QCD and Hadron Physics at CDF

Andrey Korytov

UNIVERSITY OF FLORIDA

(for the CDF Collaboration)

QCD and hadron Physics at CDF

High P_T QCD

Jets (inclusive cross section)
Dijet mass distribution
W/Z/g+jets cross sections
Heavy flavor production

Low P_T QCD

Jet fragmentation
Underlying event
Diffractive physics
Hadrons (mass/BR/t)

Tevatron upgrade: Run II vs. Run I

Original Plan: Run I → Run II

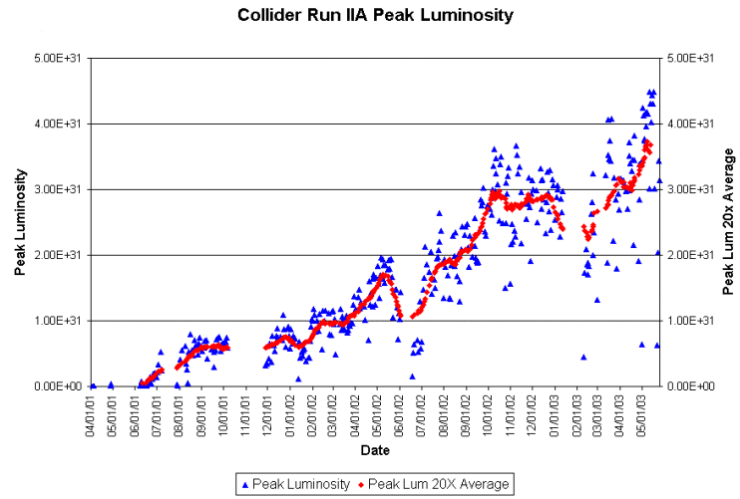
CM energy:	1.8	→	1.96 TeV
Bx spacing:	3.5	→	0.4 ms
Max luminosity:	2×10^{31}	→	50×10^{31} cm^{-2} s^{-1}
Integrated luminosity: (before LHC turn-on)	0.1	→	15 fb^{-1}

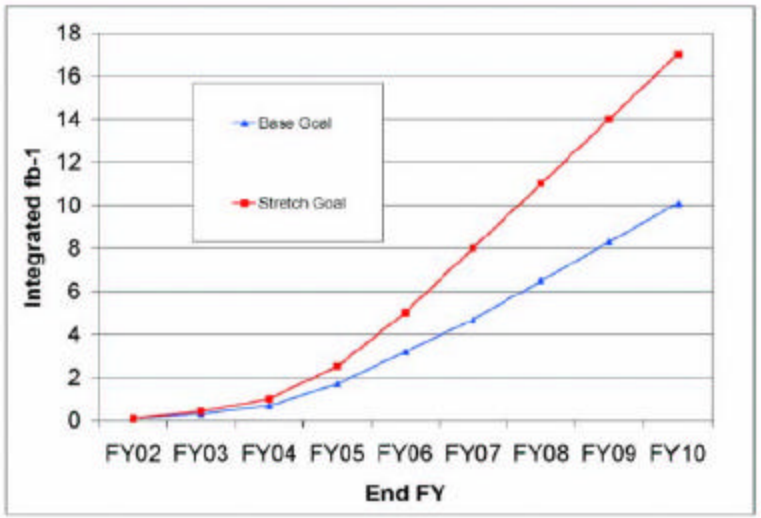
As of May 2003:

Peak luminosity so far:	4.5×10^{31} cm^{-2} s^{-1}
Total delivered (incl. commissioning):	0.24 fb^{-1}
On tape (CDF, incl. commissioning):	0.18 fb^{-1}
Good for physics (CDF)	>0.13 fb^{-1}
CDF current data taking efficiency	~90%

Long-term plan (by end of 2008):

Base goal:	6 fb^{-1}
Stretch goal:	11 fb^{-1}





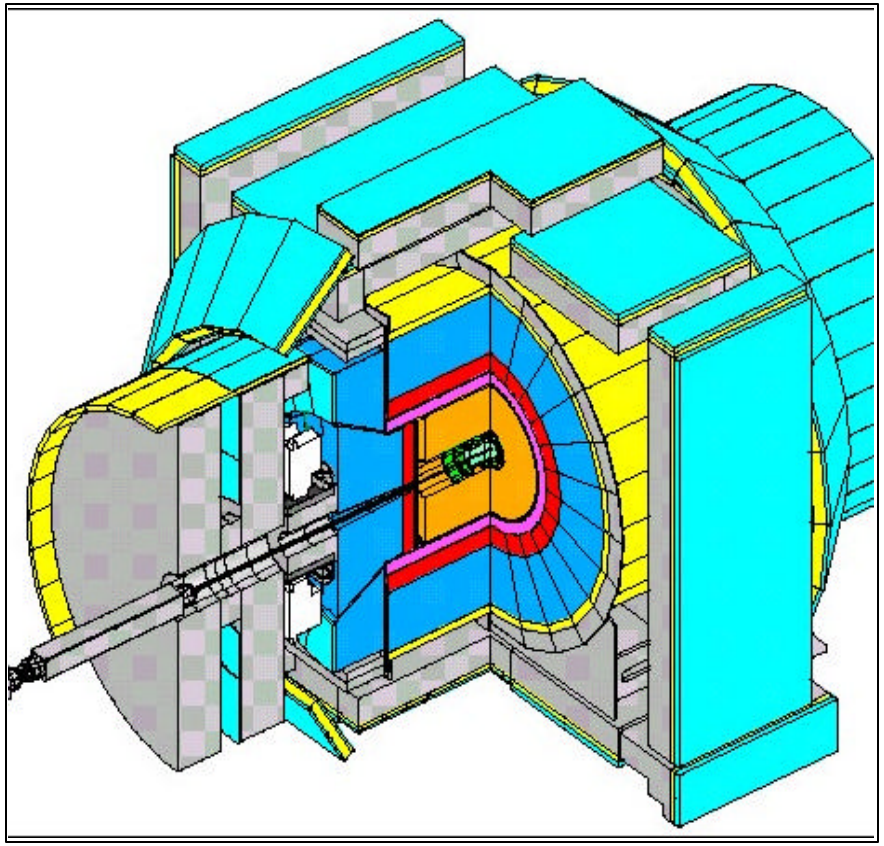
CDF upgrade: what is new

Retained from CDF I:

- Solenoid
- Central Calorimeters
- Central Muon System

Brand new in CDF II:

- 5-layer 3D vertex Si detector
- Intermediate Si layers
- Central Drift Tracker
- Plug Calorimeter
- Mini-plug calorimeter
- Time of Flight System
- Expanded Muon Coverage
- TRIGGER, now includes:
  - displaced vertex
  - track p_T>1.5 GeV/c
- Faster Front End Electronics



- 3d vertex coverage: |h|<2
- Tracking coverage: |h|<2
- Calorimeter coverage: |h|<3.6
- Mini-plug calorimeter: 3.6<|h|<5.1
- Muon coverage: |h|<1.5

QCD and hadron Physics at CDF

High P_T QCD

Jets (inclusive cross section)
Dijet mass distribution
W/Z/g+jets cross sections
Heavy flavor production

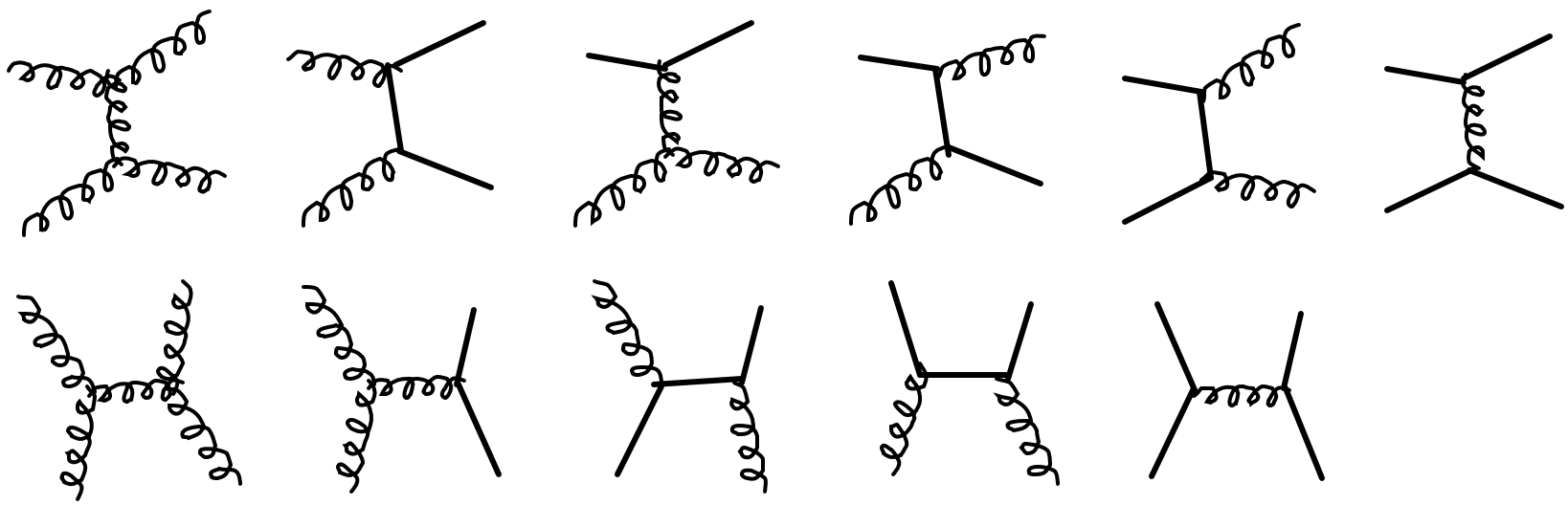
Low P_T QCD

Jet fragmentation
Underlying event
Diffractive physics
Hadrons (mass/BR/t)

Inclusive jet production: introduction

Challenges/complications:

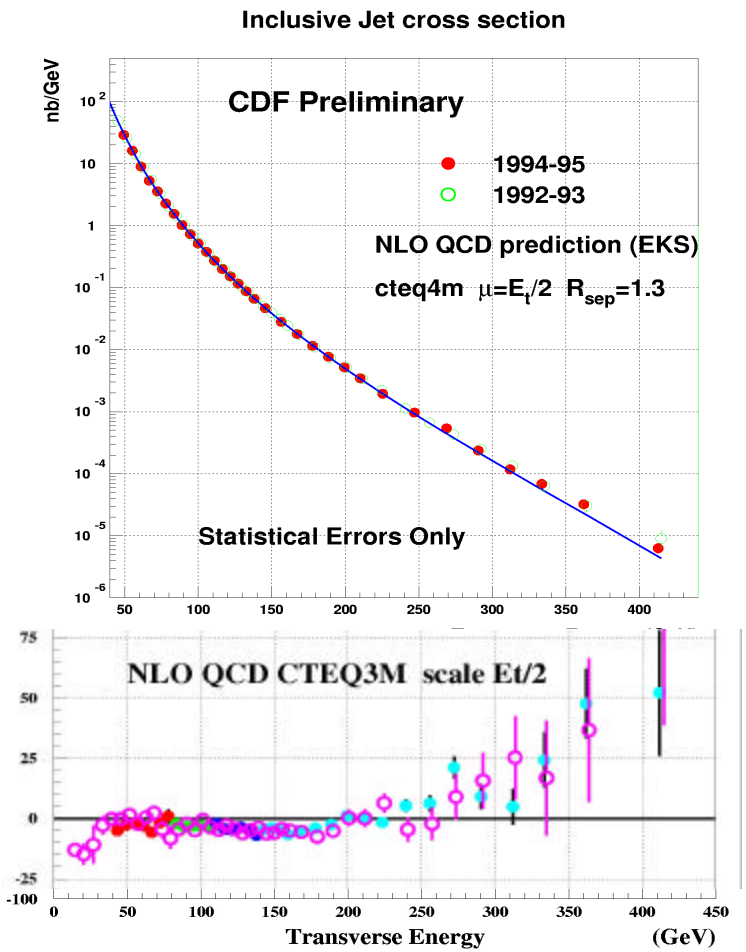
- ❑ **Large number of diagrams…**
  - **Sample of LO diagrams below**
  - **NLO calculations available**
  - **Any hope for NNLO?**
- ❑ **Uncertainties in PDFs…**
- ❑ **Confront data and theory (jets vs partons)…**



Inclusive jet production: Run I story…

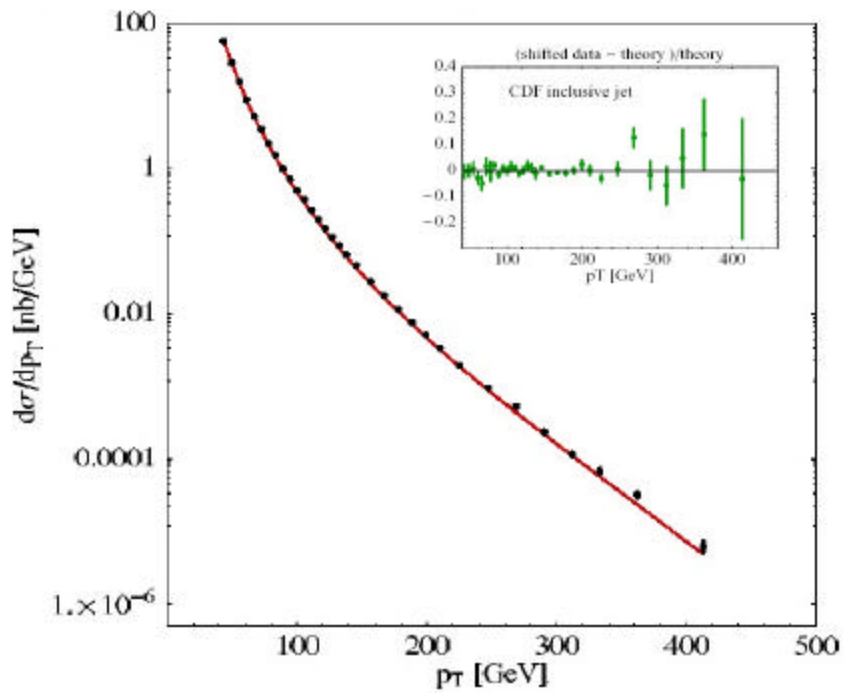
Run I data and NLO+CTEQ3M

- Excess at high E_T?



Run I data and NLO+CTEQ6M

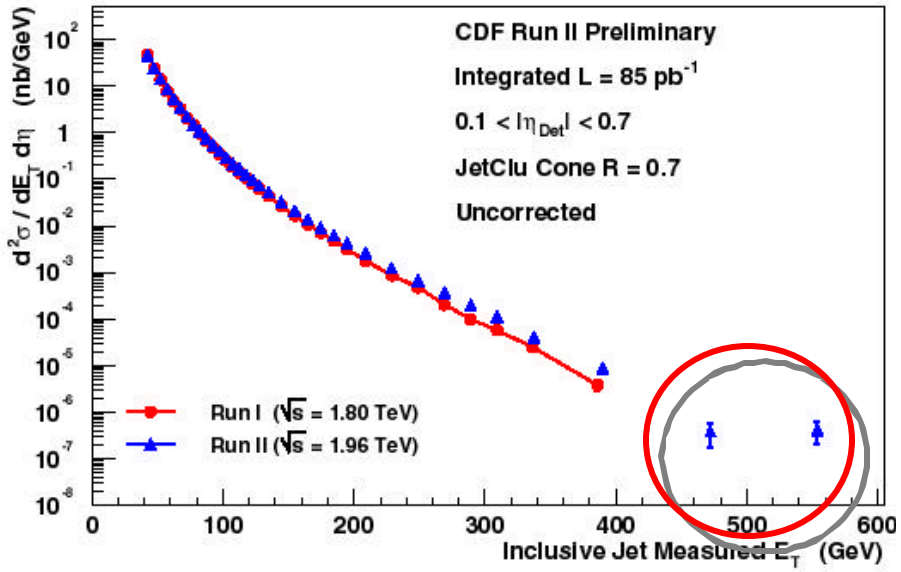
- CTEQ6:
  - New Data: H1, ZEUS, D0 (vs. h!), CDF
  - New methods: Systematic errors included
  - New features: Errors are available
- no excess, anymore…

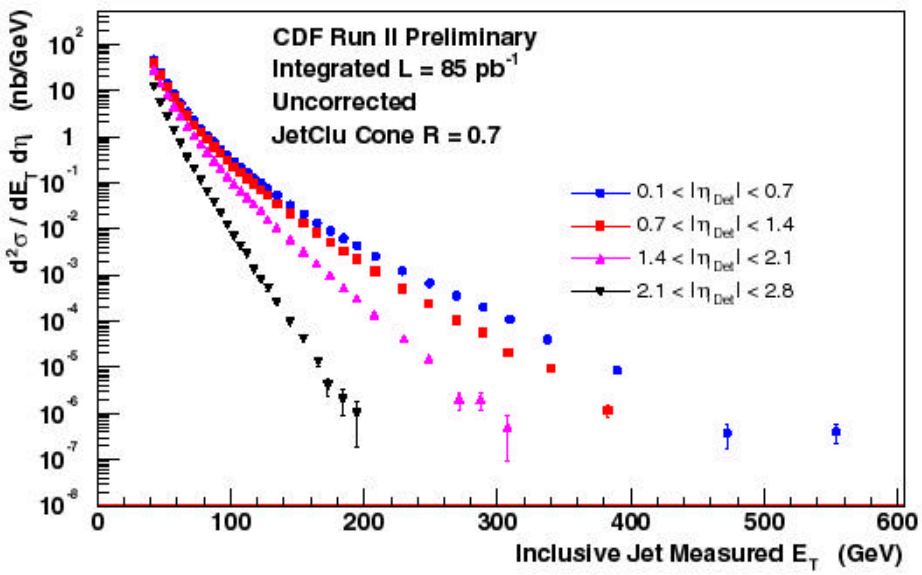


Inclusive jet production: Run II data

Run II:

- 8 orders of magnitude
- Highest E_T jets ever
- Data in h bins (new for CDF—analysis in progress)

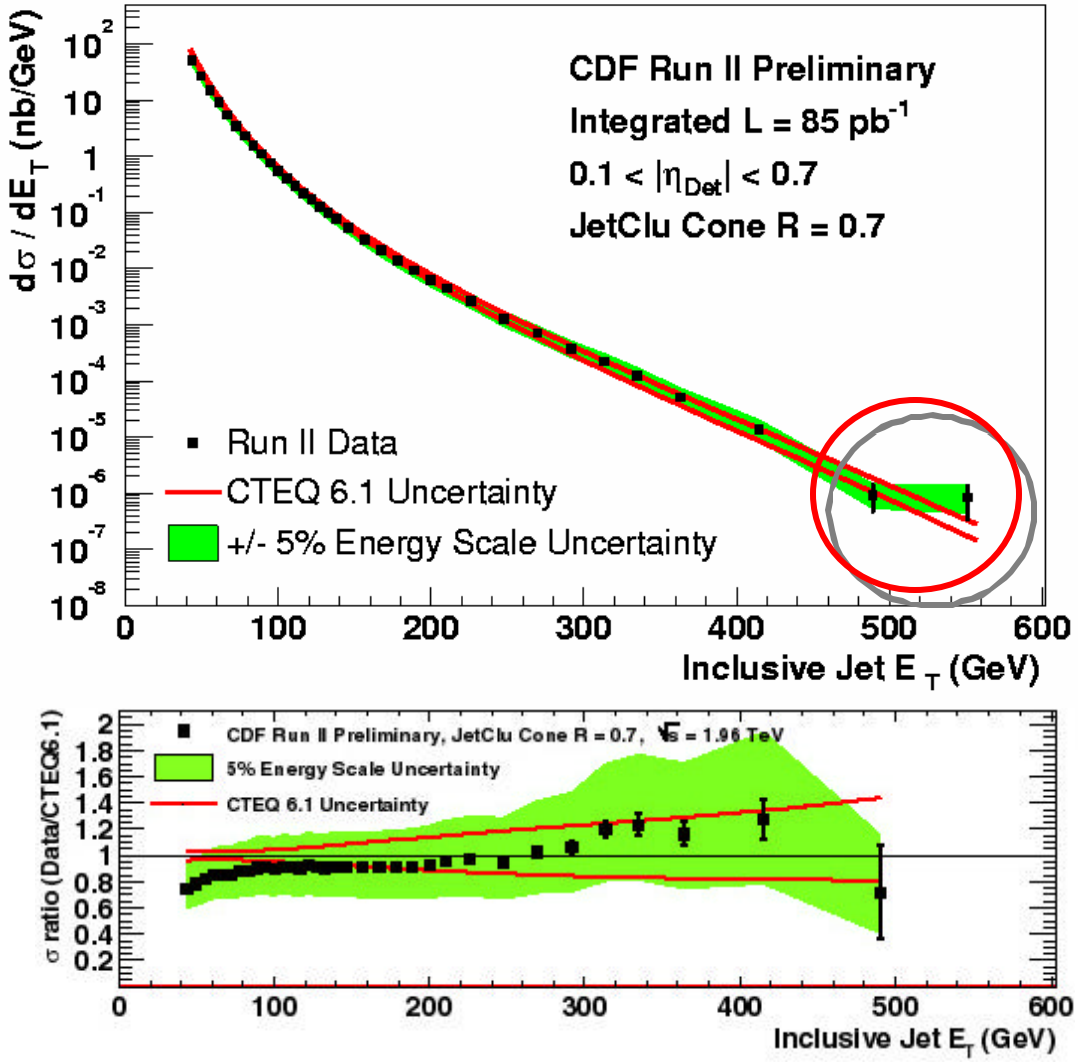




Inclusive jet production: data vs NLO

Run II data and theory:

- Good agreement with NLO pQCD and CTEQ6.1
- Expect new constraints on compositeness
- ~20% dip at lower E_T? (not present in Run I)
- Need to beat systematic errors (5% energy scale)



QCD and hadron Physics at CDF

High P_T QCD

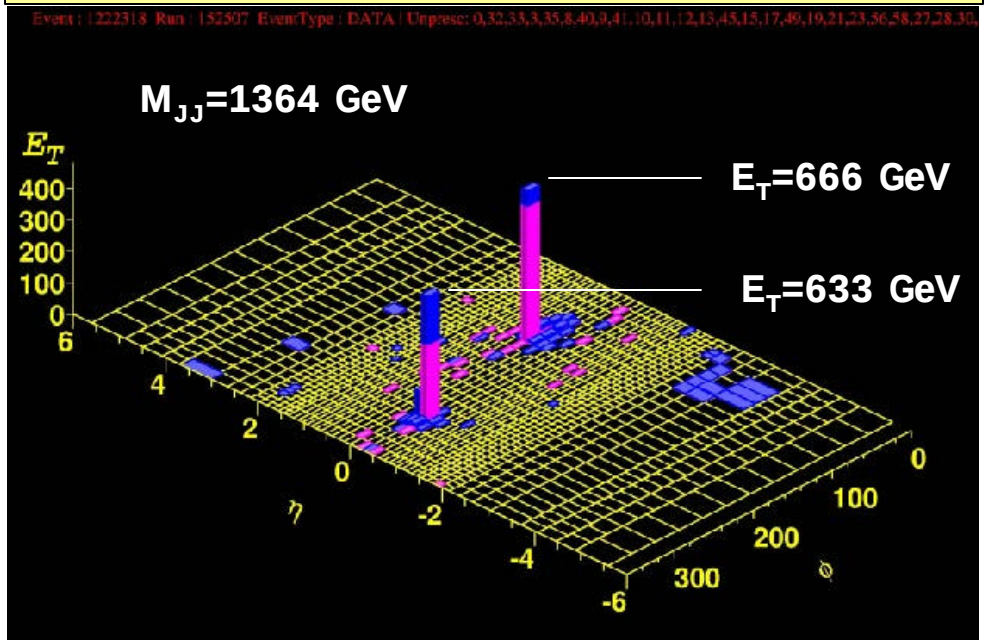
Jets (inclusive cross section)
Dijet mass distribution
W/Z/g+jets cross sections
Heavy flavor production

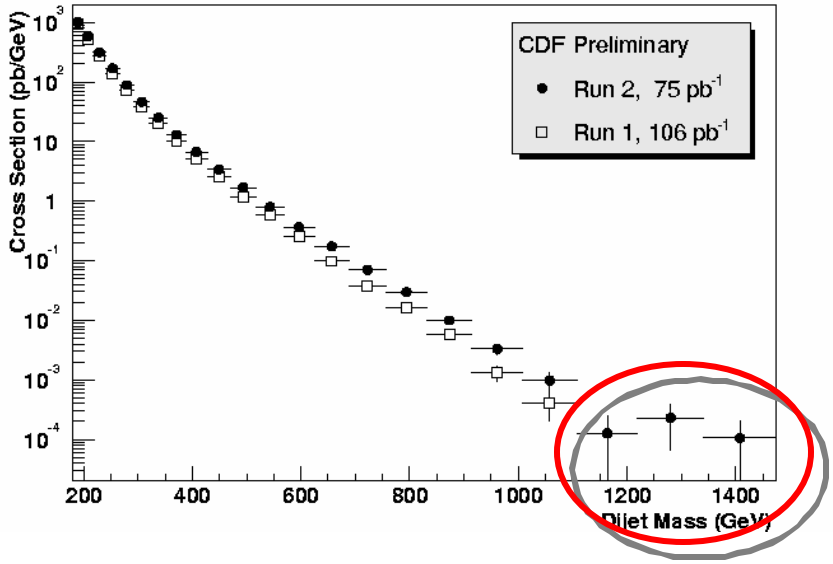
Low P_T QCD

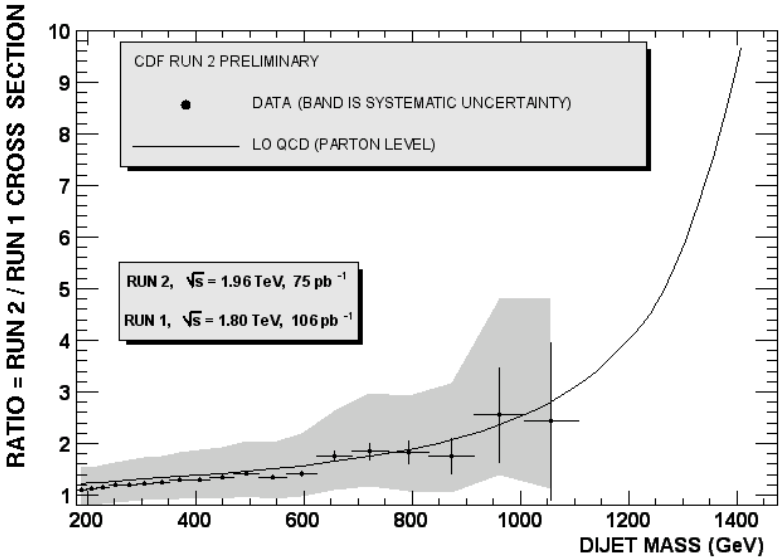
Jet fragmentation
Underlying event
Diffractive physics
Hadrons (mass/BR/t)

Dijet production: Run II data

- Ratio s (Run II) / s (Run I) agrees with LO pQCD within ~10%
- Beat on systematic errors (now >50%)
- Stay tuned for data/theory, angular distrib.

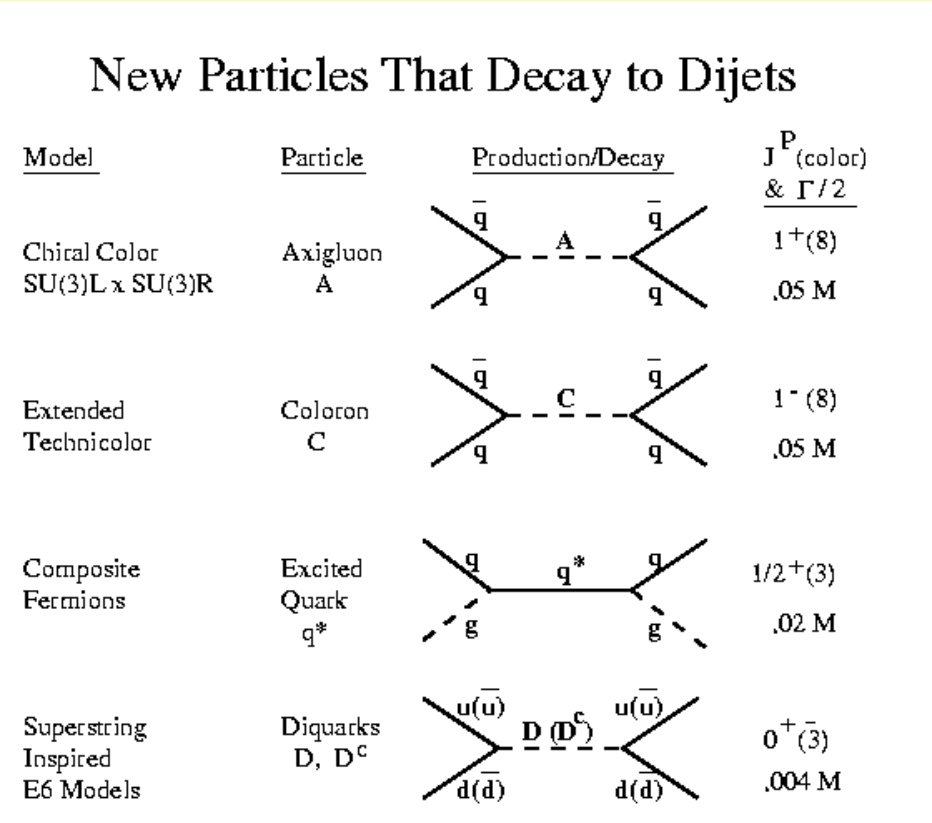




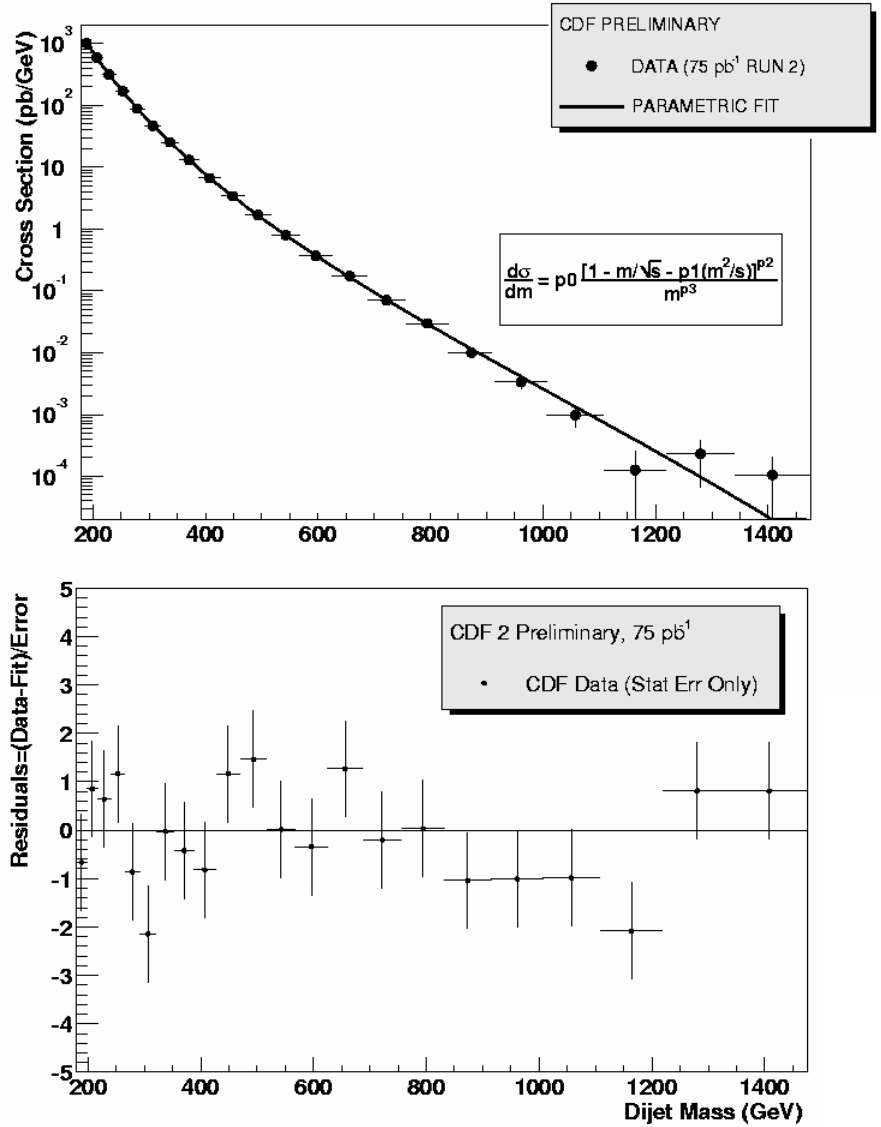


Dijet production: any new physics?

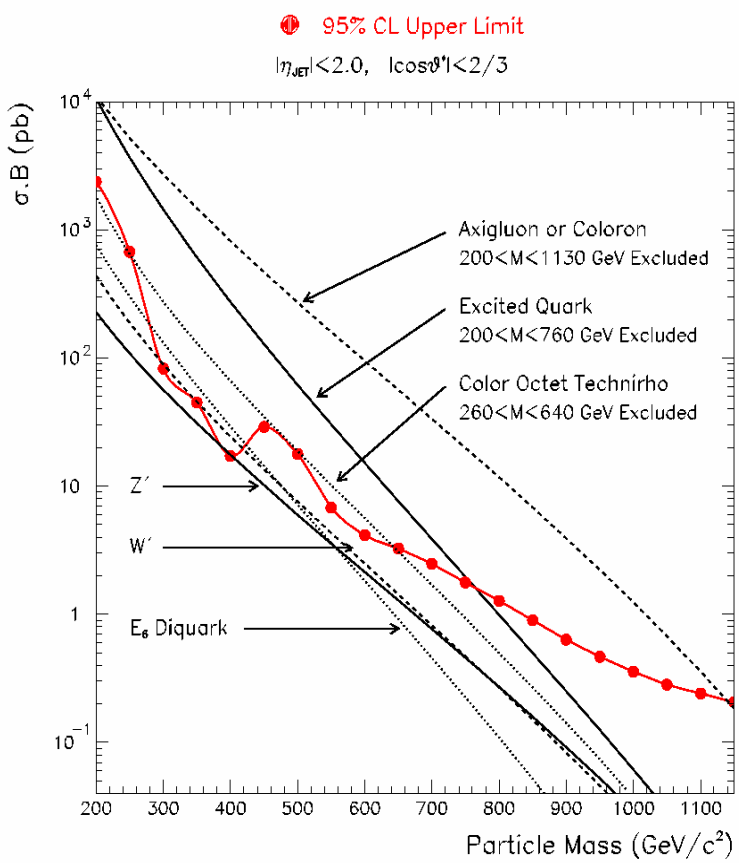
Plausible dijet resonances:



→ **Any bumps over a smooth line fit?**



Dijet production: new limits on new physics



Run II exclusion limits (95% CL)

- **Axigluons/colorons: M= 200—1130 GeV**
  Run I: 200— 980 GeV
- **excited quarks: M = 200—760 GeV**
  Run I: 200—570, 580—760 GeV
- **color octet technirhos: M=260—640 GeV**
  Run I: 260—480 GeV
- **E6 diquarks: M = 280—420 GeV**
  Run I: 290—420 GeV
- **W': M = 300—410 GeV**
  Run I: 300—420 GeV

QCD and hadron Physics at CDF

High P_T QCD

Jets (inclusive cross section)
Dijet mass distribution
W/Z/g+jets cross sections
Heavy flavor production

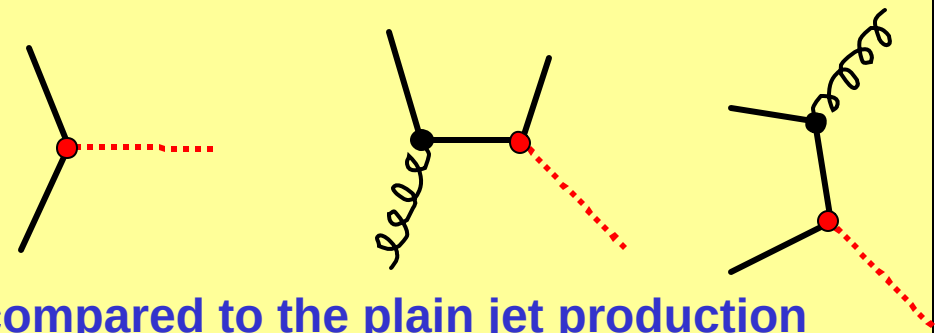
Low P_T QCD

Jet fragmentation
Underlying event
Diffractive physics
Hadrons (mass/BR/t)

W/Z/g(+jets) production: introduction

QCD-wise, are W/Z/g cross sections of interest?

- Smaller subset of diagrams, different mix of initial partons
  - Below is a set of LO diagrams for W/Z and W/Z/g + 1 jet



- → PDF contribute differently as compared to the plain jet production

- Inclusive distributions are not affected by jet finding uncertainties
  - However, W/Z/g identification algorithms have their own caveat…

More theoretical work is needed, e.g.:

- W inclusive: known at the level of NNLO
- W + 1 jet: known at the level of NLO
- W + 2, 3, 4 jets: known at the level of LO
  - (MCFM does proved W + 2 jets at NLO, it just isn't an event generator)

W(+jets) production: cross sections

s(W) · Br(W→*e*n) inclusive:

- LO is significantly off, NLO works fine, NNLO makes little difference

R_{10} = s(W + ³1 jets) / s(W) :

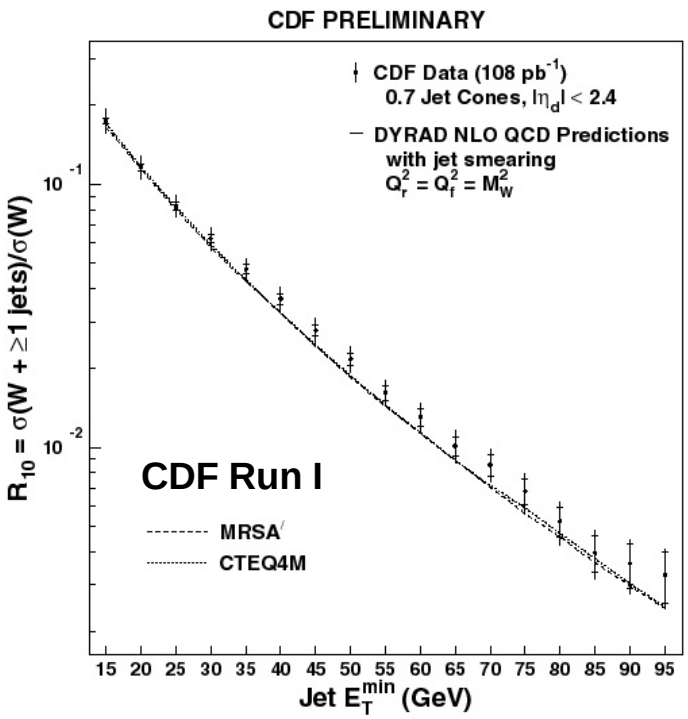
- NLO order works fine for the ratio (LO is not too different, 5-10%)

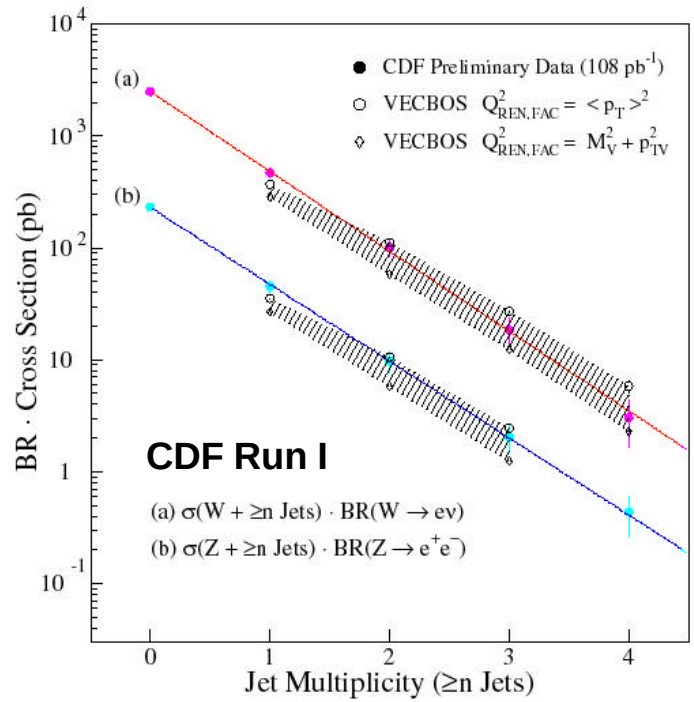
s(W + ³N jets) · Br(W→*e*n) :

- LO works fairly well (either slope or overall normalization seem to be off?)

Inclusive s (nb)

Run I (1.8 TeV):	
LO:	**1.76**
NLO:	**2.41**
NNLO:	**2.50**
CDF I:	**2.38±0.24**
Run II (1.96 TeV):	
LO:	**1.94**
NLO:	**2.64**
NNLO:	**2.73**
CDF II:	**2.64±0.18**





QCD and hadron Physics at CDF

High P_T QCD

Jets (inclusive cross section)
Dijet mass distribution
W/Z/g+jets cross sections
Heavy flavor production

Low P_T QCD

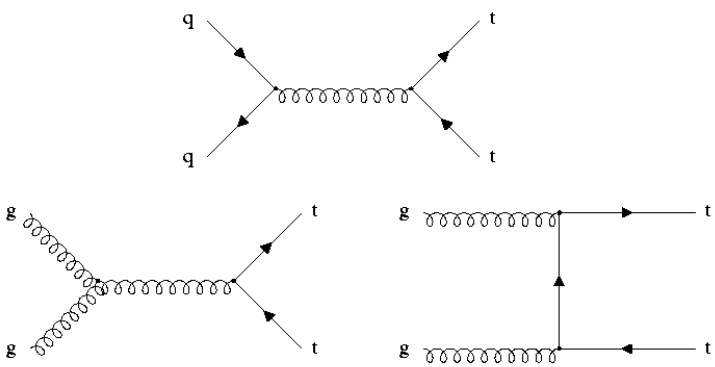
Jet fragmentation
Underlying event
Diffractive physics
Hadrons (mass/BR/t)

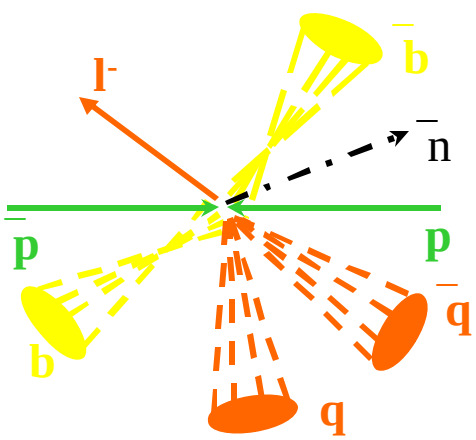
Heavy flavor production: t-quark

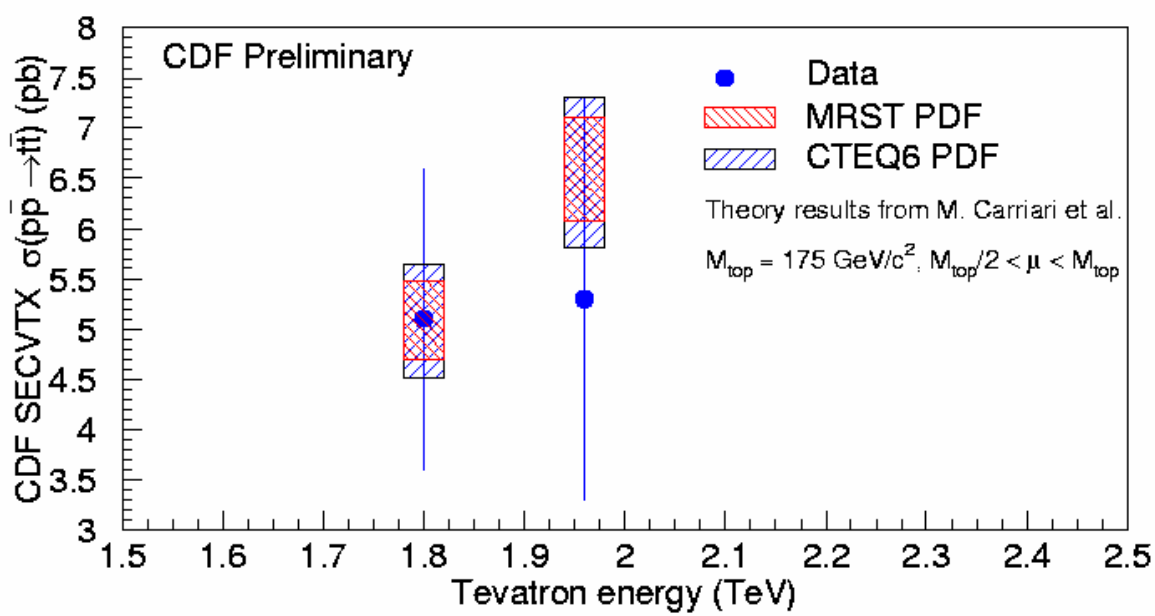
Top quark production

- QCD driven (see LO for $t\bar{t}$ production)
- Run II first results:
  - $t \rightarrow Wb \rightarrow l\nu b$, $t \rightarrow Wb \rightarrow jjb$
  - Lepton, missing E_T, jets, b-tagging
- Run II σ agrees with Run I and theory

In pairs via the strong interaction



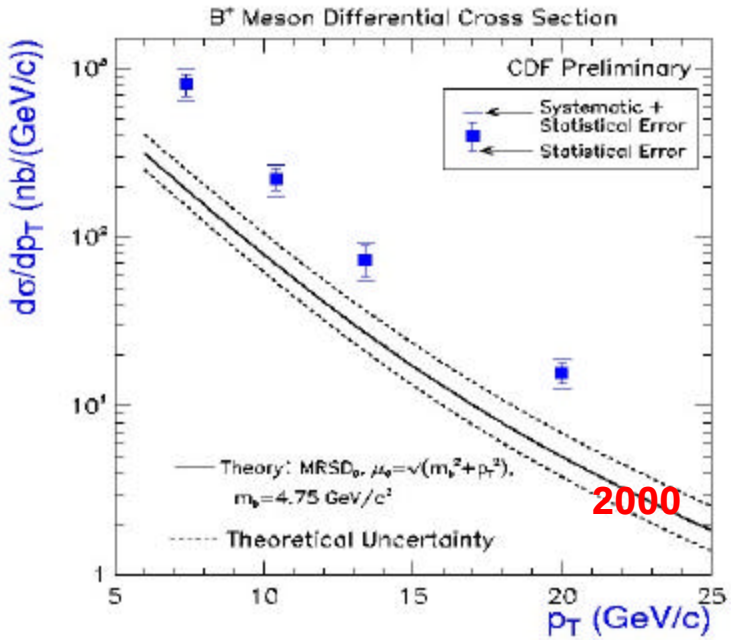


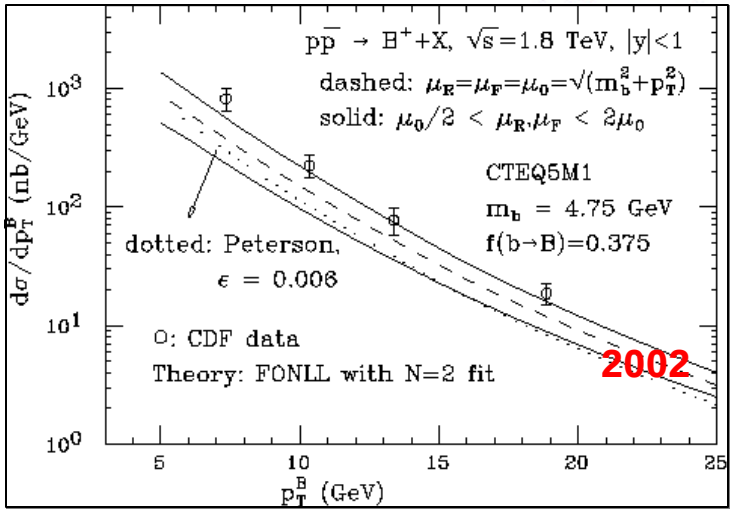


Heavy flavor production: b-quark

Bottom quark production

- 2000: (Run I data) / (Theory) =
  ~ 2.9 ± 0.5(exp) ± 0.5(theory)
- 2002: Theory revised (Cacciari, Nason)
  - FONLL =
    NLO (Fixed Order) + NLL resummation
  - Retuned Petersen fragmentation
  - New Theory goes ~1.7 times higher
- 2002: (Run I data) / (New Theory) =
  ~ 1.7 ± 0.3(exp) ± 0.5(theory)
- 2003: Run II data are forthcoming…



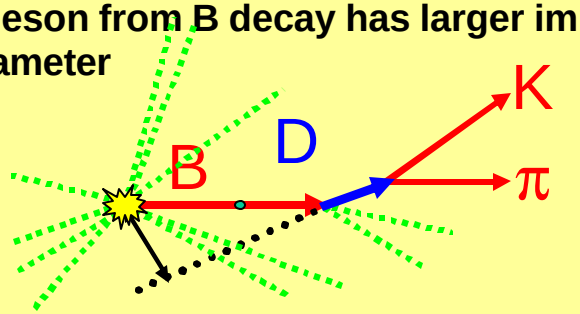


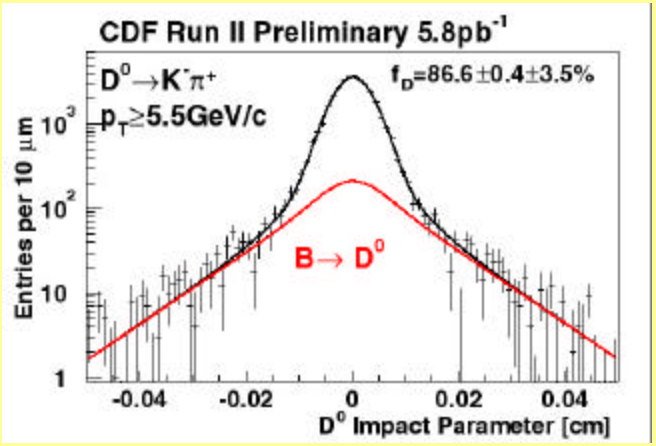
Heavy flavor production: c-quark

Direct Charm quark production

- Measure D-meson production
- Remove fraction of B→D

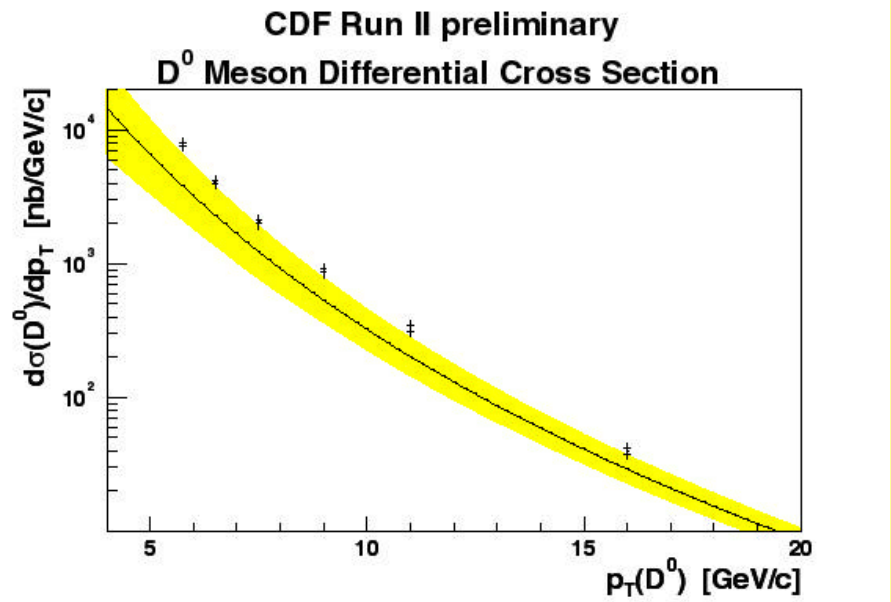
D meson from B decay has larger impact parameter





Measured cross sections

- D^0, D^+, D^{*+}, D_s
- Theory
  - FONLL (Cacciari, Nason)
  - m=1.5 GeV
  - CTEQ6M
- Data/Theory is similar for all…



QCD and hadron Physics at CDF

High P_T QCD

Jets (inclusive cross section)
Dijet mass distribution
W/Z/g+jets cross sections
Heavy flavor production

Low P_T QCD

Jet fragmentation
Underlying event
Diffractive physics
Hadrons (mass/BR/t)

Jet Fragmentation: doing it analytically

Jet fragmentation:

- parton shower development: resummed NLL approximations
  → e.g., MLLA, Modified Leading Log Approximation with single parameter $Q_{eff}=Q_{cutoff}=\Lambda_{QCD}$
- hadronization: no coherent theory
  → LPHD, hypothesis of Local Parton Hadron Duality with one parameter $K_{LPHD}=N_{hadrons}/N_{partons}$

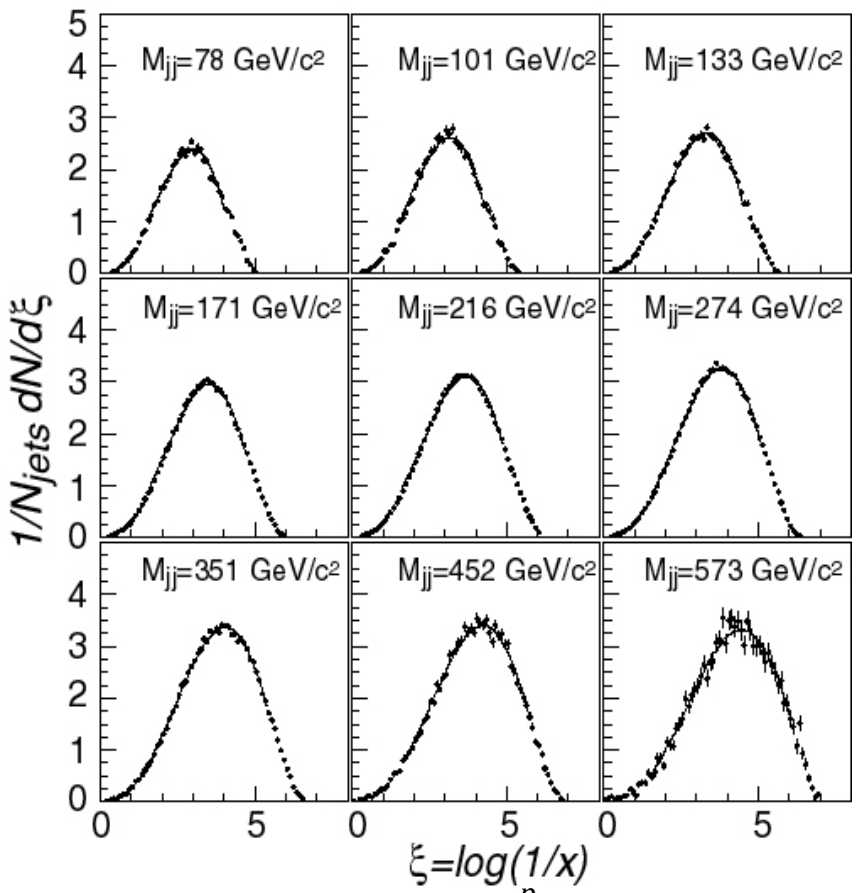
MLLA+LPHD:

- cannot describe all details…
- but all analytical…
- and works surprisingly well…

Run I (charged particles in jets):

- Q_{eff} = 230±40 MeV
- $K_{LPHD(\pm)}$ = 0.56 ± 0.10

CDF Run I
Charged particle momentum spectra (q_{cone}=0.47) and MLLA+LPHD fit

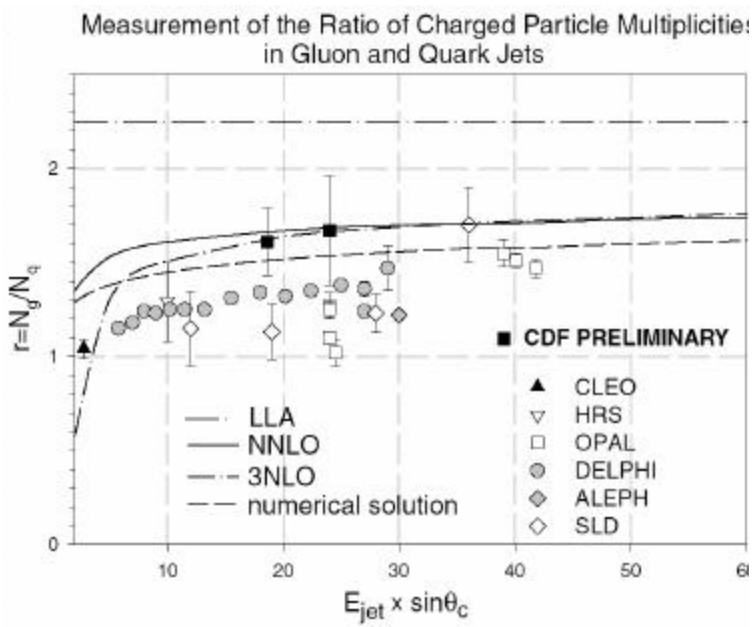


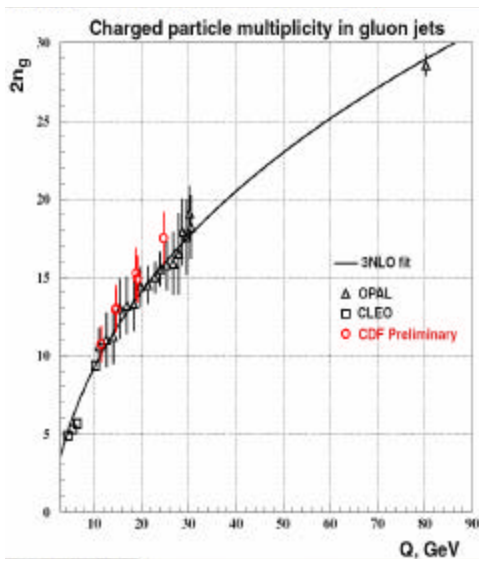
$$x = \frac{p_{particle}}{E_{jet}}$$

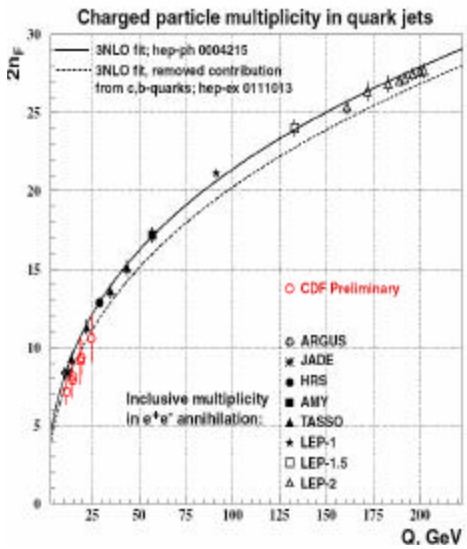
Jet Fragmentation: Gluon vs Quark jets

Difference of Gluon and Quark jets:

- $r = N_{hadrons}$(gluon jet) / $N_{hadrons}$(quark jet)
- calculations (for partons): various extensions of NLLA (r=1.5-1.7)
- data: lots of results from LEP, not all self-consistent (r = 1 to 1.5)
- CDF preliminary (Run I data, new analysis): r=1.6±0.2



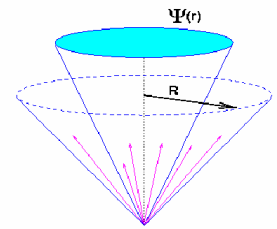




Jet Fragmentation: jet shapes and MC

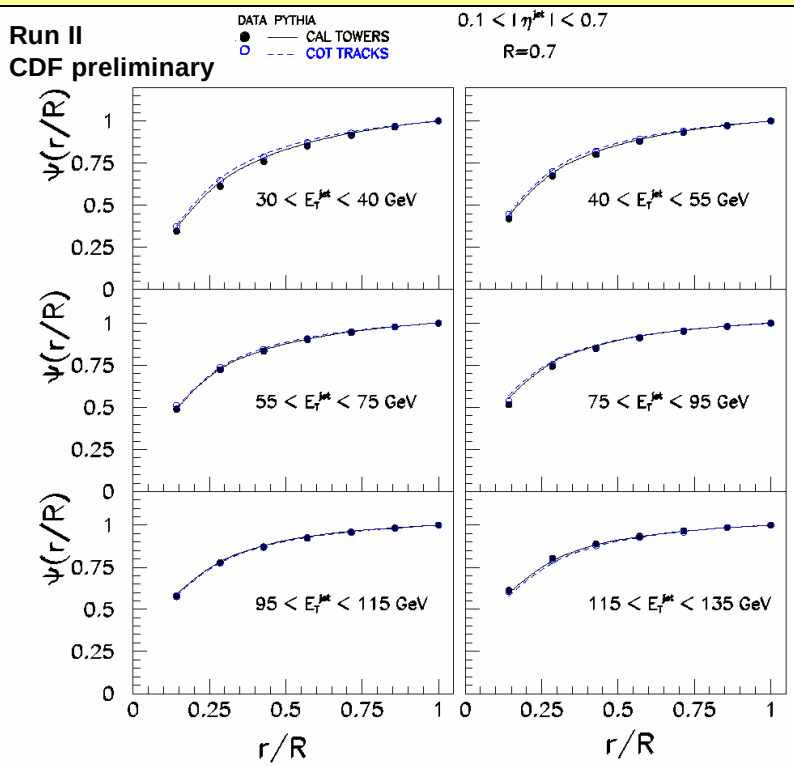
Compare jet shapes (E_T flow) to various MC generators

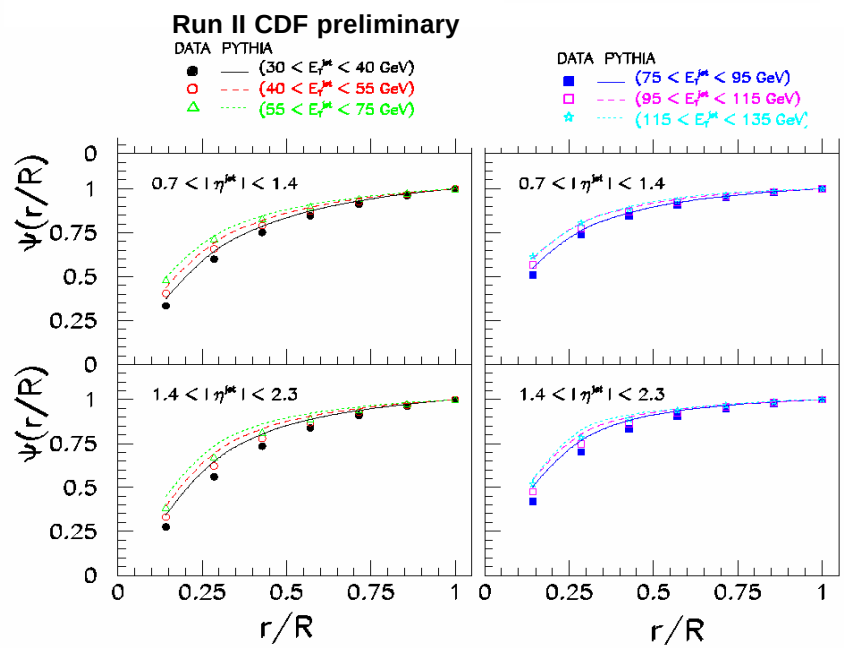
- E_T measured with calorimeter towers and charged tracks
- Central region jets agree with MC
- Forward region jets somewhat broader than MC jets
  - Tune new plug calorimeter simulation?
  - Tune MC?



$$\Psi(r) = \frac{1}{N_{\rm jets}} \Sigma_{\rm jets} \frac{E_T(0,r)}{E_T^{\rm jet}(0,R)}$$

$$\Psi(r=R) = 1$$





QCD and hadron Physics at CDF

High P_T QCD

Jets (inclusive cross section)
Dijet mass distribution
W/Z/g+jets cross sections
Heavy flavor production

Low P_T QCD

Jet fragmentation
Underlying event
Diffractive physics
Hadrons (mass/BR/t)

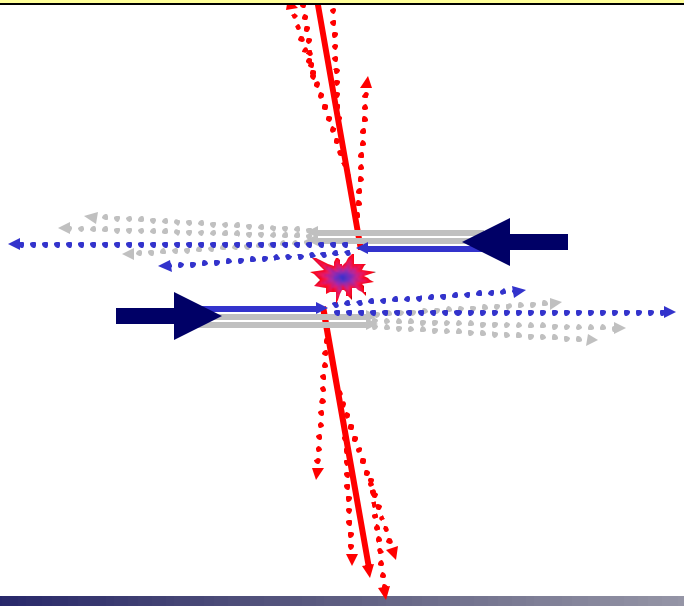
Underlying Event: introductory remarks

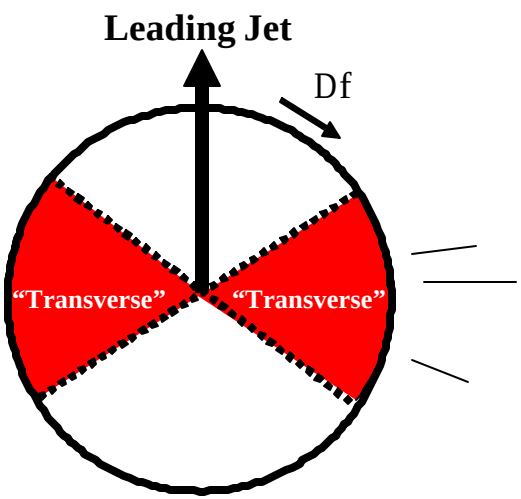
Whole Event:

- hard scattered partons
- final state radiation
- initial state radiation
- multi-parton interactions, if any
- proton remnants
- whole thing is entangled with color connections…

Underlying Event (UE) »
(whole event) – (hard part), i.e.:

- initial state radiation
- multiple parton interactions
- proton remnants
- fraction of final state radiation
- not completely independent from the hard scattering part…

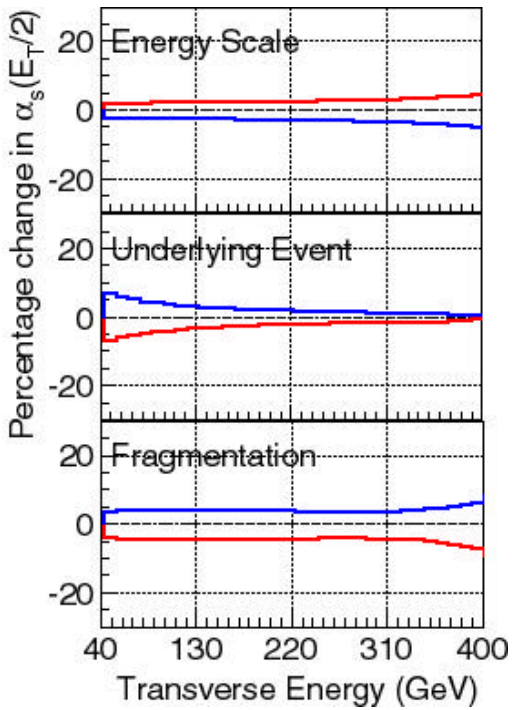


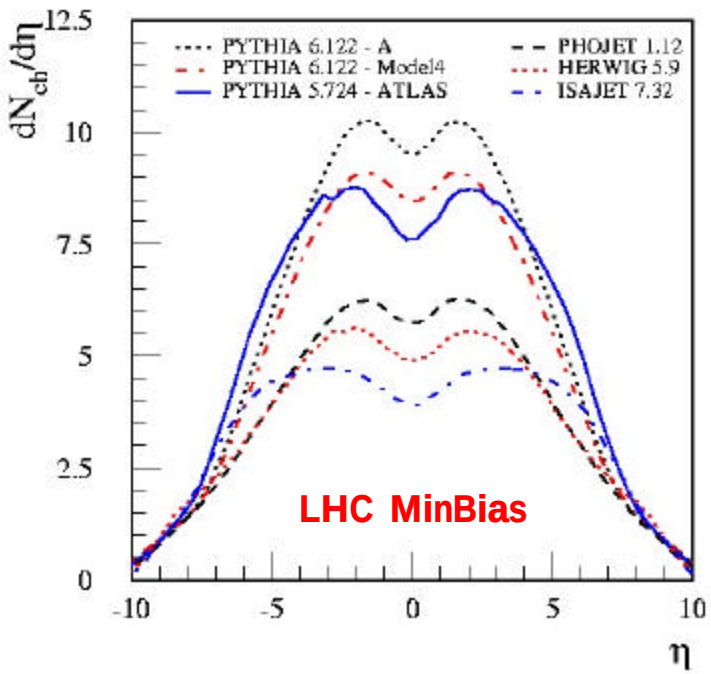


"transverse" particles as a probe of the underlying event

Underlying Event: why is it important?

- **UE pollutes many analyses:**
  - → **source of systematic errors**
- **UE Physics is poorly understood:**
  - → **MC Generators implement UE differently and with many parameters**
  - → **Even when tuned to approximately match the accessible data, MC predictions for LHC vary wildly**





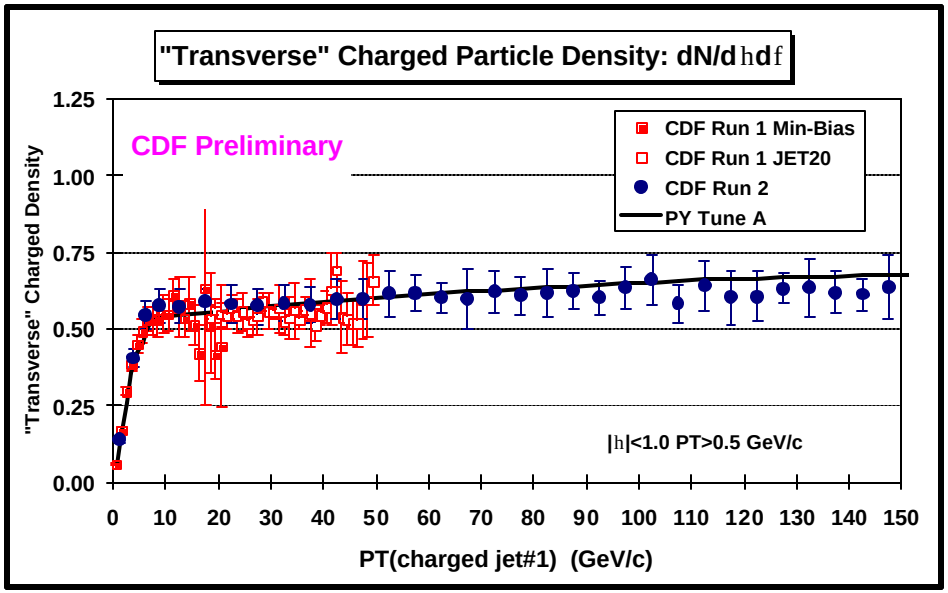
Underlying Event: Data vs MC Models

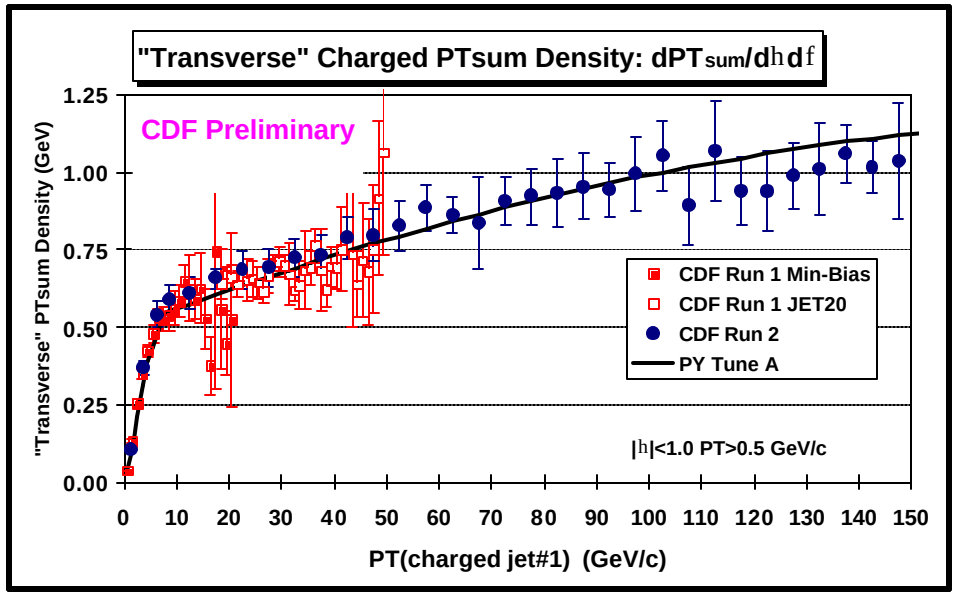
Run I:

- UE is not the same as Min-Bias: UE quite more active
- MC generators with default parameters: none describe well UE
- MC generators can be tuned: e.g. Pythia 6.206 (Tune A)

Run II:

- UE analysis expanded (range, more distributions)
- Pythia 6.206 (Tune A, based on Run I) still works—see plots below
- Other Monte Carlos will go through the same scrutiny
- Commonalities/differences between tuned MCs should shed light on UE physics





QCD and hadron Physics at CDF

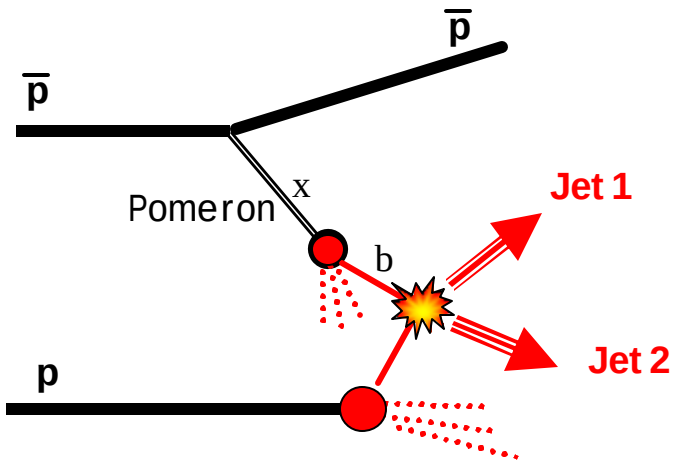
High P_T QCD

Jets (inclusive cross section)
Dijet mass distribution
W/Z/g+jets cross sections
Heavy flavor production

Low P_T QCD

Jet fragmentation
Underlying event
Diffractive physics
Hadrons (mass/BR/t)

Diffraction: introduction to diffractive dijets



ξ = fraction of the antiproton momentum carried by Pomeron (defines the rapidity gap size)

β = fraction of Pomeron momentum carried by parton participating in hard scattering

$x = \beta \cdot \xi$ fraction of the antiproton momentum carried by a parton ended up participating in hard scattering

Q^2 (average E_T of two jets)^2

Measure:

$$\text{Ratio} = \frac{\text{Single Diffraction (SD) dijet cross section}}{\text{Non-Diffractive (ND) dijet cross section}} = \frac{s_{SD}(x, x, Q^2)}{s_{ND}(x, Q^2)}$$

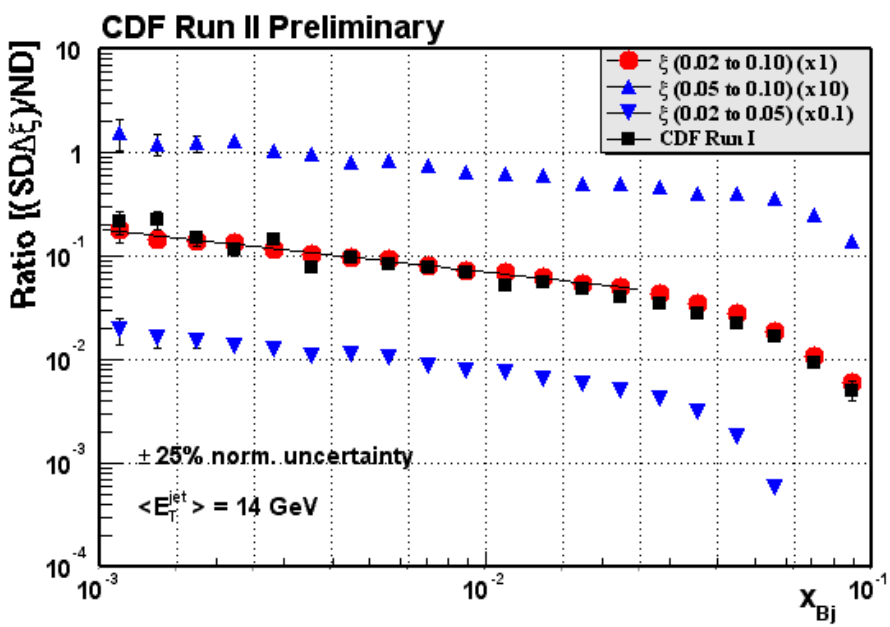
Study:

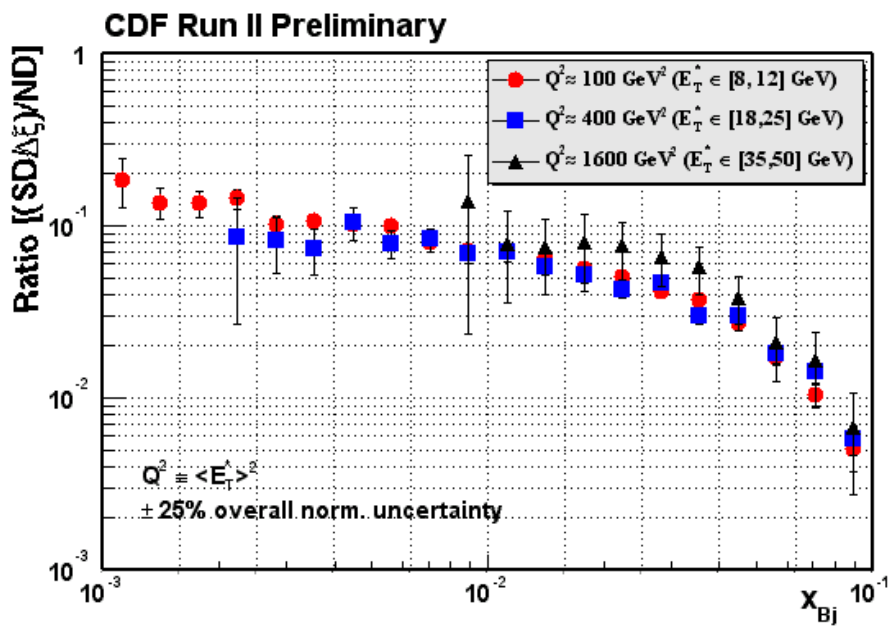
- dependence on x
- dependence on Q^2

Diffraction: diffractive dijet results

- "diffractive parton" momentum fraction x is x-independent, or, equiv., rapidity gap independent
  - Confirm Run I

- SD/ND Ratio is Q^2-independent, i.e. Q^2 evolution of "diffractive parton" $F_{jj}^{SD}(x) \sim F_{jj}^{ND}(x)$
  - Run II: larger range of Q^2





QCD and hadron Physics at CDF

High P_T QCD

Jets (inclusive cross section)
Dijet mass distribution
W/Z/g+jets cross sections
Heavy flavor production

Low P_T QCD

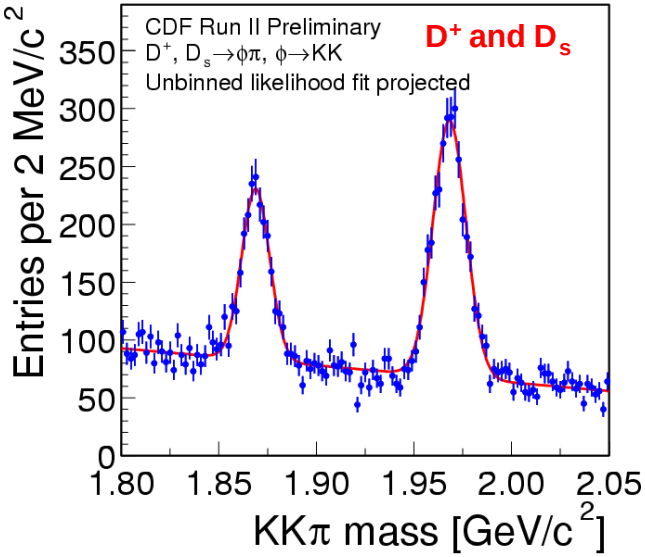
Jet fragmentation
Underlying event
Diffractive physics
Hadrons (mass/BR/t)

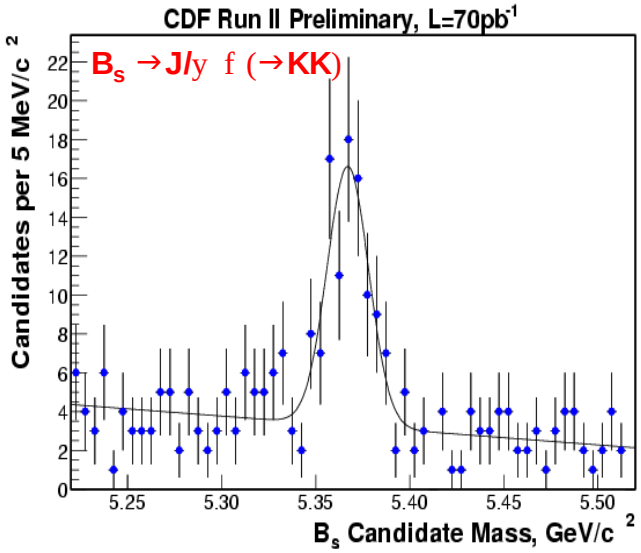
Hadron physics: hadron masses

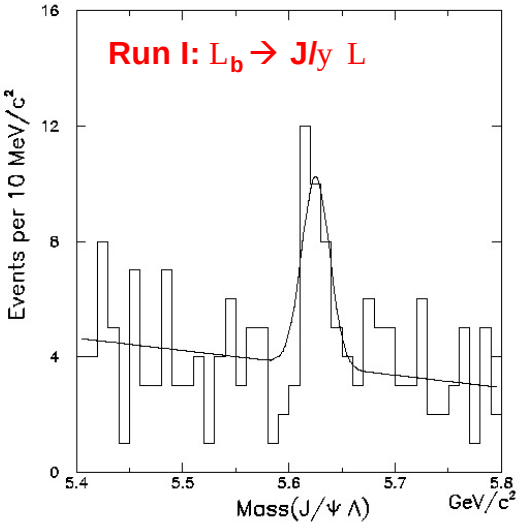
Tevatron is THE heavy flavor hadron factory

Secondary vertex trigger allows to fish them out

World largest sample of Λ_b







$M(D_s)-M(D^+)=99.28\pm0.43\pm0.27$ MeV/c²
PDG2002: 99.2 ± 0.5

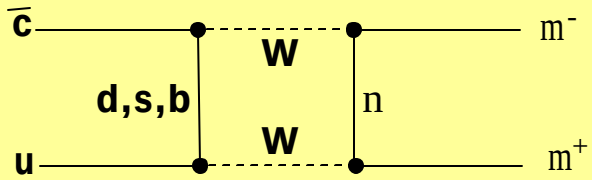
$M(B_s)=5365.50\pm1.29\pm0.94$ MeV/c²
PDG2002: 5369.6 ± 2.4

$M(\Lambda_b)=5621\pm4\pm3$ MeV/c²
PDG2002: 5624 ± 9

Hadrons: BR—any signs of new physics?

FCNC decays: $D^o \rightarrow m^+m^-$

Standard Model: BR~3´10^{-13}

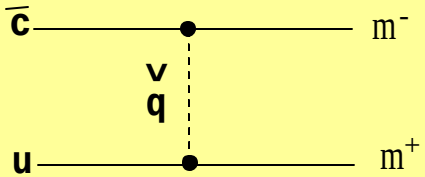


… plus more …

(³ 2 W/Z propagators)

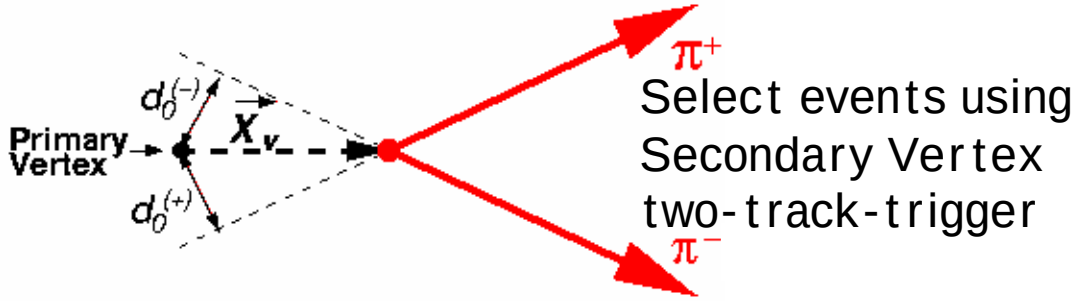
SUSY with R-parity violation:

BR up to ~ 3.5´10^{-6}



Run II: BR<2.4´10^{-6} @ 90%CL

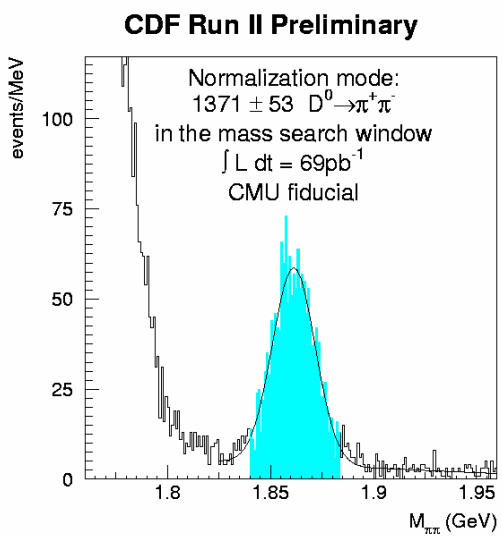
Earlier best result 4.1´10^{-6}

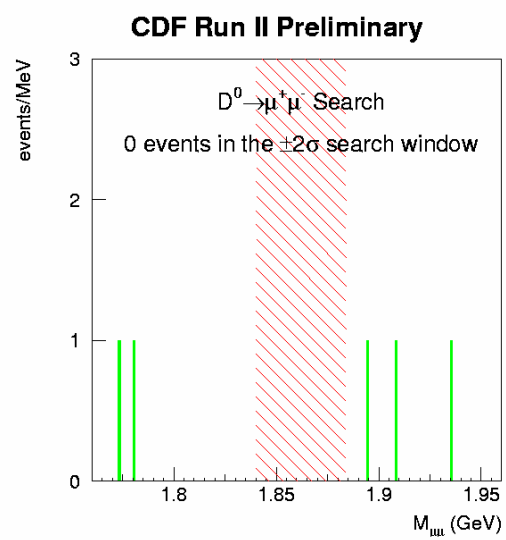


Select events using Secondary Vertex two-track-trigger

Normalization
$D^o \rightarrow \pi^+ \pi^-$

Blind search for
$D^o \rightarrow \mu^+ \mu^-$





Well, well, well… So where is a_s?

Measurements of a_s at Tevatron are hard…

- PDFs entangle results
- Theory: NLO pQCD only
  (large sensitivity to renormalization scale choice)

Options:

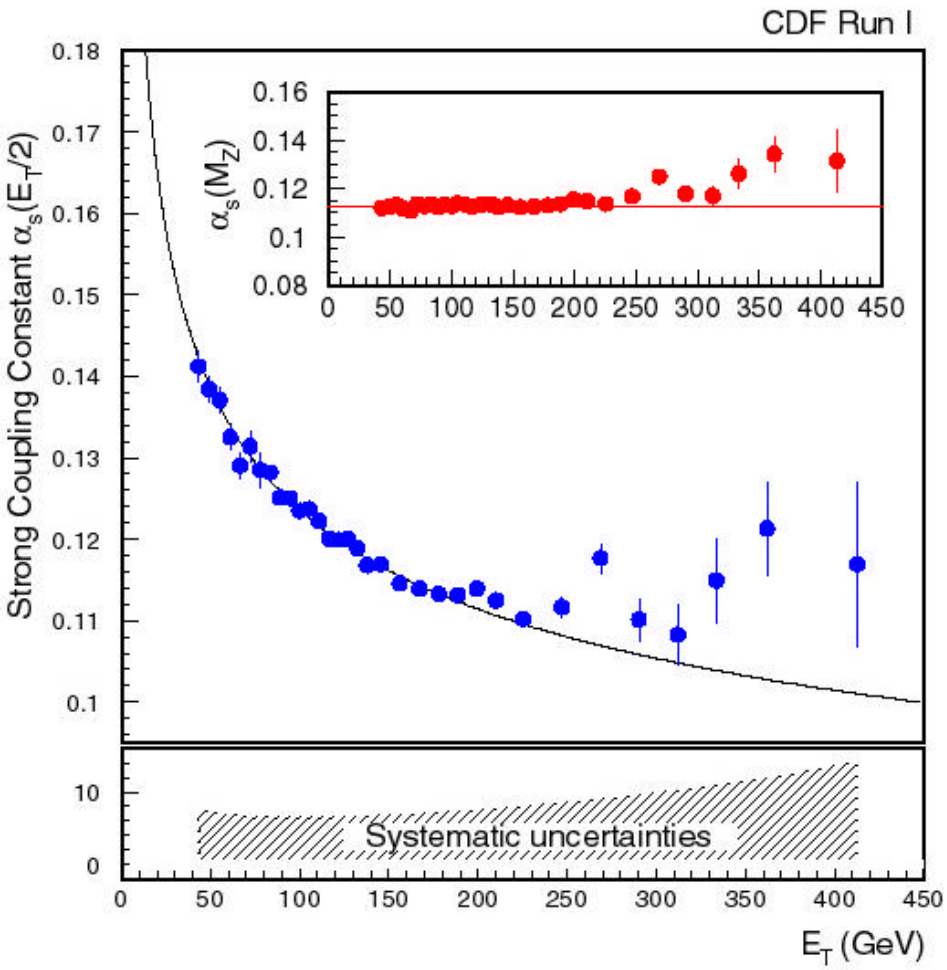
- Inclusive jets: NLO QCD
- Drell-Yan: NNLO
- W/Z/g inclusive: NLO QCD
- (W/Z/g + jet) / (inclusive): NLO QCD
- b-bbar production: NLO QCD

a_s from inclusive jet cross section

- a_s = 0.118 ± 0.011 (Run I data)
  - ±0.0001 (stat)
  - ±0.009 (exp)
  - ±0.006 (PDF choice)
  - ±0.006 (renorm/factor scales)
  - ±0.005 (estimate of higher order QCD)
- Run II: no new results as of yet

PDG2002:

- a_s = 0.117 ± 0.002 (mostly from e^+e^-)



Summary 1: what's new in high P_T QCD?

- **Jets (inclusive cross section)**
  - higher E_T data points
  - data agrees with NLO+CTEQ6.1
- **Dijet mass distribution**
  - larger M_{jj} data points
  - Run2/Run1 agrees with NLO
  - better limits on New Physics
- **W/Z/γ+jets cross sections:**
  - W inclusive agrees with NLO and NNLO

    (new W/Z/γ+jets results coming soon)
- **Heavy flavor production**
  - t-quark production agrees with NLO

    (new b-quark production results coming soon)
  - *direct* open c-quark production agrees with FONLL

Summary 2: what's new in low P_T QCD?

- **Jet fragmentation**
  - Multiplicities in gluon and quark jets agree with extended NLLA QCD and recent LEP data
  - Jet shapes agree with PYTHIA and HERWIG
- **Underlying event**
  - MC generators with default parameters do not quite work…
  - but can be tuned to match data… Any insights into UE Physics?
- **Diffractive physics**
  - Diffractive to Non-Diffractive dijet production ratio $R(x_{Bjorken}, \text{rapidity gap}, Q^2) = R(x_{Bjorken})$
  - measured over wider range of rapidity gaps and Q^2 than in Run I
- **Hadrons (mass/BR/τ)**
  - Improved mass measurements: $M(D_s)-M(D^+)$ and $M(B_s)$
  - Improved limit on FCNC $BR(D^o \rightarrow \mu^+\mu^-)$