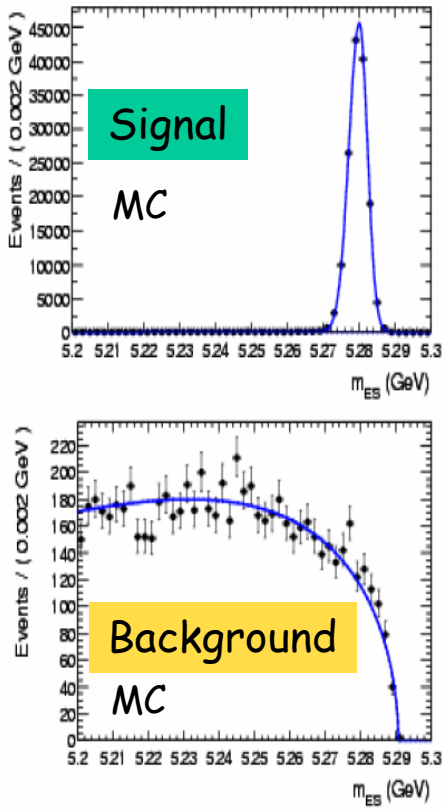


also dE/dx in Drift Chamber and Silicon Vertex detector is used

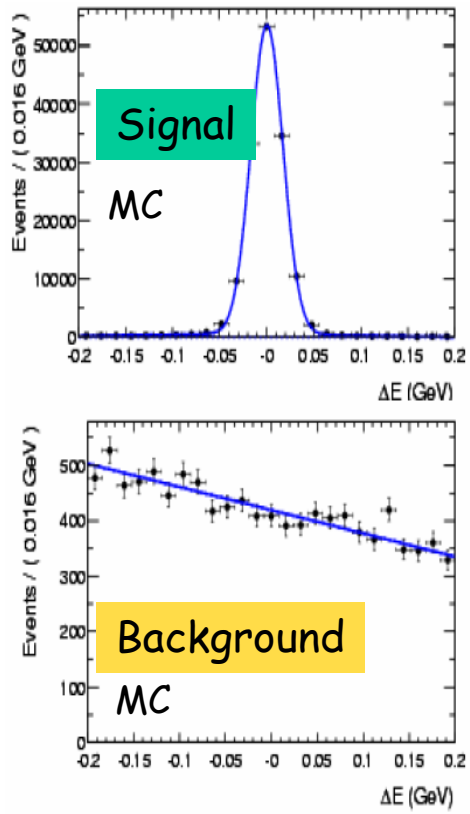
Key Analysis Techniques

Exploit kinematics of $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ for signal selection

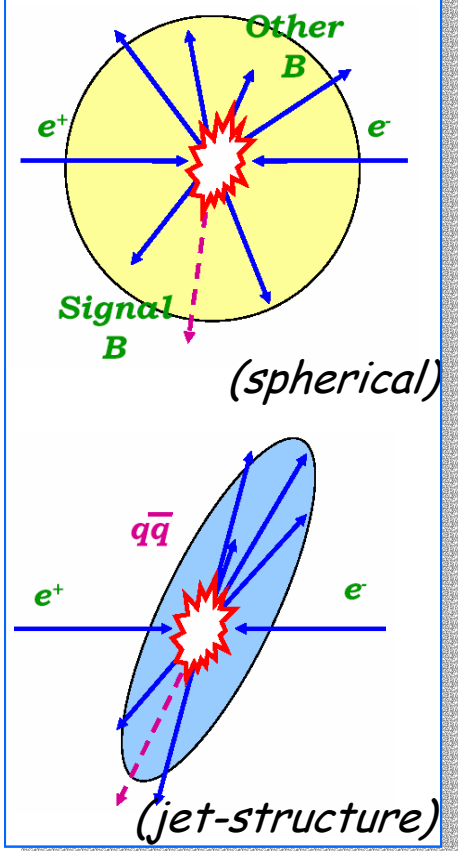
$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$$



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

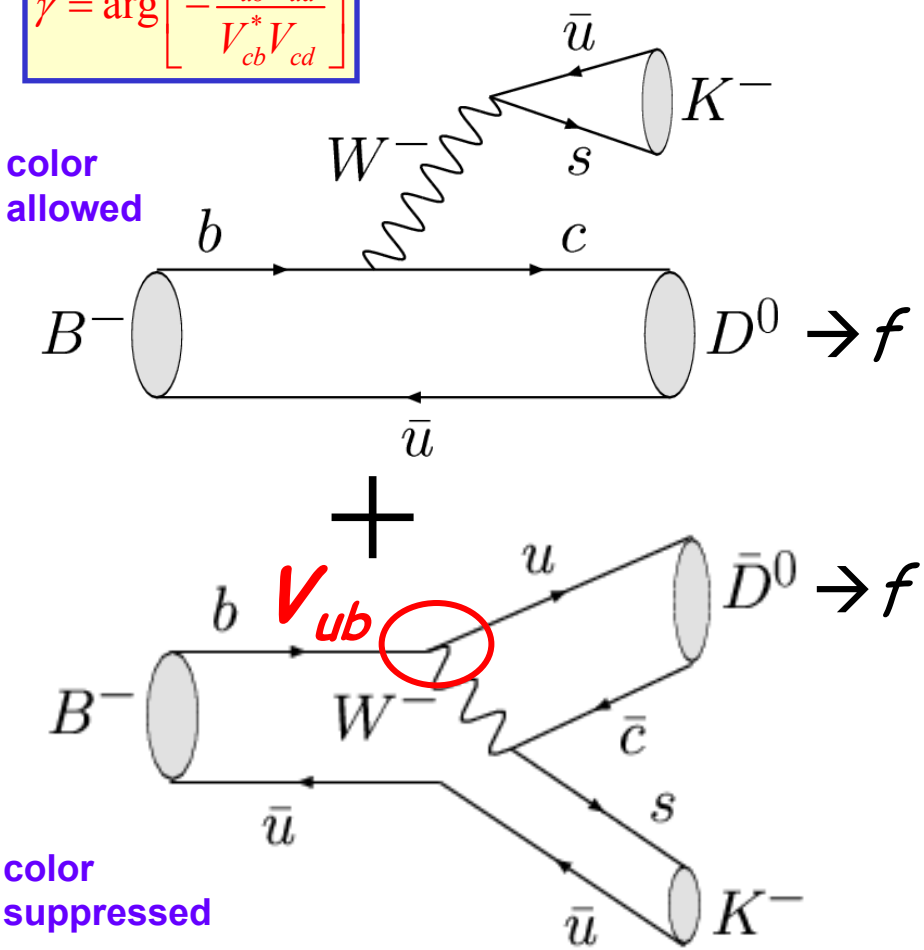


Event topology



Extraction of γ with $B \to D^0 K$

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



- $D^0/\bar{D}^0$ decay to common final state
- The interference depends on V_{ub} and therefore on γ
- Critical parameter: ratio of amplitudes:

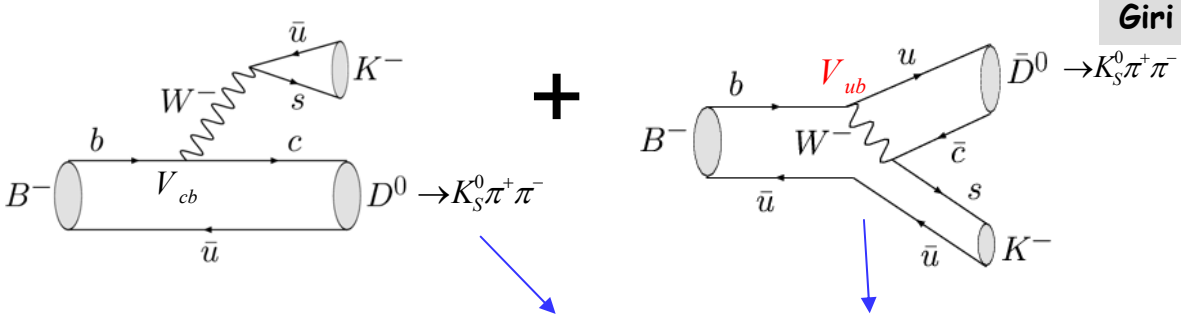
$$r_B \equiv \left|\frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)}\right| \sim 0.1$$

- Select the D^0 decays that enhance the interference:
  - 3-body (e.g. $K_S\pi\pi$): Dalitz
  - CP-eigen. (e.g. $K_S\pi^0$): GLW
  - DCS (e.g. $D^0 \to K^+\pi^-$): ADS

The Dalitz Method

The Dalitz Method ($D^0 \to K_S \pi^+ \pi^-$)

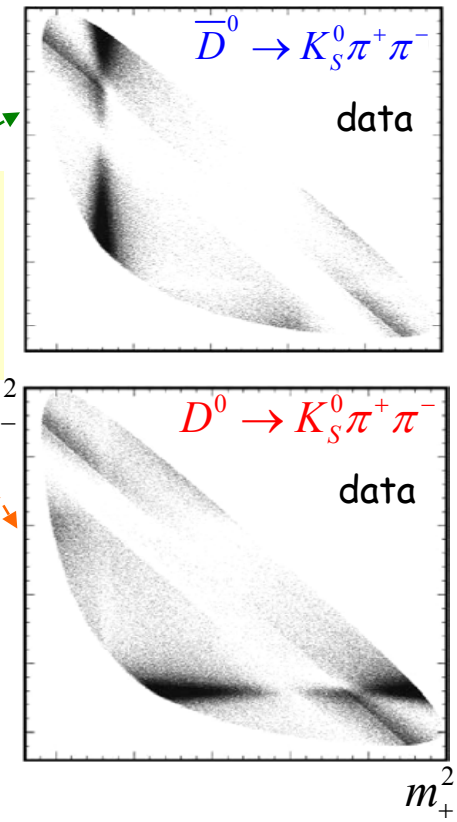
Atwood et al., PRL78, 3257 (1997)
Giri et al., PRD68,054018 (2003)



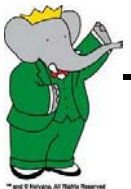
$$A_-(m_-^2, m_+^2) = \left|A(B^- \to D^0 K^-)\right| \left[A_D(m_-^2, m_+^2) + r_B e^{i\delta_B} e^{-i\gamma} A_D(m_+^2, m_-^2) \right]$$

$$A_+(m_-^2, m_+^2) = \left|A(B^+ \to \bar{D}^0 K^+)\right| \left[A_D(m_+^2, m_-^2) + r_B e^{i\delta_B} e^{+i\gamma} A_D(m_-^2, m_+^2) \right]$$

$$m_\pm^2 \equiv m^2(K_S^0 \pi^\pm)^2$$

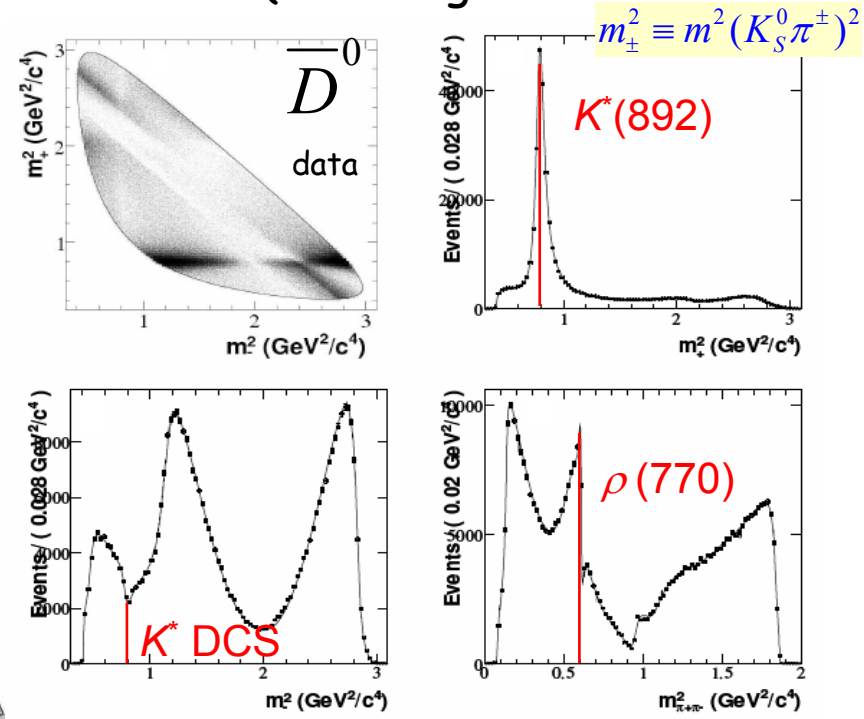


- δ_B is strong phase diff. of $A(B^- \to D^0 K^-)$ and $A(B^- \to \bar{D}^0 K^-)$
- $A_D(m_-^2, m_+^2)$ is the $D^0 \to K_S \pi\pi$ amplitude, determined from control sample
- <u>Unknowns:</u> r_B, δ_B and γ



The Dalitz Model of $D^0 \to K_S \pi^+ \pi^-$

- *From sample of 390k $D^0 \to K_S \pi\pi$ (purity 98%)*
- *Isobar Model: 16 Breit-Wigner + constant term*
  - Parameters from PDG/other experiments (except for σ and σ', fitted from data)
  - 8 alternative models to estimate the total systematic associated to the model (including K-matrix to evaluate the $\pi\pi$ S-wave)



Component	$Re\{a_r e^{i\phi_r}\}$	$Im\{a_r e^{i\phi_r}\}$	Fit fraction (%)
$K^*(892)^-$	-1.223 ± 0.011	1.3461 ± 0.0096	58.1
$K^*_0(1430)^-$	-1.698 ± 0.022	-0.576 ± 0.024	6.7
$K^*_2(1430)^-$	-0.834 ± 0.021	0.931 ± 0.022	6.3
$K^*(1410)^-$	-0.248 ± 0.038	-0.108 ± 0.031	0.1
$K^*(1680)^-$	-1.285 ± 0.014	0.205 ± 0.013	0.6
$K^*(892)^+$	0.0997 ± 0.0036	-0.1271 ± 0.0034	0.5
$K^*_0(1430)^+$	-0.027 ± 0.016	-0.076 ± 0.017	0.0
$K^*_2(1430)^+$	0.019 ± 0.017	0.177 ± 0.018	0.1
$\rho(770)$	1	0	21.6
$\omega(782)$	-0.02194 ± 0.00099	0.03942 ± 0.00066	0.7
$f_2(1270)$	-0.699 ± 0.018	0.387 ± 0.018	2.1
$\rho(1450)$	0.253 ± 0.038	0.036 ± 0.055	0.1
Non-resonant	-0.99 ± 0.19	3.82 ± 0.13	8.5
$f_0(980)$	0.4465 ± 0.0057	0.2572 ± 0.0081	6.4
$f_0(1370)$	0.95 ± 0.11	-1.619 ± 0.011	2.0
σ	1.28 ± 0.02	0.273 ± 0.024	7.6
σ'	0.290 ± 0.010	-0.0655 ± 0.0098	0.9

The 'Cartesian coordinates'

- *Goal: Fit the Dalitz plot distributions of $D^0 \to K_S \pi\pi$ from B^- and B^+ decays to extract r_B, δ_B and γ*
- *Complication: The Maximum Likelihood fit overestimates r_B and underestimates the error of γ*
- *Solution: Write the Likelihood as a function of the cartesian coordinates $x_\pm$, $y_\pm$:*

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

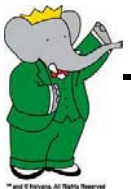
$$\Gamma(B^+) \propto |f_+|^2 + (x_+^2 + y_+^2)|f_-|^2 + 2x_+ \operatorname{Re}(f_+ f_-^*) + 2y_+ \operatorname{Im}(f_+ f_-^*)$$

$$\Gamma(B^-) \propto |f_-|^2 + (x_-^2 + y_-^2)|f_+|^2 + 2x_- \operatorname{Re}(f_- f_+^*) + 2y_- \operatorname{Im}(f_- f_+^*)$$

$$f_\mp \equiv A_D(m_\mp^2, m_\pm^2)$$

Likelihood is Gaussian and unbiased in $x_\pm$, $y_\pm$

- *Strategy: Extract $x_\pm$, $y_\pm$ from ML fit to the $D^0 \to K_S \pi\pi$ Dalitz plot and derive r_B, δ_B and γ from $x_\pm$, $y_\pm$ with stat. procedure*



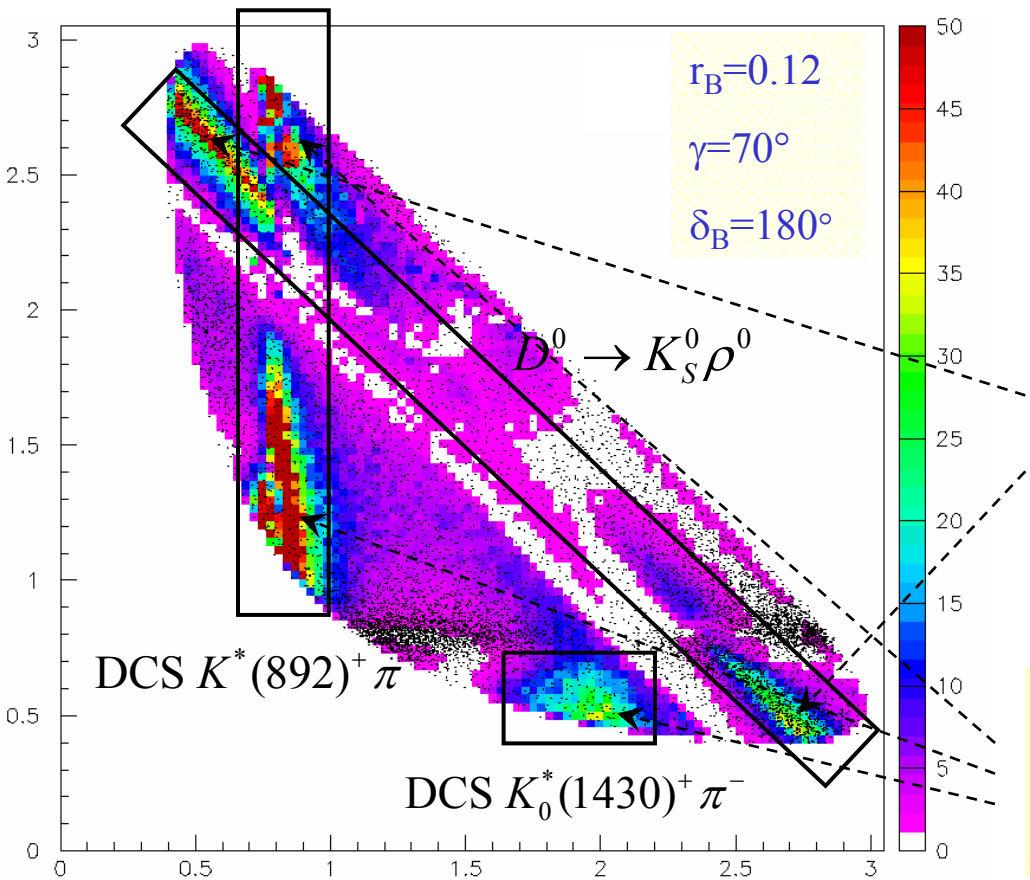
Sensitivity to gamma over the Dalitz plot

- *Sensitivity varies strongly over Dalitz plane*
- *2nd derivative of the log(L) event-by-event weighs the event*

$$\sigma^2(\gamma) \sim \frac{1}{\frac{d^2 \ln(L)}{d\gamma^2}}$$

$$\text{weight} = \frac{d^2 \ln(L)}{d\gamma^2}$$

events: points (weight = 1)



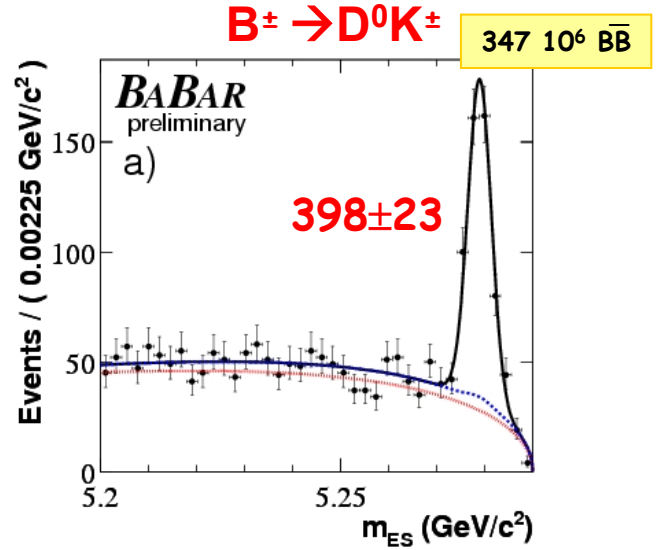
Interference of $B^- \to D^0[\to K_S^0 \rho^0]K^-$ with $B^- \to \overline{D}^0[\to K_S^0 \rho^0]K^-$ ≡ GLW like

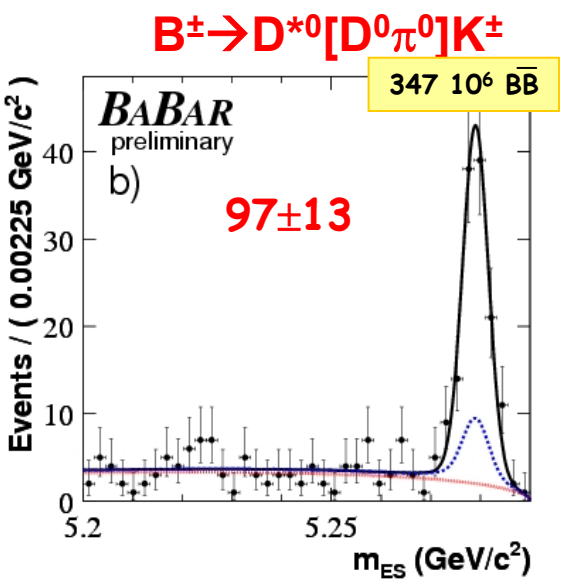
Interference of $B^- \to D^0[\to K^{*+}\pi^-]K^-$ (suppressed) with $B^- \to \overline{D}^0[\to K^{*+}\pi^-]K^-$ ≡ ADS like

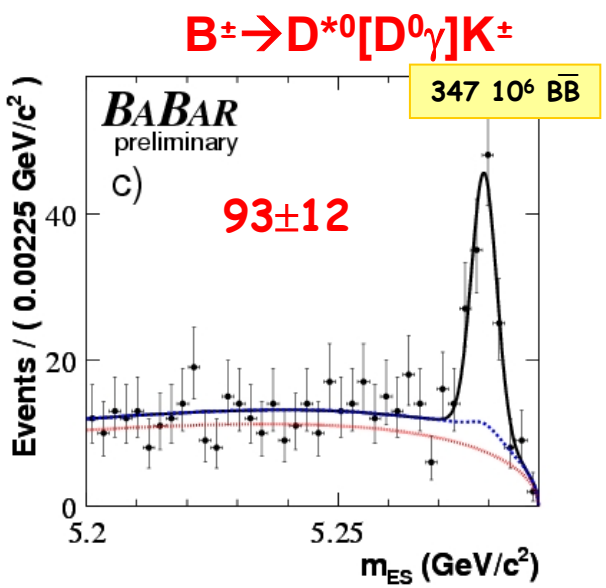
$$m_\pm^2 \equiv m^2(K_S^0 \pi^\pm)^2$$

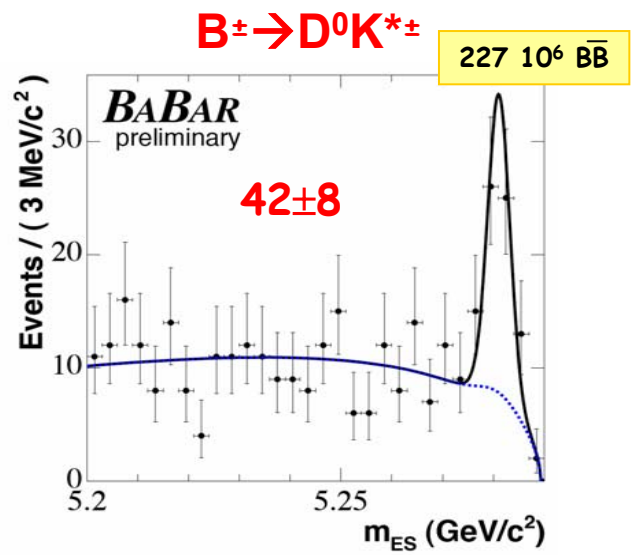
Extraction of Signal

- *Selection of $B \to D^0 K$, $B \to D^{*0} K (D^{*0} \to D^0 \pi^0/\gamma)$, $B \to D^0 K^*$*
  - Likelihood uses ΔE, m_{ES}, Fisher and Dalitz Plot $m_{\pm}^2$



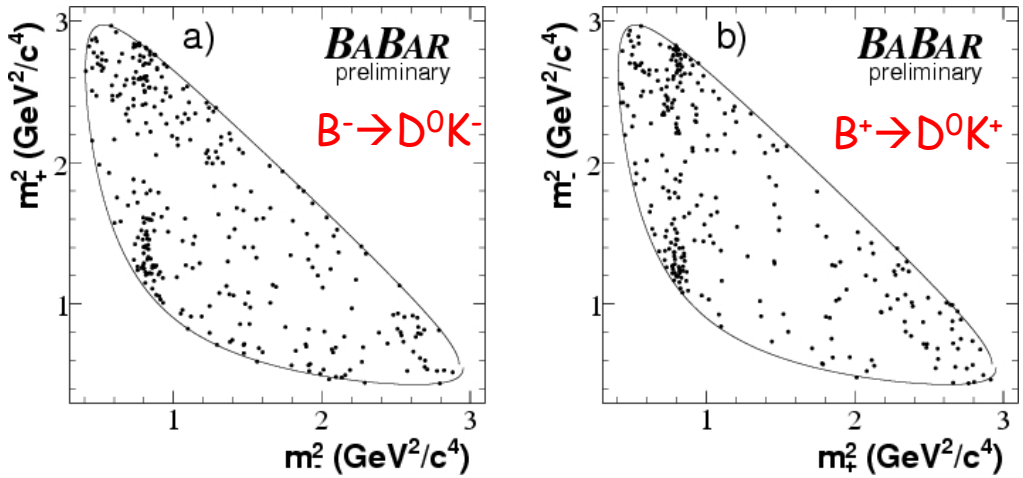






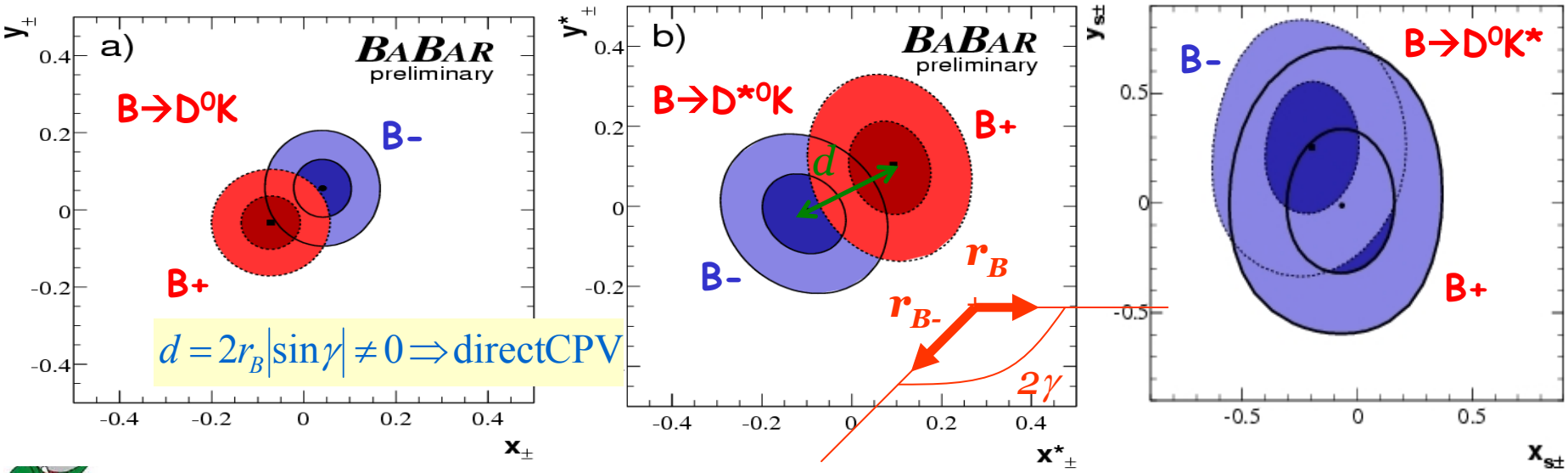
Measurement of x,y

$D \to K_S \pi\pi$ Dalitz plot distribution in signal region



$(x_\pm, y_\pm)$ are extracted from the $D^0 \to K_S \pi\pi$ Dalitz plot

Note: $(x_\pm, y_\pm)$ of D^0K, $D^{*0}K$ and D^0K^* are <u>different</u> because (r_B, δ_B) are different



$$d = 2r_B|\sin\gamma| \neq 0 \Rightarrow \text{directCPV}$$

Main systematic errors

Example: $B \to D^0 K$

CP parameter	BaBar $B^- \to D^0 K^-$
x_-	$0.041 \pm 0.059 \pm 0.018 \pm 0.011$
y_-	$0.056 \pm 0.071 \pm 0.007 \pm 0.023$
x_+	$-0.072 \pm 0.056 \pm 0.014 \pm 0.029$
y_+	$-0.033 \pm 0.066 \pm 0.007 \pm 0.018$

syst. (no Dalitz)

syst. Dalitz model

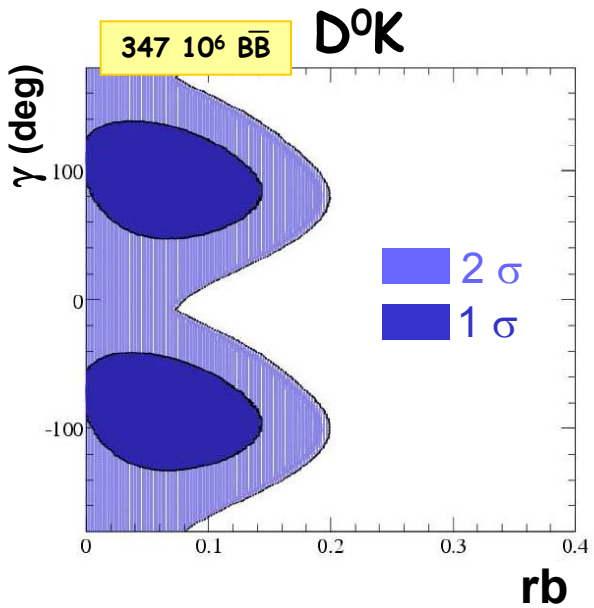
the stat. error is dominant

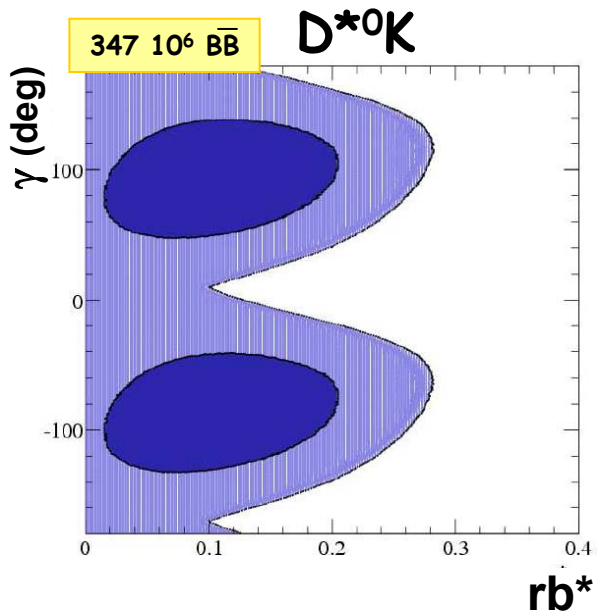
all the x,y results in the backup slides

- *systematics (no Dalitz model)*
  - shape of the ΔE, m_{ES}, Fisher PDFs
  - efficiency map in the Dalitz plot
  - fractions of D^0/D^0bar in the background
  - background Dalitz shape
  - ...
- *systematics Dalitz model*
  - used 8 alternative Dalitz Models (K-matrix for $\pi\pi$ S-wave, alternative param. for $K^{*0}(1430)$, removal of some resonances,...)

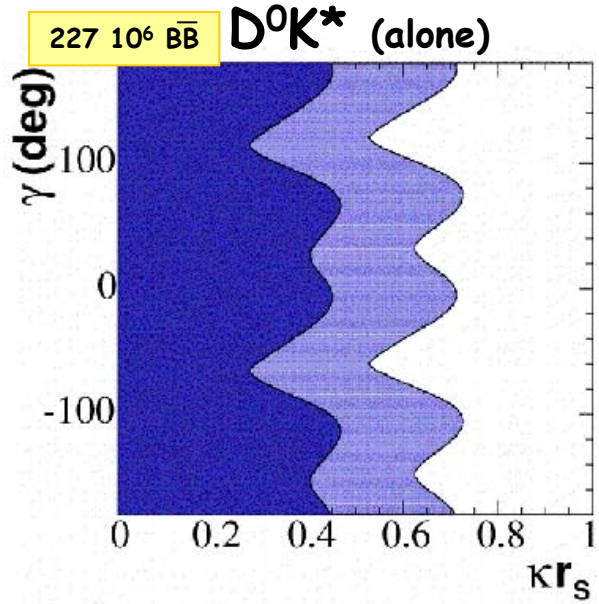
From x,y to γ

Used frequentist method to extract γ, r_B, δ_B from $(x_\pm, y_\pm)$





(5dim confidence intervals projections)



(3dim confidence intervals projections)

$$\left.\begin{array}{r} r_B < 0.142\ (r_B < 0.198) \\ 0.016 < r_B^* < 0.206\ (r_B^* < 0.282) \\ kr_s < 0.50\ (kr_s < 0.75) \end{array}\right\} 1\sigma\ (2\sigma)$$

$$\delta_B = (118 \pm 64 \pm 21 \pm 28)^\circ$$
$$\delta_B^* = (-62 \pm 59 \pm 16 \pm 13)^\circ$$

$$\boxed{\gamma = (92 \pm 41 \pm 10 \pm 13)^\circ}$$

(stat) (syst) (Dalitz)

Doesn't include D^0K^*

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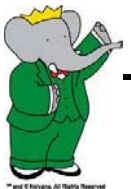
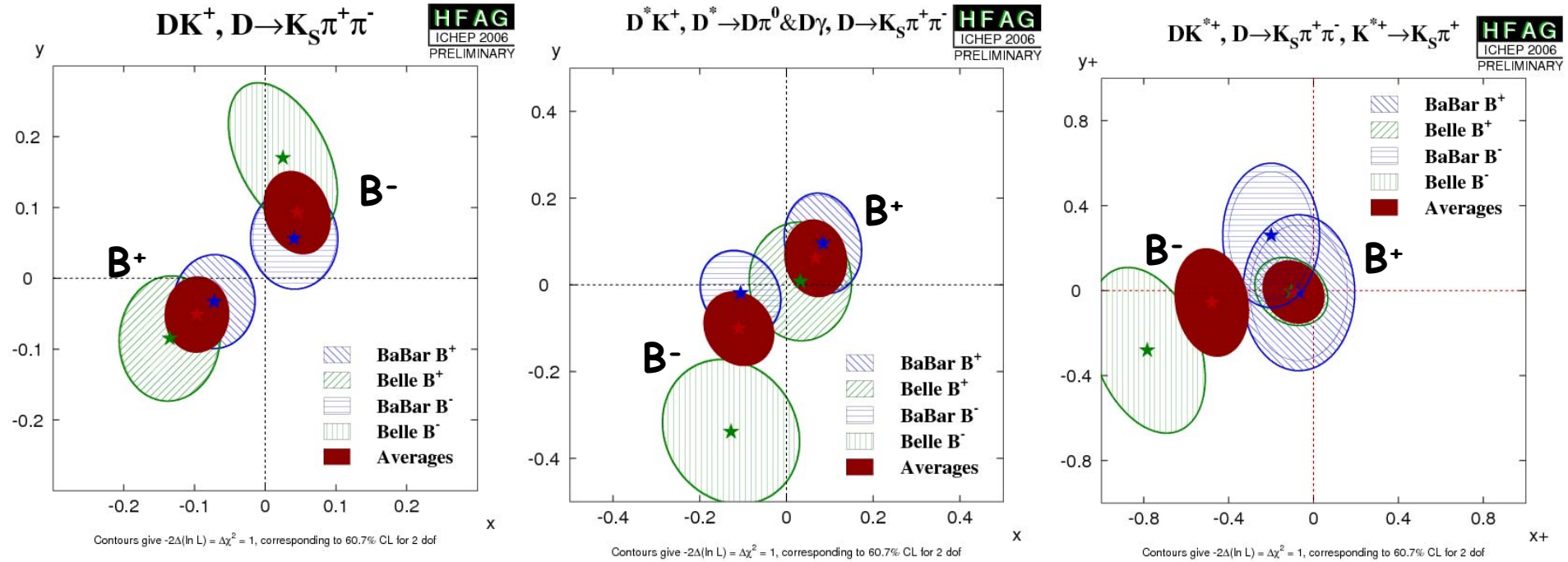
hep-ex/0507101



Comparison with Belle and role of r_B



[plots do not include Dalitz model errors]

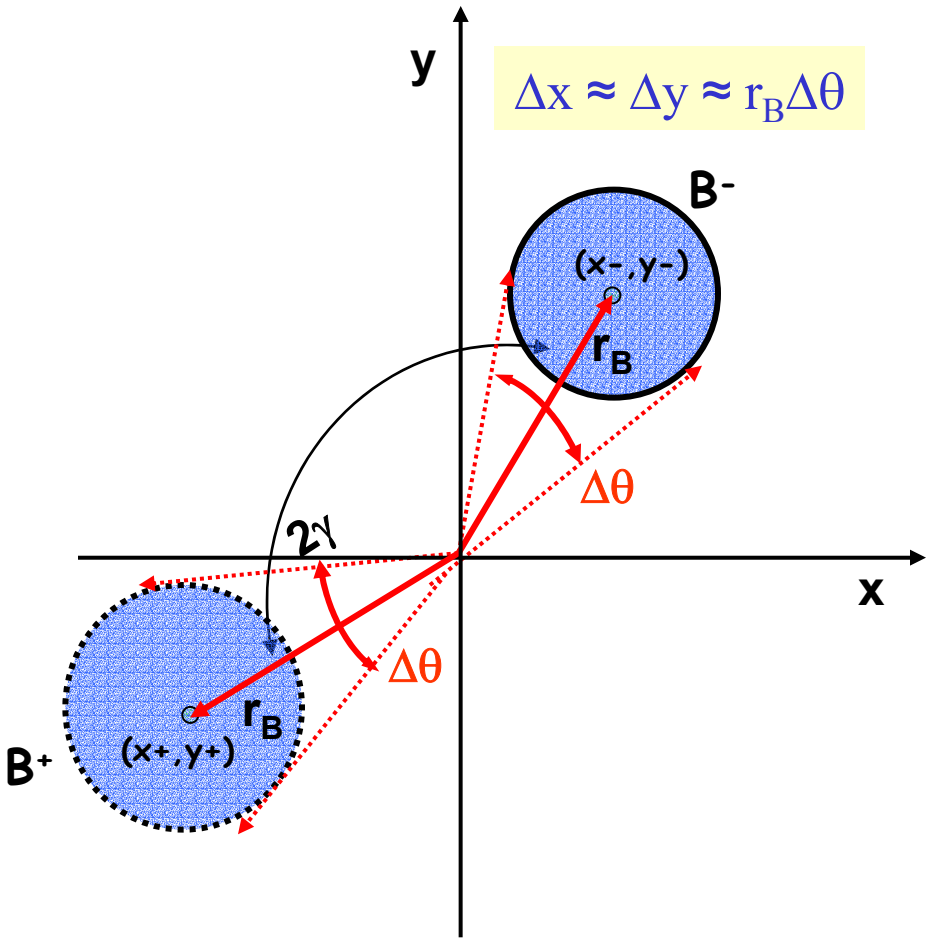
BaBar: $\gamma = (92 \pm 41 \pm 10 \pm 13)^\circ$

Belle: $\gamma = (53^{+15}_{-18} \pm 3 \pm 9)^\circ$

[D^0K^* not included]

- *better precision of BaBar (x,y) does NOT translate to a smaller error on γ. Why?*

Dependence of $\Delta\gamma$ on the measured r_B



$\Delta x \approx \Delta y \approx r_B \Delta\theta$

➔ $\Delta\gamma \sim 1/r_B$

the error of γ is ~ proportional to the uncertainty of (x,y)'s and inversely proportianal to the distance from (0,0).

Belle measurement is consistent with larger r_B.

Future prospects

- *With 2ab^{-1} (~BaBar+Belle at the end of 2008), we expect:*
  - 2300 B→D0K; 900 B→D*0K; 450 B→D0K*
  - $\sigma(x,y)$=0.030 (B→D0K), 0.046 (B→D*0K), 0.100 (B→D0K*)

Dalitz model sys. not included

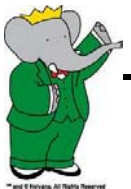
- *Difficult to predict the uncertainty on γ because the relative error on rb(*) is still large*
  - Scen1: rb(DK)=0.072; rb(D*K)=0.064; rb(DK*)=0.15: $\sigma(\gamma)$~**13°**
  - Scen 2: rb(DK)=0.098; rb(D*K)=0.104; rb(DK*)=0.24: $\sigma(\gamma)$~ 9°
  - Scen 3: rb(DK)=0.046; rb(D*K)=0.024; rb(DK*)=0.06: $\sigma(\gamma)$~25°

- *Dalitz model systematics ~10° today. It's unlikely it will ever go below ~5° using flavor-tagged D^0's.*
  ➔ Though it may not have a major impact at the B-factories…

- *… it will certainly limit this measurement at the next generations of experiments! (LHCb, superB)*
  - ➔ <u>model independent analysis</u>

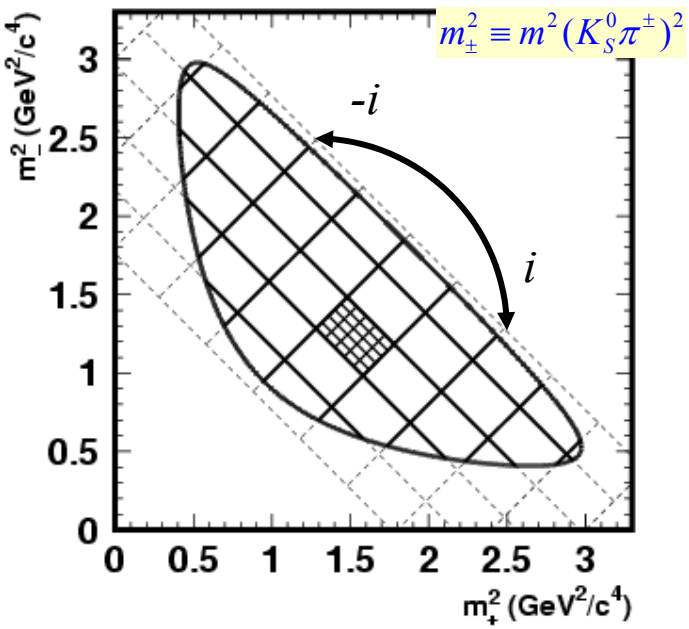
UTFit

rB(DK) = 0.072±0.026
rB(D*K) = 0.064±0.040
rB(DK*) = 0.15±0.09



Model Independent Analysis

[Giri, Grossman, Soffer, Zupan, PRD **68**, 054018 (2003)]



- *divide the D→Ksππ Dalitz plot in 2k bins (symmetric with respect to the m_+^2 vs. m_-^2 axis.)*
- *express the $B^\pm \to DK^\pm$ yields in each bin in terms of rb,γ,δ_b and a total of 2k unknowns c_i,s_i*
- *➔ 4k equations with 2k+3 unknowns, solvable for k≥2 in principle*

with this choice of binning this condition holds: $c_i = c_{-i}$, $s_i = -s_{-i}$

for example in bin i and –i (see figure):

$$\int_i d\Gamma(B^- \to (K_S\pi^-\pi^+)_D K^-) = T_i + r_B^2 T_{-i} + 2[x_- c_i - y_- s_i]$$

$$\int_{-i} d\Gamma(B^- \to (K_S\pi^-\pi^+)_D K^-) = T_i + r_B^2 T_{-i} + 2[x_+ c_i - y_+ s_i]$$

x±,y± usual cartesian coordinates

$T_i = \int_i |A_D(m_-^2, m_+^2)|^2 \, dm_-^2 dm_+^2$ is measured with flavor tagged $D^0 \to Ks\pi\pi$ data

Model Independent Analysis

- *As a matter of fact, the 4k equations system with 2k+3 unknowns (prev. slide) requires additional input to be solvable (even at LHCb or at a SuperB).*

- *Need to measure c_i from CP-tagged $D^0 \to K_S\pi\pi$ to reduce the error.*

  $\Upsilon(3770) \to D\bar{D} \to D_{CP}D(K_S\pi\pi)$ @ CLEO-c

- *If the bin size can be chosen small enough (it depends on the $B \to DK$ signal yield) it's possible to constrain also s_i with*

  $$s_i = \pm\sqrt{1-c_i^2}$$

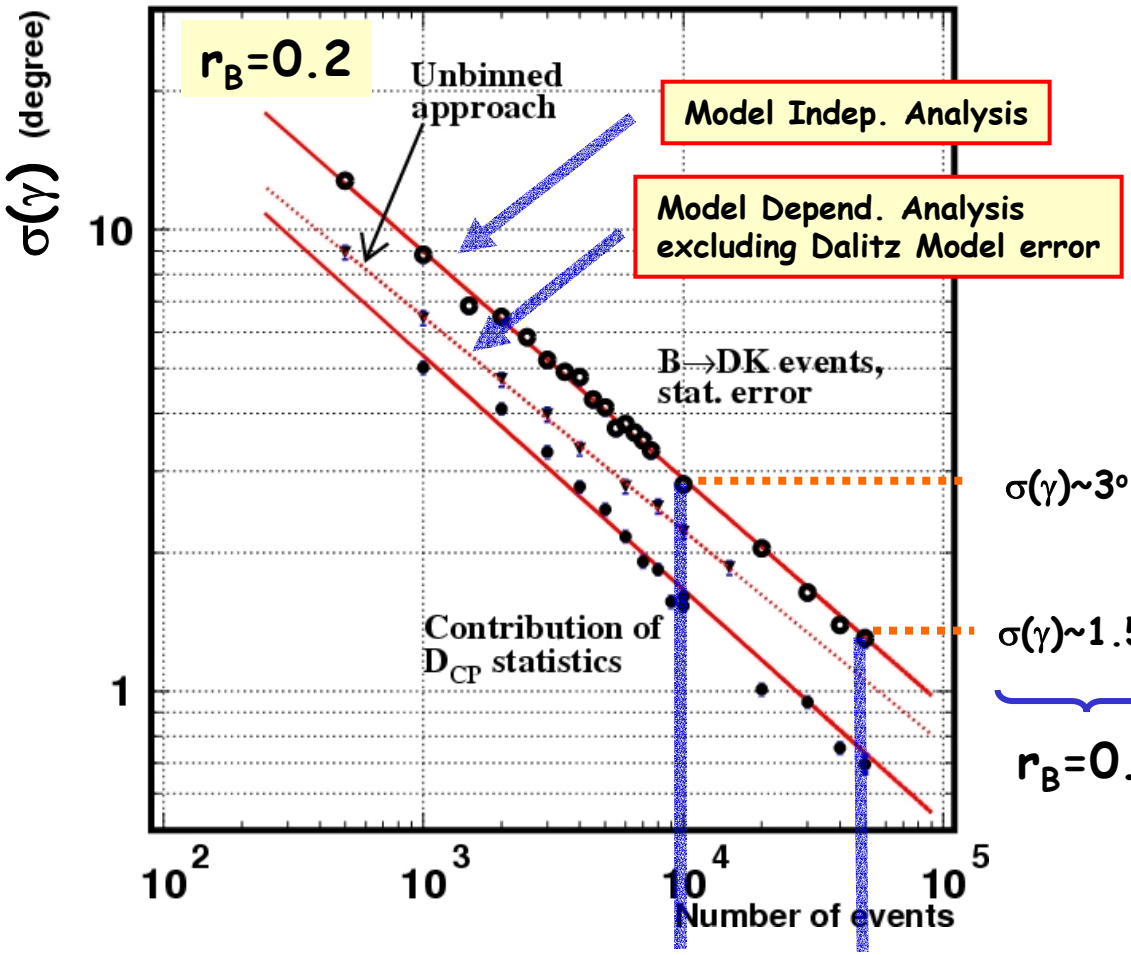
- *preliminary studies:*
  $\delta\gamma \sim 8^o$ with 5000 $B \to DK$ events (r_B=0.1)
  (but it implies a sufficient number of CP-tagged D)

  hep-ph/0510246
  and CKM2006 WG5 session

- *CLEO-c data probably not enough for LHCb precision*
  Need BES-III data (beam collisions expected in 2007)

γ with Model-Independent Analysis

Bondar and Poluetkov, hep-ph/0510246



with $50ab^{-1}$
(1year of Super B)
$\sigma(\gamma)$~4.5° if r_B=0.07
(B→D⁰K only)

$\sigma(\gamma)$~3° $\sigma(\gamma)$~9° (rB=0.07)

$\sigma(\gamma)$~1.5° $\sigma(\gamma)$~4.5° (rB=0.07)

r_B=0.2 r_B=0.07

$10ab^{-1}$ $50ab^{-1}$ ←(B→D⁰K only)

$B^{\pm} \to D^0 K^{\pm}$ with $D^0 \to \pi^+ \pi^- \pi^0$

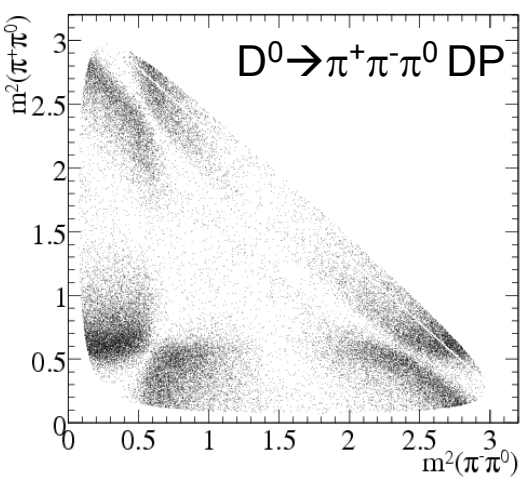
Method

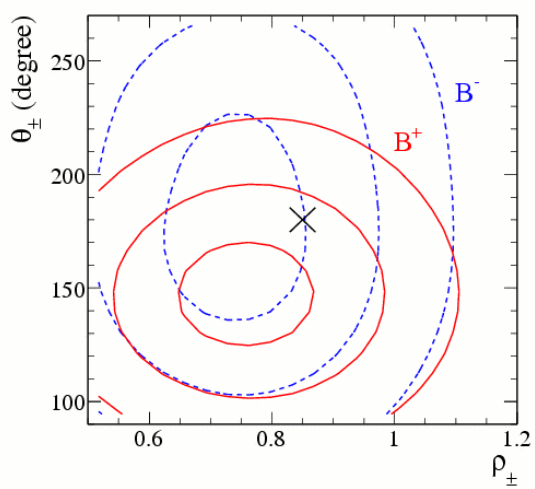
- ***First measurement** of CP parameters with this channel*
- *Compared to $B^- \to D^0 K^-$, $D^0 \to K^0_S \pi^+ \pi^-$:*
  - ~0.5 signal yield (on 324×10^6 $B\bar{B}$: 170±29 vs. 398±23)
  - larger background
  - different D Dalitz structure
  - exploits constraint of expected number of events in Likelihood
  - extracts $\rho_\pm$, $\theta_\pm$ instead of $x_\pm$, $y_\pm$, defined as:

$$x_\pm - x^0 = \rho_\pm \cos \vartheta_\pm$$
$$y_\pm = \rho_\pm \sin \vartheta_\pm$$

$$x_0 \equiv -\int \mathrm{Re}\left(f(m_+^2, m_-^2), f^*(m_-^2, m_+^2)\right) dm_+^2 dm_-^2$$

f= D Dalitz amplitude





ρ_+=0.75±0.11±0.06

ρ_-=0.72±0.11±0.06

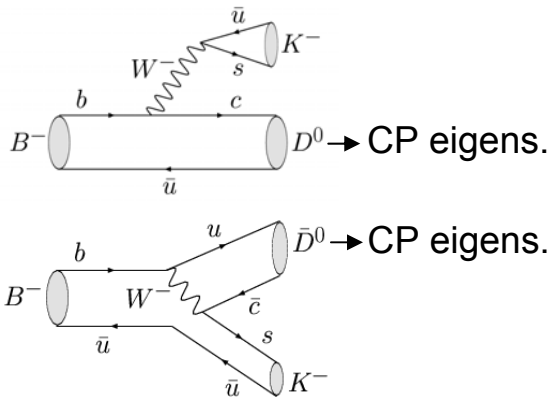
θ_+=(147±23±13)°

θ_-=(173±42±19)°

will be combined with other measurements

The Method GLW
(Gronau-London-Wyler)

The Classic Observables



selected $B \to D^0 K$, $B \to D^{*0} K$, $B \to D^0 K^*$

CP even: $D^0 \to K^+K^-, \pi^+\pi^-$

CP odd : $D^0 \to K_S\pi^0$, $K_S\omega$, $K_S\phi$

4 observables: R_{CP+}, A_{CP+}, R_{CP-}, A_{CP-}

$$R_{CP\pm} \equiv \frac{\Gamma(B^- \to D^0_{CP\pm}K^-) + \Gamma(B^+ \to D^0_{CP\pm}K^+)}{2\Gamma(B^- \to D^0 K^-)} =$$

$$= 1 \pm 2r_B \cos\gamma \cos\delta_B + r_B^2$$

$$A_{CP\pm} \equiv \frac{\Gamma(B^- \to D^0_{CP\pm}K^-) - \Gamma(B^+ \to D^0_{CP\pm}K^+)}{\Gamma(B^- \to D^0_{CP\pm}K^-) + \Gamma(B^+ \to D^0_{CP\pm}K^+)} =$$

$$= \pm 2r_B \sin\gamma \sin\delta_B / R_{CP\pm}$$

$R_{CP\pm}$, $A_{CP\pm}$ not independent:

$R_{CP+}A_{CP+} + R_{CP-}A_{CP-} = 0$

A Useful Alternative

- R_{CP+}, A_{CP+}, R_{CP-}, A_{CP-} can be combined to:

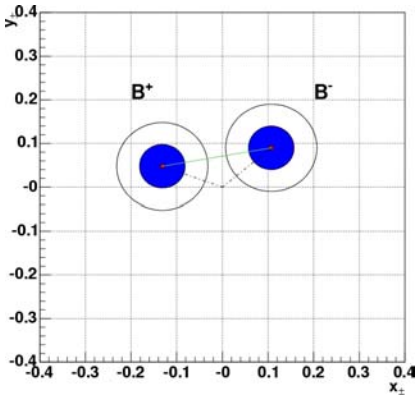
$$x_{\pm} = \frac{R_{CP+}(1 \mp A_{CP+}) - R_{CP-}(1 \mp A_{CP-})}{4}$$

$$r_b^2 = x_{\pm}^2 + y_{\pm}^2 = \frac{R_{CP+} + R_{CP-} - 2}{2}$$

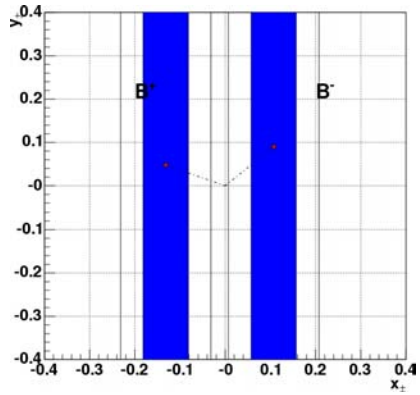
- The comparison with the Dalitz method is now straightforward:

Dalitz: x_+, y_+, x_-, y_-
GLW: x_+, x_-, r_B^2

Dalitz



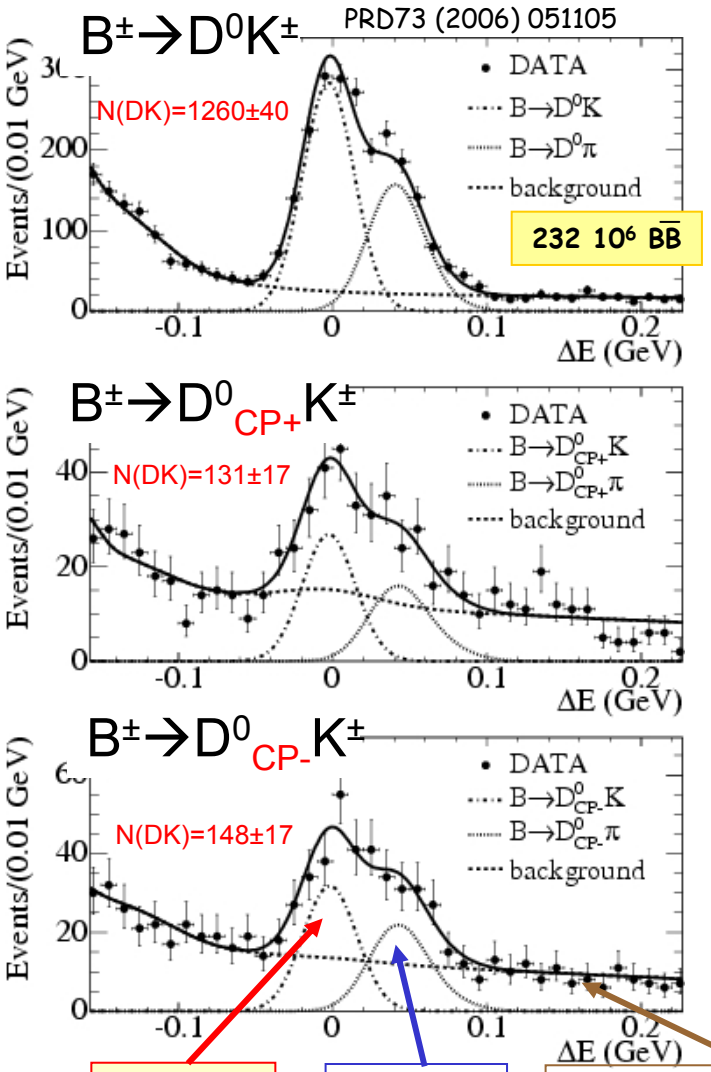
GLW



Constraint (weak) of r_b^2 not drawn

- Since the r_B^2 constraint of GLW is very weak, GLW alone can hardly constrain gamma. But it helps when joined to Dalitz. *Error of $x_\pm$ from GLW even smaller than Dalitz*

Signal Extraction



- *Yields are extracted with ML fit on ΔE and the Cherenkov angle*
- *$R_{CP\pm}$ are measured as $R_{CP\pm} \sim R\pm/R$*

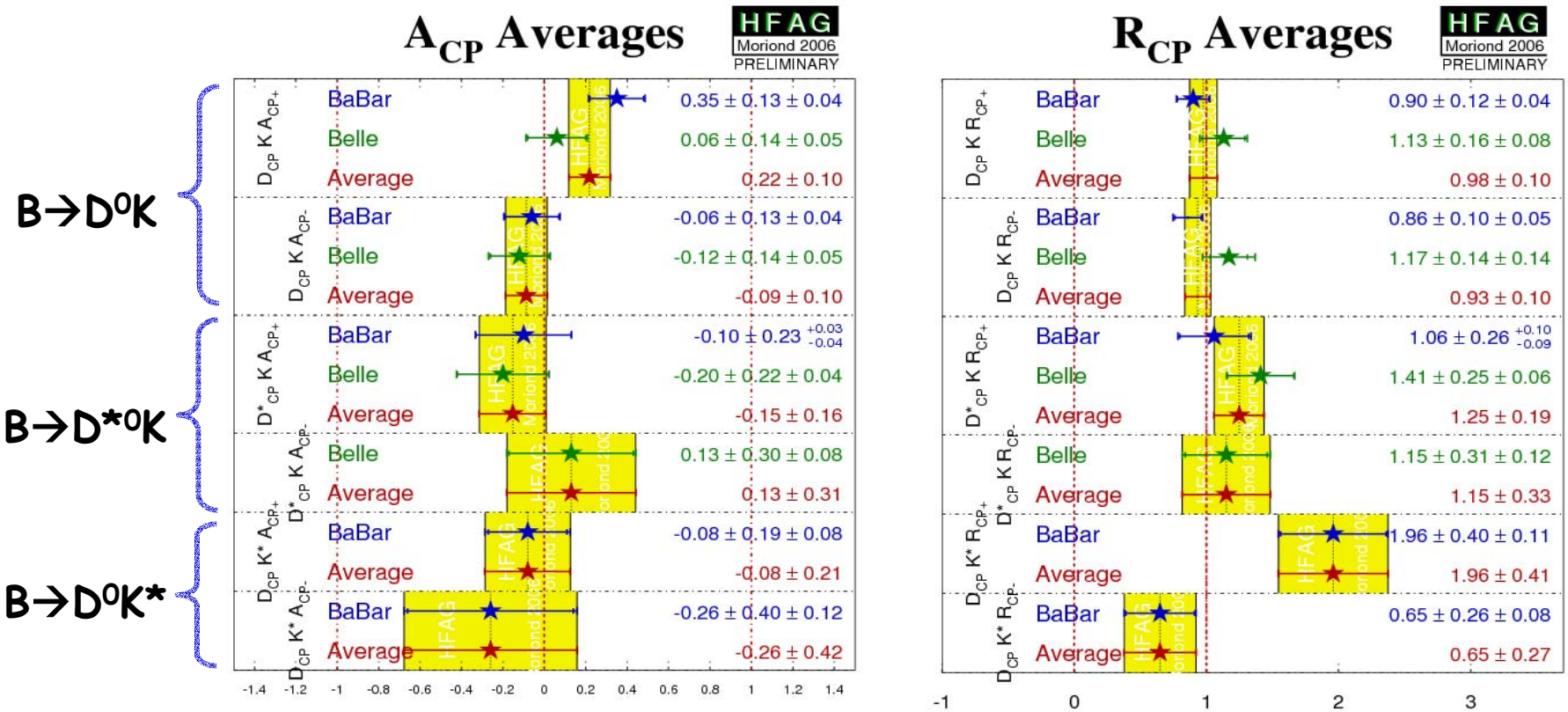
$$R = \frac{\mathcal{B}(B^- \to D^0 K^-) + \mathcal{B}(B^+ \to \bar{D}^0 K^+)}{\mathcal{B}(B^- \to D^0 \pi^-) + \mathcal{B}(B^+ \to \bar{D}^0 \pi^+)},$$

$$R_\pm = \frac{\mathcal{B}(B^- \to D^0_{CP\pm} K^-) + \mathcal{B}(B^+ \to D^0_{CP\pm} K^+)}{\mathcal{B}(B^- \to D^0_{CP\pm} \pi^-) + \mathcal{B}(B^+ \to D^0_{CP\pm} \pi^+)}$$

(Some systematic errors cancel in the ratio)

- ***most dangerous background sources:***
  - *charmless $B \to K\pi\pi/KKK$ for $D^0 \to \pi\pi/KK$*
  - *interference with $D^0 \to Ks(KK)$non-ϕ and $Ks(\pi\pi\pi^0)$non-ω for $D^0 \to Ks\phi$ and $Ks\omega$*

Summary of GLW Results



BaBar:

Phys.Rev. D73 (2006) 051105
Phys.Rev. D71 (2005) 031102
Phys.Rev. D72 (2005) 071103

Belle:

Phys.Rev. D73 (2006) 051106

Impact of GLW and Future Prospects

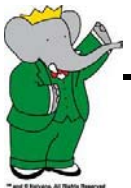
- *Projection of errors, for various assumptions on the values of r_B, at the end of 2008 (BaBar + Belle, ~2ab^{-1}).*

	Dalitz (2ab^{-1})		Dalitz+GLW (2ab^{-1})
1)	13°	→	11°
2)	9°	→	7.6°
3)	25°	→	20°

1) Current central values for r_B (D^0K + $D^{*0}K$ + D^0K^*) *

2) Current central values enhanced by 1σ

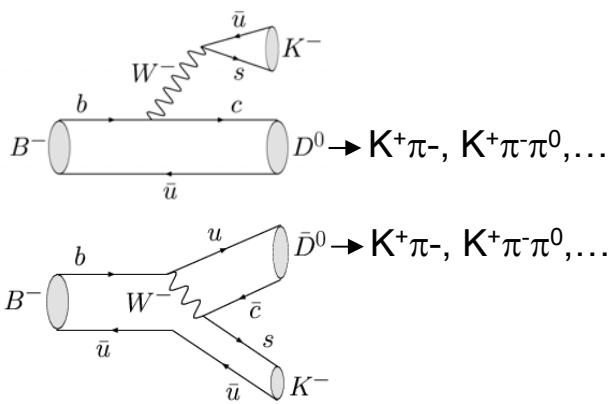
3) Current central values diminished by 1σ



* see also slide 20

The Method ADS
(Atwood-Dunietz-Soni)

Double Cabibbo Suppressed Decays



$$A_{ADS} \equiv \frac{\Gamma(B^- \to D[\to f]K^-) - \Gamma(B^+ \to D[\to \bar{f}]K^+)}{\Gamma(B^- \to D[\to f]K^-) + \Gamma(B^+ \to D[\to \bar{f}]K^+)}$$
$$= 2 r_b r_D S \sin\gamma / R_{ADS}$$

$$R_{ADS} \equiv \frac{\Gamma(B^- \to D[\to f]K^-) + \Gamma(B^+ \to D[\to \bar{f}]K^+)}{\Gamma(B^- \to D[\to \bar{f}]K^-) + \Gamma(B^+ \to D[\to f]K^+)}$$
$$= r_b^2 + r_D^2 + 2 r_b r_D C \cos\gamma$$

$D^0 \to K\pi$:

$r_D^2 \equiv \Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+)$ = (0.060±0.002)%

$S=\sin(\delta_B+\delta_D)$
$C=\cos(\delta_B+\delta_D)$

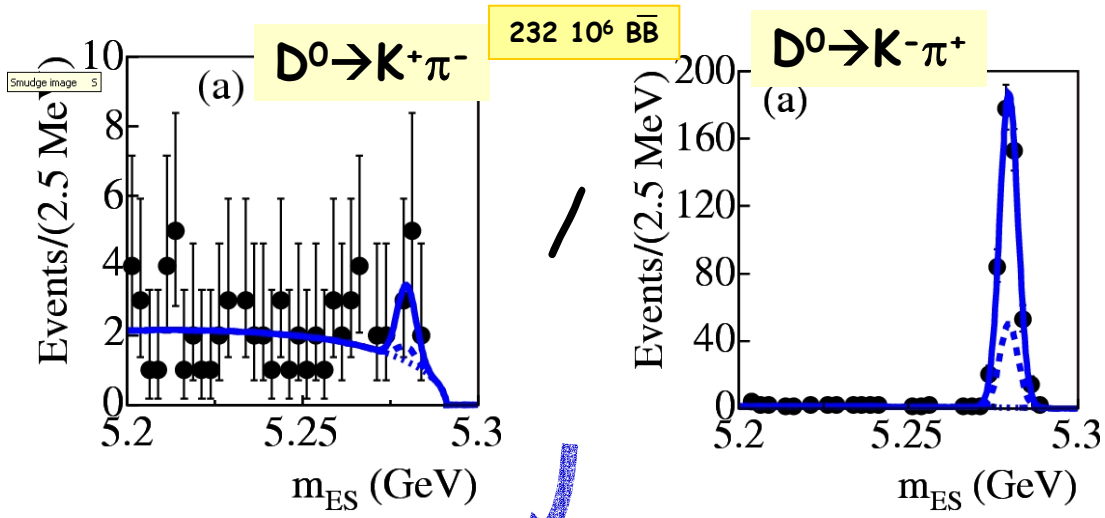
δ_D=strong phase diff. of $D^0/\bar{D}^0 \to K^+\pi^-$

- *Cons: very small BF (no signal observed yet)*
- *Pros: large b→u vs. b→c interference*

$D^0 \to K\pi$

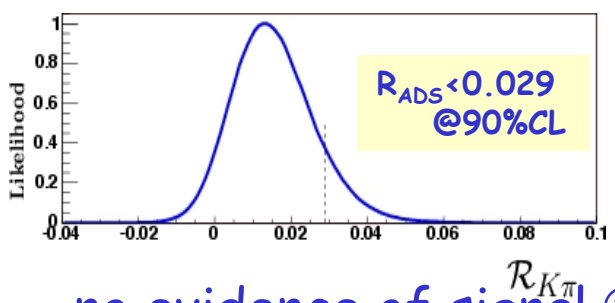
Selected $B \to D^0K$, $B \to D^{*0}K$, $B \to D^0K^*$. Below $B \to D^0K$

1)



2)

$$\mathcal{R}_{ADS(DK)} = (13^{+11}_{-9}) \times 10^{-3}$$



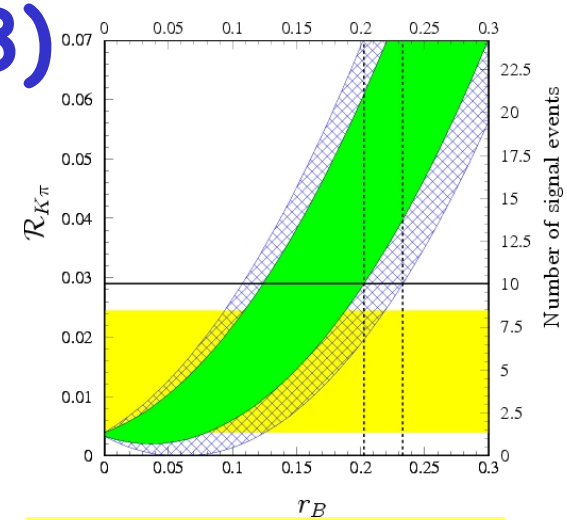
no evidence of signal ☹

set upper limit on R_{ADS}

From R_{ADS} to r_B

(using r_D=0.060±0.002)

3)



r_B<0.23 @90% CL

$D^0 \to K^+\pi^-\pi^0$

- *Compared to $D^0 \to K^+\pi^-$: 3-body decay, larger BF, more background, smaller r_D*

- *If signal were abundant then a Dalitz analysis as the $D^0 \to K_S\pi\pi$ could be done. BUT signal is very small (actually consistent with zero)*

➔ *ADS analysis:*

$$R_{ADS} \equiv \frac{\Gamma(B^- \to D[\to f]K^-) + \Gamma(B^+ \to D[\to \bar{f}]K^+)}{\Gamma(B^- \to D[\to \bar{f}]K^-) + \Gamma(B^+ \to D[\to f]K^+)}$$
$$= r_b^2 + r_D^2 + 2r_b r_D C \cos\gamma$$

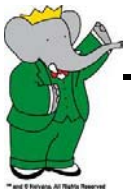
$r_D^2 \equiv \Gamma(D^0 \to K^+\pi^-\pi^0)/\Gamma(D^0 \to K^-\pi^+\pi^0)$ =(0.214±0.011)%

$$C = \frac{\int A_D(\vec{m})\bar{A}_D(\vec{m})\cos(\bar{\delta}(\vec{m}) - \delta(\vec{m}) + \delta_B)d\vec{m}}{\sqrt{\int \left|\bar{A}_D(\vec{m})\right|^2 d\vec{m} \cdot \int \left|A_D(\vec{m})\right|^2 d\vec{m}}}$$

$\vec{m}$ = point in Dalitz Plot

$\delta(m), \bar{\delta}(m)$ = strong phases of D→f and $\bar{D}$→f

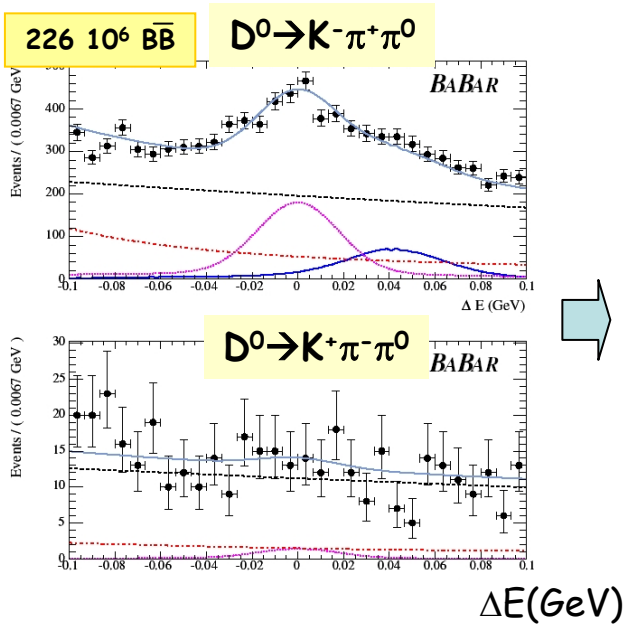
$|C| \leq 1$



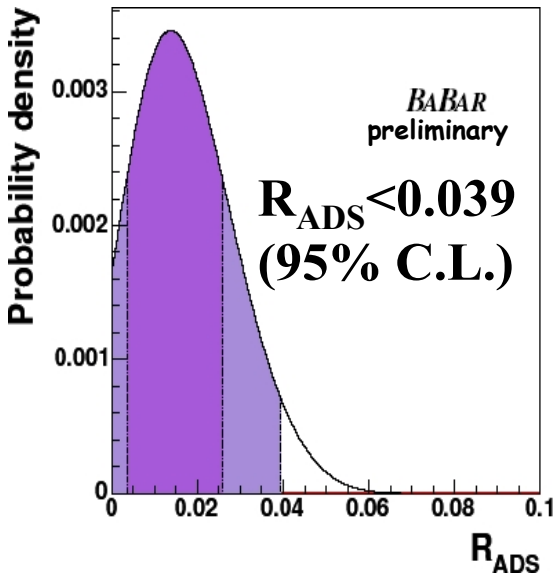
$D^0 \to K^+\pi^-\pi^0$ Results

- $B \to D^0 K$ selected with ML fit to ΔE, m_{ES} and neural network with event shape info

226 10^6 $B\bar{B}$

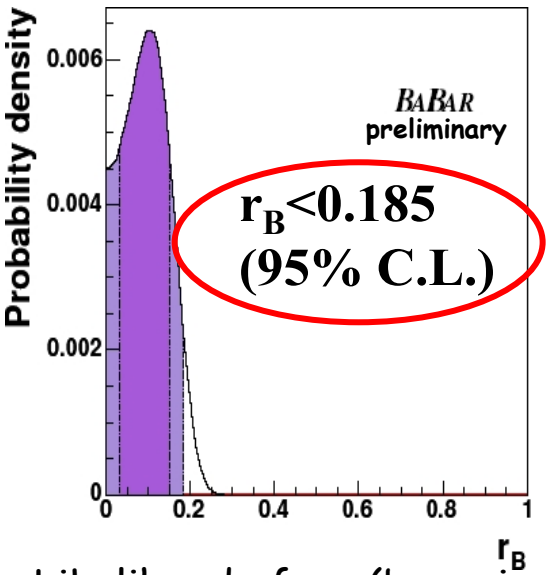


signal from ML fit



Likelihood of R_{ADS}

hep-ex/0607065



Likelihood of r_B (bayesian method with flat prior for r_B and $|C\cos\gamma|$)

submission to journal imminent

ADS: Summary of Results

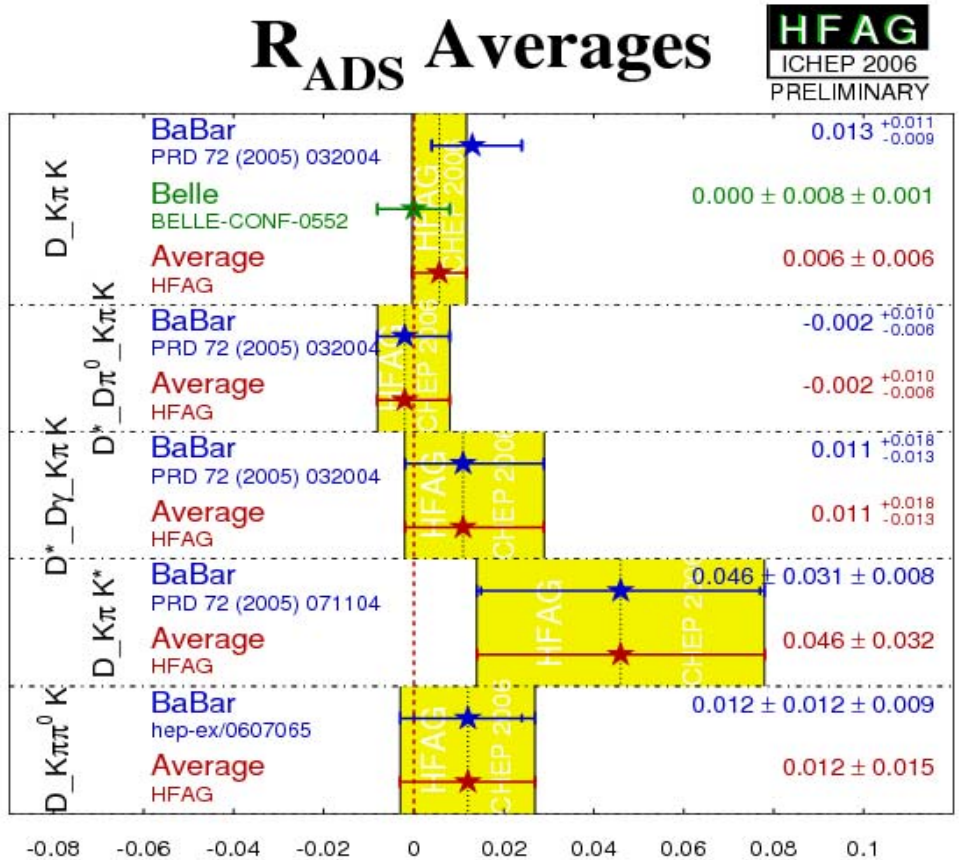
$B^- \to D^0 K^-$, $D^0 \to K^+\pi^-$

$B^- \to D^{*0}[D^0\pi^0]K^-$, $D^0 \to K^+\pi^-$

$B^- \to D^{*0}[D^0\gamma]K^-$, $D^0 \to K^+\pi^-$

$B^- \to D^0 K^{*-}$, $D^0 \to K^+\pi^-$

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

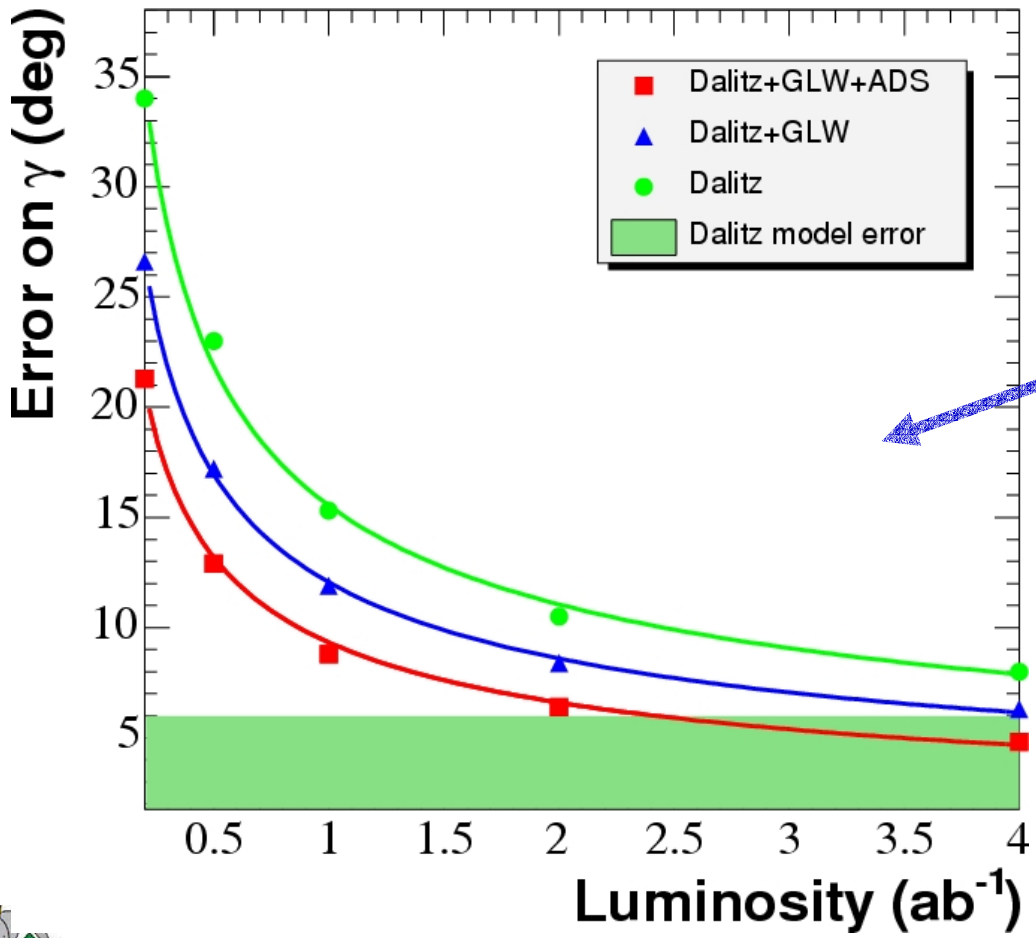


- *No signal observed so far: <u>only upper limits on r_B</u>*

γ with $1ab^{-1}$ and beyond

$D^0K + D^{*0}K + D^0K^*$

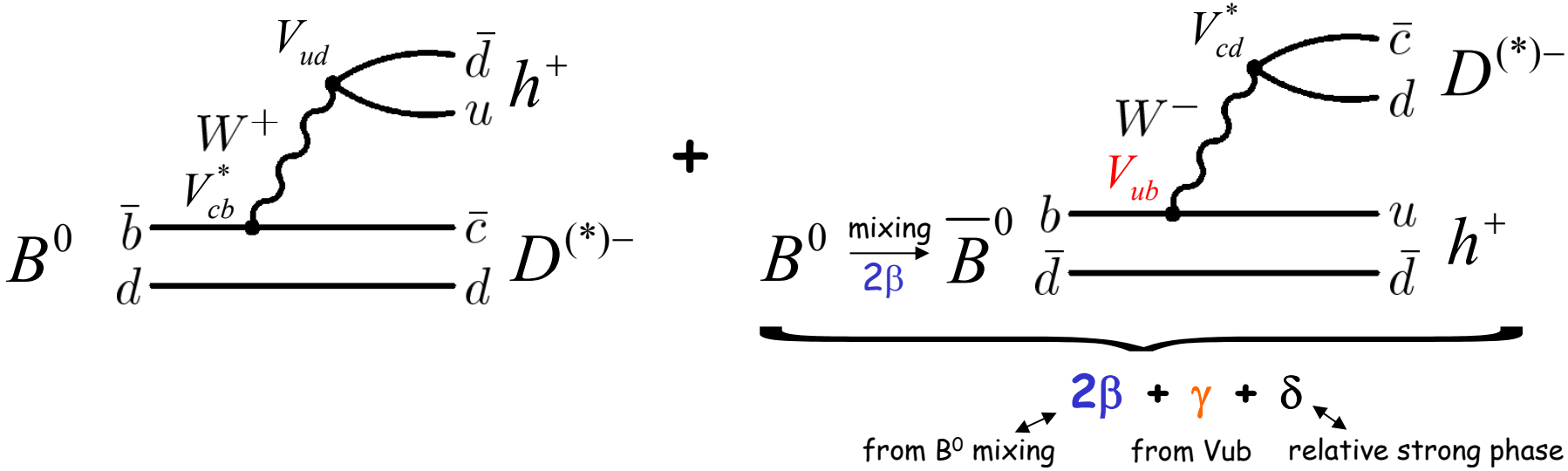
NOTE: r_B=0.1 assumption was used for each mode



gives an idea of the relative impact of different methods

$\sin(2\beta+\gamma)$ with time-dependent CP asymmetries of $B^0 \to D^{(*)-}\pi^+/\rho^+$

The Method



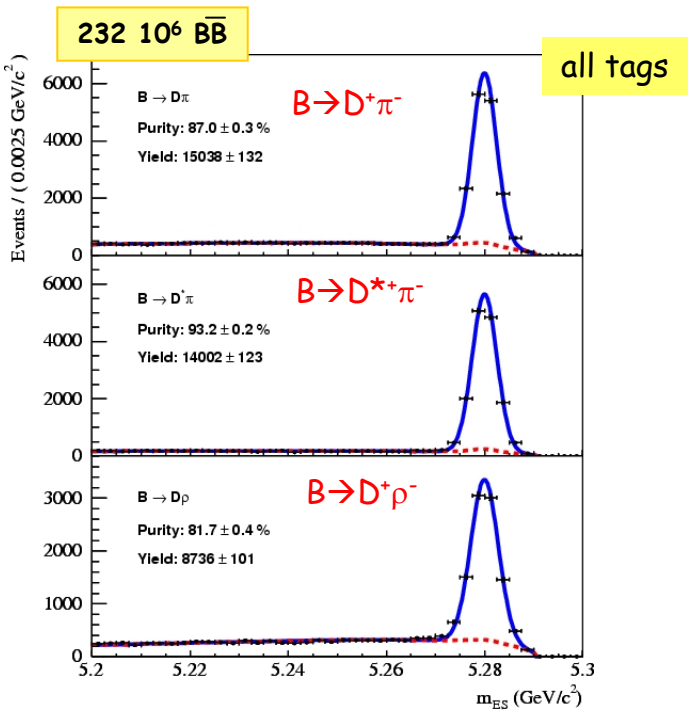
$$P(B^0 \to D^{(*)\mp} h^\pm, \Delta t) \propto 1 \pm C\cos(\Delta m_d \Delta t) + S^\mp \sin(\Delta m_d \Delta t)$$
$$P(\overline{B}^0 \to D^{(*)\mp} h^\pm, \Delta t) \propto 1 \mp C\cos(\Delta m_d \Delta t) - S^\pm \sin(\Delta m_d \Delta t)$$

$$S^\pm = \frac{2r}{1+r^2}\sin(2\beta+\gamma\pm\delta) \qquad C = \frac{1-r^2}{1+r^2} \cong 1 \qquad r = \left|\frac{A(\overline{B}^0 \to D^{(*)-}h^+)}{A(B^0 \to D^{(*)-}h^+)}\right| \sim 0.02$$

- *$S^\pm$ from time-dep. rates give $2\beta+\gamma$ once r is known*
- *BUT <u>r too small</u> to be extracted from C ==> r fixed using external input + SU(3) [see later]*

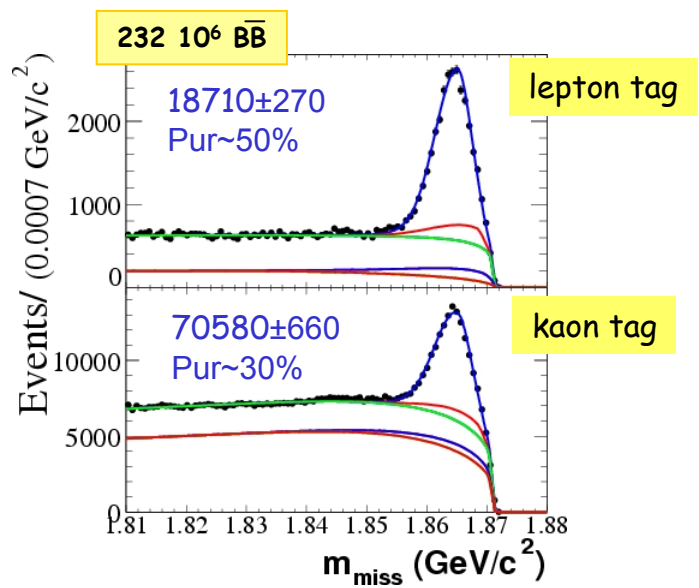
Selection of signal

- *full reconstruction of $B \to D^+\pi^-$, $D^{*+}\pi^-$, $D^+\rho^-$*



- *high purity*

- *partial reconstruction of $B \to D^{*+}\pi^-$ (in $D^{*+} \to D^0\pi^+$, D^0 is NOT reconstructed)*

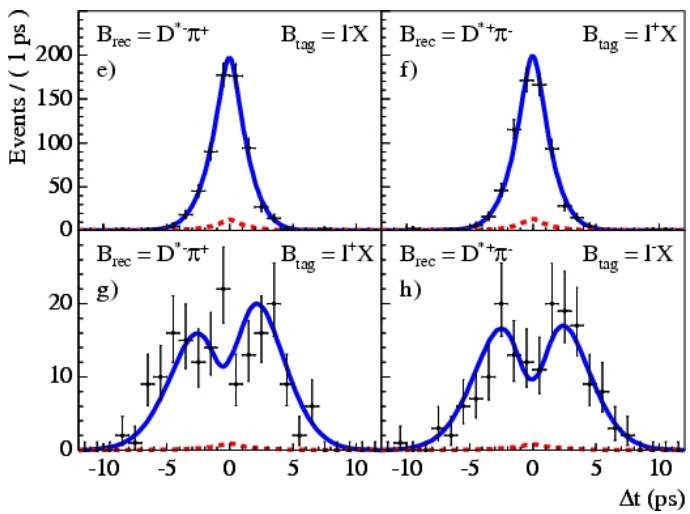


m_{miss} = missing mass of D^0

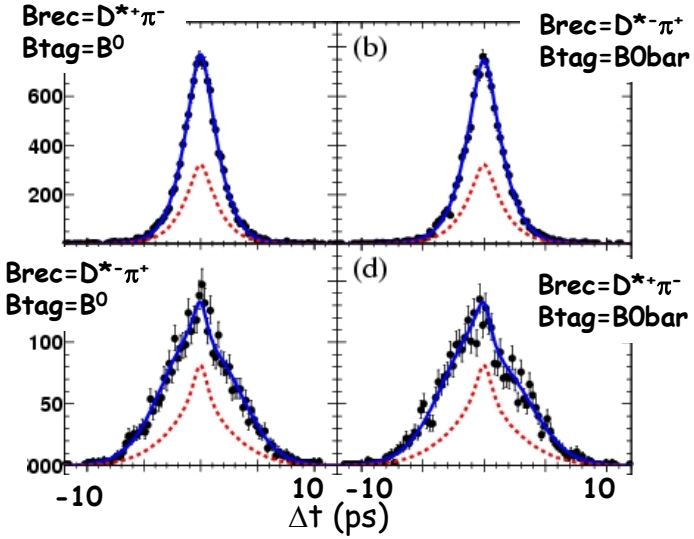
- *very high reco. efficiency*
- *lower purity (B tag-dependent)*
- *only $B^0 \to D^*\pi$*

Fit to the Time-dependent Rates

full reco, lepton tag



partial reco, lepton tag



- ***Complication:*** *Due to CPV effects on the Btag side, need to re-parameterize S±:* $S^{\pm} \rightarrow a \mp c \mp \eta \cdot b$ *, where:*

  $a = 2r\sin(2\beta+\gamma)\cos\delta$

  $b = 2r'\sin(2\beta+\gamma)\cos\delta'$

  $c = 2\cos(2\beta+\gamma)(r\sin\delta - r'\sin\delta')$

  0 with lepton tag

  (η=±1 for $D^{(*)\mp}h^{\pm}$)

O.Long et al, PRD68, 034010

➡ ***a, b, c are extracted from time-dep fit (instead of S±)***

- **only a and c (with lepton tag) are used to extract 2β+γ**

The Results

results from the time-dep fit

full reco		partial reco	
$a^{D\pi}$	$= -0.010 \pm 0.023 \pm 0.007$		—
$c^{D\pi}_{\rm lep}$	$= -0.033 \pm 0.042 \pm 0.012$		
$a^{D^*\pi}$	$= -0.040 \pm 0.023 \pm 0.010$	$a_{D^*\pi}$	$= -0.034 \pm 0.014 \pm 0.009$
$c^{D^*\pi}_{\rm lep}$	$= 0.049 \pm 0.042 \pm 0.015$	$c^{\ell}_{D^*\pi}$	$= -0.019 \pm 0.022 \pm 0.013$
$a^{D\rho}$	$= -0.024 \pm 0.031 \pm 0.009$		—
$c^{D\rho}_{\rm lep}$	$= -0.098 \pm 0.055 \pm 0.018$		

estimation of $r^{D^{(*)}h}$

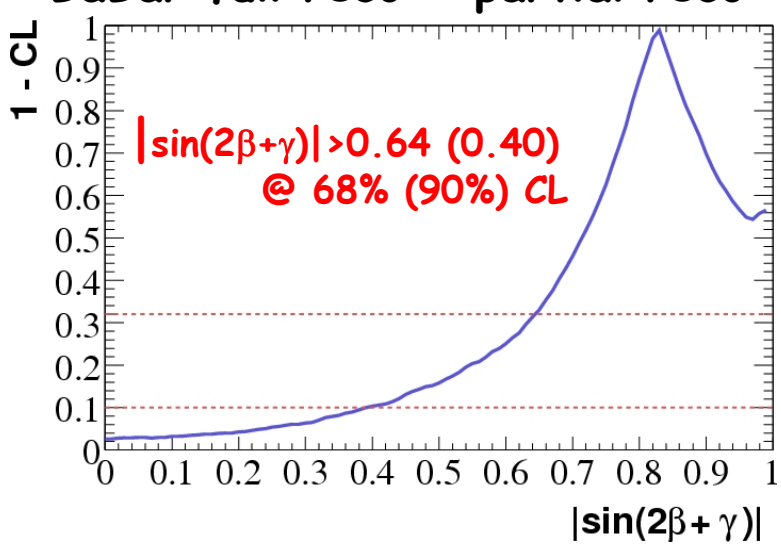
$$r^{D^{(*)}h} = \sqrt{\frac{BF(B^0 \to D_s^{(*)+}h^-)}{BF(B^0 \to D^{(*)-}h^+)}} \frac{f_{D^{(*)}}}{f_{D_s^{(*)}}} \tan(\vartheta_C)$$

- neglects exchange diagrams,
- uses f_D/f_{Ds} to take into account SU(3) break.
- assumes factorization

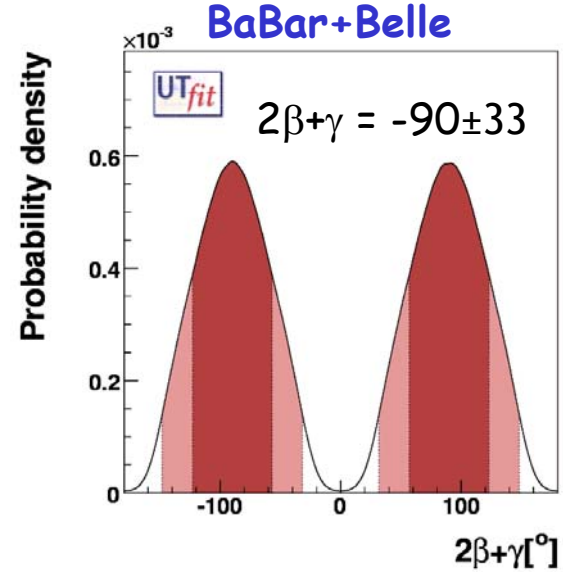
(a 30% relative error to these assumptions is applied)

see also Baak's talk at CKM2006

BaBar full reco + partial reco



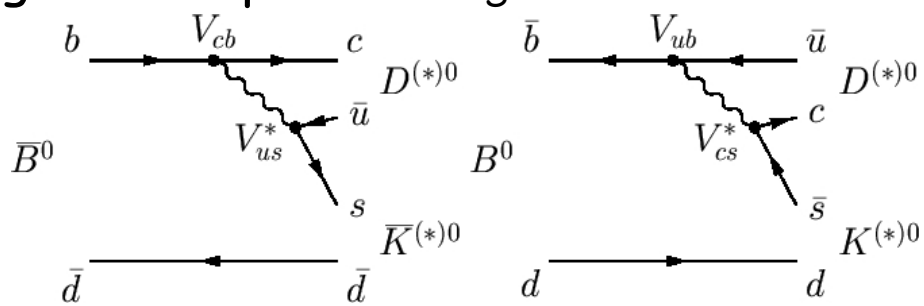
BaBar+Belle



Other Methods

$B^0 \to D^{(*)0} K^{(*)0}$

- *Interesting channel for the future.*
  - Can measure γ using $B^0 \to D^0 K^{*0}$ vs. $B^0 \to \bar{D}^0 K^{*0}$ ($K^{*0} \to K^+\pi^-$ self-tagging) as $B^- \to D^0 K^-$
  - Can measure $\sin(2\beta+\gamma)$ using time-dep $B^0 \to D^0 K_S^0$
- *expected large r_B (naïve estimate: $r_B \sim 0.4$)*



$$\mathcal{B}(\tilde{B}^0 \to D^0 \tilde{K}^0) = (5.3 \pm 0.7 \pm 0.3) \times 10^{-5}$$
$$\mathcal{B}(\tilde{B}^0 \to D^{*0} \tilde{K}^0) = (3.6 \pm 1.2 \pm 0.3) \times 10^{-5}$$

still too few sig. events for time-dep analysis

$$\mathcal{B}(\overline{B}^0 \to D^0 \overline{K}^{*0}) = (4.0 \pm 0.7 \pm 0.3) \times 10^{-5}$$
$$\mathcal{B}(\overline{B}^0 \to \overline{D}^0 \overline{K}^{*0}) = (0.0 \pm 0.5 \pm 0.3) \times 10^{-5}$$

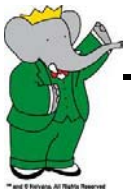
From $\mathcal{R}_i = \dfrac{\Gamma(\overline{B}^0 \to (K^+ X_i^-)_D \overline{K}^{*0})}{\Gamma(\overline{B}^0 \to (K^- X_i^+)_D \overline{K}^{*0})}$

$= \tilde{r}_B^2 + r_{D_i}^2 + 2\tilde{r}_B r_{D_i} \cos(\gamma + \delta_i)$

using bayesian procedure

$$r_B(D^0 K^{*0}) < 0.4 \quad @90\% \text{ CL}$$

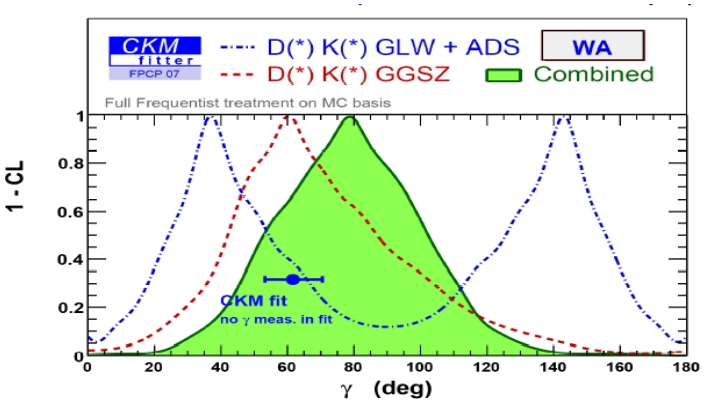
constraining γ with $B^0 \to D^{(*)0} K^{(*)0}$ could be harder than originally hoped



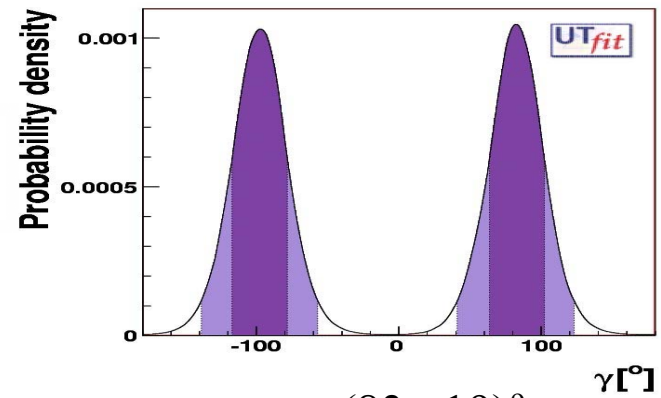
Combination BaBar + Belle

frequentist | **bayesian**

without sin(2β+γ)

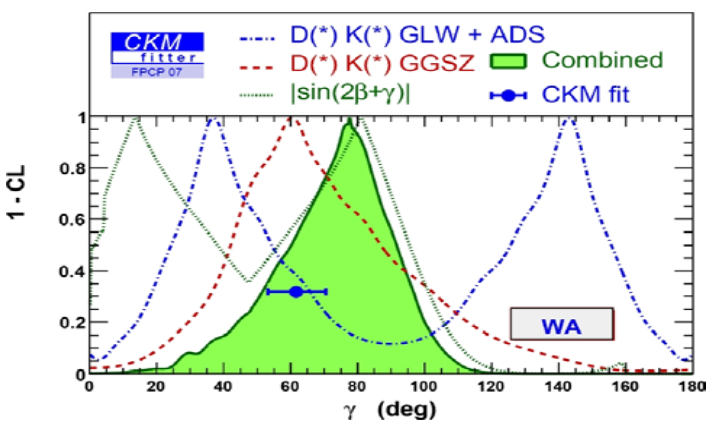


$$\gamma = (77 \pm 31)^{o}$$

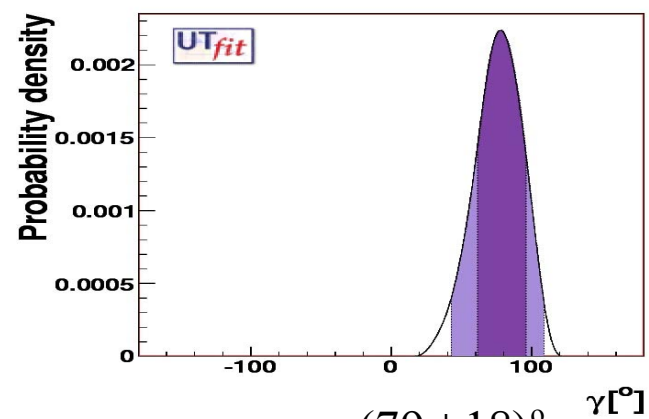


$$\gamma = (83 \pm 19)^{o}$$

with sin(2β+γ)



$$\gamma = (78^{+19}_{-26})^{o}$$

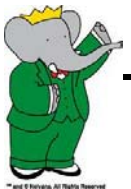


$$\gamma = (79 \pm 18)^{o}$$

*the knowledge of β is used

Summary and conclusions

- *Measurement of γ is very challenging. Considered mission impossible when the B-factories started taking data…*
- $B^{\pm} \to D^{(*)} K^{(*)\pm}$ *decays represent the main method. The extraction of γ is theoretically clean.*
- *$\sin(2\beta+\gamma)$ with time-dep rates of $B^0 \to D^{(*)} h$ help*
- *Statistics is currently too low for $B^0 \to D^{(*)0} K^{(*)0}$ (promising at LHCb or at a Super B)*
- *Difficult to predict the uncertainty of γ with larger data samples: the relative error of r_B is still too large.*



End

Likelihood used to extract signal yields and x,y

$$\mathcal{P}_j^\alpha \equiv \mathcal{P}_j^\alpha(m_{ES}, \Delta E, \mathcal{F}, m_D)\mathcal{P}_j^\alpha(s_{12}, s_{13})$$

$A(B^-) = |A_D(s_{12},s_{13}) + r_B e^{i(-\gamma+\delta_B)} A_D(s_{13},s_{12})|^2$

$|A_D(s_{12},s_{13})|^2$

$|A_D(s_{13},s_{12})|^2$

From MC and D^0 sideband data

$$\begin{aligned}
\mathcal{P}^\alpha = \; & f_{Sig}\mathcal{P}^\alpha_{Sig} + \\
& f_{Dh}\mathcal{P}^\alpha_{Dh} + \\
& f_{Cont}\left\{(1-R_{Cont})\mathcal{P}^{comb}_{Cont} + R_{Cont}\left[R^{RS}_{Cont}\mathcal{P}^\alpha_{Cont} + (1-R^{RS}_{Cont})\mathcal{P}^{\overline{\alpha}}_{Cont}\right]\right\} + \\
& f_{B\overline{B}}\left\{(1-R_{B\overline{B}})\mathcal{P}^{comb}_{B\overline{B}} + R_{B\overline{B}}\left[R^{RS}_{B\overline{B}}\mathcal{P}^\alpha_{B\overline{B}} + (1-R^{RS}_{B\overline{B}})\mathcal{P}^{\overline{\alpha}}_{B\overline{B}}\right]\right\} + \\
& \kappa_{WrongSig} f_{Sig}\left[R^{RS}_{WrongSig}\mathcal{P}^\alpha_{B\overline{B}} + (1-R^{RS}_{WrongSig})\mathcal{P}^{\overline{\alpha}}_{B\overline{B}}\right]
\end{aligned}$$

$\alpha = D^0, \overline{D^0}$

$f_{Sig,Dh,Cont,B\overline{B}}$ from data (extended likelihood $\Rightarrow$ yields)

$R_{Cont,\,B\overline{B}}$ Fraction of true D^0 from MC and data (m_{ES} sidebands)

$$R^{RS}_{Cont,B\overline{B},WrongSig} = \frac{\#B^- \to D^0 K^-}{\#B^- \to D^0 K^- + \#B^- \to \overline{D}^0 K^-}$$

Charge-flavor correlation from MC

x,y results of $B \to D^{(*)0} K^{(*)}$, $D^0 \to K_s \pi\pi$

BaBar

$347 \cdot 10^6 \; B\overline{B}$

hep-ex/0607104

CP parameter	$B^{\mp} \to \tilde{D}^{(*)0} K^{\mp}$
x_-	$0.041 \pm 0.059 \pm 0.018 \pm 0.011$
y_-	$0.056 \pm 0.071 \pm 0.007 \pm 0.023$
x_+	$-0.072 \pm 0.056 \pm 0.014 \pm 0.029$
y_+	$-0.033 \pm 0.066 \pm 0.007 \pm 0.018$
x_-^*	$-0.106 \pm 0.091 \pm 0.020 \pm 0.009$
y_-^*	$-0.019 \pm 0.096 \pm 0.022 \pm 0.016$
x_+^*	$0.084 \pm 0.088 \pm 0.015 \pm 0.018$
y_+^*	$0.096 \pm 0.111 \pm 0.032 \pm 0.017$

hep-ex/0507101

$B \to D^0 K^*$

CP parameter	Result
$x_{s-} \equiv \kappa r_s \cos(\delta_s - \gamma)$	$-0.20 \pm 0.20 \pm 0.11 \pm 0.03$
$y_{s-} \equiv \kappa r_s \sin(\delta_s - \gamma)$	$0.26 \pm 0.30 \pm 0.16 \pm 0.03$
$x_{s+} \equiv \kappa r_s \cos(\delta_s + \gamma)$	$-0.07 \pm 0.23 \pm 0.13 \pm 0.03$
$y_{s+} \equiv \kappa r_s \sin(\delta_s + \gamma)$	$-0.01 \pm 0.32 \pm 0.18 \pm 0.05$

$227 \cdot 10^6 \; B\overline{B}$

Belle

$386 \cdot 10^6 \; B\overline{B}$

Mode	x_-	y_-	x_+	y_+
$B^+ \to DK^+$	$0.025^{+0.072}_{-0.080}$	$0.170^{+0.093}_{-0.117}$	$-0.135^{+0.069}_{-0.070}$	$-0.085^{+0.090}_{-0.086}$
$B^+ \to D^*K^+$	$-0.128^{+0.167}_{-0.146}$	$-0.339^{+0.172}_{-0.158}$	$0.032^{+0.120}_{-0.116}$	$0.008^{+0.137}_{-0.136}$
$B^+ \to DK^{*+}$	$-0.784^{+0.249}_{-0.295}$	$-0.281^{+0.440}_{-0.335}$	$-0.105^{+0.177}_{-0.167}$	$-0.004^{+0.164}_{-0.156}$

hep-ex/0604054

TABLE V: Systematic errors in x, y variables.

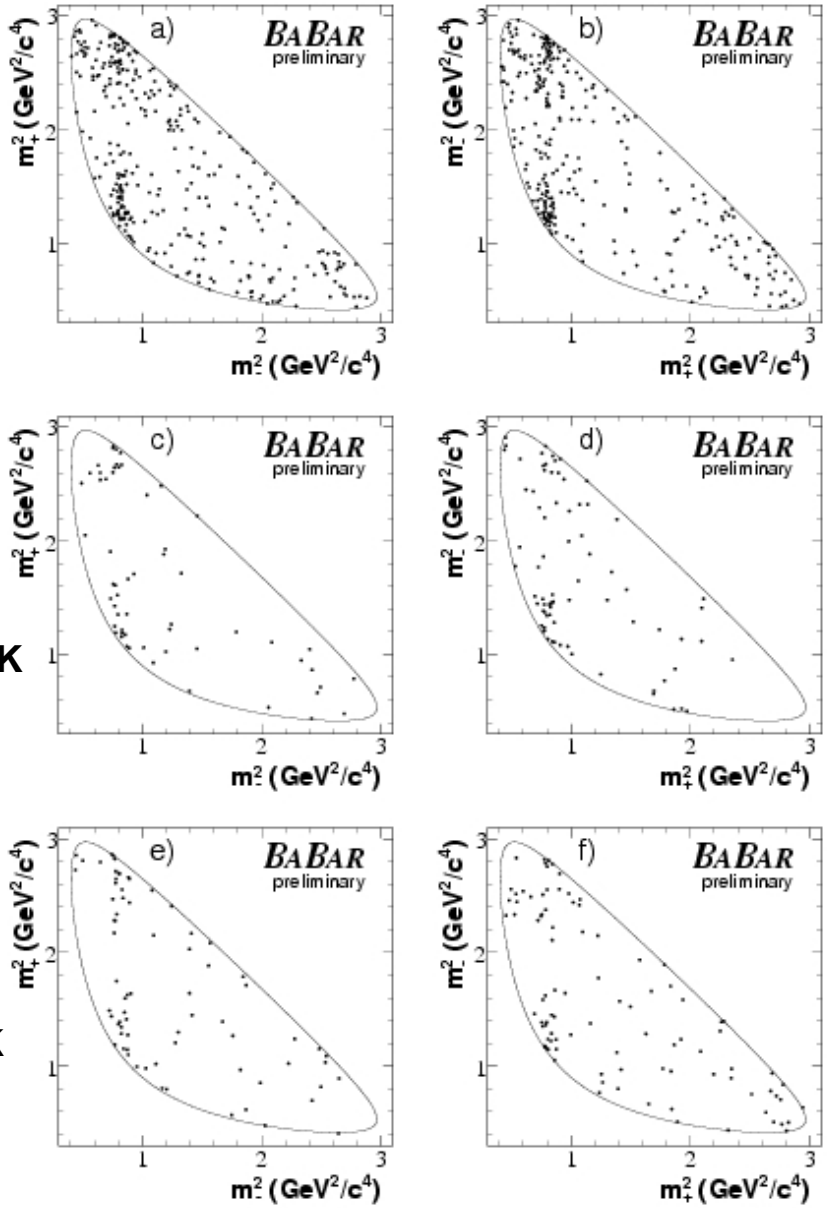
Component	$B^+ \to DK^+$ mode				$B^+ \to D^*K^+$ mode				$B^+ \to DK^{*+}$ mode			
	Δx_-	Δy_-	Δx_+	Δy_+	Δx_-	Δy_-	Δx_+	Δy_+	Δx_-	Δy_-	Δx_+	Δy_+
Total	0.013	0.016	0.017	0.009	0.023	0.027	0.004	0.011	0.029	0.046	0.006	0.013

B^- B^+

$B \to D^0 K$

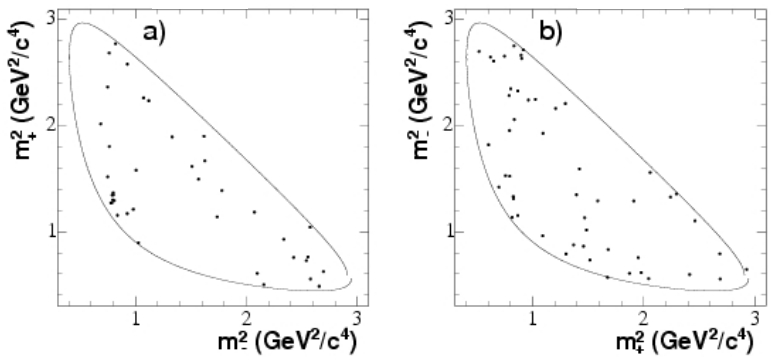
$B \to D^{*0}[D^0\pi^0]K$

$B \to D^{*0}[D^0\gamma]K$



BaBar: signal-enhanced Dalitz distributions

B^- $B \to D^0 K^*$ B^+

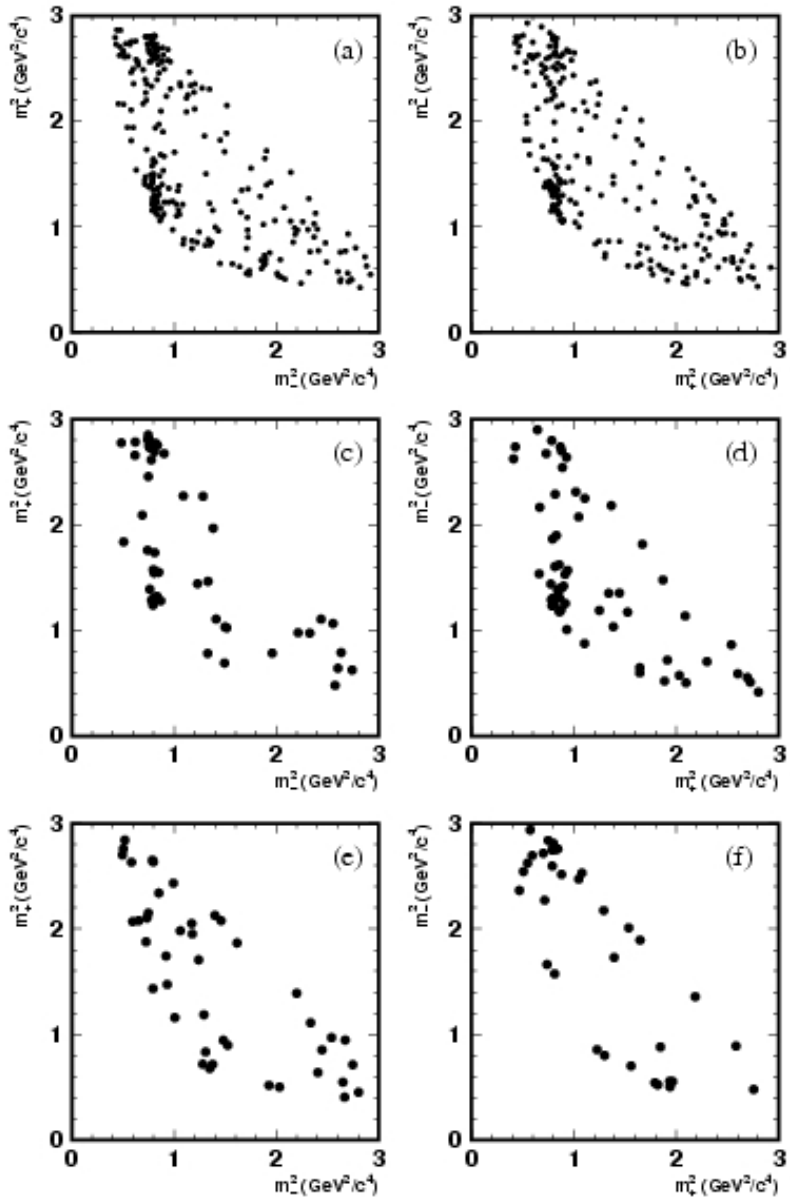


B^- B^+

$B \to D^0 K$

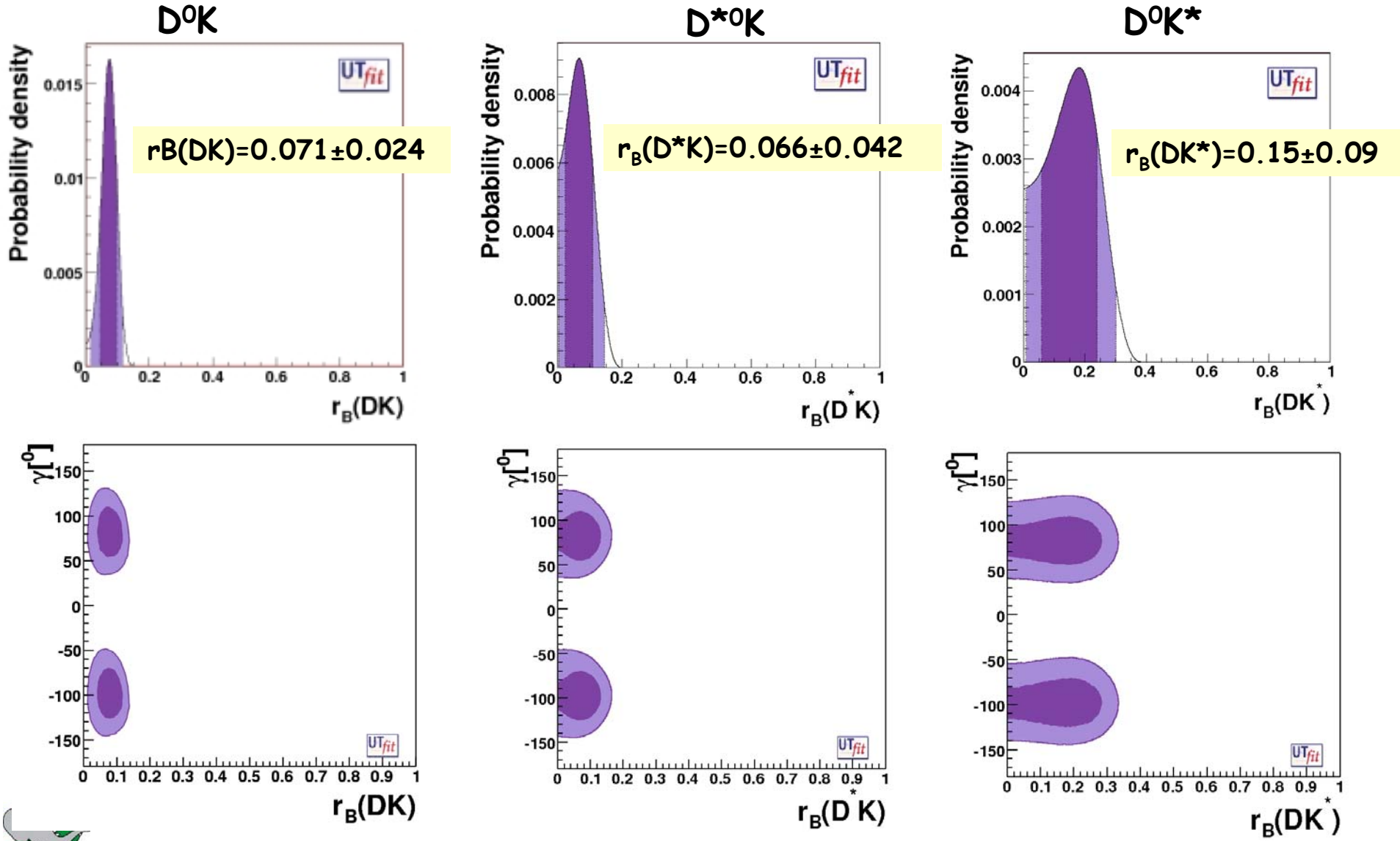
$B \to D^{*0}[D^0\pi^0]K$

$B \to D^0 K^*$



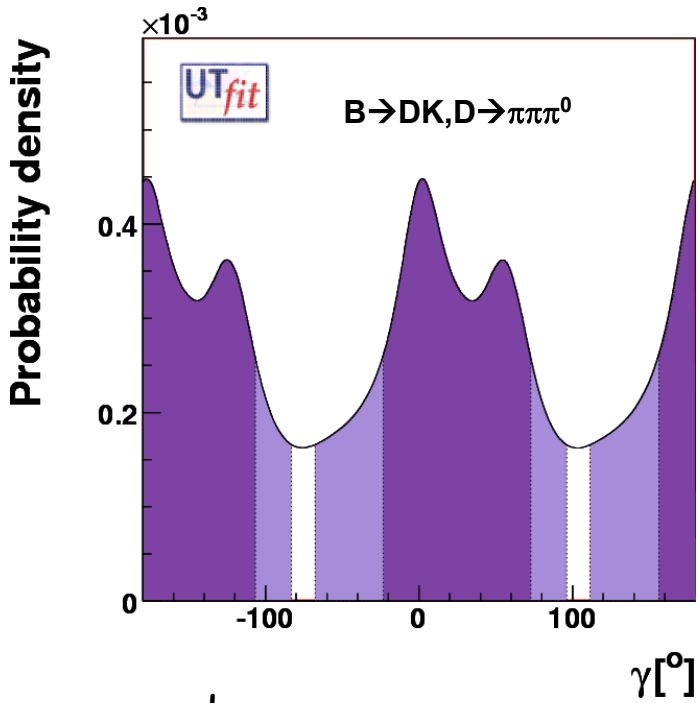
Belle: signal-enhanced Dalitz distributions

constraints on r_B



bayesian constrain on γ of $D^0 \to \pi\pi\pi^0$

*this measurement alone: γ = 25±48 @ 68%CL**
[-67,97] @ 95%CL



* UTfit, bayesian procedure