Highlights since Nagoya

Petar Maksimovic, Johns Hopkins

Outline

- A personal selection, many measurements left out
- Few details... Rather, *themes* that will be discussed this week
- *B^0*, *B^+*:
  - Status of angles: $\alpha(\phi_2)$, $\beta(\phi_1)$, $\gamma(\phi_3)$ (selected measurements)
  - Status of sides: V_{ts}/V_{td}, V_{ub}
- *B_s:*
  - $B_s \rightarrow J/\psi\phi$: lifetime, $\Delta\Gamma_s$ and CP violation in B_s system
  - Charge asymmetry in semileptonic B_s decays
- Charm: D^0 mixing
- What's hot but *not* in this talk + Conclusions

CP violation in Standard Model

- Standard Model CP violation occurs through complex phases in the unitary CKM quark mixing matrix (3 real params + one phase)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Expanded in $\lambda = \sin(\theta_{\text{Cabibbo}}) \approx 0.23$:

Large CP violation ~ λ^3

Highly suppressed CP violation ~ λ^5

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

Large CP violation ~ λ^3

Suppressed CP violation ~ λ^4

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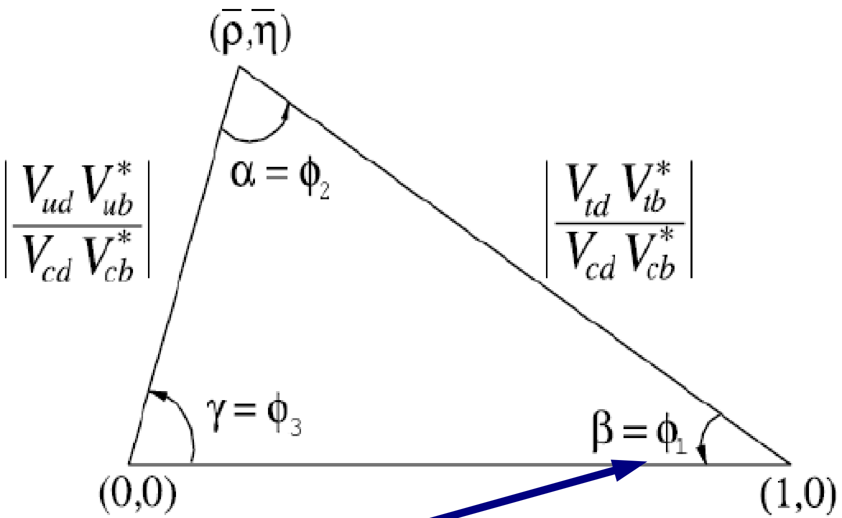
CP violation in Standard Model (2)

B_d unitarity triangle

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



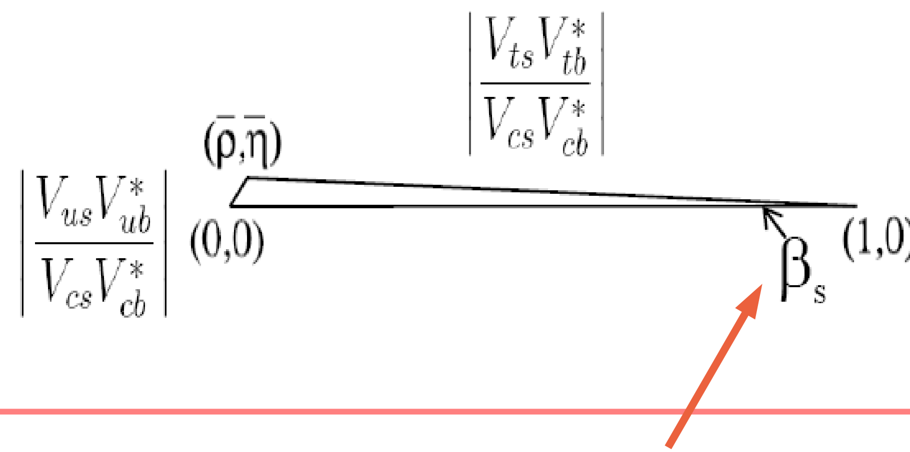
All three angles large

==> $\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$ ~ 22^0

==> Acp large

B_s unitarity triangle

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



\`Squashed' triangle ==> small β_s angle

$\beta_s = \beta' \equiv \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = \mathcal{O}(\lambda^2)$ ~1.1^0

==> Acp ~ 0

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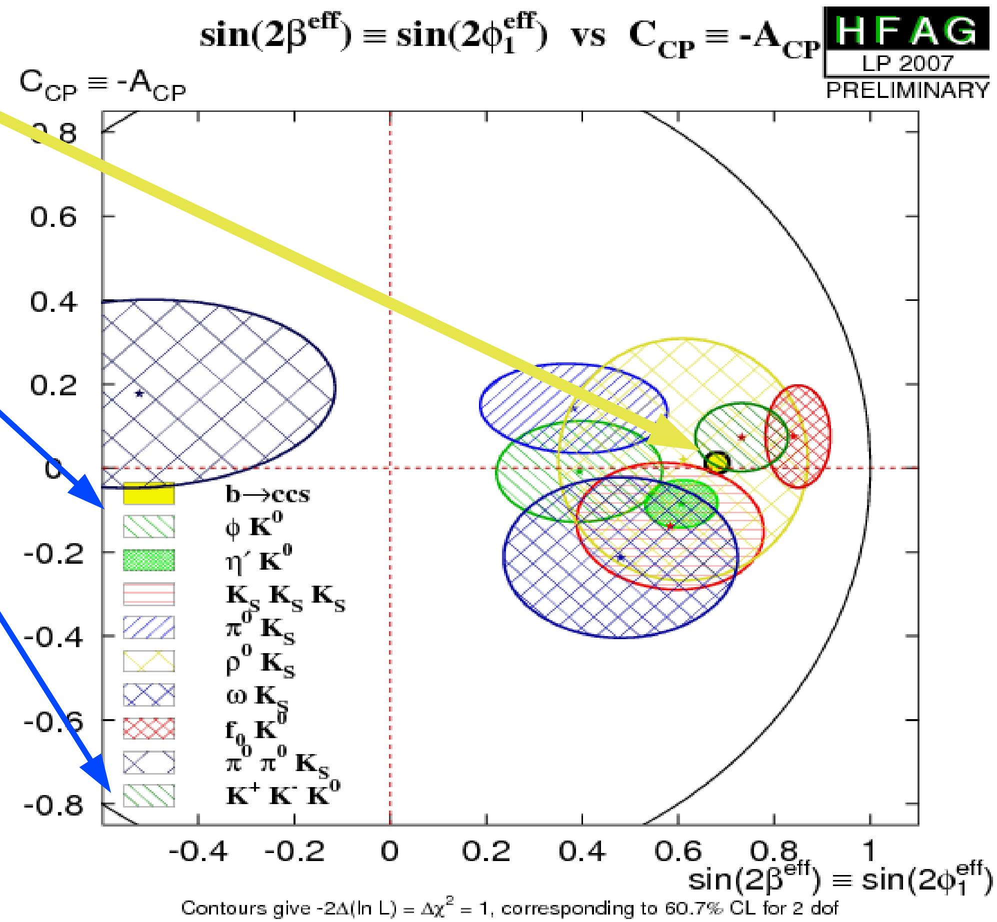
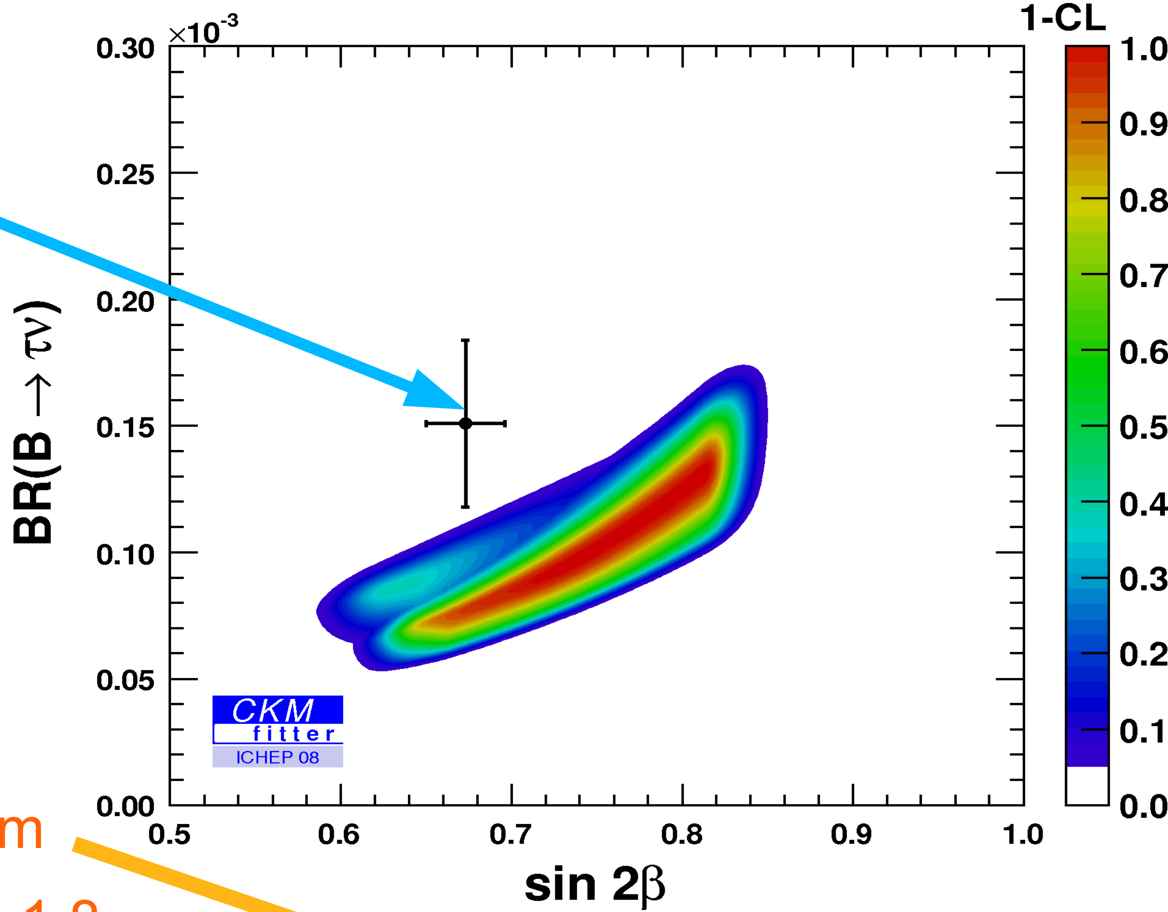
Status of measurements of β (= ϕ_1)

- Since Nagoya, central value did not move much
- Keep comparing sin2β from penguin decays to sin2β from charmonium states (dominated by $B^0 \to J/\psi K_S^0$)
- Status: penguin measurements inching closer to the charmonium average
  - But, still (on average) stay ~ 2σ away
  - Future: add new decay modes



Tension between $\sin 2\beta$ and $\mathcal{B}(B^+ \to \tau^+\nu)$

- New measurement of $\mathcal{B}(B^+ \to \tau^+\nu)$
- All other; discrepancy ~ 2.1σ
- There's a correlation between these two variables
- Can recast also as a measurement of B_{Bd} from global fit vs Lattice ==> 1.8σ

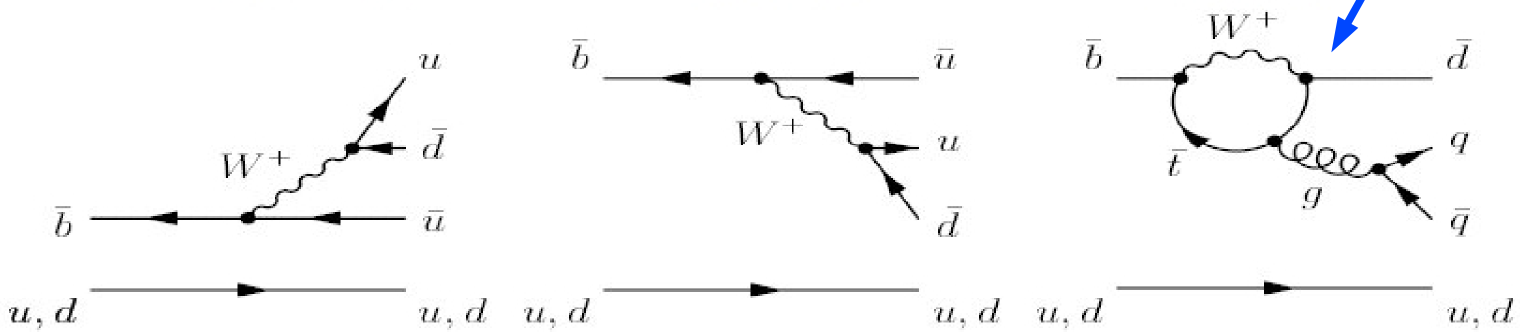


$$\frac{\mathcal{B}(B\to\tau\nu)}{\Delta m_d} = \frac{3\pi}{4}\frac{m_\tau^2}{m_W^2 S(x_t)}\left(1-\frac{m_\tau^2}{m_B^2}\right)^2 \tau_{B^+}\boxed{\frac{1}{B_{B_d}}}\frac{1}{|V_{ud}|^2}\left(\frac{\sin\beta}{\sin\gamma}\right)^2$$

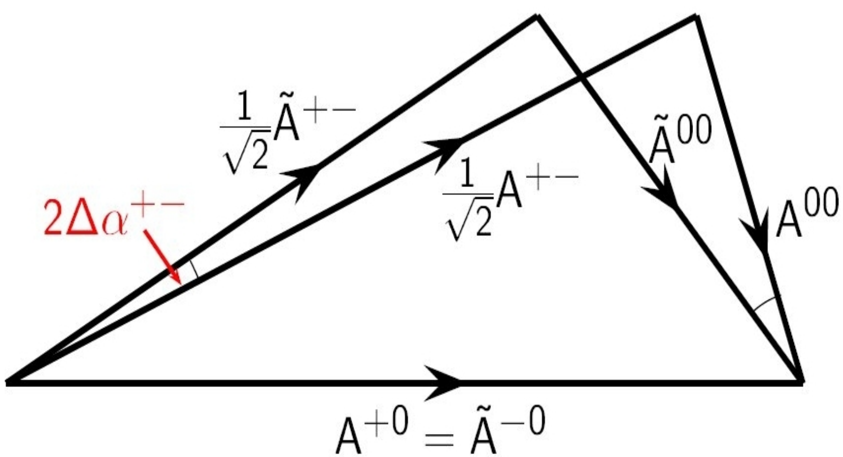
Status of measurements of α (= ϕ_2)

- Extraction of α from $B^0 \to \pi^+\pi^-$ plagued by penguin pollution

$$A = \alpha_T \cdot T + \alpha_C \cdot C + \alpha_P \cdot P$$



- Isospin analysis by Gronau & London can extract α even in the presence of substantial penguin contribution.



Time-dependence $B^0 \to (\overline{B}^0 \to)\ \pi^+\pi^-$

$$\Gamma(t) \propto \exp(-t/\tau_B) \times (1 \pm C\cos(t/\tau_{\rm mix}) \mp S\sin(t/\tau_{\rm mix}))$$

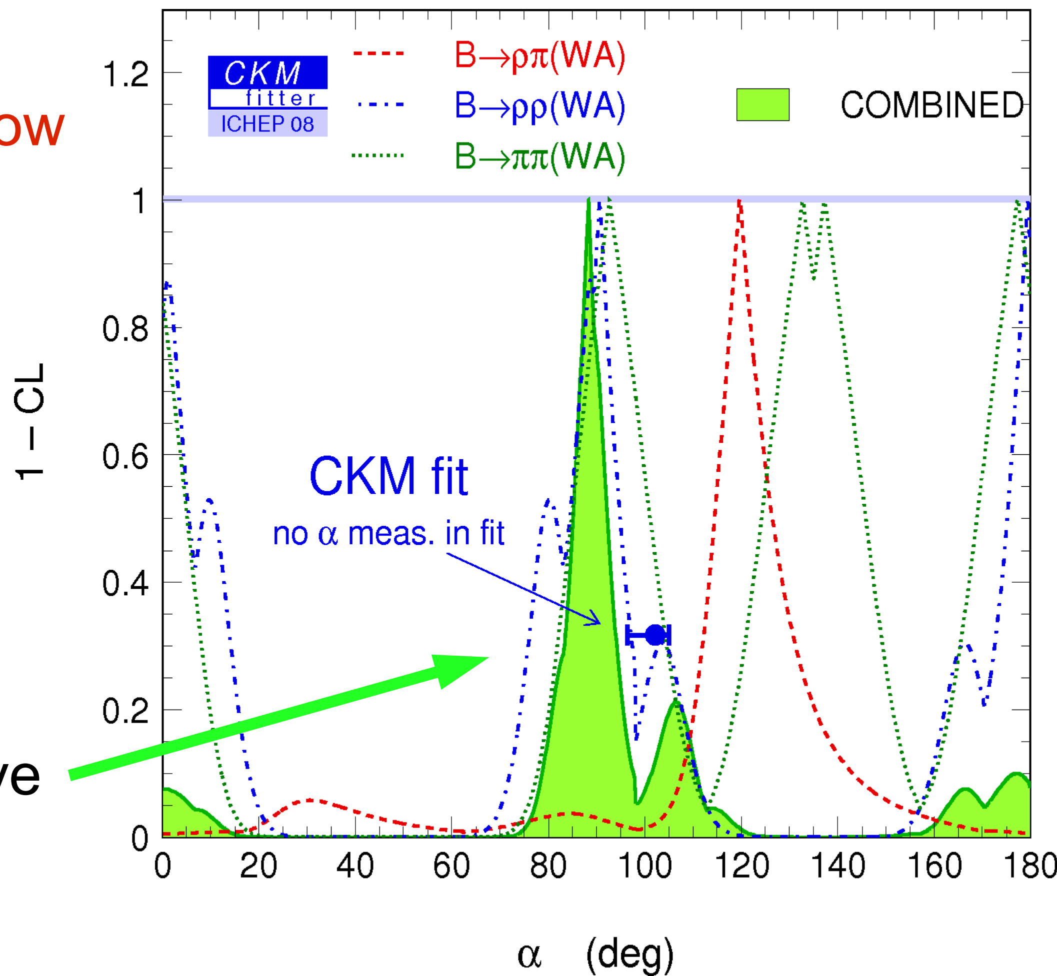
"Penguin pollution"

$$\Rightarrow S = \sqrt{1-C^2} \times \sin(2\alpha - 2\Delta\alpha^{+-})$$

Status of α (= ϕ_2)(cont'd)

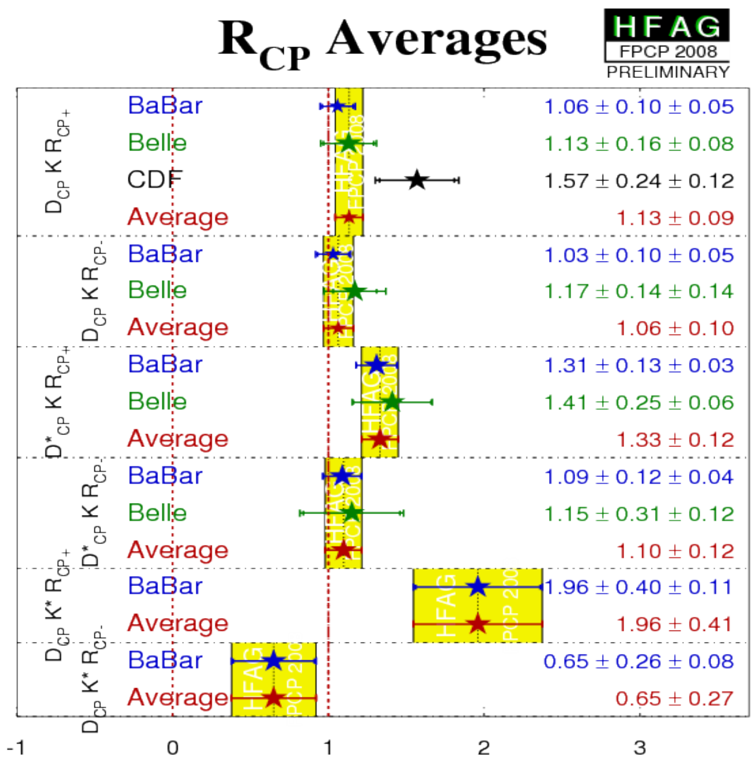
- $B^0 \to \pi^+\pi^-$ channel provides a plenty of precision
  - $\sigma(\alpha_{\rm eff})$ is small (similar to σ(sin2β) from charmonium states)

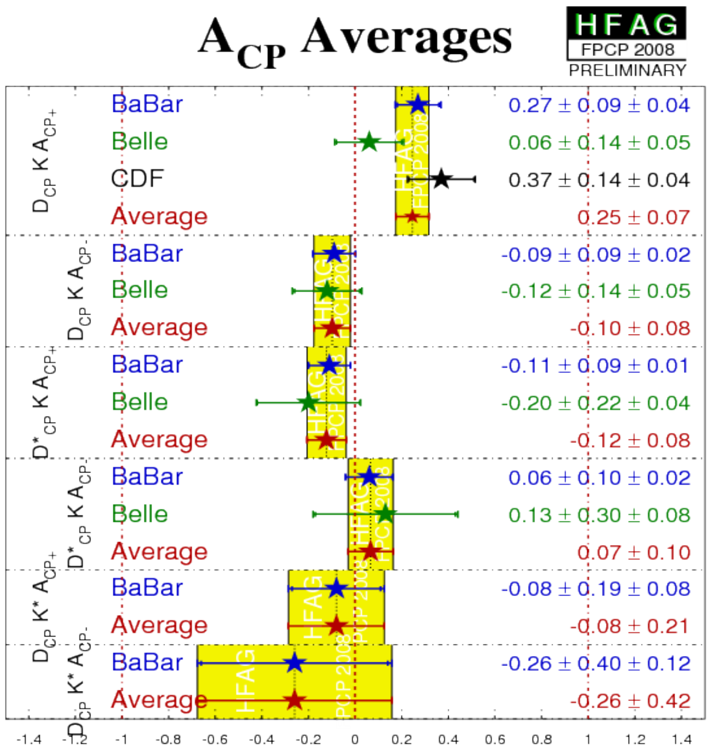
- Problem: Gronau-London procedure results in 8 narrow peaks!
- Solution: involve $B \to \rho\pi$ and $B \to \rho\rho$
- For $B \to \rho\rho$, *angular analysis* is necessary to disentangle amplitudes
- All together, very impressive



Status of measurements of $\gamma\ (= \phi_3)$

- Interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$
- GLW (Gronau, London, Wyler), relies on $B^+ \to \bar{D}^0_{\rm CP} K^+$, with $\bar{D}_{\rm CP} \to K^+K^-, \pi^+\pi^-$
- BaBar, Belle, CDF, all measure $R_{\rm CP\pm}$ and $A_{\rm CP\pm}$



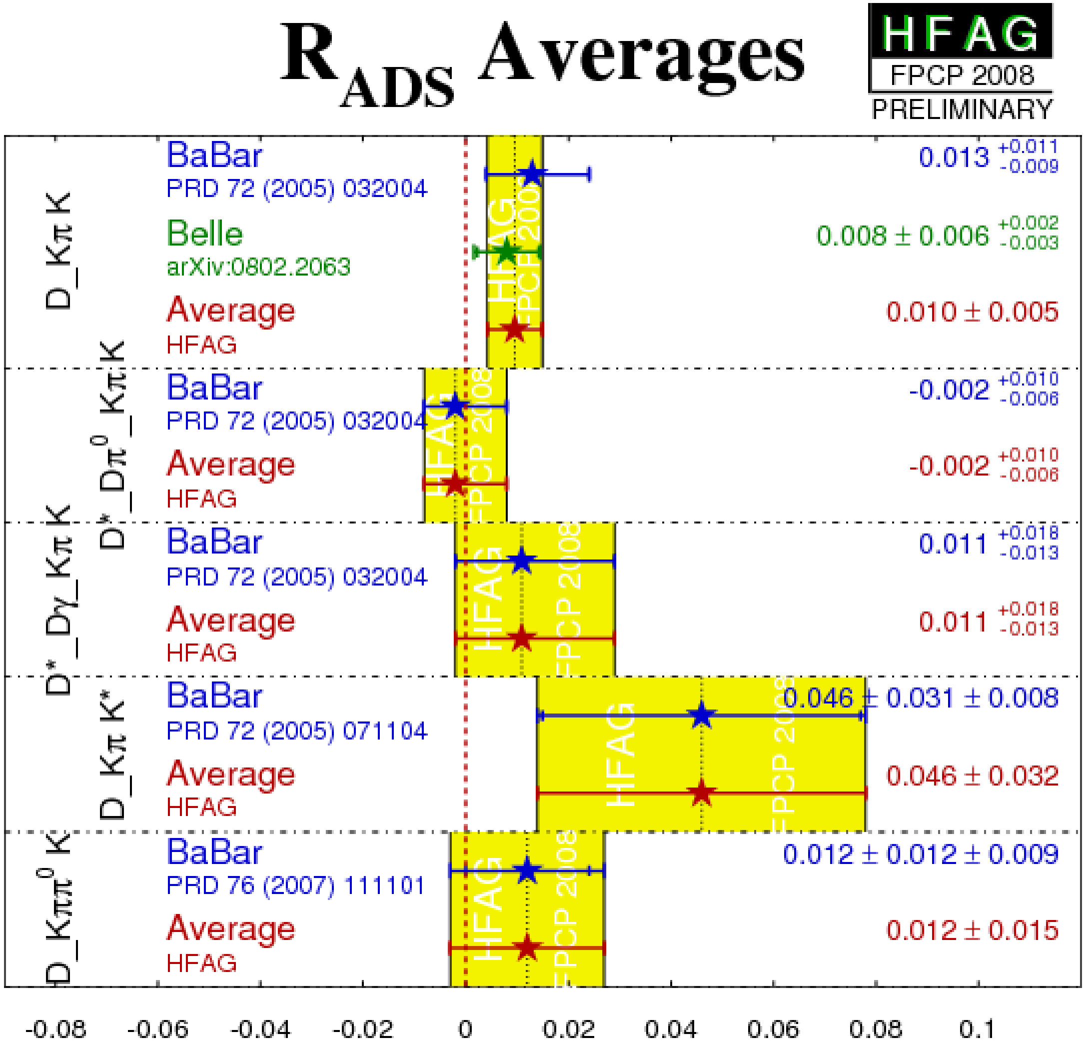


Status of angle γ $(= \phi_3)$ (ADS)

- Atwood, Dunietz, Soni:
- Cabibbo favoured ($b \to c$) B decay followed by the doubly CKM-suppressed D decay

  interferes with

- Cabibbo suppressed ($b \to u$) B decay followed by the CKM-favored D decay.
  - Similar in size ==> sizable CP asymmetry possible



Status of angle γ ($= \phi_3$) (Dalitz)

- Important recent development is *help from the Dalitz analysis* of $\bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$

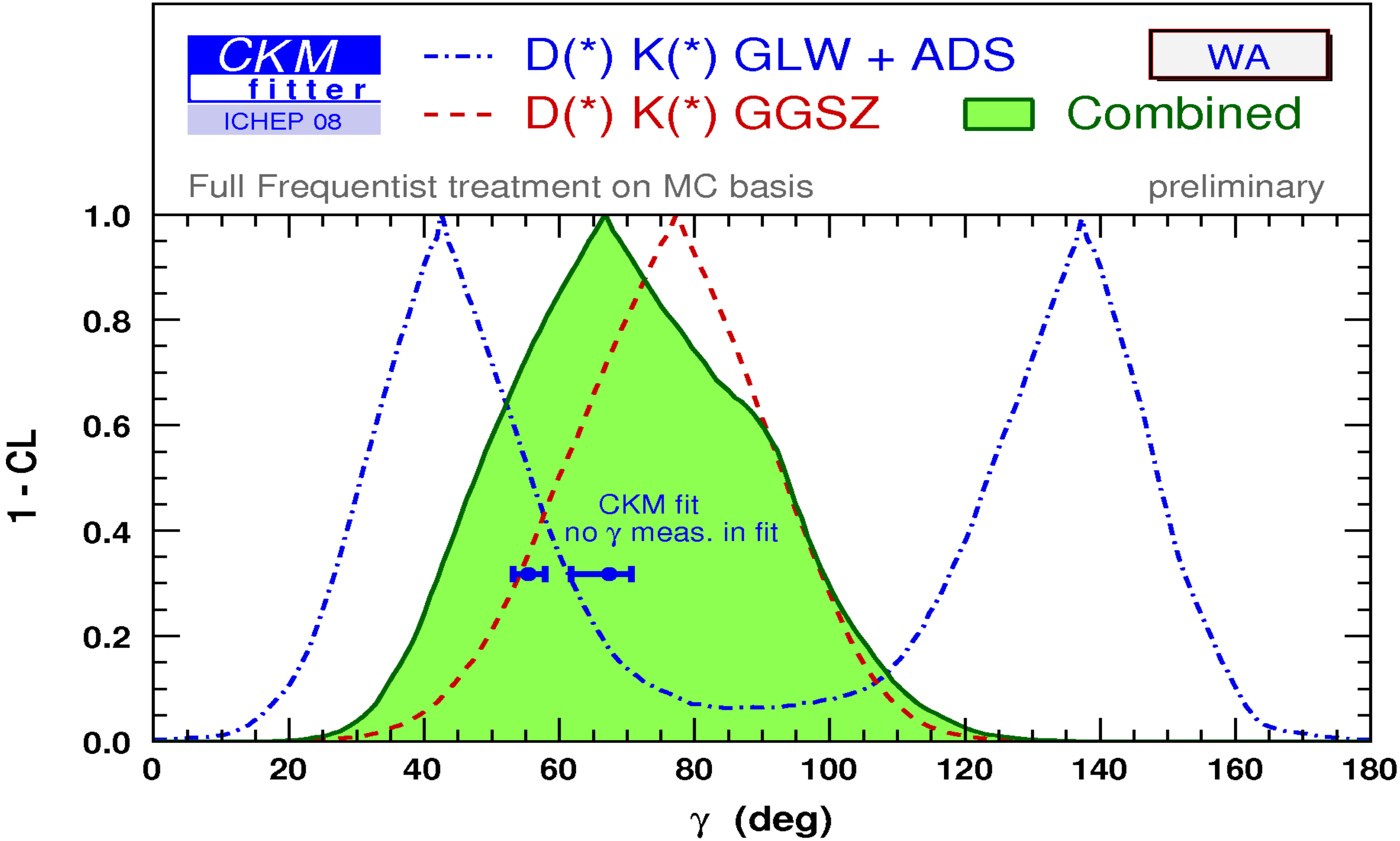
- $B^+ \rightarrow \bar{D}^0 K^+$ is followed by $D^0 \rightarrow K_S^0 \pi^+ \pi^-$
  - $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ is a mixture of states (of different CP), so:
    - one needs to do a Dalitz analysis to disentangle which one is which
    - there are ~ 15 modes in the game, a nightmare!
  - No time dependence
  - Effectively, we are comparing Dalitz structure for B+ and B-...

- Important *role of CLEO-c!*: measured bin-averaged cosines (c_i) and sines (s_i) of the differences of strong phases in $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

  ==> allows a model-independent extraction of γ

  - Significant reduction of systematics

Status of angle γ ($= \phi_3$) (all together)



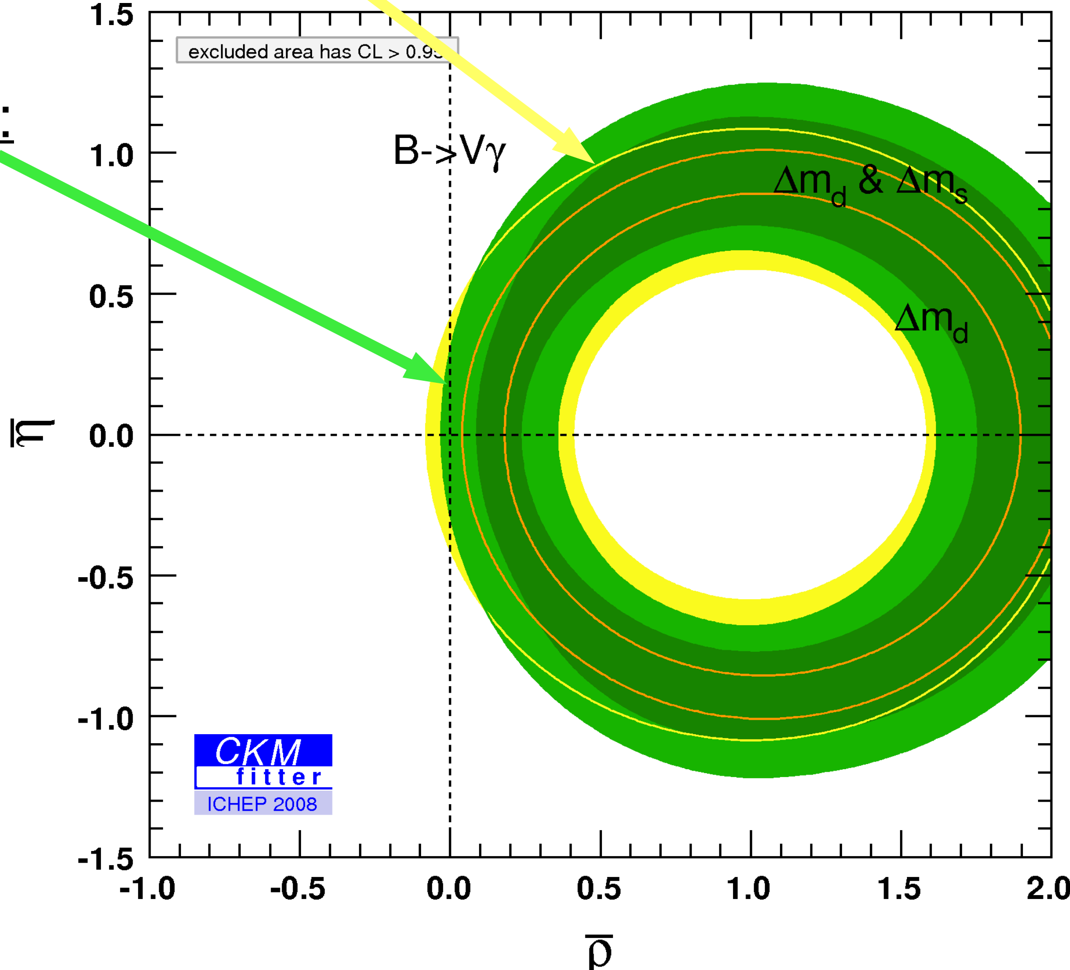
- Nobody expected the *B* factories to do so well on γ!

Status of sides: V_{ts}/V_{td}

- From mixing (*i.e.* $\Delta m_s/\Delta m_d$) :
  - no news since Nagoya (Bs mixing prominently featured then); error dominated by lattice

- From $b \to s\gamma / b \to d\gamma$:
  - $B \to K^*\gamma$
  - $B \to \rho\gamma$
  - $B \to \omega\gamma$
  - $B_s \to \phi\gamma$

==> Resulting precision comparable to V_{ts}/V_{td} from mixing!



"πK puzzle" in direct CPV in B^+ vs. B^0

- BELLE and BaBar both see a large discrepancy between direct CP violation in $B^0 \to K^\pm \pi^\mp$ and $B^\pm \to K^\pm \pi^0$:

$$A_{\rm CP}(B^0 \to K^- \pi^+) = -0.097 \pm 0.012$$
$$A_{\rm CP}(B^+ \to K^+ \pi^0) = +0.050 \pm 0.025$$

- Amplitudes (CPV via interference of...)

$$\sqrt{2} A(B^- \to K^- \pi^0) = P - (T + C) e^{-i\gamma} + P_{\rm EW}$$
$$A(B^0 \to K^- \pi^+) = P - T e^{-i\gamma}$$

- QCD predictions

$$P_{EW} = f_{\rm real} \left(\frac{m_t}{m_W} \right) (T + C)$$

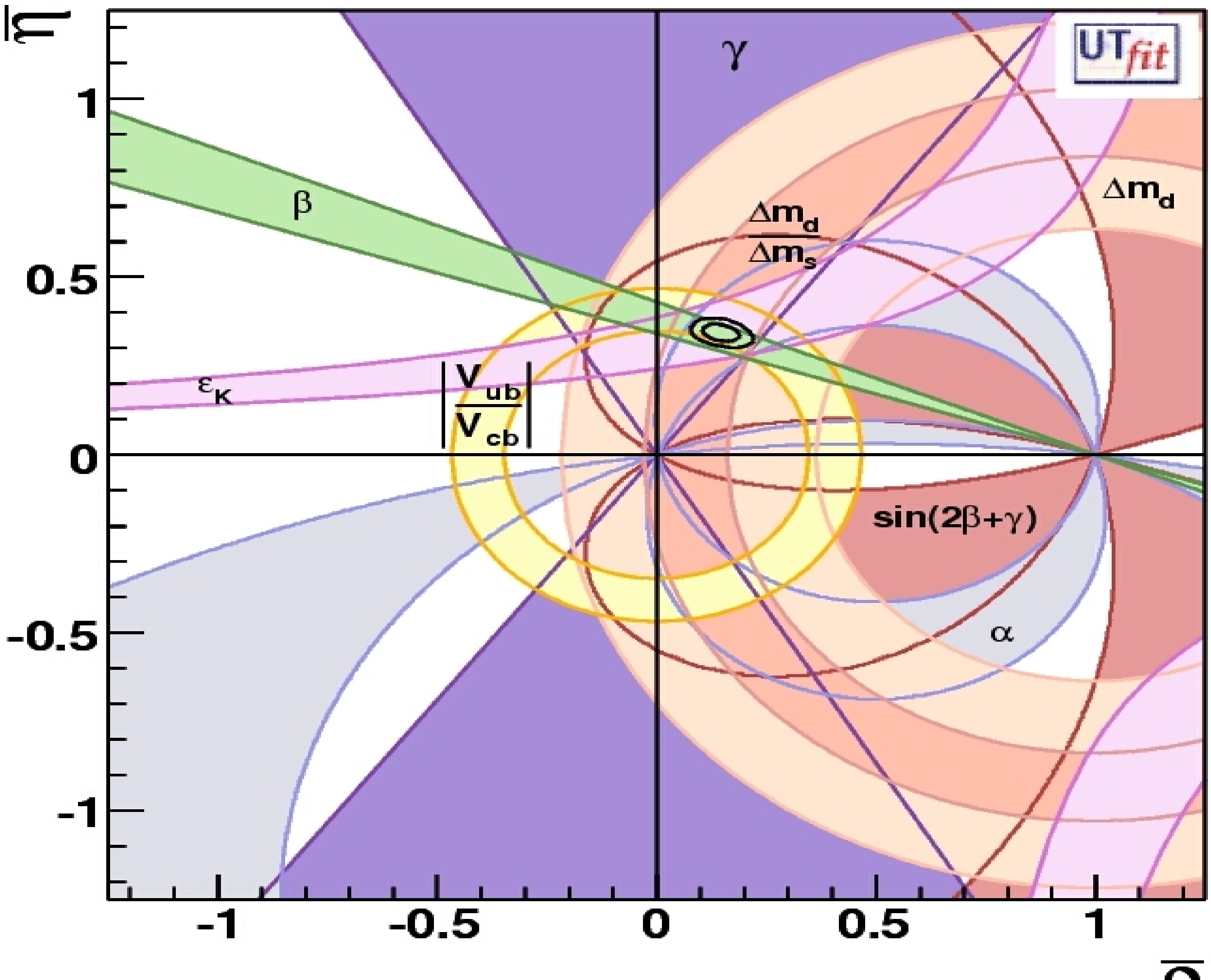
U-spin, Firtz relationships

$$\arg \left(\frac{C}{T} \right) = \mathcal{O}(\alpha_s(m_b), \Lambda_{\rm QCD}/m_b)$$

QCD factorization, SCET

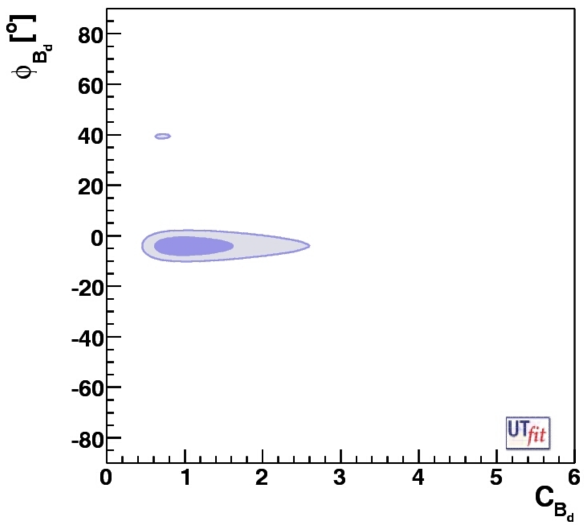
==> *Theory: Acp should have same sign, and similar magnitude?*

Unitarity Triangle now

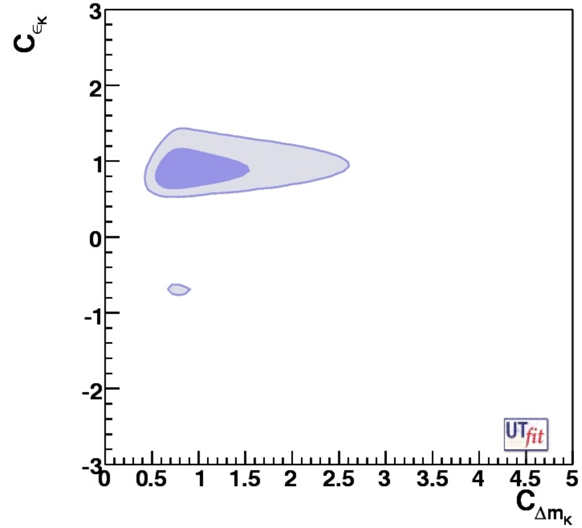


Phases in mixing – Dec '07

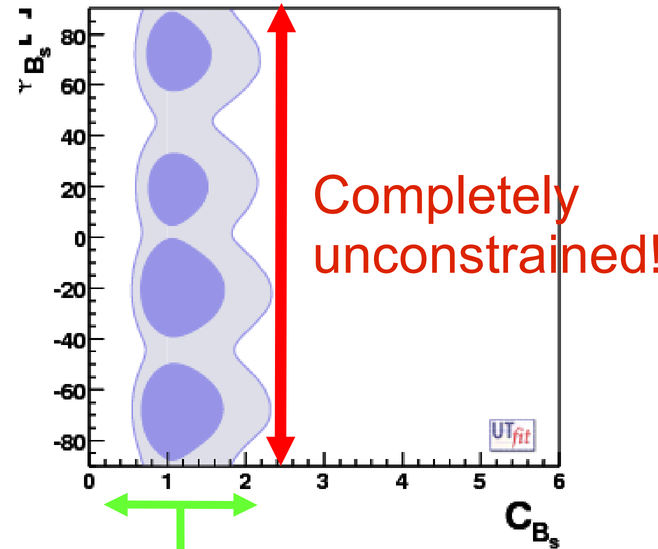
B^0 mixing



K^0 mixing



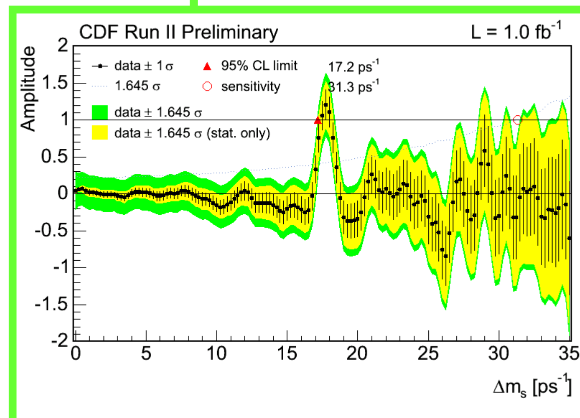
B^0_s mixing



Lattice-QCD dominated uncertainty

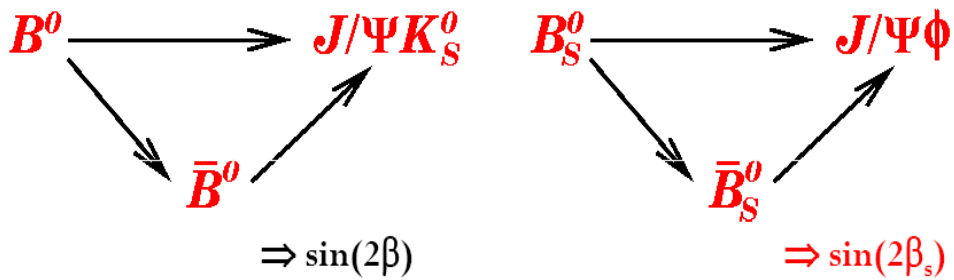
$$\frac{\langle M|H_{\rm eff}^{\rm full}|\bar{M}\rangle}{\langle M|H_{\rm eff}^{\rm SM}|\bar{M}\rangle} = C_M e^{2i\phi_M}$$

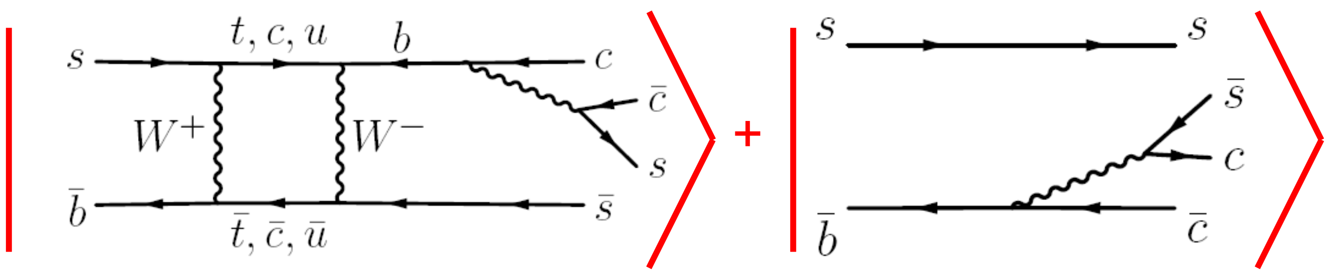
Experimentally-dominated uncertainty.



CP violation in $B_s \rightarrow J/\psi\phi$ decays

- Analogously B^0, CP violation in B_s occurs through interference of decay with and without mixing:





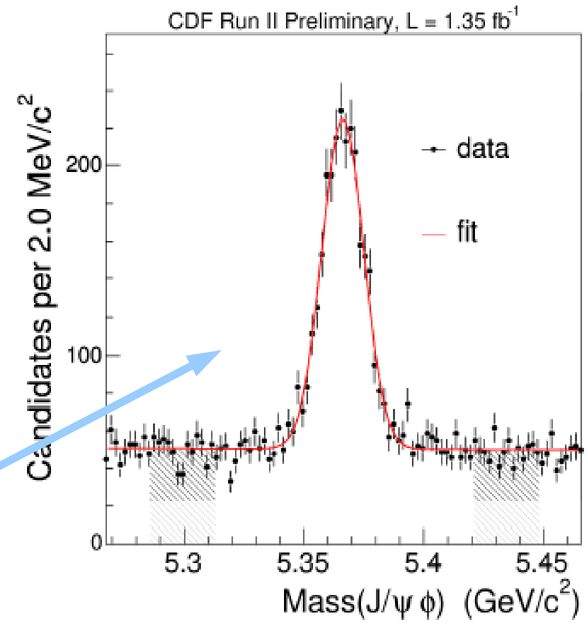
- β_s in SM is predicted to be very small: $\beta_s^{\mathrm{SM}} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \approx 0.02$

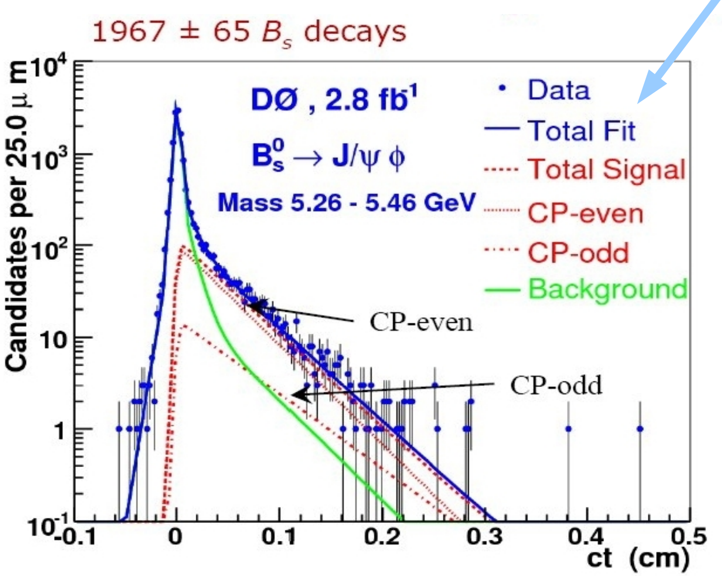
- New Physics affects the CP violation phase as: $2\beta_s = 2\beta_s^{\mathrm{SM}} - \phi_s^{\mathrm{NP}}$

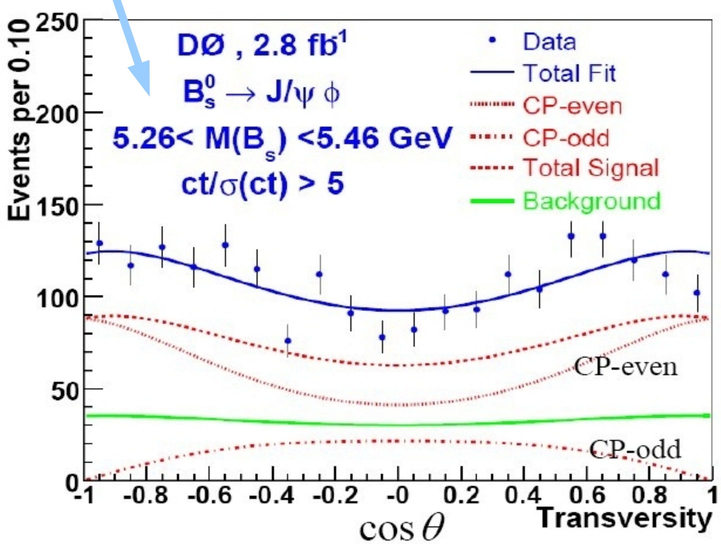
- If NP phase ϕ_s^{NP} dominates → $2\beta_s = -\phi_s^{\mathrm{NP}}$ $\quad \phi_s^{\mathrm{SM}} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$

$B_s \to J/\psi\phi$: samples, projections

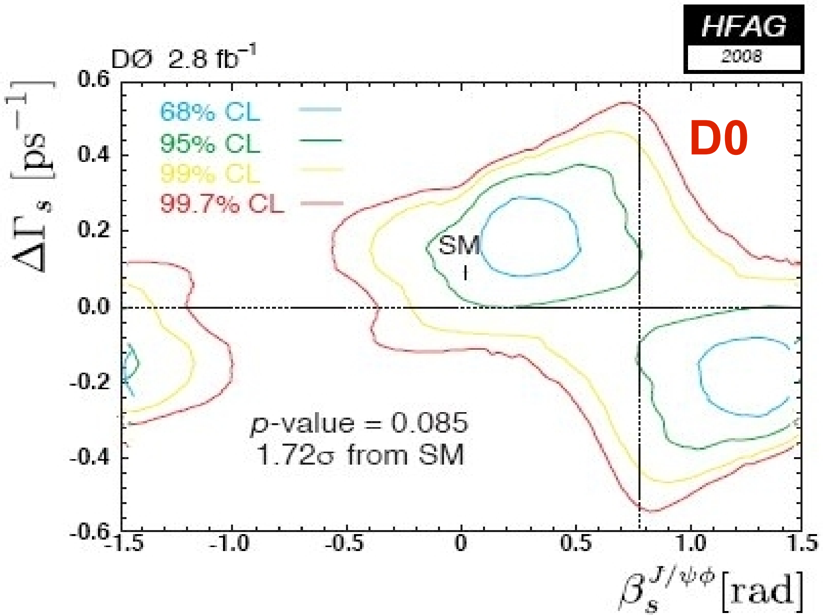
- D0: ~ 2.8 /fb ~ 2000 decays
- CDF: ~ 1.35 /fb ~ 2000 decays
- Angular analysis ($P \to VV$ decay)
- Same flavor tagging as mixing analyses
- Unbinned likelihood fit (3 projections)

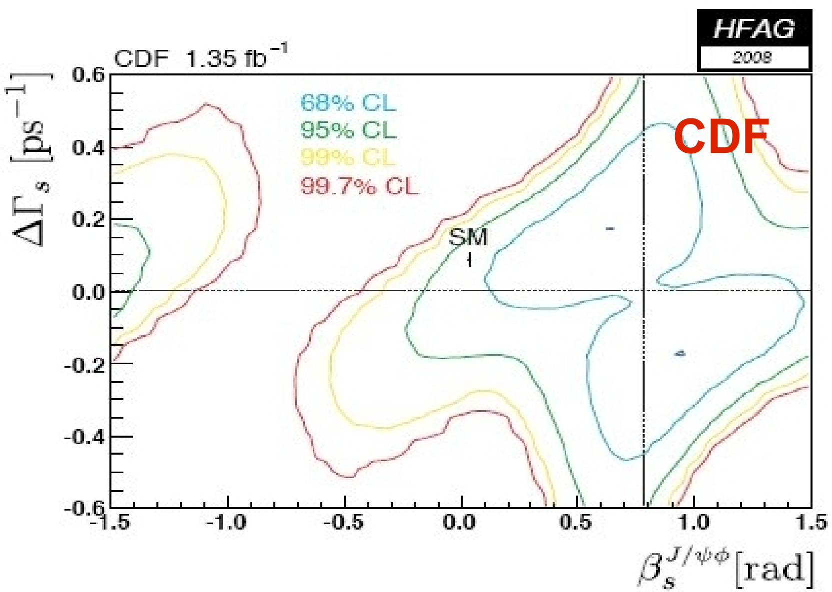


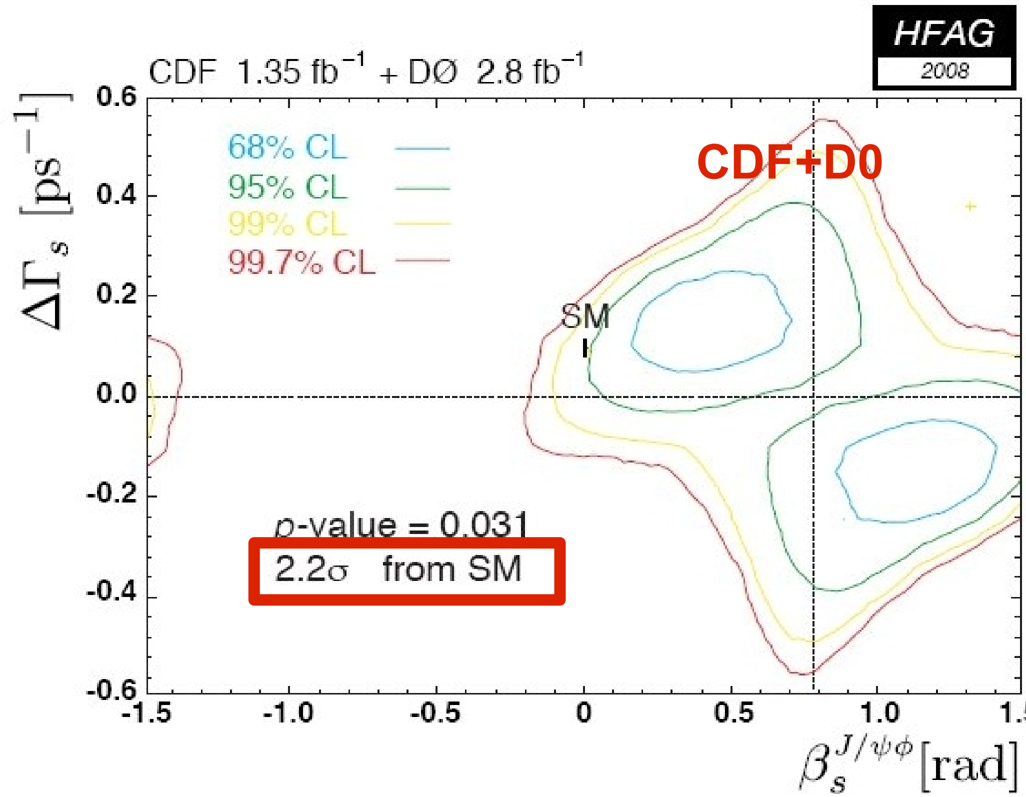




Combined D0 and CDF $\Delta\Gamma - \phi_s^{J/\psi\phi}$ contours







No external constraints!

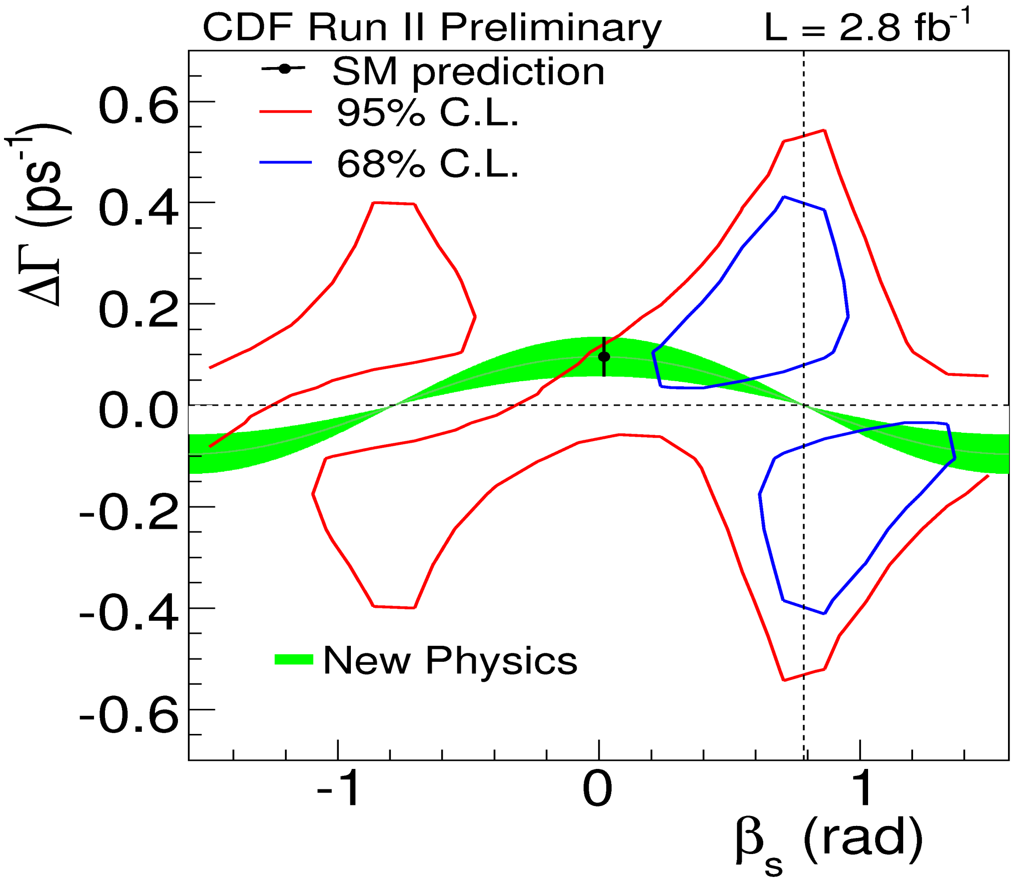
90% C.L. 1-d regions:

$$\phi_s \in [-2.85, -1.65], \quad [-1.47, -0.29]$$

$$\Delta\Gamma_s \in [-0.265, -0.036], \quad [0.036, 0.265]$$

CDF's update for 2.8/fb

- This summer, CDF updated up to 2.8 /fb ==> ~ 3200 events
- However, Same Side Tagging not used in 2nd half of sample
  ==> statistically equivalent to 2.0 /fb
- Consistency with SM decreased: 15% → 7% (~1.8σ)
- D0 and CDF will keep updating measurement of $\phi_s^{J/\psi\phi}$ as one of the Tevatron flagship measurements!



CP asymmetry in semileptonic B_s decays

- Alternative approach to ϕ_s (β_s): semileptonic CP asymmetry related to

$$A^s_{SL} = \frac{1}{2}\frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s$$

- Approach I (D0,CDF): counting ++ and -- muons

$$A_{corr} = \frac{N^{++}_{obs}(\frac{1}{\epsilon^2_+}) - N^{--}_{obs}(\frac{1}{\epsilon^2_-})}{N^{++}_{obs}(\frac{1}{\epsilon^2_+}) + N^{--}_{obs}(\frac{1}{\epsilon^2_-})} = \frac{N^{++}_{obs} - N^{--}_{obs}(\frac{\epsilon_+}{\epsilon_-})^2}{N^{++}_{obs} + N^{--}_{obs}(\frac{\epsilon_+}{\epsilon_-})^2}$$

- *Approach II (D0)*
  - Use $B_s \rightarrow \nu\ell D_s X$ decays, do flavor tagging, extend Bs mixing fit to allow for CP violation in decay

==> *Comparable statistical power, but **improved systematics.***

Parameter	RunII, $\int Ldt = 2.8$ fb^{-1}
a^s_{sl}	-0.0024 ± 0.0117
a^d_{sl}	-0.0787 ± 0.0371
a_{bg}	-0.0182 ± 0.0271
A_{fb}	0.0000 ± 0.0021
A_{det}	0.0001 ± 0.0021
A_{ro}	-0.0323 ± 0.0021
$A_{\beta\gamma}$	-0.0005 ± 0.0021
$A_{q\beta}$	0.0029 ± 0.0021

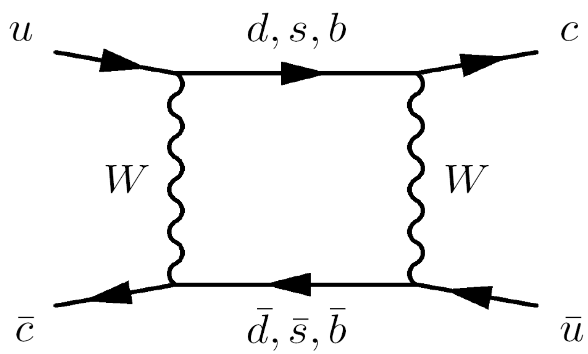
$$a^s_{sl} = -0.0024 \pm 0.0117\ (\text{stat.})\ ^{+0.0015}_{-0.0024}\ (\text{syst.})$$

DØ Run II Preliminary

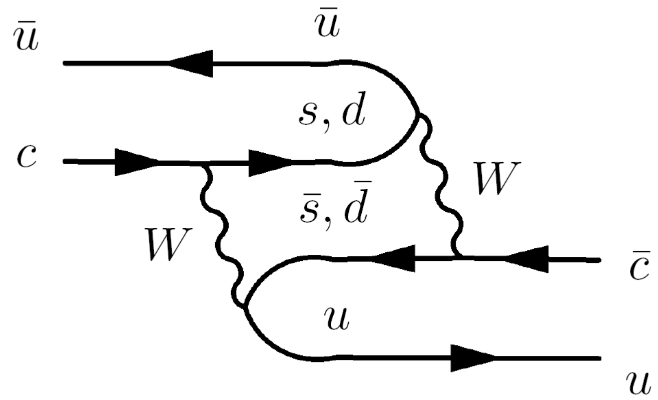
D^0 Mixing

- D^0 mixing in SM occurs through either:

'short range' processes
(negligible in SM)



'long range' processes



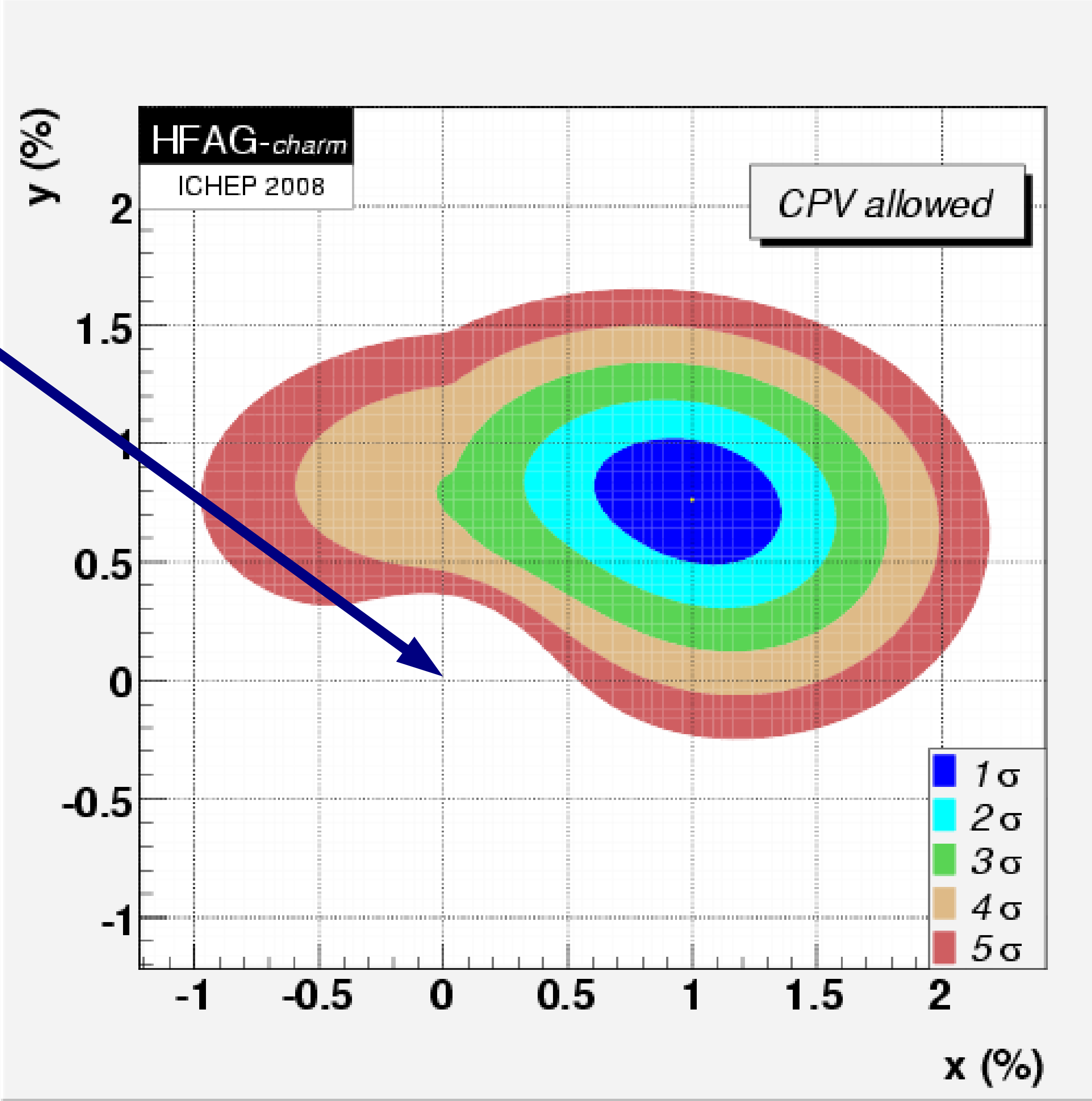
- First observed by BaBar and BELLE in early 2007

- Confirmed by CDF few months later

- Now a whole cottage industry of measurements built around it!

D^0 Mixing – all measurements combined

- The "No mixing" hypothesis: examine point: (x,y) = (0,0)
- $\Delta\chi^2$= 102.6, CL = 5.3 x 10^{-23}
- **No mixing excluded at a whopping 9.8σ !!!**



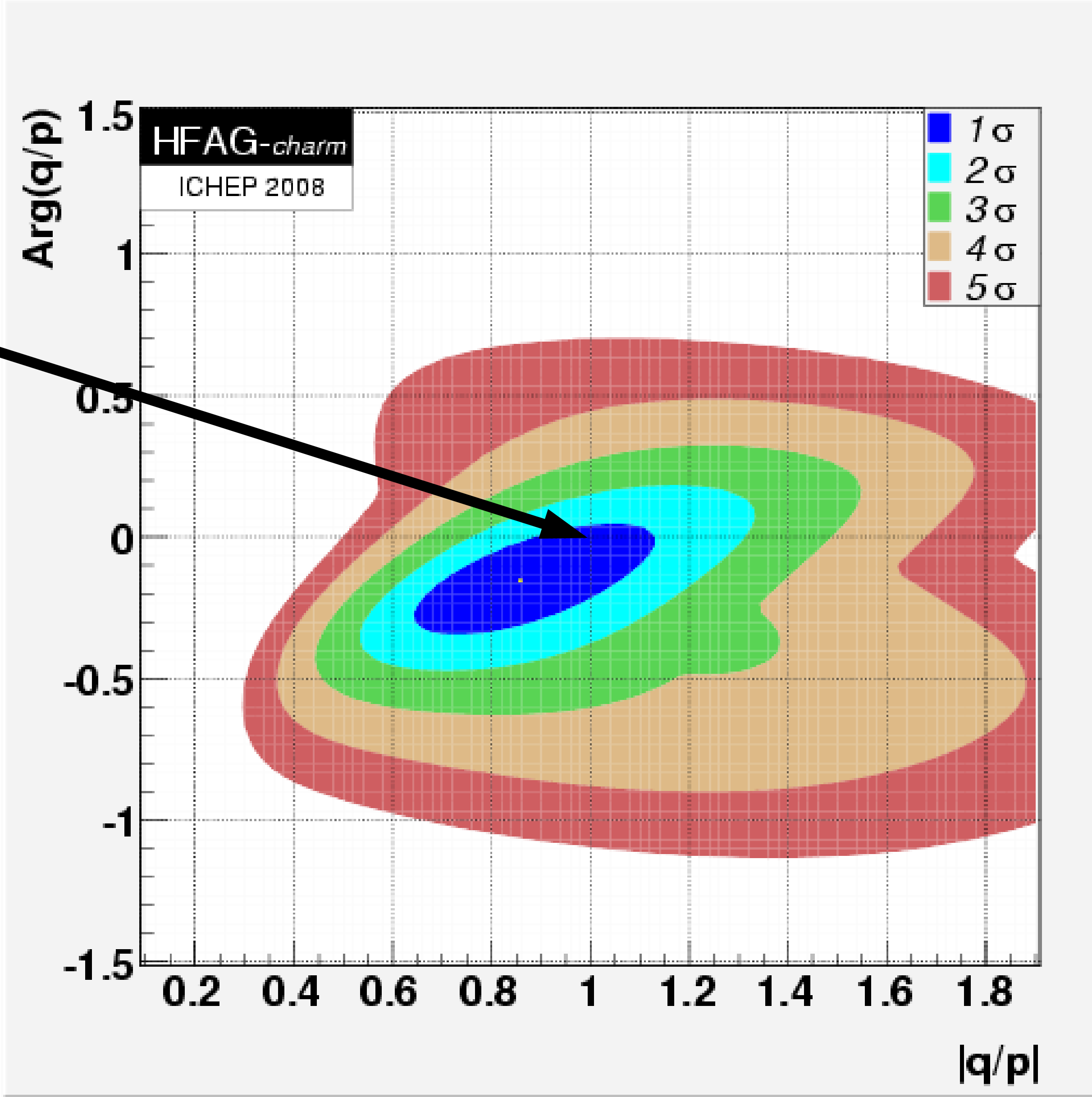
D^0 Mixing – CP violation parameters

- Examine the "No CPV" point

  (|q/p|, φ) = (1,0)

- $\Delta\chi^2$ = 1.33,
  CL = 0.486

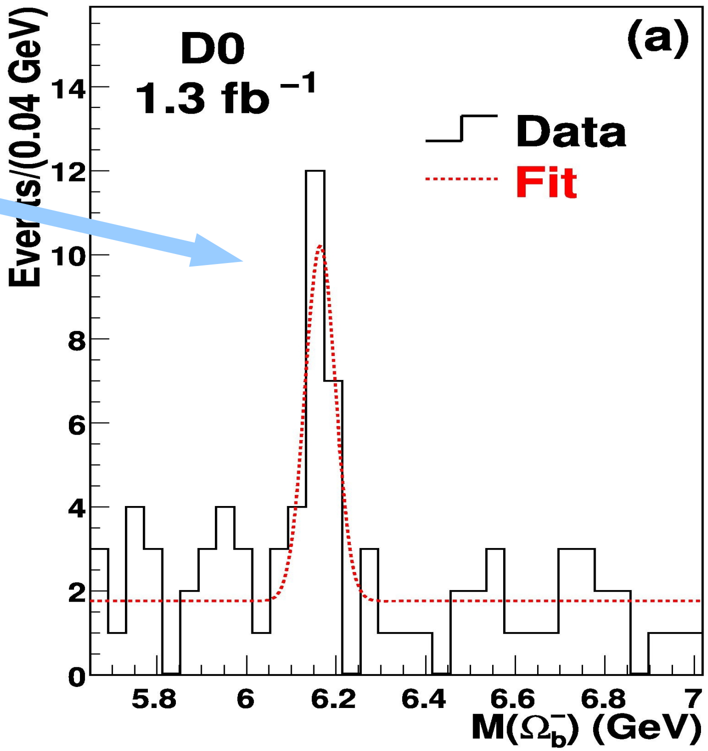
- Consistent with CP conservation

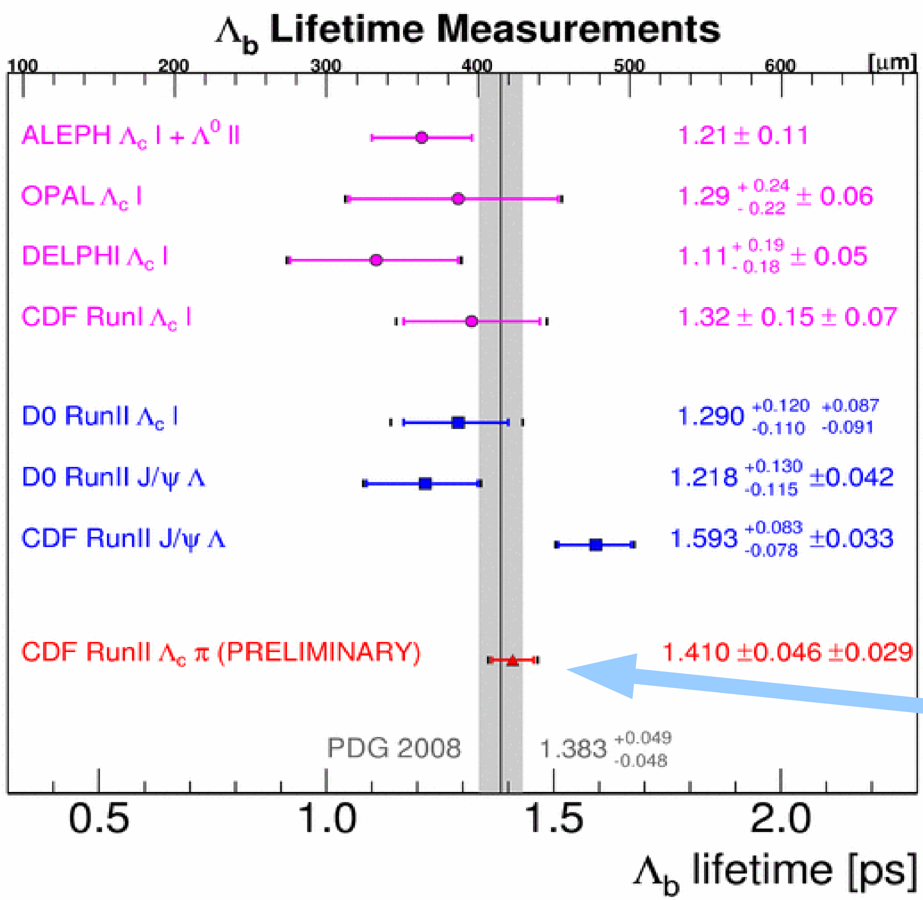


What's in the news but not in this talk

- Hot off the press! D0 discovers Ω_b!

$$\Omega_b^- \to J/\psi\Omega^- \to \mu^+\mu^- p\pi^- K^-$$





- CDF and D0 significantly improve the lifetimes of B_s and Λ_b

End of an era – and a beginning a new one!

- Measurements of angles and sides of the Unitarity Triangle improving with time
- Small discrepancies remain – not (yet!) statistically significant
- Discrepancies in other measurements which could be due to incomplete understanding of the SM?
- New area: measurements of CP violation in B_s system:
  - β_s : reduced physically allowed region by half!
  - A_{SL} is getting more precise
  - Tevatron experiments keep increasing their samples
- Is the New Physics within reach? It's tantalizing...

==> Lots of homework for LHC-b and Super-B factory

Petar Maksimovic, JHU

BACKUP

Role of CLEO-c in pinning down γ (= ϕ_3)

- could extend ADS method to $D^0 \to K3\pi$, but need to know coherence factor, $R_D^{K3\pi}$ and its associated global strong phase $\delta_D^{K3\pi}$
  - CLEO-c measured both

  ==> will significantly help in the future

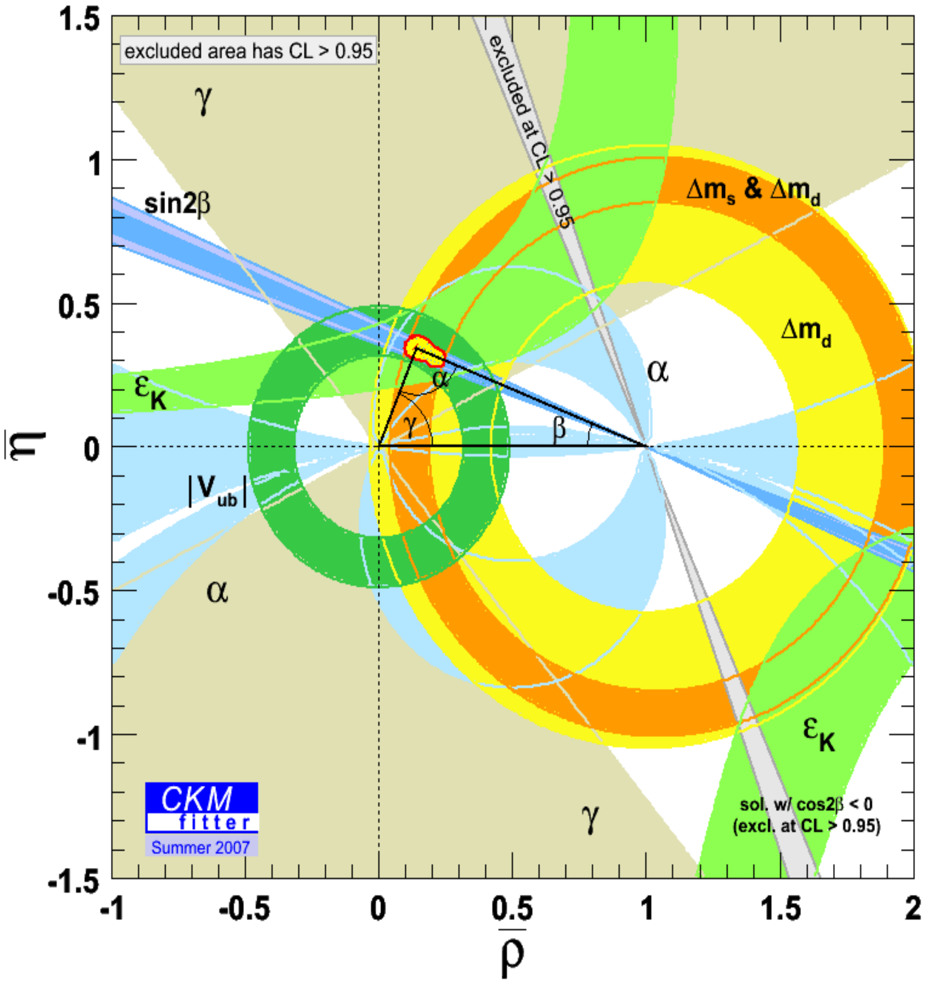
- measurement of bin-averaged cosines (c_i) and sines (s_i) of the differences of strong phases in $D^0 \to K_S^0\pi^+\pi^-$

  ==> allows a model-independent extraction of γ
  - c_i measured in CP-tagged decays
  - c_i and s_i also obtained from Kspipi-tagged decays

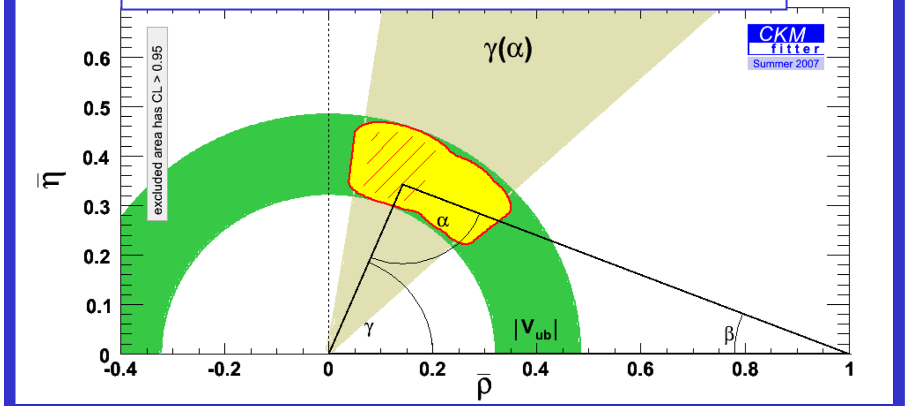
- mesurement of the strong phase in $D^0 \to K\pi$ decays, $\delta_D^{K\pi}$ also helps to determine γ via $B^+ \to D^0(\to K\pi)K^+$ decays

All measurements– Dec '07

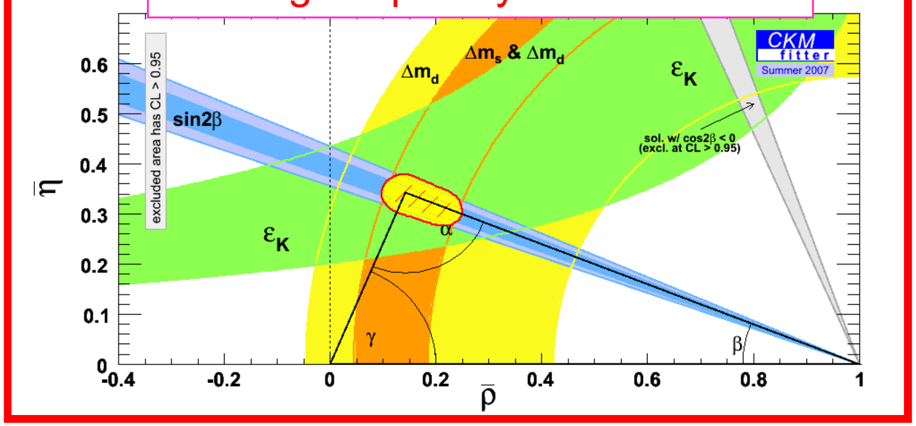
Kaon physics and *B* factories: satisfactory SM picture of CP violation – ***at least at tree level*** – in B^0 and B^+ decays.



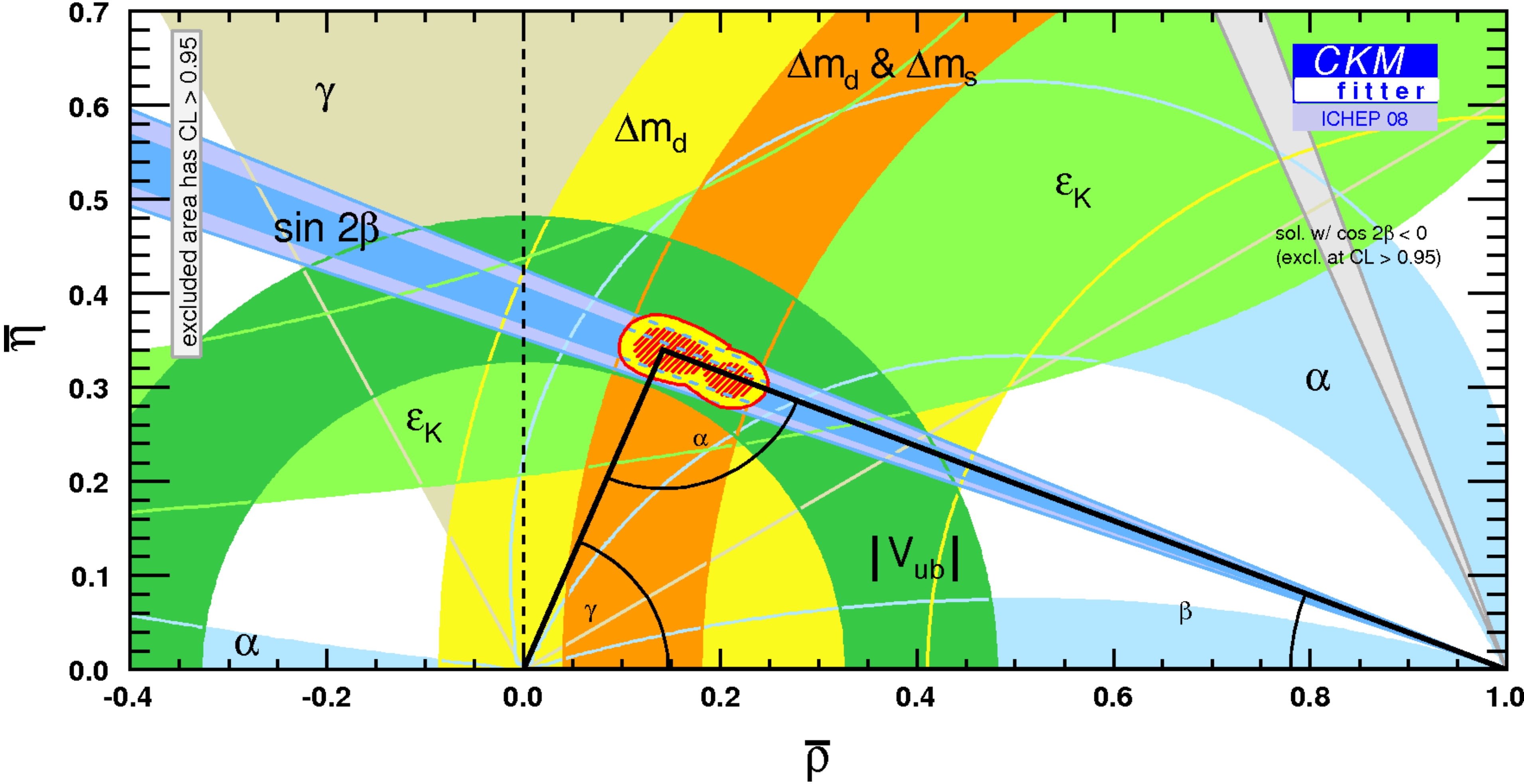
Using 'tree'-only observables



Using 'loop'-only observables



Unitarity Triangle now



Sides: discrepancy in V_{ub}?

- Small discrepancy between V_{ub} measured in exclusively and in inclusively reconstructed decays
- Exclusive: $V_{ub} = (3.7 \pm 0.2 \pm 0.5) \times 10^{-3}$
- Inclusive: $V_{ub} = (4.3 \pm 0.2 \pm 0.3) \times 10^{-3}$

  - **But:** it was pointed out (by Neubert) that if the value of m_b extracted from $b \to s\gamma$ were disregarted, that would yield a consistent value:

$$V_{ub} = (3.98 \pm 0.15 \pm 0.30) \times 10^{-3}$$

- Needs further analysis.

Neutral B_s System

- Time evolution of B_s flavor eigenstates described by Schrodinger equation:

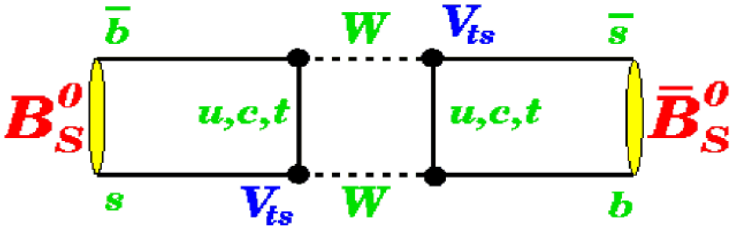
$$i\frac{d}{dt}\begin{pmatrix}|B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle\end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix}|B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle\end{pmatrix}$$

- Diagonalize mass (M) and decay (Γ) matrices
  → mass eigenstates

$$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle \qquad |B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle$$

where $q/p = \frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}$

mass eigenvalues are different ($\Delta m_s = m_H - m_L \approx 2|M_{12}|$)
→ B_s oscillates with frequency Δm_s



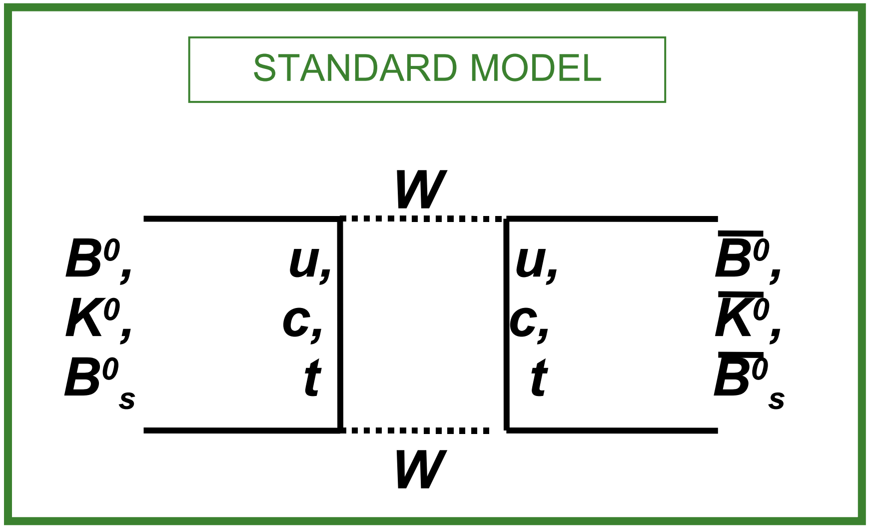
- Precisely measured by
  - CDF Δm_s = 17.77 +/- 0.12 ps^{-1}
  - DØ Δm_s = 18.56 +/- 0.87 ps^{-1}

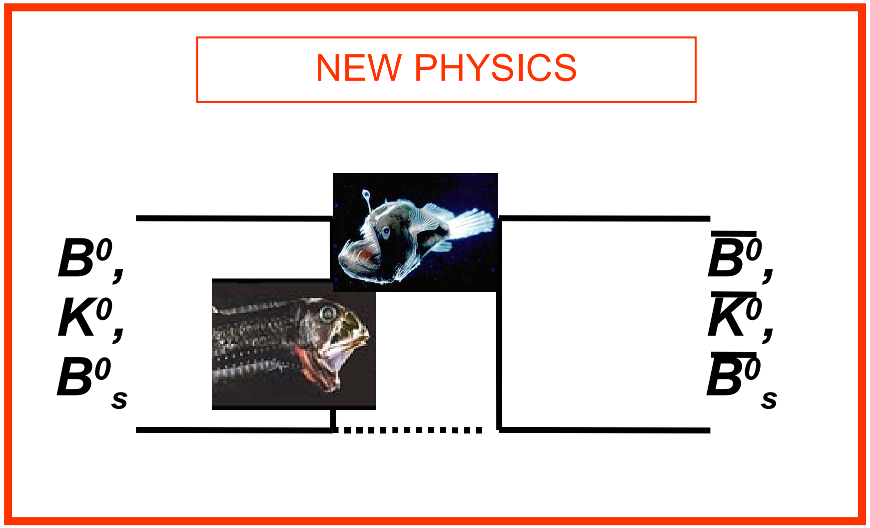
- Mass eigenstates have different decay widths
  $\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(\Phi_s)$ wher $\phi_s^{SM} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$ ≈ 4 x 10^{-3}

Petar Maksimovic, JHU

Example of possible NP contribution

New physics, if any, in suppressed processes, as flavor-mixing (or FCNC).





Effective field theory factorizes New Physics into a complex amplitude

$$\frac{\langle M|H_{\rm eff}^{\rm full}|\bar{M}\rangle}{\langle M|H_{\rm eff}^{\rm SM}|\bar{M}\rangle} = C_M e^{2i\phi_M}$$

$$C_{B_s}\, e^{2i\phi_{B_s}} = \frac{A_s^{\rm SM} e^{-2i\beta_s} + A_s^{\rm NP} e^{2i(\phi_s^{\rm NP}-\beta_s)}}{A_s^{\rm SM} e^{-2i\beta_s}} = \frac{\langle B_s|H_{\rm eff}^{\rm full}|\bar{B}_s\rangle}{\langle B_s|H_{\rm eff}^{\rm SM}|\bar{B}_s\rangle},$$

Bottom line: to constrain NP need to measure <u>magnitude and phase</u>

$B_s \to J/\psi\phi$ phenomenology

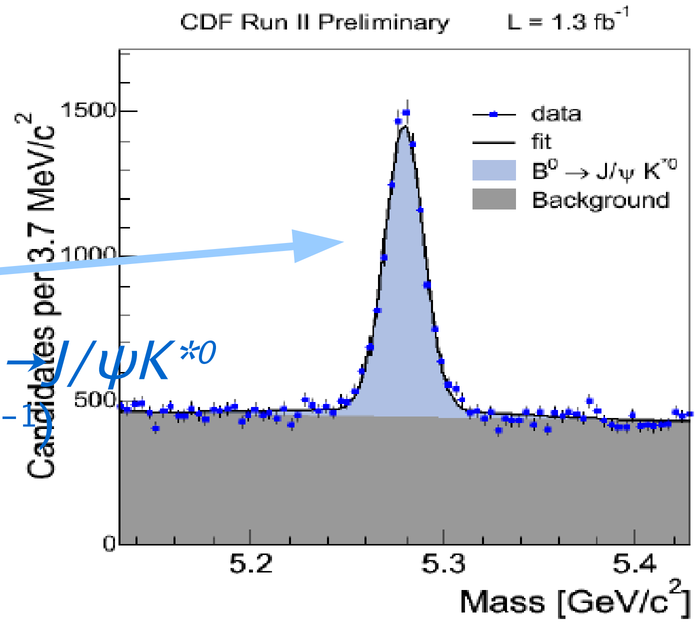
- Good approximation: $\phi_s \approx 0$
  ==> mass eigenstates $|B_s^L\rangle$ and $|B_s^H\rangle$ are CP eigenstates

  → use angular information to separate heavy and light states
  → determine decay width difference

  $$\Delta\Gamma = \Gamma_L - \Gamma_H$$

  → some sensitivity to CP violating phase β_s

  - Determine B_s flavor at production (flavor tagging)
    → improve sensitivity to β_s

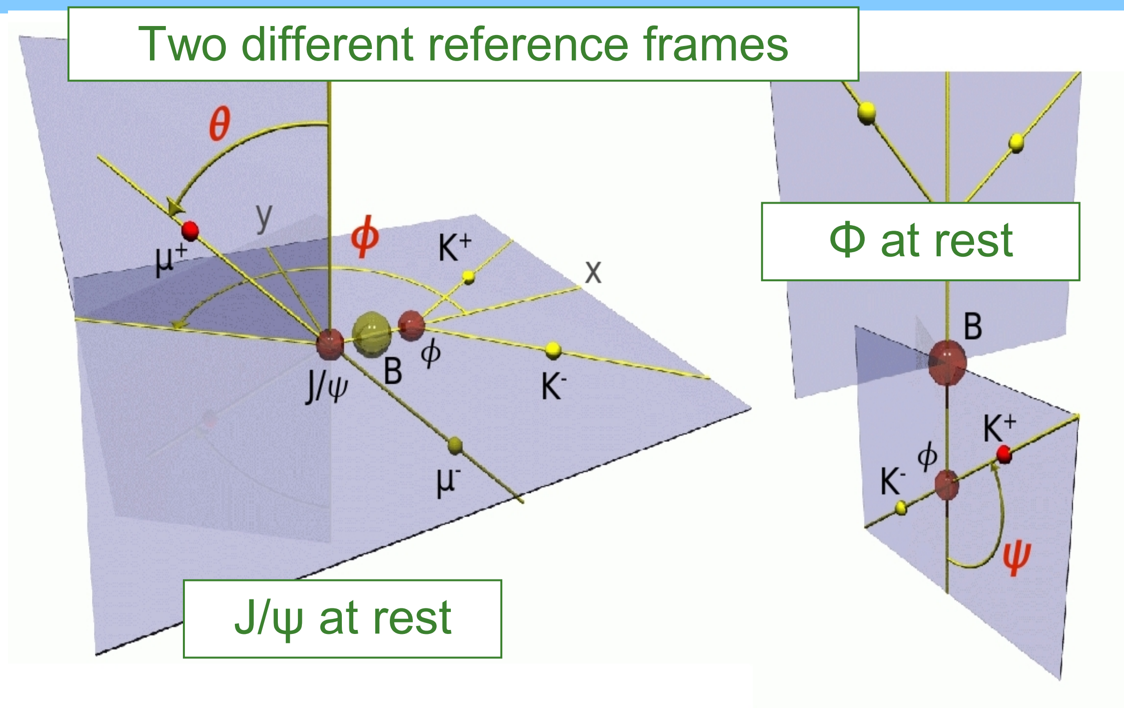


- Cross-check procedure for angular decomposition on $B^0 \to J/\psi K^{*0}$ (~7800 events from 1.3 fb^{-1})

"Transversity" Basis

- Can measure $\tau(Bs)$, $\Delta\Gamma$, and, *using known Δm_s*, CP violating phase β_s

- Decay is $P \to VV$ so 3 angular momentum states form a basis for the final $J/\psi\phi$ state



Decay amplitude decomposed (in terms of linear polarization) when J/ψ and ϕ are

A_0:	longitudinally polarized	(CP-even)
$A_{\|\|}$:	transversely polarized and $\|\|$ to each other	(CP-even)
$A_\perp$:	transversely polarized and $\perp$ to each other	(CP-odd)

=> 3 angles describe directions of final decay products

→ $\rho = \rho(\cos\theta, \phi, \cos\psi)$

"Strong" phases: $\delta_\perp = \arg[A_\perp^* A_0]$, $\delta_\| = \arg[A_\|^* A_0]$,

Decay PDF for B^0_s and $\bar{B}^0_s$

B^0_s term

$$\frac{d^4P(t,\vec{\rho})}{dt d\vec{\rho}} \propto |A_0|^2\mathcal{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2\mathcal{T}_+ f_2(\vec{\rho}) + |A_\perp|^2\mathcal{T}_- f_3(\vec{\rho}) + |A_\parallel||A_\perp|\mathcal{U}_+ f_4(\vec{\rho}) + |A_0||A_\parallel|\cos(\delta_\parallel)\mathcal{T}_+ f_5(\vec{\rho}) + |A_0||A_\perp|\mathcal{V}_+ f_6(\vec{\rho}),$$

anti-B^0_s

$$\frac{d^4\overline{P}(t,\vec{\rho})}{dt d\vec{\rho}} \propto |A_0|^2\mathcal{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2\mathcal{T}_+ f_2(\vec{\rho}) + |A_\perp|^2\mathcal{T}_- f_3(\vec{\rho}) + |A_\parallel||A_\perp|\mathcal{U}_- f_4(\vec{\rho}) + |A_0||A_\parallel|\cos(\delta_\parallel)\mathcal{T}_+ f_5(\vec{\rho}) + |A_0||A_\perp|\mathcal{V}_- f_6(\vec{\rho}),$$

A_0, $A_\parallel$, $A_\perp$: transition amplitudes in a given polarization state at time 0

$f(\rho)$: angular distribution for a given polarization state

Time Evolution with Flavor Tagging

$$\mathcal{T}_\pm = e^{-\Gamma t} \times \left[\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2) \mp \eta \sin(2\beta_s)\sin(\Delta m_s t)\right],$$

$$\mathcal{U}_\pm = \pm e^{-\Gamma t} \times \left[\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t) - \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right],$$

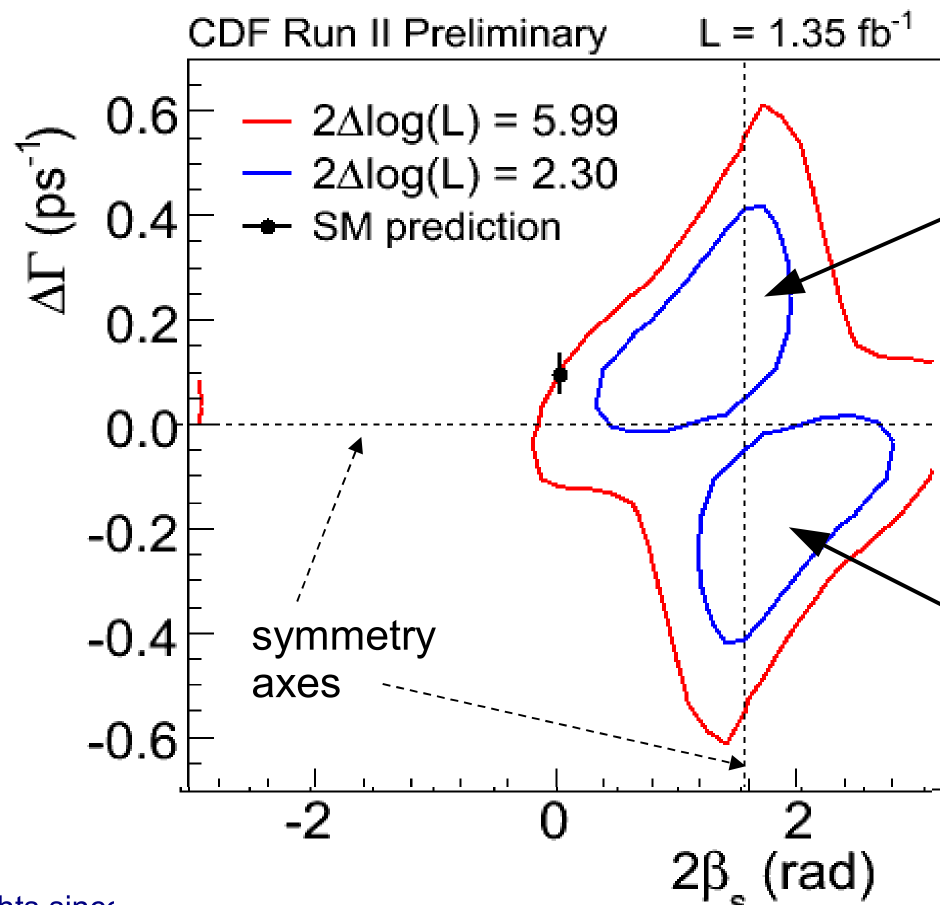
$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times \left[\sin(\delta_\perp)\cos(\Delta m_s t) - \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right].$$

β_s sensitivity

CDF result as input

Tagged $B_s \to J/\psi\phi$ analysis

- First tagged analysis of $B_s \to J/\Psi\Phi$ (1.4 fb^{-1})
- Signal B_s yield ~2000 events with S/B ~ 1



$\cos(\delta_\perp) < 0$
$\cos(\delta_\perp - \delta_\parallel) > 0$

strong phases can separate the two minima

$\cos(\delta_\perp) > 0$
$\cos(\delta_\perp - \delta_\parallel) < 0$