Recent studies of CP violation at the Tevatron

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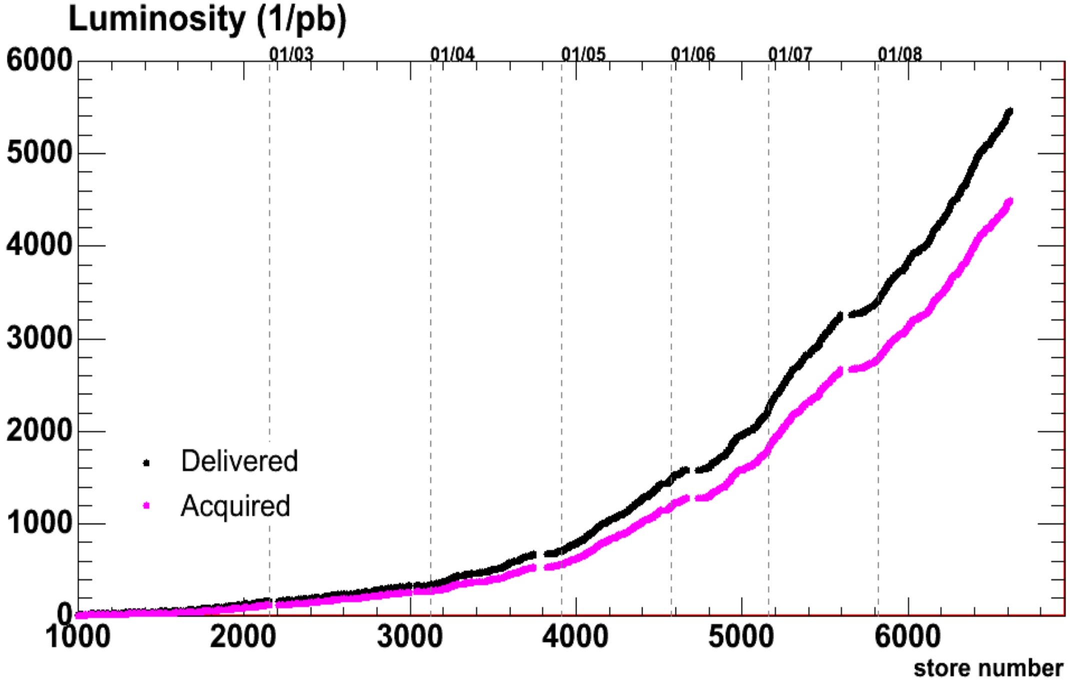
Introduction : Three Types of CP Violation

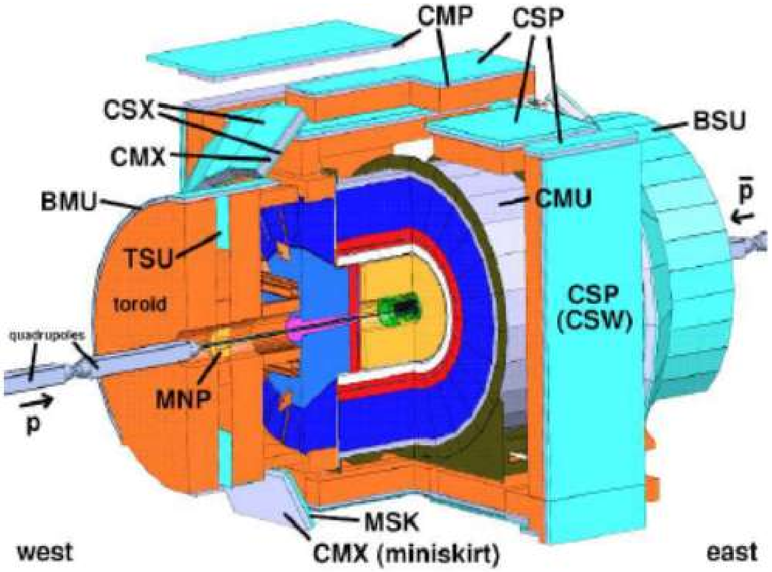
- I) Direct CPV (decay of hadrons)
  - $B^0_s \rightarrow K^- \pi^+$ [1 fb^{-1} , CDF]
  - $\Lambda_b \rightarrow p\, \pi^-$ and $\Lambda_b \rightarrow p\, K^-$ [1 fb^{-1} , CDF]
  - $B^+ \rightarrow J/\psi\, K^+ (\pi^+)$ [2.8 fb^{-1} , D0]
  - $B^+ \rightarrow DK^+$ [1 fb^{-1} , CDF]
- II) CPV in mixing (semileptonic decays of neutral mesons)
  - flavor-tagged measurement of B^0_s semileptonic asymmetry, a^s_{sl} [2.8 fb^{-1} , D0; 1.6 fb^{-1} , CDF]
- III) CPV through interference of mixing and decay
  - in $B_s^0 \rightarrow J/\psi\varphi \Rightarrow \beta_s$ [2.8 fb^{-1} , CDF & D0]
- All three types of CPV can be tested at the Tevatron
- Highlight results for the B_s sector in the following (but $B_{d,u}$ results are as good or better than B-factories for several channels)

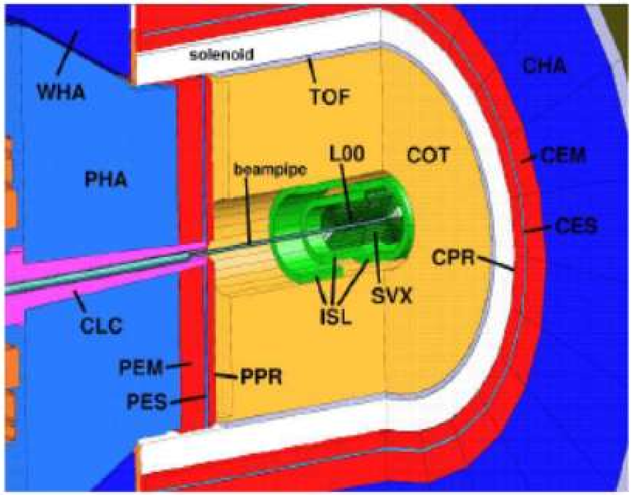
Introduction to the Tevatron



- ppbar collisions at 1.96 TeV
- Excellent performance of Tevatron accelerator
- Peak Initial Luminosity recent record : 3.6×10^{32} cm^{-2} s^{-1}
- CDF and D0 have already **>4.5 fb^{-1}** on tape
- Expect 6 fb^{-1} by 2009 (8 if 2010 extension approved)
- The analyses presented in this talk span from 1 to 2.8 fb^{-1}

CDF detector





•Drift chamber (COT)

⇒ Good tracking resolution

$\sigma(p_T)/p_T \sim 0.1\ \%\ GeV^{-1}$

• Silicon vertex detector

⇒ Good vertex resolution

⇒ Important for triggering

(using a displaced track trigger, SVT)

• TOF detector and dE/dx from COT

⇒ Good particle identification

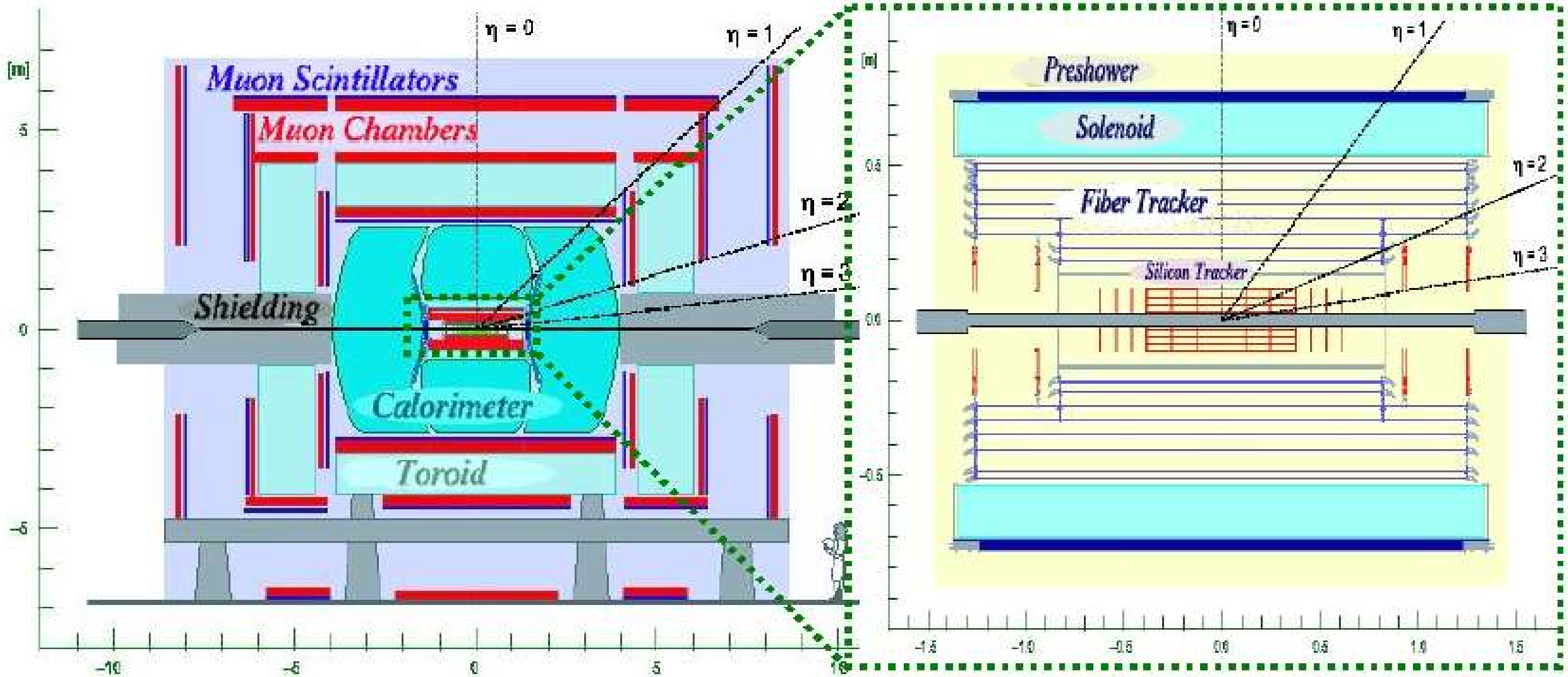
• Muon System up to $|\eta| < 1.5$

⇒ Important for triggering

D0 detector

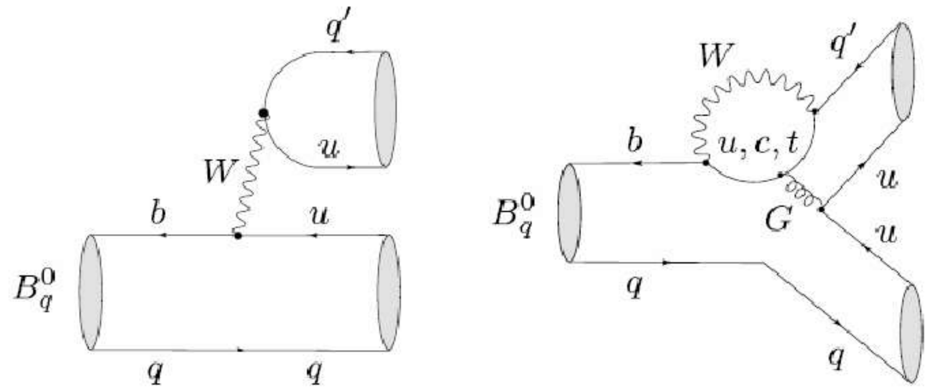
- Good coverage of Tracking and Muon system ($|\eta|<2.2$)
- Good calorimetry and electron identification
- Solenoid 2T: <u>weekly reversed polarity</u>
- High efficiency muon trigger
- Silicon vertex Detector

$\Rightarrow$ Good vertex resolution



CP violation (I) :
Direct CP Violation

Direct CP violation in $B_{d,s} \rightarrow K\,\pi$

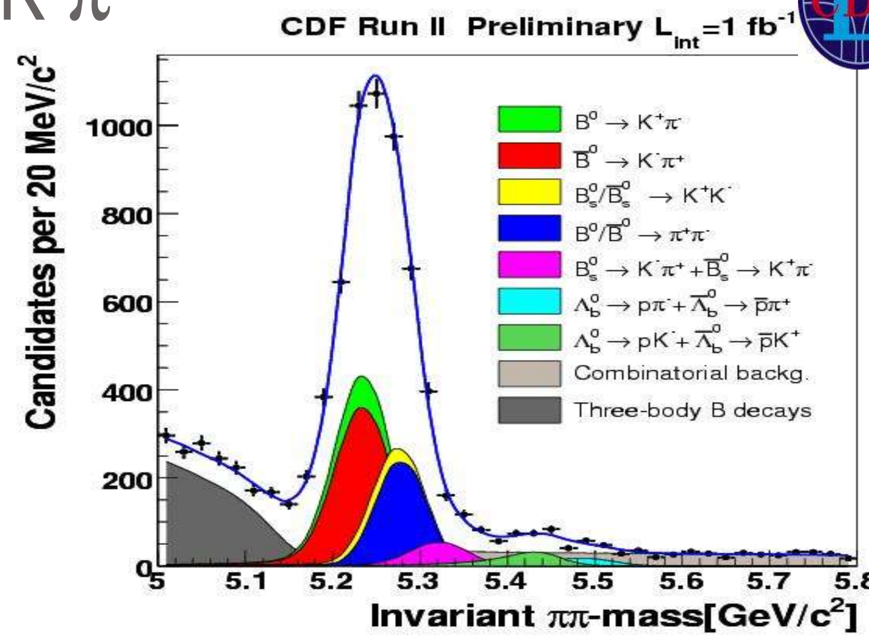


Tree and penguin topologies contributing to the U-spin-related $B_d^0 \to \pi^+\pi^-$, $B_s^0 \to K^+K^-$ and $B_d^0 \to \pi^-K^+$, $B_s^0 \to \pi^+K^-$ decays ($q, q' \in \{d, s\}$).

- Interference between Tree and Penguin amplitudes may generate sizeable direct CP violation
- Sensitive to CKM angle γ
- Theory predictions uncertain (strong phases)
- Useful combining B_d and B_s to test/use flavor symmetries (U-spin, SU(3), etc.)
- Direct CP violation is decay property, it is the difference of decay rate between $B_{d,s} \rightarrow$ final state and $\overline{B}_{d,s} \rightarrow \overline{\text{final state}}$

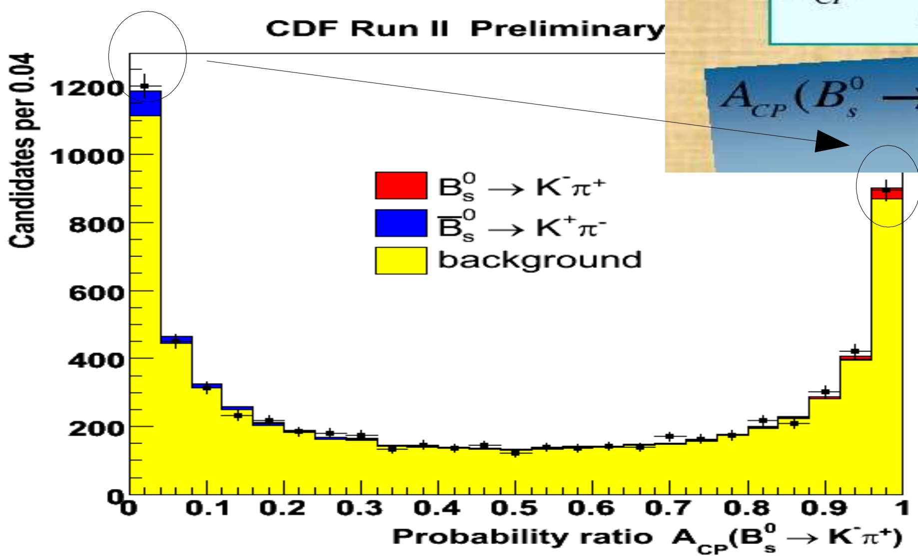
Direct CP violation in $B_{d,s} \to K\pi$

- Large signal selected through the displaced track trigger. Superposition of $B_d \to K\pi$, $B_d \to \pi\pi$, $B_s \to KK$, $B_s \to K\pi$ and Λ_b ($\to p\,\pi/K$)
- Multidimensional fit to kinematics + dE/dX information to separate components
- B0 signal yield and resolution comparable to B-factories (with $1\,fb^{-1}$ of Tevatron data)
- 1^{st} observation of $B_s \to K\pi$ mode and 1^{st} measurement of direct CPV



$$A_{CP} = \frac{N(\bar{B}^0_s \to K^+\pi^-) - N(B^0_s \to K^-\pi^+)}{N(\bar{B}^0_s \to K^+\pi^-) + N(B^0 \to K^-\pi^+)}$$

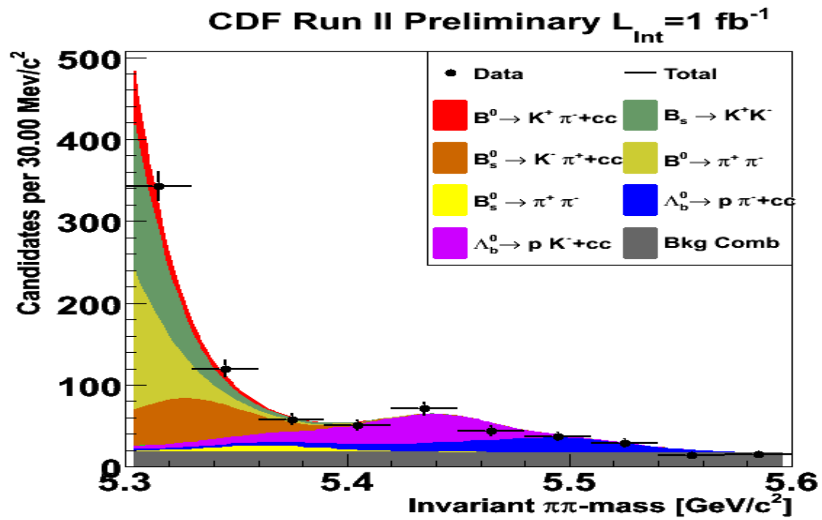
$$A_{CP}(B^0_s \to K^-\pi^+) = 0.39 \pm 0.15\ (stat) \pm 0.08\ (syst)$$

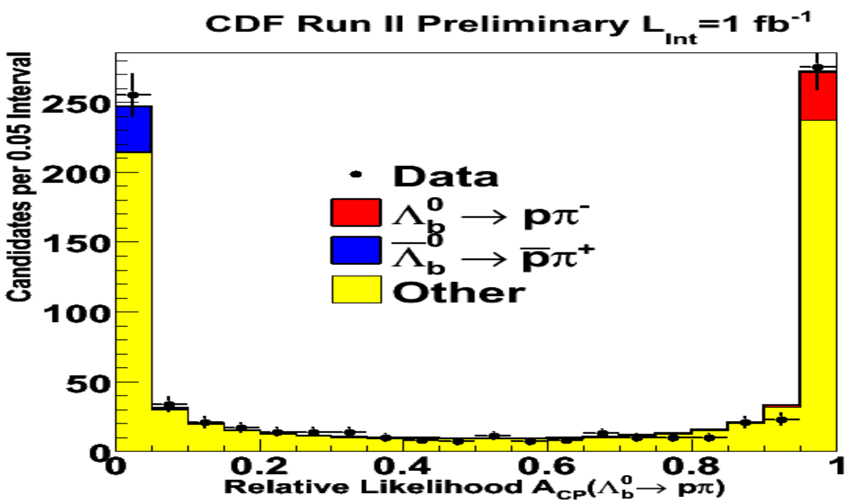


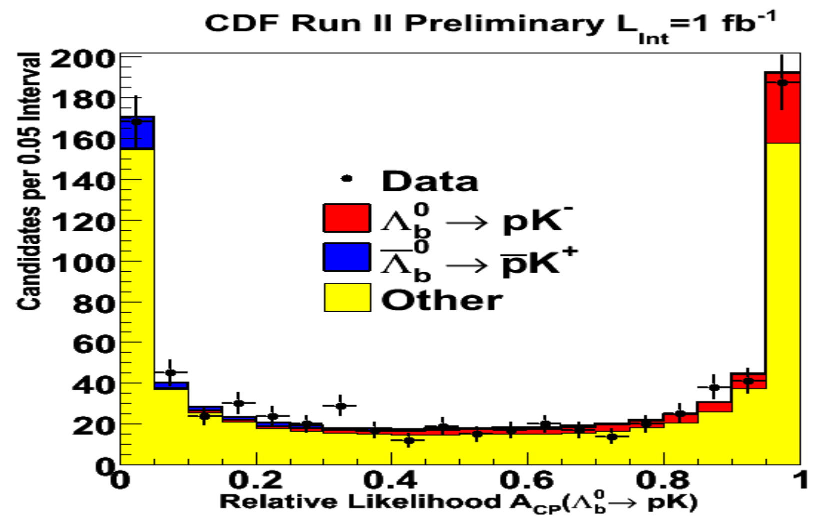
- A_{CP} is 2.5 σ different from 0
- Compatible with expectation [H.J.Lipkin, Phys. Lett. B 6212, 126 (2005)] : $A_{CP} \approx 0.37$

Results on direct CP asymmetry from $\Lambda_b \to ph$

- Same quark level transition as $B \to K\pi$
- SM expects large direct CPV for $\Lambda_b \to pK$ [O(10%)]
- Very little known from theory
- Another decay to test SM and search for new physics





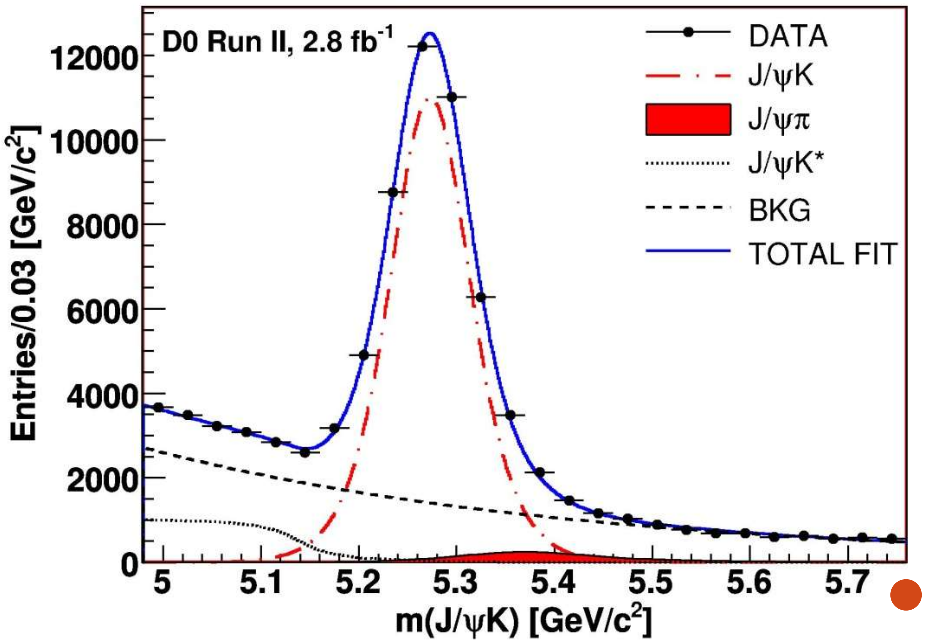


$A_{CP}(\Lambda_b \to p\pi) = 0.03 \pm 0.17 \pm 0.05$ **$A_{CP}(\Lambda_b \to pK) = 0.37 \pm 0.17 \pm 0.03$**

- 1st measurement at 2.1σ from SM expectation (still consistent with SM)

New Measurement of Direct CPV in $B^+ \to J/\psi K^+ (\pi^+)$

PRL **100**, 211802 (2008)



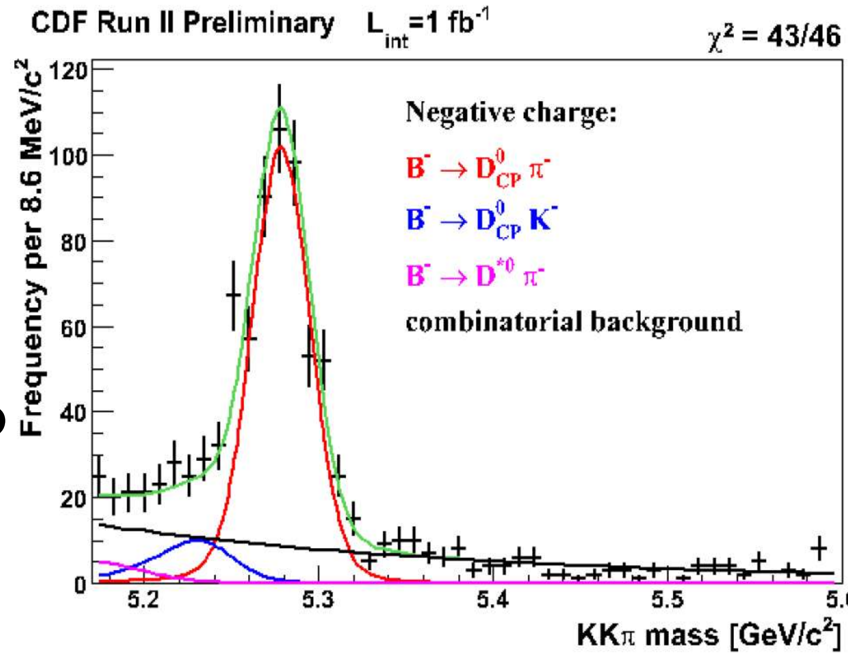
- Probes $b \to c\bar{c}s$ transition
- SM predicts $A_{CP}(B^+ \to J/\psi K^+) \sim 0.003$
- NP might produce asymmetries up to ~0.01
- D0 has around 40000 $B^+ \to J/\psi K^+$
- $$A_{CP} = \frac{N(B^- \to J/\psi K^-(\pi^-)) - N(B^+ \to J/\psi K^+(\pi^+))}{N(B^- \to J/\psi K^-(\pi^-)) + N(B^+ \to J/\psi K^+(\pi^+))}.$$
- Main effort driven to understand the detector asymmetry (using $D^{*+} \to D^0 \pi^+$ with $D^0 \to \mu^+ \nu_\mu K^-$)

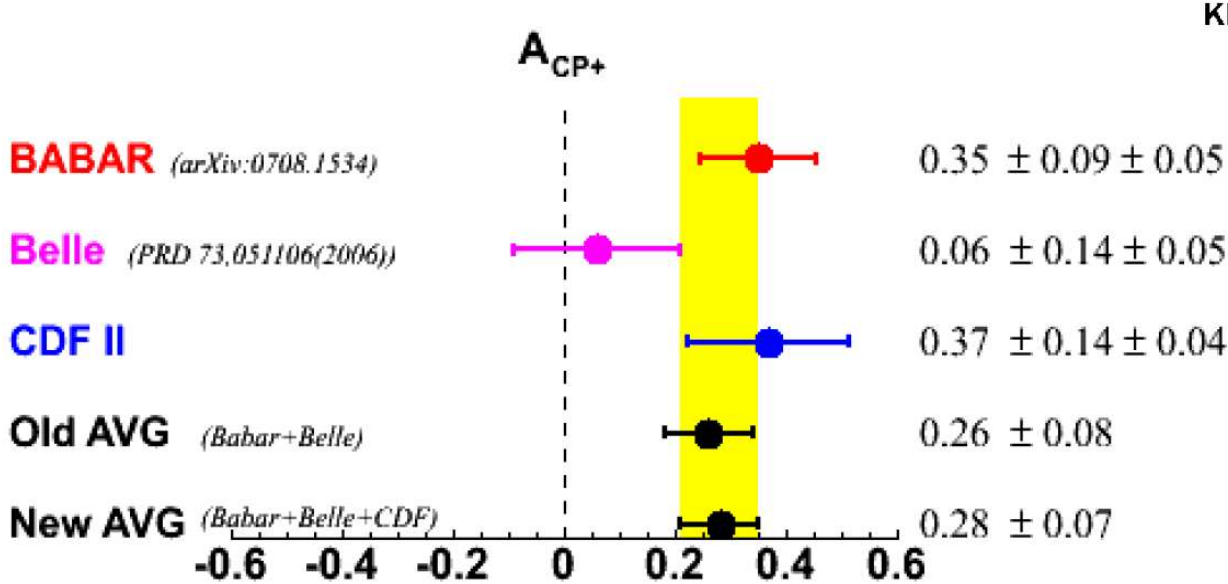
$A_{CP}(B^+ \to J/\psi K^+) = +0.0075 \pm 0.0061\ (\text{stat}) \pm 0.0027\ (\text{syst})$

$A_{CP}(B^+ \to J/\psi \pi^+) = -0.09 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst})$

Measurement of Direct CPV in $B^+ \rightarrow DK^+$

- Significant number of $B^+ \rightarrow DK^+$ events (this analysis ~ 120 $B^+ \rightarrow D_{CP}K^+$ events)
- Kinematics + PID separation allow firm establishment Cabibbo suppressed D^0 decays (CP+). Resolution as Babar/Belle

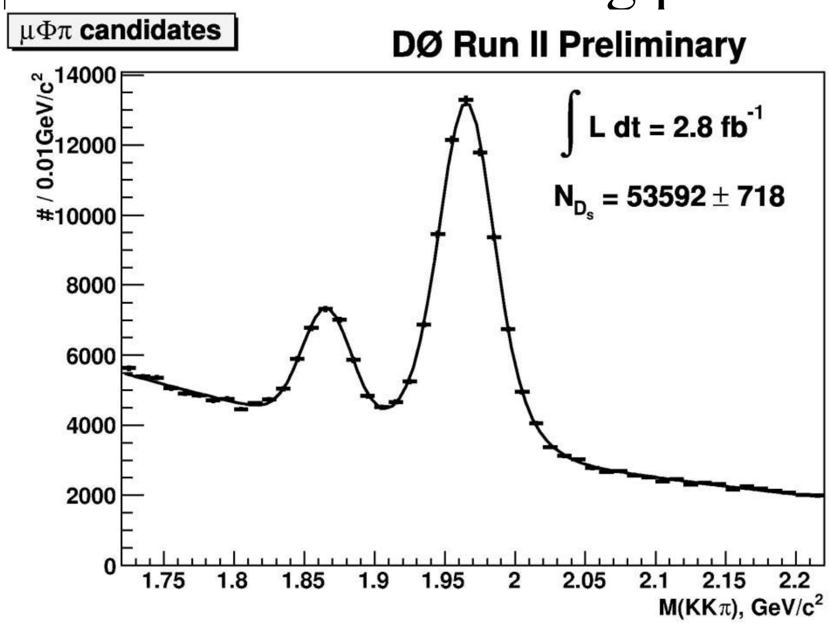




CP violation (II) :
CP Violation on mixing

B^0_s semileptonic asymmetry, a^s_{sl}

- New flavor-tagged measurement of B_s^0 semileptonic asymmetry, a^s_{sl}
  - $B_s^0 \rightarrow D_s^- \mu^+ \nu X \rightarrow [\varphi\pi^-]\, \mu^+ \nu X$
  - Muon gives the final state flavor, use flavor tagging to get flavor of initial state. D0 trigger selects 100% tagged events
  - E laborated fitting procedure depends on lifetime, $\Delta\Gamma$, Δm_s, and a^s_{sl}



Most precise measurement to date!

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

Previous, D0 untagged measurement

$a^s_{sl} = 0.0245 \pm 0.0193$ (stat) ± 0.0035 (syst)

Previous, CDF measurement (1.6 fb^{-1}) (dimuon charge asymmetry)

$a^s_{sl} = 0.020 \pm 0.021$ (stat) ± 0.018 (syst)

www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B55/

CP Violation (III) :
CPV through interference of mixing and decay

$\beta_s^{J/\psi\varphi}$, beyond the Standard Model ?

- B-factories: large new physics (NP) disfavored in 'tree' processes. If any, look in loops
- NP factorized into a complex amplitude

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

$\Delta m_s = C_M\, \Delta m_s^{SM}$: LQCD-dominated uncertainty

Experimentally-dominated uncertainty
This measurement is today's topic

To constrain NP both, strengh and phase measurements needed

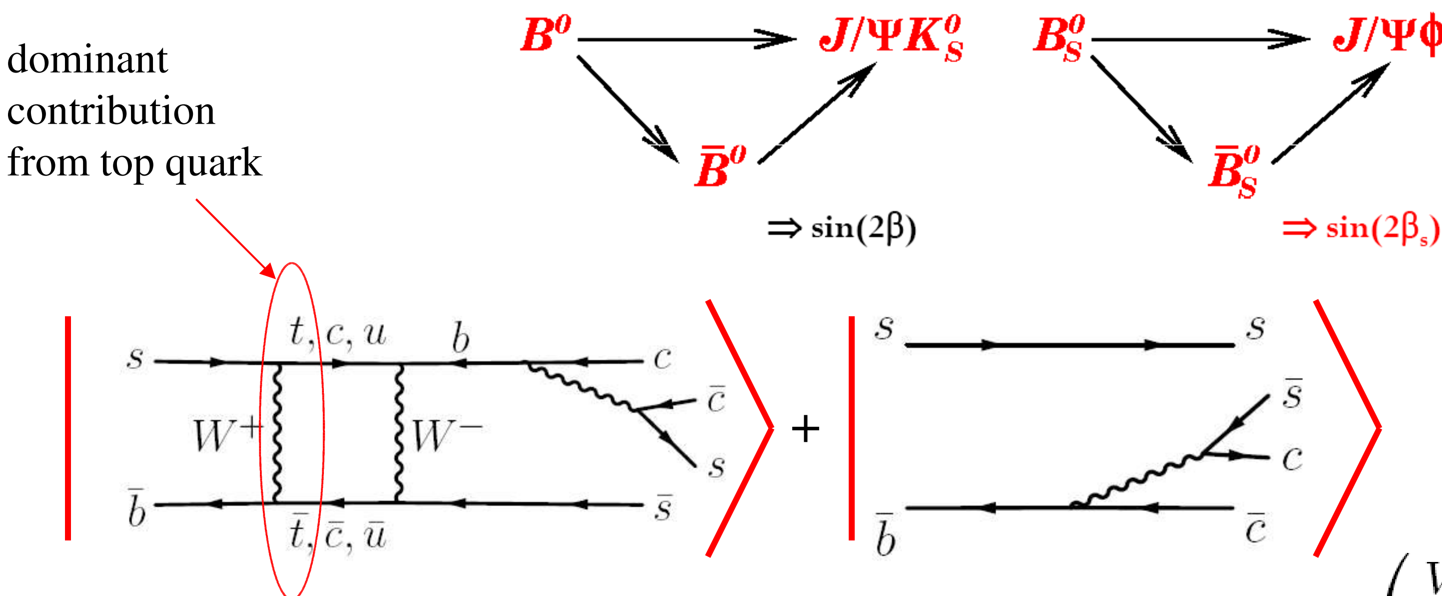
- CP violation in B^0_s predicted to be extremely small in the SM.
- Contribution from new physics could come through the enhancement of loop processes

What Is what we measure?

- look at any **difference** in properties like decay rate, angular decomposition of the amplitude, etc **between** a decay and its "mirror image" resulting from C and P transformations

CP Violation in $B_s \rightarrow J/\psi\phi$ Decays

- Analogously to the neutral B^0 system, CP violation in B_s system occurs through interference of decays with and without mixing:



$$\beta_s^{\rm SM} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$$

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

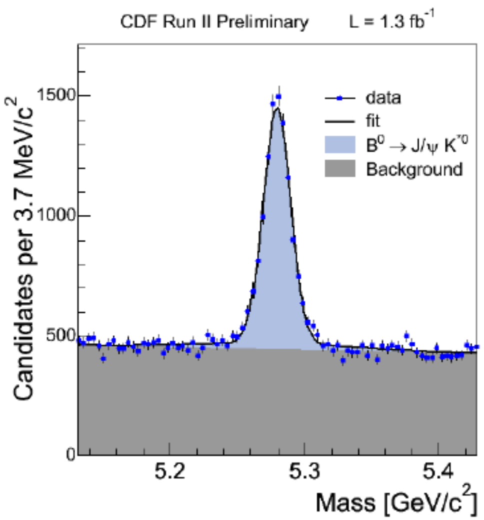
- New Physics CPV can compete or even dominate over small Standard Model CPV phase β_s, predicted to be $O(10^{-2})$
- Ideal place to search for New Physics

Measurement Strategy

- Reconstruct $B_s^0 \to J/\psi(\to \mu^+\mu^-)\ \phi(\to K^+K^-)$
- Use angular properties of the $J/\psi\ \phi$ decay to separate angular momentum states which correspond to CP eigenstates
- Identify initial state of B_s meson (flavour tagging) and thus separate time evolution of B_s^0 and $\bar{B}_s^0$ to maximize sensitivity to CP asymmetry ($\sin 2\beta_s$)
- Perform un-binned maximum likelihood fit to extract signal parameters of interest (e.g. β_s, $\Delta\Gamma=\Gamma_L-\Gamma_H$)

Data-driven checks

Angles



$c\tau = 456 \pm 6$ (stat) ± 6 (syst) μm

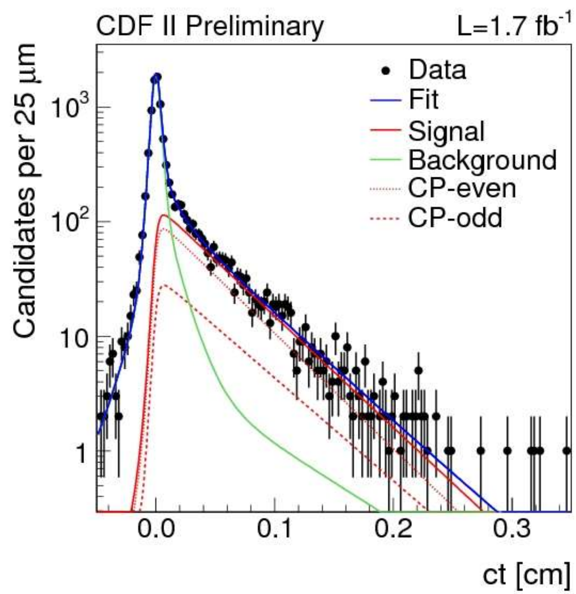
$|A_0(0)|^2 = 0.569 \pm 0.009$ (stat) ± 0.009 (syst)

$|A_\parallel(0)|^2 = 0.211 \pm 0.012$ (stat) ± 0.006 (syst)

$\delta_\parallel = -2.96 \pm 0.08$ (stat) ± 0.03 (syst)

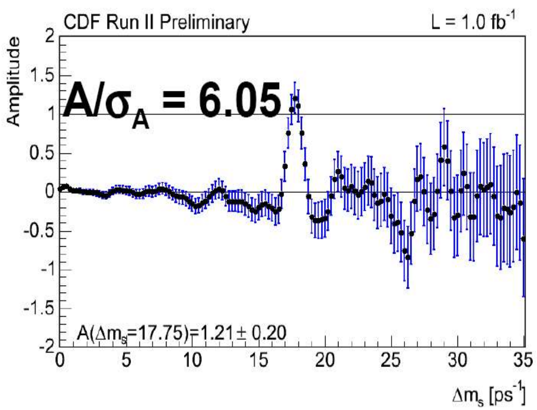
$\delta_\perp = 2.97 \pm 0.06$ (stat) ± 0.01 (syst)

Mass-lifetime



Measurement w/o flavor tagging

Flavor tagging: OST, SST



OST tuned on B^+

SST tuned on MC, checked on mixing measurement 'a posteriori'

PRD76,031102 (2007)

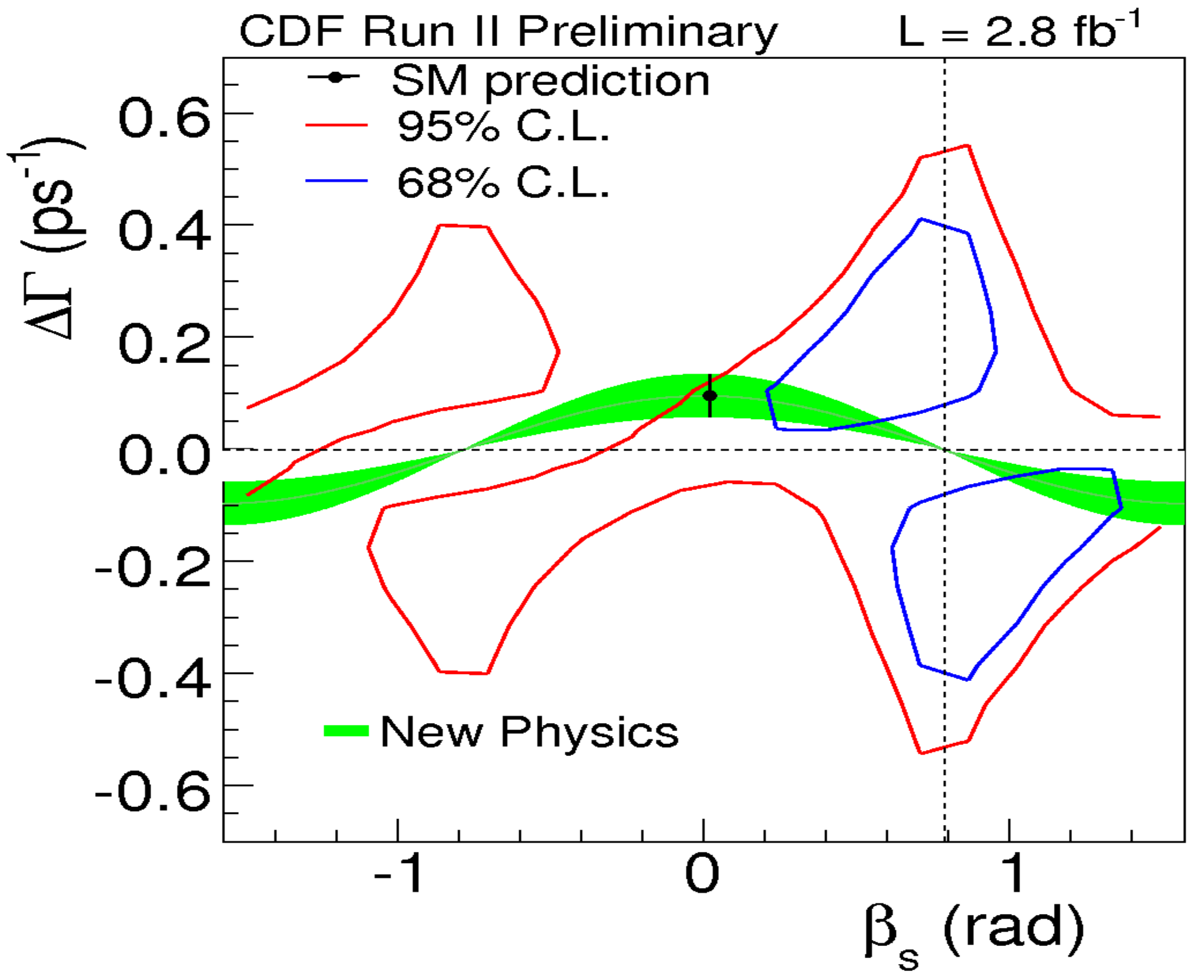
Measured polarization of $B^0 \to J/\psi K^*$: consistent w/ B-factories (and competitive!)

Recent DØ analysis shows consistency of $B^0 \to J/\psi K^{*0}$ strong phase and amplitudes w/CDF (arXiv:0810.0037v1) as well.

CDF's Flavor-Tagged $B_s^0 \to J/\psi\varphi$

- Recent update finds 1.8σ (p-value = 7%) discrepancy with SM prediction for $\beta_s^{J/\psi\varphi}$

This analysis uses 2.8 **fb^{-1}** (but equiv. to 2.0 fb^{-1}, no PID 2nd half)

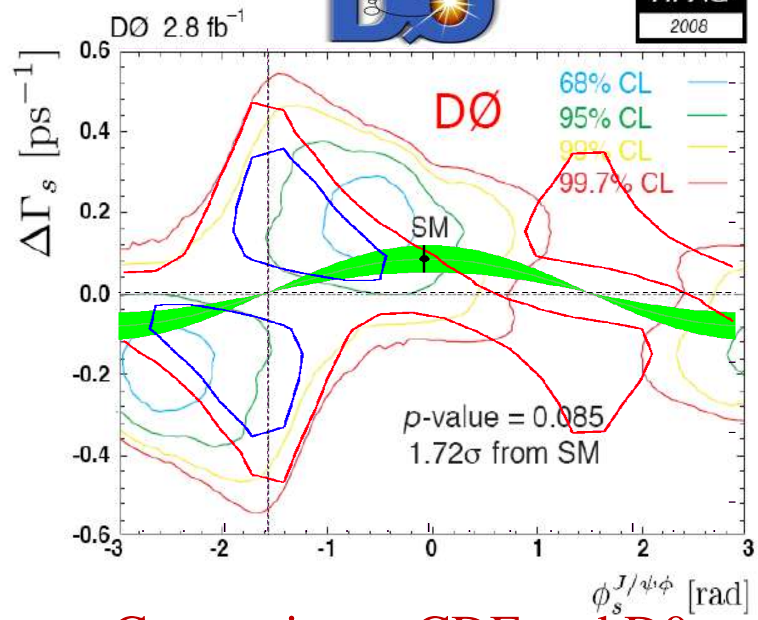


www-cdf.fnal.gov/physics/new/bottom/080724.blessed-tagged_BsJPsiPhi_update_prelim/

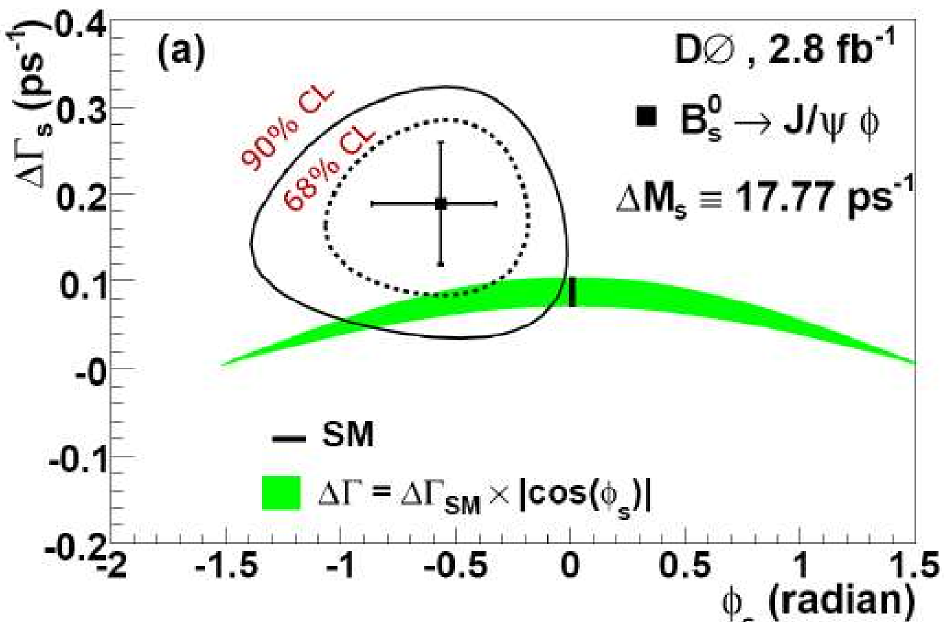
Expect further improvement in statistical precision shortly!

Similar Discrepancy Observed by D0 in Flavor-Tagged $B_s^0 \to J/\psi\varphi$

- DØ observes a fluctuation consistent with CDF
- Chooses to quote the results in terms of $\phi_s = -2\beta_s$ **(arXiv:0802.2255)**
- Discrepancy w/SM is 1.7σ, 6.6 %



Comparison : CDF and D0 trends are identical



Ambiguity in strong phases is the most severe limitation in this measurement

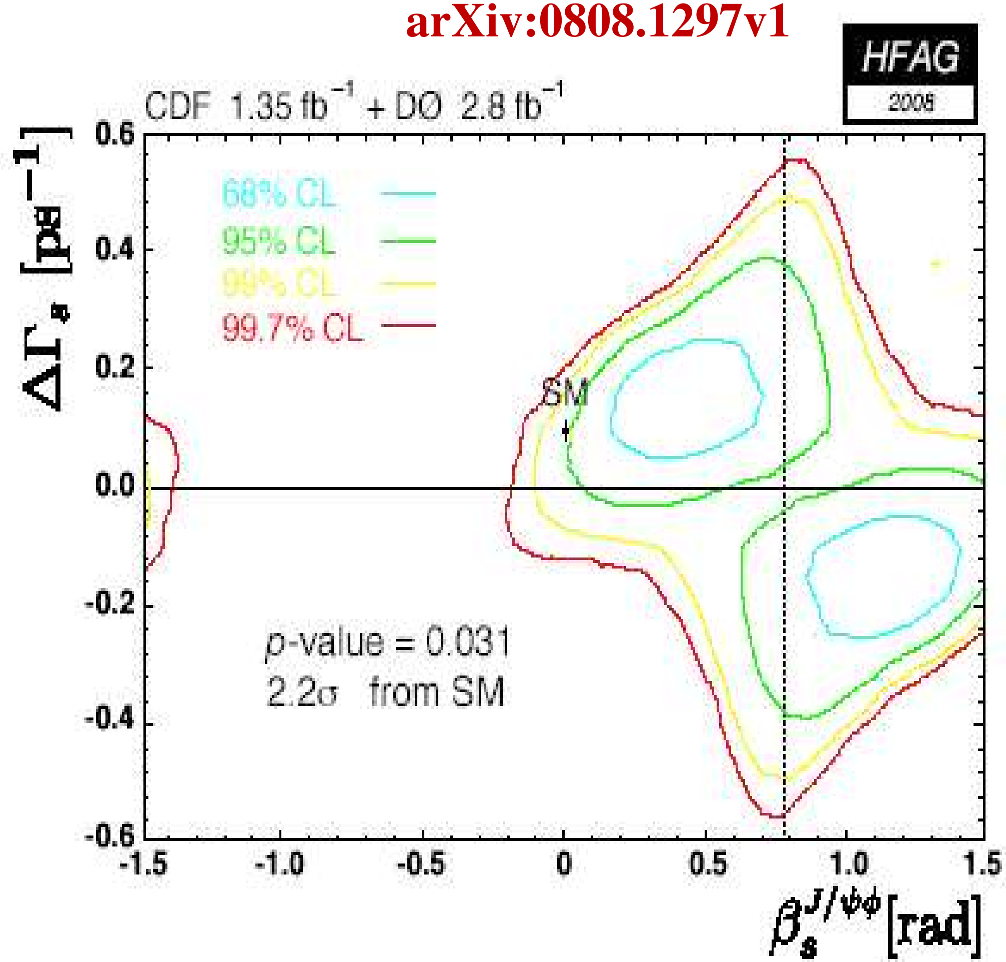
Recent DØ analysis shows consistency of strong phase and amplitudes in $B_s^0 \to J/\psi\varphi$ and $B^0 \to J/\psi\ K^{*0}$ and supports the strong phase constraint (arXiv:0810.0037v1)

Tevatron combination

arXiv:0808.1297v1

Combine CDF and D0 iso-CL regions with no constrains and previously checked for coverage:

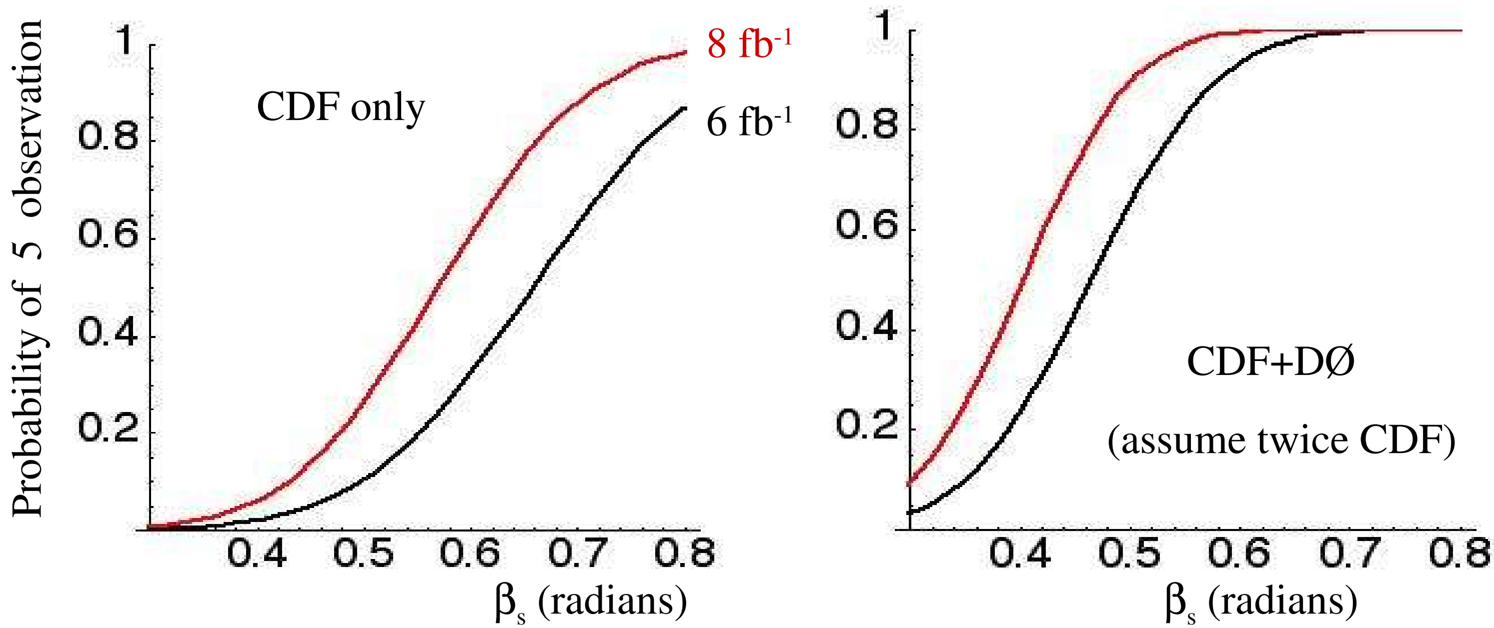
2.2σ consistency with SM.



New CDF result not included in combination!

Future

- Tevatron can search for anomalously large values of β_s
- Shown results 2.8 fb^{-1}, but 4 fb^{-1} already on tape to be analysed soon
- Expect 6-8 fb^{-1} by the end of the run 2
- Assuming no improvements (so everything as in PRL100, 161802 (2008))



- CDF analysis being improved and optimized: better flavour tagging, calibrated PID, more statistics from other triggers
- If β_s is indeed large CDF and D0 results have good chance to prove it

Conclusions

Many new and **unique** results of CPV at the Tevatron.

- Measurement in B_s using $B_s \rightarrow K\pi$ decays
- Measurement of direct CPV on b-baryon decays
- Evidence for direct CPV in the B^+ sector
- The most precise measurement of a^s_{sl} to date
- Measurements on β_s :

  * CDF update on larger dataset confirms old result and provides tighter constraints (15% to 7% agreement with SM), although several ingredients are still in the work

  * Both CDF and DØ observe 1-2 sigma β_s deviations from SM predictions. SM agreement reduces to 2.2σ when combined.

  * Interesting to see how these effects evolve with more data

Very rich physics program and still promising

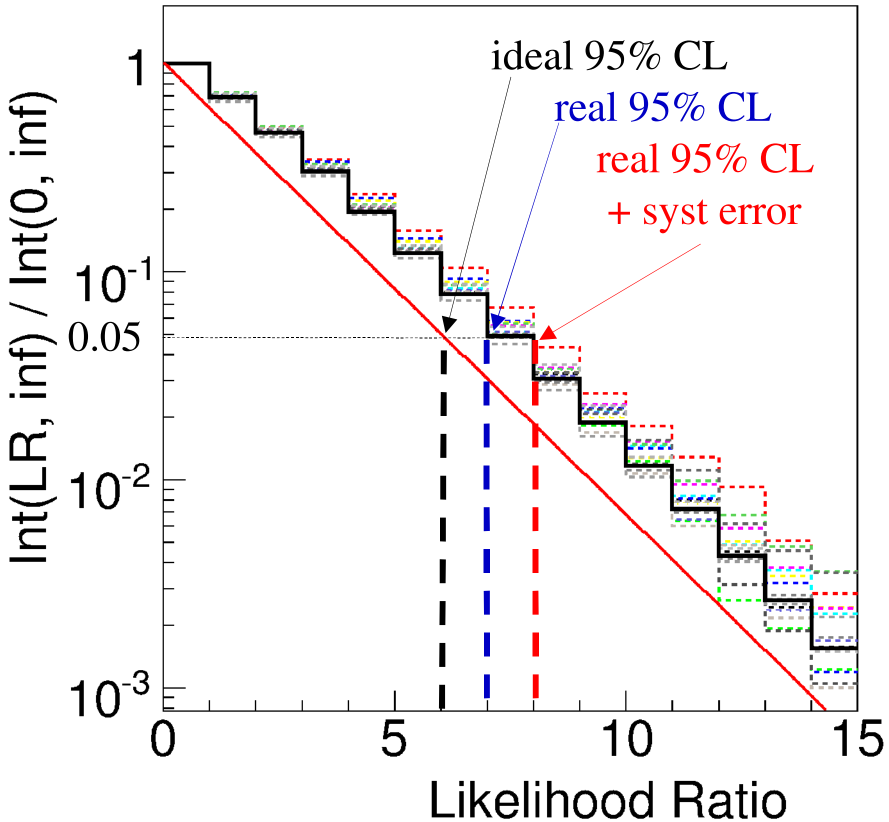
Back up

Systematics

- Systematic uncertainties studied by varying all nuisance parameters +/- 5 σ from observed values and repeating LR curves (dotted histograms)

- Nuisance parameters:
  - lifetime, lifetime scale factor uncertainty,
  - strong phases,
  - transversity amplitudes,
  - background angular and decay time parameters,
  - dilution scale factors and tagging efficiency
  - mass signal and background parameters
  - …

- Take the most conservative curve (dotted red histogram) as final result



CP violating phases : ϕ_s vs β_s

- $2\beta_s = 2\arg[-V_{ts}V_{tb}^{*} / V_{cs}V_{cb}^{*}] \sim 4.4^{o}$ (SM) phase of $b \rightarrow ccs$ transition that accounts for interference of decay and mixing+decay

- $\phi_s = \arg[-M_{12}/\Gamma_{12}] \sim 0.24^{o}$ (SM)

  $\arg[M_{12}] = \arg(V_{tb}V_{ts}^{*})^2$ matrix element that connects matter to antimatter through oscillation.

  $\arg[\Gamma_{12}] = \arg[(V_{cb}V^{*}_{cs})^2 + V_{cb}V^{*}_{cs}V_{ub}V^{*}_{us} + (V_{ub}V^{*}_{us})^2]$ width of matter and antimatter into common final states.

- Both SM values experimentally unaccessible by current experiments (assumed zero). If NP occurs in mixing:

$$\phi_s = \phi_s^{SM} + \phi_s^{NP} \sim \phi_s^{NP}$$

$$2\beta_s = 2\,\beta_s^{SM} - \phi_s^{NP} \sim -\phi_s^{NP}$$

standard approximation: $\phi_s = -2\,_{s}$

CPV Phases in B_s^0 Sensitive to New Physics

Mixing governed by Schrodinger eqn.

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

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

$\Delta m_s = m_H - m_L \approx 2|M_{12}|$ ← Measured at Tevatron in 2006!

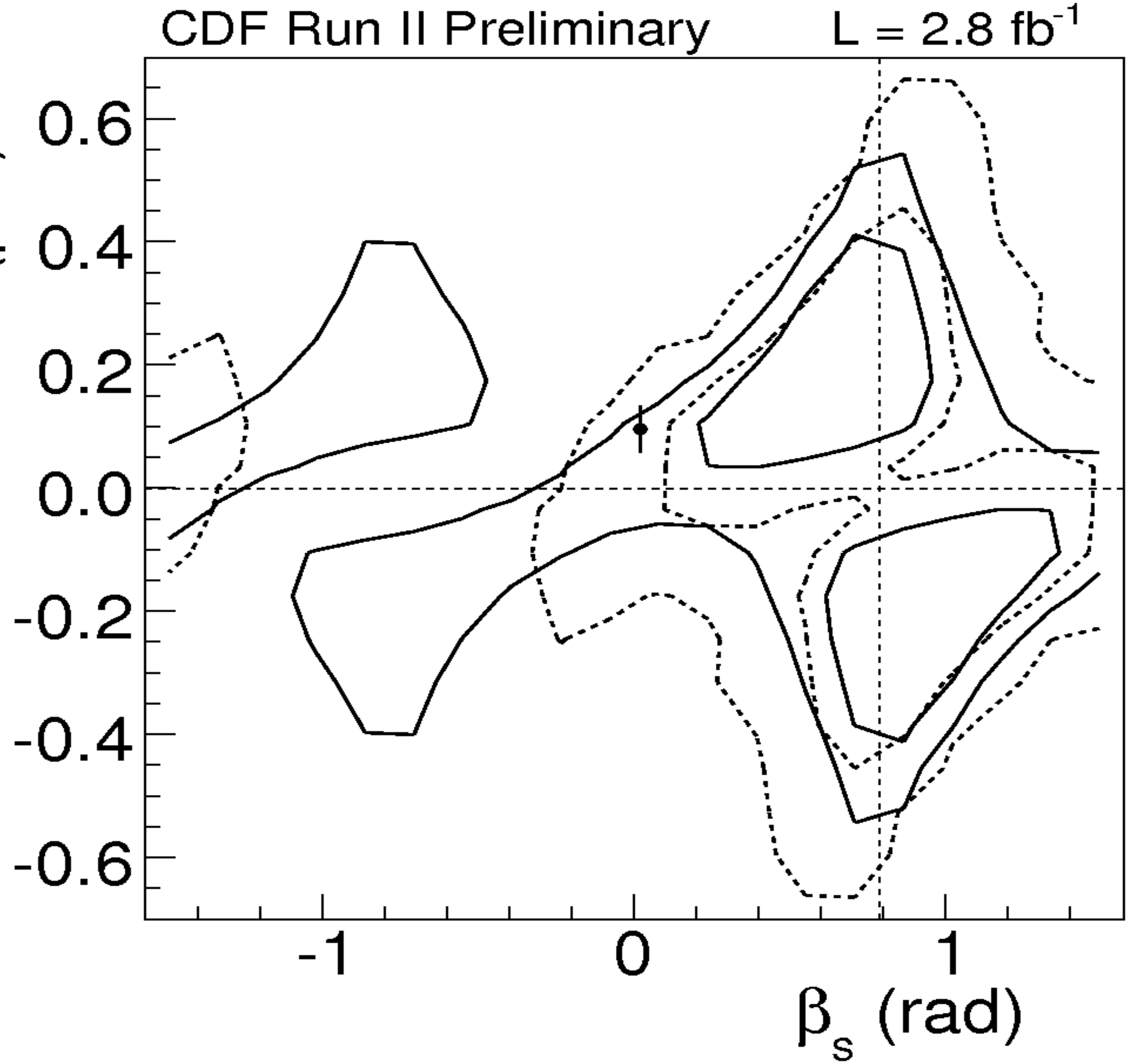
$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(\varphi_s)$,

where $\varphi_s = \arg(-M_{12}/\Gamma_{12})$ ~0.004 in SM

- CPV in $B_s^0 \to J/\psi\varphi$ gives access to phase, sensitive to NP

$$\varphi_s^{J/\psi\phi} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \sim 0.02$$

← SM prediction


CDF Run II Preliminary
L = 2.8 fb^{-1}
$\Delta\Gamma$ (ps^{-1})
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-1
0
1
β_s (rad)