Prospects in CP violation measurements at the Tevatron
(collider experiments only)

XVII^{iémes} Rencontres de Physique de la Vallée d'Aoste

February 29th – March 6th, 2004 - La Thuile

Diego Tonelli

tonel@fnal.gov

Scuola Normale Superiore and INFN – Pisa

for the CDFII and DØ Collaborations

The Tevatron $p\bar{p}$ collider

Superconducting proton-synchrotron: 36 $p \times$ 36 $\bar{p}$ bunches

collision every 396 ns at $\sqrt{s}$ = 1.96 TeV

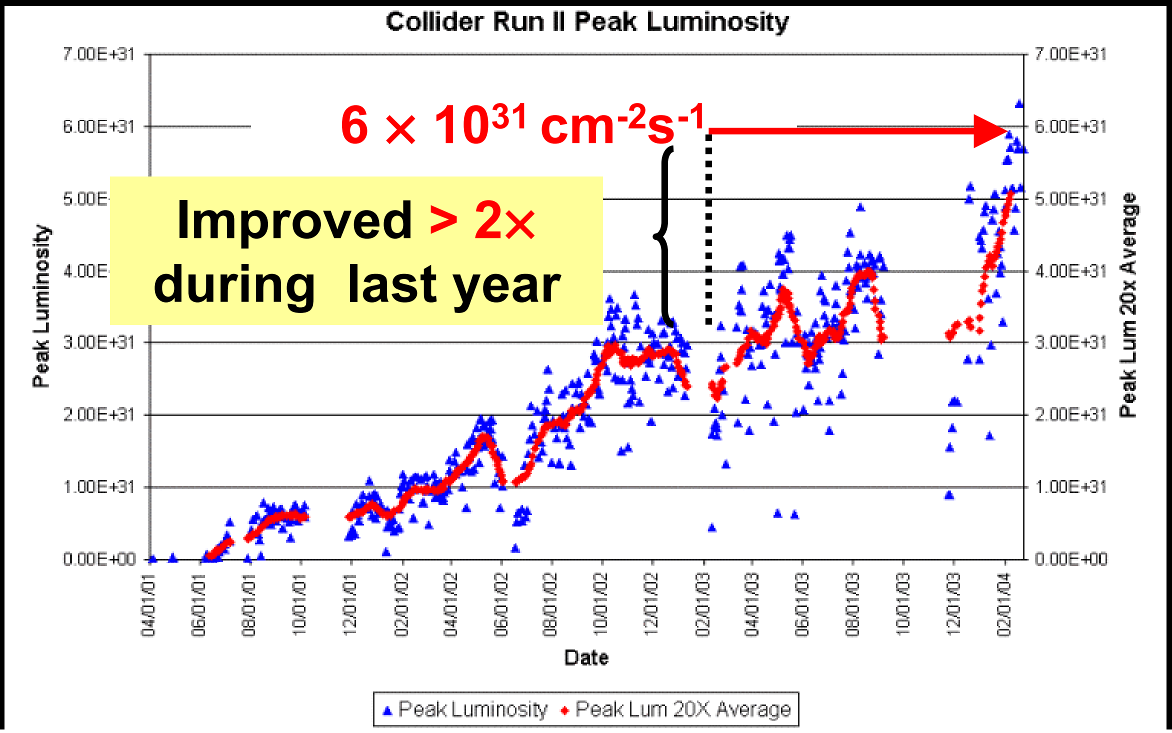
Luminosity……………………………..: record peak is 6.7×10^{31} cm^{-2} s^{-1}

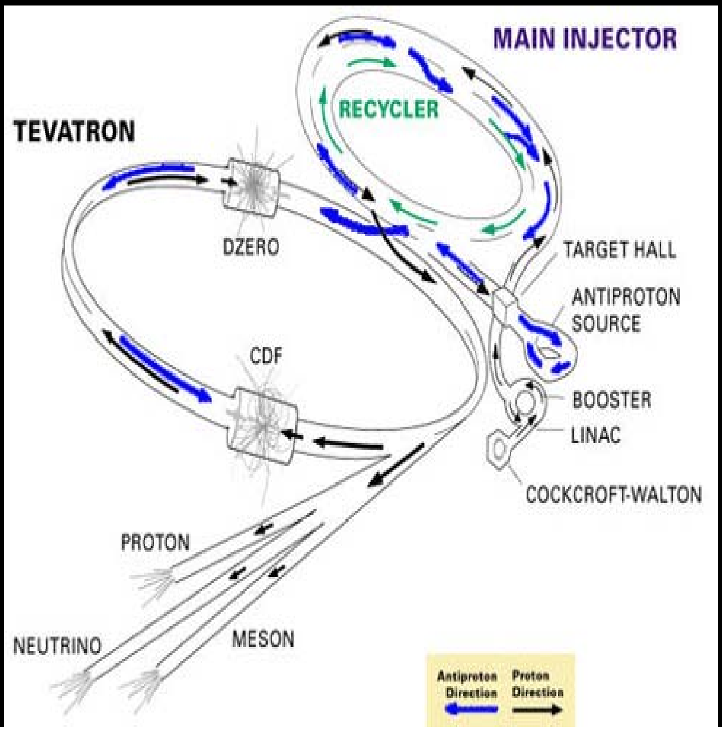
~ 10 pb^{-1} / week delivered

interactions / bunch-crossing……..: $\langle N \rangle_{poisson} = 1.5$ (at $5 \times \mathbf{10^{31}\ cm^{-2}s^{-1}}$)

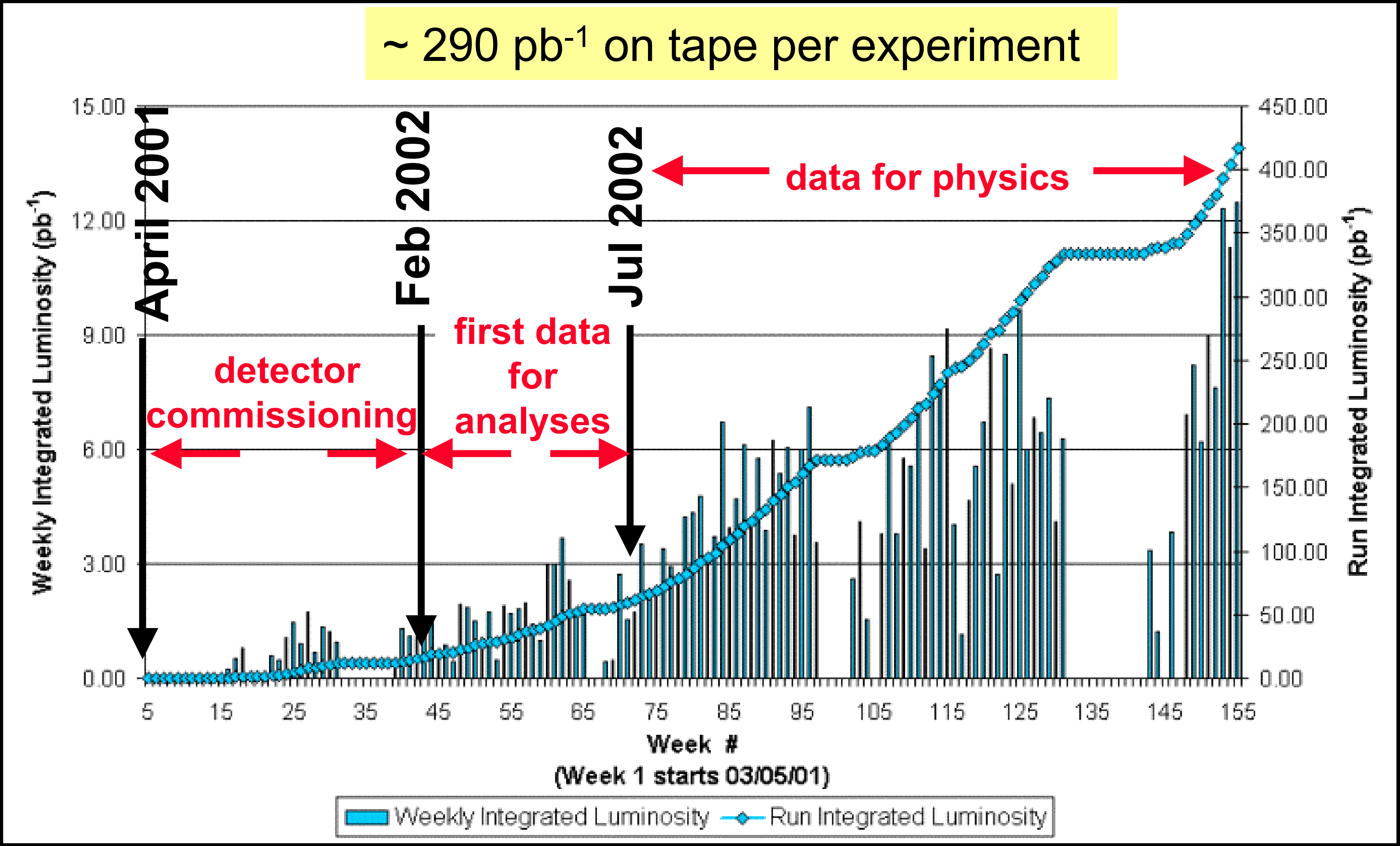
Luminous region size………………...: 30 cm (beam axis) $\times$ 30 μm (transverse)

need long Si-vertex **small wrt $c\tau$(B) ~ 450 μm**





Delivered Luminosity



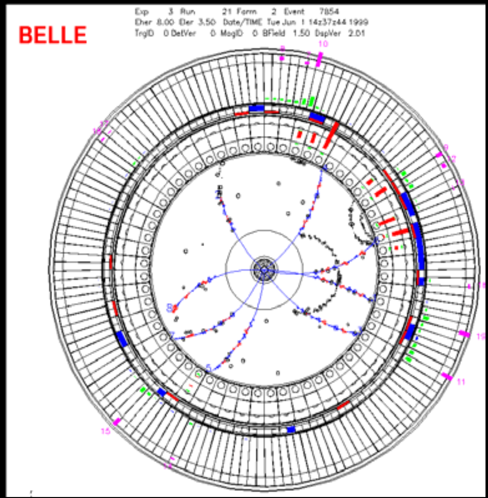
Data taking efficiency: 80 - 90%
stable for both experiments

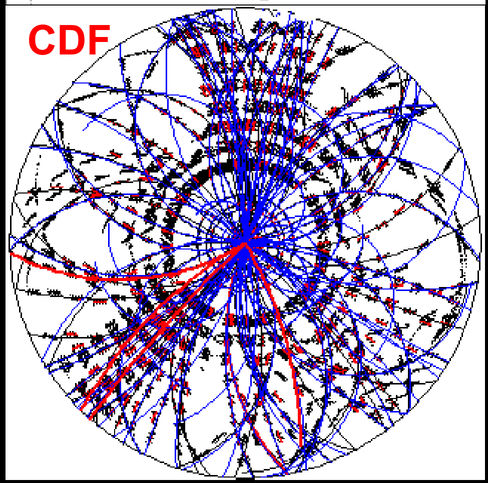
For the following results:
CDF analyses use: ~65 to ~190 pb^{-1}
DØ analyses use: ~ 47 to ~114 pb^{-1}

Heavy Flavor physics at the Tevatron

The Good

$b\bar{b}$ production x-section O(10^5) larger than e^+e^- at Υ(4S) /Z^0. Incoherent strong production of all *b*-hadrons: $B^{\pm}$, B^0, B_s, B_c, Λ_b, Ξ_b .





The Bad

Total inelastic x-section ~ $10^3 \times \sigma(b\bar{b})$.
BRs' for interesting processes O(10^{-6}).

…and The Ugly

Messy environments with large combinatorics.

Need highly selective trigger

Triggering *bs*' (and *cs*')

conventional

Di-lepton

CDF and DØ

B $\longrightarrow$ charmonium
Rare B $\longrightarrow \mu\mu$

Two muons with:

p_T> 1.5 GeV $|\eta|$< 1

p_T> 2.5-4.5 GeV $|\eta|$<2

Single-muon

DØ only

Semileptonic decays

one muon with:

p_T > 2 - 4 GeV $|\eta|$ <2

new approach

electron or μ and displaced track

CDF only

Semileptonic decays

Electron (μ) with:

p_T> 4 (1.5) GeV $|\eta|$< 1

and one track with:

p_T > 2.0 GeV IP > 120 μm

Two displaced tracks

CDF only

n-body hadronic B

Two tracks with:

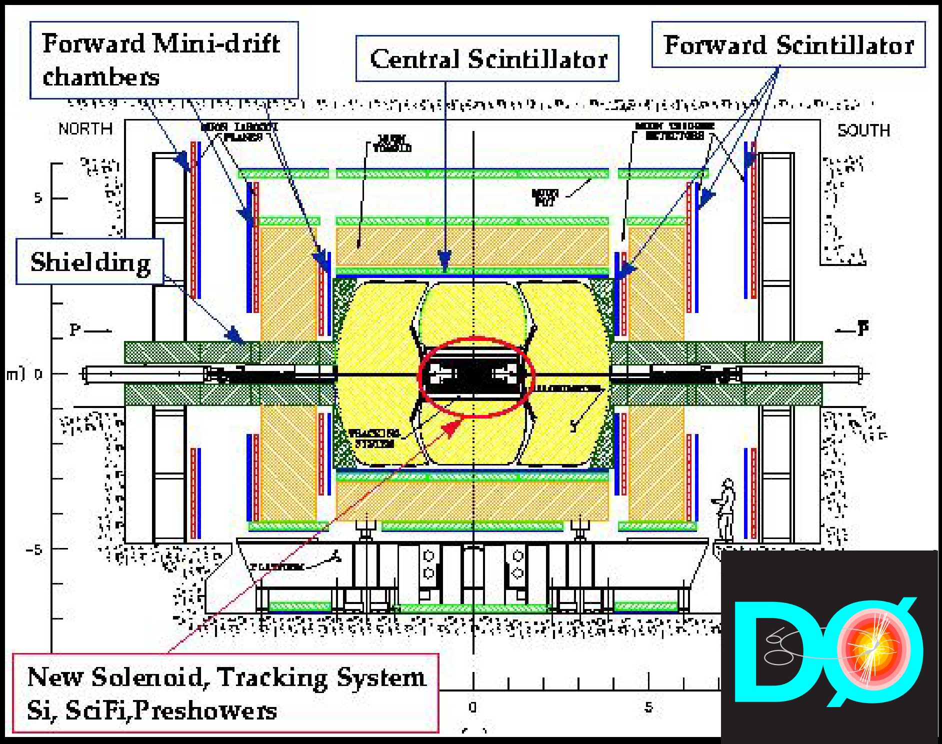
p_T > 2.0 GeV

Σp_T > 5.5 GeV

IP > 120 (100) μm

Displaced track trigger at Level 2: a revolution in hadronic environment ! Accessible rare hadronic decays with high S/B. Soon DØ too.

Detectors



DØ

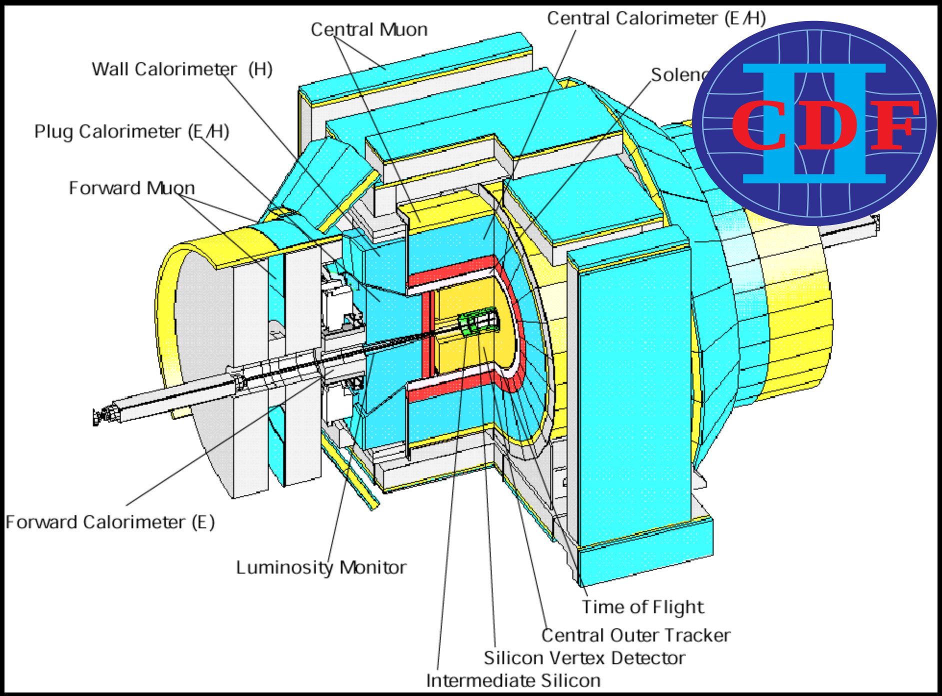
Excellent electron and muon ID
Excellent tracking acceptance

CDF

L2 trigger on displaced vertexes
Particle ID (TOF and dE/dx)
Excellent mass resolution

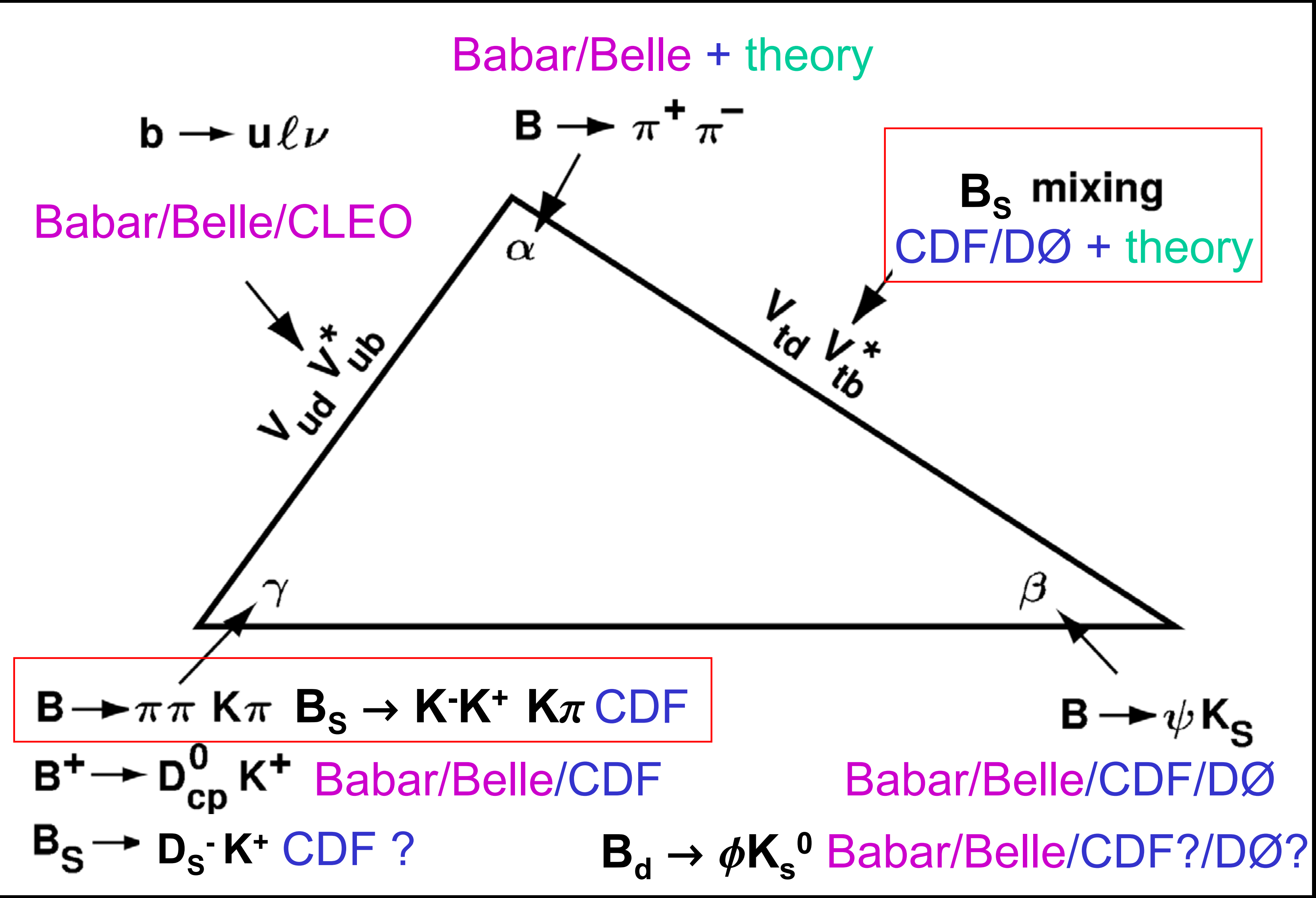
Both detectors

Silicon microvertex tracker
Axial solenoid
Central tracking
High rate trigger/DAQ
Calorimeters and muons



Overall game plan

CPV at Tevatron: mainly *b*-sector. Unique opportunity to study B_s physics. CDF explores also charm.



$B \rightarrow h^+h'^-$: towards α, γ and direct A_{CP}

Resolve the signal composition.
Admixture of (at least):

$B^0_d \rightarrow \pi^+\pi^-$ and Charge Conjugate

$B^0_d \rightarrow K^+ \pi^-$ and C. C.

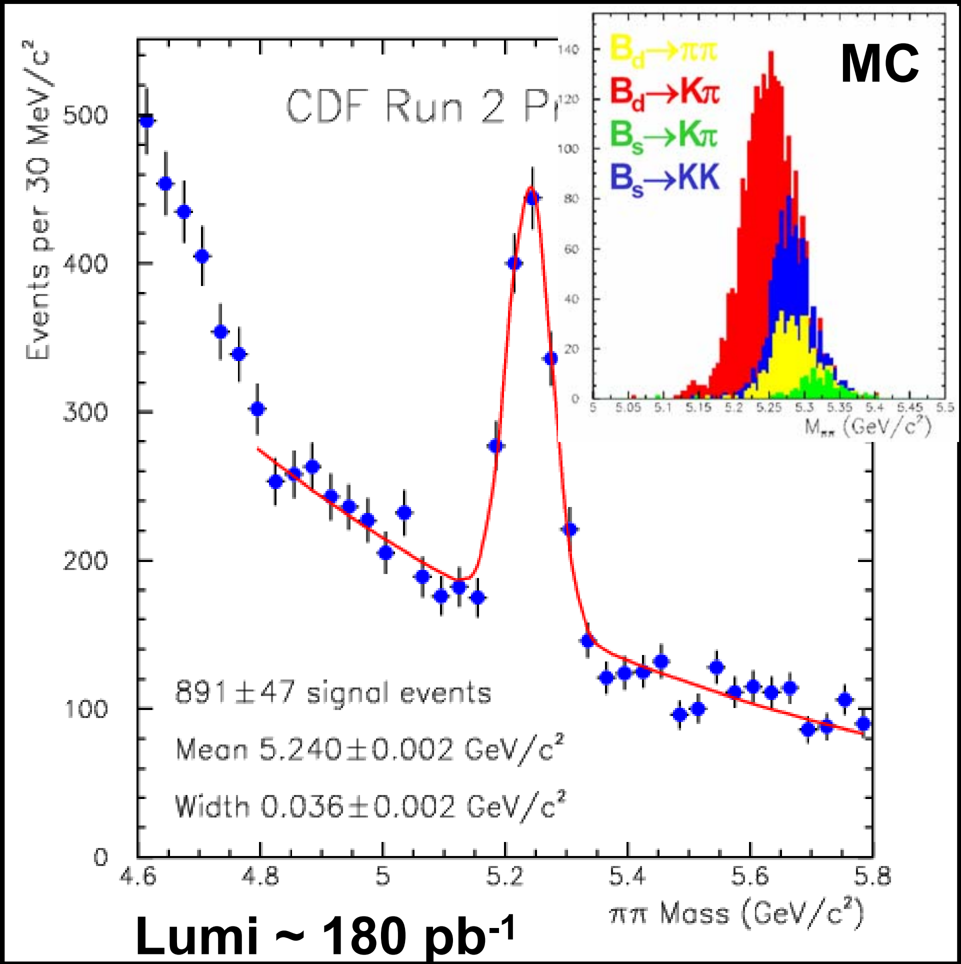
$B^0_s \rightarrow K^+K^-$ and C. C.

$B^0_s \rightarrow K^- \pi^+$ and C. C.

$p_T > 2$ GeV/c: TOF doesn't help

Combine kinematics with dE/dx to achieve statistical separation

$\pi\pi$ hypothesis



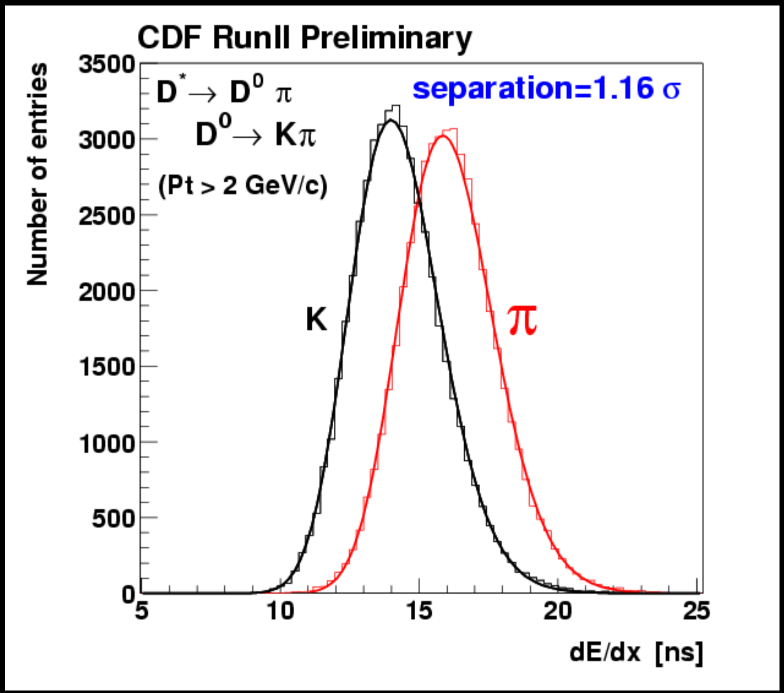
Expect ~ 6500 evts / fb^{-1}

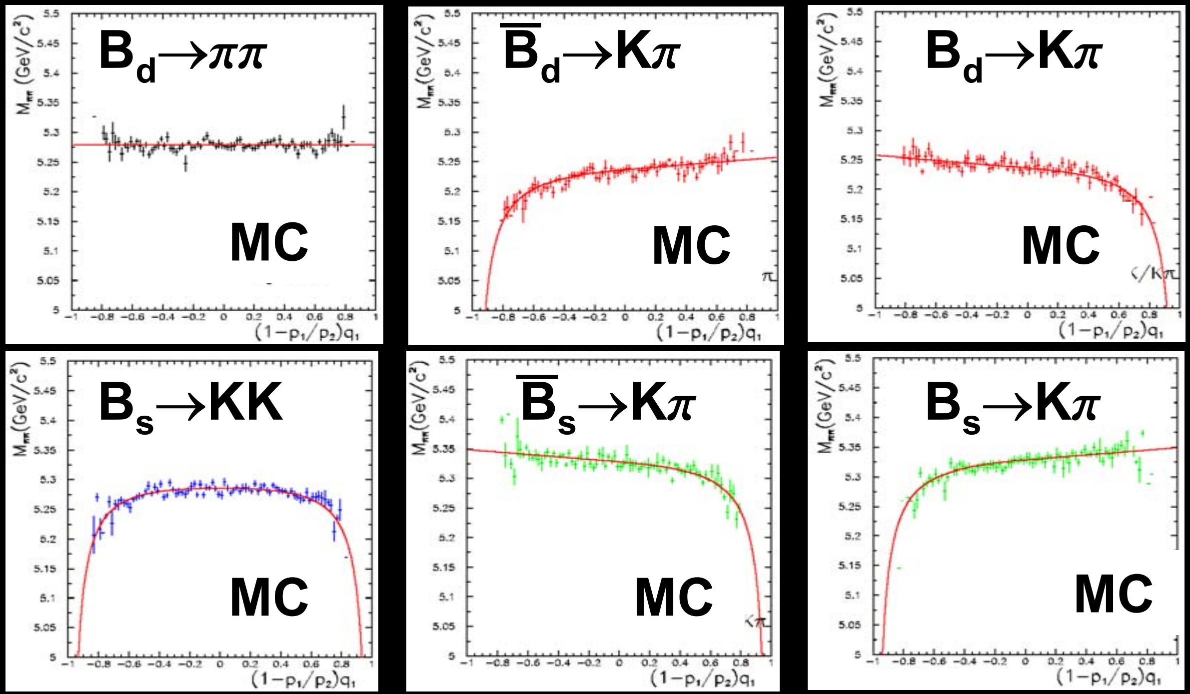
$B \to h^+h^-$: resolve peak composition

<u>Specific ionization</u>	<u>Kinematics</u>
dE/dx calibrated on 78K D* decays.	Exploit correlation between mass, charge and momentum imbalance

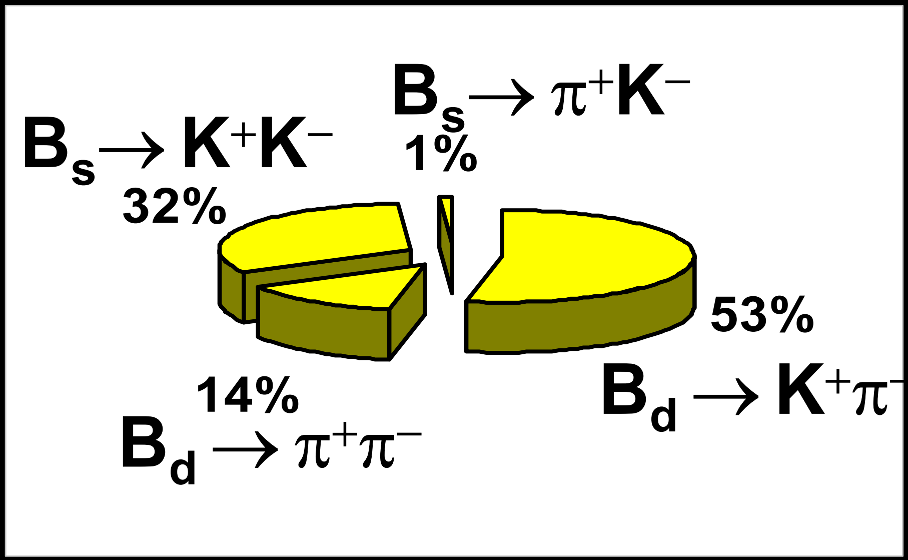
$\pi/K \Rightarrow 1.16\sigma$ (improved soon !)

$M_{\pi\pi}$ vs $(1- p_{min}/p_{max})Q_{min}$





$B \to h^+h'^-$ results (only 65/pb)



Measurement of the relative populations.
Not sensitive (yet) to $B^0_s \to K^- \pi^+$.
Dominant systematic from dE/dx calibrations

$f_s \cdot BR\ (B_s \to KK)\ /\ f_d \cdot BR\ (B_d \to K\pi) = 0.74 \pm 0.20$ (stat) $\pm\ 0.22$ (syst)

First evidence of $B_s \to K^+K^-$ decays.

Direct $A_{CP}(B_d \to K\pi) = 0.02 \pm 0.15$ (stat) $\pm\ 0.02$ (syst)

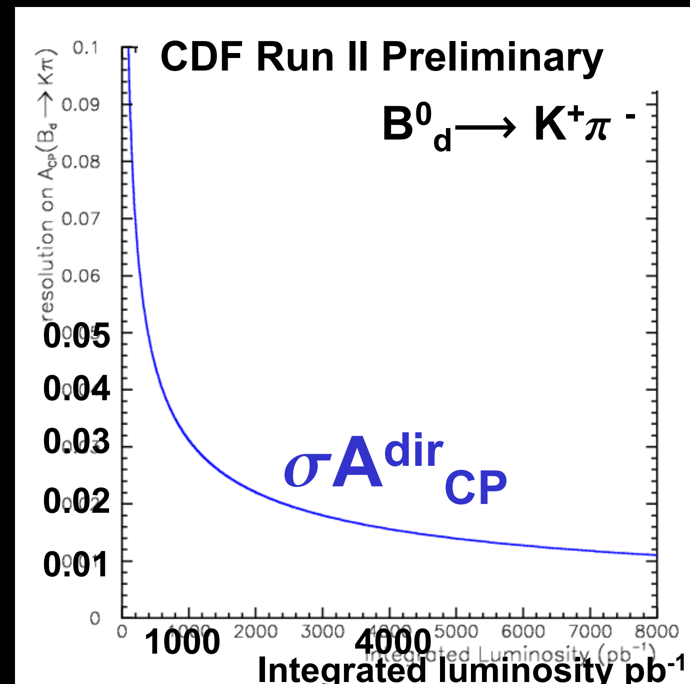
15% statistical error, systematic comparable with B-factories

$BR(B_d \to \pi\pi)\ /\ BR(B_d \to K\pi) = 0.26 \pm 0.11$ (stat) $\pm\ 0.06$ (syst)

Consistent with B-factories results.

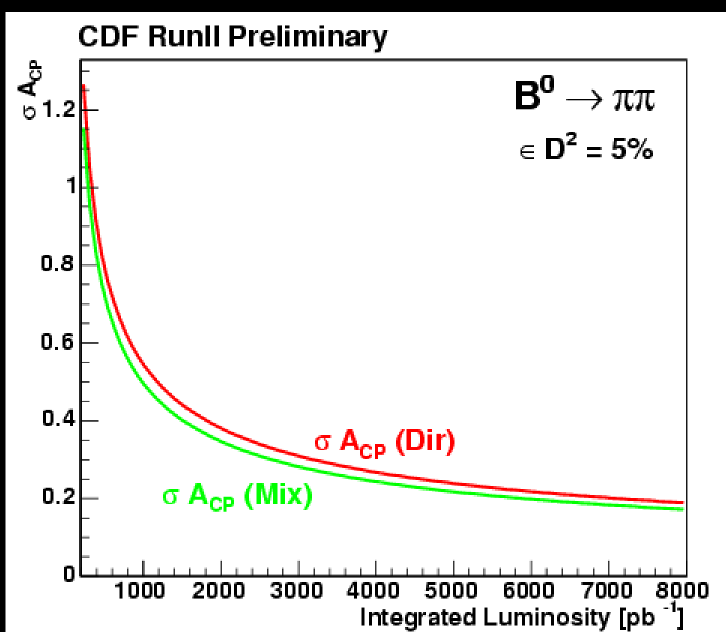
$B \rightarrow h^+h'^-$ what's next ?

Almost done: upgraded measurement on current ~200/pb: will be competitive on direct A_{CP} and sensitive to $B_s \rightarrow K\pi$.



Medium term: BRs' alone could provide, with minimal dynamic assumptions, a measurement of γ

(R. Fleischer hep-ph/0306270)

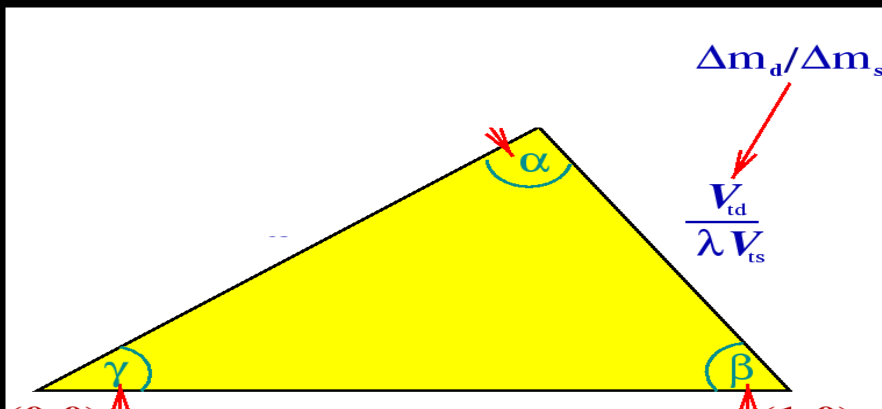


Longer time-scale: tagging + time dependent analysis measure γ w/o penguin pollution as suggested in

(Fleischer and Matias: PR D66 (2002) 054009)

B^0_s - $\overline{B}^0_s$ mixing

Explore one side of the CKM triangle

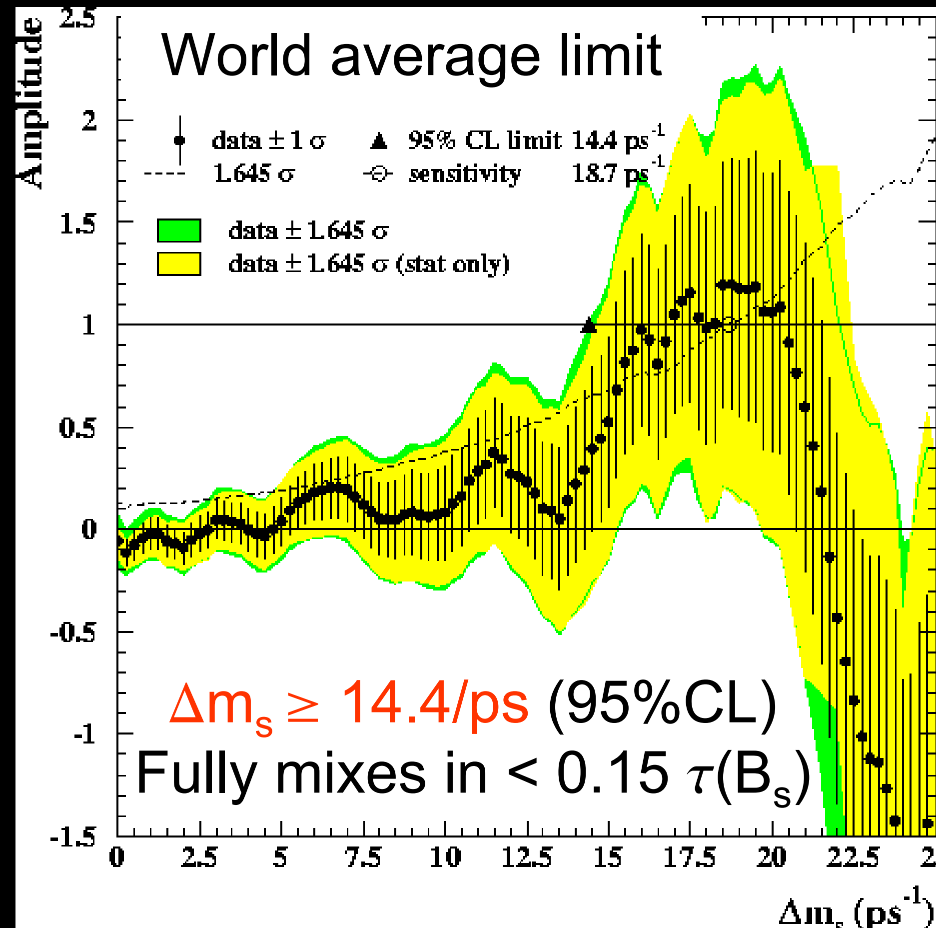


Unique opportunity at Tevatron

Key issues

- ✓ B^0_s flavor identification at decay
- ✓ B^0_s flavor identification at production
- ✓ High Yield with good S/B.
- ✓ High resolution on proper decay time

...additional difficulty wrt B_d



$$A_{mix}(t) = \frac{N_{mix}(t) - N_{unmix}(t)}{N_{mix}(t) + N_{unmix}(t)} = -D * cos(\Delta m_s t)$$

$\overline{B}^0_s$ - B^0_s mixing

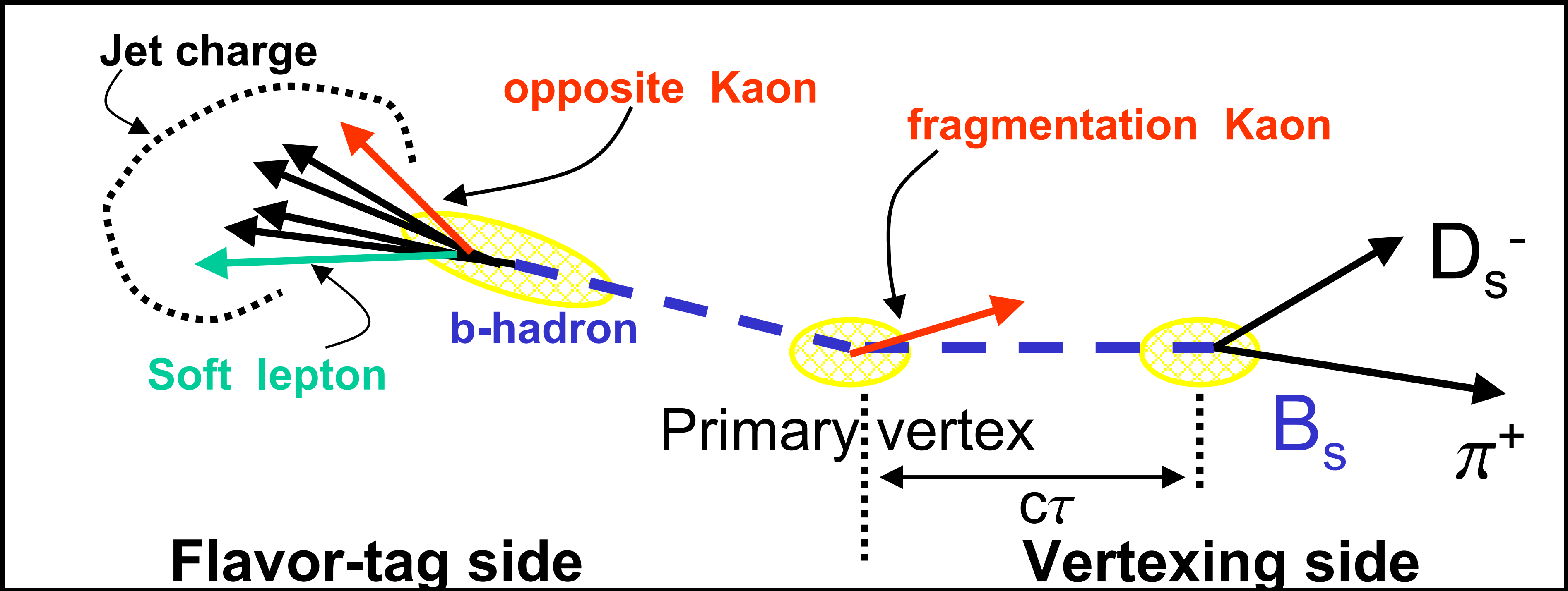
Was B_s or $\overline{B}_s$ at the time of decay ?

Triggering and reconstruction of flavor-specific final states:

high $c\tau$ resolution, low yield ➔ $B_s \longrightarrow D_s\,\pi(\pi\,\pi)$ ($D_s \longrightarrow \phi\pi \longrightarrow$[KK] π)

high yield & S/B, worse $c\tau$ resol. ➔ $B_s \longrightarrow D_s\, l\, \nu + X$ ($D_s \longrightarrow \phi\pi \longrightarrow$[KK] π)

Was B_s or $\overline{B}_s$ at production ? charge-flavor correlations and $b\overline{b}$ production:



Significance of a B^0_s mixing measurement

$$\text{SIG} \approx \sqrt{N\epsilon D^2}\, e^{-(x_s \sigma_{c\tau}/\tau)^2/2} \sqrt{\frac{S}{S+B}}$$

Units of sigma

εD^2 [%]	CDF	DØ
Soft muon	0.7 ± 0.1	1.6 ± 1.1
Soft electron	in progress	in progress
Jet charge	in progress	3.3 ± 1.7
Same side	2.4 ± 1.2	5.5 ± 2.0
Opp. side kaon	in progress	N/A
Same side kaon	in progress	N/A

$$c\tau = \frac{L_{xy}}{\beta_T \gamma} = \frac{L_{xy} m(B)}{p_T(B)}$$

vertexing and momentum resolution

$$\sigma_{c\tau} = \left(\frac{\sigma_{L_{xy}} \cdot m(B)}{p_T(B)}\right) \oplus \left(\frac{\sigma_{p_T}}{p_T(B)}\right) \cdot c\tau$$

	$\sigma_{c\tau}$ [fs]
CDF	67 (50 exp. with LØØ)
DØ	110 - 150

$$\epsilon = \frac{N^{right}}{N^{right} + N^{wrong} + N^{no-tag}}$$

$$D = \frac{N^{right} - N^{wrong}}{N^{right} + N^{wrong}}$$

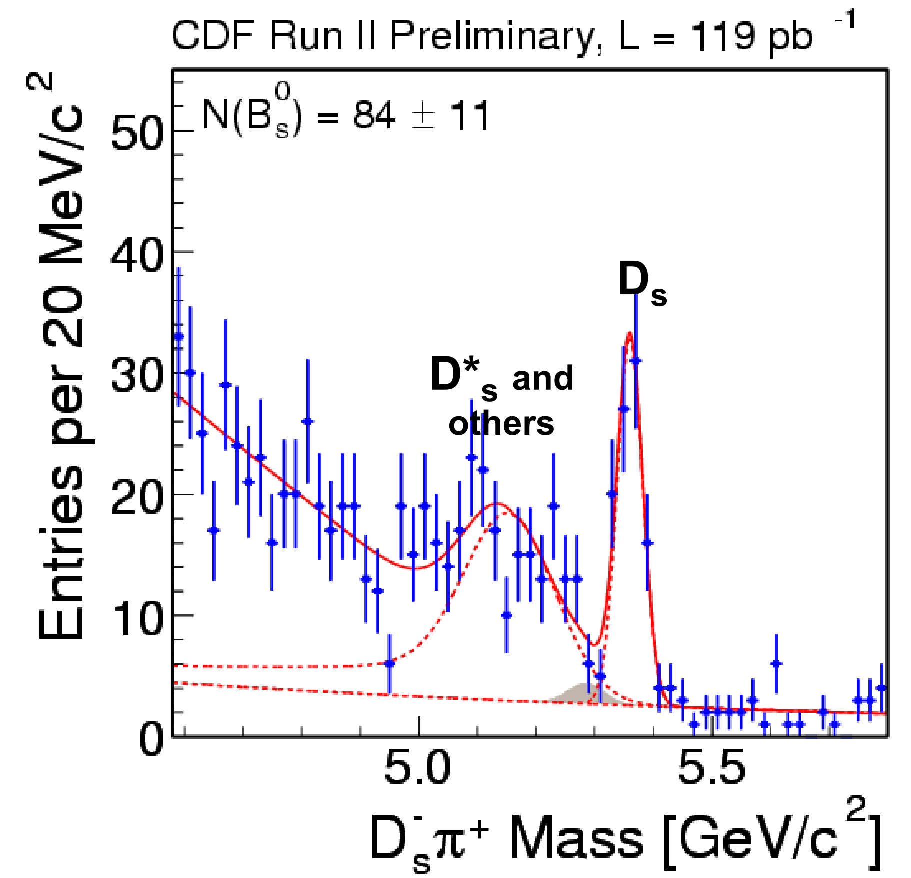
Towards B^0_s mixing – hadronic side

$B^0_s \longrightarrow D^-_s \pi^+ \longrightarrow [\phi\pi^-]\,\pi^+ \longrightarrow [[K^+K^-]\,\pi^-]\,\pi^+$ and charge conjugate

Fully reconstructed CDF "golden channel", maximum proper time resolution: resolve fast oscillations.

Low statistics: add soon $B_s \longrightarrow D_s\,\pi\pi\pi$ and $D_s \longrightarrow K^*K$ / K_sK / $\pi\pi\pi$

Reconstructed the signal with
Yield / lumi = 0.7 pb S/B ~ 2
measure BR($B_s \longrightarrow D_s\,\pi$)

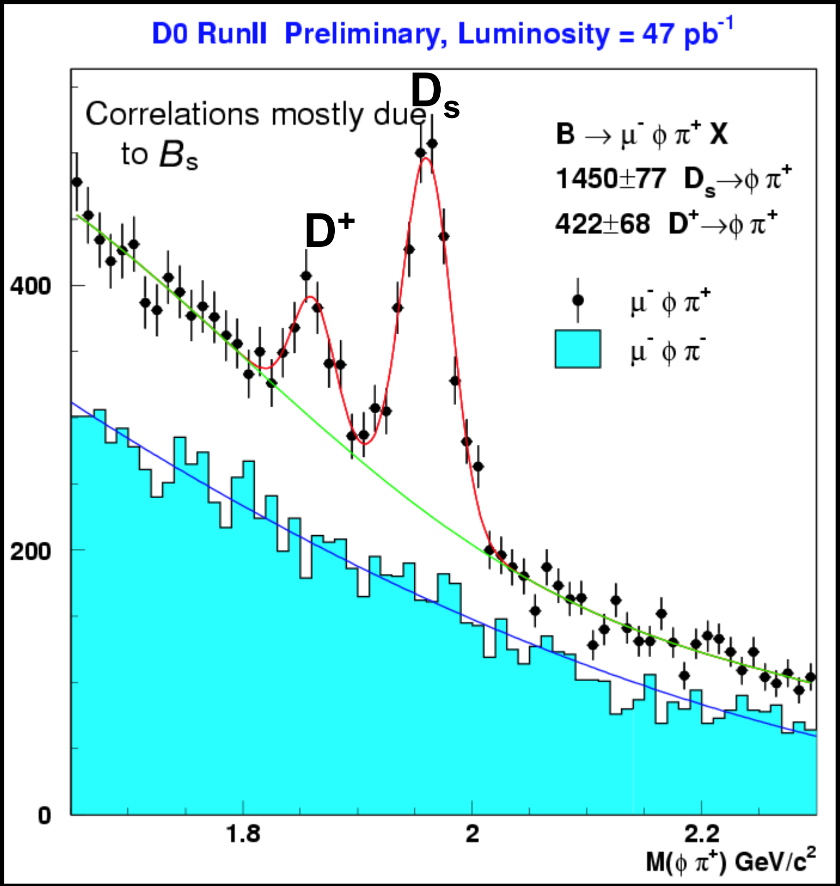


$$\frac{f_s \cdot BR(B^0_s \to D^-_s \pi^+)}{f_d \cdot BR(B^0_d \to D^- \pi^+)} = 0.35 \pm 0.05(stat) \pm 0.04(syst) \pm 0.09(BR)$$

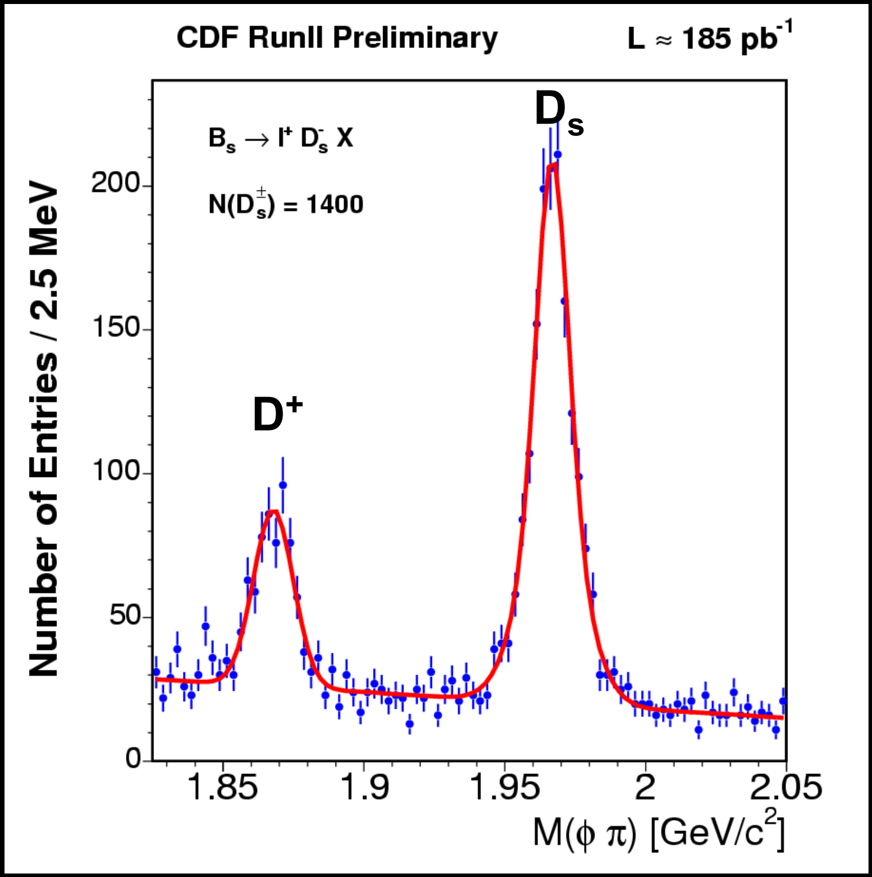
Towards B^0_s mixing – semileptonic side

$B^0_s \longrightarrow D^-_s l^+\nu + X \longrightarrow [\phi\pi^-] l^+\nu \longrightarrow [[K^+K^-]\pi^-] l^+\nu$ and C.C.

high yield and clean but neutrino: poor $\sigma_{c\tau}$

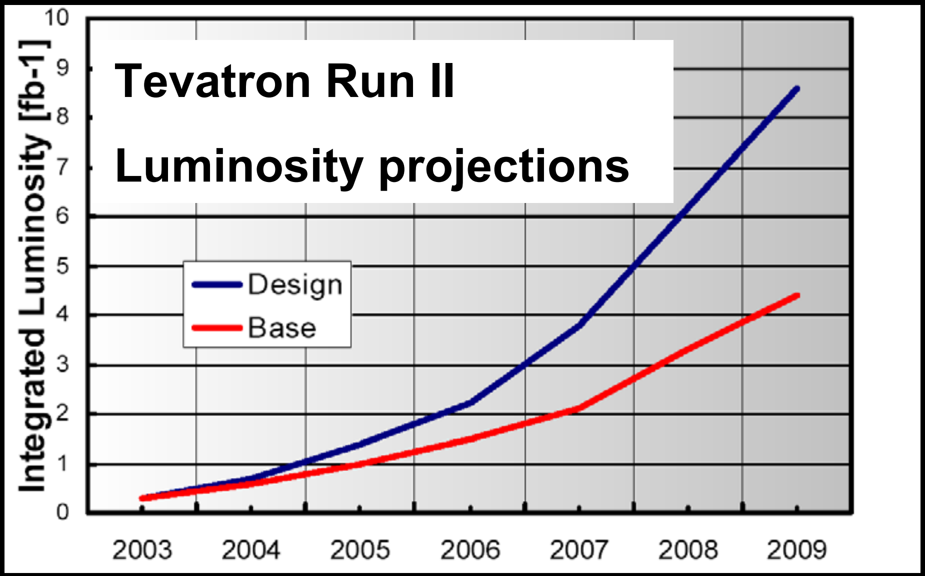


Yield / lumi ~ 31 pb just muons !



Yield / lumi ~ 7.6 pb μ & electrons

Prospects on $\overline{B}^0_s$ - B^0_s mixing



CDF today

Hadronic modes only. Performance:

1600 events/ fb^{-1} S/B ~ 2/1

$\epsilon D^2 \sim 4\%$ $\sigma_{c\tau} = 67$ fs

2σ sensitivity Δm_s=15/ps with 0.5 fb^{-1}

CDF slightly improved

Hadronic modes only. Performance:

2000 events/ fb^{-1} S/B ~ 2/1

$\epsilon D^2 \sim 5\%$ (K tagging) $\sigma_{c\tau} = 50$ fs

5σ for Δm_s = 18/ps with 1.7 fb^{-1}

5σ for Δm_s = 24/ps with 3.2 fb^{-1}

DØ projections

Semileptonic only. Performance:

Yield: 30K + 4K events/ fb^{-1}

ϵD^2 : ~ 10% - ~ 50%

S/B ~ 1/3 $\sigma_{c\tau} = 150$ fs

1.5σ for Δm_s = 15/ps with 0.5 fb^{-1}

Run I aside: CDF average time-integrated mixing probability (PRD69, 2004: 012002)

Ratio R = LS/OS of like (LS) to opposite sign (OS) dileptons in ~100 pb^{-1} of double semileptonic decays of $b\bar{b}$. 2-D fit of the impact parameter in samples of $\mu\mu$, eμ. If mixing occurs LS increases. R related to the average time-integrated mixing parameter $\bar{\chi}$:

$$\bar{\chi} = \frac{\Gamma(B^0_{d,s} \to \bar{B}^0_{d,s} \to l^+ X)}{\Gamma(b \to l^\pm X)} = f_d \cdot \chi_d + f_s \cdot \chi_s$$

numerator: only B_d and B_s
denominator: all b-hadrons

A probe for either mixing or fragmentation fractions

CDF Run Ia + Run Ib new result:

$\bar{\chi}$ = 0.152 ± 0.007(stat)± 0.011(syst)

World average (LEP): 0.118 ± 0.005

Indication of discrepancy with world average, confirms early hints from hadronic colliders ?

UA1: 0.157±0.020 ±0.032

CDF Ia: 0.131±0.020±0.016

$B^0_s \longrightarrow J/\psi\ \phi$: a probe for $sin(2\beta_s)$

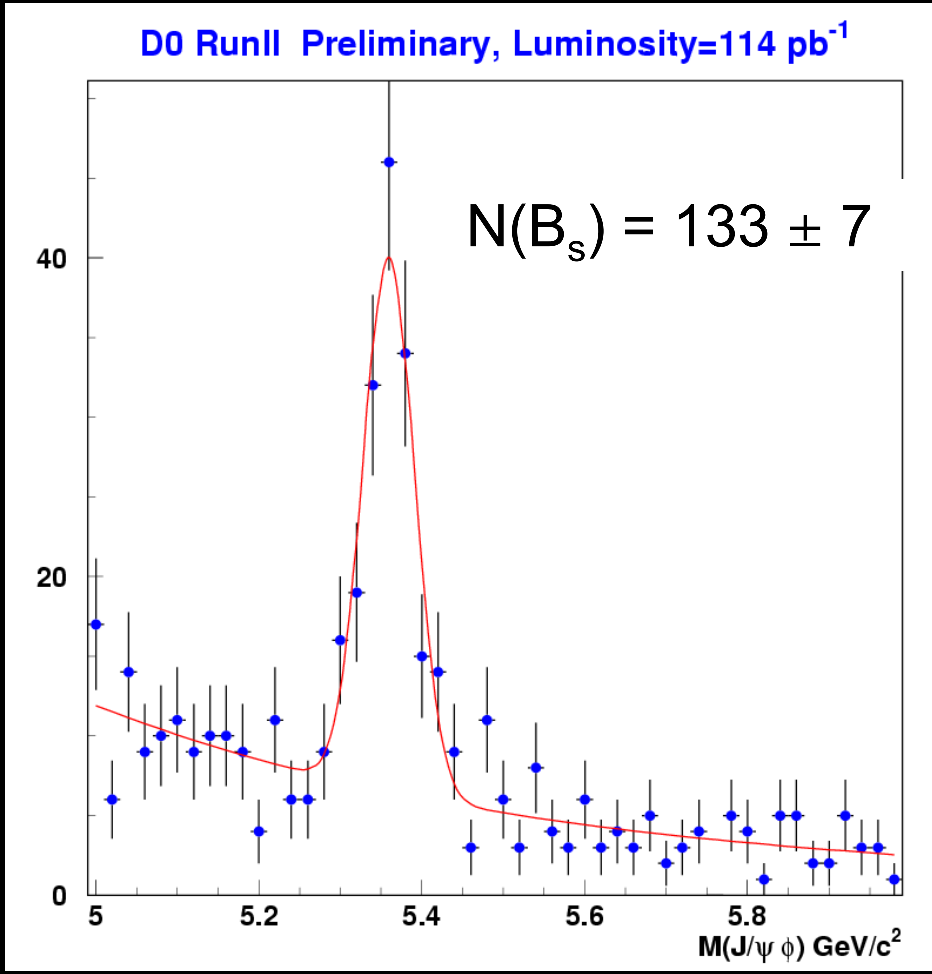
$B^0_s \longrightarrow J/\psi\ \phi \longrightarrow [\mu^+\mu^-]\ [K^+K^-]$ and Charge Conjugate

Measurement of V_{ts} weak phase

$$\beta_s \equiv \arg\left(\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right)$$

Expected very small. Anomalous CPV phases if asymmetry observed. Both experiments.

$B \longrightarrow V\ V$: CP parity of final state depends on the relative angular momentum. Need angular analysis. $\Delta\Gamma_s$ too!



CDF yield: 120 ± 13 in 140 pb^{-1}

CPV in other B → PV and B → V V

Measure direct A_{CP} in $B^+ \longrightarrow \phi K^+ \longrightarrow [K^+K^-] K^+$ and C.C. searching for $B \rightarrow V V$

$B^0_s \longrightarrow \phi\ \phi$ and c.c. ($\Delta\Gamma_s$ too!)

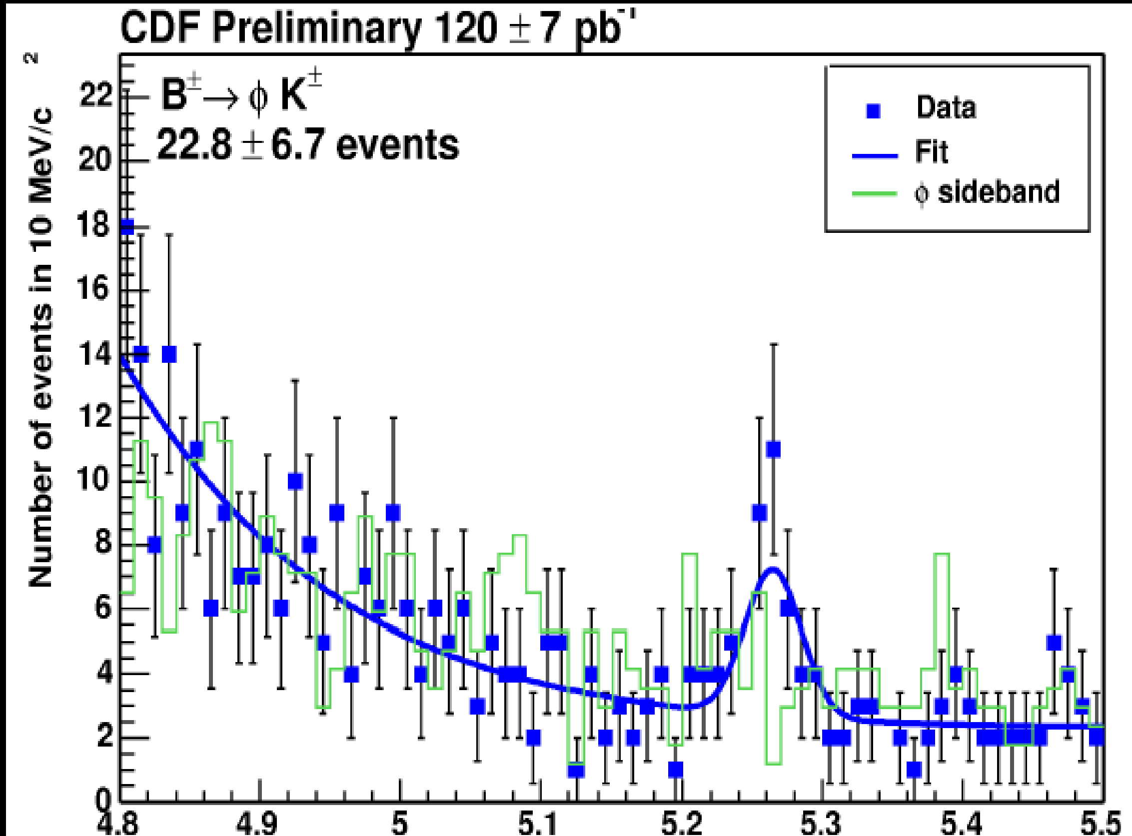
$B^0_d \longrightarrow \phi\ K^*$ and c.c.

$B^0_d \longrightarrow \phi\ K^0_s$ and c.c.

..and for baryons
(SM expects ~10% CPV)

$\Lambda^0_b \longrightarrow \phi\ \Lambda$ and c.c.

$\Lambda^0_b \longrightarrow pK^- / p\pi^-$ and c.c.



Expect ~ 200 events/fb^{-1}

$$\frac{BR(B^\pm \rightarrow \phi K^\pm)}{BR(B^\pm \rightarrow J/\psi K^\pm)} = [6.8 \pm 2.1(stat) \pm 0.7(syst)] \cdot 10^{-3}$$

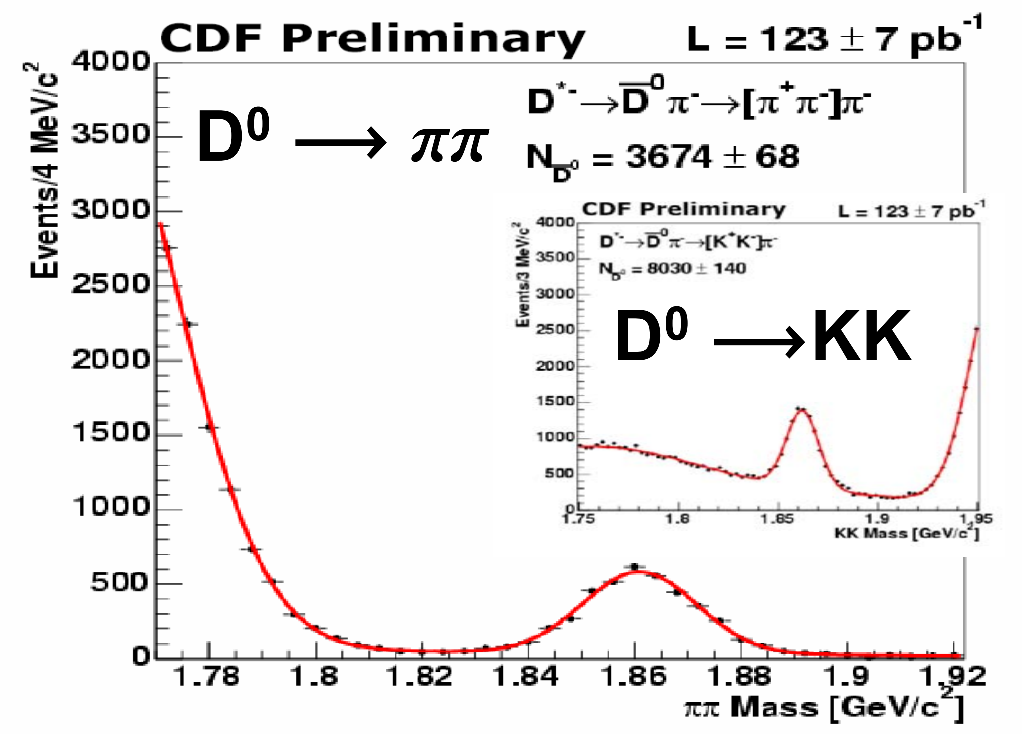
Direct A_{CP} in Cabibbo suppressed D^0

$D^0 \longrightarrow K^+K^- / \pi^+\pi^-$ and C.C.

SM expects $O(10^{-3})$ CPV in charm.
Sensitive to non-SM CPV sources.

Excellent purity through D* - tag:
$D^* \longrightarrow D^0\pi_S$ (Q = 39 MeV)
cut on M (D*) - M(D^0)

- sign (π_S) tags D^0 flavor
- eliminate reflection BCKG



Dominant syst. from detector asymmetries and BCKG subtraction

$A_{CP}(D^0 \longrightarrow KK) = 2.0 \pm 1.2\ (stat) \pm 0.6\ (syst)\ \%$

PDG world average = 0.5 ± 1.6 %

$A_{CP}(D^0 \longrightarrow \pi\pi) = 1.0 \pm 1.3\ (stat) \pm 0.6\ (syst)\ \%$

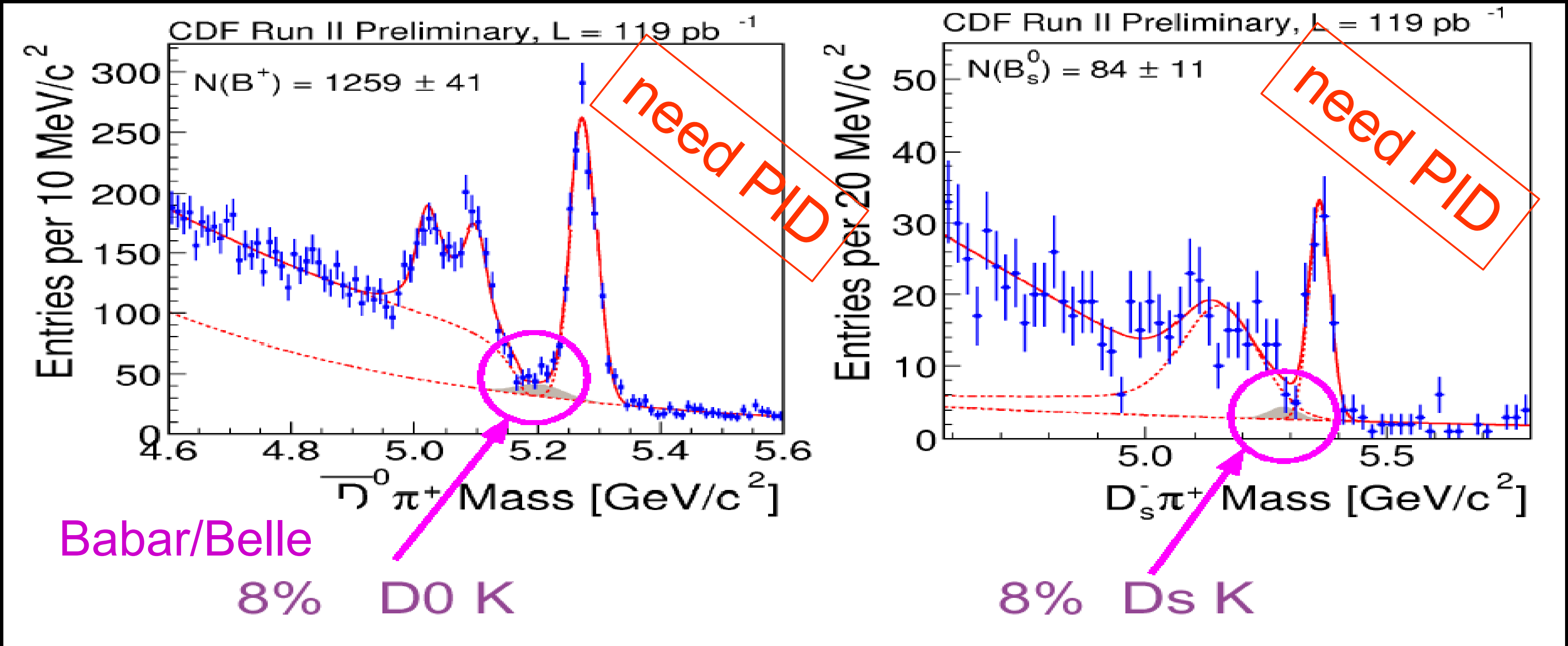
PDG world average = 2.1 ± 2.6 %

$B \longrightarrow D\,K$ (expected yields only)

Extract γ from Cabibbo suppressed B charmed decays:

$B^- \longrightarrow D^0 K^- \longrightarrow [K^-\pi^+] K^-$ and $B^- \longrightarrow \bar{D}^0 K^- \longrightarrow [K^+\pi^-] K^-$ and C. C.

$B^0_s \longrightarrow D^-_s K^+ \longrightarrow [\phi\pi^-] K^+ \longrightarrow [[K^+K^-]\pi^-] K^+$ and C. C.



$B_u \longrightarrow D\pi$: ~ 24K per fb^{-1}
$B_d \longrightarrow D\,K$: ~ 2.2K per fb^{-1}

$B_s \longrightarrow D_s\pi$: ~ 1.6K per fb^{-1}
$B_s \longrightarrow D_s K$: ~ 130 per fb^{-1}

Summary and final remarks

Substantial Tevatron improvement during last year, and performance is steadily ramping.

From masses / lifetimes transition ongoing to "second generation" measurements: CDF and DØ ready for CPV studies. Deep understanding of tracking and of most low-level tools

CDF: already world-class charm physics, soon exciting CPV results on $B \rightarrow h^+h'^-$. Less fast than expected but moving to attack B_s mixing in hadronic decays, SM favorite region accessible by the end of 2004
Many other channels in future $B \rightarrow V\,V$, $B \rightarrow DK$ ….

DØ: very high semileptonic yields, lot of progress on flavor tagging. Preparing for B_s mixing in semileptonic decays.

BACKUP SLIDES

Tevatron Collider collaborations

12 countries, 59 institutions
706 physicists

18 countries, 78 institutions
650 physicists

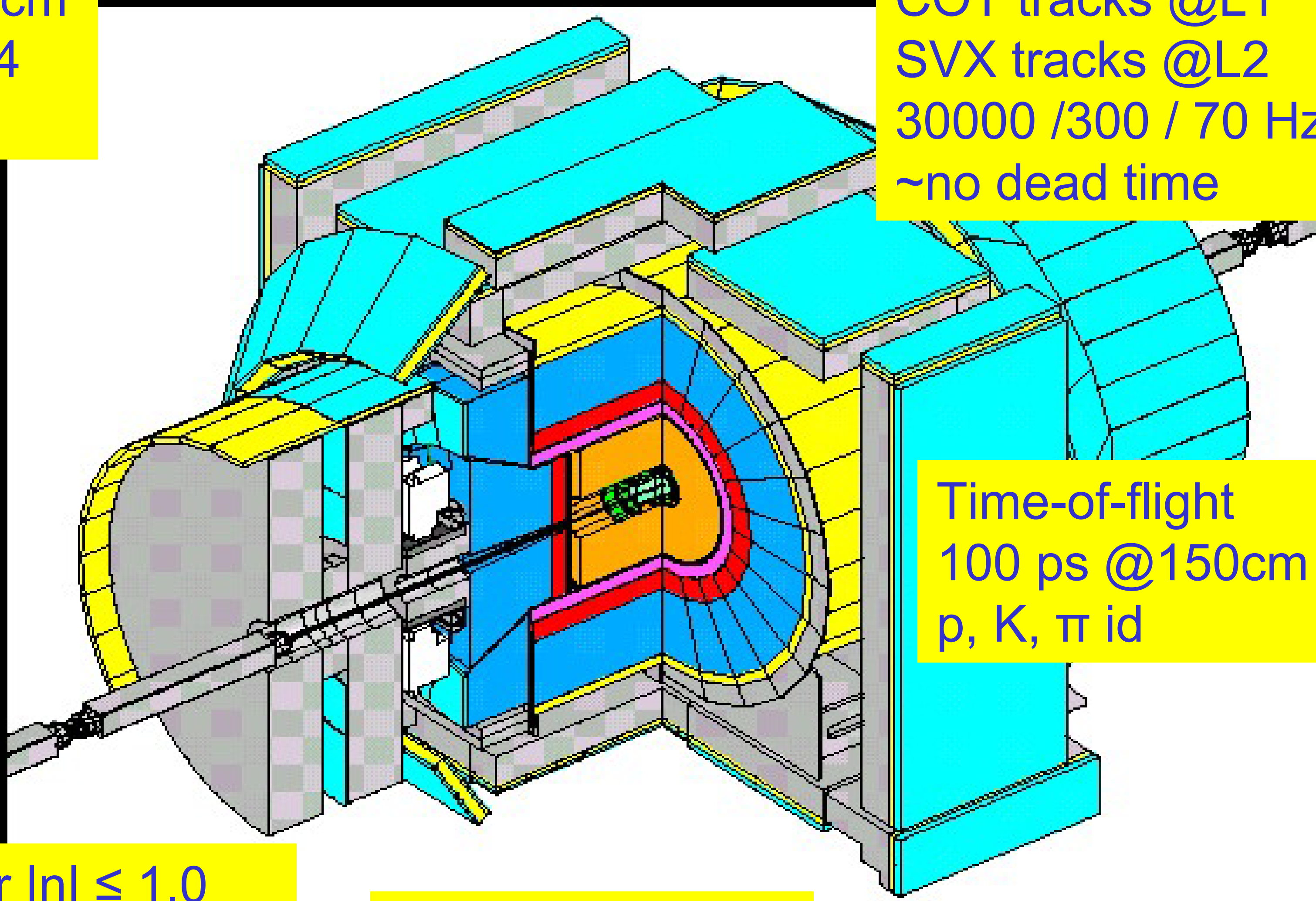
CDF Detector Upgrades

7-8 silicon layers
1.6< r <28 cm |z|<45 cm
$|\eta| \leq 2.0$, $\cos\theta = 0.964$
σ(hit) ~ 14 μm

1.4 T magnetic field
Lever arm 132 cm

132 ns front end
COT tracks @L1
SVX tracks @L2
30000 /300 / 70 Hz
~no dead time

Some resolutions:
$p_T \sim (0.7 \oplus 0.1\ p_T)\%$
J/Ψ mass ~15 MeV
EM E ~ 16%/√E
Had E ~ 100%/√E
$d_0 \sim 6+22/p_T$ μm
Primary vtx ~10 μm
Secondary vtx
r-Φ ~ 14 μm
r-z ~ 50 μm



Time-of-flight
100 ps @150cm
p, K, π id

96 layer drift chamber $|\eta| \leq 1.0$
44 < r < 132 cm, 30k channels
σ(hit) ~ 170 μm
dE/dx for p, K, π id

Tile / fiber endcap
calorimeter
$1.1 < |\eta| < 3.5$

μ coverage to
$|\eta| \leq 1.5$
80% in ϕ

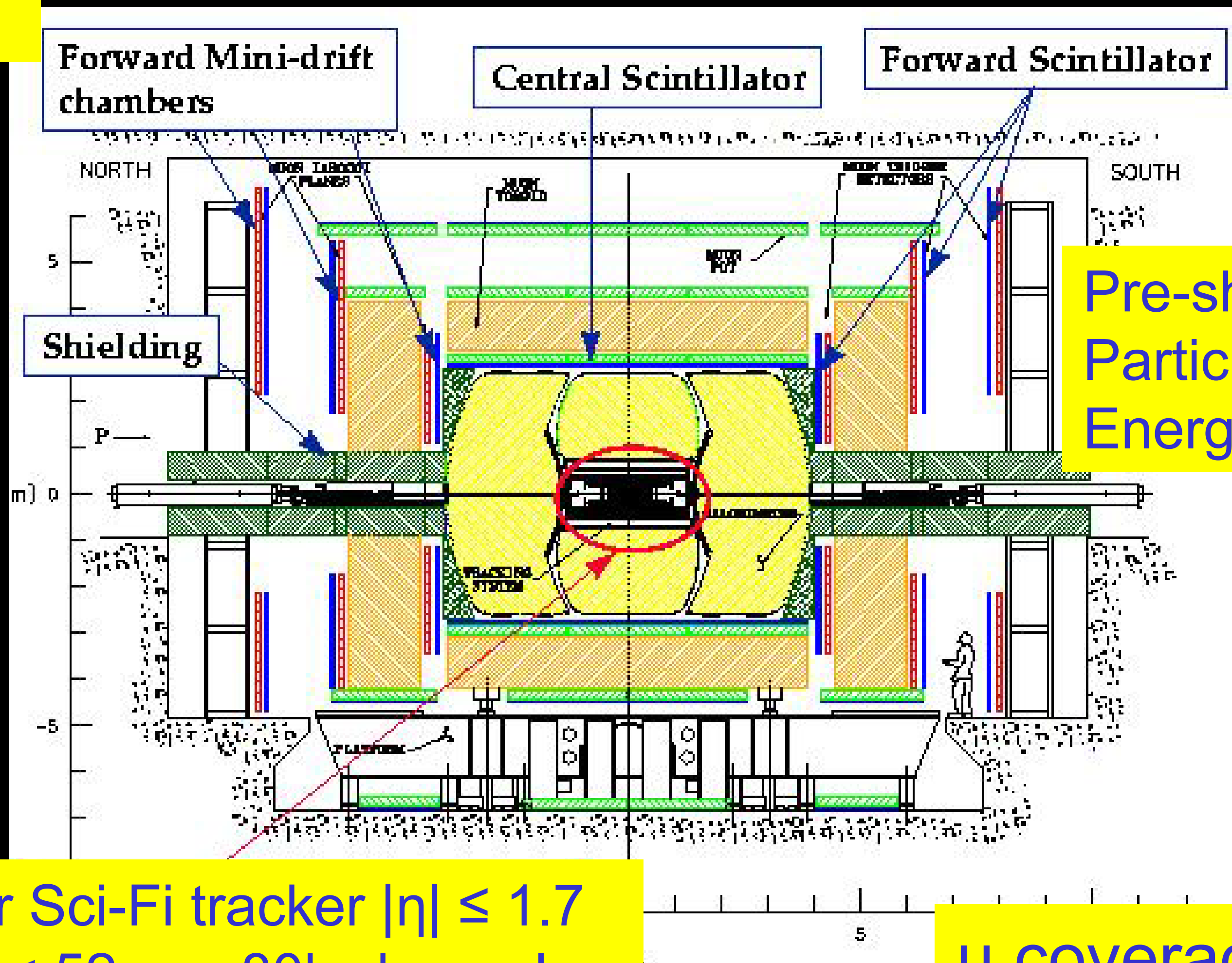
D0 Detector Upgrades

4 silicon layers+disks
Suited to limited space
$2.8 < r < 10$ cm
$|\eta| \leq 3.0$, $\cos\theta = 0.993$

2.0 T magnetic field
Lever arm 52 cm

Now! Sci-Fi tracks @ L1
Next! Silicon track s@ L2
5000 / 1000 / 50 Hz

Some resolutions:
$p_T \sim (2.0 \oplus 0.2\, p_T)\%$
J/Ψ mass ~27 MeV
EM E ~ $15\%/\sqrt{E}$
Had E ~ $80\%/\sqrt{E}$
$d_0 \sim 13+50/p_T$ μm
Primary vtx ~15 μm
Secondary vtx:
r-Φ ~ 40 μm
r-z ~ 80 μm

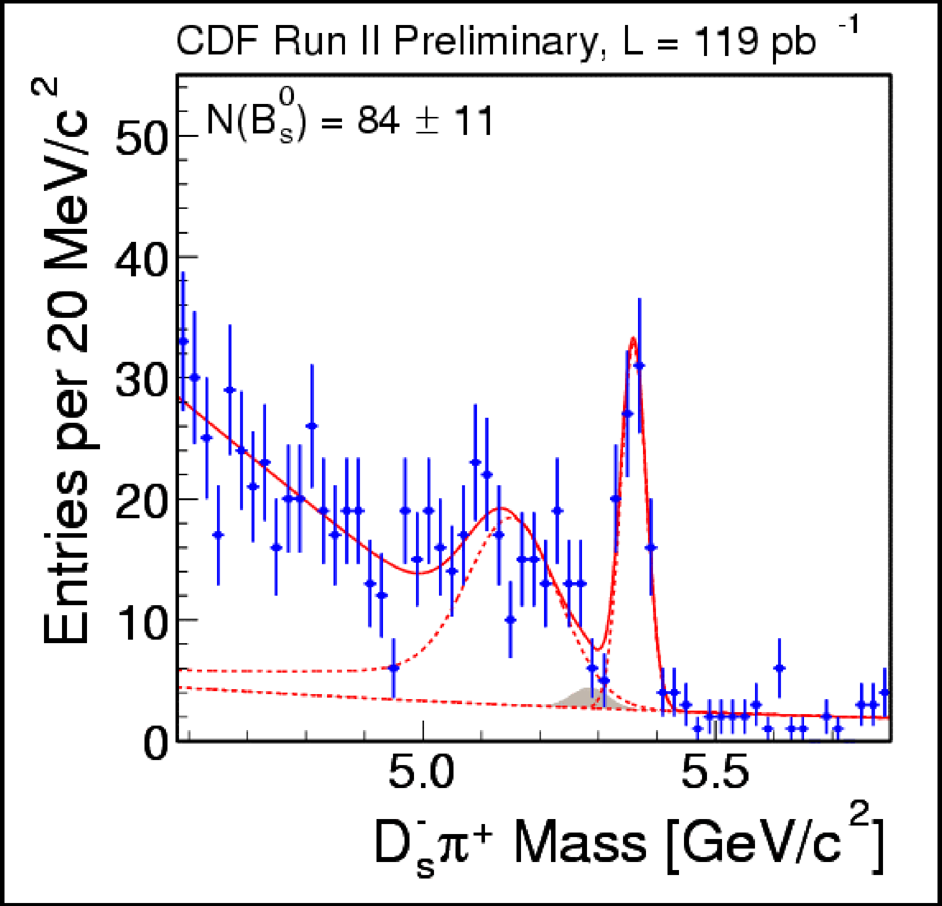


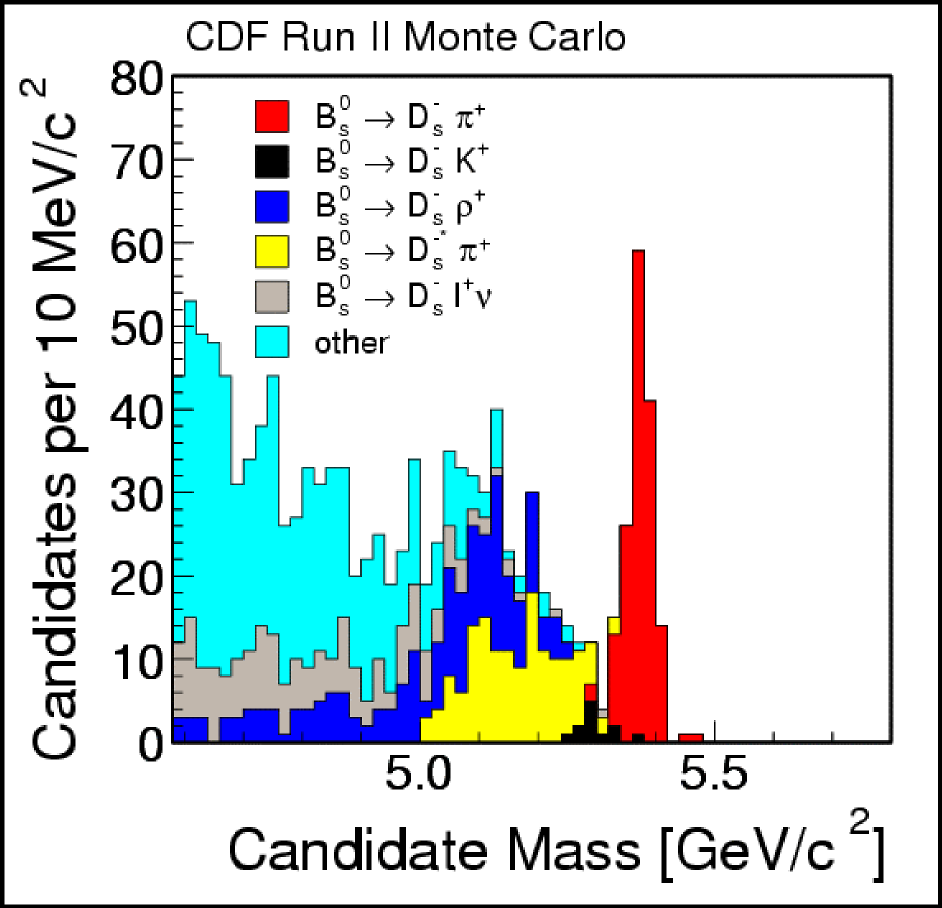
Pre-shower
Particle id
Energy

8 layer Sci-Fi tracker $|\eta| \leq 1.7$
$10 < r < 52$ cm, 80k channels
VLPC's at 9K, 85% QE
σ(hit) ~ 100 μm

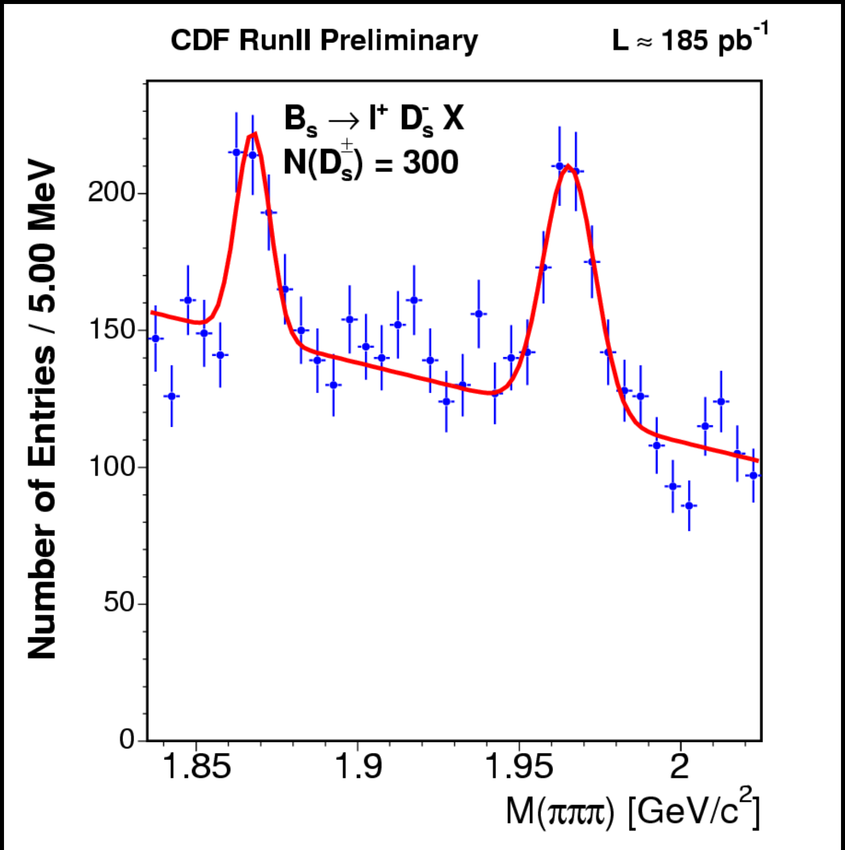
μ coverage to
$|\eta| \leq 2.0$
90% in phi

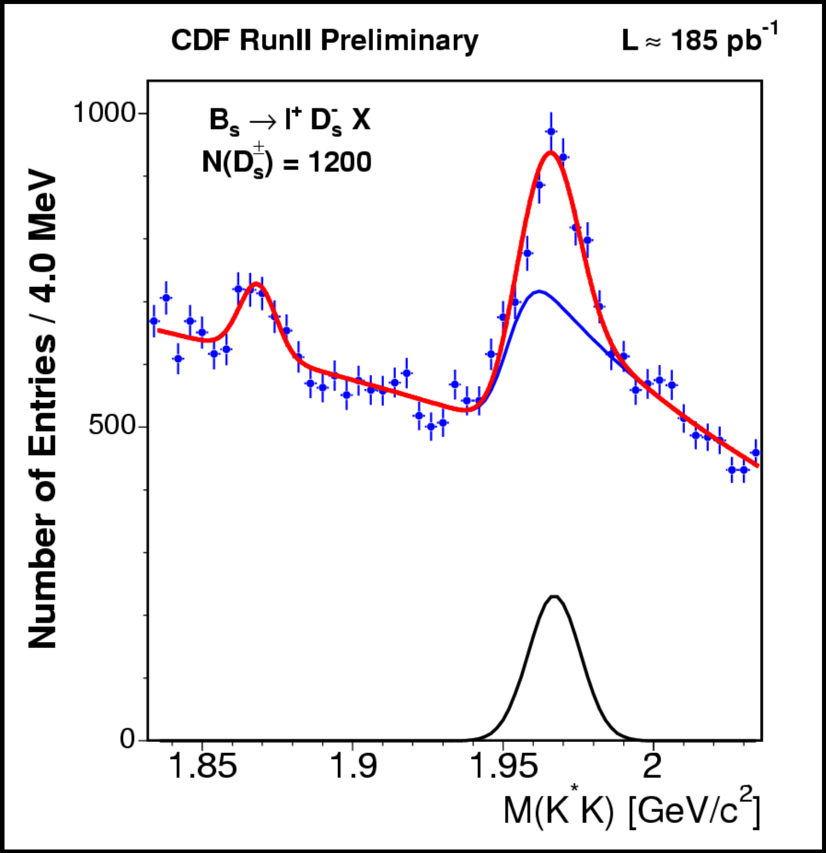
BACKUP SLIDES



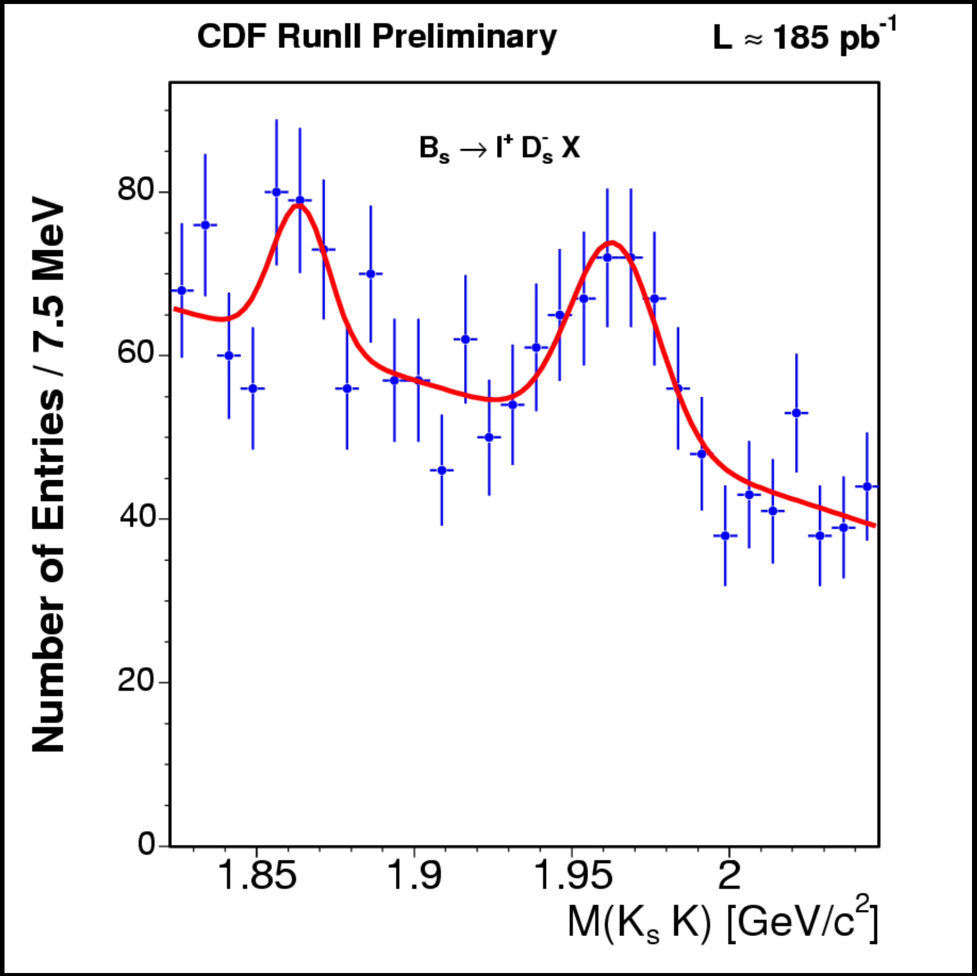


..more semileptonic B^0_s





..more semileptonic B^0_s

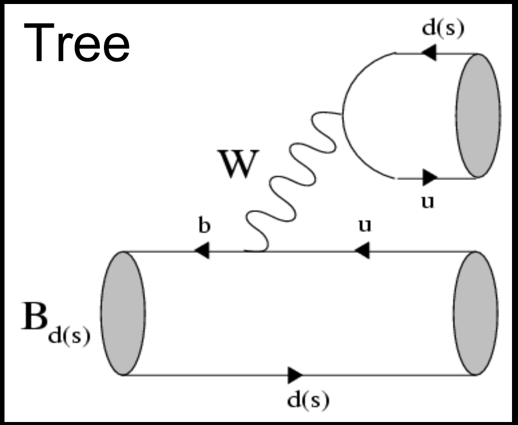


Two-body Charm-less B Decays: Physics Motivations

$B_d \to \pi^+\pi^- / K\pi$ accessible at B-factories too:

- ✓ Branching ratios
- ✓ Direct A_{CP} in $B_d \to K\pi$: $A_{CP} = (N^+ - N^-)/(N^+ + N^-)$
- ✓ Direct + mixing A_{CP} in $B_d \to \pi^+\pi^-$:

$$A_{CP}(t) = A_{CP}^{dir}\cos(\Delta m_d t) + A_{CP}^{mix}\sin(\Delta m_d t)$$

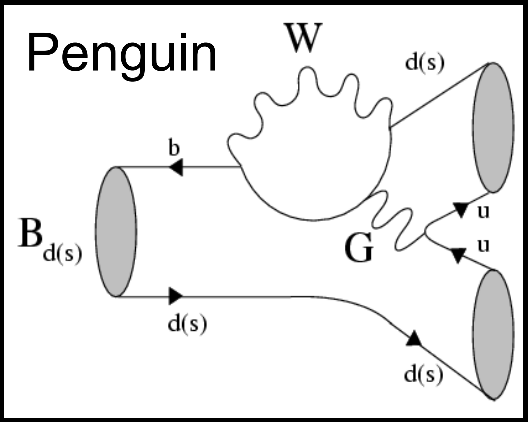


Amplitude ~ T

$B_s \to K^+K^- / K\pi$ only at Tevatron, never observed:

- ✓ Branching ratios
- ✓ Direct A_{CP} in $B_s \to K\pi$: $A_{CP} = (N^+ - N^-)/(N^+ + N^-)$
- ✓ Direct + mixing A_{CP} in $B_s \to K^+K^-$:

$$A_{CP}(t) = A_{CP}^{dir}\cos(\Delta m_s t) + A_{CP}^{mix}\sin(\Delta m_s t)$$



Amplitude ~ P

Physics Motivations (II)

The combination of B_d and B_s decays provides a promising way to extract CP-related physical parameters avoiding the "penguin pollution". *(R. Fleischer PLB45 (1999) 306)*

Assume U-spin symmetry ($d \leftrightarrow s$), the A_{CP} are function of the CKM angles β and γ and of the amplitude ratio P/T ($\sim de^{i\theta}$)
➔ 4 equation with 4 unknowns (β, γ, d, θ).
A combined fit of the 4 CP asymmetries measures β, γ and P/T ratio.

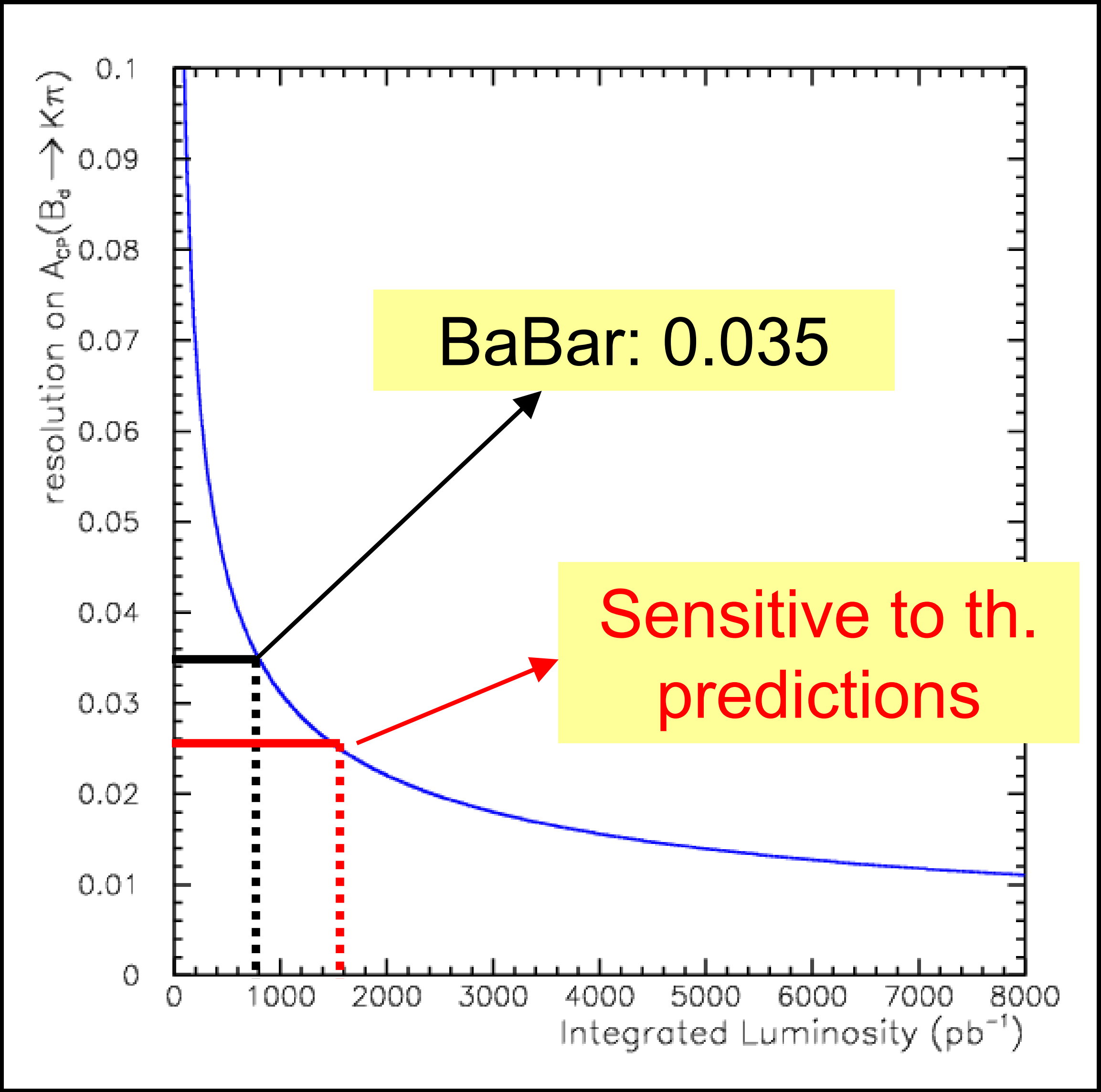
Above strategy need time-dependent analysis with tagged samples: long term goal

Statistical resolution on $A_{CP}(B_d \rightarrow K^+\pi^-)$

Best measurement today by BaBar: 0.035

CDF needs ~850 pb^{-1} to reach that accuracy.

Theory* predicts:
$A_{CP} \in [-13\%, +5\%]$
with ~1500 pb^{-1} CDF gets sensitive to it.



* Keum, Sanda hep-ph/0306004
Beneke, Neubert hep-ph/0308039

Projections on time-dependent A_{CP} on tagged samples

We do not have a resolution to extrapolate from.
Use the analytic expressions for the expected resolutions:

$$\sigma = \frac{1}{\sqrt{\epsilon D^2}} \cdot \frac{\sqrt{S+B}}{S} e^{x^2\sigma^2\Gamma^2/2} \sqrt{\frac{1+4x^2 \pm \cos\theta \mp 2x\sin\theta}{2x^2}}$$

Assume a minimal improvement scenario with:

- ✓ 6.48 pb specific yield
- ✓ + 25% in S/B (wrt current S/B)
- ✓ ϵD^2 = 5% (today is 4%)
- ✓ Proper time resol. = 50 fs (today is 67 fs)
- ✓ Trigger lifetime cut = 0.5τ
- ✓ $x_s = 30$