EPS-HEP 2013

Energy Dependence of the "Underlying Event"

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Chromo-
Dynamics

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Outline of Talk

Stockholm, Sweden, July 2013
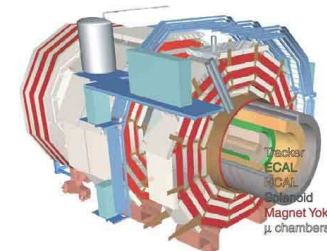

➡ New **CDF** UE data from the **Tevatron Energy Scan** (R. Field).

➡ New **CMS** UE data (M. Zakaria).

➡ Comparisons with PYTHIA 6.4 **Tune Z1** and PYTHIA 6.4 **Tune Z2***.

➡ Mapping out the energy dependence of the UE: **Tevatron** to the **LHC**!

➡ Summary & Conclusions.

CDF Run 2
300 GeV, 900 GeV, 1.96 TeV

CMS at the LHC
900 GeV, 7 & 8 TeV

Tevatron Energy Scan

Proton

AntiProton

1 mile

CDF

Chicago

p   p̄

1.96 TeV

Booster

CDF   DØ

Tevatron

p source

Main Injector & Recycler

Proton →   **1.96 TeV**   ← AntiProton

➡ **Just before the shutdown of the Tevatron CDF has collected more than 10M "min-bias" events at several center-of-mass energies!**

300 GeV 12.1M MB Events

900 GeV 54.3M MB Events

UE Observables

➡ **"Transverse" Charged Particle Density:** Number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < \eta_{cut}$) in the "transverse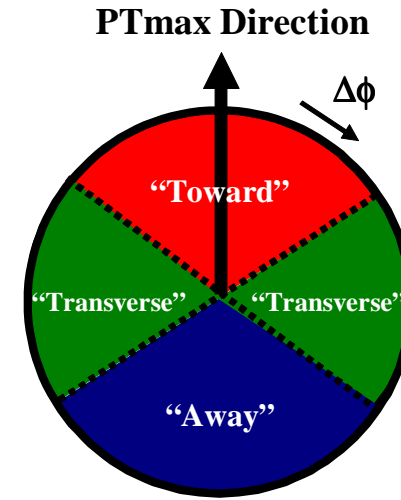" region as defined by the leading charged particle, PTmax, divided by the area in η-ϕ space, $2\eta_{cut} \times 2\pi/3$, averaged over all events with at least one particle with $p_T > 0.5$ GeV/c, $|\eta| < \eta_{cut}$.

➡ **"Transverse" Charged PTsum Density:** Scalar p_T sum of the charged particles ($p_T > 0.5$ GeV/c, $|\eta| < \eta_{cut}$) in the "transverse" region as defined by the leading charged particle, PTmax, divided by the area in η-ϕ space, $2\eta_{cut} \times 2\pi/3$, averaged over all events with at least one particle with $p_T > 0.5$ GeV/c, $|\eta| < \eta_{cut}$.

PTmax Direction

$\Delta\phi$

"Toward"

"Transverse"   "Transverse"

"Away"

➡ **"Transverse" Charged Particle Average P_T:** Event-by-event $\langle p_T \rangle$ = PTsum/Nchg for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < \eta_{cut}$) in the "transverse" region as defined by the leading charged particle, PTmax, averaged over all events with at least one particle in the "transverse" region with $p_T > 0.5$ GeV/c, $|\eta| < \eta_{cut}$.

➡ **Zero "Transverse" Charged Particles:** If there are no charged particles in the "transverse" region then Nchg and PTsum are zero and one includes these zeros in the average over all events with at least one particle with $p_T > 0.5$ GeV/c, $|\eta| < \eta_{cut}$. However, if there are no charged particles in the "transverse" region then the event is not used in constructing the "transverse" average p_T.
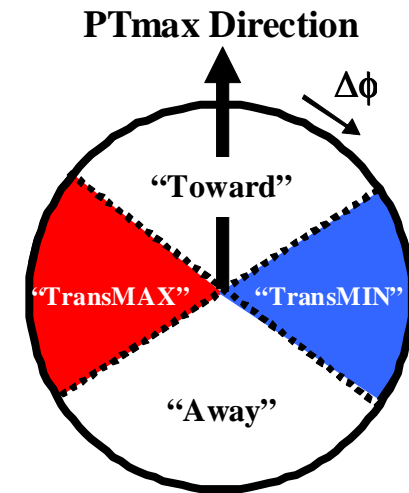
$$\eta_{cut} = 1.0 \text{ and } \eta_{cut} = 0.8$$

UE Observables

➡ **"transMAX" and "transMIN" Charged Particle Density:** **Number of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 0.8$) in the the maximum (minimum) of the two "transverse" regions as defined by the leading charged particle, PTmax, divided by the area in η-ϕ space, $2\eta_{cut} \times 2\pi/6$, averaged over all events with at least one particle with $p_T > 0.5$ GeV/c, $|\eta| < \eta_{cut}$.**

➡ **"transMAX" and "transMIN" Charged PTsum Density:** **Scalar p_T sum of charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 0.8$) in the the maximum (minimum) of the two "transverse" regions as defined by the leading charged particle, PTmax, divided by the area in η-ϕ space, $2\eta_{cut} \times 2\pi/6$, averaged over all events with at least one particle with $p_T > 0.5$ GeV/c, $|\eta| < \eta_{cut}$.**

PTmax Direction

$\Delta\phi$

"Toward"

"TransMAX"   "TransMIN"

"Away"

Note: **The overall "transverse" density is equal to the average of the "transMAX" and "TransMIN" densities. The "TransDIF" Density is the "transMAX" Density minus the "transMIN" Density**

"Transverse" Density = "transAVE" Density = ("transMAX" Density + "transMIN" Density)/2

"TransDIF" Density = "transMAX" Density - "transMIN" Density

$\eta_{cut} = 0.8$

"transMIN" & "transDIF"

➡ **The "toward" region contains the leading "jet", while the "away" region, on the average, contains the "away-side" "jet". The "transverse" region is perpendicular to the plane of the hard 2-to-2 scattering and is very sensitive to the "underlying event". For events with large initial or final-state radiation the "transMAX" region defined contains the third jet while both the "transMAX" and "transMIN" regions receive contributions from the MPI and beam-beam remnants. Thus, the "transMIN" region is very sensitive to the multiple parton interactions (MPI) and beam-beam remnants (BBR), while the "transMAX" minus the "transMIN" (_i.e._ "transDIF") is very sensitive to initial-state radiation (ISR) and final-state radiation (FSR).**

"TransMIN" density more sensitive to MPI & BBR.

"TransDIF" density more sensitive to ISR & FSR.

$$0 \leq \text{"TransDIF"} \leq 2\times\text{"TransAVE"}$$

"TransDIF" = "TransAVE" if "TransMIX" = 3×"TransMIN"

PTmax Direction

"Toward-Side" Jet

Δφ

"Toward"

"TransMAX"   "TransMIN"

Jet #3

"Away"

"Away-Side" Jet

"transMIN" & "transDIF"

➡️ **Question:** Do you expect the energy dependence of the "transMIN" and "transDIF" densities to be the same? Or do you expect that one of the two densities will increase faster with increasing energy than the other? Which one and why?

scattering and is very sensitive to the "underlying event". For events with large initial or final-state radiation the "transMAX" region defined contains the third jet while both the "transMAX" and "transMIN" regions receive contributions from the MPI and beam-beam remnants. Thus, the "transMIN" region is very sensitive to the multiple parton interactions (MPI) and beam-beam remnants (BBR), while the "transMAX" minus the "transMIN" (*i.e.* "transDIF") is very sensitive to initial-state radiation (ISR) and final-state radiation (FSR).

"TransMIN" density more sensitive to MPI & BBR.

"TransDIF" density more sensitive to ISR & FSR.

$$0 \leq \text{"TransDIF"} \leq 2 \times \text{"TransAVE"}$$

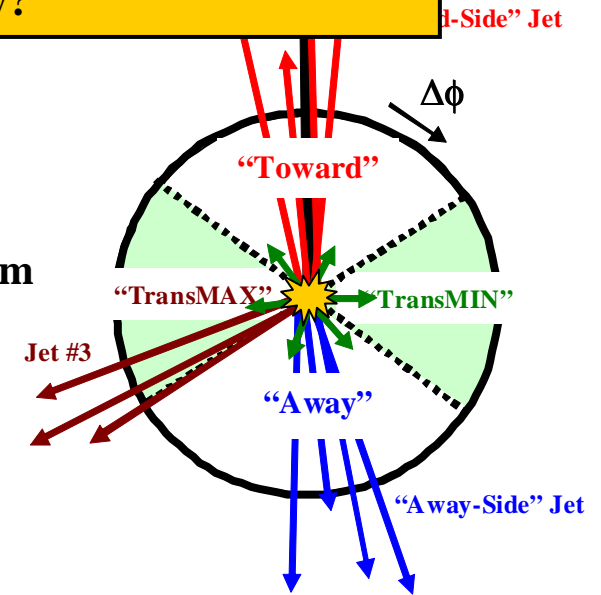$$\text{"TransDIF"} = \text{"TransAVE"} \text{ if "TransMIX"} = 3 \times \text{"TransMIN"}$$

PTmax UE Data

➡ **CDF PTmax UE Analysis: "transMAX", "transMIN", "transAVE", and "transDIF"** charged particle and PTsum densities ($p_T > 0.5$ GeV/c, $|\eta| < 0.8$) in proton-antiproton collisions at 300 GeV, 900 GeV, and 1.96 TeV (R. Field analysis).

➡ **CMS PTmax UE Analysis: "transMAX", "transMIN", "transAVE",** and "transDIF" charged particle and PTsum densities ($p_T > 0.5$ GeV/c, $|\eta| < 0.8$) in proton-proton collisions at 900 GeV and 7 TeV (M. Zakaria analysis).

➡ **CMS UE Tunes:** PYTHIA 6.4 Tune Z1 (CTEQ5L) and PYTHIA 6.4 Tune Z2* (CTEQ6L). Both were tuned to the CMS leading chgjet "transAVE" UE data at 900 GeV and 7 TeV.

PTmax Direction

$\Delta\phi$

"Toward"

"TransMAX"   "TransMIN"

"Away"

"transMAX/MIN" NchgDen

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data   1.96 TeV   "TransMAX"

"TransMIN"

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data   900 GeV   "TransMAX"

"TransMIN"

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged particle density in the **"transMAX"** and **"transMIN"** regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
corrected data   300 GeV   "TransMAX"

"TransMIN"

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data
Generator Level Theory
1.96 TeV
"TransMAX"
Tune Z2* (solid lines)
Tune Z1 (dashed lines)
"TransMIN"
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data
Generator Level Theory
900 GeV
"TransMAX"
Tune Z2* (solid lines)
Tune Z1 (dashed lines)
"TransMIN"
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data
Generator Level Theory
300 GeV
"TransMAX"
Tune Z2* (solid lines)
Tune Z1 (dashed lines)
"TransMIN"
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

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The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

"Transverse" Charged Particle Density: dN/dηdφ

1.96 TeV

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

"Transverse" Charged Particle Density: dN/dηdφ

900 GeV

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged particle density in the **"transAVE"** and **"transDIF"** regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.
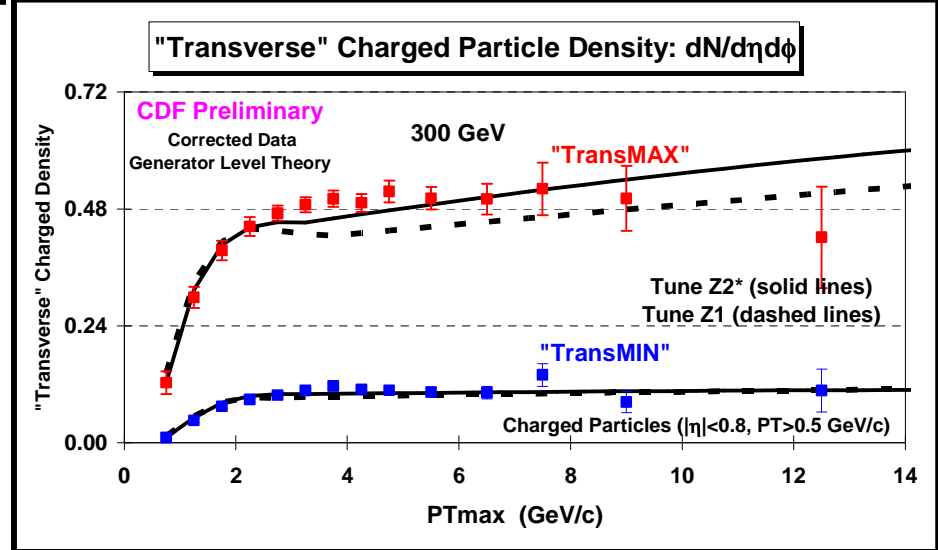

"Transverse" Charged Particle Density: dN/dηdφ

300 GeV

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data
Generator Level Theory

"TransDIF"

"TransAVE"

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

1.96 TeV

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Charged Particle Density / *PTmax (GeV/c)*

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data
Generator Level Theory

"TransDIF"

"TransAVE"

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

900 GeV

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Charged Particle Density / *PTmax (GeV/c)*

➡ **Corrected** CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transAVE" and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty. The data are compared with PYTHIA 6.4 Tune Z1 and Tune Z2*.
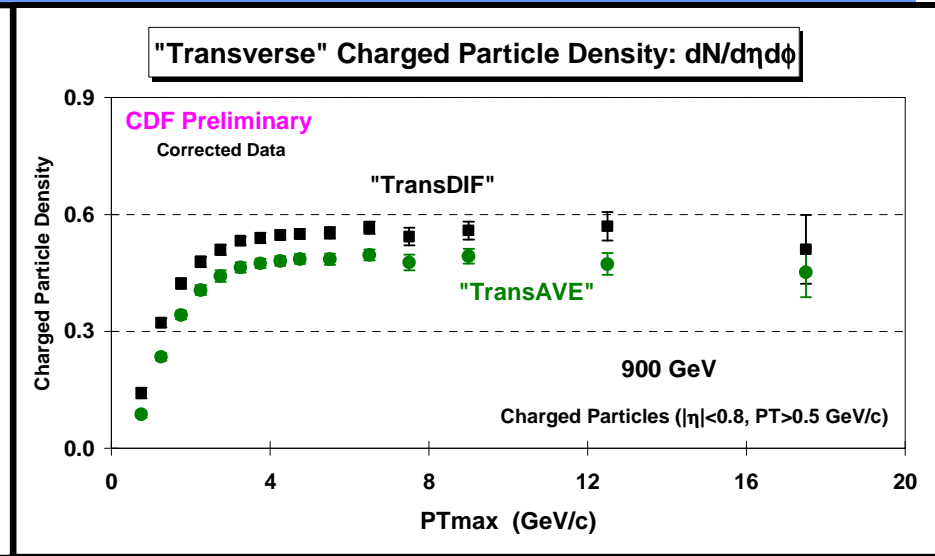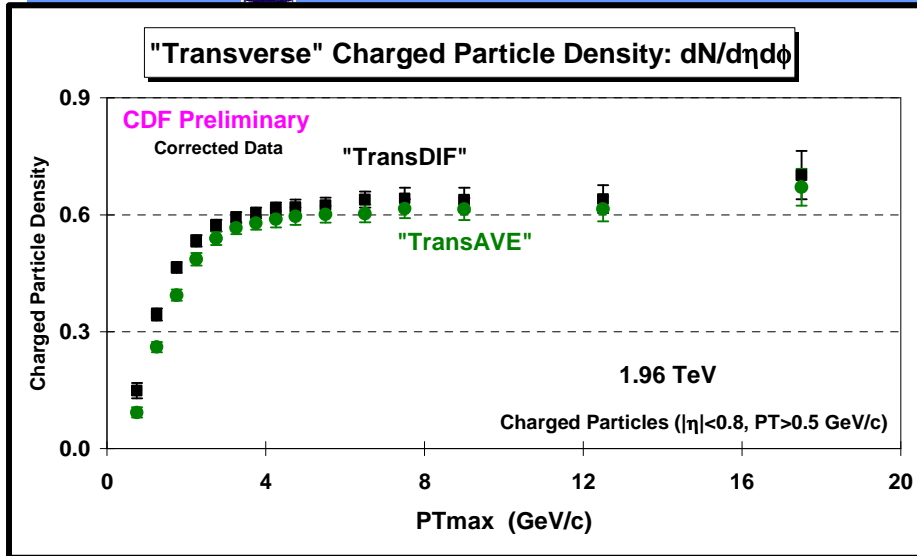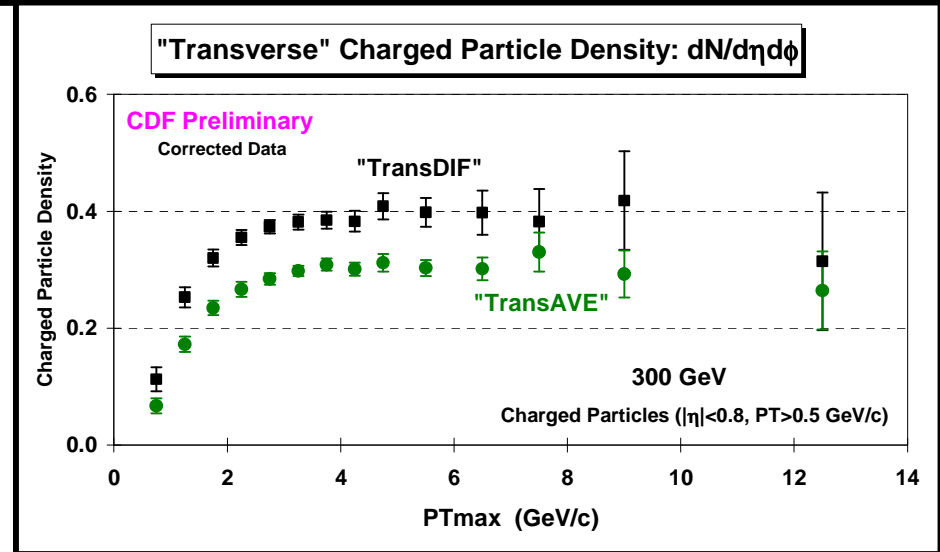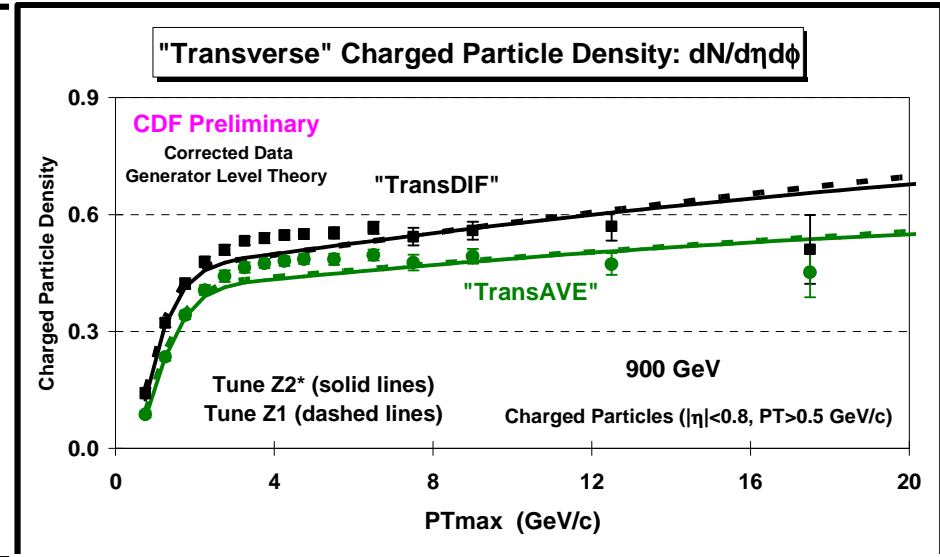

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data
Generator Level Theory

"TransDIF"

"TransAVE"

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

300 GeV

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Charged Particle Density / *PTmax (GeV/c)*

"TransMAX" Charged Particle Density: dN/dηdφ

"TransMIN" Charged Particle Density: dN/dηdφ

➡️ **Corrected** CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transMAX", "transMIN", and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.
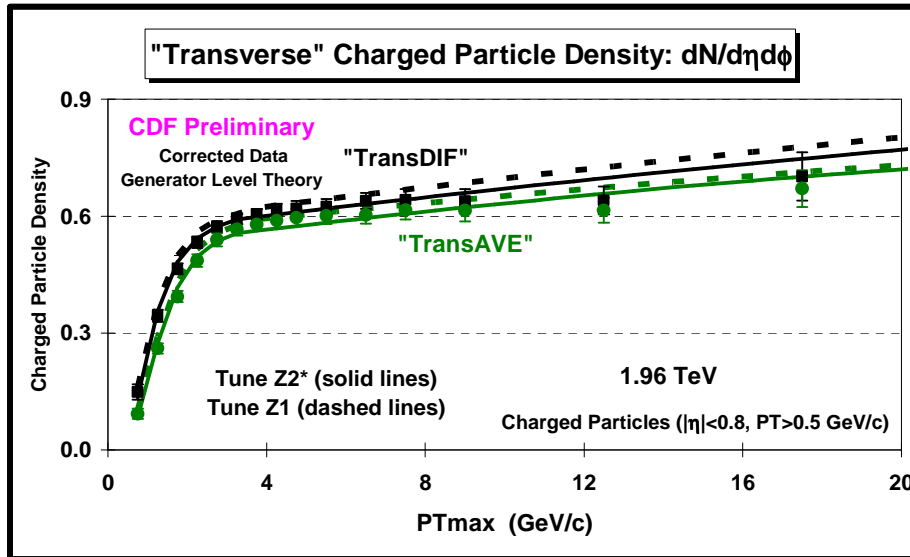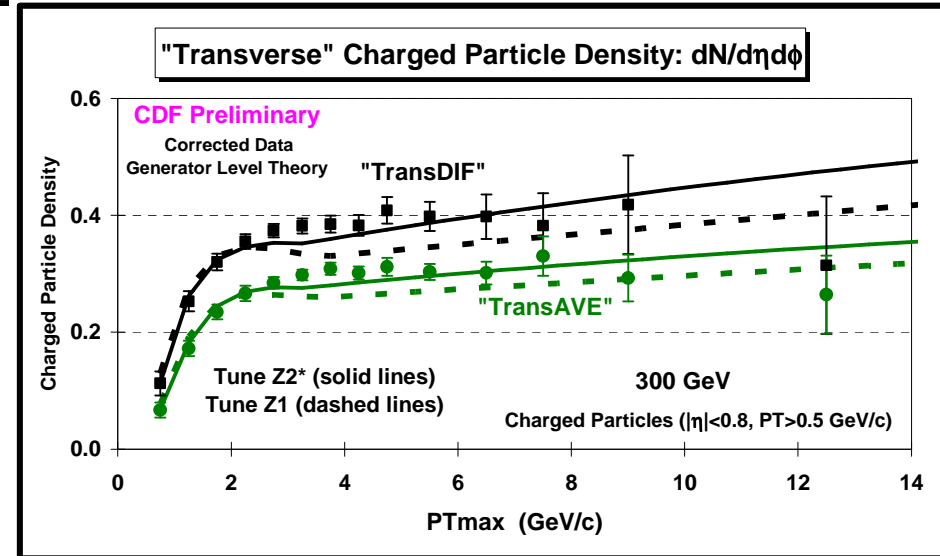

"TransDIF" Charged Particle Density: dN/dηdφ

"TransMAX" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data
Generator Level Teory

1.96 TeV

900 GeV

300 GeV

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Charged Particle Density

PTmax (GeV/c)

"TransMIN" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data
Generator Level Theory

1.96 TeV

900 GeV

300 GeV

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Charged Particle Density

PTmax (GeV/c)

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged particle density in the **"transMAX"**, **"transMIN"**, and **"transDIF"** regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|η| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.
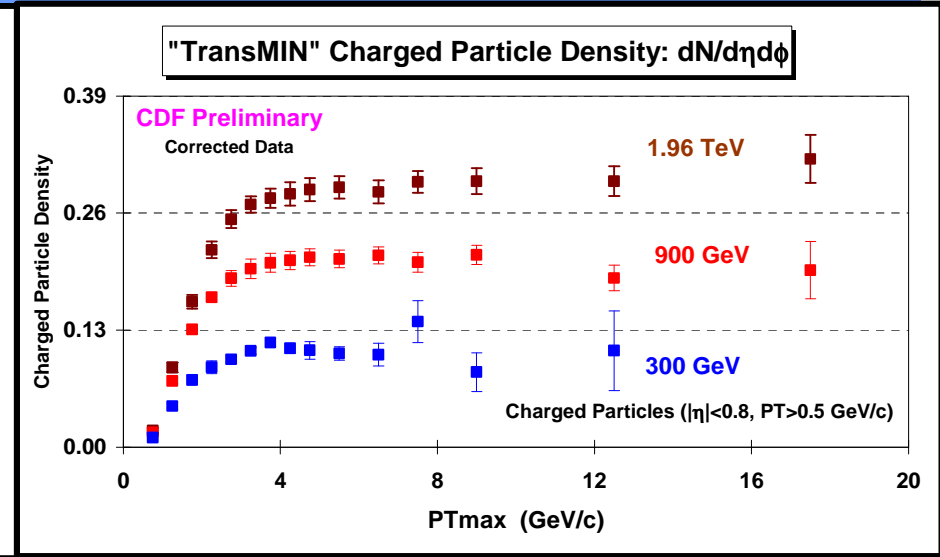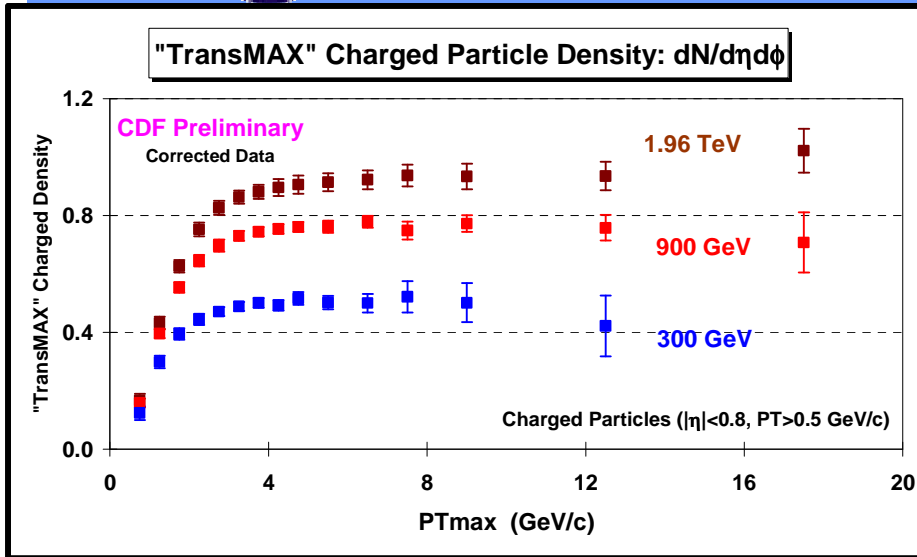
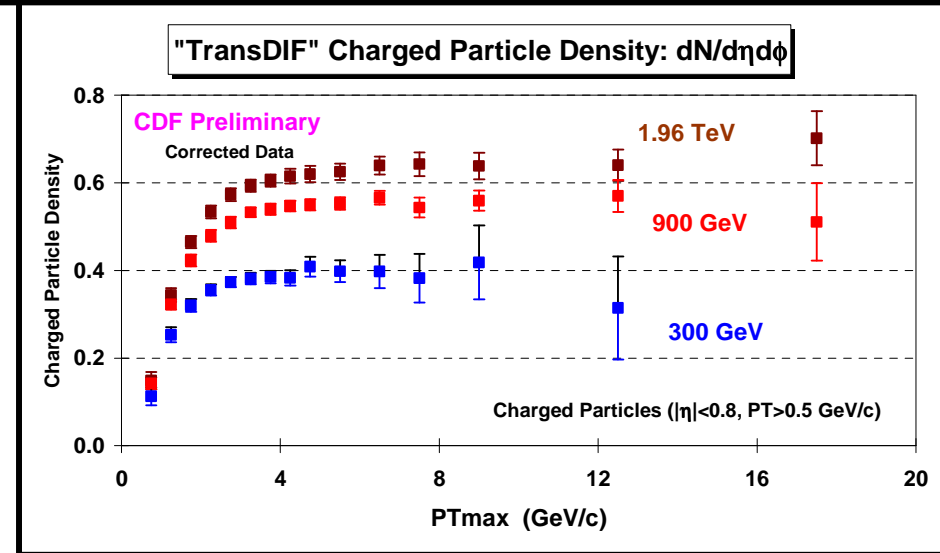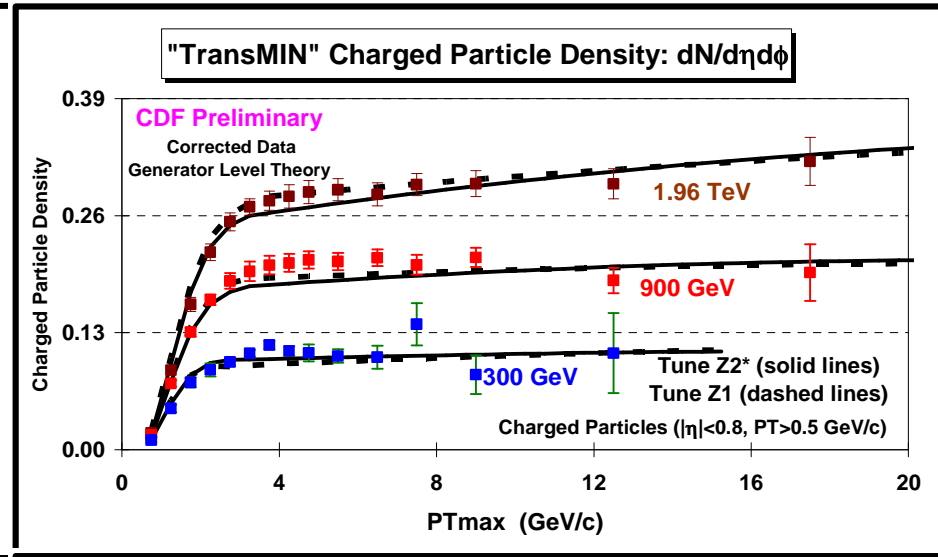The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

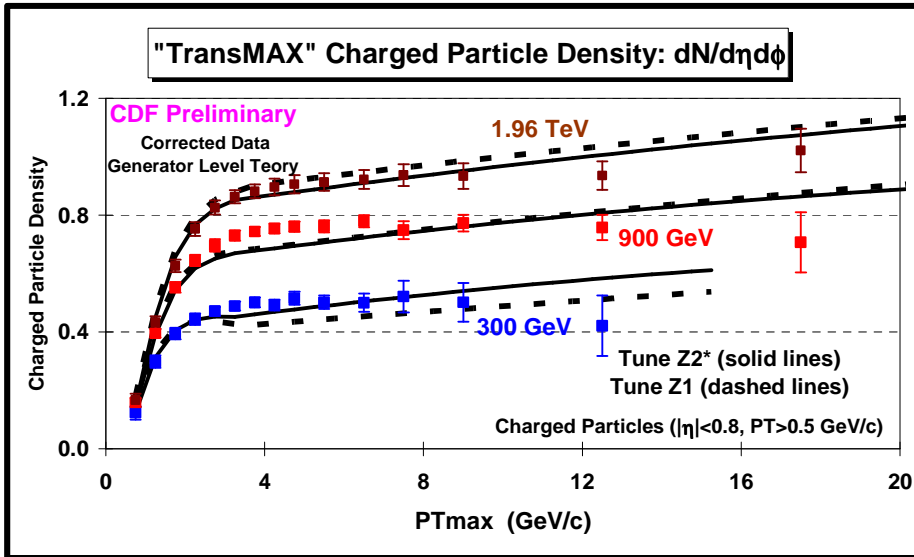**"TransDIF" Charged Particle Density: dN/dηdφ**

CDF Preliminary
Corrected Data
Generator Level Theory

1.96 TeV

900 GeV

300 GeV

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Charged Particle Density

PTmax (GeV/c)

"Transverse" Charged PTsum Density: dPT/dηdφ

1.96 TeV, "TransMAX", "TransMIN", CDF Preliminary, Corrected Data, Charged Particles (|η|<0.8, PT>0.5 GeV/c)

"Transverse" Charged PTsum Density: dPT/dηdφ

900 GeV, "TransMAX", "TransMIN", CDF Preliminary, Corrected Data, Charged Particles (|η|<0.8, PT>0.5 GeV/c)

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged PTsum density in the **"transMAX"** and **"transMIN"** regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.
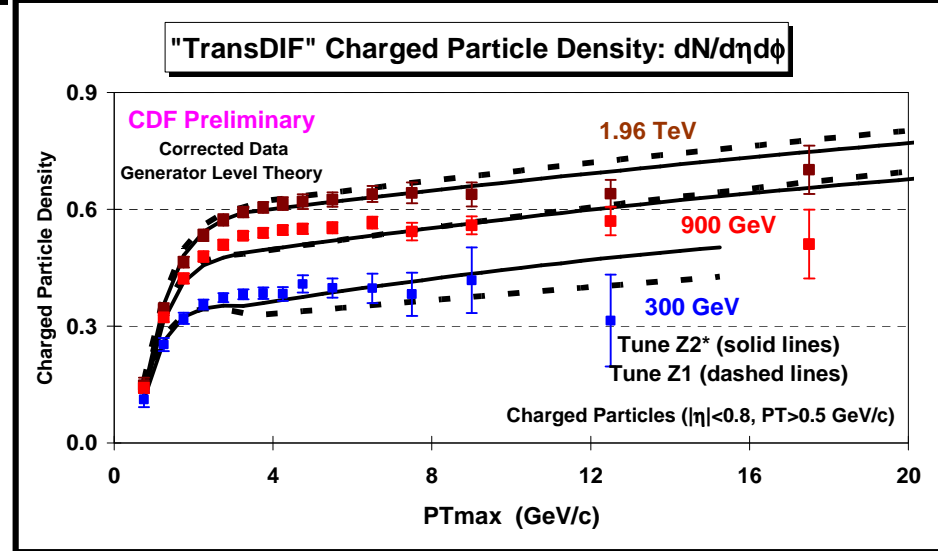

"Transverse" Charged PTsum Density: dPT/dηdφ

300 GeV, "TransMAX", "TransMIN", CDF Preliminary, Corrected Data, Charged Particles (|η|<0.8, PT>0.5 GeV/c)

"Transverse" Charged PTsum Density: dPT/dηdφ

CDF Preliminary
Corrected Data
Generator Level Theory
1.96 TeV
"TransMAX"
Tune Z2* (solid lines)
Tune Z1 (dashed lines)
"TransMIN"
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

"Transverse" Charged PTsum Density: dPT/dηdφ

CDF Preliminary
Corrected Data
Generator Level Theory
900 GeV
"TransMAX"
Tune Z2* (solid lines)
Tune Z1 (dashed lines)
"TransMIN"
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

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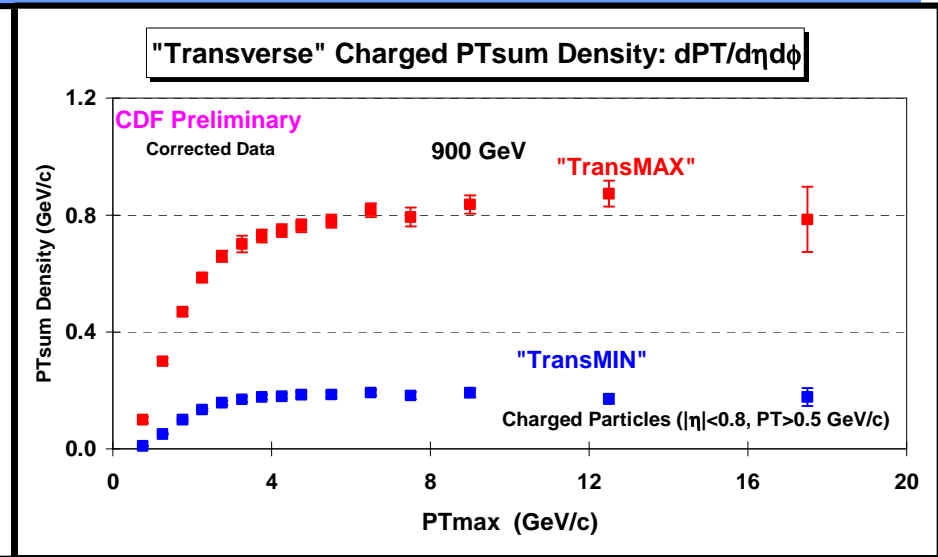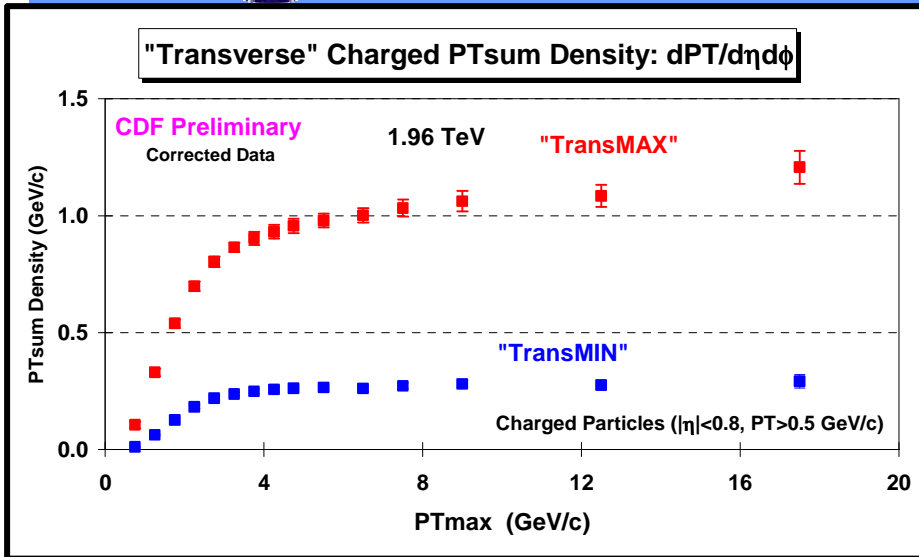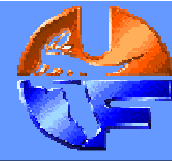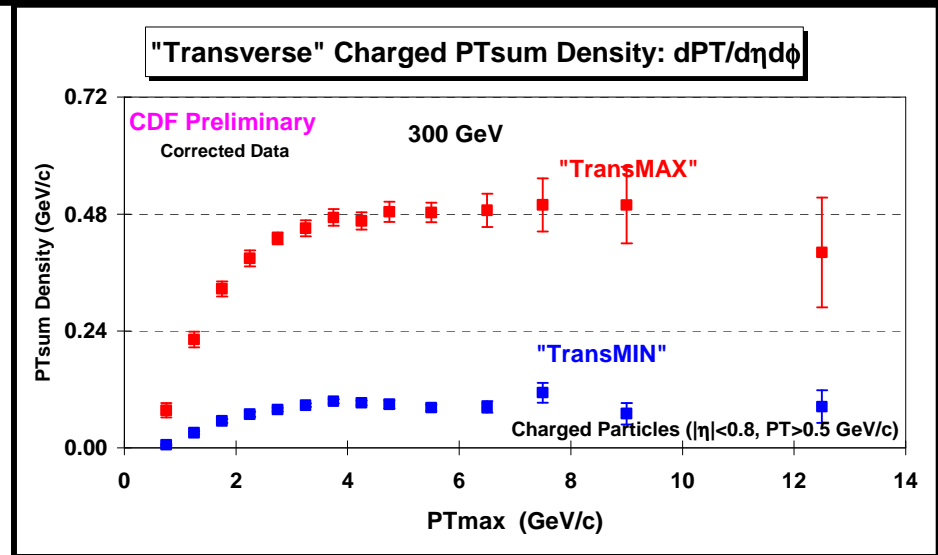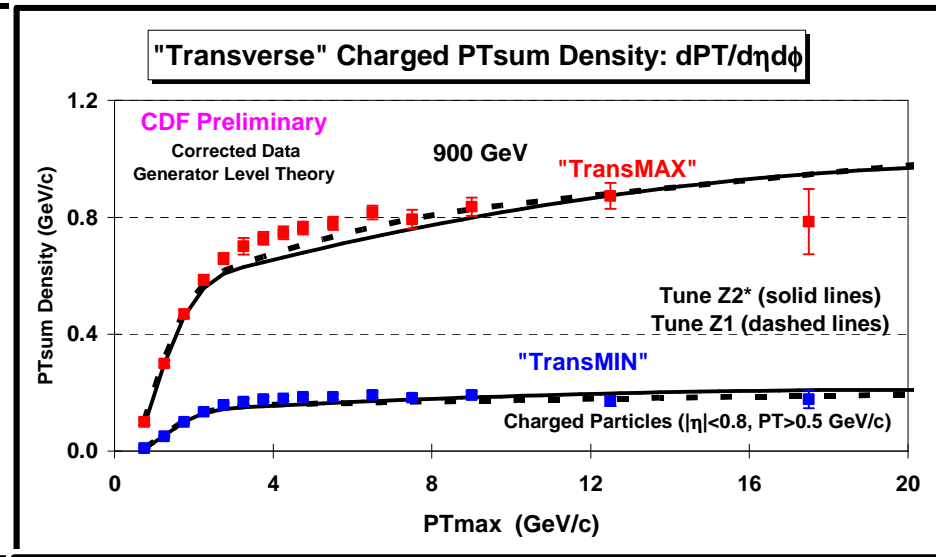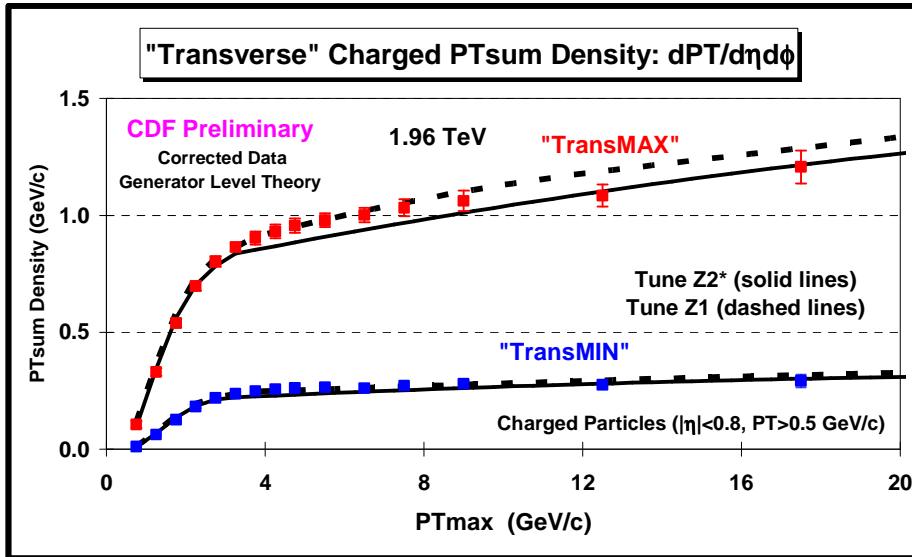The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

"Transverse" Charged PTsum Density: dPT/dηdφ

CDF Preliminary
Corrected Data
Generator Level Theory
300 GeV
"TransMAX"
Tune Z2* (solid lines)
Tune Z1 (dashed lines)
"TransMIN"
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

"Transverse" Charged PTsum Density: dPT/dηdφ

CDF Preliminary
Corrected Data
"TransDIF"
"TransAVE"
1.96 TeV
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

"Transverse" Charged PTsum Density: dPT/dηdφ

CDF Preliminary
Corrected Data
"TransDIF"
"TransAVE"
900 GeV
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

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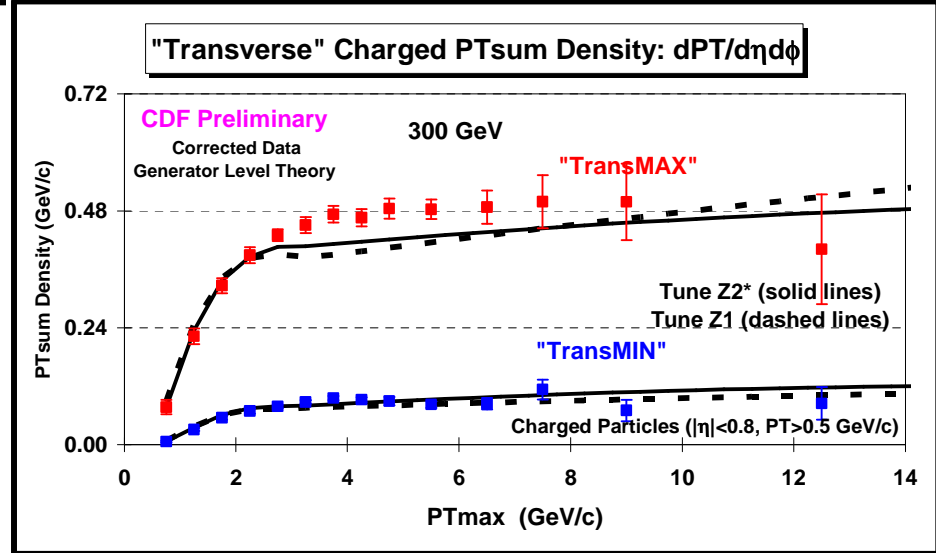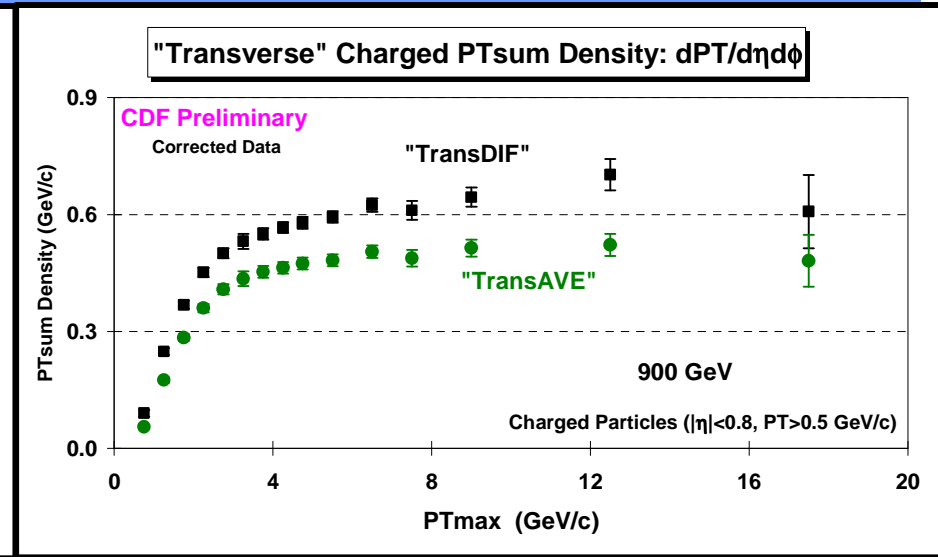

"Transverse" Charged PTsum Density: dPT/dηdφ

CDF Preliminary
Corrected Data
"TransDIF"
"TransAVE"
300 GeV
Charged Particles (|η|<0.8, PT>0.5 GeV/c)

"Transverse" Charged PTsum Density: dPT/dηdφ

CDF Preliminary
Corrected Data
Generator Level Theory

"TransDIF"

"TransAVE"

1.96 TeV

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

PTsum Density (GeV/c)

PTmax (GeV/c)

"Transverse" Charged PTsum Density: dPT/dηdφ

CDF Preliminary
Corrected Data
Generator Level Theory

"TransDIF"

"TransAVE"

900 GeV

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

PTsum Density (GeV/c)

PTmax (GeV/c)

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged PTsum density in the **"transAVE"** and **"transDIF"** regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.
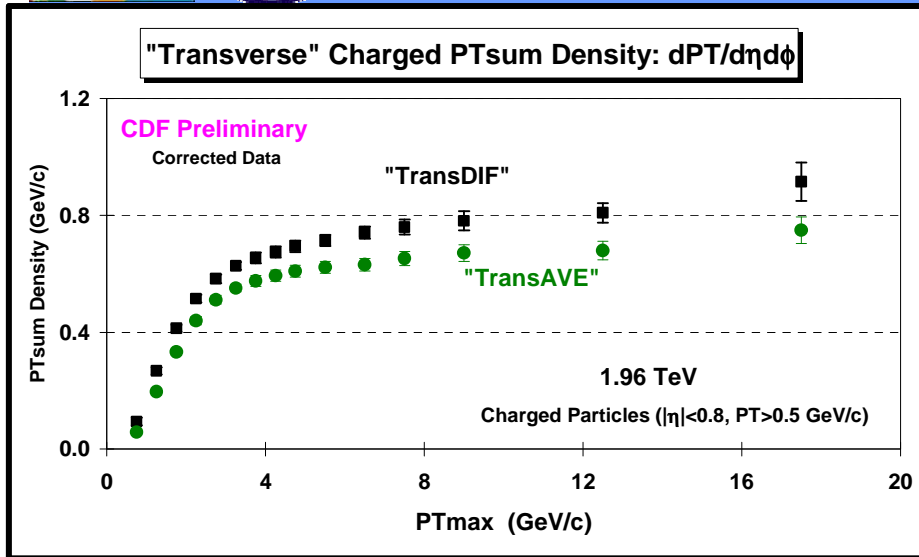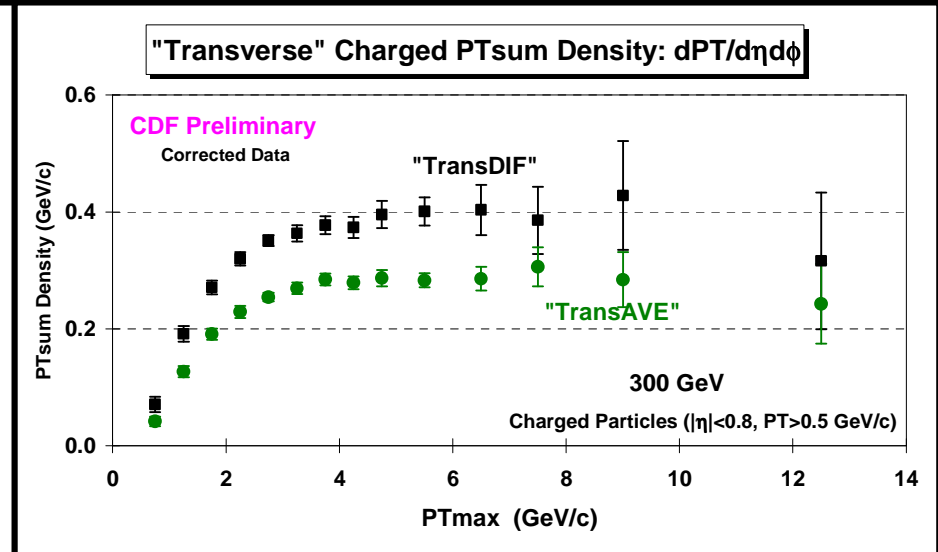
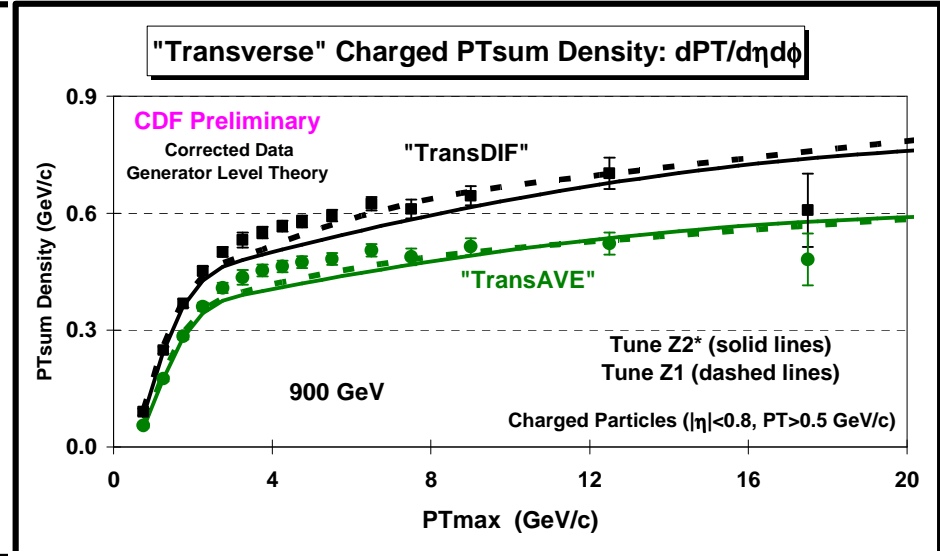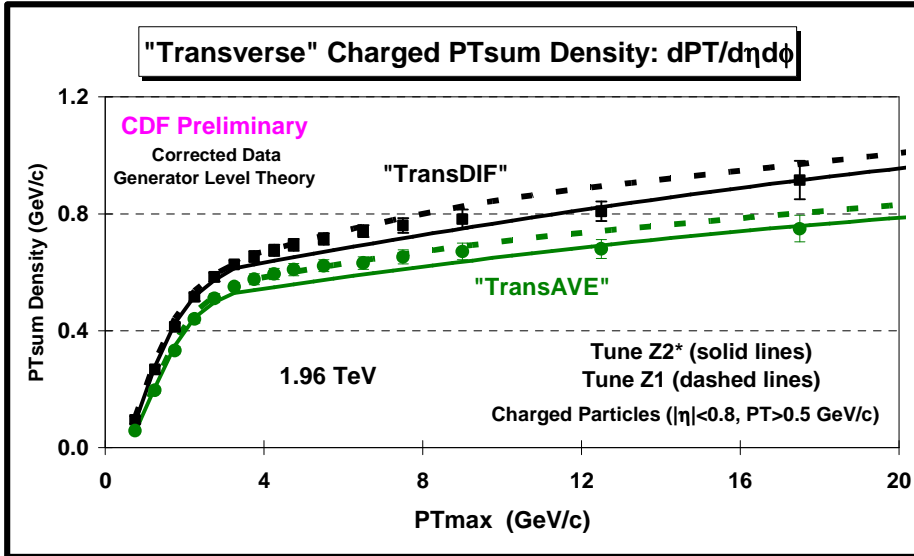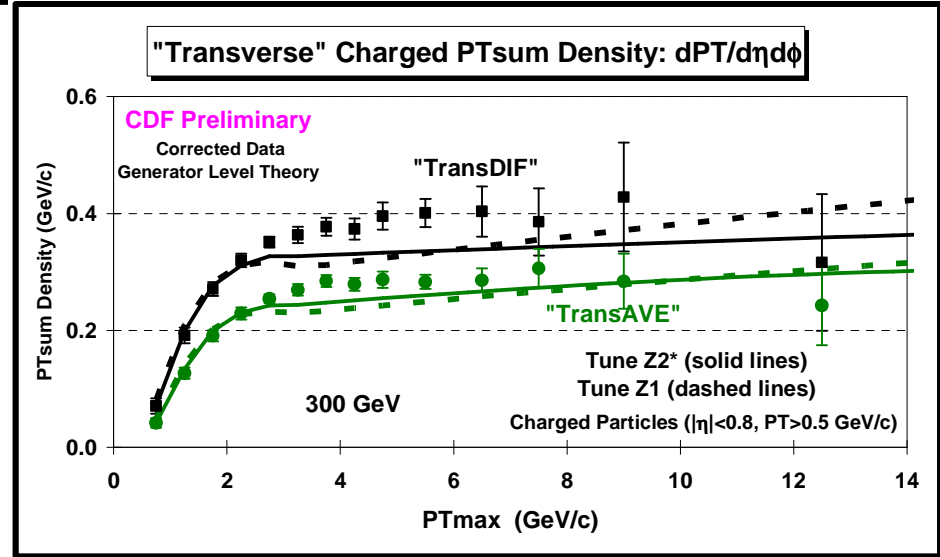The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

"Transverse" Charged PTsum Density: dPT/dηdφ

CDF Preliminary
Corrected Data
Generator Level Theory

"TransDIF"

"TransAVE"

300 GeV

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

PTsum Density (GeV/c)

PTmax (GeV/c)

"TransAVE" Density

"TransAVE" Charged Particle Density: dN/dηdφ

RDF Preliminary
Corrected Data
Generator Level Theory

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

7 TeV
1.96 TeV
900 GeV
300 GeV

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

(Y-axis: Charged Particle Density; X-axis: PTmax (GeV/c))

"Transverse" Charged PTsum Density: dPT/dηdφ

RDF Preliminary
Corrected Data
Generator Level Theory

7 TeV
1.96 TeV
900 GeV
300 GeV

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

(Y-axis: PTsum Density (GeV/c); X-axis: PTmax (GeV/c))

➡ **Corrected CMS data at 7 TeV and CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged particle density in the **"transAVE"** region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include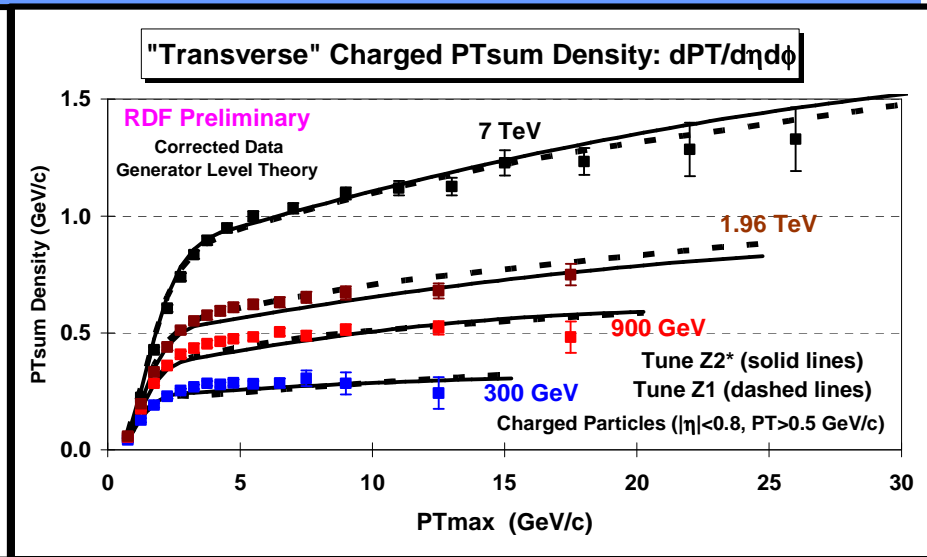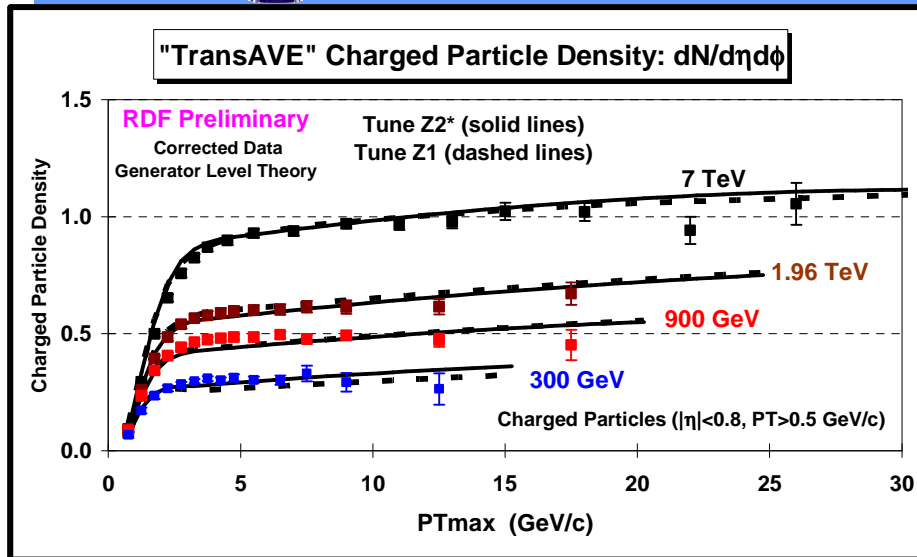 both the statistical error and the systematic uncertainty. The data are compared with PYTHIA **Tune Z1** and **Tune Z2***.

➡ **Corrected CMS data at 7 TeV and CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged PTsum density in the **"transAVE"** region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty. The data are compared with PYTHIA **Tune Z1** and **Tune Z2***.
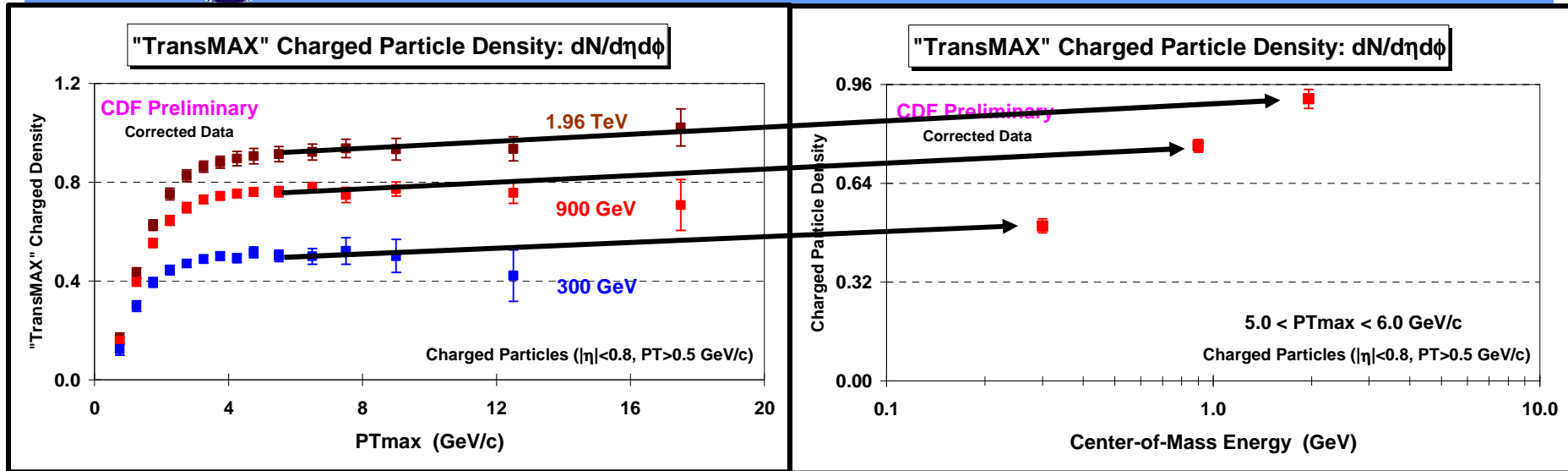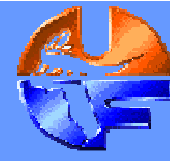
"TransMAX" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data

1.96 TeV

900 GeV

300 GeV

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

"TransMAX" Charged Density

PTmax (GeV/c)

"TransMAX" Charged Particle Density: dN/dηdφ

CDF Preliminary
Corrected Data

5.0 < PTmax < 6.0 GeV/c

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Charged Particle Density

Center-of-Mass Energy (GeV)

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged particle density in the **"transMAX"** region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.

➡ **Corrected CDF data** on the charged particle density in the **"transMAX"** region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 <$ PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*).

"Transverse" Charged Particle Density: dN/dηdφ

"Transverse" Charged PTsum Density: dPT/dηdφ

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged particle density in the **"transMAX"**, and the **"transMIN"**, regions as defined by the leading charged particle (PTmax) for charged particles with p$_T$ > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged PTsum density in the **"transMAX"**, and the **"transMIN"**, regions as defined by the leading charged particle (PTmax) for charged particles with p$_T$ > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

"TransMAX/MIN" vs E$_{cm}$

"Transverse" Charged Particle Density Ratio

CDF Preliminary
corrected data
generator level theory

CMS solid dots
CDF solid squares

5.0 < PTmax < 6.0 GeV/c

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Divided by 300 GeV Value

"TransMIN"

"TransMAX"

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Particle Density Ratio

Center-of-Mass Energy (GeV)

"Transverse" Charged PTsum Density Ratio

CDF Preliminary
corrected data
generator level theory

CMS solid dots
CDF solid squares

5.0 < PTmax < 6.0 GeV/c

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Divided by 300 GeV Value

"TransMIN"

"TransMAX"

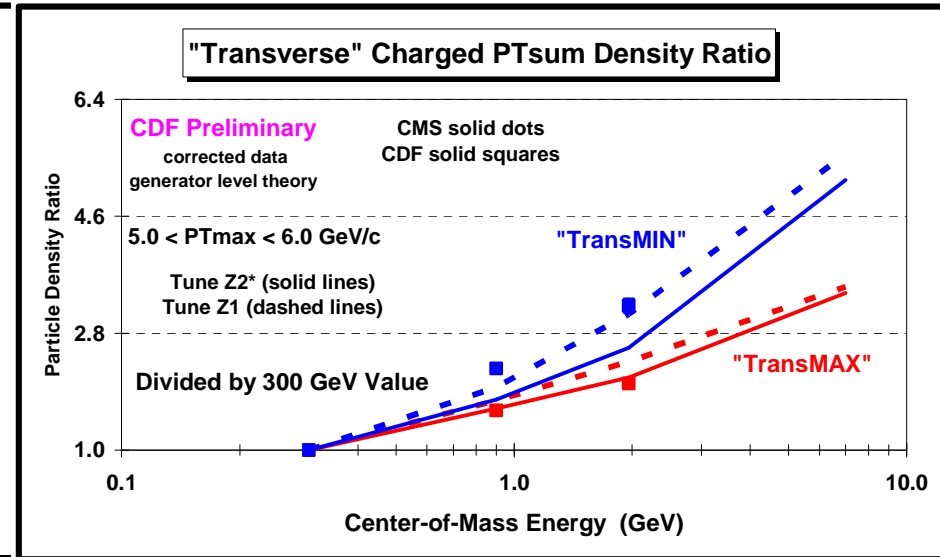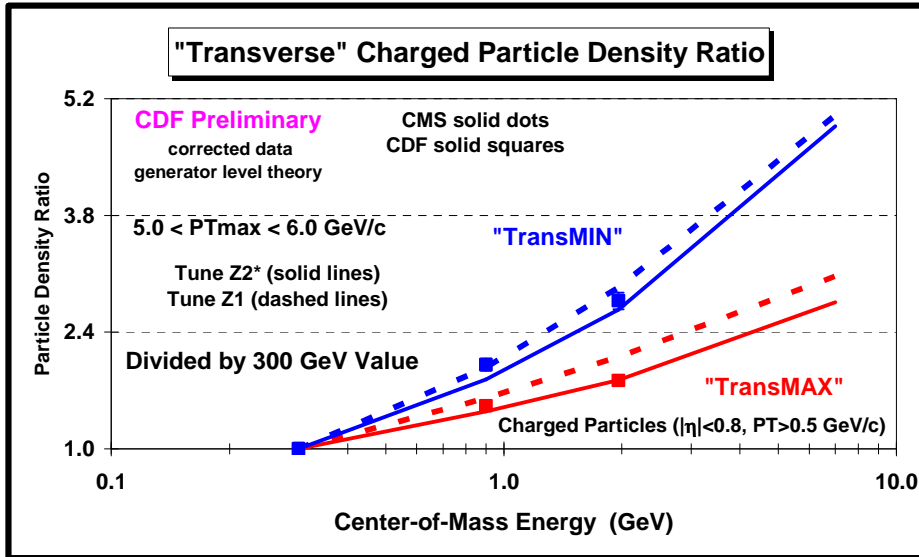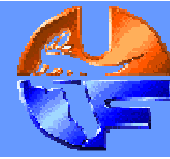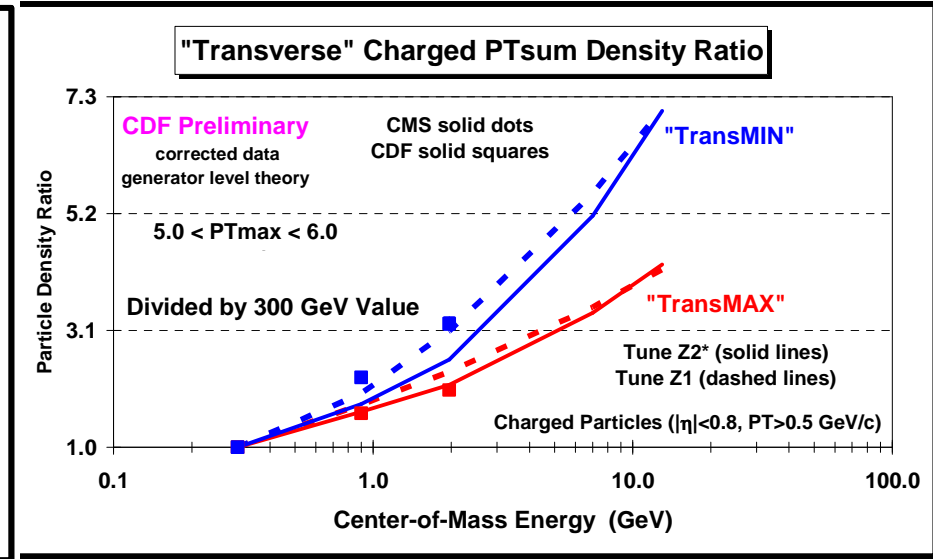Particle Density Ratio

Center-of-Mass Energy (GeV)

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged particle density in the **"transMAX"**, and the **"transMIN"**, regions as defined by the leading charged particle (PTmax) for charged particles with p$_T$ > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged PTsum density in the **"transMAX"**, and the **"transMIN"**, regions as defined by the leading charged particle (PTmax) for charged particles with p$_T$ > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

The data are "normalized" by dividing by the corresponding value at 300 GeV.

"TransMAX/MIN" vs E_{cm}

"Transverse" Charged Particle Density Ratio

CDF Preliminary
corrected data
generator level theory

5.0 < PTmax < 6.0 GeV/c

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Divided by 300 GeV Value

CMS solid dots
CDF solid squares

"TransMIN"

"TransMAX"

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Particle Density Ratio — Center-of-Mass Energy (GeV)

"Transverse" Charged PTsum Density Ratio

CDF Preliminary
corrected data
generator level theory

5.0 < PTmax < 6.0

Divided by 300 GeV Value

CMS solid dots
CDF solid squares

"TransMIN"

"TransMAX"

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Charged Particles (|η|<0.8, PT>0.5 GeV/c)
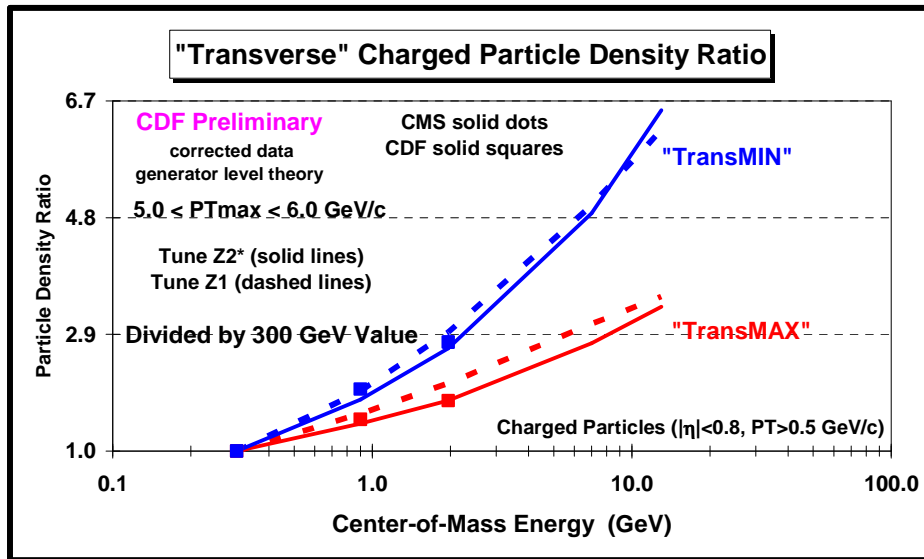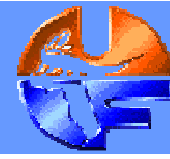
Particle Density Ratio — Center-of-Mass Energy (GeV)

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transMAX", and the "transMIN", regions as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 Tune Z1 and Tune Z2*.**
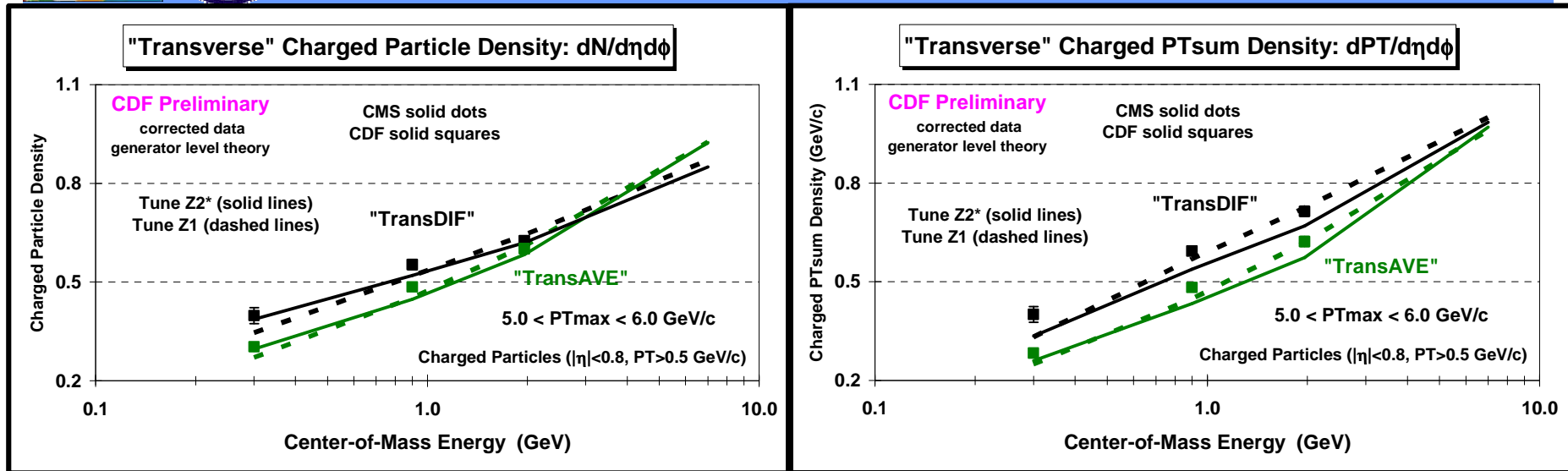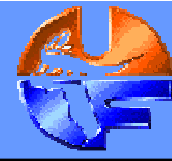
➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged PTsum density in the "transMAX", and the "transMIN", regions as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 Tune Z1 and Tune Z2*.**

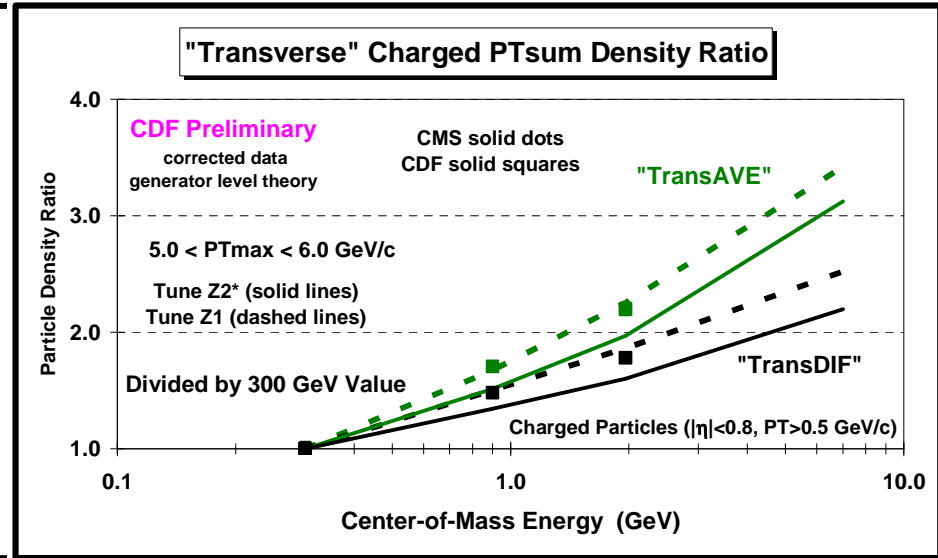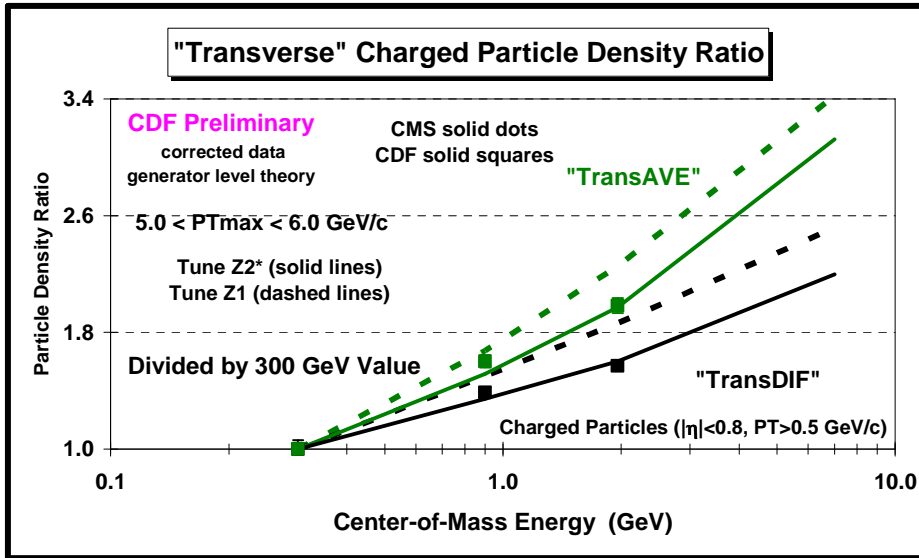**The data are "normalized" by dividing by the corresponding value at 300 GeV.**

"Transverse" Charged Particle Density: dN/dηdφ

CDF Preliminary
corrected data
generator level theory

CMS solid dots
CDF solid squares

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

"TransDIF"

"TransAVE"

5.0 < PTmax < 6.0 GeV/c

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Charged Particle Density

Center-of-Mass Energy (GeV)

"Transverse" Charged PTsum Density: dPT/dηdφ

CDF Preliminary
corrected data
generator level theory

CMS solid dots
CDF solid squares

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

"TransDIF"

"TransAVE"

5.0 < PTmax < 6.0 GeV/c

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Charged PTsum Density (GeV/c)

Center-of-Mass Energy (GeV)

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged particle density in the **"transAVE"**, and the **"transDIF"**, regions as defined by the leading charged particle (PTmax) for charged particles with p$_T$ > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged PTsum density in the **"transAVE"**, and the **"transDIF"**, regions as defined by the leading charged particle (PTmax) for charged particles with p$_T$ > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

"Transverse" Charged Particle Density Ratio

CDF Preliminary
corrected data
generator level theory

CMS solid dots
CDF solid squares

"TransAVE"

5.0 < PTmax < 6.0 GeV/c

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Divided by 300 GeV Value

"TransDIF"

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Particle Density Ratio

Center-of-Mass Energy (GeV)

"Transverse" Charged PTsum Density Ratio

CDF Preliminary
corrected data
generator level theory

CMS solid dots
CDF solid squares

"TransAVE"

5.0 < PTmax < 6.0 GeV/c

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Divided by 300 GeV Value

"TransDIF"

Charged Particles (|η|<0.8, PT>0.5 GeV/c)
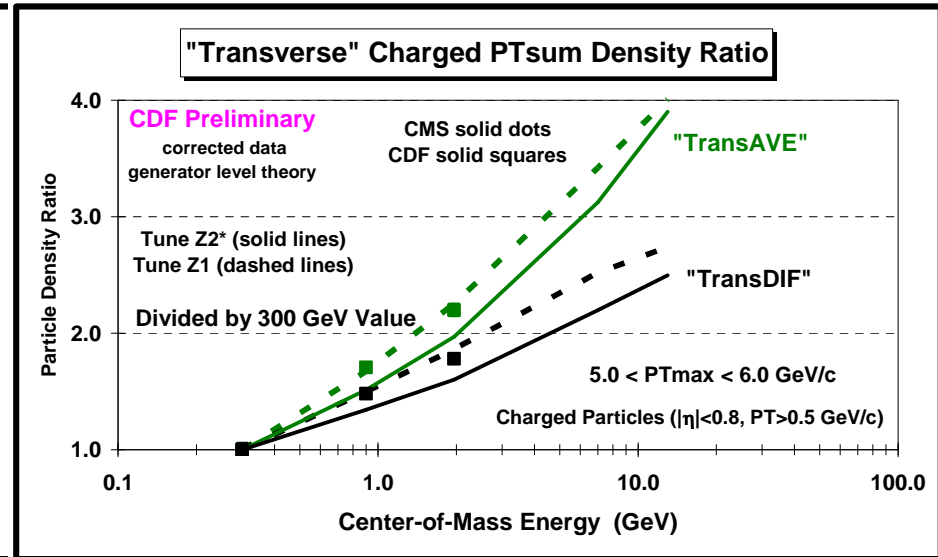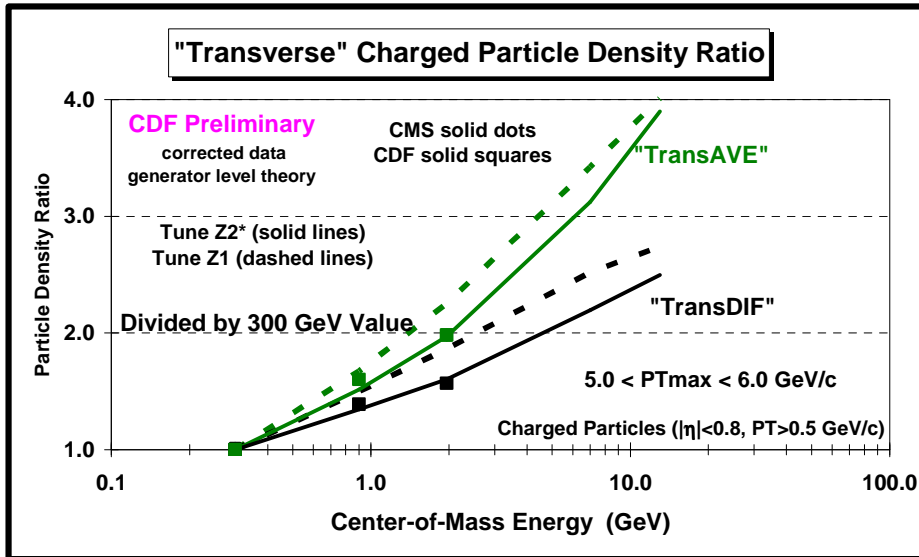
Particle Density Ratio

Center-of-Mass Energy (GeV)

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged particle density in the **"transAVE"**, and the **"transDIF"**, regions as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

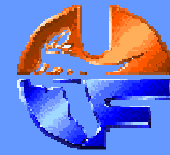➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged PTsum density in the **"transAVE"**, and the **"transDIF"**, regions as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

The data are "normalized" by dividing by the corresponding value at 300 GeV.

"Transverse" Charged Particle Density Ratio

"Transverse" Charged PTsum Density Ratio

➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged particle density in the **"transAVE"**, and the **"transDIF"**, regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 <$ PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.
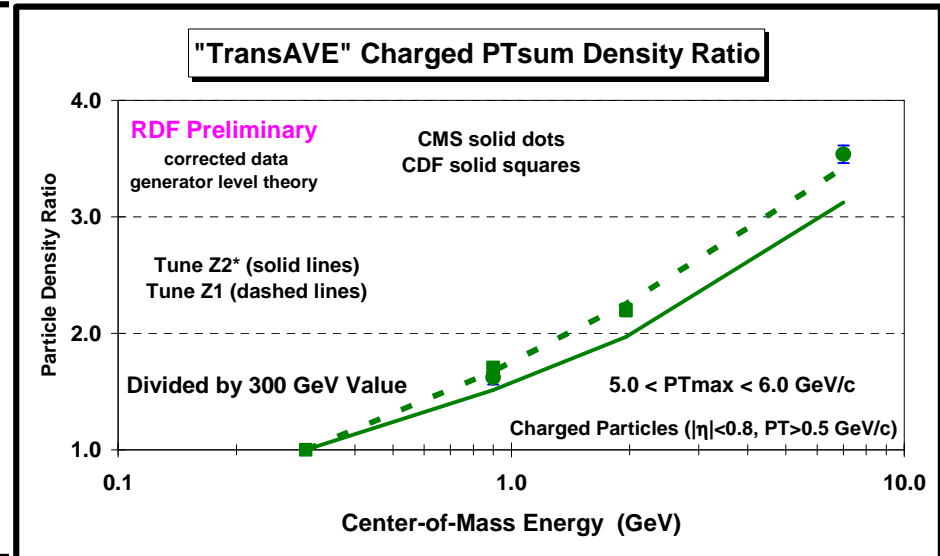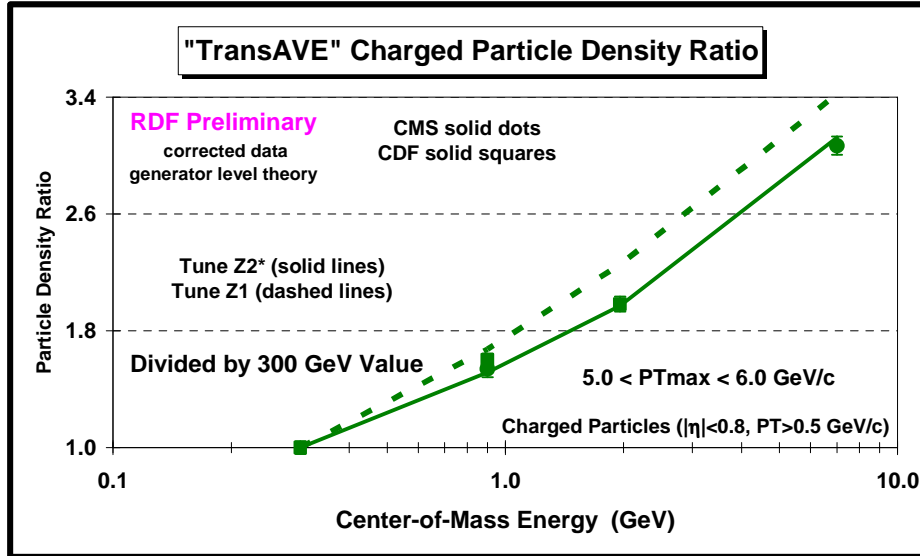
➡ **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged PTsum density in the **"transAVE"**, and the **"transDIF"**, regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 <$ PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

The data are "normalized" by dividing by the corresponding value at 300 GeV.

"TransAVE" Charged Particle Density Ratio

RDF Preliminary
corrected data
generator level theory

CMS solid dots
CDF solid squares

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Divided by 300 GeV Value

5.0 < PTmax < 6.0 GeV/c

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Particle Density Ratio

Center-of-Mass Energy (GeV)

"TransAVE" Charged PTsum Density Ratio

RDF Preliminary
corrected data
generator level theory

CMS solid dots
CDF solid squares

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Divided by 300 GeV Value

5.0 < PTmax < 6.0 GeV/c

Charged Particles (|η|<0.8, PT>0.5 GeV/c)
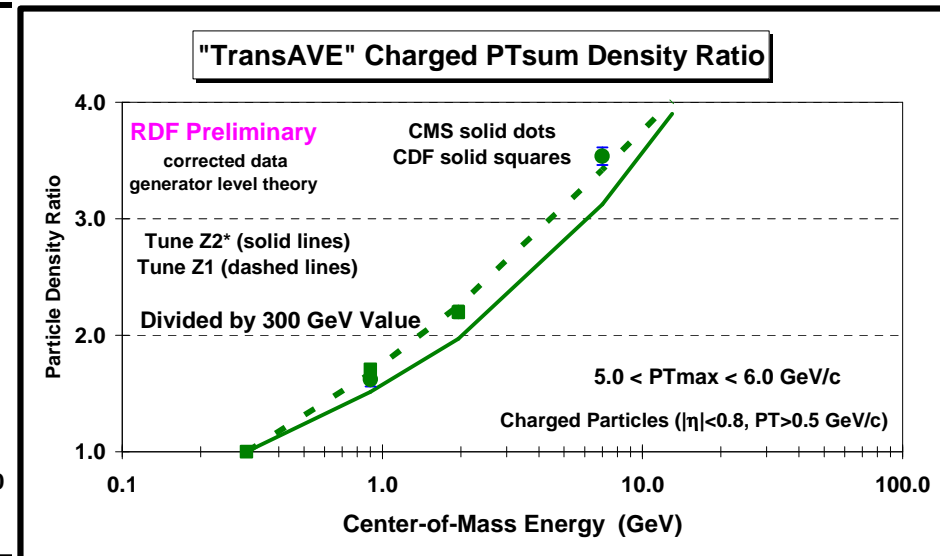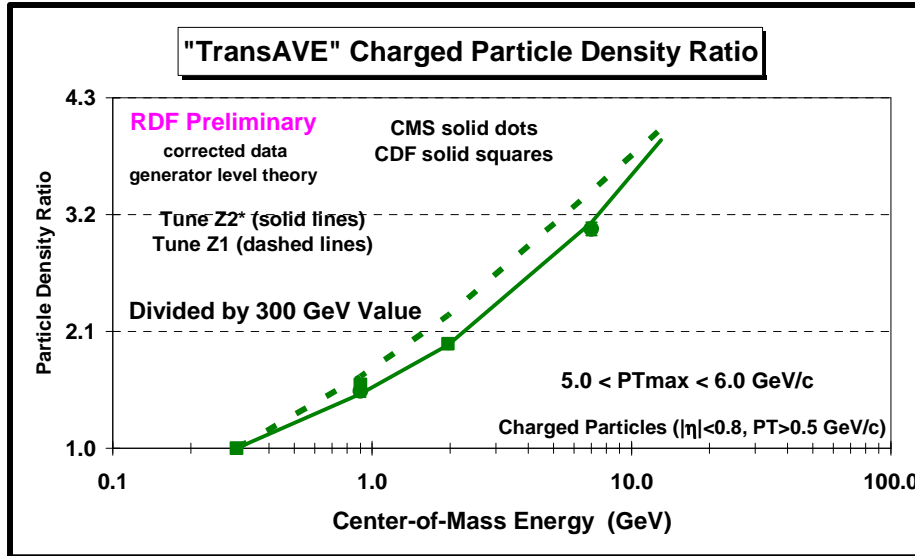
Particle Density Ratio

Center-of-Mass Energy (GeV)

➡ **Corrected CMS data at 900 GeV and 7 TeV and CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged particle density in the **"transAVE"** region as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.
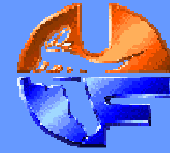
➡ **Corrected CMS data at 900 GeV and 7 TeV and CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged PTsum density in the **"transAVE"** region as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

The data are "normalized" by dividing by the corresponding value at 300 GeV.

"TransAVE" vs E_cm

"TransAVE" Charged Particle Density Ratio

RDF Preliminary
corrected data
generator level theory

CMS solid dots
CDF solid squares

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Divided by 300 GeV Value

5.0 < PTmax < 6.0 GeV/c

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Particle Density Ratio — Center-of-Mass Energy (GeV)

"TransAVE" Charged PTsum Density Ratio

RDF Preliminary
corrected data
generator level theory

CMS solid dots
CDF solid squares

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Divided by 300 GeV Value

5.0 < PTmax < 6.0 GeV/c

Charged Particles (|η|<0.8, PT>0.5 GeV/c)
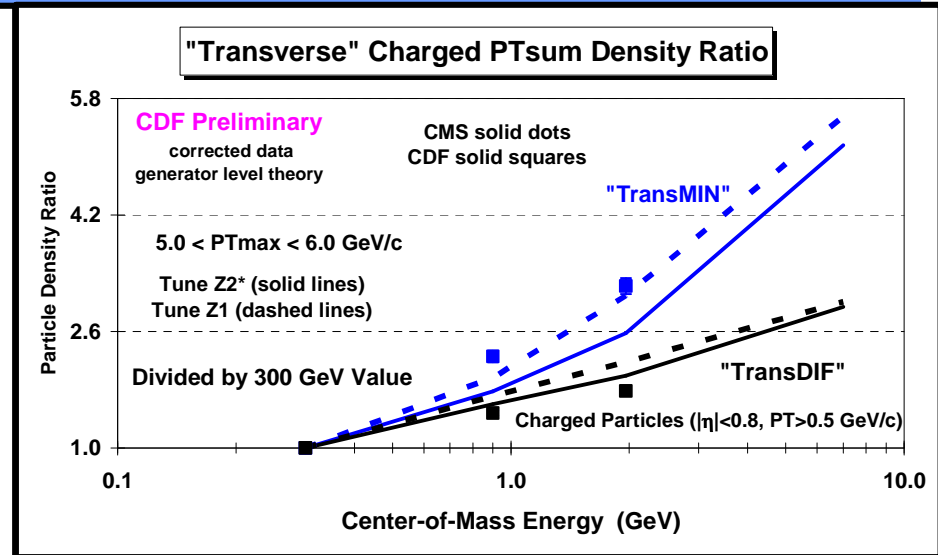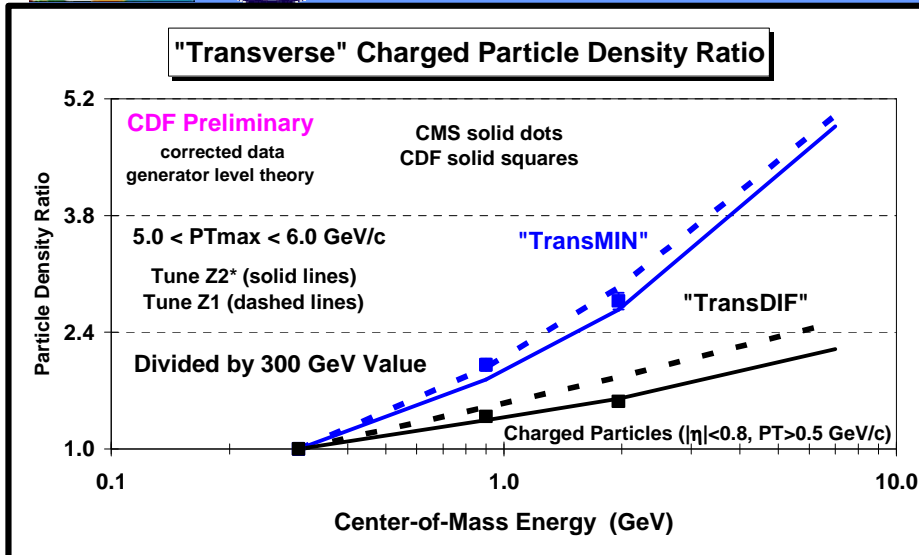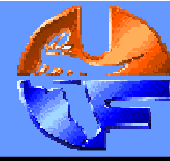
Particle Density Ratio — Center-of-Mass Energy (GeV)

➡ **Corrected CMS data at 900 GeV and 7 TeV and CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged particle density in the **"transAVE"** region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 < PTmax < 6$ GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

➡ **Corrected CMS data at 900 GeV and 7 TeV and CDF data at 1.96 TeV, 900 GeV, and 300 GeV** on the charged PTsum density in the **"transAVE"** region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 < PTmax < 6$ GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

The data are "normalized" by dividing by the corresponding value at 300 GeV.

"TransMIN/DIF" vs E_{cm}

"Transverse" Charged Particle Density Ratio

CDF Preliminary
corrected data
generator level theory

CMS solid dots
CDF solid squares

5.0 < PTmax < 6.0 GeV/c

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Divided by 300 GeV Value

"TransMIN"

"TransDIF"

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Particle Density Ratio

Center-of-Mass Energy (GeV)

"Transverse" Charged PTsum Density Ratio

CDF Preliminary
corrected data
generator level theory

CMS solid dots
CDF solid squares

5.0 < PTmax < 6.0 GeV/c

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Divided by 300 GeV Value

"TransMIN"

"TransDIF"

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Particle Density Ratio
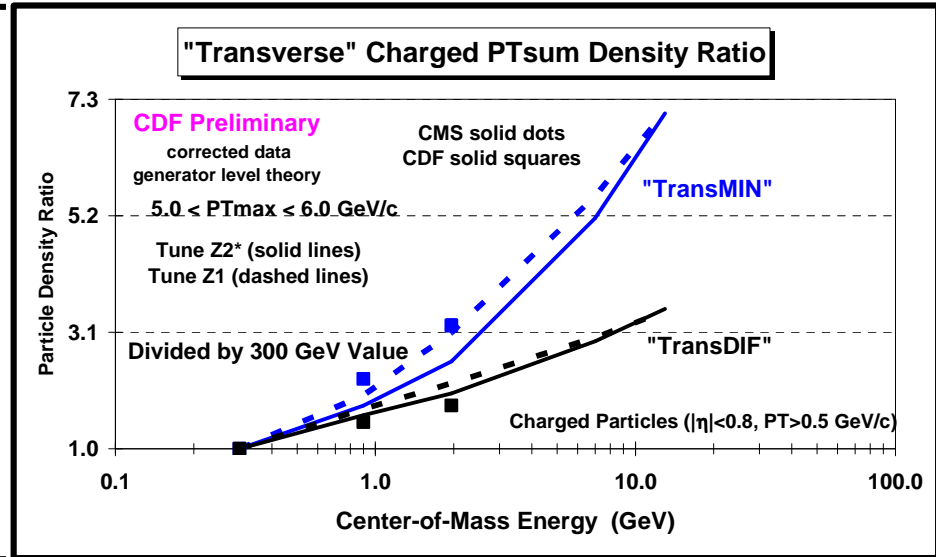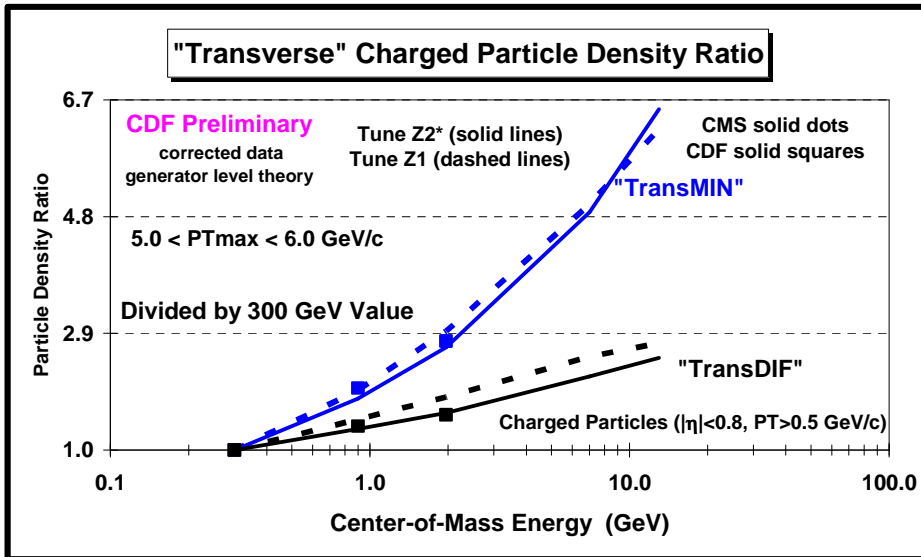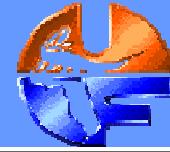
Center-of-Mass Energy (GeV)

➡ **Ratio of CDF data at 1.96 TeV, 900 GeV, and 300 GeV to the value at 300 GeV** for the charged particle density in the **"transMIN"**, and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and $|\eta|$ < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

➡ **Ratio of CDF data at 1.96 TeV, 900 GeV, and 300 GeV to the value at 300 GeV** for the charged PTsum density in the **"transMIN"**, and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and $|\eta|$ < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

The data are "normalized" by dividing by the corresponding value at 300 GeV.

"Transverse" Charged Particle Density Ratio

CDF Preliminary
corrected data
generator level theory

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

CMS solid dots
CDF solid squares

"TransMIN"

5.0 < PTmax < 6.0 GeV/c

Divided by 300 GeV Value

"TransDIF"

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Particle Density Ratio

Center-of-Mass Energy (GeV)

"Transverse" Charged PTsum Density Ratio

CDF Preliminary
corrected data
generator level theory

CMS solid dots
CDF solid squares

"TransMIN"

5.0 < PTmax < 6.0 GeV/c

Tune Z2* (solid lines)
Tune Z1 (dashed lines)

Divided by 300 GeV Value

"TransDIF"

Charged Particles (|η|<0.8, PT>0.5 GeV/c)
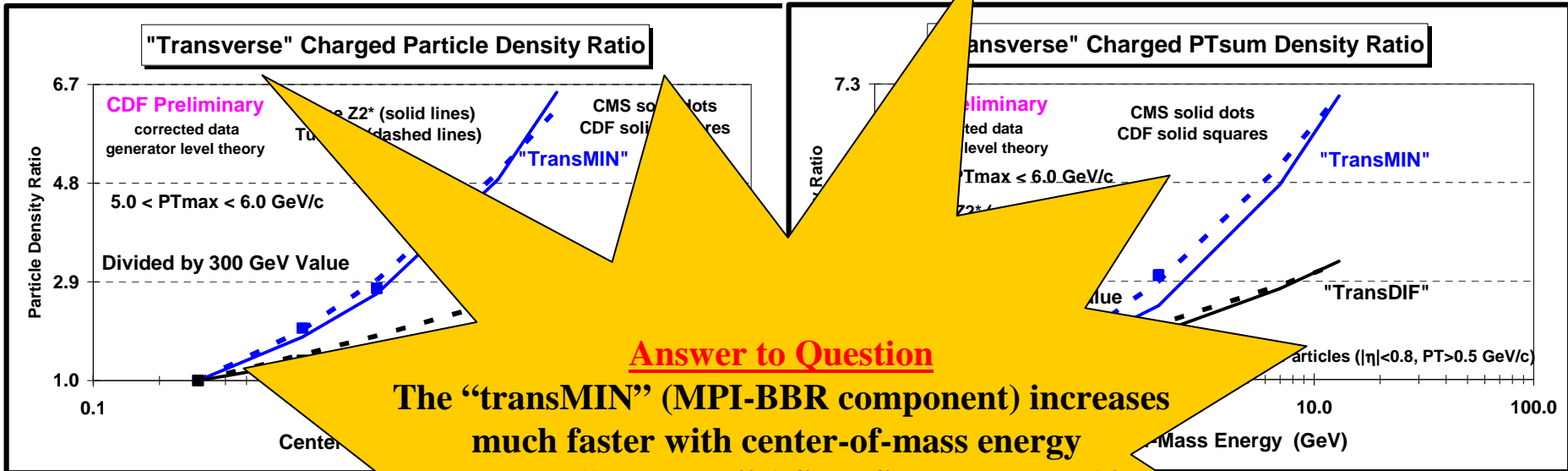
Particle Density Ratio

Center-of-Mass Energy (GeV)

➡ **Ratio of CDF data at 1.96 TeV, 900 GeV, and 300 GeV to the value at 300 GeV** for the charged particle density in the **"transMIN"**, and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and $|\eta|$ < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.
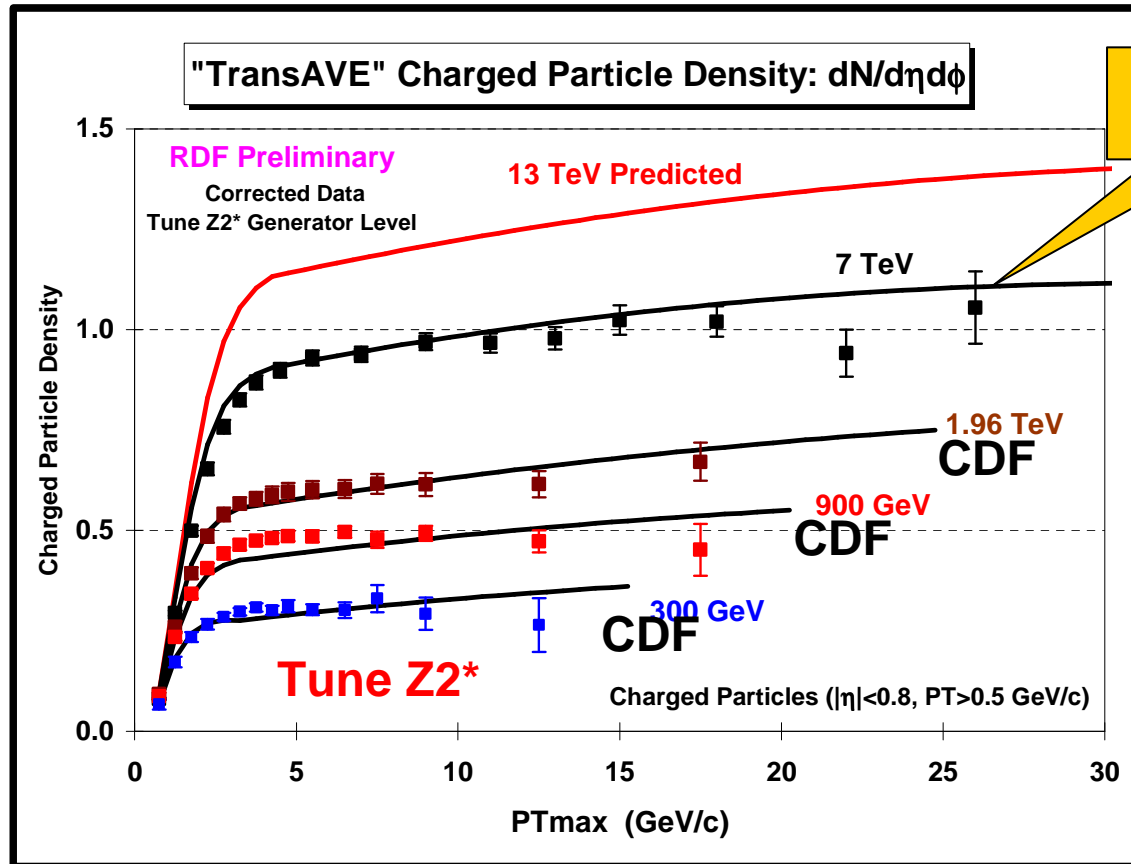
➡ **Ratio of CDF data at 1.96 TeV, 900 GeV, and 300 GeV to the value at 300 GeV** for the charged PTsum density in the **"transMIN"**, and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and $|\eta|$ < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

The data are "normalized" by dividing by the corresponding value at 300 GeV.
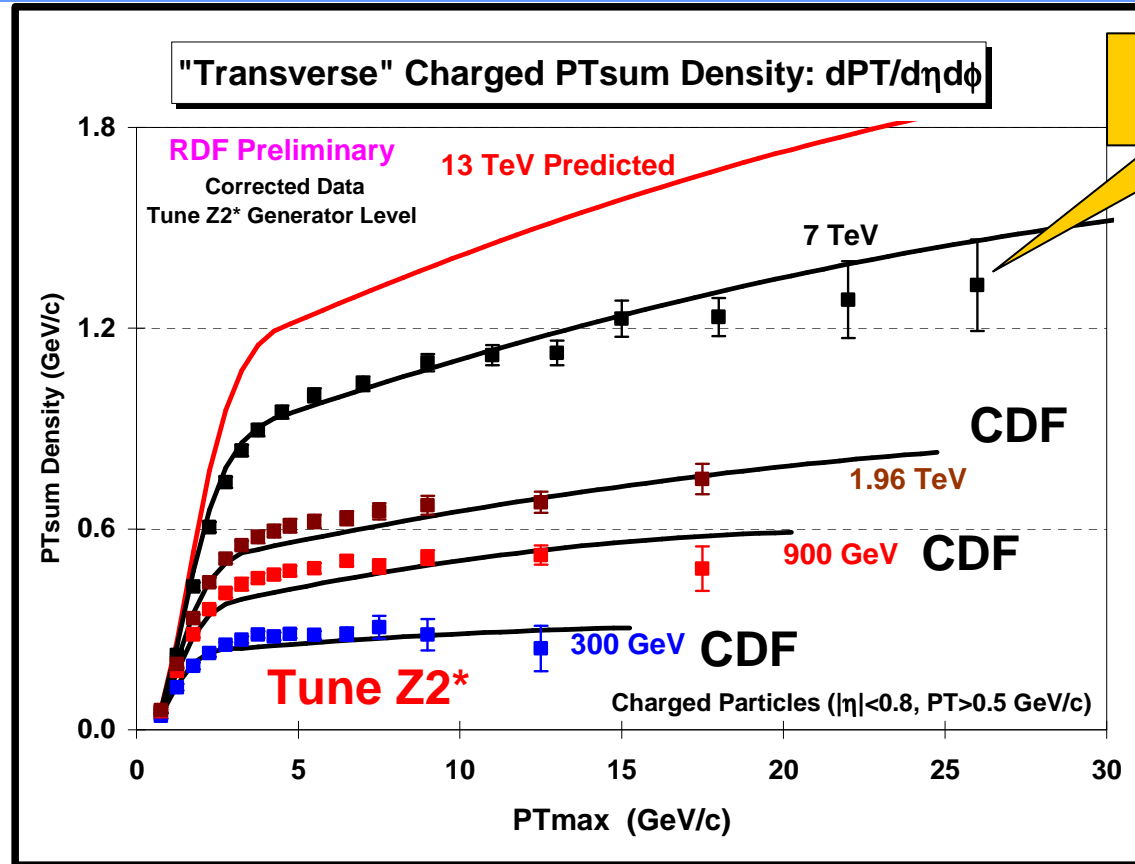
"TransMIN/DIF" vs E_cm

"Transverse" Charged Particle Density Ratio

- CDF Preliminary
  - corrected data
  - generator level theory
- Tune Z2* (solid lines)
- Tune Z1 (dashed lines)
- CMS solid dots
- CDF solid squares
- "TransMIN"
- 5.0 < PTmax < 6.0 GeV/c
- Divided by 300 GeV Value

Particle Density Ratio: 6.7, 4.8, 2.9, 1.0

Center of mass energy

"Transverse" Charged PTsum Density Ratio

- Preliminary
  - corrected data
  - level theory
- PTmax < 6.0 GeV/c
- Z2*
- CMS solid dots
- CDF solid squares
- "TransMIN"
- "TransDIF"
- particles (|η|<0.8, PT>0.5 GeV/c)

Ratio: 7.3

Mass Energy (GeV): 10.0, 100.0

Answer to Question
The "transMIN" (MPI-BBR component) increases much faster with center-of-mass energy than the "transDIF" (ISR-FSR component)!
Duh!!

➧ **Ratio** of CDF data at 1.96 TeV, 900 GeV, and 300 GeV to the value at 300 GeV for the charged particle density in the "transMIN", and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 < PTmax < 6$ GeV/c. The data are plotted versus the center-of-mass energy (*log scale*). The data are compared with PYTHIA 6.4 **Tune Z1** and **Tune Z2***.

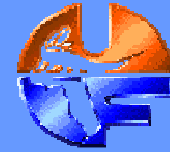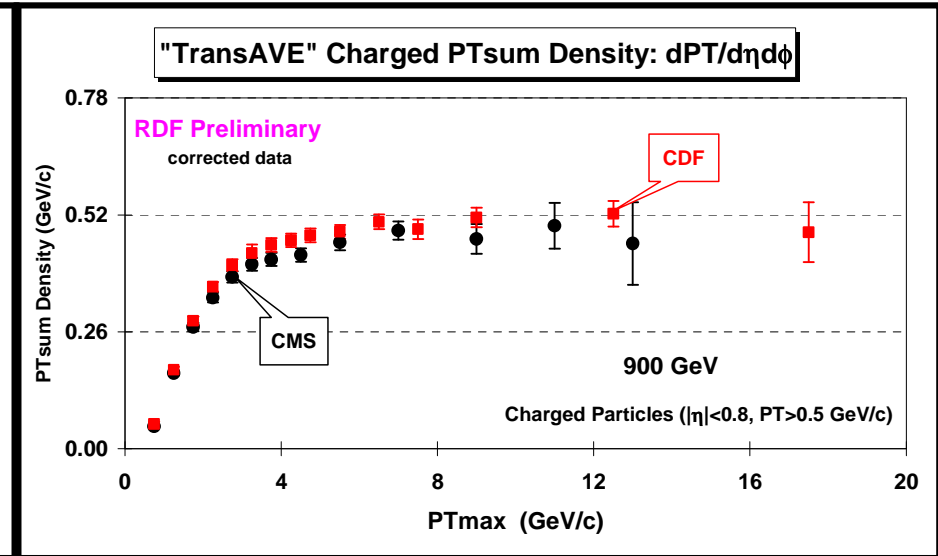The data are "normalized" by dividing by the corresponding value at 300 GeV.

"TransAVE" Charged Particle Density: dN/dηdφ

CMS

RDF Preliminary

Corrected Data
Tune Z2* Generator Level

13 TeV Predicted

7 TeV

1.96 TeV
CDF

900 GeV
CDF

300 GeV
CDF

Tune Z2*

Charged Particles (|η|<0.8, PT>0.5 GeV/c)

Charged Particle Density (y-axis)
PTmax (GeV/c) (x-axis)

CDF versus LHC

"TransAVE" Charged Particle Density: dN/dηdφ

"TransAVE" Charged PTsum Density: dPT/dηdφ

➡ **CDF and CMS data at 900 GeV/c** on the charged particle density in the "transverse" region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.

➡ **CDF and CMS data at 900 GeV/c** on the charged PTsum density in the "transverse" region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.

CDF versus LHC

➡ **CDF and CMS data at 900 GeV/c** on the charged particle density in the "transverse" region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.

➡ **CDF and CMS data at 900 GeV/c** on the charged PTsum density in the "transverse" region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty.
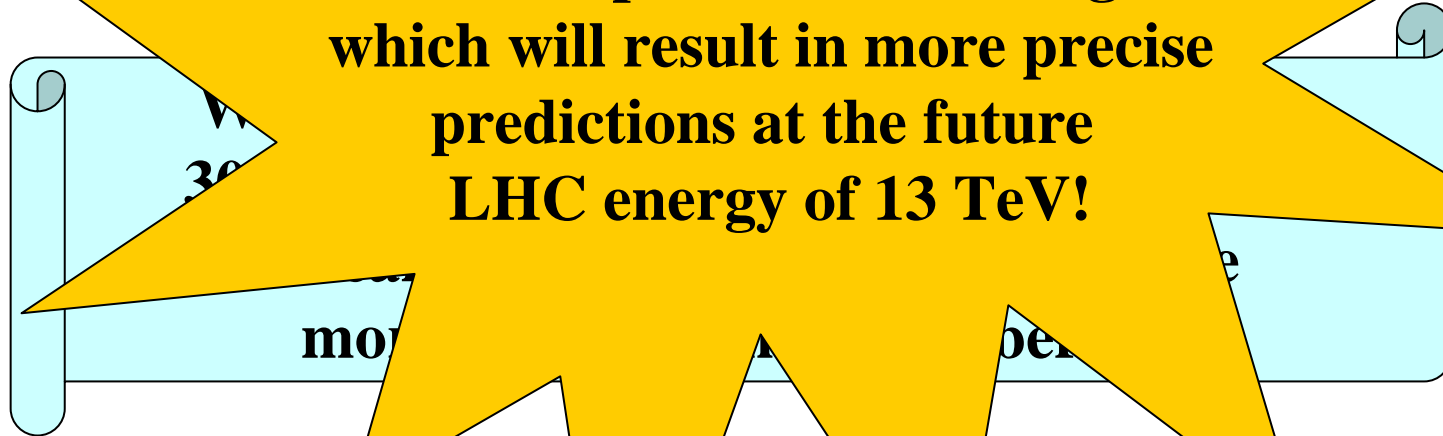
Summary & Conclusions

➡ The **"transverse"** region is not a true measure of the energy dependence of MPI since it receives large contributions from ISR and FSR.

➡ The **"transMIN"** (MPI-BBR component) increases much faster with center-of-mass energy than the **"transDIF"** (ISR-FSR component)! Previously we only knew the energy dependence of "transAVE".

> **We now have at lot of MB & UE data at 300 GeV, 900 GeV, 1.96 TeV, and 7 TeV! We can study the energy dependence more precisely than ever before!**

➡ Both PYTHIA 6.4 **Tune Z1** (CTEQ5L) and PYTHIA 6.4 **Tune Z2*** (CTEQ6L) go a fairly good job (although not perefct) in describing the energy deperdence of the UE!

➡ The **"transverse"** region is n... true mea... f the energy dependen... MPI since it ...es larg... ...butions from ISR and FSR.

➡ The **"transMIN**... ...faster with center-of-mass ...Prev...

What we are learning should allow for a deeper understanding of MPI which will result in more precise predictions at the future LHC energy of 13 TeV!

➡ Both PYTHIA 6.4 **Tune Z1** ...Q5L) a... PYTHIA 6.4 **Tune Z2*** (CTEQ6L) go a fairly good ... (although ...t perefct) in describing the energy deperdence of the U...