HEP Seminar

Studying the Energy Dependence of the Underlying Event at the Tevatron and the LHC

Rick Field

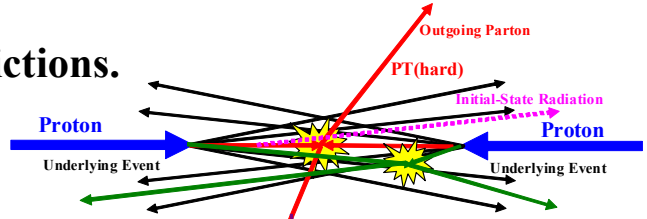
University of Florida

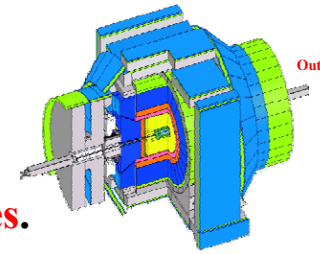
Quantum Chromo-Dynamics

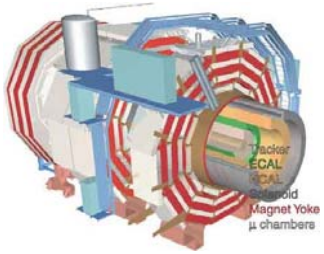
Wayne State University February 17, 2017

Outline

- Early studies the underlying event (UE) at CDF and PYTHIA Tune A.
- The CDF Tevatron PYTHIA 6.2 UE tunes (Tune A, B, D, AW, DW, D6, DWT, D6T).
- My 113 UE presentations (2000-2016) and LHC predictions.
- Early days of UE@MB at CMS and the LHC PYTHIA 6.4 tunes (AMBT1, Z1, Z2, Z2*).
- LPCC MB&UE Working group and the "common plots".
- UE@CMS at 13 TeV.
- CMS "Physics Comparisons & Generator Tunes" group and CMS PYTHIA 8 UE Tunes.
- The Tevatron Energy Scan. Mapping out the energy dependence of the UE, Tevatron to the LHC.



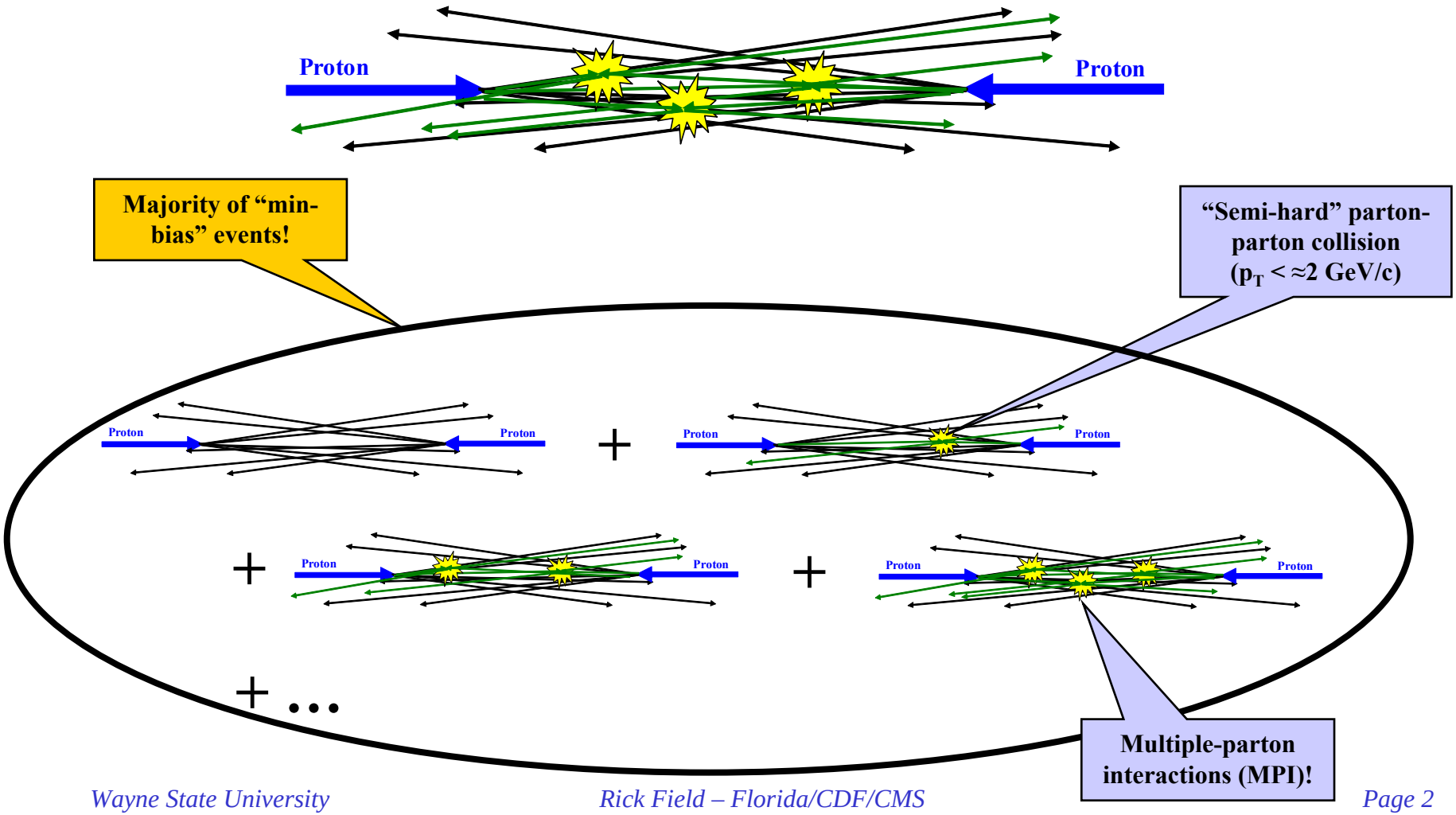




CDF Run 2
300 GeV, 900 GeV, 1.96 TeV

CMS at the LHC
900 GeV, 7, 8, & 13 TeV

The Inelastic Non-Diffractive Cross-Section



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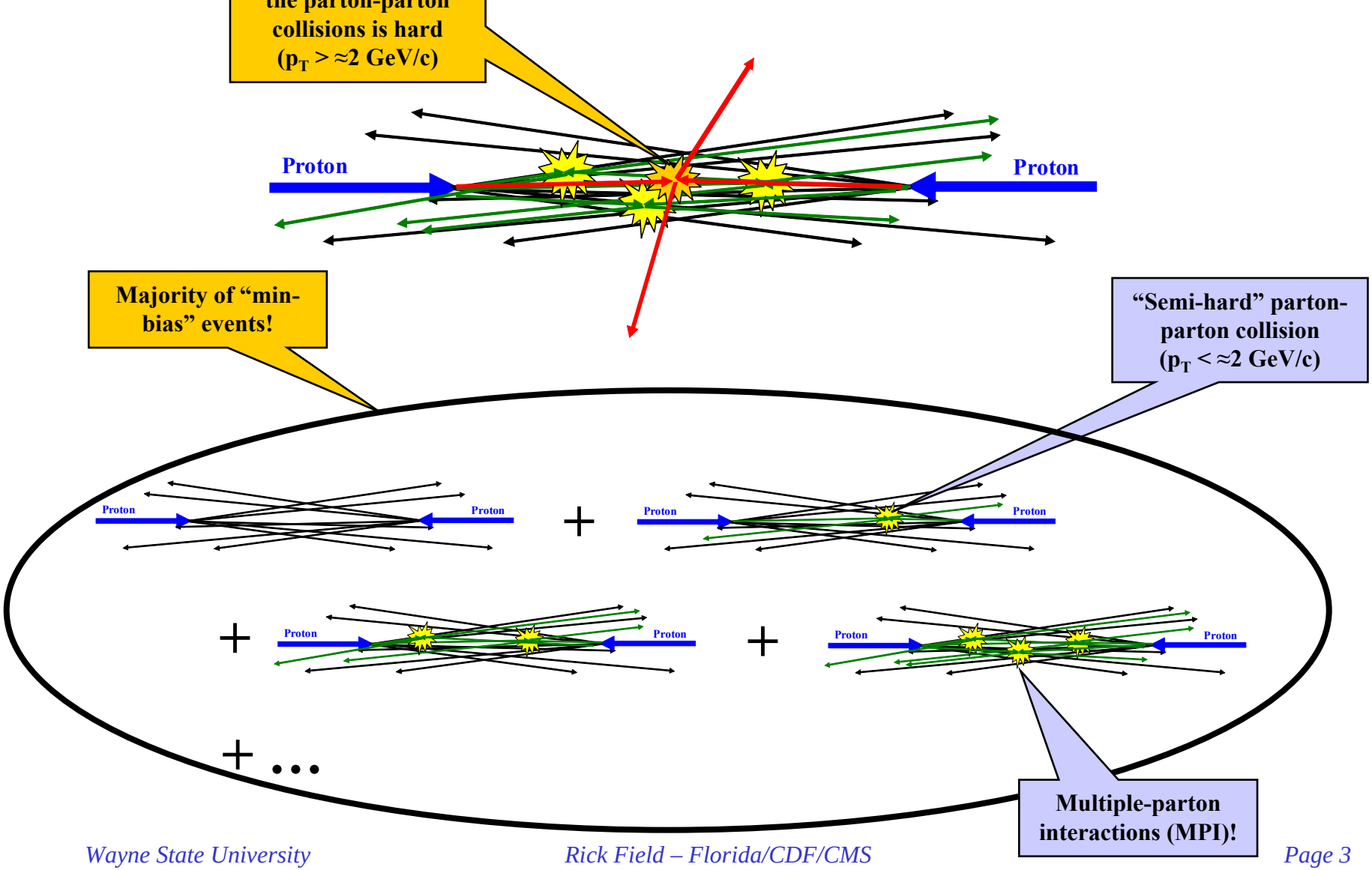
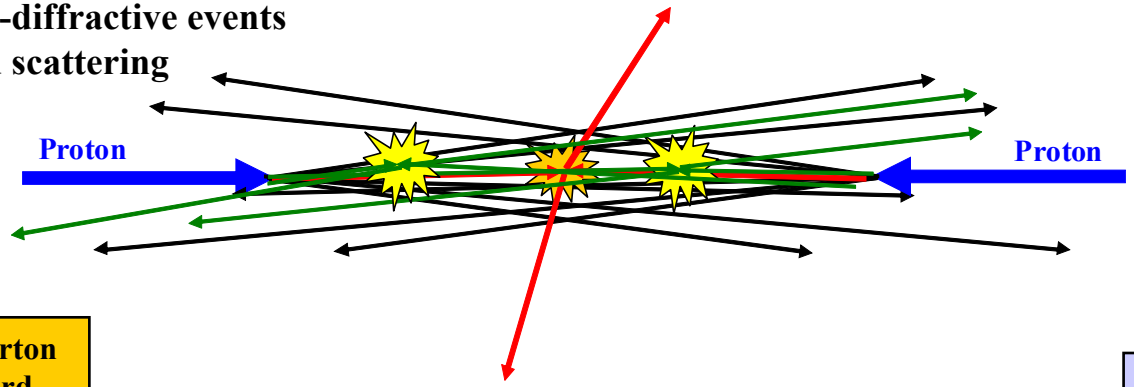


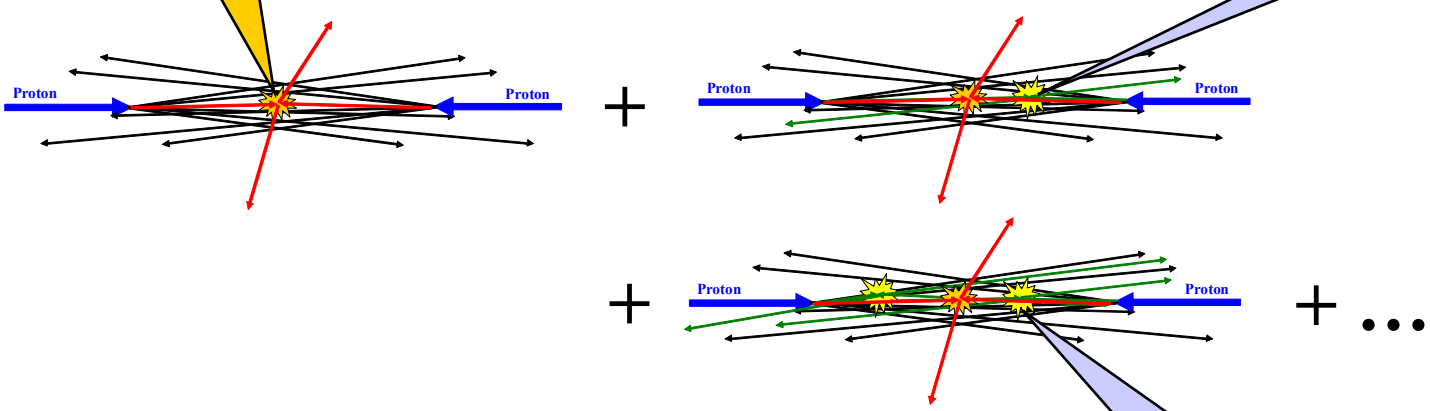
The "Underlying Event"

Select inelastic non-diffractive events that contain a hard scattering



Hard parton-parton collisions is hard ($p_T > \approx 2$ GeV/c)

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



Multiple-parton interactions (MPI)!

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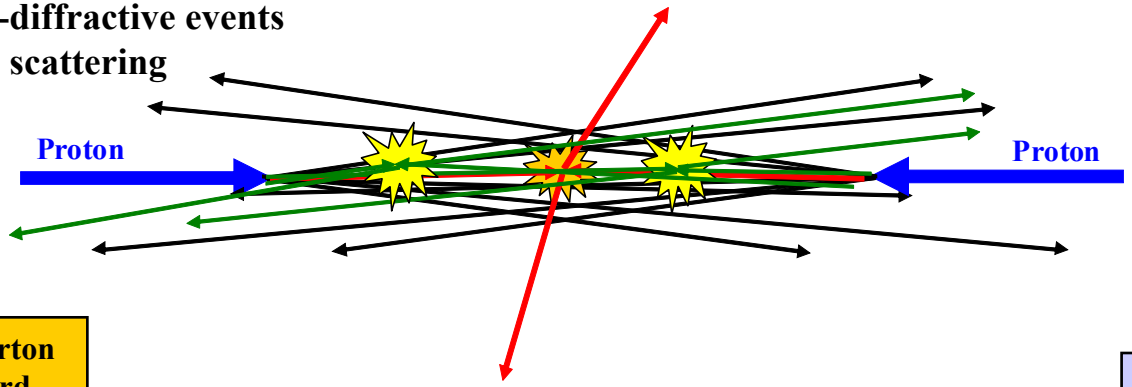
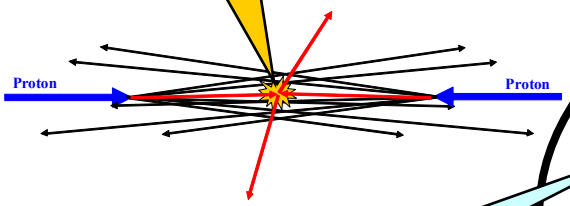
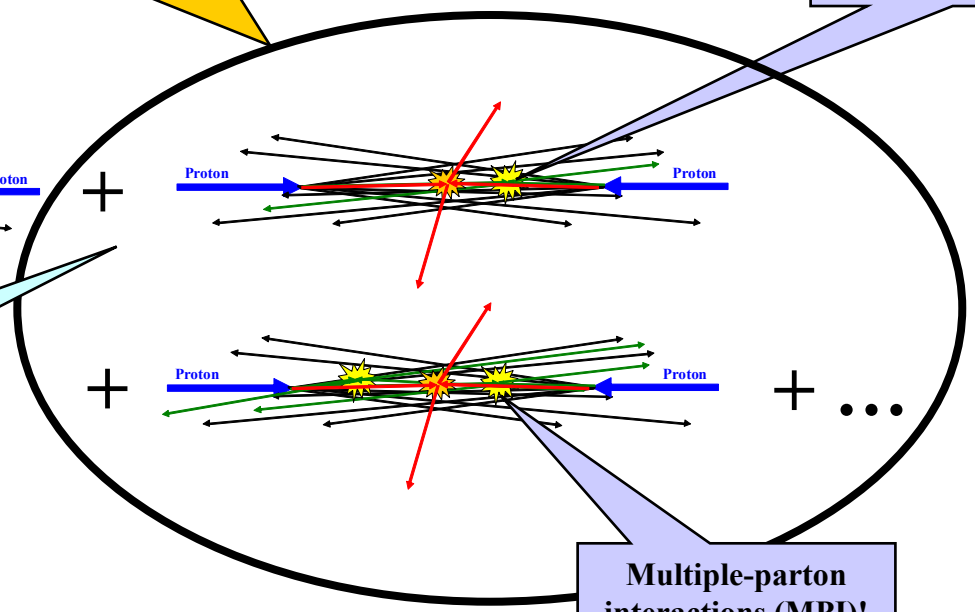


Hard parton-parton collisions is hard ($p_T > \approx 2$ GeV/c)

The "underlying-event" (UE)!

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





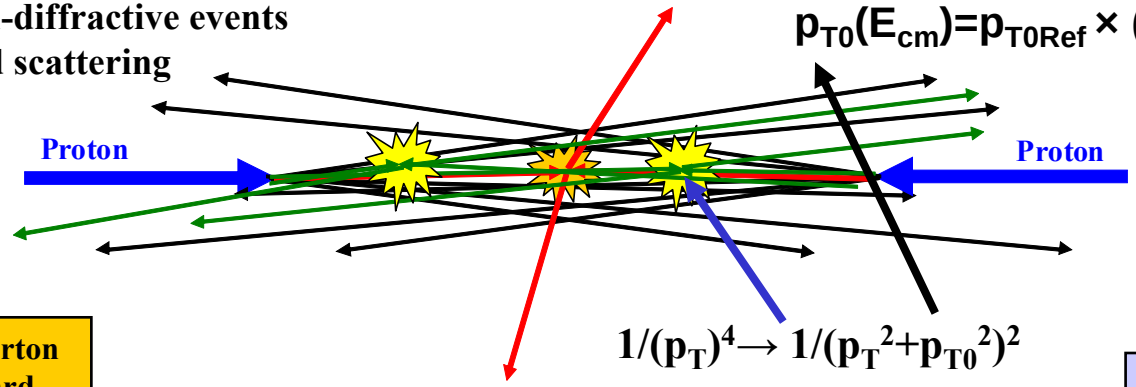
Given that you have one hard scattering it is more probable to have MPI! Hence, the UE has more activity than "min-bias".

Multiple-parton interactions (MPI)!

The "Underlying Event"

Select inelastic non-diffractive events that contain a hard scattering

$p_{T0}(E_{cm})=p_{T0Ref} \times (E_{cm}/E_{cmRef})^{ecmPow}$



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

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The "underlying-event" (UE)!

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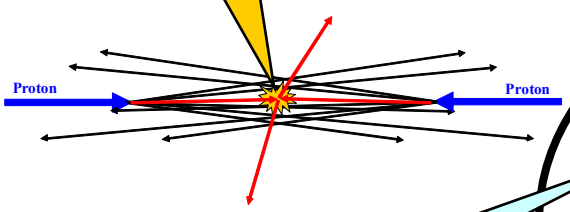

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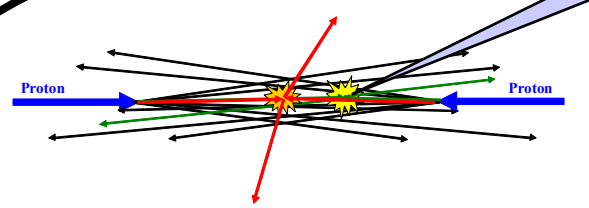

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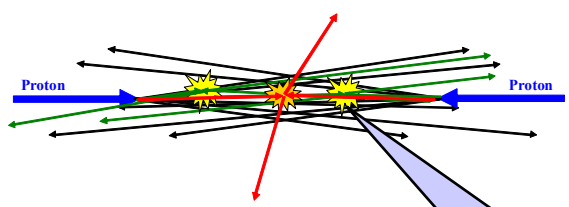

+ …

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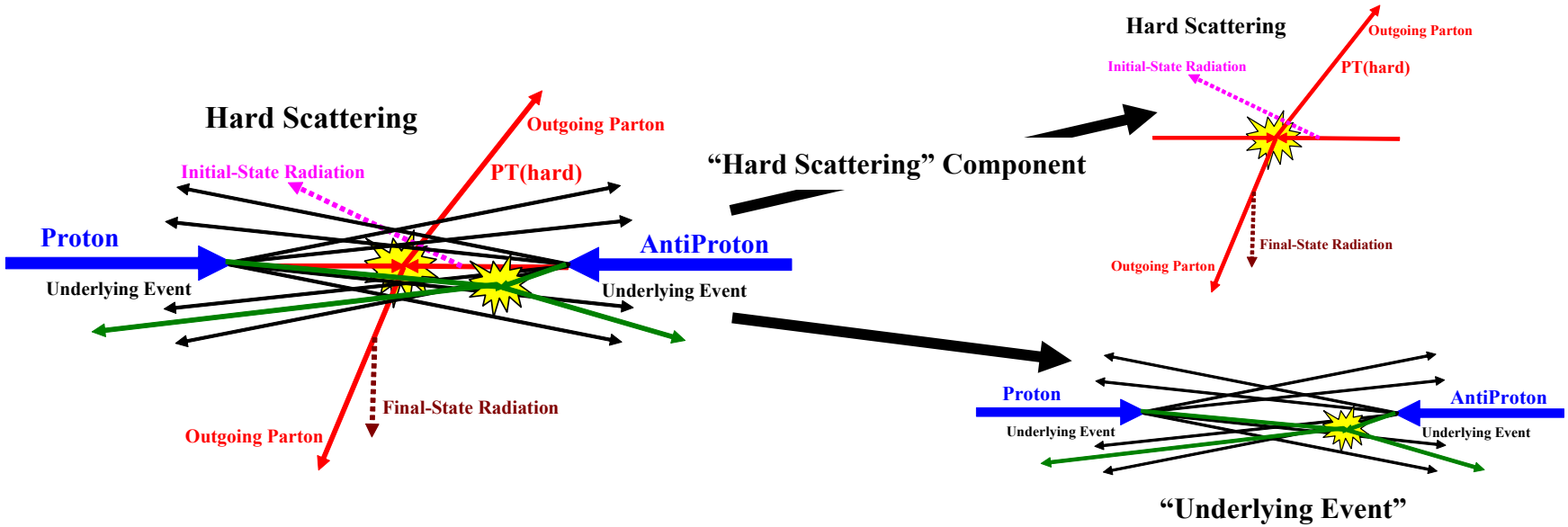
Multiple-parton interactions (MPI)!

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.

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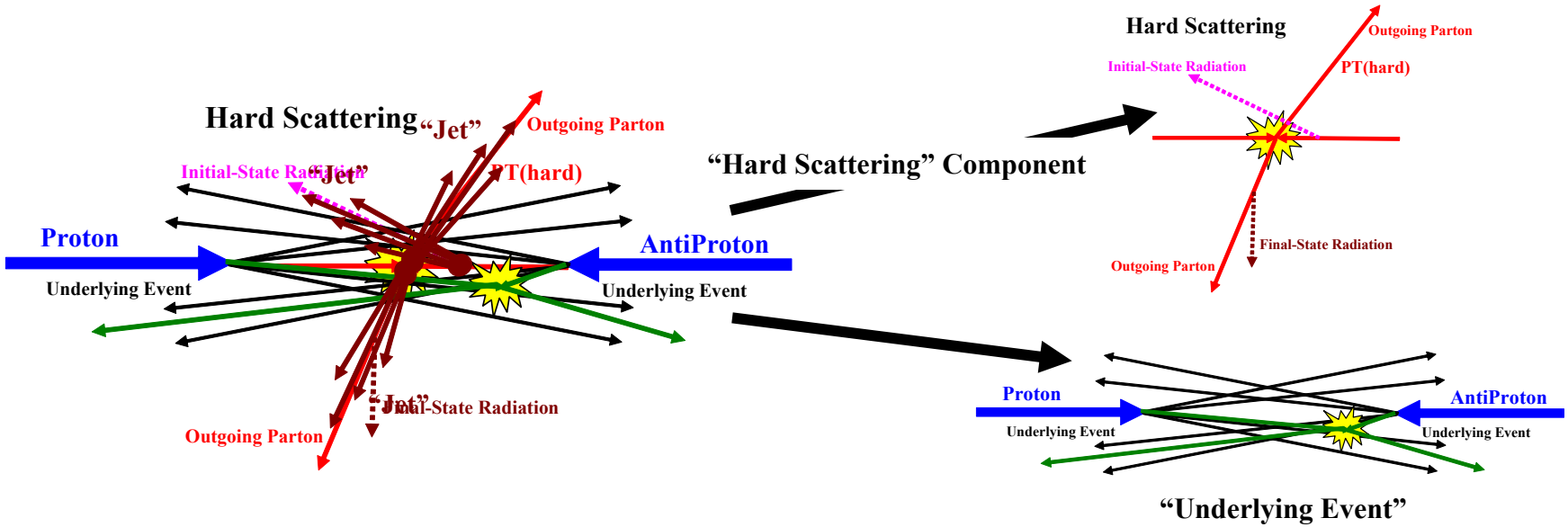

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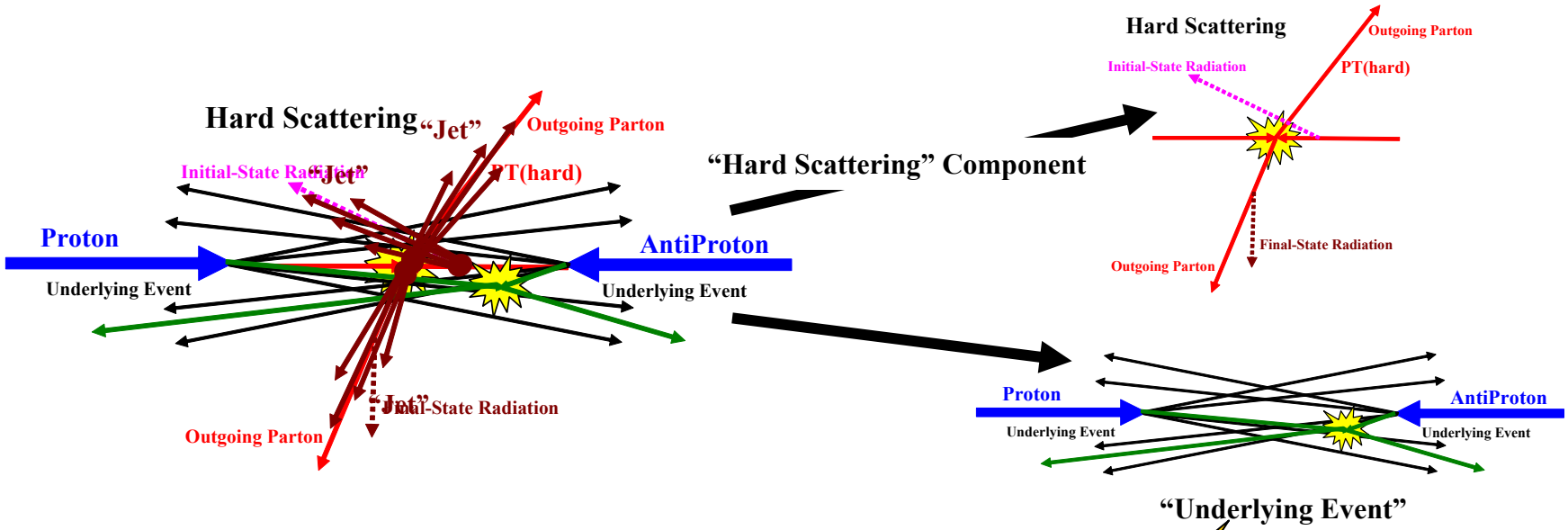

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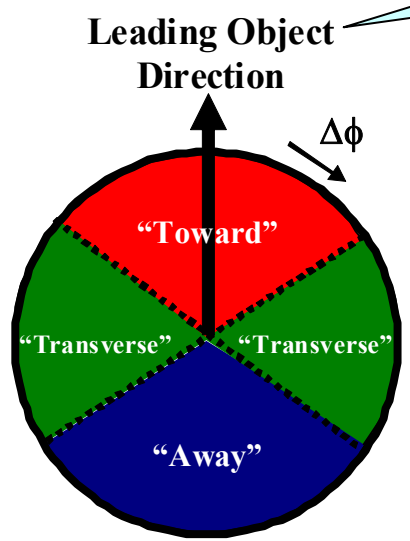
The "underlying event" is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!

Traditional Approach

Charged Particle $\Delta\phi$ Correlations

$P_T > PT_{min}$ $|\eta| < \eta_{cut}$

Leading Calorimeter Jet or Leading Charged Particle Jet or Leading Charged Particle or Z-Boson

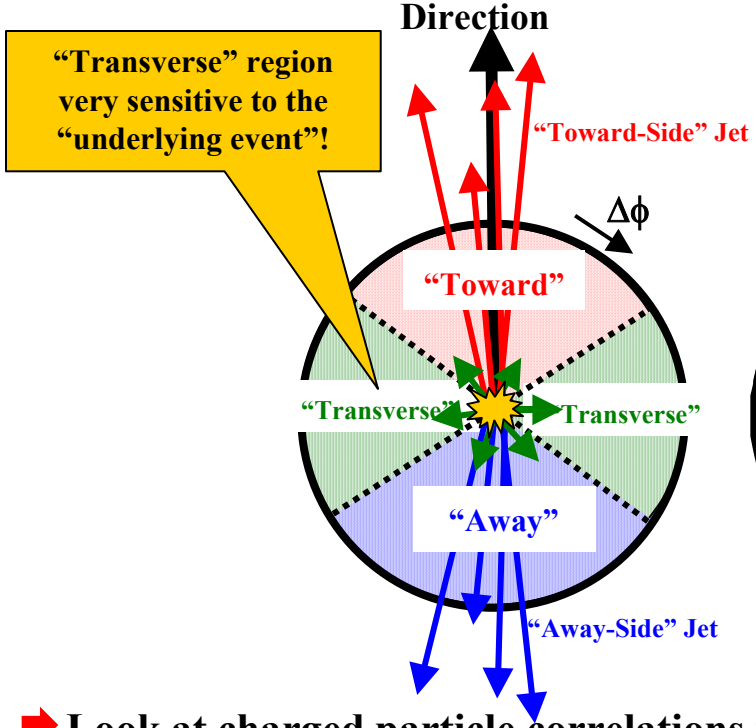


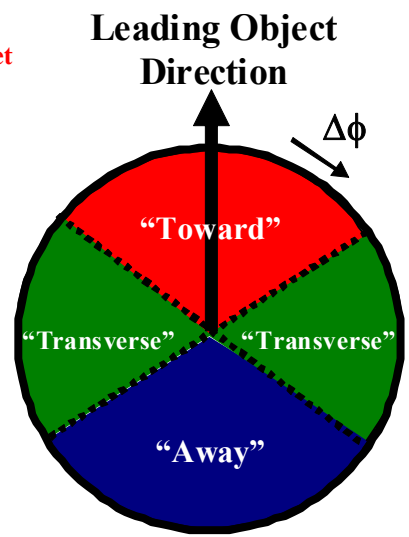
- **Look at charged particle correlations in the azimuthal angle $\Delta\phi$ relative to a leading object (*i.e.* CaloJet#1, ChgJet#1, PTmax, Z-boson). For CDF PTmin = 0.5 GeV/c η_{cut} = 1.0 or 0.8.**
- **Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as overall "Transverse", and $|\Delta\phi| > 120^o$ as "Away".**
- **All three regions have the same area in η-ϕ space, $\Delta\eta\times\Delta\phi = 2\eta_{cut}\times120^o = 2\eta_{cut}\times2\pi/3$. Construct densities by dividing by the area in η-ϕ space.**

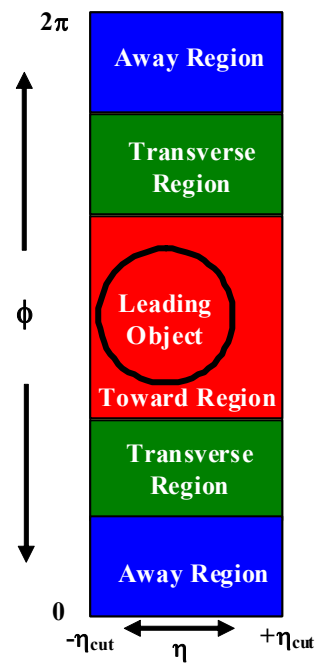
Traditional Approach

CDF Run 1 Analysis **Charged Particle $\Delta\phi$ Correlations**

$P_T > PT_{min}$ $|\eta| < \eta_{cut}$







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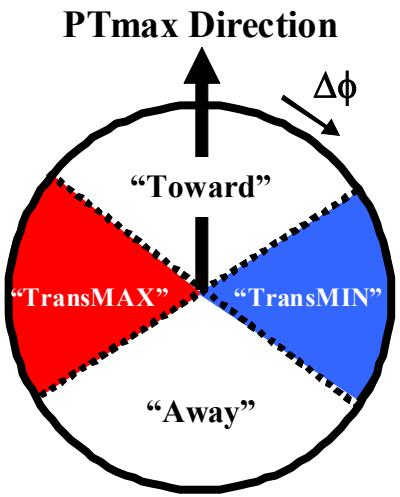
UE Observables

- **"transMAX" and "transMIN" Charged Particle Density:** Number of charged particles ($p_T > PT_{min}$, $|\eta| < \eta_{cut}$) 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 $p_T > PT_{min}$, $|\eta| < \eta_{cut}$.
- **"transMAX" and "transMIN" Charged PTsum Density:** Scalar p_T sum of charged particles ($p_T > PT_{min}$, $|\eta| < \eta_{cut}$) 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 $p_T > PT_{min}$, $|\eta| < \eta_{cut}$.



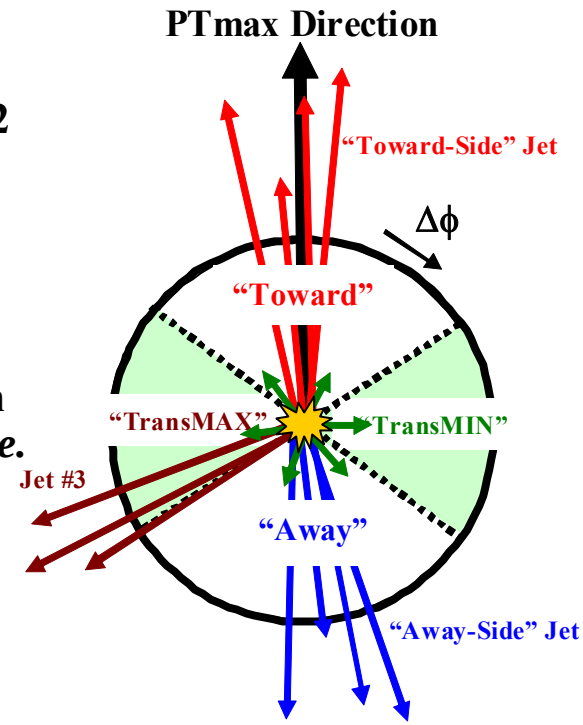
Note: The overall "transverse" density is equal to the average of the "transMAX" and "TransMIN" densities. The "TransDIF" Density is the "transMAX" Density minus the "transMIN" Density

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

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

"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).



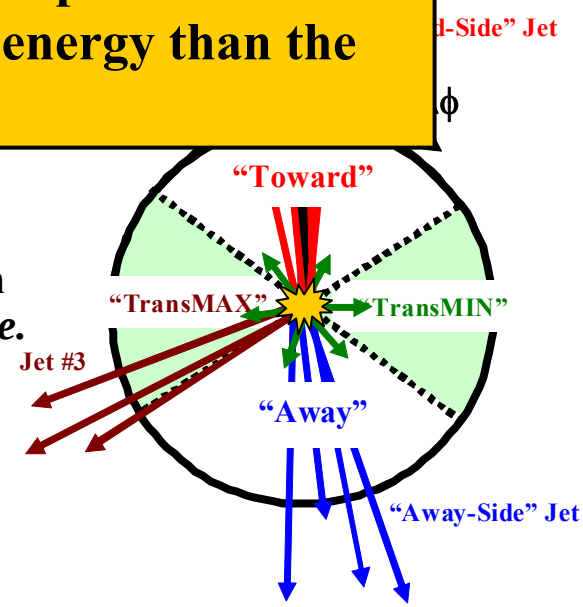
"TransMIN" density more sensitive to MPI & BBR.

"TransDIF" density more sensitive to ISR & FSR.

"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?**

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).



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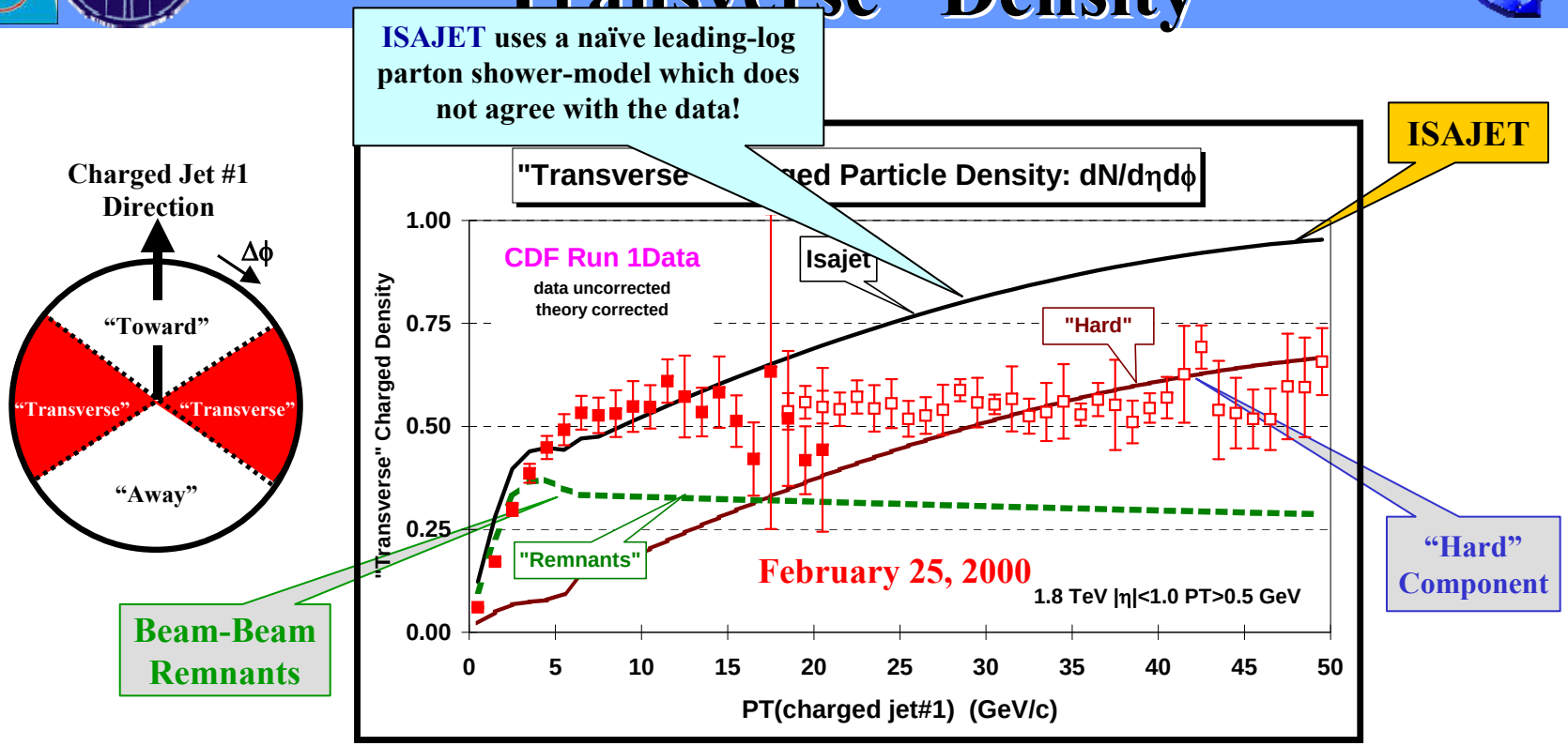
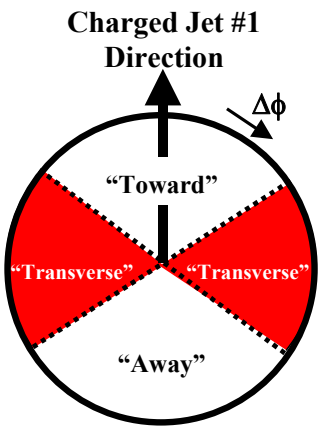
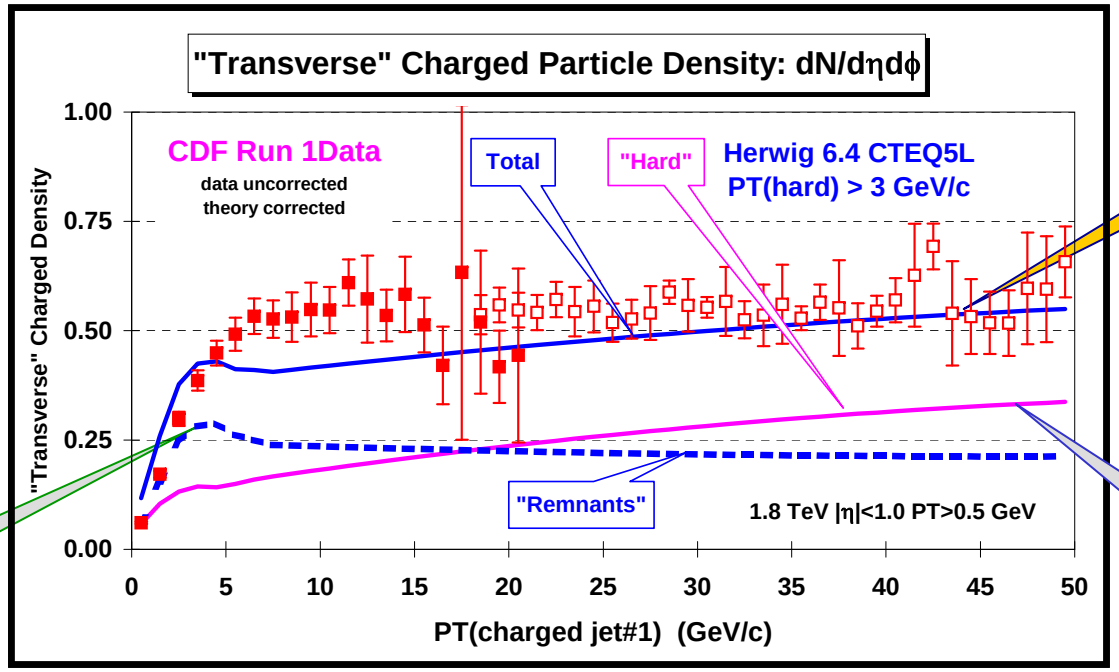
ISAJET 7.32 (without MPI) "Transverse" Density



- Plot shows average "transverse" charge particle density ($|\eta|<1$, $p_T>0.5$ GeV) versus P_T(charged jet#1) compared to the QCD hard scattering predictions of ISAJET 7.32 (default parameters with P_T(hard)>3 GeV/c) .
- The predictions of ISAJET are divided into two categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants); and charged particles that arise from the outgoing jet plus initial and final-state radiation (hard scattering component).

HERWIG 6.4 (without MPI) "Transverse" Density





HERWIG

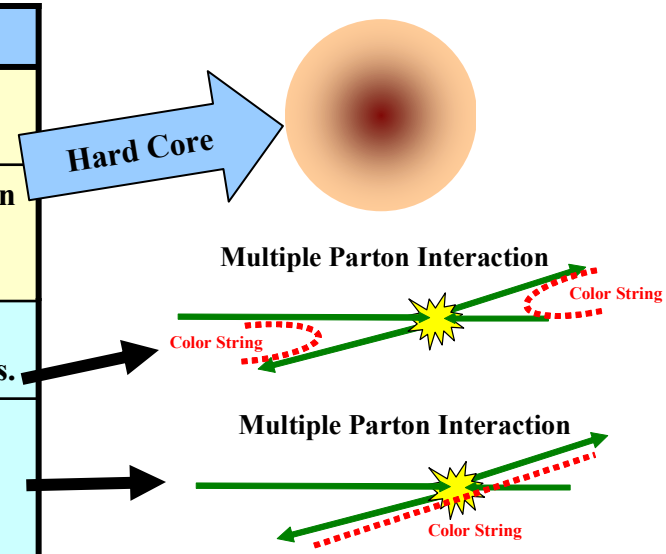
Beam-Beam Remnants

"Hard" Component

- Plot shows average "transverse" charge particle density ($|\eta|<1$, $p_T>0.5$ GeV) versus P_T(charged jet#1) compared to the QCD hard scattering predictions of HERWIG 5.9 (default parameters with P_T(hard)>3 GeV/c without MPI).
- The predictions of HERWIG are divided into two categories: charged particles that arise from the break-up of the beam and target (beam-beam remnants); and charged particles that arise from the outgoing jet plus initial and final-state radiation (hard scattering component).

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.



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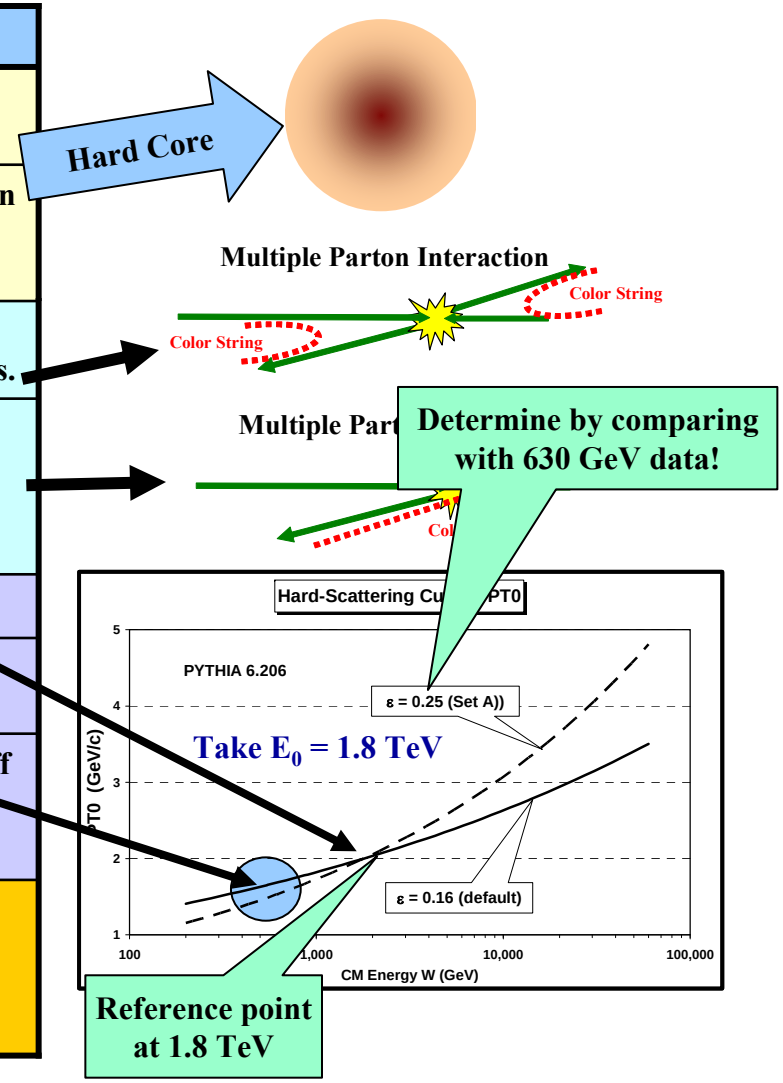
PARP(67)	1.0	A scale factor that determines the maximum parton virtuality for space-like showers. The larger the value of PARP(67) the more initial-state radiation.

Determines the energy dependence of the MPI!

Affects the amount of initial-state radiation!

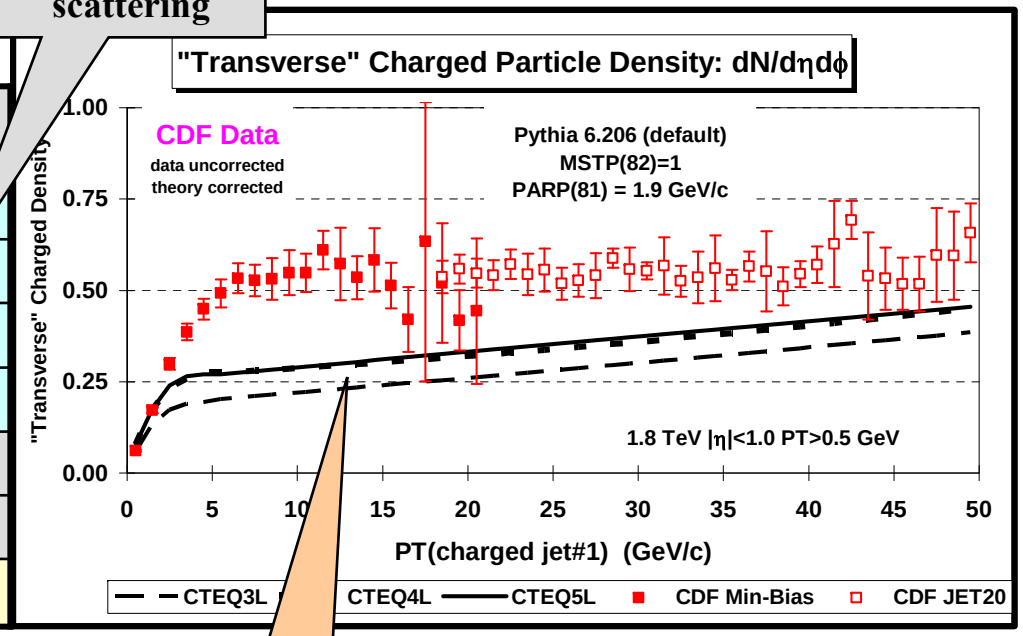


PYTHIA 6.206 Defaults

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.**

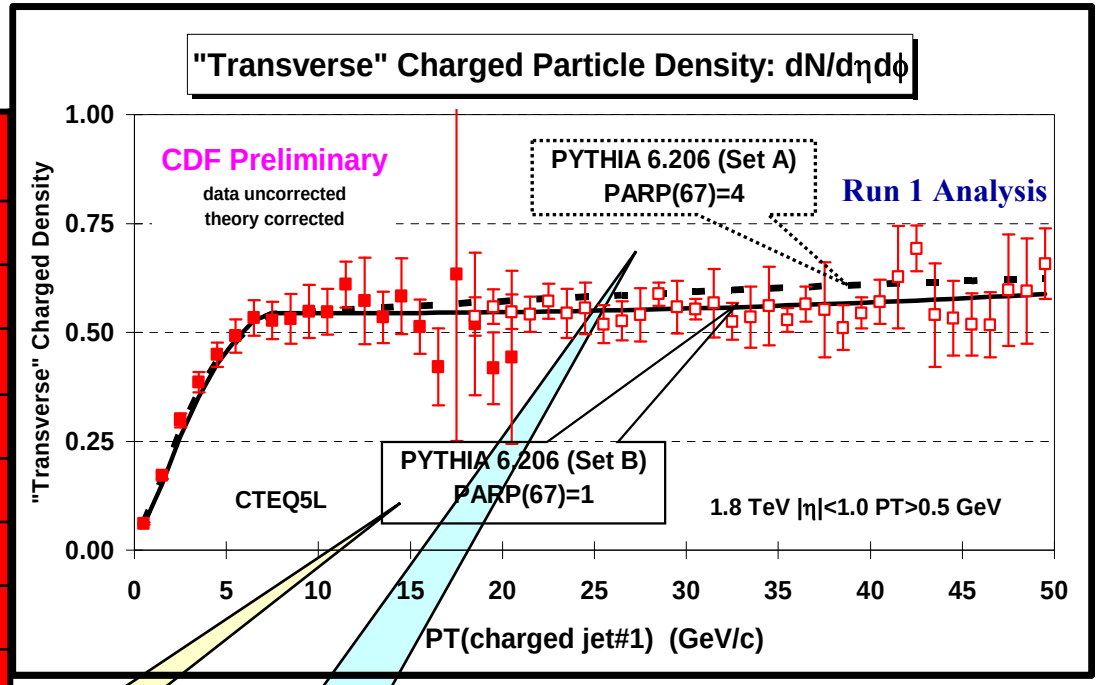
Note Change
PARP(67) = 4.0 (< 6.138)
PARP(67) = 1.0 (> 6.138)

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

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



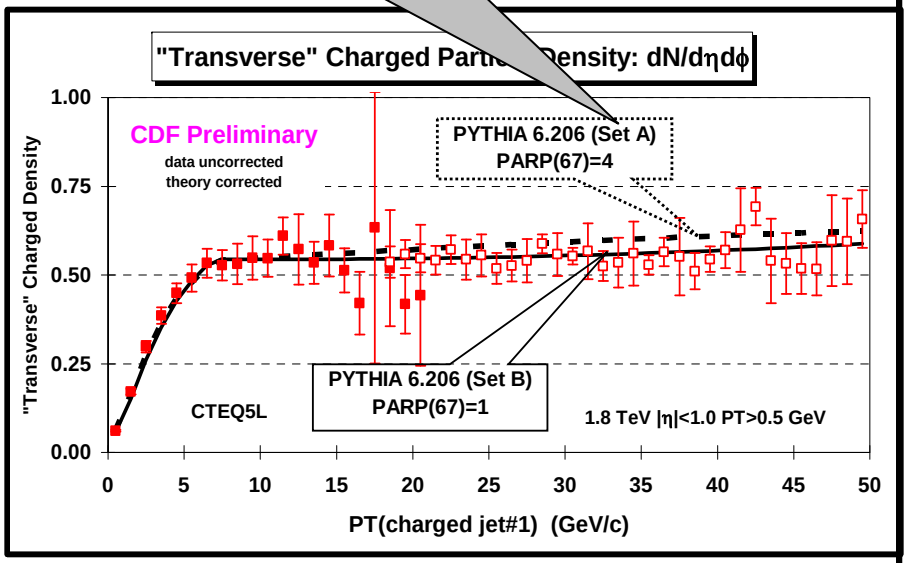
➡ **Plot shows the "transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).**

New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

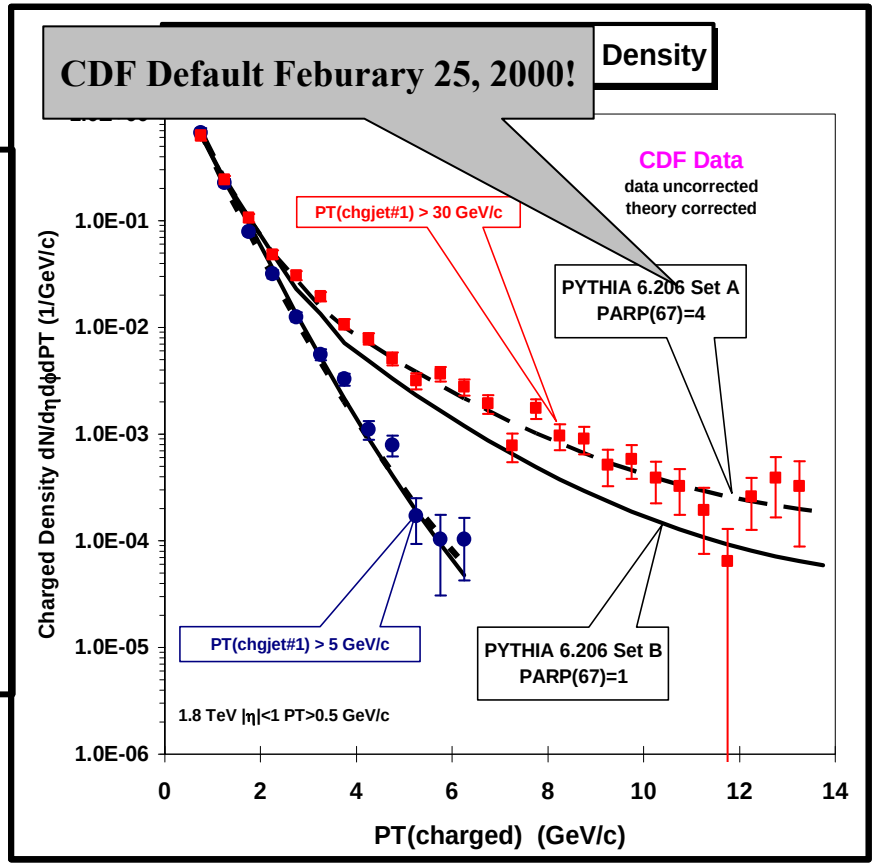
Run 1 PYTHIA Tune A

CDF Default Feburary 25, 2000!



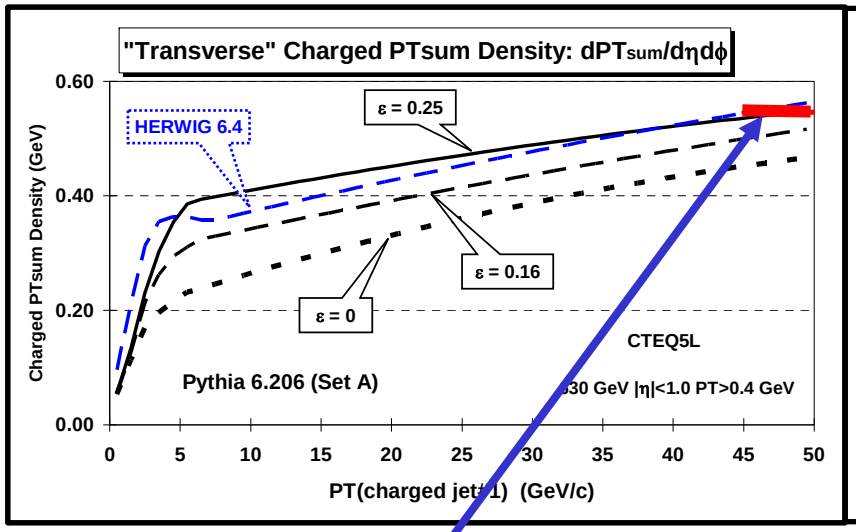
- Plot shows the "transverse" charged particle density versus PT(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

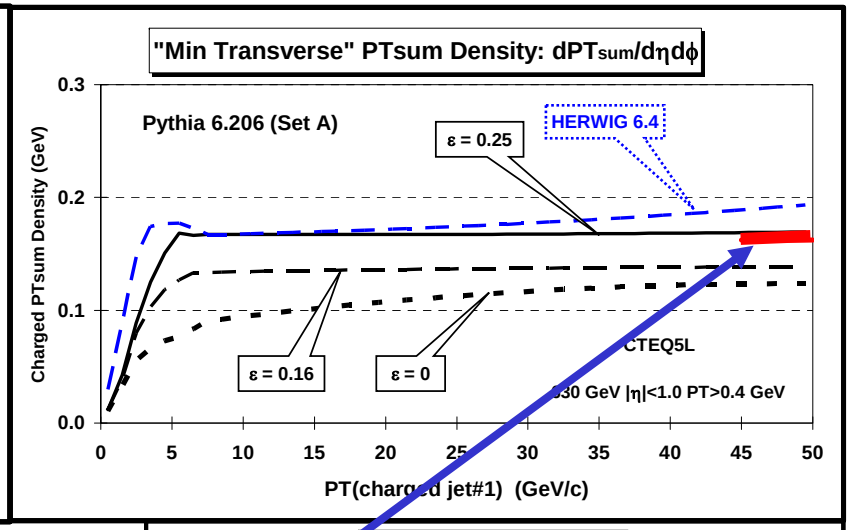
CDF Default Feburary 25, 2000!



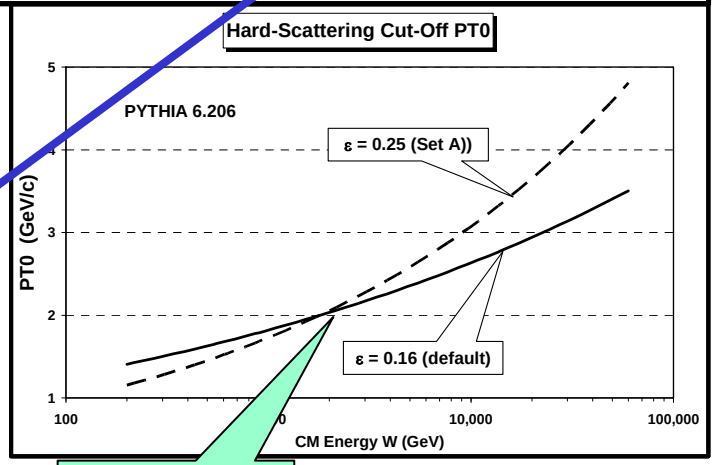
- Plot shows the p_T distribution of the "transverse" charged particle density for PT(chgjet#1) > 5 GeV/c and PT(chgjet#1) > 30 GeV/c.

"Transverse" Charged Densities
Energy Dependence



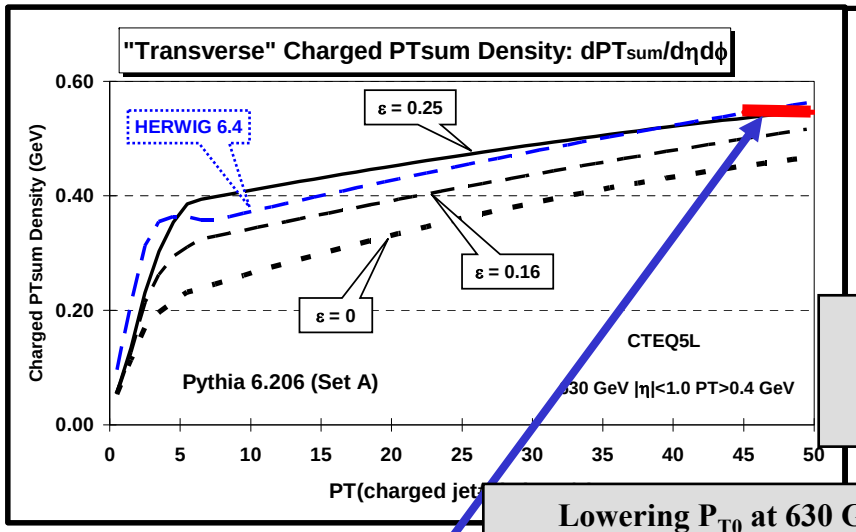


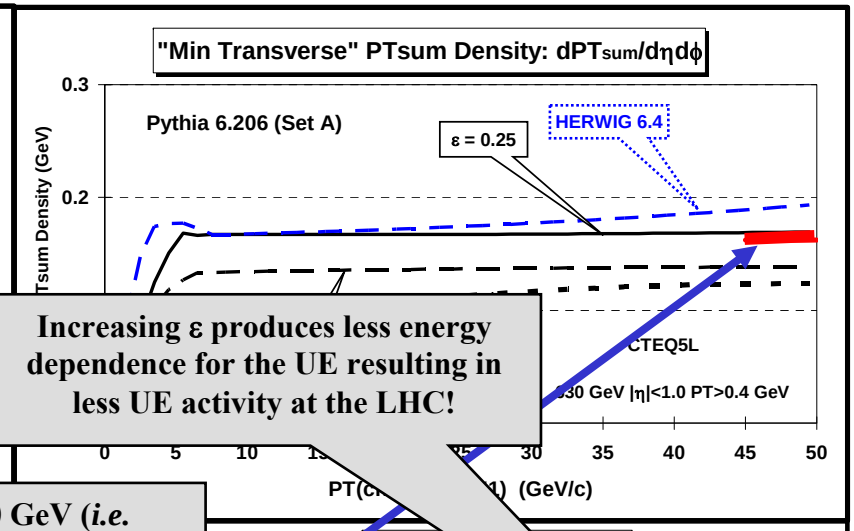
- Shows the "transverse" charged PT_{sum} density ($|\eta|<1$, $P_T>0.4$ GeV) versus P_T(charged jet#1) at 630 GeV predicted by HERWIG 6.4 (P_T(hard) > 3 GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L, Set A, $\varepsilon = 0$, $\varepsilon = 0.16$ (default) and $\varepsilon = 0.25$ (preferred)).
- Also shown are the PT_{sum} densities (0.16 GeV/c and 0.54 GeV/c) determined from the Tano, Kovacs, Huston, and Bhatti "transverse" cone analysis at 630 GeV.



Reference point
E_0 = 1.8 TeV

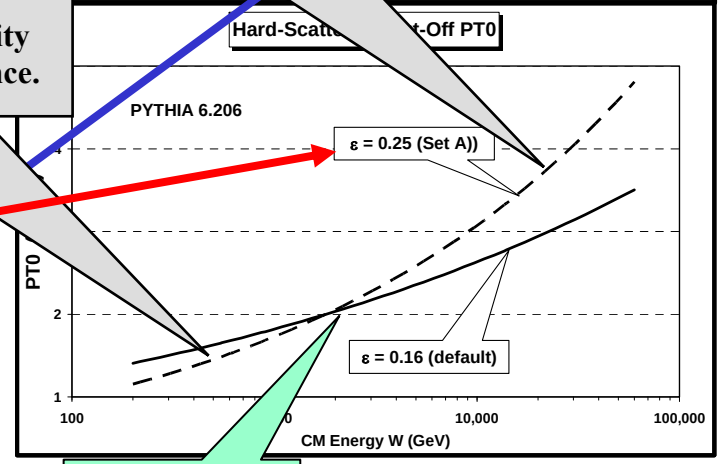
"Transverse" Charged Densities
Energy Dependence





Increasing ε produces less energy dependence for the UE resulting in less UE activity at the LHC!

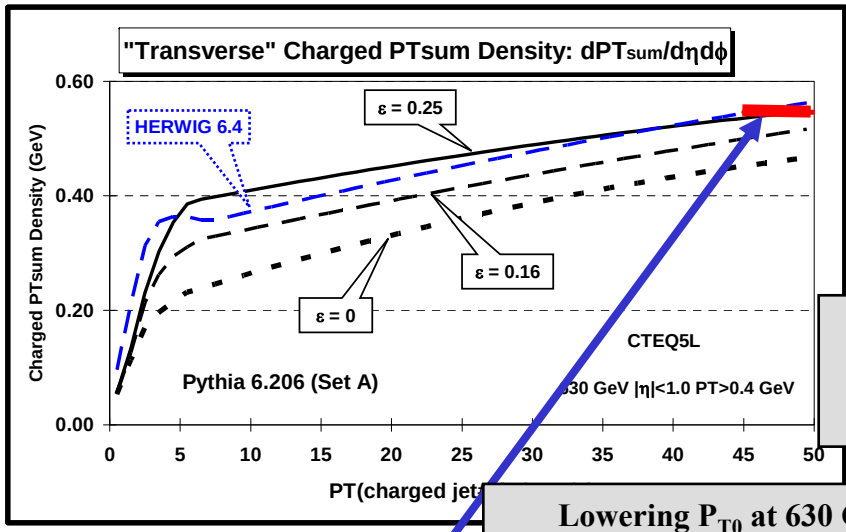
Lowering P_{T0} at 630 GeV (*i.e.* increasing ε) increases UE activity resulting in less energy dependence.

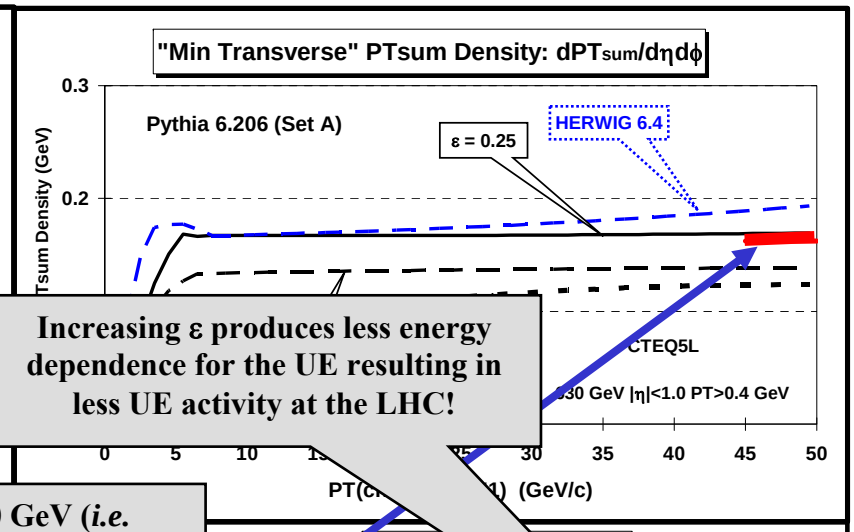


Reference point E_0 = 1.8 TeV

- Shows the "transverse" ch
(|η|<1, P_T>0.4 GeV) versus
GeV predicted by HERWIG 6.4 (P_T(hard) > 3 GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L, Set A, ε = 0, ε = 0.16 (default) and ε = 0.25 (preferred)).
- Also shown are the PT_{sum} densities (0.16 GeV/c and 0.54 GeV/c) determined from the Tano, Kovacs, Huston, and Bhatti "transverse" cone analysis at 630 GeV.

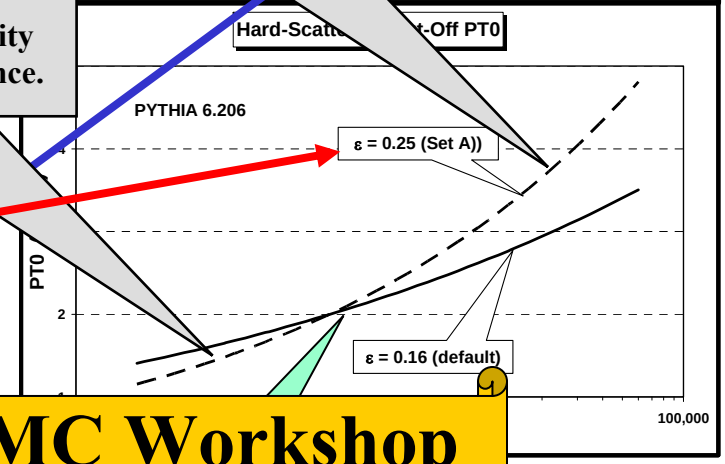
"Transverse" Charged Densities
Energy Dependence





Increasing ε produces less energy dependence for the UE resulting in less UE activity at the LHC!

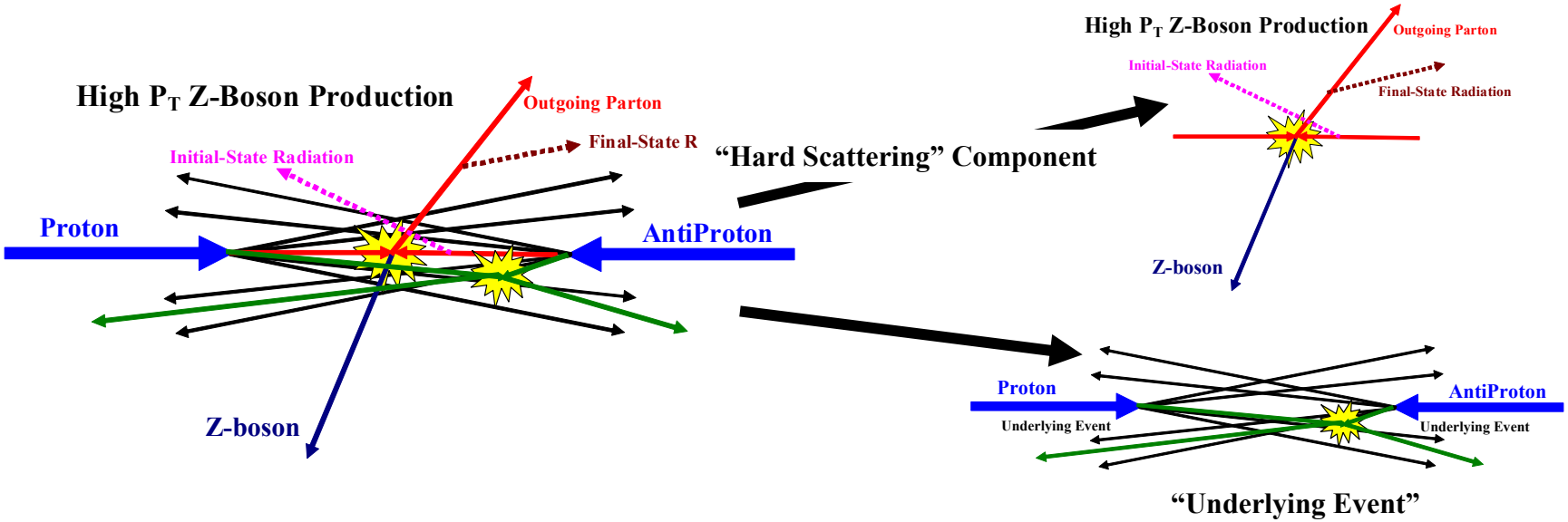
Lowering P_{T0} at 630 GeV (*i.e.* increasing ε) increases UE activity resulting in less energy dependence.



- Shows the "transverse" ch
  ($|\eta|<1$, $P_T>0.4$ GeV) versus
  GeV predicted by HERWIG 6.4 (P_T(hard) > 3 GeV/c, CTEQ5L) and a tuned version of PYTHIA 6.206 (P_T(hard) > 0, CTEQ5L, Set A, ε = 0, ε = 0.16 (default) and ε = 0.25 (preferred)).
- Also shown are the PT_{sum} densities (0.16 GeV/c and 0.54 GeV/c)
  Huston, and
  630 GeV.

Rick Field Fermilab MC Workshop October 4, 2002!

QCD Monte-Carlo Models: Lepton-Pair Production



- Start with the perturbative Drell-Yan muon pair production and add initial-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-state radiation.

CDF Run 1 $P_T(Z)$

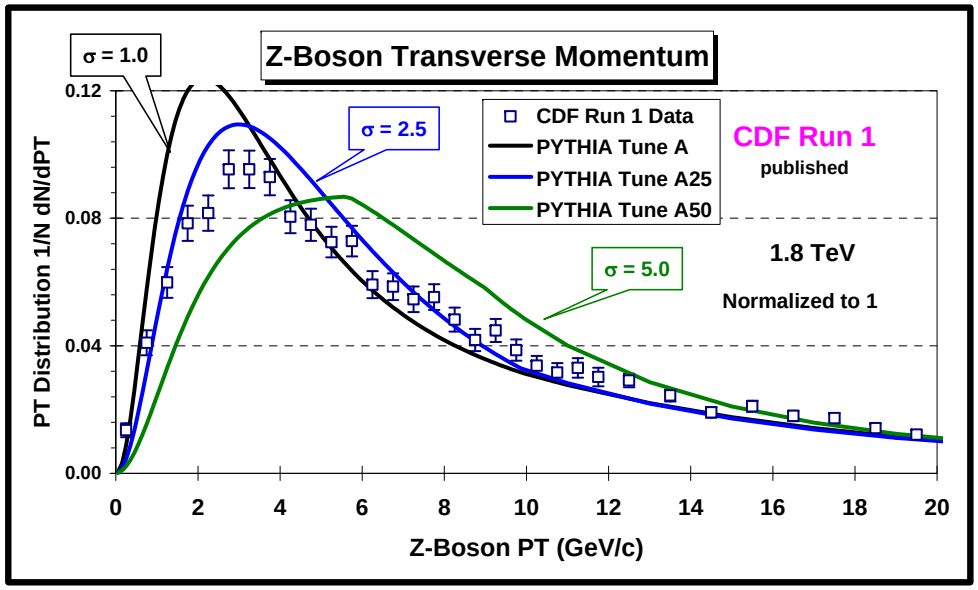
PYTHIA 6.2 CTEQ5L

UE Parameters

ISR Parameter

Intrensic KT

Parameter	Tune A	Tune A25	Tune A50
MSTP(81)	1	1	1
MSTP(82)	4	4	4
PARP(82)	2.0 GeV	2.0 GeV	2.0 GeV
PARP(83)	0.5	0.5	0.5
PARP(84)	0.4	0.4	0.4
PARP(85)	0.9	0.9	0.9
PARP(86)	0.95	0.95	0.95
PARP(89)	1.8 TeV	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25	0.25
PARP(67)	4.0	4.0	4.0
MSTP(91)	1	1	1
PARP(91)	1.0	2.5	5.0
PARP(93)	5.0	15.0	25.0



- Shows the Run 1 Z-boson p_T distribution ($\langle p_T(Z)\rangle \approx 11.5$ GeV/c) compared with PYTHIA Tune A ($\langle p_T(Z)\rangle = 9.7$ GeV/c), Tune A25 ($\langle p_T(Z)\rangle = 10.1$ GeV/c), and Tune A50 ($\langle p_T(Z)\rangle = 11.2$ GeV/c).

Vary the intrensic KT!

CDF Run 1 $P_T(Z)$

PYTHIA 6.2 CTEQ5L

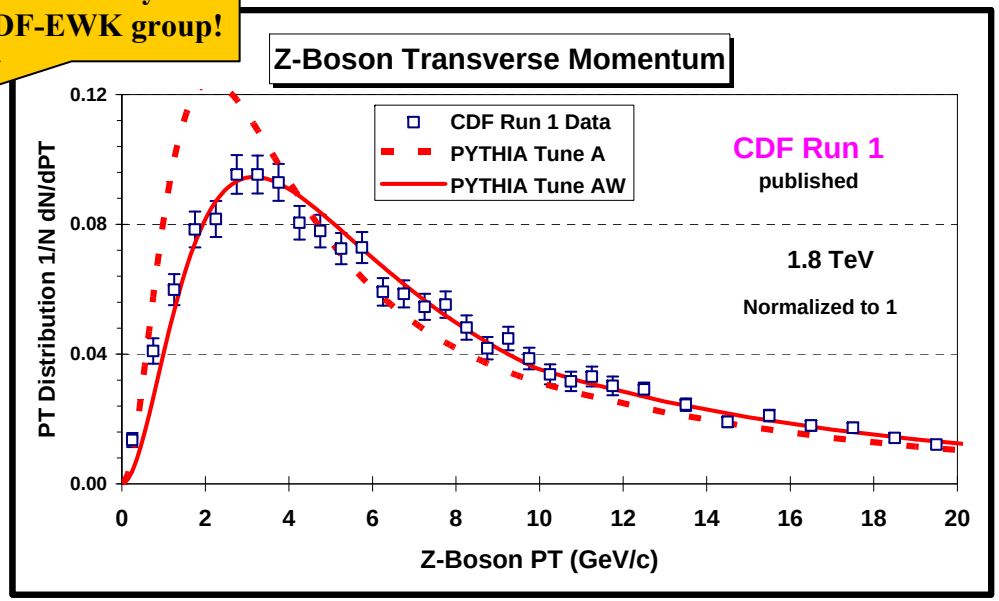
Tune used by the CDF-EWK group!

Parameter	Tune A	Tune AW
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	2.0 GeV	2.0 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	0.9	0.9
PARP(86)	0.95	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(62)	1.0	1.25
PARP(64)	1.0	0.2
PARP(67)	4.0	4.0
MSTP(91)	1	1
PARP(91)	1.0	2.1
PARP(93)	5.0	15.0

UE Parameters

ISR Parameters

Intrensic KT



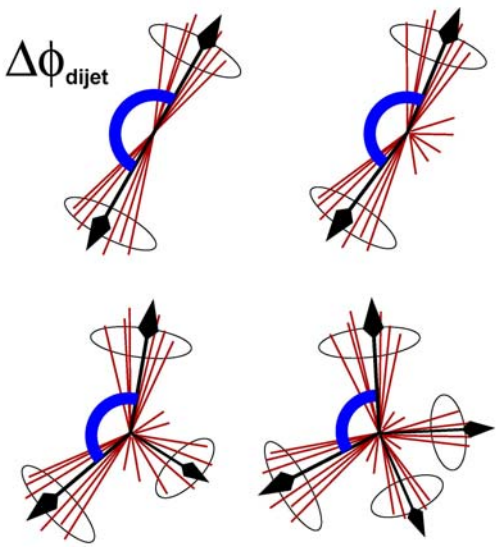
➡ **Shows the Run 1 Z-boson p_T distribution ($\langle p_T(Z)\rangle \approx 11.5$ GeV/c) compared with PYTHIA Tune A ($\langle p_T(Z)\rangle = 9.7$ GeV/c), and PYTHIA Tune AW ($\langle p_T(Z)\rangle = 11.7$ GeV/c).**

Effective Q cut-off, below which space-like showers are not evolved.

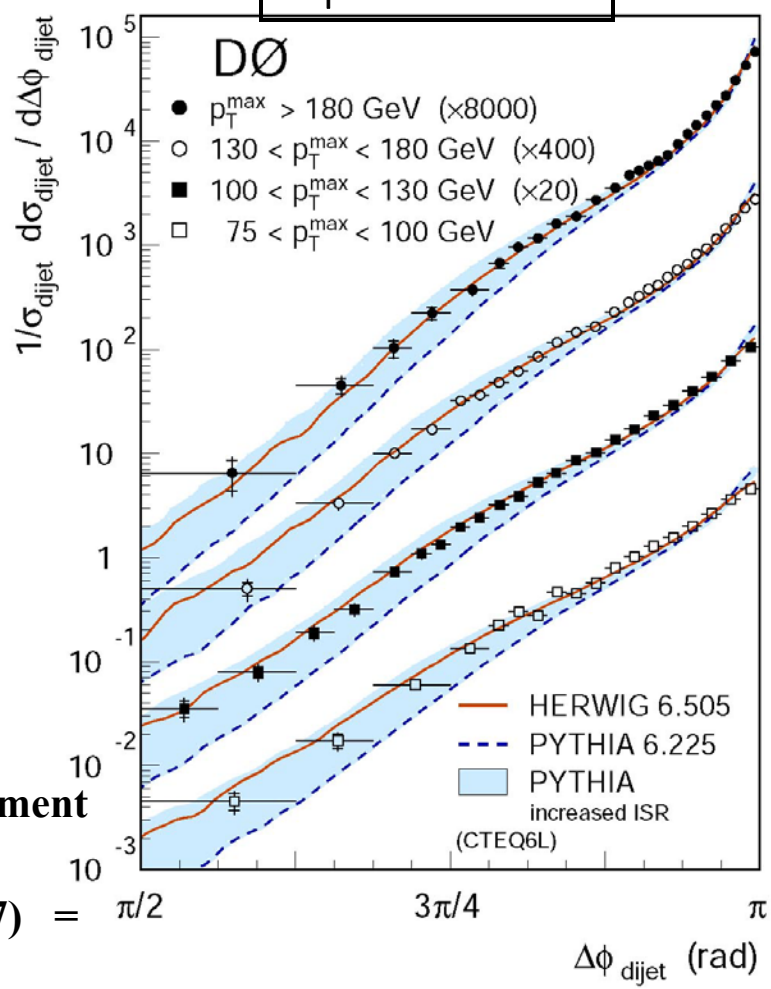
The $Q^2 = k_T^2$ in α_s for space-like showers is scaled by PARP(64)!

Jet-Jet Correlations (DØ)

Jet#1-Jet#2 Δϕ Distribution



Δϕ Jet#1-Jet#2



- **MidPoint Cone Algorithm (R = 0.7, f_{merge} = 0.5)**
- **$\mathcal{L}$ = 150 pb^{-1} (Phys. Rev. Lett. 94 221801 (2005))**
- **Data/NLO agreement good. Data/HERWIG agreement good.**
- **Data/PYTHIA agreement good provided PARP(67) = 1.0→4.0 (i.e. like Tune A, best fit 2.5).**

CDF Run 1 $P_T(Z)$

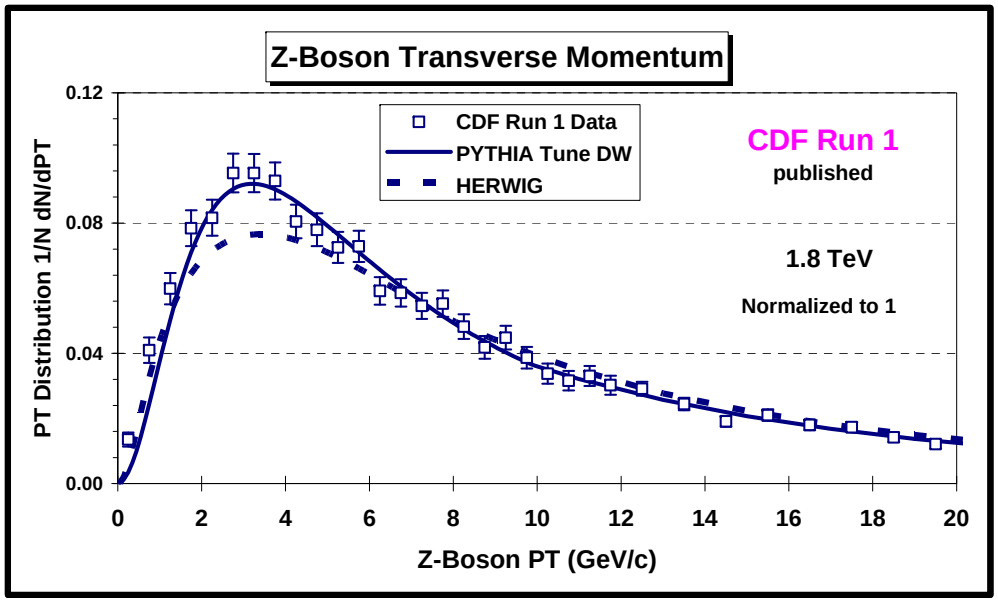
PYTHIA 6.2 CTEQ5L

Parameter	Tune DW	Tune AW
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(62)	1.25	1.25
PARP(64)	0.2	0.2
PARP(67)	2.5	4.0
MSTP(91)	1	1
PARP(91)	2.1	2.1
PARP(93)	15.0	5.0

UE Parameters

ISR Parameters

Intrensic KT



➡ **Shows the Run 1 Z-boson p_T distribution ($\langle p_T(Z)\rangle \approx 11.5$ GeV/c) compared with PYTHIA Tune DW, and HERWIG.**

Tune DW uses D0's perfered value of PARP(67)!

Tune DW has a lower value of PARP(67) and slightly more MPI!

PYTHIA 6.2 Tunes

All use LO α_s with Λ = 192 MeV!

UE Parameters

ISR Parameter

Intrinsic KT

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

Uses CTEQ6L

Tune A energy dependence!

PYTHIA 6.2 Tunes

All use LO α_s with Λ = 192 MeV!

UE Parameters

ISR Parameter

Intrinsic KT

ATLAS energy dependence!

Parameter	Tune DWT	Tune D6T	ATLAS
PDF	CTEQ5L	CTEQ6L	CTEQ5L
MSTP(81)	1	1	1
MSTP(82)	4	4	4
PARP(82)	1.9409 GeV	1.8387 GeV	1.8 GeV
PARP(83)	0.5	0.5	0.5
PARP(84)	0.4	0.4	0.5
PARP(85)	1.0	1.0	0.33
PARP(86)	1.0	1.0	0.66
PARP(89)	1.96 TeV	1.96 TeV	1.0 TeV
PARP(90)	0.16	0.16	0.16
PARP(62)	1.25	1.25	1.0
PARP(64)	0.2	0.2	1.0
PARP(67)	2.5	2.5	1.0
MSTP(91)	1	1	1
PARP(91)	2.1	2.1	1.0
PARP(93)	15.0	15.0	5.0

PYTHIA 6.2 Tunes

All use LO α_s with Λ = 192 MeV!

UE Parameters

Parameter	Tune DWT	Tune D6T	ATLAS
PDF	CTEQ5L	CTEQ6L	CTEQ5L
MSTP(81)	1	1	1
MSTP(82)	4	4	4
PARP(31)	1.9409 GeV	1.8387 GeV	1.8 GeV
[illegible]	0.5	[illegible]	0.5
[illegible]	0.4	[illegible]	[illegible]
[illegible]	1.0	[illegible]	0.33
[illegible]	1.0	[illegible]	0.66
PARP(89)	1.96 TeV	1.96 TeV	1.0 TeV
PARP(90)	0.16	0.16	0.16
PARP(62)	1.25	1.25	1.0
PARP(64)	0.2	0.2	1.0
PARP(67)	[illegible]	2.5	1.0
MSTP(91)	[illegible]	1	[illegible]
PARP(91)	[illegible]	2.1	[illegible]
PARP(93)	[illegible]	15.0	[illegible]

Parameter

ATLAS [illegible] ce!

Tune A

Tune AW

Tune B

Tune BW

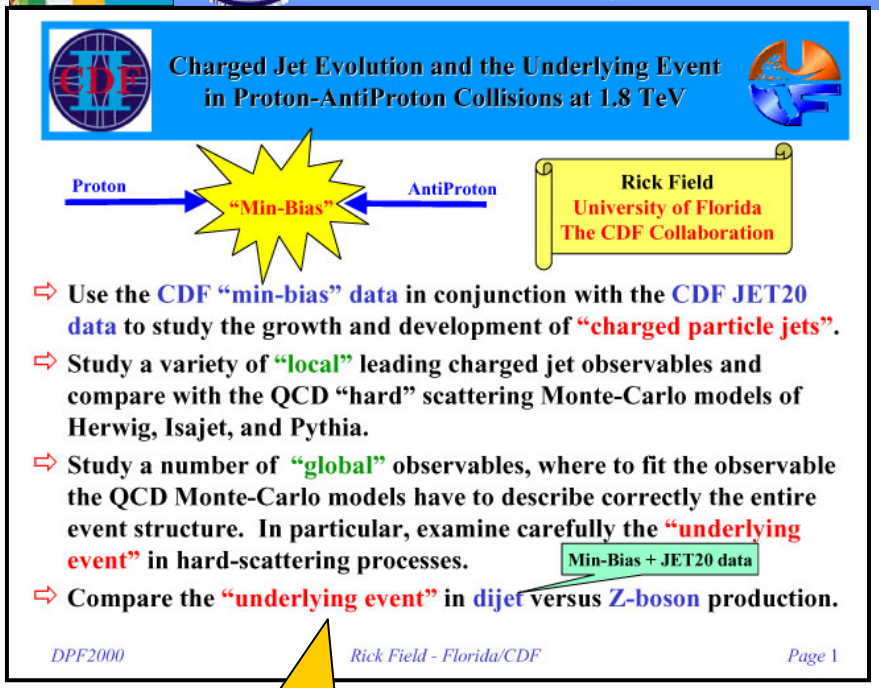
Tune D

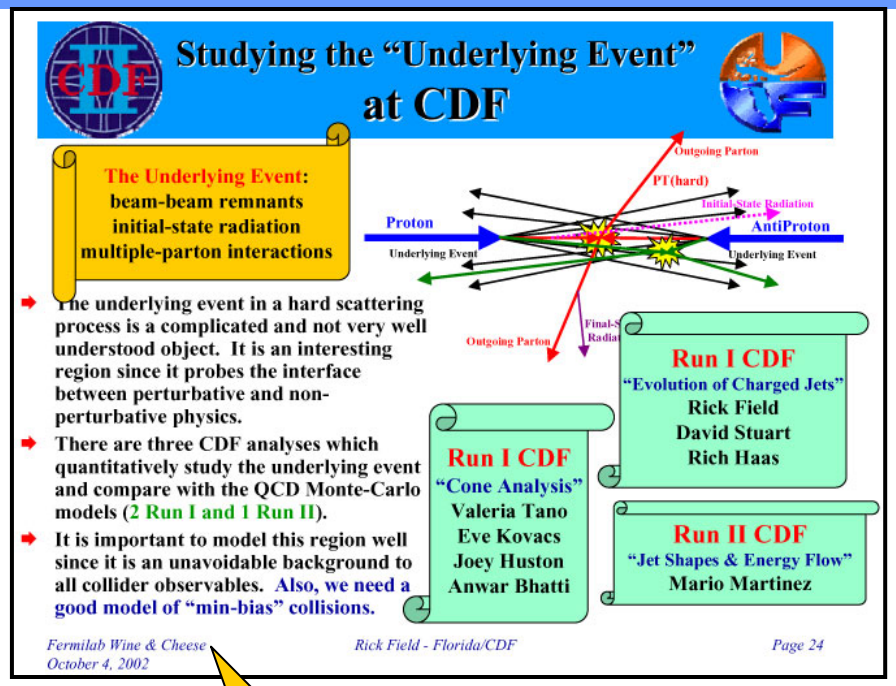
Tune DW

Tune D6

Tune D6T

Early Studies of the UE



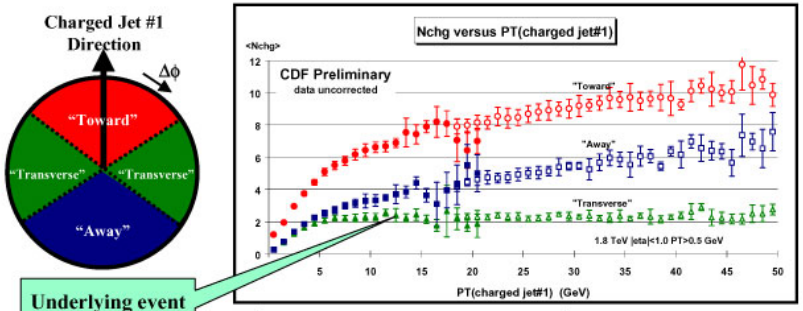


DPF 2000: My first presentation on the "underlying event"!

First CDF UE Studies
Rick Field Wine & Cheese Talk
October 4, 2002

My First Talk on the UE

DiJet: Charged Multiplicity versus PT(chgjet#1)



Underlying event "plateau"

Refer to the Min-Bias + JET20 data as the "dijet" data.

⇨ Dijet data on the average number of "toward" (|Δφ|<60°), "transverse" (60<|Δφ|<120°), and "away" (|Δφ|>120°) charged particles (P_T > 0.5 GeV, |η| < 1, including jet#1) as a function of the transverse momentum of the leading charged particle jet. Each point corresponds to the <Nchg> in a 1 GeV bin. The (open) points are the Min-Bias (JET20) data. The errors on the (*uncorrected*) data include statistical and correlated systematic uncertainties.

DPF2000 *Rick Field - Florida/CDF* *Page*

The Underlying Event: Summary & Conclusions

The "Underlying Event"

⇨ The underlying event is very similar in dijet and the Z-boson production as predicted by the QCD Monte-Carlo models. The "toward" region in Z-boson production is a direct measure of the underlying event.

⇨ The number of charged particles per unit rapidity (height of the "plateau") is at least twice that observed in "soft" collisions at the same corresponding energy.

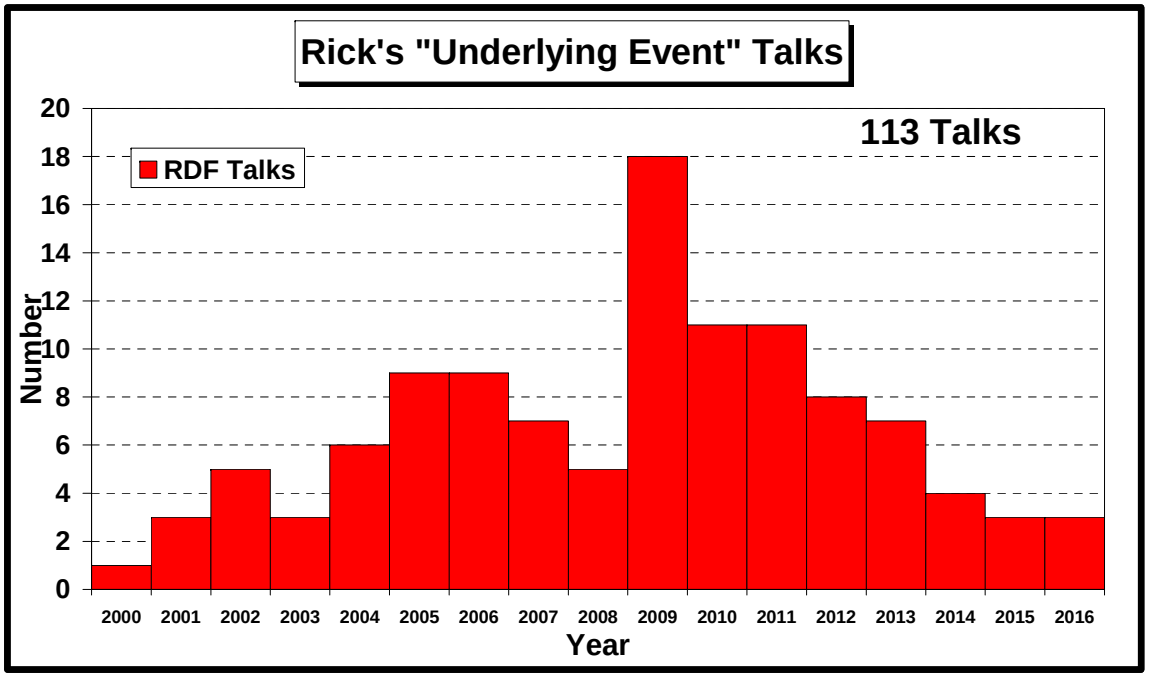
⇨ None of the QCD Monte-Carlo models correctly describe the underlying event. Herwig and Pythia 6.125 do not have enough activity in the underlying event. Pythia 6.115 has about the right amount of activity in the underlying event, but as a result produces too much overall multiplicity. Isajet has a lot of activity in the underlying event, but with the wrong dependence on P_T(jet#1) or P_T(Z). None of the Monte-carlo models have the correct P_T dependence of the beam-beam remnant component of the underlying event.

DPF2000 *Rick Field - Florida/CDF* *Page 36*

Need to "tune" the QCD MC models!

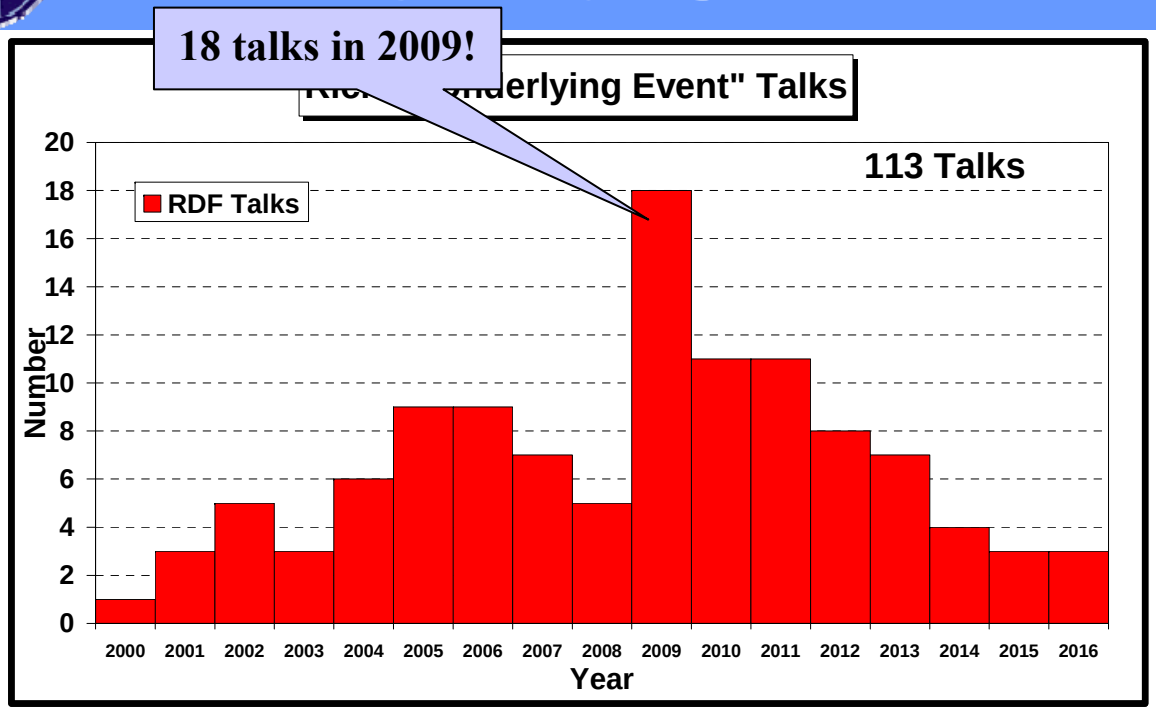
My first look at the "underlying event plateau"!

Rick's UE Talks



➡ **Rick's "underlying event" talks (2000-2016).**

Rick's UE Talks



➡ **Rick's "underlying event" talks (2000-2016).**

Rick's UE Talks 2009(1)

- ***Studying the Underlying Event at CDF and the LHC***, **seminar presented at the University of California, Berkeley, January 13, 2009.**

- ***Toward an Understanding of Hadron-Hadron Collisions***: ***From Feynman-Field to the LHC***, **research progress meeting (RPM) presented at Lawrence Berkeley Laboratory, University of California, Berkeley, January 15, 2009.**

- ***Studying the Underlying Event at CDF***, **talk presented at the Northwest Terascale Workshop: Parton Showers an Event Structure at the LHC, University of Oregon, Eugene, Oregon, February 24, 2009.**

- ***Rick's View of Hadron Collisions***, **talk presented at the 1st Joint Workshop on Energy Scaling of hadron Collisions, Fermilab, April 27, 2009.**

- ***Min-Bias and the Underlying Event***, **talk presented at the Workshop on Early Physics Opportunities at the LHC, University of California, Berkeley, May 6, 2009.**

- ***Min-Bias and the Underlying Event: From RHIC to the LHC***, **talk presented at the RHIC & AGS Annual Users' Meeting, Brookhaven National Laboratory, June 2, 2009.**

Rick's UE Talks 2009(1)

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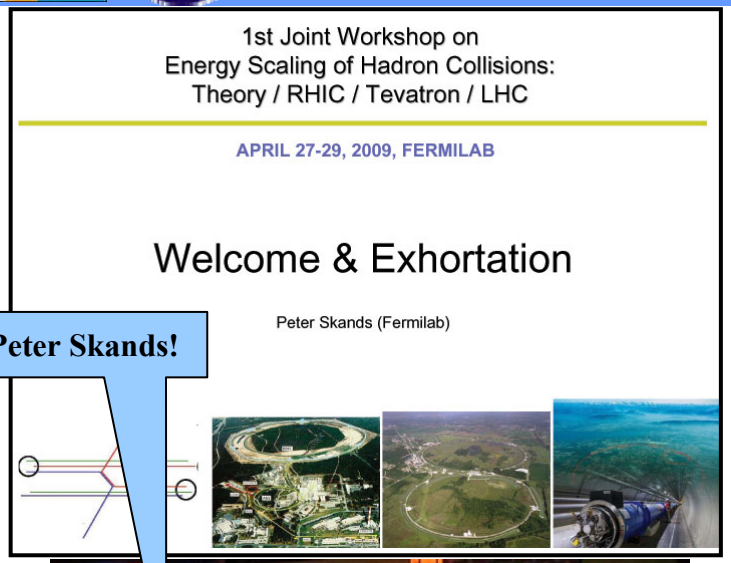
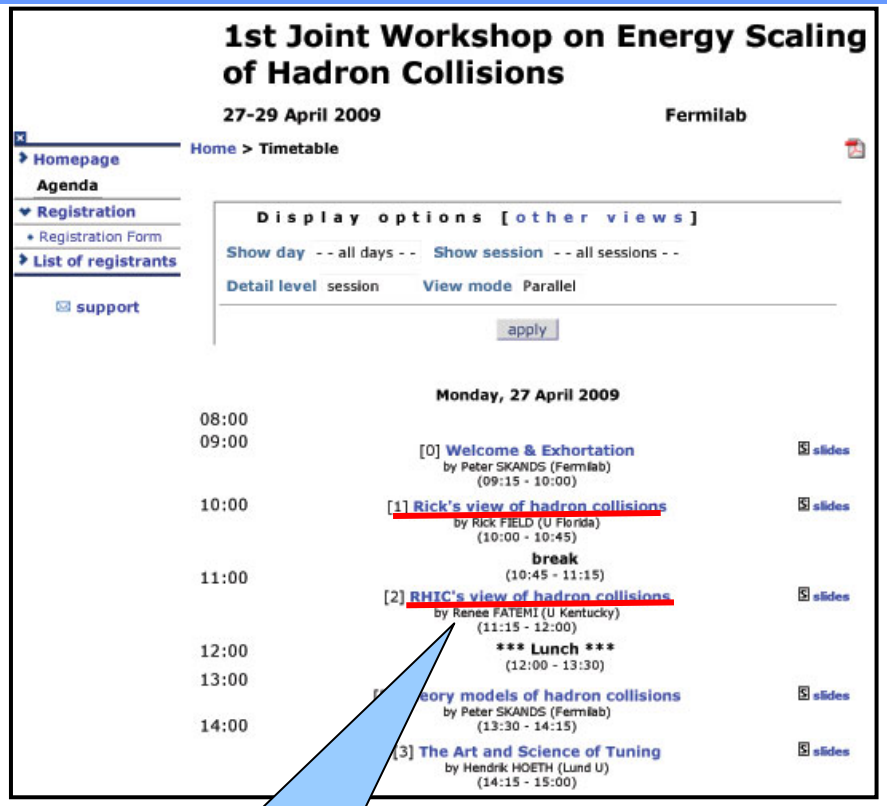
1st Workshop on Energy Scaling in Hadron-Hadron Collisions



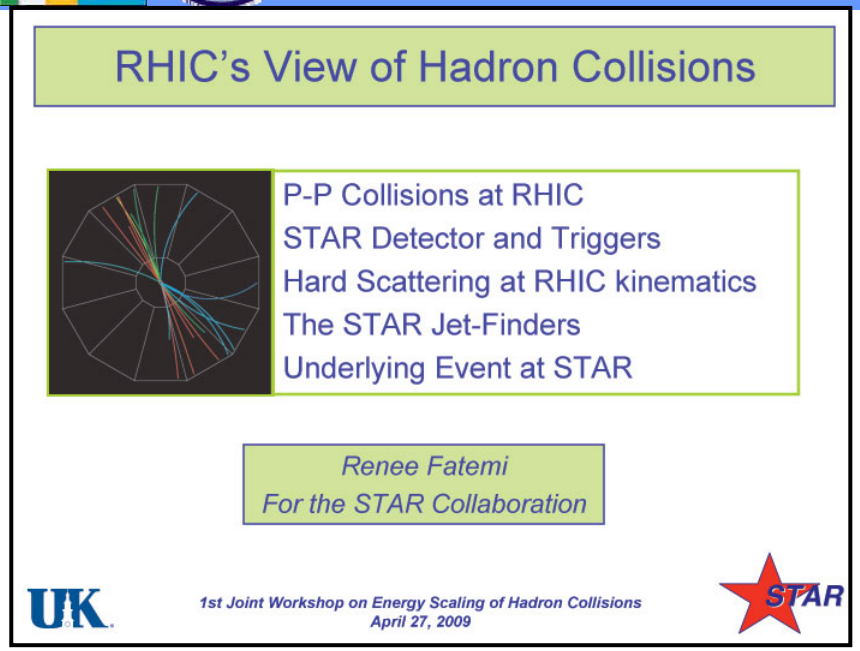
Peter Skands!

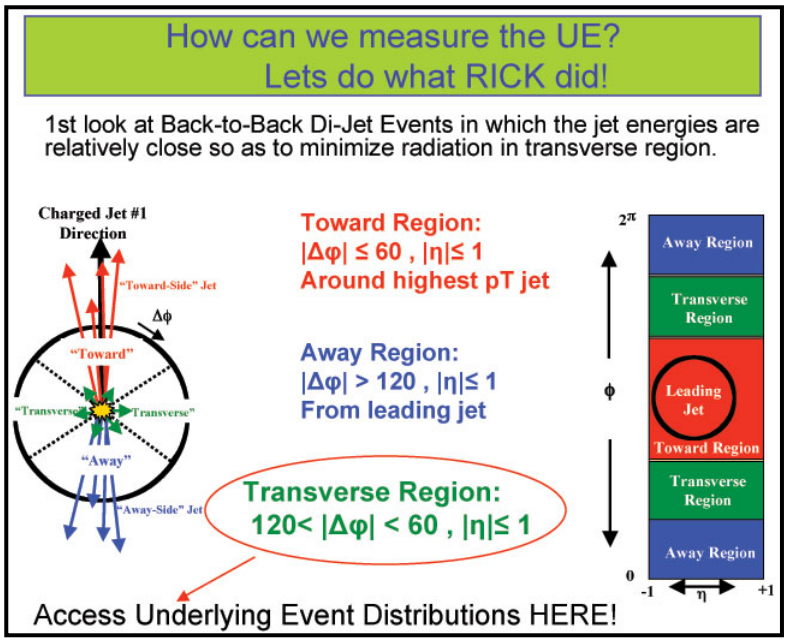
"On the Boarder" restaurant, Aurora, IL
April 27, 2009



Renee Fatemi gave a talk on the "underlying event at STAR!

The "Underlying Event" at STAR

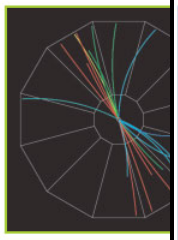




➡ **At STAR they have measured the "underlying event at W = 200 GeV ($|\eta| < 1$, $p_T > 0.2$ GeV) and compared their uncorrected data with PYTHIA Tune A + STAR-SIM.**

The "Underlying Event" at STAR

RHIC



ergies are
egion.

Conclusions

I. Hadron Collisions at RHIC take place at an order of magnitude smaller $\sqrt{s}$ than the Tevatron. Nevertheless, jets are observed and reconstructed down to pT=5 GeV and are well described by pQCD

II. Comparisons between several jetfinders reveal consistent results

III. Interest in the Underlying Event at RHIC Kinematics is driven by the need for jet energy scale corrections as well as pure physics interests (see talks by M. Lisa and H. Caines)

IV. UE at RHIC appears to be independent of jet pT and decoupled from hard interaction

V. CDF Tune A provides an excellent description of the UE at $\sqrt{s}$ =200 GeV (thanks Rick!)

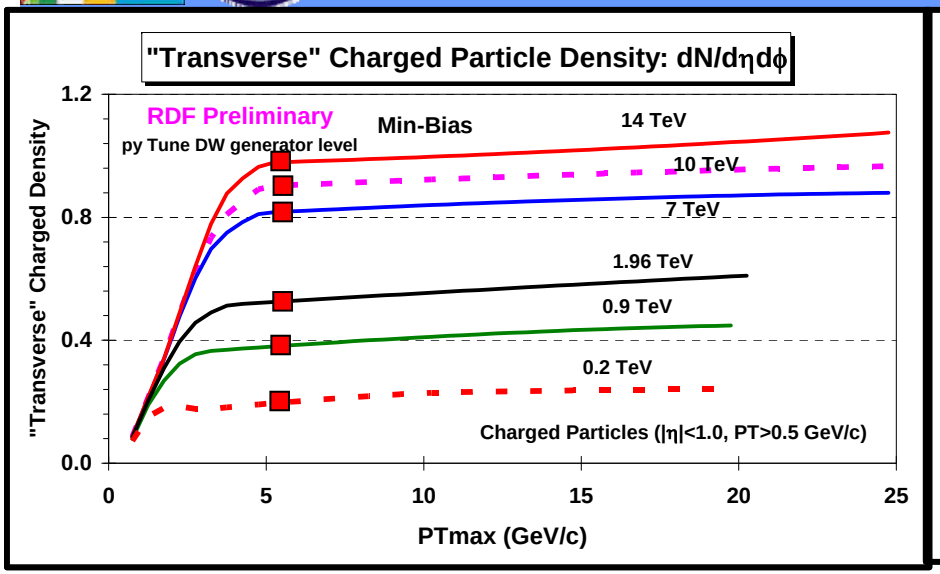
VI. Underlying Event distributions in general smaller than those at CDF. Tower & Track Multiplicities are the exception, but this may be due to the 0.2 (STAR) versus 0.5 GeV (CDF) pT/Et cut-off.

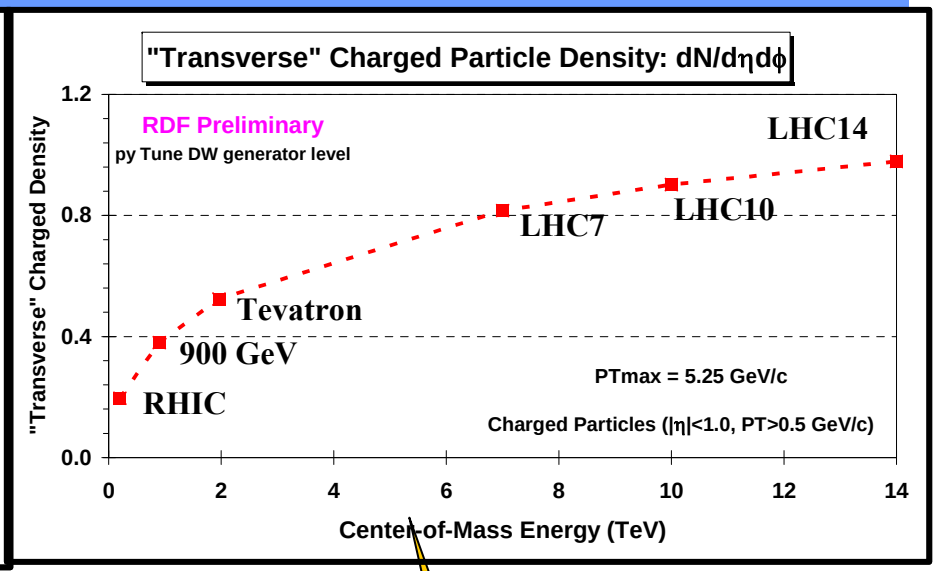
VII. For a cone jet with R=0.7 UE contributes 0.5-0.9 GeV.

VIII. Comparison of Leading Jet and Back-to-Back distributions indicate that large angle radiation contributions are small at RHIC energies.

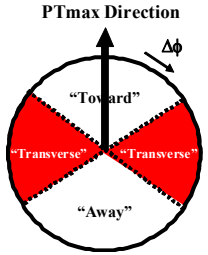
➡ **At STAR** **2 GeV)**
and com

"Transverse" Charge Density



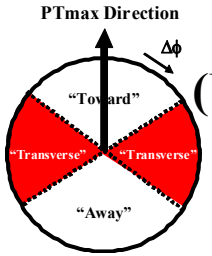


RHIC



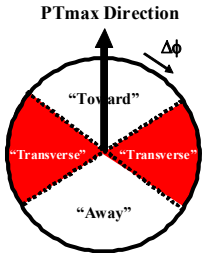
0.2 TeV → 1.96 TeV
(UE increase ~2.7 times)

Tevatron



1.96 TeV → 14 TeV
(UE increase ~1.9 times)

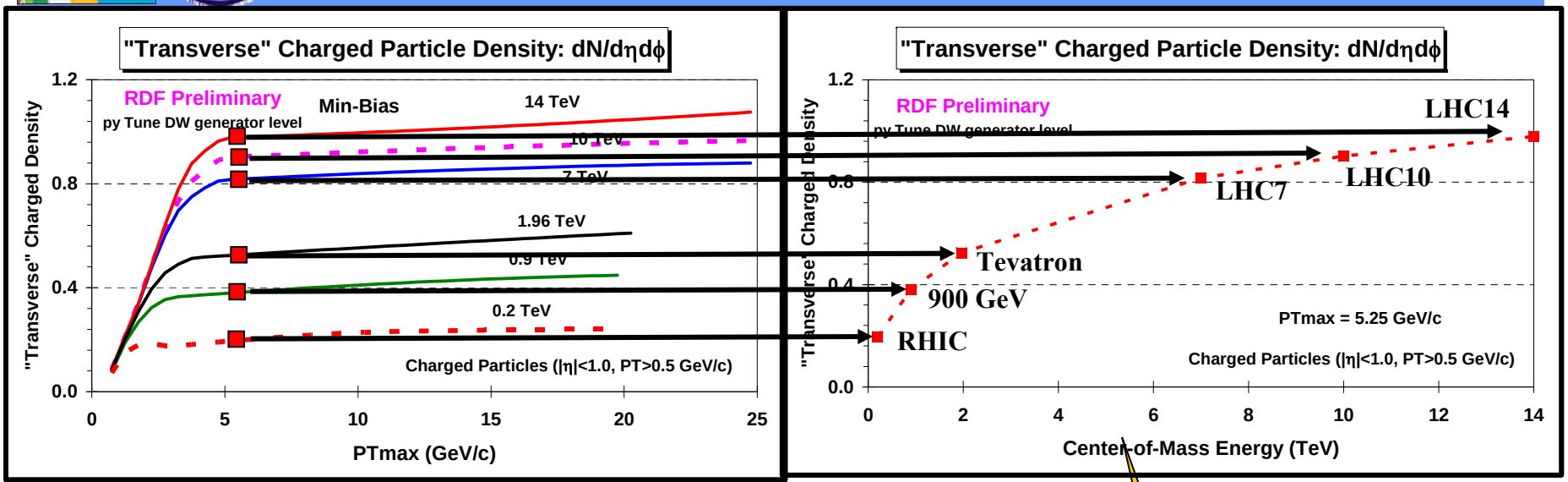
LHC

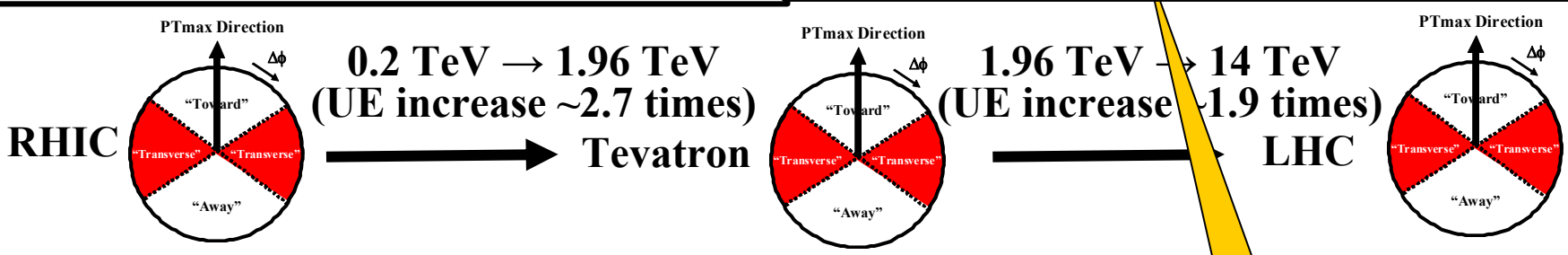


Linear scale!

➡ **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 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tune DW at the particle level (*i.e.* generator level).**

"Transverse" Charge Density





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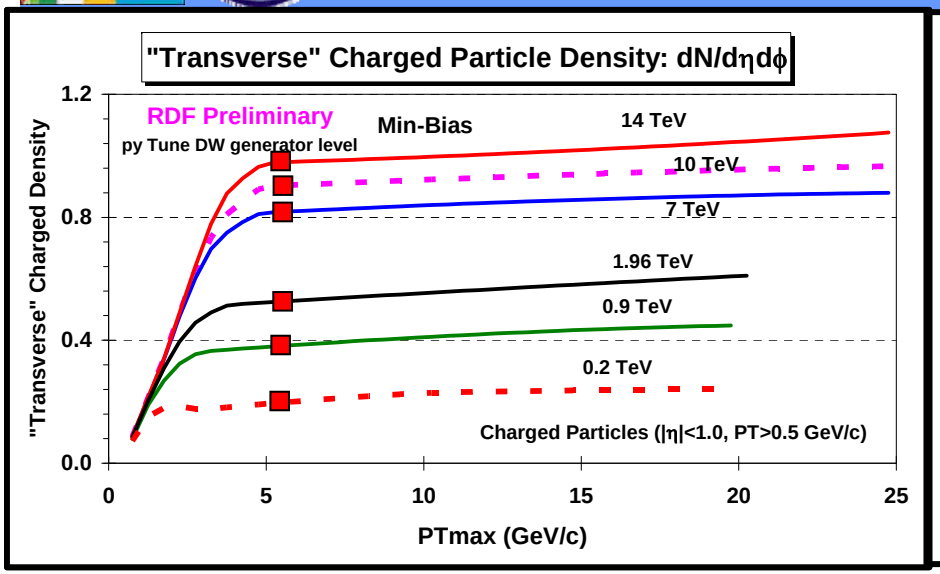
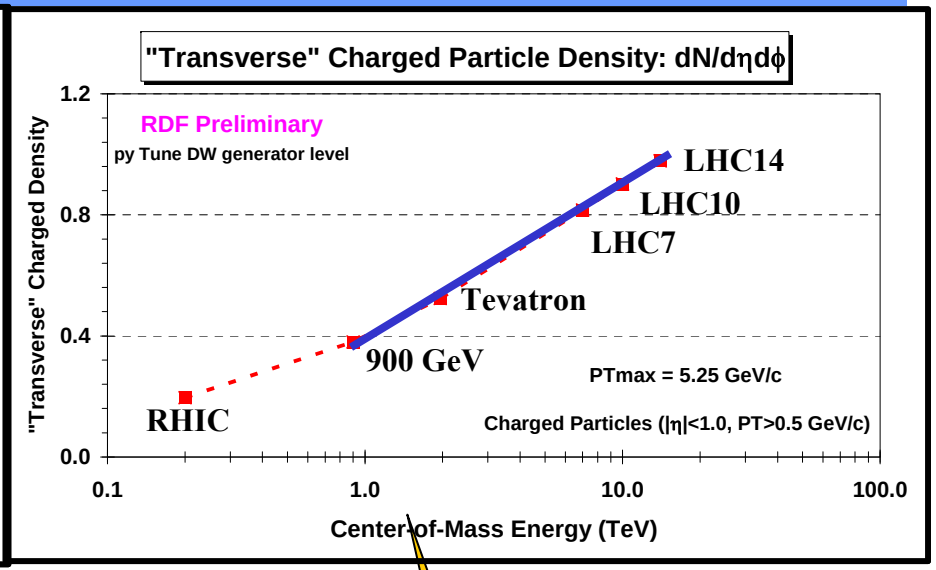
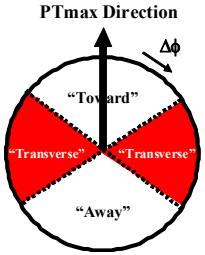
"Transverse" Charge Density





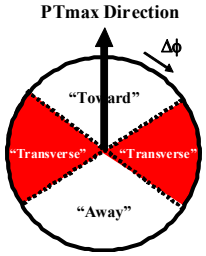
LHC7



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

Rick's UE Talks 2009(2)

- *Underlying Event Update*, **talk presented at the CMS Low PT QCD Meeting, June 5, 2009.**
- *Toward an Understanding of Hadron-Hadron Collisions: From Feynman-Field to the LHC*, **talk presented at XXIèmes Rencontres de Blois: Windows on the Universe, Blois, France, June 23, 2009.**
- *The LHC Physics Environment: Extrapolations from the Tevatron to RHIC and the LHC*, **lecture presented at the CTEQ Summer School, Madison, WI, July 1, 2009.**
- *"Min-Bias" and the "Underlying Event": Extrapolations from the Tevatron to RHIC and the LHC*, **talk presented at the CMS-QCD Group meeting, CERN, August 4, 2009.**
- *Predicting "Min-Bias" and the "Underlying Event" at the LHC*, **talk presented at the LHC09 Theory Institute: SM & BSM Physics at the LHC, CERN, August 13, 2009.**
- *Predicting "Min-Bias" and the "Underlying Event" at the LHC*, **talk presented at the Joint Experimental Meeting on Early LHC Measurements, CERN, August 14, 2009.**
- *Toward an Understanding of Hadron-Hadron Collisions: From Feynman-Field to the LHC*, **seminar presented at Rutgers University, NJ, October 13, 2009.**

Rick's UE Talks 2009(3)

- ***Physics Opportunities with Early LHC Data***, **seminar presented at the University of Florida, Gainesville, FL, October 27 & 30, 2009.**
- ***Predicting "Min-Bias" and the "Underlying Event" at the LHC*: The Early Measurements, talk presented at the MB&UE@CMS Workshop, CERN, November 6, 2009.**
- ***Predicting "Min-Bias" and the "Underlying Event" at the LHC: Important 900 GeV Measurements*, talk presented at the CMS-QCD Group meeting, CERN, November 10, 2009.**
- ***Predicting "Min-Bias" and the "Underlying Event" at the LHC*, talk presented at Minute Particulars & Hidden Symmetries: Chris Quigg Symposium, Fermilab, December 15, 2009.**
- ***Predicting "Min-Bias" and the "Underlying Event" at the LHC*, talk presented at Argonne National Laboratory, December 16, 2009.**

18 UE talks in 2009

Rick's UE Talks 2009(3)

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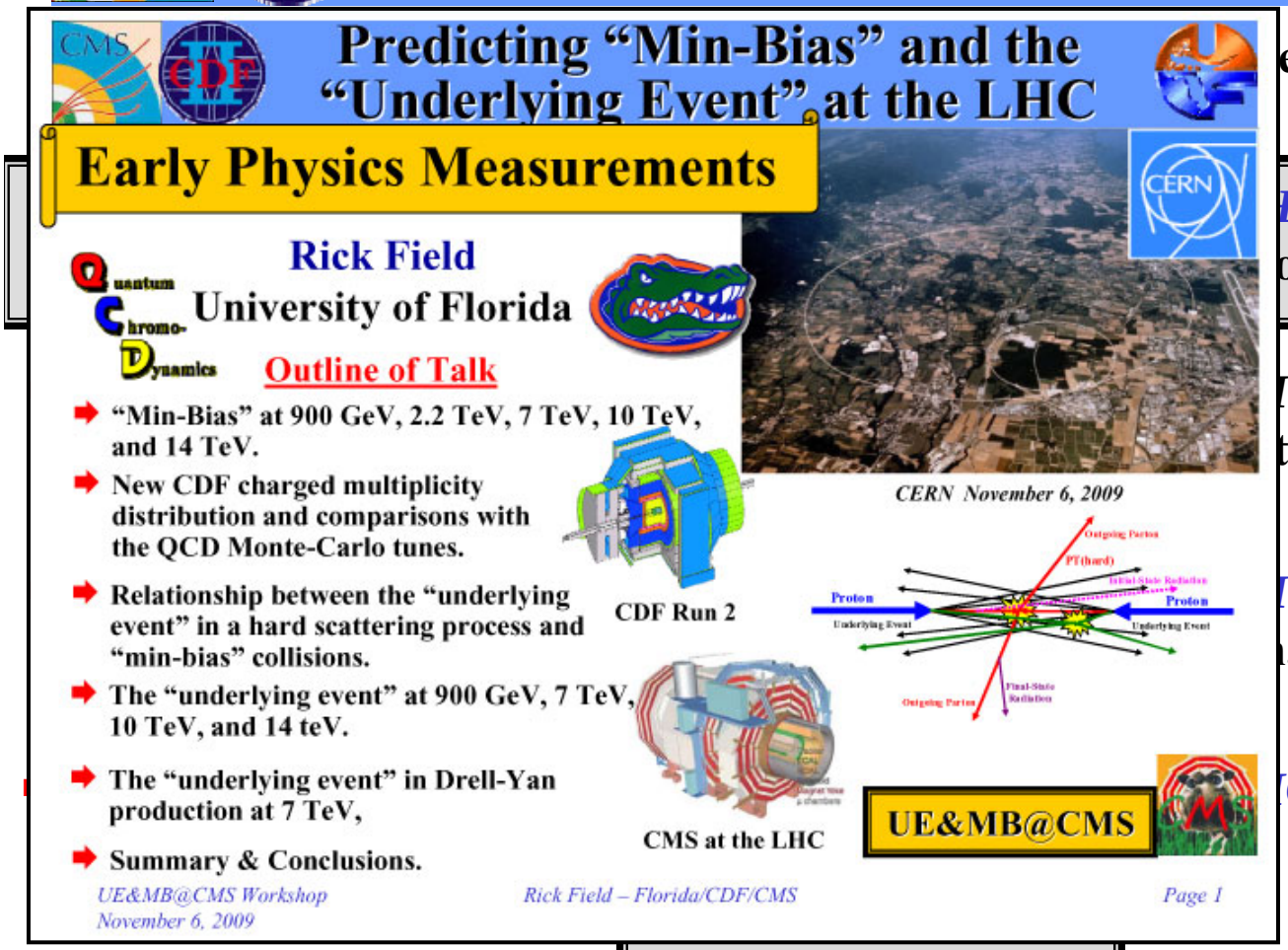
18 UE talks in 2009

Rick's UE Talks 2009(3)



ed at the University of

IC: The Early Measurements,
ovember 6, 2009.

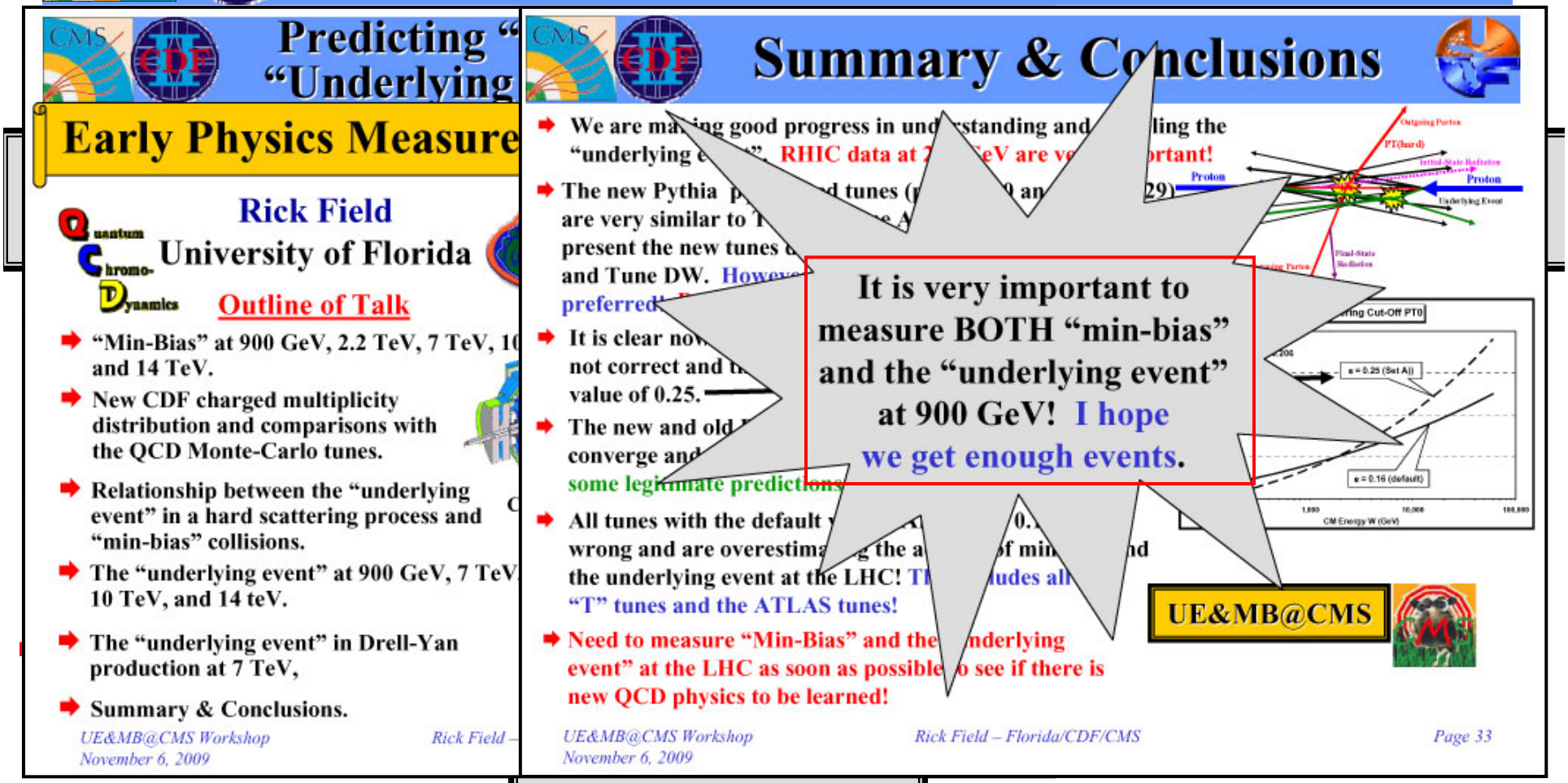
IC: *Important 900 GeV*
ting, CERN, November 10,

IC, talk presented at Minute
, Fermilab, December 15,

IC, talk presented at

18 UE talks in 2009

Rick's UE Talks 2009(3)



It is very important to measure BOTH "min-bias" and the "underlying event" at 900 GeV! I hope we get enough events.

18 UE talks in 2009

Rick's UE Talks 2009(3)

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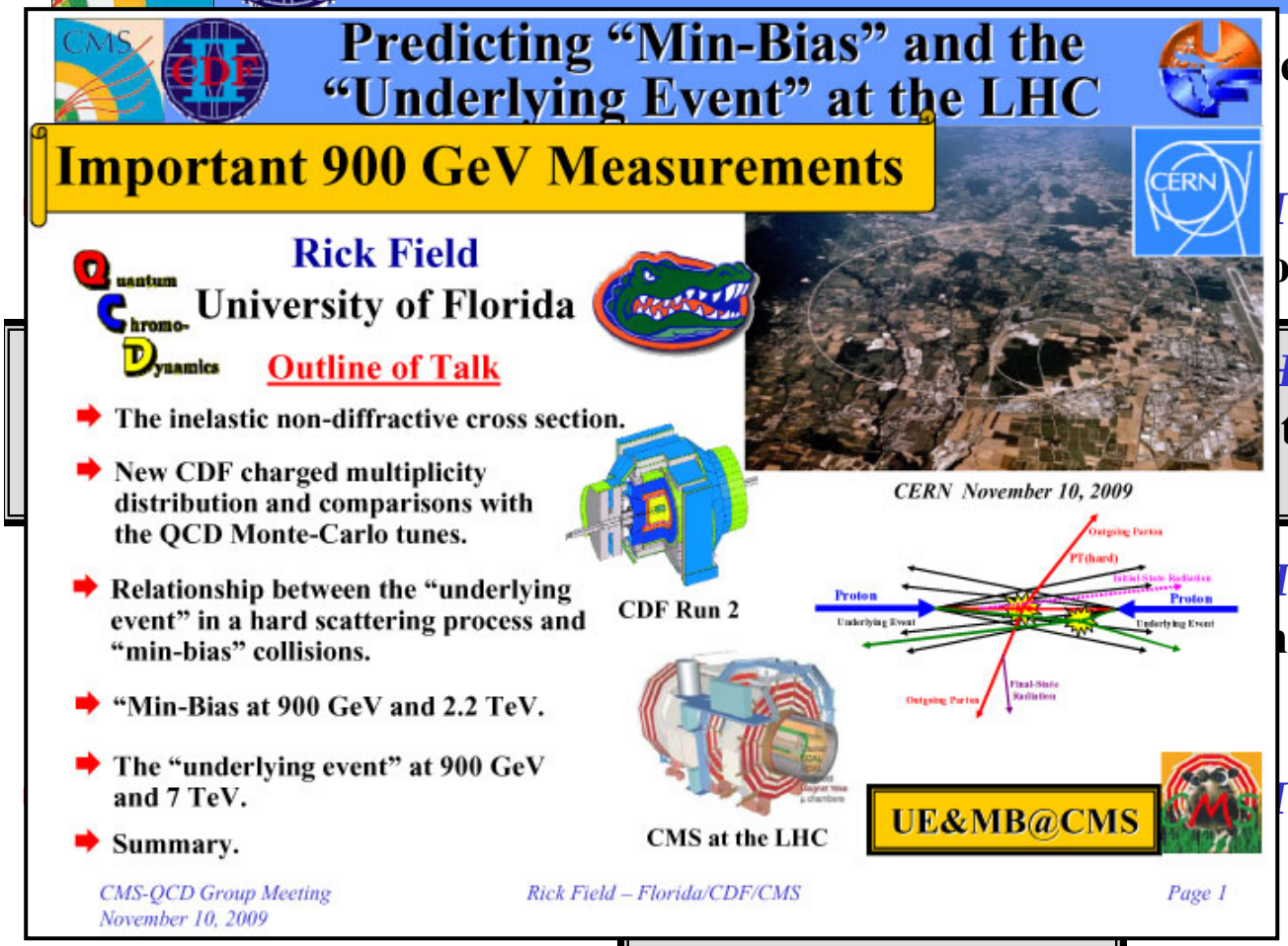
18 UE talks in 2009

Rick's UE Talks 2009(3)



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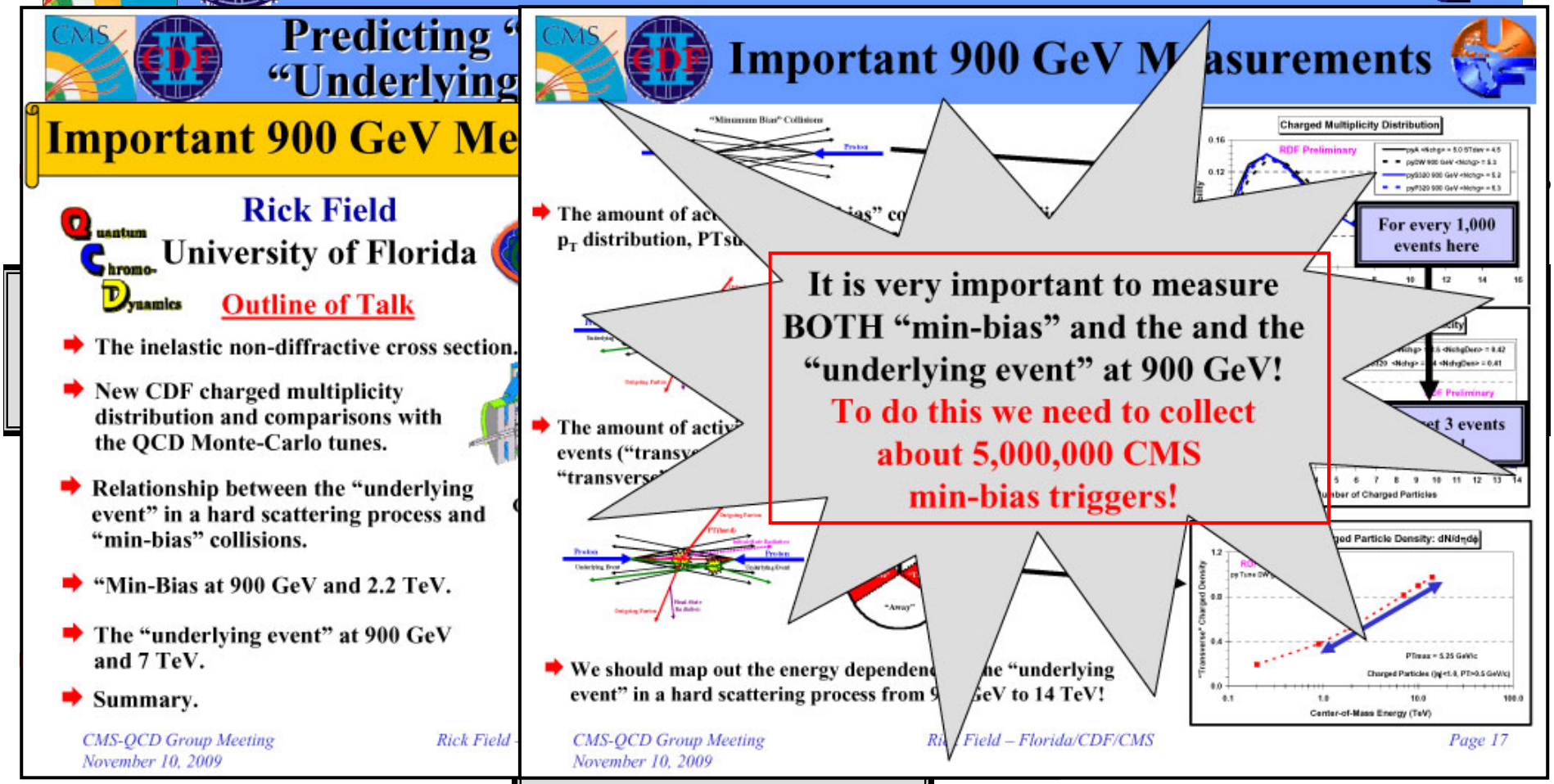
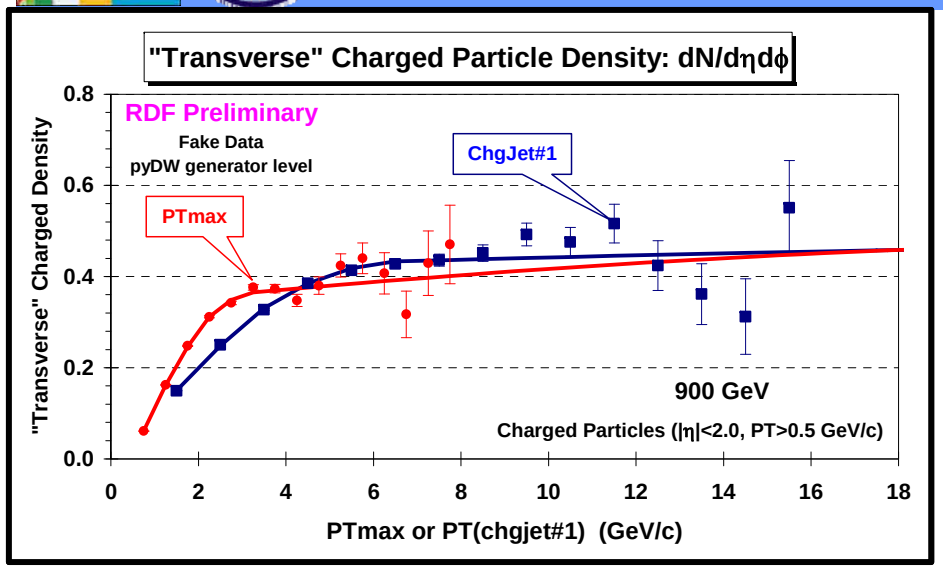
18 UE talks in 2009

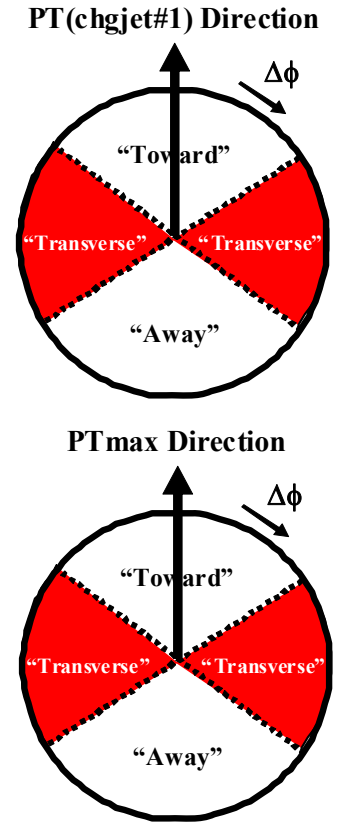
Rick's UE Talks 2009(3)



18 UE talks in 2009

"Transverse" Charged Particle Density

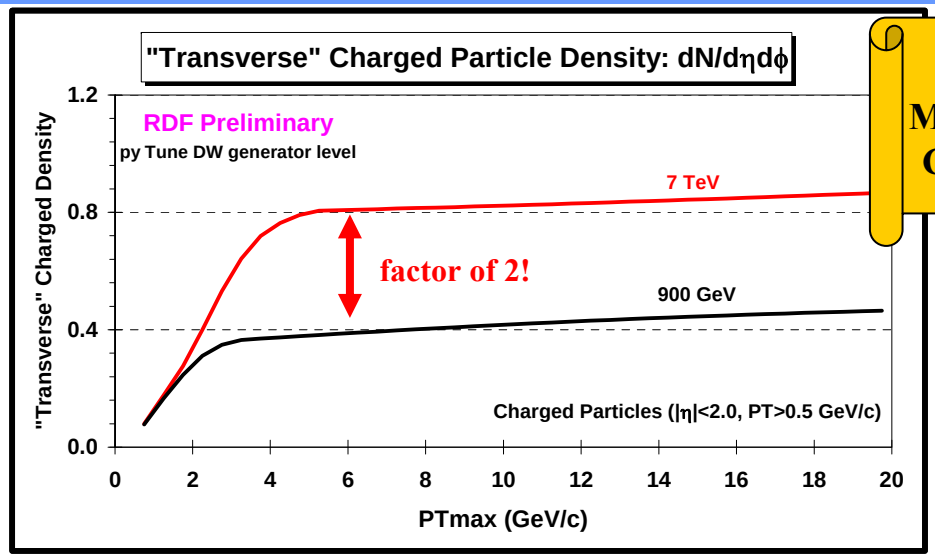




- **Fake data (from MC) at 900 GeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The fake data (from PYTHIA Tune DW) are generated at the particle level (*i.e.* generator level) assuming 0.5 M min-bias events at 900 GeV (361,595 events in the plot).**

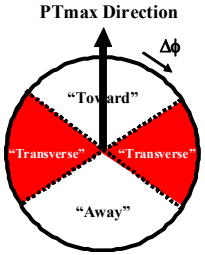
Rick Field
MB&UE@CMS Workshop
CERN, November 6, 2009

"Transverse" Charge Density



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

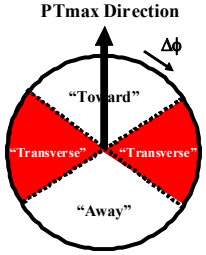
LHC 900 GeV



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).**

UE&MB@CMS

Initial Group Members

Rick Field (Florida)
Darin Acosta (Florida)
Paolo Bartalini (Florida)
Albert De Roeck (CERN)
Livio Fano' (INFN/Perugia at CERN)
Filippo Ambroglini (INFN/Perugia at CERN)
Khristian Kotov (UF Student, Acosta)

Perugia, Italy, March 2006

- **Measure Min-Bias and the "Underlying Event" at CMS**
  - **The plan involves two phases.**
  - **Phase 1 would be to measure min-bias and the "underlying event" as soon as possible (when the luminosity is low), perhaps during commissioning. We would then tune the QCD Monte-Carlo models for all the other CMS analyses. Phase 1 would be a service to the rest of the collaboration. As the measurements become more reliable we would re-tune the QCD Monte-Carlo models if necessary and begin Phase 2.**
  - **Phase 2 is "physics" and would include comparing the min-bias and "underlying event" measurements at the LHC with the measurements we have done (and are doing now) at CDF and then writing a physics publication.**

UE&MB@CMS

Florida-Perugia-CERN

University of Perugia

UE&MB@CMS

Available on CMS information server

CMS NOTE 2006-067

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

June 6th 2006

The Underlying Event at the LHC

D. Acosta[a], F. Ambroglini[b], P. Bartalini[a], A. De Roeck[c], L. Fanò[b], R. Field[a], K. Kotov[a]

a: University of Florida, FL, USA

b: Perugia University and INFN, Perugia, Italy

c: CERN, Geneva, Switzerland

Abstract

We discuss a study of "minimum bias" collisions and the "underlying event" at CMS (under nominal conditions) by measuring charged particles and muons. The underlying event is studied by examining charged particles in the "transverse" region in charged particle jet production and in the "central" region of Drell-Yan muon-pair production (after removing the muon-pair).

Perugia, Italy, March 2006

UE&MB@CMS

Florida-Perugia-CERN

University of Perugia

UE&MB@CMS

Available on CMS information server

CMS NOTE 2007/034

The Compact Muon Solenoid Experiment

Analysis Note

The content of this note is intended for CMS internal use and distribution only

12 November 2007

Measurement of the Underlying Event in Jet Topologies using Charged Particle and Momentum Densities

F. Ambroglini, L. Fanò

INFN and Università degli Studi di Perugia, Perugia, Italy

P. Bartalini

National Taiwan University, Taipei, Taiwan

R. Field

University of Florida, FL, USA

Abstract

We discuss a study of the "Underlying Event" at CMS (under nominal and start-up conditions) by measuring charged particles and momentum densities. The underlying event is studied by examining charged particles in the "transverse" region in charged particle jet production. The predictions of HERWIG (without multiple parton interactions) and several versions of PYTHIA (with different multiple parton interaction models) are compared and the possibility of discriminating between them is investigated. Exploring QCD dynamics in proton-proton collisions at 14 TeV and the importance of improving and tuning the QCD Monte Carlo models at the LHC start-up are discussed.

CMS AN-2006/040

The Underlying Event at the LHC

PTDR Volume 2 Section 3.3.2

D.Acosta, F.Ambroglini, P.Bartalini, A.De Roeck, L.Fanò, R. Field, K.Kotov

(members of the MBUE@CMS group)

Referees: Bolek Wyslouch and Sergey Slabospitsky

❖ ***Breaking news:***

- The MBUE@CMS LOGO!

ng

models

the

as and

then

UE&MB@CMS

Florida-Perugia-CERN

University of Perugia

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Available on CMS information server

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INFN

QCD contribution to the Joint QCD/HI 2007 paper

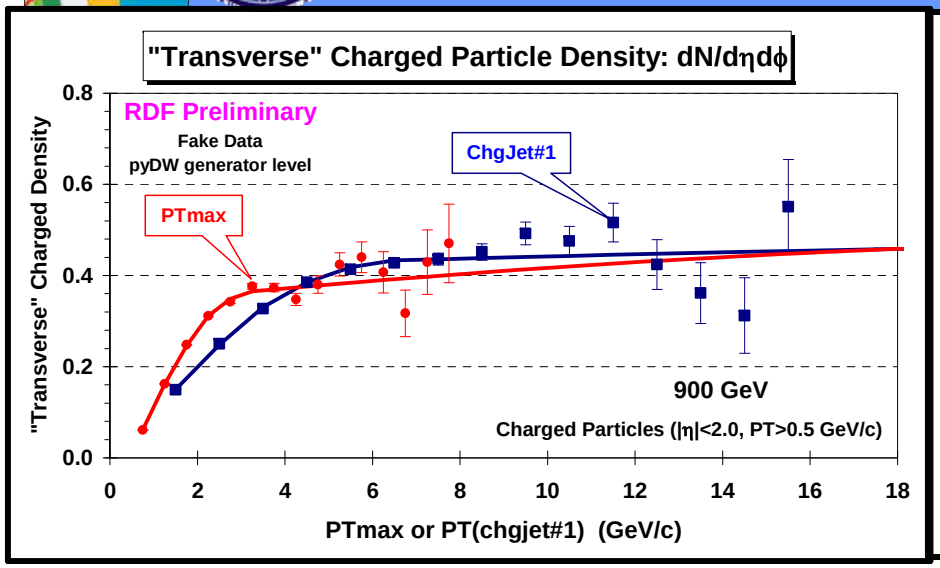
Pre-approval talk

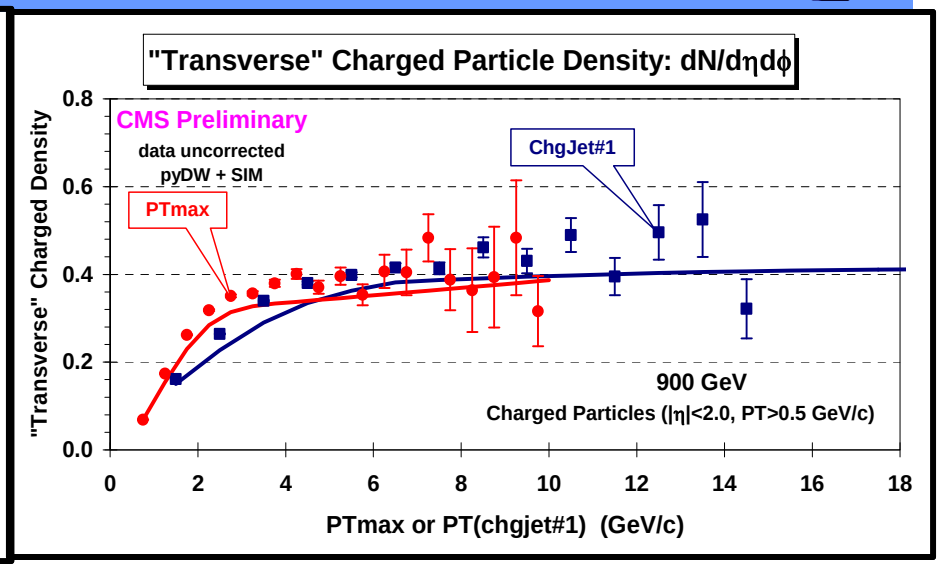
Authors:
F. Ambroglini, P. Bartalini
L. Fano', R. Field

Institutions:
INFN and Universita' di Perugia
National Taiwan University
University of Florida

Referees:
W. Adam
C. Lourenco
P. Marage

"Transverse" Charged Particle Density

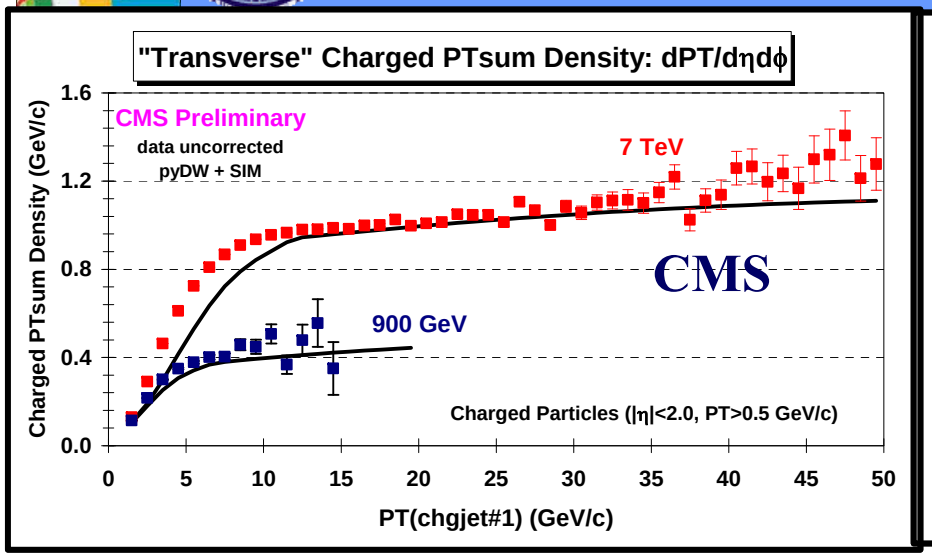


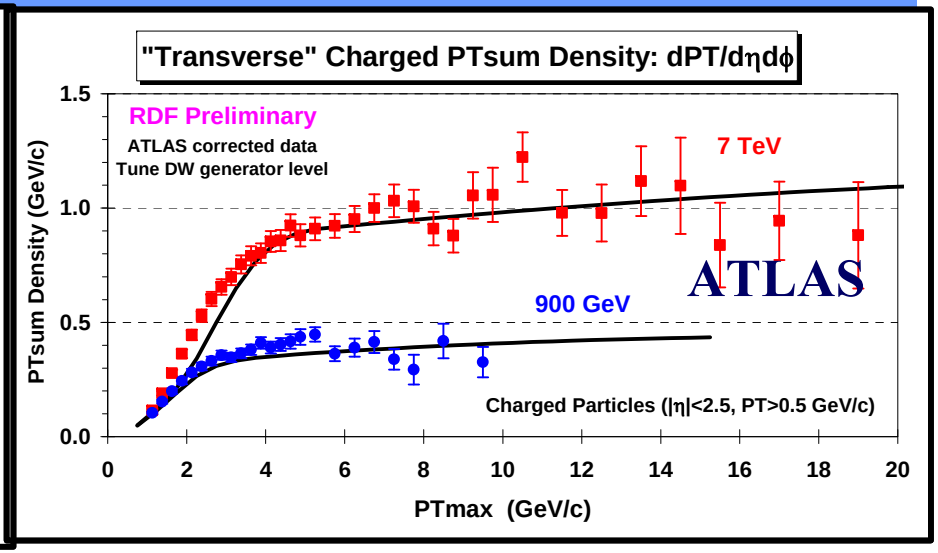


- **Fake data (from MC) at 900 GeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The fake data (from PYTHIA Tune DW) are generated at the particle level (*i.e.* generator level) assuming 0.5 M min-bias events at 900 GeV (361,595 events in the plot).**

- **CMS preliminary data at 900 GeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) and 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 (216,215 events in the plot).**

PYTHIA Tune DW

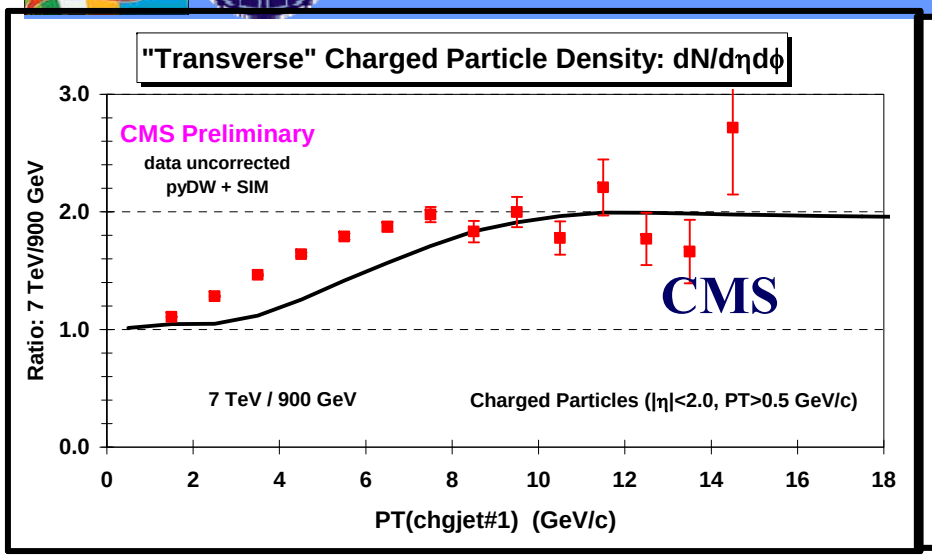


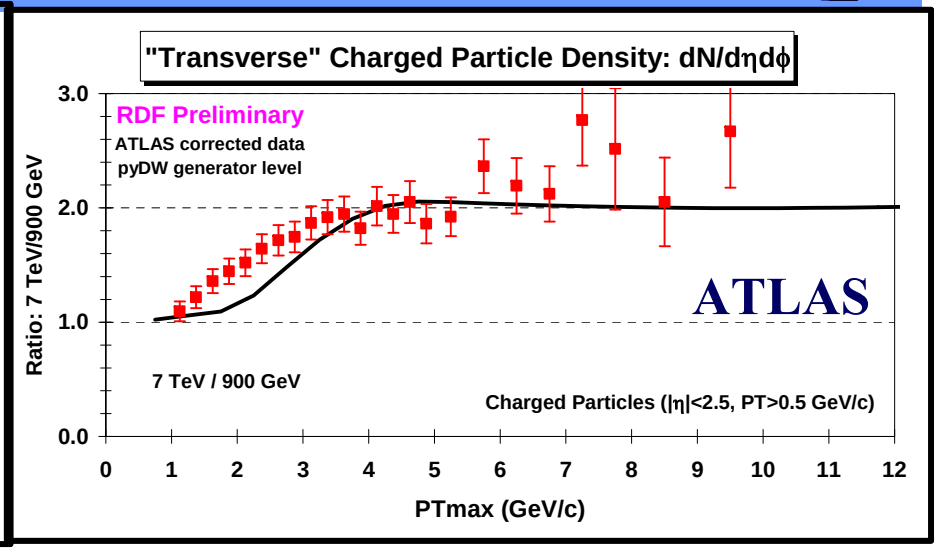


- **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged PTsum density, dPT/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.**

- **ATLAS preliminary data at 900 GeV and 7 TeV on the "transverse" charged PTsum density, dPT/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.**

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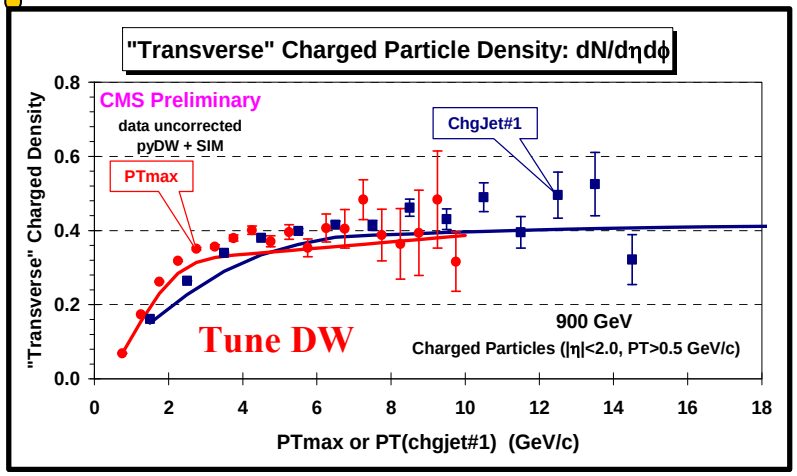
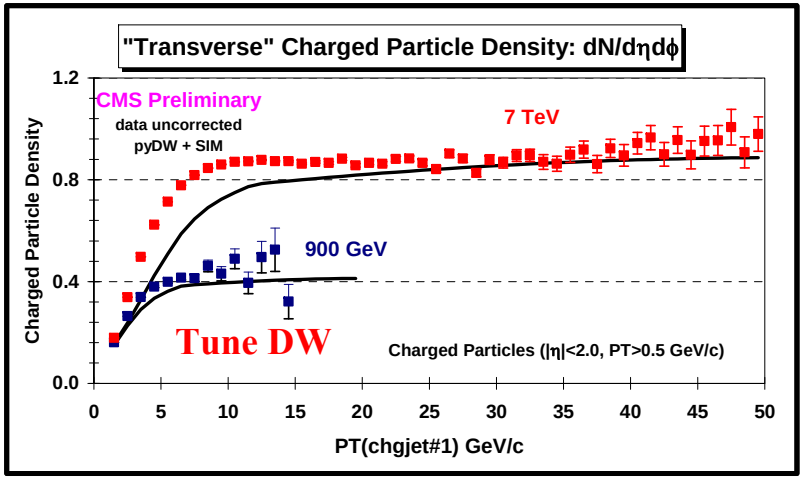
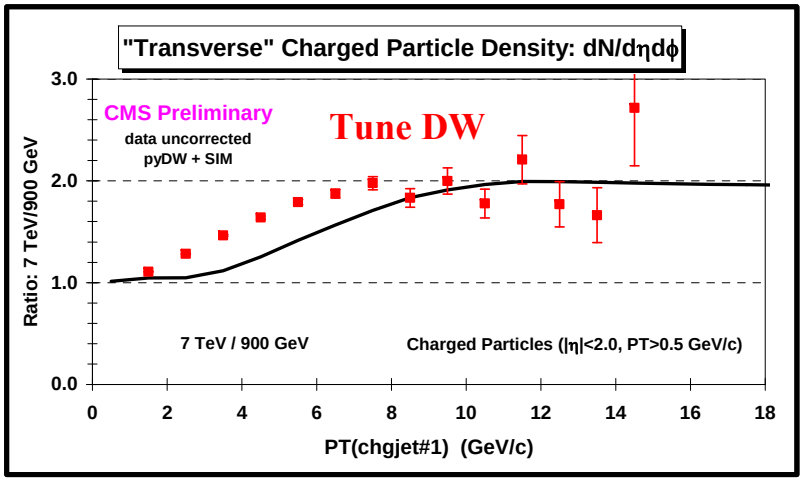
PYTHIA Tune DW

How well did we do at predicting the "underlying event" at 900 GeV and 7 TeV?



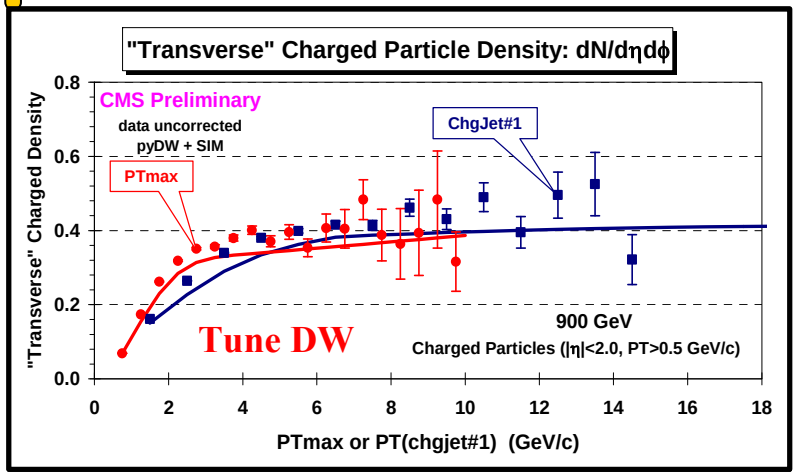


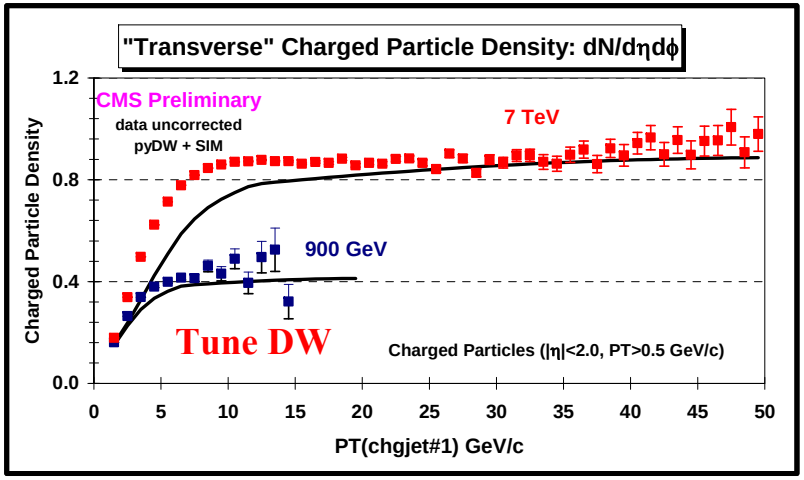
➡ **I am surprised that the Tunes did not do a better job of predicting the behavior of the "underlying event" at 900 GeV and 7 TeV!**



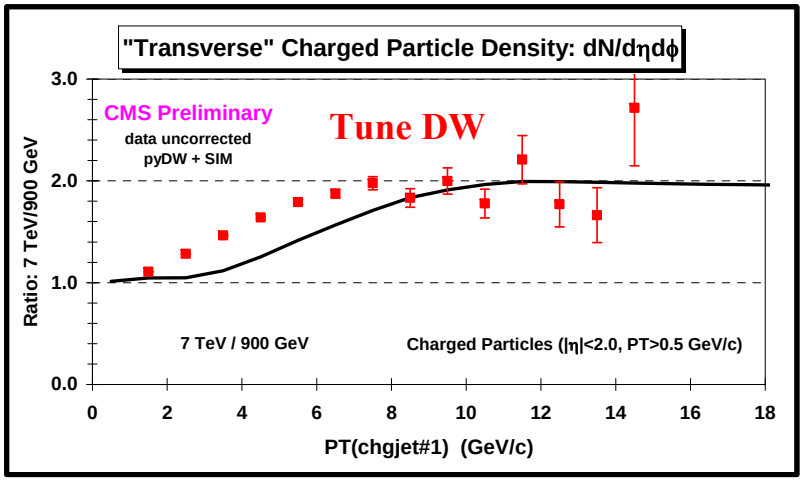
PYTHIA Tune DW

How well did we do at predicting the "underlying event" at 900 GeV and 7 TeV?



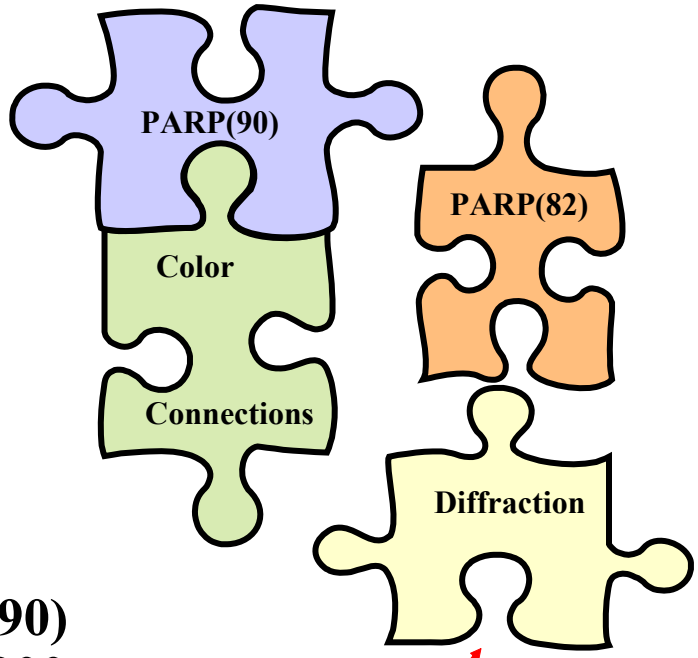


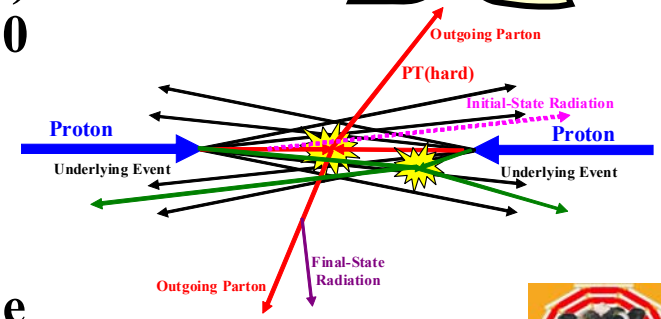
➡ **I am surprised that the Tunes did as well as they did at predicting the behavior of the "underlying event" at 900 GeV and 7 TeV!**



PYTHIA Tune Z1

- All my previous tunes (A, DW, DWT, D6, D6T, CW, X1, and X2) were PYTHIA 6.2 tunes using the old Q^2-ordered parton showers and the old MPI model!
- I believed that it was 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 was primarily a min-bias tune, while Tune Z1 was a UE tune!





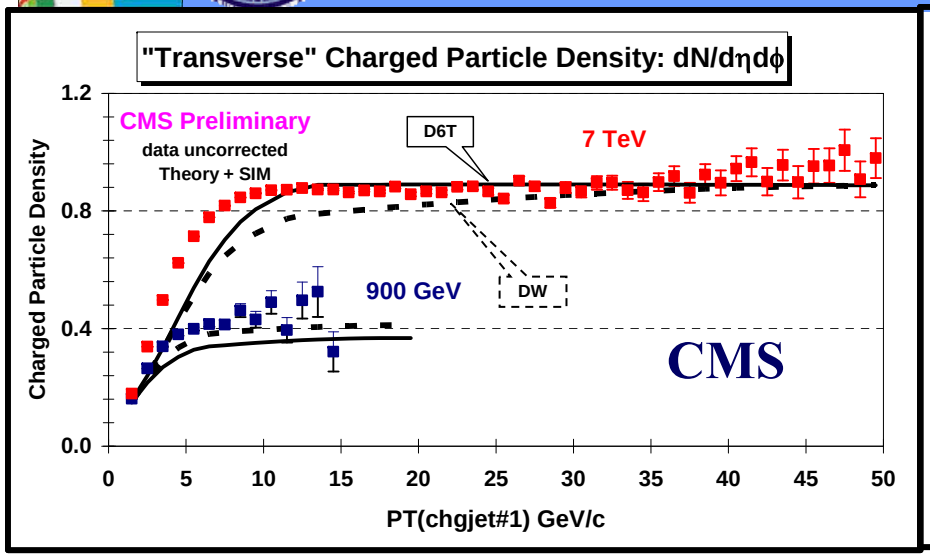
UE&MB@CMS

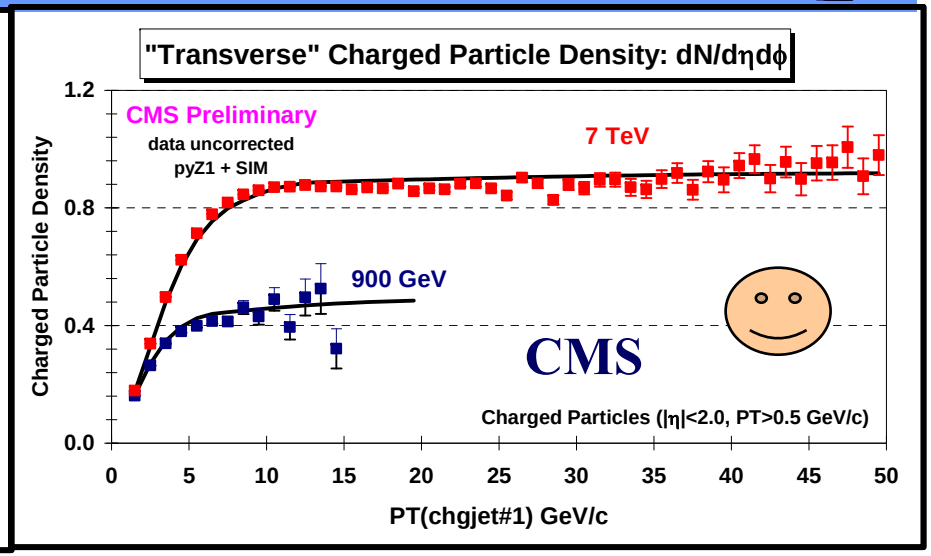
PYTHIA Tune Z1

Parameters not shown are the PYTHIA 6.4 defaults!

Parameter	Tune Z1 (R. Field CMS)	Tune AMBT1 (ATLAS)
Parton Distribution Function	CTEQ5L	LO*
PARP(82) – MPI Cut-off	1.932	2.292
PARP(89) – Reference energy, E0	1800.0	1800.0
PARP(90) – MPI Energy Extrapolation	0.275	0.25
PARP(77) – CR Suppression	1.016	1.016
PARP(78) – CR Strength	0.538	0.538
PARP(80) – Probability colored parton from BBR	0.1	0.1
PARP(83) – Matter fraction in core	0.356	0.356
PARP(84) – Core of matter overlap	0.651	0.651
PARP(62) – ISR Cut-off	1.025	1.025
PARP(93) – primordial kT-max	10.0	10.0
MSTP(81) – MPI, ISR, FSR, BBR model	21	21
MSTP(82) – Double gaussion matter distribution	4	4
MSTP(91) – Gaussian primordial kT	1	1
MSTP(95) – strategy for color reconnection	6	6

PYTHIA Tune Z1





- **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 Tune Z2

My guess!

Parameter	Tune Z1 (R. Field CMS)	Tune Z2 (R. Field CMS)
Parton Distribution Function	CTEQ5L	CTEQ6L
PARP(82) – MPI Cut-off	1.932	1.832
PARP(89) – Reference energy, E0	1800.0	1800.0
PARP(90) – MPI Energy Extrapolation	0.275	0.275
PARP(77) – CR Suppression	1.016	1.016
PARP(78) – CR Strength	0.538	0.538
PARP(80) – Probability colored parton from BBR	0.1	0.1
PARP(83) – Matter fraction in core	0.356	0.356
PARP(84) – Core of matter overlap	0.651	0.651
PARP(62) – ISR Cut-off	1.025	1.025
PARP(93) – primordial kT-max	10.0	10.0
MSTP(81) – MPI, ISR, FSR, BBR model	21	21
MSTP(82) – Double gaussion matter distribution	4	4
MSTP(91) – Gaussian primordial kT	1	1
MSTP(95) – strategy for color reconnection	6	6

Reduce PARP(82) by factor of 1.83/1.93 = 0.95
Everything else the same!

PYTHIA Tune Z2

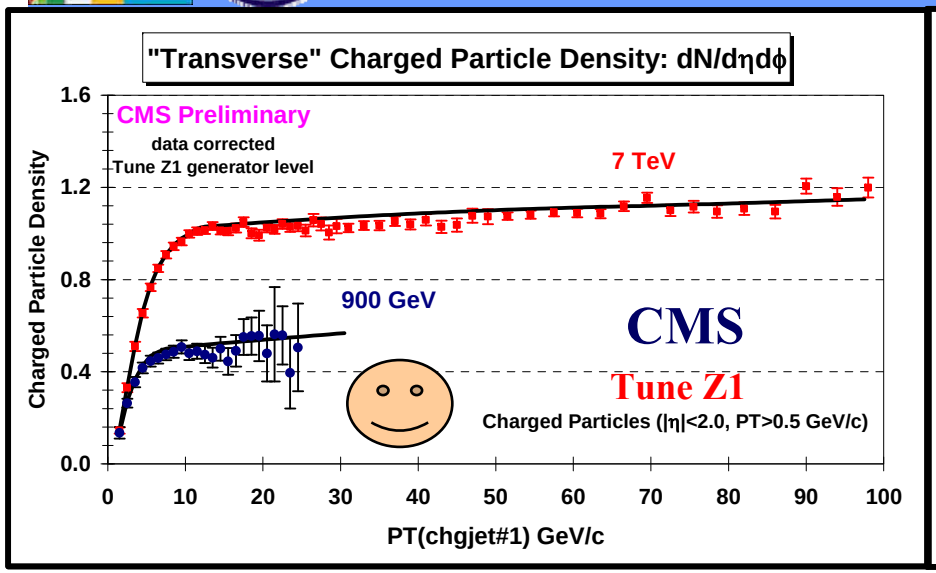
My guess!

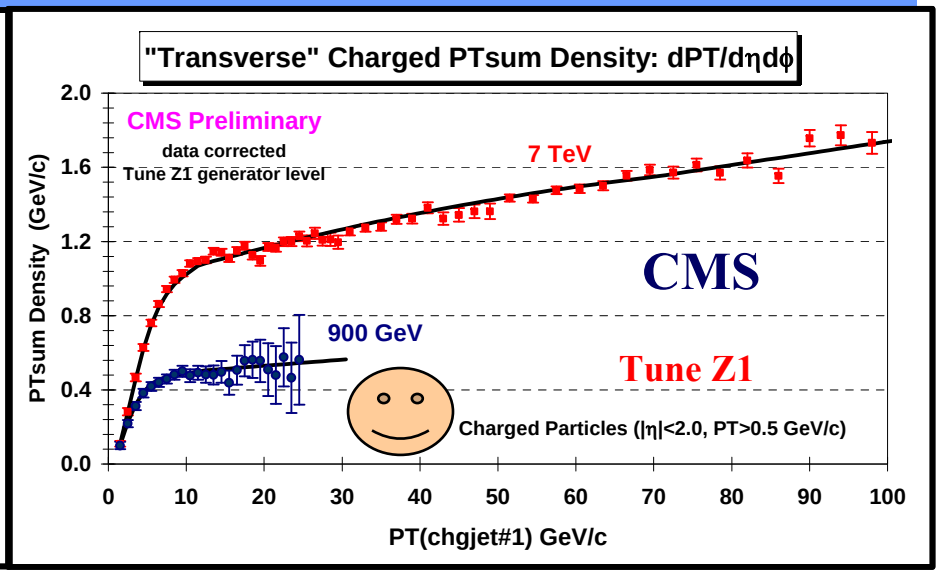
Parameter	Tune Z1 (R. Field CMS)	Tune Z2 (R. Field CMS)
Parton Distribution Function	CTEQ5L	CTEQ6L
PARP(82) – MPI Cut-off	1.932	1.832
PARP(89) – Reference energy, E0	1800.0	1800.0
PARP(90) – MPI Energy Extrapolation	0.275	0.275
PARP(77) – CR Suppression	1.016	1.016
PARP(78) – CR Strength	0.538	0.538
PARP(80) – Probability colored parton from BBR	0.1	0.1
PARP(83) – Matter fraction in core	0.356	0.356
PARP(84) – Core of matter overlap	0.651	0.651
PARP(62) – ISR Cut-off	1.025	1.025
PARP(93) – primordial kT-max	10.0	10.0
MSTP(81) – MPI, ISR, FSR, BBR model	21	21
MSTP(82) – Double gaussion matter distribution	4	4
MSTP(91) – Gaussian primordial kT	1	1
MSTP(95) – strategy for color reconnection	6	6

Reduce PARP(82) by factor of 1.83/1.93 = 0.95
Everything else the same!

PARP(90) same For Z1 and Z2!

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 corrected and compared with PYTHIA Tune Z1 at the generator level.**

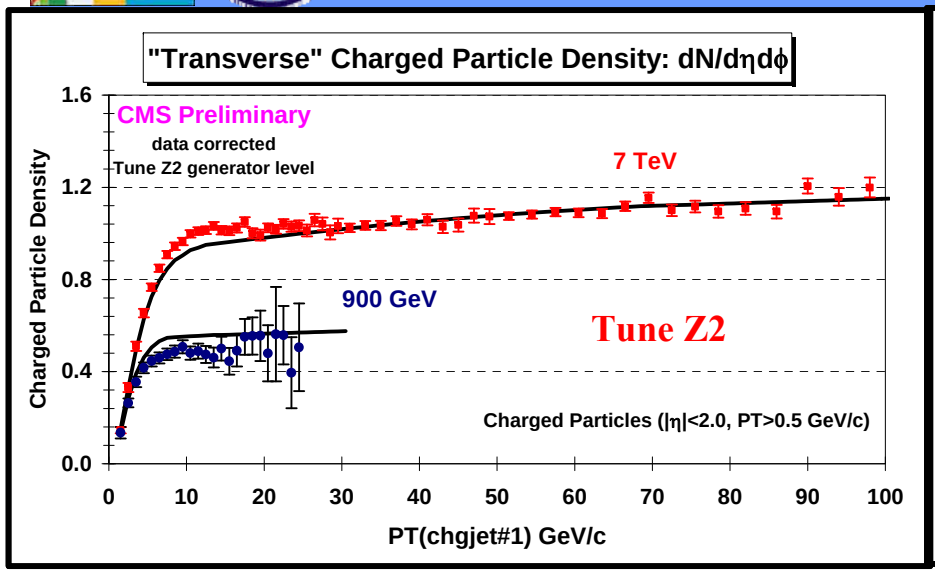
- **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged PTsum density, dPT/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$. The data are corrected and compared with PYTHIA Tune Z1 at the generator level.**

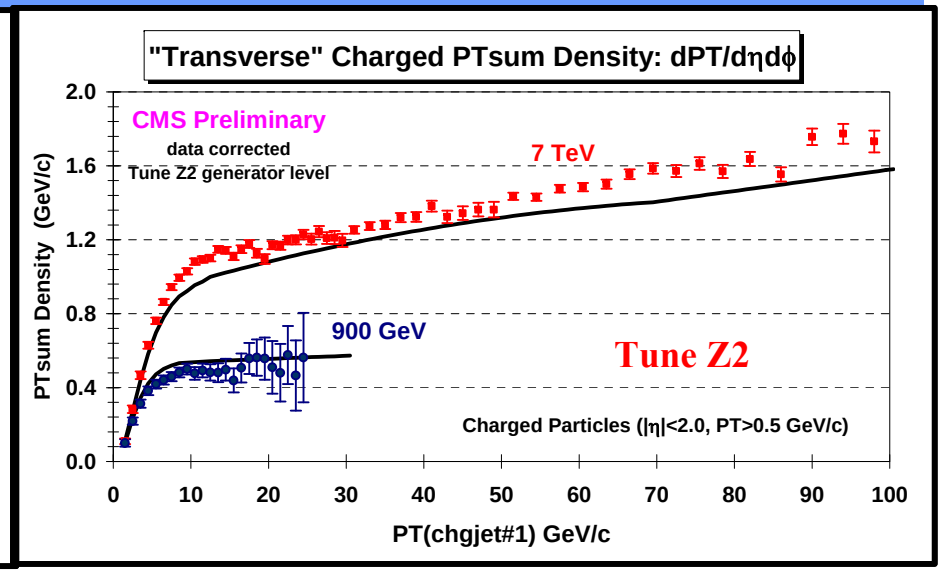
CMS corrected data!

Very nice agreement!

CMS corrected data!

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 Z2 at the generator level.**

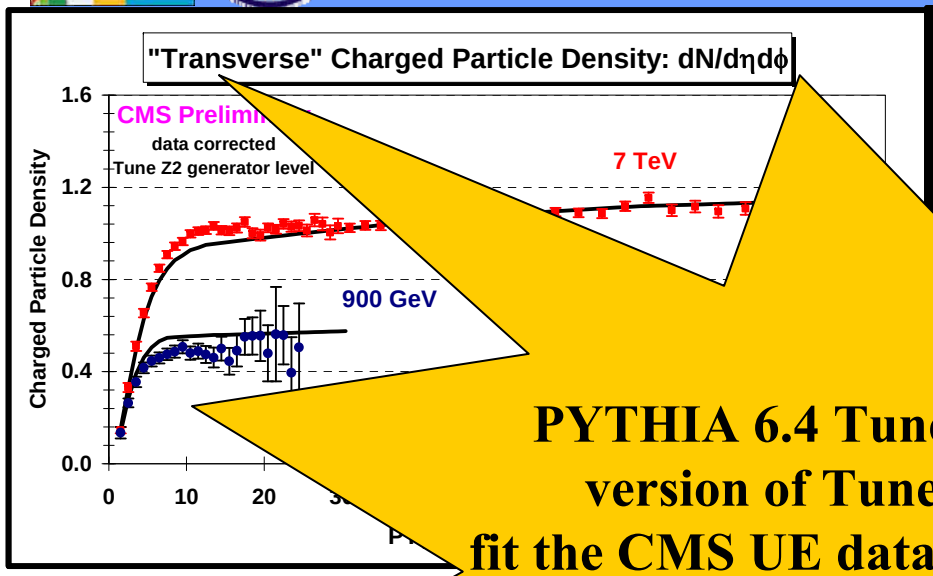
- **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged PTsum density, dPT/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$. The data are corrected and compared with PYTHIA Tune Z2 at the generator level.**

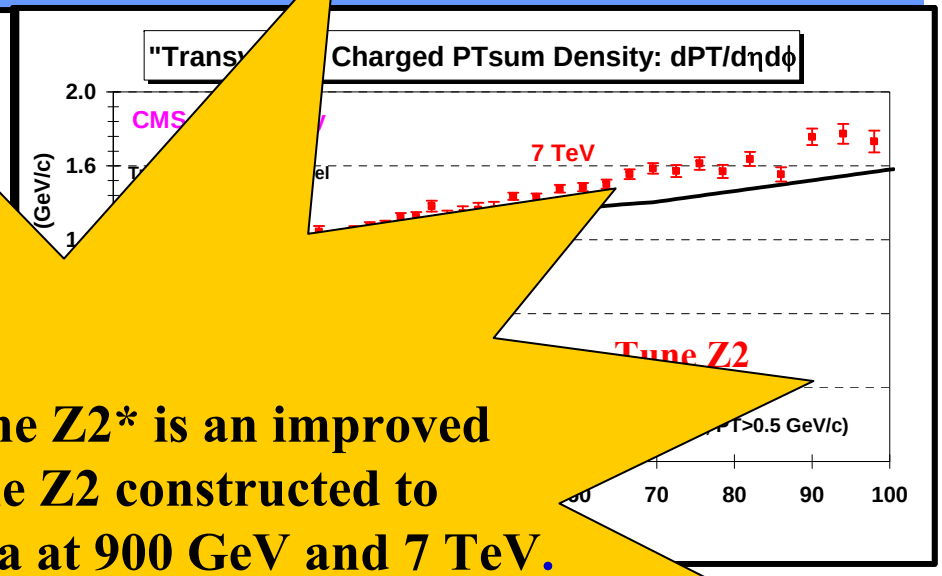
CMS corrected data!

Not good! Bad energy dependence!

CMS corrected data!

PYTHIA 6.4 Tune Z2





PYTHIA 6.4 Tune Z2* is an improved version of Tune Z2 constructed to fit the CMS UE data at 900 GeV and 7 TeV.

- **CMS preliminary** ... **nd 7 TeV** on the "t... ... ” charged PTsum density, d... ...ϕ, as defined ... fined by the leading charged particle jet (chgjet# ... rtic... et#1) for charged particles with $p_T > 0.5$ GeV ... η| < ... ith $p_T >$ ... V/c and $|\eta| < 2.0$. The data are corrected an ... ompared ... Th ... re corrected ... compared with **PYTHIA Tune Z2** at the generator lev ... **PYT ... Tune Z2** at the ge ... erator level.

CMS corrected data!

Not good! B ... d energy dependence!

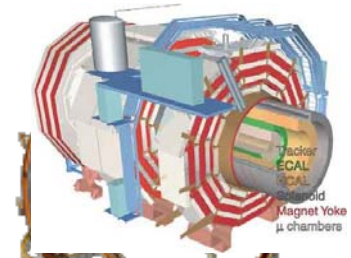
CMS corrected data!

MB&UE Working Group

LPCC LHC Physics Centre at CERN

MB & UE Common Plots

Quantum Chromo-Dynamics

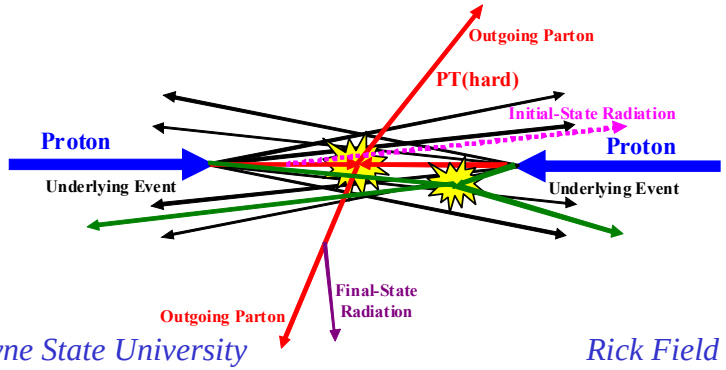


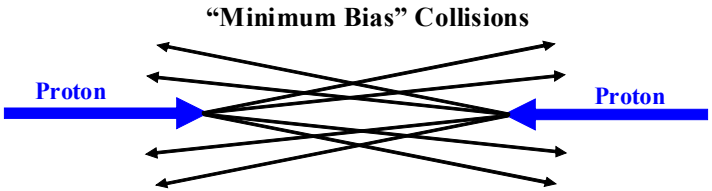
CMS

ATLAS

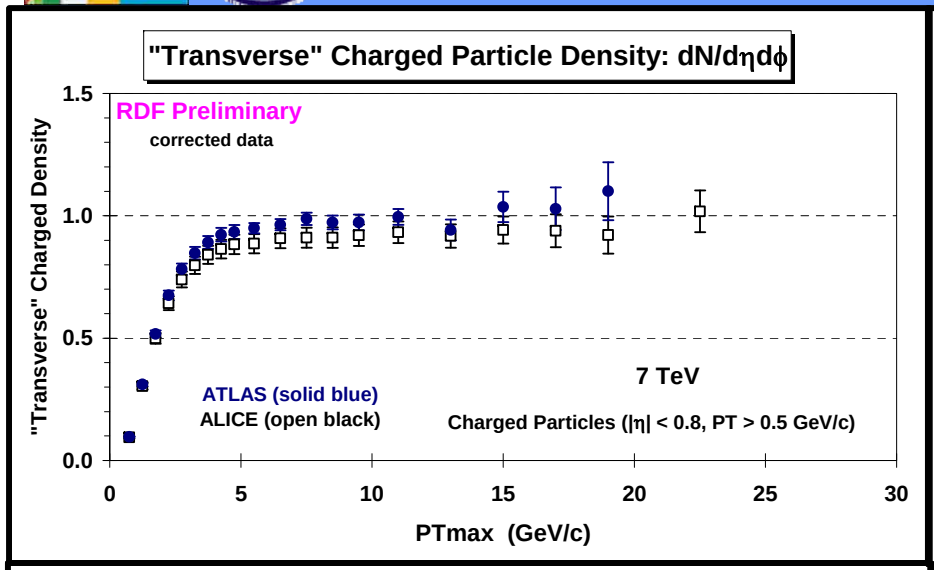
➡ **The LPCC MB&UE Working Group suggested several MB&UE "Common Plots" the all the LHC groups could produce and compare with each other.**

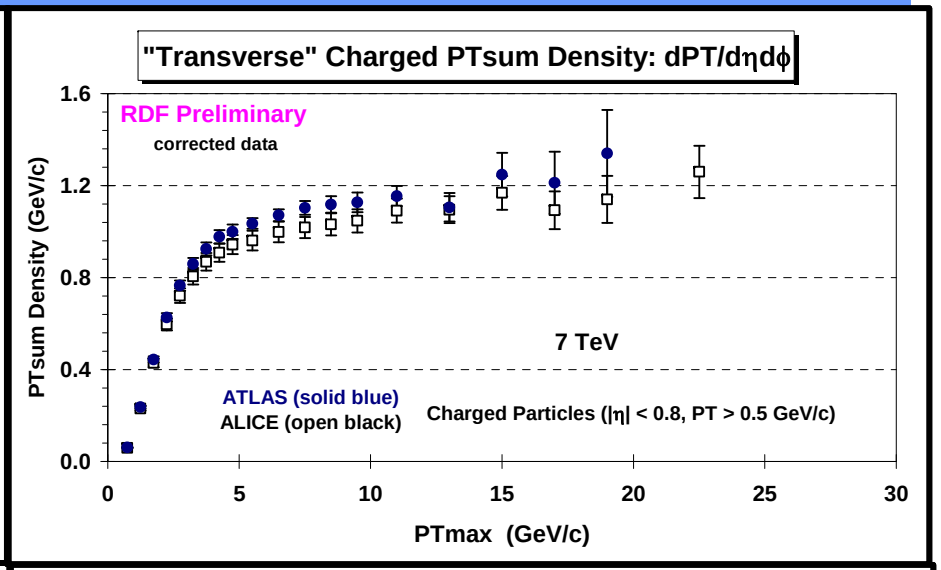
ALICE LHCb

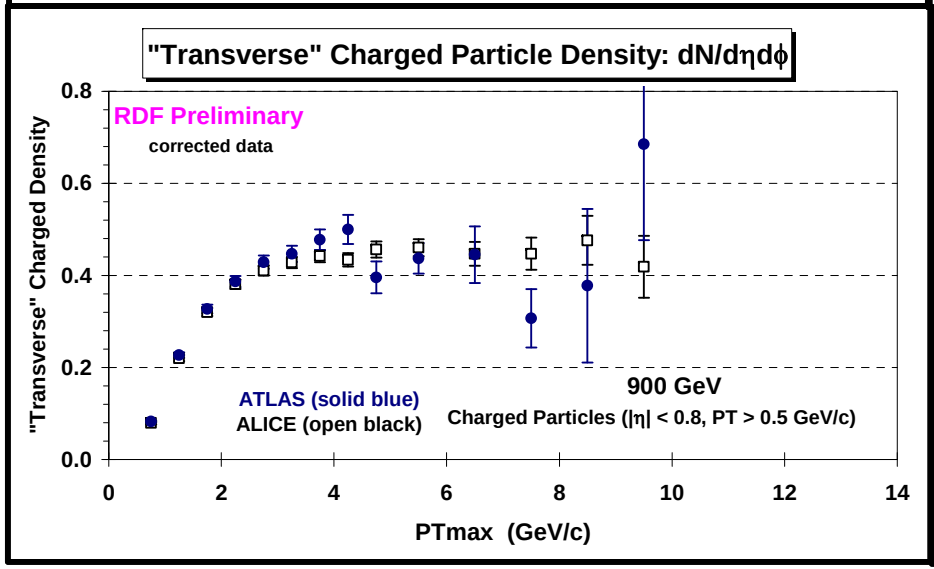


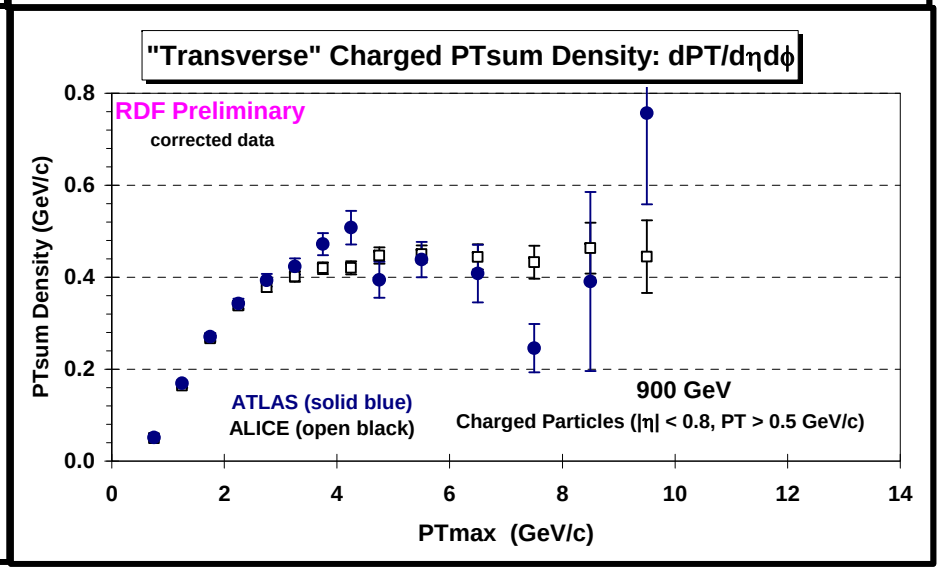


UE Common Plots

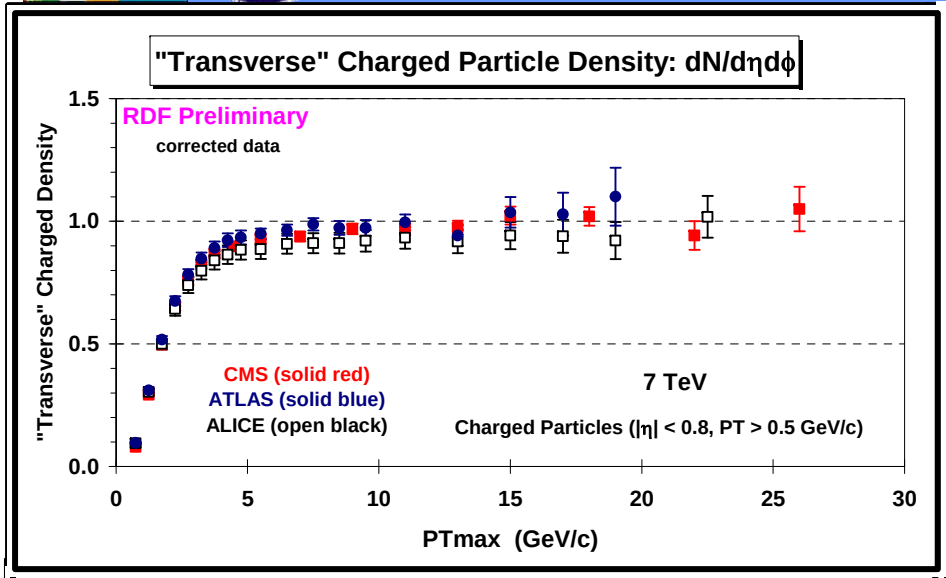


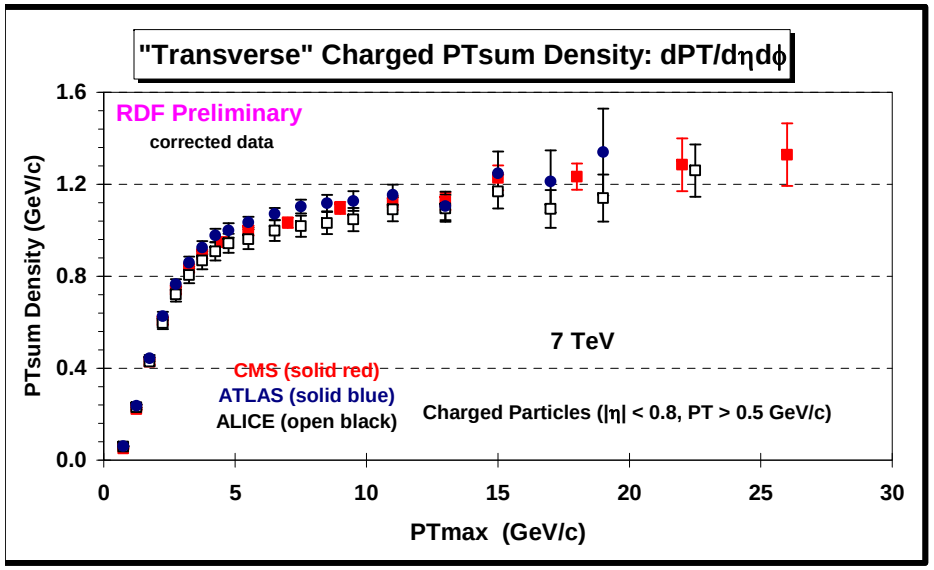


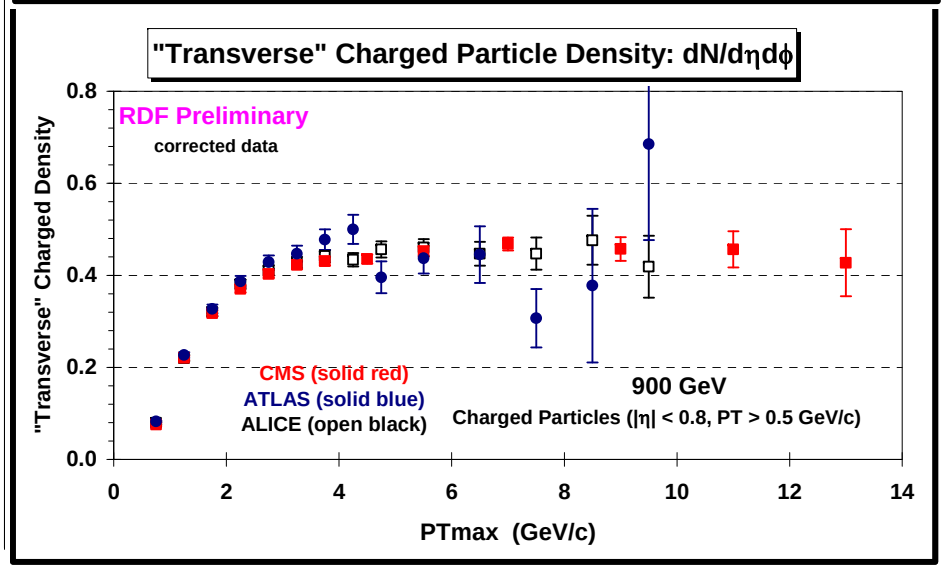


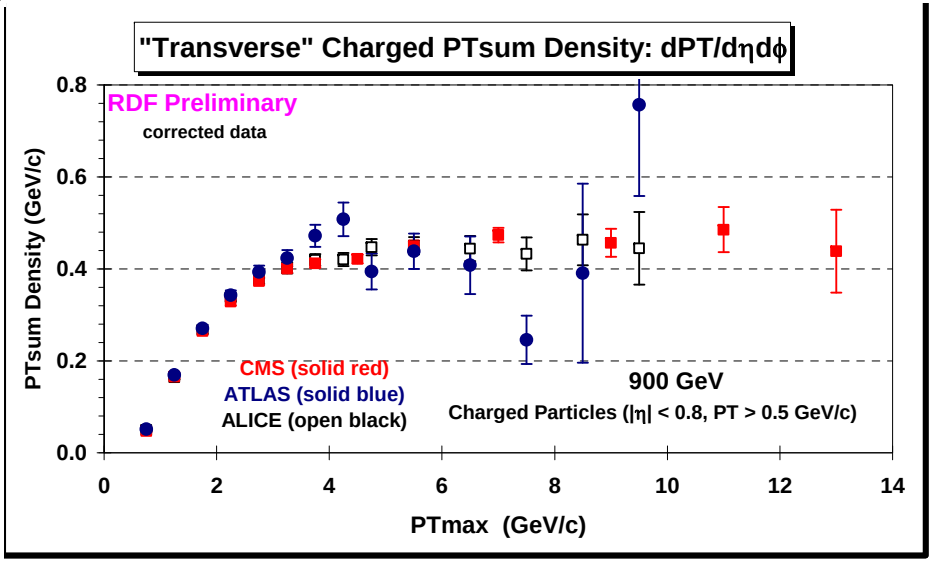


UE Common Plots

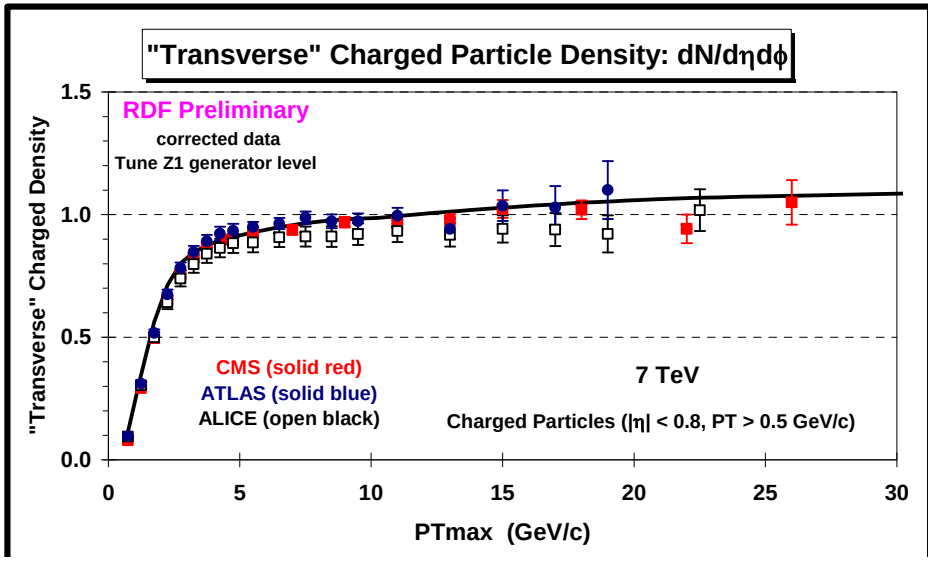


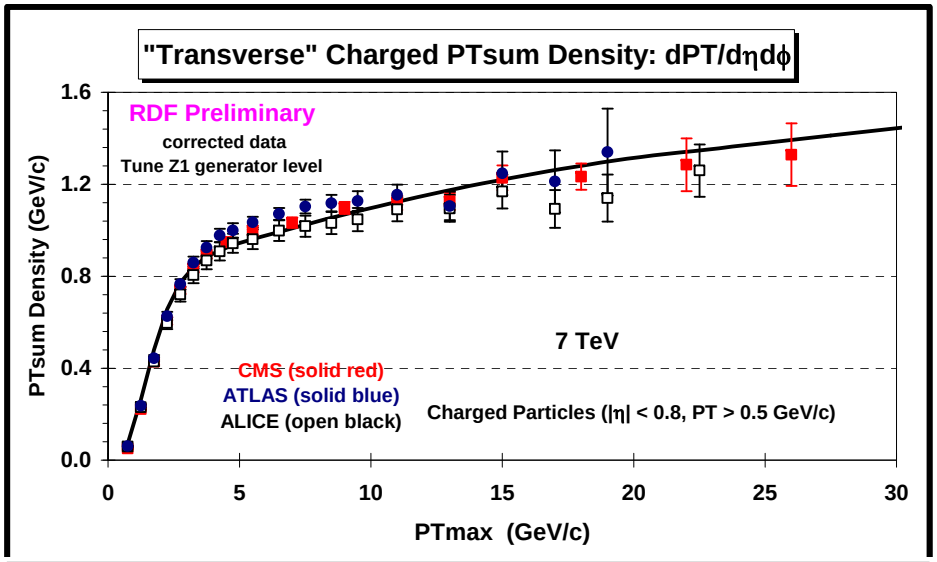


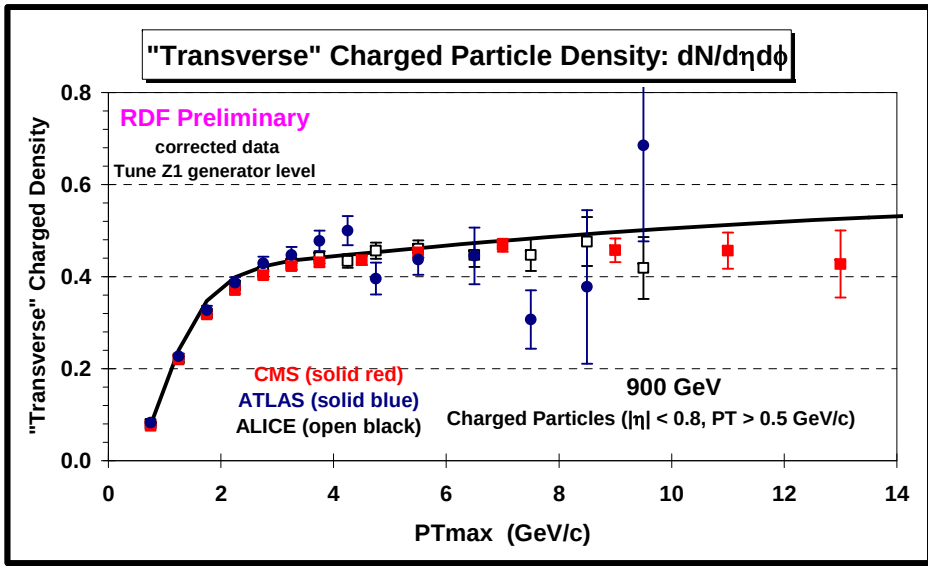


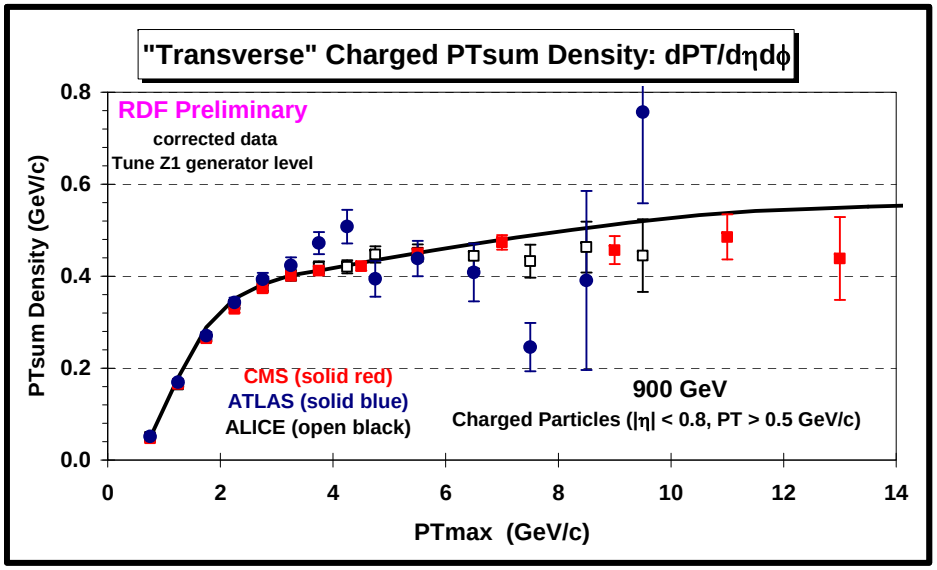


UE Common Plots

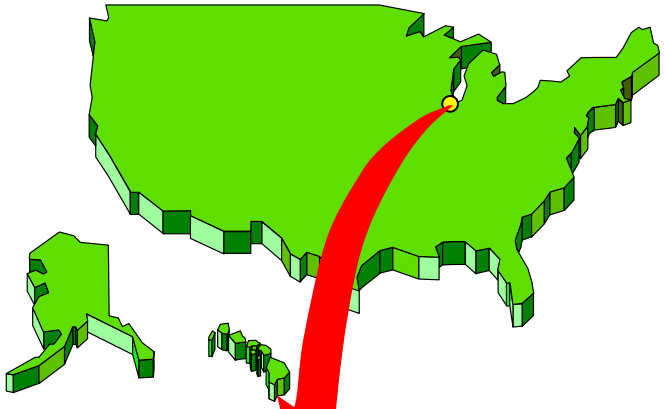


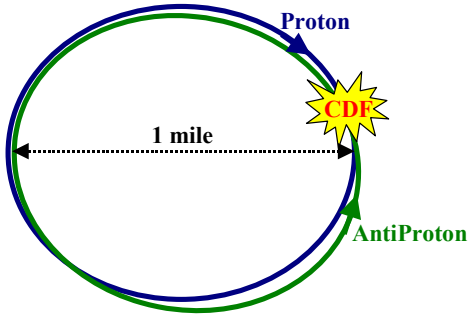


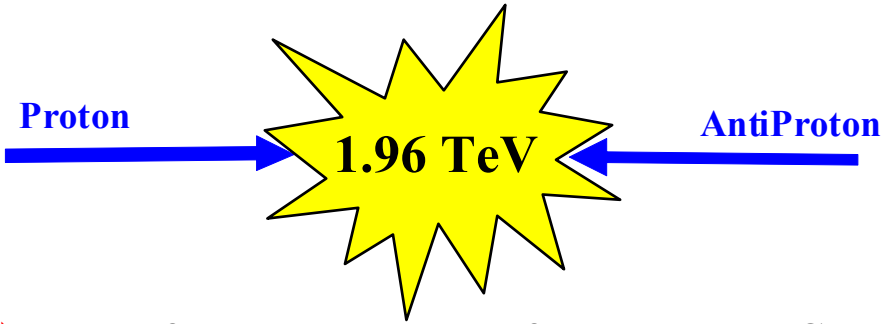




Tevatron Energy Scan





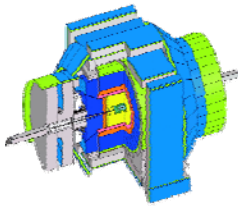


- **Just before the shutdown of the Tevatron CDF has collected more than 10M "min-bias" events at several center-of-mass energies!**

300 GeV 12.1M MB Events

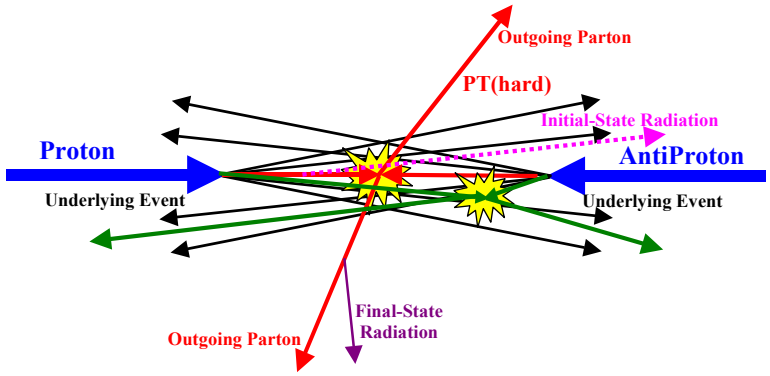
900 GeV 54.3M MB Events

Last CDF UE Publication



CDF Run 2
Tevatron Energy Scan
300 GeV, 900 GeV, 1.96 TeV

Sorry to be so slow!!



Draft PRD Version 6

Phys. Rev. D 92, 092009 – Published 23 November 2015

A Study of the Energy Dependence of the Underlying Event in Proton-Antiproton Collisions

The CDF Collaboration

August 2, 2015

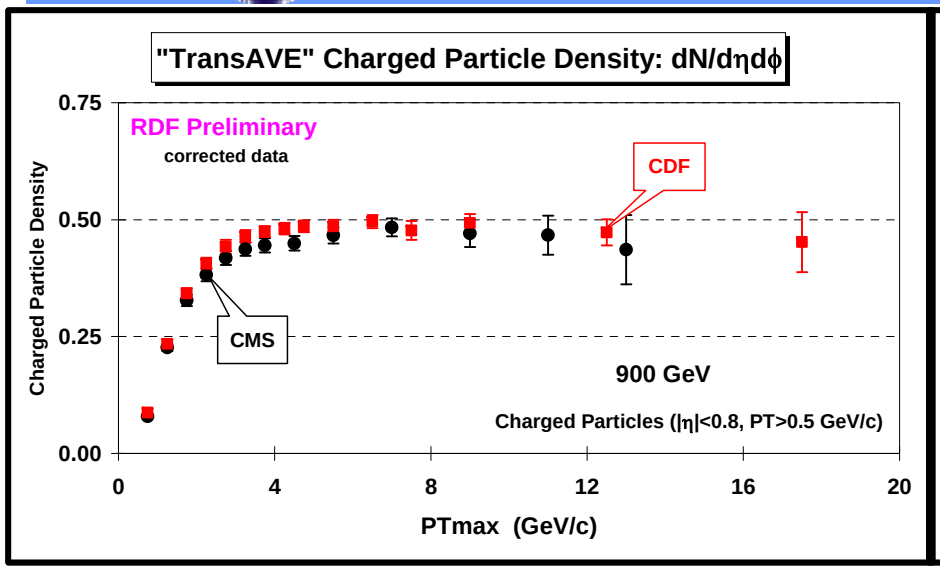
Abstract

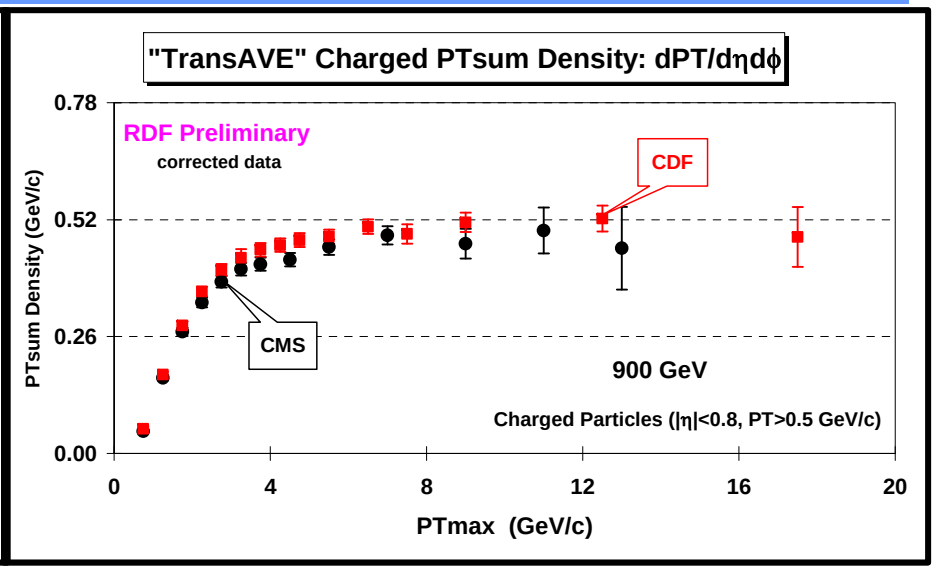
We study charged particle production ($p_T > 0.5$ GeV/c, $|\eta| < 0.8$) in proton-antiproton collisions at 300 GeV, 900 GeV, and 1.96 TeV. We use the direction of the charged particle with the largest transverse momentum in each event to define three regions of η-ϕ space; "toward", "away", and "transverse". The average number and the average scalar p_T sum of charged particles in the transverse region are sensitive to the modeling of the "underlying event". The transverse region is divided into a MAX and MIN transverse region, which helps separate the "hard component" (initial and final-state radiation) from the "beam-beam remnant" and multiple parton interaction components of the scattering. The center-of-mass energy dependence of the various components of the event are studied in detail. The data presented here can be used to constrain and improve QCD Monte Carlo models, resulting in more precise predictions at the LHC energies of 13 and 14 TeV.

The goal is to produce data (corrected to the particle level) that can be used by the theorists to tune and improve the QCD Monte-Carlo models that are used to simulate hadron-hadron collisions.

http://arxiv.org/abs/1508.05340

CDF versus LHC

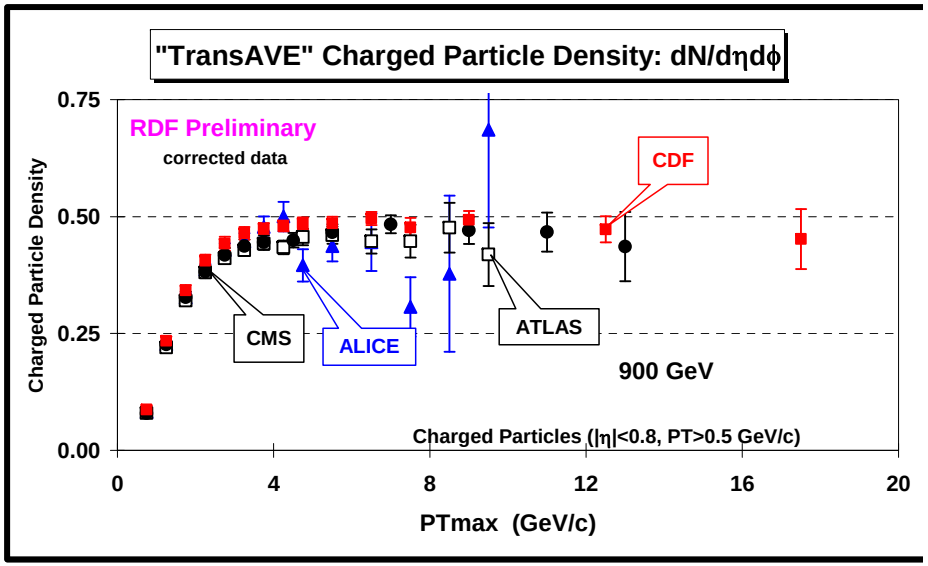


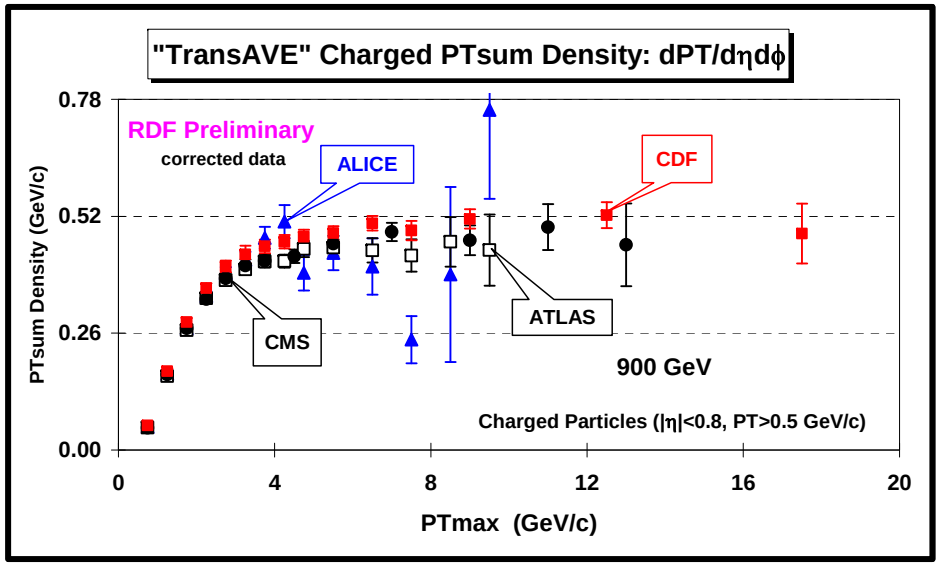


- **CDF and CMS data at 900 GeV/c on the charged particle density in the "transverse" region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error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

CDF versus LHC

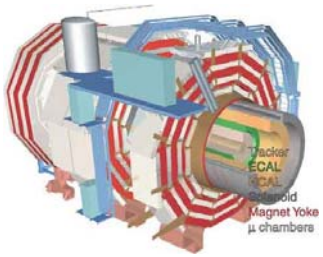




- **CDF and CMS data at 900 GeV/c on the charged particle density in the "transverse" region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error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

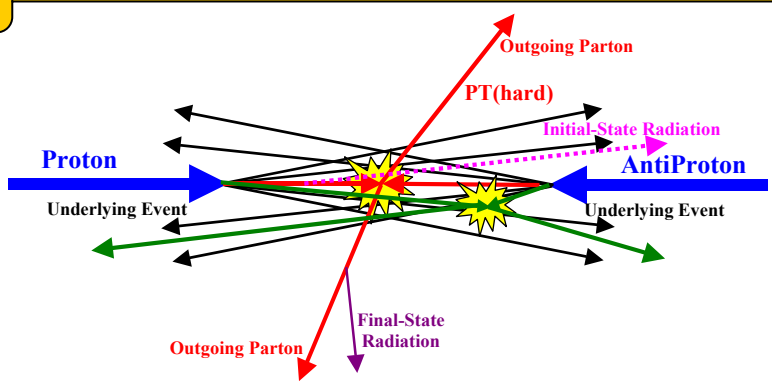
CMS Tuning Publication



CMS at the LHC

PC&GT

Physics Comparisons & Generstor Tunes



Available on the CERN CDS information server **CMS PAS GEN-14-001**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-generators@cern.ch 2014/04/29

Underlying Event Tunes and Double Parton Scattering

Eur. Phys. J. C76 (2016) 155

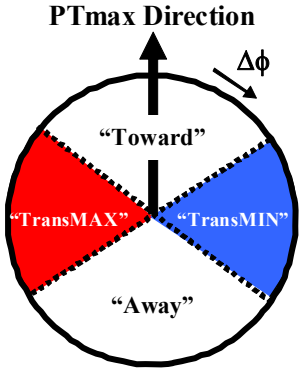
The CMS Collaboration

Abstract

Using the "Rivet" and "Professor" framework, we construct a new PYTHIA 6 tune using the CTEQ6L1 PDF and two new PYTHIA 8 UE tunes (one using CTEQ6L1 and one using the HERAPDF1.5LO). By simultaneously fitting CDF data from $\bar{p}p$ collisions at 300 GeV, 900 GeV, and 1.96 TeV together with CMS data for pp collisions at 7 TeV, we test the Underlying Event (UE) models and constrain their parameters, allowing for more precise predictions at 13 TeV and 14 TeV. The consistency of these new tunes with measurements of double-parton scattering (DPS) is also investigated.

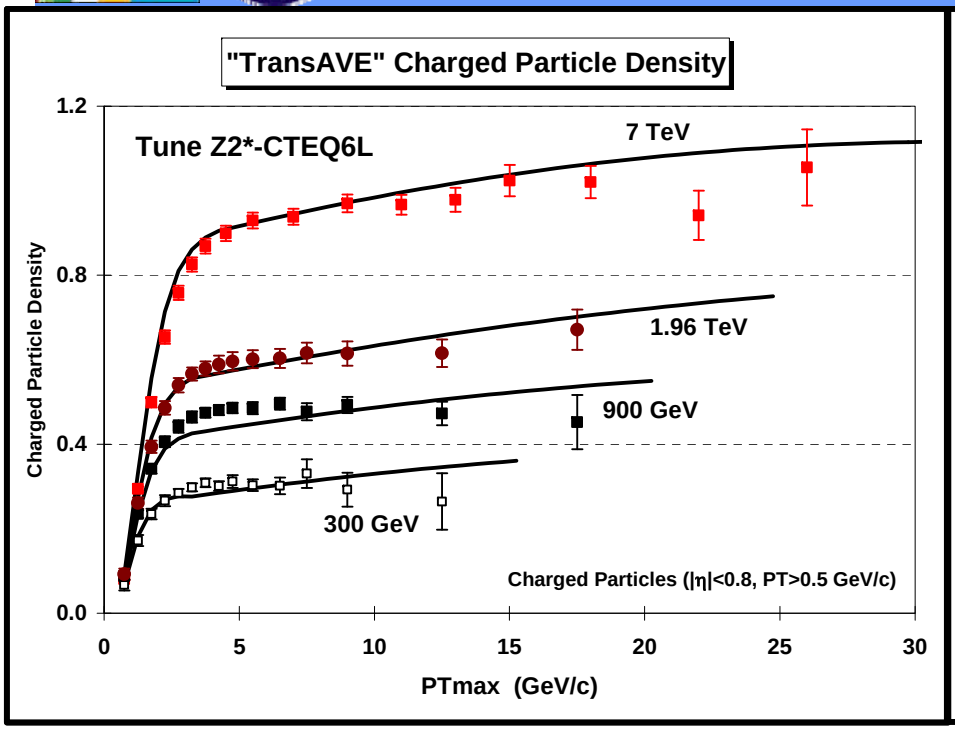
Hannes Jung, Paolo Gunnellini, Rick Field

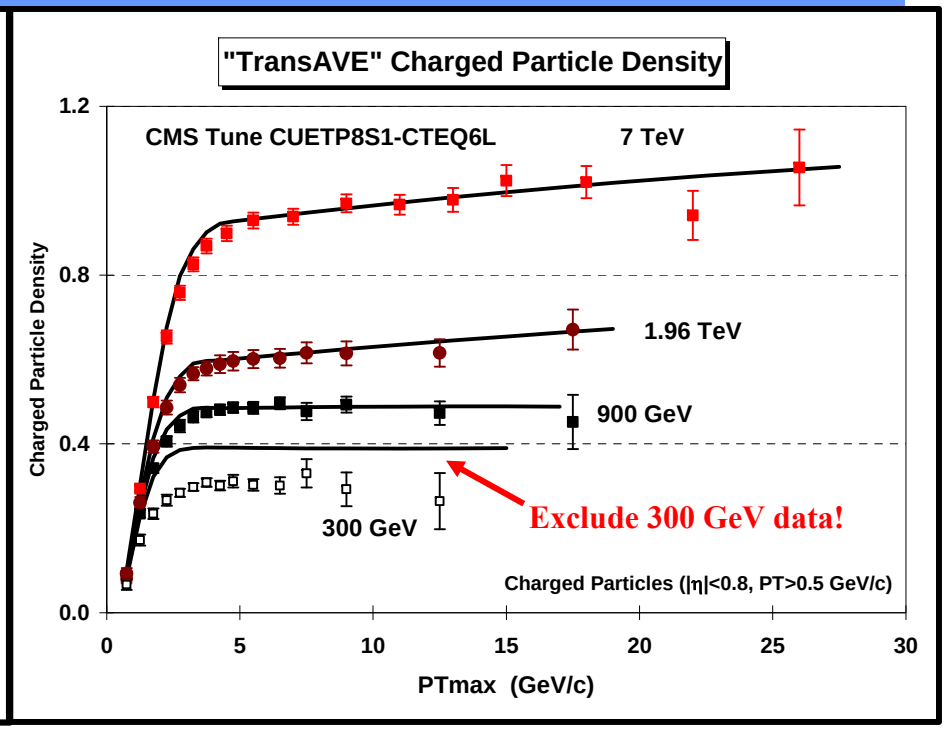
CMS UE Tunes



- **PYTHIA 6.4 Tune CUETP6S1-CTEQ6L:** Start with Tune Z2*-lep and tune to the CDF PTmax "transMAX" and "transMIN" UE data at 300 GeV, 900 GeV, and 1.96 TeV and the CMS PTmax "transMAX" and "transMIN" UE data at 7 TeV.
- **PYTHIA 6.4 Tune CUETP6S1-HERAPDF1.5LO:** Start with Tune Z2*-lep and tune to the CDF PTmax "transMAX" and "transMIN" UE data at 300 GeV, 900 GeV, and 1.96 TeV and the CMS PTmax "transMAX" and "transMIN" UE data at 7 TeV.
- **PYTHIA 8 Tune CUETP8S1-CTEQ6L:** Start with Corke & Sjöstrand Tune 4C and tune to the CDF PTmax "transMAX" and "transMIN" UE data at 900 GeV, and 1.96 TeV and the CMS PTmax "transMAX" and "transMIN" UE data at 7 TeV. **Exclude 300 GeV data.**
- **PYTHIA 8 Tune CUETP8S1-HERAPDF1.5LO:** Start with Corke & Sjöstrand Tune 4C and tune to the CDF PTmax "transMAX" and "transMIN" UE data at 900 GeV, and 1.96 TeV and the CMS PTmax "transMAX" and "transMIN" UE data at 7 TeV. **Exclude 300 GeV data.**
- **PYTHIA 8 Tune CUETP8M1-NNPDF2.3LO:** Start with the Skands Monash-NNPDF2.3LO tune and tune to the CDF PTmax "transMAX" and "transMIN" UE data at 900 GeV, and 1.96 TeV and the CMS PTmax "transMAX" and "transMIN" UE data at 7 TeV. **Exclude 300 GeV data.**
- **HERWIG++ Tune CUETHS1-CTEQ6L:** Start with the Seymour & Siódmok UE-EE-5C tune and tune to the CDF PTmax "transMAX" and "transMIN" UE data at 900 GeV, and 1.96 TeV and the CMS PTmax "transMAX" and "transMIN" UE data at 7 TeV.

CUETP8S1-CTEQ6L





- **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 compared with PYTHIA 6.4 Tune Z2*.**

- **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 compared with PYTHIA 8 Tune CUETP8S1-CTEQ6L (excludes 300 GeV in fit).**

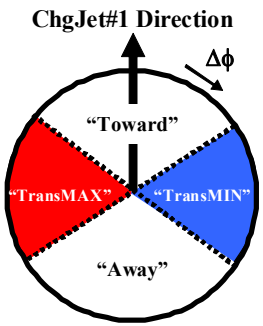
UE@CMS 13 TeV

UE@13TeV

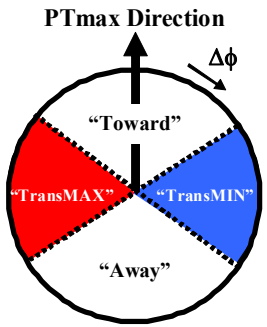
Livio Fano' (University of Perugia)
Diego Ciangottini (University of Perugia)
Rick Field (University of Florida)
Doug Rank (University of Florida)
Sunil Bansal (Panjab University Chandigarh)
Wei Yang Wang (National University of Singapore)

University of Perugia

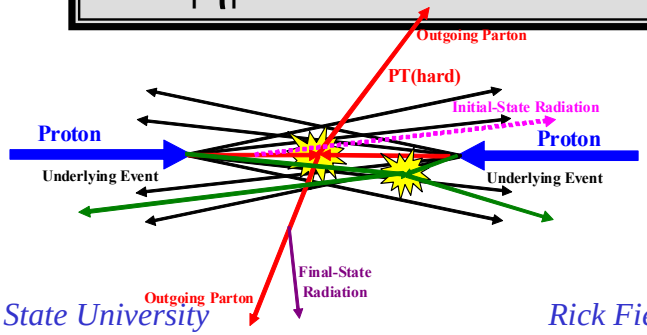
➡ Measure the "Underlying Event" at 13 TeV at CMS



Measure the UE observables as defined by the leading charged particle jet, chgjet#1, for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$.



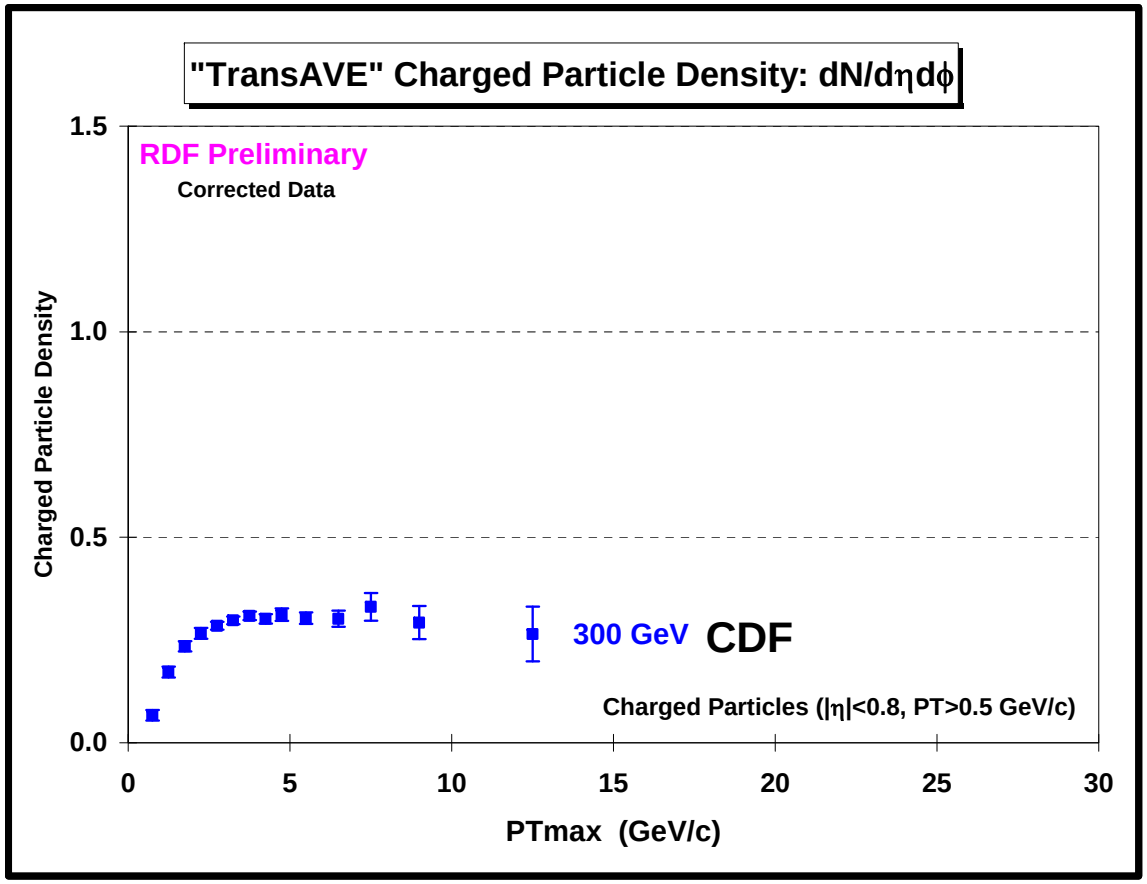
Measure the UE observables as defined by the leading charged particle, PTmax, for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$ and $|\eta| < 0.8$.



UE&MB@CMS

Livio & Rick were part of the CMS Run 1 UE&MB team!

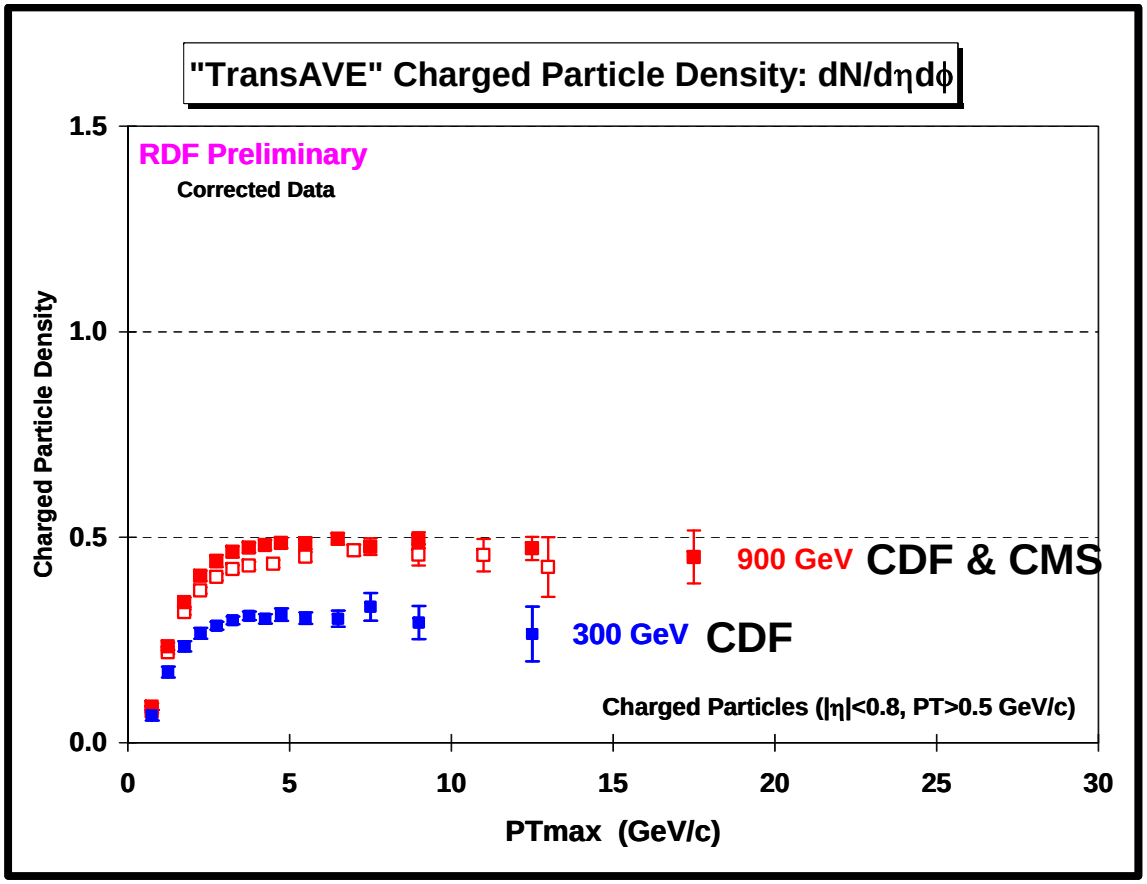
"Tevatron" to the LHC



Mapping out the Energy Dependence of the UE

(300 GeV, 900 GeV, 1.96 TeV, 7 TeV, 13 TeV)

"Tevatron" to the LHC



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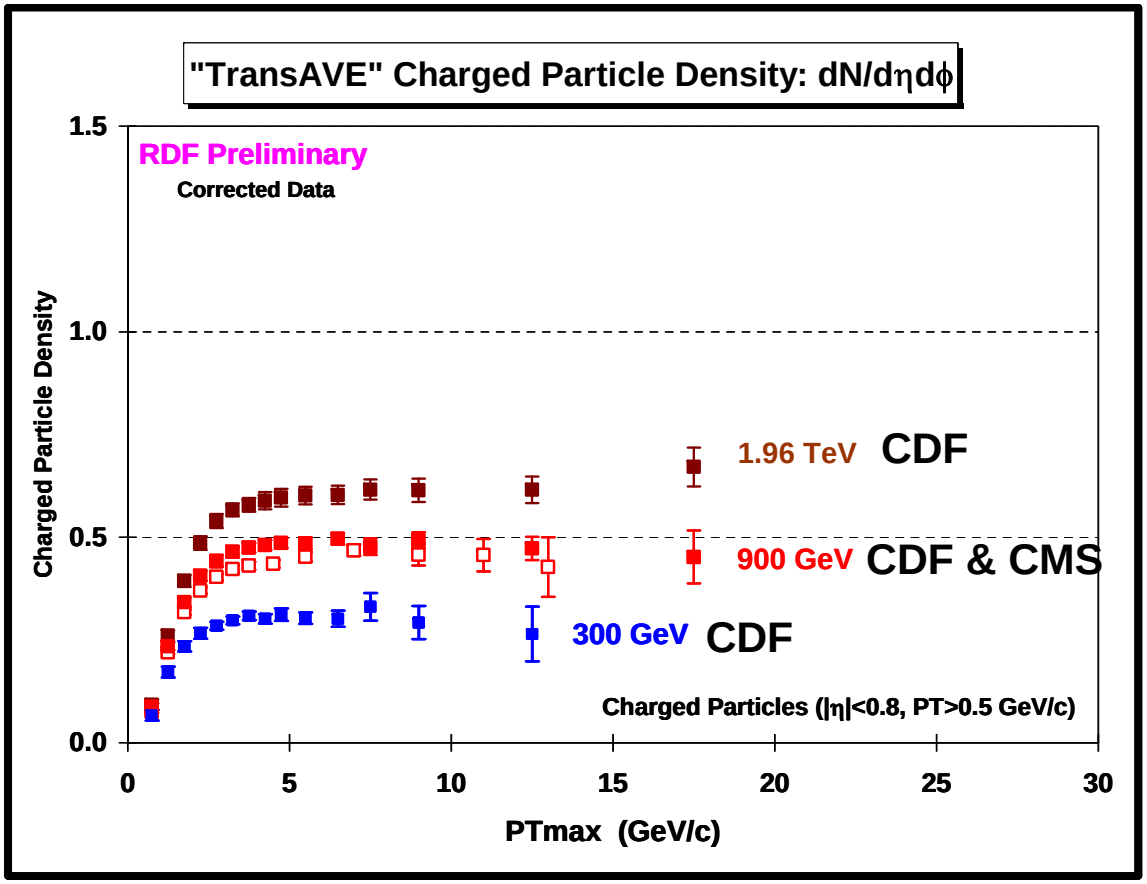
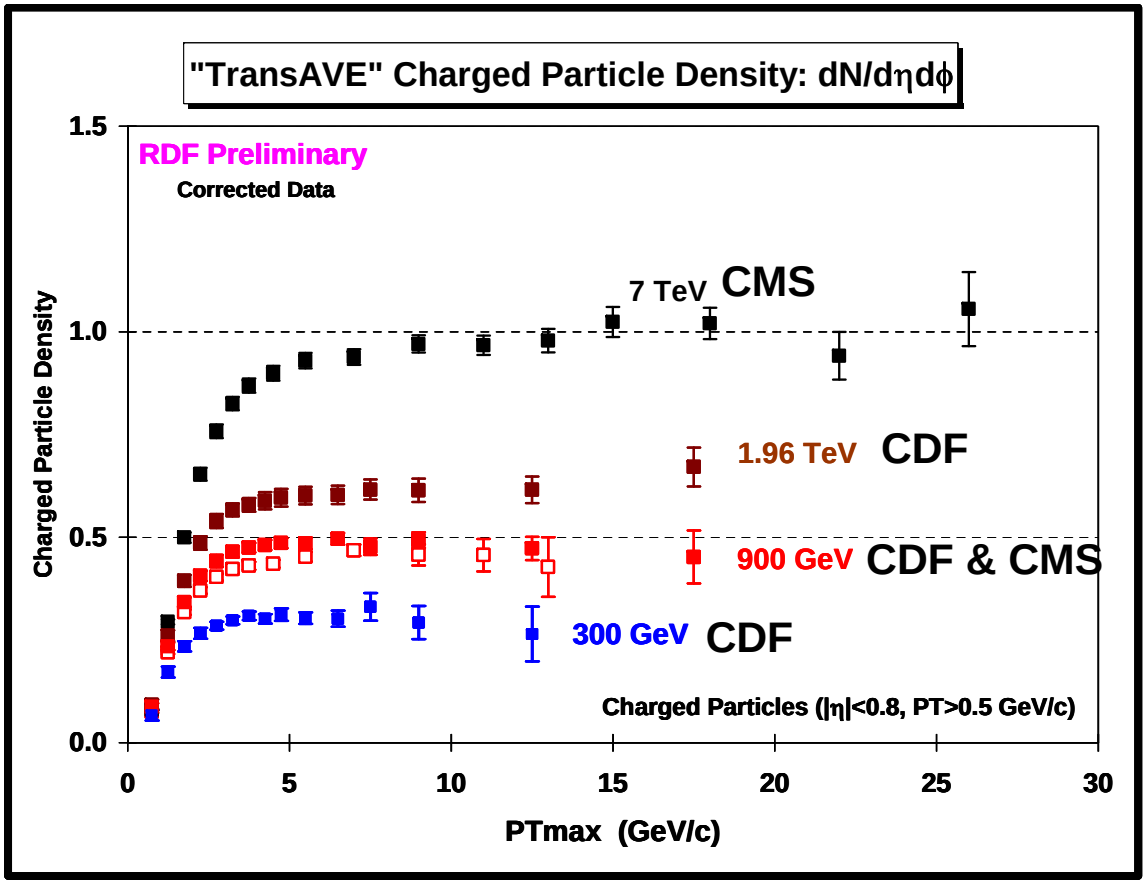
"Tevatron" to the LHC



Mapping out the Energy Dependence of the UE

(300 GeV, 900 GeV, 1.96 TeV, 7 TeV, 13 TeV)

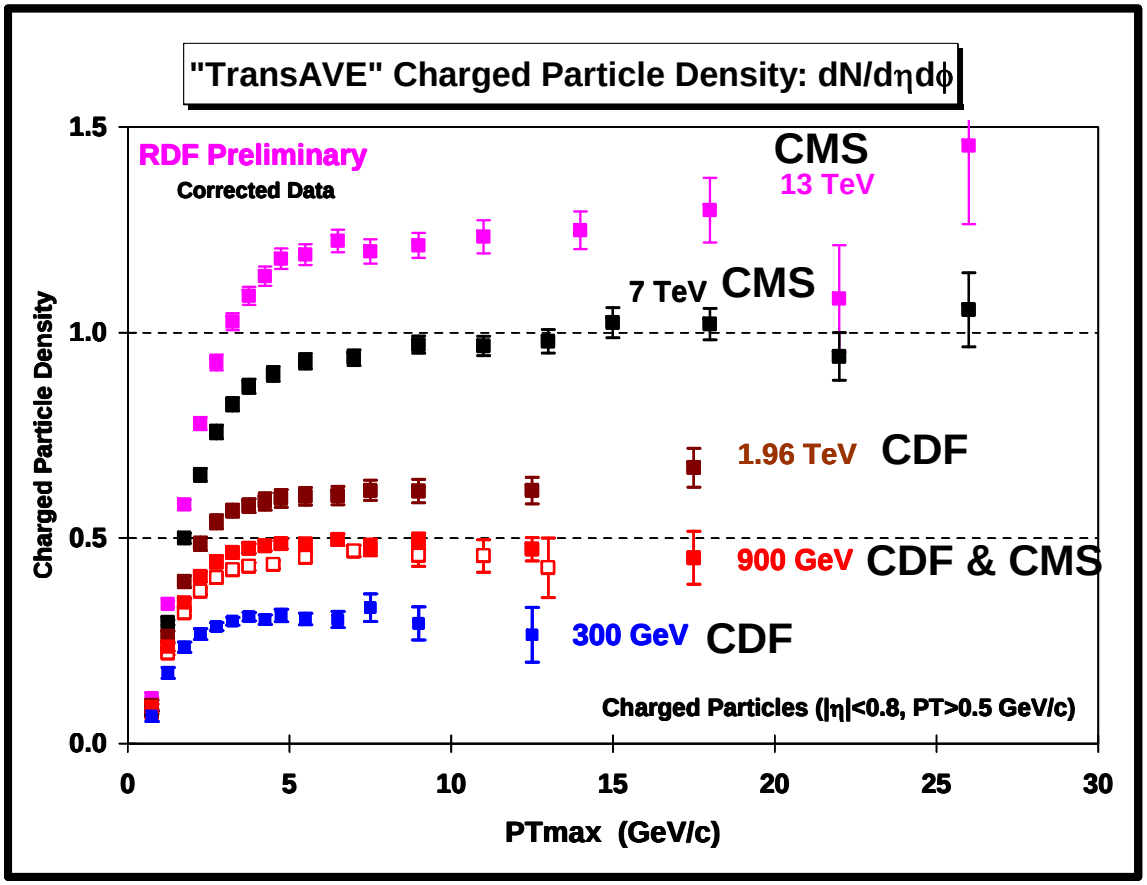
"Tevatron" to the LHC



Mapping out the Energy Dependence of the UE

(300 GeV, 900 GeV, 1.96 TeV, 7 TeV, 13 TeV)

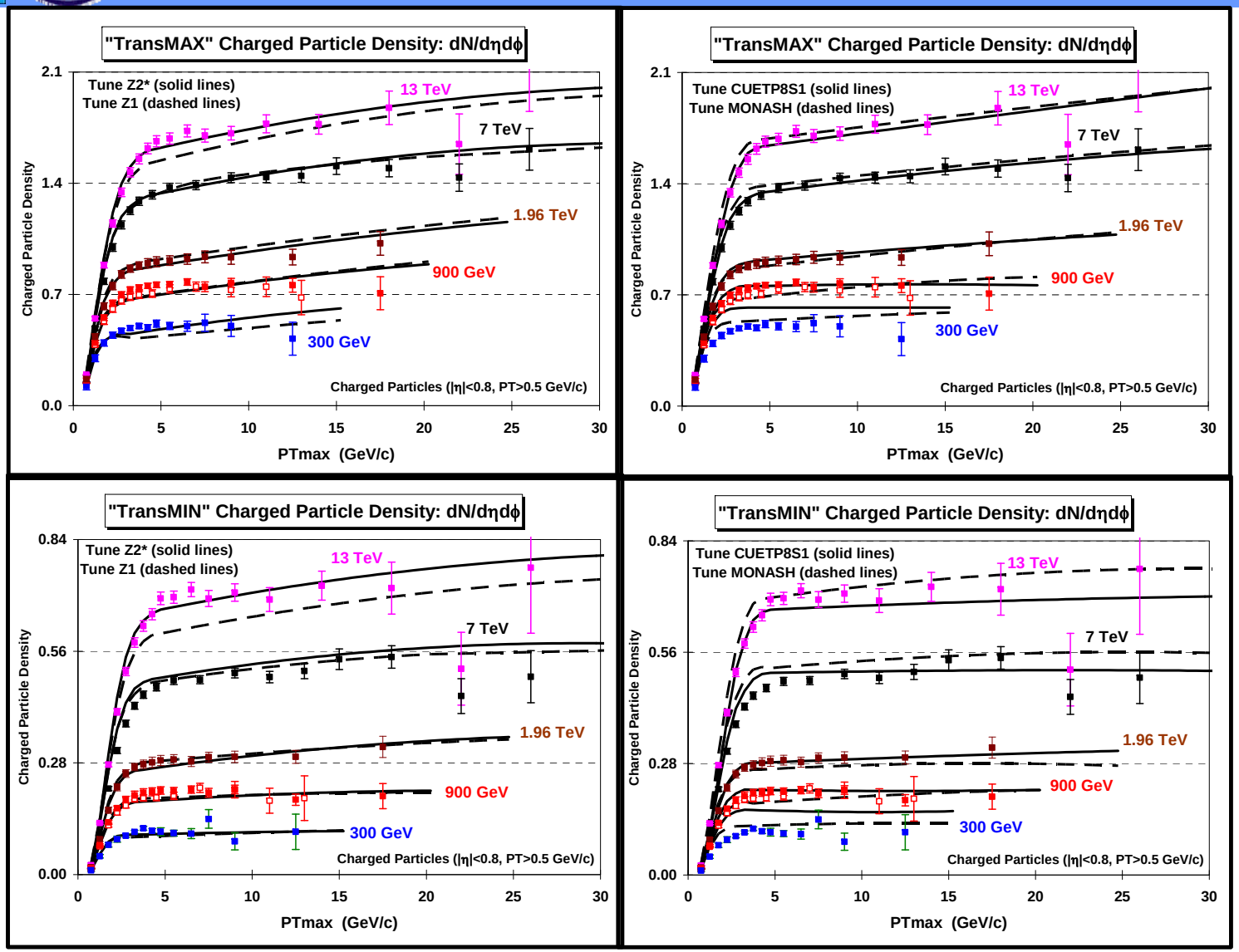
"Tevatron" to the LHC



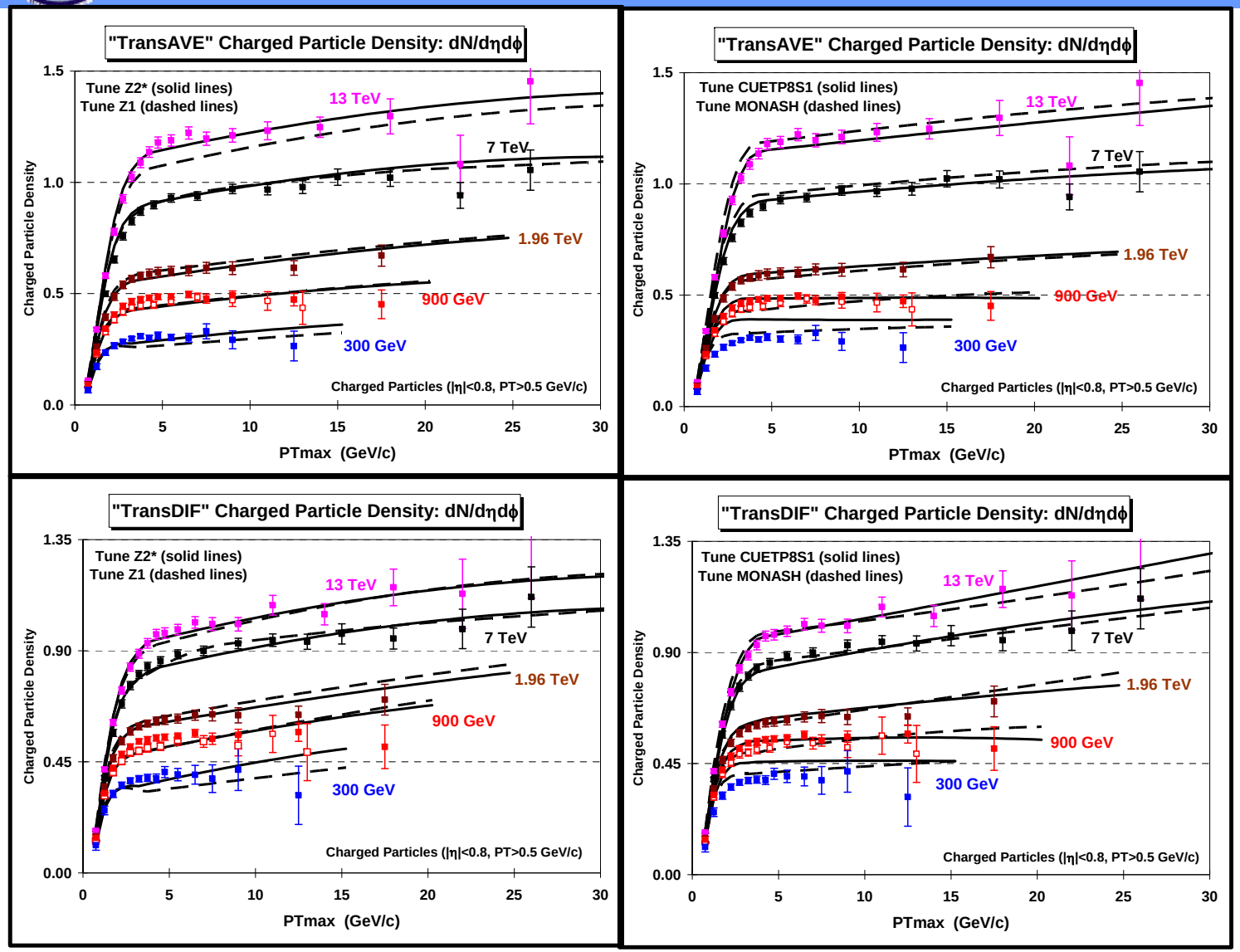
Mapping out the Energy Dependence of the UE

(300 GeV, 900 GeV, 1.96 TeV, 7 TeV, 13 TeV)

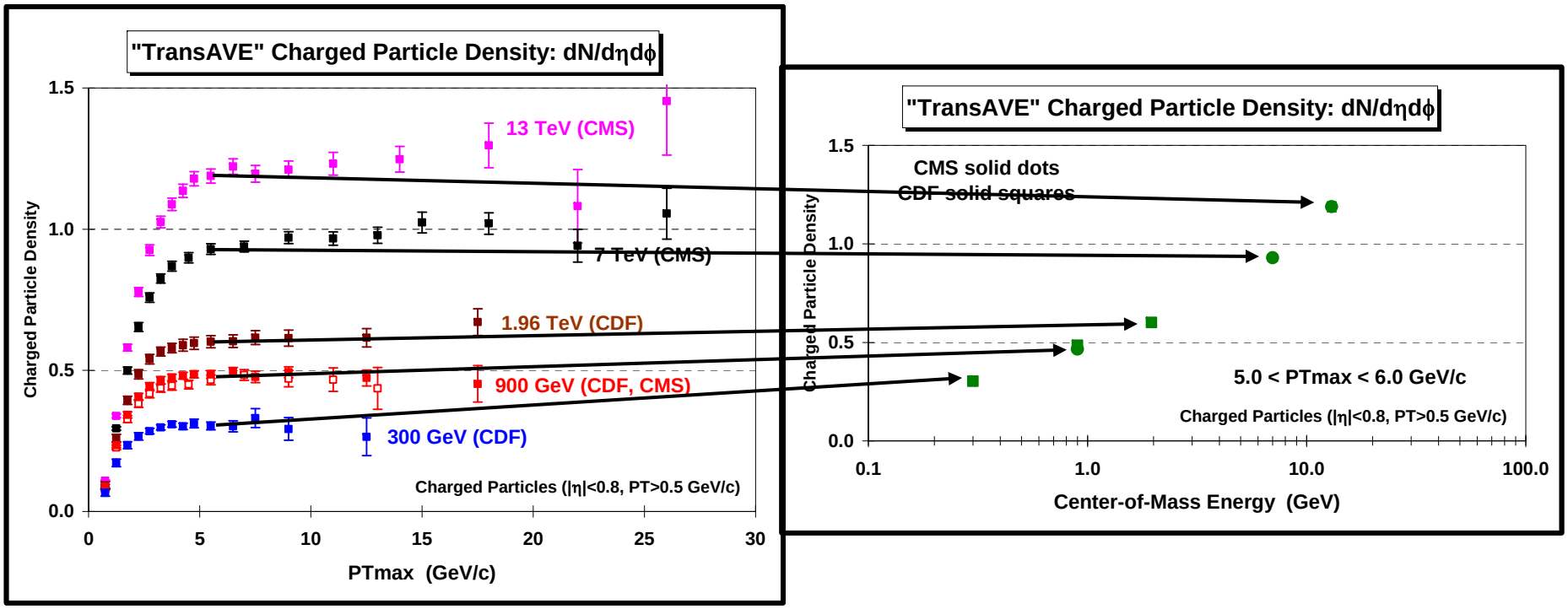
Particle Density: MAX & MIN



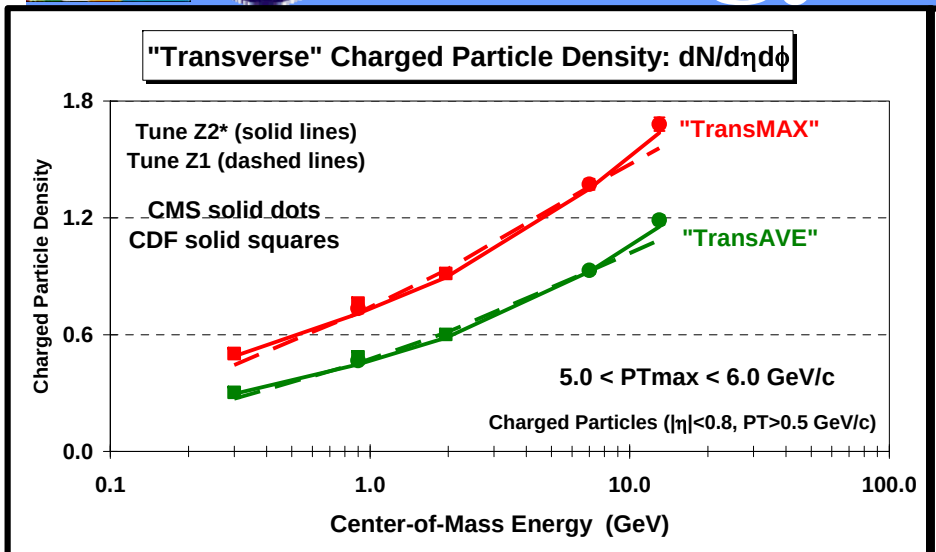
Particle Density: AVE & DIF

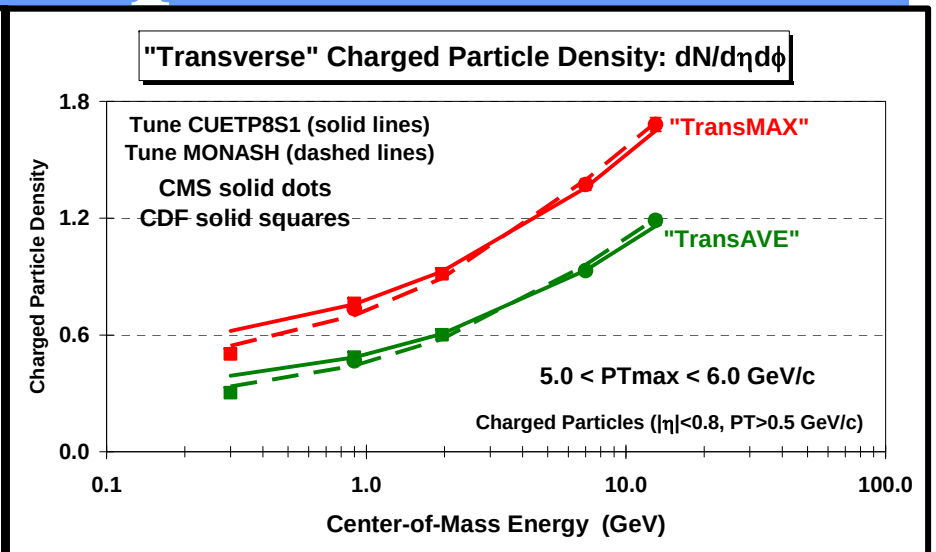


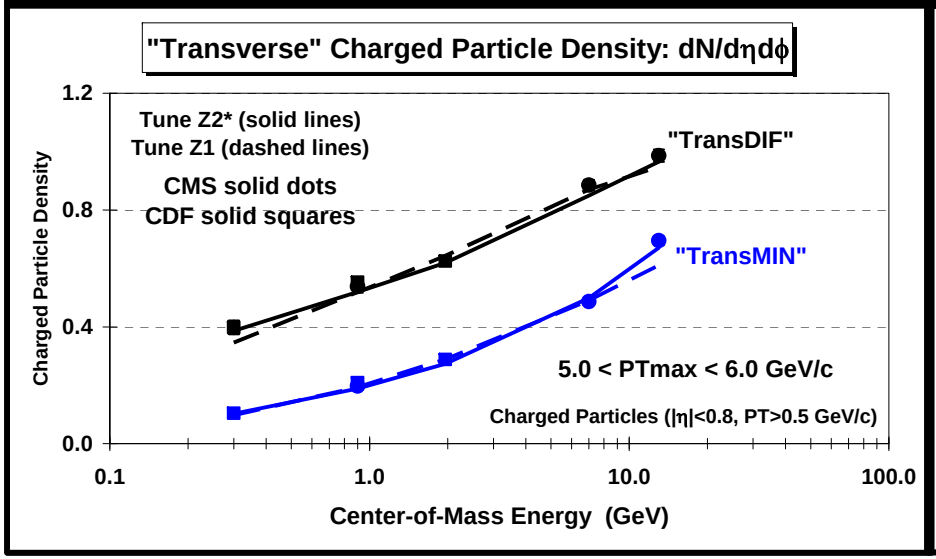
Energy Dependence

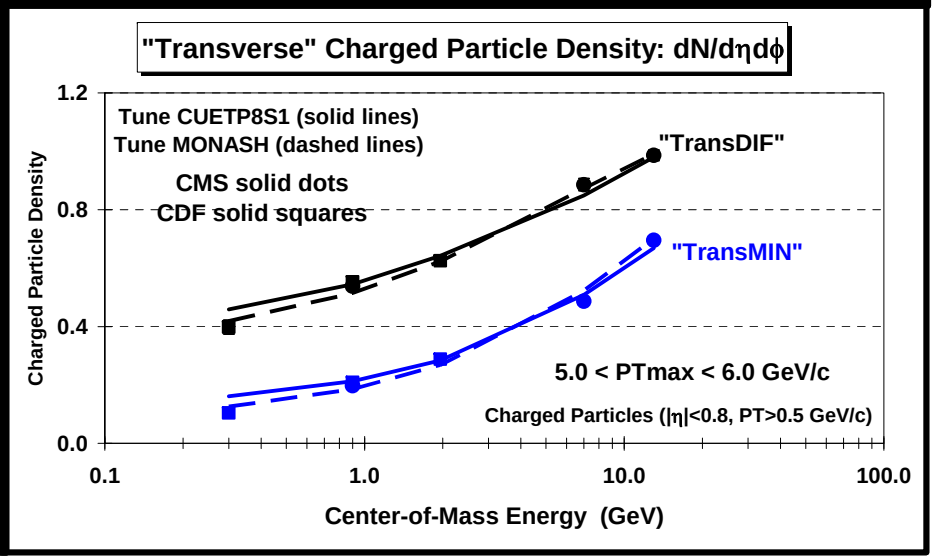


Energy Dependence

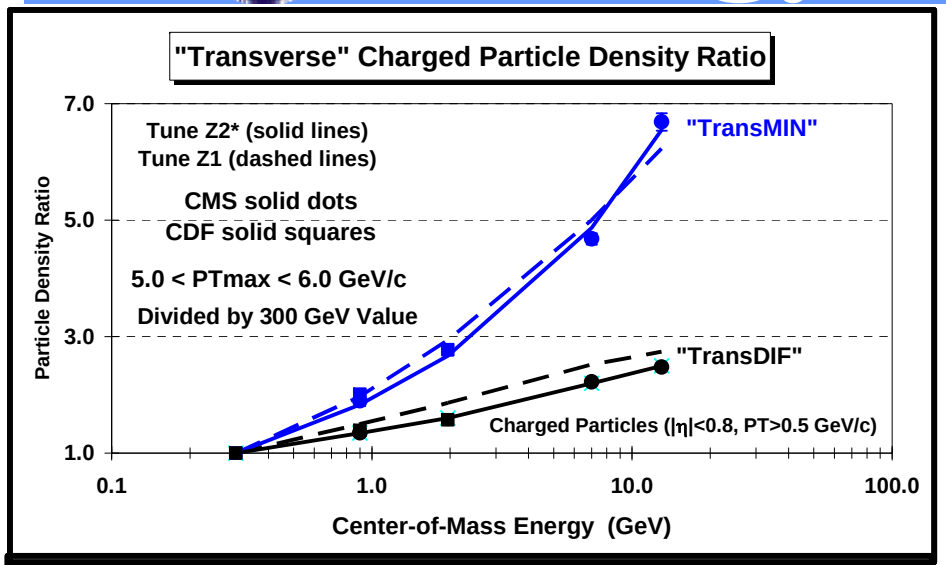


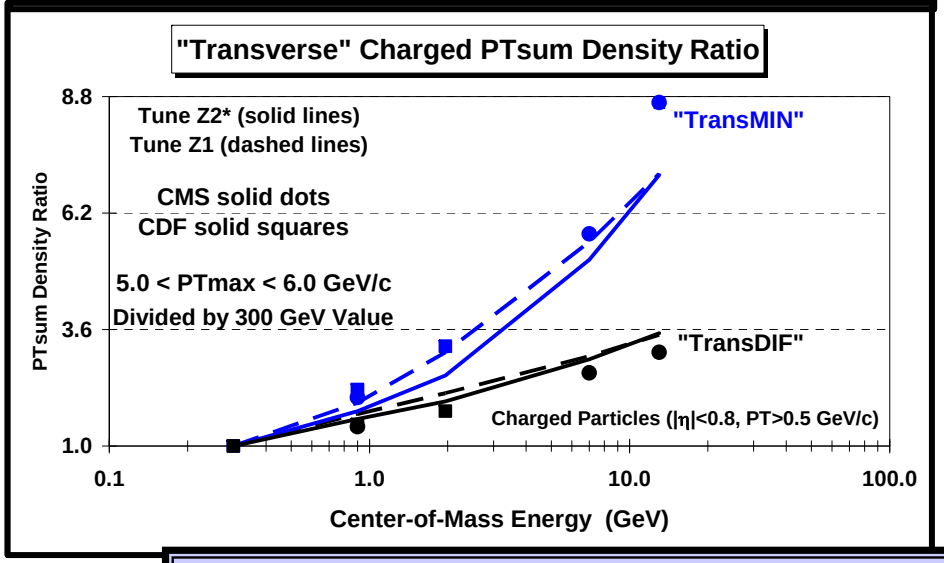






Energy Dependence



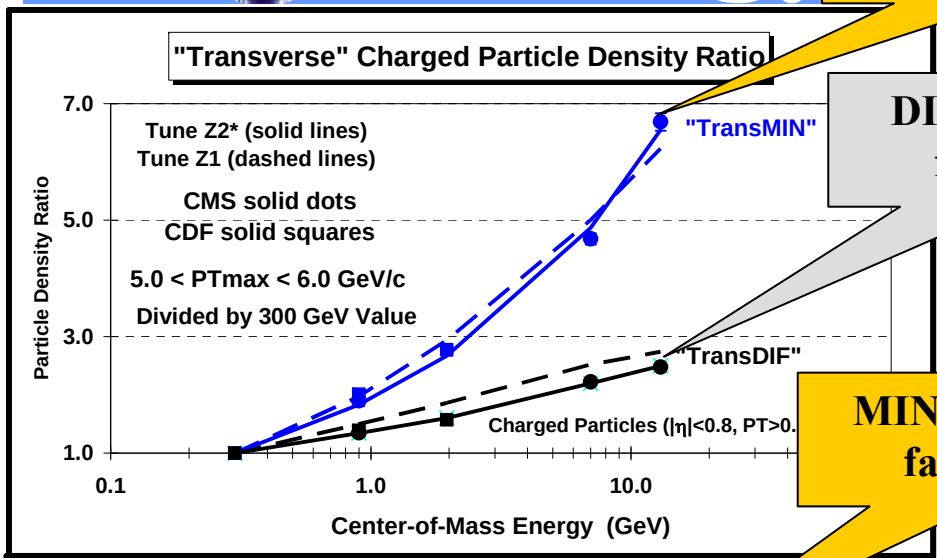


The data are "normalized" by dividing by the corresponding value at 900 GeV.

Energy dence

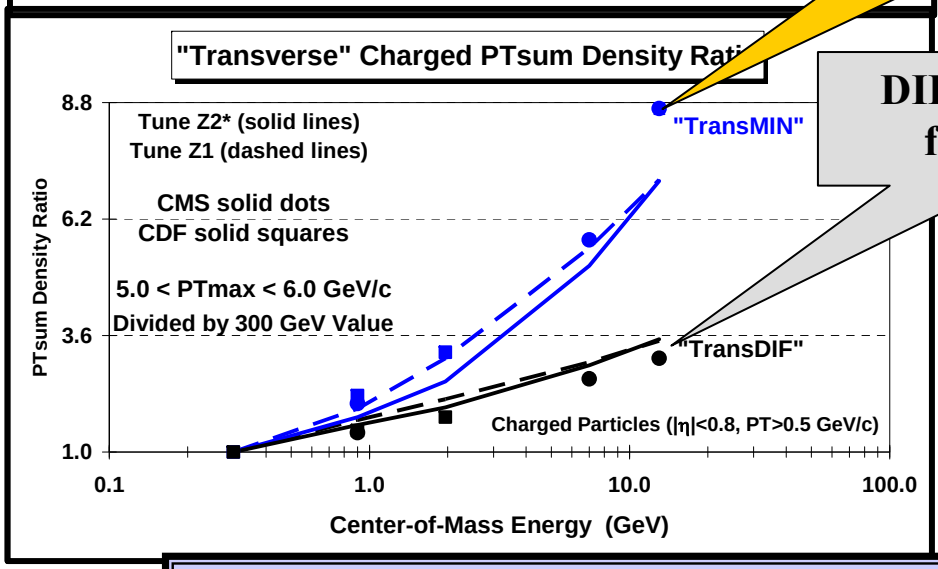
MIN increases by factor of 6.7

DIF increases by factor of 2.5



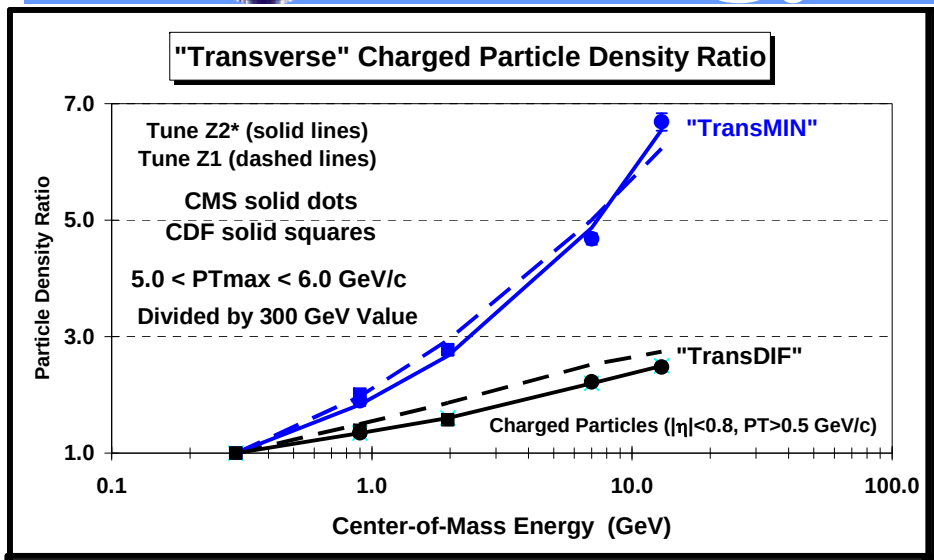
MIN increases by factor of 8.7

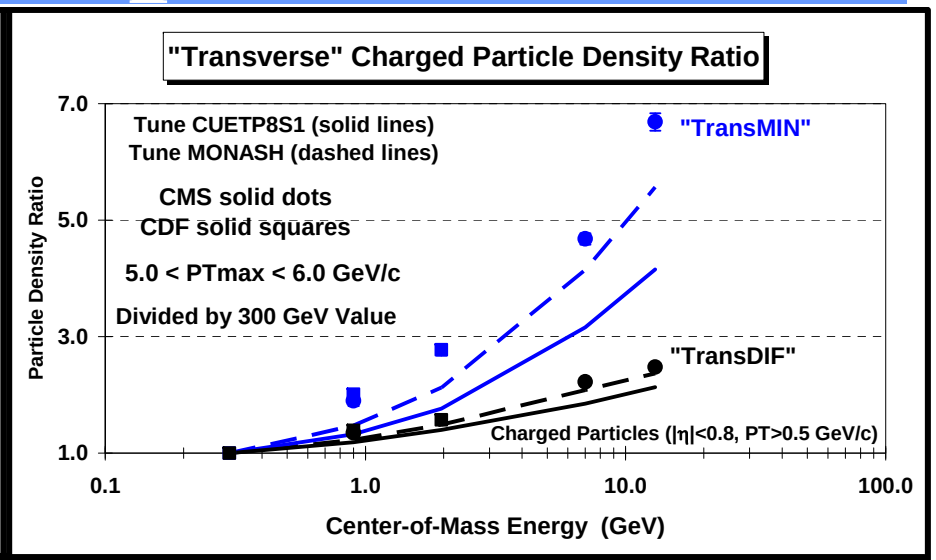
DIF increases by factor of 3.1

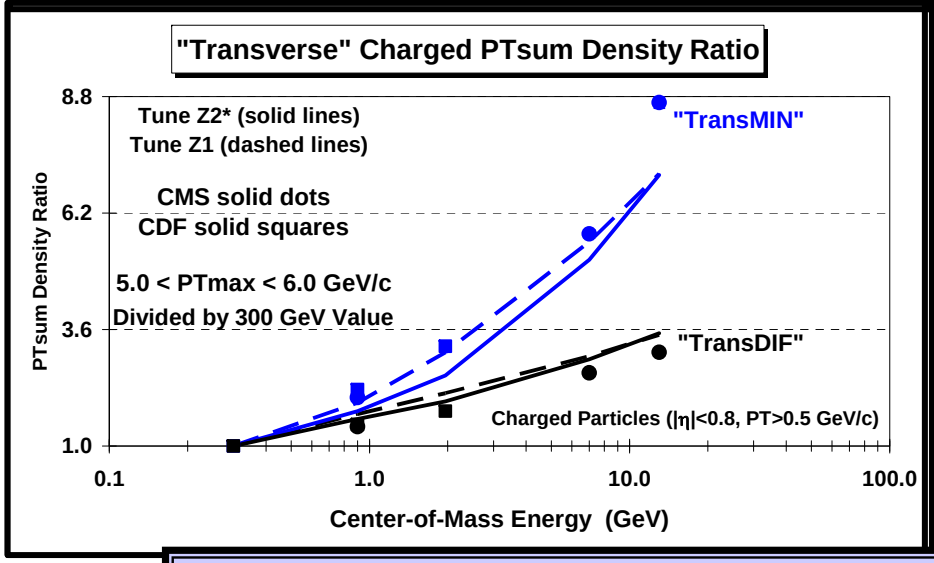


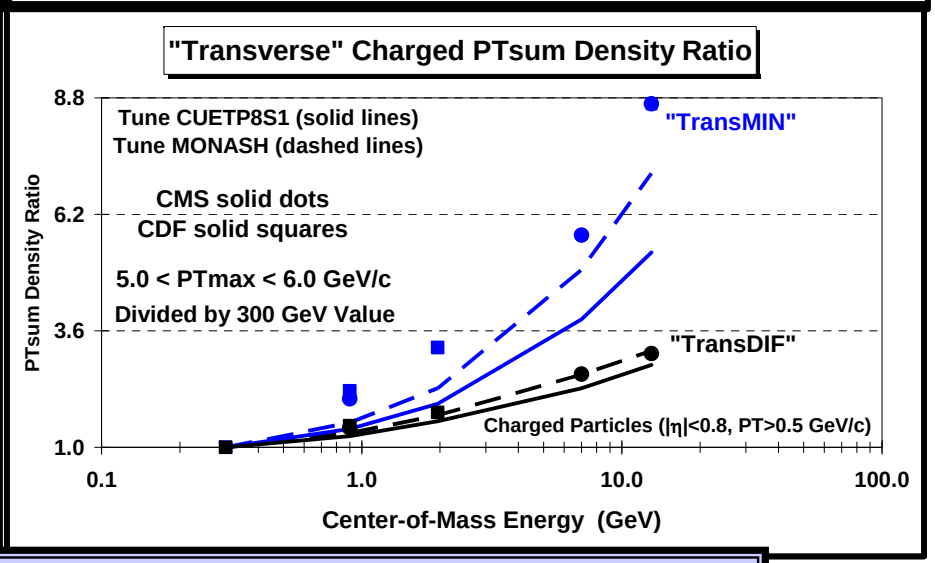
The data are "normalized" by dividing by the corresponding value at 900 GeV.

Energy Dependence



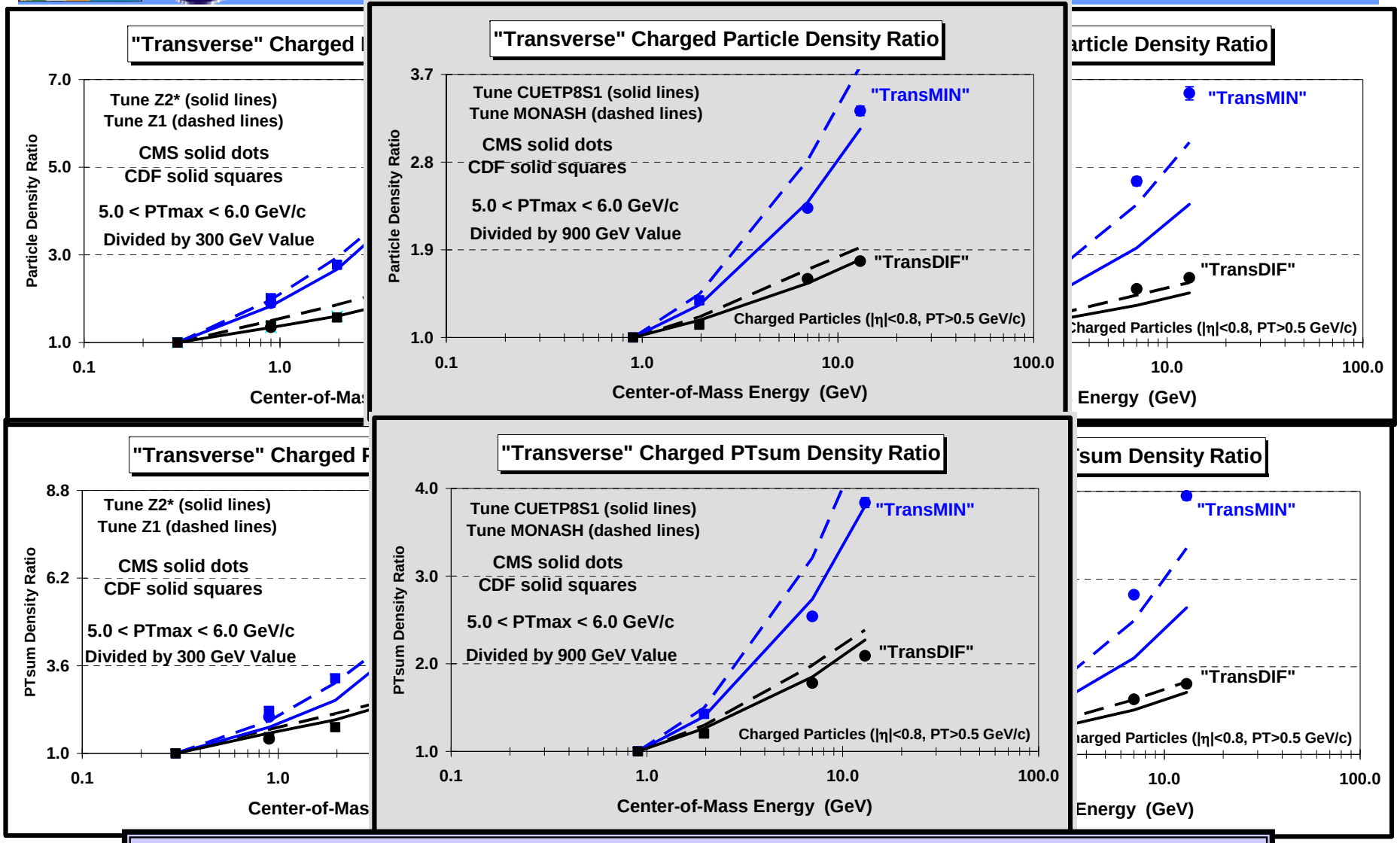






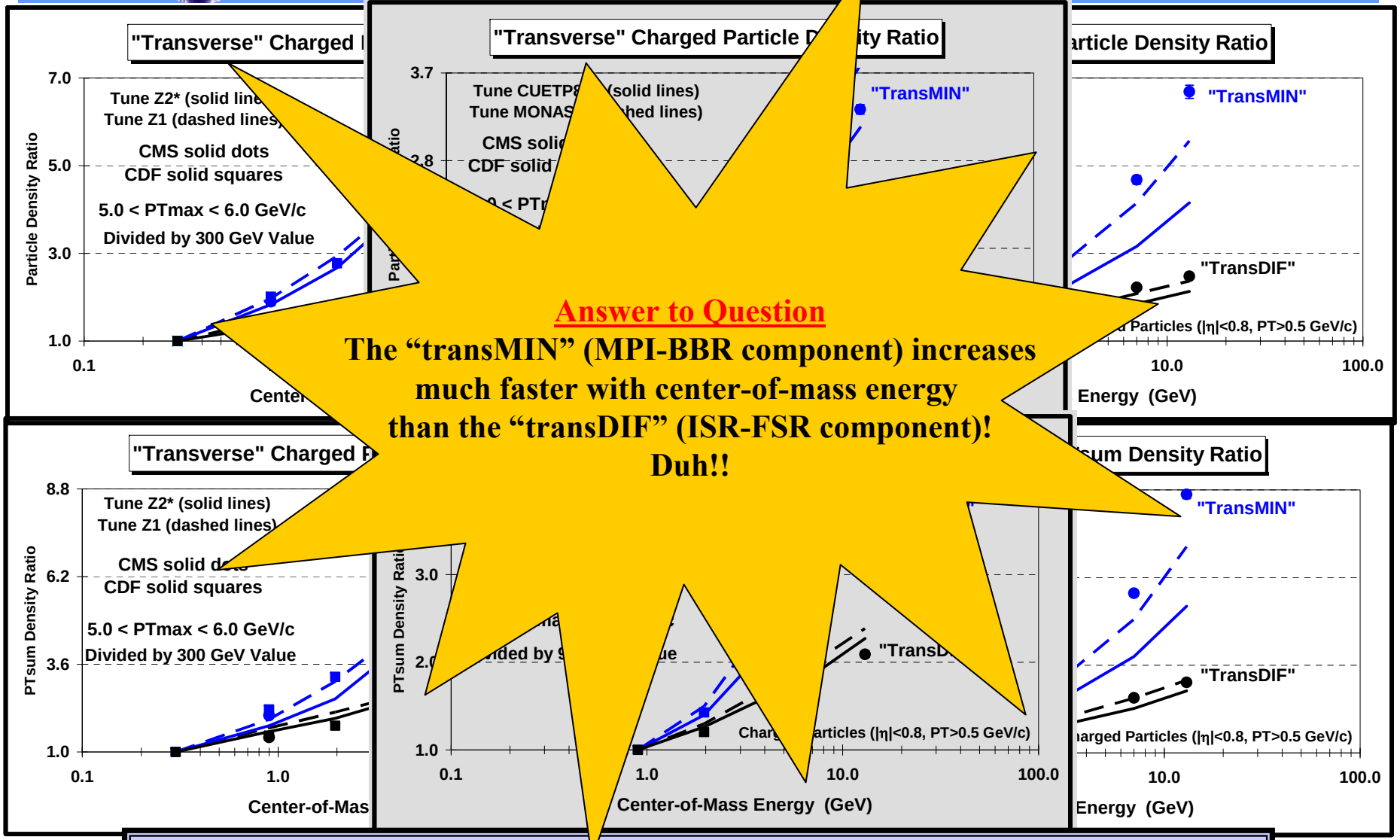
The data are "normalized" by dividing by the corresponding value at 900 GeV.

Energy Dependence



The data are "normalized" by dividing by the corresponding value at 900 GeV.

Energy Dependence



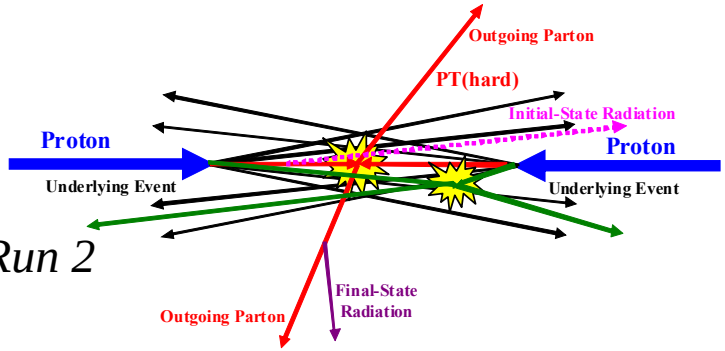
Answer to Question

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

The data are "normalized" by dividing by the corresponding value at 900 GeV.

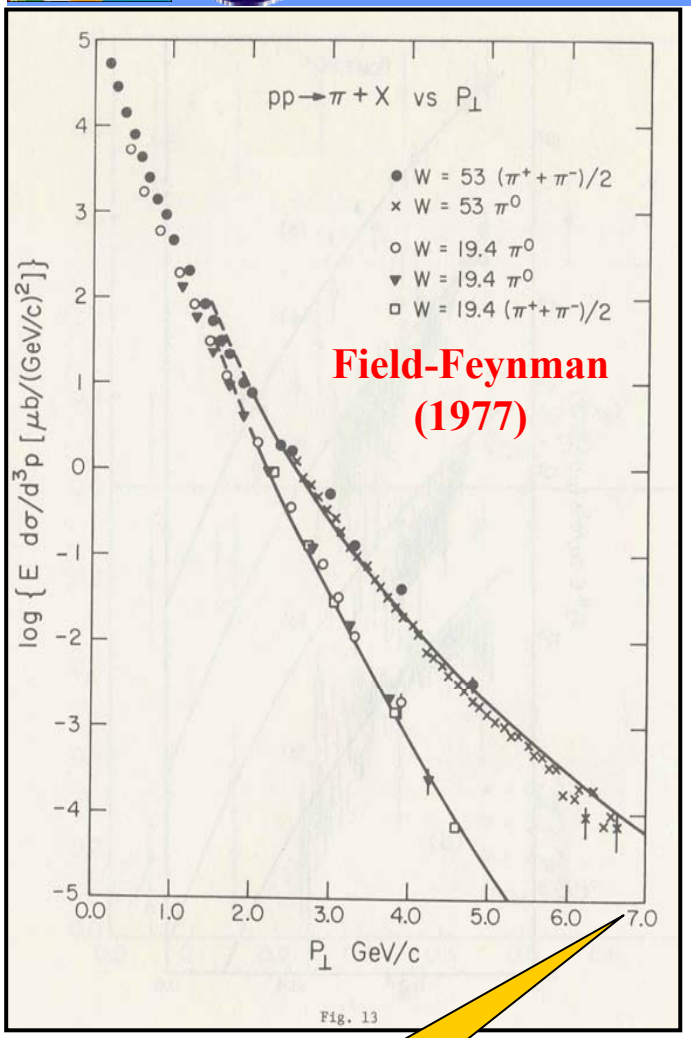
Rick's UE Graduate Students

- **Richard Haas (CDF Ph.D. 2001):** *The Underlying Event in Hard Scattering Collisions of Proton and Antiproton at 1.8 TeV.*



- **Alberto Cruz (CDF Ph.D. 2005):** *Using MAX/MIN Transverse Regions to Study the Underlying Event in Run 2 at the Tevatron.*
- **Craig Group (CDF Ph.D. 2006):** *The Inclusive Jet Cross Section in Run 2 at CDF*. After receiving his Ph.D Craig helped in Deepak Kar's UE analyses (2008) and the "Tevatron Energy Scan" UE analysis (2015).
- **Deepak Kar (CDF Ph.D. 2008):** *Studying the Underlying Event in Drell-Yan and High Transverse Momentum Jet Production at the Tevatron.*
- **Mohammed Zakaria (CMS Ph.D. 2013):** *Measurement of the Underlying Event Activity in Proton-Proton Collisions at the LHC using Leading Tracks at 7 TeV and Comparison with 0.9 TeV.*
- **Doug Rank (CMS Ph.D. 2016):** *The Underlying Event via Leading Track and Track Jet at 13 TeV.*

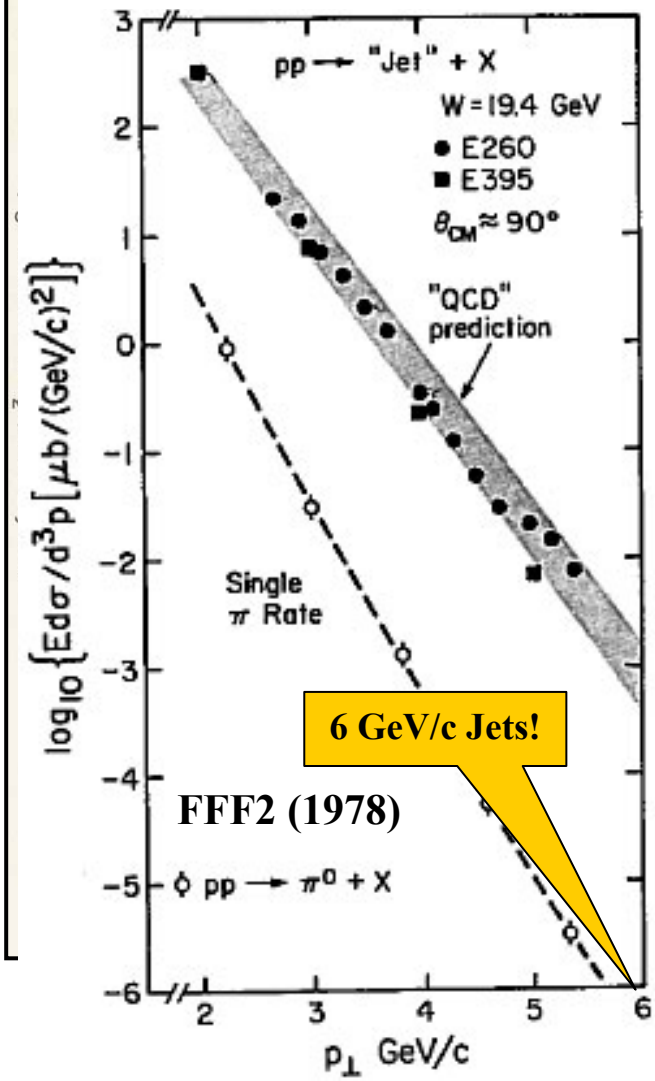
A Wonderful Journey



7 GeV/c π^0's!

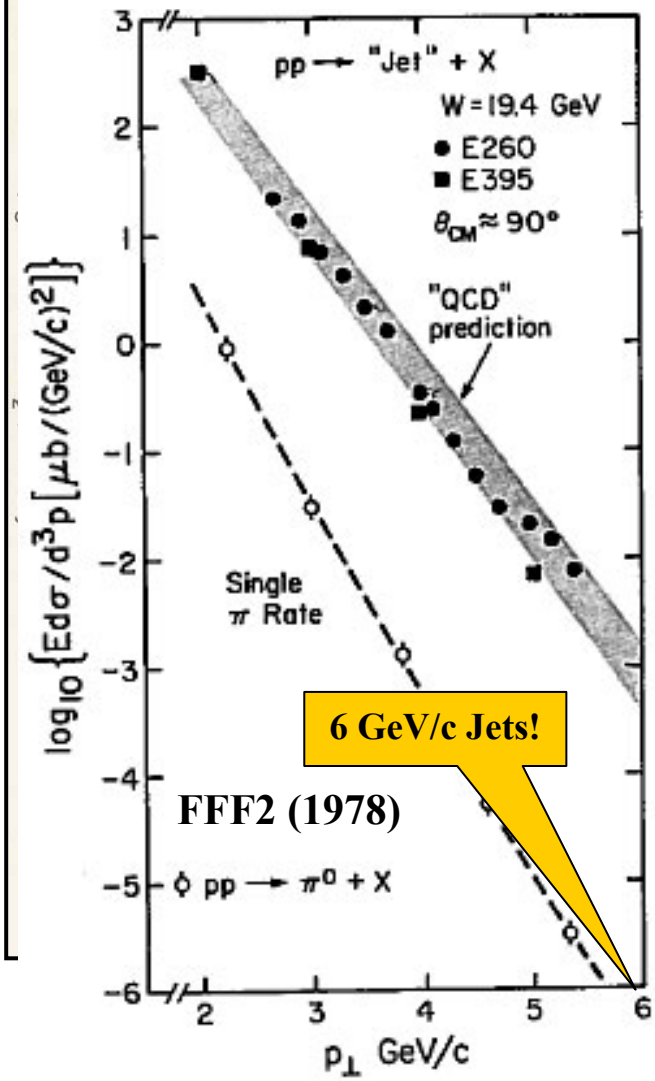
A Wonderful Journey

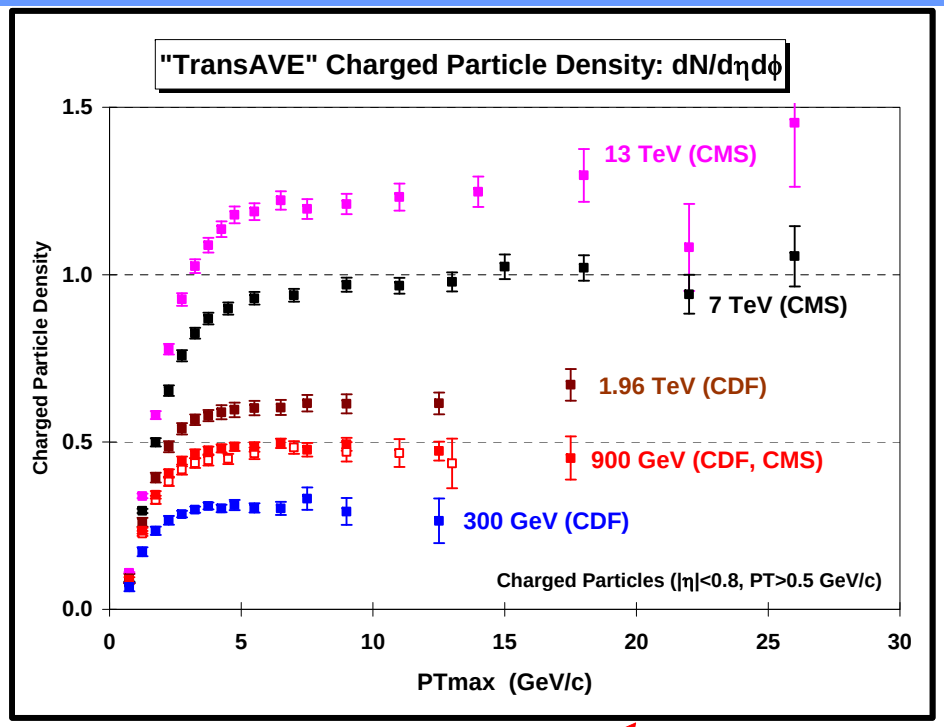
QCD Improved Parton Model

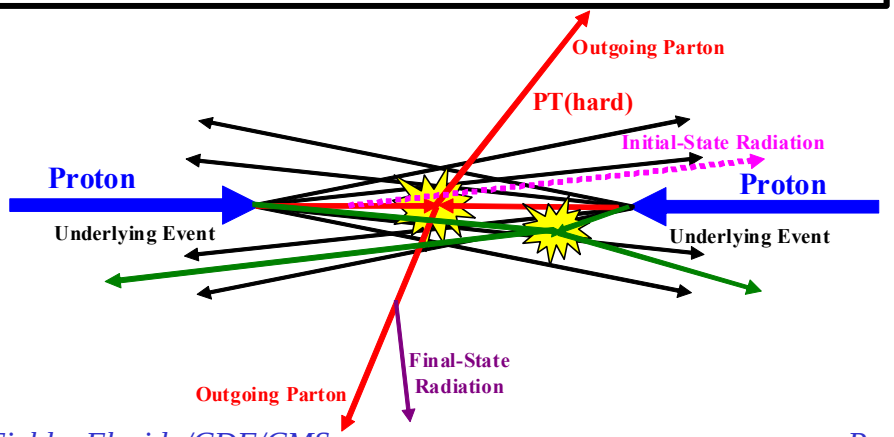


A Wonderful Journey

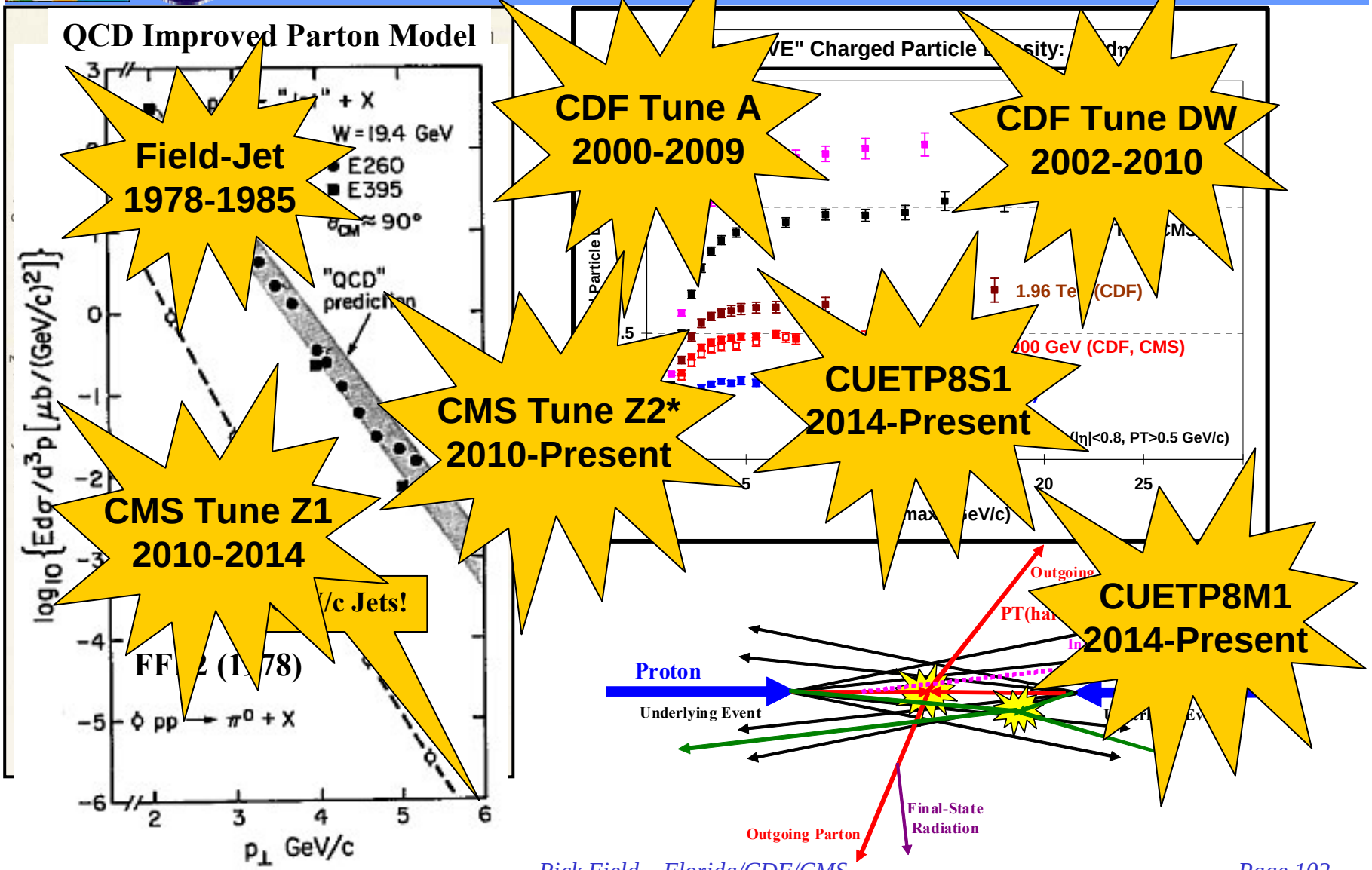
QCD Improved Parton Model







A Wonderful Journey

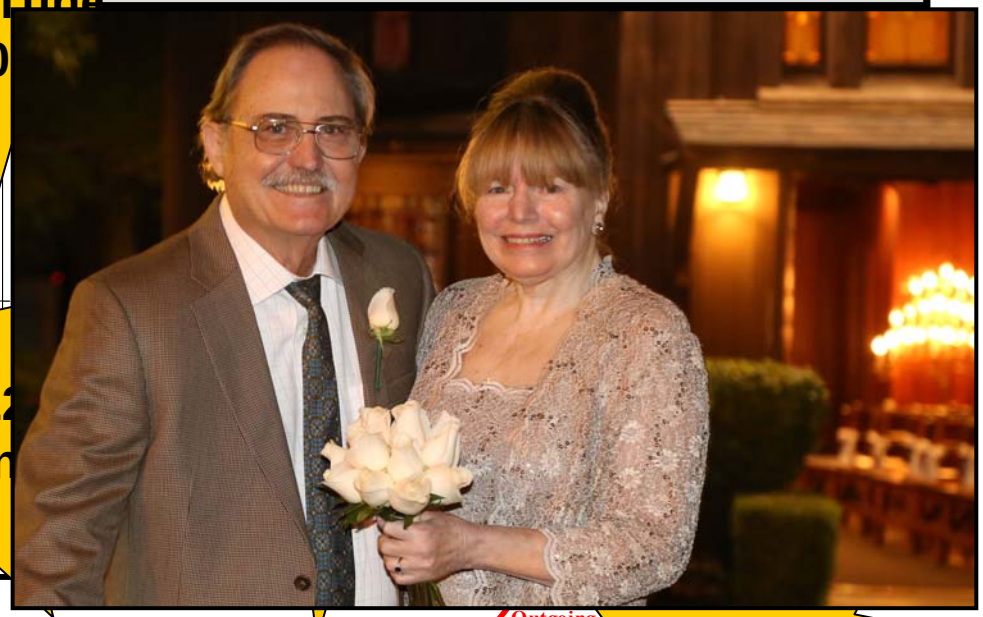


A Wonderful Journey

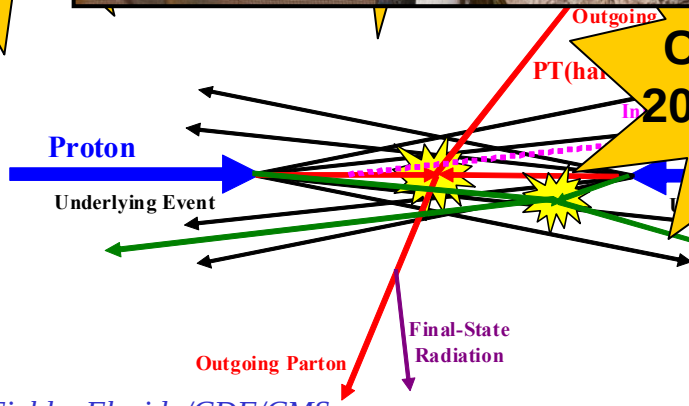
QCD Improved Parton Model

Rick & Jimmie Wedding November 24, 1966
***Little Chapel of the West*, Las Vegas**

Rick & Jimmie Celebration November 24, 2016
***Little Chapel of the West*, Las Vegas**



CUETP8M1
2014-Present



A Wonderful Journey

QCD Improved Parton Model

Rick & Jimmie Wedding November 24, 1966
Little Chapel of the West, Las Vegas

Rick & Jimmie Celebration November 24, 2016
Little Chapel of the West, Las Vegas

Family, Children, & Grandchildren November 24, 2016
Little Chapel of the West, Las Vegas