BABAR™

Recent Results from BaBar on the CKM Angles

Moritz Karbach

BaBar

Technische Universität Dortmund, Germany
Lehrstuhl experimentelle Physik 5

UNIVERSITÄT DORTMUND

April 2008

outline

1. BaBar and PEP-II
2. CKM angles
3. recent results
   - on **β**
   - on **α**
   - on **γ**
4. summary

Moritz Karbach
TU Dortmund

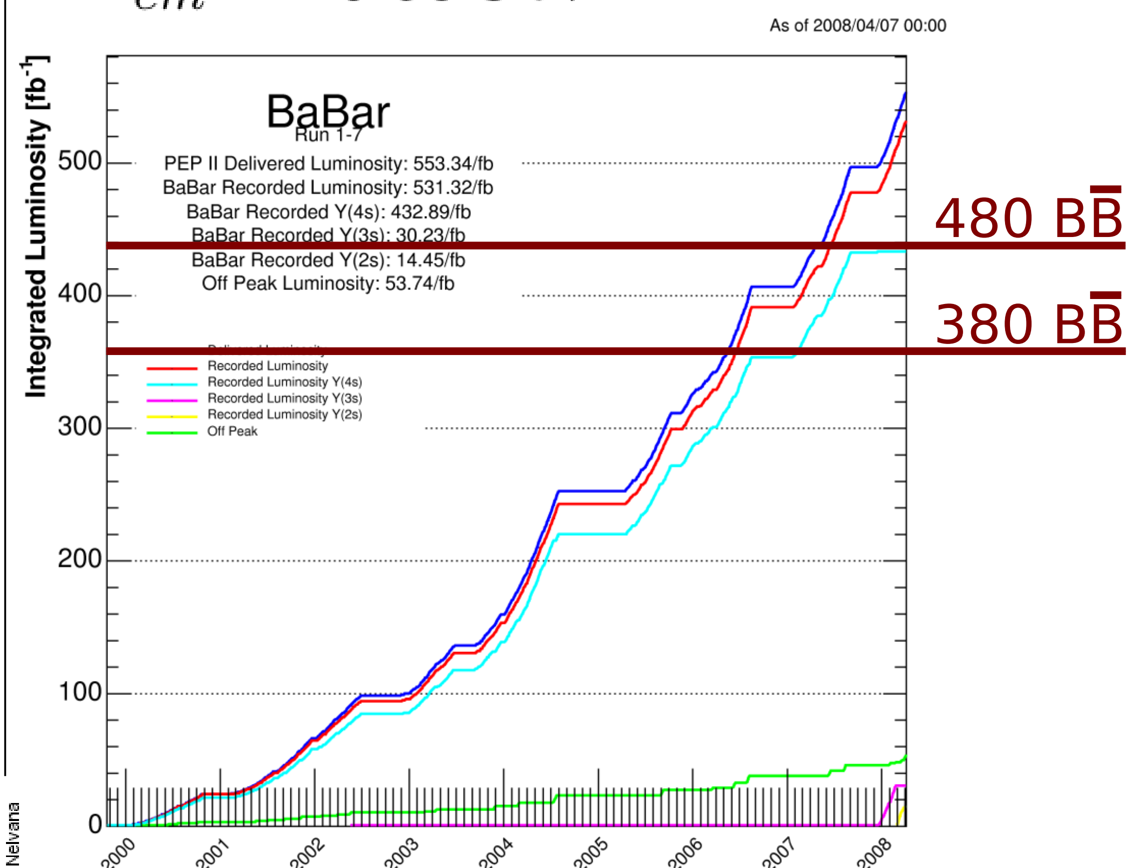
BaBar and PEP-II

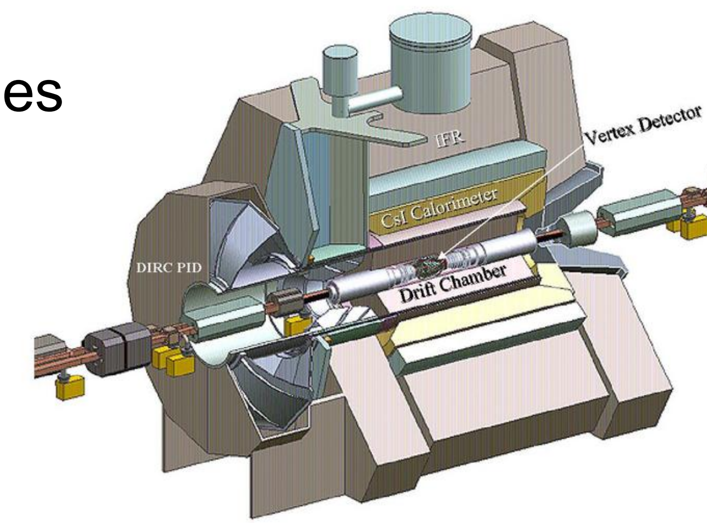
- B-Factory took data till April 7th, 2008.

480 ·10⁶ BB pairs final $\Upsilon(4S)$ dataset
380 ·10⁶ BB pairs used by most analyses

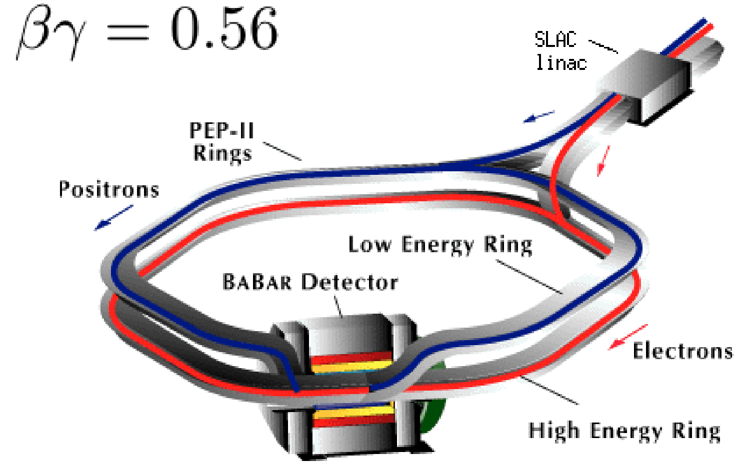
$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0,\ B^+B^-$$

$$E_{cm} = 10.58\,GeV$$





$$E(e^+) = 3.1\,GeV$$
$$E(e^-) = 9.0\,GeV$$
$$\beta\gamma = 0.56$$



CKM quark mixing mechanism

Moritz Karbach
TU Dortmund

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

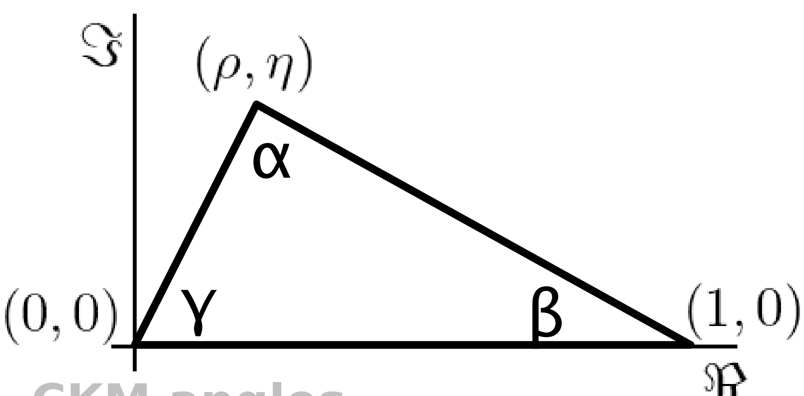
- flavor eigenstates are not mass eigenstates → relate them through a unitary matrix
- irreducible phase is the only source of CP violation in the Standard Model
- test the SM by over-constraining the unitarity triangle

Cabibbo
Kobayashi
Maskawa

$\lambda \approx 0.23$
$A \approx 0.8$
$\rho \approx 0.2$
$\eta \approx 0.4$

$$V^\dagger V = 1$$

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



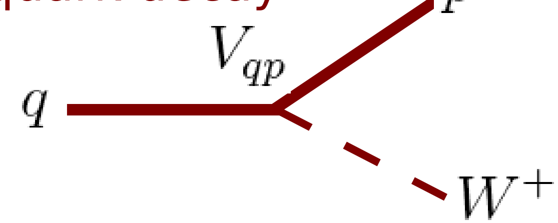
CKM angles

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

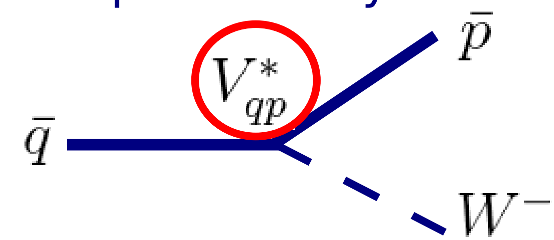
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

quark decay



anti-quark decay



β from $B^0 \rightarrow J/\Psi\ \pi^0$

Moritz Karbach
TU Dortmund

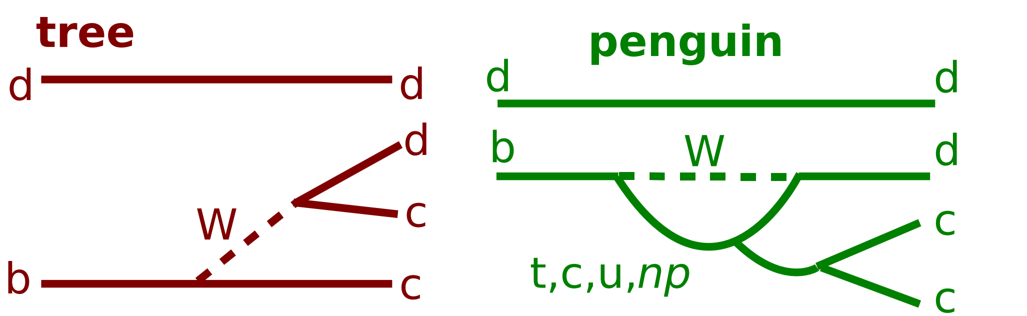
PHENO
April 28th 2008

466 ·10⁶ BB
April 2008 ***new!***
arxiv:0804.0896

- Cabibbo suppressed $b \rightarrow c\bar{c}d$ transition to CP even final state. $B^0 - \bar{B}^0$ mixing amplitude contains β.
- time dependent measurement to extract S and C

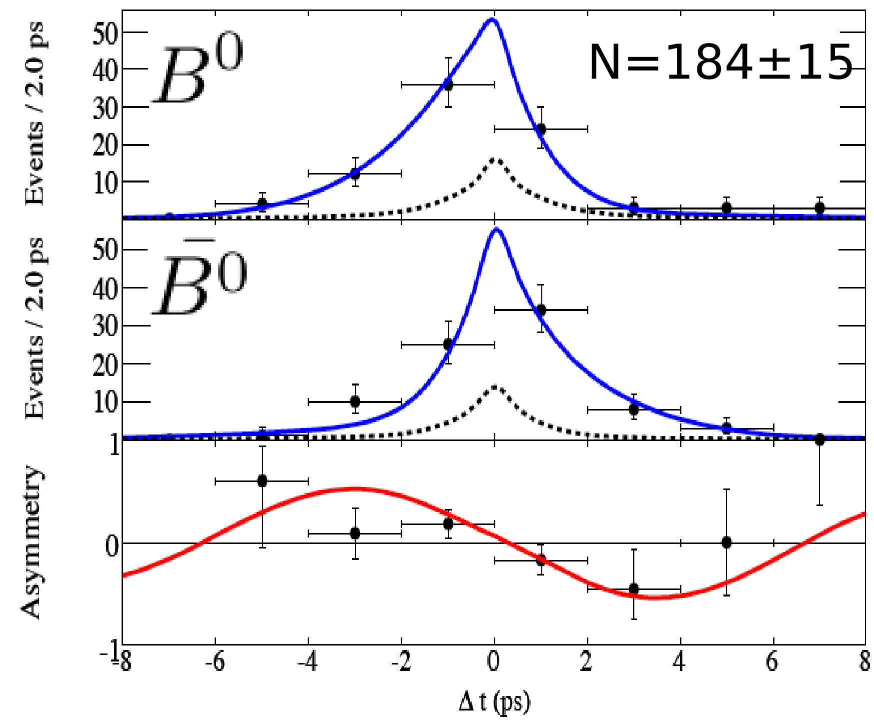
$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 \pm S\sin(\Delta m_d \Delta t) \mp C\cos(\Delta m_d \Delta t)]$$

- Tree level expectation is *S = -sin2β* and *C = 0*. If there is a significant penguin amplitude this mode could be sensitive to new physics.



$$\mathcal{B} = (1.69 \pm 0.14(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-5},$$
$$S = -1.23 \pm 0.21(\text{stat}) \pm 0.04(\text{syst}),$$
$$C = -0.20 \pm 0.19(\text{stat}) \pm 0.03(\text{syst}),$$

non-zero at 4.0σ !
Consistent with tree dominated SM.



β – more results

$B^0 \to c\bar{c}s$

- precision measurement

$J/\psi K^0_S$, $J/\psi K^0_L$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$, and $J/\psi K^{*0}$

$$\sin 2\beta = 0.714 \pm 0.032(\mathrm{stat}) \pm 0.018(\mathrm{syst})$$

383 ·10⁶ BB
October 2007
PRL99, 171803

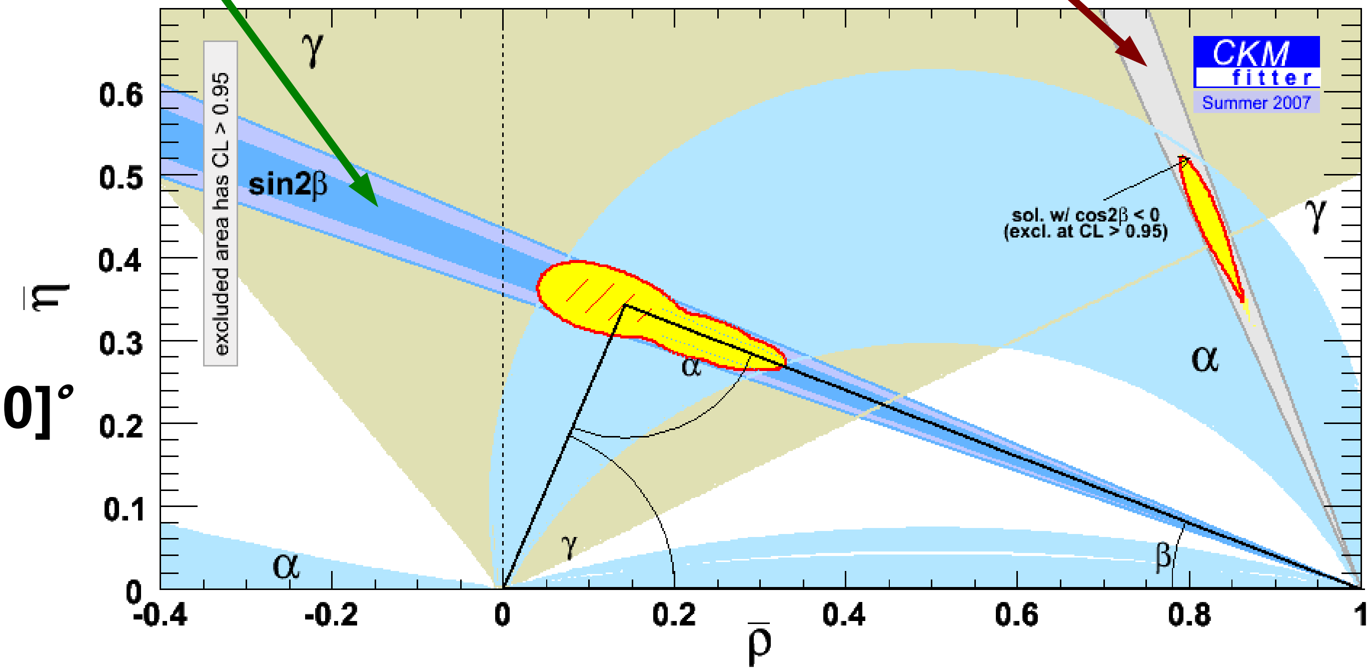
383 ·10⁶ BB
August 2007
PRL99, 231802

$\cos 2\beta > 0$ @86% C.L.

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

excludes region

β = 21.5° [+1.0 -1.0]°
CKMfitter



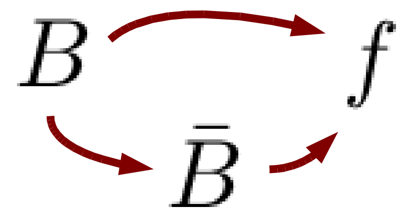
α from $B^0 \to \pi^0\pi^0$, $B^+ \to \pi^+\pi^0$, $B^+ \to K^+\pi^0$

Moritz Karbach
TU Dortmund

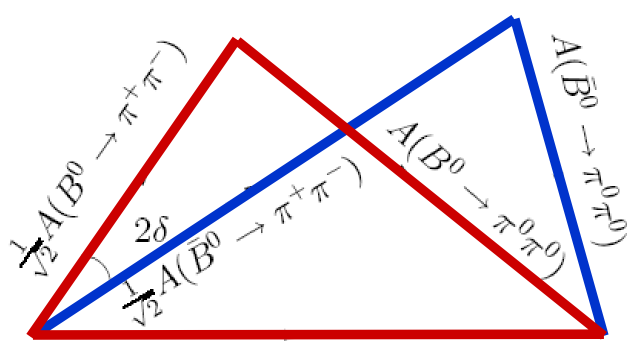
PHENO
April 28th 2008

383 ·10⁶ BB
November 2007
PRD76, 091102

- Measure α through interference of $b \to u$ decays with and w/o B^0 mixing.



- But BR measurements of $B \to \pi\pi$ indicate penguins are large, so only sensitive to $\alpha_{eff} = \alpha + \delta$
- use isospin relations to decouple penguin contribution



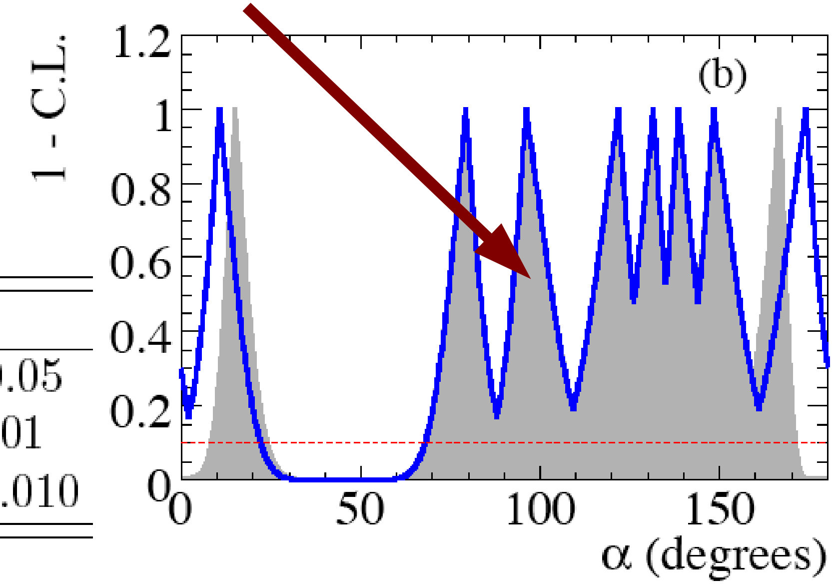
8-fold ambiguity

$|A(B^- \to \pi^-\pi^0)| = |A(B^+ \to \pi^+\pi^0)|$

$\delta < 39^\circ$ @90% C.L.

$\alpha = (96^{+10}_{-6})^\circ$ most compatible with SM

Mode	$\mathcal{B}(10^{-6})$	Asymmetry
$B^0 \to \pi^0\pi^0$	$1.47 \pm 0.25 \pm 0.12$	$-0.49 \pm 0.35 \pm 0.05$
$B^\pm \to \pi^\pm\pi^0$	$5.02 \pm 0.46 \pm 0.29$	$0.03 \pm 0.08 \pm 0.01$
$B^\pm \to K^\pm\pi^0$	$13.6 \pm 0.6 \pm 0.7$	$0.030 \pm 0.039 \pm 0.010$



Moritz Karbach
TU Dortmund

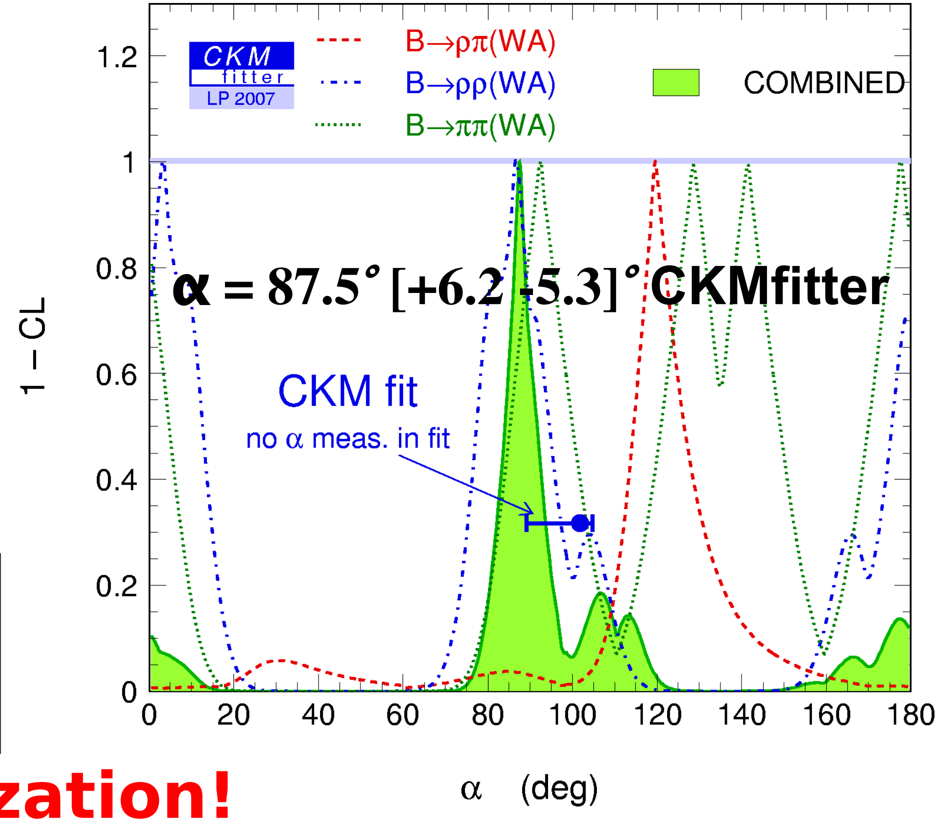
α – more results

B→(ρπ)⁰

375 ·10⁶ BB
July 2007
PRD76, 012004

$$\alpha = (87^{+45}_{-13})^\circ$$

- Measure coefficients of time-dependent decay rate over Dalitz plot → no isospin analysis



B⁰→ρ⁺ρ⁻

384 ·10⁶ BB
July 2007
PRD76, 052007

polarization!

- Vector-Vector final state is a mixture of CP even & odd states → angular analysis required (f_L, S_L, C_L)
- Flavor SU(3) analysis

$\alpha = [83.3, 105.8]^\circ$ @68% C.L.

B⁰→ρ⁰ρ⁰

427 ·10⁶ BB
August 2007
arxiv:0708.1630

- isospin analysis more effective

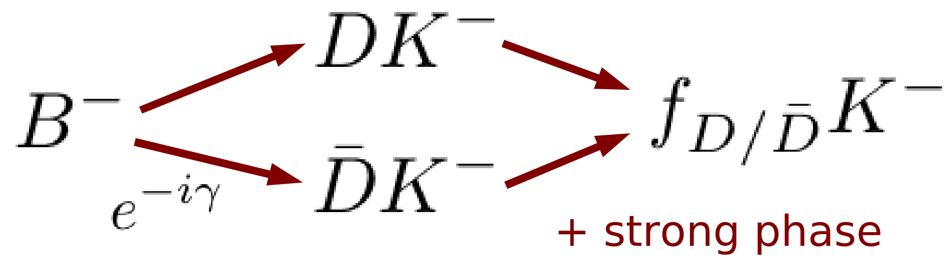
BR(B→ρ⁰ρ⁰) < BR(B→π⁰π⁰) :

$$|\alpha - \alpha_{\rm eff}| < 16.5^\circ$$

Moritz Karbach
TU Dortmund

γ from B → DK

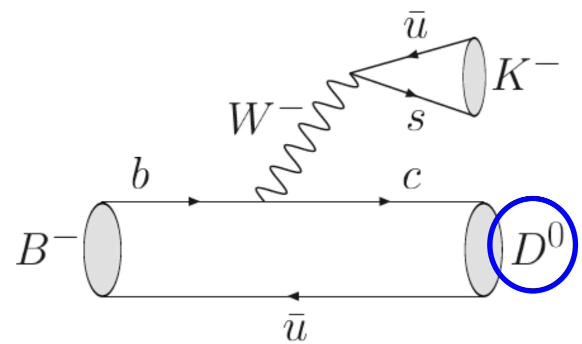
- γ is the least well known CKM angle.
- Methods use final states accessible for both D^0 and $\bar{D}^0$. Tree dominated, no new physics.

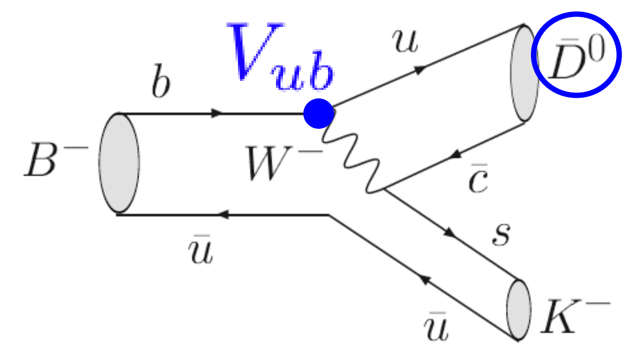


- Sensitivity on γ depends on amplitude ratio r. The uncertainty scales roughly like **1/r**.

$$r = \frac{|A(B \to \bar{D}^{(*)0}K)|}{|A(B \to D^{(*)0}K)|}$$

$$r \approx 0.1$$





- Several D final states can be used:
  - CP eigenstates (**GLW**)
  - Flavor eigenstates (**ADS**)
  - 3-body states (**GGSZ Dalitz**)

Gronau & London, PLB 253, 483 (1991)
Gronau & Wyler, PLB 265, 172 (1991)
Atwood, Dunietz, & Soni, PRL 78, 3257 (1997),
Atwood, Dunietz, & Soni, PRD 63, 036005 (2001)
Giri, Grossman, Soffer, & Zupan, PRD 68, 054018 (2003)
Bondar, PRD 70, 072003 (2004)

Moritz Karbach
TU Dortmund

PHENO
April 28th 2008

γ from $B^+ \rightarrow D^0 K^+$

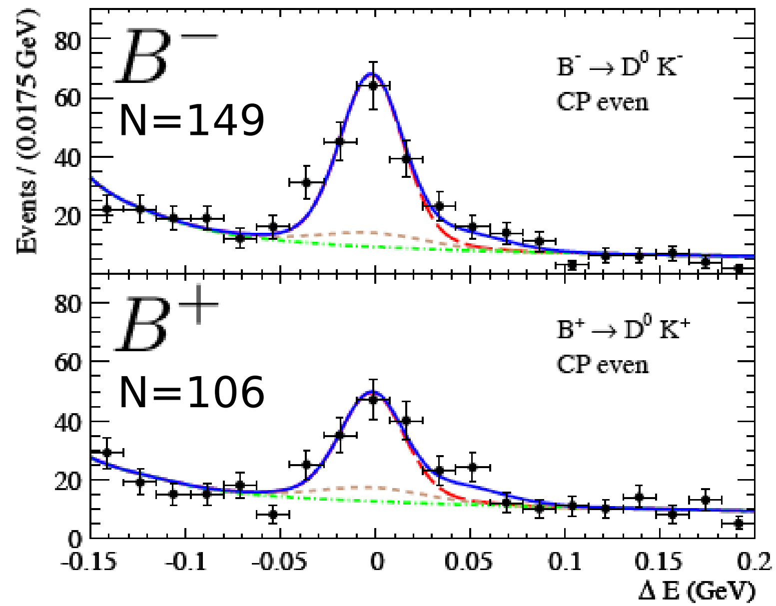
381 ·10⁶ BB
Feb 2008 ***new!***
arxiv:0802.4052

- **GLW** method uses CP final states accessible for both D^0 and $\bar{D}^0$.
- based on triangle relations of amplitudes → inherent 8-fold ambiguity

$$R_{CP\pm} = 1 + r^2 \pm 2r\cos\delta\cos\gamma$$
$$A_{CP\pm} = \pm 2r\sin\delta\sin\gamma / R_{CP\pm}$$

$$R_{CP\pm} = \frac{\Gamma(B^- \to D^0_{CP\pm}K^-) + \Gamma(B^+ \to D^0_{CP\pm}K^+)}{\left[\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to \bar{D}^0 K^+)\right]/2}$$

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



D^0 mode	R_{CP}	A_{CP}
$CP+$	$1.06 \pm 0.10 \pm 0.05$	$0.27 \pm 0.09 \pm 0.04$
$CP-$	$1.03 \pm 0.10 \pm 0.05$	$-0.09 \pm 0.09 \pm 0.02$

compatible with no CP violation **@2.8σ**!

At current statistics the sensitivity on γ is low. Combine results with GGSZ Dalitz!

Moritz Karbach
TU Dortmund

γ : $B^+ \to D^{(*)0} K^{(*)+}$ with $D^0 \to K^0K^+K^-$, $K^0\pi^+\pi^-$

383 ·10⁶ BB
April 2008 ***new!***
arxiv:0804.2089

- The **GGSZ** (Dalitz) method is the most precise single measurement of γ
- Dalitz plot shows dynamics of the matrix element.

$$m_-^2 = m(K_S^0\pi^-)^2 \qquad m_+^2 = m(K_S^0\pi^+)^2$$

- Dalitz amplitude depends on amplitude ratios r, the weak phase and a strong phase

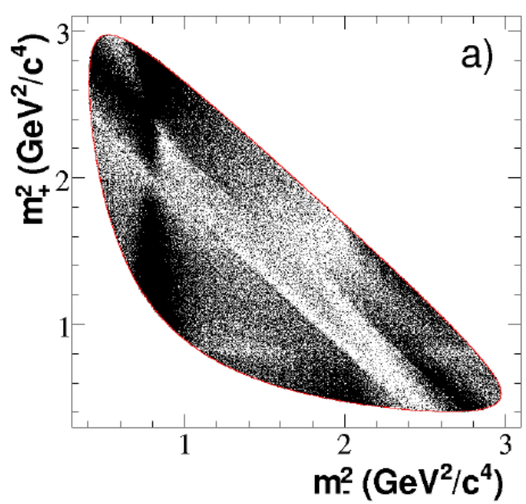
$$\mathcal{A}_{\mp}^{(*)}(m_-^2, m_+^2) \propto \mathcal{A}_{D\mp} + \lambda r_B^{(*)} e^{i(\delta_B^{(*)} \mp \gamma)} \mathcal{A}_{D\pm}$$

- obtain a Dalitz model $\mathcal{A}_{D\mp}$ from a high statistics control sample, fit it to the DK data

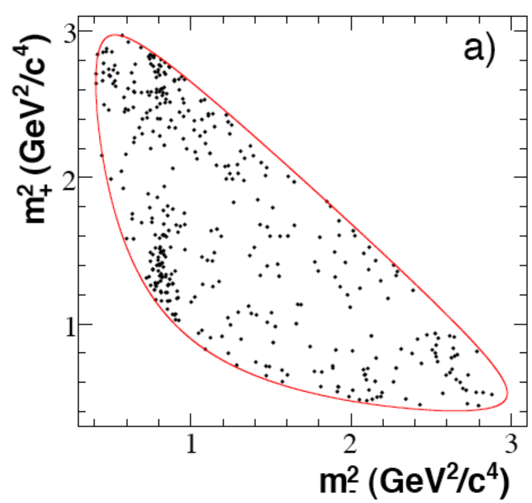
Cartesian coordinates:
(almost gaussian errors)

$$x_{\mp}^{(*)} = r_B^{(*)} \cos(\delta_B^{(*)} \mp \gamma)$$
$$y_{\mp}^{(*)} = r_B^{(*)} \sin(\delta_B^{(*)} \mp \gamma)$$

$D^* \to D\pi$, $D \to K_S\pi\pi$



$B^- \to DK^-$, $D \to K_S\pi\pi$



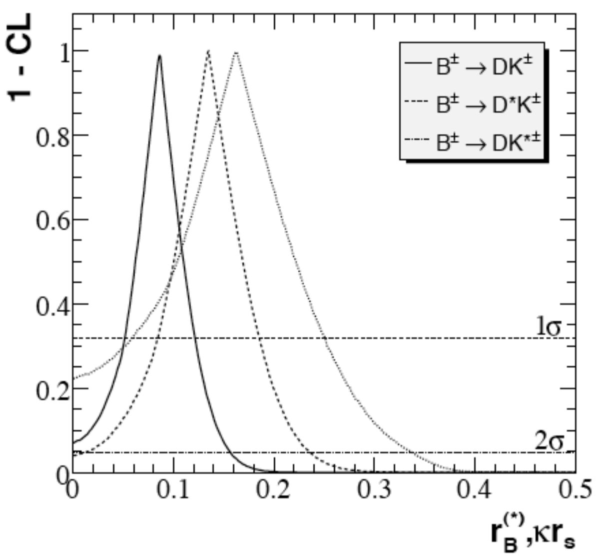
γ : GGSZ continued

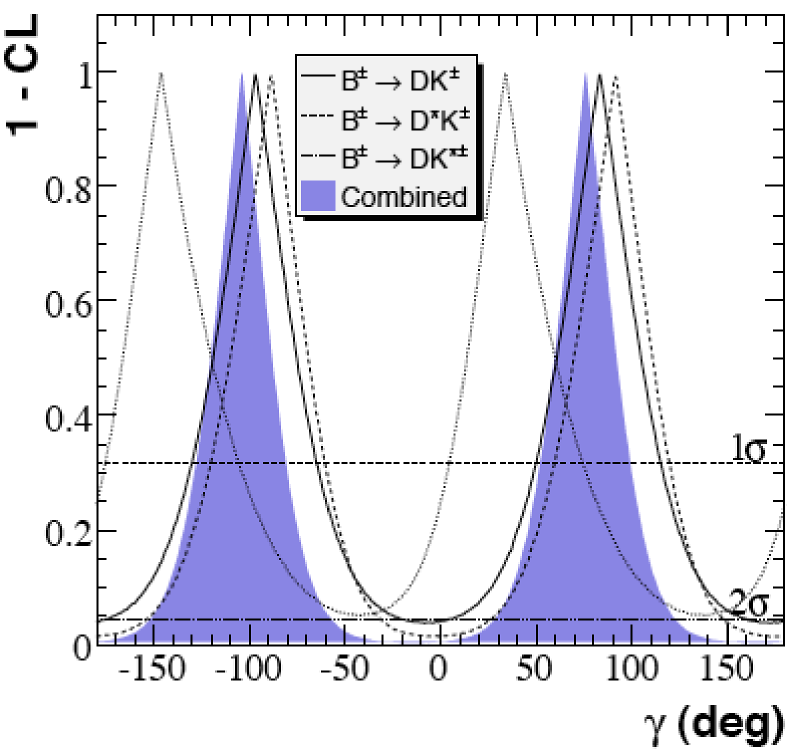
Parameters	$B^- \to \tilde{D}^0 K^-$	$B^- \to \tilde{D}^{*0} K^-$	$B^- \to \tilde{D}^0 K^{*-}$
x_- , x_-^* , x_{s-}	$0.090 \pm 0.043 \pm 0.015 \pm 0.011$	$-0.111 \pm 0.069 \pm 0.014 \pm 0.004$	$0.115 \pm 0.138 \pm 0.039 \pm 0.014$
y_- , y_-^* , y_{s-}	$0.053 \pm 0.056 \pm 0.007 \pm 0.015$	$-0.051 \pm 0.080 \pm 0.009 \pm 0.010$	$0.226 \pm 0.142 \pm 0.058 \pm 0.011$
x_+ , x_+^* , x_{s+}	$-0.067 \pm 0.043 \pm 0.014 \pm 0.011$	$0.137 \pm 0.068 \pm 0.014 \pm 0.005$	$-0.113 \pm 0.107 \pm 0.028 \pm 0.018$
y_+ , y_+^* , y_{s+}	$-0.015 \pm 0.055 \pm 0.006 \pm 0.008$	$0.080 \pm 0.102 \pm 0.010 \pm 0.012$	$0.125 \pm 0.139 \pm 0.051 \pm 0.010$

- Obtain ratios, strong phases and γ using a frequentist method.

$$r_B = 0.086 \pm 0.035$$
$$r_B^* = 0.135 \pm 0.051$$
$$r_s = 0.181^{+0.100}_{-0.118}$$

$$\gamma = (76 \pm 22 \pm 5 \pm 5)^\circ \pmod{180^\circ}$$
stat syst Dalitz





CPV significance:

$B \to DK$	2.2σ
$B \to D^*K$	2.5σ
$B \to DK^*$	1.5σ
combined	3.0σ

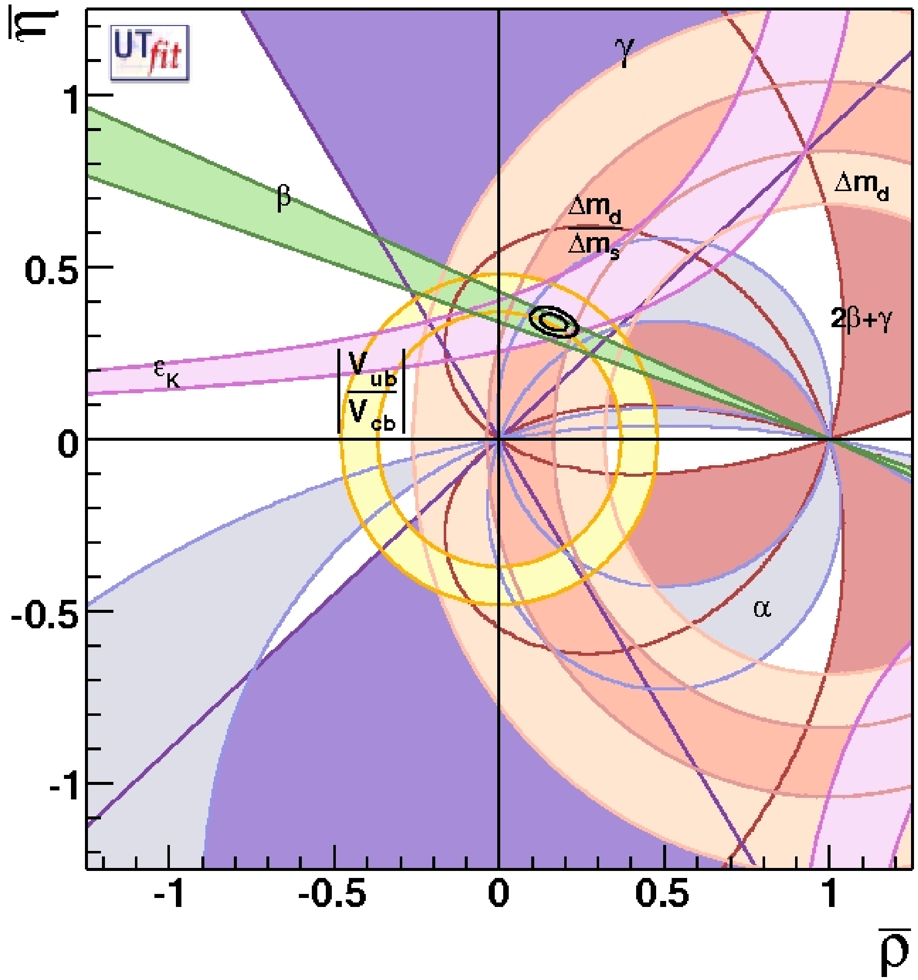
Moritz Karbach TU Dortmund

PHENO April 28th 2008

BABAR

TM & ©Nelvana

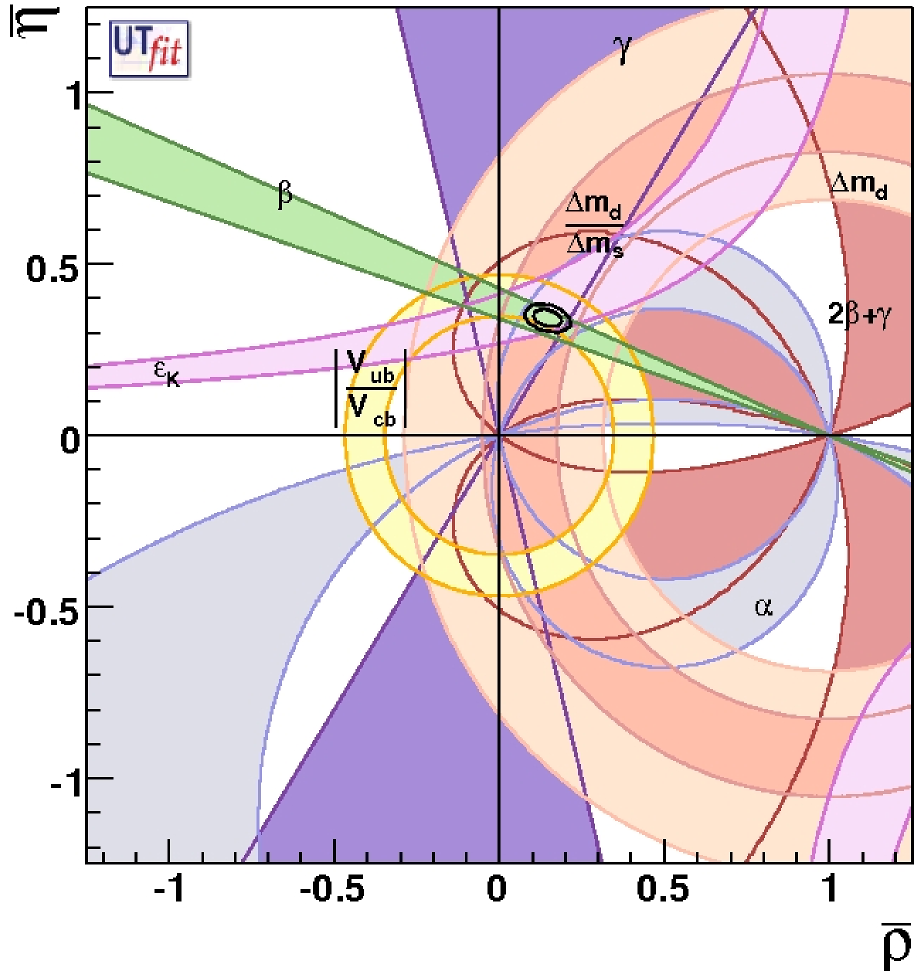
improvements on the apex



UTfit

before the 2008 Winter Conferences

improvements on the apex



UTfit Moriond 08

combinations of direct measure-ments of the angles:

$\gamma = 80^\circ\ [+13\ -13]^\circ$
UTfit Moriond 08

$\alpha = 87.5^\circ\ [+6.2\ -5.3]^\circ$
CKMfitter LP/EPS 07

$\beta = 21.5^\circ\ [+1.0\ -1.0]^\circ$
CKMfitter LP/EPS 07

summary

- BaBar has published many results on the CKM angles for the Winter conferences, some are covered in this presentation.
- **CKM α :** Accessible in **B → ππ** (and higher resonances). But penguin contributions need to be controlled. $\alpha = (96^{+10}_{-6})^\circ$
- **CKM β :** Precision measurements in the **B → $c\bar{c}s$** system are available: $\sin 2\beta = 0.714 \pm 0.032(\mathrm{stat}) \pm 0.018(\mathrm{syst})$
- **CKM γ :** Clean tree only environment in **B → DK**. GGSZ Dalitz method measures $\gamma = (76 \pm 22 \pm 5 \pm 5)^\circ$

The datataking period of BaBar has ended by April 7th.

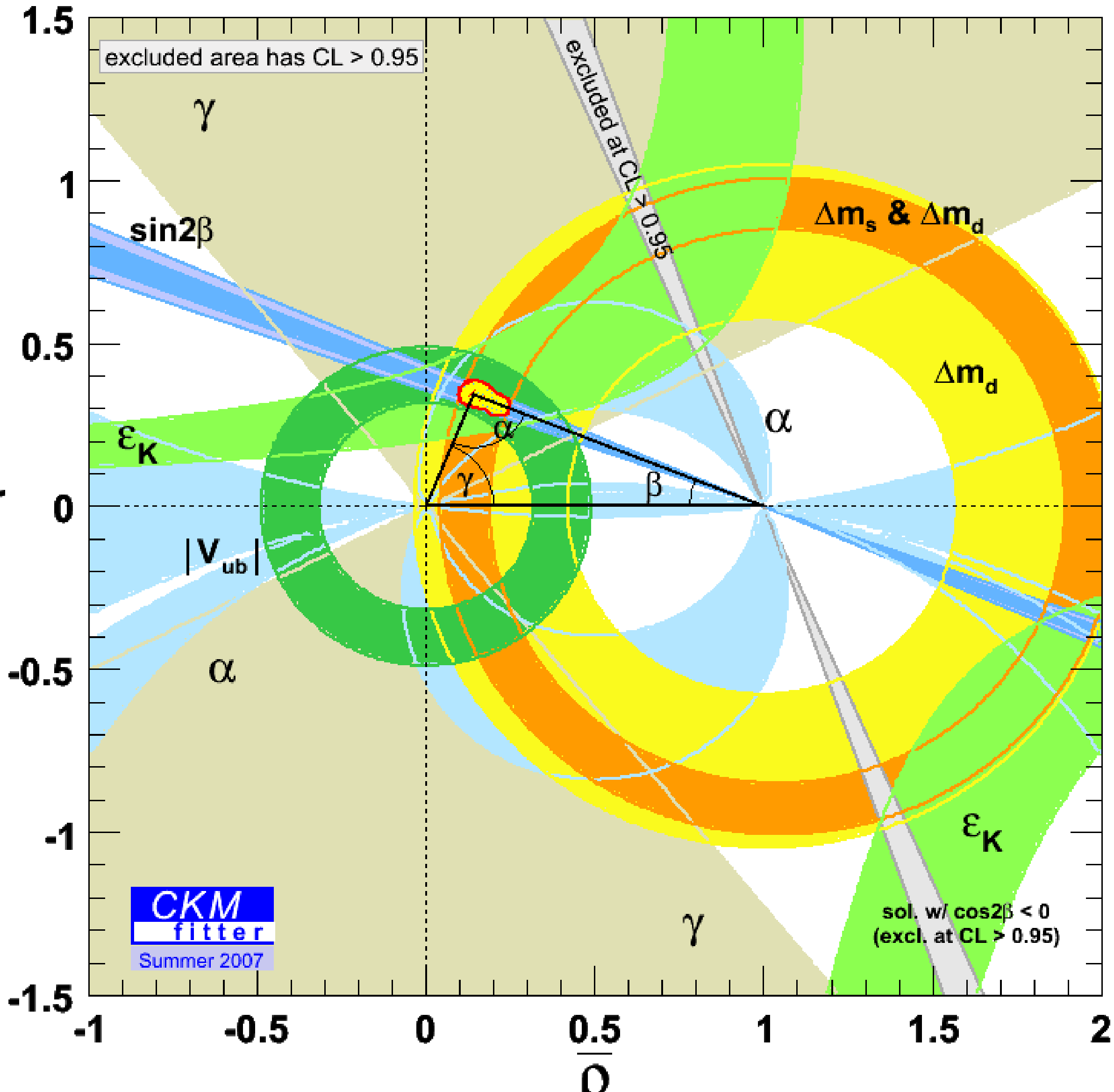
thanks to: Sören Prell, Viola Sordini, Cecilia Voena

moritz.karbach@slac.stanford.edu

backup

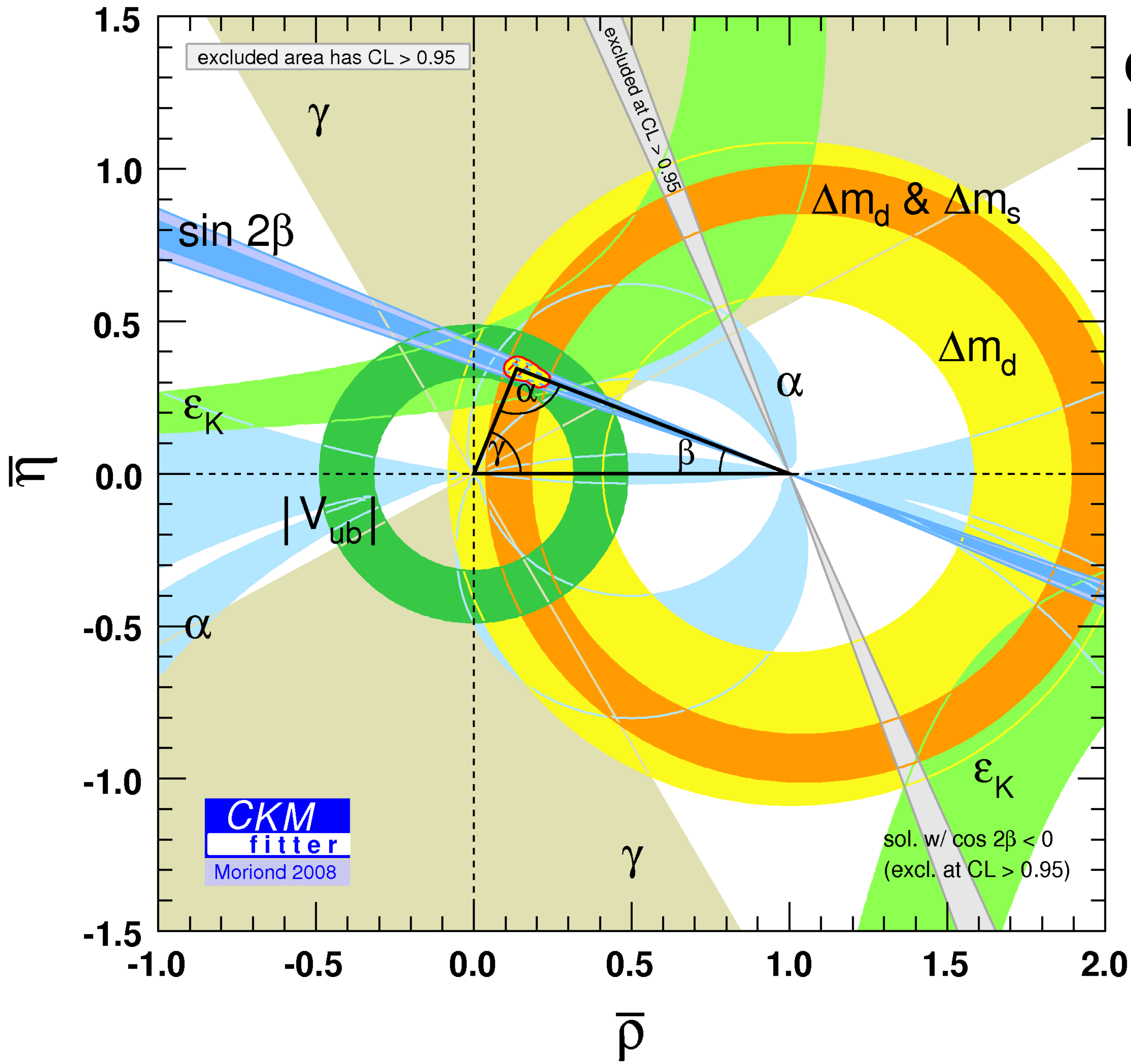
Moritz Karbach
Technische Universität
Dortmund

CKMfitter



CKMfitter Summer 07

CKMfitter



CKMfitter Moriond 08

thanks to Stephane T'Jampens

Moritz Karbach
TU Dortmund

PHENO
April 28th 2008

references

Moritz Karbach
TU Dortmund

PHENO
April 28th 2008

CKMfitter Group (J. Charles et al.),
Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184],
http://ckmfitter.in2p3.fr

TM & © Nelvana

Moritz Karbach
TU Dortmund

α from $B \to (\rho\pi)^0$

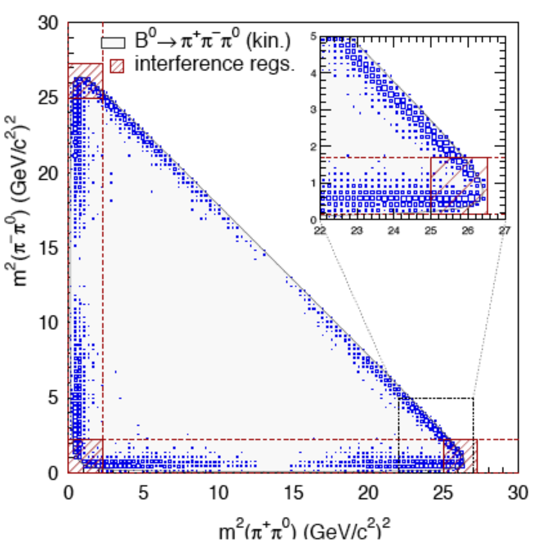
$375 \cdot 10^6$ BB
July 2007
PRD76, 012004

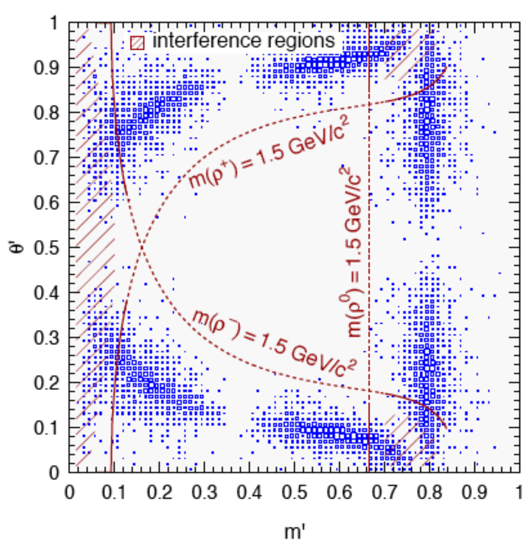
- full time-dependent Dalitz plot analysis of $(\pi\pi\pi)^0$

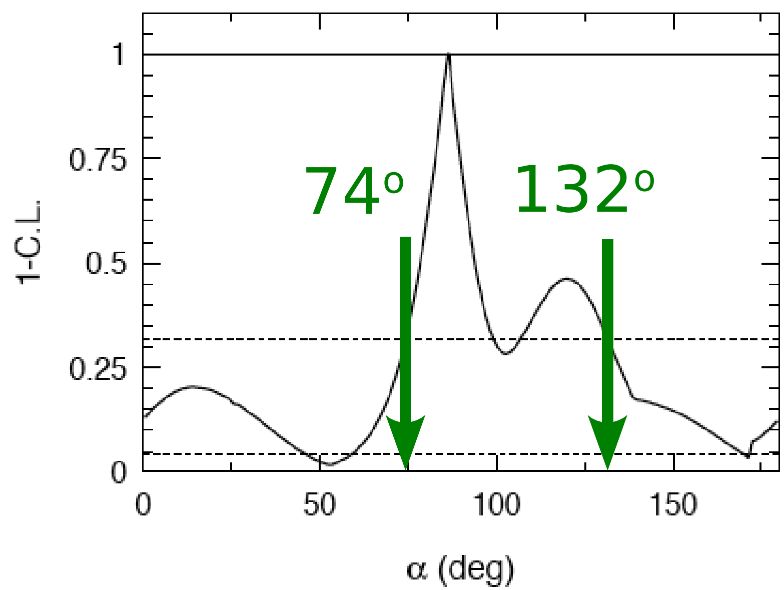
$$f_{\pm}(\Delta t) \sim \frac{e^{-|\delta t|/\tau_B}}{4\tau_B}\left(1 \pm \eta_f S \sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)\right)$$

- strong phases of the ρ vary over the dalitz plot – no isospin analysis needed to resolve ambiguities!
- fit for 26 form factor coefficiencts, combine them to S, ΔS, C, ...

$$\delta_{+-} = (37 \pm 37)^\circ$$
$$\alpha = \left(87\,^{+45}_{-13}\right)^\circ$$







Moritz Karbach
TU Dortmund

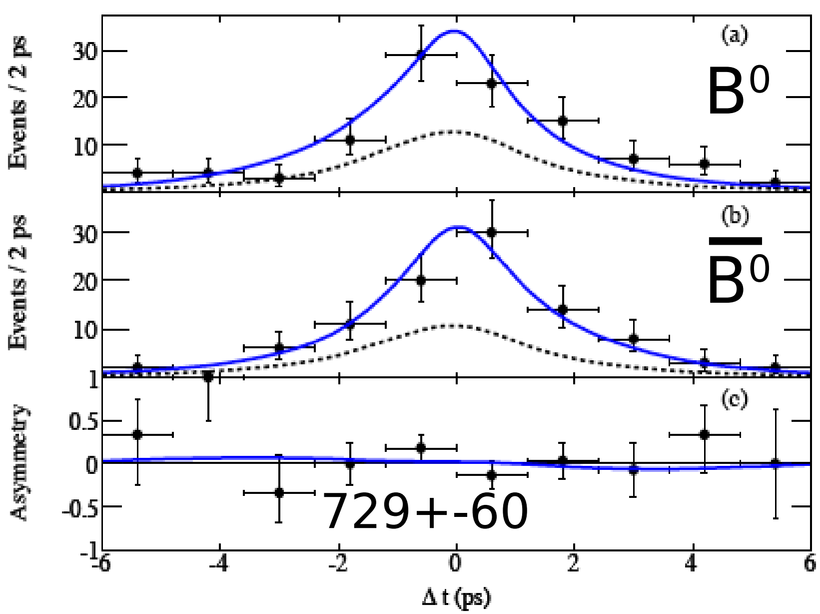
α from $B^0 \to \rho^+\rho^-$ and $B^0 \to \rho^0\rho^0$

384 ·10⁶ BB
July 2007
PRD76, 052007

- Vector-Vector final state is a mixture of CP even & odd states → angular analysis required (f_L, S_L, C_L)
- Flavor SU(3) analysis

$$\alpha = [83.3, 105.8]^\circ$$ @68% C.L.

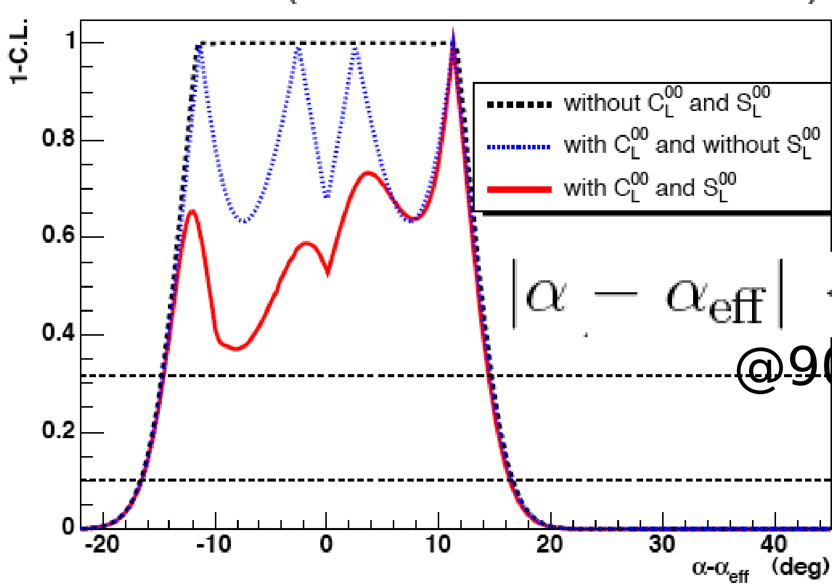
$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (25.5 \pm 2.1(\text{stat})^{+3.6}_{-3.9}(\text{syst}))\times 10^{-6}$$



427 ·10⁶ BB
August 2007
arxiv/0708.1630

- tracks in final state enable time-dependent analysis
- BR($B \to \rho^0\rho^0$) < BR($B \to \pi^0\pi^0$) : isospin analysis more effective

$$S_L^{00} = 0.5 \pm 0.9 \pm 0.2$$
$$C_L^{00} = 0.4 \pm 0.9 \pm 0.2$$
$$f_L = 0.70 \pm 0.14 \pm 0.05$$
$$\mathcal{B} = (0.84 \pm 0.29 \pm 0.17) \times 10^{-6}$$



β from $B^0 \to c\bar{c}s$

$383 \cdot 10^6$ BB
October 2007
PRL99, 171803

- this is a precision measurement
  $J/\psi K^0_S$, $J/\psi K^0_L$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$, and $J/\psi K^{*0}$
- time dependent decay rate is governed by a sin (CPV in mixing) and cos (direct CPV) term

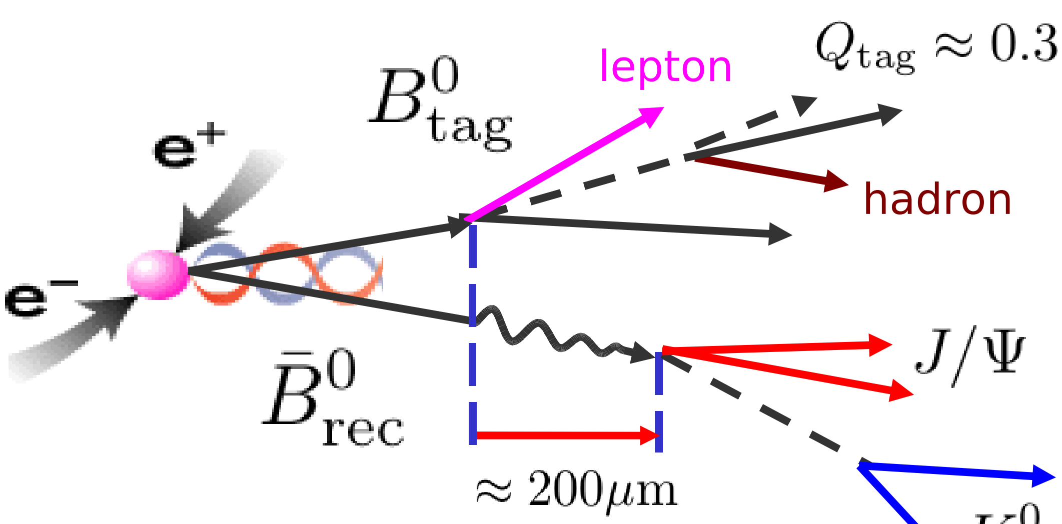
$$\lambda = (q/p)(\bar{A}/A)$$

$$\sin 2\beta = 0.714 \pm 0.032(\text{stat}) \pm 0.018(\text{syst})$$

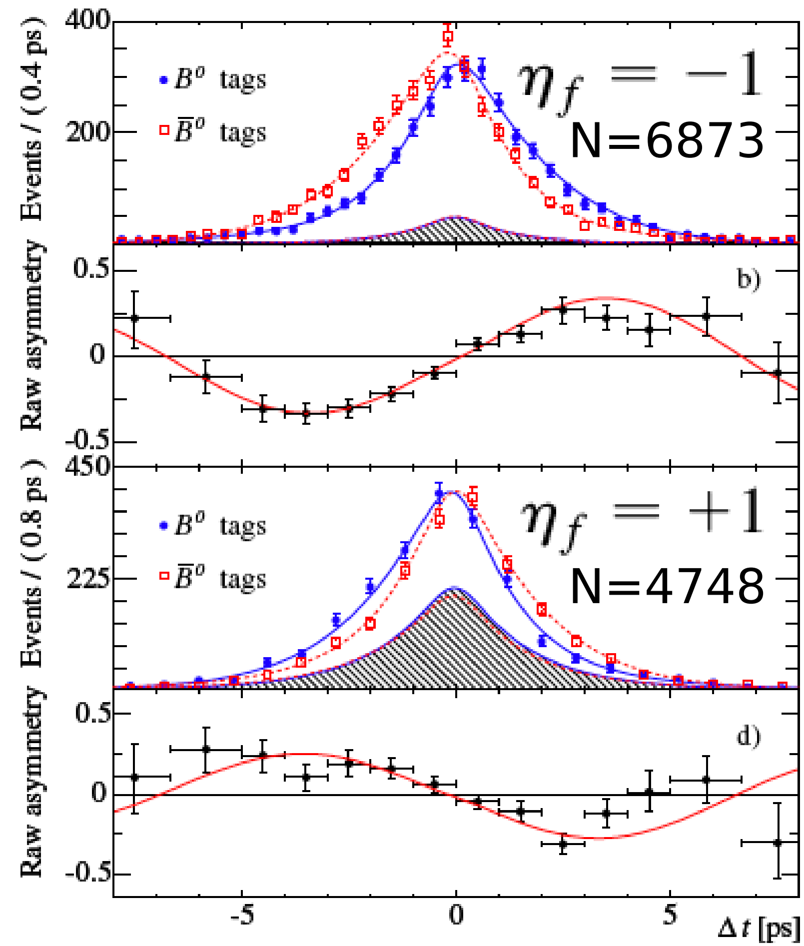
$$|\lambda| = 0.952 \pm 0.022(\text{stat}) \pm 0.017(\text{syst})$$

- in SM direct CPV and CPV in mixing are negligible in $b \to c\bar{c}s$. Easy access to sin2β:

$$A_{CP}(\Delta t) = -(1-2w)\eta_f \sin 2\beta \sin(\Delta m_d \Delta t)$$



$$\Delta t \approx \Delta z / \beta c \gamma_{\Upsilon(4S)}$$



Moritz Karbach
TU Dortmund

PHENO
April 28th 2008

$\sin(2\beta+\gamma)$: $B^0 \to D_s^{(*)+}\pi^-$, $D_s^{(*)+}\rho^-$, $D_s^{(*)+}K^{(*)-}$

381 $\cdot 10^6$ BB
March 2008 ***new!***
arxiv:0803.4296

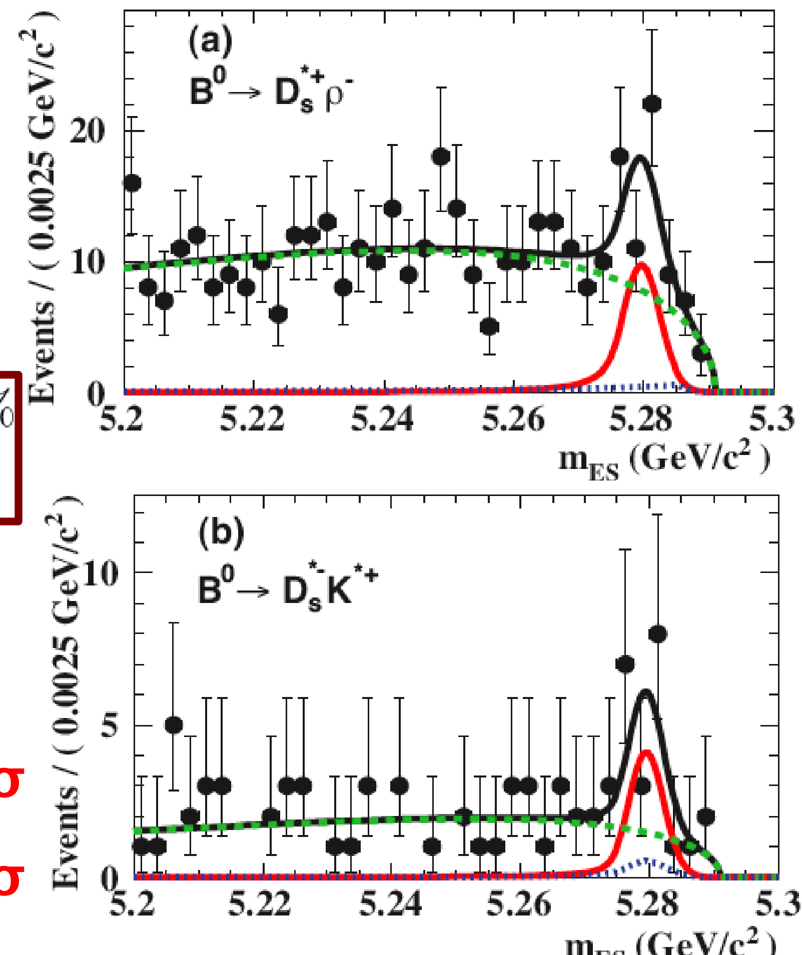
- There is theoretically clean sensitivity to $\sin(2\beta+\gamma)$ from $B^0 \to D^{(*)+}\pi^-$ and $B^0 \to D^{(*)+}\rho^-$ decays.
- The method requires knowledge of r, ratio of interfering amplitudes. This is challenging because r is small in the $D^{(*)+}\pi^-$ system: $r \approx 0.02$
- Use flavor SU(3) to relate it to the $D_s^{(*)+}\pi^-$ system:

$$r(D^{(*)}\pi) = \tan\theta_c \frac{f_{D^{(*)}}}{f_{D_s^{(*)}}}\sqrt{\frac{\mathcal{B}(B^0 \to D_s^{(*)+}\pi^-)}{\mathcal{B}(B^0 \to D^{(*)-}\pi^+)}}$$

$$r(D\pi) = [1.75 \pm 0.14\,(\mathrm{stat}) \pm 0.09\,(\mathrm{syst}) \pm 0.10\,(\mathrm{th})]\%$$
$$r(D^*\pi) = [1.81^{+0.17}_{-0.14}\,(\mathrm{stat}) \pm 0.12\,(\mathrm{syst}) \pm 0.10\,(\mathrm{th})]\%$$
$$r(D\rho) = [0.71^{+0.29}_{-0.26}\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst}) \pm 0.04\,(\mathrm{th})]\%$$
$$r(D^*\rho) = [1.50^{+0.22}_{-0.21}\,(\mathrm{stat}) \pm 0.16\,(\mathrm{syst}) \pm 0.08\,(\mathrm{th})]\%$$

$$\mathcal{B}(B^0 \to D_s^{*+}\rho^-) = [4.4^{+1.3}_{-1.2} \pm 0.8] \times 10^{-5}$$ **3.9σ**

$$\mathcal{B}(B^0 \to D_s^{*-}K^{*+}) = [3.0^{+1.4}_{-1.2} \pm 0.3] \times 10^{-5}$$ **3.1σ**



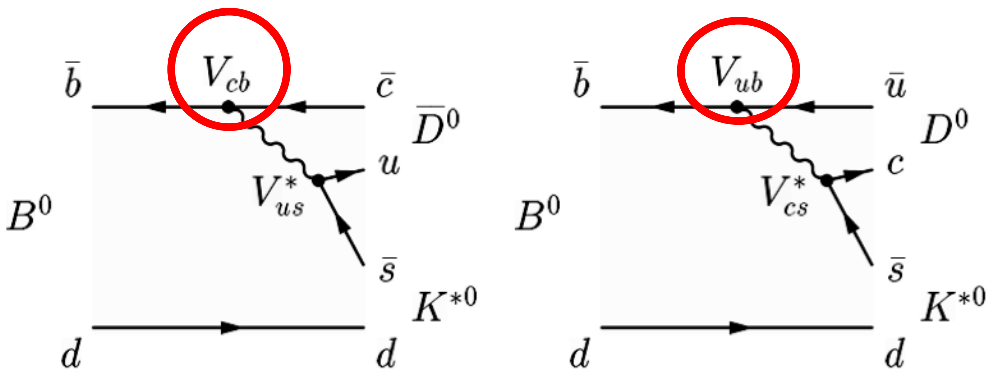
Moritz Karbach
TU Dortmund
PHENO
April 28th 2008

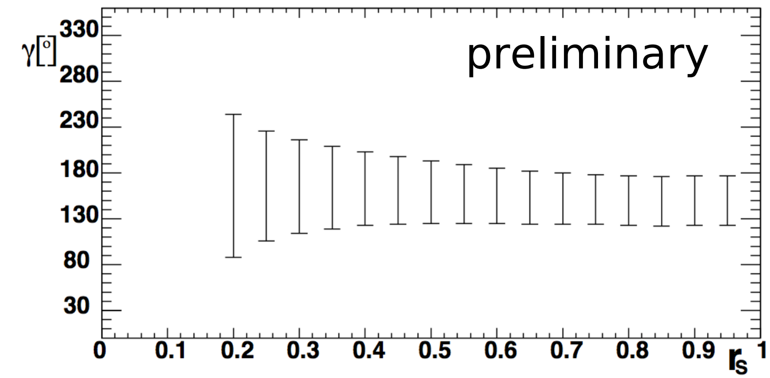
Moritz Karbach
TU Dortmund

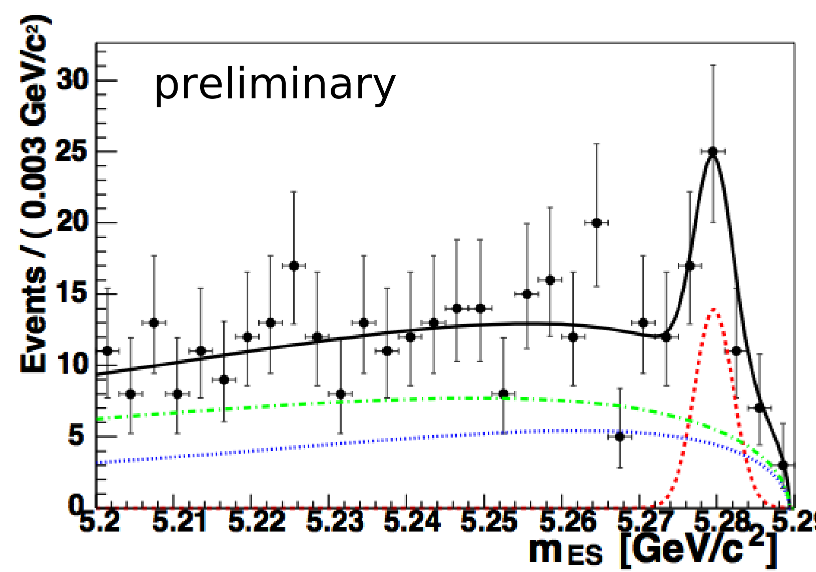
γ from $B^0 \to D^0 K^{*0}$ with $D^0 \to K^0 \pi^+ \pi^-$

$371 \cdot 10^6$ BB
April 2008
preliminary

- Novel technique! Works similar to the GGSZ Dalitz method. Same CKM elements are involved.
- The charge of the K from the K^{*0} decay tags the B flavor – no time dependent analysis needed.
- At current statistics, r_S = [0.3, 0.5] needs to be plugged in from external studies to obtain limits on γ







preliminary

$$\gamma = (162 \pm 56)^\circ \text{ or } (342 \pm 56)^\circ;$$
$$\delta_S = (62 \pm 57)^\circ \text{ or } (242 \pm 57)^\circ;$$
$$r_S < 0.55 \text{ at } 95\% \text{ probability.}$$

Moritz Karbach
TU Dortmund

PHENO
April 28th 2008

sin(2β) : b → s penguins

- Most theorists expect
  S(b→sss) – S(b→ccs) > 0
- Most experiments measure
  ΔS < 0
- HFAG averages need to be taken with great care.
  For instance, $S(f^0K_S)$ from $K_S\pi^-\pi^+$ Dalitz analysis has highly non-gaussian errors
- $K_S\pi^-\pi^+$ is in the process of publication.
  arxiv:0708.2097
- most BaBar measurements use 380M BB pairs – updates are expected.