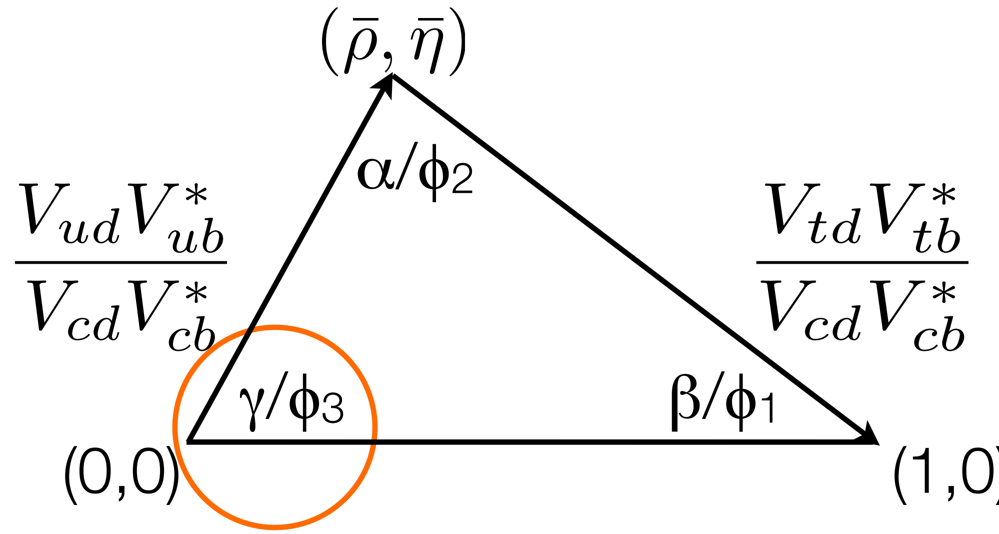
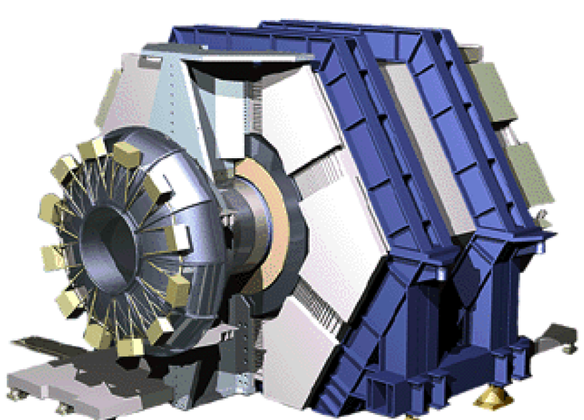


BABAR time-integrated γ/ϕ_3 measurements

Giovanni Marchiori
on behalf of the BABAR collaboration

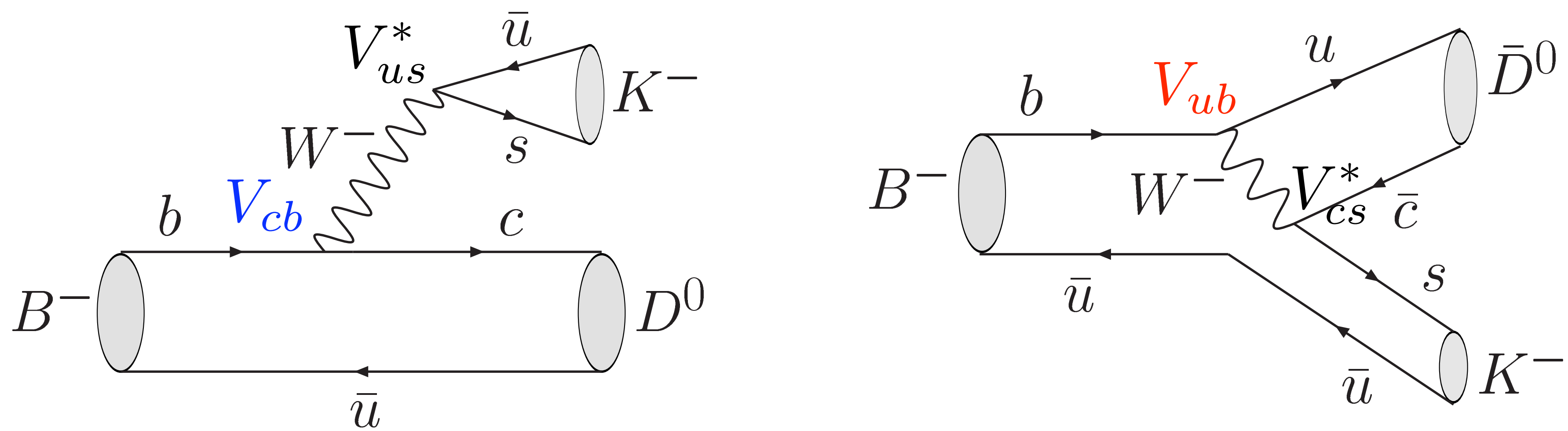
Laboratoire de Physique Nucléaire et des Hautes Energies (Paris)
IN2P3/CNRS



CKM workshop 2010, Warwick
September 2010

Time-integrated γ measurements from $B \to D^{(*)}K^{(*)}$: how?

- Exploit **interference** between tree diagrams $b \to c$ and $b \to u$ ($V_{ub} \propto e^{-i\gamma}$) in charged $B \to D^{(*)0}K^{(*)}$ or self-tagging neutral $B^0 \to D^{(*)0}K^{*0}$ ($K^{*0} \to K^+\pi^-$) decays



  - use final states accessible from both $D^{(*)0}$ and $\bar{D}^{(*)0}$
    - **GLW**: **CP eigenstates** (Cabibbo suppressed): many modes, small asymmetries
    - **ADS**: **doubly Cabibbo suppressed:** smaller rates, larger asymmetries
    - **GGSZ**: Cabibbo favored **multibody decays**: larger rates, asymmetry varying across the Dalitz plane
  - **hadronic parameters** $r_B = |A(b \to u)/A(b \to c)|$ and δ_B=strong phase (CP conserving) between $A(b \to u)$ and $A(b \to c)$ **determined experimentally**
  - largely **unaffected by New Physics** 
  - **difficult** because of **small BFs** (few events) and **small r_B** (small interference)

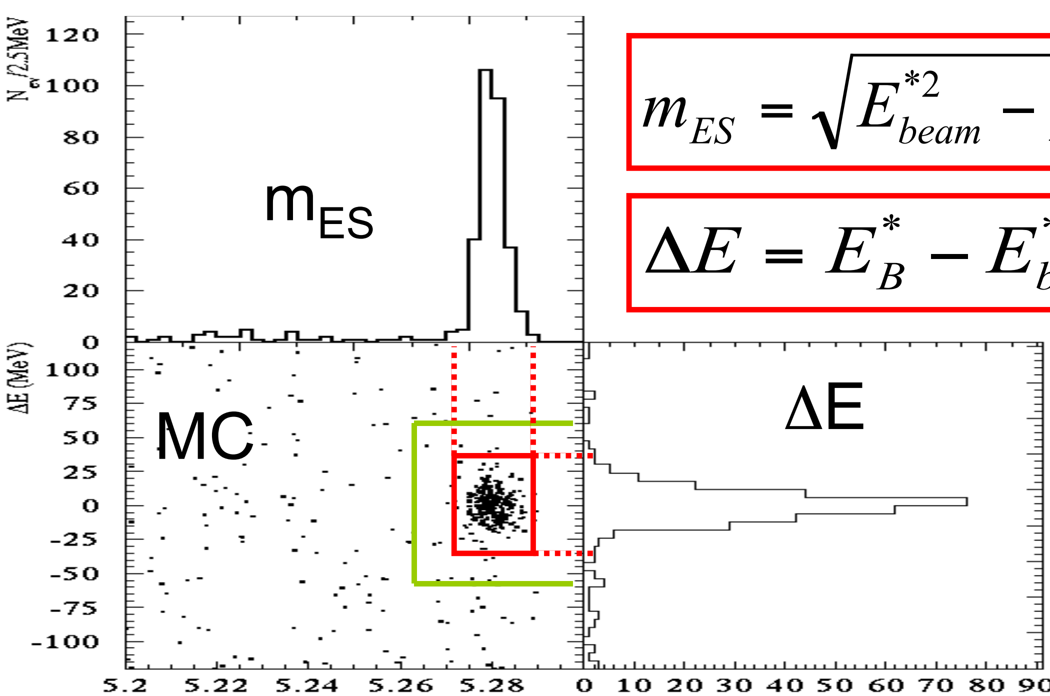
News since CKM2008

- **Full Υ(4S) data set** exploited in many measurements (**468M $B\bar{B}$ pairs**)
- **Latest reprocessing** of data using optimized algorithms: **higher charged particle reconstruction and identification efficiency and purity**

Measurement	**CKM 2008**		**CKM 2010**		**changes**
	N($B\bar{B}$)	**pub. status**	**N($B\bar{B}$)**	**pub. status**	
GGSZ $D^{(*)0}K^{(*)}$	383M	PRD 78, 034023 (2008)	468M	arXiv:1005.1096 **accepted by PRL**	updated Dalitz model, added DK* (D→KsKK)
GLW D^0K	382M	PRD 77, 111102 (2008)	467M	arXiv:1007.0504 **accepted by PRD**	improved fit technique, added CL scan of γ
ADS $D^{(*)0}K$	232M	PRD 72, 032004 (2005)	467M	arXiv:1006.4241 **accepted by PRD**	improved fit technique, better statistical analysis, CL scan of γ
GLW+ADS D^0K^*	379M	preliminary	379M	PRD 80, 092001 (2009)	added CL scan of γ
GLW $D^{*0}K$	382M	submitted to PRD	382M	PRD 78, 092002 (2008)	no changes
ADS D^0K^{*0}	465M	preliminary	465M	PRD 80, 031102 (2009)	no changes
GGSZ D^0K^{*0}	371M	preliminary	371M	PRD 79, 072003 (2009)	no changes

Experimental techniques

Exclusive reconstruction of B decay; kinematic constraint from beam energies

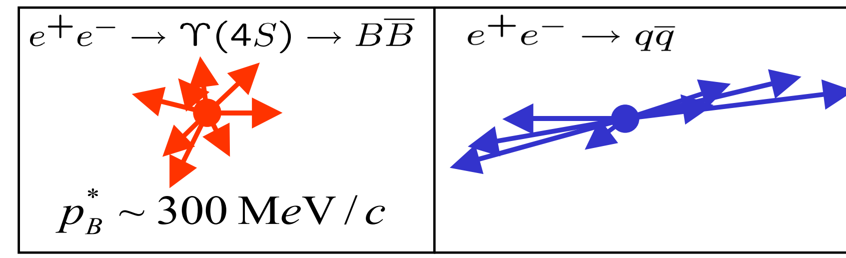


$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

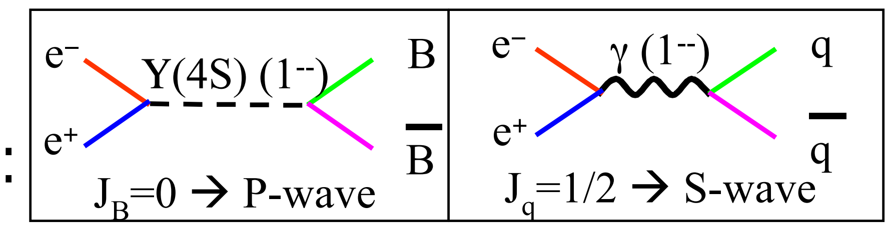
$$\Delta E = E_B^* - E_{beam}^*$$

Continuum ($q\bar{q}$) bkg suppression

Topology:

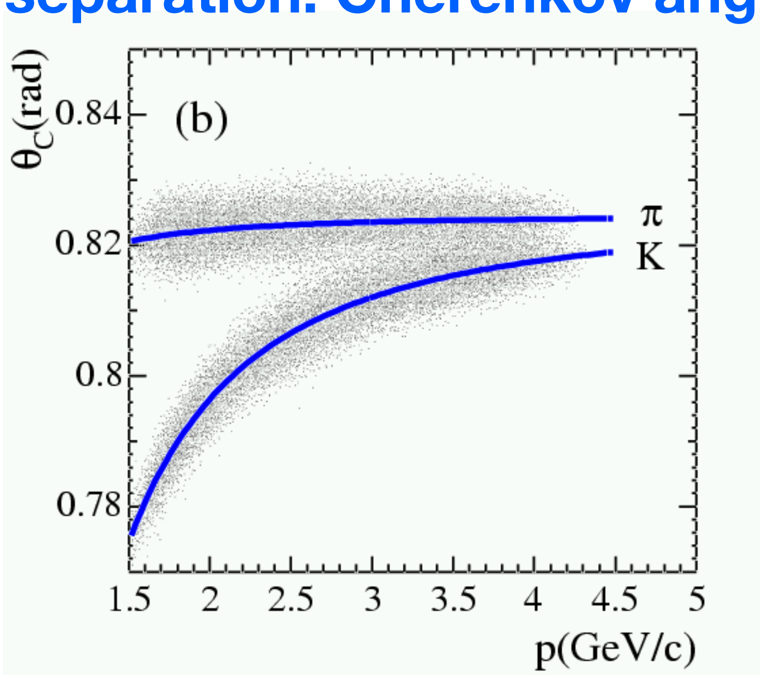


Angular distribution:



Multivariate analysis (NN, Fisher)

K/π separation: Cherenkov angle + dE/dx



Excellent separation between 1.5 and 4 GeV/c

Data control samples ($B \to D^{(*)}\pi$)

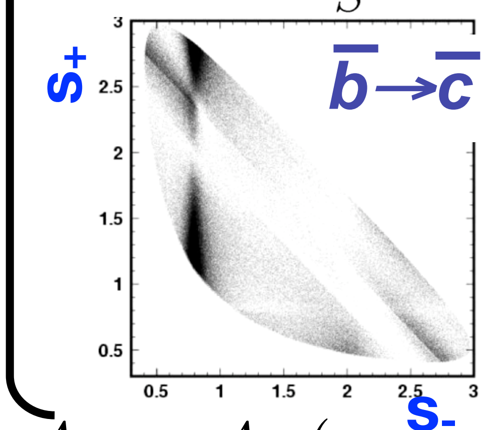
- nearly identical to the signal (except PID)
- abudant: BF 12 times higher than $D^{(*)}K$
- r_B~0.01: negligible CPV, useful x-check

$B^- \rightarrow D^{(*)}K^{(*)-}$, GGSZ method: basics

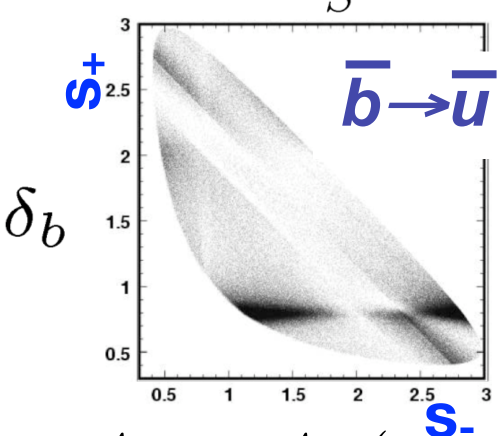
Giri, Grossman, Soffer, Zupan – Phys. Rev. D68 (2003) 054018

- $D \rightarrow K_S\pi^+\pi^-$, $K_S K^+ K^-$: reasonable BF (~10^{-5}), good efficiency & purity (only $\pi^\pm/K^\pm$)
- Neglecting CPV and mixing in D system:

$$A(B^+) = |A(B^+ \rightarrow \overline{D}^0 K^+)| \times \Big[\overline{D}^0 \rightarrow K_S^0\pi^+\pi^- \quad\quad + \; r_b e^{+i\gamma + i\delta_b} \; D^0 \rightarrow K_S^0\pi^+\pi^- \Big]$$



$A_{D+} = A_D(s_+, s_-)$

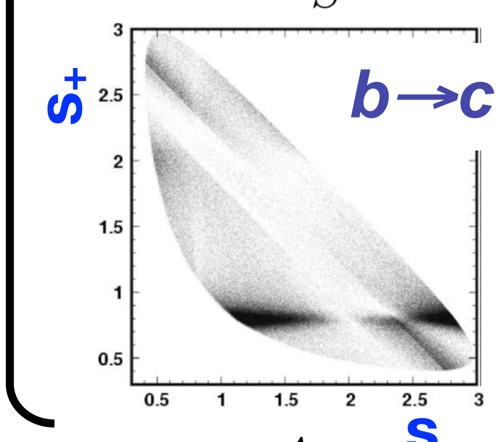


$A_{D-} = A_D(s_-, s_+)$

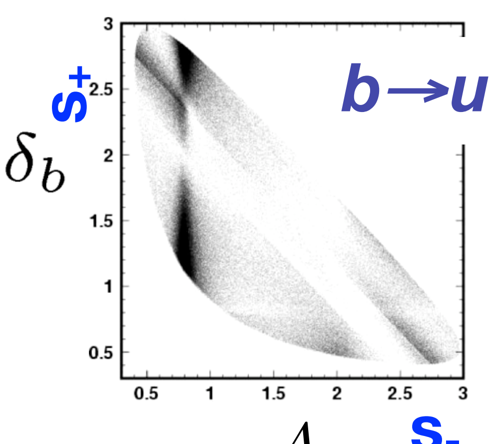
$s_\pm = m^2(K_S h^\pm)$
$A_{D\mp}$ = $D^0/\bar{D}^0 \rightarrow K_S^0 h^+ h^-$
decay amplitudes

Relative weak phase (gamma) changes sign

$$A(B^-) = |A(B^- \rightarrow D^0 K^-)| \times \Big[D^0 \rightarrow K_S^0\pi^+\pi^- \quad\quad + \; r_b e^{-i\gamma + i\delta_b} \; \overline{D}^0 \rightarrow K_S^0\pi^+\pi^- \Big]$$



A_{D-}



A_{D+}

$B^- \to D^{(*)}K^{(*)-}$, GGSZ method: observables

Giri, Grossman, Soffer, Zupan – Phys. Rev. D68 (2003) 054018

- Extract γ from fit to **Dalitz-plot distribution of D daughters**:
  - **$D^{(*)}K$:**

$$\Gamma_{\mp}(s_-, s_+) \propto |\mathcal{A}_{D\mp}|^2 + r_B^{(*)2}|\mathcal{A}_{D\pm}|^2 + 2\lambda\{x_{\mp}^{(*)}Re[\mathcal{A}_{D\mp}\mathcal{A}^*_{D\pm}] + y_{\mp}^{(*)}Im[\mathcal{A}_{D\mp}\mathcal{A}^*_{D\pm}]\}$$

$x^{(*)}_{\pm}=r_B^{(*)}\cos(\delta_B^{(*)}\pm\gamma)$
$y^{(*)}_{\pm}=r_B^{(*)}\sin(\delta_B^{(*)}\pm\gamma)$
$r_B^{(*)2}=x^{(*)2}+y^{(*)2}$

λ = +1 for $B\to D^0K$, $D^{*0}[D^0\pi^0]K$
-1 for $B\to D^{*0}[D^0\gamma]K$

  - **DK^*:**

$$\Gamma_{\mp}(s_-, s_+) \propto |\mathcal{A}_{D\mp}|^2 + r_S^2|\mathcal{A}_{D\pm}|^2 + 2\{x_{s\mp}Re[\mathcal{A}_{D\mp}\mathcal{A}^*_{D\pm}] + y_{s\mp}Im[\mathcal{A}_{D\mp}\mathcal{A}^*_{D\pm}]\}$$

$x_{s\pm}=kr_S\cos(\delta_S\pm\gamma)$
$y_{s\pm}=kr_S\sin(\delta_S\pm\gamma)$
$k^2r_S^2=x^{(*)2}+y^{(*)2}$

$k<1$ (0.9±0.1) because of interfering non-K^* $B\to DK_S\pi$ bkg

- **2-fold γ ambiguity**: $(\gamma, \delta_B^{(*)}, \delta_S) \to (\gamma+\pi, \delta_B^{(*)}+\pi, \delta_S+\pi)$

Measurement ingredients

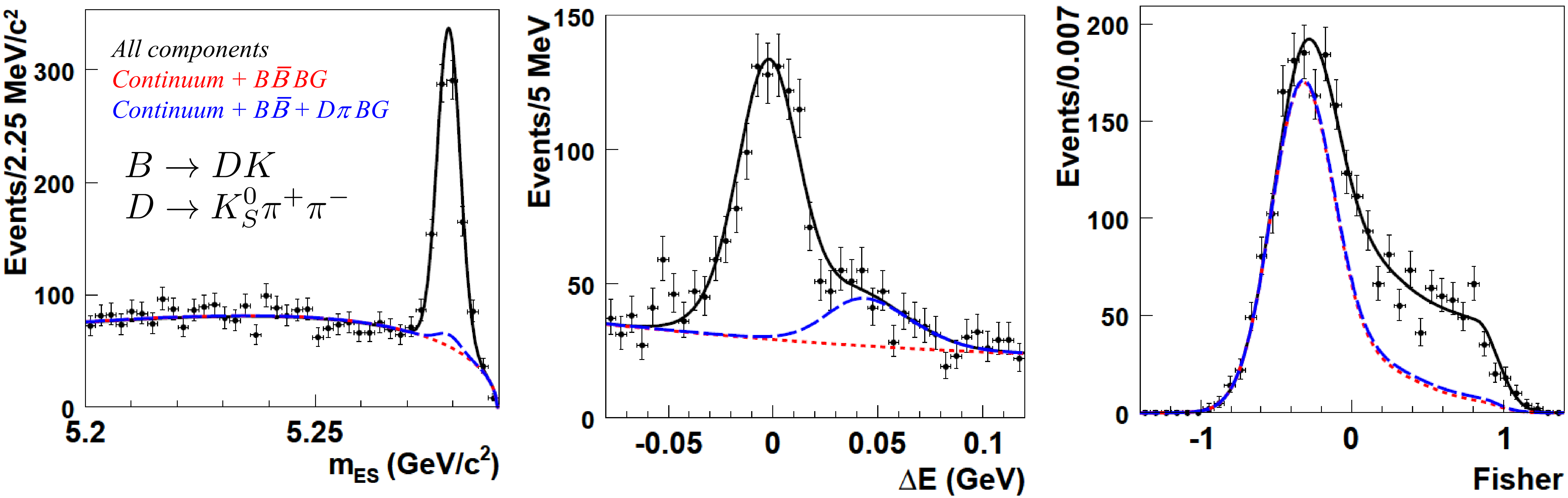
- **Selection optimized for S/sqrt(S+B)** based on:
  - K: particle identification π^0: invariant mass, CM momentum
  - K_S: invariant mass, angle between momentum and line of flight, flight length
  - K^*: invariant mass, helicity angle of decay products
  - D: invariant mass, vertex fit probability D^*: D^*-D mass difference
  - B: vertex fit probability
- **Yield fit**: **ML fit to {m_{ES}, ΔE, F}**, F=linear combination (Fisher) of evt. shape vars:
  - $\cos(\theta_T^*)$: angle between thrust axes of B and rest-of-event (ROE) ($q\bar{q}$ ~1, signal ~uniform)
  - $\cos(\theta_B^*)$: polar angle of B in CM frame ($q\bar{q}$ ~$1+\cos^2\theta_B^*$, signal ~ $\sin^2\theta_B^*$)
  - $L_0 = \sum_i^{ROE} p_i^*,\ L_2 = \sum_i^{ROE} p_i^* (\cos\theta_i^*)^2$ (L_2/L_0: $q\bar{q}$ ~1, ~0.5 for signal)
- **CP fit**: **ML fit to {m_{ES}, ΔE, shape vars, s_-, s_+}** to determine x,y based on observed D Dalitz plot distribution:
  - yields and shape parameters fixed (obtained from previous step)
  - **true $D^0 \to K_S h^+ h^-$** decay amplitude from **flavor tagged** D^0 from $D^{*+} \to D^0 \pi^+$
  - **fake $D^0 \to K_S h^+ h^-$** distribution from **data/MC bkg control samples**

Yield and shape parameter extraction

arXiv:1005.1096, accepted by Phys. Rev. Lett. (August 2010)

$N_{B\bar{B}} = 468 \times 10^6$

- Signal and background **yields** in selected sample determined **from ML fit** (use $B \to D^{(*)0}\pi$ and $B \to D^0 a_1$ as control samples):



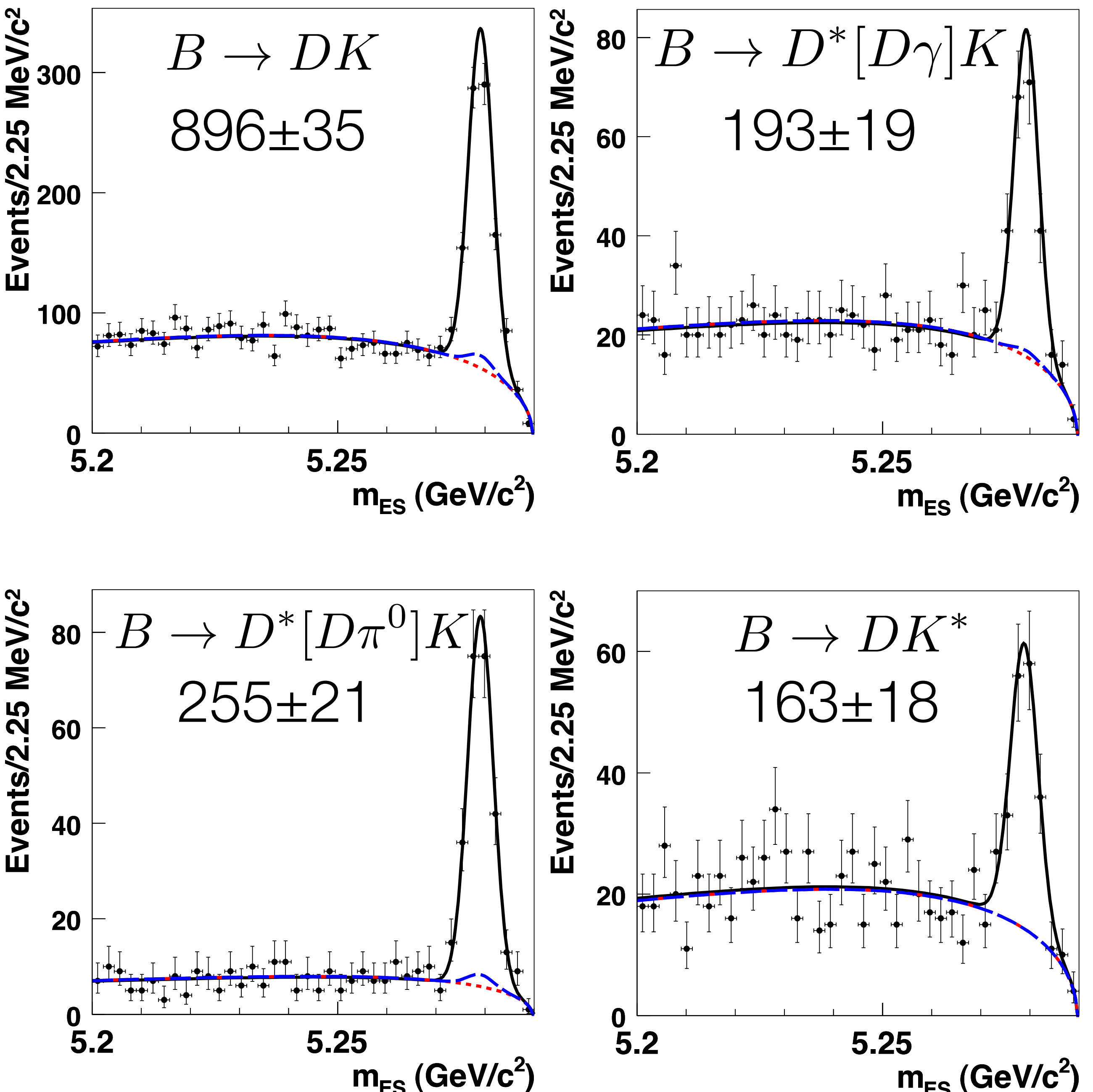
- **Yields increased by ~50%** wrt to previous BaBar measurement: +22% more data and **20-40% relative increase in selection efficiency**
  - reprocessed data with improved track reconstruction
  - improved particle identification

Yields

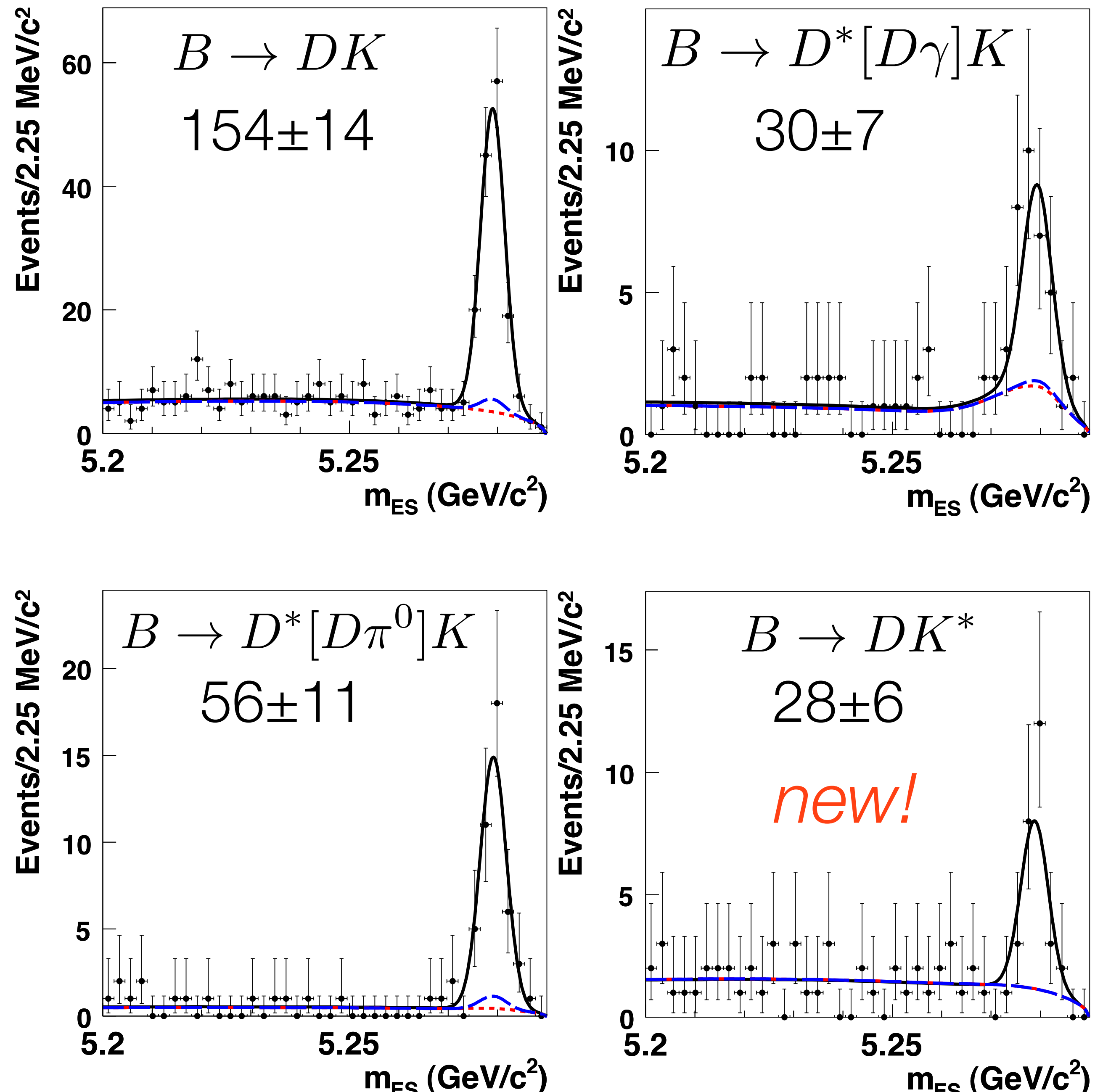
arXiv:1005.1096, accepted by Phys. Rev. Lett. (August 2010)

$N_{B\bar{B}} = 468 \times 10^6$

1507 $D^0 \rightarrow K_S\pi\pi$ events



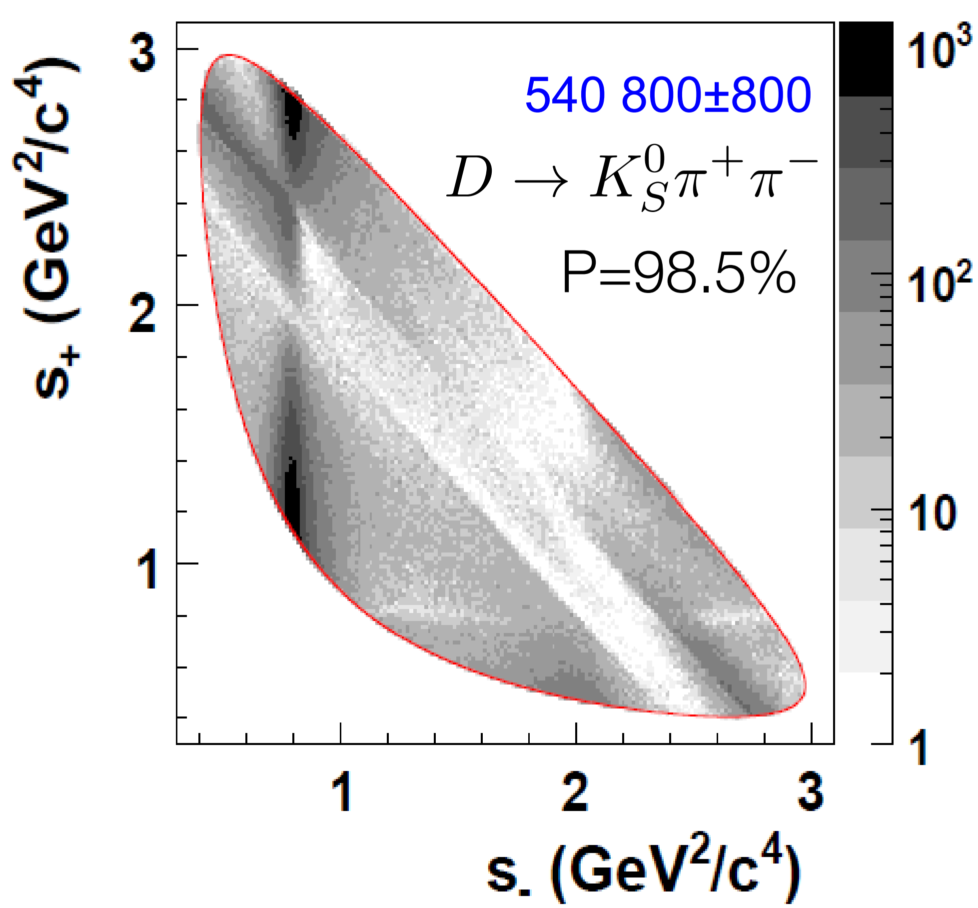
268 $D^0 \rightarrow K_SKK$ events

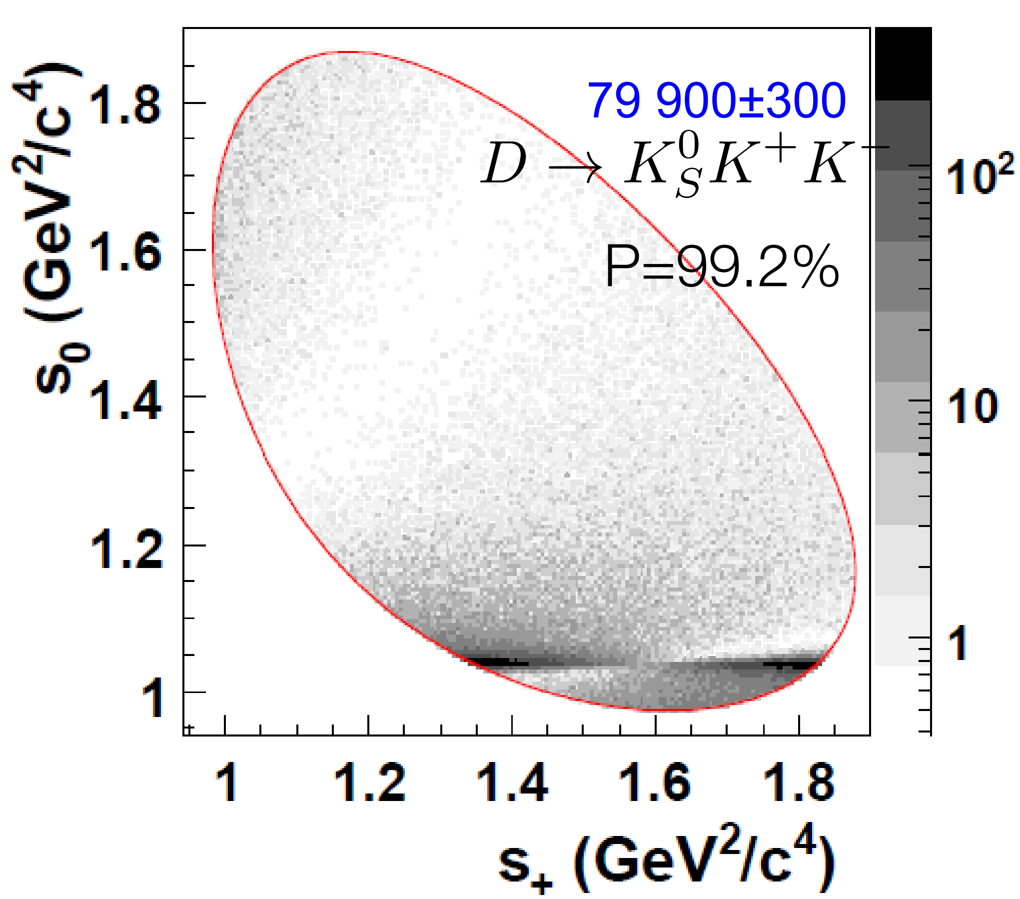


D→$K_S h^+ h^-$ decay amplitude analysis

arXiv:1004.5053, accepted by Phys. Rev. Lett. (2010)

- Extract D decay amplitude **from independent analysis of flavor-tagged D^0 mesons ($D^{*+} \to D^0 \pi^+$)**
- **Nominal** model determined **without D-mixing** (⇒ syst. uncertainties)
- Fit for amplitudes relative to $K_S\rho(770)$ and $K_S a_0(980)$, assume no direct CPV





D→$K_S h^+ h^-$ decay amplitude isobar model

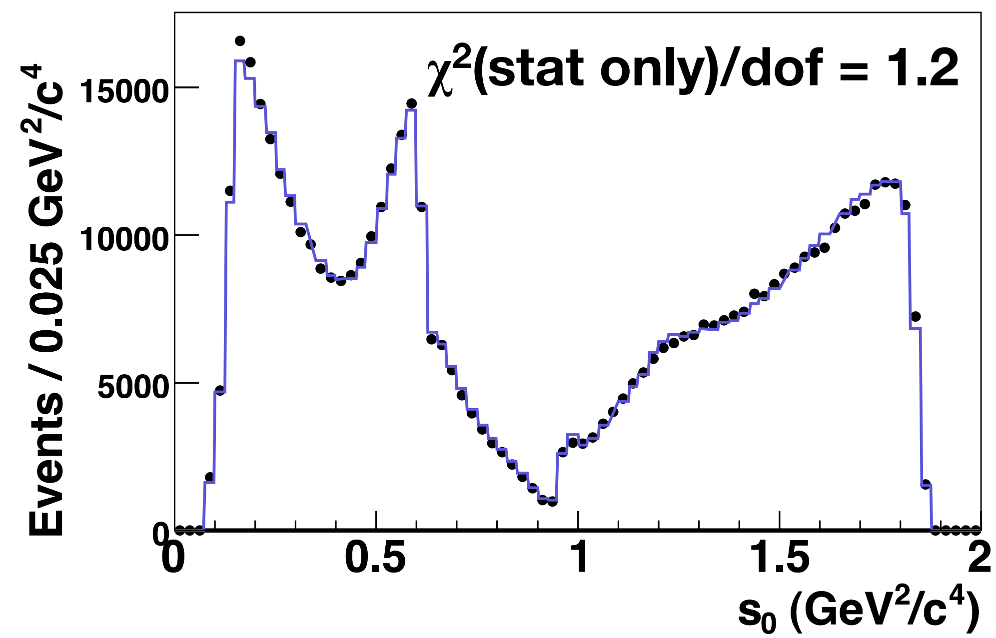
arXiv:1004.5053, accepted by Phys. Rev. Lett. (2010)

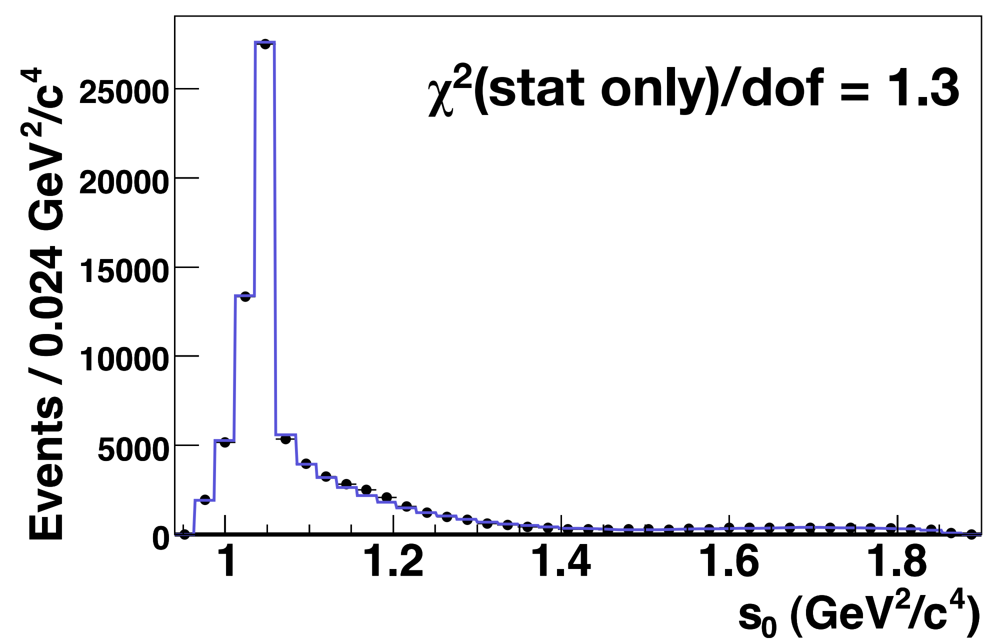
$D \to K_S^0 \pi^+ \pi^-$

Wave	Parameterization
ππ S-wave	K-matrix
K_Sπ S-wave	K-matrix (LASS)
ππ P-wave	BW: ω(782), G.S. ρ(770)
K_Sπ P-wave	BW: CA and DCS K*(892), CA K*(1680)
ππ D-wave	BW $f_2(1270)^0$
K_Sπ D-wave	BW: CA and DCS $K_2^*(1430)$

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

Wave	Parameterization
KK_S S-wave	BW: CA and DCS $a_0(980)$, CA $a_0(1450)$
KK S-wave	Flatte $a_0(980)$, BW $a_0(1450)$, $f_0(1370)$
KK P-wave	BW ϕ(1020)
KK D-wave	BW $f_2(1270)^0$





Good fit quality taking into account statistical, experimental and model uncertanties

$B^- \to D^{(*)} K^{(*)-}$ GGSZ results: x,y, direct CPV

arXiv:1005.1096, accepted by Phys. Rev. Lett. (August 2010)

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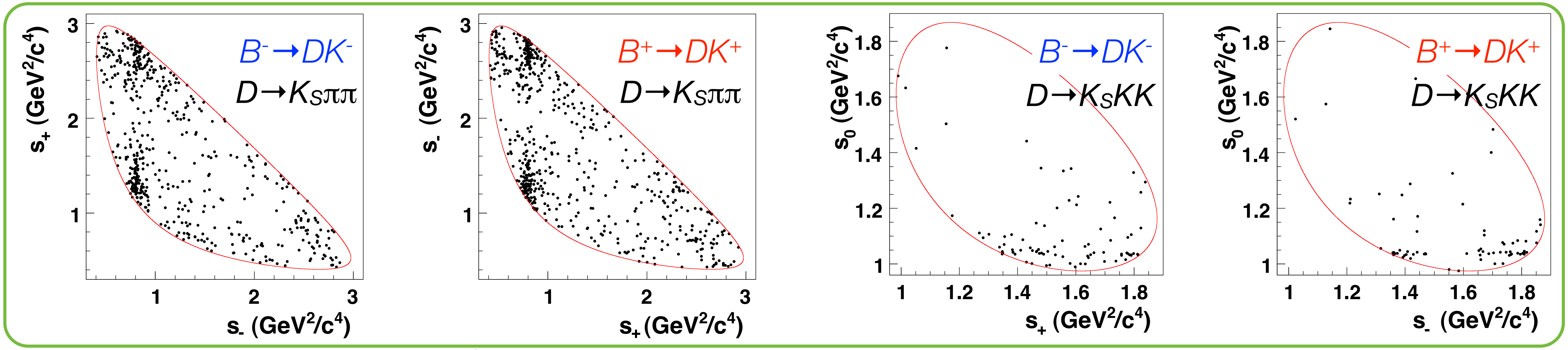

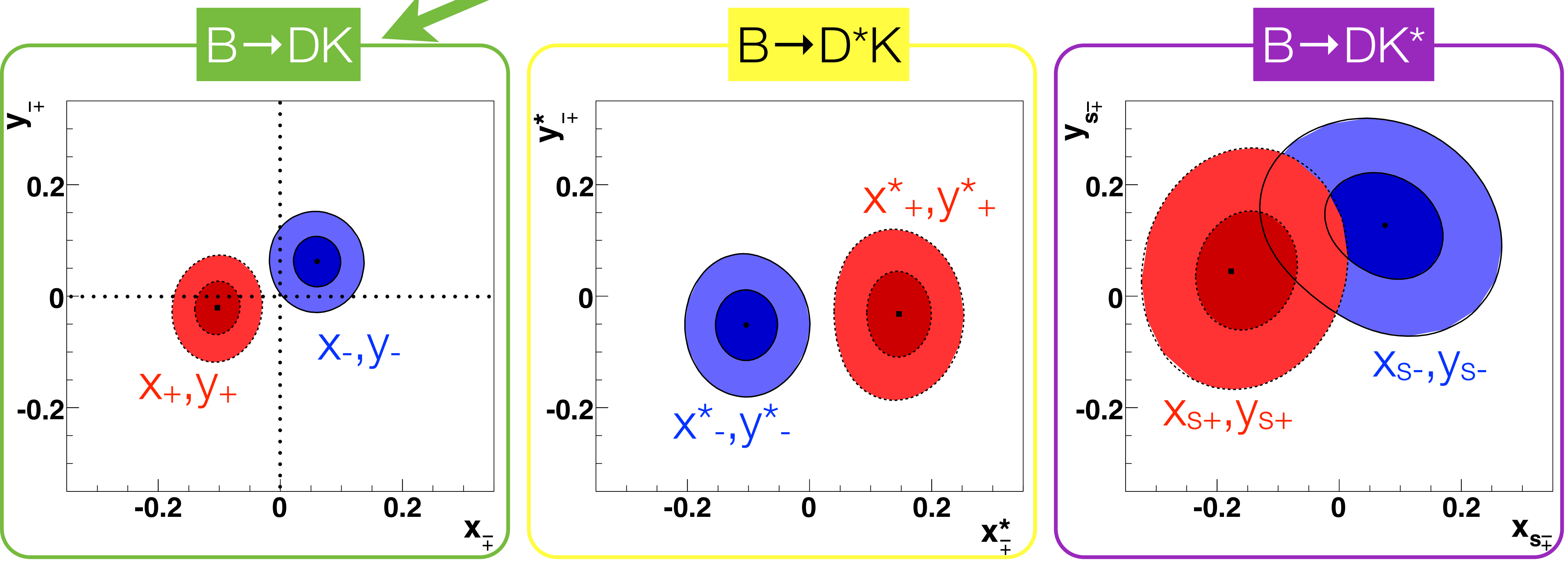

39.3% and 86.5% 2D CL contours

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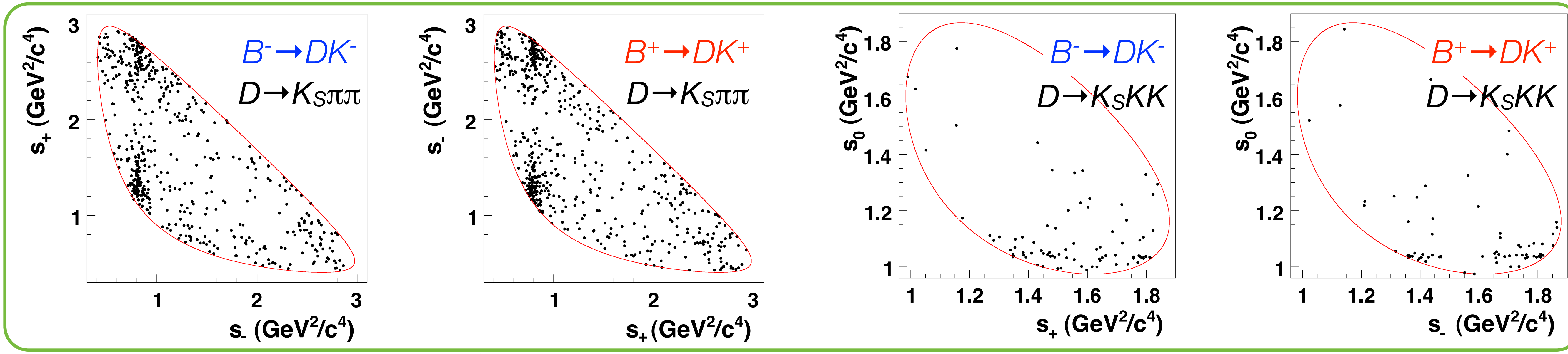

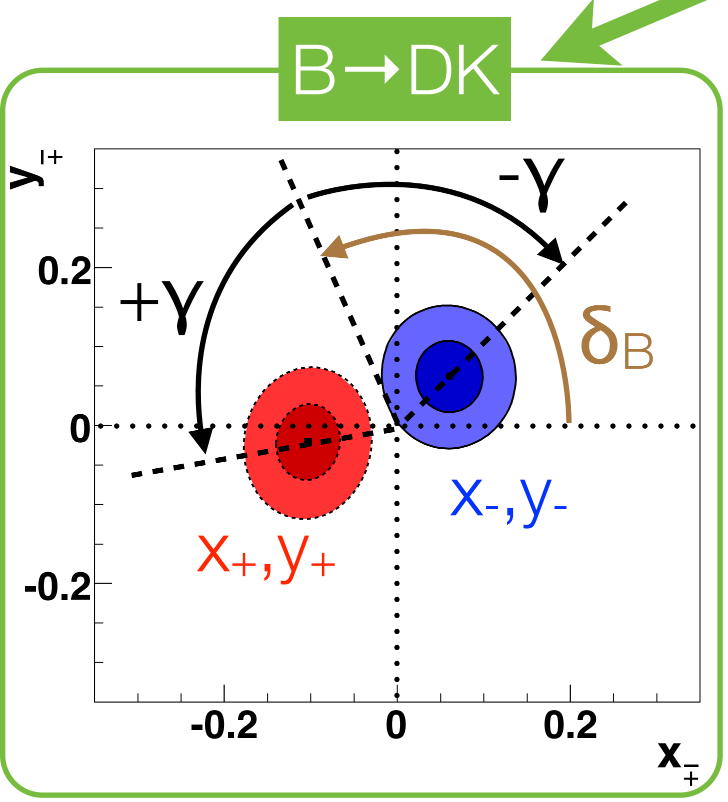

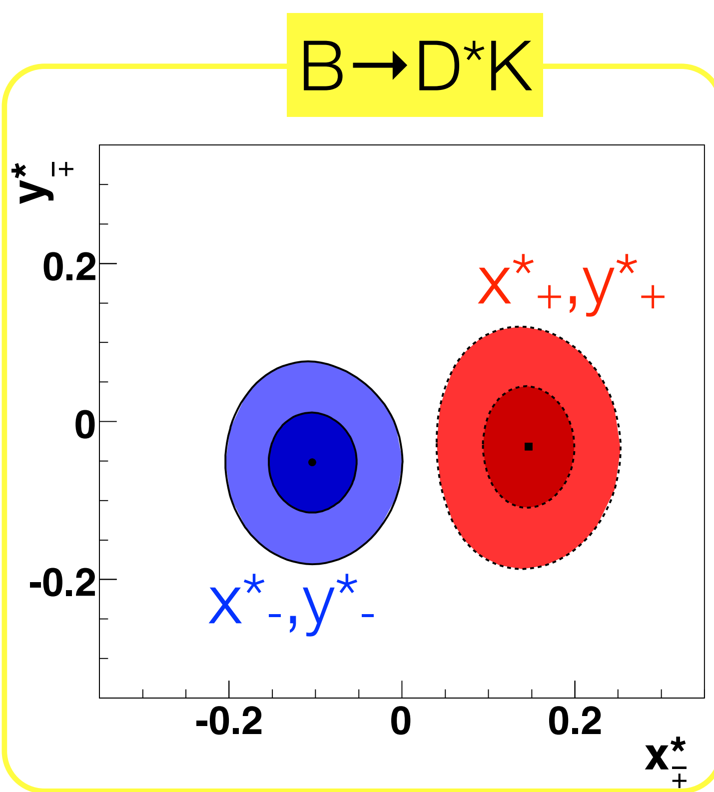

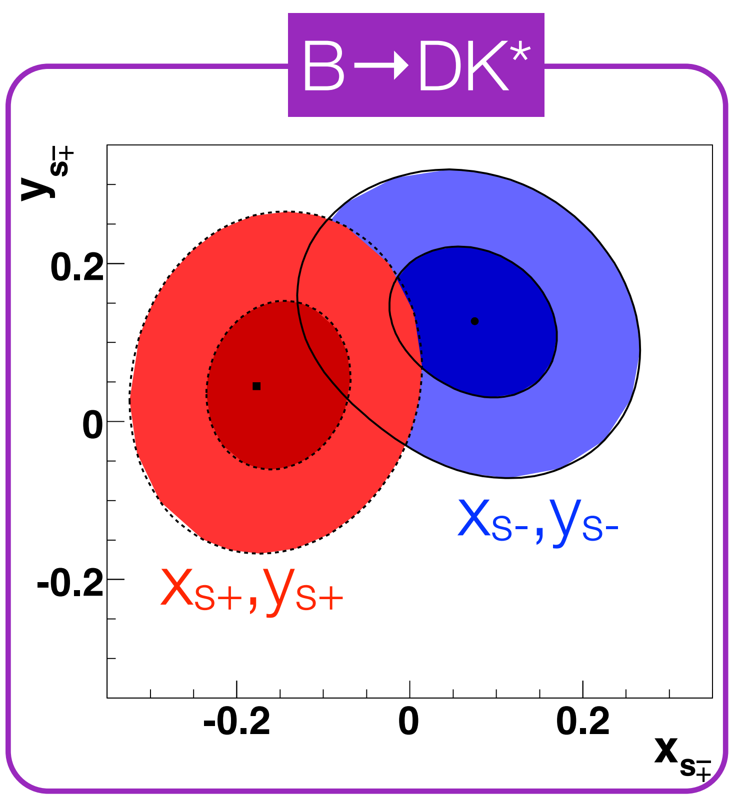

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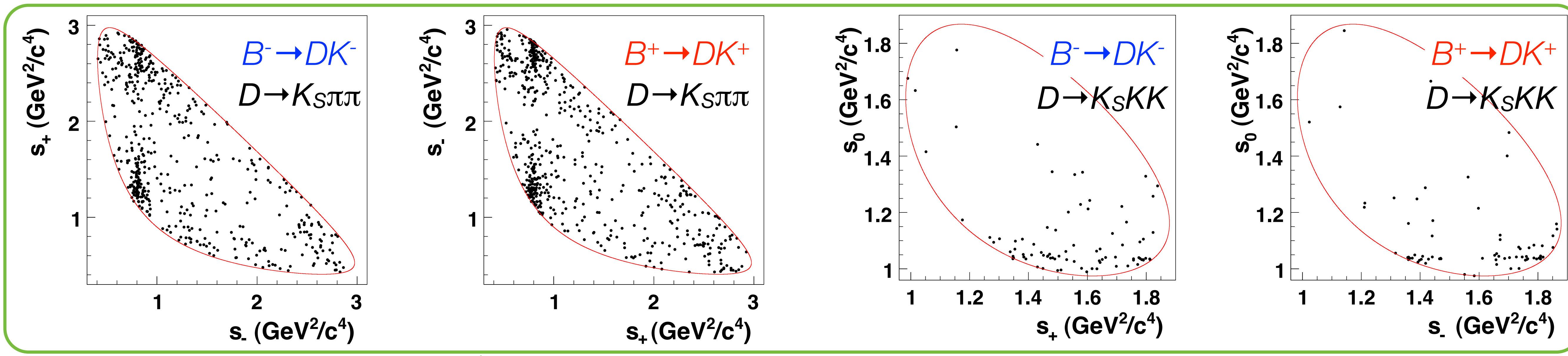
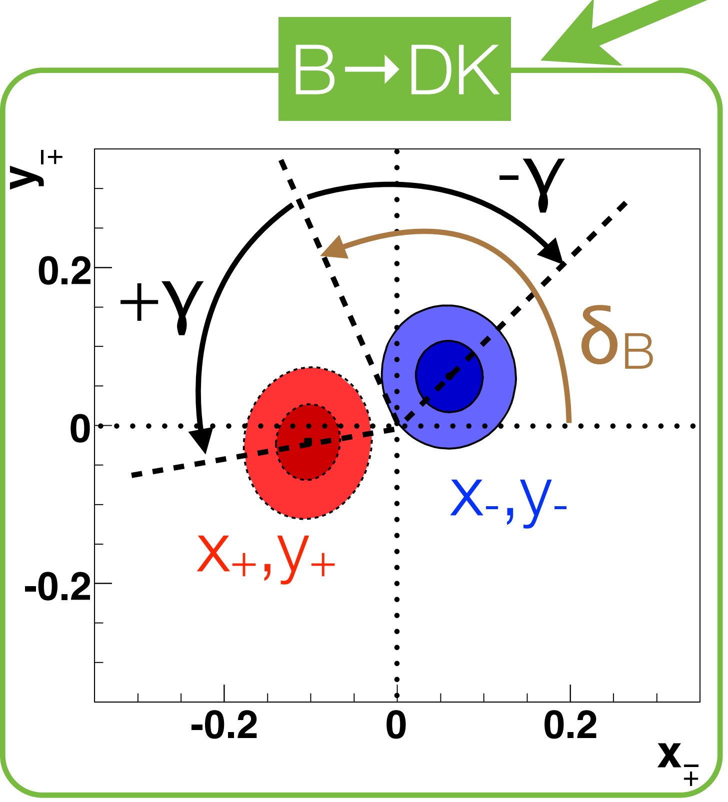
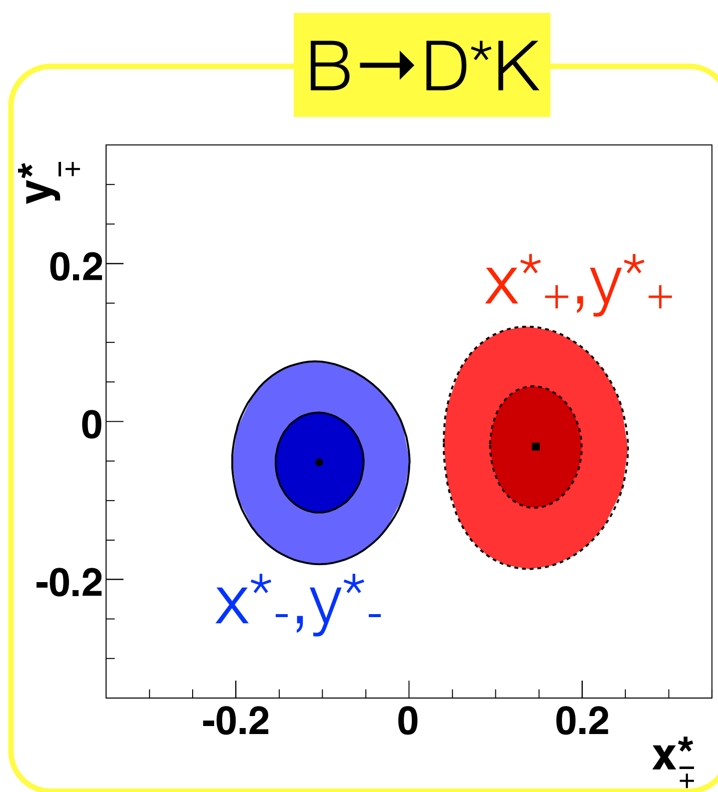
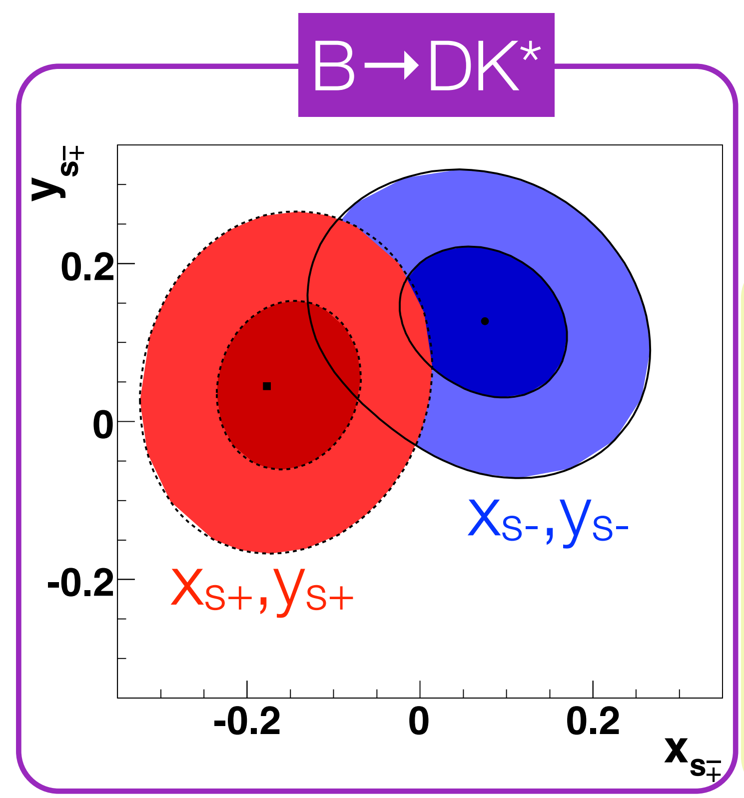
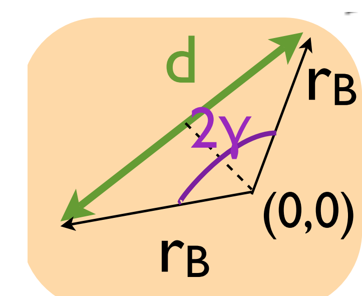










$d = 2r_B|\sin\gamma| \neq 0$
$\Rightarrow$direct CPV

Significance:
B→DK: 2.7σ
B→D*K: 2.8σ
B→DK*: 1.9σ
combined: 3.5σ

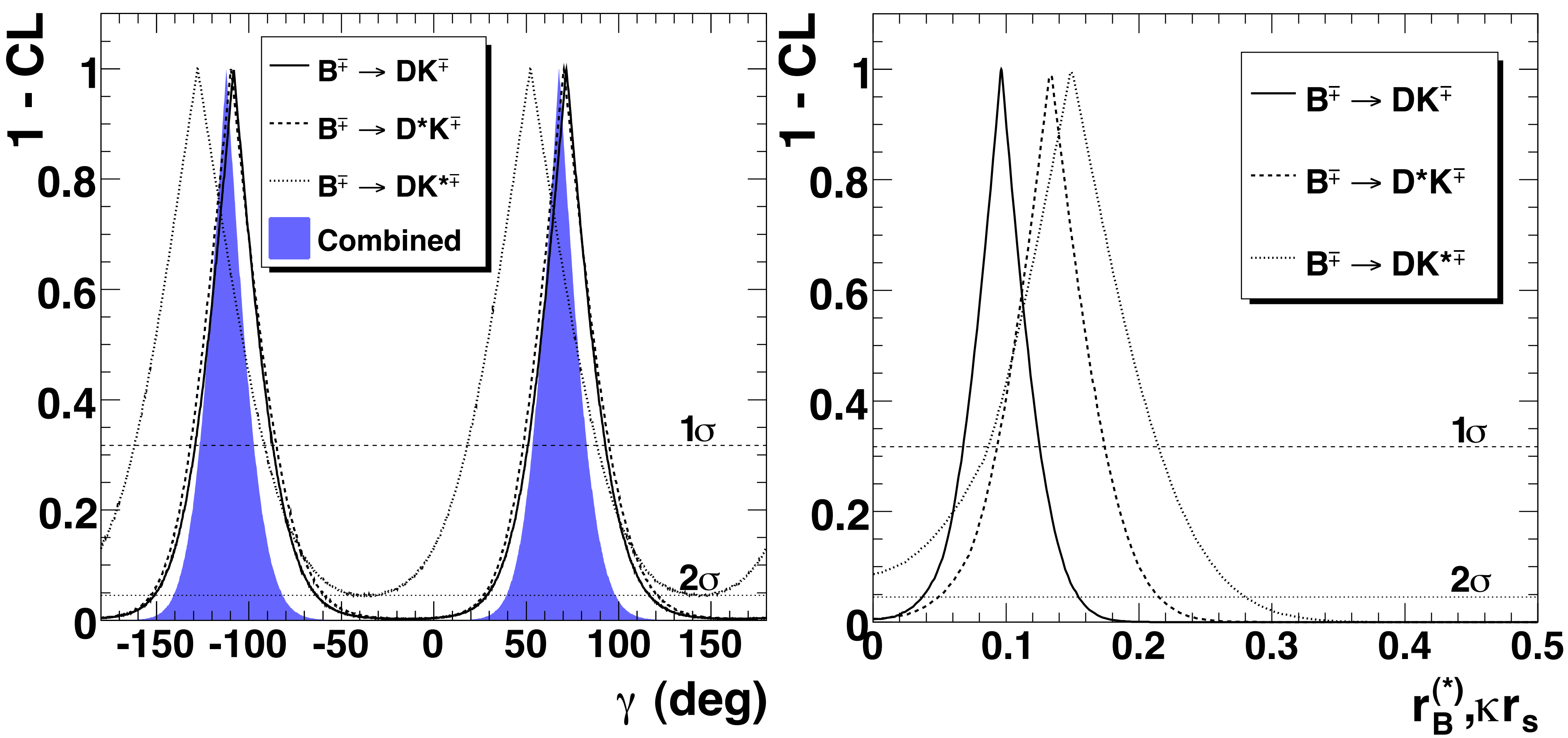
39.3% and 86.5% 2D CL contours

$B^- \to D^{(*)}K^{(*)-}$ GGSZ results: γ, r, δ

arXiv:1005.1096, accepted by Phys. Rev. Lett. (August 2010)

$N_{B\overline{B}} = 468\text{x}10^6$

- Use a **frequentist method** to obtain the common weak phase γ **and the 3 (r_B, δ_B)** from the 3 **($x_\pm$,$y_\pm$) sets (12 observables)**



$$\begin{aligned} r_B(DK) &= 0.096 \pm 0.029 \\ r_B^*(D^*K) &= 0.133^{+0.042}_{-0.039} \\ kr_S(DK^*) &= 0.149^{+0.066}_{-0.062} \end{aligned}$$

$$\begin{aligned} \delta_B(DK) &= (119^{+19}_{-20})^\circ \\ \delta_B^*(D^*K) &= (-82 \pm 21)^\circ \\ \delta_S(DK^*) &= (111 \pm 32)^\circ \end{aligned}$$

$$(\text{mod } 180^\circ)$$

$$\gamma(\text{mod}180^\circ) = (68 \pm 14 \pm 4 \pm 3)^\circ$$

stat syst model

our previous result: $(76 \pm 22 \pm 5 \pm 5)^\circ$

- Still statistically limited (small r_B ~0.1). Consistent with Belle

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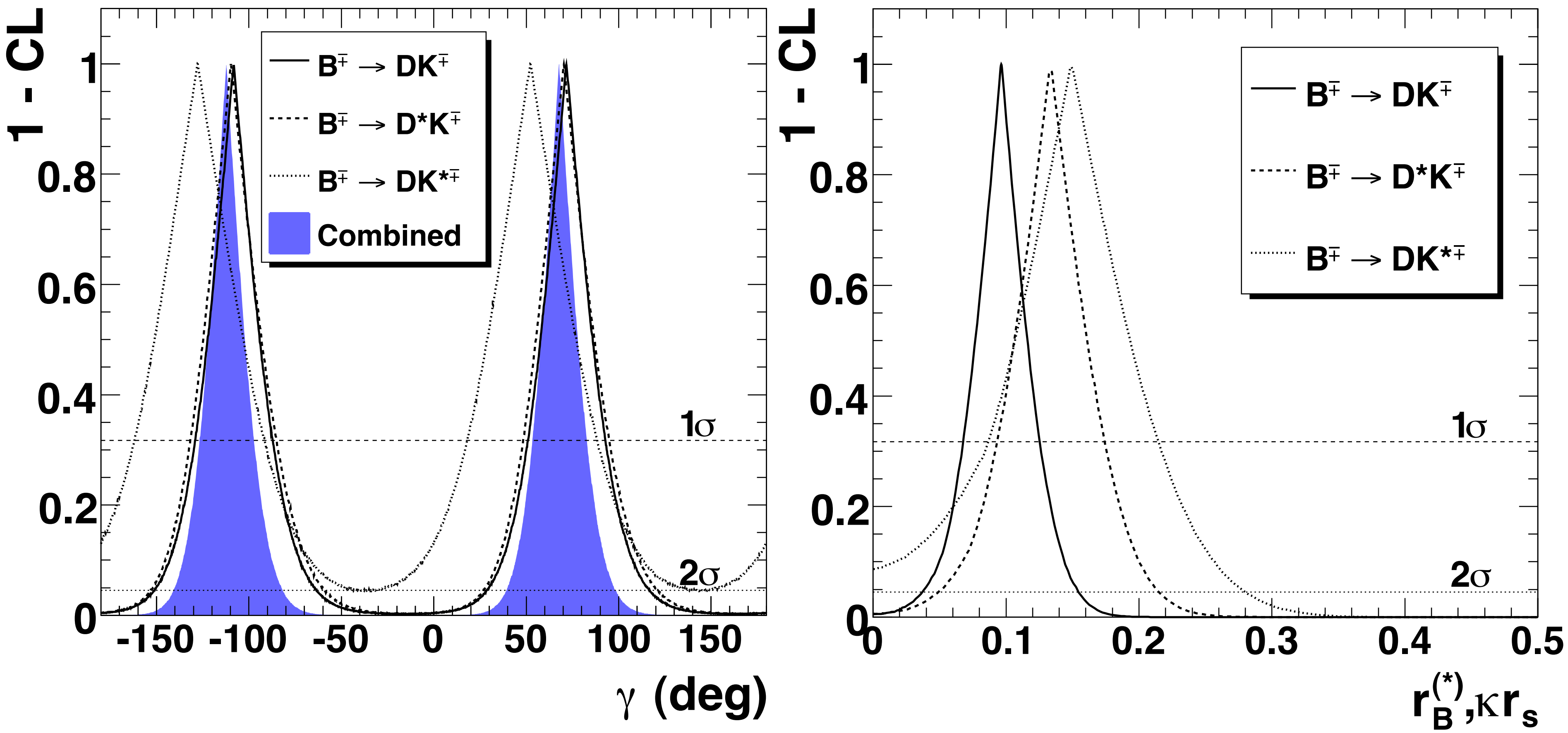

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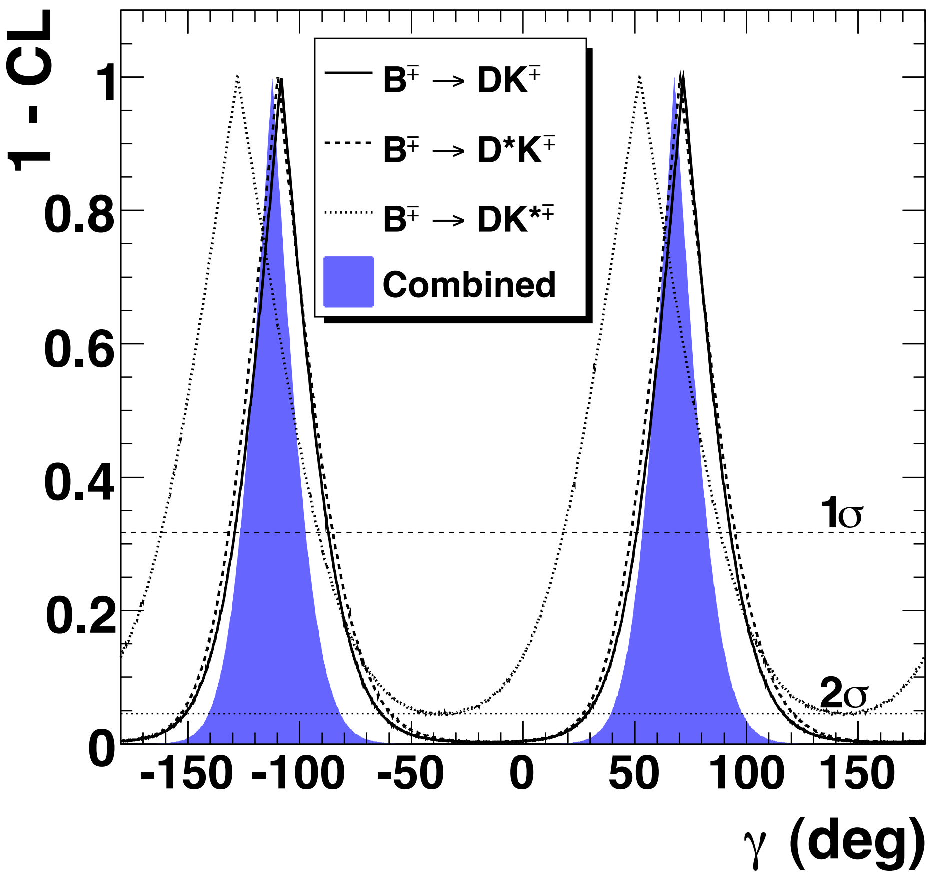

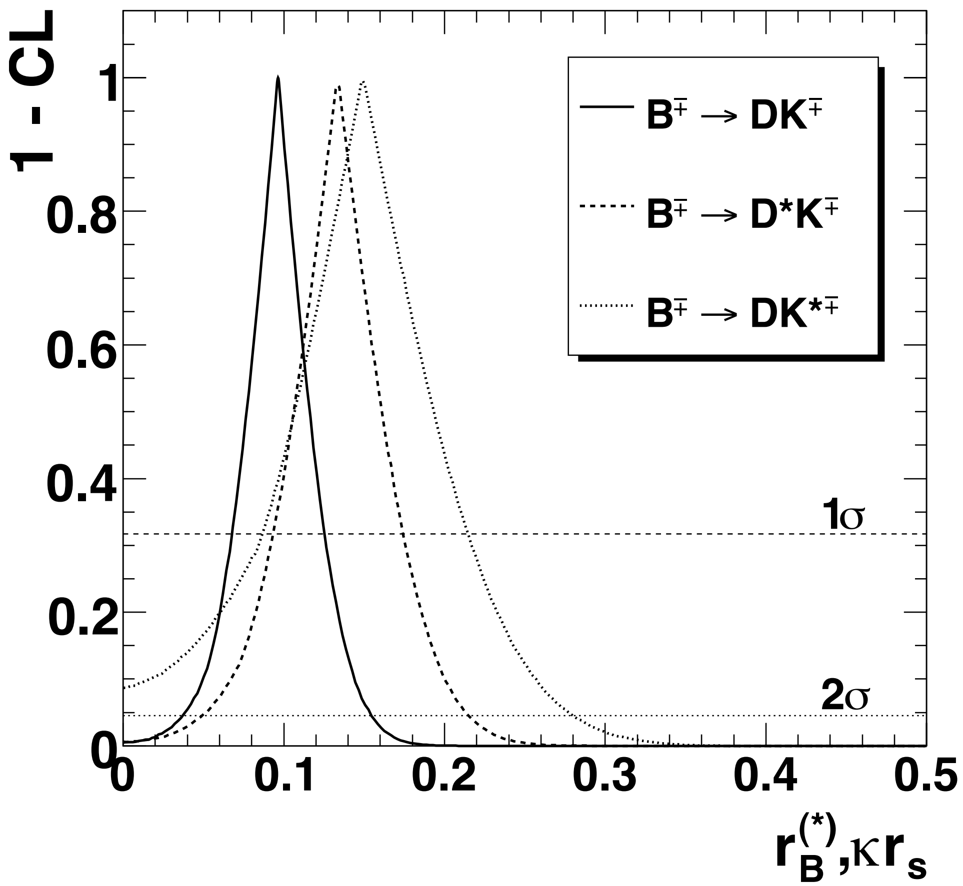

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- Still statistically limited (small r_B ~0.1). Consistent with Belle
- Smaller stat. error: more data, improved reconstruction, slightly higher r_B ($\sigma_\gamma \approx 1/r_B$)
- Smaller syst. error: larger data/MC samples; improved analysis of tagged $D \to K_S hh$

Systematic uncertainties

- **Experimental uncertainties**: many contributions, most important are:
  - dominant contribution for DK^*: non-K^* $DK_S\pi$ bkg (k=0.9+-0.1)
  - fixed PDF shape parameters: vary by $\pm 1\sigma$
  - bkg DP distribution: replace $B\overline{B}$ bkg DP distribution from MC with phase space distribution; replace $q\overline{q}$ bkg DP distribution from data sidebands with MC PDF
  - fraction of bkg events containing a real D and either a K^+ or a K^- (from fit only for $q\overline{q}$ bkg in $K_S\pi\pi$, fixed from MC in other cases): vary between nominal value and 0.5

- **True D decay amplitude uncertainties**: several contributions of ~similar size
  - uncertainties on the amplitude and phases from the analysis of the D^* control sample
  - use alternative models (add/remove resonances; vary BW parameters; replace K-matrix with BW; vary form factors; use helicity formalism instead of Zemach tensors; ...)

$B^- \to DK^-$, GLW method

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

- D reconstructed in **CP−eigenstates** (CP=+: K^+K^-, $\pi^+\pi^-$; CP=-: $K_S\pi^0$, $K_S\omega$, $K_S\phi$) and in Cabibbo-allowed $K\pi$ final state
- Use measured $B^\pm$ yields to determine the 4 **GLW-observables**:

2 BF ratios

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

2 CP asymmetries

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

4 observables (3 independent), 3 unknowns: r_B, δ_B, γ

- 8-fold γ ambiguity: $(\gamma, \delta_B) \leftrightarrow (\gamma + \pi, \delta_B + \pi)$ $(\gamma, \delta_B) \leftrightarrow (-\gamma, -\delta_B)$ $(\gamma, \delta_B) \leftrightarrow (\delta_B, \gamma)$
- BFs ~ 10^{-6} (Cabibbo suppression of D decays to CP eigenstates)
- small asymmetries (<~ 20-30%) because of small r_B
- Extract also $x_\pm$ for combination with Dalitz-analysis results ($K_S\phi$ removed):

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

Measurement strategy

- **Selection optimized for S/sqrt(S+B)**, based on kinematic quantities similar to GGSZ measurement (+ ϕ/ω selection)
- **Use $B \to D\pi$** as **normalization** and **control** sample
  - split selected samples in two: "$B \to DK$" (track from B passes tight kaon ID) and "$B \to D\pi$" (track from B fails tight kaon ID)
- **Yield fit: ML fit to $\{m_{ES}, \Delta E, F\}$** (F = Fisher discriminant based on same variables used in GGSZ measurement + ratio of 2nd and 0th order Fox-Wolfram moments)
  - simultaneous fit to the subsamples corresponding to different D decays $\Rightarrow$ **constrain common parameters** to the same value (e.g. $A_{CP\pm}$, $R_{CP\pm}$, ..)
  - simultaneous fit to B^+ and B^- subsamples $\Rightarrow$ extract **A_{CP}** likelihood
  - simultaneous fit to $B \to DK$ and $B \to D\pi$ control sample
    - obtain from data ($B \to D\pi$) the $B \to DK$ signal shape parameters
    - obtain from data the K/π mistag rate
    - normalize $BF(B \to DK)$ to $BF(B \to D\pi)$ in order to reduce systematic uncertainties from: reconstruction efficiencies, PID, secondary BFs, $K_S/\pi^0/D$... efficiencies

$B^- \to D_{(CP)}K^-$: GLW results

$N_{B\bar{B}} = 467\times10^6$

arXiv:1007.0504, accepted by Phys. Rev. D (August 2010)

Using the full Y(4S) dataset:

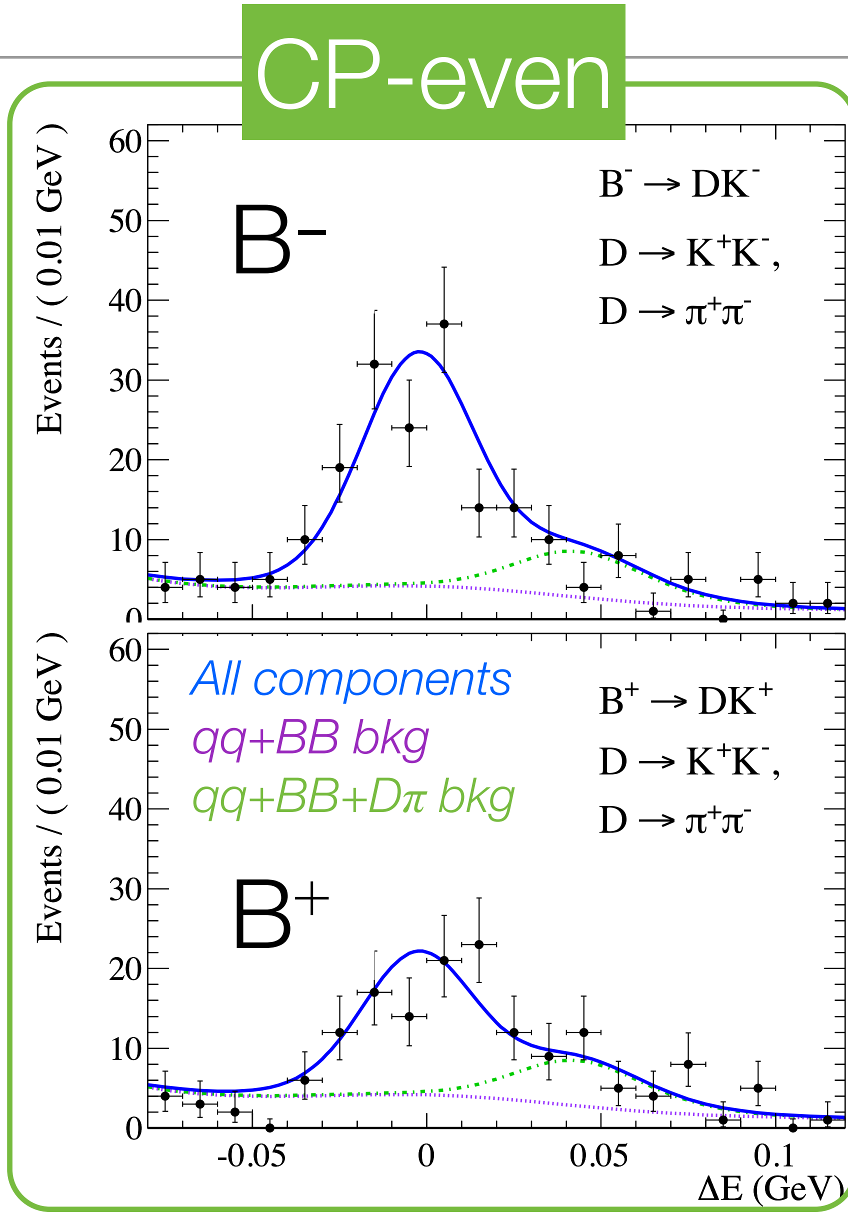
$N_{CP+} = 477\pm28$

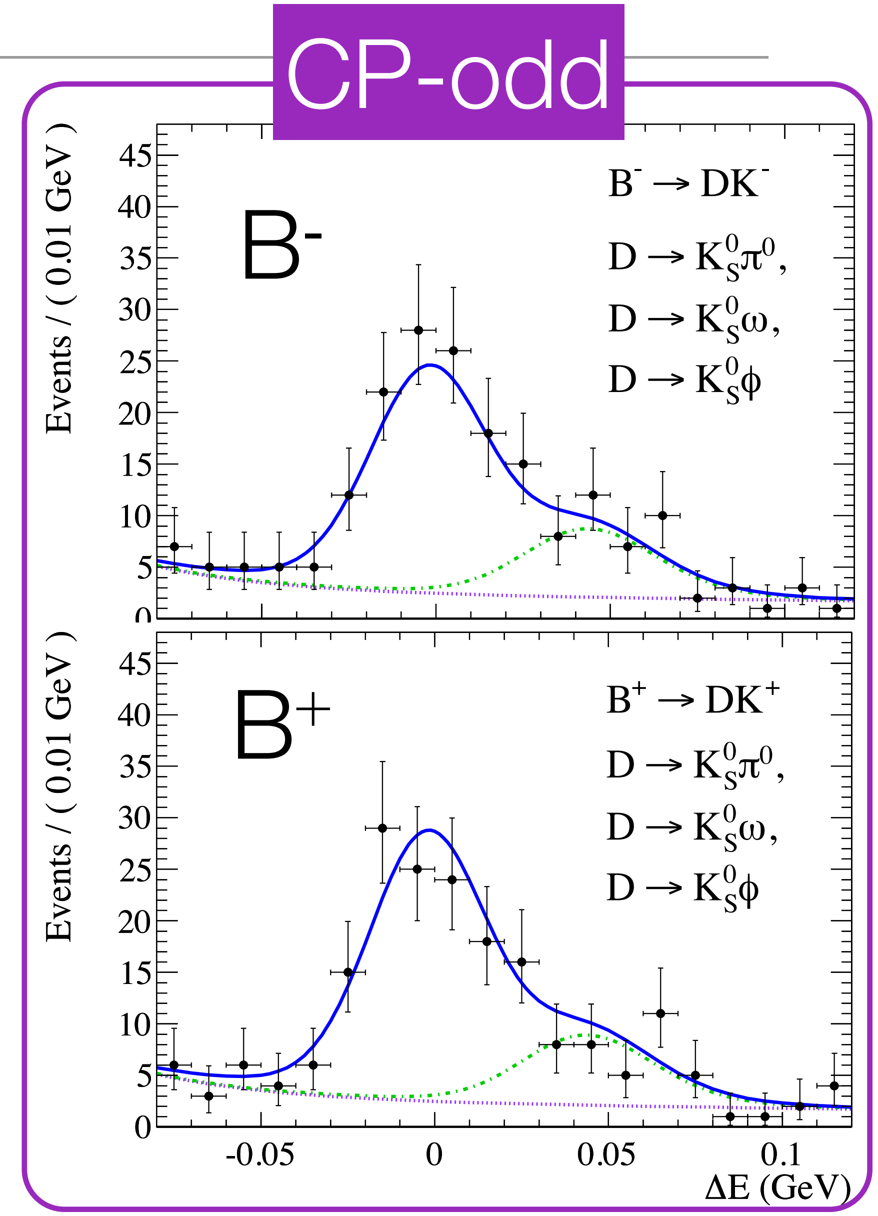
$N_{CP-} = 506\pm26$

$N_{K\pi} = 3361\pm82$

$$A_{CP+} = 0.25 \pm 0.06 \pm 0.02$$
$$A_{CP-} = -0.09 \pm 0.07 \pm 0.02$$
$$R_{CP+} = 1.18 \pm 0.09 \pm 0.05$$
$$R_{CP-} = 1.07 \pm 0.08 \pm 0.04$$

$$x_+ = -0.057 \pm 0.039 \pm 0.015$$
$$x_- = 0.132 \pm 0.042 \pm 0.018$$
$$r_B^2 = 0.105 \pm 0.067 \pm 0.035$$





- **Yields increased by 100%** compared to previous publication: +22% more data, +80% from latest reprocessing, improved selection, revised fit strategy (no cut on F)
- **Direct CPV at 3.6σ** in $B \to D_{CP+}K$ decays !
- most precise measurement of $A_{CP\pm}$ and $R_{CP\pm}$; $x_\pm$ competitive with Dalitz-analysis results
- large value of r_B favored (but large uncertainty: less than 2σ from 0)

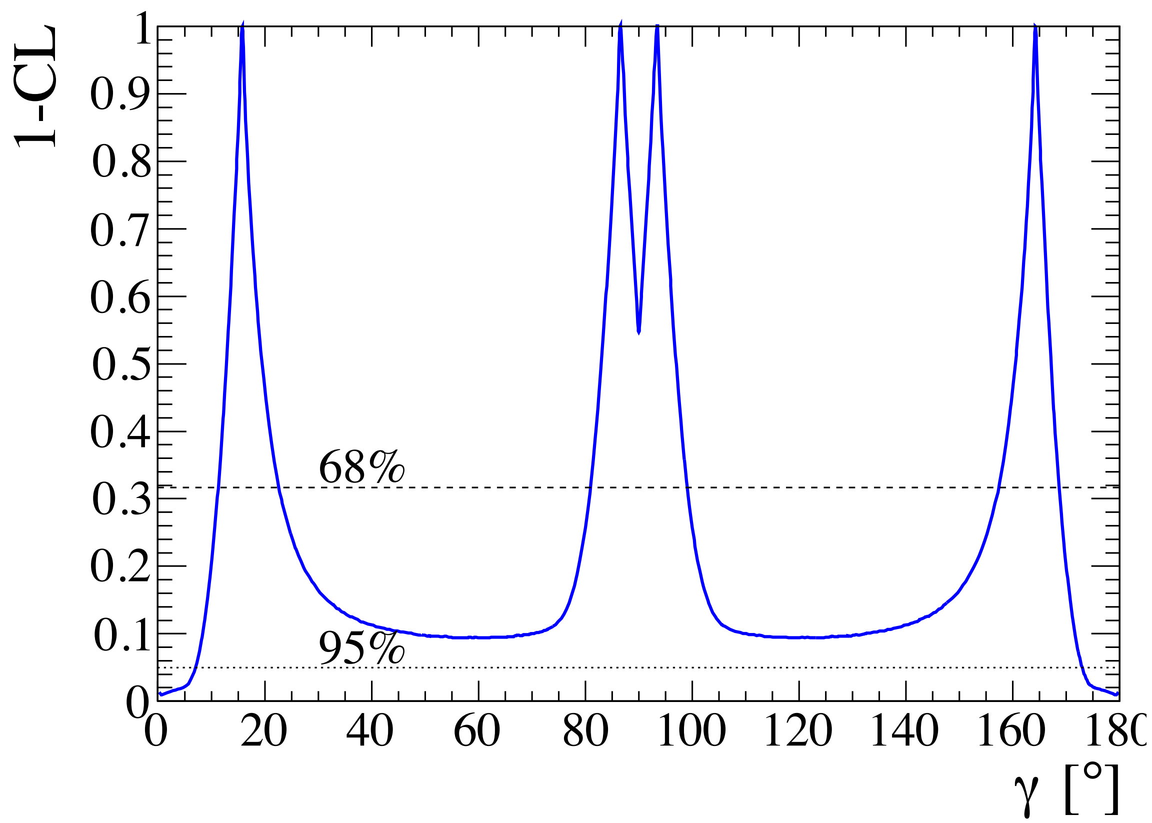
γ from $B^- \to D_{(CP)}K^-$ (GLW method)

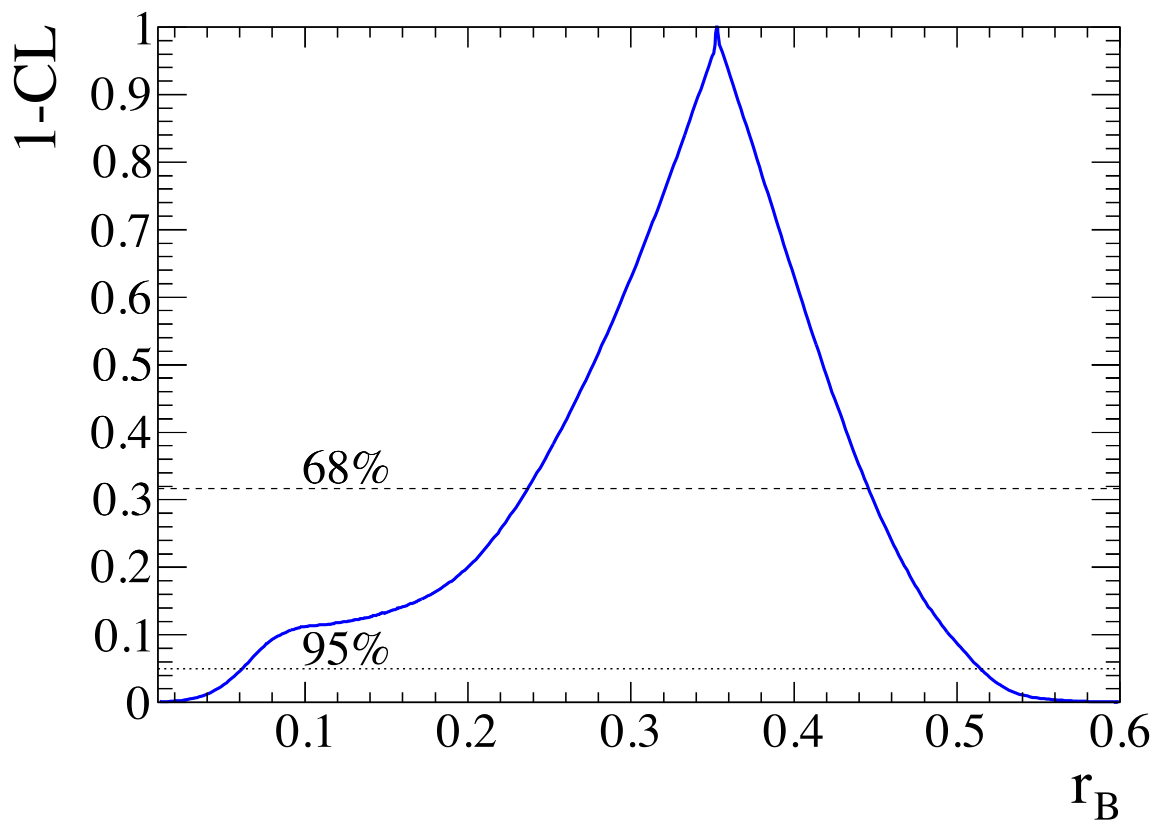
arXiv:1007.0504, accepted by Phys. Rev. D (August 2010)

$N_{B\bar{B}} = 467 \times 10^6$

- Use **frequentist interpretation** (similar to Dalitz plot method) to obtain weak phase γ and hadronic parameters r_B, δ_B from $R_{CP\pm}$, $A_{CP\pm}$

	$\gamma \mod 180\,[^\circ]$	r_B
68% CL	[11.3, 22.7]	[0.24, 0.45]
	[80.9, 99.1]	
	[157.3, 168.7]	
95% CL	[7.0, 173.0]	[0.06, 0.51]





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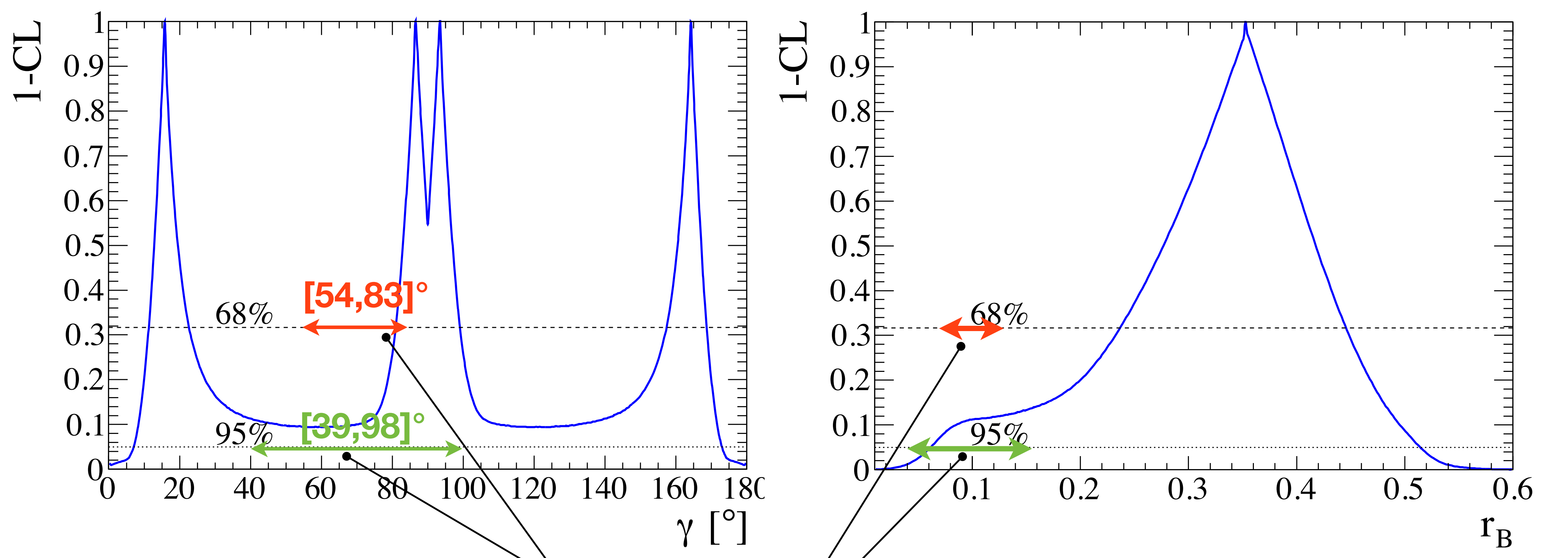


BaBar GGSZ result (68% and 95% CL)

$B^- \to D^{(*)}K^-$, ADS method

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

- Reconstruct **DCS D^0 final states** $[f]_D = K^+\pi^-$ in order to **equalize the magnitude of the interfering amplitudes**:

$$B^- \to D^0 K^- \quad \text{followed by} \quad D^0 \to K^+\pi^-$$

favored $(b \to c)$ — *suppressed* $(c \to d)$

interferes with

$$B^- \to \bar{D}^0 K^- \quad \text{followed by} \quad \bar{D}^0 \to K^+\pi^-$$

suppressed $(b \to u)$ — *favored* $(\bar{c} \to \bar{s})$

  - CP asymmetry can be very large, O(50%)
  - Very small BFs ($\sim 10^{-7}$)

- Use **CA** final states as **normalization channel** and **control sample,** measure

$$\mathcal{R}^{(*)\pm} \equiv \frac{\Gamma([K^{\mp}\pi^{\pm}]_D K^{\pm})}{\Gamma([K^{\pm}\pi^{\mp}]_D K^{\pm})} = r_B^{(*)2} + r_D^2 + 2\lambda r_B^{(*)} r_D \cos(\pm\gamma + \delta_D + \delta_B^{(*)})$$

  - compare events with opposite-sign (DCS) and same-sign (CA) kaons
  - reconstruct DK, D*K ($D^* \to D\pi^0$) and D*K ($D^* \to D\gamma$) $\Rightarrow$ **6 observables, 5 unknowns**
  - **4 discrete ambiguities**: $(\gamma, \delta_B^{(*)}) \leftrightarrow (\gamma + \pi, \delta_B^{(*)} + \pi) \quad (\gamma, \delta_B^{(*)}) \leftrightarrow (-\gamma, -\delta_B^{(*)} - 2\delta_D)$

Measurement strategy

- Very low BF
  - use entire Υ(4S) data sample: **2x more data** wrt previous measurement
  - **reduce bkg as much as possible**
- **Selection**: PID + kinematic quantities (similar to previous analyses); veto bkg from $B^- \to DK^-$, $D \to K^-\pi^+$ ($K \leftrightarrow \pi$ misid) and $B^- \to D\pi^-$, $D \to K^+K^-$
- **Dominant bkg: $q\bar{q}$** (esp. $c\bar{c} \to D^0\bar{D}^0X$, CA $D^0 \to K^-\pi^+$ and $\bar{D}^0 \to K^+X$): discriminated from signal using **neural network (NN) of 8 variables**
  - use same 4 evt. shape vars as in GGSZ analysis, + 4 for additional discrimination (example: vertex separation between 2 B candidates; presence of leptons)
  - trained with simulated signal and continuum bkg events
  - validated on off-peak data and signal-enriched same-sign data control sample
- **Yield fit**: simultaneous **ML fit to {m_{ES}, NN}** distributions of same-sign and opposite-sign subsamples to discriminate bkg and extract $R^{(*)\pm}$

$B^- \to D^{(*)}K^-$: ADS results

arXiv:1006.4241, accepted by Phys. Rev. D (September 2010)

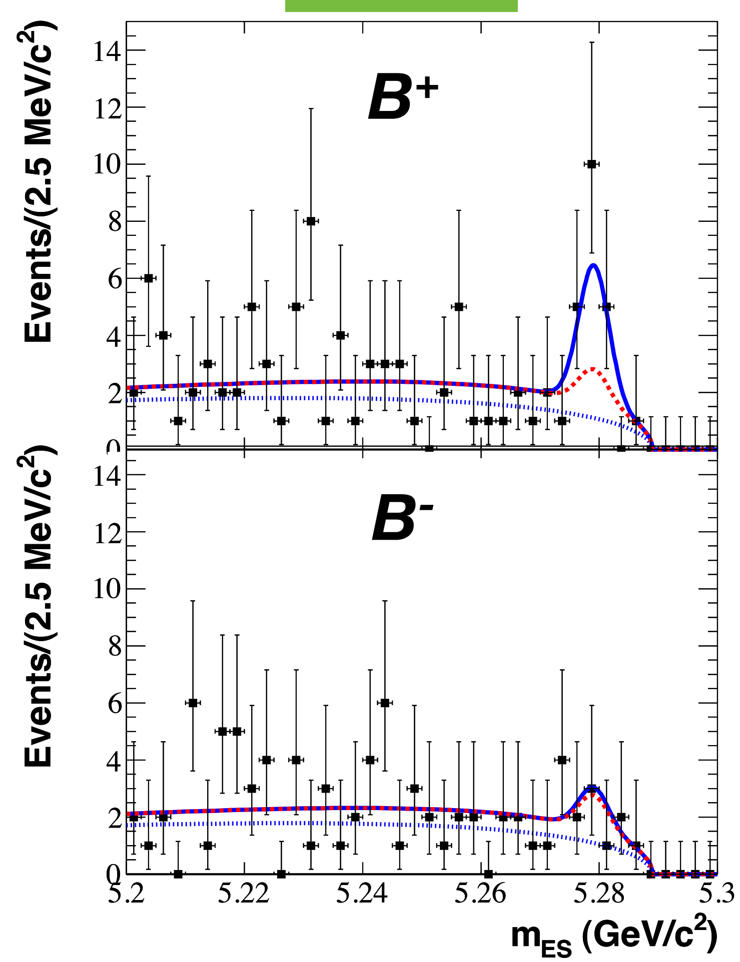
$$\mathcal{R}_{DK} \equiv \frac{1}{2}\left(\mathcal{R}^+_{DK} + \mathcal{R}^-_{DK}\right)$$

$$\mathcal{A}_{DK} \equiv \frac{\mathcal{R}^-_{DK} - \mathcal{R}^+_{DK}}{\mathcal{R}^-_{DK} + \mathcal{R}^+_{DK}}$$

$N_{B\bar{B}} = 467 \times 10^6$

- **Hint** of ADS signals in $B^\pm \to DK^\pm$ (2.1σ) and $B^\pm \to D^*K^\pm$ (2.2σ)
- **Large CP asymmetries**

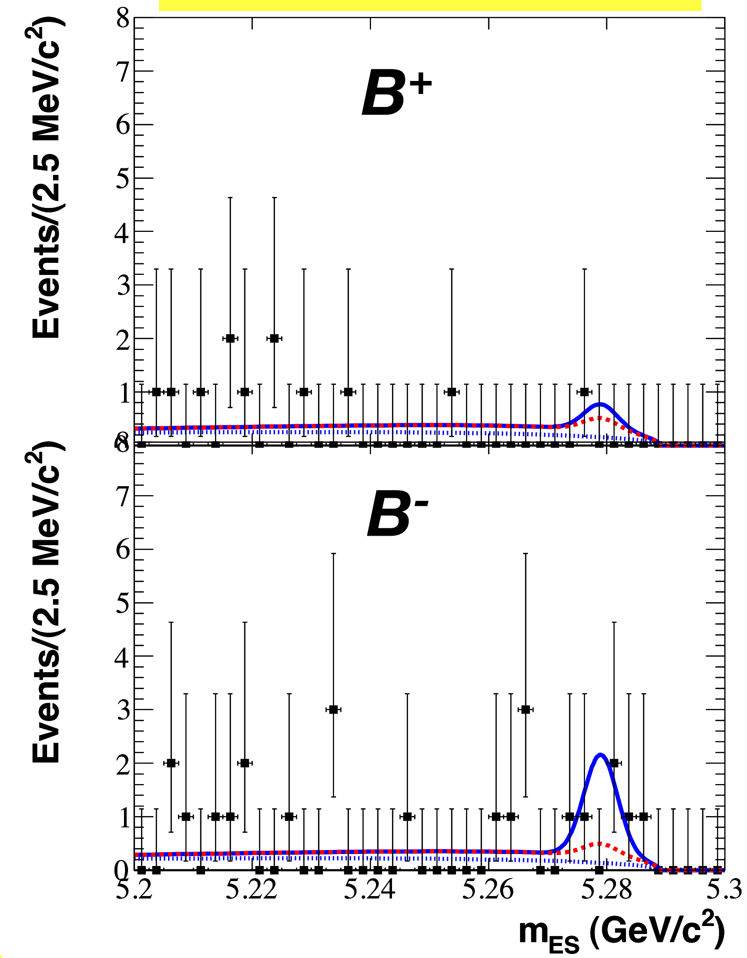
$B \to DK$



$$\mathcal{R}_{DK} = (1.1 \pm 0.6 \pm 0.2) \times 10^{-2}$$
$$\mathcal{A}_{DK} = -0.86 \pm 0.47\ ^{+0.12}_{-0.16}$$

Nsig = 19+-10

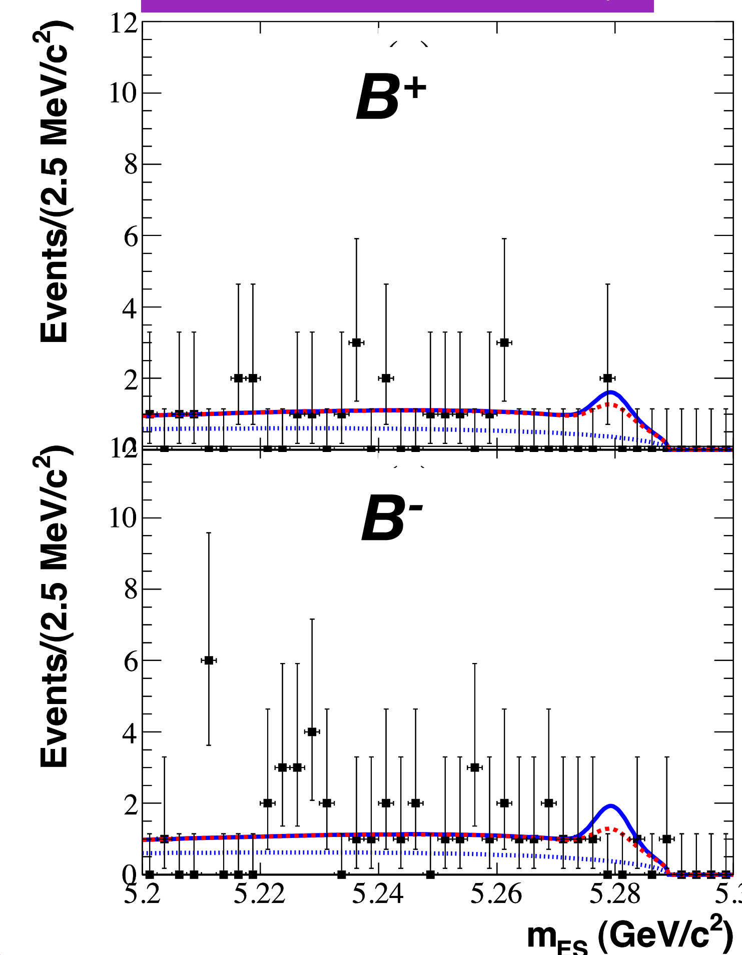
$B \to D^*K$ ($D^* \to D\pi^0$)



$$\mathcal{R}^*_{(D\pi^0)K} = (1.8 \pm 0.9 \pm 0.4) \times 10^{-2}$$
$$\mathcal{A}^*_{(D\pi^0)K} = +0.77 \pm 0.35 \pm 0.12$$

Nsig = 10+-5

$B \to D^*K$ ($D^* \to D\gamma$)



$$\mathcal{R}^*_{(D\gamma)K} = (1.3 \pm 1.4 \pm 0.8) \times 10^{-2}$$
$$\mathcal{A}^*_{(D\gamma)K} = +0.36 \pm 0.94^{+0.25}_{-0.41}$$

Nsig = 6+-6

γ from ADS $B^- \to D^{(*)} K^-$

arXiv:1006.4241, accepted by Phys. Rev. D (September 2010)

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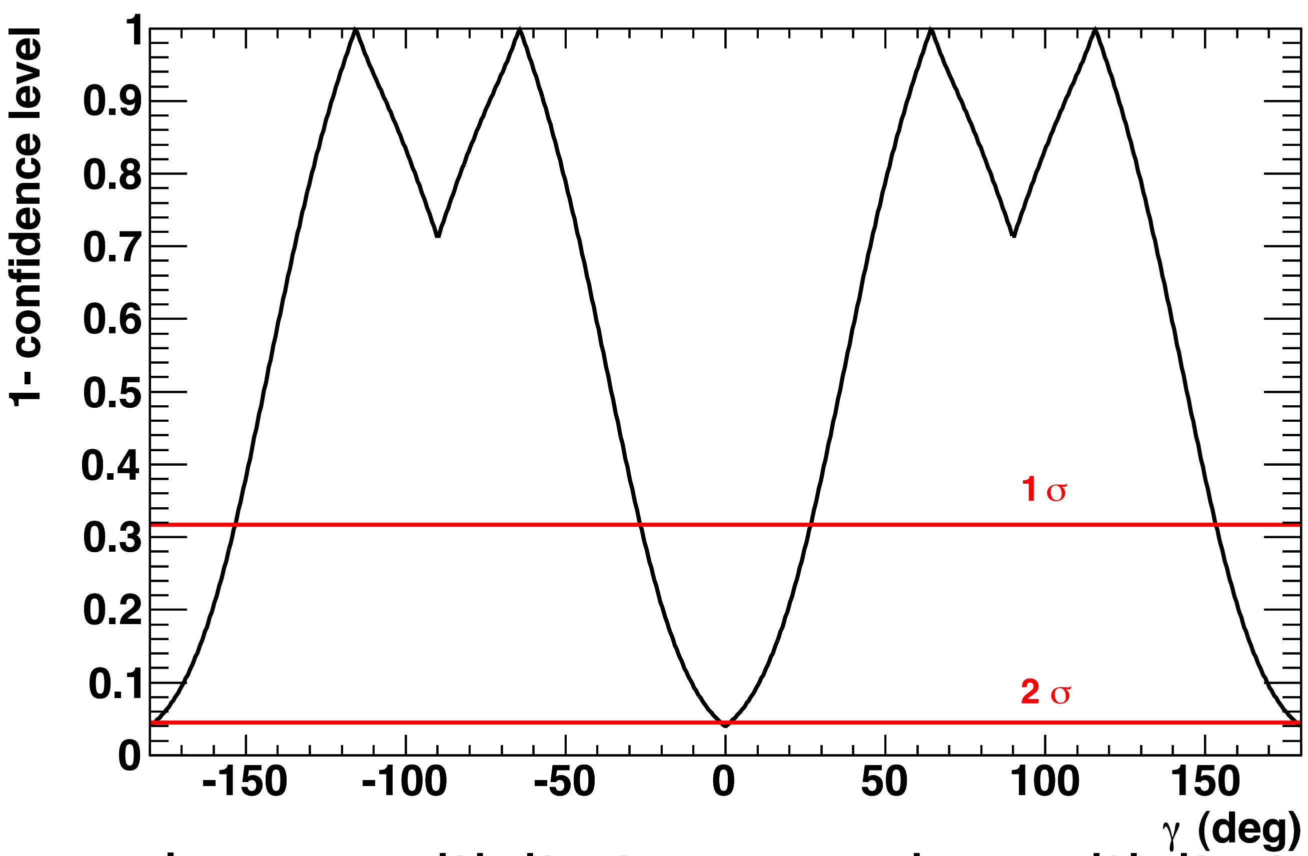
- Use **frequentist interpretation** (similar to Dalitz plot method) to obtain weak phase γ and hadronic parameters $r^{(*)}_B$, $\delta^{(*)}_B$ from $R^{(*)\pm}$

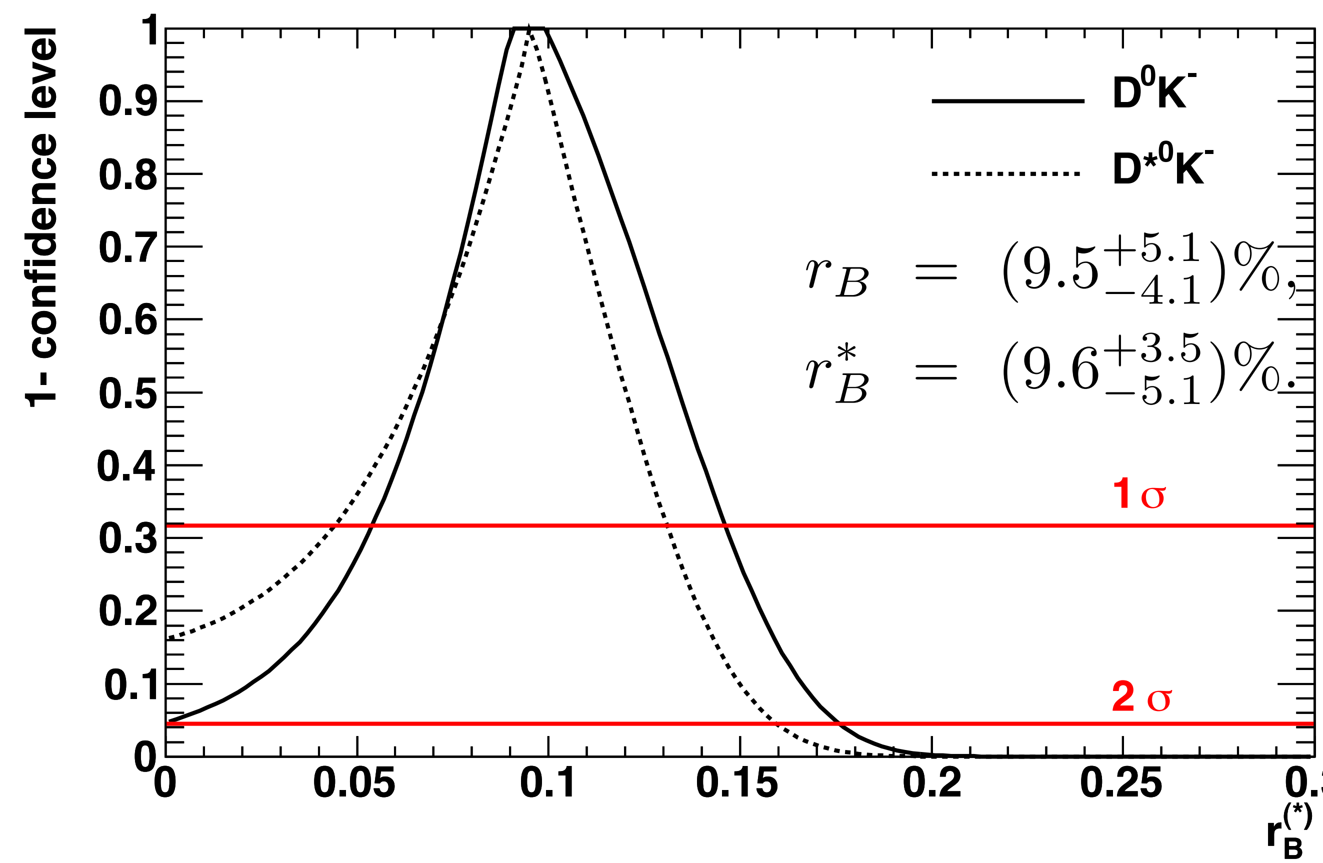
inputs:

$$r_D \equiv \left| \frac{A(\overline{D}^0 \to K^-\pi^+)}{A(D^0 \to K^-\pi^+)} \right| = (5.78 \pm 0.08)\%$$

$$\delta_D \equiv \arg \frac{A(\overline{D}^0 \to K^-\pi^+)}{A(D^0 \to K^-\pi^+)} = (201.9^{+11.4}_{-12.4})^\circ$$

HFAG





- low sensitivity to γ, good sensitivity to r_B

γ from ADS $B^- \rightarrow D^{(*)}K^-$

arXiv:1006.4241, accepted by Phys. Rev. D (September 2010)

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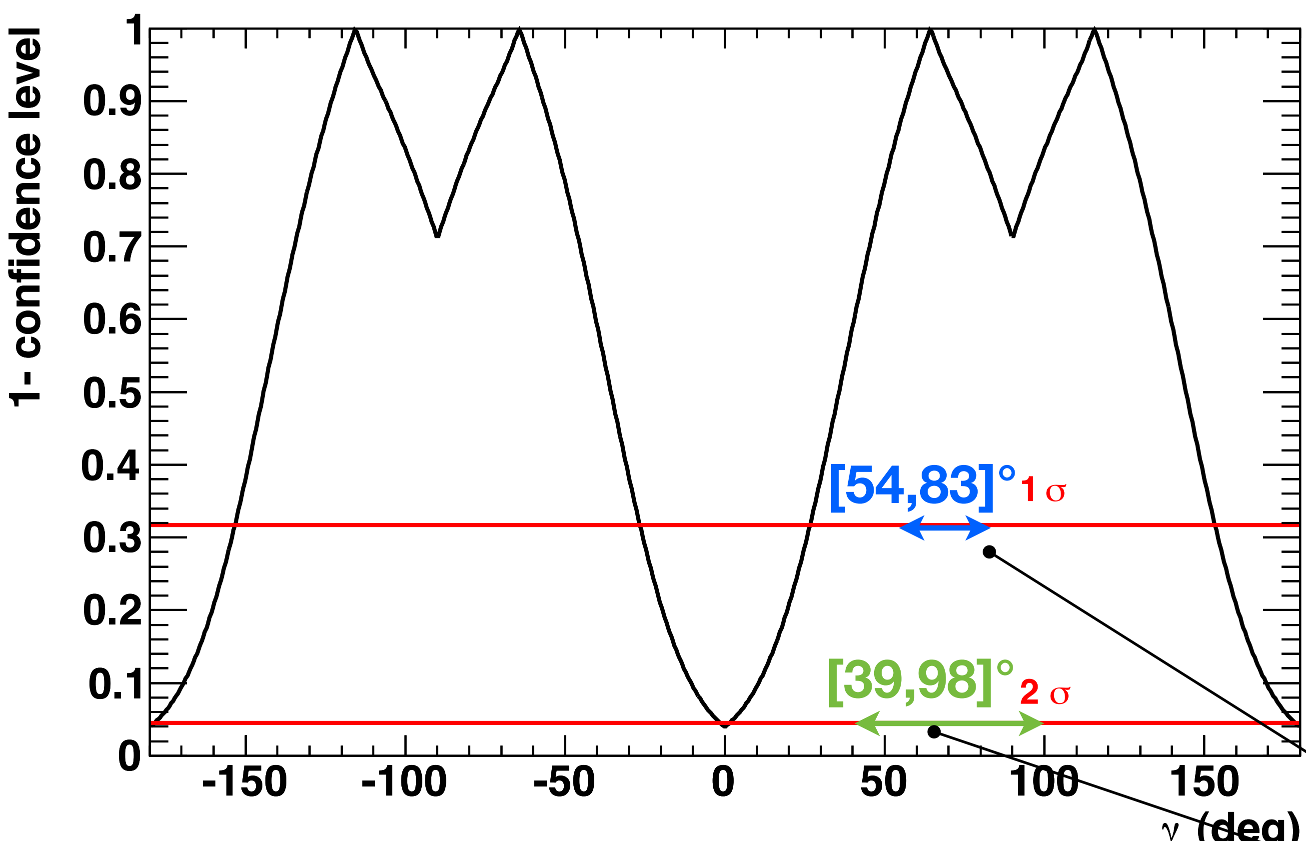

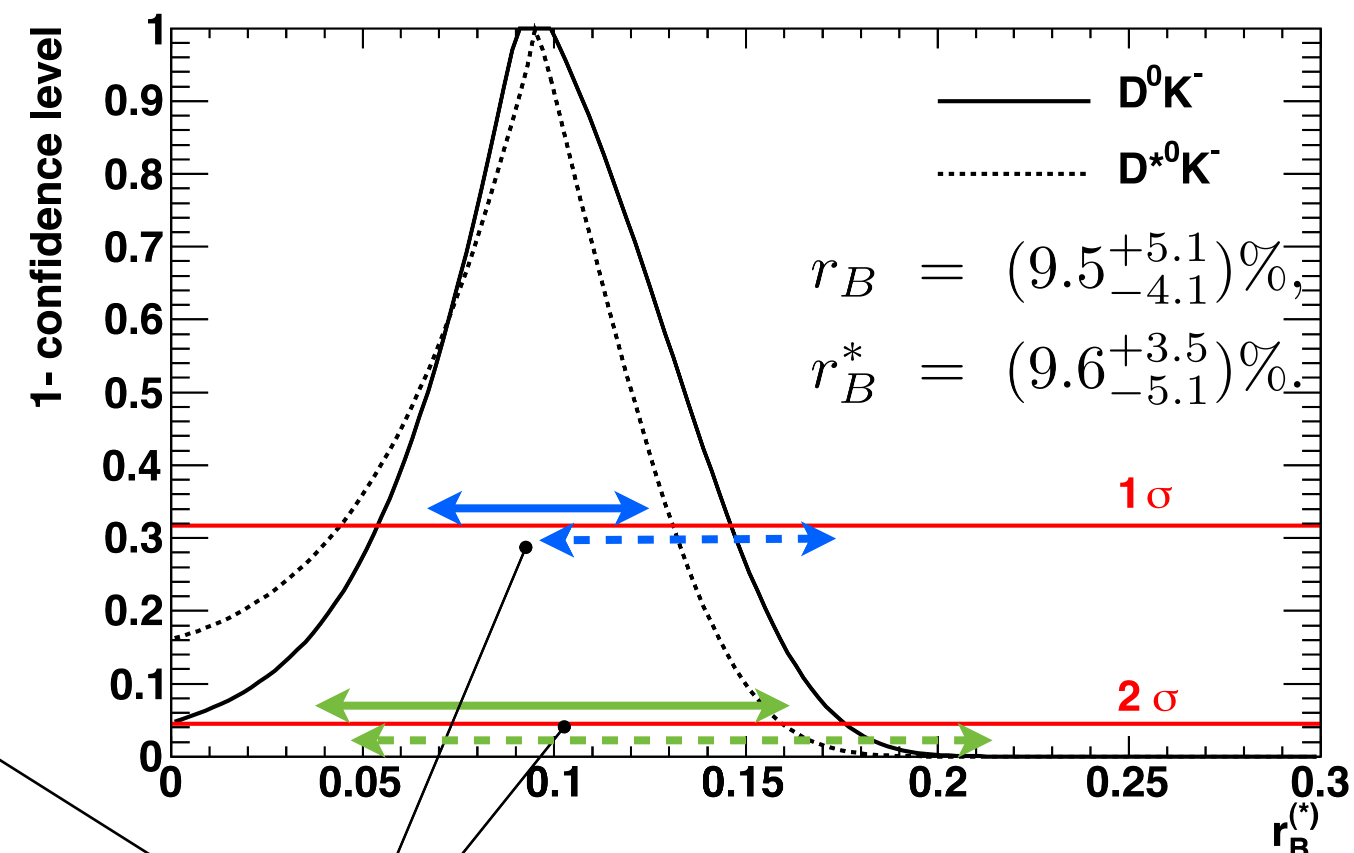

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BaBar GGSZ result (68% and 95% CL)

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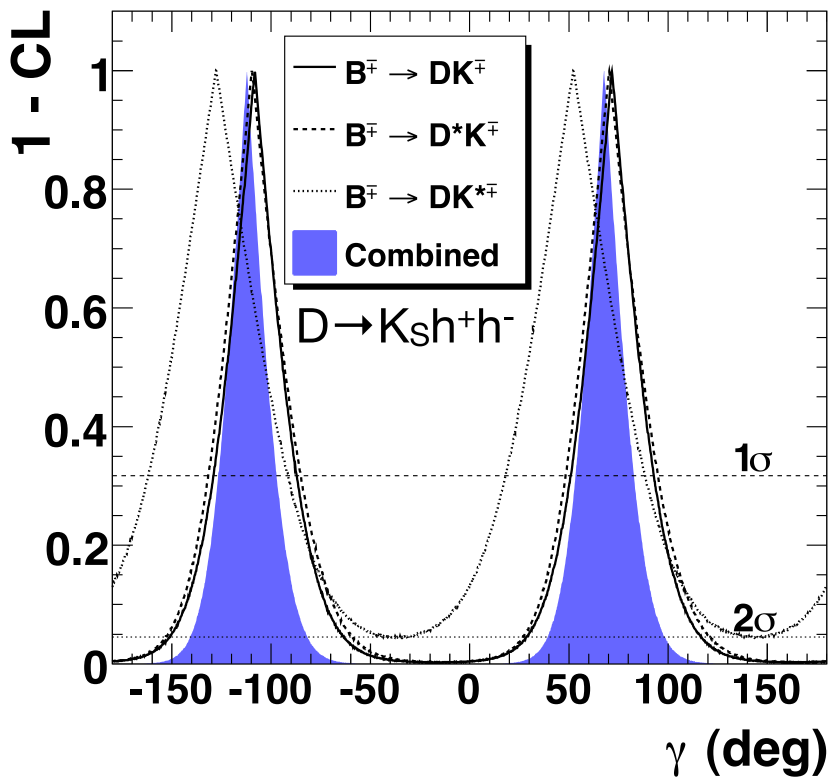

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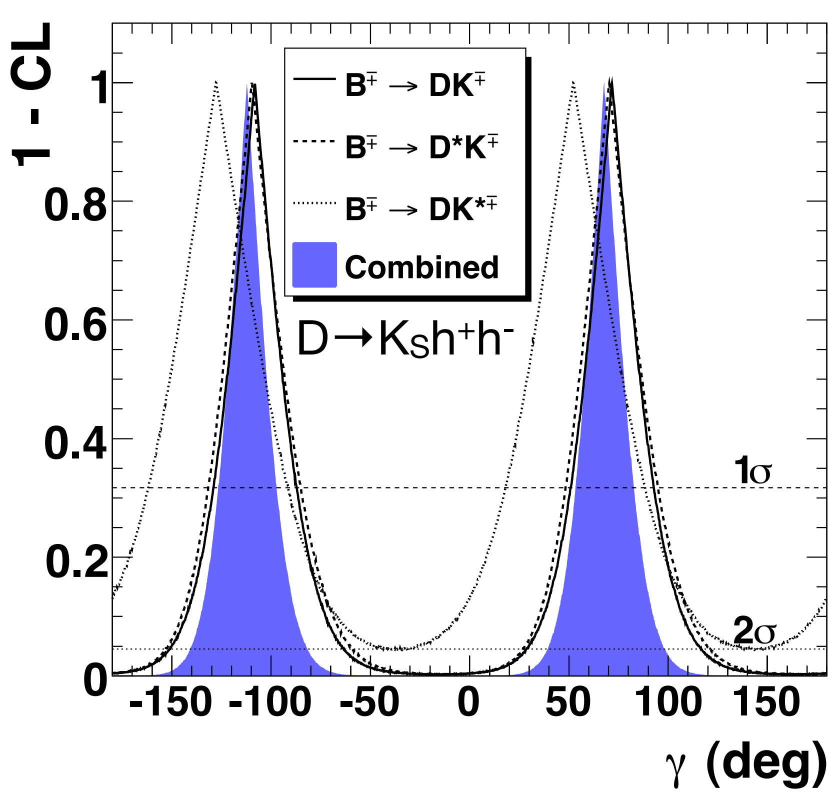

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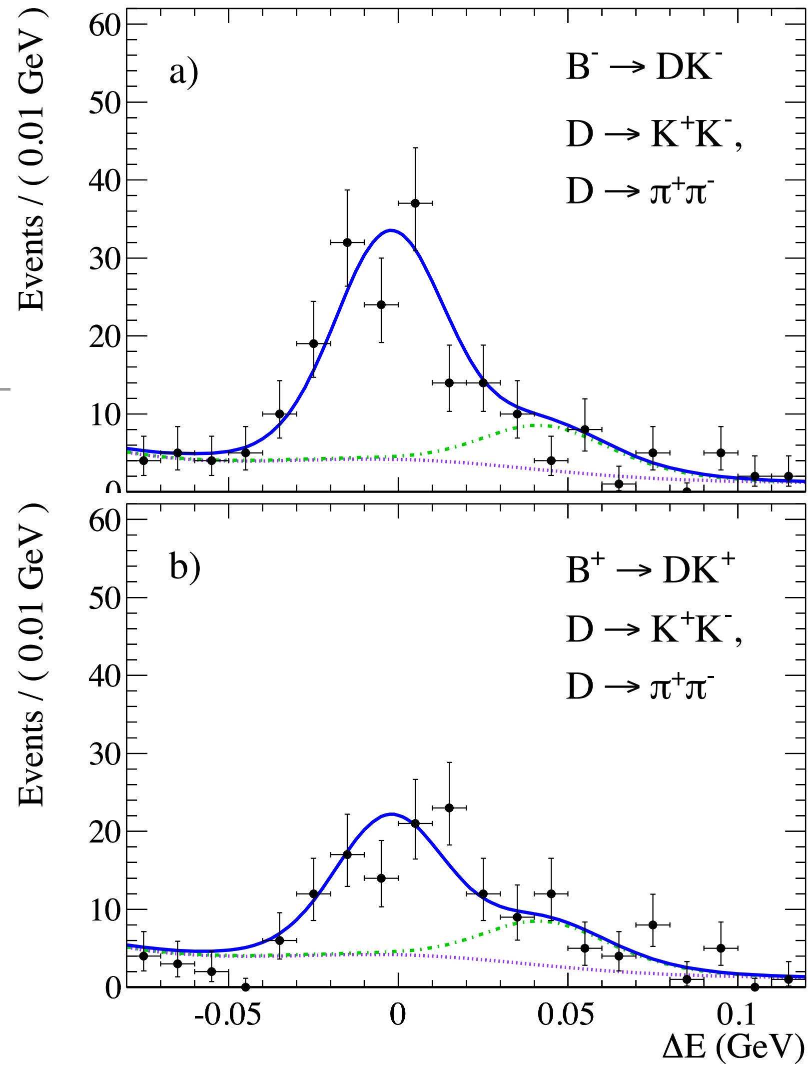

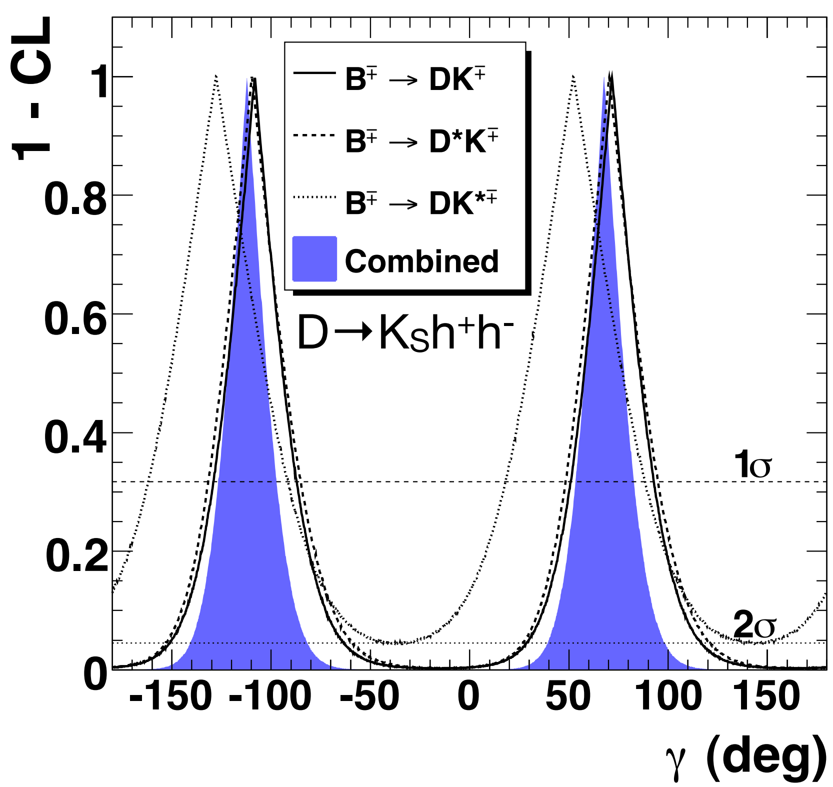

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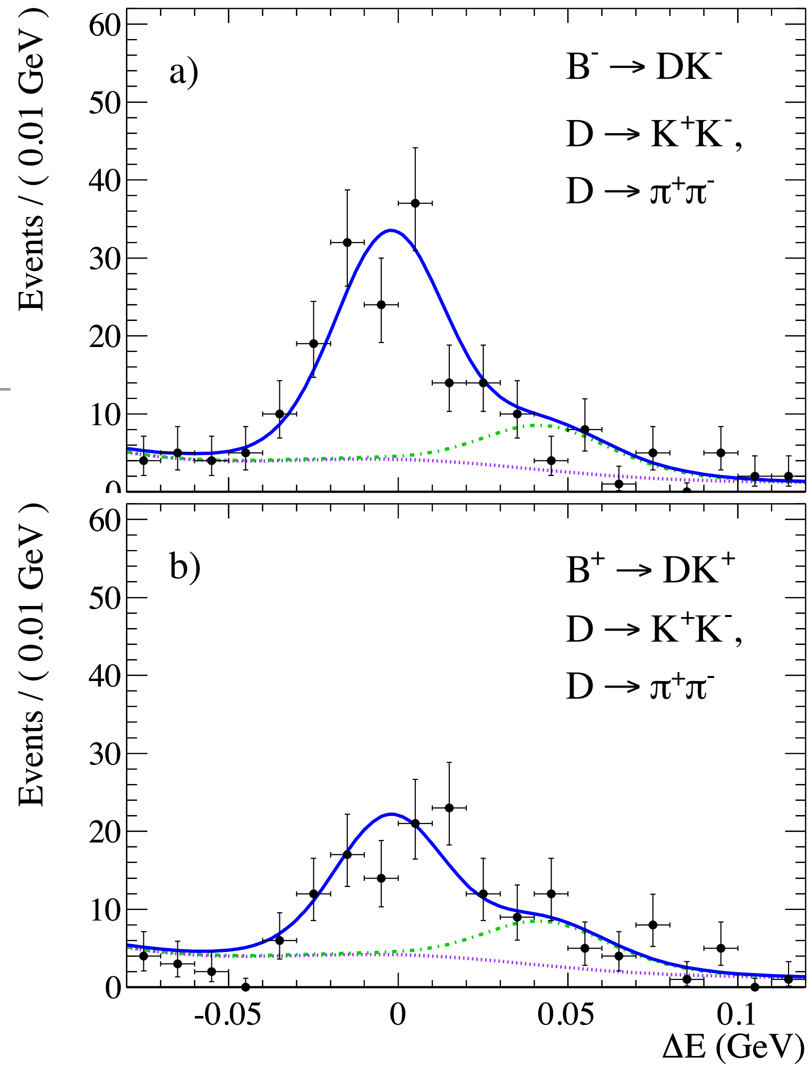

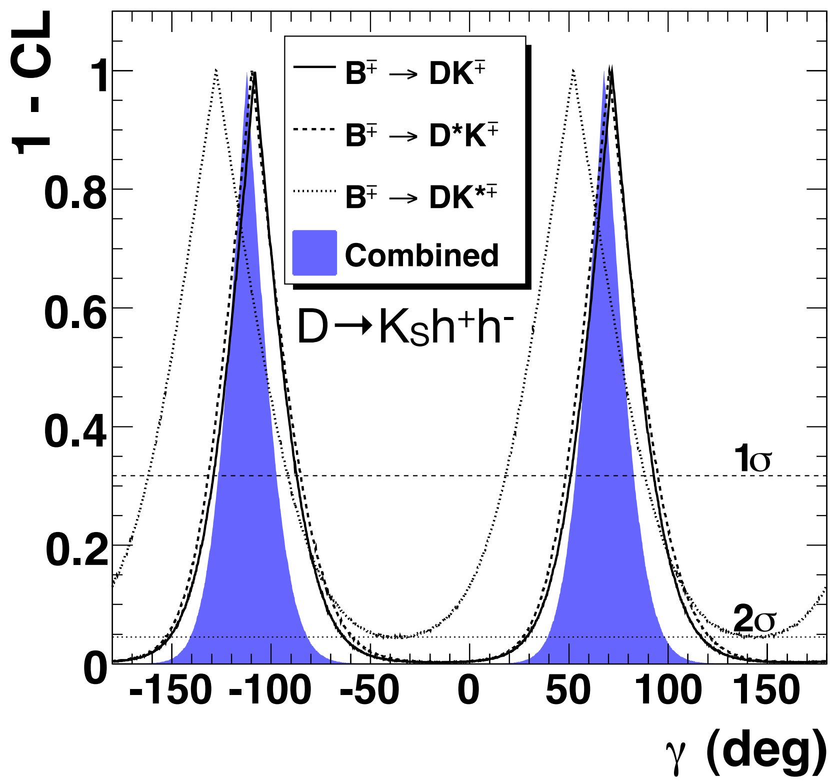

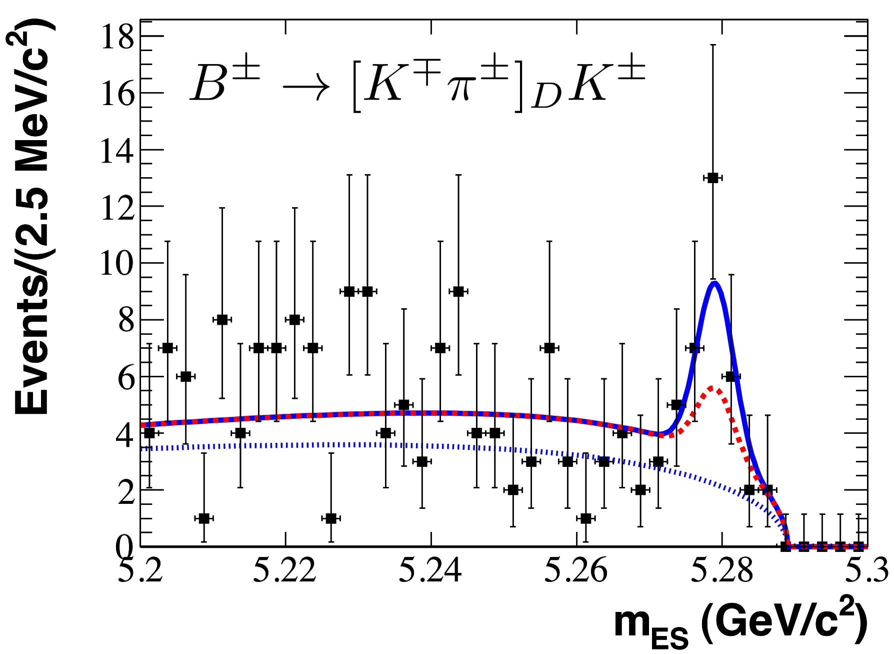

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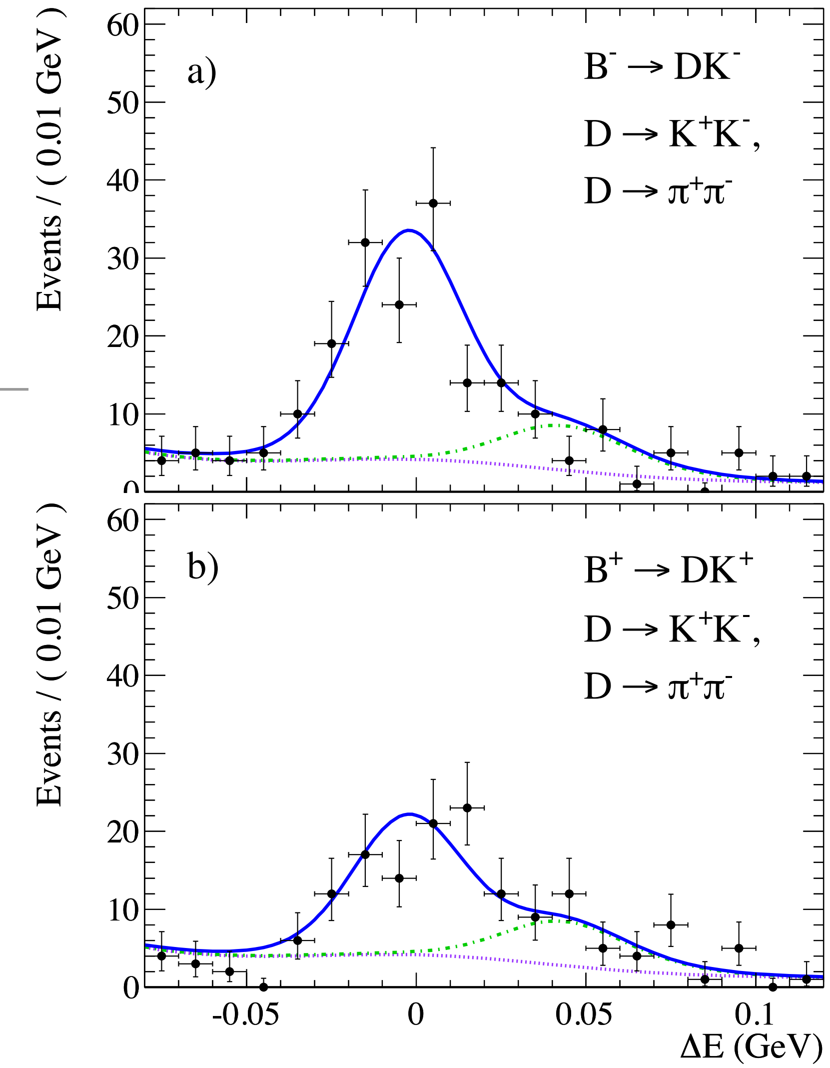

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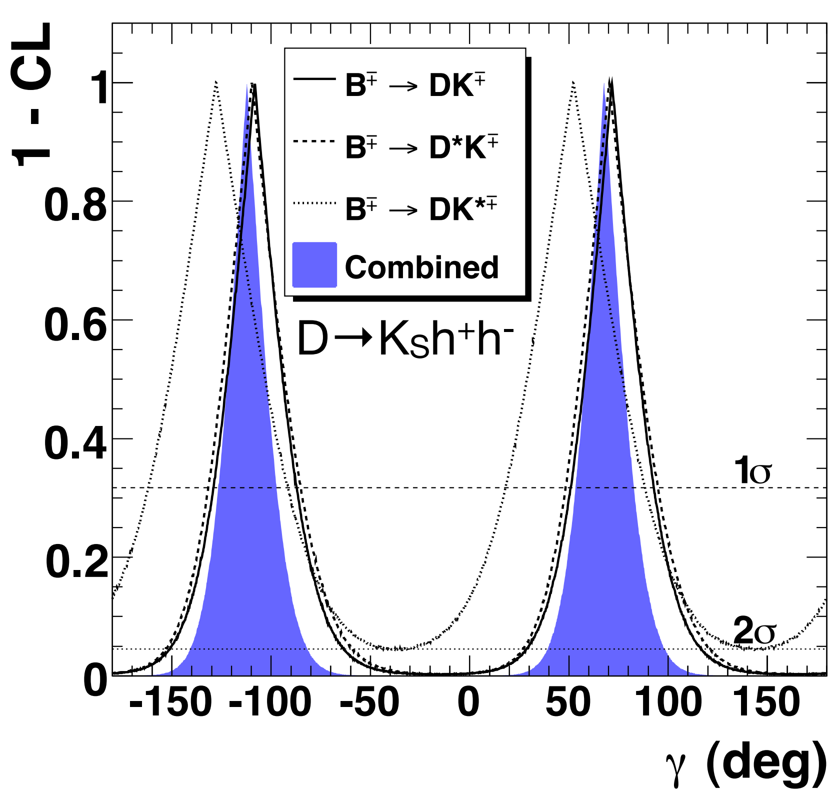
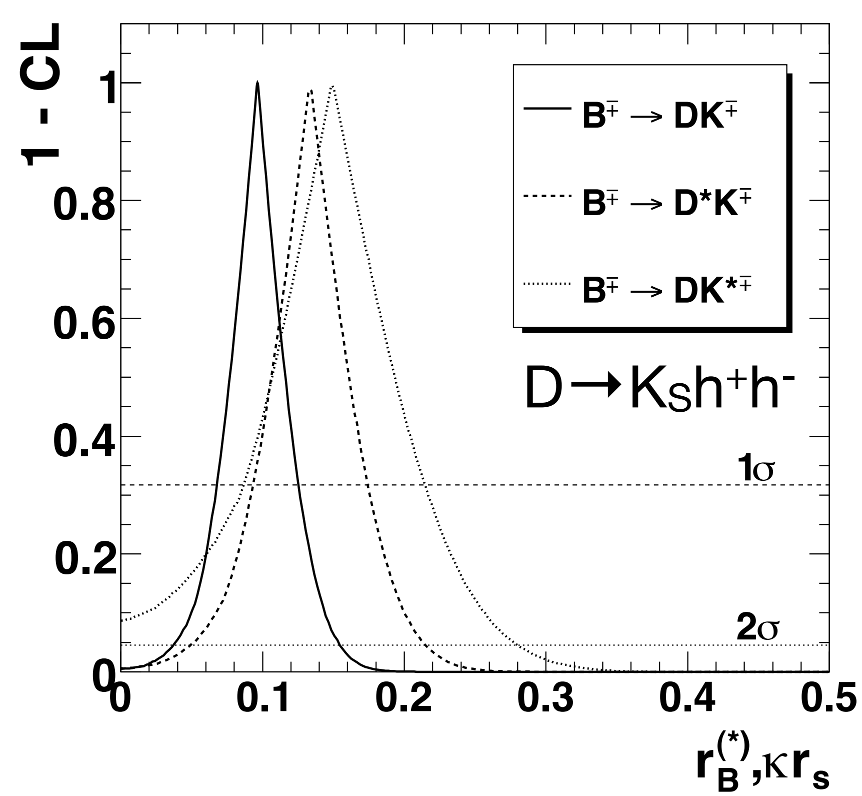
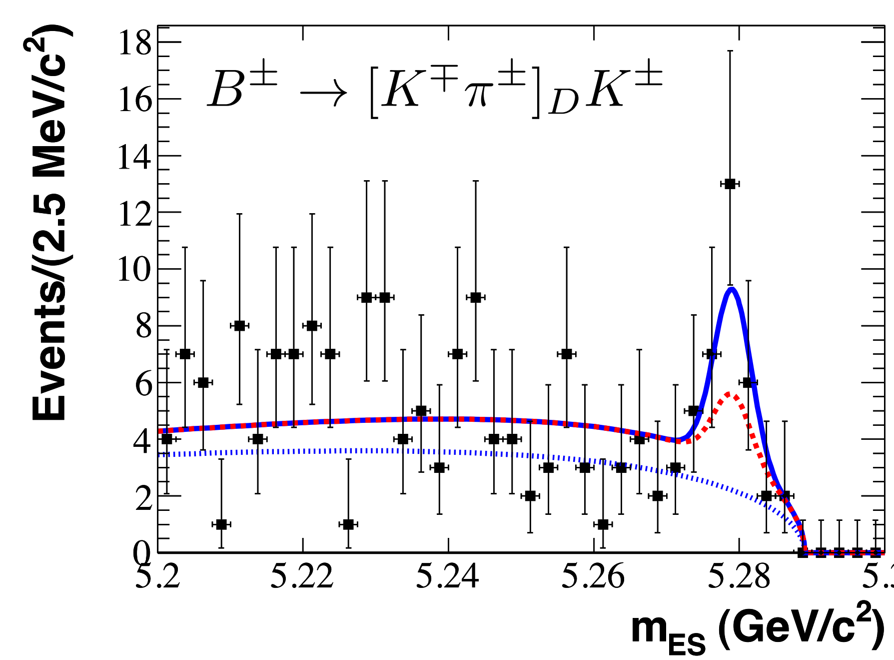
- Interference effects (r) confirmed to be small for charged B decays (0.1-0.2)

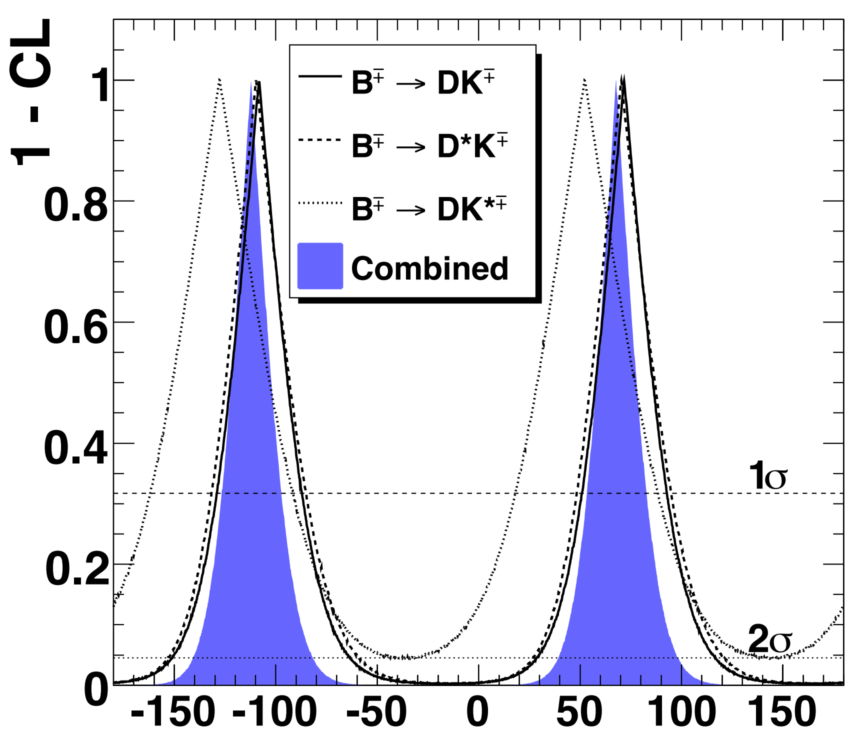




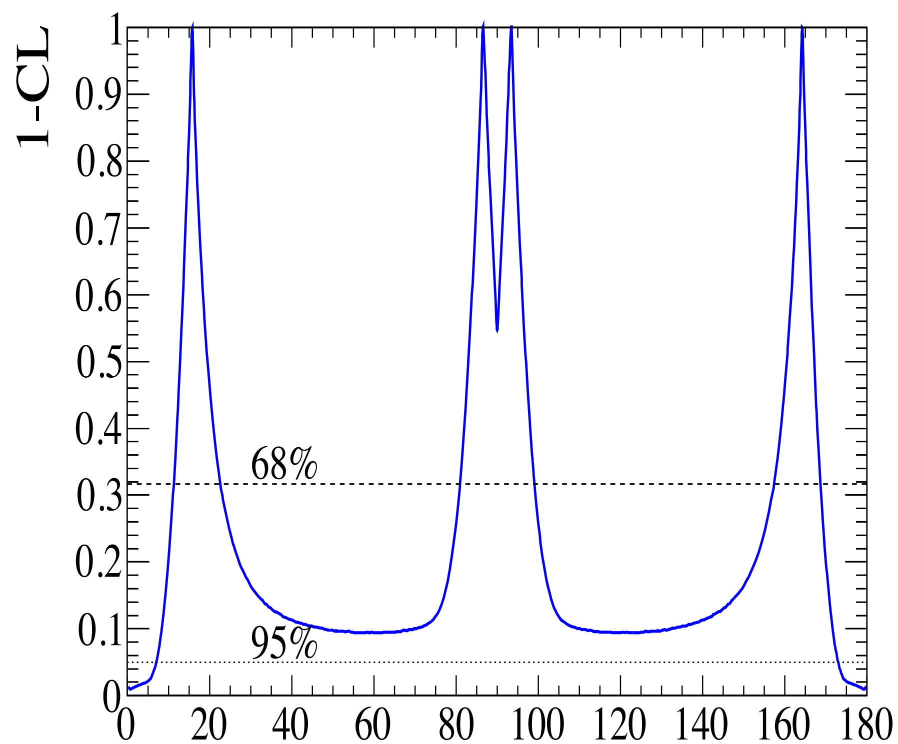


Outlook

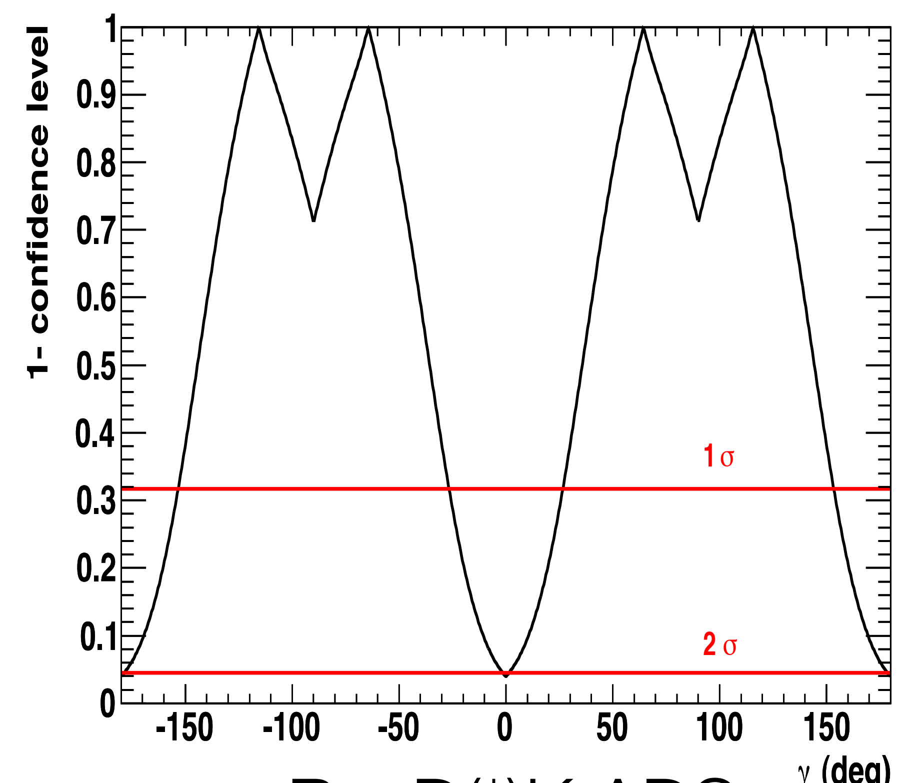
- Close to last word from BaBar
  - still statistically limited (need ≈100x to reach σ_γ=1°)
  - BaBar “legacy” γ average from GLW, ADS and GGSZ methods in progress



B→D(*)K(*) GGSZ



B→DK GLW



B→D(*)K ADS

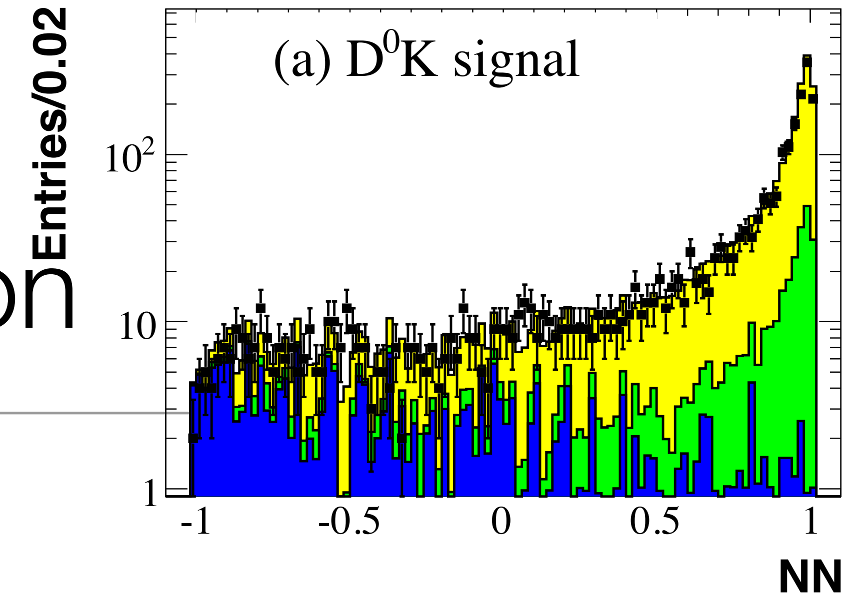
+ older results from: B→D*K GLW, B→DK* GLW+ADS, B^0→DK^{*0} ADS+GGSZ

More details..

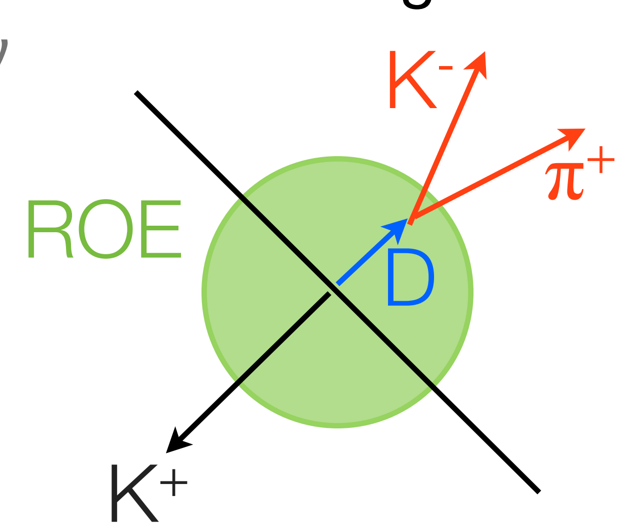
ADS: $B^- \rightarrow D^{(*)}K^-$ selection

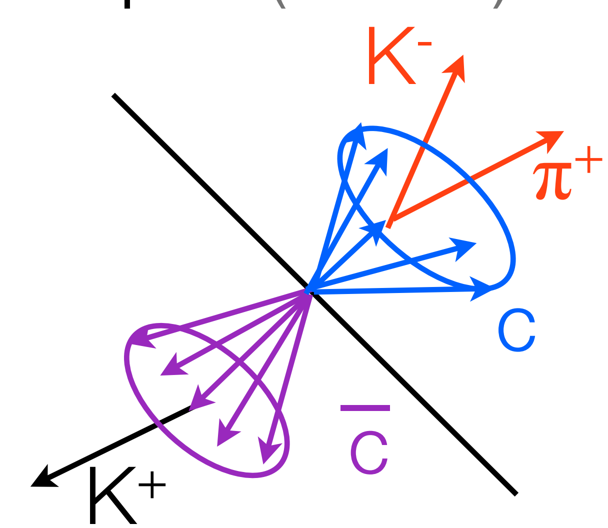
- K, π identification: ~85% efficiency, 3% misidentification
- D^0: $|m-m_{PDG}|<20$ MeV
- D^{*0}: $|\Delta m-\Delta m_{PDG}|<4$ MeV ($D\pi^0$), 15 MeV ($D\gamma$)
- B: m_{ES} in [5.2, 5.29) GeV, $|\Delta E|<40$ MeV
- vetoes for $B^- \rightarrow D[K^-K^+]\pi^-$ and $B^- \rightarrow D[K^-\pi^+]K^-$: $|m-m_{PDG}(D)|<20$ MeV
- arbitration (<multiplicity> ~1.4 in DK and ~2 in D*K): min $|\Delta E|$
    - ε=27% (DK), 13% ($D\pi^0K$), 17% ($D\gamma K$)
    - remaining peaking bkg (undistinguishable from signal):
        - charmless $B^- \rightarrow K^-K^+\pi^-$, estimated from BF(PDF) and efficiency(MC), checked with D mass sidebands (6.0+-0.8 for DK, negligible for D(*)K)
        - $B^- \rightarrow Dh^-$ failing the vetoes: 2.6+-0.4
        - other B decays: 4+-3 events (fit to mES in BB MC)

ADS: NN variables for $c\bar{c}$ suppression



- Use L_0, L_2, $\cos(\theta_T^*)$, $\cos(\theta_B^*)$, and additionally:
  - Δt between two B decays: $\sim\tau_B$ for signal, ~0 for bkg (random combinations of particles assigned to B and ROE)
  - $\Delta q = \sum_{i \notin B}^{D\ hemi} q_i^{trk} - \sum_{i \notin B}^{other\ hemi} q_i^{trk}$: ~0 for signal (tracks from ROE randomly assigned to 2 hemispheres); [2/3 - (1-1)] - [-2/3 - 1] = 7/3 for fake B+
  - $q_B \times \sum_{i \notin B} q_i^K$: ~ -1 for signal (K^- often produced from other B^- in b→c→s), ~0 for bkg (typically no additional kaons)
  - invariant mass between K from B and highest momentum lepton (0 if no l): fewer leptons in $c\bar{c}$, from D→Klν





ADS: $B^- \to D^{(*)}K^-$ systematic uncertainties

- R:
  - signal NN: replace PDF from MC OS DK with that from SS Dpi data sample
  - non-peaking BB bkg NN: replace PDF from DK with that from BB MC
  - qq bkg NN: use off-peak data
  - BB comb bkg shape: vary ARGUS param
  - peaking bkg: vary by +-1σ BFs, yields
  - BB comb. bkg (fixed in D*K): vary by +-25%

Error source	$\Delta\mathcal{R}(10^{-2})$ DK	$\Delta\mathcal{R}(10^{-2})$ $D^*_{D\pi^0}K$	$\Delta\mathcal{R}(10^{-2})$ $D^*_{D\gamma}K$
Signal NN	±0.1	±0.1	±0.3
$B\overline{B}$ background NN	±0.1	±0.3	±0.4
$q\bar{q}$ background NN	±0.1	±0.1	±0.1
$B\overline{B}$ comb. bkg shape ($m_{\rm ES}$)	±0.1	±0.1	±0.1
Peaking background WS	±0.2	±0.3	±0.6
Peaking background RS	±0.0	±0.1	±0.1
Floating $B\overline{B}$ comb. bkg	-	±0.1	±0.2
Combined	±0.2	±0.4	±0.8

- A:
  - detector charge asymmetry: +-0.01 (from Dpi control sample)
  - WS peaking bkg (indendent B+ and B- Poisson fluctuations): +0.11 -0.14
  - $K^-K^+\pi^-$ peaking bkg Acp (0+-10%)

GLW: $B^- \to D_{CP}K^-$ selection

- improvements: +22% more data; +30% from no cut on Fisher; +10-15% from inclusion of dE/dx likelihood for DK/Dpi discrimination; +20% reco efficiency
- π^0: $|m-m_{PDG}|<2.5\sigma$ (σ~6 MeV); E>O(200) MeV
- K_S: $|m-m_{PDG}|<2.5\sigma$ (σ~2.1 MeV); flight length significance>2
- ϕ: $|m-m_{PDG}|<6.5$ MeV (σ~1 MeV, Γ~4.3 MeV); $|\cos\theta_{hel}|>0.4$
- ω: $|m-m_{PDG}|<17$ MeV (σ~6.9 MeV, Γ~8.5 MeV); $\cos^2\theta_N \sin^2\theta_{\pi\pi}>0.046$
- D^0: $|m-m_{PDG}|<2\sigma$ (6-45MeV); $|\cos\theta_D|<0.74$ ($\pi\pi$), 0.99 ($K_S\pi^0$)
- B: m_{ES} in [5.2, 5.29) GeV, -80<ΔE<120 MeV (~1.5σ)
- arbitration (multiple candidates in ~16% of events): min χ^2(B, D, ω, ϕ, K_S, π^0) (probability > 98%, no impact on mD shape)
  - ε=10-44% (CP), 52% (CA)

D^0 mode	Efficiency after full selection	Efficiency in signal-enriched subsample	Purity in signal-enriched subsample
$K^-\pi^+$	52%	22%	96%
K^+K^-	44%	18%	85%
$\pi^+\pi^-$	38%	17%	68%
$K^0_S\pi^0$	24%	10%	83%
$K^0_S\phi$	20%	9%	91%
$K^0_S\omega$	10%	4%	71%

GLW: $B^- \to D_{CP}K^-$ systematic uncertainties

Overall

Source	A_{CP+}	A_{CP-}	R_{CP+}	R_{CP-}
Fixed fit parameters	0.004	0.005	0.026	0.022
Peaking background	0.014	0.005	0.017	0.013
Bias correction	0.004	0.004	0.006	0.005
Detector charge asym.	0.014	0.014	-	-
Opposite-CP background	-	0.003	-	0.006
$R_{CP\pm}$ vs. $R_\pm$	-	-	0.026	0.023
Signal self cross-feed	0.000	0.001	-	-
$\varepsilon(\pi)/\varepsilon(K)$	-	-	0.009	0.008
$\Delta E_{\mathtt{shift}}$ PDFs	0.007	0.011	0.029	0.024
Total	0.022	0.020	0.051	0.043

$$C_{(\mathrm{syst})}[\vec{y}] = \begin{pmatrix} 1 & 0.56 & -0.06 & 0 \\ & 1 & 0 & 0 \\ & & 1 & 0.13 \\ & & & 1 \end{pmatrix}$$

Peaking bkg: vary by +-1 sigma; $|A_{CP}|$<10% (KKK, KKpi), 20% other modes

Fit bias: half the bias

R_{CP} vs R: $$\frac{1 + r_{B\pi}^2 r_D^2 + 2 r_{B\pi} r_D \cos(\delta_{B\pi} - \delta_D)\cos\gamma}{1 + r_{B\pi}^2 \pm 2 r_{B\pi}\cos\delta_{B\pi}\cos\gamma}$$ $$r_{B\pi} = r_B \tan^2\theta_C$$

Detector charge asymmetry: (-0.95+-0.44)%

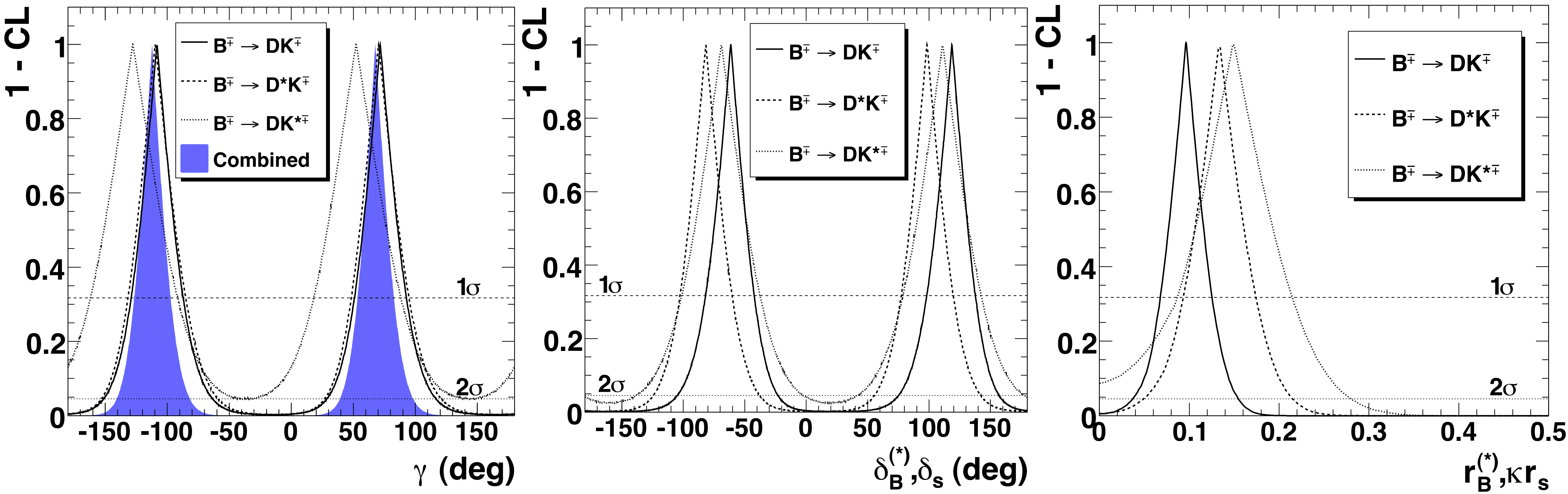
Opposite CP bkg: ~22% $K_s\phi$, <10% in $K_s\omega$, from helicity distribution in $D\pi$

$$S_{\mathrm{stat}} = \sqrt{2\ln(\mathcal{L}_{\mathrm{nom}}/\mathcal{L}_{\mathrm{null}})} = 3.7.$$ $$S_{\mathrm{stat+syst}} = \frac{S_{\mathrm{stat}}}{\sqrt{1 + \frac{\sigma^2_{\mathrm{syst}}}{\sigma^2_{\mathrm{stat}}}}} = 3.6.$$

GGSZ: $B^- \to D^{(*)}K^{(*)-}$ selection

- K_S: $|m-m_{PDG}|<9$ MeV; flight length significance>10, $\cos(\alpha)>-0.99$
- K^*: $|m-m_{PDG}|<55$ MeV; $|\cos\theta_{hel}|>0.35$
- D^0: $|m-m_{PDG}|<12$ MeV, $\chi^2(vtx)>0$
- D^{*0}: $|\Delta m-\Delta m_{PDG}|<2.5$ MeV ($D\pi^0$), 10 MeV ($D\gamma$)
- B: m_{ES} in [5.2, 5.29) GeV, $\chi^2(vtx)>0$, $-80<\Delta E<120$ MeV (yield fit) / $|\Delta E|<30$ MeV (CP fit)
- arbitration (multiple candidates in ~10% of events): min $\chi^2(D, \Delta m, K^*, \pi^0)$
  - ε=14-26%

GGSZ: results



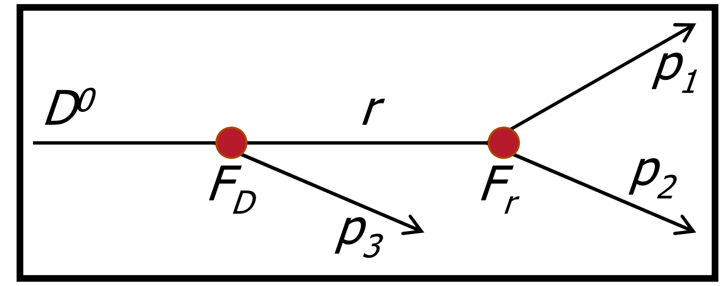
Parameter	68.3% CL	95.4% CL
γ ($^\circ$)	68^{+15}_{-14} $\{4, 3\}$	$[39, 98]$
r_B (%)	9.6 ± 2.9 $\{0.5, 0.4\}$	$[3.7, 15.5]$
r_B^* (%)	$13.3^{+4.2}_{-3.9}$ $\{1.3, 0.3\}$	$[4.9, 21.5]$
κr_s (%)	$14.9^{+6.6}_{-6.2}$ $\{2.6, 0.6\}$	< 28.0
δ_B ($^\circ$)	119^{+19}_{-20} $\{3, 3\}$	$[75, 157]$
δ_B^* ($^\circ$)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

Value ± total error {± syst., ± model }

GGSZ: isobar model

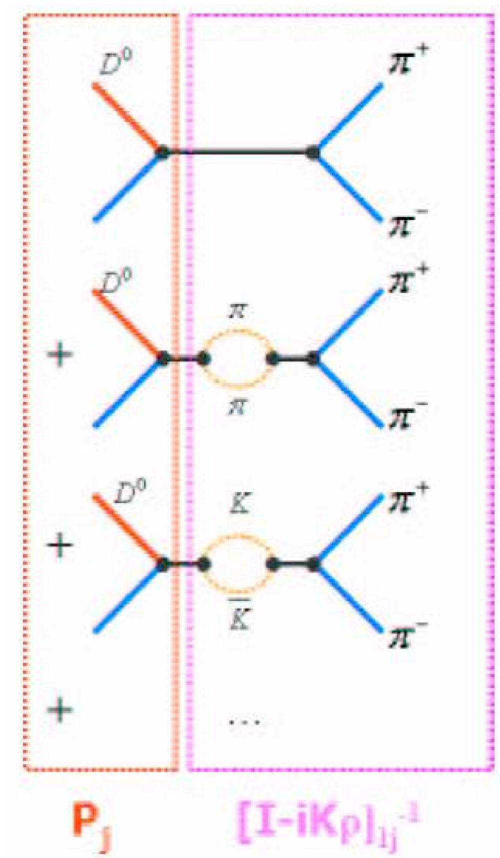
$$A_D(\mathbf{m}^2) = a_{\rm NR} e^{i\delta_{\rm NR}} + \sum_r a_r e^{i\delta_r} A_r^J(\mathbf{m}^2)$$

Non resonant term | Fit params. | Resonance description



$$A_r^J(\mathbf{m}^2) = F_D F_r M_r^J T_r(\mathbf{m}^2)$$

- Vertex form factors
  - Blatt-Weisskopf (R=1.5GeV^{-1})
- Angular distribution for spin J
  - Zemach Tensors
- Resonance propagator
  - Relativistic BW
  - Gounaris-Sakurai ρ lineshape
  - K-matrix approach for ππ and Kπ S-waves in $D^0 \rightarrow K_S\pi\pi$



$$F_1\left(m_{\pi\pi}^2\right) = \sum_j \left[I - K\left(m_{\pi\pi}^2\right)\rho\left(m_{\pi\pi}^2\right)\right]_{1j}^{-1} P_j\left(m_{\pi\pi}^2\right)$$

$$K_{ij}\left(m_{\pi\pi}^2\right) = \left[f_{ij}^{\rm scatt}\frac{1-s_0^{\rm scatt}}{m_{\pi\pi}^2-s_0^{\rm scatt}} + \sum_\alpha \frac{g_i^{(\alpha)}g_j^{(\alpha)}}{m_\alpha^2-m_{\pi\pi}^2}\right]\left\{\frac{1-s_{A0}}{m_{\pi\pi}^2-s_{A0}}\left(m_{\pi\pi}^2-\frac{s_A m_\pi^2}{2}\right)\right\}$$

$$P_j\left(m_{\pi\pi}^2\right) = f_{11}^{\rm prod} f_{r,1j}^{\rm prod}\frac{1-s_0^{\rm prod}}{m_{\pi\pi}^2-s_0^{\rm prod}} + \sum_\alpha \frac{\beta_\alpha g_j^{(\alpha)}}{m_\alpha^2-m_{\pi\pi}^2}$$

m_α	$g^\alpha_{\pi^+\pi^-}$	$g^\alpha_{K\bar{K}}$	$g^\alpha_{4\pi}$	$g^\alpha_{\eta\eta}$	$g^\alpha_{\eta\eta'}$
0.65100	0.22889	−0.55377	0.00000	−0.39899	−0.34639
1.20360	0.94128	0.55095	0.00000	0.39065	0.31503
1.55817	0.36856	0.23888	0.55639	0.18340	0.18681
1.21000	0.33650	0.40907	0.85679	0.19906	−0.00984
1.82206	0.18171	−0.17558	−0.79658	−0.00355	0.22358
$s_0^{\rm scatt}$	$f_{11}^{\rm scatt}$	$f_{12}^{\rm scatt}$	$f_{13}^{\rm scatt}$	$f_{14}^{\rm scatt}$	$f_{15}^{\rm scatt}$
−3.92637	0.23399	0.15044	−0.20545	0.32825	0.35412
s_{A0}	s_A				
−0.15	1				

GGSZ: systematic uncertainties

- Dominant error is statistical
- Similar contributions to total syst. error from Dalitz model and exp.

TABLE II: Summary of the main contributions to the D^0 decay amplitude model systematic uncertainty on the *CP* parameters. We evaluate the different contributions using a similar, but not identical, procedure to that adopted in our previous analysis [9]. The reference D^0 decay amplitude models and parameters are used to generate 10 data-sized signal samples of pseudo-experiments of $D^{*+} \to D^0\,\pi^+$ and $D^{*-} \to \overline{D}^0\,\pi^-$ events, and 10 $B^{\mp} \to D^{(*)}\,K^{\mp}$ and $B^{\mp} \to D\,K^{*\mp}$ signal samples 100 times larger than each measured signal yield in data, with $D^0 \to K^0_S h^+ h^-$. The *CP* parameters are generated with values in the range found in data. We then compare experiment-by-experiment the values of $\mathbf{z}_{\mp}^{(*)}$ and $\mathbf{z}_{s\mp}$ obtained from the *CP* fits using the reference amplitude models and a set of alternative models obtained by repeating the $D^0 \to K^0_S h^+ h^-$ amplitude analyses on the pseudo-experiments with alternative assumptions [13]. This technique, although it requires large computing resources, helps

Source	x_-	y_-	x_+	y_+	x_-^*	y_-^*	x_+^*	y_+^*	x_{s-}	y_{s-}	x_{s+}	y_{s+}
Mass and width of Breit-Wigner's	0.001	0.001	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.002
$\pi\pi$ S-wave parameterization	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.002
$K\pi$ S-wave parameterization	0.001	0.004	0.003	0.008	0.001	0.006	0.002	0.004	0.003	0.002	0.003	0.007
Angular dependence	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.002	0.002	0.001	0.002	0.001
Blatt-Weisskopf radius	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001
Add/remove resonances	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.002
DP efficiency	0.003	0.002	0.003	0.001	0.001	0.001	0.001	0.001	0.004	0.002	0.003	0.001
Background DP shape	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Mistag rate	0.003	0.003	0.002	0.001	0.001	0.001	0.001	0.001	0.003	0.003	0.001	0.001
Effect of mixing	0.003	0.001	0.003	0.001	0.001	0.001	0.001	0.001	0.003	0.001	0.003	0.001
DP complex amplitudes	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.002	0.002	0.001	0.001	0.002
Total D^0 decay amplitude model	0.006	0.006	0.007	0.009	0.002	0.007	0.003	0.006	0.007	0.006	0.006	0.008

Dalitz model:
used alternative models, with different resonance parameters or parameterizations, add/remove resonances

Source	x_-	y_-	x_+	y_+	x_-^*	y_-^*	x_+^*	y_+^*	x_{s-}	y_{s-}	x_{s+}	y_{s+}
m_{ES}, ΔE, $\mathcal{F}$ shapes	0.001	0.001	0.001	0.001	0.004	0.006	0.008	0.004	0.006	0.003	0.004	0.002
Real D^0 fractions	0.002	0.001	0.001	0.001	0.003	0.003	0.002	0.002	0.004	0.001	0.001	0.001
Charge-flavor correlation	0.003	0.003	0.002	0.001	0.005	0.005	0.008	0.002	0.001	0.001	0.003	0.001
Efficiency in the DP	0.003	0.001	0.003	0.001	0.001	0.001	0.001	0.001	0.003	0.001	0.002	0.001
Background DP distributions	0.005	0.002	0.005	0.003	0.003	0.002	0.004	0.004	0.010	0.004	0.007	0.002
$B^- \to D^{*0} K^-$ cross-feed	–	–	–	–	0.002	0.003	0.009	0.002	–	–	–	–
CP violation in $D\pi$ and $B\overline{B}$	0.002	0.001	0.001	0.001	0.017	0.001	0.008	0.004	0.017	0.002	0.011	0.001
Non-K^* $B^- \to DK^0_S\pi^-$ decays	–	–	–	–	–	–	–	–	0.020	0.026	0.025	0.036
Total experimental	0.007	0.004	0.006	0.004	0.019	0.009	0.017	0.008	0.029	0.027	0.029	0.036

Experimental contributions:
vary PDF parameters; assume flat efficiency; use background Dalitz shape from MC instead of data sideband, or flat shape

GGSZ: interference between DK* and DKπ

- GGSZ formulae still valid after replacement

$$x_{\mp}^{(*)} \rightarrow x_{s\mp} = \kappa r_s \cos(\delta_s \mp \gamma) \qquad r_s^2 = \frac{\int A_u^2(p)\mathrm{d}p}{\int A_c^2(p)\mathrm{d}p} \;,\; \kappa e^{i\delta_s} = \frac{\int A_c(p) A_u(p) e^{i\delta(p)}\mathrm{d}p}{\sqrt{\int A_c^2(p)\mathrm{d}p \int A_u^2(p)\mathrm{d}p}}.$$

$$y_{\mp}^{(*)} \rightarrow y_{s\mp} = \kappa r_s \sin(\delta_s \mp \gamma)$$

- Additional parameter k (0..1) can be evaluated using a Dalitz isobar model B for the decay amplitude (including, for B^-: $K^*(892)^-$, $K^*_0(1410)^-$, $K^*_2(1430)^-$, $D^*(2010)^-$, $D^*_2(2460)^-$) by randomly varying magnitudes (+/-30%) and phases (0..2π), A_u/A_c fixed to ~0.4

  - $B^- \rightarrow D^0 K^{*-}$: k = 0.9±0.1

  - $B^0 \rightarrow$ anti-$D^0 K^{*0}$: k = 0.95±0.03

Frequentist procedure for extracting γ

- From the measured $\mathbf{z}=\{x^{(*)}_{(s)\pm}, y^{(*)}_{(s)\pm}\}$ with covariance matrix $\mathbf{V}_{\mathbf{stat+syst}}$, construct a multivariate gaussian PDF for the physical parameters $\mathbf{p}=\{\gamma, r^{(*)}_{B,s}, \delta^{(*)}_{B,s}\}$:

$$\mathcal{L}(\mathbf{z};\mathbf{p};V) \;=\; \frac{1}{(2\pi)^{n/2}\sqrt{|V|}} e^{-\frac{1}{2}(\mathbf{z}-\mathbf{z}^{(\mathbf{t})})^T V^{-1}(\mathbf{z}-\mathbf{z}^{(\mathbf{t})})} \equiv \frac{1}{(2\pi)^{n/2}\sqrt{|V|}} e^{-\frac{1}{2}\chi^2(\mathbf{z};\mathbf{p};V)}$$

- For each value μ_0 of the parameter μ, minimize $\chi^2_{min}(\mu_0,\mathbf{q})=-2\ln L$ with respect to the other parameters, $\mathbf{q}=\mathbf{p}-\{\mu\}$: $\chi^2_{min}(\mu_0,\mathbf{q}_0)$.

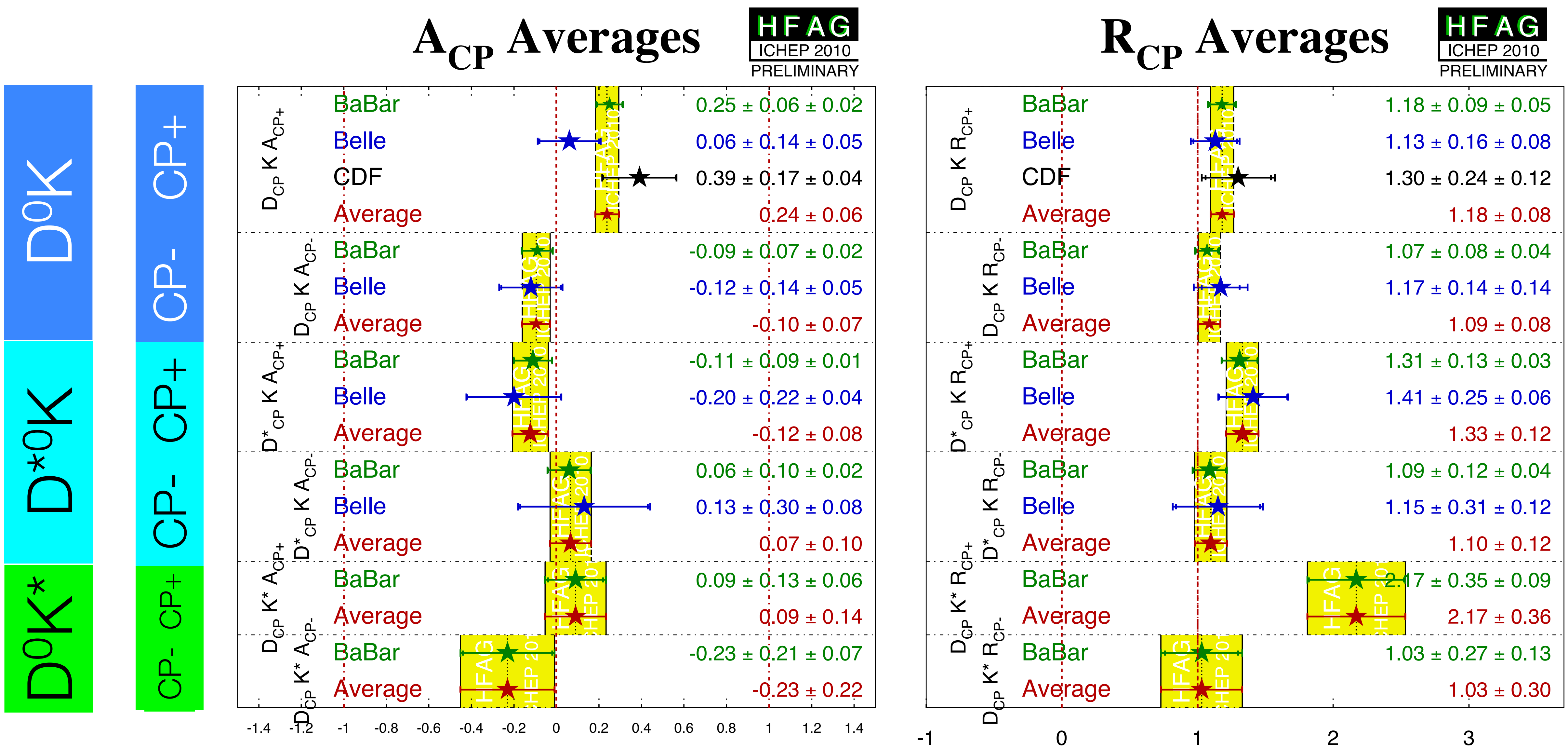
- In a 100% gaussian case, the CL is given by

$$\Delta\chi^2(\mu_0) \;=\; \chi^2_{\min}(\mu_0,\mathbf{q_0}) - \chi^2_{\min}$$

$$\mathrm{CL} = 1-\alpha \;=\; Prob(\Delta\chi^2(\mu_0), \nu=1) = \frac{1}{\sqrt{2^\nu}\Gamma(\nu/2)} \int_{\Delta\chi^2(\mu_0)}^{\infty} e^{-t/2} t^{\nu/2-1} dt$$

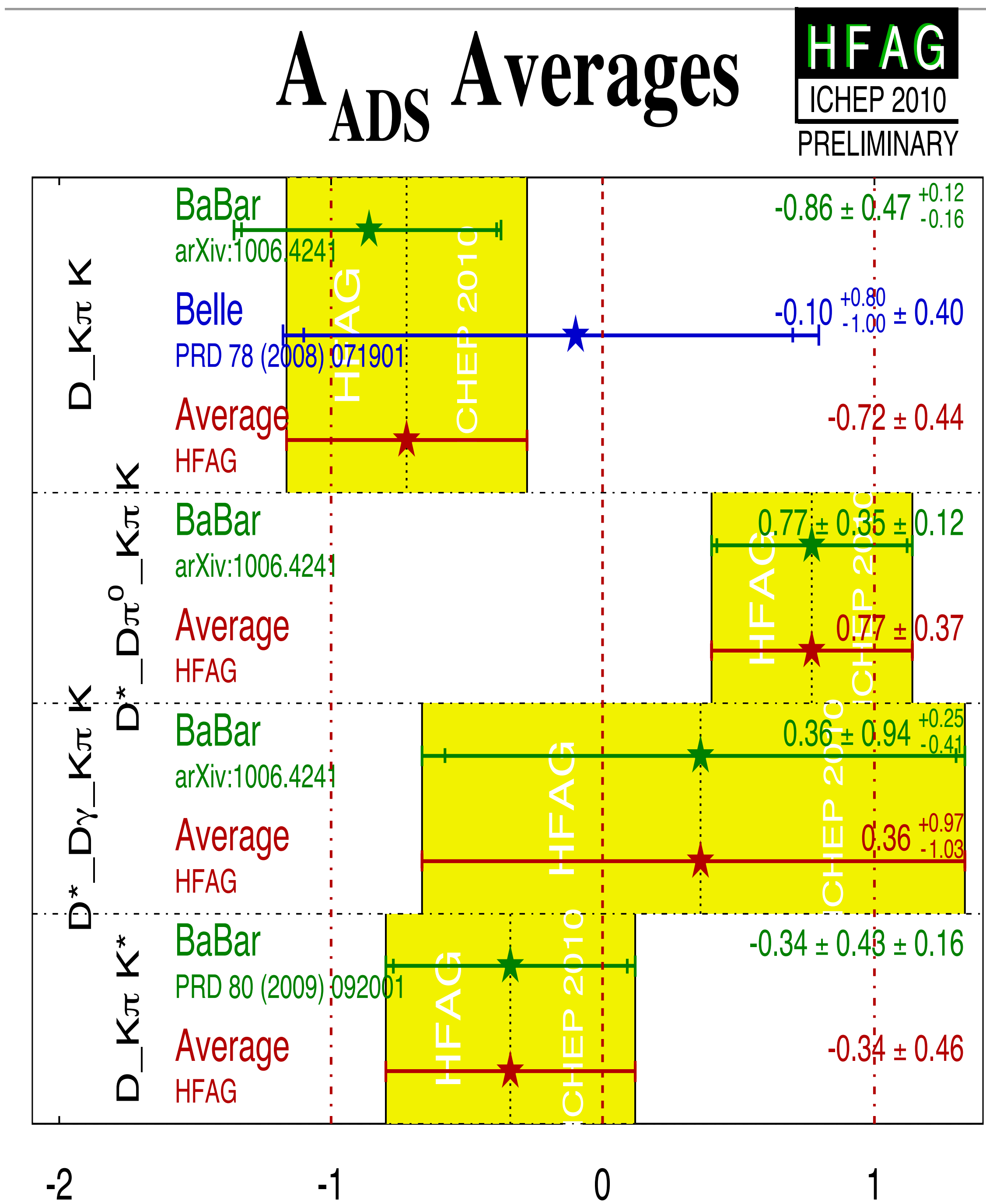
- In practice, use toy MC to evaluate CL:
  - generate a sample of **z'** according to V and assuming **z(true)**=**z**(μ_0,$\mathbf{q}_0$)
  - determine $\Delta\chi^{2\prime}(\mu_0)=\chi^{2\prime}_{min}(\mu_0,\mathbf{q}_0')-\chi^{2\prime}_{min}$ (letting **q** free to vary)
  - count how many times $\Delta\chi^{2\prime}(\mu_0)<\Delta\chi^2(\mu_0)$

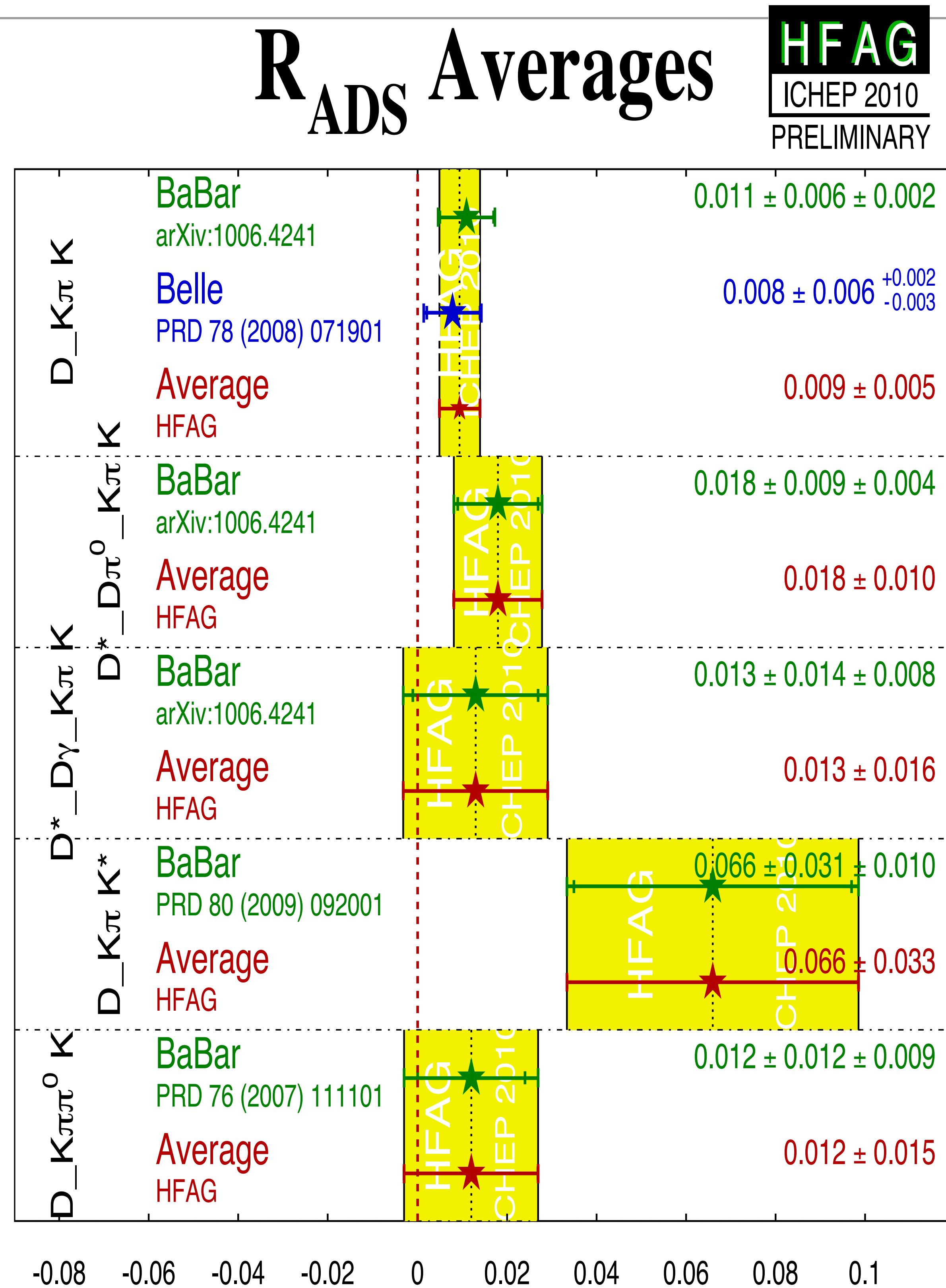
R_{CP}, A_{CP}: comparison with other experiments



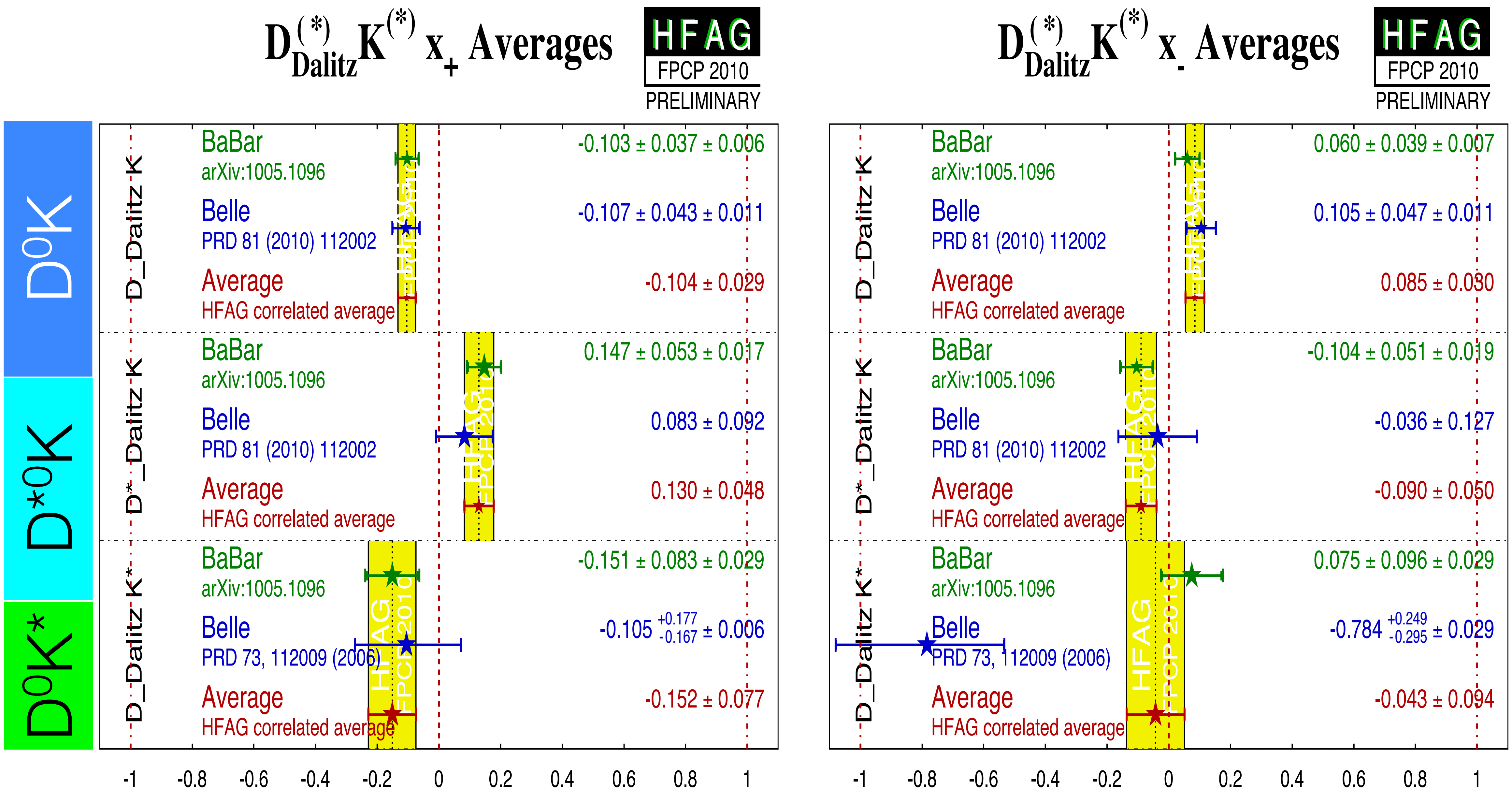
- **Consistency** with other experiments' determinations
- World's **most precise** measurement of $A_{CP\pm}$ and $R_{CP\pm}$

R_{ADS}, A_{ADS}: comparison with other experiments

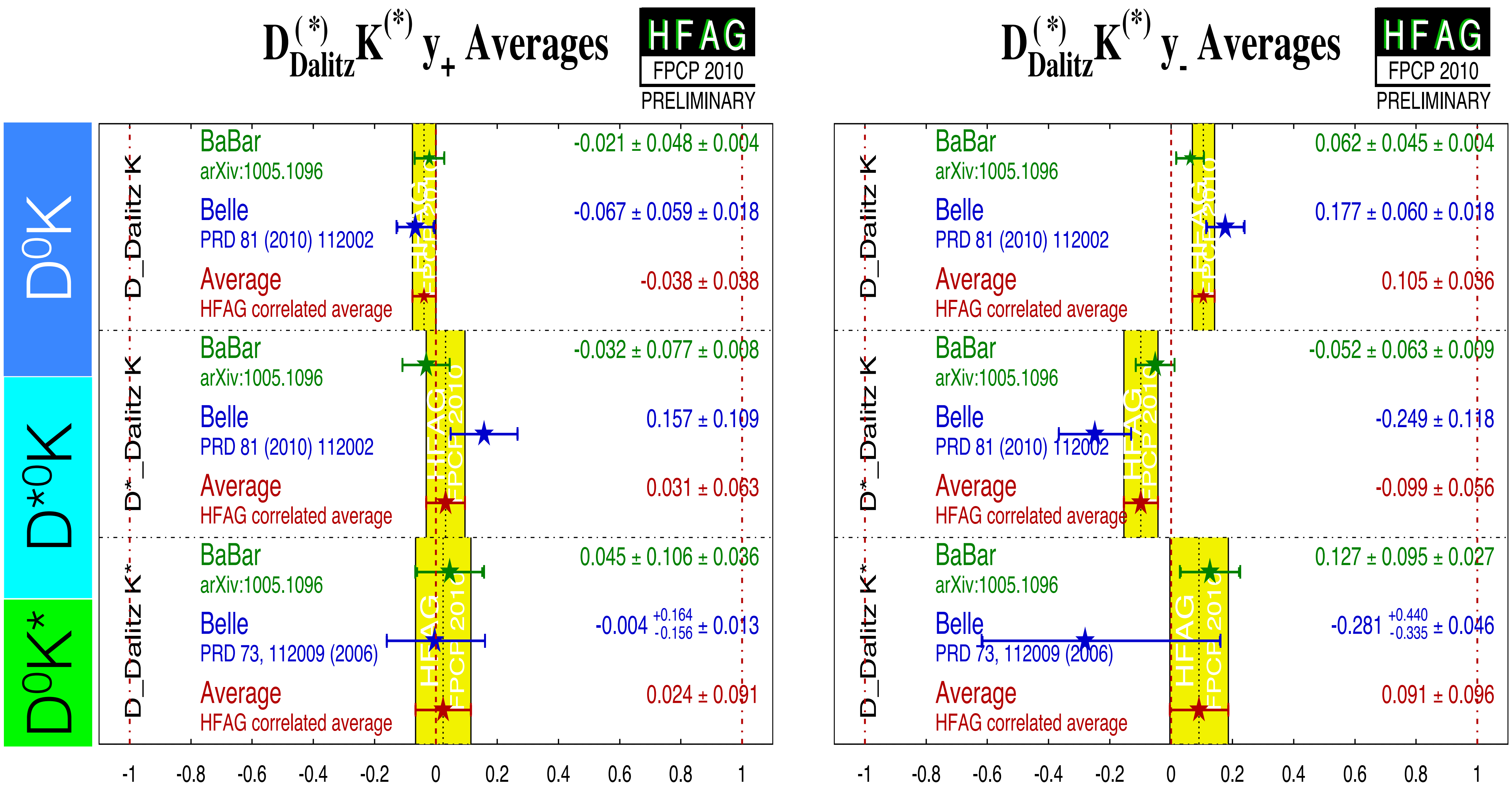




x (GGSZ): comparison with Belle



y (GGSZ): comparison with Belle



x (DK): GGSZ vs GLW