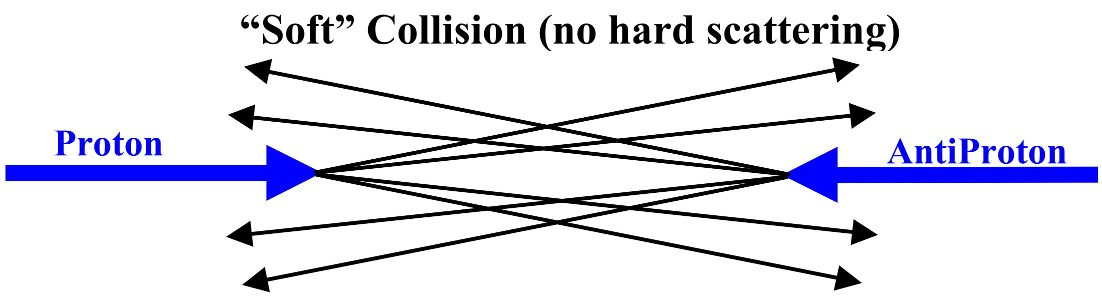
"Min-Bias" Physics:
Jet Evolution & Event Shapes

CDF analysis with
David Stuart

We are working on this!

- Study the **CDF "min-bias" data** with the goal of finding a Mone-Carlo generator that will describe the data (**important for Run II**).
- Would like to describe (approximately) all the features of the inelastic ("hard core") cross section at both low and high PT.
- Look at data (**plot many observables**) and compare with "soft" scattering models of Isajet, Herwig, and MBR; and the QCD "hard" scattering models of Herwig, Isajet, and Pythia.
- The "min-bias" data are a mixture of "soft" and "hard" scattering. **Fitting the data requires a superposition of "hard" and "soft" Monte-Carlo models.**

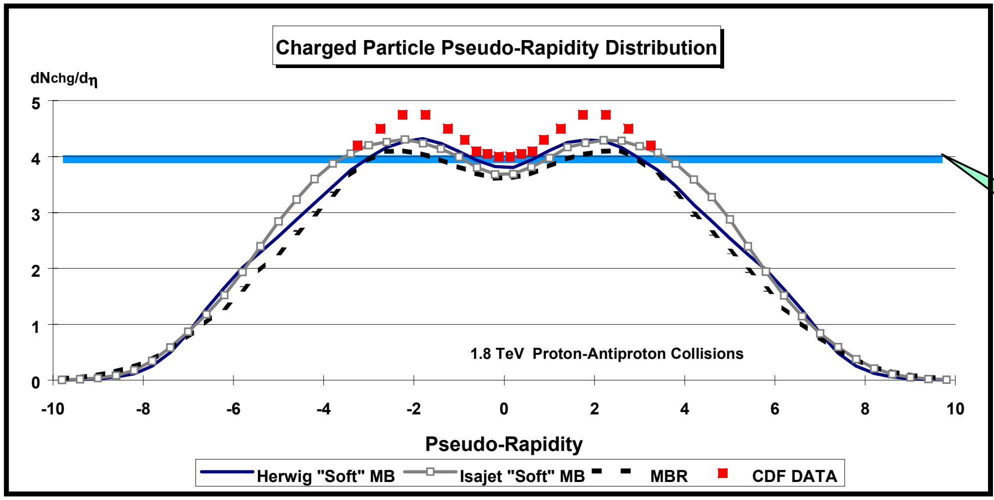
"Soft" Proton-Antiproton Collisions



Isajet and Herwig "min-bias" and MBR are "Soft" scattering models

- **In a "soft" collision the proton and antiproton ooze through each other and break apart with no hard scattering.**
- **Isajet "min-bias", Herwig "min-bias" and the Rockefeller MBR program are models (*i.e.* parameterizations) of "soft" collisions.**
- **At 1.8 TeV the "Soft" models have about 4 charged particles per unit rapidity with a <PT> of around 500 MeV and no correlations except for resonances and momentum conservation.**

Charged Particle Rapidity Distribution

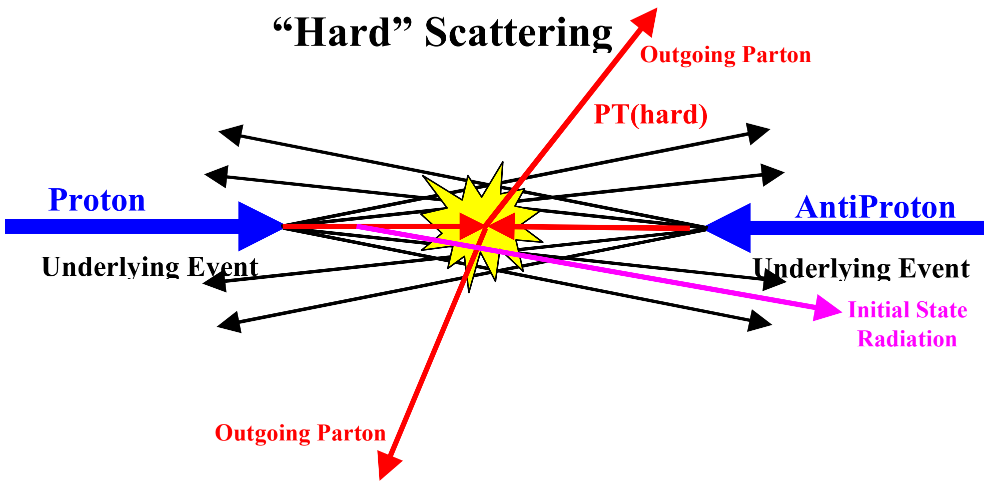


Monte-Carlo events are required to satisfy the CDF min-bias trigger

4 charged particles per unit rapidity

- Plot shows **charged particle pseudo-rapidity distribution** for 1.8 TeV proton-antiproton "min-bias" collisions.
- The data (**squares**) are from a CDF publication and the curves are the Monte-Carlo predictions of Herwig and Isajet "soft" scattering and the Rockefeller MBR "soft" scattering.
- **Plot shows dNchg/dη for all charged particles** (PT > 0 GeV).

"Hard" Proton-Antiproton Collisions

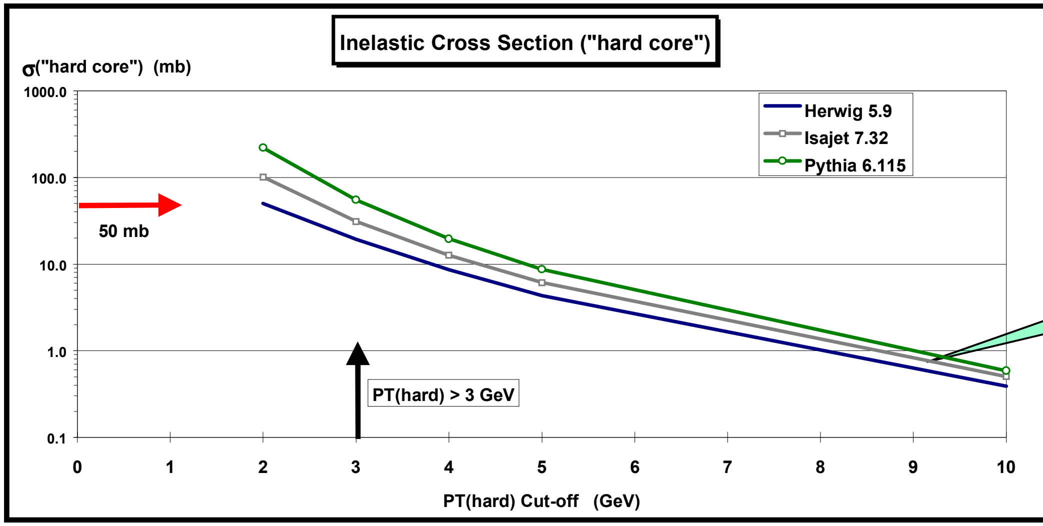


The "underlying event" consists of the beam-beam remnants and initial-state radiation

- Illustration of a proton-antiproton collision in which a "hard" 2-to-2 parton scattering with transverse momentum, PT(hard), has occurred (we take PT(hard) > 3 GeV).
- Isajet, Herwig, and Pythia are QCD "hard" scattering Monte-Carlo models.

Isajet 7.32
Herwig 5.9
Pythia 6.115
Pythia 6.125
Pythia No MS

“Hard” Scattering PT(hard) Cut-off



Perturbative inelastic cross section diverges as PT(hard) becomes small.

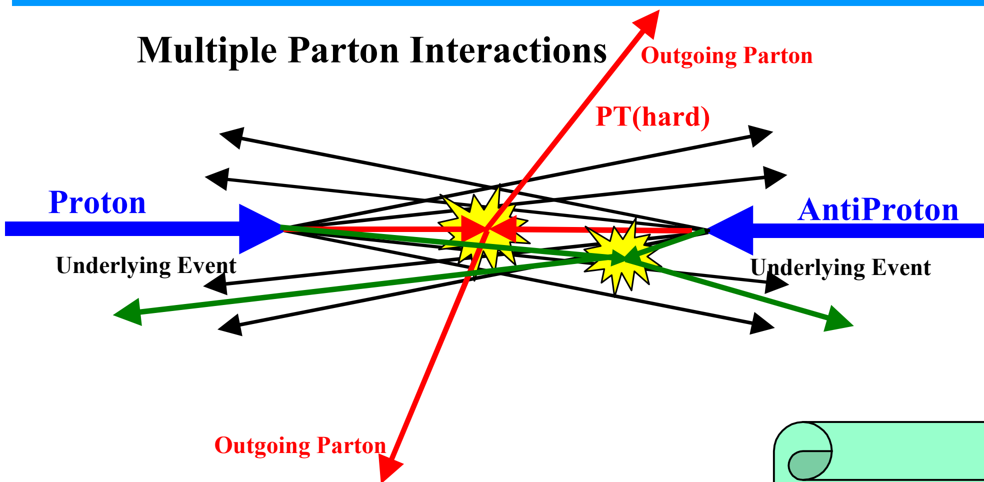
Select PT(hard) > 3 GeV for this study.

Single Diffraction

Double Diffraction

- **The inelastic cross section has a single-diffractive, double-diffractive, and “hard core” component as follows:**
  σ(inelastic) = σ_{HC} + s_{SD} + s_{DD}
- **For proton-antiproton collisions at 1.8 TeV:**
  σ(inelastic) = 60 mb, s_{SD} = 9 mb, s_{DD} = 1 mb, and s_{HC} = 50 mb.
- **Of course, “hard core” does not necessarily mean “hard” scattering.**

Multiple Parton Interactions



Pythia uses multiple parton interactions to enhace the underlying event.

Pythia 6.115 and 6.125 differ in the amount of multiple parton interactions.

Isajet 7.32
Herwig 5.9
Pythia 6.115
Pythia 6.125
Pythia No MS

No multiple parton interactions.

- Pythia uses multiple parton scattering to enhance the underlying event.
- Isajet and Herwig do not include multiple parton interactions.

Min-Bias Data Procedure

Field-Stuart

Min-Bias Data

Select "clean" region

- Zero or one vertex
- |zc-zv| < 2 cm, |CTC d0| < 1 cm
- Require PT > 0.5 GeV, |η| < 1
- Errors include both statistical and correlated systematic uncertainties

Uncorrected data

compare

Theory Monte-Carlo

Make efficiency corrections

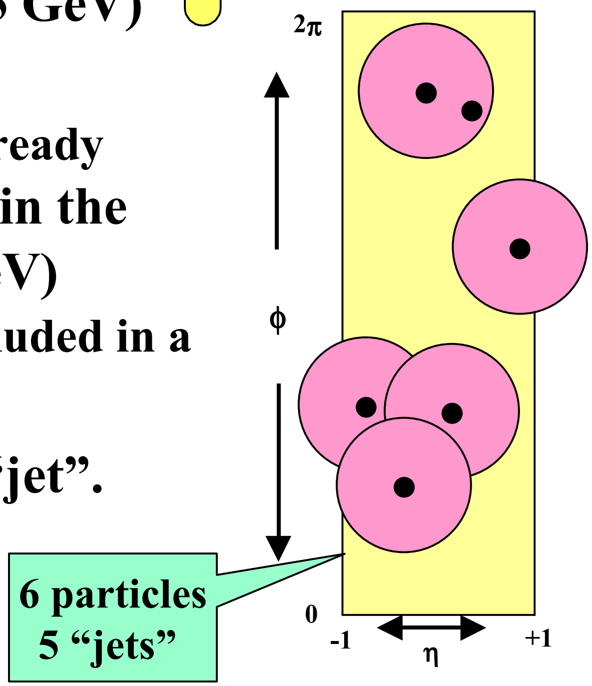
- Require satisfy Min-Bias trigger
- Require PT > 0.5 GeV, |η| < 1
- Assume a uniform CTC efficiency of 92%
- Errors (statistical plus systematic) of around 5%

Corrected theory

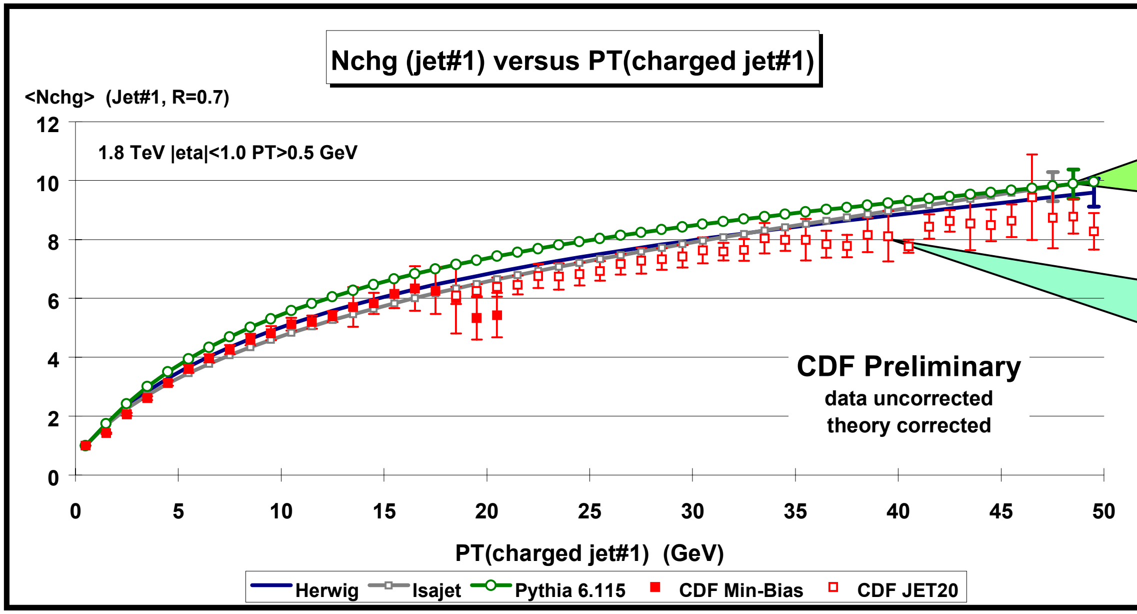
Define "Jets" as Circular Regions in η-ϕ Space

- Order Charged Particles in P_T ($|\eta| < 1$ $P_T > 0.5$ GeV).
- Start with highest P_T particle and include in the "jet" all particles ($|\eta| < 1$ $P_T > 0.5$ GeV) within radius R = 0.7.
- Go to next highest P_T particle (not already included in a previous jet) and include in the "jet" all particles ($|\eta| < 1$ $P_T > 0.5$ GeV) within radius R = 0.7 (not already included in a previous jet).
- Continue until all particles are in a "jet".
- Maximum number of "jet" is about $2(2)(2\pi)/(\pi(0.7)^2)$ or 16.

"Jets" contain particles from the underlying event in addition to particles from the outgoing partons.



The Evolution of "Jets" from 0.5 to 50 GeV



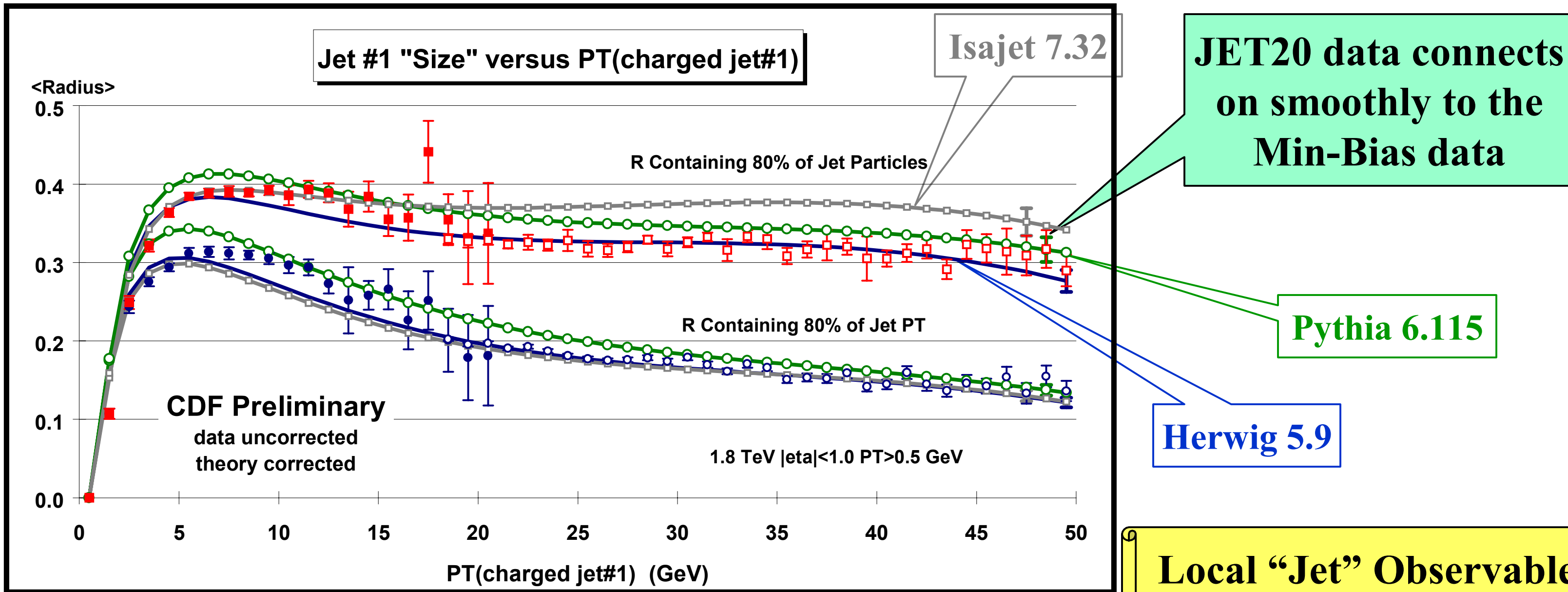
QCD "hard" scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115

JET20 data connects on smoothly to the Min-Bias data

Local "Jet" Observable

- Compares data on the average number of charged particles within Jet#1 (leading jet, R = 0.7) with the QCD "hard" scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115.
- Use the JET20 data to extend the range to 0.5 < PT(jet#1) < 50 GeV. Plot shows <Nchg(jet#1)> versus PT(jet#1).
- Only charged particles with $|\eta| < 1$ and $P_T > 0.5$ GeV are included and the theory has been corrected for efficiency.

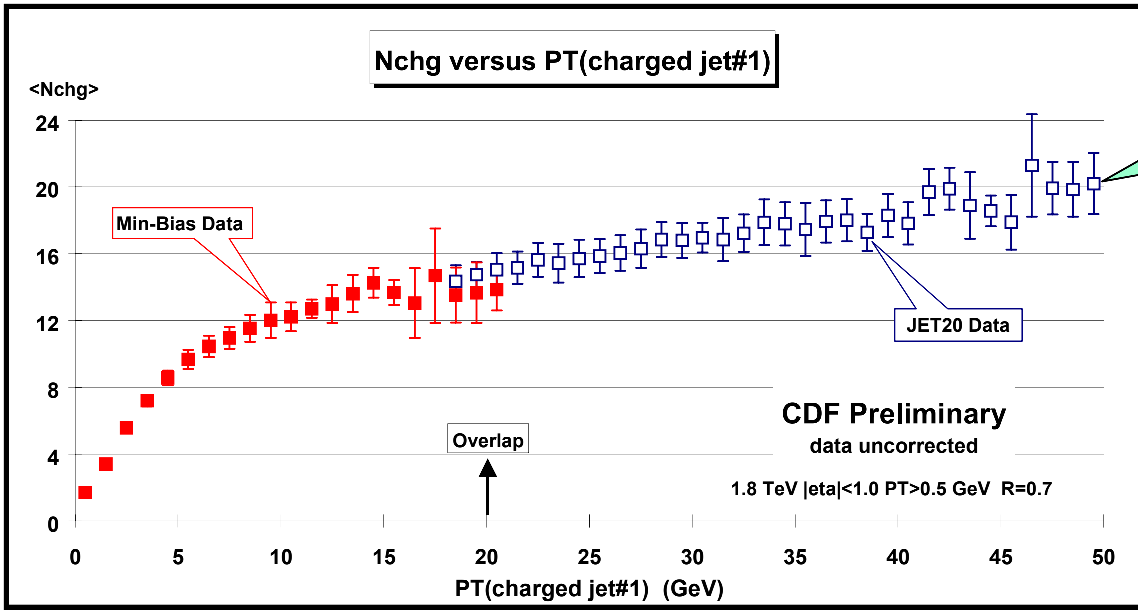
Jet#1 “Size” vs PT(jet#1)



Local “Jet” Observable

- **Compares data on the average radius containing 80% of the particles and 80% of the PT of Jet#1 (leading jet) with the QCD “hard” scattering predictions of Herwig 5.9.**
- **Use the JET20 data to extend the range to 0.5 < PT(jet#1) < 50 GeV. Plot shows <R(jet#1)> versus PT(jet#1).**
- **Only charged particles with |η| < 1 and P_T > 0.5 GeV are included and the theory has been corrected for efficiency.**

Charged Multiplicity versus PT(jet#1)

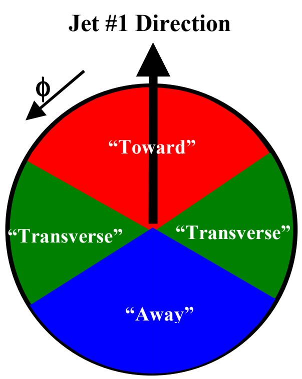


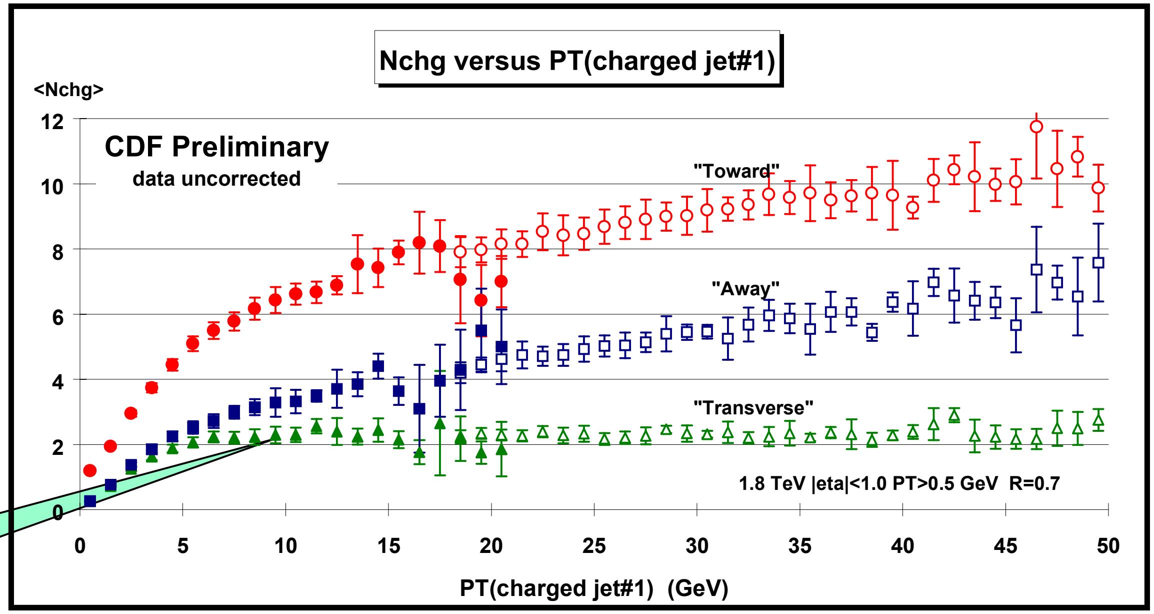
JET20 data connects on smoothly to the Min-Bias data

Global Observable

- **Plot shows <Nchg> versus PT(jet#1). Each point corresponds to the <Nchg> in a 1 GeV bin (*including jet#1*).**
- **Only consider charged particles with $|\eta| < 1$ and $P_T > 0.5$ GeV where the efficiency is good and use the JET20 data to extend the range to 0.5 < PT(jet#1) < 50 GeV.**

Distribution of Nchg Relative to Jet#1

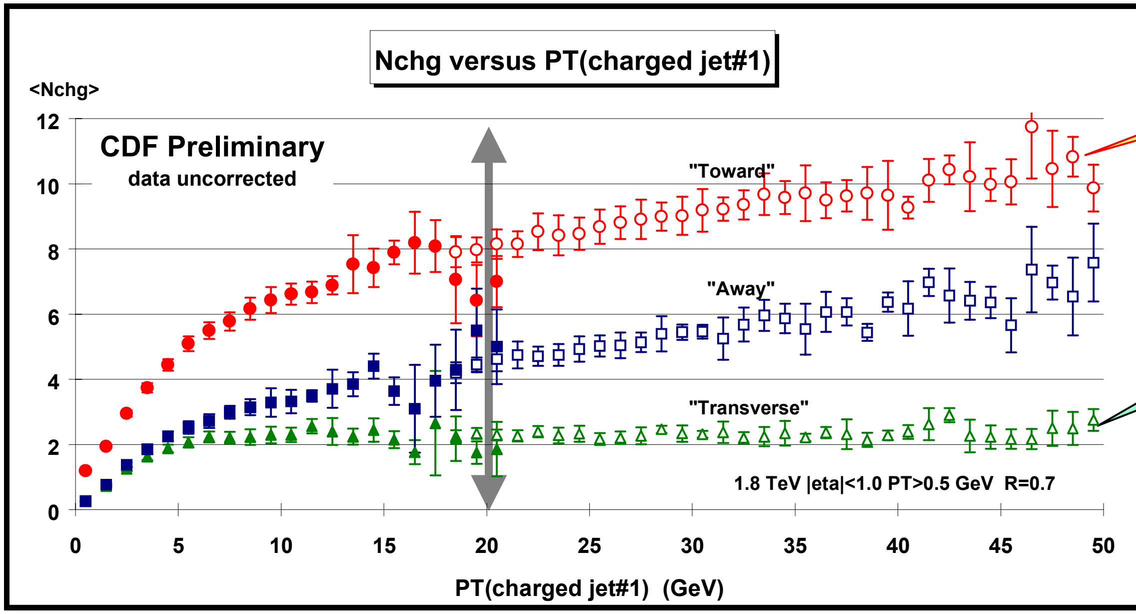




Underlying event "plateau"

- **Look at the charged multiplicity flow in ϕ relative to the direction of jet#1 (|η| < 1 P_T > 0.5 GeV). Use the JET20 data to extend the range to 0.5 < PT(jet#1) < 50 GeV.**
- **Define "Toward" |ϕ-ϕjet| < 60^o (includes jet#1), "Transverse" 60^o < |ϕ-ϕjet| < 120^o, and "Away" |ϕ-ϕjet| < 120^o region.**
- **Plot shows <Nchg> in the three regions versus PT(jet#1).**

Shape of an Average Event with PT(jet#1) = 20 GeV

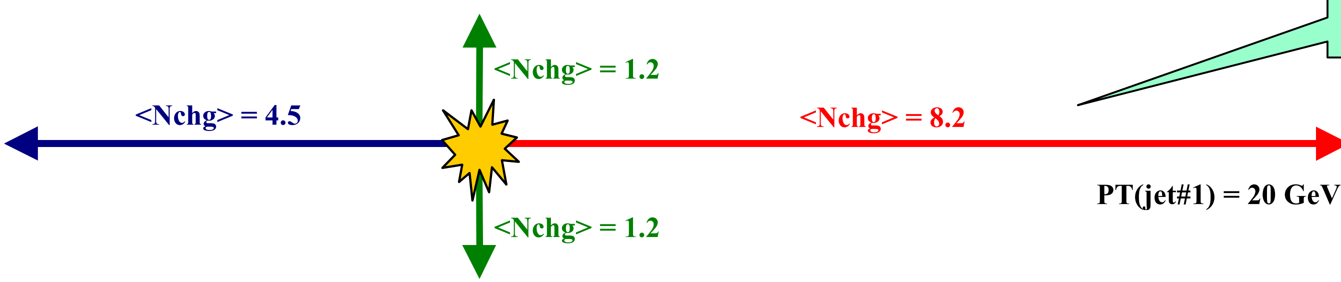


Includes Jet#1

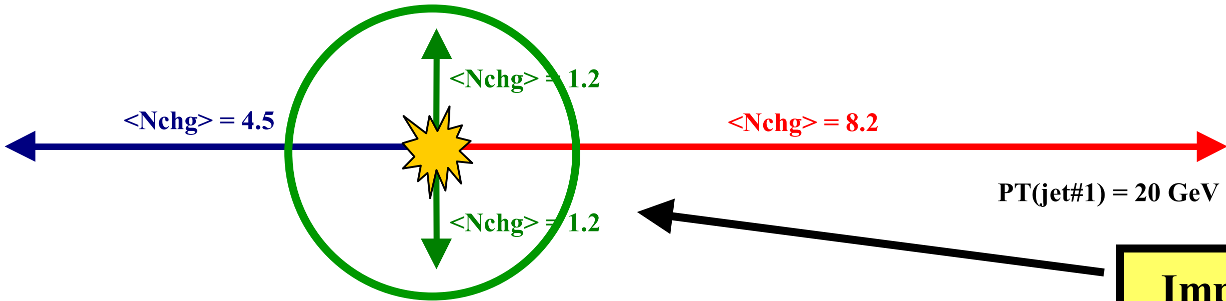
Underlying event "plateau"

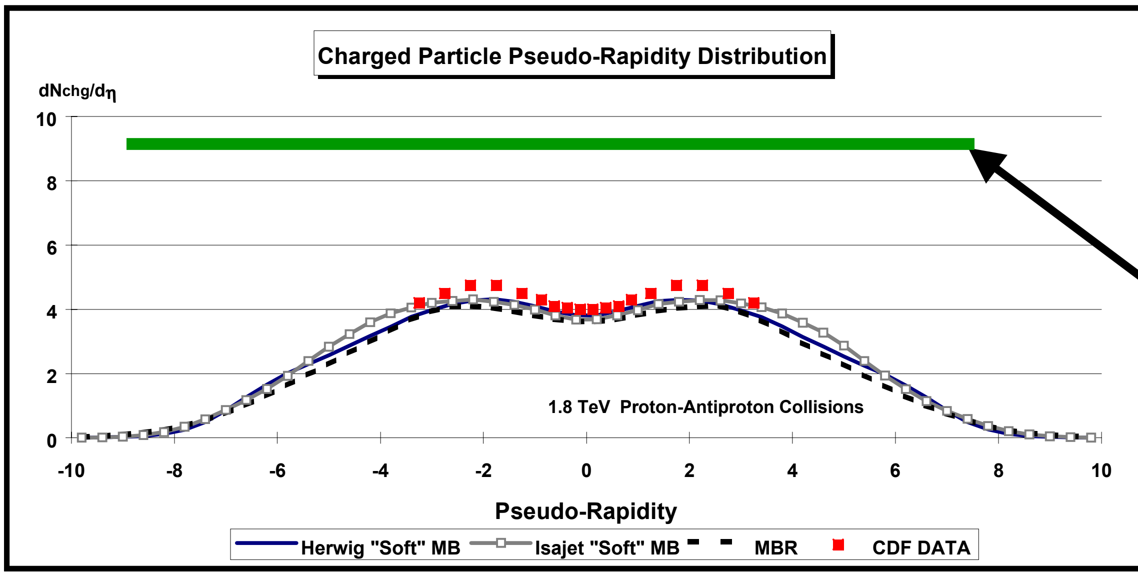
Remember
$|\eta| < 1$ $P_T > 0.5$ GeV

Shape in Nchg



"Height" of the Underlying Event "Plateau"

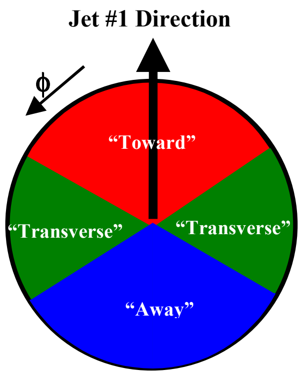


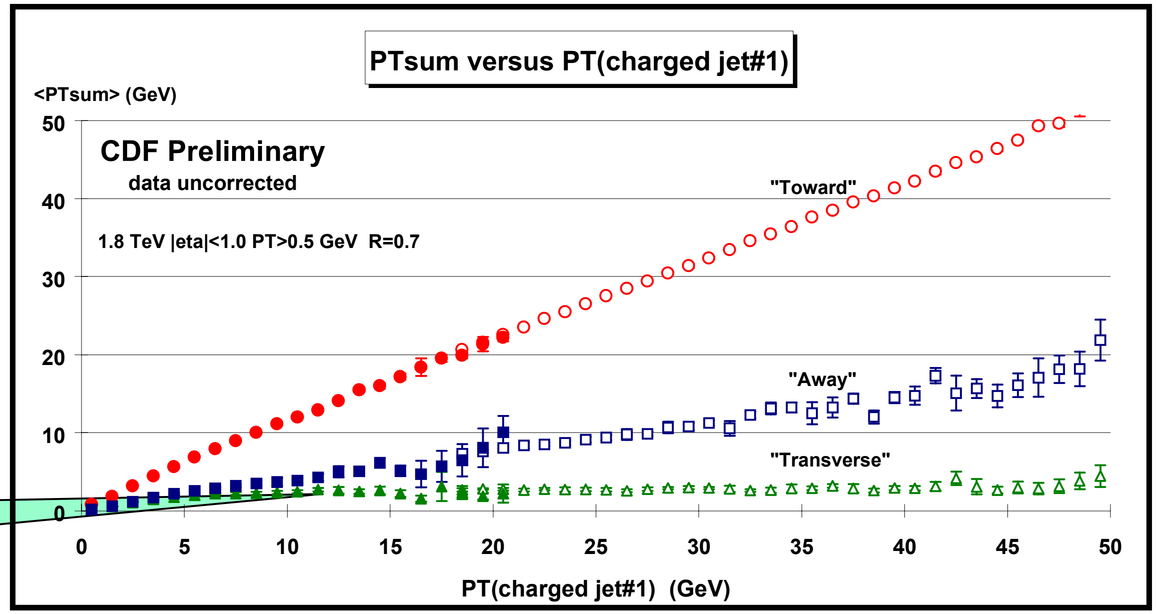


Implies 1.09*3(2.4)/2 = 3.9 charged particles per unit η with PT > 0.5 GeV.

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

Distribution of PTsum Relative to Jet#1

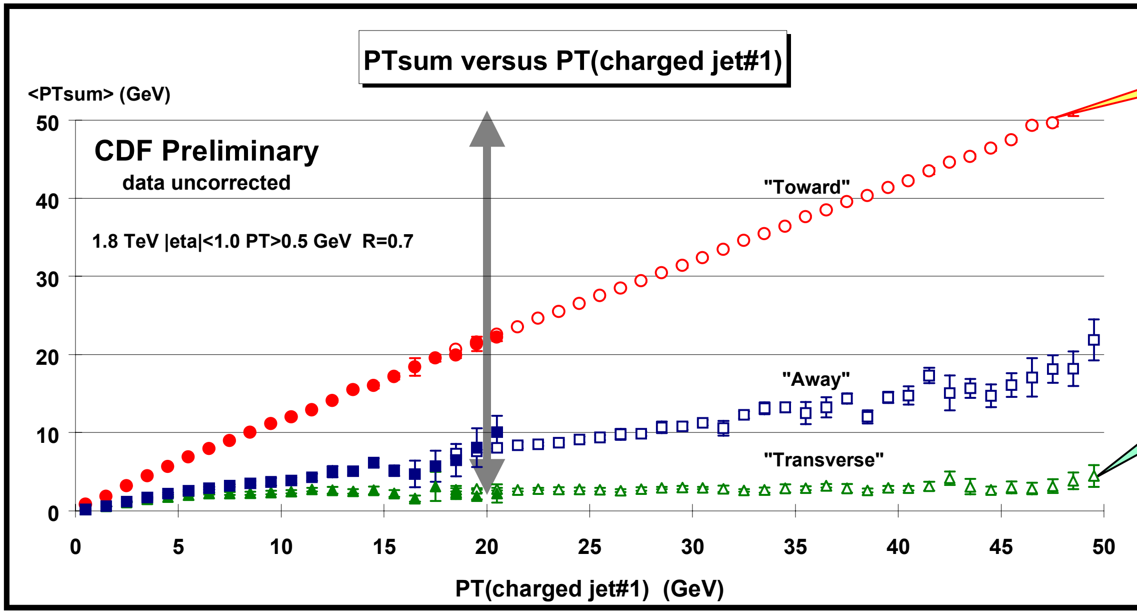




Underlying event "plateau"

- Look at the PT flow in ϕ relative to the direction of jet#1 ($|\eta| < 1$ $P_T > 0.5$ GeV). Use the **JET20** data to extend the range to 0.5 < PT(jet#1) < 50 GeV.
- Define "Toward" $|\phi-\phi_{jet}| < 60^o$ (includes jet#1), "Transverse" $60^o < |\phi-\phi_{jet}| < 120^o$, and "Away" $|\phi-\phi_{jet}| < 120^o$ region.
- Plot shows <PTsum> in the three regions versus PT(jet#1).

Shape of an Average Event with PT(jet#1) = 20 GeV

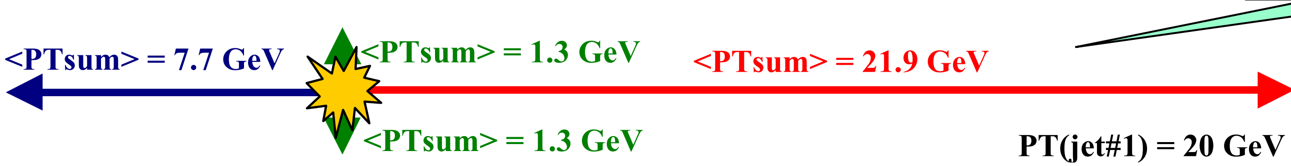


Includes Jet#1

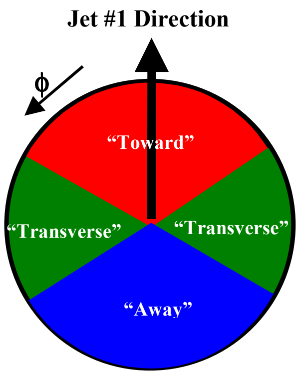
Underlying event "plateau"

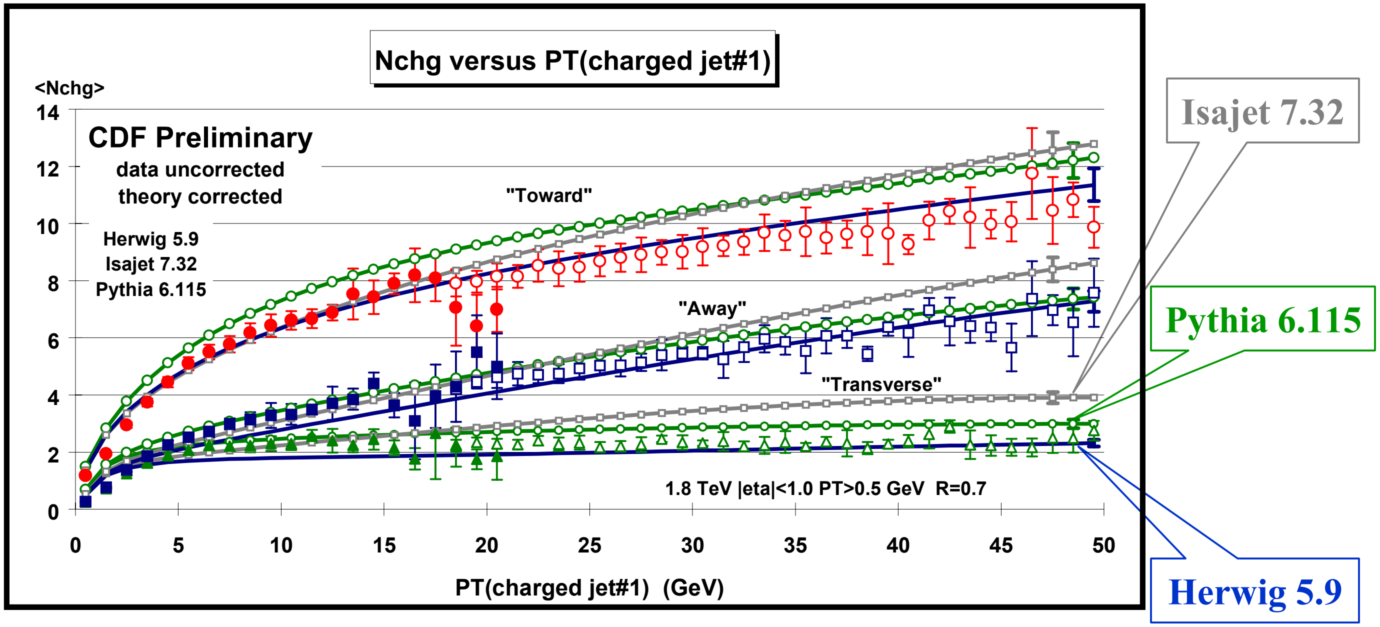
Remember
$|\eta| < 1$ $P_T > 0.5$ GeV

Shape in charged PT



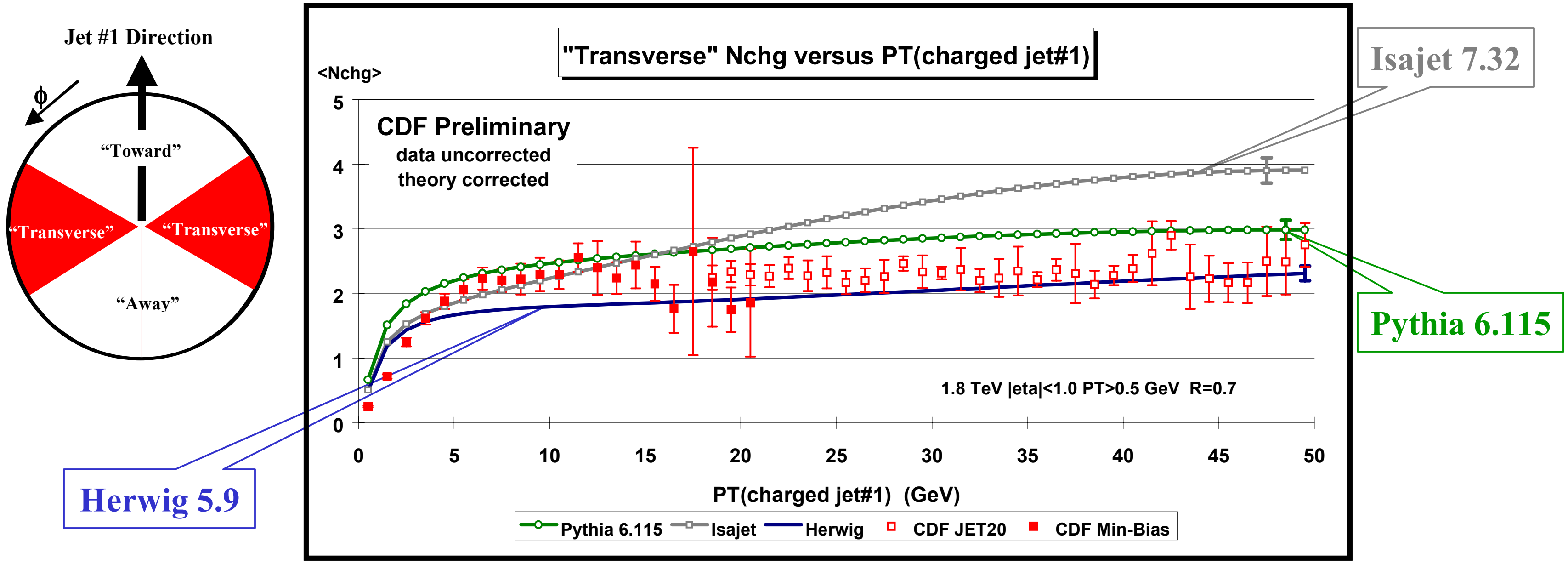
Distribution of Nchg Relative to Jet#1





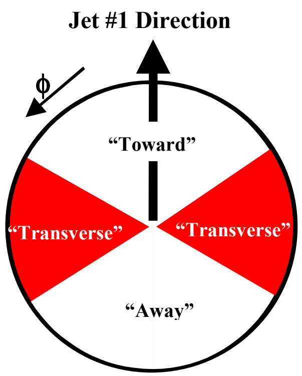
- Look at the charged multiplicity flow in ϕ relative to the direction of jet#1 ($|\eta| < 1$ $P_T > 0.5$ GeV). Use the JET20 data to extend the range to 0.5 < PT(jet#1) < 50 GeV.
- Define “Toward” $|\phi-\phi_{jet}| < 60^o$ (includes jet#1), “Transverse” $60^o < |\phi-\phi_{jet}| < 120^o$, and “Away” $|\phi-\phi_{jet}| < 120^o$ region.
- Plot shows <Nchg> in the three regions versus PT(jet#1) compared with the QCD “hard” scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115.

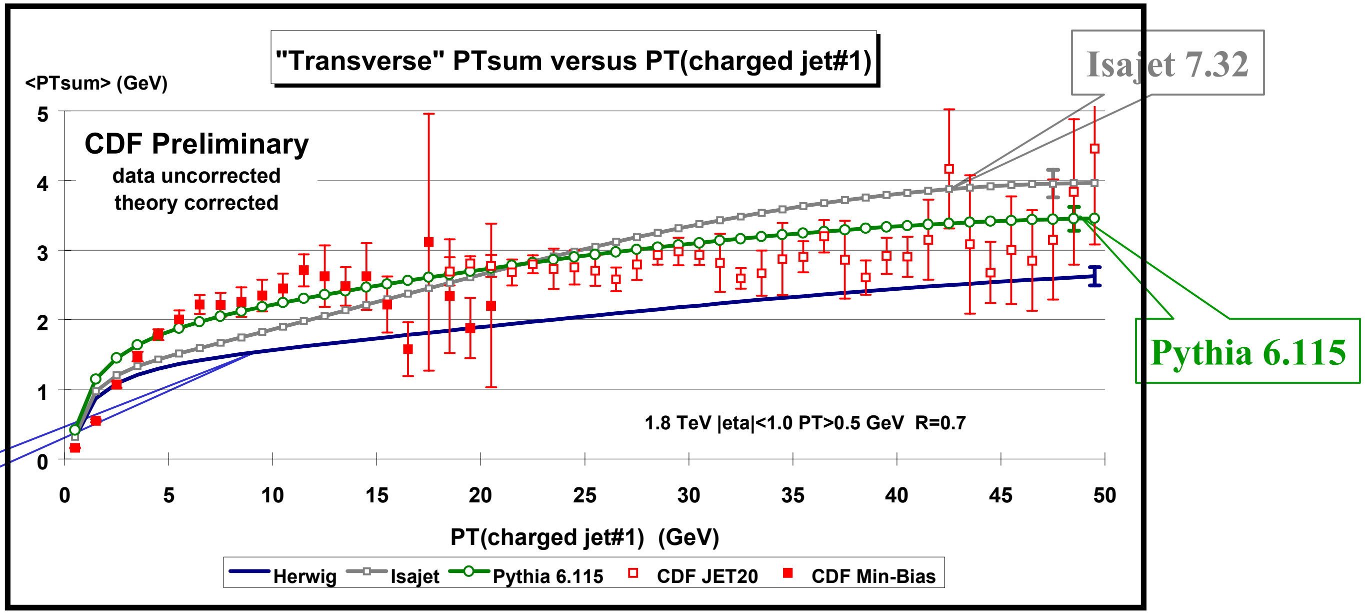
“Transverse” Nchg versus PT(jet#1)



- Look at the charged multiplicity flow in ϕ relative to the direction of jet#1 ($|\eta| < 1$ $P_T >$ 0.5 GeV). Use the JET20 data to extend the range to 0.5 < PT(jet#1) < 50 GeV. Define “Transverse” $60^o < |\phi - \phi jet| < 120^o$.
- Plot shows “Transverse” <Nchg> in the vs PT(jet#1) compared to the QCD “hard” scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115.

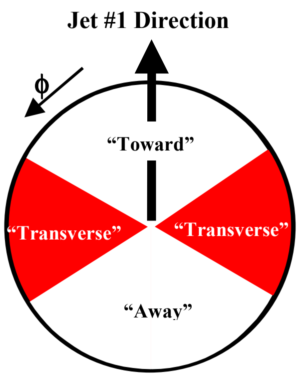
“Transverse” PTsum versus PT(jet#1)

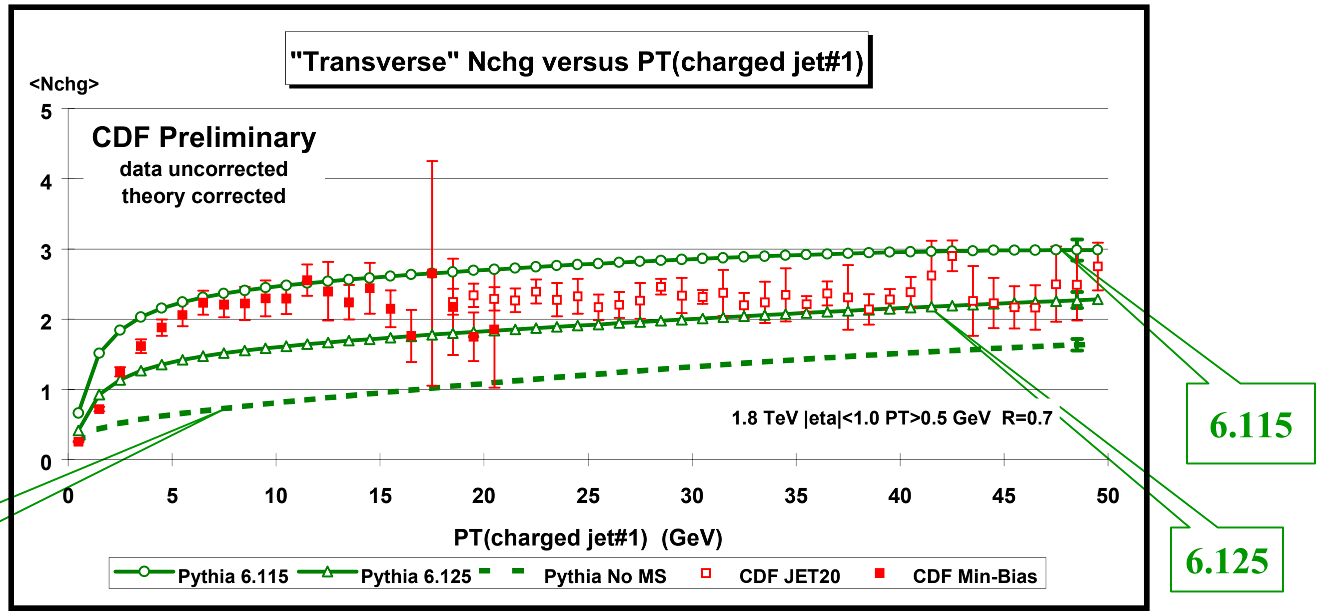




- Look at the charged PT flow in ϕ relative to the direction of jet#1 (|η| < 1 P_T > 0.5 GeV). Use the JET20 data to extend the range to 0.5 < PT(jet#1) < 50 GeV. Define “Transverse” $60^o < |\phi-\phi jet| < 120^o$.
- Plot shows “Transverse” <PTsum> in the vs PT(jet#1) compared to the QCD “hard” scattering predictions of Herwig 5.9, Isajet 7.32, and Pythia 6.115.

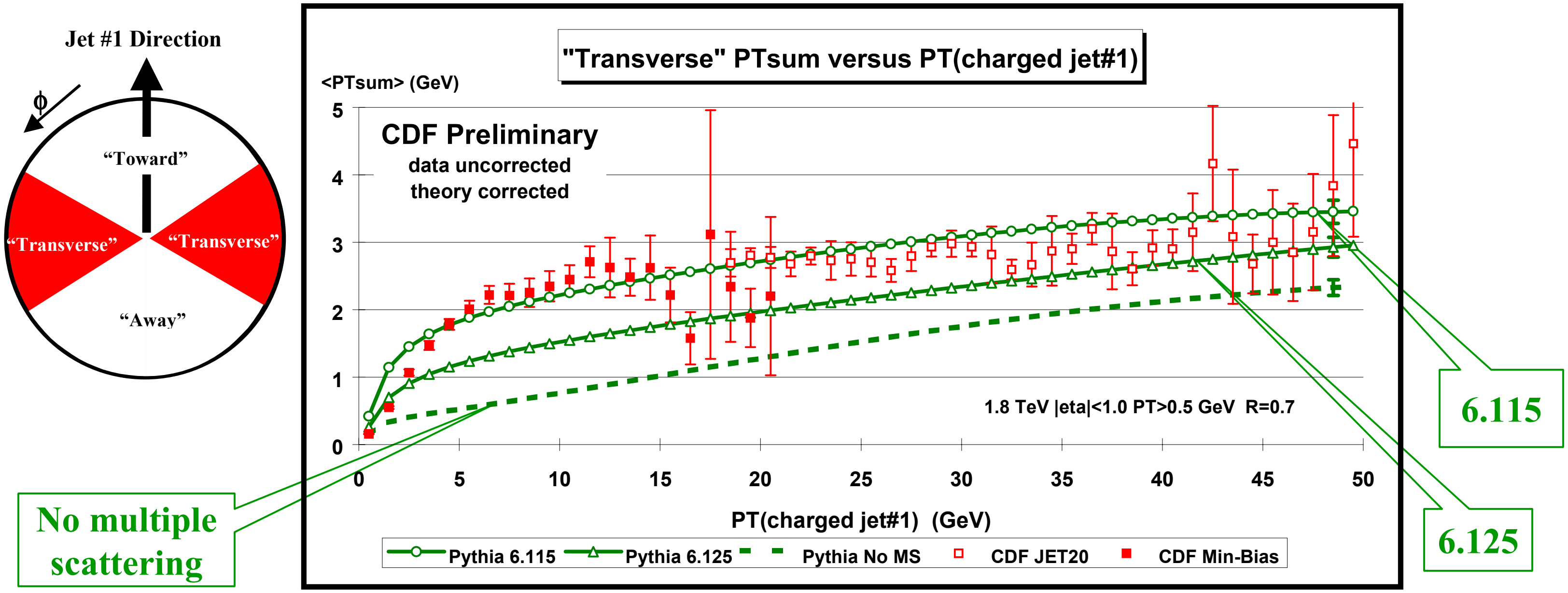
"Transverse" Nchg versus PT(jet#1)





- Look at the charged multiplicity flow in ϕ relative to the direction of jet#1 ($|\eta| < 1$ $P_T >$ 0.5 GeV). Use the JET20 data to extend the range to 0.5 < PT(jet#1) < 50 GeV. Define "Transverse" $60^o < |\phi-\phi jet| < 120^o$.
- Plot shows "Transverse" <Nchg> in the vs PT(jet#1) compared to the QCD "hard" scattering predictions of four versions of Pythia (6.115, 6.125, no multiple interactions).

"Transverse" PTsum versus PT(jet#1)



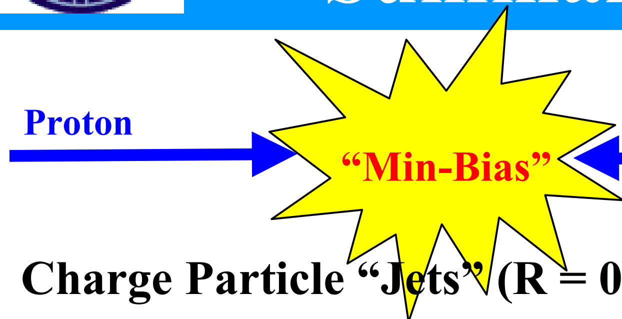
- Look at the charged PT flow in ϕ relative to the direction of jet#1 ($|\eta| < 1$ $P_T > 0.5$ GeV). Use the **JET20** data to extend the range to 0.5 < PT(jet#1) < 50 GeV. Define "Transverse" $60^o < |\phi-\phi jet| < 120^o$.
- Plot shows **"Transverse" <PTsum> in the vs PT(jet#1)** compared to the QCD "hard" scattering predictions of four versions of **Pythia** (6.115, 6.125, no multiple interactions).

"Min-Bias" Physics: Summary & Conclusions

"Soft" versus "Hard" Collisions

- **The "soft" Monte-Carlo models do not describe the Min-Bias data because the "soft" models have no "hard" scattering and no "jets" and the data show "jet" structure for PTmax > 1 GeV.**
- **The QCD "hard" scattering models (with PT(hard) > 3 GeV) qualitatively fit the data for PTmax or PTjet greater than about 2 GeV.**
- **Below 2 GeV that data are a mixture of "hard" and "soft" and to describe this region we will have to combine a model for the "soft" collisions with a QCD perturbative Monte-Carlo model of the "hard" collisions. We are working on this!**

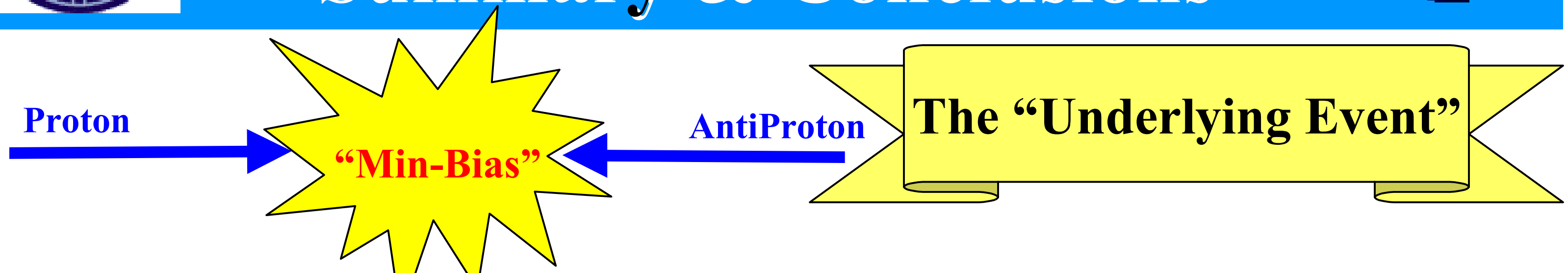
"Min-Bias" Physics: Summary & Conclusions



The Evolution of "Jets"

- **Charge Particle "Jets" (R = 0.7) are "born" somewhere around PT(jet) of about 1 GeV with, on the average, about 2 charged particles, and grow to, on the average, about 10 charged particles at 50 GeV.**
- **The QCD "hard" scattering Monte-Carlo models agree qualitatively well with the multiplicity distribution of the charged particles within a "jet", the flow of charged multiplicity and PTsum around the jet direction, the "size" of the jets, and with the charged jet "fragmentation functions". They agree as well with 2 GeV "jets" as they do with 50 GeV "jets"!**
- **The "jets" in the Min-Bias data are simply the extrapolation (*down to small P_T*) of the high transverse momentum "jets" observed in the JET20 data. Our analysis suggests that at 1.8 TeV "hard" scattering makes up at least one-half of the "hard core" inelastic cross section. At the LHC, lots of "min-bias" events will contain 20 GeV "jets"!**

"Min-Bias" Physics: Summary & Conclusions



- The "underlying event" is formed from the "beam-beam remnants", initial-state radiation, and possibly from multiple parton interactions..
- The Min-Bias data show that the charged multiplicity in the "underlying event" grows very rapidity with PTmax or with P_T(jet#1) and then forms an approximately constant "plateau". The height of this "plateau" is at least twice that observed in "soft" collisions at the same corresponding energy.
- None of the QCD Monte-Carlo models correctly describe the structure of the underlying event seen in the data. Herwig 5.9 and Pythia 6.125 do not have enough activity in the underlying event. Pythia 6.115 has about the right amount of activity in the underlying event, but as a result produces too much overall multiplicity. Isajet 7.32 has a lot of activity in the underlying event, but with the wrong dependence on P_T(jet#1).