University of Glasgow

Tevatron Energy Scan: Findings & Surprises

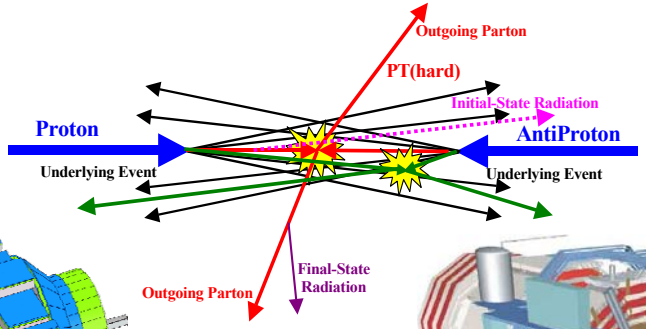
Rick Field

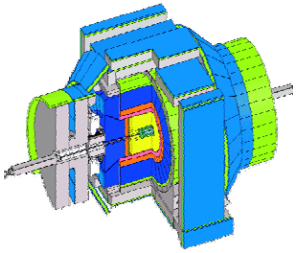
University of Florida

Quantum Chromo-Dynamics

Outline of Talk

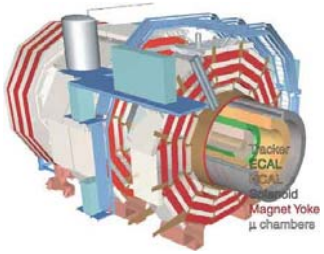
- **Simulating hadron-hadron collisions:** The early days of **Feynman-Field Phenomenology**.
- The **CDF** QCD Monte-Carlo Model tunes.
- The **CMS** QCD Monte-Carlo Model tunes.
- New CDF data from the **Tevatron Energy Scan**.
- Mapping out the energy dependence: **Tevatron** to the **LHC**.
- Summary & Conclusions.





CDF Run 2

300 GeV, 900 GeV, 1.96 TeV



CMS at the LHC

900 GeV, 7 & 8 TeV

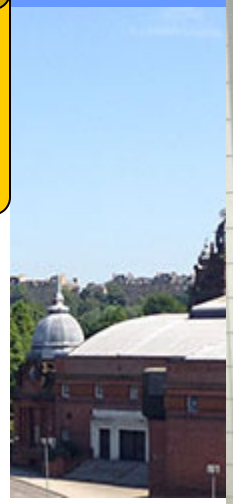
University of Glasgow

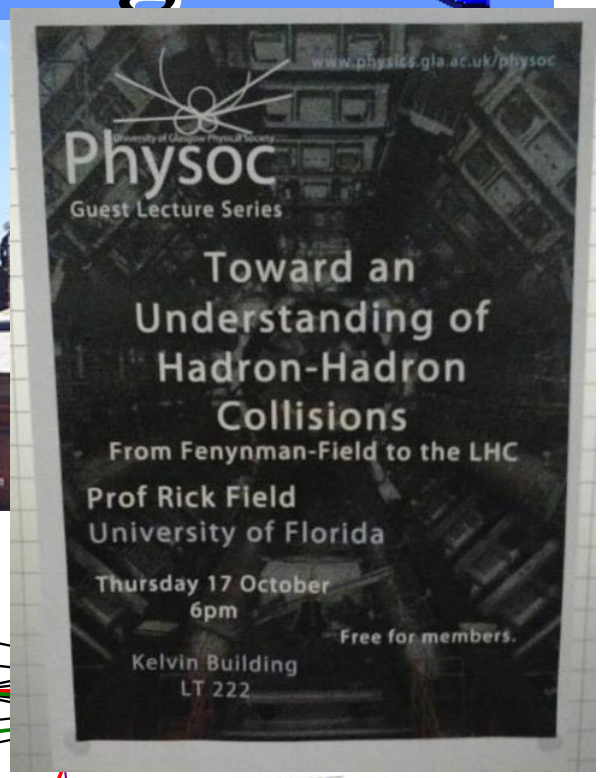
Tevatron Energy Scan: Findings & Surprises

Rick Field

University of Florida

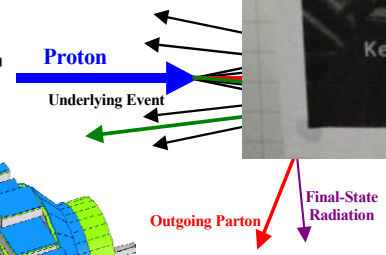
Quantum Chromo-Dynamics

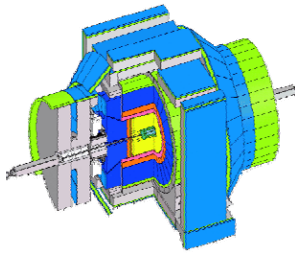




Outline of Talk

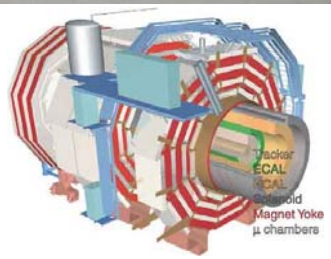
- **Simulating hadron-hadron collisions: The early days of Feynman-Field Phenomenology.**
- **The CDF QCD Monte-Carlo Model tunes.**
- **The CMS QCD Monte-Carlo Model tunes.**
- **New CDF data from the Tevatron Energy Scan.**
- **Mapping out the energy dependence: Tevatron to the LHC.**
- **Summary & Conclusions.**





CDF Run 2

300 GeV, 900 GeV, 1.96 TeV

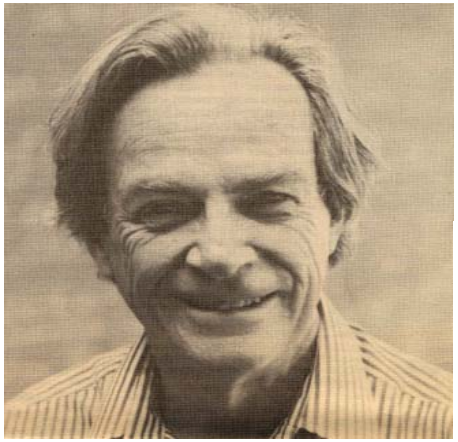


CMS at the LHC

900 GeV, 7 & 8 TeV

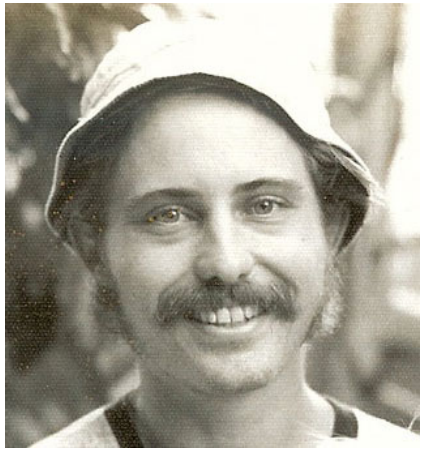
Toward an Understanding of Hadron-Hadron Collisions

Feynman-Field Phenomenology



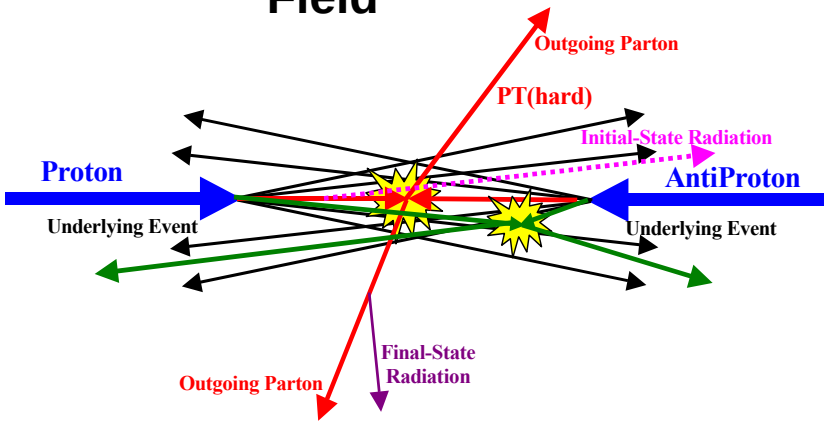
Feynman

and



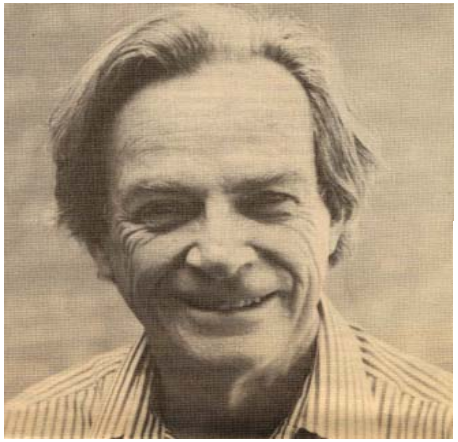
Field

- **From 7 GeV/c π^0's to 1 TeV Jets. The early days of trying to understand and simulate hadron-hadron collisions.**



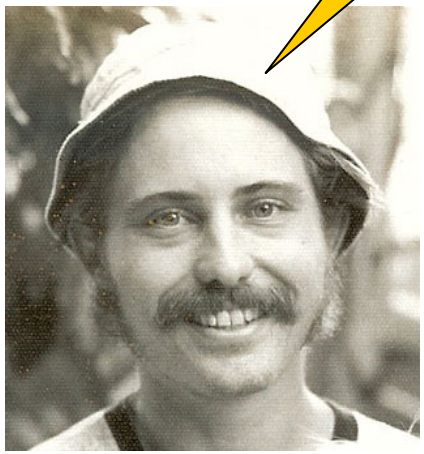
Toward an Understanding of Hadron-Hadron Collisions

Feynman-Field Phenomenology



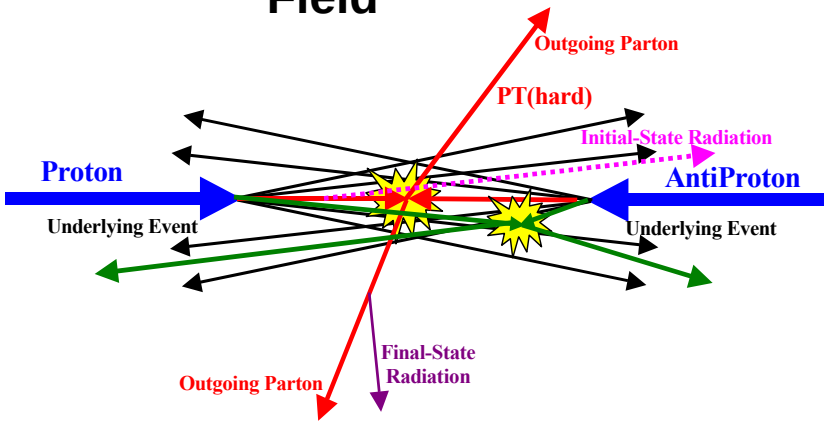
Feynman

and



Field

- **From 7 GeV/c π^0's to 1 TeV Jets. The early days of trying to understand and simulate hadron-hadron collisions.**



The Feynman-Field Days

1973-1983

"Feynman-Field Jet Model"

- **FF1: "Quark Elastic Scattering as a Source of High Transverse Momentum Mesons"**, R. D. Field and R. P. Feynman, Phys. Rev. D15, 2590-2616 (1977).
- **FFF1: "Correlations Among Particles and Jets Produced with Large Transverse Momenta"**, R. P. Feynman, R. D. Field and G. C. Fox, Nucl. Phys. B128, 1-65 (1977).
- **FF2: "A Parameterization of the properties of Quark Jets"**, R. D. Field and R. P. Feynman, Nucl. Phys. B136, 1-76 (1978).
- **F1: "Can Existing High Transverse Momentum Hadron Experiments be Interpreted by Contemporary Quantum Chromodynamics Ideas?"**, R. D. Field, Phys. Rev. Letters 40, 997-1000 (1978).
- **FFF2: "A Quantum Chromodynamic Approach for the Large Transverse Momentum Production of Particles and Jets"**, R. P. Feynman, R. D. Field and G. C. Fox, Phys. Rev. D18, 3320-3343 (1978).

- **FW1: "A QCD Model for e^+e^- Annihilation"**, R. D. Field and S. Wolfram, Nucl. Phys. B213, 65-84 (1983).

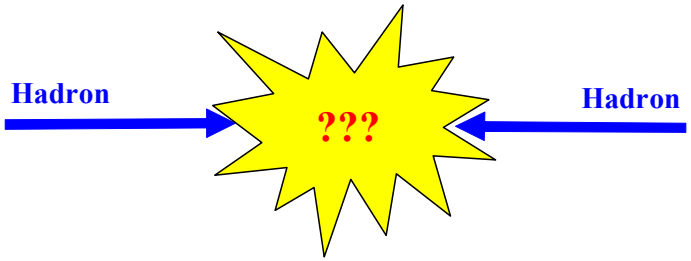
My 1st graduate student!

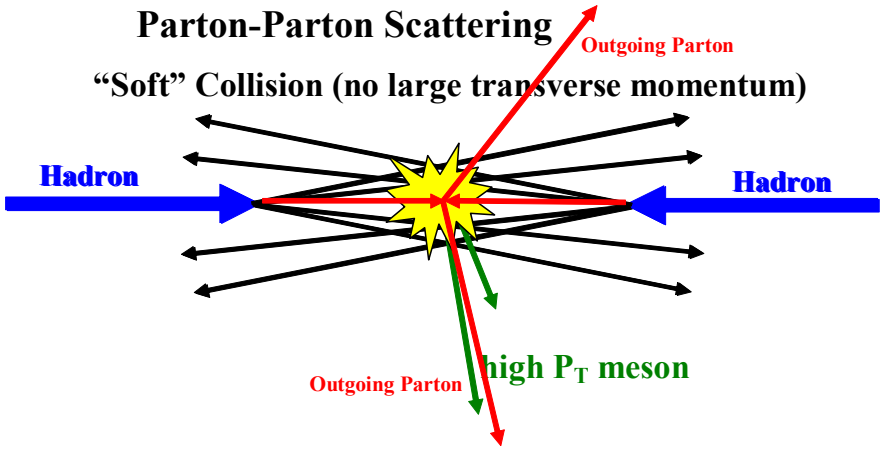
Hadron-Hadron Collisions

FF1 1977

- **What happens when two hadrons collide at high energy?**
- **Most of the time the hadrons ooze through each other and fall apart (*i.e.* no hard scattering). The outgoing particles continue in roughly the same direction as initial proton and antiproton.**
- **Occasionally there will be a large transverse momentum meson. Question: Where did it come from?**
- **We assumed it came from quark-quark elastic scattering, but we did not know how to calculate it!**

"Black-Box Model"





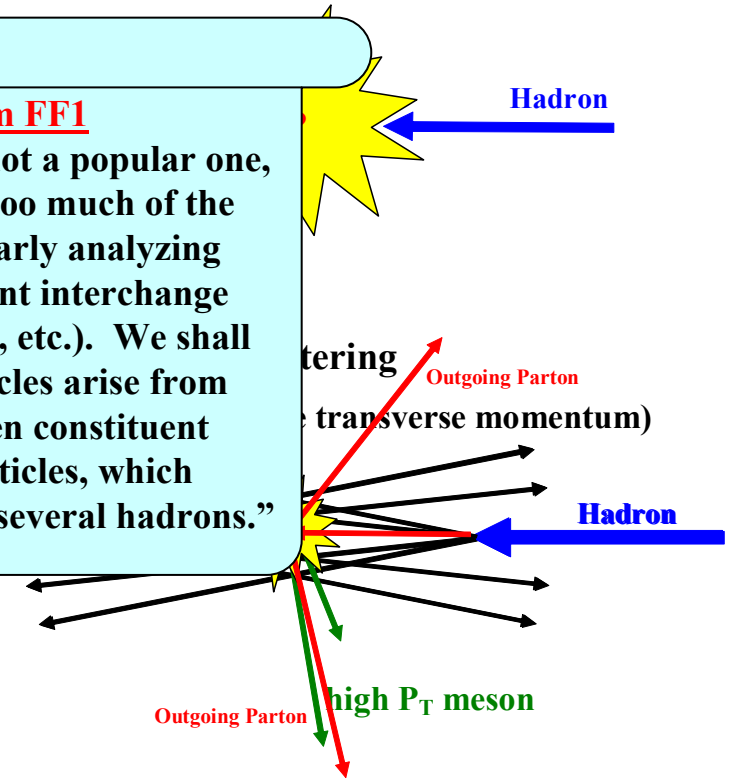
Hadron-Hadron Collisions

FF1 1977

- What happens whe
  collide at high ener
- Most of the time th
  through each other
  no hard scattering)
  particles continue i
  direction as initial p
  antiproton.
- Occasionally th
  transverse momentum meson.
  Question: Where did it come from?
- We assumed it came from quark-quark elastic scattering, but we did not know how to calculate it!

Feynman quote from FF1

"The model we shall choose is not a popular one, so that we will not duplicate too much of the work of others who are similarly analyzing various models (e.g. constituent interchange model, multiperipheral models, etc.). We shall assume that the high P_T particles arise from direct hard collisions between constituent quarks in the incoming particles, which fragment or cascade down into several hadrons."



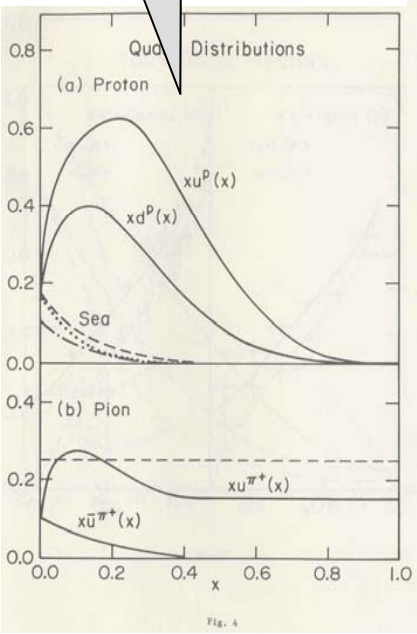
"Black-Box Model"

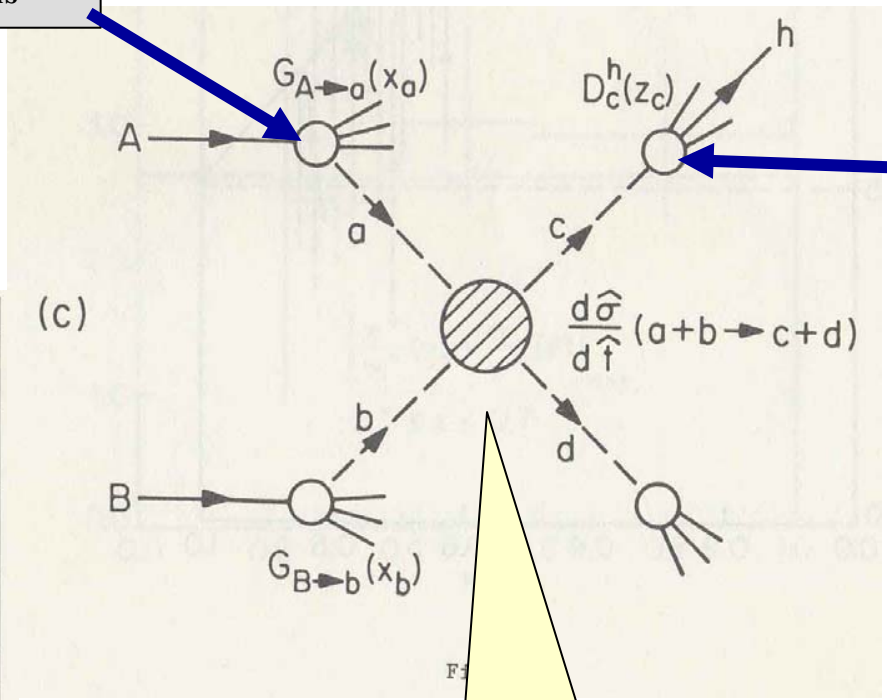
Quark-Quark Black-Box Model

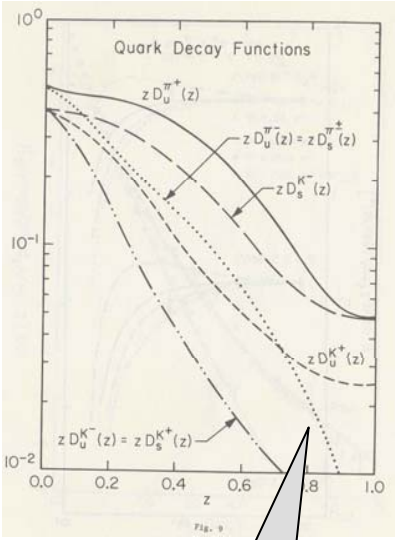
FF1 1977

No gluons!

Quark Distribution Functions
determined from deep-inelastic lepton-hadron collisions







Quark-Quark Cross-Section
Unknown! Deteremined from hadron-hadron collisions.

Quark Fragmentation Functions
determined from e^+e^- annihilations

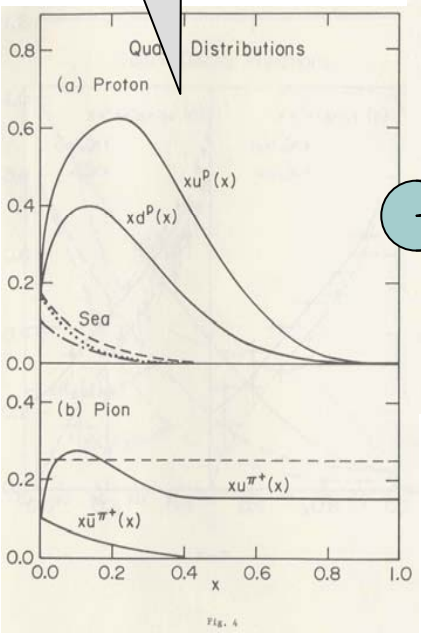
Quark-Quark Black-Box Model

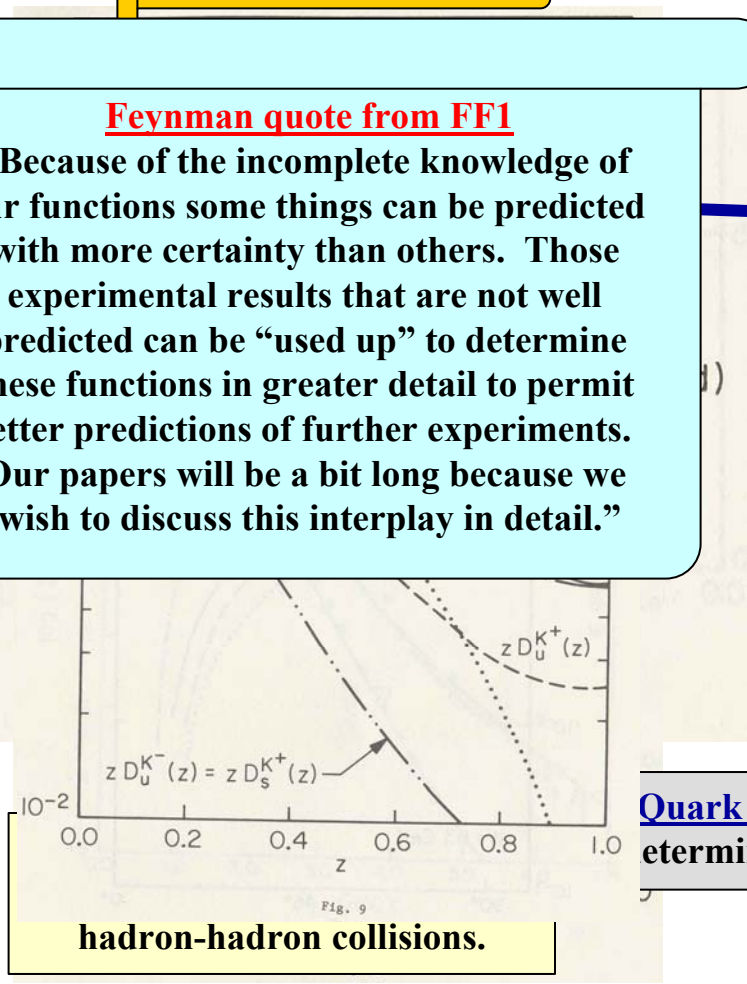
FF1 1977

No gluons!

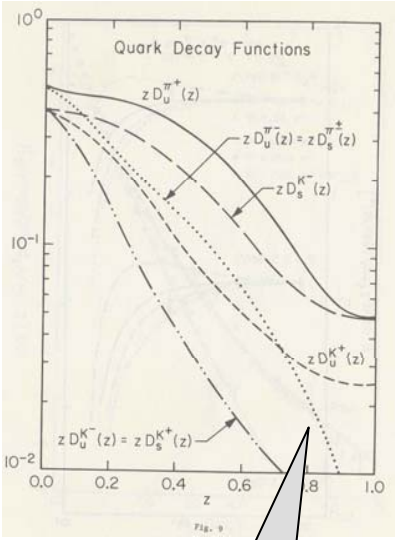
Quark Distribution Functions
determined from deep-inelastic lepton-hadron collisions

Feynman quote from FF1
"Because of the incomplete knowledge of our functions some things can be predicted with more certainty than others. Those experimental results that are not well predicted can be "used up" to determine these functions in greater detail to permit better predictions of further experiments. Our papers will be a bit long because we wish to discuss this interplay in detail."





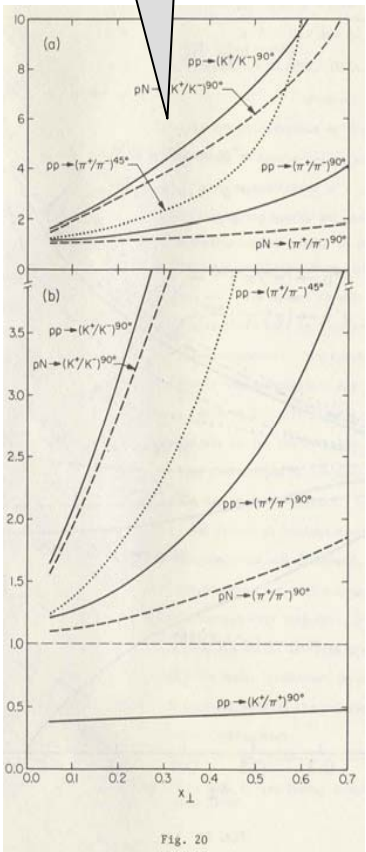
hadron-hadron collisions.



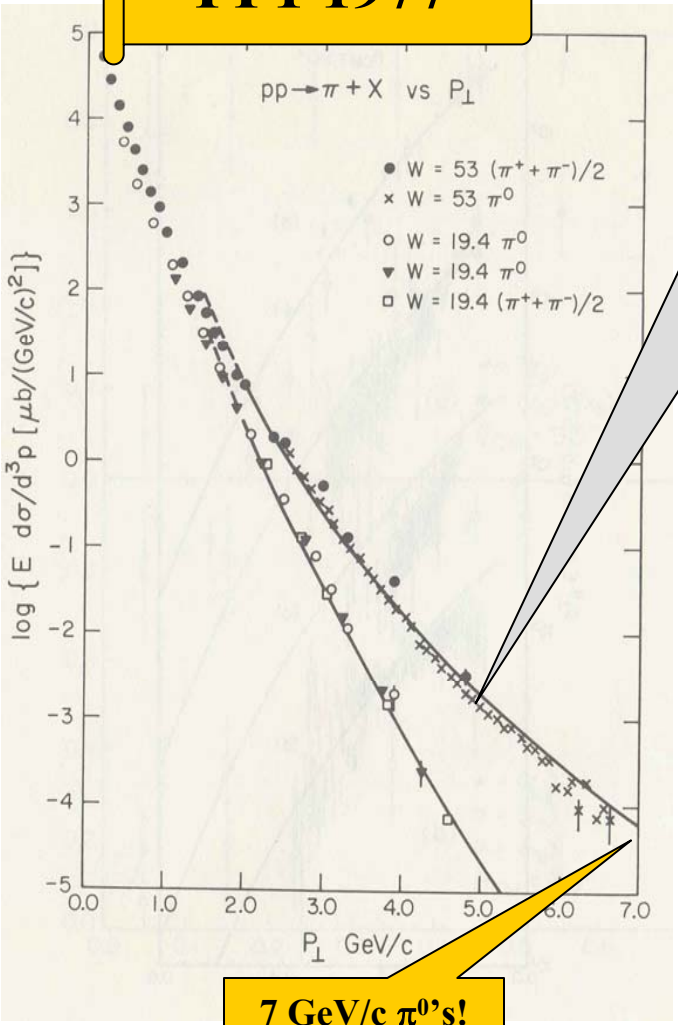
Quark Fragmentation Functions
determined from e^+e^- annihilations

Quark-Quark Black-Box Model

Predict
particle ratios

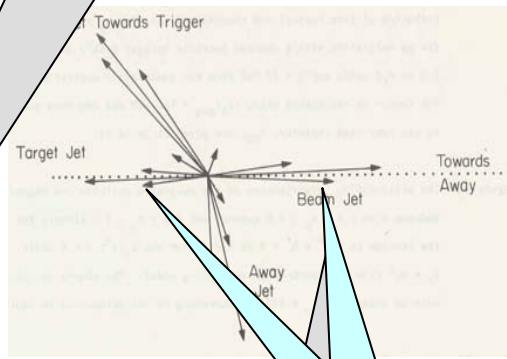


FF1 1977



7 GeV/c π^0's!

Predict
increase with increasing CM energy W



"Beam-Beam Remnants"

Predict
overall event topology (FFF1 paper 1977)

Telagram from Feynman

July 1976

western union

Telefax

ICS IPMIINA IISS

IISS FK WUI 19 0249

PMS PASADENA CA

UWA1871 PSX555 310384W 7290

UWNX CO FRXX OIS

CHAMONIXMONTBLANC

RICK FIELD CALTECH

PASADENA/CALIF

SAW CRONIN AM NOW CONVINCED WERE RIGHT TRACK QUICK WRITE

FEY

NBAM

Telagram from Feynman

July 1976

western union

Telefax

ICS IPMIINA IISS

IISS FK WUI 19 0249

PMS PASADENA CA

UWA1871 PSX555 310384W 7290

UWNX CO FRXX OIS

CHAMONIXMONTBLANC

RICK FIELD CALTECH

PASADENA/CALIF

SAW CRONIN AM NOW CONVINCED WERE RIGHT TRACK QUICK WRITE

FEY

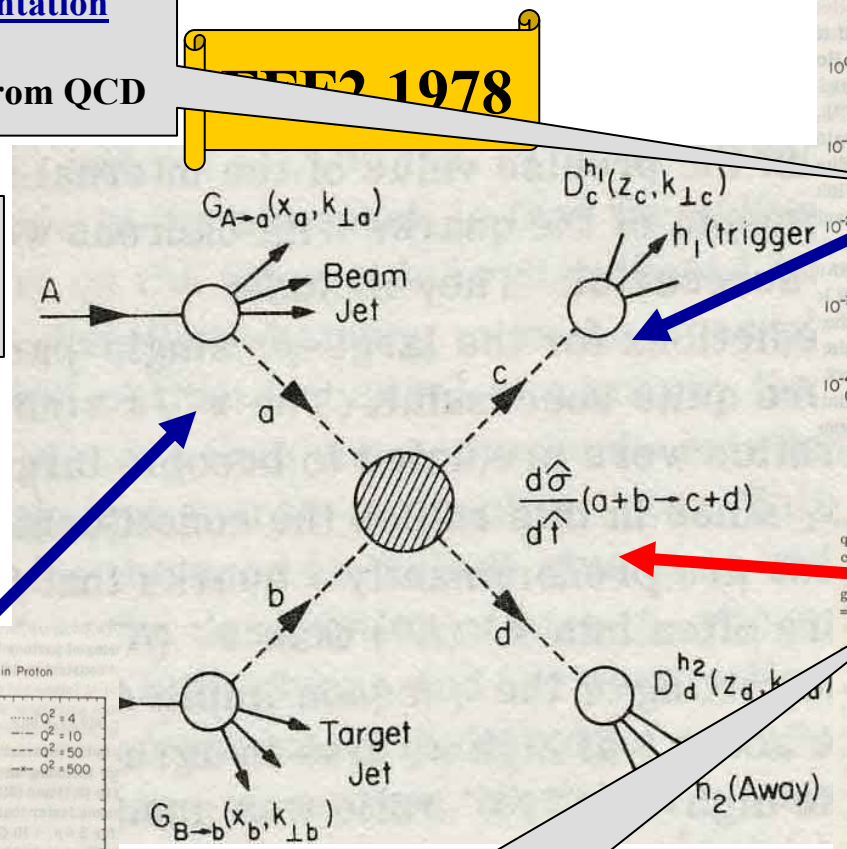
NMAM

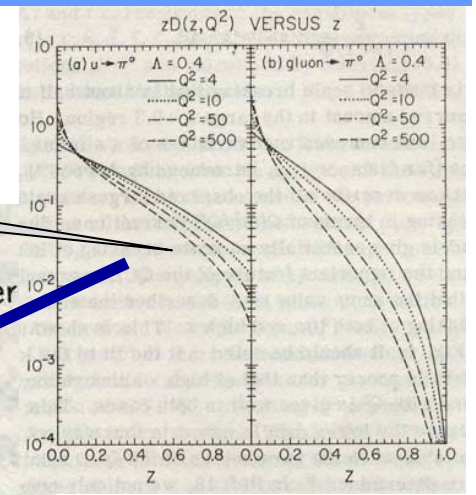
SAW CRONIN AM NOW CONVINCED WERE RIGHT TRACK QUICK WRITE FEYNMAN

QCD Approach: Quarks & Gluons

Quark & Gluon Fragmentation Functions
Q^2 dependence predicted from QCD

Parton Distribution Functions
Q^2 dependence predicted from QCD





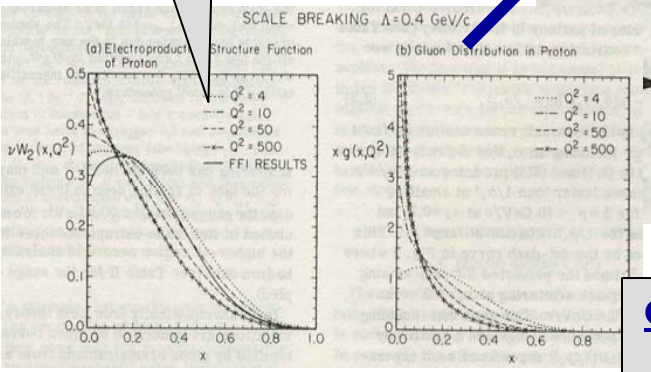


TABLE I. Cross sections for the various constituent quark-quark, quark-gluon, and gluon-gluon subprocesses.[a] The differential cross section is given by $d\hat{\sigma}/d\hat{t} = \alpha_s^2(Q^2)|A|^2/\hat{s}^2$, where $\alpha_s(Q^2)$ is the effective coupling given by Eq. (3.1).

	Subprocess	$\lvert A\rvert^2$
1.	$q_i q_j \to q_i q_j$, $q_i \bar{q}_j \to q_i \bar{q}_j$ $(i \neq j)$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
2.	$q_i q_i \to q_i q_i$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$
3.	$q_i \bar{q}_i \to q_i \bar{q}_i$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$
4.	$q_i \bar{q}_i \to gg$	$\frac{32}{27}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}\right)-\frac{8}{3}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right)$
5.	$gg \to q_i \bar{q}_i$	$\frac{1}{6}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}\right)-\frac{3}{8}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right)$
6.	$q_i g \to q_i g$	$-\frac{4}{9}\left(\frac{\hat{u}^2+\hat{s}^2}{\hat{u}\hat{s}}\right)+\left(\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}\right)$
7.	$gg \to gg$	$\frac{9}{2}\left(3-\frac{\hat{u}\hat{t}}{\hat{s}^2}-\frac{\hat{u}\hat{s}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$

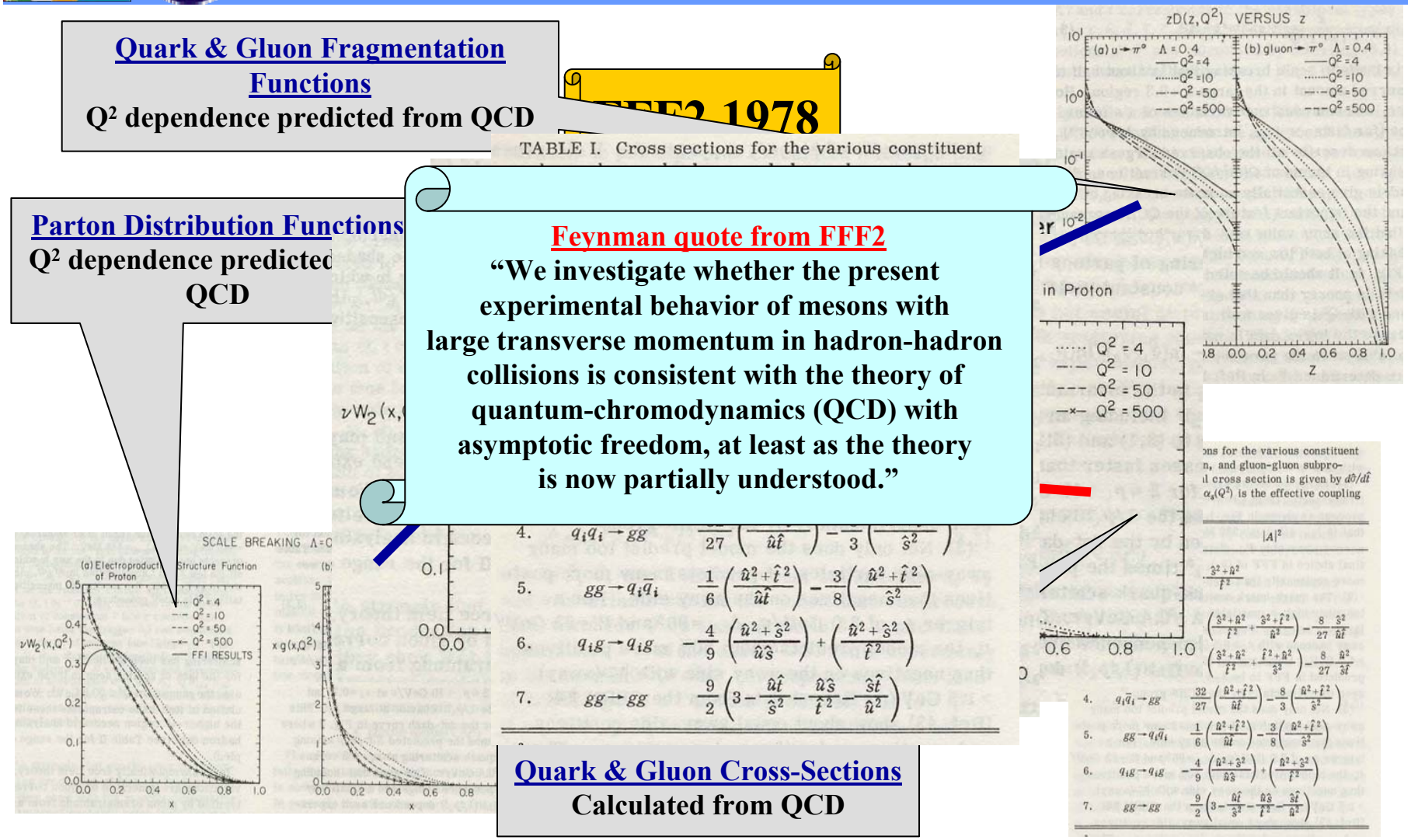
Quark & Gluon Cross-Sections
Calculated from QCD

QCD Approach: Quarks & Gluons

Quark & Gluon Fragmentation Functions
Q^2 dependence predicted from QCD

Parton Distribution Functions
Q^2 dependence predicted QCD

Feynman quote from FFF2
"We investigate whether the present experimental behavior of mesons with large transverse momentum in hadron-hadron collisions is consistent with the theory of quantum-chromodynamics (QCD) with asymptotic freedom, at least as the theory is now partially understood."



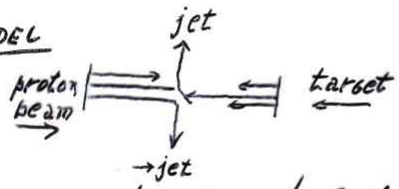
Quark & Gluon Cross-Sections
Calculated from QCD

Feynman Talk at Coral Gables
(December 1976)

1st transparency

Field & Feynman CALT-68-565
Fox (Brookhaven APS) CALT-68-573

MODEL



Quark - Quark Collision.
But $P_\perp^{-8}$ Not $P_\perp^{-4}$?

Need: (a) Quark distribution in hadron. (Pion?)
(b) The way quark makes hadron jet.
FROM EXPERIMENTS WITH LEPTONS.
(c) Quark-Quark scattering x-section.

$$\frac{d\hat{\sigma}}{dt} = \frac{2300\ \text{mb}}{s(-t)^3}$$

Try to fit all correlation experiments with no new parameters.

Last transparency

WORK IN PROGRESS

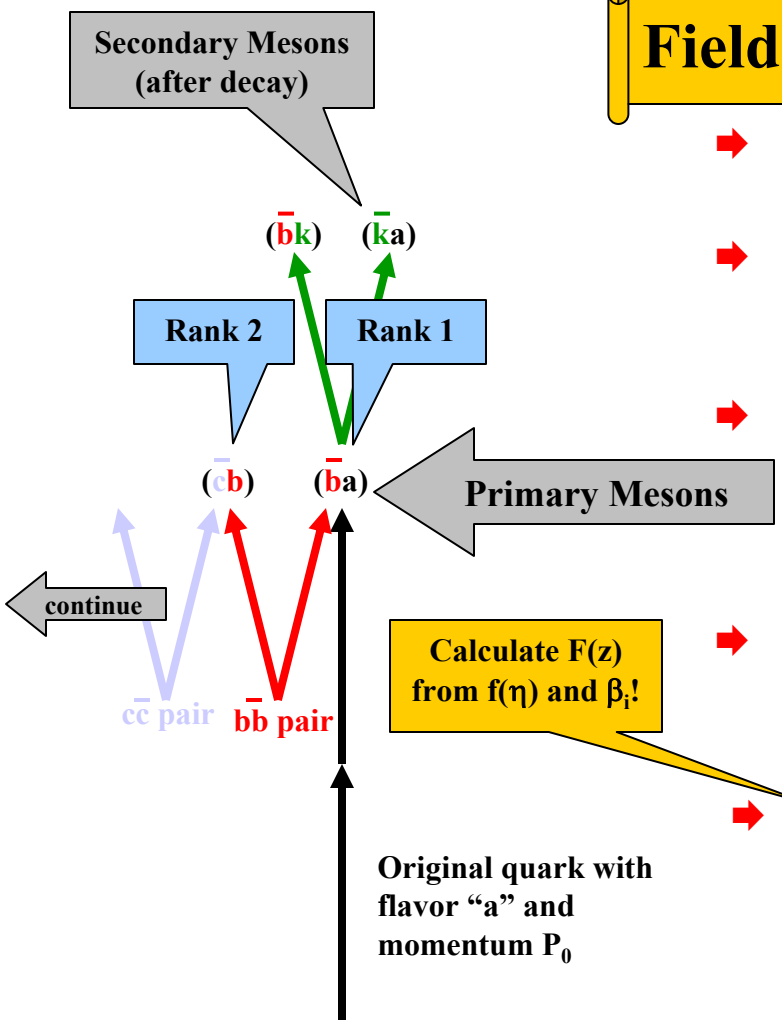
a) More detailed Calculations
b) Theory of $q \to$ hadron cascade

"Feynman-Field Jet Model"

FUTURE.

Protons & baryons at high $P_\perp$.
Single γ's at high $P_\perp$.
Nuclear targets.
Are we really in trouble from $P_{transverse}$ of quarks?
Unify theory to that of main collision at low $P_\perp$.

A Parameterization of the Properties of Jets

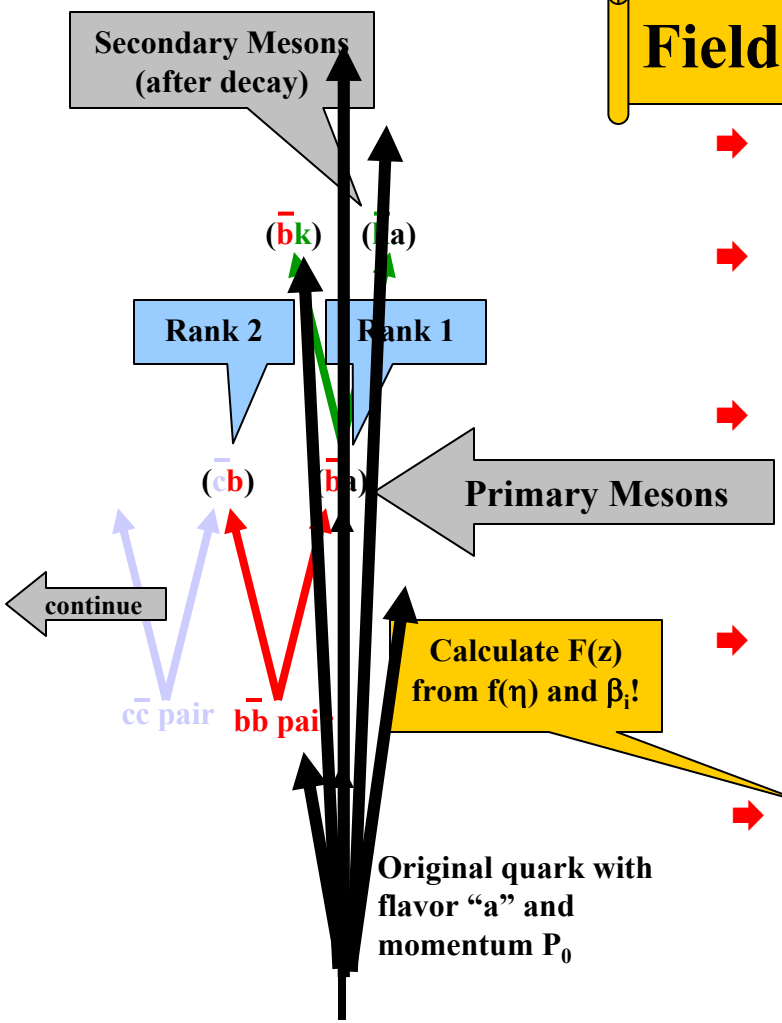


Field-Feynman 1978

- Assumed that jets could be analyzed on a "recursive" principle.
- Let $f(\eta)d\eta$ be the probability that the rank 1 meson *leaves* fractional momentum η to the remaining cascade, leaving quark "b" with momentum $P_1 = \eta_1 P_0$.
- Assume that the mesons originating from quark "b" are distributed in presisely the same way as the mesons which came from quark a (*i.e.* same function $f(\eta)$), leaving quark "c" with momentum $P_2 = \eta_2 P_1 = \eta_2 \eta_1 P_0$.
- Add in flavor dependence by letting β_u = probabliity of producing u-ubar pair, β_d = probability of producing d-dbar pair, etc.
- Let F(z)dz be the probability of finding a meson (*independent of rank*) with fractional mementum z of the original quark "a" within the jet.

Calculate F(z) from $f(\eta)$ and β_i!

A Parameterization of the Properties of Jets



Field-Feynman 1978

- Assumed that jets could be analyzed on a "recursive" principle.
- Let $f(\eta)d\eta$ be the probability that the rank 1 meson *leaves* fractional momentum η to the remaining cascade, leaving quark "b" with momentum $P_1 = \eta_1 P_0$.
- Assume that the mesons originating from quark "b" are distributed in presisely the same way as the mesons which came from quark a (*i.e.* same function $f(\eta)$), leaving quark "c" with momentum $P_2 = \eta_2 P_1 = \eta_2 \eta_1 P_0$.
- Add in flavor dependence by letting β_u = probabliity of producing u-ubar pair, β_d = probability of producing d-dbar pair, etc.
- Let F(z)dz be the probability of finding a meson (*independent of rank*) with fractional mementum z of the original quark "a" within the jet.

Calculate F(z) from $f(\eta)$ and β_i!

Monte-Carlo Simulation of Hadron-Hadron Collisions

FF1-FFF1 (1977)
"Black-Box" Model

F1-FFF2 (1978)
QCD Approach

FF2 (1978)
Monte-Carlo simulation of "jets"

FFFW "FieldJet" (1980)
QCD "leading-log order" simulation of hadron-hadron collisions

"FF" or "FW" Fragmentation

the past

yesterday

ISAJET
("FF" Fragmentation)

HERWIG
("FW" Fragmentation)

PYTHIA 6.4

today

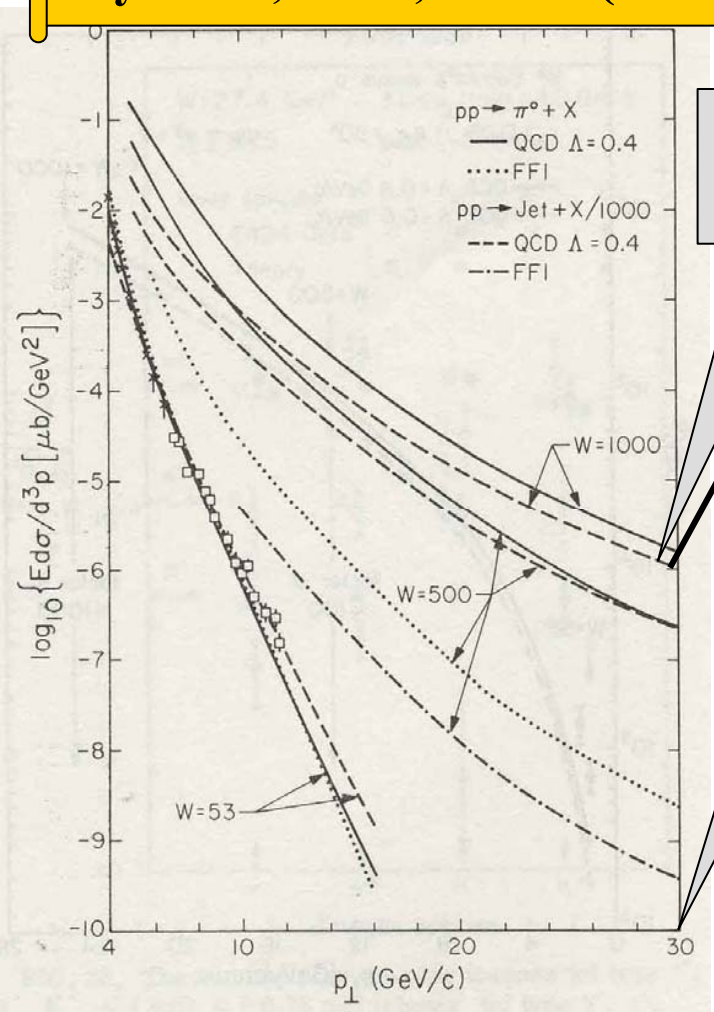
SHERPA

PYTHIA 8

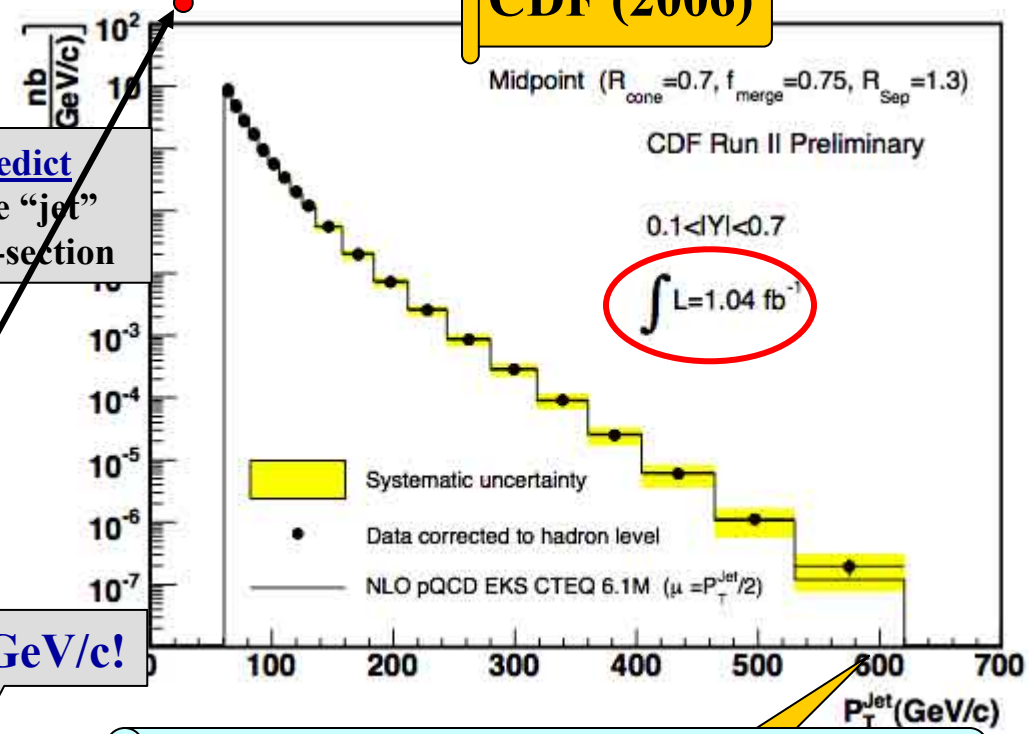
HERWIG++

High P_T Jets

Feynman, Field, & Fox (1978)



CDF (2006)



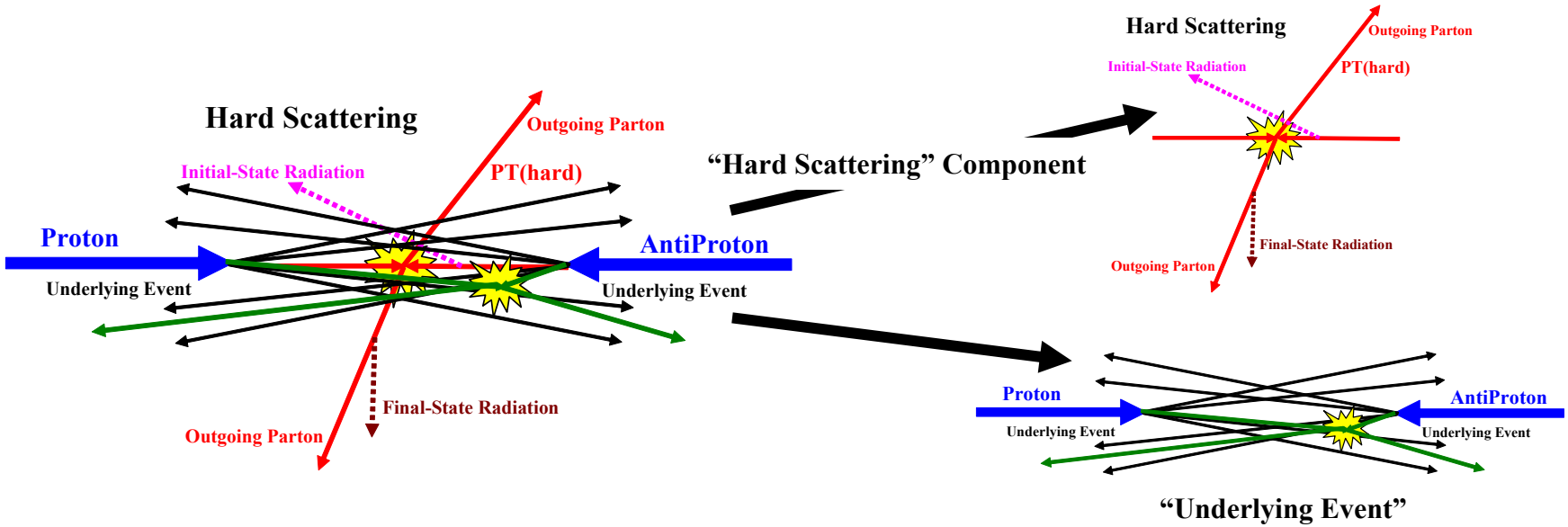
Predict large "jet" cross-section

30 GeV/c!

Feynman quote from FFF

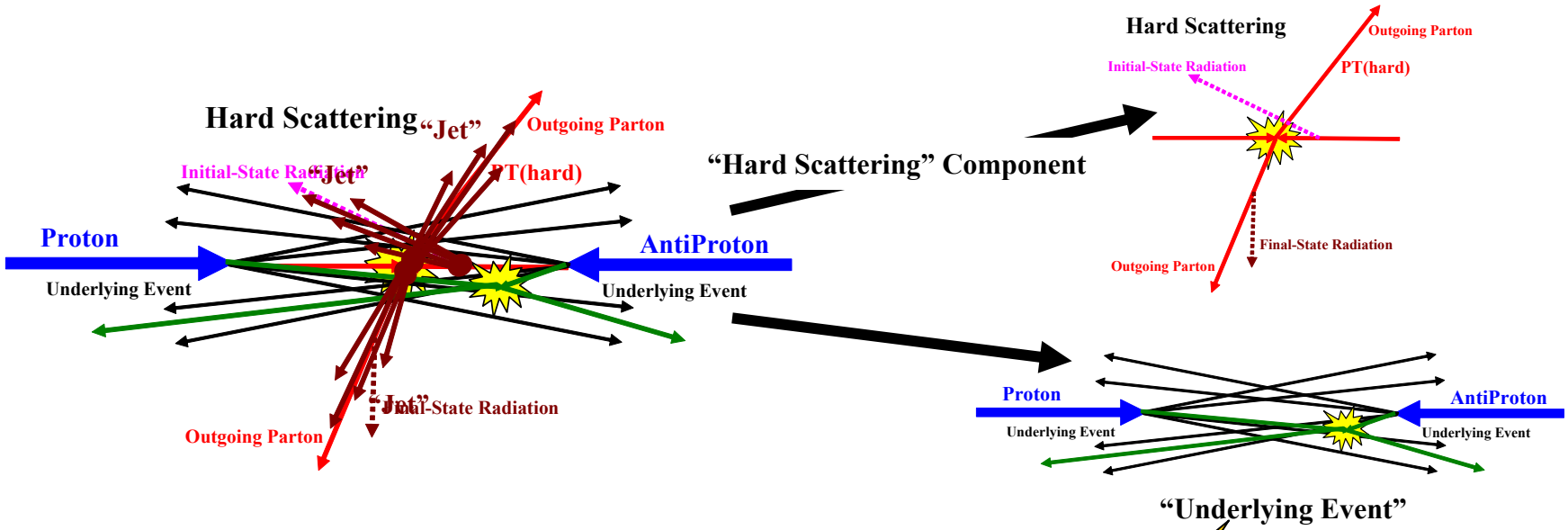
"At the time of this writing, there is still no sharp quantitative test of QCD. An important test will come in connection with the phenomena of high P_T discussed here."

QCD Monte-Carlo Models: High Transverse Momentum Jets



- Start with the perturbative 2-to-2 (or sometimes 2-to-3) parton-parton scattering and add initial and final-state gluon radiation (in the leading log approximation or modified leading log approximation).
- The "underlying event" consists of the "beam-beam remnants" and from particles arising from soft or semi-soft multiple parton interactions (MPI).
- Of course the outgoing colored partons fragment into hadron "jet" and inevitably "underlying event" observables receive contributions from initial and final-state radiation.

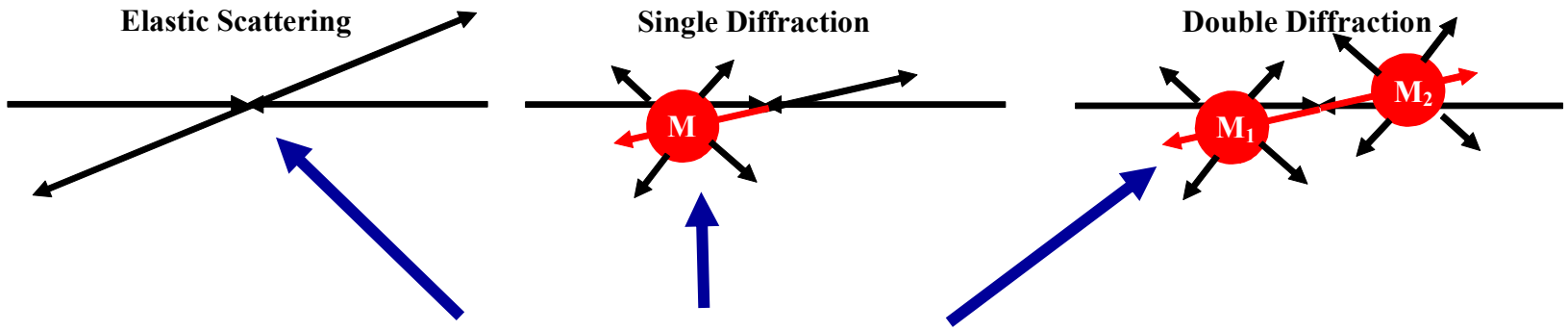
QCD Monte-Carlo Models: High Transverse Momentum Jets



- Start with the perturbative 2-to-2 (or sometimes 2-to-3) parton-parton scatter g and add initial and final-state gluon radiation (in the leading log approximation or modified leadin g approximation).
- The "underlying event" consists of the "beam-beam remnants" and articles arising from soft or semi-soft multiple parton interactions (MPI).
- Of course the outgoing colored parton ly "underlying event" observables receive contributions fron

The "underlying event" is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!

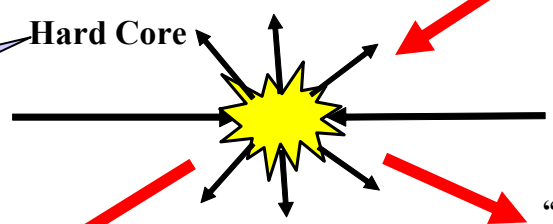
Proton-Proton Collisions

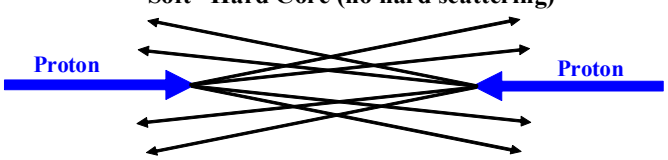


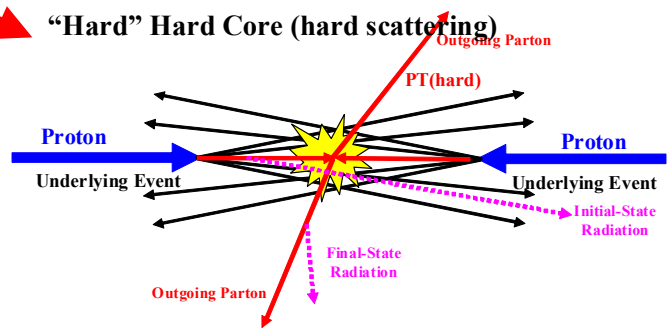
$$\sigma_{tot} = \sigma_{EL} + \sigma_{SD} + \sigma_{DD} + \sigma_{ND}$$

"Inelastic Non-Diffractive Component"

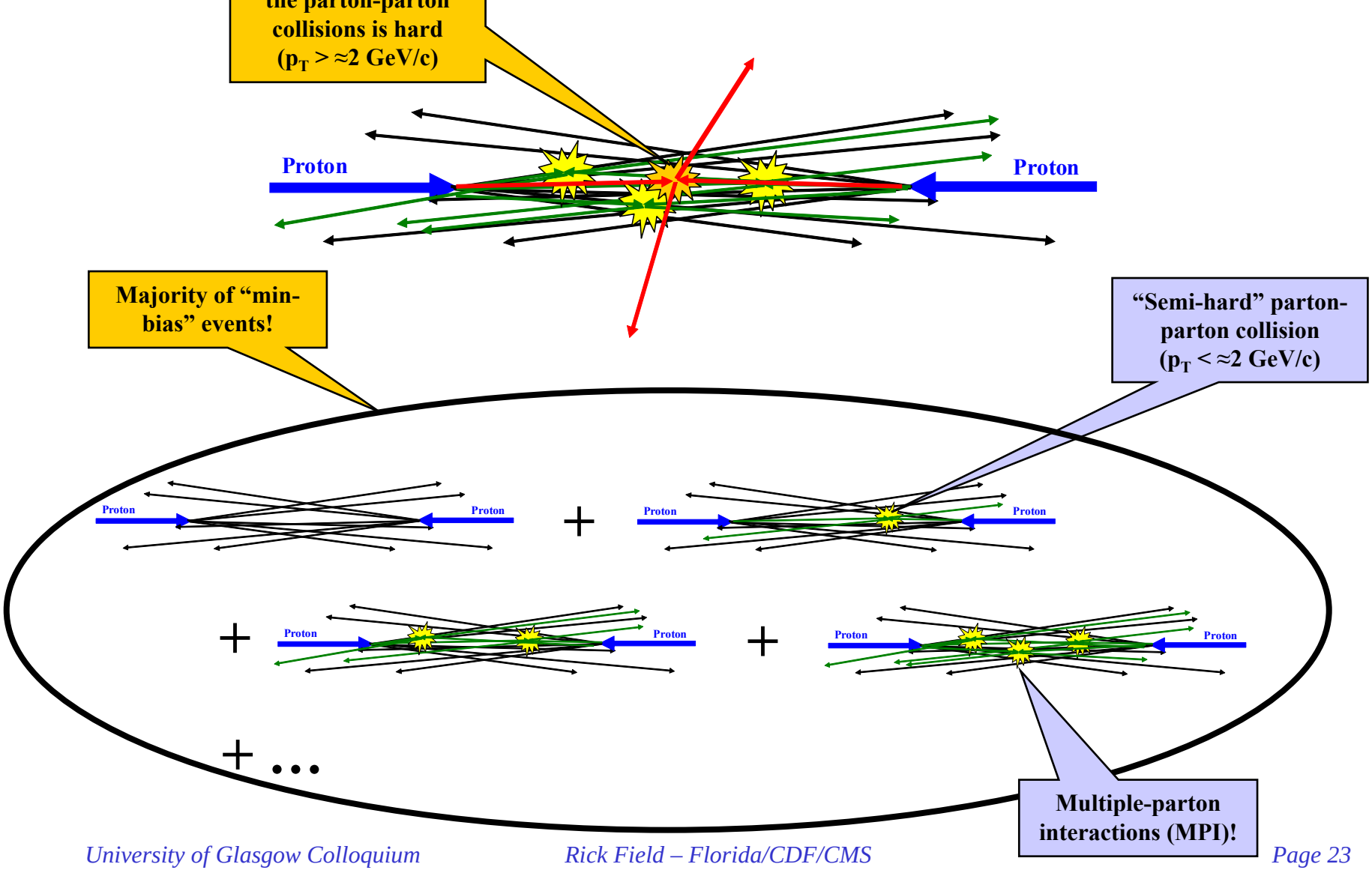
The "hard core" component contains both "hard" and "soft" collisions.





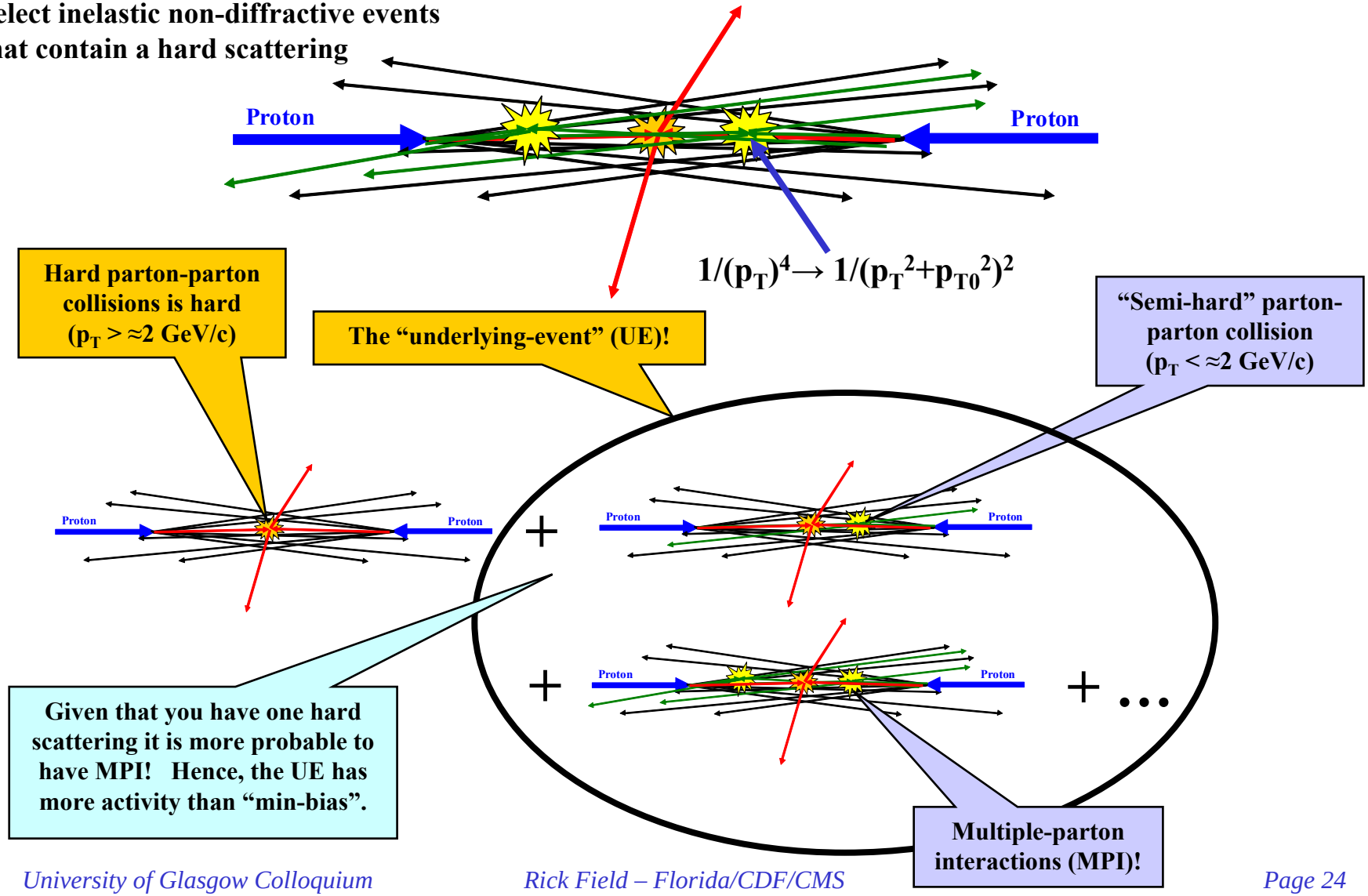


The Inelastic Non-Diffractive Cross-Section



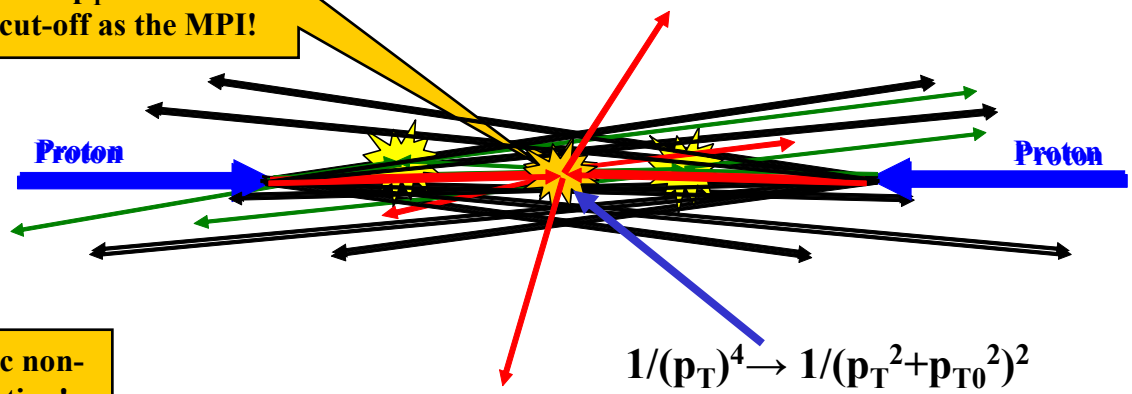
The "Underlying Event"

Select inelastic non-diffractive events that contain a hard scattering



Model of σ_{ND}

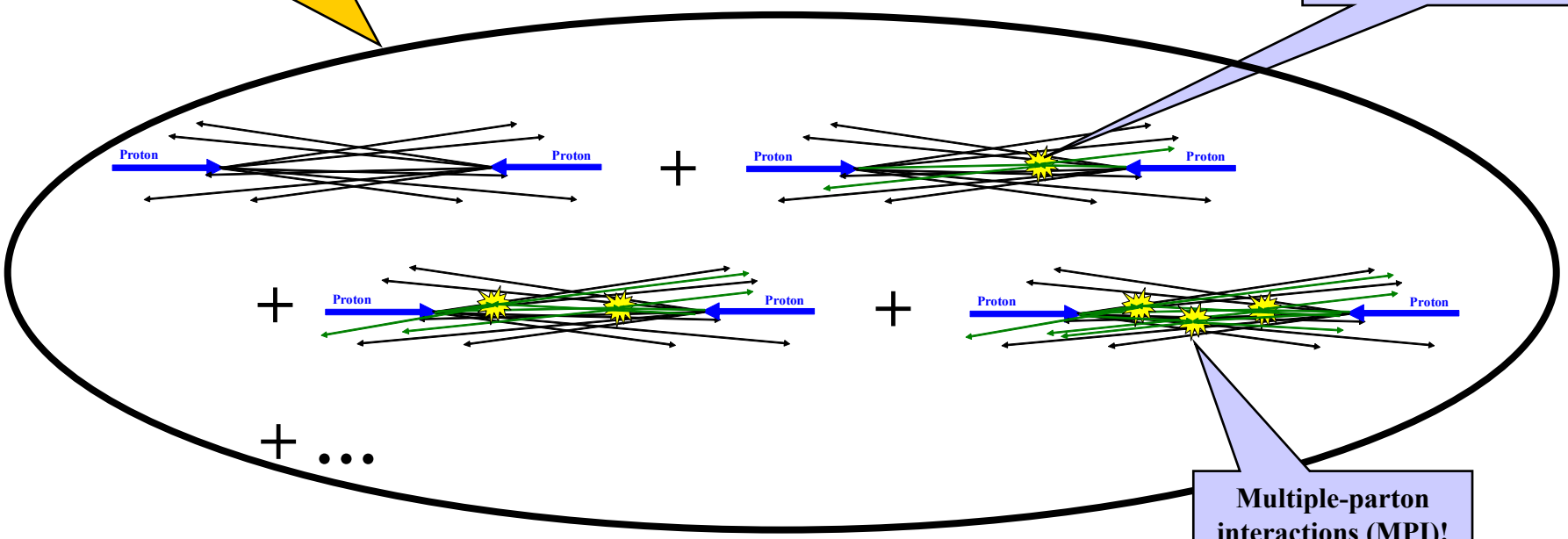
Allow leading hard scattering to go to zero p_T with same cut-off as the MPI!



$1/(p_T)^4 \rightarrow 1/(p_T^2+p_{T0}^2)^2$

Model of the inelastic non-diffractive cross section!

"Semi-hard" parton-parton collision ($p_T < \approx 2$ GeV/c)



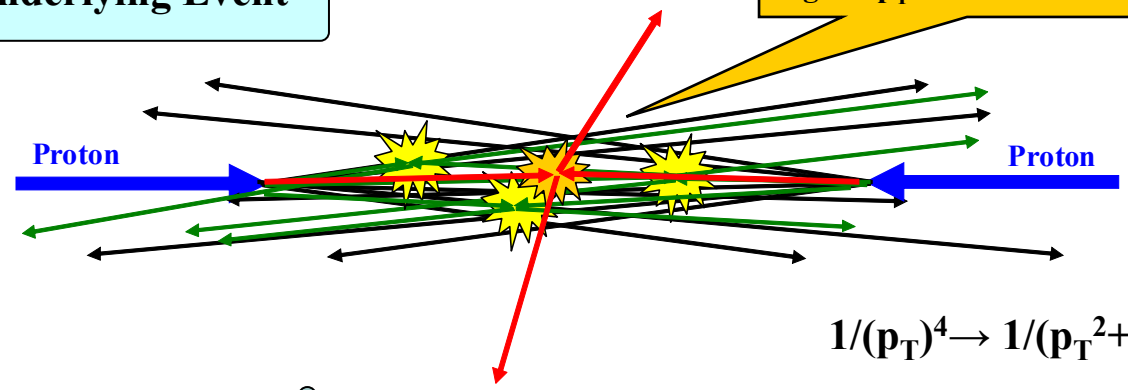
Multiple-parton interactions (MPI)!

UE Tunes

"Underlying Event"

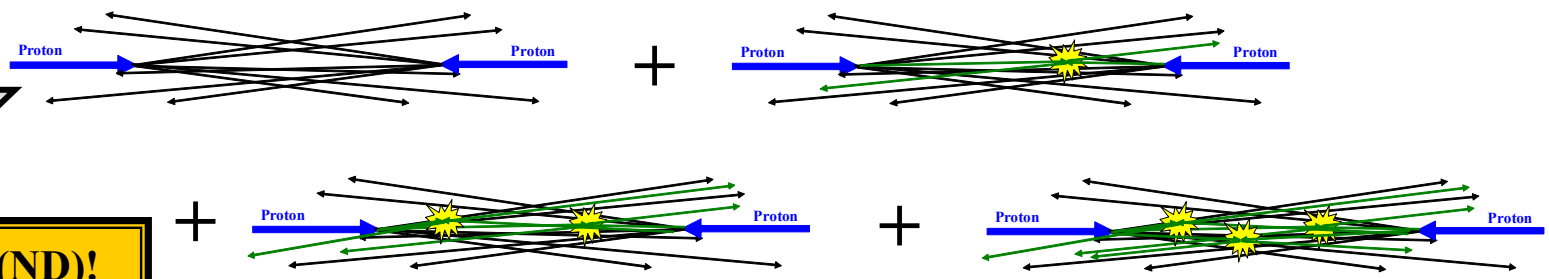
Allow primary hard-scattering to go to $p_T = 0$ with same cut-off!

Fit the "underlying event" in a hard scattering process.



$$1/(p_T)^4 \rightarrow 1/(p_T^2+p_{T0}^2)^2$$

"Min-Bias" (ND)



Predict MB (ND)!

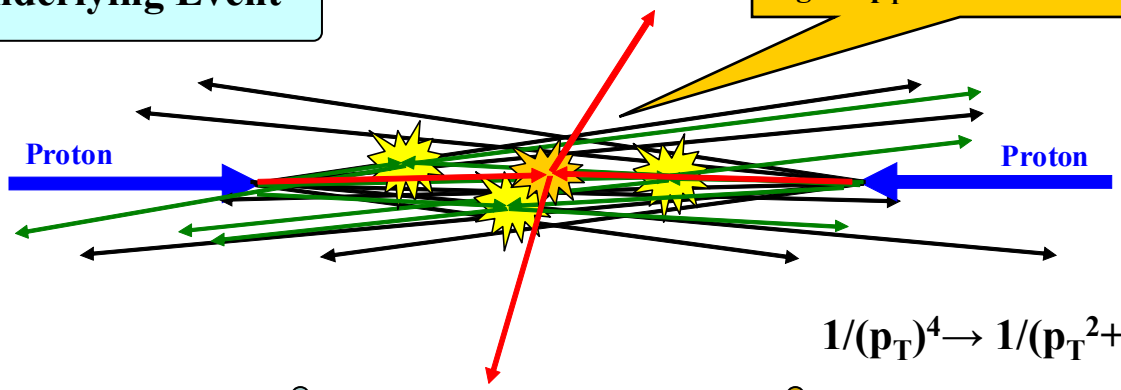
+ …

UE Tunes

"Underlying Event"

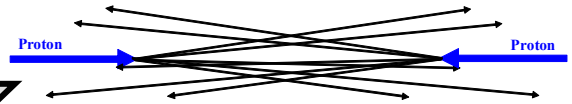
Allow primary hard-scattering to go to $p_T = 0$ with same cut-off!

Fit the "underlying event" in a hard scattering process.



$1/(p_T)^4 \rightarrow 1/(p_T^2+p_{T0}^2)^2$

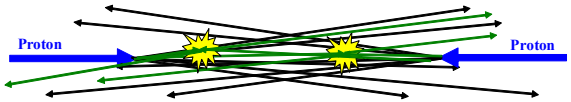
"Min-Bias" (add single & double diffraction)



+

Predict MB (ND)!

+



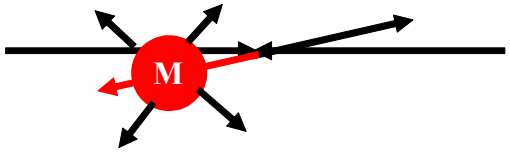
Single Diffraction

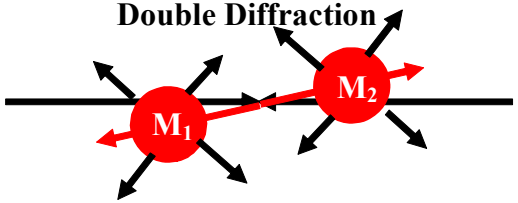
+

Double Diffraction

Predict MB (IN)!

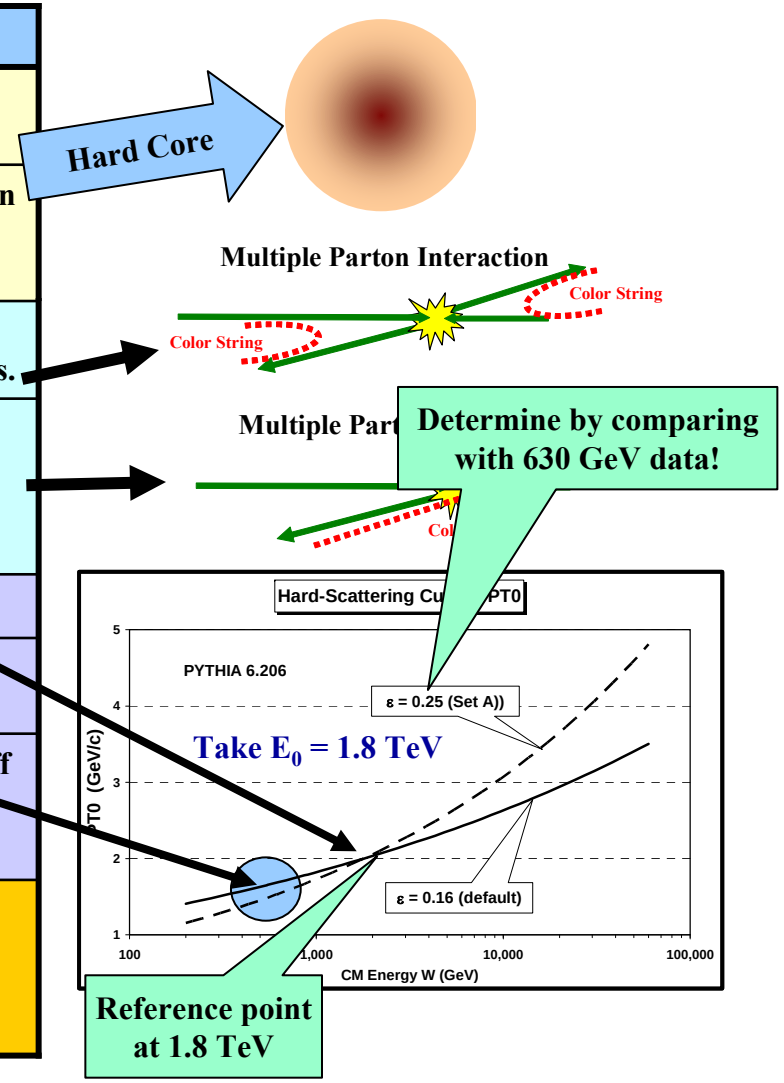
+ …





Tuning PYTHIA 6.2:
Multiple Parton Interaction Parameters

Parameter	Default	Description
PARP(83)	0.5	Double-Gaussian: Fraction of total hadronic matter within PARP(84)
PARP(84)	0.2	Double-Gaussian: Fraction of the overall hadron radius containing the fraction PARP(83) of the total hadronic matter.
PARP(85)	0.33	Probability that the MPI produces two gluons with color connections to the "nearest neighbors.
PARP(86)	0.66	Probability that the MPI produces two gluons either as described by PARP(85) or as a closed gluon loop. The remaining fraction consists of quark-antiquark pairs.
PARP(89)	1 TeV	Determines the reference energy E_0.
PARP(82)	1.9 GeV/c	The cut-off P_{T0} that regulates the 2-to-2 scattering divergence $1/PT^4 \rightarrow 1/(PT^2+P_{T0}^2)^2$
PARP(90)	0.16	Determines the energy dependence of the cut-off P_{T0} as follows $P_{T0}(E_{cm}) = P_{T0}(E_{cm}/E_0)^{\varepsilon}$ with ε = PARP(90)
PARP(67)	1.0	A scale factor that determines the maximum parton virtuality for space-like showers. The larger the value of PARP(67) the more initial-state radiation.

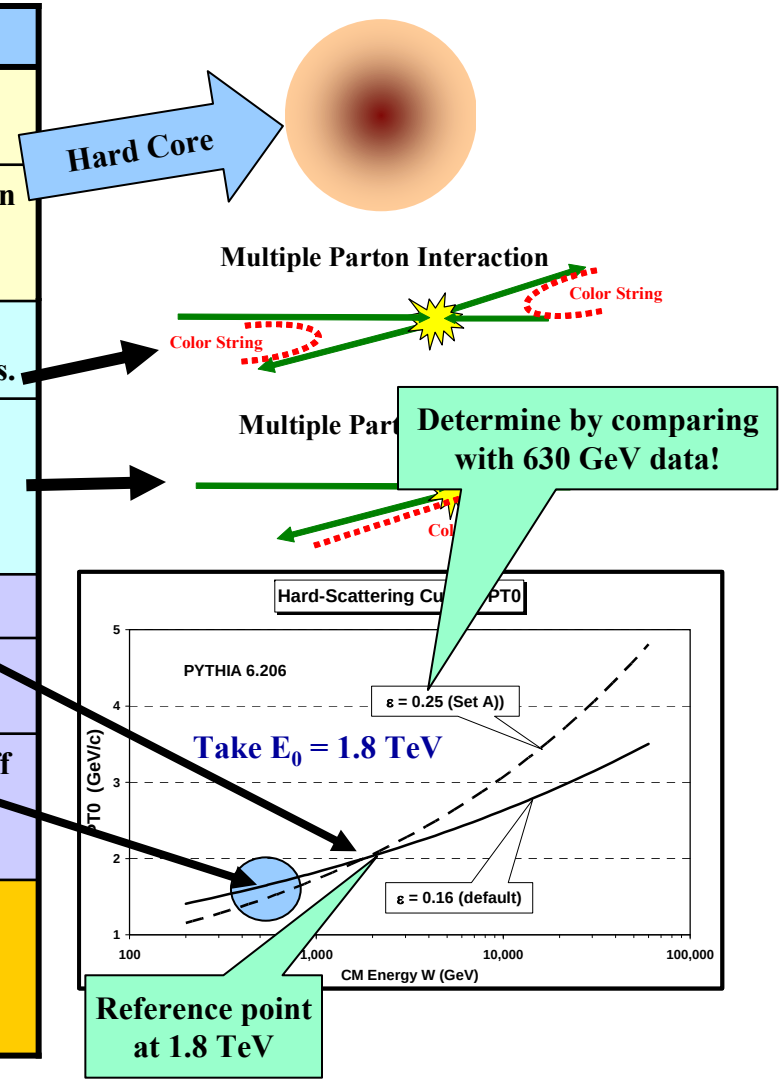


Tuning PYTHIA 6.2:
Multiple Parton Interaction Parameters

Parameter	Default	Description
PARP(83)	0.5	Double-Gaussian: Fraction of total hadronic matter within PARP(84)
PARP(84)	0.2	Double-Gaussian: Fraction of the overall hadron radius containing the fraction PARP(83) of the total hadronic matter
PARP(85)	0.33	Pr[illegible] uces two gluons w[illegible] nearest neighbors.
PARP(86)	0.66	Prob[illegible] luons eit[illegible] s des[illegible] closed [illegible] loop. [illegible] ists of [illegible] ark-antiqua[illegible] s.
PARP(89)	1 Te[illegible]	Determin[illegible] reference energy E_0.
PARP(82)	[illegible].9 GeV/c	The c[illegible] of P_{T0} that regulates the 2-to-2 sc[illegible]ring divergence $1/PT^4 \rightarrow 1/(PT^2+P_{T0}^2)^2$
PARP(90)	0.16	Determines the energy dependence of the cut-off P_{T0} as follows $P_{T0}(E_{cm}) = P_{T0}(E_{cm}/E_0)^{\varepsilon}$ with ε = PARP(90)
PARP(67)	1.0	A scale factor that determines the maximum parton virtuality for space-like showers. The larger the value of PARP(67) the more initial-state radiation.

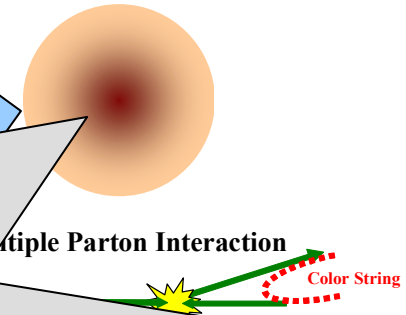
Determines the energy dependence of the MPI!

Affects the amount of initial-state radiation!



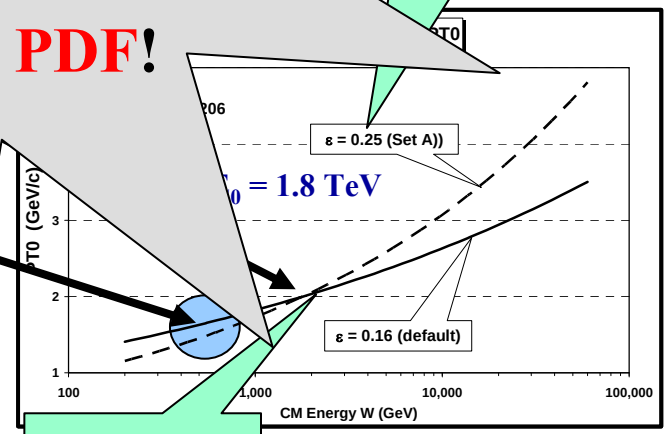
Tuning PYTHIA 6.2:
Multiple Parton Interaction Parameters

Parameter	Default	Description
PARP(83)	0	Double-Gaussian: Frac total hadron r within PARP(8
PARP(84)	0.2	ian: Fr ra tota
PARP(85)	0.33	D
PARP(86)		
PARP(89)	1 Te	
PARP(82)	GeV/c	scattering c
PARP(90)	0.16	Determine or P_{T0} as fol $_{T0}(E_{cm})$ $E_0)^{\varepsilon}$ w ε = PAR 0)
PARP(67)	1.0	A scale factor that dete the maximum parton virtuality for spa e showers. The larger the value of PAR the more initial-state radiation.



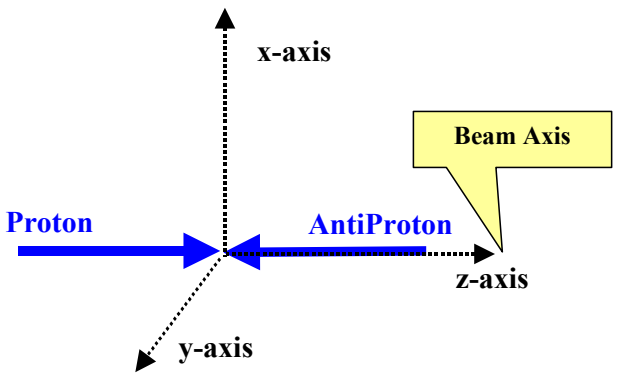
Remember the energy dependence of the "underlying event" activity depends on both the ε = PARP(90) and the PDF!

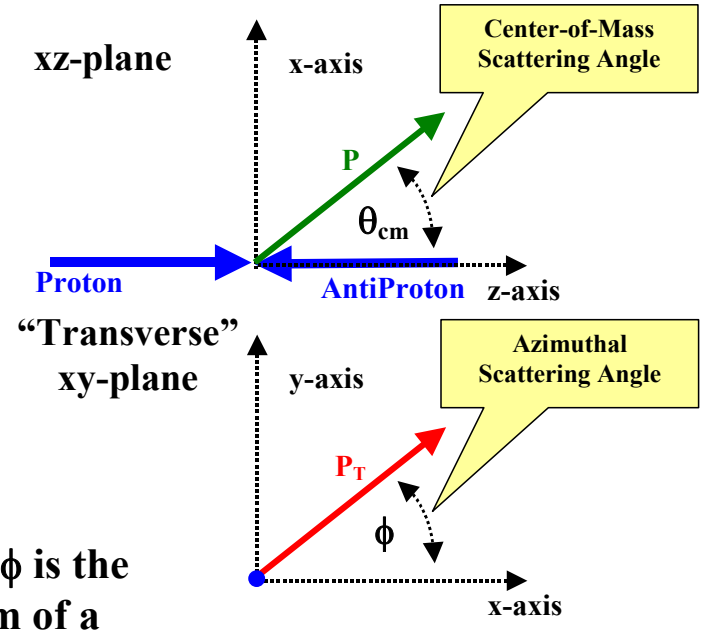
Determine by comparing with 630 GeV data!



Reference point at 1.8 TeV

Collider Coordinates

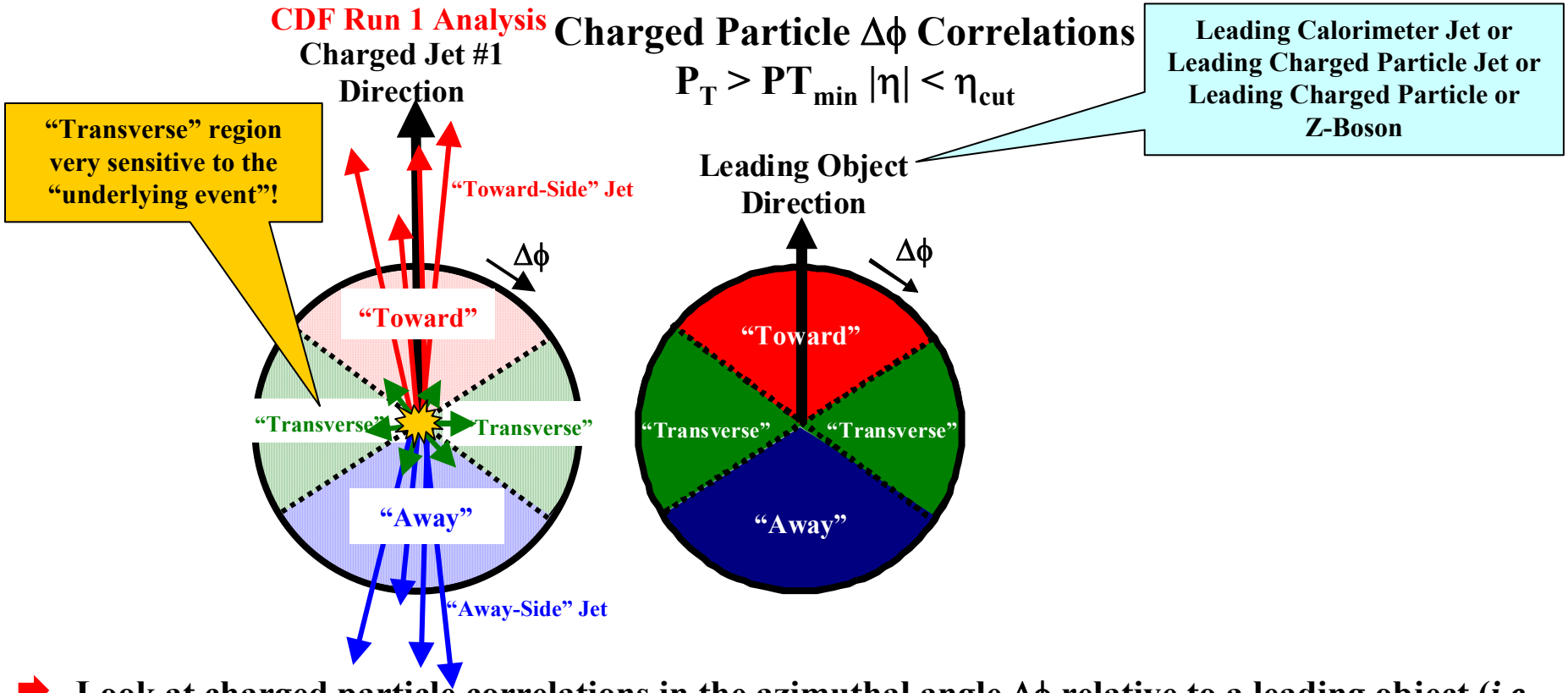




- The z-axis is defined to be the beam axis with the xy-plane being the "transverse" plane.
- θ_{cm} is the center-of-mass scattering angle and ϕ is the azimuthal angle. The "transverse" momentum of a particle is given by $P_T = P \cos(\theta_{cm})$.
- Use η and ϕ to determine the direction of an outgoing particle, where η is the "pseudo-rapidity" defined by $\eta = -\log(\tan(\theta_{cm}/2))$.

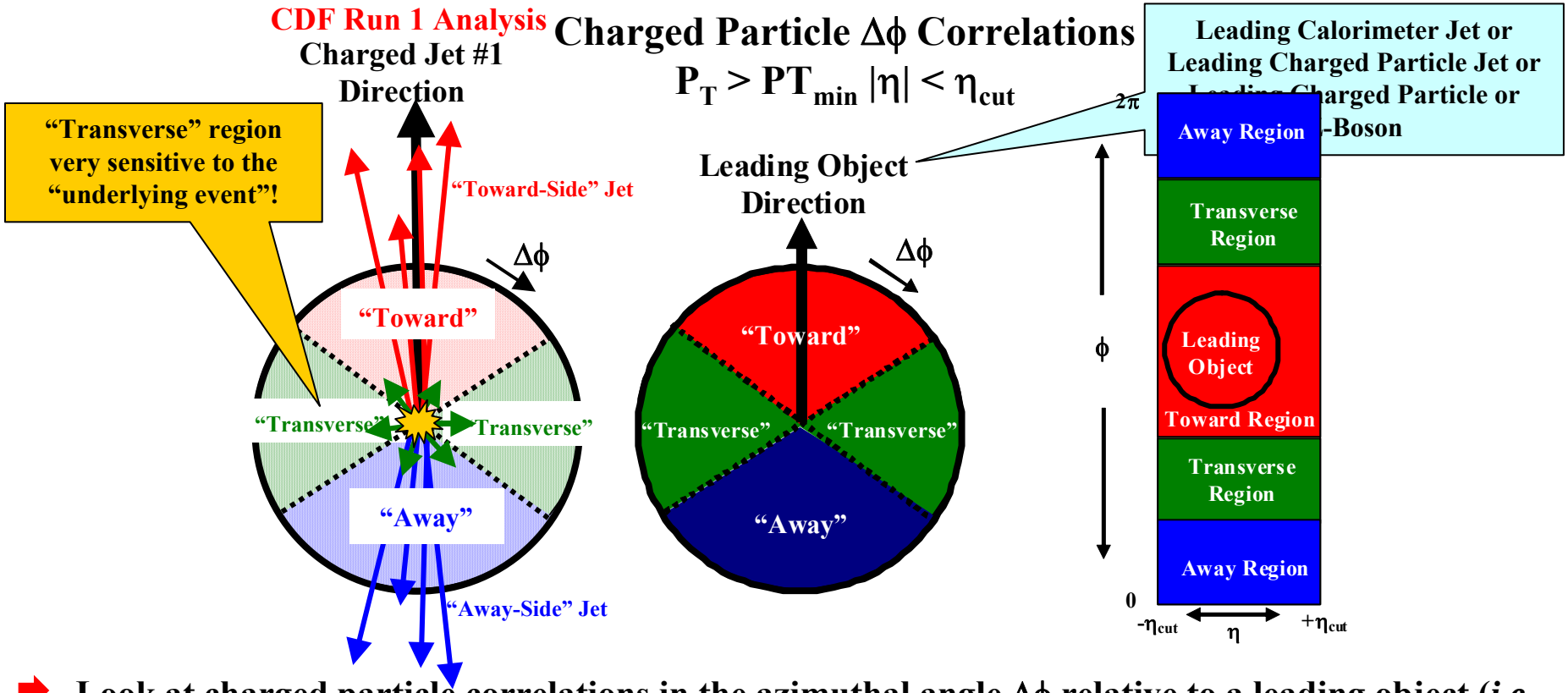
η	θ_{cm}
0	90°
1	40°
2	15°
3	6°
4	2°

Traditional Approach



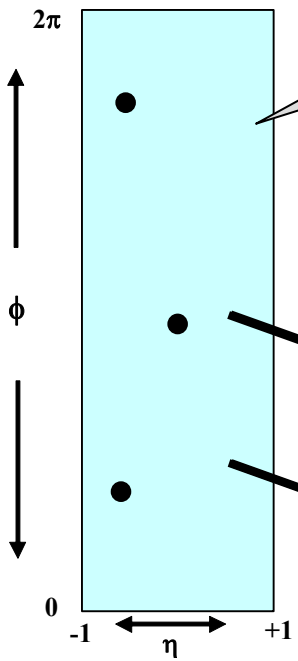
- Look at charged particle correlations in the azimuthal angle Δϕ relative to a leading object (*i.e.* CaloJet#1, ChgJet#1, PTmax, Z-boson). For CDF PTmin = 0.5 GeV/c $\eta_{cut} = 1$.
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away".
- All three regions have the same area in η-ϕ space, $\Delta\eta\times\Delta\phi = 2\eta_{cut}\times 120^o = 2\eta_{cut}\times 2\pi/3$. Construct densities by dividing by the area in η-ϕ space.

Traditional Approach



- Look at charged particle correlations in the azimuthal angle Δϕ relative to a leading object (*i.e.* CaloJet#1, ChgJet#1, PTmax, Z-boson). For CDF PTmin = 0.5 GeV/c $\eta_{cut} = 1$.
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away".
- All three regions have the same area in η-ϕ space, $\Delta\eta\times\Delta\phi = 2\eta_{cut}\times 120^o = 2\eta_{cut}\times 2\pi/3$. Construct densities by dividing by the area in η-ϕ space.

Particle Densities



$\Delta\eta\Delta\phi = 4\pi = 12.6$

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

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

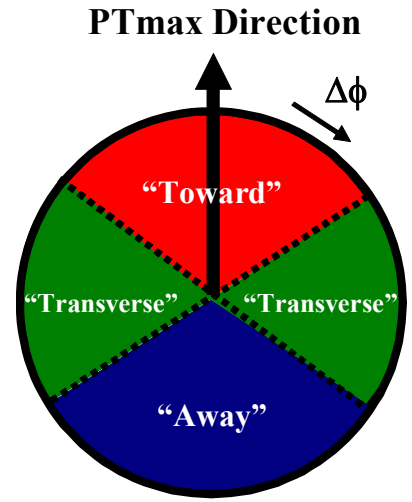
3 GeV/c PTsum → $dPT_{sum}/d\eta d\phi = 3/4\pi$ GeV/c = 0.24 GeV/c

Divide by 4π

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

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, $|\eta| < \eta_{cut}$.



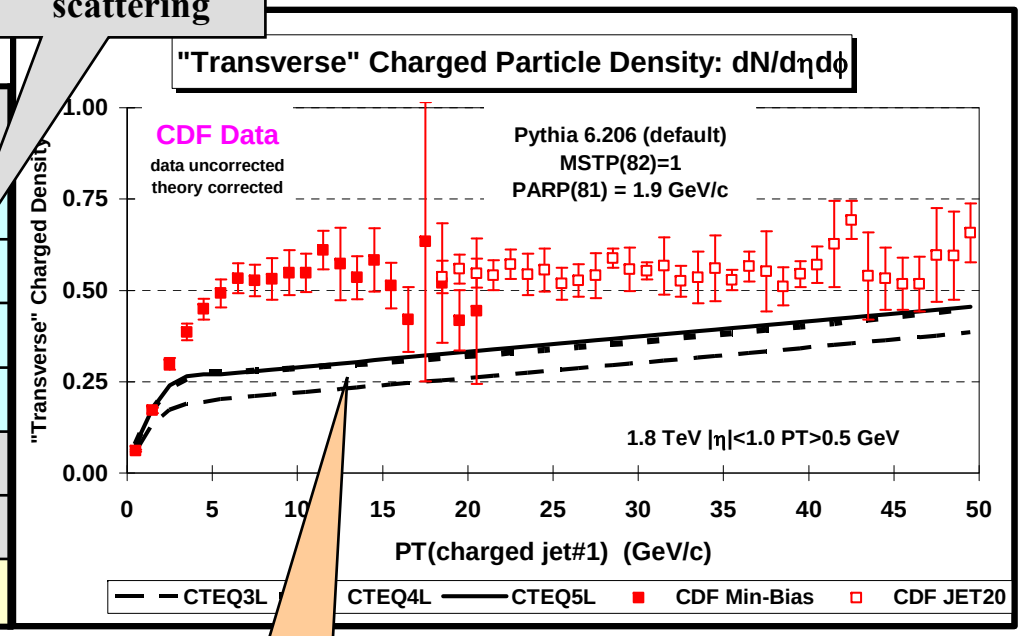
- **"Transverse" Charged PTsum Density:** Scalar p_T sum of the charged particles ($p_T > 0.5$ GeV/c, $|\eta| < \eta_{cut}$) in the "transverse" region as defined by the leading charged particle, PTmax, divided by the area in η-ϕ space, $2\eta_{cut}\times 2\pi/3$, averaged over all events with at least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

PYTHIA 6.206 Defaults

PYTHIA default parameters

Parameter	6.115	6.125	6.158	6.206
MSTP(81)	1	1	1	1
MSTP(82)	1	1	1	1
PARP(81)	1.4	1.9	1.9	1.9
PARP(82)	1.55	2.1	2.1	1.9
PARP(89)		1,000	1,000	1,000
PARP(90)		0.16	0.16	0.16
PARP(67)	4.0	4.0	1.0	1.0

MPI constant probability scattering



➡ **Plot shows the "Transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of PYTHIA 6.206 (P_T(hard) > 0) using the default parameters for multiple parton interactions and CTEQ3L, CTEQ4L, and CTEQ5L.**

Note Change
PARP(67) = 4.0 (< 6.138)
PARP(67) = 1.0 (> 6.138)

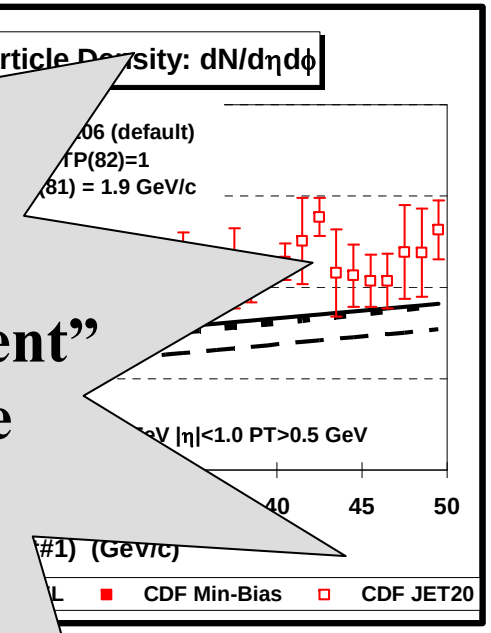
Default parameters give very poor description of the "underlying event"!

PYTHIA 6.206 Defaults

MPI constant probability cattering

PYTHIA d lt parameters

Parameter	6.115	6.2
MSTP(81)	1	1
MSTP(82)	1	
PARP(81)		
PARP(82)	1.55	
PARP(89)		1,
PARP(90)		
PARP(67)		



Remember the "underlying event" activity depends on both the cut-off p_{T0} and the PDF!

➡ Plot shows the "Trans rt vers gjet#1) compared to the QCD hard scatte predi PY .06 (P_T(h > 0) using the default parameters for mult ple parton ctions a EQ3L, CTE L, and CTEQ5L.

Note Change
PARP(67) = 4.0 (< 6.138)
PARP(67) = 1.0 (> 6.138)

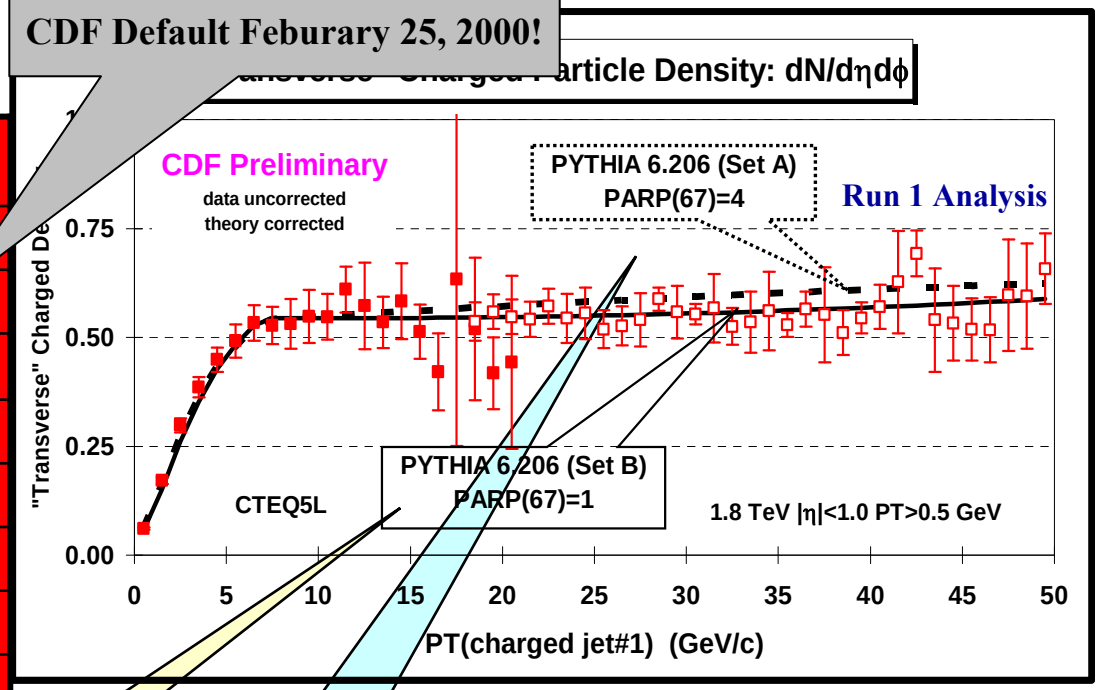
D t parameters e v poor description of th underlying event"!

Run 1 PYTHIA Tune A

PYTHIA 6.206 CTEQ5L

Parameter	Tune B	Tune A
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	1.9 GeV	2.0 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	1.0	0.9
PARP(86)	1.0	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(67)	1.0	4.0

CDF Default Feburary 25, 2000!



Plot shows the "transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

PYTHIA 6.2 Tunes

All use LO α_s with Λ = 192 MeV!

UE Parameters

ISR Parameter

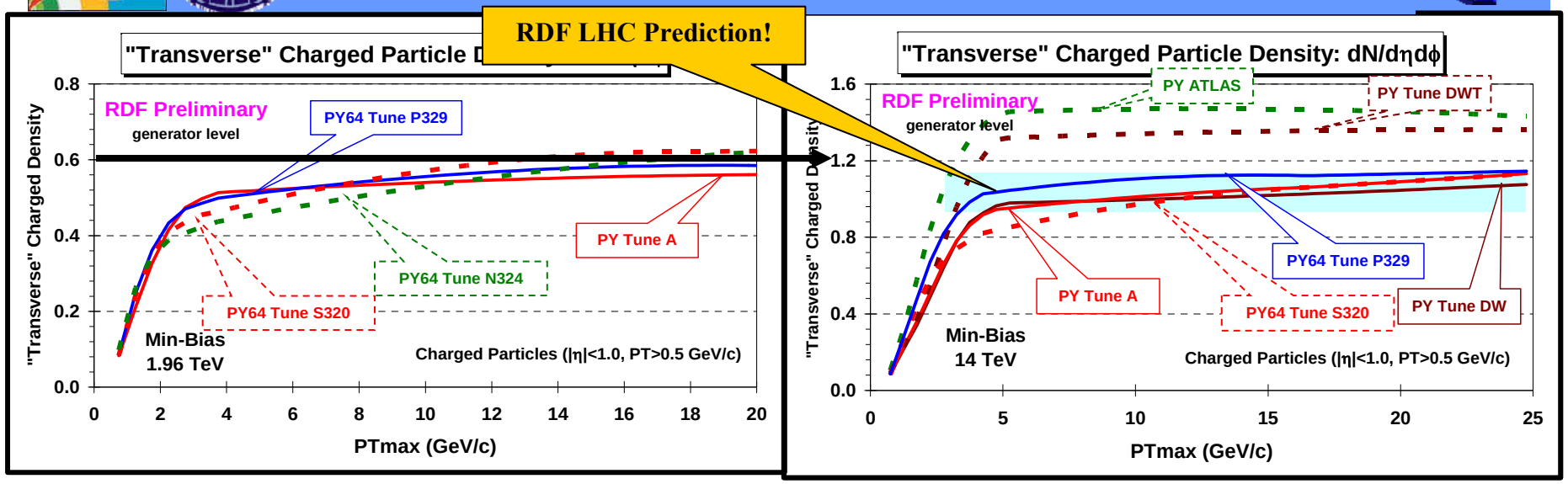
Intrinsic KT

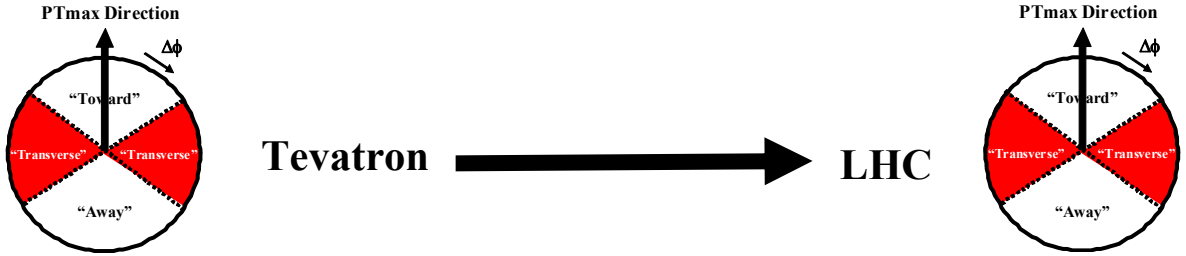
Uses CTEQ6L

Tune A energy dependence!

Parameter	Tune AW	Tune DW	Tune D6
PDF	CTEQ5L	CTEQ5L	CTEQ6L
MSTP(81)	1	1	1
MSTP(82)	4	4	4
PARP(82)	2.0 GeV	1.9 GeV	1.8 GeV
PARP(83)	0.5	0.5	0.5
PARP(84)	0.4	0.4	0.4
PARP(85)	0.9	1.0	1.0
PARP(86)	0.95	1.0	1.0
PARP(89)	1.8 TeV	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25	0.25
PARP(62)	1.25	1.25	1.25
PARP(64)	0.2	0.2	0.2
PARP(67)	4.0	2.5	2.5
MSTP(91)	1	1	1
PARP(91)	2.1	2.1	2.1
PARP(93)	15.0	15.0	15.0

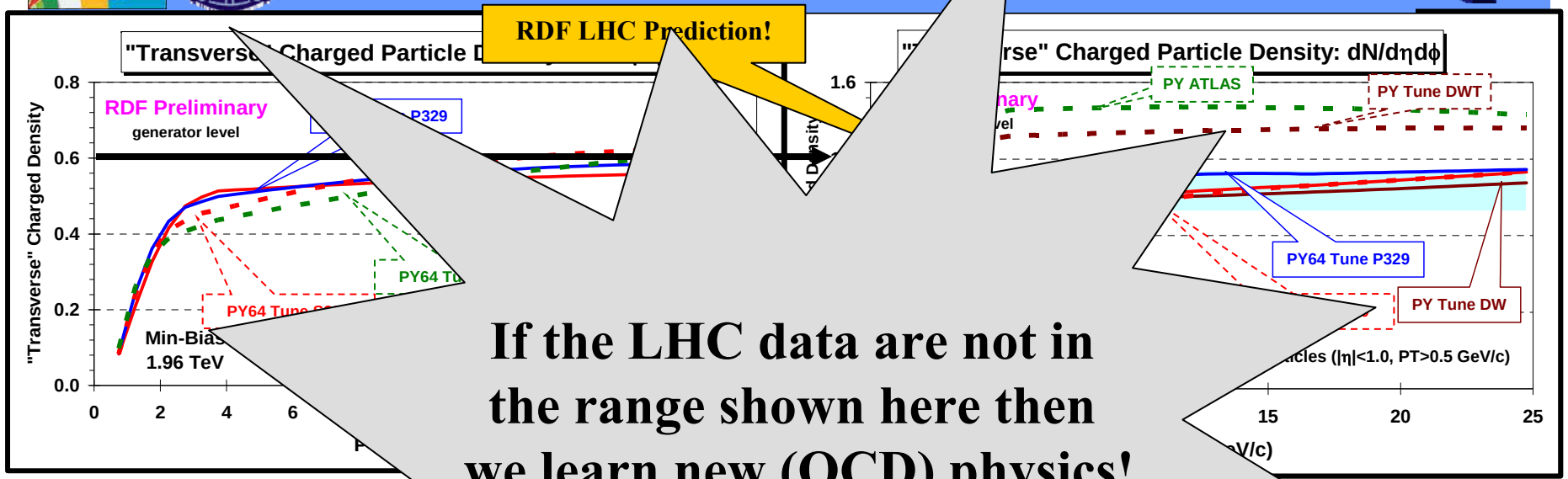
Transverse Charged Particle Density





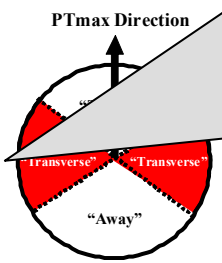
- **Shows the "associated" charged particle density in the "transverse" region as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min-bias" events at 1.96 TeV from PYTHIA Tune A, Tune S320, Tune N324, and Tune P329 at the particle level (*i.e.* generator level).**
- **Extrapolations of PYTHIA Tune A, Tune DW, Tune DWT, Tune S320, Tune P329, and pyATLAS to the LHC.**

Transverse Charged Particle Density



If the LHC data are not in the range shown here then we learn new (QCD) physics!

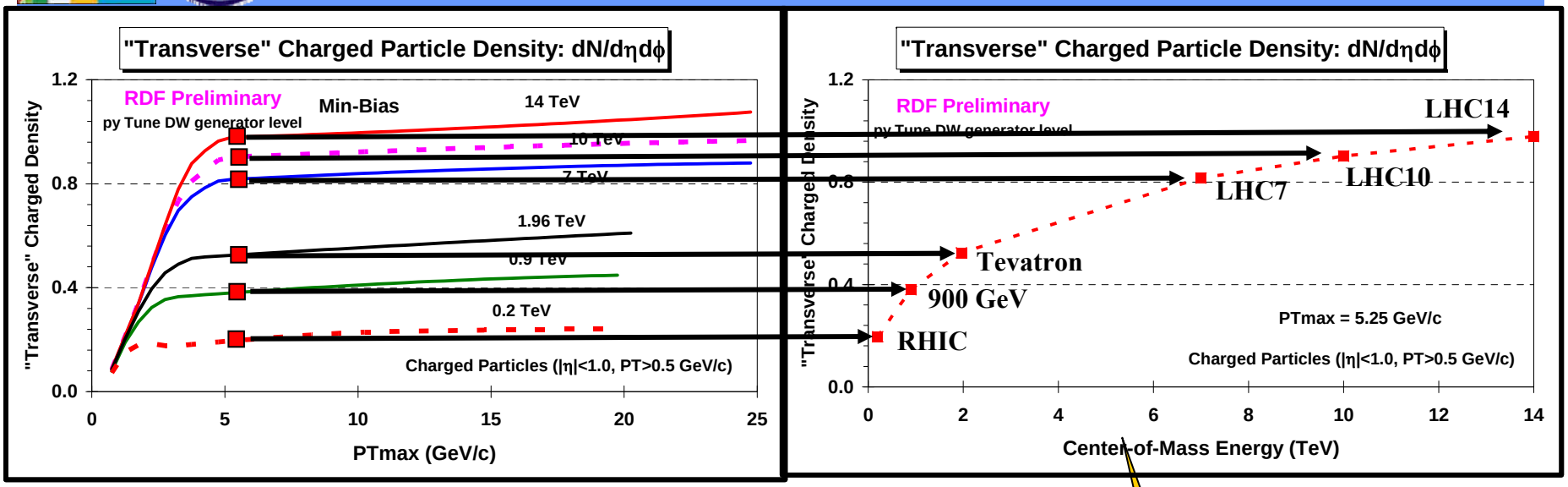
Rick Field October 13, 2009

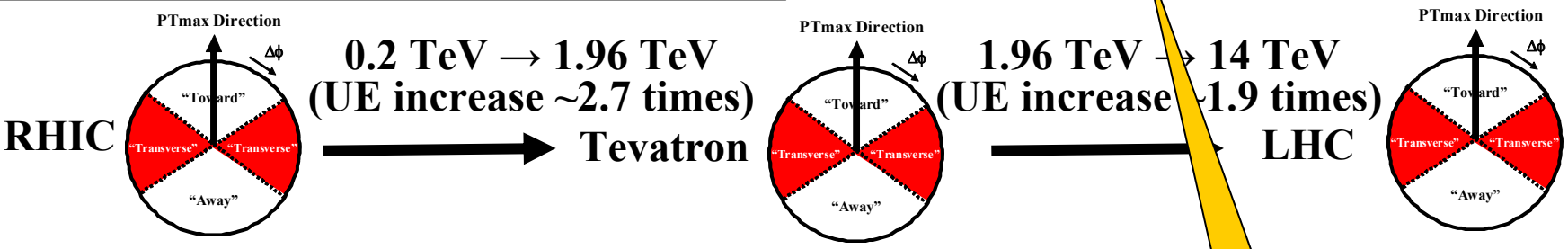


Teva

- Shows the "associated" charged par[illegible]nsity in [illegible]ransverse" [illegible]on as a function of PTmax for charged particles (p_T > 0.[illegible]/c, |η| < [illegible] *including PTmax*) for "min-bias" events at 1.96 TeV from PYTHIA Tune A, T[illegible] S320, Tune [illegible]24, and Tune P329 at the particle level (*i.e.* generator level).
- Extrapolations of PYTHIA Tune A, Tune D[illegible], Tune DWT, Tune S320, Tune P329, and pyATLAS to the LHC.

"Transverse" Charged Particle Density

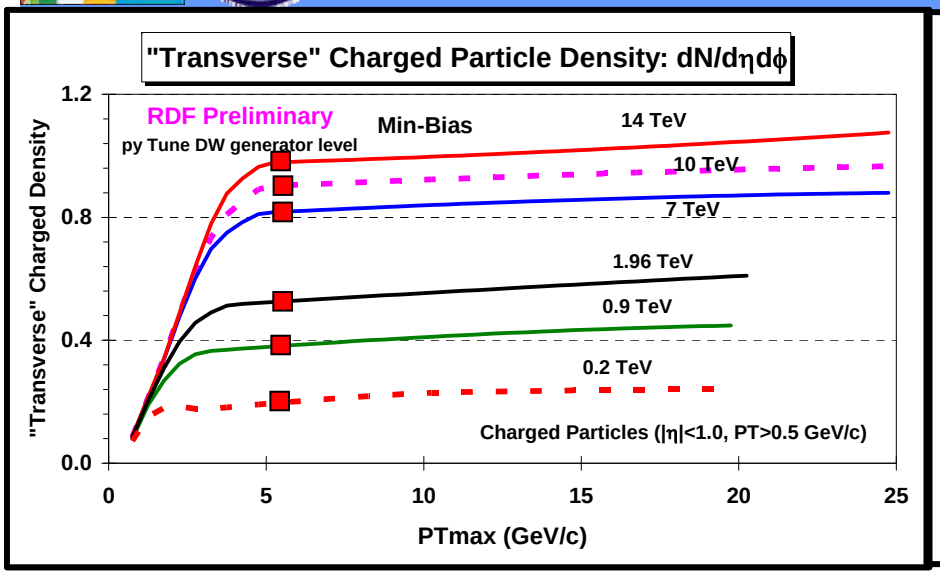


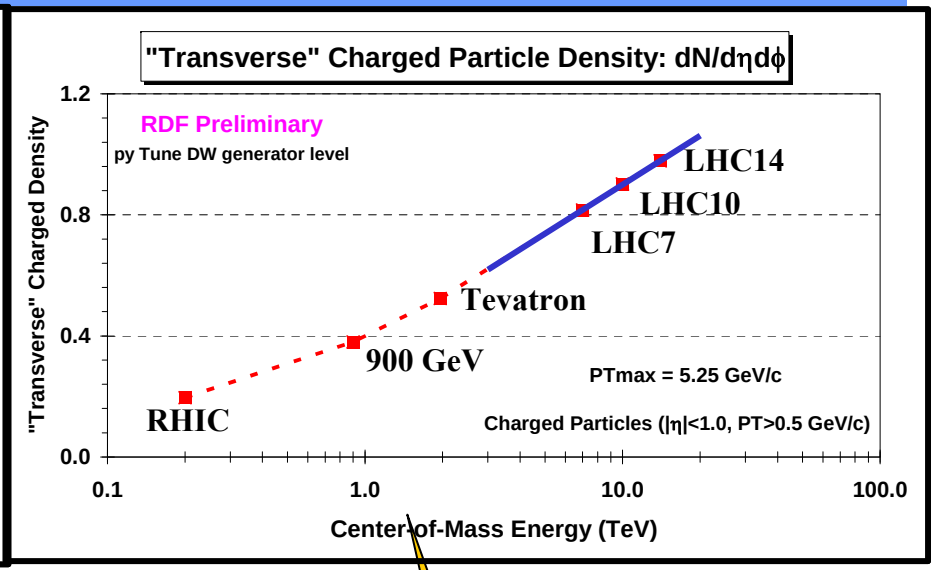


- Shows the "associated" charged particle density in the "transverse" region as a function of PTmax for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, *not including PTmax*) in "min-bias" events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA py Tune DW at the particle level (*i.e.* generator level).

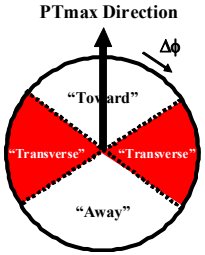
Linear scale!

"Transverse" Charged Particle Density





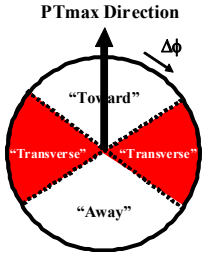
LHC7



7 TeV → 14 TeV
(UE increase ~20%)

Linear on a log plot!

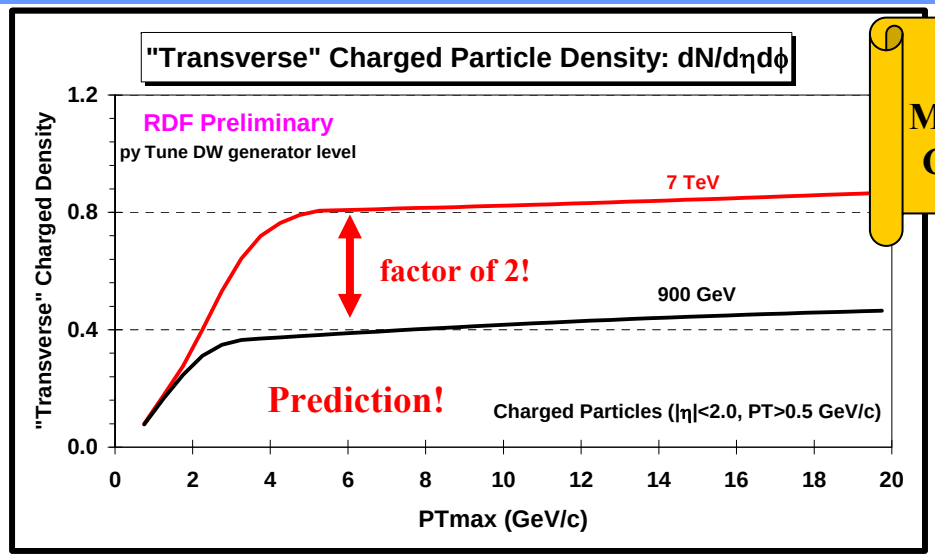
LHC14



Log scale!

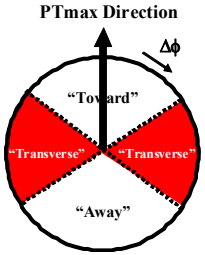
- **Shows the "associated" charged particle density in the "transverse" region a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) "min-bias" events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTH at the particle level (*i.e.* generator level).**

"Transverse" Charge Density



Rick Field
MB&UE@CMS Workshop
CERN, November 6, 2009

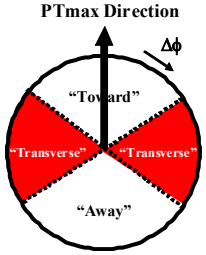
LHC 900 GeV



900 GeV → 7 TeV
(UE increase ~ factor of 2)

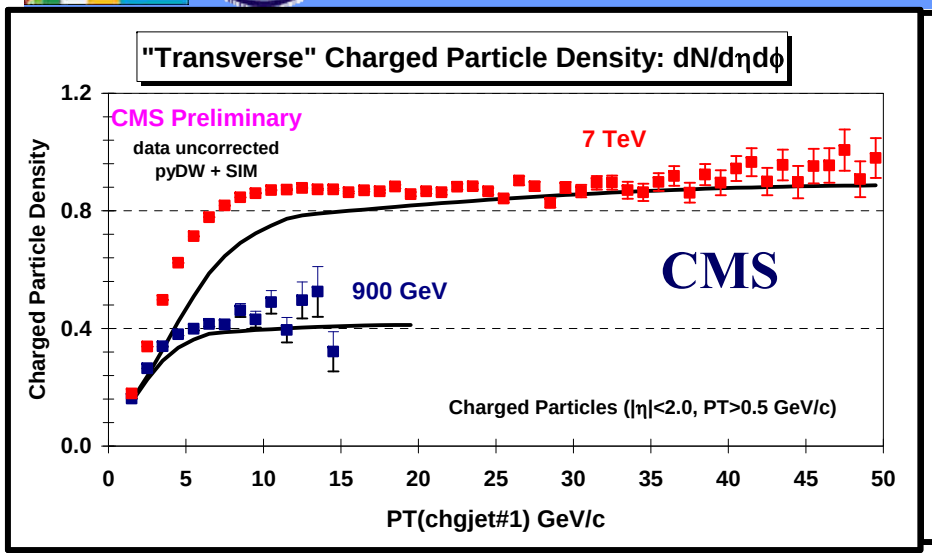
~0.4 → ~0.8

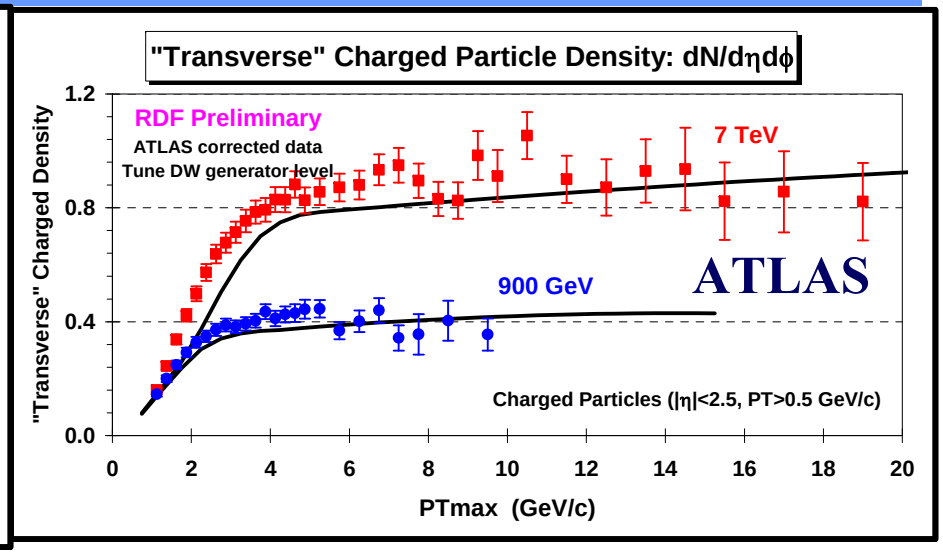
LHC 7 TeV



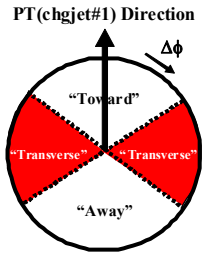
- **Shows the charged particle density in the "transverse" region for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 2$) at 900 GeV and 7 TeV as defined by PTmax from PYTHIA Tune DW and at the particle level (*i.e.* generator level).**

PYTHIA Tune DW

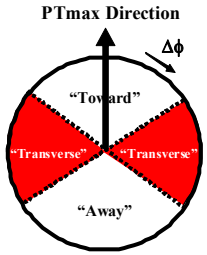




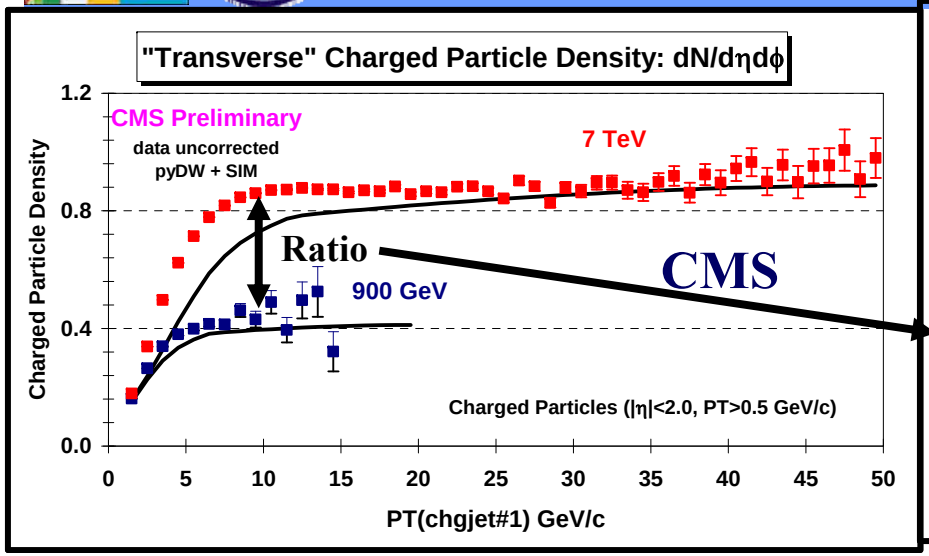
➡ **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.**

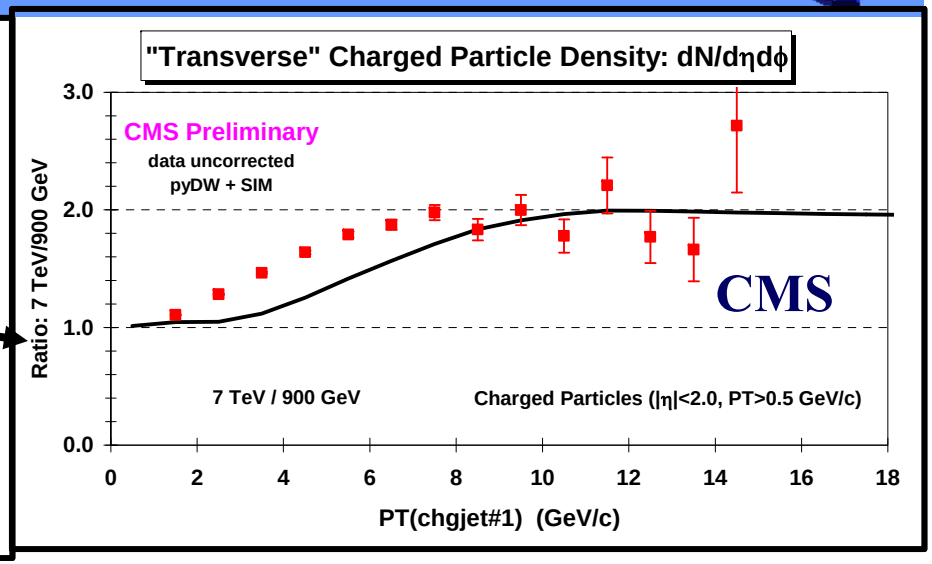


➡ **ATLAS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune DW at the generator level.**

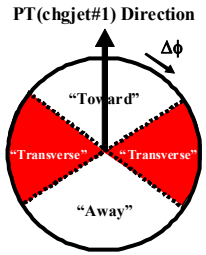


PYTHIA Tune DW

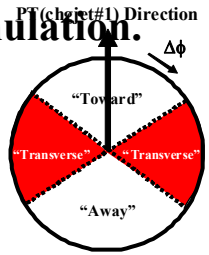




- **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.**

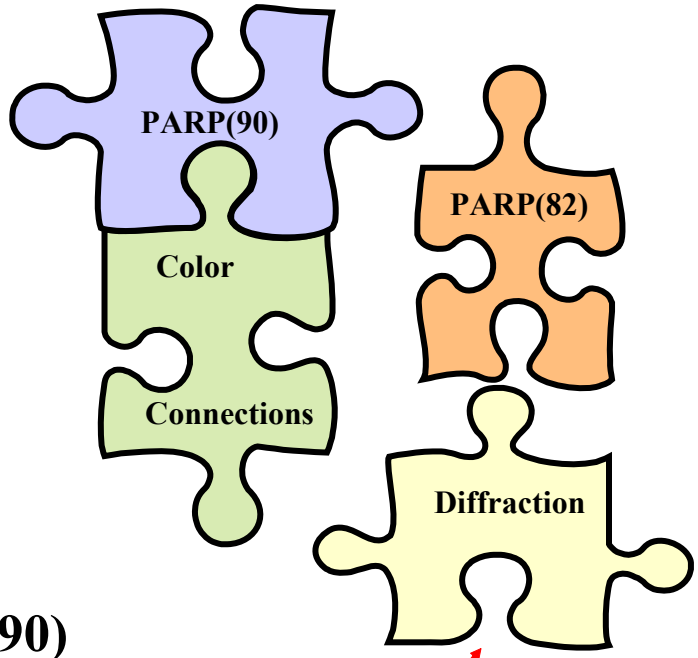


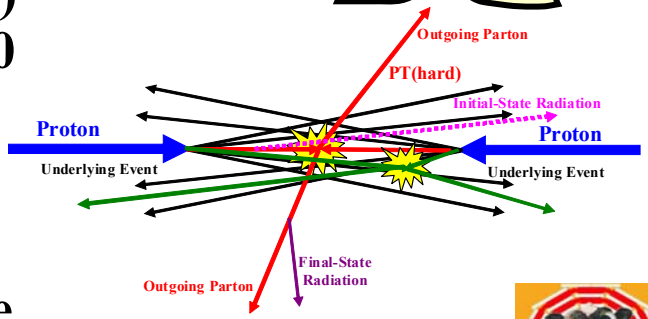
- **Ratio of CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.**



PYTHIA Tune Z1

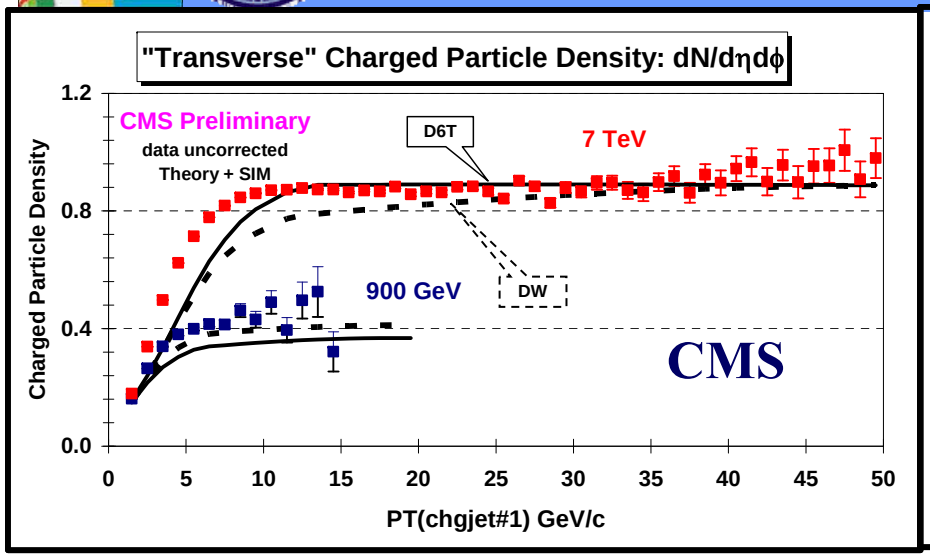
- All my previous tunes (A, DW, DWT, D6, D6T, CW, X1, and X2) were PYTHIA 6.4 tunes using the old Q^2-ordered parton showers and the old MPI model (really 6.2 tunes)!
- I believe that it is time to move to PYTHIA 6.4 (p_T-ordered parton showers and new MPI model)!
- Tune Z1: I started with the parameters of ATLAS Tune AMBT1, but I changed LO* to CTEQ5L and I varied PARP(82) and PARP(90) to get a very good fit of the CMS UE data at 900 GeV and 7 TeV.
- The ATLAS Tune AMBT1 was designed to fit the inelastic data for Nchg ≥ 6 and to fit the PTmax UE data with PTmax > 10 GeV/c. Tune AMBT1 is primarily a min-bias tune, while Tune Z1 is a UE tune!

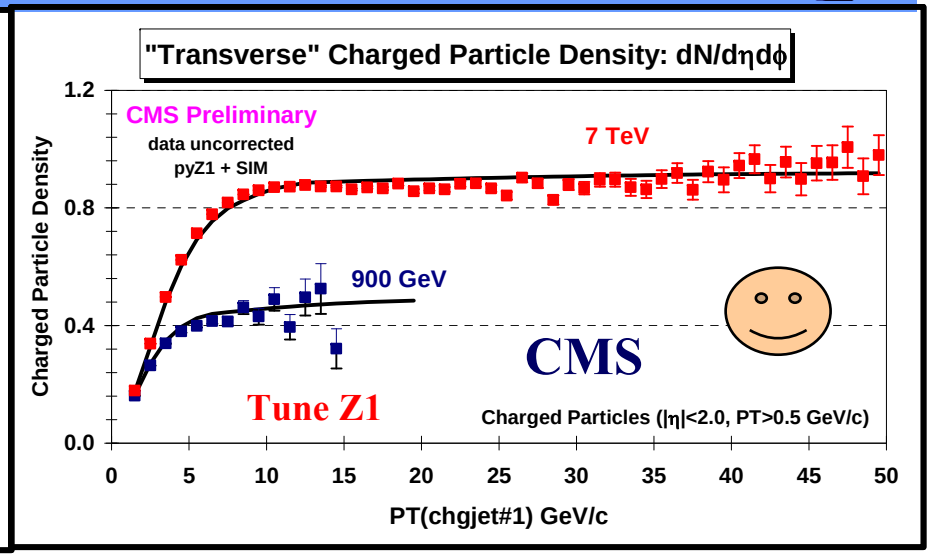




UE&MB@CMS

CMS UE Data





- **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$. The data are uncorrected and compared with PYTHIA Tune DW and D6T after detector simulation (SIM).**

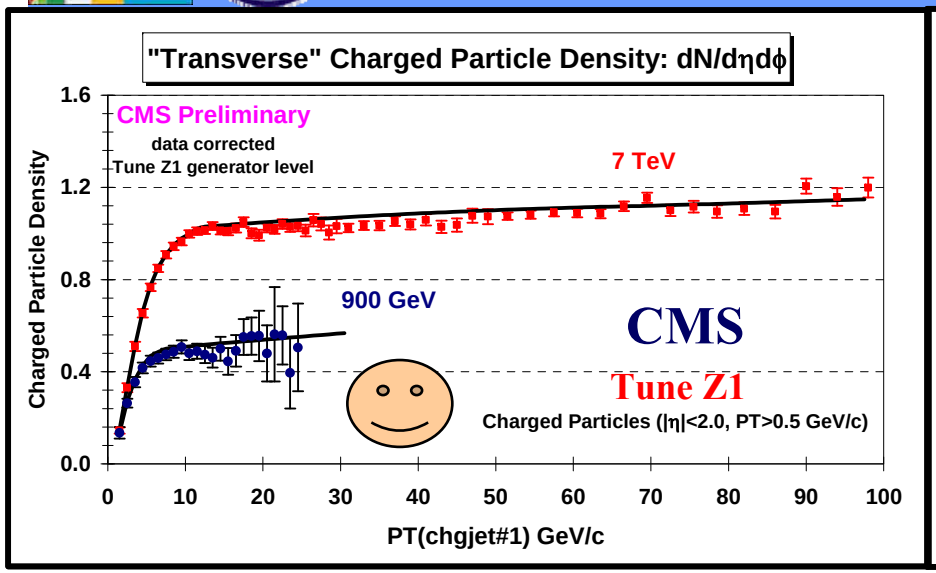
- **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$. The data are uncorrected and compared with PYTHIA Tune Z1 after detector simulation (SIM).**

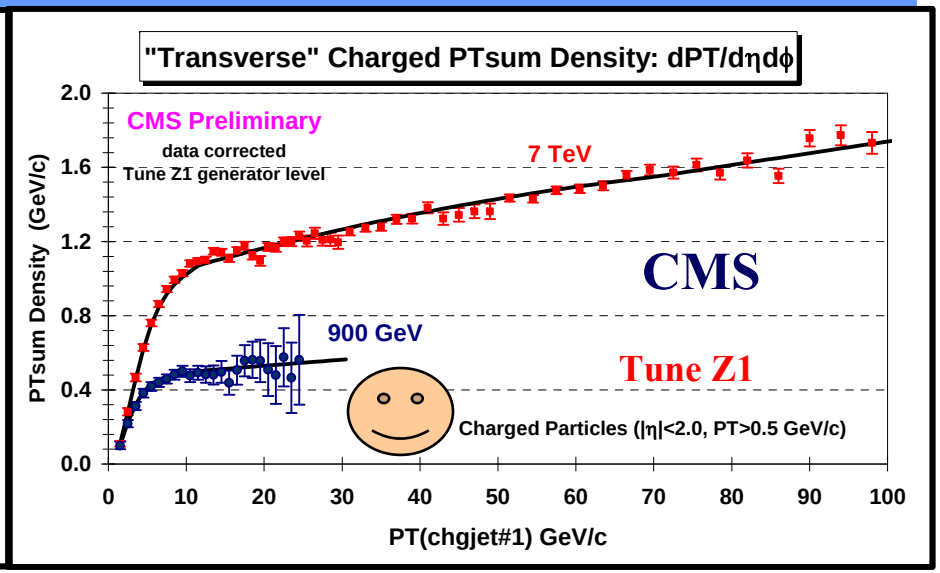
Color reconnection suppression.
Color reconnection strength.

Tune Z1 (CTEQ5L)
PARP(82) = 1.932
PARP(90) = 0.275
PARP(77) = 1.016
PARP(78) = 0.538

Tune Z1 is a PYTHIA 6.4 using p_T-ordered parton showers and the new MPI model!

PYTHIA 6.4 Tune Z2





- **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$. The data are corrected and compared with PYTHIA Tune Z1 at the generator level.**

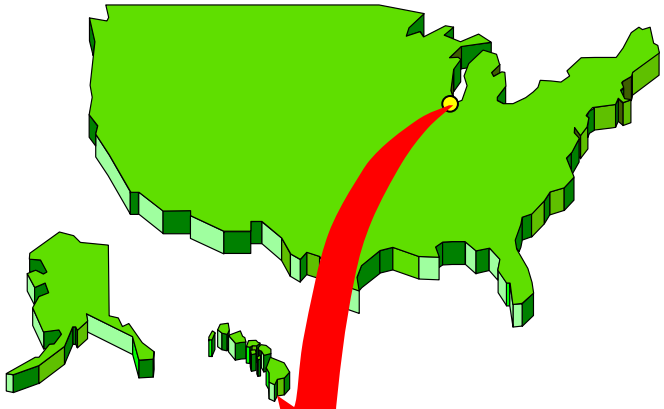
- **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged PTsum density, dPT/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$. The data are corrected and compared with PYTHIA Tune Z1 at the generator level.**

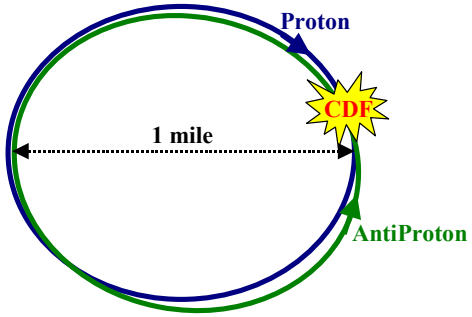
CMS corrected data!

Very nice agreement!

CMS corrected data!

Tevatron Energy Scan





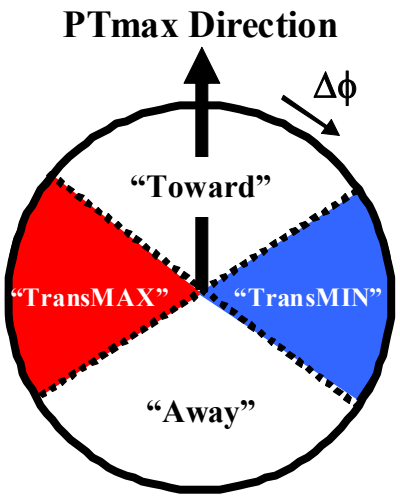
- **Just before the shutdown of the Tevatron CDF has collected more than 10M "min-bias" events at several center-of-mass energies!**

300 GeV 12.1M MB Events

900 GeV 54.3M MB Events

New 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, $|\eta| < \eta_{cut}$.



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

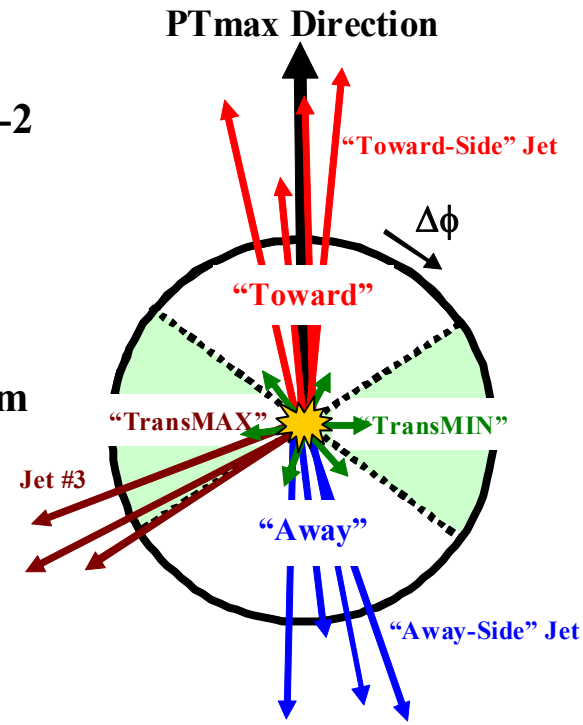
"Transverse" Density = "transAVE" Density = ("transMAX" Density + "transMIN" Density)/2

"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 ≤ "TransDIF" ≤ 2×"TransAVE"

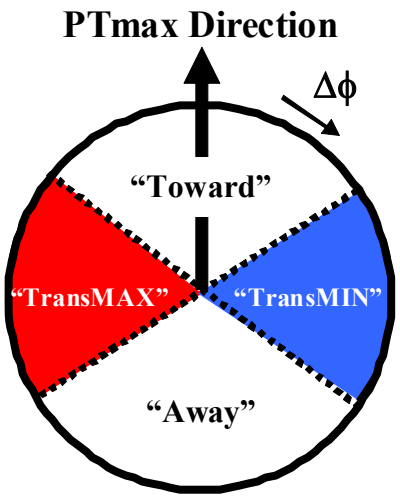
"TransDIF" = "TransAVE" if "TransMIX" = 3×"TransMIN"

PTmax UE Data

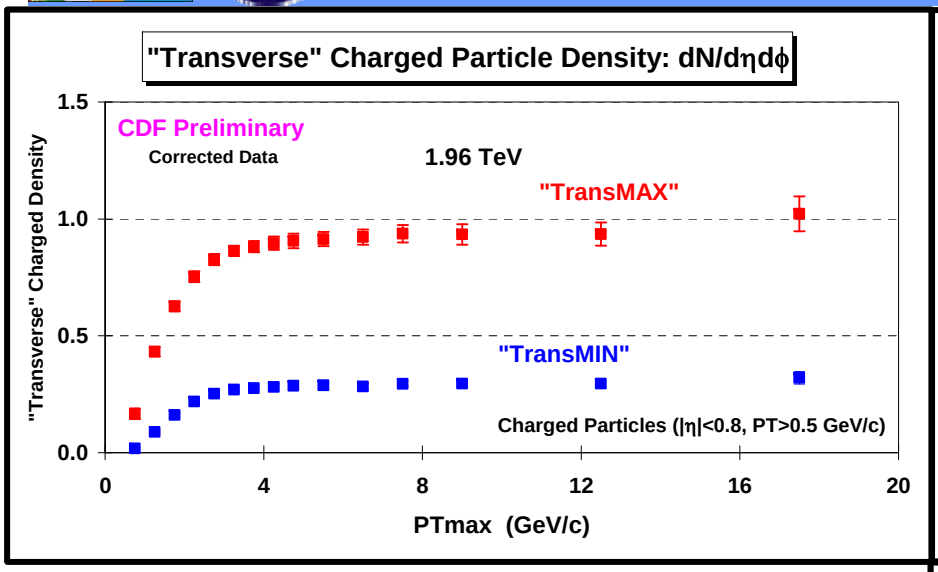
- **CDF PTmax UE Analysis: "transMAX", "transMIN", "transAVE", and "transDIF" charged particle and PTsum densities (p_T > 0.5 GeV/c, |η| < 0.8) in proton-antiproton collisions at 300 GeV, 900 GeV, and 1.96 TeV (R. Field analysis).**

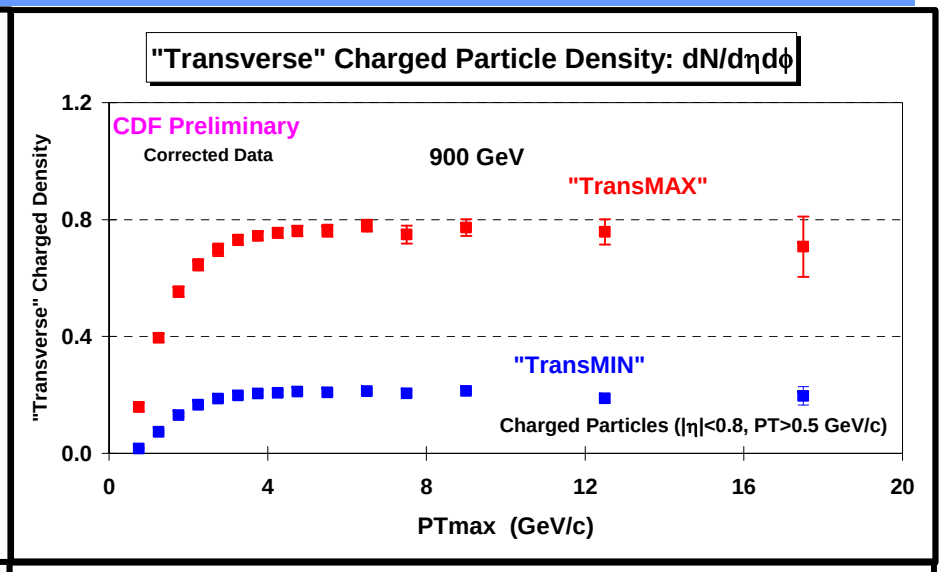
- **CMS PTmax UE Analysis: "transMAX", "transMIN", "transAVE", and "transDIF" charged particle and PTsum densities (p_T > 0.5 GeV/c, |η| < 0.8) in proton-proton collisions at 900 GeV and 7 TeV (M. Zakaria analysis). The "transMAX", "transMIN", and "transDIF" are not yet approved so I can only show "transAVE" which is approved.**

- **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.**

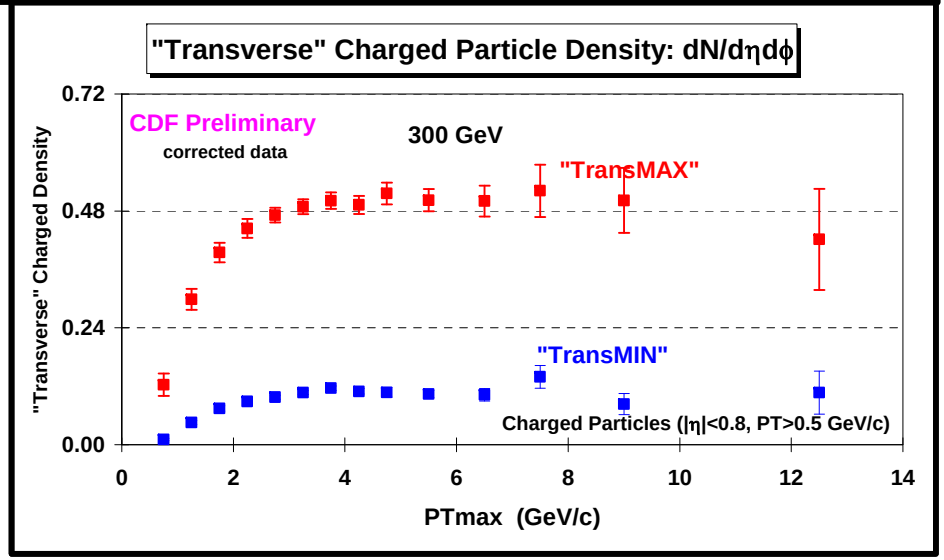


"transMAX/MIN" NchgDen

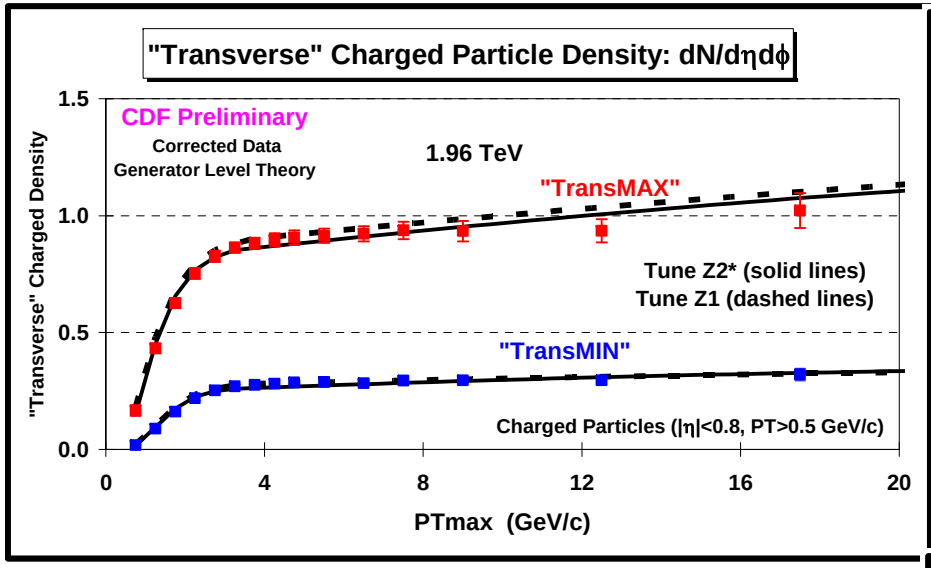


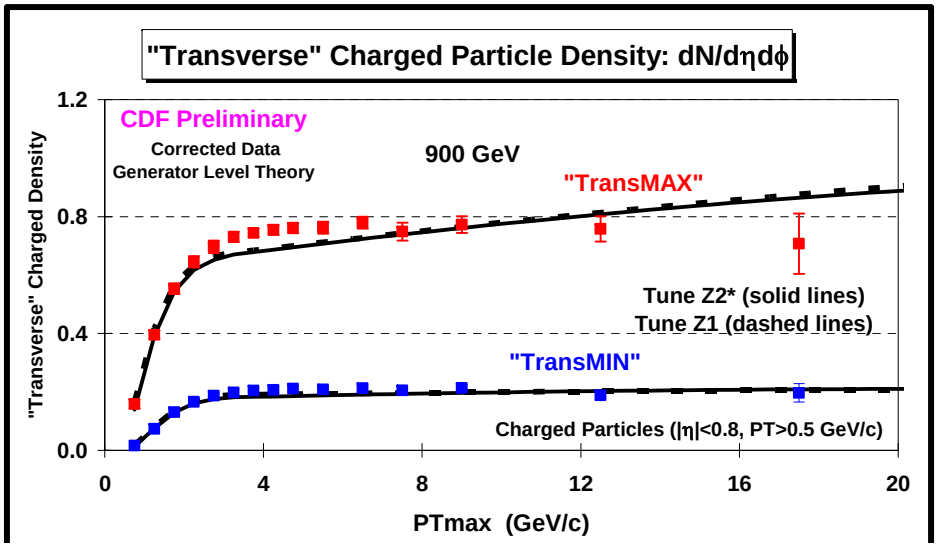


- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transMAX" and "transMIN" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors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



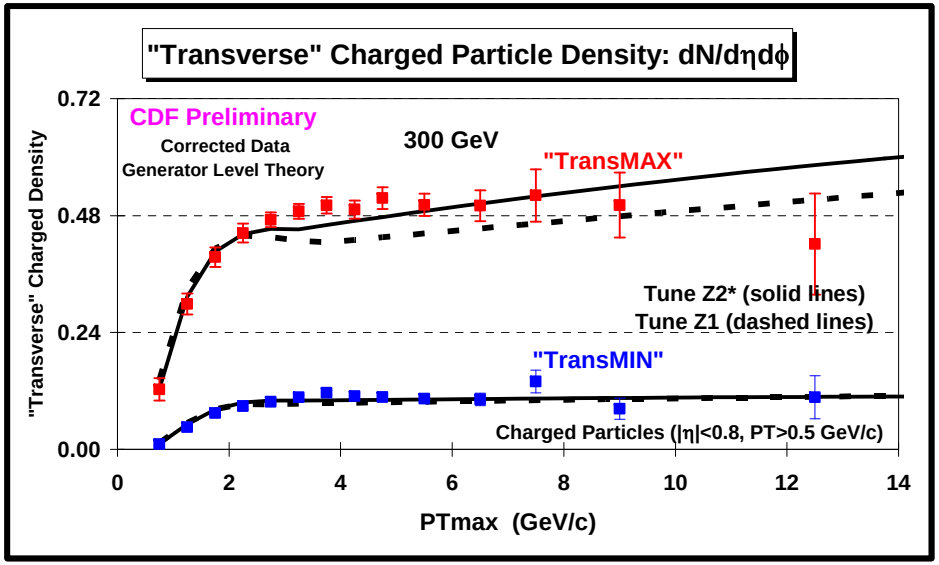
"transMAX/MIN" NchgDen



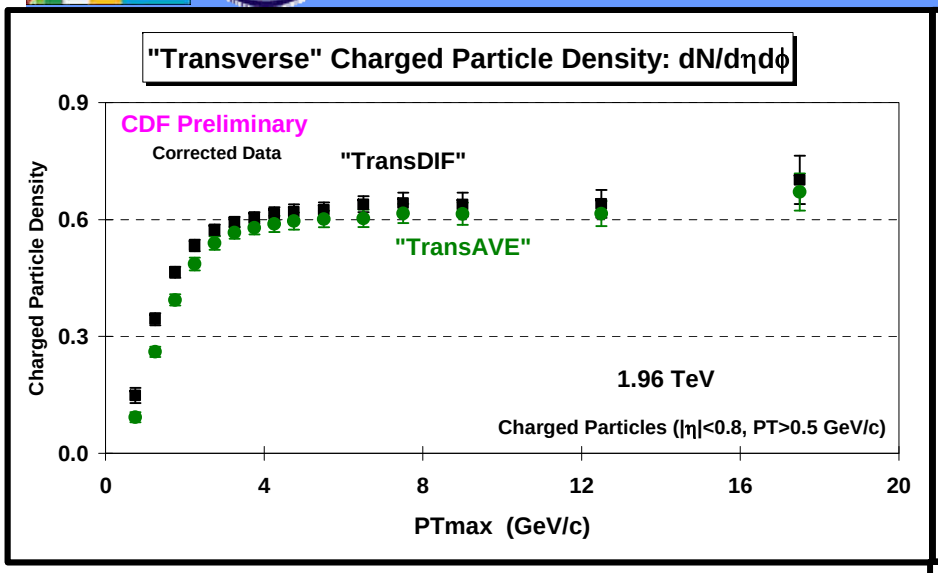


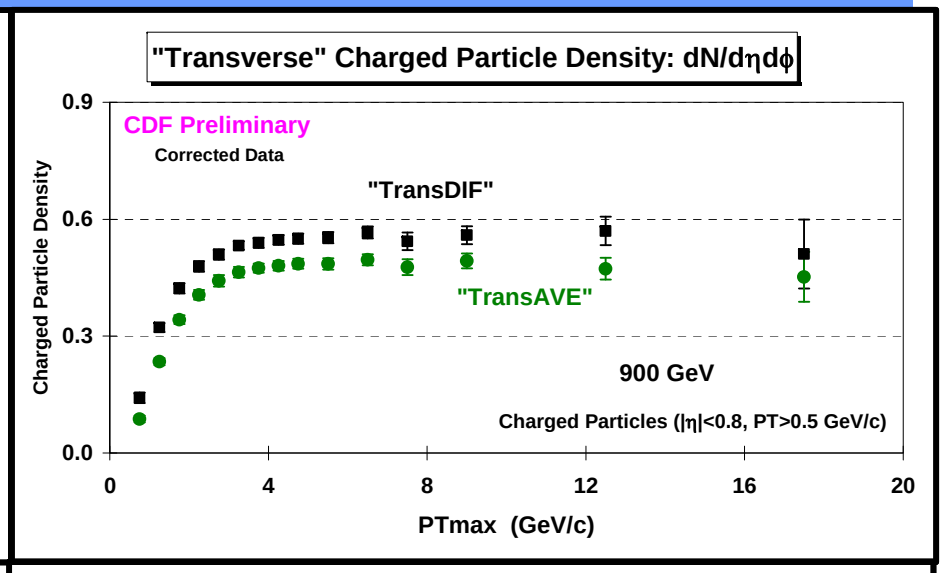
- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transMAX" and "transMIN" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors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

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

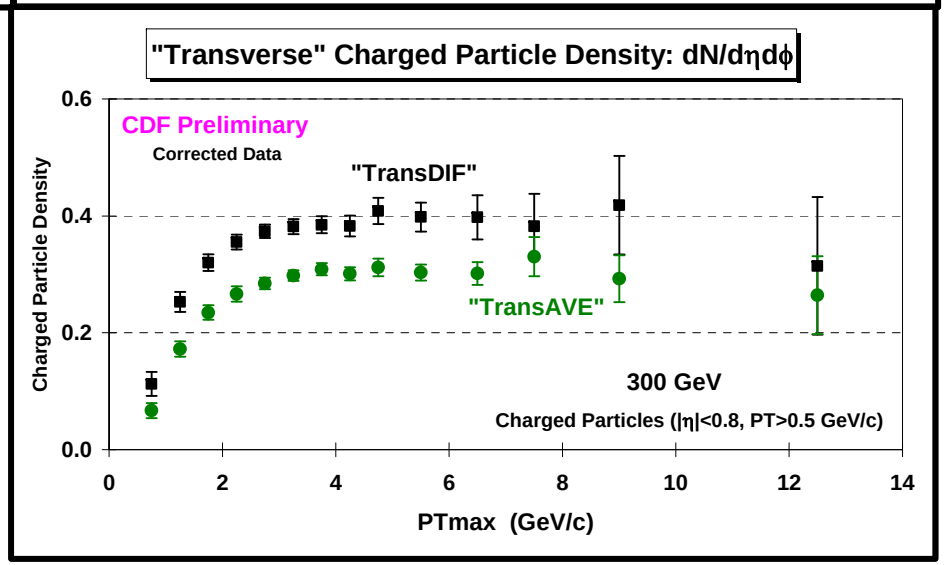


"transDIF/AVE" NchgDen

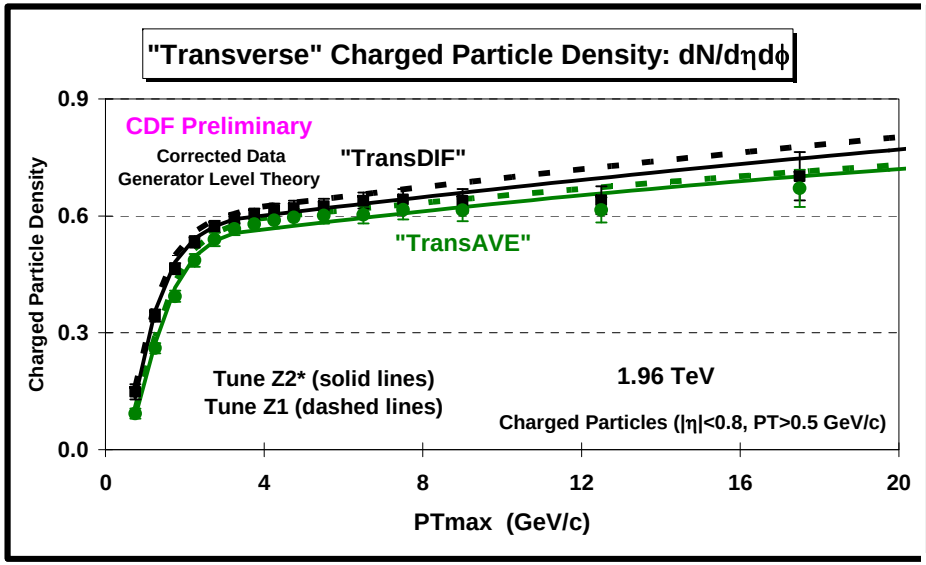


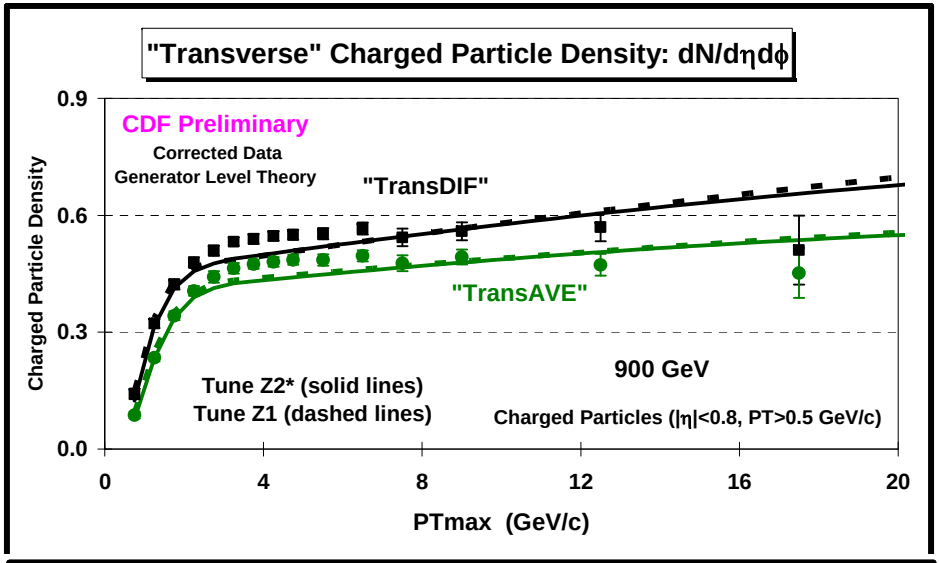


- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transAVE" and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors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

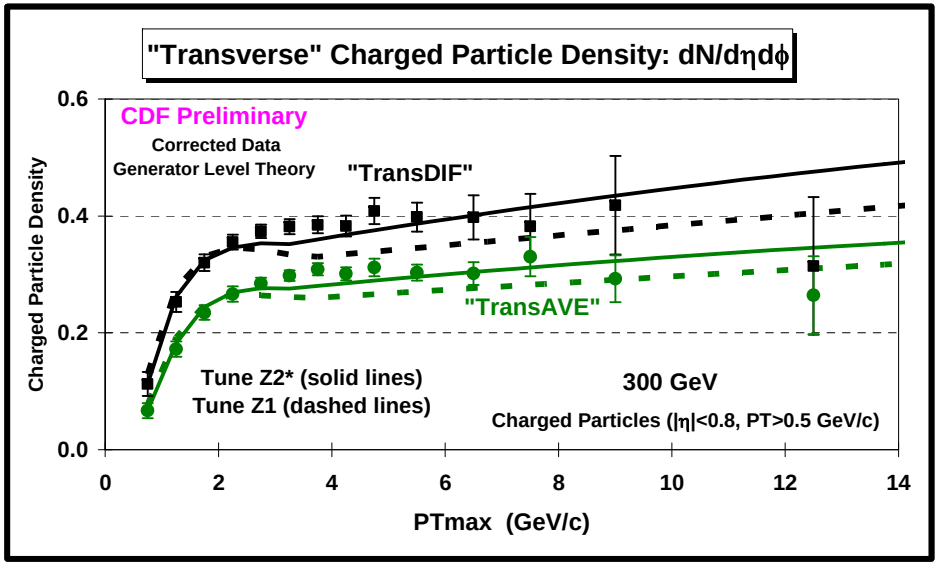


"transDIF/AVE" NchgDen

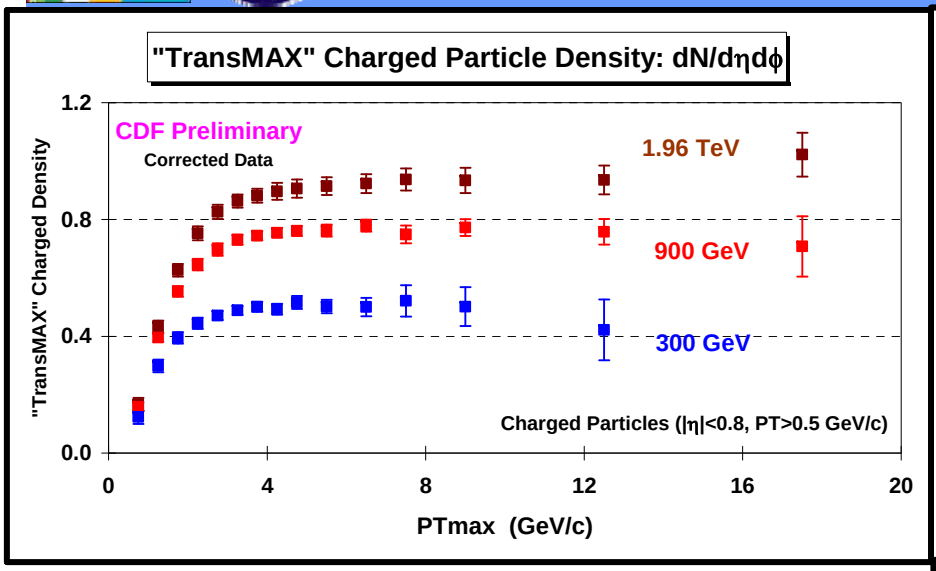


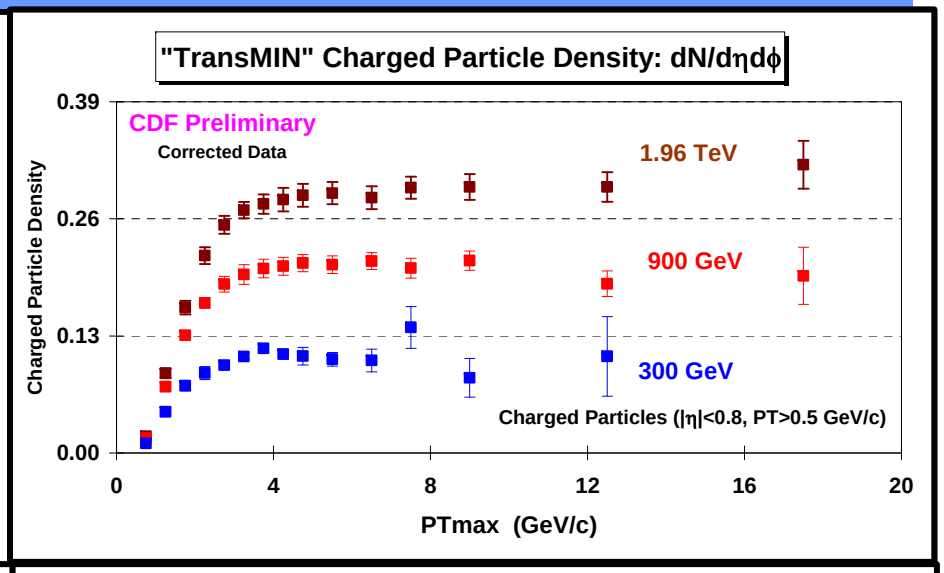


- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transAVE" and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors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

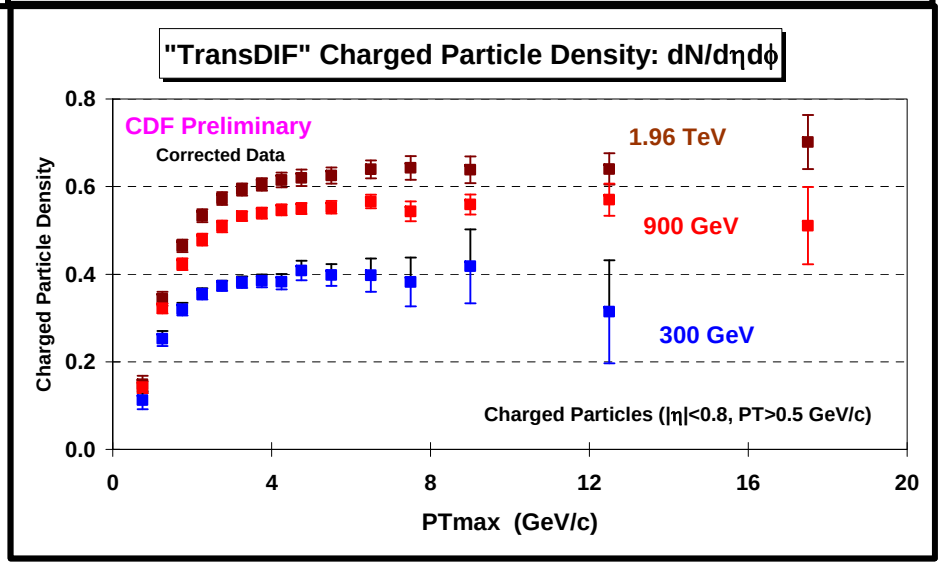


"transMAX/MIN" NchgDen

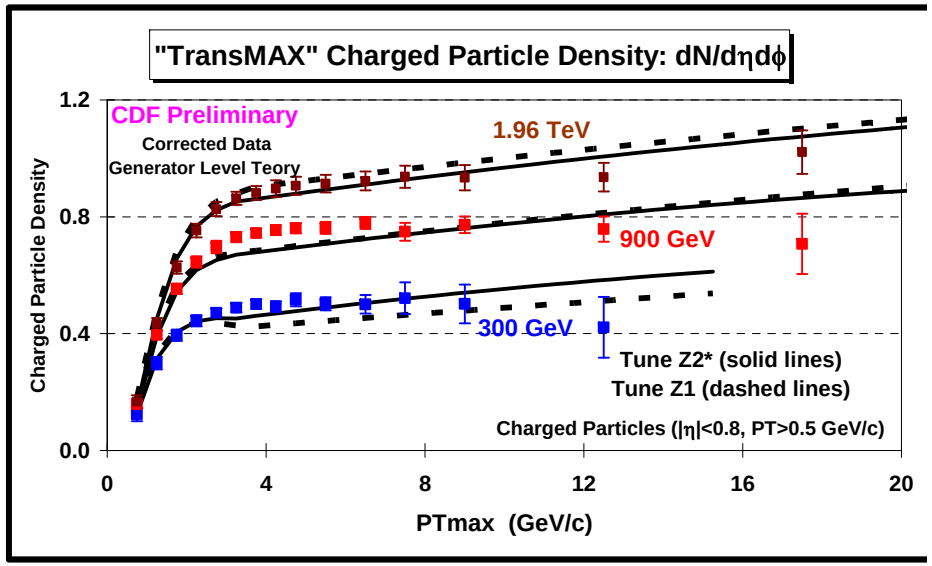


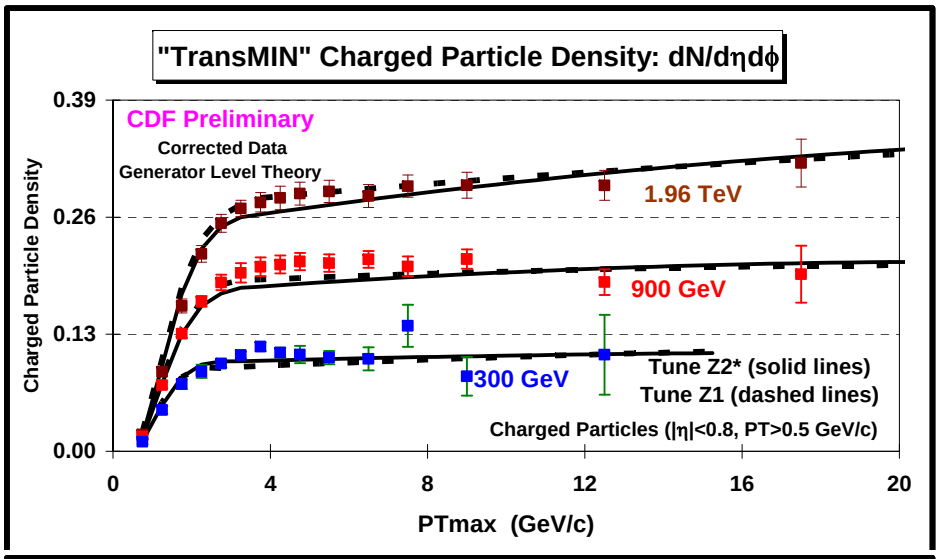


- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transMAX", "transMIN", and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level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



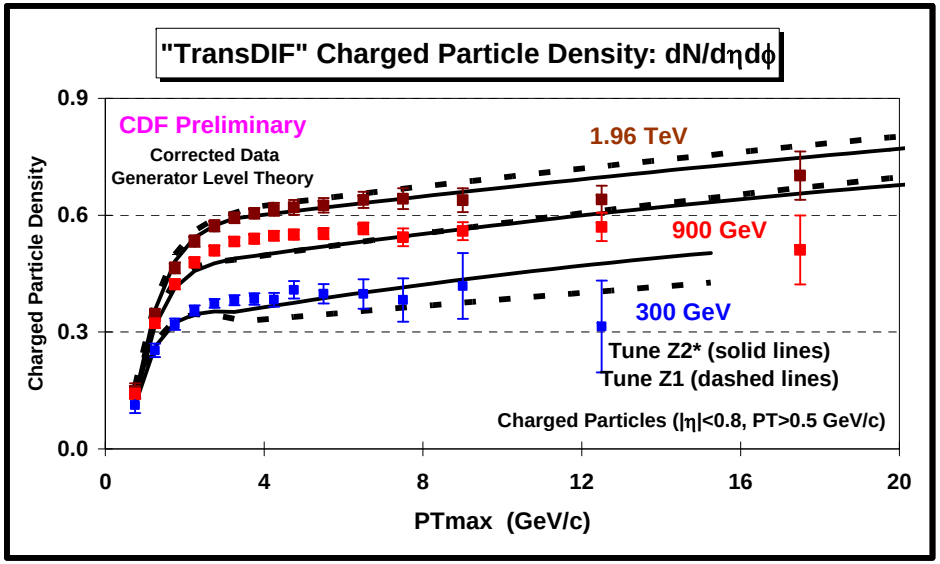
"transMAX/MIN" NchgDen



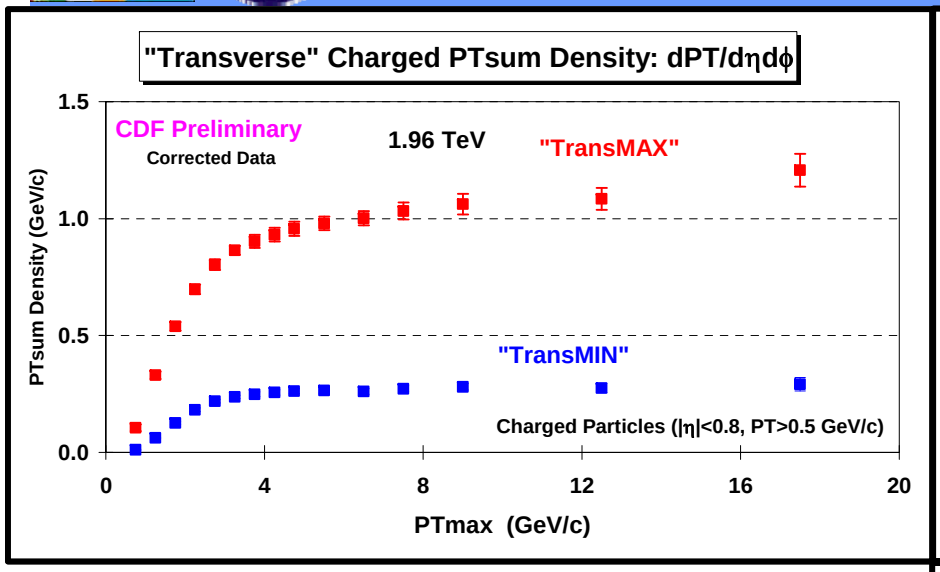


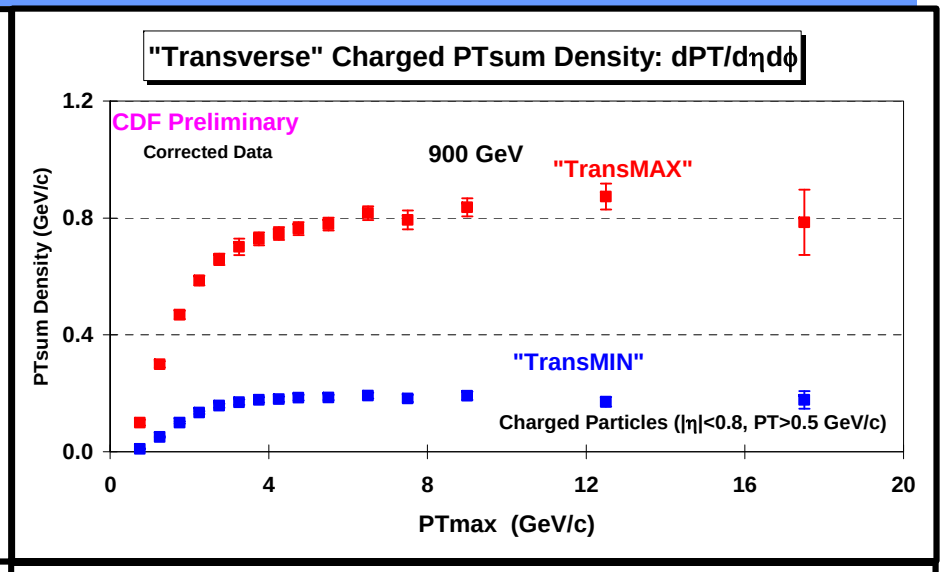
- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transMAX", "transMIN", and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level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

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

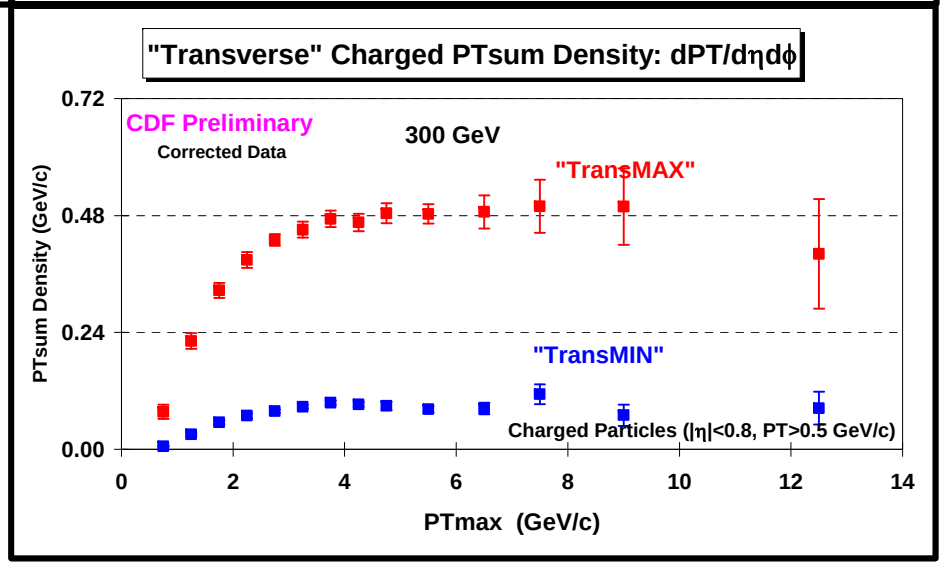


"transMAX/MIN" PTsumDen

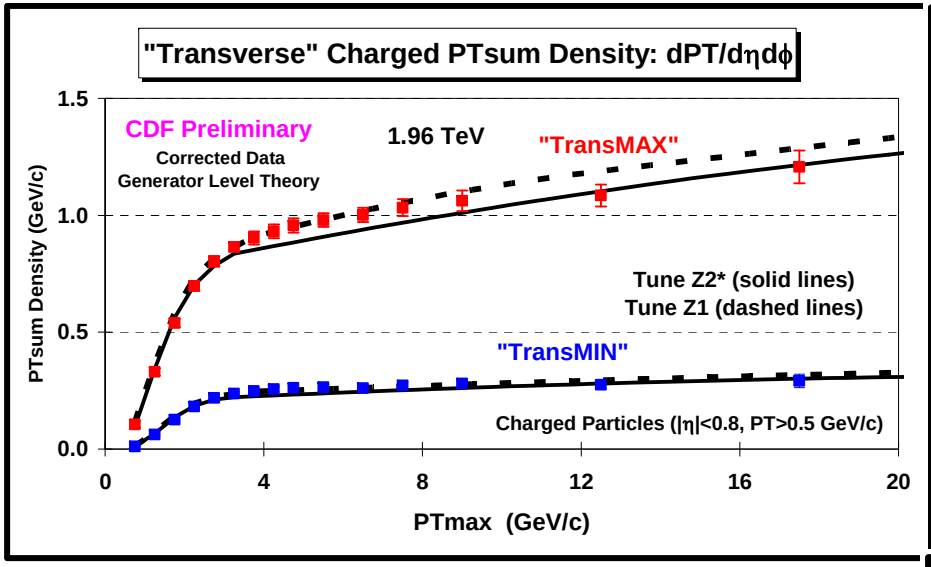


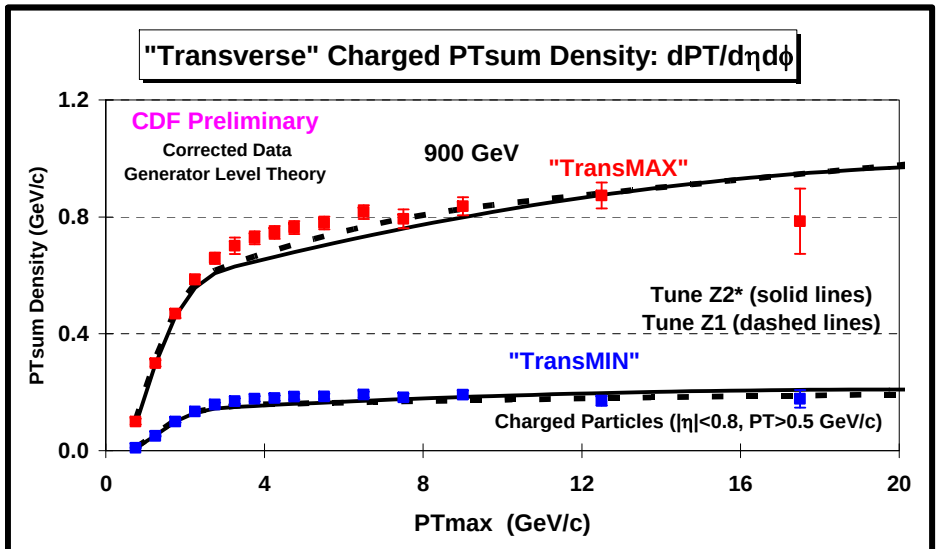


- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged PTsum density in the "transMAX" and "transMIN" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that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



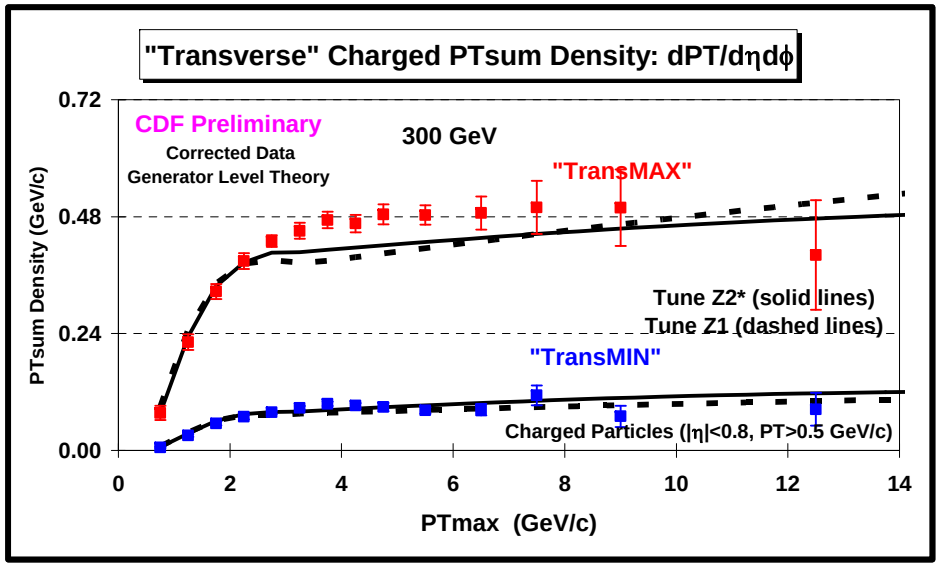
"transMAX/MIN" PTsumDen



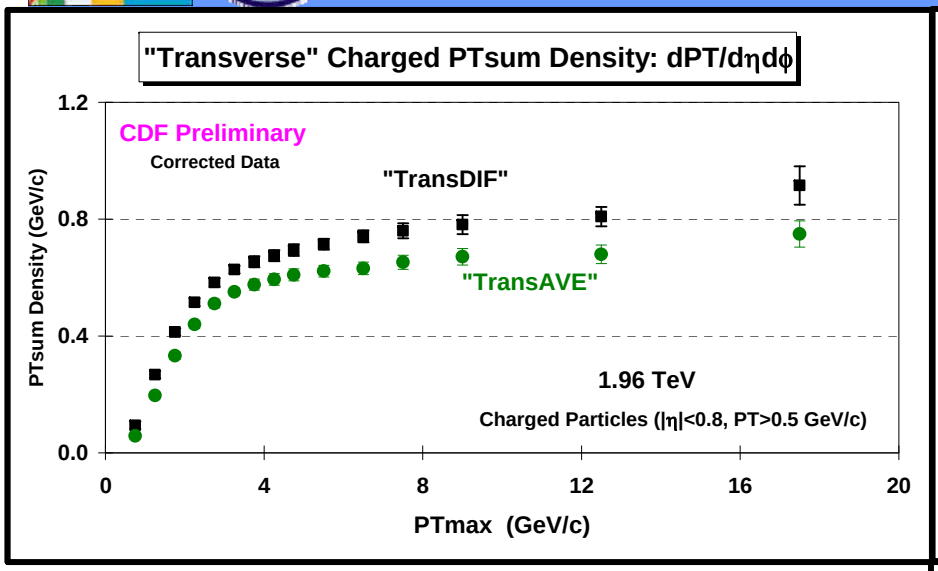


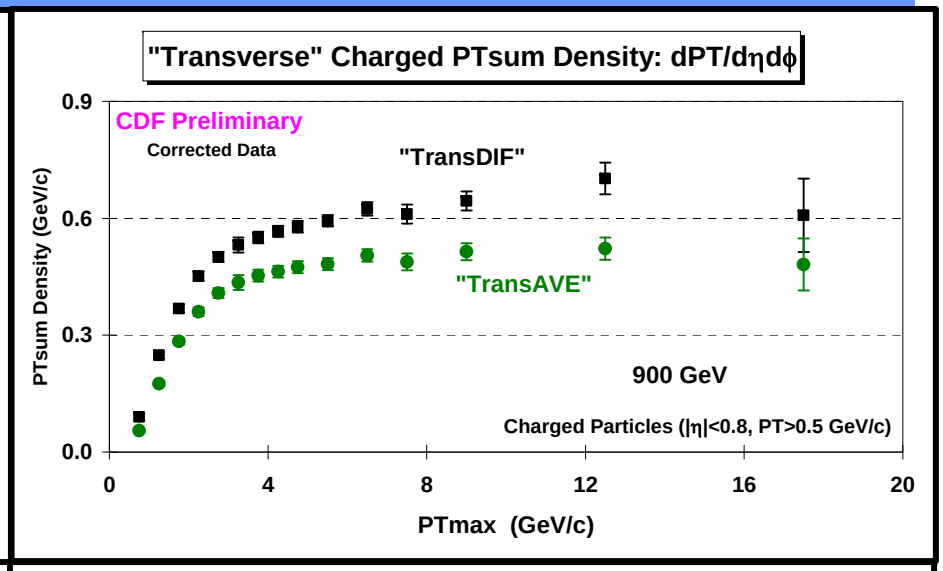
- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged PTsum density in the "transMAX" and "transMIN" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that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

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

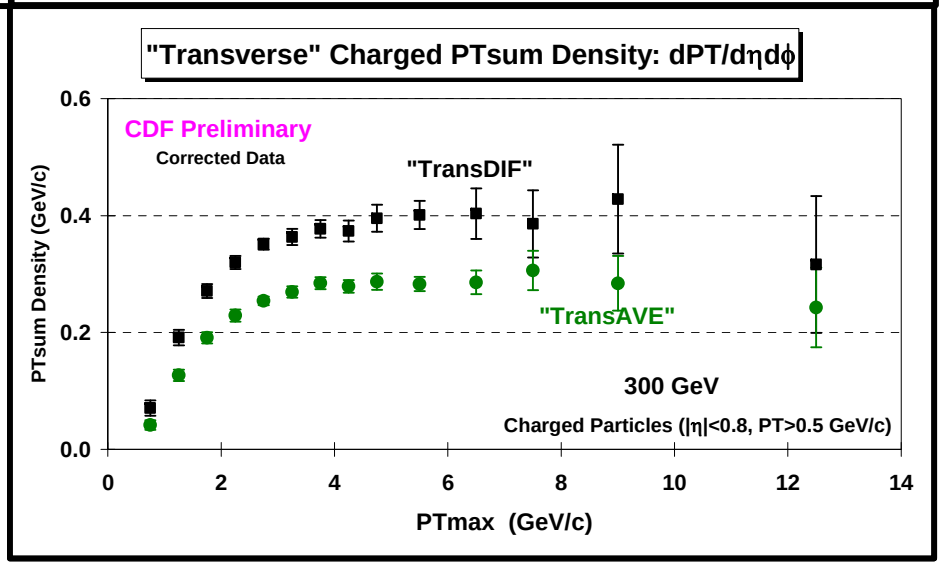


"transDIF/AVE" PTsumDen

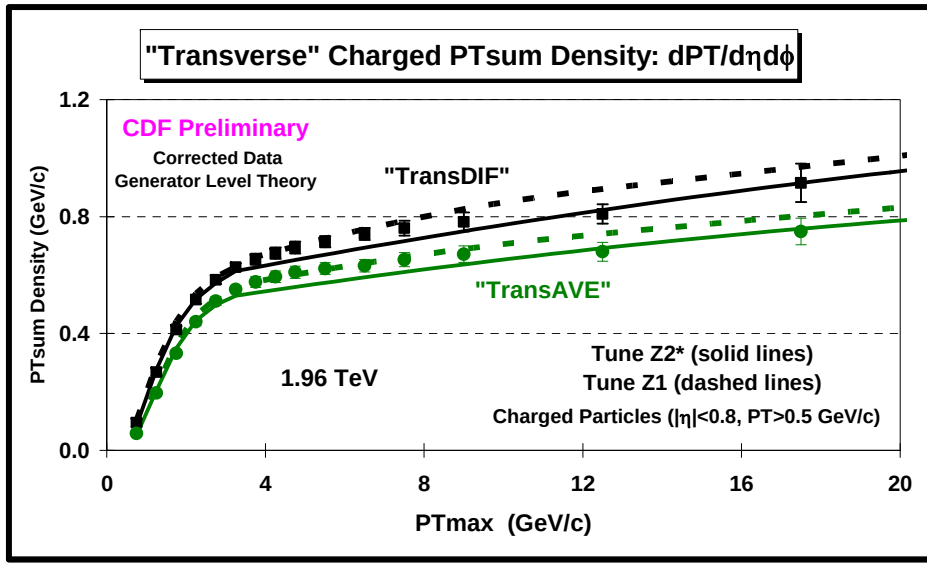


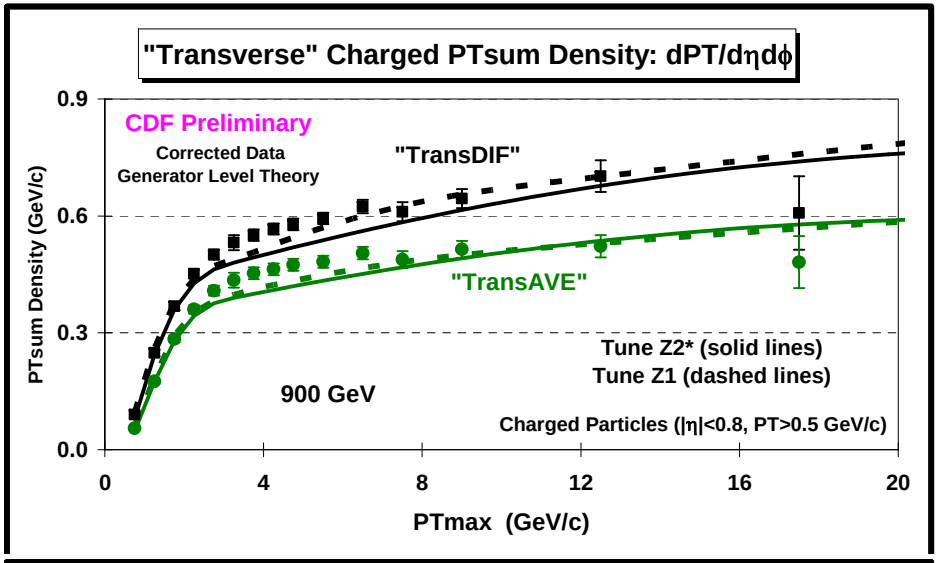


- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged PTsum density in the "transAVE" and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that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



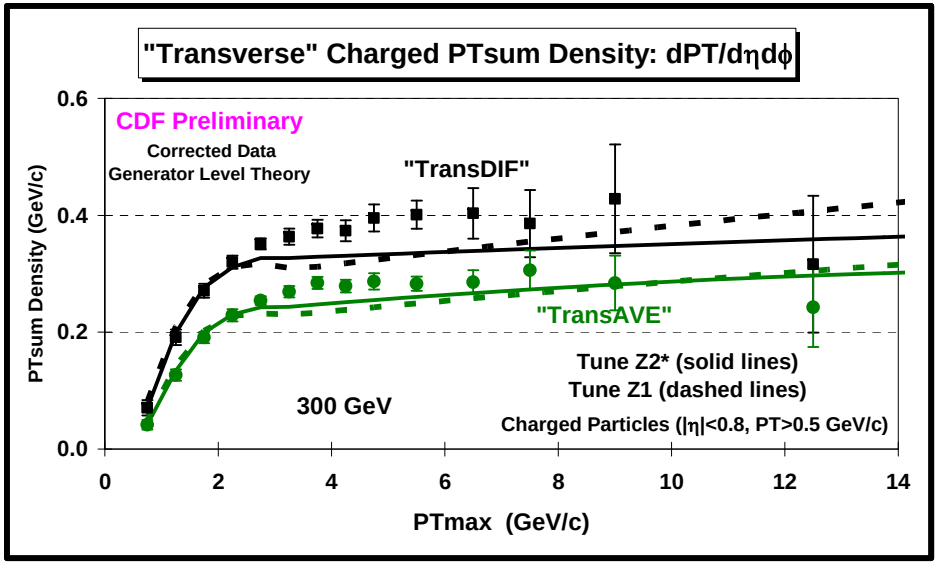
"transDIF/AVE" PTsumDen



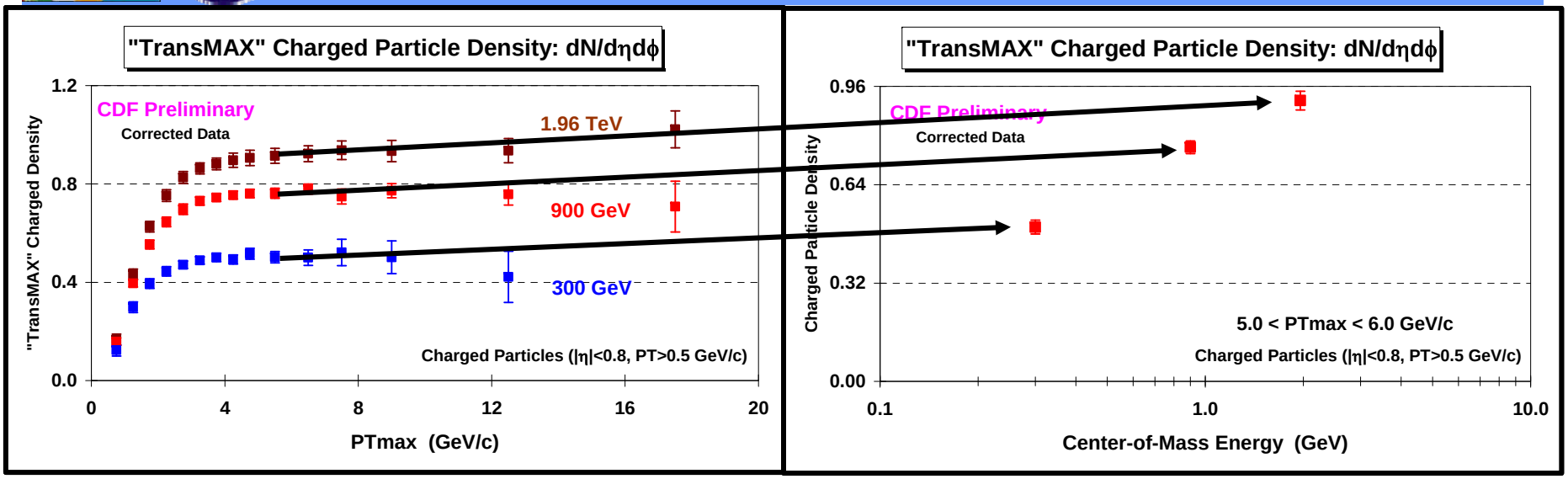


- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged PTsum density in the "transAVE" and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that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

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



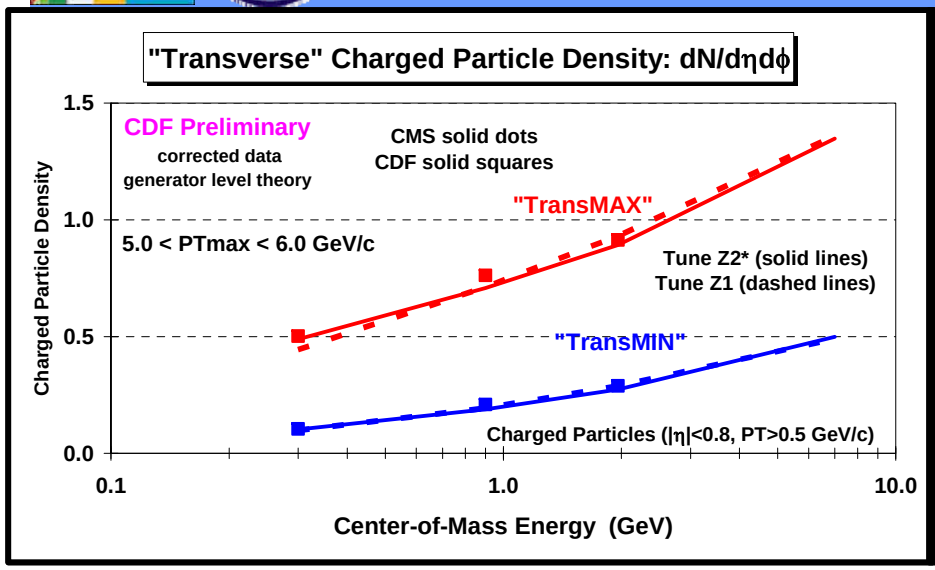
"transMAX" NchgDen vs E_{cm}

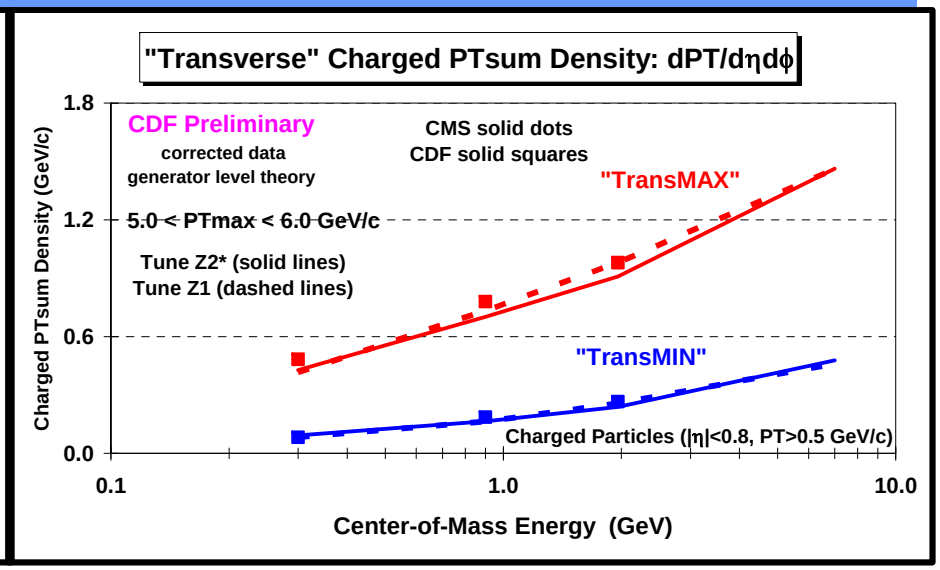


- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transMAX" region as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8. The data are corrected to the particle level with errors that include both the 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 |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*).**

"TransMAX/MIN" vs E_{cm}

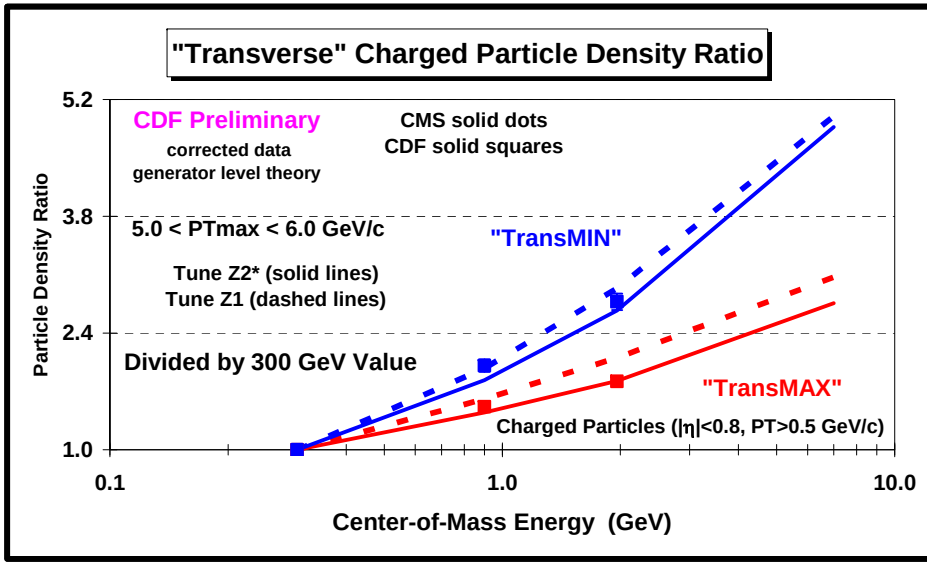


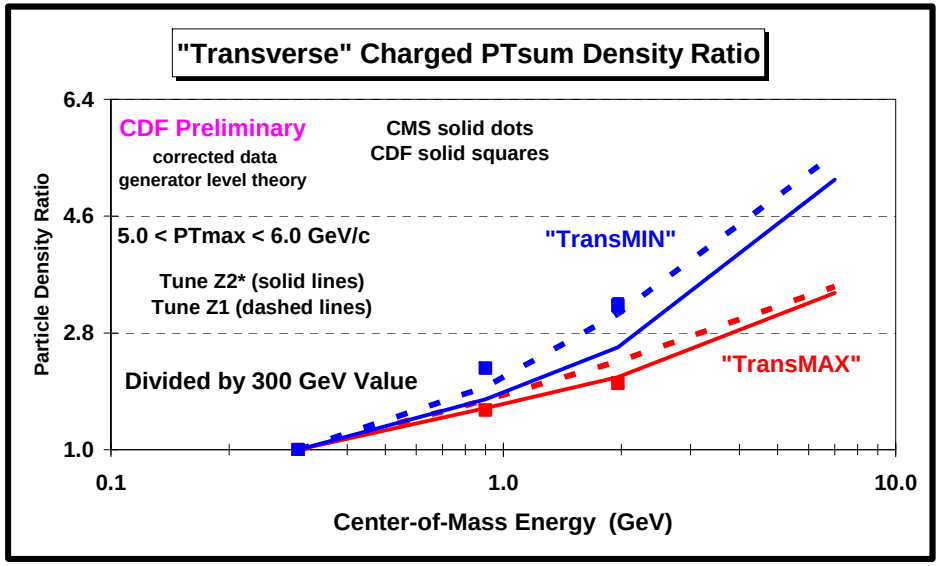


- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transMAX", and the "transMIN", regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 < PTmax < 6$ GeV/c. The data are plotted versus 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 "transMAX", and the "transMIN", 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*.**

"TransMAX/MIN" vs E_{cm}



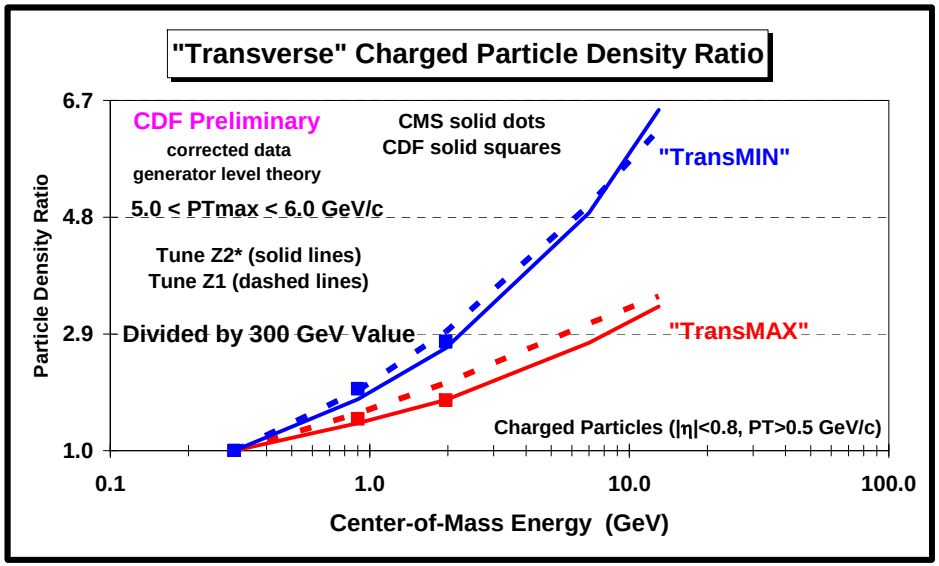


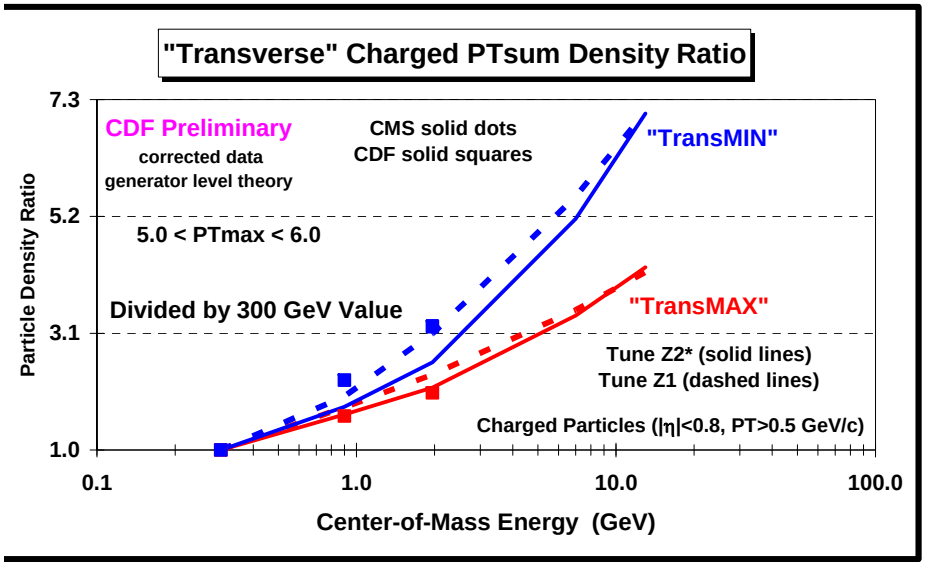
- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transMAX", and the "transMIN", regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 < PTmax < 6$ GeV/c. The data are plotted versus 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 "transMAX", and the "transMIN", 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.

"TransMAX/MIN" vs E_{cm}



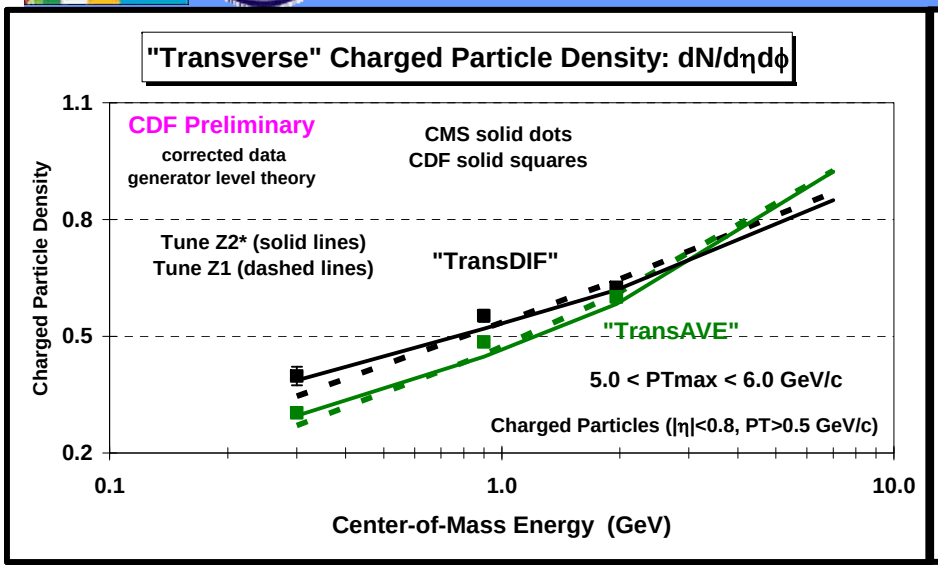


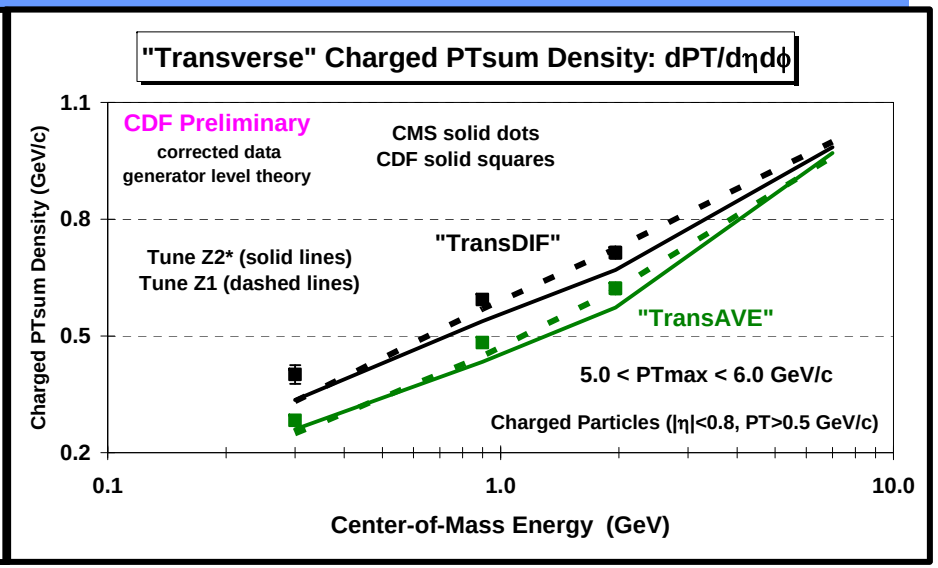
- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transMAX", and the "transMIN", regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 < PTmax < 6$ GeV/c. The data are plotted versus 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 "transMAX", and the "transMIN", 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.

"TransDIF/AVE" vs E_{cm}

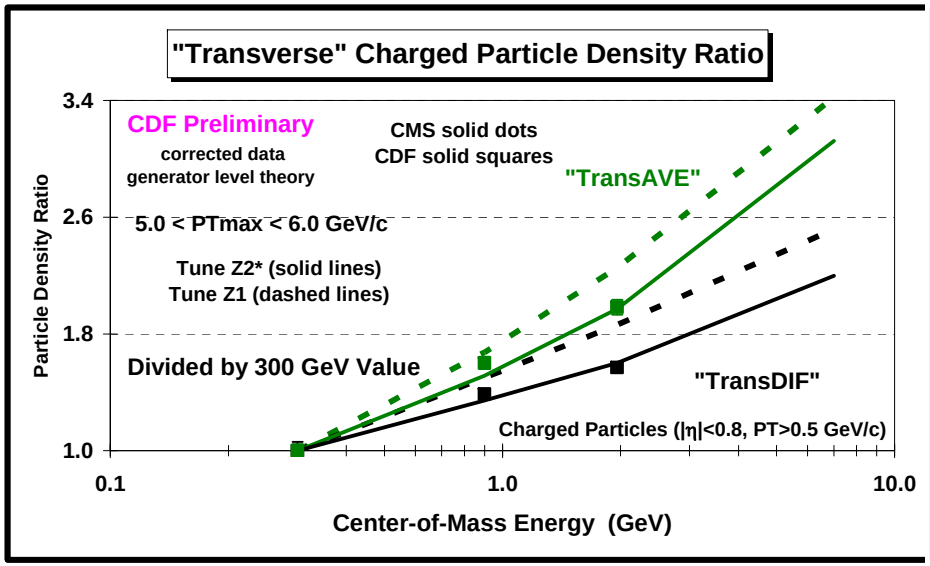


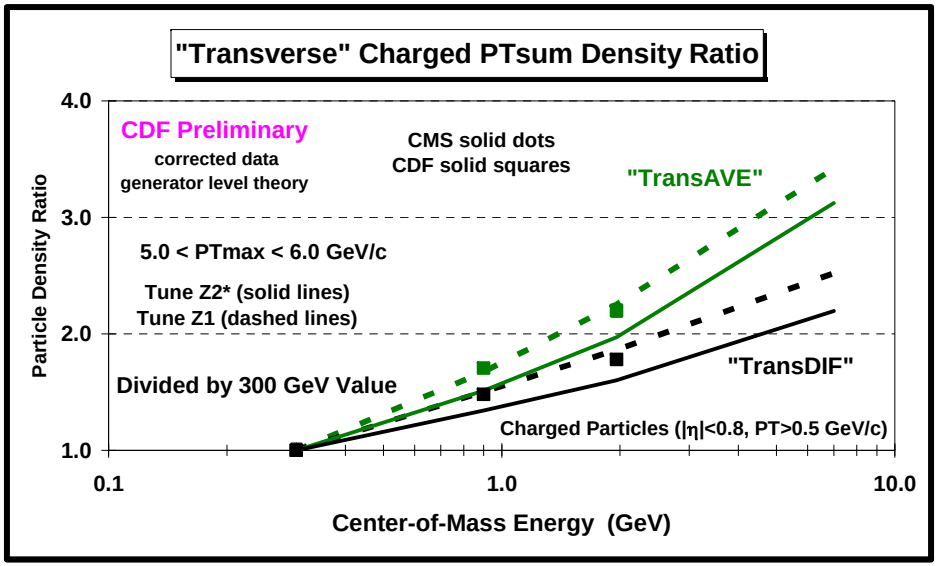


- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transAVE", and the "transDIF", regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 <$ PTmax < 6 GeV/c. The data are plotted versus 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*.**

"TransDIF/AVE" vs E_{cm}



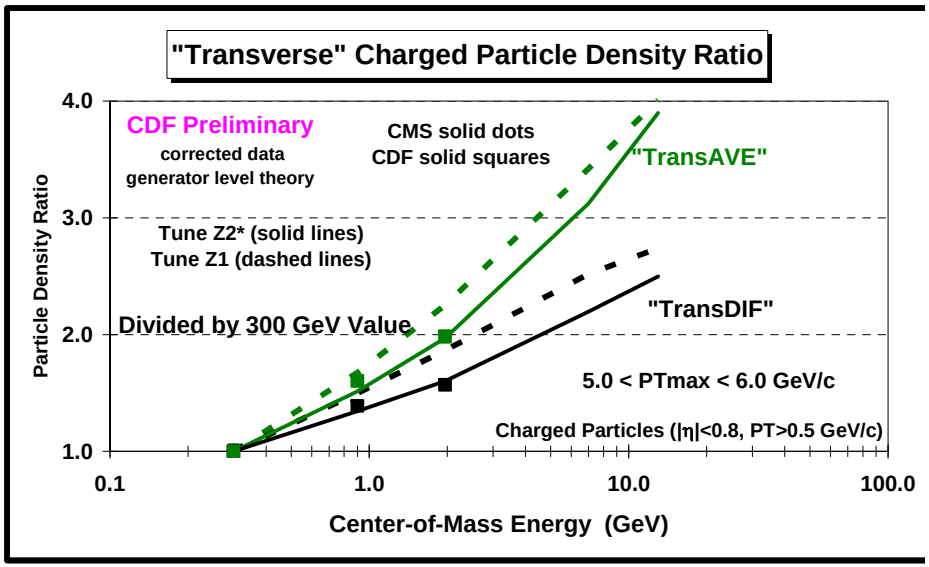


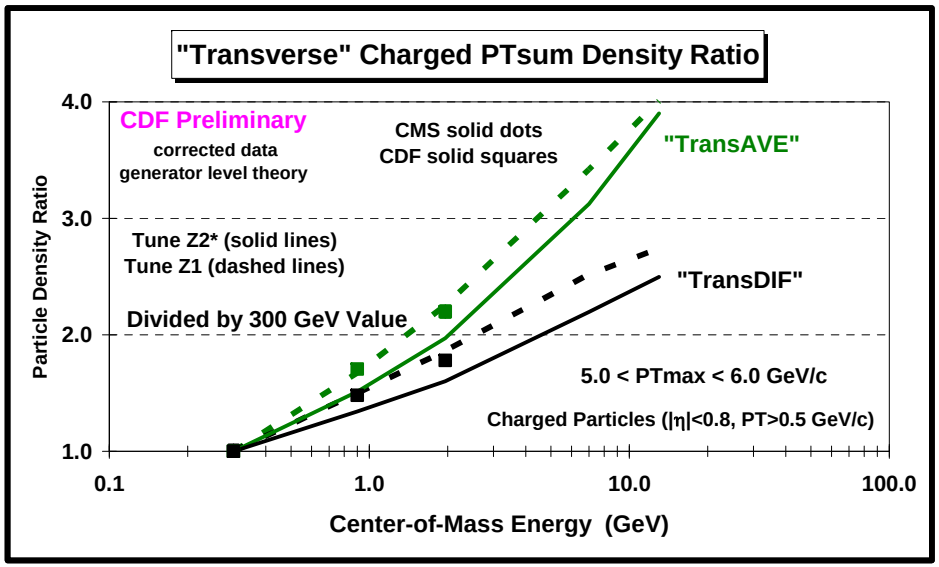
- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transAVE", and the "transDIF", regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 < PTmax < 6$ GeV/c. The data are plotted versus 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.

"TransDIF/AVE" vs E_{cm}



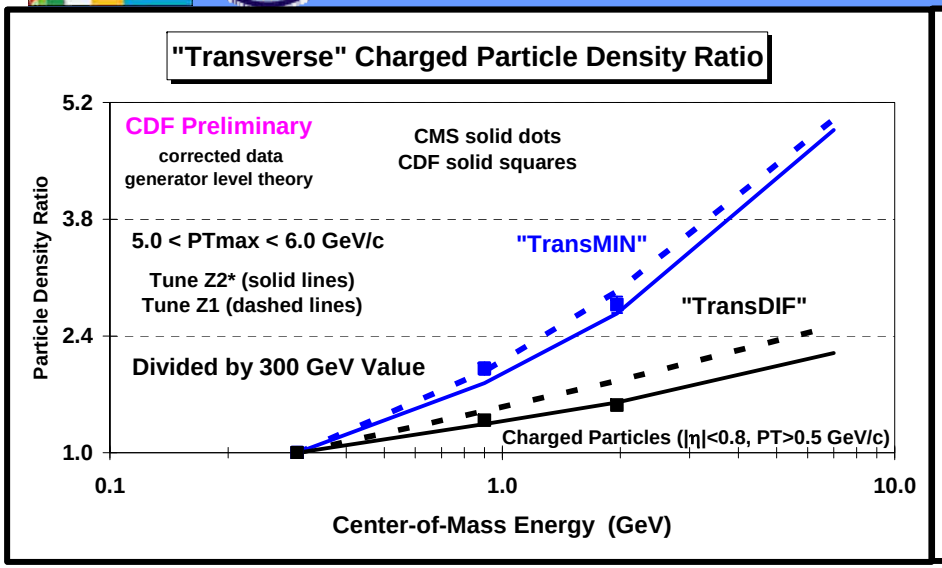


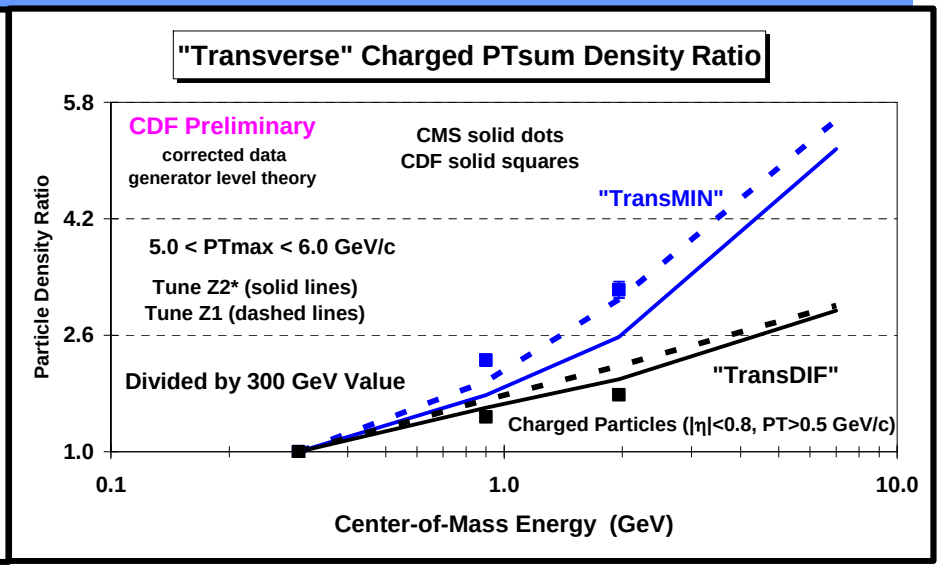
- **Corrected CDF data at 1.96 TeV, 900 GeV, and 300 GeV on the charged particle density in the "transAVE", and the "transDIF", regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 <$ PTmax < 6 GeV/c. The data are plotted versus 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.

"TransMIN/DIF" vs E_{cm}



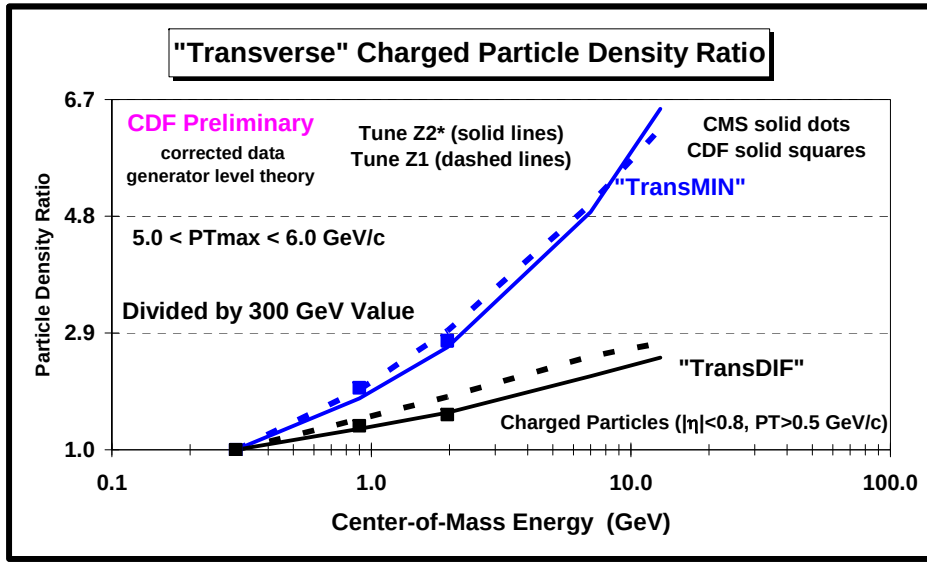


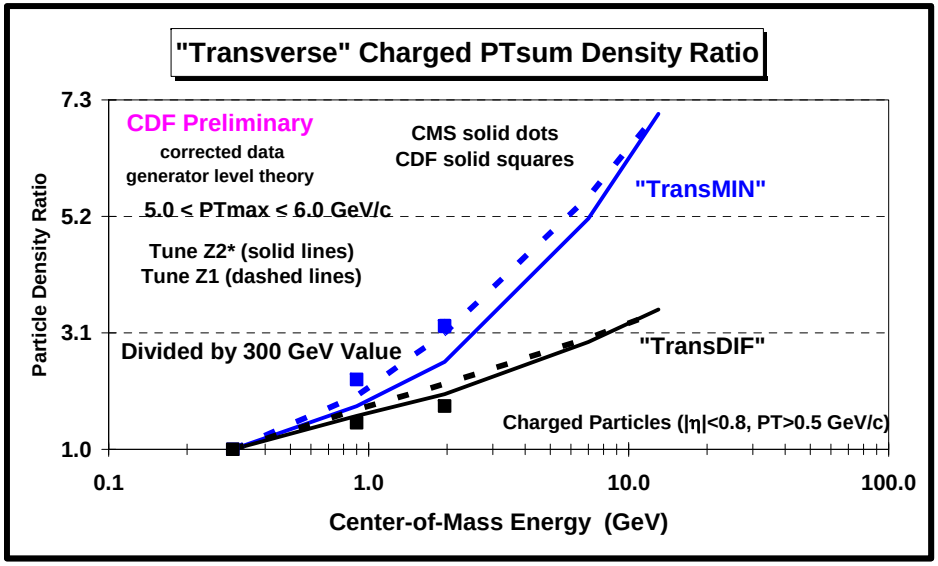
- **Ratio of CDF data at 1.96 TeV, 900 GeV, and 300 GeV to the value at 300 GeV for the charged particle density in the "transMIN", and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 < PTmax < 6$ GeV/c. The 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}



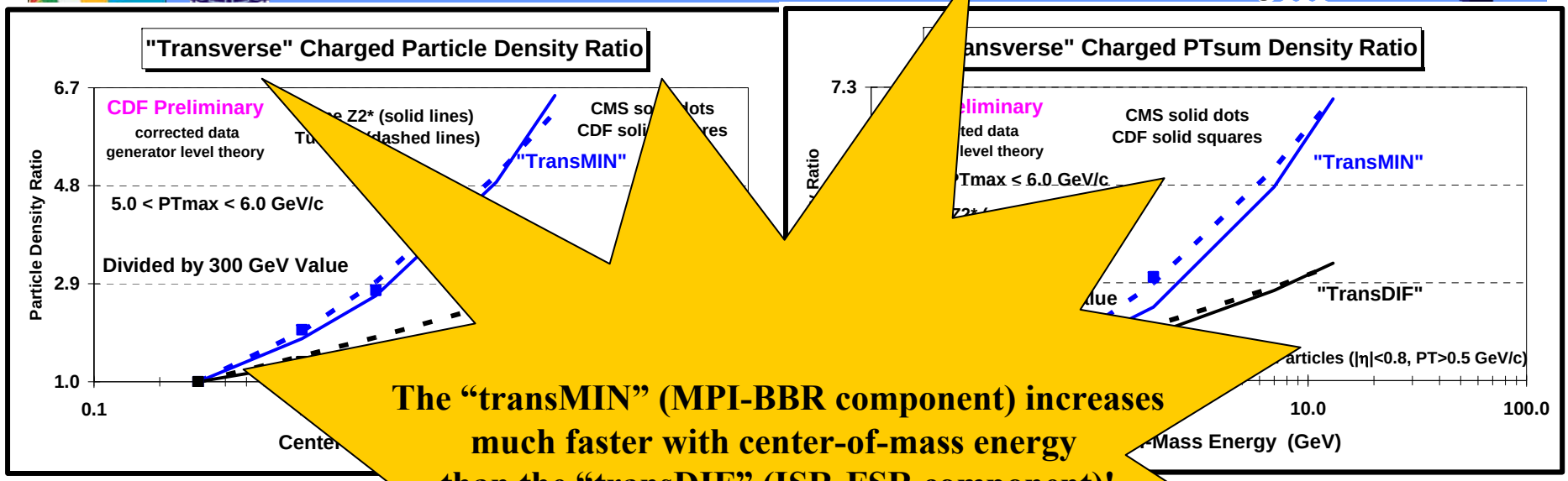


- **Ratio of CDF data at 1.96 TeV, 900 GeV, and 300 GeV to the value at 300 GeV for the charged particle density in the "transMIN", and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with $5 < PTmax < 6$ GeV/c. The 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}

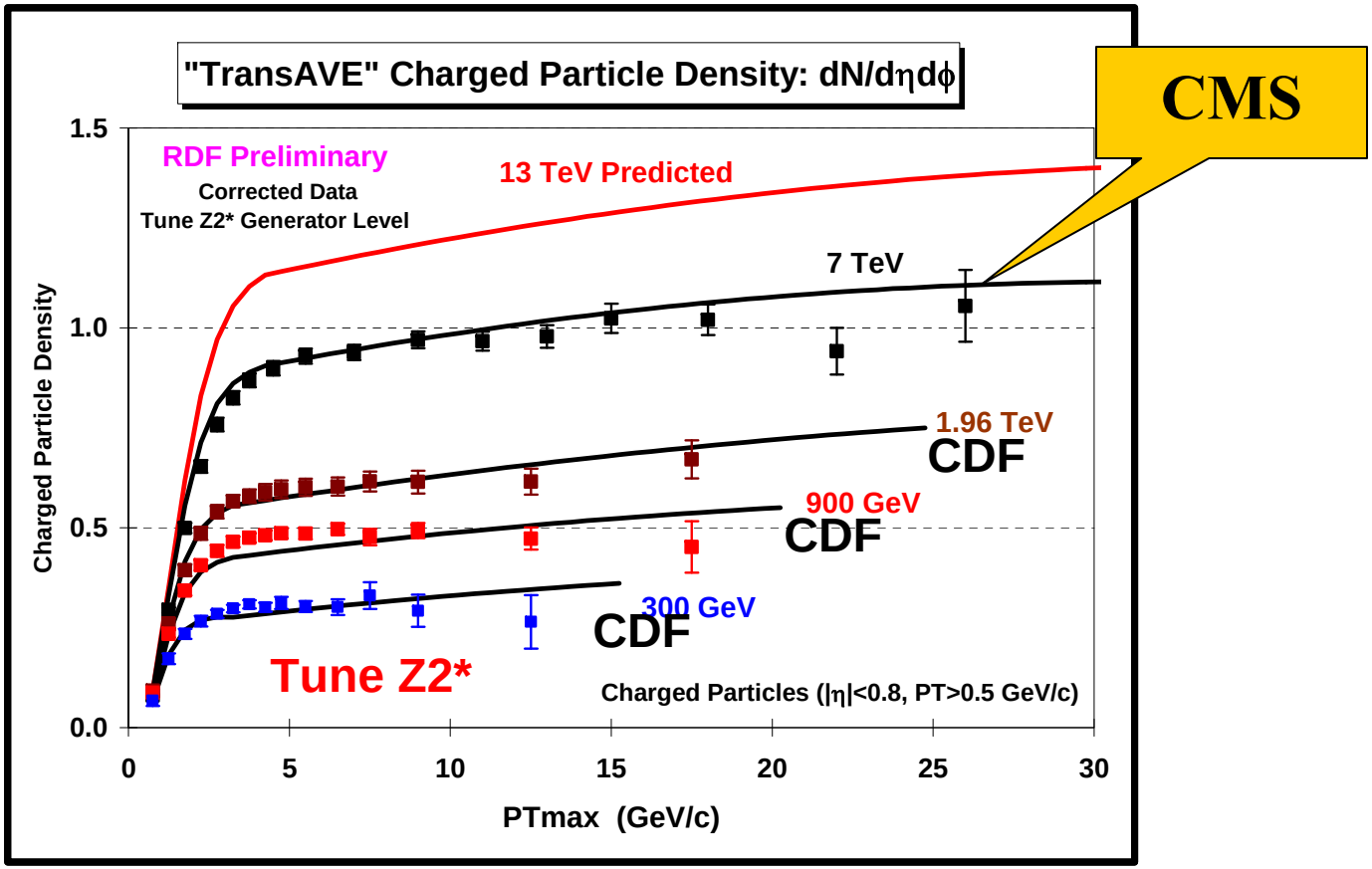


The "transMIN" (MPI-BBR component) increases much faster with center-of-mass energy than the "transDIF" (ISR-FSR component)!

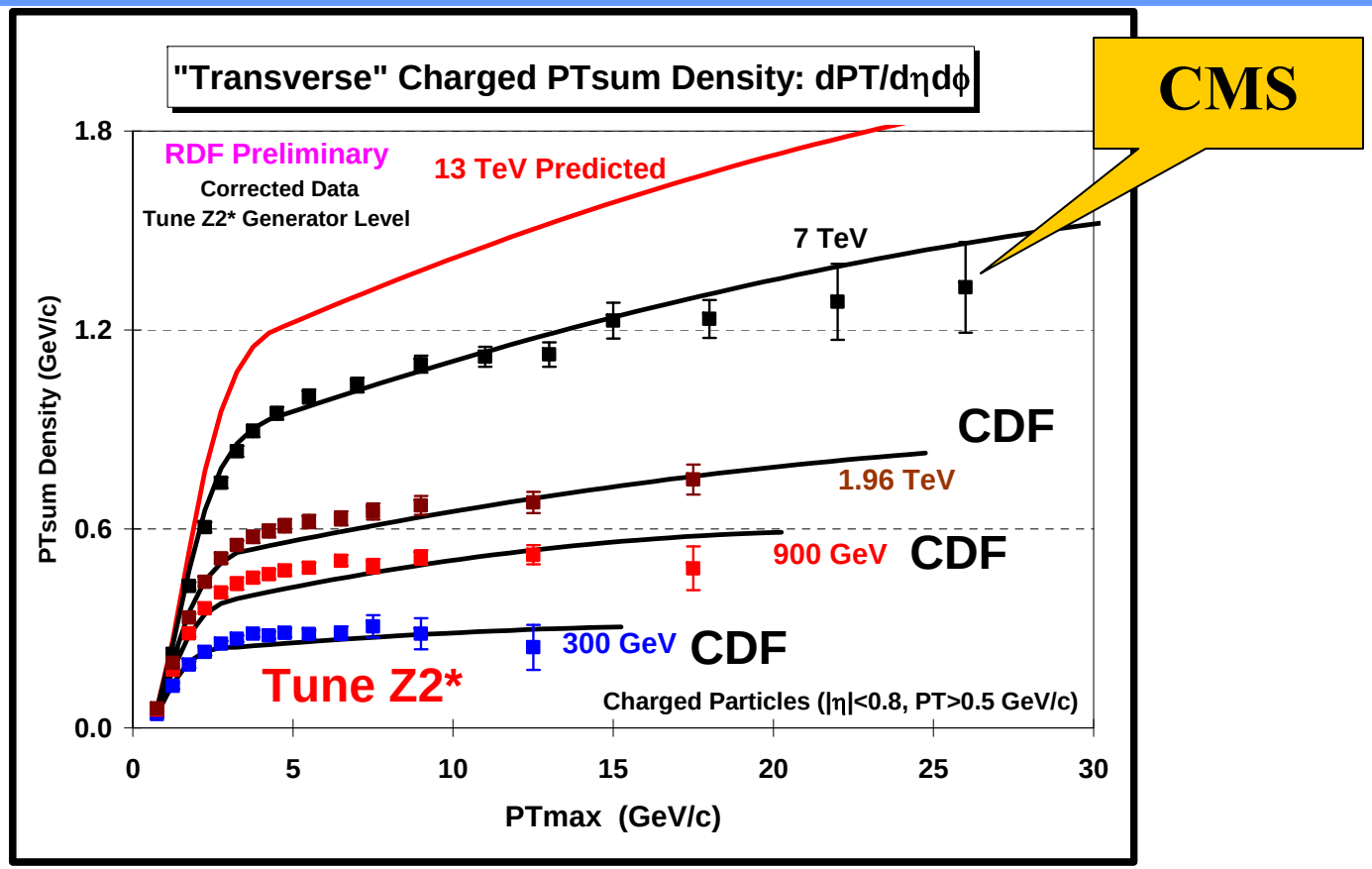
➡ **Ratio of CDF data at 1.96 TeV, 900 GeV, and 300 GeV to the value at 300 GeV for the charged particle density in the "transMIN", and "transDIF" regions as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 0.8 with 5 < PTmax < 6 GeV/c. The data are 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.

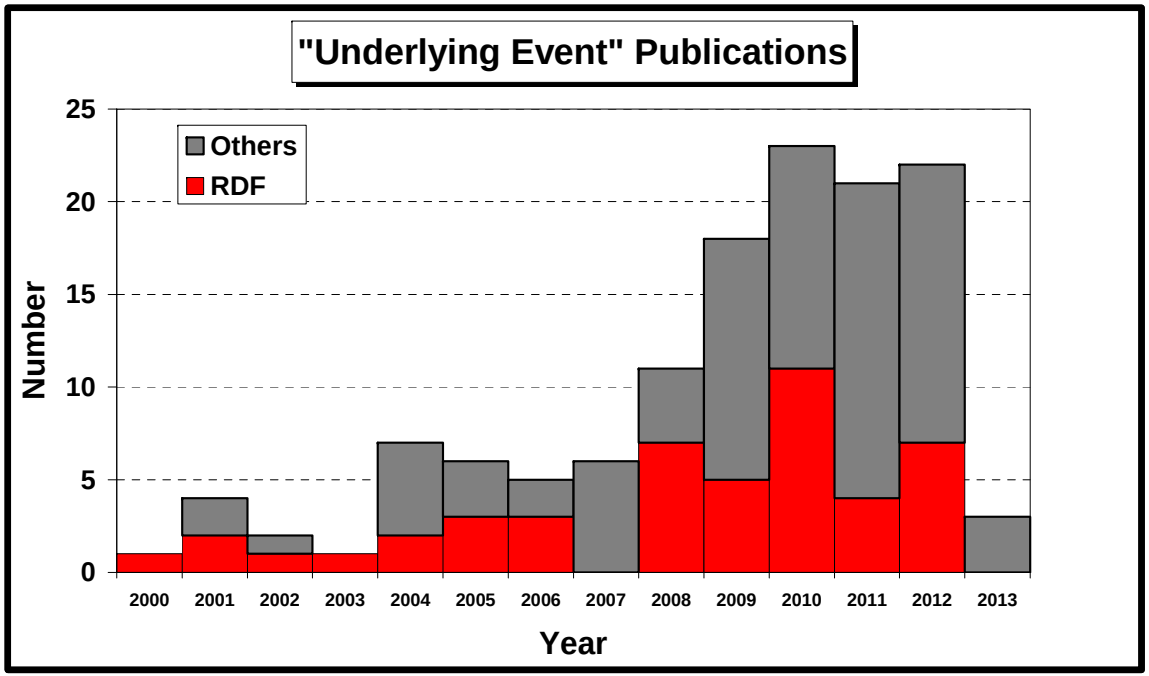
"Tevatron" to the LHC



"Tevatron" to the LHC

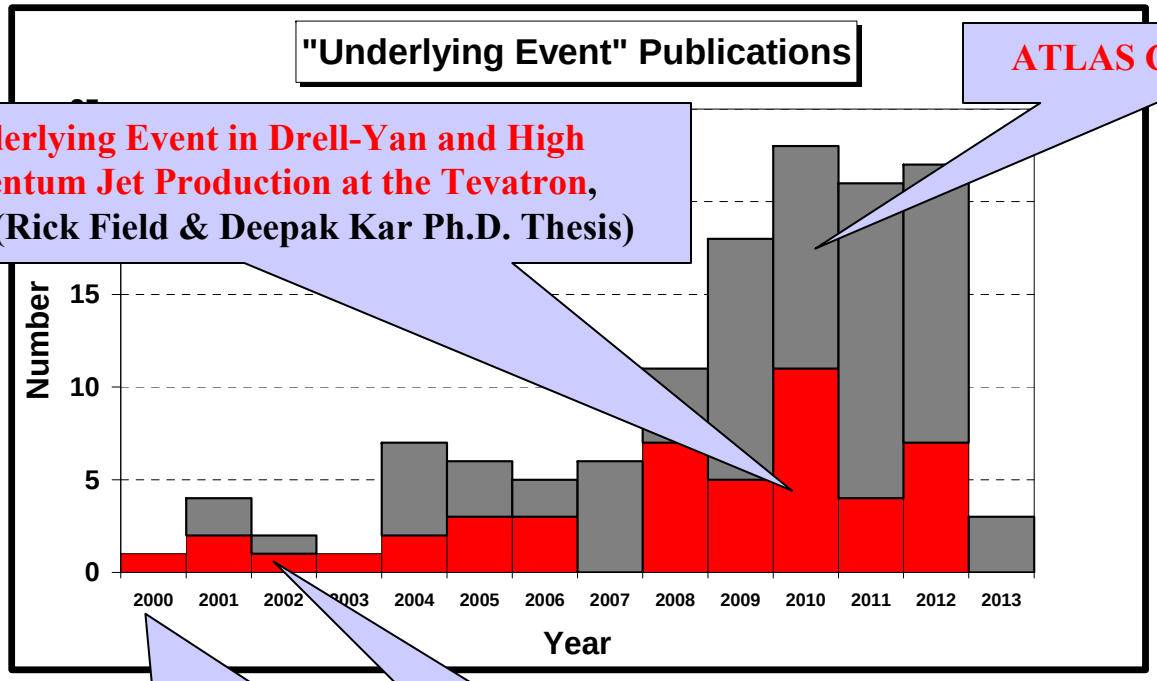


UE Publications



➡ **Publications with "underlying event" in the title.**

UE Publications



ATLAS Collaboration!

Studying the Underlying Event in Drell-Yan and High Transverse Momentum Jet Production at the Tevatron, CDF Collaboration (Rick Field & Deepak Kar Ph.D. Thesis)

- **Publications with "ur g event the title.**

The Underlying Event in Large Transverse Momentum Charged Jet and Z−boson Production at CDF, R. Field, published in the proceedings of DPF 2000.

Charged Jet Evolution and the Underlying Event in Proton-Antiproton Collisions at 1.8 TeV, CDF Collaboration, Phys. Rev. D65 (2002) 092002.

Summary & Conclusions

- The "transverse" density increases faster with center-of-mass energy than the overall density (Nchg ≥ 1)! However, the "transverse" = "transAVE" 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 perfect) in describing the energy deperdence of the UE!

Summary & Conclusions

- The "transverse" density increases faster with center-of-mass energy than the overall density (Nch/Δη)! How the "transverse" = "transAVE" is not a [illegible] dependence of MPI since it re[illegible] SR.
- The "transMIN" [illegible] with cente[illegible]! Previous[illegible] VE".

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!

W[illegible] ev!

We ca[illegible]

mo[illegible] ha[illegible] befo[illegible]

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