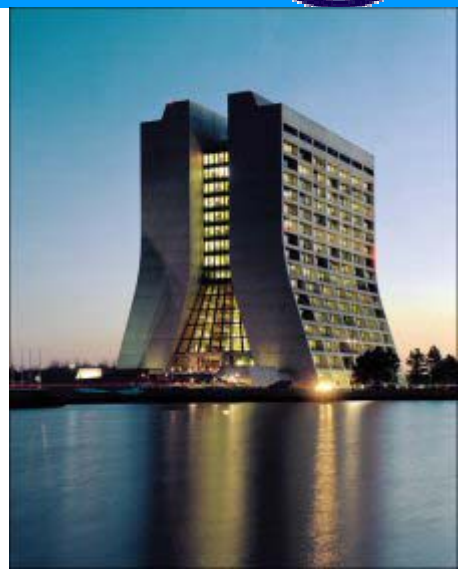
TeV4LHC Workshop

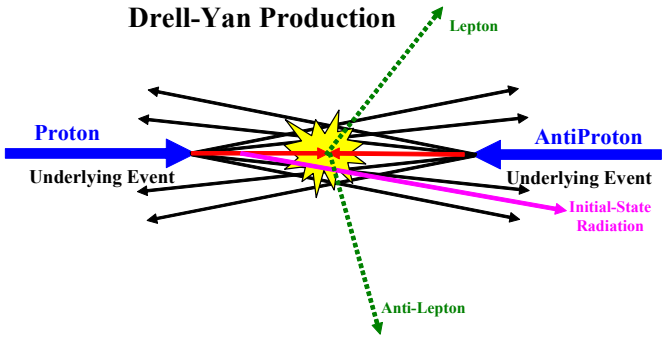
Talk #2

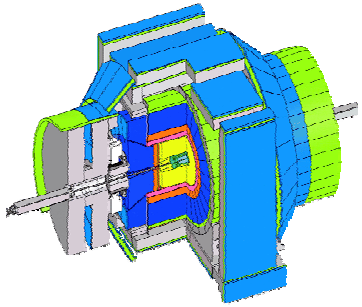
Quantum Chromo-Dynamics

Rick Field
University of Florida

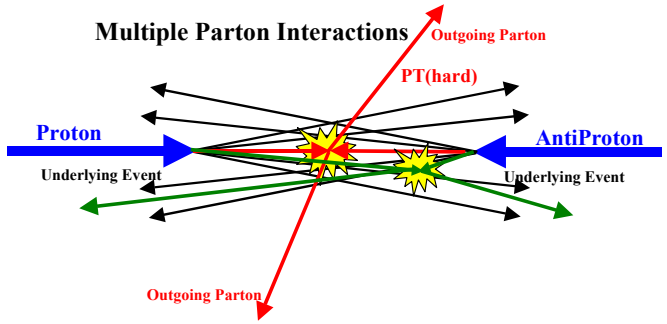
TeV4LHC



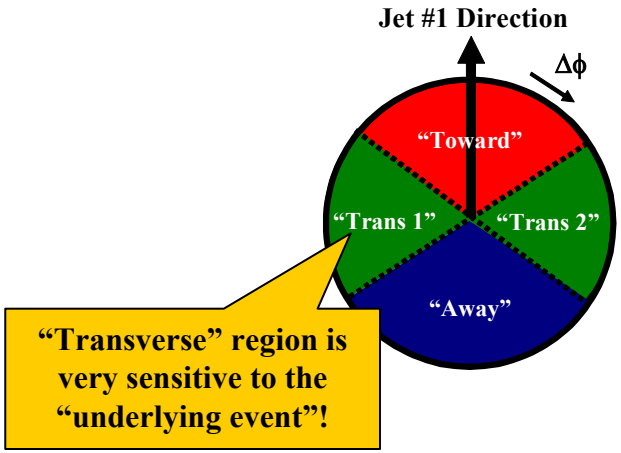




CDF Run 2

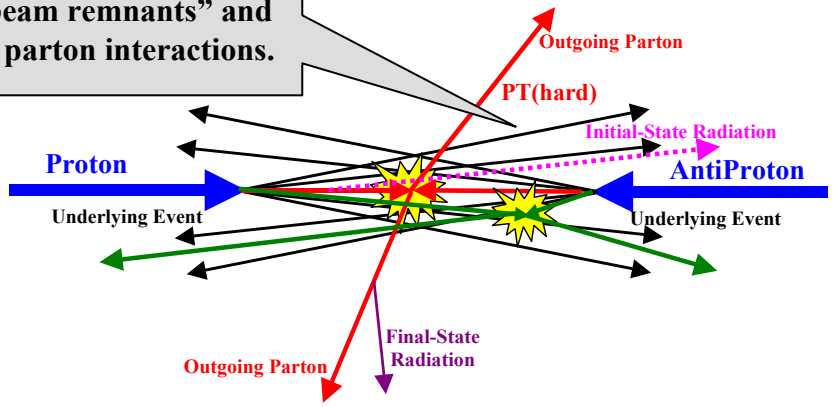


Recent CDF Run 2 "Underlying Event" Results



"Transverse" region is very sensitive to the "underlying event"!

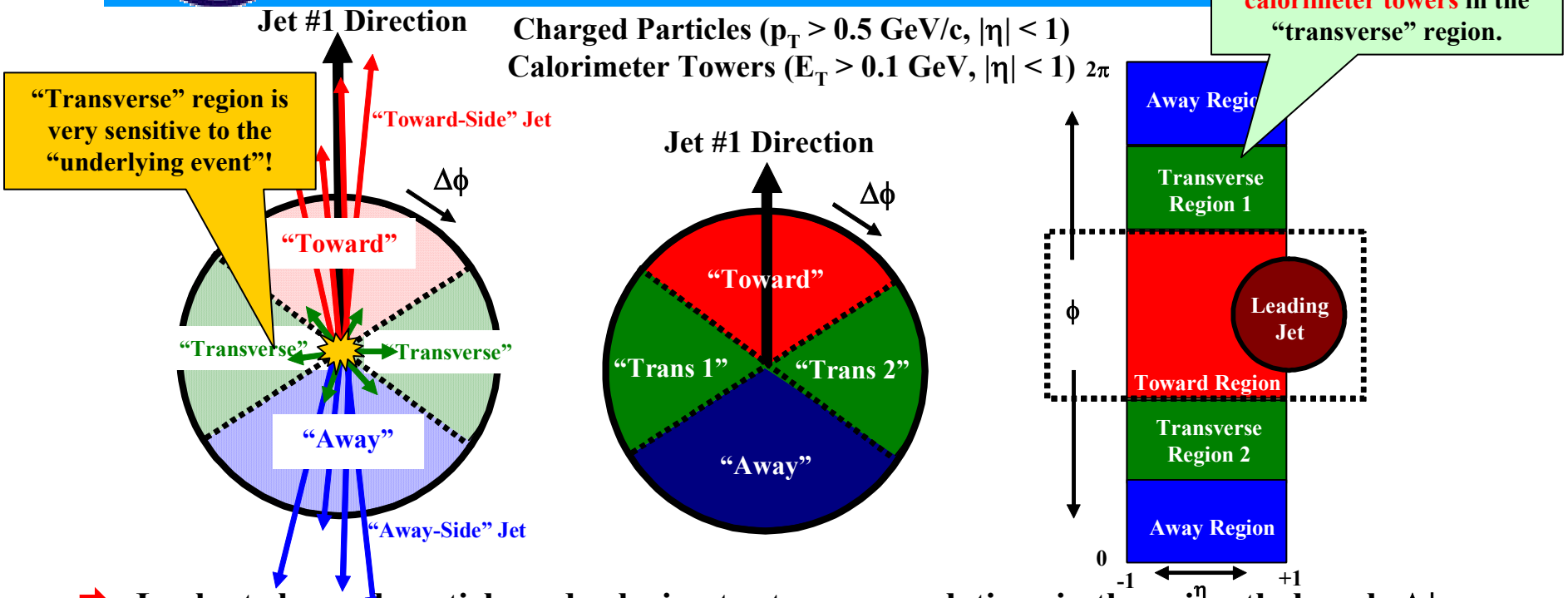
The "underlying event" consists of hard initial & final-state radiation plus the "beam-beam remnants" and possible multiple parton interactions.



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



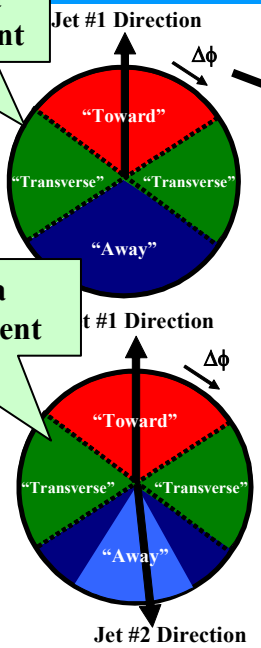
- Look at charged particle and calorimeter tower correlations in the azimuthal angle Δφ relative to the leading calorimeter jet (MidPoint, R = 0.7, f_{merge} = 0.75, |η| < 2).
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < -\Delta\phi < 120^o$ and $60^o < \Delta\phi < 120^o$ as "Transverse 1" and "Transverse 2", and $|\Delta\phi| > 120^o$ as "Away". Each of the two "transverse" regions have area $\Delta\eta\Delta\phi = 2x60^o = 4\pi/6$. The overall "transverse" region is the sum of the two transverse regions ($\Delta\eta\Delta\phi = 2x120^o = 4\pi/3$).

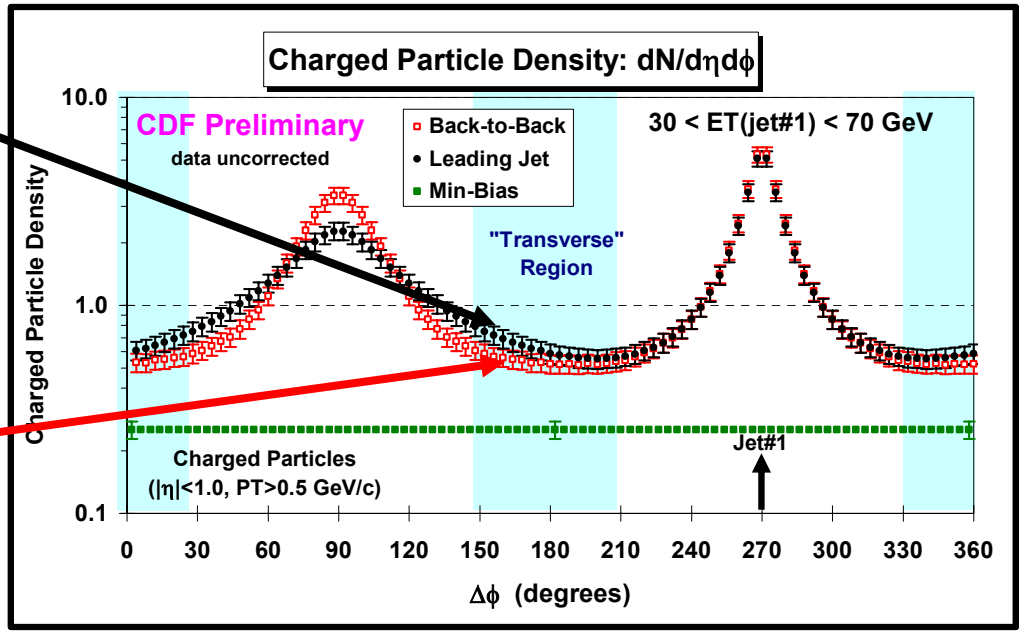
Charged Particle Density Δϕ Dependence

Refer to this as a "Leading Jet" event

Subset

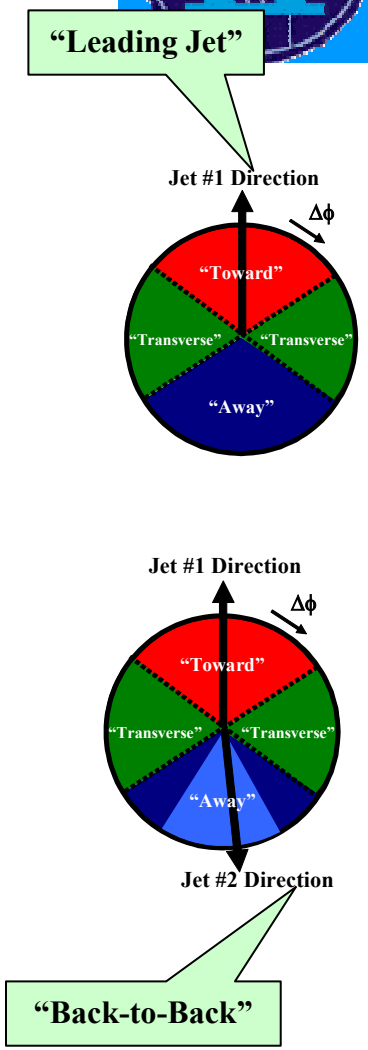
Refer to this as a "Back-to-Back" event





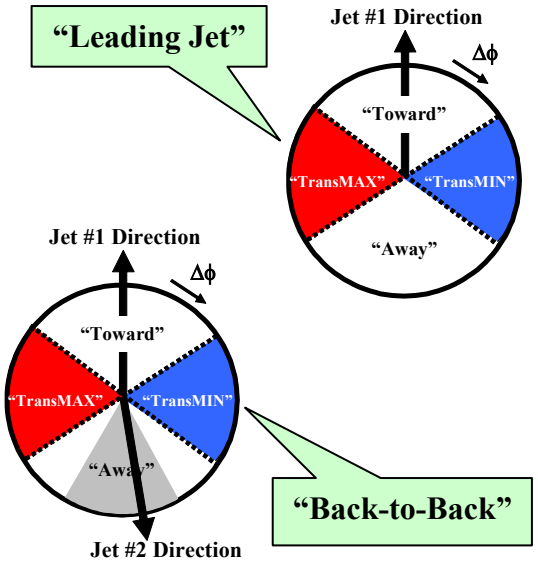
- Look at the "transverse" region as defined by the leading jet ($|\eta| < 2$) or by the leading two jets ($|\eta| < 2$). "Back-to-Back" events are selected to have at least two jets with Jet#1 and Jet#2 nearly "back-to-back" ($\Delta\phi_{12} > 150^o$) with almost equal transverse momenta ($P_T(\text{jet\#2})/P_T(\text{jet\#1}) > 0.8$) and $P_T(\text{jet\#3}) < 15$ GeV/c.
- Shows the Δϕ 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°) for $30 < E_T(\text{jet\#1}) < 70$ GeV for "Leading Jet" and "Back-to-Back" events.

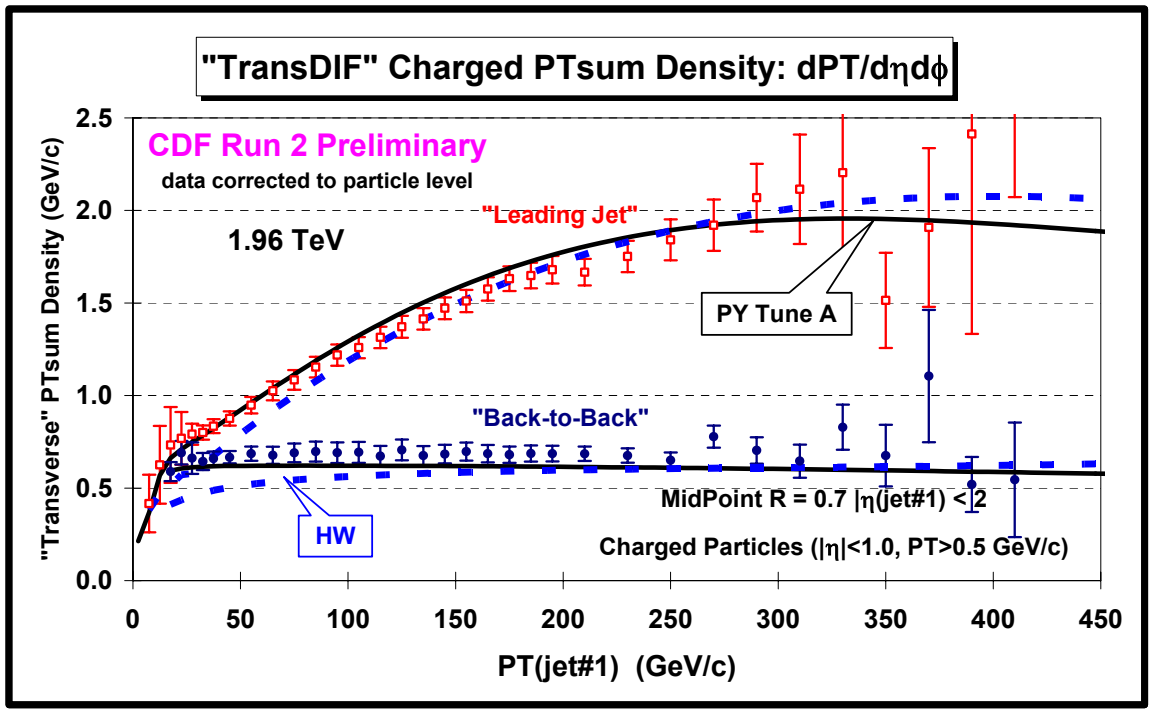
"Transverse" Observables Particle and Detector Level



Observable	Particle Level	Detector Level
dNchg/dηdϕ	Number of charged particles per unit η-ϕ ($p_T > 0.5$ GeV/c, $\|\eta\| < 1$)	Number of "good" charged tracks per unit η-ϕ ($p_T > 0.5$ GeV/c, $\|\eta\| < 1$)
dPTsum/dηdϕ	Scalar p_T sum of charged particles per unit η-ϕ ($p_T > 0.5$ GeV/c, $\|\eta\| < 1$)	Scalar p_T sum of "good" charged tracks per unit η-ϕ ($p_T > 0.5$ GeV/c, $\|\eta\| < 1$)
$\langle p_T \rangle$	Average p_T of charged particles ($p_T > 0.5$ GeV/c, $\|\eta\| < 1$)	Average p_T of "good" charged tracks ($p_T > 0.5$ GeV/c, $\|\eta\| < 1$)
PTmax	Maximum p_T charged particle ($p_T > 0.5$ GeV/c, $\|\eta\| < 1$) PTmax = 0 for no charged particle	Maximum p_T "good" charged tracks ($p_T > 0.5$ GeV/c, $\|\eta\| < 1$) PTmax = 0 for no "good" charged track
dETsum/dηdϕ	Scalar E_T sum of all particles per unit η-ϕ (all p_T, $\|\eta\| < 1$)	Scalar E_T sum of all calorimeter towers per unit η-ϕ ($E_T > 0.1$ GeV, $\|\eta\| < 1$)
PTsum/ETsum	Scalar p_T sum of charged particles ($p_T > 0.5$ GeV/c, $\|\eta\| < 1$) divided by the scalar E_T sum of all particles (all p_T, $\|\eta\| < 1$)	Scalar p_T sum of "good" charged tracks ($p_T > 0.5$ GeV/c, $\|\eta\| < 1$) divided by the scalar E_T sum of calorimeter towers ($E_T > 0.1$ GeV, $\|\eta\| < 1$)

"TransDIF" PTsum Density
PYTHIA Tune A vs HERWIG

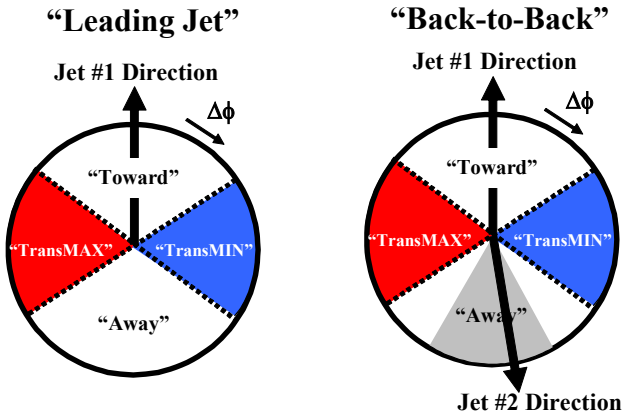




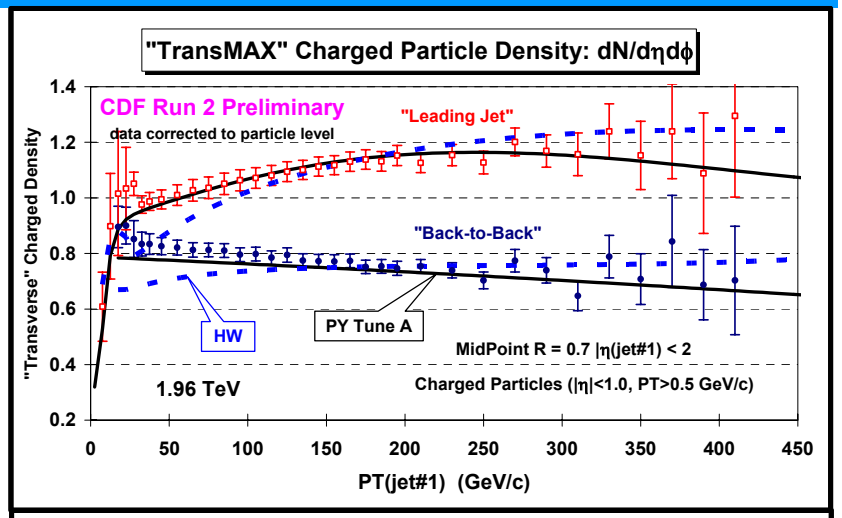
"transDIF" is very sensitive to the "hard scattering" component of the "underlying event"!

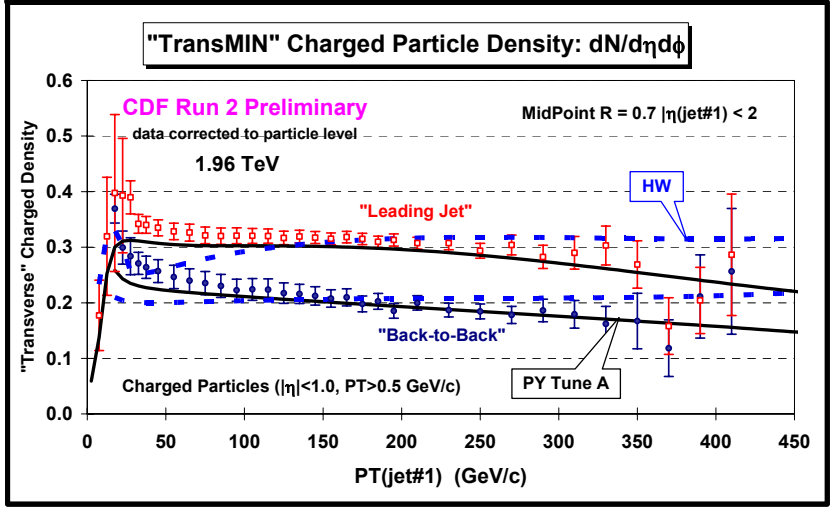
- **Use the leading jet to define the MAX and MIN "transverse" regions on an event-by-event basis with MAX (MIN) having the largest (smallest) charged PTsum density.**
- **Shows the "transDIF" = MAX-MIN charge PTsum density, $dPT_{sum}/d\eta d\phi$, for $p_T > 0.5$ GeV/c, $|\eta| < 1$ versus P_T(jet#1)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

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

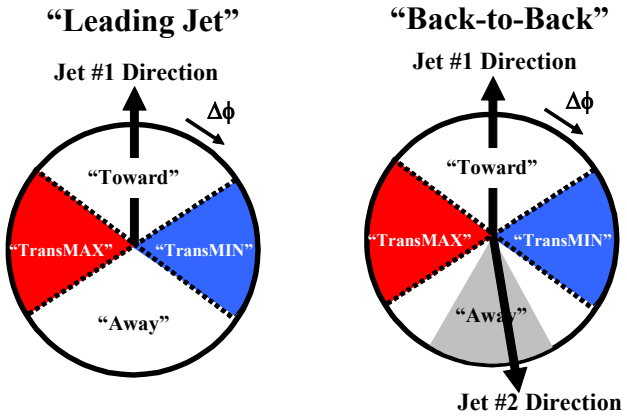


- Shows the charged particle density, $dN_{chg}/d\eta d\phi$, in the "transMAX" and "transMIN" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- Compares the (*corrected*) data with PYTHIA Tune A (with MPI) and HERWIG (without MPI) at the particle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





"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.
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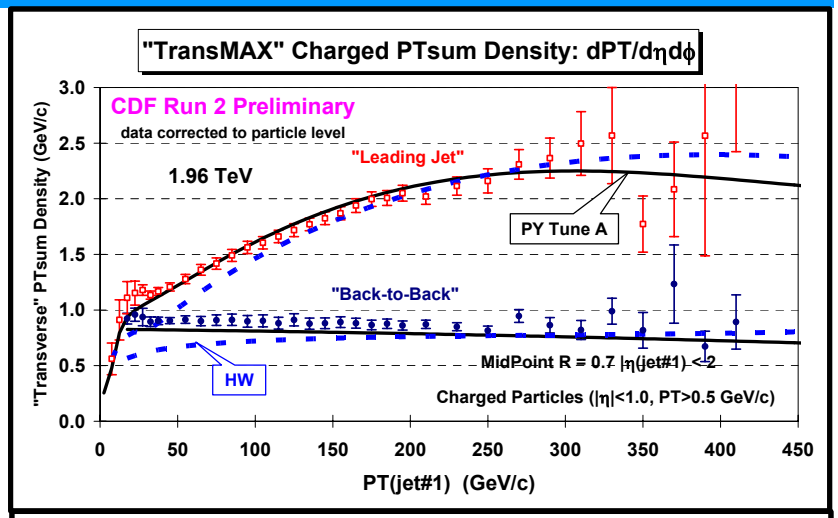
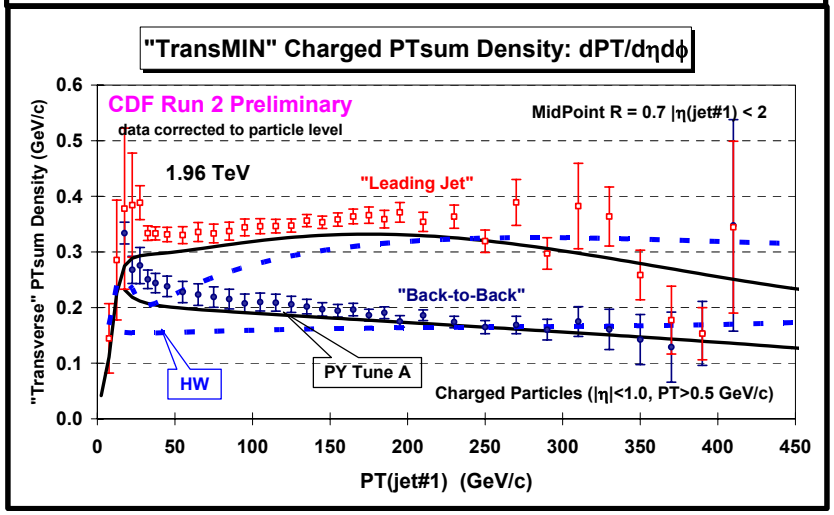
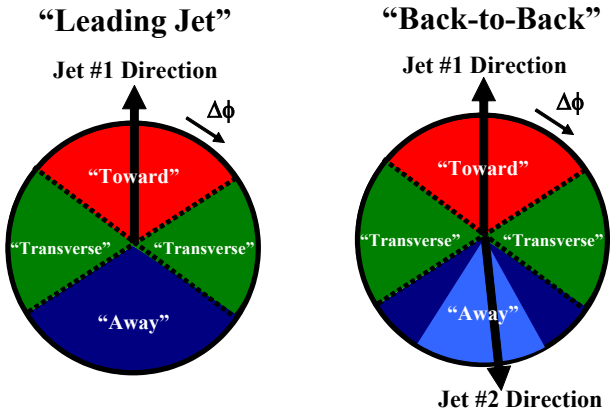
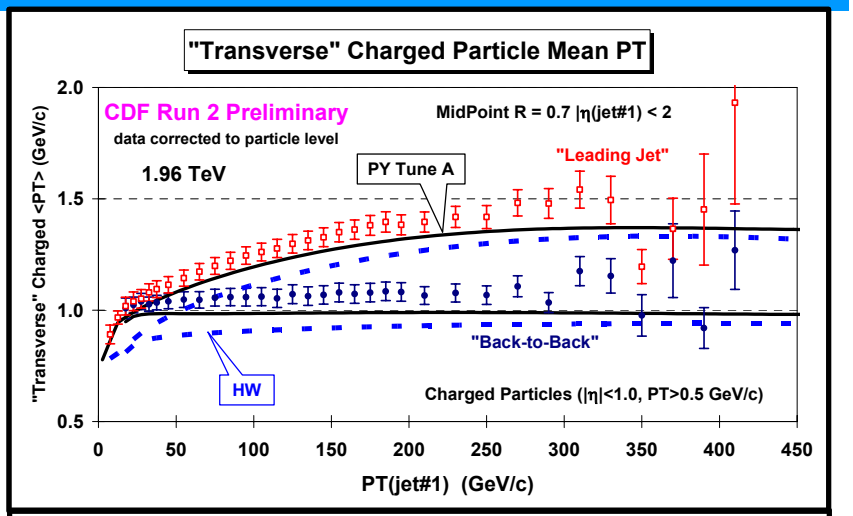
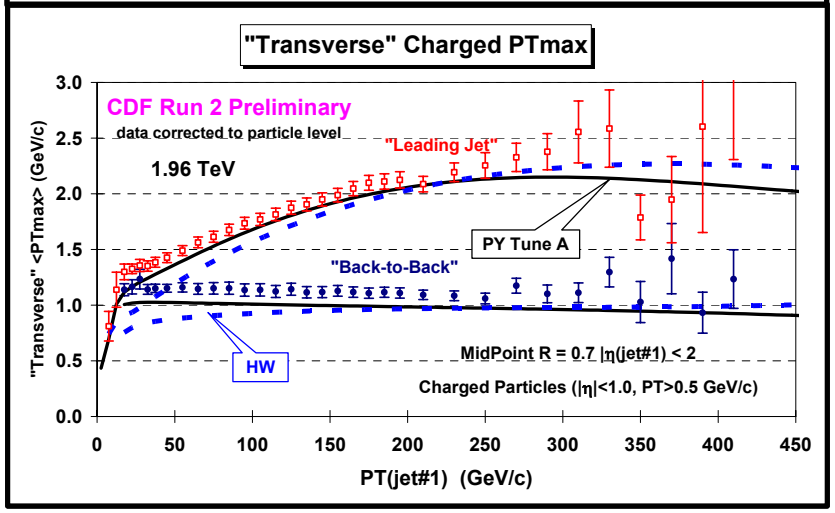




"Transverse" $\langle P_T \rangle$ and $\langle PTmax \rangle$ PYTHIA Tune A vs HERWIG

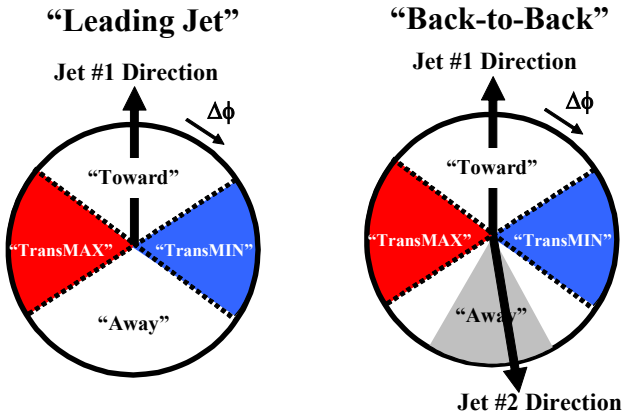






- Shows the average transverse momentum, $\langle P_T \rangle$, and $\langle PTmax \rangle$ for charged particles in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- Compares the (*corrected*) data with PYTHIA Tune A (with MPI) 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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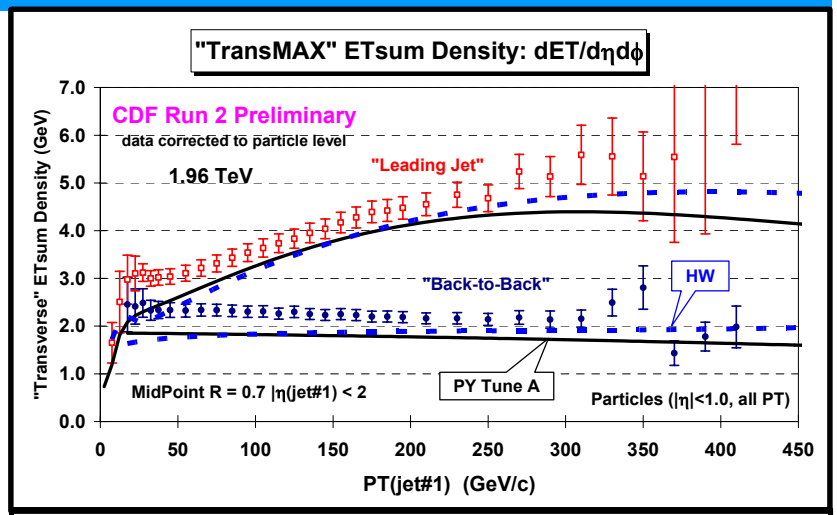
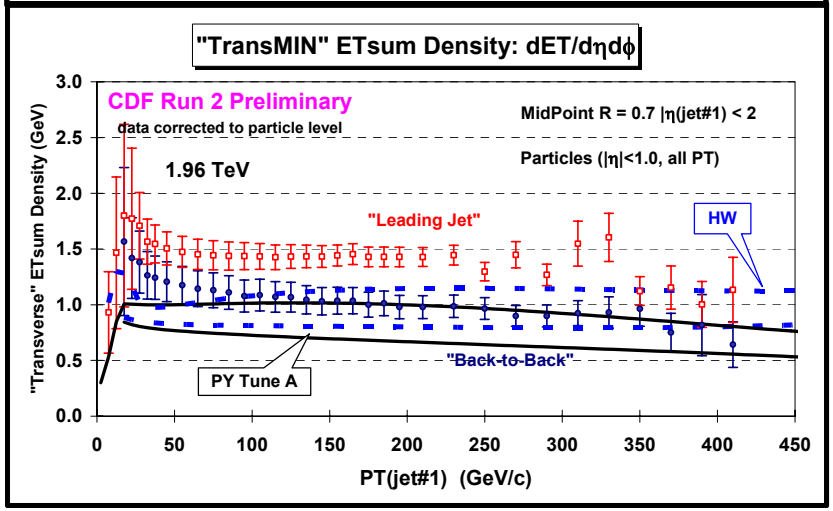
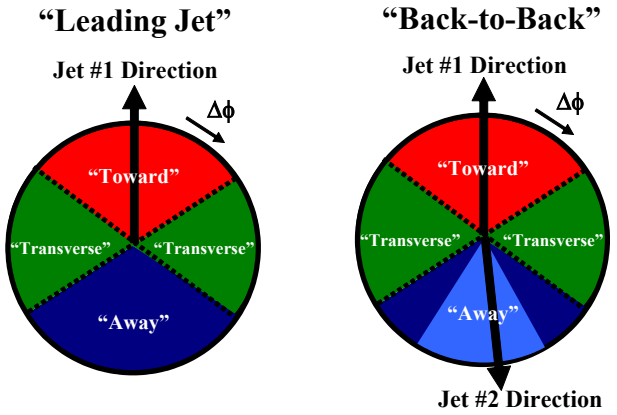
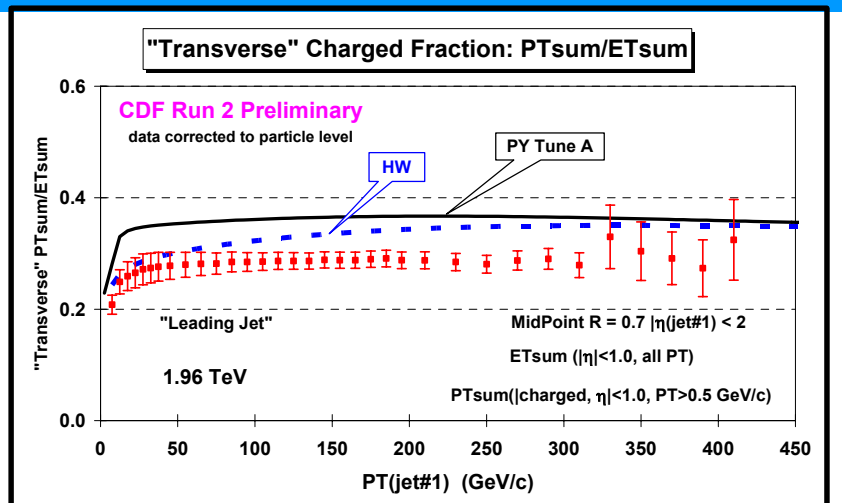
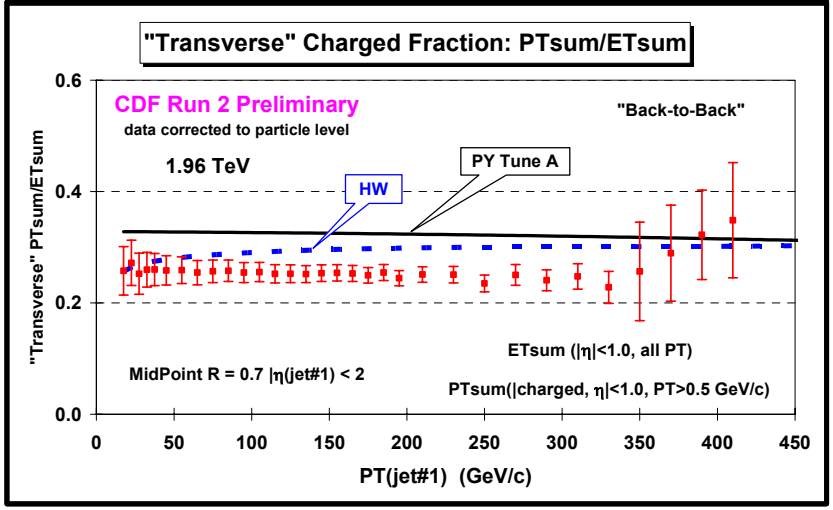




"Transverse" Charged Fraction
PYTHIA Tune A vs HERWIG

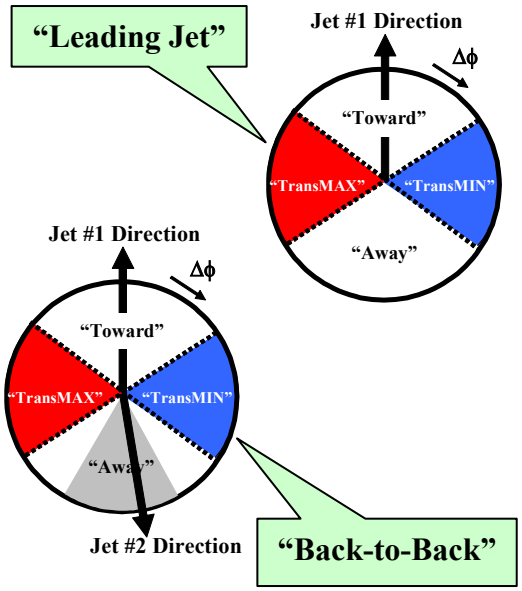


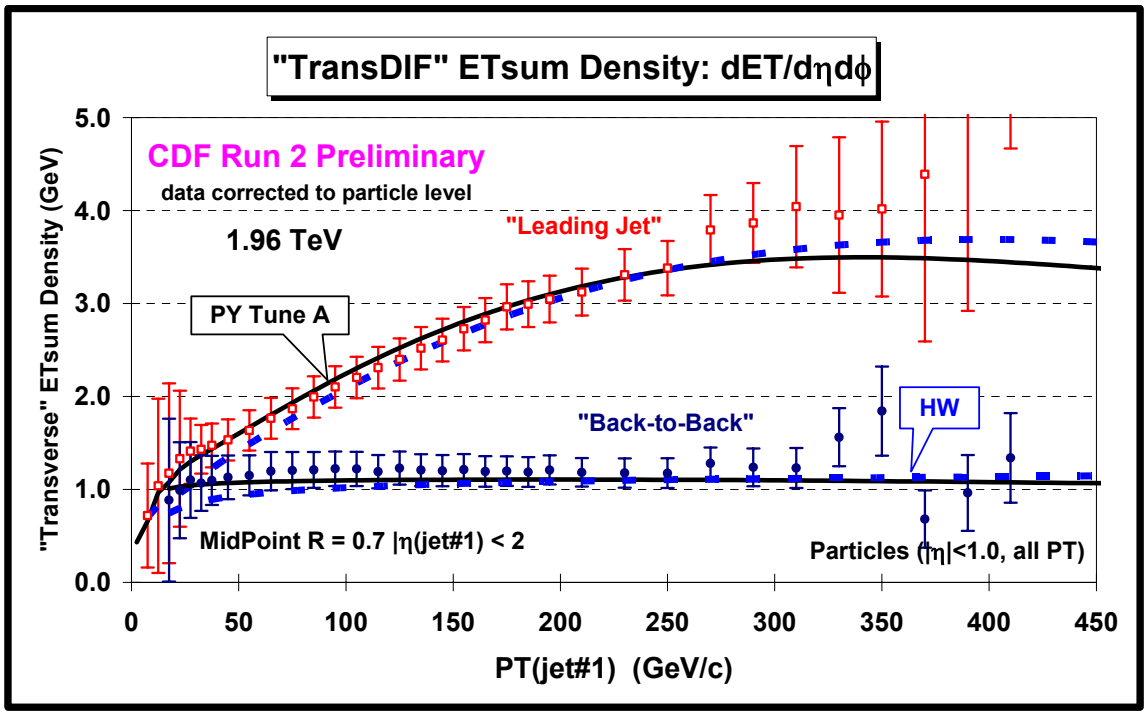




- Shows the PTsum/ETsum in the "transverse" region versus P_T(jet#1) for "Leading Jet" and "Back-to-Back" events, where PTsum is the *scalar* P_T sum of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) and ETsum is the *scalar* E_T sum of all particles ($|\eta| < 1$).
- Compares the (*corrected*) data with PYTHIA Tune A (with MPI) and HERWIG (without MPI) at the particle level.

"TransDIF" ETsum Density
PYTHIA Tune A vs HERWIG

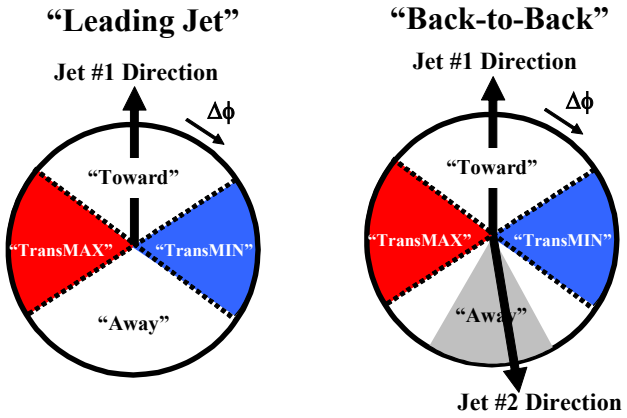




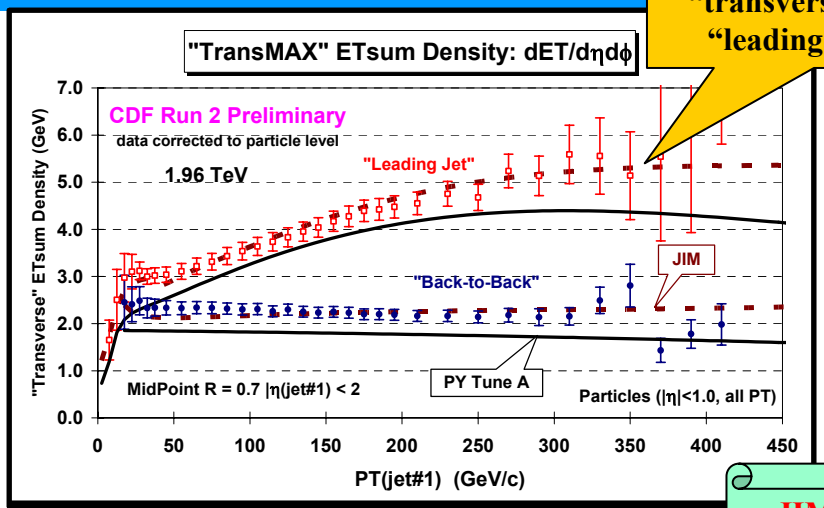
"transDIF" is very sensitive to the "hard scattering" component of the "underlying event"!

- 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 ETsum density, $dET_{sum}/d\eta d\phi$, for all particles ($|\eta| < 1$) versus P_T(jet#1) for "Leading Jet" and "Back-to-Back" events.

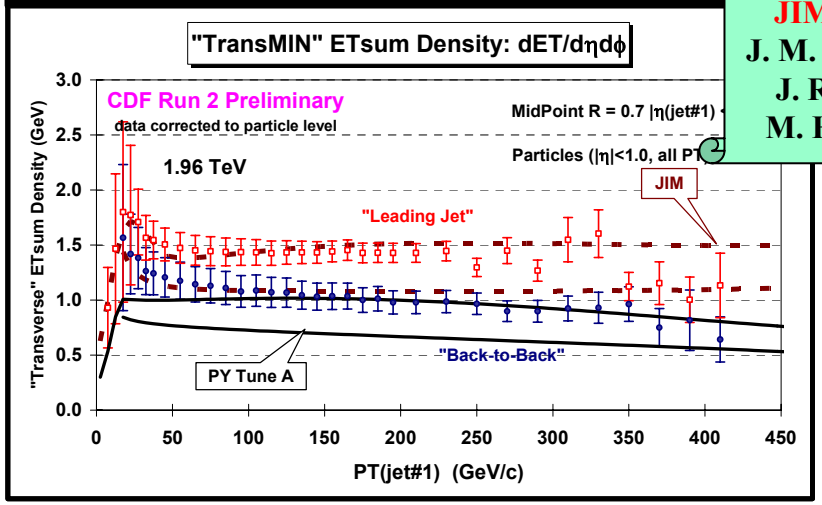
"TransMAX/MIN" ETsum Density
PYTHIA Tune A vs JIMMY



- 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, default = 2.5 GeV/c) at the particle level.



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



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

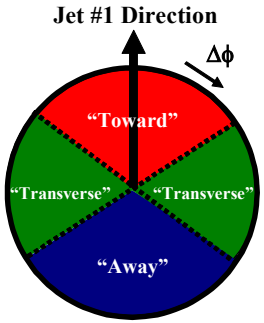
JIMMY at CDF

JIMMY
Runs with HERWIG and adds multiple parton interactions!

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

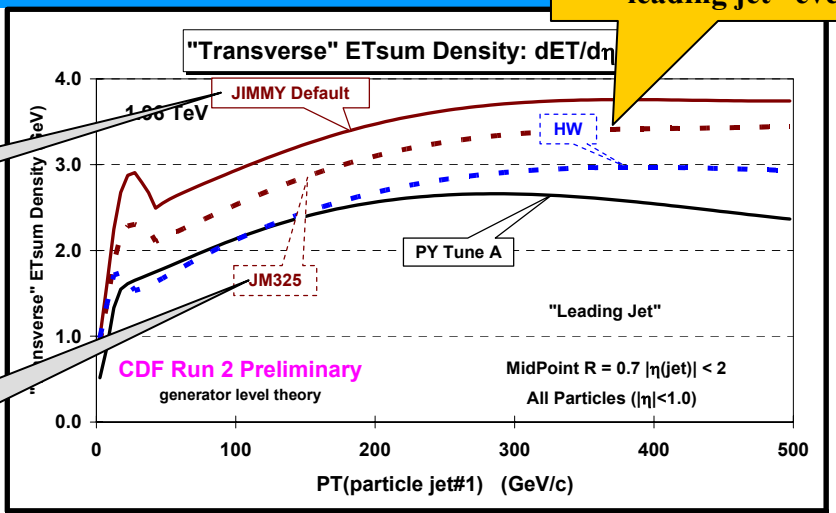
The Energy in the "Underlying Event" in High P_T Jet Production

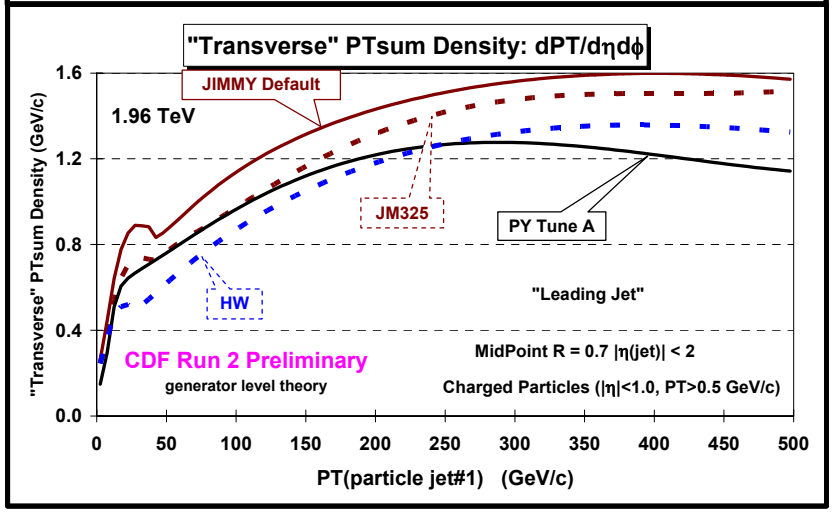
JIMMY: MPI
J. M. Butterworth
J. R. Forshaw
M. H. Seymour

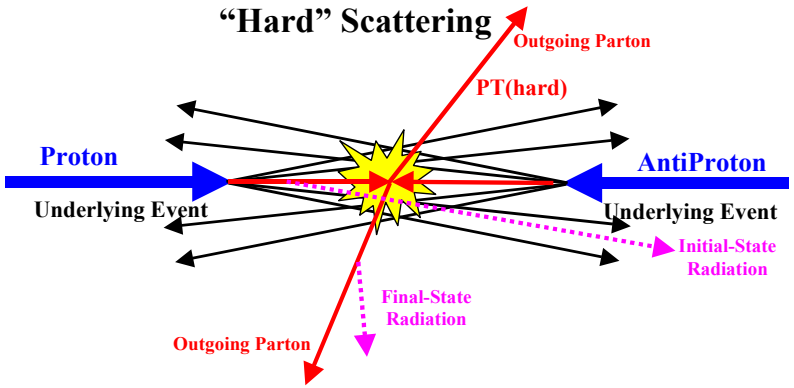


PT(JIM)= 2.5 GeV/c.

PT(JIM)= 3.25 GeV/c.

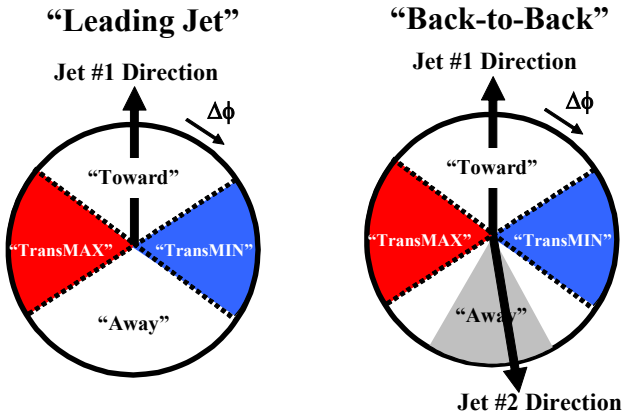


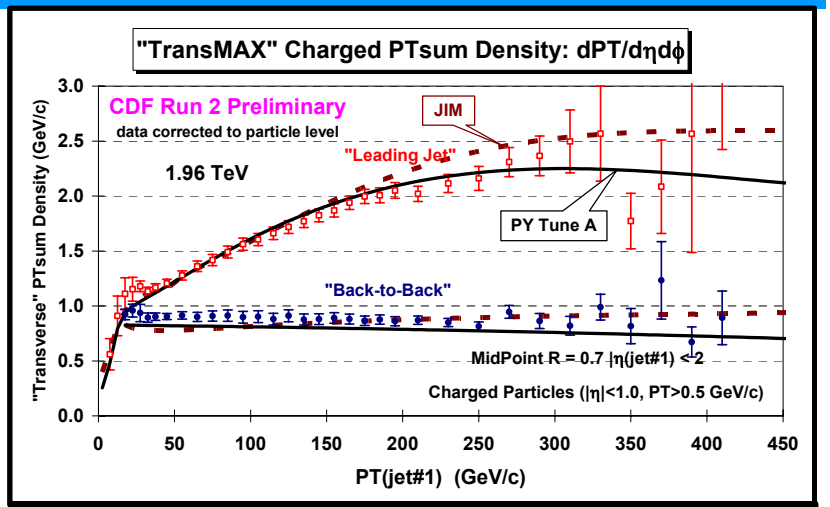


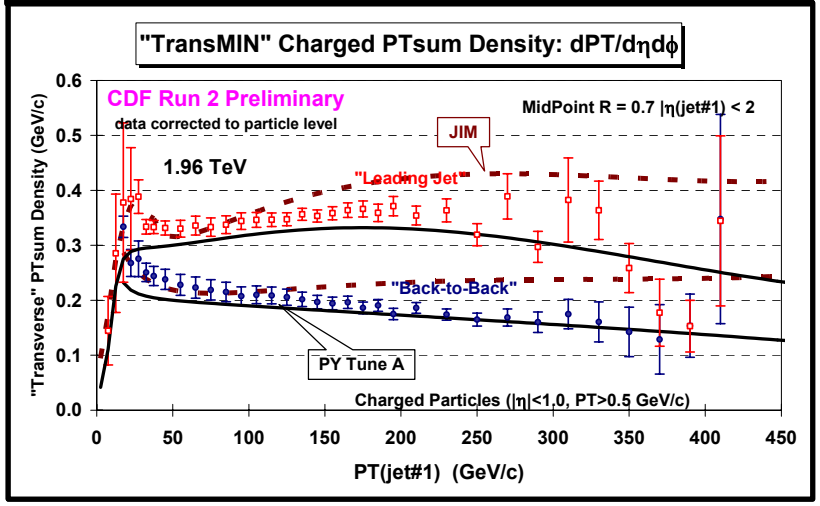


"Transverse" <Densities> vs P_T(jet#1)

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

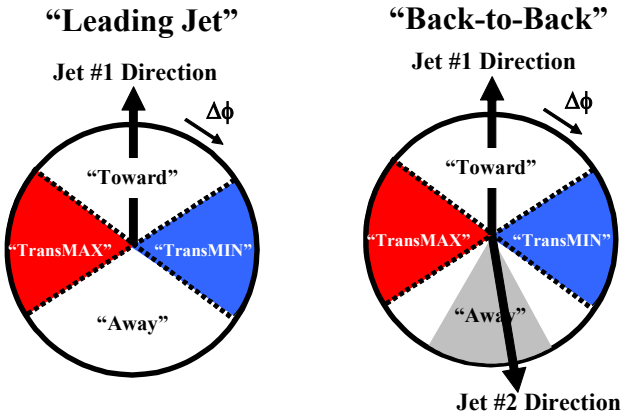




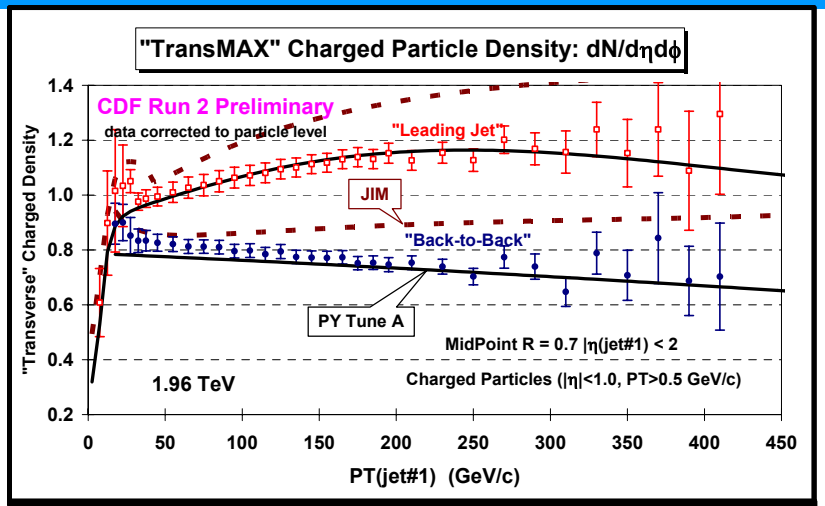


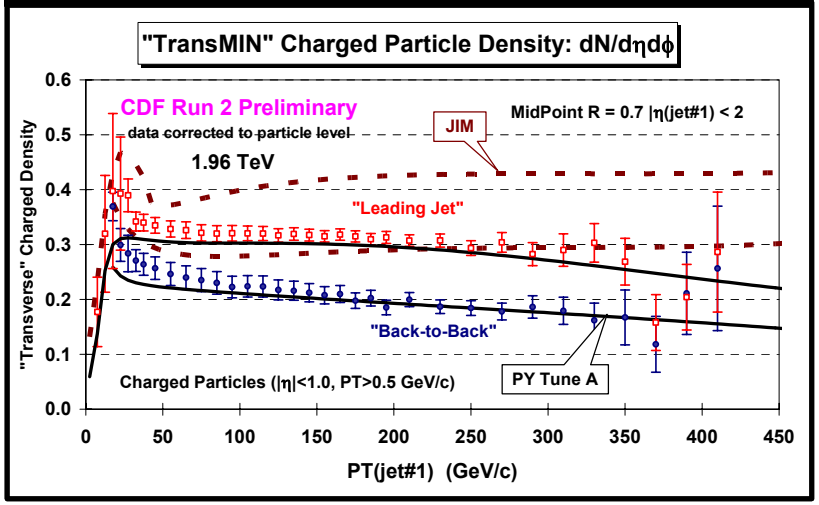
- Shows the charged PTsum density, $dET_{sum}/d\eta d\phi$, in the "transMAX" and "transMIN" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- Compares the (*corrected*) data with PYTHIA Tune A (with MPI) and a tuned version of JIMMY (with MPI,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

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

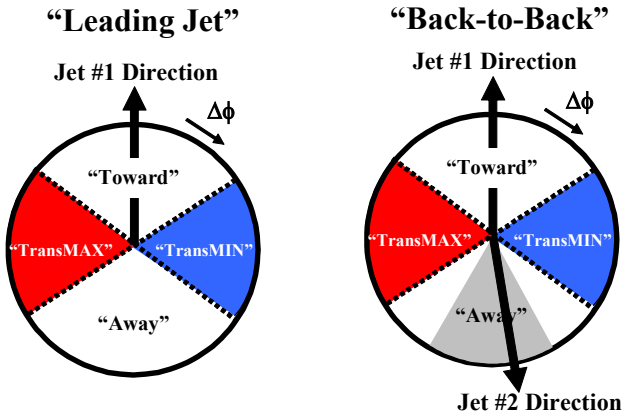


- Shows the charged particle density, $dN_{chg}/d\eta d\phi$, in the "transMAX" and "transMIN" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- Compares the (*corrected*) data with PYTHIA Tune A (with MPI) and a tuned version of JIMMY (with MPI,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

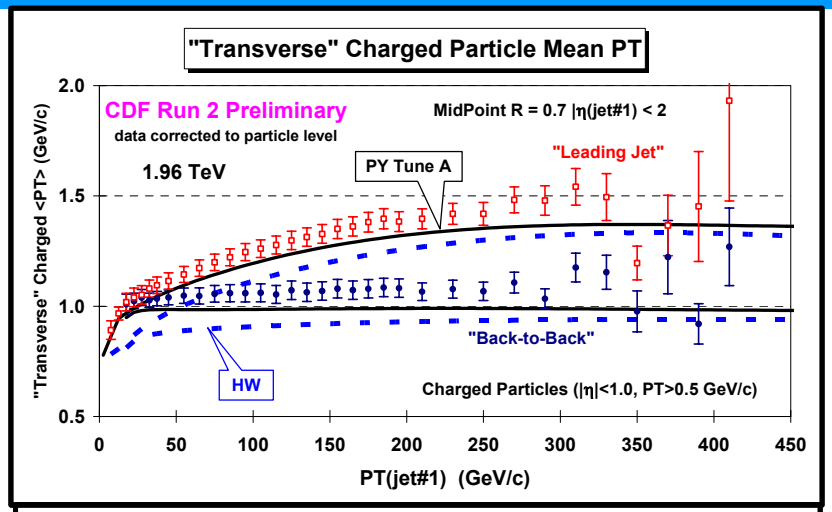


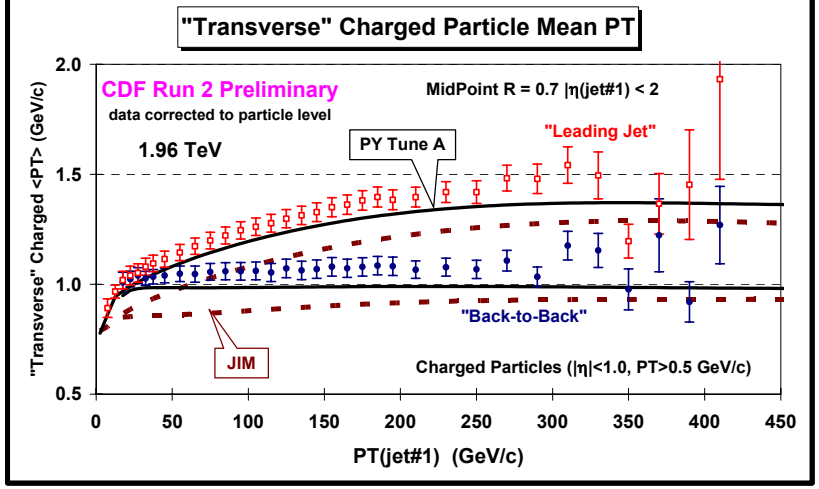


"Transverse" $\langle P_T \rangle$ PYTHIA Tune A vs JIMMY

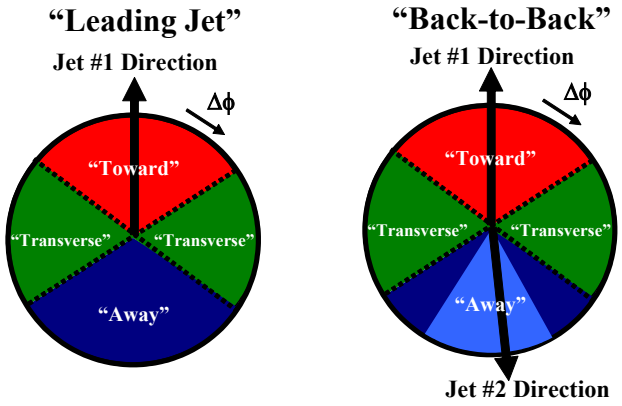


- Shows the charged particle $\langle P_T \rangle$ in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- Compares the (*corrected*) data with PYTHIA Tune A (with MPI) and HERWIG and a tuned version of JIMMY (with MPI, PTJIM = 3.25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

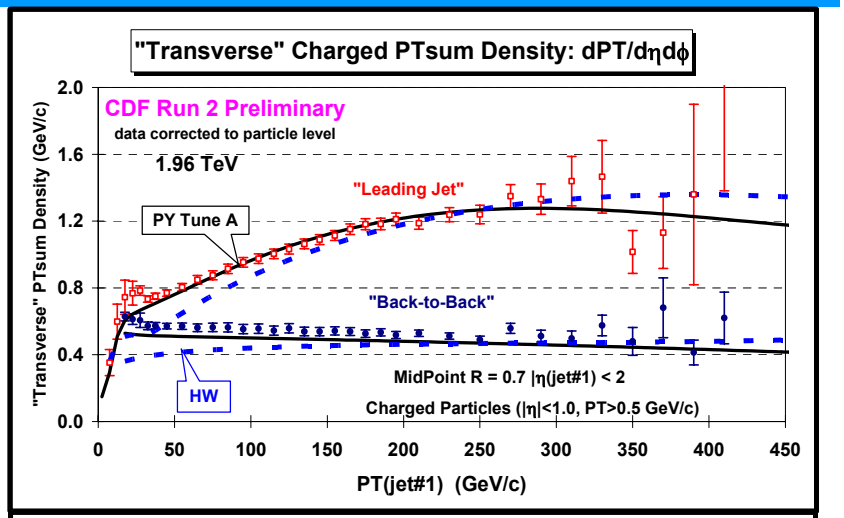


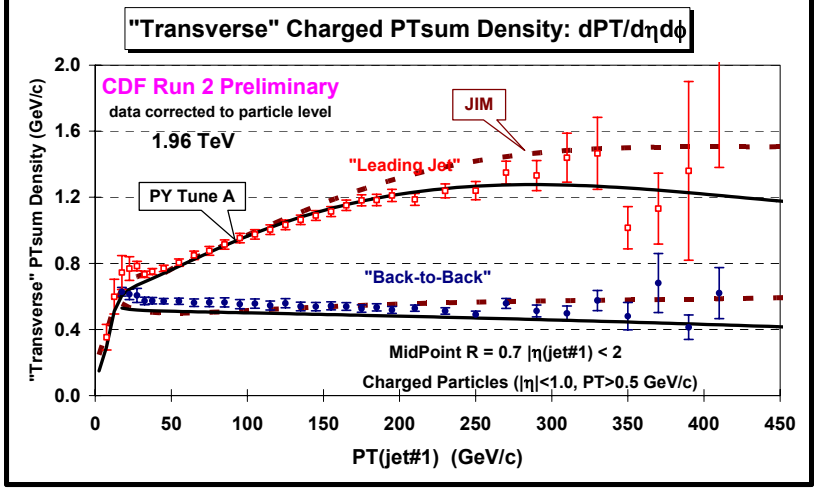


"Transverse" PTsum Density PYTHIA Tune A vs JIMMY



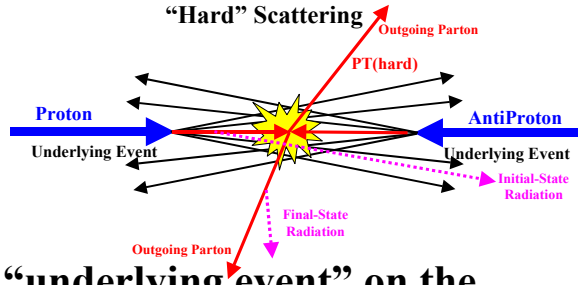
- Shows the charged PTsum density in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus P_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- Compares the (*corrected*) data with PYTHIA Tune A (with MPI) and HERWIG and a tuned version of JIMMY (with MPI, PTJIM = 3.25 GeV/c) at the particle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





Summary

- **Particle Level Data:** CDF has new data on the "underlying event" that is corrected to the particle level so that it can be used to tune the QCD Monte-Carlo models without requiring CDF detector simulation!



- **Interesting Physics:** We see interesting dependence of the "underlying event" on the transverse momentum of the leading jet (*i.e.* the Q^2 of the hard scattering). For the "leading jet" case the "transMAX" densities rise with increasing P_T(jet#1), while for the "back-to-back" case they fall. The rise in the "leading jet" case is due to hard initial and final-state radiation, which has been suppressed in the "back-to-back" events. The "back-to-back" data show a decrease in the "transMIN" densities with increasing P_T(jet#1) which is very interesting.

- **PYTHIA Tune A does not produce enough energy in the "underlying event"! JIMMY 325 (PTJIM = 3.25 GeV/c) fits the energy in the "underlying event" but does so by producing too many particles (*i.e.* it is too soft).**

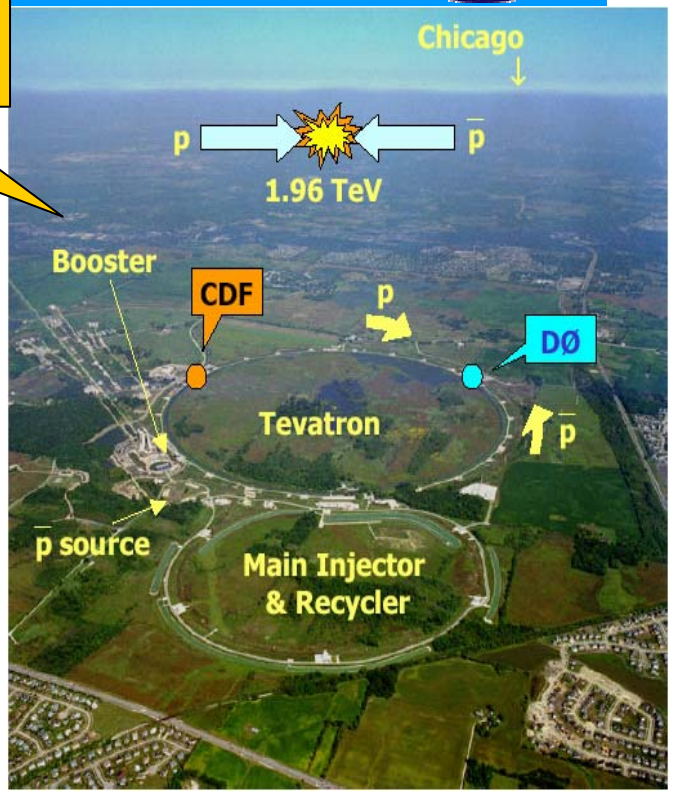
- **We are making good progress in understanding and modeling the "underlying event". However, we do not yet have a perfect fit to all the features of the "underlying event"!**

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 $L = 1\ fb^{-1}$!
- **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 $1fb^{-1}$ of data by Winter 2006!