Averaging Results

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WHEPPXI
Workshop on High Energy Physics Phenomenology

January 2010

Heavy Flavor Averaging Group

- Current chairs:
  - Alan Schwartz (Belle), Gianluca Cavoto (BaBar)
- HFAG operates as a set of quasi-autonomous subgroups:
  - Oscillations & lifetimes (Olivier Schneider)
  - Semileptonic (Christoph Schwanda)
  - Rare decays (Paoti Chang)
  - Unitarity Triangle (Tim Gershon)
  - B to Charm (Simon Blyth)
  - Charm (Alan Schwartz & Jon Coleman)
  - Tau (Swagato Banerjee)

Heavy Flavor Averaging Group

- History:
  - evolved from LEP B physics averaging group
  - founded at first CKM workshop (CERN 2002)
  - initial chairs:
    - David Kirkby (BaBar) & Yoshi Sakai (Belle) (2002-2005?)
    - succeeded by Soeren Prell (BaBar) & Simon Eidelman (Belle) (2006-2007?)
  - initially four subgroups; additional groups added according to demand
  - manpower within subgroups evolves at a rate that differs significantly between subgroups

Heavy Flavor Averaging Group

- Webpage:

  http://www.slac.stanford.edu/xorg/hfag/

- Documentation:
  - preprints updated irregularly
    - end of 2007 update arXiv:0808.1297 [hep-ex]
    - end of 2006 update arXiv:0704.3575 [hep-ex]
    - end of 2005 update hep-ex/0603003
    - winter 2005 update hep-ex/0505100
    - summer 2004 update hep-ex/0412073
  - end of 2009 update in preparation

Heavy Flavor Averaging Group

- Relations with other groups
  - PDG
    - Some HFAG members are also PDG members/contributors
    - HFAG provides some averages for PDG (at their request)
  - Experiments (BaBar, Belle, CDF, D0, LEP, CLEO, BES …)
    - Subgroups contain representatives of relevant experiments
    - Close relations (heritage of LEP B physics WG)
  - CKMfitter & UTfit
    - Some HFAG members are CKMfitter/UTfit members
    - Aim for strict independence (but friendly relations)
  - Theorists
    - Discussions warmly encouraged
    - Care to avoid bias possible due to preferences for particular theoretical models

HFAG: Unitarity Triangle Parameters

- Mission

- Provide world averages for measurements **related to the angles of the Unitarity Triangle**. In particular, we provide world averages of measurements of **time-dependent CP violation**, and related parameters. We also prepare averages of time-independent measurements that have a clean relation to the UT angles (especially in the B→DK system).
- Identify common experimental and theoretical uncertainties and treat them coherently in the averages. Rescale the measurements if updated input parameters are available.
- In cases where effective UT angles are measured no attempts are made to derive the fundamental quantities, if this requires input from QCD calculations.
- If straightforward, an interpretation of the results is given.

- Members

Contact Persons	Experiment
Tim Gershon (*)	BABAR and LHCb
Gianluca Cavoto	BABAR
Owen Long	BABAR
Achille Stocchi	BABAR
Yoshi Sakai	Belle
Karim Trabelsi	Belle
Diego Tonelli	CDF
Hal Evans	DO
David Asner	CLEOc

HFAG: Unitarity Triangle Parameters

Φ_s ($B_s \rightarrow J/\psi\phi$) handled by HFAG lifetimes & oscillations
(actually handled directly by CDF & D0 at present)

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HFAG: Unitarity Triangle Parameters

- Averaging procedure
  - For measurements with Gaussian uncertainties
    - perform simultaneous average of all physics parameters that are determined in the fits taking (linear) correlations into account (NB. different to PDG)
    - encourage experiments to use parameters that have Gaussian uncertainties, and to report all physics parameters and correlations
  - For measurements with non-Gaussian uncertainties (ie. asymmetric errors)
    - perform uncorrelated averages using the PDG prescription
  - Correlations between measurements from different experiments are handled
    - can arise due to dependence on external nuisance parameters
    - rescaling of external parameters can be handled
  - If measurements do not agree, we discuss with the experiments and try to find the cause
    - we do NOT inflate the uncertainties (NB. the PDG does)

HFAG: Unitarity Triangle Parameters

- Averaging procedure
  - Standard minimum χ^2 procedure
    - *i* independent measurements of parameter x
    - Values x_i and uncertainties σ_i

$$\sum_i (\mathrm{x}_i - \overline{\mathrm{x}})^2 / \sigma_i^2$$

    - Generalisation to *i* sets of measurements of correlated parameters
    - x_i is now a vector, C_i the covariance matrix ($\sigma_{i,a} = \sqrt{(C_{i,aa})}$)

$$\sum_i (\mathrm{x}_i - \overline{\mathrm{x}})_a^T (C_i^{-1})_{ab} (\mathrm{x}_i - \overline{\mathrm{x}})_b$$

  - Solved analytically

HFAG: Unitarity Triangle Parameters

- "The PDG prescription:"
  - See section 5.2 of the PDG RPP

When experimenters quote asymmetric errors $(\delta x)^+$ and $(\delta x)^-$ for a measurement x, the error that we use for that measurement in making an average or a fit with other measurements is a continuous function of these three quantities. When the resultant average or fit $\overline{x}$ is less than $x - (\delta x)^-$, we use $(\delta x)^-$; when it is greater than $x + (\delta x)^+$, we use $(\delta x)^+$. In between, the error we use is a linear function of x. Since the errors we use are functions of the result, we iterate to get the final result. Asymmetric output errors are determined from the input errors assuming a linear relation between the input and output quantities.

HFAG: Unitarity Triangle Parameters

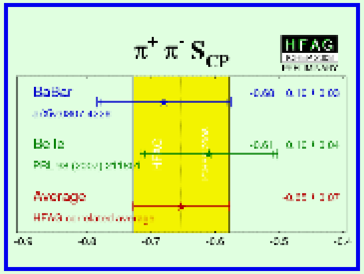
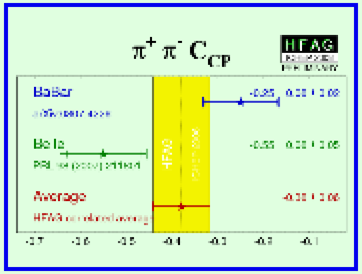
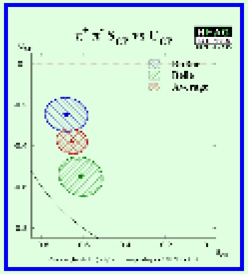
- Inclusion of results
  - We include all published and many preliminary results (NB. different to PDG)

  - We strongly encourage written documentation to accompany preliminary results
    - preferably collaboration authored (ie. not proceedings)
    - preferably available on arXiv (not hidden on web-pages)

  - We exclude preliminary results which remain unpublished for a long time (> 2 years) and/or for which no publication is planned

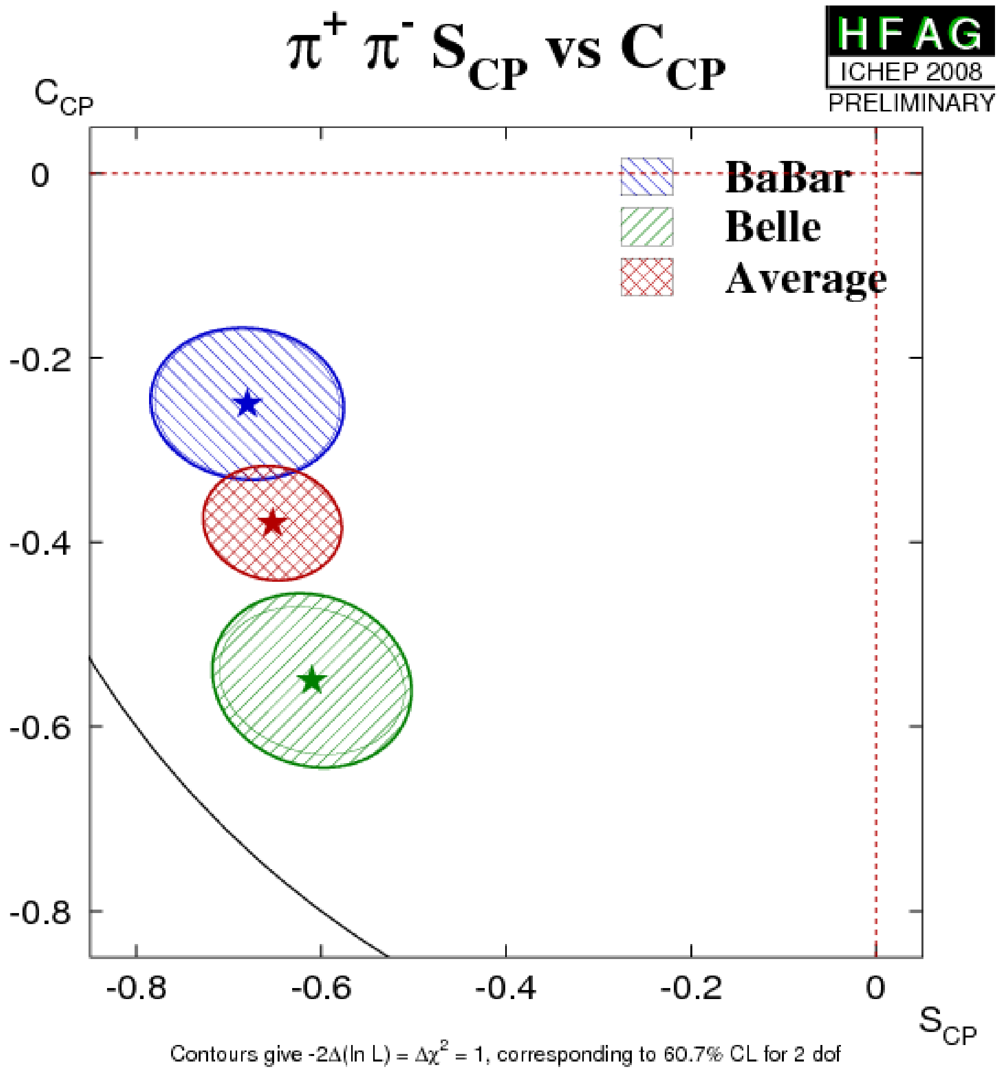
Example: $B^0 \to \pi^+\pi^-$

- Statistically dominated
  - No need to worry about correlations of systematic uncertainties

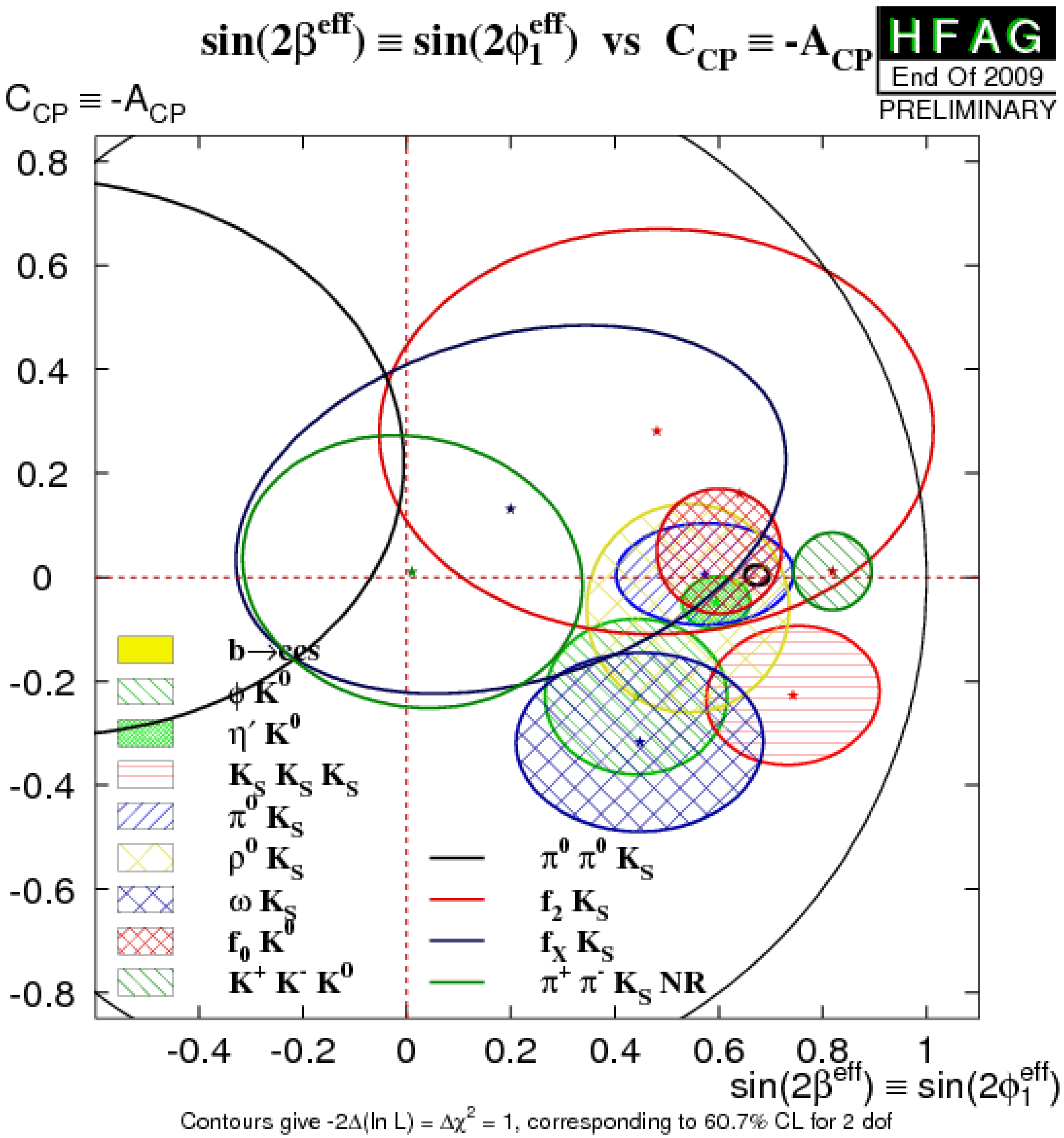
Experiment	S_{CP} $(\pi^+\pi^-)$	C_{CP} $(\pi^+\pi^-)$	Correlation	Reference
BaBar N(BB)=467M	$-0.68 \pm 0.10 \pm 0.03$	$-0.25 \pm 0.08 \pm 0.02$	-0.06 (stat)	arXiv:0807.4226
Belle N(BB)=535M	$-0.61 \pm 0.10 \pm 0.04$	$-0.55 \pm 0.08 \pm 0.05$	-0.15 (stat)	PRL 98 (2007) 211801
Average	-0.65 ± 0.07	-0.38 ± 0.06	-0.08	HFAG correlated average χ^2 = 5.8/2 dof (CL=0.055 ⇒ 1.9σ)
Figures:	 eps.gz png	 eps.gz png		 eps.gz png

Example: $B^0 \to \pi^+\pi^-$

- Recall: we do NOT inflate uncertainties

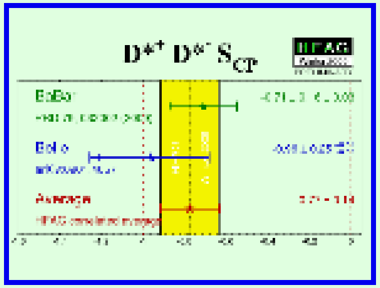
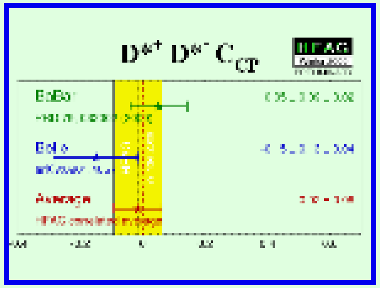
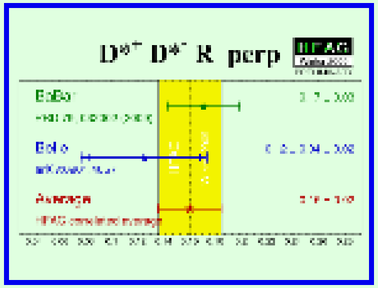
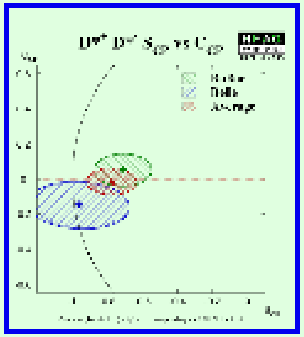


Example: b→qqs penguins



Example: $B^0 \to D^{*+}D^{*-}$

- Correlations with additional non-CP parameters

Experiment	S_{CP} (D^{*+} D^{*-})	C_{CP} (D^{*+} D^{*-})	$R_\perp$ (D^{*+} D^{*-})	Correlation	Reference
BaBar N(BB)=467M	$-0.71 \pm 0.16 \pm 0.03$	$0.05 \pm 0.09 \pm 0.02$	0.17 ± 0.03	(stat)	PRD 79, 032002 (2009)
Belle N(BB)=657M	$-0.96 \pm 0.25\ ^{+0.12}_{-0.16}$	$-0.15 \pm 0.13 \pm 0.04$	$0.12 \pm 0.04 \pm 0.02$	(stat)	arXiv:0901.4057
Average	-0.77 ± 0.14	-0.02 ± 0.08	0.16 ± 0.02	(stat)	HFAG correlated average χ^2 = 2.9/3 dof (CL=0.41 ⇒ 0.8σ)
Figures:	 eps.gz png	 eps.gz png	 eps.gz png		 eps.gz png

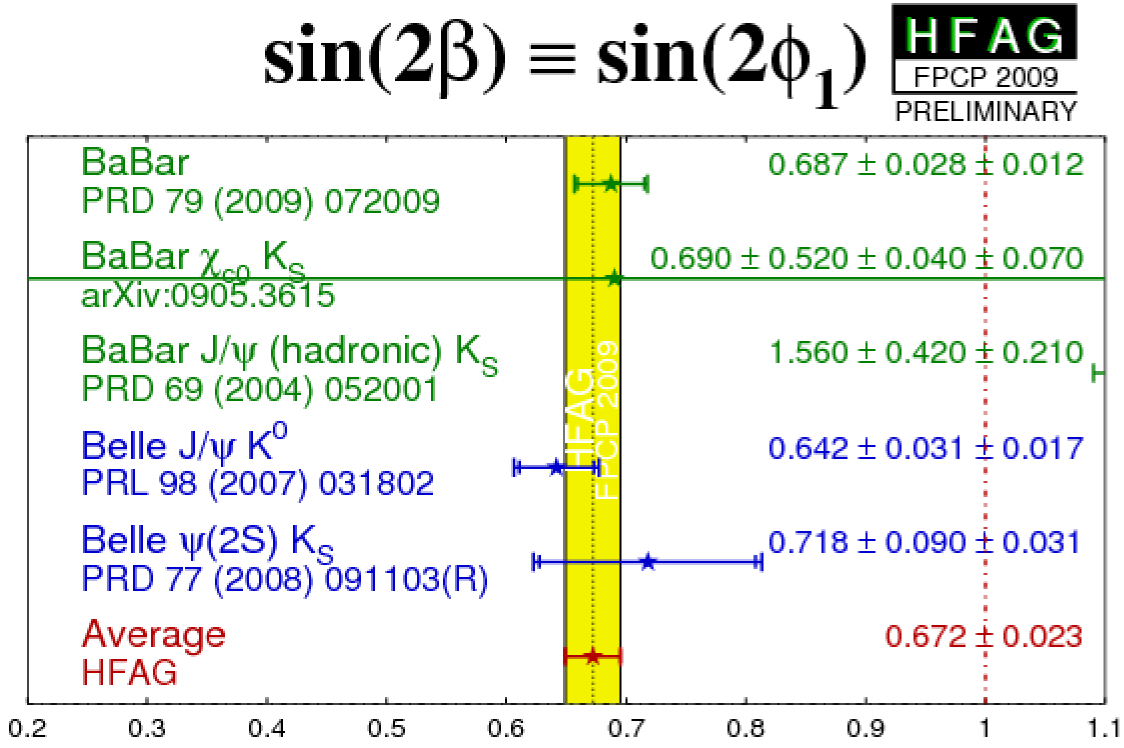
Example: $B^0 \rightarrow J/\psi K_S$

- Systematic correlations (external nuisance parameters) taken into account

Parameter: $\sin(2\beta) \equiv \sin(2\varphi_1)$				
Mode	**BaBar**	**Belle**	**Average**	**Reference**
Charmonium:	N(BB)=465M	N(BB)=535M	-	BaBar (PRD 79 (2009) 072009) Belle (PRL 98 (2007) 031802)
$J/\psi K_S$ (η_{CP}=-1)	0.657 ± 0.036 ± 0.012	0.643 ± 0.038_{stat}		
$J/\psi K_L$ (η_{CP}=+1)	0.694 ± 0.061 ± 0.031	0.641 ± 0.057_{stat}		
$J/\psi K^0$	0.666 ± 0.031 ± 0.013	0.642 ± 0.031 ± 0.017	0.655 ± 0.0244 (0.022 stat-only)	CL = 0.62
$\psi(2S)K_S$ (η_{CP}=-1)	0.897 ± 0.100 ± 0.036	0.718 ± 0.090 ± 0.031 N(BB)=657M	0.798 ± 0.071 (0.067 stat-only)	BaBar (PRD 79 (2009) 072009) Belle (PRD77 (2008) 091103(R))
$\chi_{c1}K_S$ (η_{CP}=-1)	0.614 ± 0.160 ± 0.040	-	-	BaBar (PRD 79 (2009) 072009)
$\eta_c K_S$ (η_{CP}=-1)	0.925 ± 0.160 ± 0.057	-		
$J/\psi K^{*0}$ ($K^{*0} \rightarrow K_S\pi^0$) ($\eta_{CP}$= 1-2$\lvert A_\perp \rvert^2$)	0.601 ± 0.239 ± 0.087	-		
All charmonium	0.687 ± 0.028 ± 0.012	0.650 ± 0.029 ± 0.018	0.670 ± 0.023 (0.020 stat-only)	CL = 0.52
$\chi_{c0}K_S$ (η_{CP}=+1)	0.69 ± 0.52 ± 0.04 ± 0.07 (*) N(BB)=383M	-	-	BaBar (PRD 80 (2009) 112001)
$J/\psi K_S$, $J/\psi \rightarrow$ hadrons (η_{CP}=+1)	1.56 ± 0.42 ± 0.21 (**) N(BB)=88M	-	-	BaBar (PRD 69 (2004) 052001)
All charmonium (incl. $\chi_{c0}K_S$ *etc.*)	0.691 ± 0.031 (0.028 stat-only)	0.650 ± 0.029 ± 0.018	0.672 ± 0.023 (0.020 stat-only)	CL = 0.30

Example: $B^0 \to J/\psi K_S$

- Systematic correlations (external nuisance parameters) taken into account



When Averages Get Difficult

- Experiments measure different parameters
- Badly behaved parameters, eg. due to
  - low statistics
  - choice of parametrisation
    - NB. “good” choice of parameters from a physics perspective may be a statistically “bad” choice
  - “badly behaved” could mean
    - Non-Gaussian (including non-linear correlations)
    - Dependence of uncertainty of one parameter on central value of another
- Complicated dependence on external nuisance parameters

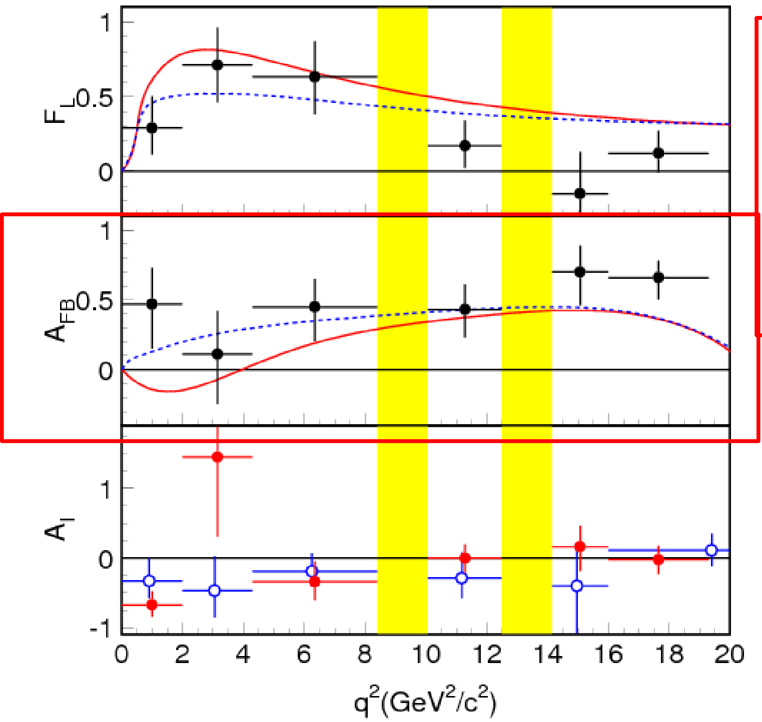
Example: A_{FB} ($B \rightarrow K^*ll$) distributions

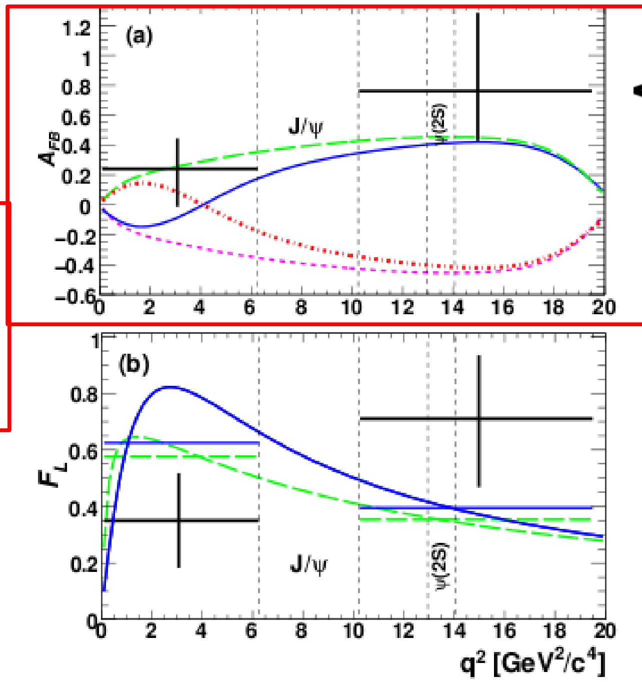
Experiments are using different binnings – cannot be combined

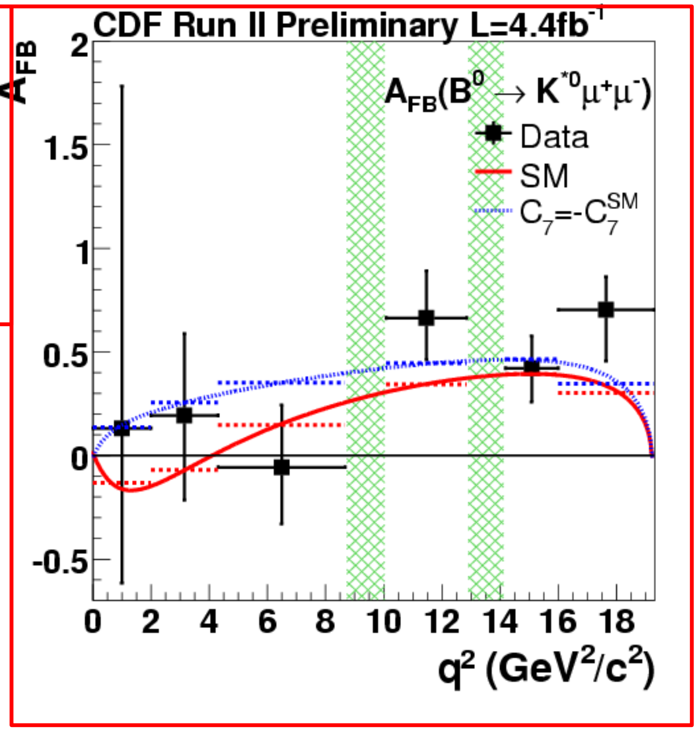
Belle PRL 103 (2009) 171801

BABAR PRD 79 (2009) 031102(R)

CDF note 09-11-12







Example: $B_s \to J/\psi\phi$

Differential decay rate:

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt\, d\cos\theta\, d\varphi\, d\cos\psi} \equiv \frac{d^4\Gamma}{dt\, d\Omega} \propto \sum_{k=1}^{6} h_k(t)\, f_k(\Omega)$$

- $A_0(0) \to$ CP even
- $A_{\parallel}(0) \to$ CP even
- $A_{\perp}(0) \to$ CP odd

k	$h_k(t)$ (Bs)	$h_k(t)$ ($\overline{\text{Bs}}$)	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0(t)\rvert^2$	$\lvert \bar{A}_0(t)\rvert^2$	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$
2	$\lvert A_{\parallel}(t)\rvert^2$	$\lvert \bar{A}_{\parallel}(t)\rvert^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
3	$\lvert A_{\perp}(t)\rvert^2$	$\lvert \bar{A}_{\perp}(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im\{A_{\parallel}^*(t)A_{\perp}(t)\}$	$\Im\{\bar{A}_{\parallel}^*(t)\bar{A}_{\perp}(t)\}$	$\sin^2\psi\sin 2\theta\sin\varphi$
5	$\Re\{A_0^*(t)A_{\parallel}(t)\}$	$\Re\{\bar{A}_0^*(t)\bar{A}_{\parallel}(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
6	$\Im\{A_0^*(t)A_{\perp}(t)\}$	$\Im\{\bar{A}_0^*(t)\bar{A}_{\perp}(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$

± signs differ for B_s and $\bar{B}_s$

$$|\bar{A}_0(t)|^2 = |\bar{A}_0(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right],$$

$$|\bar{A}_{\parallel}(t)|^2 = |\bar{A}_{\parallel}(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right],$$

$$|\bar{A}_{\perp}(t)|^2 = |\bar{A}_{\perp}(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right],$$

$$\Im\{\bar{A}_{\parallel}^*(t)\bar{A}_{\perp}(t)\} = |\bar{A}_{\parallel}(0)||\bar{A}_{\perp}(0)|e^{-\Gamma_s t}\Big[-\cos(\delta_\perp-\delta_\parallel)\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t) + \cos(\delta_\perp-\delta_\parallel)\cos\Phi\sin(\Delta m_s t)\Big],$$

$$\Re\{\bar{A}_0^*(t)\bar{A}_{\parallel}(t)\} = |\bar{A}_0(0)||\bar{A}_{\parallel}(0)|e^{-\Gamma_s t}\cos\delta_\parallel\Big[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\Big] \text{ and}$$

$$\Im\{\bar{A}_0^*(t)\bar{A}_{\perp}(t)\} = |\bar{A}_0(0)||\bar{A}_{\perp}(0)|e^{-\Gamma_s t}\Big[-\cos\delta_\perp\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\delta_\perp\cos(\Delta m_s t) + \cos\delta_\perp\cos\Phi\sin(\Delta m_s t)\Big].$$

Example: $B_s \rightarrow J/\psi\varphi$

- Very complicated expression
- Assumes no direct CP violation (full expression even more complicated!)
- Dependence of physical observables on φ_s goes as
  - $\cos(\varphi_s)\ \sinh(\Delta\Gamma_s t/2)$
  - $\sin(\varphi_s)\ \sin(\Delta m_s t)$
  - and similar expressions in interference terms with further dependence on strong phase differences
- Fit performed with free (physics) parameters

$$\varphi_s, \Delta\Gamma_s, R_\perp, R_\parallel, \delta_\perp, \delta_\parallel\ (\tau_s, \Delta m_s)$$

- Non-Gaussian effects not surprising (unavoidable?)

± signs differ for B_s and $\bar{B}_s$

Φ_s ($B_s \rightarrow J/\psi\varphi$)

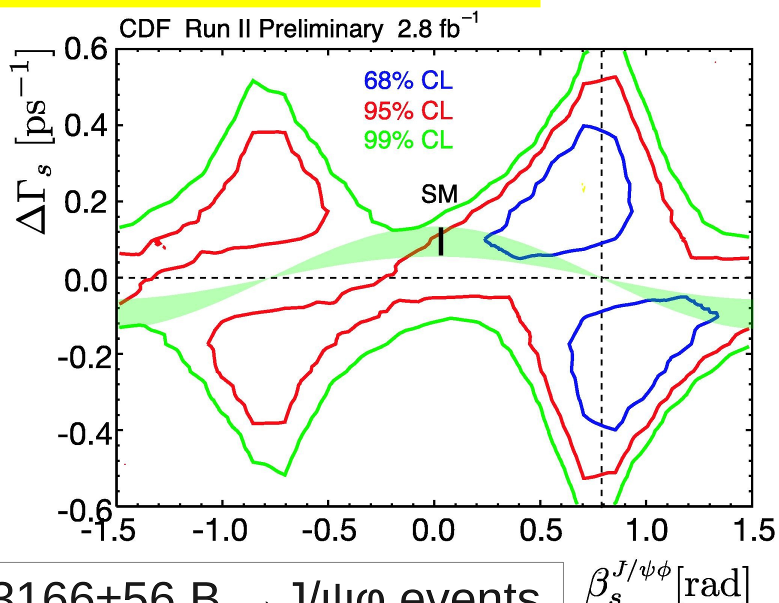
G.Punzi at EPS 2009

Tevatron measurements using tagged $B_s \rightarrow J/\psi\varphi$

Angular analyses of vector-vector final state

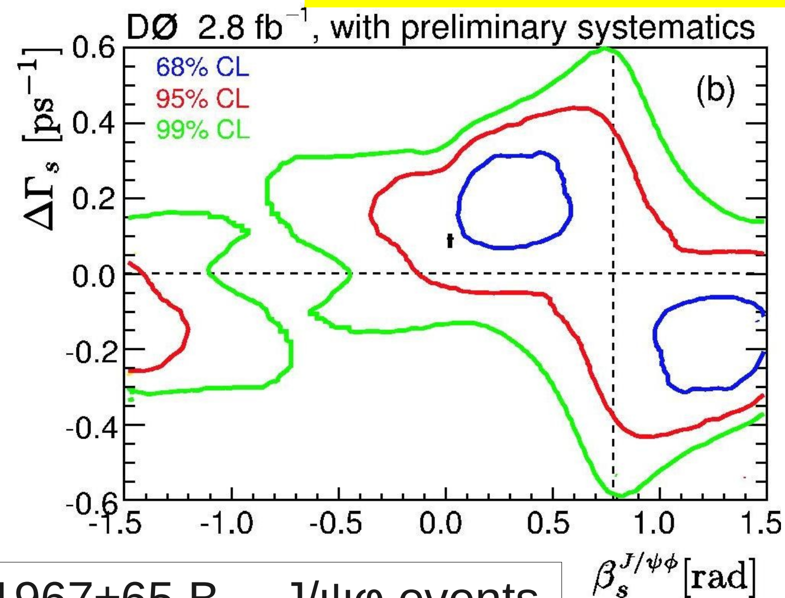
Results depend on $\Delta\Gamma$

CDF note 9787



3166±56 $B_s \rightarrow J/\psi\varphi$ events

D0 5928-CONF



1967±65 $B_s \rightarrow J/\psi\varphi$ events

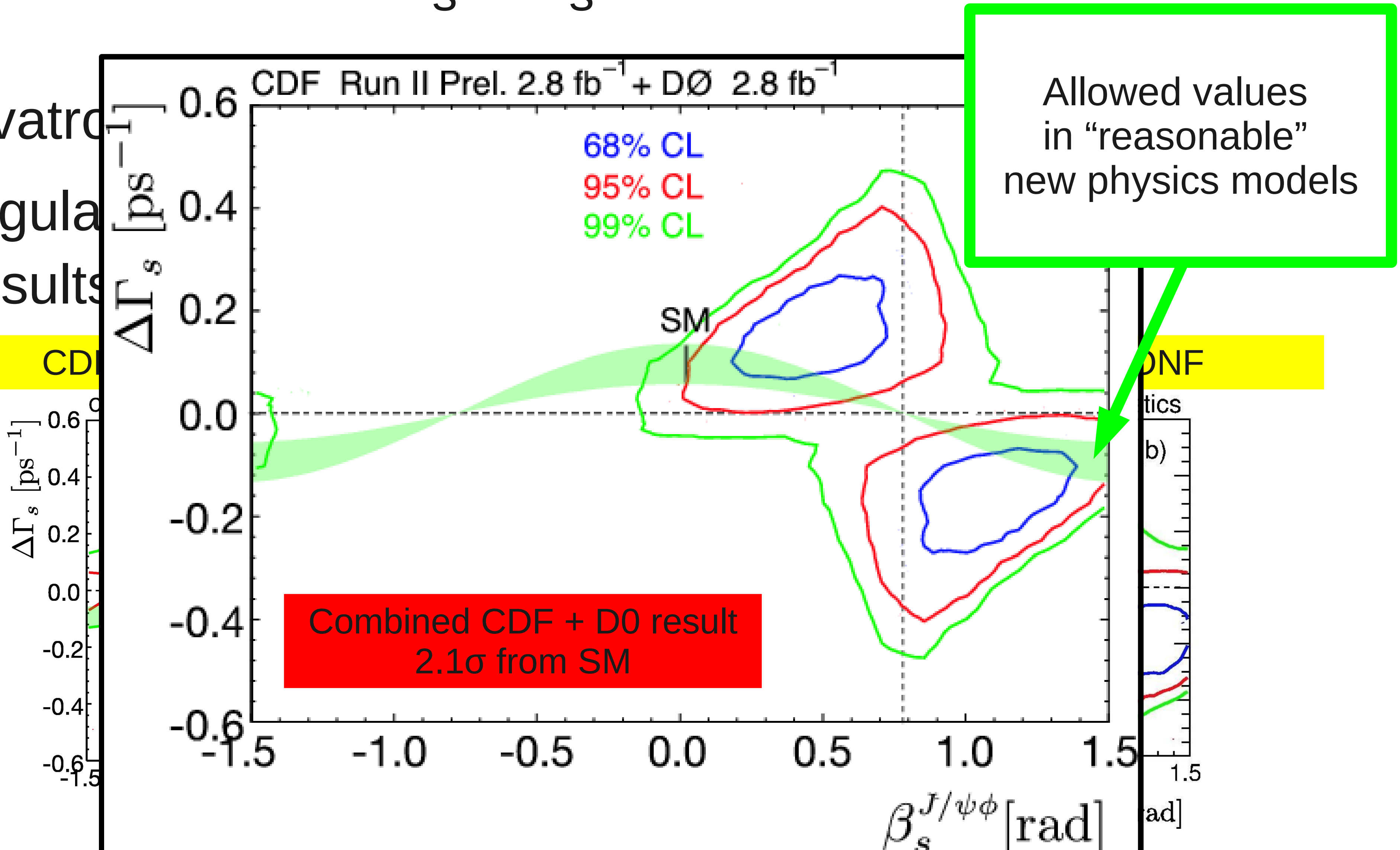
Φ_s ($B_s \rightarrow J/\psi\phi$)

Tevatro

Angula

Results

CDI … ONF



68% CL interval: Φ_s in [0.27, 0.59]∪[0.97, 1.30] rad

95% CL interval: Φ_s in [0.10, 1.42] rad

$B_s \to J/\psi\phi$: Latest Combination of results

Latest combination huge improvement on previous efforts

The two experiments perform very similar analyses

Two dimensional ($\Delta\Gamma_s$ *vs.* ϕ_s) log-likelihoods are added

But:

- Non-Gaussian regime
  - Uncertainty on ϕ_s strongly depends on value of $\Delta\Gamma_s$
- $B_s \to J/\psi\phi$ is not a two-dimensional problem
  - Consistency of results on other variables?
  - Higher dimensional combination would be better
  - Most practical way is simultaneous fit of both data sets

complicated reparametrisation could improve matters?

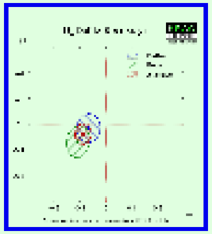
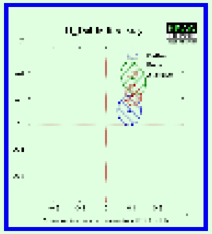
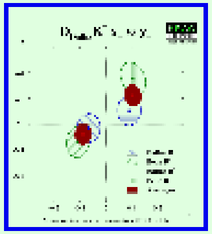
  - Work ongoing at the Tevatron ...

Example: $B \to DK$, $D \to K_S\pi^+\pi^-$

- Three physics parameters (r_B, δ_B, γ)
- Dependence of observables as

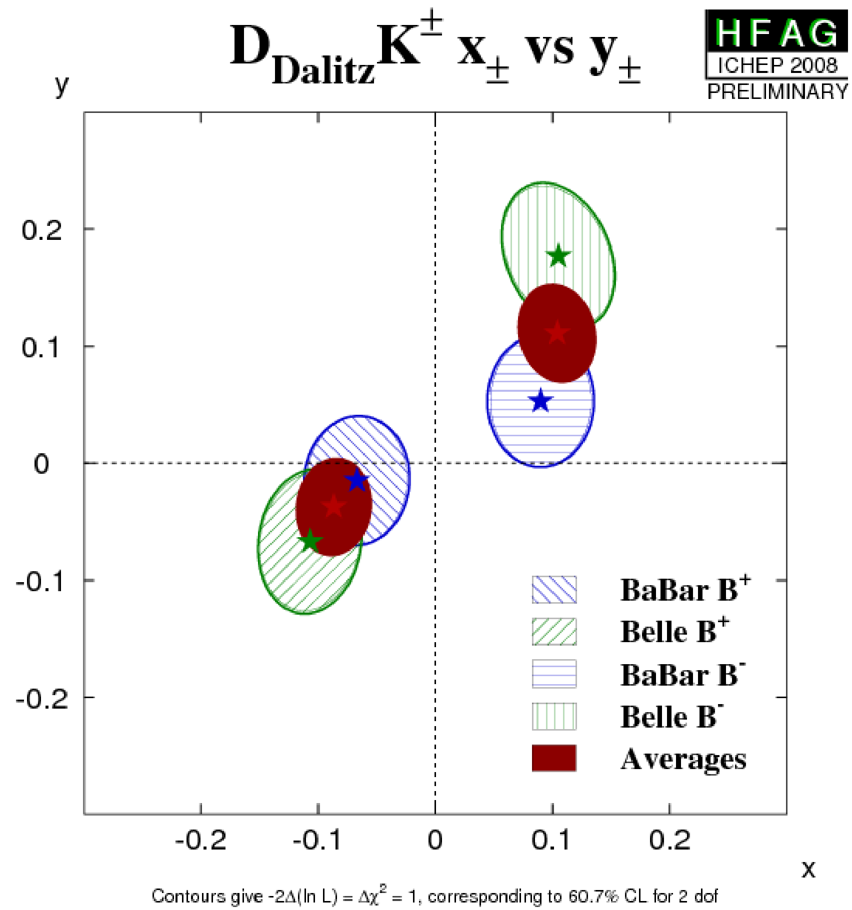
$$x_\pm = r_B\cos(\delta_B \pm \gamma),\ y_\pm = r_B\sin(\delta_B \pm \gamma)$$

- Using these parameters addresses the problem that $\sigma(\gamma) \sim (r_B)^{-1}$

Mode	Experiment	x+	y+	x-	y-	Correlation	Reference
DK^-	BaBar N(BB)=383M	−0.067 ± 0.043 ± 0.014 ± 0.011	−0.015 ± 0.055 ± 0.006 ± 0.008	0.090 ± 0.043 ± 0.015 ± 0.011	0.053 ± 0.056 ± 0.007 ± 0.015	(stat) (syst) (model)	PRD 78 (2008) 034023
	Belle N(BB)=657M	−0.107 ± 0.043 ± 0.011 ± 0.055	−0.067 ± 0.059 ± 0.018 ± 0.063	0.105 ± 0.047 ± 0.011 ± 0.064	0.177 ± 0.060 ± 0.018 ± 0.054	(stat) (model)	arXiv:0803.3375
	Average No model error	−0.087 ± 0.032	−0.037 ± 0.041	0.104 ± 0.033	0.111 ± 0.042	(stat+syst)	HFAG correlated average χ^2 = 3.1/4 dof (CL=0.54 ⇒ 0.6σ)
Figures: NB. The contours in these plots do not include model errors.	 eps.gz png		 eps.gz png		 eps.gz png		

Example: $B \to DK$, $D \to K_S \pi^+ \pi^-$

- Three physics parameters (r_B, δ_B, γ)
- Dependence of observables as
- Using these … at $\sigma(\gamma) \sim (r_B)^{-1}$



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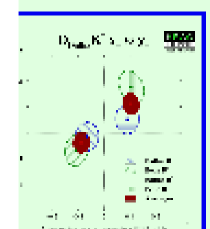
Figures: NB. The contours in these plots do not include model errors.			 eps.gz png	

Example: $B \to DK$, $D \to K_S \pi^+ \pi^-$

- Problem is the complicated dependence on the Dalitz plot model
  - Effectively, a 4-dimensional nuisance parameter ...

    (A typical nuisance parameter is 0-dimensional)

  - … that depends on position in the ($x_\pm$, $y_\pm$) plane
  - Experiments use different models & assign different uncertainties
  - Ideally, HFAG should
    - Rescale results to a common model
    - Then perform the average
    - Assign a model uncertainty to the result of the average

Example: $B \to DK$, $D \to K_S\pi^+\pi^-$

- Problem is the complicated dependence on the Dalitz plot model
  - Effectively, a 4-dimensional nuisance parameter ...

    (A typical nuisance parameter is 0-dimensional)

  - … that depends on position in the $(x_\pm, y_\pm)$ plane
  - Experiments use different models & assign different uncertainties
  - Ideally, HFAG should
    - Rescale results to a common model

      almost impossible – do nothing

    - Then perform the average

      OK

    - Assign a model uncertainty to the result of the average

      very difficult – do nothing

CKM 2010

http://ckm2010.warwick.ac.uk/

University of Warwick, UK, September 6-10, 2010

Please come!