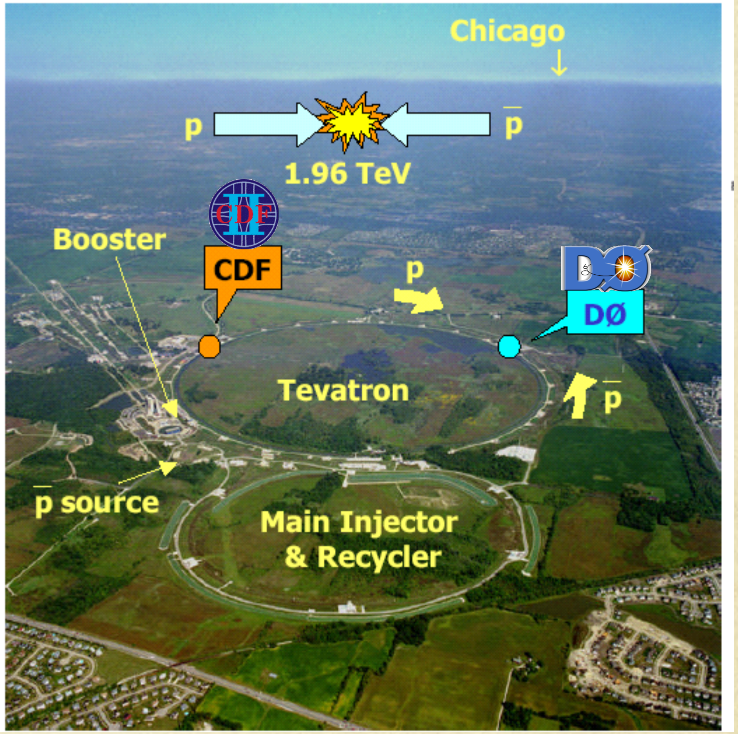
B Physics at the TeVatron

Incontri di Fisica delle Alte Energie
Perugia,27-29 Aprile 2011
Michael J. Morello (for the CDF and DØ Collaborations)

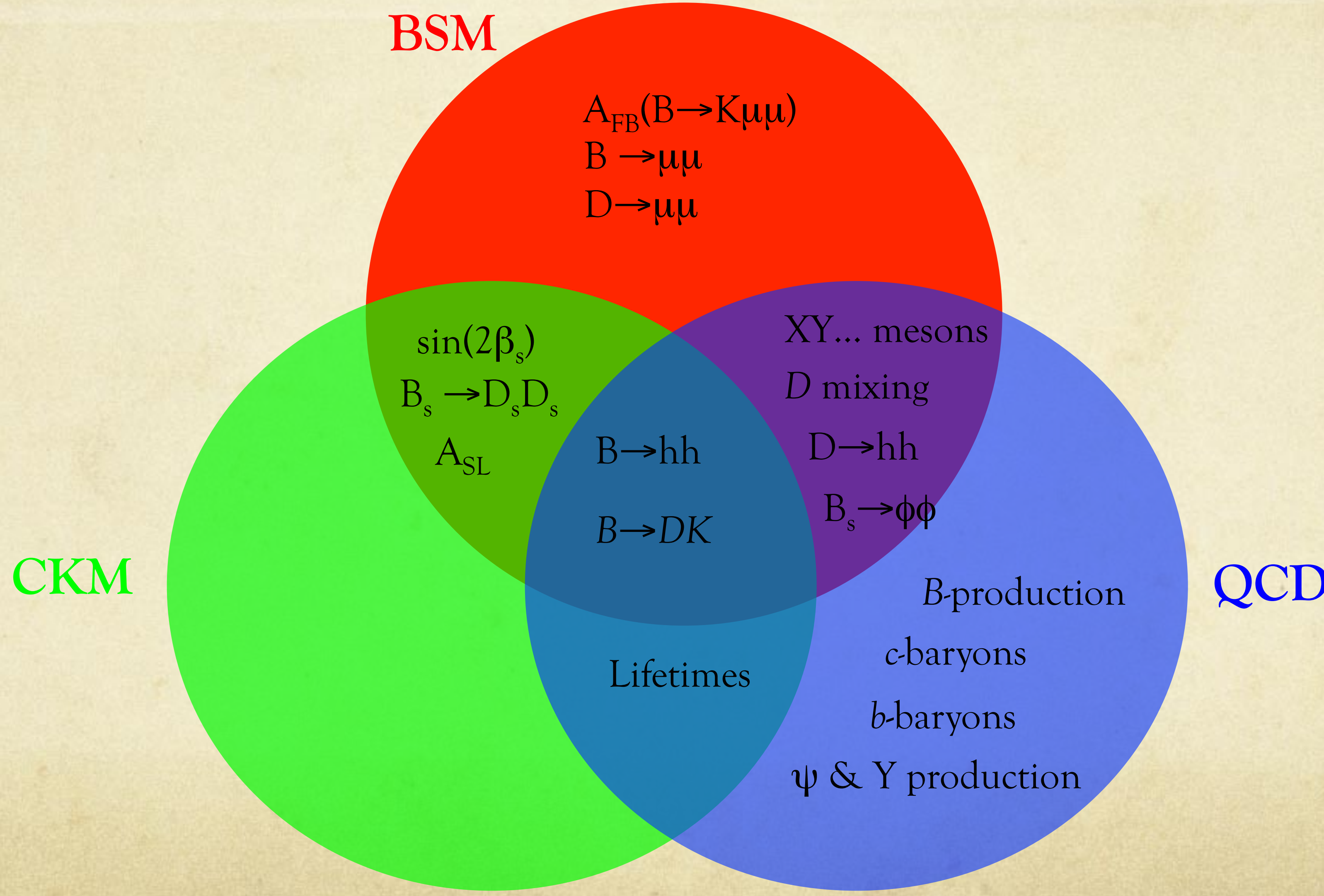
Fermilab Tevatron

- $p\bar{p}$ collisions at 1.96 TeV
- 1.7MHz collision rate (396 ns bunch spacing)
- Peak luminosity $3.5-4 \times 10^{32} cm^{-2}s^{-1}$
  - Average ~ 6 $p\bar{p}$ interactions per bunch crossing.
- ~8 fb^{-1} "good" data on tape per experiment.
- End of operation by September 2011.

Results today on 1.6-7 fb^{-1} of data collected.



B-Physics program



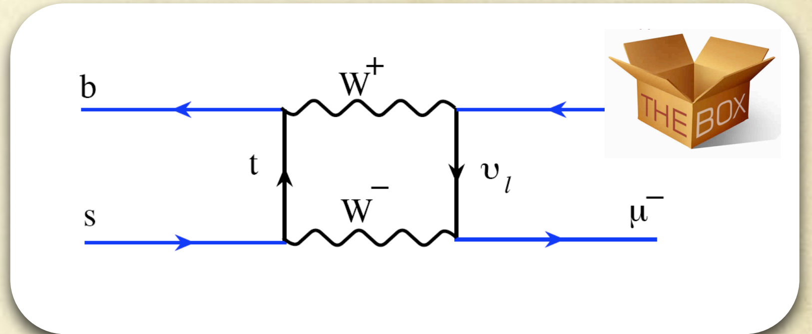
$B^0_s \to \mu^+\mu^-$

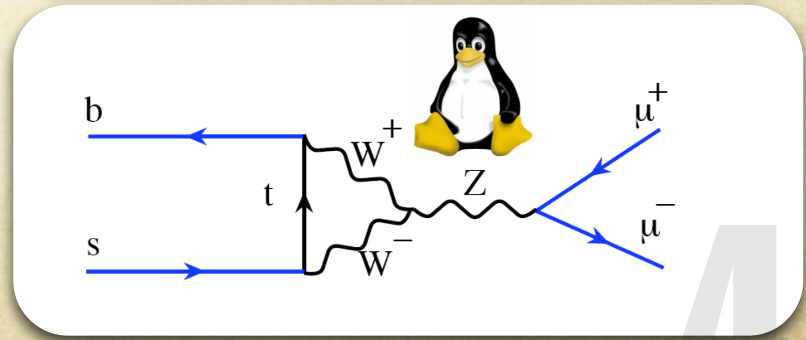
$B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are the most studied FCNC processes. CKM, GIM and helicity suppression in SM lead to:

$BR(B^0_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ $(|V_{ts}|^2)$
$BR(B^0 \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$ $(|V_{td}|^2)$

NP can enhance up to 100×
MSSM: $BR \propto \tan^6(\beta)$.
RPV SUSY enhances also at low $\tan(\beta)$.

Very hot! Either observation or null result provides crucial information.





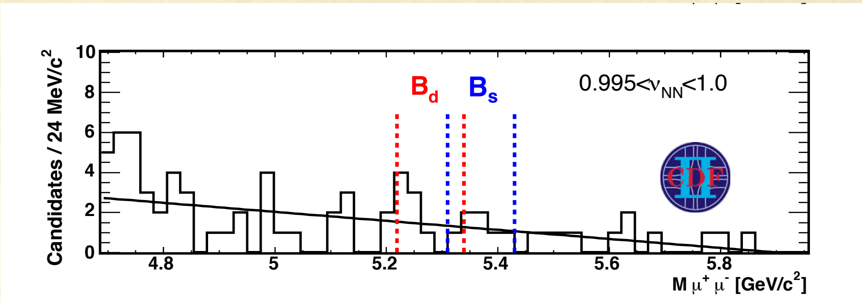
$B^0_s \rightarrow \mu^+\mu^-$ – Results

World's best from CDF II 3.7 fb^{-1}
$BR(B^0_s \rightarrow \mu^+\mu^-) < 4.3\times10^{-8}$ @ 95 %CL
$BR(B^0 \rightarrow \mu^+\mu^-) < 7.6\times10^{-9}$ @ 95%CL

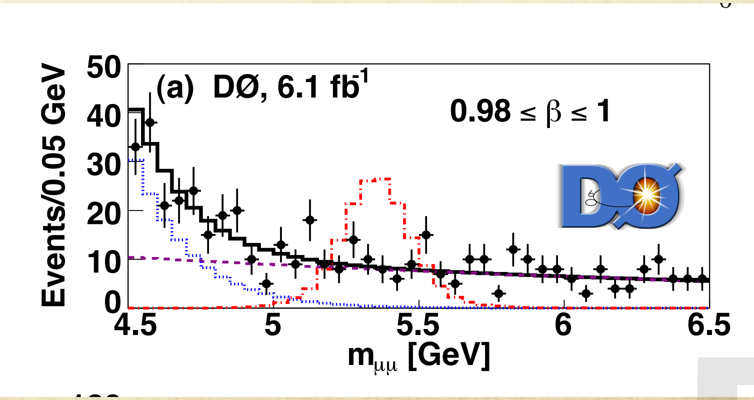
Most recent DØ results on 6.1fb^{-1}
$BR(B^0_s \rightarrow \mu^+\mu^-) < 5.1\times10^{-8}$ @ 95%CL

CDF Single Event Sensitivity = 3.2×10^{-9} →
expected 1.2 SM events, 0.7 in $\nu_{NN}>0.995$
~10*SM with 3.7 fb^{-1}.
Plenty of NP models already excluded.

CDF-Pub-9892, 3.7 fb^{-1}



Phys. Lett. B 693, 539 (2010), 6.1 fb^{-1}



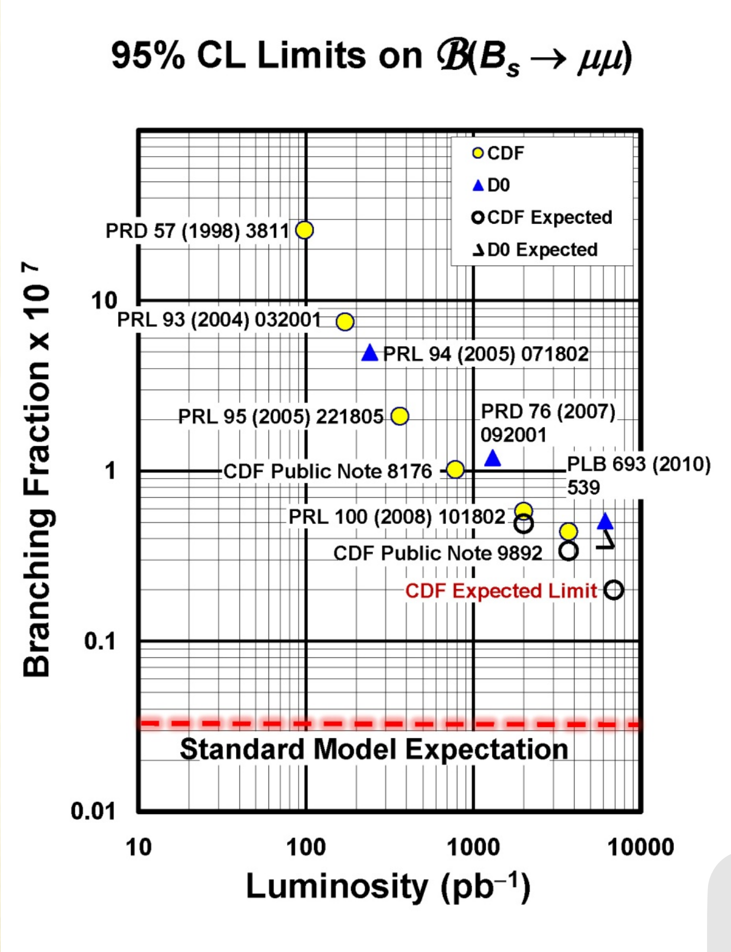
$B^0_s \to \mu^+\mu^-$ – Prospect

CDF is working to update analysis on $7 fb^{-1}$:

- 2x in statistics ($3.7 \to 7\ fb^{-1}$),
- increased muon acceptance,
- better signal efficiency from new ANN,
- more accurate background estimate.

The expected limit is:
$BR(B^0_s \to \mu^+\mu^-) < 2 \times 10^{-8}$ @ 95% CL

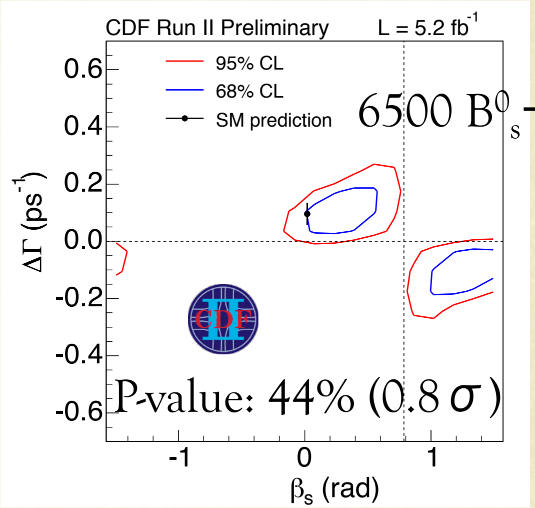
New strong player in the game LHCb on $35\ pb^{-1}$
$BR(B^0_s \to \mu^+\mu^-) < 5.6 \times 10^{-8}$ @ 95% CL
$BR(B^0 \to \mu^+\mu^-) < 1.5 \times 10^{-8}$ @ 95% CL



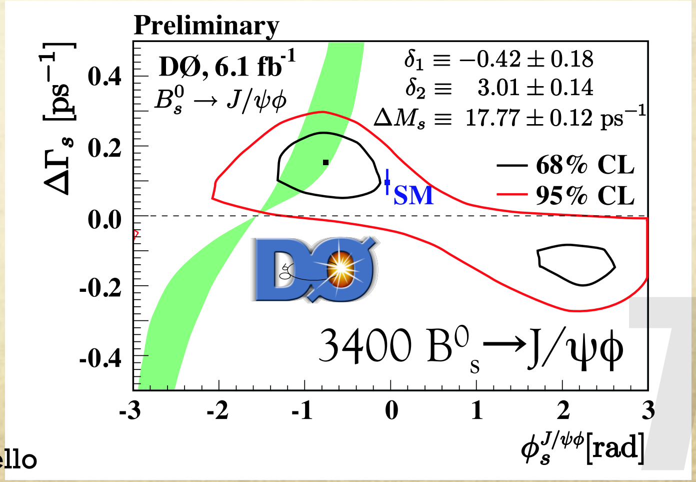
β_s from $B^0_s \to J/\psi\phi$ – status

- CP violation in $B^0_s \to J/\psi\phi$ occurs though interference of decays with and without mixing.
- SM predicts small value for the mixing phase $2\beta_s = -\phi_s$.
- New particles could enter weak mixing box diagrams and enhance CP violation
- Time evolution $(\Gamma_L, \Gamma_H, \Delta\Gamma, \beta_s)$ very sensitive to NP contributions.
- Trends are the same as in the past, both experiments now see SM consistency at about 1σ level.

CDF-Pub-10206



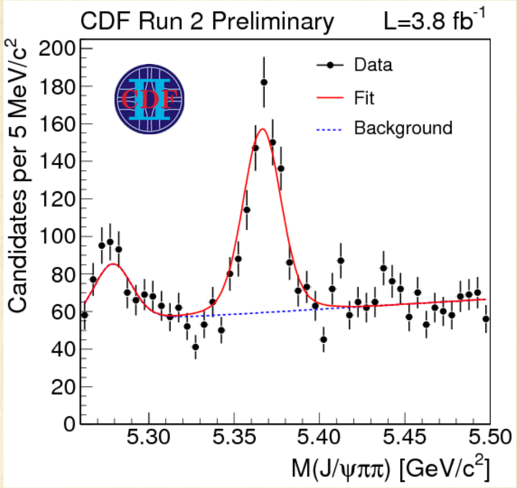
D0Note 6098-CONF



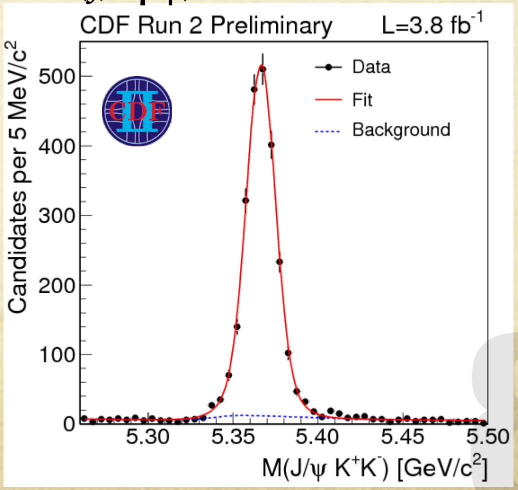
$B^0_s \to J/\psi f_0(980)$

- This is a CP=+1 eigenstate
  - Unambiguous measure of lifetime $1/\Gamma_H$
  - Clean measure B^0_s mixing phase βs
  - $B^0_s \to J/\psi\phi$ requires complex angular analysis for vector-vector final state
  - Understand S-wave contributions to βs measurement in $Bs \to J/\psi\phi$
- BR measurement
  - Neural Net Selection
  - Use identical selection for $Bs \to J/\psi\phi$ reference mode
  - Simultaneous log-likelihood fit to signal and normalization mode.

$N(J/\psi\ f_0)=571\pm37$



$N(J/\psi\phi)=2302\pm50$



BR($B^0_s \to J/\psi f_0(980)$)

~18σ significant (*CDF-Pub-10404*):

$$\frac{BR(B_s^0 \to J/\psi f_0, f_0 \to \pi^+\pi^-)}{BR(B_s^0 \to J/\psi \phi, \phi \to K^+K^-)} = 0.292 \pm 0.020(stat) \pm 0.017(syst)$$

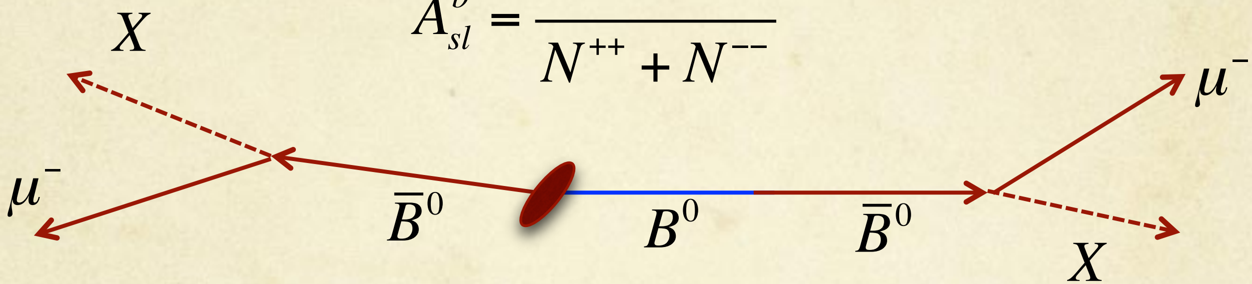
$$BR(B_s^0 \to J/\psi f_0(980)) \cdot BR(f_0(980) \to \pi^+\pi^-) = (1.85 \pm 0.13 \pm 0.57) \times 10^{-4}$$

- First observation from LHCb [PLB 698,115,2011.]
  - $$\frac{BR(B_s^0 \to J/\psi f_0, f_0 \to \pi^+\pi^-)}{BR(B_s^0 \to J/\psi \phi, \phi \to K^+K^-)} = 0.252^{+0.046+0.027}_{-0.032-0.033}$$
- Confirmed by Belle [PRL106,121802,2011]:
  - $$BR(B_s^0 \to J/\psi f_0, f_0 \to \pi^+\pi^-) = (1.15^{+0.31+0.15+0.26}_{-0.19-0.17+0.18}) \times 10^{-4}$$

Di-muon charge asymmetry

- Search for CP Violation in mixing using same sign dimuon events from semileptonic B decays:

$$A_{sl}^{b} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$



- N_b^{++} and N_b^{--} are the number of events with two b-hadrons decaying semileptoncally producing two same-sign muons
  - One muon comes from direct semileptonic decay $b\to\mu^- X$
  - Second muon comes from direct semileptonic decay after mixing $\bar{b}\to b\to\mu^- X$
  - A the TeVatron, both B^0_s and B^0 contribute.
- Lots of subtleties in the analysis, but two main experimental issues:
  - Asymmetric backgrounds from kaons faking μ
  - Asymmetric μ^+ and μ^- acceptance/efficiency

Di-muon charge asymmetry

- In 6 fb^{-1} DØ measures:

$$A_{sl}^{b} = (-0.957 \pm 0.251 \pm 0.146)\%$$

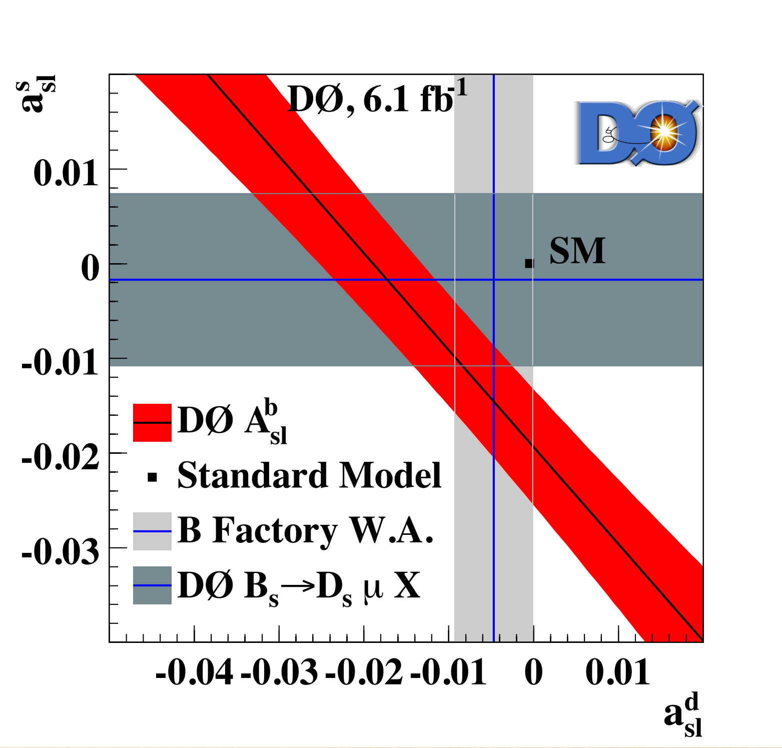
- SM prediction is:
  - Using prediction of a^d_{sl} and a^s_{sl} from *JHEP 0706, 072 (2007)*

$$A_{sl}^{b} = (-0.023^{+0.005}_{-0.006})\%$$

- Differs from SM by ~3.2σ

- Results from $B^0_s \to J/\psi\phi$ consistent with dimuon asymmetry.

PRD82,032001(2010)



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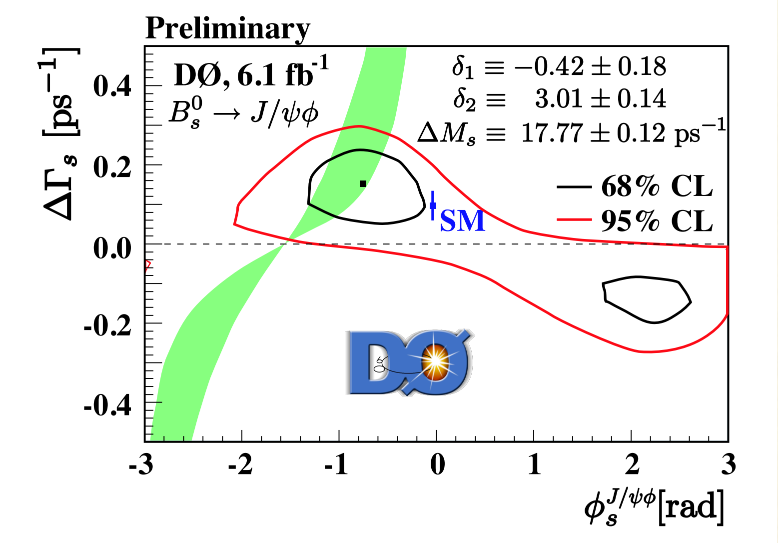
Green band from A^{b}_{sl}



What about CDF?

- CDF cannot reverse magnet polarity.
  - Probably not a major concern.
  - Dominant charge biases can be measured with data.
- DØ has better muon coverage at high $|\eta|$
- Scaling statistical uncertainty of previous CDF measurement 0.9% (*CDF-Pub-9015*) on 1.6 fb^{-1}, on 7 fb^{-1} we expect ~0.3-0.4%
- The main point is the systematic uncertainty! In the meanwhile.....

Time integrated mixing probability of B mesons

Defined as: $\bar{\chi} = \frac{\Gamma(B^0 \to \bar{B}^0 \to l^+ X)}{\Gamma(B \to l^\pm X)} = f_d \cdot \chi_d + f_s \chi_s$

where the numerator includes B^0_d and B^0_s. It derives from the measurement of the ratio R:

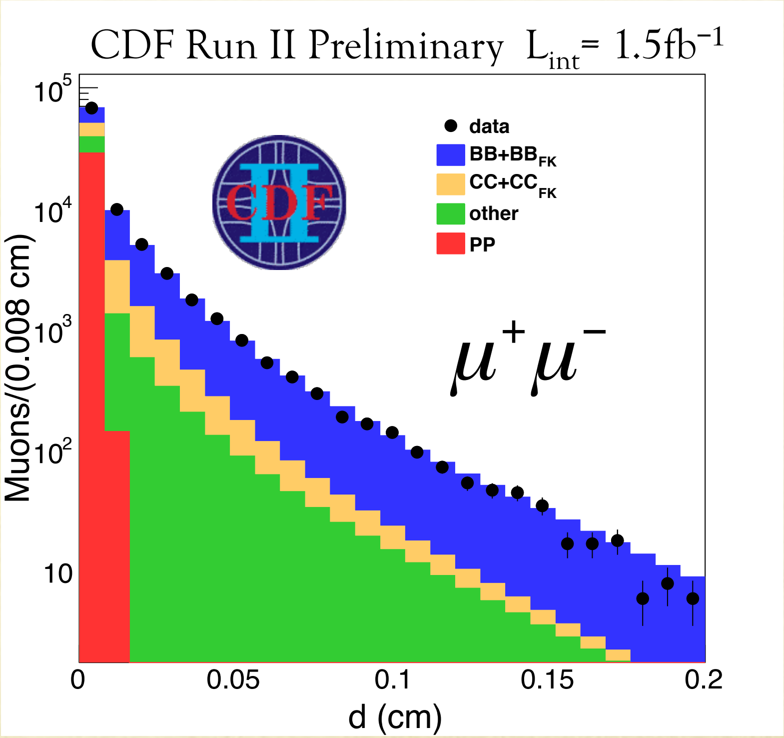
$$R = \frac{N(\mu^+\mu^+) + N(\mu^-\mu^-)}{N(\mu^+\mu^-)}$$

Use impact parameter (d) to identify source of muons: b, c, prompt components
2D fit of impact parameter using MC templates.

$$R = 0.472 \pm 0.011 \pm 0.007 \Rightarrow \bar{\chi} = 0.126 \pm 0.008$$

In agreement with LEP measurement: 0.1259±0.0042.

CDF-Pub-10335



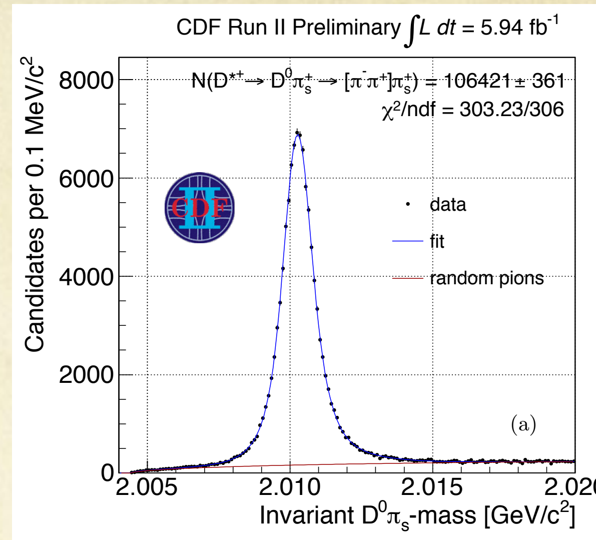
Fit projection of impact parameter

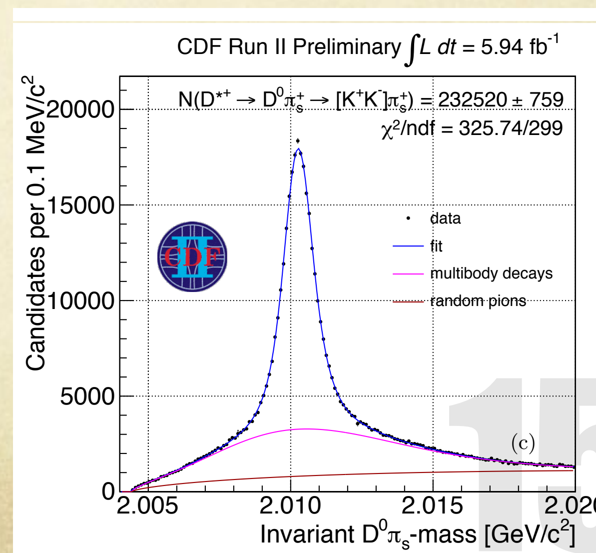
CPV in $D^0 \to h^+h^-$

- Charm is a unique because it probes up-quark sector (unaccessible through t or u quarks).
- Negligible penguin contribution the charm decays in SM
  - CPV in charm would point to NP

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

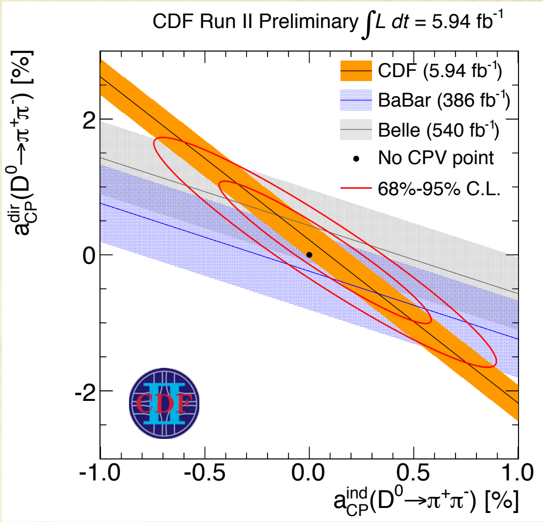
Time-integrated → $A_{CP} = a_{CP}^{dir} + \frac{<t>}{\tau} a_{CP}^{ind}$

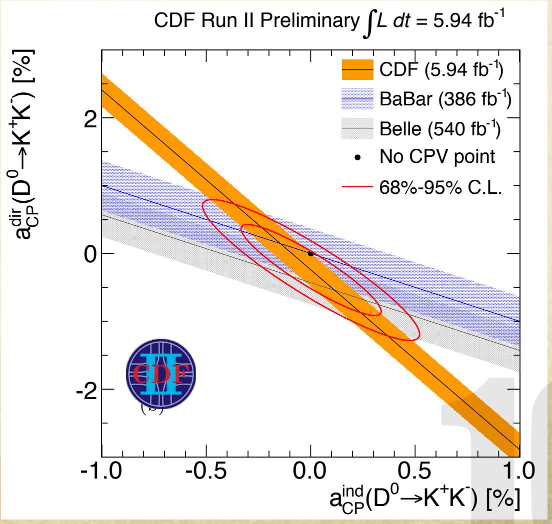




CPV in $D^0 \rightarrow h^+h^-$

CDF-Pub-10296





- The main challenge: suppressing detector charge asymmetries at the per mille level.
- Fully data driven technique using huge sample of Cabibbo-favored tagged and untagged $D^0 \rightarrow K^-\pi^+$
- Basic assumption: ppbar strong interactions are charge symmetric.

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

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

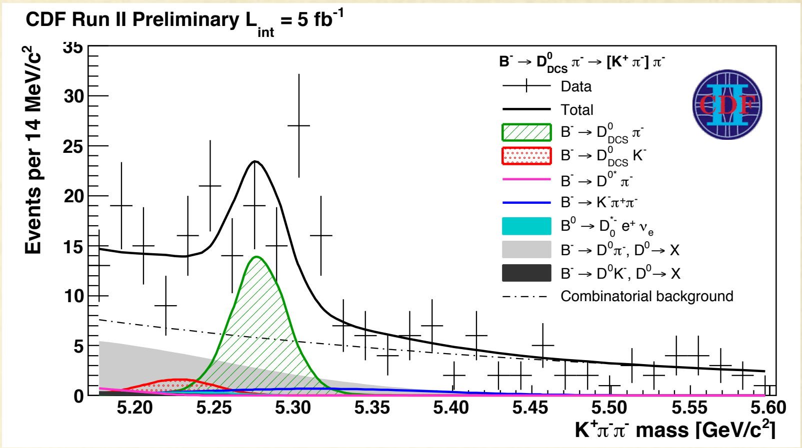
- World's best measurements.
  - CDF very sensitive to mixing induced effects, because of impact parameter requirements.
- Fully consistent with small CP violation.

γ from B→DK

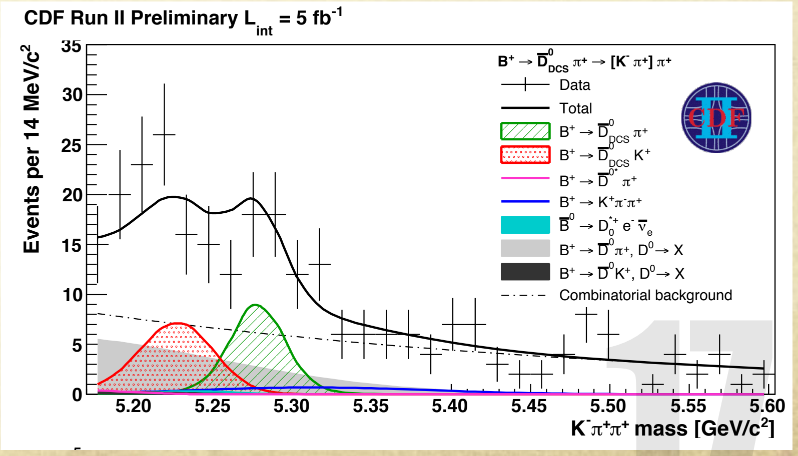
CDF-Pub-10309

- Study of B→DK is the cleanest way to access γ.
  - From the interference between b→c ubar s ($B^- \to D^0 K^-$) and b→u cbar s ($B^- \to$ anti$D^0 K^-$) with the D0 and aD0 decay in the same final state.
- Several methods to extract γ.
  - No tagging or time-dependent analysis required.
- ADS method(*PRL78,3257;PRD63,036005*) uses Doubly Cabibbo Suppressed $D^0 \to K^+\pi^-$ decays.
- Simultaneous ML fit combining mass and PID estimates:
  - $N(B \to D_{DCS}K) = 34 \pm 14$
  - $N(B \to D_{DCS}\pi) = 73 \pm 16$
  - Significance ($D_{DCS}\pi$ + $D_{DCS}K$) >5σ

$B^- \to D\pi^- \to [K^+\pi^-]\pi^-$



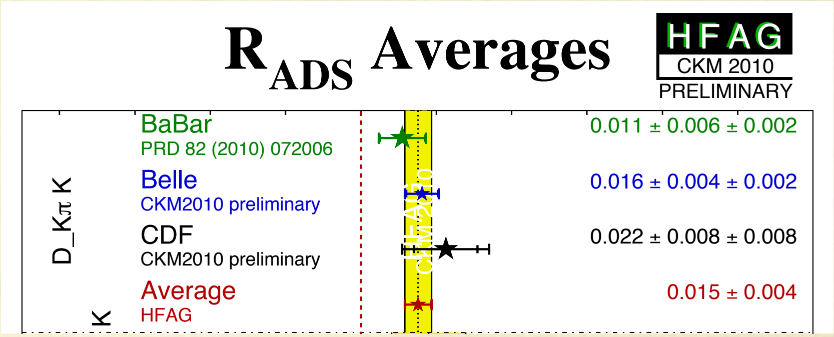
$B^+ \to D\pi^- \to [K^-\pi^+]\pi^+$

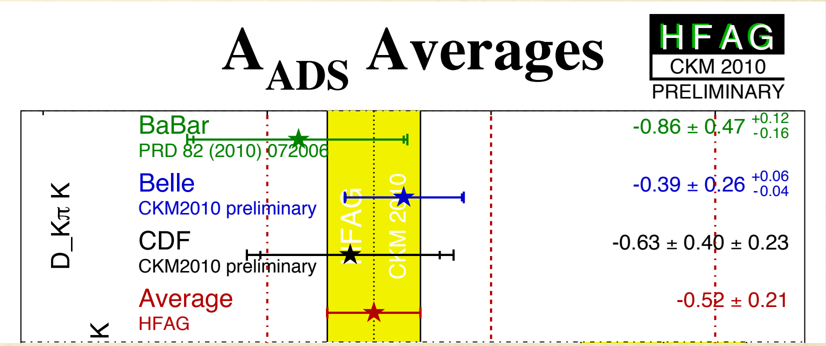


Observables: R_{ADS} and A_{ADS}

$$R_{ADS} = \frac{BR(B^- \to [K^+\pi^-]_{D^0} K^-) + BR(B^+ \to [K^-\pi^+]_{D^0} K^+)}{BR(B^- \to [K^-\pi^+]_{D^0} K^-) + BR(B^+ \to [K^+\pi^-]_{D^0} K^+)}$$

$$A_{ADS} = \frac{BR(B^- \to [K^+\pi^-]_{D^0} K^-) - BR(B^+ \to [K^-\pi^+]_{D^0} K^-)}{BR(B^- \to [K^+\pi^-]_{D^0} K^-) + BR(B^+ \to [K^-\pi^+]_{D^0} K^+)}$$





- R_{ADS} and A_{ADS} are functions of γ angle.
- First measurements of these quantities at hadron collisions.
- Results in agreement and competitive with other experiments.
- Analysis on $7 fb^{-1}$ is in progress. $D_{DCS}K$ significance $>3\sigma$.

See P. Garosi's talk for more details.

Conclusions

- TeVatron continuing to produce a rich and exciting program in heavy flavor physics.
  - Complementary to e^+e^- machines and LHC experiments.
- Many interesting results will benefit from more data.
  - Anticipate ~$10fb^{-1}$ per experiment for analysis by the end of this year.
- Results will continue beyond the end of the Run.

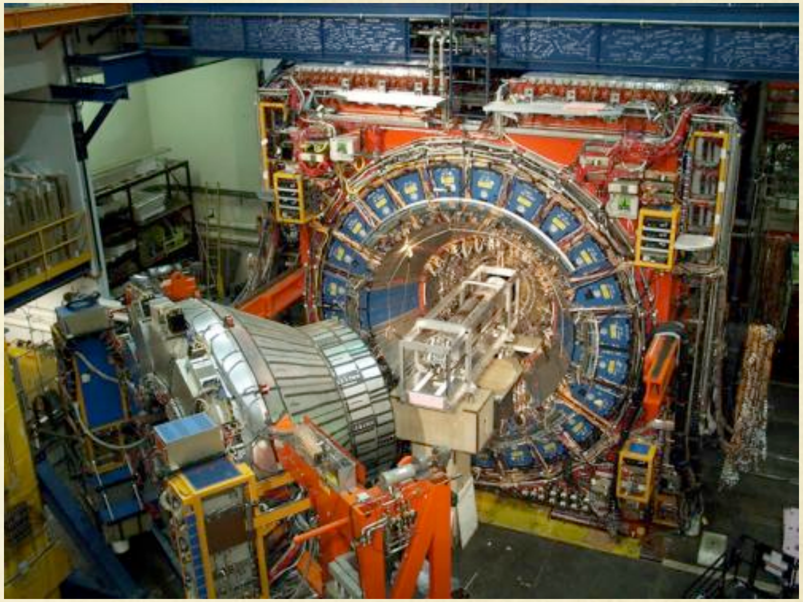
Topic not covered here (or in the pipeline)

- $A_{FB}(b \to s\mu\mu)$
- World's most precise lifetime measurements (e.g $\Lambda_b \to J/\psi\ \Lambda$)
- BR&ACP in $B \to hh$
- γ from GLW $B \to DK$
- D^0-mixing and $D^0 \to \mu\mu$ search (in general Charm Physics).
- More B^0_s ($B^0_s \to D_s D_s$, $B^0_s \to J/\psi K_s$, $B^0_s \to J/\psi K^*$, CPV in $B_s \to \mu D_s$, $B^0_s \to \phi\phi$, ….)
- Baryons (Properties, Decays, Excited states, Ω_b, ….)
  - For instance see P.Barria's poster on $\Lambda_b \to \Lambda_c\ \pi\pi\pi$
- B_c (decays, properties)
- Production measurements
- X(3872), Y(4140),Y(4274) …
- … and many others.

Backup

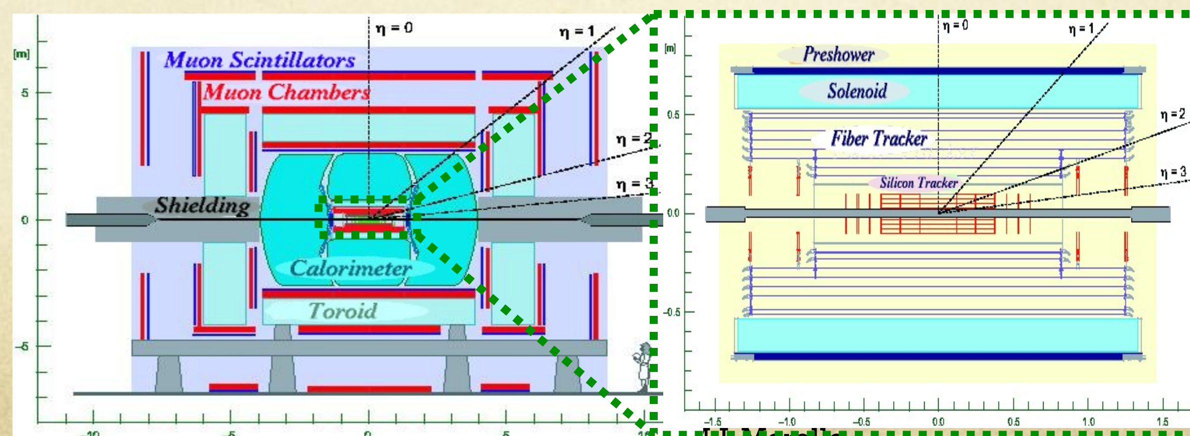
CDFII detector

- Central Drift Chamber
  - $\delta p_T / p_T \sim 0.0015\ (GeV/c)^{-1} p_T$
- Silicon Vertex Detector
  — Silicon Vertex Trigger
- Particle identification
  — dE/dX and TOF
- Good electron and muon identification by calorimeters and muon chambers.



DØ detector

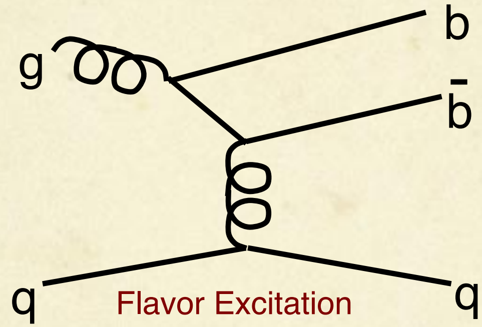
- Excellent coverage of Tracking and Muon Systems
- Excellent calorimetry and electon ID
- 2 T Solenoid, polarity reversed weekly
- High efficiency muon trigger with muon p_T measurement at Level1 by toroids



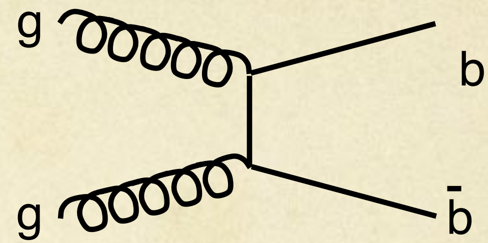
B Physics at the Tevatron

Mechanisms for b production in ppbar collisions at 1.96 TeV:

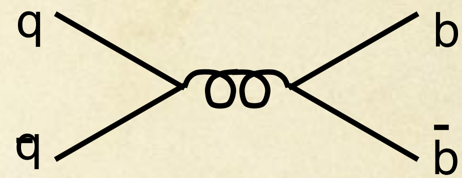
Gluon Splitting



Flavor Excitation



Flavor Creation (gluon fusion)



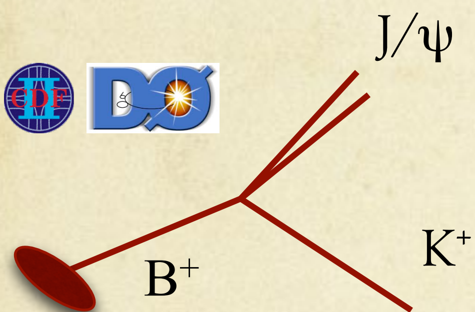
Flavor Creation (annihilation)

- At Tevatron, large b production cross section
- Plethora of states accessible: B^0_s, B_c, Λ^0_b, Ξ_b, Σ_b...
- Total σ(inelastic) at Tevatron is ~1000 larger that b cross section
  - — large backgrounds suppressed by triggers that target specific decays.

B Triggers

J/ψ

- $p_T(\mu) > 1.5 GeV$
- J/ψ mass requirement
- Opposite charge



$B^0 \rightarrow J/\psi\, K^{0*}$
$B^+ \rightarrow J/\psi\, K^+$
$\Lambda_b \rightarrow J/\psi\, \Lambda$
$B_c \rightarrow J/\psi\, \pi$
$B^0_s \rightarrow J/\psi\, \phi$
Ξ_b, B^{**}

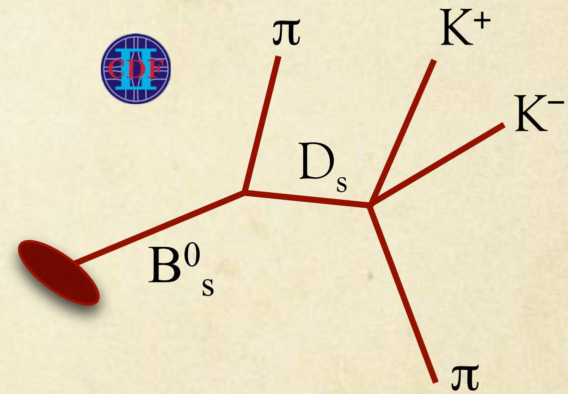
Dimuon

- $p_T(\mu) > 1.5$ or 2 GeV
- Triggers with/without charge requirement

$B \rightarrow \mu\mu$+hadrons
$B \rightarrow \mu\mu$
$bb \rightarrow \mu\mu$
$cc \rightarrow \mu\mu$

Displaced Track

- $p_T(track) > 2 GeV$
- IP(track)>80 or 120 μm
- Opposite charge



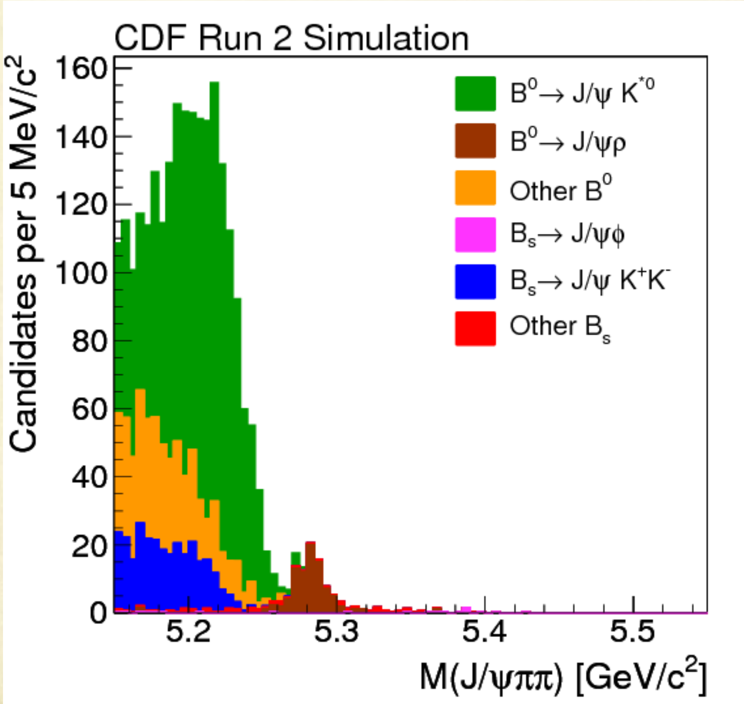
$B \rightarrow Dh$
$B \rightarrow hh$
$\Lambda_b \rightarrow ph$
$D \rightarrow hh$

$B^0_s \to J/\psi f_0(980)$

- CP=+1 eigenstate
- Unambiguous measure of lifetime $1/\Gamma_H$
- Clean measure of CP violating parameter β_s
  - $B_s \to J/\psi\, \phi$ requires complex angular analysis for vector-vector final state
- Understand S-wave contributions to β_s measurement in $B_s \to J/\psi\, \phi$

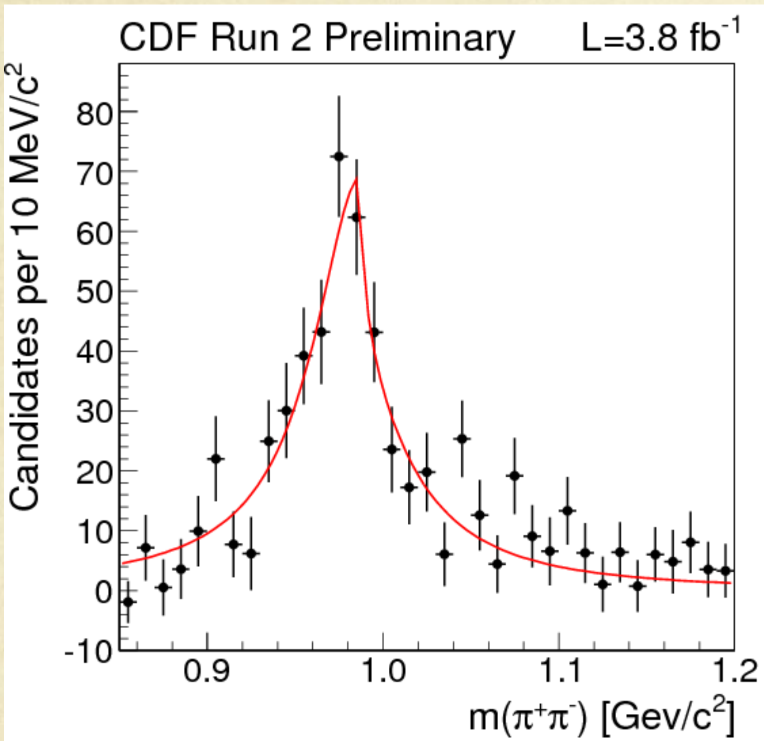
$B^0_s \to J/\psi f_0(980)$ - Analysis

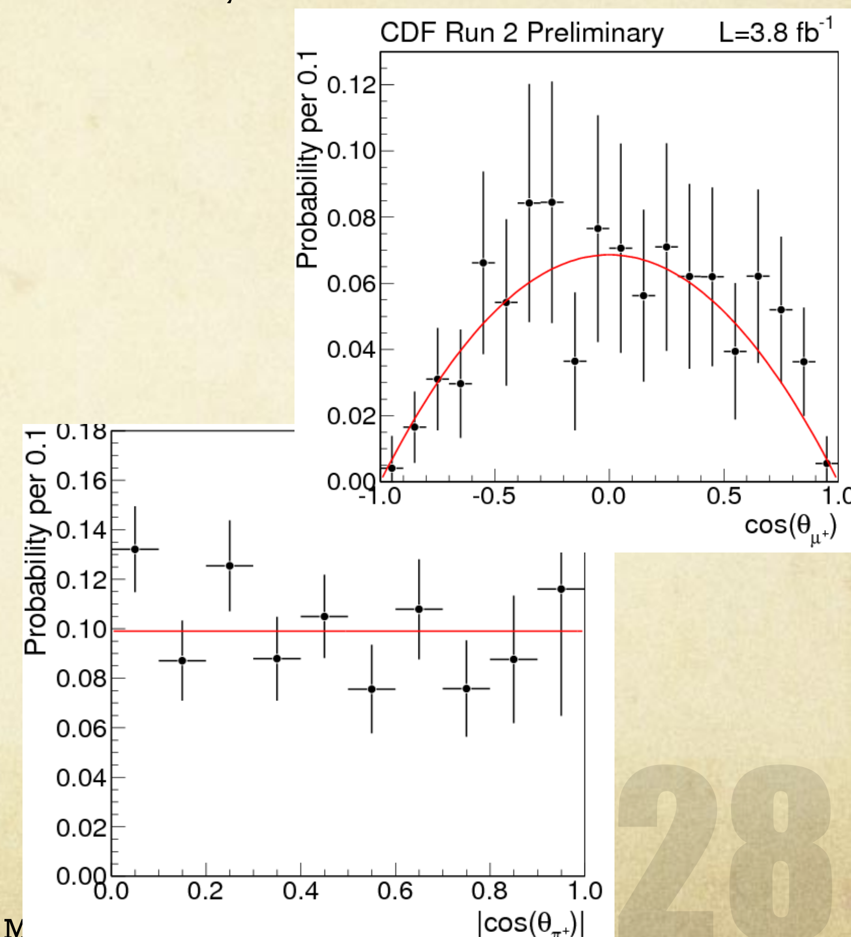
- Start with loose selection of $\mu\mu\pi\pi$ candidates
  - f_0 is wide, so $0.85<M(\pi\pi)<1.2$ GeV
- Neural Net Selection
- Kinematic variables, track & vertex displacement, isolation
- High-mass sideband only for background model
- Use identical selection for $Bs \to J/\psi\ \phi$ reference mode
- Physics backgrounds from Monte Carlo



Confirmation of $f_0(980)$

Helicity angles consistent with P→PV decay
After efficiency correction

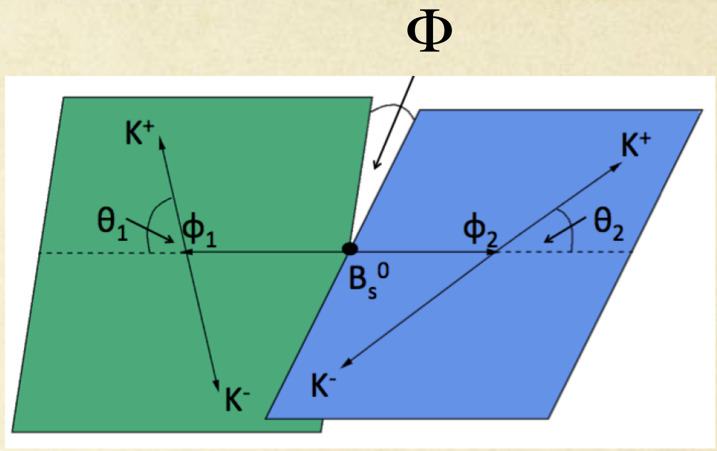




Di-pion mass distribution consistent with f_0. Shape parameters from BES.

$B^0_s \to \phi\phi$ at the TeVatron

- First measurement of BR (*CDF-Pub-10064*) and first measurement of polarization (*CDF-Pub-10120*).
  - Found large transverse polarization $(|A_{||}|^2+|A_\perp|^2)/|A_0|^2 = 1.9\pm0.2$ in disagreement with SM, naïvely <<1



- CP violation expected very tiny, however NP could enhance it.
- The best hard way: full tagged and time-dependent analysis, but statistics still too small.
- However Triple Products (TP) Asymmetries are expected zero in SM. NP could affect those.

$$\mathcal{A}_{\rm TP} = \frac{\Gamma(\vec{p}\cdot(\vec{\varepsilon}_1\times\vec{\varepsilon}_2)>0)-\Gamma(\vec{p}\cdot(\vec{\varepsilon}_1\times\vec{\varepsilon}_2)<0)}{\Gamma(\vec{p}\cdot(\vec{\varepsilon}_1\times\vec{\varepsilon}_2)>0)+\Gamma(\vec{p}\cdot(\vec{\varepsilon}_1\times\vec{\varepsilon}_2)<0)},$$

- Experimentally accessed by asymmetry of distribution of two angular function u and v. Theoretical details in *Int. J. of Mod. Phys. A, 19:2505 (2004) and arXiv:1103.2442*.

$$u = \cos\Phi\sin\Phi \longrightarrow A_{||}A_\perp$$

$$v = \begin{cases}\sin\Phi & \text{if } \cos\vartheta_1\cos\vartheta_2>0\\ \sin(-\Phi) & \text{if } \cos\vartheta_1\cos\vartheta_2<0\end{cases} \longrightarrow A_0A_\perp$$

First measurement of CPV in $B^0_s \to \phi\phi$

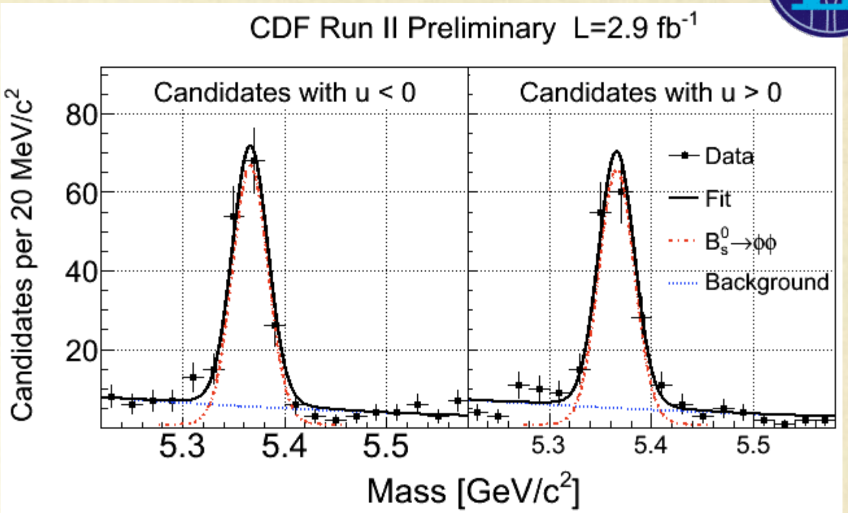
CDF-Pub-10424

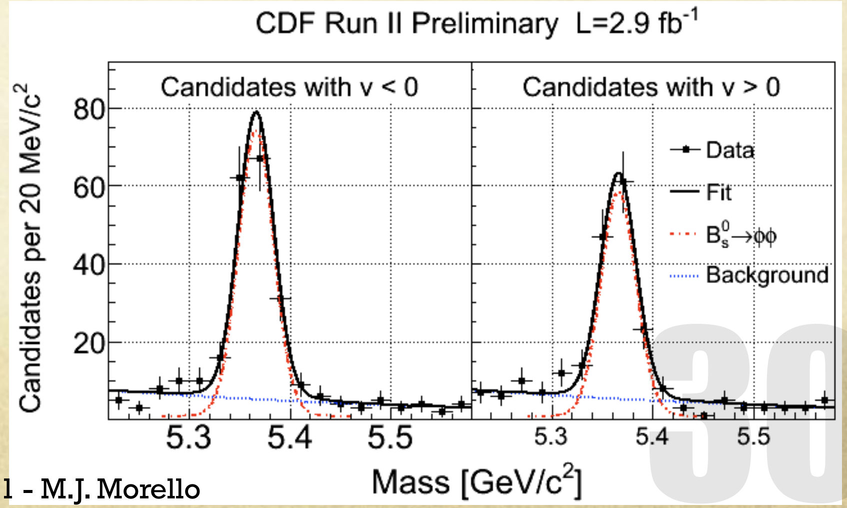
- No tagging and time-dependent analysis is required.
- Unbinned ML fit:
  - Signal asymmetry enter directly the Likelihood.
  - Backg. Asymmetry consistent with 0.

$$A_u = (-0.8 \pm 6.4 \pm 1.8)\%$$

$$A_v = (-12.0 \pm 6.4 \pm 1.6)\%$$

- Sensitive to CP Violation both in mixing and decay.





$\bar{\chi}$: New CDF Measurement

- Dimuon data sample
  - 1.4 fb^{-1}
  - Use impact parameter to identify source of muons: *b*, *c*, prompt
    - Same technique as *bb* cross-section measurement
    - 2D fit of d_0 using templates from Monte Carlo
    - Constraints on $b,c \rightarrow K,\pi \rightarrow \mu$ also from MC
    - Much tighter selection than earlier measurements
      - Requires hit in silicon layer 1.7cm far from beam

Extracting $\bar{\chi}$

- Many sources of dimuons in bb events
  - b semileptonic decay
  - $b \rightarrow c \rightarrow \mu$ sequentials
  - $b \rightarrow \psi \rightarrow \mu$
  - Hadron fakes
- Use MC to derive wrong-charge fraction
- Result: $\bar{\chi}=0.127 \pm 0.008$
  - Includes systematic uncertainty on wrong-charge correction
  - Compare to LEP: 0.126 ± 0.004

CPV in $D^0 \to h^+h^-$

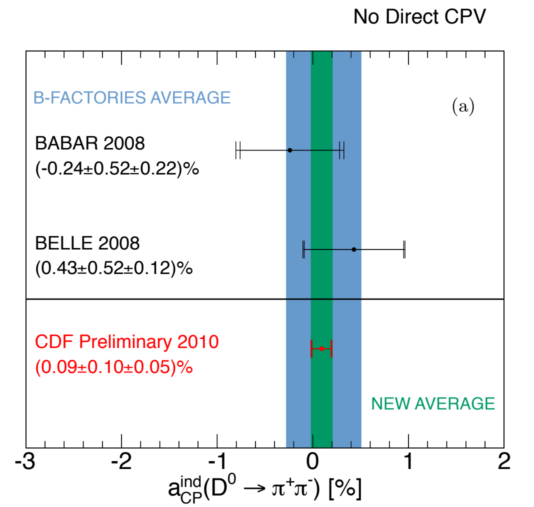
- The main challenge: suppressing detector charge asymmetries at the per mille level.
- Fully data driven technique using huge sample of Cabibbo-favored tagged and untagged $D^0 \to K^-\pi^+$
- Basic assumption: ppbar strong interactions are charge symmetric.

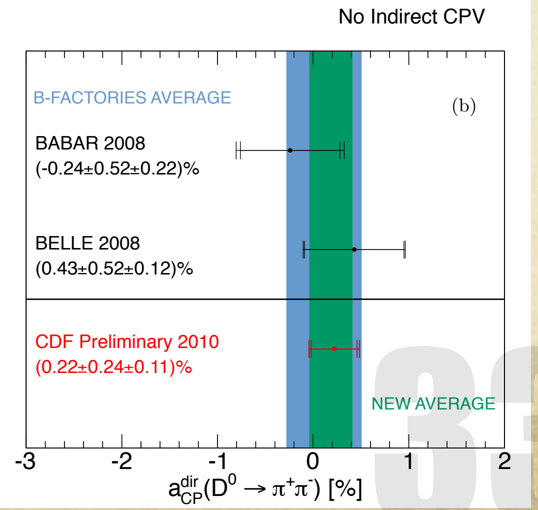
$$A_{CP}(D^0 \to \pi^+\pi^-) = [+0.22 \pm 0.24 \pm 0.11]\%$$

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

- World's best measurements.
  - CDF very sensitive to mixing induced effects, because of impact parameter requirements.
- Fully consistent with small CP violation.

CDF-Pub-10296





$B \to \mu^+\mu^-$ – Strategy

$BR(B^0_s \to \mu^+\mu^-)$ is obtained by normalizing to the number of $B^+ \to J/\psi K^+ \to [\mu^+\mu^-]K^+$ where $\mu^+\mu^-$ vertex is reconstructed in the "same" manner (similar for B^0).

$B^0_s \to \mu^+\mu^-$ decays at 95%CL

TriggerAcceptance ratio from MC

Rec. efficiency ratio from MC/DATA

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \frac{N_s}{N_+} \cdot \frac{\alpha_+}{\alpha_s} \cdot \frac{\epsilon_+}{\epsilon_s} \cdot \frac{1}{\epsilon_N} \cdot \frac{f_u}{f_s} \cdot \mathcal{B}(B^+),$$

From PDG08

$B^+ \to J/\psi K+$ decays from data

Efficiency of NN requirement from MC

$B \to \mu^+\mu^-$ – Selection

Selection based on following kinematics discriminating variables:

Transverse momentum of candidate $p_T^{\mu+\mu-}$ (>4GeV)
Transverse lower momentum of muon track p_T
Proper decay time $\lambda = L_{3D} \times M_{\mu\mu} / |p^{\mu+\mu-}|$
Significance of proper decay time λ/σ_λ (>2)
3D opening angle $\Delta\alpha$ (<0.7 rad)
Isolation of B candidate I (>0.5)