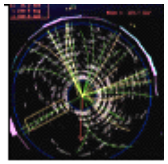
New Charm(onium) Results from CDF

Arnd Meyer, RWTH Aachen / Fermilab
DIS 2003, St. Petersburg
23 April 2003

- The Fermilab accelerator complex
- The CDF II detector
- Production
  - J/ψ cross section
  - Charm cross section
- Cabibbo suppressed D decays
- D_s, D^+ Mass Difference
- Search for $D^0 \rightarrow \mu^+\mu^-$
- Summary

Fermi National Accelerator Laboratory

inquiring minds



Fermilab Accelerator Complex

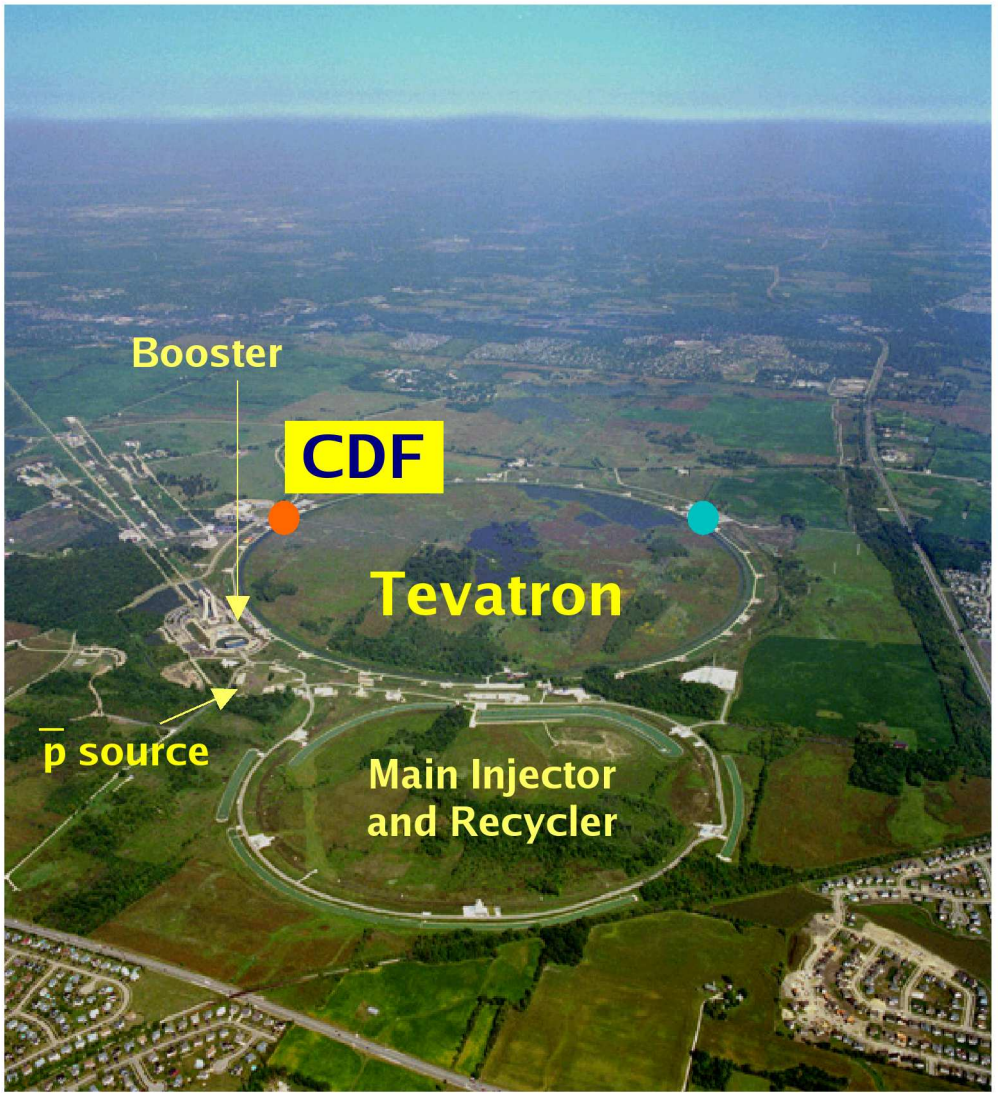
$p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV (up from 1.8TeV)

Increased # of bunches:

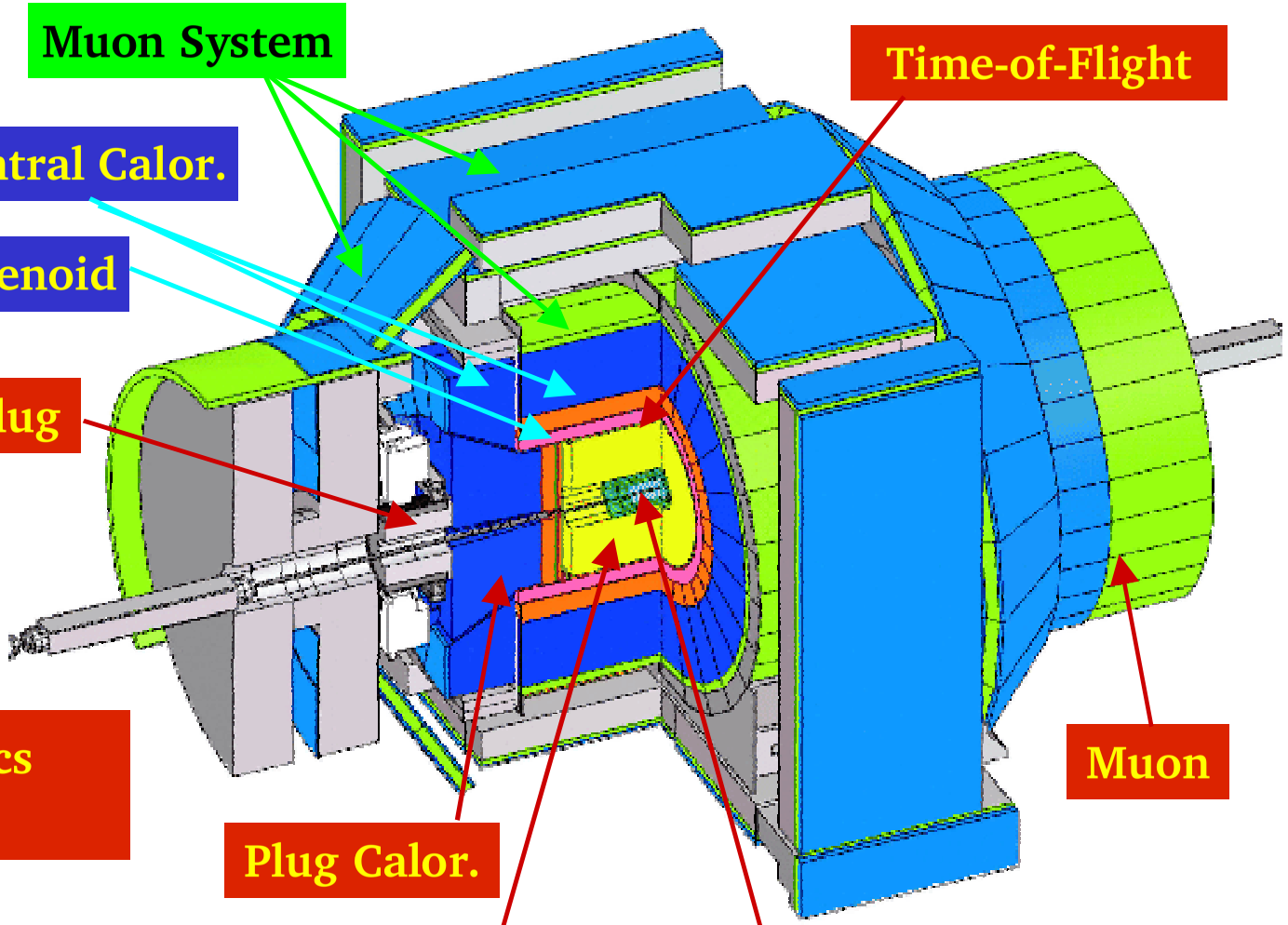
6 (3500 ns)

→ 36 (396 ns)

Main Injector
(p storage ring up to 150GeV)
replaces Main Ring



- Peak luminosity
  - $0.16 \cdot 10^{32} cm^{-2} s^{-1}$ (Run I)
  - → $0.8 \cdot 10^{32} cm^{-2} s^{-1}$ (Run IIa)
  - → $2\text{-}4 \cdot 10^{32} cm^{-2} s^{-1}$ (Run IIb)
- Run IIa: $\int L\,dt \simeq 2\ fb^{-1}$ by 2005
  (factor 20 compared to Run I)
- Run IIb $\int L\,dt \simeq 10 - 15\ fb^{-1}$
  (before "LHC physics")

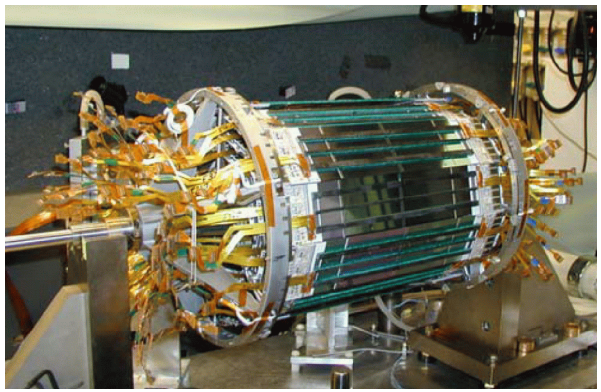


New

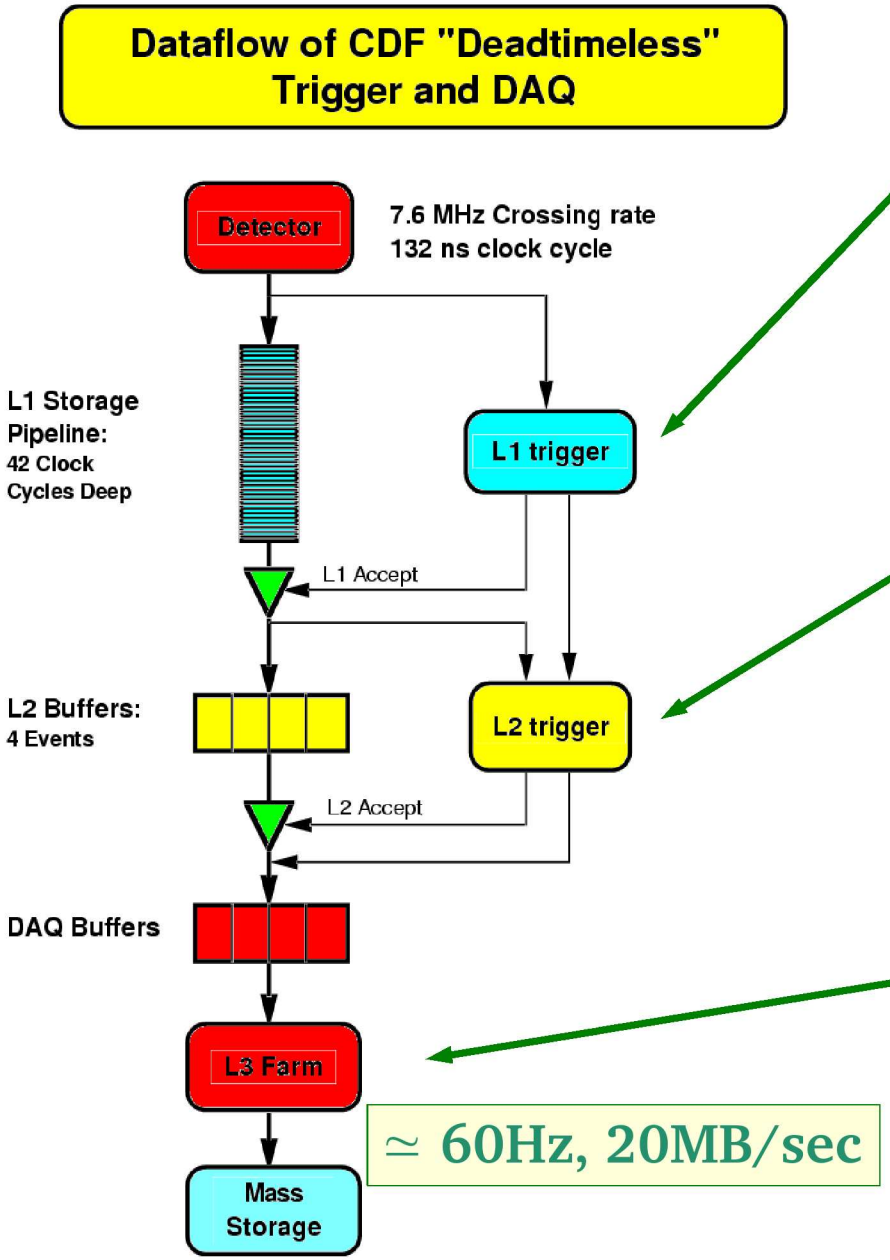
Old

Partially New

Front End Electronics
Trigger / DAQ



Trigger Overview

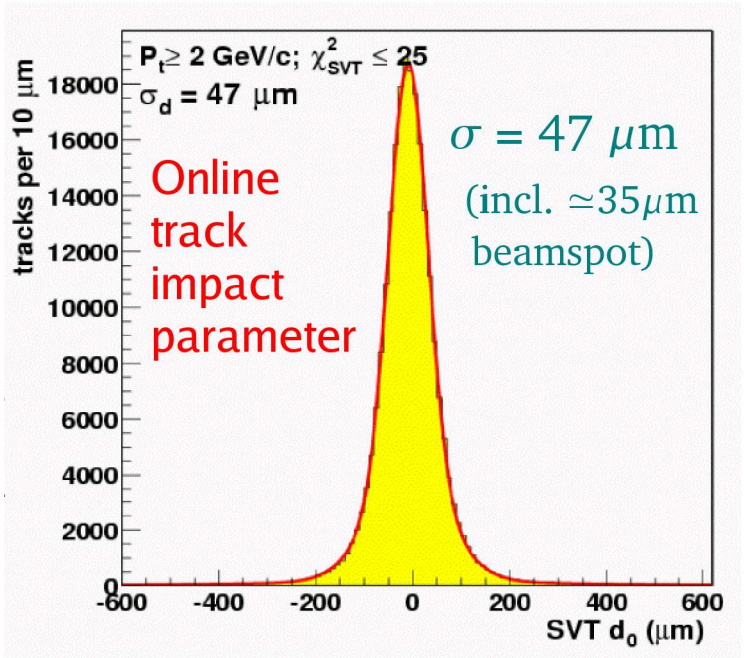


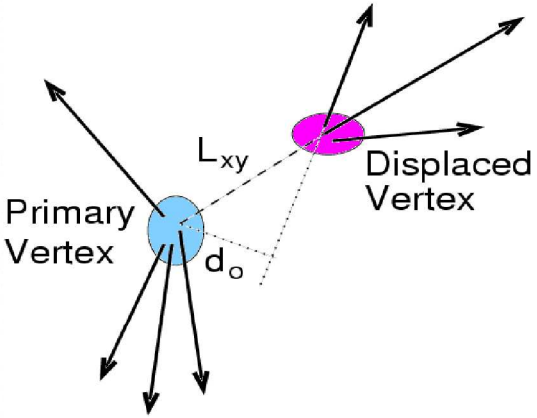
- **Level 1 (5.5μs latency) :**
  - Every front-end system stores data in 42 clock cycles deep pipeline
  - 18kHz accept rate ($\rightarrow$ 40−50 kHz)
  - On L1 accept, data is stored in one of four L2 buffers. Si readout starts.
- **Level 2 (asynchronous):**
  - Nominal 20μs decision time
  - Trigger algorithms run on custom Alpha boards (up to 4)
  - 300Hz accept rate ($\rightarrow$ 1kHz)
  - Event readout starts on L2A
- **Level 3:**
  - $\simeq$ 250 dual-CPU Linux boxes
- *"Deadtimeless"*: DT only incurred when all L2 or DAQ buffers are full

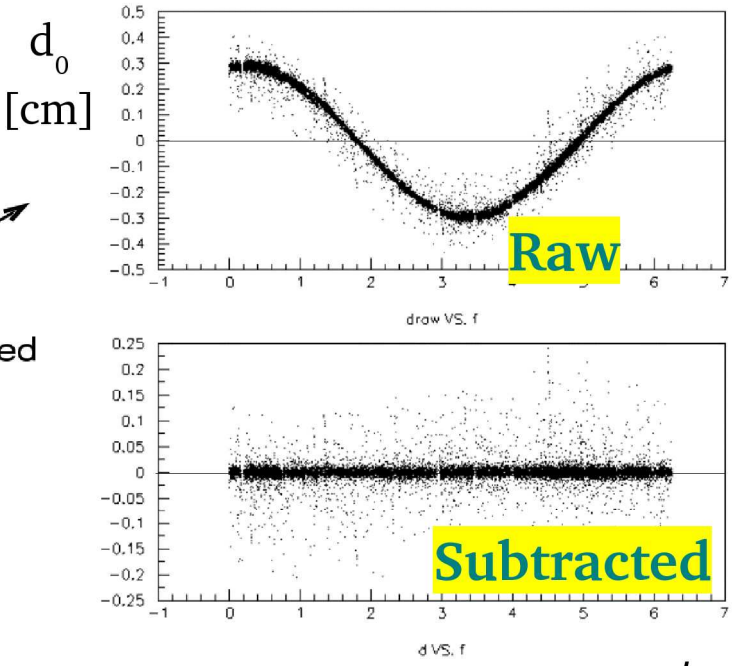
L2: Silicon Vertex Tracker

- Major rate reduction at L2 from revolutionary **displaced vertex trigger (SVT)**
- Seeded by L1 (drift chamber) tracks (XFT=eXtremely Fast Tracker), ≃150 VME boards find and fit Silicon tracks, with offline accuracy, in a 15μs pipeline
- Increases physics sensitivity of CDF
  - CDF as "Charm Factory"
  - Purely hadronic B trigger, e.g. $B^0 \rightarrow \pi^+\pi^-$, $B_s \rightarrow D_s\pi$
  - Higgs/new particles decaying into b/c quarks

Online fit and subtraction of beamline



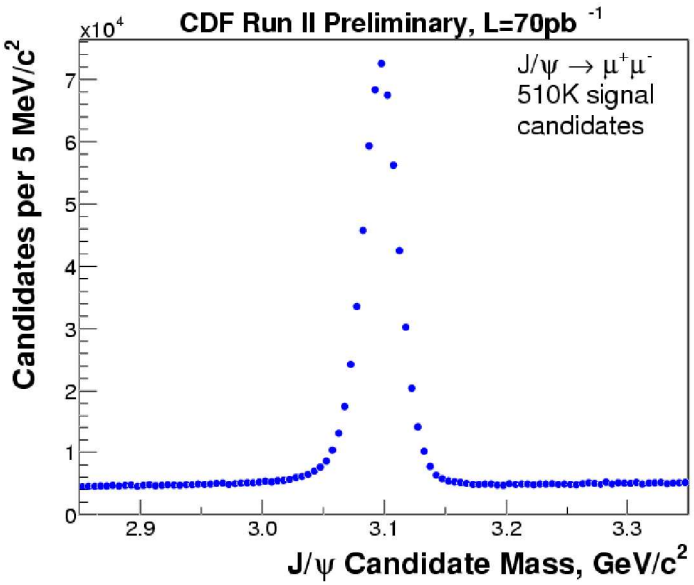




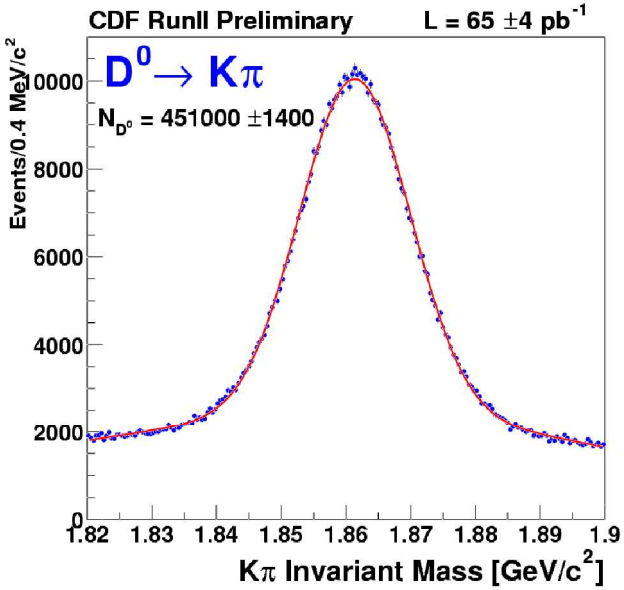
Triggers for B/Charm

- CDF has three dedicated triggers for B/Charm physics

Di-muon	Lepton + Track	Two-Track
$J/\psi \rightarrow \mu^+\mu^-$	Semileptonic Decays	Hadronic Decays
2 central μ ($\lvert\eta\rvert < 1.0$)	1 μ/e with $p_T > 4$ GeV	2 tracks with $p_T > 2$ GeV,
with $p_T > 1.5$ GeV	1 addl. track with $p_T > 2$ GeV and	SVT $d_0 > 120\mu$m and
(Run I: > 2.2 GeV)	SVT $d_0 > 120\mu$m	$\Sigma p_T > 5.5$ GeV
0.5 Million $J/\psi \rightarrow \mu^+\mu^-$	0.5 Million $B \rightarrow \ell$ X in datasets of $\simeq$ 70 pb^{-1} each	0.5 Million $D^0 \rightarrow K\pi$

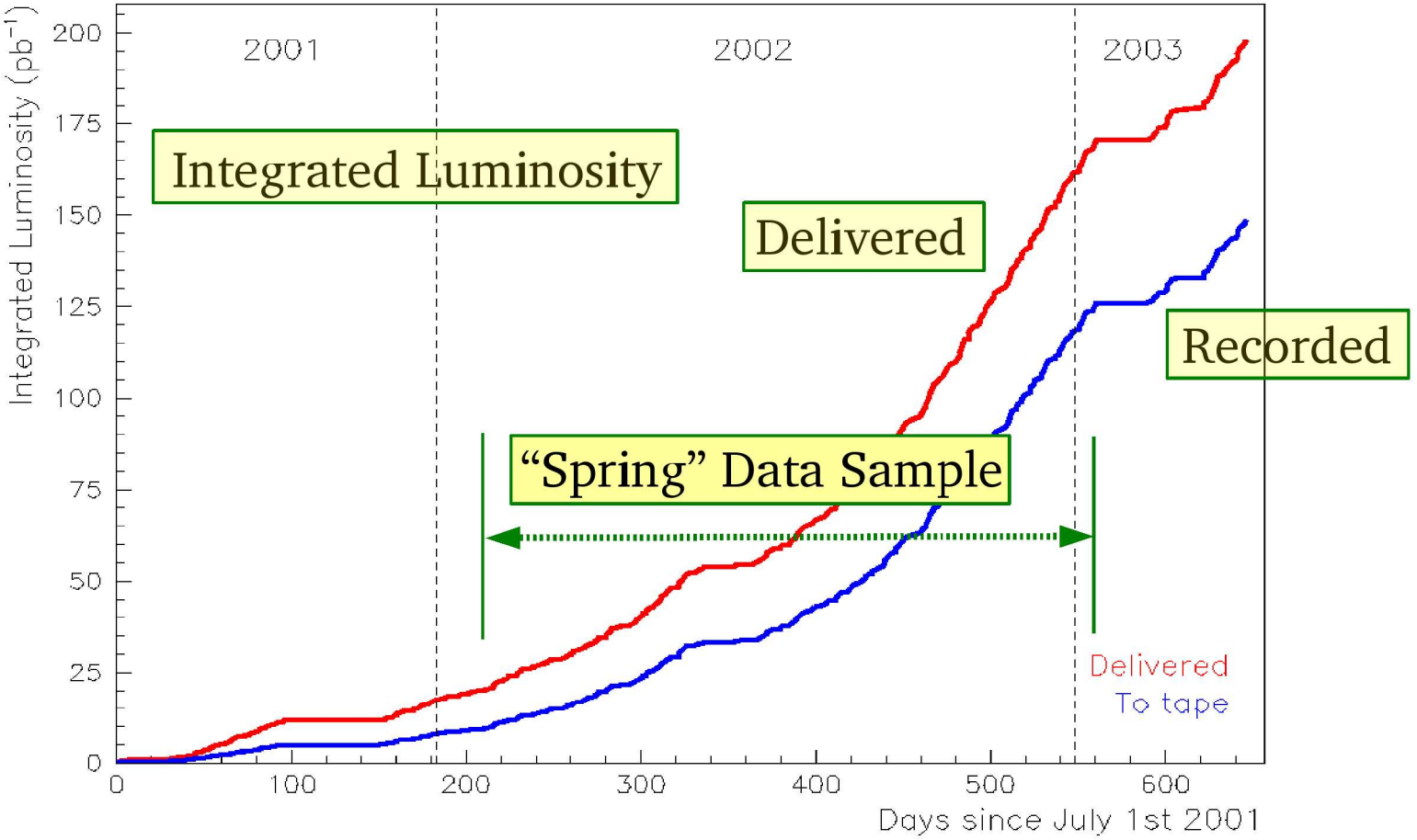


More than
one million
fully reconstructed
charm decays
per 100 pb^{-1}



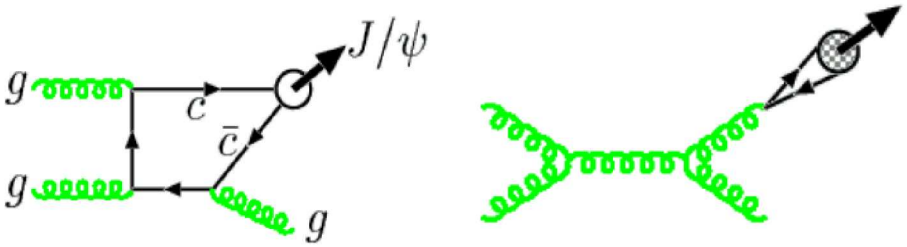
Data Taking

- Run II total: $\int L\,dt \simeq 200\ pb^{-1}$ **delivered, CDF wrote 150 pb^{-1} to tape**
- Present analyses make use of up to $\simeq 70\ pb^{-1}$ (Run I $\simeq 110\ pb^{-1}$)
- $1fb^{-1}$ at BaBar corresponds to about $1pb^{-1}$ at CDF (# of reconstructed c mesons)

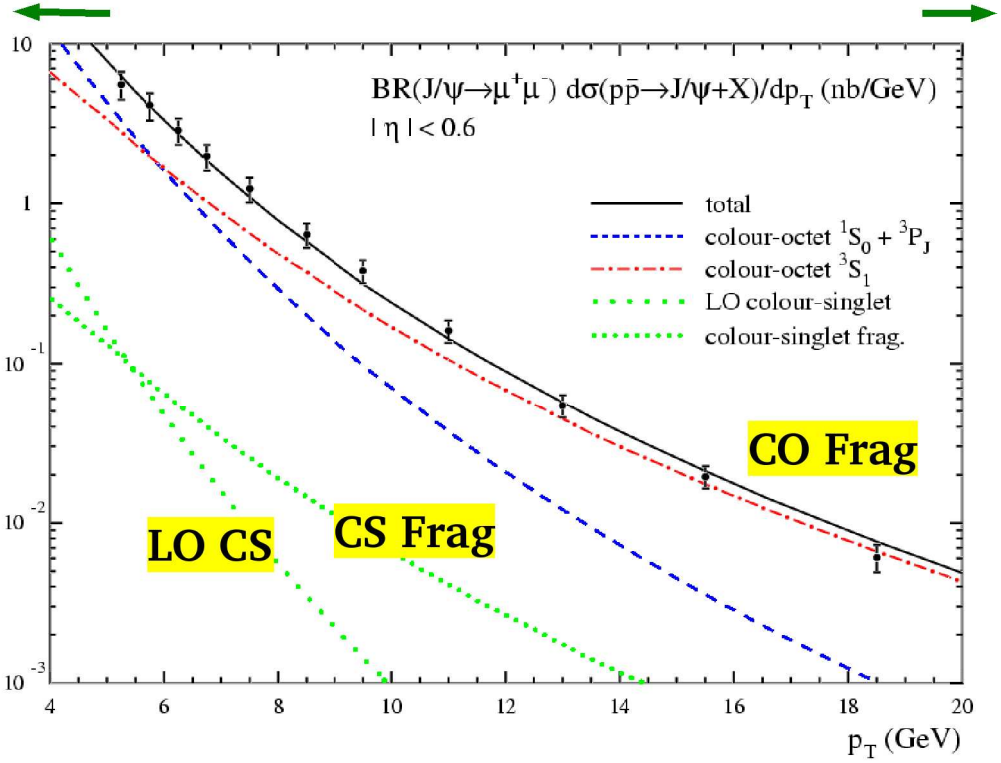


J/ψ: Following up on Run I

- Pre-Tevatron: Colour singlet fusion
  - Low by orders of magnitude



- Two new ingredients:
  - Gluon fragmentation important (e.g. CS fragmentation)
  - Colour octet states important- e.g. NRQCD expansion:
    - $d\sigma(H) = \sum_n d\sigma[c\bar{c}(n)]\ \langle O^H(n)\rangle$
    - n includes colour singlet and octet states
    - Expansion in α_s and v (relative velocity of quark and anti-quark)

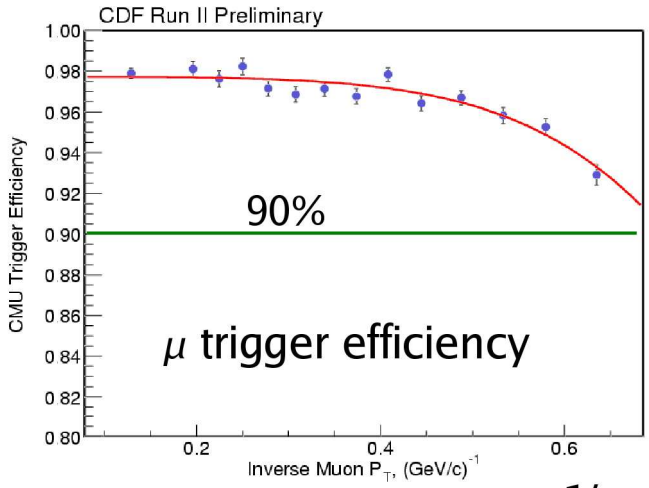


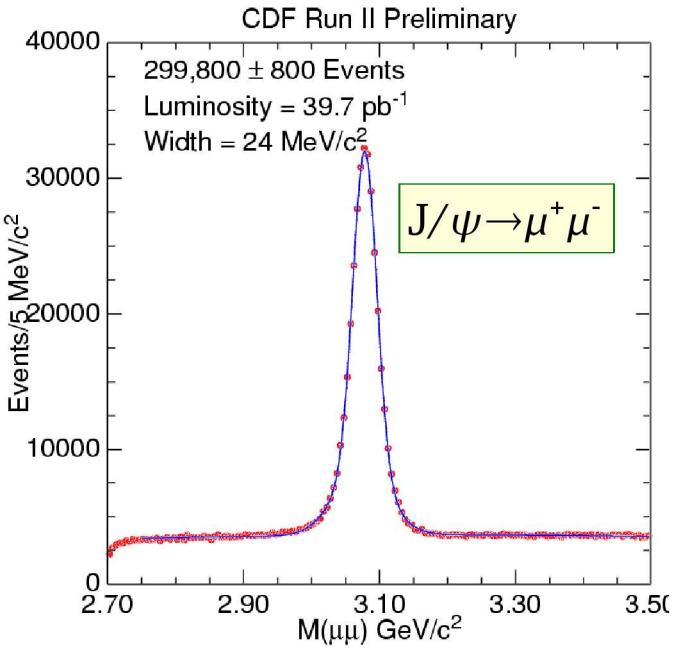
Beneke, Krämer, PRD 55(1997) 5269
CDF Data: PRL 79(1997) 572
(Run 1A data, 18 pb^{-1})

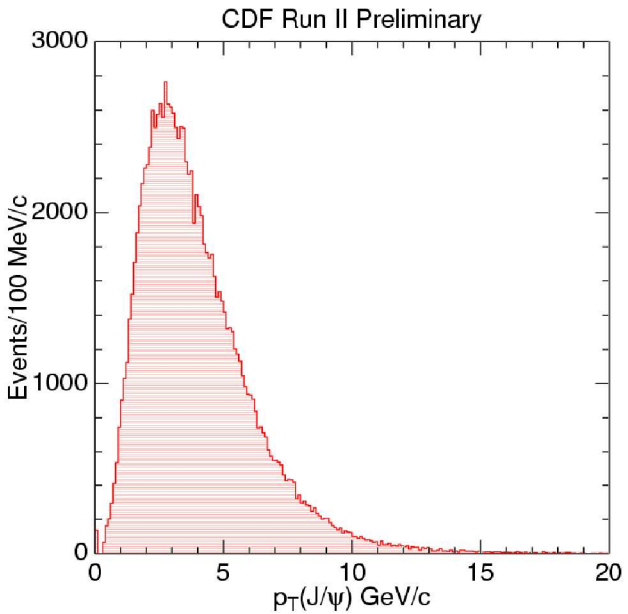
Colour octet fragmentation dominates at high p_T

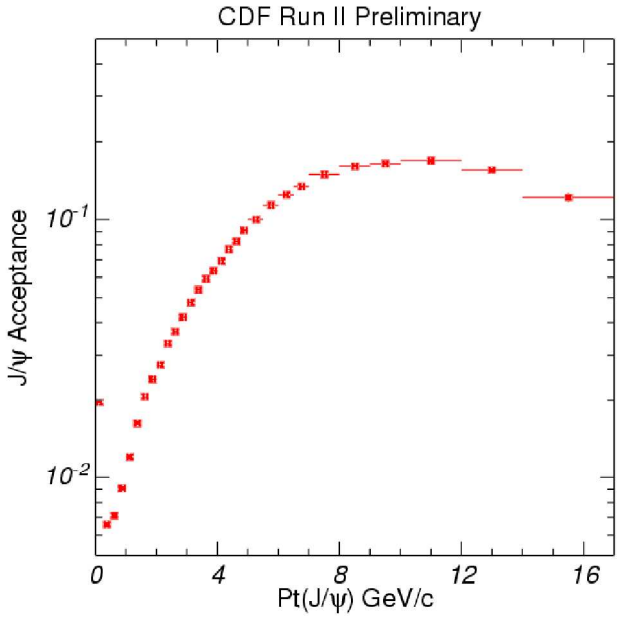
J/ψ Cross Section

- Increased cms energy 1.8TeV → 1.96TeV
- Dimuon trigger threshold lowered to 1.5GeV
  - Acceptance down to J/ψ at rest ($P_T(J/\psi) > 5$GeV in Run I)
  - $J/\psi \to \mu^+\mu^-$ yield: 3nb (Run I) → 9nb (Run II)
- Cross section measurement based on data taken in February to October 2002, $\int L\,dt = 40pb^{-1}$





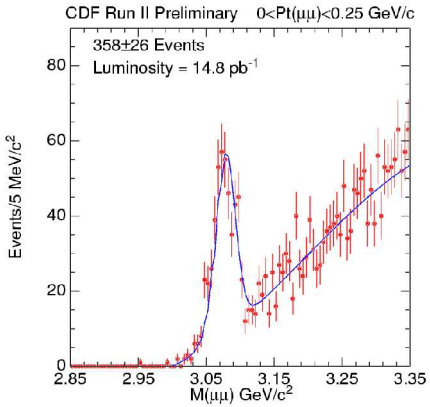




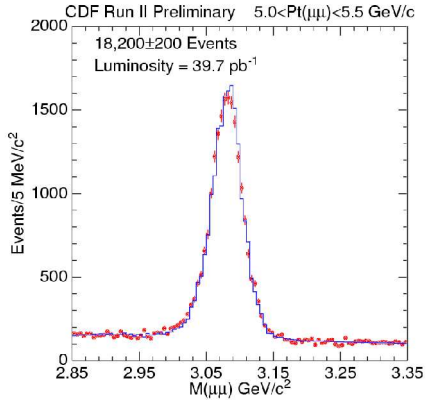
J/ψ Cross Section cont.

- Fit mass spectra using templates from signal MC (including radiative tail from internal bremsstrahlung)
  - + Chebyshev polynomial for background
- Systematic uncertainties

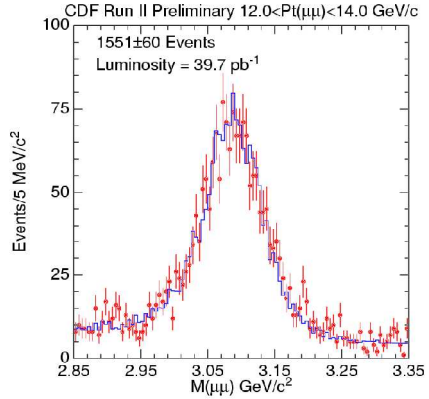
J/ψ polarization	4 – 10%	(p_T dep.)
J/ψ p_T spectrum	3 – 30%	(p_T dep.)
L1 trigger efficiency	–7% to +13%	(p_T dep.)
Mass fits	–1% to +13%	(p_T dep.)
SVXII material description	–3% to +6%	(p_T dep.)
Momentum scale	–0.1% to +0.7%	(p_T dep.)
Luminosity	6%	
CMU simulation	1.4%	
Data quality	1.0%	
Reconstruction efficiency	+2.1 –2.7%	
L1 trigger efficiency	0.2%	
Total	$7\% \oplus \sigma(p_T(J/\psi))$	



low

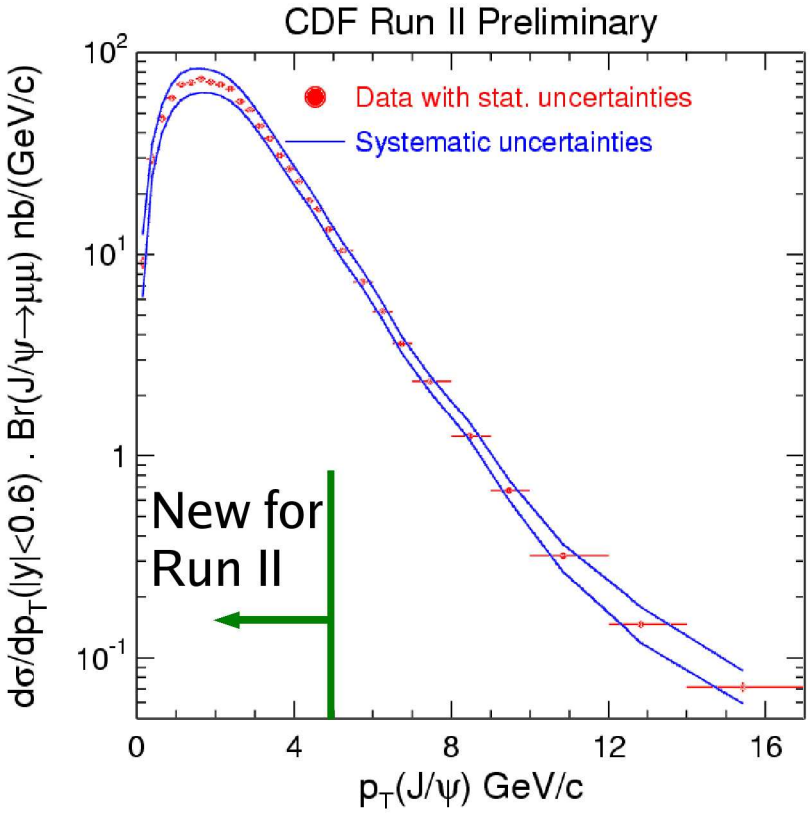


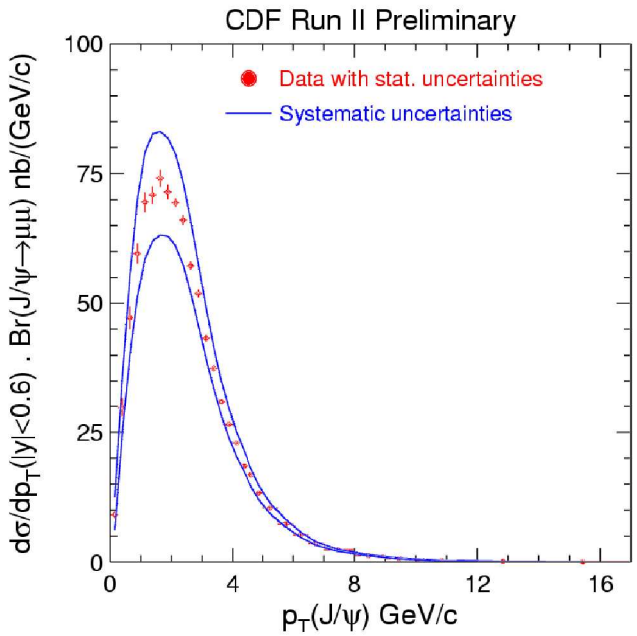
medium p_T



high

Inclusive J/ψ Cross Section





- Soon: separate prompt from B → J/ψ X

Prompt J/ψ cross section includes
- χ_c decays ($\chi_c \rightarrow J/\psi\gamma$)
- $\psi(2S)$ feed-down
- Direct J/ψ (64±6% Run 1)

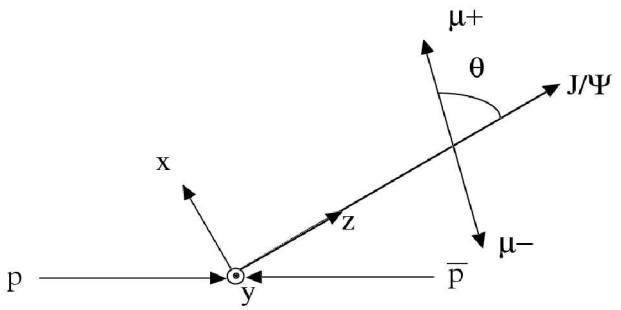
Run II vs. Run I:

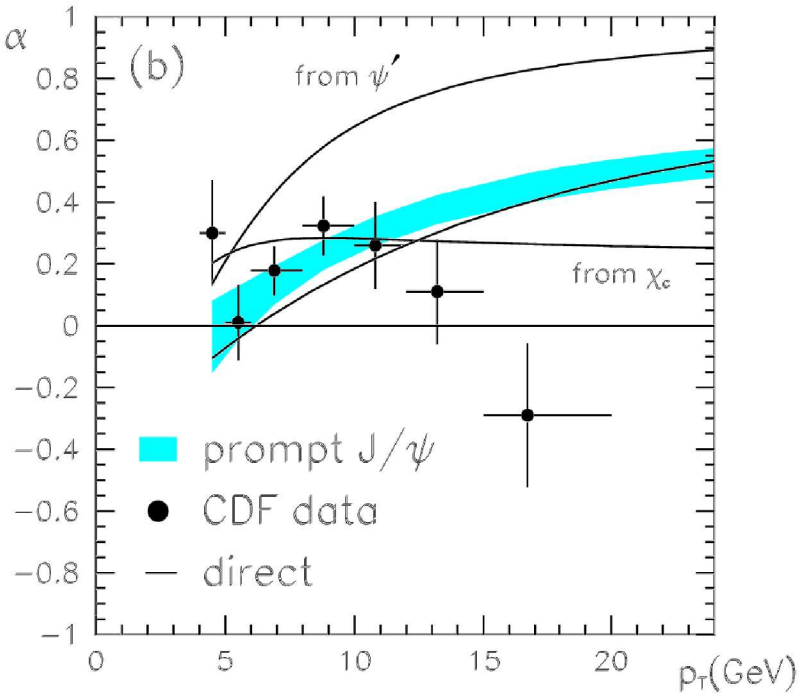
$\sigma(p\,\bar{p} \rightarrow J/\psi X, |y|<0.6) \cdot BR = 240 \pm 1\ (stat)\ {}^{+35}_{-28}\ (syst)$ nb

$\sigma(p\,\bar{p} \rightarrow J/\psi X, |\eta|<0.6, p_T(J/\psi)>5GeV) \cdot BR = 17.4 \pm 0.1\ (stat)\ {}^{+2.6}_{-2.8}\ (syst)$ nb

Future Onia Measurements

- $\psi(2S) \rightarrow$ cleaner (prompt $\equiv$ direct)
- High p_T ($p_T^2 \gg m^2$ theoretically reliable)
- Polarization
- $\Upsilon(1S,2S,3S)$ cross section/polarization



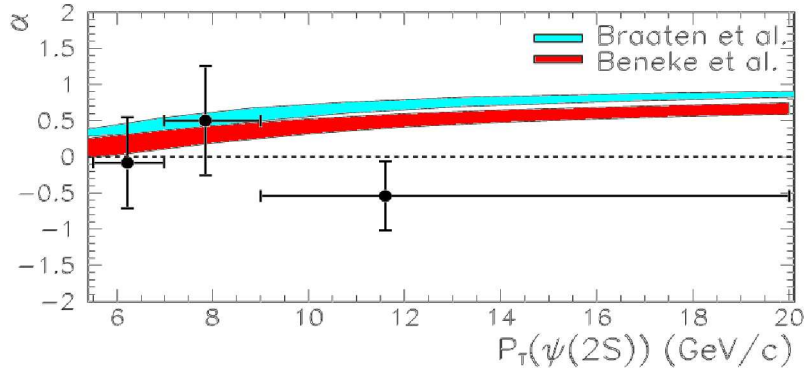


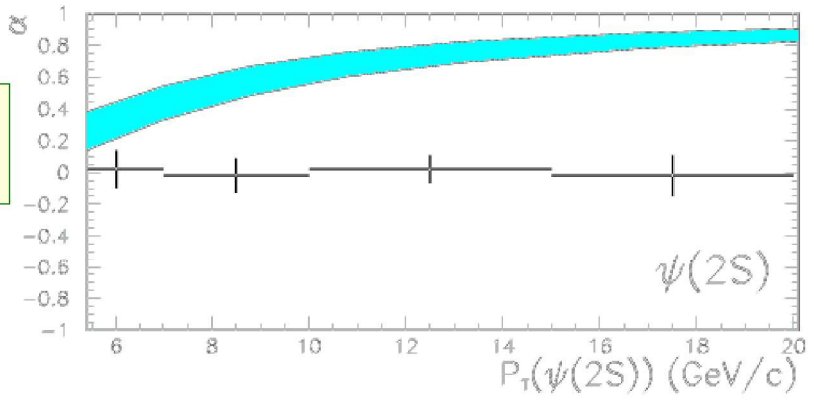
Braaten, Kniehl, Lee
hep-ph/9911436

CDF, PRL 85 (2000) 2886

Run I

Run II
(expected)

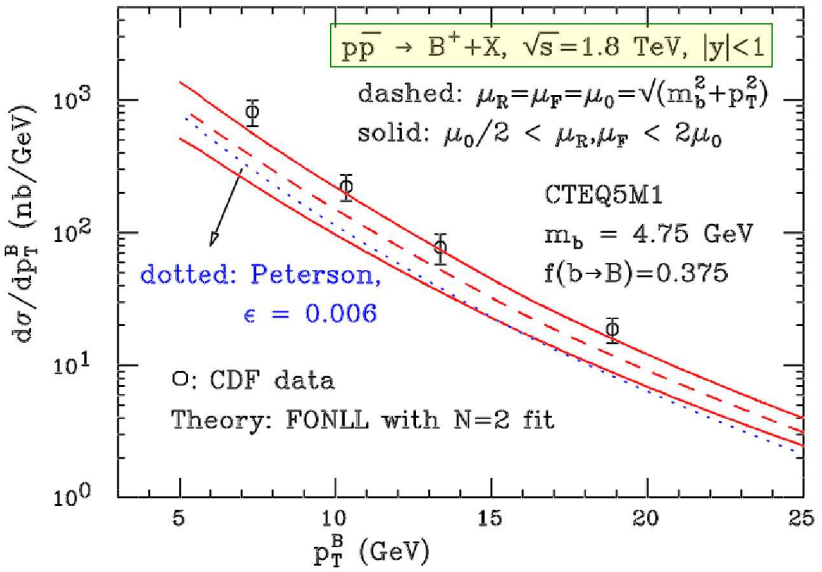




Open Charm Production

- Accumulating large amounts of fully reconstructed charm final states through hadronic "B" trigger
  - Small amount of integrated luminosity is sufficient
- There is no published charm cross section measurement from the Tevatron
  - Unpublished CDF measurement using muons with p_T>8GeV ($D^* \to D^0 \pi_s$, $D^0 \to \mu \nu KX$)

- Of particular interest due to the somewhat large b cross section - what about Charm?
  - Larger discrepancy? (Stronger nonperturbative effects)
  - Smaller discrepancy? (Charm produced further from threshold; softer fragmentation is better understood)



Charm Cross Section Recipe

1. Reconstruct and count charm mesons
2. Measure direct charm meson fraction
   (Direct vs. secondary from B mesons)
3. Trigger and reconstruction efficiency
4. Luminosity
5. Calculate cross section

$$\sigma_i = \frac{N_i / 2 \cdot f_{D,i}}{\int L\,dt \cdot \varepsilon_i \cdot BR}$$

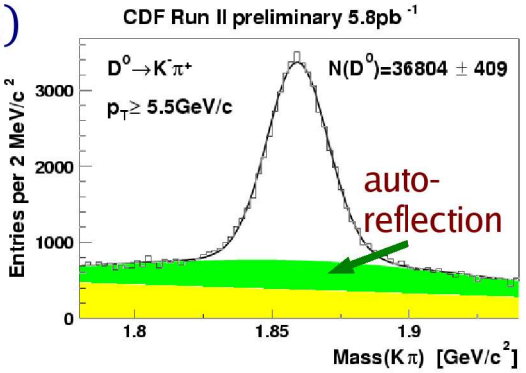
- Data sample: 5.7pb^{-1} (Feb-Mar 2002)
- Two-Track Trigger-like selection
- In addition, minimum p_T, L_{xy}
- Pure 2D-Reconstruction

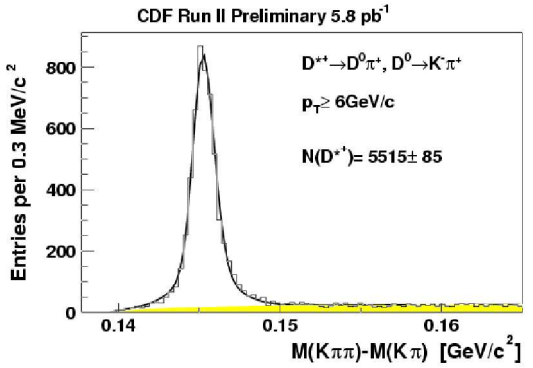
$D^0 \to K^-\pi^+$

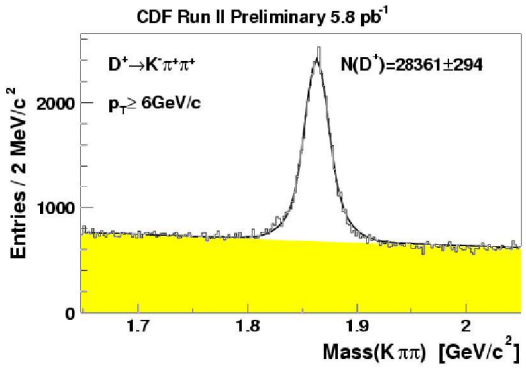
$D^{*+} \to D^0\pi_s^+$ with $D^0 \to K^-\pi^+$

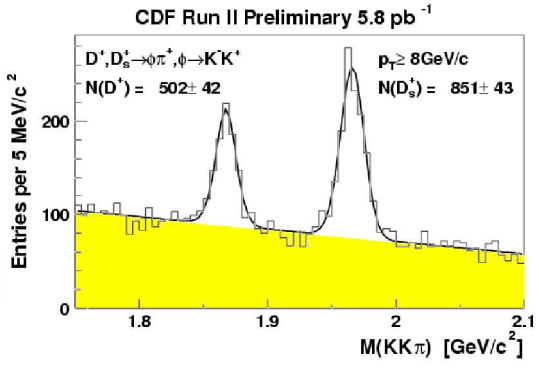
$D^+ \to K^-\pi^+\pi^+$

$D_s^+ \to \phi\pi^+$ with $\phi \to K^+K^-$



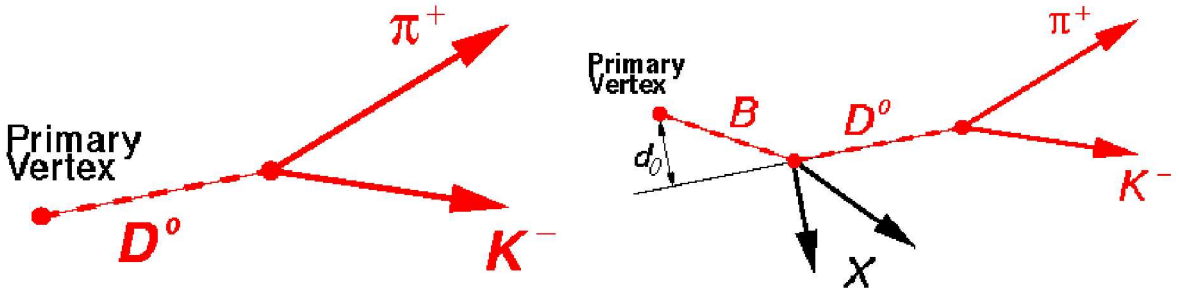




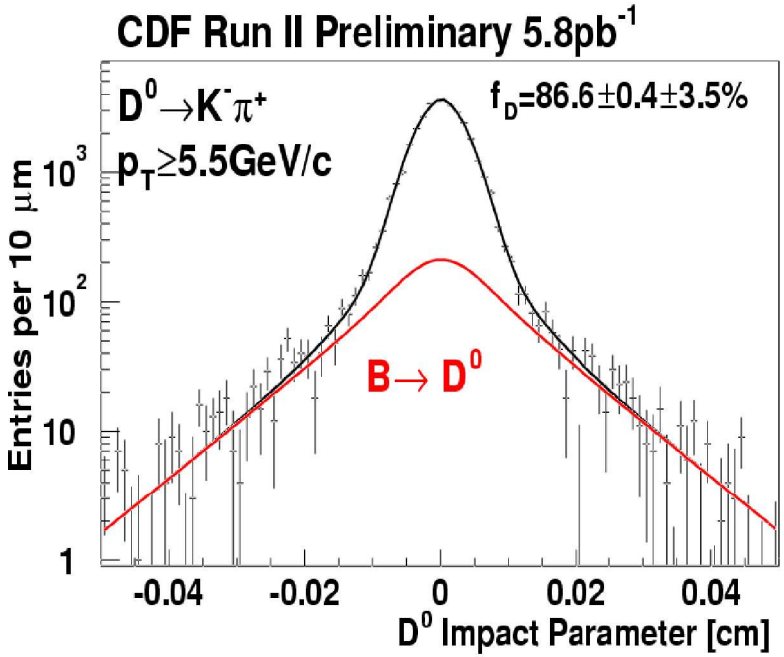


Charm Cross Section: Direct Charm

Use D^0 impact parameter distribution to determine direct component



Secondary D has finite impact parameter



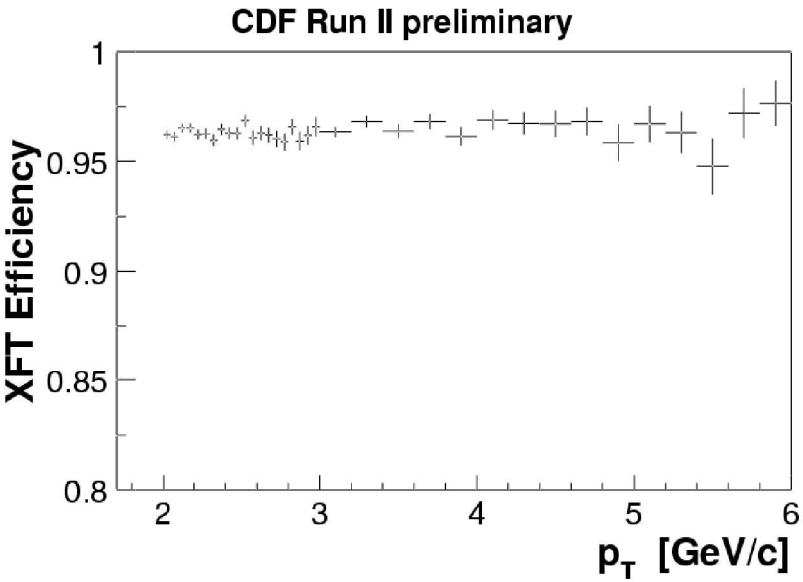
Direct charm meson fraction:

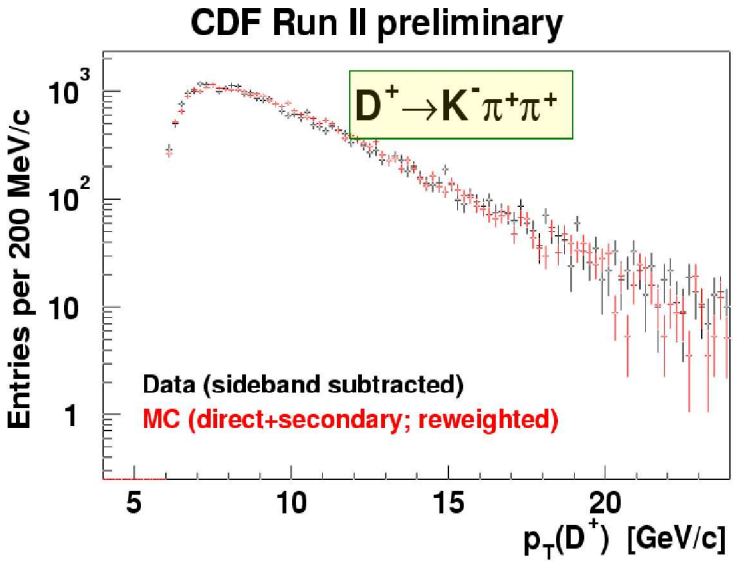
$D^0 \to K^-\pi^+$	$86.5 \pm 0.4 \pm 3.5$ %
$D^{*+} \to D^0\pi_s^+$	$88.1 \pm 1.1 \pm 3.9$ %
$D^+ \to K^-\pi^+\pi^+$	$89.1 \pm 0.4 \pm 2.8$ %
$D_s^+ \to \phi\pi^+$	$77.3 \pm 4.0 \pm 3.4$ %

Most reconstructed charm mesons are direct

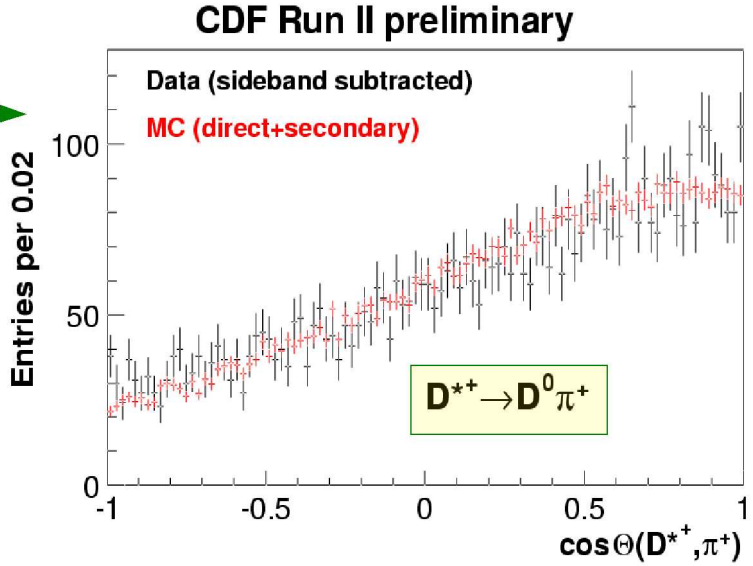
Charm Cross Section: Efficiencies

- Most efficiencies (XFT, SVT, SVX) and resolutions (XFT, SVT, SVX) determined from data
- Example: XFT efficiency
- COT track efficiency determined from MC track embedding in real data
- Reweight Monte Carlo simulation with measured p_T spectra





Decay angle of π in D* rest frame



Charm Cross Section

Total cross sections (PDG2002 BR's), |y|<1:

$\sigma(D^0, p_T>5.5\text{GeV}) =$

$13.3 \pm 0.2 \pm 1.5\ \mu b$

$\sigma(D^{*+}, p_T>6\text{GeV}) =$

$5.2 \pm 0.1 \pm 0.8\ \mu b$

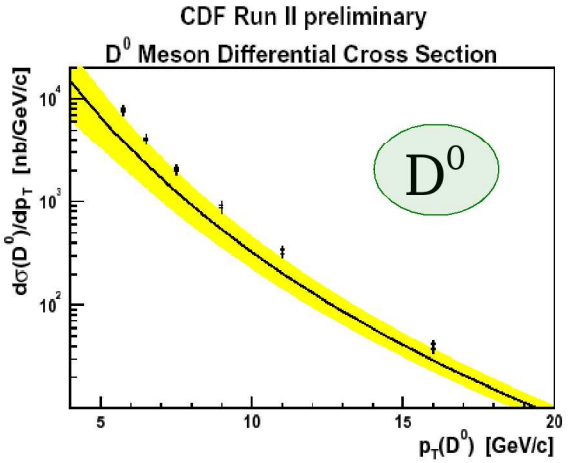
$\sigma(D^+, p_T>6\text{GeV}) =$

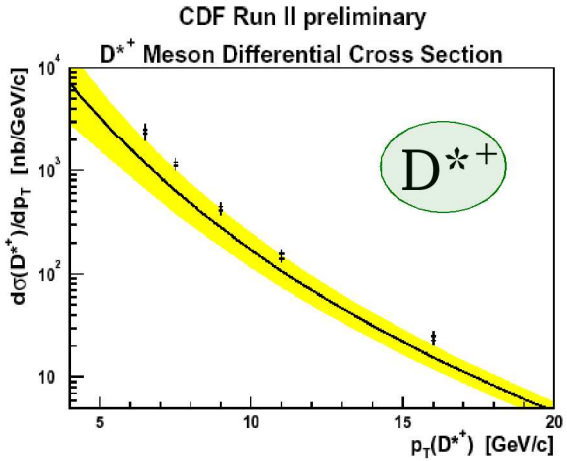
$4.3 \pm 0.1 \pm 0.7\ \mu b$

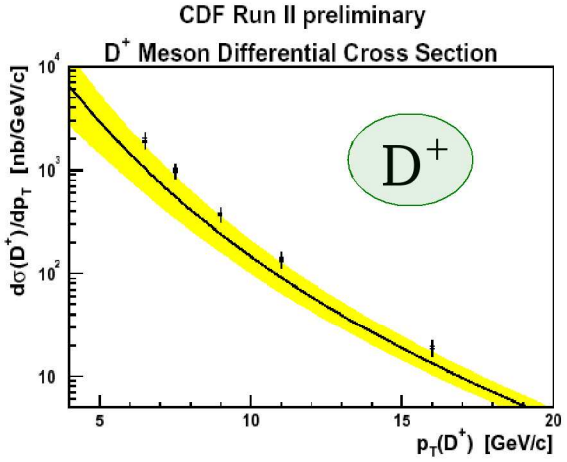
$\sigma(D_S^+, p_T>8\text{GeV}) =$

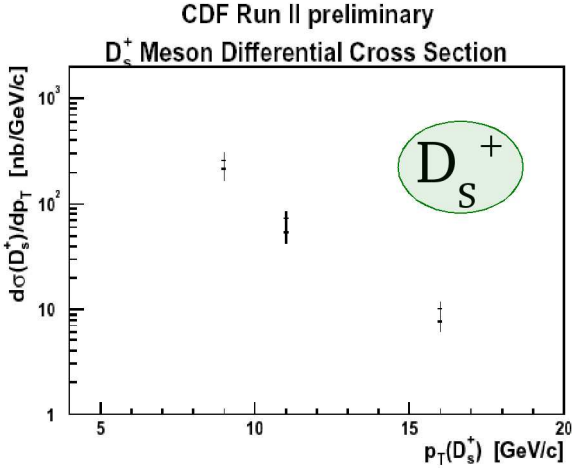
$0.75 \pm 0.05 \pm 0.22\ \mu b$

Differential cross sections





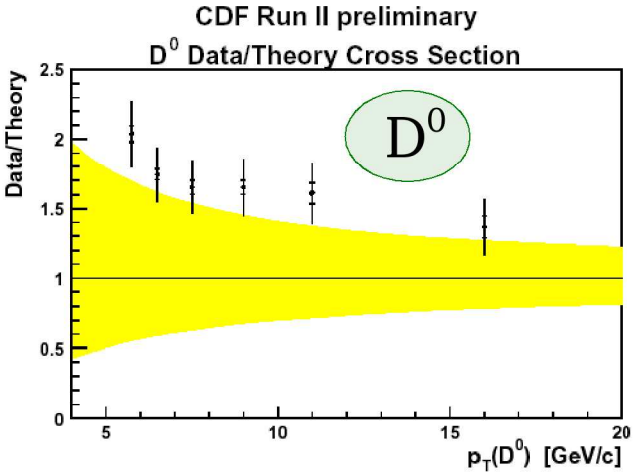


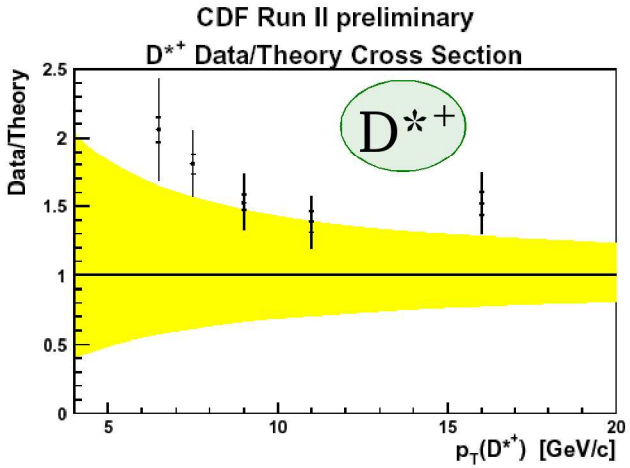


Charm Cross Section cont.

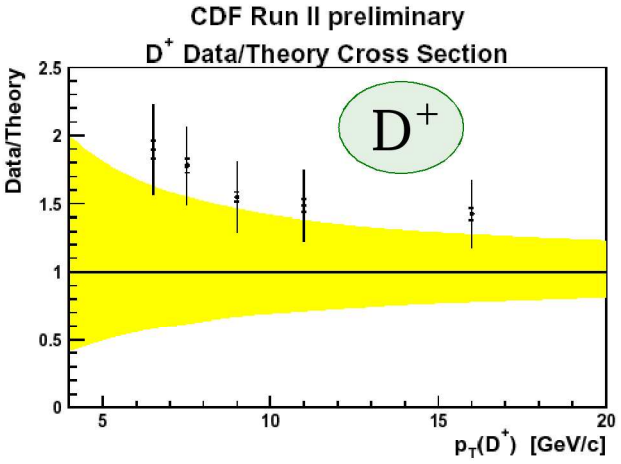
Calculation from M.Cacciari and P.Nason: Resummed pQCD (FONLL)

Ratio of measured to predicted cross section:





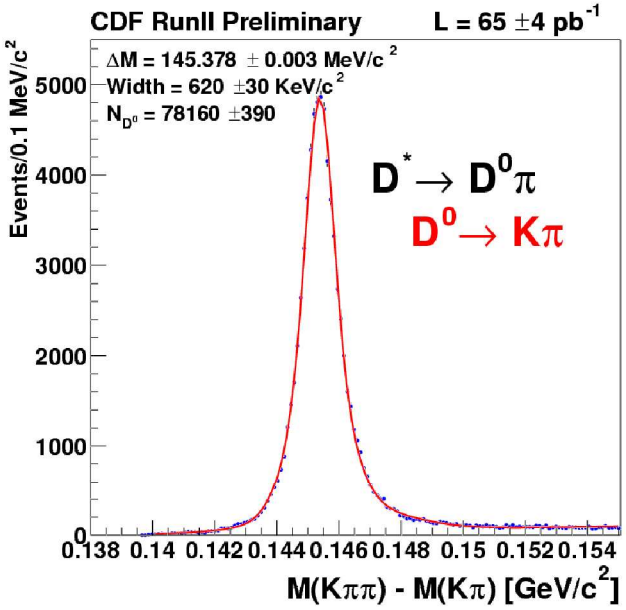
CTEQ6M PDF
m_c = 1.5GeV
Fragm.function:
from Aleph meas.
Renorm.and fact.scale:
$m_T=(m_c^2+p_T^2)^{1/2}$
Uncertainty:
vary scale from .5 to 2

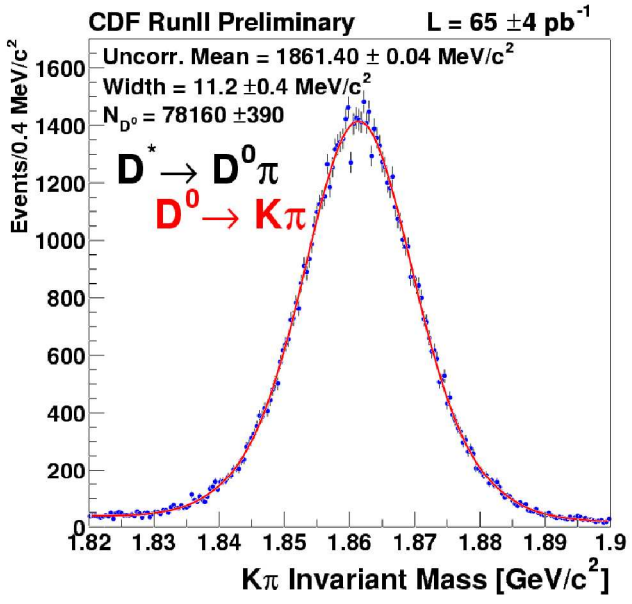


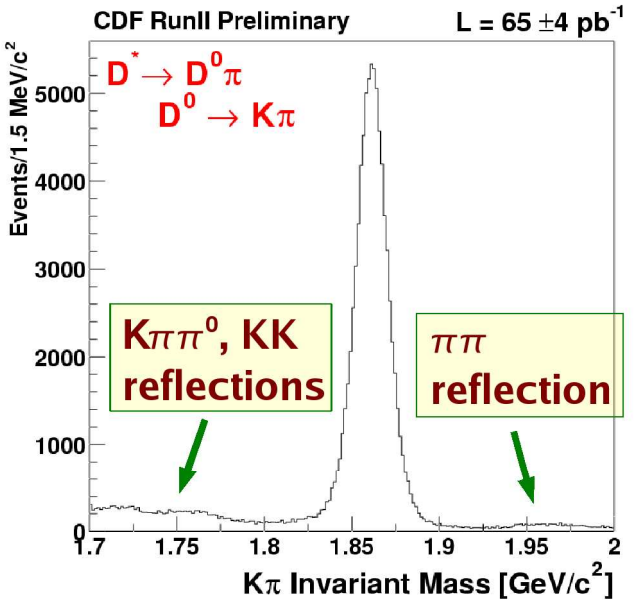
- Measured cross section higher
- Not incompatible with uncertainties
- p_T shape consistent for D mesons

$D^0 \rightarrow K\pi$, KK, $\pi\pi$

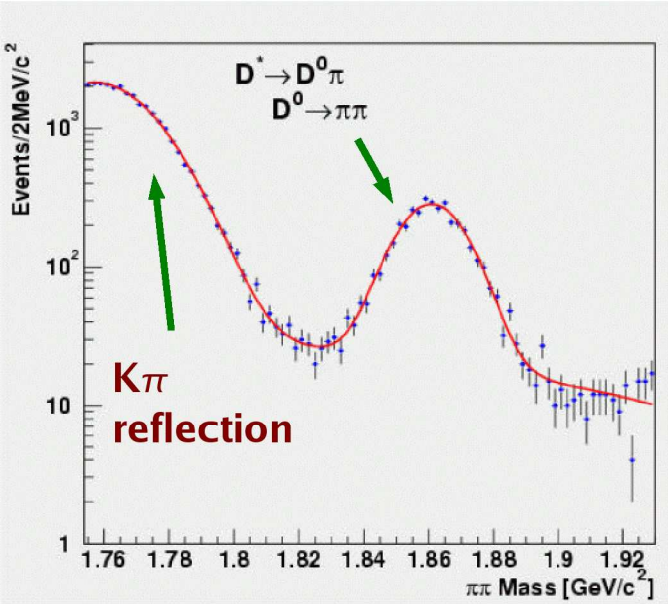
- Relative branching fraction for Cabibbo suppressed D^0 decays
  - Ratio of branching ratios → many systematics cancel (normalize to dominant $D^0 \rightarrow K\pi$)
  - Relative acceptance of the KK and $\pi\pi$ modes is within 10% of $D^0 \rightarrow K\pi$
- Measure CP-violating decay asymmetries for $D^0 \rightarrow$ KK and $\pi\pi$ with respect to $K\pi$
  - Need to control intrinsic detector charge asymmetry
  - Tag D^0 through soft pion charge correlation in the D* sample: $D^{*+} \rightarrow D^0\pi^+$ vs. $D^{*-} \rightarrow \bar{D}^0\pi^-$

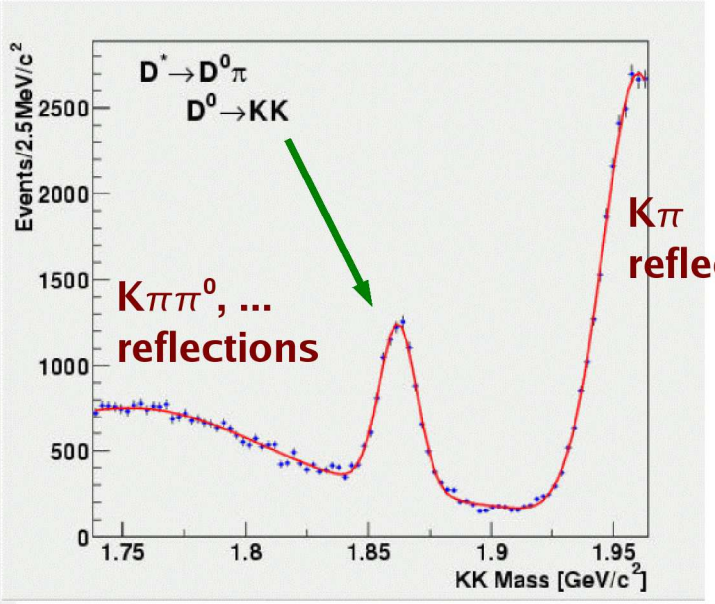






$D^0 \to K\pi, KK, \pi\pi$





$$\Gamma(D \to KK) / \Gamma(D \to K\pi) = 9.41 \pm 0.18 \ (stat) \pm 0.13 \ (syst) \ \%$$
$$\Gamma(D \to \pi\pi) / \Gamma(D \to K\pi) = 3.686 \pm 0.076 \ (stat) \pm 0.084 \ (syst) \ \%$$

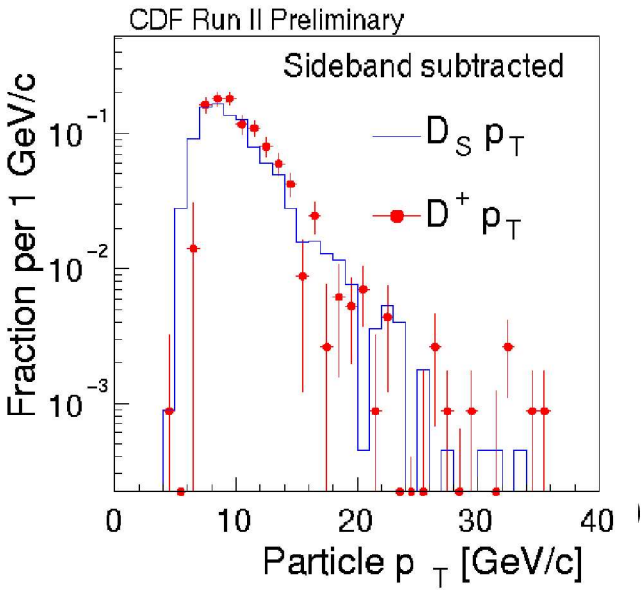
FOCUS 2003: 9.93 ± 0.20 % (KK/Kπ)
3.53 ± 0.13 % (ππ/Kπ)

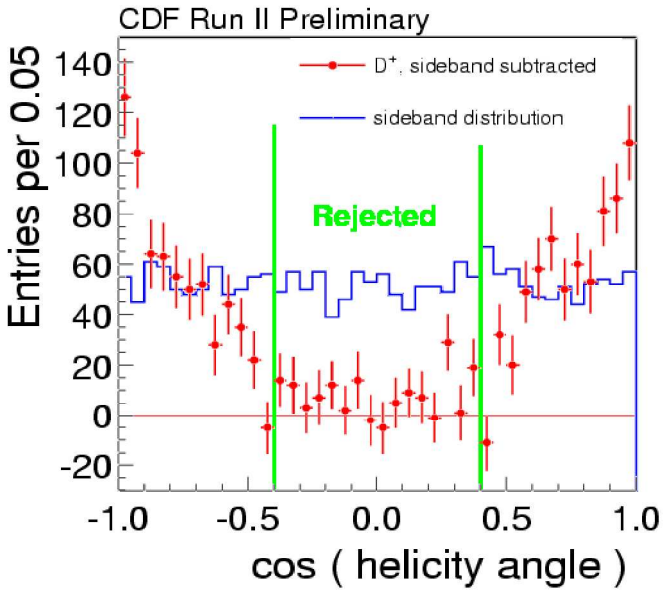
Uncertainties for CP-asymmetry limit are also comparable to best measurement

D_s, D^+ Mass Difference

- **$m(D_s)$-$m(D^+)$ enters the global PDG fit for all charmed meson masses**
- Reconstruct both mesons in the decay channel $D \to \phi\,\pi$
  - kinematically very similar
  - many systematics cancel
- Spring 2002 data, $\int L\,dt \simeq 11.6\ pb^{-1}$, Two-Track Trigger
- Exploit polarization of ϕ coming from D decay: $|\cos\alpha| > 0.4$, where α is the helicity angle (angle between K and D direction in the ϕ rest frame)

$$D^+ \to \phi\ \pi$$
$$D_s \to \phi\ \pi$$
$$\hookrightarrow KK$$

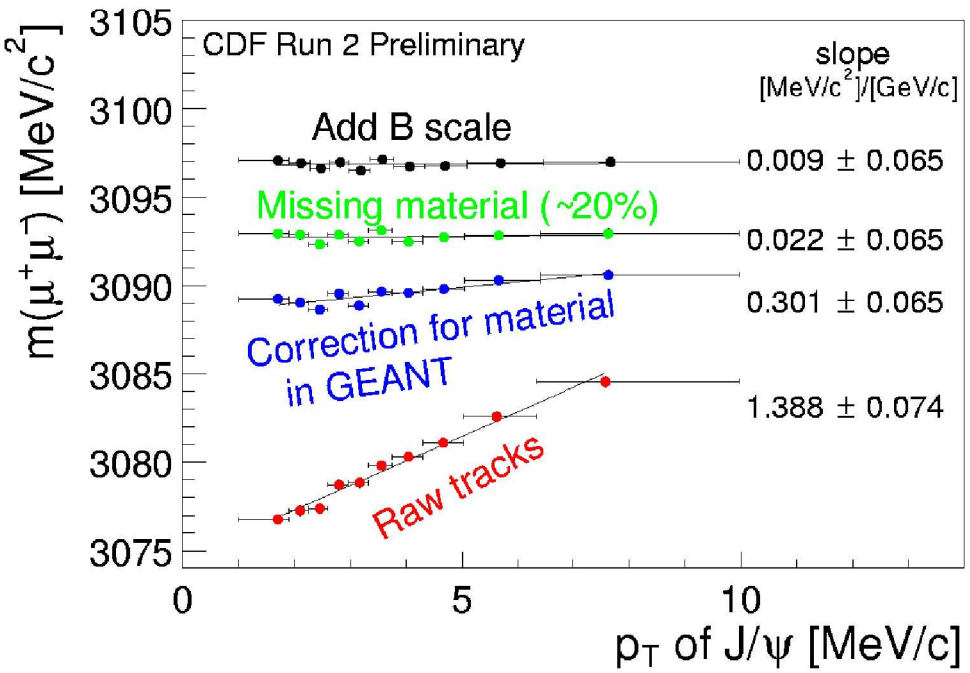




Tracking: Energy Loss and B Field

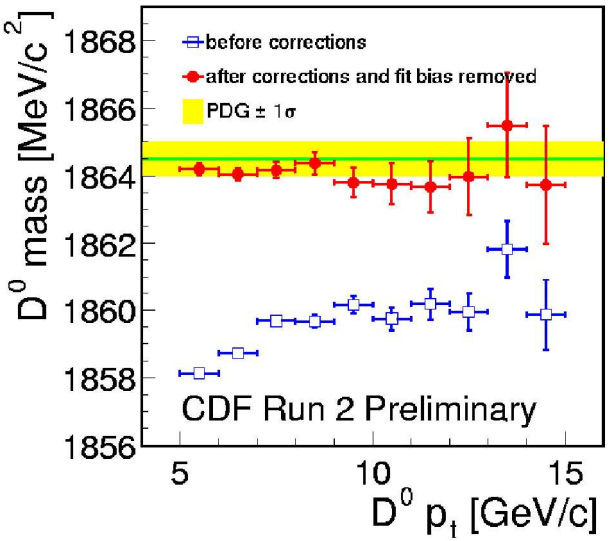
For mass measurements, need excellent understanding of energy loss and magnetic field

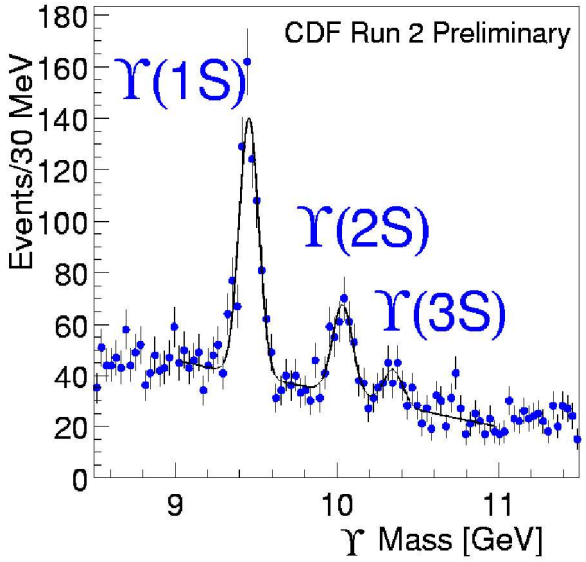
Calibrate with J/ψ



Reconstructed J/ψ mass as function of p_T(J/ψ)

Verify with other decays

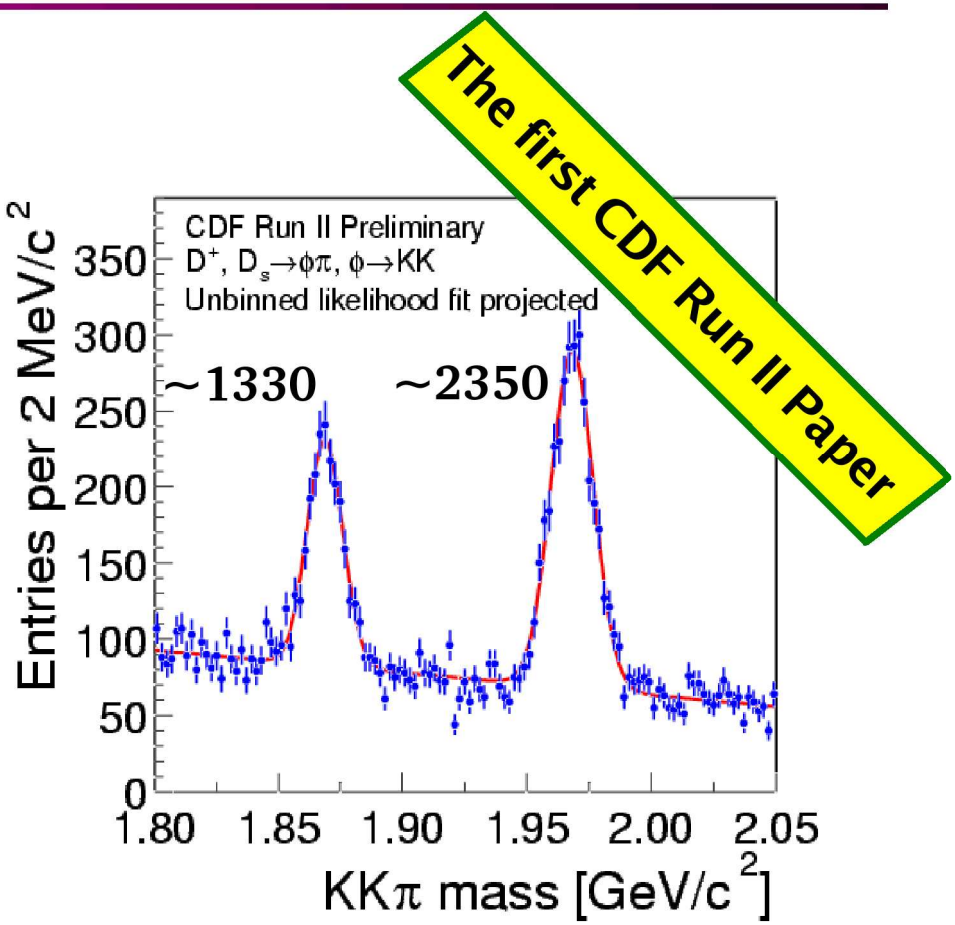




D_s, D^+ Mass Difference cont.

- Unbinned maximum likelihood fit on all candidates that pass the selection criteria within $1.80 < m < 2.05$ GeV
- Fitting method tested against toy Monte Carlo to check for *fitting biases* and other problems
- Main systematic uncertainties

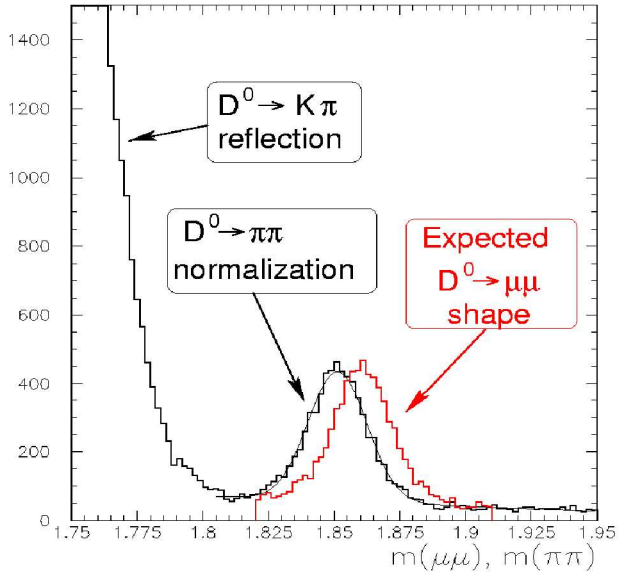
Selection	0.11 MeV
"false curvature", momentum scale, ...	0.12 MeV
Fitting procedure	0.14 MeV
Total syst. uncertainty	**0.21 MeV**

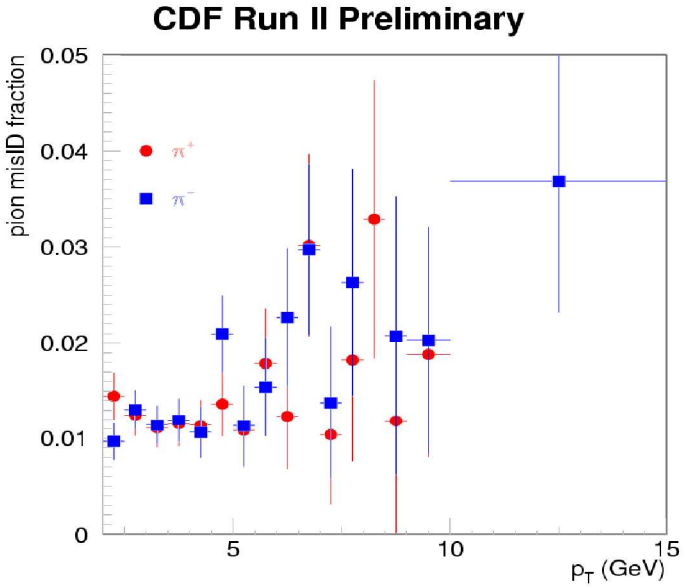


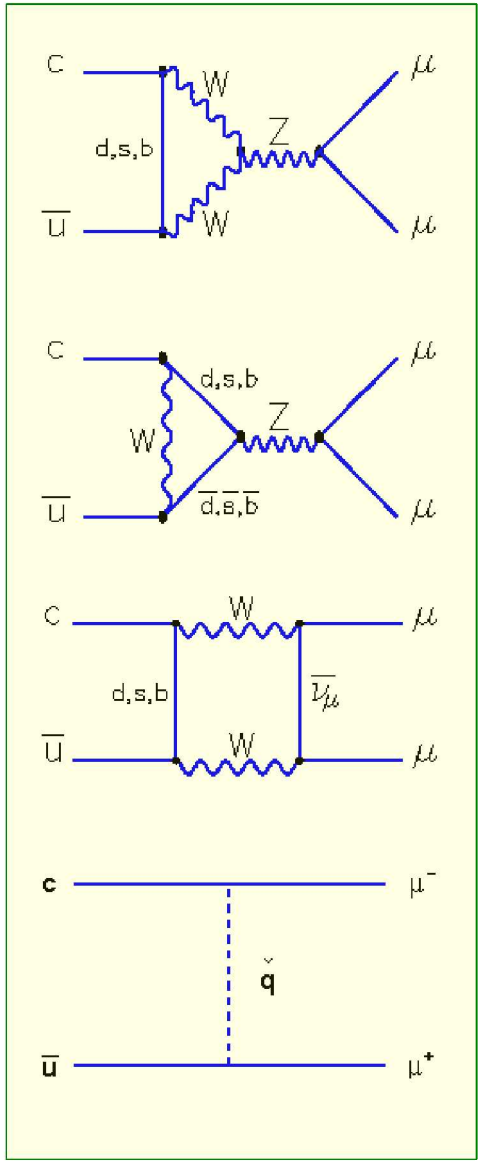
$$m(D_s) - m(D^+) = 99.41 \pm 0.38\ (stat) \pm 0.21\ (syst)\ \text{MeV}$$

(PDG: 99.2 ± 0.5 MeV)

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

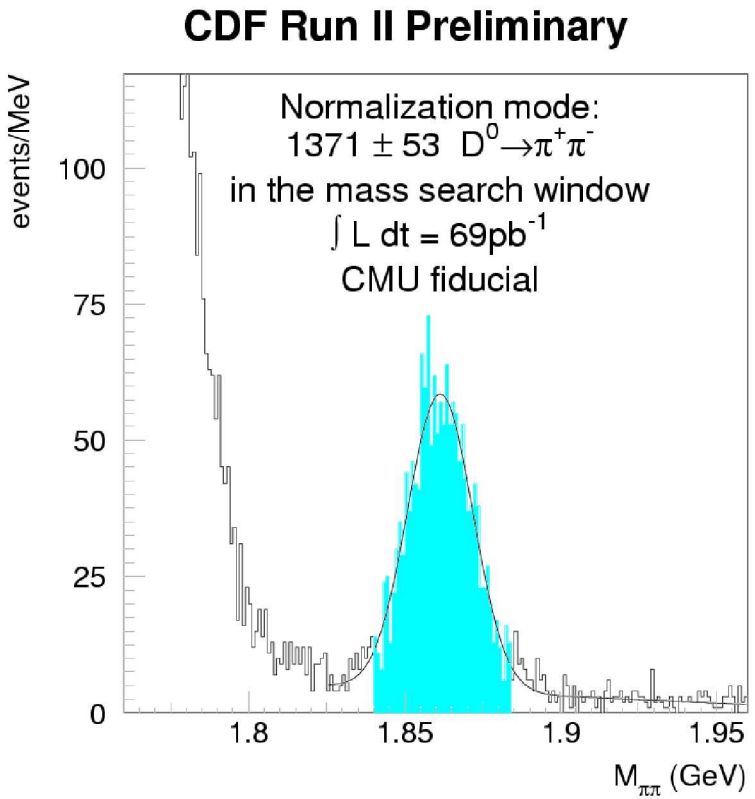


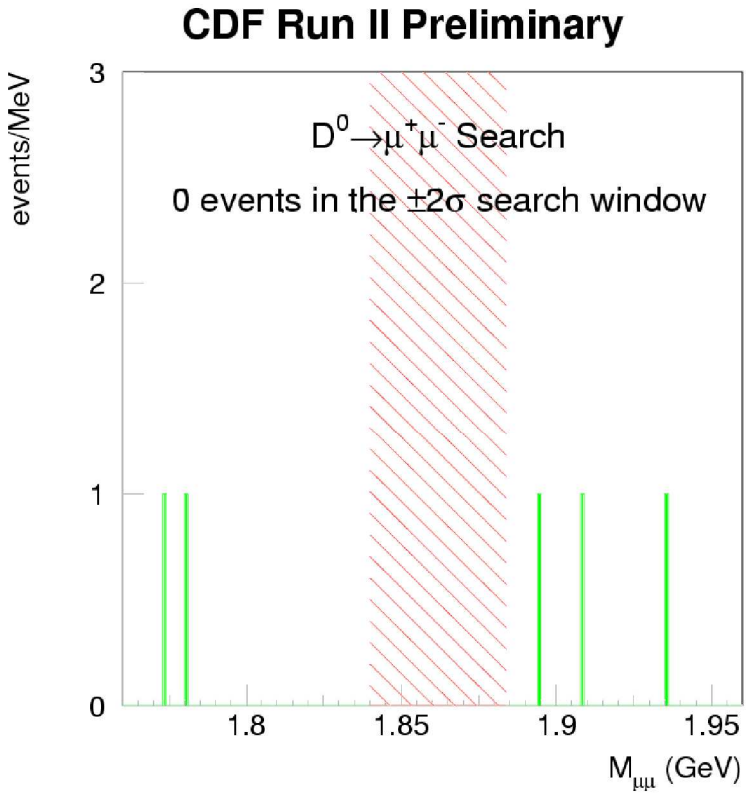




- Standard Model expectation $\mathbf{BR(D^0 \to \mu^+\mu^-) \simeq 3 \cdot 10^{-13}}$
  - Clean territory for new physics search
  - R-parity violating SUSY models: **BR up to 3-4 · 10^{-6}**
- Use $D^{*+} \to D^0 \pi^+$ to reduce background
- Normalize to $D^0 \to \pi^+\pi^-$
- Background: a) Combinatorics (from high mass sideband)
  b) Muon fake rates (from $D^0 \to K^-\pi^+$)

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





- In $\int L\,dt \simeq 69pb^{-1}$ of data collected with Two-Track Trigger: no signal events observed, 1.8 ± 0.7 expected background events
- $$\frac{\mathcal{B}(D^0 \to \mu^+\mu^-)}{\mathcal{B}(D^0 \to \pi^+\pi^-)} = \frac{N_{CL}^{upper}(D^0 \to \mu^+\mu^-)}{N(D^0 \to \pi^+\pi^-)} \times \frac{\epsilon(D^0 \to \pi^+\pi^-)}{\epsilon(D^0 \to \mu^+\mu^-)}$$

$BR(D^0 \to \mu^+\mu^-) \leq 2.4 \cdot 10^{-6}$ at 90% CL (PDG: $BR(D^0 \to \mu^+\mu^-) \leq 4.1 \cdot 10^{-6}$)

Summary

- **The Silicon Vertex Trigger turned CDF into a Charm factory**
  - $O(10^7)$ $D^0 \to K\pi$ expected in 2 fb^{-1}
- J/ψ cross section in new kinematic region
- First measurement of charm cross section at the Tevatron
- Several competitive measurements
  - $BR(D^0 \to \mu^+\mu^-)$, $BR(D^0 \to K\pi/KK/\pi\pi)$ ratios, $m(D_s) - m(D^+)$
- The first Run II CDF paper is out
  - "Measurement of the Mass Difference $m(D_s^+) - m(D^+)$ at CDF II"