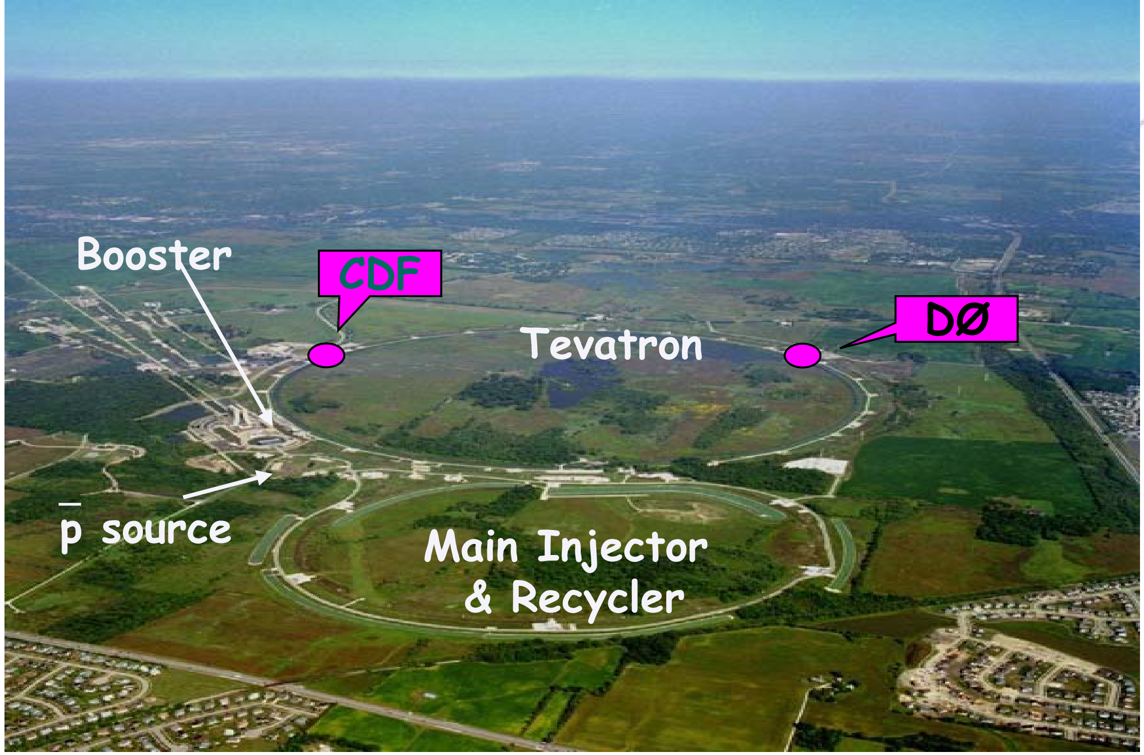

Status and prospects for *B* physics and discrete symmetries at Tevatron

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DISCRETE 2010
Sapienza Università di Roma
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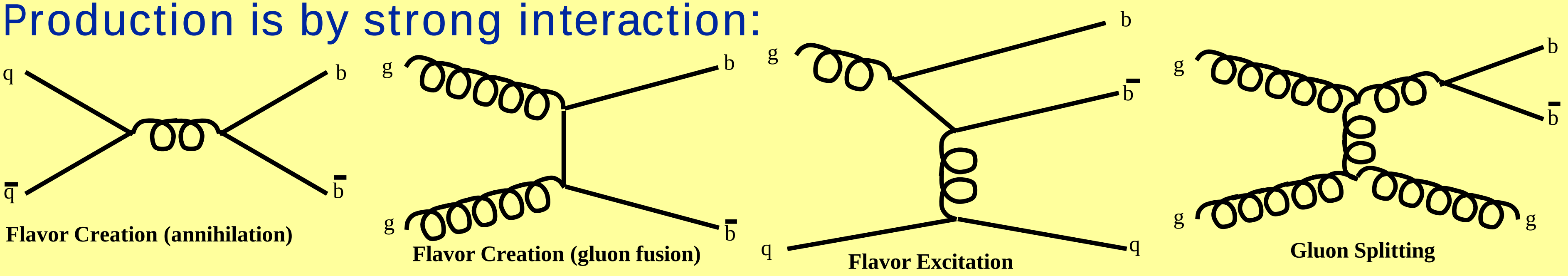
Outline

- Introduction
  - *B* physics at the Tevatron
  - Detectors & datasets
- Physics with (semi)leptonic final states
  - $B_s \to J/\psi\phi$
  - Dimuon *CP* asymmetry
  - Rare decays: $B_s \to \mu^+\mu^-$, $\mu^+\mu^-\phi$
- Physics with hadronic final states
  - A bit of history
  - $B \to D^0 K$
  - Charmless two-body decays ($b \to u\bar{u}d$, $u\bar{u}s$, $s\bar{s}s$)
  - *CP* asymmetry in $D^0 \to \pi^+\pi^-$
- A bit more on prospects
- Conclusion

B Physics at the Tevatron

Production is by strong interaction:



Pros

- **Large cross-section**
  - **~3-5 μbarn "reconstructable"**
  - At $2\times10^{32}\text{cm}^{-2}\text{s}^{-1} \Rightarrow$ ~800Hz of reconstructable *BB*!!
- **All *B* species produced**
  - $B_u, B_d, B_s, B_c, \Lambda_b$,…
- ***CP* symmetric initial state**
  - Equal numbers of *q* and $\bar{q}$

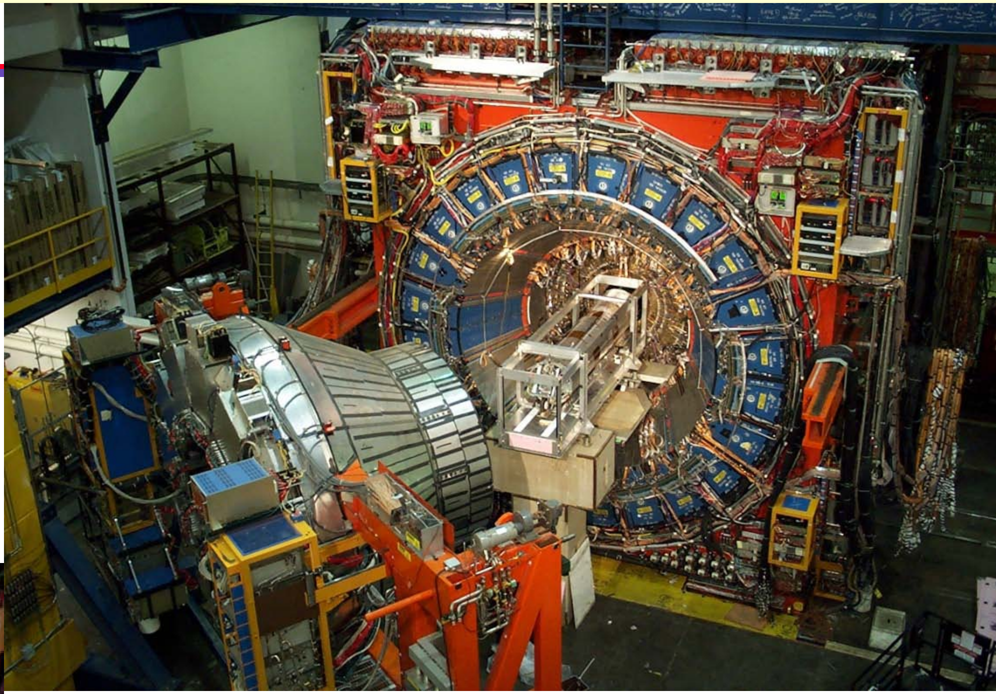
Cons

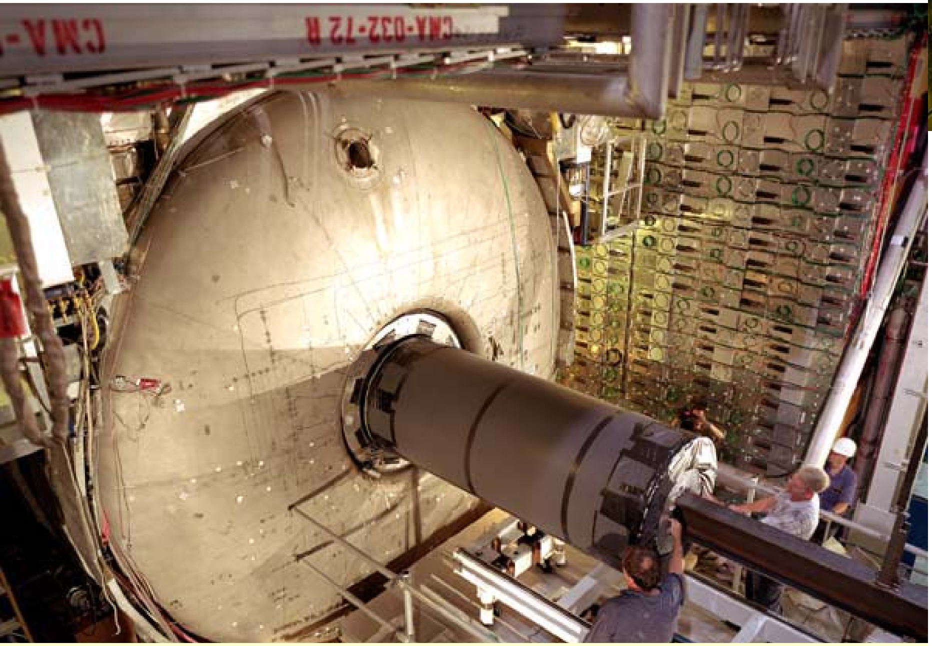
- **Large inelastic background**
  - **Triggering and reconstruction are challenging**
  - **Modes with π^0's are tough**
- **Reconstruct a *B* hadron,~20-40% chance 2nd *B* is within detector acceptance**
- **p_T spectrum relatively soft**
  - **Typical $p_T(B)$~10-15 GeV for reconstructed *B*'s ($\beta\gamma \approx$ 2-3)**

Detectors

- Both detectors
  - ➔ silicon microvertex detectors
  - ➔ axial solenoid
  - ➔ central tracking
  - ➔ high rate trigger/DAQ system
  - ➔ calorimeter & muon systems

CDF silicon detector installation



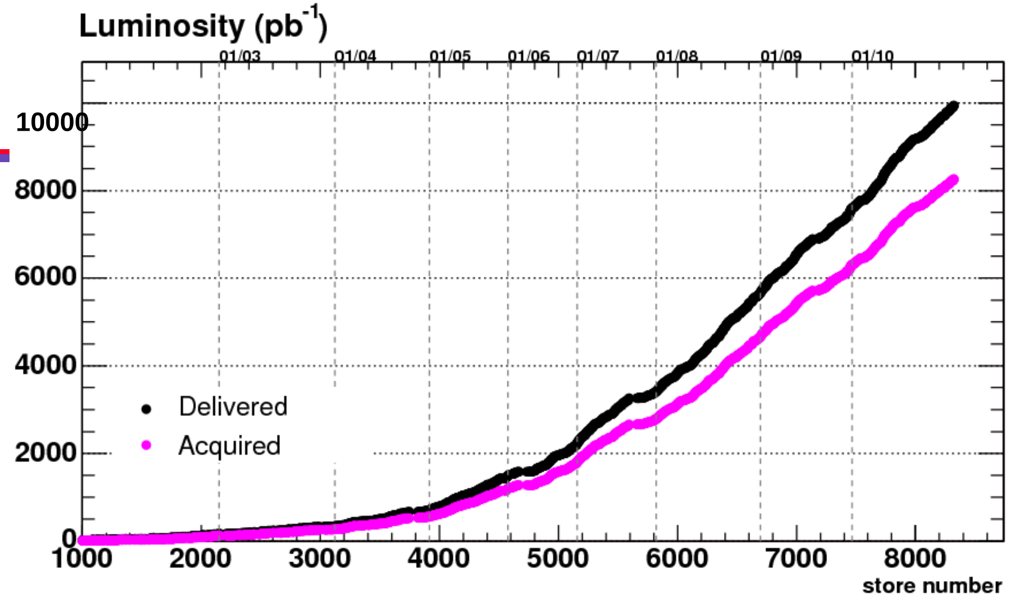


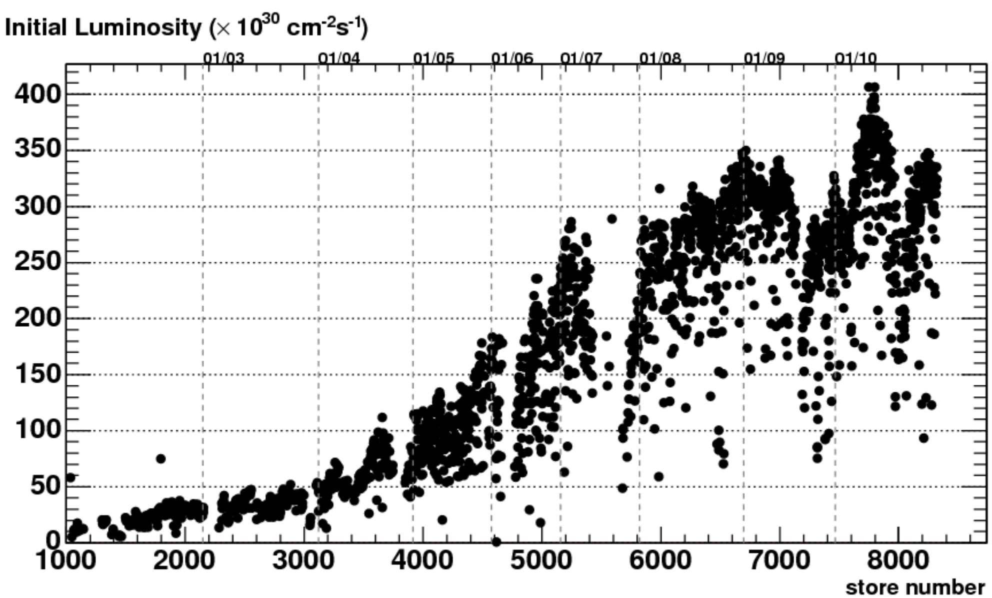
DØ fiber tracker installation

- DØ
  - ➔ Excellent electron & muon ID
  - ➔ Excellent tracking acceptance
- CDF
  - ➔ Silicon vertex trigger
  - ➔ Particle ID (TOF and dE/dx)
  - ➔ Excellent mass resolution

Datasets

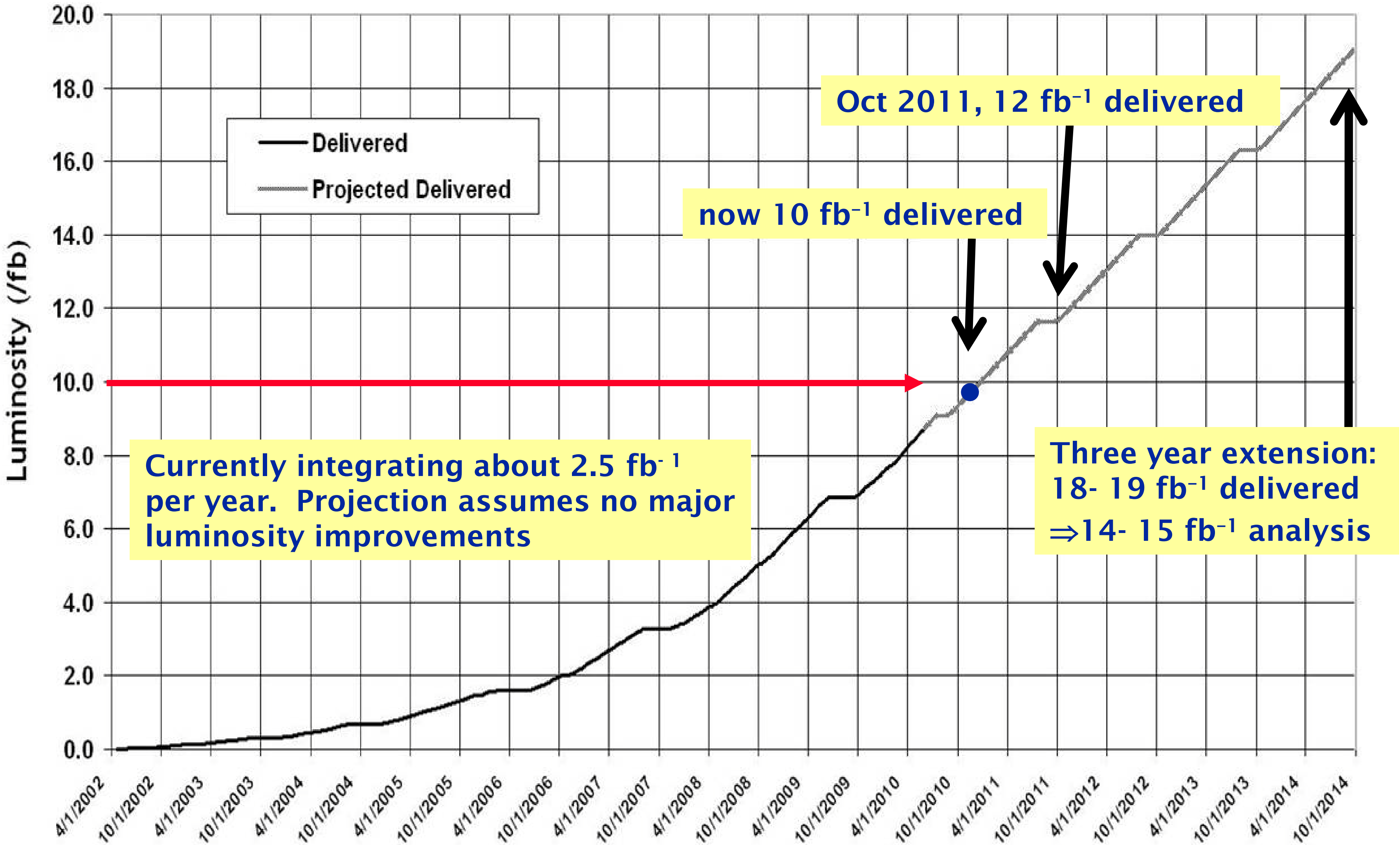
- **Tevatron performing well**
  - Delivering 2.5 fb^{-1}/year
- **Run II total: 10 fb^{-1} delivered**
  - analyze 75-80% of delivered
  - Show 1-6 fb^{-1} results today





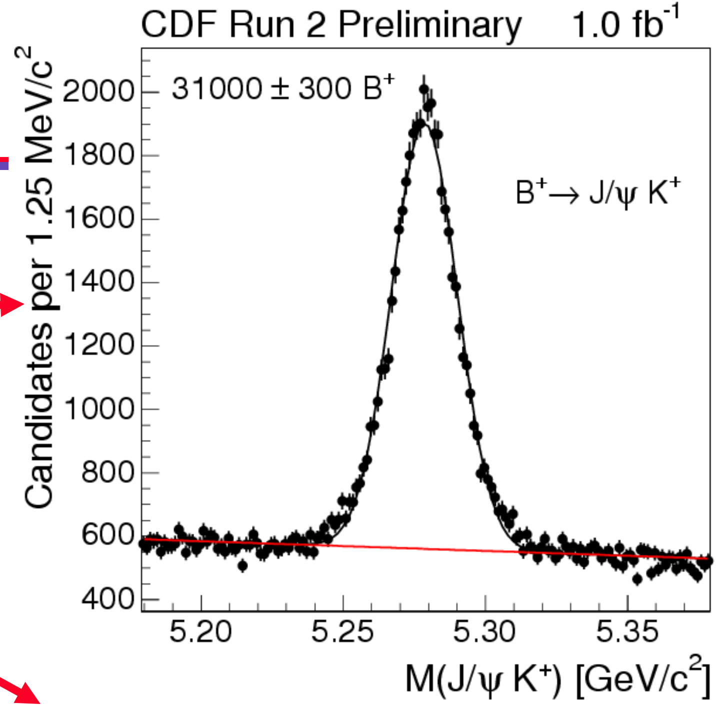
- **Peak $\mathcal{L}_{inst}$ 3.5-4x10^{32} cm^{-2} s^{-1}**
- **6-8 interactions per crossing**
- **Reduced efficiency for flavor physics at high $\mathcal{L}_{inst}$**

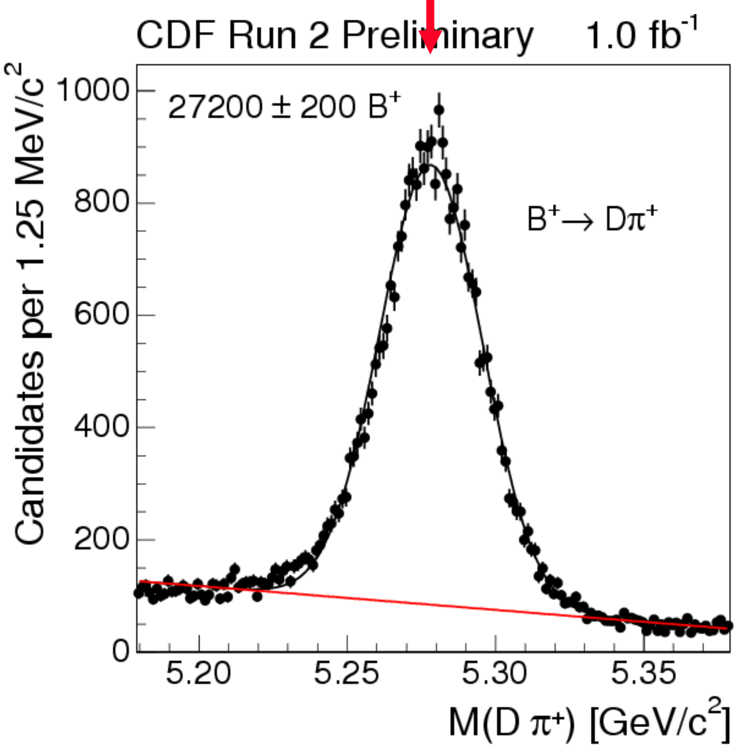
Tevatron run extension?

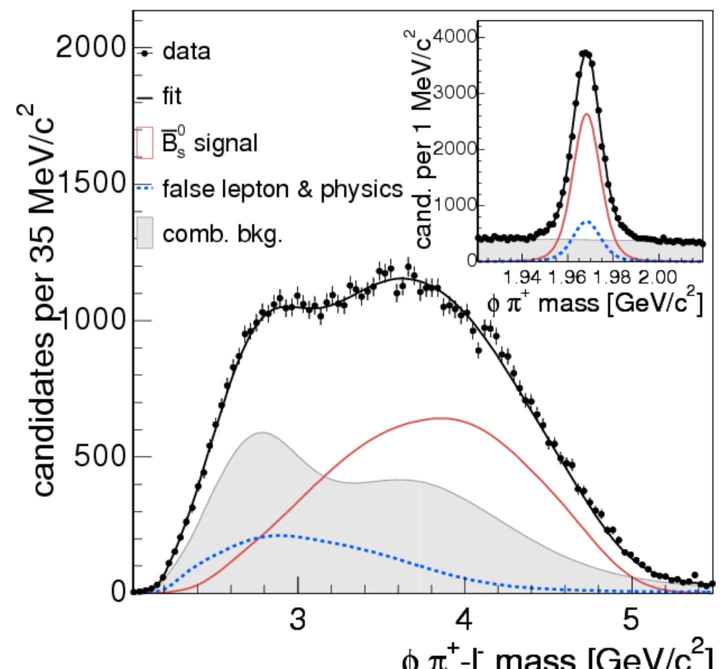


Trigger Strategies

- Dimuons
  - Clean signatures, less background
  - Get lots of $B \to J/\psi$ modes
  - Also rare decays ($B \to \mu\mu$, $\mu\mu X$)
- Single electrons/muons
  - Semileptonic decays
- Track only
  - Hadronic modes





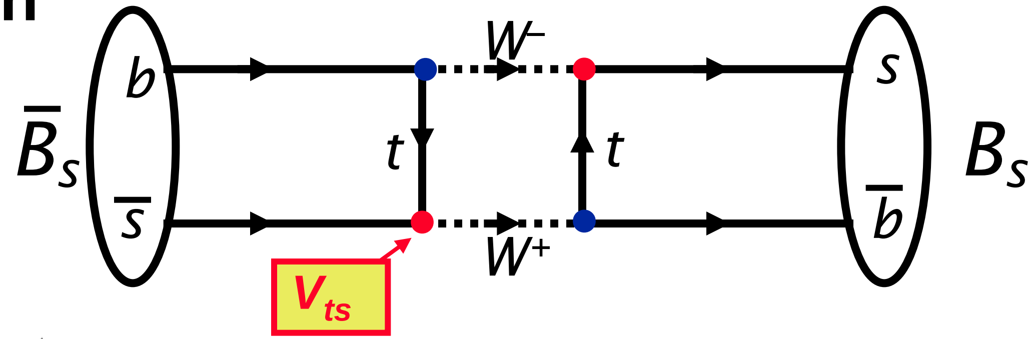


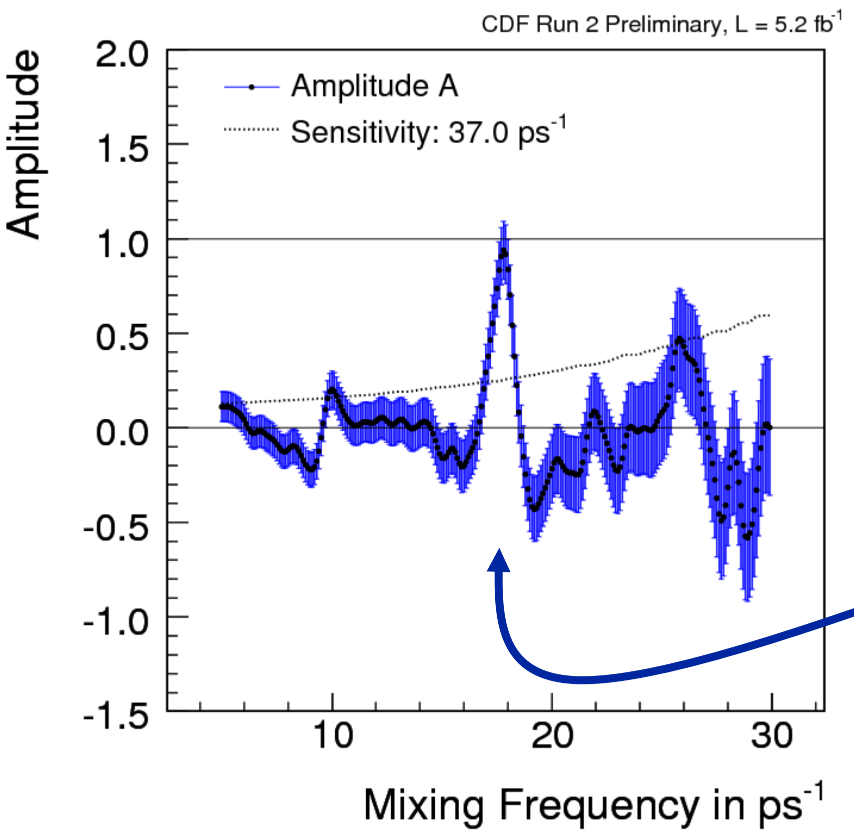
Comments

- Tevatron experiments primarily contribute measurements of B_s, B_c, b-baryons
  - ➔ Can contribute to B^0 and B^+ in a few places
    - $B \to DK$, $\mathcal{A}_{CP}(B^0 \to K\pi)$, $B^0 \to \mu^+\mu^-$, $B^0 \to \mu^+\mu^- K^*$, $\mathcal{A}_{CP}(B^+ \to J/\psi K^+)$, $B^+ \to \phi K^+$, τ_{B+}/τ_{B0}
  - ➔ In many cases (*e.g.* lifetimes, mixing) B^0 and B^+ are calibration or normalization modes…
- In all cases, trigger imposes a significant bias (kinematic, decay time) that must be dealt with…
- Other than a few special modes, typically require all-charged final state
- Experiments are mature, analyses have developed well beyond their original projections.

B_s Mixing

- **Mixing proceeds through "box" diagrams:**





- **oscillation frequency, Δm_s**

  $\Delta m_s \propto |V_{ts}|^2$ and $|V_{ts}|/|V_{td}| \approx 6$

- **Updated CDF analysis**

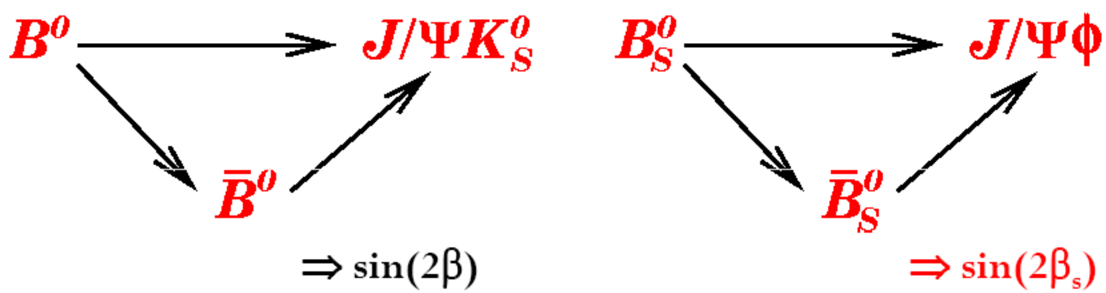
  (used for flavor tagging calibration)

  $\Delta m_s = 17.79 \pm 0.07$ (stat) ps^{-1}

- **What about the phase of V_{ts}?**

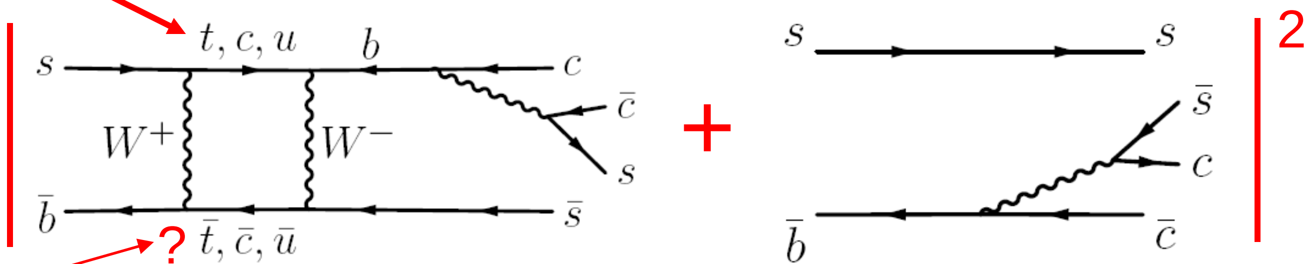
CP Violation in $B_s \to J/\psi\,\phi$ Decays

Analogous to the neutral B^0 system, *CP* violation in B_s system is accessible through interference of decays with and without mixing:



dominant contribution from top quark

Decay rate ~



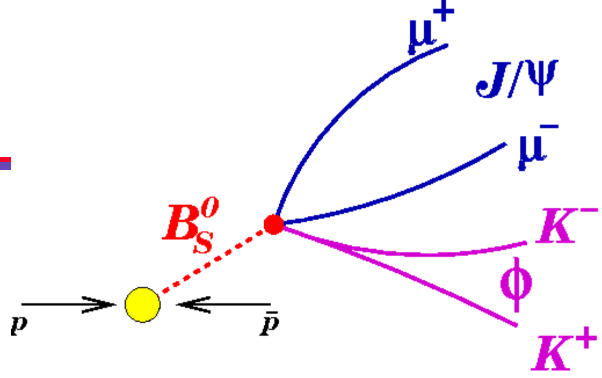
New Physics?

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

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

- ***CP* violation phase β_s in SM is predicted to be very small, *O($\sin^2\theta_c$)***
- **New physics particles running in the mixing diagram may enhance β_s**

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



-Technique:

  -Use flavor tagging to determine B_s vs. $\overline{B}_s$ produced

  -Measure decay time and angular distributions

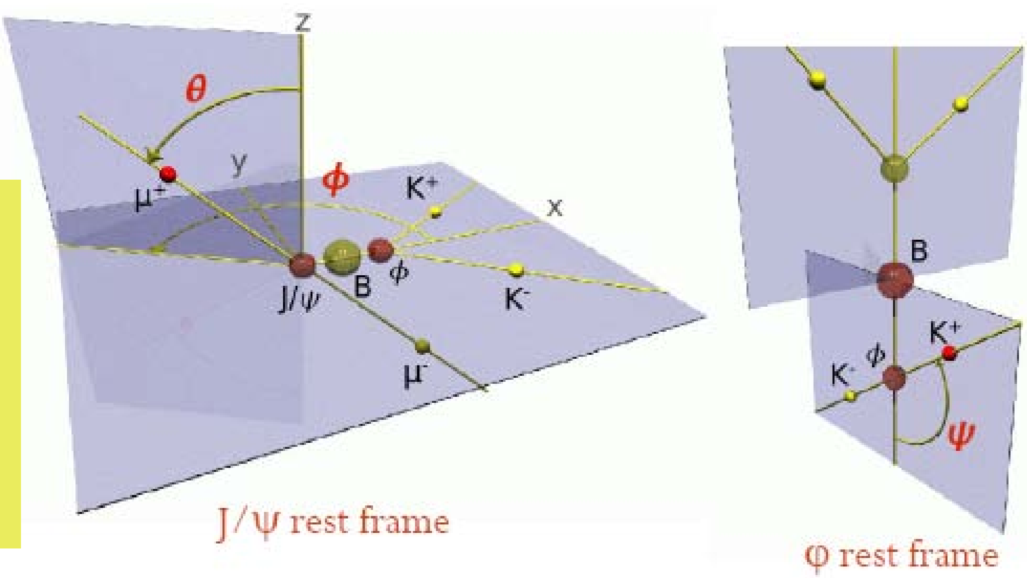
-Decay of B_s (spin 0) to J/ψ (spin 1) and ϕ (spin 1) leads to:

  $L = 0$ (s-wave), 2 (d-wave) → *CP even* (= short lived or light B_s if no *CPV*)

  $L = 1$ (p-wave) → *CP odd* (= long lived or heavy B_s if no *CPV*)

-Extract:

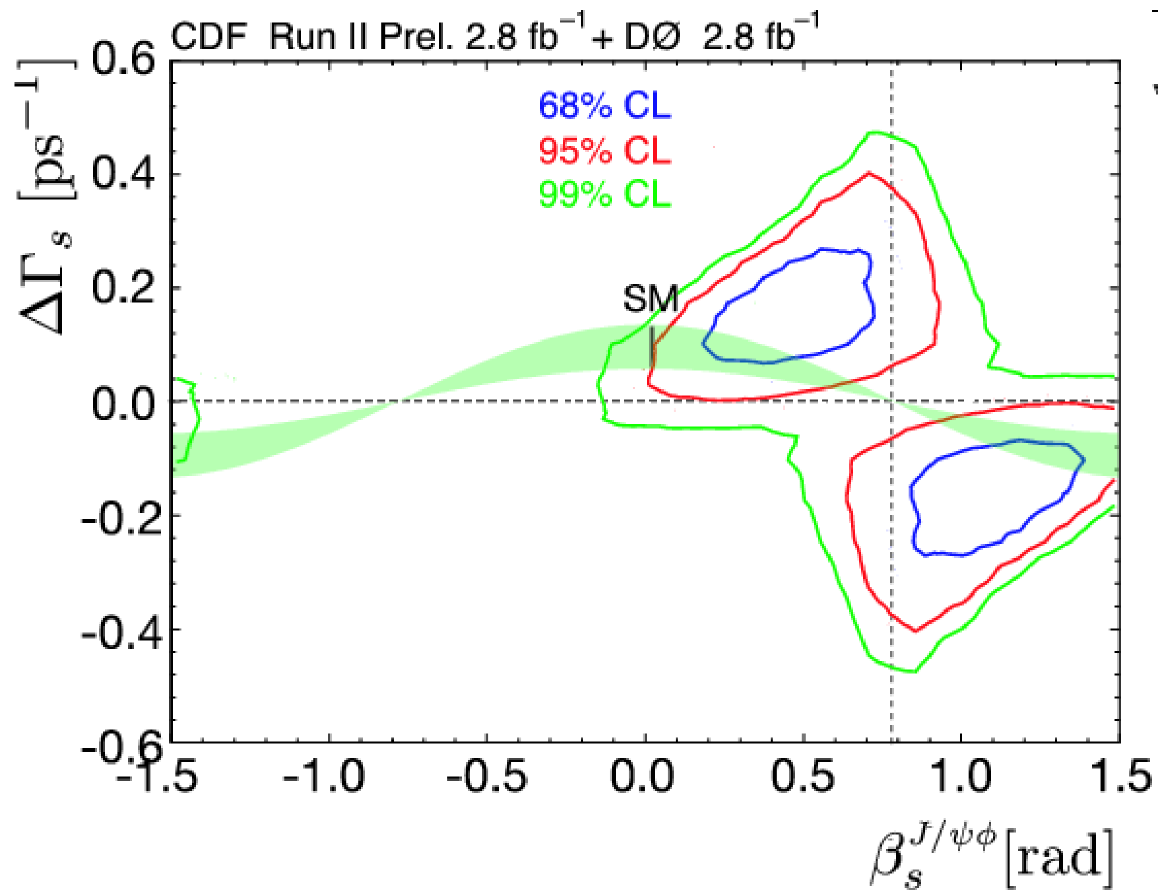
- B_s lifetime τ_s
- B_{sH}, B_{sL} decay width difference
  $\Delta\Gamma_s = 1/\Gamma_{s,L} - 1/\Gamma_{s,H}$
- *CP* violating phase β_s



$B_s \rightarrow J/\psi\phi$ Summer 2009

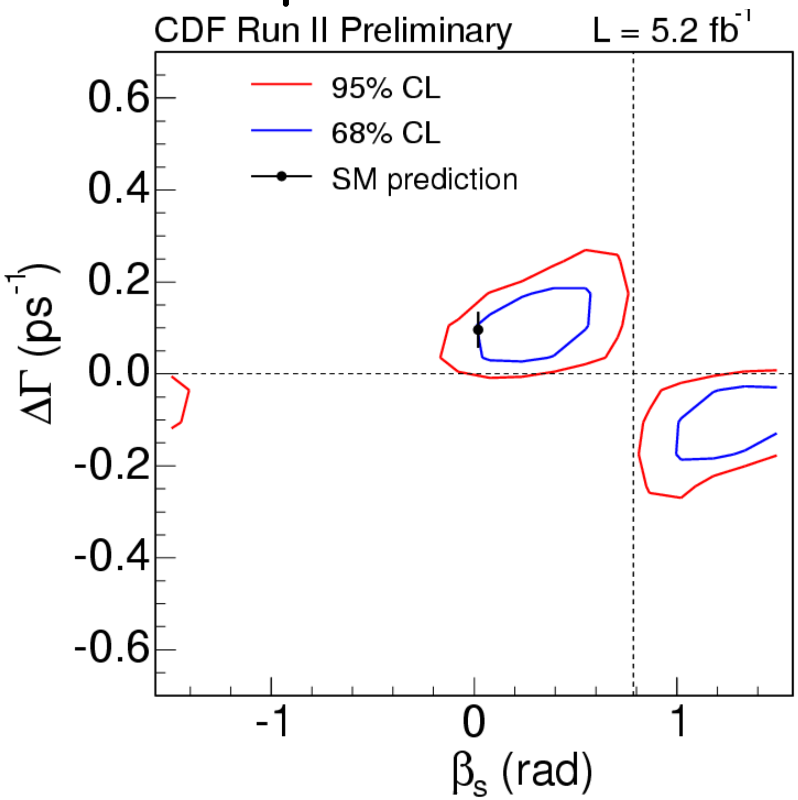
- CDF + DØ combination done by the Tevatron B Working Group: http://tevbwg.fnal.gov/

- Combination of 2.8 fb^{-1} analyses showed 2.1σ deviation from SM

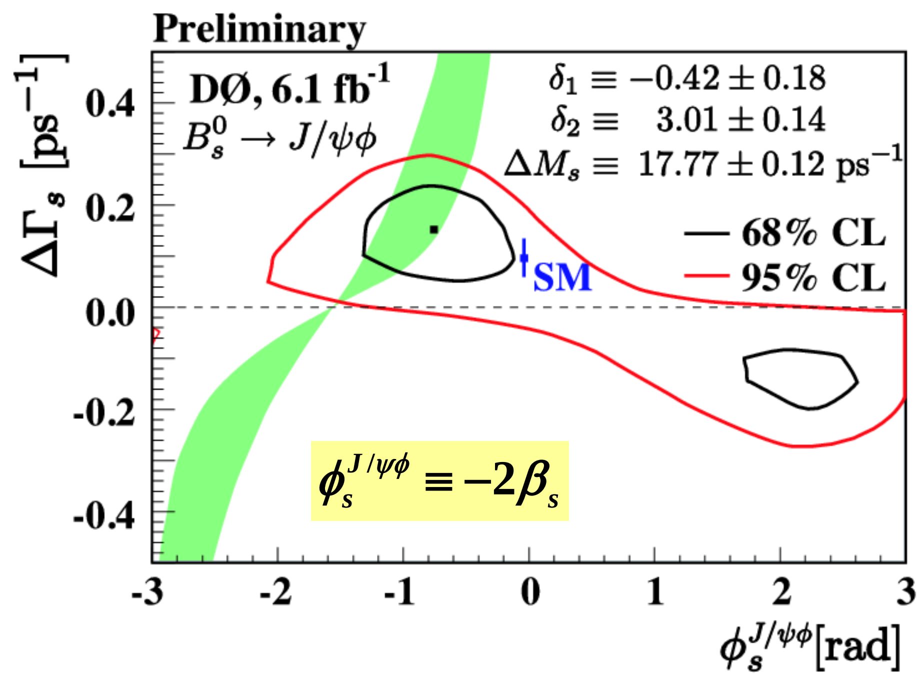


$B_s \to J/\psi\phi$ New Results

- **CDF**
  - 6500 signal events
  - Include s-wave *KK* component in fit.
  - Better particle ID



- **DØ**
  - 3435 signal events
  - Check for s-wave *KK* in data
  - No same-side tagging
  - Include strong phase constraints

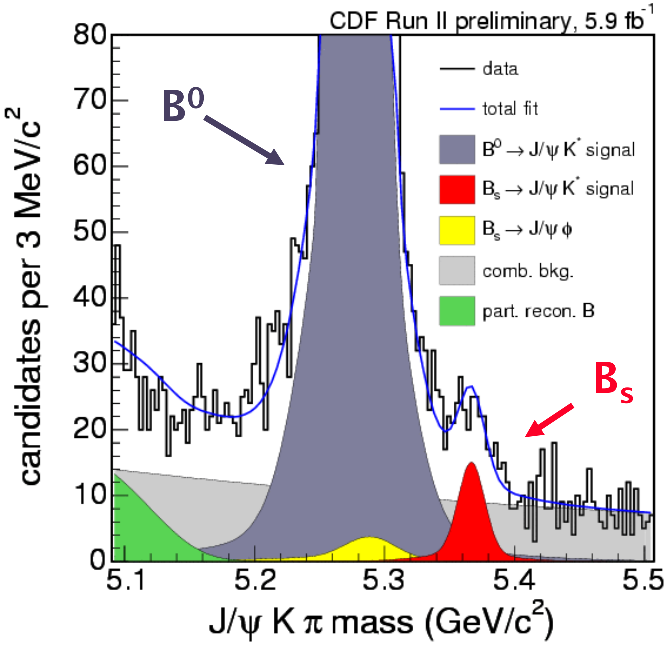


Trends are the same as before, but both experiments now see SM consistency at about 1σ

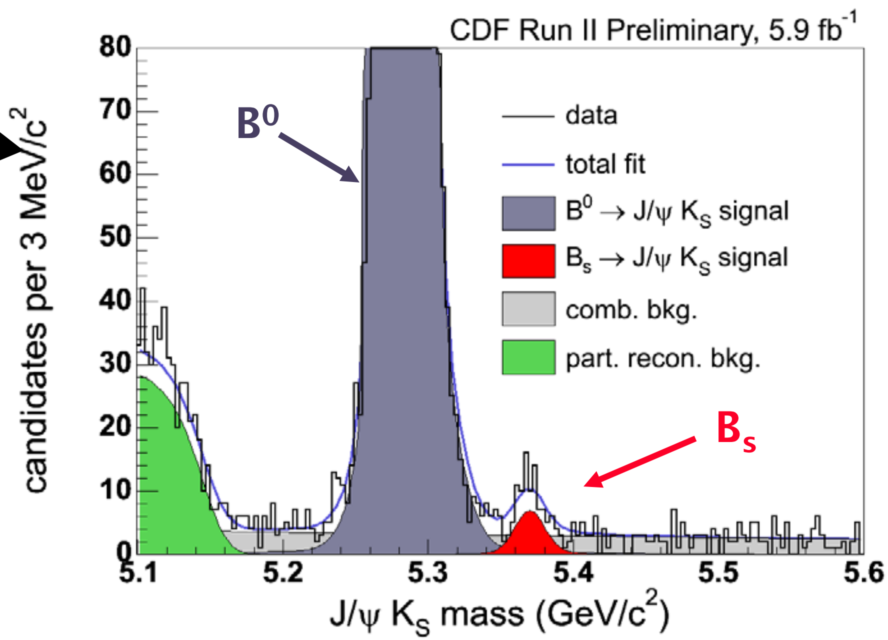
see Louise Oakes' talk on Friday

$B_s \to J/\psi\ K$

- **Cabibbo suppressed $b \to c\bar{c}d$**
  - Smaller tree contribution larger relative penguin contribution
- **$B_s \to J/\psi\, K^{*0}(892)$**
  - Analagous to $B_s \to J/\psi\phi$

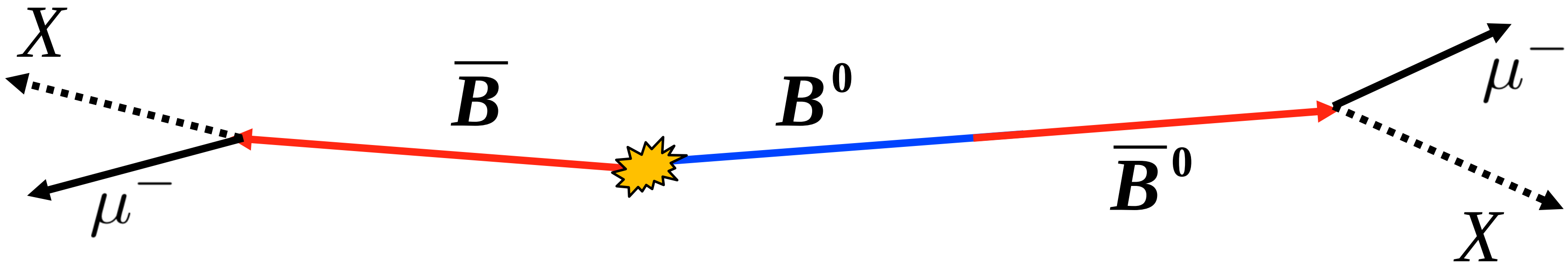


- **$B_s \to J/\psi\, K_S$**
  - *CP* eigenstate, 100% B_s heavy



- **First observations, branching ratios consistent with spectator estimate**

Dimuon charge asymmetry



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

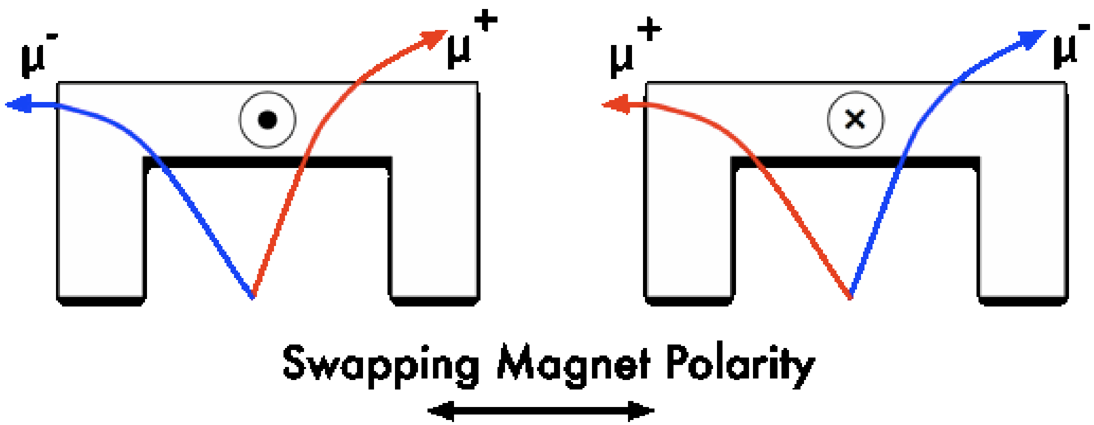
$$A_{sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

  - N_b^{++}, N_b^{--} – number of events with two *b* hadrons decaying semileptonically 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 $\overline{b} \to b \to \mu^- X$
  - Derived from dimuon and inclusive muon asymmetries:

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}, \text{ and } a \equiv \frac{n^+ - n^-}{n^+ + n^-}$$

Experimental issues

- use one muon as the "tag" and the other as the "probe".
- At Tevatron, both B^0 and B_s contribute.
- Lots of subtleties, but two main issues:
  1. Asymmetric backgrounds from kaons faking μ ⟶
  2. Asymmetric μ^+ and μ^- acceptance/efficiency



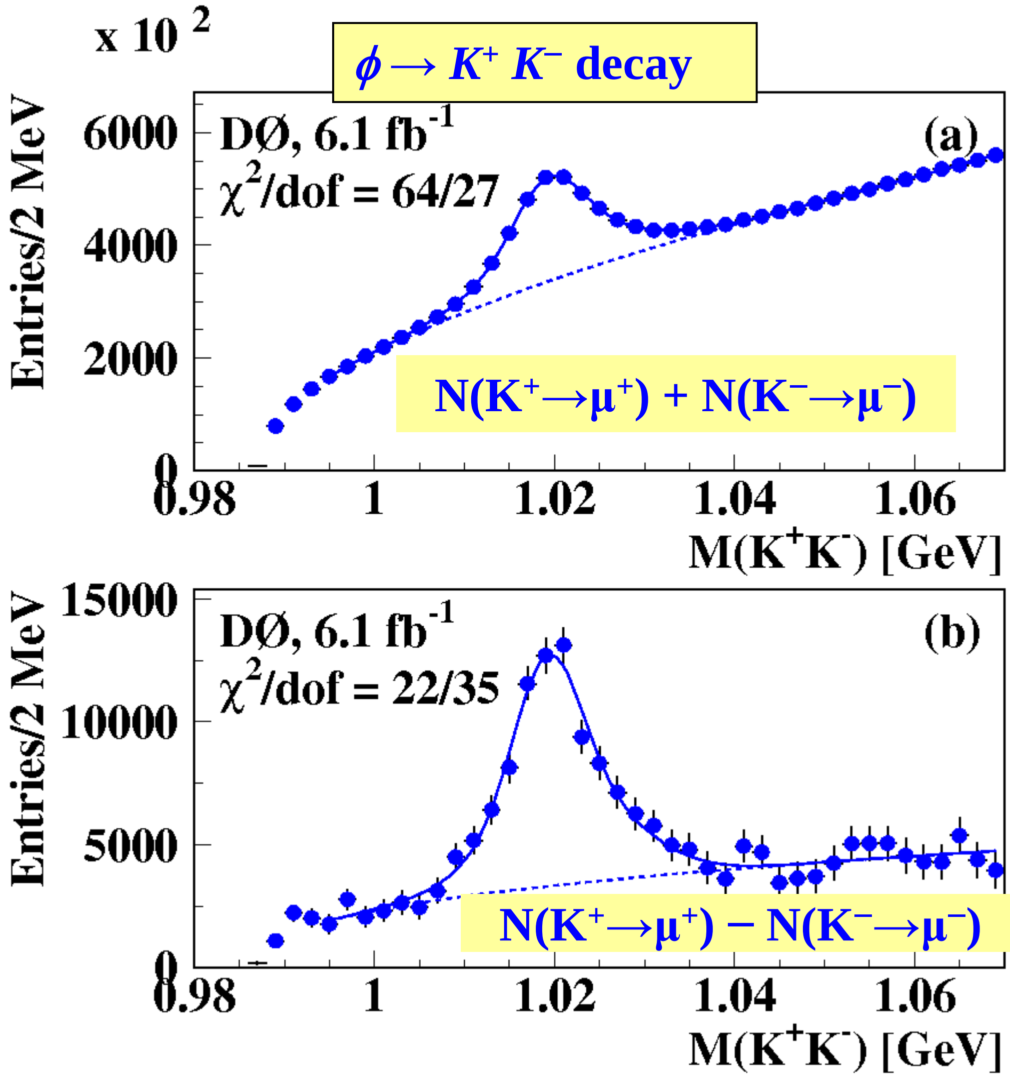
- Deal with acceptance/efficiency issue by periodically reversing polarity on central solenoid and muon toroids.
  - Check residual asymmetry with data.

Fake muon backgrounds

- $\sigma(K^+N) < \sigma(K^-N)$
  - ➔ more K^+ get through calorimeter making fake μ
- **Need to know:**
  - ➔ Number K faking μ
  - ➔ $K^+ \to \mu^+$ vs. $K^- \to \mu^-$
- **Define sources of kaons:**

$$K^{*0} \to K^+\pi^-$$
$$\varphi(1020) \to K^+K^-$$

- **Require that the kaon is identified as a muon**
- **Compute asymmetry from observed +/– yields**



$\mu\mu$ charge asymmetry result

- **DØ 6.1 fb^{-1} analysis yields:**

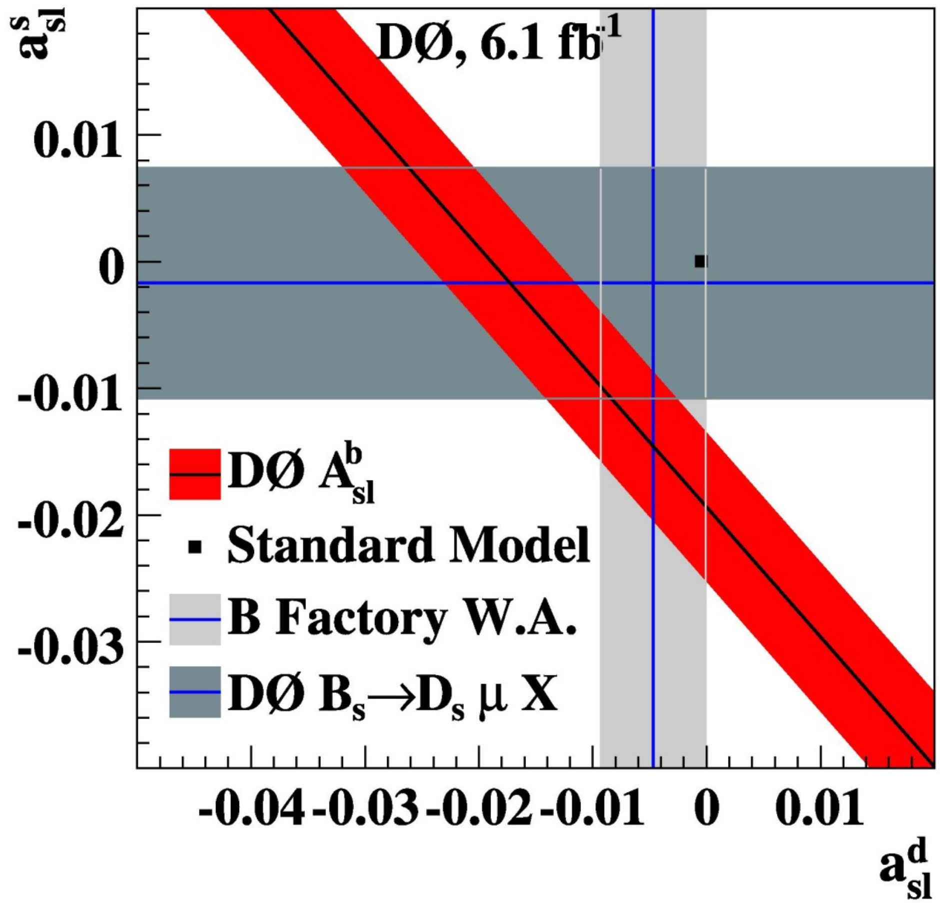
$$A_{sl}^{b} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%$$

- **SM prediction:**

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

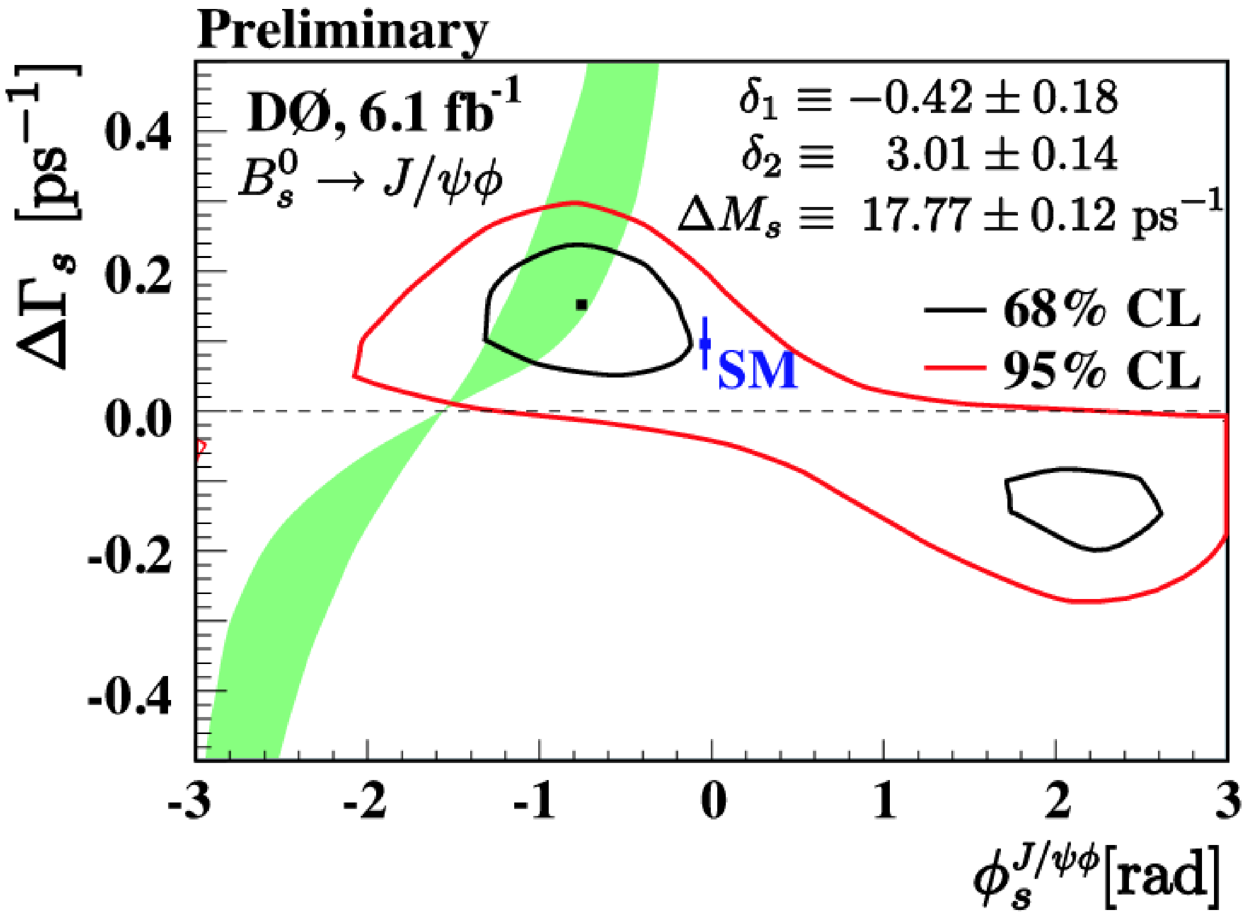
  - ⇒ using prediction of a^d_{sl} and a^s_{sl} from A. Lenz, U. Nierste, hep-ph/0612167

- **Differers from SM by ~3.2 σ**



DØ Combined results

- **Result from $B_s \rightarrow J/\psi\phi$ consistent with dimuon asymmetry**



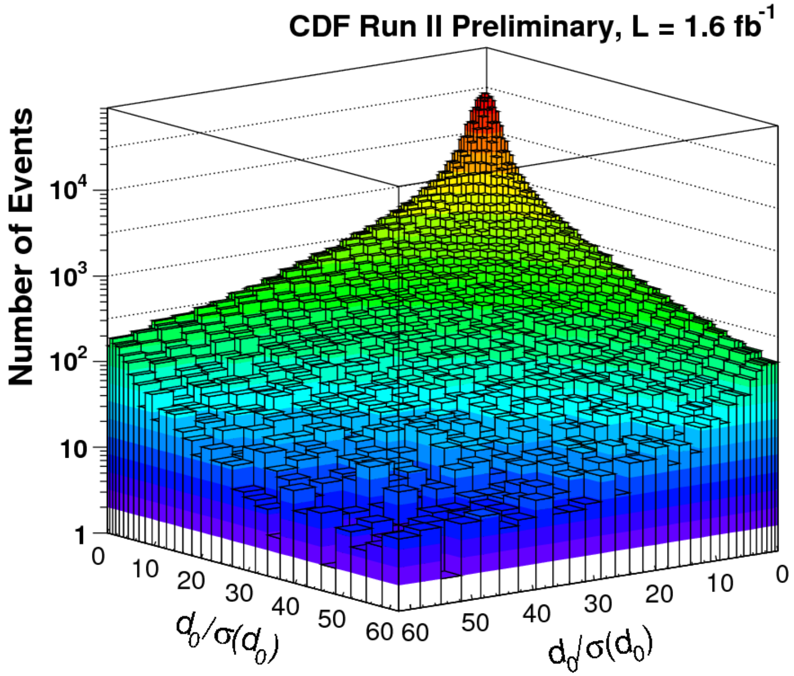
Projections for dimuon A_{CP}

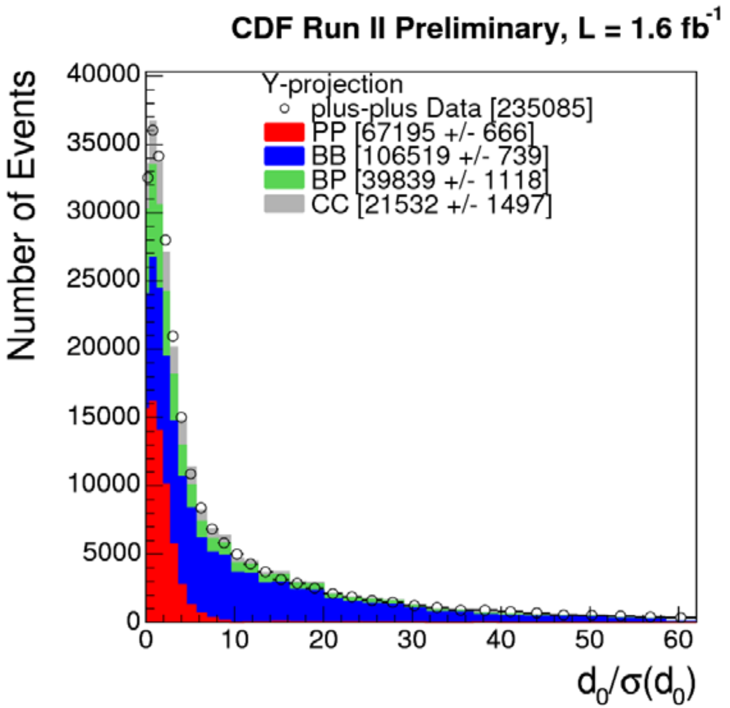
- DØ dimuon A_{CP} has a statistical error of 0.25% using 6.1 fb^{-1}

- Can CDF perform this measurement?
  - ➔ Cannot reverse magnet polarity
    - – Probably not a major concern, CDF axially symmetric
    - – Dominant charge bias is in central tracker at low momentum, can be measured with other modes.
  - ➔ DØ has better muon coverage at high $|\eta|$

CDF 1.6 fb^{-1} dimuon analysis

- **CDF used a different technique**
  - Use muon impact parameter information to fit for sample composition.
  - A_{SL} = 0.0080 ± 0.0090(stat) ± 0.0068(syst)

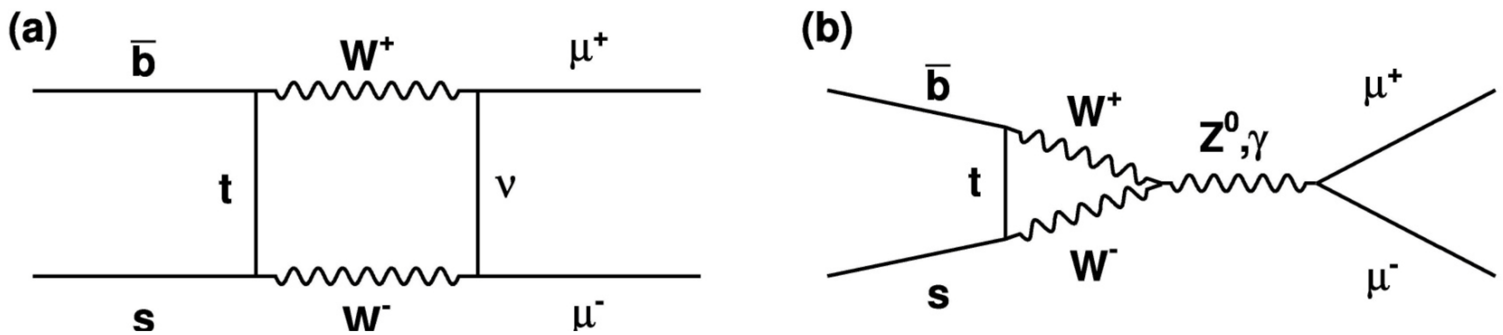


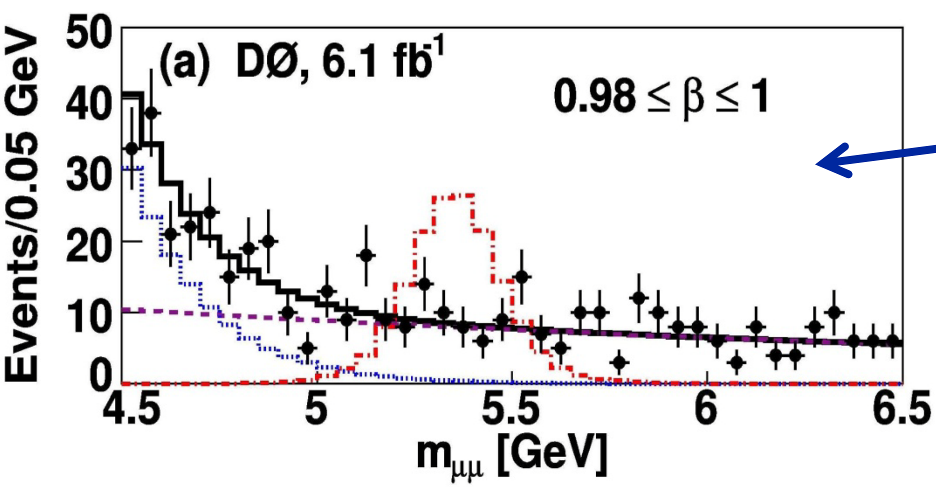


  - Scaling to 7 fb^{-1} would have statistical error of 0.45%
  - Unclear if systematics scale with statistics using CDF technique

$B_s \rightarrow \mu^+\mu^-$

- $B_s \rightarrow \mu\mu$ is highly suppressed in SM
- Some new physics models enhance BR significantly.

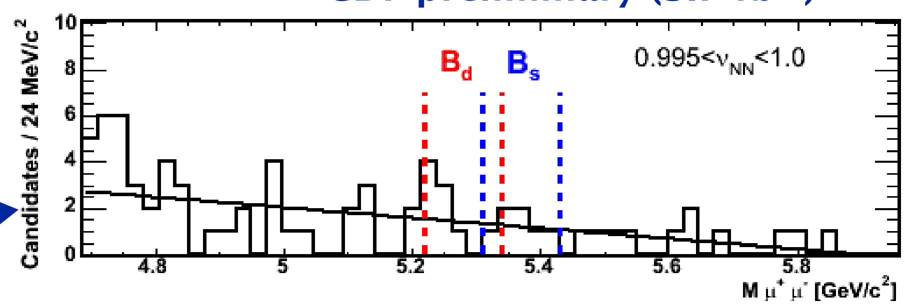




D0 arXiv:1006.3469 (6.1 fb^{-1})

BR($B_s \rightarrow \mu^+\mu^-$) < 5.1x 10^{-8} @ 95%CL

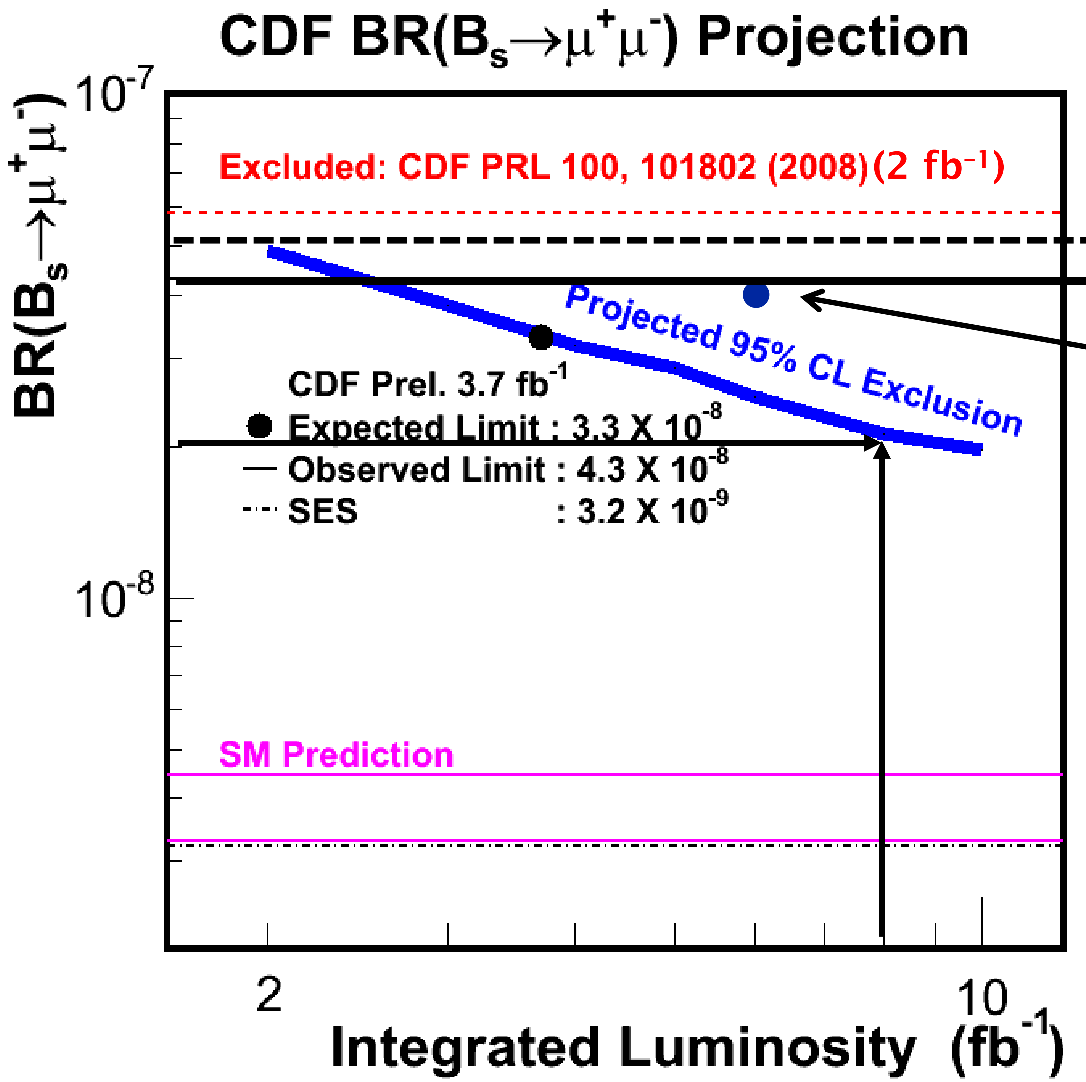
CDF preliminary (3.7 fb^{-1})



CDF preliminary (3.7 fb^{-1})

BR($B_s \rightarrow \mu^+\mu^-$) < 4.3x 10^{-8} @ 95%CL

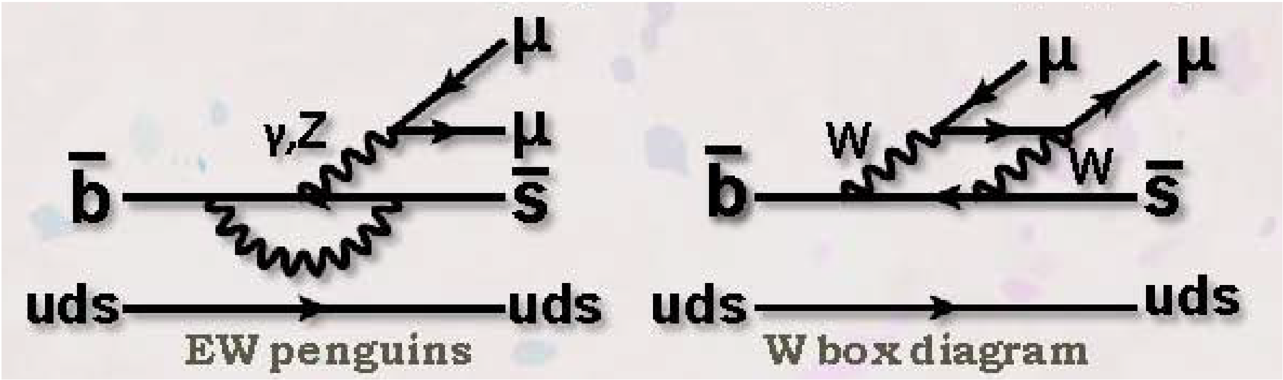
Projection for $B_s \to \mu^+\mu^-$



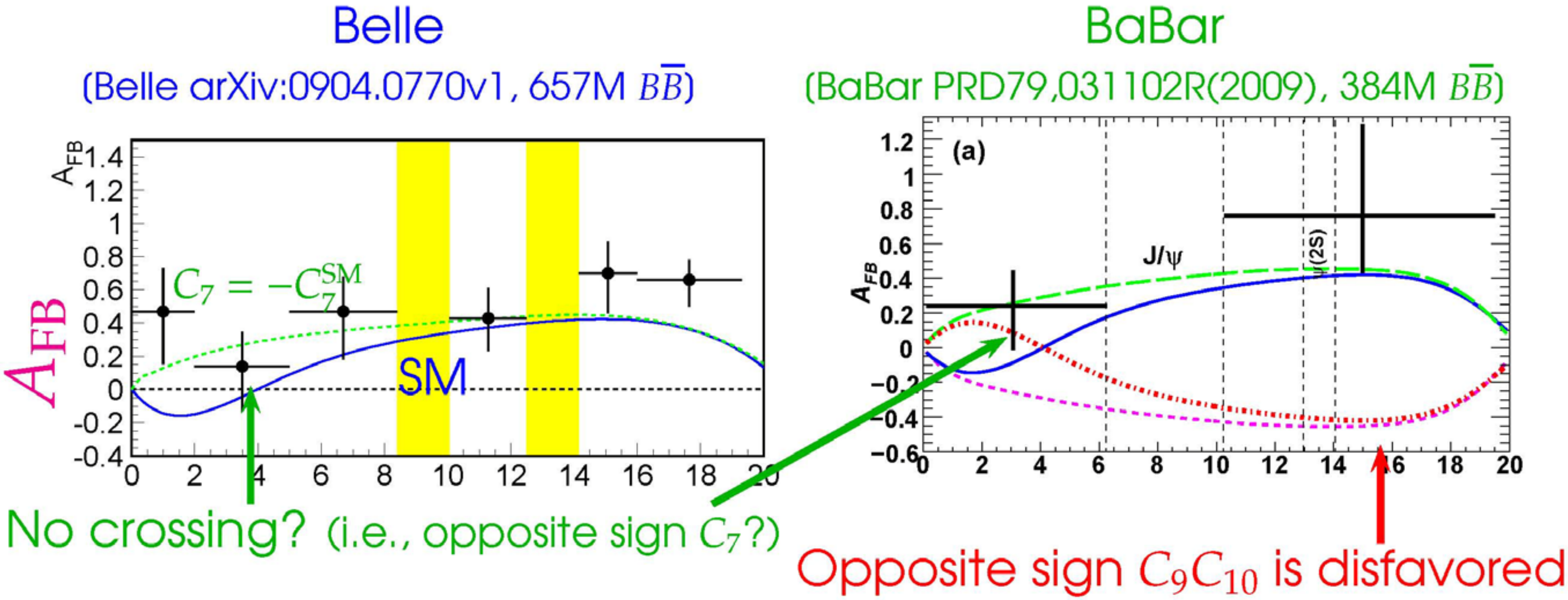
With 8 fb^{-1} project 95% confidence limit of $BR(B_s \to \mu\mu) < 2 \times 10^{-8}$

SM prediction
$BR(B_s \to \mu\mu) = (3.42 \pm 0.54) \times 10^{-9}$

$B_s \to \mu^+\mu^- h$

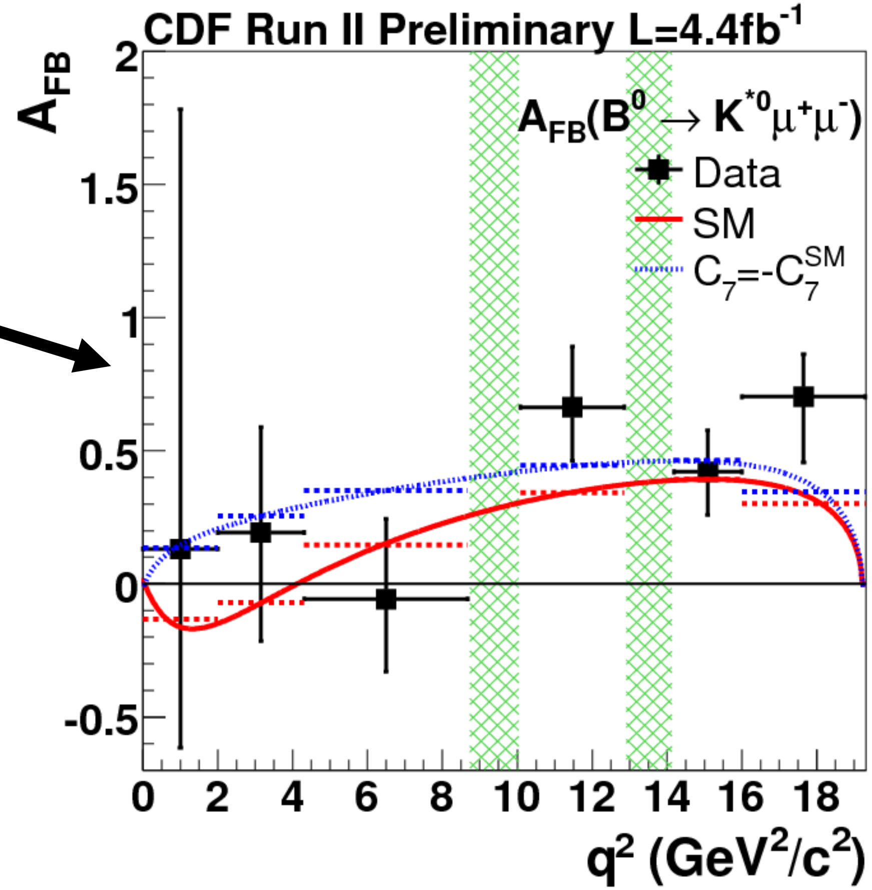


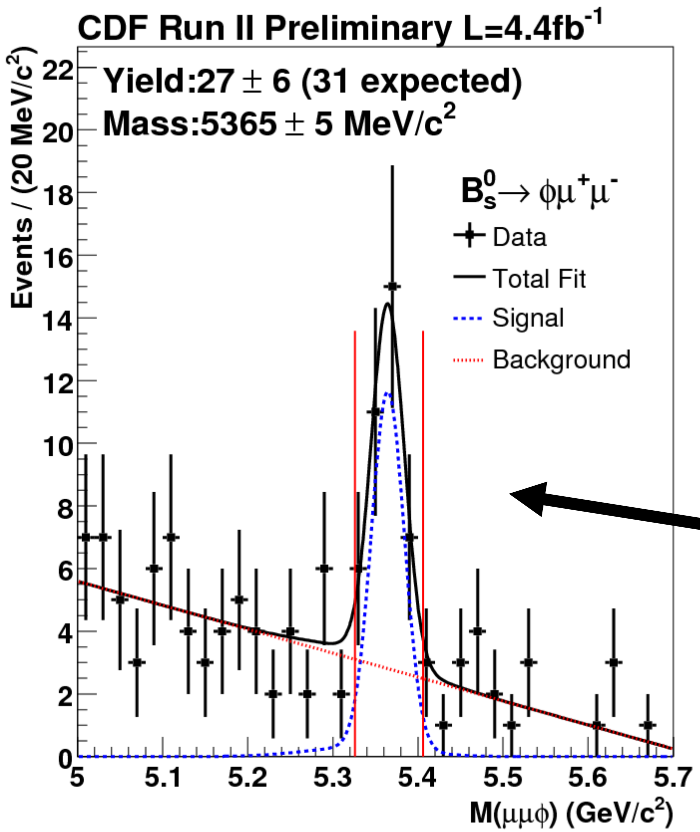
- e^+e^- *B* factory results for $A_{fb}(B^0 \to \mu^+\mu^- K^*)$ shows interesting behavior



$B_s \to \mu^+\mu^- h$

- CDF 4.4 fb^{-1} analysis
  - ➔ A_{fb} in $B^0 \to \mu^+\mu^- K^*$
  - ➔ *101±12 signal events*





- first observation of $B_s \to \mu^+\mu^- \phi$
  - ➔ *27±6 signal events*
  - ➔ *(SM expectation 31 events)*
  - ➔ *Signal significance: 6.3σ*

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  - Dimuon CP asymmetry
  - Rare decays: $B_s \rightarrow \mu^+\mu^-$, $\mu^+\mu^-\phi$
- Physics with hadronic final states
  - A bit of history
  - $B \rightarrow D^0 K$
  - Charmless two-body decays ($b \rightarrow u\bar{u}d$, $u\bar{u}s$, $s\bar{s}s$)
  - CP asymmetry in $D^0 \rightarrow \pi^+\pi^-$
- A bit more on prospects
- Conclusion

We’ve come a long way…

- **Success of the Tevatron *B* program has benefitted from:**
  - More luminosity
  - Better detectors, triggers, DAQ systems
  - Better understanding of heavy flavor production
  - Improved of analysis techniques

- **Two major transitions:**
  1. silicon microvertex detector (~1991)
  2. utilizing silicon in the trigger (~2002)

Aldo Menzione

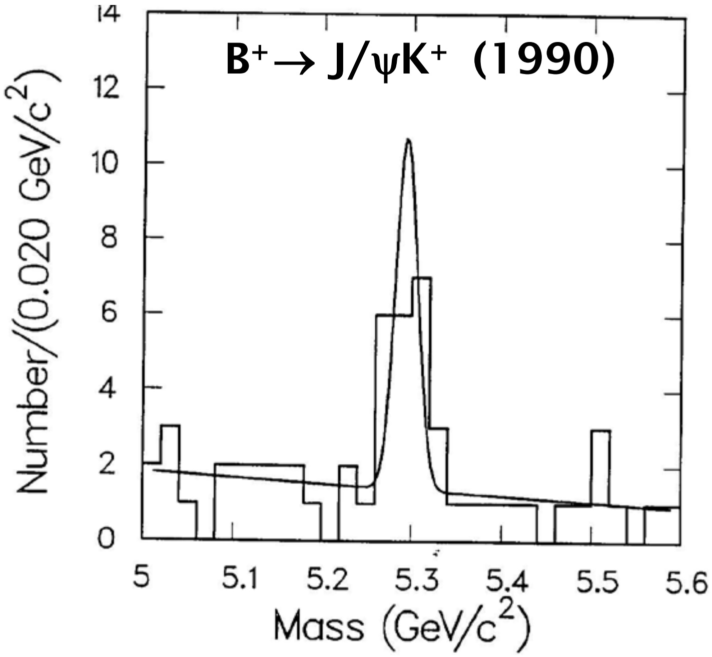
Luciano Ristori

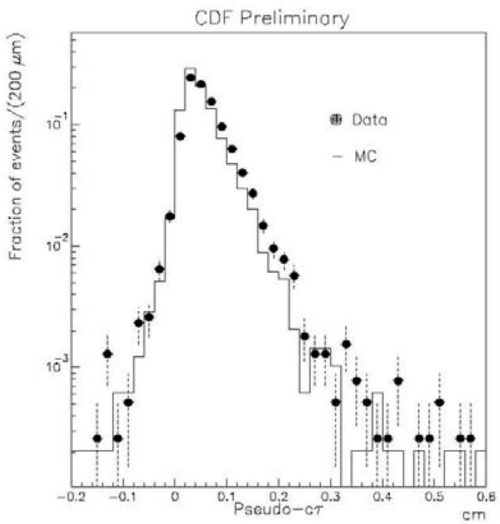
2009 Panofsky Prize recipients

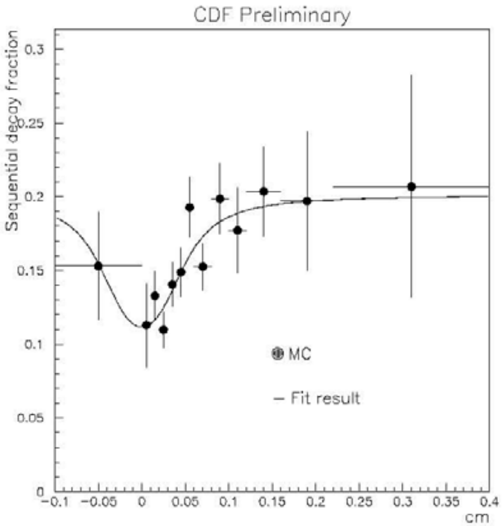
The early days…

- Before silicon

- After silicon





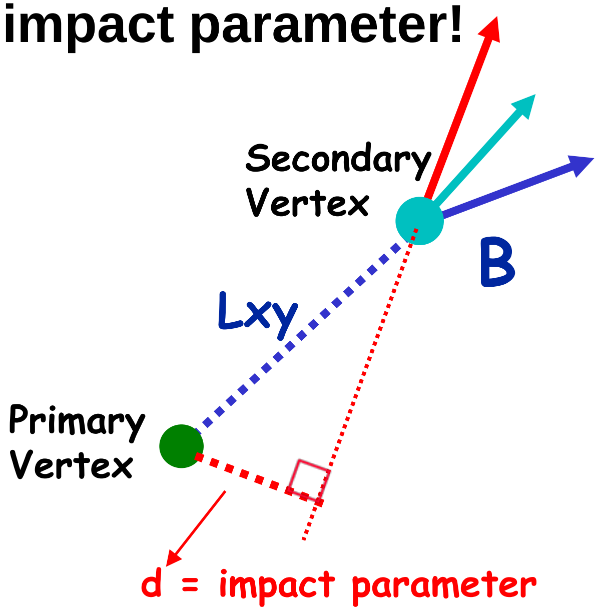


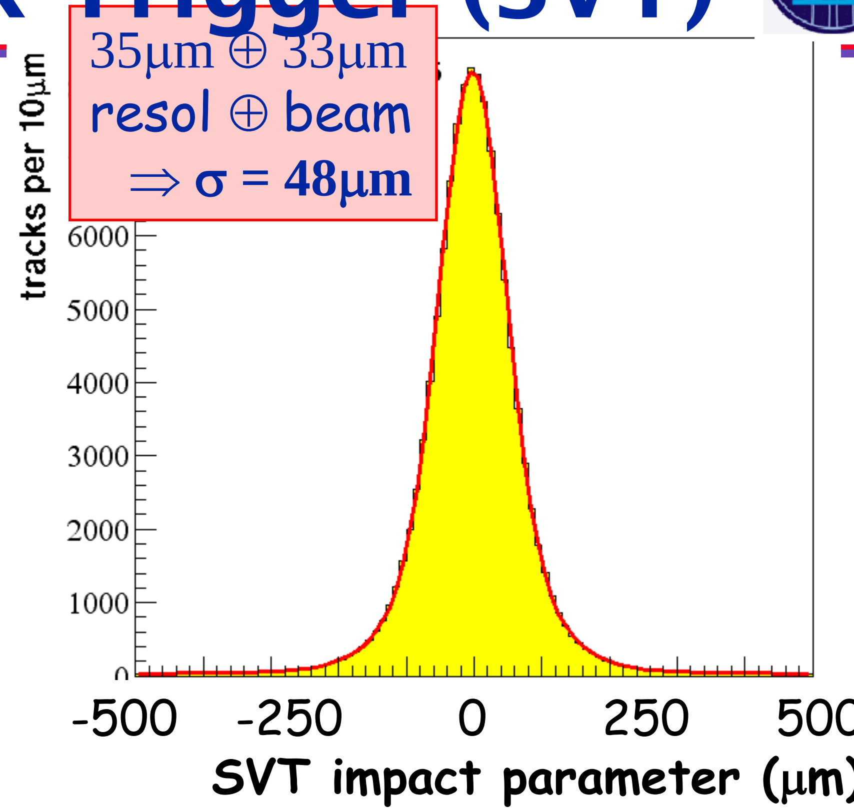
B^0 mixing

F. Bedeschi, D. Lucchesi et al.

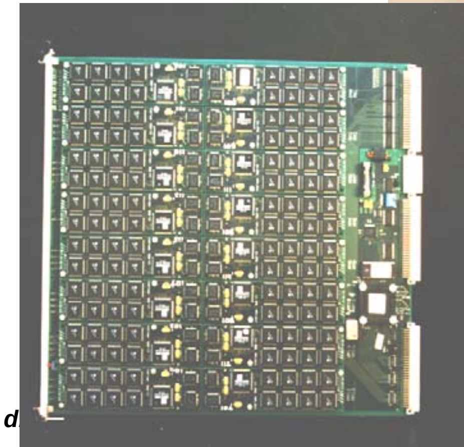
Silicon Vertex Trigger (SVT)

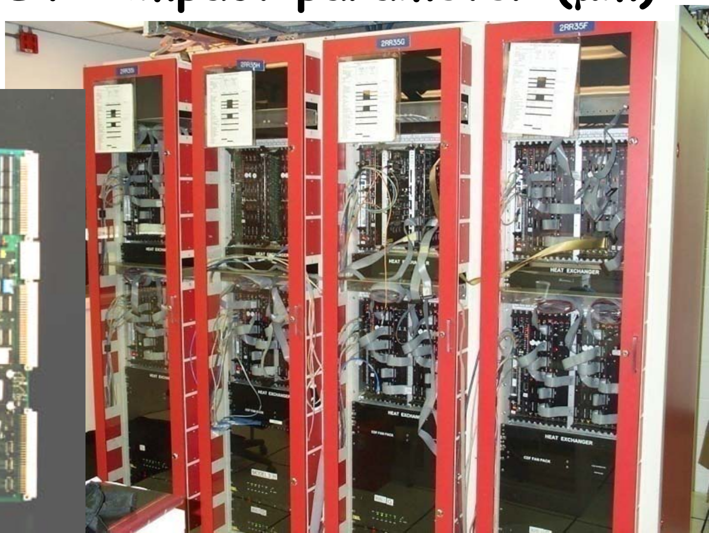
- **SVT incorporates silicon info in the Level 2 trigger… select events with large impact parameter!**



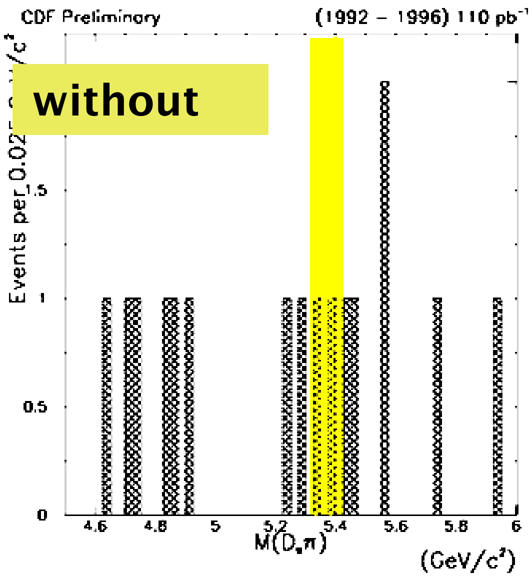


- **Uses fitted beamline**
- **impact parameter per track**
- **System is “deadtimeless”:**
  - ~35μsec/event for readout + clustering + track fitting

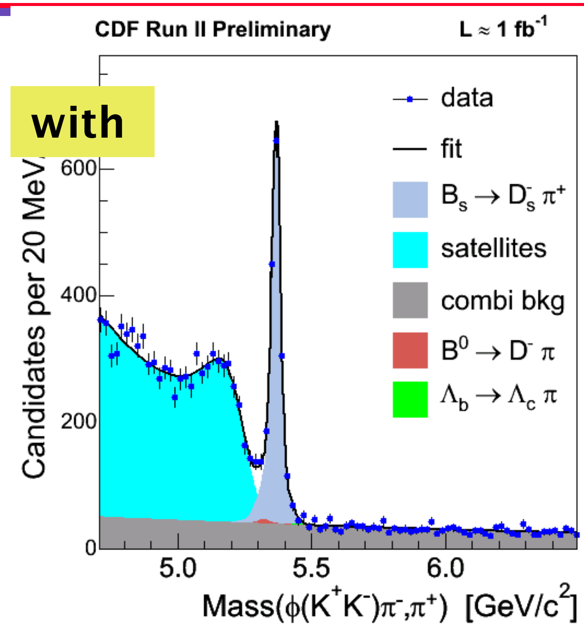


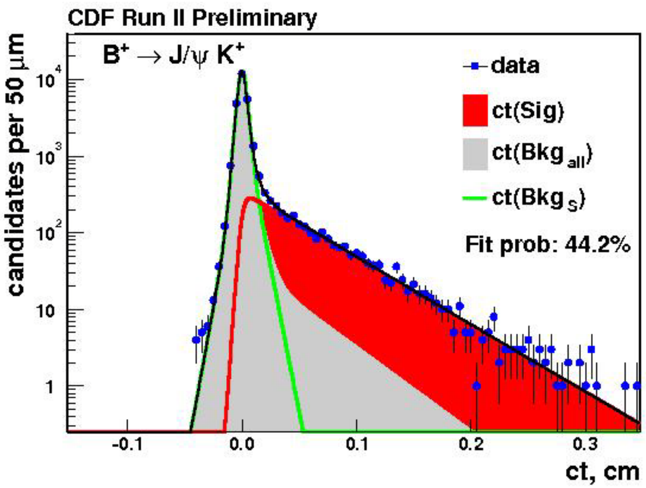


What do we get with the SVT?



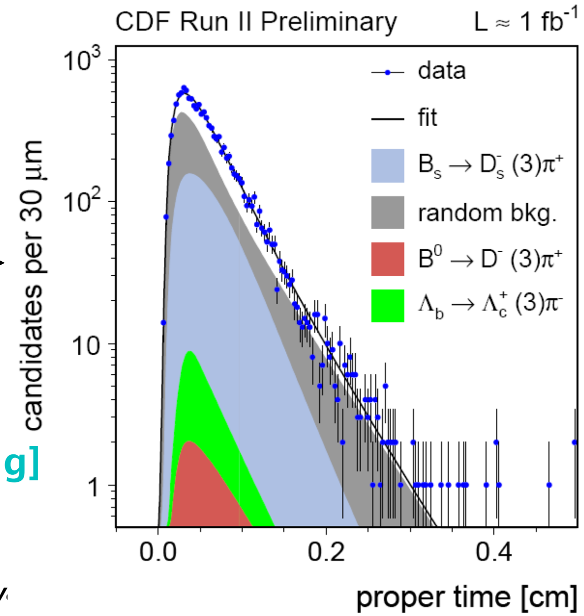
Access to many new modes





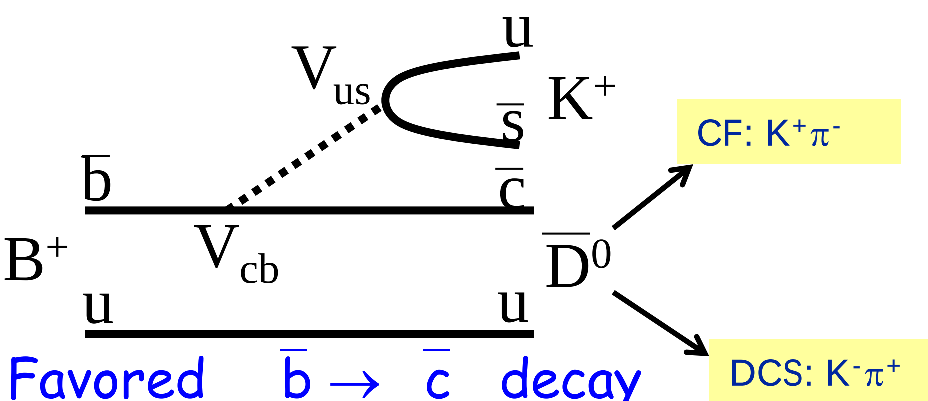
inefficiency for events with low decay time

[can be accounted for *e.g.* B_s lifetimes/mixing]



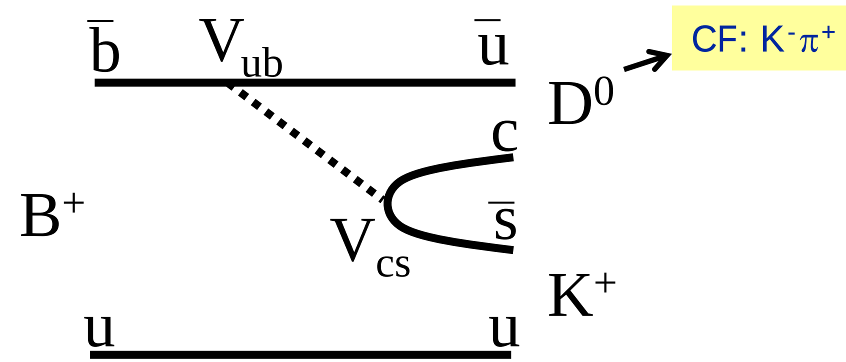
Towards CP angle γ from $B^- \to D^0 K^-$

γ could be extracted by exploiting the **interference** between the processes $\bar{b} \to \bar{c}u\bar{s}$ $(B^+ \to \bar{D}^0 K^+)$ and $\bar{b} \to \bar{u}c\bar{s}$ $(B^+ \to D^0 K^+)$



Favored $\bar{b} \to \bar{c}$ decay

$A_1 \sim V_{cb}V_{us}^* \sim \lambda^3$



Color suppressed $\bar{b} \to \bar{u}$ decay

$A_2 \sim V_{ub}V_{cs}^* \sim \lambda^3 r_B e^{-i\delta B} e^{-i\gamma}$

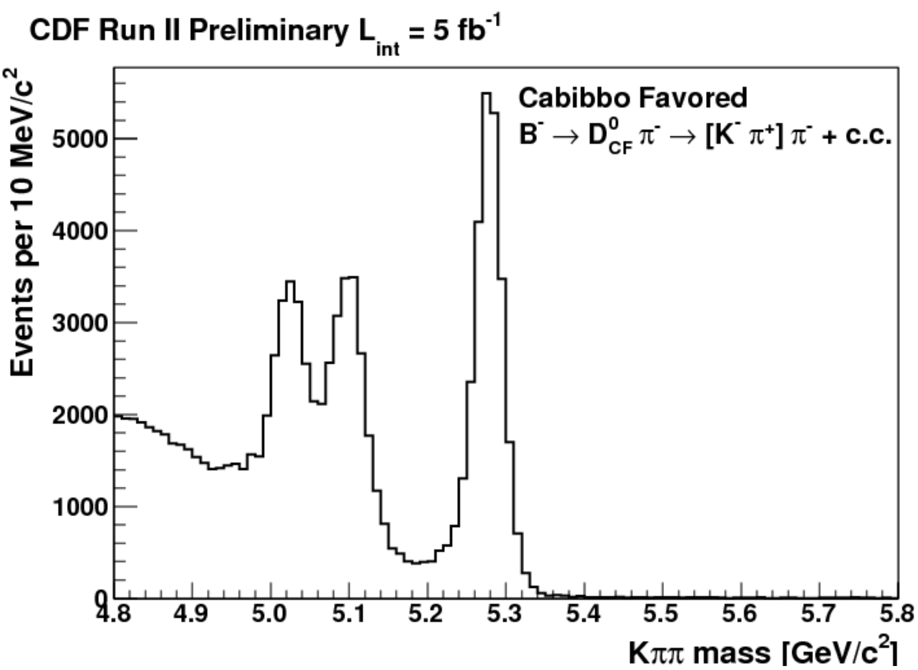
- **ADS (Atwood-Dunietz-Soni) method** *([PRL78,3257;PRD63,036005])*

uses the $B^\pm \to D K^\pm$ decays with D reconstructed in the doubly cabibbo suppressed $D^0_{DCS} \to K^+\pi^-$

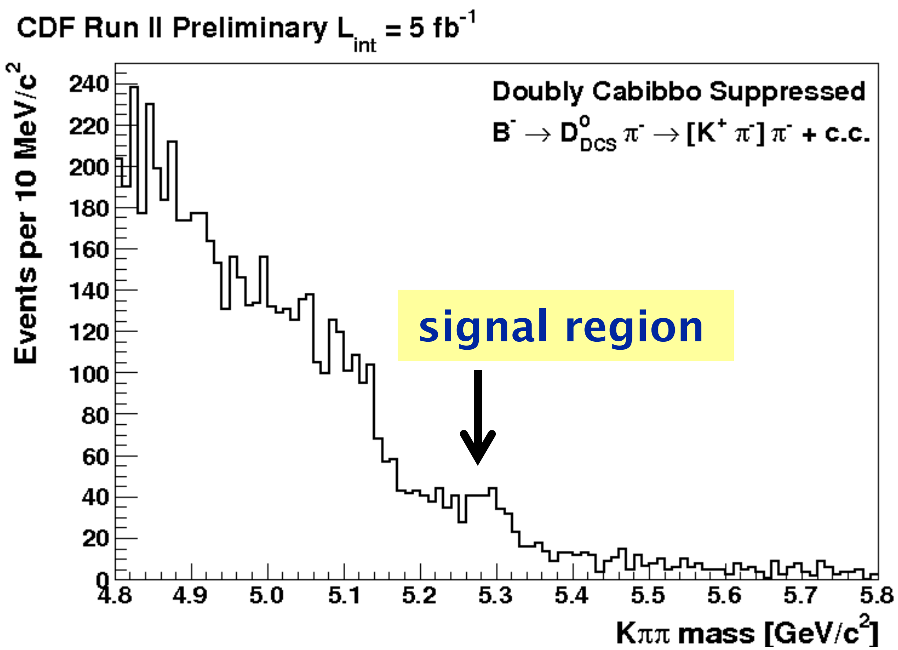
Only requires extraction of yields by charge, Does not require flavor tagging or time dependent measurement

ADS analysis

- **Looking for "wrong sign" $B^+ \to [K^- \pi^+]K^+$ decays from:**
  - Color suppressed $B^+ \to D^0 K^+$ with $D^0 \to K^- \pi^+$
  - Cabibbo favored $B^+ \to \overline{D}^0 K^+$ with DCS $\overline{D}^0 \to K^- \pi^+$



Cabibbo favored $B^+ \to [K^+\pi^-]\pi^+$

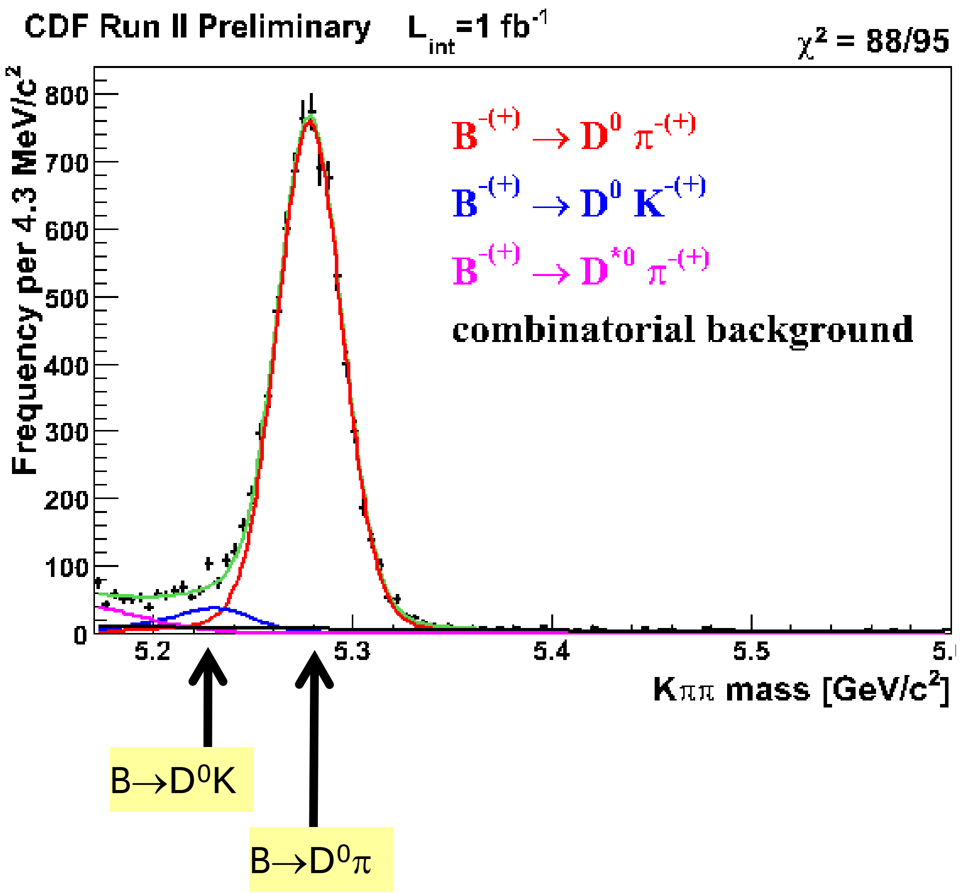


Color suppressed + DCS D decay $B^+ \to [K^-\pi^+]\pi^+$

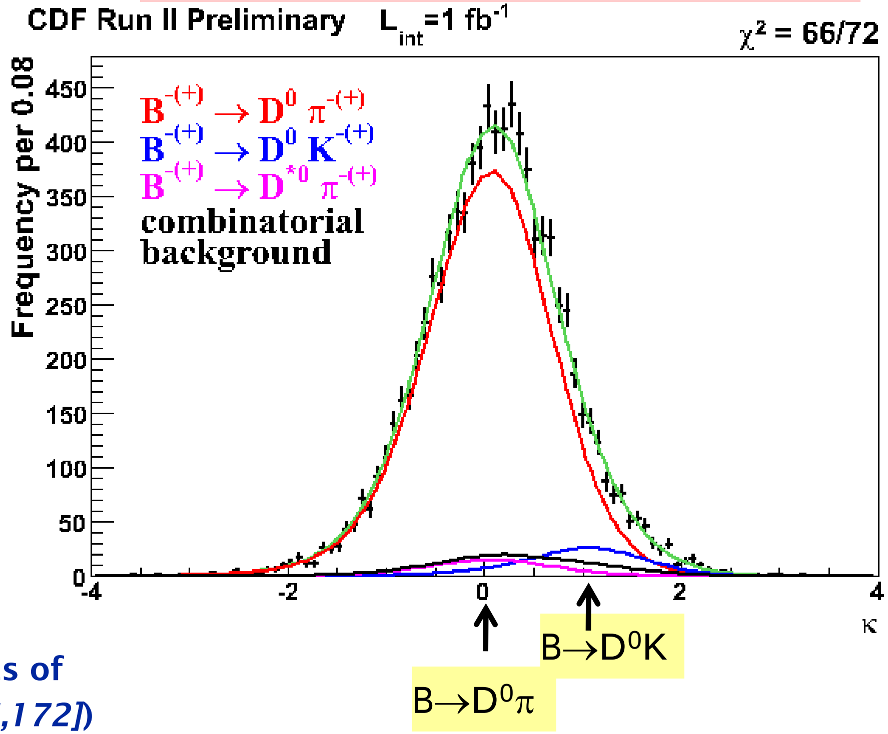
- Total sample about 19,000 $B^\pm \to DK/D\pi$ events

$B^{\pm} \to D^0 K / D^0 \pi$

- **Use kinematic and particle ID information to extract D^0K component**
- **Cabibbo favored modes:**



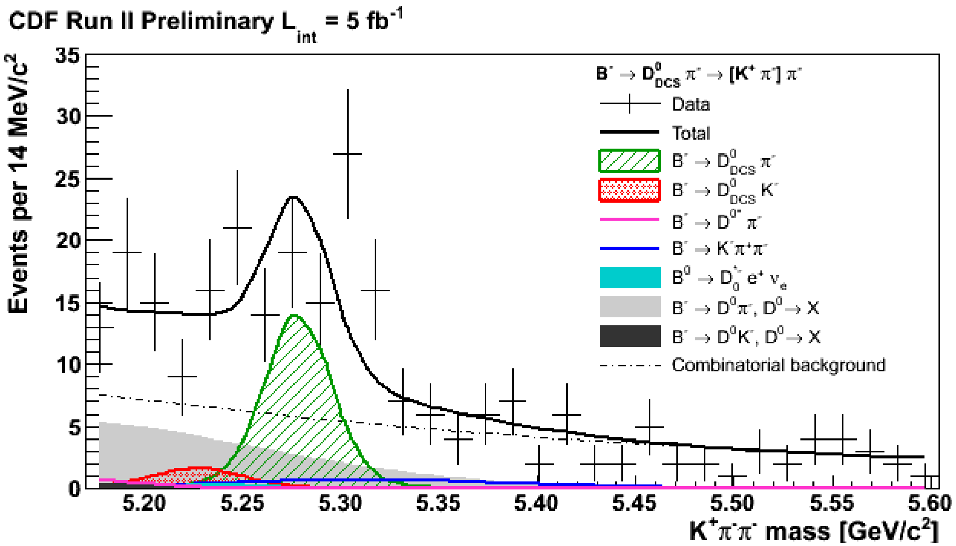
Particle ID (dE/dx) information on hadron (h) from $B \to D^0 h$

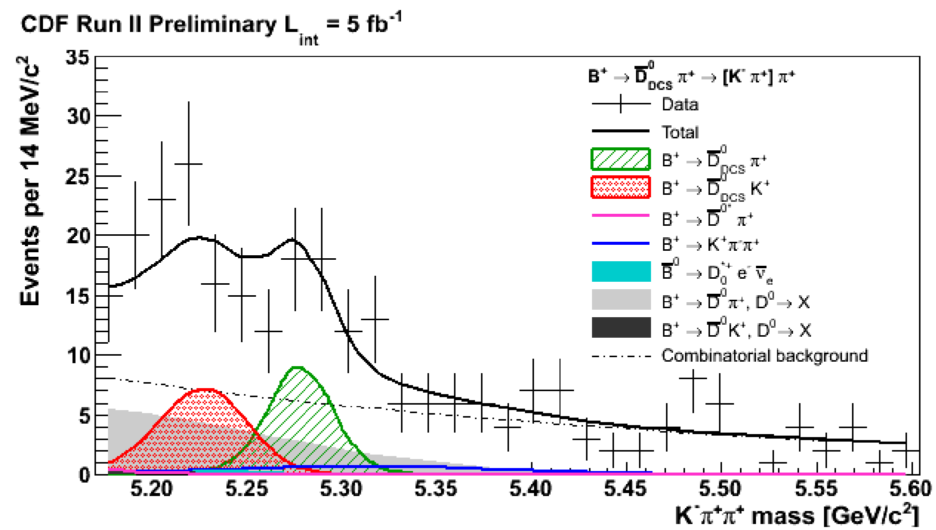


From (*PRD81:031105,2010) a*nalysis of CP even components of GLW (Gronau- London- Wyler) method (*[PLB253,483 PLB265,172]*) uses the $B^{\pm} \to D K^{\pm}$ decays with D_{CP} decay modes. $D_{CP+} \to \pi^+\pi^-, K^+K^-$

ADS results

- **Color suppress/doubly Cabibbo suppressed modes**
- **Combined significance (is there anything there?) >5σ**

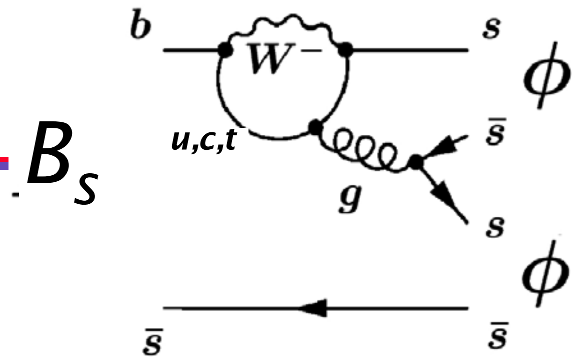


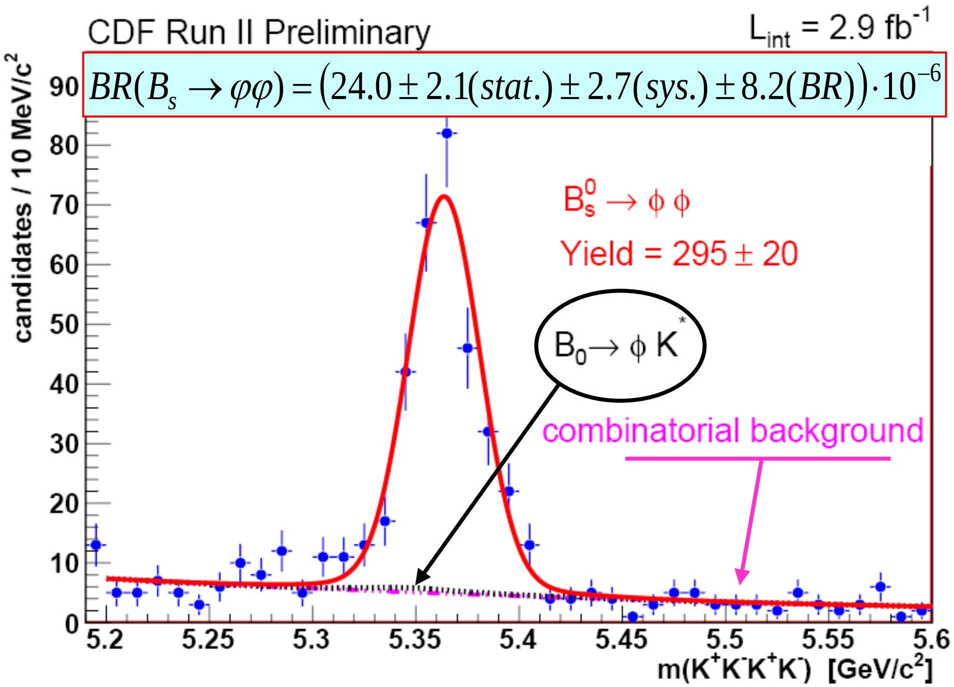


$$R_{ADS}(\pi) = 0.0041 \pm 0.0008(stat) \pm 0.0004(syst)$$
$$A_{ADS}(\pi) = 0.22 \pm 0.18(stat) \pm 0.06(syst)$$
$$R_{ADS}(K) = 0.0225 \pm 0.0084(stat) \pm 0.0079(syst)$$
$$A_{ADS}(K) = -0.63 \pm 0.40(stat) \pm 0.23(syst)$$

see Paola Garosi's talk on Thursday

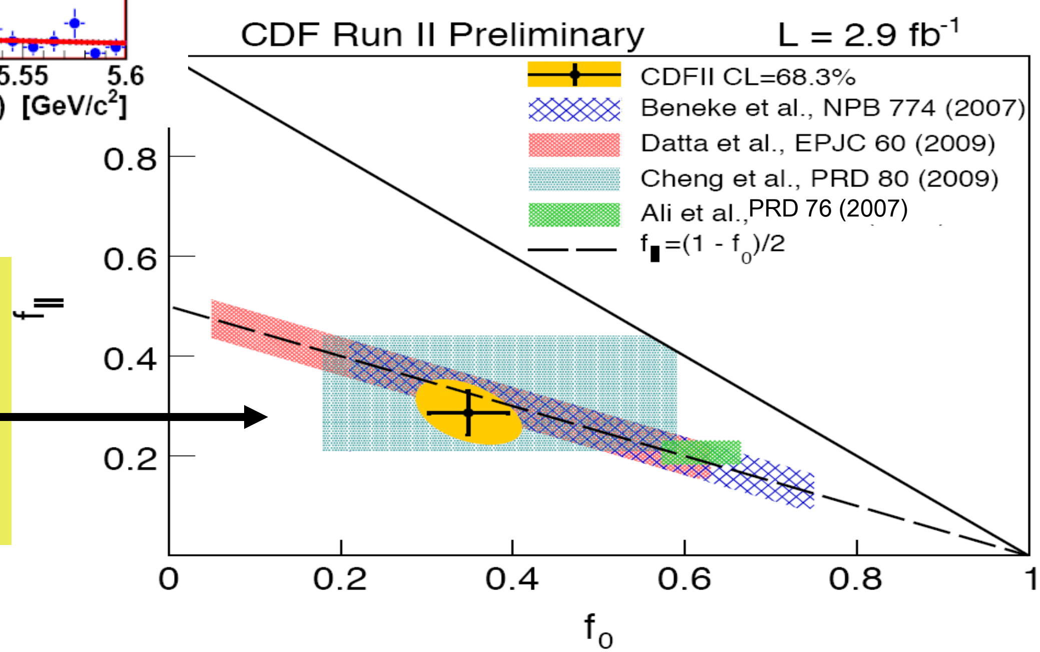
$B_s \rightarrow \phi\phi$





- Penguin decay
- Normalize observed yield to $B_s \rightarrow J/\psi\phi$
- Measured BR consistent with expectation.

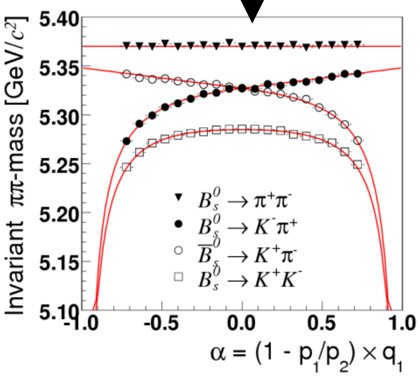
- $B_s \rightarrow \phi\phi$ is P→VV transition
- polarization sensitive to penguins, new physics.
- Analysis similar to $B_s \rightarrow J/\psi\phi$

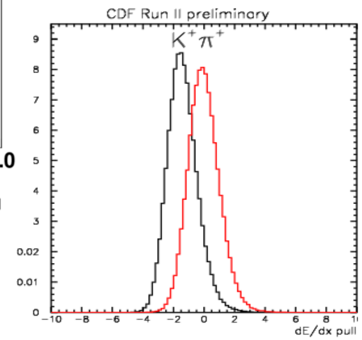


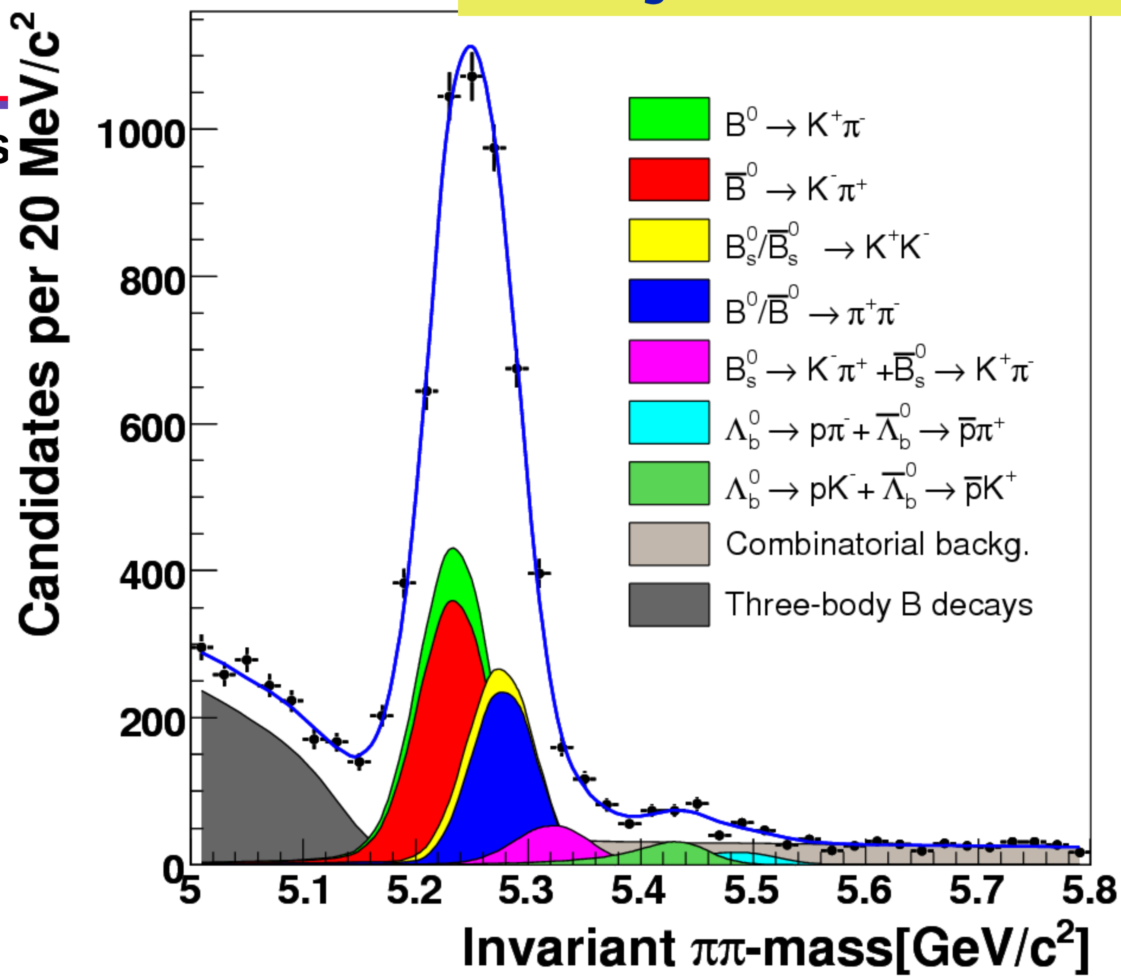
$B \to h^+ h^-$

7000 signal events in 1 fb^{-1}

- Charmless two-body modes
- kinematics and particle ID







- measure:
  - BR and Direct CP asymmetry in 4 modes
    - $B^0 \to K^+\pi^-$, $B_s \to K^-\pi^+$
    - $\Lambda_b \to p\pi^-$, $\Lambda_b \to pK^-$
  - BR in 2 modes
    - $B^0 \to \pi^+\pi^-$, $B_s \to K^+K^-$
  - BR limits on 2 modes
    - $B^0 \to K^+K^-$, $B_s \to \pi^+\pi^-$

Next iteration:

- Reduced uncertainties on direct *CP* uncertainties
- Flavor tagged indirect CPV search

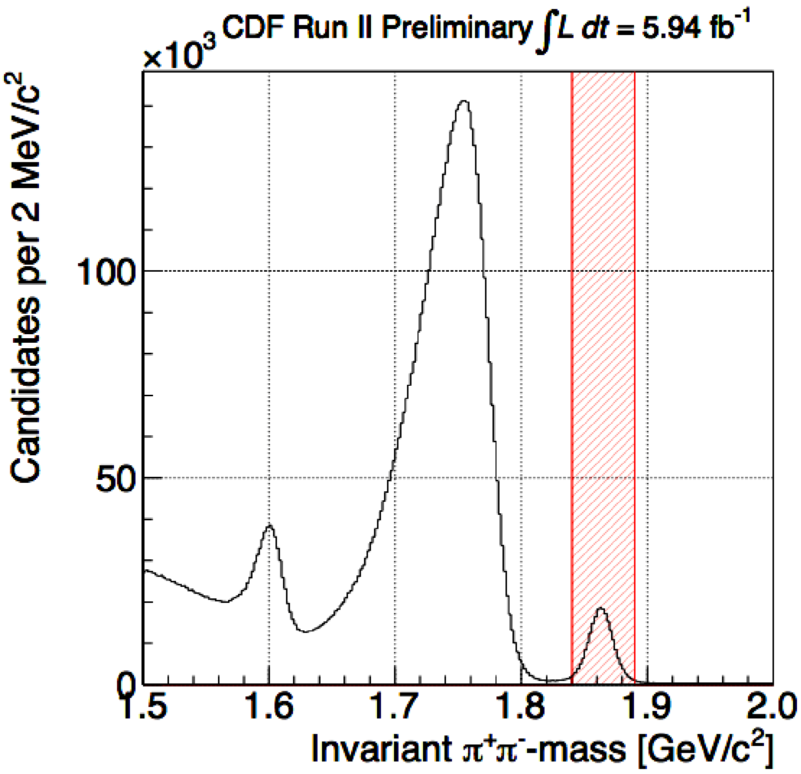
Search for charm *CP* violation

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

- **Tagging the D^0 with D*:** $\begin{cases} D^{*+} \to D^0 \pi_s^+ \\ D^{*-} \to \bar{D}^0 \pi_s^- \end{cases}$

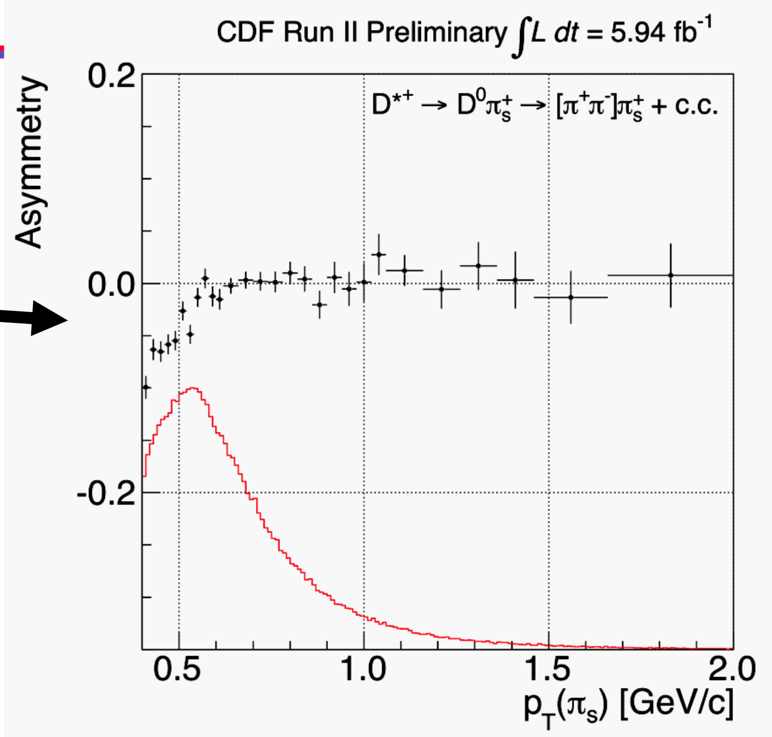
- **CP symmetric initial state (p-pbar) ensures charge symmetric production**

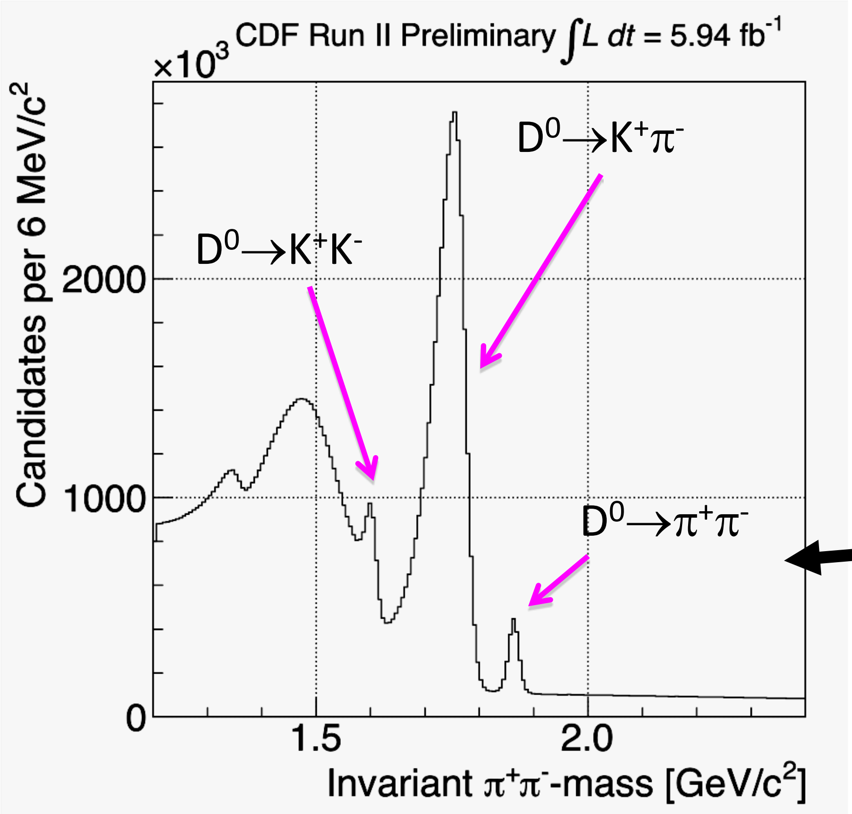
- **215,000 $D^* \to D^0 \pi$ with $D^0 \to \pi\pi$.**



Search for charm *CP* violation

- **Use tagged and untagged $D^0 \to K^- \pi^+$ (data driven) to quantify soft pion charge bias.**
  - → Bias significant at low p_T





- **Untagged samples:**
  - → $N(D^0 \to \pi^+ \pi^-) \approx 1.2 \times 10^6$
  - → $N(D^0 \to K^+ K^-) \approx 3 \times 10^6$
  - → $N(D^0 \to K^- \pi^+) \approx 30 \times 10^6$

CP Asymmetry in $D^0 \to \pi^+\pi^-$

- **In 5.94 fb^{-1} result:**

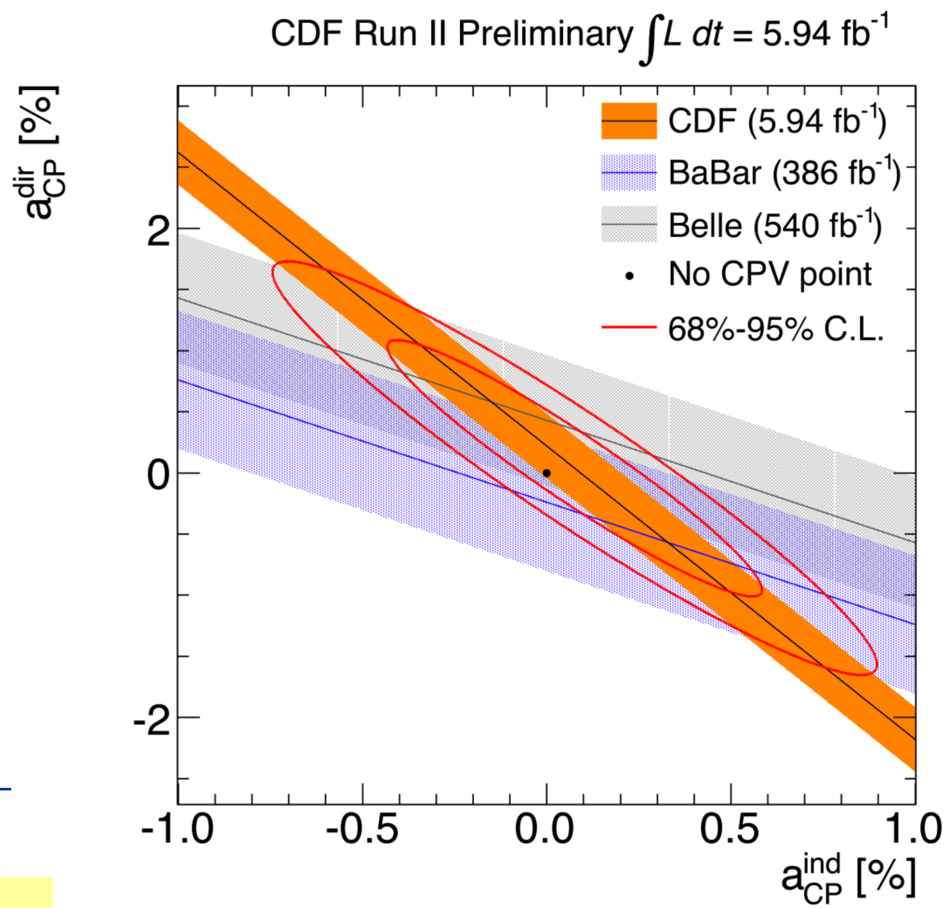
$$A_{CP}(D^0 \to \pi^+\pi^-) = (+0.22 \pm \underbrace{0.24}_{\text{stat}} \pm \underbrace{0.11}_{\text{syst}})\%$$

- **Because of displaced track trigger, CDF measures a different combination of direct and indirect CP components**

- **D^0 mixing parameters are small ($x\tau, y\tau \ll 1$), then the integrated asymmetry at the first order can be written as:**

$$A_{CP}(D^0 \to \pi^+\pi^-) \approx a_{CP}^{dir} + \frac{\langle t \rangle}{\tau} a_{CP}^{ind}$$

- **Coming: *CP* asymmetry in $D^0 \to K^+K^-$**



see Fabrizio Ruffini's talk on Friday

Topics Not Covered (or in the pipeline…)

- ***Lifetimes (e.g. $\Lambda_b \rightarrow J/\psi\ \Lambda$)***
- ***More B_s***
  - $B_s \rightarrow D_s\ D_s$
  - CPV in $B_s \rightarrow \mu D_s$
  - Other Bs modes
- ***Baryons***
  - Properties
  - Excited states
  - Ω_b
- ***B_c***
  - Decays
  - properties
- ***$D^0 \rightarrow \mu\mu$***
- **Production**
- **X(3872), Y(4140), Z(4430)**

Conclusion

- **Tevatron continuing to produce a rich program in heavy flavor physics.**
  - ➔ Complementary to e^+e^- machines and LHC experiments
- **Many interesting results will benefit from more data.**
  - ➔ Anticipate 9 fb^{-1} per experiment for analysis by end of FY11
  - ➔ If run is extended, ultimate sample could be 15 fb^{-1}
- **Results will continue beyond the end of the run**

Where the Real Info Is…

- **T, C, P, CP symmetries, accidental symmetries 7 (Thursday afternoon)**
  - ➔ **Paola Garosi**

  First ADS analysis of B→DK in hadron collisions

- **T, C, P, CP symmetries, accidental symmetries 9 (Friday afternoon)**
  - ➔ **Louise Oakes**

  Measurement of Bs mixing phase and observation of suppressed Bs decays at CDF

- **T, C, P, CP symmetries, accidental symmetries 10 (Friday afternoon)**
  - ➔ **Fabrizio Ruffini**

  Precision measurements of direct CP violation in $D^0 \to \pi\pi$ at CDF