New physics and CP violation measurements at LHCb

Tim Gershon
University of Warwick

LHCb week, Firenze
Common session with the Galileo Galilei Institute

22nd September 2009

Contents

- The CKM Matrix and CP violation
  - The need for a clean measurement of γ
- Flavour oscillations and CP violation
  - Where are we now and where will LHCb take us?
  - B_d, B_s and charm systems
- Alternative γ, β and $β_s$ measurements

The Cabibbo-Kobayashi-Maskawa Quark Mixing Matrix

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

- A 3x3 unitary matrix
- Described by 4 real parameters – allows CP violation
  - PDG (Chau-Keung) parametrisation: θ_{12}, θ_{23}, θ_{13}, δ
  - Wolfenstein parametrisation: λ, A, ρ, η
- Highly predictive

CP violation and New Physics

- CKM ansatze is highly predictive
- Measurements of flavour phenomena overconstrain the SM parameters
- Consistency of different measurements tests for presence of new physics
- For example, compare
  - Clean SM reference points (from theory or measurement)
  - New physics sensitive measurements
- Recall past success of CP violation in discovering new physics

CKM Matrix – Phases

P.Harrison *et al.*, arXiv:0904.3077 [hep-ph]

- Can form a matrix of angles between pairs of CKM matrix elements
  - Φ_{ij} = phase between remaining elements when row i and column j removed
  - unitarity implies sum of phases in any row or column = 180°

$$\Phi = \begin{matrix} & d & s & b \\ u & \Phi_{ud} & \Phi_{us} & \Phi_{ub} \\ c & \Phi_{cd} & \Phi_{cs} & \Phi_{cb} \\ t & \Phi_{td} & \Phi_{ts} & \Phi_{tb} \end{matrix} \simeq \begin{matrix} & d & s & b \\ u & 1^o & 22^o & 157^o \\ c & 67^o & 90^o & 23^o \\ t & 112^o & 68^o & 0^o \end{matrix}$$

$\beta \equiv \varphi_1$ (22°)

$\alpha \equiv \varphi_2$ (90°)

$\gamma \equiv \varphi_3$ (68°)

"The Unitarity Triangle" (the s column)

CKM Matrix – Phases

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- Can form a matrix of angles between pairs of CKM matrix elements
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$$\Phi = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} \Phi_{ud} & \Phi_{us} & \Phi_{ub} \\ \Phi_{cd} & \Phi_{cs} & \Phi_{cb} \\ \Phi_{td} & \Phi_{ts} & \Phi_{tb} \end{pmatrix} \end{array} \simeq \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1^o & 22^o & 157^o \\ 67^o & 90^o & 23^o \\ 112^o & 68^o & 0^o \end{pmatrix} \end{array}$$

$\beta_s \approx \varphi_s/2$ (1^o)

$\beta \equiv \varphi_1$ (22^o)

$\alpha \equiv \varphi_2$ (90^o)

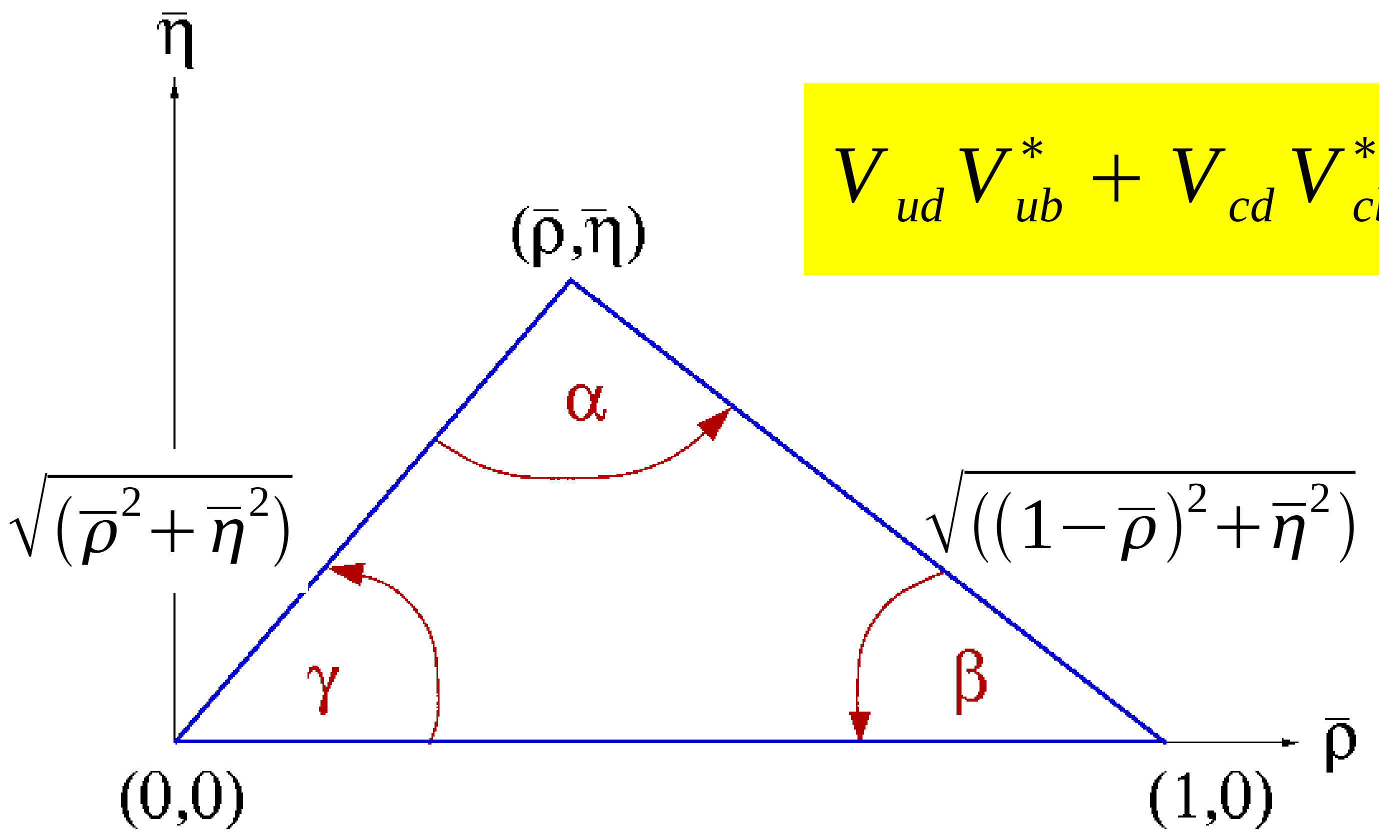
$\varphi_D/2$ (0^o)

$\gamma \equiv \varphi_3$ (68^o)

“The Unitarity Triangle” (column s)

The Unitarity Triangle

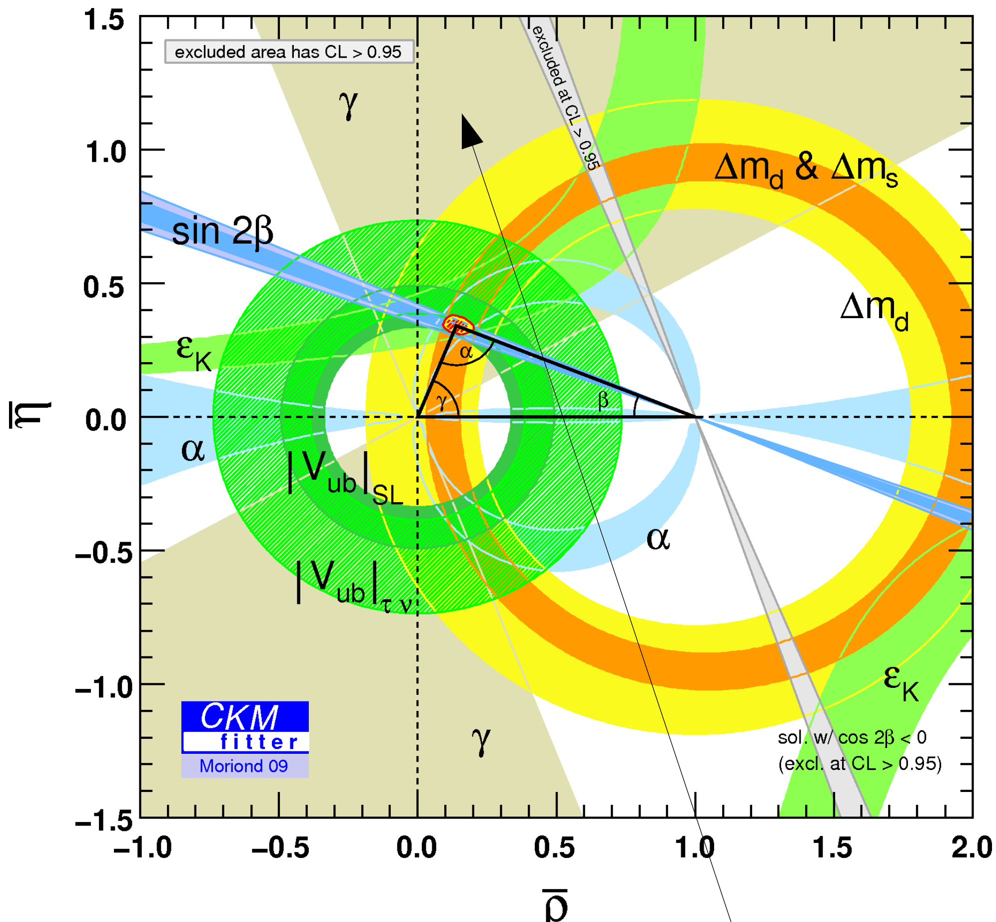
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



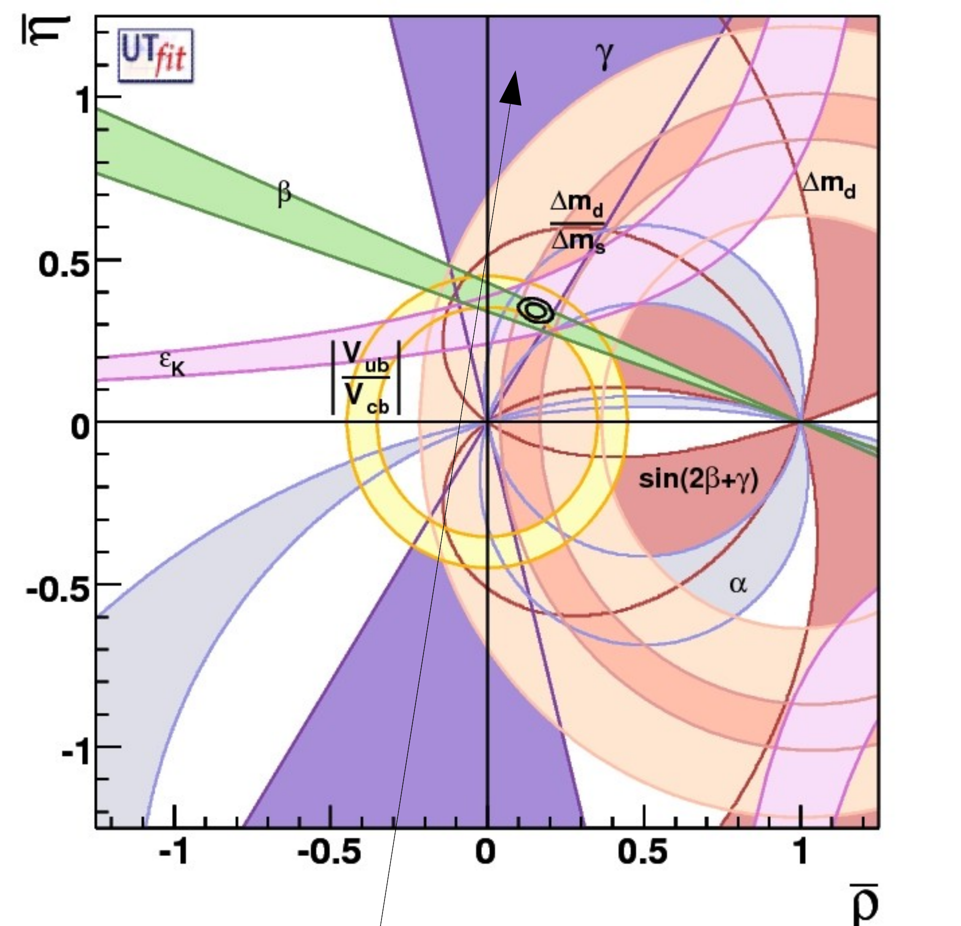
$$\alpha \equiv \phi_2 = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \quad \beta \equiv \phi_1 = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right], \quad \gamma \equiv \phi_3 = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

Today's Constraints on the Unitarity Triangle

http://ckmfitter.in2p3.fr/



http://www.utfit.org/



Note the relatively poor constraint on γ

Importance of γ

- γ plays a unique role in flavour physics

the only CP violating parameter that can be measured through tree decays (*)

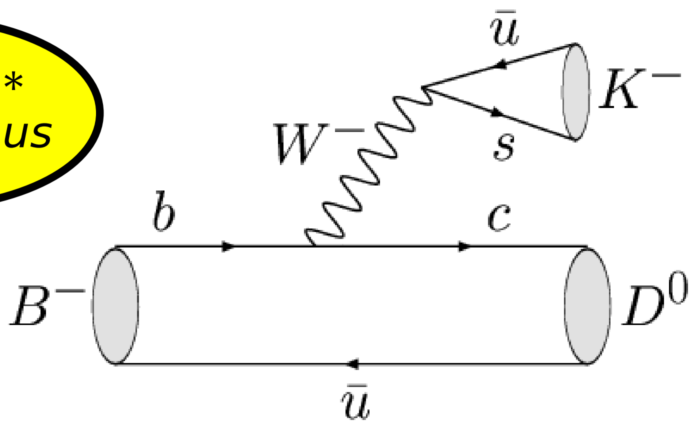
(*) more-or-less

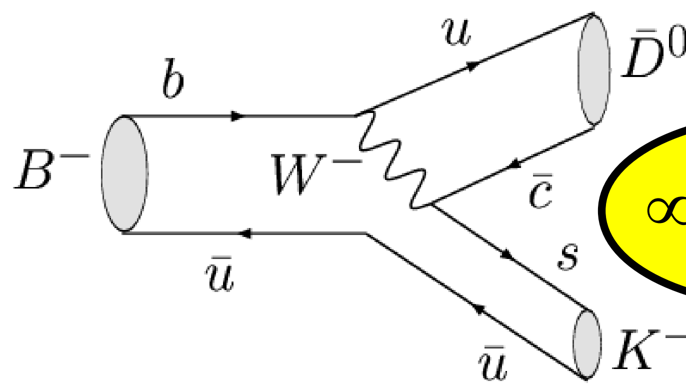
- A benchmark Standard Model reference point
  - doubly important after New Physics is observed
- How precise is precise enough?
  - 10% Ⓧ At 3 sigma hardly exclude anything
  - 1% ☆ Seems the right level to test NP
  - 0.1% Ⓧ Good luck if you can get the funding ...

How To Measure γ

- Focus on theoretically pristine measurement
  - Interference between

$\propto V_{cb} V^*_{us}$





$\propto V_{ub} V^*_{cs}$

- colour allowed
- final state contains D^0

- colour suppressed
- final state contains $\bar{D}^0$

- Use D decay final states accessible to both amplitudes
  - KK (GLW), Kπ (ADS), $K_s\pi\pi$ (GGSZ)
- Use also B_d decays to DK^{*0} (untagged)
- Use also B_s decays to D_sK (tagged, time-dependent)

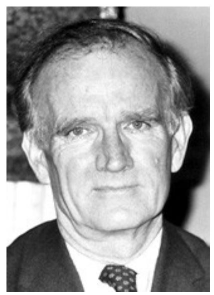
LHCb sensitivity to γ

δ_{B^0} (°)	0	45	90	135	180
σ_γ for 0.5 fb^{-1} (°)	8.1	10.1	9.3	9.5	7.8
σ_γ for 2 fb^{-1} (°)	4.1	5.1	4.8	5.1	3.9

- Numbers assume nominal LHC performance
- Sensitivity to δ_{B0} inherent to $B^0 \to DK^{*0}$ ("quasi-two-body") analysis
- Precision can be further improved:
  - CLEOc results on $D \to K\pi\pi^0$ allow it to be used in ADS analysis
  - $B^0 \to DK\pi$ Dalitz plot analysis gives improved sensitivity to γ with reduced dependence on δ_{B0}

Flavour oscillations, CP violation and Nobel Prizes

- 1964 – Discovery of CP violation in K^0 system
- 1980 – Nobel Prize to Cronin and Fitch

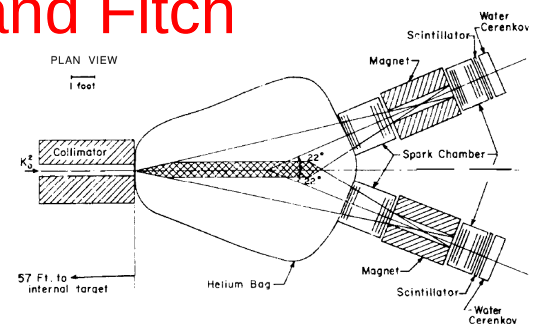


Fig. 1. Plan view of the apparatus as located at the A. G. S.

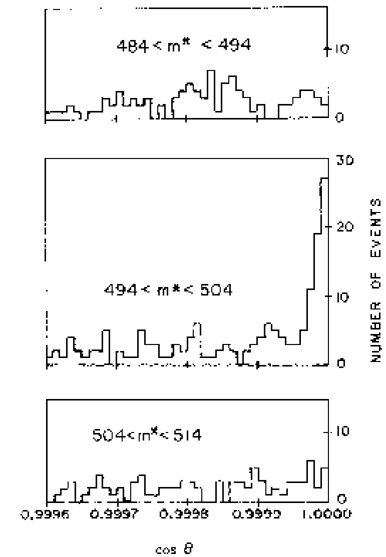
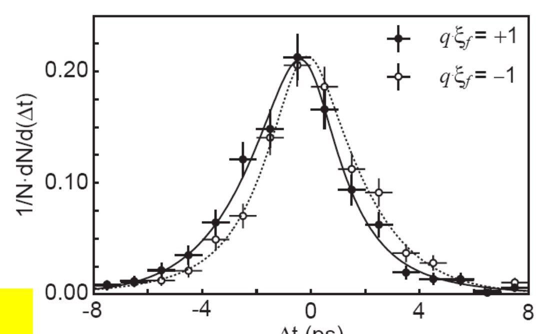


FIG. 3. Angular distribution in three mass ranges for events with cos θ > 0.9995.

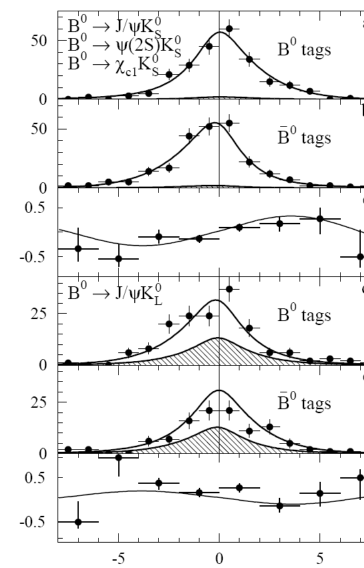
PRL 13 (1964) 138

- 2001 – Discovery of CP violation in B_d system
- 2008 – Nobel Prize to Kobayashi and Maskawa


Prog.Theor.Phys. 49 (1973) 652



Belle PRL 87 (2001) 091802

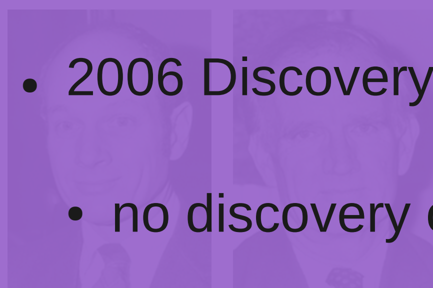


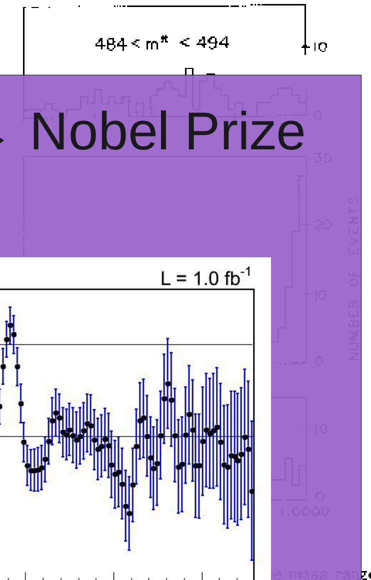
BABAR PRL 87 (2001) 091801

Flavour oscillations, CP violation and Nobel Prizes

- Discovery of oscillations → discovery of CP violation → Nobel Prize
  - can take 30 years

- 1964 – Discovery of CP violation in K system
- 1980 – Nobel Prize to Cronin and Fitch

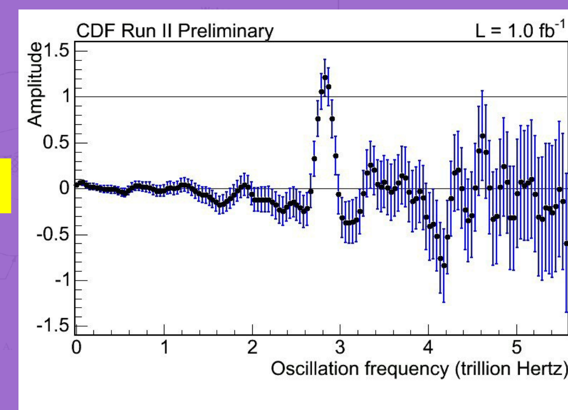




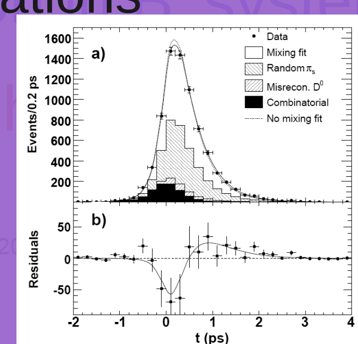
PRL 13 (1964) 138

- 2006 Discovery of B_s oscillations
  - no discovery of CP violation yet

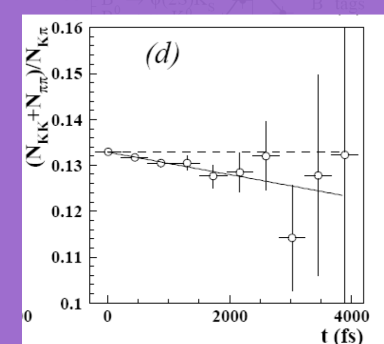
CDF PRL 97 (2006) 242003



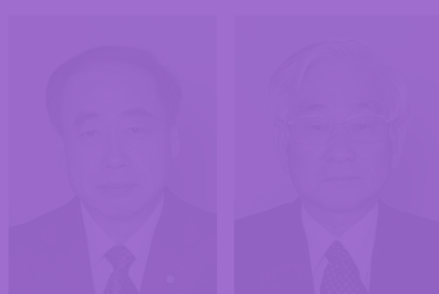
- 2001 – Discovery of CP violation in B system
- 2007 Discovery of charm oscillations
  - no CP violation yet
- 2008 – Nobel Prize to Kobayashi and Maskawa



BABAR PRL 98 (2007) 211802



Belle PRL 98 (2007) 211803



Prog.Theor.Phys. 49 (1973) 652

Belle PRL 87 (2001) 091802

BABAR PRL 87 (2001) 091801

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$
$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} + \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) + \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma \, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \, \sin\left(\Delta m \, t\right) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t}$$
$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} - \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) + \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma \, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \, \sin(\Delta m \, t) \right] .$$

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CP violating asymmetries

CP conserving parameter

$$(A_{CP}^{dir})^2 + (A_{\Delta\Gamma})^2 + (A_{CP}^{mix})^2 = 1$$

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1 + |\lambda_f|^2}{2} \, e^{-\Gamma t}$$

$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} \quad\quad + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma \, t}{2} \quad\quad \right]$$

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$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} \quad\quad + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma \, t}{2} \quad\quad \right] .$$

- Untagged analyses still sensitive to some interesting physics

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t} \times \left[\cosh\frac{\Delta\Gamma\, t}{2} + \boxed{0} \; + \mathcal{A}_{\Delta\Gamma} \sinh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m\, t) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1 + \boxed{0}) \, e^{-\Gamma t} \times \left[\cosh\frac{\Delta\Gamma\, t}{2} - \boxed{0} \; + \mathcal{A}_{\Delta\Gamma} \sinh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m\, t) \right] .$$

- In some channels, expect no direct CP violation
- and/or no CP violation in mixing

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$

$$\times \left[1 + \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m \, t) + 0 + \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m \, t) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t}$$

$$\times \left[1 - \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m \, t) + 0 - \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m \, t) \right] .$$

- In some channels, expect no direct CP violation
- B_d case: $\Delta\Gamma$ negligible

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t} \times \left[1 + \mathcal{A}_{CP}^{dir} \; 1 + \mathcal{A}_{\Delta\Gamma} \; y\Gamma t + \mathcal{A}_{CP}^{mix} \; x\Gamma t \right]$$

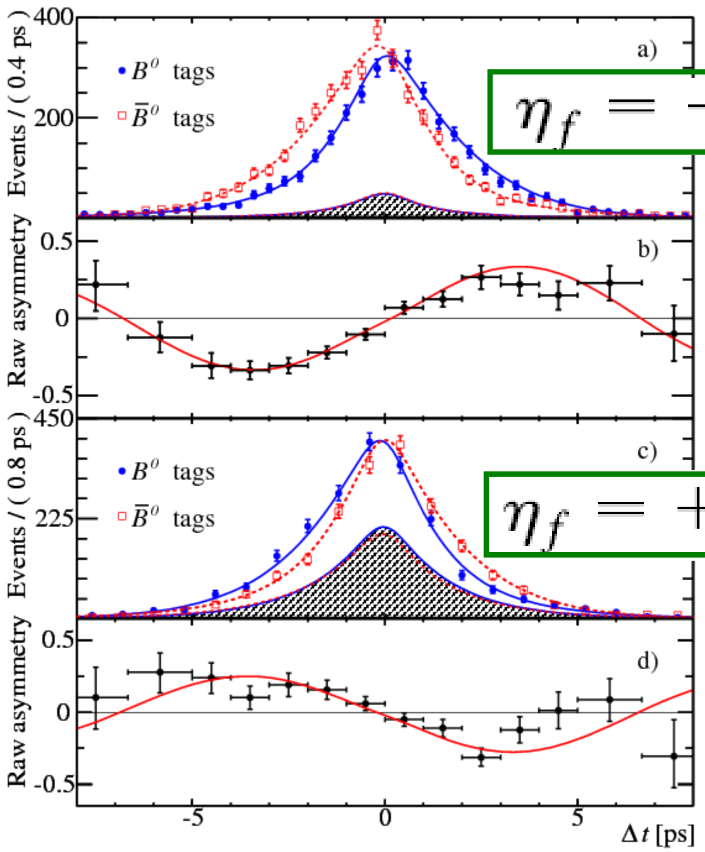
$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t} \times \left[1 - \mathcal{A}_{CP}^{dir} \; 1 + \mathcal{A}_{\Delta\Gamma} \; y\Gamma t - \mathcal{A}_{CP}^{mix} \; x\Gamma t \right] .$$

- In some channels, expect no direct CP violation
- B_d case: ΔΓ negligible
- D^0 case: both x = Δm/Γ and y=ΔΓ/2Γ small

(Almost) latest measurements of β

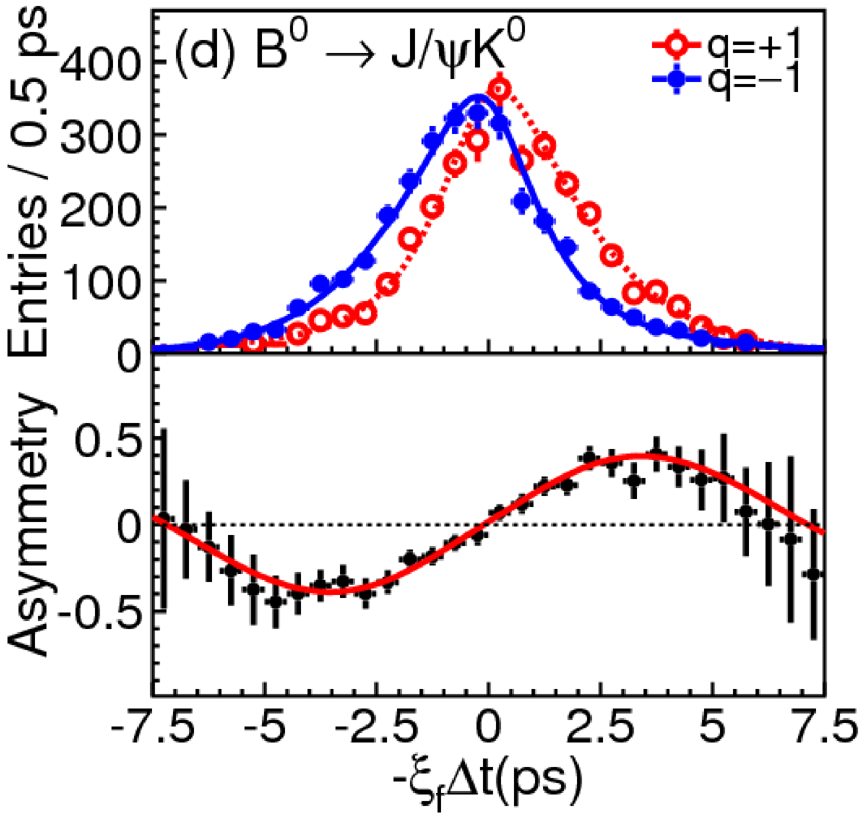
$B^0 \to J/\psi K^0$

BABAR



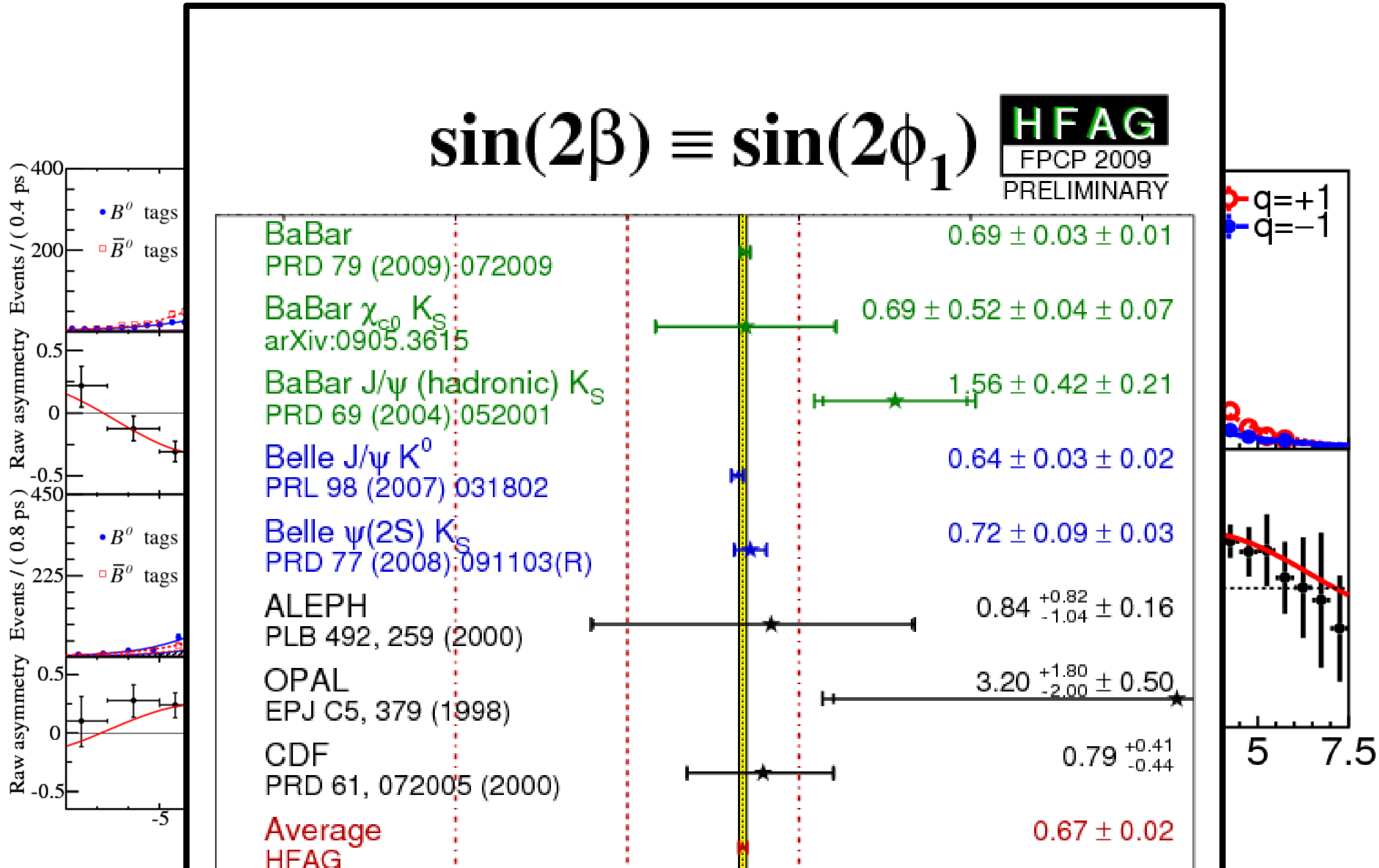
PRL 99, 171803 (2007)

BELLE



PRL 98 (2007) 031802

(Almost) latest measurements of β



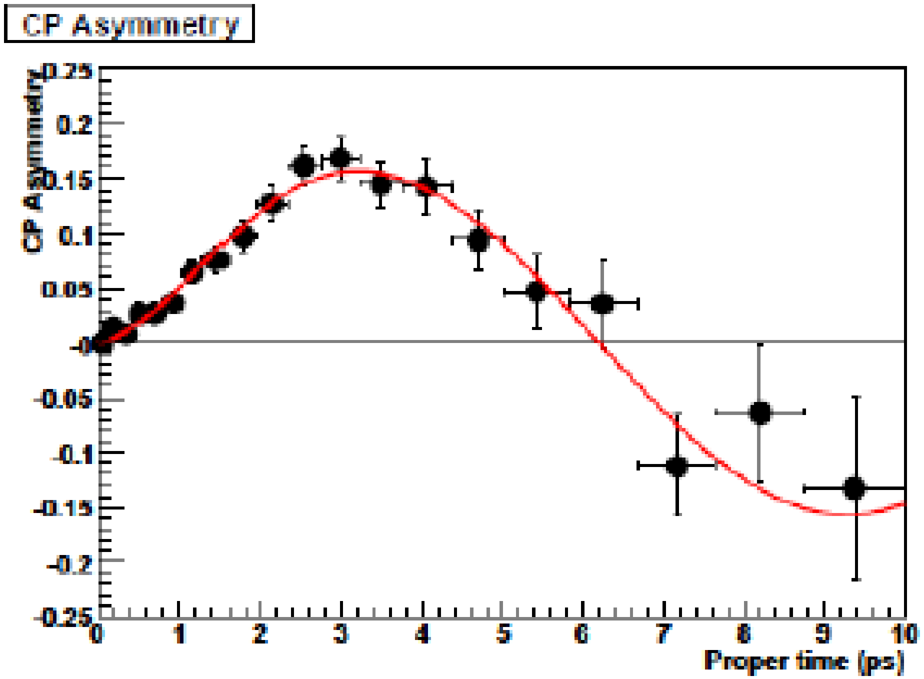
PRL 99 ... **1802**

Tim Gershon

New Physics & CP Violation

LHCb prospects for β

- "Yesterday's sensation is tomorrow's calibration"



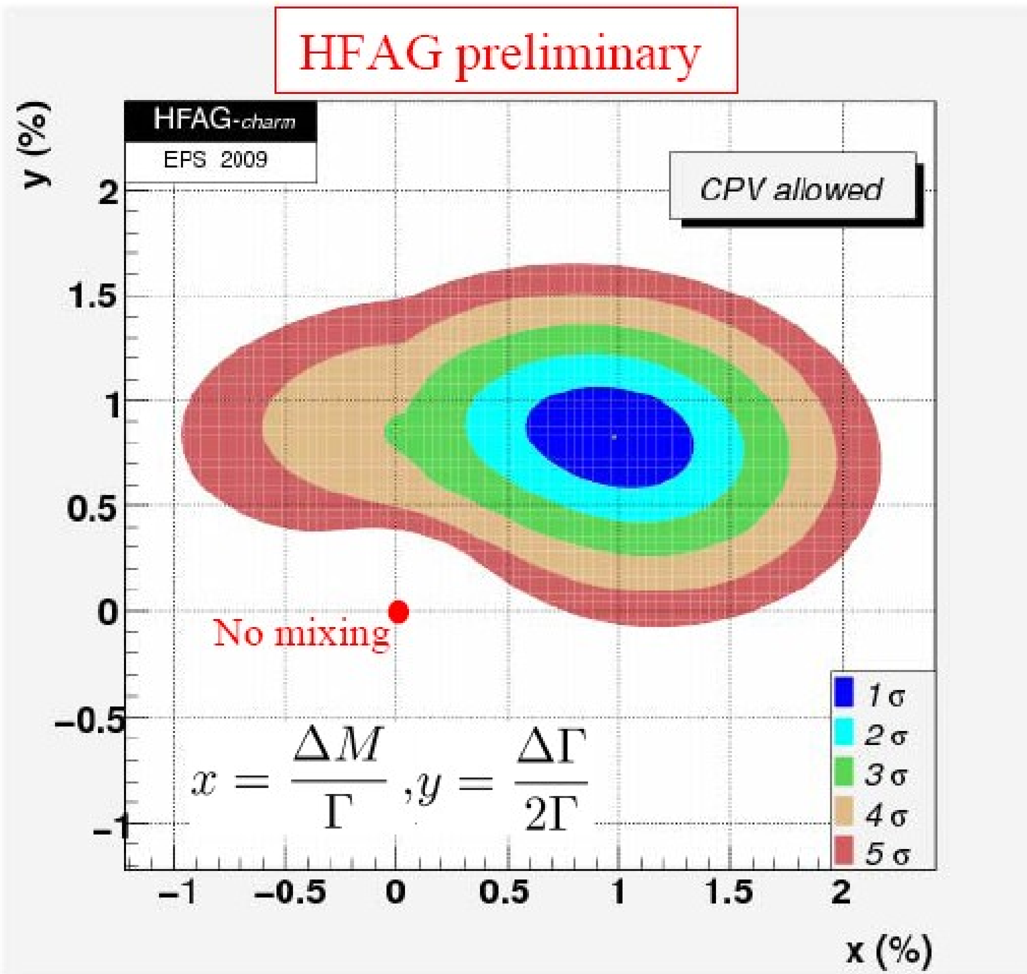
- Sensitivity σ(sin(2β)) ≈ 0.06 with 200/pb of data
- Validate selection, vertexing, resolution, tagging

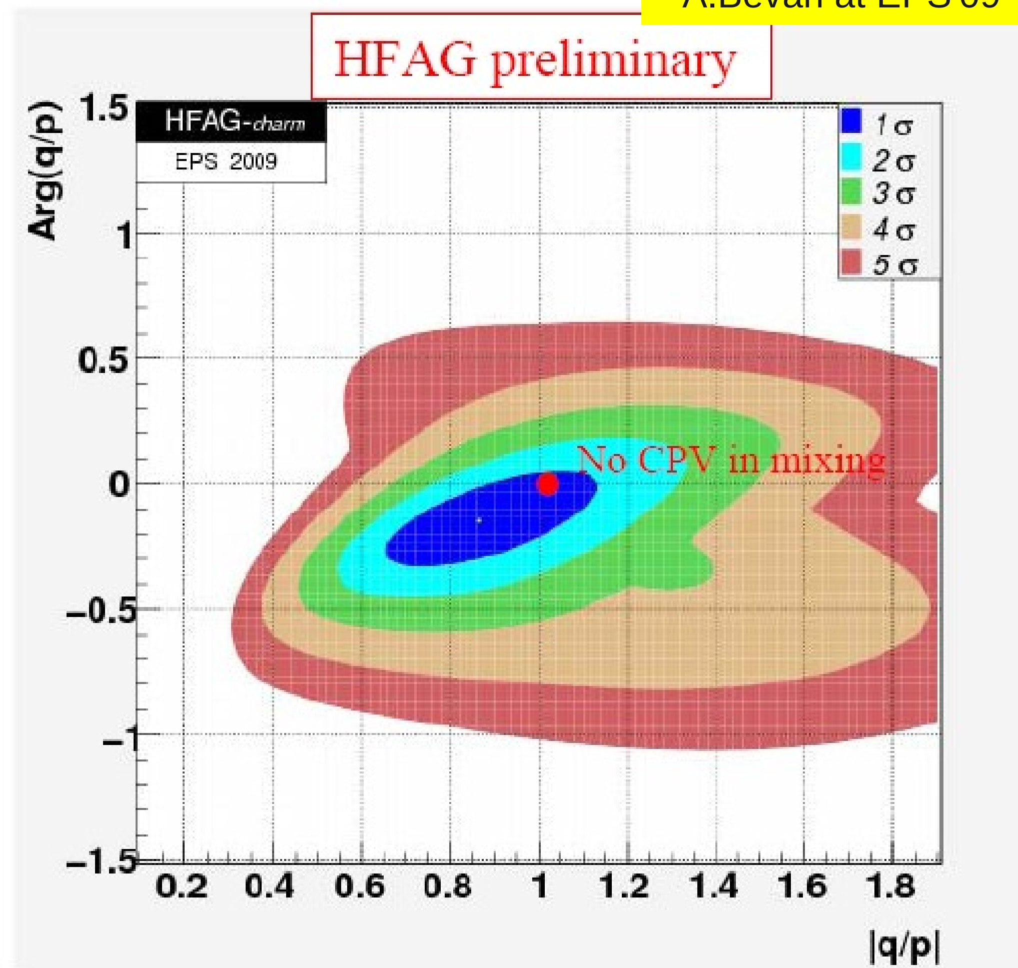
Charm mixing and CP violation

Including results from BABAR, Belle, CDF, CLEO(c), FOCUS

Latest new results Belle arXiv:0905.4185 [hep-ex] BABAR arXiv:0908.0761 [hep-ex]

A.Bevan at EPS'09



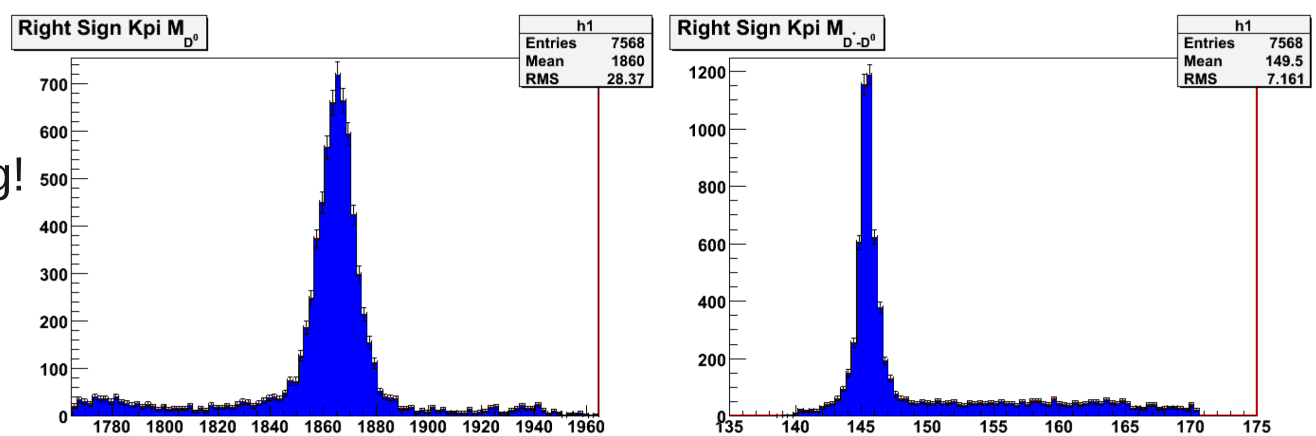


- Mixing established (though still no single measurement > 5σ)
- No indication of CP violation

LHCb Prospects for Charm

- Most sensitive channels
  - $D \to K^+K^-$, π^+K^-, $K_S\pi^+\pi^-$
  - All well-suited to LHCb
- Tagging provided by $D^{*\pm} \to D\pi^\pm$
- Huge cross-section for prompt charm production
  - plus large rates of secondary charm
- With 100/pb accumulate ~ 2.5M tagged $D \to K^+K^-$

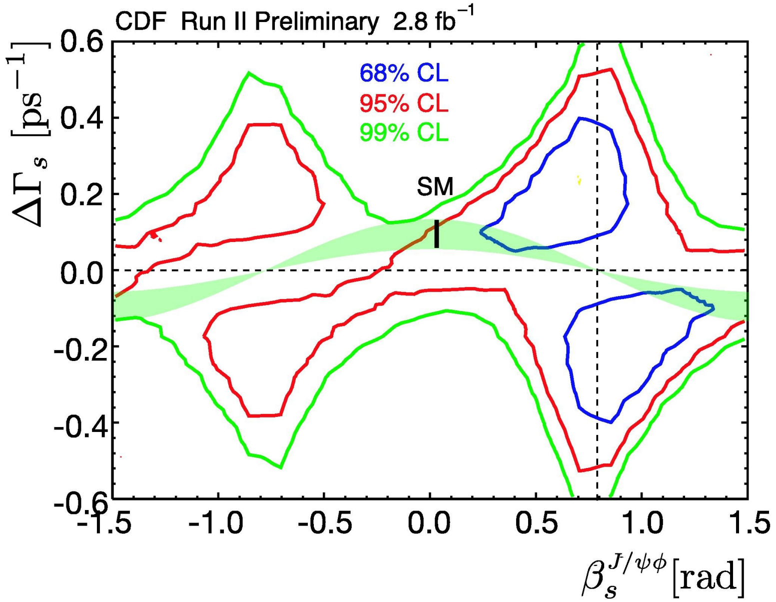
Expected $D \to \pi^+K^-$ yields from 15 minutes of running!



B_s oscillations and CP violation

- Tevatron measurements using tagged $B_s \to J/\psi\phi$
- Angular analyses of vector-vector final state
- Results depend on $\Delta\Gamma$

CDF note 9787



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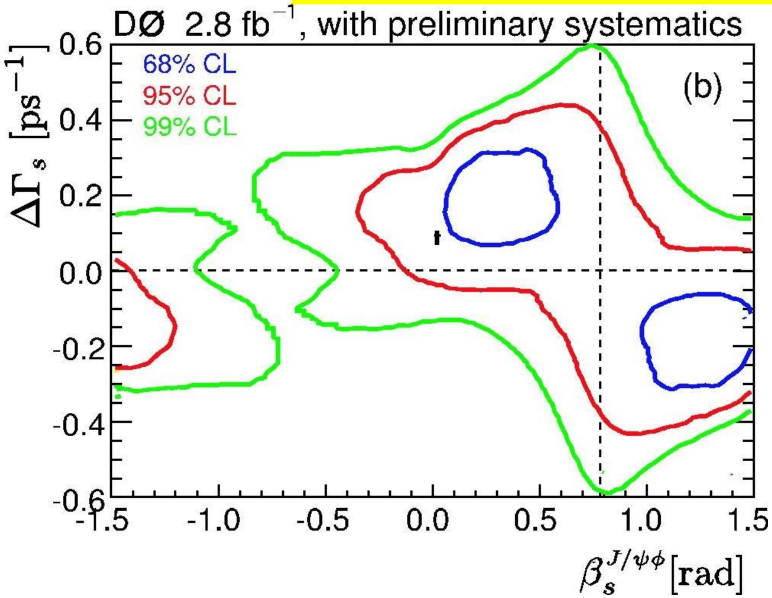
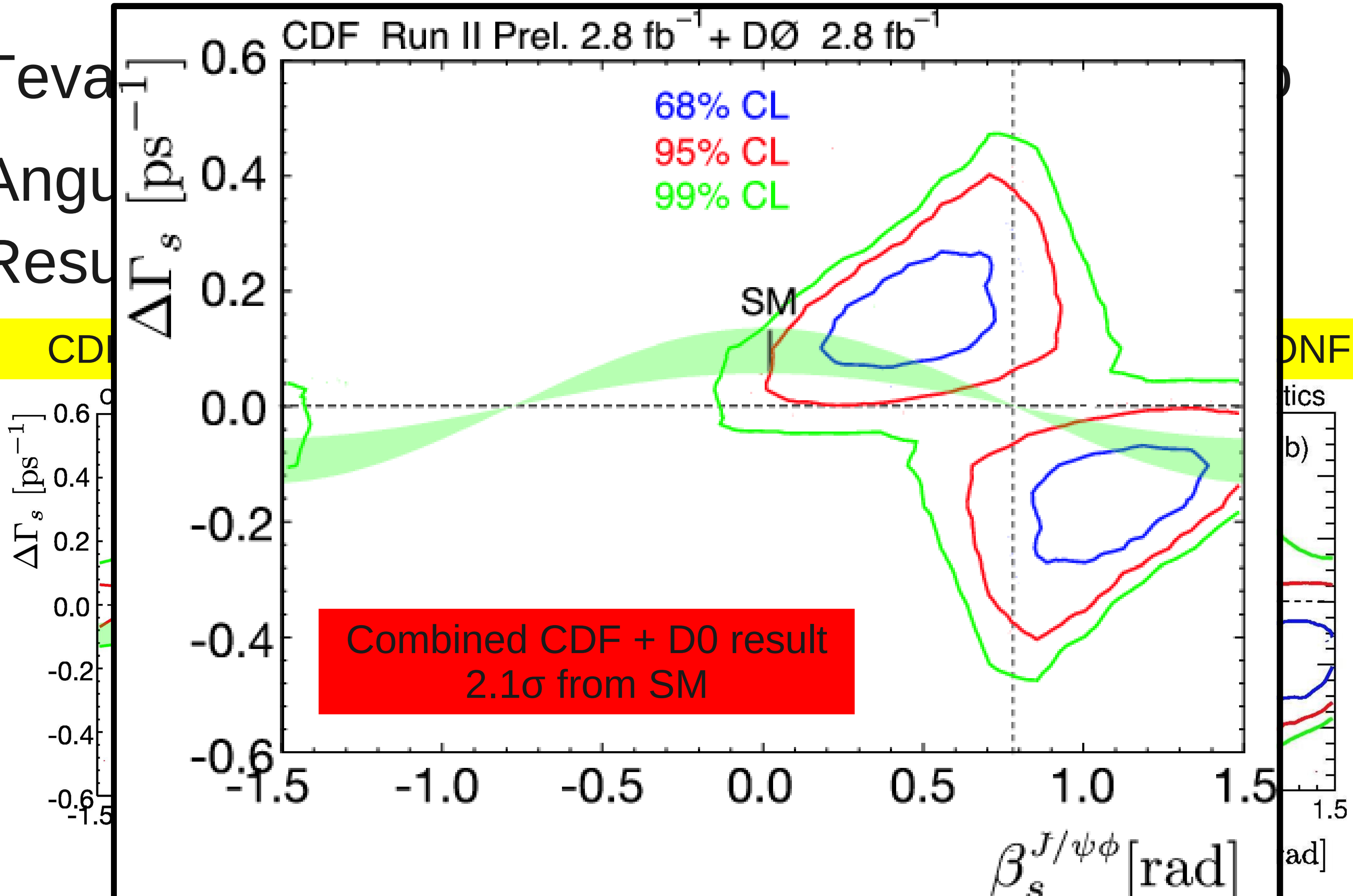


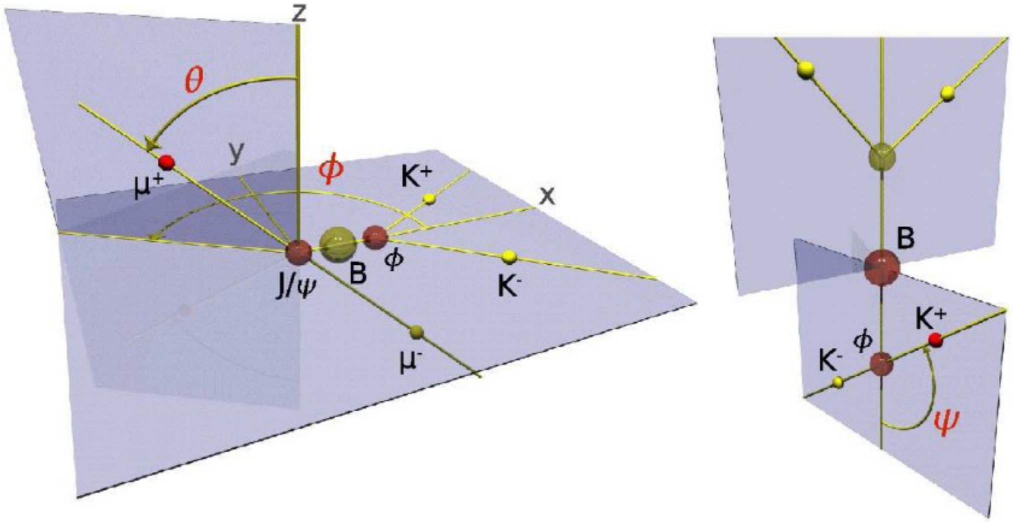
B_s oscillations and CP violation

- Teva…
- Angu…
- Resu…

CD… …ONF

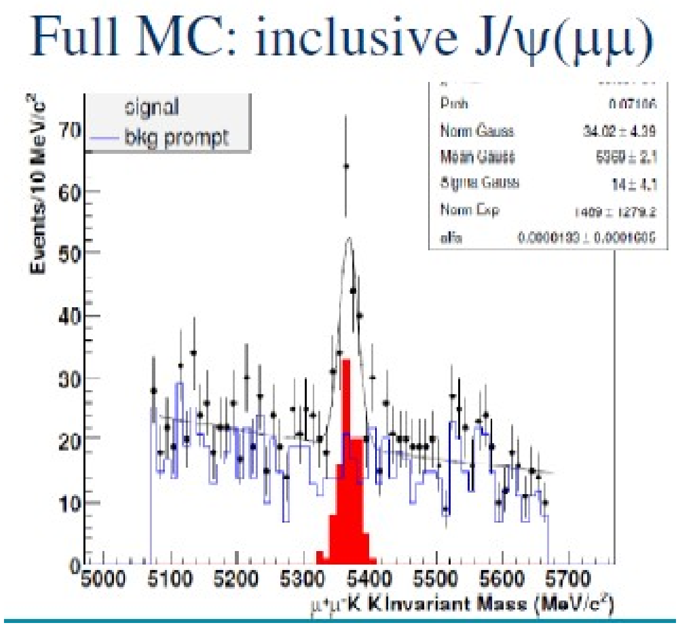


Complications of $B_s \to J/\psi\phi$

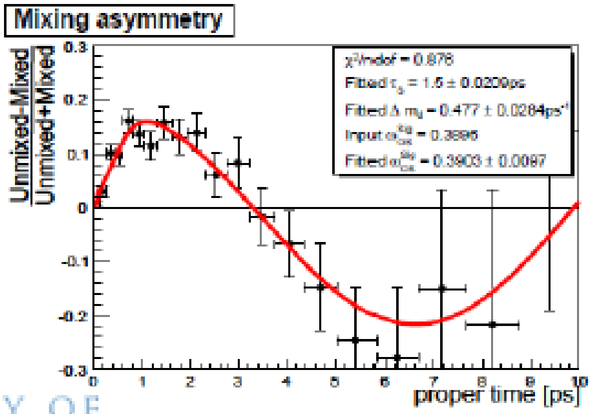


- VV final state
  - three helicity amplitudes – mixture of CP-even and CP-odd
  - can be disentangled using angular & time-dependent distributions → additional sensitivity
- Φ width not negligible
  - contribution from KK S-wave can be handled in the analysis
  - $B_s \to J/\psi f_0$, $f_0 \to \pi\pi$ can also be studied (CP-eigenstate)

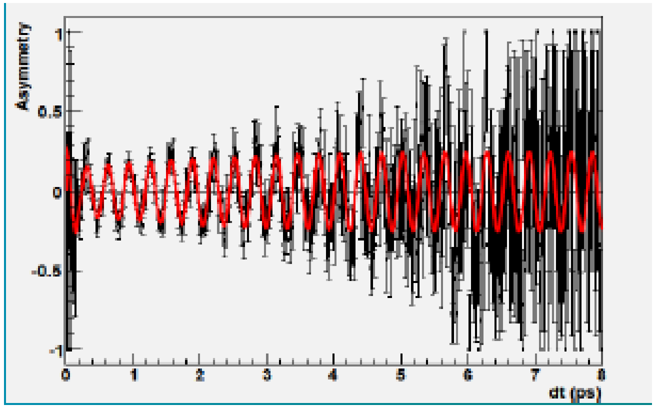
Aspects of $B_s \to J/\psi\phi$ analysis



- Selection
  - $O(10^5)$ signal events/2/fb
  - High efficiency for dimuon trigger
  - Largest background from prompt J/ψ
- Use of control samples
  - Calibrate and validate resolution, acceptance, tagging



$B_d \to J/\psi K^{*0}$

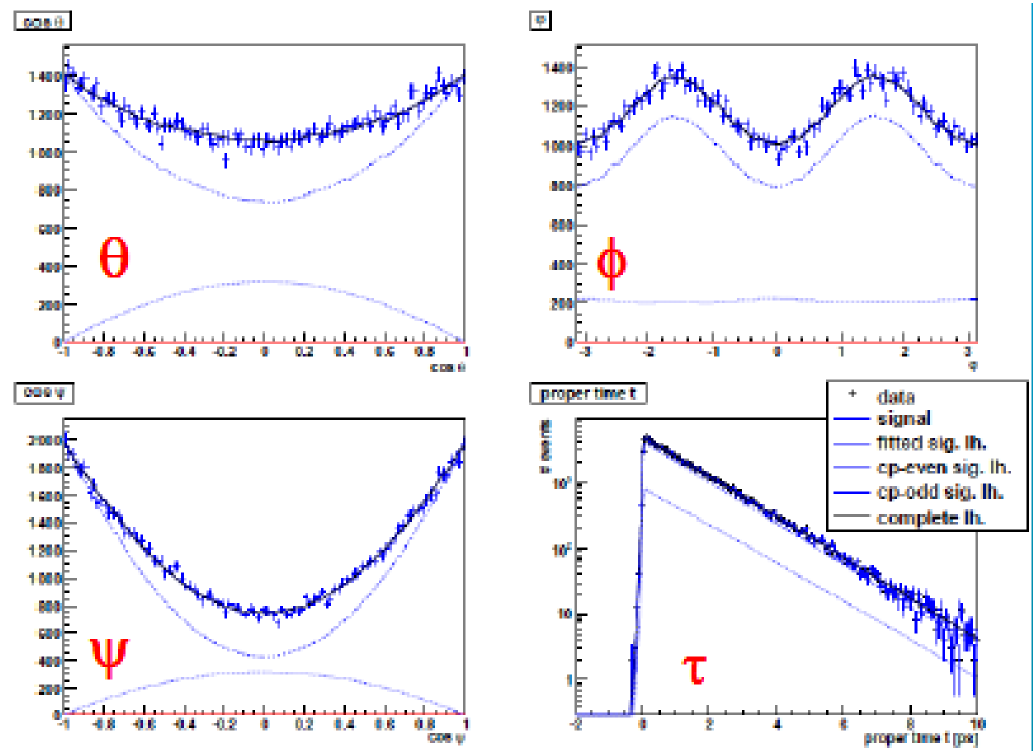


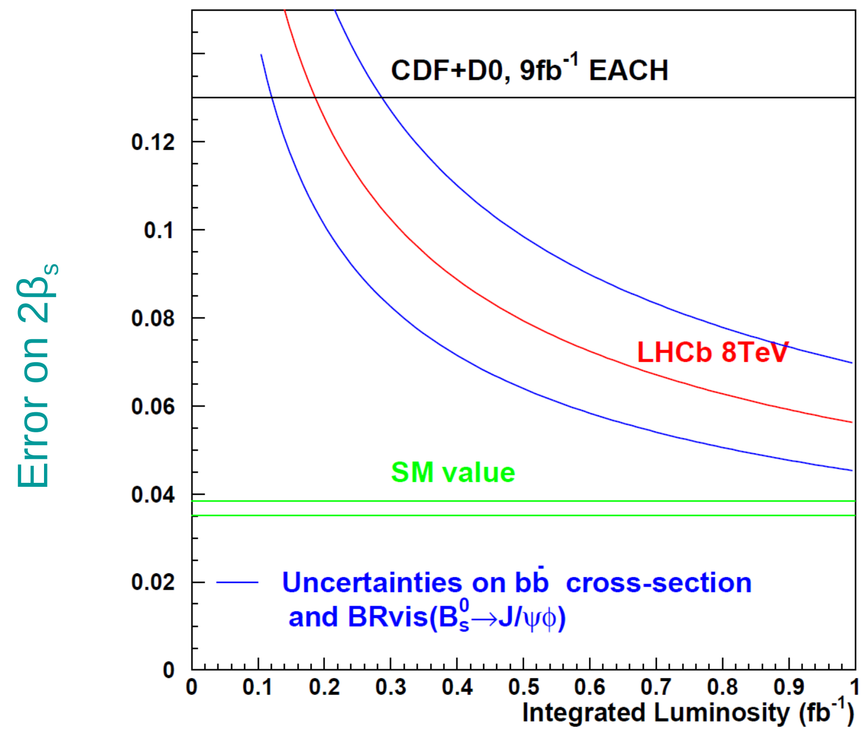
$B_s \to D_s\pi$

Note Δm_s oscillations

Sensitivity to β_s

Expect $\sigma(2\beta_s) \approx 0.03$ from 2/fb

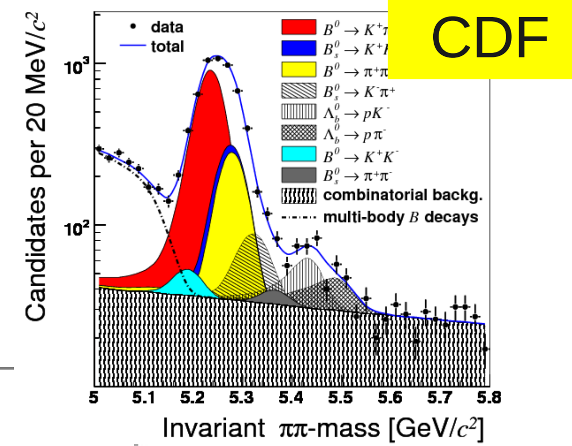




If true β_s value is at current Tevatron central value, can measure it with 200/pb (even with reduced LHC energy)

Alternative approaches to γ, β and β_s

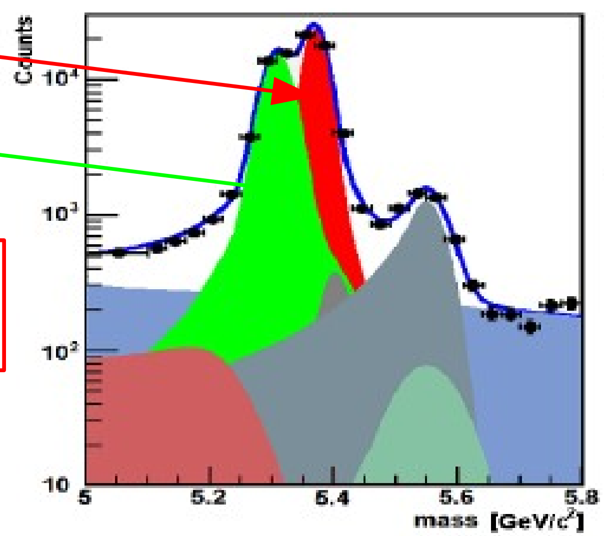
- All methods discussed so far use $b \rightarrow c$ decay transitions
- Search for new physics by testing if $b \rightarrow s$ loop dominated decays give consistent results
- γ: $B_{(s)} \rightarrow hh'$ decays
  - eg. $B_s \rightarrow K^+K^-$ cf. $B_d \rightarrow \pi^+\pi^-$ via U-spin

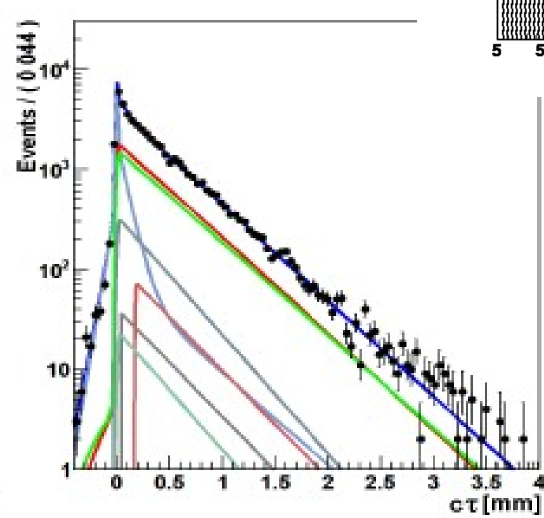


$B_s \rightarrow K^+K^-$

$B_d \rightarrow K^+\pi^-$

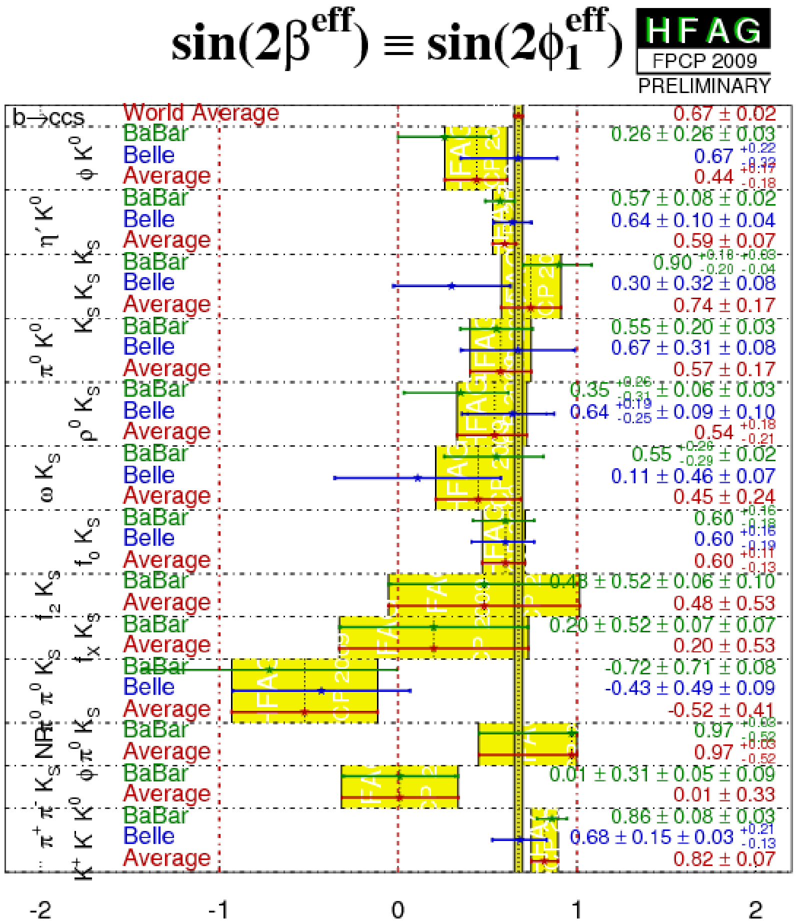
kaon identification applied





Alternative approaches to γ, β and β_s

- All methods discussed so far use $b \to c$ decay transitions
- Search for new physics by testing if $b \to s$ loop dominated decays give consistent results
- β and β_s
  - Promising sensitivity for
    - $B_d \to \varphi K_S$
    - $B_s \to \varphi\varphi$



Conclusion

LHCb well placed to further our understanding of CP violation …

... and, perhaps, to find new phyiscs!

$B_s \to J/\psi\varphi$ formalism

Differential decay rate:

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

Bs | $\overline{\text{Bs}}$

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

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

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

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

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

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

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

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