Measurements of γ/ϕ_3

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CKM angle γ/ϕ_3

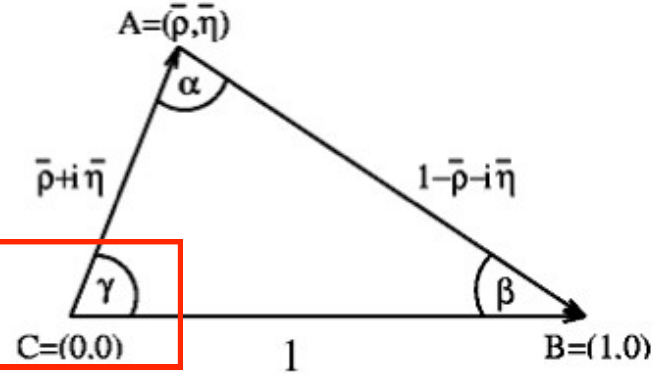
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ \lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}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

Wolfenstein parameterization

$\lambda \sim 0.22$ $A \sim 0.8$

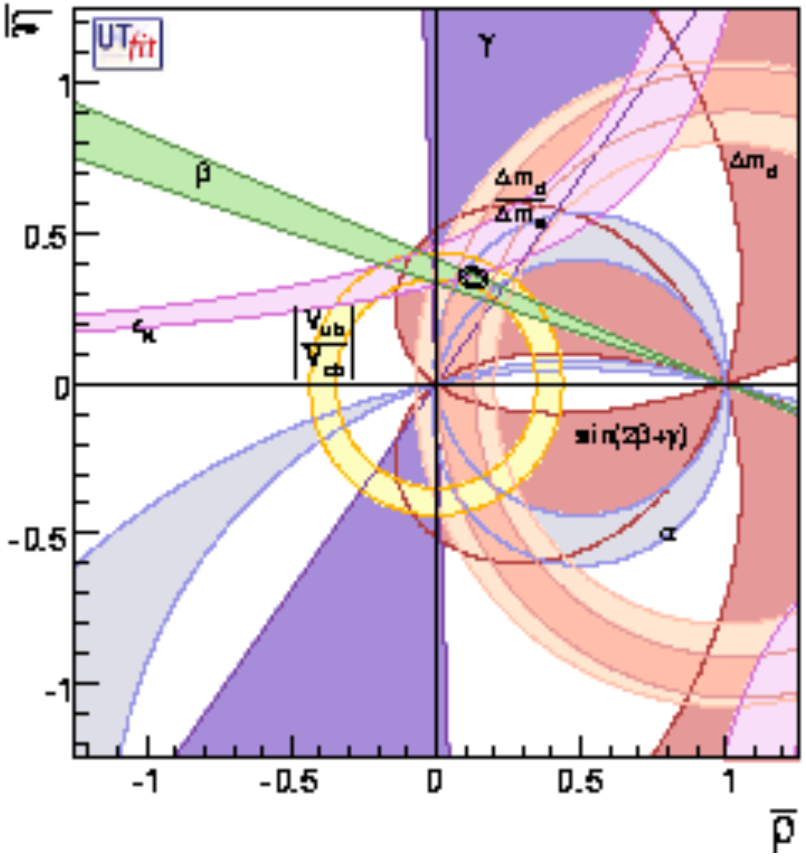
$\rho \sim 0.16$ $\eta \sim 0.34$

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



Motivation and importance of measuring γ

γ is still the less precisely known UT angle.
Its determination is important also because (together with V_{ub} contraint) it selects ρ−η value valid in most of the NP extensions



Experiments providing most of analyses today

3.1 GeV e^+
9 GeV e^-
468M BB pairs

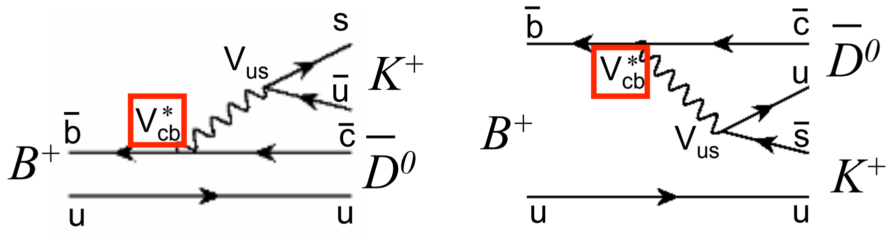
3.5 GeV e^+
8 GeV e^-
657M BB pairs

Experiments that can also give results in near future

Planned facilities

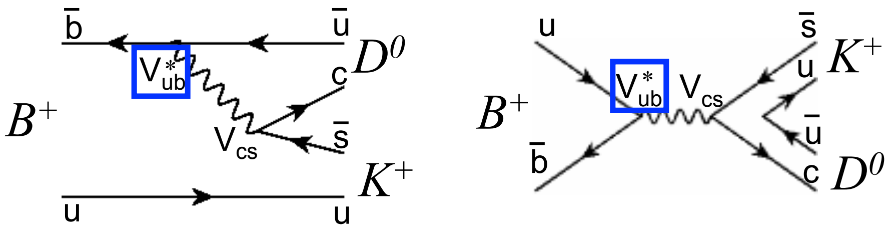
γ measurements from $B \to D^{(*)} K^{(*)}$

b→c



relative phase γ

b→u



Advantages:
- Only tree decays.
- Largely unaffected by the New Physics scenarios
- Clear theoretical interpretation

Disadvantages:
- Rare decays and low r_B

Related variables (depend on the *B* meson decay channel):

$$r_B = \frac{|A_{b\to u}|}{|A_{b\to c}|}$$

$r_B \sim 0.1$ For charged *B* mesons

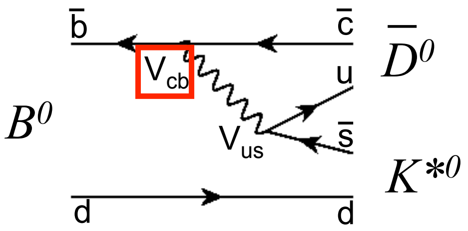
$r_B \sim 0.3$ For neutral *B* mesons

δ_B strong phase (*CP* conserving)

Experimentally not easy to measure.
Three ways to extract the information:
- GLW
- ADS
- Dalitz

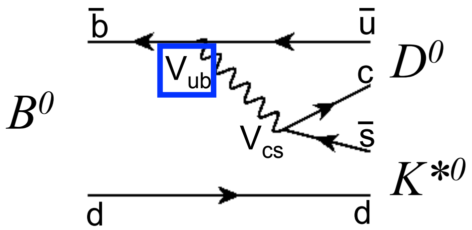
γ measurements from $B \to D^{(*)} K^{(*)}$

b→c ($V_{cb,}$ real)



relative phase γ

b→u ($V_{ub,} = |V_{ub}|\, e^{-i\gamma}$)



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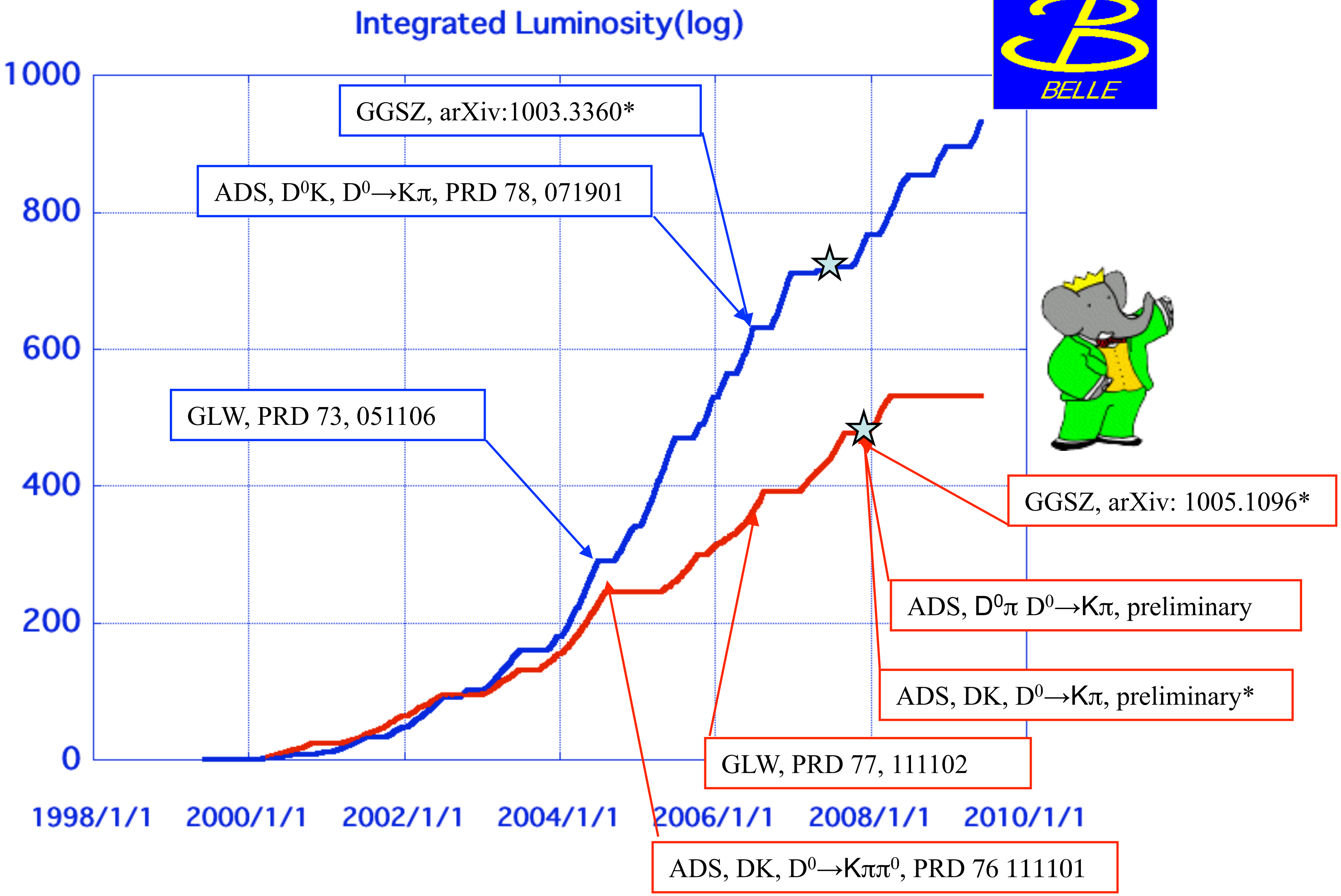
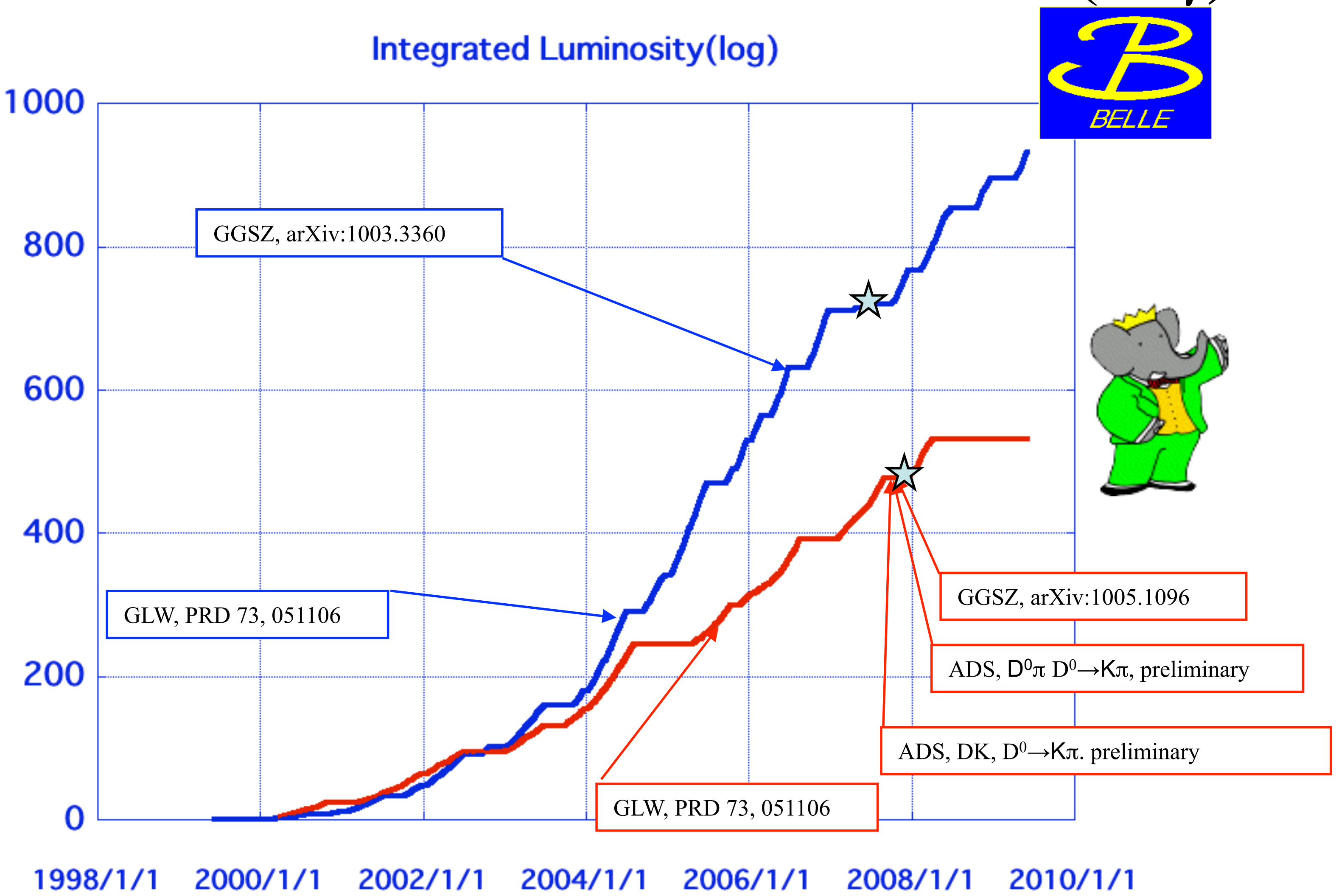
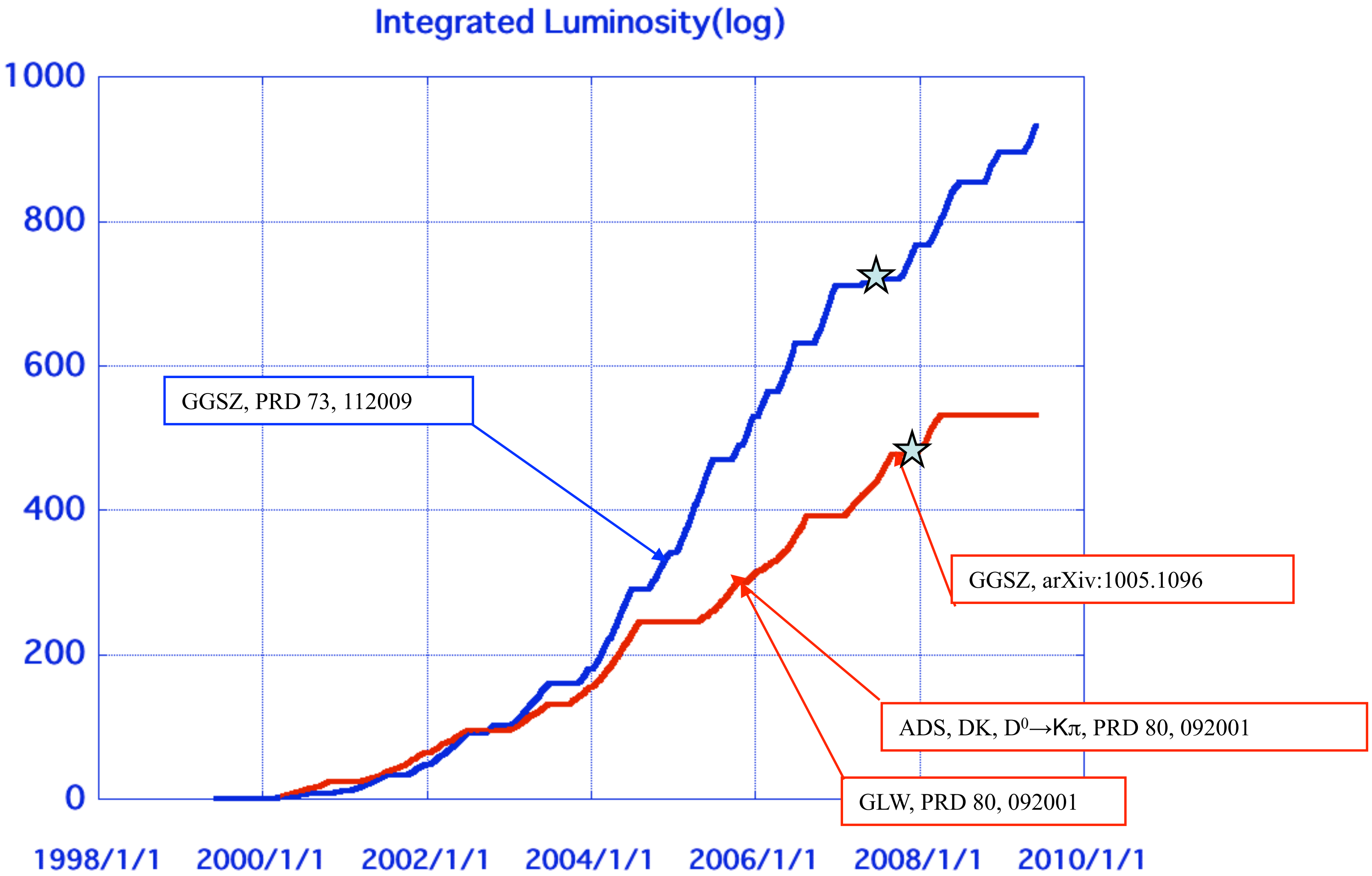
Results from $B^+ \to D^0 K^+$



Results from $B^+ \to D^{*0}K^+$, $D^{*0} \to D^0\pi^0 (D^0\gamma)$



Results from $B^+ \rightarrow D^0 K^{*+}$



γ measurements from B→DK (GGSZ)

Dalitz Method

A. Giri, Yu. Grossman, A. Soffer, J. Zupan, PRD **68**, 054018 (2003)

Modes:

$K_s\pi^+\pi^-$

$K_sK^+K^-$

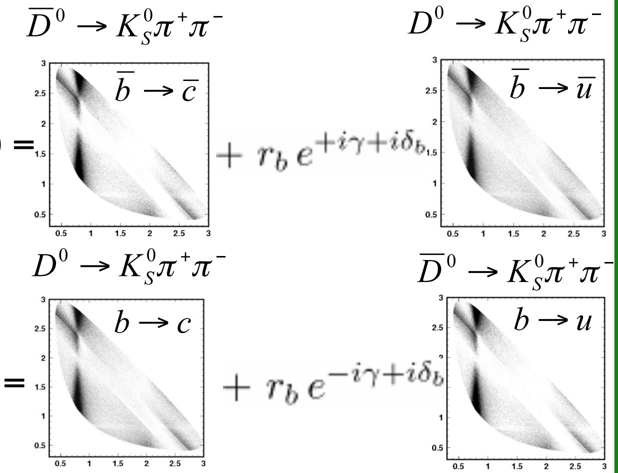
$\pi^+\pi^-\pi^0$

$$x_\pm = \mathrm{Re}(r_B e^{i(\delta\pm\gamma)}) = r_B\cos(\delta\pm\gamma)$$

$$y_\pm = \mathrm{Im}(r_B e^{i(\delta\pm\gamma)}) = r_B\sin(\delta\pm\gamma)$$

$$A_D^{B+}(m^2_{K_S\pi^+}, m^2_{K_S\pi^-}) = [\bar{D}^0\to K_S^0\pi^+\pi^-,\ \bar{b}\to\bar{c}] + r_b\, e^{+i\gamma+i\delta_b} [D^0\to K_S^0\pi^+\pi^-,\ \bar{b}\to\bar{u}]$$

$$A_D^{B-}(m^2_{K_S\pi^+}, m^2_{K_S\pi^-}) = [D^0\to K_S^0\pi^+\pi^-,\ b\to c] + r_b\, e^{-i\gamma+i\delta_b} [\bar{D}^0\to K_S^0\pi^+\pi^-,\ b\to u]$$



Advantages:

- large interferences in some Dalitz regions
- strong phases varying over the Dalitz plane

ADS Method

Modes:

$K^+\pi^-$,

$K^+\pi^-\pi^0$,

$K^+\pi^-\pi^+\pi^-$

$$R_{ADS} = \frac{\Gamma([K^+\pi^-\pi^0]K^-)+\Gamma([K^-\pi^+\pi^0]K^+)}{\Gamma([K^-\pi^-\pi^0]K^-)+\Gamma([K^+\pi^+\pi^0]K^+)}$$

$$A_{ADS} = \frac{\Gamma([K^+\pi^-\pi^0]K^-)-\Gamma([K^-\pi^+\pi^0]K^+)}{\Gamma([K^+\pi^-\pi^0]K^-)+\Gamma([K^-\pi^+\pi^0]K^+)}$$

GLW Method

D^0 Modes:

CP+

CP-

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

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

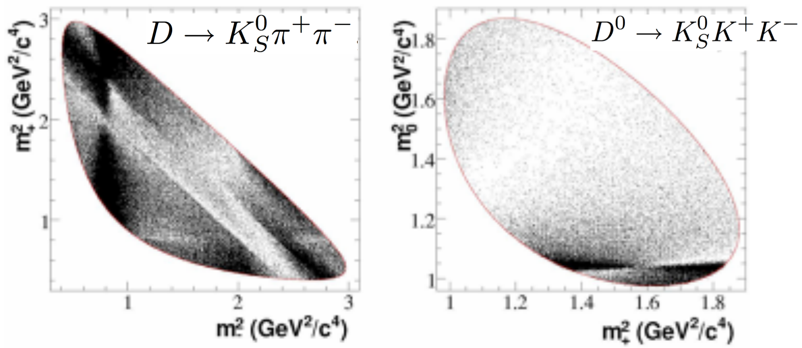
γ measurements from B→DK (BaBar)

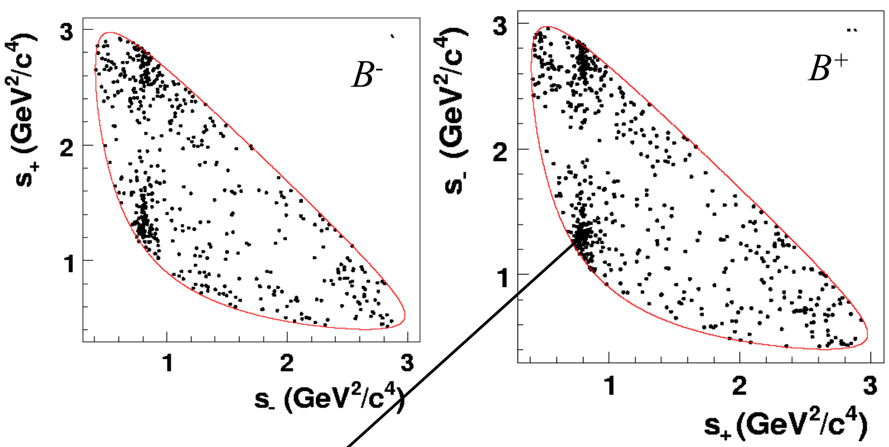
Dalitz Method

BaBar $425\ fb^{-1}$
(468 MBB)

BaBar only!

$$D \to K_S^0\pi^+\pi^-, \quad K_S^0K^+K^-$$

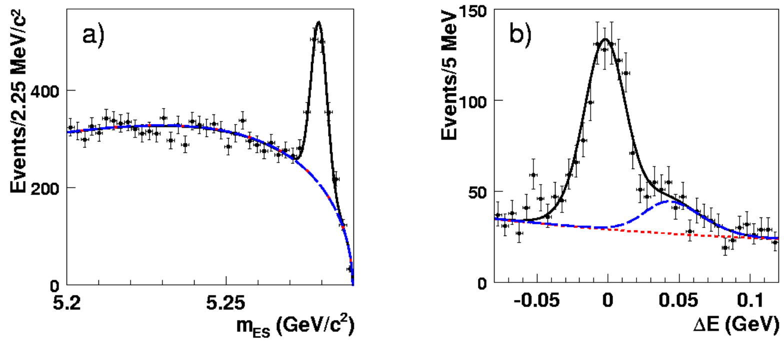




Resonance structure provides an important information on the phases

Signal is separated from background using m_{ES}, *Fisher* (on event shape variables), ΔE, ($s-$, $s+$).

$$m_{ES} = \sqrt{E_{beam}^2 - p_B^2} \qquad \Delta E = E_B - E_{beam}$$



The reconstruction efficienciy is 22%
Fit for yields and *CP* violating parameters

arXiv:1005.1096

γ measurements from B→DK (Belle)

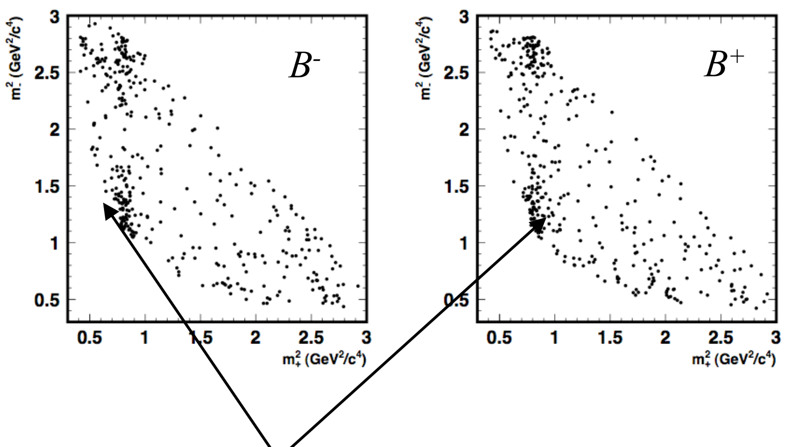
Dalitz Method

Belle 605 fb^{-1} (657 MBB)

$$D \rightarrow K_S^0 \pi^+ \pi^-$$

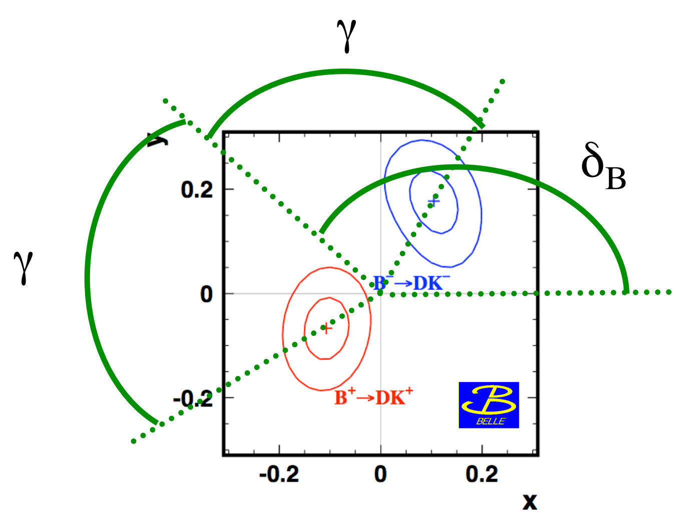
Signal events yield

	Belle ($K_s\pi\pi$) 657 MBB	BaBar ($K_s\pi\pi$) 468 MBB	BaBar (K_sKK) 468 MBB
$B^\pm \rightarrow DK^\pm$	757 ± 30	920 ± 35	142 ± 14



Resonance structure provides an important information on the phases

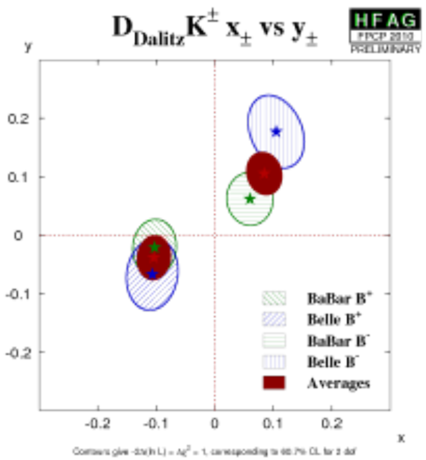
$$x_\pm = \mathrm{Re}(r_B e^{i(\delta \pm \gamma)}) = r_B \cos(\delta \pm \gamma)$$
$$y_\pm = \mathrm{Im}(r_B e^{i(\delta \pm \gamma)}) = r_B \sin(\delta \pm \gamma)$$



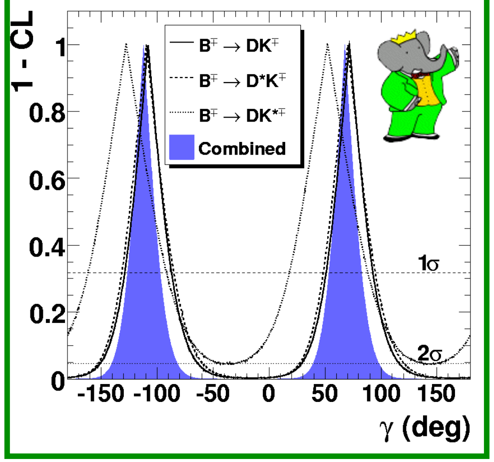
arXiv:1003.3360

γ measurements from B→DK

Dalitz Method



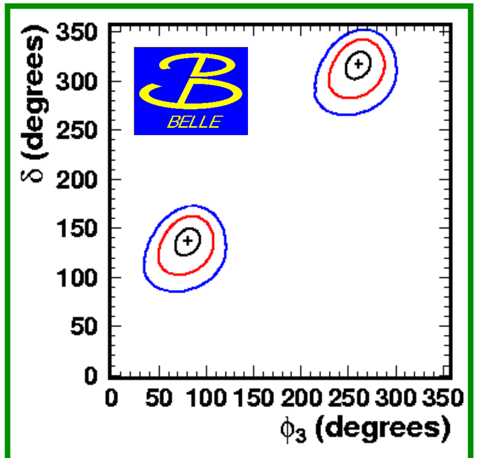
Not an easy task to average the results, the model errors are not easy to be combined



Main differences in $D^0 \to K_s\pi^+\pi^-$:

– BaBar: K-matrix formalism for ππ S-wave, LASS model for *K*π S-wave.

– Belle: Includes σ_1 and σ_2 ππ scalar resonances. K*0(1430) for *K*π Swave.



See Nicola Neri's talk!

BaBar result now also includes $D^0 \to K_sK^+K^-$

γ measurements from B→DK (ADS)

Dalitz Method

Modes:

$K_s\pi^+\pi^-$

$K_sK^+K^-$

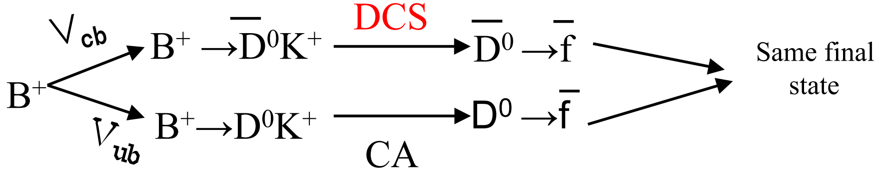
$\pi^+\pi^-\pi^0$

$$x_\pm = r_B \cos(\delta \pm \gamma)$$

$$y_\pm = r_B \sin(\delta \pm \gamma)$$

D. Atwood, I. Dunietz and A. Soni, PRL **78**, 3357 (1997).

Interplay between Doubly-Cabibbo-Suppressed and Cabibbo allowed *D* meson decay



Branching fraction of processes is quite low (~10 -7)

ADS Method

D^0 Modes:

$K^+\pi^-$,

$K^+\pi^-\pi^0$,

$K^+\pi^-\pi^+\pi^-$

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

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

$$r_D = \frac{|A_{c\to u}|}{|A_{c\to s}|}$$

Parameters:

$\{\gamma;\ r_B;\ \delta_B\}$

$$k_D e^{i\delta_D} = \frac{\int A_D \bar{A}_D e^{i(\bar{\delta}(m)-\delta(m))} dm}{\sqrt{\int |A_D|^2 dm \int |\bar{A}_D|^2 dm}}$$

External Inputs:

$\{r_D;\ \delta_D;\ k_D\}$

(CLEO-C, see talk by Chris Thomas)

γ measurements from B→DK (BaBar)

Dalitz Method

Modes:

$K_s\pi^+\pi^-$

$K_sK^+K^-$

$\pi^+\pi^-\pi^0$

$$x_\pm = r_B \cos(\delta \pm \gamma)$$

$$y_\pm = r_B \sin(\delta \pm \gamma)$$

ADS Method

BaBar 425 fb^{-1}
(468 MBB)

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

Two decay chains:

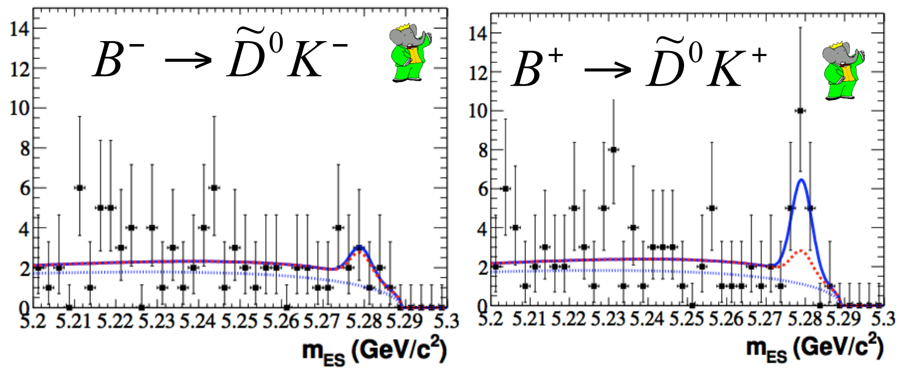
$B^- \to D^0K^-, D^0 \to K^-\pi^+$ Same sign

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

Simultaneous fit to m_{ES} and NN
(based on Event shape variables Tagging variables)
for both decay chains.

Fitting directly R_{ADS} and R^+, R^- to reconstruct asymmetry.

$$A_{ADS} = \frac{R^- - R^+}{R^- + R^+}$$



γ measurements from B→DK (results)

Dalitz Method

Modes:

$K_s\pi^+\pi^-$

$K_sK^+K^-$

$\pi^+\pi^-\pi^0$

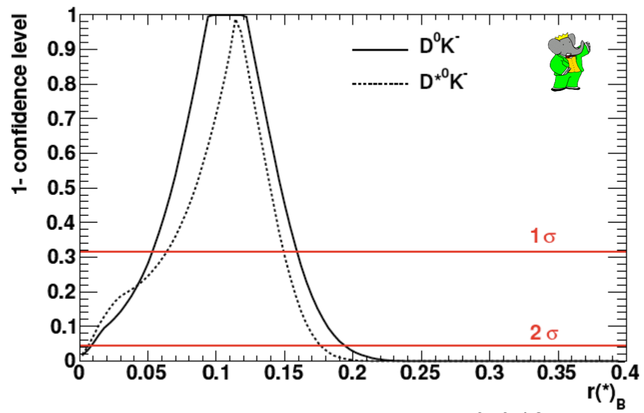
$$x_\pm = r_B \cos(\delta \pm \gamma)$$

$$y_\pm = r_B \sin(\delta \pm \gamma)$$

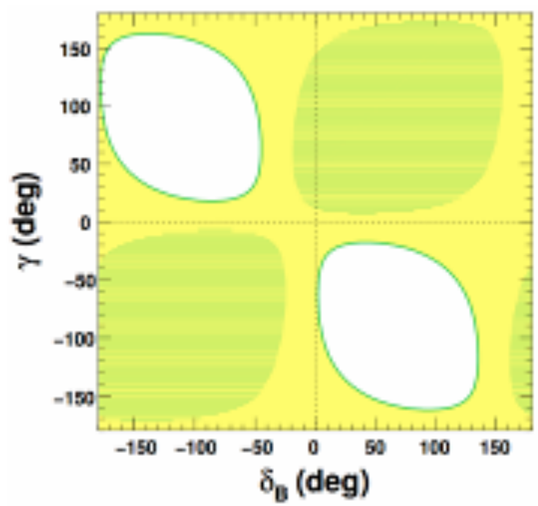
ADS Method

$$B^+ \rightarrow \overline{D}^0 K^+$$

$$\overline{D}^0 \rightarrow K^- \pi^+$$



$$r_B(DK) = 0.109^{+0.049}_{-0.056}$$



γ measurements from B→DK (GLW)

Dalitz Method

Modes:

$K_S\pi^+\pi^-$

$K_SK^+K^-$

$\pi^+\pi^-\pi^0$

$$x_\pm = r_B\cos(\delta\pm\gamma)$$

$$y_\pm = r_B\sin(\delta\pm\gamma)$$

ADS Method

Modes:

$K^+\pi^-$,

$K^+\pi^-\pi^0$,

$K^+\pi^-\pi^+\pi^-$

$$R_{ADS} = \frac{\Gamma([K^+\pi^-\pi^0]K^-)+\Gamma([K^-\pi^+\pi^0]K^+)}{\Gamma([K^-\pi^-\pi^0]K^-)+\Gamma([K^+\pi^+\pi^0]K^+)}$$

$$A_{ADS} = \frac{\Gamma([K^+\pi^-\pi^0]K^-)-\Gamma([K^-\pi^+\pi^0]K^+)}{\Gamma([K^+\pi^-\pi^0]K^-)+\Gamma([K^-\pi^+\pi^0]K^+)}$$

M. Gronau, D. London, D. Wyler, PLB253,483 (1991); PLB 265, 172 (1991)

Theoretically very clean to determine γ (with four observable)

Many D^0 Modes reconstructed:

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

$$CP-: D^0 \to K_S^0\pi^0, K_S^0\omega, K_S^0\phi, (K_S^0\eta)$$

CDF also gave the results with this type of analysis

GLW Method

D^0 Modes:

CP+

CP-

$$R_{CP\pm} = \frac{\Gamma(B^-\to D^0_{CP\pm}K^-)+\Gamma(B^+\to D^0_{CP\pm}K^+)}{2\Gamma(B^+\to D^0K^+)} = 1 + r_B^2 \pm 2r_B\cos\gamma\cos\delta_B$$

$$A_{CP\pm} = \frac{\Gamma(B^-\to D^0_{CP\pm}K^-)-\Gamma(B^+\to D^0_{CP\pm}K^+)}{\Gamma(B^-\to D^0_{CP\pm}K^-)+\Gamma(B^+\to D^0_{CP\pm}K^+)} = \pm 2r_B\cos\gamma\cos\delta_B / R_{CP\pm}$$

Coombination of A_{cp+} measurements gives > 3σ difference from no CPV case

Final Dalitz interpretation

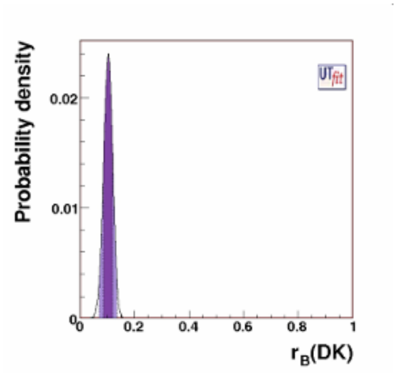
Parameter	68.3% CL	95.4% CL
γ ($^\circ$)	68^{+15}_{-14} {4, 3}	[39, 98]
r_B (%)	9.6 ± 2.9 {0.5, 0.4}	[3.7, 15.5]
r^*_B (%)	$13.3^{+4.2}_{-3.9}$ {1.3, 0.3}	[4.9, 21.5]
κr_s (%)	$14.9^{+6.6}_{-6.2}$ {2.6, 0.6}	< 28.0
δ_B ($^\circ$)	119^{+19}_{-20} {3, 3}	[75, 157]
δ^*_B ($^\circ$)	-82 ± 21 {5, 3}	[−124, −38]
δ_s ($^\circ$)	111 ± 32 {11, 3}	[42, 178]

Parameter	1σ interval	2σ interval	Systematic error	Model uncertainty
ϕ_3	$(78.4^{+10.8}_{-11.6})^\circ$	$54.2^\circ < \phi_3 < 100.5^\circ$	3.6°	8.9°
r_{DK}	$0.160^{+0.040}_{-0.038}$	$0.084 < r_{DK} < 0.239$	0.011	$^{+0.050}_{-0.010}$
r_{D^*K}	$0.196^{+0.072}_{-0.069}$	$0.061 < r_{D^*K} < 0.271$	0.012	$^{+0.062}_{-0.012}$
δ_{DK}	$(136.7^{+13.0}_{-15.8})^\circ$	$102.2^\circ < \delta_{DK} < 162.3^\circ$	4.0°	22.9°
δ_{D^*K}	$(341.9^{+18.0}_{-19.6})^\circ$	$296.5^\circ < \delta_{D^*K} < 382.7^\circ$	3.0°	22.9°

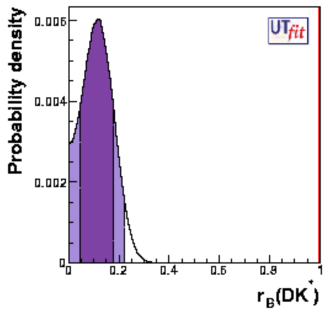
BaBar obtains
$\gamma = (68\ ^{+15}_{-14} \pm 4 \pm 3)^\circ$
(from DK−, D*K−, DK*−)

Belle obtains
$\varphi_3 = (78\ ^{+11}_{-12} \pm 4 \pm 9)^\circ$
(from DK− & D*K−)

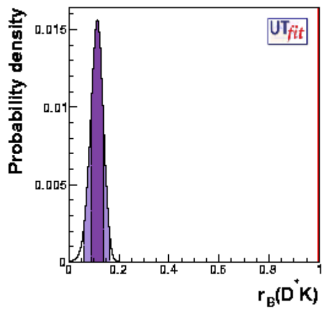
Combination of the methods



$$r_B(D^0K^+) = (0.106 \pm 0.016)$$



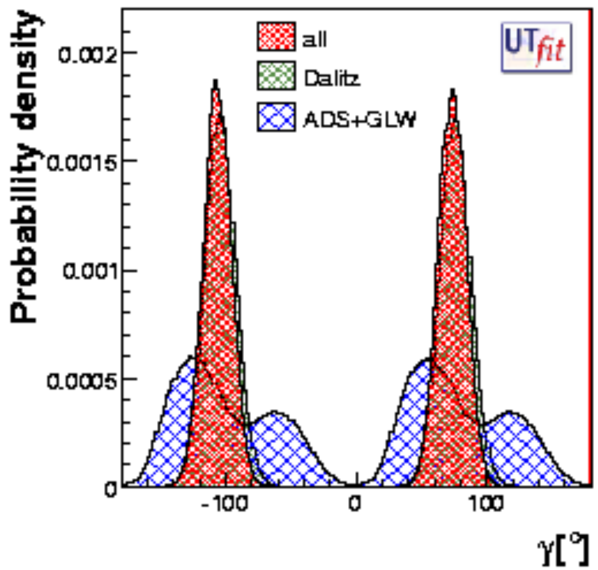
$$r_B(D^0K^{*+}) = (0.11 \pm 0.07\ )$$



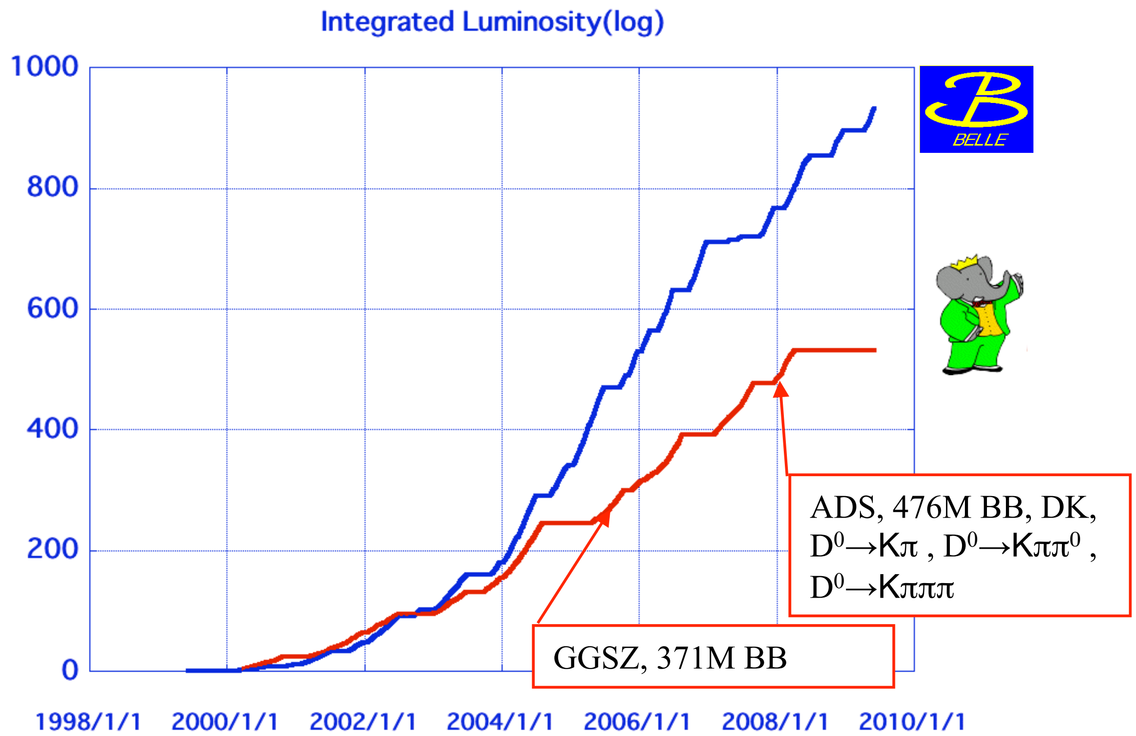
$$r_B(D^{*0}K^+) = (0.113 \pm 0.025)$$

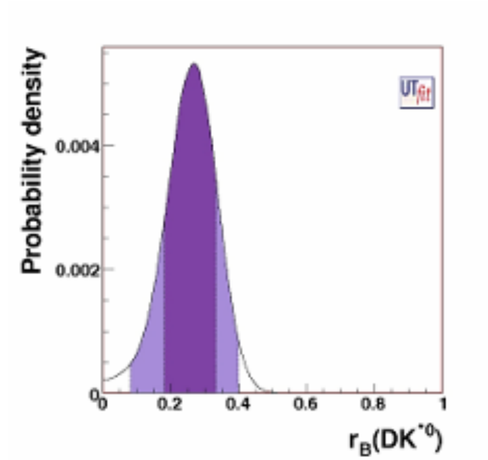
The combination
of all the methods can
be performed giving

$$\gamma\ = (74 \pm 11)^\circ$$

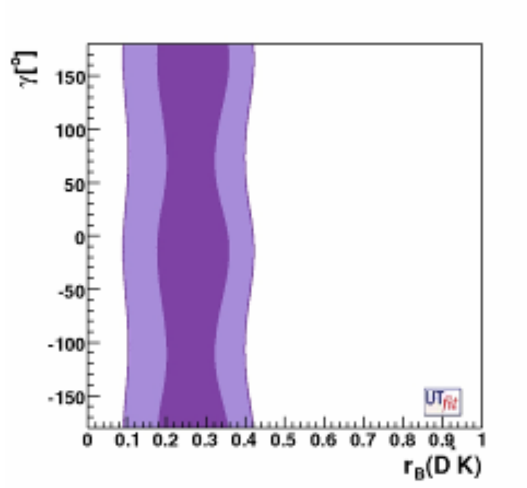


Results from $B^0 \to D^0 K^{*0}$





$$r_B(D^0K^{*0}) = (0.26 \pm 0.076)$$



Promising channel at future experiments for measuring γ due to large value of r_B.
More statistics needed
D sector measurements play an important role.

Conclusions

Combining all B-factory results, there is a strong evidence of CP violation in $B \rightarrow D^{0(*)} K^{(*)}$

Many analyses contribute. Big contributors are DK decay modes using Dalitz method.

The combination of all the method gives

$$\gamma = (74 \pm 11)^{\circ} \text{ (Bayesian approach)}$$

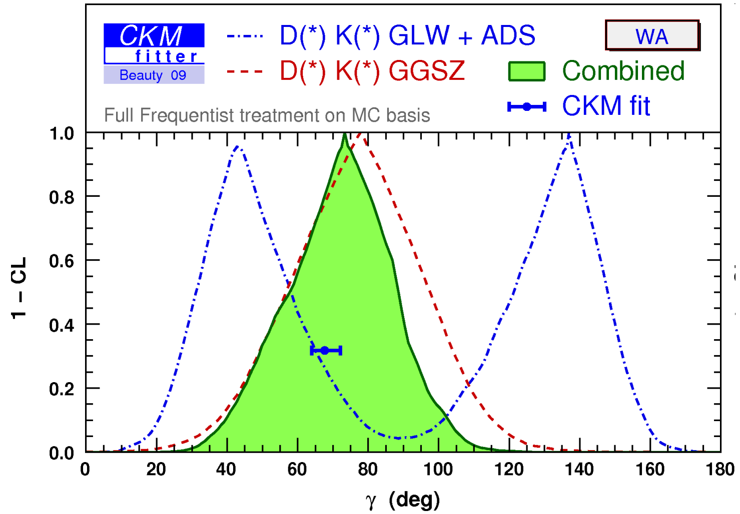
$$\gamma = (73^{+22}_{-25})^{\circ} \text{ (Frequentist approach)}$$

Well compatible with the prediction from SM

$$\gamma = (69.6 \pm 3.0)^{\circ} \text{ (Bayesian approach)}$$

$$\gamma = (67.7\ ^{+4.5}_{-3.7})^{\circ} \text{ (Frequentist approach)}$$

Need to reduce the error in order to see possible deviations:



$$r_B(D^0K^+) = (0.106 \pm 0.016)$$

$$r_B(D^{*0}K^+) = (0.113 \pm 0.025)$$

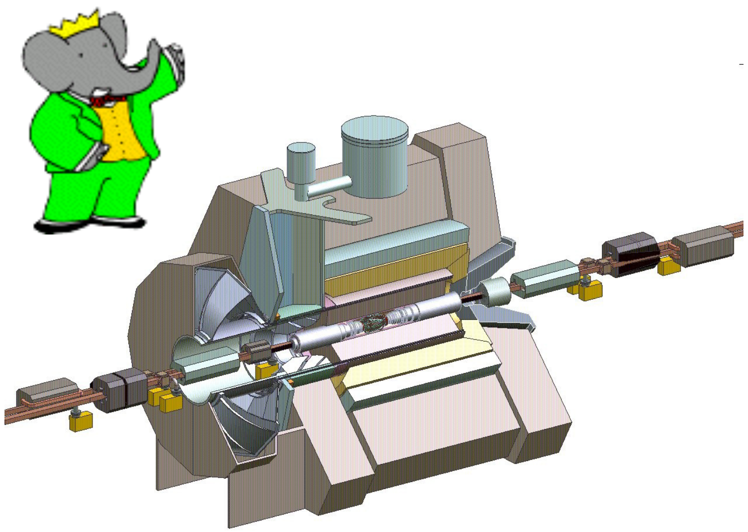
$$r_B(D^0K^{*+}) = (0.11 \pm 0.07)$$

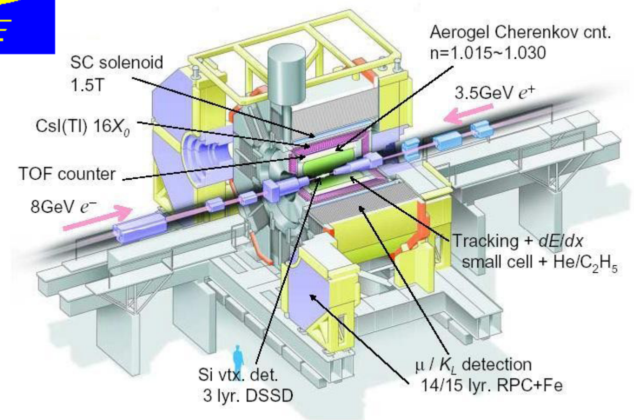
$$r_B(D^0K^{*0}) = (0.26 \pm 0.076)$$

(Bayesian approach)

Current Setups

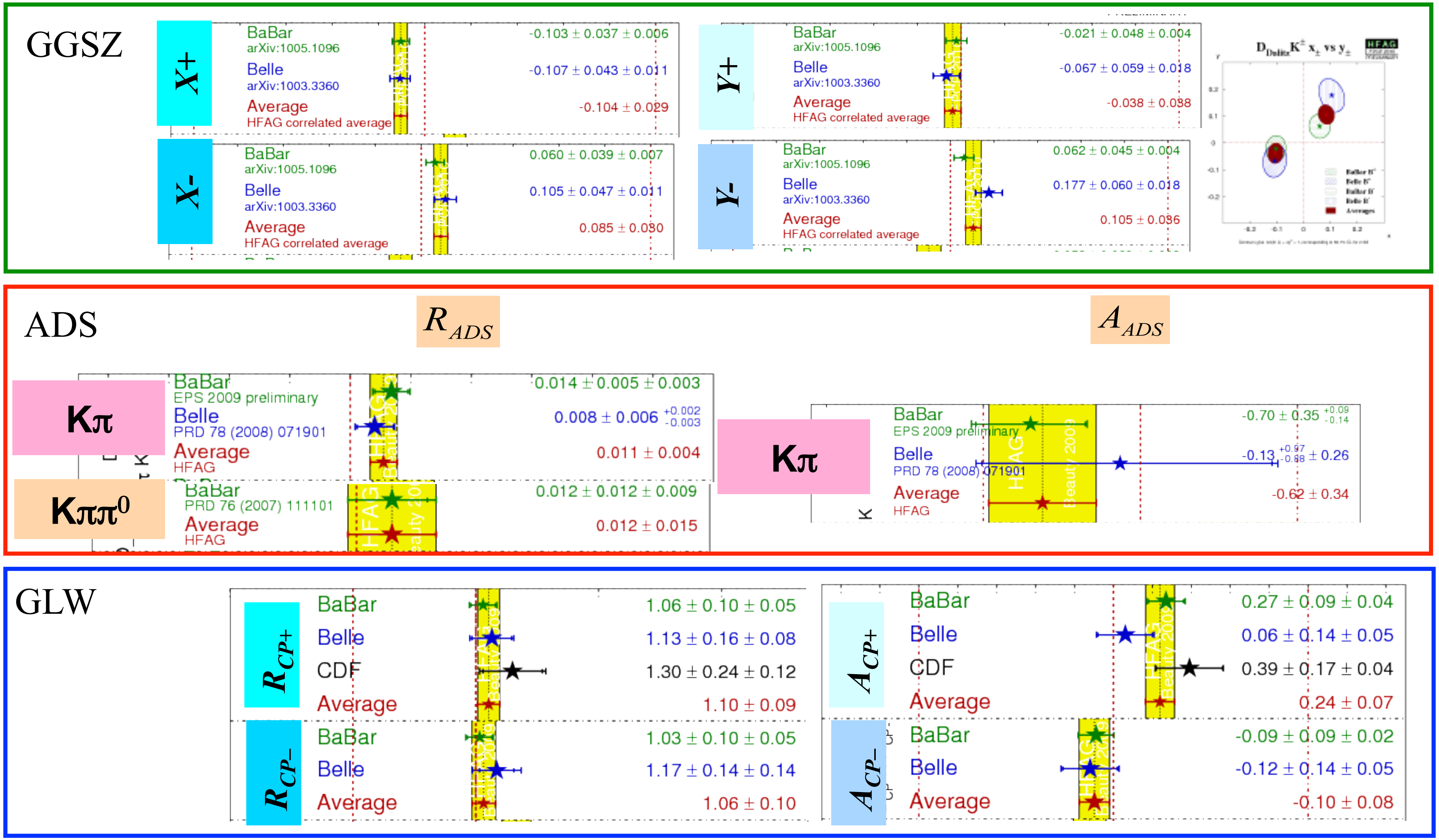
3.1 GeV e^{+} & 9 GeV e^{-} beams
$L = 1.2 \times 10^{34}\ cm^{-2}s^{-1}$
$\int L\,dt = 428\ fb^{-1}$ @ $Y(4S)$+off (~10%)



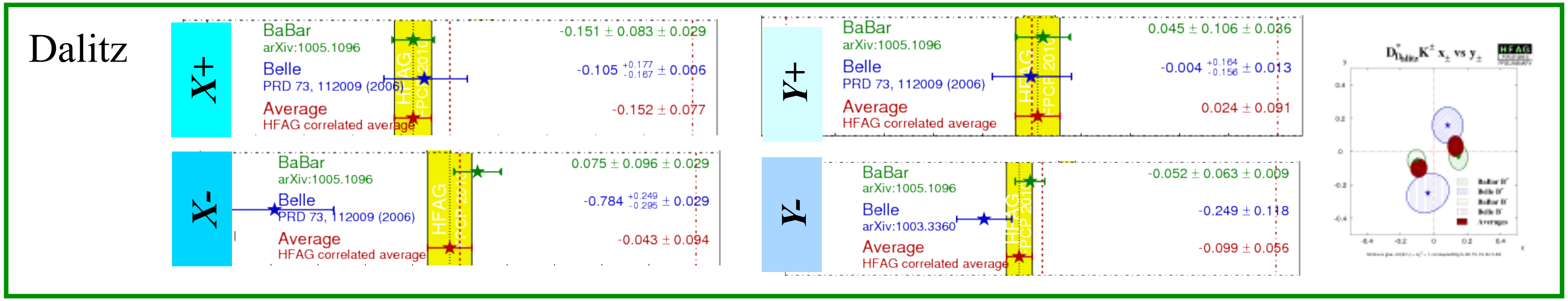


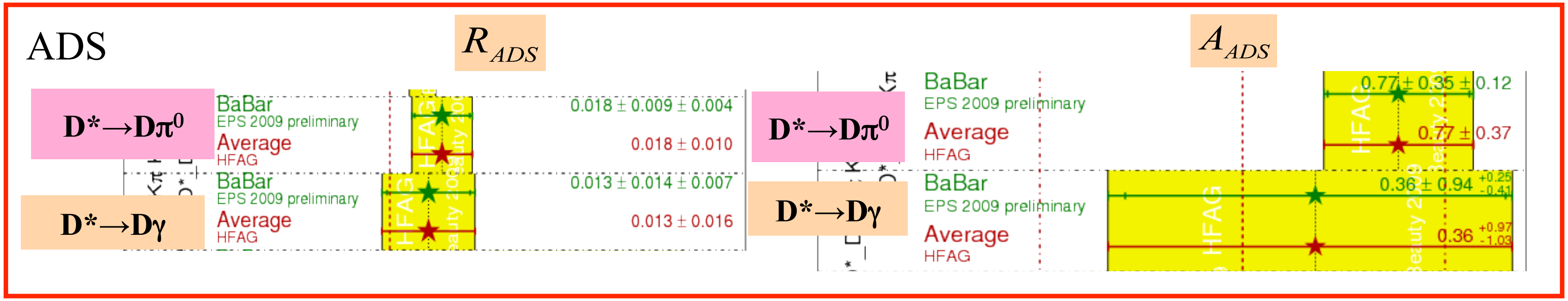
3.5 GeV e^{+} & 8 GeV e^{-} beams
$L = 1.7 \times 10^{34}\ cm^{-2}s^{-1}$
$\int L dt = 820\ fb^{-1}$ @ $Y(4S)$+off(~10%)

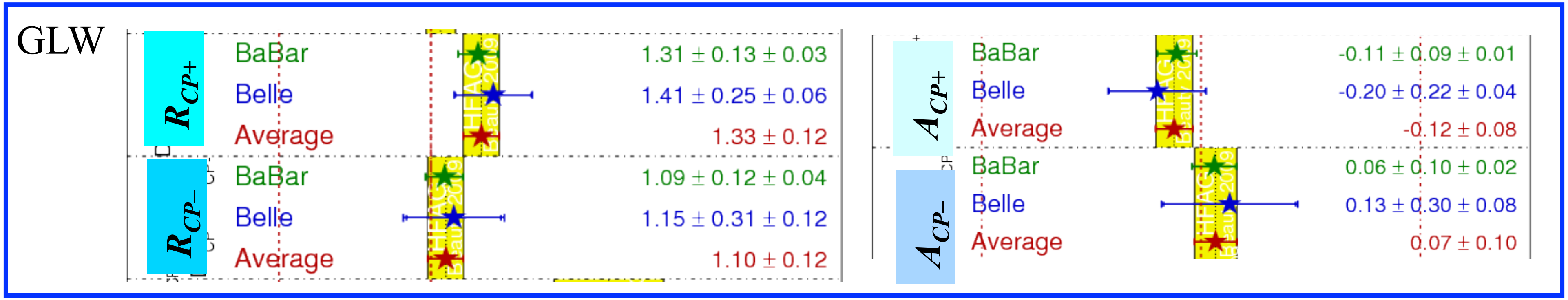
Results from $B^+ \to D^0 K^+$



Results from $B^+ \to D^{*0} K^+$, $D^{*0} \to D^0 \pi^0 (D^0 \gamma)$

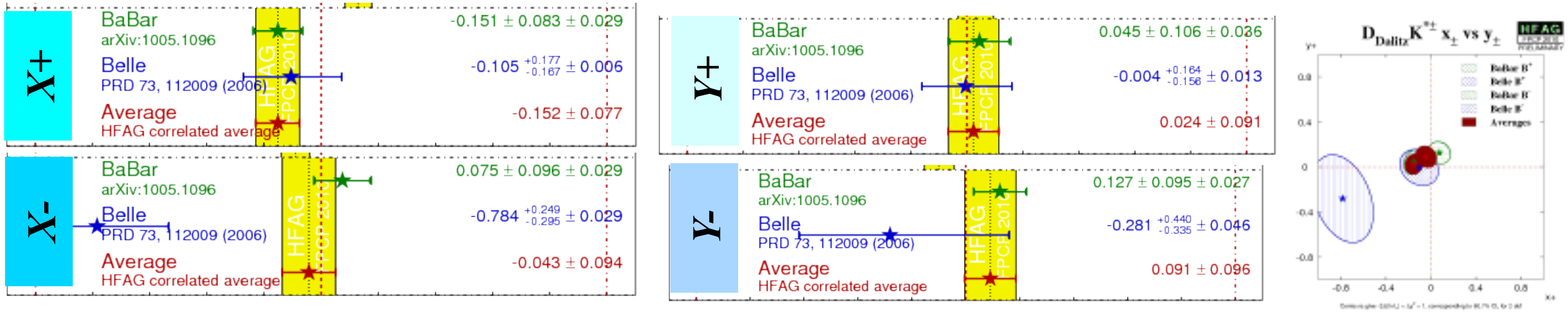






Results from $B^{+} \rightarrow D^{0} K^{*+}$

GGSZ



ADS

GLW