



# Soft QCD Phenomena in High- $E_T$ Jet Events at Tevatron

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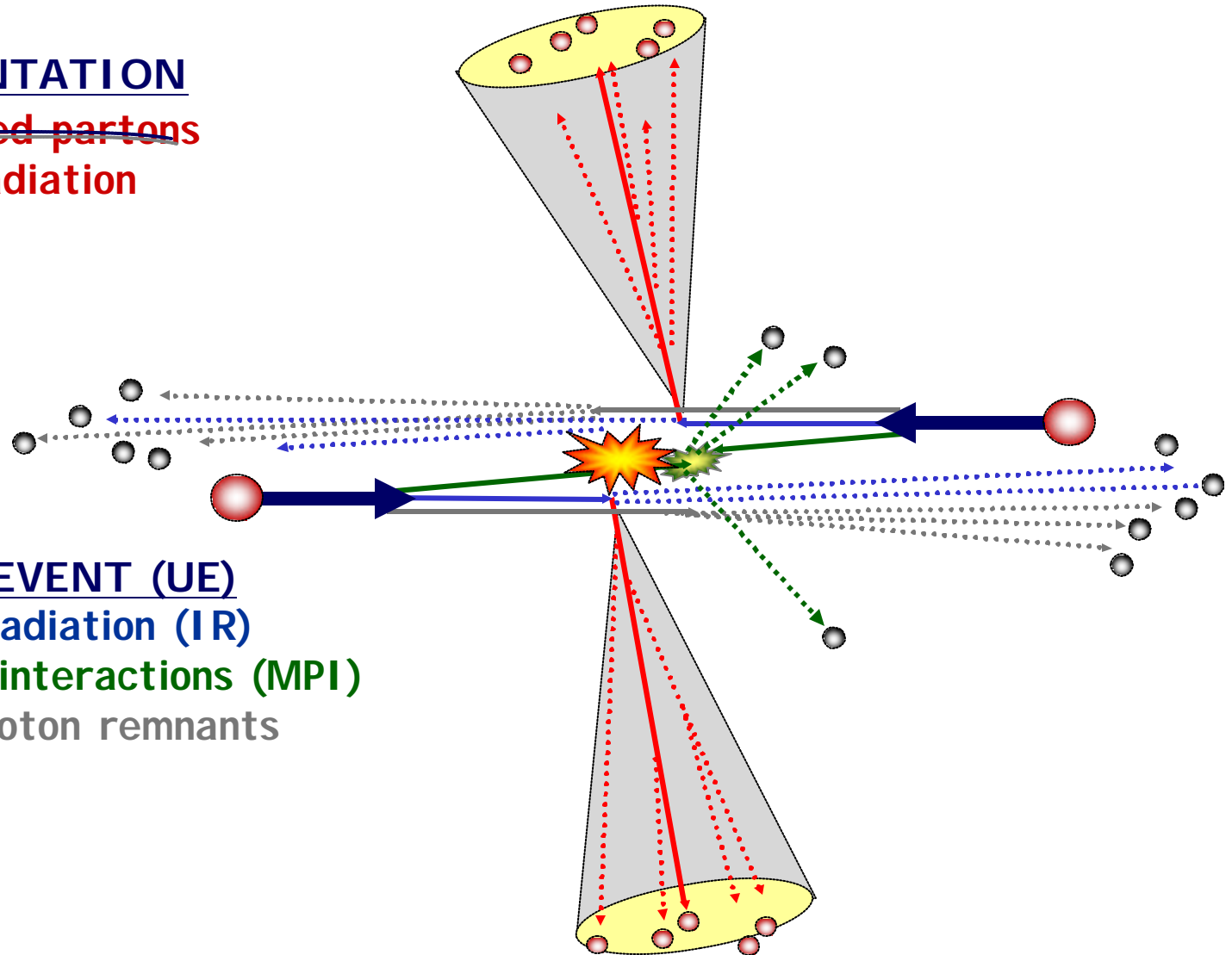
for CDF Collaboration



# Soft QCD Phenomena in High- $E_T$ Jet Events at Tevatron

## JET FRAGMENTATION

- ◆ ~~hard scattered partons~~
- ◆ final state radiation
- ◆ hadronization



## UNDERLYING EVENT (UE)

- ◆ initial state radiation (IR)
- ◆ multi-parton interactions (MPI)
- ◆ proton/antiproton remnants
- ◆ hadronization

☞ ALL ENTANGLED WITH COLOR CONNECTIONS (!)



# Jet Fragmentation

## Jet Fragmentation

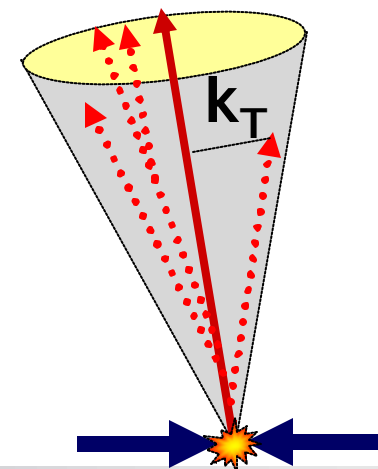
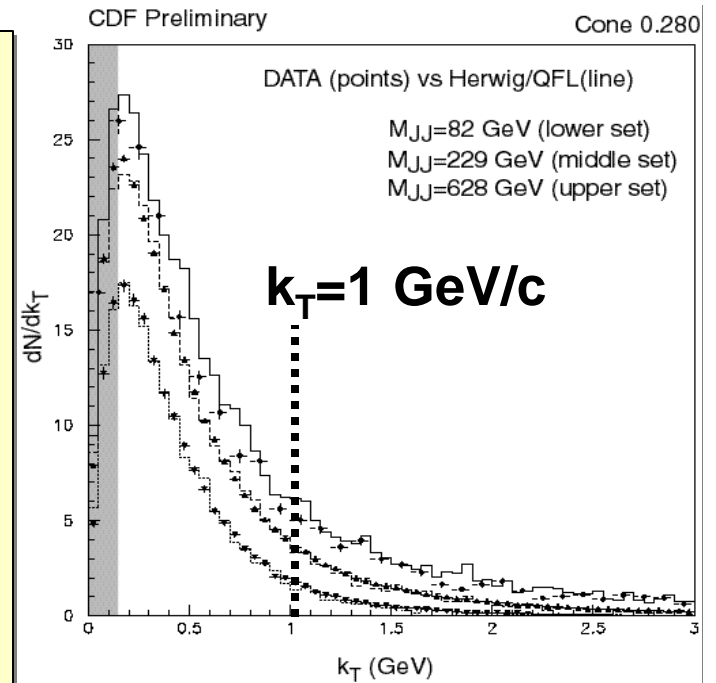
- Driven by soft QCD ( $k_T \ll 1$  GeV) 

## Why bother?

- Good stuff:**
  - ~ Lots of phenomena
  - ~ Theoretical challenge (pQCD at  $k_T \sim \Lambda_{\text{QCD}}$ )
  - ~ Hadronization stage remains a mystery
- Many high- $E_T$  physics analyses depend on good understanding of jet properties**

## Tools available

- Re-summed pQCD approximations**
  - ~ analytic, but only for a few observables
- Monte Carlo generators**
  - ~ generic, but many tuning knobs





# Underlying Event

## Underlying event processes

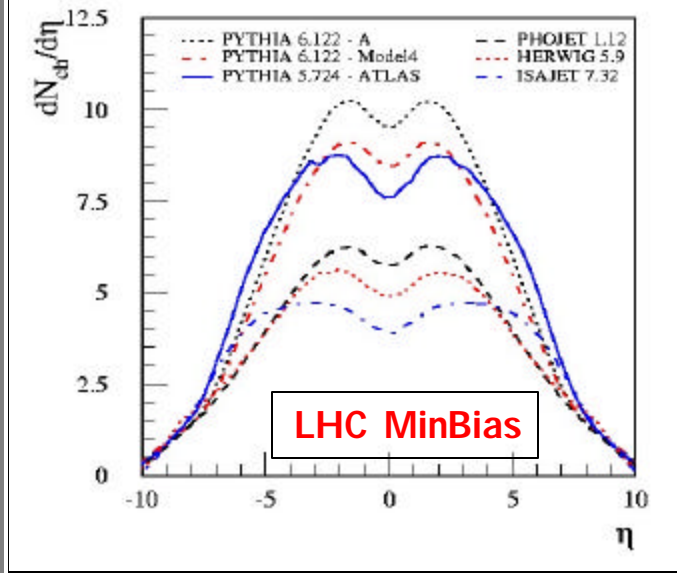
- IR, MPI, pp remnants, hadronization
- all are very soft

## Why bother?

- **Physics is poorly understood:**
  - ~ Implementations in MC's are very different
  - ~ Default predictions for LHC vary wildly
- **UE pollutes many analyses and is source of systematic errors**

## Tools available

- **any analytic predictions?**
  - ~ hardly any... (color flow away from jets)
- **Monte Carlo generators**
  - ~ generic, but many (too many?) tuning knobs



## LHC:

- 25 events per bunch crossing
- Jet cone pollution (R=0.7):
  - 15 GeV
  - 10 charged particles

Different MC's disagree by more than a factor of 2



# Results presented in this talk

## Jets Fragmentation « NLLA

- ◆ Momentum distribution of charged particles in jets
- ◆ Multiplicities of charged particles in g- and q-jets

## Underlying Event « MC

- ◆ Energy flow in transverse direction away from a jet
- ◆ Charged particle multiplicity flow away from a jet
- ◆ Momenta of away-from-jet charged particles



# Jet fragmentation: doing it analytically

- ◆ **Parton shower development: NLL**

- ↪ Modified Leading Log Approximation

- with one  $k_T$ -cutoff parameter:  $k_T > Q_{\text{cutoff}} = L_{\text{QCD}} (=Q_{\text{eff}})$

- ↪ Various next-to-NLL extensions

- ◆ **Hadronization: LPHD**

- ↪ Hypothesis of Local Parton Hadron Duality

- with one parameter  $K_{\text{LPHD}} = N_{\text{hadrons}}/N_{\text{partons}}$

- ◆ **MLLA+LPHD**

- ↪ cannot describe all details...

- ↪ but all analytical...

- ↪ and works surprisingly well...



# Jets: particle momentum spectra

## Momenta of charged particles in jets (MLLA+LPHD, next-to-NLL normalization corrections)

### Measurement

- ◆ central dijet events with  $M_{jj} \sim 80\text{-}600$  GeV
- ◆ di-jet center of mass frame:  $E_{jet} = \frac{1}{2}M_{jj}$
- ◆ charged particles in cones with opening angle  $q$  from  $\sim 0.3$  to  $\sim 0.5$  rad
- ◆ energy scale  $Q = 2E_{jet}\tan(q/2) \gg E_{jet}q$

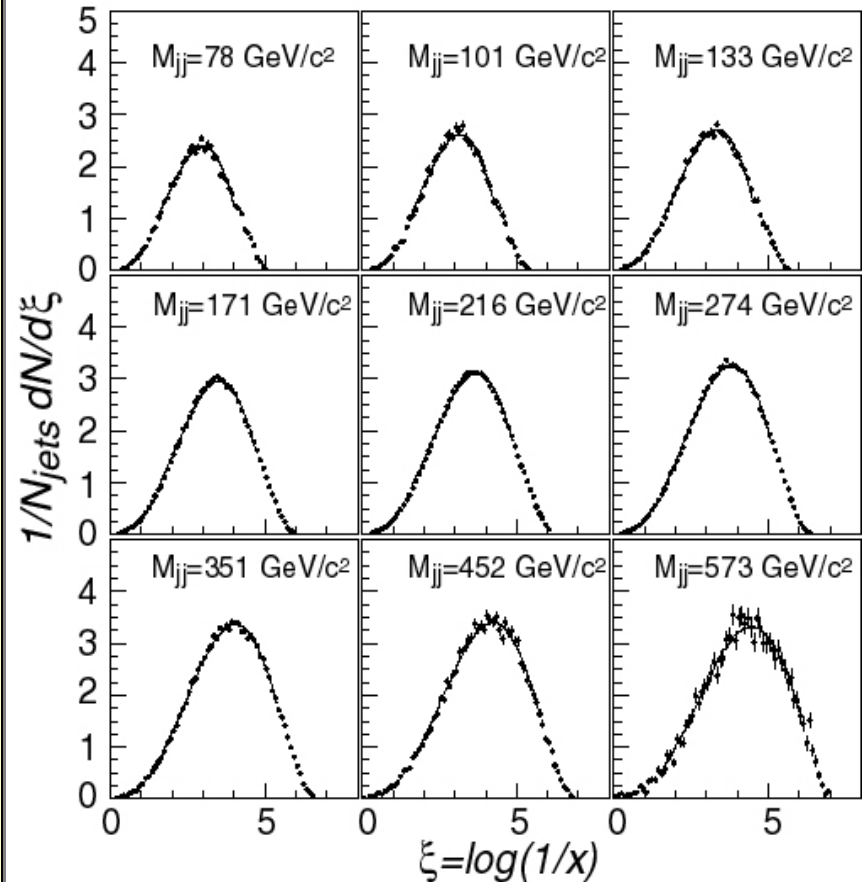
### Results

Phys. Rev. D 68, 012003 (2003)

- ◆  $Q_{eff} = 240 \pm 40$  MeV  
k<sub>T</sub>-cutoff can be set as low as  $L_{QCD}$
- ◆  $K_{LPHD(\pm)} = 0.56 \pm 0.10$   
number of hadrons  $\gg$  number of partons

CDF

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

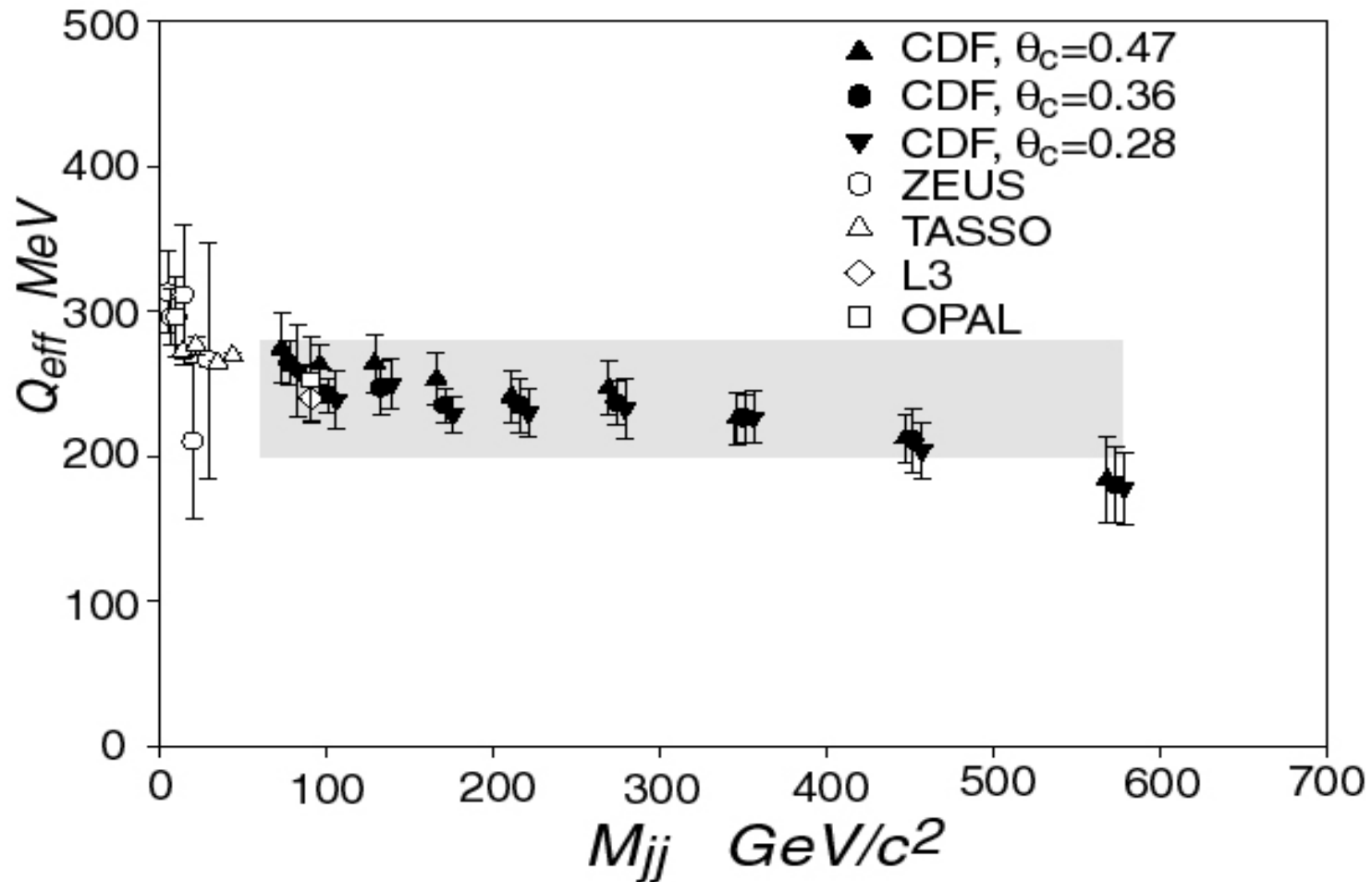


$$x = \frac{P_{particle}}{E_{jet}}$$



# $Q_{\text{eff}}$ at CDF vs Other Experiments

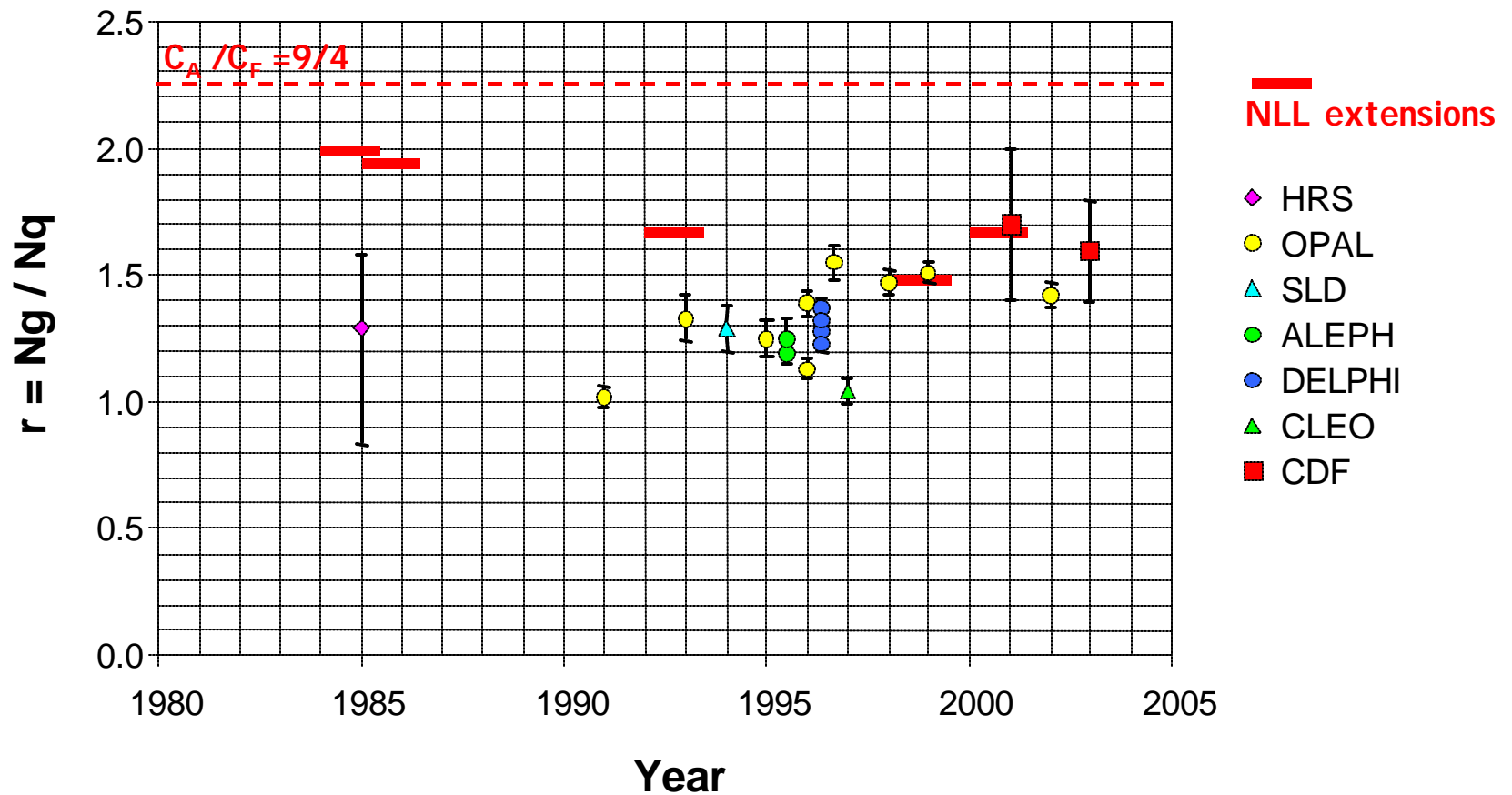
$Q_{\text{eff}}$  for all 9  $M_{jj}$ 's and  
3 opening angles  $q_{\text{cone}}$ 's





# Jets: multiplicities in quark & gluon jets

$$\text{Ratio } r = N_{\text{ch}}(\text{gluon jet}) / N_{\text{ch}}(\text{quark jet})$$





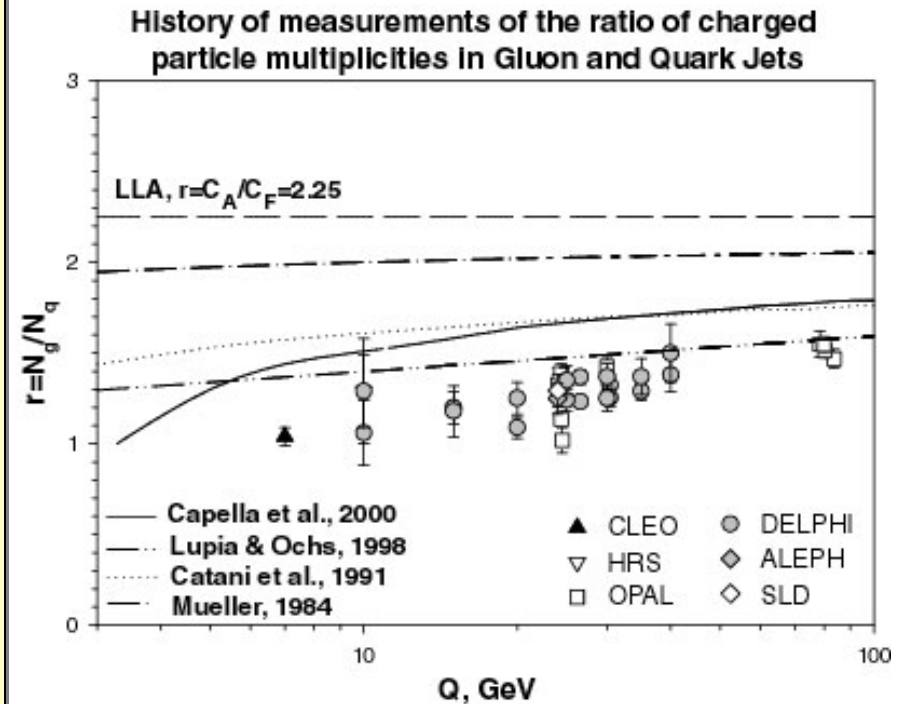
# Jets: multiplicities in quark & gluon jets

## Theory:

- ◆ Next-Leading-Log extensions
- ◆  $r = N_{ch}(\text{gluon jet}) / N_{ch}(\text{quark jet})$   
= 1.5-1.8 (Q=20-100 GeV)

## $e^+e^-$ Data:

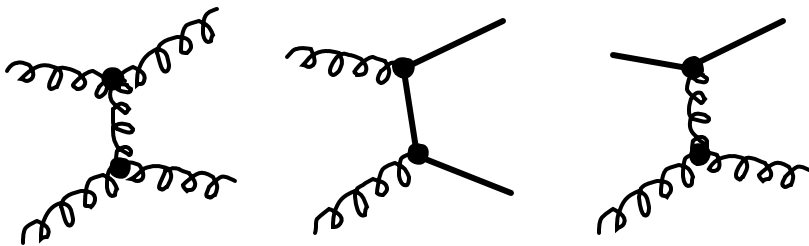
- ◆ 15+ papers (mostly last 10 yrs)
- ◆ Results range from 1.0 to 1.6
- ◆ Diversity of results:
  - ~ biases due to using events of different topologies (qqg and qq)
  - ~ energy scale confusion
  - ~ “catch-22” analyses
  - ~ model-dependent analyses
  - ~ recent unbiased/model-independent



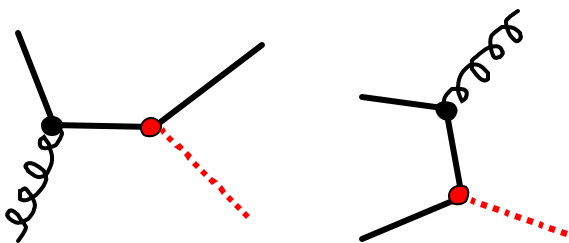


# Gluon vs Quark jets at Tevatron

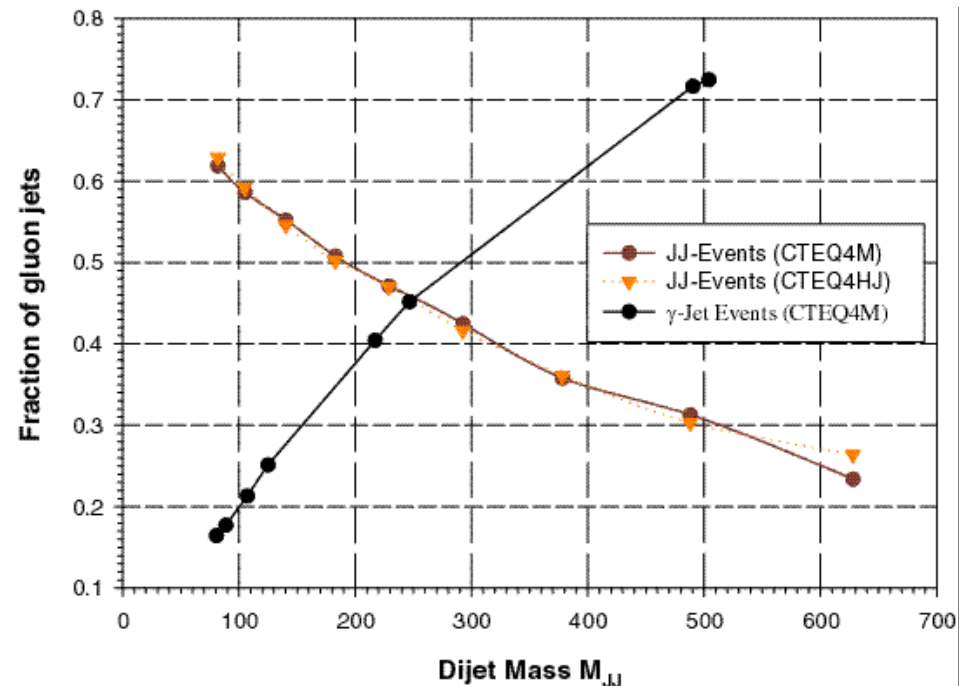
- ◆ Dijet and g-jet events with  $M_{jj}$  and  $M_{gj} \sim 80-100$  GeV
  - ↪ tracks are not used in jet reconstruction
- ◆ di-jet events ( $\sim 60\%$  gluon jets) and g-jet events ( $\sim 80\%$  quark jets)
  - ↪ very stable for the energies used
- ◆ di-jet or g-jet center of mass frame:  $E_{jet} = \frac{1}{2}M_{jj}$  or  $\frac{1}{2}M_{gj}$
- ◆  $N_{ch}$  multiplicity in cones with opening angle  $q$  from  $\sim 0.3$  to  $\sim 0.5$  rad
- ◆ Energy scale  $Q = 2E_{jet}\tan(q/2) \gg E_{jet}q$



Leading diagrams for dijet events



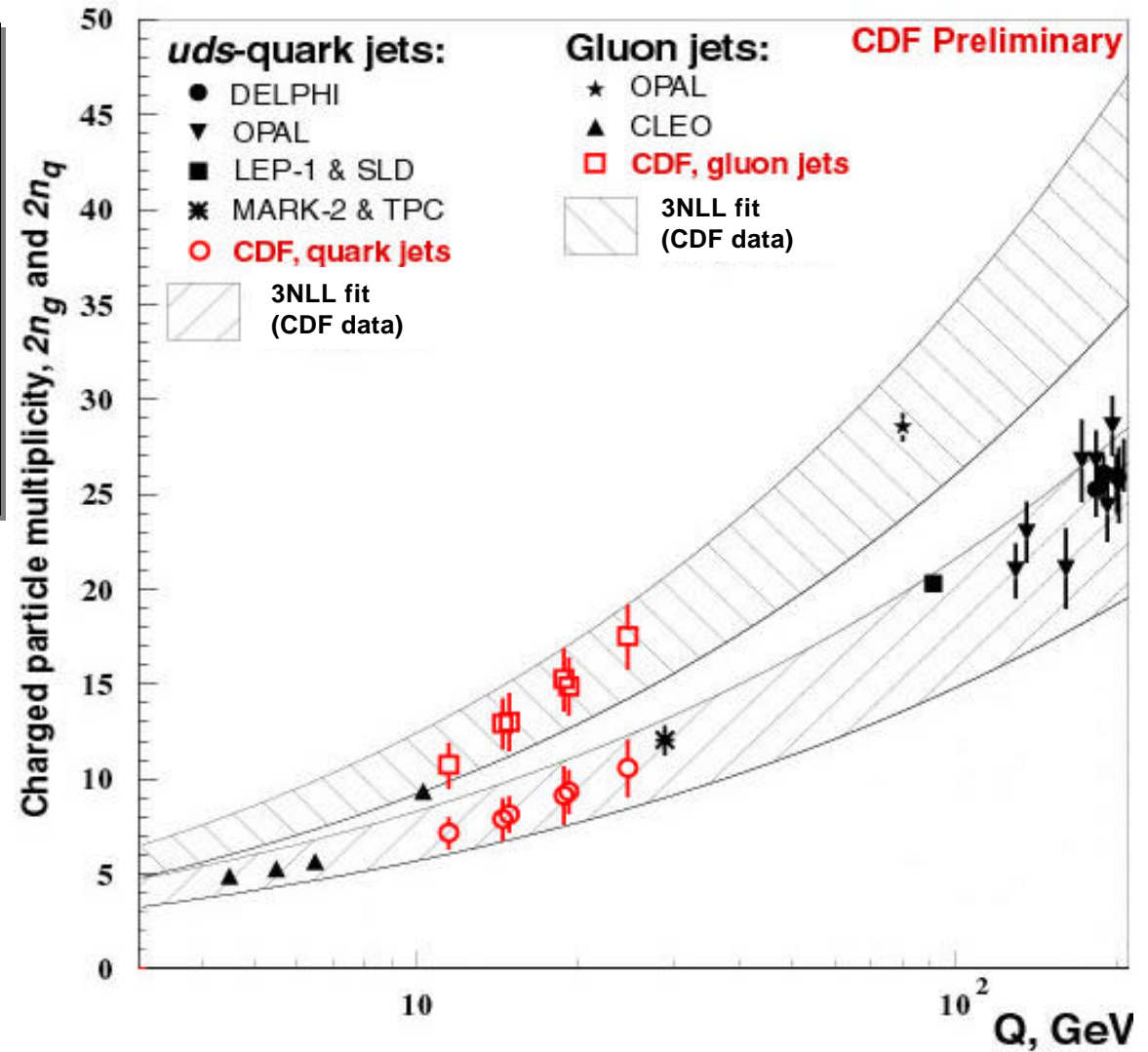
Leading diagrams for g-jet events





# $N_{ch}$ multiplicities in gluon and quark jets

- Tevatron and  $e^+e^-$  data (except for CLEO) agree
- Tevatron and  $e^+e^-$  data (except for CLEO) follow 3NLL trends

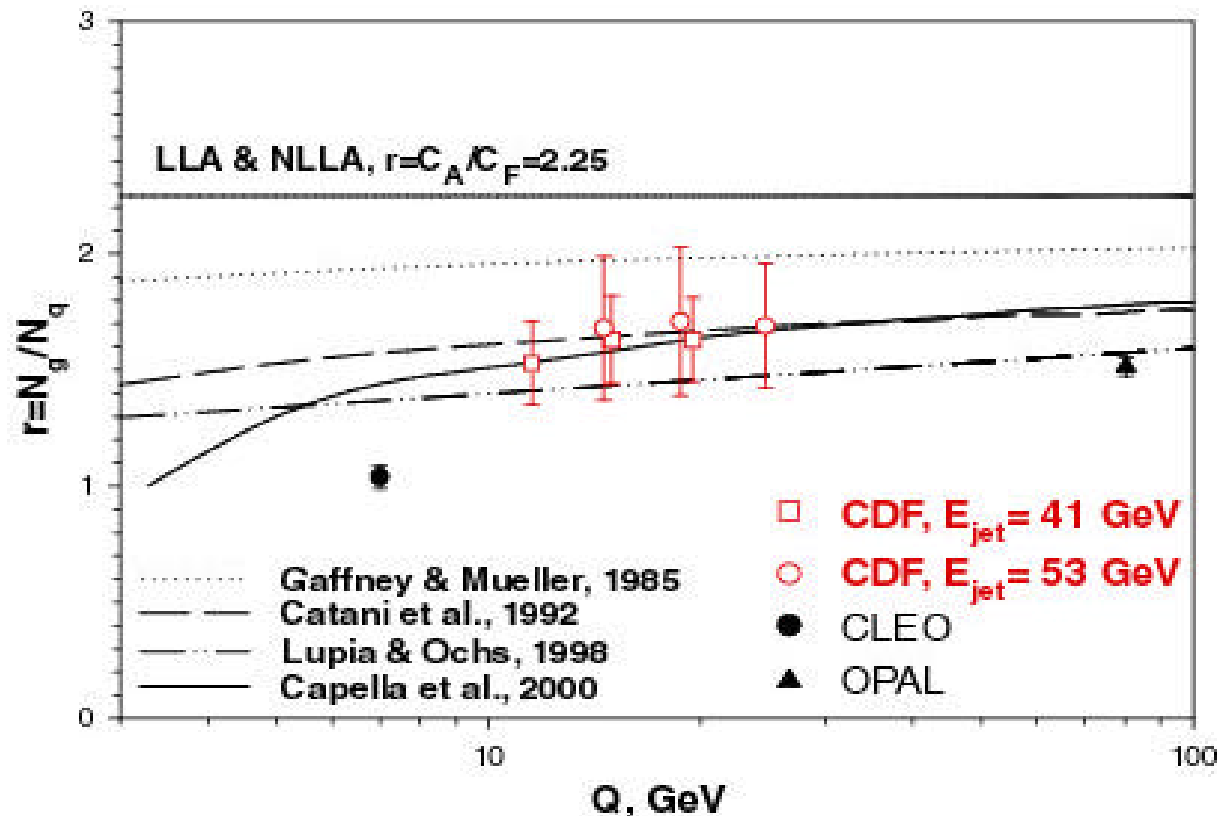




# $N_{ch}$ multiplicities in gluon and quark jets

- ◆ Tevatron: Ratio  $r=1.6\pm 0.2$  for typical  $Q\gg 20$  GeV
- ◆ Tevatron and recent OPAL “unbiased” data ( $r=1.51\pm 0.04$  at  $Q=80$  GeV) agree
- ◆ and follow trends obtained in the recent NLL extensions
- ◆ CLEO “unbiased” results at small  $Q\sim 7$  GeV fall out...

CDF Preliminary





# Underlying Event (UE)

## Event sample:

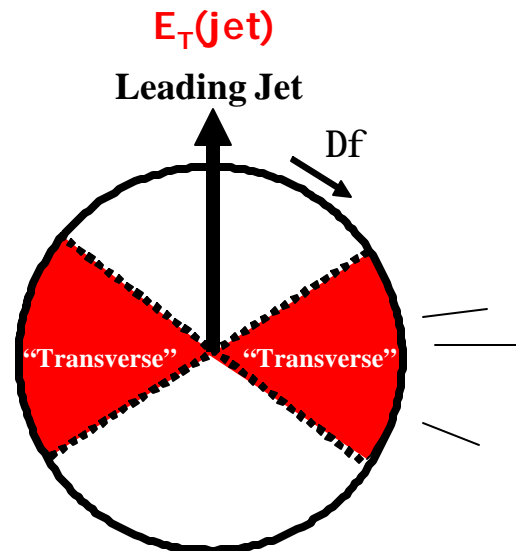
- min-bias
- central jet events

## In direction transverse to the leading jet, we measure:

- $n = dN / dA$  -- average density of charged particles:
- $dn / dp_T$  --  $p_T$  spectrum of charged particles:
- $dP_T^{\text{sum}} / dA$  -- average density of energy flow (summed over charged particles)
- -- compare sides with maximum and minimum activities

## Confront Monte Carlo with Data:

- identify relevant importance of various Monte Carlo knobs/parameters



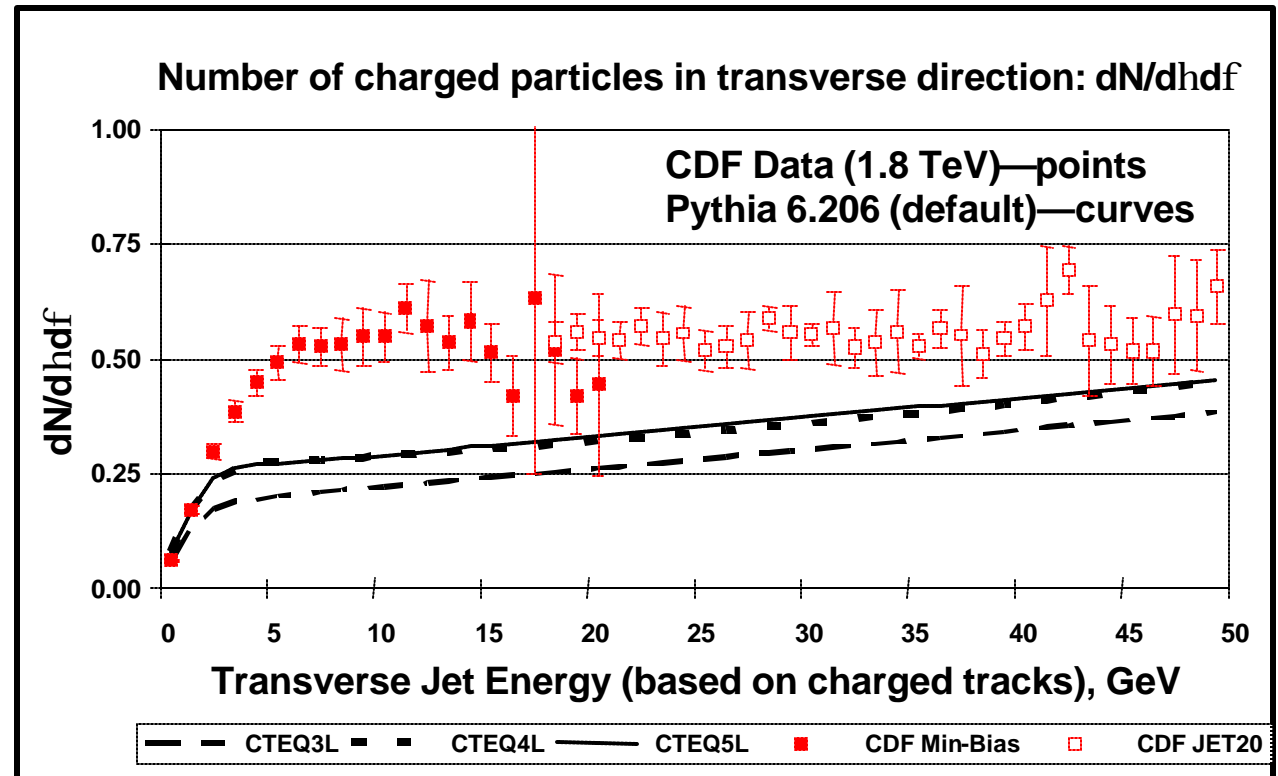
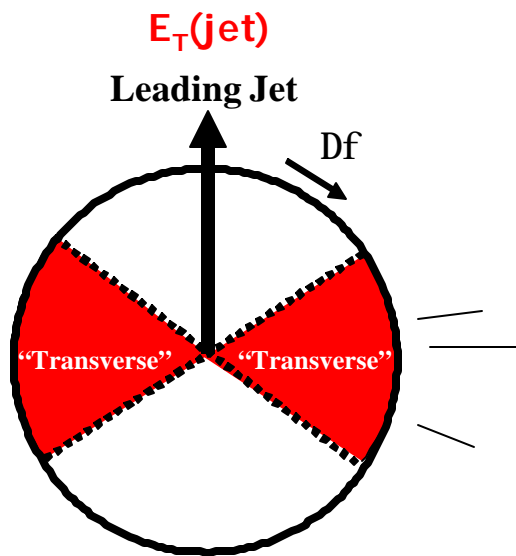
"transverse" charged particles  
as a probe of the underlying event

$$dA = df dh$$



# UE: Default Pythia 6.206 fails to reproduce data

- ✗ Number of charged tracks in transverse direction is underestimated
- ✓  $P_T$  distribution of charged tracks in transverse direction is OK
- ✗ Average energy flow in transverse direction is no good

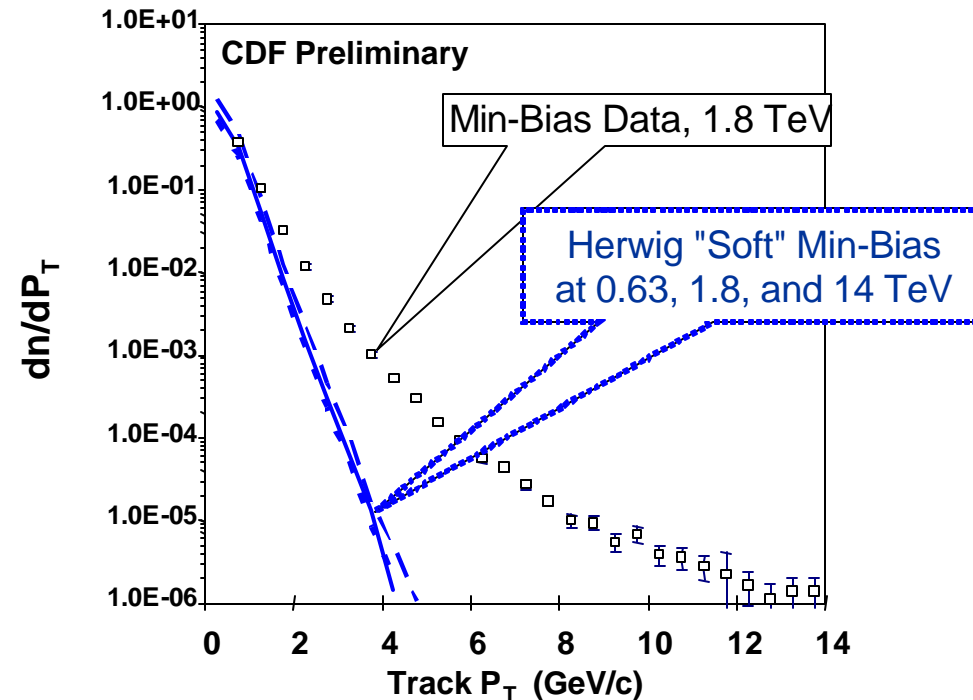
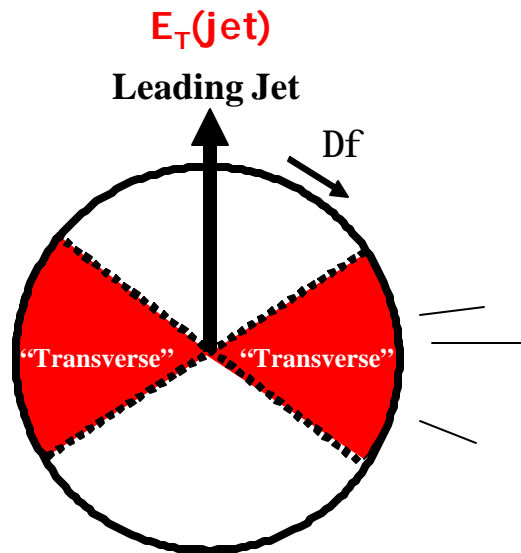




# UE: Default Herwig 6.4 fails to reproduce data

- ✓ Number of charged tracks in transverse direction is OK
- ✗ No (or too soft) tail in the spectrum for particles in transverse direction in minbias events and events with small  $E_T$  jets
  - missing multi-parton interaction being added...
- ✓ Average energy flow in transverse direction is more or less OK

Spectrum of charged particle momenta in transverse direction





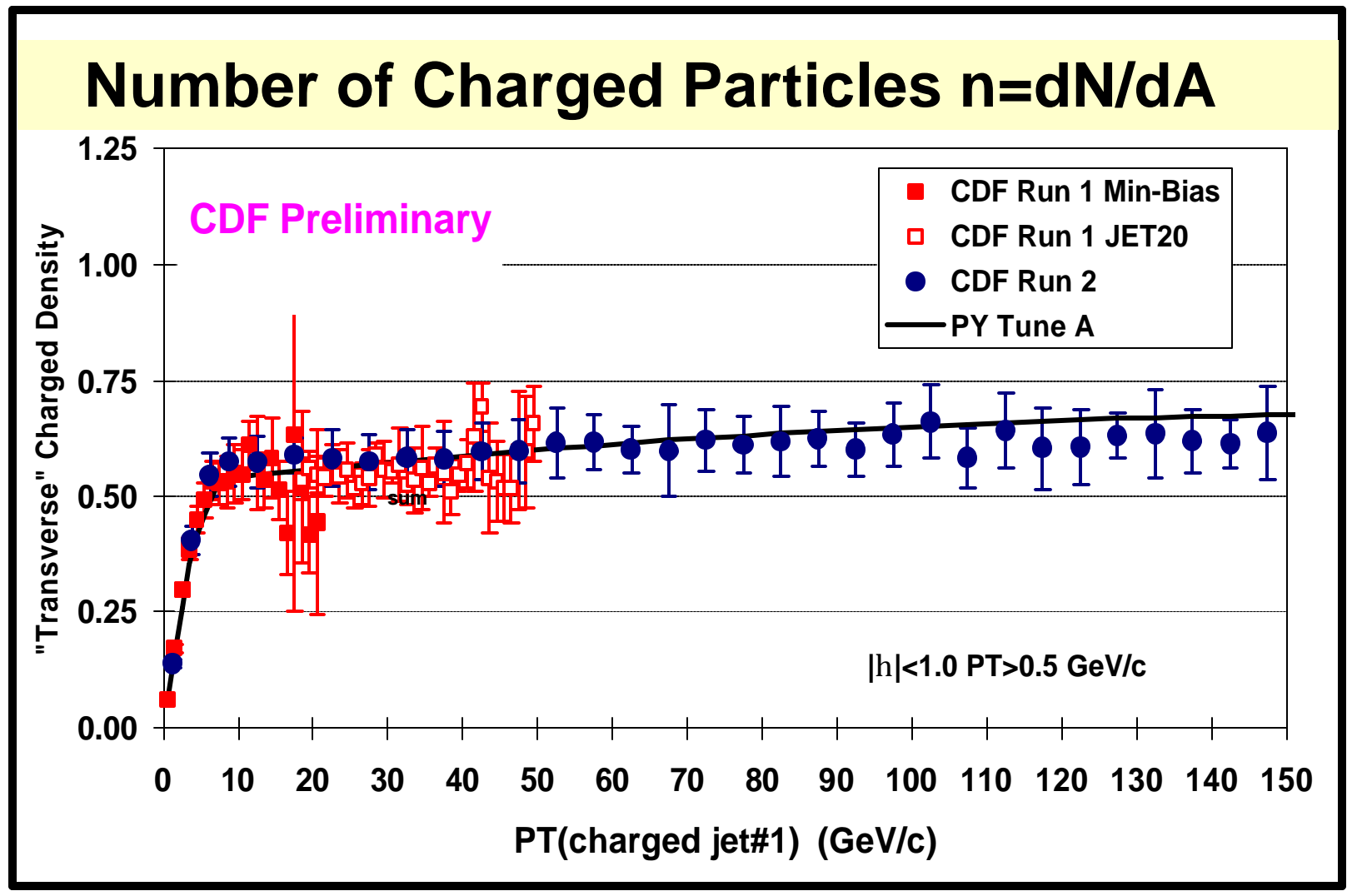
# UE: Tune Pythia to match CDF data

## CDF Tune A vs. Pythia 6.206 default parameters

- ◆ **Enhance initial state radiation**  
~ from  $\text{PARP}(67) = 1$  to 4
- ◆ **Smooth out probability of Multi-Parton Interactions vs. impact parameter**  
~ from solid opaque disk to 50-50 double-Gaussian distribution ( $r=0.4R$ )
- ◆ **Make more di-gluons than q-qbar pairs in Multi-Parton Interactions**  
~ from 66% to 95%
- ◆ **Enhance color connection probability for MPI gluons and p-pbar remnants**  
~ from 33% to 90%
- ◆ **Reduce Multi-Parton Interaction dependence on CM Energy**  
~ to better connect Tevatron and lower energy data  
~ this approximately halves the LHC underlying event activity...

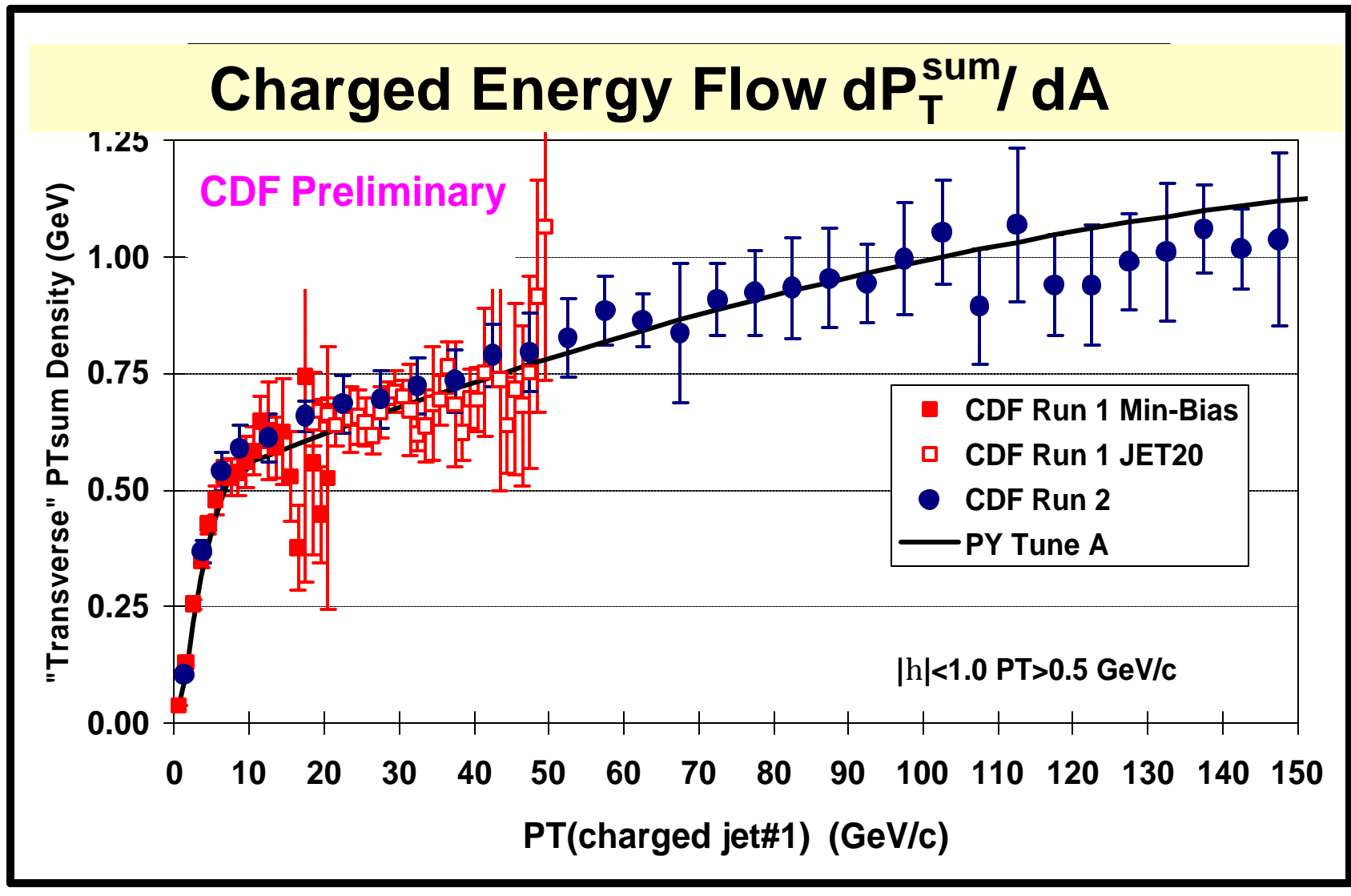


# UE: Pythia Tune A describes Data



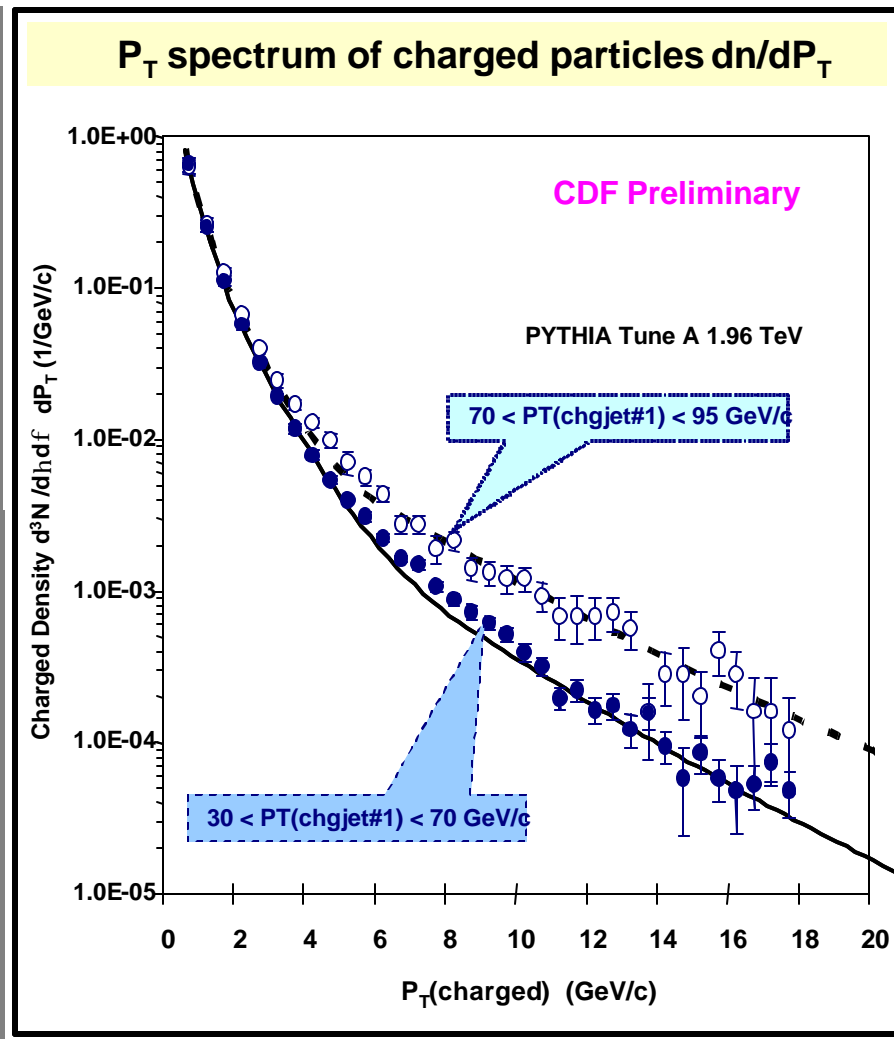
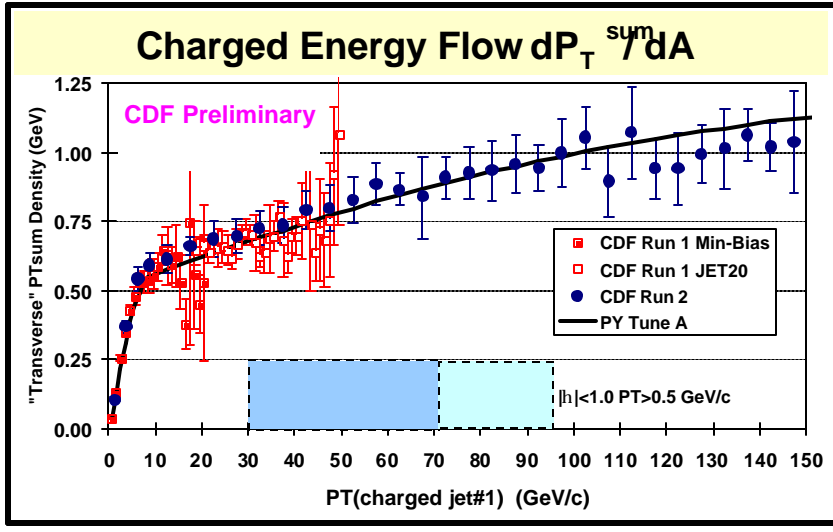
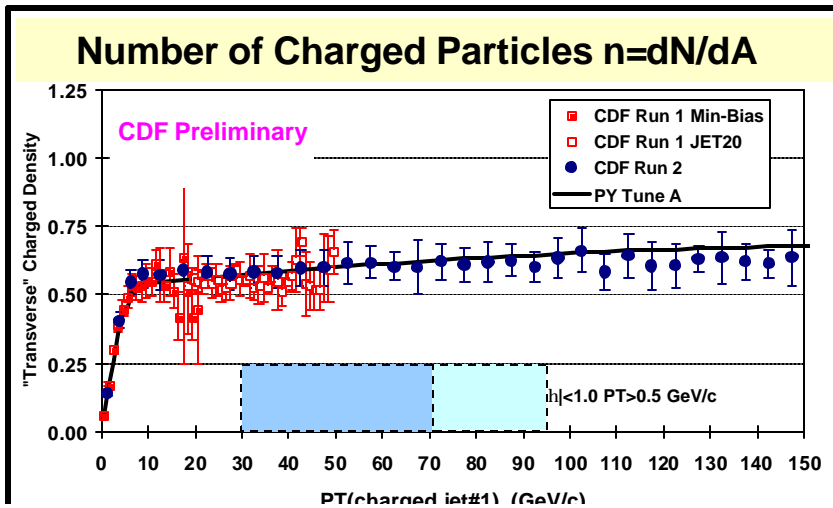


# UE: Pythia Tune A describes Data





# UE: Pythia Tune A describes Data





# Summary (Soft QCD in High- $E_T$ Jet Events...)

## Jet fragmentation

- ◆ **Momenta of charged particles in jets are well described by NLLA pQCD:**
  - ↪ MLLA  $k_T$ -cutoff  $Q_{\text{eff}} = 240 \pm 40$  MeV  
 *$k_T$ -cutoff can be set as low as  $\sim L_{\text{QCD}}$*
  - ↪ LPHD  $N_{\text{hadrons}}/N_{\text{partons}} = K_{\text{KLPHD}(\pm)} = 0.56 \pm 0.10$   
*number of hadrons  $\sim$  number of partons*
- ◆ **Ratio of charged particle multiplicities in gluon/quark jets  $r = 1.6 \pm 0.2$** 
  - ↪ multiplicities and their ratio agree with next-to-NLLA and recent LEP data

## Underlying event

- ◆ **MC generators with default parameters do not quite work, but can be tuned to match data...**
  - ↪ Pythia tuned for Run I continues to work in Run II for broader range...
  - ↪ Did we gain any insights into UE physics?
    - Need to compare Pythia Tune A and Herwig Tune "X" (work in progress)