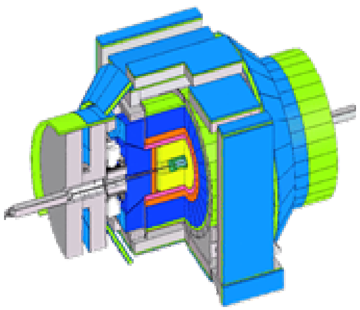
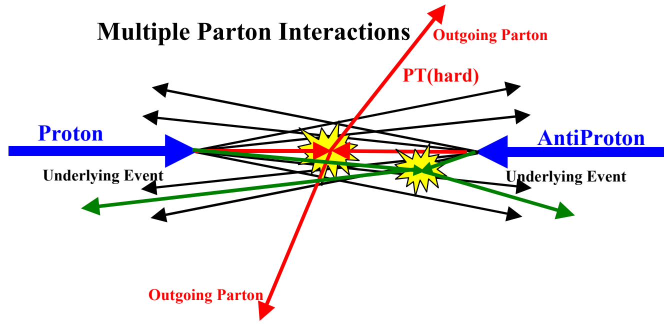
FRONTIERS IN CONTEMPORARY PHYSICS - III



QCD Working Group

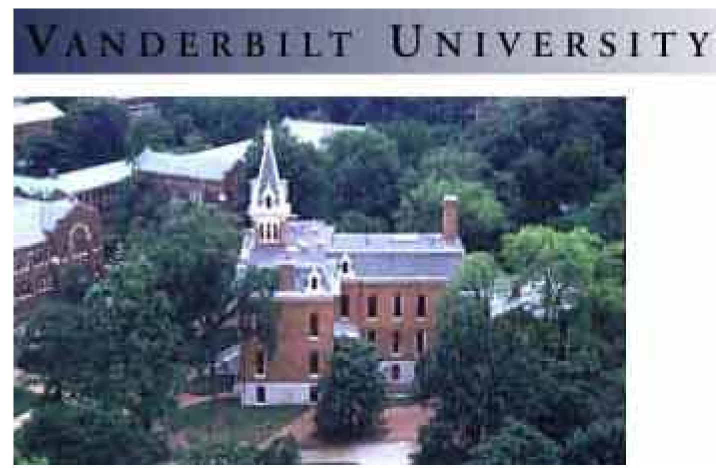


in memory of Bob Panvini

Rick Field

University of Florida

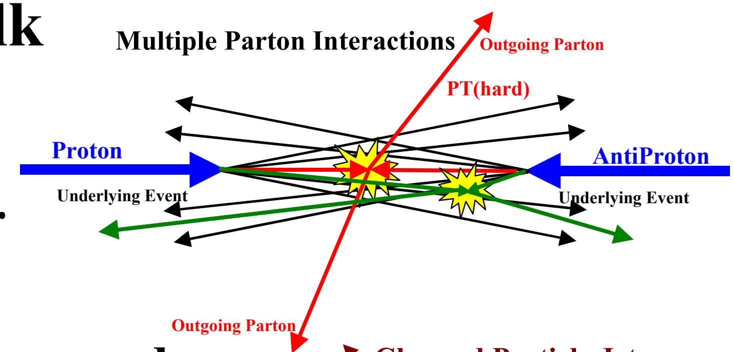
(*for the CDF Collaboration*)



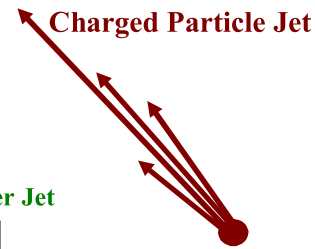
May 23-28, 2005

Studying the "Underlying Event" at CDF

Outline of Talk



- Discuss briefly the components of the **"underlying event"** of a hard scattering as described by the QCD parton-shower Monte-Carlo Models.

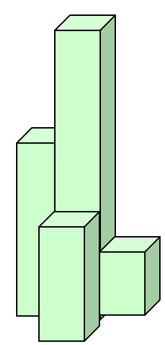


- Review the CDF Run 1 analysis which was used to tune the multiple parton interaction parameters in PYTHIA (*i.e.* **Tune A**).

- Review the study the **"underlying event"** in CDF Run 2 and compare with **PYTHIA Tune A** (*with MPI*) and **HERWIG** (*without MPI*).

- Look at **"what's next"**: CDF Run 2 publication, more realistic Monte-Carlo models.

Calorimeter Jet



JetClu R = 0.7

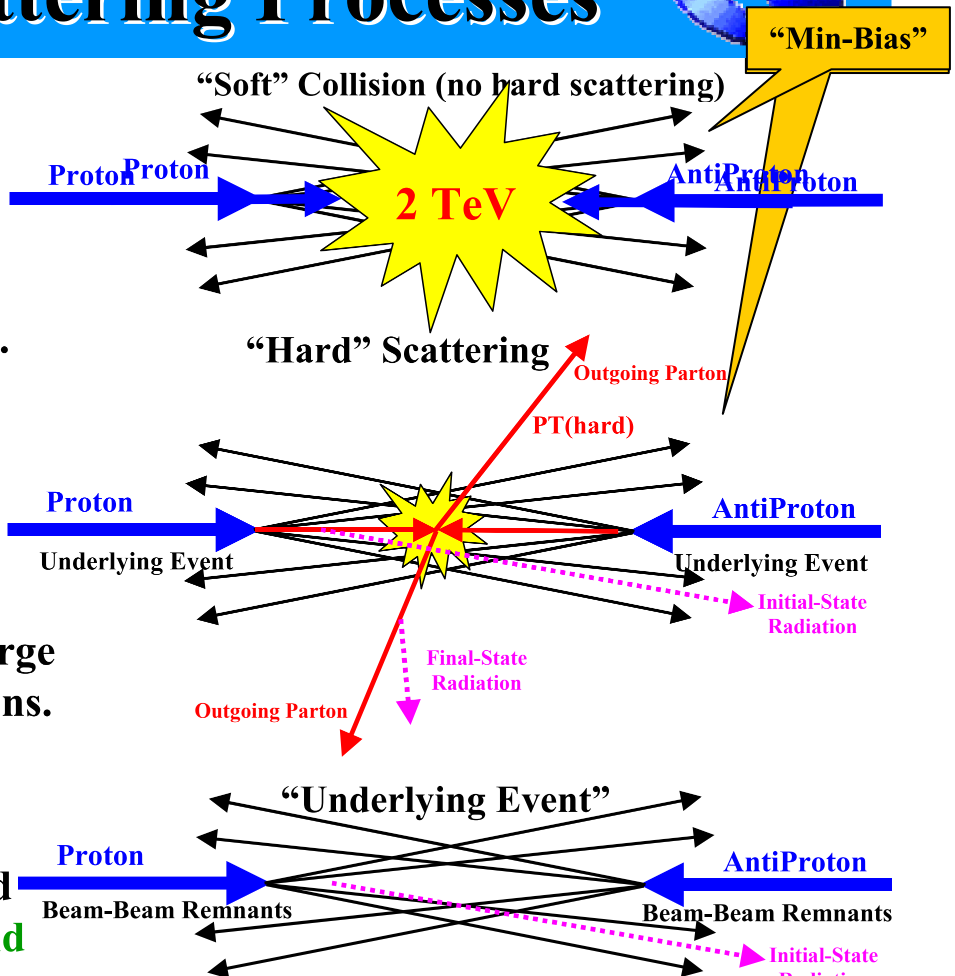
HERWIG + JIMMY

PYTHIA 6.3

SHERPA

The "Underlying Event" in Hard Scattering Processes

- What happens when a high energy proton and an antiproton collide?
- Most of the time the proton and antiproton ooze through each other and fall apart (*i.e.* no hard scattering). The outgoing particles continue in roughly the same direction as initial proton and antiproton. A "Min-Bias" collision.
- Occasionally there will be a "hard" parton-parton collision resulting in large transverse momentum outgoing partons. Also a "Min-Bias" collision.
- The "underlying event" is everything except the two outgoing hard scattered "jets". It is an unavoidable background to many collider observables.



"underlying event" has initial-state radiation!

The "Underlying Event" in Hard Scattering Processes

- What happens when a high energy proton and an antiproton collide?
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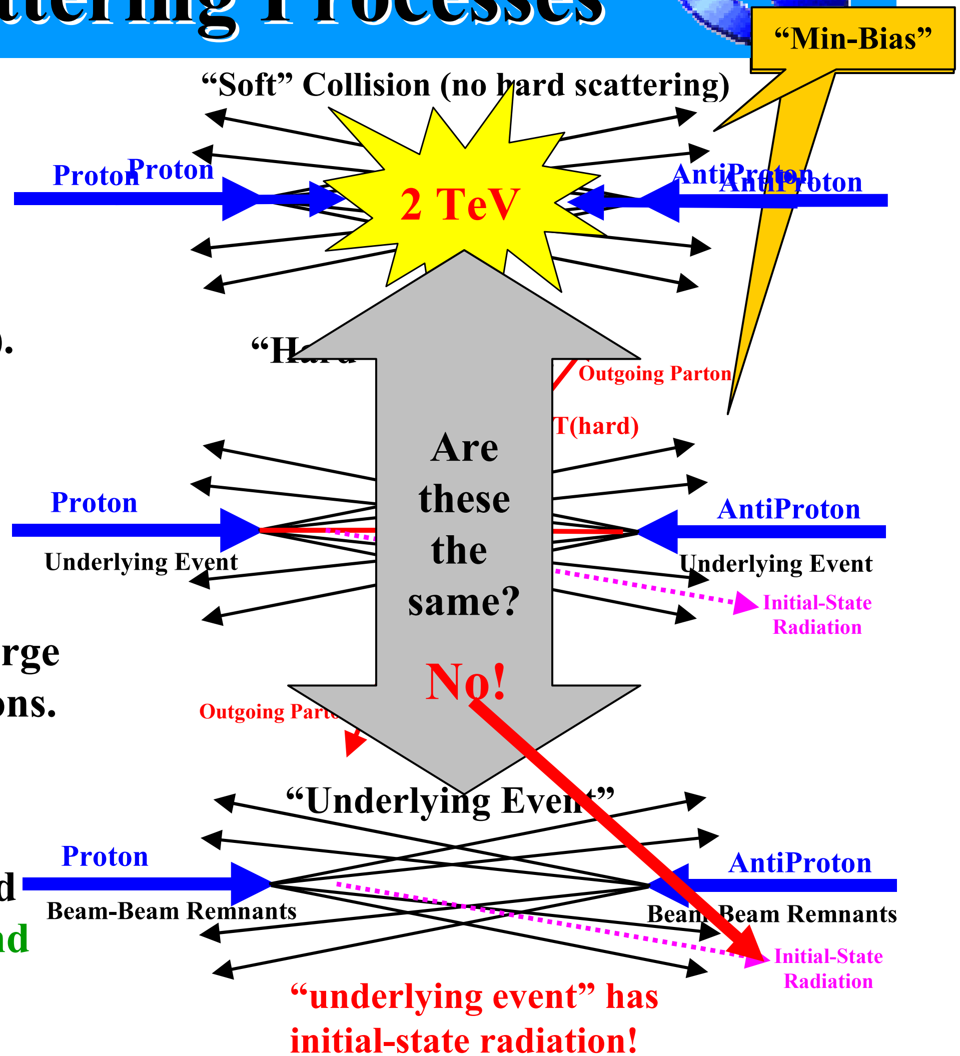
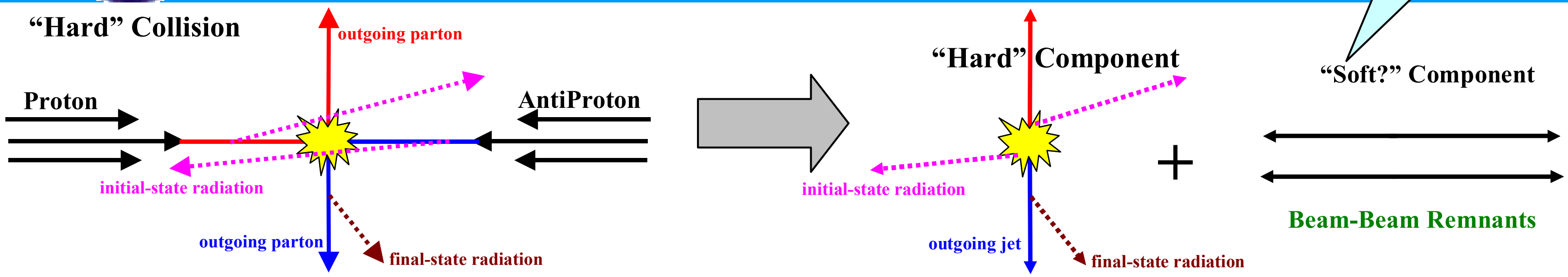
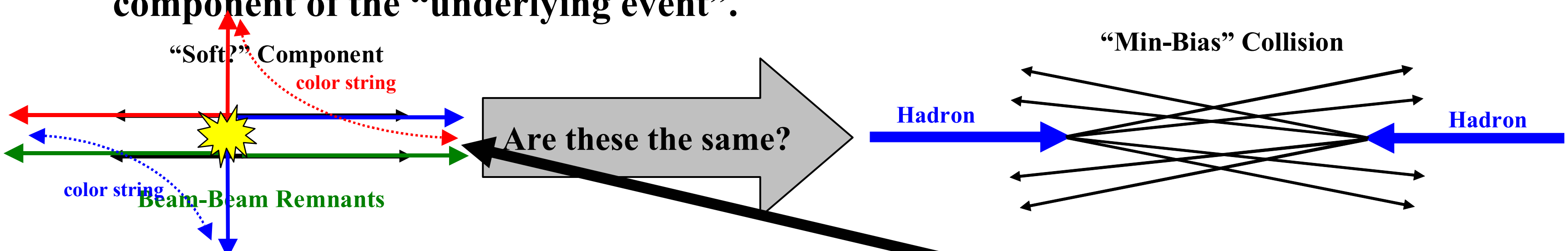


Beam-Beam Remnants

Maybe not all “soft”!



- The underlying event in a hard scattering process has a “hard” component (particles that arise from initial & final-state radiation and from the outgoing hard scattered partons) and a “soft?” component (“beam-beam remnants”).
- Clearly? the “underlying event” in a hard scattering process should not look like a “Min-Bias” event because of the “hard” component (*i.e.* initial & final-state radiation).
- However, perhaps “Min-Bias” collisions are a good model for the “beam-beam remnant” component of the “underlying event”.

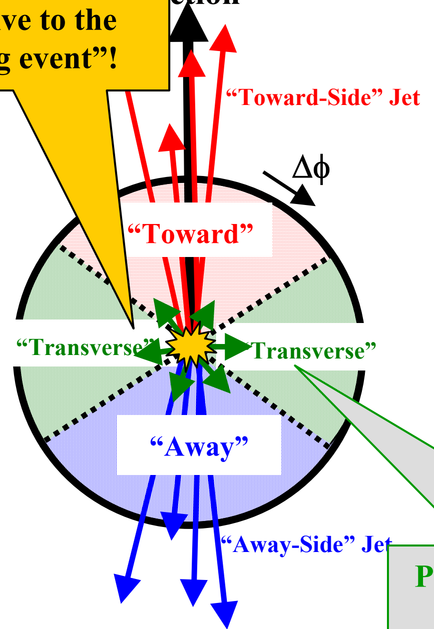


- The “beam-beam remnant” component is, however, color connected to the “hard” component so this comparison is (at best) an approximation.

CDF Run 1 analysis!

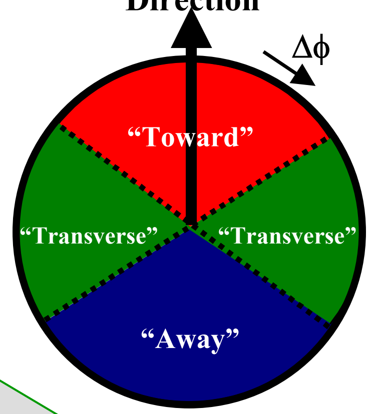
"Underlying Event"
as defined by "Charged particle Jets"

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

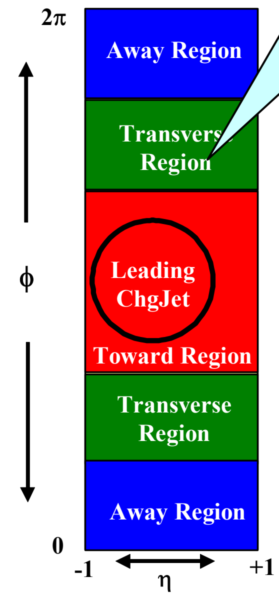


Perpendicular to the plane of the 2-to-2 hard scattering

Charged Particle Δϕ Correlations
$p_T > 0.5$ GeV/c $|\eta| < 1$

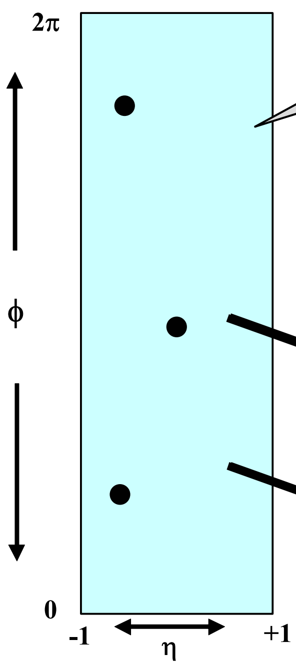


Look at the charged particle density in the "transverse" region!



- Look at charged particle correlations in the azimuthal angle Δϕ relative to the leading charged particle jet.
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away" and look at the density of charged particles and the charged PTsum density.
- All three regions have the same size in η-ϕ space, $\Delta\eta x \Delta\phi = 2x120^o = 4\pi/3$.

Particle Densities



$\Delta\eta\Delta\phi = 4\pi = 12.6$

Charged Particles
$p_T > 0.5$ GeV/c $|\eta| < 1$

CDF Run 2 "Min-Bias"

	CDF Run 2 "Min-Bias" Observable	Average	Average Density per unit η-φ
Nchg	Number of Charged Particles ($p_T > 0.5$ GeV/c, $\lvert\eta\rvert < 1$)	3.17 +/- 0.31	0.252 +/- 0.025
PTsum (GeV/c)	Scalar p_T sum of Charged Particles ($p_T > 0.5$ GeV/c, $\lvert\eta\rvert < 1$)	2.97 +/- 0.23	0.236 +/- 0.018

Divide by 4π

3 charged particles

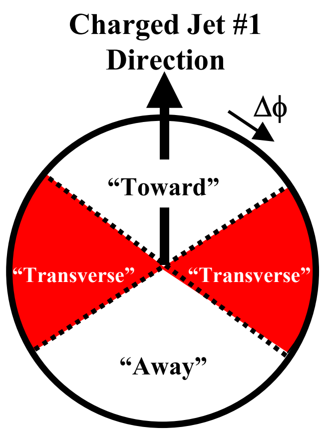
$dN_{chg}/d\eta d\phi = 3/4\pi = 0.24$

3 GeV/c PTsum

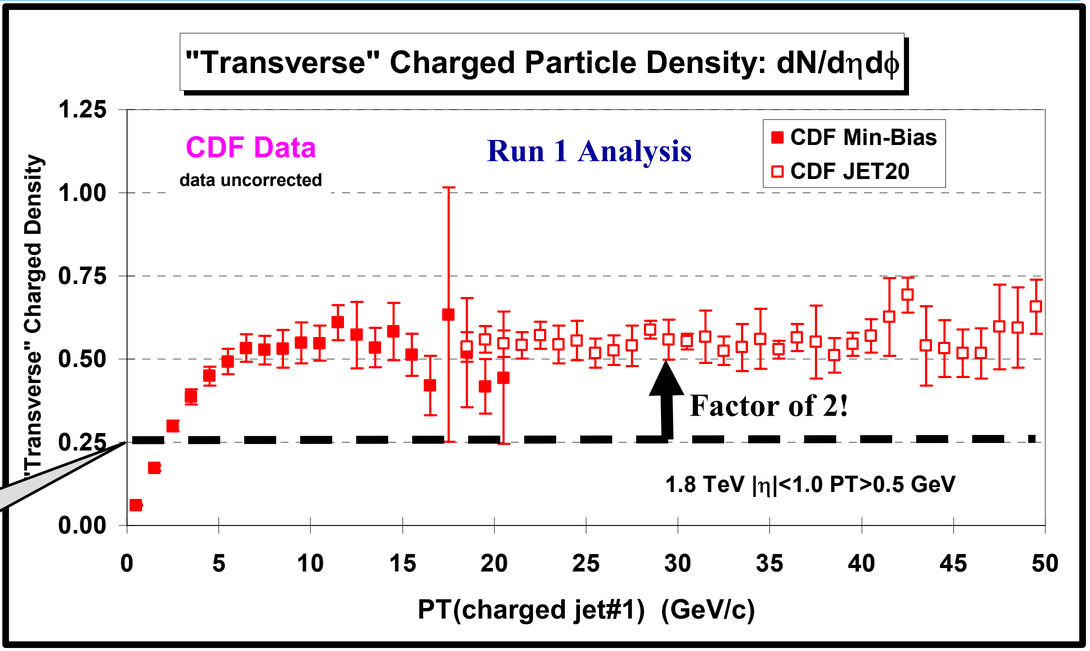
$dPT_{sum}/d\eta d\phi = 3/4\pi$ GeV/c $= 0.24$ GeV/c

- **Study the charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) and form the charged particle density, $dN_{chg}/d\eta d\phi$, and the charged scalar p_T sum density, $dPT_{sum}/d\eta d\phi$.**

Run 1 "Transverse" Charged Particle Density

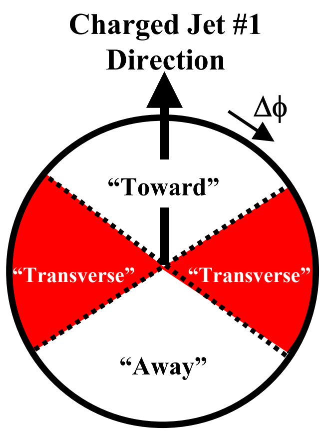


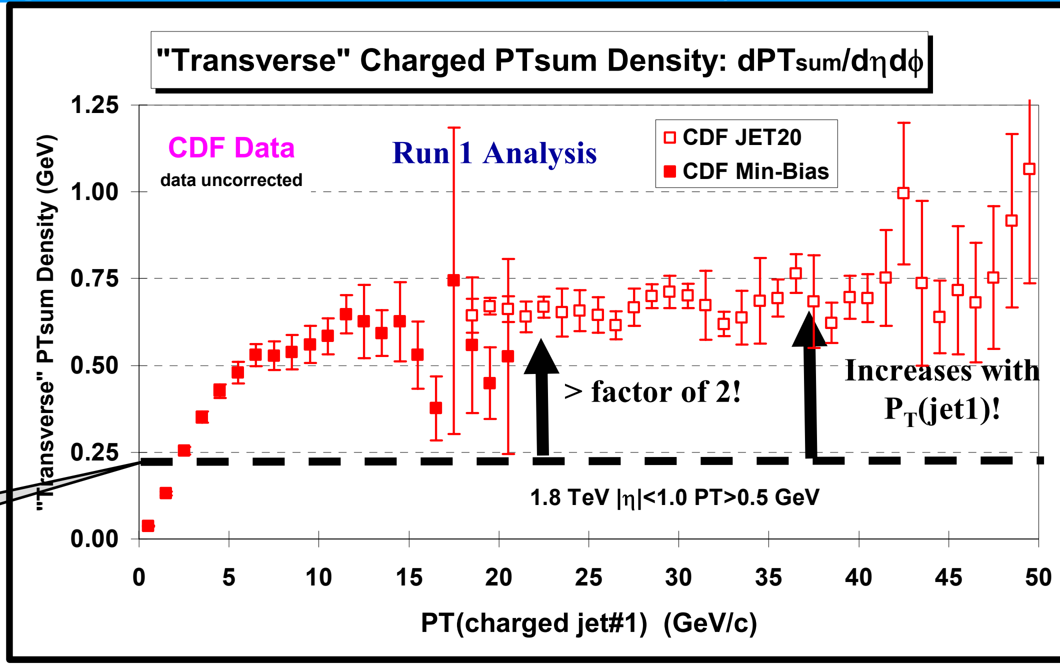
CDF "Min-Bias" data
($|\eta|<1$, $P_T>0.5$ GeV)
$<dN_{chg}/d\eta d\phi> = 0.25$



- Data on the average charge particle density ($p_T > 0.5$ GeV, $|\eta| < 1$) in the **"transverse" (60<|Δφ|<120°) region** as a function of the transverse momentum of the leading charged particle jet. Each point corresponds to the $<dN_{chg}/d\eta d\phi>$ in a 1 GeV bin. The solid (open) points are the Min-Bias (JET20) data. The errors on the (*uncorrected*) data include both statistical and correlated systematic uncertainties.

Run 1 "Transverse" Charged PTsum Density



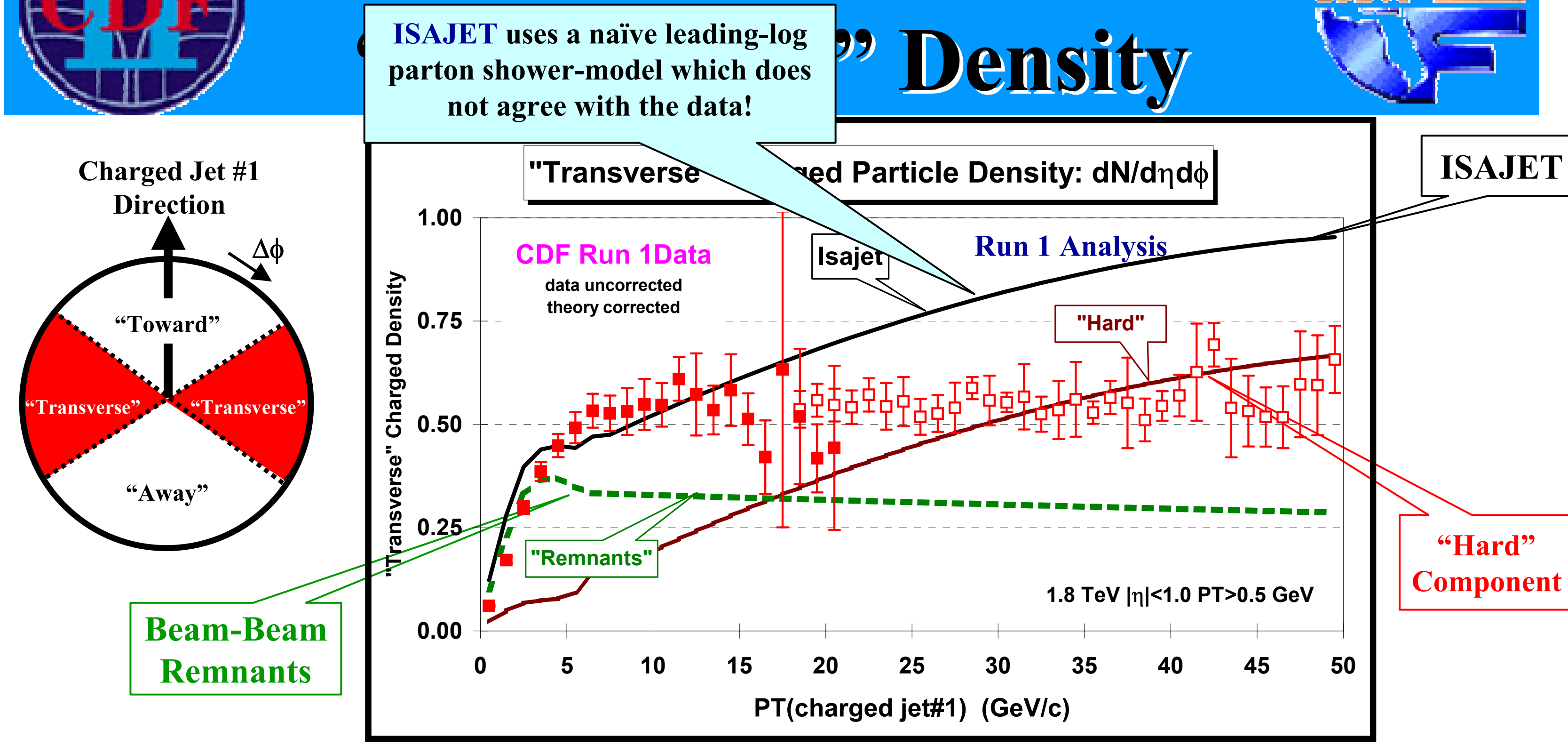


CDF "Min-Bias" data
($|\eta|<1$, $P_T>0.5$ GeV)
$\langle dPT_{sum}/d\eta d\phi \rangle = 0.23$ GeV/c

- **Data on the average charge scalar PT_{sum} density ($p_T > 0.5$ GeV, $|\eta| < 1$) in the "transverse" ($60<|\Delta\phi|<120^o$) region as a function of the transverse momentum of the leading charged particle jet. Each point corresponds to the $\langle dPT_{sum}/d\eta d\phi \rangle$ in a 1 GeV bin. The solid (open) points are the Min-Bias (JET20) data. The errors on the (*uncorrected*) data include both statistical and correlated systematic uncertainties.**

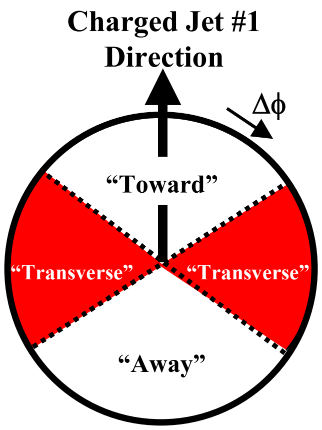
ISAJET 7.32

“ ” Density

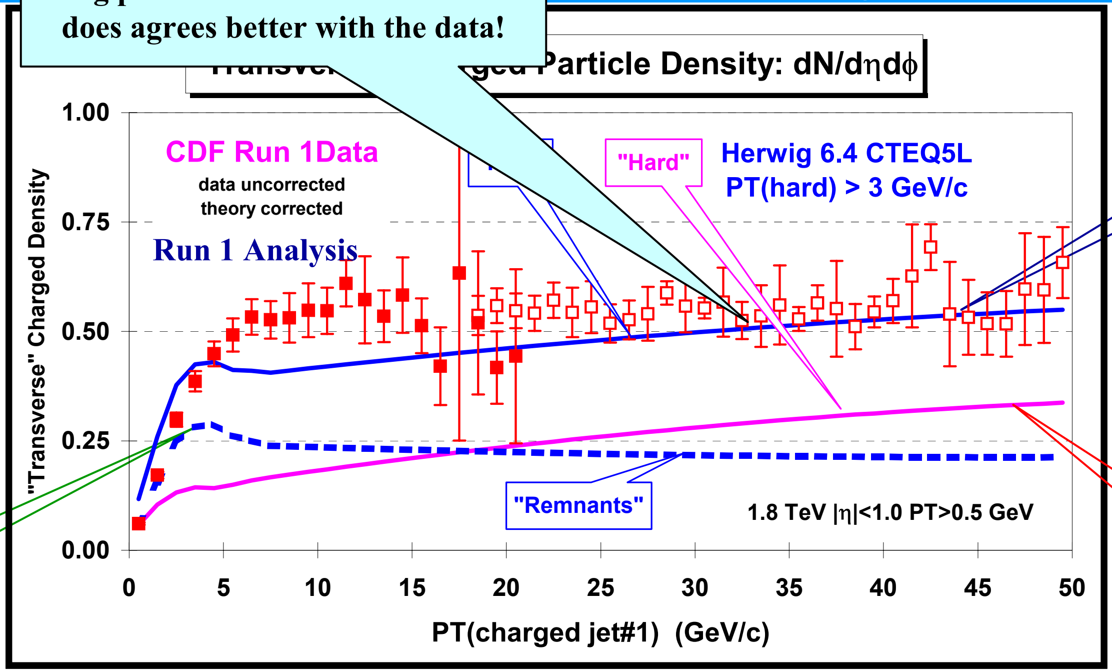


- Plot shows average “transverse” charge particle density (|η|<1, p_T>0.5 GeV) versus P_T(charged jet#1) compared to the QCD hard scattering predictions of ISAJET 7.32 (default parameters with P_T(hard)>3 GeV/c) .
- The predictions of ISAJET are divided into two categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants); and charged particles that arise from the outgoing jet plus initial and final-state radiation (hard scattering component).

HERWIG 6.4
“T ” Density



HERWIG uses a modified leading-log parton shower-model which does agrees better with the data!



HERWIG

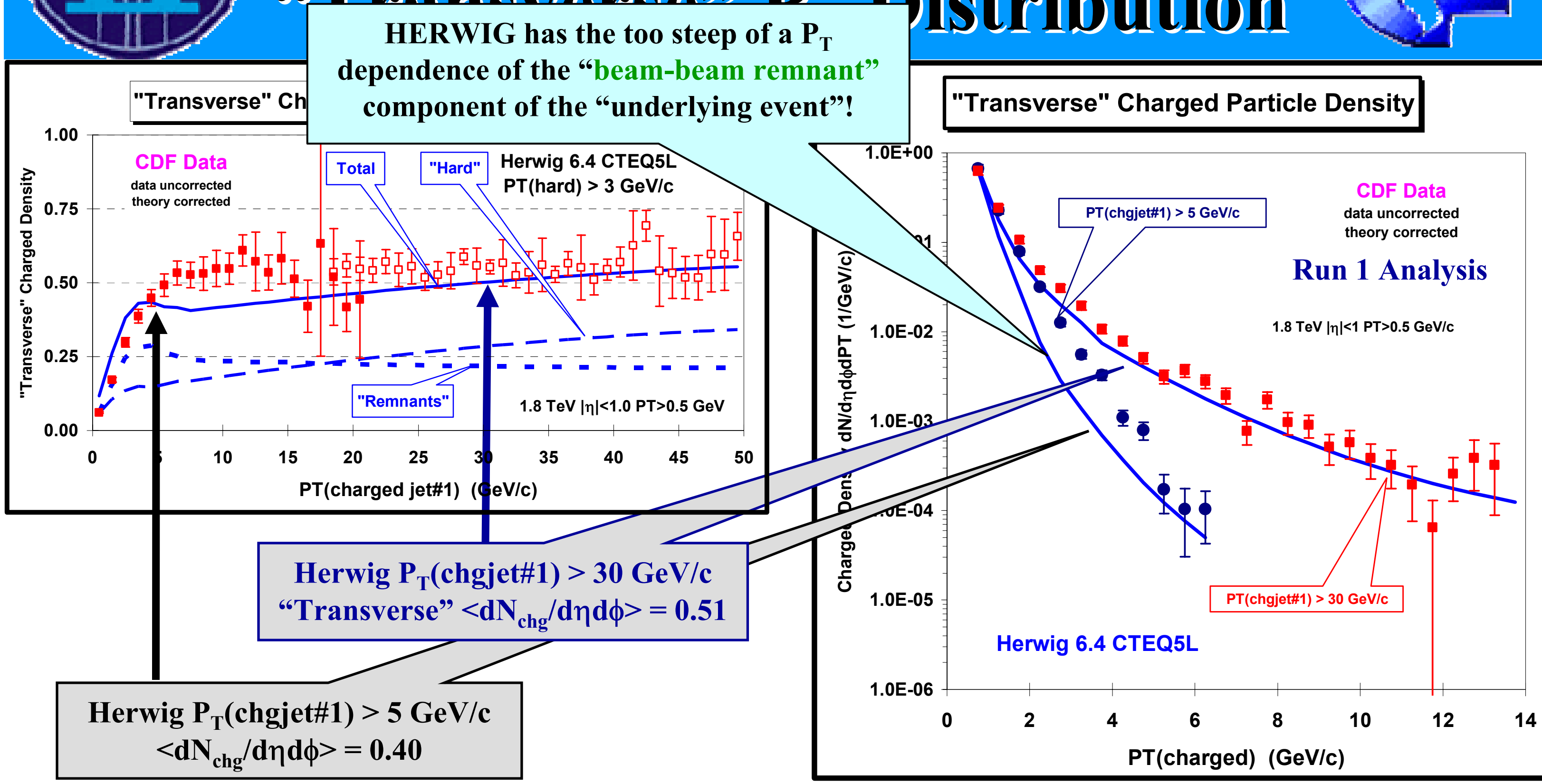
Beam-Beam Remnants

“Hard” Component

- Plot shows average “transverse” charge particle density ($|\eta|<1$, $p_T>0.5$ GeV) versus P_T(charged jet#1) compared to the QCD hard scattering predictions of HERWIG 5.9 (default parameters with P_T(hard)>3 GeV/c).
- The predictions of HERWIG are divided into two categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants); and charged particles that arise from the outgoing jet plus initial and final-state radiation (hard scattering component).

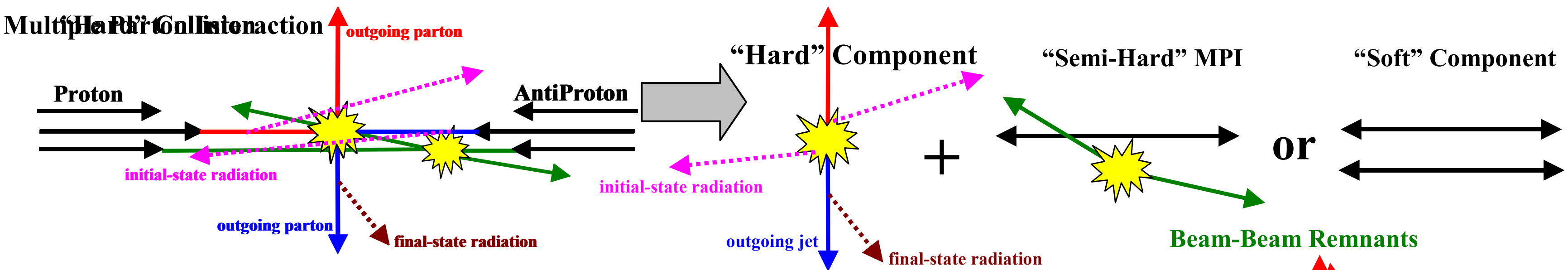
HERWIG 6.4

“Transverse” P_T Distribution

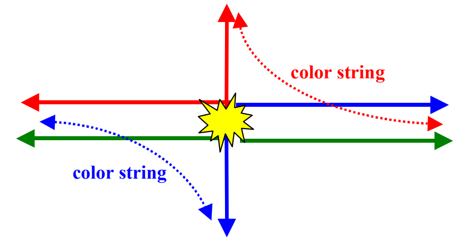


- Compares the average “transverse” charge particle density ($|\eta|<1$, $p_T>0.5$ GeV) versus P_T(charged jet#1) and the p_T distribution of the “transverse” density, $dN_{chg}/d\eta d\phi dp_T$ with the QCD hard scattering predictions of **HERWIG 6.4** (default parameters with P_T(hard)>3 GeV/c. Shows how the “transverse” charge particle density is distributed in p_T.

MPI: Multiple Parton Interactions



- PYTHIA models the “soft” component of the underlying event with color string fragmentation, but in addition includes a contribution arising from multiple parton interactions (MPI) in which one interaction is hard and the other is “semi-hard”.



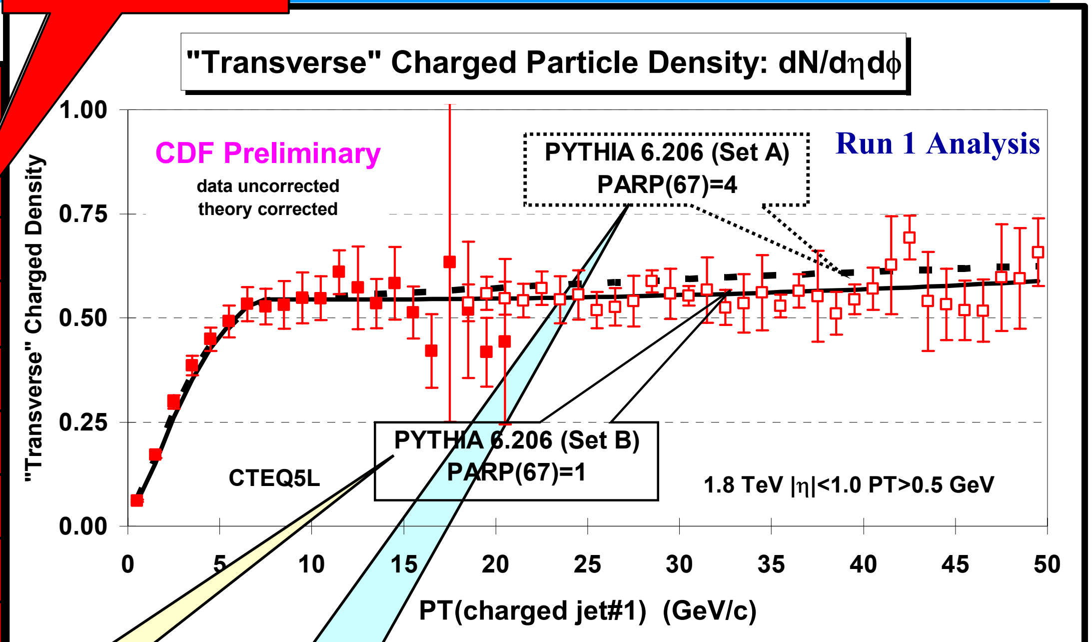
- The probability that a hard scattering events also contains a semi-hard multiple parton interaction can be varied but adjusting the cut-off for the MPI.
- One can also adjust whether the probability of a MPI depends on the P_T of the hard scattering, P_T(hard) (constant cross section or varying with impact parameter).
- One can adjust the color connections and flavor of the MPI (singlet or nearest neighbor, q-qbar or glue-glue).
- Also, one can adjust how the probability of a MPI depends on P_T(hard) (single or double Gaussian matter distribution).

Tuned PYTHIA 6.206

Tune A CDF Run 2 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

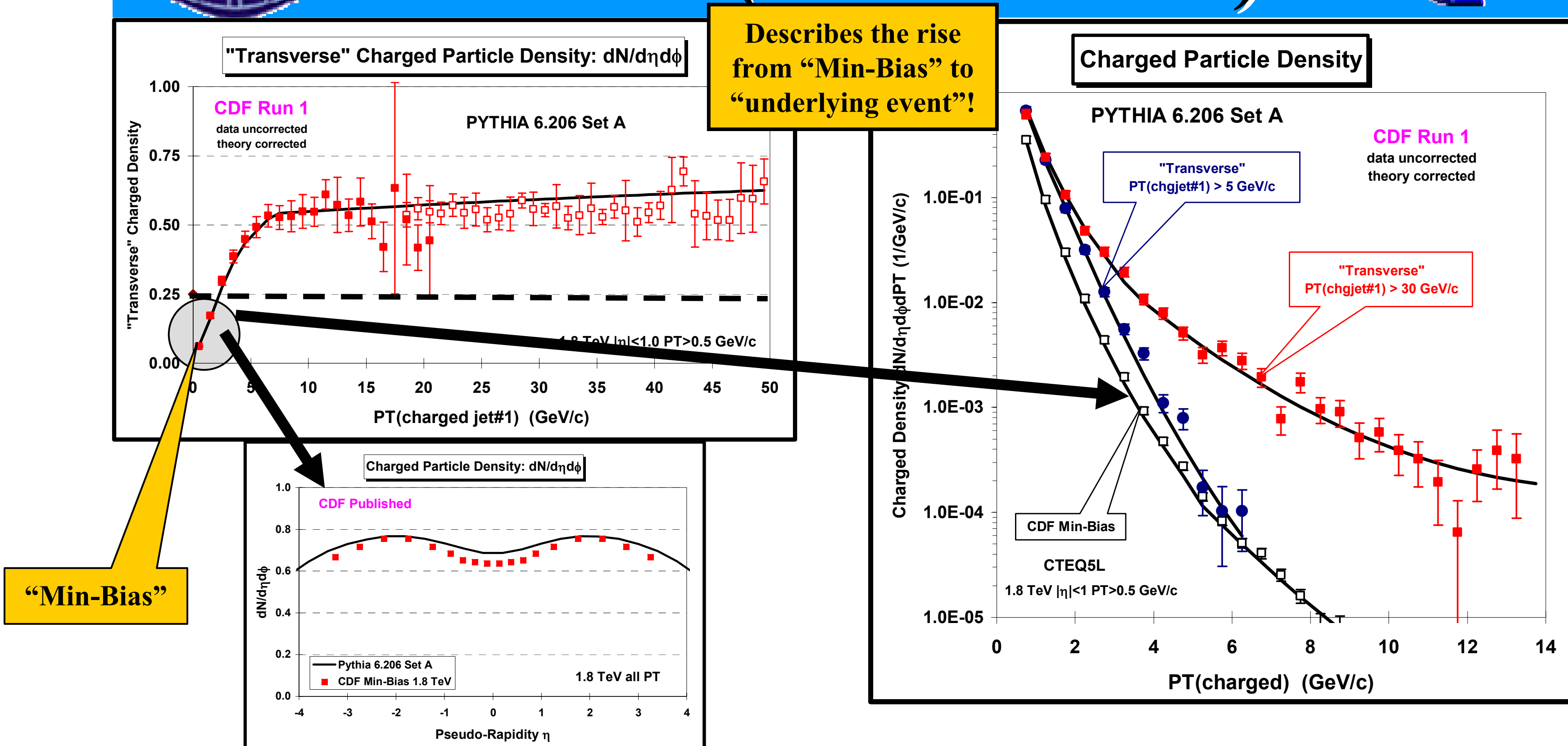


- Plot shows the "Transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

New PYTHIA default (less initial-state radiation)

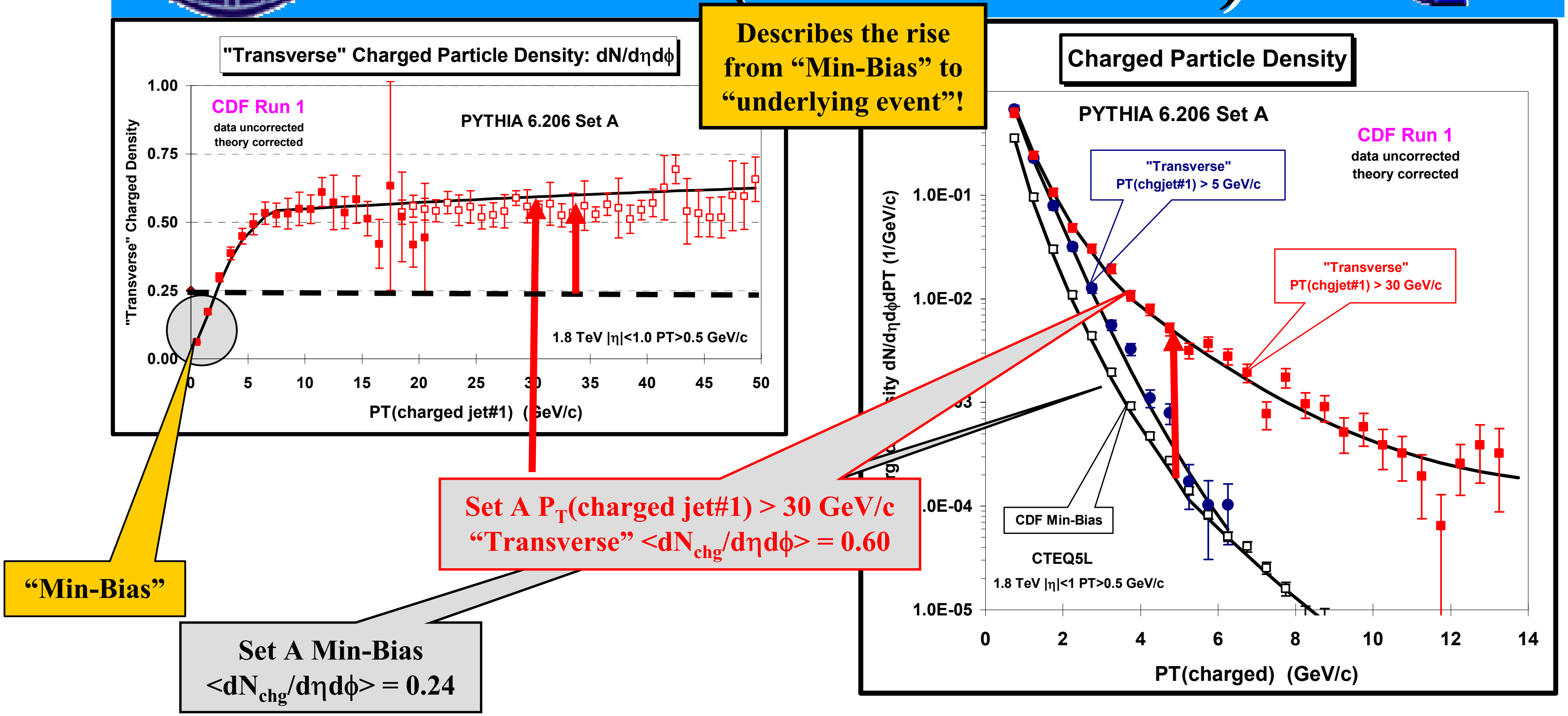
Old PYTHIA default (more initial-state radiation)

PYTHIA 6.206
Tune A (CDF Default)



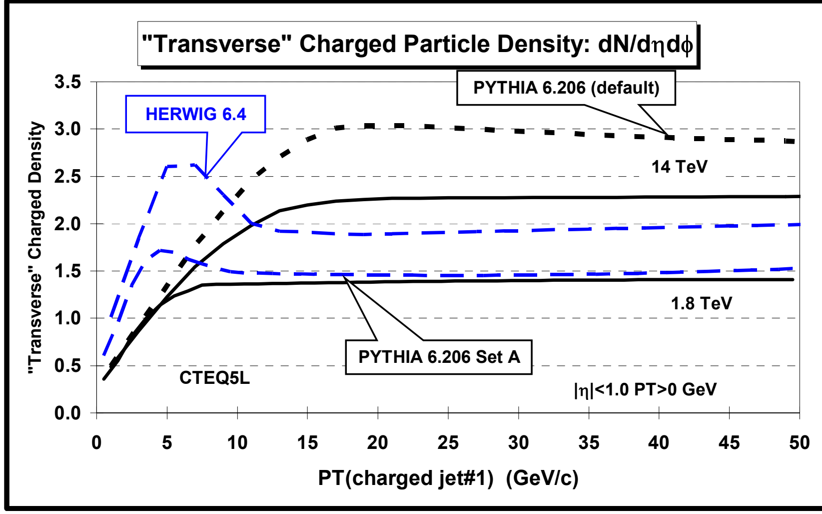
- Compares the average "transverse" charge particle density ($|\eta|<1$, $p_T>0.5$ GeV) versus P_T(charged jet#1) and the p_T distribution of the "transverse" and "Min-Bias" densities with the QCD Monte-Carlo predictions of a tuned version of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L, Set A). Describes "Min-Bias" collisions! Describes the "underlying event"!

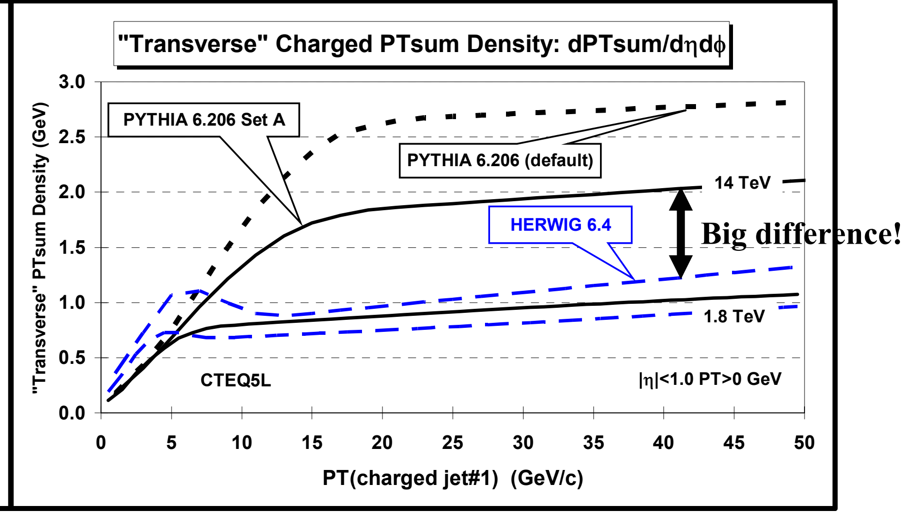
PYTHIA 6.206 Tune A (CDF Default)



- Compares the average "transverse" charge particle density ($|\eta|<1$, $p_T>0.5$ GeV) versus P_T(charged jet#1) and the p_T distribution of the "transverse" and "Min-Bias" densities with the QCD Monte-Carlo predictions of a tuned version of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L, Set A). Describes "Min-Bias" collisions! Describes the "underlying event"!

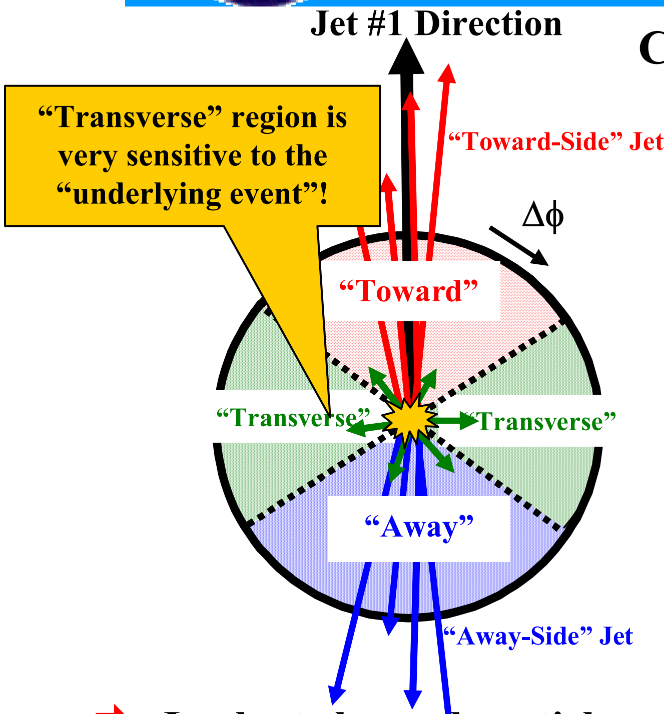
Tuned PYTHIA (Tune A) LHC Predictions



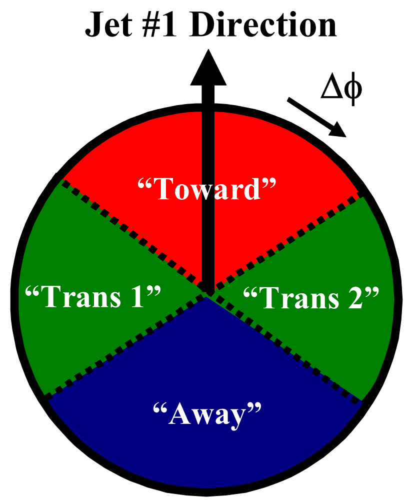


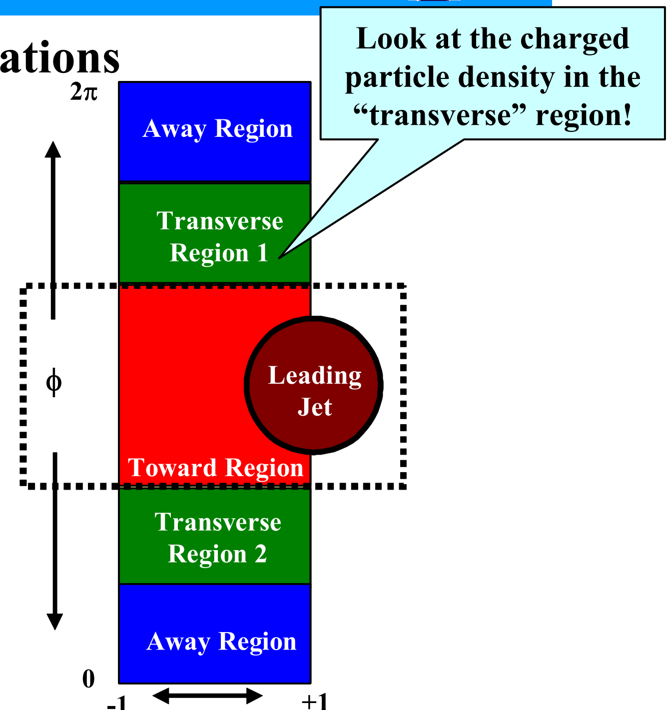
- Shows the average "transverse" charge particle and PT_{sum} density ($|\eta|<1$, $P_T>0$) versus P_T(charged jet#1) predicted by HERWIG 6.4 (P_T(hard) > 3 GeV/c, CTEQ5L). and a tuned version of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L, Tune A) at 1.8 TeV and 14 TeV. Also shown is the 14 TeV prediction of PYTHIA 6.206 with the default value $\varepsilon = 0.16$.
- Tuned PYTHIA (Tune A) predicts roughly 2.3 charged particles per unit η-φ ($p_T > 0$) in the "transverse" region (14 charged particles per unit η) which is larger than the HERWIG prediction and less than the PYTHIA default prediction.

The "Transverse" Regions as defined by the Leading Jet



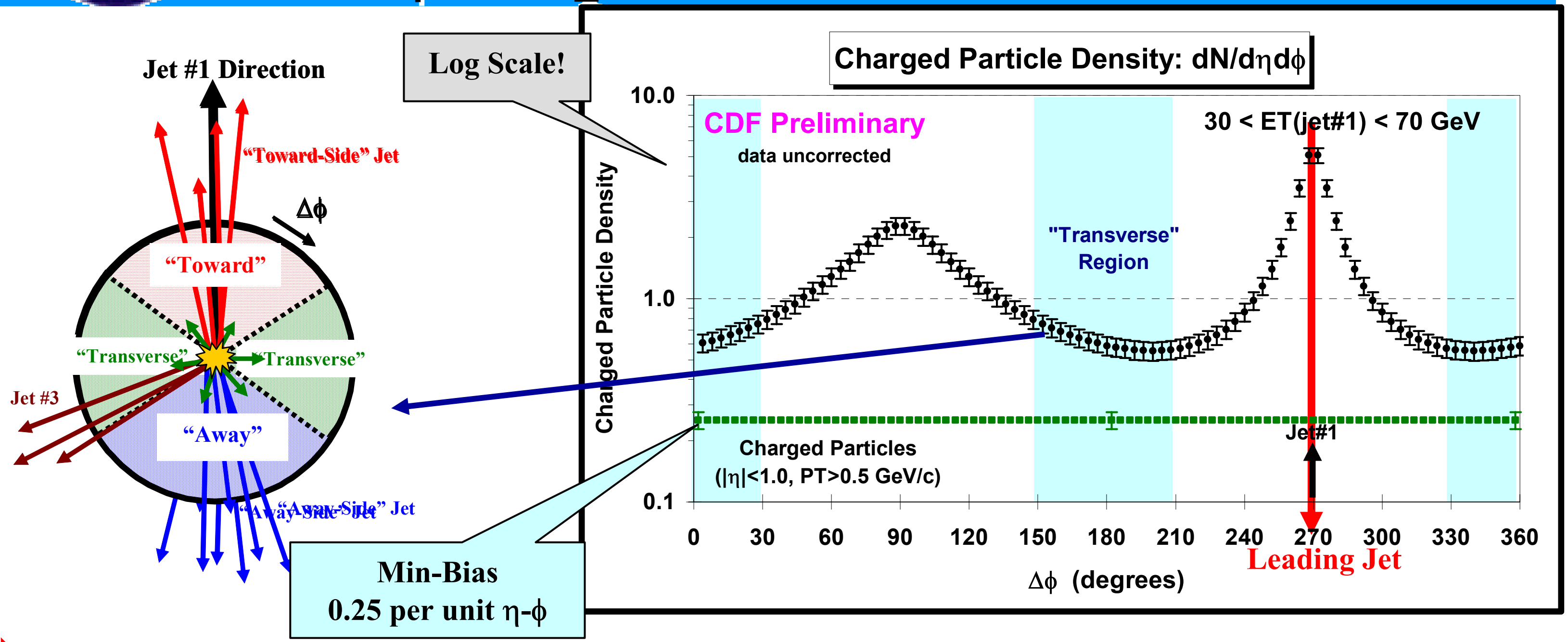
Charged Particle Δφ Correlations
$p_T > 0.5$ GeV/c $|\eta| < 1$





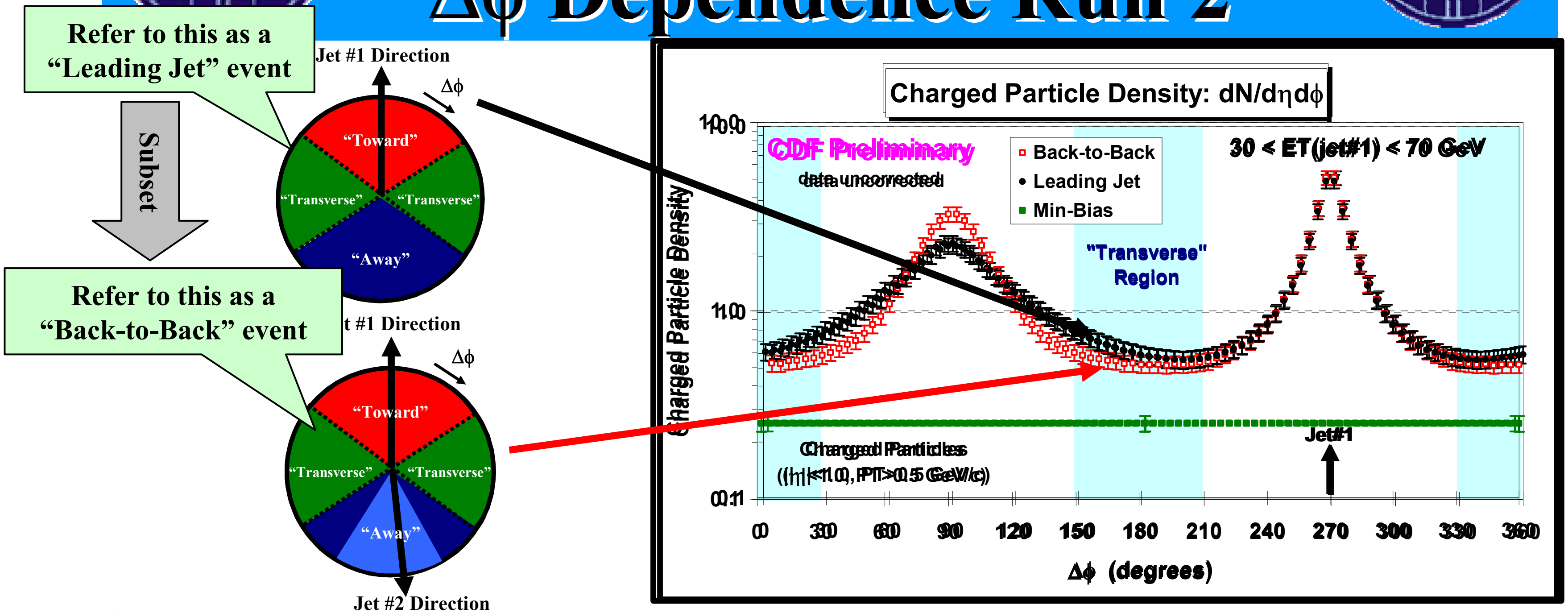
- Look at charged particle correlations in the azimuthal angle Δφ relative to the leading calorimeter jet (JetClu R = 0.7, |η| < 2).
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < -\Delta\phi < 120^o$ and $60^o < \Delta\phi < 120^o$ as "Transverse 1" and "Transverse 2", and $|\Delta\phi| > 120^o$ as "Away". Each of the two "transverse" regions have area $\Delta\eta\Delta\phi = 2\text{x}60^o = 4\pi/6$. 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 Δφ Dependence Run 2



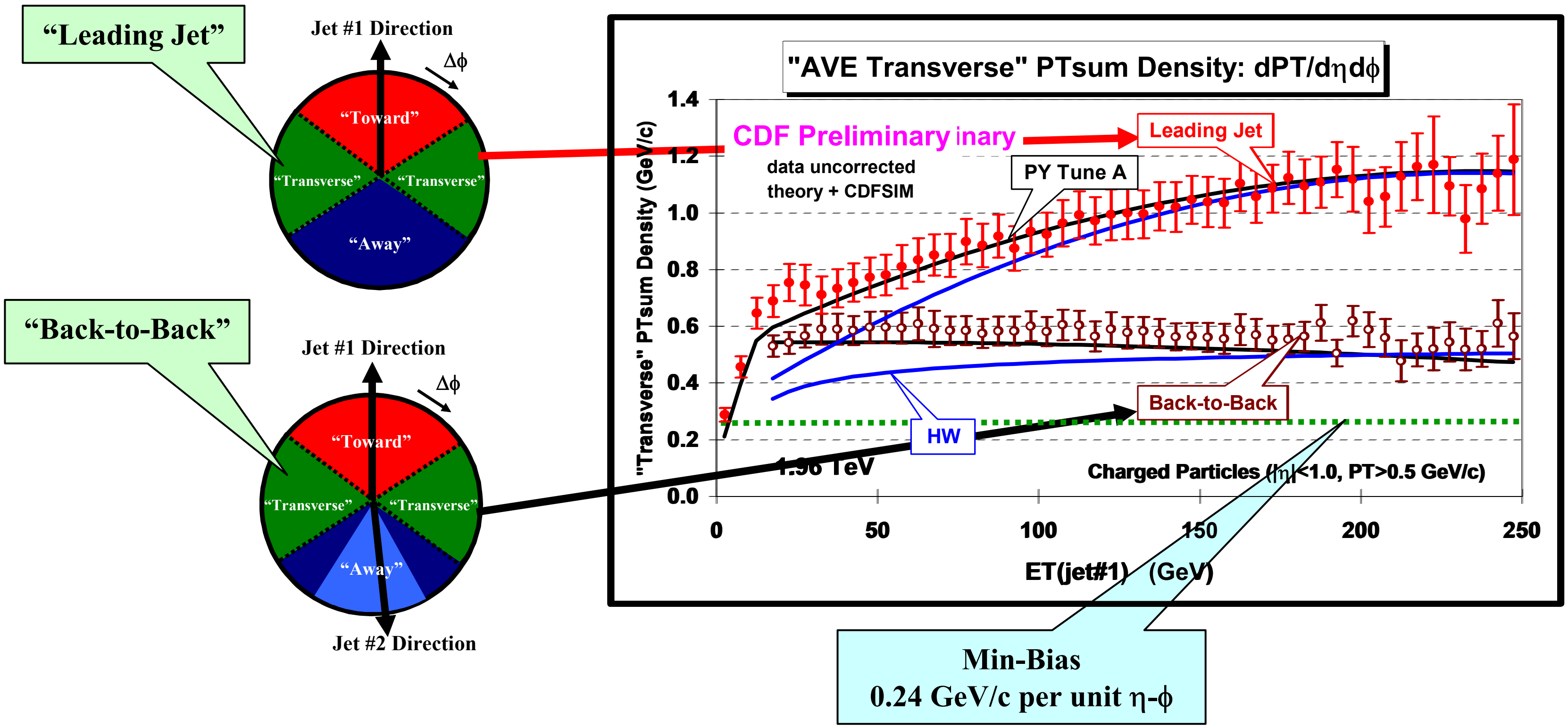
- Shows the **Δφ dependence of the charged particle density**, $dN_{chg}/d\eta d\phi$, for charged particles in the range $p_T > 0.5$ GeV/c and $|\eta| < 1$ relative to jet#1 (rotated to 270°) for **"leading jet"** events $30 < E_T(\text{jet\#1}) < 70$ GeV.
- Also shows charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles in the range $p_T > 0.5$ GeV/c and $|\eta| < 1$ for **"min-bias"** collisions.

Charged Particle Density $\Delta\phi$ Dependence Run 2



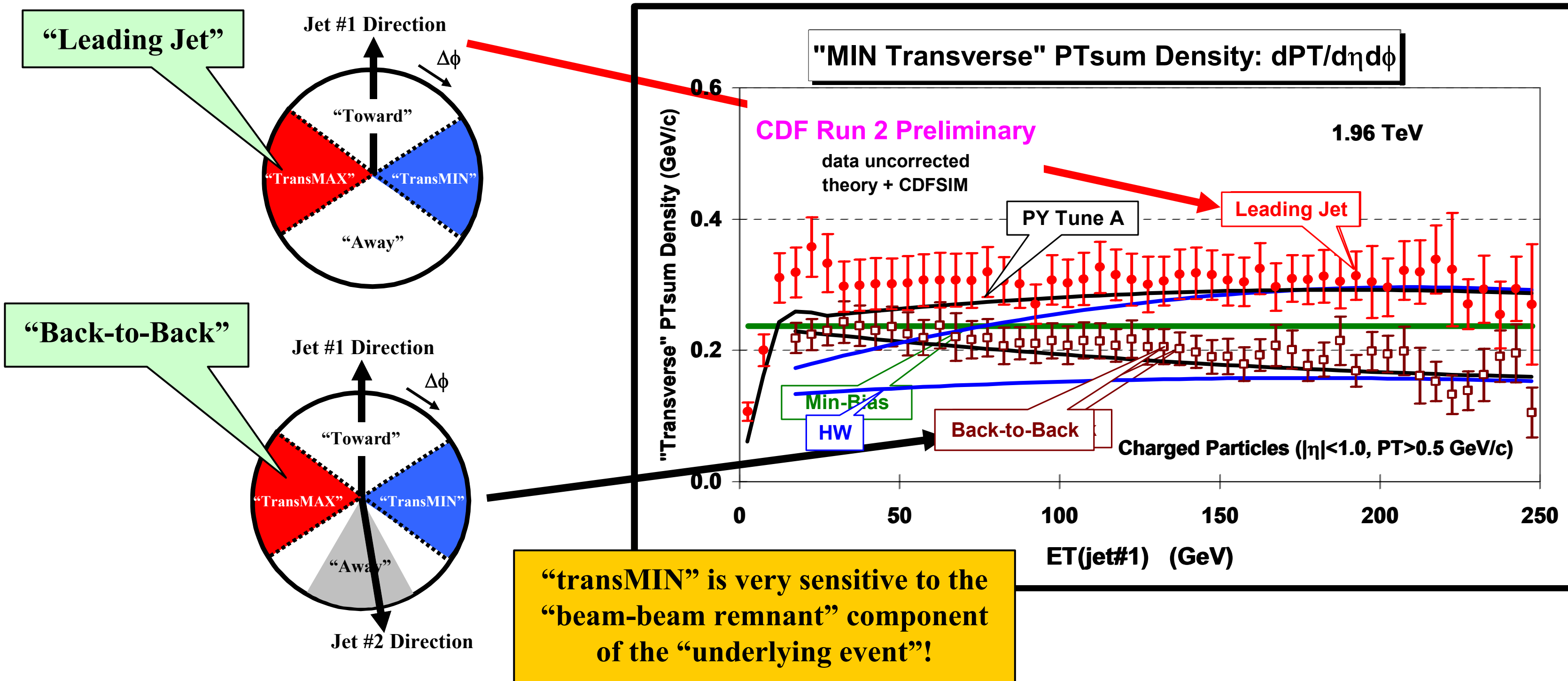
- Look at the **"transverse" region** as defined by the leading jet (JetClu R = 0.7, |η| < 2) or by the leading two jets (JetClu R = 0.7, |η| < 2). **"Back-to-Back"** events are selected to have at least two jets with Jet#1 and Jet#2 nearly "back-to-back" ($\Delta\phi_{12} > 150^o$) with almost equal transverse energies (E_T(jet#2)/E_T(jet#1) > 0.8) and E_T(jet#3) < 15 GeV.
- 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 |η| < 1 relative to jet#1 (rotated to 270°) for 30 < E_T(jet#1) < 70 GeV for **"Leading Jet"** and **"Back-to-Back"** events.

"Transverse" PTsum Density versus E_T(jet#1) Run 2



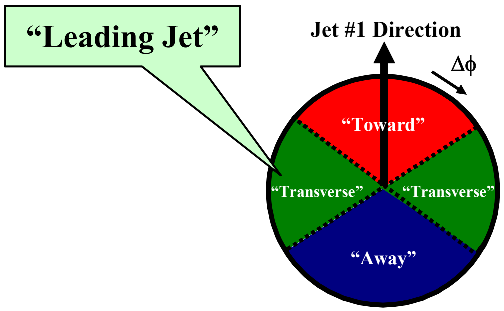
- Shows the **average charged PTsum density**, $dPT_{sum}/d\eta d\phi$, in the **"transverse" region** (p_T > 0.5 GeV/c, $|\eta|$ < 1) versus E_T(jet#1) for **"Leading Jet"** and **"Back-to-Back"** events.
- Compares the (*uncorrected*) data with **PYTHIA Tune A** and **HERWIG** after CDFSIM.

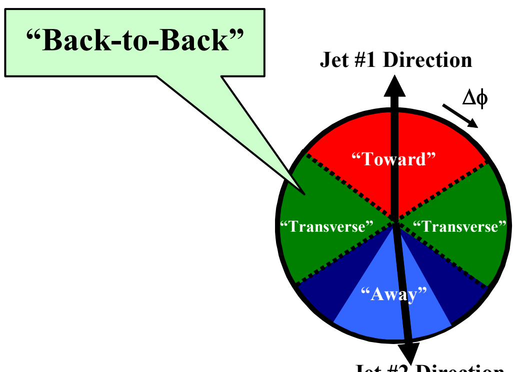
"TransMIN" PTsum Density versus E_T(jet#1)

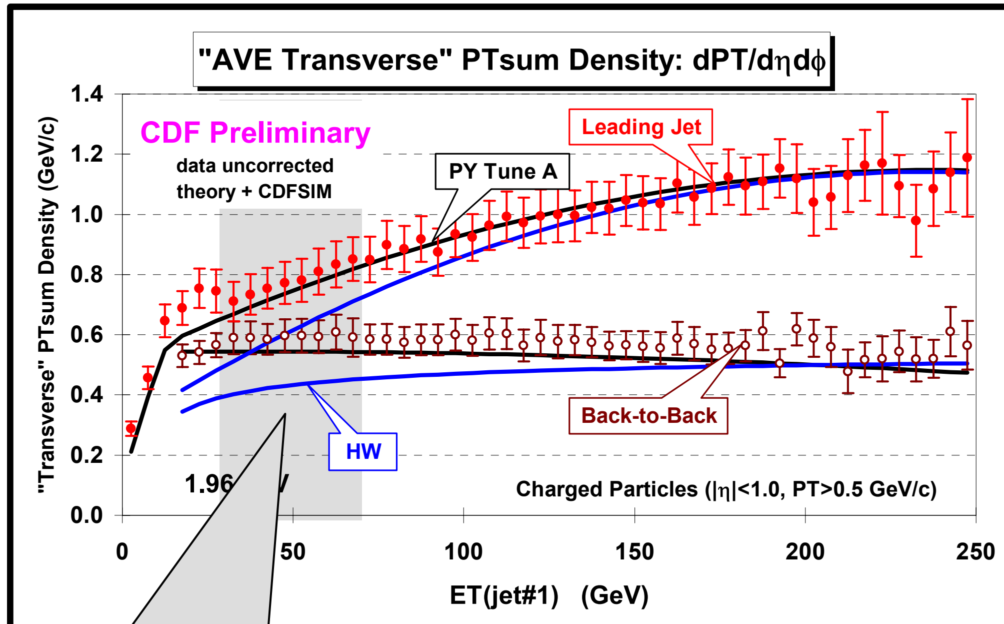


- Use the leading jet to define the MAX and MIN "transverse" regions on an event-by-event basis with MAX (MIN) having the largest (smallest) charged particle density.
- Shows the **"transMIN" charge particle density**, $dN_{chg}/d\eta d\phi$, for $p_T > 0.5$ GeV/c, $|\eta| < 1$ versus E_T(jet#1) for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

"Transverse" PTsum Density
PYTHIA Tune A vs HERWIG





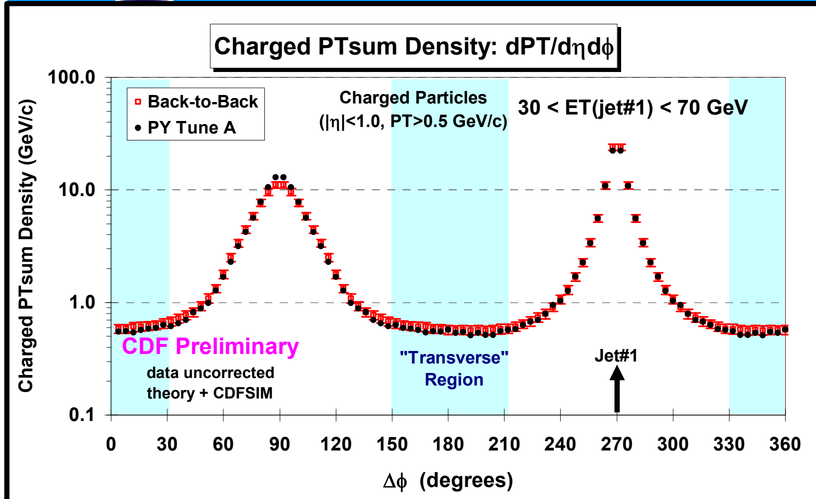


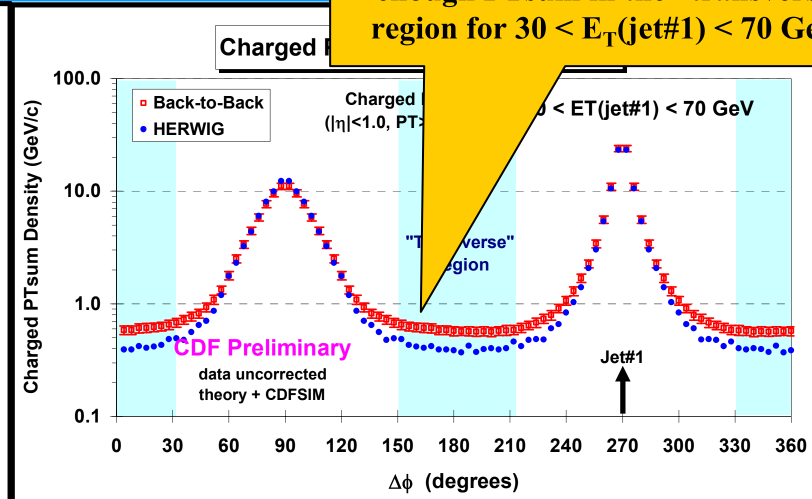
Now look in detail at "back-to-back" events in the region $30 < E_T(\text{jet\#1}) < 70$ GeV!

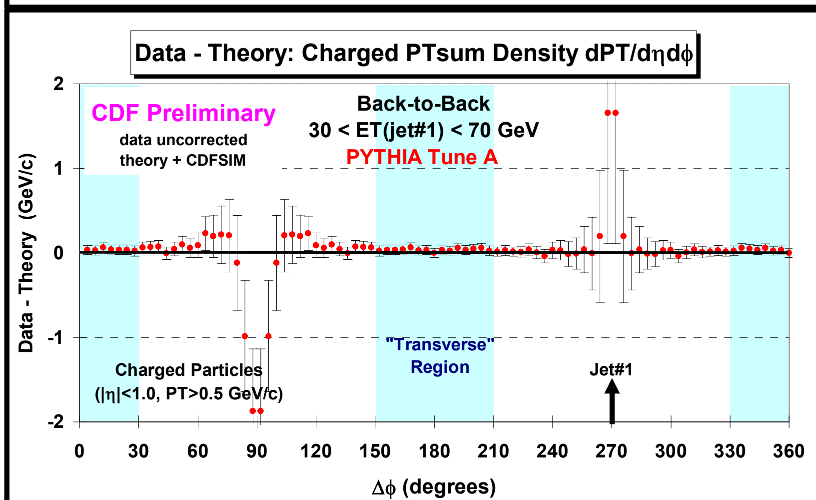
- **Shows the average charged PTsum density, $dPT_{sum}/d\eta d\phi$, in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events.**
- **Compares the (*uncorrected*) data with PYTHIA Tune A and HERWIG after CDFSIM.**

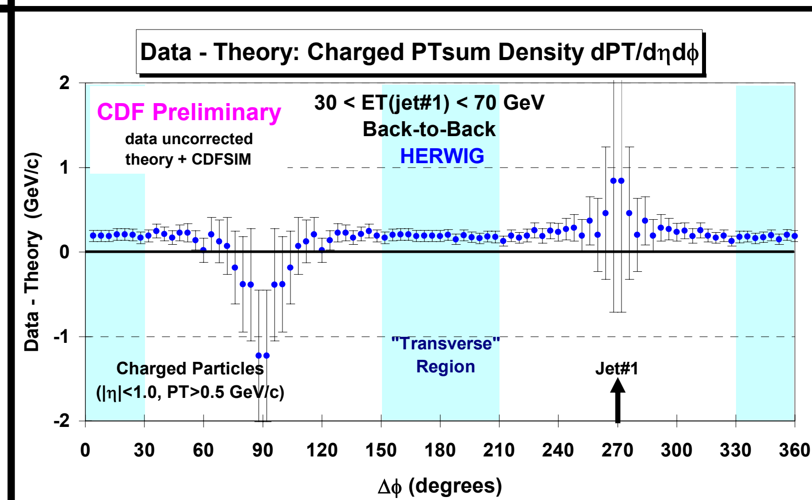
Charged PTsum Density
PYTHIA Tune A vs HERWIG

HERWIG (*without multiple parton interactions*) does not produces enough PTsum in the "transverse" region for 30 < E_T(jet#1) < 70 GeV!





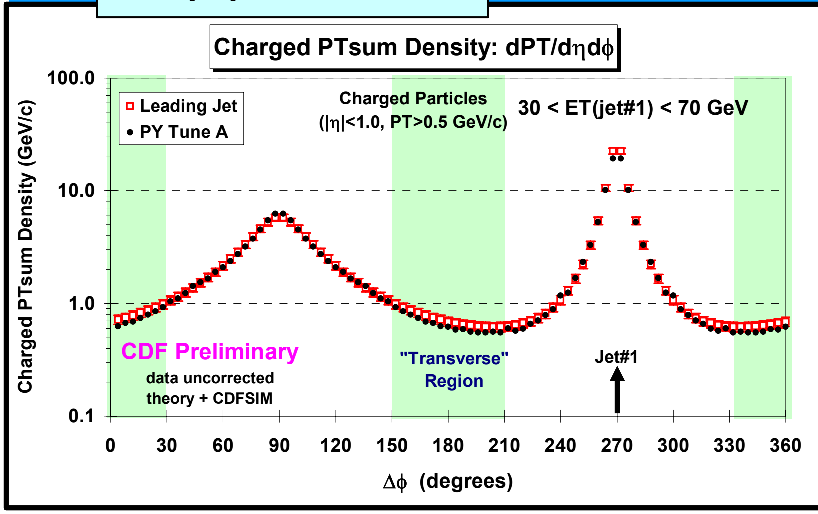


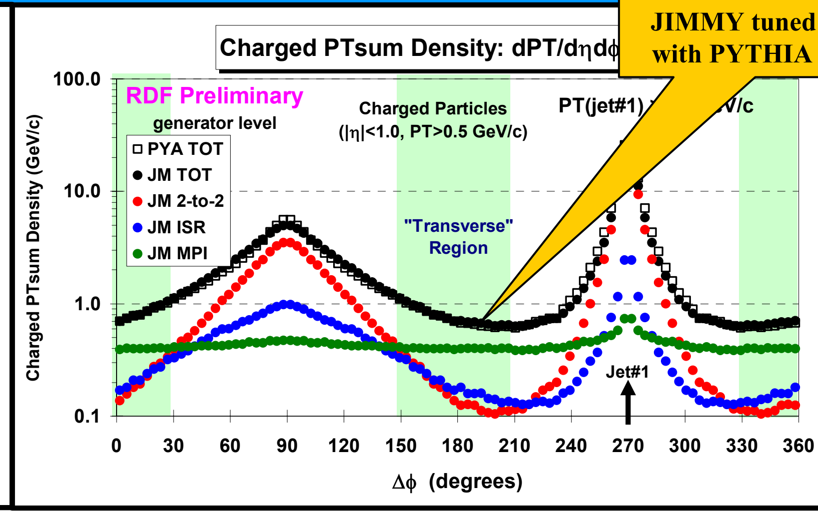


Tuned JIMMY versus PYTHIA Tune A

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

JIMMY
Runs with HERWIG and adds multiple parton interactions!

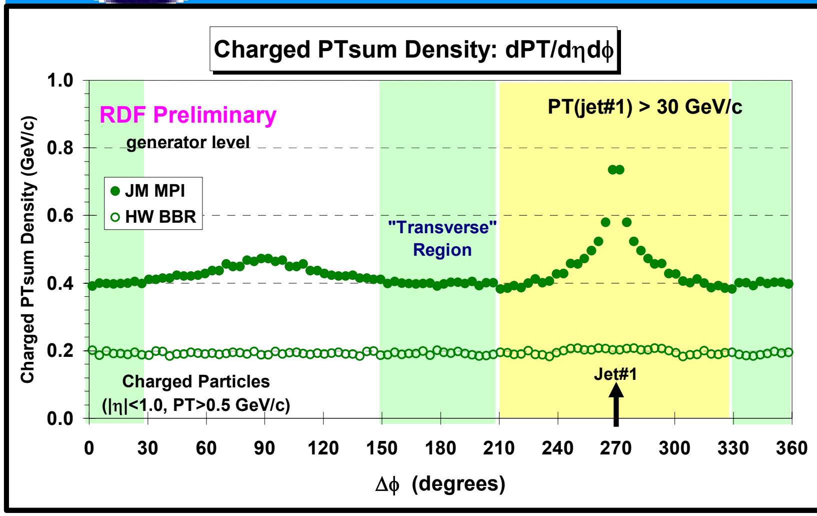


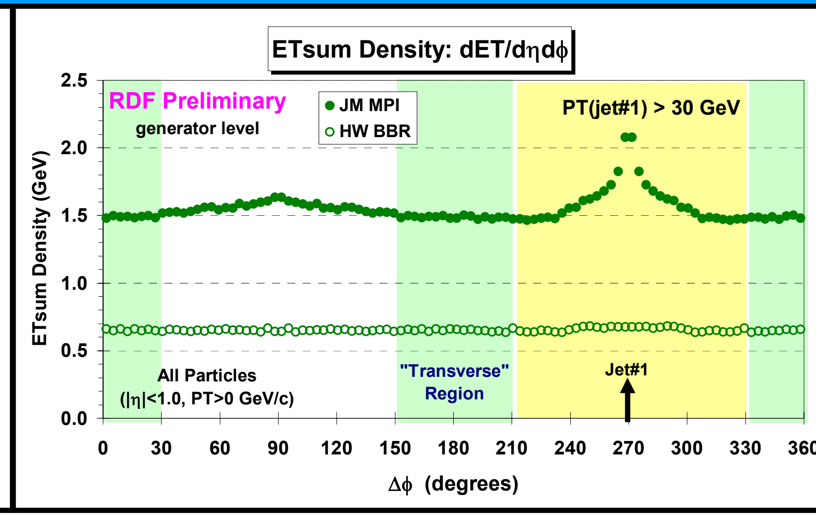


JIMMY tuned to agree with PYTHIA Tune A!

- (*left*) Shows the Run 2 data on the Δφ dependence of the charged *scalar* PTsum density (|η|<1, p_T>0.5 GeV/c) relative to the leading jet for 30 < E_T(jet#1) < 70 GeV/c compared with PYTHIA Tune A (*after CDFSIM*).
- (*right*) Shows the generator level predictions of PYTHIA Tune A and a tuned version of JIMMY (PT_{min}=1.8 GeV/c) for the Δφ dependence of the charged *scalar* PTsum density (|η|<1, p_T>0.5 GeV/c) relative to the leading jet for PT(jet#1) > 30 GeV/c. The tuned JIMMY and PYTHIA Tune A agree in the "transverse" region.
- (*right*) For JIMMY the contributions from the multiple parton interactions (MPI), initial-state radiation (ISR), and the 2-to-2 hard scattering plus finial-state radiation (2-to-2+FSR) are shown.

JIMMY (MPI) versus HERWIG (BBR)





- (*left*) Shows the generator level predictions of JIMMY (MPI, PT_{min}=1.8 GeV/c) and HERWIG (BBR) for the Δφ dependence of the charged *scalar* PTsum density (|η|<1, p_T>0.5 GeV/c) relative to the leading jet for P_T(jet#1) > 30 GeV/c.
- (*right*) Shows the generator level predictions of JIMMY (MPI, PT_{min}=1.8 GeV/c) and HERWIG (BBR) for the Δφ dependence of the *scalar* ETsum density (|η|<1, p_T>0 GeV/c) relative to the leading jet for P_T(jet#1) > 30 GeV/c.
- The "multiple-parton interaction" (MPI) contribution from JIMMY is about a factor of two larger than the "beam-beam remnant" (BBR) contribution from HERWIG. The JIMMY program replaces the HERWIG BBR with its MPI.

New Models: SHERPA

SHERPA

- Uses the CKKW approach for combining matrix elements and parton showers.
- Uses T. Sjöstand's multiple parton interaction formalism with parton showers for the multiple interactions.
- Combines multiple parton interactions with the CKKW merging procedure.

The SHERPA Group

Tanju Gleisberg
Stefan Höche
Frank Krauss
Caroline Semmling
Thomas Laubrich
Andreas Schälicke
Steffen Schumann
Jan Winter

New Models: SHERPA

Taken from Stefan Höche's talk at HERA-LHC Workshop, DESY, March 21, 2005.

SHERPA

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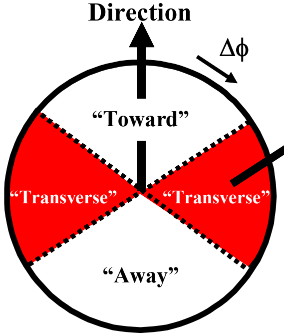
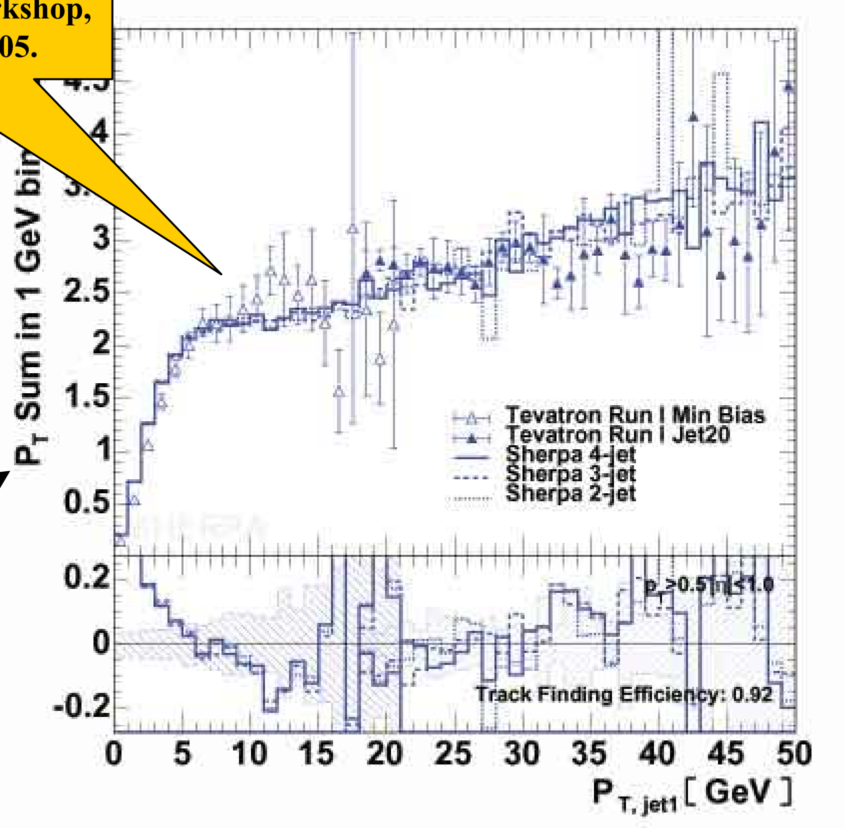


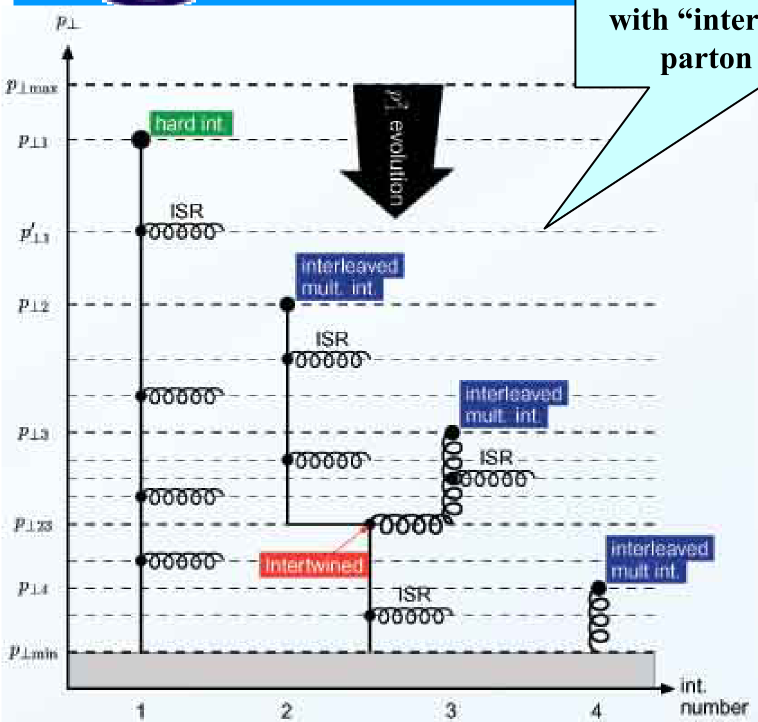


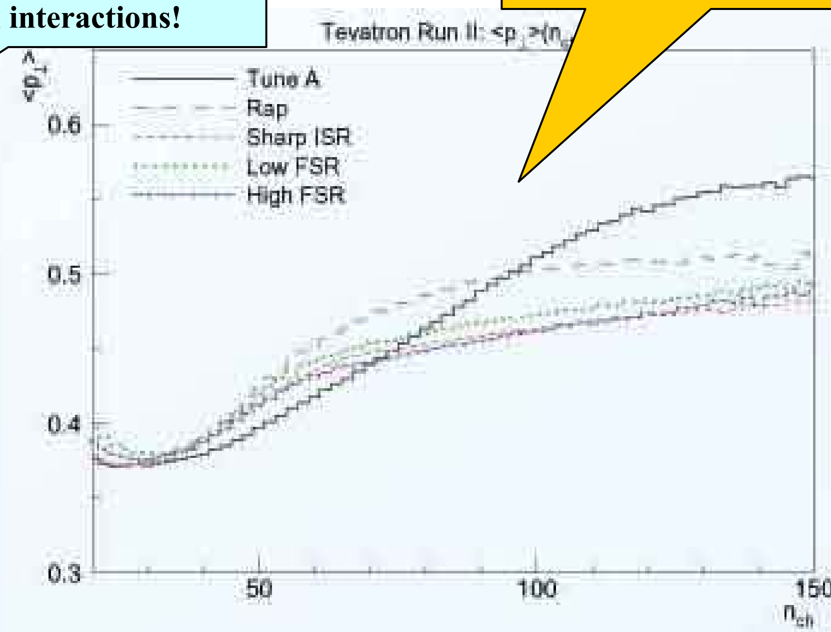
- Shows the published CDF (Run 1) data on the average "transverse" charged PTsum ($|\eta|<1$, $p_T>0.5$ GeV) as a function of the transverse momentum of the leading charged particle jet compared with SHERPA.

New Models: PYTHIA 6.3

New parton shower model with "interleaved" multiple parton interactions!

Taken from Peter Skand's TeV4LHC talk, December, 2004.



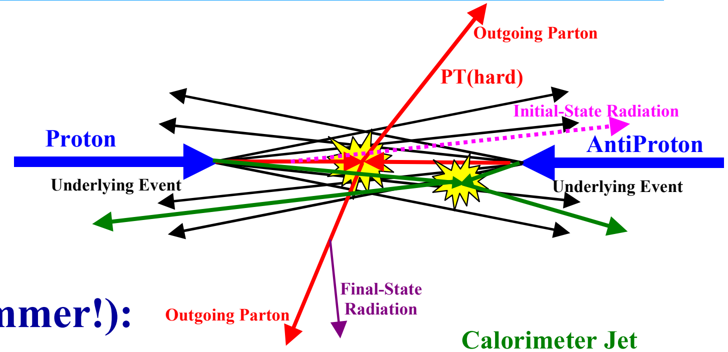


- T. Sjöstand and P. Skands, "Transverse-Momentum Ordered Showers and Interleaved Multiple Interactions", hep-ph/0408302. T. Sjostand and P. Skands, "Multiple Interactions and the Structure of Beam Remnants", JHEP 0403 (2004) 053.

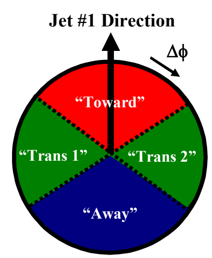
- Compares PYTHIA 6.3 with PYTHIA 6.2 Tune A for the average P_T of charged particles versus the number of charged particles.

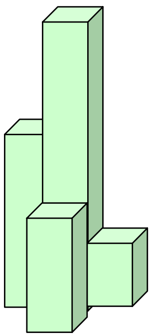
Outlook

- We have made a lot of progress in understanding the “underlying event” at CDF!



- **More to come from CDF!**
  - **Run 2 “underlying event” publication (this summer!):**
    - MidPoint algorithm.
    - “Leading Jet” and “Back-to-Back” events.
    - Data corrected to the particle level.
    - Energy as well as charged particles.
  - **HERWIG + JIMMY running within CDF framework.**
  - **PYTHIA 6.3 running within CDF framework.**
  - **SHERPA running within CDF framework.**



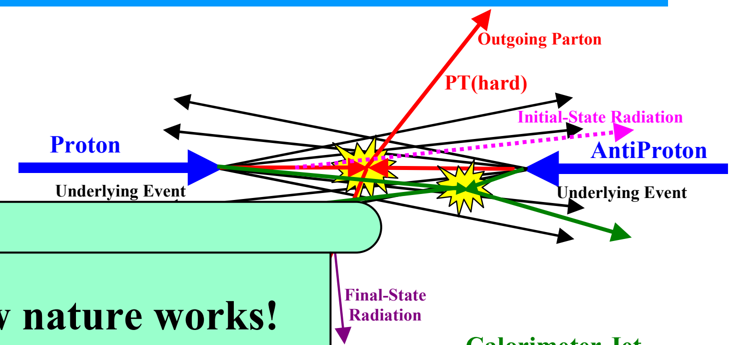


- The theorists are making good progress in constructing more realistic models of multiple parton interactions and the “underlying event”!

HERWIG + JIMMY **PYTHIA 6.3** **SHERPA**

Outlook

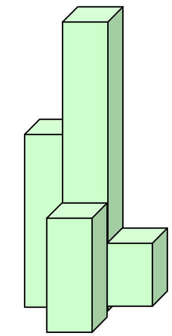
- We have made a lot of progress in understanding the "underlying event" at CDF!



- **More to come**
  - Run 2 "und
    - MidPo
    - "Leadi
    - Data c
    - Energy
  - HERWIG
  - PYTHIA 6.3 running within CDF framework.
  - SHERPA running within CDF framework.

We are learning more about how nature works! Although we cannot yet predict what the "underlying event" will look like at the LHC, we are improving the analysis "tools" that will be used at the next generation collider.

Calorimeter Jet



MidPoint Algorithm

- The theorists are making good progress in constructing more realistic models of multiple parton interactions and the "underlying event"!

HERWIG + JIMMY — PYTHIA 6.3 — SHERPA