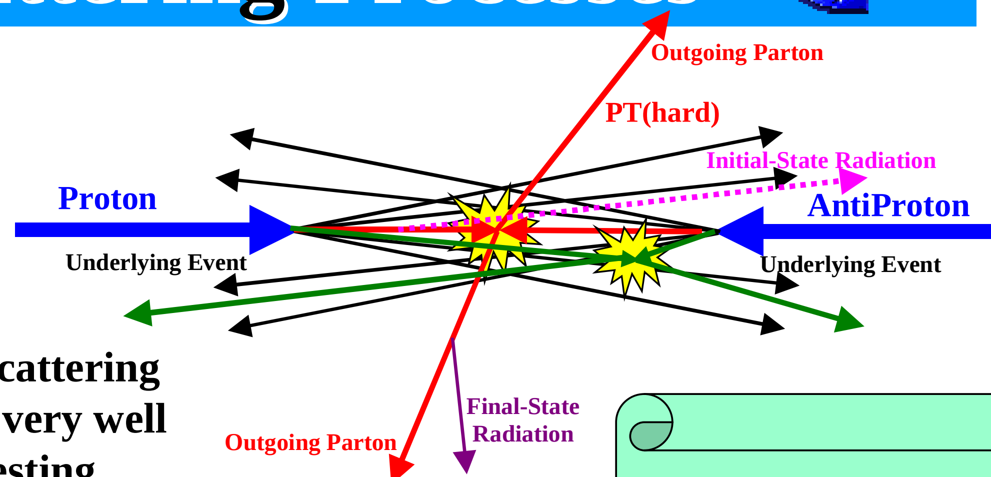
The Underlying Event in Hard Scattering Processes

The Underlying Event:
beam-beam remnants
initial-state radiation
multiple-parton interactions



- **The underlying event in a hard scattering process is a complicated and not very well understood object. It is an interesting region since it probes the interface between perturbative and non-perturbative physics.**
- **It is important to model this region well since it is an unavoidable background to all collider observables.**
- **I will report on two CDF analyses which quantitatively study the underlying event and compare with the QCD Monte-Carlo models.**

CDF
QFL+Cones
Valeria Tano
Eve Kovacs
Joey Huston
Anwar Bhatti

CDF
WYSIWYG+Δφ
Rick Field
David Stuart
Rich Haas

Ph.D. Thesis

WYSIWYG: Comparing Data with QCD Monte-Carlo Models

Charged Particle Data

Select "clean" region

- Zero or one vertex
- $|z_c - z_v| < 2$ cm, $|\text{CTC } d_0| < 1$ cm
- Require $P_T > 0.5$ GeV, $|\eta| < 1$
- Assume a uniform track finding efficiency of 92%
- Errors include both statistical and correlated systematic uncertainties

Uncorrected data

WYSIWYG
What you see is what you get.
Almost!

Look only at the charged particles measured by the CTC.

compare

QCD Monte-Carlo

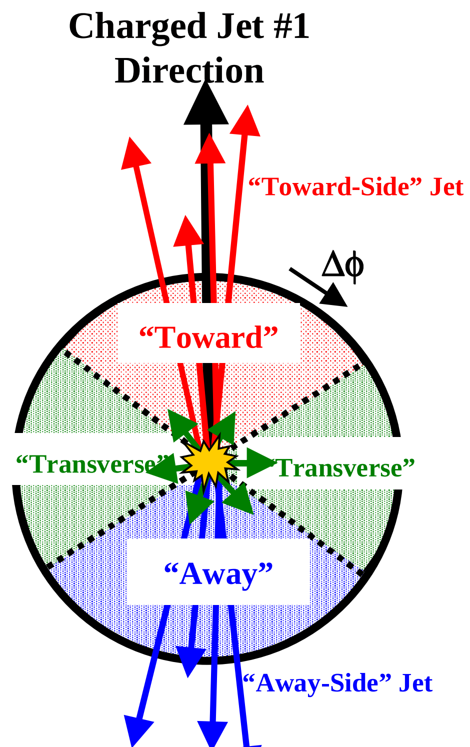
Make efficiency corrections

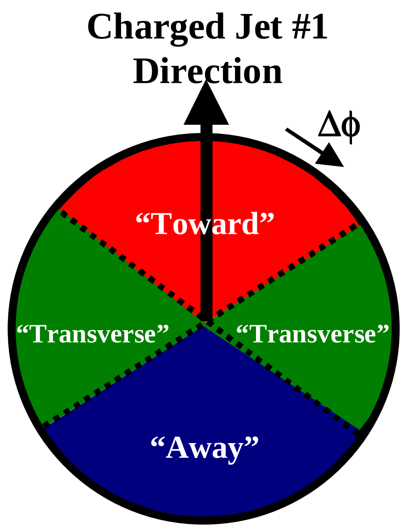
- Require $P_T > 0.5$ GeV, $|\eta| < 1$
- Make an 8% correction for the track finding efficiency
- Errors (statistical plus systematic) of around 5%

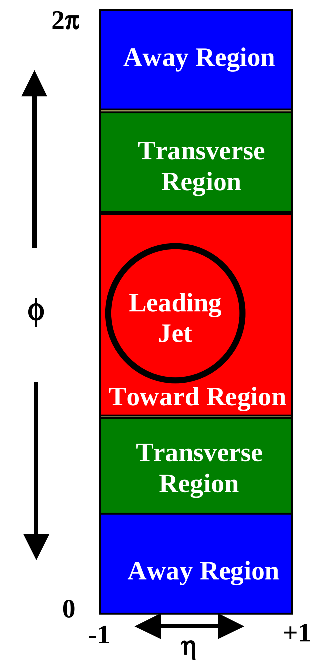
Corrected theory

Small Corrections!

Charged Particle $\Delta\phi$ Correlations

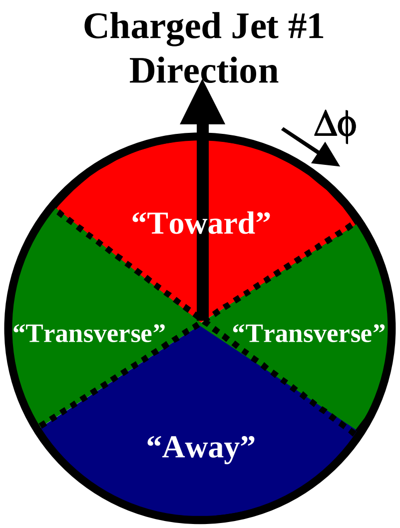


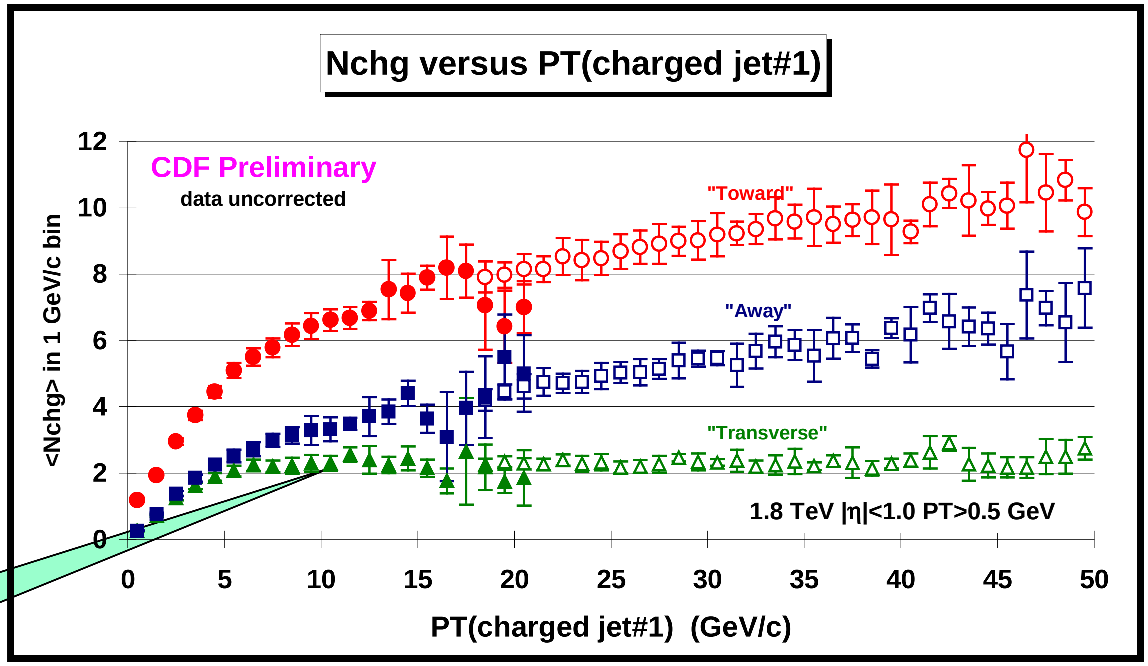




- **Look at charged particle correlations in the azimuthal angle $\Delta\phi$ relative to the leading charged particle jet.**
- **Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away".**
- **All three regions have the same size in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

Charged Multiplicity versus P_T(chgjet#1)

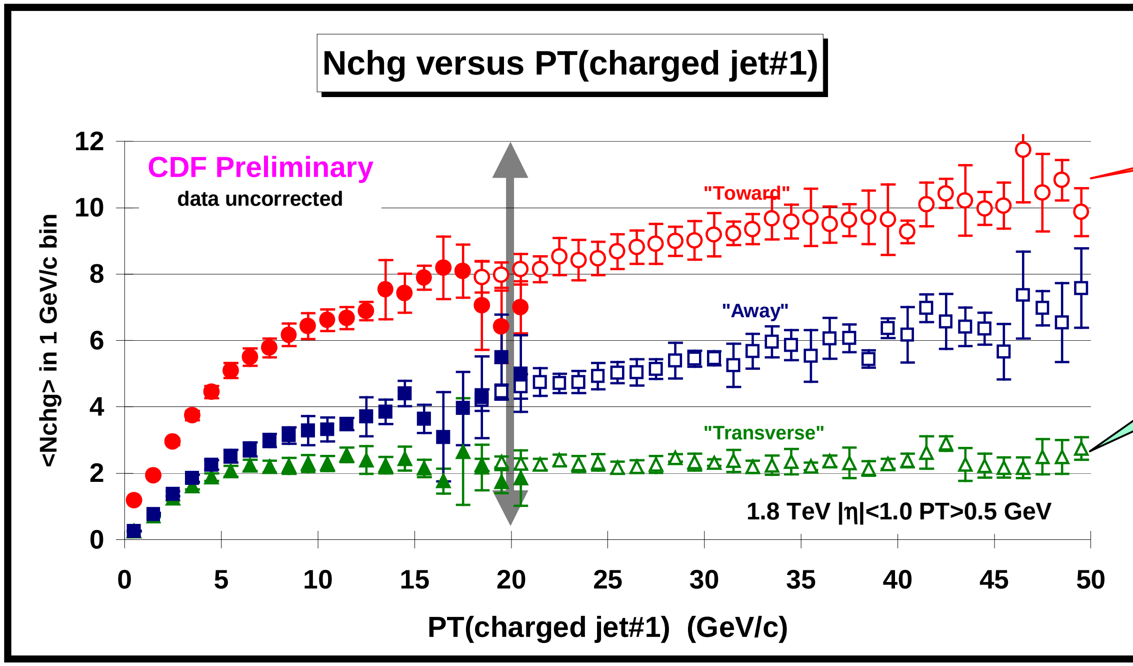




Underlying Event “plateau”

- **Data on the average number of “toward” (|Δφ|<60°), “transverse” (60<|Δφ|<120°), and “away” (|Δφ|>120°) charged particles (P_T > 0.5 GeV, |η| < 1, including jet#1) as a function of the transverse momentum of the leading charged particle jet. Each point corresponds to the <Nchg> 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.**

Shape of an Average Event with P_T(chgjet#1) = 20 GeV/c

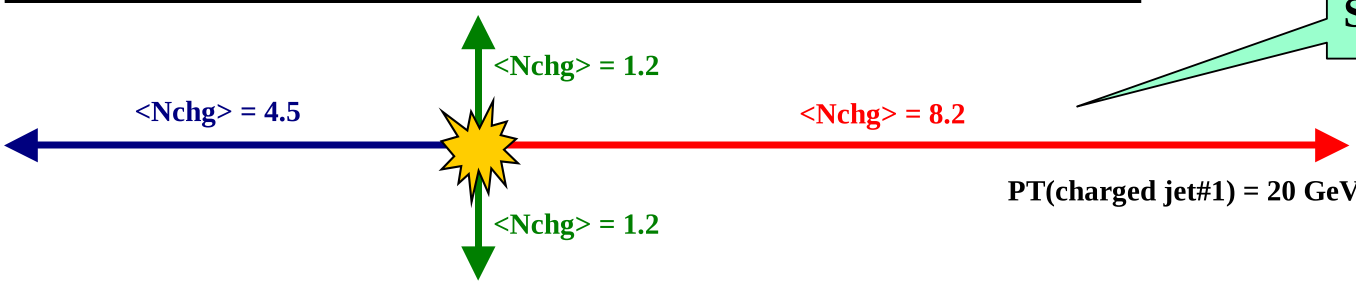


Includes Jet#1

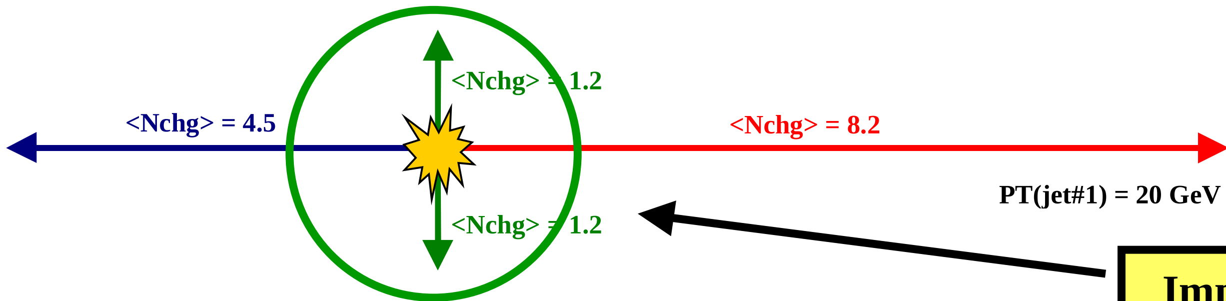
Underlying event “plateau”

Remember
|η| < 1 P_T > 0.5 GeV

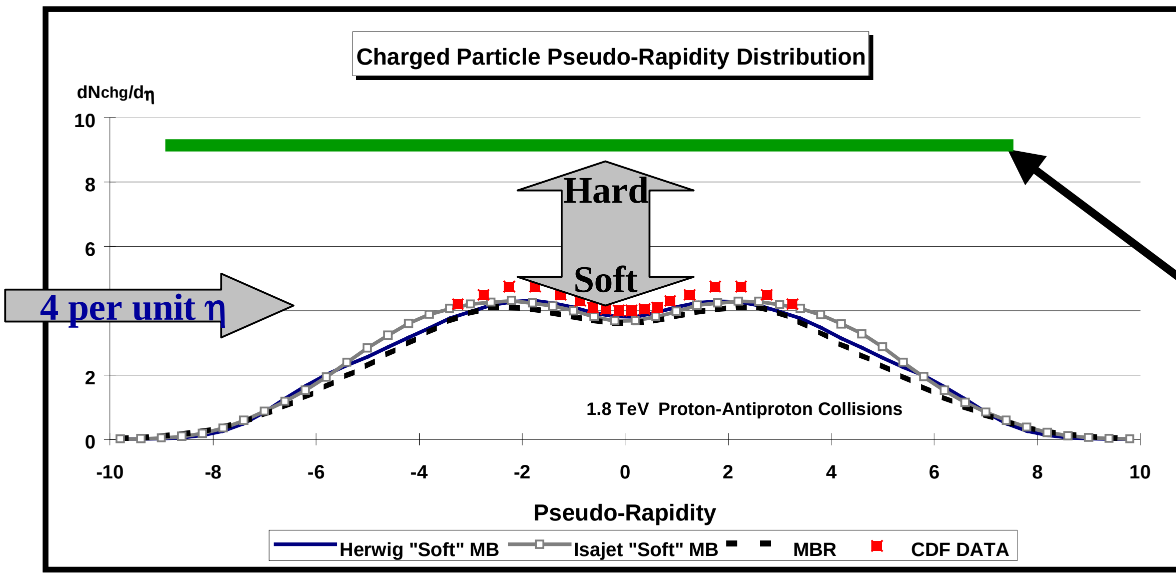
Shape in Nchg



“Height” of the Underlying Event “Plateau”

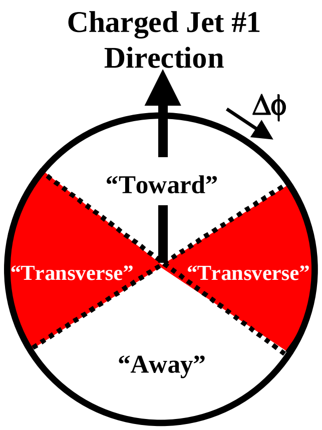


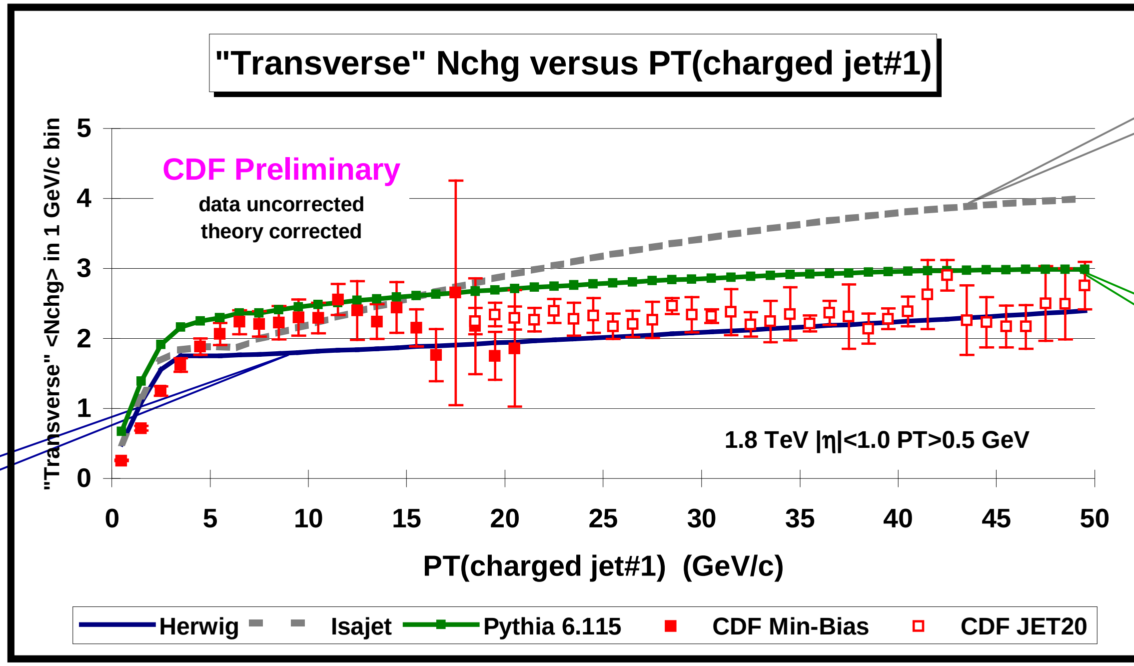
Implies 1.09*3(2.4)/2 = 3.9 charged particles per unit η with P_T > 0.5 GeV.



Implies 2.3*3.9 = 9 charged particles per unit η with P_T > 0 GeV which is a factor of 2 larger than “soft” collisions.

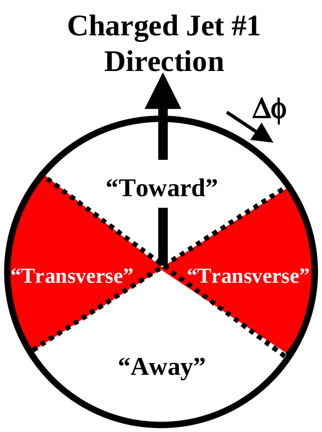
“Transverse” Nchg versus P_T(chgjet#1)

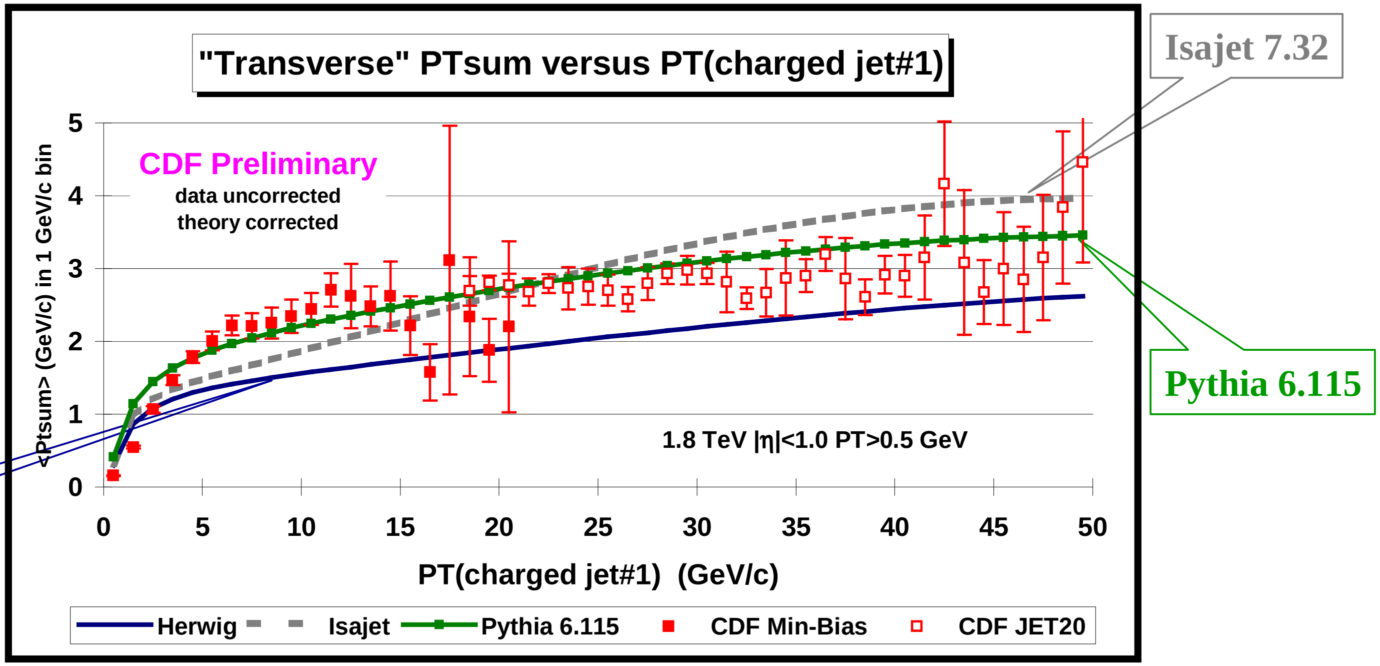




- **Plot shows the “Transverse” <Nchg> versus P_T(chgjet#1) compared to the the QCD hard scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115 (default parameters with P_T(hard)>3 GeV/c).**
- **Only charged particles with $|\eta| < 1$ and $P_T > 0.5$ GeV are included and the QCD Monte-Carlo predictions have been corrected for efficiency.**

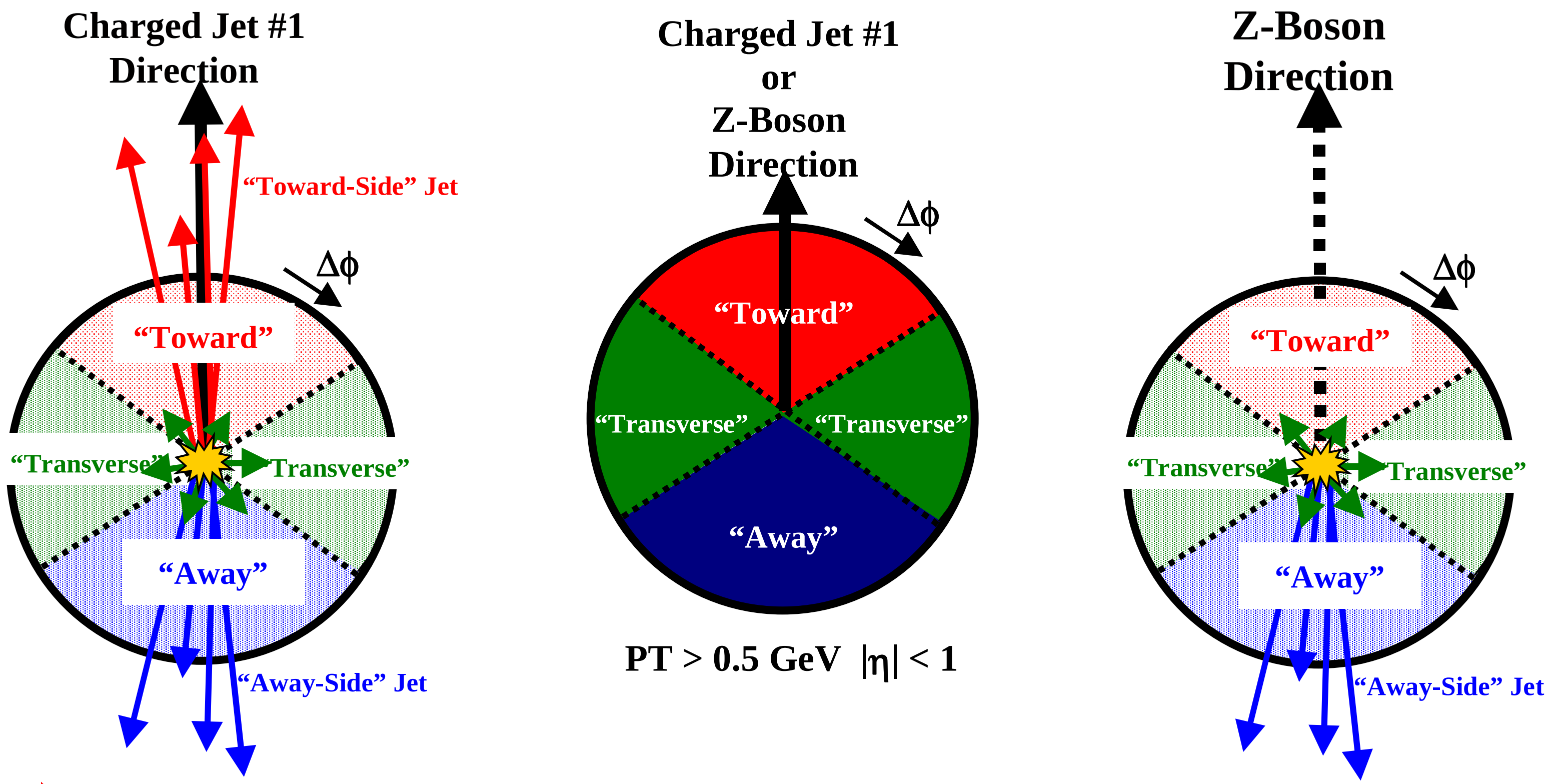
"Transverse" PTsum versus P_T(chgjet#1)





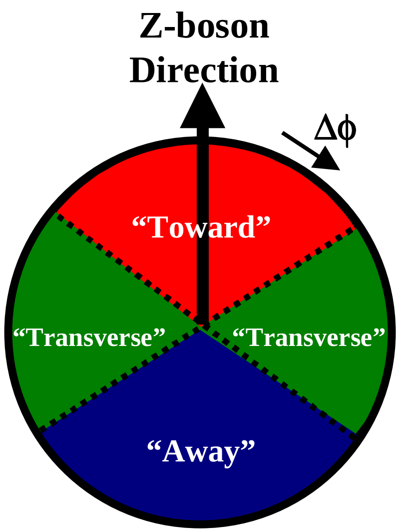
- Plot shows the "Transverse" <PTsum> versus P_T(chgjet#1) compared to the the QCD hard scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115 (default parameters with P_T(hard)>3 GeV/c).
- Only charged particles with $|\eta| < 1$ and $P_T > 0.5$ GeV are included and the QCD Monte-Carlo predictions have been corrected for efficiency.

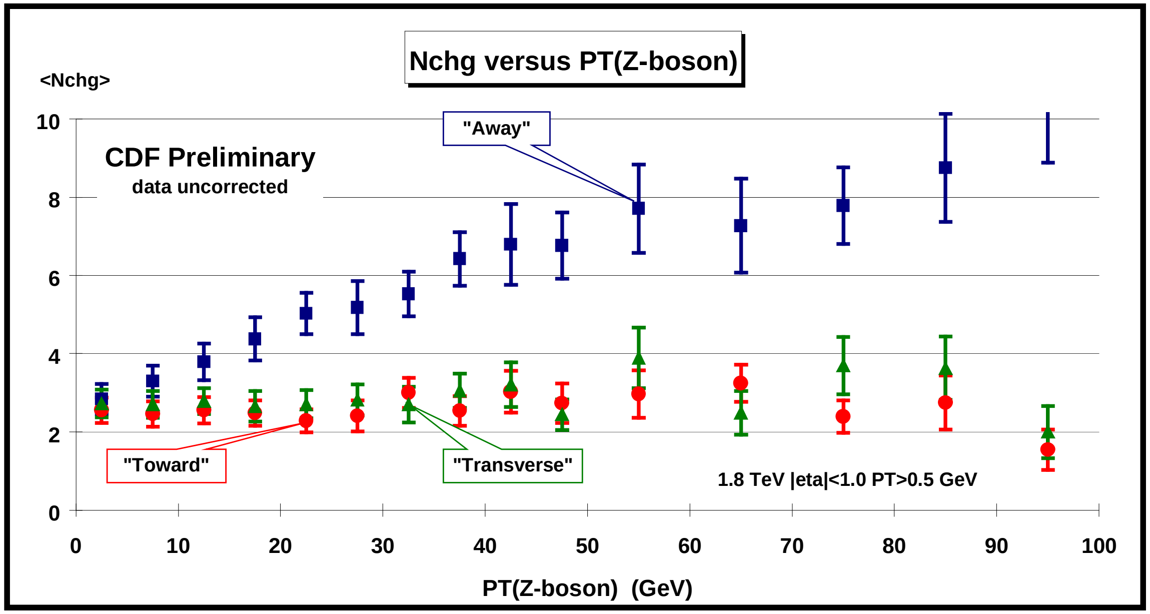
The Underlying Event: DiJet vs Z-Jet



- **Look at charged particle correlations in the azimuthal angle $\Delta\phi$ relative to the leading charged particle jet or the Z-boson.**
- **Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away".**
- **All three regions have the same size in η-ϕ space, $\Delta\eta \times \Delta\phi = 2 \times 120^o = 4\pi/3$.**

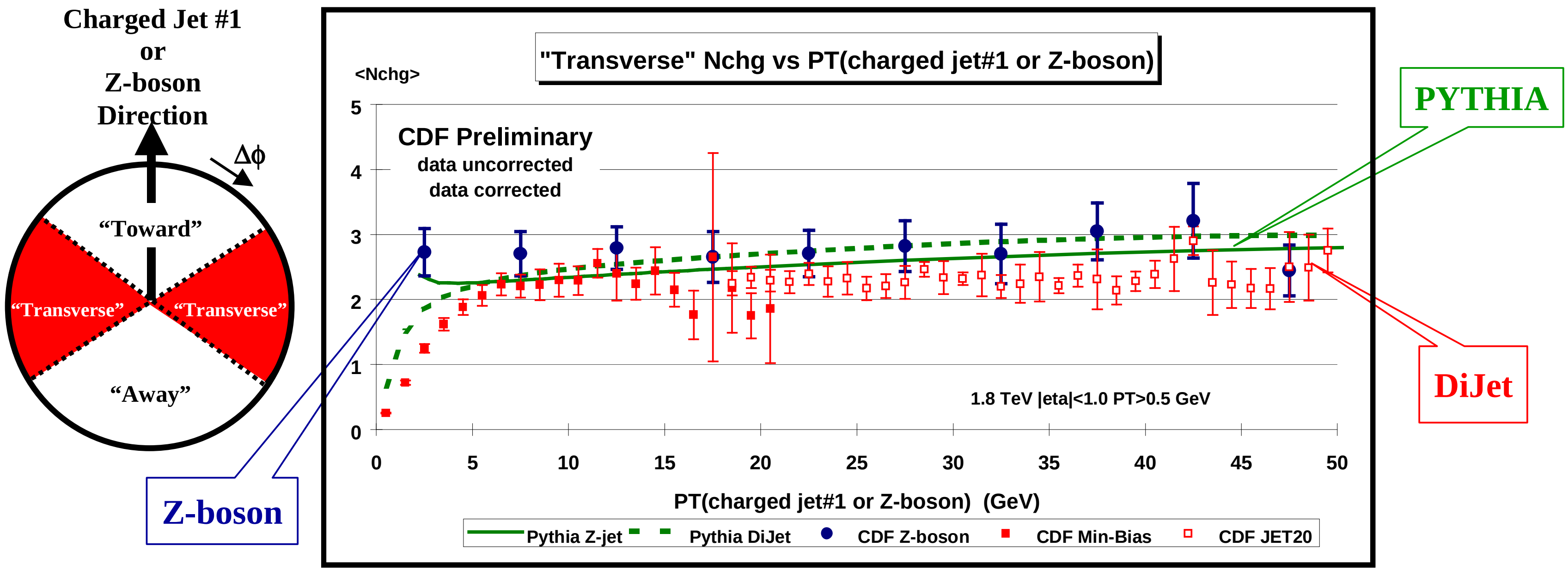
Z-boson: Charged Multiplicity versus $P_T(Z)$





- **Z-boson data on the average number of "toward" (|Δϕ|<60°), "transverse" (60<|Δϕ|<120°), and "away" (|Δϕ|>120°) charged particles (P_T > 0.5 GeV, |η| < 1, excluding decay products of the Z-boson) as a function of the transverse momentum of the Z-boson. The errors on the (*uncorrected*) data include both statistical and correlated systematic uncertainties.**

DiJet vs Z-Jet
"Transverse" Nchg



- Comparison of the dijet and the Z-boson data on the average number of charged particles (P_T > 0.5 GeV, $|\eta|$ <1) for the "transverse" region.
- The plot shows the QCD Monte-Carlo predictions of PYTHIA 6.115 (default parameters with P_T(hard)>3 GeV/c) for dijet (dashed) and "Z-jet" (solid) production.

QFL: Comparing Data with QCD Monte-Carlo Models

Charged Particle And Calorimeter Data

Look only at both the charged particles measured by the CTC and the calorimeter data.

QCD Monte-Carlo

Select region

Tano-Kovacs-Huston-Bhatti

QFL detector simulation

- Calorimeter: tower threshold = 50 MeV, E_{tot} < 1800 GeV, $|\eta_{lj}| < 0.7$, $|zvtx| < 60$ cm, 1 and only 1 class 10, 11, or 12 vertex
- Tracks: $|z_c - z_v| < 5$ cm, $|CTC\ d_0| < 0.5$ cm, $P_T > 0.4$ GeV, $|\eta| < 1$

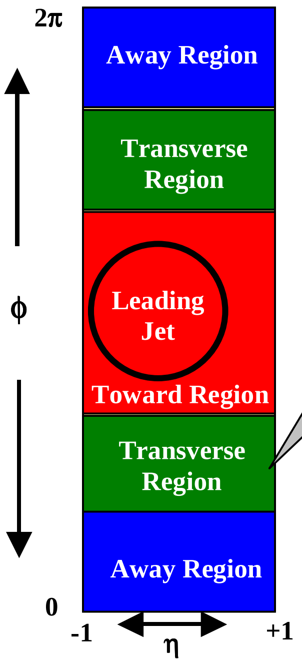
compare

- Require $P_T > 0.4$ GeV, $|\eta| < 1$
- Correct for track finding efficiency

Uncorrected data

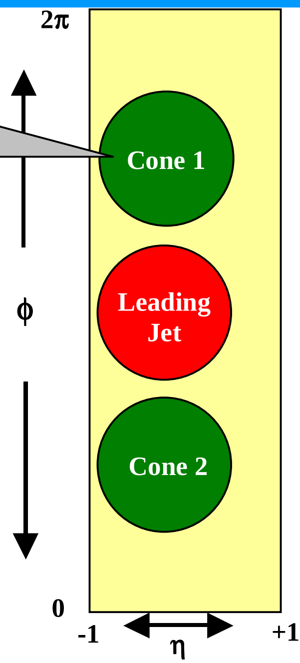
Corrected theory

"Transverse" Cones



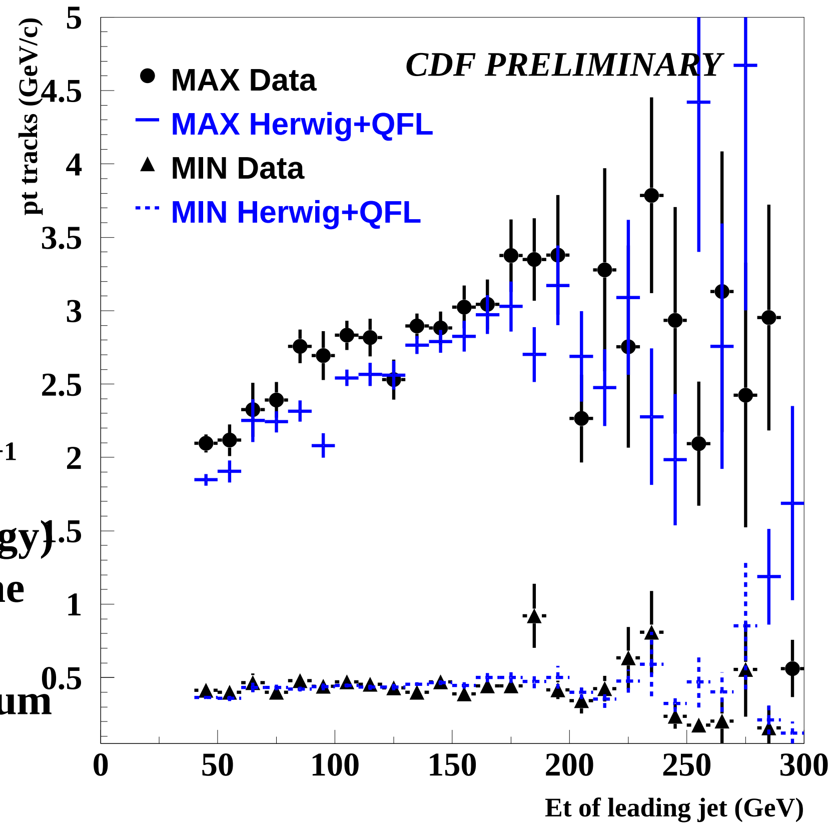
Transverse Cone: $\pi(0.7)^2=0.49\pi$

Transverse Region: $2(\pi/3)=0.66\pi$



Tano-Kovacs-Huston-Bhatti

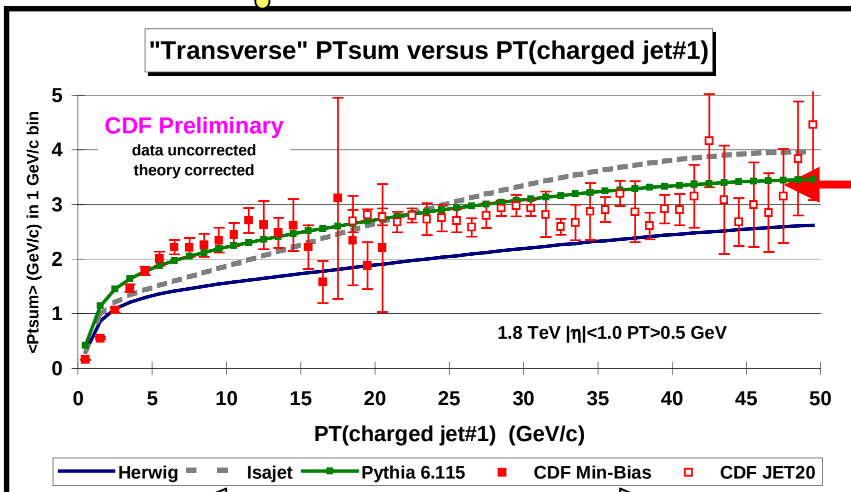
Pt track in max and min cone



- Sum the P_T of charged particles (or the energy) in two cones of radius 0.7 at the same η as the leading jet but with $|\Delta\Phi| = 90^o$.
- Plot the cone with the maximum and minimum PT_{sum} versus the E_T of the leading (calorimeter) jet..

Transverse Region vs Transverse Cones

Field-Stuart-Haas

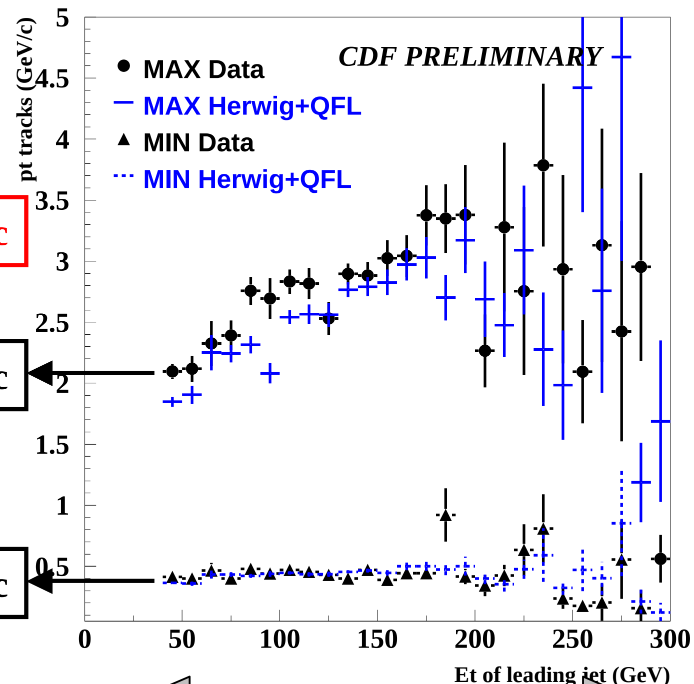


3.4 GeV/c

2.1 GeV/c

0.4 GeV/c

Pt track in max and min cone



0 < P_T(chgjet#1) < 50 GeV/c

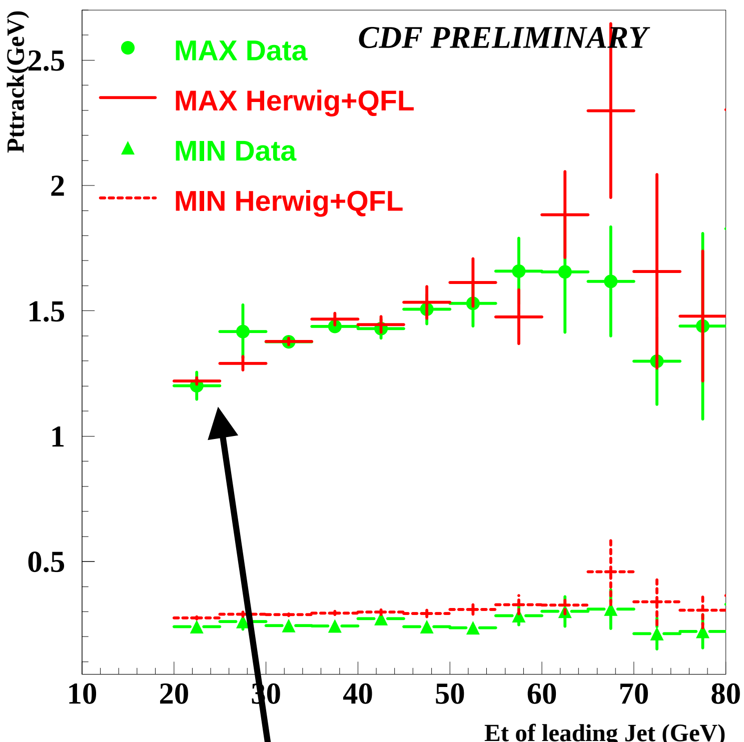
0 < E_T(jet#1) < 50 GeV/c

- **Add max and min cone: 2.1 GeV/c + 0.4 GeV/c = 2.5 GeV/c.**
- **Multiply by ratio of the areas: (2.5 GeV/c)(1.36) = 3.4 GeV/c.**
- **The two analyses are consistent!**

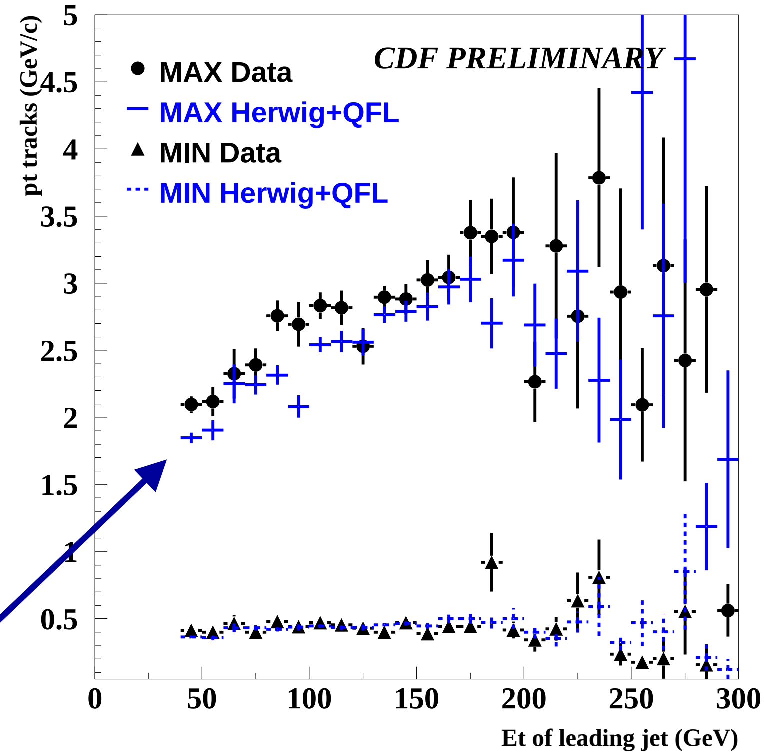
Tano-Kovacs-Huston-Bhatti

Max/Min Cones at 630 GeV/c

Pt track in max and min cone at 630 GeV



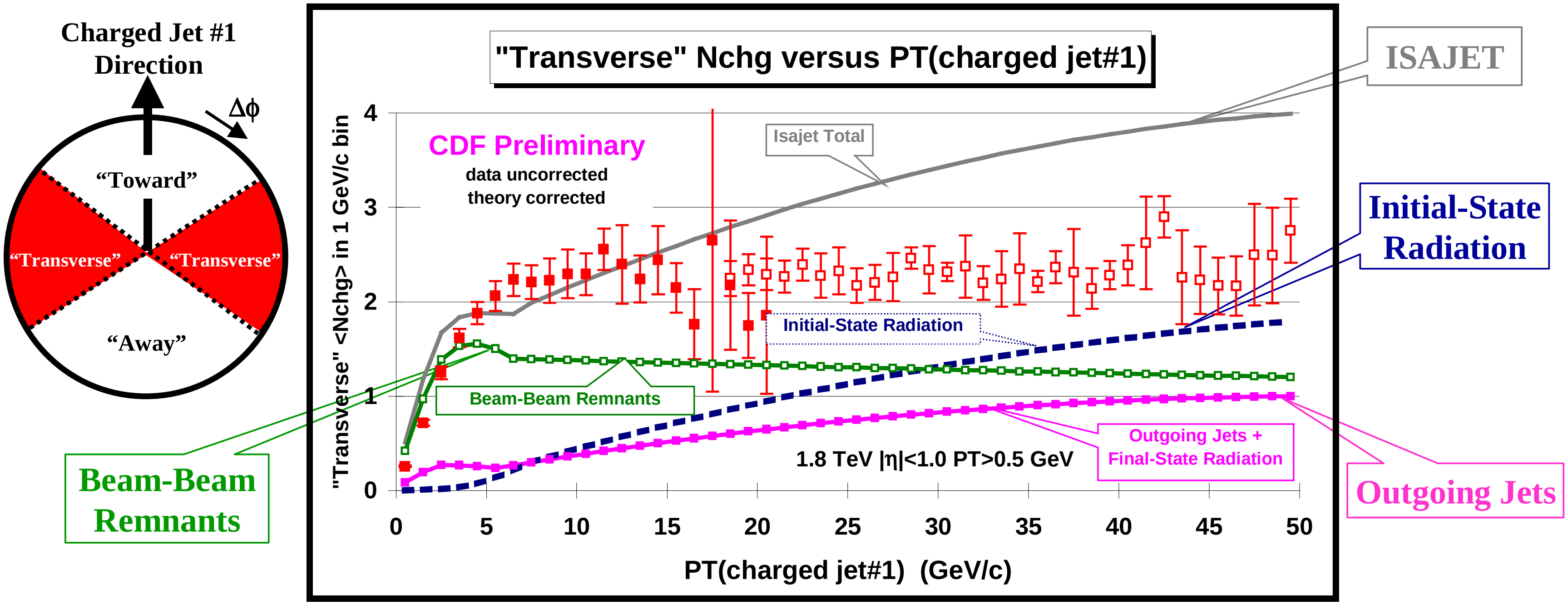
Pt track in max and min cone



- **HERWIG+QFL slightly lower at 1,800 GeV/c agrees at 630 GeV/c.**

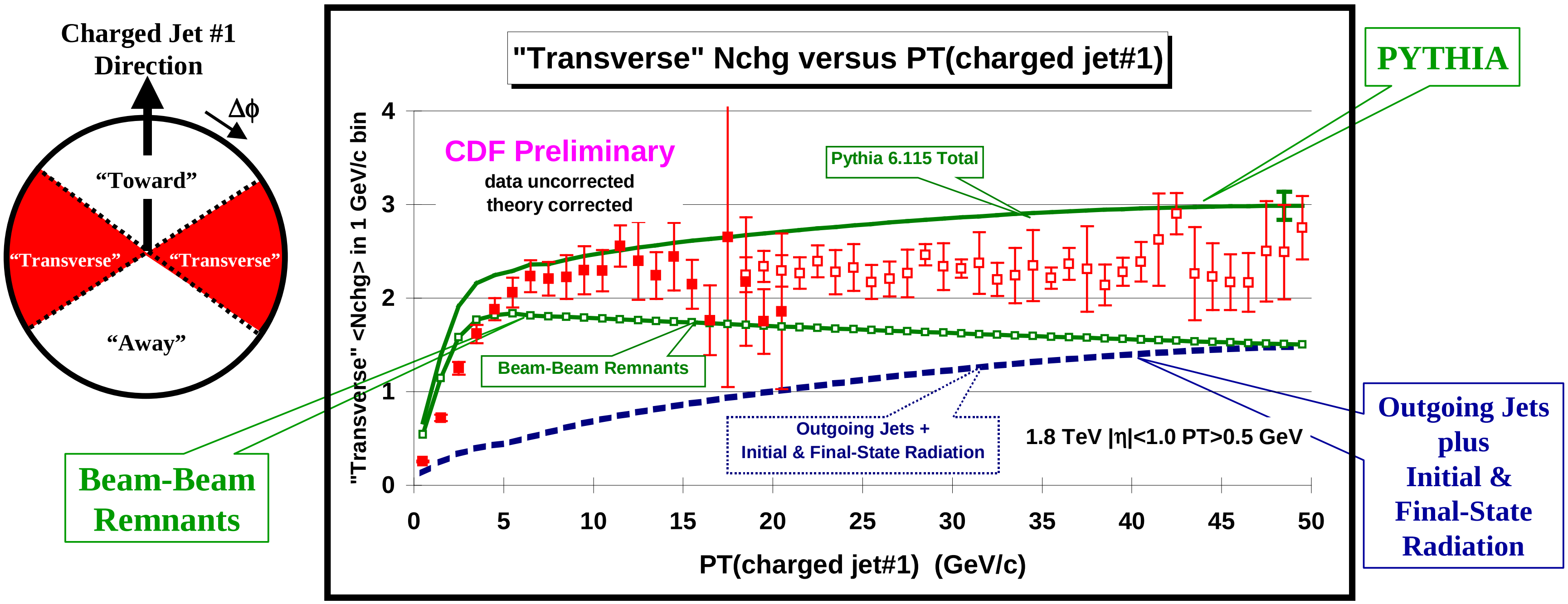
Tano-Kovacs-Huston-Bhatti

ISAJET: "Transverse" Nchg versus P_T(chgjet#1)



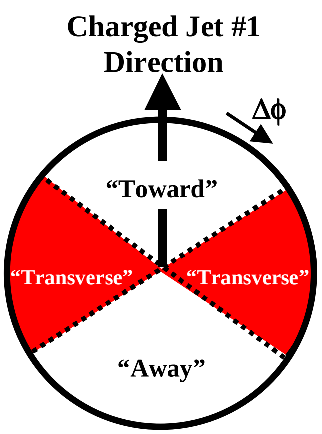
- Plot shows the **"transverse" <Nchg> vs P_T(chgjet#1)** compared to the QCD hard scattering predictions of **ISAJET 7.32** (default parameters with P_T(hard)>3 GeV/c) .
- The predictions of ISAJET are divided into three categories: charged particles that arise from the break-up of the beam and target (**beam-beam remnants**), charged particles that arise from **initial-state radiation**, and charged particles that result from the **outgoing jets plus final-state radiation**.

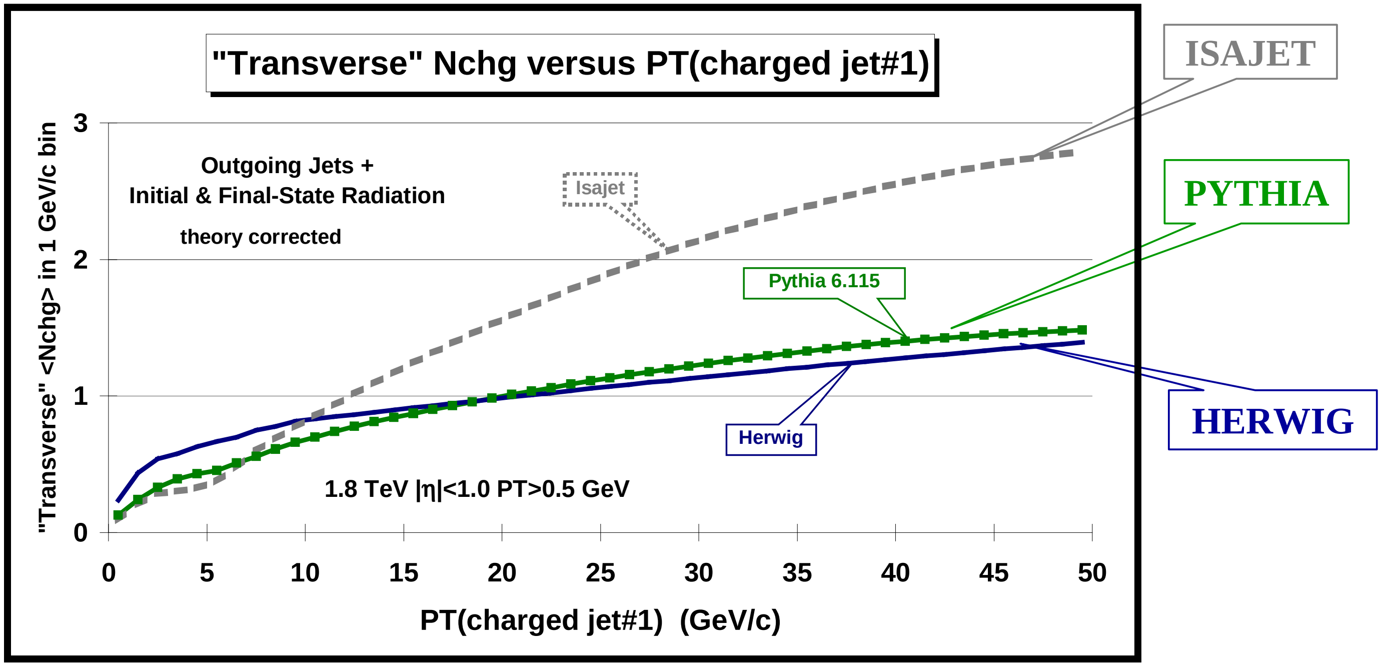
PYTHIA: "Transverse" Nchg versus P_T(chgjet#1)



- Plot shows the "transverse" <Nchg> vs P_T(chgjet#1) compared to the QCD hard scattering predictions of PYTHIA 6.115 (default parameters with P_T(hard)>3 GeV/c).
- The predictions of PYTHIA 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).

Hard Scattering Component: "Transverse" Nchg vs P_T(chgjet#1)

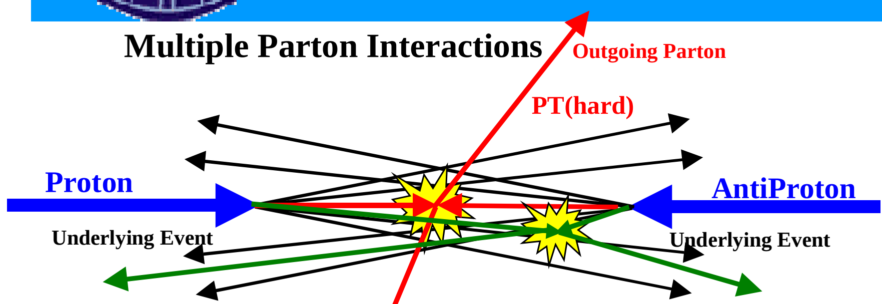




- **QCD hard scattering predictions of HERWIG 5.9, ISAJET 7.32, and PYTHIA 6.115.**
- **Plot shows the dijet "transverse" <Nchg> vs P_T(chgjet#1) arising from the outgoing jets plus initial and finial-state radiation (hard scattering component).**
- **HERWIG and PYTHIA modify the leading-log picture to include "color coherence effects" which leads to "angle ordering" within the parton shower. Angle ordering produces less high P_T radiation within a parton shower.**

PYTHIA: Multiple Parton Interactions

Multiple Parton Interactions

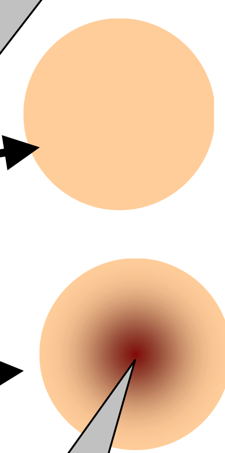


Pythia uses multiple parton interactions to enhace the underlying event.

and new HERWIG!

Parameter	Value	Description
MSTP(81)	0	Multiple-Parton Scattering off
	1	Multiple-Parton Scattering on
MSTP(82)	1	Multiple interactions assuming the same probability, with an abrupt cut-off $P_T$min=PARP(81)
	3	Multiple interactions assuming a varying impact parameter and a hadronic matter overlap consistent with a single Gaussian matter distribution, with a smooth turn-off P_{T0}=PARP(82)
	4	Multiple interactions assuming a varying impact parameter and a hadronic matter overlap consistent with a double Gaussian matter distribution (governed by PARP(83) and PARP(84)), with a smooth turn-off P_{T0}=PARP(82)

Multiple parton interaction more likely in a hard (central) collision!

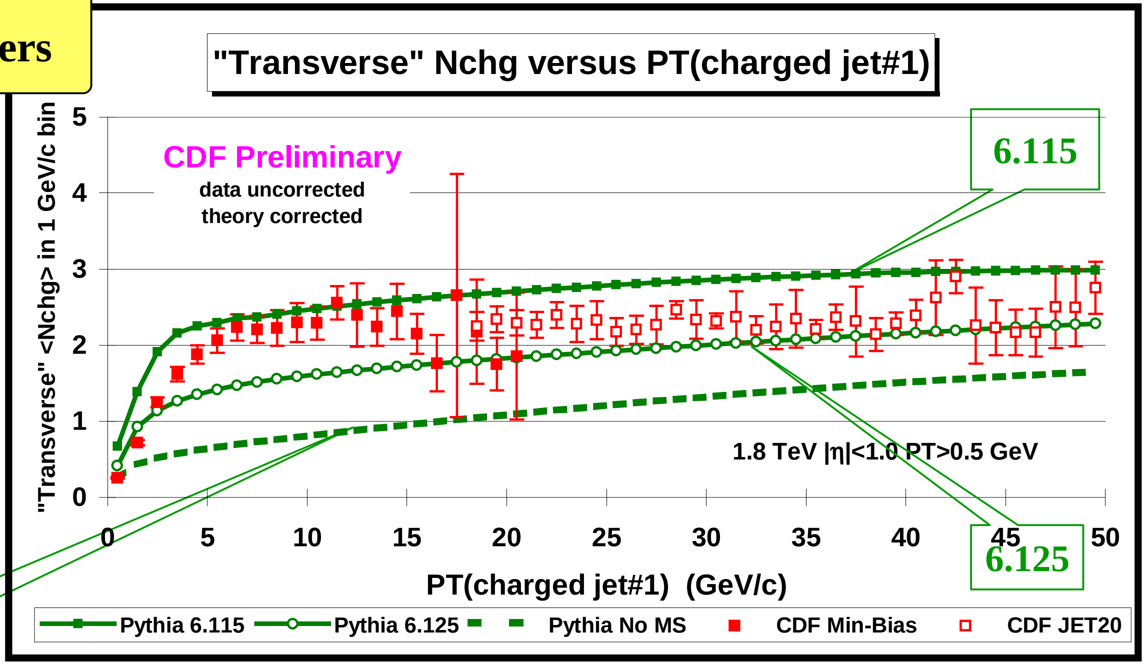


Hard Core

PYTHIA
Multiple Parton Interactions

PYTHIA default parameters

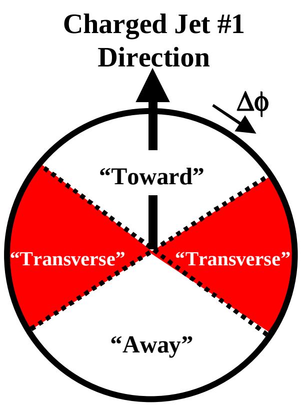
Parameter	6.115	6.125
MSTP(81)	1	1
MSTP(82)	1	1
PARP(81)	1.4 GeV/c	1.9 GeV/c
PARP(82)	1.55 GeV/c	2.1 GeV/c

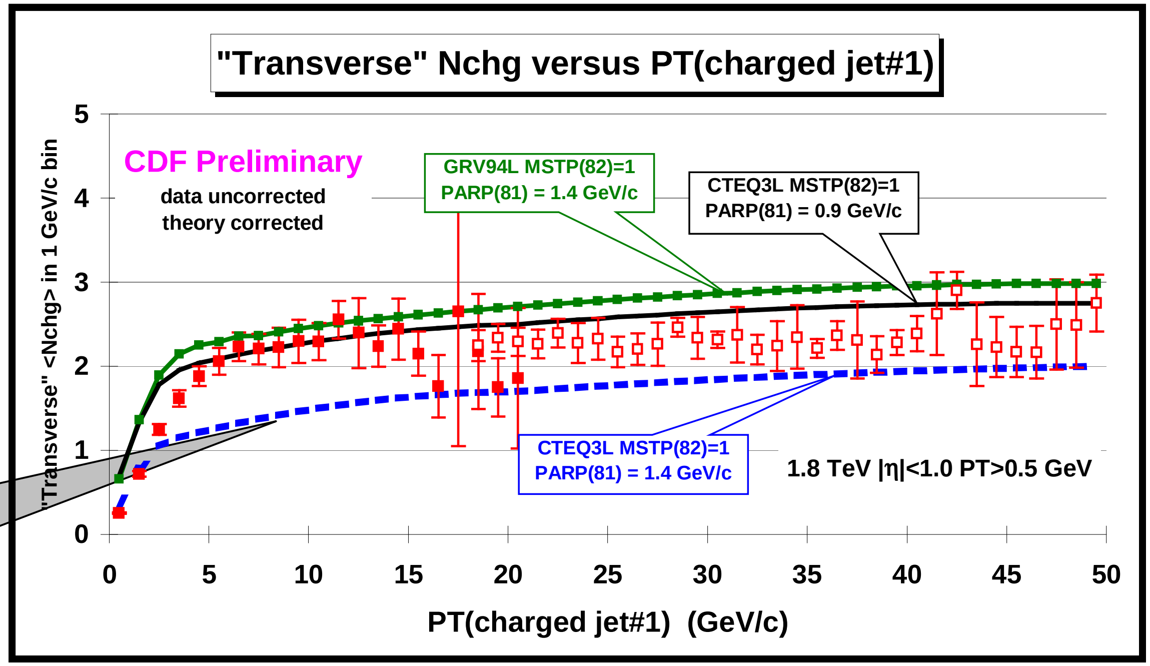


- Plot shows "Transverse" <Nchg> versus PT(chgjet#1) compared to the QCD hard scattering predictions of PYTHIA with P_T(hard) > 3 GeV.
- PYTHIA 6.115: GRV94L, MSTP(82)=1, $P_T$min=PARP(81)=1.4 GeV/c.
- PYTHIA 6.125: GRV94L, MSTP(82)=1, $P_T$min=PARP(81)=1.9 GeV/c.
- PYTHIA 6.115: GRV94L, MSTP(81)=0, no multiple parton interactions.

Constant Probability Scattering

PYTHIA
Multiple Parton Interactions



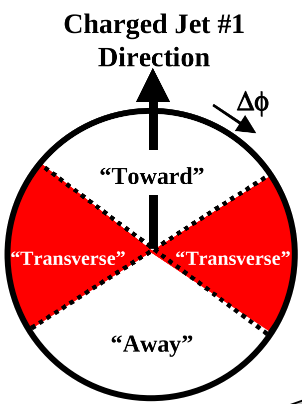


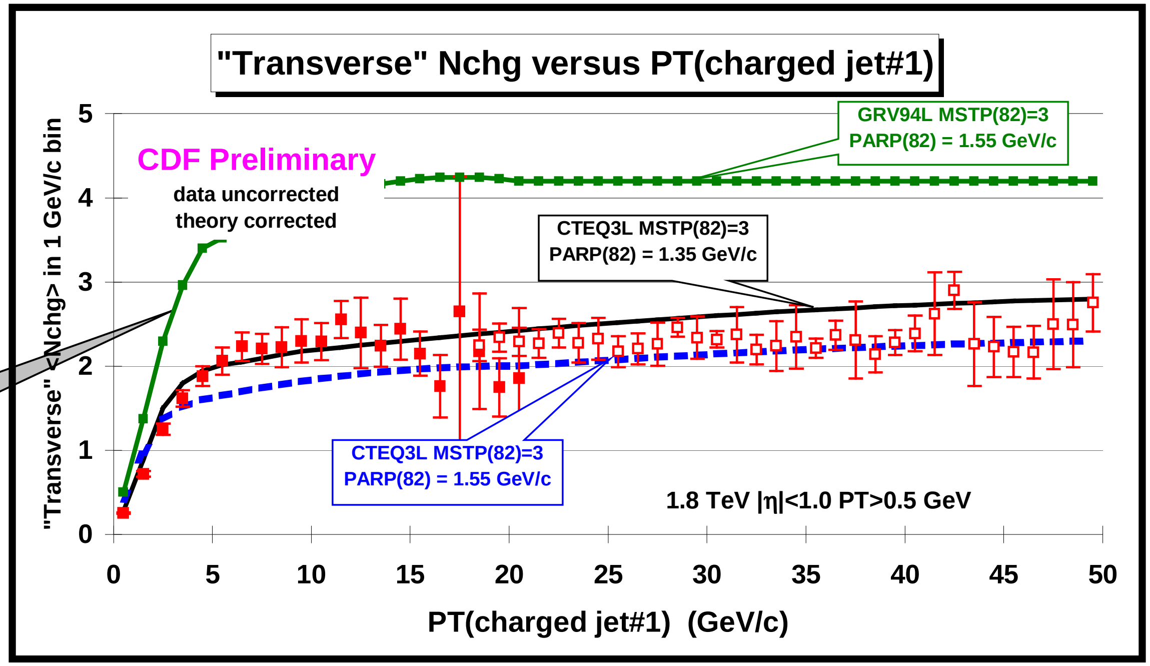
Note: Multiple parton interactions depend sensitively on the PDF's!

- Plot shows **"Transverse" <Nchg> versus PT(chgjet#1)** compared to the QCD hard scattering predictions of **PYTHIA** with **P_T(hard) > 0 GeV**.
- **PYTHIA 6.115: GRV94L, MSTP(82)=1, $P_T$min=PARP(81)=1.4 GeV/c.**
- **PYTHIA 6.115: CTEQ3L, MSTP(82)=1, $P_T$min =PARP(81)=1.4 GeV/c.**
- **PYTHIA 6.115: CTEQ3L, MSTP(82)=1, $P_T$min =PARP(81)=0.9 GeV/c.**

Constant Probability Scattering

PYTHIA
Multiple Parton Interactions



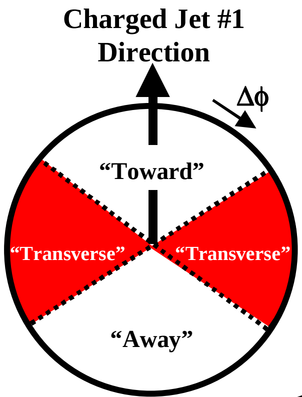


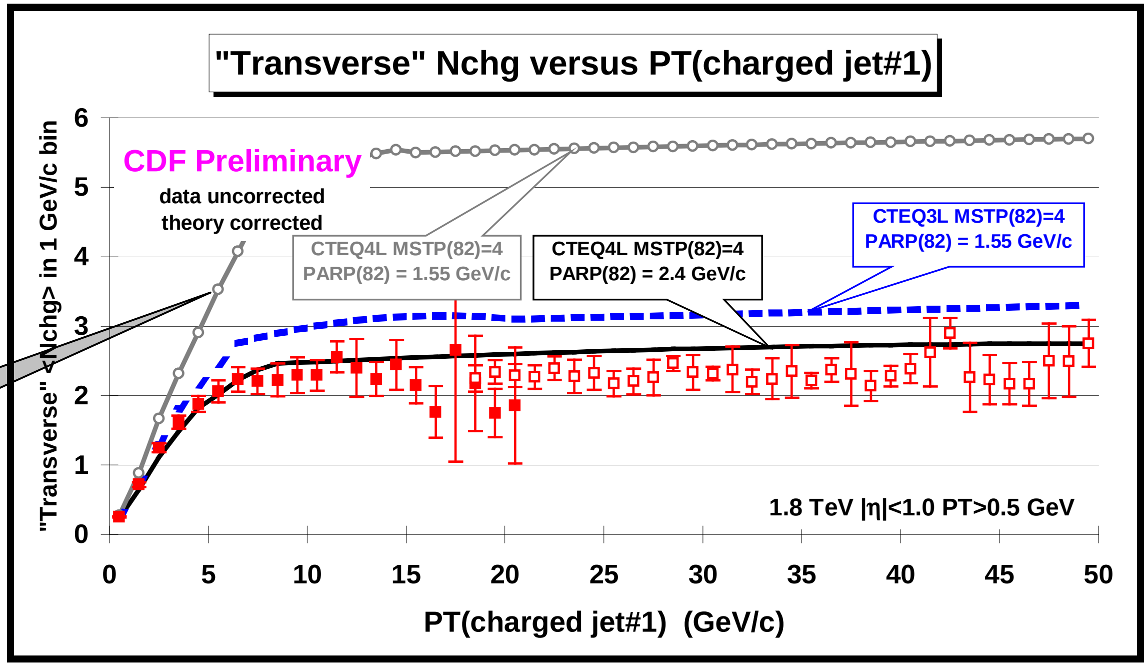
Note: Multiple parton interactions depend sensitively on the PDF's!

- Plot shows **"Transverse" <Nchg> versus PT(chgjet#1)** compared to the QCD hard scattering predictions of **PYTHIA** with **P_T(hard) > 0 GeV**.
- **PYTHIA 6.115: GRV94L, MSTP(82)=3, P_{T0}=PARP(82)=1.55 GeV/c.**
- **PYTHIA 6.115: CTEQ3L, MSTP(82)=3, P_{T0}=PARP(82)=1.55 GeV/c.**
- ★ **PYTHIA 6.115: CTEQ3L, MSTP(82)=3, P_{T0}=PARP(82)=1.35 GeV/c.**

Varying Impact Parameter

PYTHIA
Multiple Parton Interactions



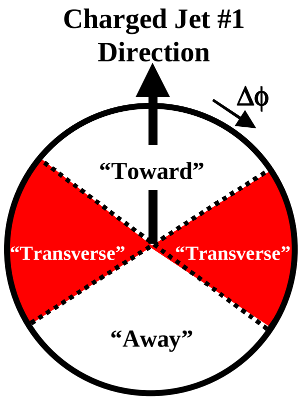


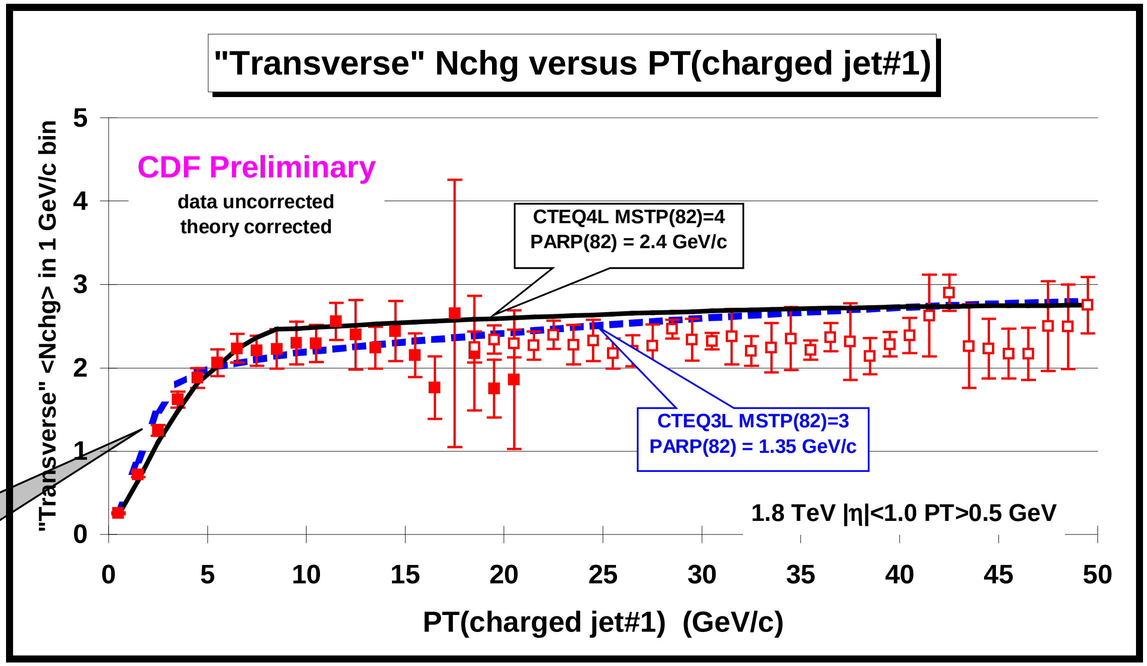
Note: Multiple parton interactions depend sensitively on the PDF's!

- **Plot shows "Transverse" <Nchg> versus PT(chgjet#1) compared to the QCD hard scattering predictions of PYTHIA with P_T(hard) > 0 GeV.**
- **PYTHIA 6.115: CTEQ4L, MSTP(82)=4, P_{T0}=PARP(82)=1.55 GeV/c.**
- **PYTHIA 6.115: CTEQ3L, MSTP(82)=4, P_{T0}=PARP(82)=1.55 GeV/c.**
- **PYTHIA 6.115: CTEQ4L, MSTP(82)=4, P_{T0}=PARP(82)=2.4 GeV/c.**

Varying Impact Parameter
Hard Core

PYTHIA Multiple Parton Interactions



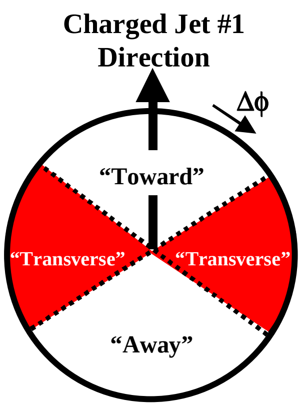


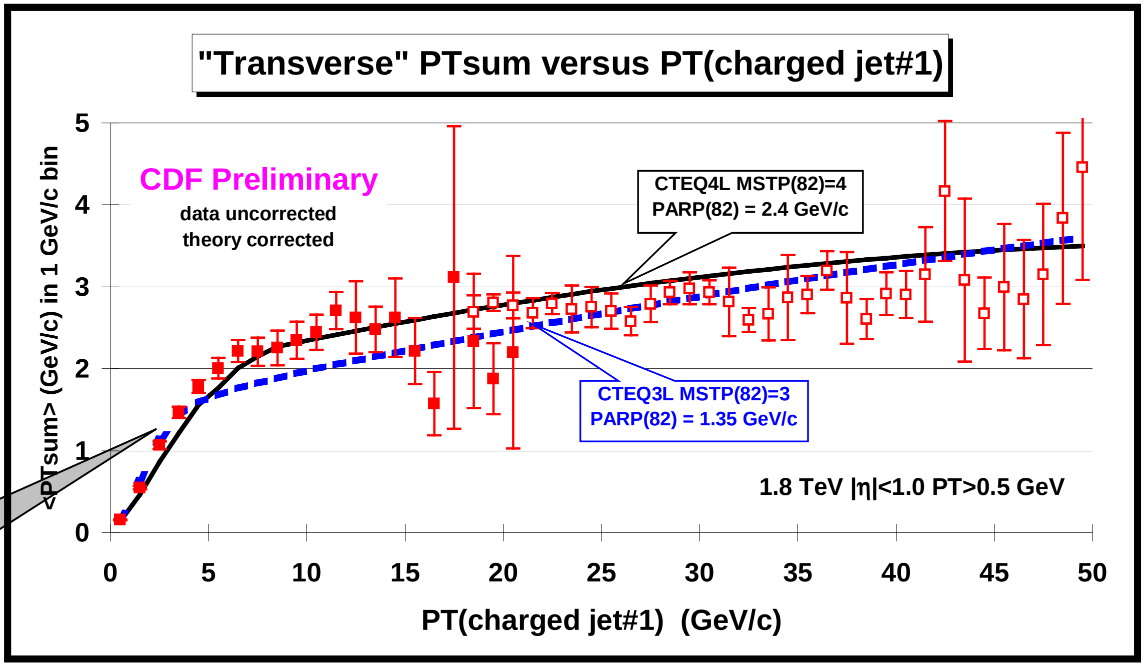
Describes correctly the rise from soft-collisions to hard-collisions!

- **Plot shows "Transverse" <Nchg> versus PT(chgjet#1) compared to the QCD hard scattering predictions of PYTHIA with P_T(hard) > 0 GeV.**
- **PYTHIA 6.115: CTEQ3L, MSTP(82)=3, P_{T0}=PARP(82)=1.35 GeV/c.**
- **PYTHIA 6.115: CTEQ4L, MSTP(82)=4, P_{T0}=PARP(82)=2.4 GeV/c.**

Varying Impact Parameter

PYTHIA
Multiple Parton Interactions



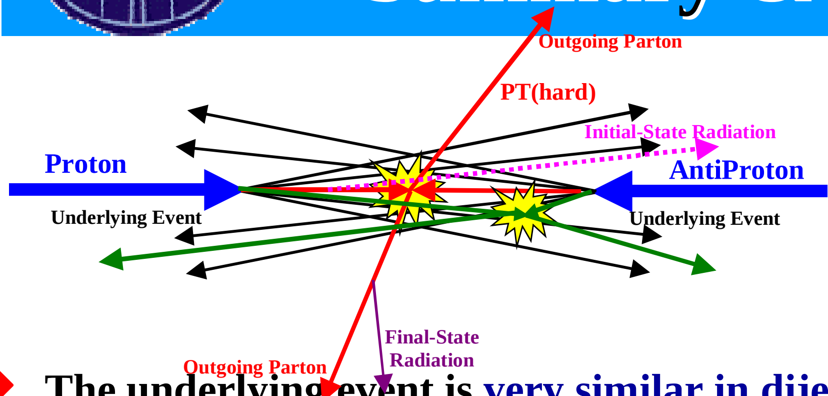


Describes correctly the rise from soft-collisions to hard-collisions!

- Plot shows "Transverse" <PTsum> versus PT(chgjet#1) compared to the QCD hard scattering predictions of PYTHIA with P_T(hard) > 0 GeV.
- PYTHIA 6.115: CTEQ3L, MSTP(82)=3, P_{T0}=PARP(82)=1.35 GeV/c.
- PYTHIA 6.115: CTEQ4L, MSTP(82)=4, P_{T0}=PARP(82)=2.4 GeV/c.

Varying Impact Parameter

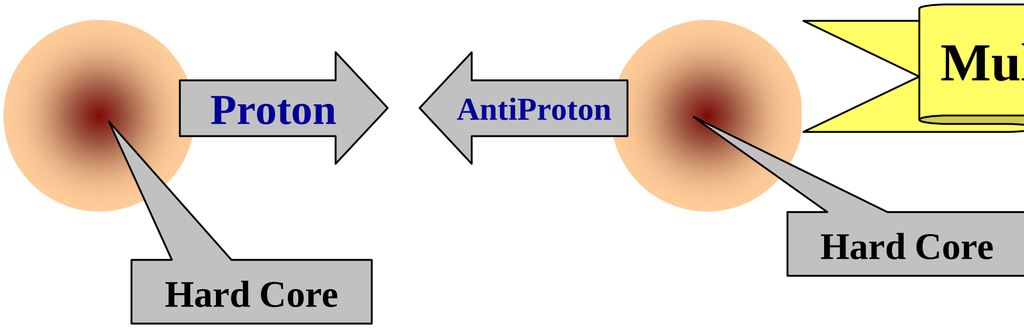
The Underlying Event: Summary & Conclusions



The "Underlying Event"

- **The underlying event is very similar in dijet and the Z-boson production as predicted by the QCD Monte-Carlo models.**
- **The number of charged particles per unit rapidity (height of the "plateau") is at least twice that observed in "soft" collisions at the same corresponding energy.**
- **ISAJET (with independent fragmentation) produces too many (soft) particles in the underlying event with the wrong dependence on P_T(jet#1) or P_T(Z). HERWIG and PYTHIA modify the leading-log picture to include "color coherence effects" which leads to "angle ordering" within the parton shower and do a better job describing the underlying event. HERWIG 5.9 does not have enough activity in the underlying event.**
- **PYTHIA (with multiple parton interactions) does the best job in describing the underlying event.**
- **Combining the two CDF analyses gives a quantitative study of the underlying event from very soft collisions to very hard collisions.**

Multiple Parton Interactions: Summary & Conclusions



Multiple Parton Interactions

- The increased activity in the underlying event in a hard scattering over a soft collision cannot be explained by initial-state radiation.
- Multiple parton interactions gives a natural way of explaining the increased activity in the underlying event in a hard scattering. A hard scattering is more likely to occur when the hard cores overlap and this is also when the probability of a multiple parton interaction is greatest. For a soft grazing collision the probability of a multiple parton interaction is small.
- PYTHIA (with varying impact parameter) describes the data very nicely! I need to check out the new version of HERWIG.

  Slow!
- Multiple parton interactions are very sensitive to the parton structure functions. You must first decide on a particular PDF and then tune the multiple parton interactions to fit the data.