Results on QCD and Heavy Flavors Production at the Tevatron

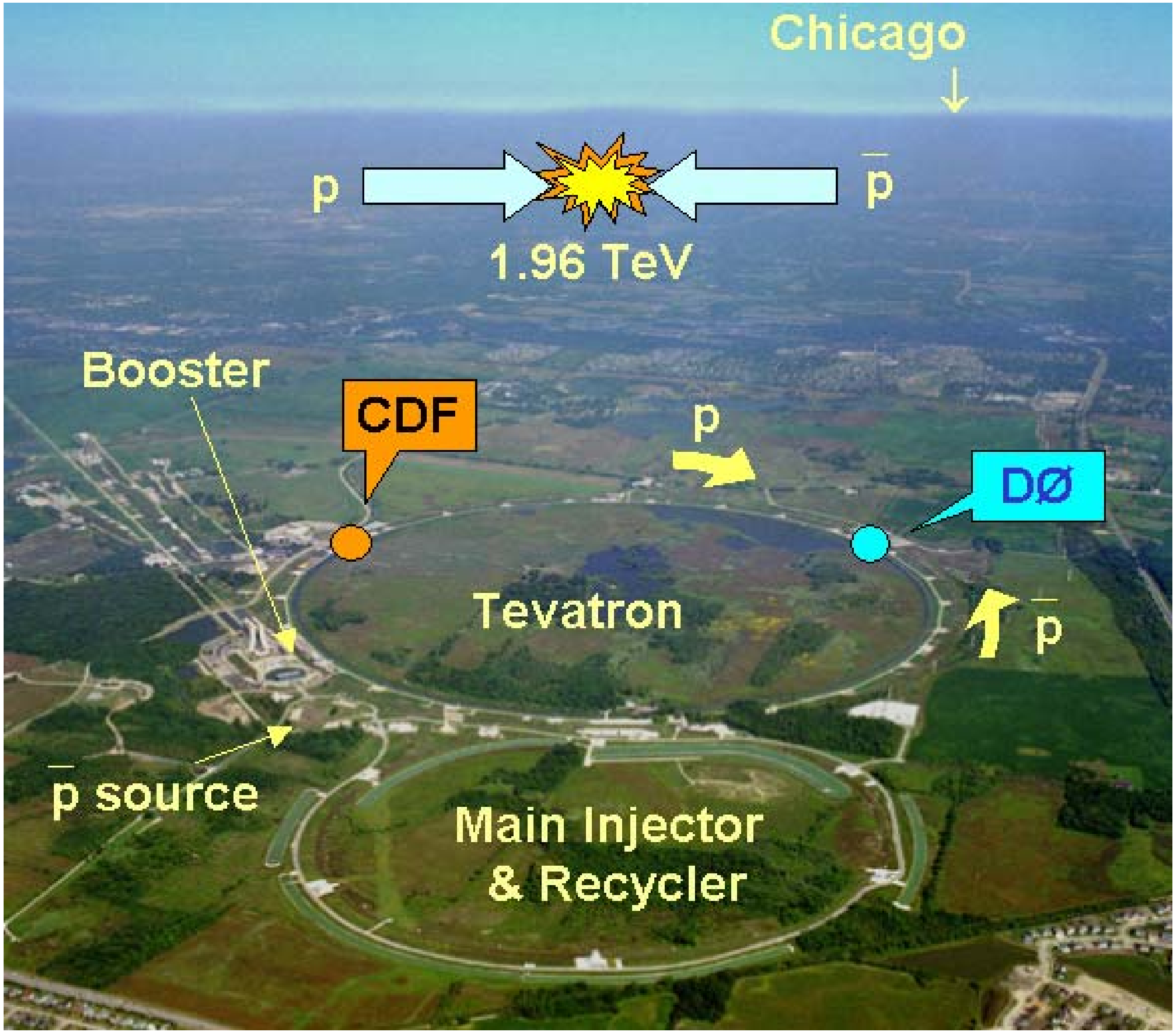
Donatella Lucchesi
INFN and University of Padova

October 21 – Padova

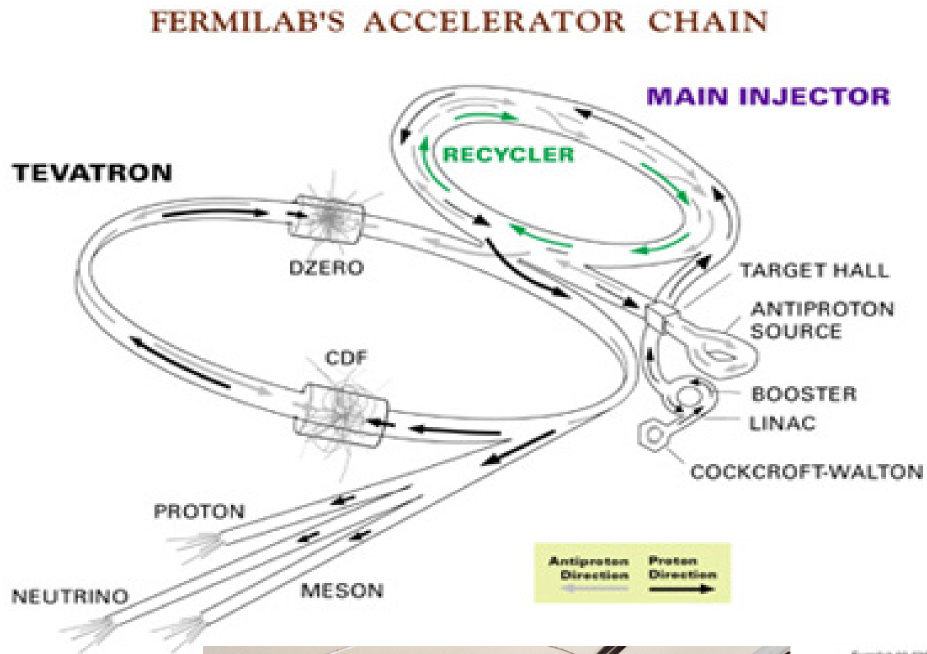
Outline:

- Machine and detector description
- Latest results on QCD
- Heavy Flavor: c and b production
- Pentaquarks searches
- Conclusions

The Machine


Chicago
p
$\bar{p}$
1.96 TeV
Booster
CDF
p
DØ
Tevatron
$\bar{p}$
$\bar{p}$ source
Main Injector
& Recycler

Tevatron Parameter

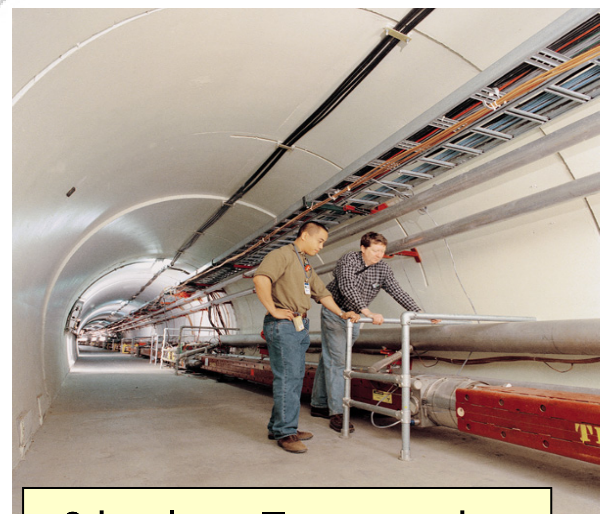


Substantial upgrades for Run II:

→10% energy increase $\sqrt{s}$: 1.8 → 1.96

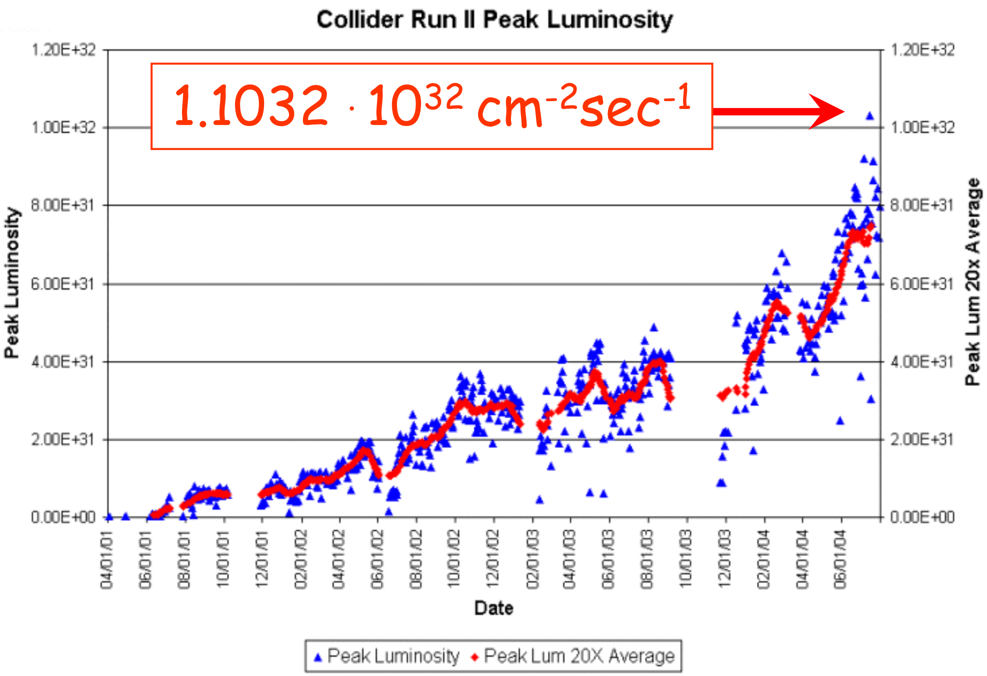
→integrated luminosity increase: x50

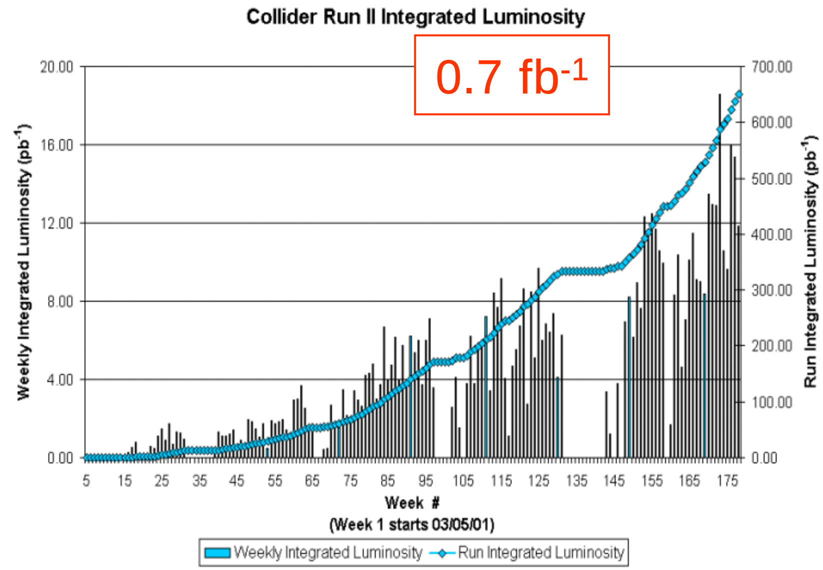
	1992-1995	2001-2009	
	Run I	Run IIa	Run IIb
Bunches in Turn	6 × 6	36 × 36	36 ×36
$\sqrt{s}$ (TeV)	1.8	1.96	1.96
Typical L ($cm^{-2}s^{-1}$)	1.6 ×10^{30}	9 ×10^{31}	3 ×10^{32}
∫ Ldt (pb^{-1}/week)	3	17	50
Bunch crossing (ns)	3500	396	396
Interactions/crossing	2.5	2.3	8



6 km long Tevatron ring

Tevatron Run II Performances





Peak luminosity is above $1 \cdot 10^{32}$ cm^{-2}sec^{-1}

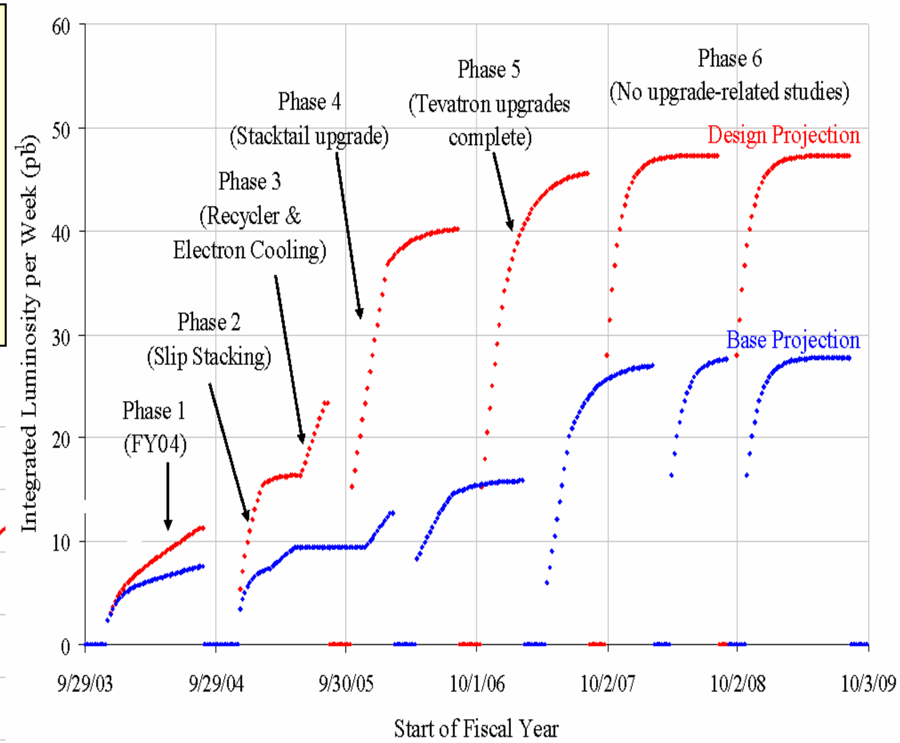
Reliable operation
→ in stores ~120 hours/week

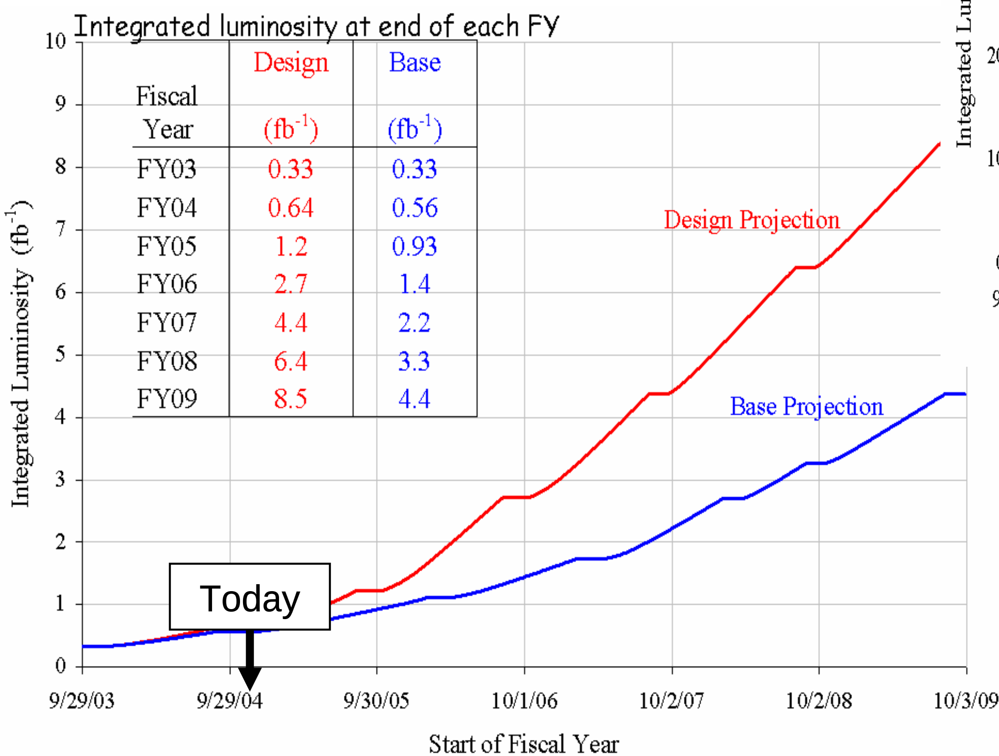
Total ~0.7 fb^{-1} delivered in Run II→ as planned

Tevatron Long Term Luminosity Plan

Increase in number of antiprotons
→ the key for higher luminosity

Expected peak luminosity
→ $3 \cdot 10^{32}$ $cm^{-2}sec^{-1}$ by 2007

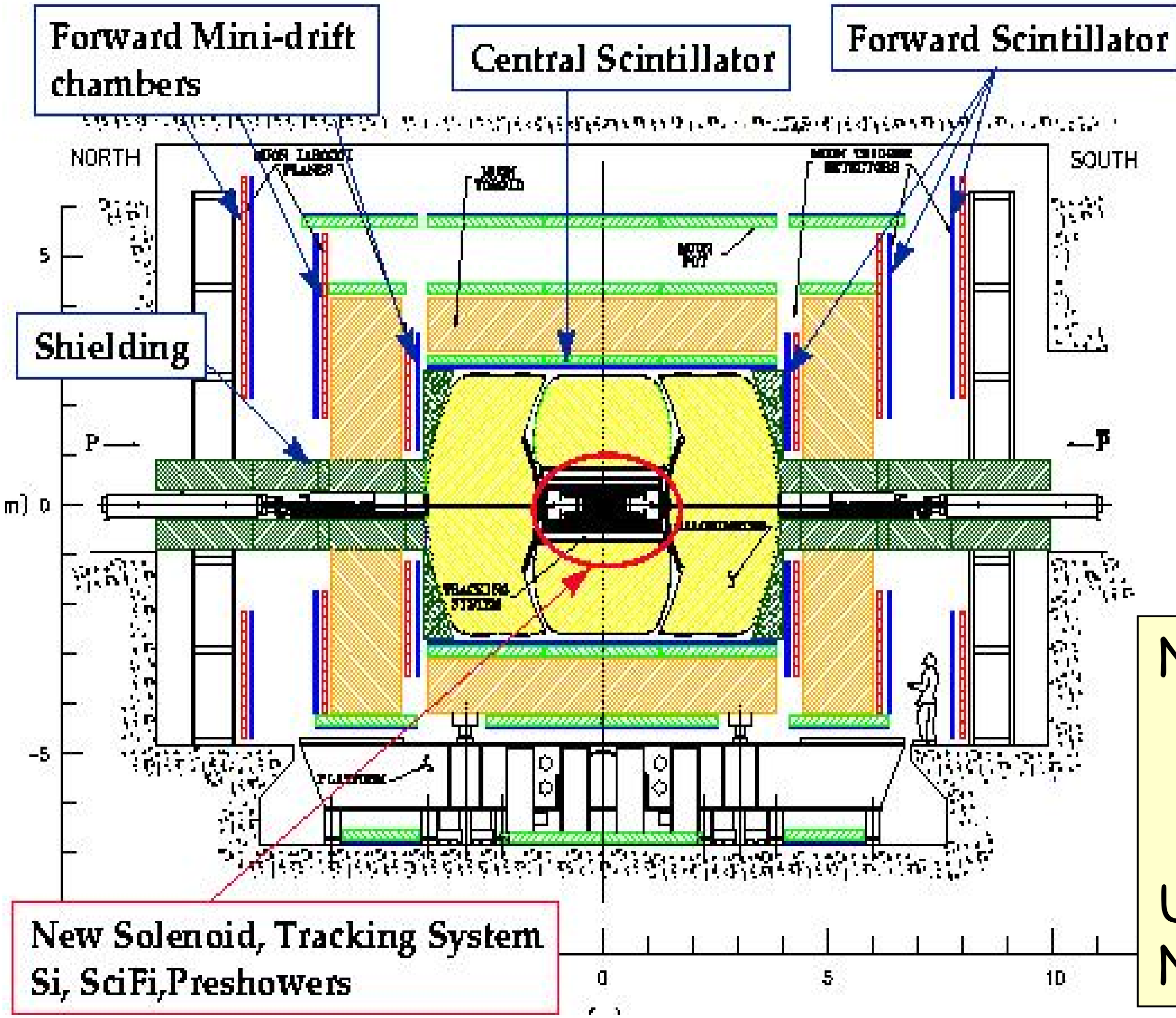




Fiscal Year	Design (fb^{-1})	Base (fb^{-1})
FY03	0.33	0.33
FY04	0.64	0.56
FY05	1.2	0.93
FY06	2.7	1.4
FY07	4.4	2.2
FY08	6.4	3.3
FY09	8.5	4.4

Currently expecting delivered luminosity to each experiment 4-8 fb^{-1} by the end of 2009

The D0 Detector



New
- Silicon Detector
- 2 T solenoid
- Central Fiber Tracker

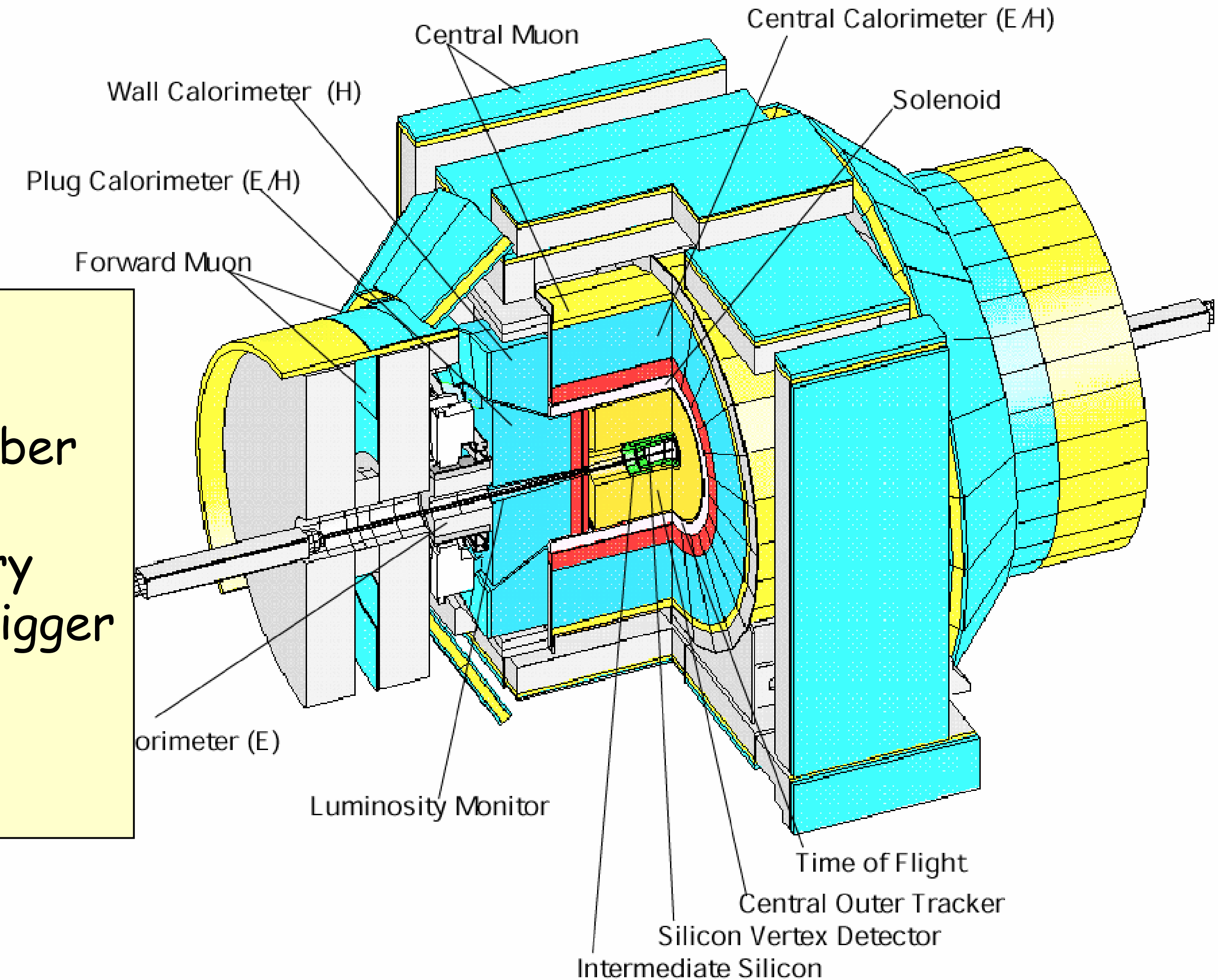
Upgraded muon system

New electronics

The CDF Detector

New
Silicon Detector
Central Drift Chamber
PID
End Plug Calorimetry
Displaced Track Trigger

Extended
muon coverage



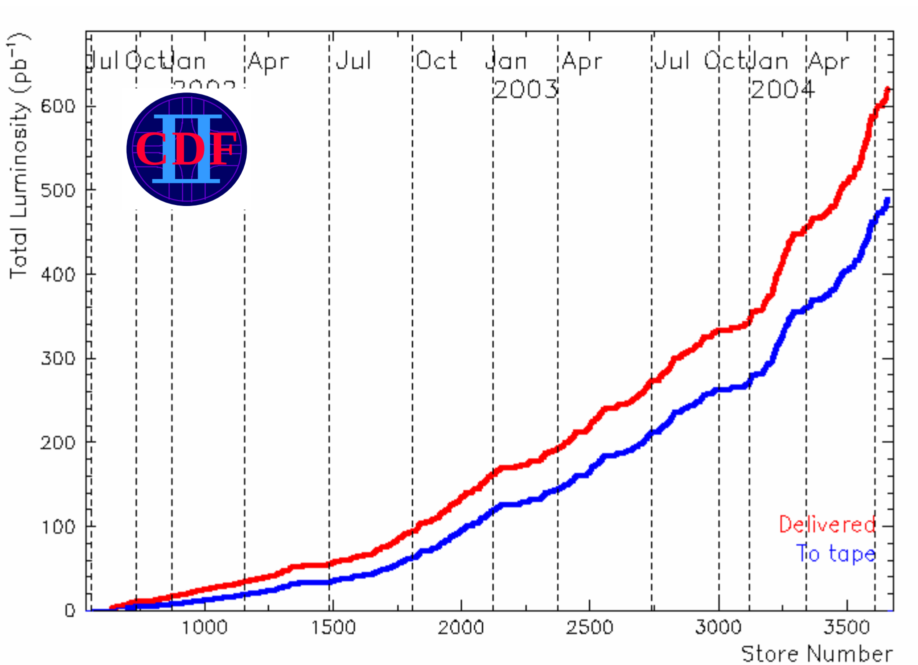
Data Collection

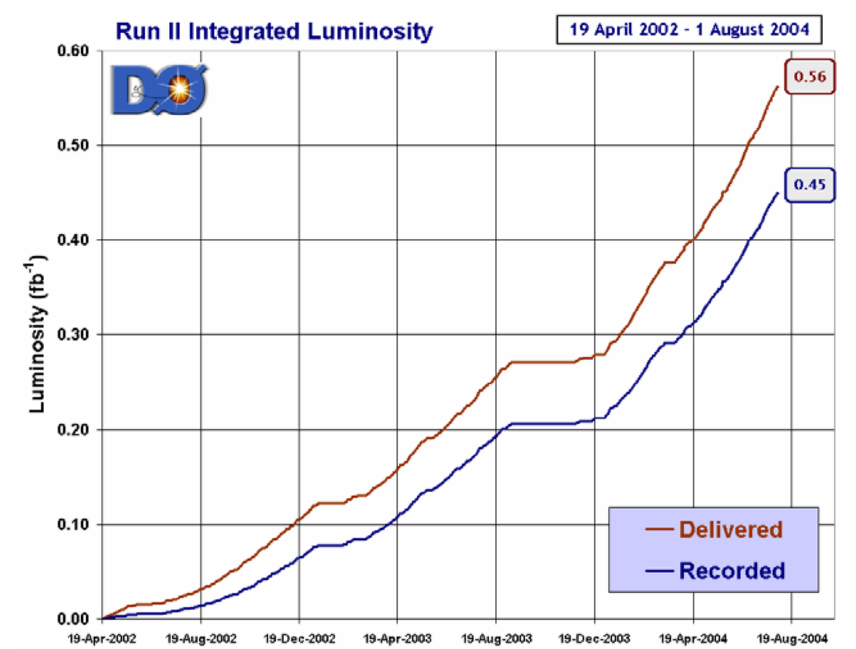
CDF and D0 experiments are very complex

Typical ratio of "recorded" to "delivered" luminosity is 80%-90%

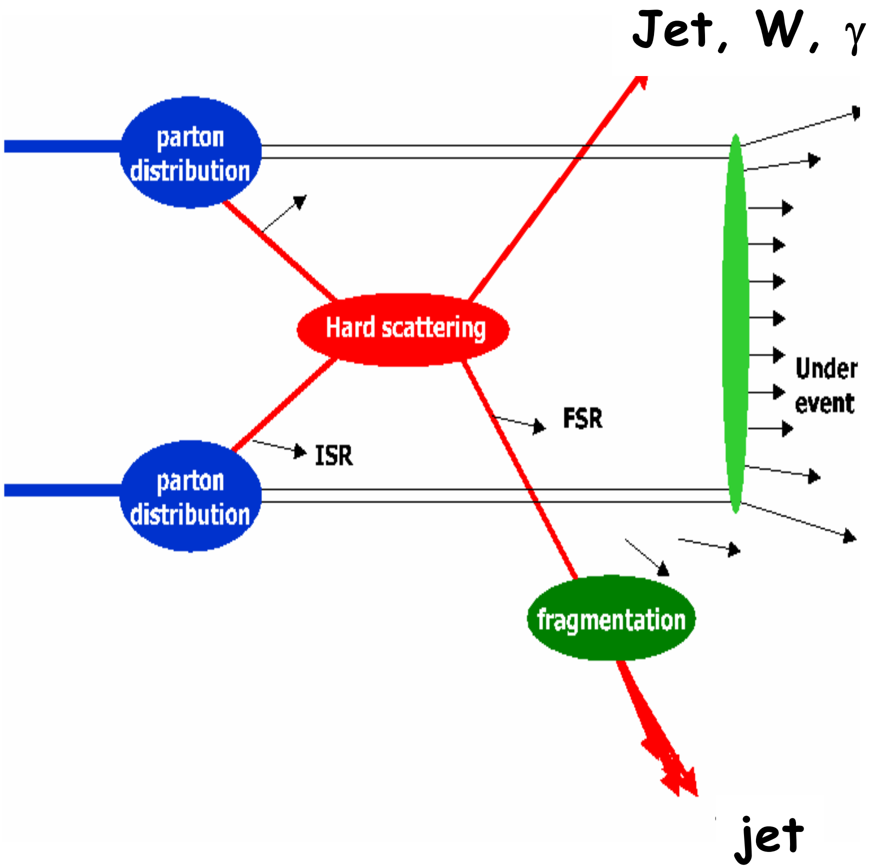
As of now both experiments recorded ~0.5 fb^{-1}

Results presented correspond to ~0.2 fb^{-1}



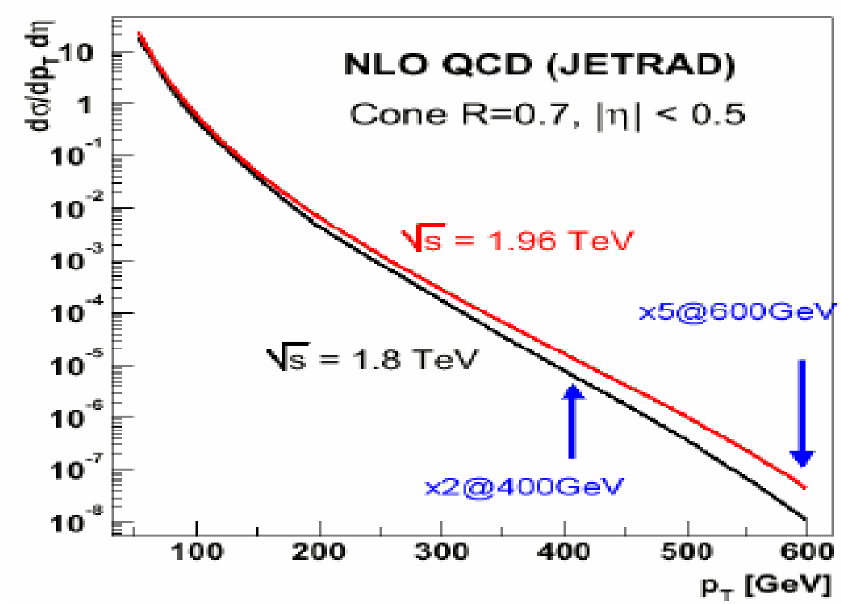


Jet Physics at 2 TeV

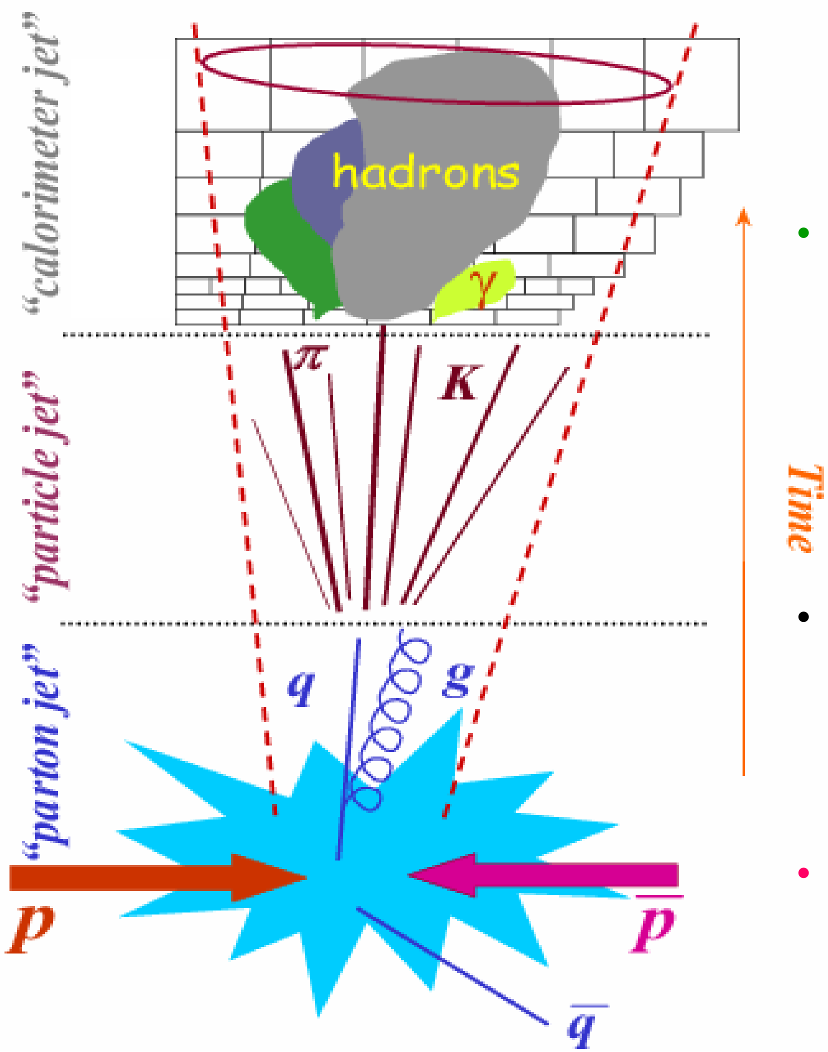


- Jet Cross Sections:
  - new physics and PDFs uncertainties @ high P_T
  - soft contribution @low P_T
- Dijet $\Delta\phi$ correlations
- W + jet production

Why @ 2 TeV?
Big increase in cross section thanks to new $\sqrt{s}$

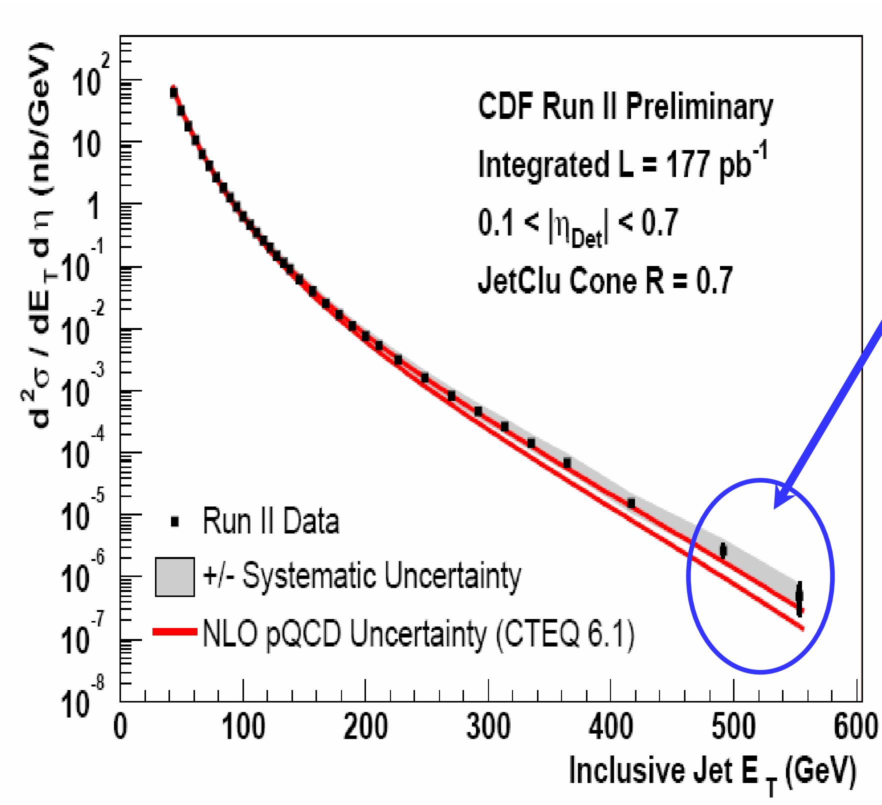


Jet Physics at 2 TeV : Jet algorithm



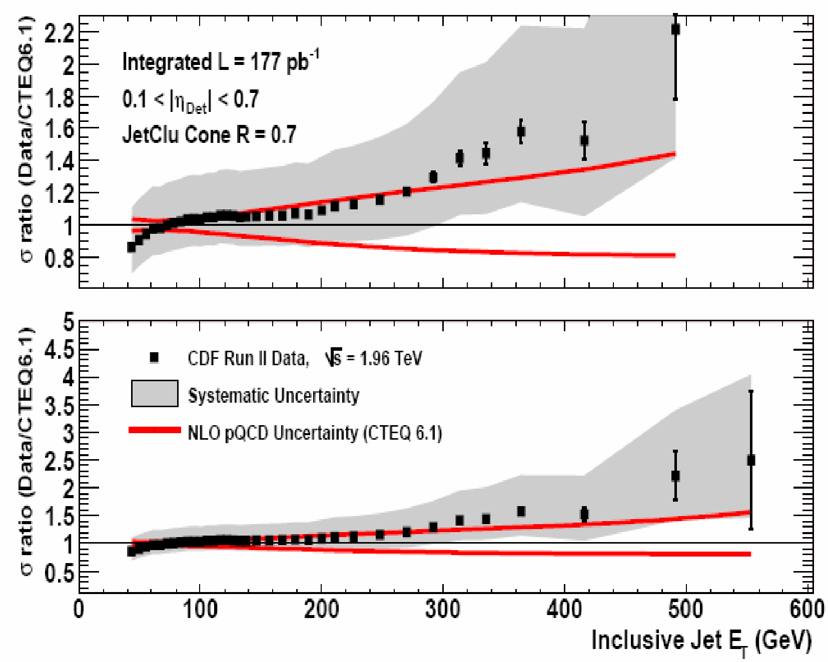
- Final state partons are revealed through collimated flows of hadrons called jets
- Measurements are performed at hadron level. Theory is at parton level:
  hadron → parton transition will depend on parton shower modeling
- Precise jet search algorithms necessary to compare with theory and to define hard physics
- Natural choice is to use a cone-based algorithm in $\eta-\phi$ space (invariant under longitudinal boost)

Inclusive Jet Cross section



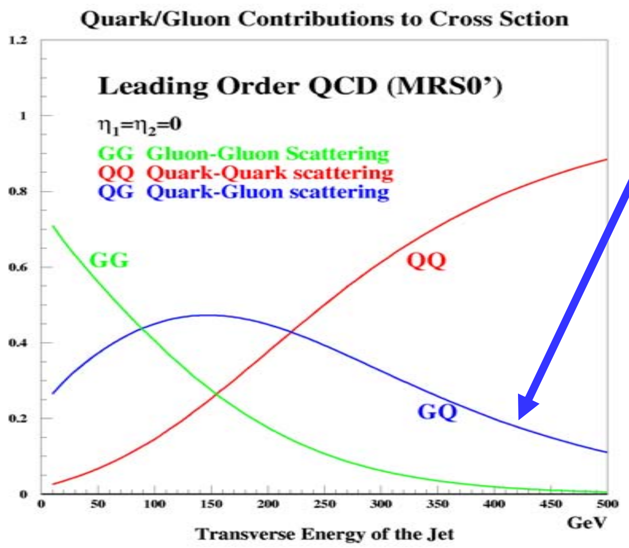
- Run I cone algorithm & unfolding
- E_T^{jet} range increased by ~150 GeV

Comparison with pQCD NLO
(over almost nine orders of magnitude)



Data dominated by jet energy scale
NLO error mainly from gluon at high x

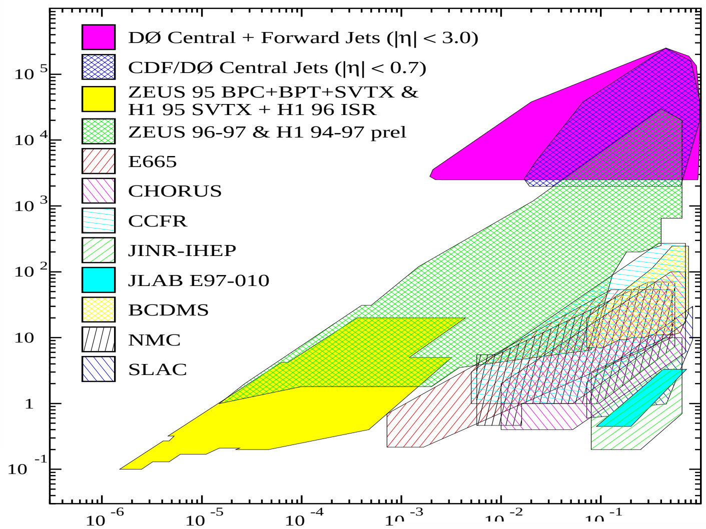
Inclusive Jet Cross section vs y



Important gluon-gluon and gluon-quark contributions at high- E_T

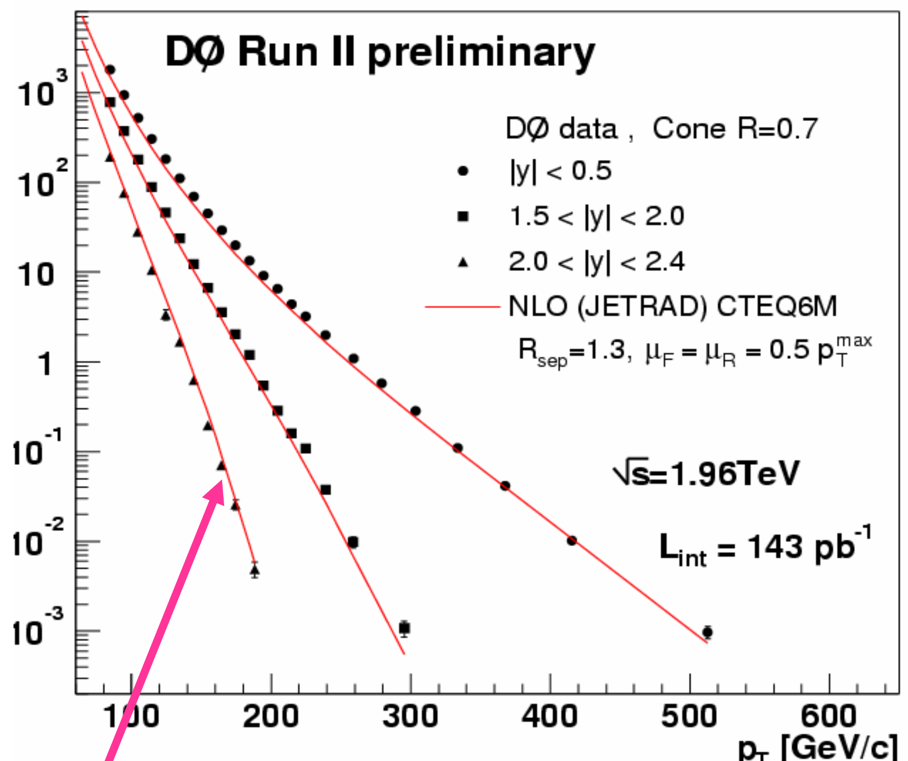
Gluon pdf at high-x not well known

...room for SM explanation....



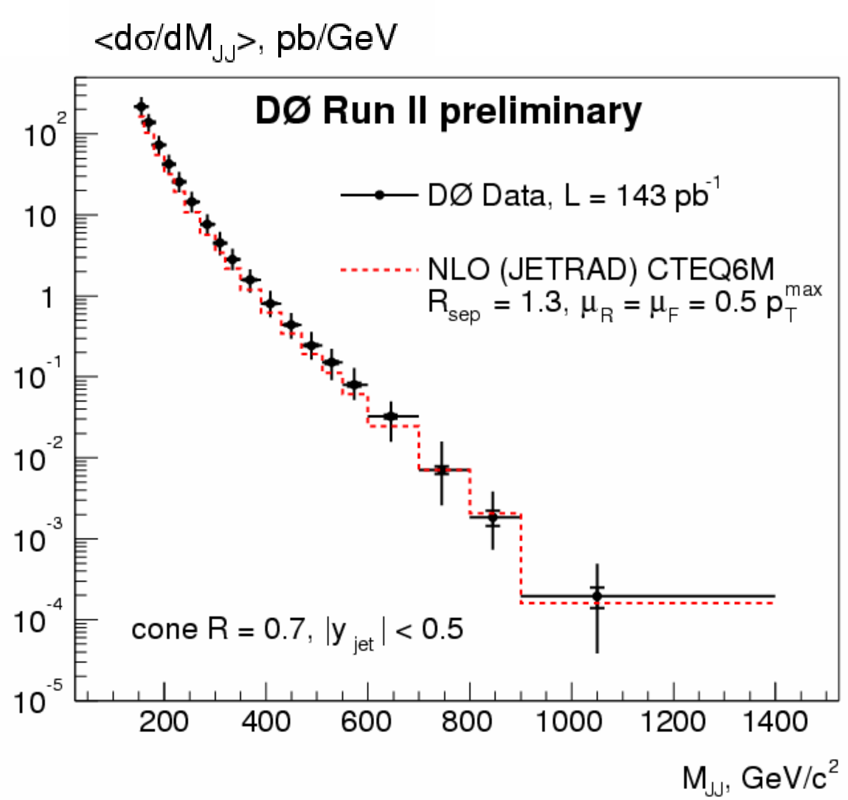
$Q^2 = 2E_T^2 \cosh^2\eta^*(1-\tanh\eta^*)$

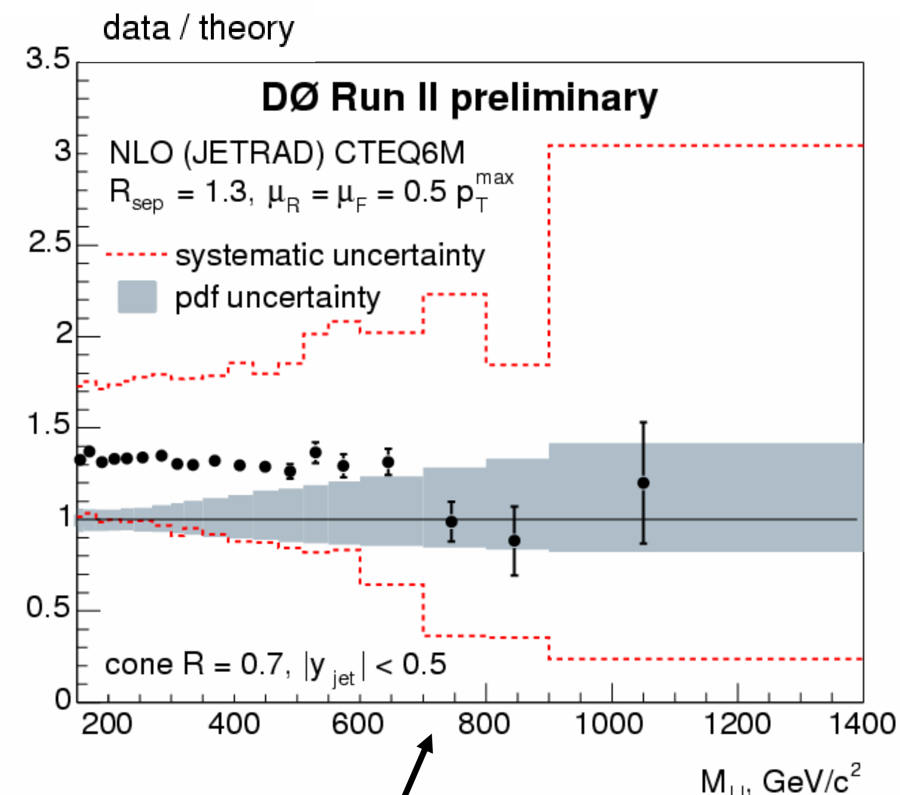
$x_1 = \frac{E_T}{\sqrt{s}}(e^{+\eta_1} + e^{+\eta_2})$



Constrain on gluon distribution at high x

Dijet Mass Cross section



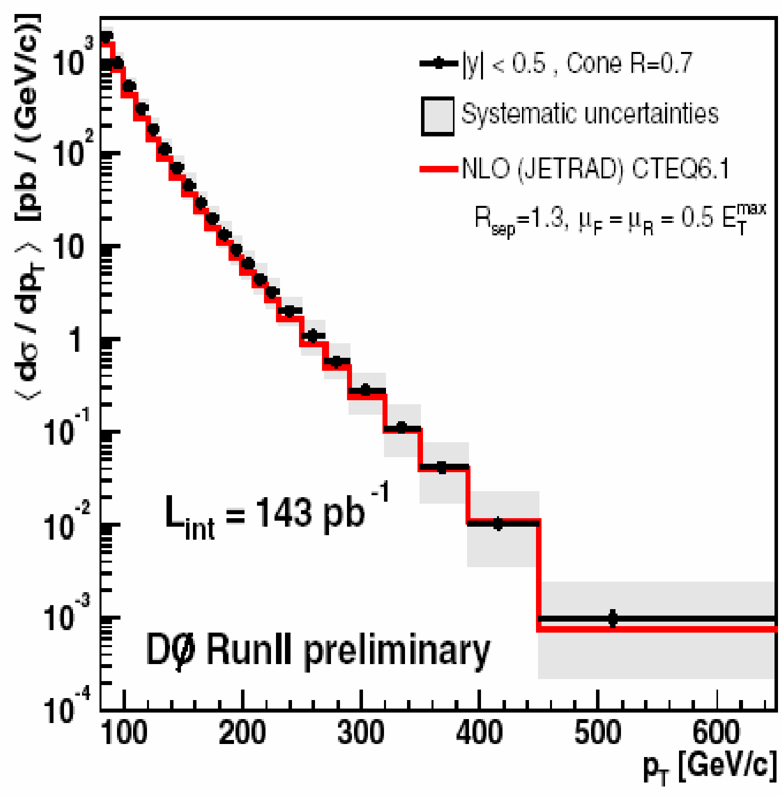


Resonances or excess at high mass:

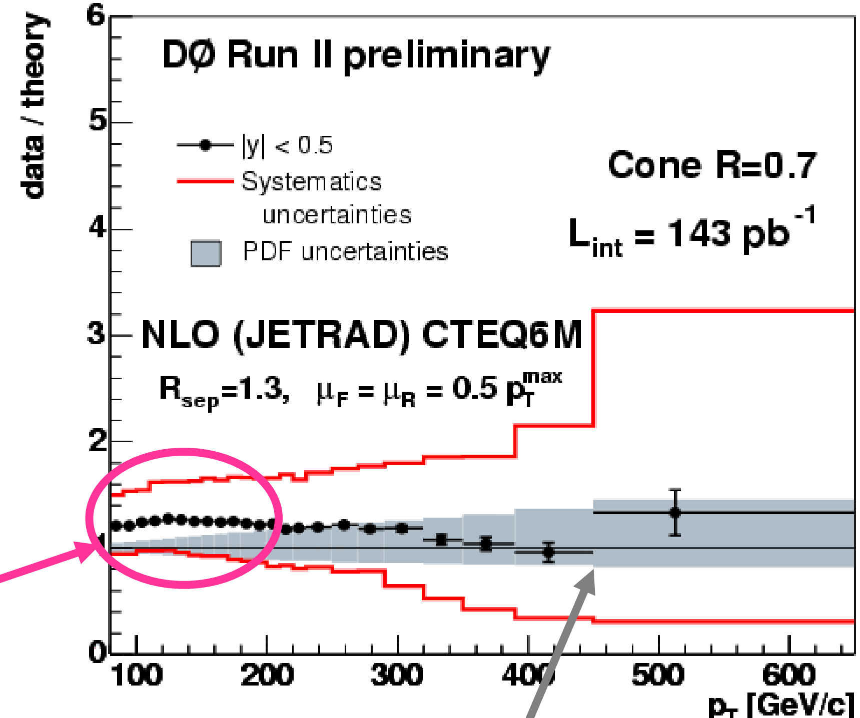
- o new particles
- o quark compositeness

data/theory agree within large systematic errors (mainly jet-energy scale)

Inclusive Jet P_T Cross section



Agreement with theory within systematic uncertainties (dominated by jet-energy scale)



Hadronization correction needed?

NLO uncertainty due to gluon @ high x

Inclusive Jet Cross section: K_T algorithm

- Inclusive K_T algorithm

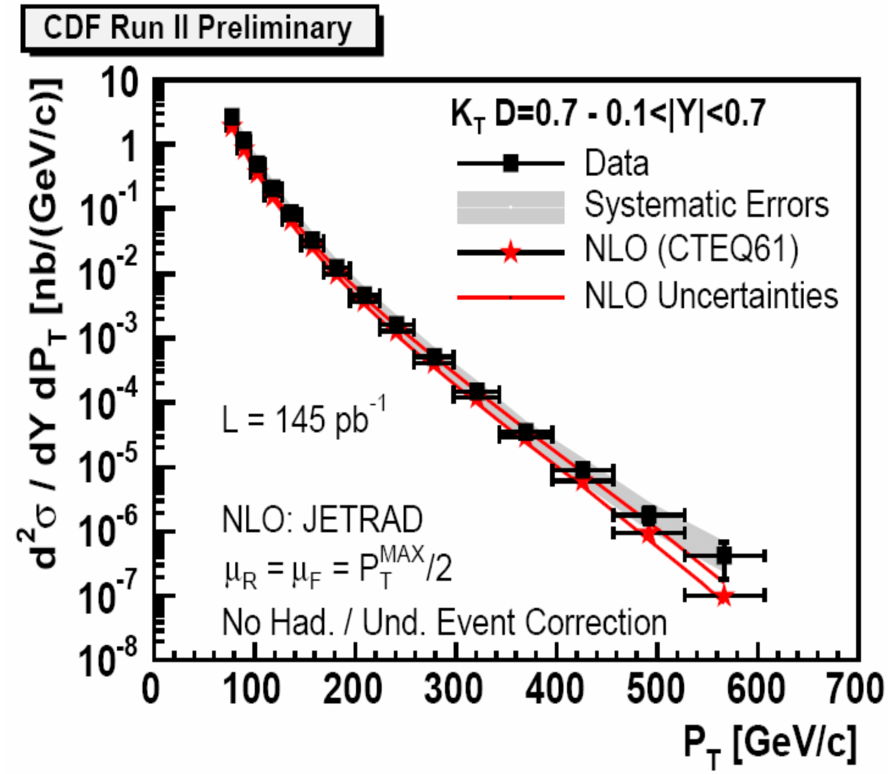
$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j}) \frac{\Delta R^2}{D^2}$$

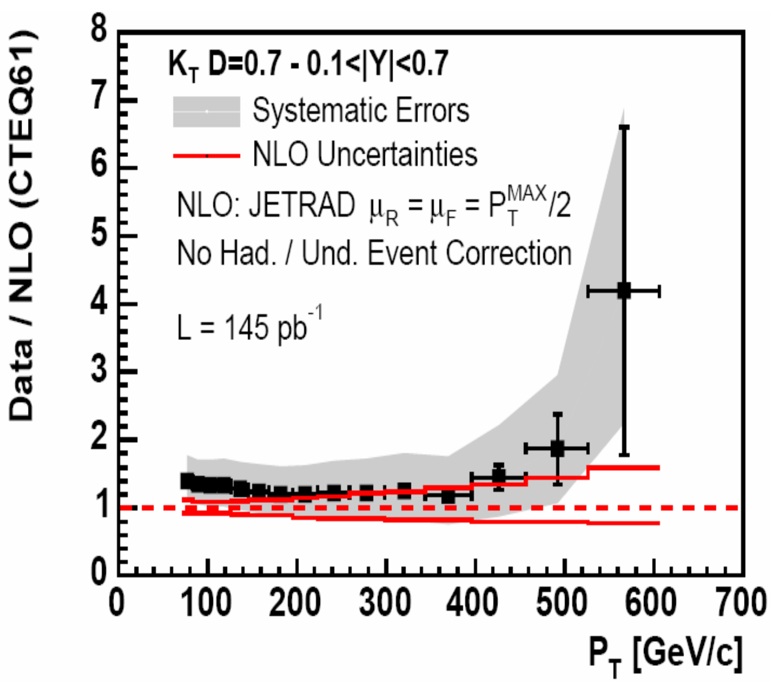
$\Delta R^2 \rightarrow (y_i - y_j)^2 + (\varphi_i + \varphi_j)^2$

$D \rightarrow$ jet size

$$d_i = (P_{T,i})^2$$

- Infrared and collinear safe
- No merging / splitting





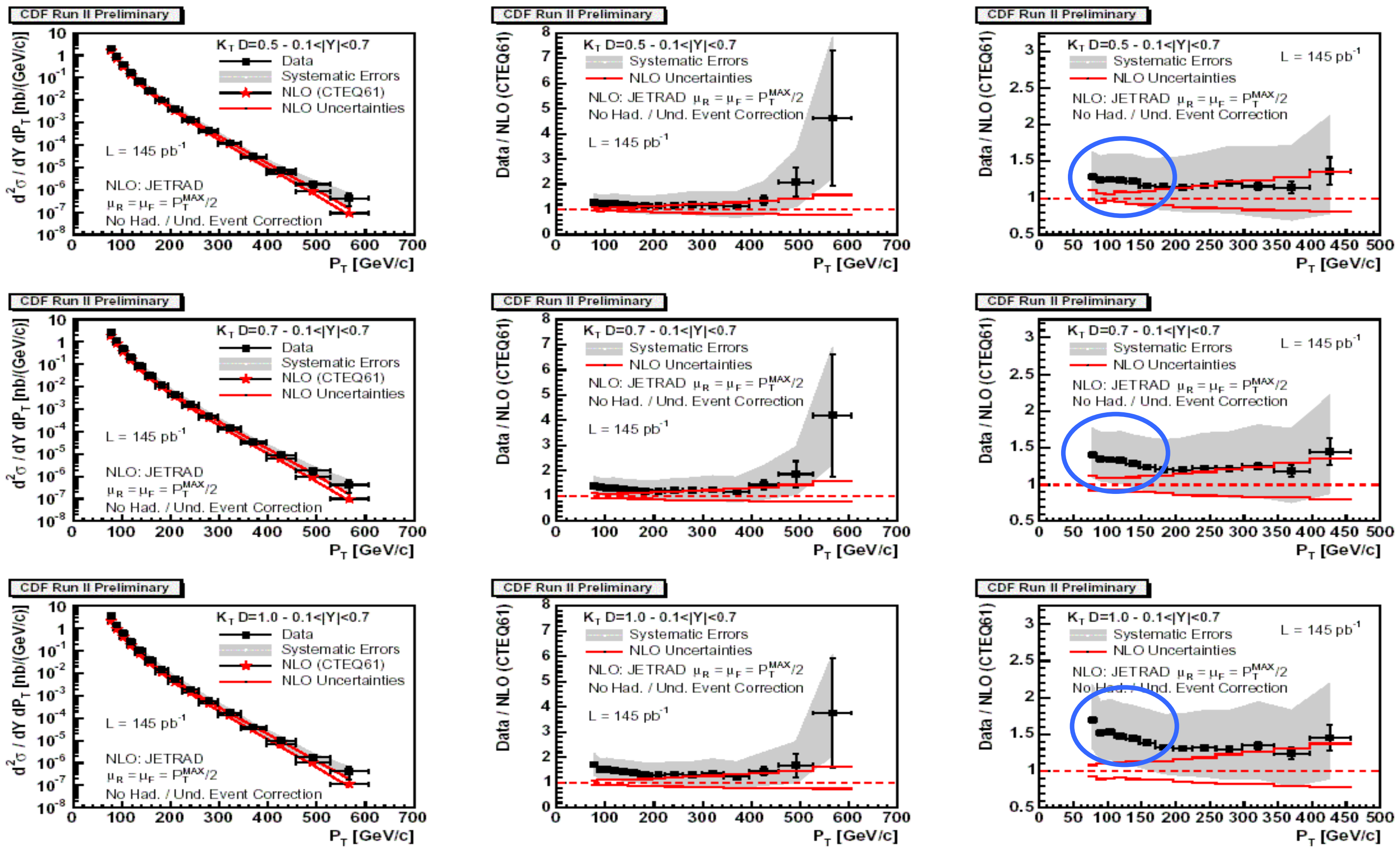
- Reasonable data-theory agreement
- NLO still needs to be corrected for Hadronization /Underlying Event

Inclusive Jet Cross Section K_T vs D

D=0.5

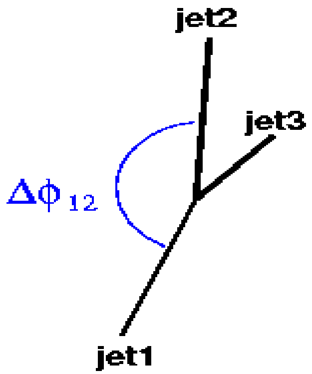
D=0.7

D=1

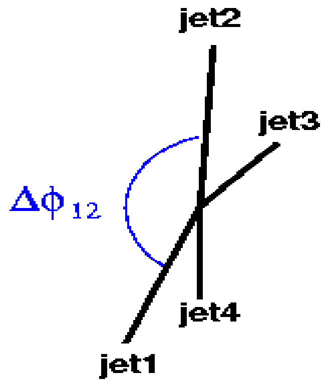


Increasing D data departs from pQCD NLO
⇒ more soft contributions

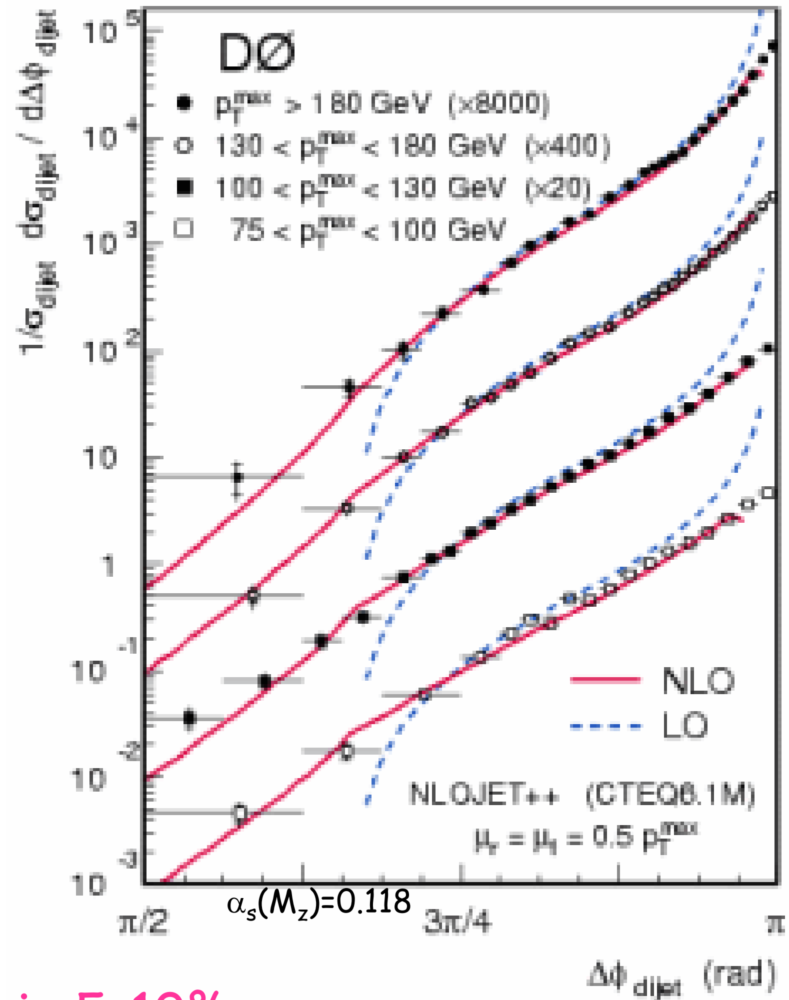
Dijet Azimuthal Decorrelations



LO in $\Delta\phi$



NLO in $\Delta\phi$



- LO no additional radiative effects: 2 jets correlated in ϕ ($\Delta\phi_{jets}=\pi$)
- LO + Additional soft radiation: 2 leading jets decorrelated
- Additional hard interaction: $\Delta\phi_{jets}$ significantly lower than π

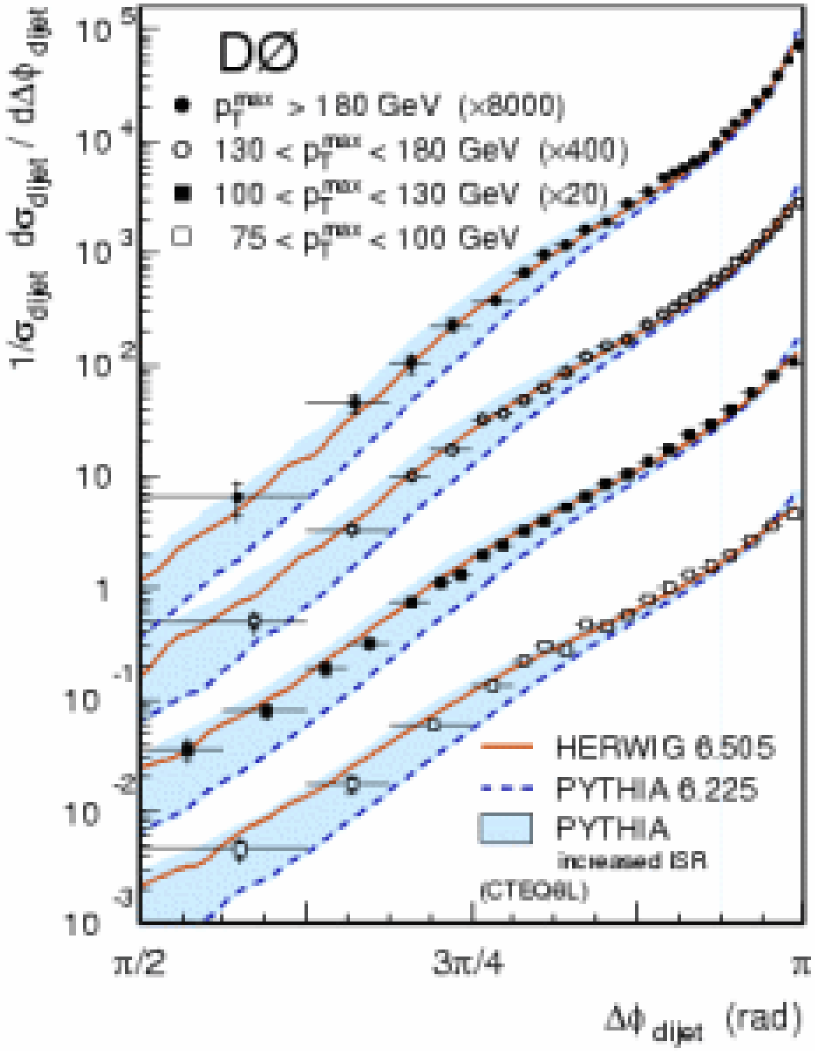
NLO and data agree within 5-10%
At very large $\Delta\phi_{jets}$ calculation not predictive

Dijet Azimuthal Decorrelations: Monte Carlo - Data comparison

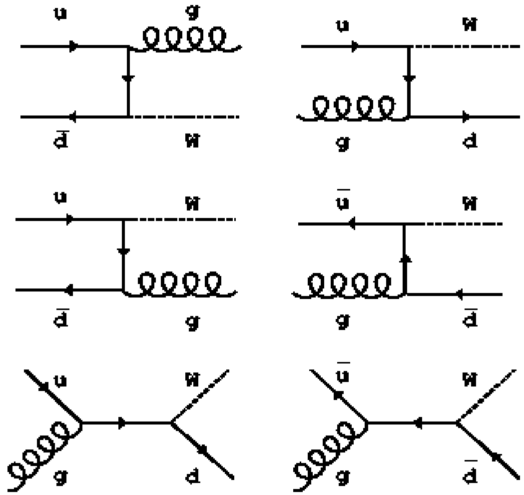
$\Delta\phi$ distribution shows sensitivity to different modeling of parton cascades

PYTHIA with enhanced ISR (Tune A) provides best description across the different regions in jet p_T

HERWIG similar to PYTHIA Tune A (underestimates radiation close to leading jets)

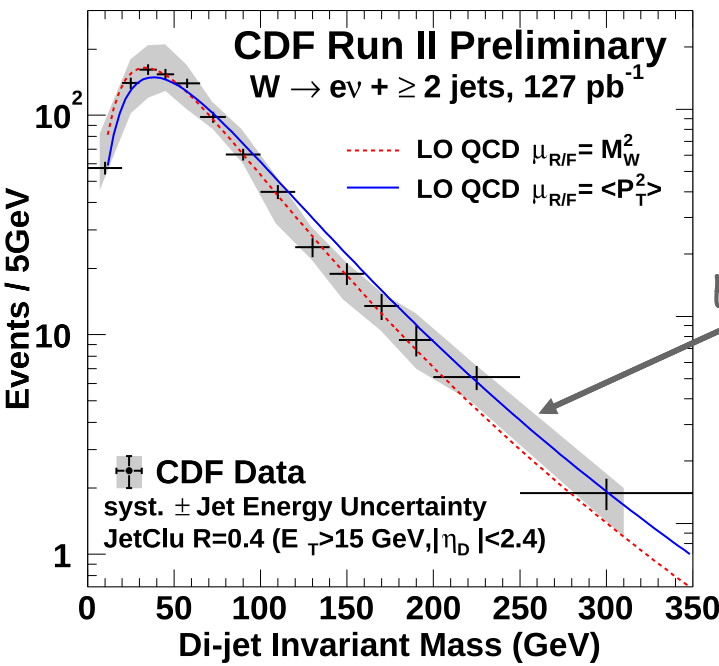


W + jets production

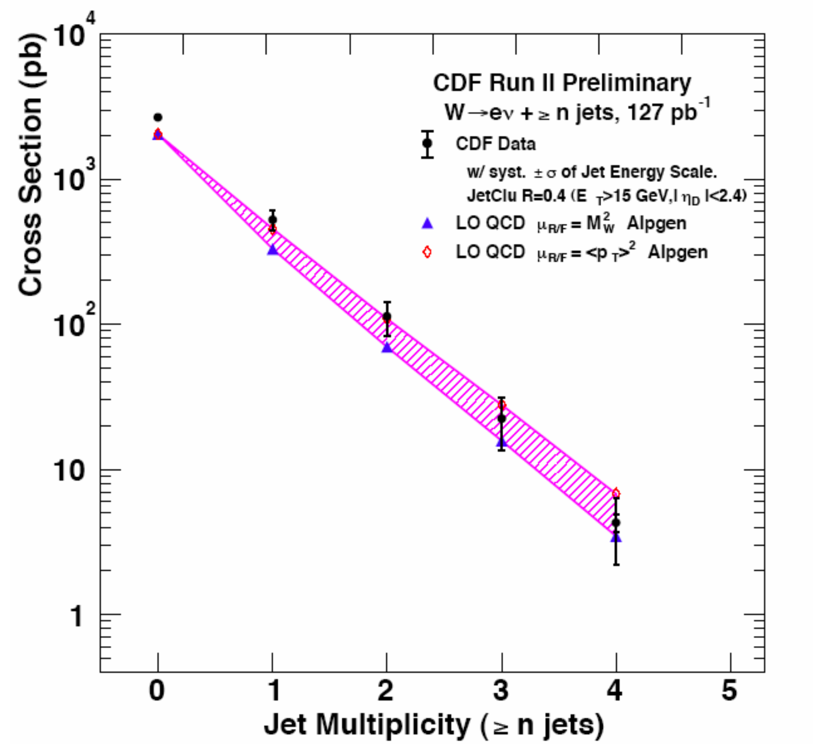


LO
W+jets

- Background to top and Higgs Physics
- Stringent test of pQCD predictions
- Test Ground for Matrix-Element + Parton Shower techniques
  (Alpgen Monte Carlo + Herwig Monte Carlo)



Energy scale



Charm and Beauty production at Tevatron

- Brief introduction: Theory and experiments

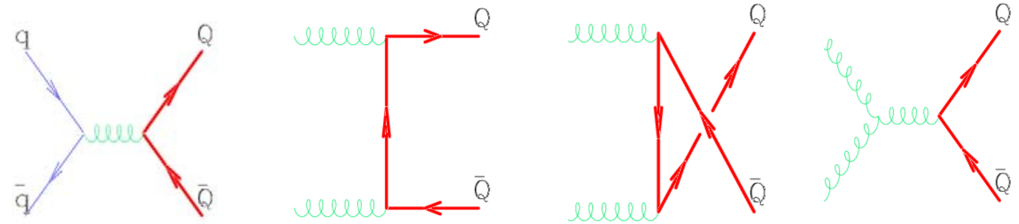
- Run II measurements:
  - Open Charm production cross section
  - J/ψ Production Cross section measurements

  - New Υ Production Studies
  - b quark and hadron Cross Section

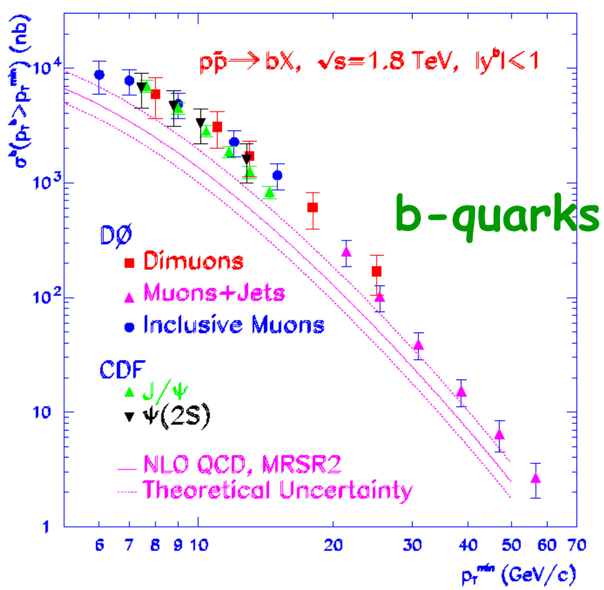
Charm and Beauty production at Tevatron

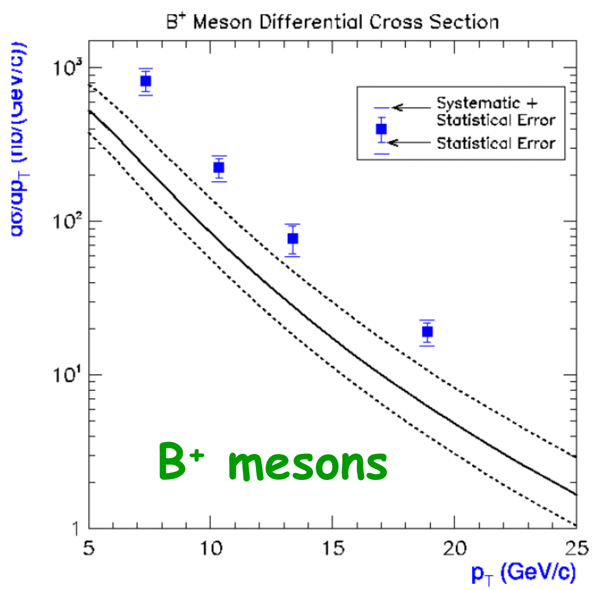
Since $m_Q \gg \Lambda_{QCD}$ for c and b quarks, heavy quark production at the Tevatron should be well-calculable in QCD.

Diagrams at leading order:



Full calculations have been done up to NLO (and beyond…)
Therefore how do we explain Run 1 Tevatron results?





Experiment wrong?

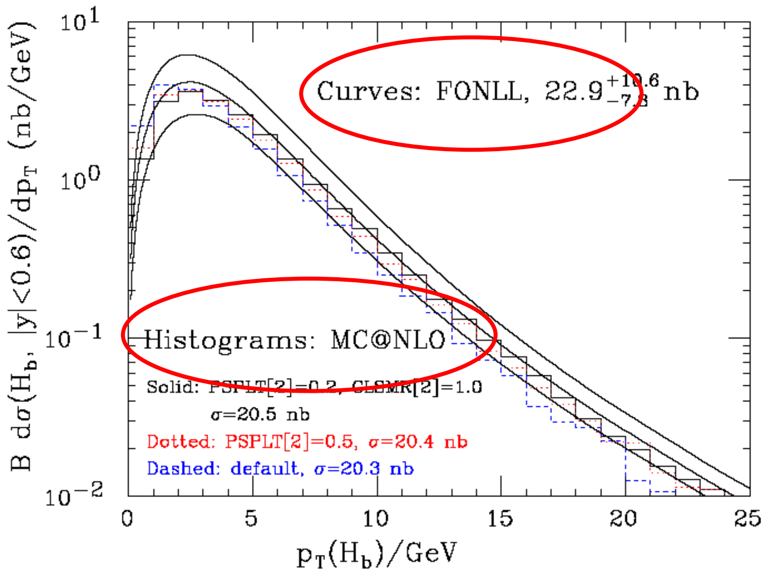
Theory prediction incomplete?

New physics?

Recent developments

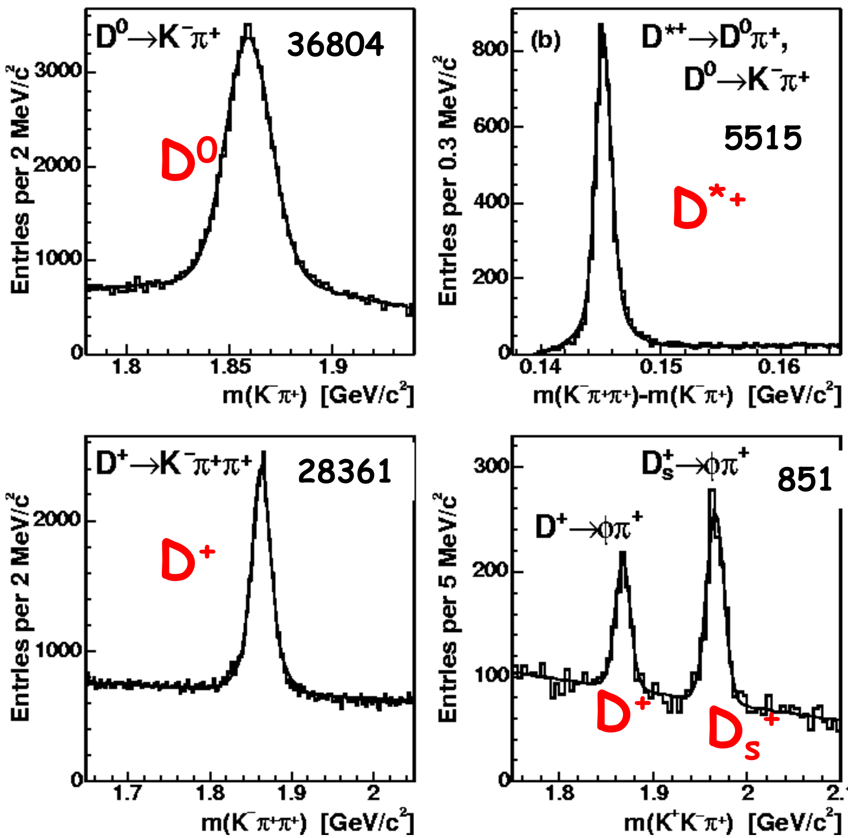
In past years many (theoretical) developments:

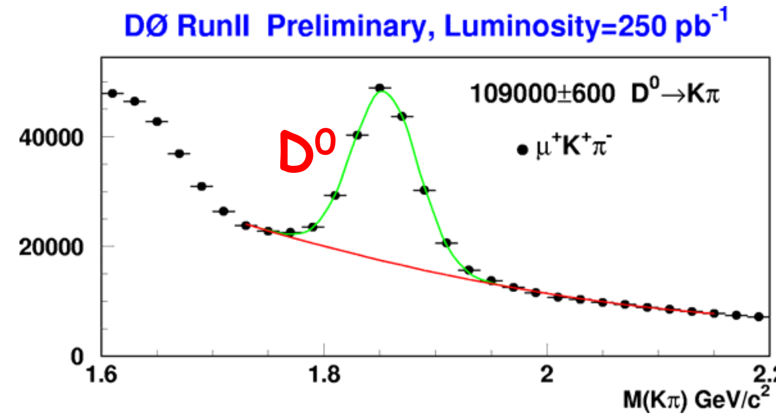
- Use b-jets (B meson) rather than b-quarks: less dependent on unfolding and fragmentation uncertainties
- Beyond NLO: resummation of $\log(p_T/m)$ terms → FONLL (Cacciari et al). Important for medium/high p_T region
- Extraction of fragmentation function parameters from LEP data in this scheme: substantially different ε_b
- new PDF's
- MC@NLO → match NLO calculation with PS formalism in HERWIG (Frixione, Nason, Webber)

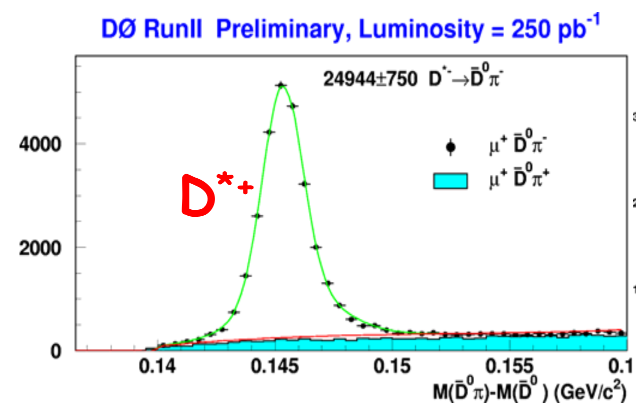


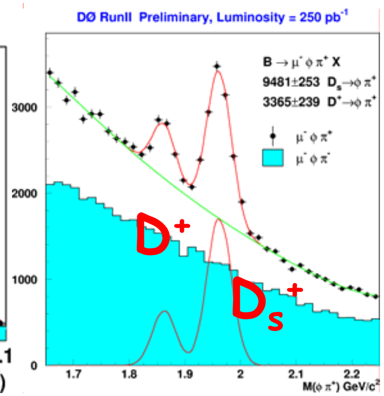
Charm Production: Open Charm meson

CDF: 5.8 pb^{-1} , taken with displaced track trigger. >80% prompt production





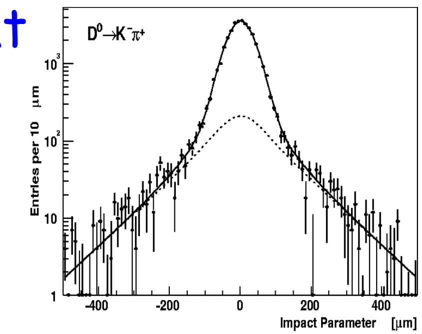




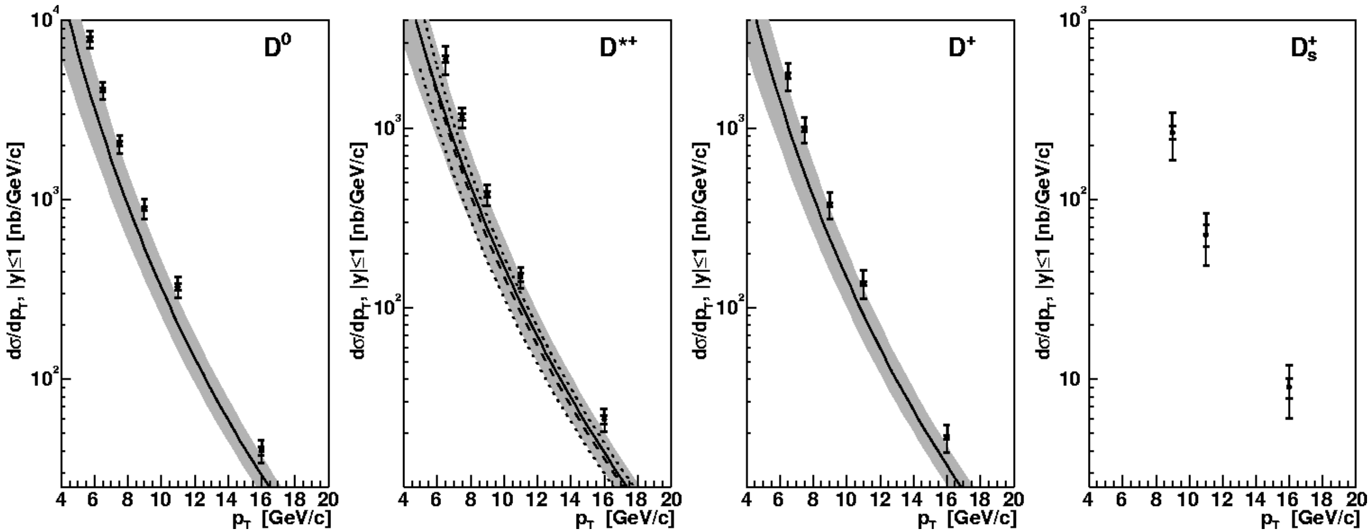
D0: 250 pb^{-1}, taken with muon trigger
Most D mesons from B decay with associated muon.

Open Charm Cross Section at CDF

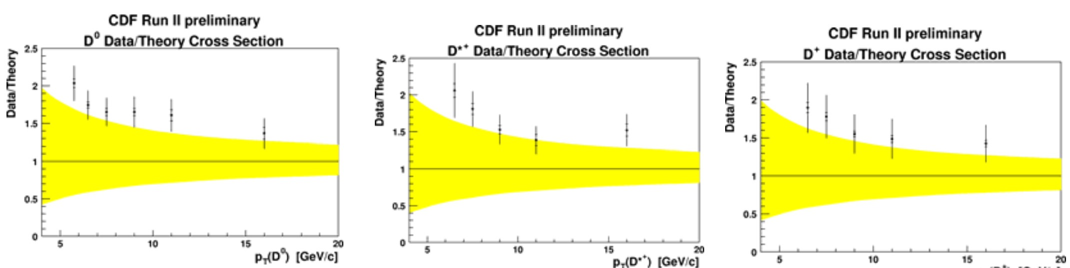
Prompt charm production component extracted looking at impact parameter of reconstructed D meson



Compare to FONLL theory (Cacciari and Nason):



Prompt fraction:
D^0: 86.6 ± 0.4%
D^{*+}: 88.1 ± 1.1%
D^+: 89.1 ± 0.4%
D_s^+: 77.3 ± 3.8%
(±3-4% syst. err.)



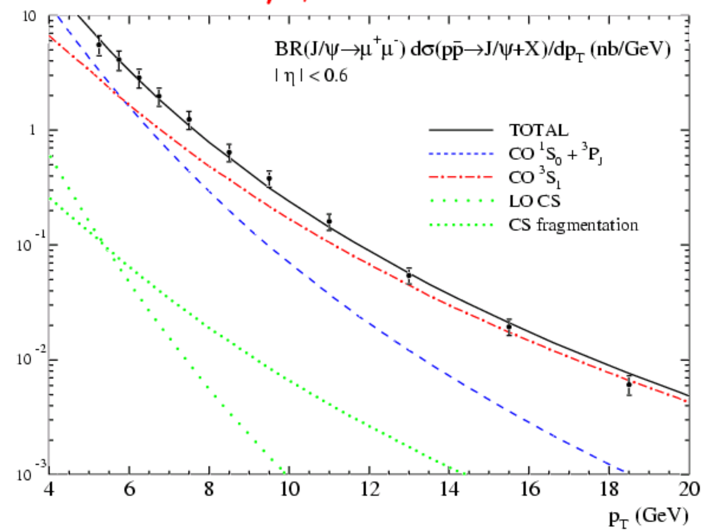
Cross sections for |y|<1:
$D^0(p_T>5.5$ GeV): 13.3±1.5 μb
$D^{*+}(p_T>6.0$ GeV): 5.2±0.8 μb
$D^+(p_T>6.0$ GeV): 4.3±0.7 μb
$D_s^+(p_T>8.0$ GeV): 0.75±0.23 μb

Theory uncertainty: vary renormalization/factorization scales
data at upper limits of theory prediction

Heavy Quarkonium Production

Prompt production of heavy quarkonium (J/ψ, ψ', Υ,…) described by non-relativistic QCD (NRQCD).

CDF J/ψ Data, Run I



Run 1 data has shown that color singlet component only (QQ state has quantum numbers of cc pair produced in hard scattering) is not sufficient. (by a factor 50 or so…)

Color octet component in NRQCD described by matrix elements that must be fit from data but are **universal**!
(CO OK: soft gluons take care of color flow)

Interesting to study high p_T region and polarization

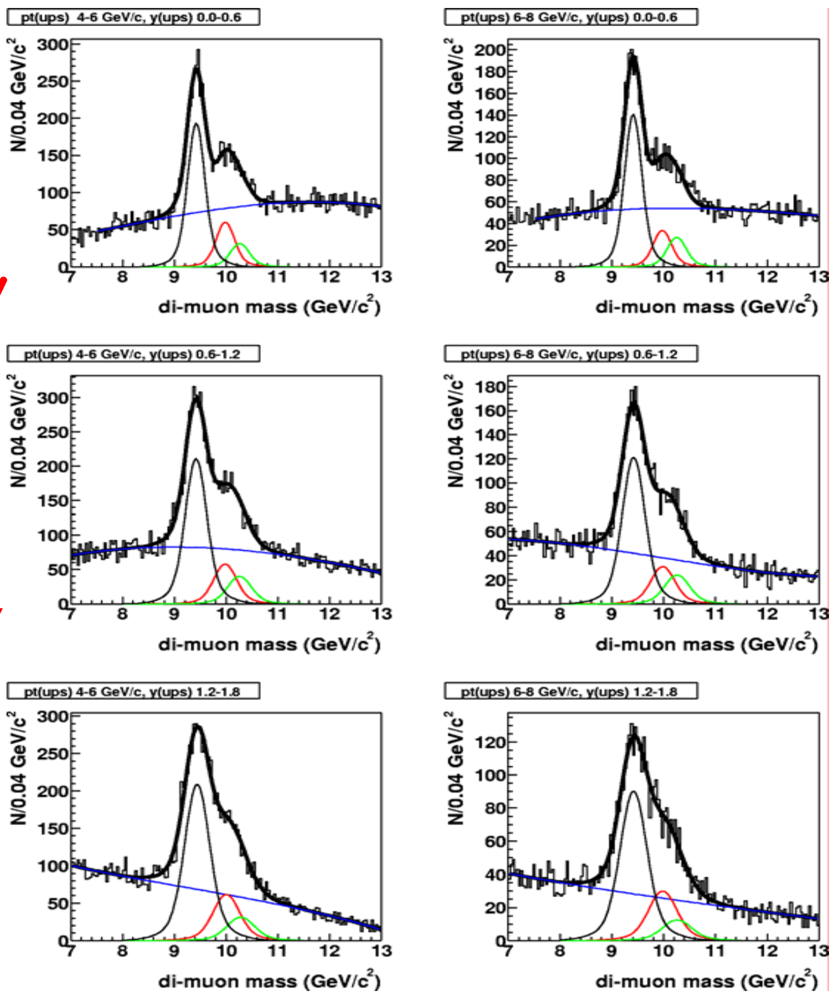
Υ Production

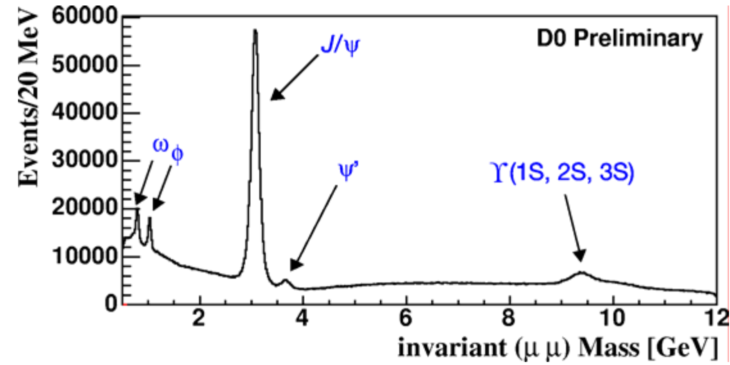
D0: 159 pb^{-1} of data taken with dimuon trigger:

p_T →

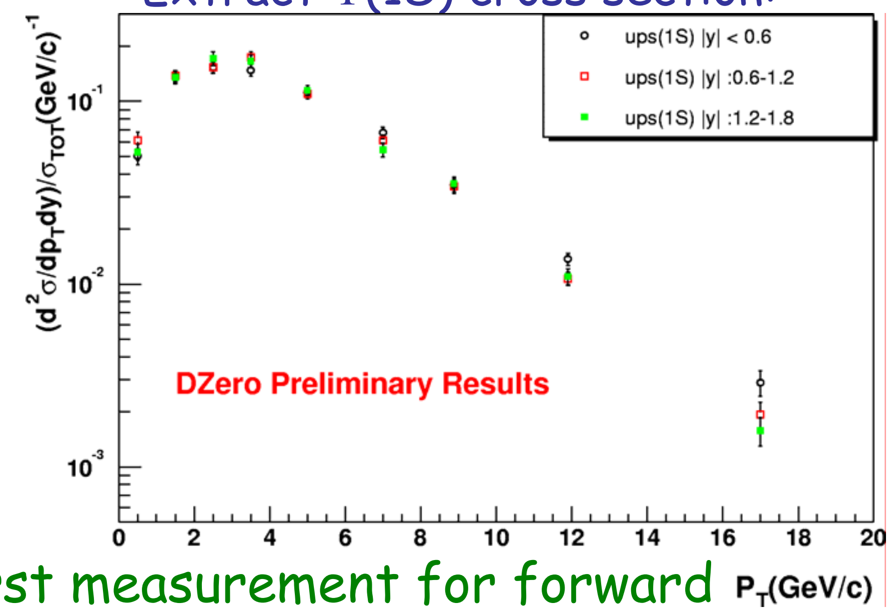
Fit Υ(1S), Υ(2S), Υ(3S) components:

y ↓





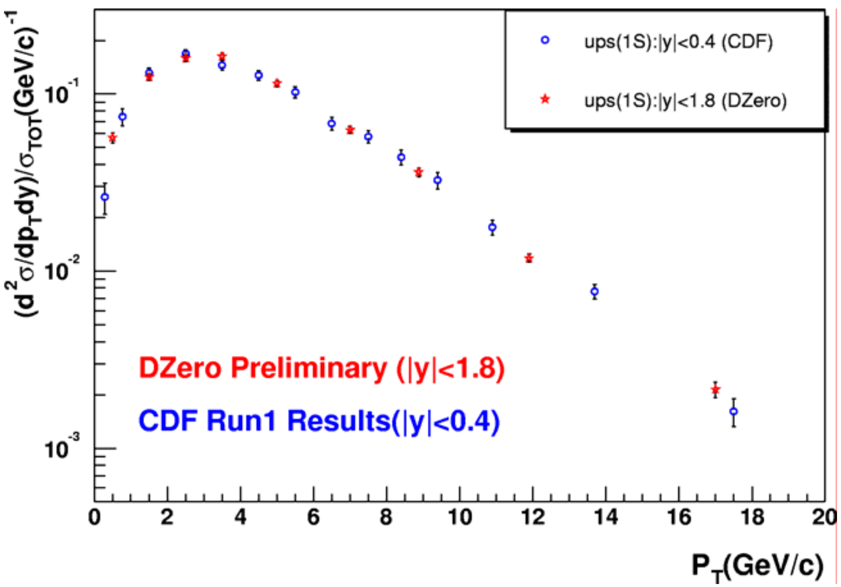
Extract Υ(1S) cross section:



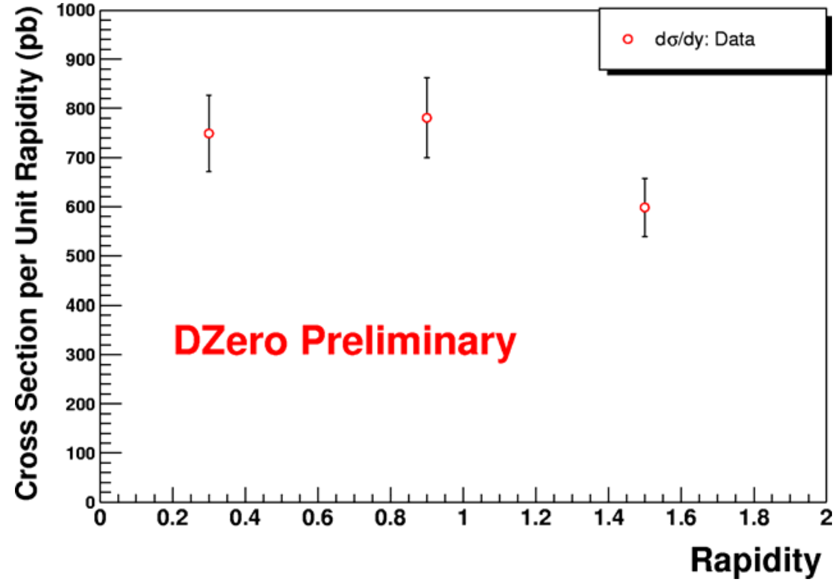
First measurement for forward rapidities: p_T spectrum varies only very little

Υ Production cont'd

Compare to CDF Run 1 result:



Cross section per unit of rapidity: (includes Br(Υ→μμ))



|y|<1.8: 695 ± 12 ± 65 ± 45 pb

CDF: $\sqrt{s}$ = 1.8 TeV, |y|<0.4: dσ/dy*Br = 680 ± 15 ± 18 ± 26 pb

D0: $\sqrt{s}$ = 1.96 TeV, |y|<0.6: dσ/dy*Br = 749 ± 20 ± 75 ± 49 pb

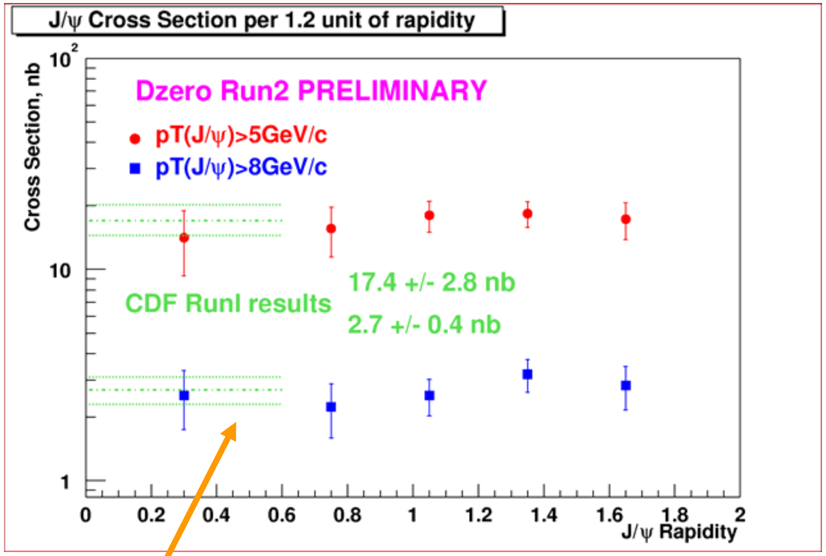
(PYTHIA predicts factor 1.11 between 1.96 and 1.8 TeV)

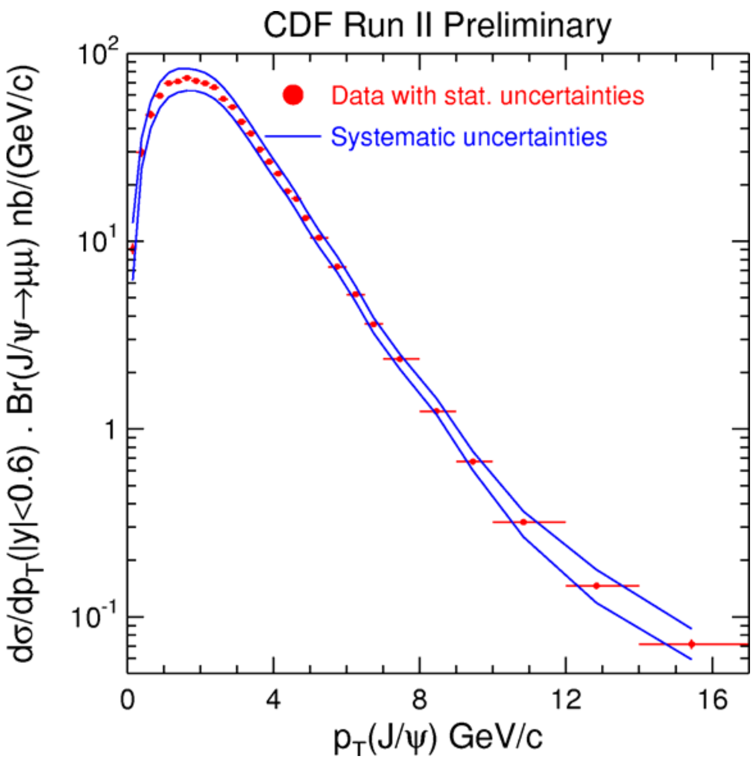
Polarization measurement is in progress…

J/ψ Production

D0: 4.7 pb^{-1}
J/ψ: $p_T > 5$ GeV $|y|<1.8$

CDF: 39.7 pb^{-1}





81% prompt J/ψ

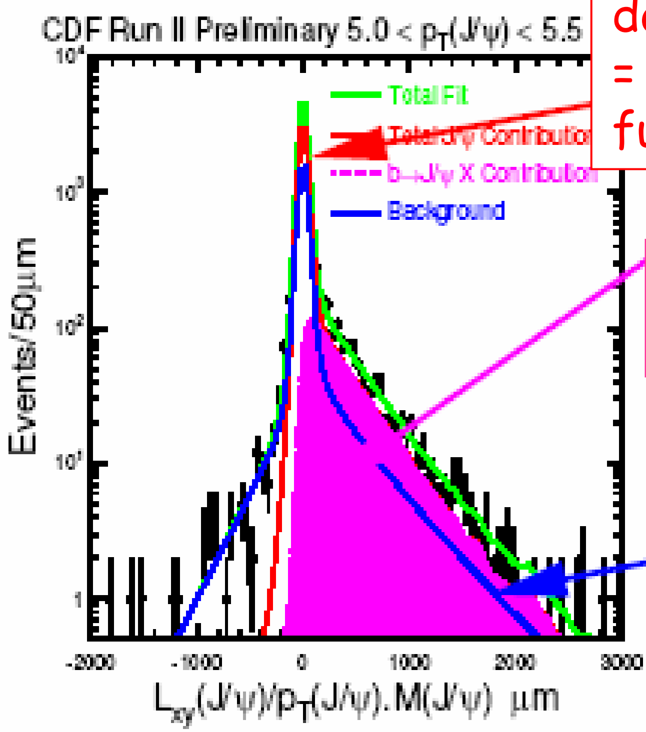
Depending on p_T, 10-40% of J/ψ are from b-decay.
81% prompt J/ψ

Possible to explore pT~ 0

J/ψ Production Cross Section

Separate prompt J/ψ from $B \rightarrow J/\psi$ using lifetime

CDF: 39.7 pb^{-1}

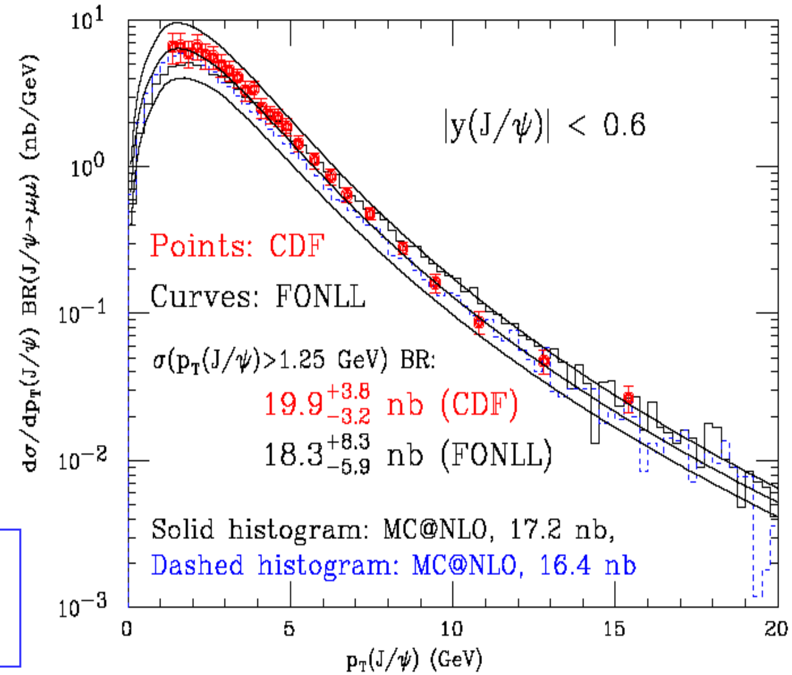


Prompt J/ψ: double Gaussian = resolution function

$B \rightarrow J/\psi X$: From MC

Parameterized background

Cacciari, Frixione, Mangano, Nason, Ridolfi have compared these results to FONLL and MC@NLO: (JHEP07 (2004) 033)



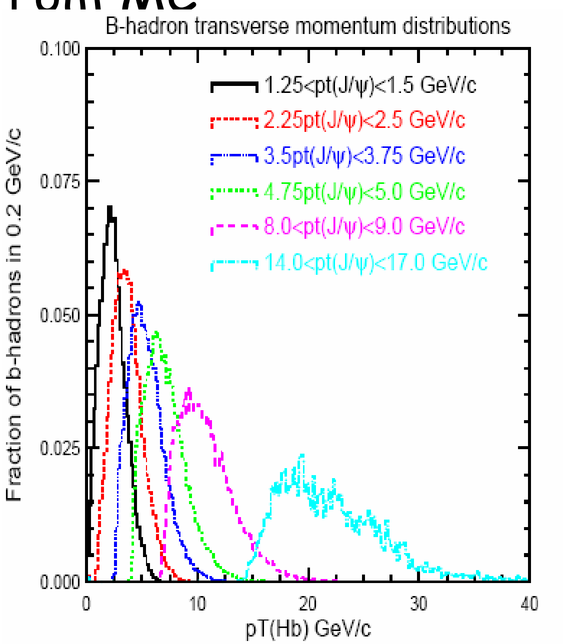
Truly remarkable agreement!

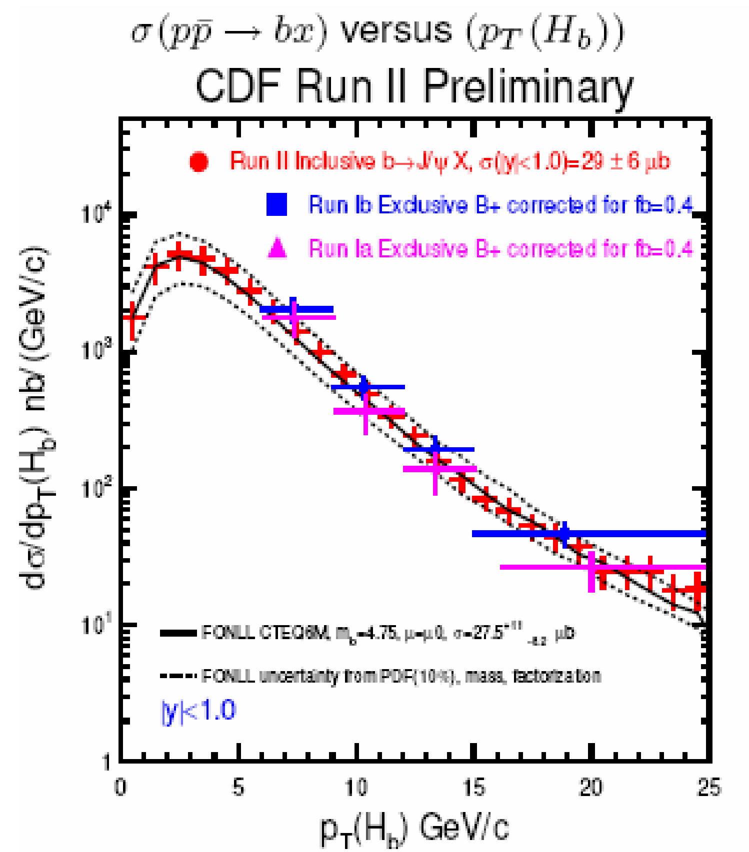
b-hadron from J/ψ Production at CDF

To extract $d\sigma/dp_T(H_b)$:
Count the observed number of b-hadrons in a given $p_T(H_b)$ bin:

$$N_i^b = \sum_{j=1}^{N} w_{ij} N_j^{J/\psi}$$

w_{ij} is the fraction of b events in the i^{th} $p_T(H_b)$ from the j^{th} $p_T(J/\psi)$ b in obtained from MC

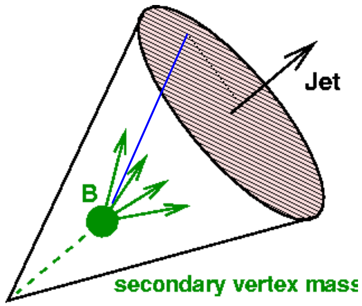




$\sigma(J/\psi \text{ from } H_b) = 19.9 \pm 3.8$ nb

$\sigma(H_b \to J/\psi, |y|<0.6) = 24.5 \pm 4.7$ nb

B-jet Production

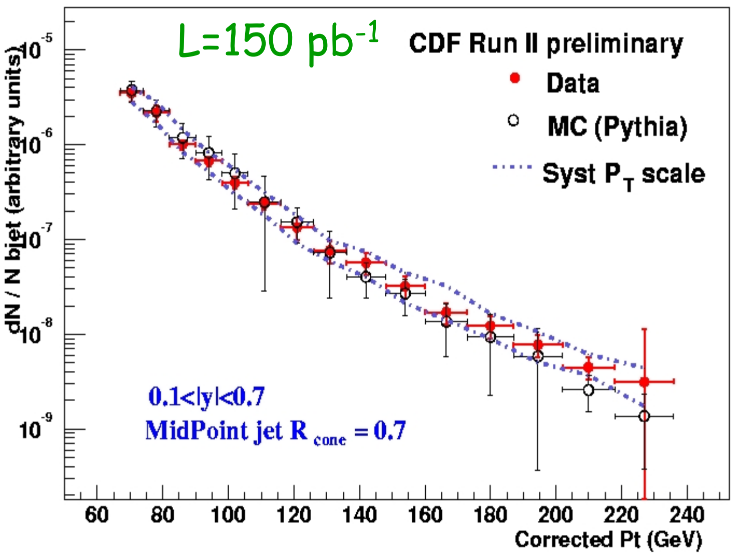


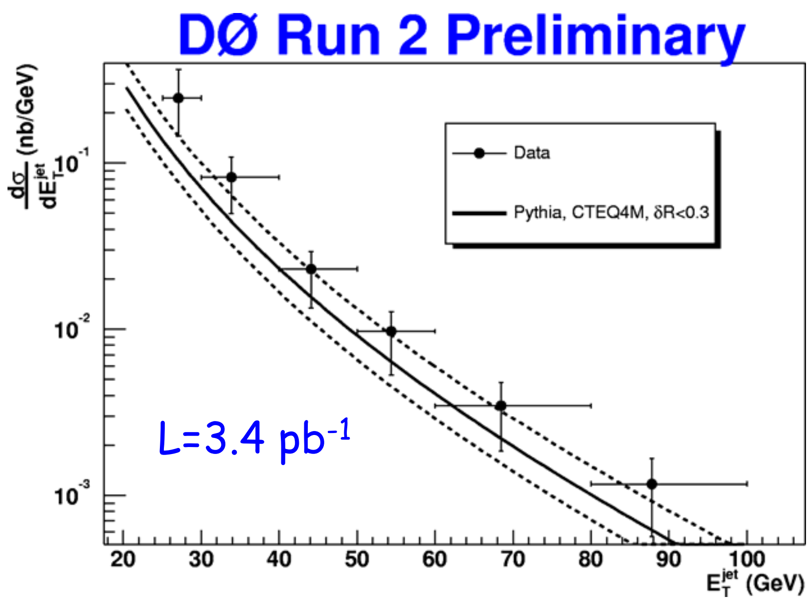
CDF:

- b-quark tagged using displaced secondary vertices
- invariant mass of tracks belonging to these vertices determines b fraction

DO:

- muon+jets data
- b-tagging using p_T of muon relative to jet axis.





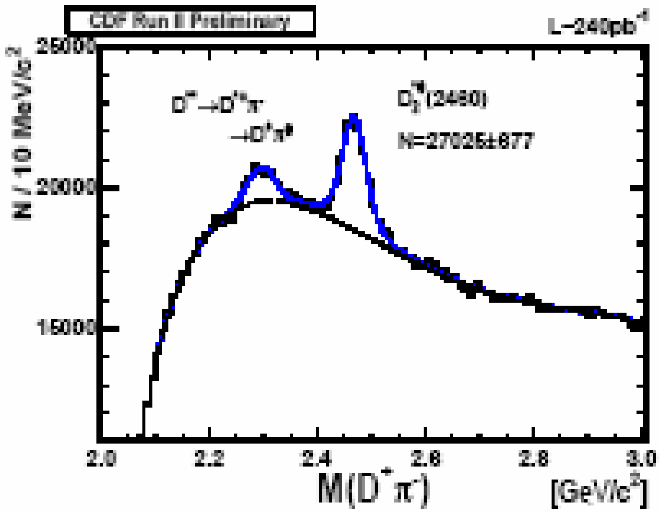
Pentaquarks search

$uudd\bar{s}$	Θ^+	$\to pK^0_s,$	$K^0_s \to \pi^+\pi^-$
$ddss\bar{u}$	$\Xi^{--}_{3/2}$	$\to \Xi^-\pi^-,$	$\Xi^- \to \Lambda\pi^-,\ \Lambda \to p\pi^-$
$uuss\bar{d}$	$\Xi^0_{3/2}$	$\to \Xi^-\pi^+,$	$\Xi^- \to \Lambda\pi^-,\ \Lambda \to p\pi^-$
$uudd\bar{c}$	Θ^0_c	$\to D^{*-}p,$	$D^{*-} \to \bar{D}^0\pi^-,\ \bar{D}^0 \to K^-\pi^+$
$uudd\bar{c}$	Θ^0_c	$\to D^-p,$	$D^- \to K^-\pi^+\pi^+$
$uuud\bar{c}$	Θ^+_c	$\to \bar{D}^0p,$	$\bar{D}^0 \to K^-\pi^+$
$\bar{u}uudc$	Θ^+_c	$\to D^0p,$	$D^0 \to K^+\pi^-$

Data: 250 pb^{-1}

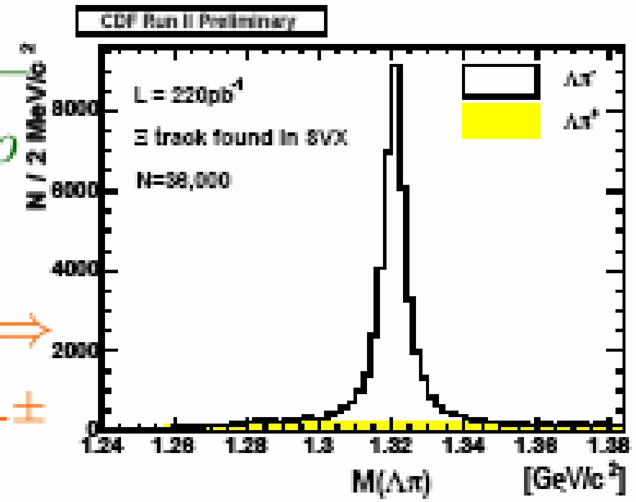
- hadronic trigger data:
  - at least 2 displaced tracks
  - dominated by $c\bar{c}$ and $b\bar{b}$
- jet20 data
  - at least 1 jet with E=20 GeV/c
  - dominated by light quarks
- minimun bias and zero bias data
  - soft inelastic scattering

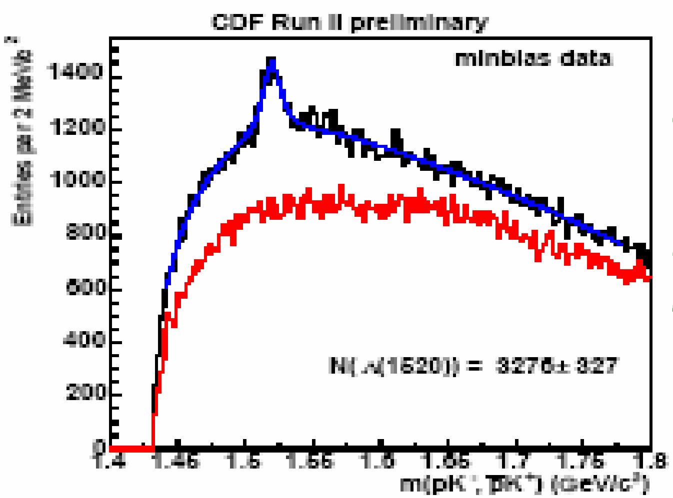
Pentaquarks reference signal



$\Leftarrow$ $D^{**} \to D^{*+}\pi^-$ for $\Theta_c \to D^{*+}p$

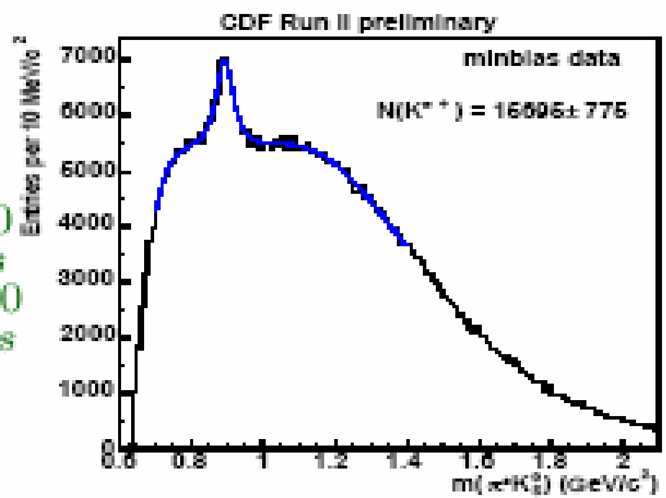
$\Xi \to \Lambda\pi$ for $\Xi_{\frac{3}{2}} \to \Xi^+\pi^\pm$ $\Rightarrow$





$\Leftarrow$ $\Lambda \to pK^-$

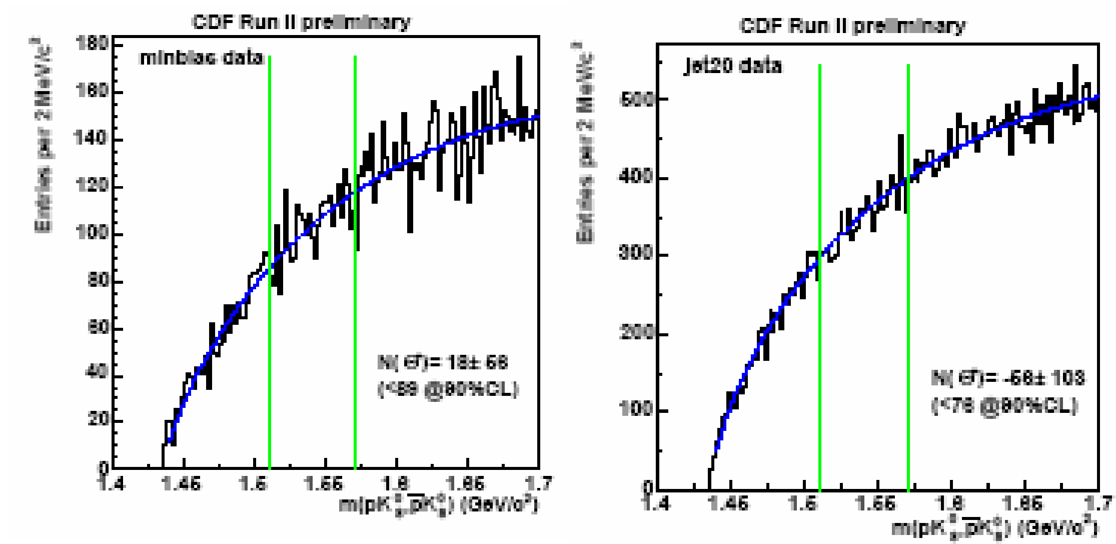
$K^{*+} \to \pi^+ K_s^0$ for $\Theta^+ \to pK_s^0$ $\Rightarrow$



Search for Θ^+ and $\Xi_{3/2}$

Search for $\Theta^+ \rightarrow pK_s$

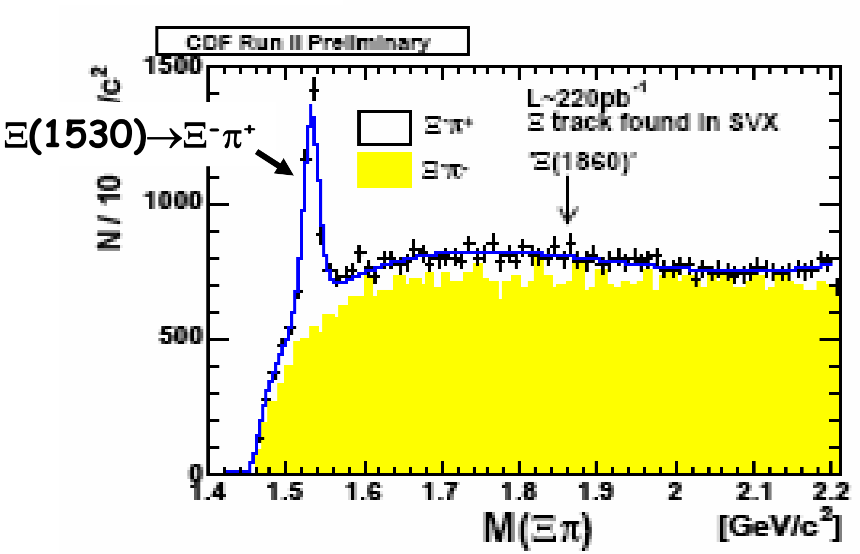
No signal found



Search for $\Xi^{0,--}{}_{3/2}$

$\Xi^{0--}{}_{3/2} \rightarrow \Xi^- \pi^\pm$, $\Xi^- \rightarrow \Lambda \pi^-$

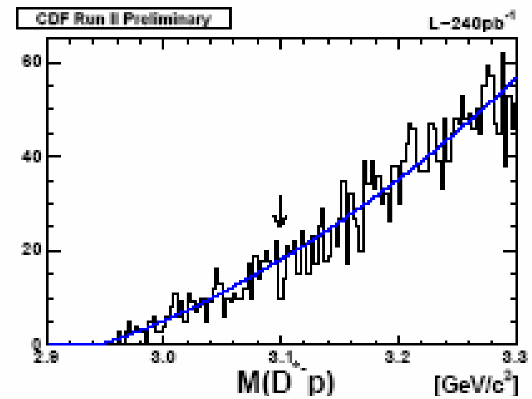
channel	yield	
	fit	limit
$\Xi^-\pi^+$	57±51	<144
$\Xi^-\pi^-$	-54±47	<63

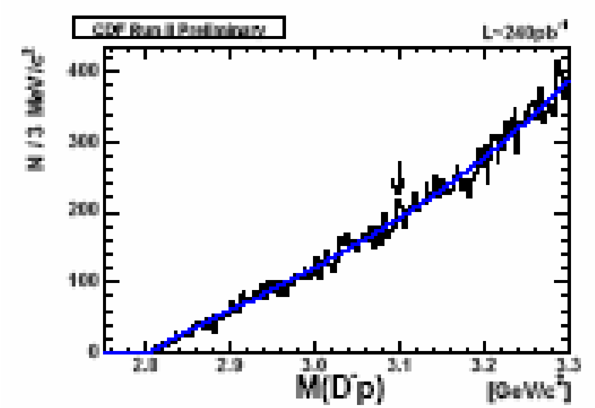


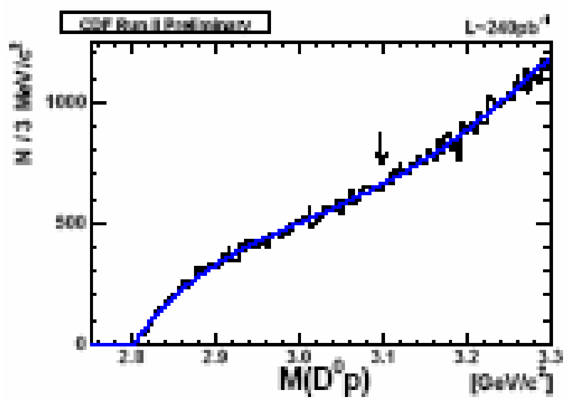
Search for Θ_c

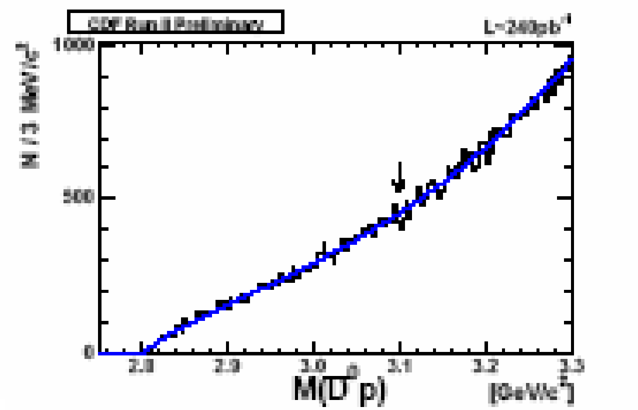
Decay channels:

$$\Theta_c^0 \to D^{*-}p, \quad D^{*-} \to \bar{D}^0\pi^-$$
$$\Theta_c^0 \to D^{-}p, \quad D^{-} \to K^-\pi^+\pi^-$$
$$\Theta_c^+ \to \bar{D}^0p, \quad \bar{D}^0 \to K^-\pi^+$$
$$\Theta_c^+ \to D^0p, \quad D^0 \to K^+\pi^-$$









No signal found

Search channels	
$\Theta_c \to D^{*+}p$	$< 21@90\%CL$
$\Theta_c \to D^{-}p$	$< 89@90\%CL$
$\Theta_c \to \bar{D}^0p$	$< 87@90\%CL$
$\Theta_c \to D^0p$	$< 97@90\%CL$

Summary & Conclusions

- QCD
  - Measurement of jet cross section:
    - ✓ to search for new physics
    - ✓ to study soft production
    - ✓ constrain gluon PDFs at high x
  - Test of NLO
  - Study boson +jet physics
- Heavy Flavor
  - Charmed meson production measured for the first time
  - New J/ψ and Υ production analysis in progress
  - b-jet analyses in progress
  - b-hadron production: Tevatron b quark "excess" not an excess anymore
- Pentaquark search: No evidence. Production in fragmentation may be severely suppressed with respect to normal baryons

lots more data coming: 400 pb^{-1} in the bag, 1.5 fb^{-1} summer 2006…

Backup slides

Improved Jet Clustering Algorithms

JetClu: *Run I Jet Algorithm*

Not infrared safe (at NNLO)

Preclustering and Ratcheting: → *difficult to implement at the parton/hadron level, depends on the detector geometry*

More difficult to compare to theory and between experiments

MidPoint: *Run II Cone Algorithm*

Uses rapidity, y, instead of pseudorapidity, η and transverse momentum p_T instead of transverse energy, E_T

Infrared safe and well defined

No preclustering, no ratcheting

→ *Able to make more direct comparisons with theory and between experiments*

Kt Clustering:

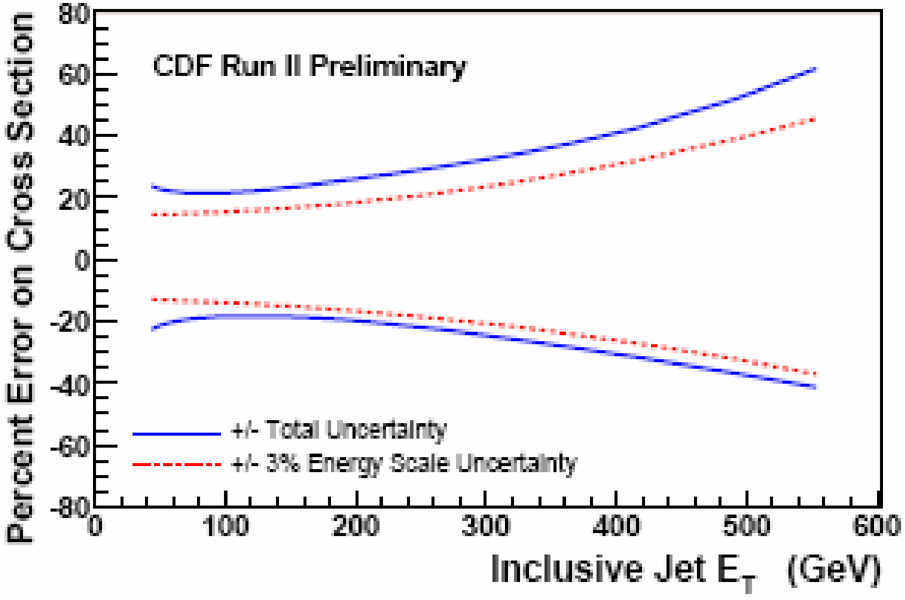
Precluster towers with $P_T > 0.1$GeV

Merge preclusters until all jets are separated by $\Delta R > D$ where D is the scale of the jet.

No use of seeds → infrared and collinear safe

Towers uniquely assigned to jets → no splitting/merging

Uncertainty in the energy scale is the dominant source of systematic error, can expect this to improve...

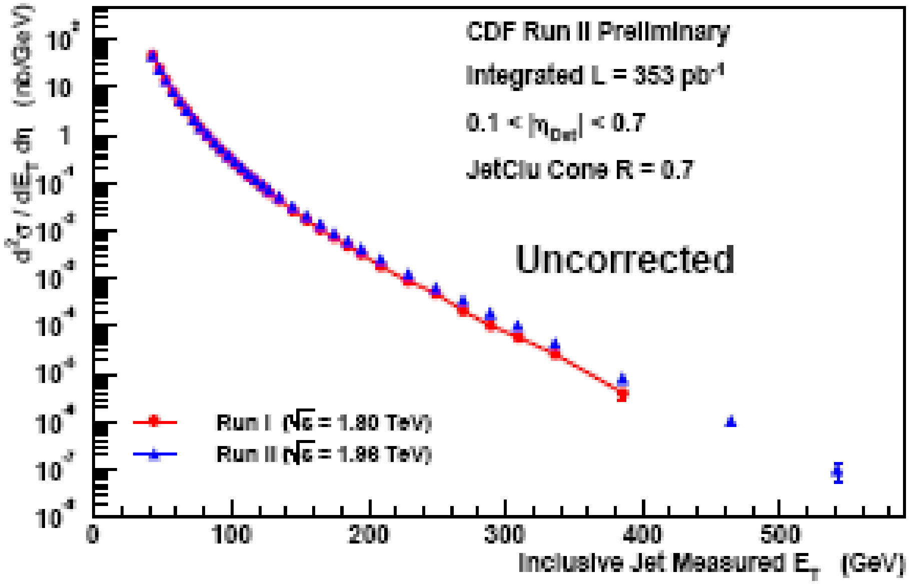


The effect of a 3% energy scale uncertainty contribution to the total systematic error

For a faster falling E_T spectrum, the error on the measured cross section becomes larger

→ *Errors become larger when measuring forward jets*

We now have even more data available (plot includes 353 pb^{-1})



The increased center-of-mass energy enables us to extend our Run I results by about 200 GeV

→ *Able to probe shorter distances with higher precision*

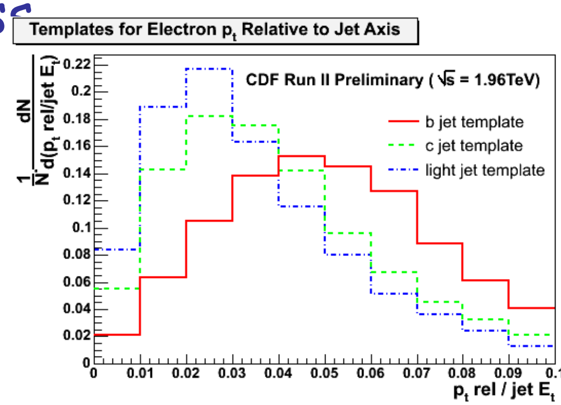
→ *When including more data, rise at high E_T is not as dramatic*

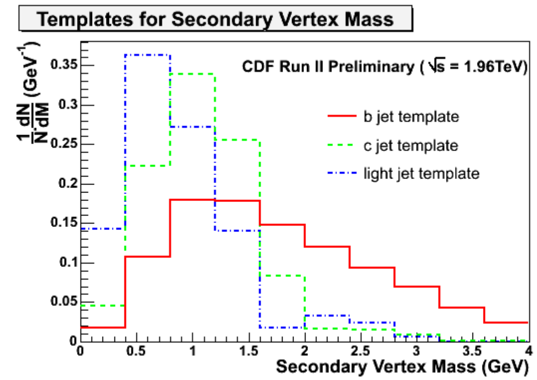
In addition to being able to study the high E_T region we have more data in the low E_T region.

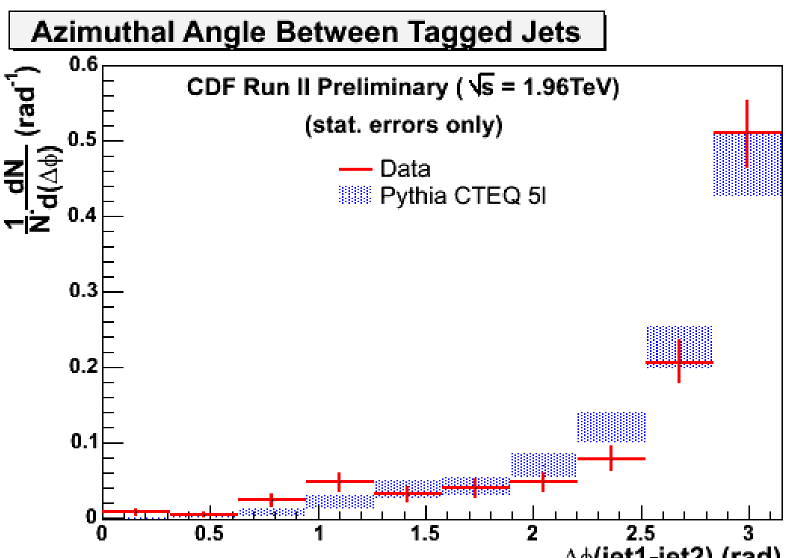
B-$\bar{B}$ di-jet Production

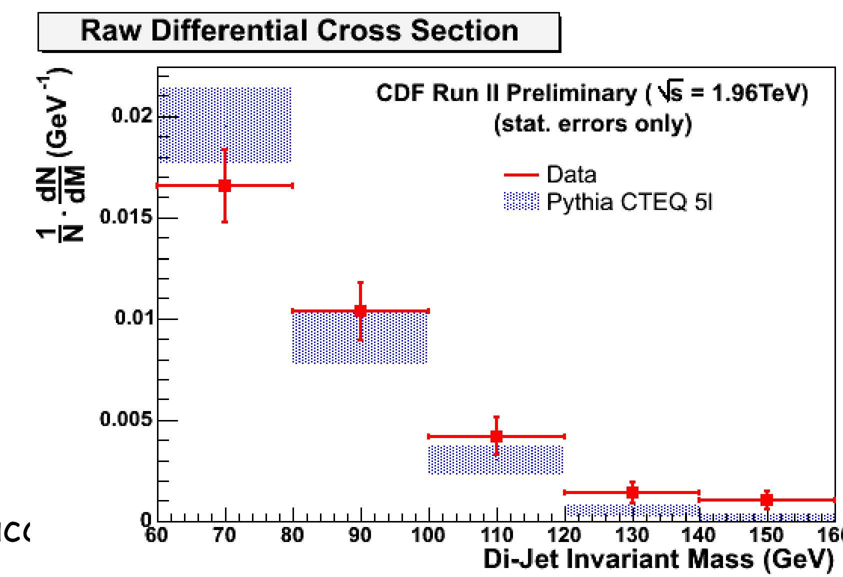
CDF: study b-bbar di-jet production at high p_T, $|\eta|<1.2$

Tag b-quarks with secondary vertex tag, determine b-fractions by using additional soft electron tag, fit templates of p_T of electron relative to jet axis, and vertex mass









X(3872) Observation at CDF

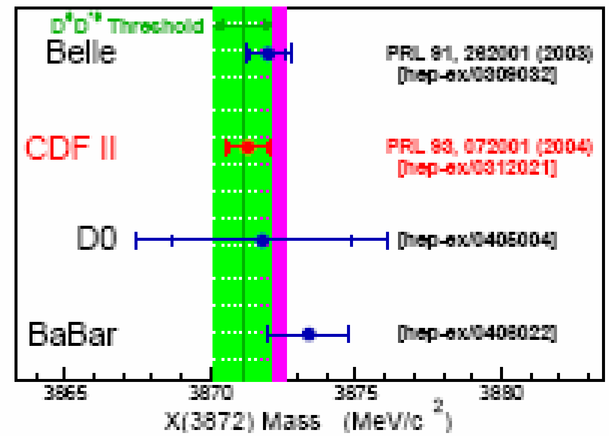
Belle announces in August 2003

$$B \to K J/\Psi \pi^+ \pi^-$$

CDF confirms within a month:

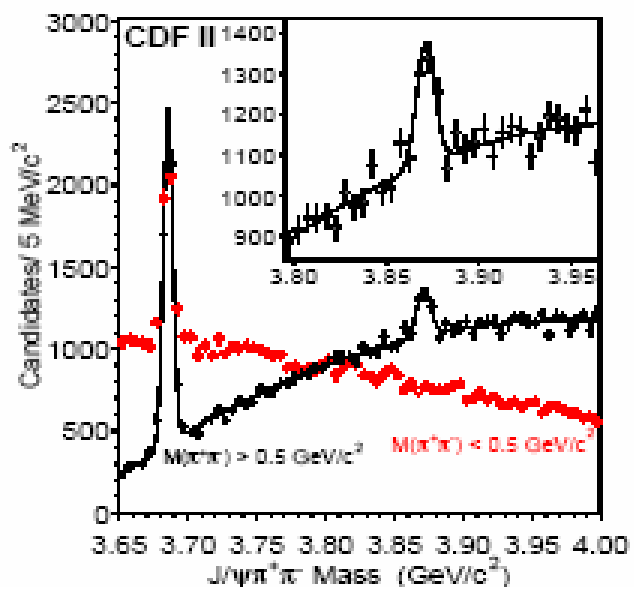
$$X(3872) \to J/\Psi \pi^+ \pi^-$$

both at $> 10\sigma$ level



The mass:

- not easily explained as $^3D_2\ c\bar{c}$
- CDF: m_X =3871.3±0.7±0.4 MeV/c^2



The width:

- compatible with zero
- CDF: σ=5.44±0.72 MeV/c^2
- Belle: Γ=1.4±0.7 MeV/c^2

Nature of X(3872)

Primary hypotheses:

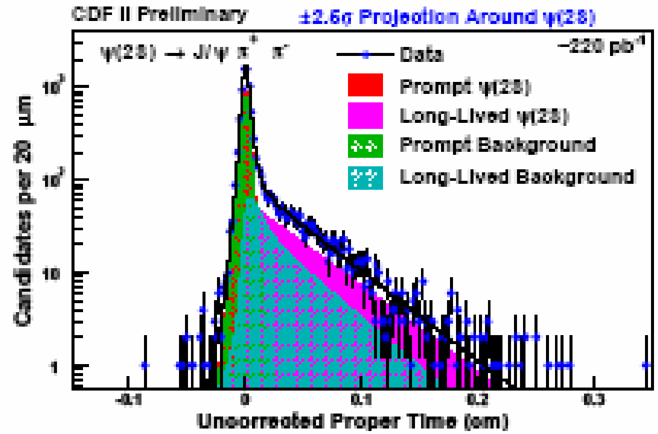
- a charmonium state?
  - 1^3D_2 most natural choice
  - others possible, hep-ex/0407033
  - problems in each case!
- a DD* molecule? not clear

Measure properties:

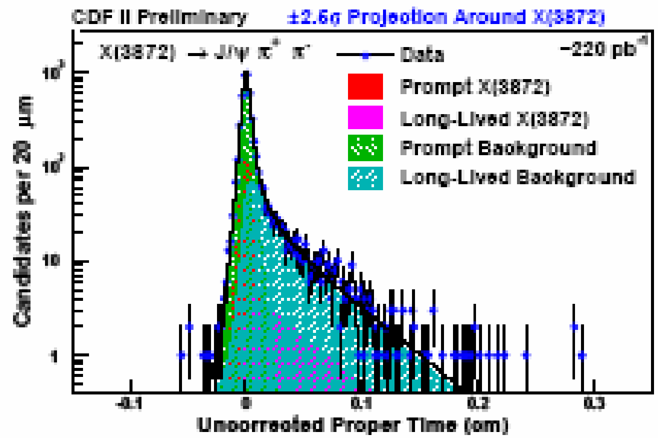
- quantum numbers, other decays
- "lifetime", production, $m_{\pi\pi}$

At CDF:

- measure lifetimes
  - charmonium-like production
- study $m_{\pi\pi}$
  - signal enhancement for high $m_{\pi\pi}$
    - $\Rightarrow$ possibly $X(3872) \to J/\Psi\rho$
  - $m_{\pi\pi}$ shape analysis in progress



$$f^{\Psi(2S)}_{longlived} : 28.3 \pm 1.0 \pm 0.7\%$$



$$f^{X(3872)}_{longlived} : 16.1 \pm 4.9 \pm 2.0\%$$