Measurements of CP Violation at the Tevatron

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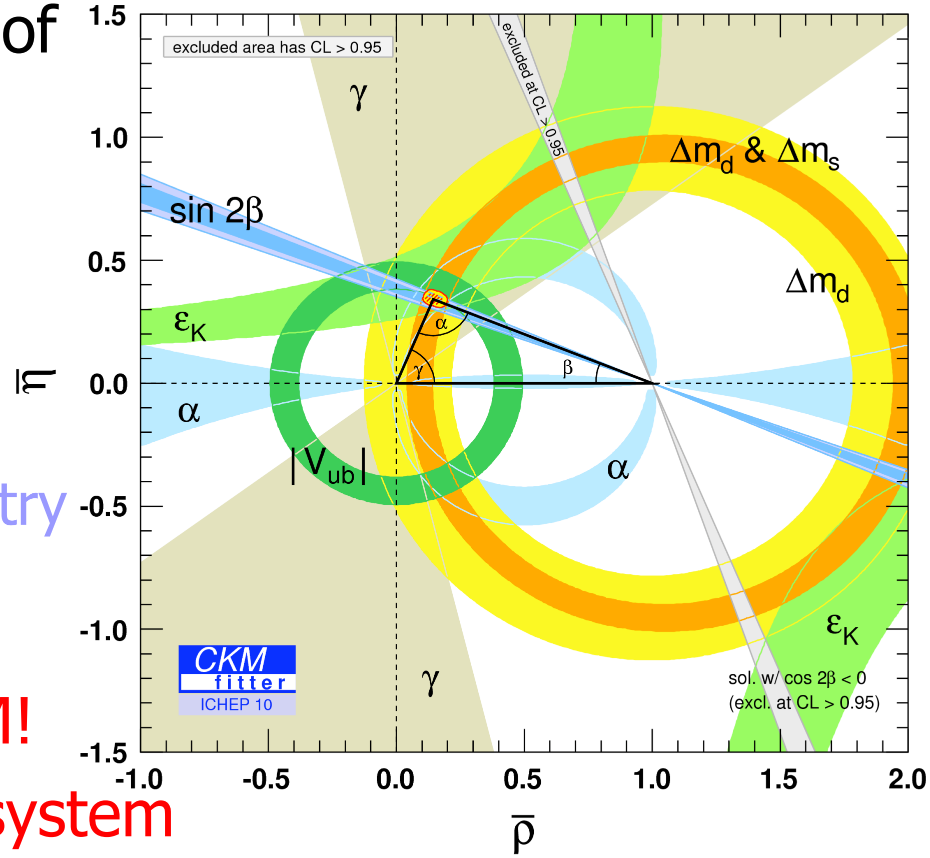
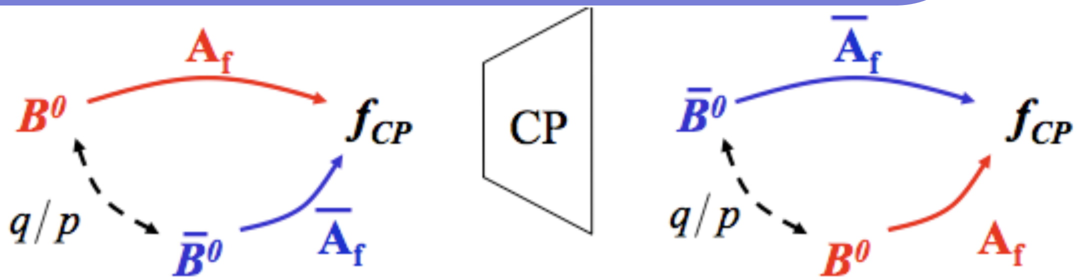
SM Success and Failure

- B meson mixing and decays probe 5 of the 9 elements of the CKM matrix
  - Measure angles and sides independently
  - CP Violation: A~3x10^{-5}
  - Fails to accommodate observed baryon asymmetry by about 10 orders of magnitude!
  - Need Physics beyond SM!
  - B_s is the least explored system
  - Charm
  - Predicted CP phases are very small in SM – search for large deviations



CP Violation in B_s

- Assume no CPV in decays
- CPV is possible through mixing
  - 2 phases involved
  - β_s access through $B_s \to J/\psi\phi$
  - ϕ_s access through semileptonic decays

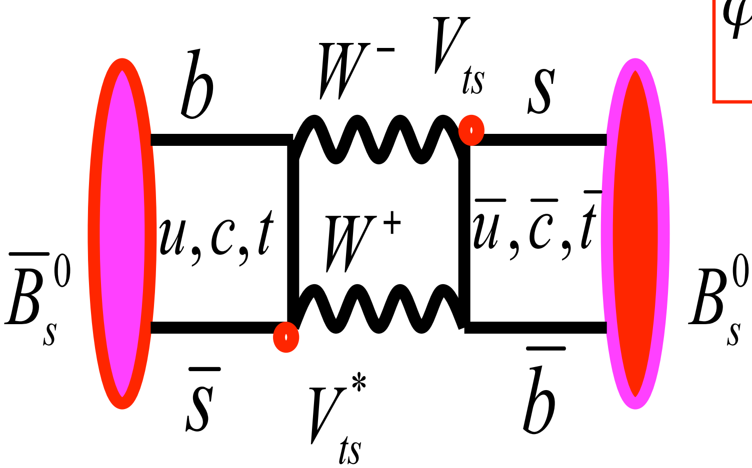


Interference between mixing and decay to a CP eigenstate

$$\Rightarrow \Gamma\left(B^0_{phys}(t) \to f_{CP}\right) \neq \Gamma\left(\bar{B}^0_{phys}(t) \to f_{CP}\right)$$

$$\beta_s^{SM} = \arg\left[-V_{ts}V_{tb}^* / V_{cs}V_{cb}^*\right] = \lambda\eta^2 \approx 1^\circ \ (\beta = 22^\circ)$$

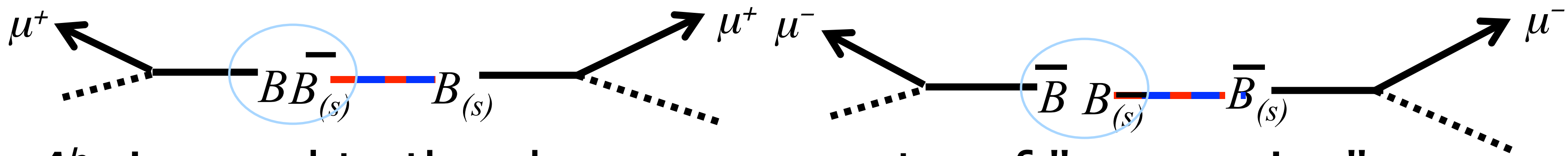
$$\varphi_s = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) = (4.2 \pm 1.3) \times 10^{-3}$$



- Contribution of new particles in the box diagram can enhance both:
- $2\beta_s = 2\beta^{SM}_s - \phi_s^{NP}$
- $\phi_s = \phi^{SM}_s - \phi_s^{NP}$ with $\phi_s^{NP} >> \phi^{SM}_s, 2\beta^{SM}_s$
- $-2\beta_s \sim \phi_s \sim \phi_s^{NP}$

A^b_{sl} in neutral B mesons

- Measurement of the charge asymmetry induced by *B* mixing



- A^b_{sl} is equal to the charge asymmetry of "wrong sign" semileptonic B decays:

$$A^b_{SL} = \frac{\Gamma(\overline{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\overline{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)} = \frac{1}{2f}\left[A^d_{SL} + \frac{f_s \chi_{s0}}{f_d \chi_{d0}} A^s_{SL}\right]$$

$$\mathrm{A}^{(s)}_{\mathrm{SL}} = \mathrm{Im}\frac{\Gamma_{12}}{\mathrm{M}_{12}} = \left|\frac{\Gamma_{12}}{\mathrm{M}_{12}}\right| \sin\varphi_{(s)} = \frac{\Delta\Gamma_{(s)}}{\Delta m_{(s)}} \cdot \tan\varphi_{(s)}$$

$$\boxed{A^s_{sl} = (-0.023 \pm 0.006)\%}$$

- Since both B_d and B_s are produced at the Tevatron, A^b_{sl} is a linear combination of a^d_{sl} and a^s_{sl} :

$$A^b_{sl} = (0.506 \pm 0.043)a^d_{sl} + (0.494 \pm 0.043)a^s_{sl}$$

  - B factories provide independent measurement of a^d_s

Analysis Strategy

1 Experimentally, we measure two quantities:

- Like-sign dimuon charge asymmetry (3.731×10^6 events):

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = KA_{sl}^{b} + A_{bkg} = (+0.564 \pm 0.053)\%$$

- Inclusive muon charge asymmetry (1.495×10^9 muons):

$$a \equiv \frac{n^{+} - n^{-}}{n^{+} + n^{-}} = kA_{sl}^{b} + a_{bkg} = (+0.955 \pm 0.003)\%$$

- N^{++}, N^{--} – the number of events with two same charge dimuons
- n^{+}, n^{-} – the number of muons with given charge
- Both A and a linearly depend on the charge asymmetry A^{b}_{sl}

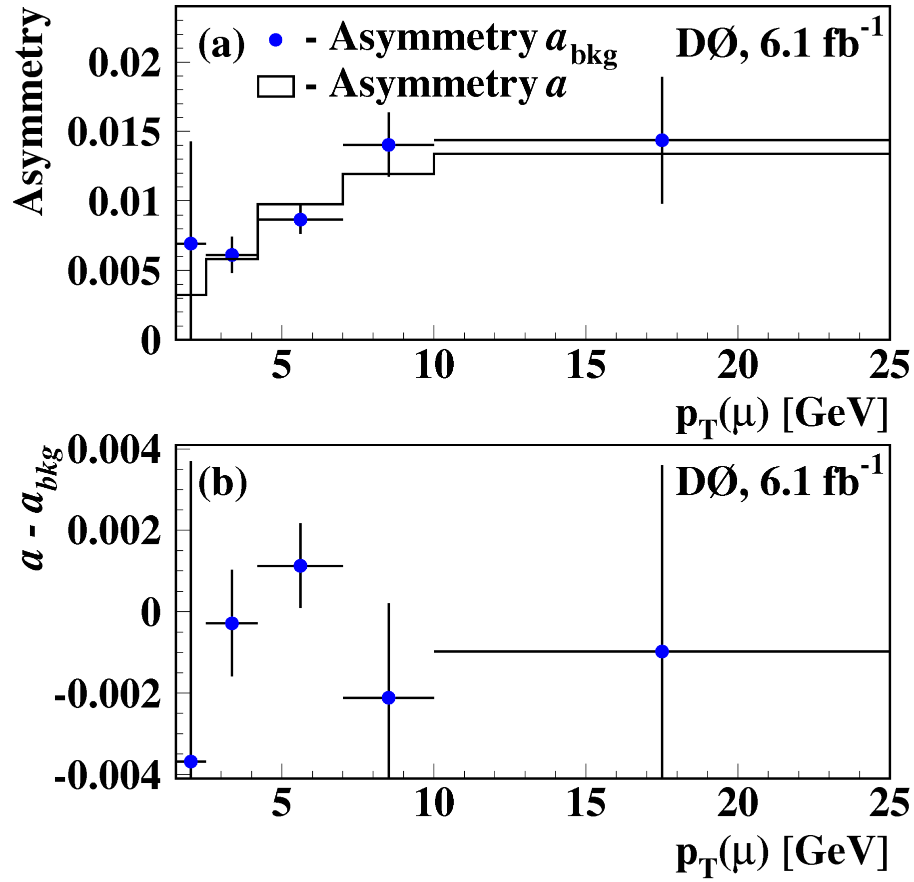
2 Determine the background contributions A_{bkg} and a_{bkg} from other processes plus detector-related backgrounds

3 Determine Fractions K and k from mixed B hadron decays

4 Exploit different signal and correlated background content to extract A^{b}_{sl}

Closure Test

- The value of a is mainly determined by the background asymmetry a_{bkg}
  - A^b_{sl} is suppressed by k = 0.041±0.003
- Construct a_{bkg} from
  f_K, f_π, f_p, a_K, a_π, a_p and δ,
  verify how well does it describe the observed asymmetry a
- a and a_{bkg} are compared as a function of muon p_T
- χ^2/dof = 2.4/5 for the difference between these two distributions



Excellent agreement between the expected and observed values of a, including a p_T dependence

Final Result

- From $A' = A - a$ a we obtain a value of A^b_{sl} :

$$A^b_{sl} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%$$

- To be compared with the SM prediction:

$$A^b_{sl}(SM) = (-0.023^{+0.005}_{-0.006})\%$$

- This result differs from the SM prediction by ~3.2 σ

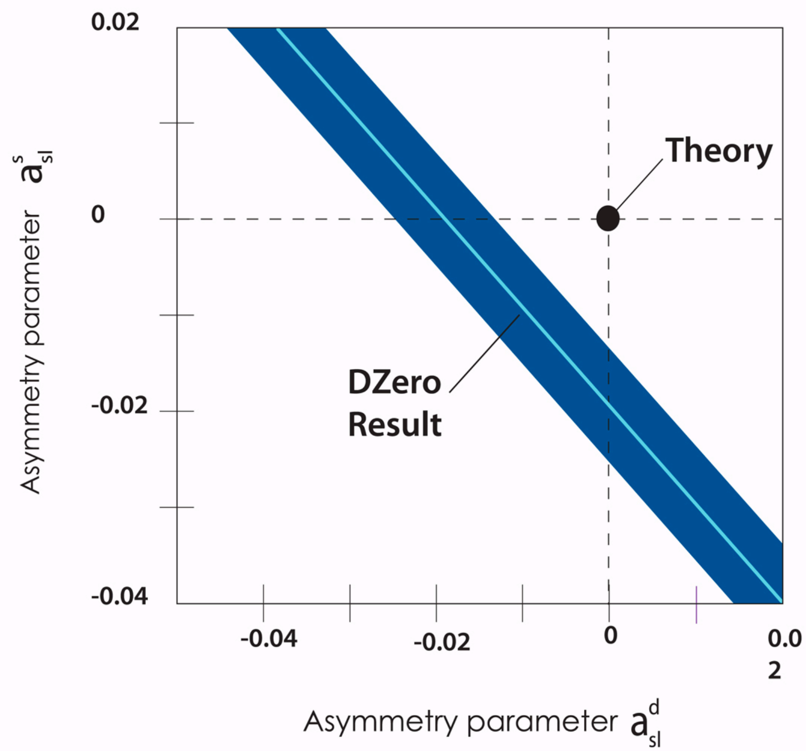
Phys. Rev. Lett. 105, 081801 (2010)

Phys. Rev. D 82, 032001, (2010)

- Previous D0 measurement

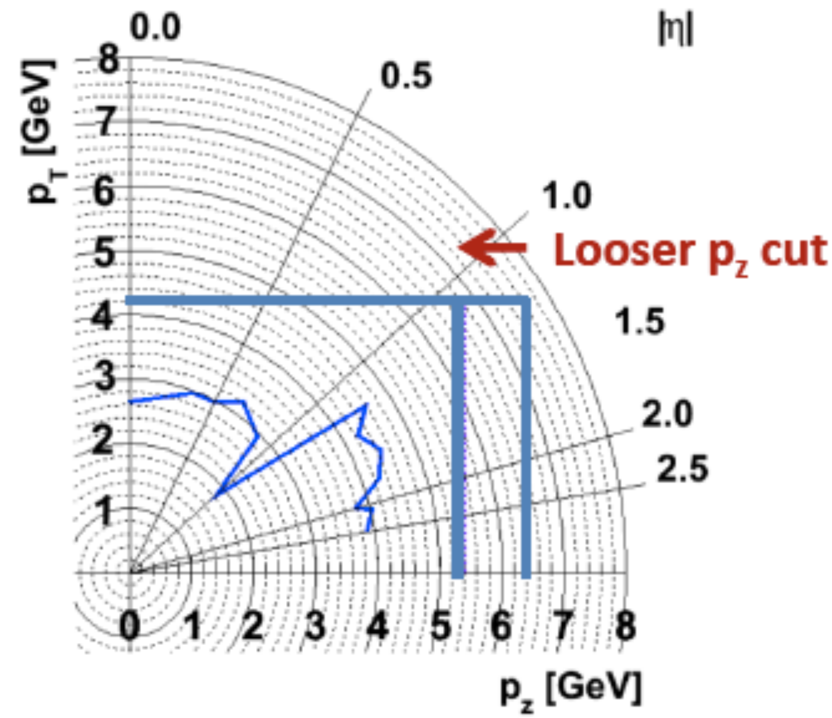
$$A_{SL} = (-0.92 \pm 0.44 \pm 0.32)\%$$

Phys. Rev. D 74, 092001 (2006)



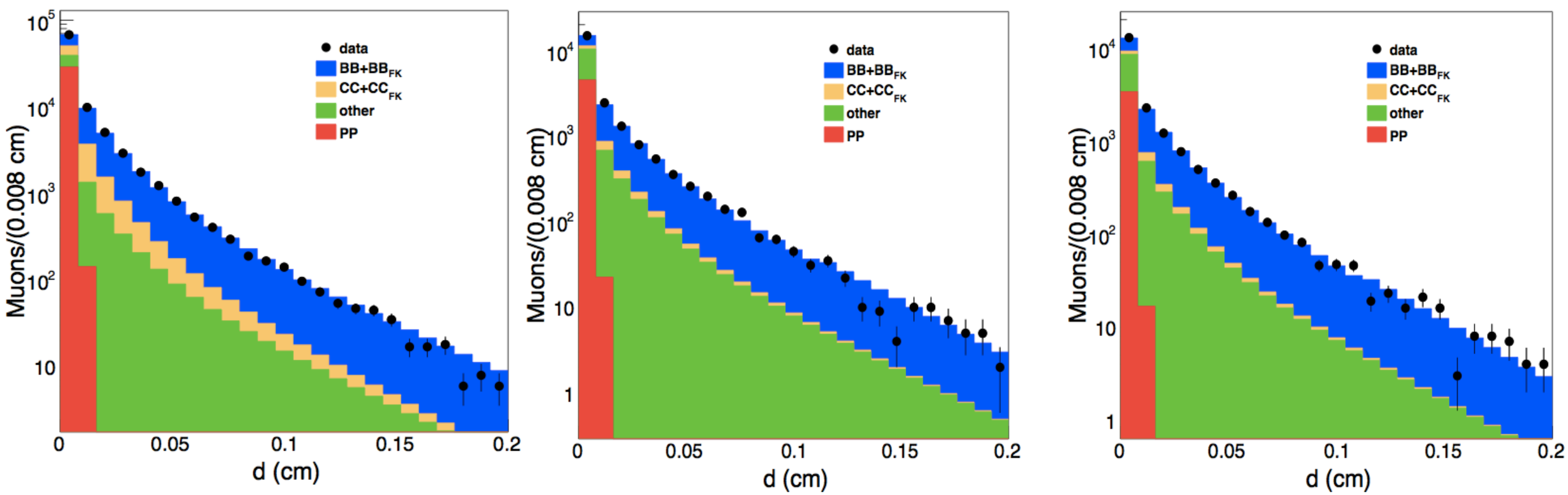
Further Improvements

- Precision of current result is dominated by statistical uncertainties
  - 6 fb-1 → 9 fb-1
  - Improve event selection - 12% increase in number of like sign muons
- New measurement technique takes advantage of correlated uncertainties in f_K and F_K measurement
  - *Reduce uncertainties by ~30%*
- Anticipate ~30% reduction in final uncertainty on A^b_{sl}



Minimum muon momentum required to penetrate toroid and calorimeter to reach outer muon chambers

Time Integrated Mixing



- Use muon impact parameter distribution to separate bb contribution from other sources
- Plot the IP distributions (d1,d2) for opposite sign (OS) and same sign (++, --) muons.
- Simultaneously fit the distributions for muons from b-pairs (BB), c-pairs (CC), sequential decays (BC), Drell-Yan (PP), and D.I.F.'s or misID's with a muon or in pairs (BB_{FK}, CC_{FK}, and other).

Time Integrated Mixing

CDF Note 10335

- Average mixing probability:

$$\overline{\chi}_b = \frac{\Gamma(B^0 \to \bar{B}^0 \to \ell^+ X)}{\Gamma(B \to \ell^\pm X)} = f_d\chi_d + f_s\chi_s$$

- Measure through:

$$R = \frac{N^{++} + N^{--}}{N^{OS}} \qquad R = \frac{f\left[\overline{\chi}^2 + (1-\overline{\chi})^2\right] + 2\overline{\chi}(1-\overline{\chi})(1-f)}{(1-f)\left[\overline{\chi}^2 + (1-\overline{\chi})^2\right] + 2\overline{\chi}(1-\overline{\chi})f}$$

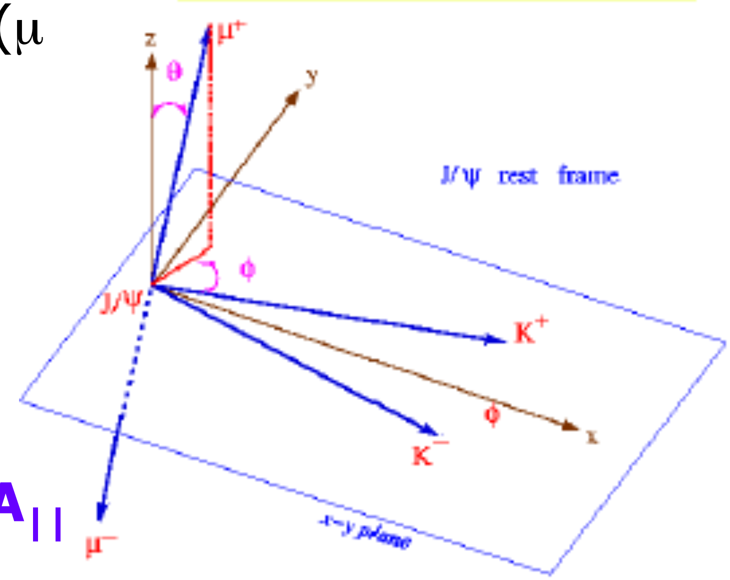
- f = 0.176 ± 0.011 accounts for sequential and other b -decays
- Extracted value: 0.126 ± 0.008 (0.006 due to f)

  Compare to LEP: 0.1259 ± 0.0042
  - Previous measurement PRD 82.032001; PRL.105.081801
- A^b_{SL} measurement to follow with larger dataset

$\varphi^{J/\psi\varphi}_s$ in $B_s \rightarrow J/\psi\varphi$

- Measure $\varphi^{J/\psi\varphi}_s(\beta_s)$ and $\Delta\Gamma_s$ by studying time evolution of flavor tagged $B_s \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decays
  - Pseudoscalar → Vector Vector
  - 3 possible angular momentum states
- The mass eigenstates are expected to be almost pure CP-eigenstates
  - **S,D** (CP even): linear combination of $\mathbf{A_0}$, $\mathbf{A_{||}}$
  - **P** (CP odd): $\mathbf{A_\perp}$
- Decay parameterized by three angles

cosθ=transversity



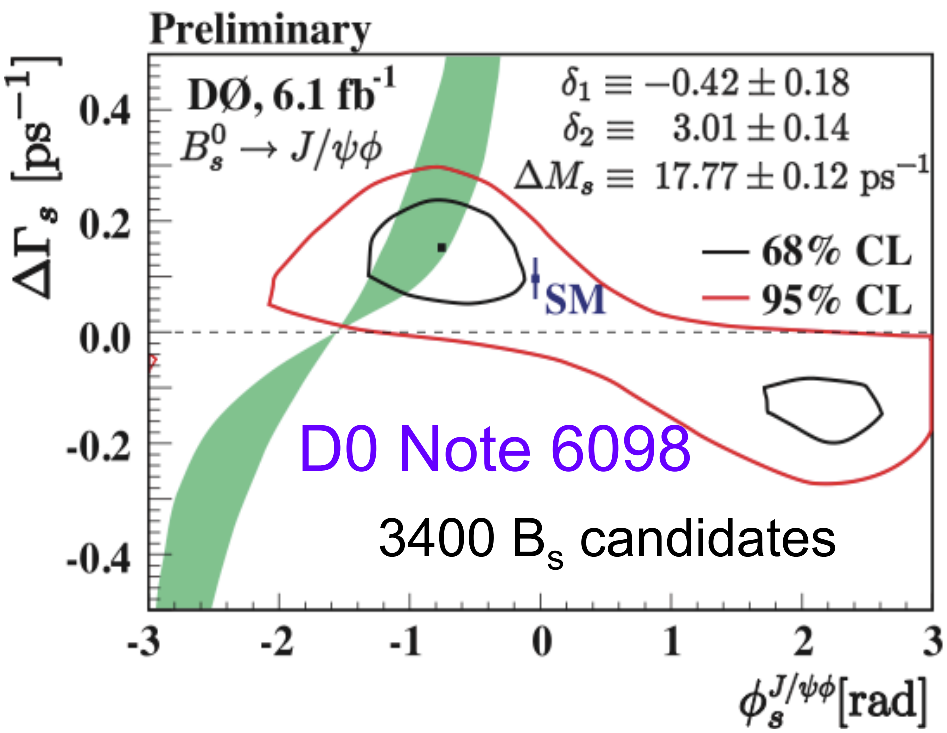
$$\Gamma(t) \approx \left|A_{even}(\theta,\psi,\varphi,t)\right|^2 + \left|A_{odd}(\theta,\psi,\varphi,t)\right|^2$$

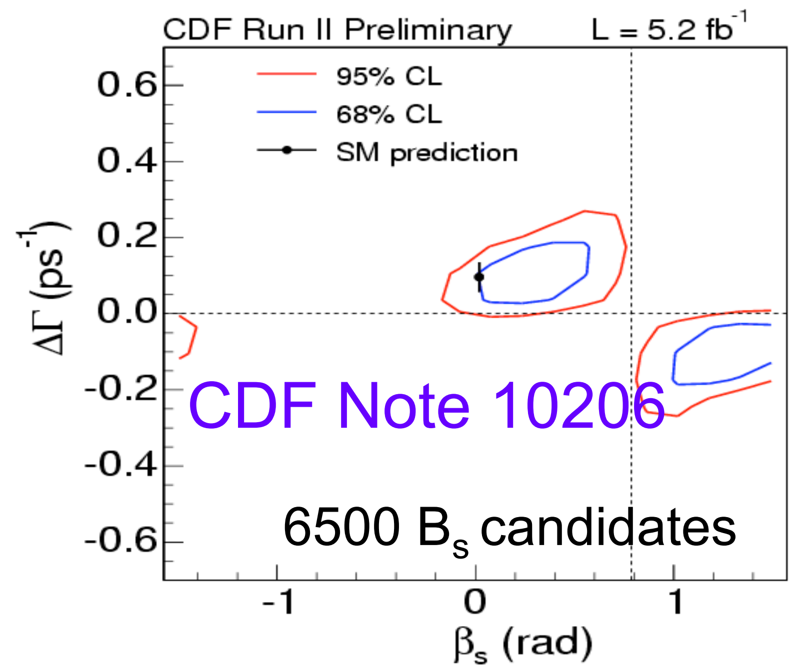
$$+A^* A(CPC)$$ CP-conserving interference

$$+A^* A(CPV)(e^{-\Gamma_L t} - e^{-\Gamma_H t})\sin\phi_s^{J/\psi\varphi}$$ CP-violating interference

- CP eigenstates - well separated in transversity (cosθ)

$\varphi^{J/\psi\varphi}_s$ in $B_s \rightarrow J/\psi\varphi$



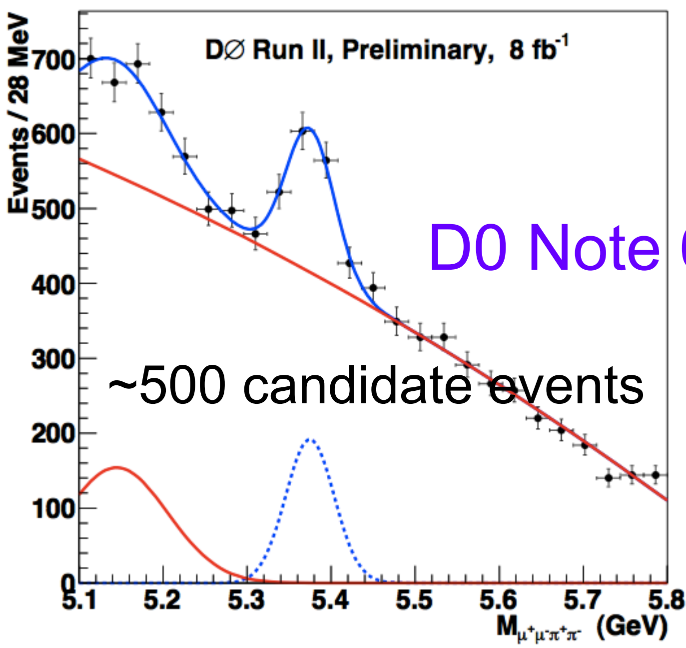


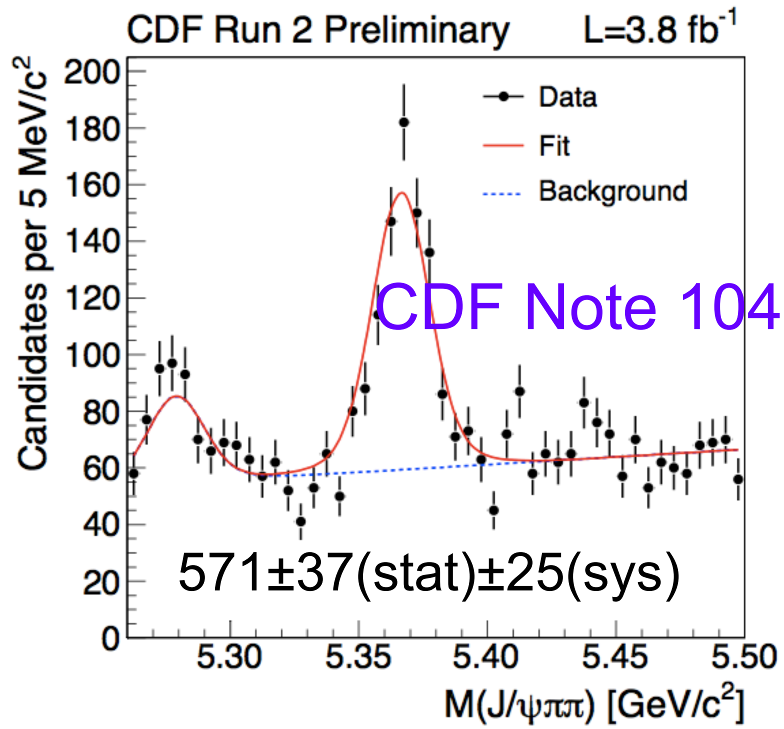
- $\varphi^{J/\psi\varphi}_s$=-0.76 ± 0.37(stat) ± 0.02 (syst)
- $\Delta\Gamma_s$ = 0.15 ± 0.06(stat) ± 0.01 (syst) ps^{-1}

- β_s within [0.02,0.52] U [1.08,1.55] at 68% C.L.
  p-value (SM) = 0.44 (~0.8 σ)
- $\Delta\Gamma_s$ = 0.075 ± 0.035(stat) ± 0.01 (syst) ps^{-1}

fitted fraction of S-wave contamination is < 6.7 % @ 95 % C.L.

Additional channels for β_s





- $R_{f0/\varphi}$=[BF($B_s \rightarrow J/\psi f_0(980)$)BF($f_0(980) \rightarrow \pi^+\pi^-$)]/[BF($B_s \rightarrow J/\psi\varphi$)BF($\varphi \rightarrow K^+K^-$)]

  CDF: 0.292 ± 0.020(stat) ± 0.017(sys)

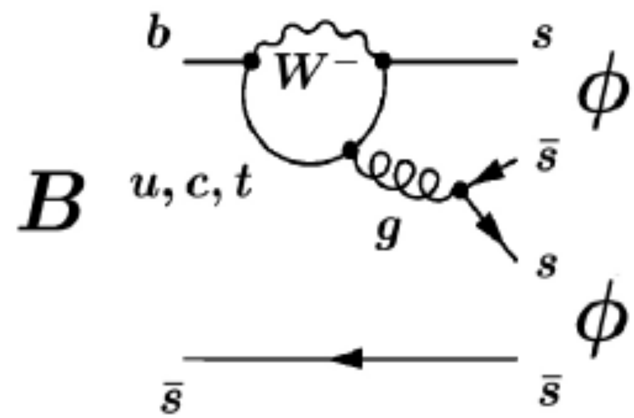
  D0 : 0.210 ± 0.032 (stat) ± 0.036(sys)

BF($B_s \rightarrow J/\psi f_0(980)$)BF($f_0(980) \rightarrow \pi^+\pi$-) = (1.85±0.13(stat)±0.11(sys)±0.57(pdg))10^{-4}

Since $f_0(980)$ is scalar no angular analysis needed

Search for CPV in $B_s \rightarrow \varphi\varphi$

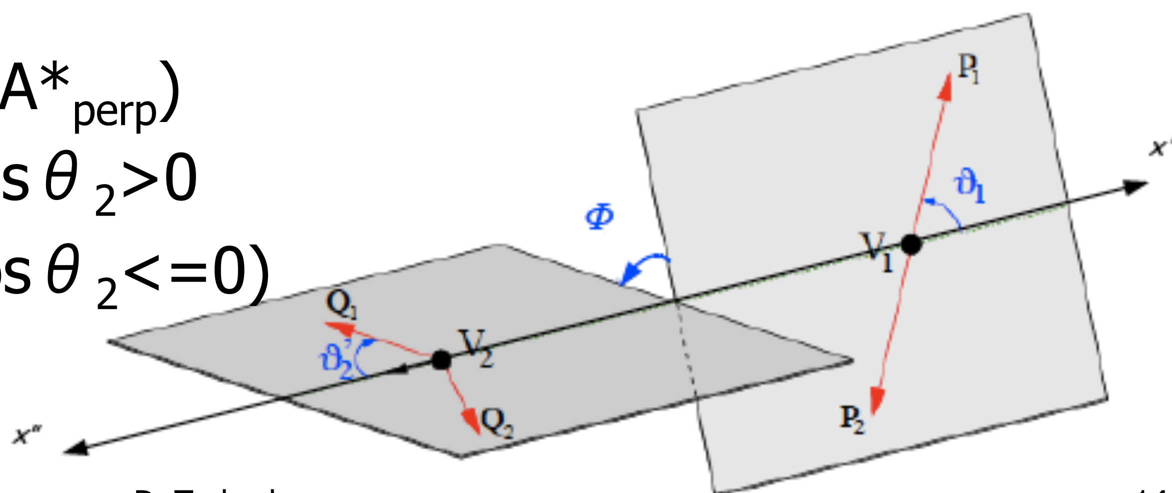
- Decay and mixing phases cancel out
  - CPV is predicted to be 0
  - Large deviation points to New Physics
- Limited sample statistics (~300) does not allow time – dependent analysis
  - Use Triple Products asymmetries
  - Odd under time reversal (T)
  - Sensitive to CP if CPT is conserved



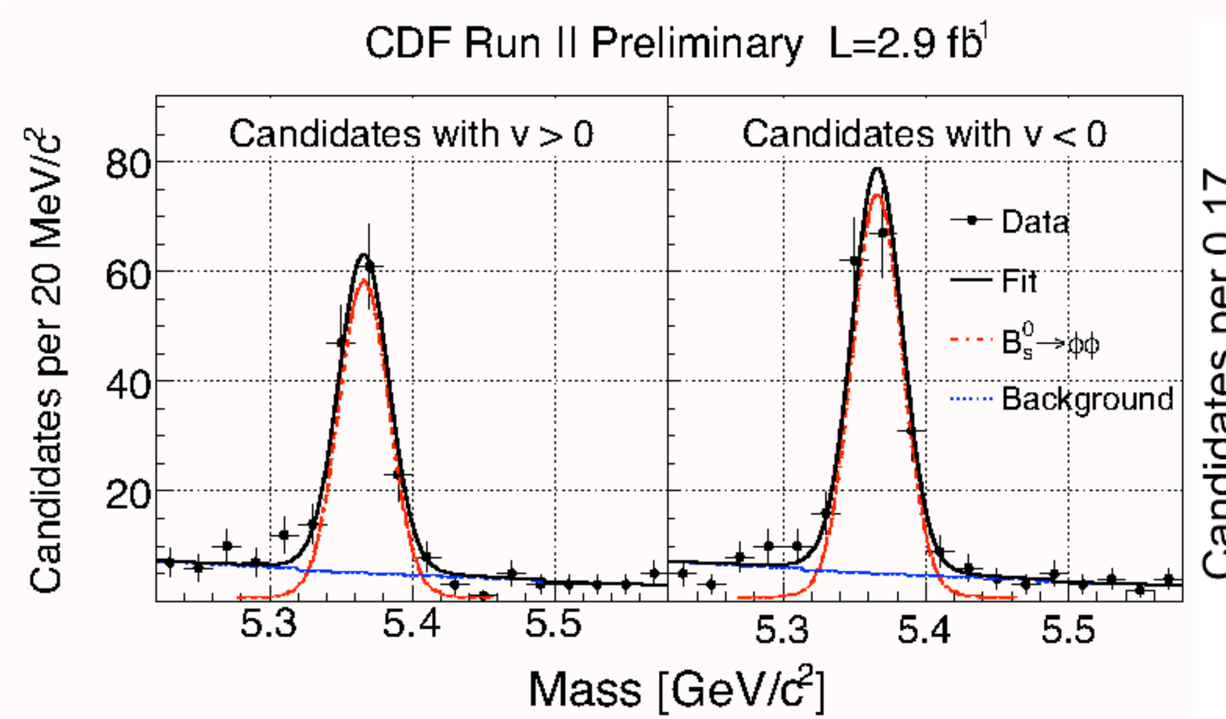
- Define:
- $u=\cos\phi\sin\phi \sim \mathrm{Im}(A_{||}A^*_{perp})$
- $v=\sin\phi$ for $\cos\theta_1\cos\theta_2>0$

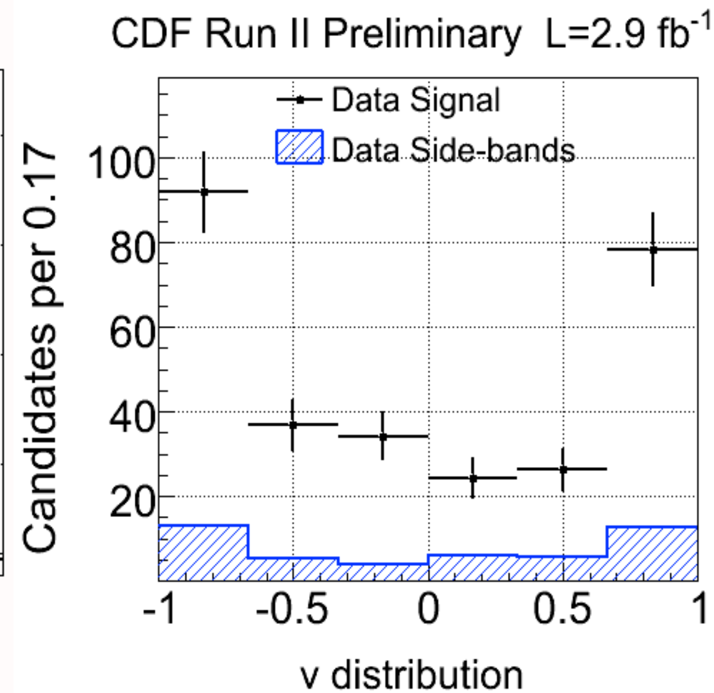
  $\sin(-\phi)$ for $\cos\theta_1\cos\theta_2<=0)$

  $\sim\mathrm{Im}(A_0A^*_{perp})$



Search for CPV in $B_s \to \varphi\varphi$





Construct asymmetries: $A_{u,v} = \dfrac{N^+ - N^-}{N^+ + N^-}$

CDF Note 10424

- A_u = -0.007±0.064 (stat) ±0.018 (syst)
- A_v = -0.120±0.064 (stat) ±0.016 (syst) 1.8σ effect

Time Integrated A_{CP} in $D^0 \to h^+h^-$ Decays

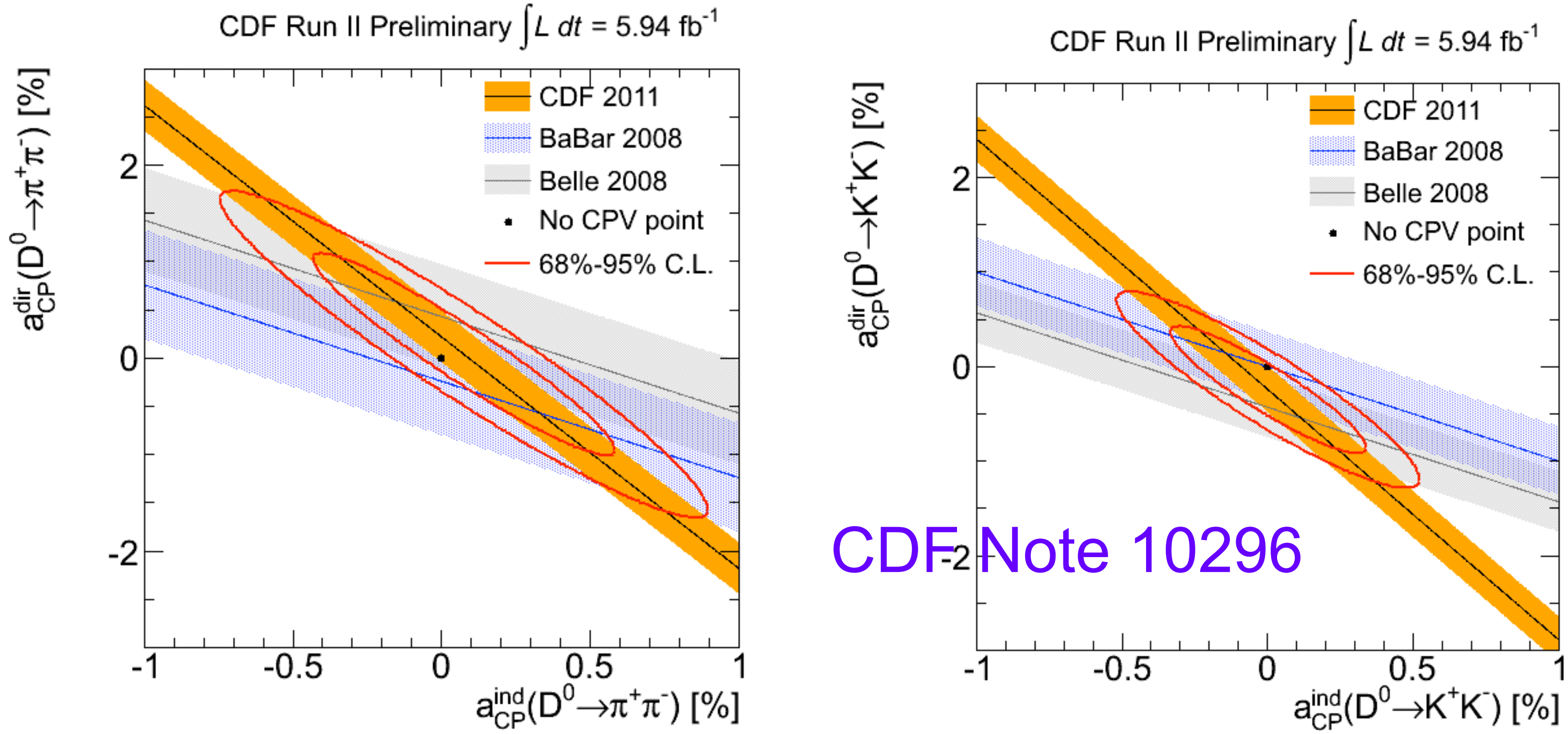
- CP violation significantly larger than ~1% in singly -Cabibbo suppressed transitions $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ would point to presence of NP
- Extract asymmetries

$$A_{\mathrm{CP}}(h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)}.$$

- From $A_{\mathrm{CP}}(h^+h^-) = A_{\mathrm{CP}}^{\mathrm{raw}}(hh^\star) - A_{\mathrm{CP}}^{\mathrm{raw}}(K\pi^\star) + A_{\mathrm{CP}}^{\mathrm{raw}}(K\pi).$

  using D*-tagged $D^0 \to h^+h^-$ and $D^0 \to \pi^+K^-$ decays, and untagged $D^0 \to \pi^+K^-$
  - Soft pion determines flavor
  - Non-zero asymmetry is due to CP violation or detector /reconstruction

Time Integrated A_{CP} in $D^0 \to h^+h^-$ Decays



$$A_{CP}(h^+h^-) = a_{CP}^{dir}(h^+h^-) + \frac{\langle t \rangle}{\tau} a_{CP}^{ind}(h^+h^-)$$

$A_{CP}(D^0 \to \pi^+\pi^-) = [+0.22 \pm 0.24\ (\text{stat}) \pm 0.11\ (\text{syst})]\%$

$A_{CP}(D^0 \to K^+K^-) = [-0.24 \pm 0.22\ (\text{stat}) \pm 0.10\ (\text{syst})]\%$

Summary and Conclusions

- Mature Tevatron experiments producing exciting results
- The observed A^b_{SL} asymmetry is inconsistent with the SM prediction at a 3.2σ level
  - Observed number of produced particles of matter (negative muons) is almost 50 times larger than the number of produced particles of antimatter
  - Result is consistent with other Tevtron measurements of CP violation in mixing
  - Dominant uncertainty is statistical – precision can be improved with more luminosity!
- Most precise experimental results on the CPV phase ϕ_s and the mass eigenstates width difference $\Delta\Gamma_s$ from the Tevatron, using reconstructed $Bs \to J/\psi\,\phi$ decays
  - Doubling of data sets by the end of the Tevatron run
  - Addition of new channels allows better precision
- Word's most precise measurement of mixing-induced CP violation in charm sector