Beauty and Charm Physics

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Tevatron and CDF II

First Measurements:

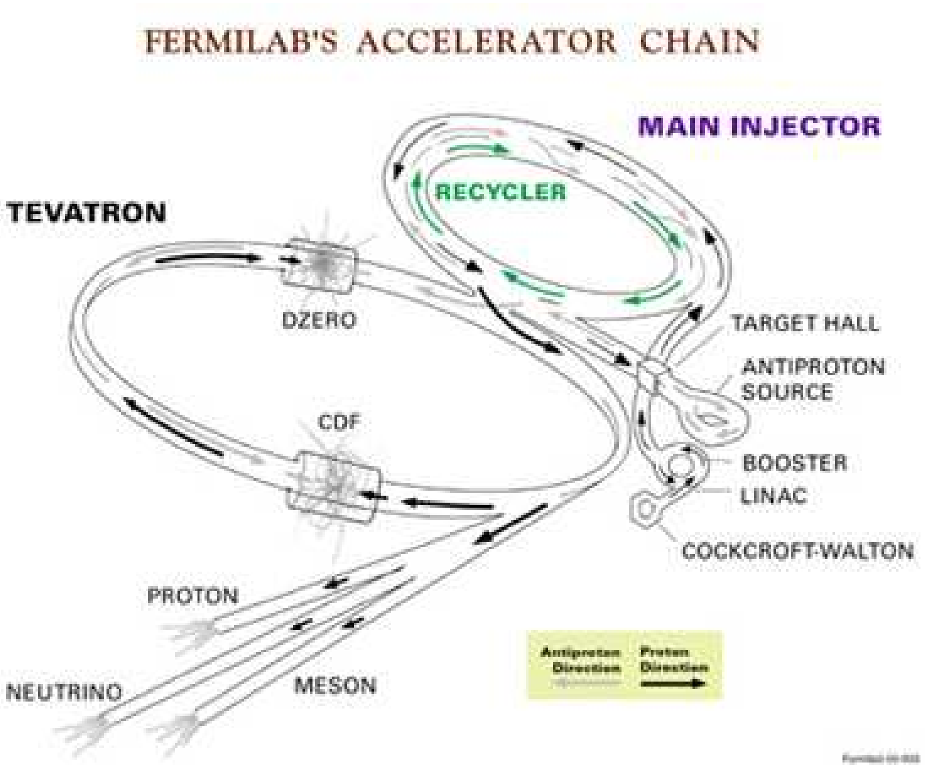
Beauty

Charm

Summary and Prospects

Particle Physics Seminar - SLAC: June 10, 2003

Tevatron Upgrade



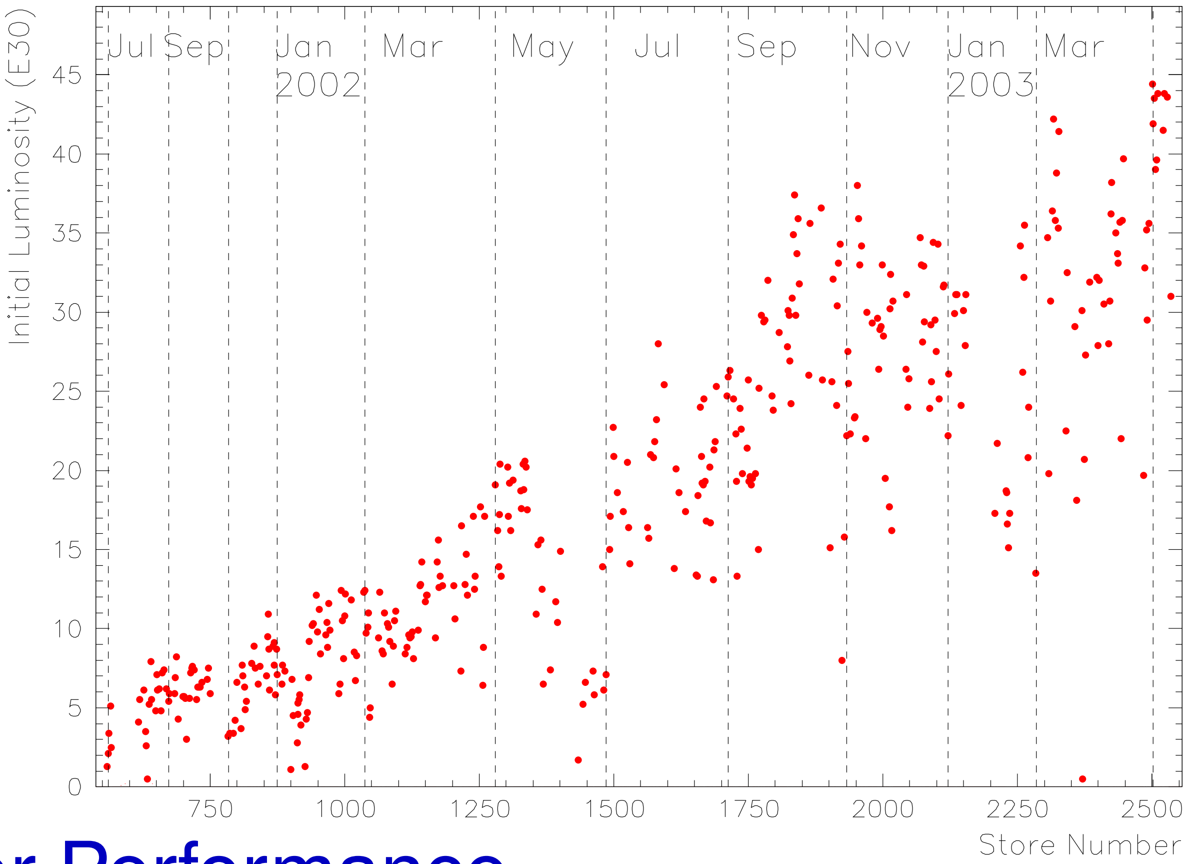
Main Injector

- New injection stage for Tevatron
- Accelerate and deliver higher intensity of protons
- More efficient $\bar{p}$ transfer
- $\bar{p}$ recycler (in progress)

Overall improvements:

- Higher Collision Rate: 396 ns (36×36 bunches) $\rightarrow$ 5-10 higher luminosity than Run I
- Higher Center-of-Mass Energy Run I – 1.8 TeV $\rightarrow$ Run II – 1.96 TeV

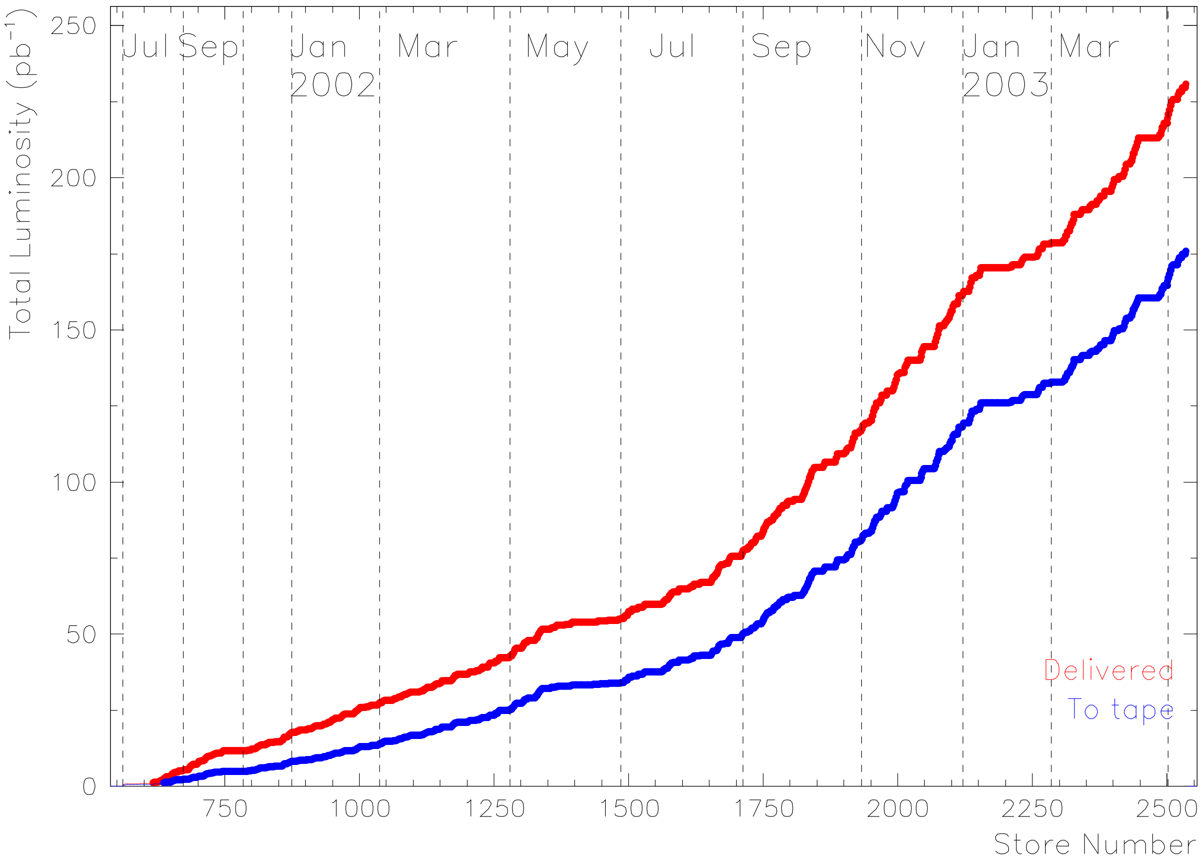
Performance: Instantaneous Luminosity



Accelerator Performance

- record: $4.4 \times 10^{31}\ cm^{-2}s^{-1}$
- below expectations by about factor of 2(4)
- improving slowly
- 4-7 pb^{-1} per week

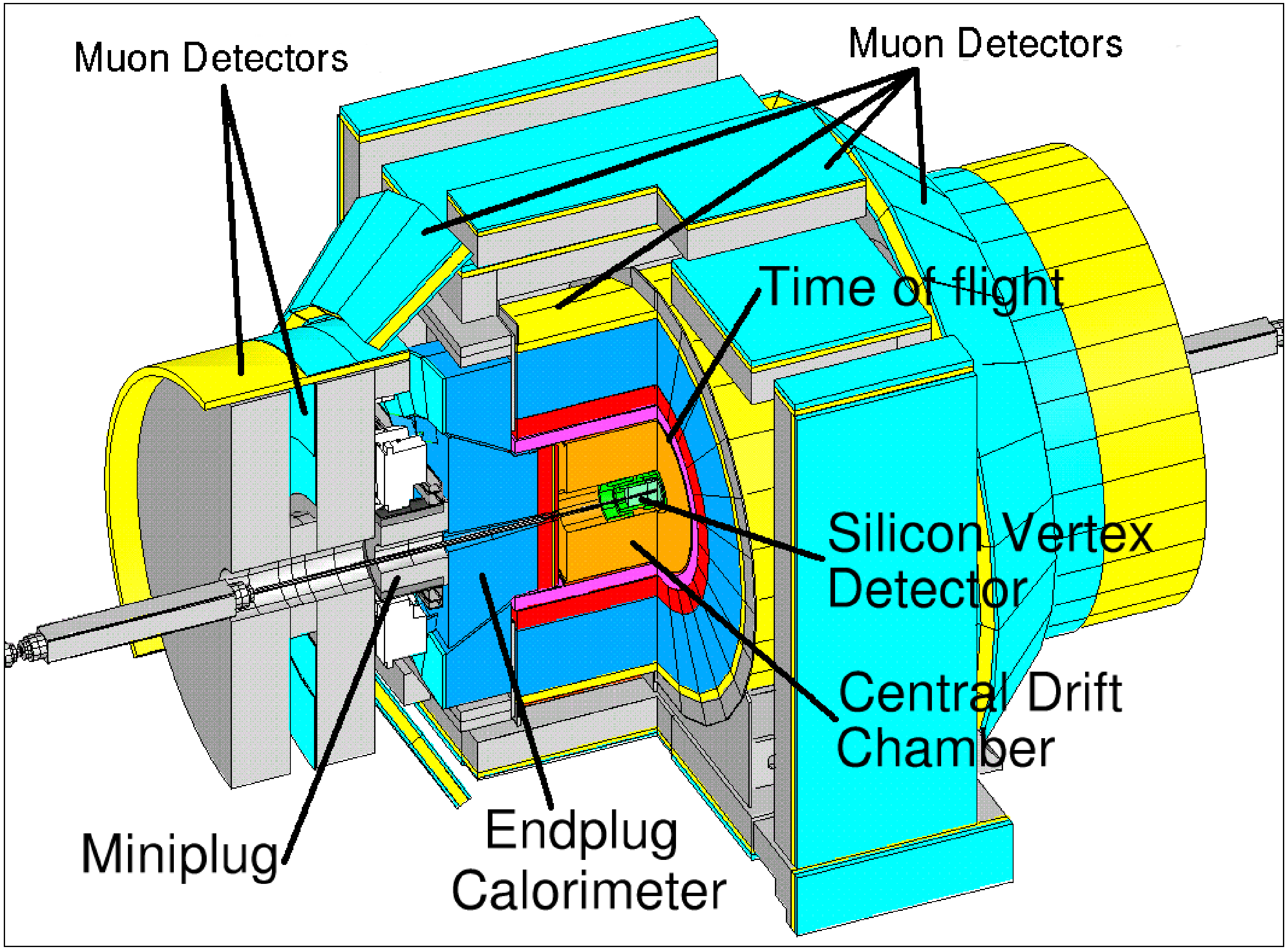
Performance: Data Taking



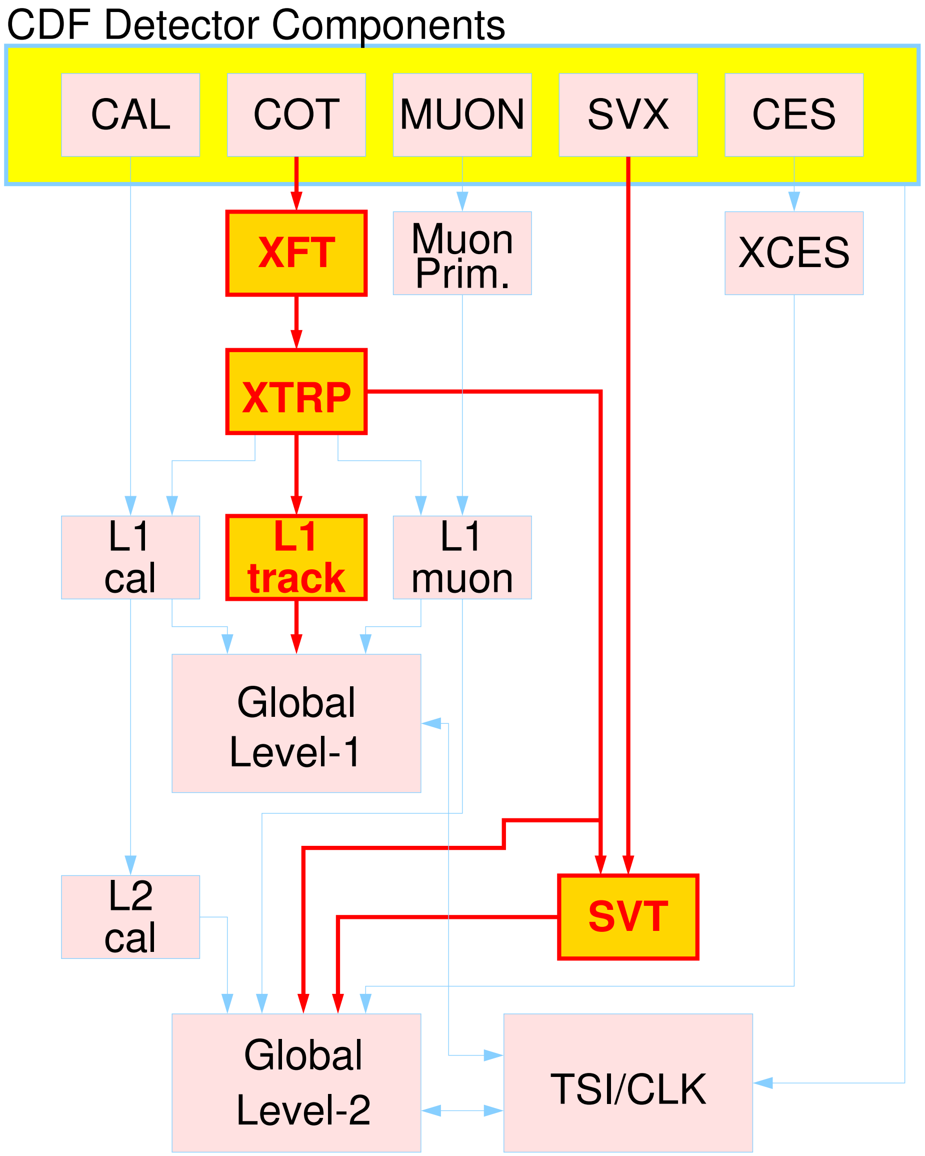
For CDF:

- Current 230 pb^{-1}, 175 pb^{-1} to tape
- For analysis 180 pb^{-1}, 130 pb^{-1} to tape
- 65 pb^{-1} with all important systems on
- 65 pb^{-1} used for most analyses shown in following

CDF II Detector



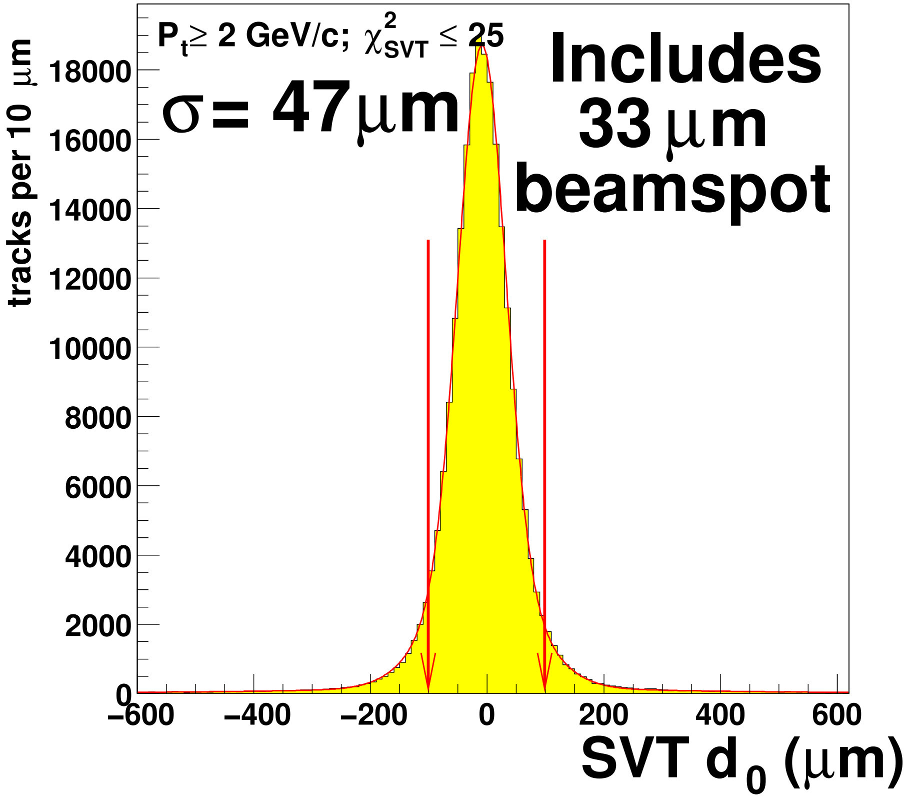
Run II Upgrades: Hadronic Trigger



Level1 track trigger: high p_T

Level2 track trigger: large d_0

Improves Run I sensitivity by 4-5 orders of magnitude



Charm signals from here

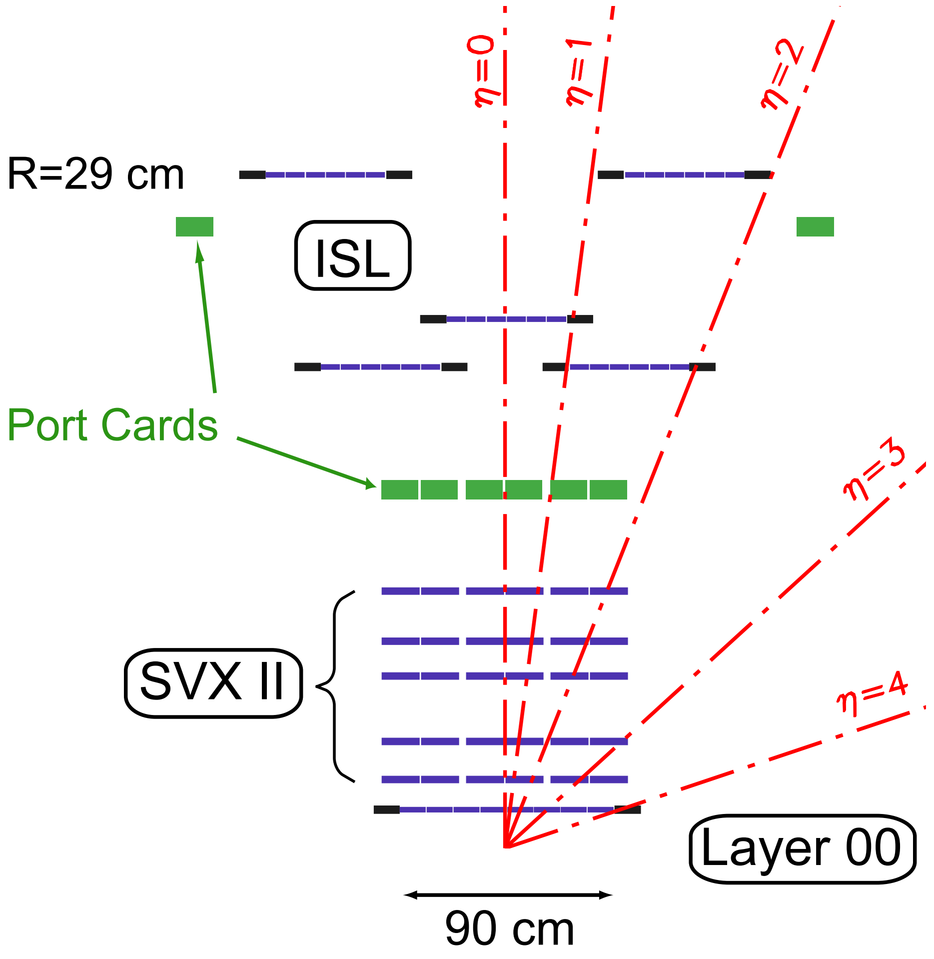
Run II Upgrades: Silicon Detector

Inner Silicon: L00 and SVX

Number of Layers	6
Number of Barrels	3
Active length	29 cm
Readout	$\phi + z/\phi + \phi'$
Inner Radius	$\approx$ 1 cm
Outer Radius	10.6 cm

Outer Silicon: ISL

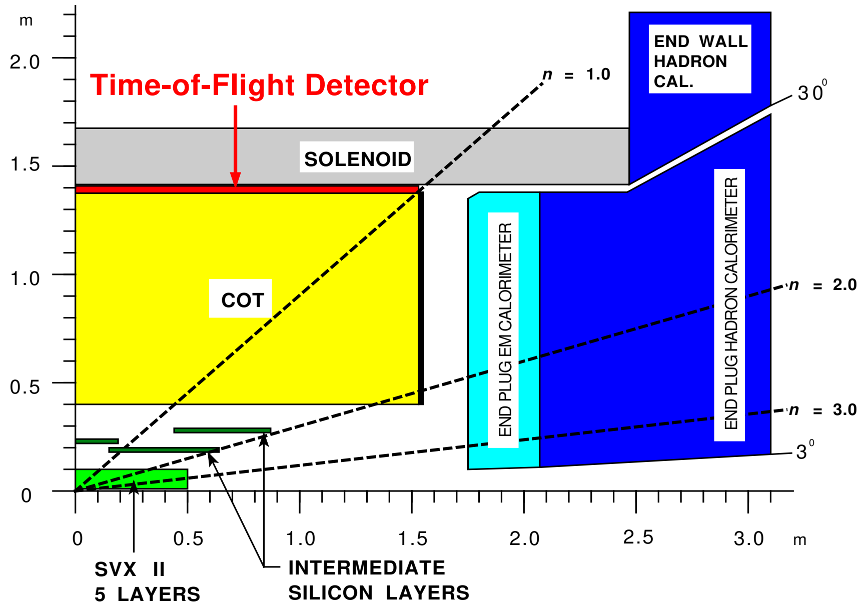
Number of Layers	1 or 2
Number of Barrels	3
Readout	$\phi + z$
Inner Radius	$\approx$ 20 cm
Outer Radius	$\approx$ 30 cm



Run II Upgrades: Time-of-Flight Detector

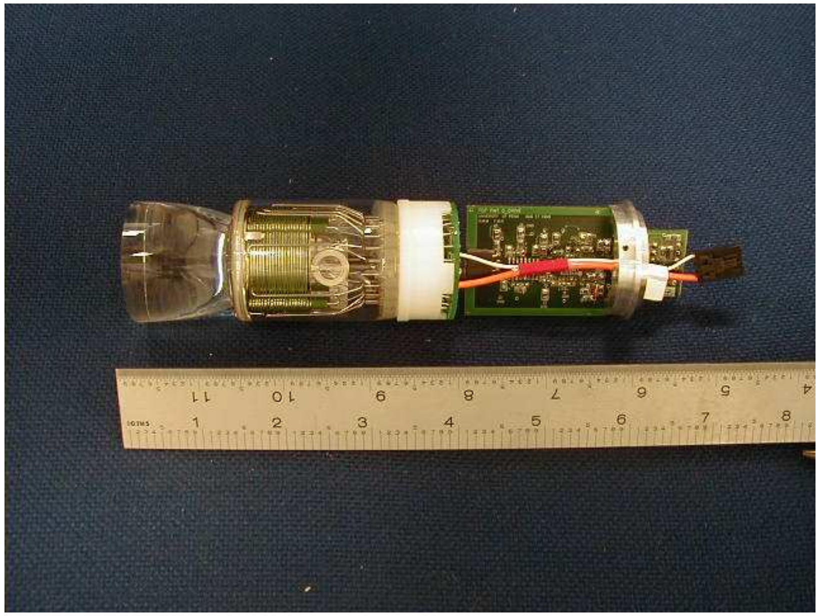
Characteristics of the system

Scintillator Bars	216 (1.7°)
Radius	140 cm
Bar Cross Section	4×4 cm^2
Bar Length Bar	300 cm
Coverage	$\|\eta\| < 1$
Scintillator Material	Bicron–408
Photomultipliers	Hamamatsu
Readout of the Bars	two–sided
Design Resolution	100 ps



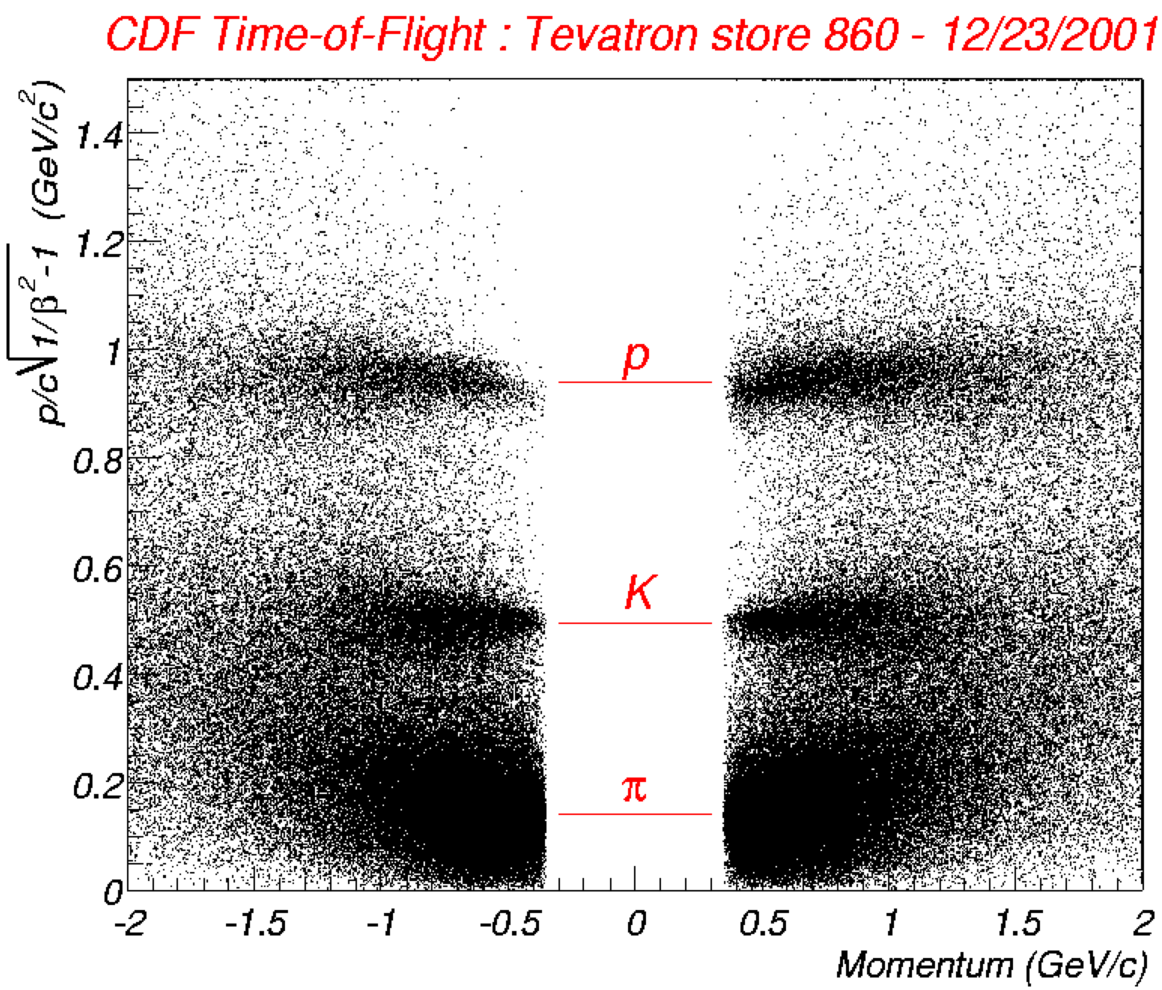
Hamamatsu photomultiplier

Type	fine mesh, R7761
Stages	19
Geometry	1.5 inch diam.



PMT operates in 1.4 T B field

Time of Flight Performance



Detector functions very well

Occupancy is somewhat higher than expected

Work on improving reconstruction ongoing

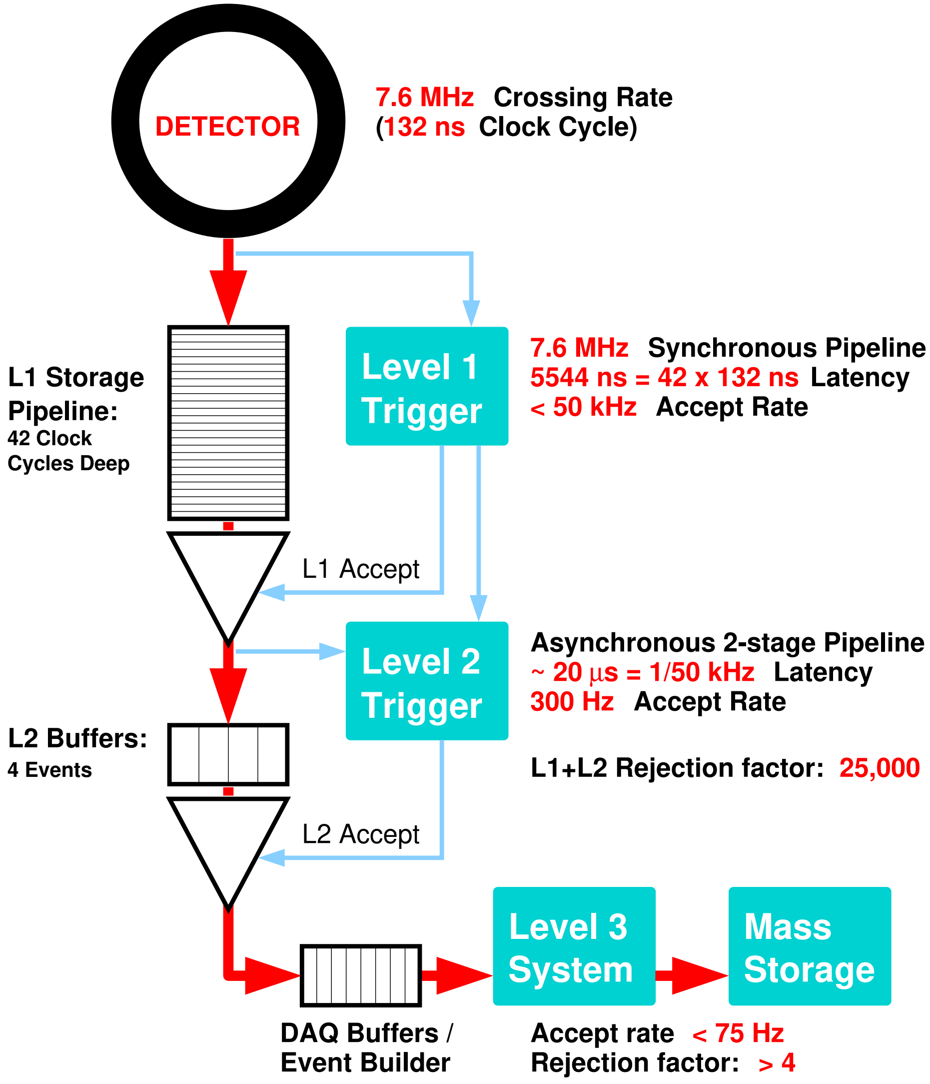
Run II Upgrades: DAQ System

Event Building in Run II

ATM switch	32 ports
input rate [kHz]	0.3 (1)
event size [kB]	150 (250)
total flow [MB/s]	44 (244)

Level-3 Processing for Run II

PC farm (Linux)	250 PCs
input rate [kHz]	0.3 (1)
output rate [Hz]	30 (75)
rejection rate	≈ 10
logging flow [MB/s]	4.4 (18)



Flagship Measurements planned for CDF Run II

Determination of $|V_{td}/V_{ts}|$:

from B_s-$\overline{B}_s$ mixing: $|V_{td}/V_{ts}| = f(x_s/x_d)$

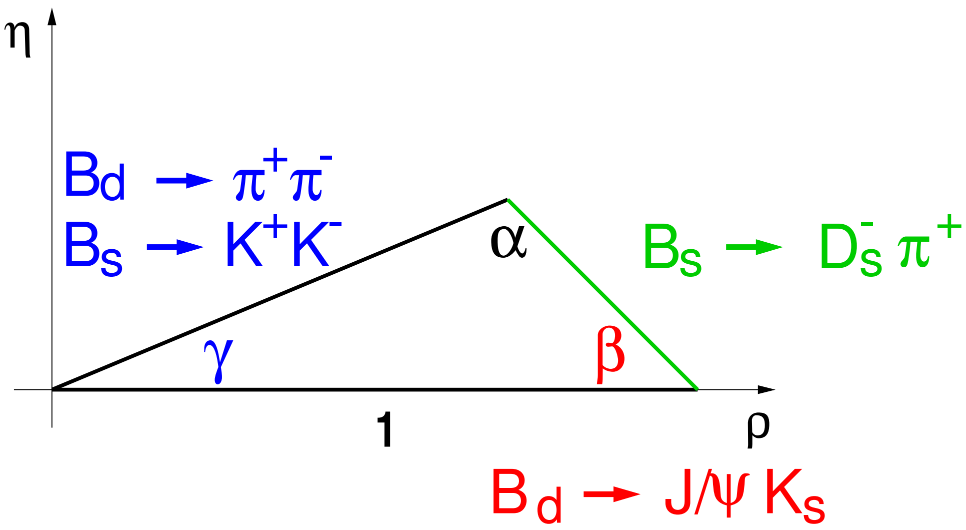
CP violation parameter γ

use: $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$

CP violation parameter $\sin 2\beta$

measured in channel: $B^0 \to J/\psi K^0_S$

B_s physics unique at Tevatron



Clean relation with mixing parameter

$$\frac{\Delta m_s}{\Delta\Gamma} \simeq -\frac{2}{3\pi}\frac{m_t^2}{m_b^2}\left(1-\frac{8}{3}\frac{m_c^2}{m_b^2}\right)^{-1} h\left(\frac{m_t^2}{M_W^2}\right)$$

Test new *CP* violating physics

Measurement at CDF

- measure *CP* lifetime *CP* mixed:
  $B_s \to \nu\ell^+D_s^-X$, $B_s \to D_s^-\pi^+$
- compare to *CP* even modes:
  $B_s \to J/\psi\phi$, $B_s \to D_s^+D_s^-$

More Complete List of Measurements

Measurements with more than 50 pb^{-1}

- high statistics charm physics: rare decays, *CPV*, mixing
- heavy flavor cross sections
- B_s and Λ_b masses and lifetimes
- B_s and b baryon relative branching ratios
- $B \to hh'$ using particle id
- semileptonic decays
- B^0 mixing

Measurements with more than 200 pb^{-1}

- first B_s mixing limit/measurement
- *CPV* in $J/\psi K_S$ and $J/\psi\phi$
- *CPV* in $B \to hh'$
- B_c and Ξ_b search
- rare decays: $B_s \to \mu\mu$, $B^+ \to \mu\mu K^+$

Practical Organization of Analysis - Trigger

$J/\psi \to \mu^+\mu^-$ trigger

- ☞ 2 muons: $p_T > 1.5$ GeV (Run I: 2 GeV)
- ☞ momentum scale - masses, vertexing - lifetimes
- ☞ charmonium, rare decays: $B_s \to \mu^+\mu^-$
- ☞ $\sin 2\beta$: $B^0 \to J/\psi K_S$

Lepton (e, μ) and displaced track trigger

- ☞ lepton: $p_T > 4$ GeV (Run I: 8 GeV)
  + track: $p_T > 2$ GeV, $d_0 > 120\ \mu$m
- ☞ semileptonic decays ($B \to \nu\ell X$, $B \to \nu\ell DX$)
- ☞ precision lifetimes, tagging, ..

Displaced two track trigger

- ☞ 2 tracks: $p_T > 2$ GeV, $d_0 > 120(100)\ \mu$m, $\sum p_T > 5.5$ GeV
- ☞ charm high statistics physics
- ☞ two/multi body hadronic B decays, $B \to hh'$, $B_s \to D_s\pi$, ..

Heavy Quark Production

Cross Sections
Differential Cross Sections

Bottom/Charm Production - Overview

Compare $\sigma(b\bar{b})$:

$\Upsilon(4S)$	$\approx$ 1 nb (only B^0, B^+)
Z^0	$\approx$ 7 nb
$p\bar{p}$	$\approx$ 100 μb

Light quark σ(inelastic) 10^3 larger

b-hadron triggers is crucial

Run I: $B^+ \to J/\psi K^+$ ($p_T > 6$ GeV, $|Y| < 1$)

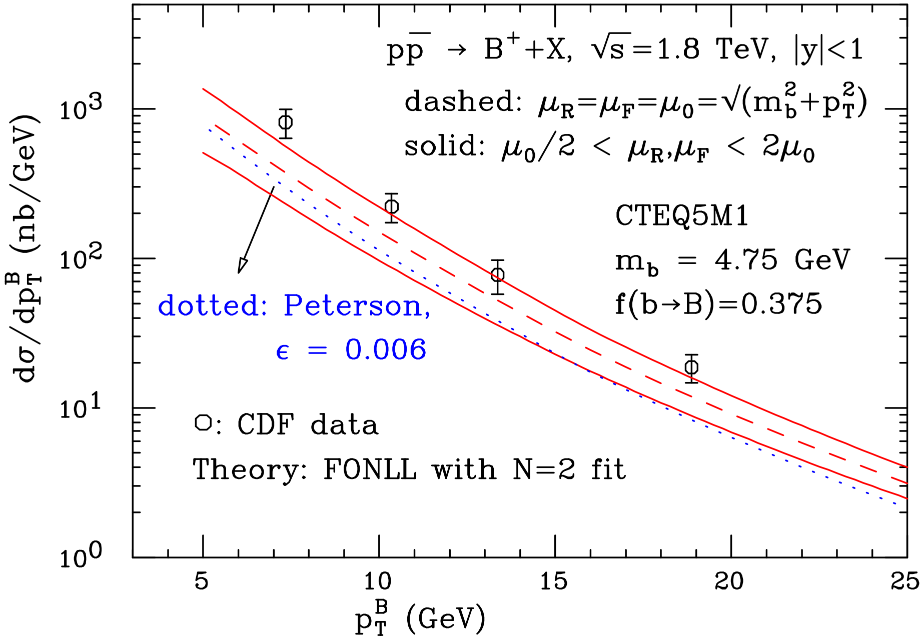
- single inclusive (B^+): $3.6 \pm 0.6\ \mu$b
- Peterson fragmentation: $\varepsilon_b = 0.006 \pm 0.002$
- $\sigma_{\text{data}}/\sigma_{\text{theory}} = 2.9$

Run II: $D^+ \to K\pi\pi$ ($p_T > 6$ GeV, $|Y| < 1$)

- single inclusive (D^+): $4.3 \pm 0.7\ \mu$b

Run II: $D^0 \to K\pi$ ($p_T > 6$ GeV, $|Y| < 1$)

- single inclusive (D^0): $9.3 \pm 1.1\ \mu$b



Updated theory bottom production

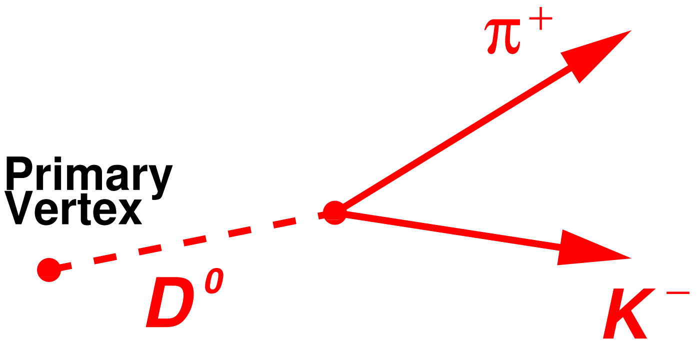
- Peterson fragm. tuned for LL
- different parameter: $\varepsilon_b = 0.002$
- better even different fragm.
- theory update FONLL Cacciari, Nason
- $\sigma_{\text{data}}/\sigma_{\text{theory}} = 1.7$
- data do not contradict theory

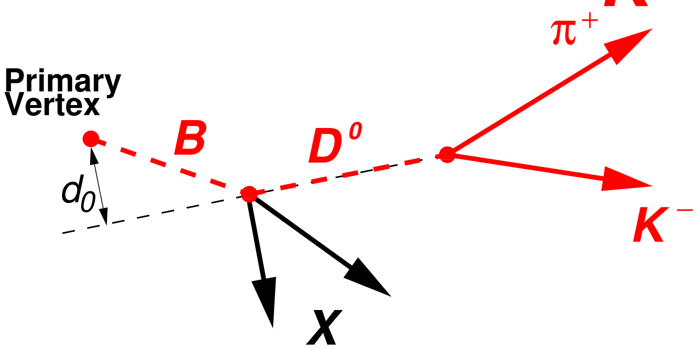
Prompt versus Secondary Charm

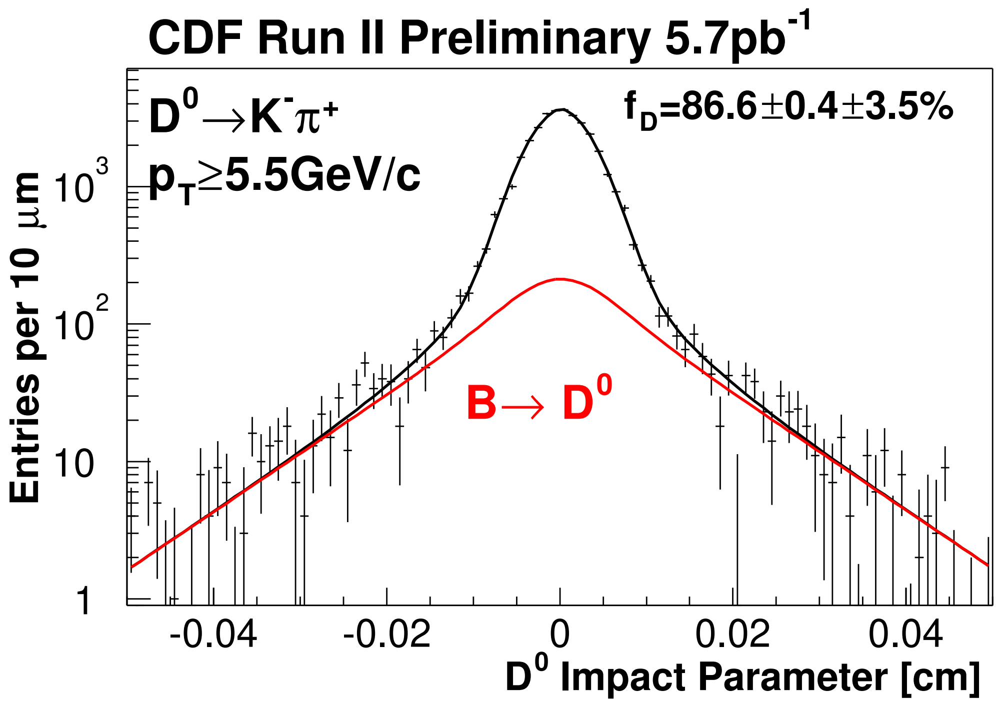
distinguish prompt/secondary

discriminating variable

- meson impact parameter







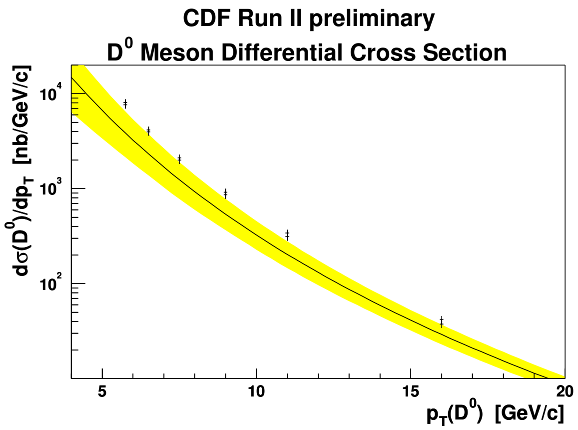
most charm is prompt

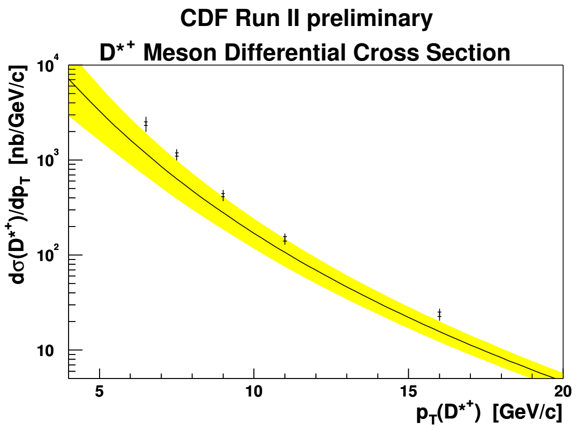
d_0 resolution function

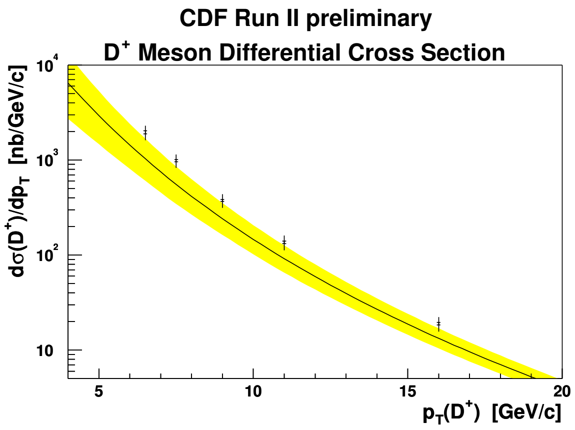
- from $K^0_S \to \pi^+\pi^-$ decays

$$f_D(D^0) = 86.6 \pm 0.4 \pm 3.5\%$$
$$f_D(D^{*+}) = 88.1 \pm 1.1 \pm 3.9\%$$
$$f_D(D^+) = 89.1 \pm 0.4 \pm 2.8\%$$
$$f_D(D_s^+) = 77.3 \pm 3.8 \pm 2.1\%$$

Charm Cross Section Measurements





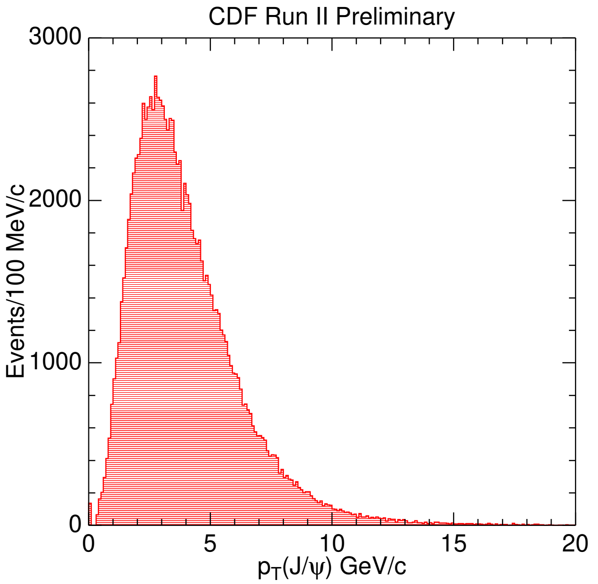


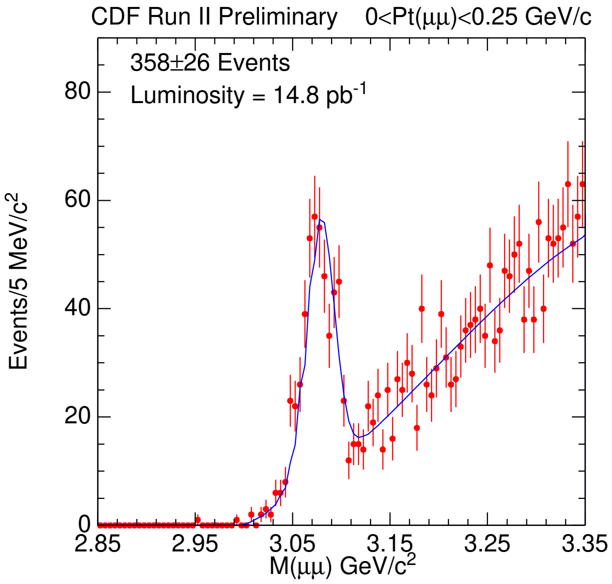
Preliminary Run II measurements

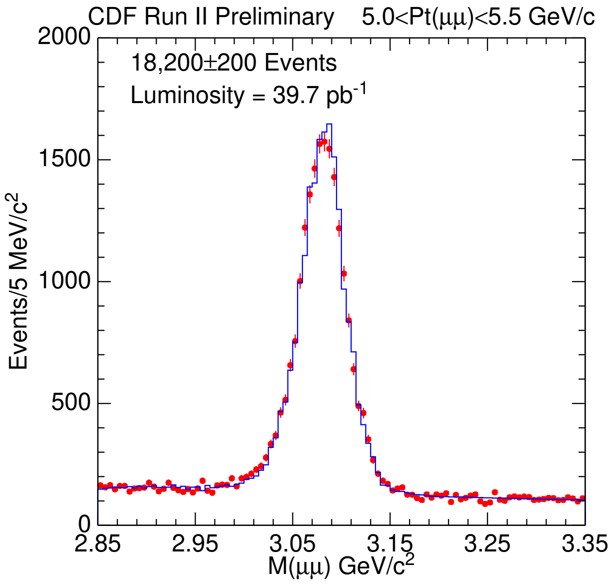
$$\sigma(D^0, p_T > 5.5\ \mathrm{GeV}) = 13.3 \pm 0.2 \pm 1.5\ \mu\mathrm{b}$$
$$\sigma(D^{*+}, p_T > 6.0\ \mathrm{GeV}) = 5.2 \pm 0.1 \pm 0.8\ \mu\mathrm{b}$$
$$\sigma(D^+, p_T > 6.0\ \mathrm{GeV}) = 4.3 \pm 0.1 \pm 0.7\ \mu\mathrm{b}$$
$$\sigma(D_s^+, p_T > 8.0\ \mathrm{GeV}) = 0.75 \pm 0.05 \pm 0.22\ \mu\mathrm{b}$$

all measurements refer to rapidity range $|Y| < 1$

J/ψ Cross Section Measurements

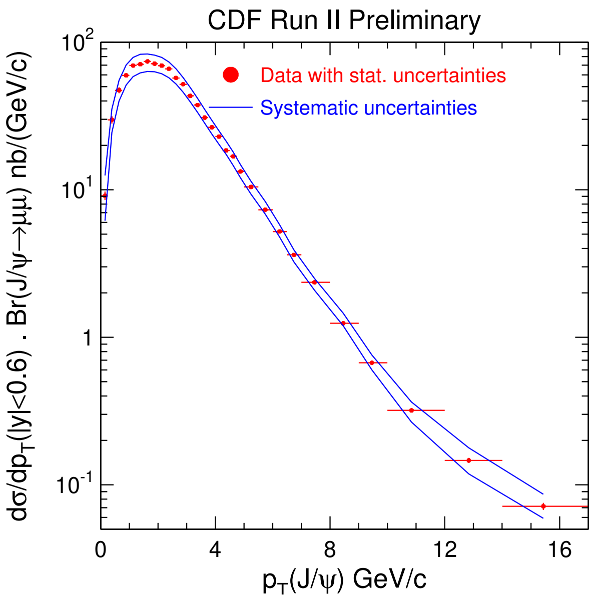






Use sample of 300k $J/\psi \to \mu^+\mu^-$

- $|y(J/\psi)| < 0.6$ as Run I but
- $p_T(\mu) > 1.5$ GeV $\to p_T(J/\psi) \geq 0$ GeV
- first time at hadron collider
- $\sigma(p_T > 0, |\eta| < 0.6) =$
  $240 \pm 1(stat) \pm 35/28(syst)$



Momentum Calibration

Mass Differences
Mass Measurements

Momentum Scale Calibration

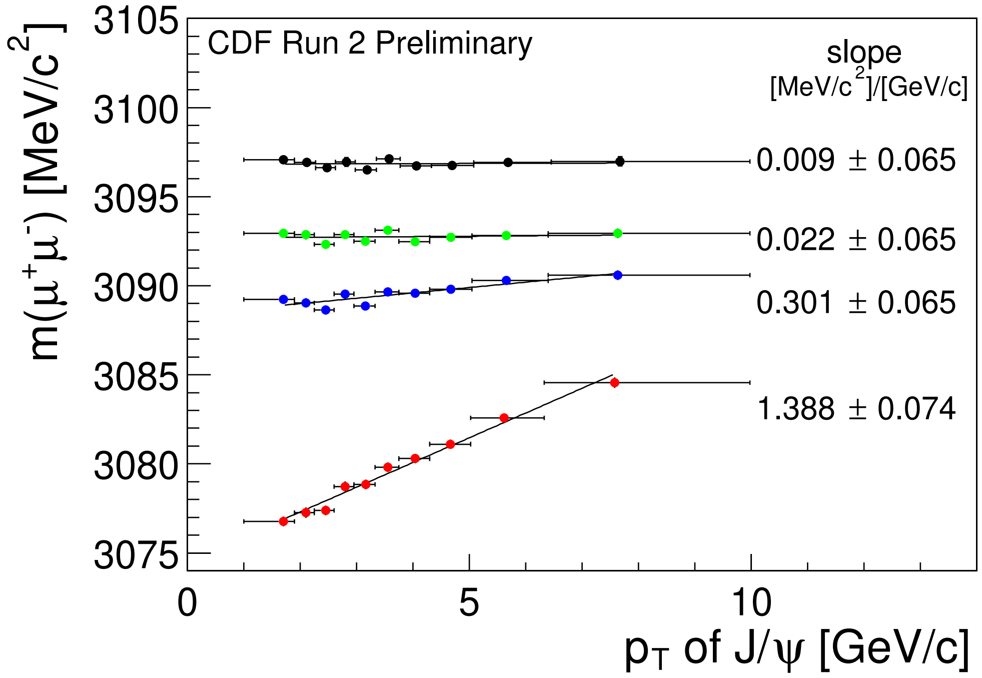
Momentum mostly from COT

- $\Delta p_T/p_T = (0.7 \oplus 0.1 \cdot p_T)\%$

Calibration of the tracking

- use: $J/\psi \to \mu^+\mu^-$ (500k)
- measure material in detector
- measure momentum scale
  $\to$ adjust B field
- new method invented for Run II
- more sophisticated than Run I
- more material than in Run I

Building up tools step by step



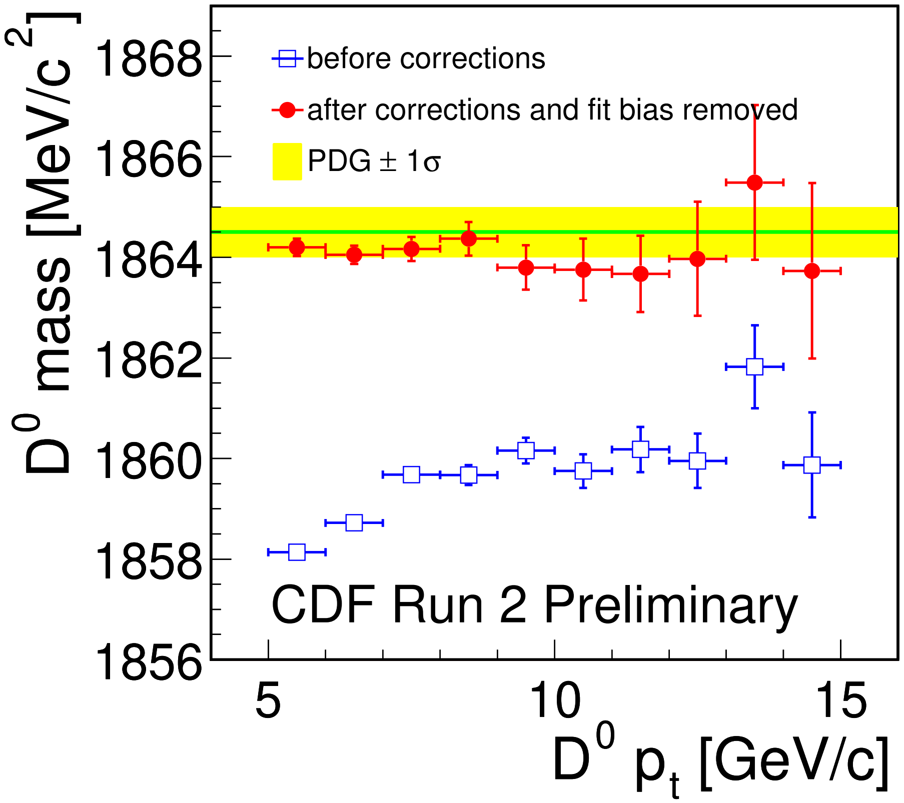
Calibration procedure

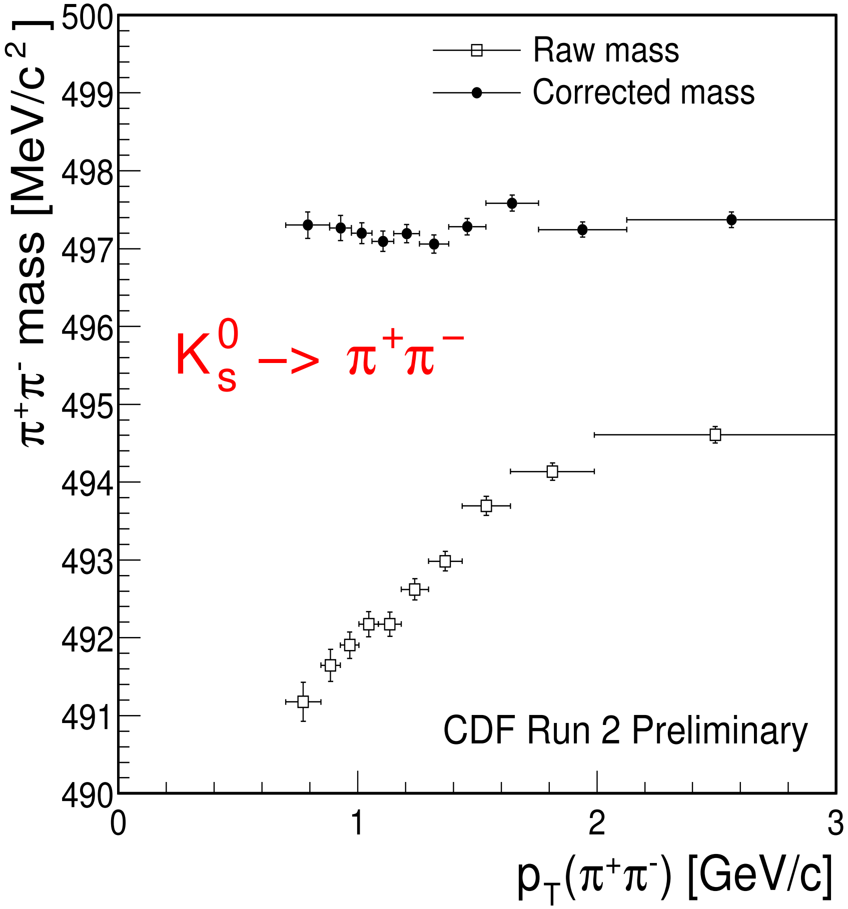
- raw tracks
- nominal E loss corrections
- fine tuned E loss corrections
- adjust overall scale (B field)

Momentum Scale Calibration

Using J/ψ calibration

- low momentum (π): $K_s \to \pi^+\pi^-$
- high stat. (K, π): $D^0 \to K^+\pi^-$
- high momentum (μ): $\Upsilon \to \mu^+\mu^-$

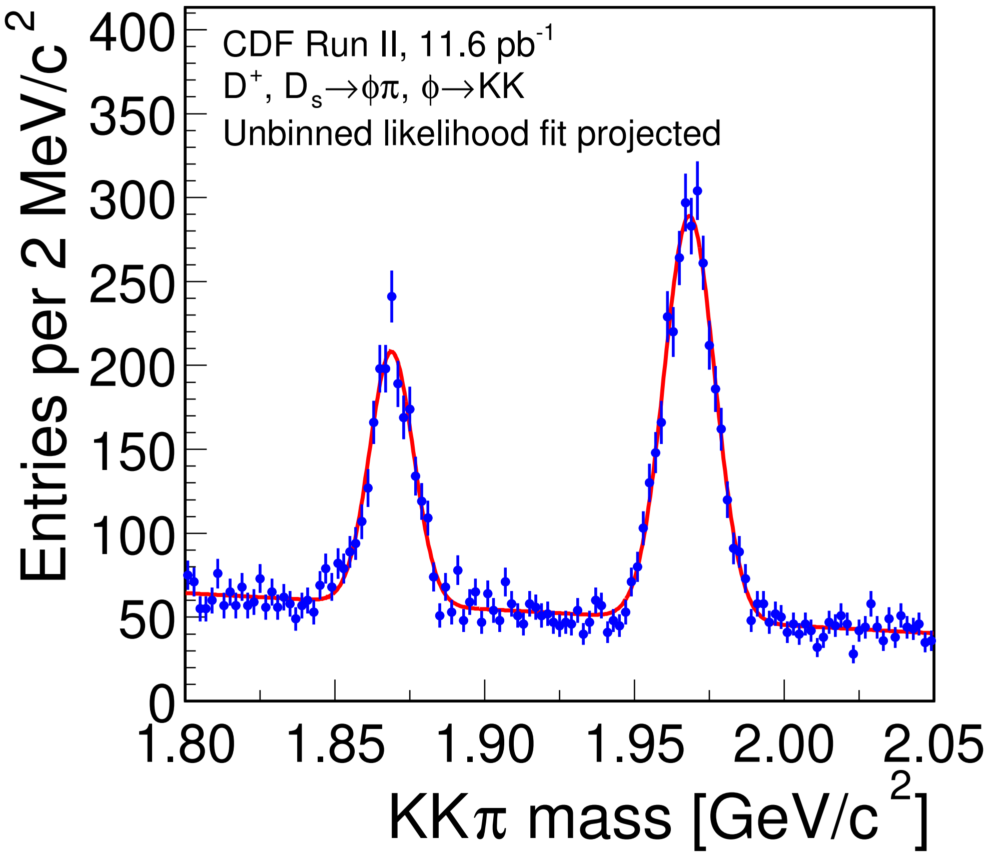




D Meson Mass Difference - First Tevatron Publication

Conceptual idea

- $D_s^+ \to \phi\pi^+(\phi \to K^+K^-)$
- $D^+ \to \phi\pi^+(\phi \to K^+K^-)$
- almost identical kinematics
- measure difference
- basically no systematics



Result $m(D_s^+) - m(D^+)$:

99.41 $\pm$ 0.38 (stat) $\pm$ 0.21 (syst) MeV/c^2

About the measurement

- first Tevatron Run II publication
- uses new SVT trigger
- agrees with old world average 99.5 $\pm$ 0.50 MeV/c^2

Recent BaBar:

PRD 65(2002)091104

98.4 $\pm$ 0.1 (stat) $\pm$ 0.3 (syst) MeV/c^2

B Hadron Masses

Largest J/ψ modes

- $B^+ \to J/\psi K^+$
- $B^0 \to J/\psi K^{*0}$, $B^0 \to J/\psi K^0_S$
- $B^0_s \to J/\psi \phi$
- $\Lambda^0_b \to J/\psi \Lambda$

B meson masses in MeV/c^2

preliminary

B^+ : 5279.32 ± 0.68 (stat) ± 0.94, (sys)

B^0 : 5280.30 ± 0.92 (stat) ± 0.92 (sys)

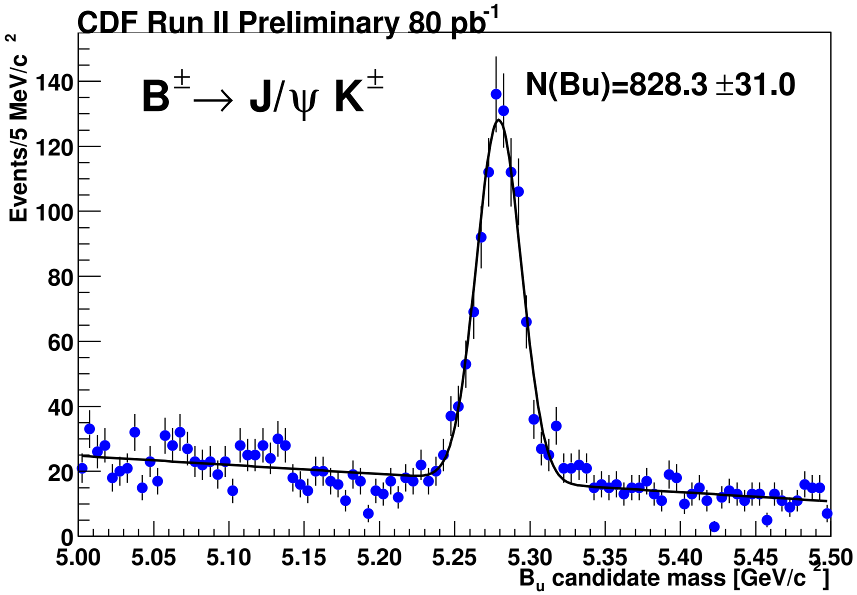
B_s : 5365.5 ± 1.3 (stat) ± 0.94 (sys)

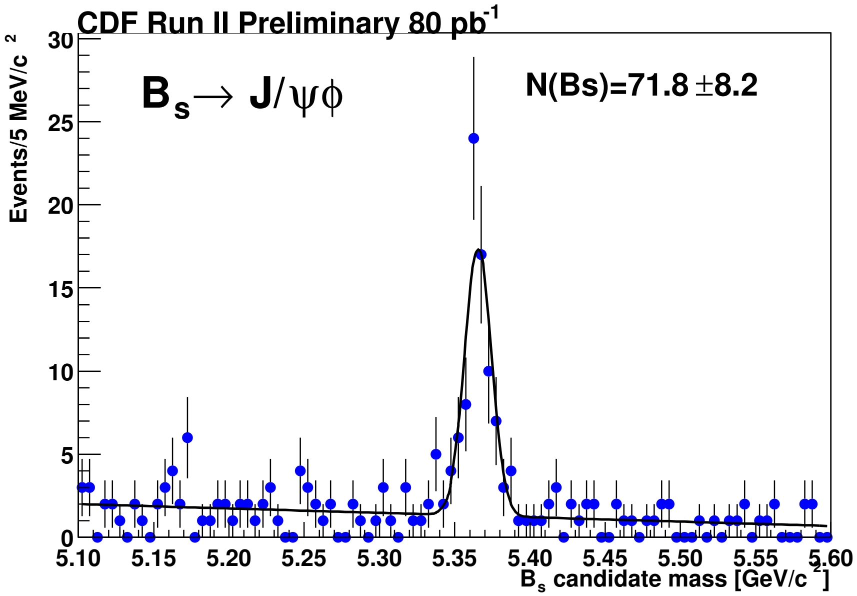
in the pipeline: Λ_b, $B^0 \to J/\psi K^0_S$

publishing soon!!

CDF Momentum scale

- best B_s in the world (soon Λ_b)
- best systematic around ..
- excellent prerequisite





Precision Vertexing

Lifetime Measurements

B Hadron Lifetimes

Large sample of $J/\psi \rightarrow \mu^+\mu^-$ events

- calibrate resolution
- understand alignment
- measure inclusive B lifetime
- so far only r-ϕ silicon used

Inclusive J/ψ (preliminary)

$c\tau_{incl} = 458 \pm 10\ \text{(stat)} \pm 11\ \text{(sys)}\ \mu\text{m}$

Exclusive J/ψ (preliminary)

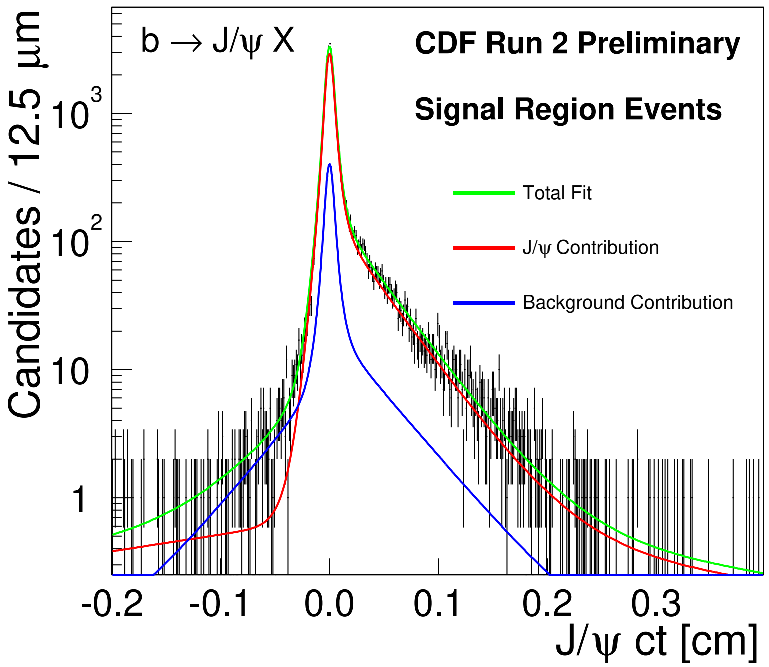
$c\tau_{B^+} = 470 \pm 20\ \text{(stat)} \pm 6\ \text{(sys)}\ \mu\text{m}$

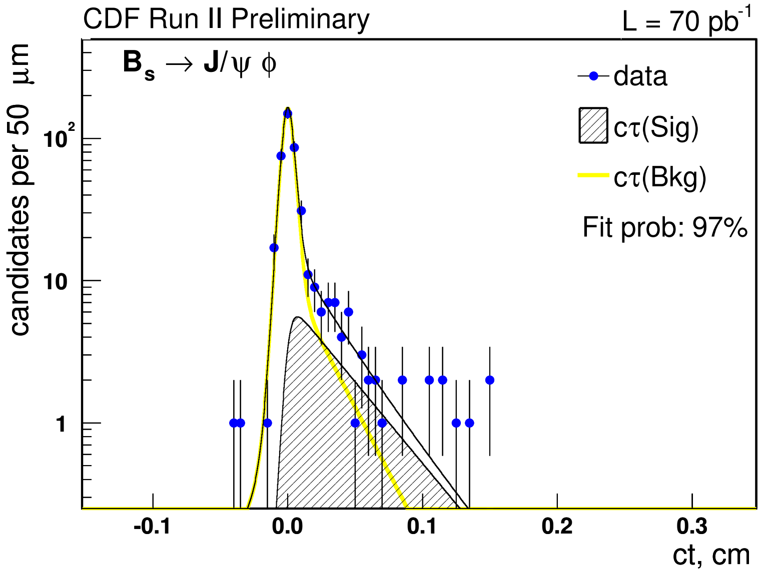
$c\tau_{B^0} = 425 \pm 28\ \text{(stat)} \pm 6\ \text{(sys)}\ \mu\text{m}$

$c\tau_{B^0_s} = 379 \pm 59\ \text{(stat)} \pm 6\ \text{(sys)}\ \mu\text{m}$

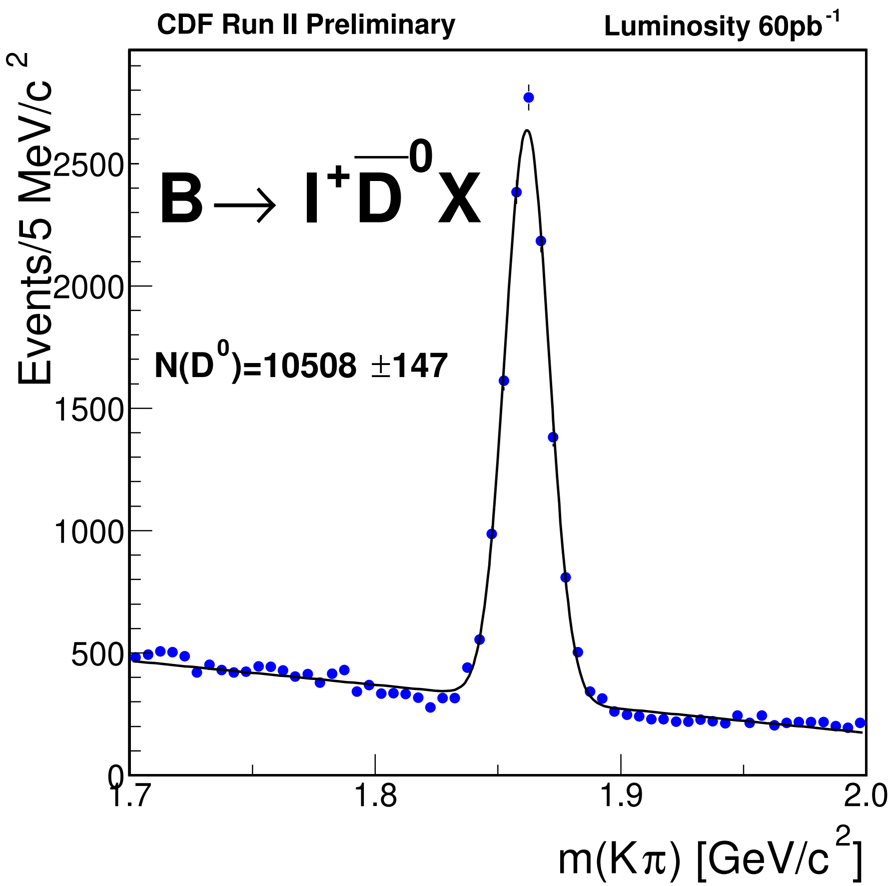
About results

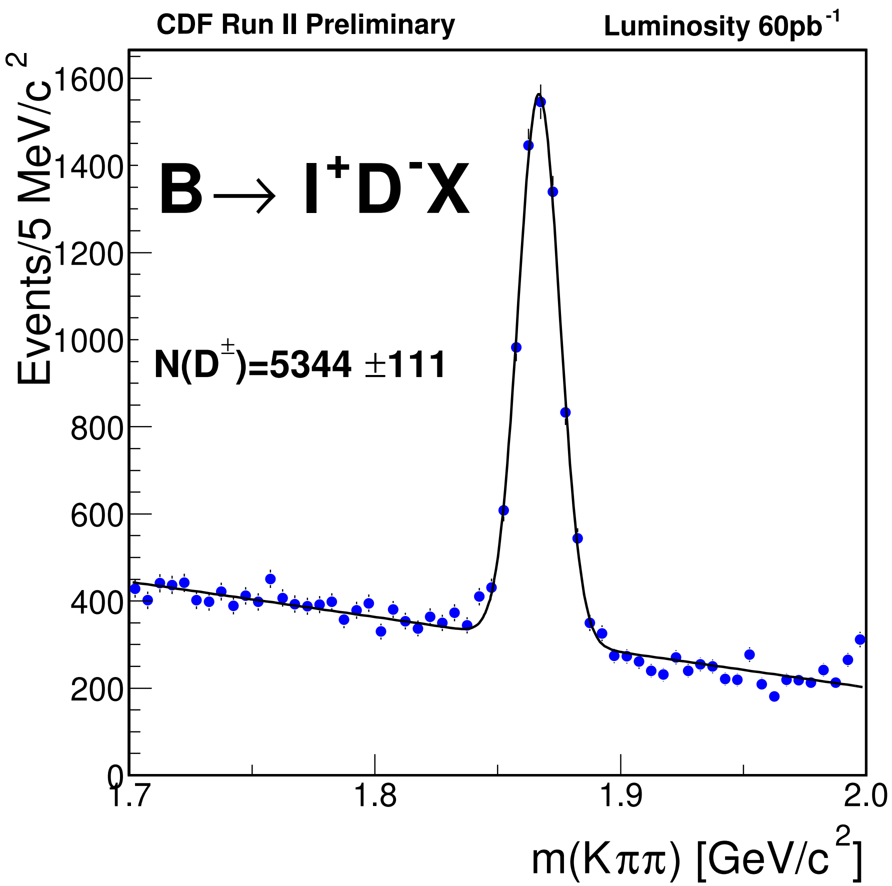
- silicon already well understood
- prerequisite for $\Delta\Gamma_s$
- major improvements expected: Layer 00, 3D tracking, alignments
- important for B_s mixing





Precision Lifetimes



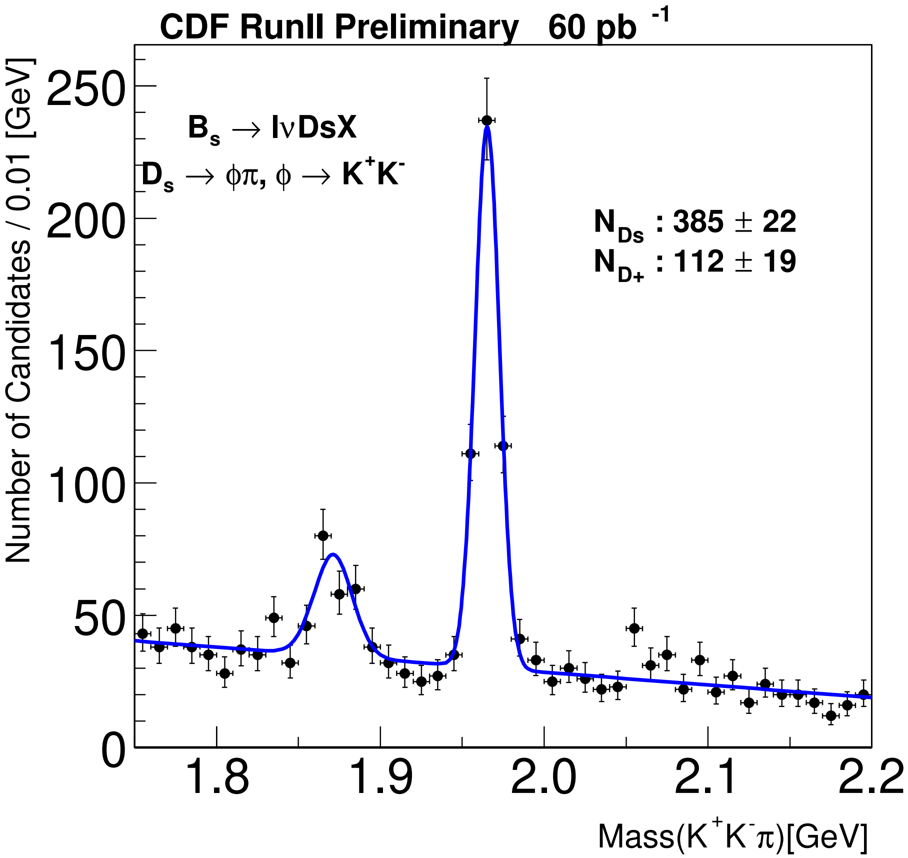


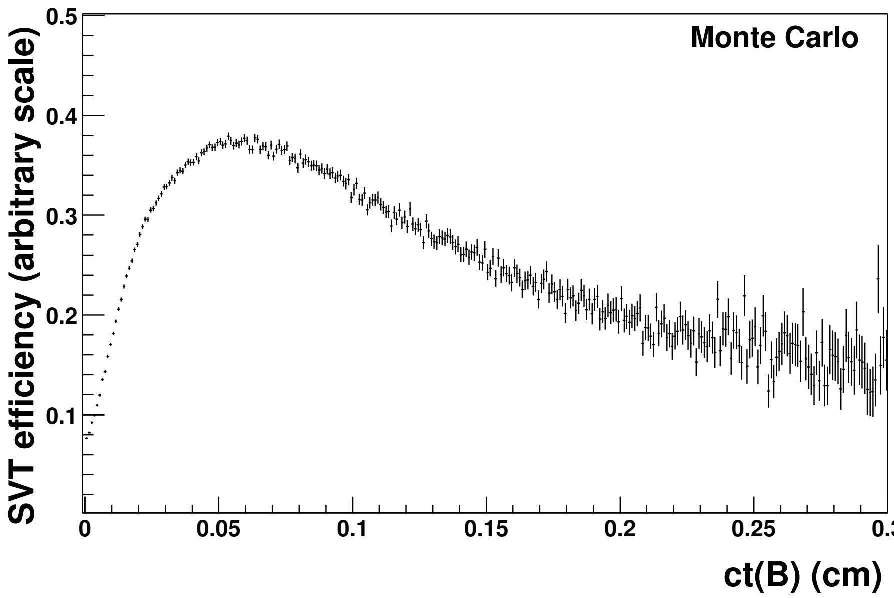
Large semileptonic decay sample: $B \rightarrow \nu \ell D X$

excellent to calibrate B^0, B^+ lifetimes

prototype same side tagging and B^0 mixing

Displaced Track - Trigger Bias





$\nu\ell D_s$ sample

- clean and large sample
- Yield/Lumi $\approx 3 \times$ Run I
- S/N $\approx 2 \times$ Run I
- limited B_s mixing reach

SVT trigger bias

- trigger d_0 cuts bias lifetime
- careful modeling necessary
- at present not yet fully understood
- expected lifetime errors $\pm\, 8\mu$m($stat$)
- understanding at 40 μm level

Hope to finalize measurements soon

Rare Decays

$D^0 \rightarrow \mu^+\mu^-$

Search for $D^0 \to \mu^+\mu^-$ (FCNC)

Standard Model prediction very small

$BR \approx 3 \times 10^{-13}$

Some R parity violating SUSY

$BR \approx 3.5 \times 10^{-6}$

Use $D^0 \to \pi^+\pi^-$ to normalize

add muon tags
determine mistag
determined combinatorics

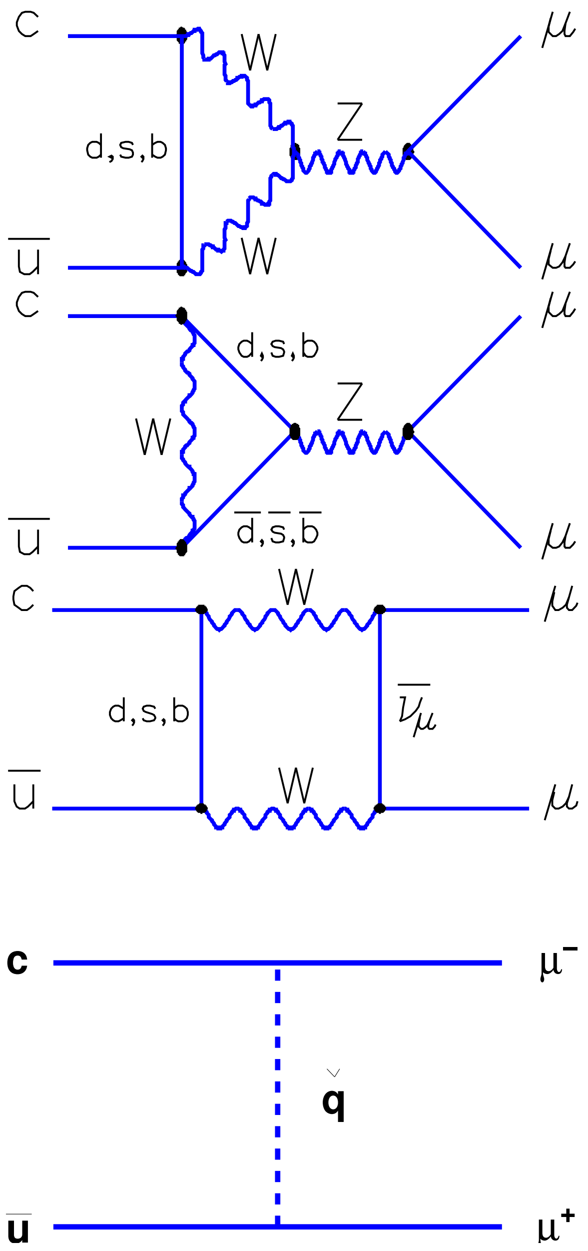
muon fake rate $\approx 1\%$

Prospects

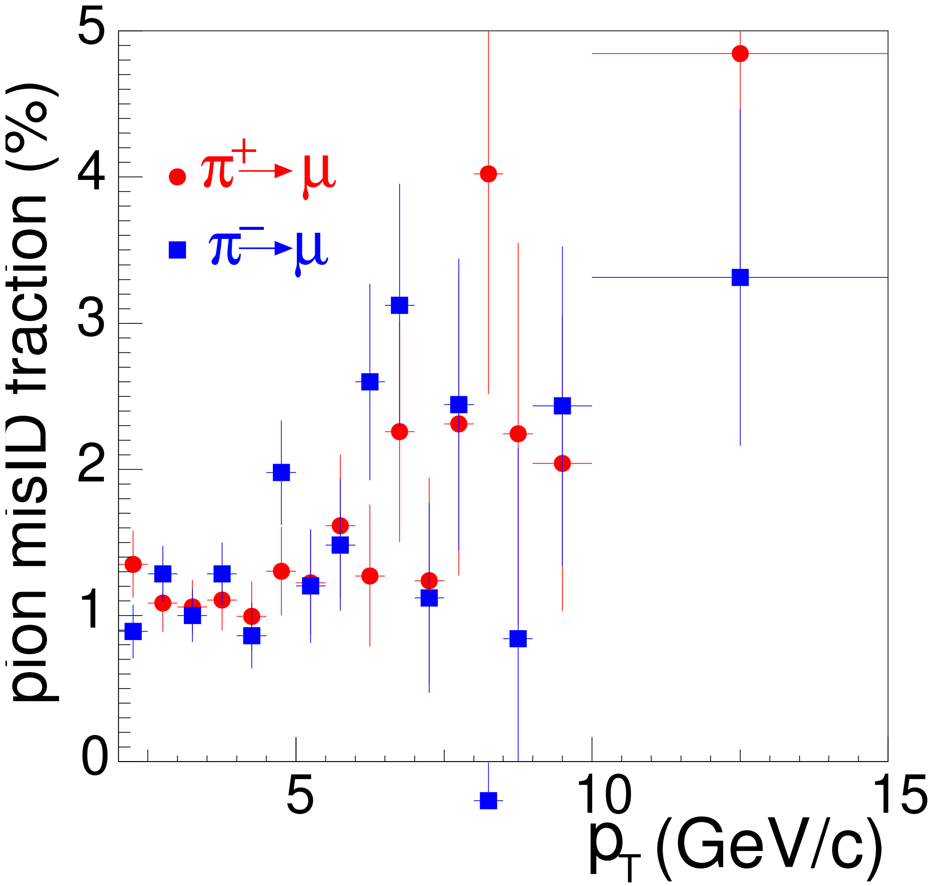
excellent training ground for

$B_s \to \mu\mu,\ B^+ \to \mu\mu K^+, ...$

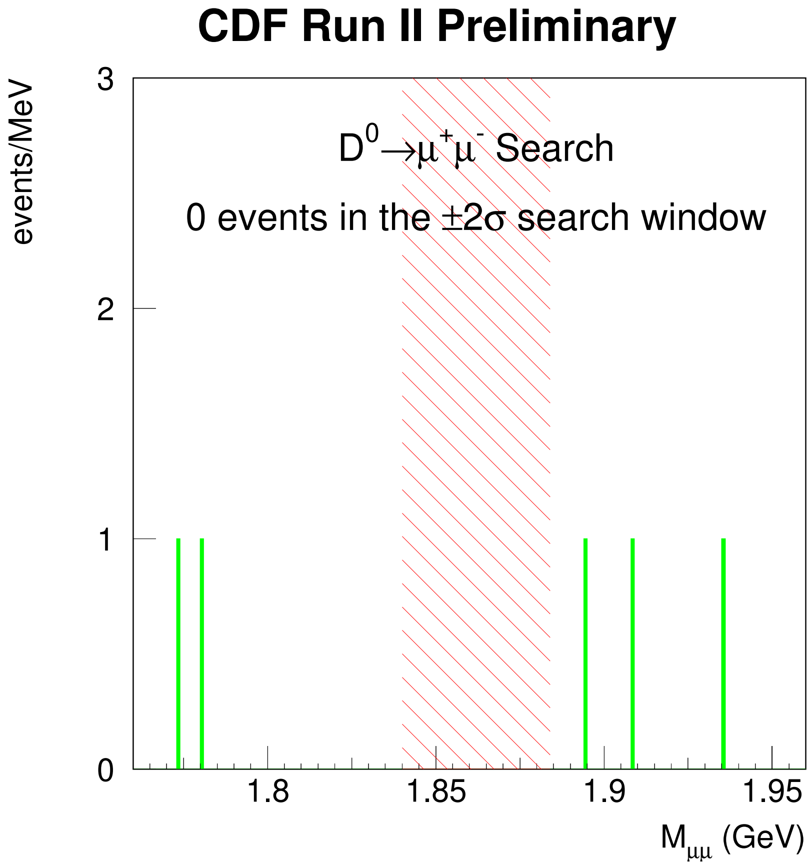
ready for the summer ....



Search for $D^0 \to \mu^+\mu^-$



muon fake rates



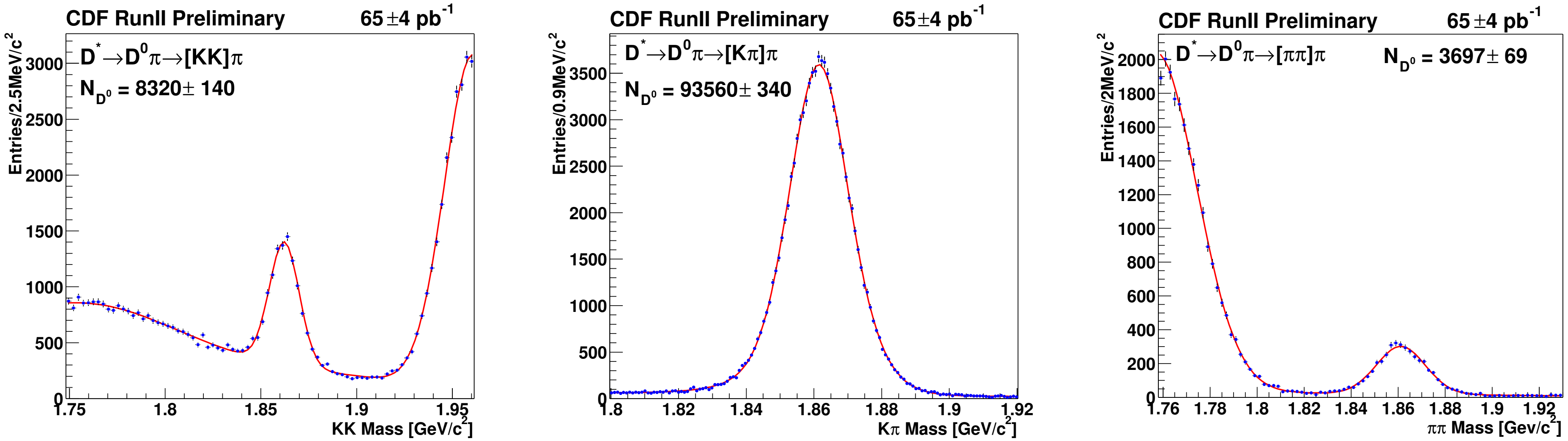
No event observed in window

- ☞ $BR(D^0 \to \mu^+\mu^-) < 2.4 \times 10^{-6}$ at 90% CL
- ☞ starts to cut into SUSY expectation
- ☞ world best limit

Cabibbo Suppressed Decays and *CP* Violation

$$D^0 \rightarrow KK/\pi\pi(K\pi)$$

Cabibbo suppressed D^0 decays



Correct for relative trigger and reconstruction efficiencies

$$\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^-\pi^+)} = (9.38 \pm 0.18 \pm 0.10)\%$$

$$\frac{\Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = (3.686 \pm 0.076 \pm 0.036)\%$$

Competitive with FOCUS 2003:

$$\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^-\pi^+)} = (9.93 \pm 0.14 \pm 0.14)\% \qquad \frac{\Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = (3.53 \pm 0.12 \pm 0.06)\%$$

Cabibbo suppressed D^0 decays - *CPV*

Key features of analysis

- ☞ use D^* signal to clean signal peaks
- ☞ largest systematics from background model

Measure *CP* violation

- ☞ $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ are *CP* eigenstates

$$A_{CP}(D^0 \to K^+K^-) = (1.0 \pm 1.7 \pm 0.6)\%$$

$$A_{CP}(D^0 \to \pi^+\pi^-) = (3.0 \pm 1.9 \pm 0.6)\%$$

Competitive with CLEO 2001:

$A_{CP}(D^0 \to K^+K^-) = (0.0 \pm 2.2 \pm 0.8)\%$ $A_{CP}(D^0 \to \pi^+\pi^-) = (1.9 \pm 3.2 \pm 0.8)\%$

Prospects

- ☞ very high statistics preparation for $B \to h^+h'^-$ analysis
- ☞ all detector issues should be settled

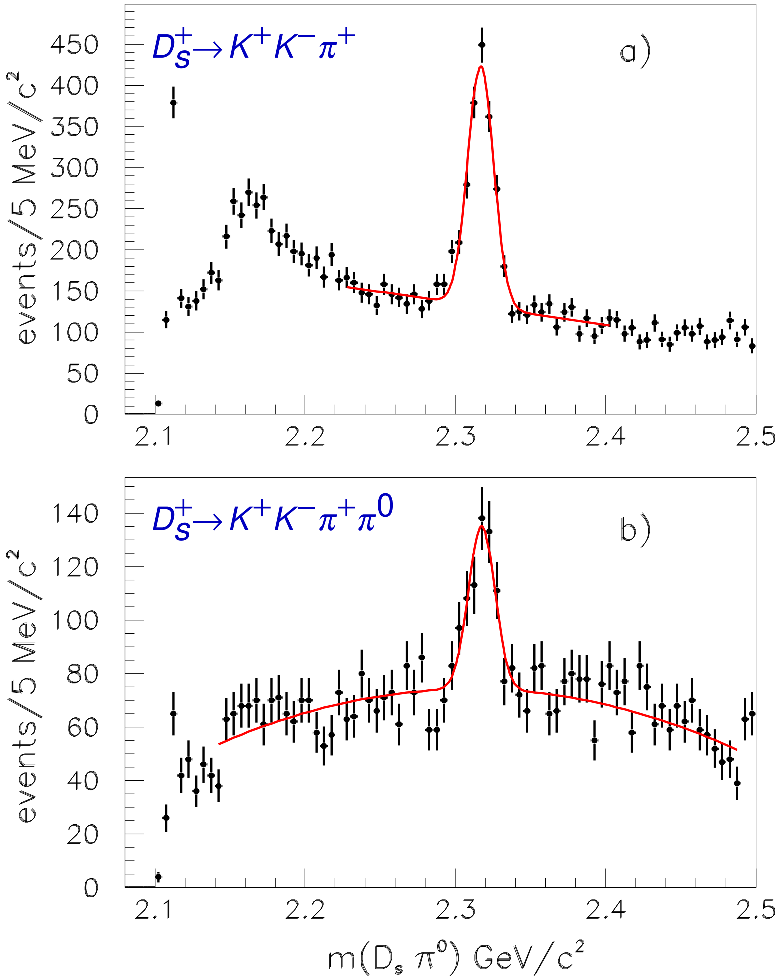
Search for Exotic States

$D_s^- \pi^+$ and $D_s^- \pi^+ \pi^-$

Exotic D_s

BaBar $D_s\pi^0$ signal

hep-ex/0304021

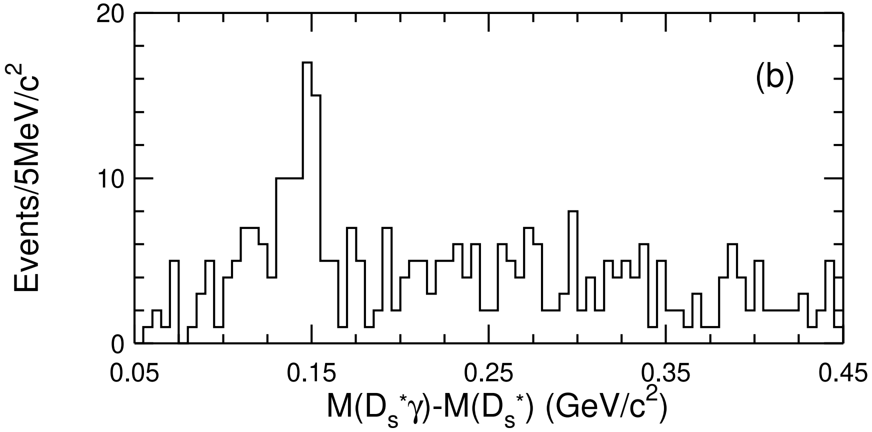


D_s^{**} in conflict with potential models?

generally accepted as 0^+ D_s^{**}

CLEO claims discovery of $D_{sJ}^+(2463)$ in $D_s^{*+}\pi^0$

hep-ex/0305017



looks like the standard 1^+ D_s^{**}

interesting: *wrong* mass

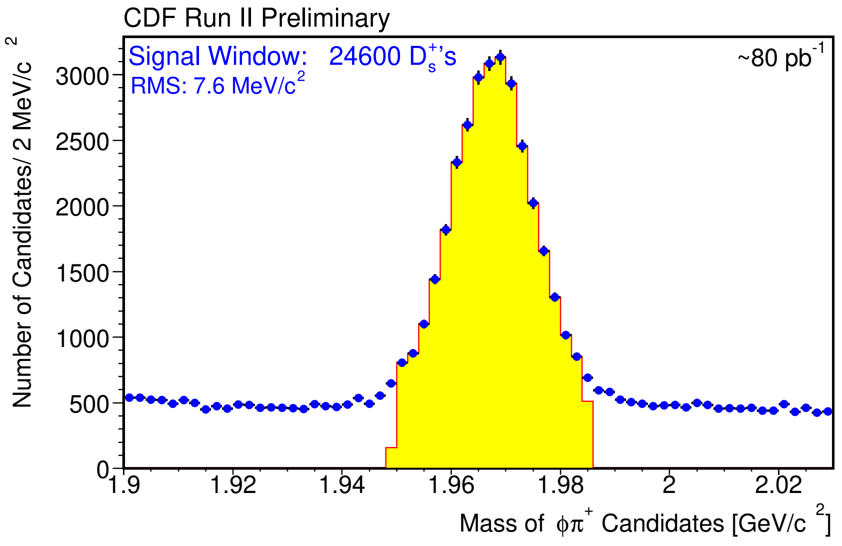
At CDF

- π^0 very tough
- analog charged modes/states?
- try known $D_{(s)}^{**}$ states
- look for $D_s^-\pi^+$ and $D_s^-\pi^+\pi^-$

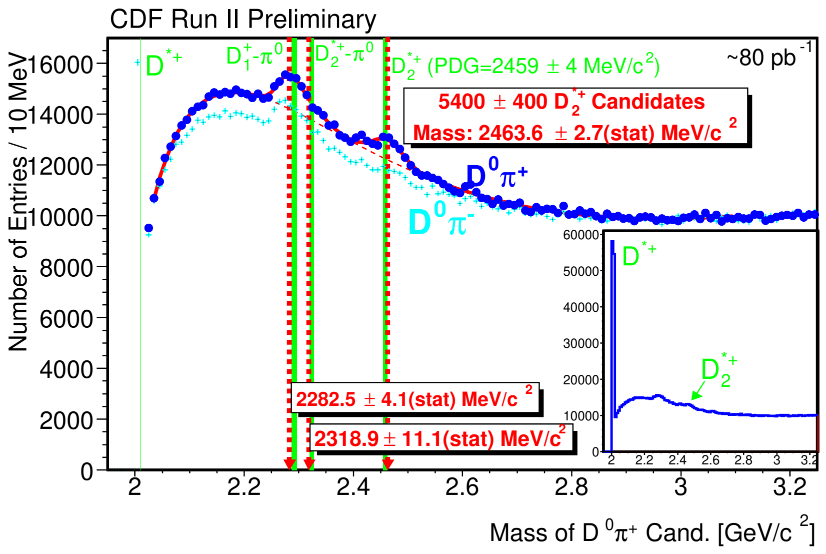
Exotic D_s

CDF D Reconstruction

- ☞ 0.750 million $D^0 \to K^-\pi^+$
- ☞ 0.500 million $D^+ \to K^-\pi^+\pi^+$
- ☞ look for $D_s^-\pi^+$ and $D_s^-\pi^+\pi^-$



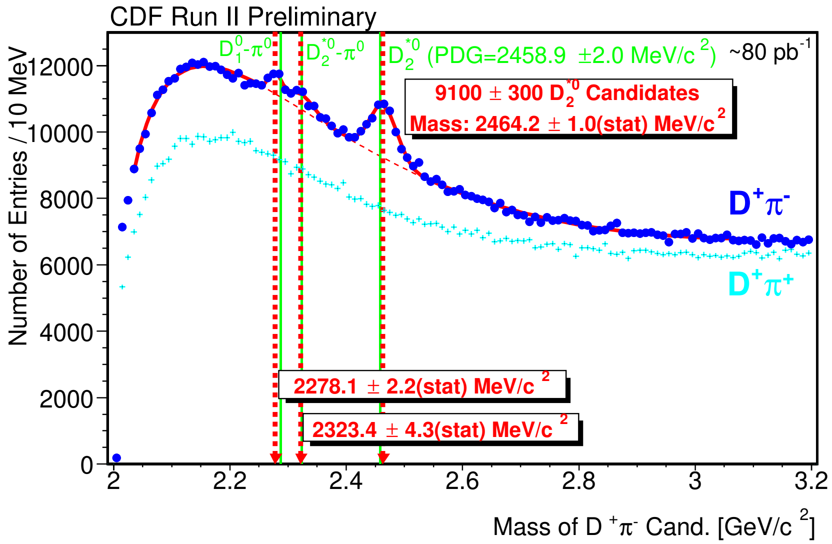
CDF $D^0\pi^+$ Reconstruction



- ☞ clear $D_2^{*+} \to D^0\pi^+$
- ☞ indirect sign: $D_2^{*+}, D_1^+ \to D^{*0}\pi^+$ with lost soft pion
- ☞ D^0 auto reflection visible

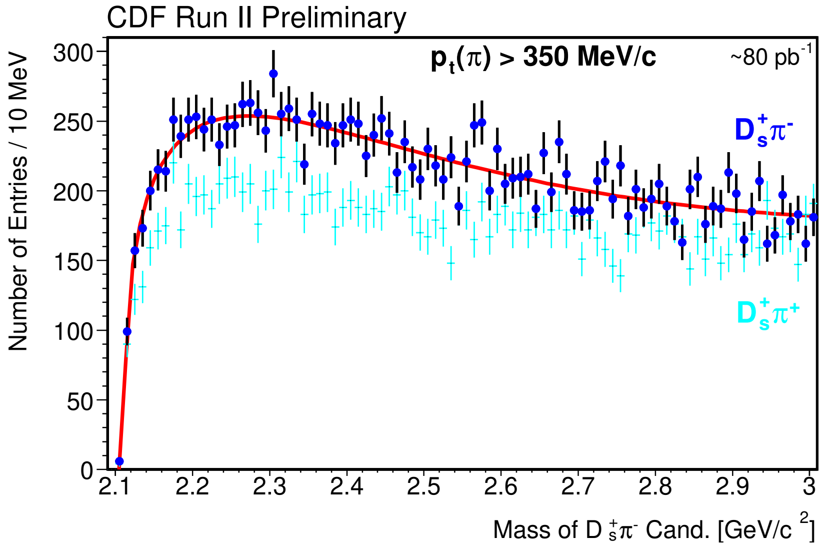
Exotic D_s

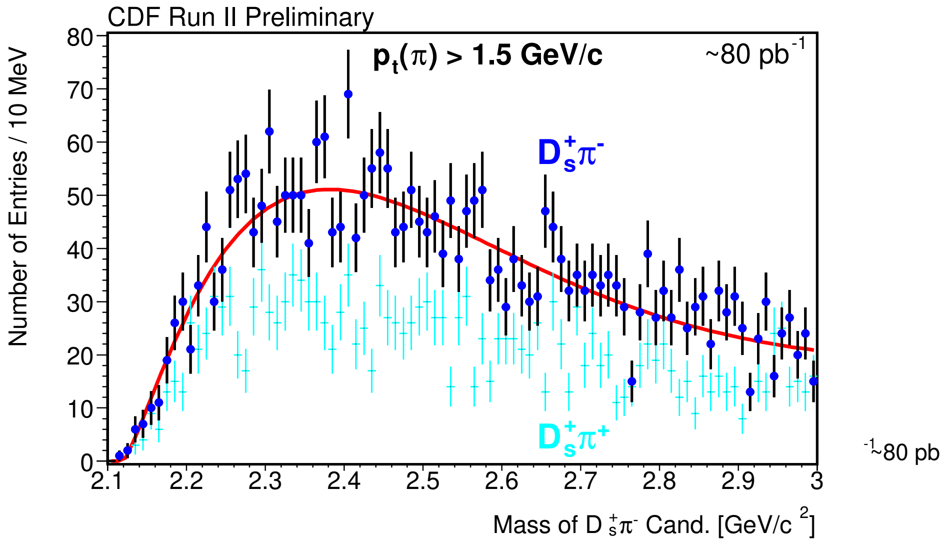
CDF $D^+\pi^-$ Reconstruction



- ☞ clear $D_2^{*0} \to D^+\pi^-$
- ☞ indirect sign: $D_2^{*0}, D_1^0 \to D^{*+}\pi^-$ with lost soft pion

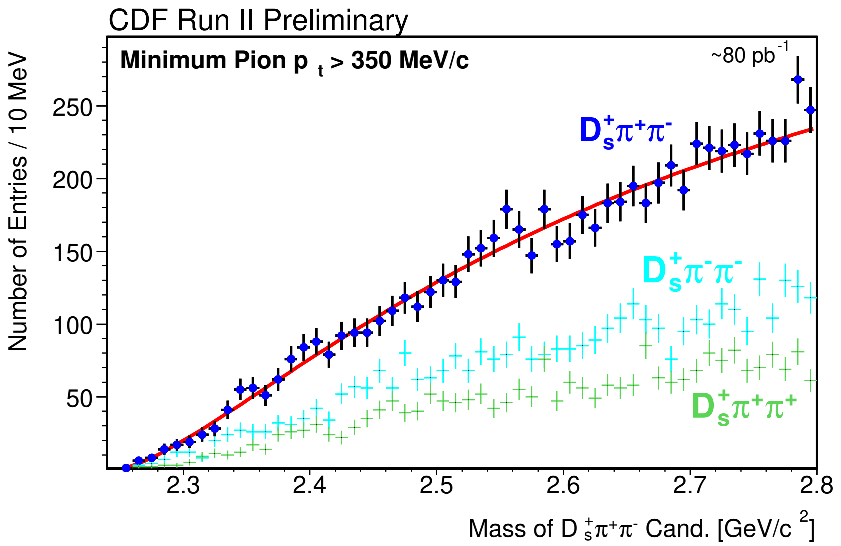
Search in $D_s^+\pi^-$

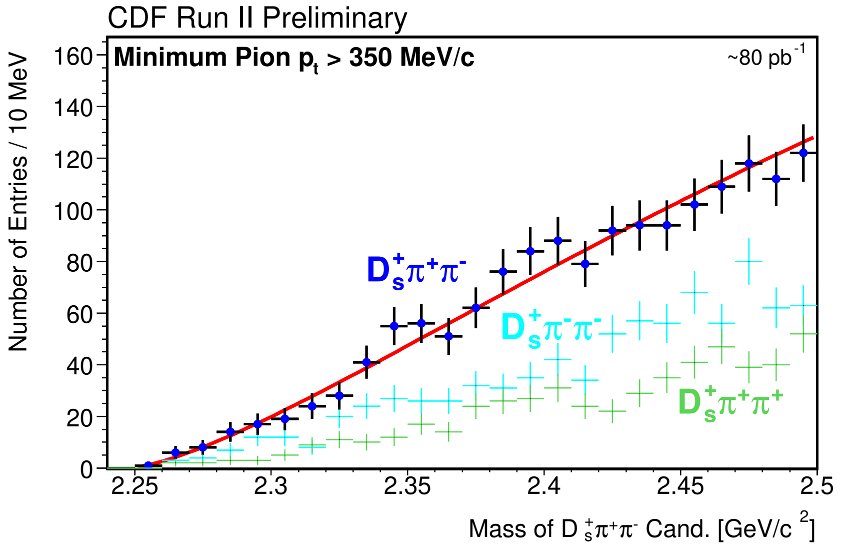




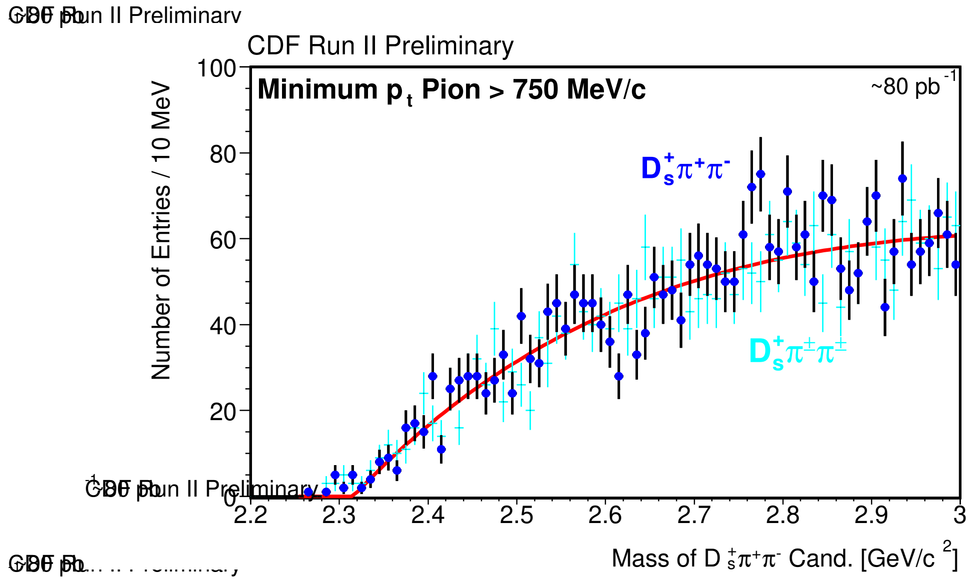
Exotic D_s

Search in $D_s^+\pi^-\pi^+$





Search in $D_s^+\pi^-\pi^+$



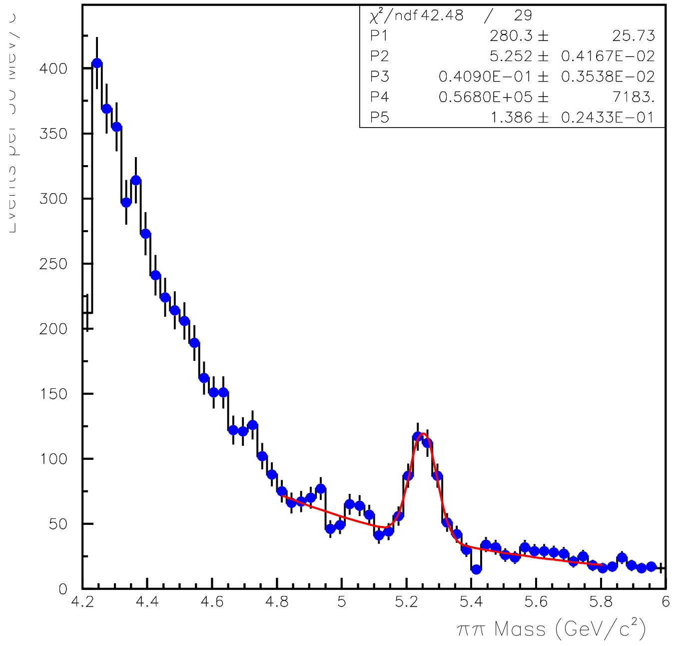
Exclusive Hadronic Reconstruction

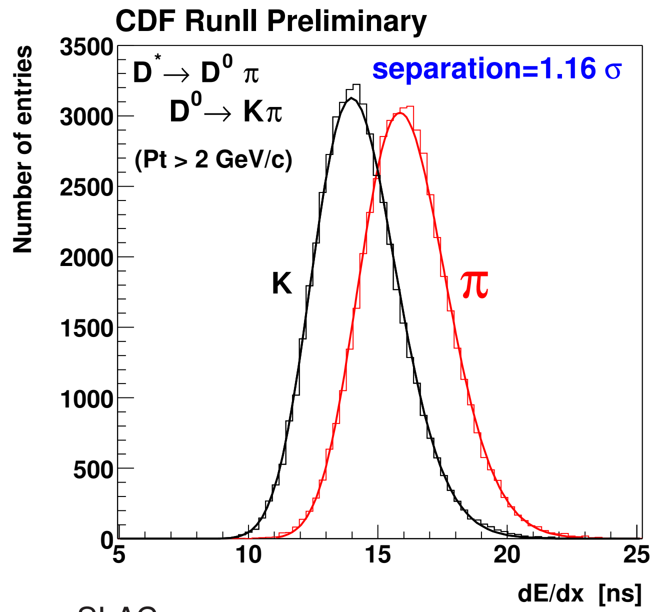
$$B \to h^+ h'^-,\ \Lambda_b \to \Lambda_c^- \pi^+,\ B_s \to D_s^- \pi^+$$

Two Body Charmless B Decays

$B \to h^+ h'^-$ observed at CDF

- about 280 candidates,
  S:N = 2:1 (1:1 expected)
- peak is a mix of
  $B^0, B_s \to \pi\pi, K\pi, KK$
- kinematic and dE/dx to disentangle
- full analysis imminent
- isolation variables not finalized





2 kinematics variables

- $m(\pi\pi)$
- $\alpha = (1 - p_1/p_2)q_1$
  with $p_1 < p_2$

Two Body Charmless B Decays

Raw fit results

- $N(B^0 \to K\pi) = 148 \pm 17$
- $N(B^0 \to \pi\pi) = 39 \pm 14$
- $N(B_s \to KK) = 90 \pm 17$
- $N(B_s \to K\pi) = 3 \pm 11$

$$\frac{BR(B^0 \to \pi\pi)}{BR(B^0 \to K\pi)} = 0.26 \pm 0.11 \pm 0.055$$

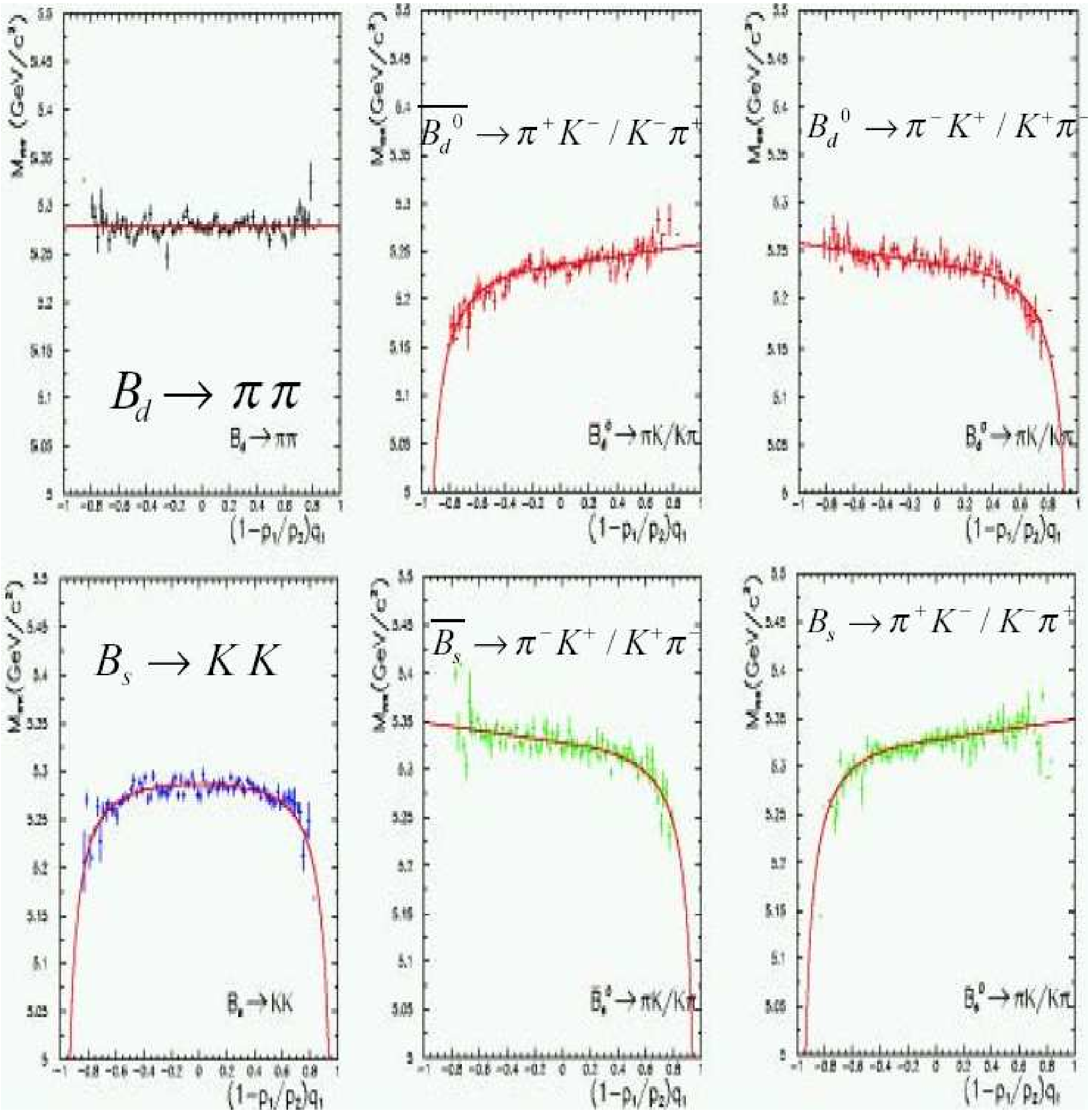
Conclusion

- significant $B_s \to KK$
- $\frac{BR(B^0 \to \pi\pi)}{BR(B^0 \to K\pi)}$ measured
- agree with Belle/BaBar

Plans

- measure CP asymmetry
- measure angle γ

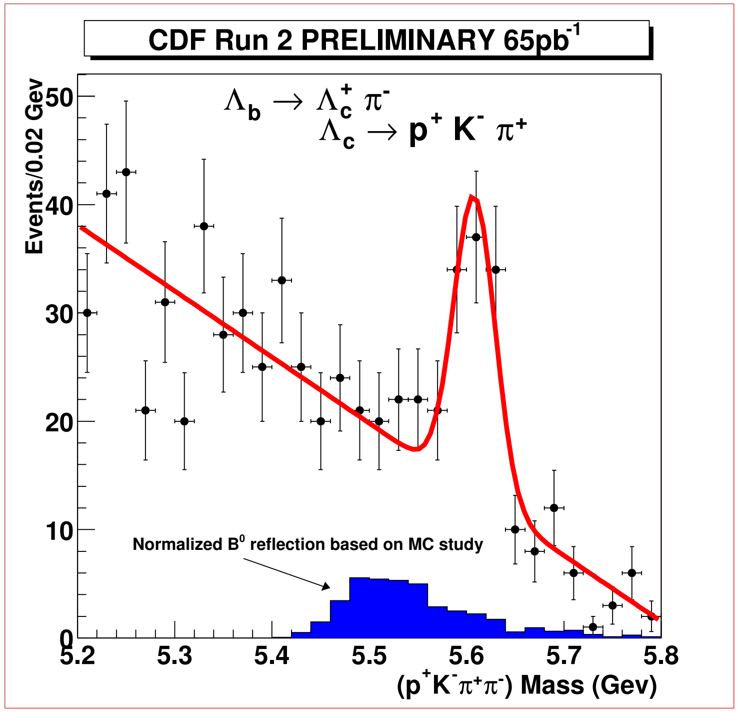
Fleischer PLB 459 (1999) 306



Λ_b Hadronic Decays

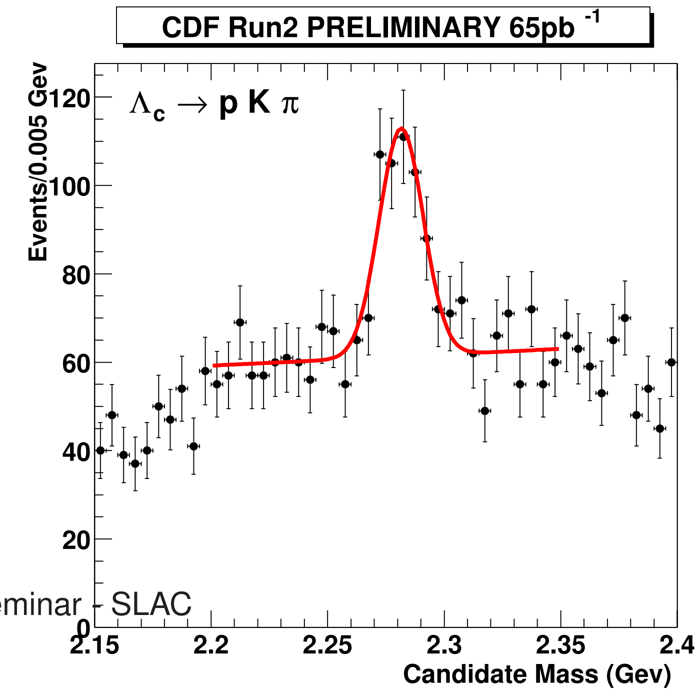
$\Lambda_b \to \Lambda_c\pi(\Lambda_c \to pK\pi)$ observed at CDF

- about 90 candidates
- reflections are quite significant
- no particle ID used yet
- *BR* ratio measurement imminent

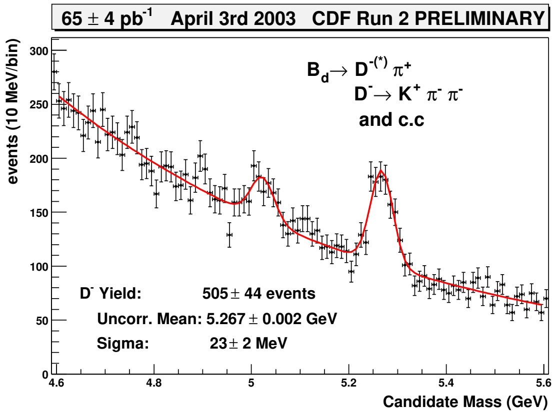


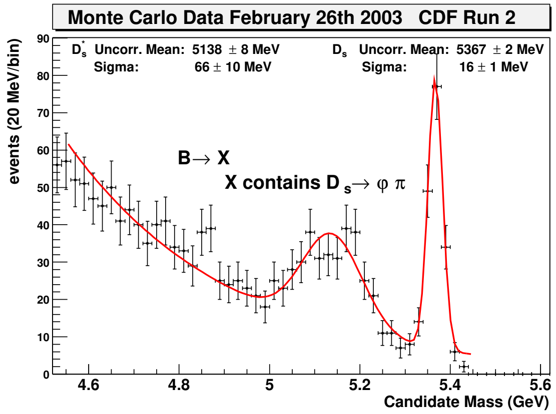
Next steps

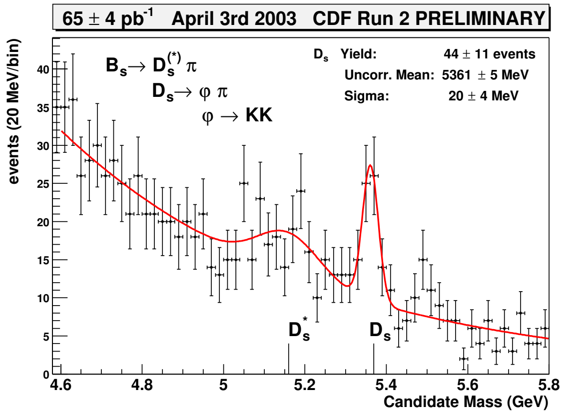
- measure mass, lifetime
- and lifetime ratio $\tau(\Lambda_b)/\tau(B^0)$
- later: polarization



Towards B_s Mixing ....







Fully reconstructed hadronic final state

- two track trigger essential
- exquisite *ct* resolution $\to$ B_s mixing
- production rate understood
- ratio of branching ratio cancels most systematics

Measurement of ratio of branching ratios

$$\frac{f_s}{f_d}\frac{BR(B_s \to D_s^-\pi^+)}{BR(B^0 \to D^-\pi^+)} = 0.42 \pm 0.11(stat) \pm 0.11(BR) \pm 0.07(syst)$$

A Word about B_s Mixing

The Yellow Book Predictions

- need about 100 pb^{-1} to cover Standard Model prediction
- measure B_s mixing with the first month of data
- easy and quick analysis?

That was the plan ....

Back to Reality

- machine delivered slow $\rightarrow$ more than a year for 100 pb^{-1}
- CDF did not take data very efficiently
- silicon detector not as complete/efficient
- trigger not as efficient
- tagging probably not as good as hoped for (TOF for kaons)
- detailed predictions and improvements in the works (Summer '03)
- very tough analysis!

Need very careful planning and coordinated execution

Summary and Conclusion

Machine and Detector Performance

- Tevatron and CDF had slow startup
- Machine slowly but steadily improving
- Record $\mathcal{L} = 4.4 \times 10^{31}\ cm^{-2}s^{-1}$
- CDF operation is getting more stable
- Last week typically 90% CDF data taking efficiency

First Physics Measurements

- Detector well understood: systematics better than Run I
- Publishing exciting world class charm measurements
- Lots of Preliminary Results *B* and Charm
- B_s Mixing Analysis is going to be tough

  but progress is being made: see signal, work on yields

Tune in for the summer ... lots of new stuff coming