Niccolo’ Moggi
INFN Bologna
On behalf of
CDF and D0 Collaborations

Soft QCD studies at the Tevatron

Les Rencontres de Physique de la Vallee d’Aoste
La Thuile - 03/03/2009
“Soft” interactions are the largest – but most unknown – part of the inelastic Xs at colliders

Understand the whole “event” (not just the pQCD part)

Provide data to tune MC models of MB (in general) and of UE (specifically)

MB is a cocktail of hard (pQCD) and soft processes:

- No MC generator can reproduce all MB observables at the same time

MB is important (“pile-up”) in high luminosity environments

UE is a background to most collider high $p_T$ observables
Terminology

pp Event

Inelastic

Min-Bias (experimental trigger)

Soft --- parton-parton scattering --- Hard ISR+FSR

Underlying Event

Multiple Parton-parton Interactions

Beam-Beam Remnants

Elastic

Pile-Up (another of the above)
“Minimum Bias” is defined by its trigger!

- CDF triggers MB with forward particles in $3.7 < |\eta| < 4.7$ (<3deg)
- Requires coincidence of both sides (forw+backw)
- Implemented with Cerenkov counters (CLC)

- The trigger is biased so to favor high $p_T$ interactions
- Will affect also the *shape* of inclusive distributions
- This presentation → only observables in the central region ($|\eta| < 1.0$)
This talk is only about non-diffractive collisions

- 506 pb-1
- Max Inst. \( \mathcal{L} = 90 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1} \)
- Average Inst. \( \mathcal{L} = 20 \times 10^{30} \)
- Select crossings with only 1 primary (pp) vertex.
- Background from undetected primary vertices \( \sim 3\% \) ("PileUp")

Data used for this analysis

Primary vertex Z resolution \( \sim 3\text{cm} \)

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"Soft QCD at the Tevatron"
\frac{d\sigma}{\Delta\phi \Delta\eta \, dE_T} = \frac{N_{ev}}{\text{Lum} \, \Delta\phi \Delta\eta \, dE_T}

- First attempt of really inclusive measure with neutral particles
- Calorimeter response is very sensitive to the MC model
- Large total systematic (~15% + 6%): comparison with MC little significant

Corrected to hadron level
Finite $E_T$ resolution unfolding included

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“Soft QCD at the Tevatron”
Single Particle $p_T$ Spectrum

\[
E \frac{d^3 \sigma}{dp_T^3} = \frac{d^3 \sigma}{p_T \Delta \phi \Delta y \, dp_T} = \frac{N_{ch}}{(\varepsilon \times A)} = \frac{L \, p_T \, \Delta \phi \, \Delta y \, dp_T}{3 \, dp_T}
\]

- Modeling of the distribution:

\[
f = A \left( \frac{p_0}{p_T + p_0} \right)^n + B \left( \frac{1}{p_T} \right)^s
\]

- Fits are good, but merely empirical
- $\chi_s(2 \, \text{TeV}) \sim 1.04 \, \chi_s(1.8 \, \text{TeV})$
- Extends previous measurement (CDF 1988) from 10 to 150 GeV/c

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“Soft QCD at the Tevatron”
Pythia v6.2. MB description relies on a $p_T$ cutoff parameter that regulates both:
- 2-to-2 parton perturbative Xs at low $p_T$
- Additional parton-parton scatterings (MPI)

Data has much more particle production in $p_T > 20$ GeV

TuneA produces no particles at all above ~50 GeV/c

All tracks are assumed to be $\pi$

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“Soft QCD at the Tevatron”
Correlations among charged particle indicate a jet structure in MB as low as ~1 GeV

Very similar to that in back-to-back jet transverse region

Pythia more “jetty” than data
Leading Jet: 2.2 fb-1
- High $p_T$ jet in $|\eta|<2$
- MidPoint, $R=0.7$ $f_{\text{merge}}=0.75$
- Back-to-back Jet (not shown)
- Third jet suppression

Drell Yan: 2.7 fb-1
- $e^\pm, \mu^\pm E_T>20$ GeV, $|\eta|<1$, Iso$>0.4$
- $70<|M_{\text{pair}}|<110$ GeV
- $|\eta_{\text{pair}}|<6$

UE and ISR/FSR particles cannot be resolved experimentally. Use specific event topologies where ISR/FSR effects can be dumped or enhanced.
The transverse regions

Leading Jet:
- **TransMAX** = BBR + ISR/FSR
- **TransMIN** = BBR
- **MAX-MIN** = ISR/FSR

Drell-Yan:
- No FSR!
- Exclude leptons
- Toward = Trans

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Systematic study of many observables to tune and improve QCD MonteCarlo models of the underlying event

- **Observables**
  - Charged particle density
  - PTsum density
  - Average particle PT
  - Max particle PT
  - Others

- **MC generators**
  - Pythia TuneA
    - Fit to CDF UE (Run1)
  - Pythia Tune AW
    - A+Fit to pT(Z)
  - Pythia Tune DW
    - AW+Fit dijet Dphi (D0)
  - Herwig (noMPI)
    - Fit to pT(Z)
  - Herwig+JIM
  - Others

X 3 event topologies!
MAX receives BBR+ISR+FSR
MIN receives BBR and less of ISR+FSR

Herwig no MPI:
- not enough particles
- in DY more disagreement because the lack of MPI is more evident in absence of FSR

Pythia A/AW ~ ok
Toward and TransMIN regions in Drell-Yan events are more sensitive to UE since are less likely to receive contributions from ISR

Pythia DW ~ ok
Herwig no MPI
- too few particles
- too soft
Herwig+JIM
- too many particles
- too soft
Most poorly reproduced by MC. To reproduce this, we need the correct recipe to mix:

- soft and hard collisions + soft and hard components of single collisions
- With only soft and hard 2-to-2 scatterings, large $N_{ch}$ would give too high $<p_T>$
- MPI provide a mechanism to produce larger $N_{ch}$ with $<p_T>$ softer than in the primary parton-parton interaction

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“Soft QCD at the Tevatron”
Same structure as in MB
- Confirmed MPI importance
- Universality of MPI?
Pythia A/AW ~ok but not perfect
Herwig noMPI too hard
Herwig+JIM too soft
Herwig can’t be compared to MB as Xs diverges when $p_T$(hard)$\rightarrow 0$
Pythia v > 6.3 introduces new MPI model with ad hoc color correlations between the hard process and MPI.

Top mass measurement may be sensitive to CR: 
+-0.5 GeV from non-pQCD effects?

Preliminary D0 & CDF estimates with tuneA v6.4 confirm?

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We have provided a set of precision measurements of MB and of UE to tune MC models

All data distributions studied:
- favor models with MPI
- show continuous soft/hard transition

Pythia tunes A/AW ~ Ok for inclusive distributions

No model reproduces correctly the final-state correlations

For LHC: Pythia predicts a more active UE than at the Tevatron, Herwig predicts roughly same activity

Understanding of MB and UE is becoming important for precision high PT measurements
BACKUP SLIDES
CDF Run II Preliminary

- Data Run II
  - fit Run II
  - fit Run 1988 (x 2)

\[ \frac{d^2\sigma}{dp_T^2 d\eta} \text{ [mb/(GeV/c)]} \]

- Data Run II
  - fit Run II
  - fit Run 1988 (x 2)

\[ \eta \leq 1 \]

\[ p_T \geq 0.4 \text{ GeV/c} \]

Total uncertainty
Systematic uncertainty
6% luminosity uncertainty not included
### Pythia tunes

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- A=fits UE
- W=fits Drell-Yan
- D=fits $\Delta \phi$(dijet)
Trans-DIF and Away region

"TransDIF" Charged Particle Density: $dN/d\eta d\phi$

Most sensitive to ISR(+FSR)

Similar in Leading-jet and Drell-Yan events
Drell-Yan extrapolation to LHC

"Toward" Charged Particle Density: $dN/d\eta d\phi$

Data CDF, Pythia 2, 10 and 14 TeV

Pythia 2 and 14 TeV
Herwig 2 and 14 TeV

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“Soft QCD at the Tevatron”
Trigger: acceptance is function of many variables
- # primary detected vertices, Luminosity, # tracks, CLC calibration...
- In short, acceptance increases with the total activity in the *crossing*. Plateau at ~98%
- Measurable with 0-Bias sample

Primary Vertex (after trigger):
- Clustered by the tracking system
- Flat in $|Z_{\text{vertex}}| < 40$ cm, outside affected by tracking inefficiencies
- Depends on #PV, # tracks, Luminosity
This measurement was published by CDF in 2002 (PRD D65 072005)

\[
\langle p_T \rangle (N_{ch}) = \frac{\sum_{ev} \sum_{i}^{N_{ch}} p_T^i}{N_{ev_{ch}}^{N_{ch}} \times N_{ch}}
\]

Correction procedure

1. Tracking efficiency: correct the \( \langle p_T \rangle \) for each reconstructed \( N_{ch} \)
2. Smearing: generate matrix of \( P(N_r,N_g) \)
   Then apply this unfolding factor bin by bin

\[
\langle p_T \rangle_{N_r=m} = \sum_{i}^{n_g} (\langle p_T \rangle_{N_r=i} \times P_{n_r=m}^{n_g=i})
\]

\( \langle p_T \rangle \) at \( N_r \) \( \langle p_T \rangle \) at \( N_g \)

(\( \text{.. works as long as } \langle p_T \rangle \) at \( N_{ch}=\text{gen} \) is the same that at \( N_{ch}=\text{rec} \))
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“Soft QCD at the Tevatron”
Corrections to Sum $E_T$ Xs

- Many step correction:
  - Single tower relative cal response $f(\eta, Z_{\text{vertex}})$
  - Absolute response to $\sum E_T$
  - Acceptance vs $Z_{\text{vertex}}$
  - Pile-Up
  - Undetected low-$p_T$ charged particles
  - Trigger and vertex acceptance
  - Unfolding (spread of events due to finite energy resolution)

$$N_{ev}^{\text{corrected}} = N_{ev}^{\text{raw}} \left( \frac{\sum E_T}{C_{\text{tower-}\eta} C_{\text{absolute}} A_{\text{vertex-Z}}} + C_{\text{low-}p_T} \right) \frac{C_{\text{pile-up}} \times C_{\text{unfolding}}}{A_{\text{trigger and vertex}}}$$

- Cut at $p_T \sim 0.3 \text{ GeV/c}$ at CDF
  - 1 to 2 GeV/c at CMS and Atlas