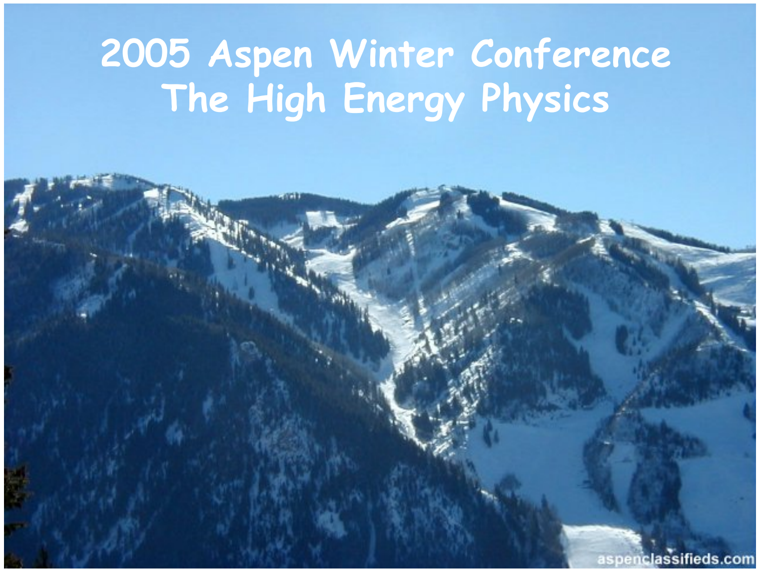


QCD Physics at Tevatron
(for CDF and D0 Collaborations)

Andrey Korytov
UNIVERSITY OF FLORIDA

QCD Physics at Tevatron

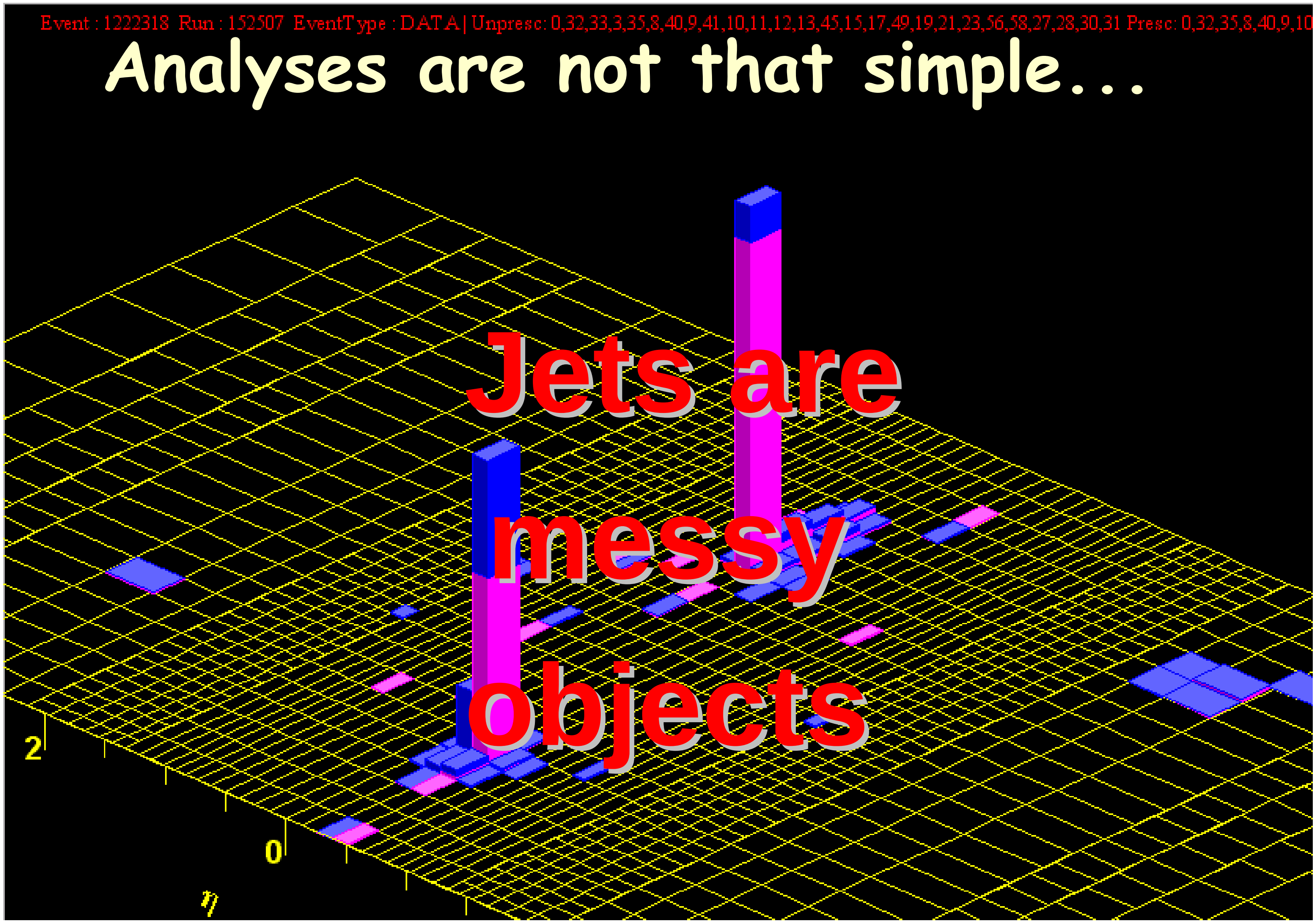
<u>High P_T QCD</u>

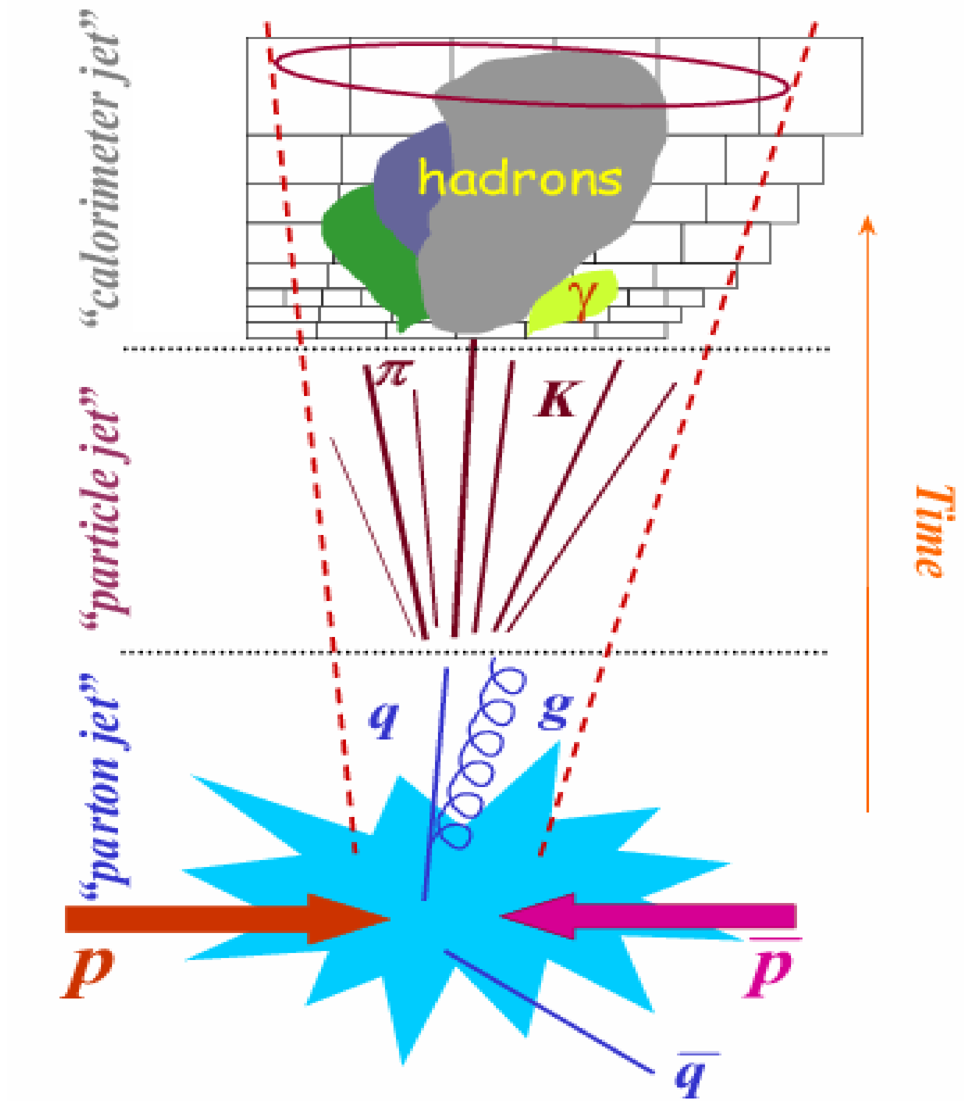
Jet production (g and uds)
Heavy flavor quark production (t, b, c) – Michael Weber (t), Friday Talk? (b, c?)
Vector boson production (W, Z, γ) – Pasha Murat

<u>Low P_T QCD</u>

Jet fragmentation
Hadron spectroscopy
Underlying Event
Diffractive physics – Konstantin Goulianos

Jets


Event : 1222318 Run : 152507 EventType : DATA | Unpresc: 0,32,33,3,35,8,40,9,41,10,11,12,13,45,15,17,49,19,21,23,56,58,27,28,30,31 Presc: 0,32,35,8,40,9,10
Analyses are not that simple...
Jets are messy objects
2
0
η



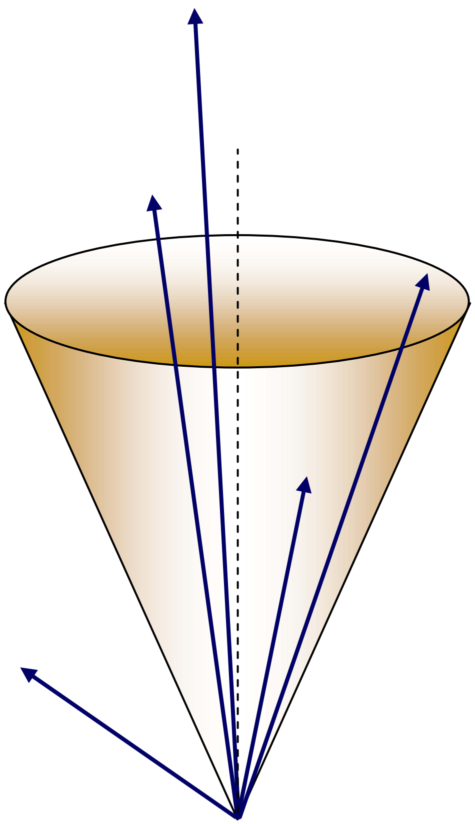
Calorimeter level:
calorimeter towers lumped together according to an experimentalist's favored algorithm

Hadron level:
sprays of long lived observable particles

Parton level 2 (resummed pQCD):
outgoing parton accompanied by a few soft QCD bremsstrahlung

Parton level 1 (NLO pQCD at Tevatron):
outgoing 1 parton or 2 partons lumped together to mimic a particular experimental jet finding algorithm

Jets: jet finding algorithms



Cone Algorithm:

- cluster together calorimeter towers by their "angular" proximity in (η, ϕ) space
- merging/splitting of overlapping cones is not infrared stable (at NNLO)
- ad hoc R_{sep}=1.3 to match theory and exp.
- Tevatron Run I legacy

MidPoint Cone Algorithm:

- cone algorithm with modifications improving infrared stability

k_T Algorithm:

- cluster together calorimeter towers by their k_T proximity
- infrared stable (no splitting/merging)
- no clusters left out → underlying event contribution unclear
- favored choice at e+e- colliders

Jets: jet energy measurements

Jet Energy Resolution (stochastic):

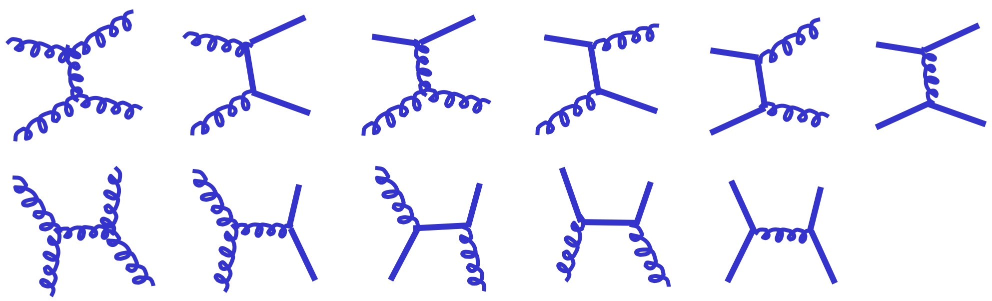
$$\frac{\delta E_T}{E_T} \approx \frac{70\%}{\sqrt{E_T(GeV)}} \oplus 6\%$$

Absolute Scale Uncertainty (systematic):

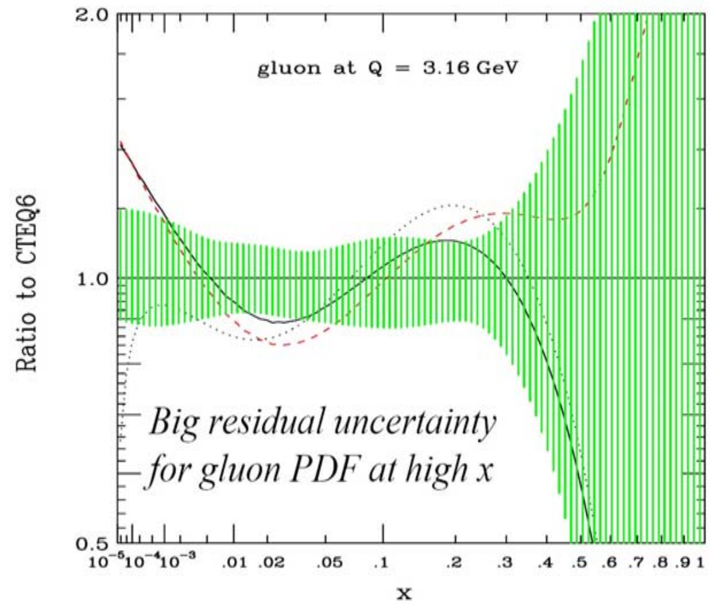
$$\frac{\delta E_T}{E_T} \approx 5\%$$

Jets: theory

- Very large number of diagrams to tackle…
  - NLO calculations available…
  - but still very sensitive to scale choices…
  - NNLO "soon to become available" for many years…
- Uncertainties in Parton Density Functions (PDFs)
  - especially g(x) at large x…



Sample of LO diagrams (2 → 2)



Inclusive jet production

$$p + \overline{p} \rightarrow Jet(E_T, \eta) + X$$

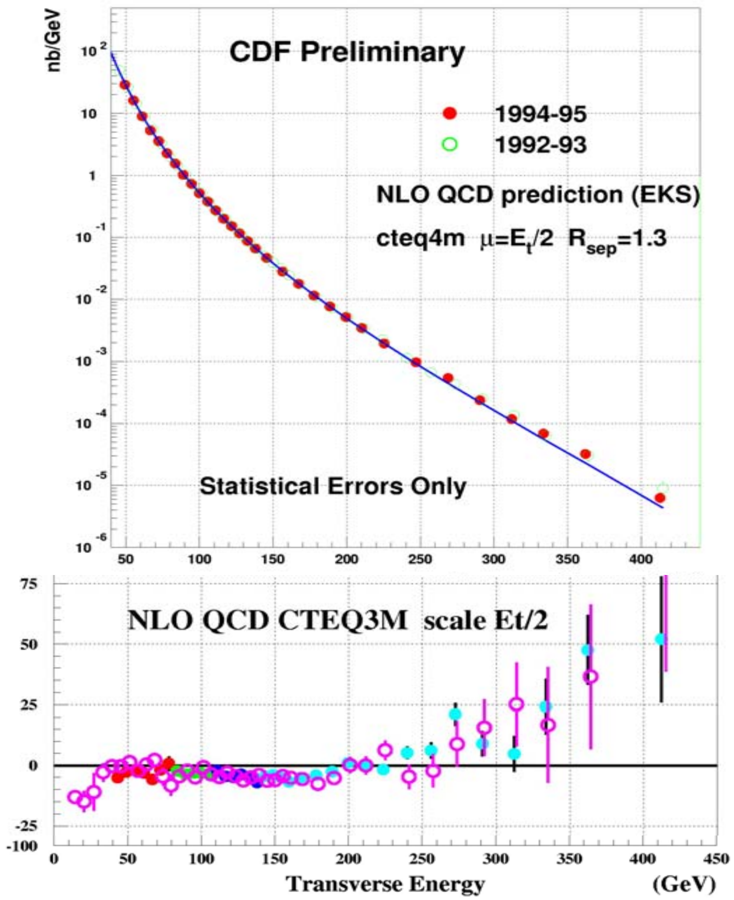
E_T spectra

different η-bins…

Jets: Inclusive jets in Run I

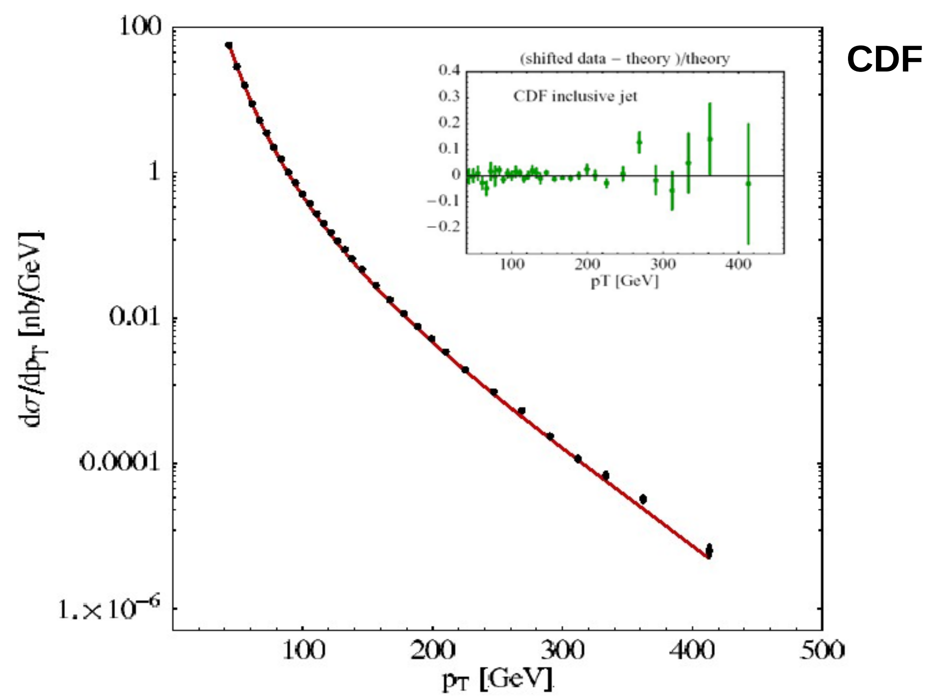
Run I data and NLO+CTEQ3M

- ❑ CDF: Excess at high E_T?
- ❑ Compositness?



Run I data and NLO+CTEQ6M

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

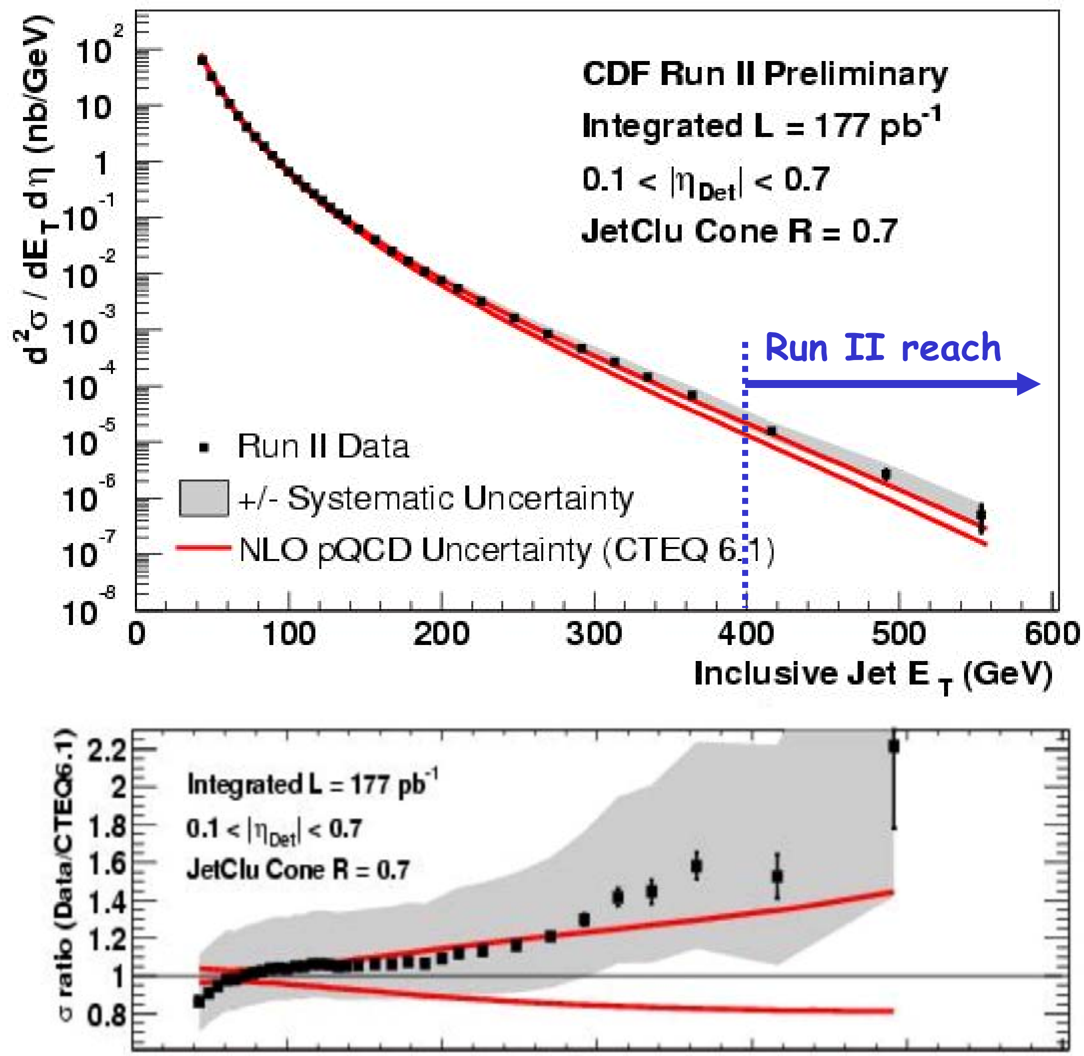


Jets: Inclusive jets in Run II data vs NLO

Quite reasonable agreement with NLO+CTEQ6.1, but...

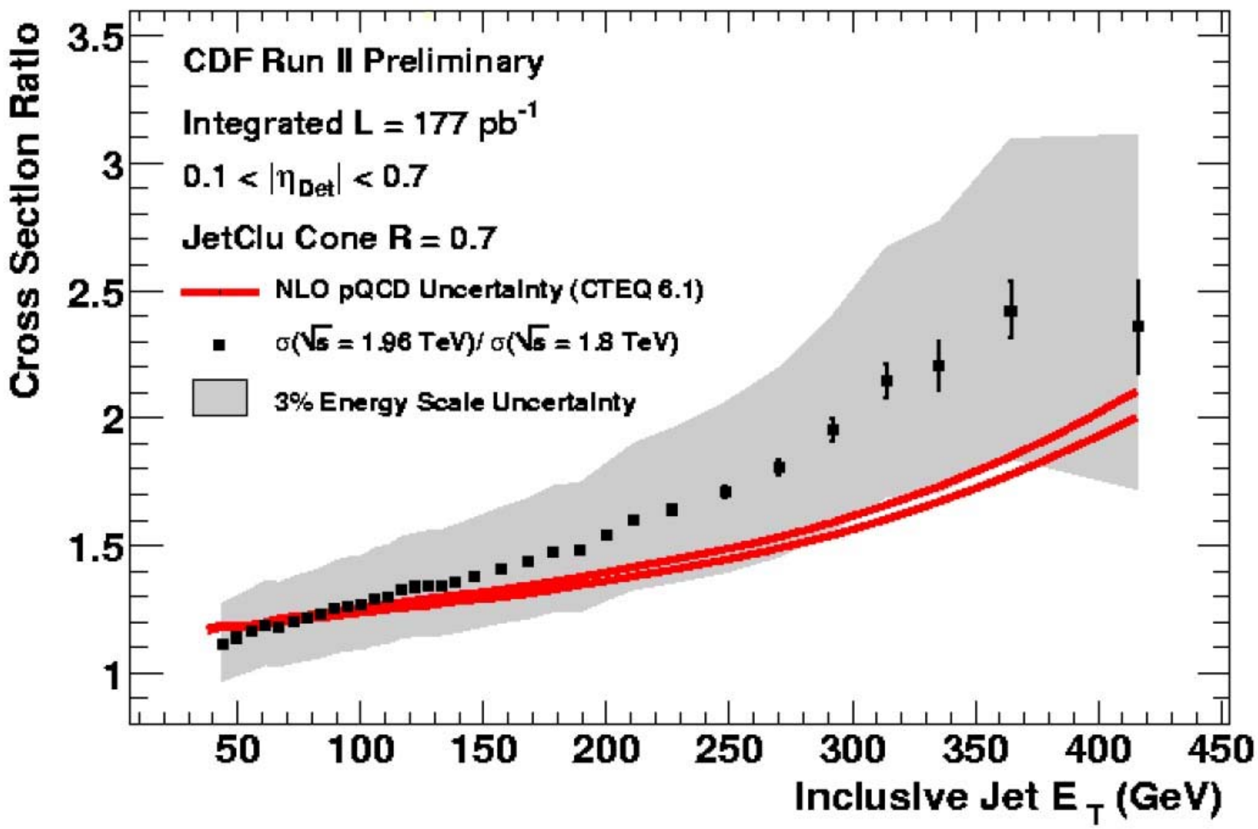
- **déjà vu:**
  "high-E_T excess" again?
- **~20% dip at lower E_T? (not present in Run I)**
- **all within systematic errors...**

- **must beat systematic errors down:**
  - **Theory: PDFs, NNLO?**
  - **Experiment: energy scale, hadronization corrections?**



Jets: Inclusive jets in Run II vs Run I

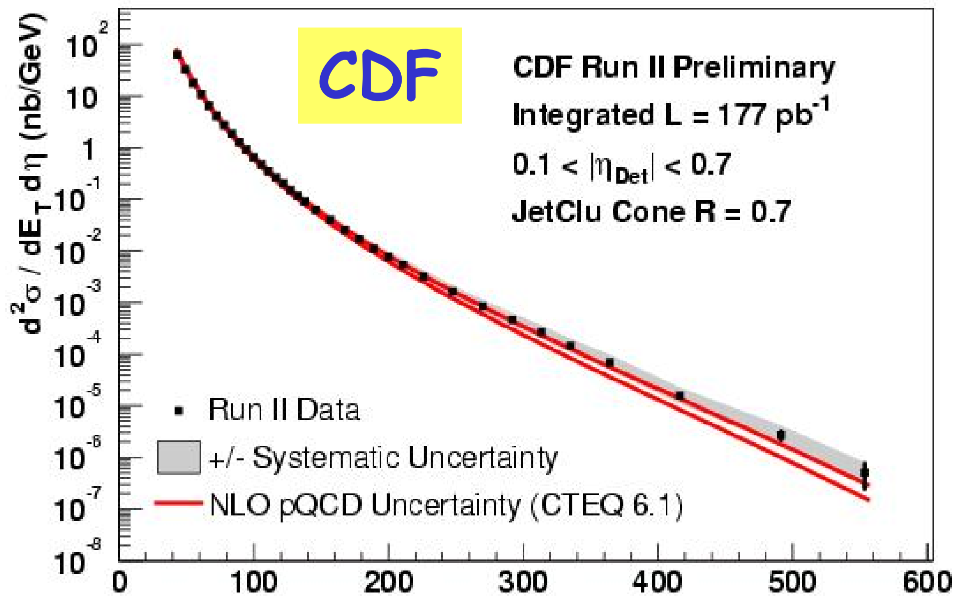
$\sigma(\text{Run II}) / \sigma(\text{Run I})$

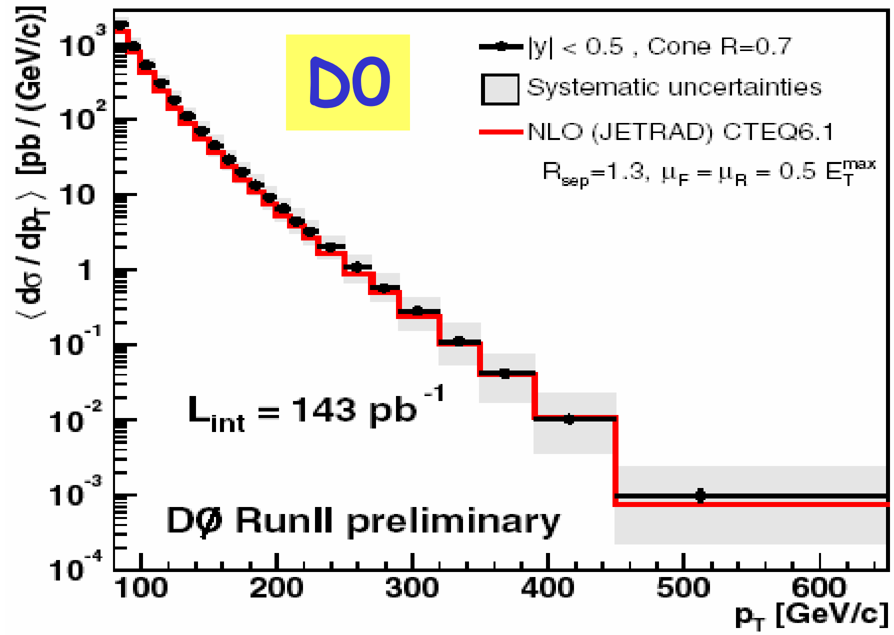


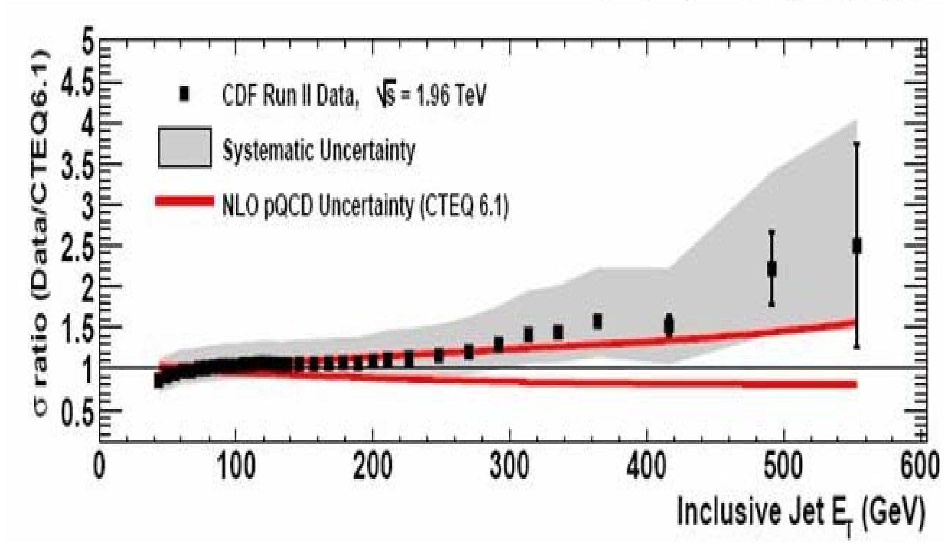
CDF

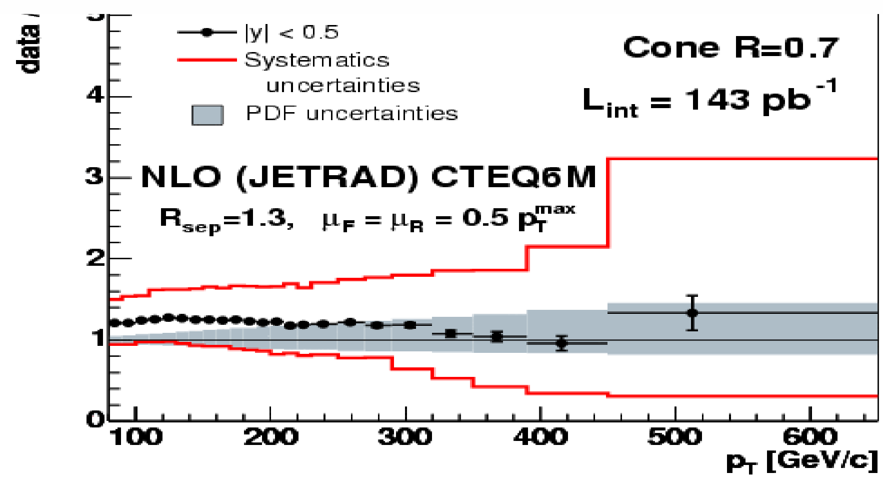
- PDF uncertainties largely cancel out
- Energy scale errors are really annoying…

Jets: Inclusive jets by D0 and CDF

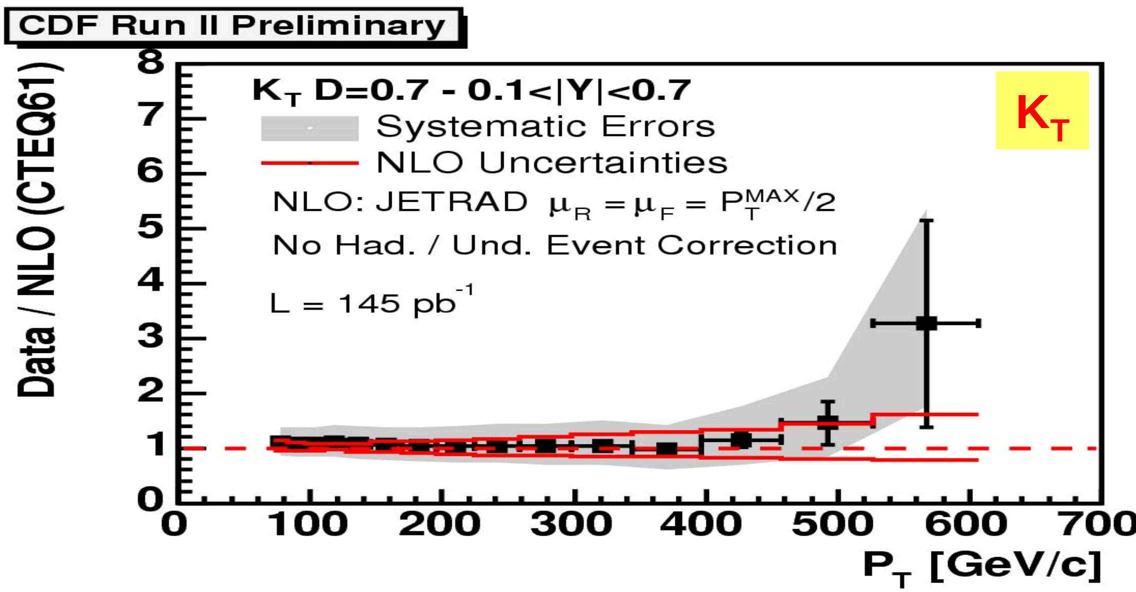




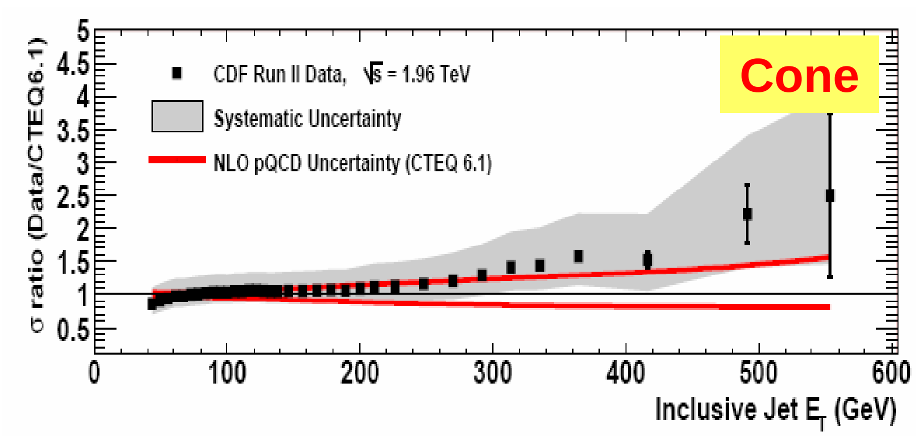




Jets: k_T vs Cone algorithm



CDF



CDF

Shapes of Data/Theory differ…

Why? (work in progress)

Jets: dijet production

$$p + \overline{p} \to Jet_1 + Jet_2 + X$$

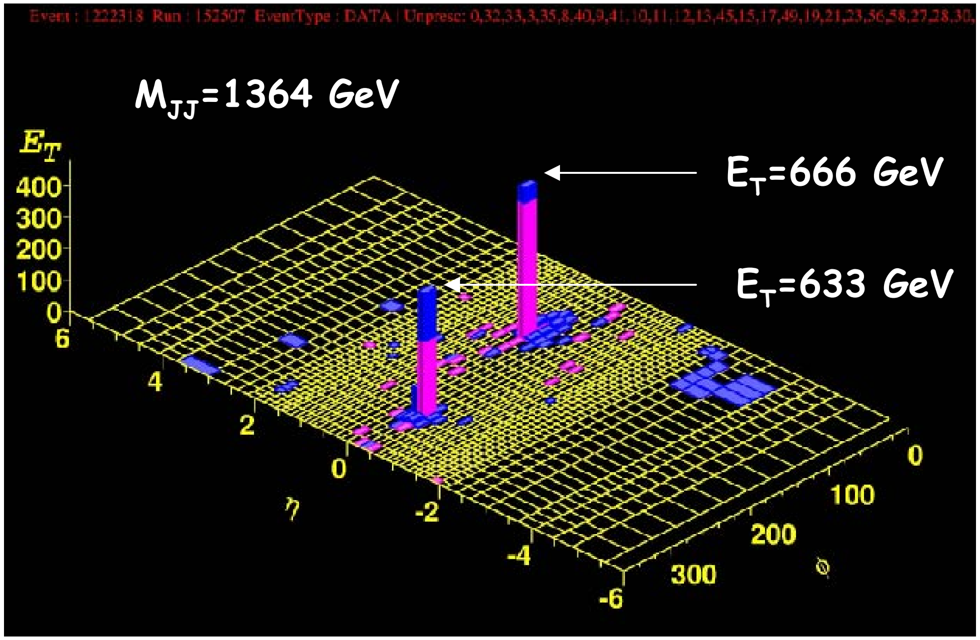
What one might want to look at:

M_{JJ}

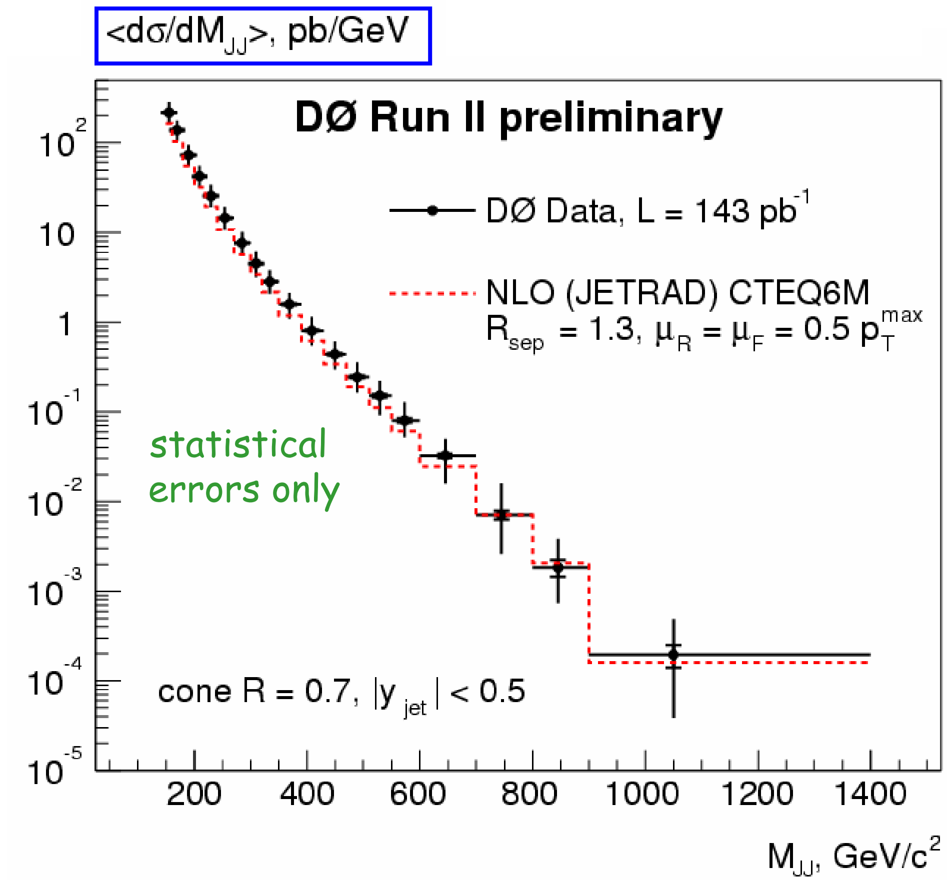
θ_{cm}

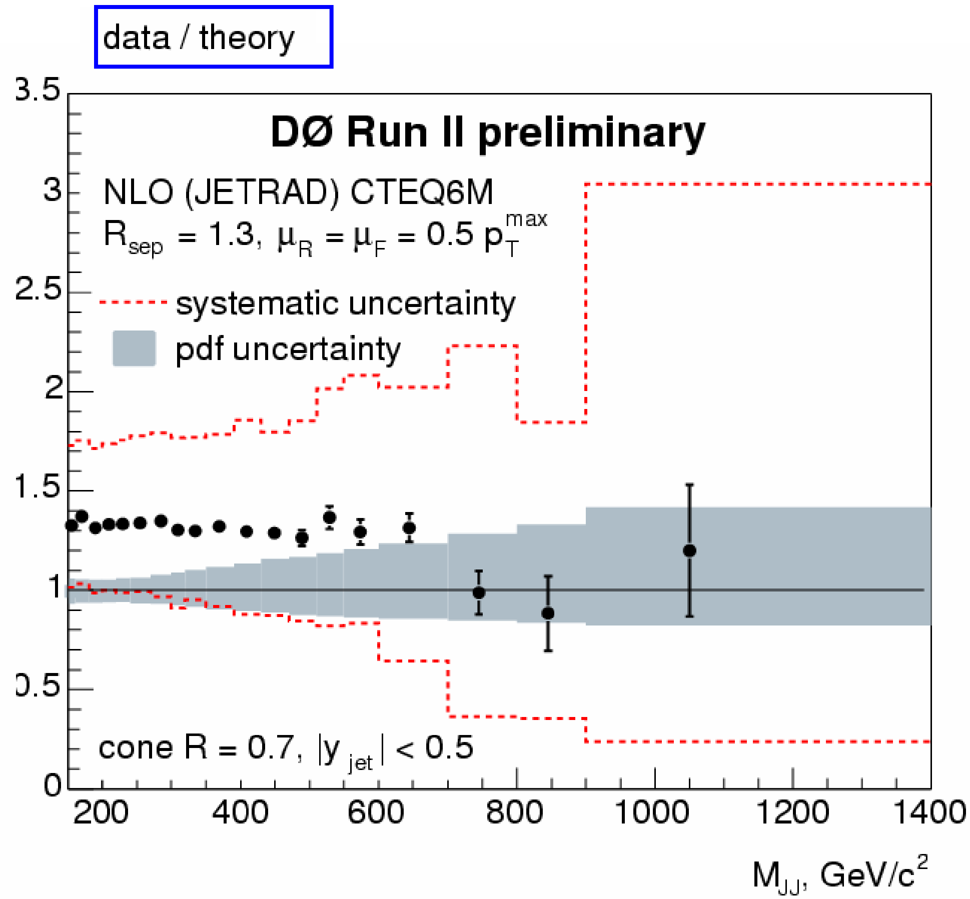
$\Delta\phi_{12}$

...



Jets: Dijet production

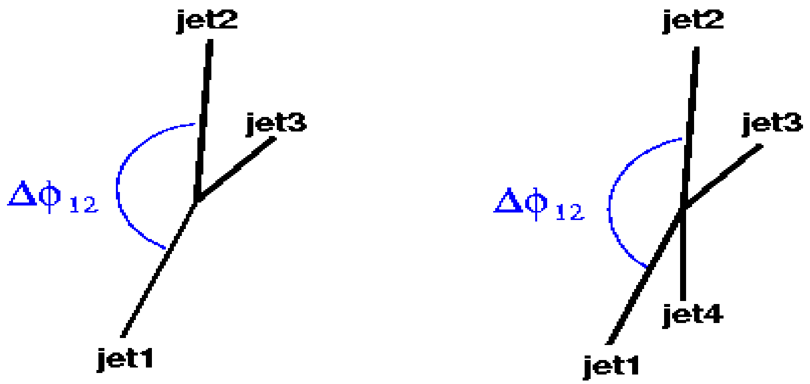




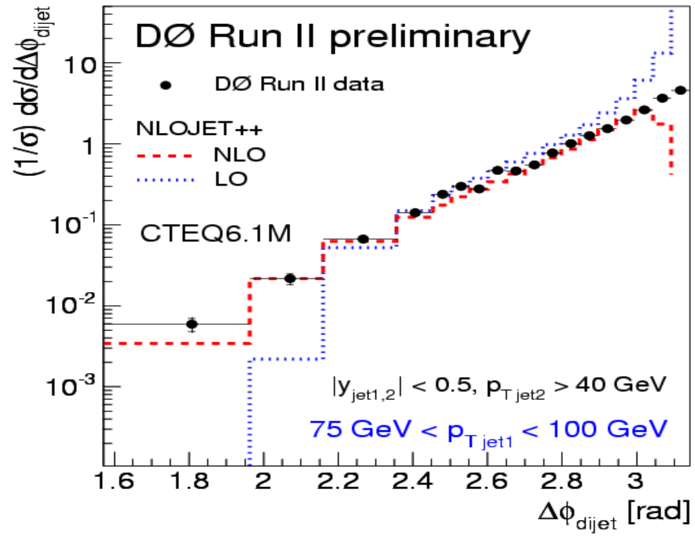
Look for narrow resonance peaks in Dijet Mass spectrum—seen none

Data/theory agree—within large systematic errors (jet-energy scale)

Jets: Dijet $\Delta\phi_{12}$



LO in $\Delta\phi$ NLO in $\Delta\phi$

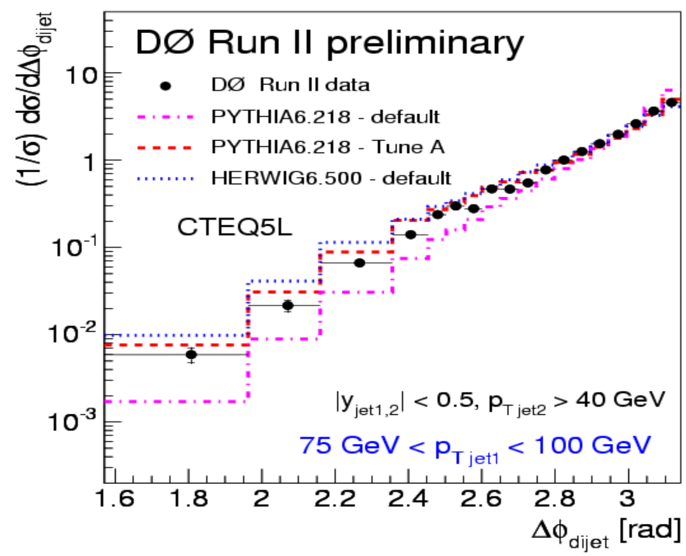


LO is very poor at $\Delta\phi\sim\pi/2$ and $\Delta\phi\sim\pi$

NLO fixes $\Delta\phi\sim\pi/2$, but still no good at $\Delta\phi\sim\pi$

Herwig is quite good everywhere

Pythia needs ISR enhancement for $\Delta\phi\sim\pi/2$

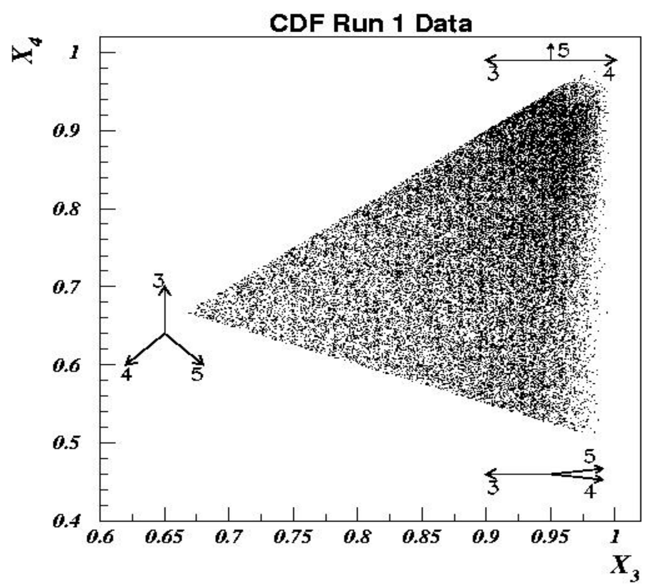


Jets: three-jet production

$$p + \overline{p} \rightarrow Jet_1 + Jet_2 + Jet_3 + X$$

Many more variables to play with...

No surprises...



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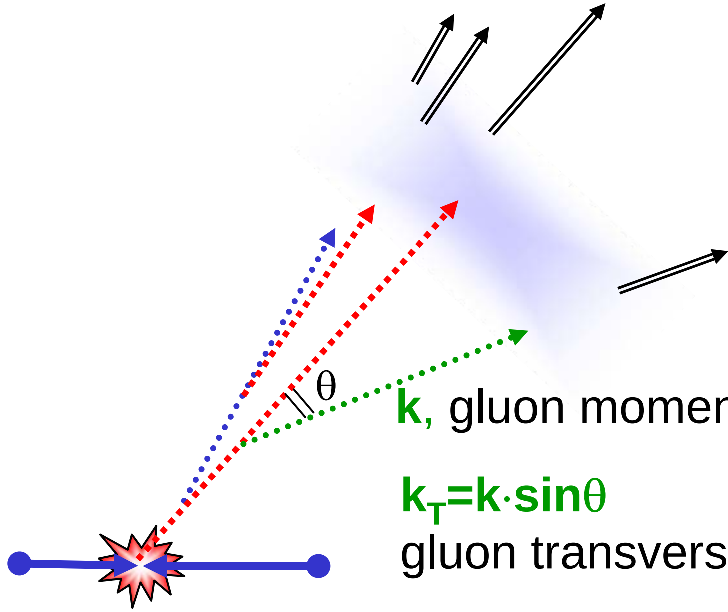
Jet fragmentation

Hadron spectroscopy

Underlying event

Diffractive physics – Konstantin Goulianos

Jet Fragmentation: intrinsically soft QCD



k, gluon momentum

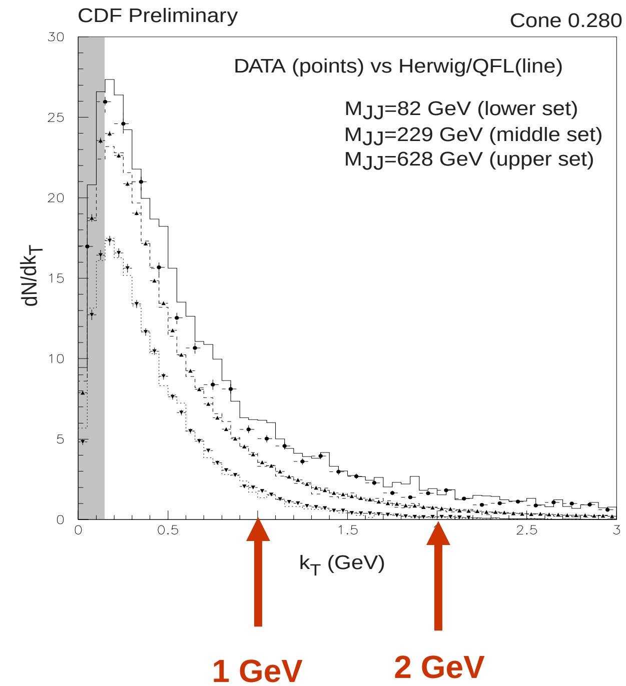
$k_T = k \cdot \sin\theta$
gluon transverse momentum

Differential probabilities of gluon emission:

$$dw \sim \alpha_S \frac{dk}{k}\frac{dk_T}{k_T}, \qquad \alpha_S = \frac{2\pi}{9\ln\left(k_T / \Lambda_{QCD}\right)}$$

Perturbative methods will NOT work for k_T<1 GeV

k_T distribution of particles in jets



From data we know that most particles have k_T<1 GeV

THEORY ANY HOPE? EXPERIMENT

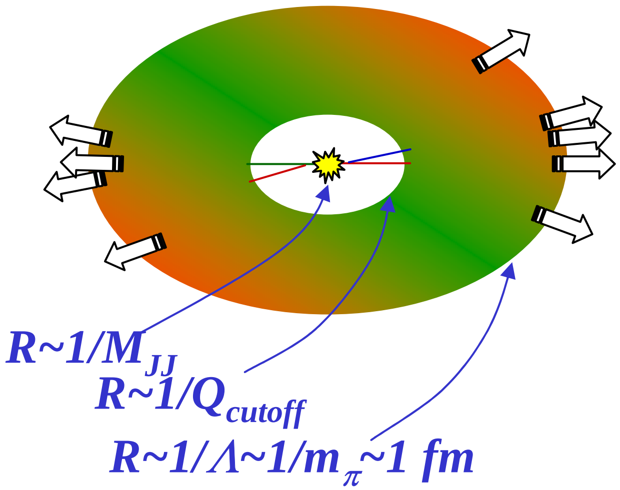
<u>Jet Fragmentation</u>: doing it analytically

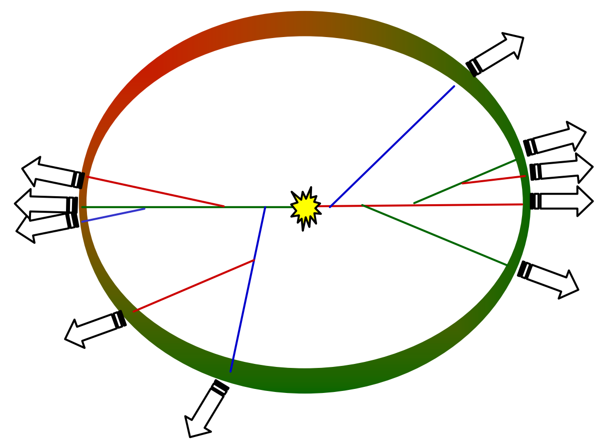
Jet fragmentation in pQCD:

- 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…
- does it work at all?





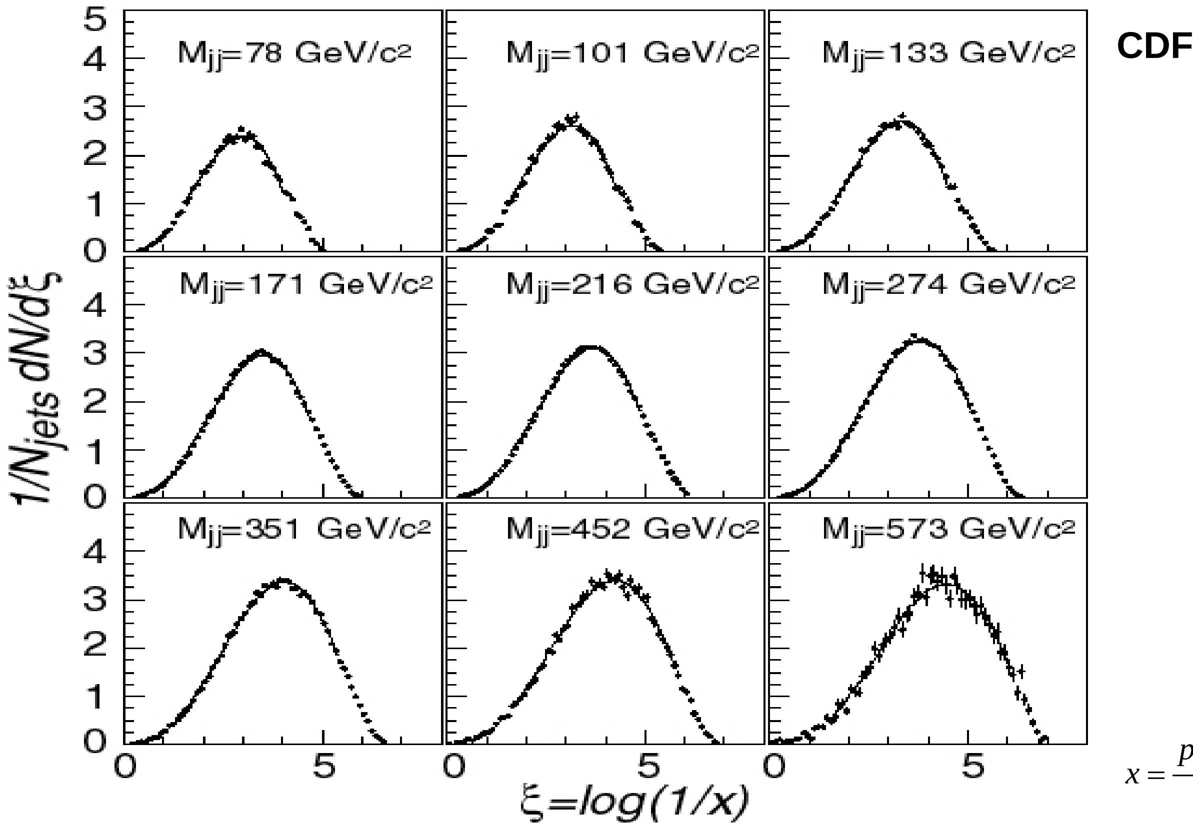
Jet Fragmentation: data vs resummed pQCD

Charged particles in jets

Two parameter fit:

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

- ☞ k_T-cutoff can be set as low as ~Λ_{QCD}
- ☞ number of hadrons ≈ number of partons

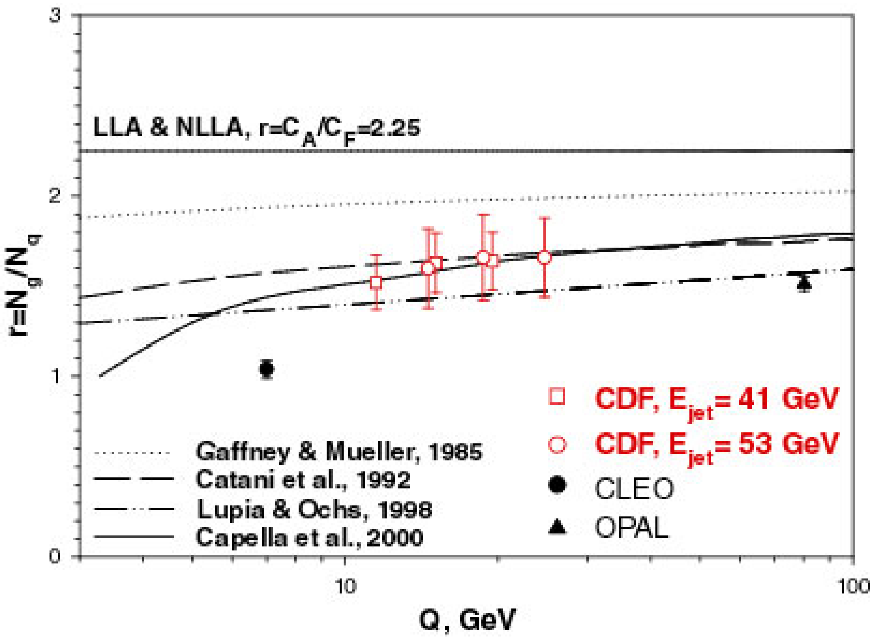


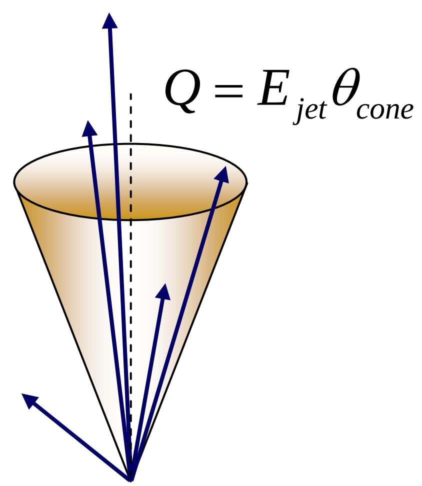
$$x = \frac{p_{particle}}{E_{jet}}$$

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: 15+ papers from e+e-, not all self-consistent (r = 1 to 1.5)
- CDF: r=1.6±0.2





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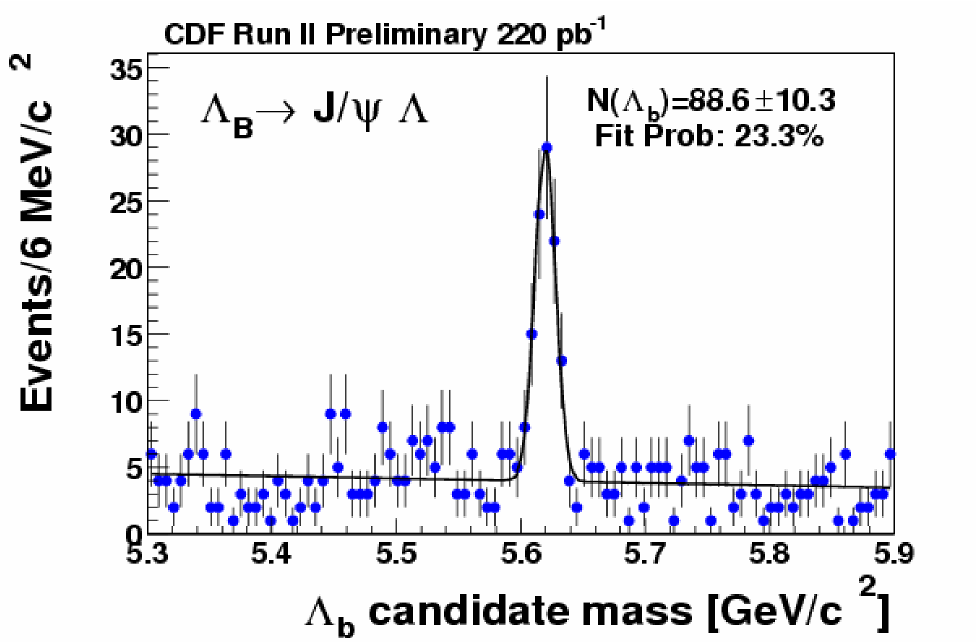
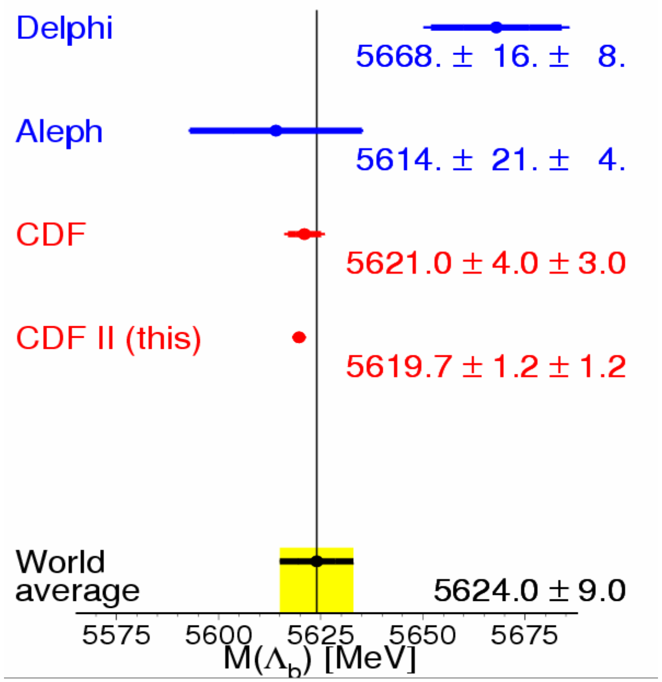
Hadrons: Λ_b mass

Tevatron is THE heavy flavor hadron factory (not very clean though...)
Secondary vertex trigger allows to fish them out
World largest sample of Λ_b



$M(\Lambda_b)$=5619±1.2±1.2 MeV/c^2
PDG2002: 5624 ± 9



Hadrons: X(3872)

Aug 2003: Belle announced discovery of X(3872) → $J/\psi\ \pi^+\pi^-$

- M=3872.0±0.6 ±0.5 MeV
- Γ < 2.3 MeV
- $\pi\pi$ masses are always high (>500 MeV)

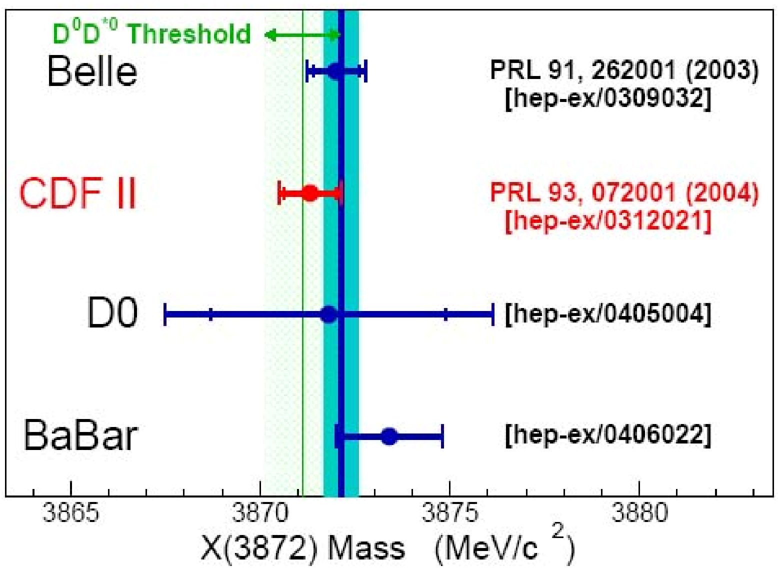
Confirmed by CDF, D0, BaBar

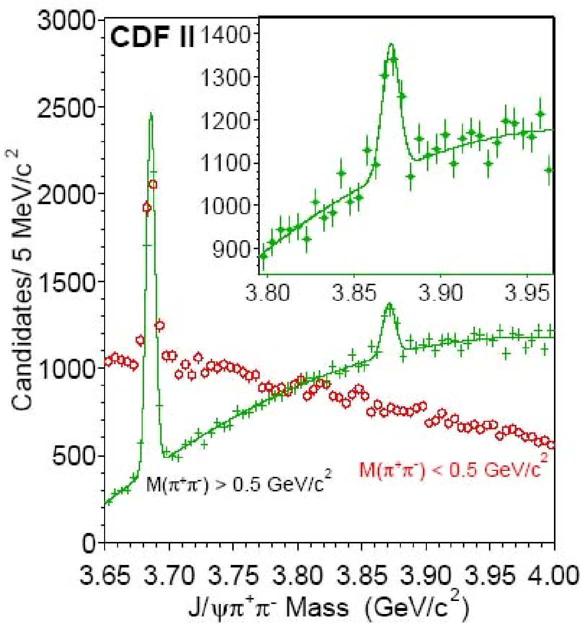
Interpretation still remains unclear:

- $^3D_2$ charmonium? $c\bar{c}$
  - too heavy for it (expected M~3810-3840)
  - also, not seen to decay to $\chi_1\gamma$
- $M(X) \sim M(D^0)+M(D^{*0})$ = 1864.6 + 2006.7 = 3871 MeV
  - DD* molecule? $\bar{c}u$-$c\bar{u}$
- Quadra-quark? cu-$\bar{c}\bar{u}$
- $M(J/\psi)+M(\rho)$ = 3097+770 = 3867 MeV
  - ???

Hadrons: X(3872) at CDF

- M=3871.3±0.7 ±0.4 MeV
- M(ππ) invariant masses are all high (>500 MeV)
- high yield:
  - ~1/8 of ψ(2S)
  - ~85% are prompt, not B-decays!





Hadrons: pentaquarks

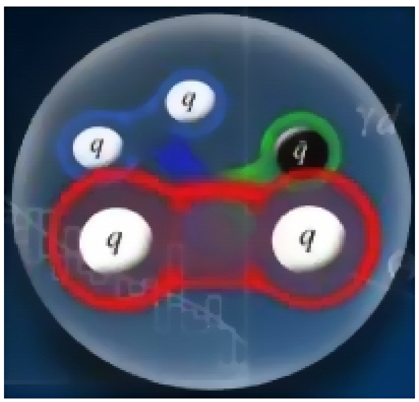
***Penta-quark states predicted by Diakonov, Petrov, Polyakov(1997)*:**

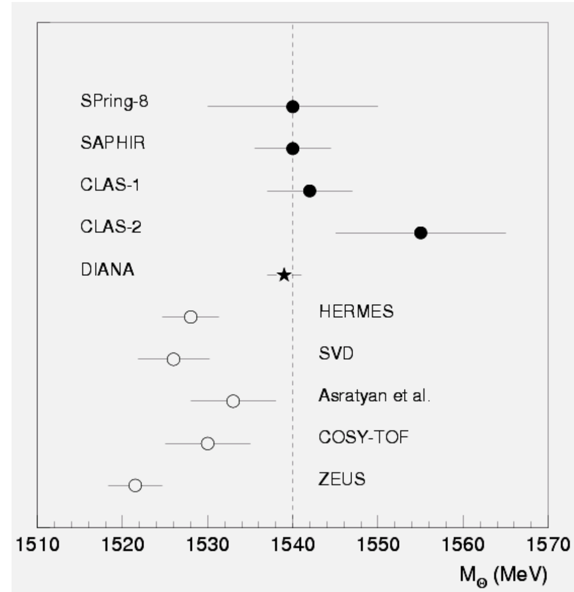
Θ^+ : uudd$\bar{s}$

Mass ~ 1530 MeV

Width ~ 15 MeV

Decays equally to nK^+ and pK^0





10 experiments report evidence: *see above*

3 experiments report no observation: *HERA-B, PHENIX, BES*

In addition,

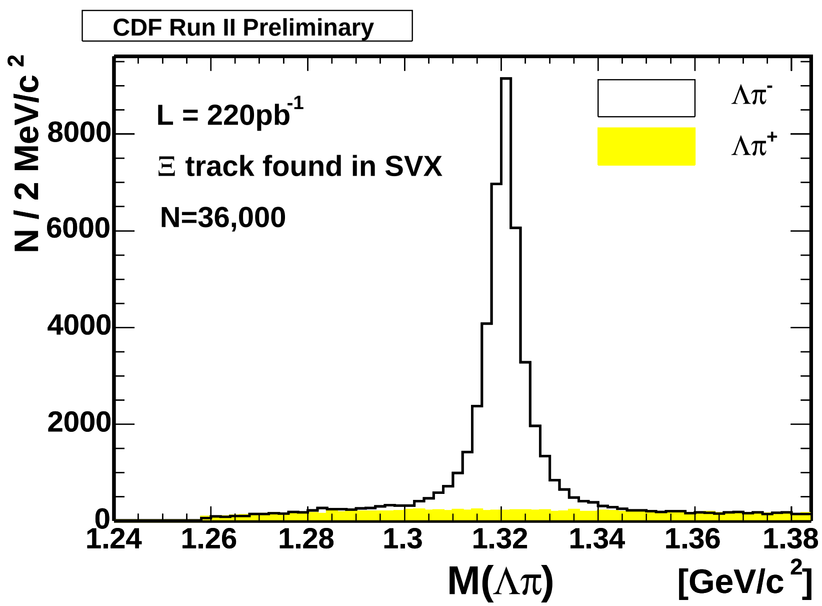
NA49 at SPS/CERN (pp collider, Ecm = 17.2 GeV): ssdd$\bar{u}$(1862) $\Xi^{++/--}_{3/2} \rightarrow \Xi^{+/-} \pi^{+/-}$

H1 at HERA ep collider: D^{*-} p state: Θ_c=uudd$\bar{c}$(3099)

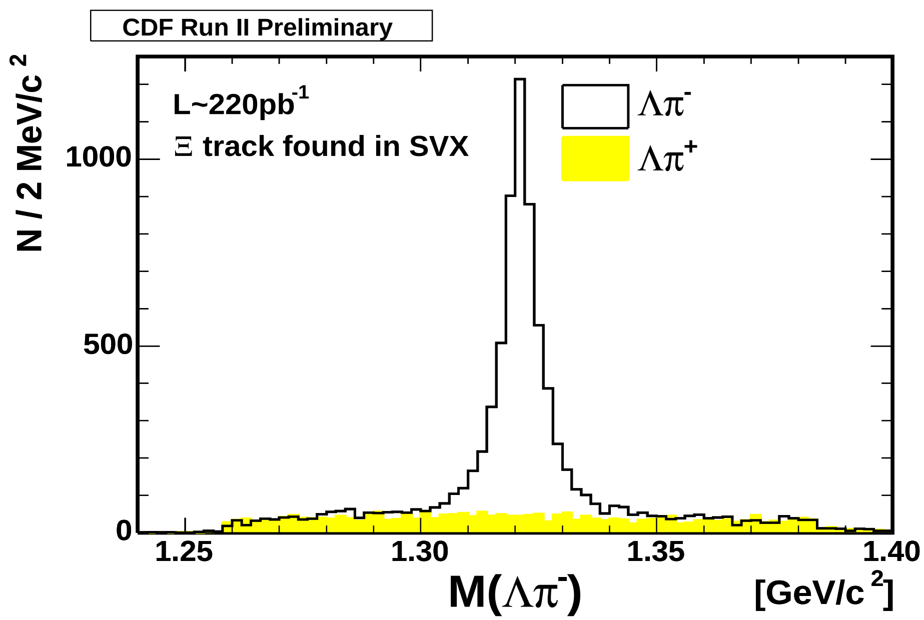
STATISTICAL SIGNIFICANCE VARIES FROM ~4σ to ~8σ

Hadrons: Ξ–hyperon track sample at CDF

• CDF developed tracking of long lived hyperons (Ξ and Ω) in the SVX detector



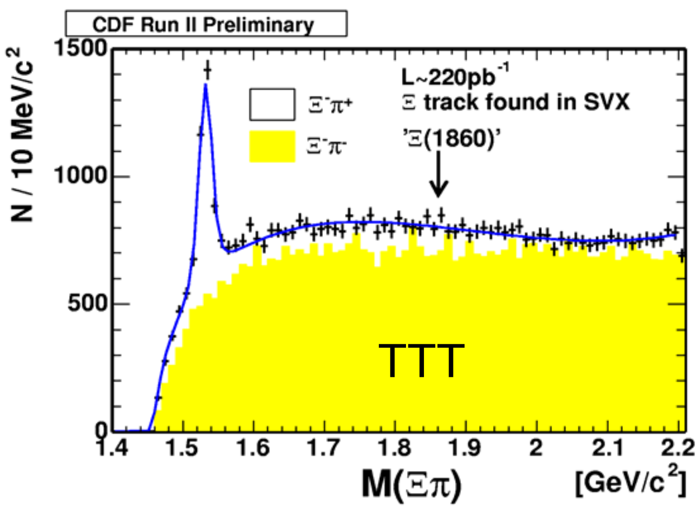
Two Track Trigger

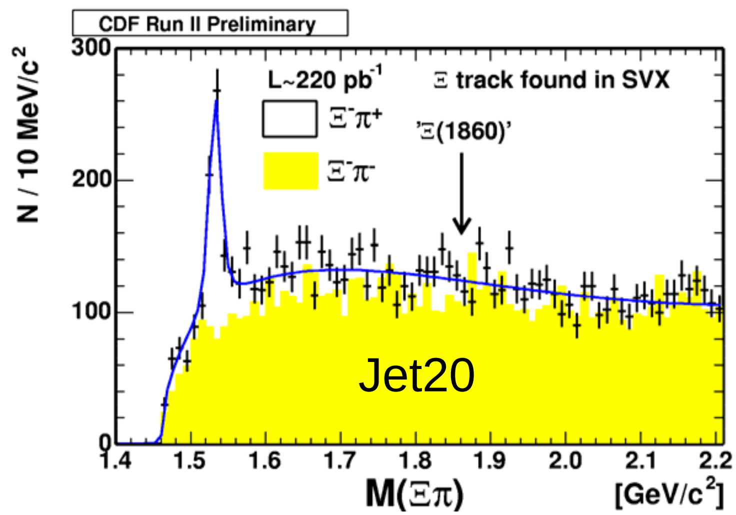


Jet 20 Trigger

Two Track Trigger: N_{TTT} ~ 18 times larger than NA49 data
Jet20 Trigger: N_{Jet20} ~ 2 times larger than NA49 data

Hadrons: Ξ^{--} (1860) is not found at CDF





Channel (TTT)	# of events	$R(\Xi_{1860}/\Xi_{1530})$ U. L. 95% C.L.	$R(\Xi_{1860}/\Xi_{1530})$ NA49
$\Xi^-\pi^+$	57+/-51	<0.07	~0.21
$\Xi^-\pi^-$	-54+/-47	<0.04	~0.24
$\Xi^-\pi^{+/-}$	47+/-70	<0.08	~0.45

Hadrons: Pentaquark Searches

CDF Collaboration have searched for Θ^+, Θ_c^0, $\Xi_{3/2}$

No evidence for these states have been found

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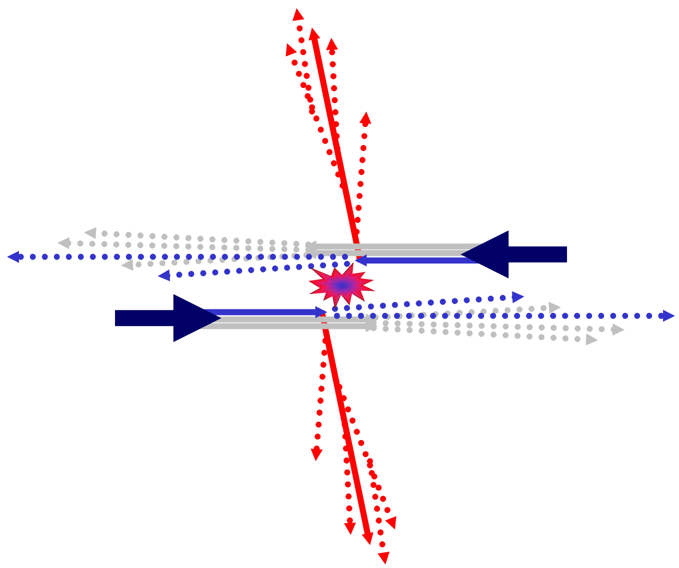
Underlying Event: introductory remarks

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…

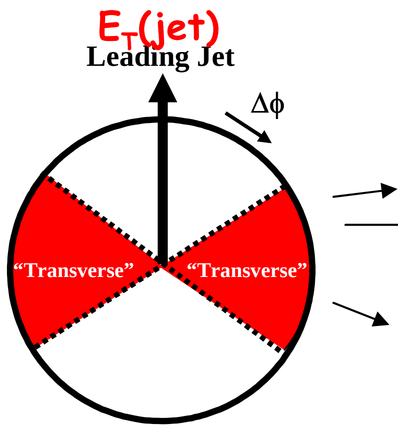
Underlying Event (UE) ≈ (whole event) – (hard part), i.e.:

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



- **UE Physics is poorly understood:**
  - → MC Generators implement UE differently (many parameters)
  - → even when tuned to current data, MC predictions for LHC vary wildly (factor of 3)
  - → UE event pollutes many analyses (source of systematic errors)

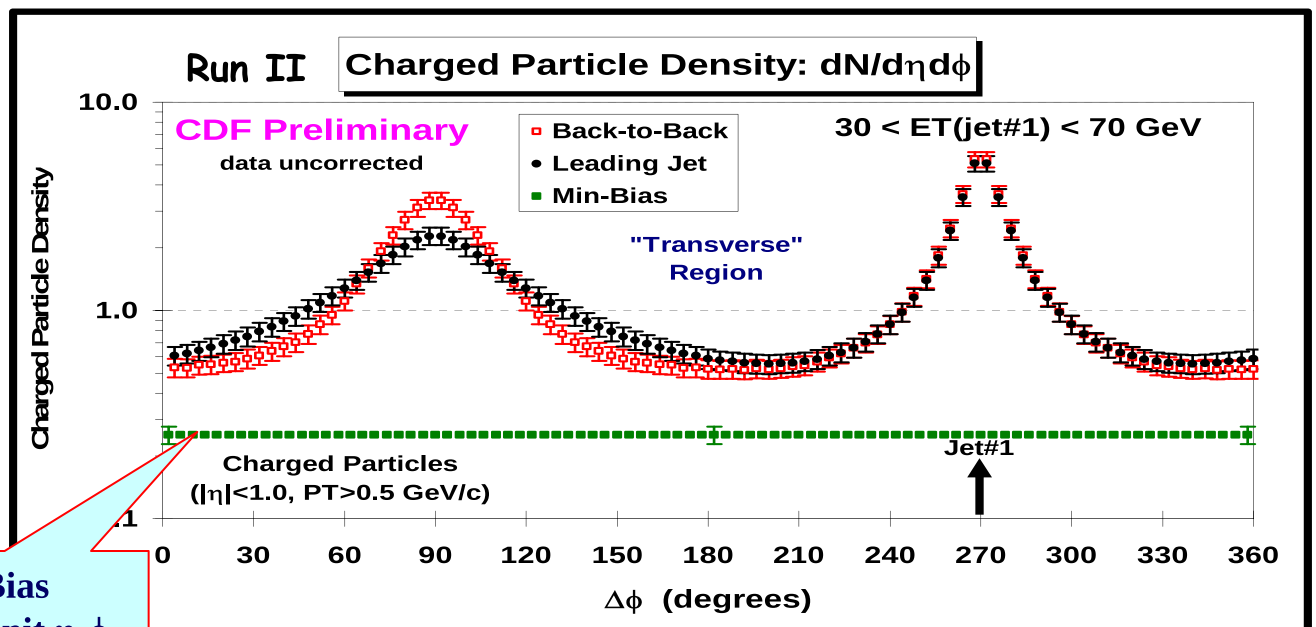
Underlying Event: studies with charged tracks



"transverse" particles as a probe of the underlying event

Charged tracks:

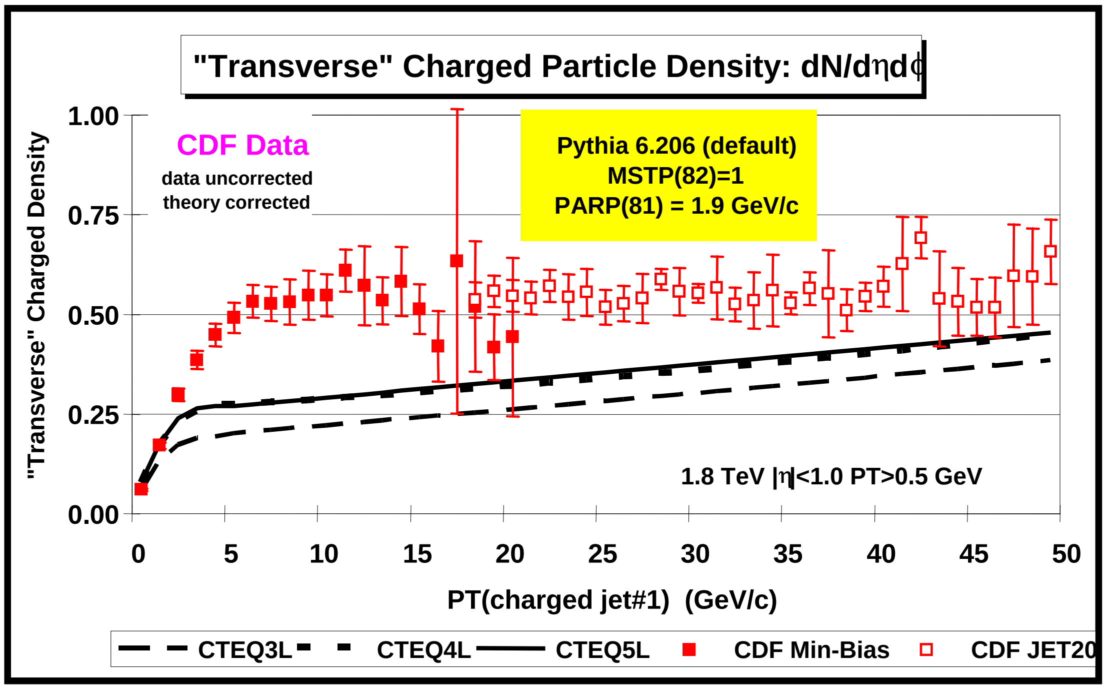
- $d^2N/d\phi d\eta$
- $d^3N/d\phi d\eta dP_T$
- $d^2E_T/d\phi d\eta$

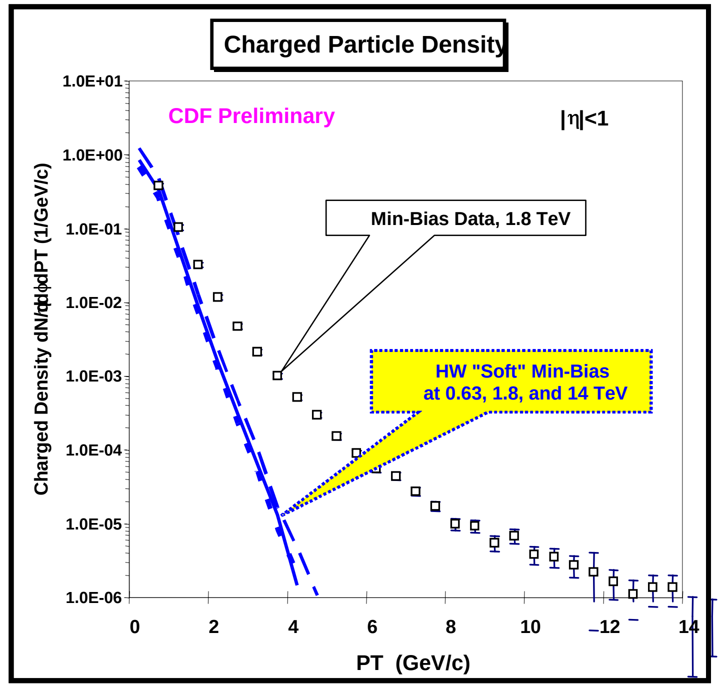


Underlying Event: default Pythia and Herwig

Default Pythia and Herwig fail to reproduce data one way or another, e.g.:

- Pythia 6.206 underestimates number of tracks in transverse direction…
- Herwig 6.4 gives too soft spectrum for particles in transverse direction, especially in events with small E_T jets (missing MPI now have been added)



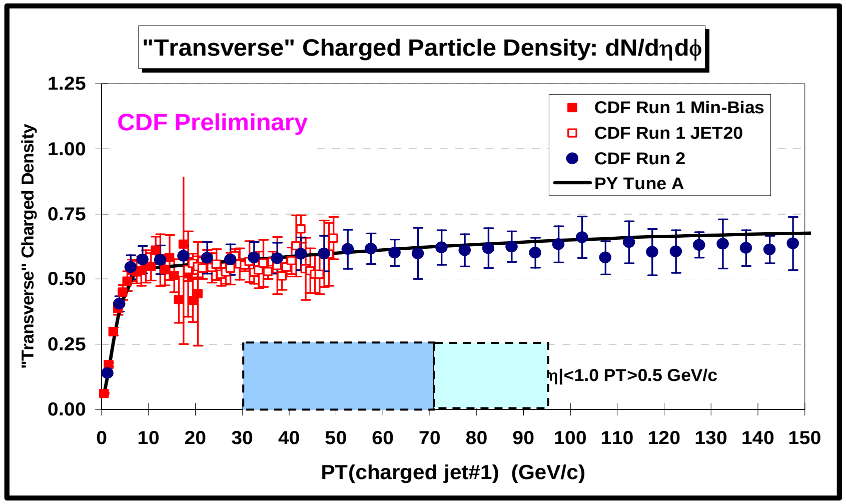


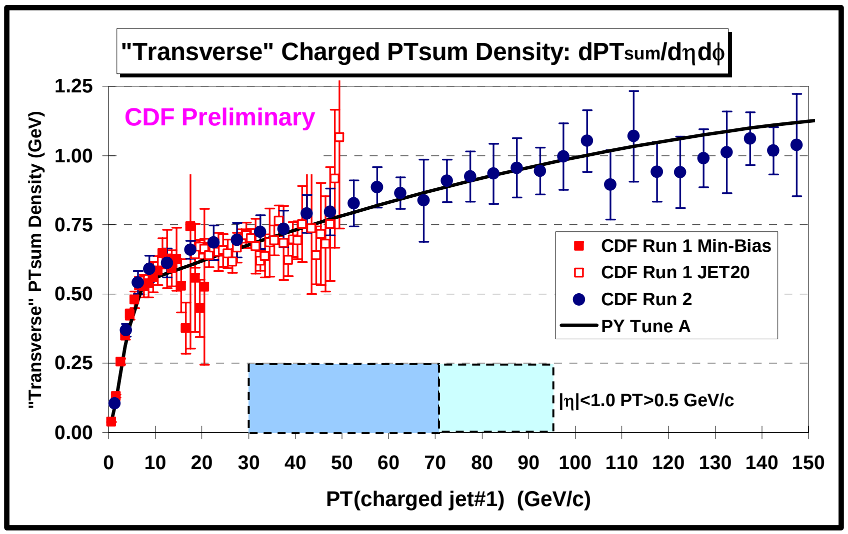
UE: tune Pythia to match CDF data

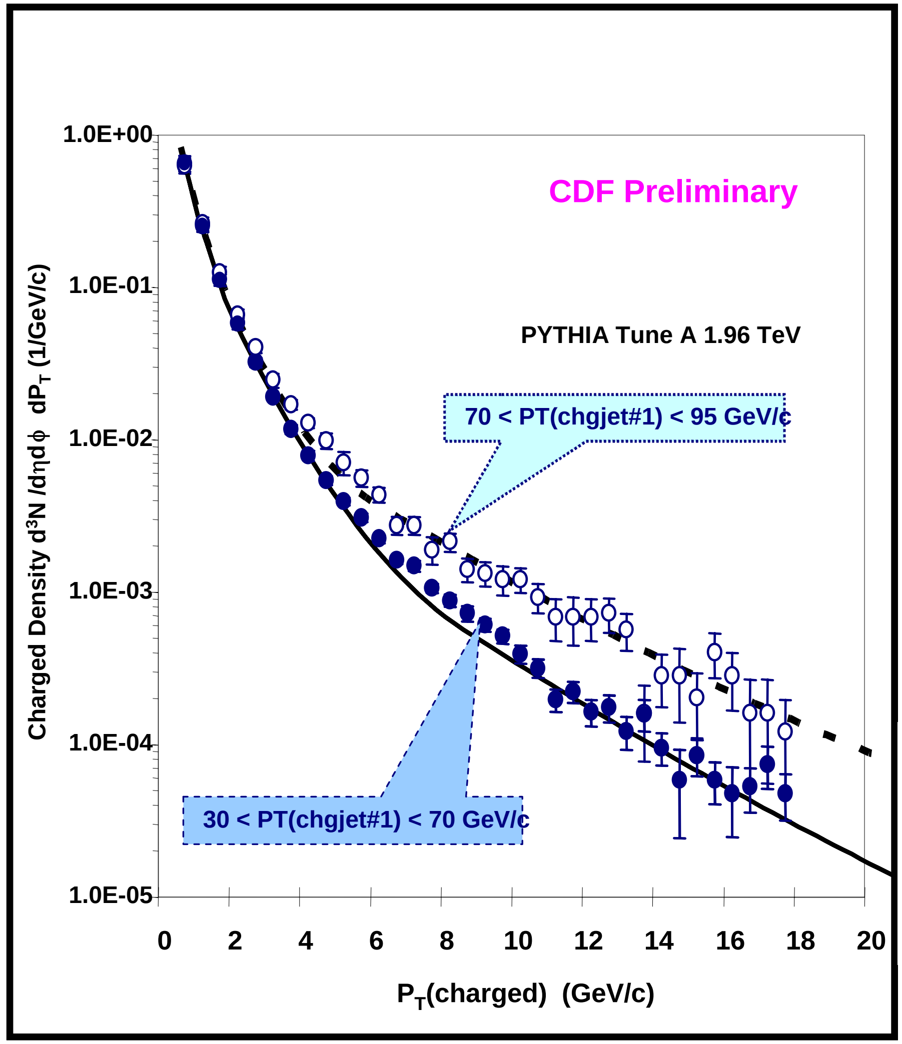
Pythia: CDF Tune A vs. Default 6.206

- **Enhanced Initial State Radiation (ISR)**
- **Smoothed out probability of Multi-Parton Interactions (MPI) vs. impact**
- **MPIs are more likely to produce gluons than quark-antiquark pairs and MPI gluons are more likely to have color connection to p-pbar remnants**
- **…**

UE: Pythia Tune A at work







Summary

High P_T QCD

- all checks within systematic errors
- we must beat systematic errors down to move towards precision QCD measurements

Low P_T QCD

- interesting developments despite all the challenges for applying pQCD in this domain

Progmatic

- new physics is likely to be born in a QCD process
- QCD is likely to be the nastiest background for the Signal
- we'd better tame this beast...