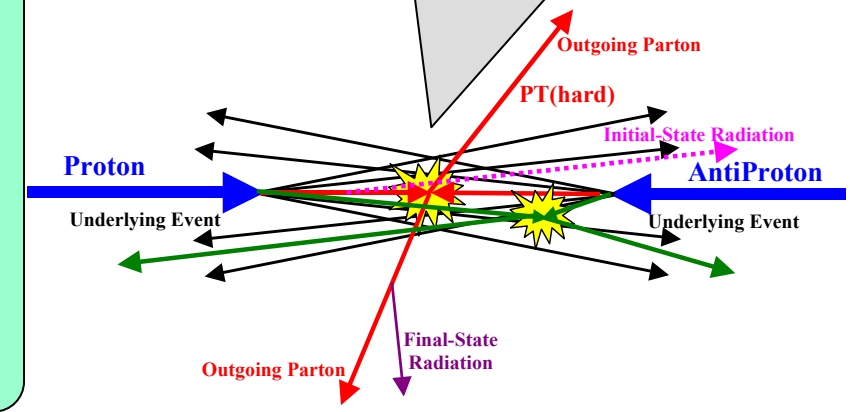
A Closer Look at the Underlying Event in Run 2 a

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

CERN MC4LHC Workshop

July 2003

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.



New CDF Run 2 results!

- **Two Classes of Events:** "Leading Jet" and "Back-to-Back".
- **Two "Transverse" regions:** "transMAX", "transMIN", "transDIF".
- **PTmax** and **PTmaxT** distributions and averages.
- **$\Delta\phi$ Distributions:** "Density" and "Associated Density".
- **$\langle p_T \rangle$ versus charged multiplicity:** "min-bias" and the "transverse" region.
- **Correlations between the two "transverse" regions:** "trans1" vs "trans2".

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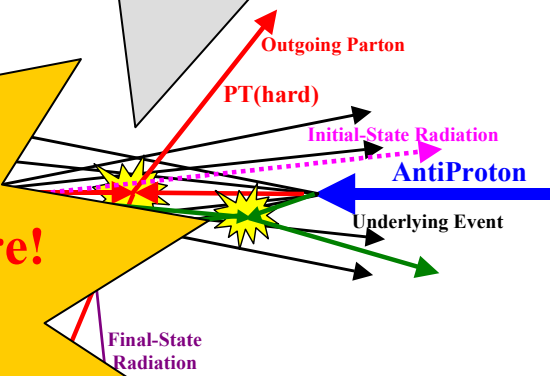

CERN MC4LH Workshop

July 200

During the workshop the theori
experimenters, and I constructed a
from CDF relating to "m
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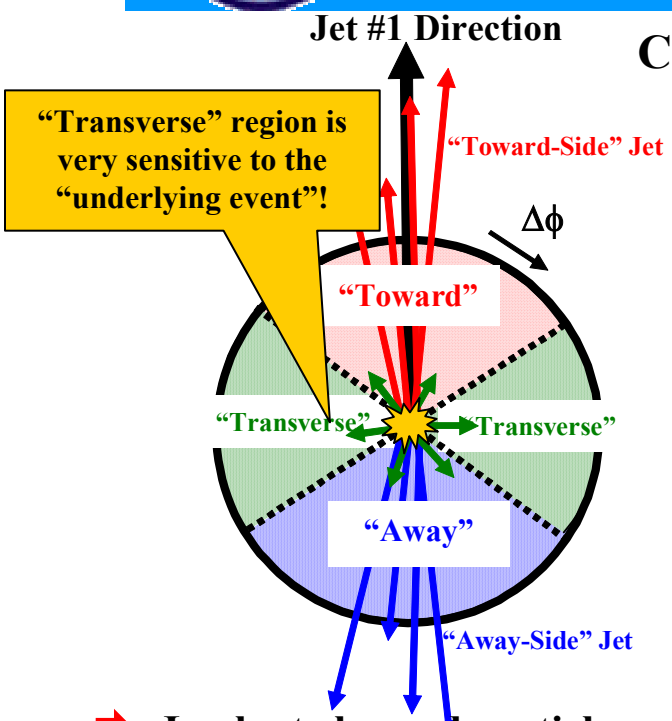
Much more new Run 2 results than I can show here!
I will make the plots available in the CDF "blessed plots" area soon!

New CDF Run 2 re

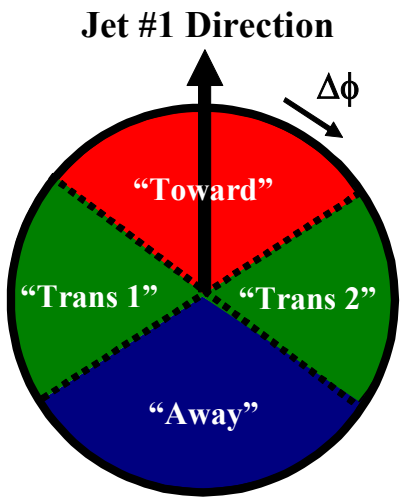
- **Two Classes of Events: "L ng an ck-to ck".**
- **Two "Transverse" regions: "tran AX", nsMIN", "transDIF".**
- **PTmax and PTmaxT distribution nd aver ges.**
- **Δϕ Distributions: "Density" and "ssociated Density".**
- **$<p_T>$ versus charged multiplicity: "min-bias" and the "transverse" region.**
- **Correlations between the two "transverse" regions: "trans1" vs "trans2".**

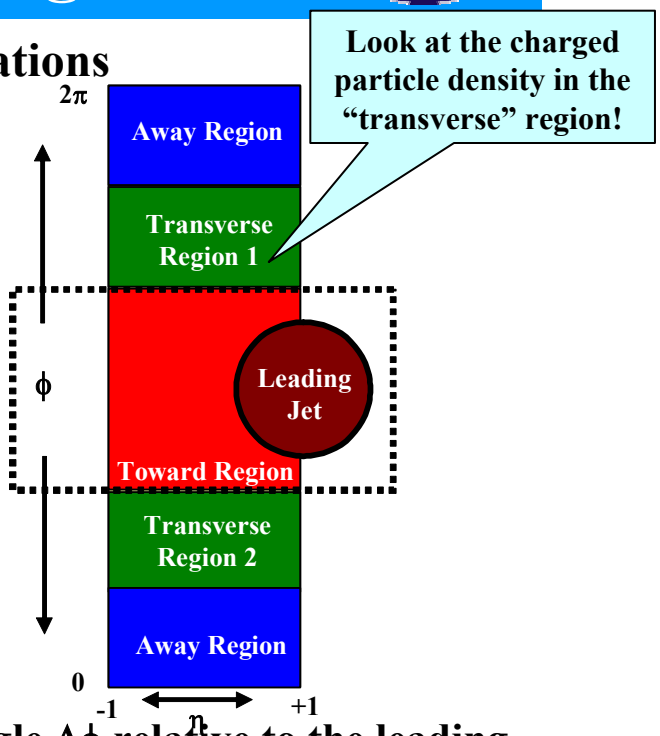
The "Transverse" Regions
as defined by the Leading Jet



Charged Particle Δϕ Correlations

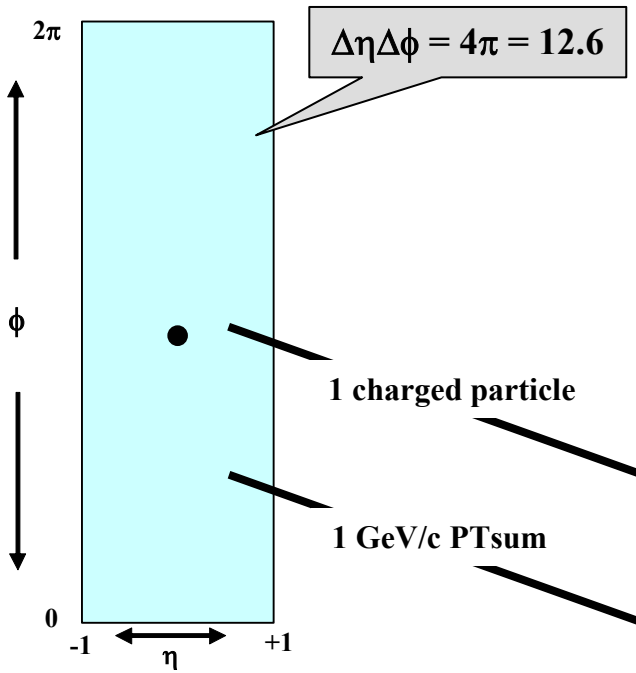
$p_T > 0.5$ GeV/c $|\eta| < 1$





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

Particle Densities



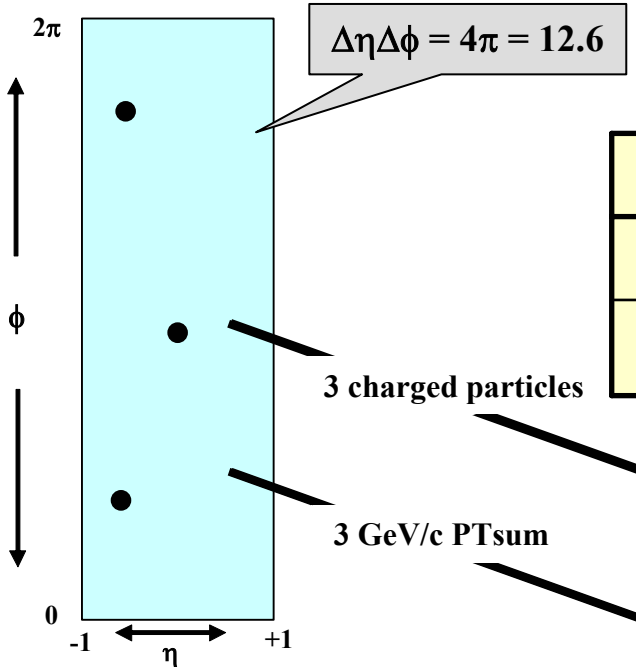
Charged Particles
$p_T > 0.5$ GeV/c $|\eta| < 1$

1 charged particle → **$dN_{chg}/d\eta d\phi = 1/4\pi = 0.08$**

1 GeV/c PTsum → **$dPT_{sum}/d\eta d\phi = 1/4\pi$ GeV/c = 0.08 GeV/c**

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

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

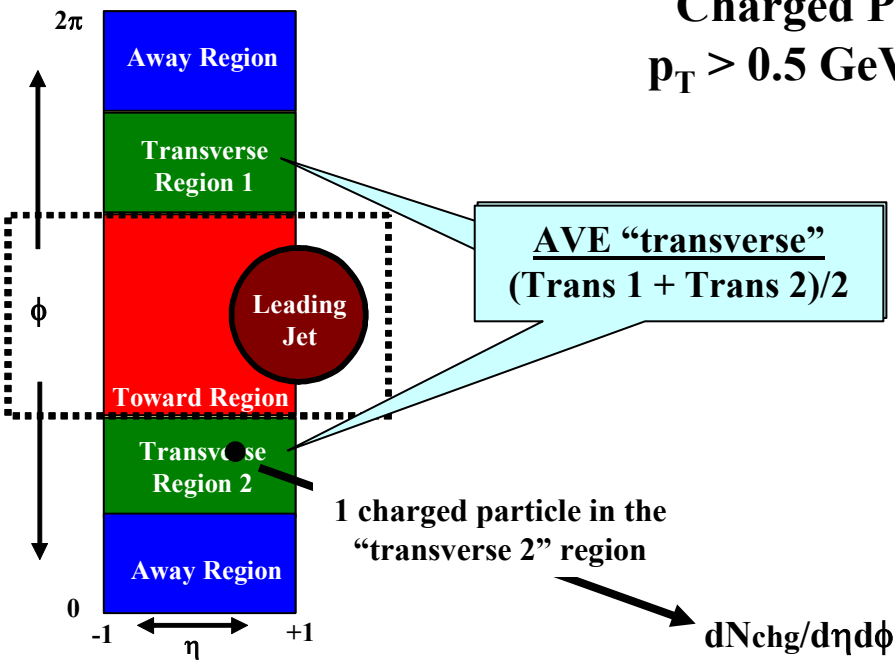
$dN_{chg}/d\eta d\phi = 3/4\pi = 0.24$

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

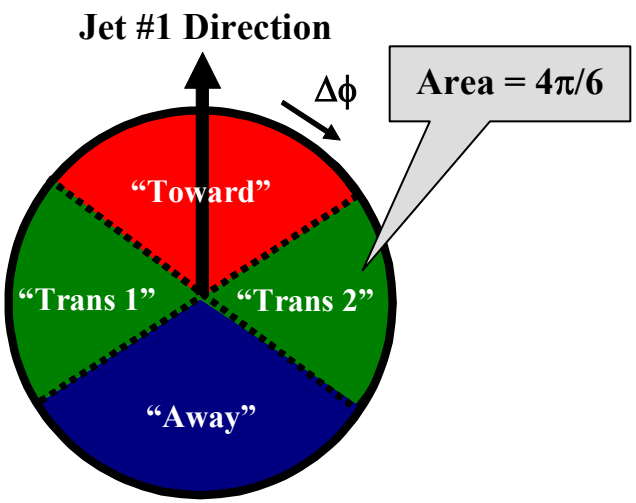
- **Study the charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) and form the charged particle density, $dN_{chg}/d\eta d\phi$, and the charged scalar p_T sum density, $dPT_{sum}/d\eta d\phi$.**

"Transverse" Particle Densities

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

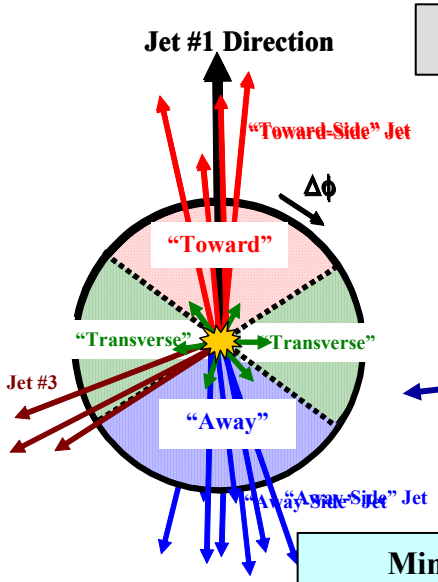


$dN_{chg}/d\eta d\phi = 1/(4\pi/6) = 0.48$

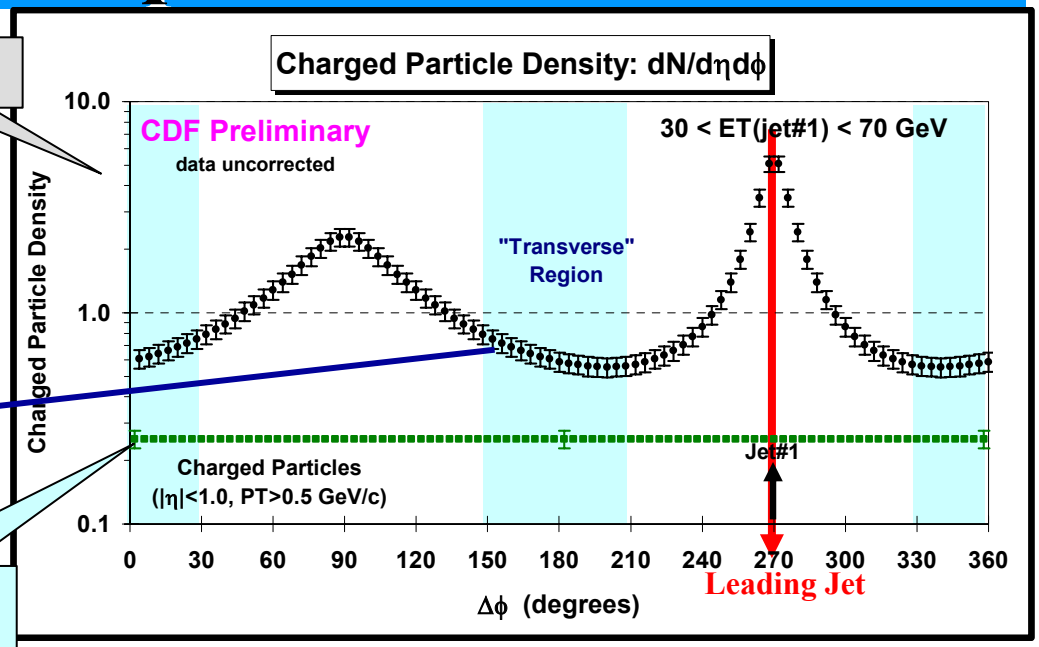


- Study the charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) in the "Transverse 1" and "Transverse 2" and form the charged particle density, $dN_{chg}/d\eta d\phi$, and the charged scalar p_T sum density, $dPTsum/d\eta d\phi$.
- The average "transverse" density is the average of "transverse 1" and "transverse 2".

Charged Particle Density
Δϕ Dependence



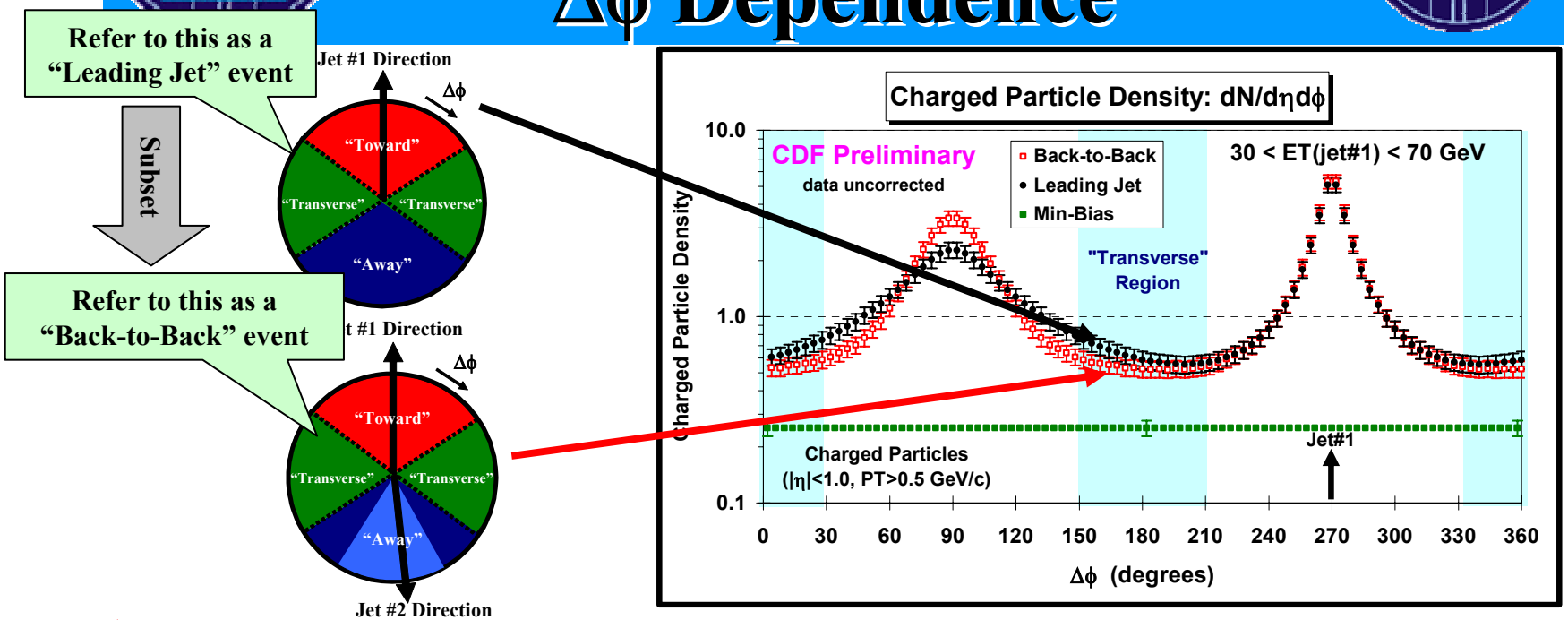
Log Scale!



Min-Bias
0.25 per unit η-ϕ

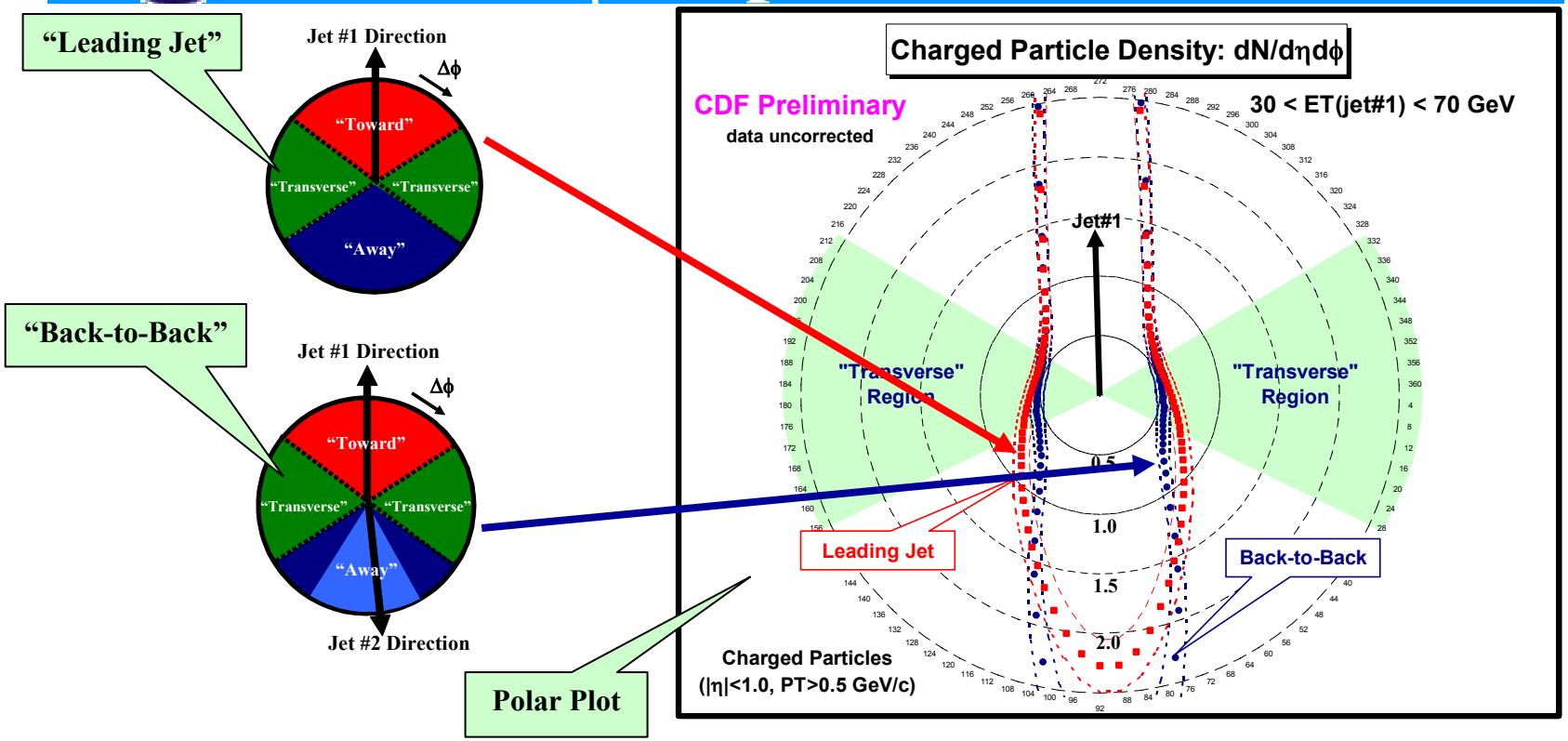
- Shows the Δϕ dependence of the charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles in the range $p_T > 0.5$ GeV/c and $|\eta| < 1$ relative to jet#1 (rotated to 270°) for "leading jet" events $30 < E_T(\text{jet\#1}) < 70$ GeV.
- Also shows charged particle density, $dN_{chg}/d\eta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

Charged Particle Density
Δϕ Dependence



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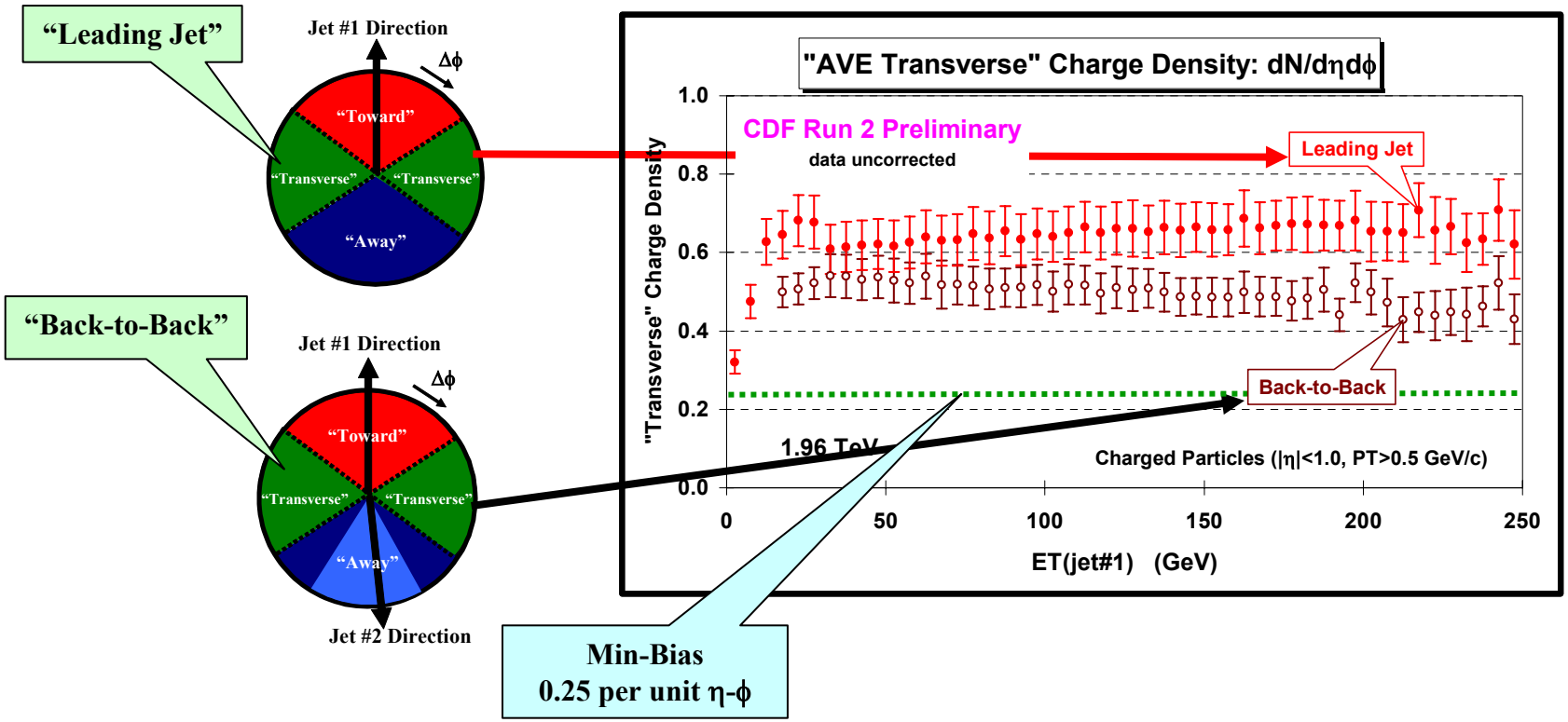
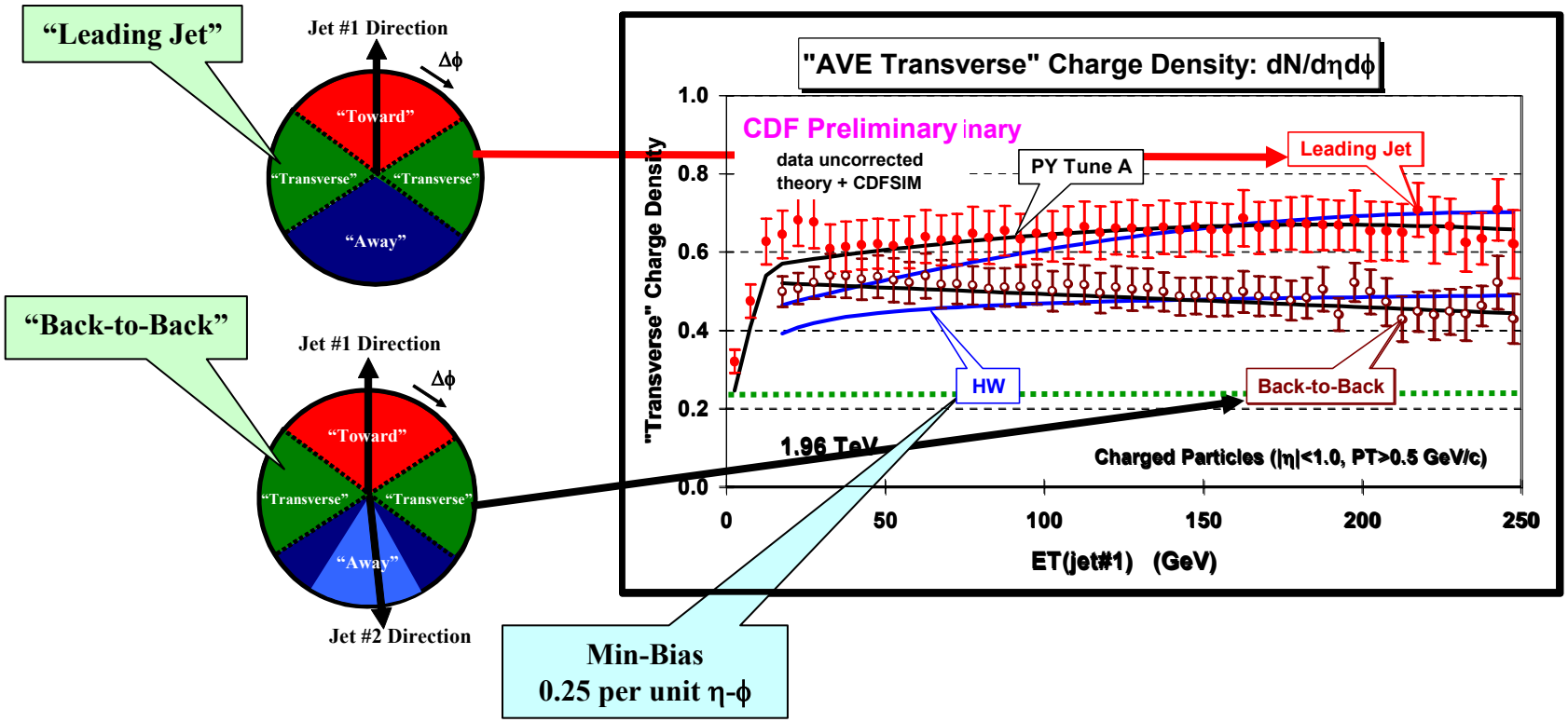
"Transverse" Charge Density versus E_T(jet#1)



- 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.
- Compares the (*uncorrected*) data with PYTHIA Tune A and HERWIG after CDFSIM.

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



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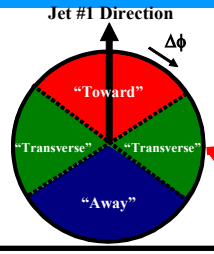
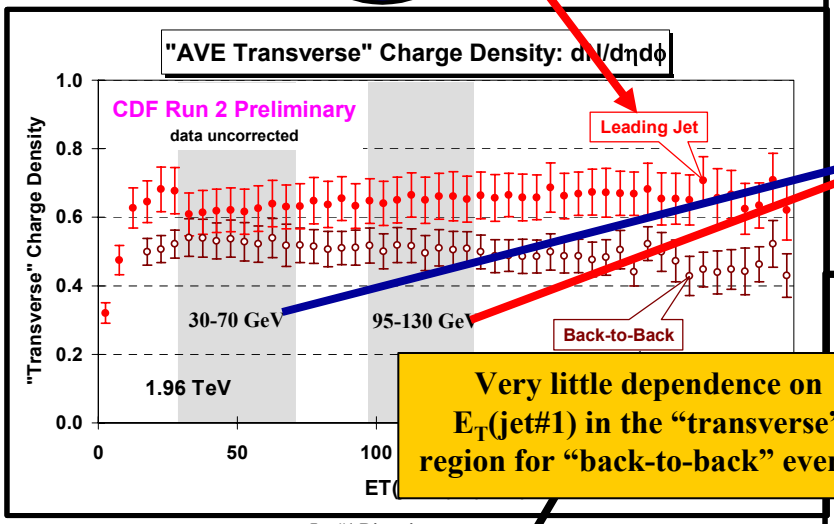
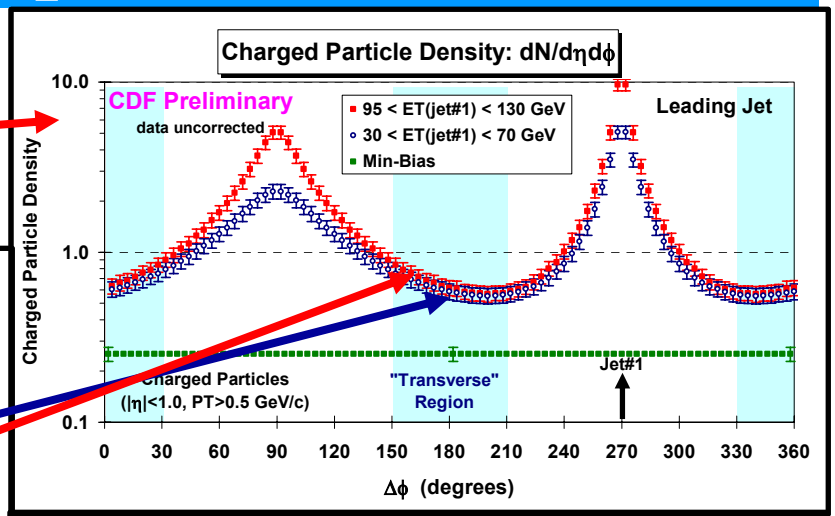
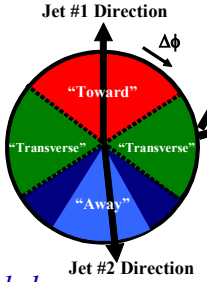
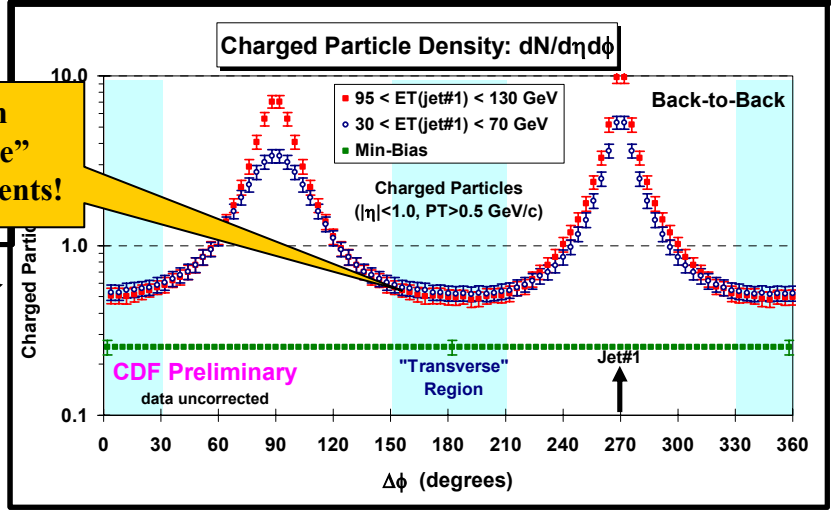




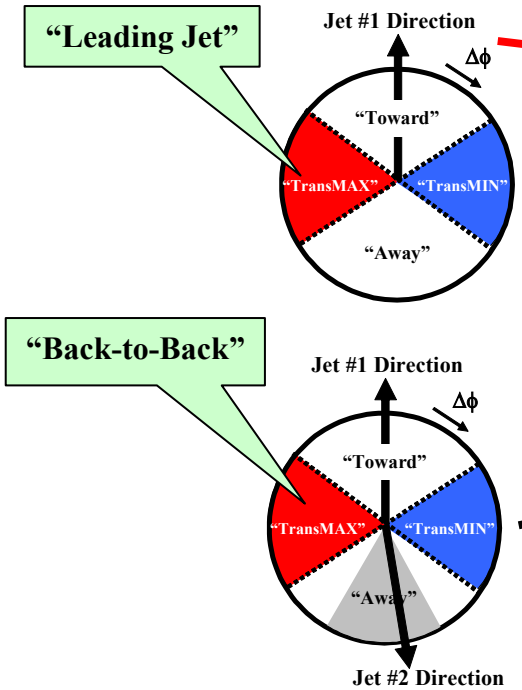


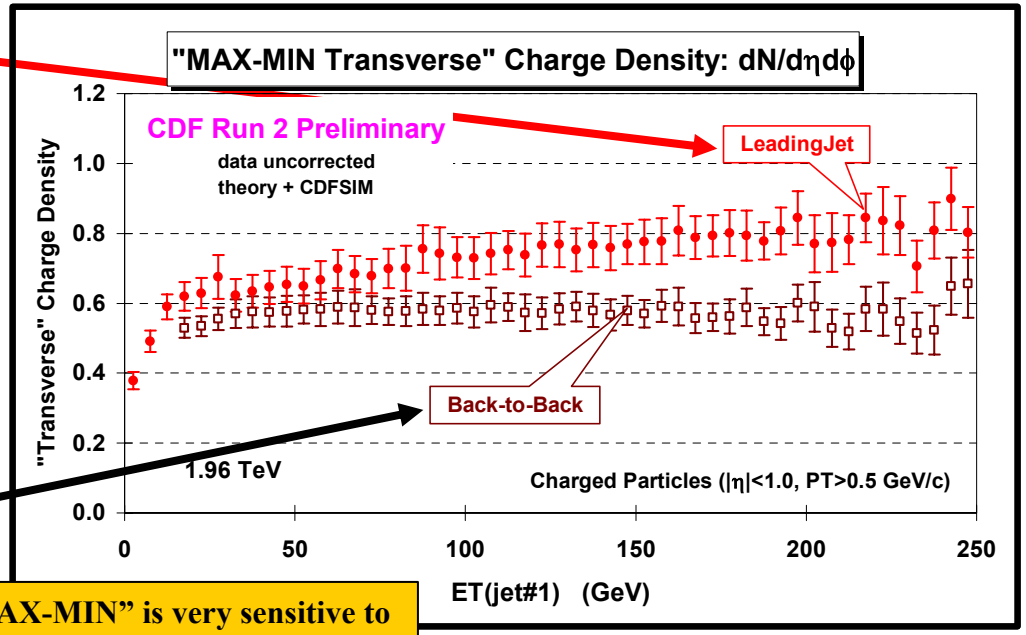
Very little dependence on E_T(jet#1) in the "transverse" region for "back-to-back" events!





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

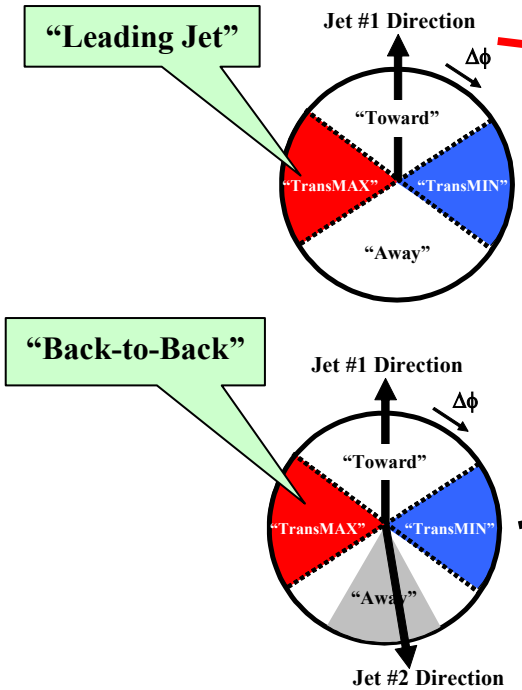


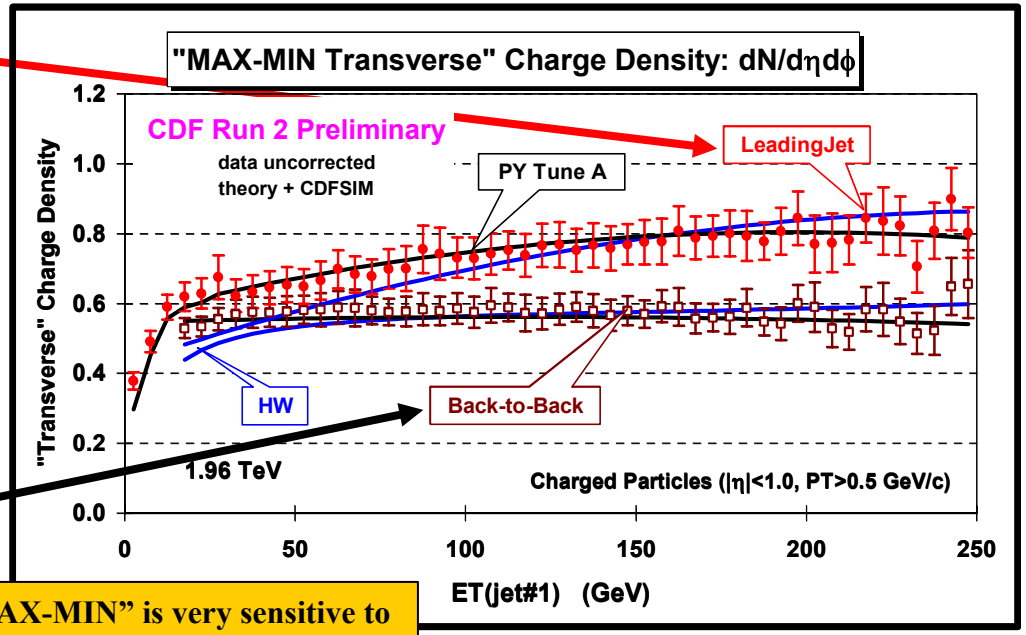


"MAX-MIN" is very sensitive to the "hard scattering" component of the "underlying event"!

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

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





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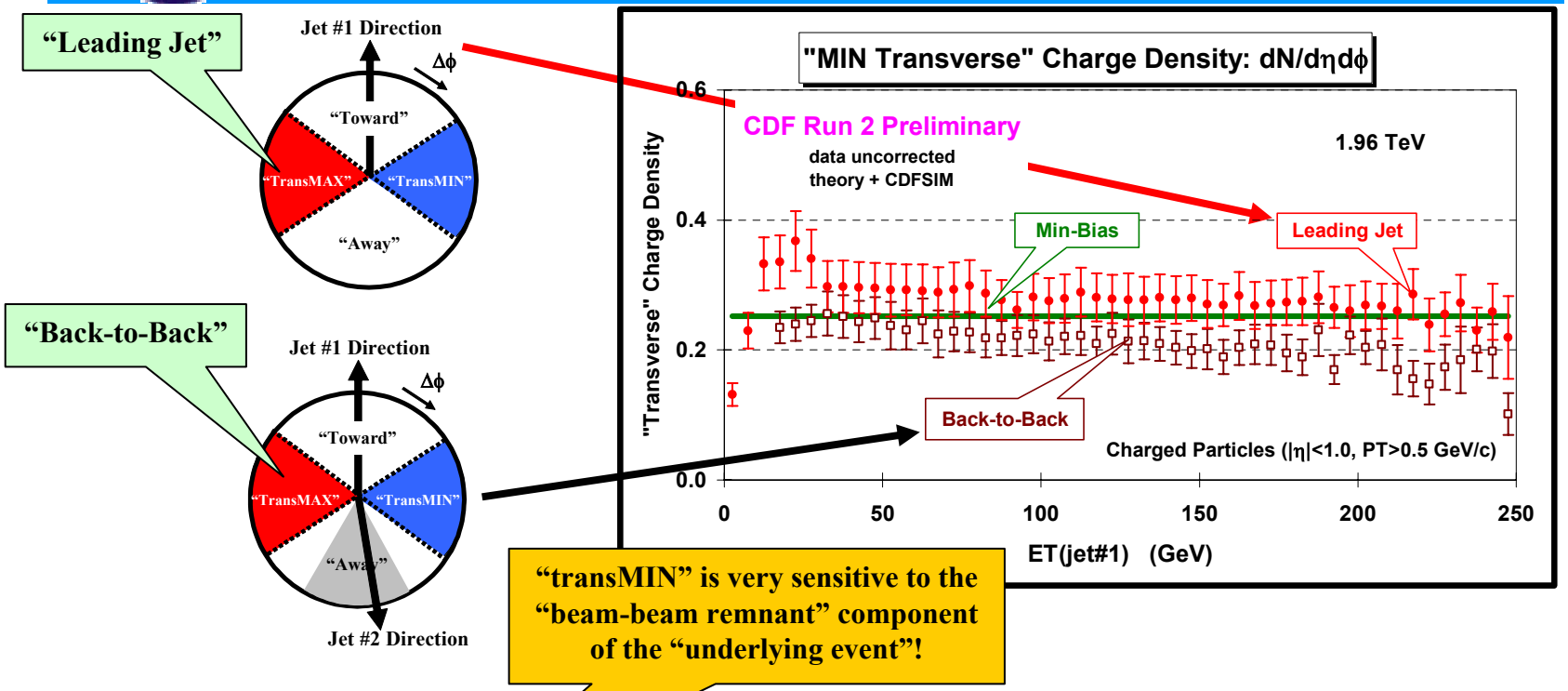
"TransMIN" Charge Density versus E_T(jet#1)



"transMIN" is very sensitive to the "beam-beam remnant" component of the "underlying event"!

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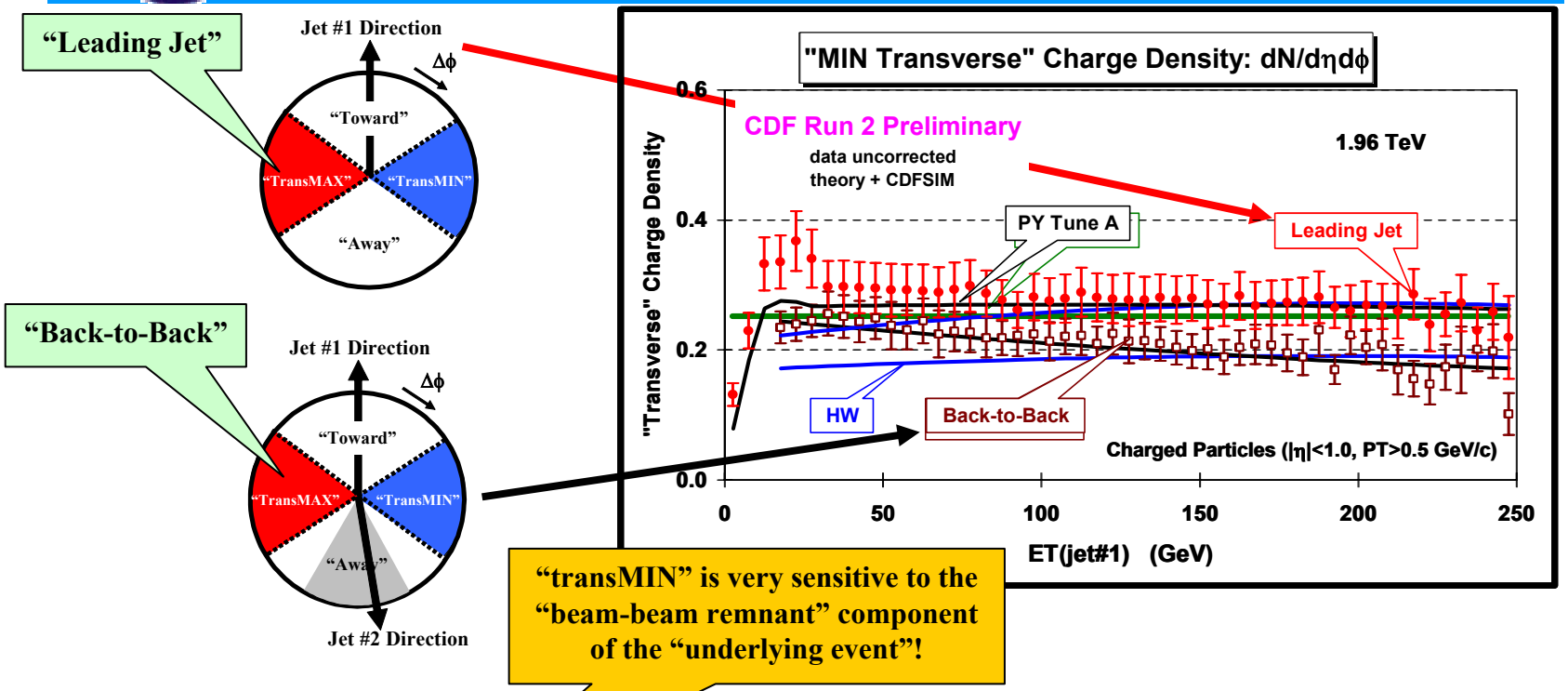
"TransMIN" Charge Density versus E_T(jet#1)



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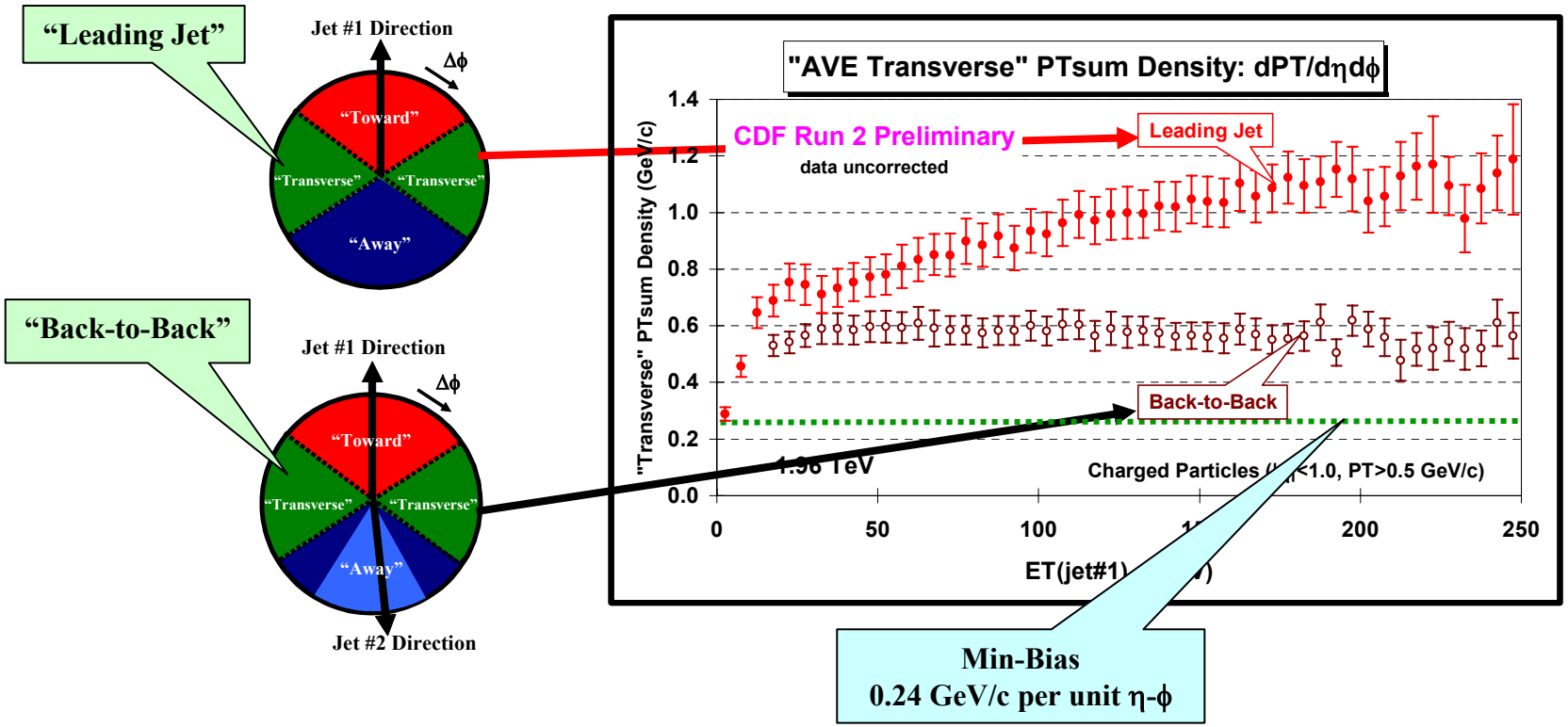
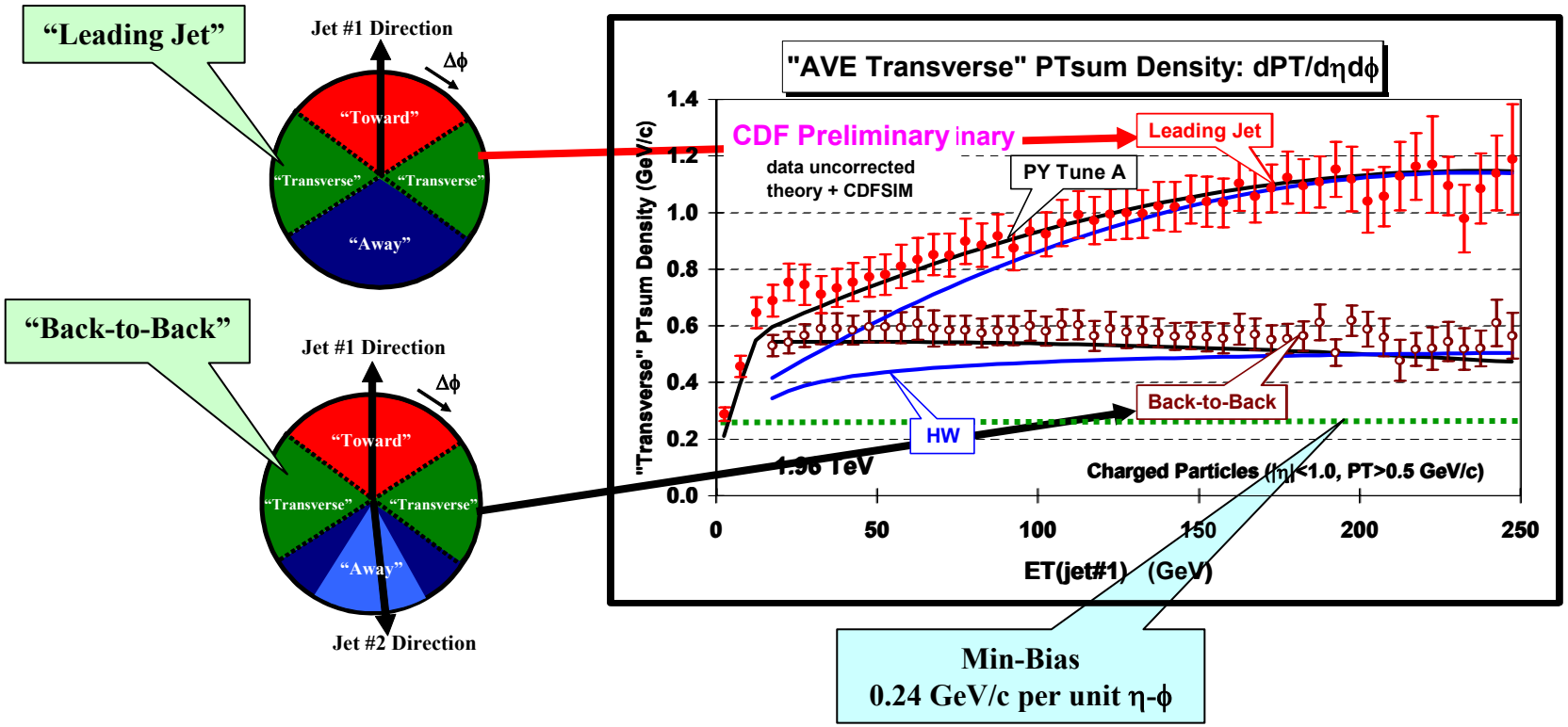
"Transverse" PTsum Density versus E_T(jet#1)



- 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.
- Compares the (*uncorrected*) data with PYTHIA Tune A and HERWIG after CDFSIM.

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



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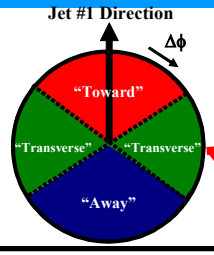
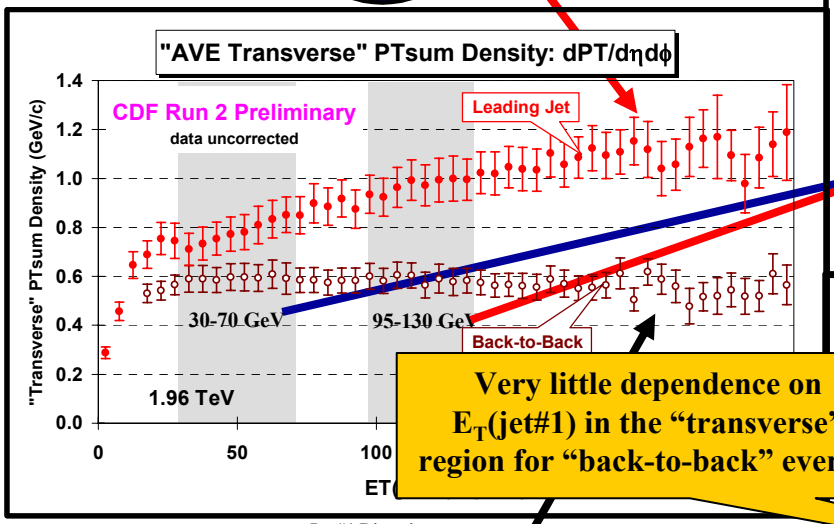
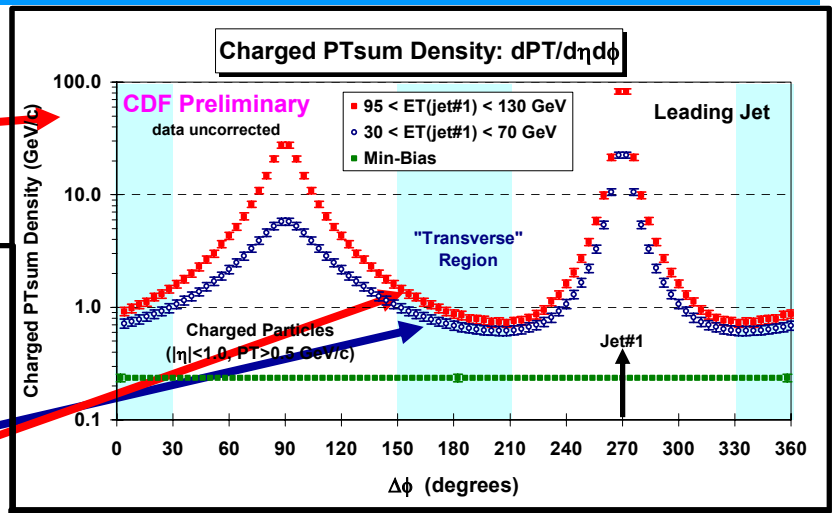
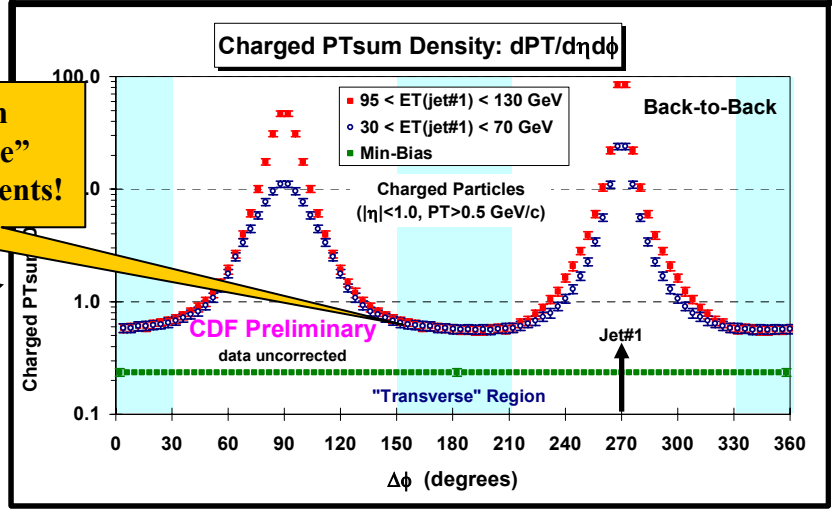
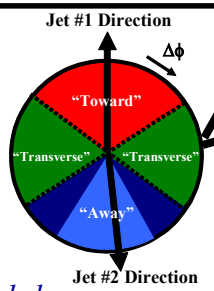




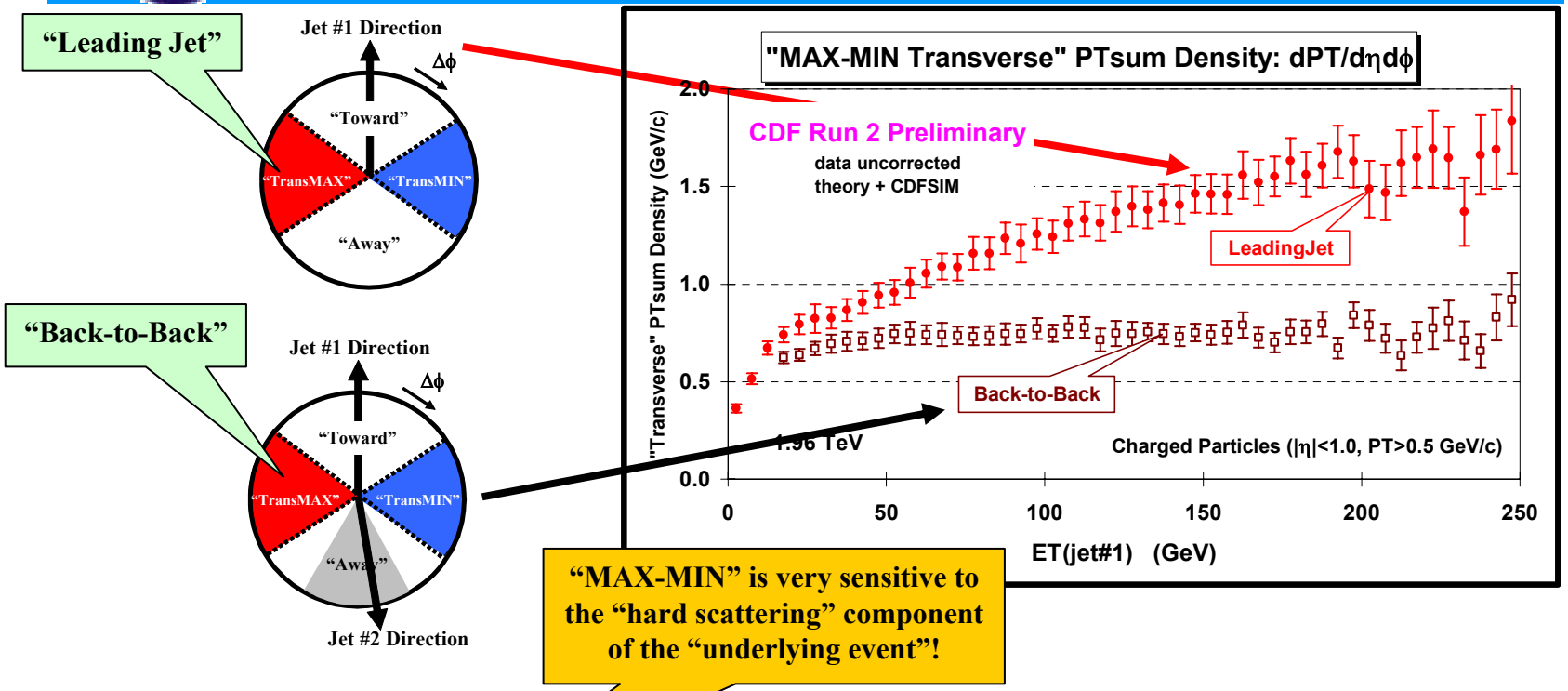


Very little dependence on E_T(jet#1) in the "transverse" region for "back-to-back" events!





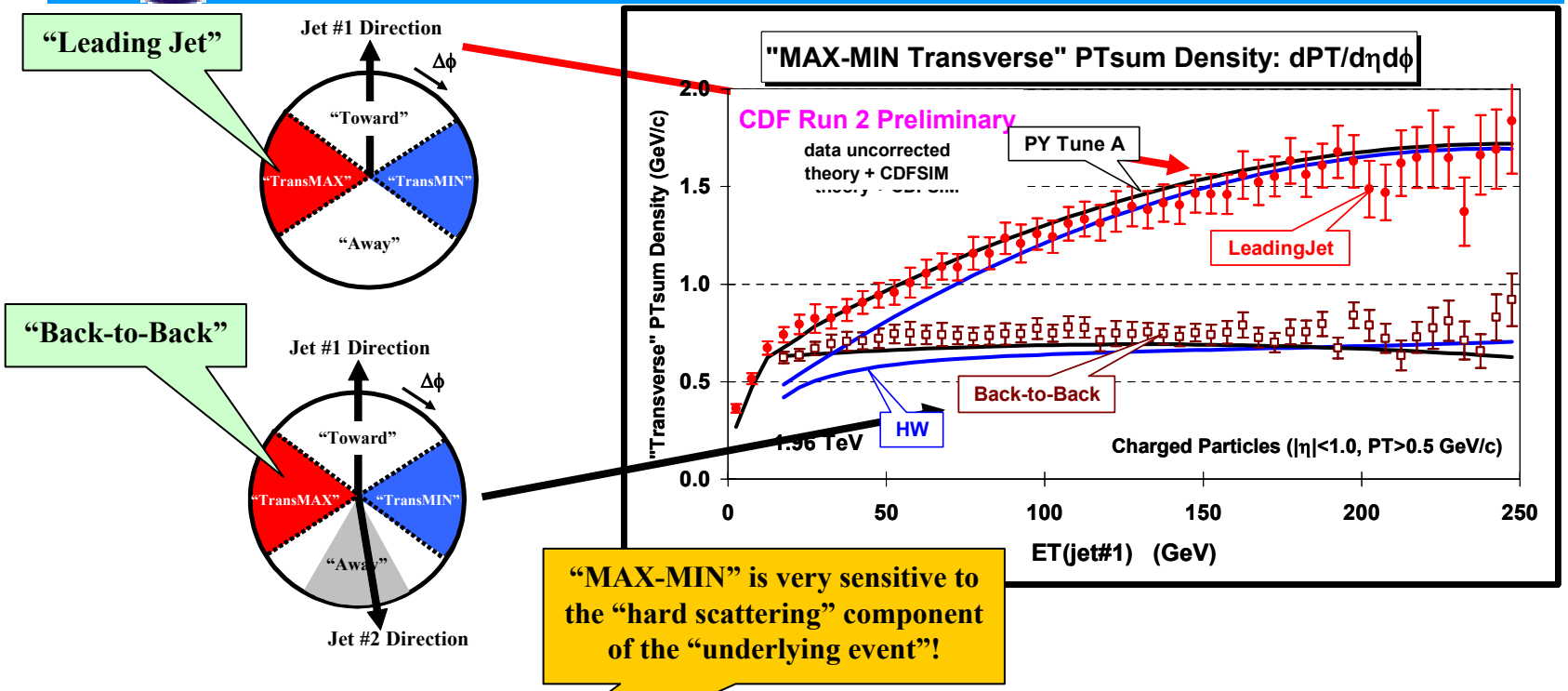
"TransDIF" PTsum Density versus E_T(jet#1)



"MAX-MIN" is very sensitive to the "hard scattering" component of the "underlying event"!

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

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



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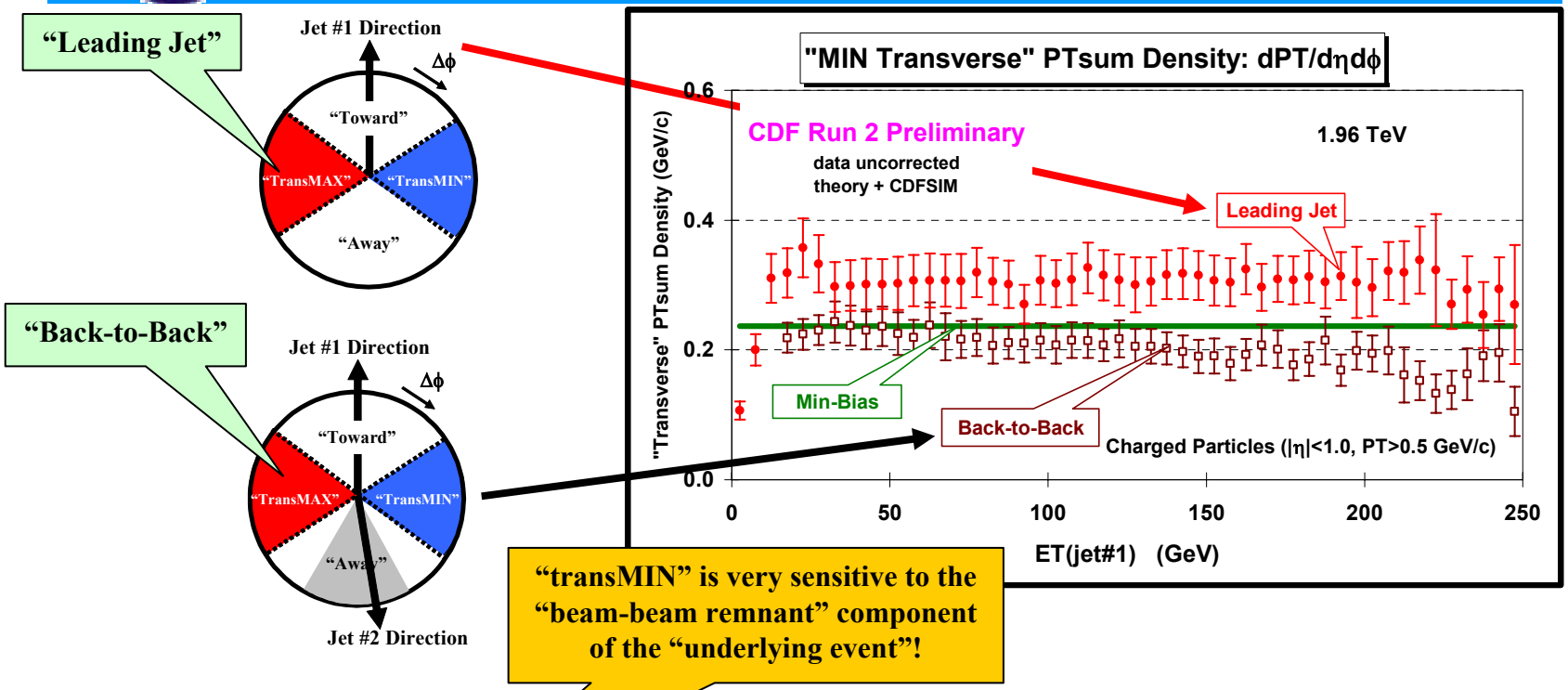
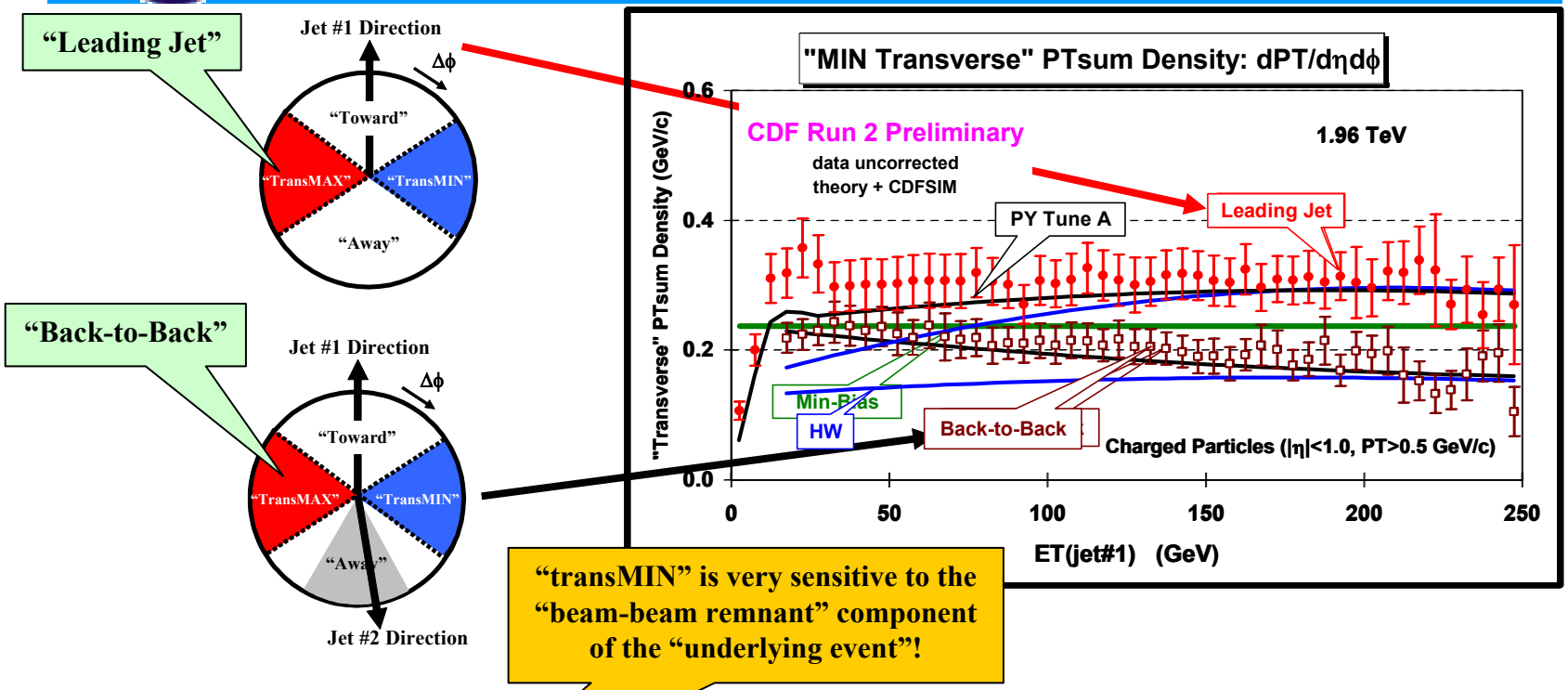
"TransMIN" PTsum Density versus E_T(jet#1)



"transMIN" is very sensitive to the "beam-beam remnant" component of the "underlying event"!

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

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



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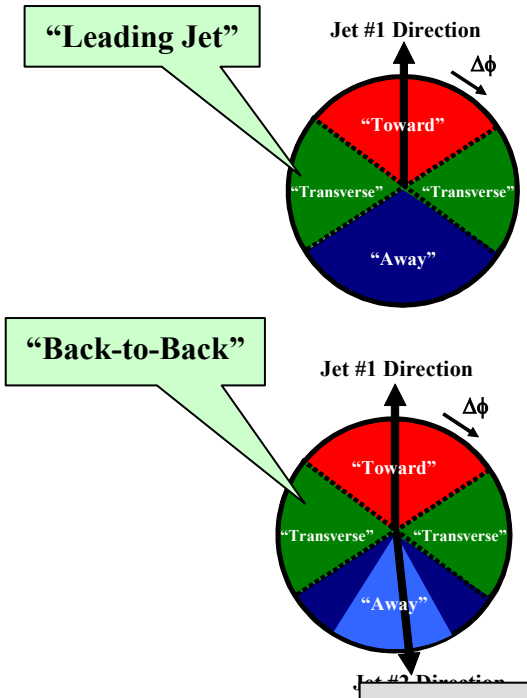
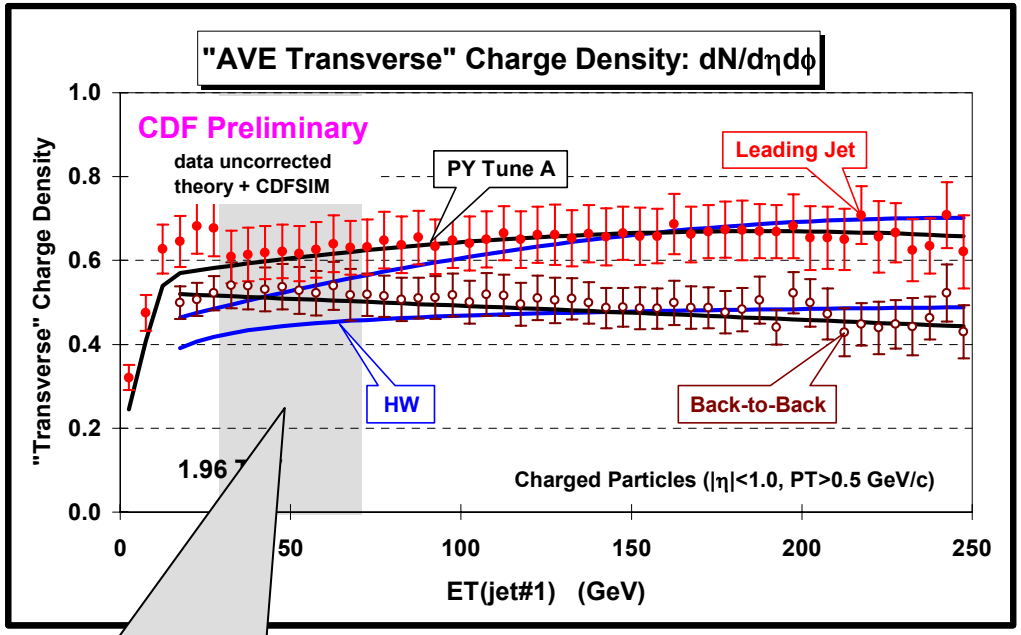
"Transverse" Charge Density
PYTHIA Tune A vs HERWIG



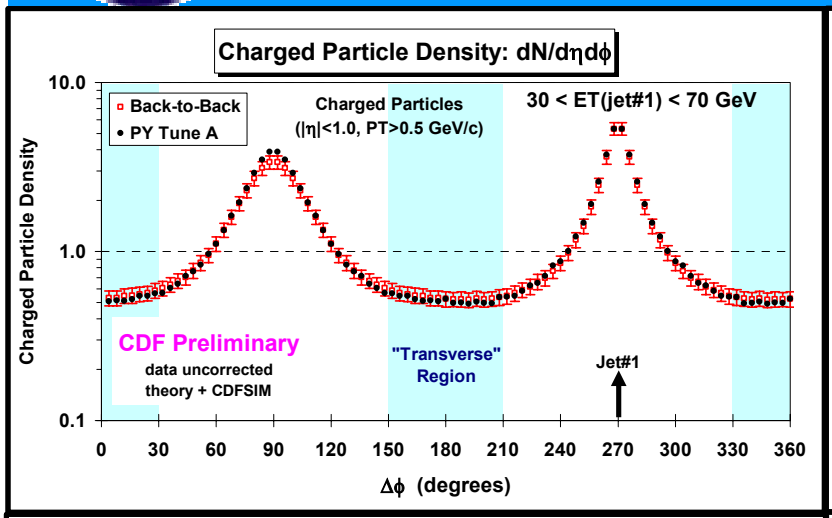


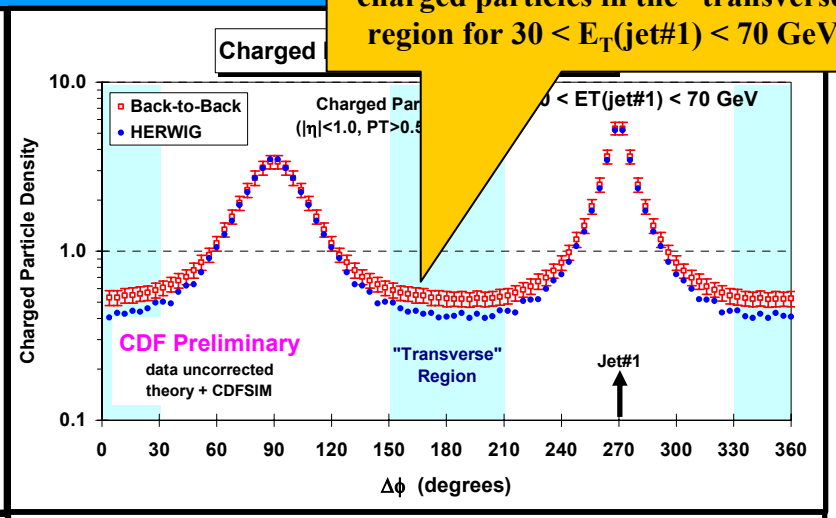
Now look in detail at "back-to-back" events in the region $30 < E_T(\text{jet\#1}) < 70$ GeV!

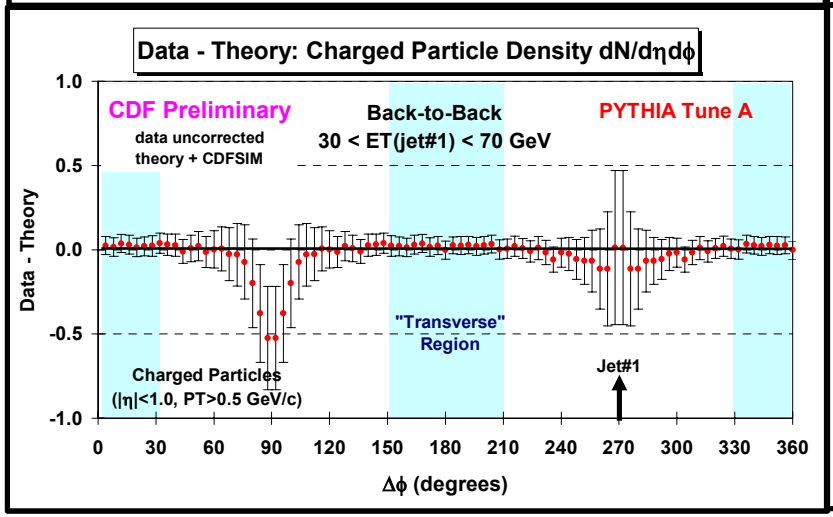
- Shows the average charged particle density, $dN_{chg}/d\eta d\phi$, in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- Compares the (*uncorrected*) data with PYTHIA Tune A and HERWIG after CDFSIM.

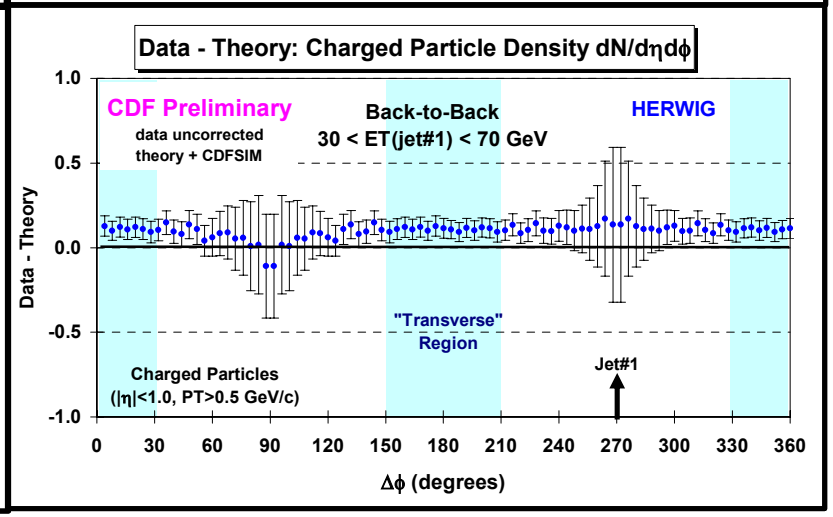
Charged Particle Density
PYTHIA Tune A vs HE

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

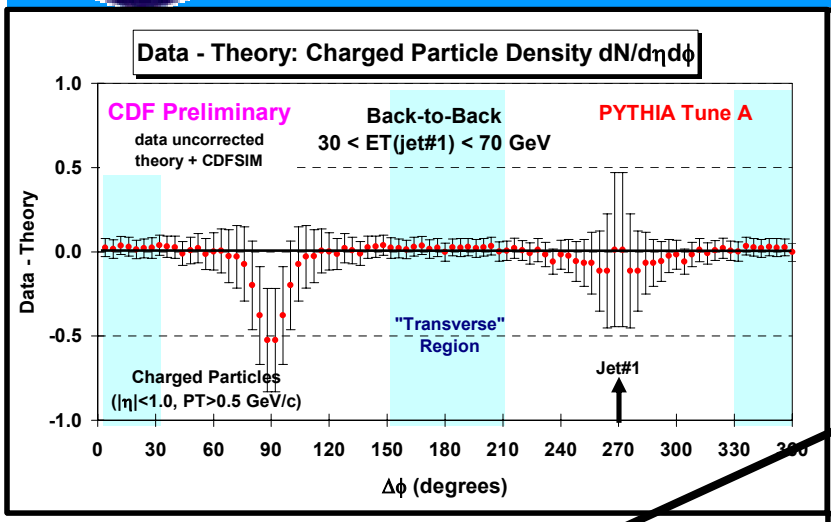


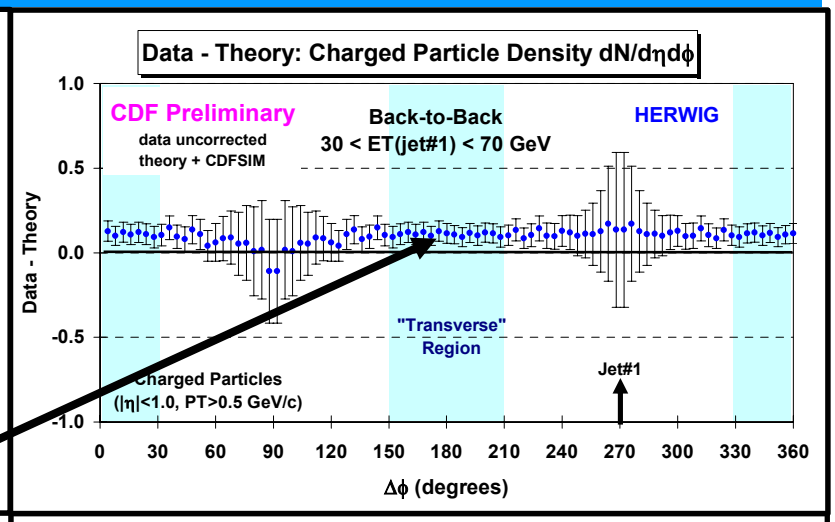




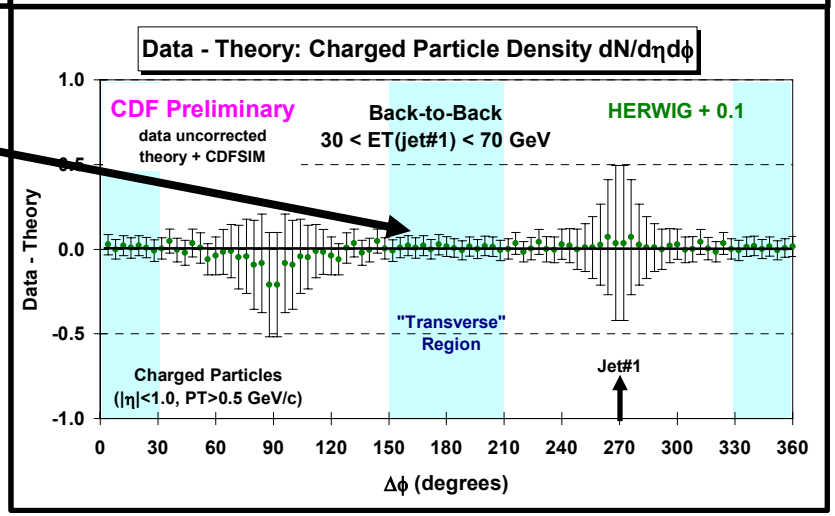


Charged Particle Density
PYTHIA Tune A vs HERWIG



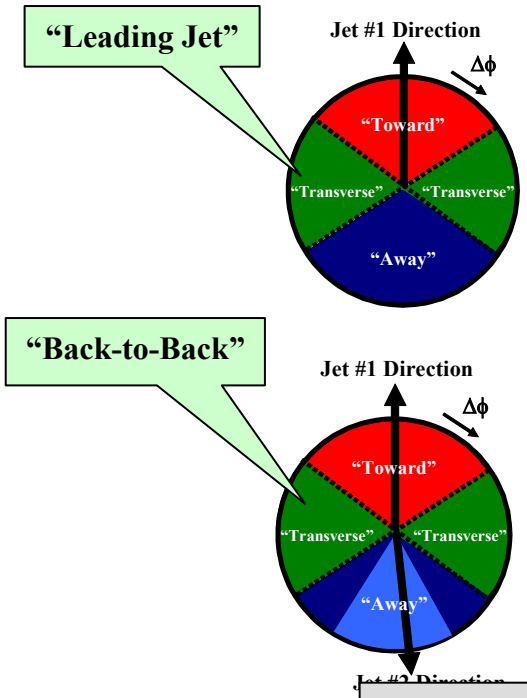


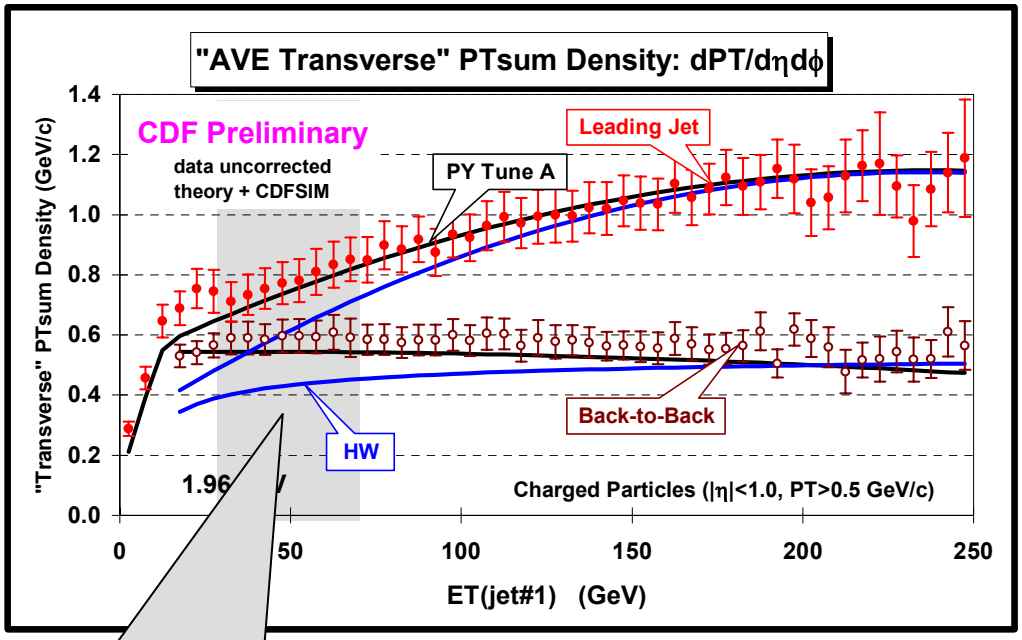
$dN/d\eta d\phi + 0.1$



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

"Transverse" PTsum Density
PYTHIA Tune A vs HERWIG



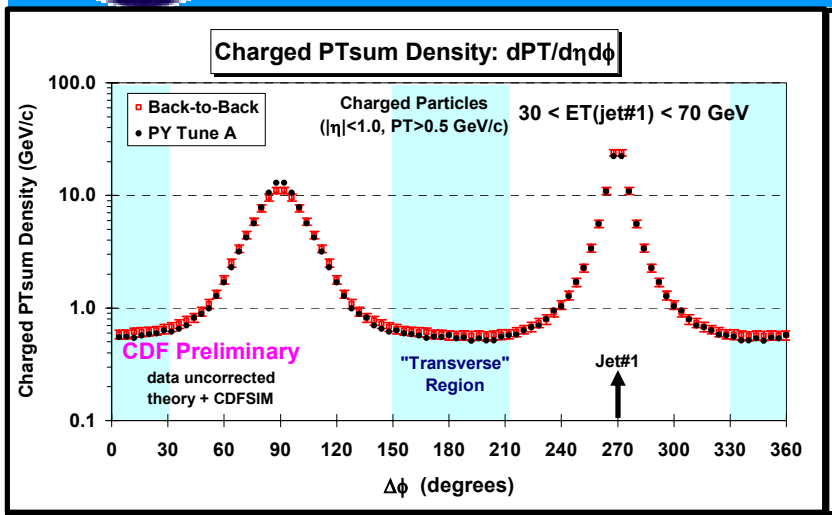


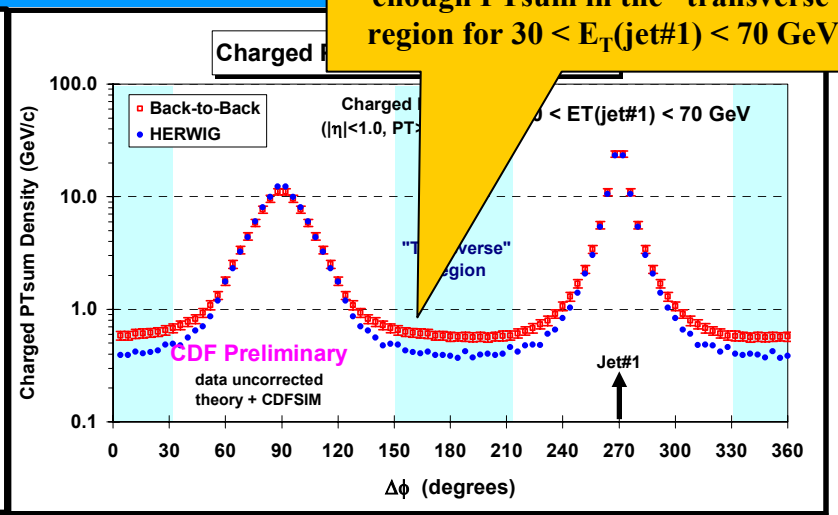
Now look in detail at "back-to-back" events in the region $30 < E_T(\text{jet\#1}) < 70$ GeV!

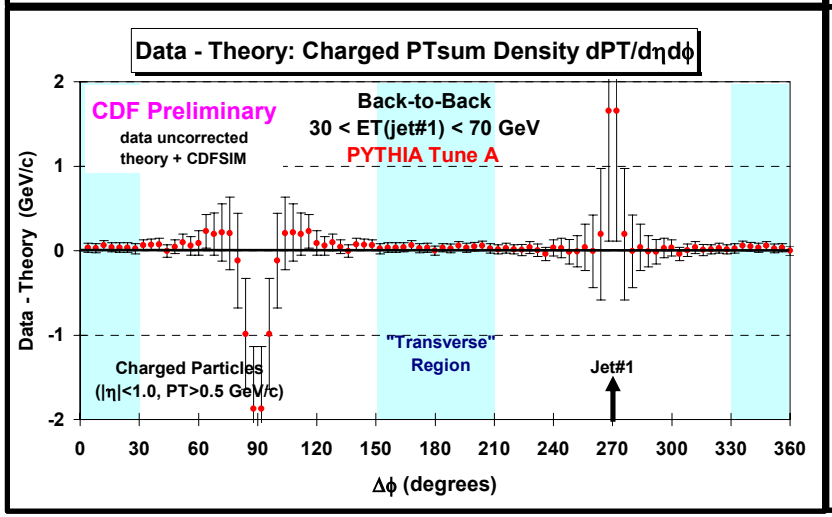
- Shows the average charged PTsum density, $dPT_{sum}/d\eta d\phi$, in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
- Compares the (*uncorrected*) data with PYTHIA Tune A and HERWIG after CDFSIM.

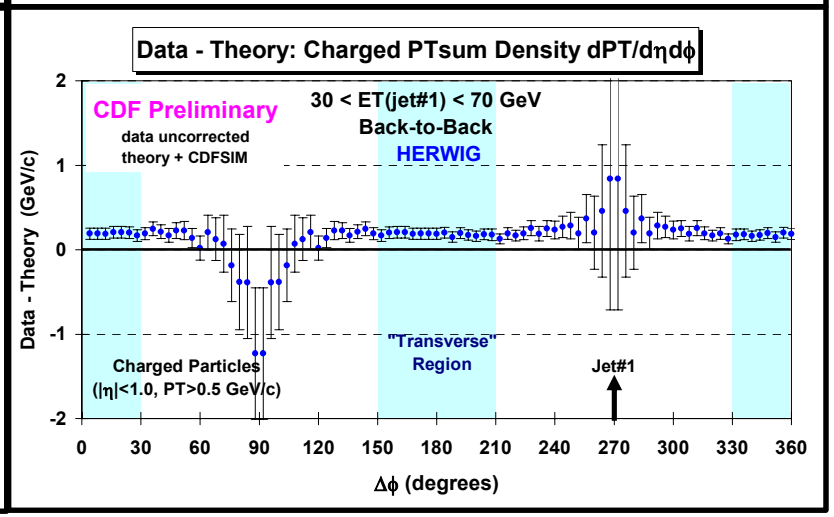
Charged PTsum Density
PYTHIA Tune A vs HE

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

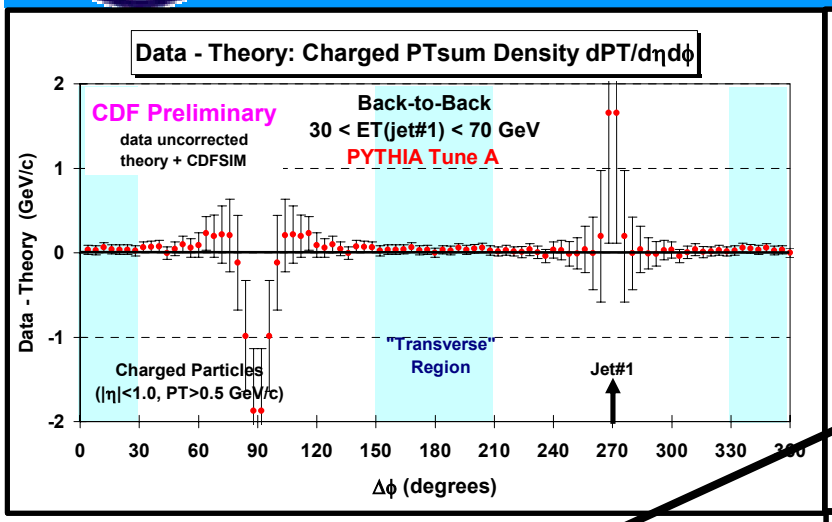


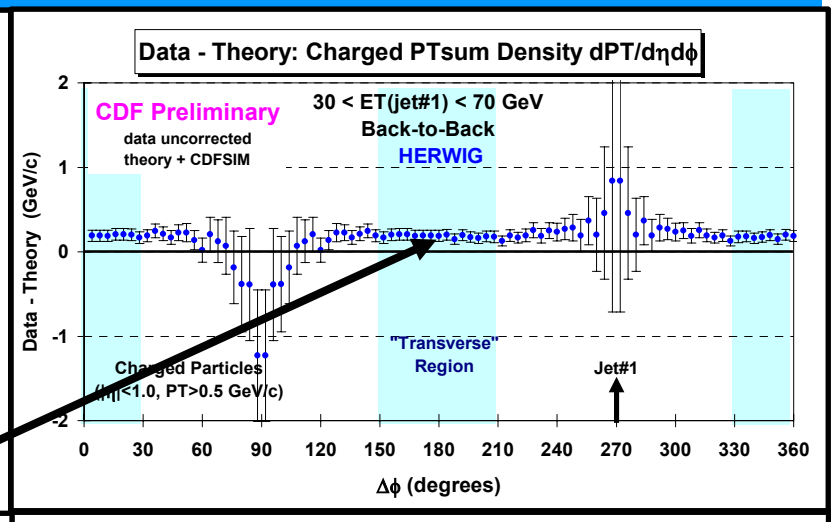






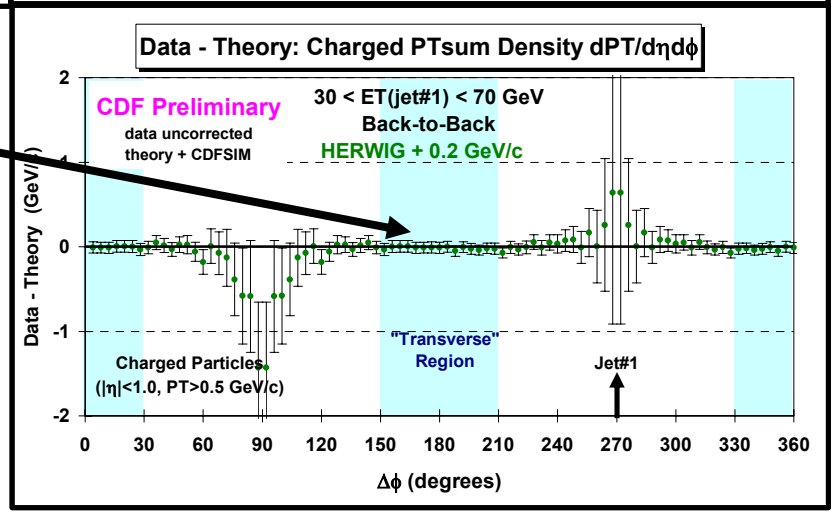
Charged PTsum Density
PYTHIA Tune A vs HERWIG





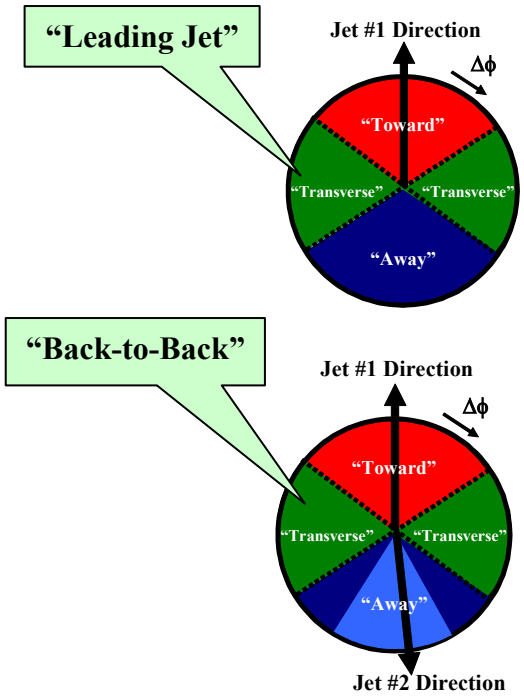
308 MeV in R = 0.7 cone!

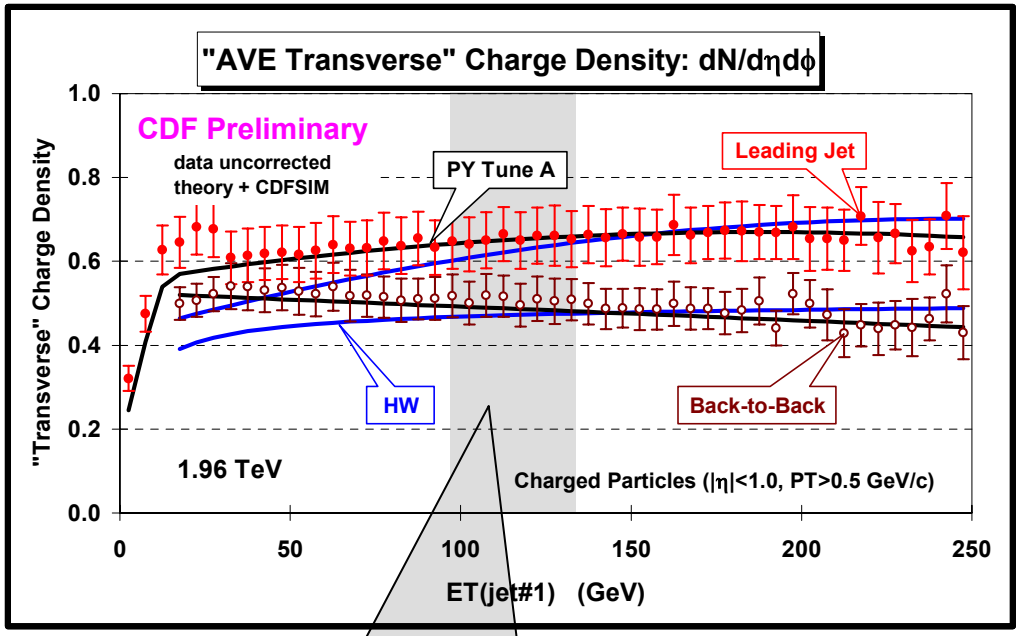
dPT/dηdϕ + 0.2 GeV/c



- 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, $|\eta| < 1$.

"Transverse" Charge Density
PYTHIA Tune A vs HERWIG



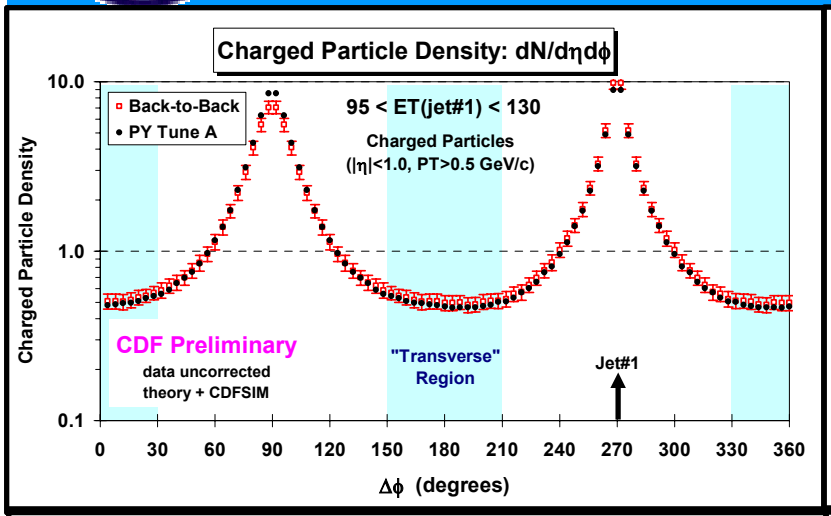


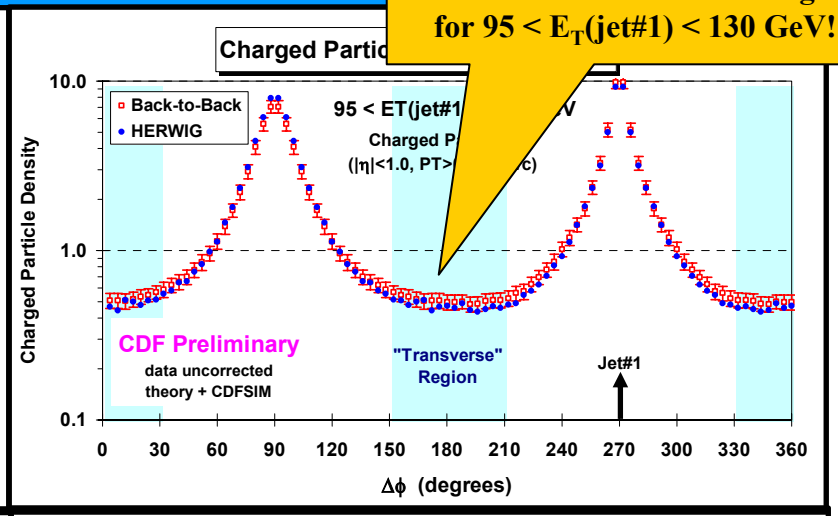
Now look in detail at "back-to-back" events in the region 95 < E_T(jet#1) < 130 GeV!

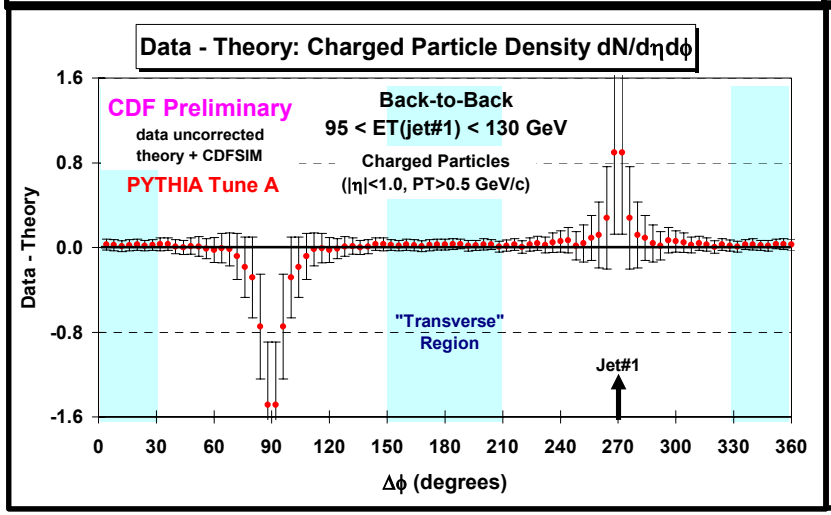
- Shows the average charged particle density, $dN_{chg}/d\eta d\phi$, in the "transverse" region (p_T > 0.5 GeV/c, $|\eta|$ < 1) versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events compared with PYTHIA Tune A and HERWIG after CDFSIM.

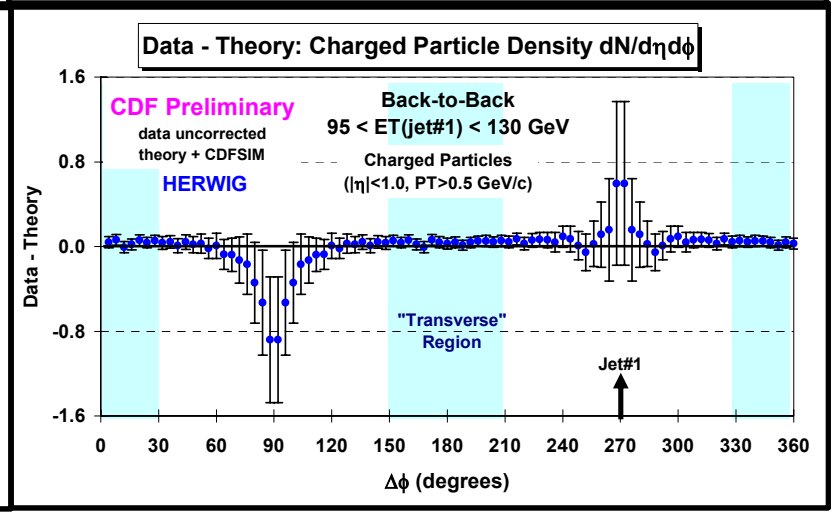
Charged Particle Density
PYTHIA Tune A vs HER

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

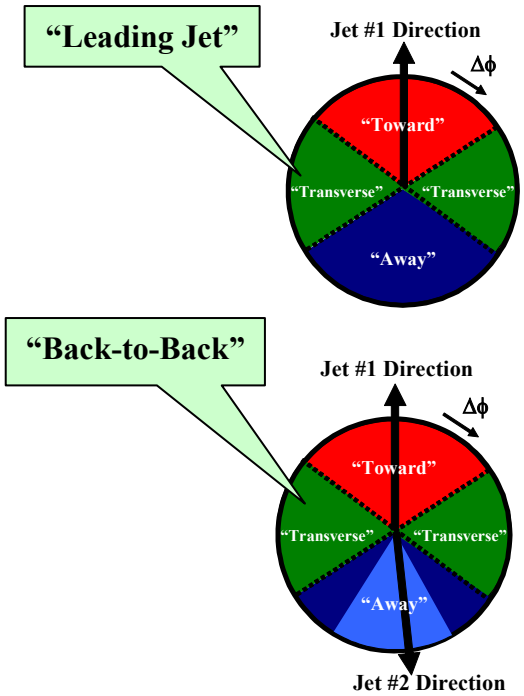


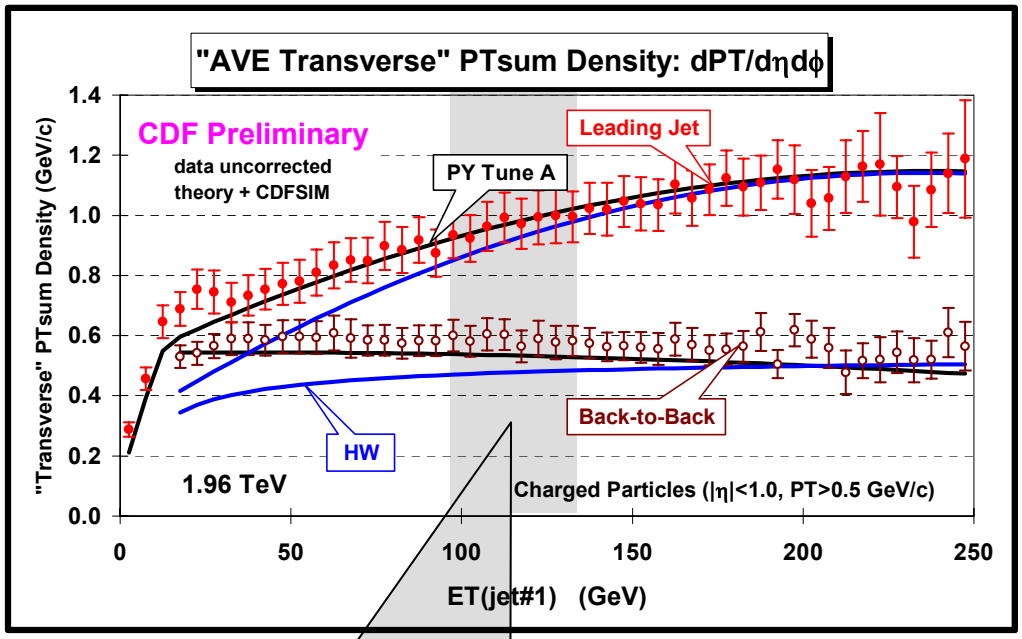






"Transverse" PTsum Density
PYTHIA Tune A vs HERWIG



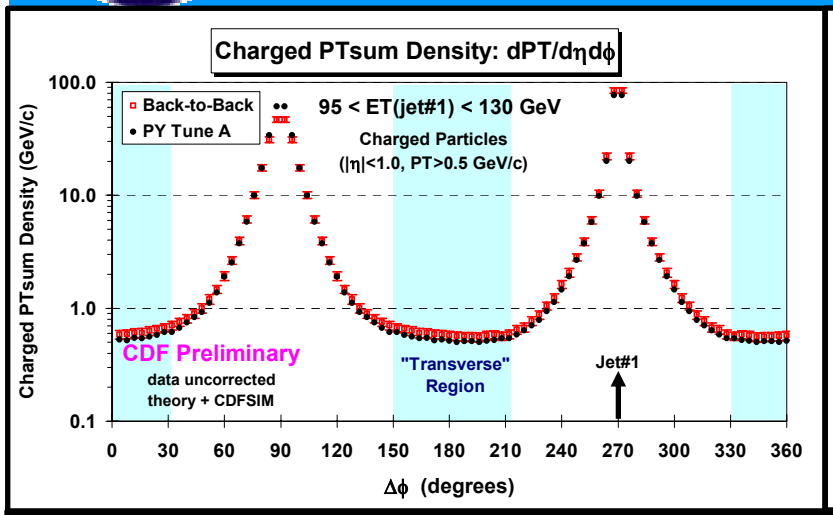


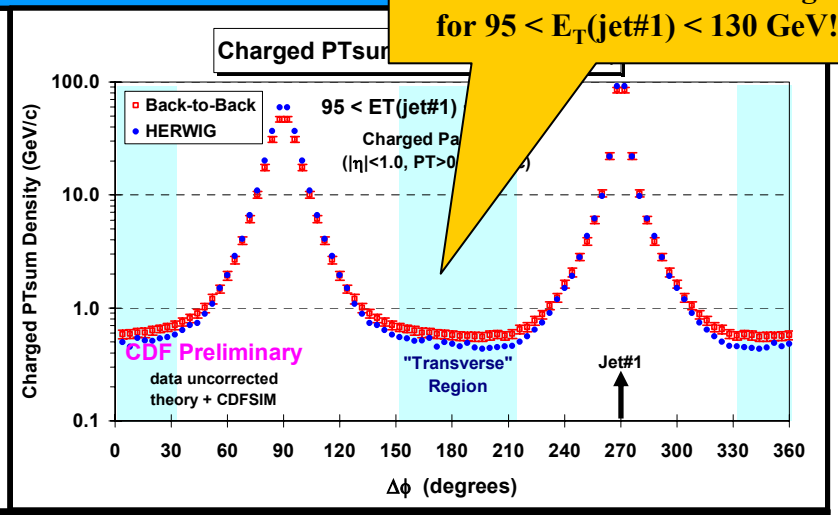
Now look in detail at "back-to-back" events in the region 95 < E_T(jet#1) < 130 GeV!

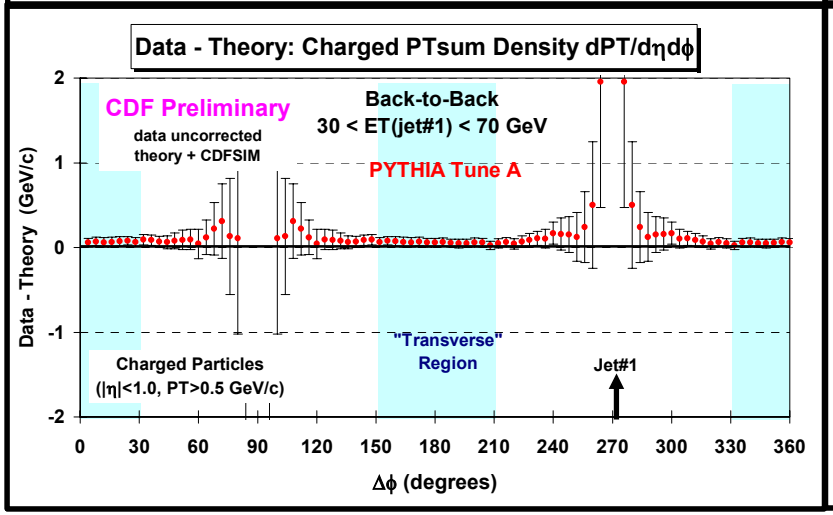
- Shows the average charged PTsum density, $dPT_{sum}/d\eta d\phi$, in the "transverse" region (p_T > 0.5 GeV/c, $|\eta|$ < 1) versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events compared with PYTHIA Tune A and HERWIG after CDFSIM.

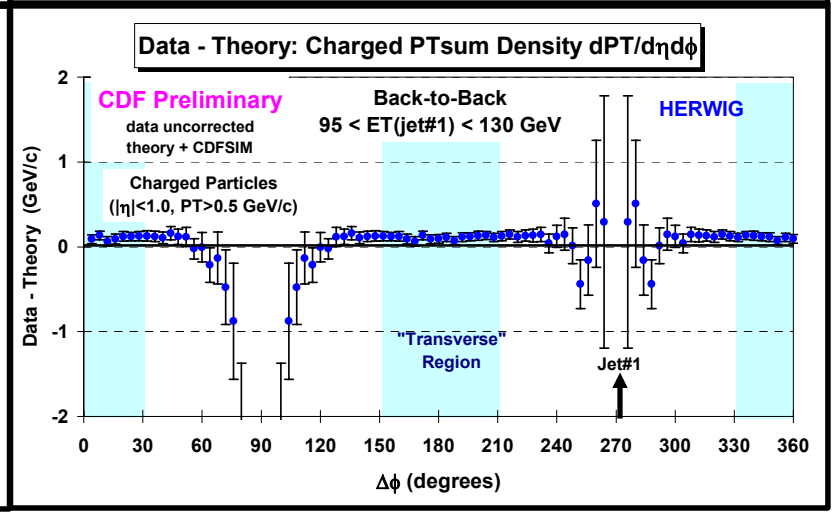
Charged PTsum Density
PYTHIA Tune A vs HER

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

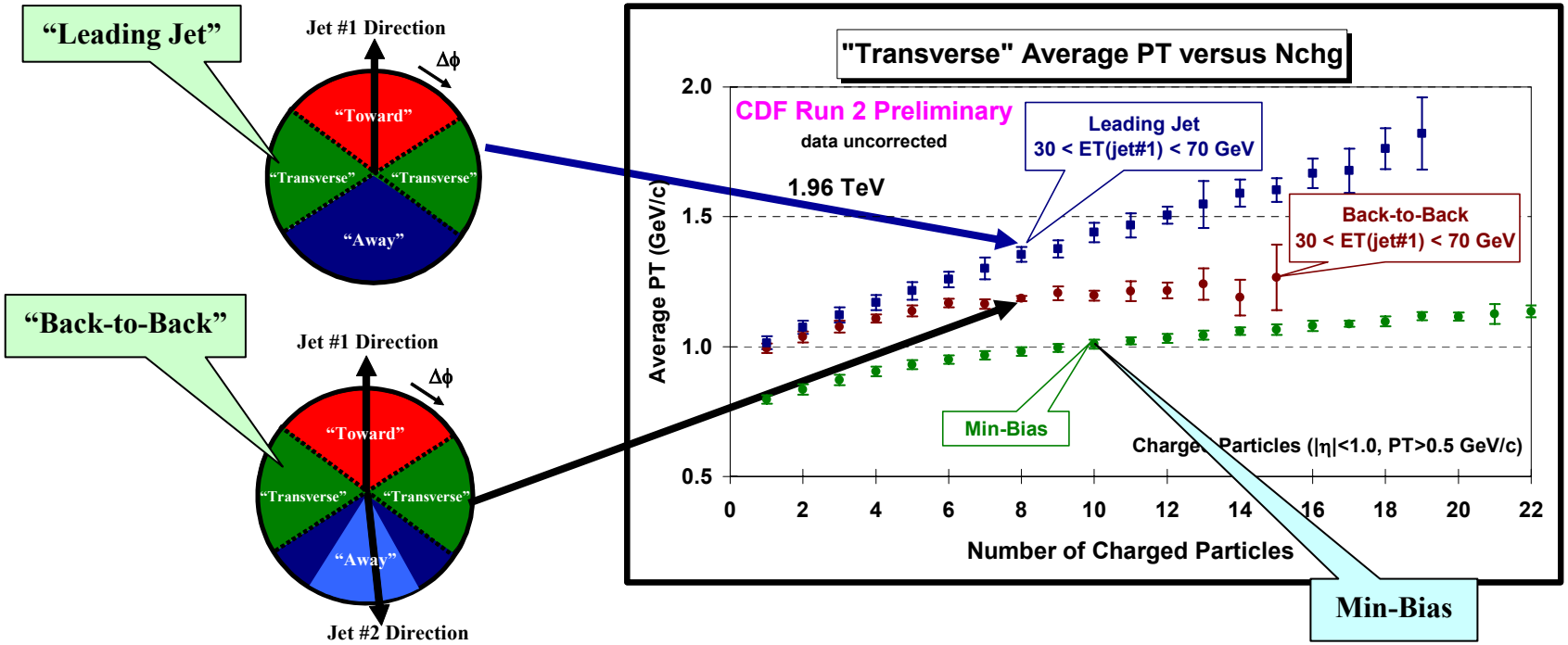






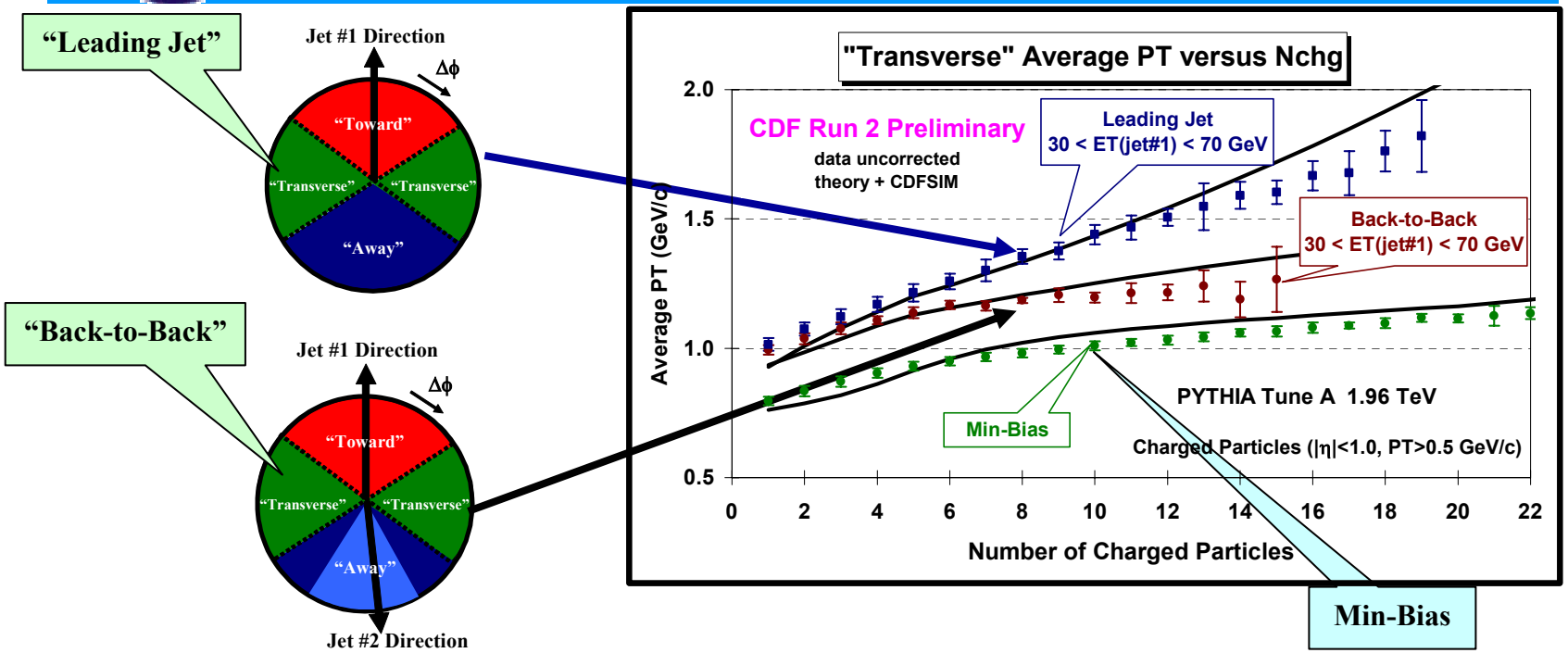


"Transverse" $\langle p_T \rangle$ versus "Transverse" Nchg



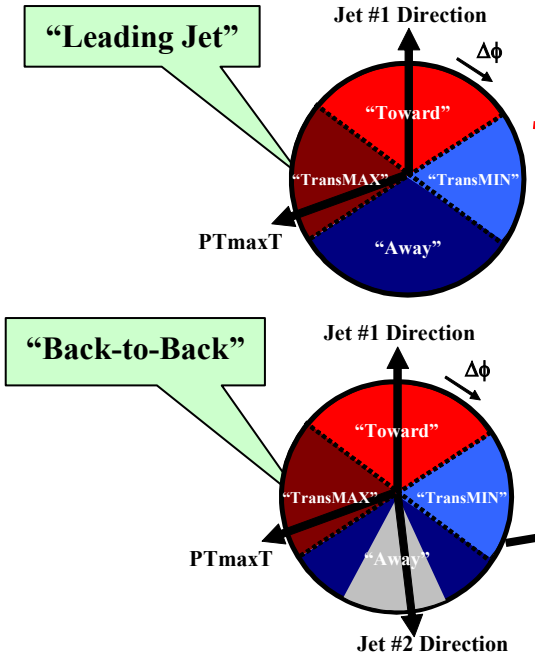
- Look at the $\langle p_T \rangle$ of particles in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus the number of particles in the "transverse" region: $\langle p_T \rangle$ vs Nchg.
- Shows $\langle p_T \rangle$ versus Nchg in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) for "Leading Jet" and "Back-to-Back" events with $30 < E_T(\text{jet}\#1) < 70$ GeV compared with "min-bias" collisions.

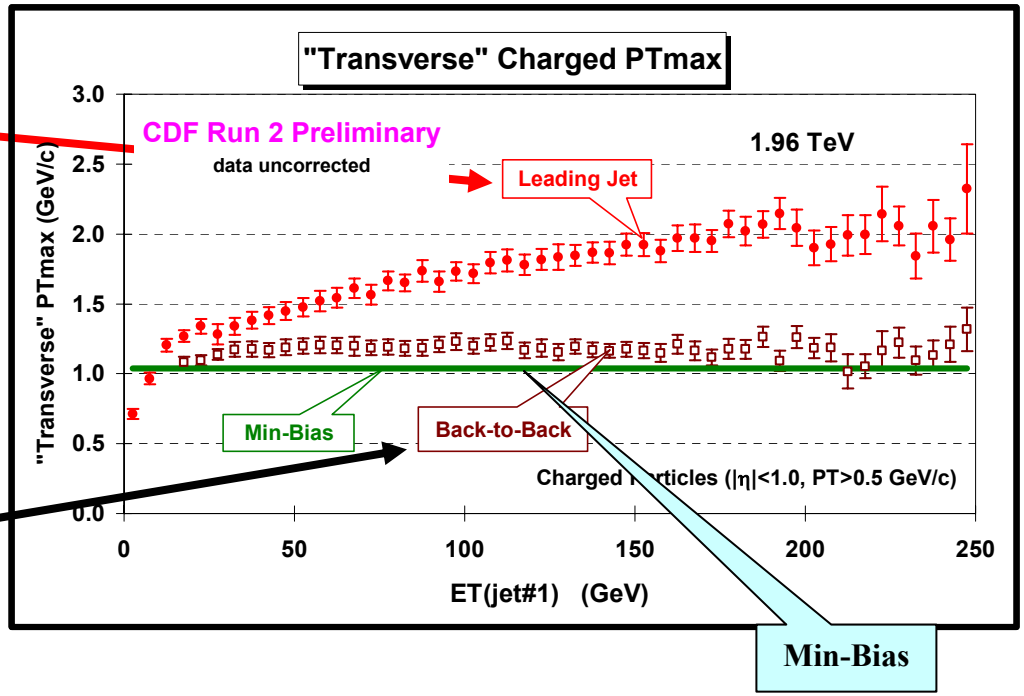
"Transverse" $\langle p_T \rangle$ versus "Transverse" Nchg



- Look at the $\langle p_T \rangle$ of particles in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus the number of particles in the "transverse" region: $\langle p_T \rangle$ vs Nchg.
- Shows $\langle p_T \rangle$ versus Nchg in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) for "Leading Jet" and "Back-to-Back" events with $30 < E_T(\text{jet\#1}) < 70$ GeV compared with "min-bias" collisions.

"Transverse" PTmax versus E_T(jet#1)

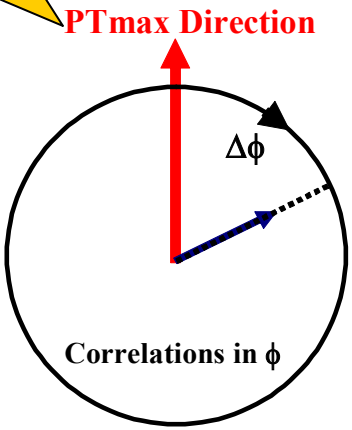




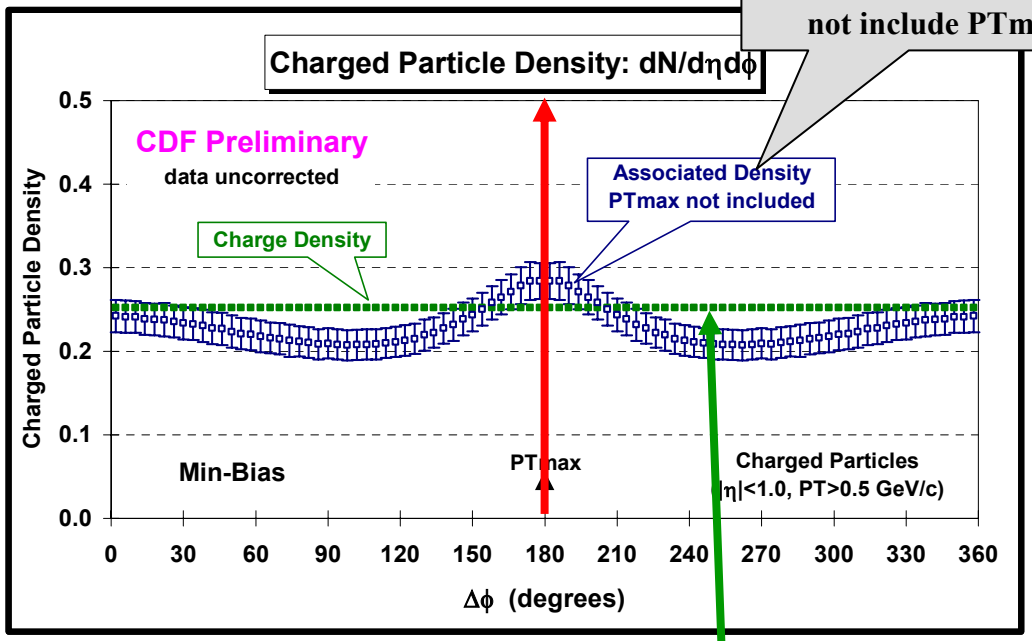
- Use the leading jet to define the "transverse" region and look at the maximum p_T charged particle in the "transverse" region, PTmaxT.
- Shows the average PTmaxT, in the "transverse" region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events compared with the average maximum p_T particle, PTmax, in "min-bias" collisions ($p_T > 0.5$ GeV/c, $|\eta| < 1$).

Min-Bias "Associated" Charged Particle Density

Highest p_T charged particle!

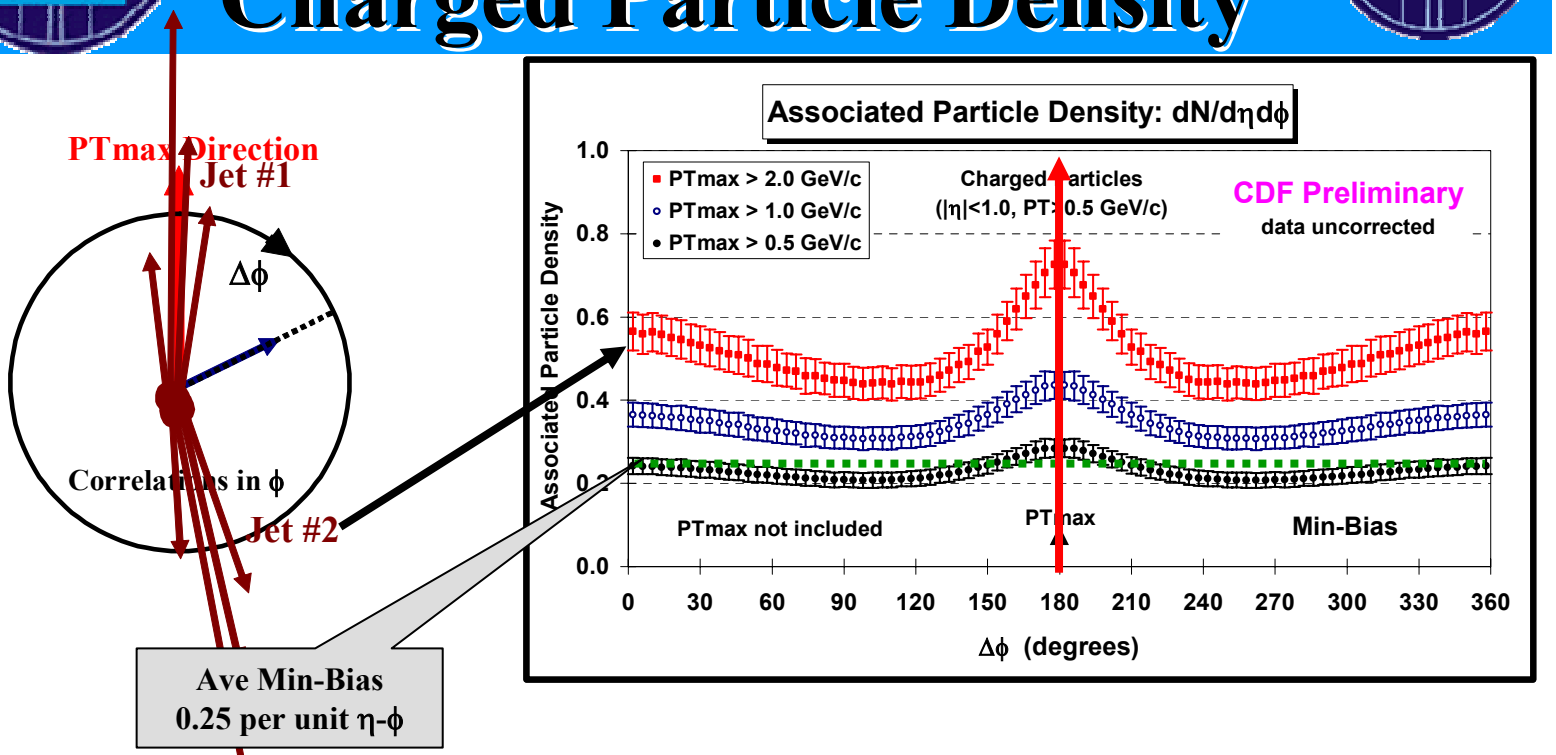


"Associated" densities do not include PTmax!



- 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 **Δϕ 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.**

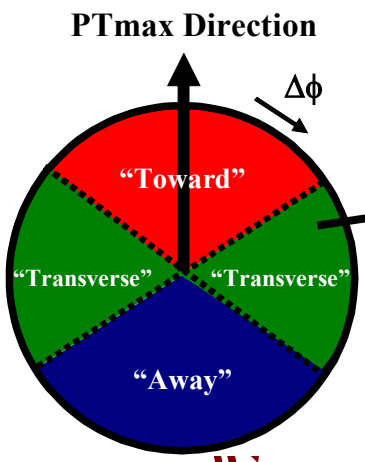
Min-Bias "Associated" Charged Particle Density

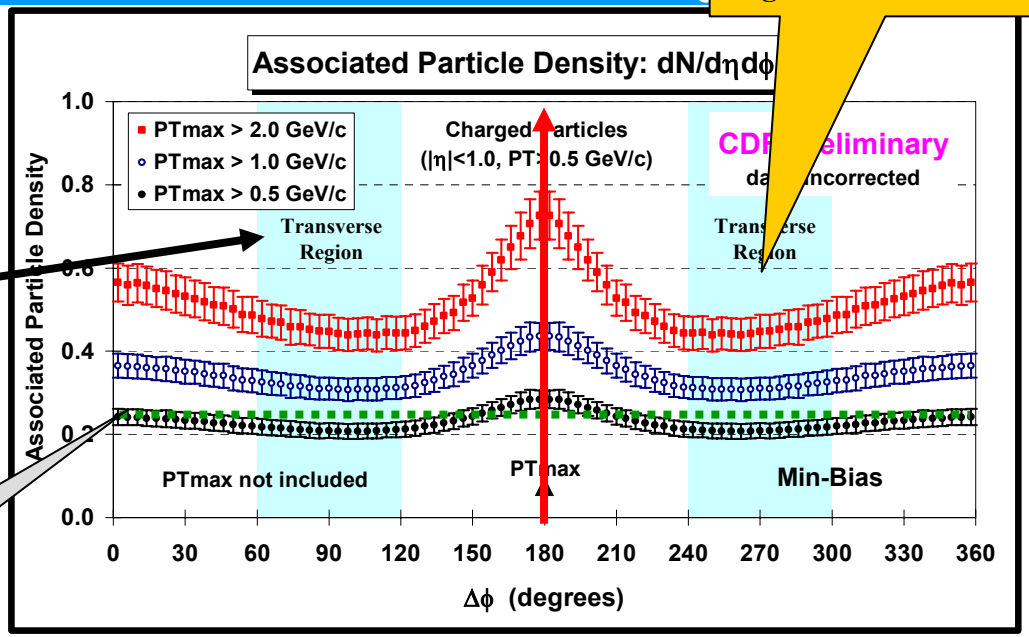


- Shows the data on the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 0.5, 1.0, and 2.0 GeV/c.
- Shows "jet structure" in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



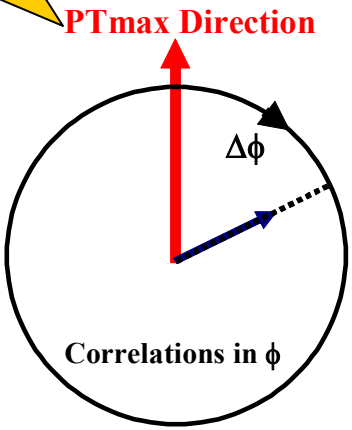


Ave Min-Bias
0.25 per unit η-ϕ

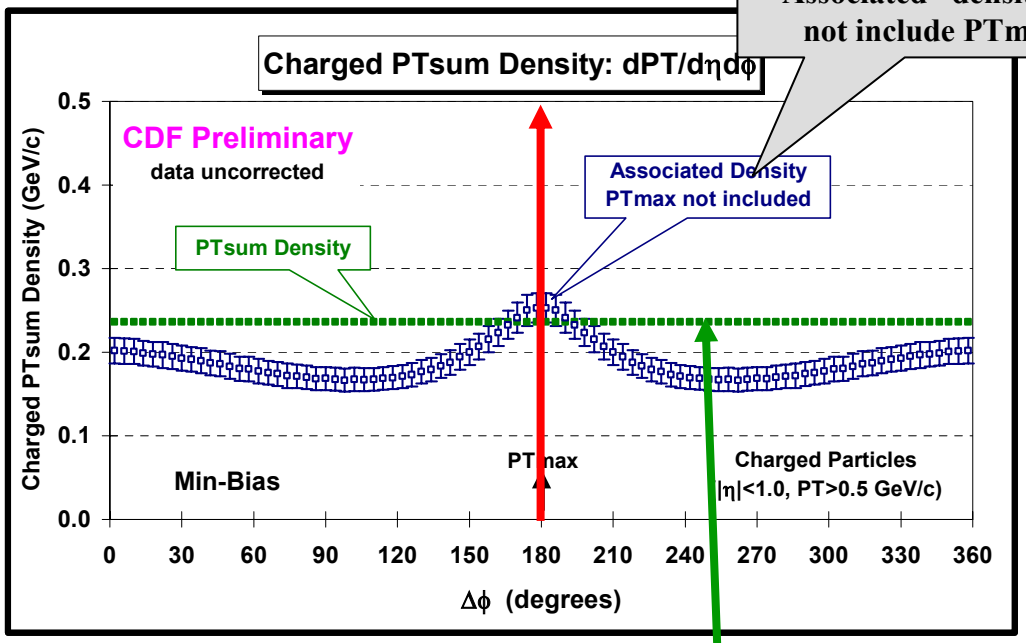
- Shows the data on the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, *not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 0.5, 1.0, and 2.0 GeV/c.
- Shows "jet structure"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

Min-Bias "Associated" Charged PTsum Density

Highest p_T charged particle!

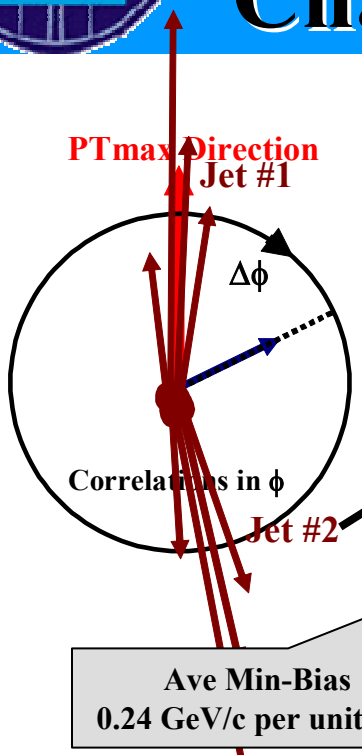


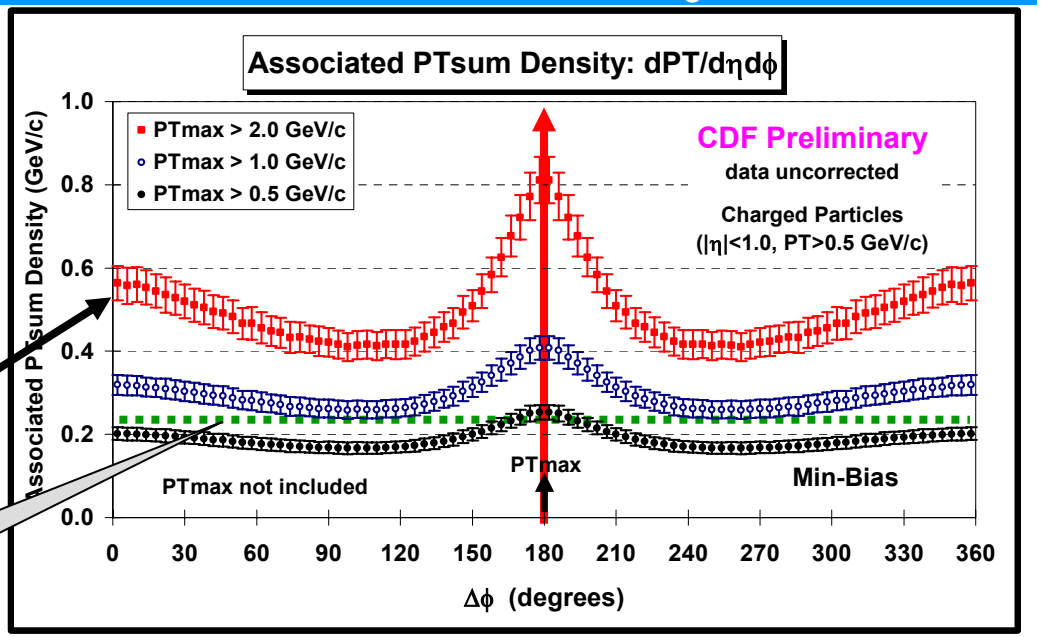
"Associated" densities do not include PTmax!



- 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, $|\eta| < 1$, *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**.

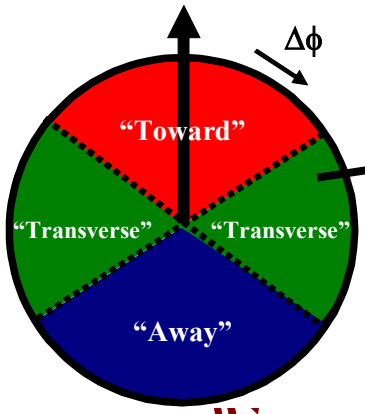
Min-Bias "Associated" Charged PTsum Density

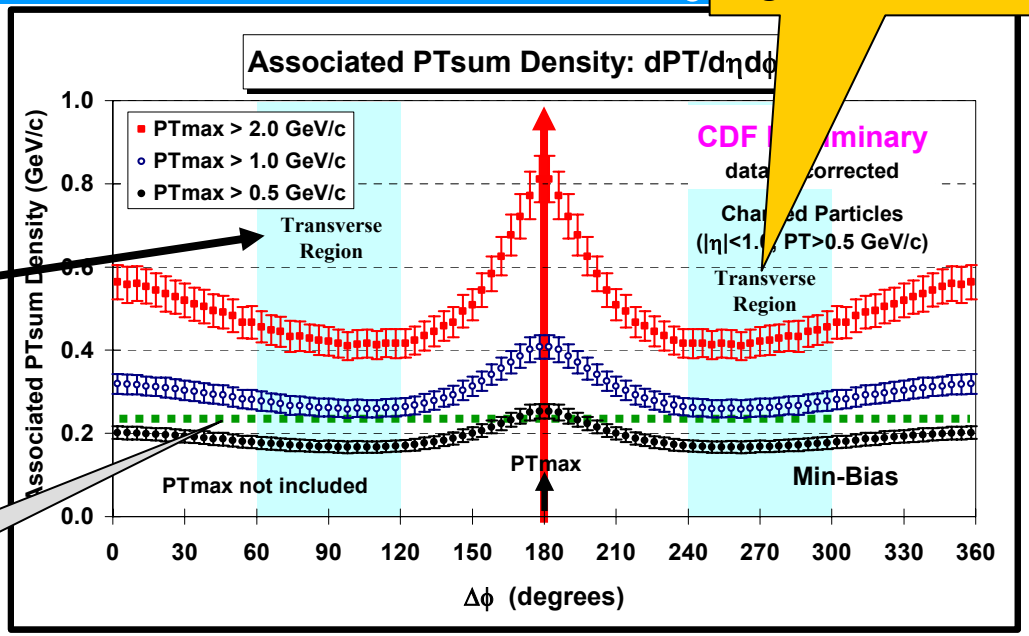




- Shows the data on the Δϕ dependence of the "associated" charged PTsum density, $dPT_{sum}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, *not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 0.5, 1.0, and 2.0 GeV/c.
- Shows "jet structure"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

Min-Bias "Associated" Charged PTsum Density



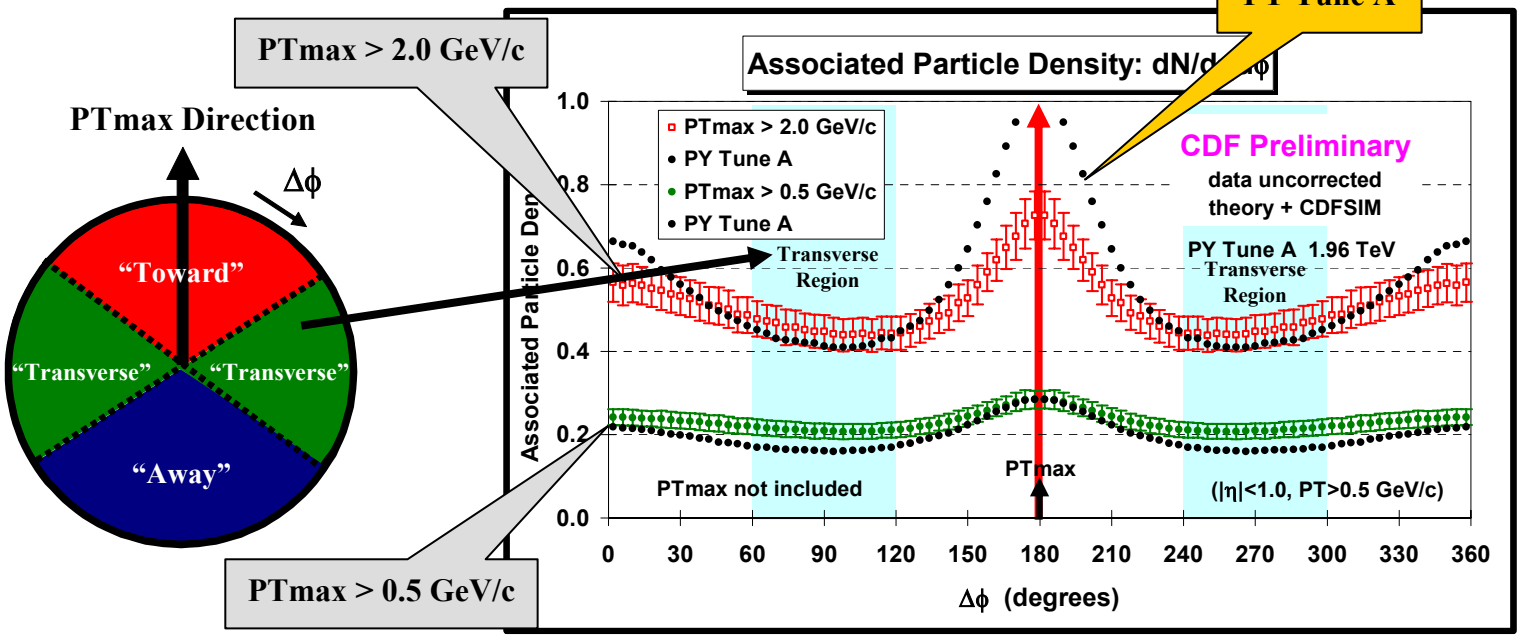


Rapid rise in the PTsum density in the "transverse" region as PTmax increases!

Ave Min-Bias
0.24 GeV/c per unit η-ϕ

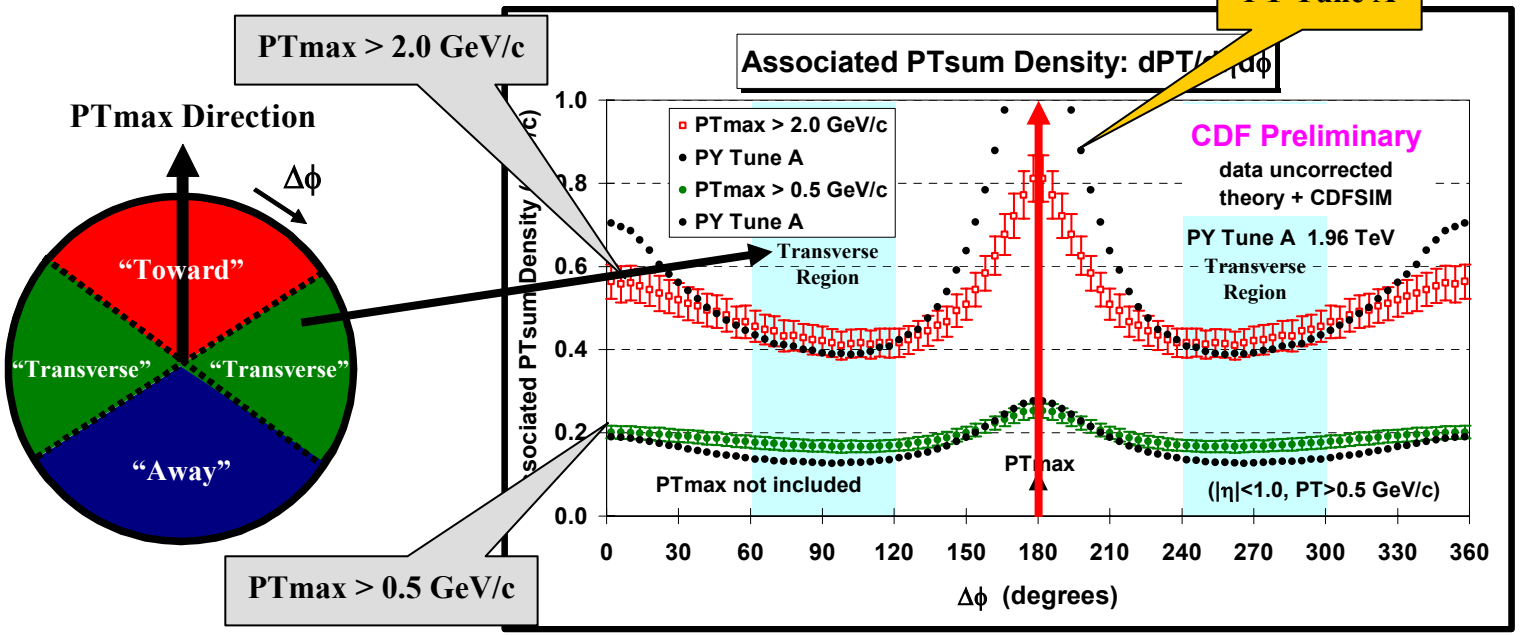
- Shows the data on the Δϕ dependence of the "associated" charged PTsum density, $dPT_{sum}/d\eta d\phi$, for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, *not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 0.5, 1.0, and 2.0 GeV/c.
- Shows "jet structure"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

Min-Bias "Associated" Charged Particle Density



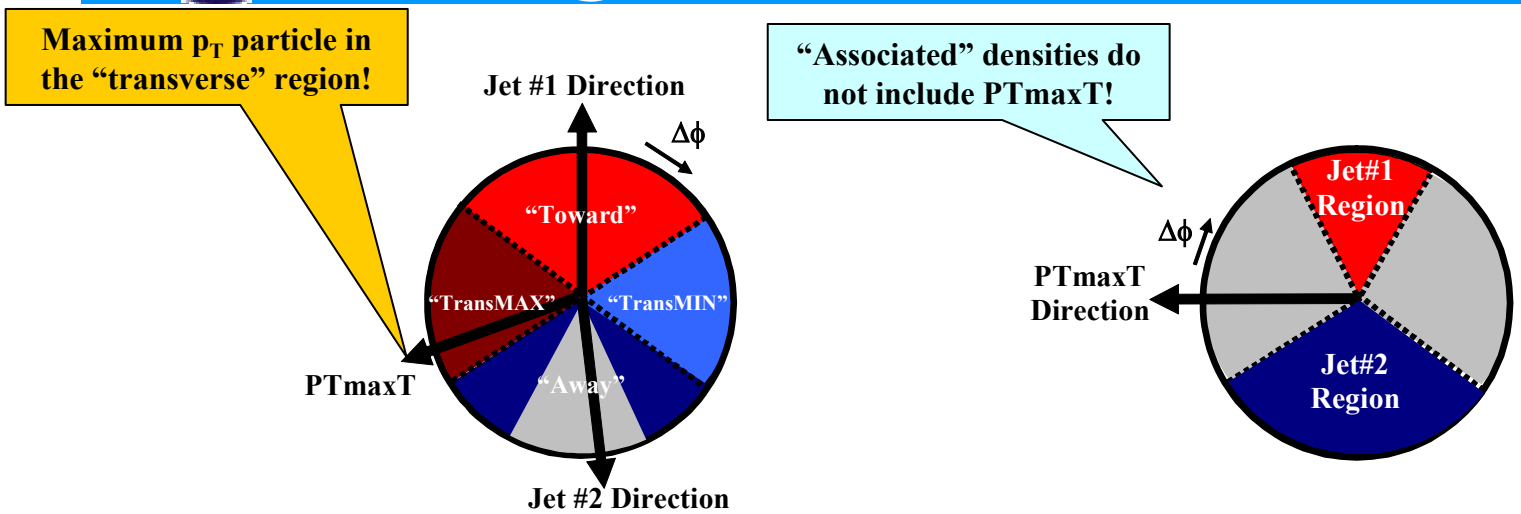
- **Shows the data on the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 0.5 GeV/c and PTmax > 2.0 GeV/c compared with PYTHIA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

Min-Bias "Associated" Charged PTsum Density



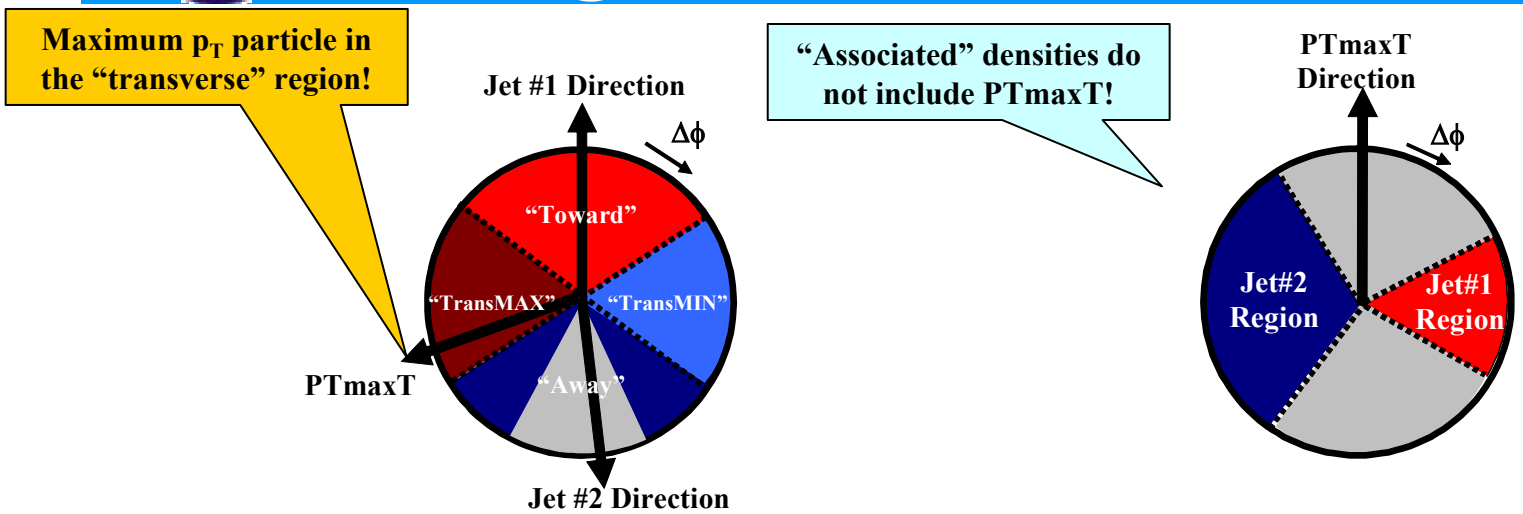
- Shows the data on the Δϕ dependence of the "associated" charged PTsum density, $dPT_{sum}/d\eta d\phi$, for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 0.5 GeV/c and PTmax > 2.0 GeV/c compared with PYTHIA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



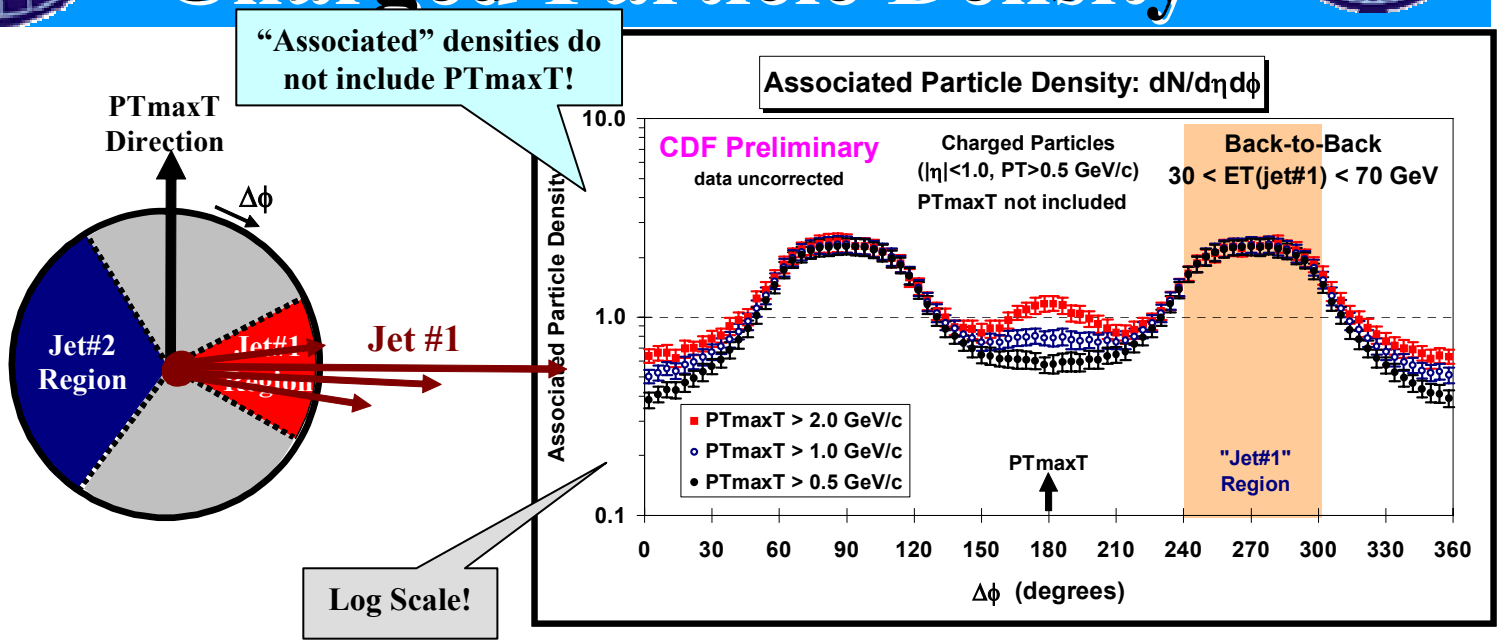
- Use the leading jet in "back-to-back" events to define the "transverse" region and look at the maximum p_T charged particle in the "transverse" region, PTmaxT.
- Look at the Δϕ dependence of the "associated" charged particle and PTsum densities, $dN_{chg}/d\eta d\phi$ and $dPT_{sum}/d\eta d\phi$ for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

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°).

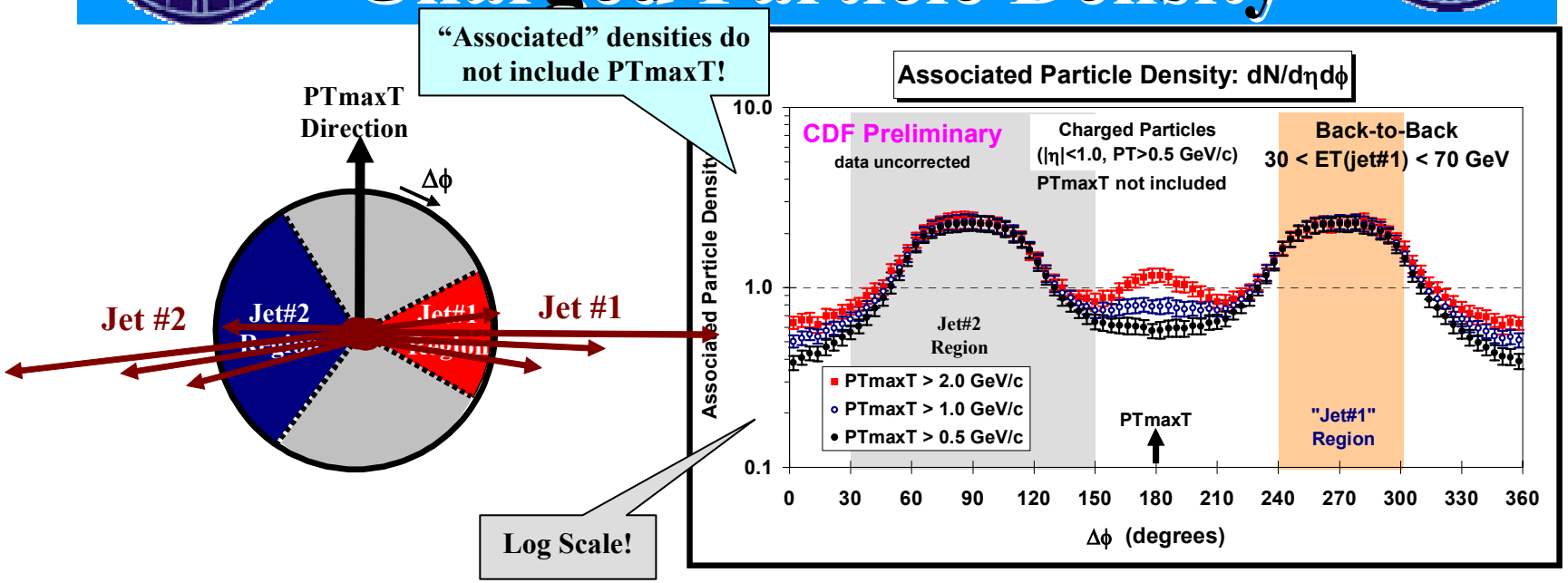
Back-to-Back "Associated" Charged Particle Density



- 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 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).

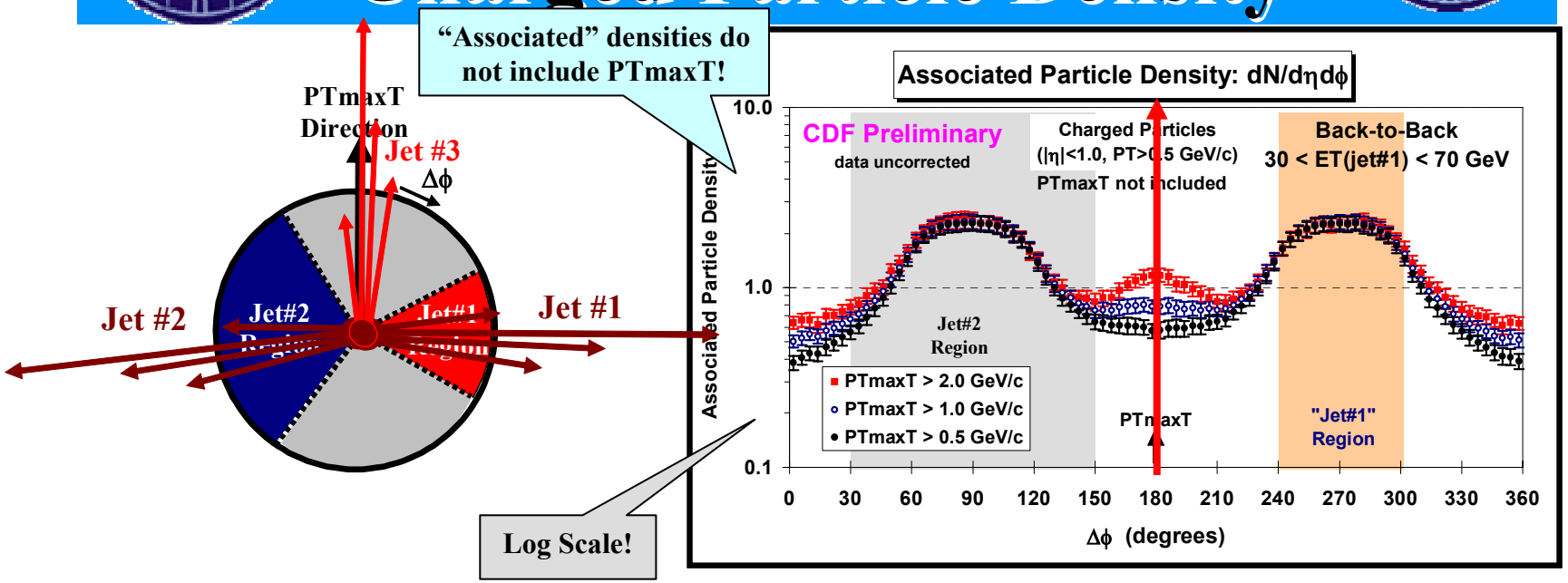
Back-to-Back "Associated" Charged Particle Density



- 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, $|\eta| < 1$, *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 $30 < E_T(\text{jet\#1}) < 70$ GeV .

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

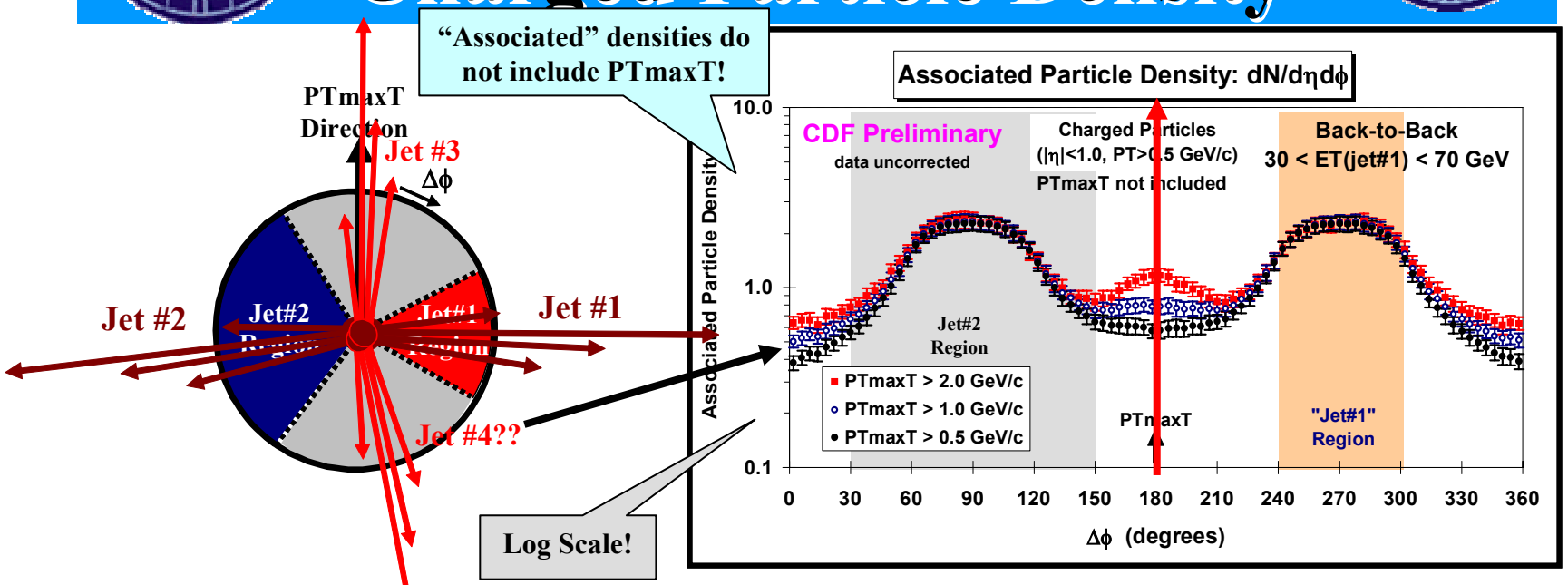
Back-to-Back "Associated" Charged Particle Density



- 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).

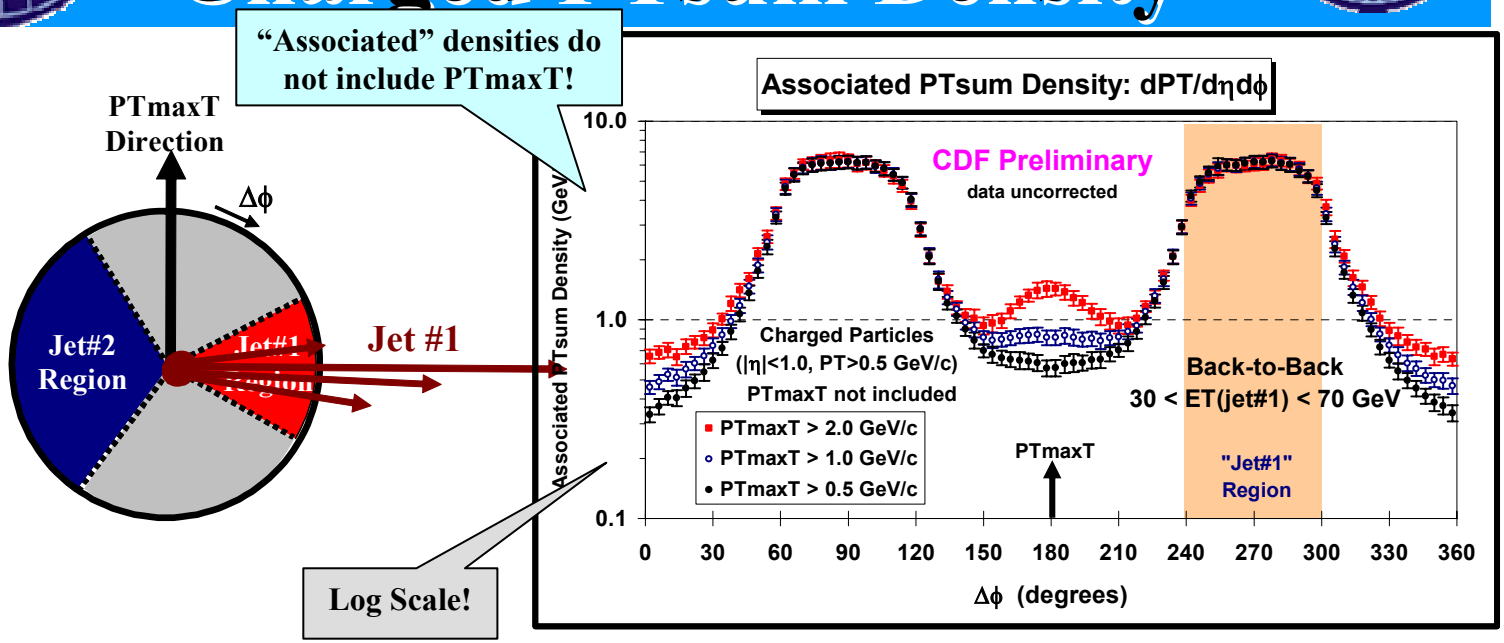
Back-to-Back "Associated" Charged Particle Density



- 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).

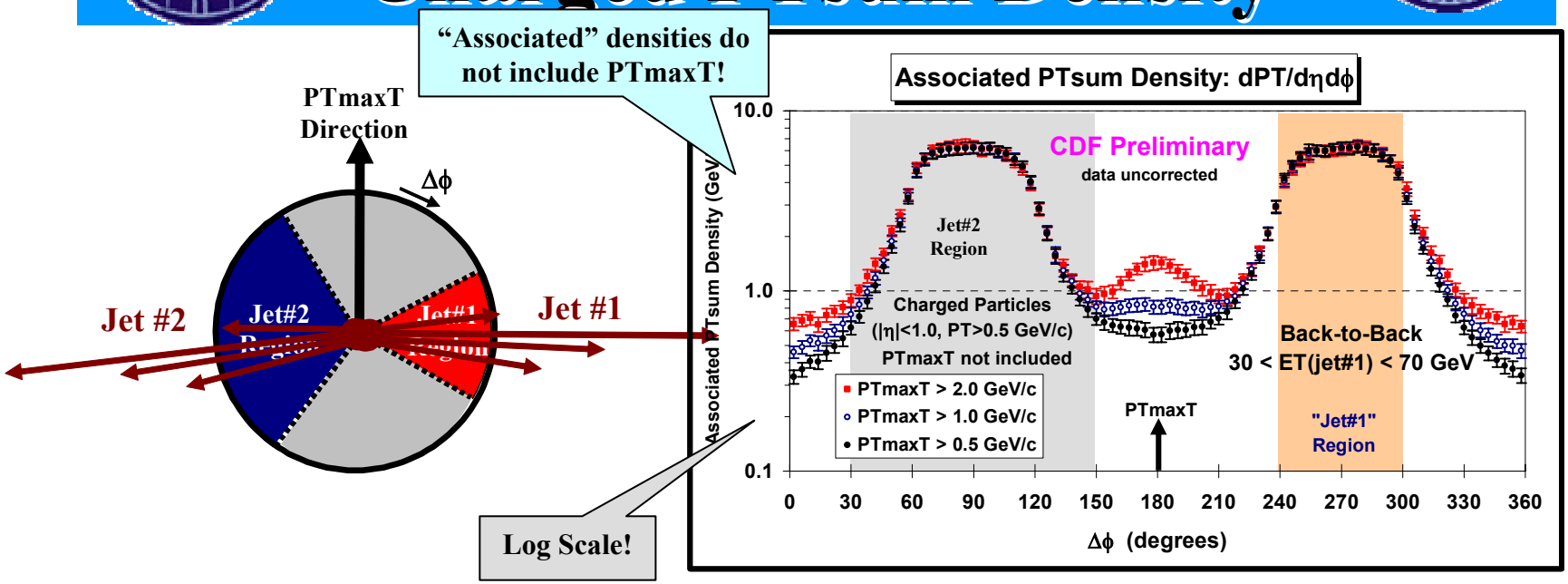
Back-to-Back "Associated" Charged PTsum Density



- 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).

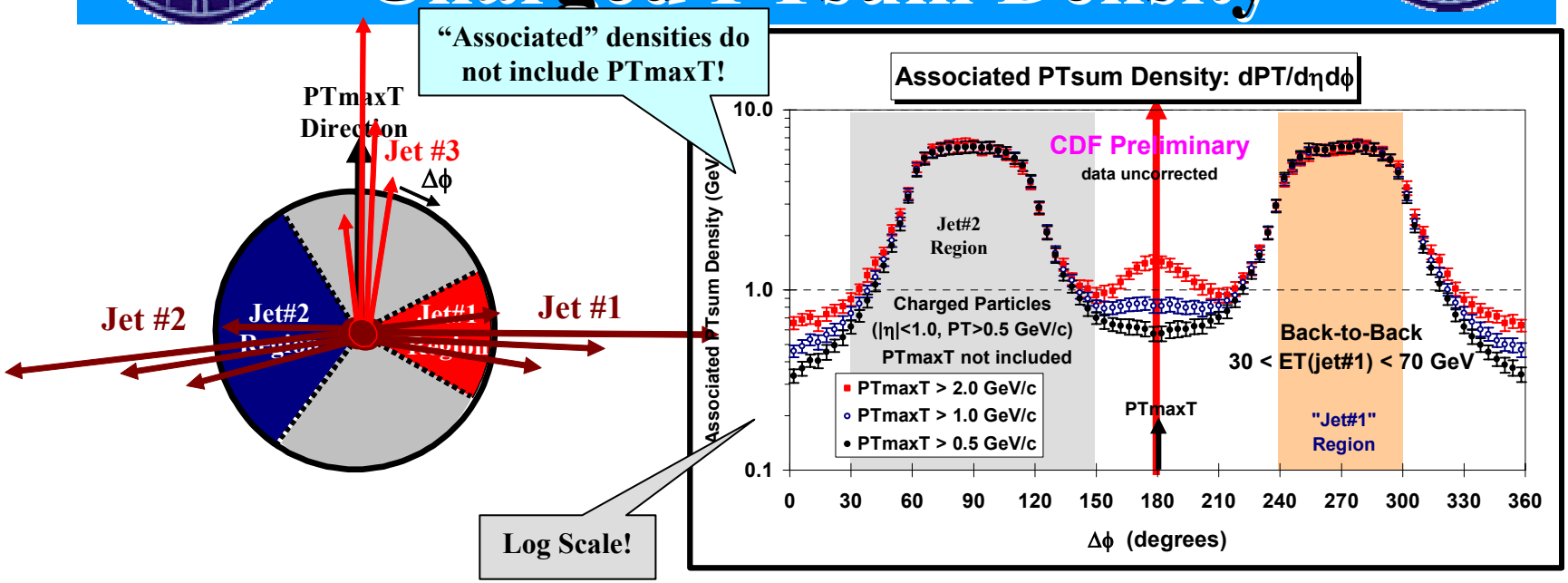
Back-to-Back "Associated" Charged PTsum Density



- 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, $|\eta| < 1$, *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 $30 < E_T(\text{jet\#1}) < 70$ GeV .

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

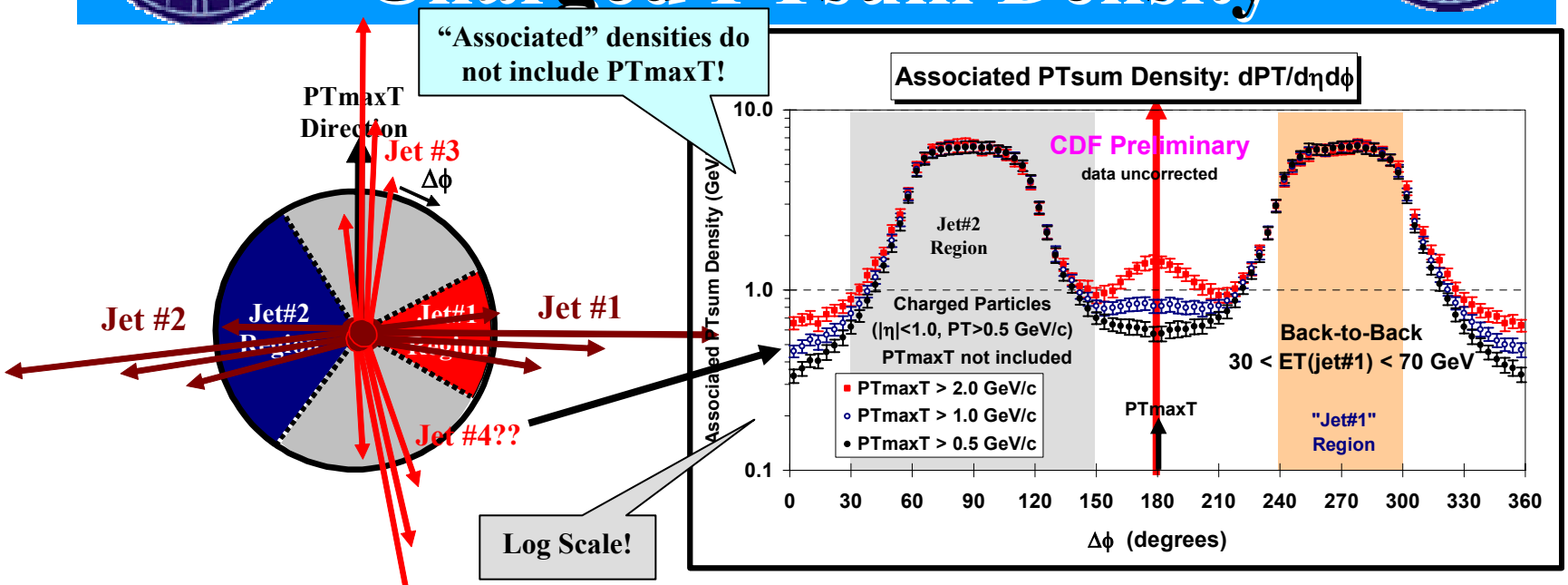
Back-to-Back "Associated" Charged PTsum Density



- 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).

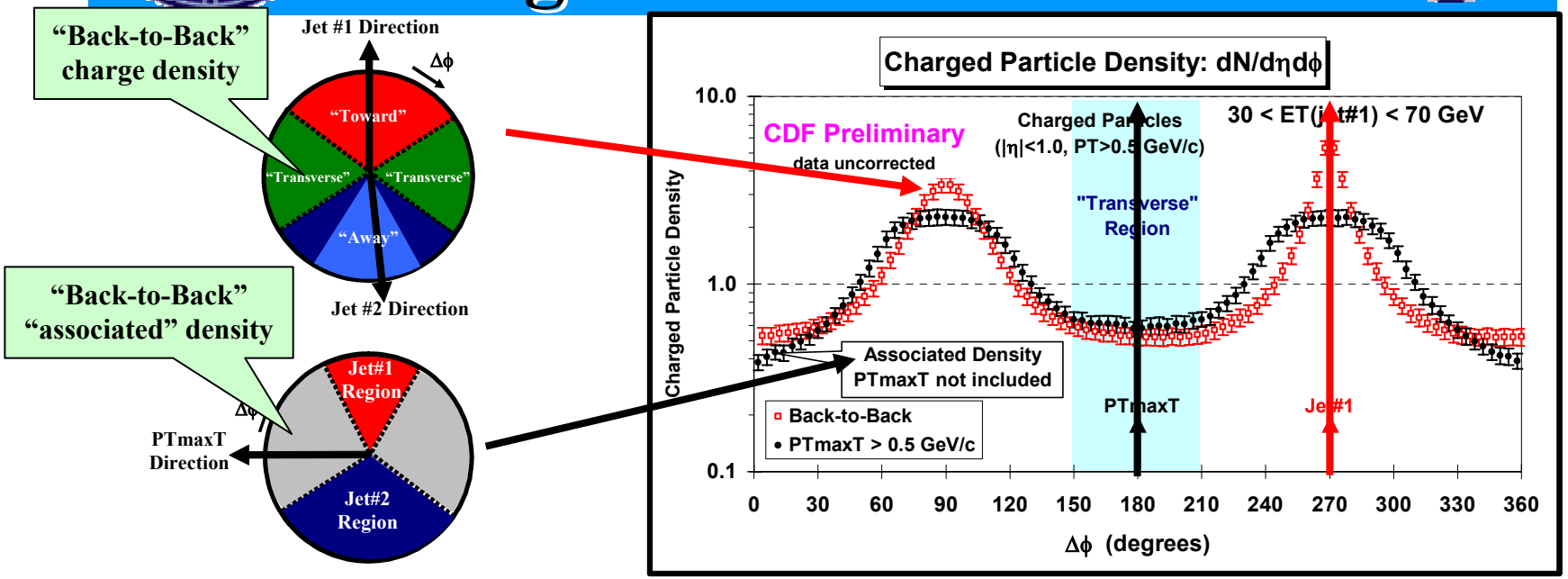
Back-to-Back "Associated" Charged PTsum Density



- 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 .

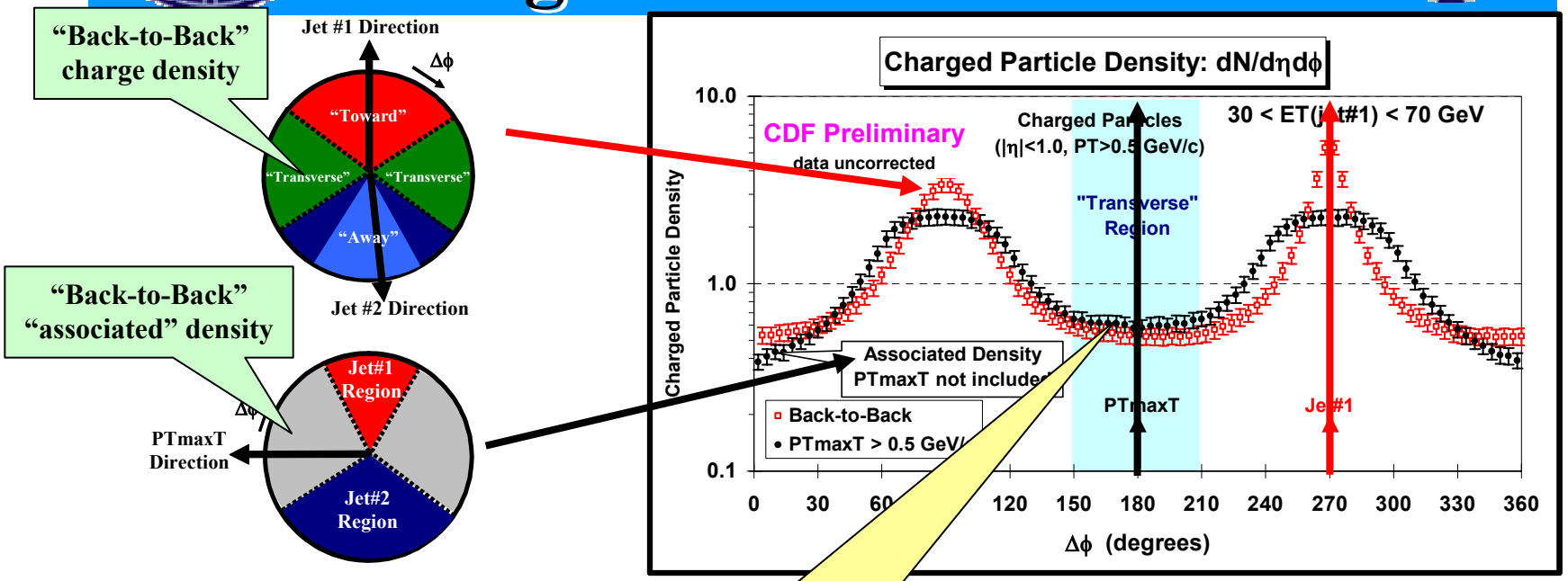
- Shows "jet structure" in the "transverse" region (*i.e.* the "birth" of the 3rd & 4th jet).

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, $|\eta| < 1$, *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 $30 < E_T(\text{jet\#1}) < 70$ GeV.
- Shows Δφ dependence of the charged particle density, $dN_{chg}/d\eta d\phi$ for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$) relative to jet#1 (rotated to 270°) for "back-to-back events" with $30 < ET(\text{jet\#1}) < 70$ GeV.

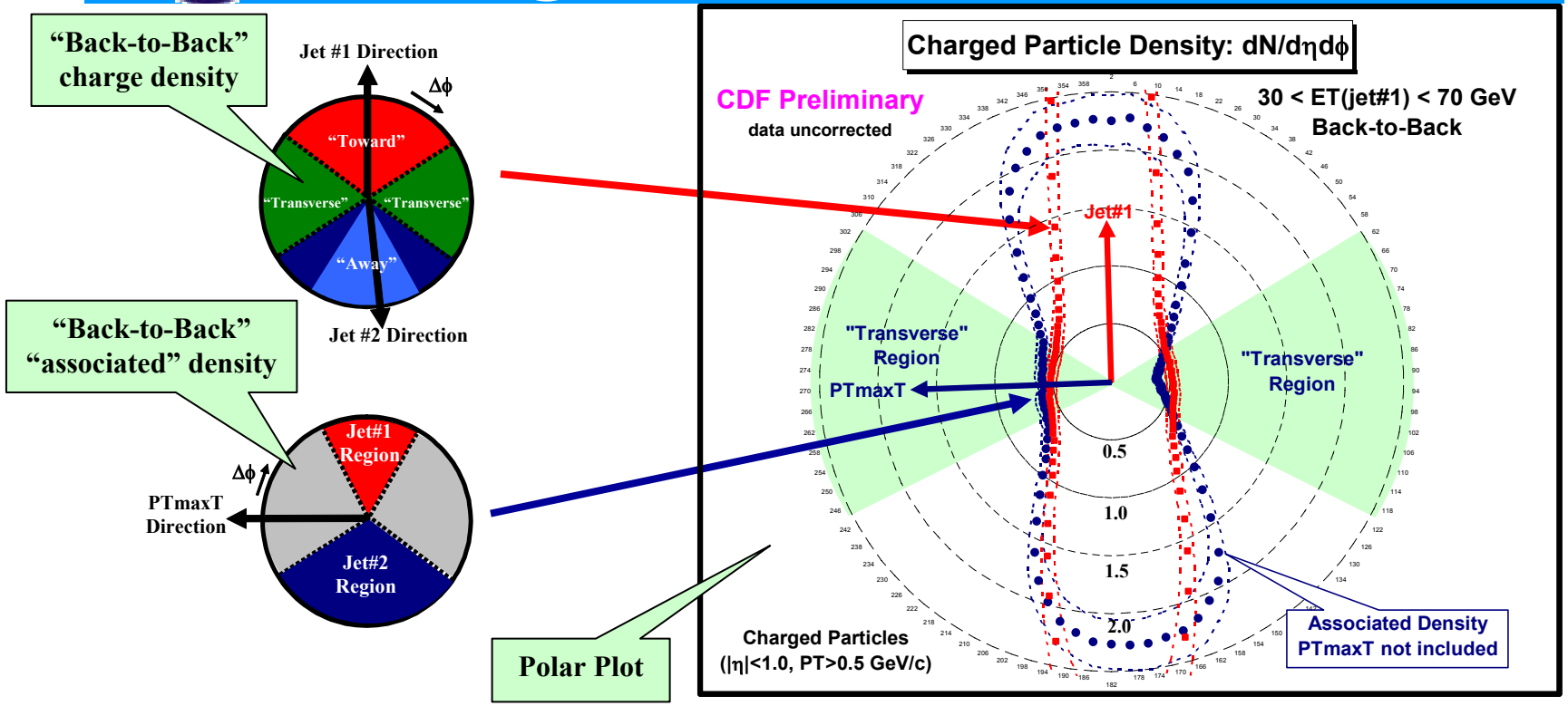
Back-to-Back "Associated" Charged Particle Densities



- 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 180° [illegible]T > 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 270°) for "back-to-back events" with 30 < ET(jet#1) < 70 GeV.

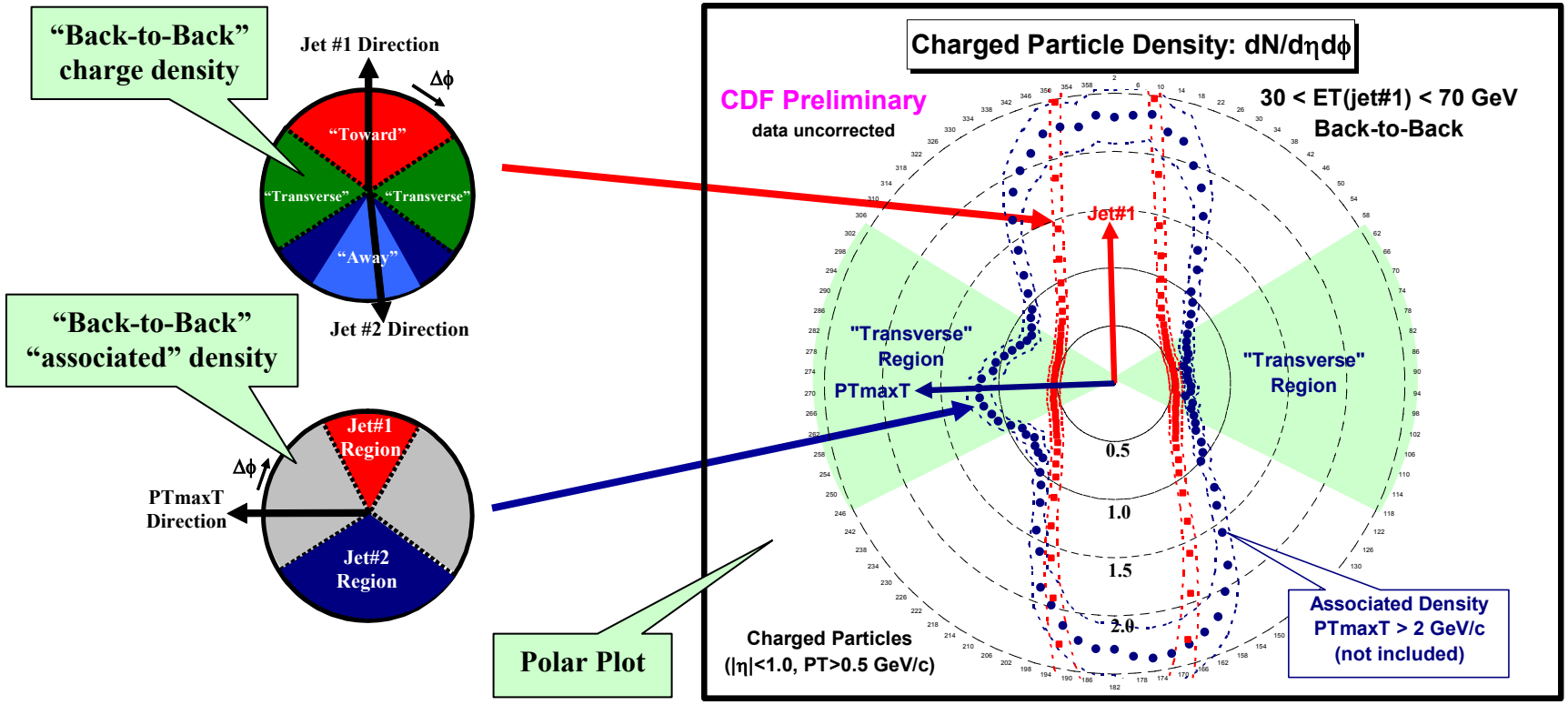
It is more probable to find a particle accompying PTmaxT than it is to find a particle in the "transverse" region!

Back-to-Back "Associated" Charged Particle Densities



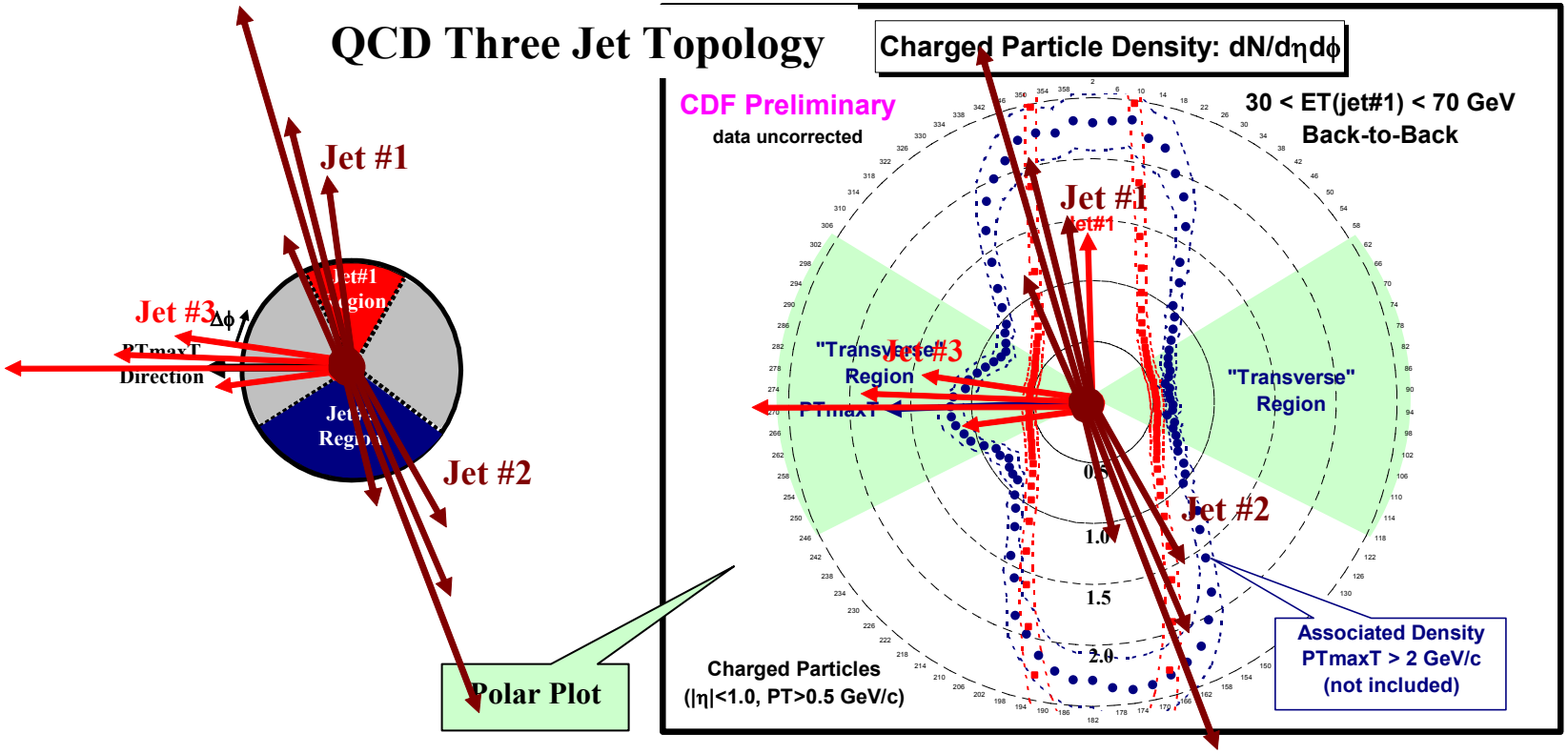
➡ **Shows the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$ (*not including PTmaxT*) relative to PTmaxT (rotated to 180°) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$ relative to jet#1 (rotated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

Back-to-Back "Associated" Charged Particle Densities



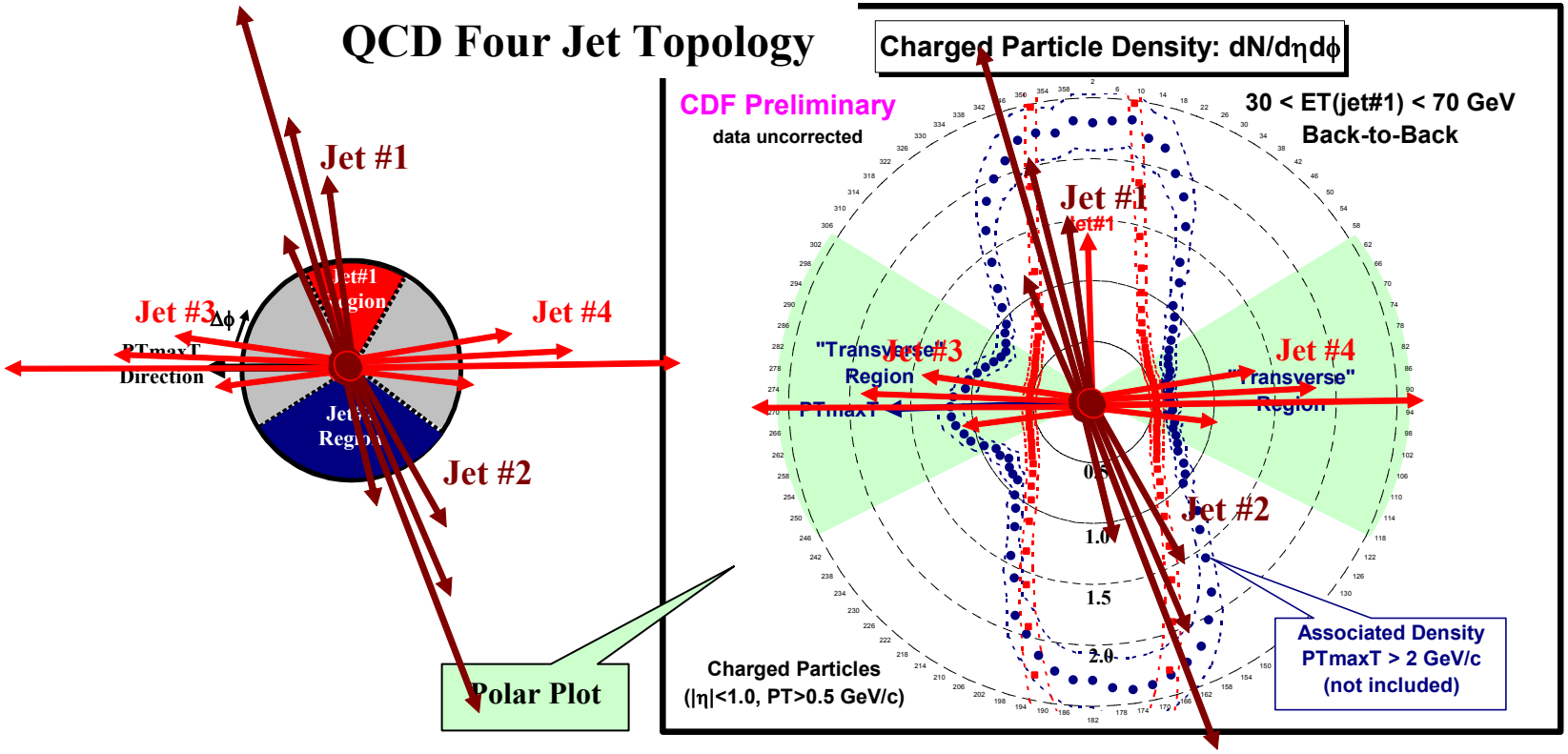
➡ **Shows the Δφ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$, PTmaxT > 2.0 GeV/c (*not including PTmaxT*) relative to PTmaxT (rotated to 180°) and the charged particle density, $dN_{chg}/d\eta d\phi$, $p_T > 0.5$ GeV/c, $|\eta| < 1$,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

Jet Topologies



➡ **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 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.**

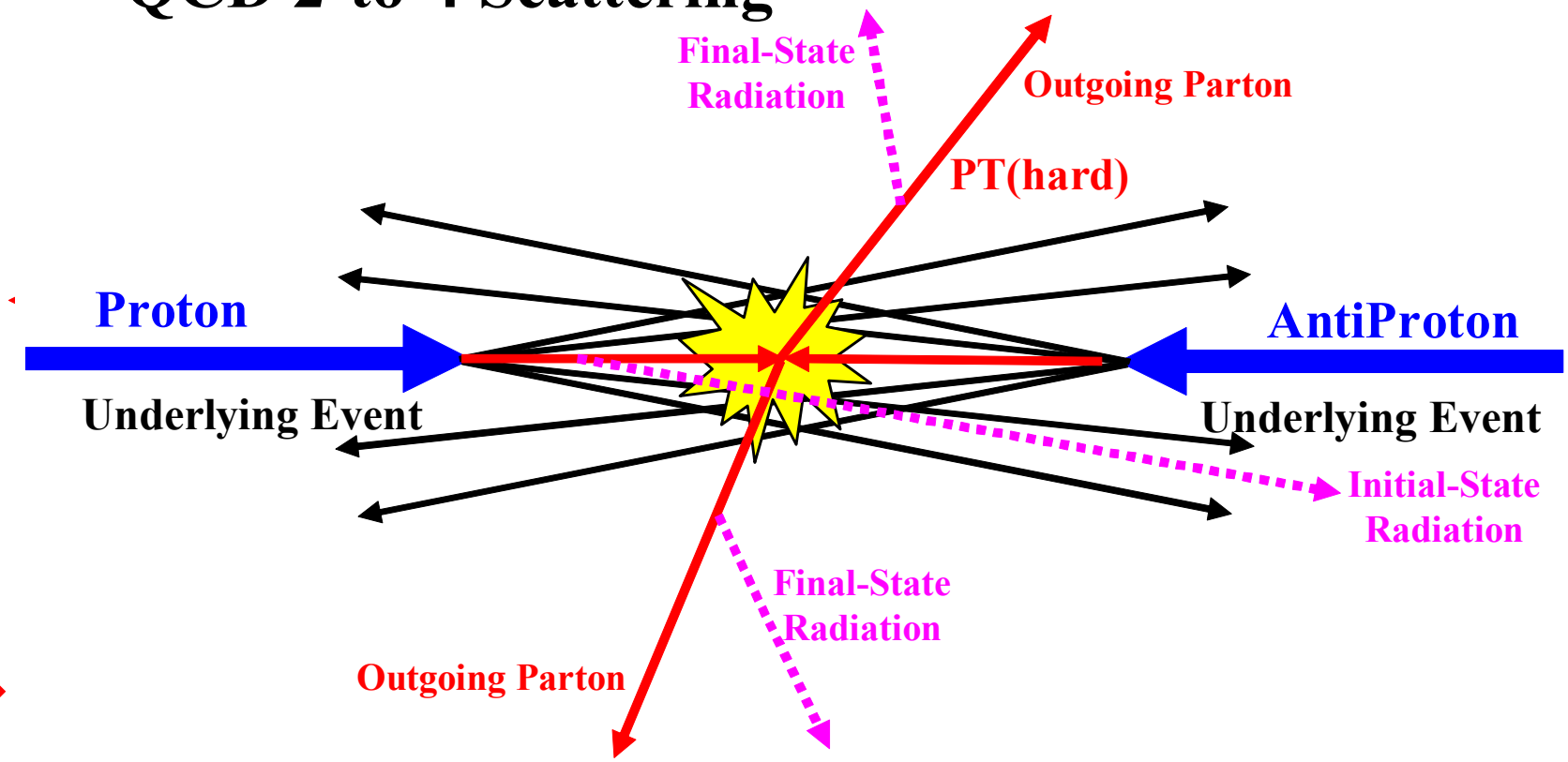
Jet Topologies



- **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 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

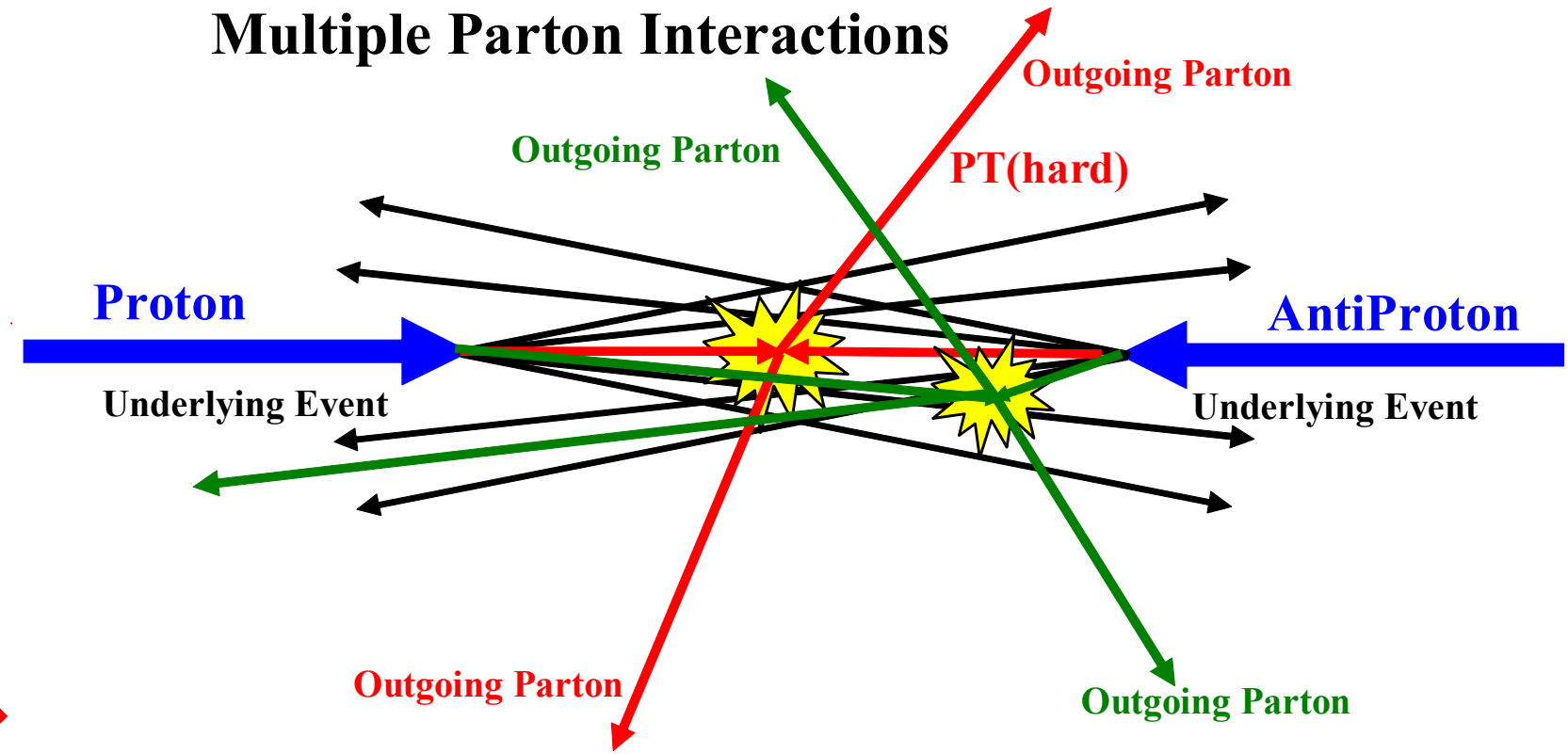
QCD 2-to-4 Scattering



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.

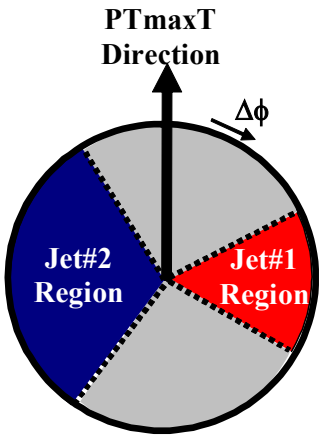
Jet Topologies

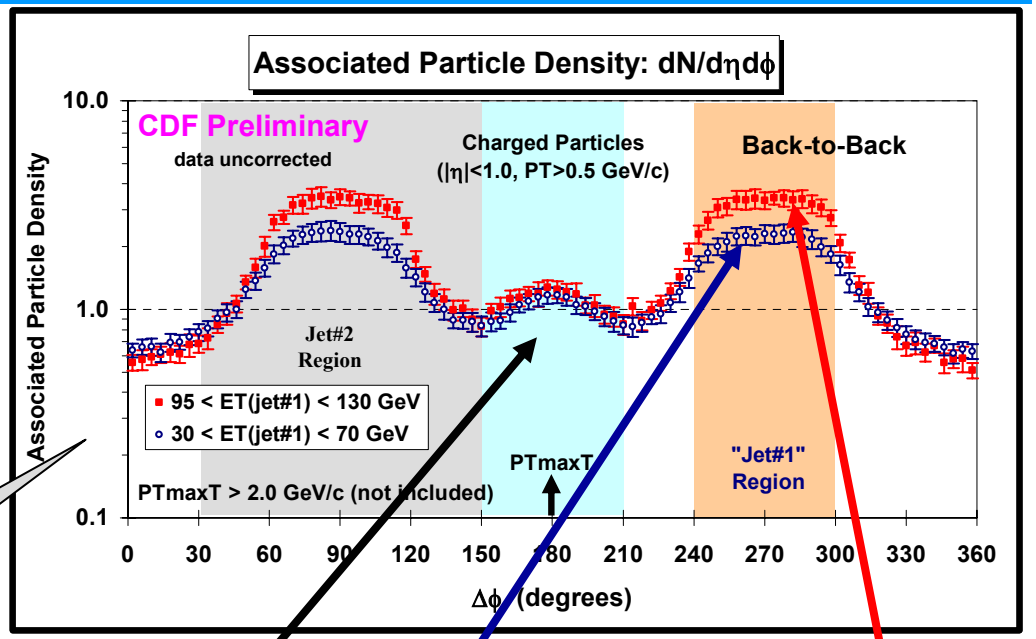
Multiple Parton Interactions



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.

Back-to-Back "Associated" Charged Particle Density



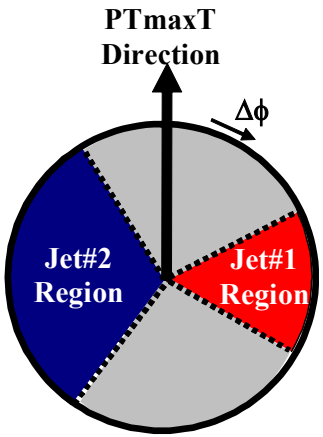


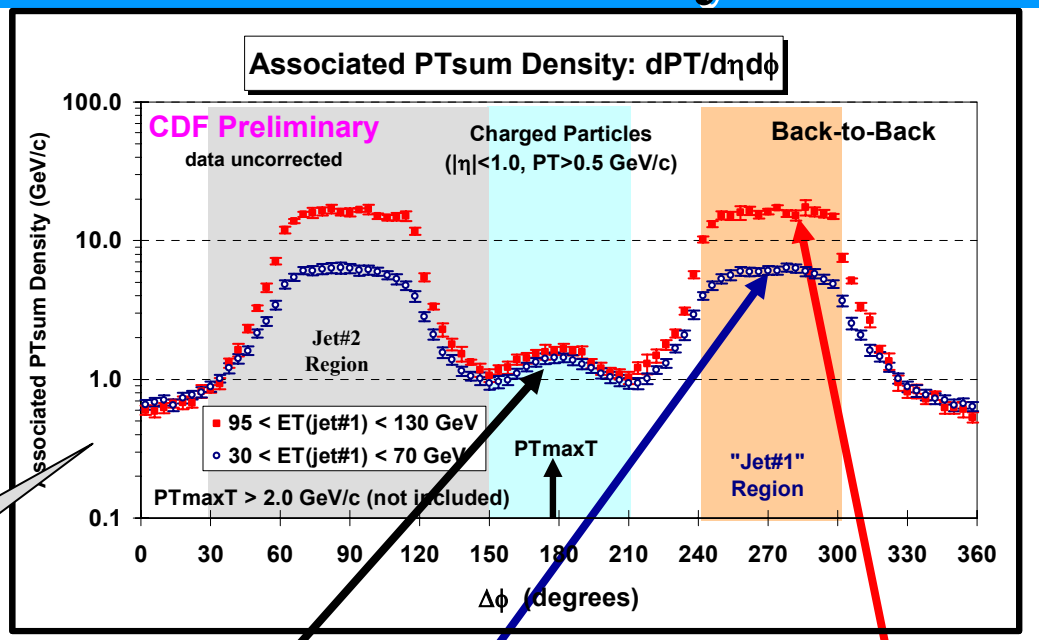
Log Scale!

- 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 180°) 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



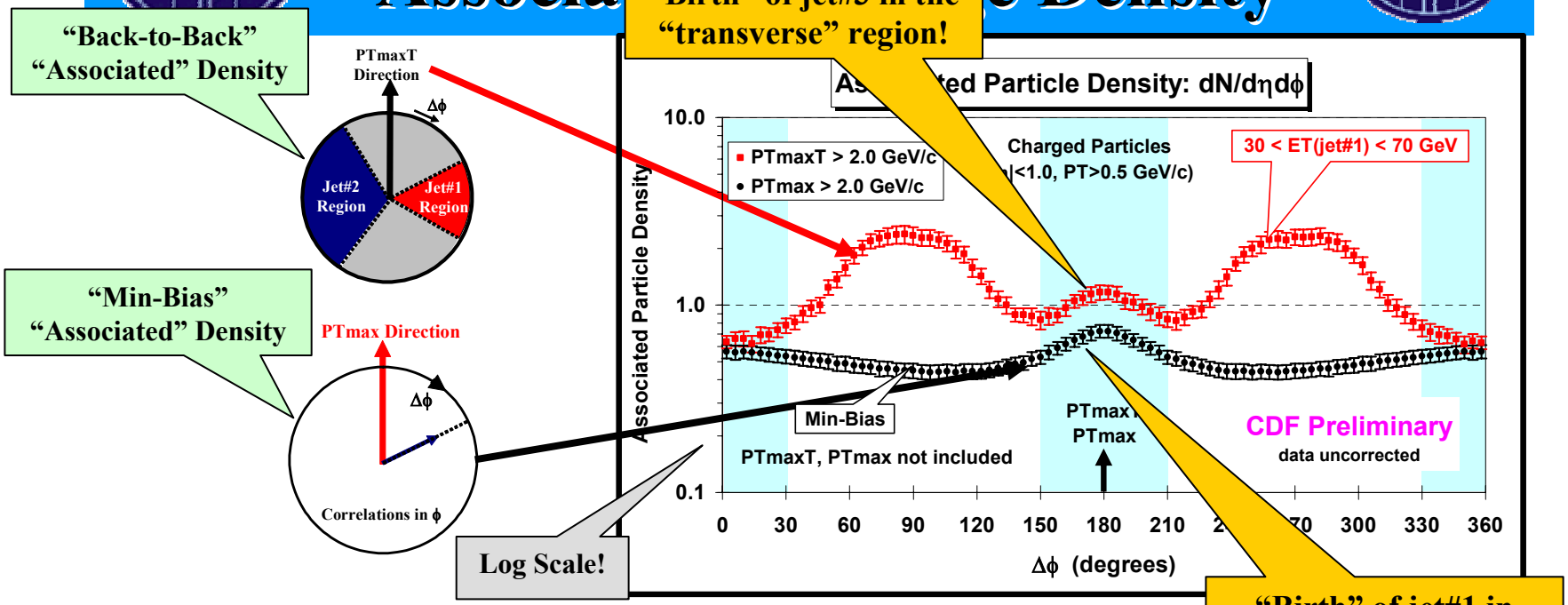


Log Scale!

- 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 180°) 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" "Associa[illegible]e Density

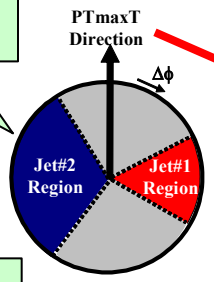


- Shows the Δϕ dependence of the "associated" charged particle densi[illegible] p_T > 0.5 GeV/c, |η| < 1 (*not including PTmaxT*) relative to PTmaxT ([illegible]) for PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV.

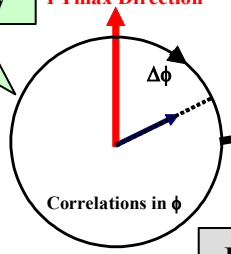
- Shows the data on the Δϕ dependence of the "associated" charged particle density, $dN_{chg}/d\eta d\phi$, p_T > 0.5 GeV/c, |η| < 1 (*not including PTmax*) relative to PTmax (rotated to 180°) for "min-bias" events with PTmax > 2.0 GeV/c.

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

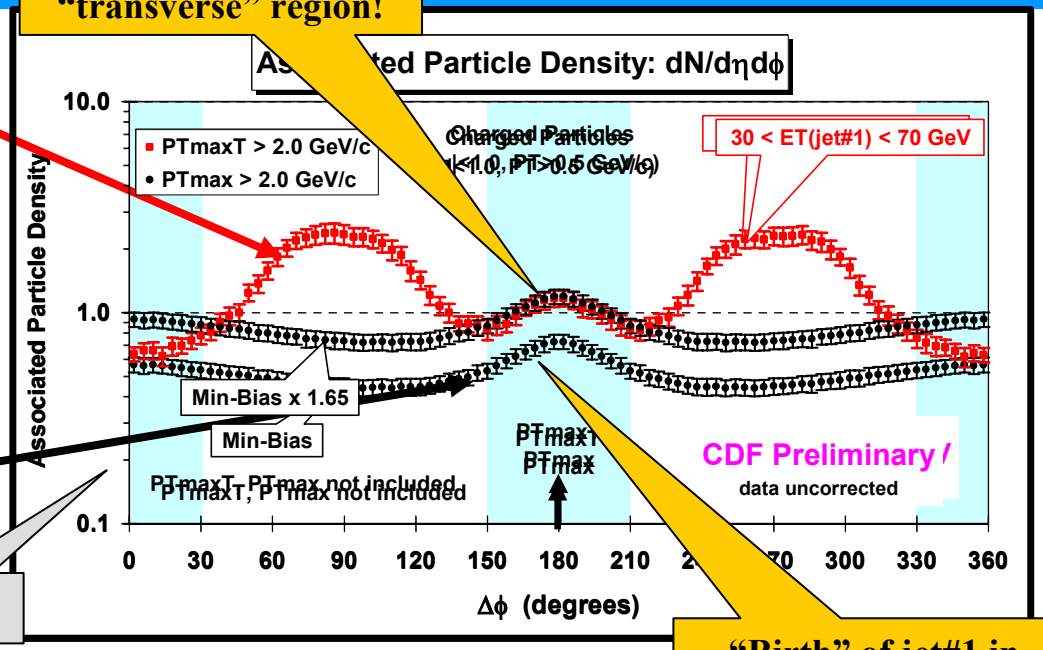
"Back-to-Back" "Associated" Density



"Min-Bias" "Associated" Density



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

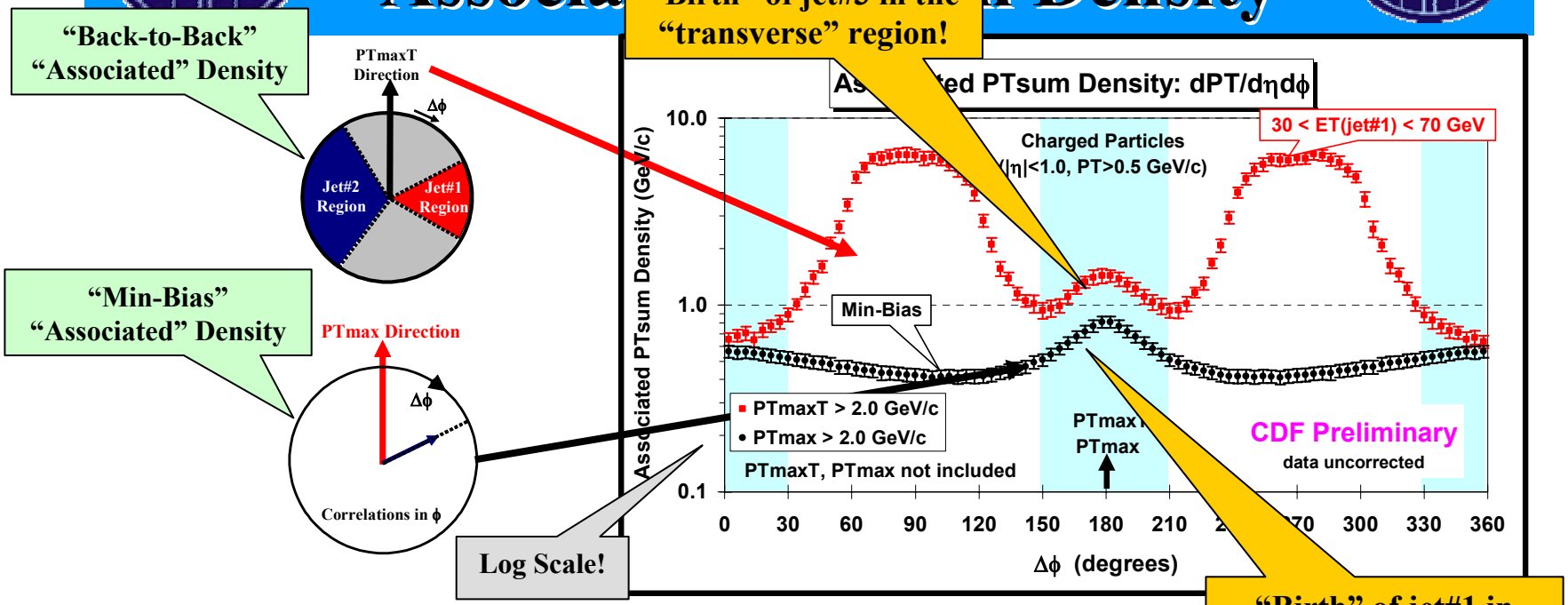


Log Scale!

"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.

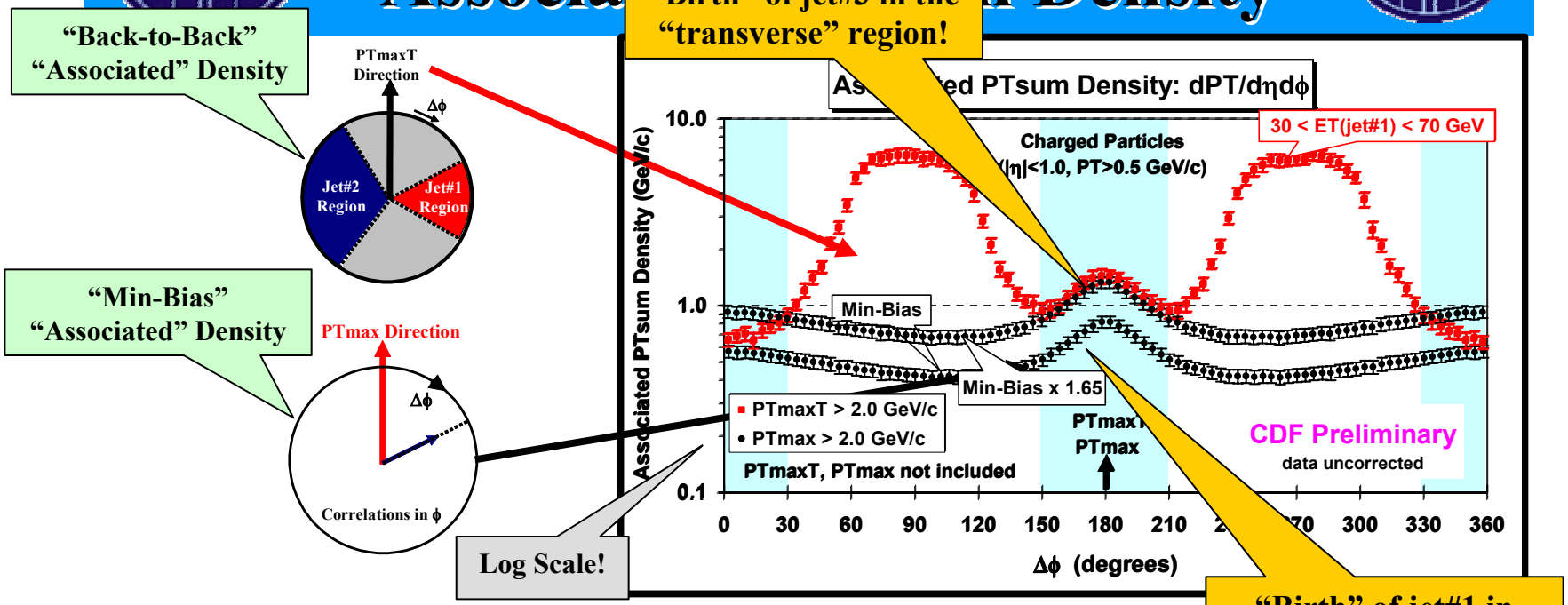
"Back-to-Back" vs "MinBias" "Associated" PTsum Density



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



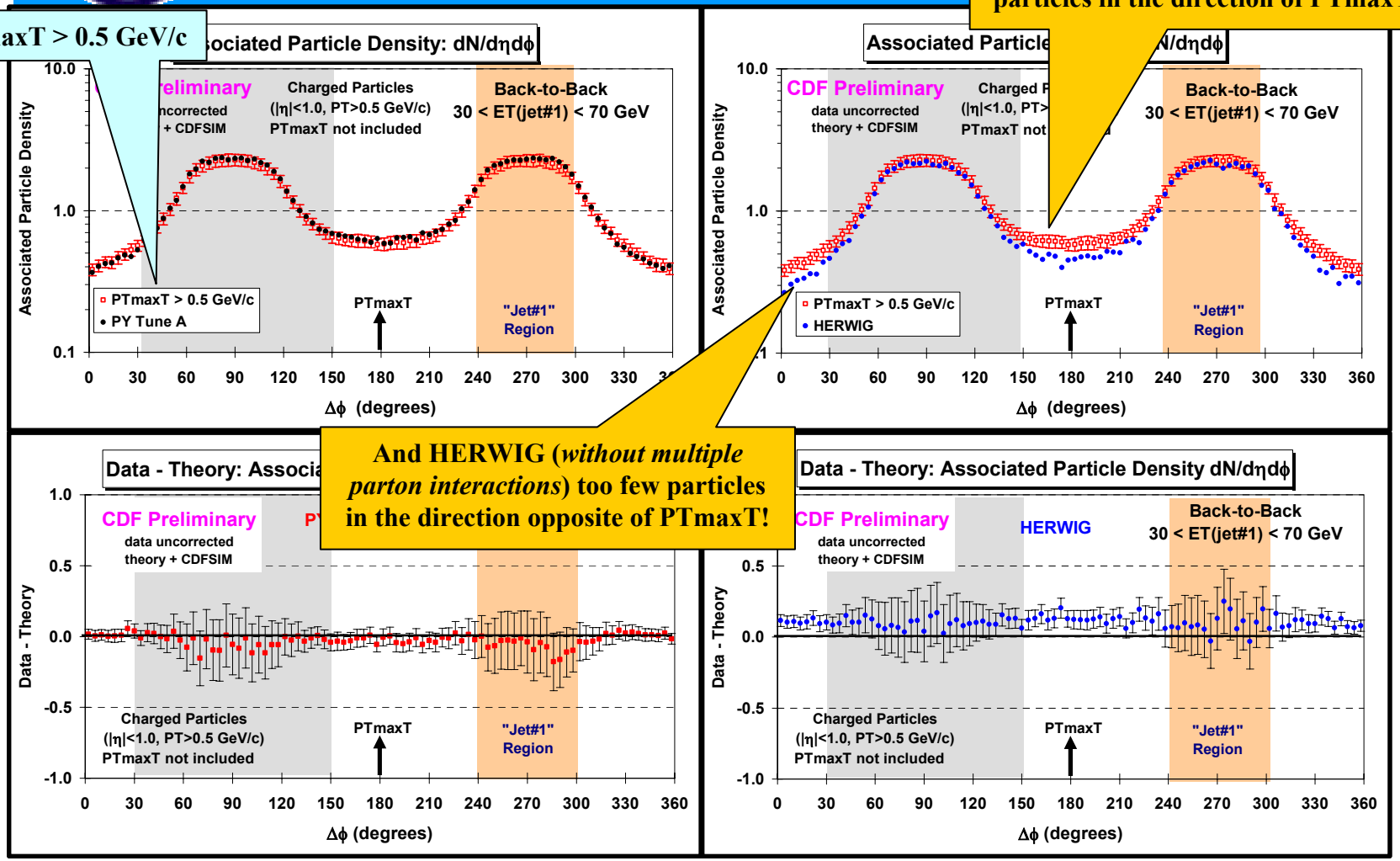
- Shows the Δϕ dependence of the "associated" charged particle densi[illegible] p_T > 0.5 GeV/c, |η| < 1 (*not including PTmaxT*) relative to PTmaxT ([illegible]) for PTmaxT > 2.0 GeV/c, for "back-to-back" events with 30 < E_T(jet#1) < 70 GeV.

- 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 HE

PTmaxT > 0.5 GeV/c

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

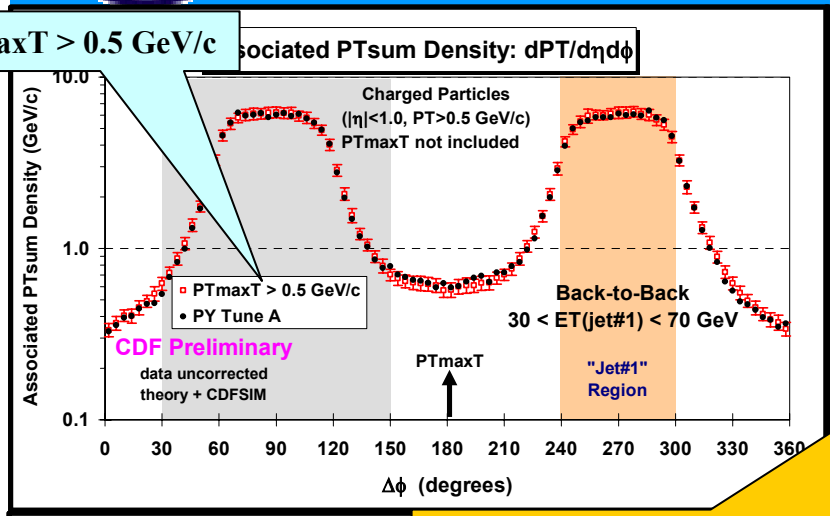


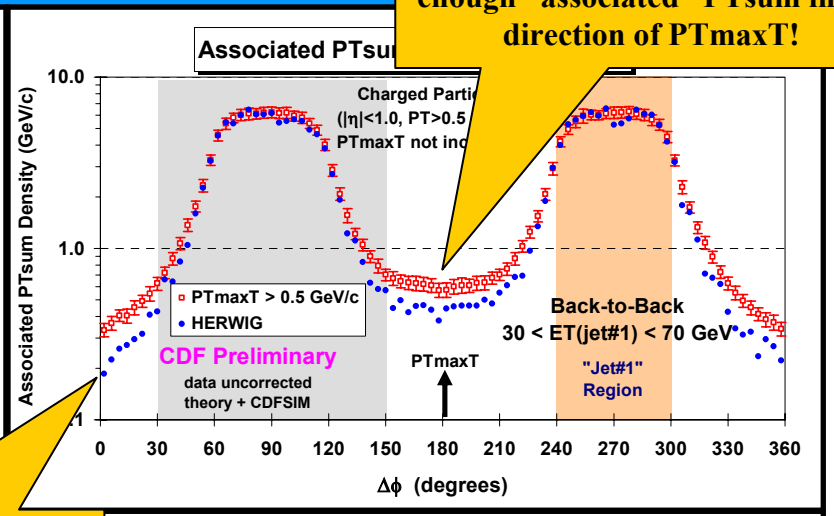
And HERWIG (*without multiple parton interactions*) too few particles in the direction opposite of PTmaxT!

"Associated" PTsum Density
PYTHIA Tune A vs HERW

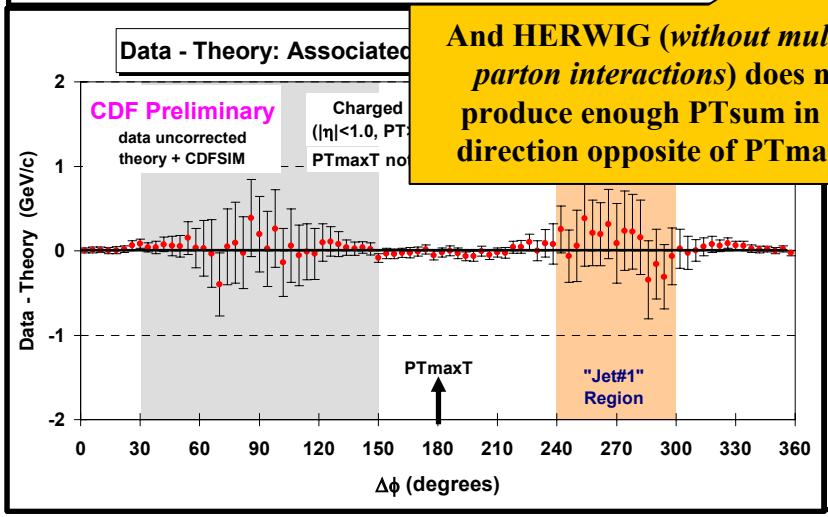
PTmaxT > 0.5 GeV/c

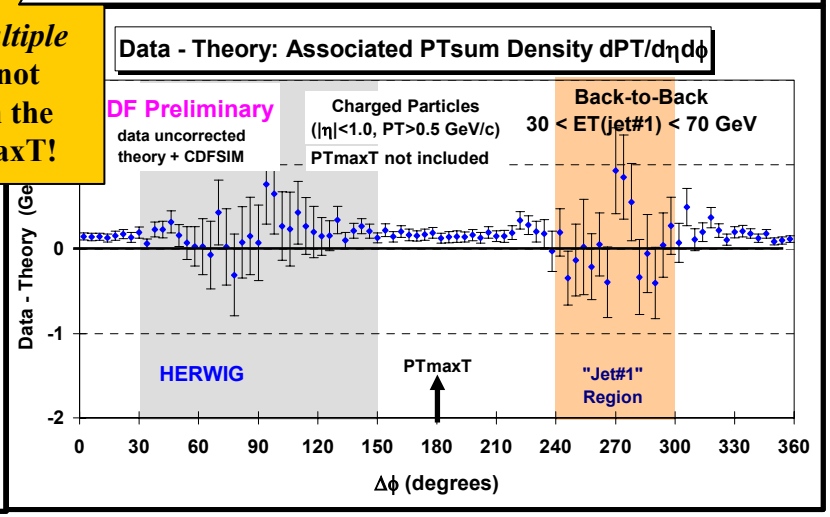
HERWIG (*without multiple parton interactions*) does not produce enough "associated" PTsum in the direction of PTmaxT!





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

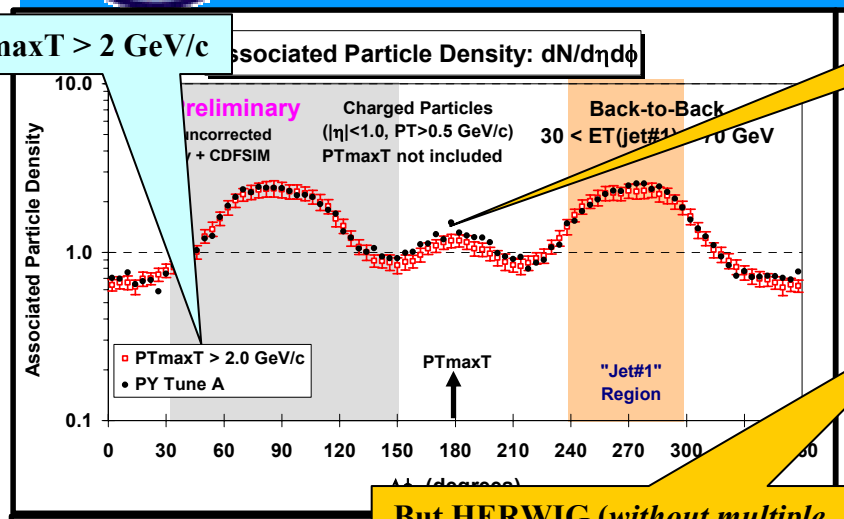


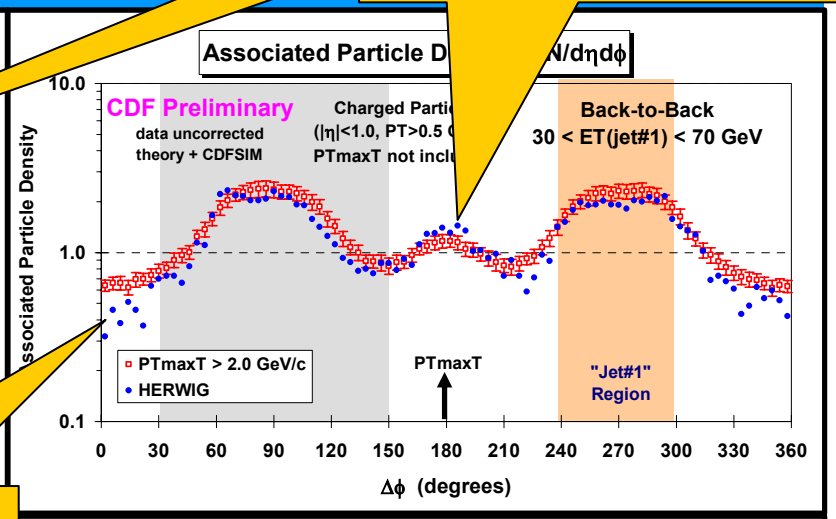


"Associated" Charge De
PYTHIA Tune A vs HE

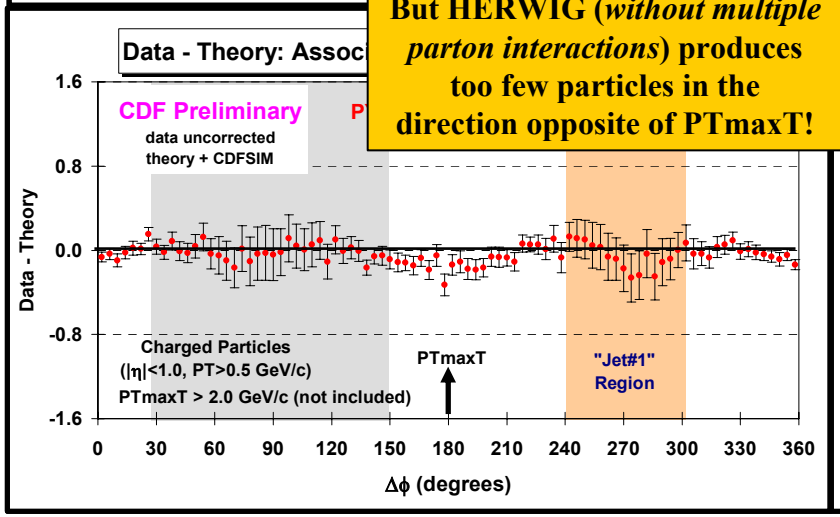
For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too many "associated" particles in the direction of PTmaxT!

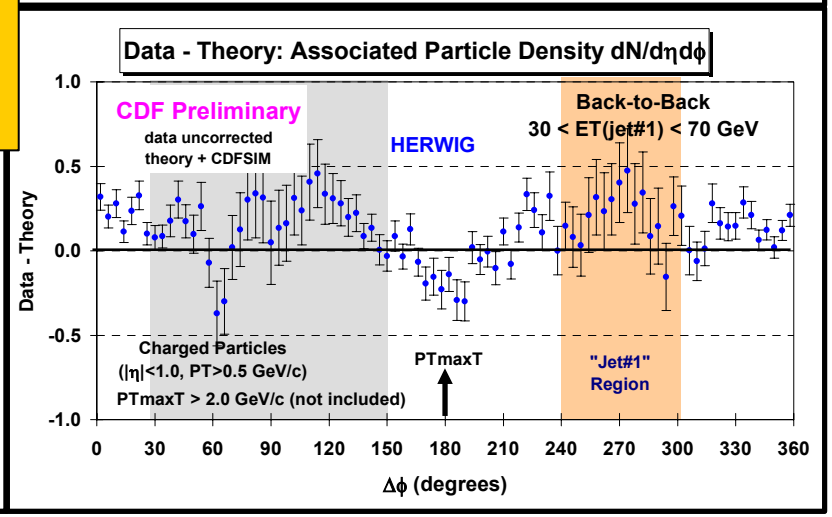
PTmaxT > 2 GeV/c





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

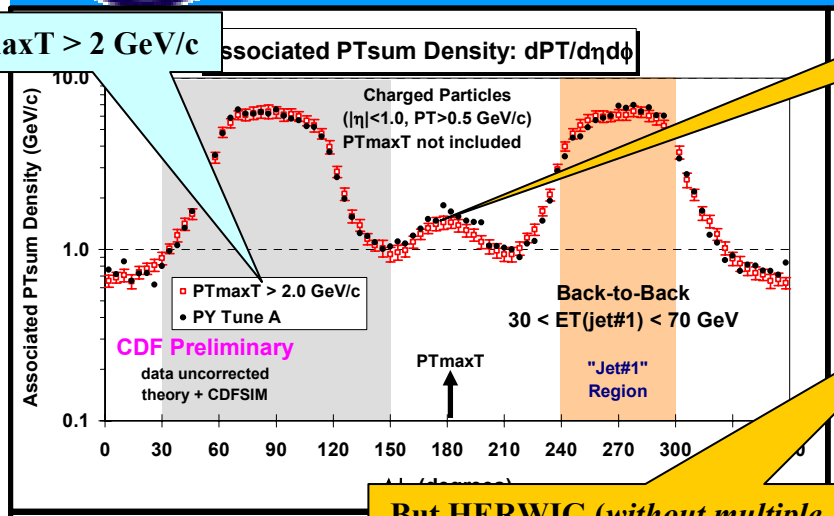


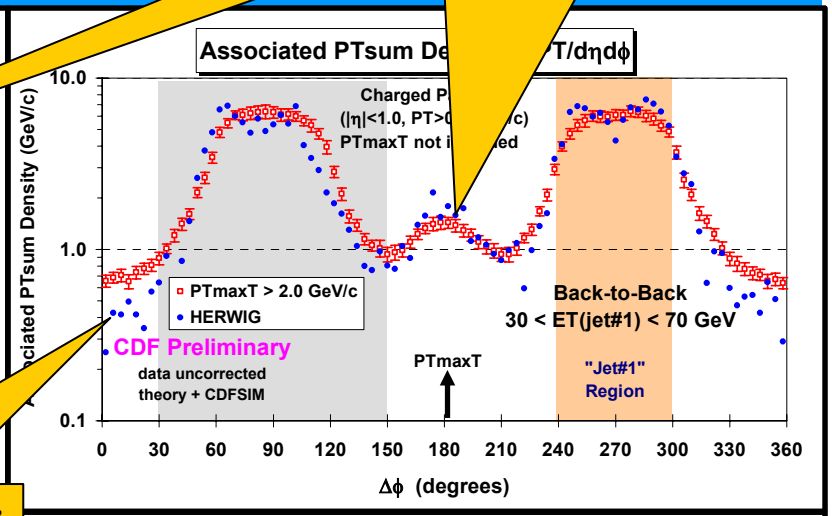


"Associated" PTsum De
PYTHIA Tune A vs HE

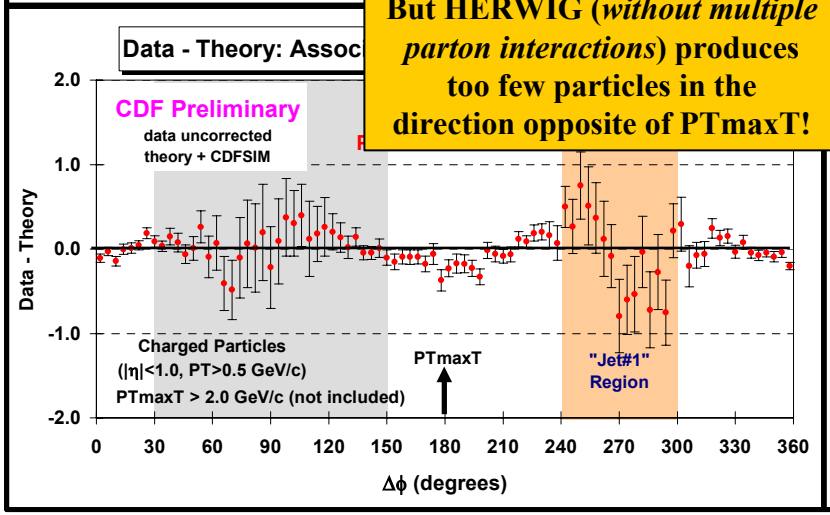
For PTmaxT > 2.0 GeV both PYTHIA and HERWIG produce slightly too much "associated" PTsum in the direction of PTmaxT!

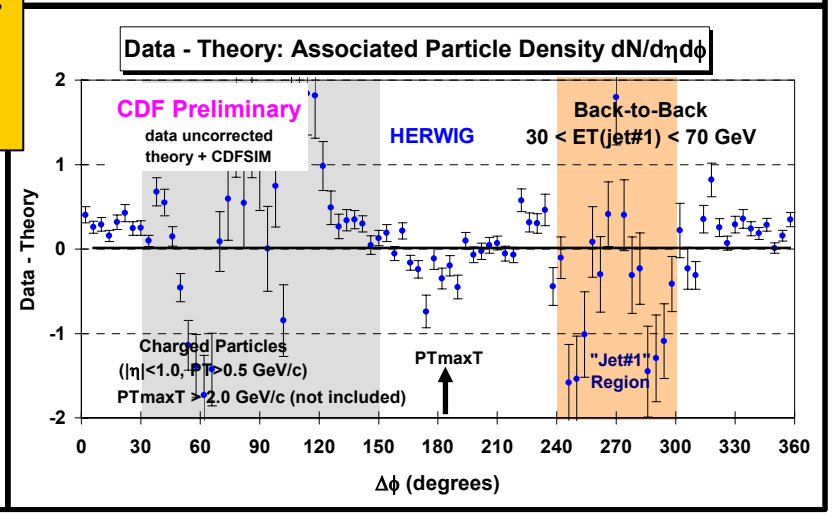
PTmaxT > 2 GeV/c



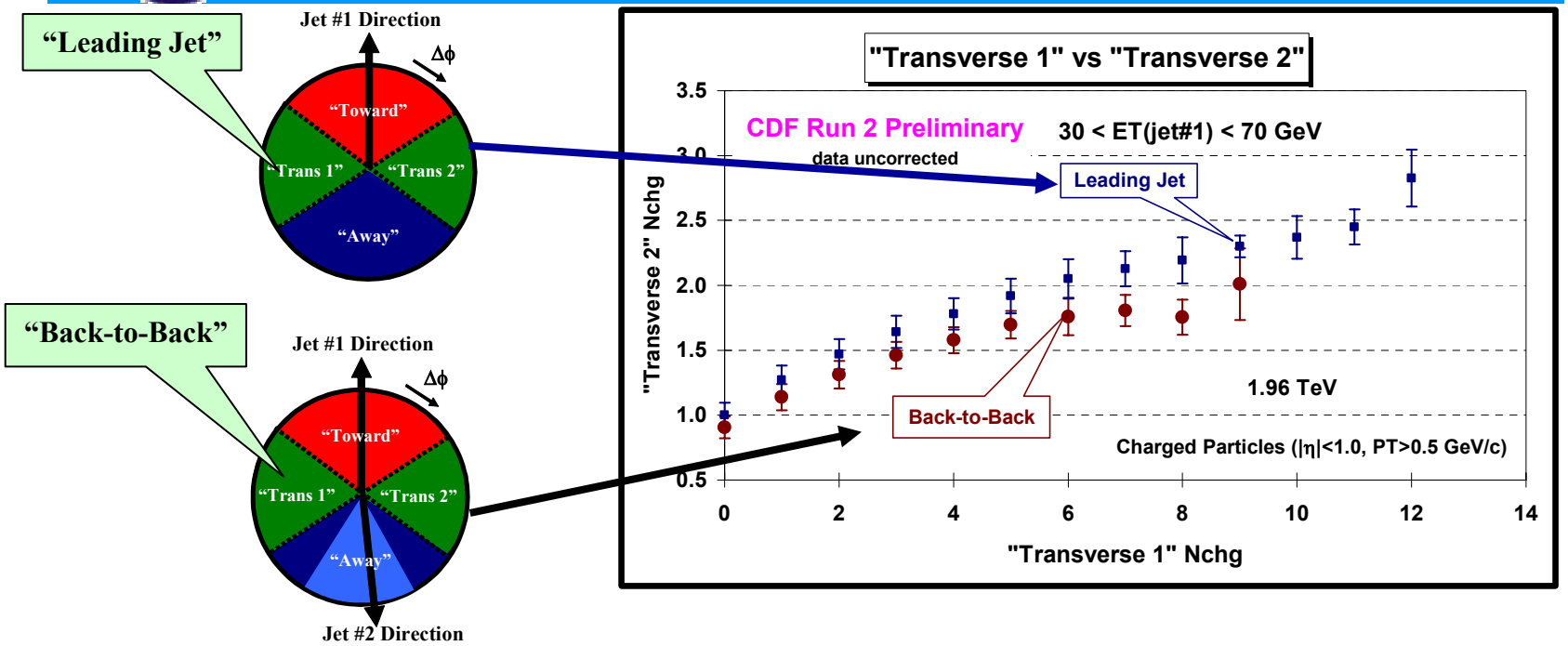


But HERWIG (*without multiple parton interactions*) produces too few particles in the direction opposite of PTmaxT!



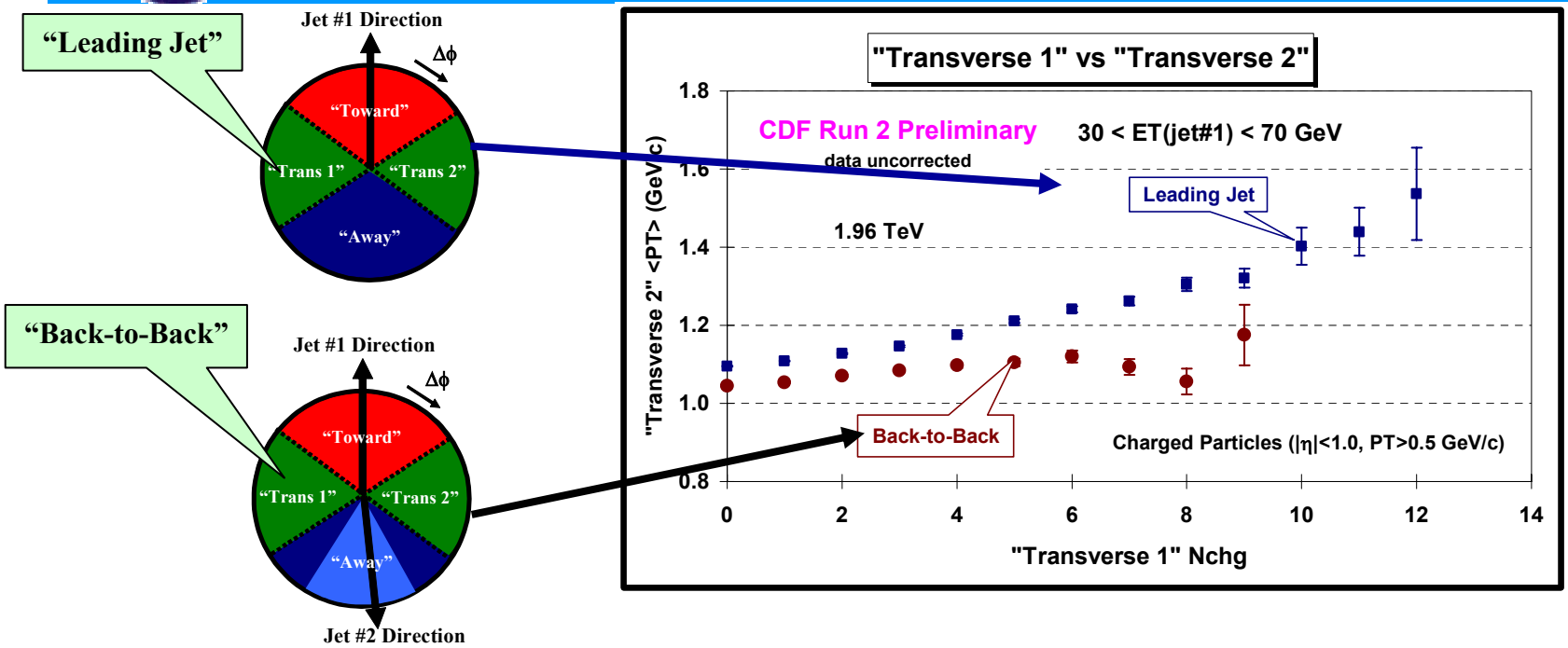


"Transverse 1" Region vs "Transverse 2" Region



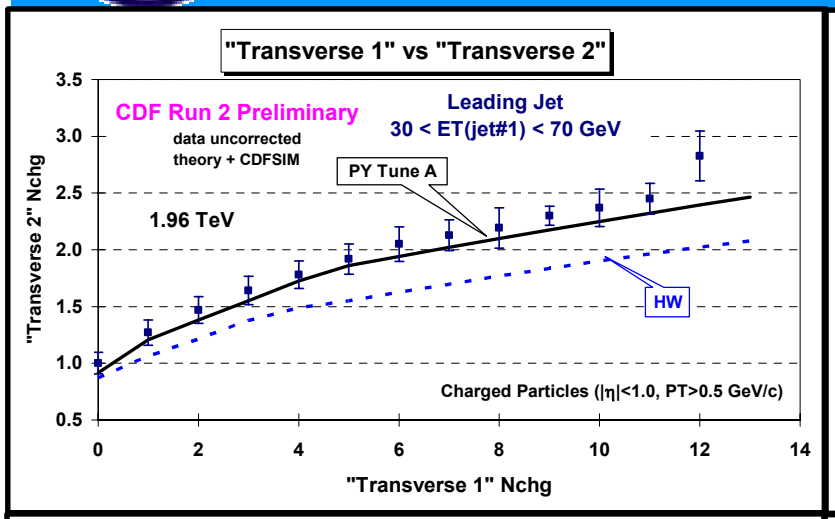
- Use the leading jet to define two "transverse" regions and look at the correlations between "transverse 1" and "transverse 2".
- Shows the average number of charged particles in the "transverse 2" region versus the number of charged particles in the "transverse 1" region for $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "Leading Jet" and "Back-to-Back" events.

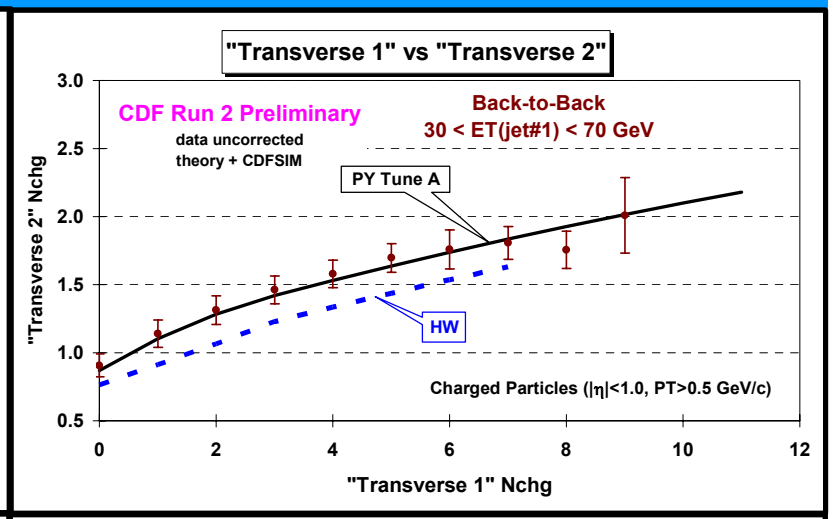
"Transverse 1" Region vs "Transverse 2" Region

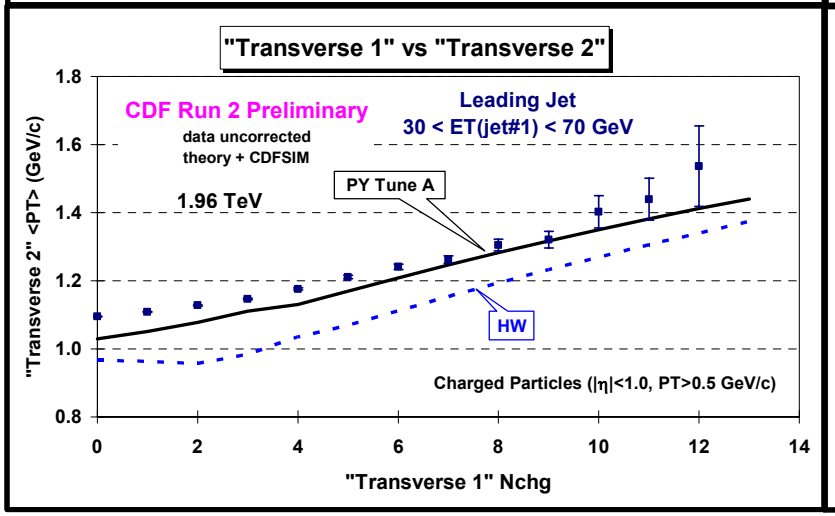


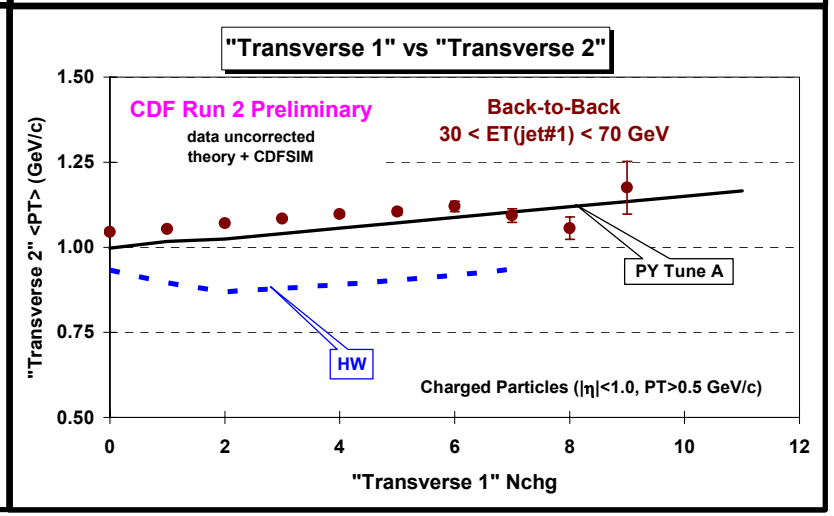
- Use the leading jet to define two "transverse" regions and look at the correlations between "transverse 1" and "transverse 2".
- Shows the average p_T of charged particles in the "transverse 2" region versus the number of charged particles in the "transverse 1" region for $p_T > 0.5$ GeV/c and $|\eta| < 1$ for "Leading Jet" and "Back-to-Back" events.

"Transverse 1" Region vs "Transverse 2" Region

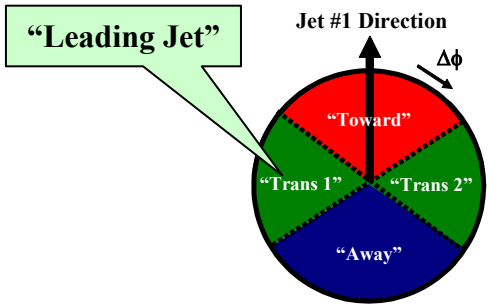


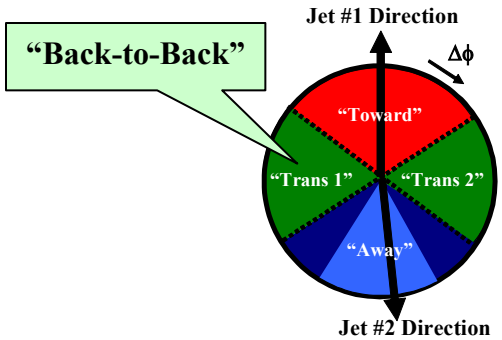






Summary



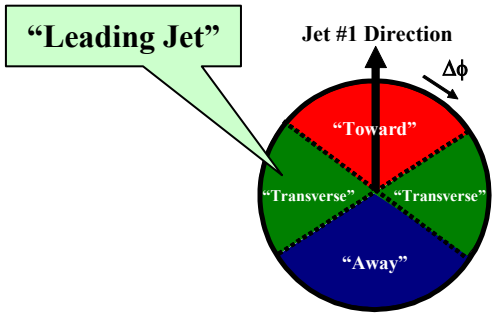


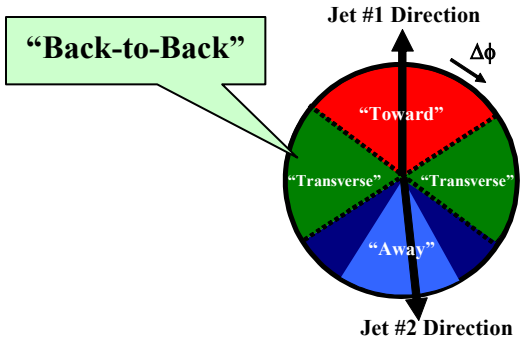
- **There are some interesting correlations between the "transverse 1" and "transverse 2" regions both for "Leading-Jet" and "Back-to-Back" events!**

- **PYTHIA Tune A (*with multiple parton scattering*) does a much better job in describing these correlations than does HERWIG (*without multiple parton scattering*).**

Question: Is this a probe of multiple parton interactions?

Summary

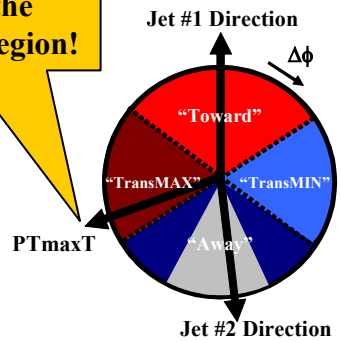




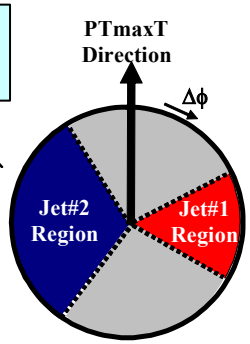
- **"Back-to-Back" events have less "hard scattering" (*initial and final state radiation*) component in the "transverse" region which allows for a closer look at the "beam-beam remnant" and multiple parton scattering component of the "underlying" event.**
- **PYTHIA Tune A (*with multiple parton scattering*) does a much better job in describing the "back-to-back" events than does HERWIG (*without multiple parton scattering*).**

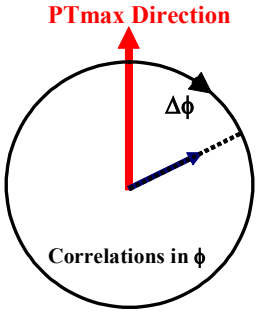
Summary

Max p_T in the "transverse" region!



"Associated" densities do not include PTmaxT!





- The "associated" densities show strong correlations (*i.e.* jet structure) in the "transverse" region both for "Leading Jet" and "Back-to-Back" events.

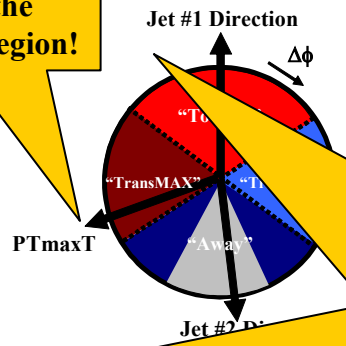
- The "birth" of the 1st jet in "min-bias" collisions looks very similar to the "birth" of the 3rd jet in the "transverse" region of hard scattering "Back-to-Back" events.

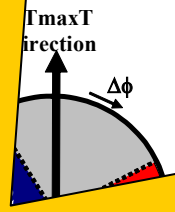
Question: Is the topology 3 jet or 4 jet?

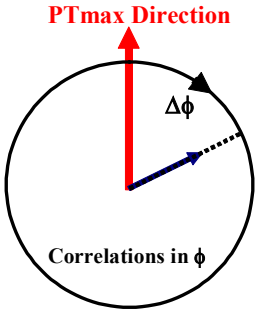
Summary

Max p_T in the "transverse" region!

"Associated" densities do not include PTmaxT!







Next Step

Look at the jet topologies (2 jet vs 3 jet vs 4 jet etc). See if there is an excess of 4 jet events due to multiple parton interactions!

- The "associated" ... jet structure) in the "transverse" region ... -Back" events.
- The "birth" of the ... s very similar to the "birth" of the 3rd jet in the ... l scattering "Back-to-Back" events.

Question: Is the ... logy 3 jet or 4 je...