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

XVII[iémes] Rencontres de Physique de la Vallée d'Aoste

February 29[th] – March 6[th], 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

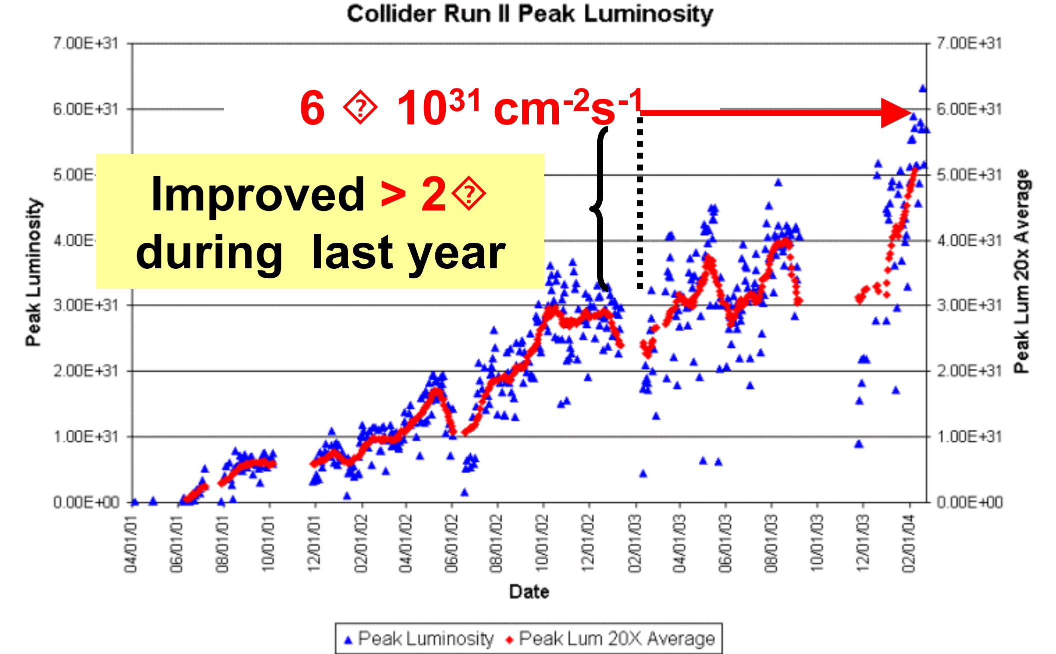
Luminosity……………………………: record peak is $6.7 \times 10^{31}\ cm^{-2}\ s^{-1}$

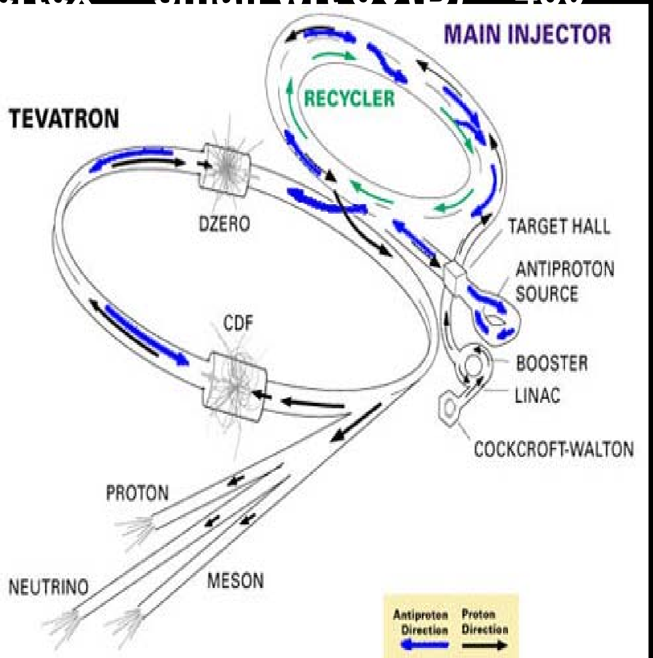
~ 10 pb^{-1} / week delivered

interactions / bunch-crossing……..: $< N >_{poisson} = 1.5$ (at 5 ⟐ $10^{31}\ cm^{-2}s^{-1}$)

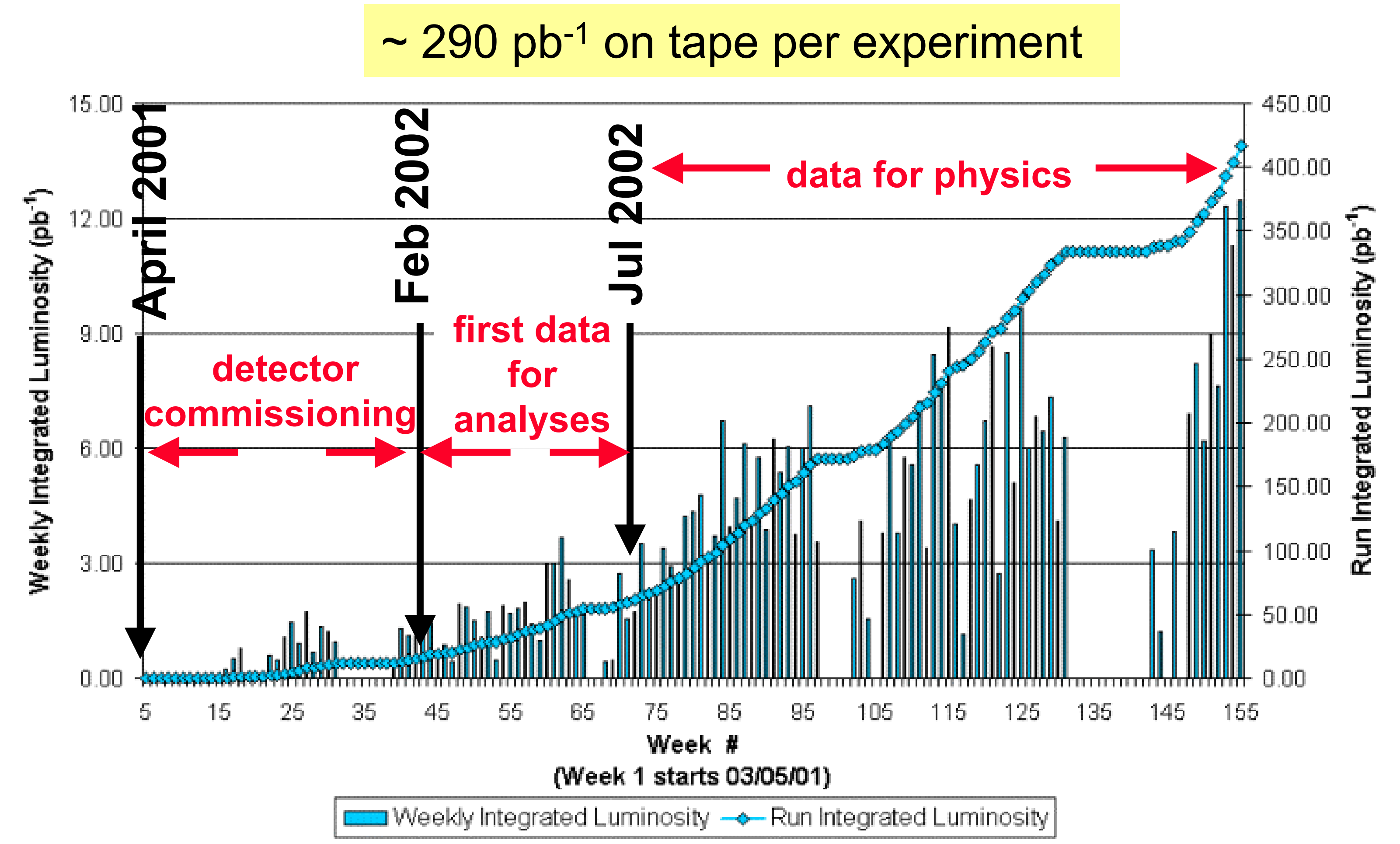
Luminous region size………………..: 30 cm (beam axis) ⟐ 30 ❍m (transverse)

need long Si-vertex   small wrt c♦(B) ~ 450





Delivered Luminosity



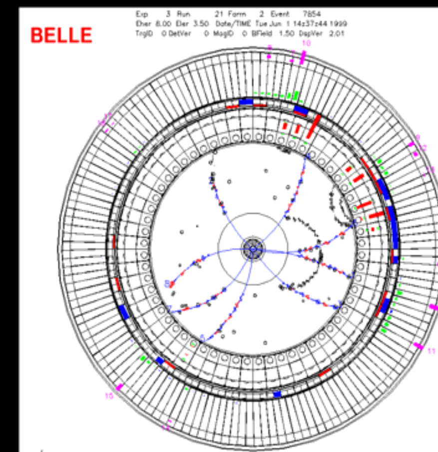
Data taking efficiency: 80 - 90%
stable for both experiments

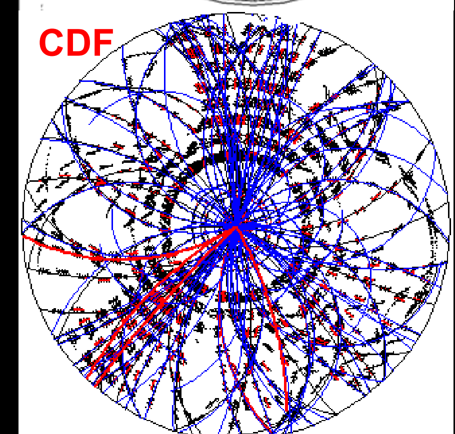
For the following results:
CDF analyses use: ~65 to ~190 pb^{-1}
DØ analyses use: ~ 47 to ~114 pb^{-1}

Heavy Flavor physics at the Tevatron

The Good

$b\bar{b}$ production x-section O(10^5) larger than e^+e^- at $\Upsilon(4S)$ /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 ♋ charmonium Rare B ♋ ❍❍

Two muons with:

p_T> 1.5 GeV |♒|< 1

p_T > 2.5-4.5 GeV |♒|<2

Single-muon

DØ only

Semileptonic decays

one muon with:

p_T > 2 - 4 GeV |♒| <2

new approach

electron or ❍ and displaced track

CDF only

Semileptonic decays

Electron (❍) with:

p_T> 4 (1.5) GeV |♒|< 1

and one track with:

p_T > 2.0 GeV IP > 120 ❍m

Two displaced tracks

CDF only

n-body hadronic B

Two tracks with:

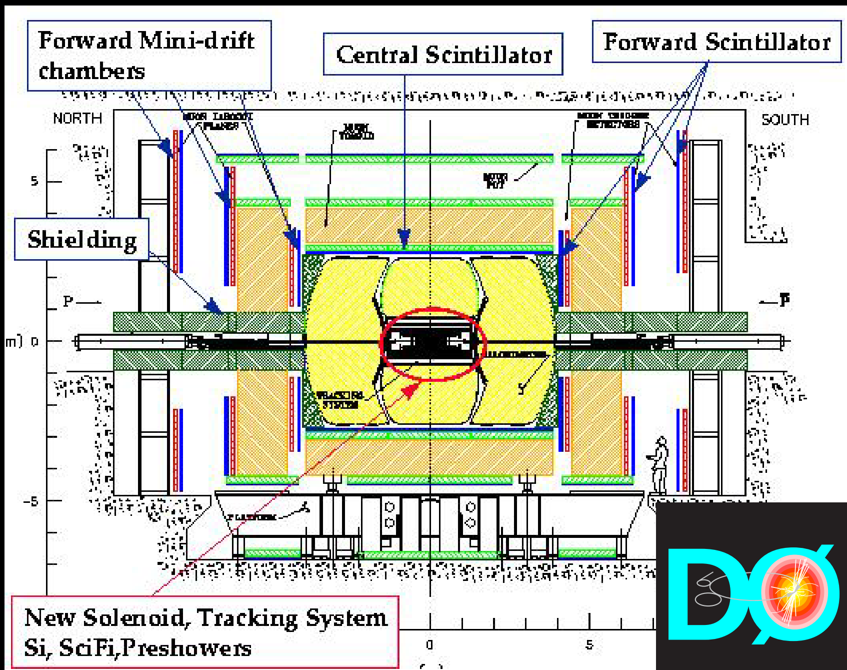
p_T > 2.0 GeV

💧p_T > 5.5 GeV

IP > 120 (100) ❍m

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

Detectors



Both detectors

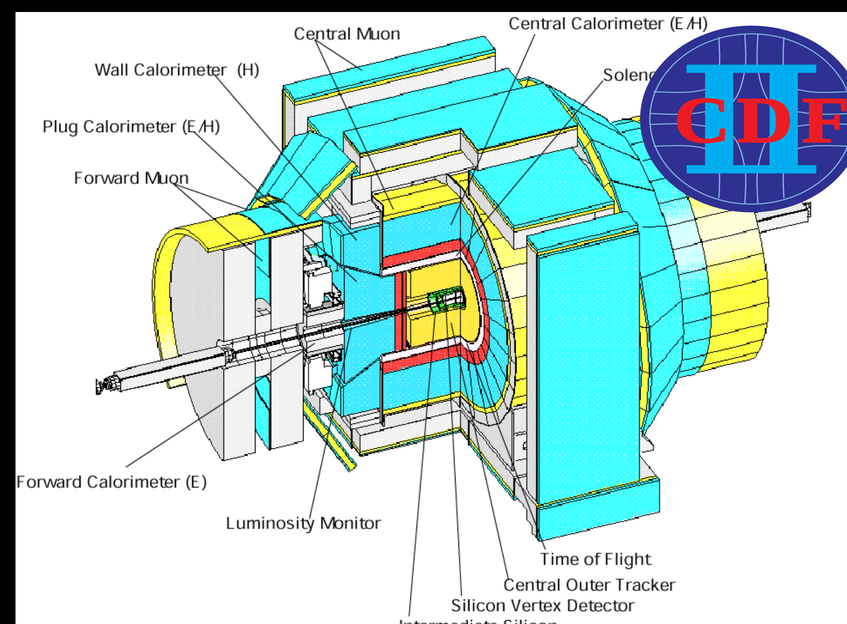
Silicon microvertex tracker
Axial solenoid
Central tracking
High rate trigger/DAQ
Calorimeters and muons

DØ

Excellent electron and muon ID
Excellent tracking acceptance

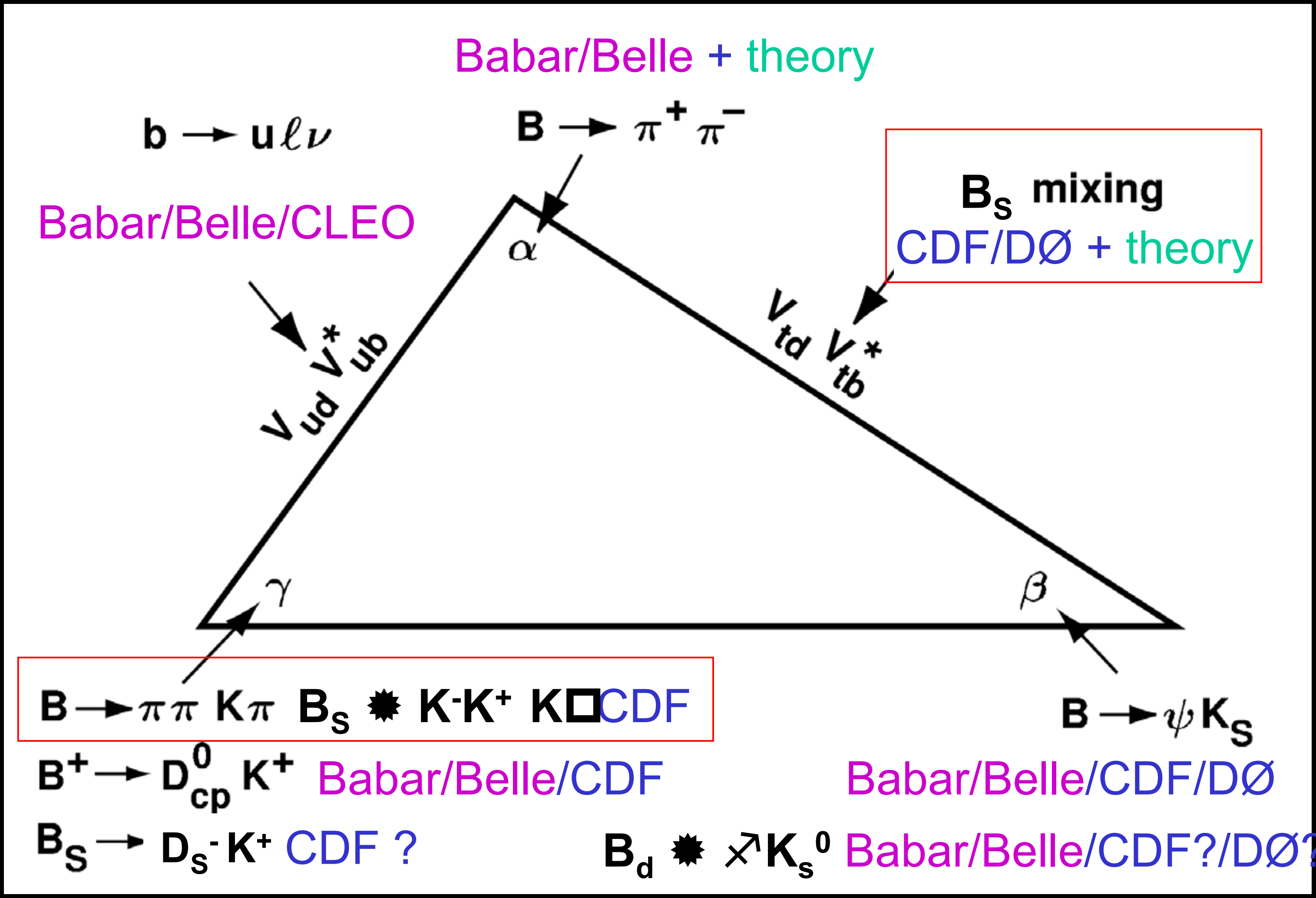
CDF

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



Overall game plan

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



B ✹ $h^+h'^-$: towards ♋, ♑ and direct A_{CP}

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

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

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

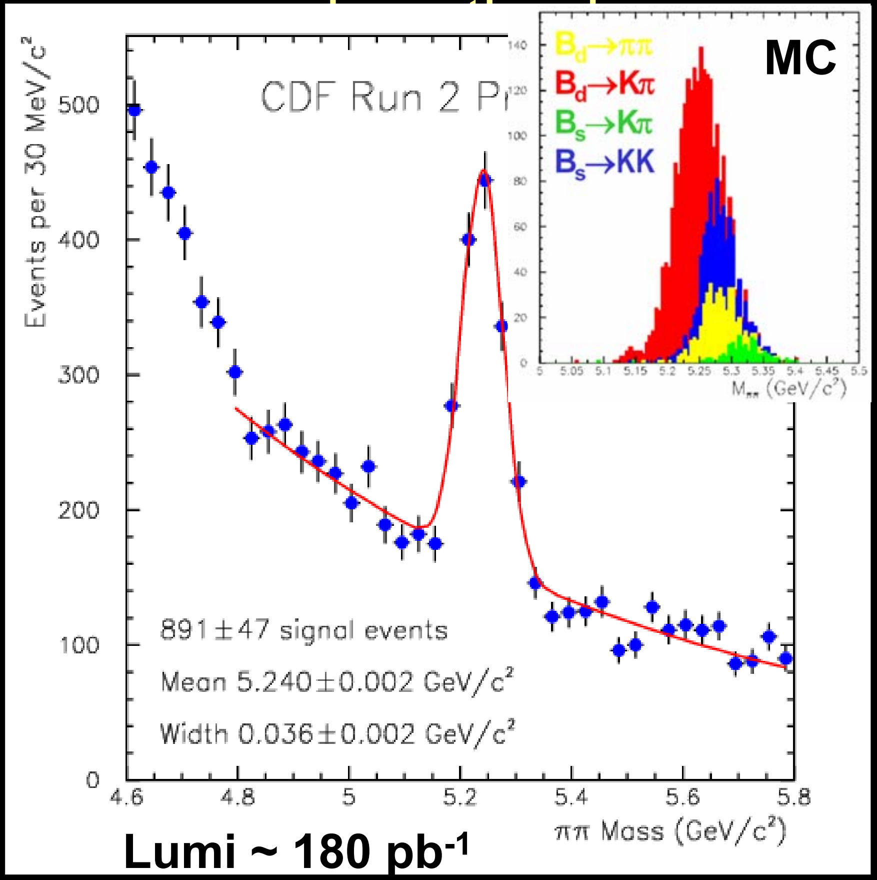
$B^0_s \to K^+K^-$ and C. C.

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

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

Combine kinematics with dE/dx to achieve statistical separation

□□



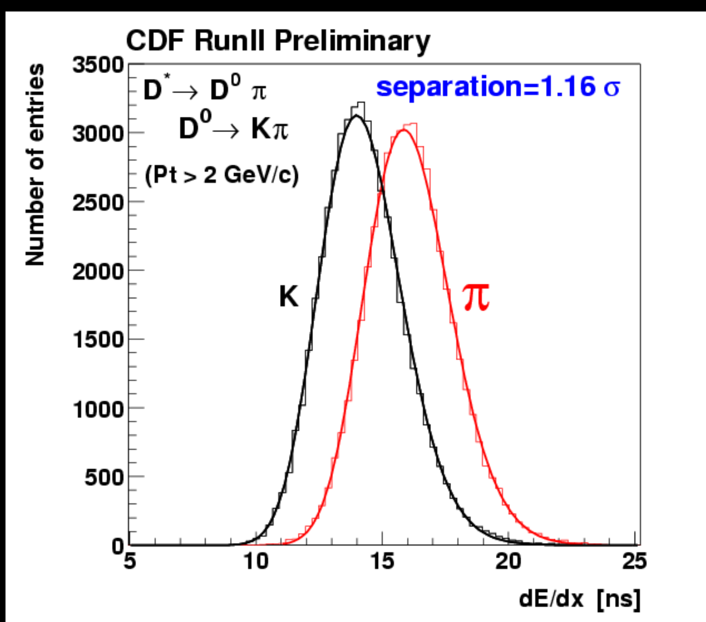
Expect ~ 6500 evts / fb^{-1}

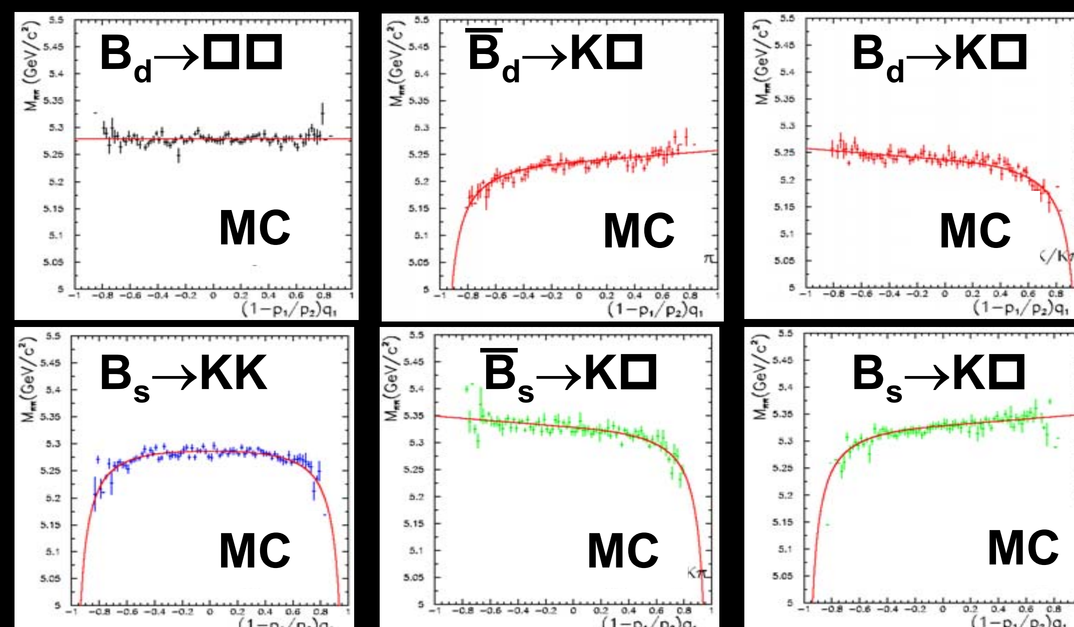
B ✸ $h^+h'^-$: resolve peak composition

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

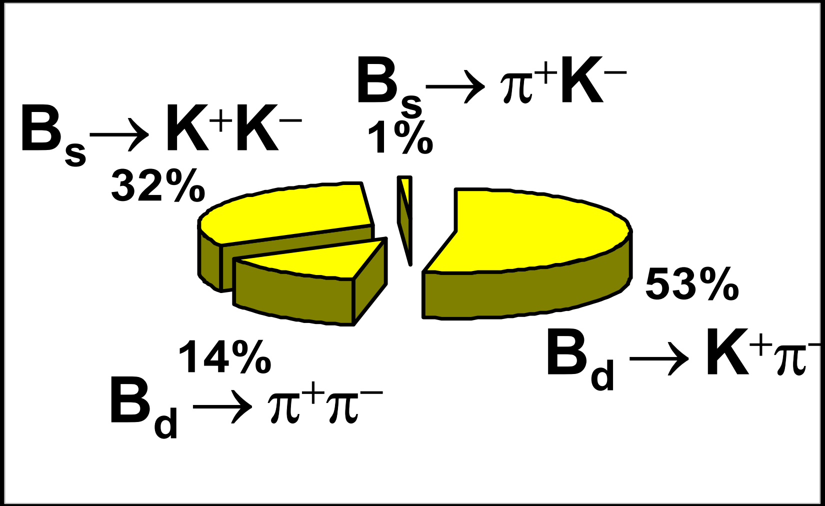
□/K ⇒ 1.16♦ (improved soon !)

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





B ✹ $h^+h'^-$ 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

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

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

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

15% statistical error, systematic comparable with B-factories

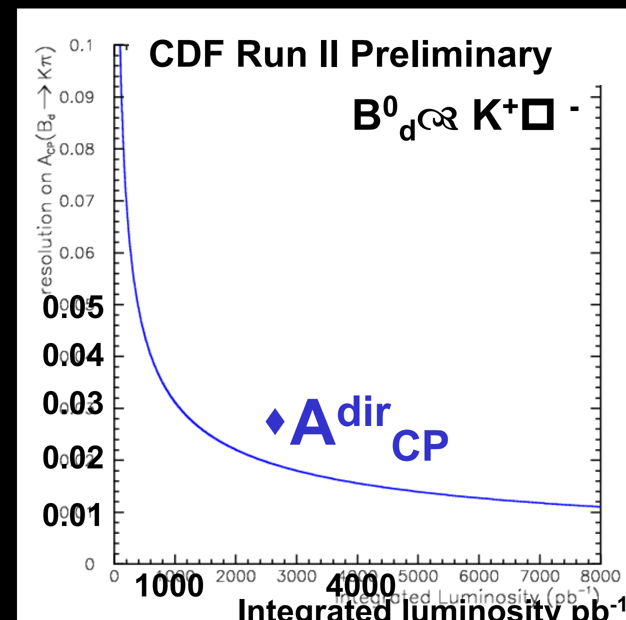
$BR(B_d \to \square\square)\ /\ BR(B_d \to K\square)\quad = 0.26 \pm 0.11$ (stat) $\pm\ 0.06$ (syst)

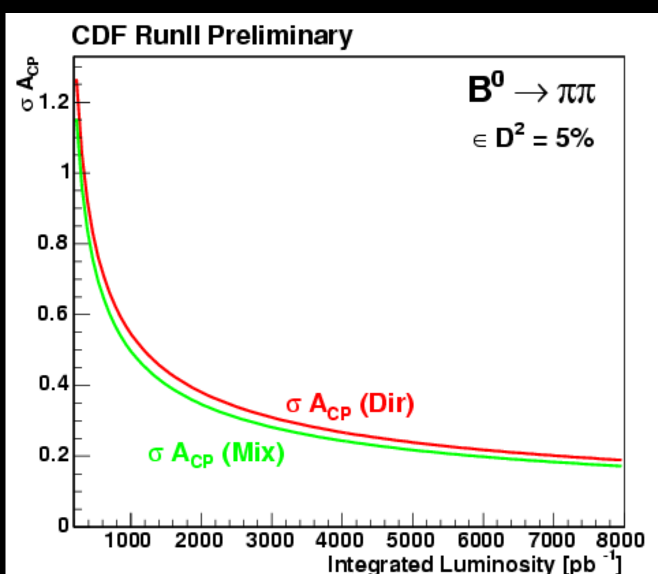
Consistent with B-factories results.

B ✸ $h^+h'^-$ what's next ?

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

Medium term: BRs' alone could provide, with minimal dynamic assumptions, a measurement of ♑ *(R. Fleischer hep-ph/0306270)*

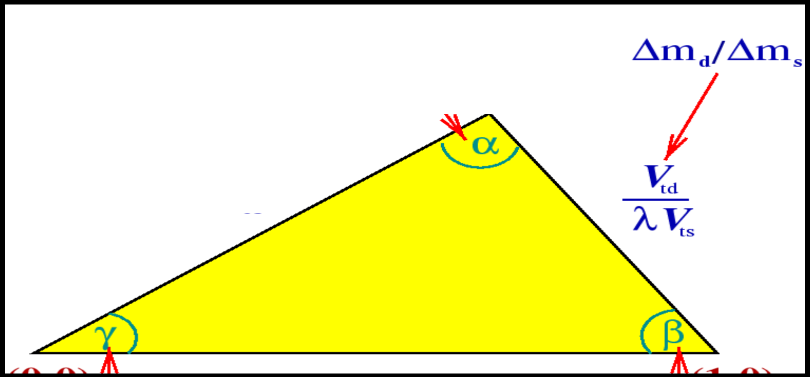




Longer time-scale: tagging + time dependent analysis measure ♑ w/o penguin pollution as suggested in *(Fleischer and Matias: PR D66 (2002) 054009)*

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

Explore one side of the CKM triangle

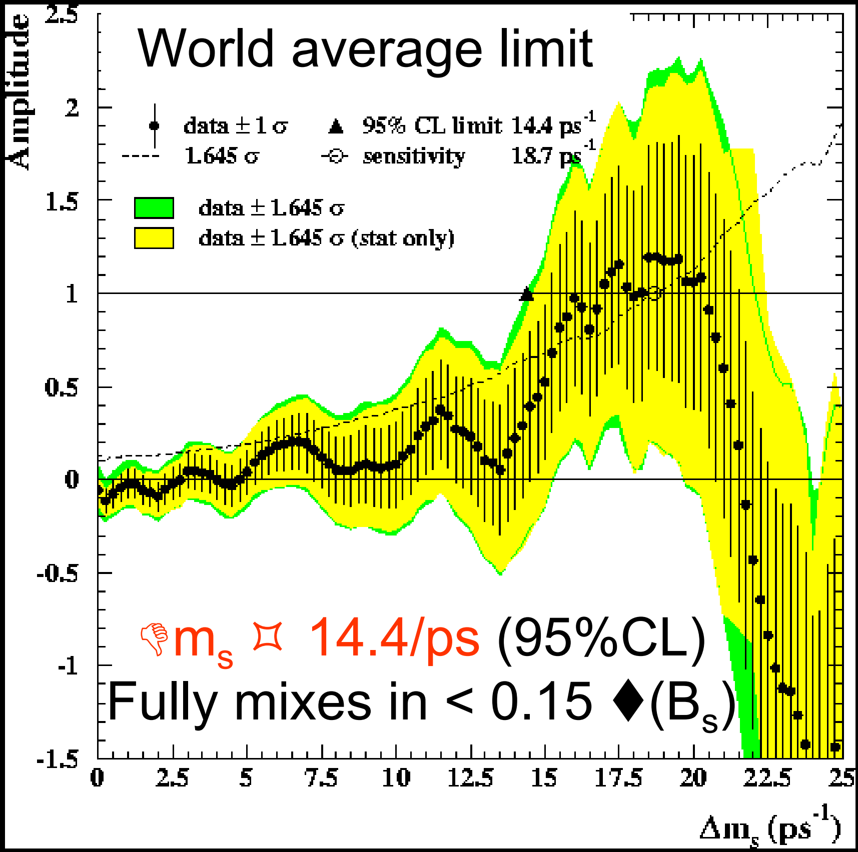


Unique opportunity at Tevatron

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



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

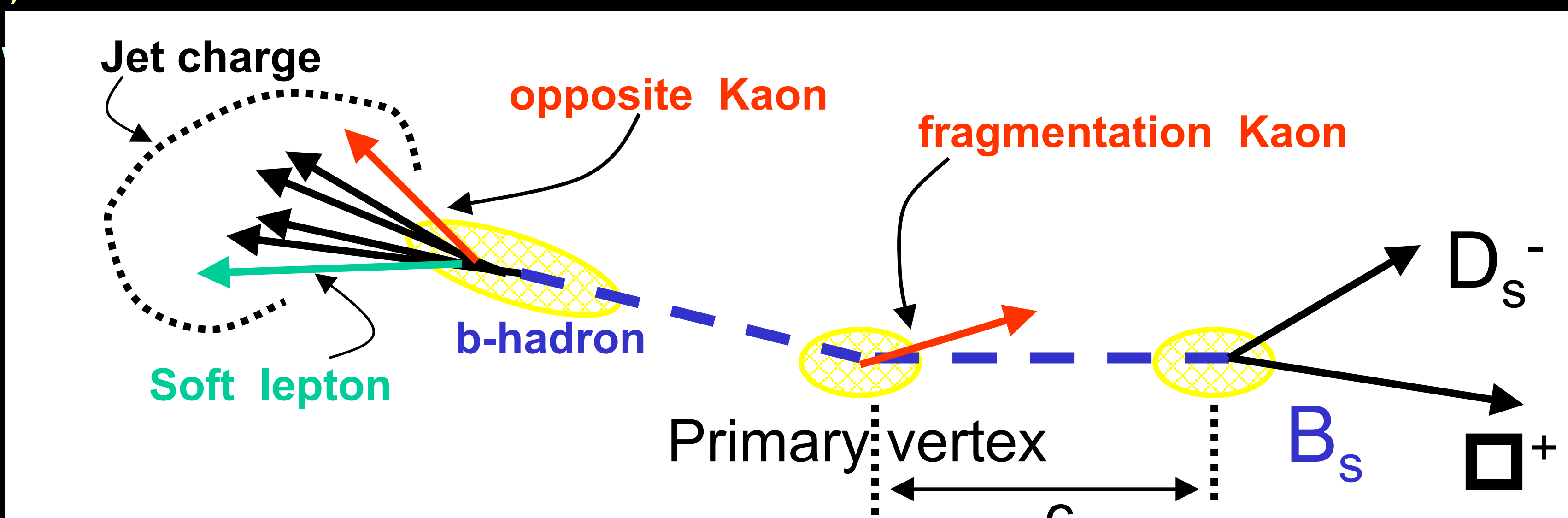
$\overline{B}^0_s$ - B^0_s mixing

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

Triggering and reconstruction of flavor-specific final states:

high c♦ resolution, low yield ➔ B_s ര D_s □(□ □) (D_s ര ♂□ ര[KK] □)

high yield & S/B, worse c♦ resol. ➔ B_s ര D_s l ■ + X (D_s ര ♂□ ര[KK] □)



B^0_s mixing: significance depends on yield, tagging,dilution and $\sigma_{c\tau}$

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

Units of sigma

εD^2 [%]	CDF	DØ
Soft muon	0.66 ± 0.09	1.6 ± 1.1
Soft electron	in progress	In progress
Jet charge	in progress	3.3 ± 1.7
Same side	1.9 ± 0.9	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

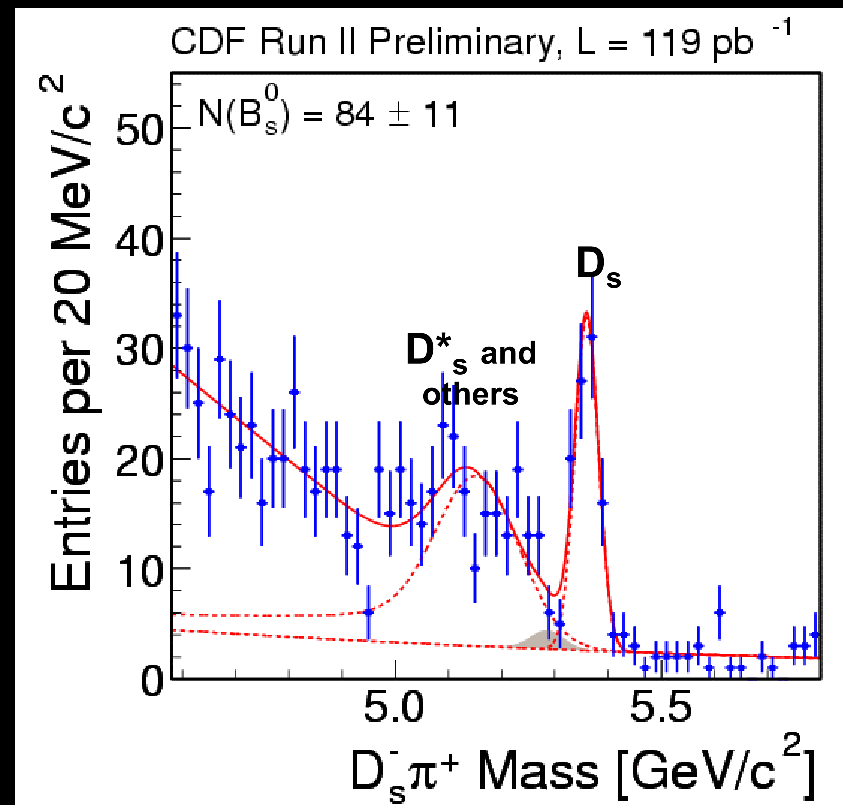
$$\epsilon = \frac{N^{right}}{N^{right} + N^{wrong} + N^{no-tag}}$$

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

Towards B^0_s mixing – hadronic side

B^0_s ꝏ D^-_s □$^+$ꝏ [↗□ -] □$^+$ꝏ[[K^+K^-] □$^-$] □$^+$ and charge conjugate

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



Low statistics: add soon B_s ꝏ D_s □□□ and D_s ꝏ K*K / K_sK / □□□

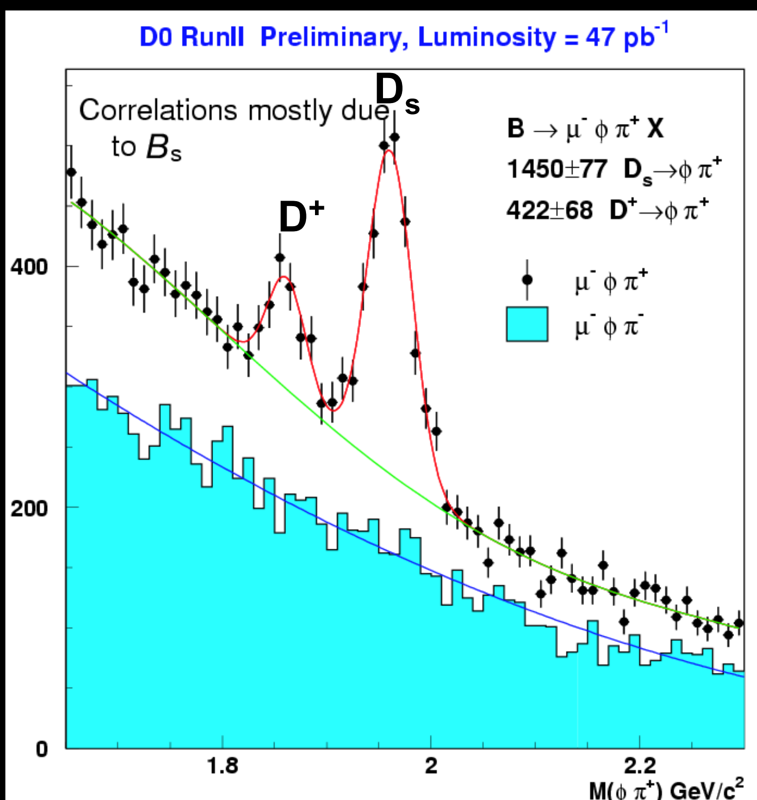
Reconstructed the signal with
Yield / lumi = 0.7 pb S/B ~ 2
measure BR(B_sꝏ D_s □)

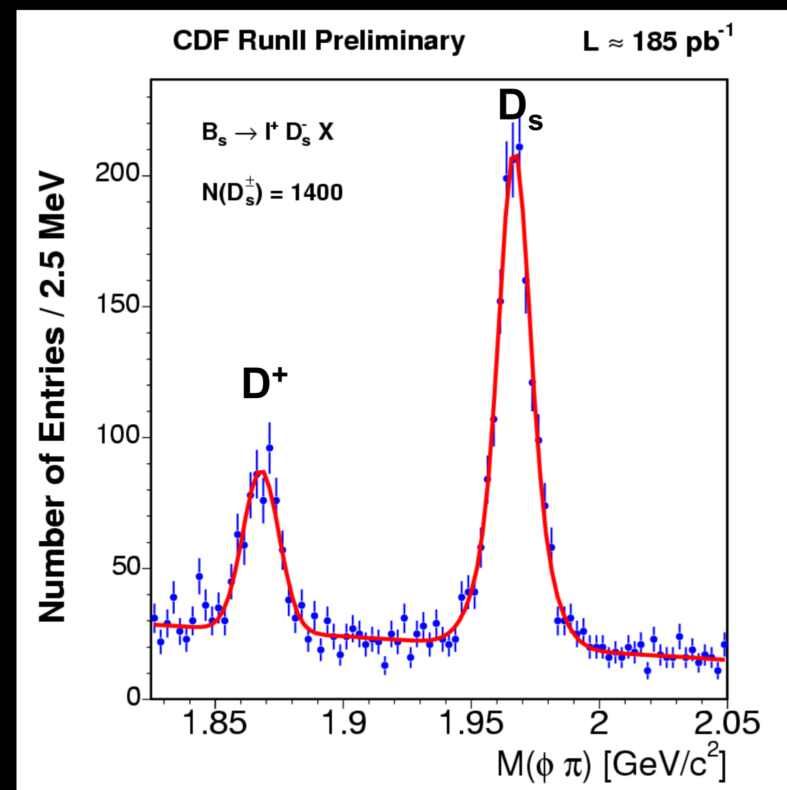
$$\frac{f_s \cdot BR(B^0_s \to D^-_s \pi^+)}{f_d \cdot BR(B^0_d \to D^- \pi^+)} = 0.35 \pm 0.05(stat) \pm 0.04(syst) \pm 0.09(BR)$$

Towards B^0_s mixing – semileptonic side

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

high yield and clean but neutrino: poor ♦c♦

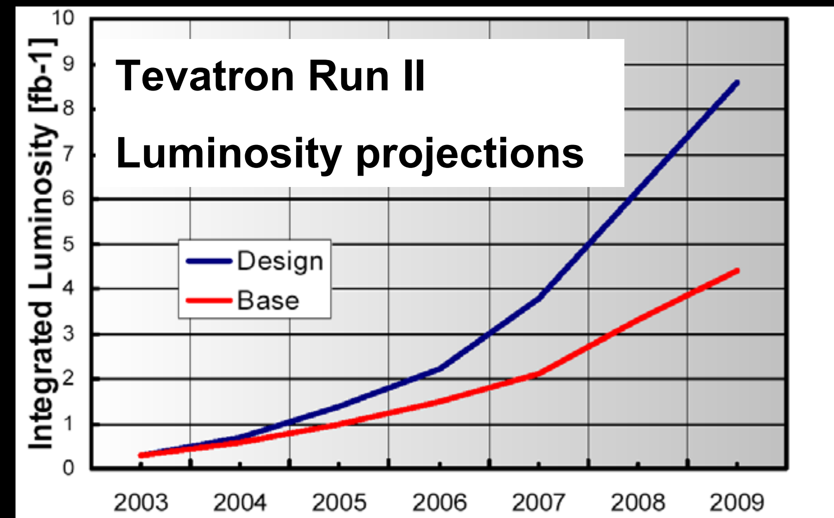




Yield / lumi ~ 31 pb just muons !

Yield / lumi ~ 7.6 pb ❍ & 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

ϵD^2 ~ 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

ϵD^2 ~ 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}

CDF Run I: 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 ❍❍, e❍. If mixing occurs LS increases. R related to the average time-integrated mixing parameter ♍:

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

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:

–
♍= 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

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

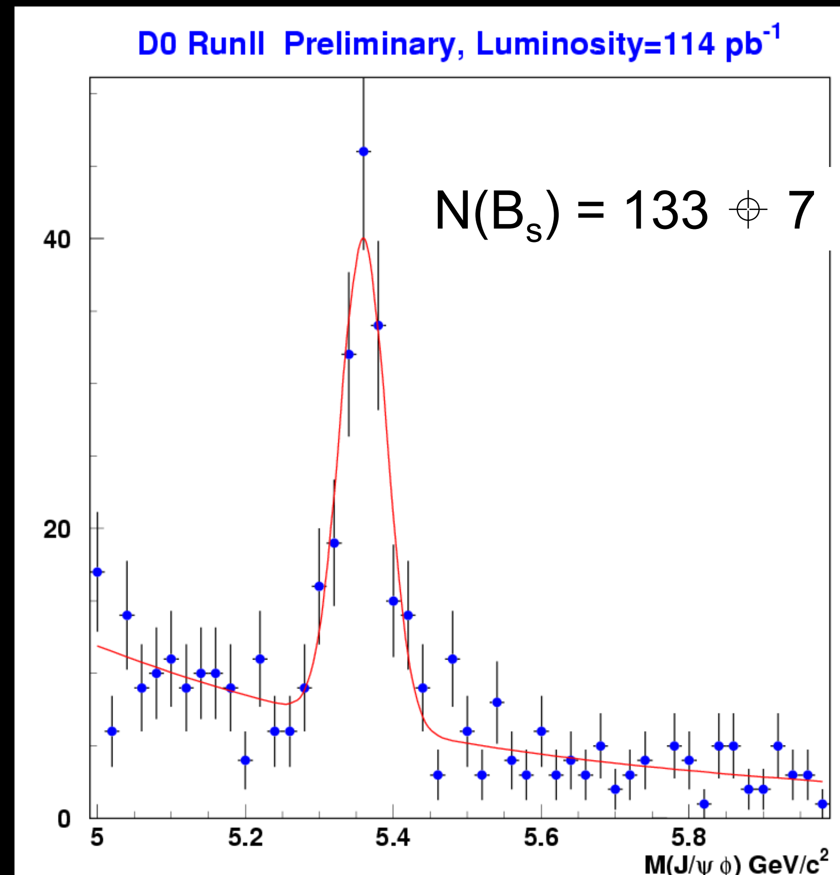
$B^0_s \to J/\psi\,\phi \to [\mu^+\mu^-]\,[K^+K^-]$ and Charge Conjugate

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.

$B \to V\,V$: 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^+ ꝏ ♐K^+ ꝏ $[K^+K^-]$ K^+ and C.C.

searching for B ✸ V V

B^0_s ꝏ ♐ ♐ and c.c. (👎☝$_s$ too!)

B^0_d ꝏ ♐ K* and c.c.

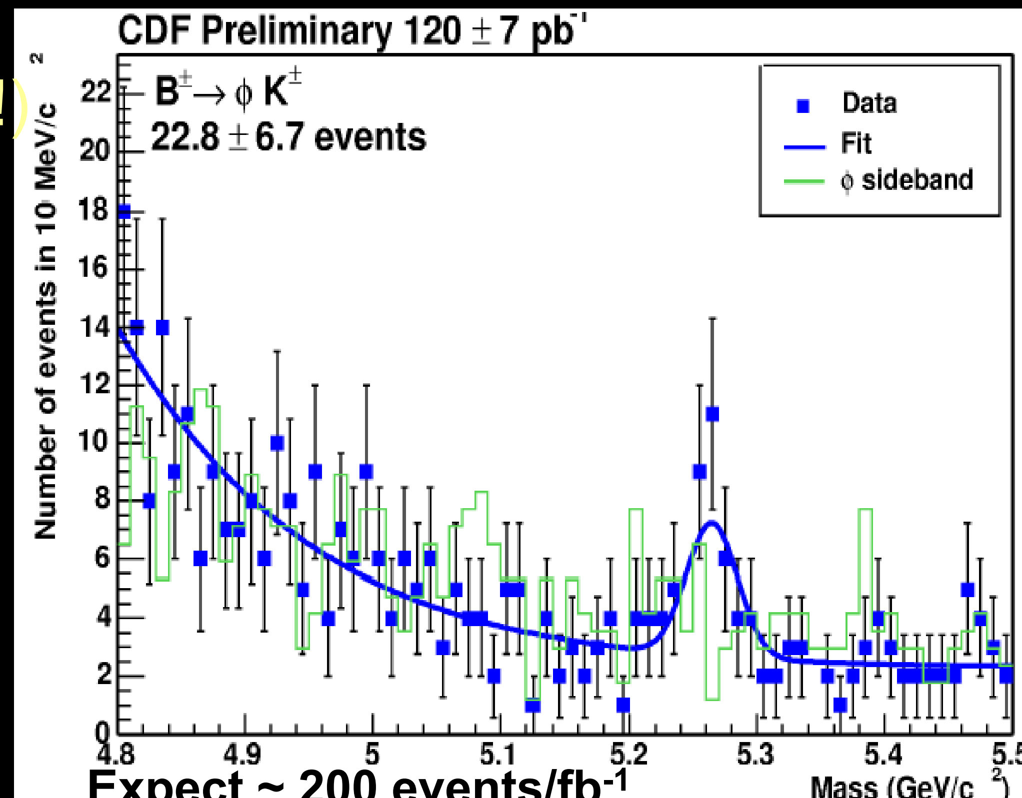
B^0_d ꝏ ♐ K^0_s and c.c.

..and for baryons

(SM expects ~10% CPV)

☹^0_b ꝏ ♐ ☹ and c.c.

☹^0_b ꝏ pK^- / p□ $^-$ and c.c.



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

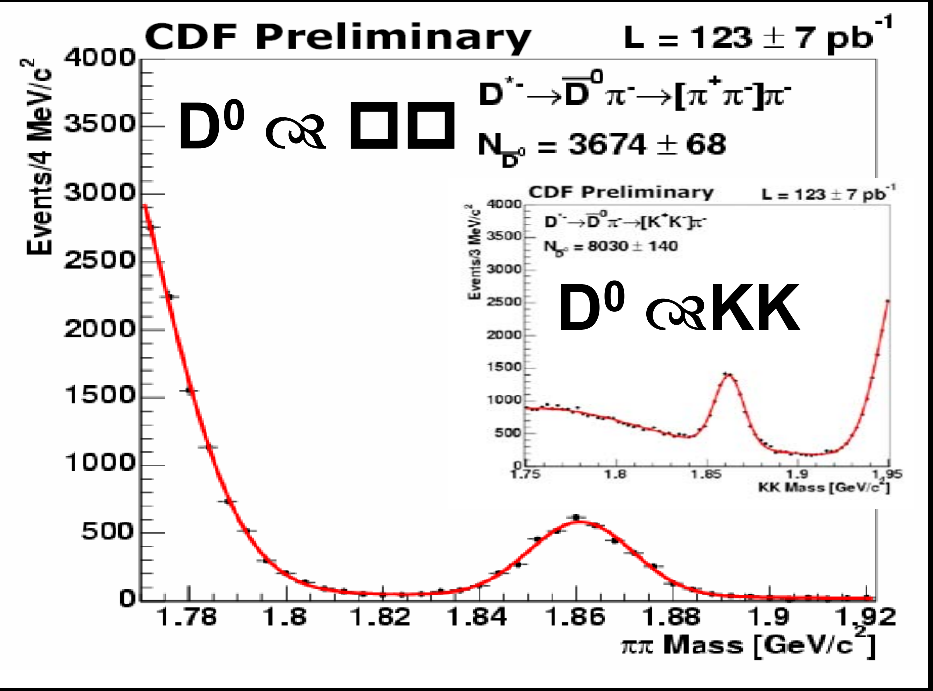
Direct A_{CP} in Cabibbo suppressed D^0

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

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

Excellent purity through D* - tag:
$D^* \to D^0\pi_S$ (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

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

PDG world average = 0.5 ± 1.6 %

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

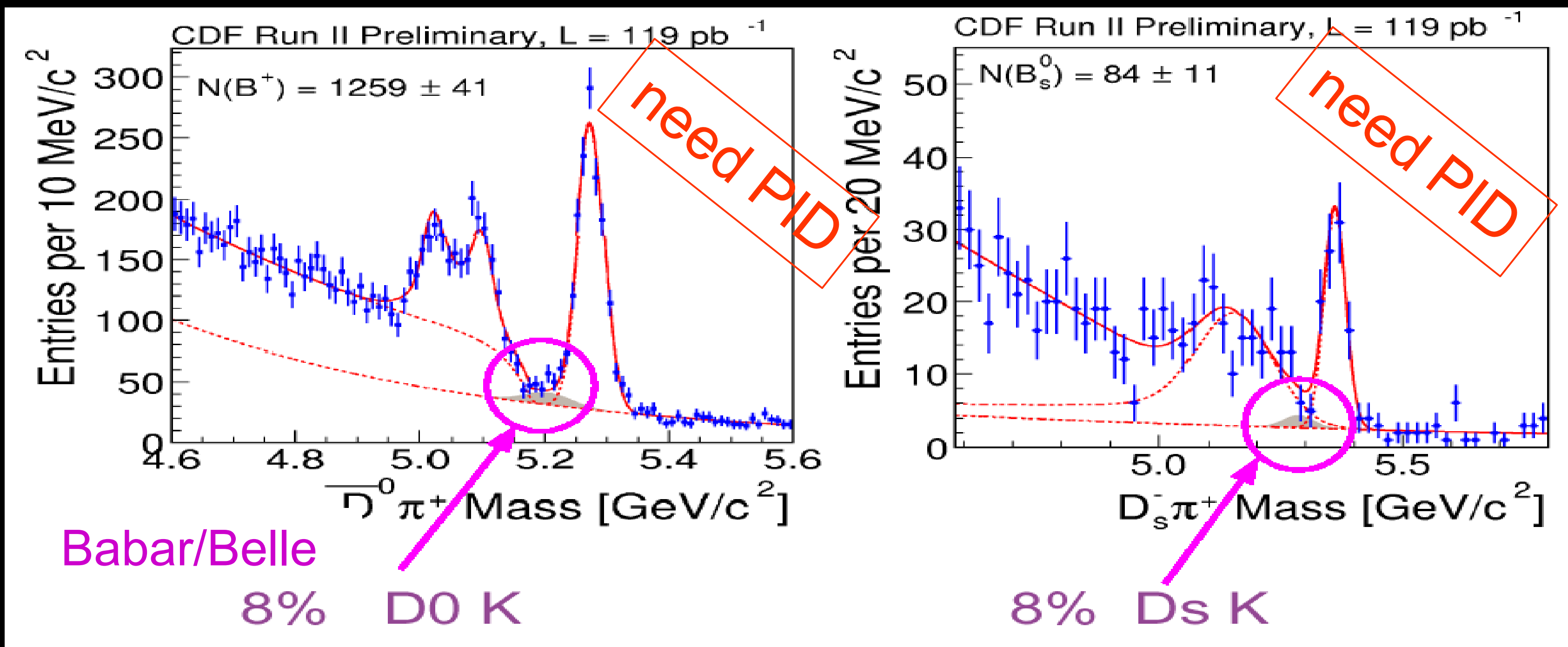
PDG world average = 2.1 ± 2.6 %

B → D K (expected yields only)

Extract γ from Cabibbo suppressed B charmed decays:

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

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



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

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

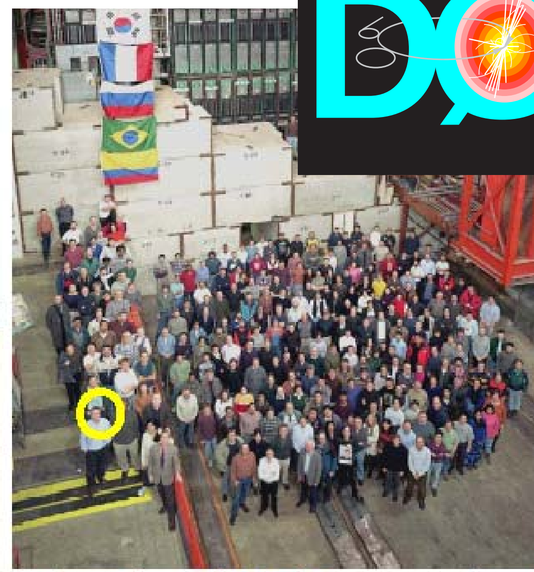
CDF: already world-class charm physics, soon exciting CPV results on B ✸ $h^+h'^-$. Less fast than expected but moving to attack B_s mixing in hadronic decays, SM favorite region accessible by the end of 2004
Many other channels in future B ✸ V V, B ✸ DK ….

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

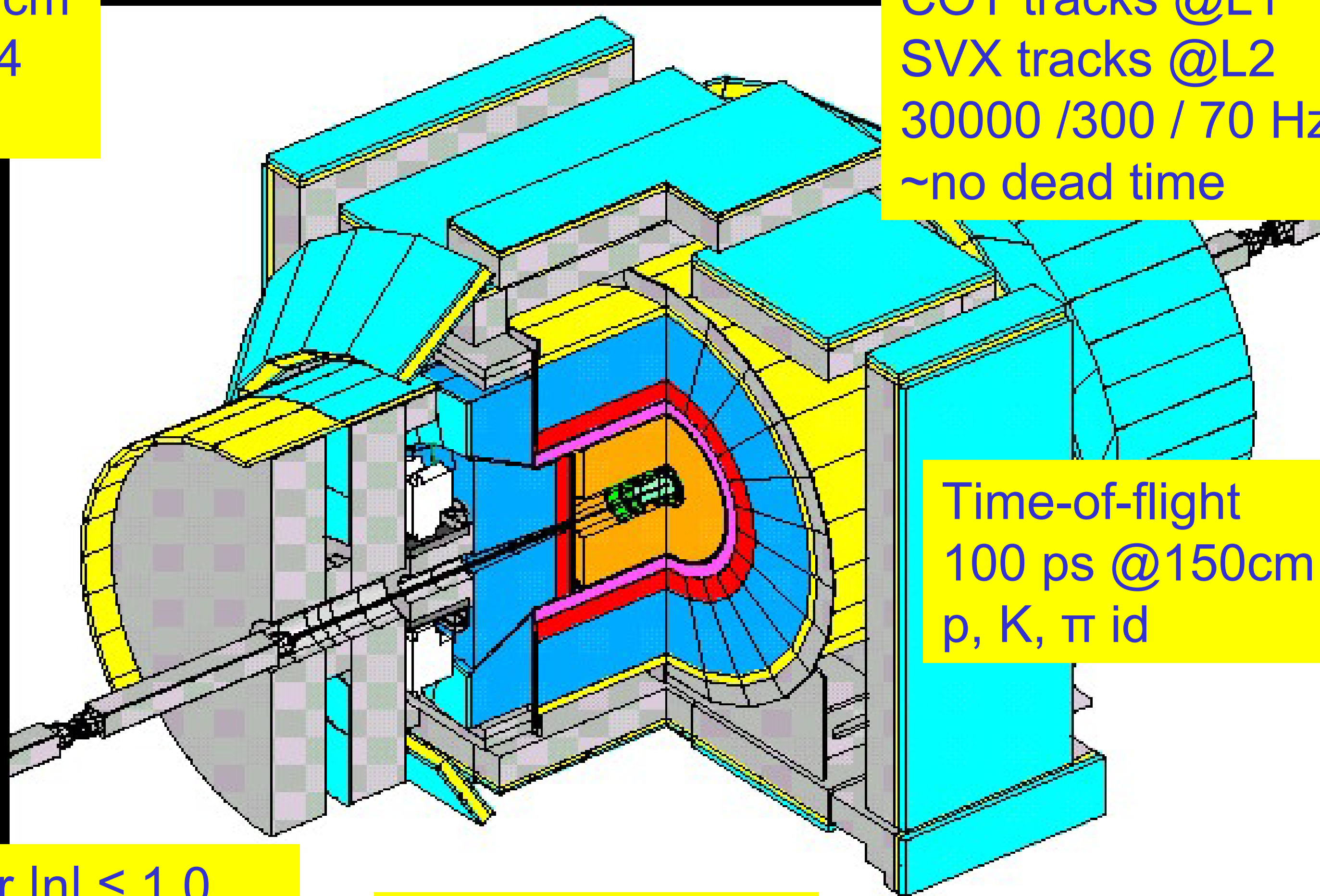
CDF Detector Upgrades

1.4 T magnetic field
Lever arm 132 cm

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

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

Some resolutions:
p_T ~ $(0.7 \oplus 0.1\ p_T)$%
J/Ψ mass ~15 MeV
EM E ~ 16%/√E
Had E ~ 100%/√E
d_0 ~ 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 ♐

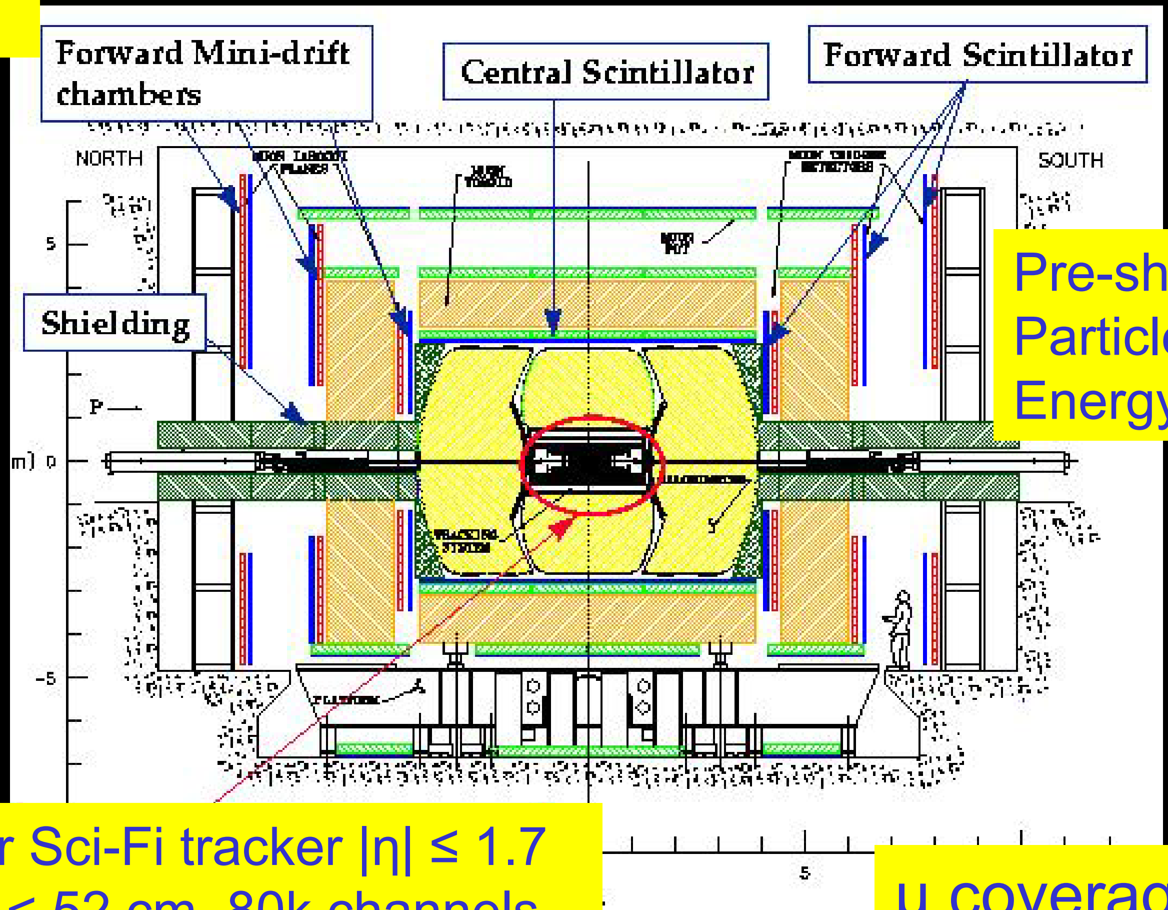
D0 Detector Upgrades

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%/√E
Had E ~ 80%/√E
$d_0 \sim 13+50/p_T$ μm
Primary vtx ~15 μm
Secondary vtx:
r-Φ ~ 40 μm
r-z ~ 80 μm

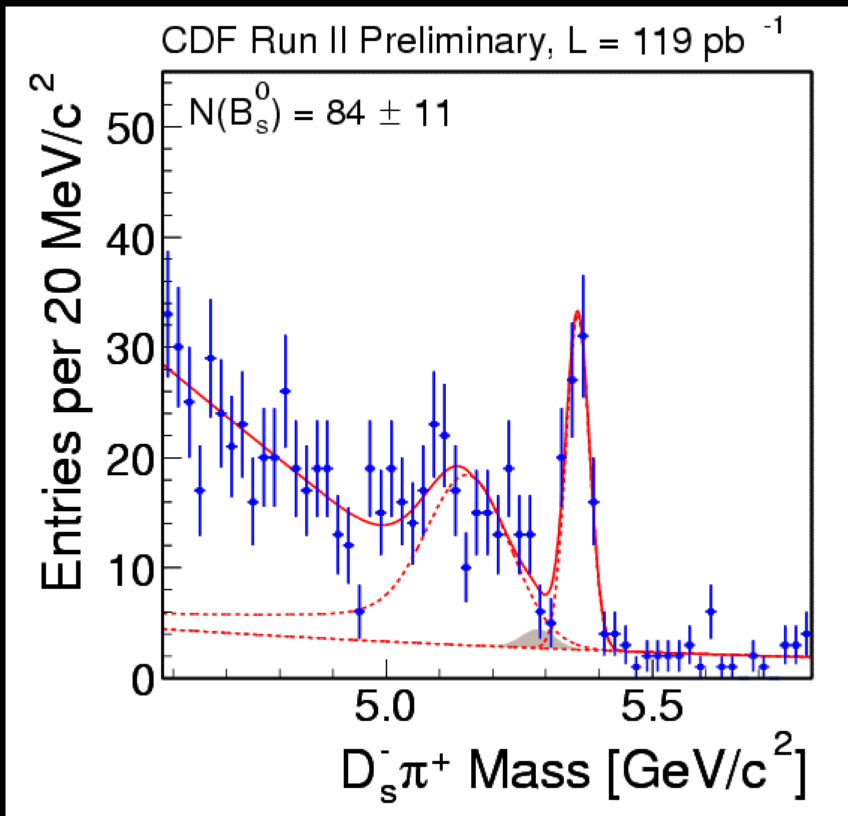


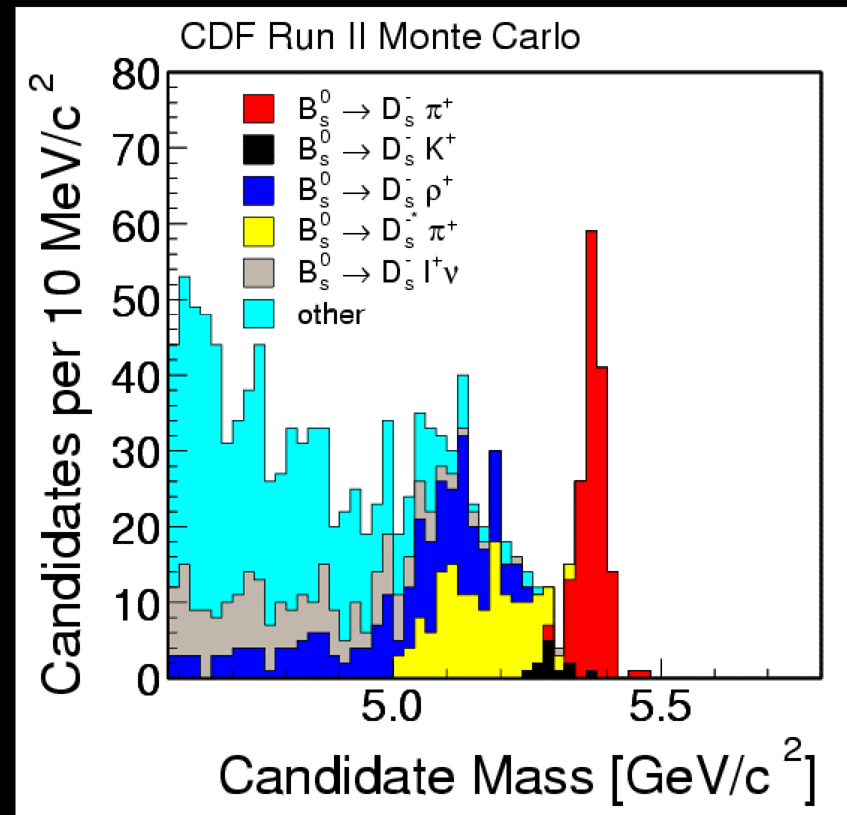
Pre-shower
Particle id
Energy

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

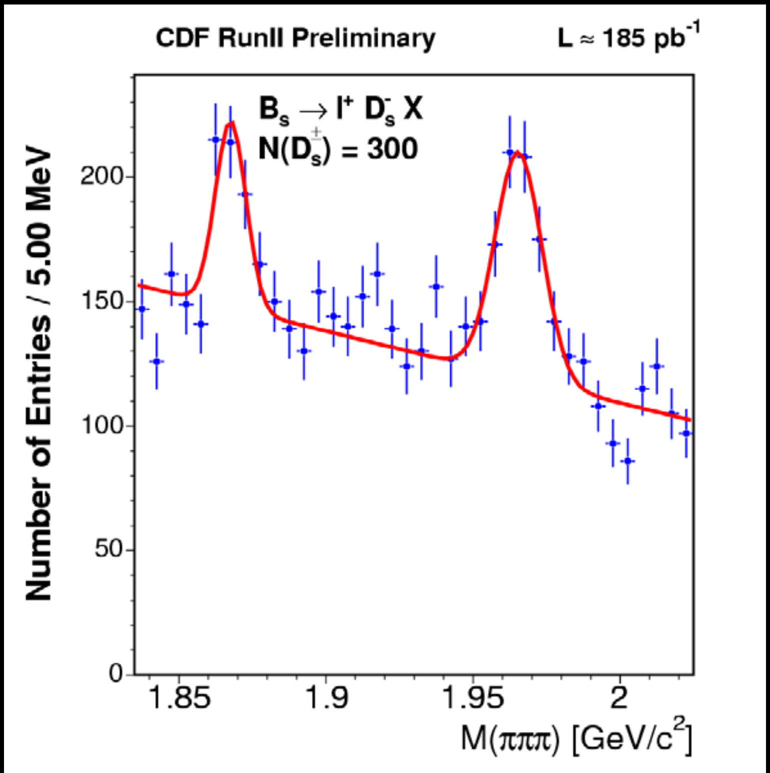
μ coverage to
$|\eta| \leq 2.0$
90% in phi

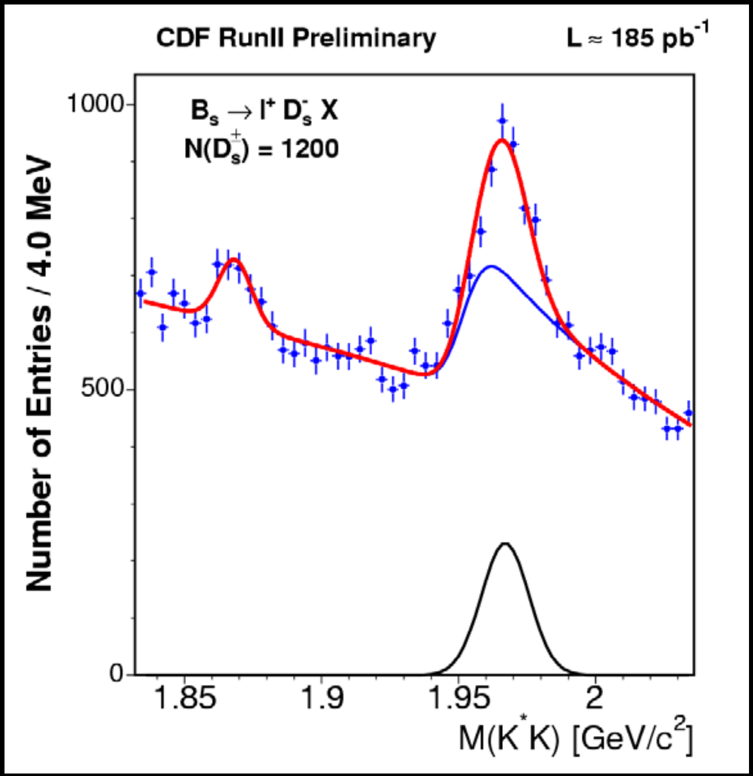
BACKUP SLIDES



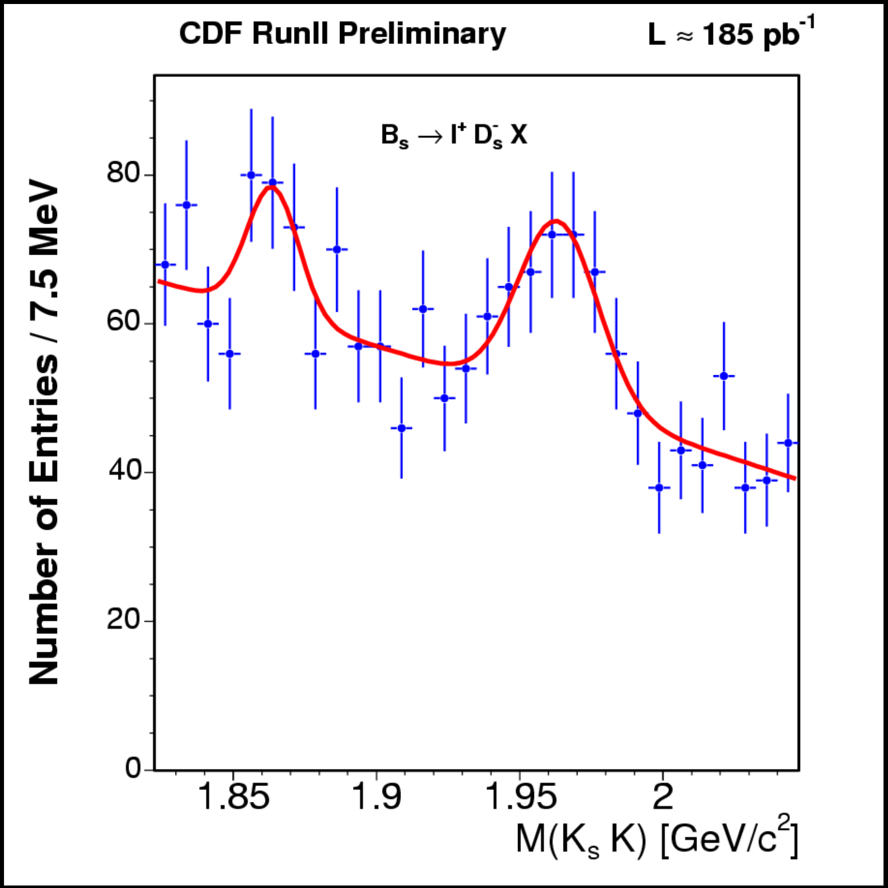


..more semileptonic B^0_s





..more semileptonic B^0_s

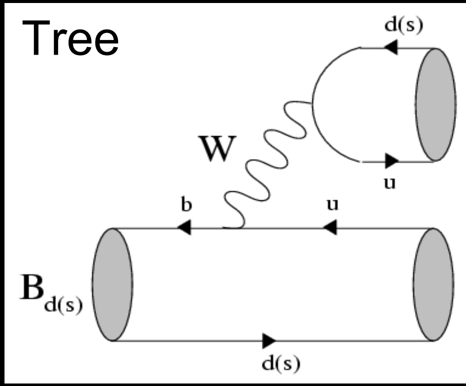


Two-body Charm-less B Decays: Physics Motivations

$B_d \to \pi^+\pi^- / K\pi$ 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 $B_d \to \pi^+\pi^-$:

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

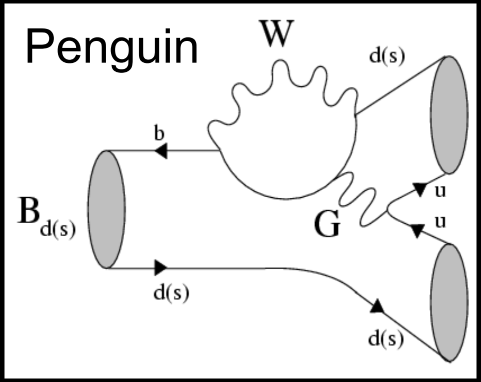


Amplitude ~ T

$B_s \to K^+K^- / K\pi$ 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 ★ s), the A_{CP} are function of the CKM angles ♌ and ♑ and of the amplitude ratio P/T (~ de$^{i❑}$)
➔ 4 equation with 4 unknowns (♌, ♑, d, ❑).
A combined fit of the 4 CP asymmetries measures ♌, ♑ and P/T ratio.

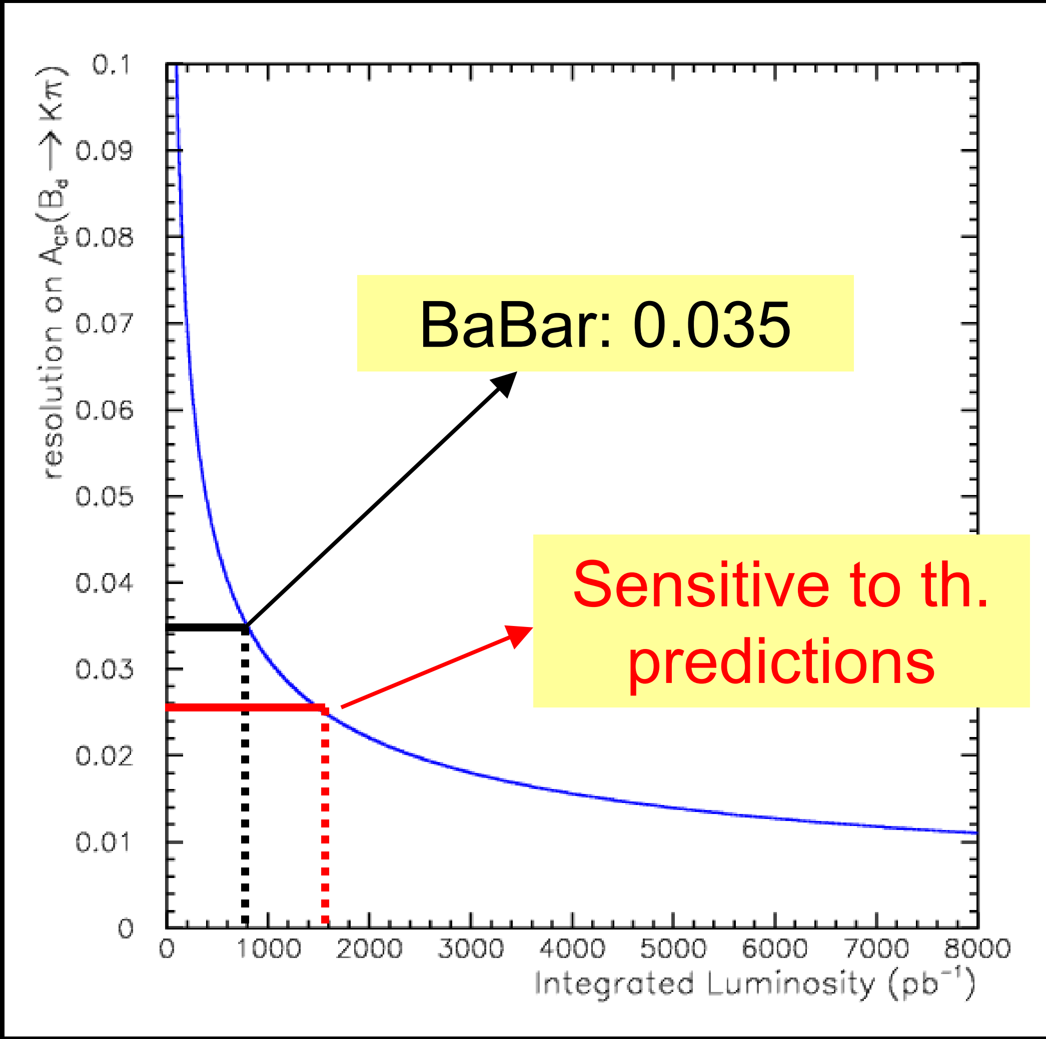
Above strategy need time-dependent analysis with tagged samples: long term goal

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

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:

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

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 = 0.5♦
- ✓ x_s = 30