Min-Bias and the Underlying Event in Run 2

CERN MC4LH

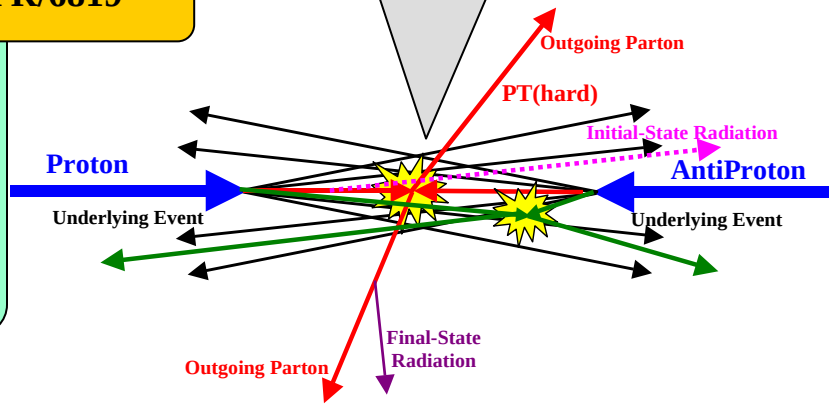
July 2

During the workshop the theorists, ATLAS/CMS experimenters, and I constructed a "wish list" of data from CDF relating to "min-bias" and the "underlying event" and I promised to do the analysis and have the data available by the time of the Santa Barbara workshop in February 2004.

CDF Notes

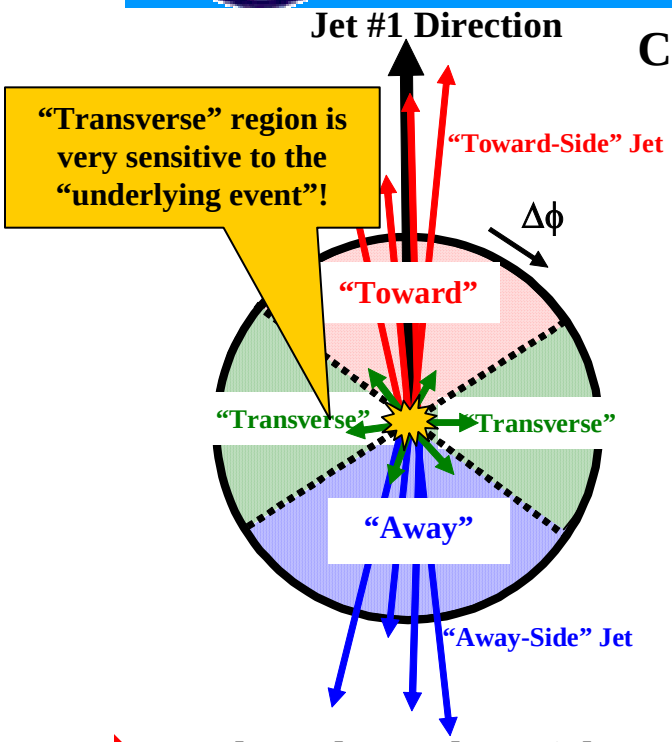
CDF/ANAL/CDF/CDFR/6403
CDF/ANAL/CDF/CDFR/6759
CDF/ANAL/CDF/CDFR/6819

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



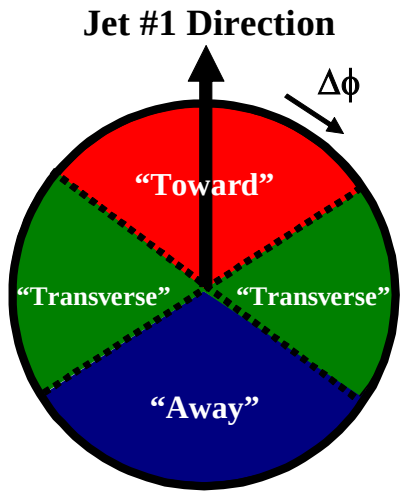
- **Min-Bias and the "Underlying Event" in Run II at CDF: The Run 2 analysis gives a more detailed look at the "underlying event" in hard scattering processes and compares the (*uncorrected*) data with PYTHIA Tune A and HERWIG after CDFSIM.**
- **My graduate student, Alberto Cruz, will take over this analysis and bring it to "publication level" (*within the next year!*).**

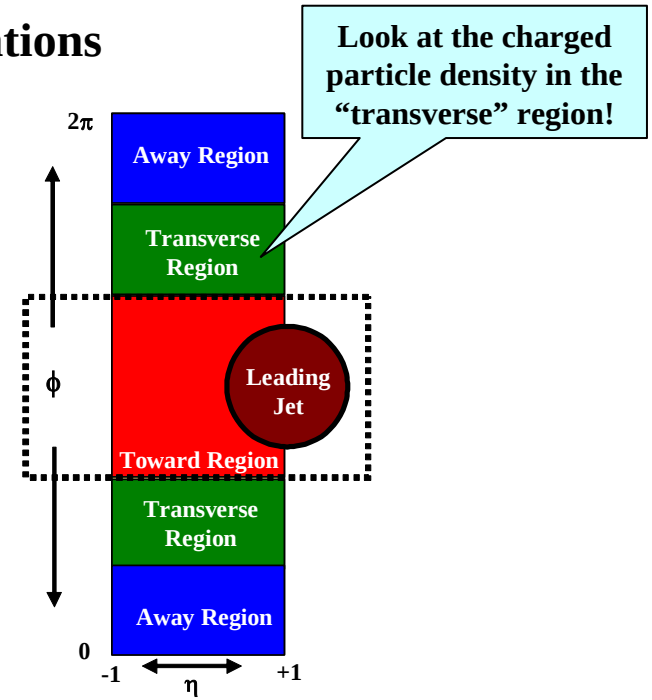
"Transverse" Region
as defined by the Leading Jet



Charged Particle Δϕ Correlations

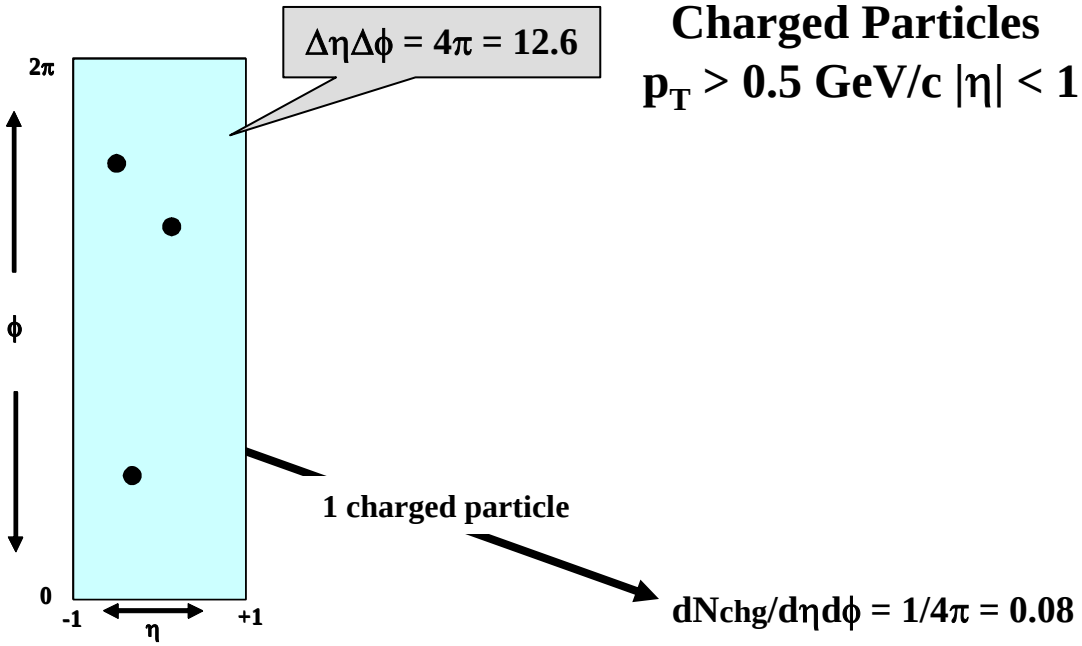
p_T > 0.5 GeV/c |η| < 1





- 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", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away". The "transverse region" is very sensitive to the "underlying event".
- All three regions have the same size in η-ϕ space, $\Delta\eta x\Delta\phi = 2x120^o = 4\pi/3$.

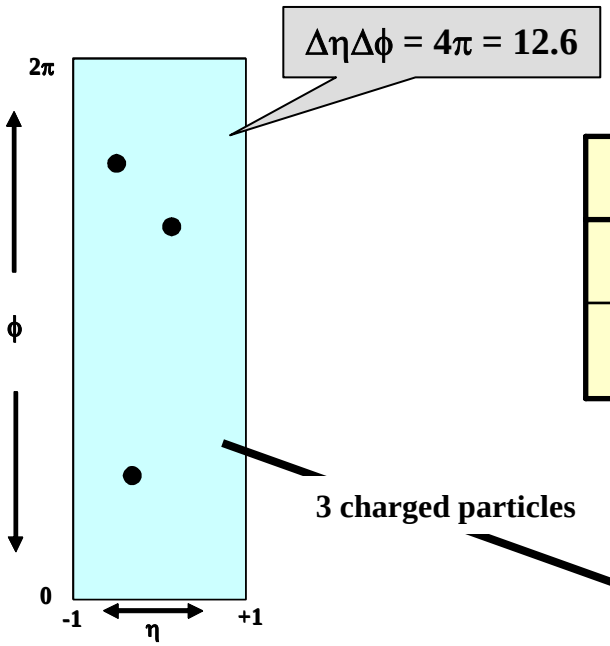
Particle Densities



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

- **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, $dPT_{sum}/d\eta d\phi$.**

Particle Densities



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, $\|\eta\| < 1$)	3.17 +/- 0.31	0.252 +/- 0.025
PTsum (GeV/c)	Scalar p_T sum of Charged Particles ($p_T > 0.5$ GeV/c, $\|\eta\| < 1$)	2.97 +/- 0.23	0.236 +/- 0.018

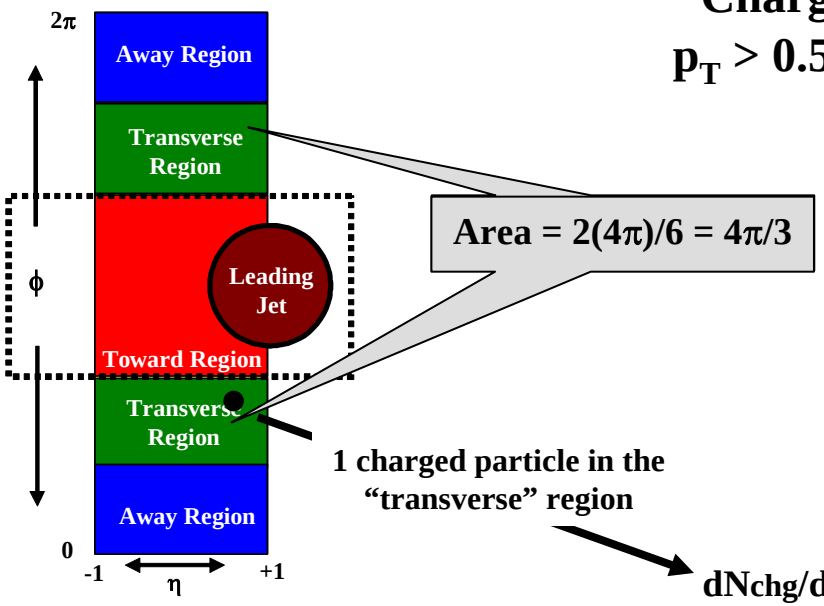
Divide by 4π

- **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, $dPT_{sum}/d\eta d\phi$.**

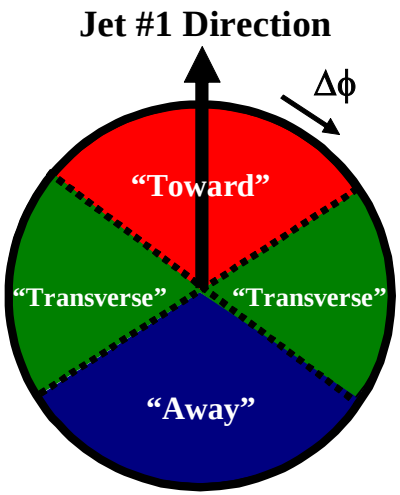
"Transverse" Particle Densities

Charged Particles

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

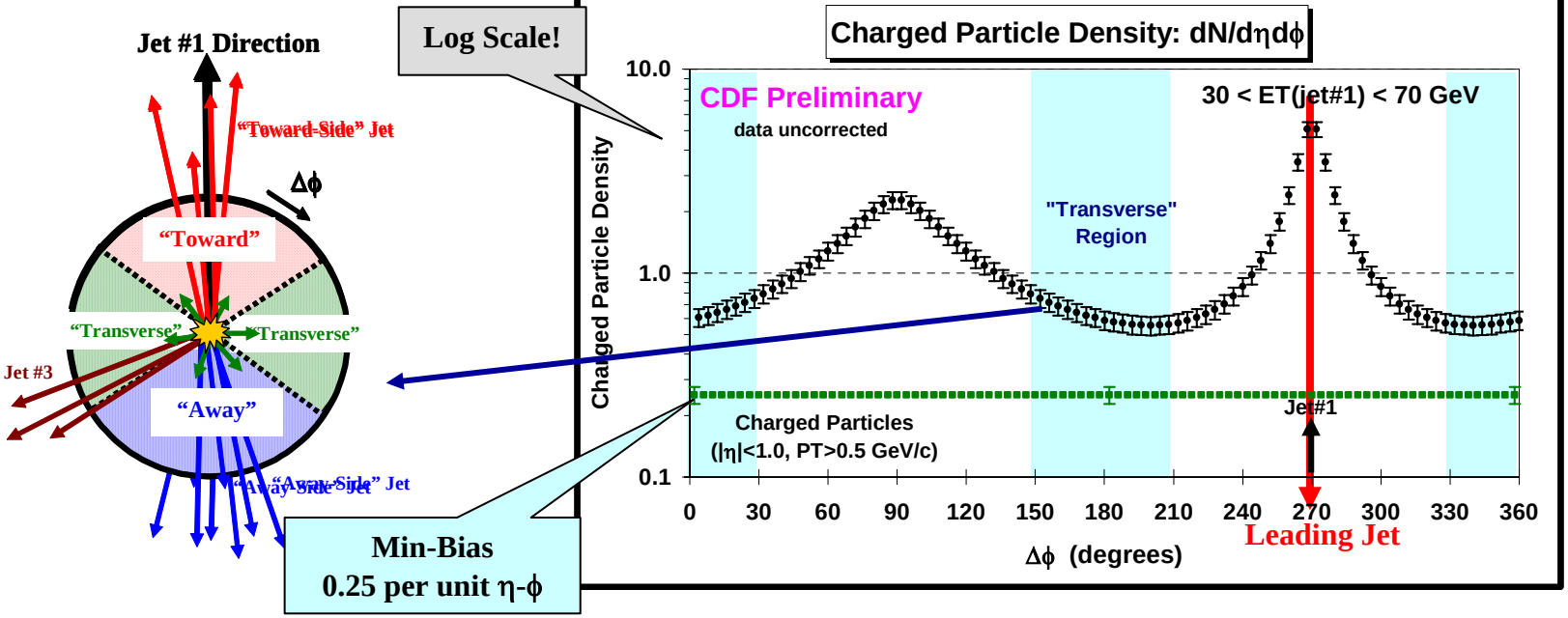


$dN_{chg}/d\eta d\phi = 1/(4\pi/3) = 0.24$



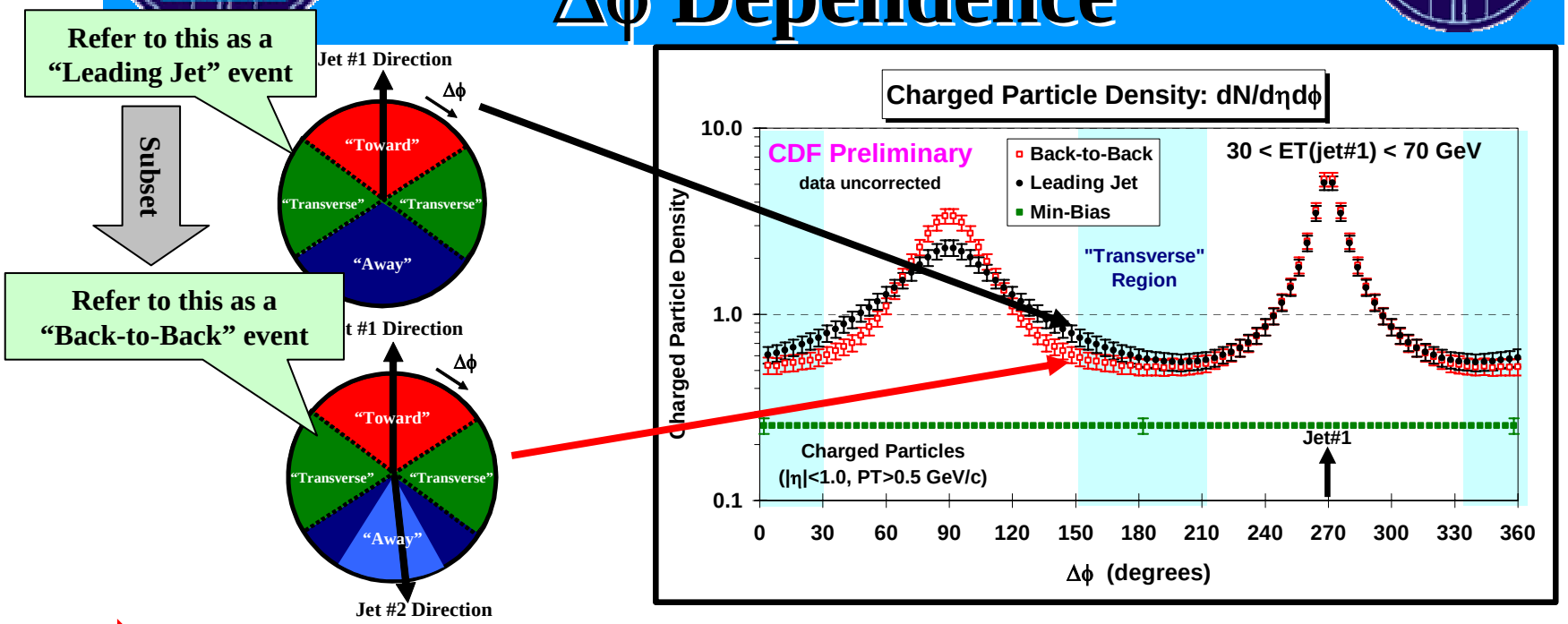
- **Study the charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) in the "transverse" region and form the charged particle density, $dN_{chg}/d\eta d\phi$, and the charged scalar p_T sum density, $dPT_{sum}/d\eta d\phi$.**

Charged Particle Density
Δϕ Dependence



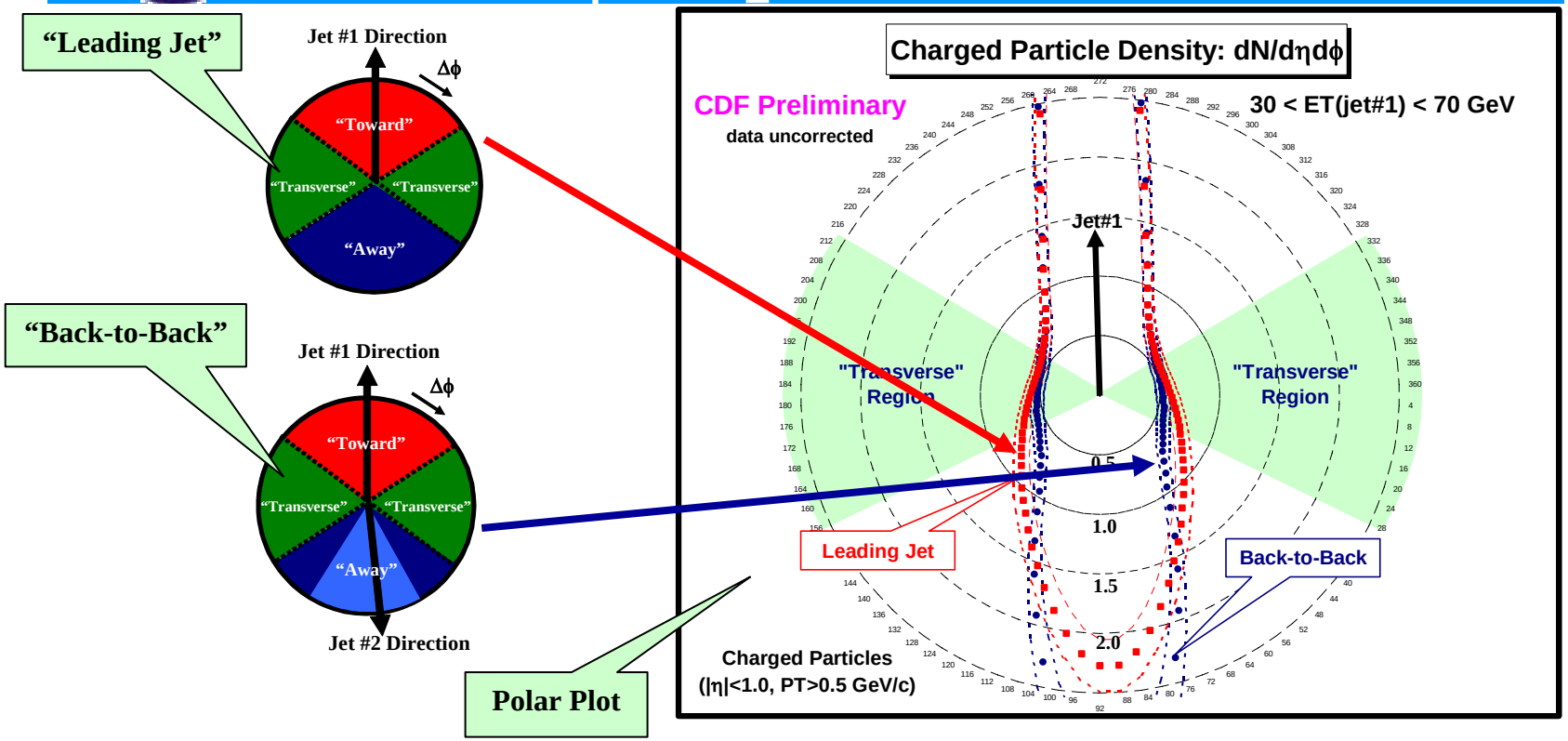
- Shows the Δϕ dependence of the charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles in the range $p_T > 0.5$ GeV/c and $|\eta| < 1$ relative to jet#1 (rotated to 270°) for "leading jet" events $30 < E_T(\text{jet\#1}) < 70$ GeV.
- Also shows charged particle density, $dN_{chg}/d\eta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

Charged Particle Density
Δϕ Dependence



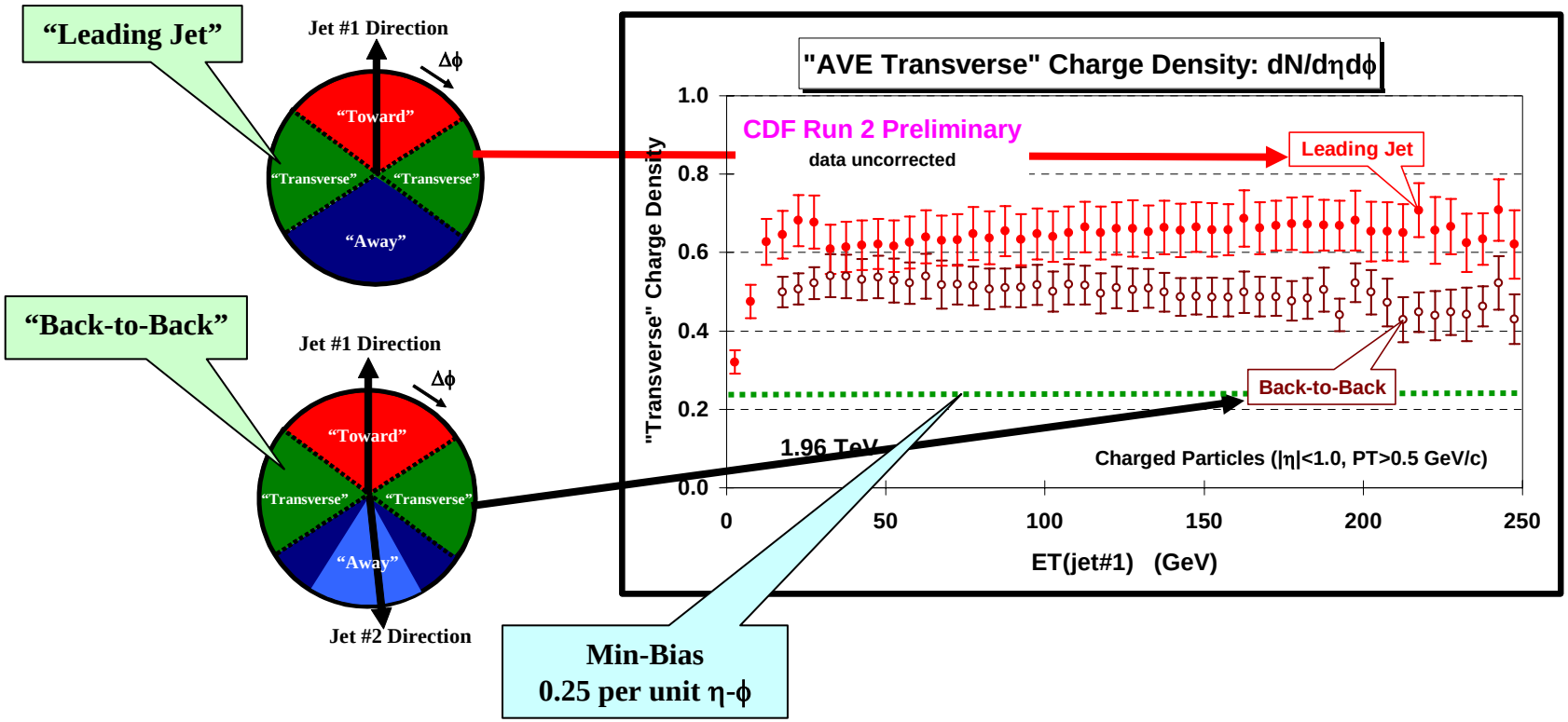
- Look at the "transverse" region as defined by the leading jet (JetClu R = 0.7, $|\eta| < 2$) or by the leading two jets (JetClu R = 0.7, $|\eta| < 2$). "Back-to-Back" events are selected to have at least two jets with Jet#1 and Jet#2 nearly "back-to-back" ($\Delta\phi_{12} > 150^o$) with almost equal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

Charged Particle Density
Δϕ Dependence



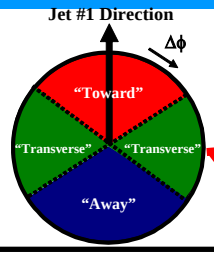
➡ **Shows the Δϕ dependence of the charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles in the range $p_T > 0.5$ GeV/c and $|\eta| < 1$ relative to jet#1 (rotated to 270º) for 30 < E_T(jet#1) < 70 GeV for "Leading Jet" and "Back-to-Back" events.**

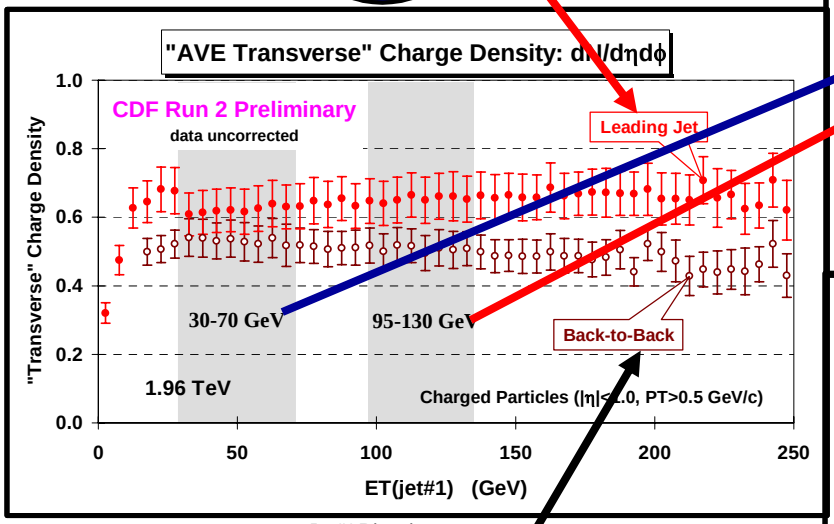
"Transverse" Charge Density versus E_T(jet#1)

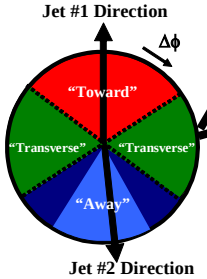


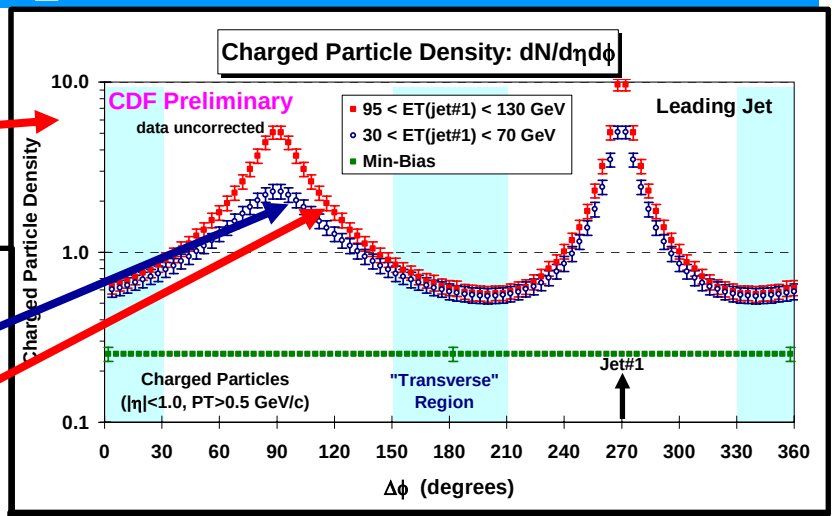
- **Shows the average charged particle density, $dN_{chg}/d\eta d\phi$, in the "transverse" region (p_T > 0.5 GeV/c, $|\eta|$ < 1) versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events.**

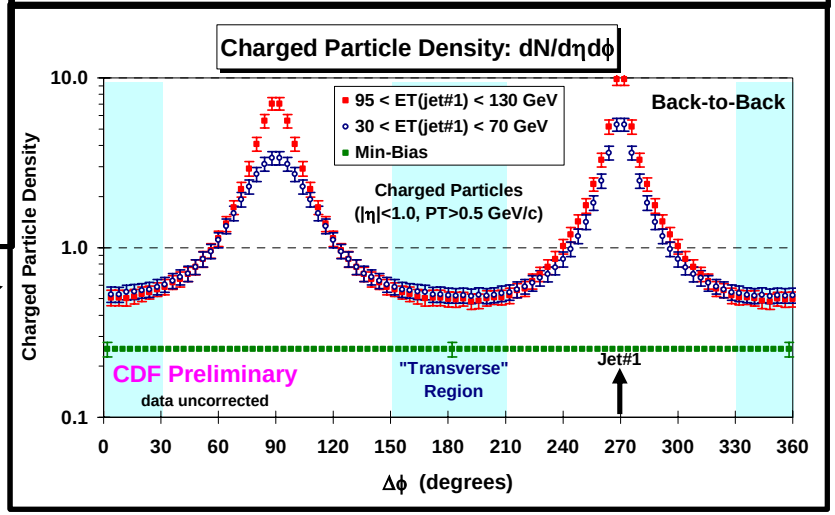
"Transverse" Charge Density versus E_T(jet#1)



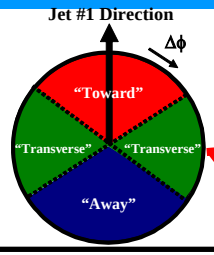


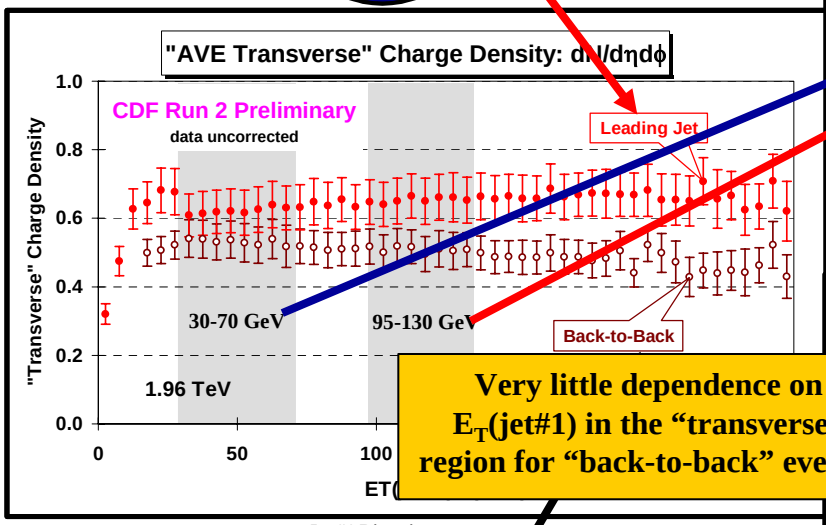


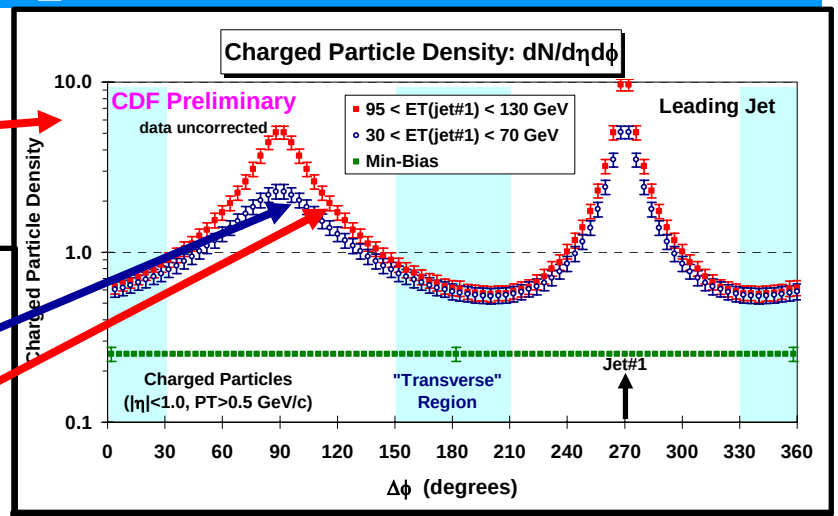


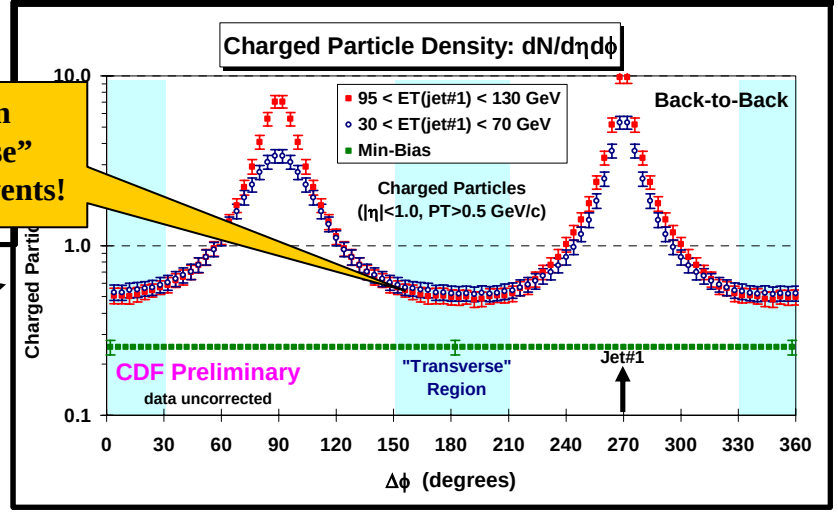


"Transverse" Charge Density versus E_T(jet#1)

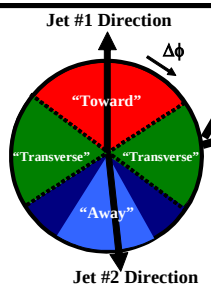




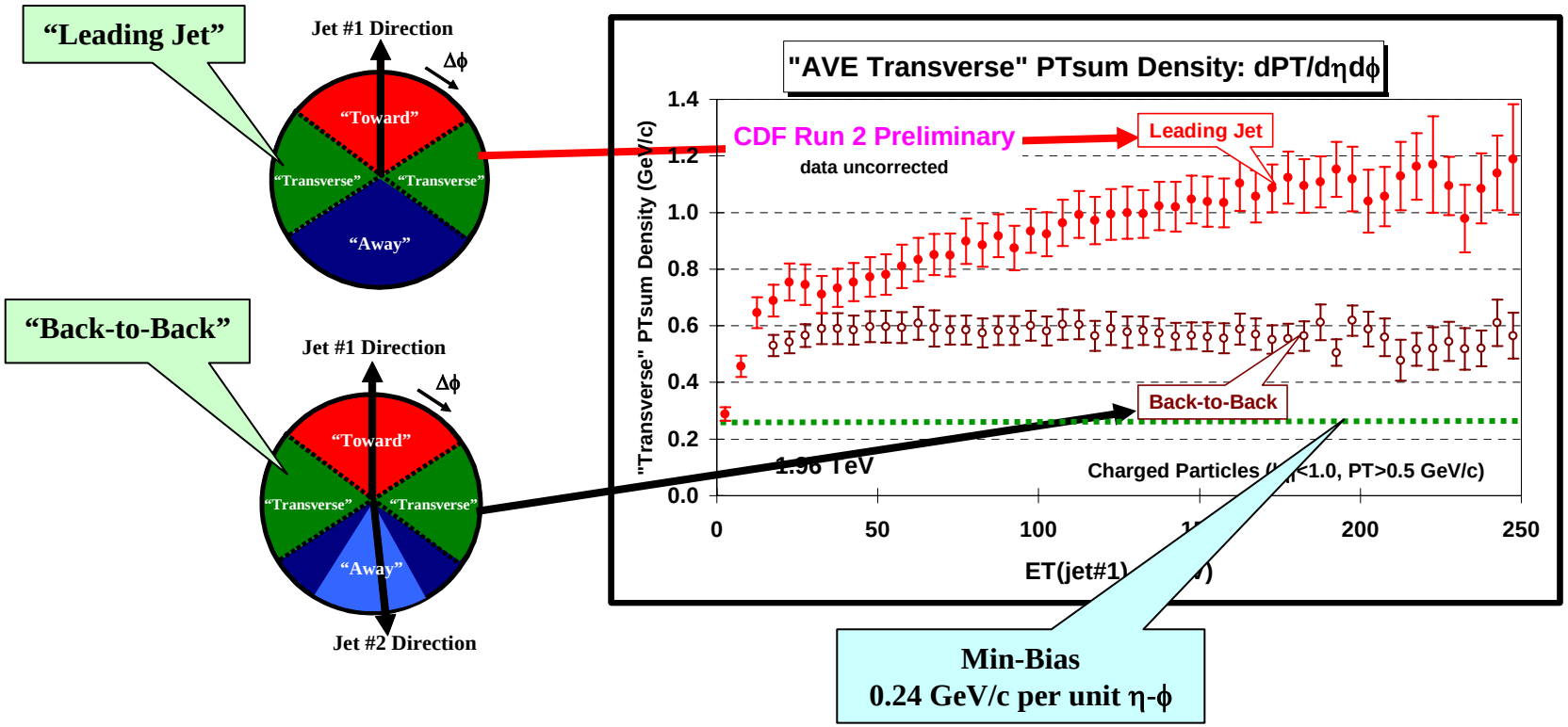




Very little dependence on E_T(jet#1) in the "transverse" region for "back-to-back" events!

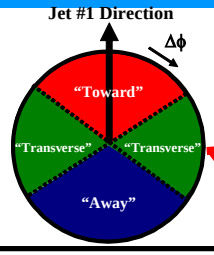


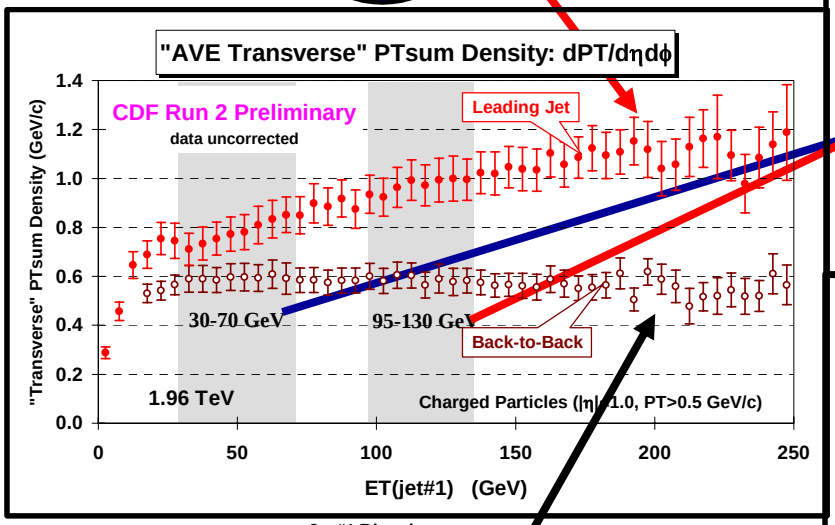
"Transverse" PTsum Density versus E_T(jet#1)

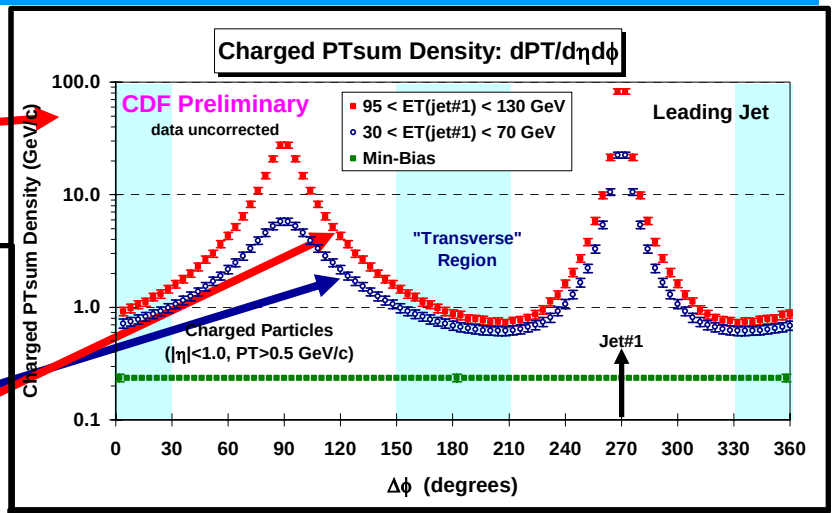


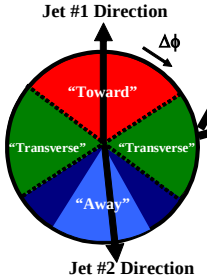
➡ **Shows the average charged PTsum density, $dPT_{sum}/d\eta d\phi$, in the "transverse" region (p_T > 0.5 GeV/c, $|\eta| < 1$) versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events.**

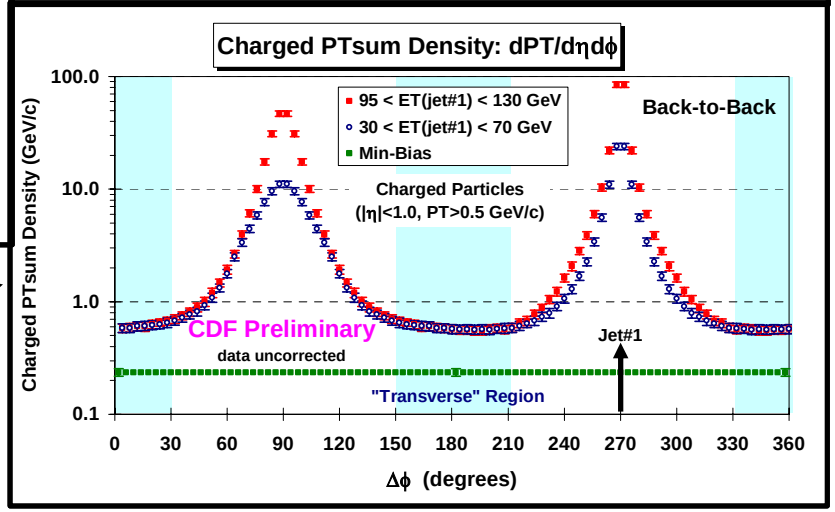
"Transverse" PTsum Density versus E_T(jet#1)



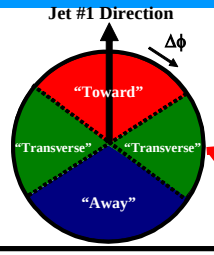


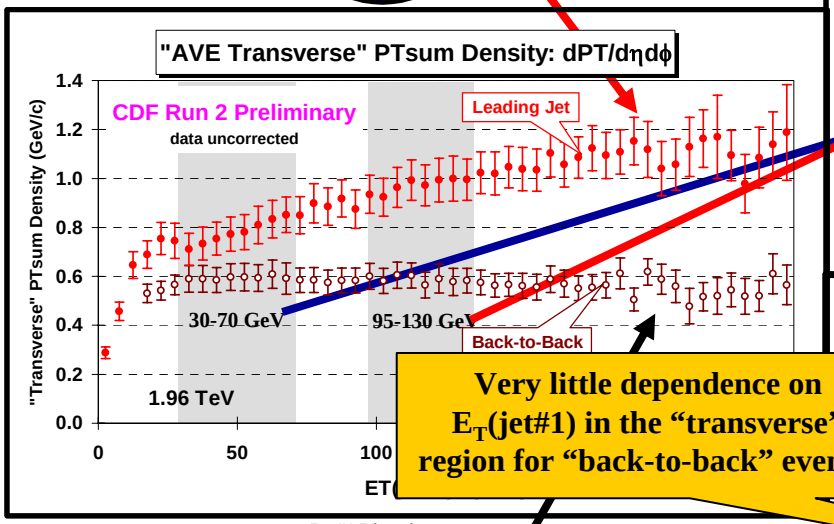


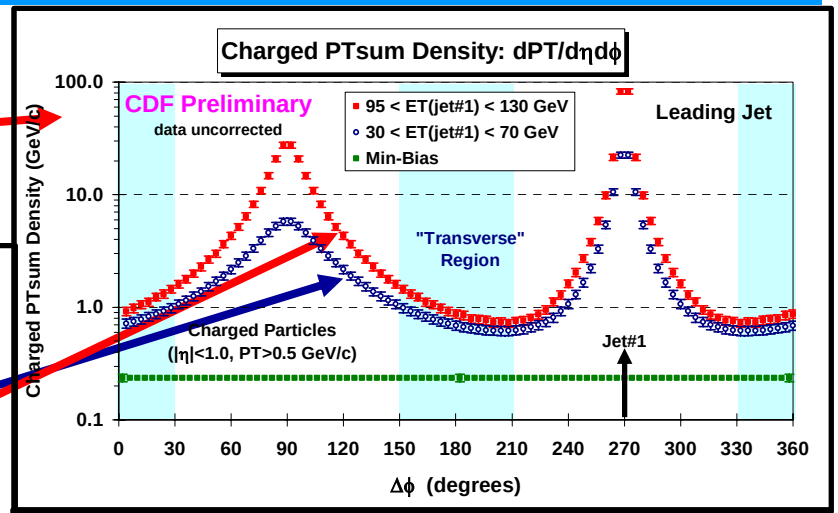


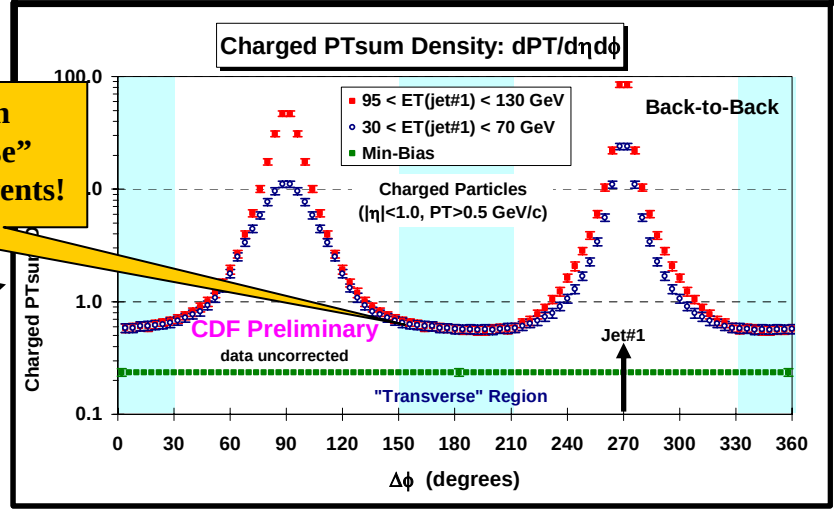


"Transverse" PTsum Density versus E_T(jet#1)

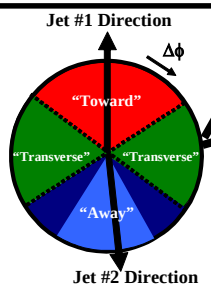




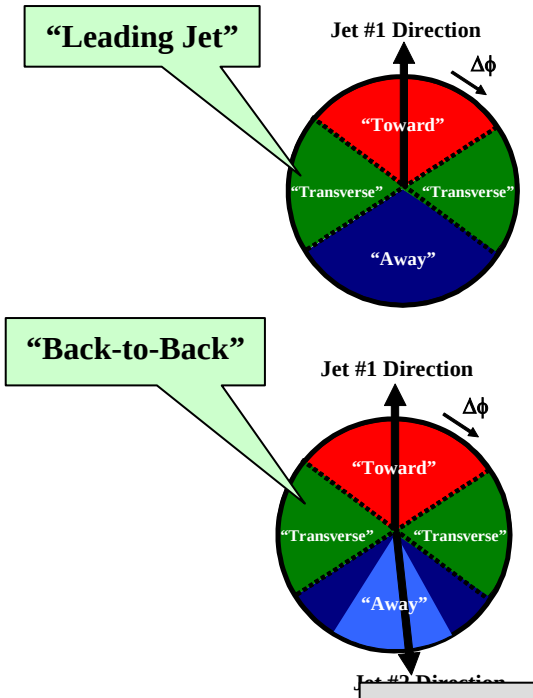


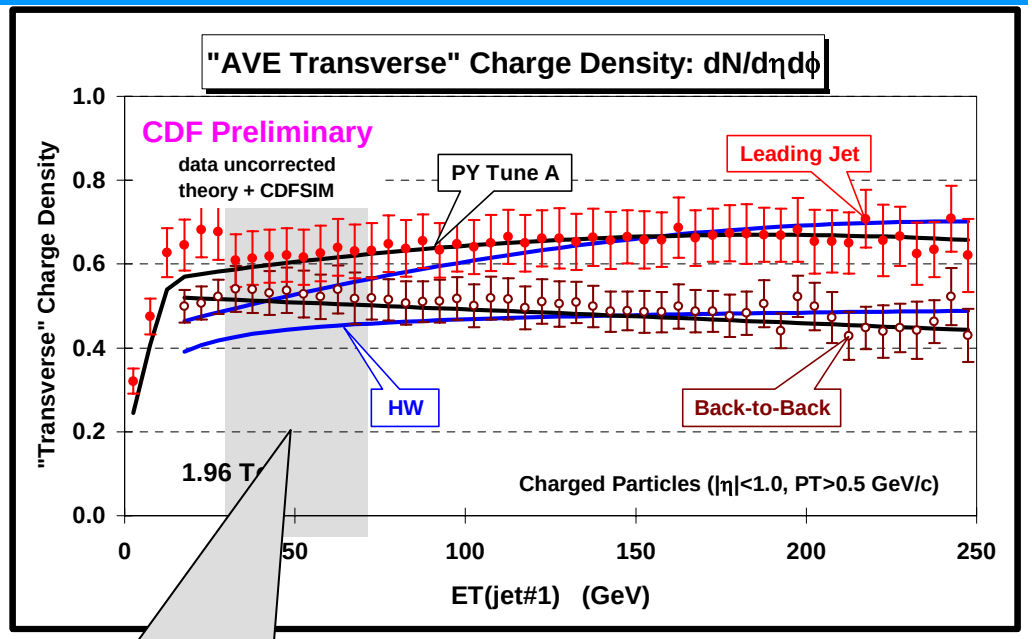


Very little dependence on E_T(jet#1) in the "transverse" region for "back-to-back" events!



"Transverse" Charge Density
PYTHIA Tune A vs HERWIG



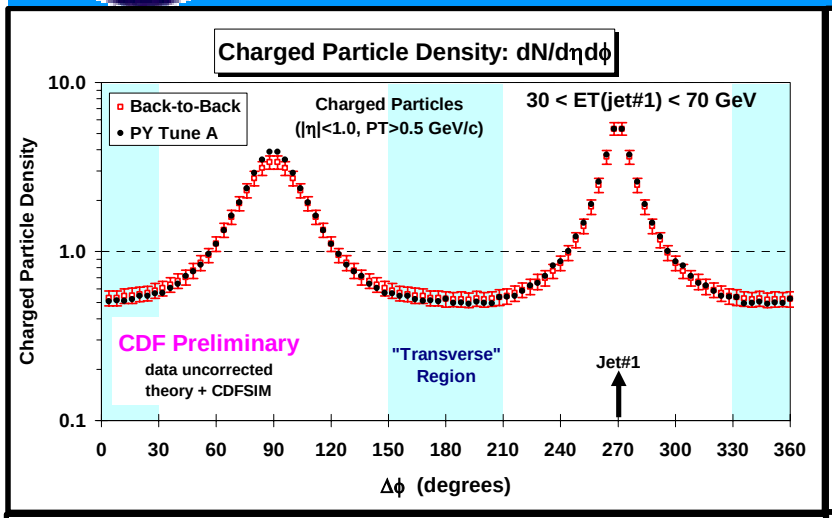


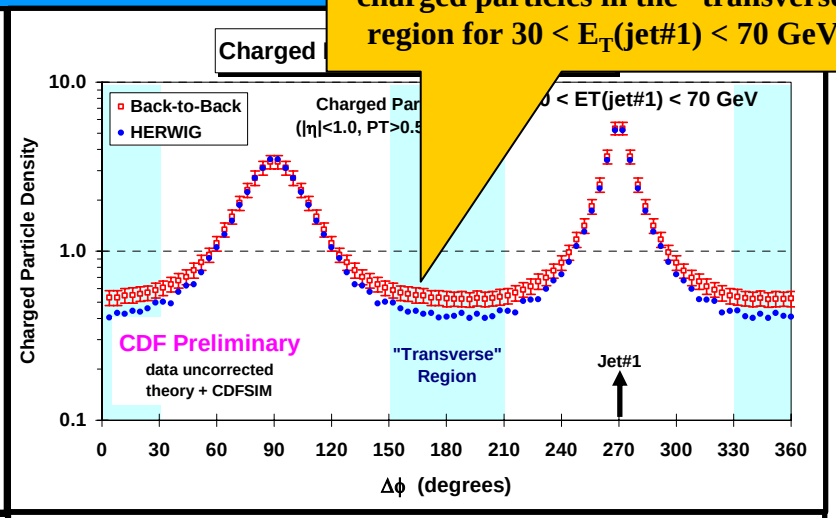
Now look in detail at "back-to-back" events in the region 30 < E_T(jet#1) < 70 GeV!

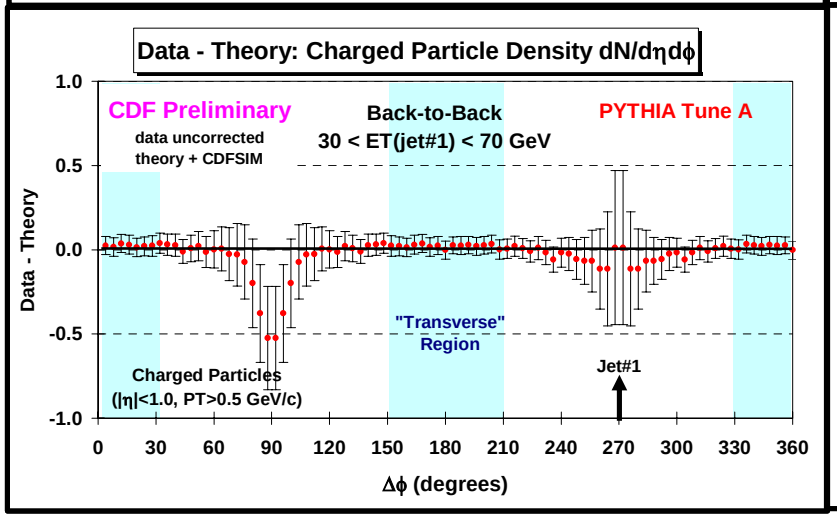
- Shows the average charged particle density, $dN_{chg}/d\eta d\phi$, in the "transverse" region (p_T > 0.5 GeV/c, $|\eta|$ < 1) versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- Compares the (*uncorrected*) data with PYTHIA Tune A and HERWIG after CDFSIM.

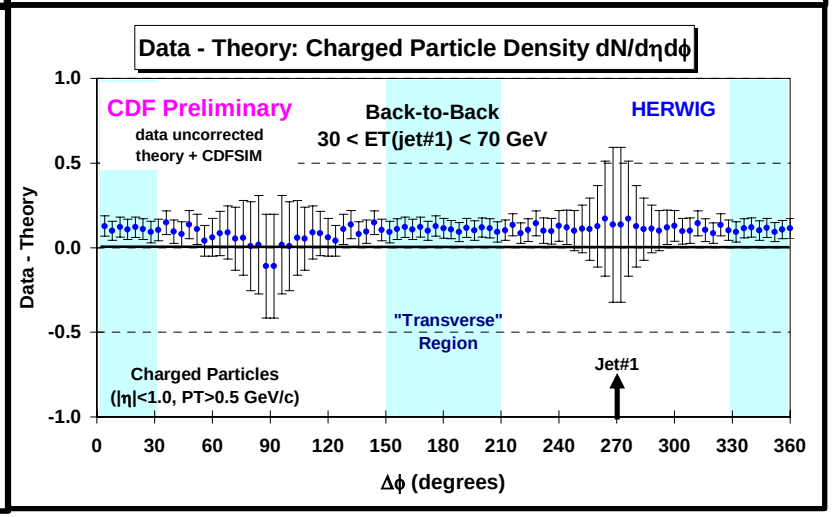
Charged Particle Density
PYTHIA Tune A vs HE

HERWIG (*without multiple parton interactions*) produces too few charged particles in the "transverse" region for 30 < E_T(jet#1) < 70 GeV!

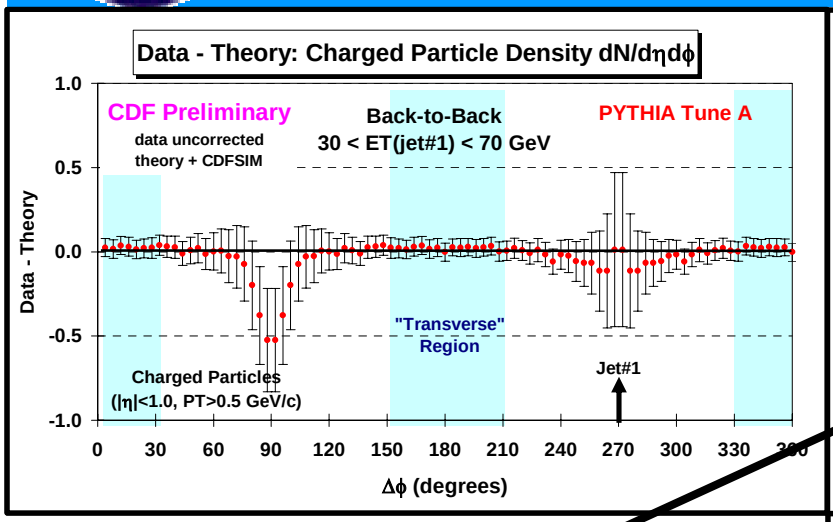


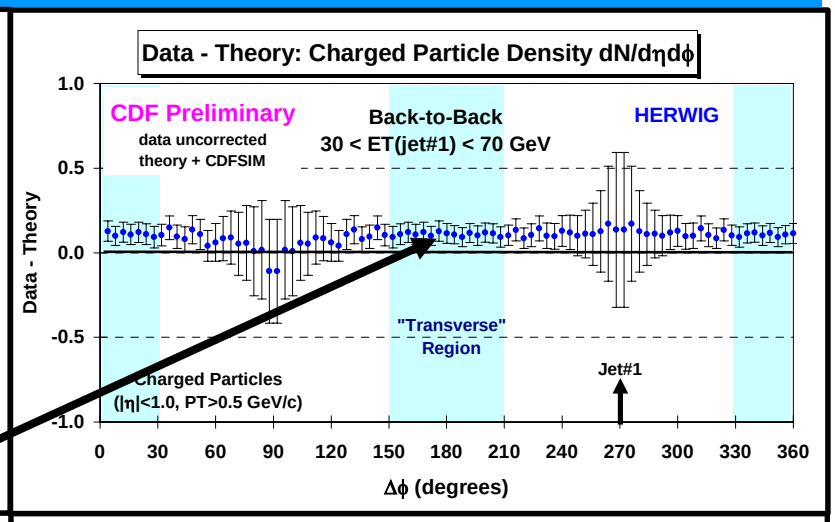




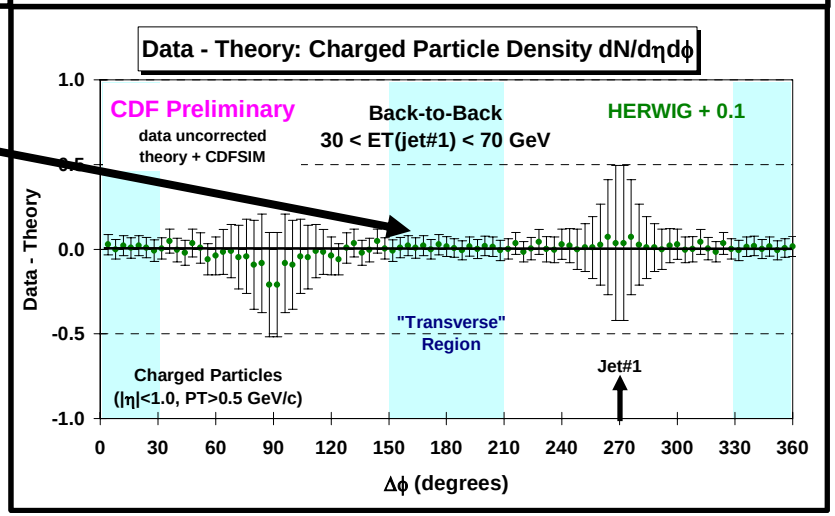


Charged Particle Density
PYTHIA Tune A vs HERWIG



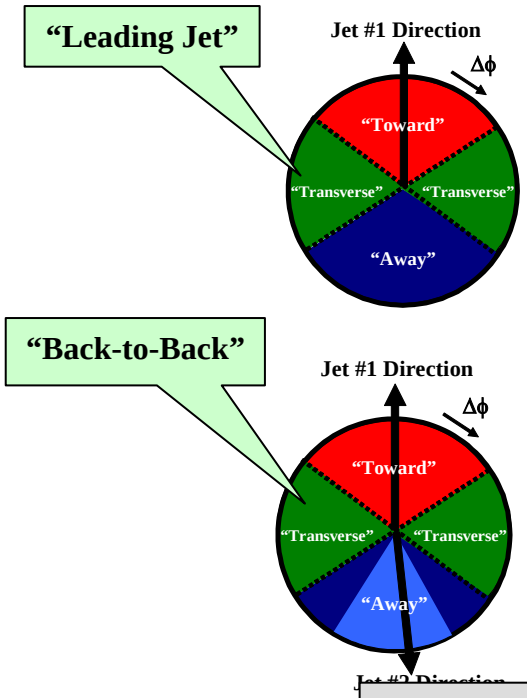


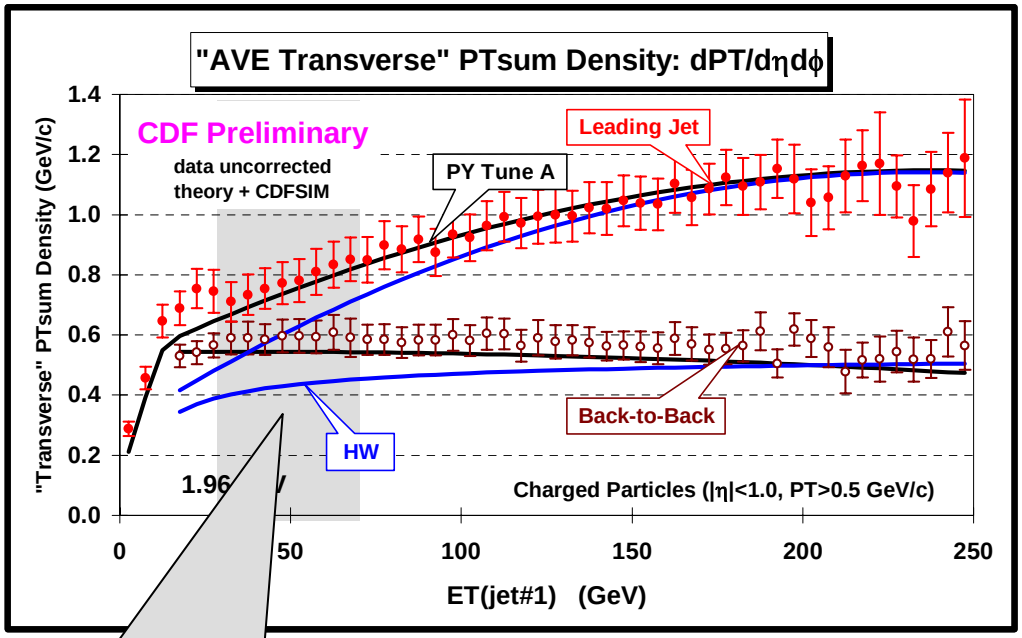
dN/dηdϕ + 0.1



- **Add 0.1 charged particles per unit η-ϕ to HERWIG density, $dN_{chg}/d\eta d\phi$.**
- **This corresponds to 0.1 x 4π = 1.3 particles in the entire range $p_T > 0.5$ GeV/c, $|\eta| < 1$.**

"Transverse" PTsum Density
PYTHIA Tune A vs HERWIG



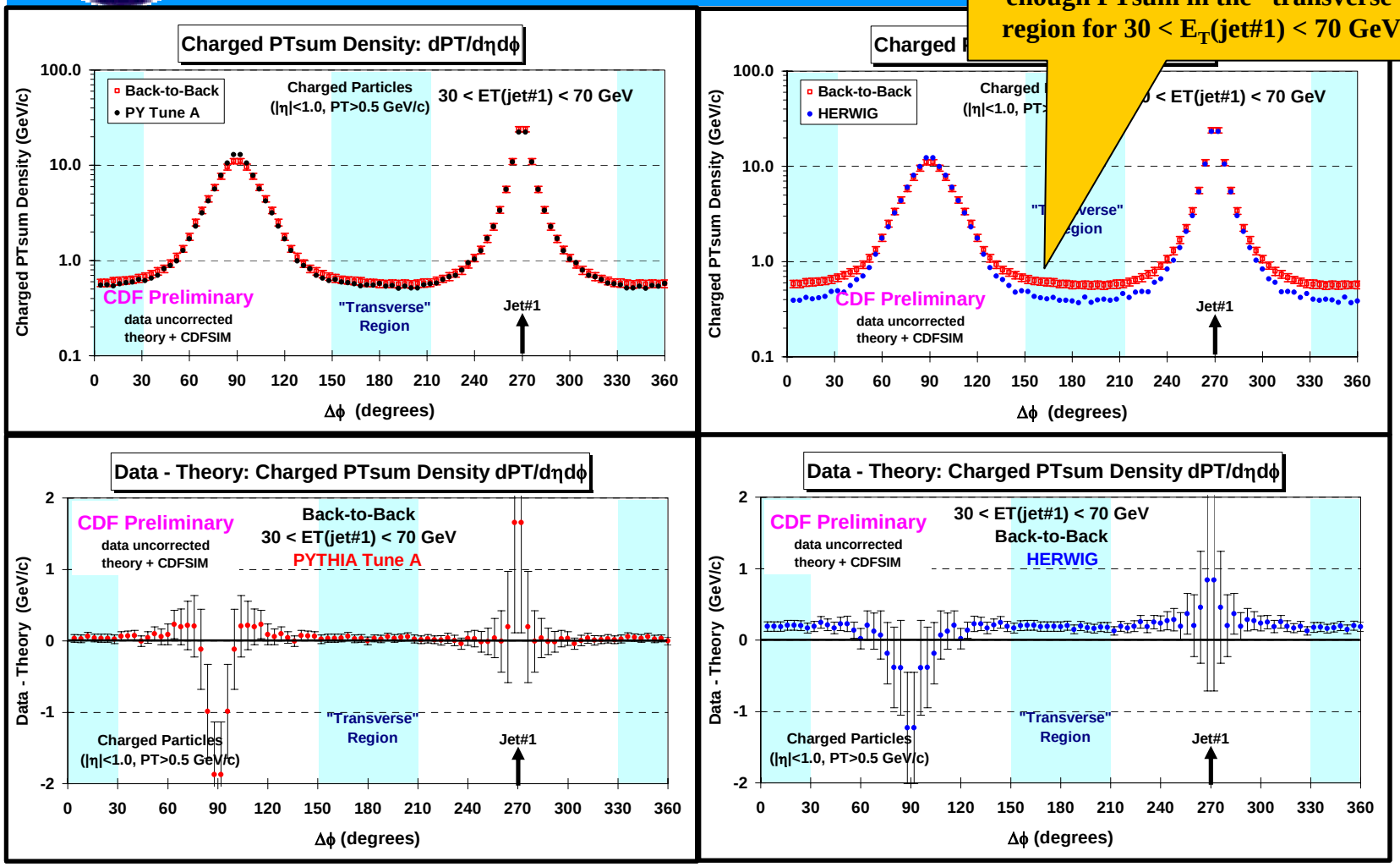


Now look in detail at "back-to-back" events in the region 30 < E_T(jet#1) < 70 GeV!

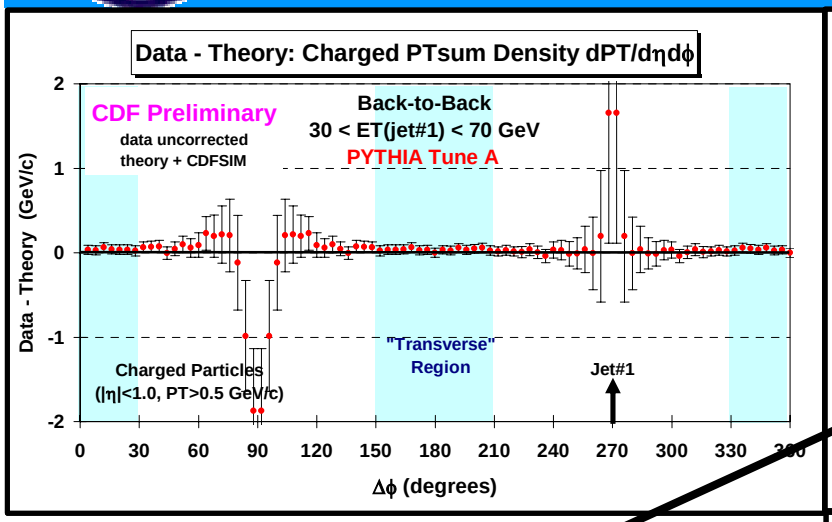
- Shows the average charged PTsum density, $dPT_{sum}/d\eta d\phi$, in the "transverse" region (p_T > 0.5 GeV/c, $|\eta|$ < 1) versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- Compares the (*uncorrected*) data with PYTHIA Tune A and HERWIG after CDFSIM.

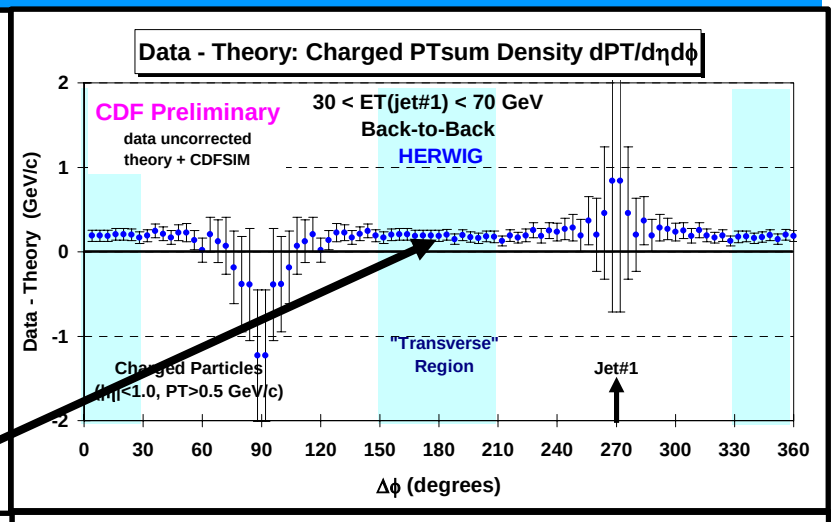
Charged PTsum Density
PYTHIA Tune A vs HE

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



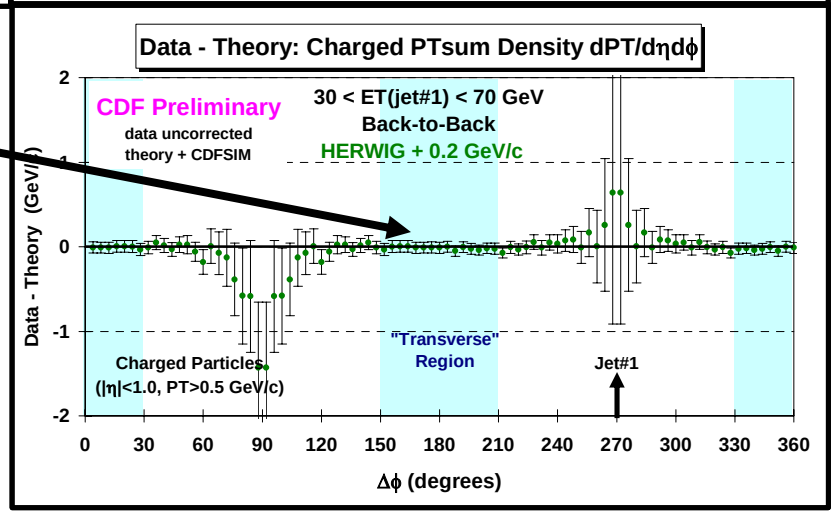
Charged PTsum Density
PYTHIA Tune A vs HERWIG





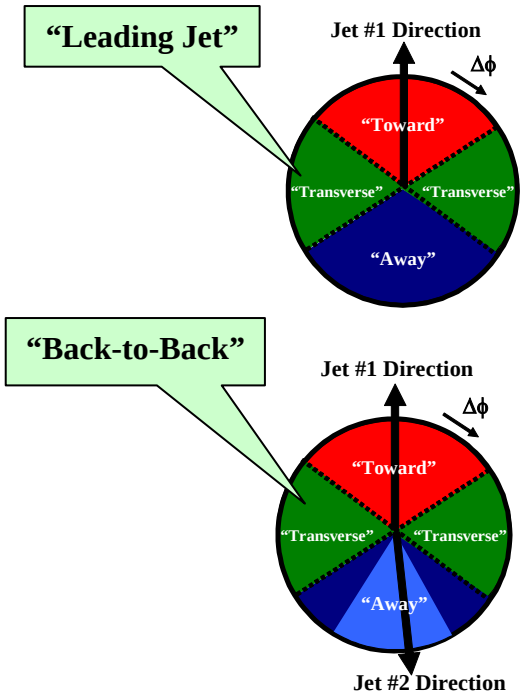
308 MeV in R = 0.7 cone!

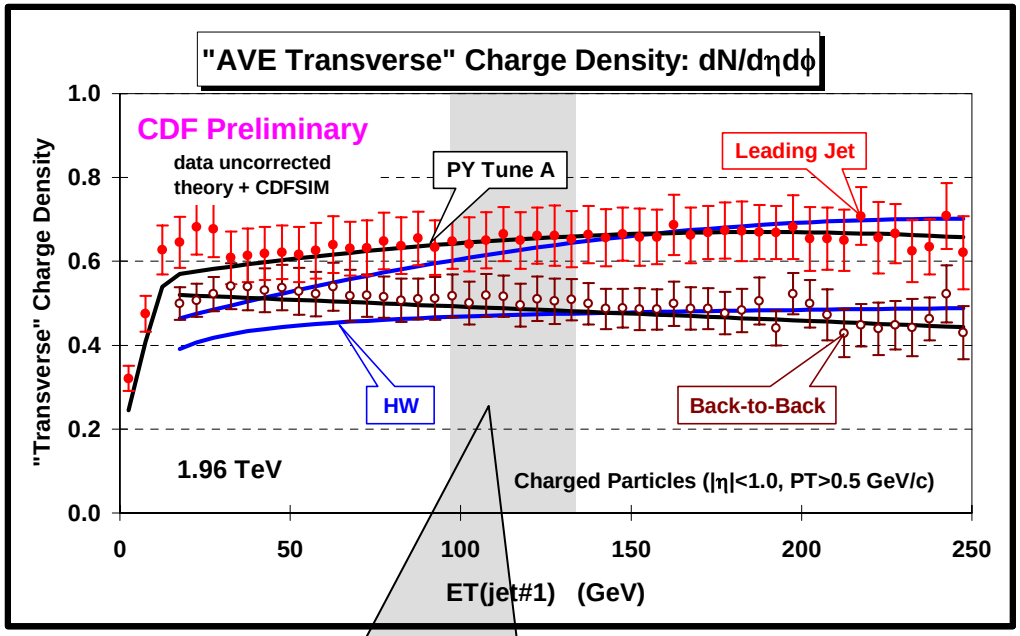
dPT/dηdϕ + 0.2 GeV/c



- **Add 0.2 GeV/c per unit η-ϕ to HERWIG scalar PTsum density, $dPT_{sum}/d\eta d\phi$.**
- **This corresponds to 0.2 x 4π = 2.5 GeV/c in the entire range p_T > 0.5 GeV/c, |η| < 1.**

"Transverse" Charge Density
PYTHIA Tune A vs HERWIG



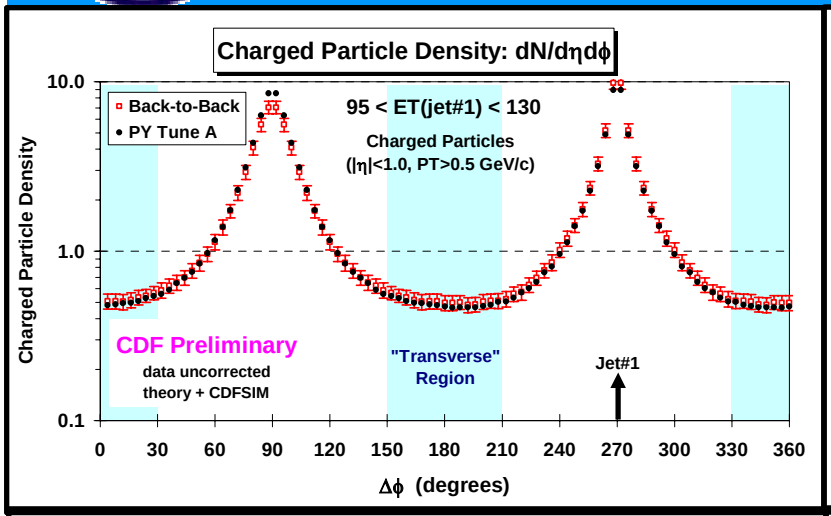


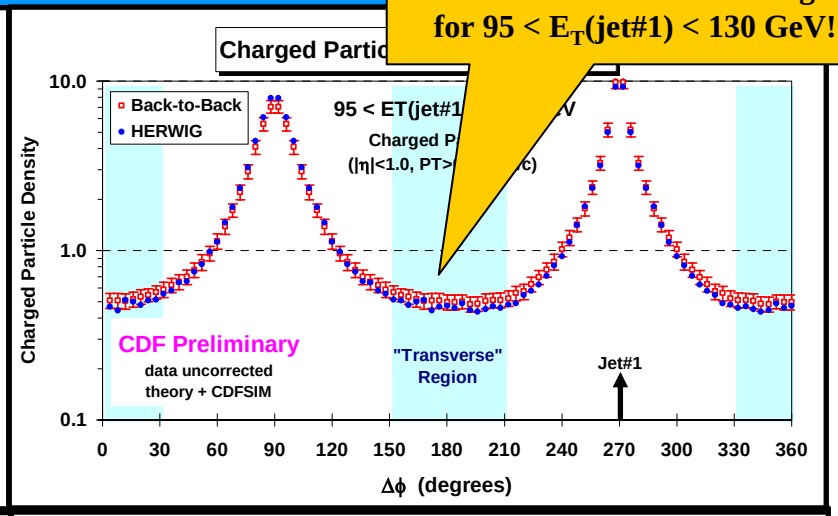
Now look in detail at "back-to-back" events in the region 95 < E_T(jet#1) < 130 GeV!

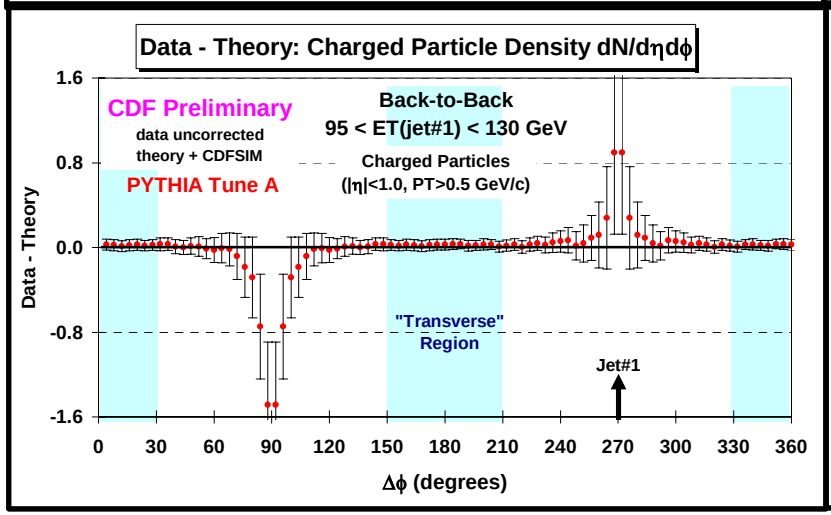
- Shows the average charged particle density, $dN_{chg}/d\eta d\phi$, in the "transverse" region (p_T > 0.5 GeV/c, |η| < 1) versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events compared with PYTHIA Tune A and HERWIG after CDFSIM.

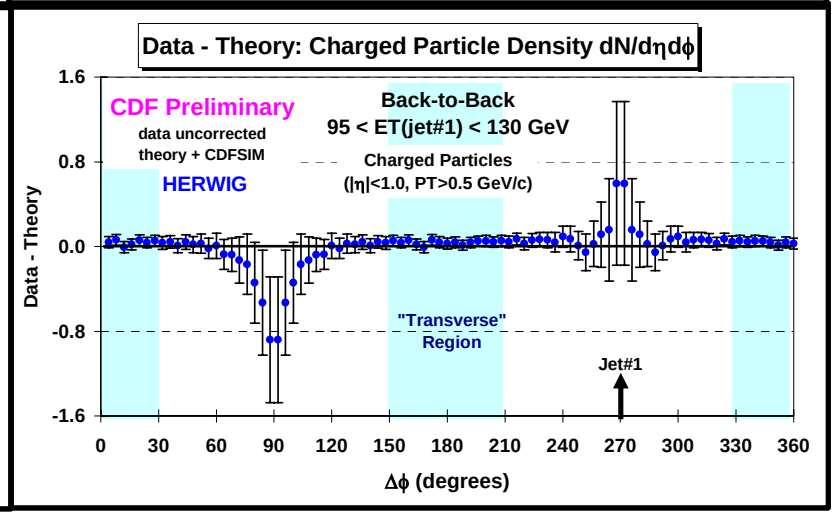
Charged Particle Density
PYTHIA Tune A vs HER

HERWIG (*without multiple parton interactions*) agrees much better in the "transverse" region for 95 < E_T(jet#1) < 130 GeV!

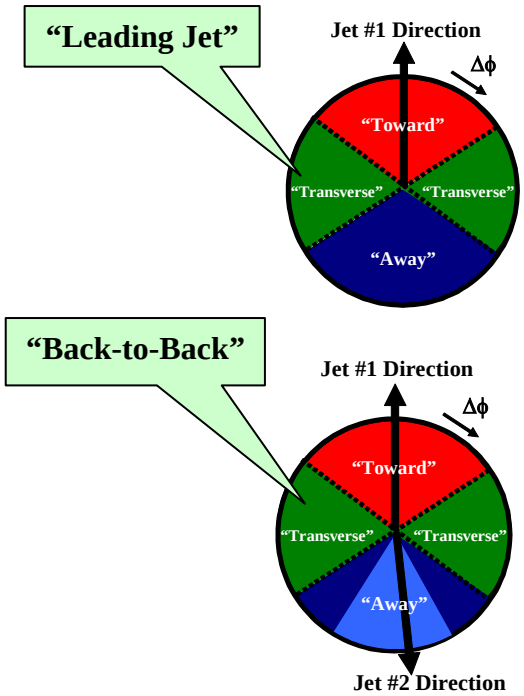


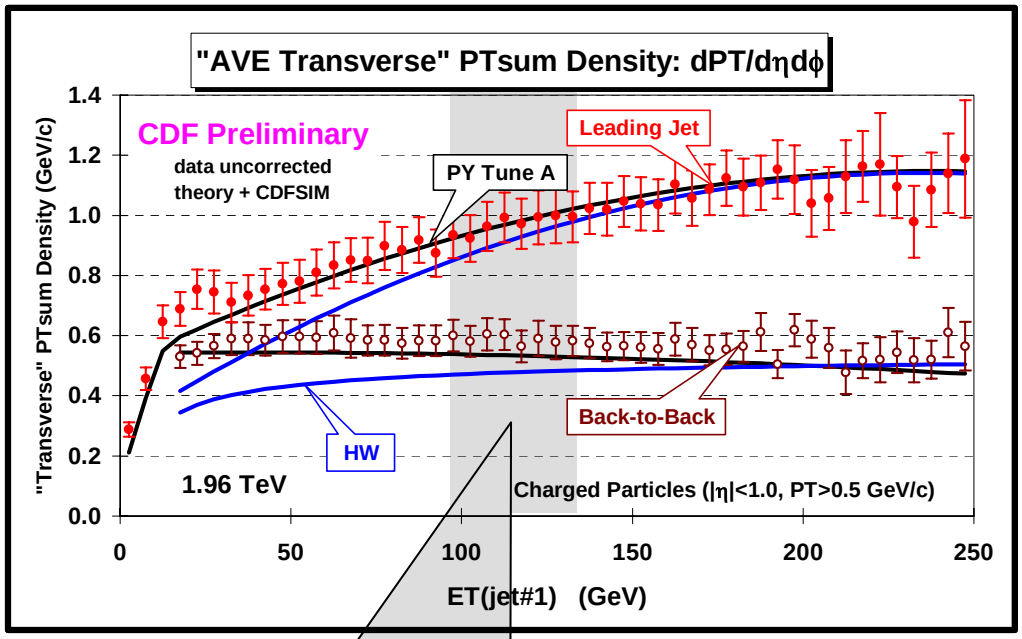






"Transverse" PTsum Density
PYTHIA Tune A vs HERWIG



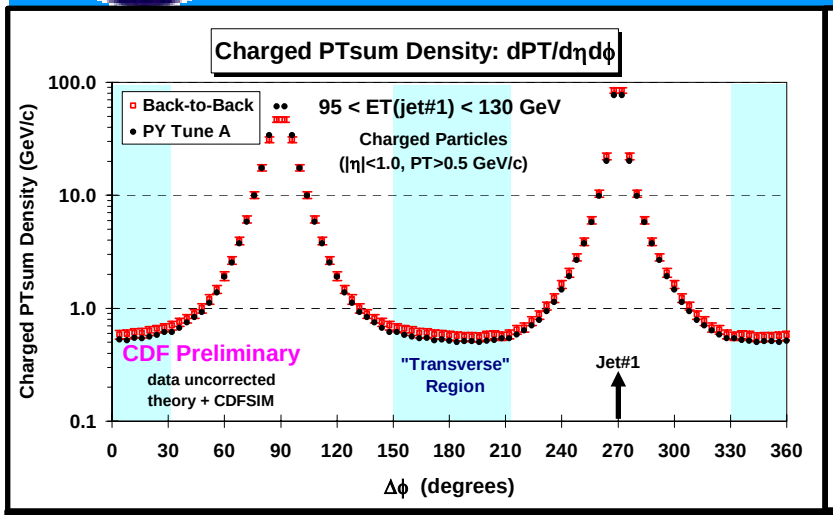


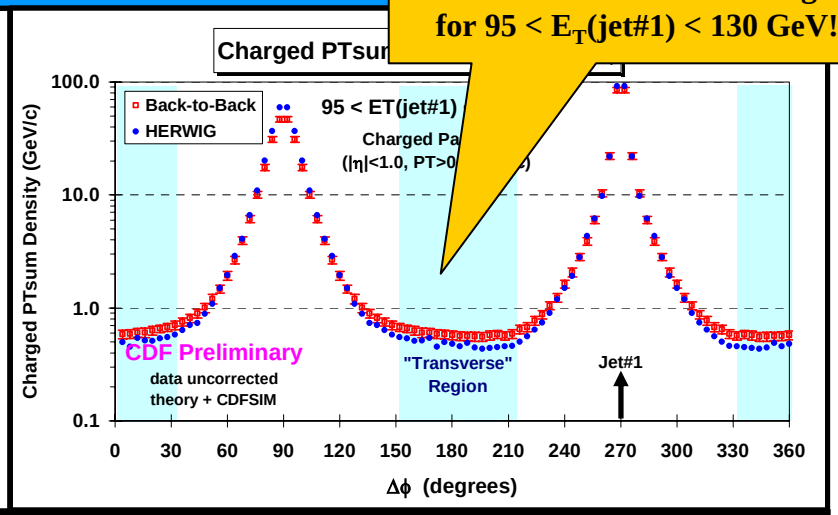
Now look in detail at "back-to-back" events in the region 95 < E_T(jet#1) < 130 GeV!

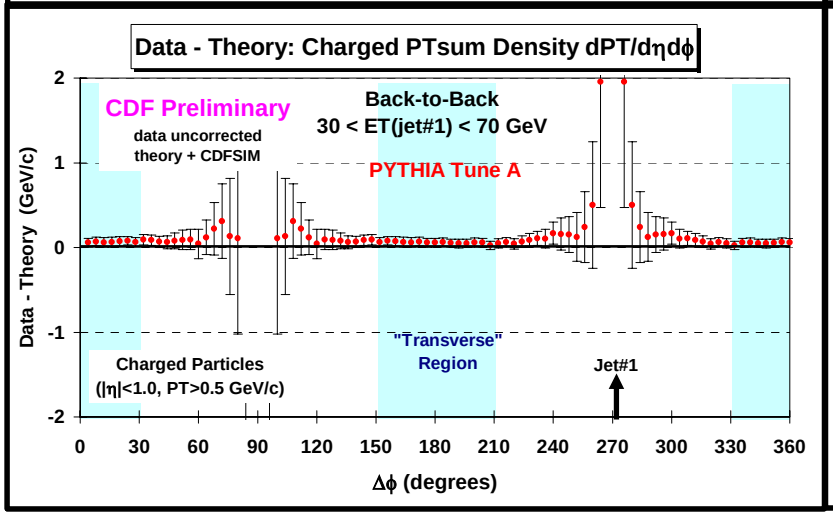
- Shows the average charged PTsum density, $dPT_{sum}/d\eta d\phi$, in the "transverse" region (p_T > 0.5 GeV/c, $|\eta|$ < 1) versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events compared with PYTHIA Tune A and HERWIG after CDFSIM.

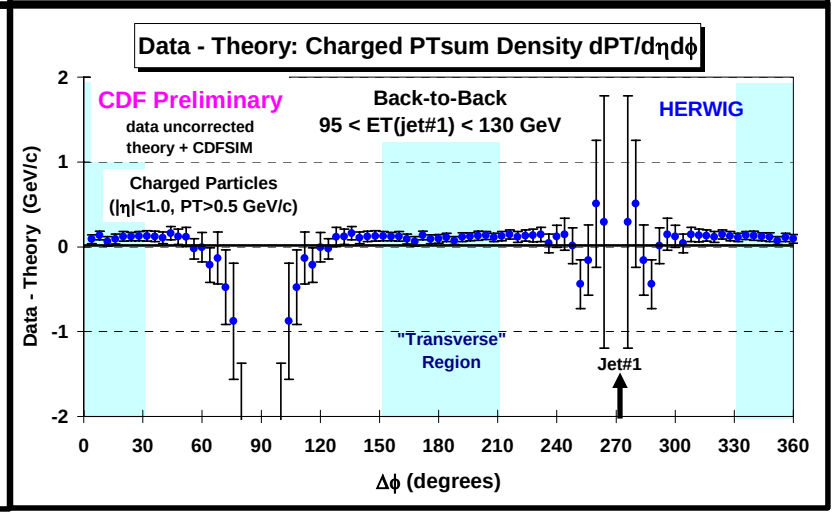
Charged PTsum Density
PYTHIA Tune A vs HER

HERWIG (*without multiple parton interactions*) agrees much better in the "transverse" region for 95 < E_T(jet#1) < 130 GeV!



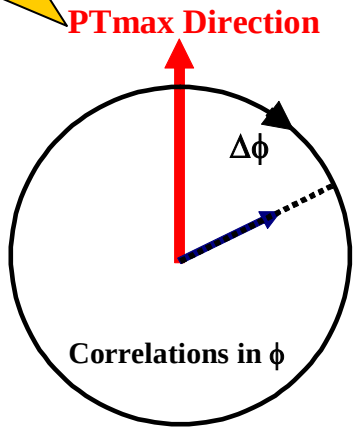




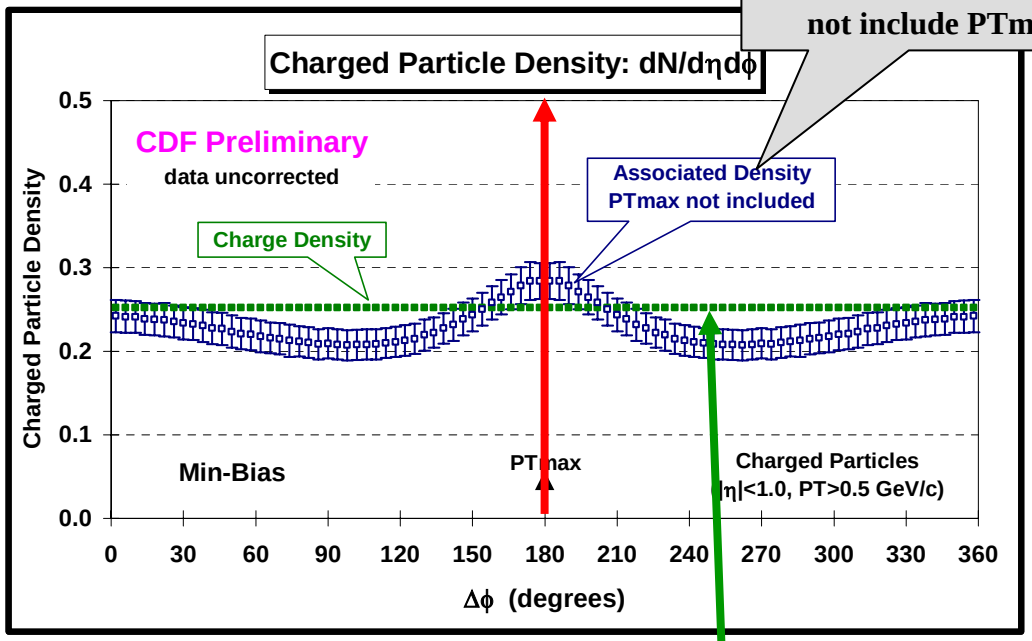


Min-Bias "Associated" Charged Particle Density

Highest p_T charged particle!

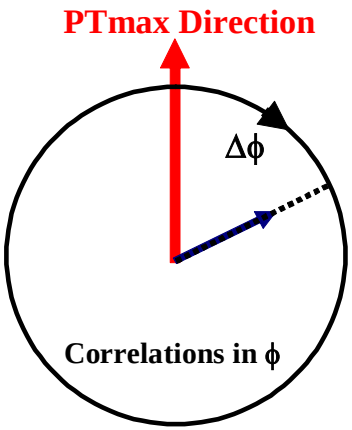


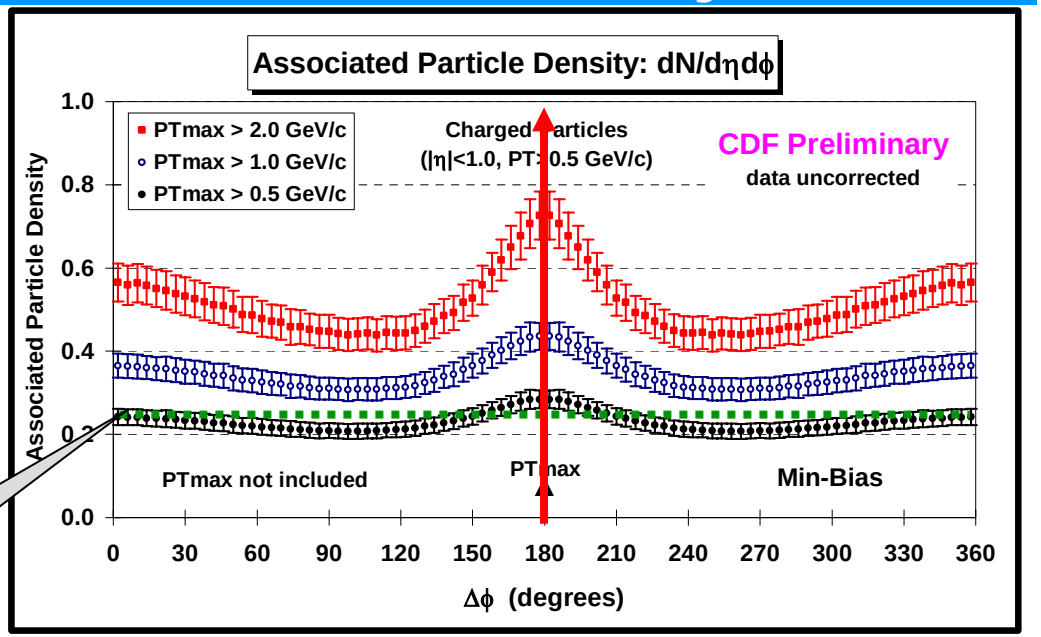
"Associated" densities do not include PTmax!



- Use the **maximum p_T charged particle in the event, PTmax**, to define a direction and look at the the "associated" density, $dN_{chg}/d\eta d\phi$.
- Shows the data on the **$\Delta\phi$ dependence of the "associated" charged particle density**, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, $|\eta|$ < 1, *not including PTmax*) relative to PTmax (rotated to 180°) for **"min-bias" events**. **Also shown is the average charged particle density, $dN_{chg}/d\eta d\phi$, for "min-bias" events**.

Min-Bias "Associated" Charged Particle Density

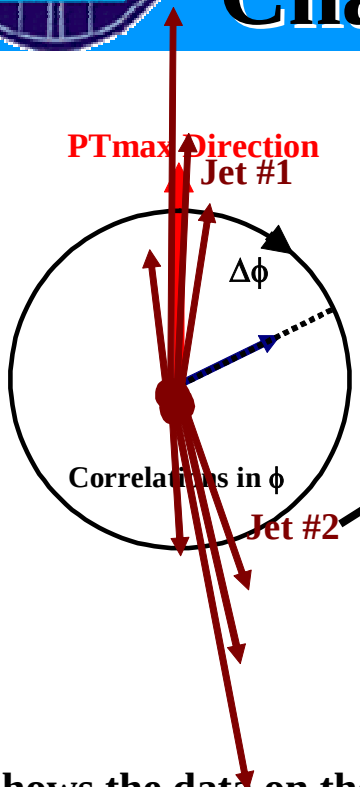


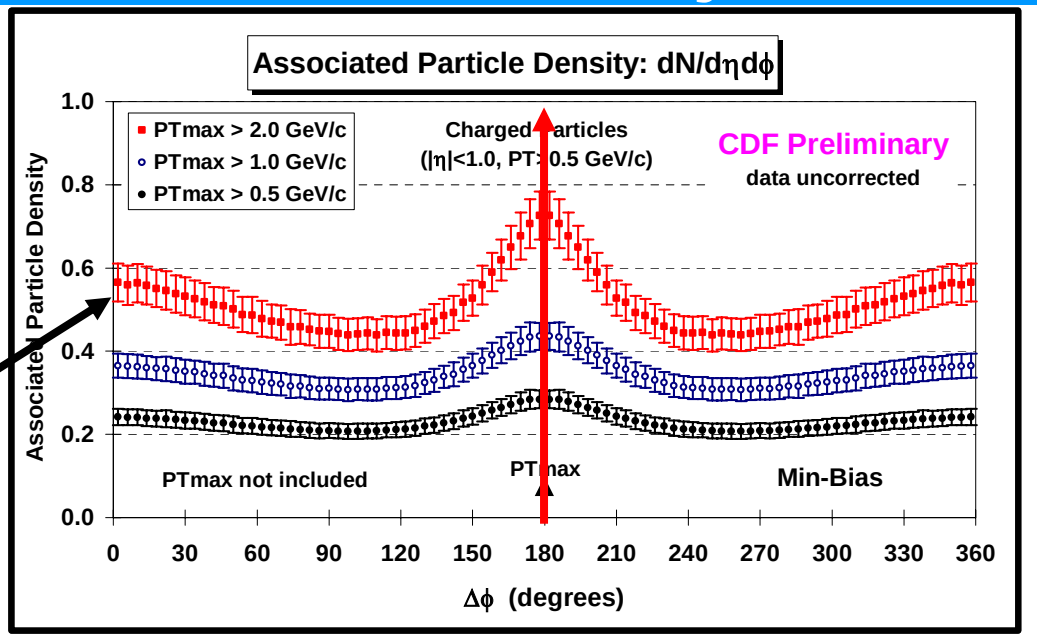


Ave Min-Bias
0.25 per unit η-ϕ

- **Shows the data on the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180º) for "min-bias" events with PTmax > 0.5, 1.0, and 2.0 GeV/c.**

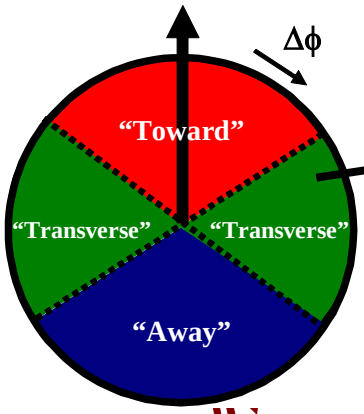
Min-Bias "Associated" Charged Particle Density

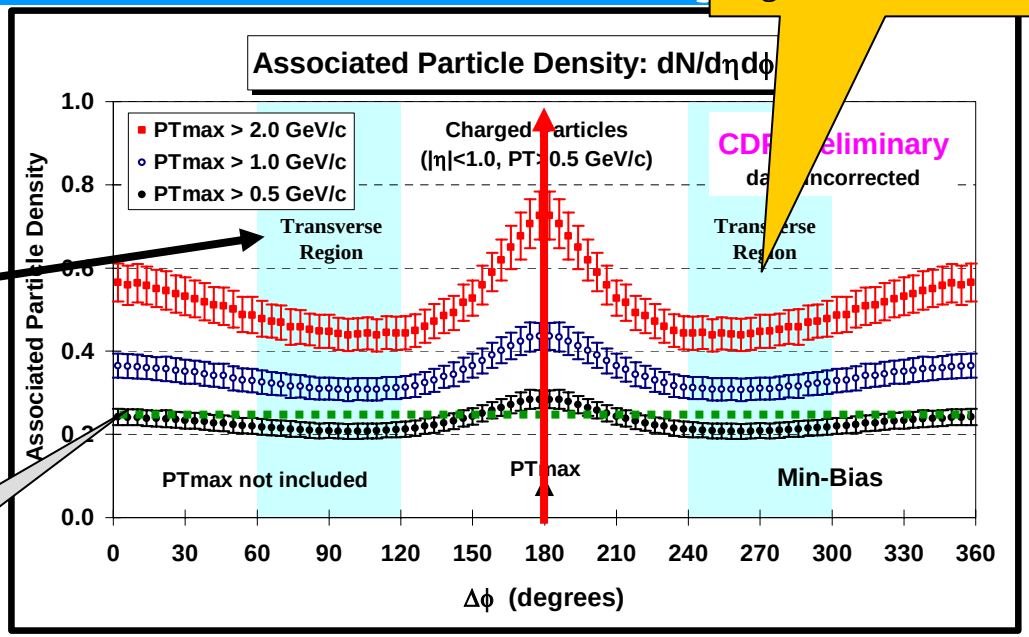




- **Shows the data on the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180º) for "min-bias" events with PTmax > 0.5, 1.0, and 2.0 GeV/c.**
- **Shows "jet structure" in "min-bias" collisions (*i.e.* the "birth" of the leading two jets!).**

Min-Bias "Associated" Charged Particle Density





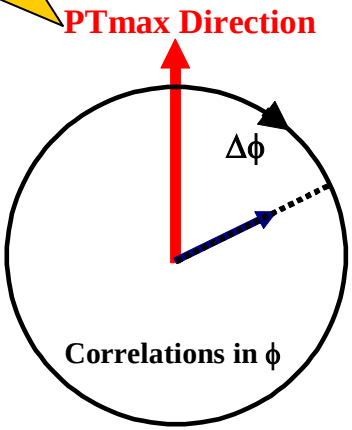
Rapid rise in the particle density in the "transverse" region as PTmax increases!

Ave Min-Bias
0.25 per unit η-ϕ

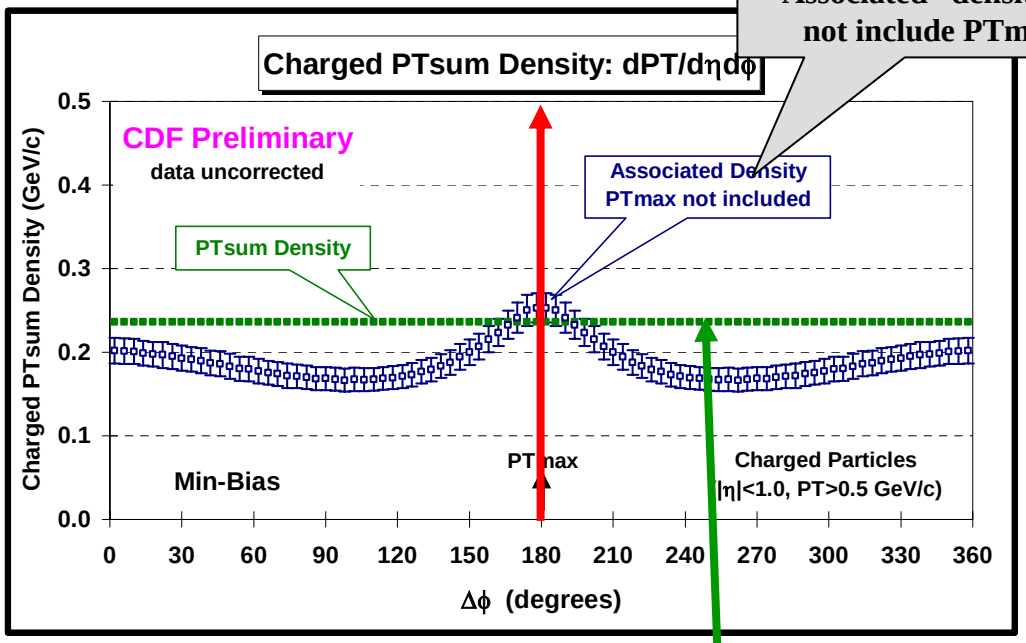
- Shows the data on the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180º) for "min-bias" events with PTmax > 0.5, 1.0, and 2.0 GeV/c.
- Shows "jet structure" in "min-bias" collisions (*i.e.* the "birth" of the leading two jets!).

Min-Bias "Associated" Charged PTsum Density

Highest p_T charged particle!

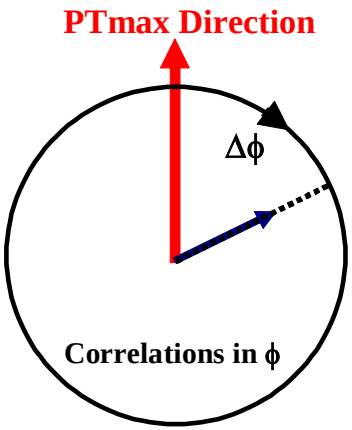


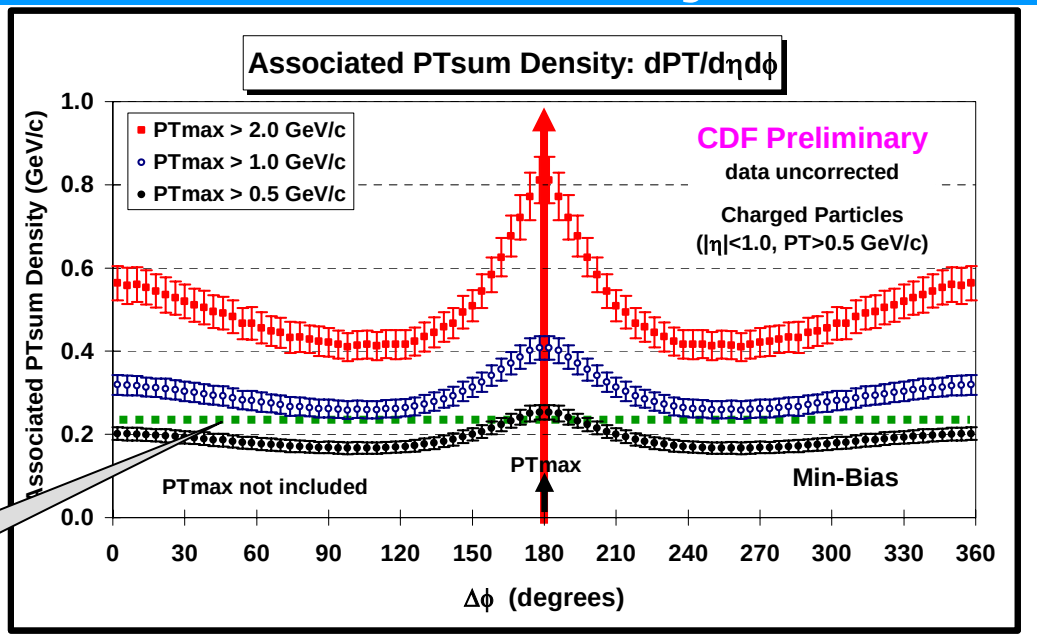
"Associated" densities do not include PTmax!



- Use the **maximum p_T charged particle in the event, PTmax**, to define a direction and look at the the "associated" PTsum density, $dPT_{sum}/d\eta d\phi$.
- Shows the data on the **Δϕ dependence of the "associated" charged PTsum density**, $dPT_{sum}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180°) for **"min-bias" events**. **Also shown is the average charged particle density, $dPT_{sum}/d\eta d\phi$, for "min-bias" events**.

Min-Bias "Associated" Charged PTsum Density

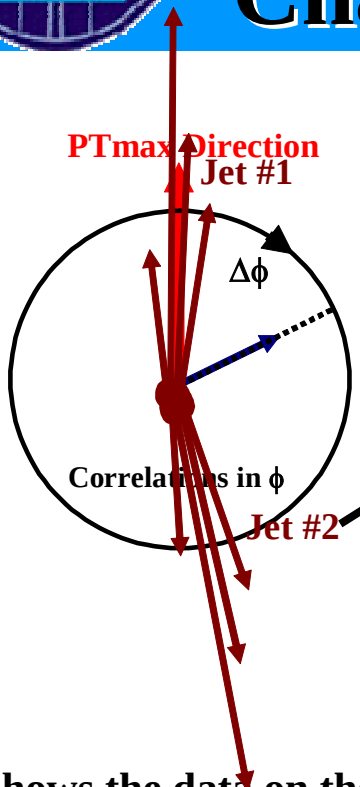


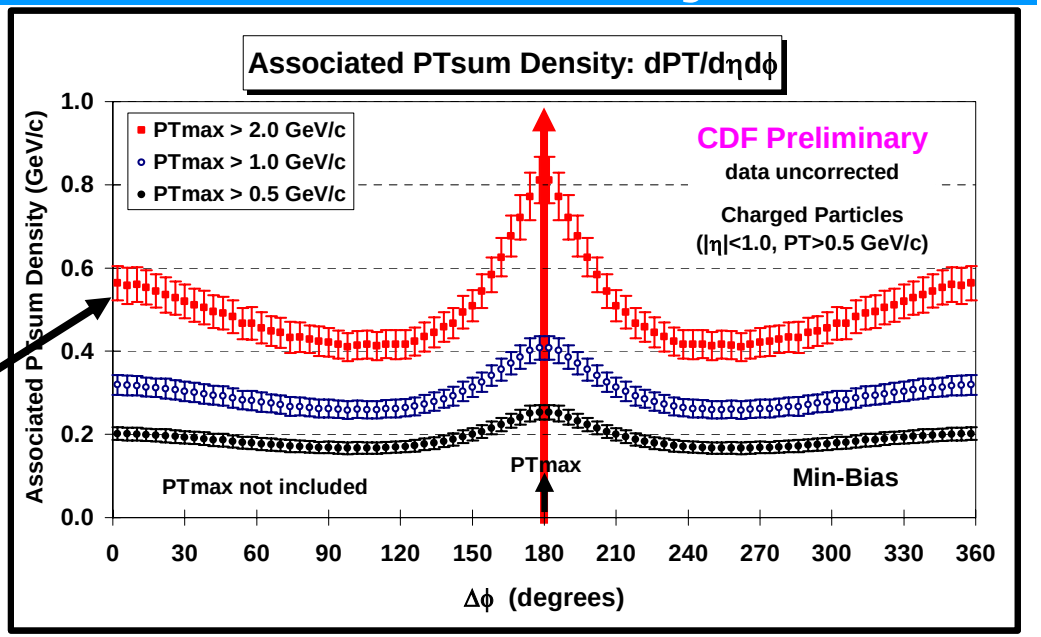


Ave Min-Bias
0.24 GeV/c per unit η-ϕ

- **Shows the data on the Δϕ dependence of the "associated" charged PTsum density, $dPT_{sum}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180º) for "min-bias" events with PTmax > 0.5, 1.0, and 2.0 GeV/c.**

Min-Bias "Associated" Charged PTsum Density

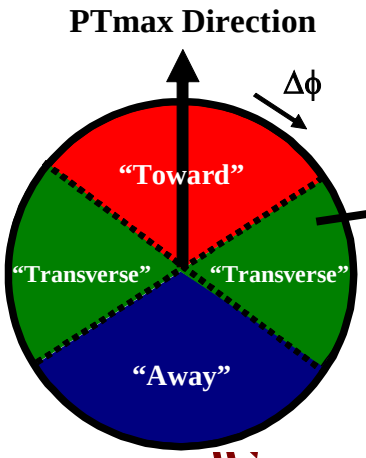


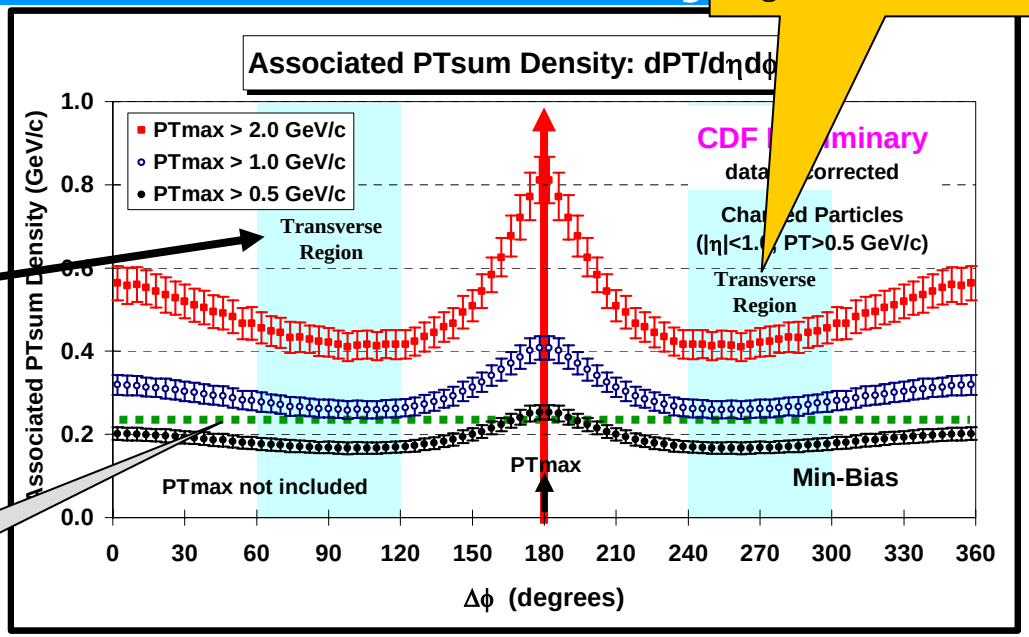


- **Shows the data on the Δϕ dependence of the "associated" charged PTsum density, $dPT_{sum}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180º) for "min-bias" events with PTmax > 0.5, 1.0, and 2.0 GeV/c.**
- **Shows "jet structure" in "min-bias" collisions (*i.e.* the "birth" of the leading two jets!).**

Min-Bias "Associated" Charged PTsum Density

Rapid rise in the PTsum density in the "transverse" region as PTmax increases!

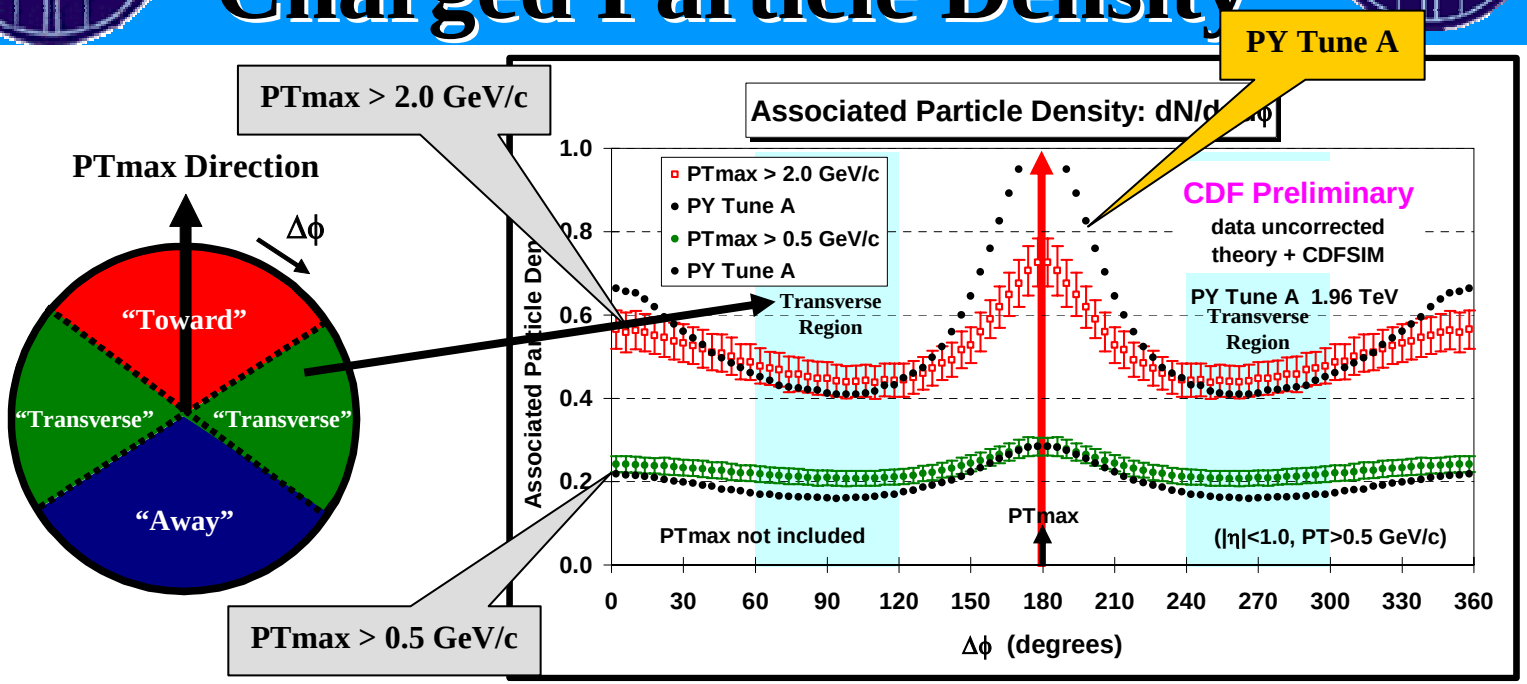




Ave Min-Bias
0.24 GeV/c per unit η-ϕ

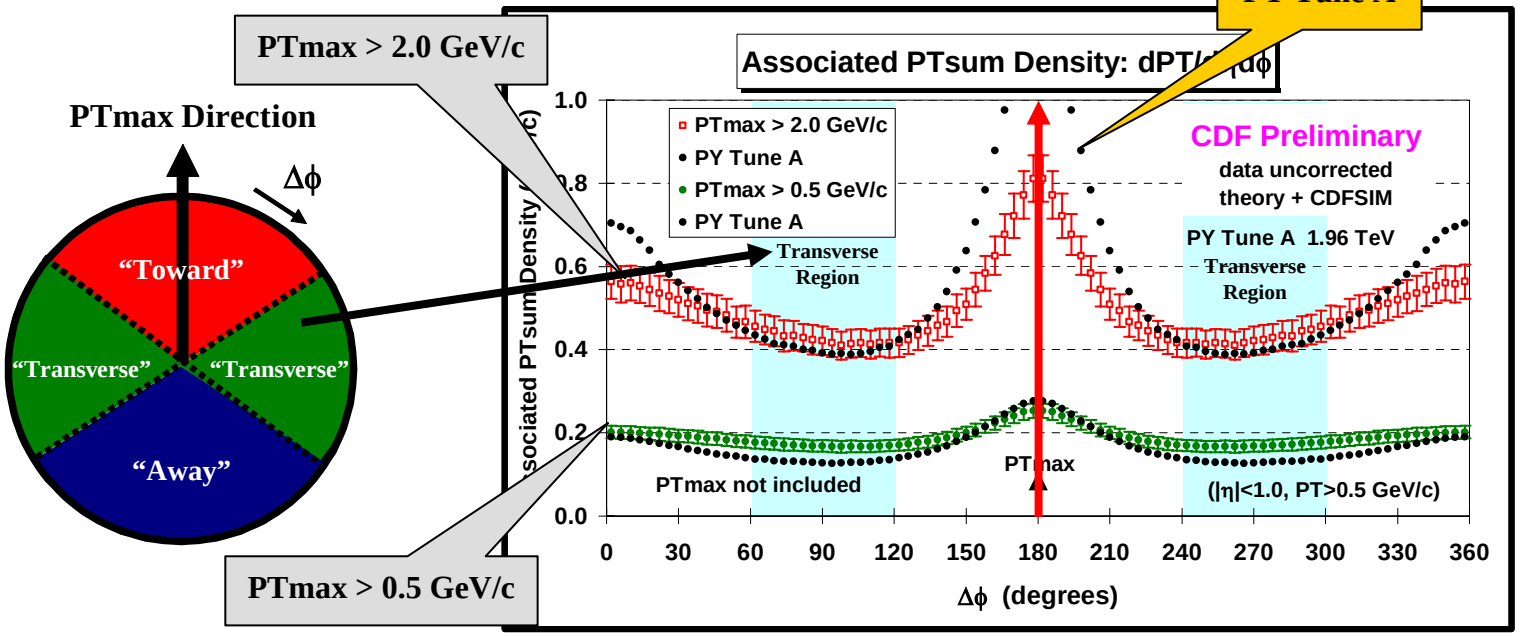
- Shows the data on the Δϕ dependence of the "associated" charged PTsum density, $dPT_{sum}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180º) for "min-bias" events with PTmax > 0.5, 1.0, and 2.0 GeV/c.
- Shows "jet structure" in "min-bias" collisions (*i.e.* the "birth" of the leading two jets!).

Min-Bias "Associated" Charged Particle Density



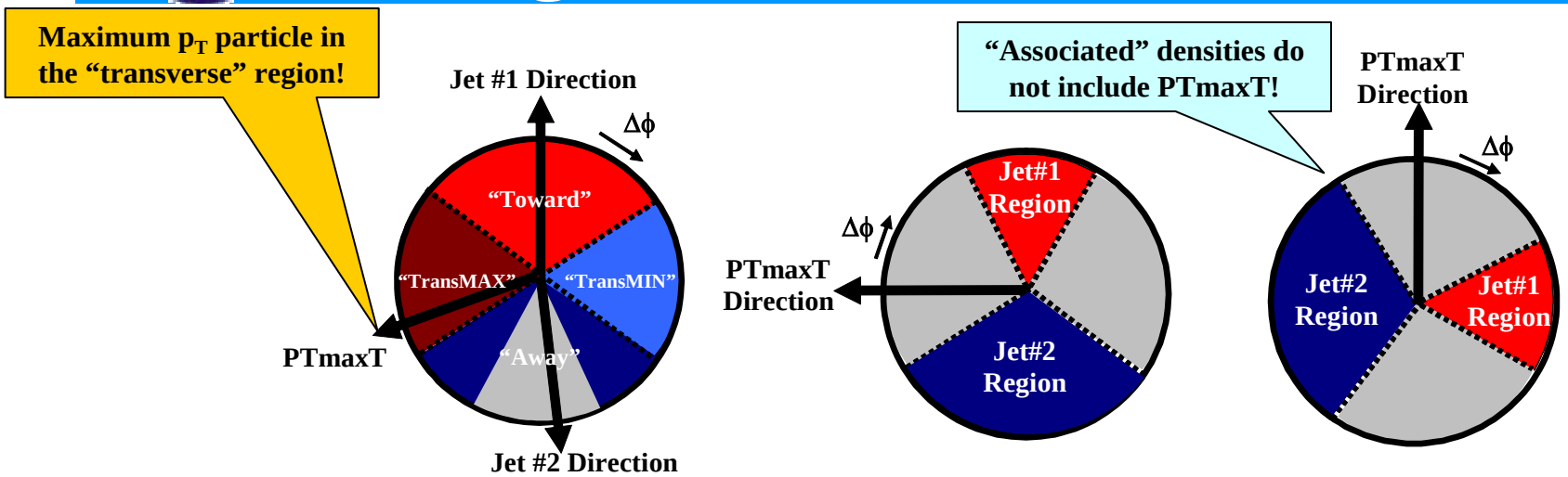
- **Shows the data on the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180º) for "min-bias" events with PTmax > 0.5 GeV/c and PTmax > 2.0 GeV/c compared with PYTHIA Tune A (after CDFSIM).**
- **PYTHIA Tune A predicts a larger correlation than is seen in the "min-bias" data (*i.e.* Tune A "min-bias" is a bit too "jetty").**

Min-Bias "Associated" Charged PTsum Density



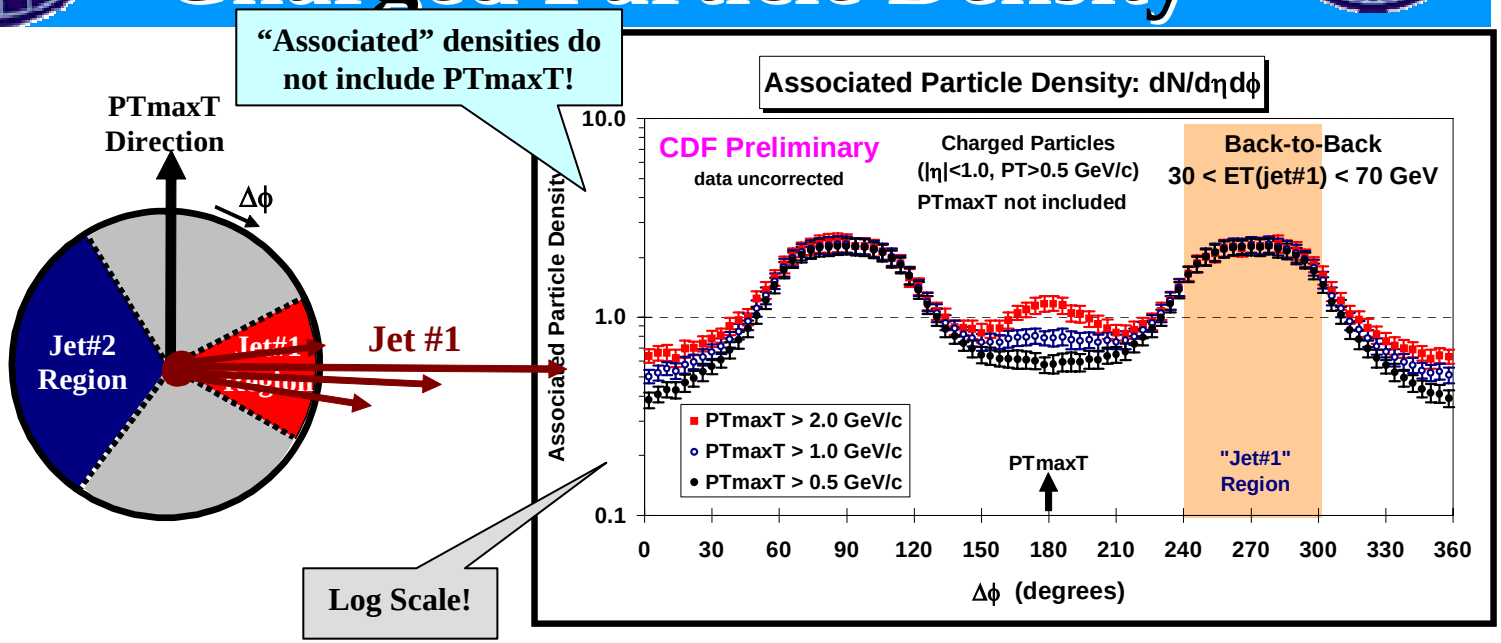
- Shows the data on the Δϕ dependence of the "associated" charged PTsum density, $dPT_{sum}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 0.5 GeV/c and PTmax > 2.0 GeV/c compared with PYTHIA Tune A (after CDFSIM).
- PYTHIA Tune A predicts a larger correlation than is seen in the "min-bias" data (*i.e.* Tune A "min-bias" is a bit too "jetty").

Back-to-Back "Associated" Charged Particle Densities



- Use the leading jet in "back-to-back" events to define the "transverse" region and look at the maximum p_T charged particle in the "transverse" region, PTmaxT.
- Look at the Δϕ dependence of the "associated" charged particle and PTsum densities, $dN_{chg}/d\eta d\phi$ and $dPT_{sum}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, *not including PTmaxT*) relative to PTmaxT.
- Rotate so that PTmaxT is at the center of the plot (*i.e.* 180°).

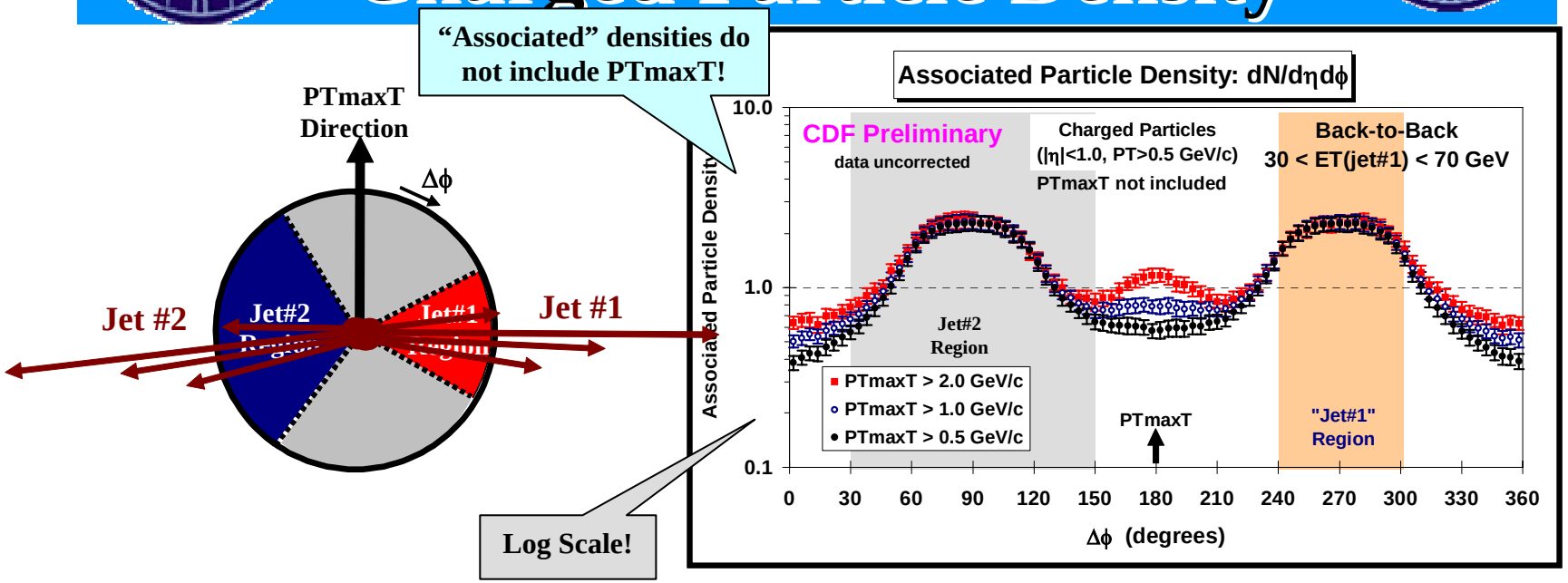
Back-to-Back "Associated" Charged Particle Density



- Look at the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$ for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmaxT*) relative to PTmaxT (rotated to 180º) for PTmaxT > 0.5 GeV/c, PTmaxT > 1.0 GeV/c and PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV .

- Shows "jet structure" in the "transverse" region (*i.e.* the "birth" of the 3rd & 4th jet).

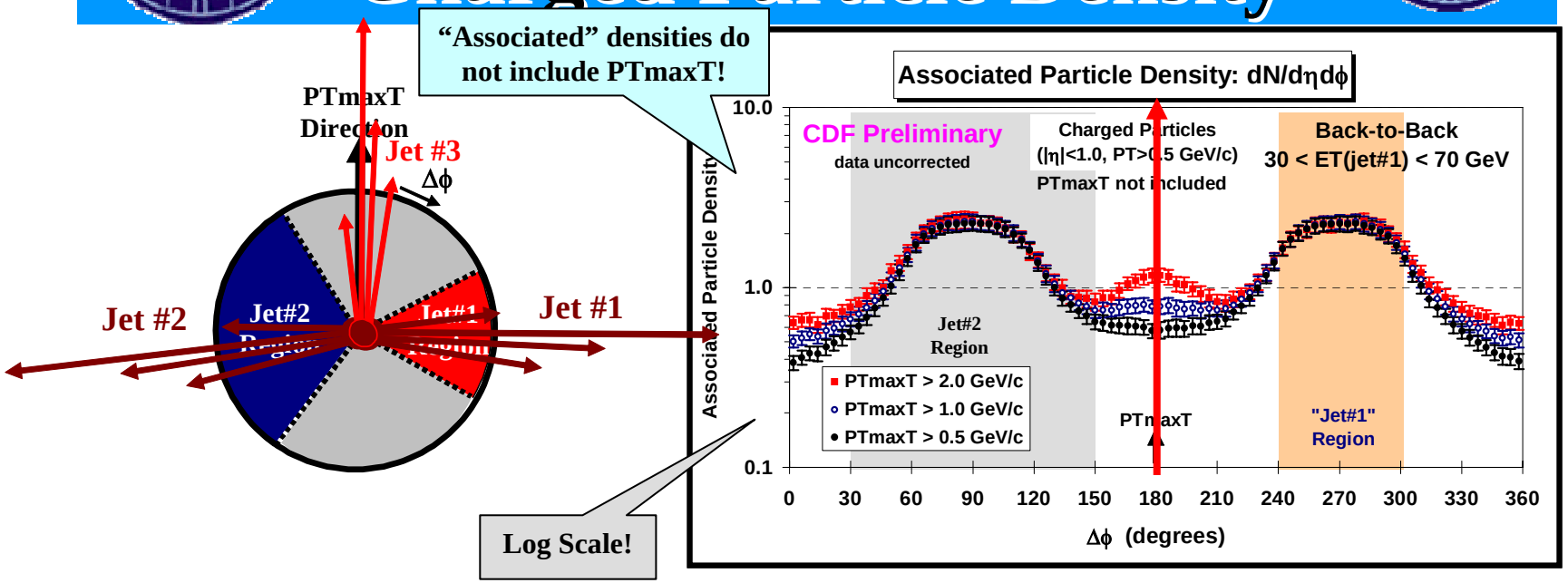
Back-to-Back "Associated" Charged Particle Density



- Look at the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$ for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmaxT*) relative to PTmaxT (rotated to 180º) for PTmaxT > 0.5 GeV/c, PTmaxT > 1.0 GeV/c and PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV .

- Shows "jet structure" in the "transverse" region (*i.e.* the "birth" of the 3rd & 4th jet).

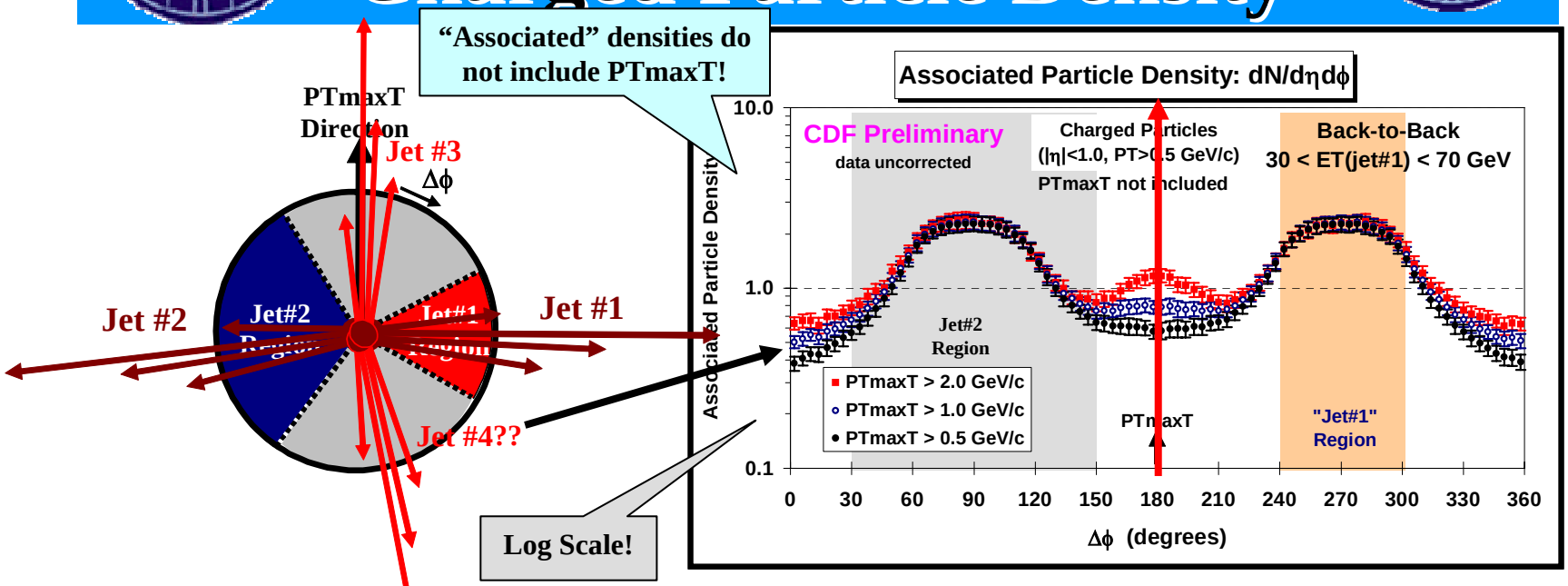
Back-to-Back "Associated" Charged Particle Density



- Look at the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$ for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmaxT*) relative to PTmaxT (rotated to 180º) for PTmaxT > 0.5 GeV/c, PTmaxT > 1.0 GeV/c and PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV .

- Shows "jet structure" in the "transverse" region (*i.e.* the "birth" of the 3rd & 4th jet).

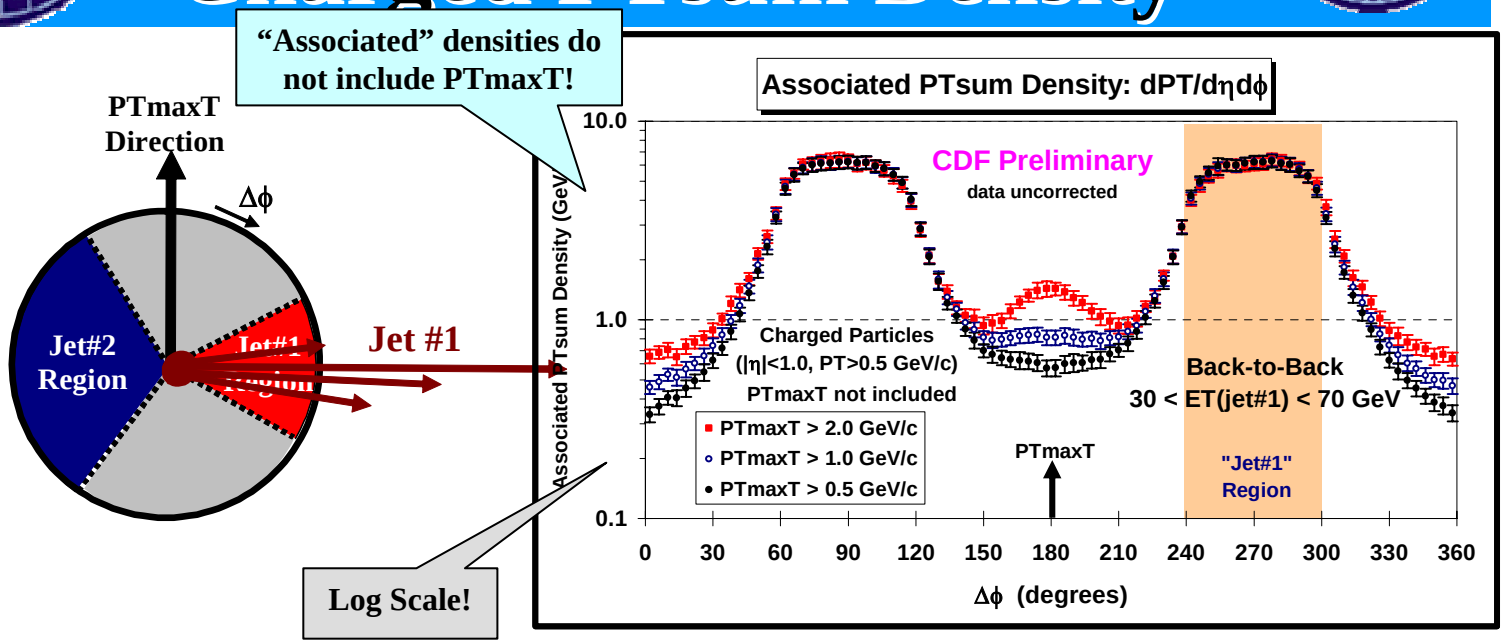
Back-to-Back "Associated" Charged Particle Density



- Look at the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$ for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmaxT*) relative to PTmaxT (rotated to 180°) for PTmaxT > 0.5 GeV/c, PTmaxT > 1.0 GeV/c and PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV .

- Shows "jet structure" in the "transverse" region (*i.e.* the "birth" of the 3rd & 4th jet).

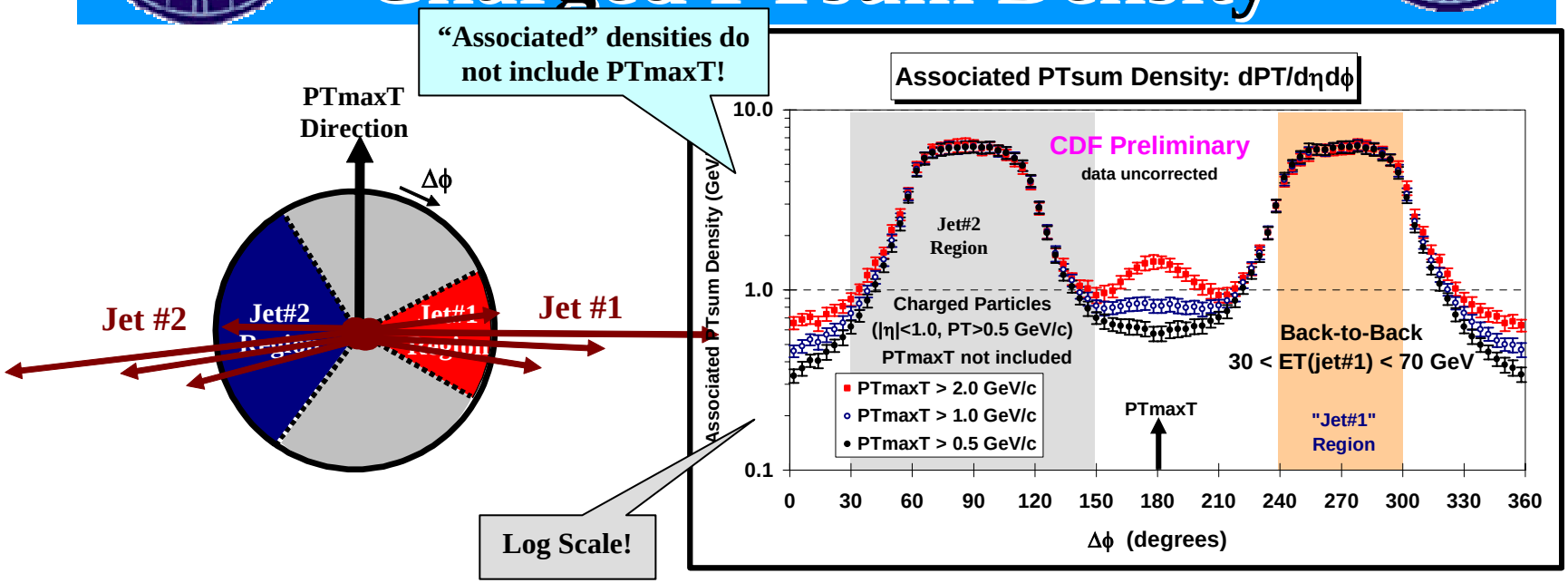
Back-to-Back "Associated" Charged PTsum Density



- Look at the Δϕ dependence of the "associated" charged particle density, $dPT_{sum}/d\eta d\phi$ for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmaxT*) relative to PTmaxT (rotated to 180°) for PTmaxT > 0.5 GeV/c, PTmaxT > 1.0 GeV/c and PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV .

- Shows "jet structure" in the "transverse" region (*i.e.* the "birth" of the 3rd & 4th jet).

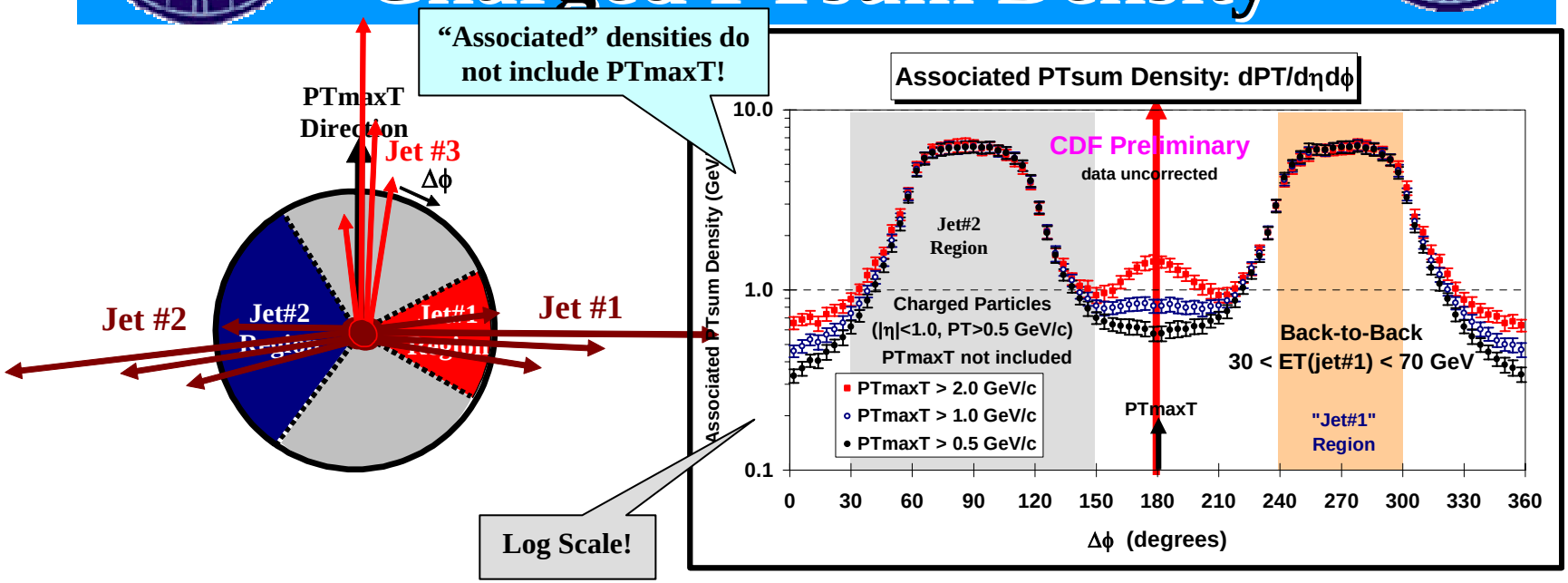
Back-to-Back "Associated" Charged PTsum Density



- Look at the Δϕ dependence of the "associated" charged particle density, $dPT_{sum}/d\eta d\phi$ for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmaxT*) relative to PTmaxT (rotated to 180°) for PTmaxT > 0.5 GeV/c, PTmaxT > 1.0 GeV/c and PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV .

- Shows "jet structure" in the "transverse" region (*i.e.* the "birth" of the 3rd & 4th jet).

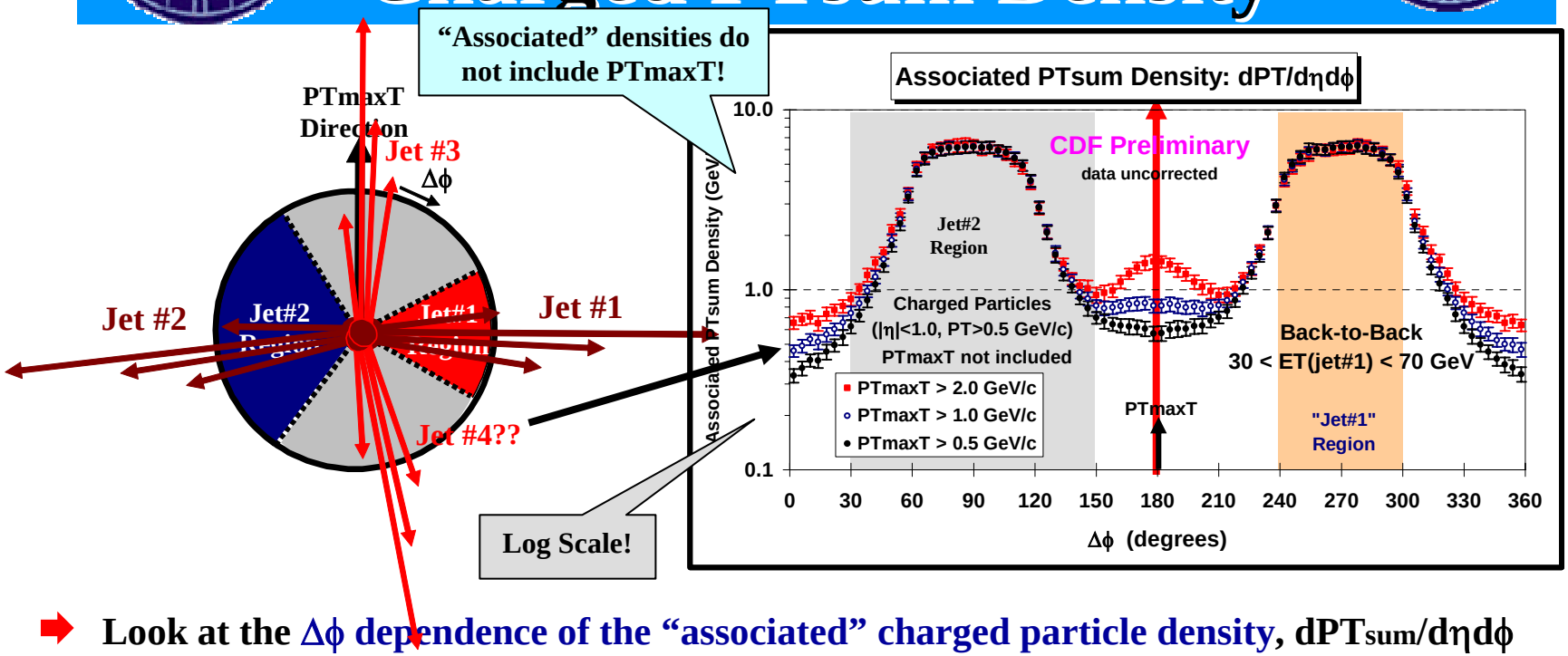
Back-to-Back "Associated" Charged PTsum Density



- Look at the Δϕ dependence of the "associated" charged particle density, $dPT_{sum}/d\eta d\phi$ for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmaxT*) relative to PTmaxT (rotated to 180°) for PTmaxT > 0.5 GeV/c, PTmaxT > 1.0 GeV/c and PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV .

- Shows "jet structure" in the "transverse" region (*i.e.* the "birth" of the 3rd & 4th jet).

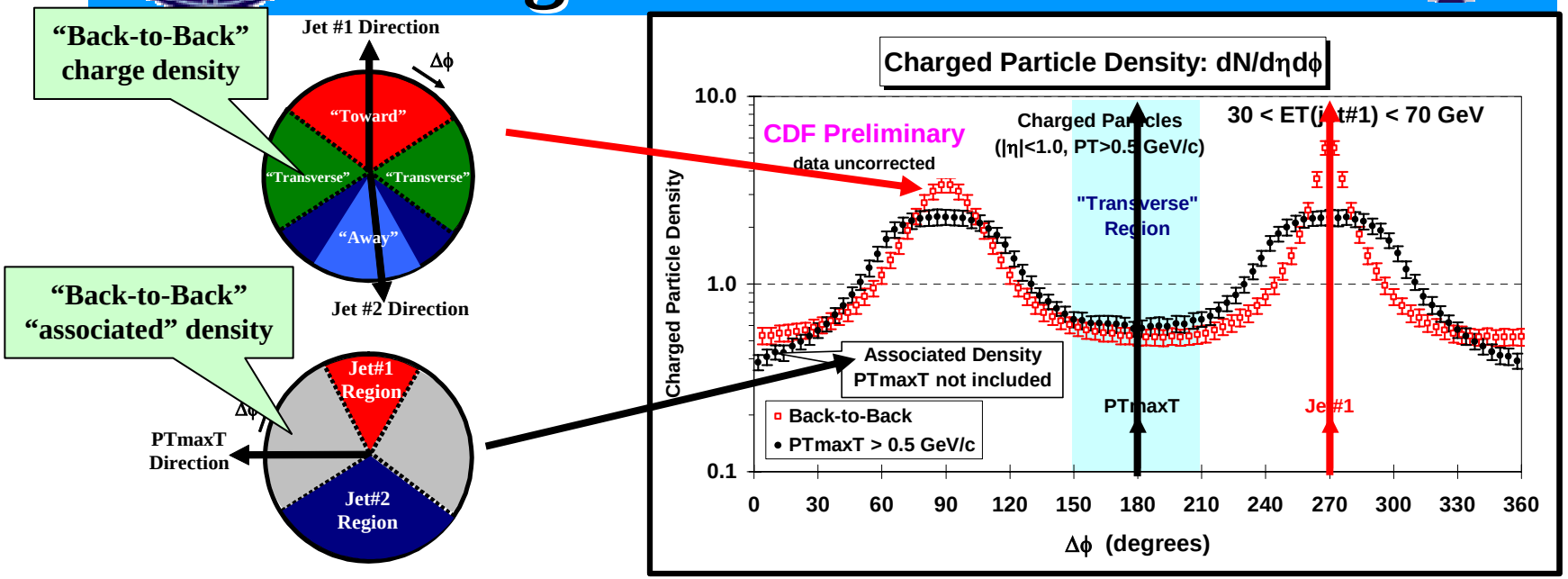
Back-to-Back "Associated" Charged PTsum Density



- Look at the Δϕ dependence of the "associated" charged particle density, $dPT_{sum}/d\eta d\phi$ for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmaxT*) relative to PTmaxT (rotated to 180°) for PTmaxT > 0.5 GeV/c, PTmaxT > 1.0 GeV/c and PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV .

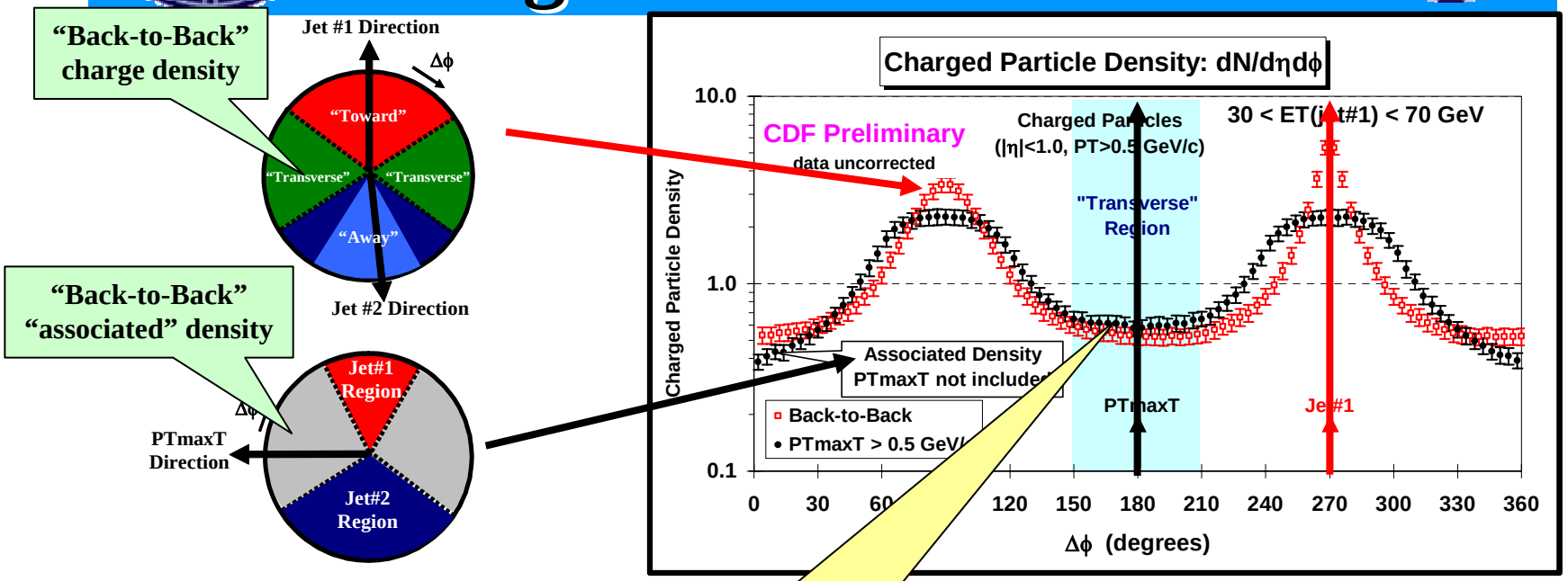
- Shows "jet structure" in the "transverse" region (*i.e.* the "birth" of the 3rd & 4th jet).

Back-to-Back "Associated" Charged Particle Densities



- Shows the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$ for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmaxT*) relative to PTmaxT (rotated to 180°) for PTmaxT > 0.5 GeV/c, PTmaxT > 1.0 GeV/c and PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV.
- Shows Δφ dependence of the charged particle density, $dN_{chg}/d\eta d\phi$ for charged particles (p_T > 0.5 GeV/c, |η| < 1) relative to jet#1 (rotated to 270°) for "back-to-back events" with 30 < ET(jet#1) < 70 GeV.

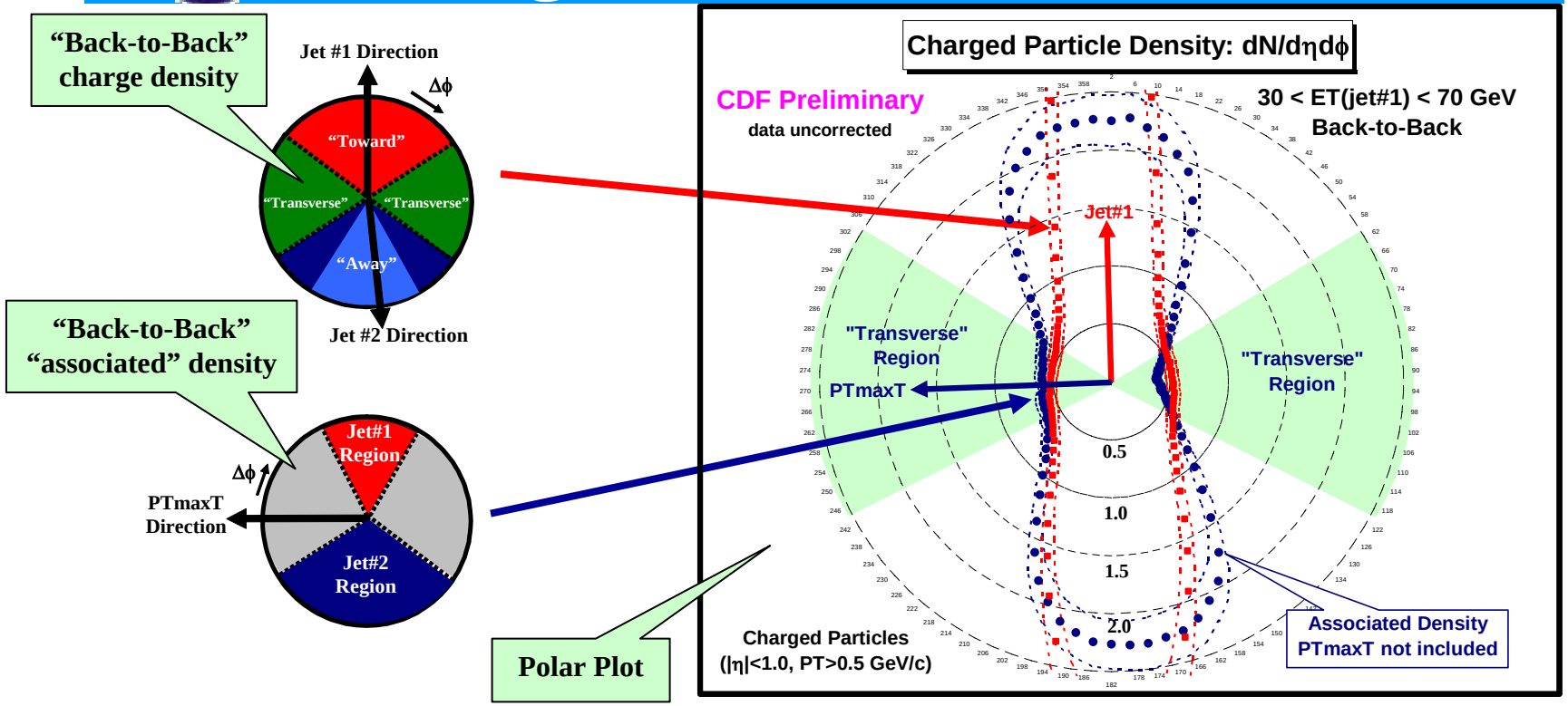
Back-to-Back "Associated" Charged Particle Densities



- Shows the Δφ dependence of the "associ[illegible]harged particle density, $dN_{chg}/d\eta d\phi$ for charged particles (p_T > 0.5 GeV/c, |η| [illegible] *including PTmaxT*) relative to PTmaxT (rotated to 180º [illegible]xT > 1.0 GeV/c and PTmaxT > 2.0 GeV/c, for "bac[illegible]#1) < 70 GeV.
- Shows Δφ deper[illegible]sity, $dN_{chg}/d\eta d\phi$ for charged particles (p_T > 0.5 GeV/c, [illegible]o 270º) for "back-to-back events" with 30 < ET(jet#1) < 70 GeV.

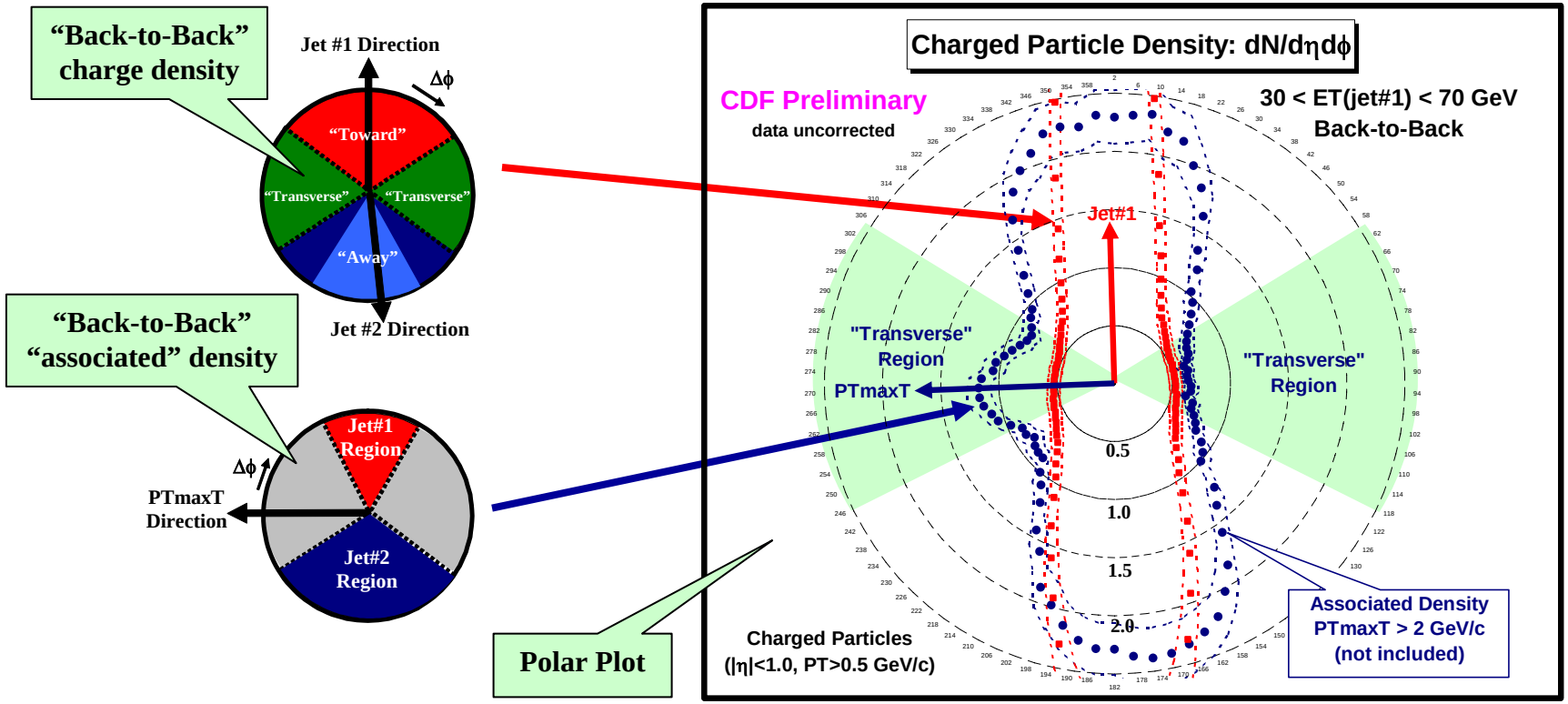
It is more probable to find a particle accompying PTmaxT than it is to find a particle in the "transverse" region!

Back-to-Back "Associated" Charged Particle Densities



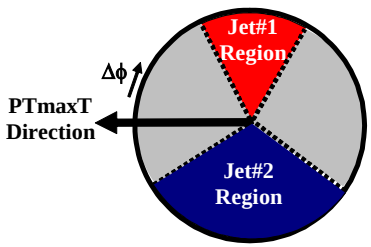
➡ **Shows the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (*not including PTmaxT*) relative to PTmaxT (rotated to 180º) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$ relative to jet#1 (rotated to 270º) for "back-to-back events" with $30 < E_T(\text{jet\#1}) < 70$ GeV.**

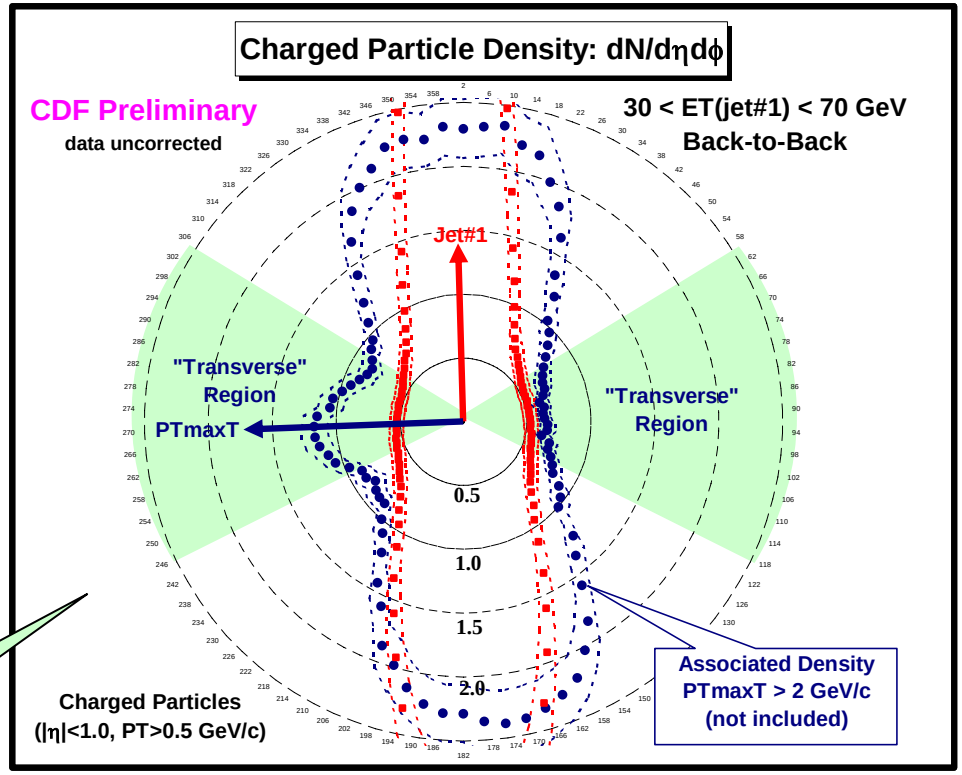
Back-to-Back "Associated" Charged Particle Densities



➡ **Shows the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180º) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270º) for "back-to-back events" with $30 < E_T(\text{jet\#1}) < 70$ GeV.**

Jet Topologies

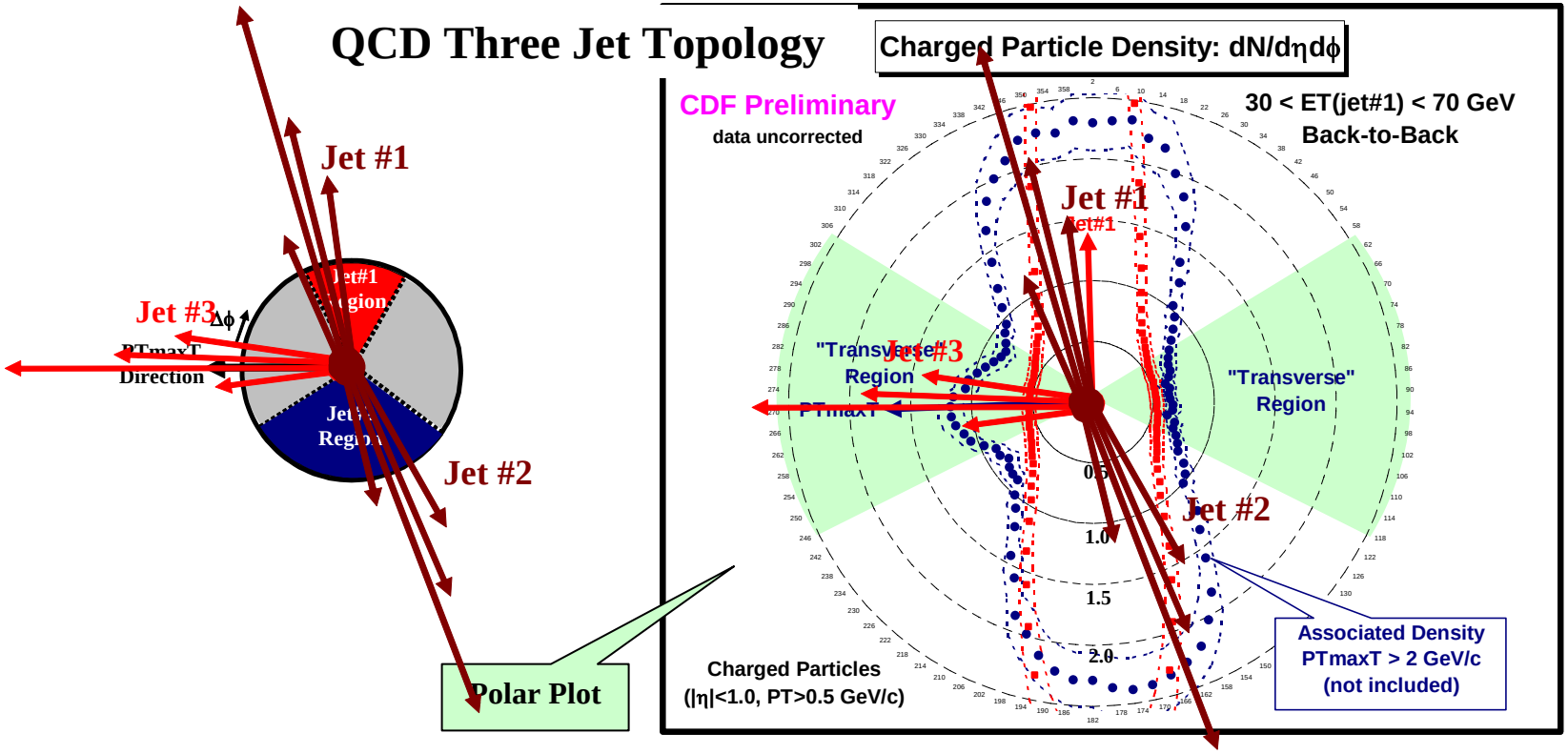




Polar Plot

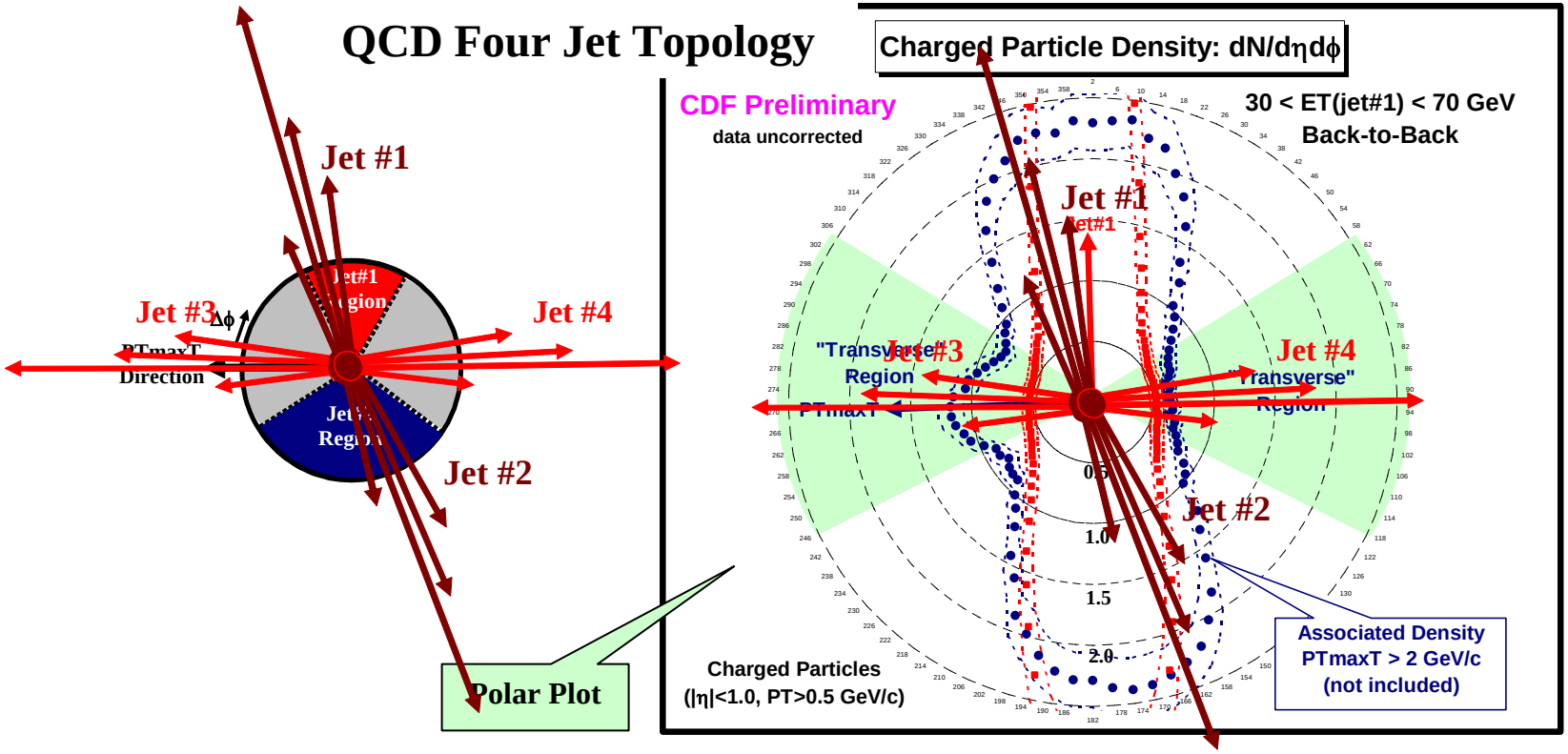
- **Shows the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180º) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270º) for "back-to-back events" with $30 < E_T(\text{jet\#1}) < 70$ GeV.**

Jet Topologies



- **Shows the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180º) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270º) for "back-to-back events" with $30 < E_T(\text{jet\#1}) < 70$ GeV.**

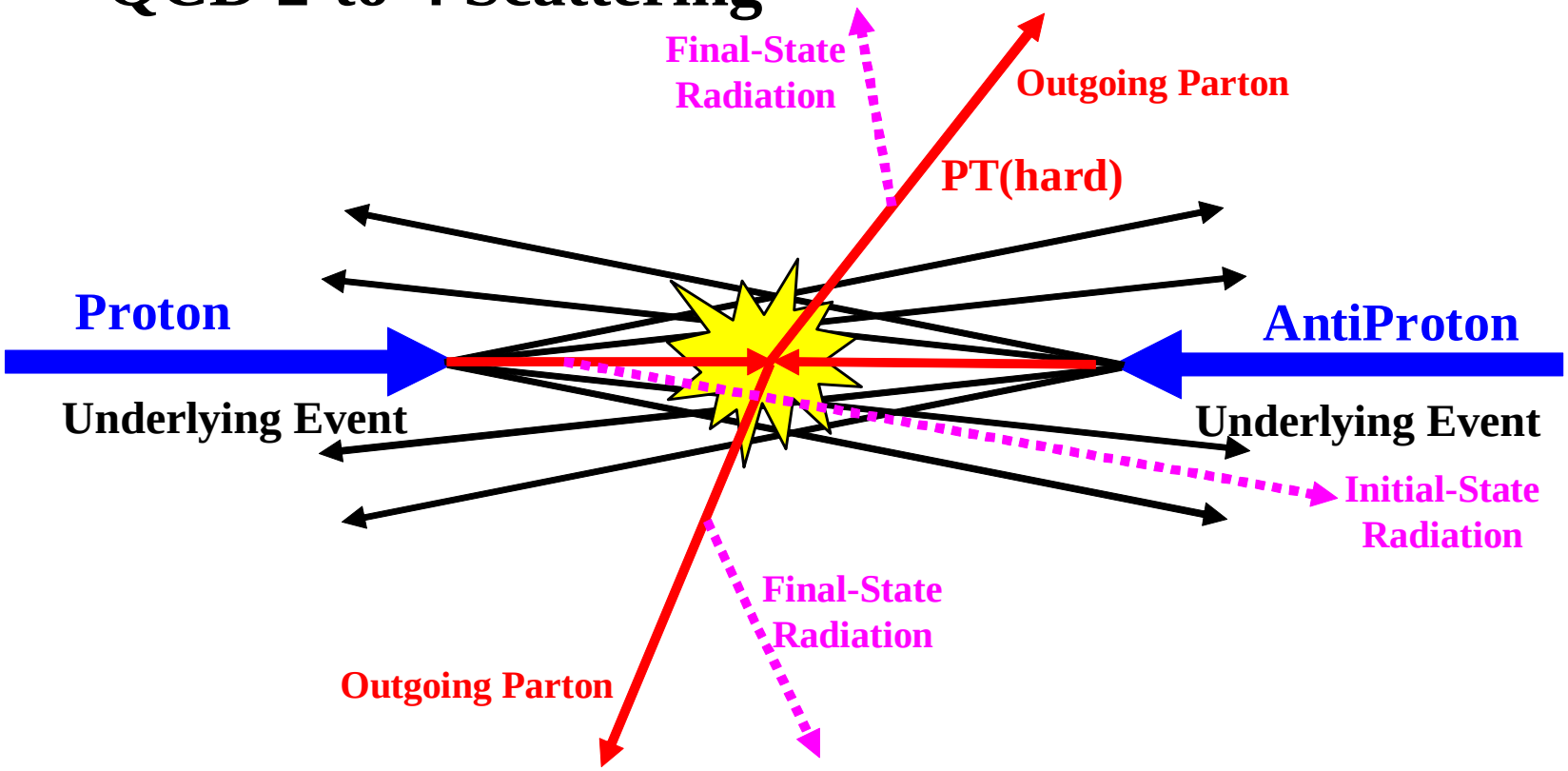
Jet Topologies



➡ **Shows the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180º) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270º) for "back-to-back events" with $30 < E_T(\text{jet\#1}) < 70$ GeV.**

Jet Topologies

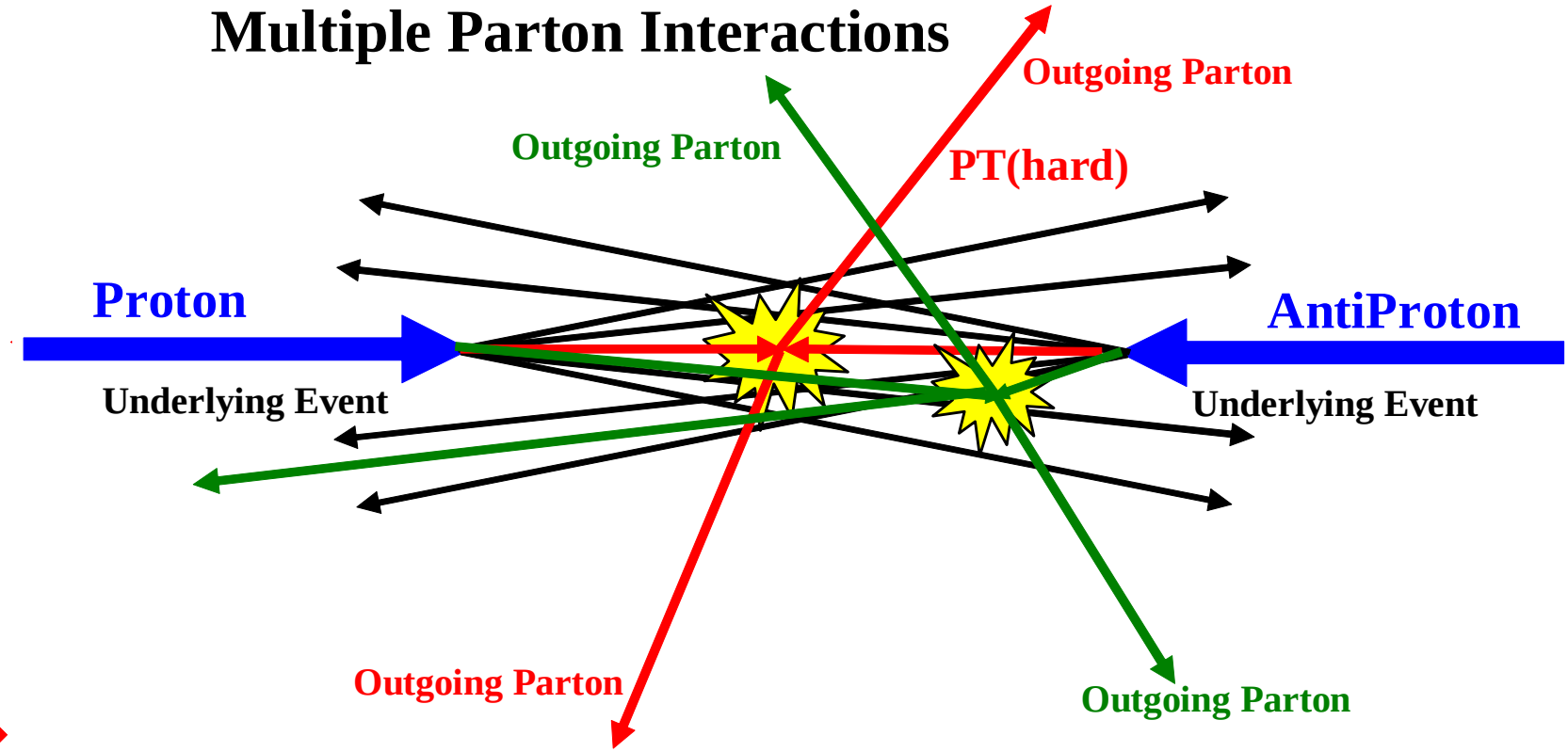
QCD 2-to-4 Scattering



➡ .5 to 180°) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, relative to jet#1 (rotated to 270°) for "back-to-back events" with $30 < E_T(\text{jet\#1}) < 70$ GeV.

Jet Topologies

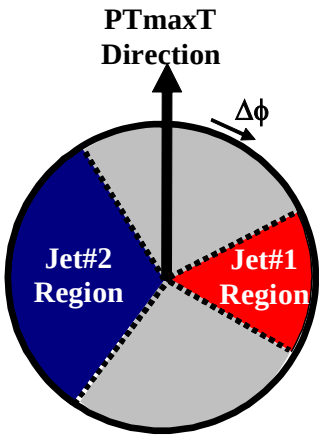
Multiple Parton Interactions

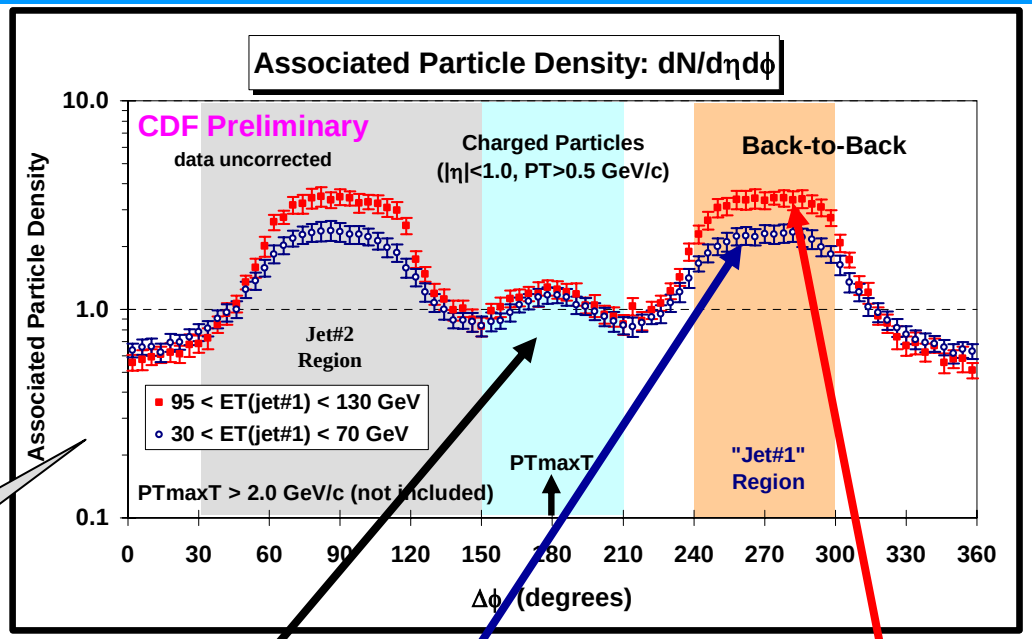


.5

GeV/c, |η| < 1, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180º) and the charged particle density, $dN_{chg}/d\eta d\phi$, p_T > 0.5 GeV/c, |η| < 1, relative to jet#1 (rotated to 270º) for "back-to-back events" with 30 < E_T(jet#1) < 70 GeV.

Back-to-Back "Associated" Charged Particle Density



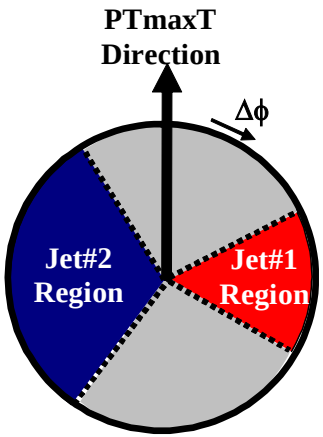


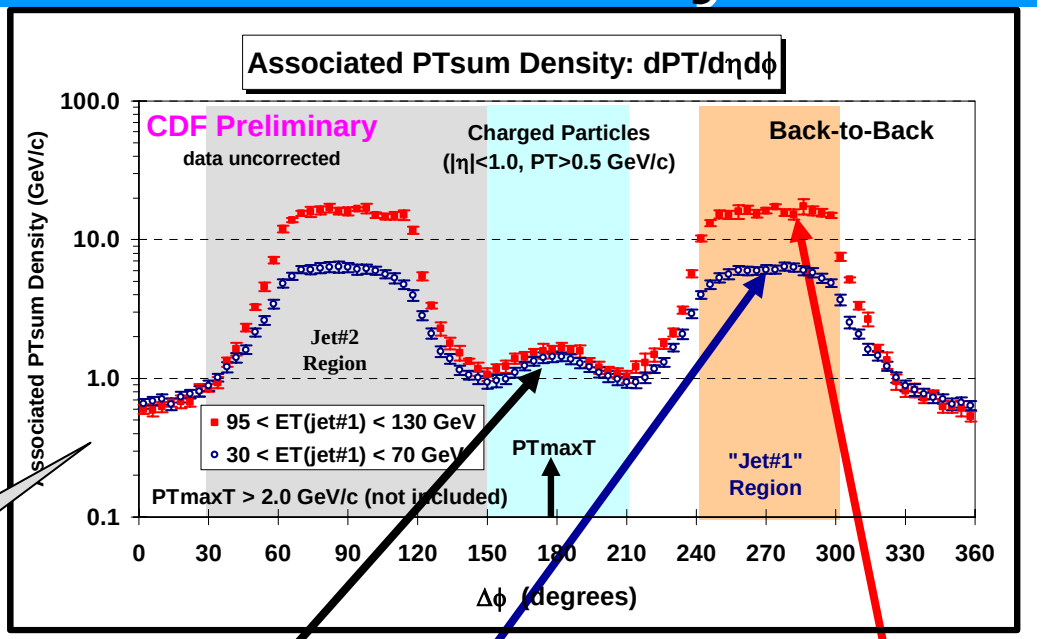
Log Scale!

- Look at the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, p_T > 0.5 GeV/c, |η| < 1 (*not including PTmaxT*) relative to PTmaxT (rotated to 180º) for PTmaxT > 2.0 GeV/c for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV and 95 < E_T(jet#1) < 130 GeV.

- Very little dependence on E_T(jet#1) in the "transverse" region for "back-to-back" events!

Back-to-Back "Associated" Charged Particle Density



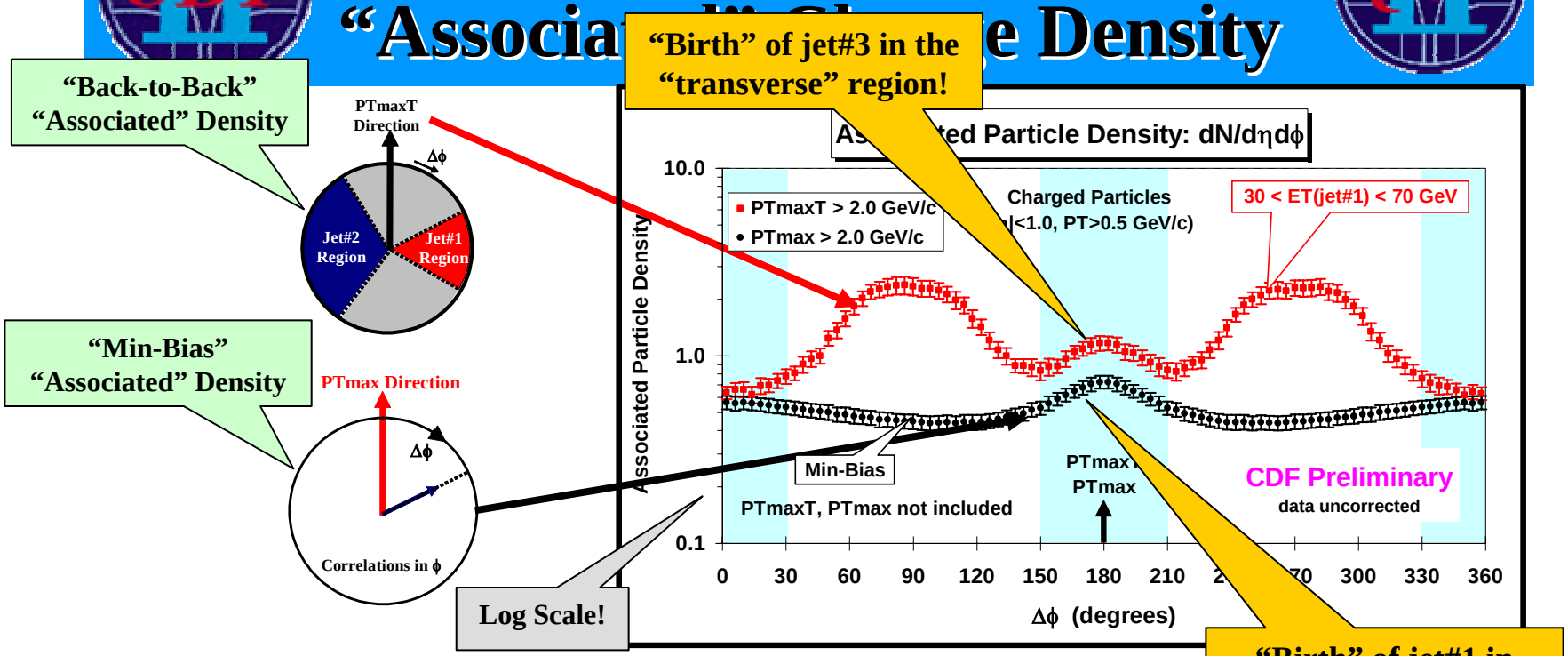


Log Scale!

- Look at the Δϕ dependence of the "associated" charged PTsum density, $dPT_{sum}/d\eta d\phi$, p_T > 0.5 GeV/c, |η| < 1 (*not including PTmaxT*) relative to PTmaxT (rotated to 180º) for PTmaxT > 2.0 GeV/c for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV and 95 < E_T(jet#1) < 130 GeV.

- Very little dependence on E_T(jet#1) in the "transverse" region for "back-to-back" events!

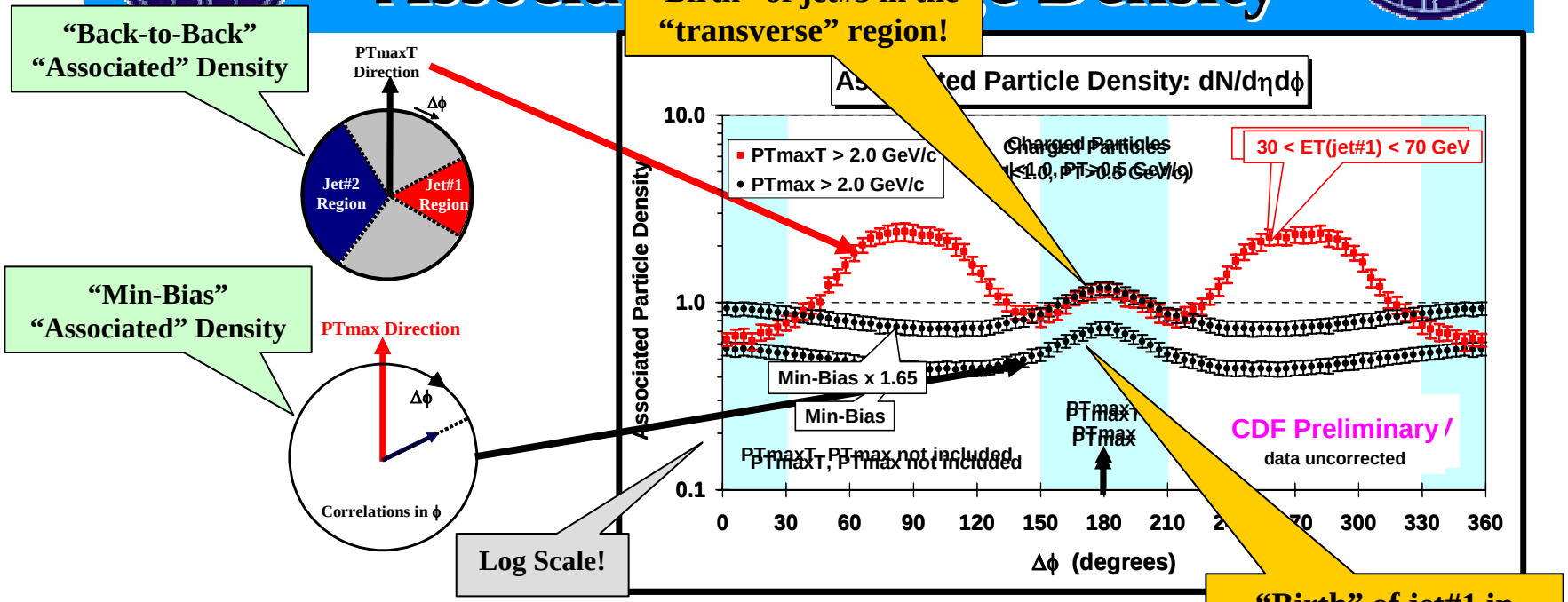
"Back-to-Back" vs "MinBias" "Associated" Charge Density



- **Shows the Δφ dependence of the "associated" charged particle densi**
  p_T > 0.5 GeV/c, |η| < 1 (*not including PTmaxT*) relative to PTmaxT (
  PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV.

- **Shows the data on the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, p_T > 0.5 GeV/c, |η| < 1 (*not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 2.0 GeV/c.**

"Back-to-Back" vs "MinBias" "Associated" Charge Density

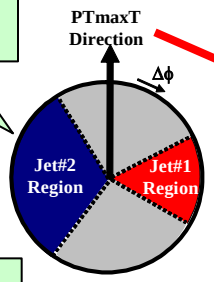


- Shows the Δϕ dependence of the "associated" charged particle densi
  p_T > 0.5 GeV/c, |η| < 1 (*not including PTmaxT*) relative to PTmaxT (
  PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV.

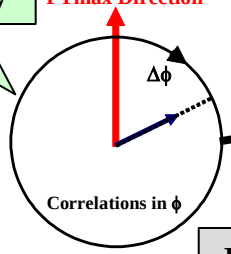
- Shows the data on the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, p_T > 0.5 GeV/c, |η| < 1 (*not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 2.0 GeV/c.

"Back-to-Back" vs "MinBias" "Associated" PTsum Density

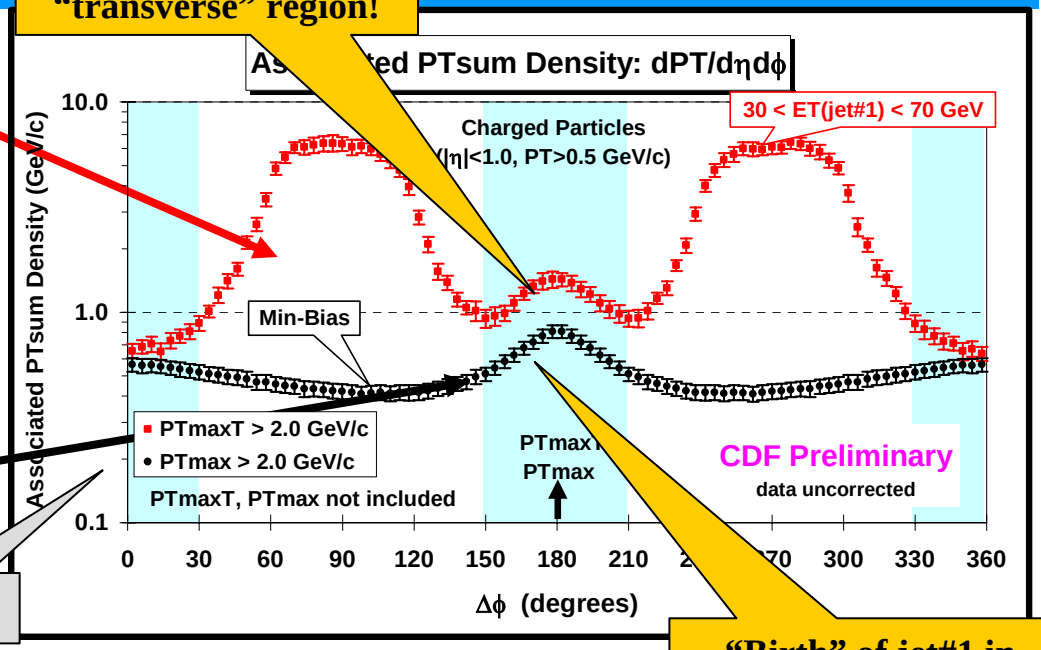
"Back-to-Back" "Associated" Density



"Min-Bias" "Associated" Density



"Birth" of jet#3 in the "transverse" region!



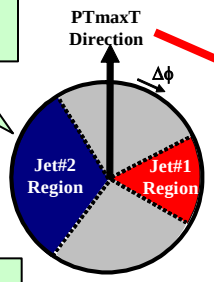
Log Scale!

"Birth" of jet#1 in "min-bias" collisions!

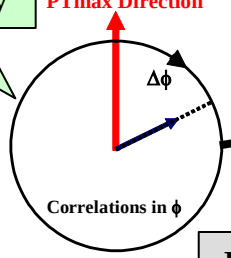
- Shows the Δϕ dependence of the "associated" charged particle densi[illegible] p_T > 0.5 GeV/c, |η| < 1 (*not including PTmaxT*) relative to PTmaxT ([illegible]) for PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV.
- Shows the data on the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, p_T > 0.5 GeV/c, |η| < 1 (*not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 2.0 GeV/c.

"Back-to-Back" vs "MinBias" "Associa[illegible]n Density

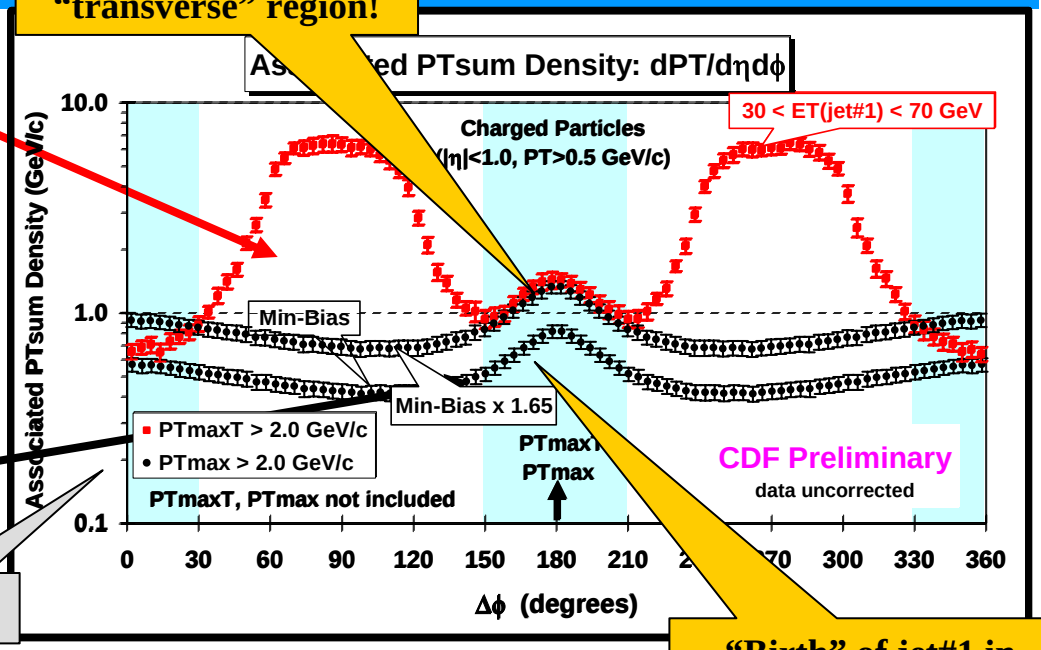
"Back-to-Back" "Associated" Density



"Min-Bias" "Associated" Density



"Birth" of jet#3 in the "transverse" region!

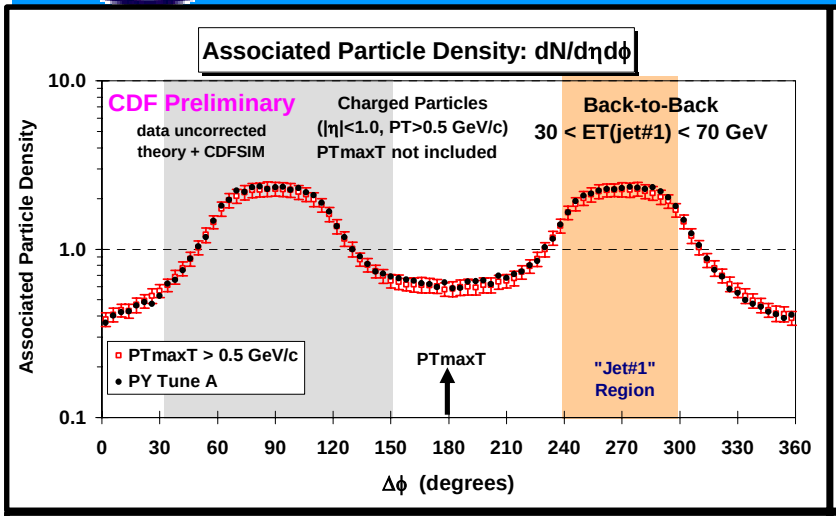


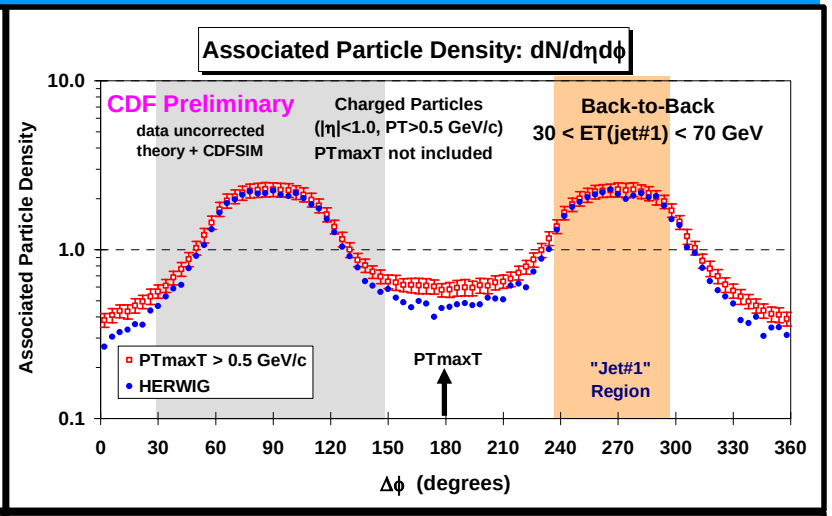
Log Scale!

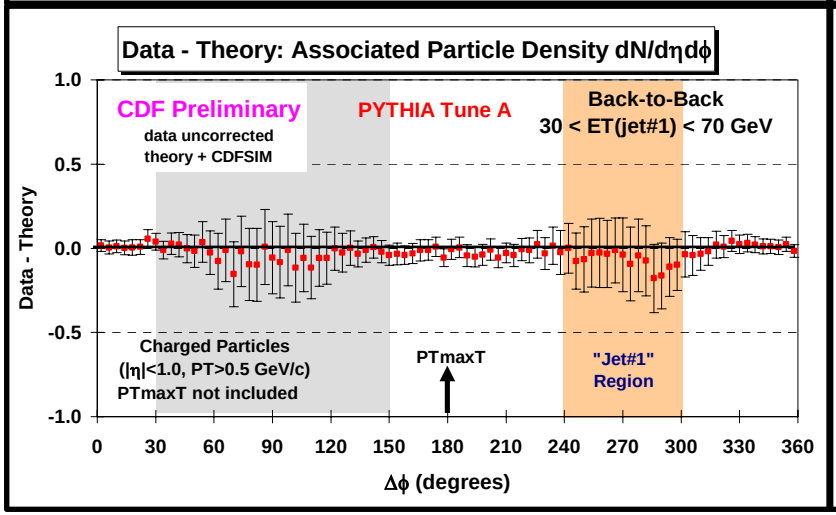
"Birth" of jet#1 in "min-bias" collisions!

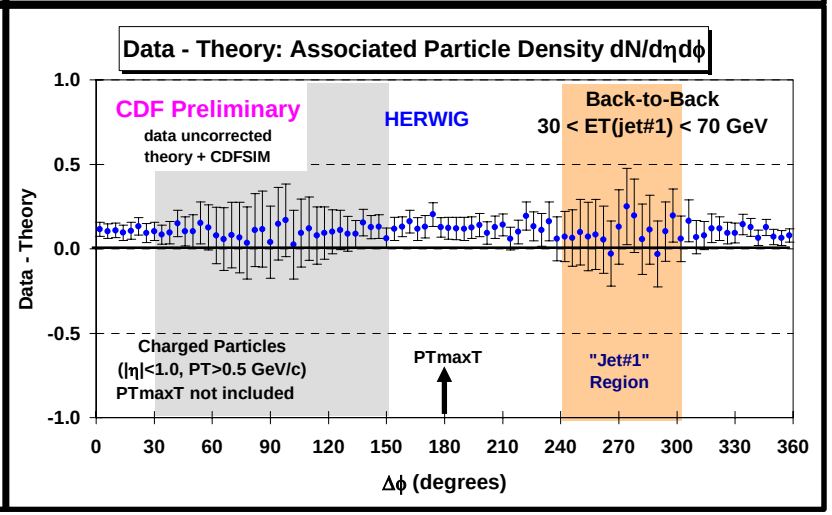
- Shows the Δϕ dependence of the "associated" charged particle densi[illegible] p_T > 0.5 GeV/c, |η| < 1 (*not including PTmaxT*) relative to PTmaxT ([illegible]) for PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV.
- Shows the data on the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, p_T > 0.5 GeV/c, |η| < 1 (*not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 2.0 GeV/c.

"Associated" Charge Density
PYTHIA Tune A vs HERWIG



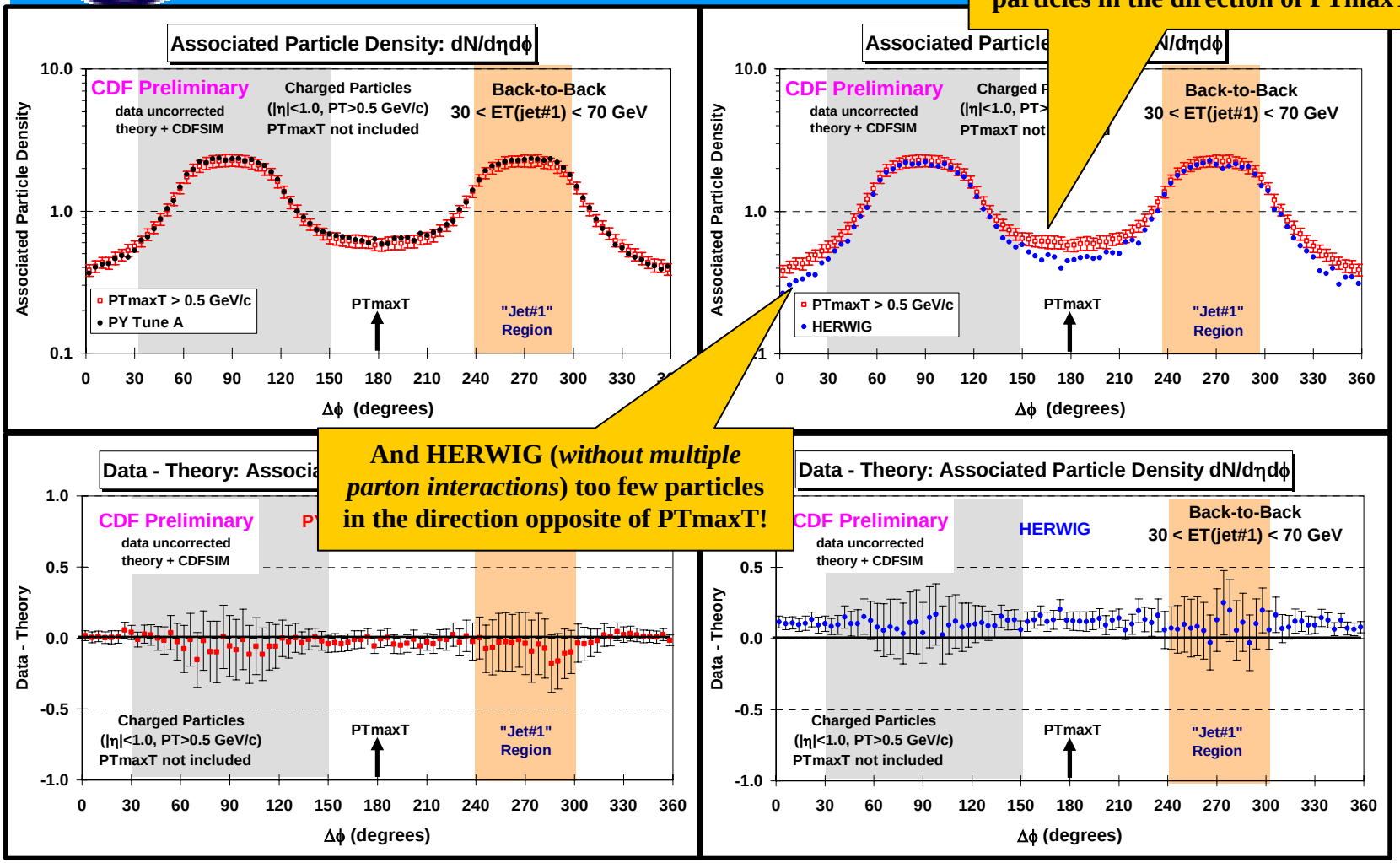






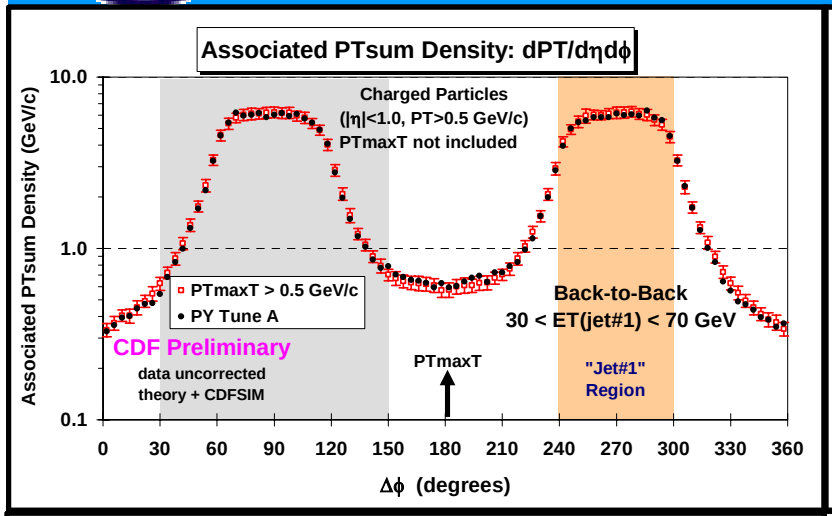
"Associated" Charge Density
PYTHIA Tune A vs HE

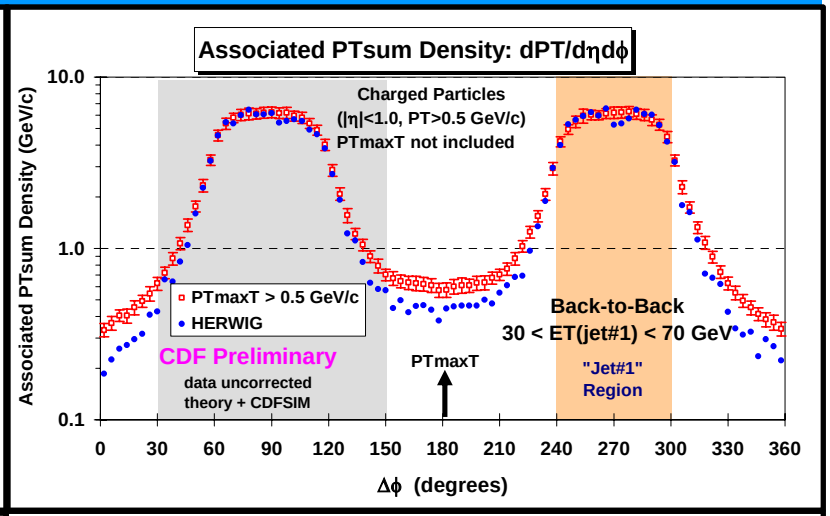
HERWIG (*without multiple parton interactions*) too few "associated" particles in the direction of PTmaxT!

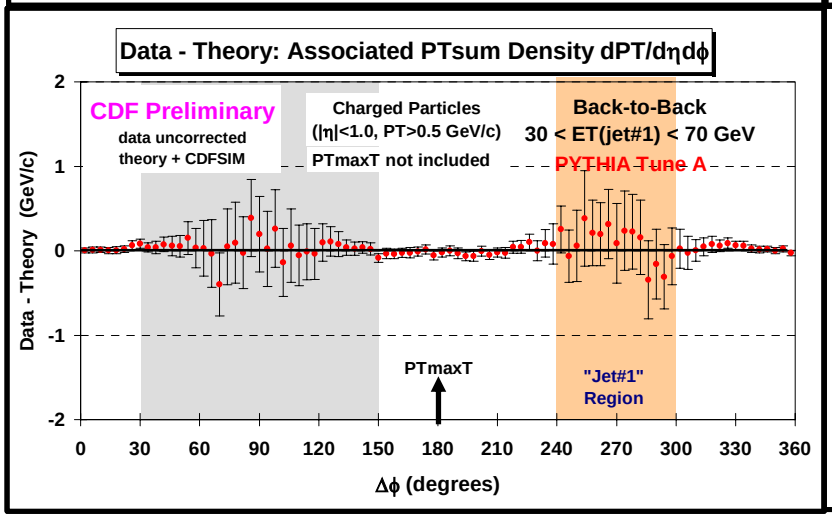


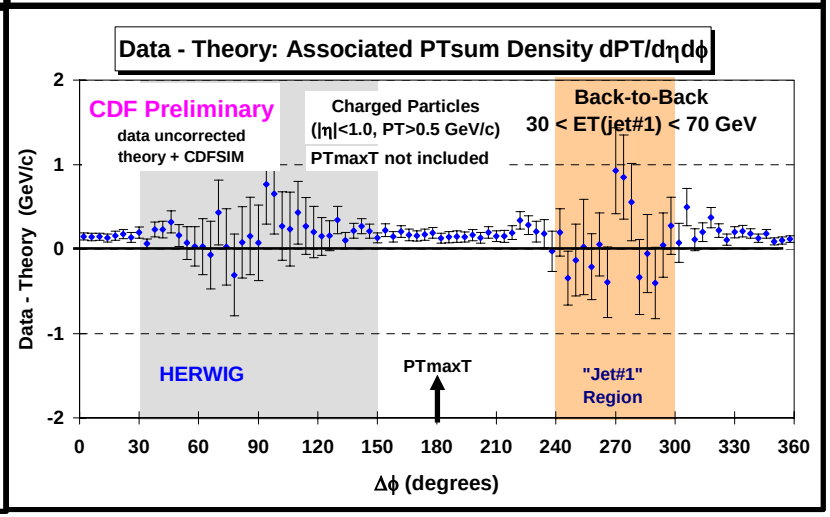
And HERWIG (*without multiple parton interactions*) too few particles in the direction opposite of PTmaxT!

"Associated" PTsum Density
PYTHIA Tune A vs HERWIG



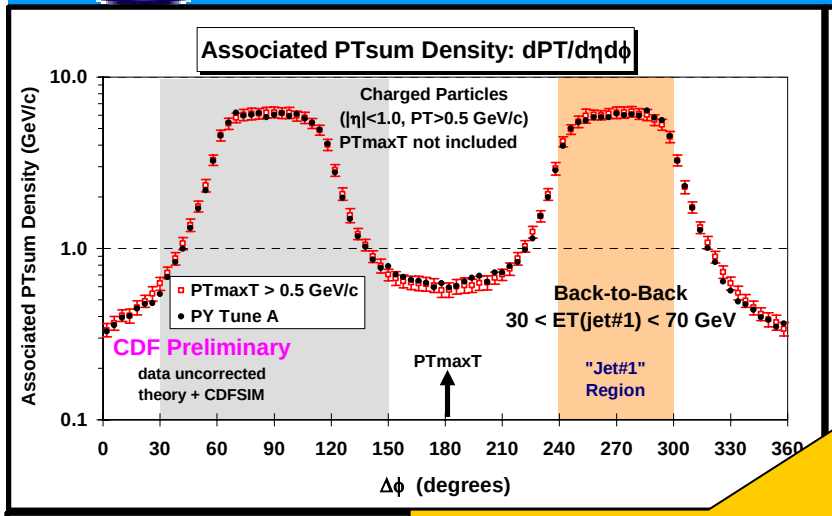


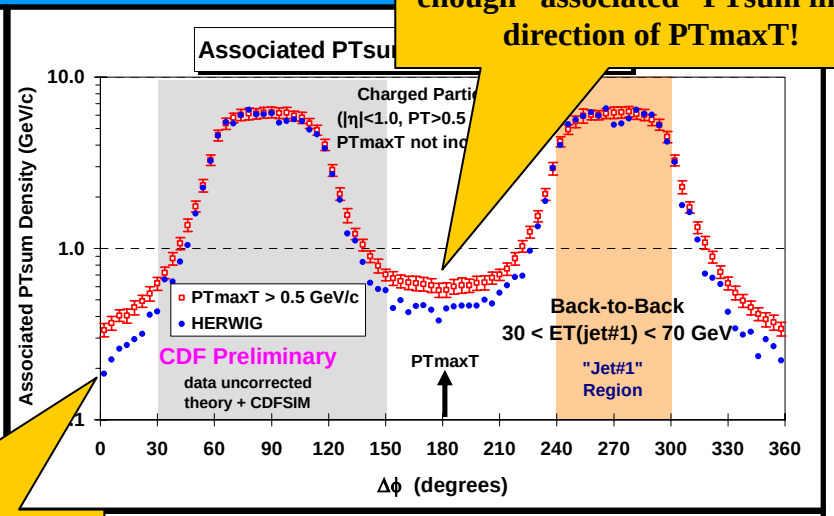




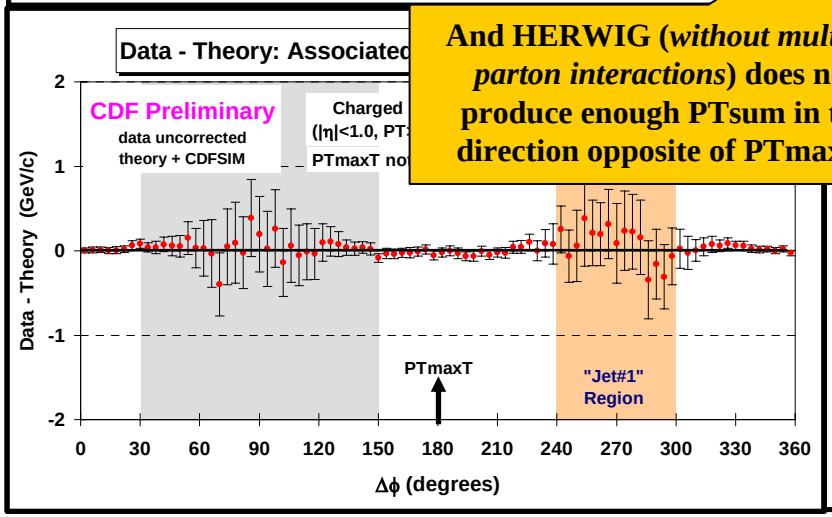
"Associated" PTsum Density
PYTHIA Tune A vs HERW

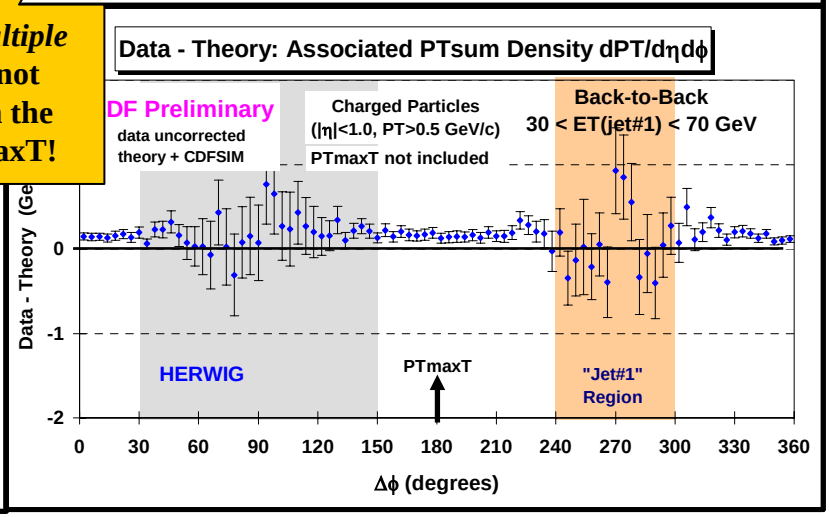
HERWIG (*without multiple parton interactions*) does not produce enough "associated" PTsum in the direction of PTmaxT!



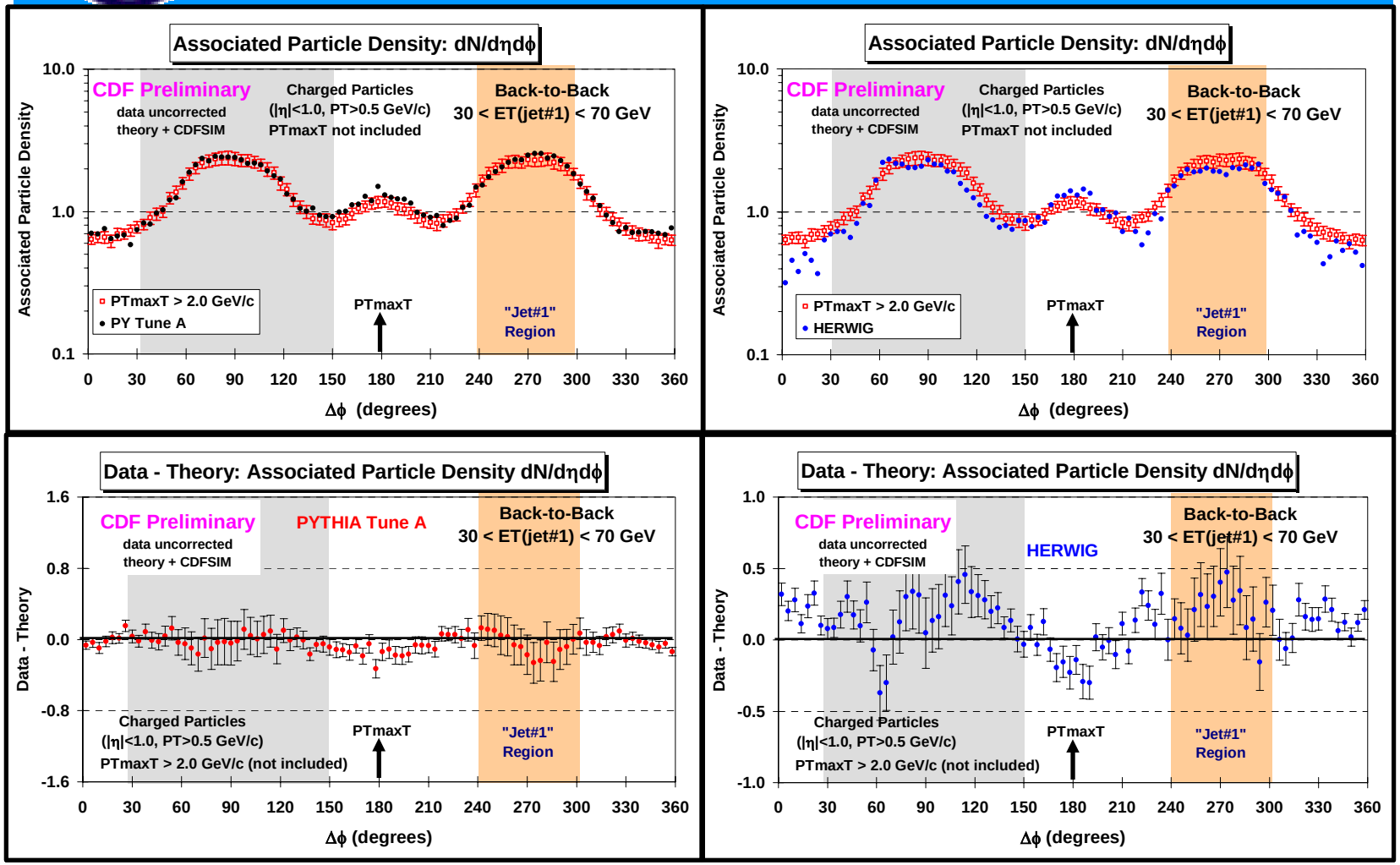


And HERWIG (*without multiple parton interactions*) does not produce enough PTsum in the direction opposite of PTmaxT!



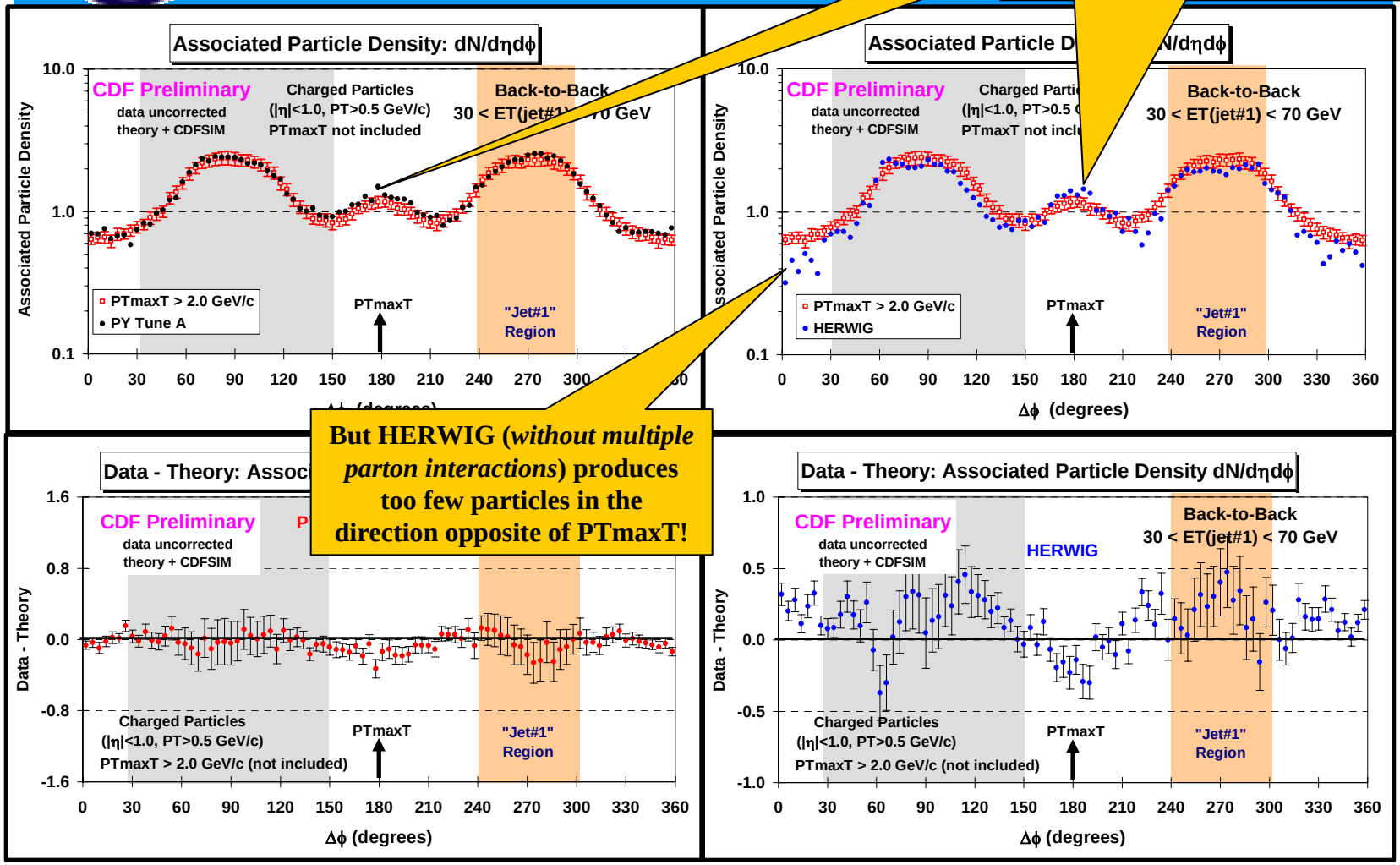


"Associated" Charge Density
PYTHIA Tune A vs HERWIG



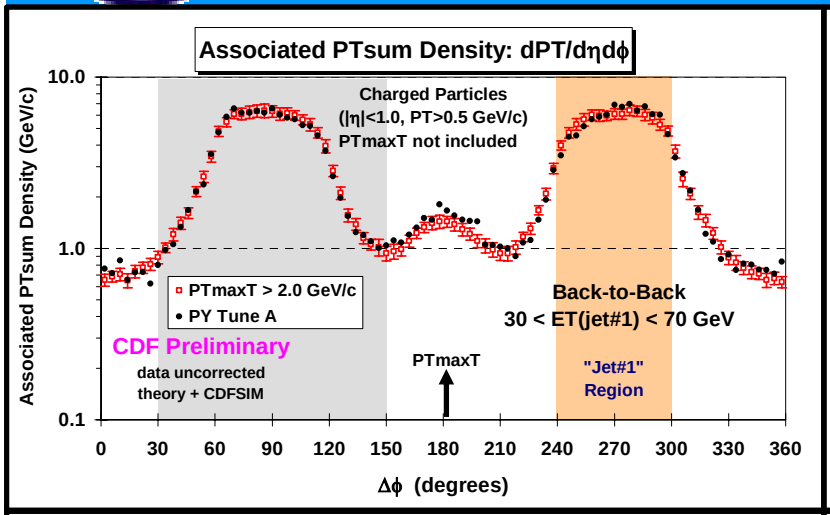
"Associated" Charge De
PYTHIA Tune A vs HE

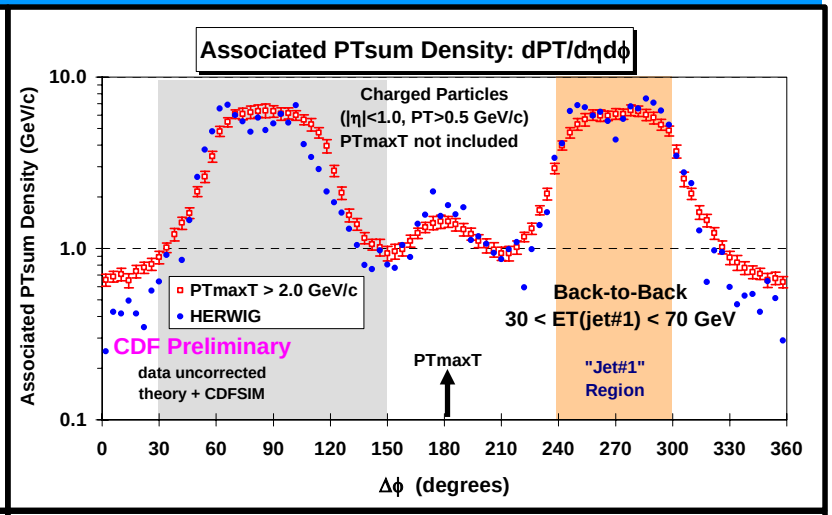
For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too many "associated" particles in the direction of PTmaxT!

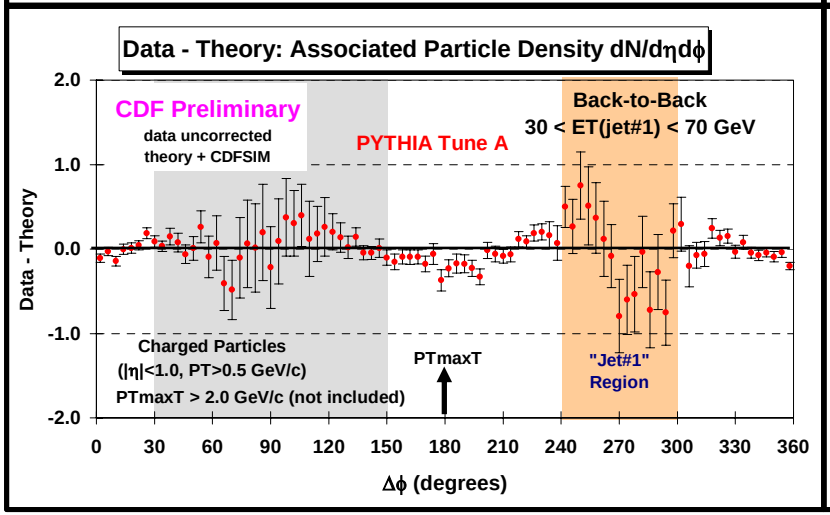


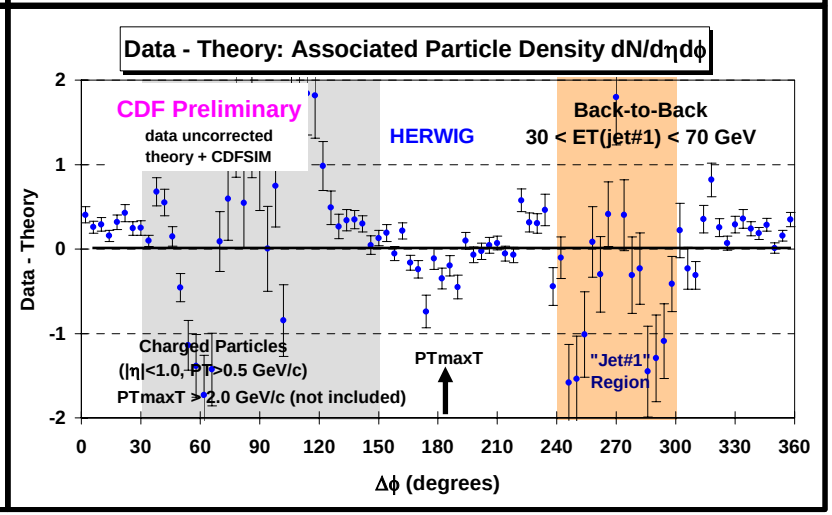
But HERWIG (*without multiple parton interactions*) produces too few particles in the direction opposite of PTmaxT!

"Associated" PTsum Density
PYTHIA Tune A vs HERWIG



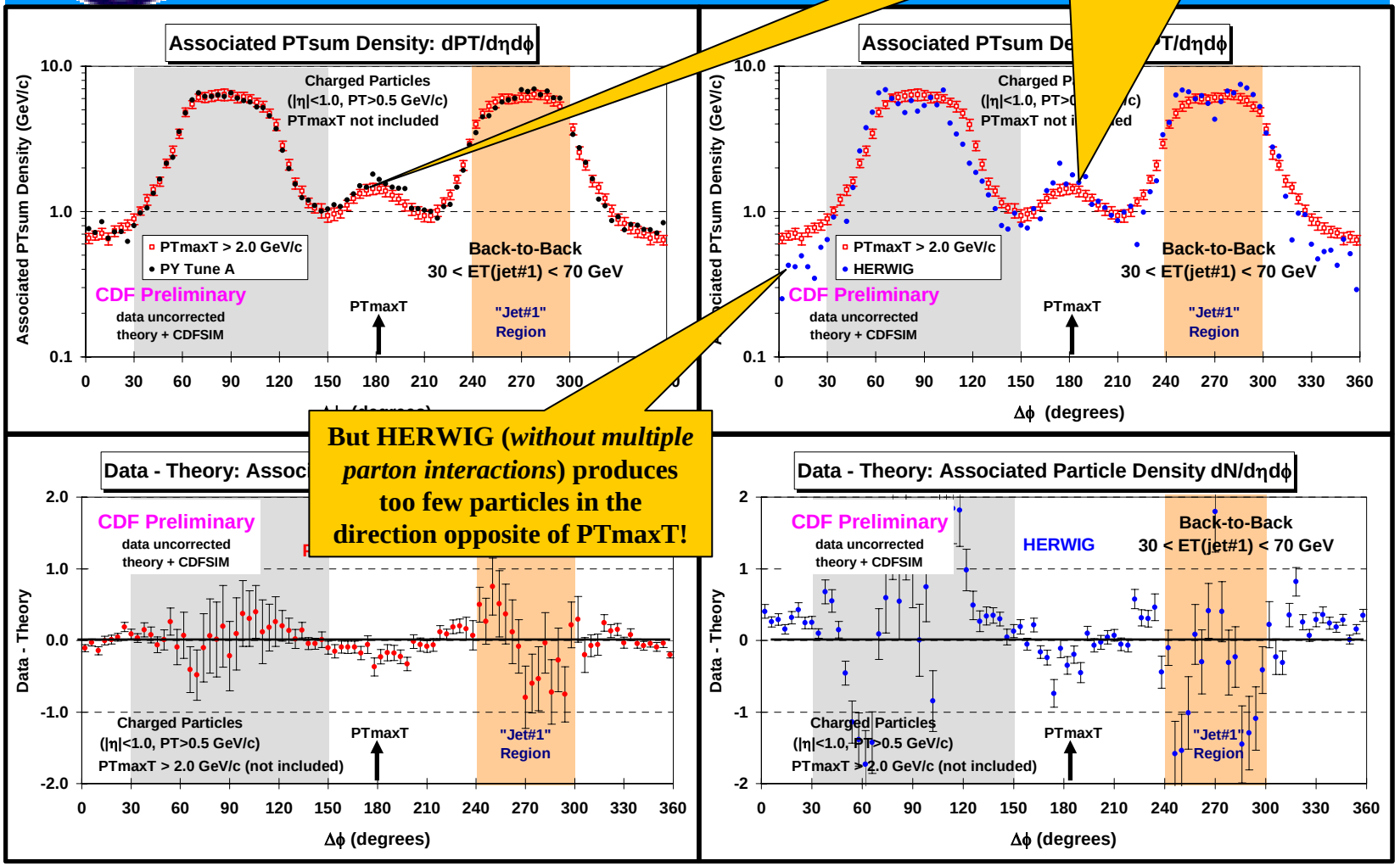






"Associated" PTsum De
PYTHIA Tune A vs HE

For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too much "associated" PTsum in the direction of PTmaxT!



But HERWIG (*without multiple parton interactions*) produces too few particles in the direction opposite of PTmaxT!