XXXV International Symposium on Multiparticle Dynamics 2005

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(for the CDF & D0 Collaborations)

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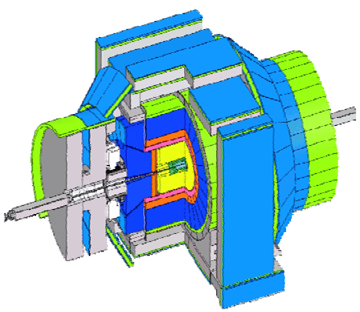
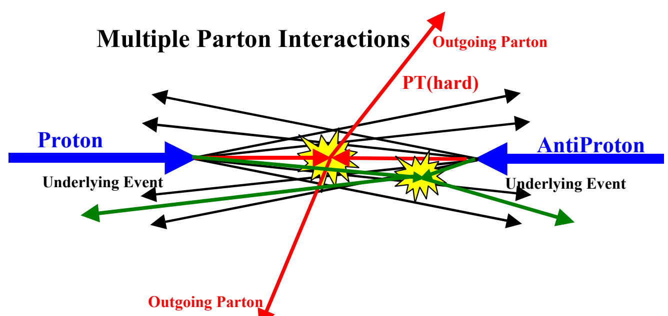
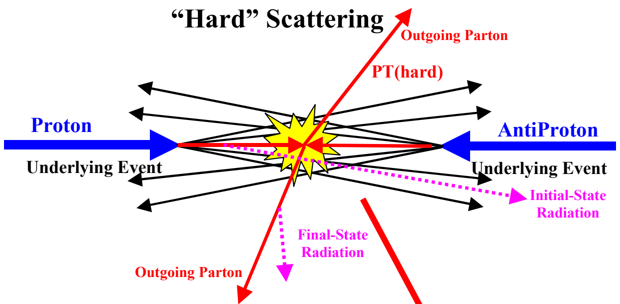


CDF Run 2

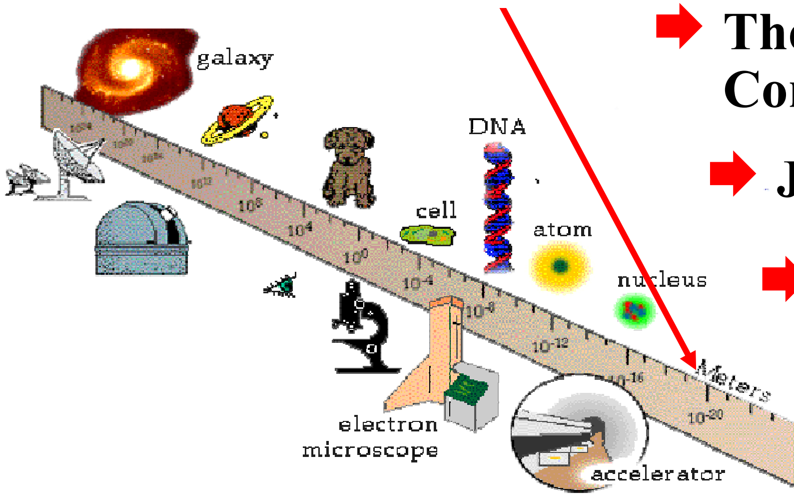


Quantum
Chromo-
Dynamics

Jet Physics and the Underlying Event at the Tevatron



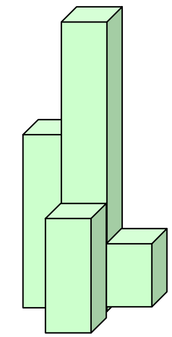
High P_T "jets" probe short distances!



Outline of Talk

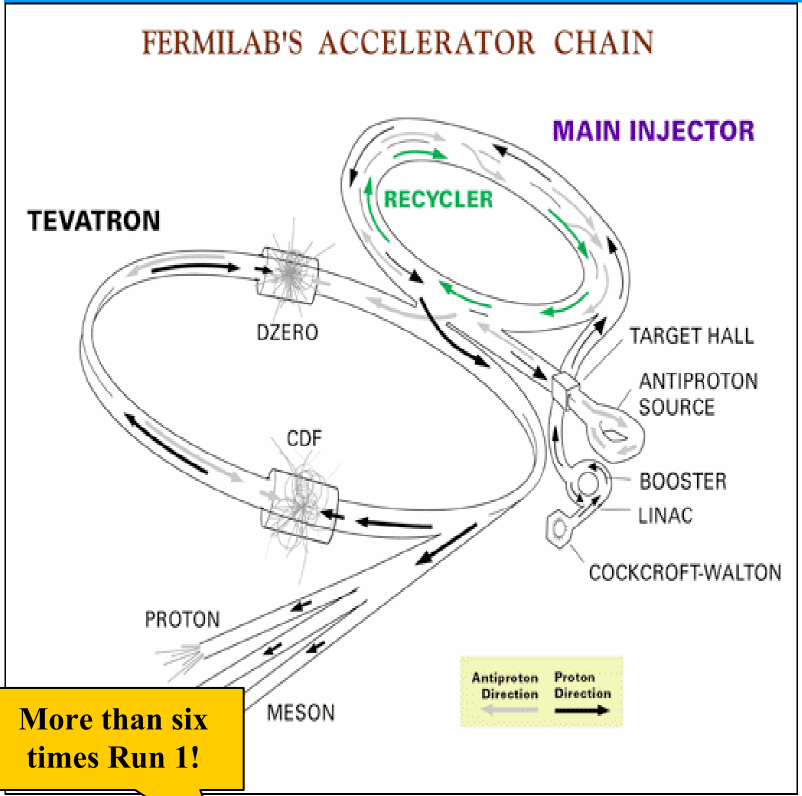
- The Jet Cross Section in Run 2 at the Tevatron: MidPoint Algorithm (CDF/D0) and K_T Algorithm (CDF).
- The b-Jet Inclusive Cross Section in Run 2 at the Tevatron (CDF/D0).
- The b-bbar Jet Cross Section and Correlations (CDF).
- Jet-Jet Correlations (D0).
- Understanding and Modeling the "Underlying Event" in Run 2 at CDF.

Calorimeter Jet



K_T Algorithm

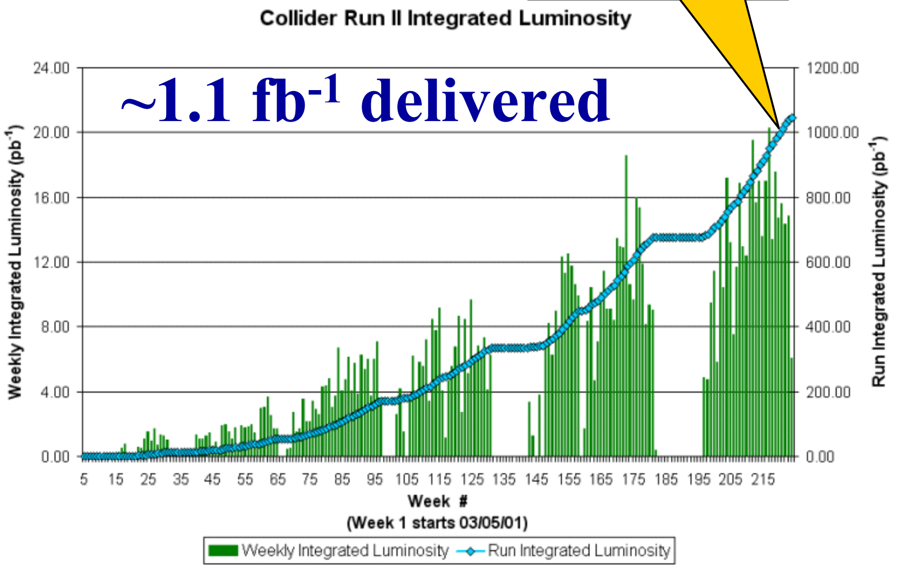
The TeVatron



More than six times Run 1!

CDF has ~900 pb^{-1} on tape!

1 fb^{-1} milestone!

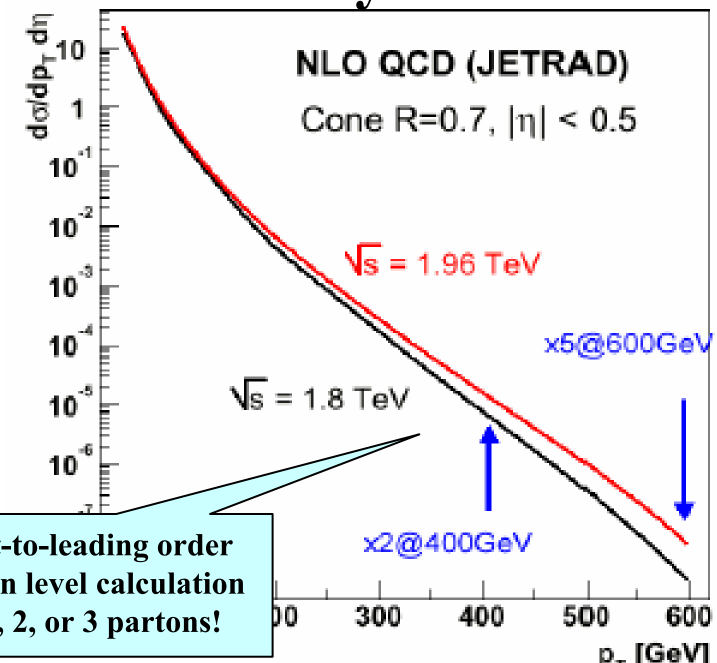


- **Proton-antiproton collisions**
- **$\sqrt{s}$ = 1.96 TeV (Run 1 = 1.8 TeV)**
- **36 bunches: 396 ns crossing time**
- **Peak luminosity ~ 10^{32} cm^{-2} s^{-1}**
- **12-20 pb^{-1} per week!**

The TeVatron delivered more than 350 pb^{-1} in 2004!

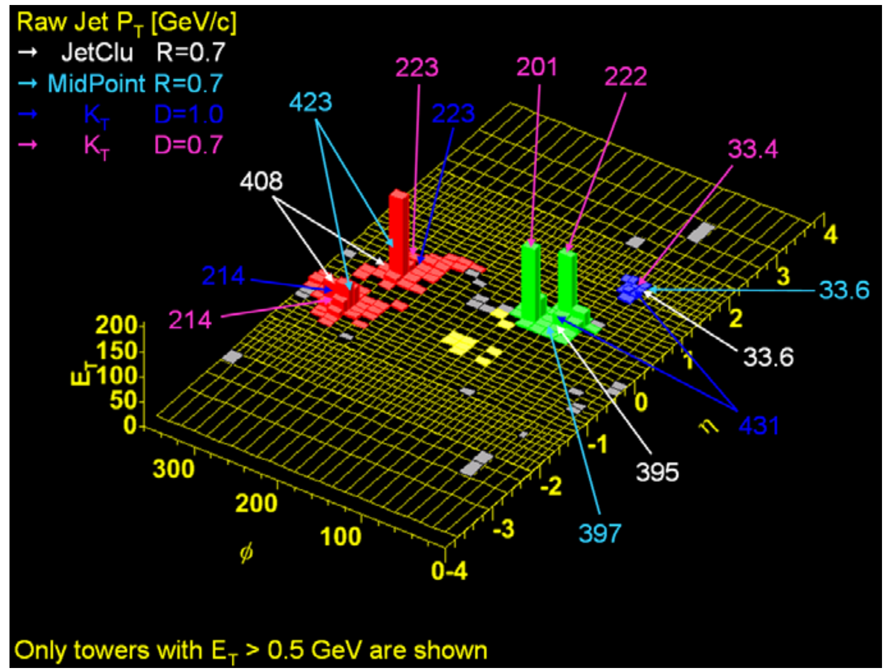
Jets at 1.96 TeV

"Theory Jets"



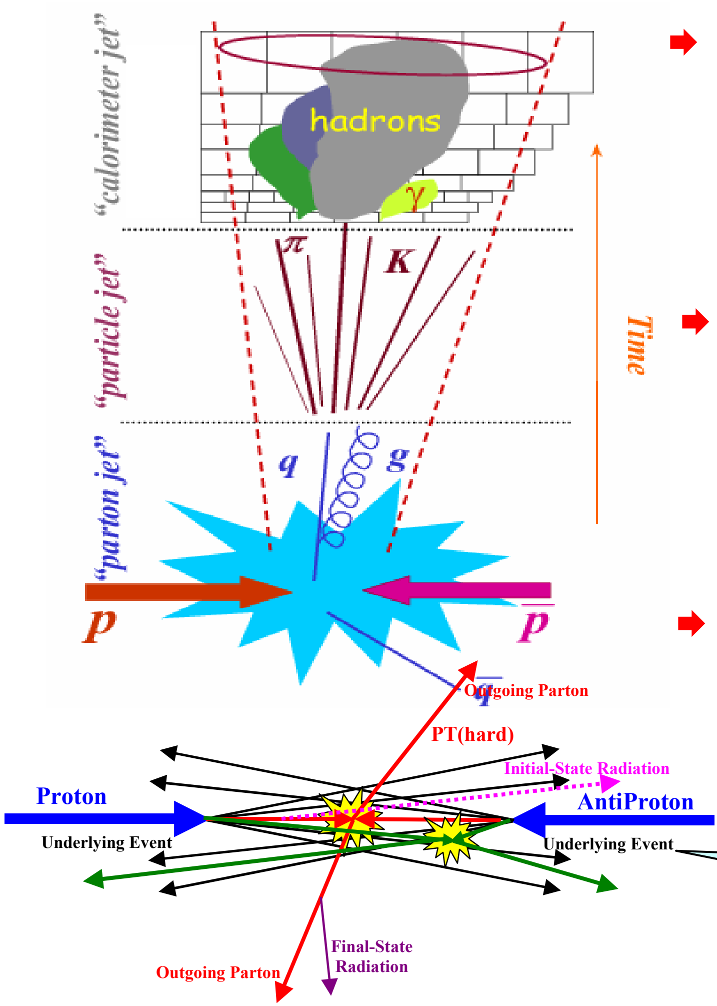
Next-to-leading order parton level calculation 0, 1, 2, or 3 partons!

"Real Jets"



- **Experimental Jets:** The study of "real" jets requires a "jet algorithm" and the different algorithms correspond to different observables and give different results!
- **Experimental Jets:** The study of "real" jets requires a good understanding of the calorimeter response!
- **Experimental Jets:** To compare with NLO parton level (and measure structure functions) requires a good understanding of the "underlying event"!

Jet Corrections

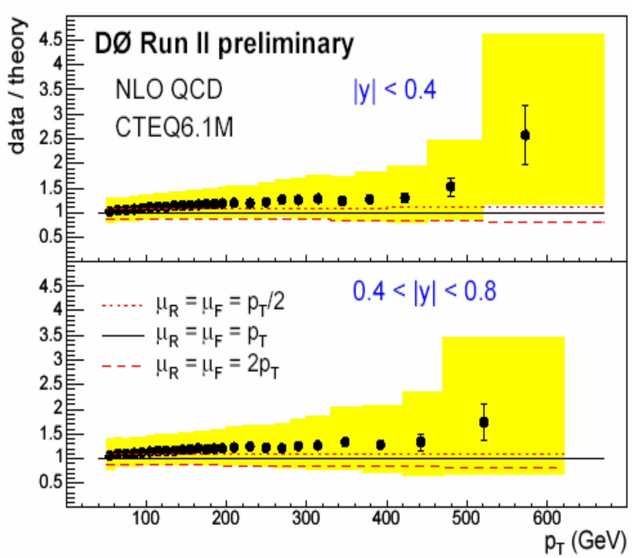


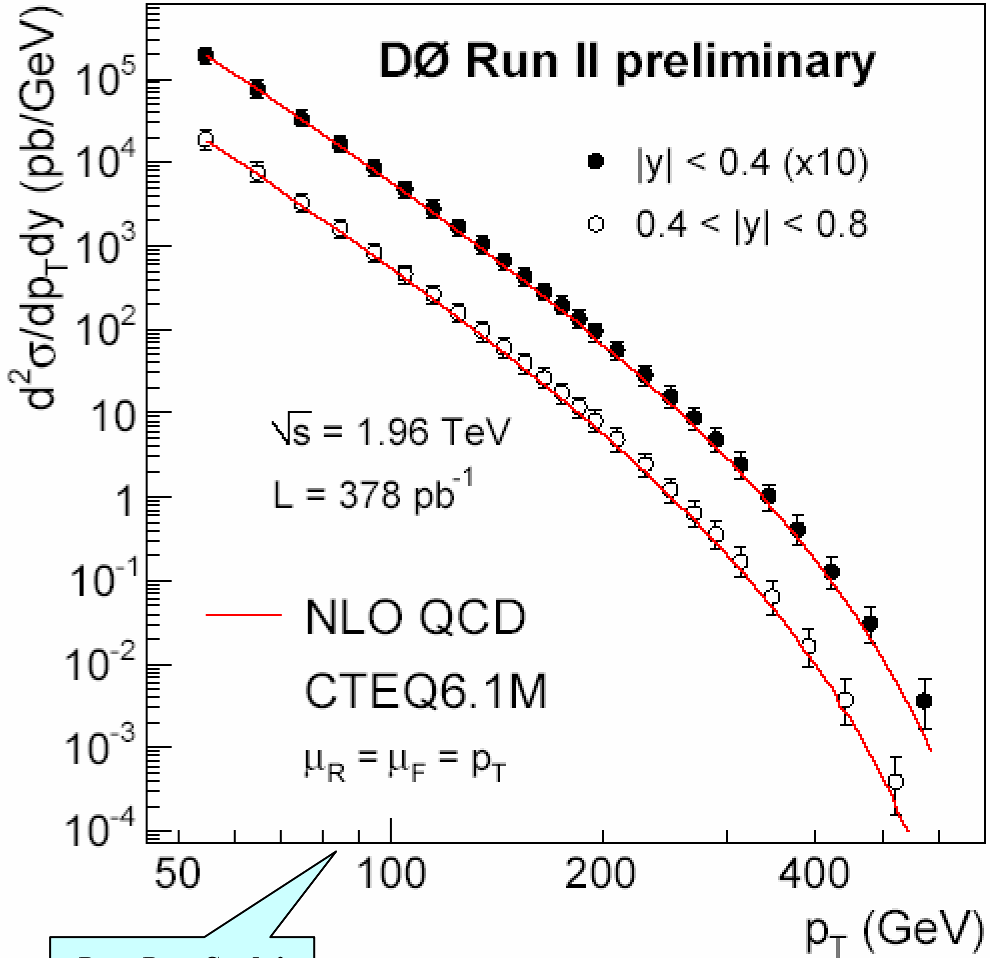
- **Calorimeter Jets:**
  - **We measure "jets" at the "hadron level" in the calorimeter.**
  - **We certainly want to correct the "jets" for the detector resolution and effieciency.**
  - **Also, we must correct the "jets" for "pile-up".**
  - **Must correct what we measure back to the true "particle level" jets!**
- **Particle Level Jets:**
  - **Do we want to make further model dependent corrections?**
  - **Do we want to try and subtract the "underlying event" from the "particle level" jets.**
  - **This cannot really be done, but if you trust the Monte-Carlo models modeling of the "underlying event" you can try and do it by using the Monte-Carlo models (use PYTHIA Tune A).**
- **Parton Level Jets:**
  - **Do we want to use our data to try and extrapolate back to the parton level?**
  - **This also cannot really be done, but again if you trust the Monte-Carlo models you can try and do it by using the Monte-Carlo models.**

The "underlying event" consists of hard initial & final-state radiation plus the "beam-beam remnants" and possible multiple parton interactions.

DØ Inclusive Jet Cross Section

- MidPoint Cone Algorithm ($R = 0.7$, $f_{merge} = 0.5$)
- $\mathcal{L} = 380\ pb^{-1}$
- Two rapidity bins
- Highest P_T jet is 630 GeV/c
- Compared with NLO QCD (JetRad, $R_{sep} = 1.3$?)

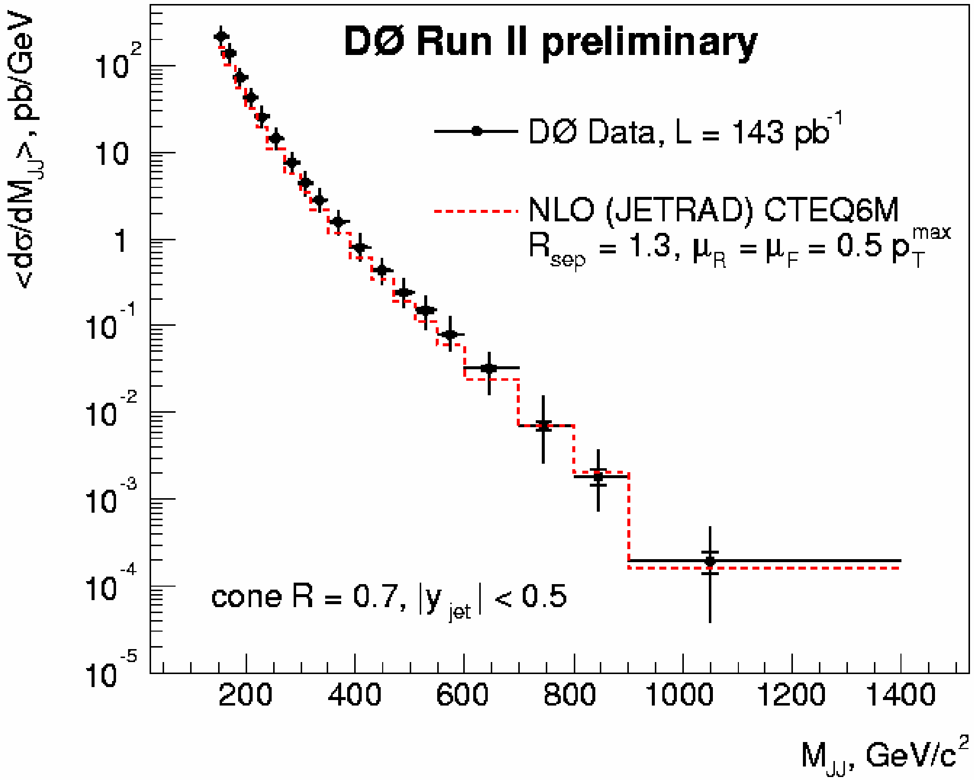


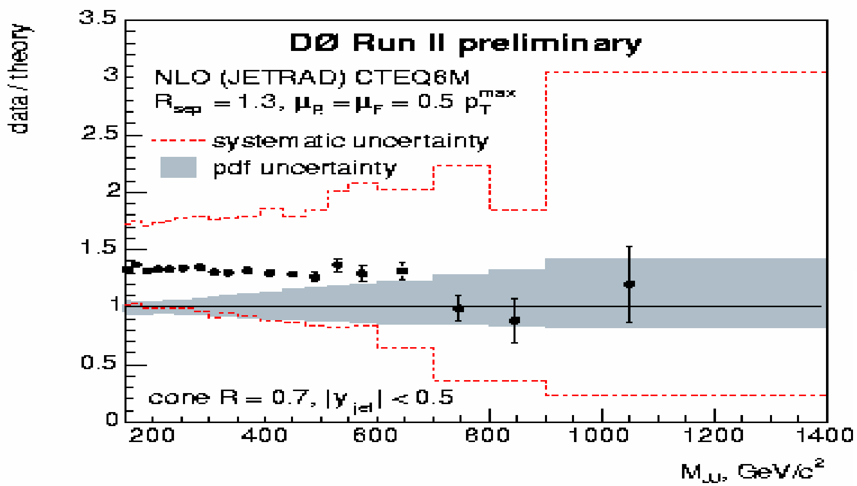


Log-Log Scale!

DØ Di-Jet Cross Section

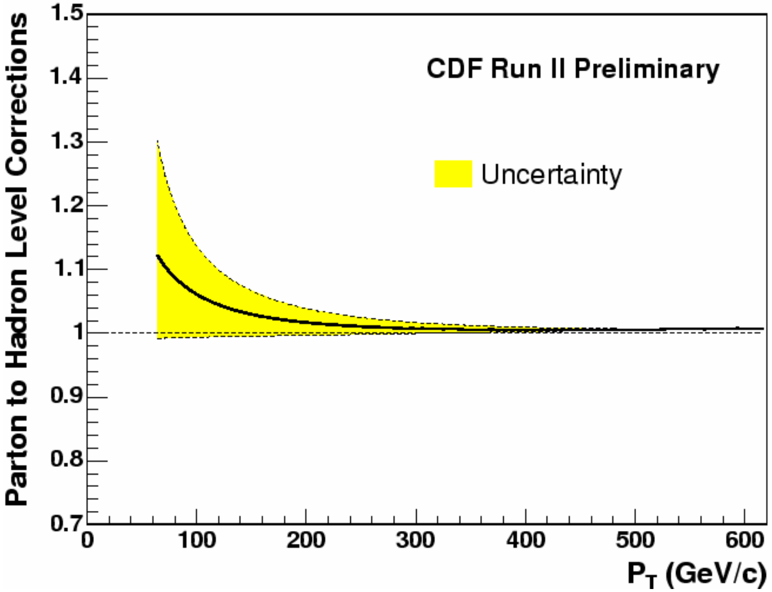
- MidPoint Cone Algorithm ($R = 0.7$, $f_{merge} = 0.5$)
- $\mathcal{L} = 143\ pb^{-1}$
- $|y_{jet}| < 0.5$
- Compared with NLO QCD (JetRad, $R_{sep} = 1.3$)
- Update expected this Winter

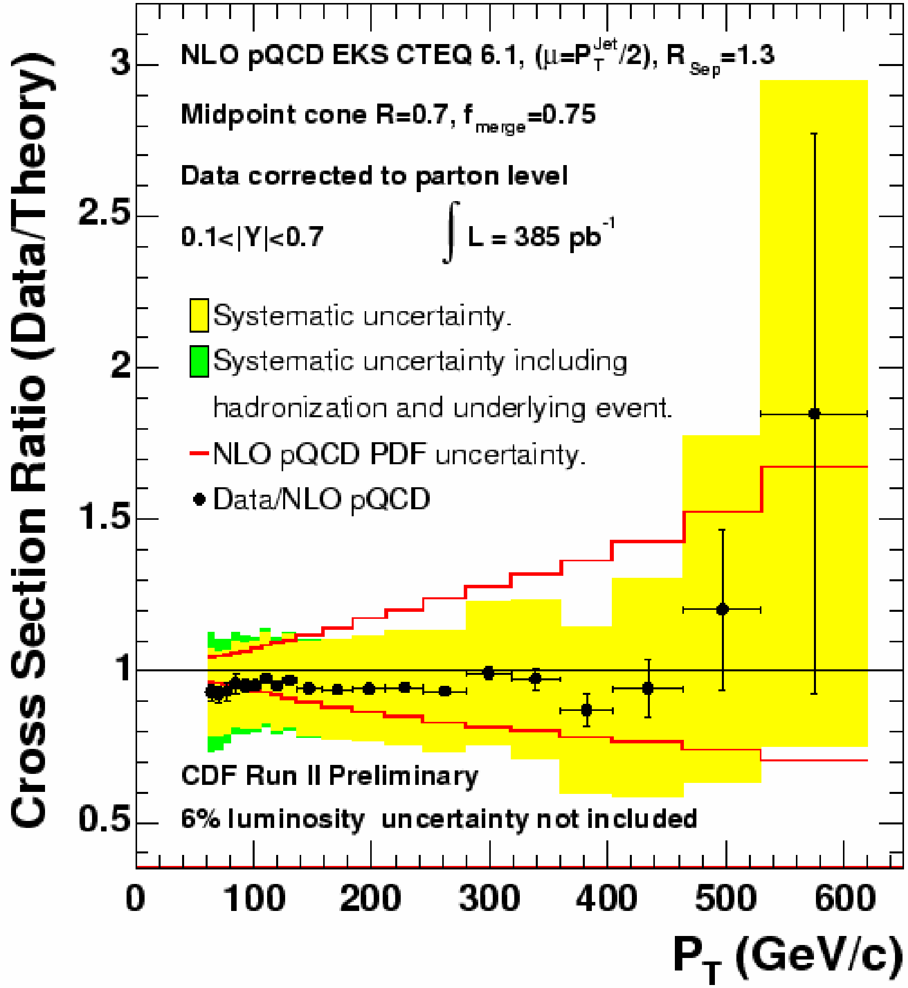




CDF Inclusive Jet Cross Section

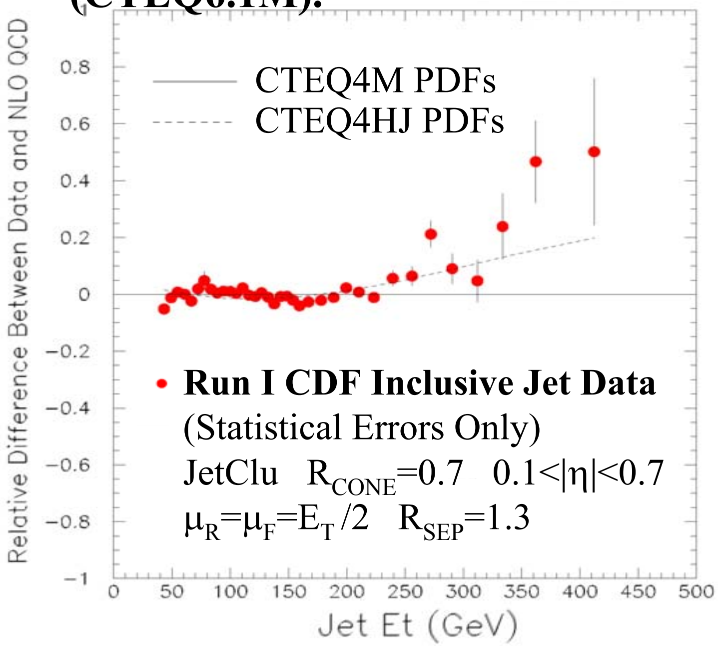
- MidPoint Cone Algorithm ($R = 0.7$, $f_{merge} = 0.75$)
- Data corrected to the parton level
- $\mathcal{L} = 385\ pb^{-1}$
- $0.1 < |y_{jet}| < 0.7$
- Compared with NLO QCD (JetRad, $R_{sep} = 1.3$)

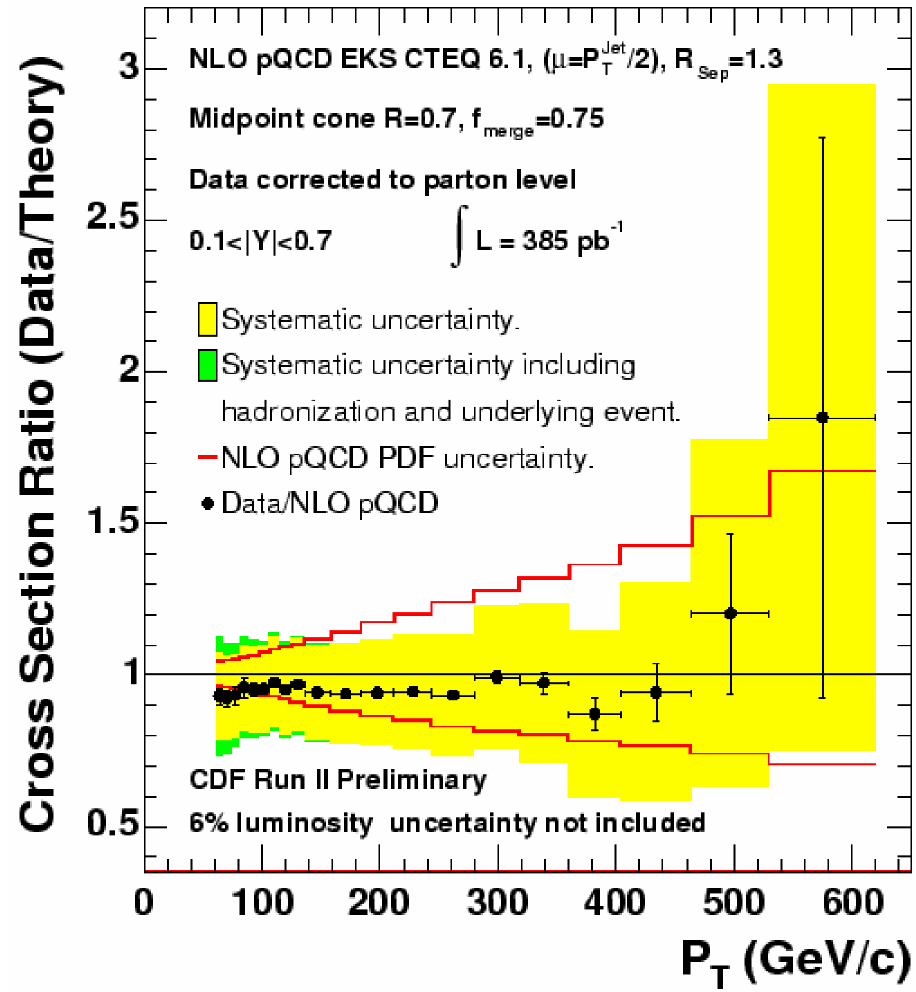




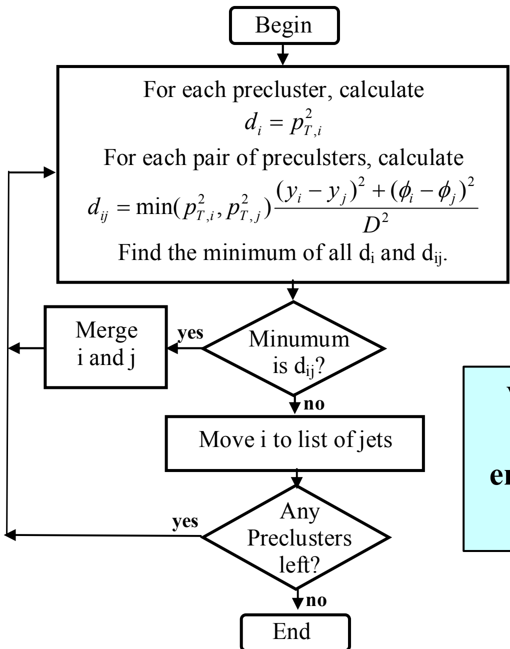
CDF Inclusive Jet Cross Section

- Run 1 showed a possible excess at large jet E_T (see below).
- This resulted in new PDF's with more gluons at large x.
- The Run 2 data are consistent with the new structure functions (CTEQ6.1M).



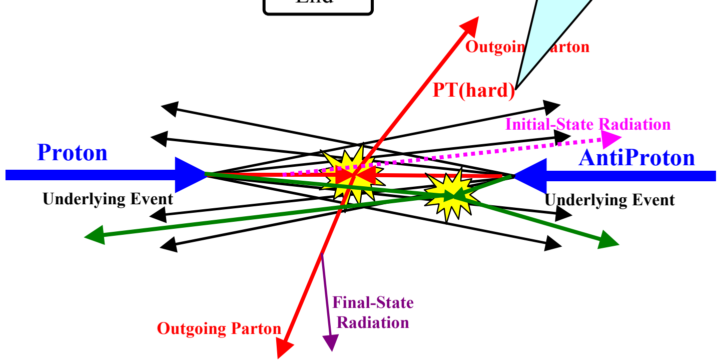


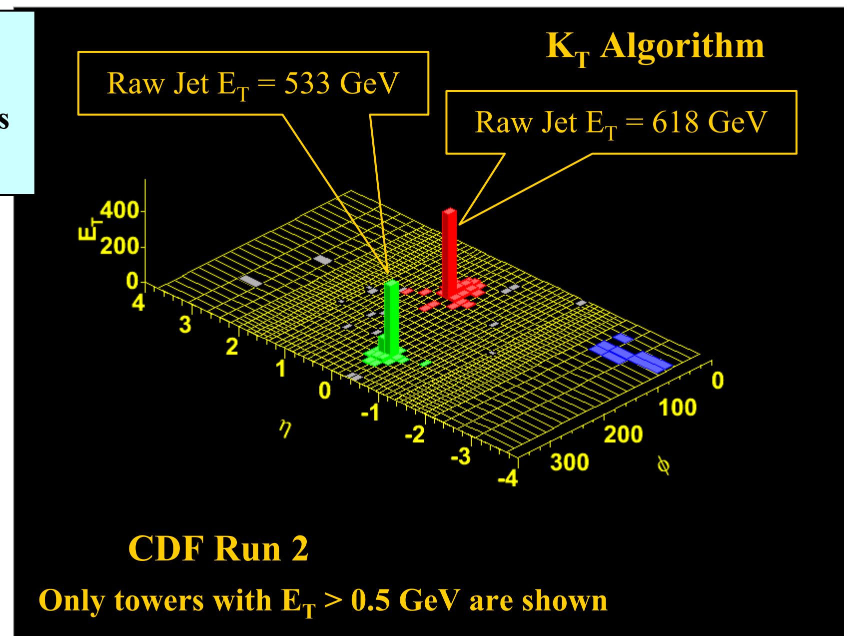
K_T Algorithm



- **k_T Algorithm:**
  - Cluster together calorimeter towers by their k_T proximity.
  - Infrared and collinear safe at all orders of pQCD.
  - No splitting and merging.
  - No ad hoc R_{sep} parameter necessary to compare with parton level.
  - Every parton, particle, or tower is assigned to a "jet".
  - No biases from seed towers.
  - Favored algorithm in e^+e^- annihilations!

Will the K_T algorithm be effective in the collider environment where there is an "underlying event"?

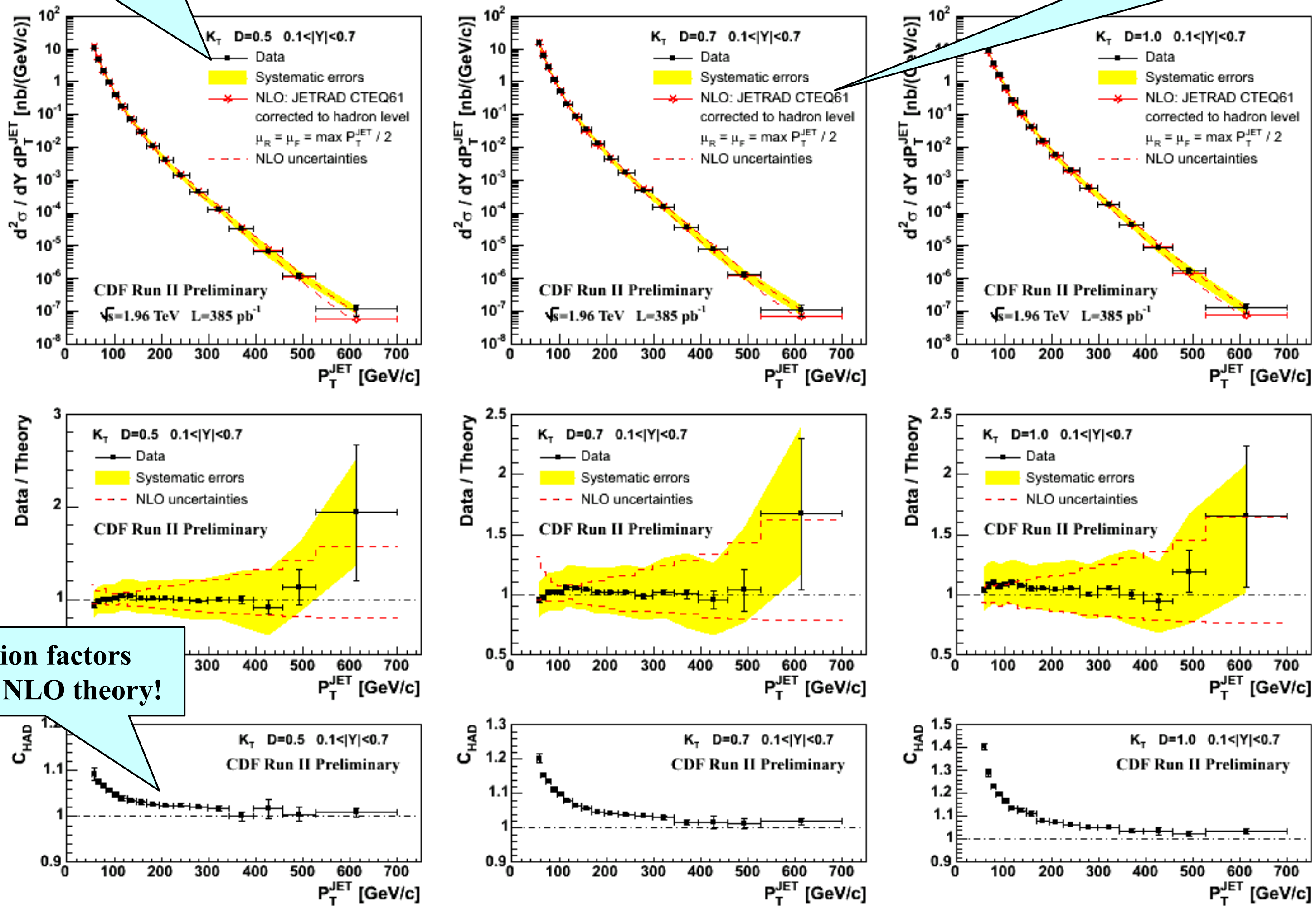




K_T Jet Cross-Section

Data at the "particle level"!

NLO parton level theory corrected to the "particle level"!

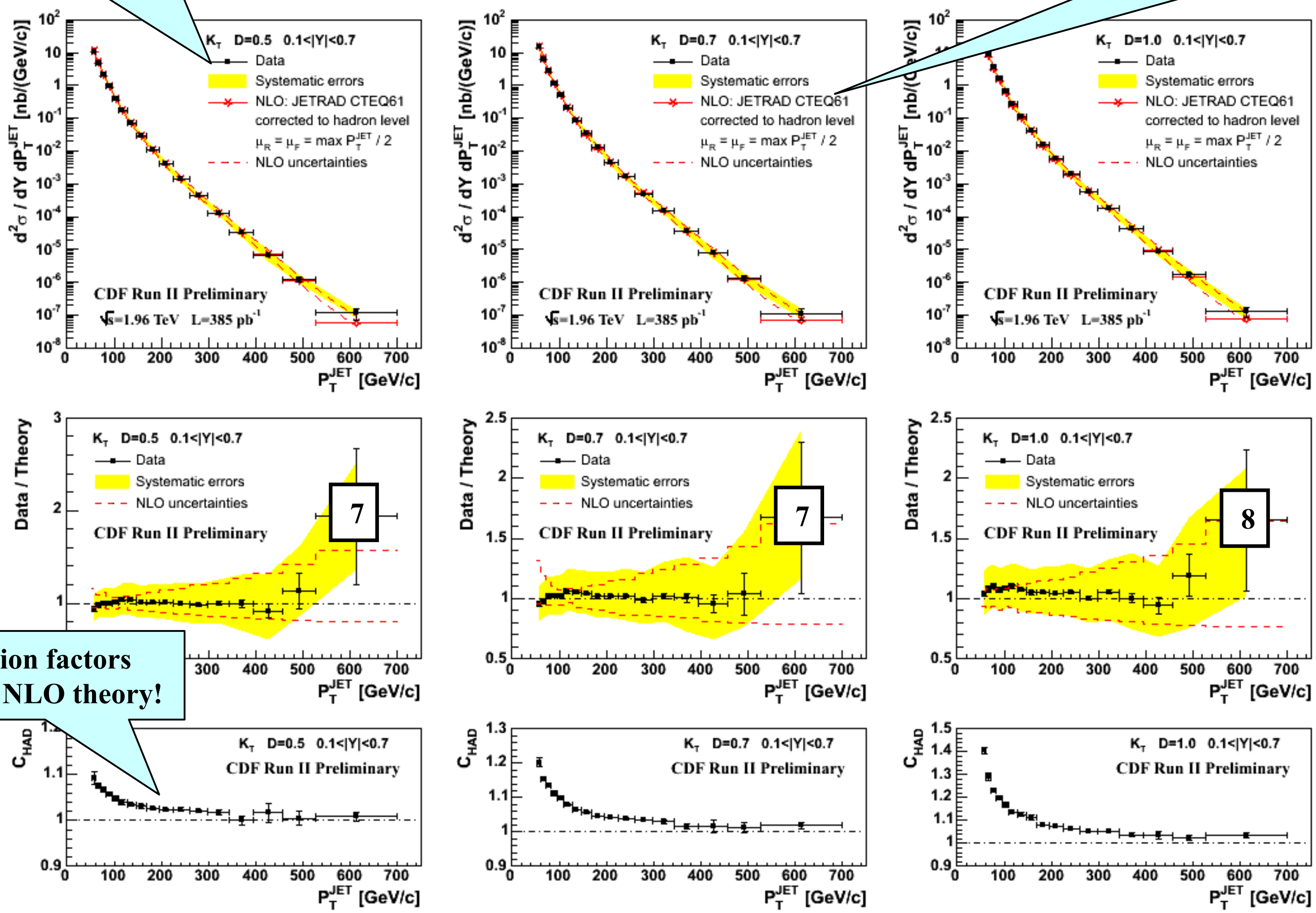


Correction factors applied to NLO theory!

K_T Jet Cross-Section

Data at the “particle level”!

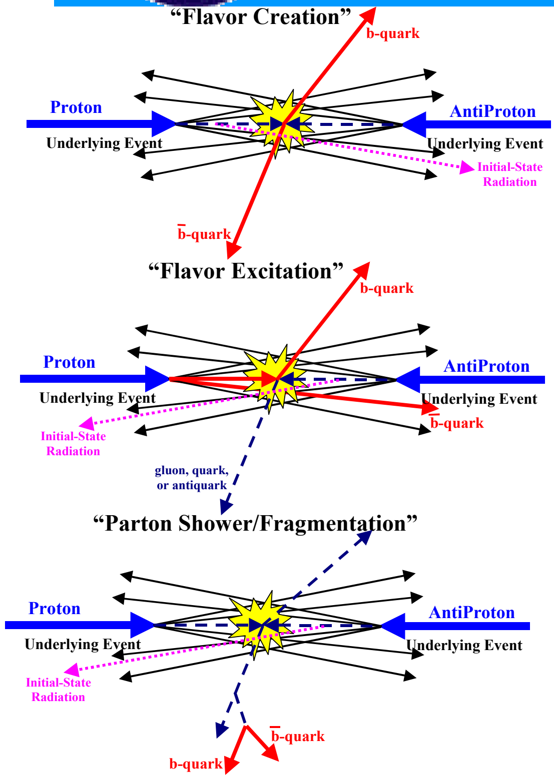
NLO parton level theory corrected to the “particle level”!

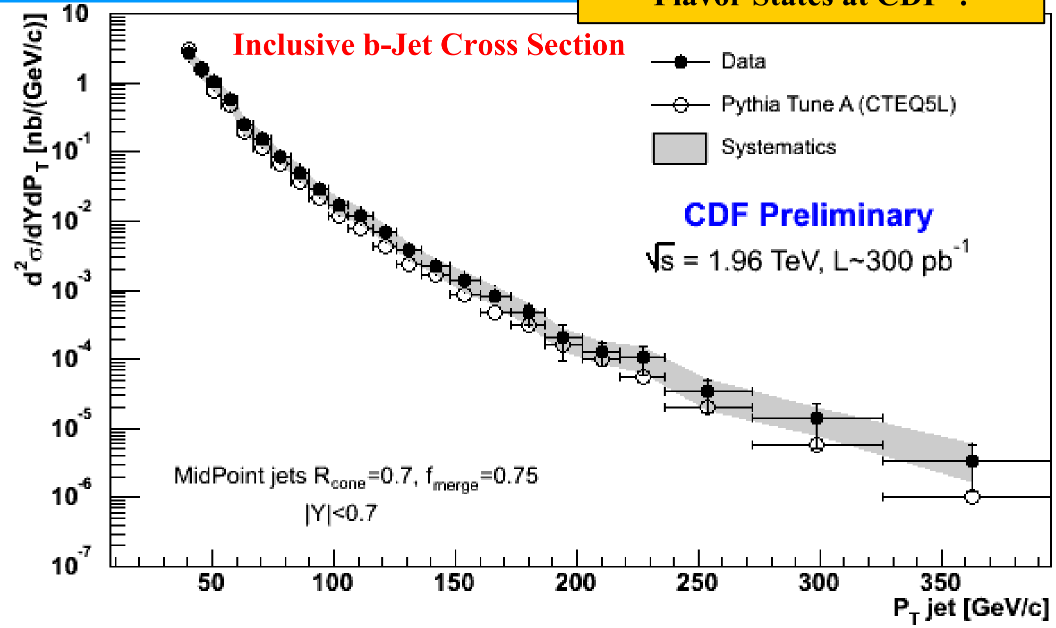


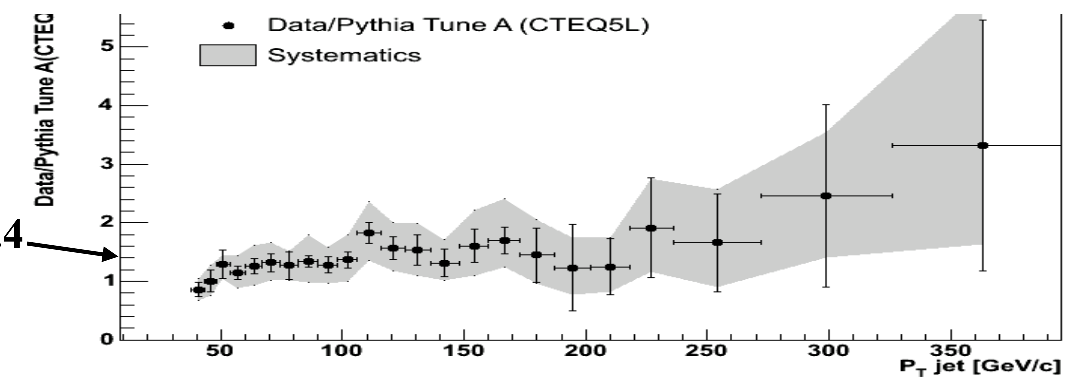
Correction factors applied to NLO theory!

The b-Jet Inclusive Cross-Section

See the talk later this week by Mario Campanelli on "Heavy Flavor States at CDF"!

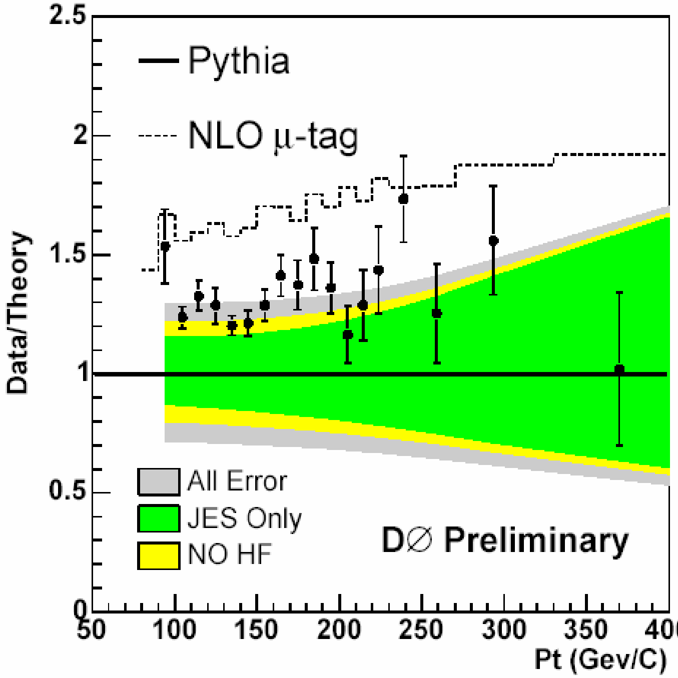




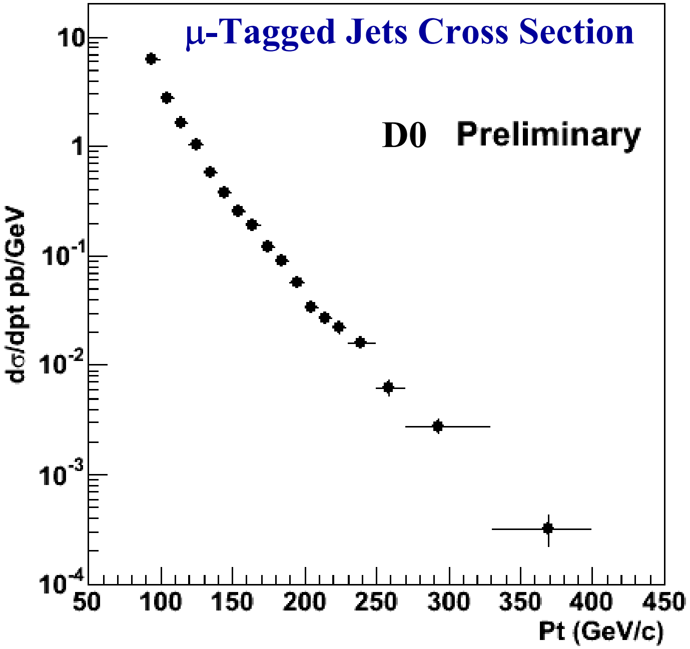


- The data are compared with PYTHIA (tune A)! Data/PYA ~ 1.4
- Comparison with MC@NLO coming soon!

DØ μ-Tagged Jets Correlations



- MidPoint Cone Algorithm (R = 0.5)
- Require muon in R = 0.5.
- $\mathcal{L}$ = 300 pb^{-1}
- $|y_{jet}| < 0.5$
- $P_T(\mu) > 5$ GeV/*c*



- Jets containing heavy flavor often contain muons (*e.g.* b→c +W→ μ+ν).
- Searching for muons in jets enhances the heavy flavor content.
- Data/PYTHIA flat ~ 1.3.

The b-bbar DiJet Cross-Section

- E_T(b-jet#1) > 30 GeV, E_T(b-jet#2) > 20 GeV, |η(b-jets)| < 1.2.

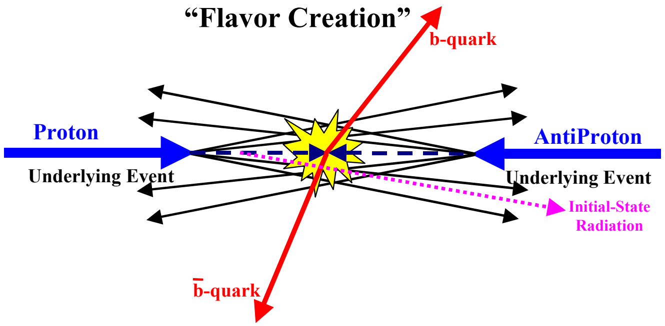
Preliminary CDF Results:

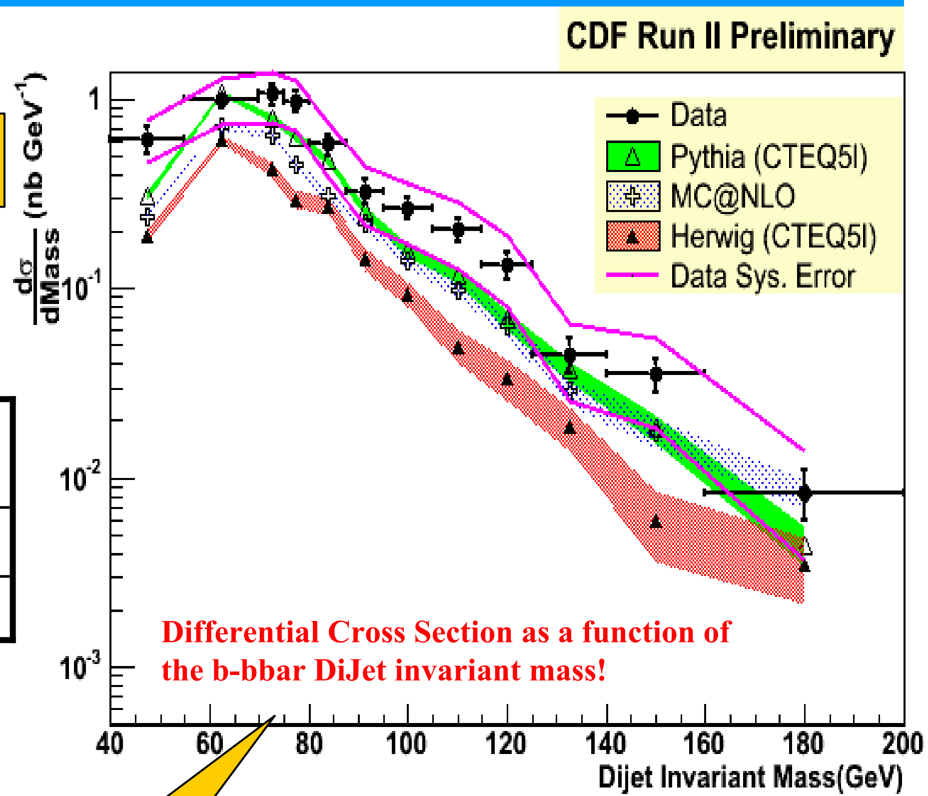
Systematic Uncertainty

$$\sigma_{bb} = 34.5 \pm 1.8 \pm 10.5 \text{ nb}$$

QCD Monte-Carlo Predictions:

PYTHIA Tune A CTEQ5L	38.71 ± 0.62nb
HERWIG CTEQ5L	21.53 ± 0.66nb
MC@NLO	28.49 ± 0.58nb





Predominately Flavor creation!

- Large Systematic Uncertainty:
  - Jet Energy Scale (~20%).
  - b-tagging Efficiency (~8%)

The b-bbar DiJet Cross-Section

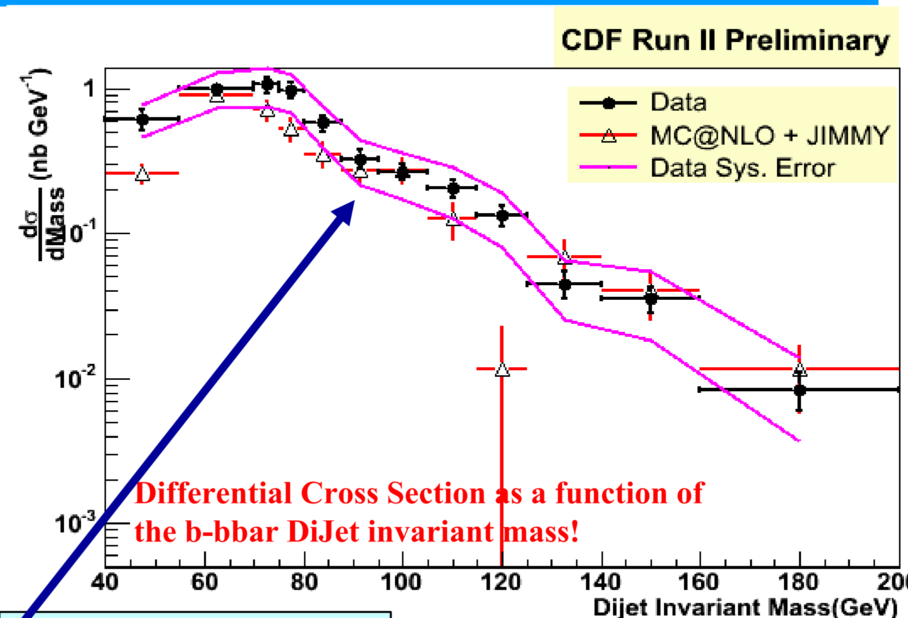
- E_T(b-jet#1) > 30 GeV, E_T(b-jet#2) > 20 GeV, |η(b-jets)| < 1.2.

Preliminary CDF Results:

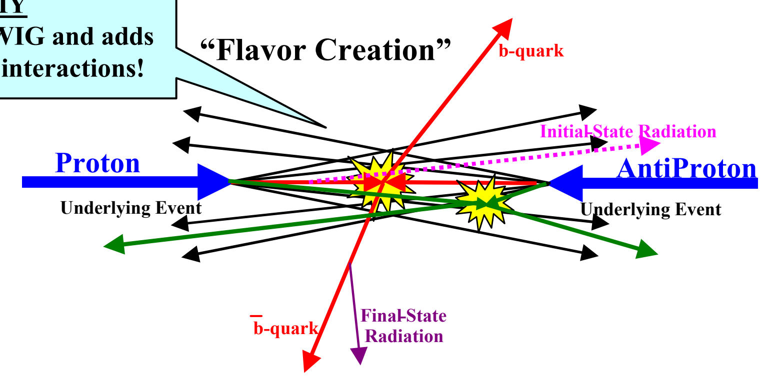
$$\sigma_{bb} = 34.5 \pm 1.8 \pm 10.5 \text{ nb}$$

QCD Monte-Carlo Predictions:

PYTHIA Tune A CTEQ5L	38.7 ± 0.6 nb
HERWIG CTEQ5L	21.5 ± 0.7 nb
MC@NLO	28.5 ± 0.6 nb
MC@NLO + JIMMY	35.7 ± 2.0 nb



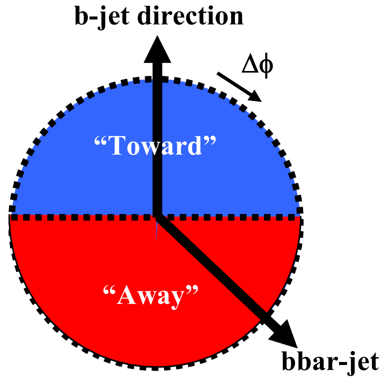
JIMMY
Runs with HERWIG and adds multiple parton interactions!

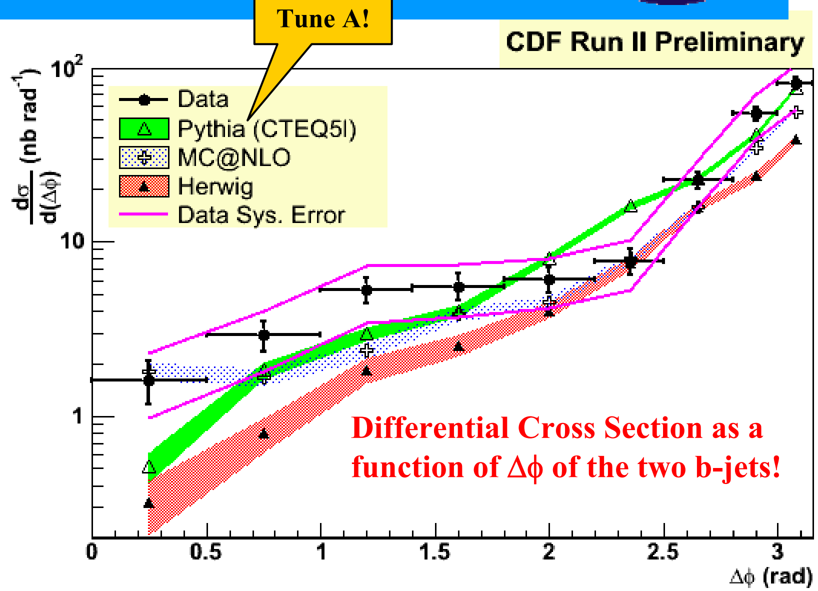


JIMMY: MPI
J. M. Butterworth
J. R. Forshaw
M. H. Seymour

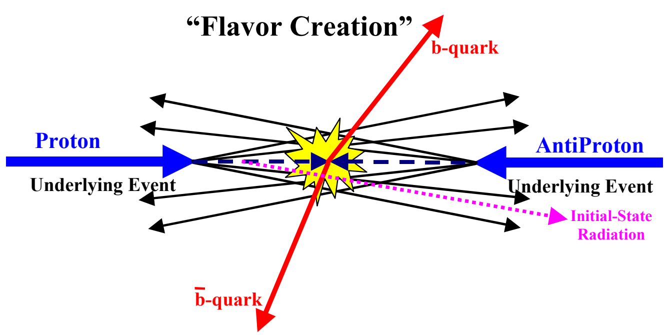
Adding multiple parton interactions (*i.e.* JIMMY) to enhance the "underlying event" increases the b-bbar jet cross section!

b-bbar DiJet Correlations





- The two b-jets are predominately "back-to-back" (*i.e.* "flavor creation")!

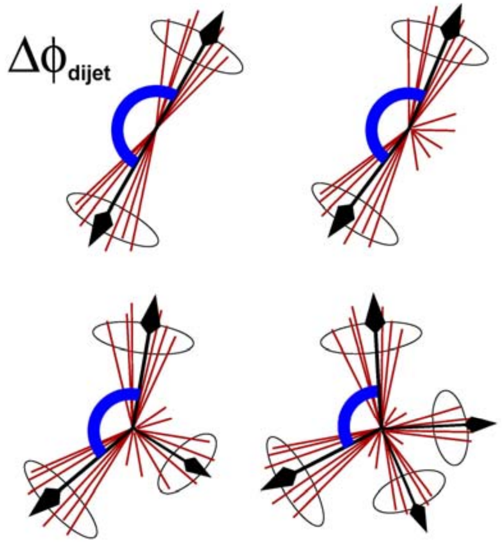


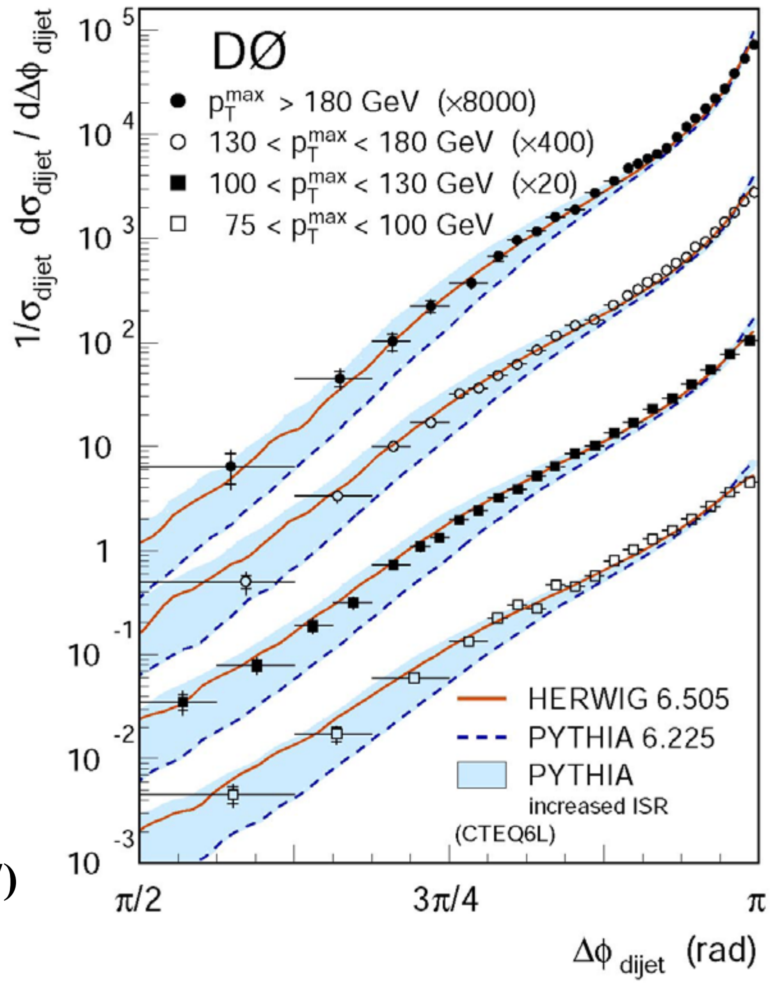
- Pythia Tune A agrees fairly well with the Δφ correlation!

Not an accident!

DØ Jet-Jet Correlations

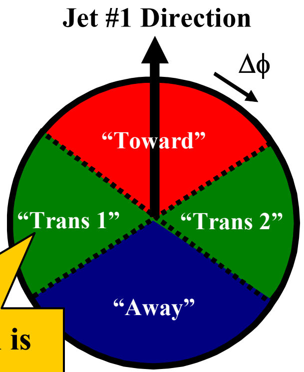
Jet#1-Jet#2 Δφ Distribution





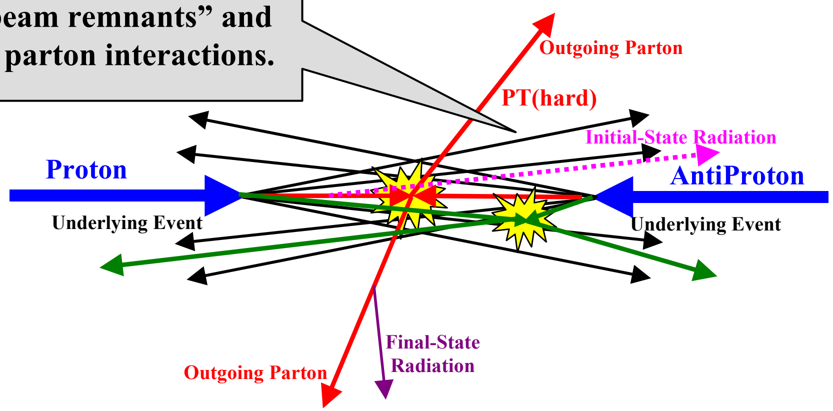
- **MidPoint Cone Algorithm (R = 0.7, f_{merge} = 0.5)**
- **$\mathcal{L}$ = 150 pb^{-1} (Phys. Rev. Lett. 94 221801 (2005))**
- **Data/NLO agreement good. Data/HERWIG agreement good.**
- **Data/PYTHIA agreement good provided PARP(67) = 1.0→4.0 (i.e. like Tune A).**

The “Underlying Event” in Run 2 at CDF



“Transverse” region is very sensitive to the “underlying event”!

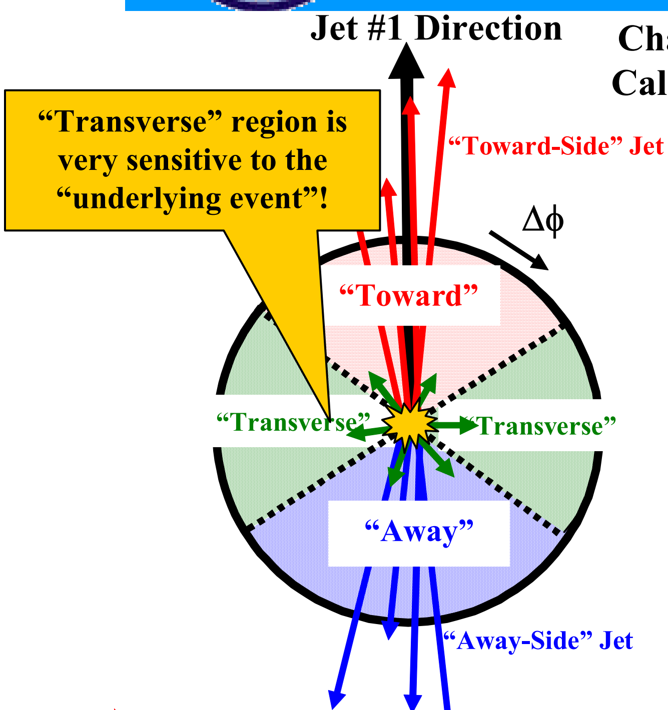
The “underlying event” consists of hard initial & final-state radiation plus the “beam-beam remnants” and possible multiple parton interactions.



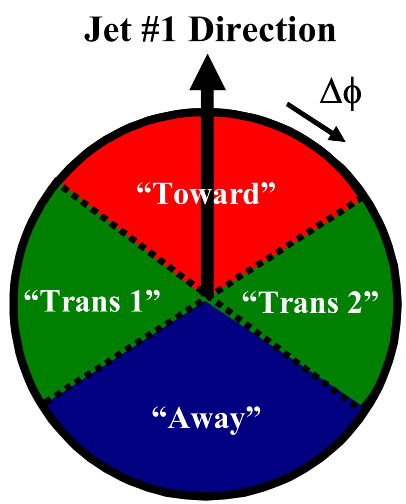
New CDF Run 2 results ($\mathcal{L}$ = 385 pb^{-1}) :

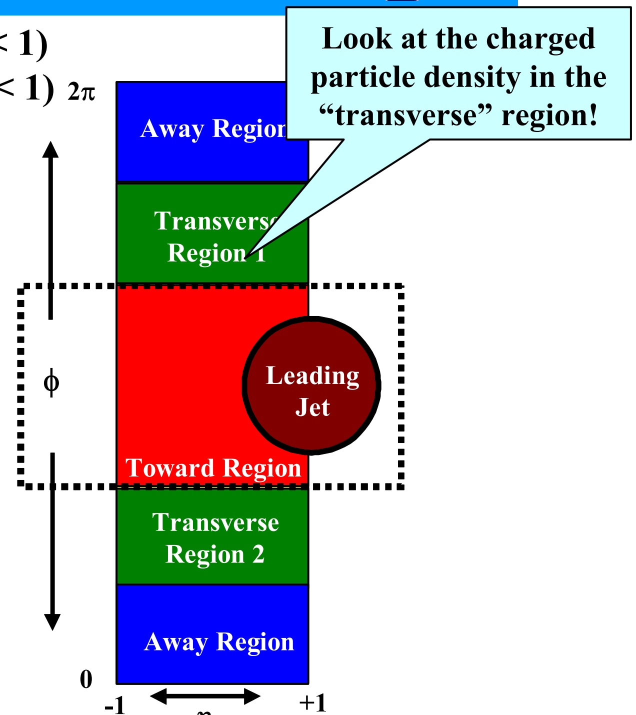
- **Two Classes of Events:** “Leading Jet” and “Back-to-Back”.
- **Two “Transverse” regions:** “transMAX”, “transMIN”, “transDIF”.
- **Data corrected to the particle level:** unlike our previous CDF Run 2 “underlying event” analysis which used JetClu to define “jets” and compared uncorrected data with the QCD Monte-Carlo models after detector simulation, this analysis uses the MidPoint jet algorithm and corrects the observables to the particle level. The corrected observables are then compared with the QCD Monde-Carlo models at the particle level.
- For the 1st time we study the **energy density** in the “transverse” region.

The "Transverse" Regions as defined by the Leading Jet



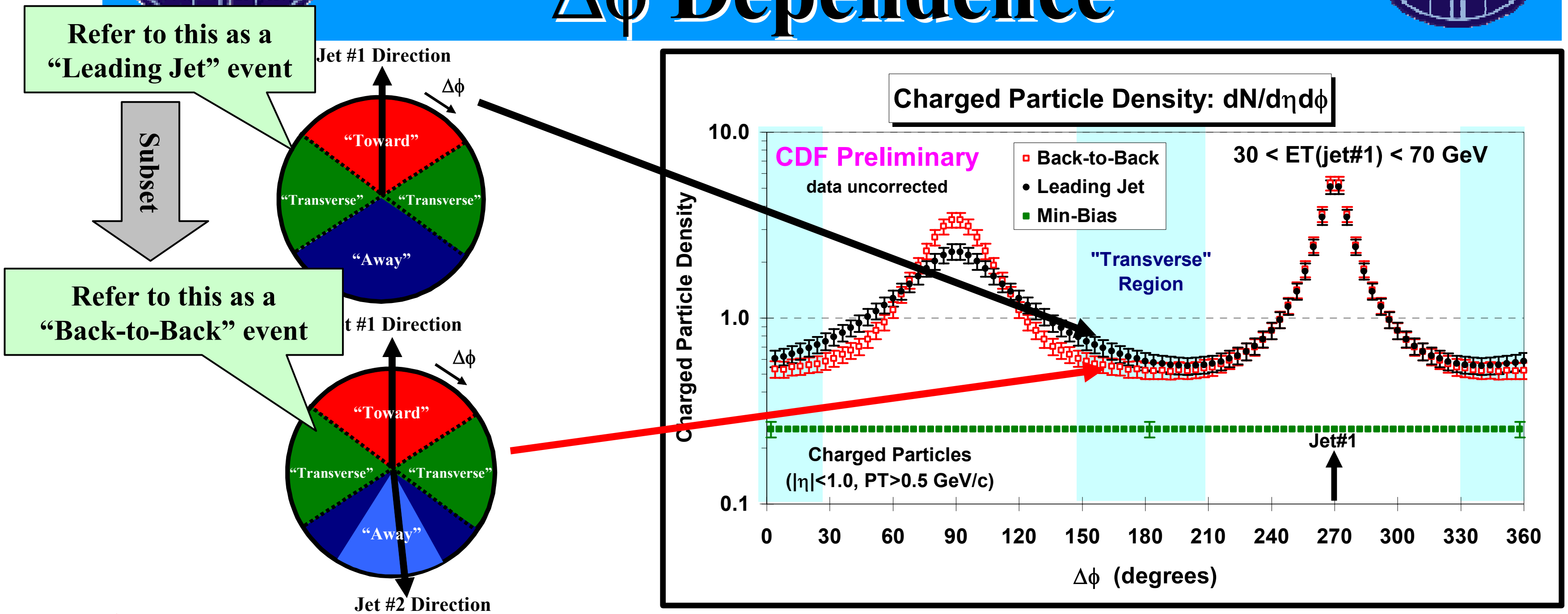
Charged Particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$)
Calorimeter Towers ($E_T > 0.1$ GeV, $|\eta| < 1$)





- Look at charged particle and calorimeter tower correlations in the azimuthal angle $\Delta\phi$ relative to the leading calorimeter jet (MidPoint, R = 0.7, $f_{merge} = 0.75$, $|\eta| < 2$).
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < -\Delta\phi < 120^o$ and $60^o < \Delta\phi < 120^o$ as "Transverse 1" and "Transverse 2", and $|\Delta\phi| > 120^o$ as "Away". Each of the two "transverse" regions have area $\Delta\eta\Delta\phi = 2\text{x}60^o = 4\pi/6$. The overall "transverse" region is the sum of the two transverse regions ($\Delta\eta\Delta\phi = 2\text{x}120^o = 4\pi/3$).

Charged Particle Density
$\Delta\phi$ Dependence



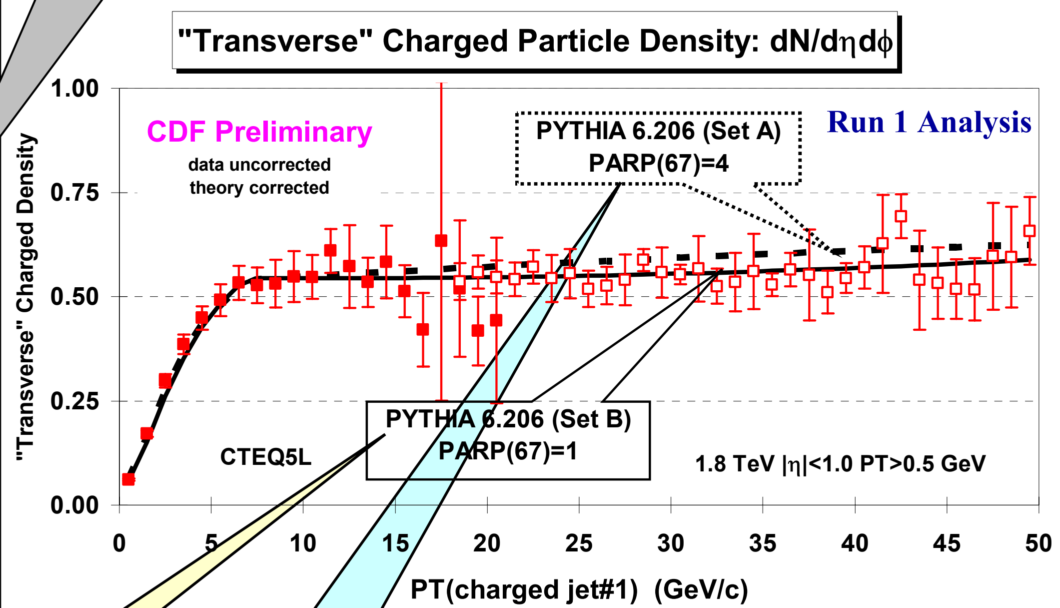
- Look at the "transverse" region as defined by the leading jet ($|\eta| < 2$) or by the leading two jets ($|\eta| < 2$). "Back-to-Back" events are selected to have at least two jets with Jet#1 and Jet#2 nearly "back-to-back" ($\Delta\phi_{12} > 150^o$) with almost equal transverse momenta (P_T(jet#2)/P_T(jet#1) > 0.8) and P_T(jet#3) < 15 GeV/c.
- Shows the $\Delta\phi$ dependence of the charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles in the range $p_T > 0.5$ GeV/c and $|\eta| < 1$ relative to jet#1 (rotated to 270^o) for 30 < E_T(jet#1) < 70 GeV for "Leading Jet" and "Back-to-Back" events.

Tuned PYTHIA 6.206

CDF Default!

PYTHIA 6.206 CTEQ5L

Parameter	Tune B	Tune A
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	1.9 GeV	2.0 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	1.0	0.9
PARP(86)	1.0	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(67)	1.0	4.0

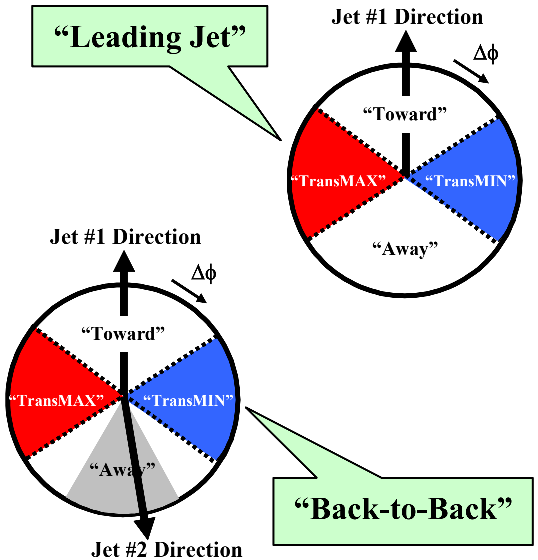


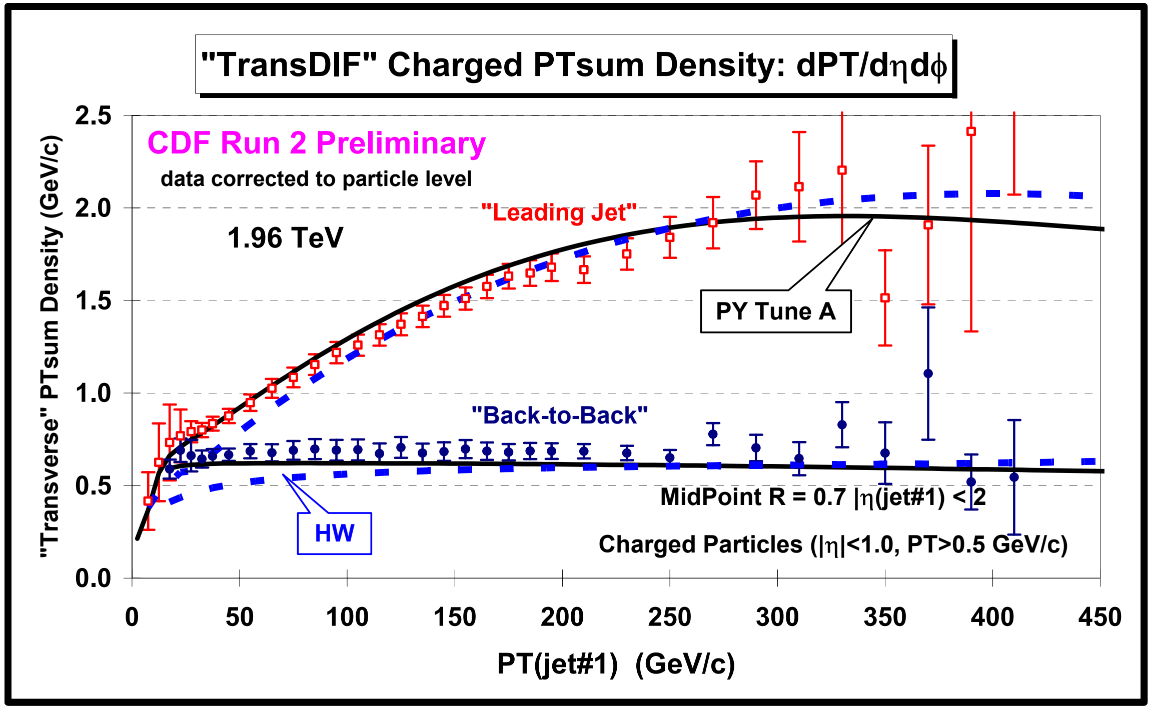
- Plot shows the "Transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

"TransDIF" PTsum Density
PYTHIA Tune A vs HERWIG

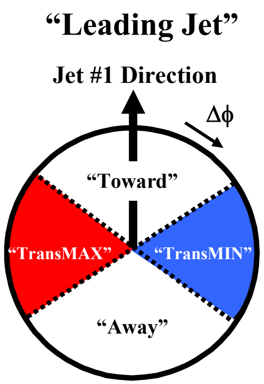


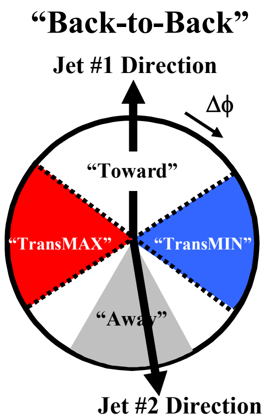


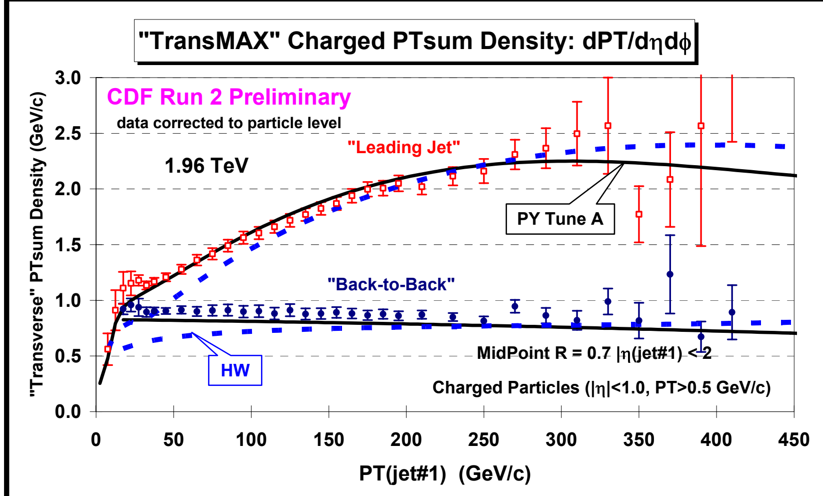
"transDIF" is very sensitive to the "hard scattering" component of the "underlying event"!

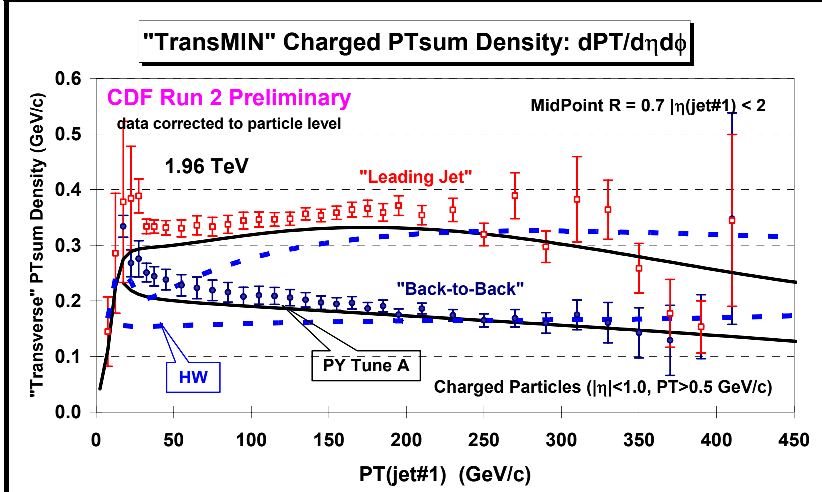
- **Use the leading jet to define the MAX and MIN "transverse" regions on an event-by-event basis with MAX (MIN) having the largest (smallest) charged PTsum density.**
- **Shows the "transDIF" = MAX-MIN charge PTsum density, $dPT_{sum}/d\eta d\phi$, for $p_T > 0.5$ GeV/c, $|\eta| < 1$ versus P_T(jet#1) for "Leading Jet" and "Back-to-Back" events.**

"TransMAX/MIN" PTsum Density PYTHIA Tune A vs HERWIG



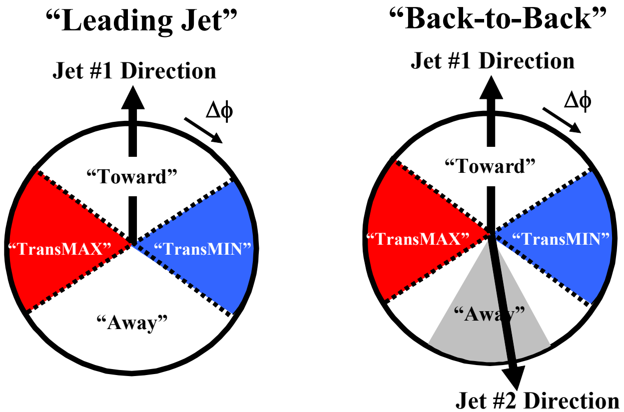


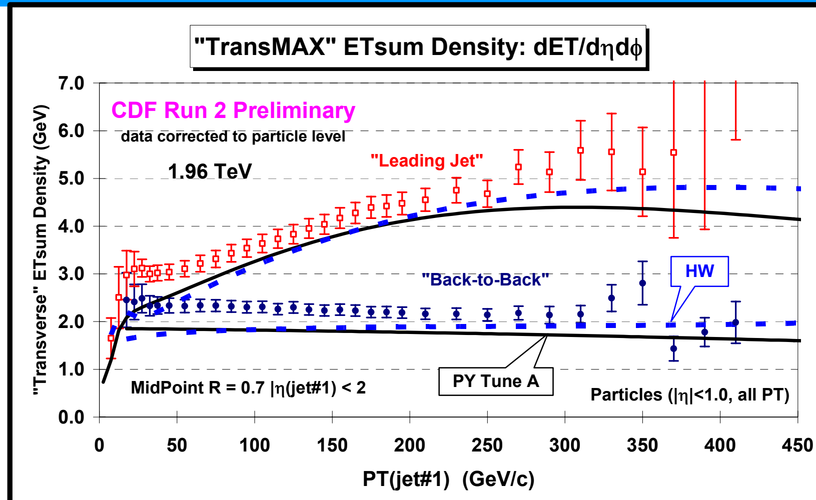


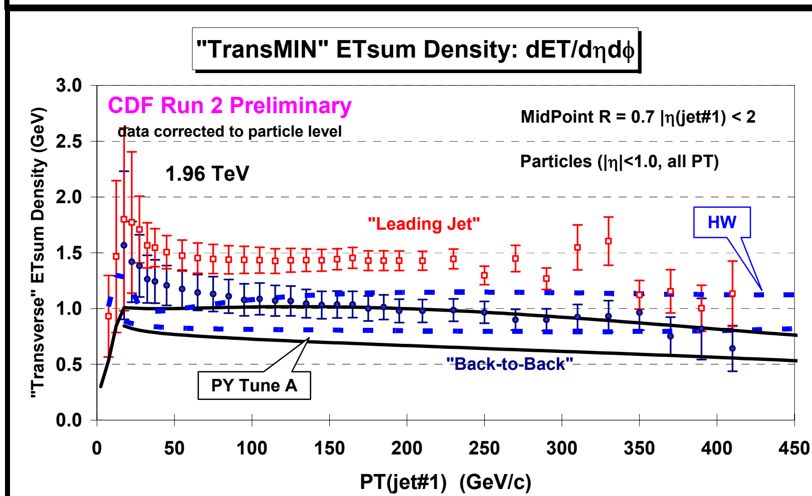


- Shows the **charged PTsum density**, $dPT_{sum}/d\eta d\phi$, in the **"transMAX" and "transMIN" region** ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) for **"Leading Jet"** and **"Back-to-Back"** events.
- Compares the (*corrected*) data with **PYTHIA Tune A (with MPI)** and **HERWIG (without MPI)** at the particle level.

"TransMAX/MIN" ETsum Density PYTHIA Tune A vs HERWIG







- Shows the **ETsum density**, $dET_{sum}/d\eta d\phi$, in the **"transMAX" and "transMIN" region** (all particles $|\eta| < 1$) versus P_T(jet#1) for **"Leading Jet"** and **"Back-to-Back"** events.
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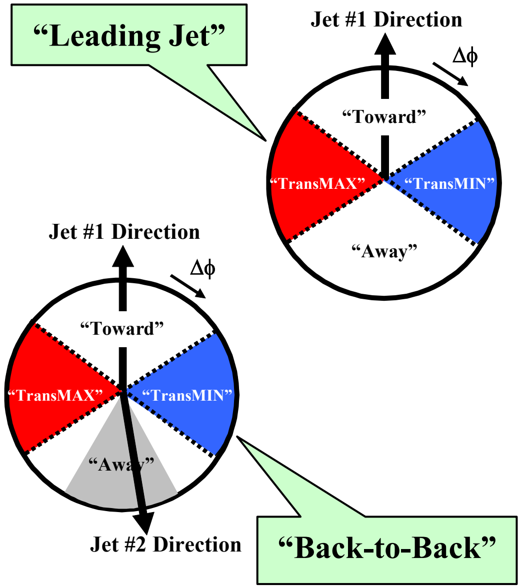
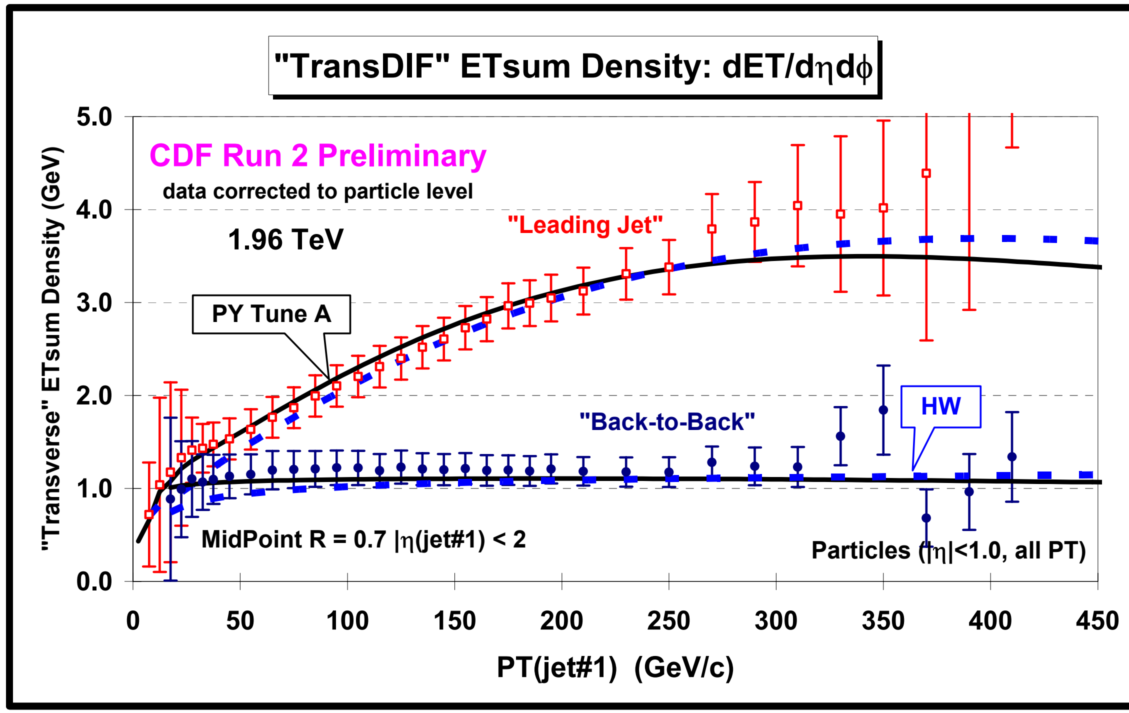
"TransDIF" ETsum Density PYTHIA Tune A vs HERWIG





"transDIF" is very sensitive to the "hard scattering" component of the "underlying event"!

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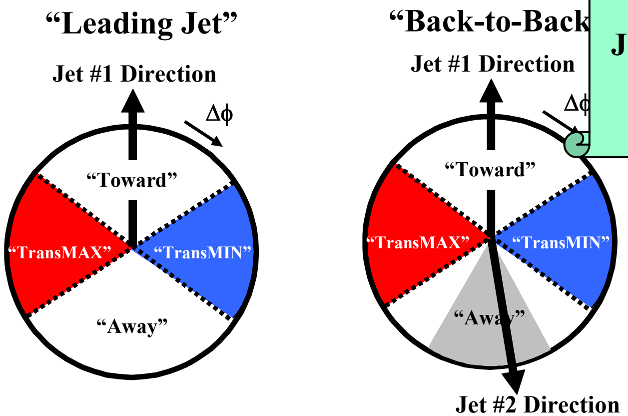
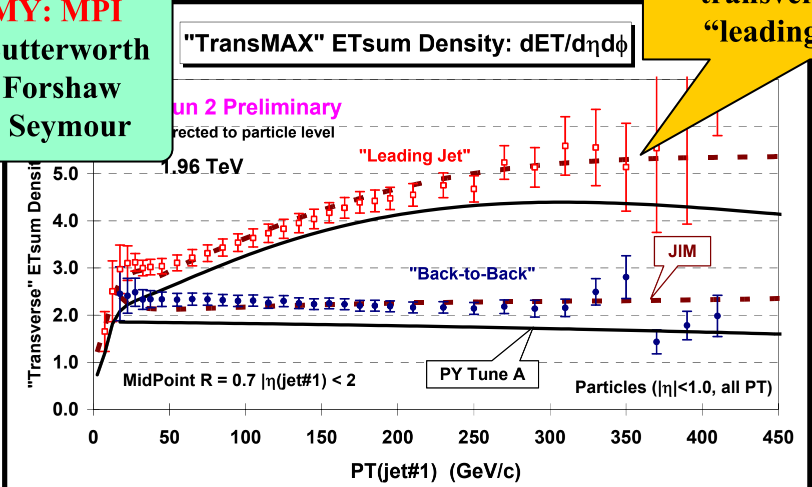
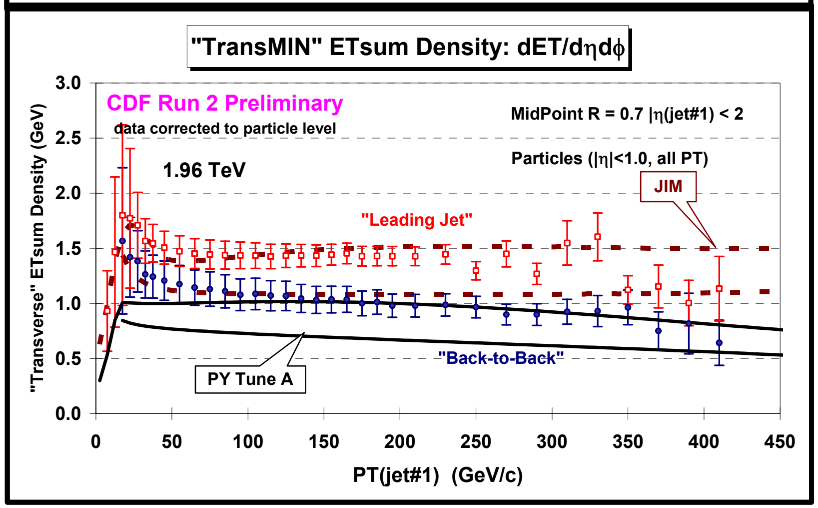
"TransMAX/MIN" ETsum Density
PYTHIA Tune A vs JIMMY



JIMMY: MPI
J. M. Butterworth
J. R. Forshaw
M. H. Seymour

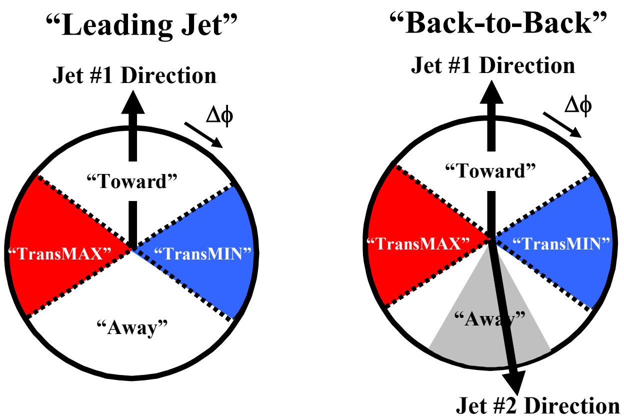
JIMMY was tuned to fit the energy density in the "transverse" region for "leading jet" events!

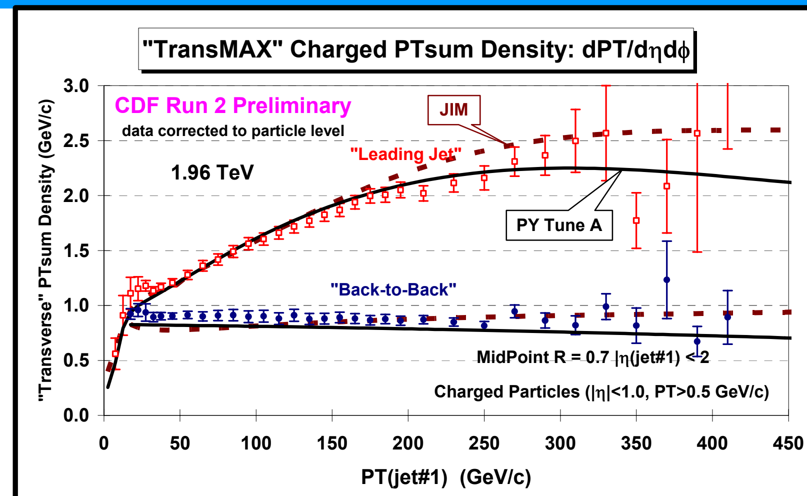


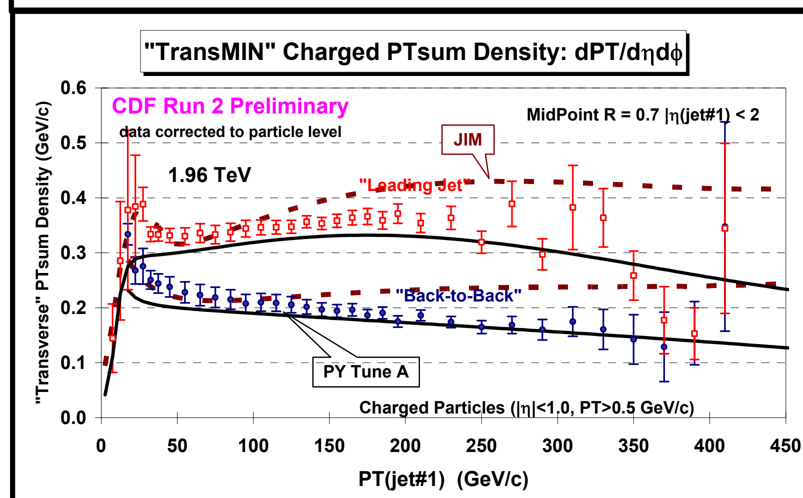


- Shows the **ETsum density**, $dET_{sum}/d\eta d\phi$, in the **"transMAX" and "transMIN" region** (all particles $|\eta| < 1$) versus P_T(jet#1) for **"Leading Jet"** and **"Back-to-Back"** events.
- Compares the (*corrected*) data with **PYTHIA Tune A (with MPI)** and a tuned version of **JIMMY (with MPI, PTJIM = 3.25 GeV/c)** at the particle level.

"TransMAX/MIN" PTsum Density
PYTHIA Tune A vs JIMMY



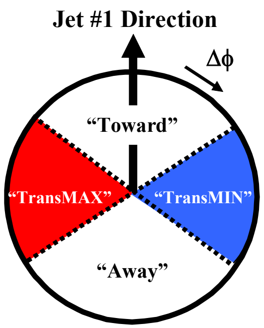




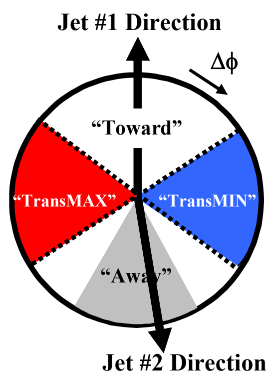
- Shows the **charged PTsum density**, $dET_{sum}/d\eta d\phi$, in the **"transMAX" and "transMIN" region** ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) for **"Leading Jet"** and **"Back-to-Back"** events.
- Compares the (*corrected*) data with **PYTHIA Tune A (with MPI)** and a tuned version of **JIMMY (with MPI, PTJIM = 3.25 GeV/c)** at the particle level.

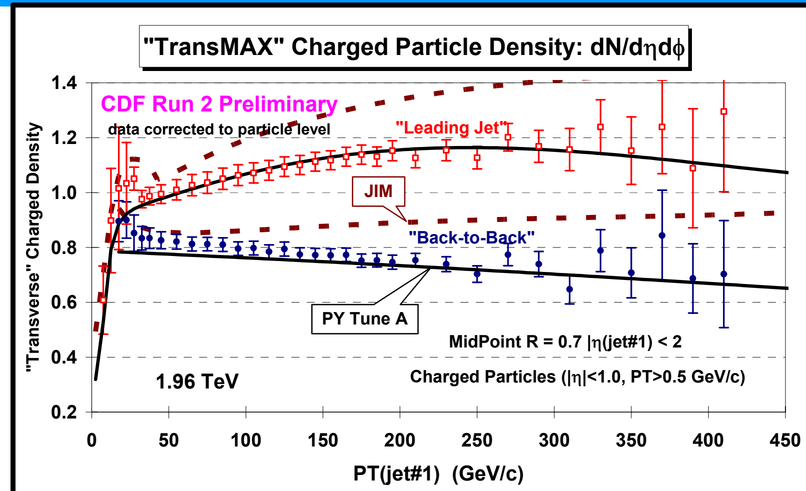
"TransMAX/MIN" Nchg Density PYTHIA Tune A vs JIMMY

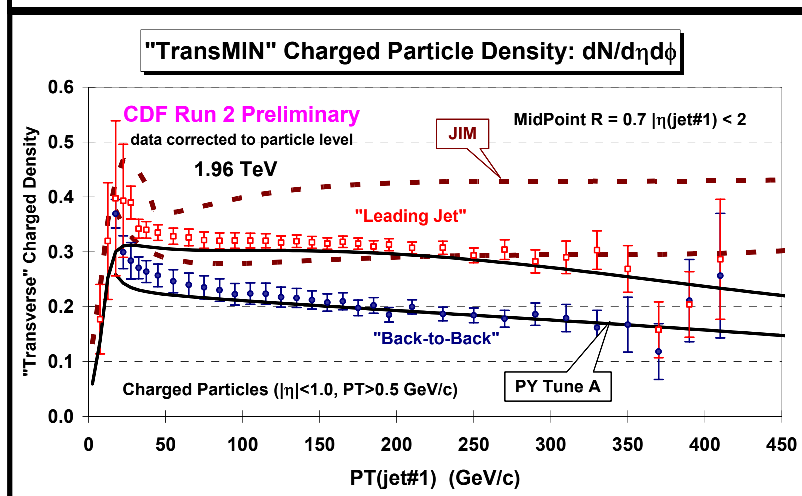
"Leading Jet"



"Back-to-Back"

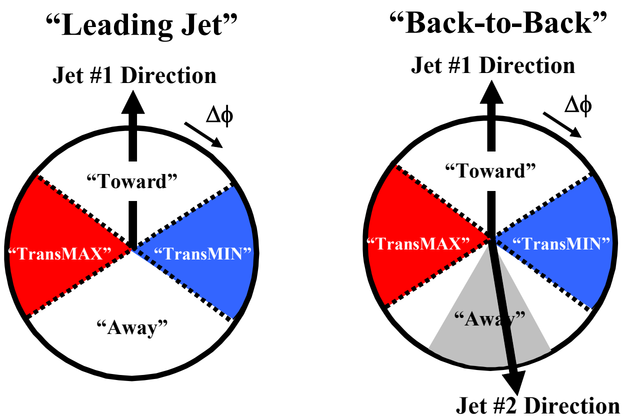


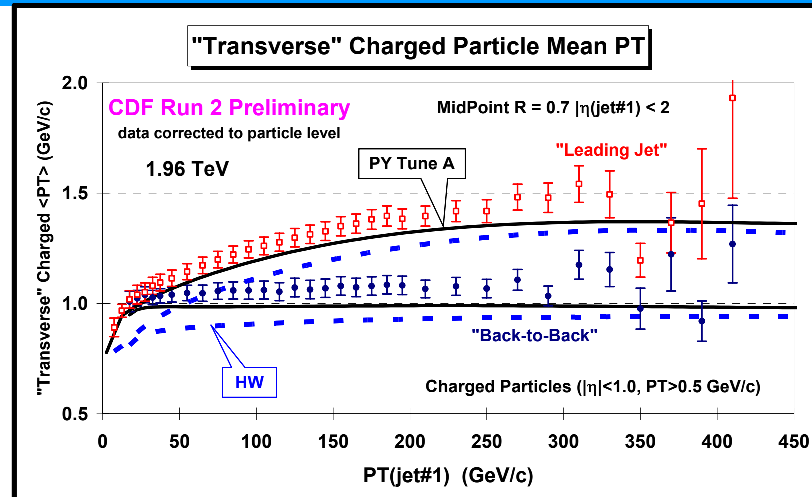


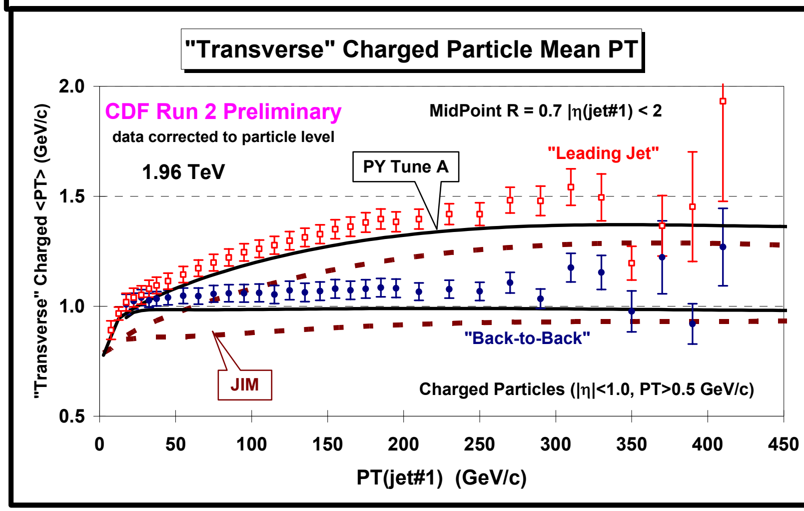


- Shows the **charged particle density**, $dN_{chg}/d\eta d\phi$, in the **"transMAX" and "transMIN" region** ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) for **"Leading Jet"** and **"Back-to-Back"** events.
- Compares the (*corrected*) data with **PYTHIA Tune A (with MPI)** and a tuned version of **JIMMY (with MPI, PTJIM = 3.25 GeV/c)** at the particle level.

"TransMAX/MIN" <P_T>
PYTHIA Tune A vs JIMMY



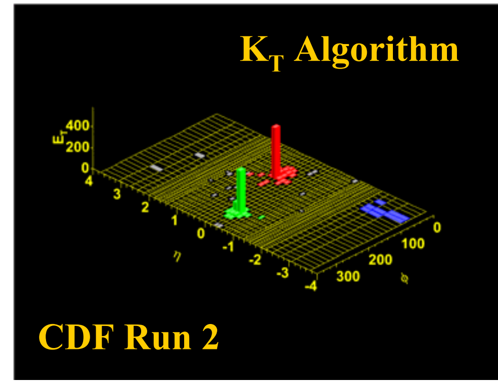


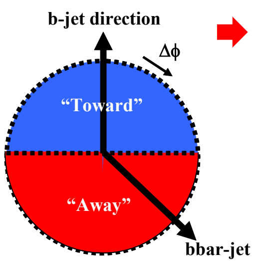


- Shows the **charged particle <P_T> in the "transMAX" and "transMIN" region** ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) for **"Leading Jet"** and **"Back-to-Back"** events.
- Compares the (*corrected*) data with **PYTHIA Tune A (with MPI)** and **HERWIG** and a tuned version of **JIMMY (with MPI, PTJIM = 3.25 GeV/c)** at the particle level.

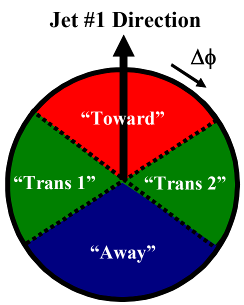
Summary

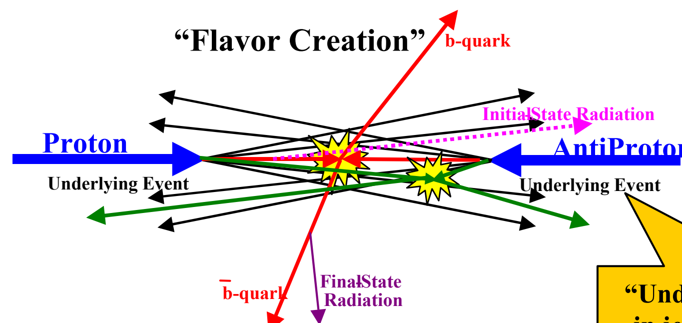
- The MidPoint jet cross section at the Tevatron is consistent with theory (CTEQ61M) over 9 decades!
- The K_T algorithm works fine at the Tevatron and theory/data (CTEQ61M) look flat!





- The measured the inclusive b-jet section, b-bbar jet cross section and correlations, are behaving as expected from theory - nothing goofy!



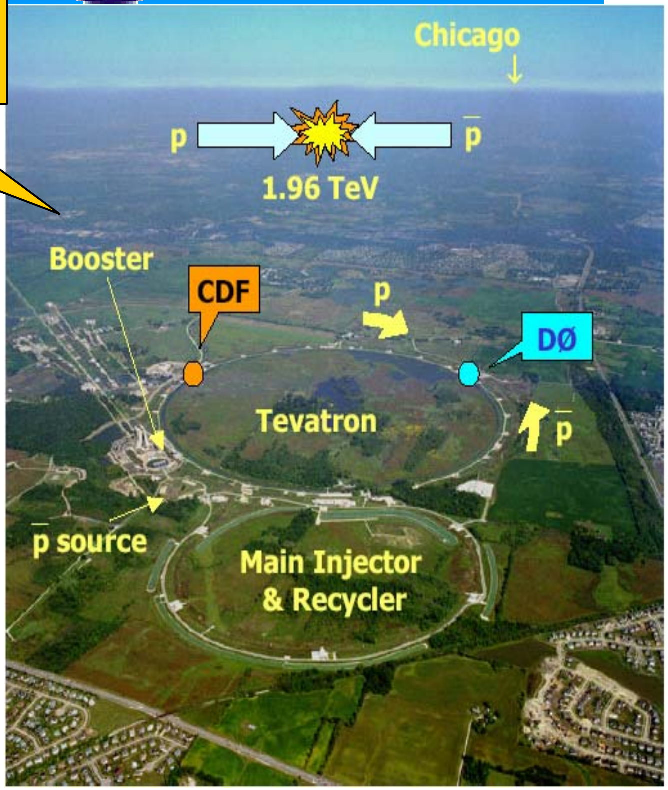


"Underlying event" important in jet (and b-jet) production!

- We are making good progress in understanding and modeling the "underlying event". We have PYTHIA Tune A and JIMMY tune A, however, we do not yet have a perfect fit to all the features of the "underlying event". We are working on new improved Run 2 tunes!

The Future

Much more QCD physics to come from the Tevatron!



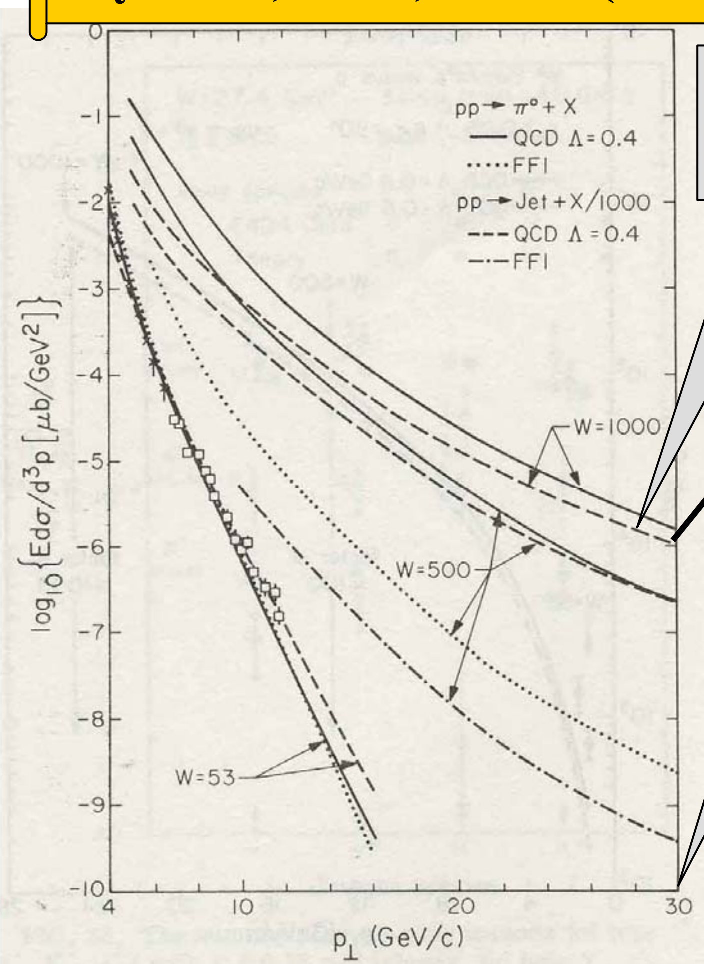
Some CDF-QCD Group Analyses!

- Jet Cross Sections and Correlations: MidPoint and KT algorithms with $L = 1\ \mathrm{fb}^{-1}$!
- DiJet Mass Distributions: $\Delta\phi$ distribution, compositness.
- Heavy Flavor Jets: b-jet and b-bbar jet cross sections and correlations.
- Z and W Bosons plus Jets: including b-jets.
- Jets Fragmentation: jet shapes, momentum distributions, two-particle correlations.
- Underlying Event Studies: distributions as well as averages for charged particles and energy for jet, jet+jet, γ+jet, Z+jet, and Drell-Yan.
- Pile-Up Studies: modeling of pile-up.
- Monte-Carlo Tuning: New Run 2 PYTHIA tune, tuned JIMMY, PYTHIA 6.3, Sherpa, etc..

Analyses using $1\mathrm{fb}^{-1}$ of data by Winter 2006!

The Past

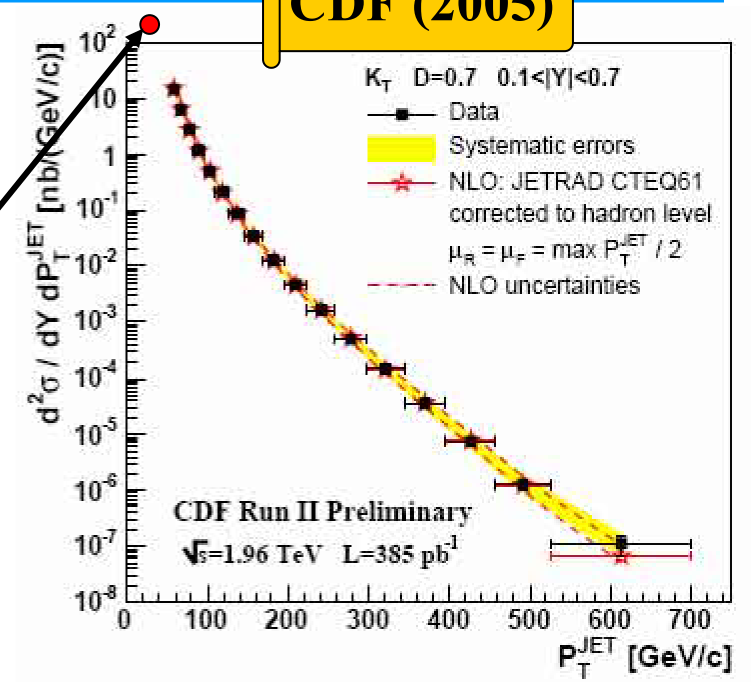
Feynman, Field, & Fox (1978)



Predict
large "jet" cross-section

30 GeV/c!

CDF (2005)



Feynman quote from FFF:
"At the time of this writing, there is still no sharp quantitative test of QCD. An important test will come in connection with the phenomena of high P_T discussed here."