# CP Violation

*Meeting of the APS Division of Particles and Fields*
*Brown University*
August 13, 2011

*Hassan Jawahery*
*University of Maryland*

# A brief status report

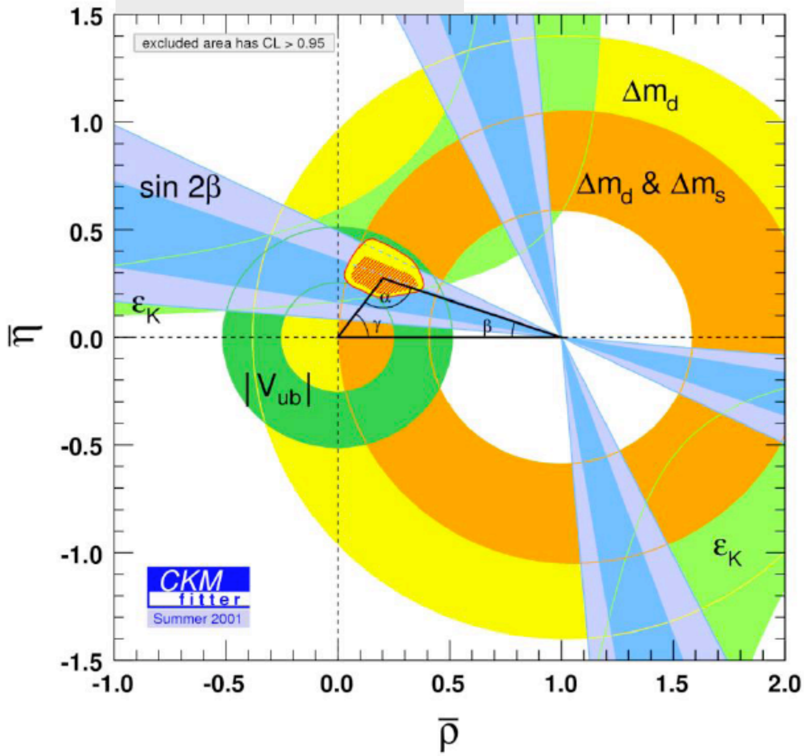
- CP violation remains a rare phenomenon:
  - CPV is observed- so far- only in Weak decays of K and B mesons.
  - No evidence for CPV in the up-quark sector, the lepton sector,… EDM..
  - CPV is required for explaining the matter dominance of the universe

- The existing data are consistent with the Standard Model- the CKM mechanism with a single CPV parameter- as the dominant source of the laboratory observed CPV effects. (Nobel 2008)
  - The conclusion of 5 decades of flavor physics- with enormous progress made in the past decade.

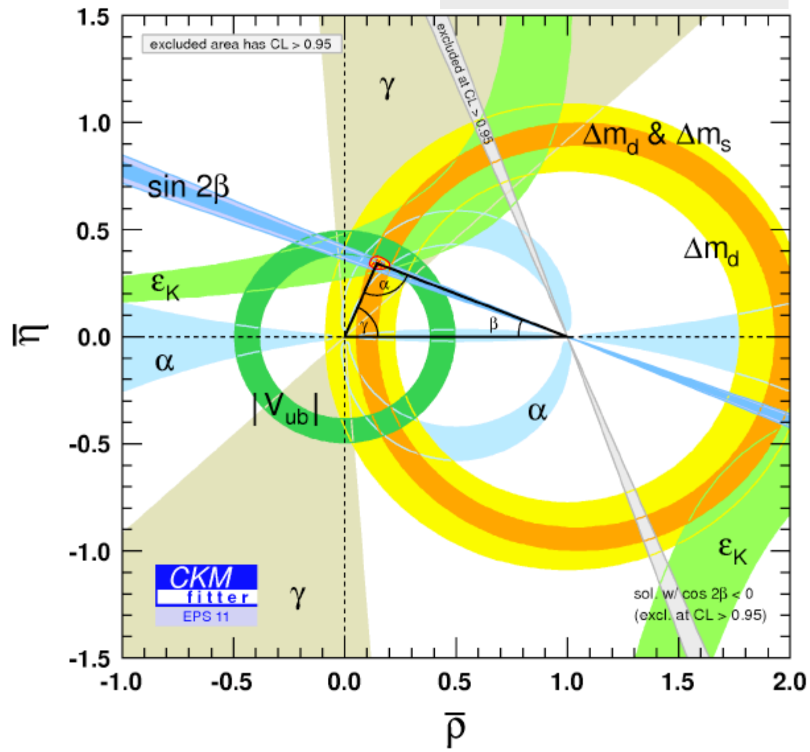
- The search for CPV sources beyond SM remains a major focus of the field, including the LHC, & future Neutrino and Super Flavor expt's.
  - Baryogenesis with SM CPV fails to come up with $n_B/n_\gamma \sim 10^{-10}$
  - Most extensions of SM contain new sources of CPV & the CKM test (now at O(10%) accuracy) allows plenty of room for it.
  - CPV in the neutrino sector is yet to be observed or seriously constrained- the primary goal of the long- baseline neutrino expt's.

Huge progress was made in the past decade
Driven by data at the B factories,Tevatron and the charm factories
and significant theoretical inputs

2001




2011




Figures from Valentin Niess
(CKMfitter) at EPS 2011

# Outline of the talk

- Status of the CKM test:
  - CPV in B decays & measurements of the CKM Unitarity angles
- Search for New Physics in CPV measurements- Anomalies, puzzles,..
  - CPV in $B^0_s$ decays
  - The "Kp" puzzle
  - CPV in loop dominated decays,..
  - CPV in charm decays
- Experimental outlook
- Topics not covered:
  - CPV in Kaons: A very mature field with the major focus now on improved QCD calculations of CPV observables, and current and future experiments on rare decays (See A. Soni's talk at this meeting)
  - CPV in tau decays: Extensive searches, but no evidence of CPV found
  - CPV in neutrino interactions: Covered in other talks

Many excellent talks were given at this meeting on experimental results & theoretical interpretation of the results- including these review talks:

- J. Zupan –CP Violation mini-review (Tuesday)
- A. Soni - Lattice Matrix Elements and CP violation in the LHC era (Wednesday)
- G. Giurgiu, Heavy Flavor at Tevatron (Friday)
- M. Artuso, Heavy Flavor at LHC (Friday)
- W. Wittmer, Status of SuperB Factory Design (Accelerator section,Tuesday)

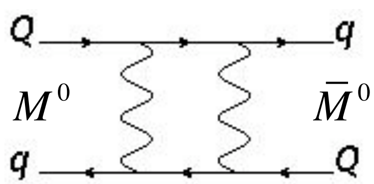
# Manifestation of CP Violation in Meson Decays

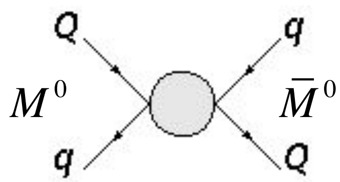
- CP Violation in decay amplitude (Direct CPV)

$$|A(M \to f)| \neq |A(\bar{M} \to \bar{f})|$$

Requires interference of (at least) two amplitudes with different strong (CP conserving) & weak (CP Violating) phases.

- CP Violation in Neutral Meson Mixing:




$$M_H = p|M^0> - q|\bar{M}^0>$$

$$M_L = p|M^0> + q|\bar{M}^0>$$

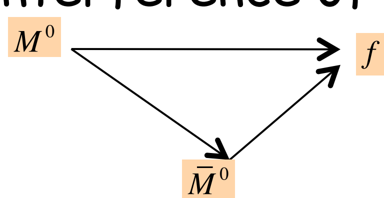
Mass Eigenstates $\neq$ CP Eigenstates

$$|q/p| \neq 1 \qquad \arg(q/p) \neq 0$$

All of these observables are sensitive to New Physics

- NP can interfere with SM amplitude ➔ Direct CPV
- NP can contribute through mixing➔ alter |q/p|, arg(q/p), $|\lambda_f|$ & $\arg(\lambda_f)$

- Interference of Decay and Mixing:



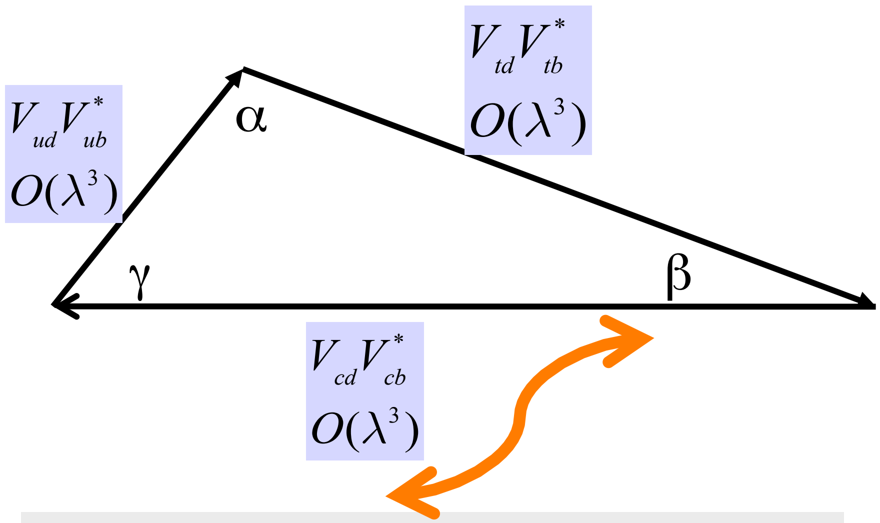

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \neq 0$$

# CP Violation in B decays

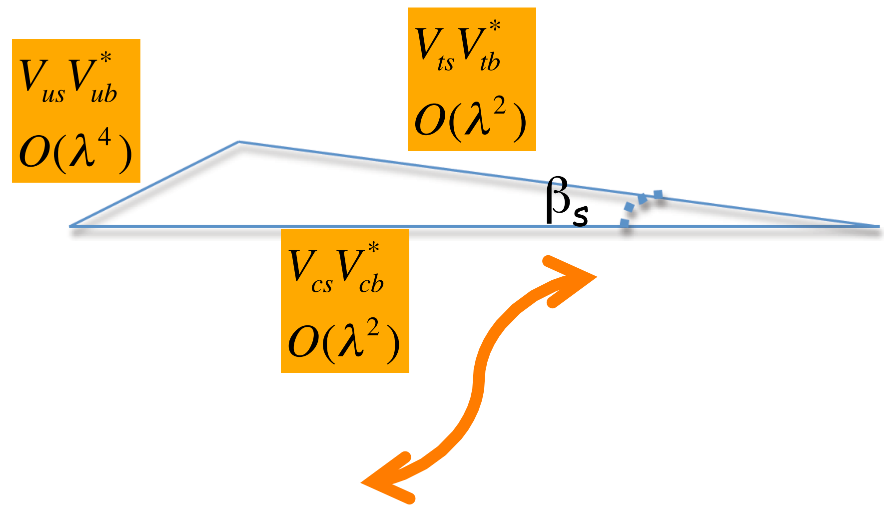
- The ideal system for testing the CKM picture through unitarity triangles.

$$V_{ui}V_{uj}^{*} + V_{ci}V_{cj}^{*} + V_{ti}V_{tj}^{*} = 0 \qquad (i \neq j)$$

$B_d$ triangle



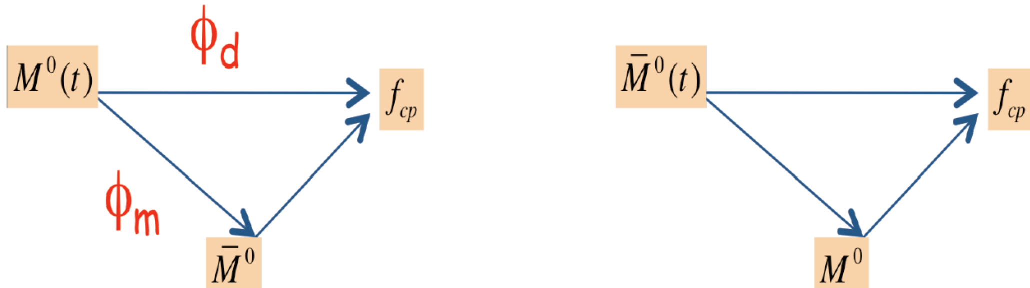

$B_s$ triangle




Experimentally the most accessible triangle- with large angles: $\beta$~23°
==> large indirect CPV in $B_d$ decays.
Ideal for testing the CKM picture

A nearly flat triangle: $\beta_s$ ~1°
small indirect CPV in $B_s$ decays.
An opportunity for NP searches

# “Golden” CPV observables: Time-Dependent CPV



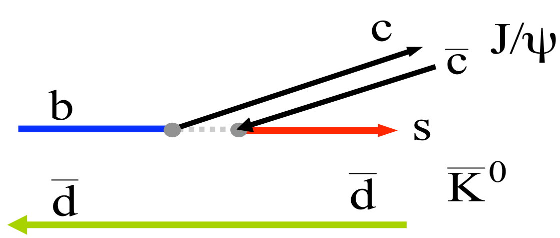

$$A_{cp}(t) = \frac{\Gamma(M^0(t)\to f_{cp}) - \Gamma(\bar{M}^0(t)\to f_{cp})}{\Gamma(M^0(t)\to f_{cp}) + \Gamma(\bar{M}^0(t)\to f_{cp})} =$$

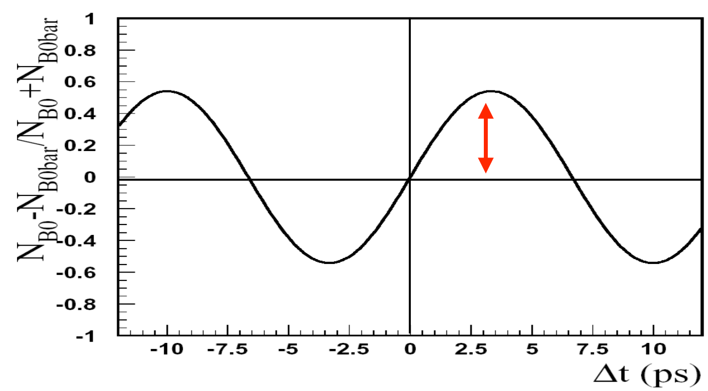
$$= S_{f_{cp}} \sin\Delta mt - C_{f_{cp}} \cos\Delta mt$$

In a few special cases, all hadronic parameters in the amplitude ratio cancel

$$S_f = \mathrm{Im}(\eta_{cp}\frac{q}{p}\frac{\bar{A}_f}{A_f}) = \eta_{cp}\sin(\phi_m+\phi_d)\sin\Delta mt$$

e.g. $f_{cp}$ $B_d \to J/\psi\, K^0_s$ or $B_s \to J/\psi\phi$ (with angular analysis) ($\beta_s$)

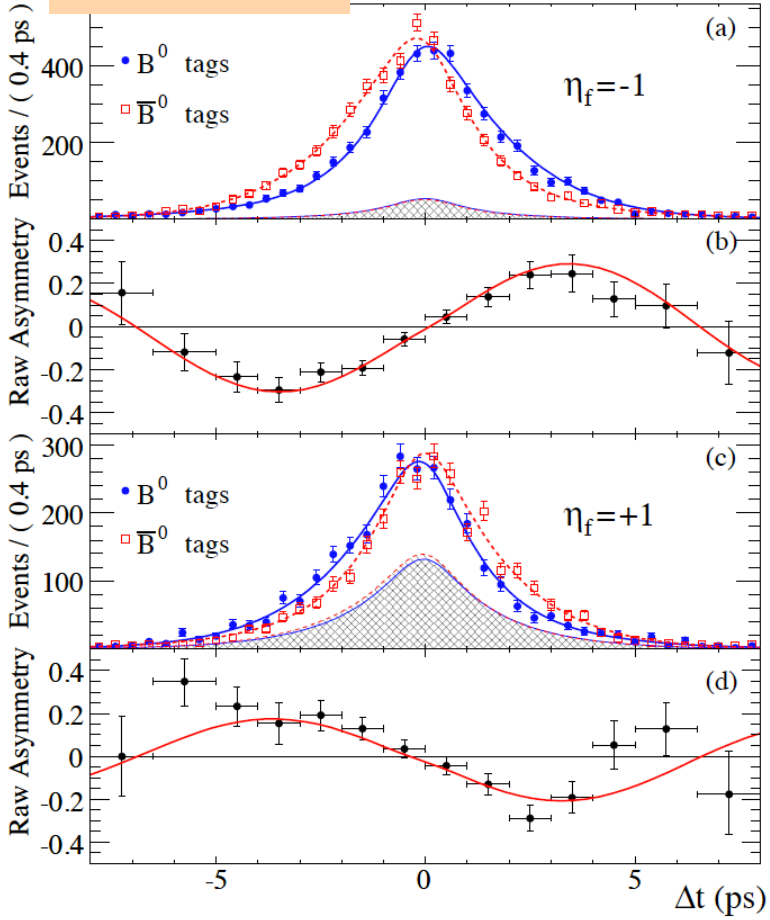


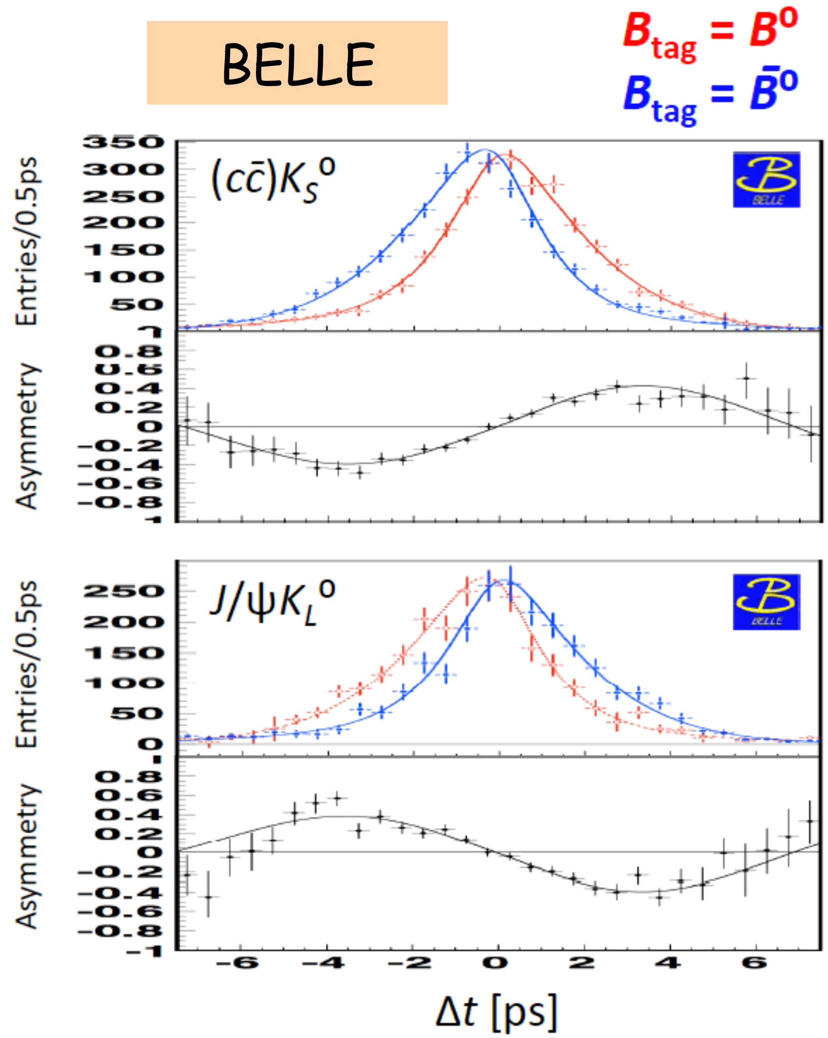

$$\phi_m + \phi_d = 2\beta$$
$$A_{CP}(t) = \sin 2\beta \sin(\Delta mt)$$

# Measurement of sin2β at the B factories via $B^0 \to c\bar{c}\, K^0$

BABAR



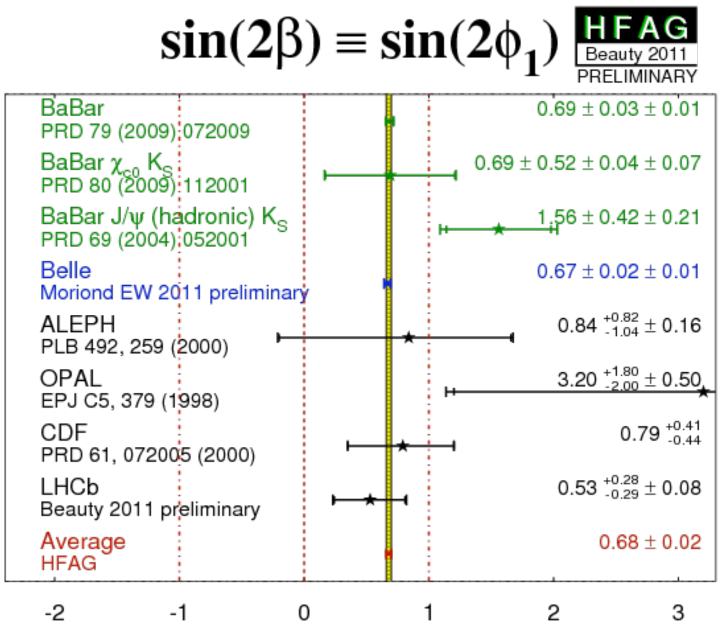

BELLE



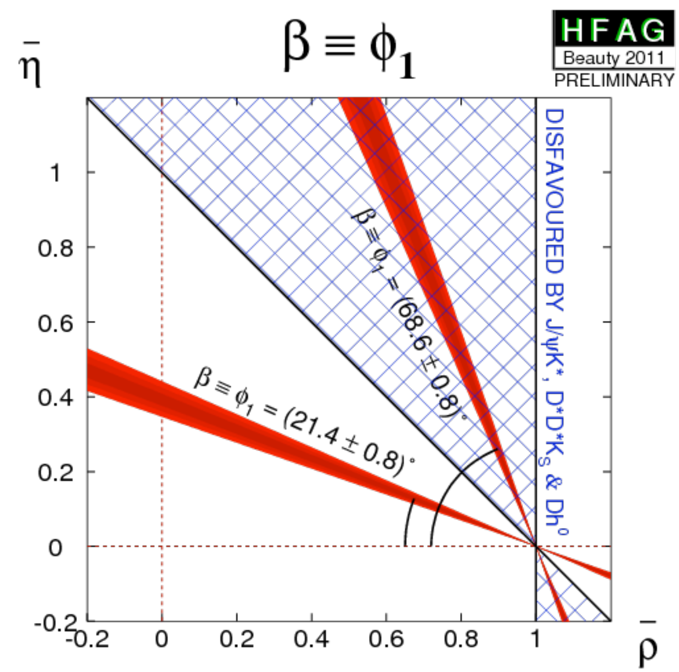

$$\sin 2\beta = 0.678 \pm 0.020$$

# Measurement of sin2β

- B factories have probably said their "final" word on $\beta(\phi_1)$




$$\beta = (21.4 \pm 0.8)^o$$

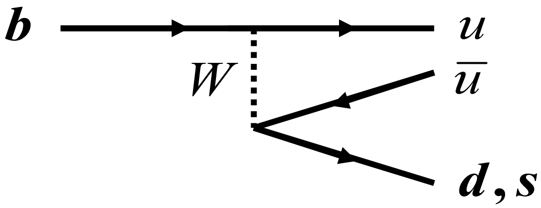



The other solution- disfavored at >3σ

It will be a while before there is further improvement in the precision of sin2β

# Measurement of the angle $\alpha$

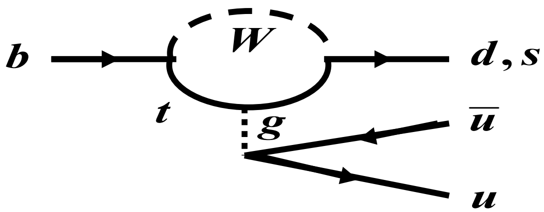
- The b->u dominated decays, [$B \rightarrow \pi\,\pi$: ($\pi^+\pi^-$, $\pi^+\pi^0$, $\pi^0\pi^0$ ), $\rho\pi$, $\rho\rho$] serve as the "golden" modes for measuring $\alpha$




$$\lambda = \eta \frac{V_{tb}^* V_{td} V_{ub} V_{ud}^*}{V_{tb} V_{td}^* V_{ub}^* V_{ud}} = e^{i2\alpha}$$

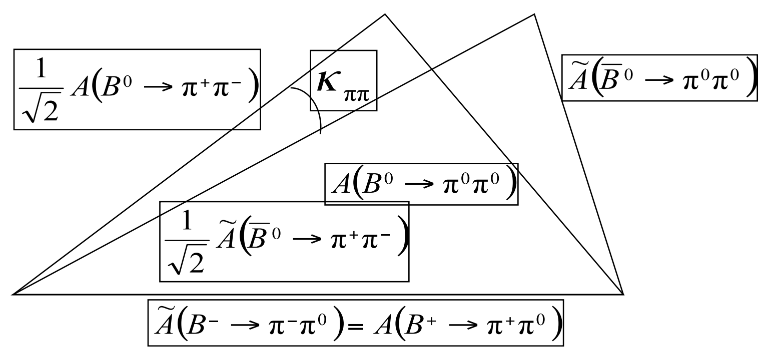
$$C = 0 \qquad \& \qquad S = \sin(2\alpha)$$

But in reality there are other contributors, which complicate life:



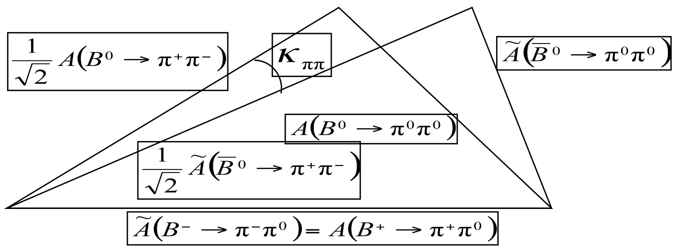

$$\lambda = e^{2i\alpha} \frac{1+|\frac{P}{T}|e^{i\delta}e^{i\gamma}}{1+|\frac{P}{T}|e^{i\delta}e^{-i\gamma}}$$

Isospin analysis comes to the rescue:
Need all elements of $B^0$ and $B^0 \rightarrow \pi\pi$
$\rightarrow$ $\alpha$ with 8- fold ambiguity [Gronau & London]



# Measurement of the angle α

Br& CPV in B→ππ

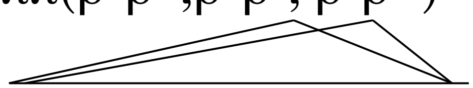


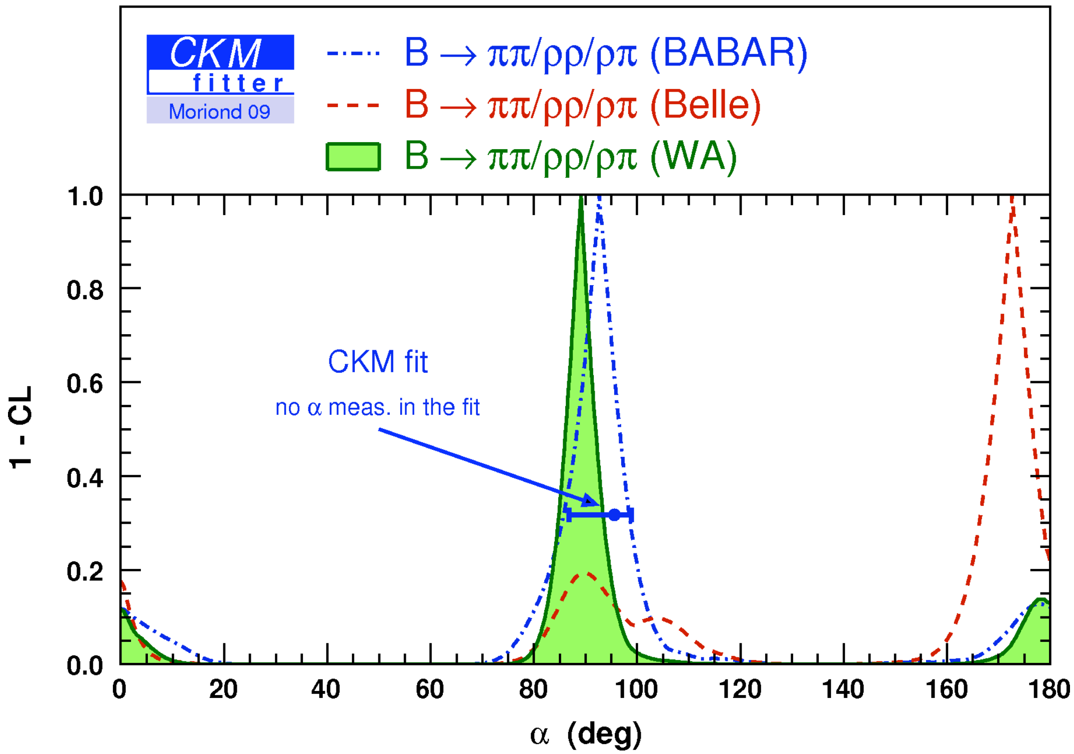

The full Time-dependent Dalitz Analysis of

B→πππ($\rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$, $\pi^+\pi^-\pi^0$ )

The entire B→ρρ components for isospin analysis & Time-dependent CPV

B→πππ($\rho^+\rho^-$, $\rho^+\rho^0$, $\rho^0\rho^0$ )

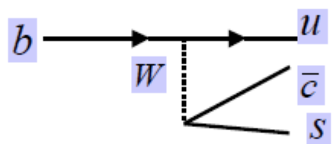





$$a = (89.0^{+4.4}_{-4.2})^o$$

# Measurement of $\gamma$

$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ is measured by exploiting direct CPV in modes involving :
b->c & b->u - Tree level processes unaffected by NP.

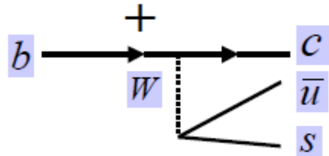



$\propto A\lambda^3(\rho + i\eta)$

$B^- -> \bar{D}^0 K^-$

$\gamma+\delta_u$

+




$\propto A\lambda^3$

$B^- -> D^0 K^-$

$\delta_c$

f - common to $D^0$ & $\bar{D}^0$

Rare processes with effective $Br \sim 10^{-7}$

$$\boxed{A[B^- \to (D \to f)K^-] = A_c A_f e^{i(\delta_c + \delta_f)} + A_u A_{\bar{f}} e^{i(\delta_u + \delta_{\bar{f}} - \gamma)}}$$

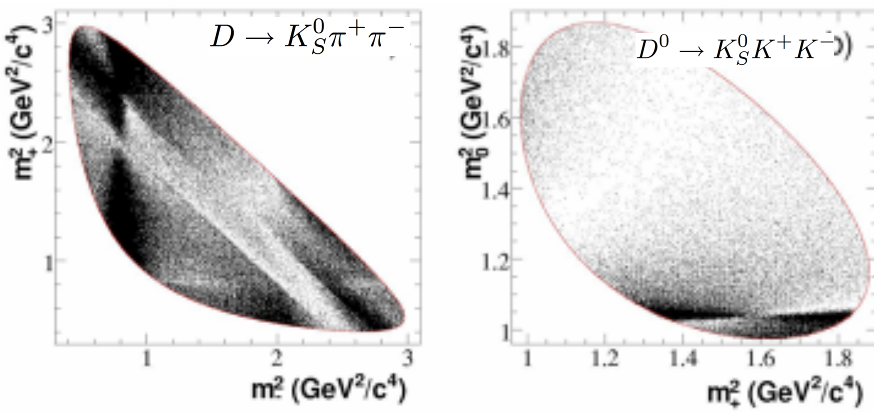
$$r_B = \left| \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right|$$

Rates and CP asymmetries depend on $\gamma$, $r_B$ & strong phases $\delta_B = \delta_u - \delta_c$ & $\delta_D = \delta_f - \delta_{\bar{f}}$

- D->$f_{cp}$ ($K^+K^-$, $\pi^+\pi^-$, $K^0_s\pi^0$...) (GLW- Gronau, London, Wyler)
- D→Cabibbo Favord (b->u) & Doubly Cabibbo suppressed Decay (b->c) (ADS – Atwood, Dunietz, Soni) [ Belle, LHCB, CDF now report obs. of the suppressed decay]
- D->3-body ($K_s\pi^+\pi^-$, $K_sK^+K^-$) – Dalitz analysis –combining both features – (GGSZ-Giri, Grossman, Soffer, Zupan)
- Extract $\gamma$, $r_B$, $\delta_B$ from data
  - Needs external input for $\delta_d$ (ADS & GGSZ) - a major sources of uncertainty

# Measurement of $\gamma$ – GGSZ method

Currently the measurememt of $\gamma$ is dominated by GGSZ method:
Dalitz analysis of D->3-body ($K_s\pi^+\pi^-$, $K_sK^+K^-$)



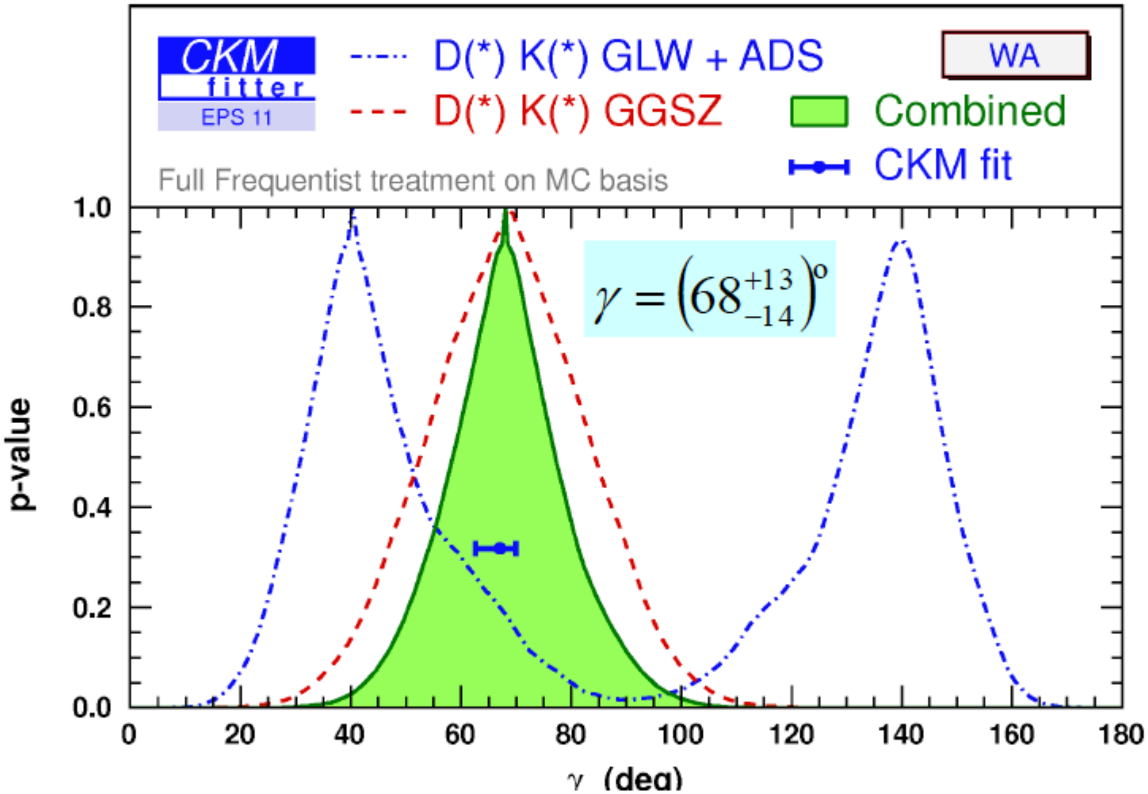

•Inteference in certain regions- dominated by resonances- provides sensitivity to $\gamma$

•Strong phase $\delta_D$ vary across the Dalitz plot- requires a model or independent binned measurements.

•BABAR: modeled the phase & amplitude of resonances across DP (Isobar model): $\gamma == (68 \pm 14 \pm 4 \pm 3(\mathrm{mod}\,el))^o$

•Recent Belle results use CLEO-c's binned- model independent-info on D decay phase across DP: $\gamma == (77.3^{+15.1}_{-14.9} \pm 4.2 \pm 4.3(phase))^o$

# Measurement of γ




- The next major experimental improvement on γ to come from LHCb
  - Hadron machines have access to a new γ-sensitive channel: $B_s \rightarrow K^+K^-$ - Use of U-spin symmetry of strong interactions connect with $B_d \rightarrow \pi^+\pi^-$ to extract both γ and strong interaction parameters.

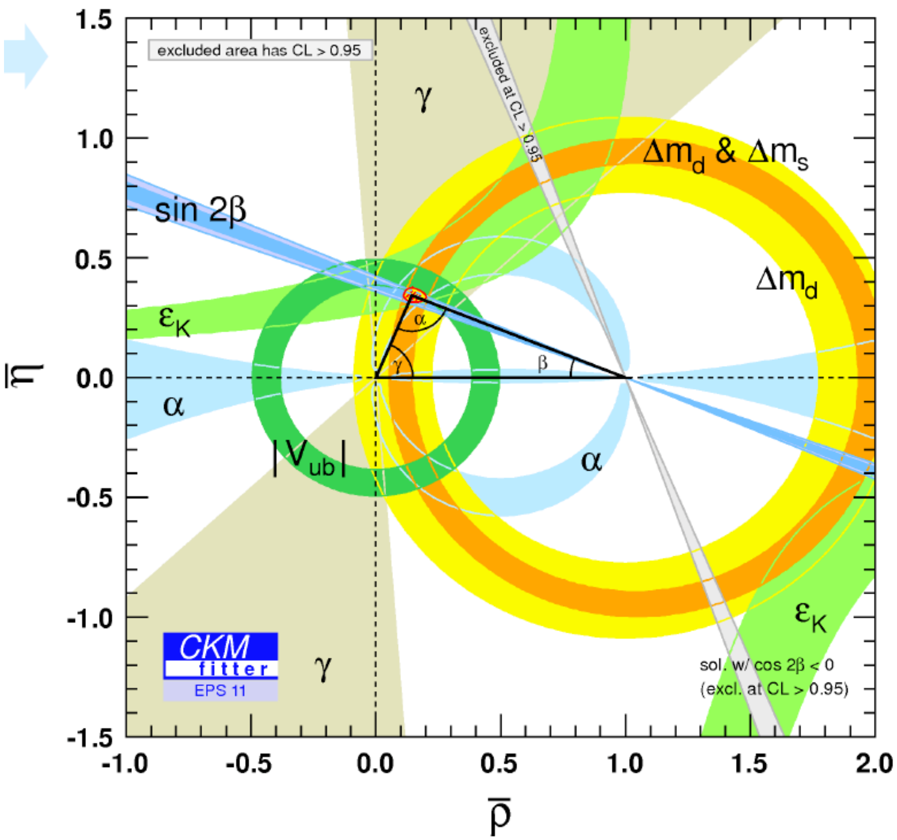
  - Consistency of γ measurements from different channels provides a check on NP contributions.

# Status of the CKM picture

All is well with the CKM picture at O(10%) level:

- Unitarity triangle passes the test: $\alpha + \beta + \gamma = (178.4 \pm 14.7)^o$

- Direct measurements of the UT are consistent with the expected values from CP conserving quantities.




| Direct | CKM fit |
|---|---|
| $\alpha = \left(89.0^{+4.4}_{-4.2}\right)^o$ | $\left(97.0^{+1.6}_{-8.1}\right)^o$ |
| $\beta = \left(21.4 \pm 0.8\right)^o$ | $\left(28.07^{+0.69}_{-1.69}\right)^o$ |
| $\gamma = \left(68^{+13}_{-14}\right)^o$ | $\left(67.2^{+3.9}_{-3.9}\right)^o$ |

CKMFitter: $\bar{\rho} = 0.144^{+0.027}_{-0.018}$

$\bar{\eta} = 0.343 \pm 0.014$

Some tension is present

$\sin 2\beta = 0.678 \pm 0.02(meas) \qquad 0.832^{+0.013}_{-0.033}(fit) \quad (2.7\sigma)$

Driven by $V_{ub}$ from B->$\tau\nu$

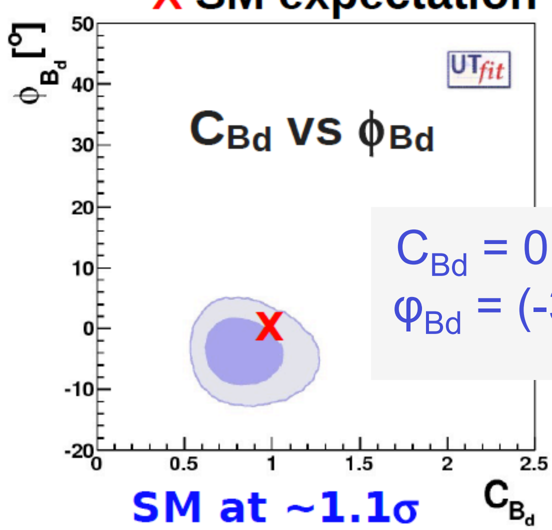
A motivation, along with other anomalies for 4-generation model of Lunghi & Soni

# Any room for CPV beyond SM?

Model independent approach -if NP enters through mixing amplitude:
(Utfit & CKMfitter)

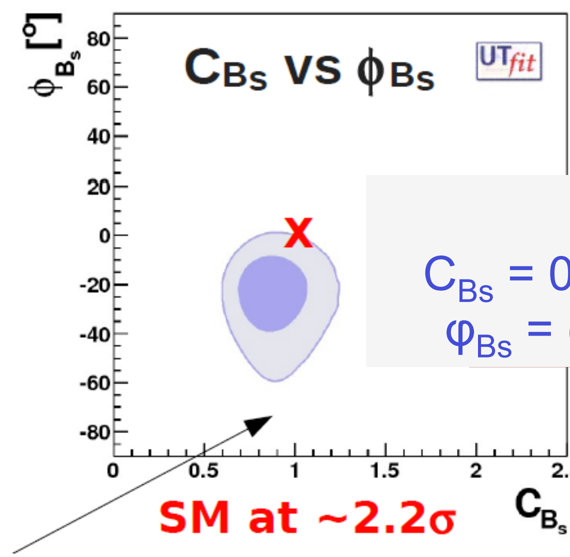
$$C_{B_q} e^{2i\varphi_{B_q}} = \frac{< B_q \mid H_{eff}^{Full} \mid \overline{B}_q >}{< B_q \mid H_{eff}^{SM} \mid \overline{B}_q >}$$

$$SM : C_{B_q} = 1 \qquad \varphi_{B_q} = 0$$




$C_{Bd}$ = 0.82 ± 0.14
$\varphi_{Bd}$ = (-3.9 ± 3.6)°

M. Bona (EPS 2011)




$C_{Bs}$ = 0.87 ± 0.12
$\varphi_{Bs}$ = (-23 ± 10)°

While there is room for CPV beyond SM, the allowed amplitude is not large (~SM)

What does this mean for NP? (see e.g, Grossman, Ligeti, Nir (arXiv: 0904.4262) M. Bona et al (UTfit) hep-ph-0509219, Y. Nir arXiv:0708.1872) ,also Lunghi& Soni arXiv:0807.1971 (fourth generation possibility)

- Strong constraints on flavor changing couplings in NP, or alternatively for generic flavor couplings, constraint on the energy scale of NP (>> TeV)

# Search for CPV Beyond SM

$B^0_s$ System

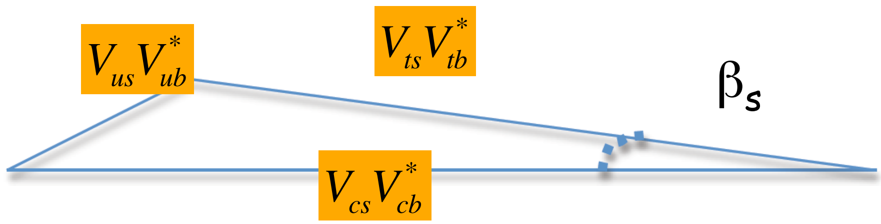
Direct CPV in B decays

CPV in Loop dominated B Decays

CPV in charm decays

# CPV in $B^0_s$ Decays

Key Observable in the $B^0_s$ system




SM: $\beta_s \sim$ 0.02 (~1°)

$\Delta M_s \qquad \Delta\Gamma_s$

$$a^s_{sl} = \frac{\Gamma(B^0_s \to l^+\nu_l X) - \Gamma(\bar{B}^0_s \to l^-\bar{\nu}_l X)}{\Gamma(B^0_s \to l^+\nu_l X) - \Gamma(\bar{B}^0_s \to l^-\bar{\nu}_l X)} = \frac{\Delta\Gamma_s}{\Delta M_s}\tan\phi^M_s$$

$\phi^M_s \sim 0.004$

$$a^s_{sl}(SM) = (2.06 \pm 0.57) \times 10^{-5}$$

For NP contribution through mixing

$$\varphi_s = \varphi_s^{SM} + \varphi^{NP} \approx \varphi^{NP} \approx -2\beta_s \qquad a^s_{sl} \approx \frac{\Delta\Gamma_s}{\Delta M_s}\tan\phi_s$$

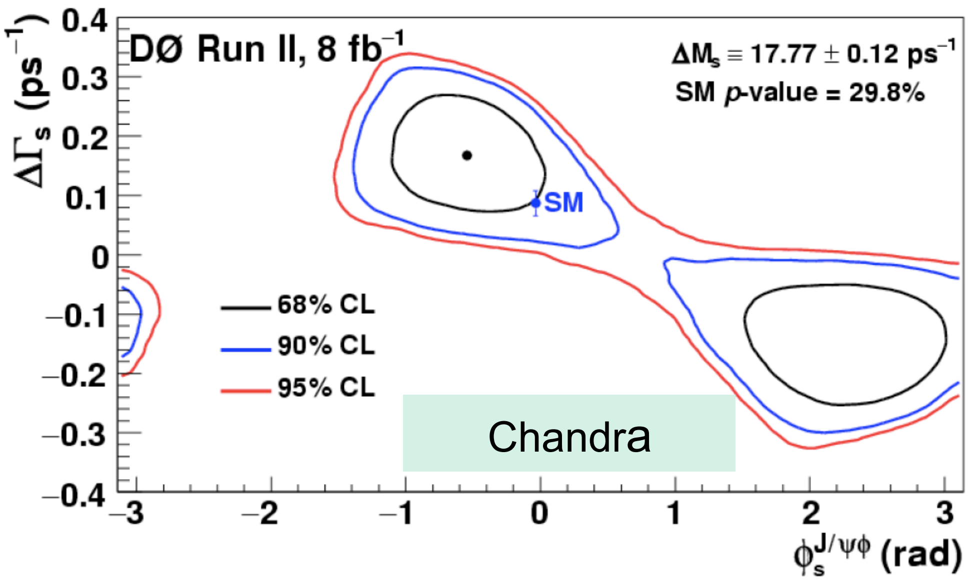
So a large $\beta_s$ or semileptonic asymmetry is a sign of NP

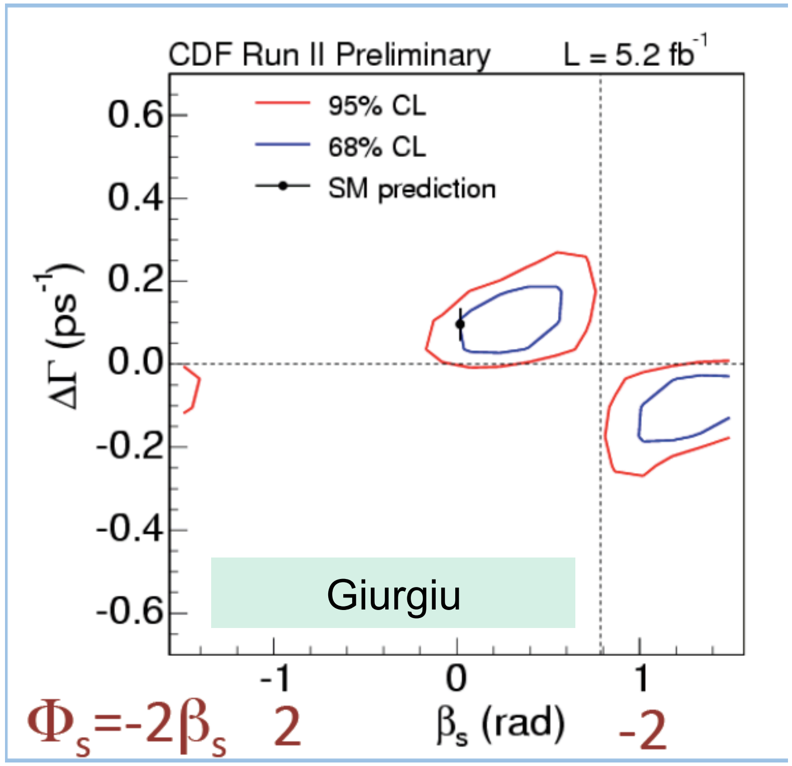
Measurements at Tevatron & LHC

- $\Delta\Gamma$ & $\phi_s$ from time-dependent angular analysis of $B^0_s \to J/\psi\phi$
- $a_{sl}$ from inclusive or like-sign Dimuon rate asymmetry

# Measurement of $B_s$ mixing phase ($\phi_s^{J/\psi\phi}$)

Using time-dependent angular analysis of $B_s \to J/\psi\phi$ with flavor tagging




| | |
|---|---|
| $\Delta\Gamma_s$ | $0.163^{+0.065}_{-0.064}$ ps$^{-1}$ |
| $\phi_s^{J/\psi\phi}$ | $-0.55^{+0.38}_{-0.36}$ |

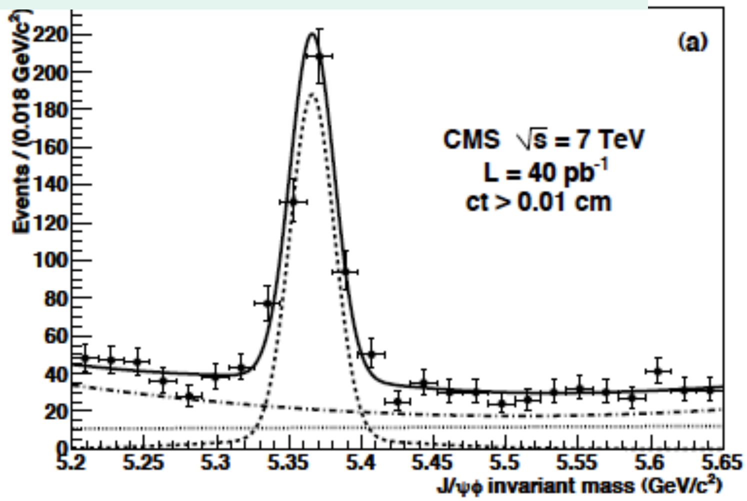
***$\beta_s$ in [-0.02,0.52] U [1.08,1.55] at 68% CL***

Both results are consistent with SM
But a large mixing phase ($\phi_s^{J/\psi\phi}$) is not excluded

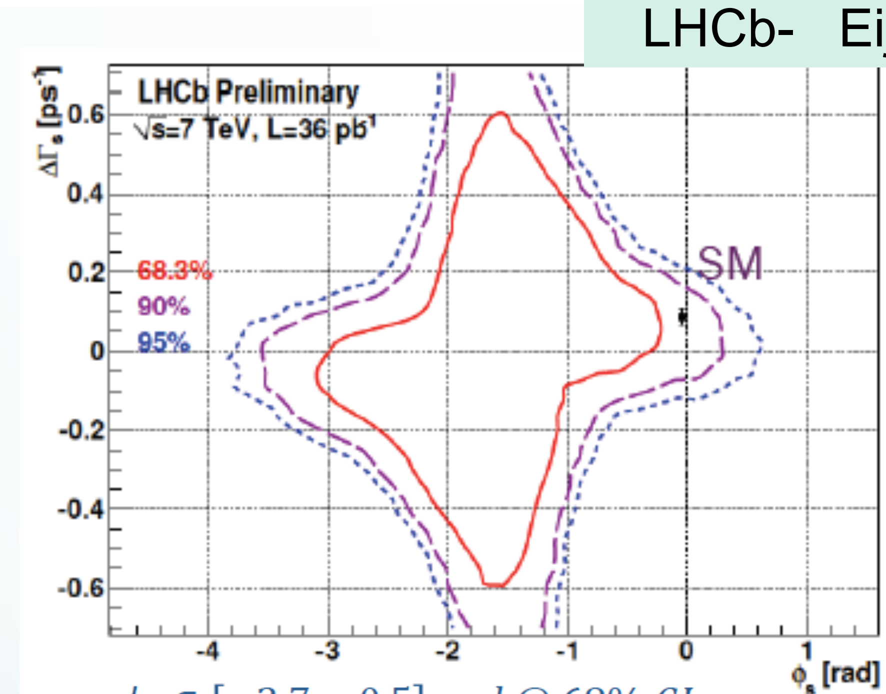
# Measurement of $B_s$ mixing phase ($\phi_s^{J/\psi\phi}$)-LHC

CMS- Cerizza

Moving towards $\Delta\Gamma$ meas.




LHCb- Eijk




$\phi_s \in [-2.7, -0.5]$ $rad$ @ 68% $CL$

LHCb $\phi_s^{J/\psi\phi}$ is consistent with SM & Tevatron results
Moving towards a precision measurement
Future measurements can also use Bs→J/Ψf – with no need for angular analyses
LHCb Results with x10 statistics expected soon.

# Measurement of like-sign Di-muon Asymmetry

B. Hoeneisen

## D0 results: the basic observation

$$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = (+0.126 \pm 0.041)\%$$

$$a = \frac{n^{+} - n^{-}}{n^{+} + n^{-}} = (+0.688 \pm 0.002)\%$$

Both related to $A_{SL}$

$$A = KA^{b}_{sl} + A_{bkg}$$

$$a = kA^{b}_{sl} + a_{bkg}$$

The tasks is to determine $A_{bkg}$, $a_{bkg}$ & related asymmetries and K and k

Using data: they determine the fraction of various components of background sources and the related charge asymmetry of each component

Background has significant charge asymmetry-dominated by kaons-determined and checked with data & found to be consistent with MC

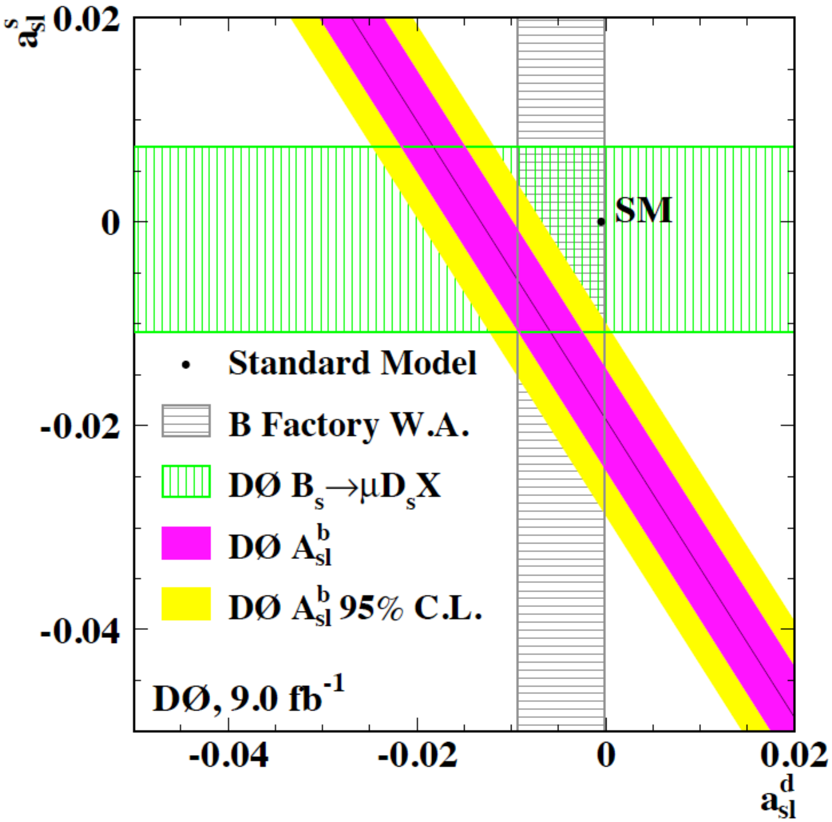
| Source | inclusive muon | like-sign dimuon |
|---|---|---|
| $(f_K a_K$ or $F_K A_K) \times 10^2$ | $+0.776 \pm 0.021$ | $+0.633 \pm 0.031$ |
| $(f_\pi a_\pi$ or $F_\pi A_\pi) \times 10^2$ | $+0.007 \pm 0.027$ | $-0.002 \pm 0.023$ |
| $(f_p a_p$ or $F_p A_p) \times 10^2$ | $-0.014 \pm 0.022$ | $-0.016 \pm 0.019$ |
| $[(1 - f_{bkg})\delta$ or $(2 - F_{bkg})\Delta] \times 10^2$ | $-0.047 \pm 0.012$ | $-0.212 \pm 0.030$ |
| $(a_{bkg}$ or $A_{bkg}) \times 10^2$ | $+0.722 \pm 0.042$ | $+0.402 \pm 0.053$ |
| $(a$ or $A) \times 10^2$ | $+0.688 \pm 0.002$ | $+0.126 \pm 0.041$ |
| $[(a - a_{bkg})$ or $(A - A_{bkg})] \times 10^2$ | $-0.034 \pm 0.042$ | $-0.276 \pm 0.067$ |

# D0 measurement of Charge Asymmetry in Leptons ($A^b_{sl}$)

$$A^b_{sl} = (-0.787 \pm 0.172 \pm 0.093)\%$$

$$A^b_{sl}(SM) = C_d a^d_{sl} + C_s a^s_{sl} = (-0.028^{+0.005}_{-0.006})\%$$

"Tension" with SM is at 3.9 $\sigma$




If confirmed, this represent a clear signal for NP
A task for CDF(?), and LHCb
also with precise $\phi_s$ measurements

See J. Zupan's talk for theoretical implications- "consistent with NP CPV"

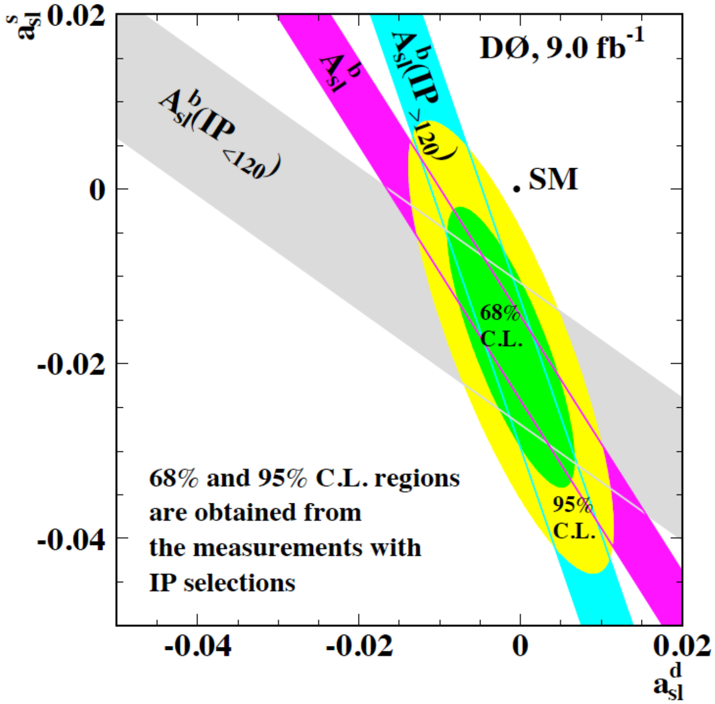
The result is consistent with current $\phi_s$ measurements

# D0 measurement of Charge Asymmetry in Leptons ($A^b_{sl}$)

- Does the result survive a different level of "B enrichment"?
- Is this a $B^0_s$ effect?

- They apply an impact parameter (IP) cut and divide the data into two parts: IP>120 μm ($B_d$ rich) and IP<120 μm ($B_s$ rich) - Perform the same analysis & determine $a^d_{sl}$ and $a^s_{sl}$

$$\boxed{\begin{aligned} a^d_{sl} &= (-0.12 \pm 0.52)\% \\ a^s_{sl} &= (-1.81 \pm 1.06)\% \end{aligned}}$$




They also extend the analysis to different IP thresholds & find consistent results

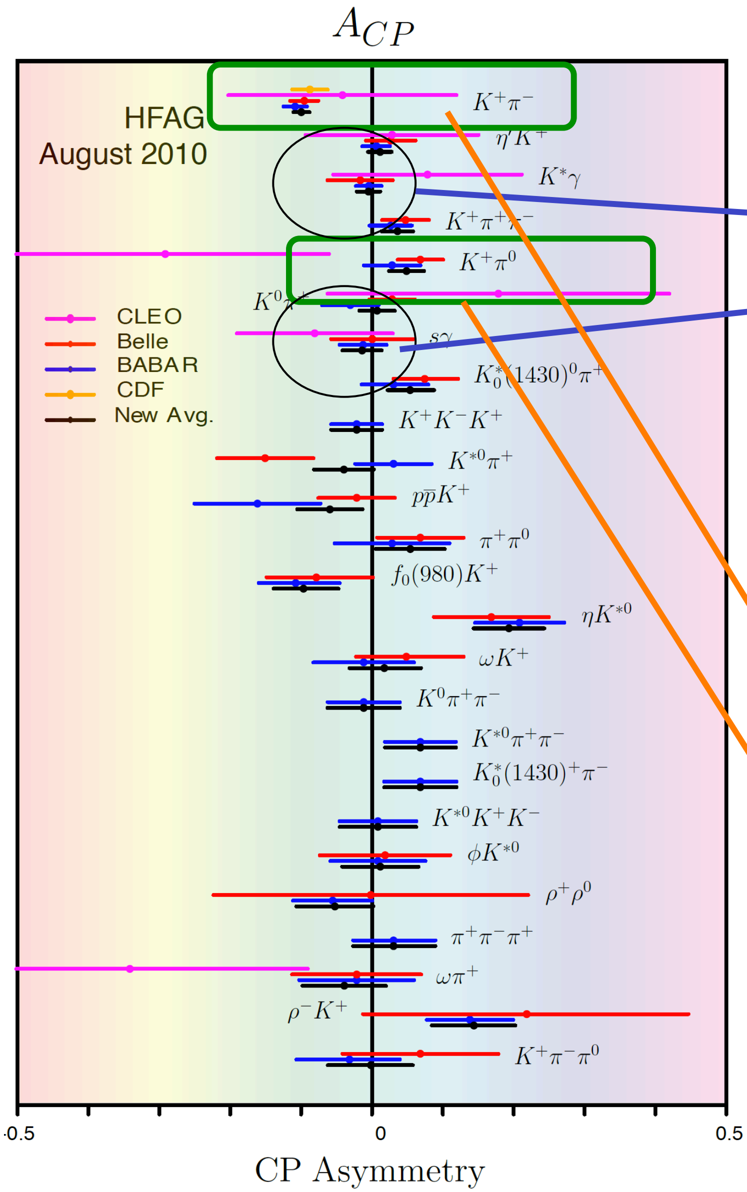
| Quantity | muon IP threshold | | |
|---|---|---|---|
| | 50 $\mu m$ | 80 $\mu m$ | 120 $\mu m$ |
| $a^d_{sl} \times 10^2$ | $+1.51 \pm 0.93$ | $+0.42 \pm 0.68$ | $-0.12 \pm 0.52$ |
| $a^s_{sl} \times 10^2$ | $-4.76 \pm 1.79$ | $-2.57 \pm 1.34$ | $-1.81 \pm 1.06$ |
| $\rho_{ds}$ | $-0.912$ | $-0.857$ | $-0.799$ |

*__But now there is some small cause for concern:__*
The asymmetry tends to increase with lowering IP threshold- more pronounced at lower IP- dominated by BKG tracks.
Further study of IP effect is needed-

# Direct CP Violation in B decays

CP asymmetry in decay amplitude:
Compilation by HFAG

$$A_{CP} = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})}$$




Within SM: Expect $A_{cp}(b \to s\gamma) \sim 0$

| | |
|---|---|
| $K^*\gamma$ | $-0.003 \pm 0.017$ |
| $s\gamma$ | $-0.012 \pm 0.028$ |
| $(s+d)\gamma$ | $-0.11 \pm 0.12$ |
| $s\ell\ell$ | $-0.22 \pm 0.26$ |
| $K^*e^+e^-$ | $-0.18 \pm 0.15$ |
| $K^*\mu^+\mu^-$ | $-0.03 \pm 0.13$ |
| $K^*\ell\ell$ | $-0.07 \pm 0.08$ |

No evidence of deviation from SM yet.

Observed by BaBar, Belle, CDF & now impressive 1st results from LHCb – new averages

$$A_{cp}(B^0(\bar{b}d) \to K^+\pi^-) = -0.085 \pm 0.010$$

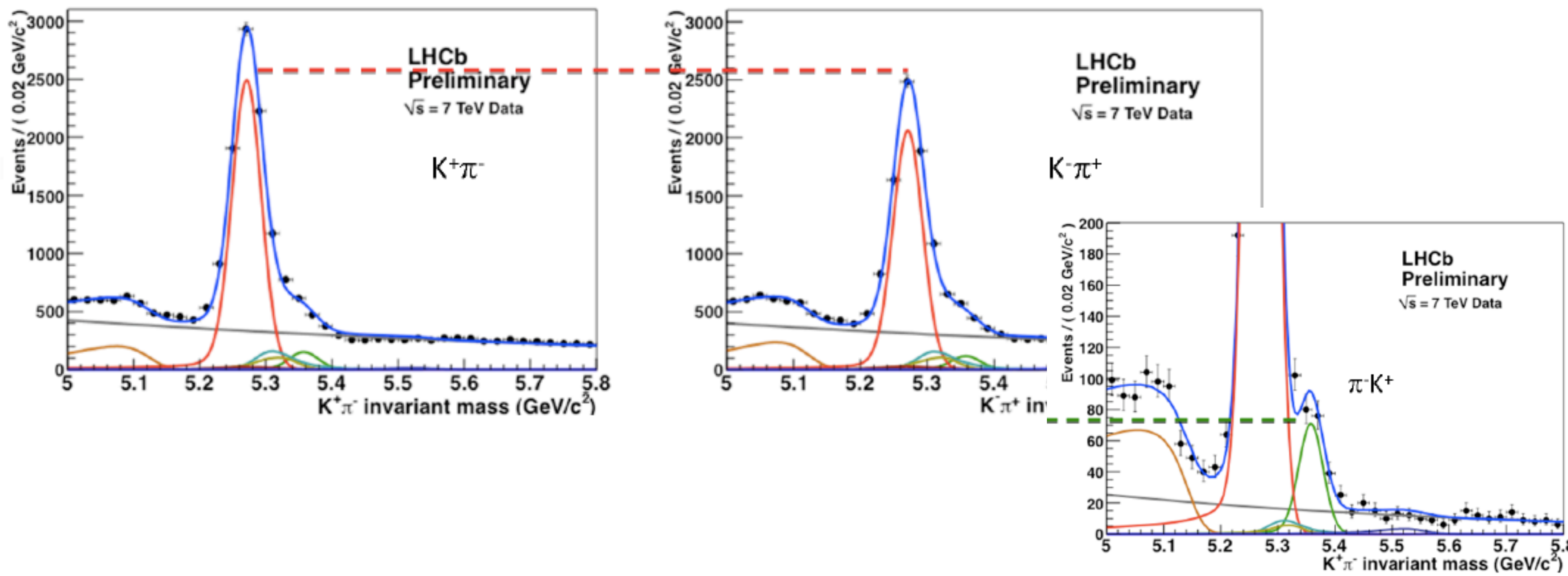
$$A_{CP}(B^+(\bar{b}u) \to K^+\pi^0) = +0.038 \pm 0.018$$

The puzzle: changing the spectator quark leads to a drastic change in CPV asymmetry

# Direct CPV (cont)

First LHCb results- much more to come soon

P. Sail & M. Artuso




**LHCb measurements (320 pb$^{-1}$)**

- $A_{CP}(B^0 \to K^+\pi^-) = -0.088 \pm 0.011$ (stat) $\pm$ 0.008 (syst)
- $A_{CP}(B_s^0 \to \pi^+K^-) = 0.27 \pm 0.08$ (stat) $\pm$ 0.02 (syst)

# Direct CP Violation in B decays- the "Kπ" puzzle

- The measurement: $A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.123 \pm 0.020$

A >5 σ deviation from simple expectation- assuming dominance of tree and penguin diagrams $\mathrm{A}_{cp}(\mathrm{B}^0 \to \mathrm{K}^+\pi^-) \approx \mathrm{A}_{cp}(\mathrm{B}^+ \to \mathrm{K}^+\pi^0)$

<u>Possible explanation:</u>

•A more complex SM background (enhanced color suppressed, EW penguins, annihilation.)

•New Physics

Before invoking NP- a more accurate test of SM processes is in order – proposed sum rule by ( Gronau, Rosner) & (Atwood, Soni), also suggestions by Lipkin,..

$$\mathrm{A}_{cp}(\mathrm{K}^+\pi^-) + \mathrm{A}_{cp}(\mathrm{K}^0\pi^+)\frac{B(\mathrm{K}^0\pi^+)}{B(\mathrm{K}^+\pi^-)}\frac{\tau_0}{\tau_+} \approx \mathrm{A}_{cp}(\mathrm{K}^+\pi^0)\frac{2B(\mathrm{K}^+\pi^0)}{B(\mathrm{K}^+\pi^-)}\frac{\tau_0}{\tau_+} + \mathrm{A}_{cp}(\mathrm{K}^0\pi^0)\frac{2B(\mathrm{K}^0\pi^0)}{B(\mathrm{K}^+\pi^-)}\frac{\tau_0}{\tau_+}$$

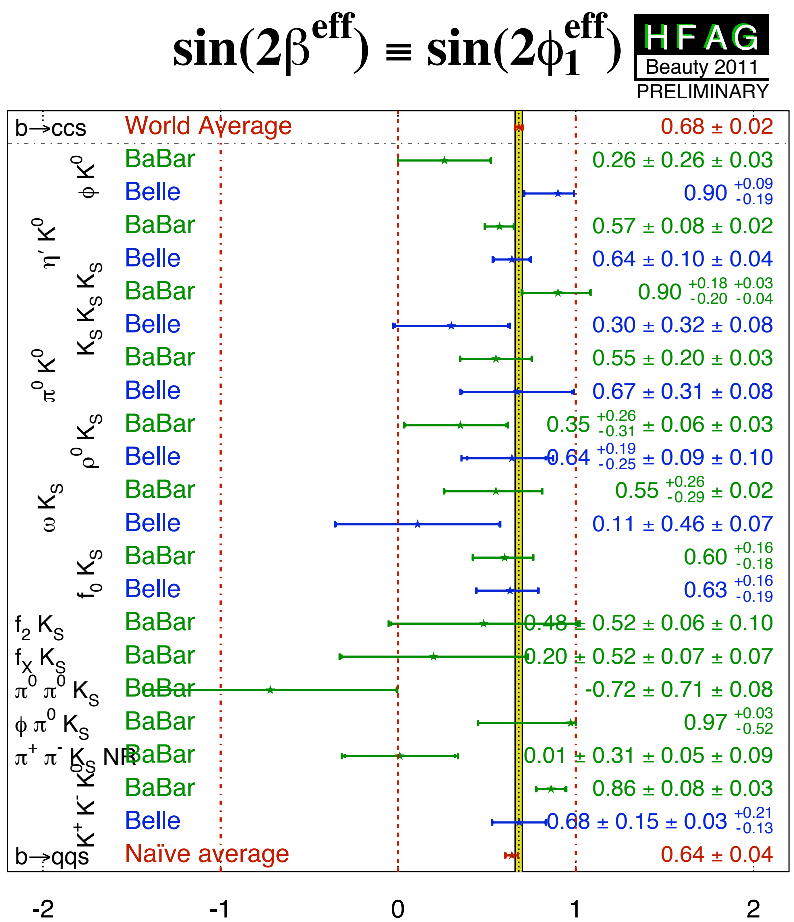
$A_{cp}(B^+ \to K^+\pi^0) = +0.038 \pm 0.018$ $\quad$ $A_{cp}(B^+ \to K^0\pi^+) = -0.009 \pm 0.025$

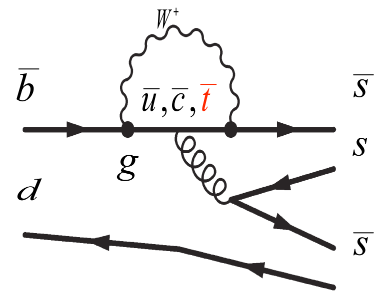
$A_{cp}(B^0 \to K^+\pi^-) = -0.085 \pm 0.010$ $\quad$ $A_{cp}(B^0 \to K^0\pi^0) = +0.01 \pm 0.10$

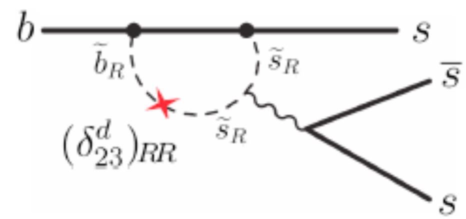
- The current data satisfies the sum rule
- The precision of the test is limited by measurement of CPV in $B^0 \to K^0\pi^0$
- Requires the statistics of Super Flavor experiments to disentangle NP & SM.

# Time-dependent CPV in gluonic penguins

## Measurement of Sin2$\beta_{penguin}$




➢In SM: Sin2$\beta_{penguin}$ ~ sin2$\beta$ (Subject to channel dependent QCD corrections)

➢Looking for a $\Delta$S=Sin2$\beta_{penguin}$-sin2$\beta$, sensitive to New Physics effects at loop level.

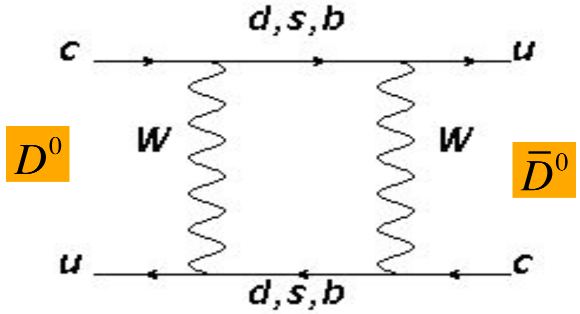
➢To be a useful test Must understand SM predictions for $\Delta$S - requires:

- Reliable QCD calculations
- Comprehensive measurements of many channels and the use of symmetries to relate them.

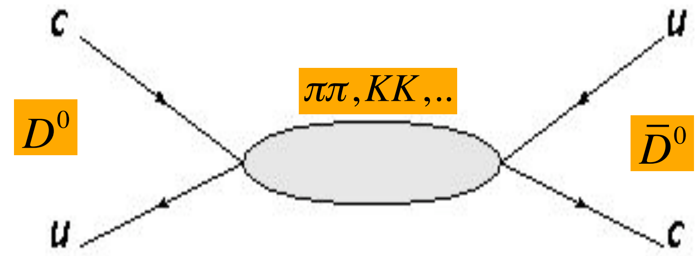
•The current "naïve average" is consistent with SM.

# CP Violation in the Charm System

- Within SM, Mixing & CPV in charm system are very small:




CKM & GIM suppressed: x, y<$10^{-3}$




Mixing through intermediate states can boost x, y~1%

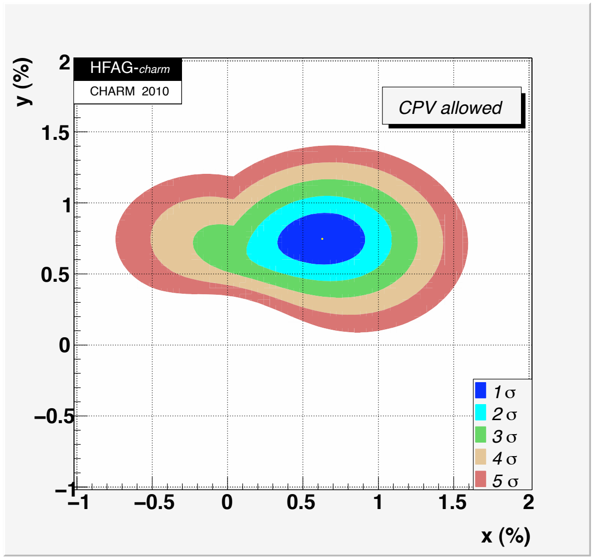
The dominant couplings are from the 1st two generations, involving the real part of the CKM matrix (no relative CPV phase)

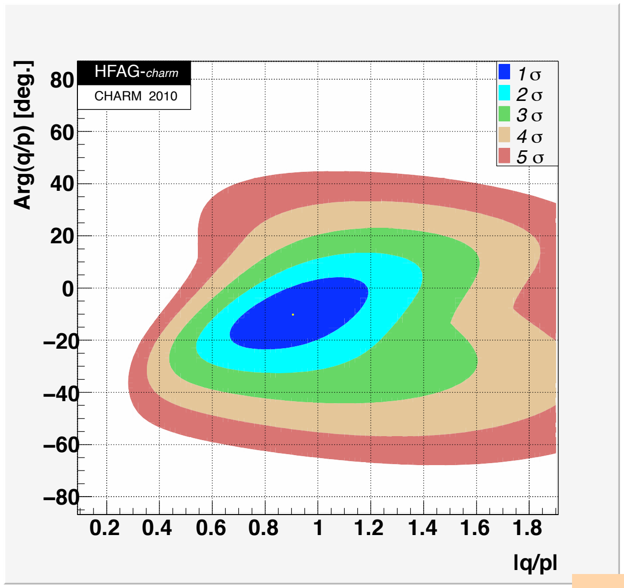
Any CPV ~ $O(|V_{ub}V^*_{cb}/V_{us}V^*_{cs}|)$ ~ $10^{-3}$ or less

Any sizeable CPV in the charm sector- if observed- indicates the presence of New Physics

# CP Violation in the Charm System

- Mixing in $D^0$ system is now established via 30 observables:
- Time evolution of doubly-cabibbo-suppressed $D^0 \to K^+\pi^-$
- Lifetime difference in CP-odd and CP-even modes
- Dalitz analysis of $D^0 \to K_s\pi^+\pi^-$ $K_sK^+K^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, ...
- Simultaneously fit for indirect CPV:




$$\left|\frac{q}{p}\right| = 0.91^{+0.18}_{-0.16}$$

$$\varphi(\deg) = -10.0^{+9.4}_{-8.9}$$

SM : $\phi$ <0.6 (deg)

$$x = \frac{\Delta M}{\Gamma} = (0.63 \pm 0.20)\%$$

$$x = \frac{\Delta \Gamma}{2\Gamma} = (0.80 \pm 0.13)\%$$

$D^0$ mixing is now on firm ground
Zero mixing is excluded at >10 $\sigma$

No evidence for
indirect CPV in $D^0$

# Direct CPV in the charm system

- Search for direct CPV in charm decays performed by CLEO, FOCUS, E791, BaBar, Belle, CDF & LHCb

Measure:

$$A_{cp} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

The full list can be found at HFAG:

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

The most sensitive channels:

| Channel | $A_{cp}$ (%) |
|---|---|
| $D^0 \to \pi^+\pi^-$ | $+0.20 \pm 0.22$ |
| $D^0 \to K^0_s\pi^0$ | $-0.27 \pm 0.21$ |
| $D^0 \to K^+K^-$ | $-0.23 \pm 0.17$ |
| $D^+ \to K^0_s\pi^+$ | $-0.52 \pm 0.14$ |
| $D^+ \to K^0_sK^+$ | $-0.09 \pm 0.63$ |
| $D^+_s \to K^0_sK^+$ | $+0.28 \pm 0.41$ |
| $D^+_s \to K^0_s\pi^+$ | $-6.53 \pm 2.46$ |

No evidence found for Direct CPV in charm decays
Sensitivities in some channels approaching $\sim 10^{-3}$

$>3\sigma$ Expect $A_{cp} \sim -0.33\%$ induced by indirect CPV in $K^0$

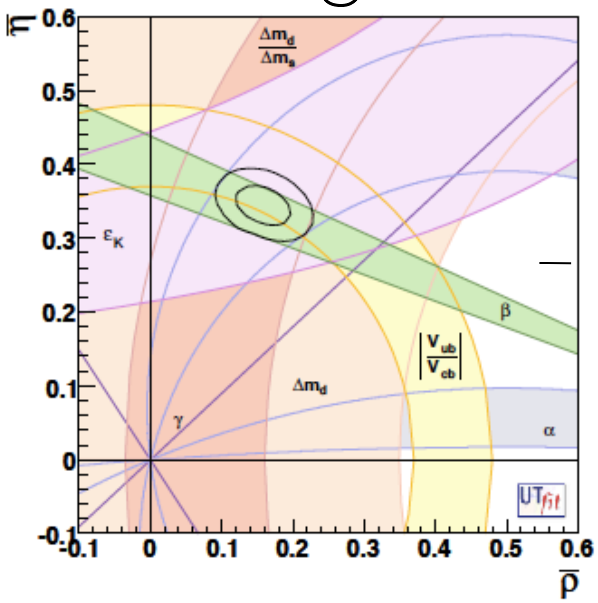
Hadron colliders are now big players in charm CPV – results from CDF & LHCb

## Outlook

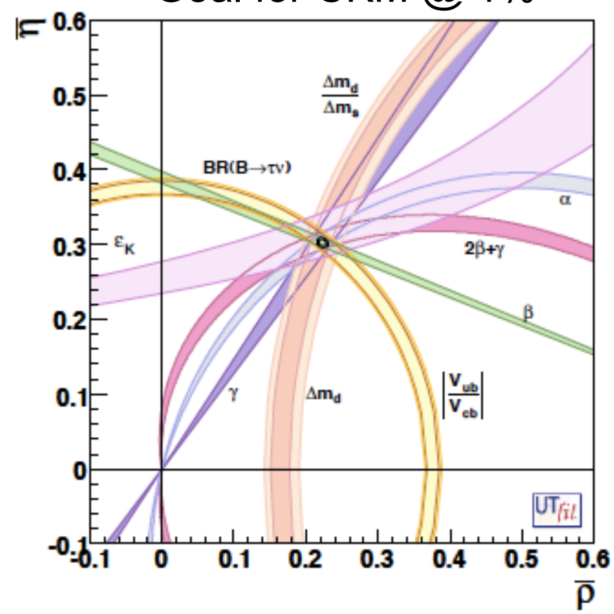
For order of magnitude improvement in precision of CPV observables

# The dream for the CKM parameters

Now at CKM @ 10%




Goal for CKM @ 1%




•<u>This is an enormous undertaking for both experiment & theory:</u>

To reach this goal, accuracy of the theoretical inputs must match the experimental precision:

- Improved Lattice QCD calculations of decay constants & form factors are needed for B mixing parameters, leptonic decays, $|V_{ub}|$, $|V_{cb}|$,..

- The experience of B factories shows that comprehensive measurements of a broad set of channels -connected through known symmetries, e.g. Isospin, SU(3) etc- are needed to control theoretical uncertainties.

# Next generation of Flavor/CPV Experiments

At LHC:

- LHCb:

  At L~2x$10^{32}$/cm$^2$/s

  Expect ~5/fb by 2018

  Incoming rate ~$10^{12}$ B's/Yr(2/fb)

  +trigger

  $B_d$, $B_u$, $B_s$, $B_c$, $\Lambda_b$,...

  Excellent early results has already appeared

- CMS and ATLAS players in B->$\mu\mu$ – not so much in CPV

- LHCb upgrade (in planning/ design)- aiming for 2018

  To operate at L~$10^{33}$/cm$^2$/s

  expect ~10/fb/year

- In design: (Super B factories)
- Asymmetric energy $e^+$ + $e^-$ colliders to operate in the $\Upsilon(4S)$ region as well as in the charm threshold region.
  - SuperB, Italy
  - Super KEKB in Japan
- At L ~$10^{36}$ /cm$^2$/s

  Aiming for a data set of ~ 50 to 75/ab in 5 yrs of running.
  - ~$10^{11}$ B decays
  - ~$10^{11}$ tau decays
  - ~$10^{11}$ charm decays

  For comparison

  ➔BaBar+Belle (~1.4/ab) : ~$10^9$ B's

# Summary

- Uncovering new sources of CP Violation remains a major task for the field:
  - Experimental data are still consistent with the Standard Model as the dominant source of CP Violation:
    - Signs of deviations from the SM are emerging, but these results need confirmation- some will be resolved with data from LHC.
  - Any New Physics is expected to contain new sources of CPV. The absence of significant evidence for CPV beyond SM is already posing a problem for NP at the TeV scale.
    - A program of precision measurements of the CKM parameters and loop dominated processes will be a major companion to the NP searches at the LHC.