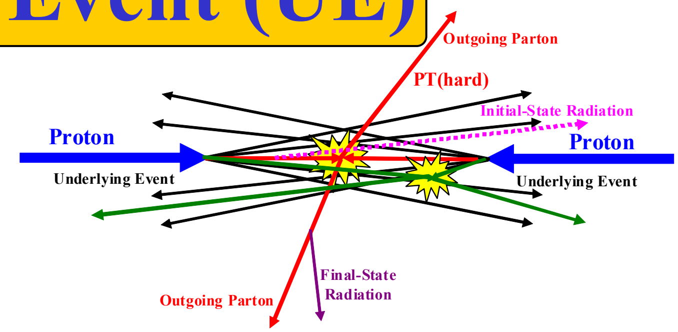
PHYSICS at the UNIVERSITY of VIRGINIA

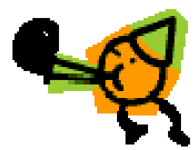
Rick’s Story of the Underlying Event (UE)

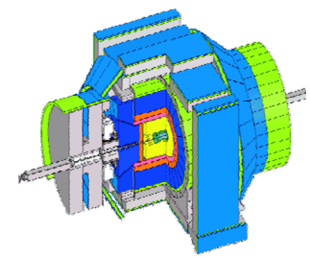
Rick Field
University of Florida



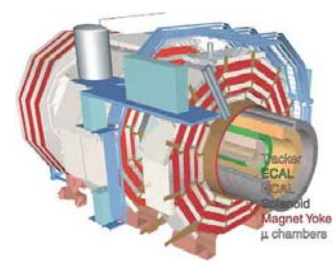
Outline

- Early days of Field-Feynman phenomenology.
- Early studies the underlying event at CDF and Tune A.
- Early days of UE@MB at CMS.
- LPCC MB&UE Working group and the “common plots”.
- UE@CMS at 13TeV.
- CMS “Physics Comparisons & Generator Tunes” group and CMS UE & DPS Tunes.
- My last CDF UE Publication.
- Mapping out the energy dependence of the UE, Tevatron to the LHC.





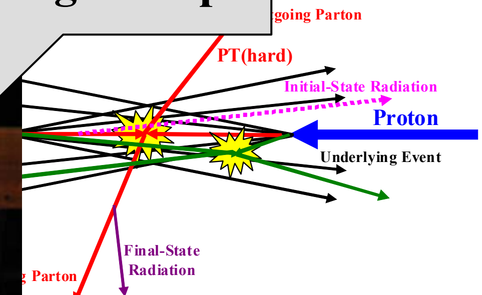
CDF Run 2
300 GeV, 900 GeV, 1.96 TeV



CMS
900 GeV, 7 TeV, 8 TeV, 13 TeV

PHYSICS at the UNIVERSITY of VIRGINIA

Rick's S… Underlying Ev…



- Early days of Fi…
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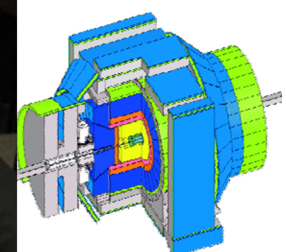
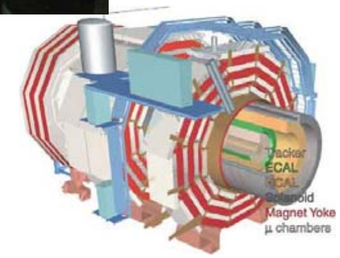


CDF Run 2

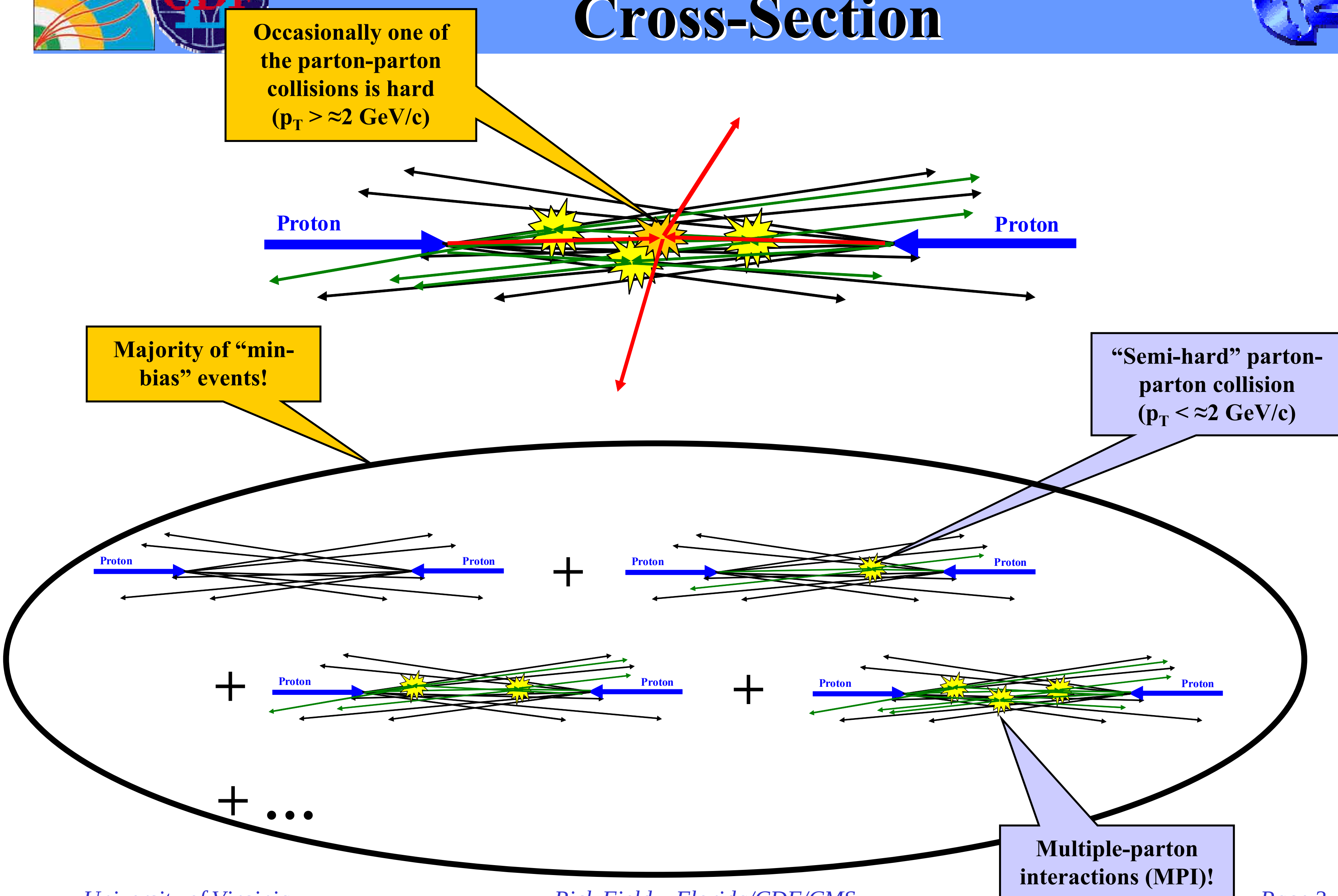
GeV, 900 GeV, 1.96 TeV



CMS

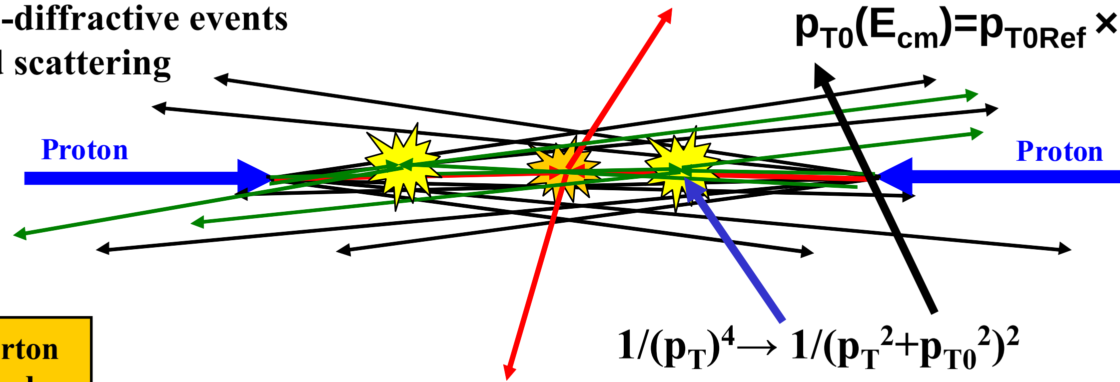
900 GeV, 7 TeV, 8 TeV, 13 TeV

The Inelastic Non-Diffractive Cross-Section



The "Underlying Event"

Select inelastic non-diffractive events that contain a hard scattering



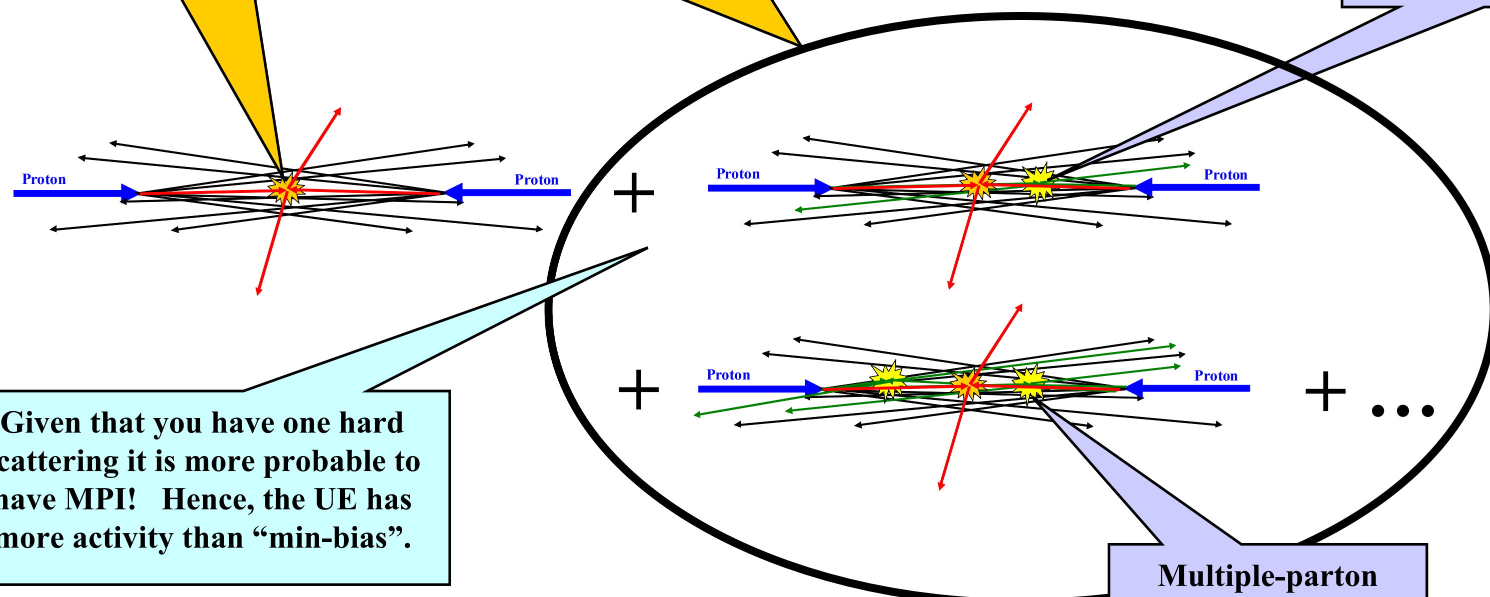
$p_{T0}(E_{cm}) = p_{T0Ref} \times (E_{cm}/E_{cmRef})^{ecmPow}$

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

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

The "underlying-event" (UE)!

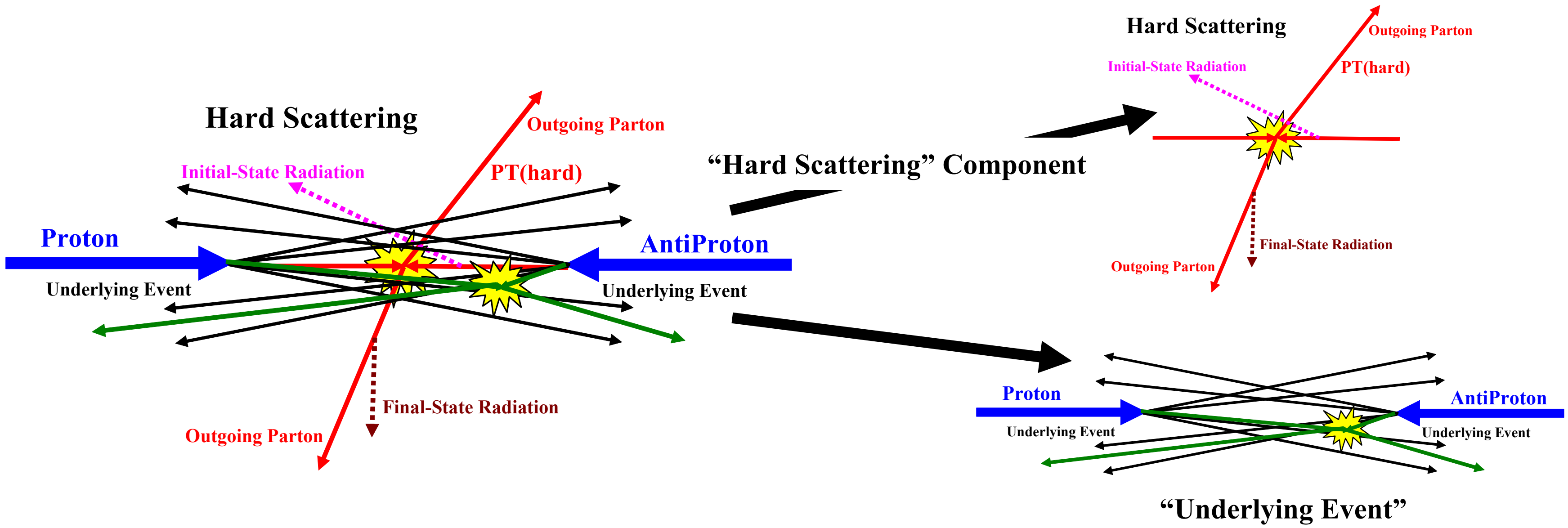
"Semi-hard" parton-parton collision ($p_T < \approx 2$ GeV/c)



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

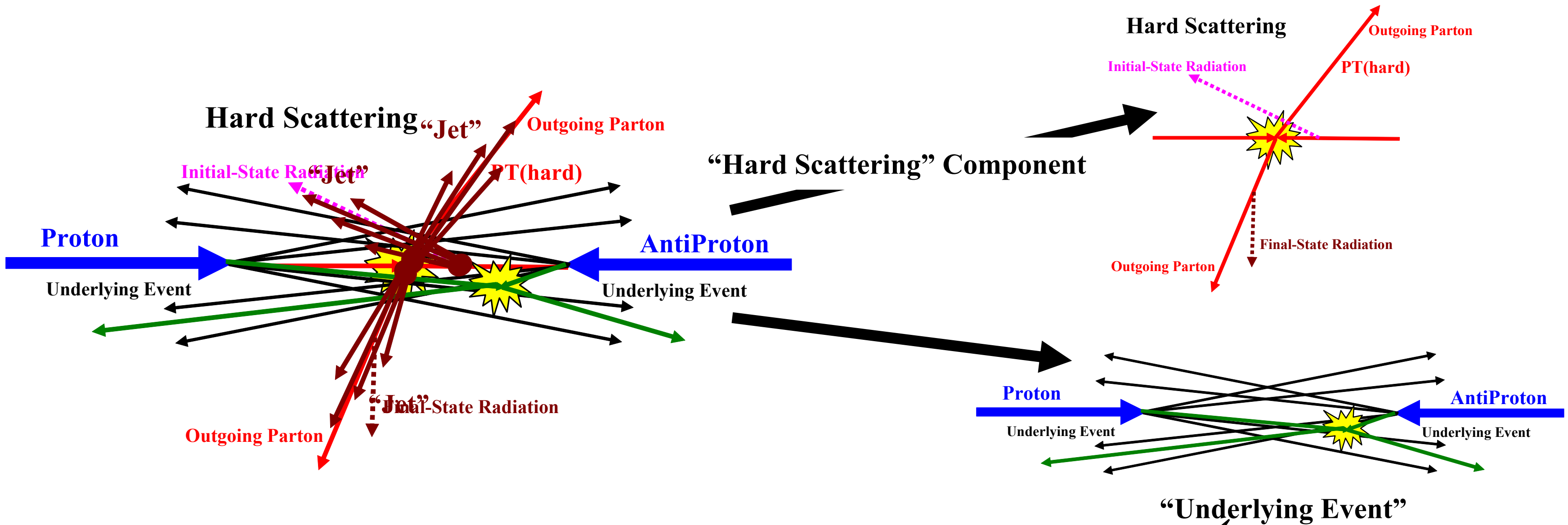
Multiple-parton interactions (MPI)!

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



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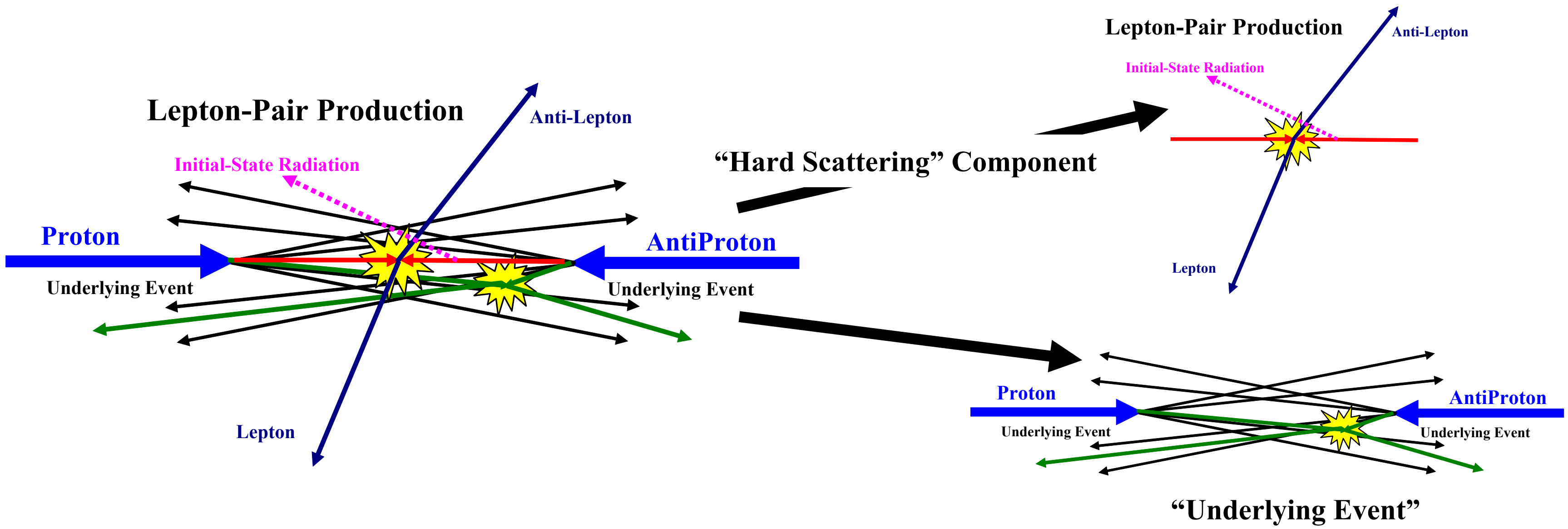
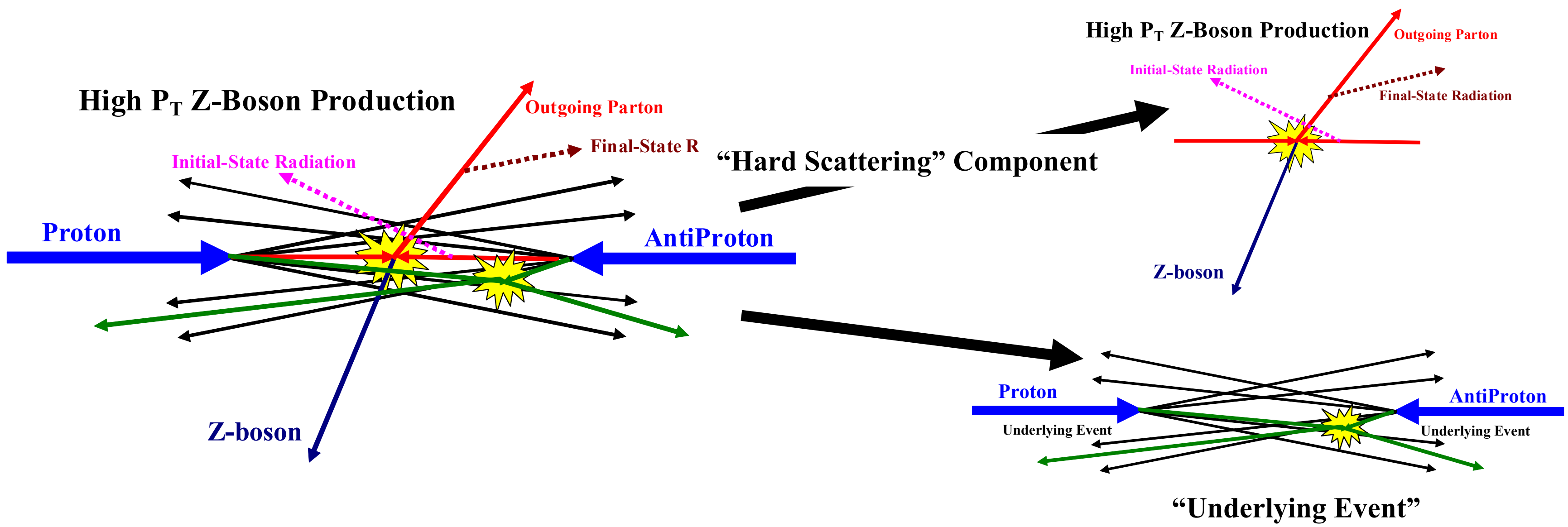
The "underlying event" is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!

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.**

QCD Monte-Carlo Models: Lepton-Pair Production



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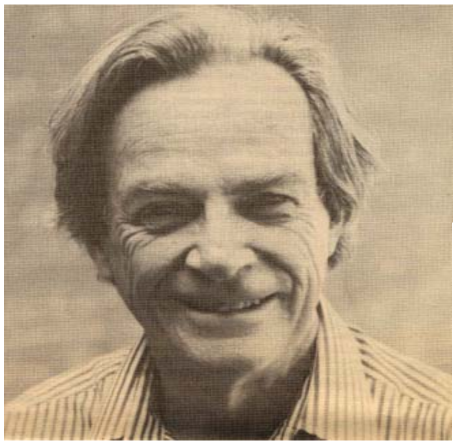
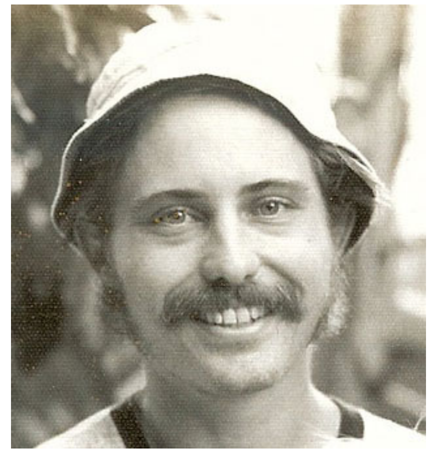
Feynman-Field Phenomenology



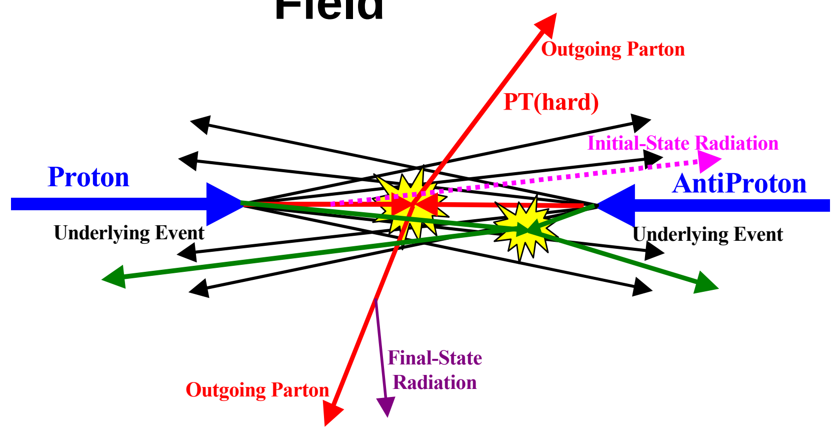
Feynman

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

- **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).

"Feynman-Field Jet Model"

- **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

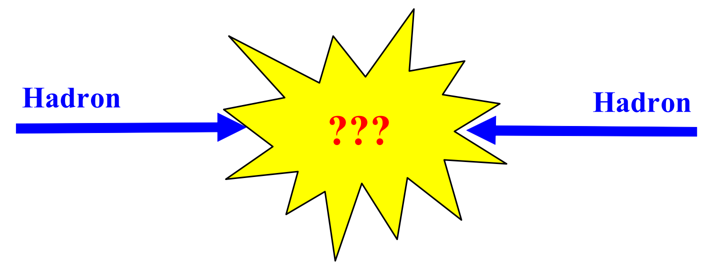
- **What happens when two hadrons collide at high energy?**

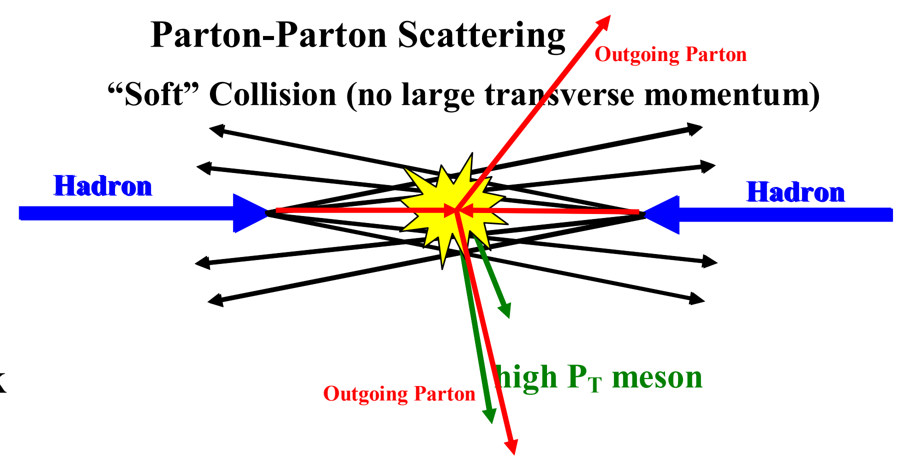
- **Most of the time the hadrons ooze through each other and fall apart (*i.e.* no hard scattering). The outgoing particles continue in roughly the same direction as initial proton and antiproton.**

- **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

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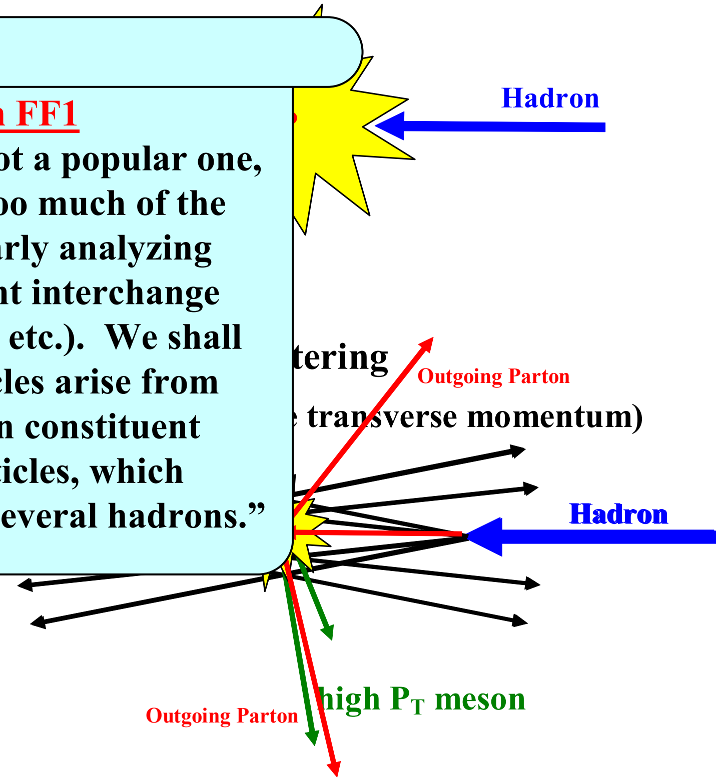
__Feynman quote from FF1__

"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"

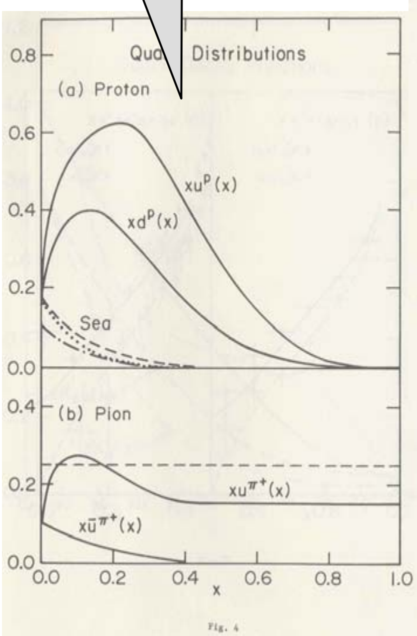


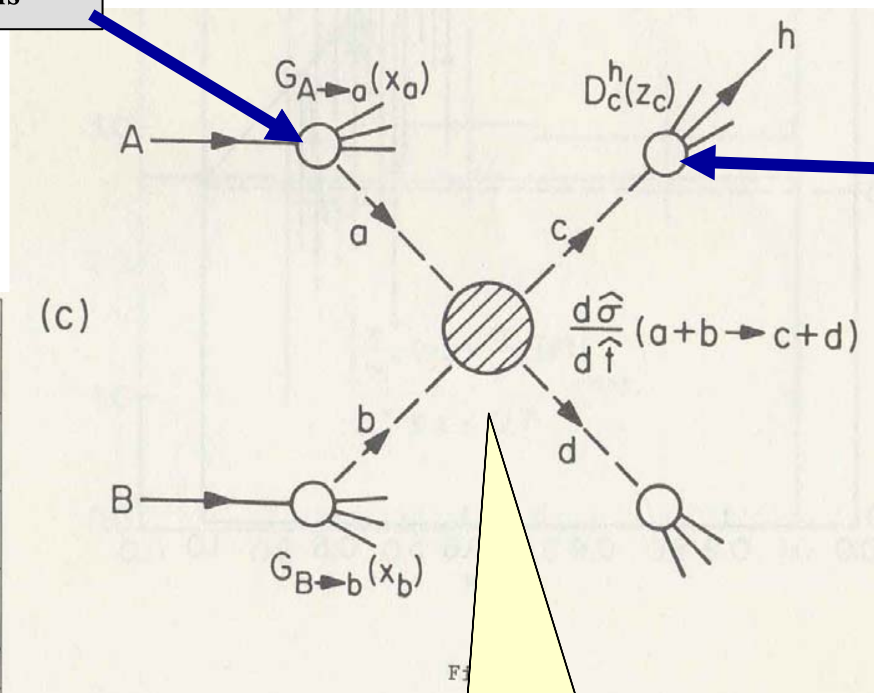
Quark-Quark Black-Box Model

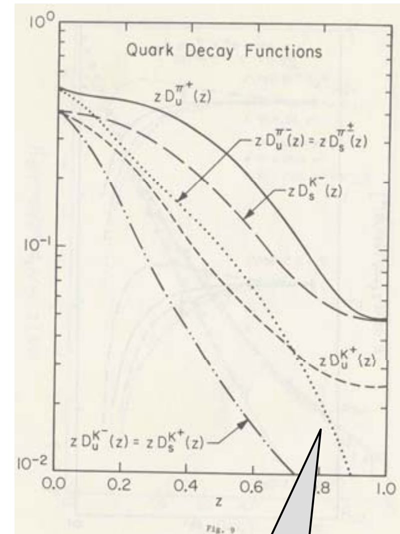
FF1 1977

No gluons!

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







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

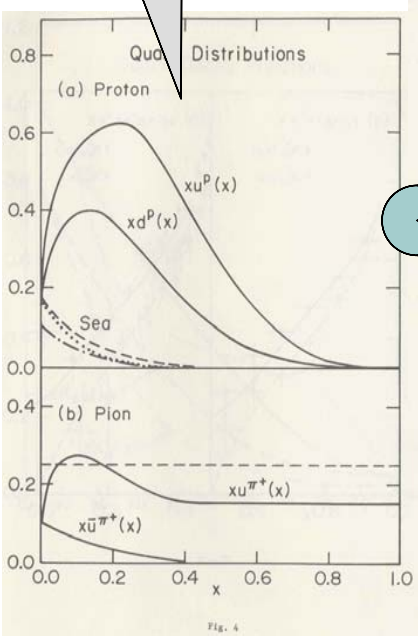
Quark Fragmentation Functions
determined from e^+e^- annihilations

Quark-Quark Black-Box Model

FF1 1977

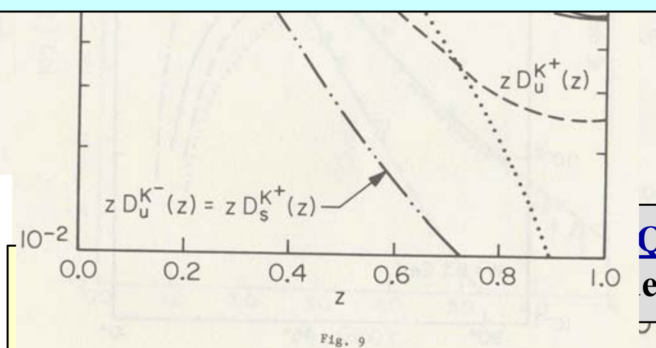
No gluons!

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

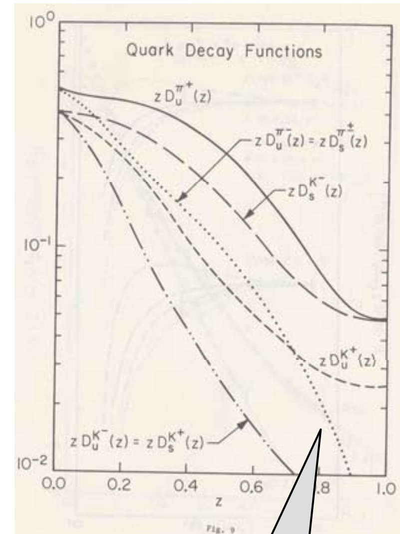


Feynman quote from FF1

"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."



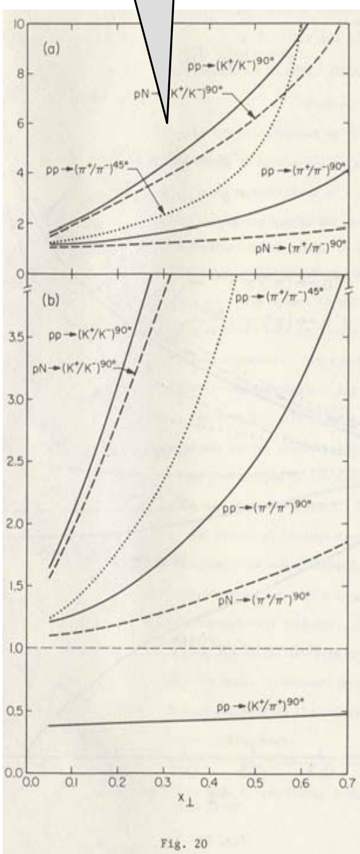
hadron-hadron collisions.



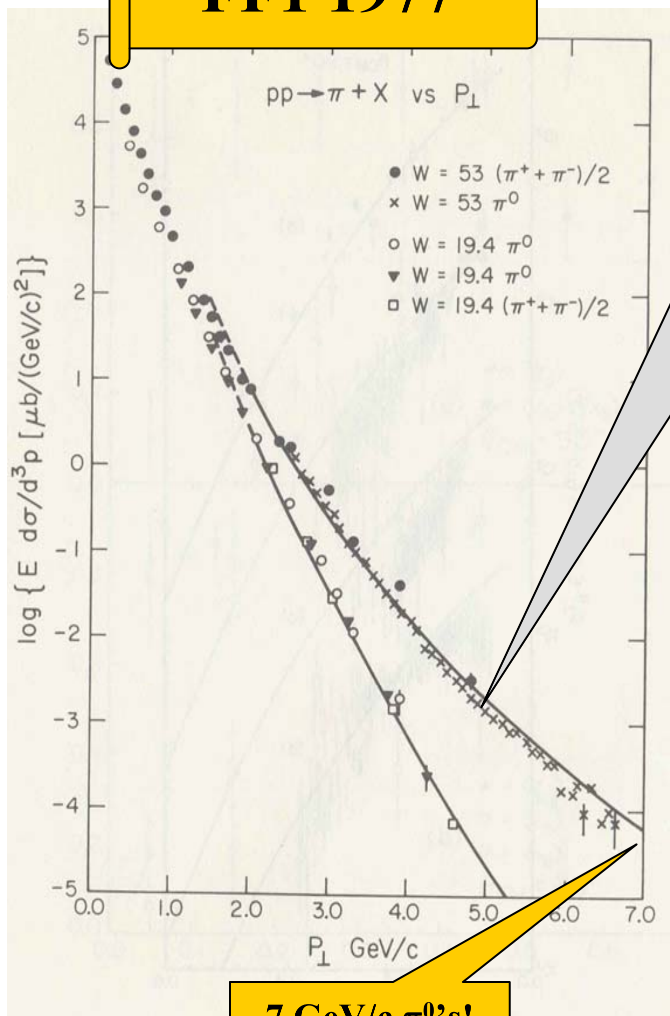
Quark Fragmentation Functions etermined from e^+e^- annihilations

Quark-Quark Black-Box Model

Predict particle ratios

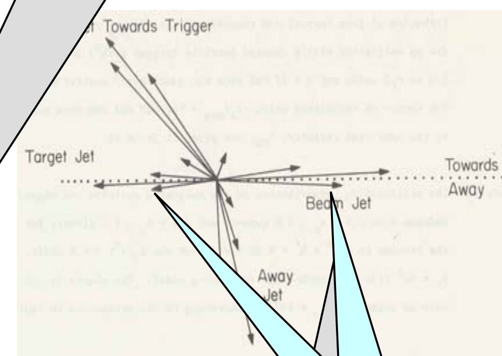


FF1 1977



7 GeV/c π^0's!

Predict increase with increasing CM energy W

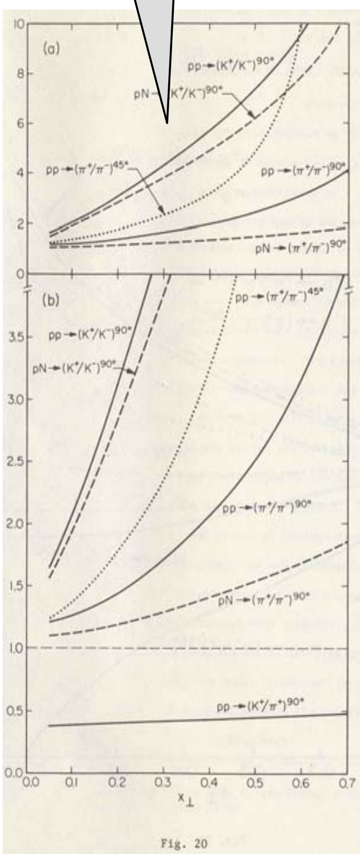


"Beam-Beam Remnants"

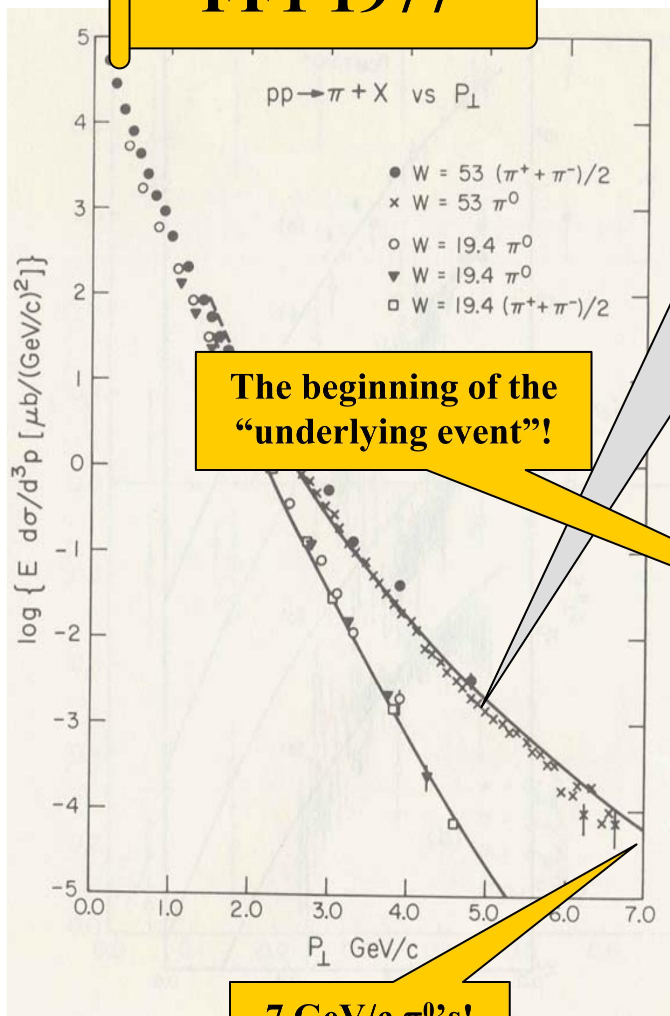
Predict overall event topology (FFF1 paper 1977)

Quark-Quark Black-Box Model

Predict particle ratios



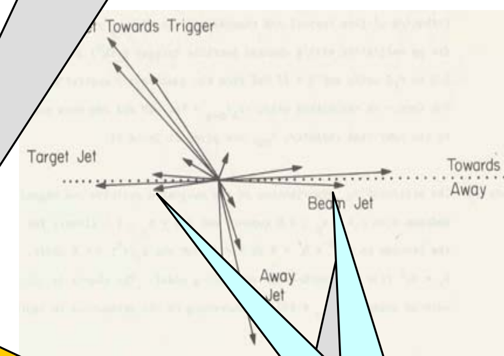
FF1 1977



Predict increase with increasing CM energy W

The beginning of the "underlying event"!

7 GeV/c π^0's!



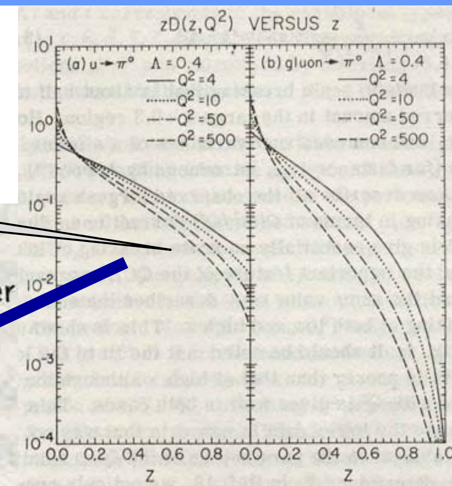
"Beam-Beam Remnants"

Predict overall event topology (FFF1 paper 1977)

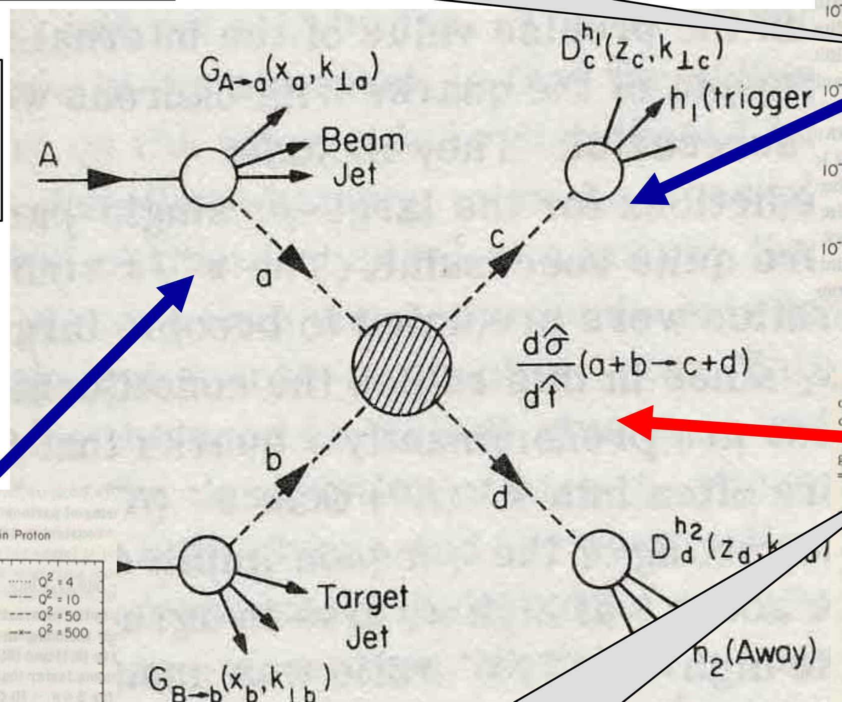
QCD Approach: Quarks & Gluons

FFF2 1978

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



Parton Distribution Functions
Q^2 dependence predicted from QCD



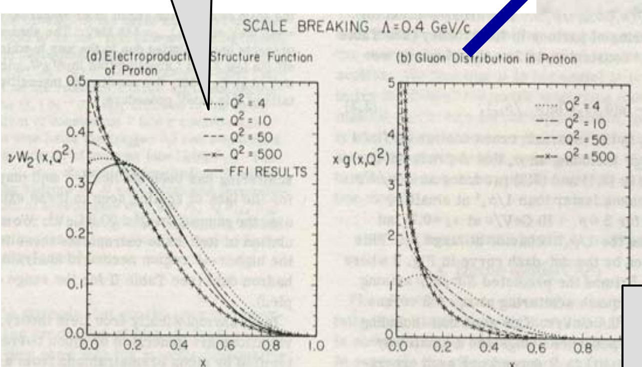


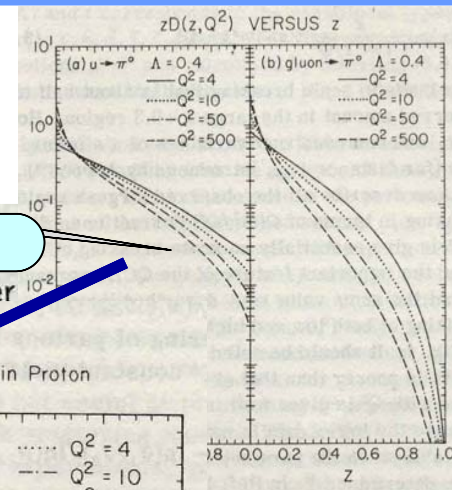
TABLE I. Cross sections for the various constituent quark-quark, quark-gluon, and gluon-gluon subprocesses.[a] The differential cross section is given by $d\hat\sigma/d\hat t = \pi\alpha_s^2(Q^2)|A|^2/\hat s^2$, where $\alpha_s(Q^2)$ is the effective coupling given by Eq. (3.1).

	Subprocess	$\lvert A\rvert^2$
1.	$q_iq_j \to q_iq_j$ $q_i\bar q_j \to q_i\bar q_j$ $(i \neq j)$	$\frac{4}{9}\frac{\hat s^2+\hat u^2}{\hat t^2}$
2.	$q_iq_i \to q_iq_i$	$\frac{4}{9}\left(\frac{\hat s^2+\hat u^2}{\hat t^2}+\frac{\hat s^2+\hat t^2}{\hat u^2}\right)-\frac{8}{27}\frac{\hat s^2}{\hat u\hat t}$
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.	$q_ig \to q_ig$	$-\frac{4}{9}\left(\frac{\hat u^2+\hat s^2}{\hat u\hat s}\right)+\left(\frac{\hat u^2+\hat s^2}{\hat t^2}\right)$
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



FFF2 1978

Parton Distribution Functions
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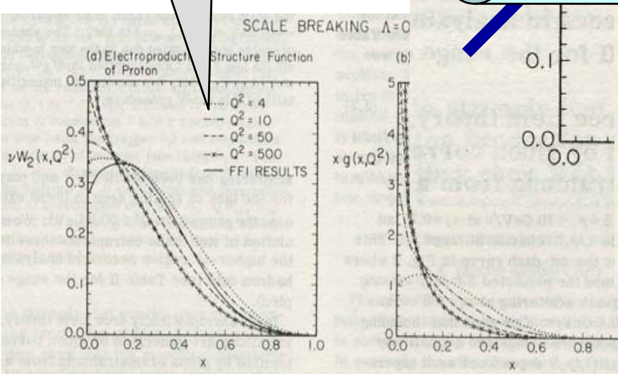


Feynman quote from FFF2

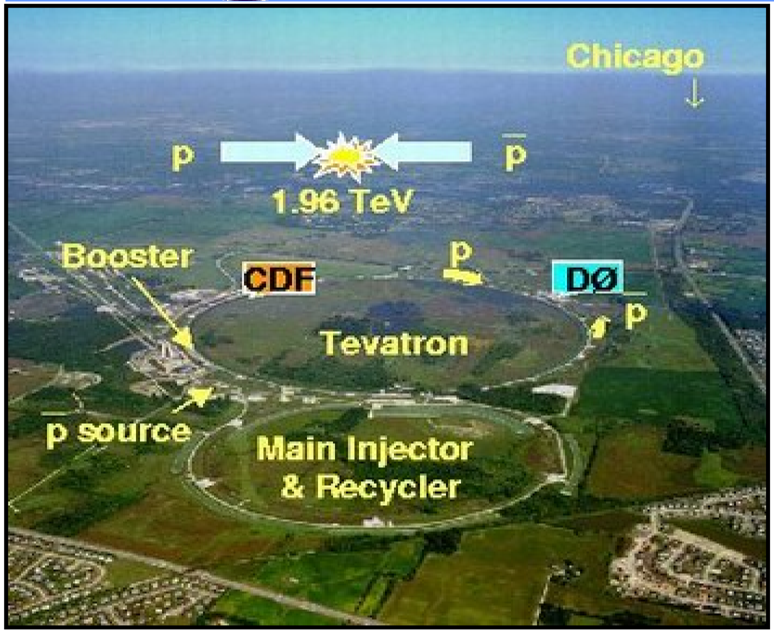
"We investigate whether the present experimental behavior of mesons with large transverse momentum in hadron-hadron collisions is consistent with the theory of quantum-chromodynamics (QCD) with asymptotic freedom, at least as the theory is now partially understood."

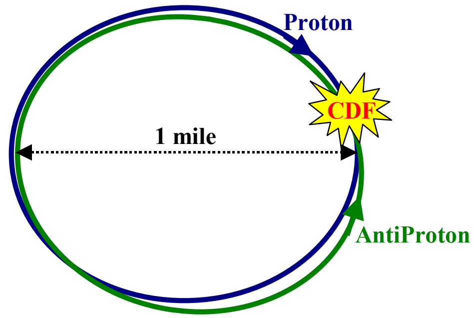
TABLE I. Cross sections for the various constituent

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

The Fermilab Tevatron



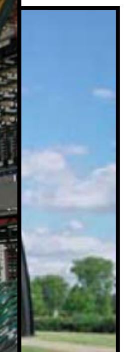


➡ **I joined CDF in January 1998.**

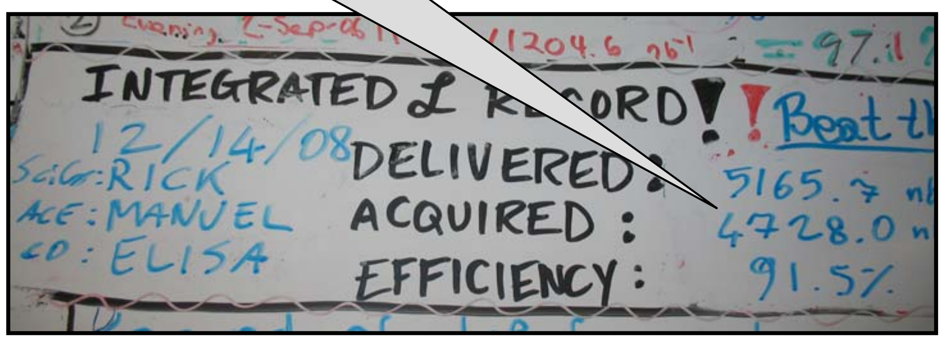
The Fermilab Tevatron

CDF "SciCo" Shift December 12-19, 2008

My wife Jimmie on shift with me!

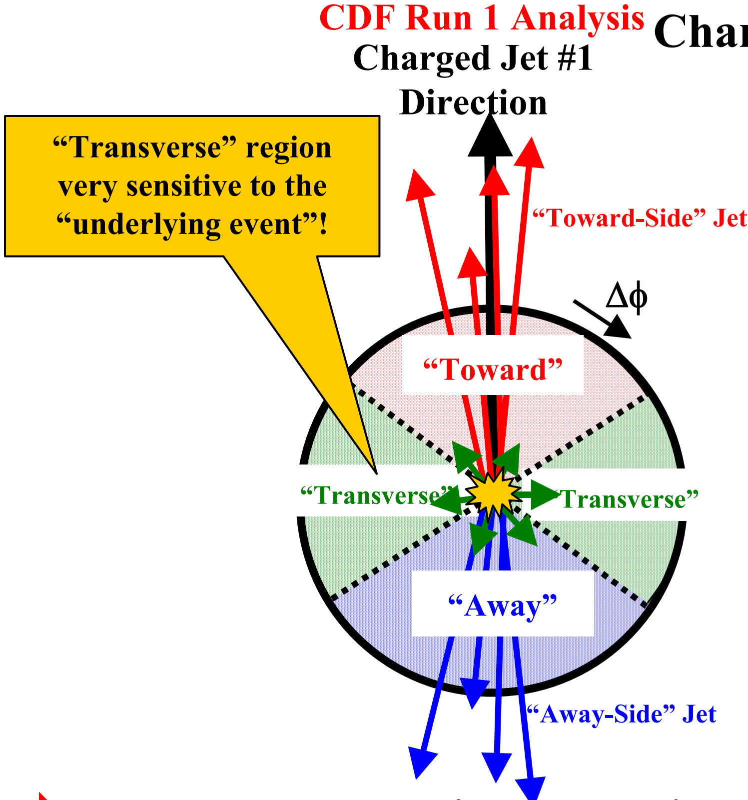


Acquired 4728 nb^{-1} during 8 hour "owl" shift!



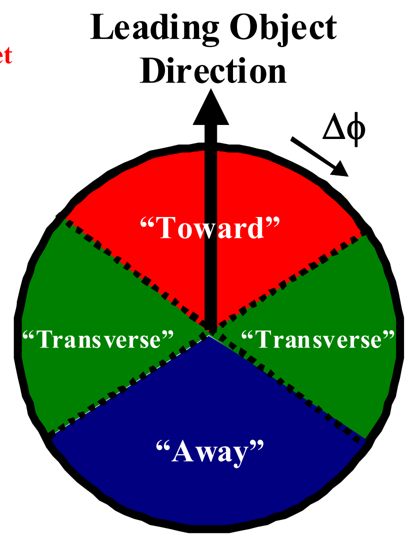
- **I joined CDF in January 1998.**

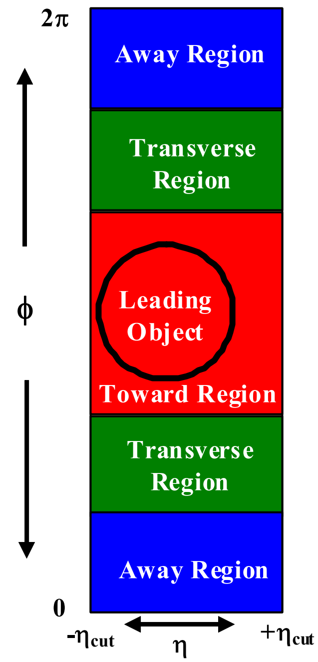
Traditional Approach



Charged Particle Δϕ Correlations

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



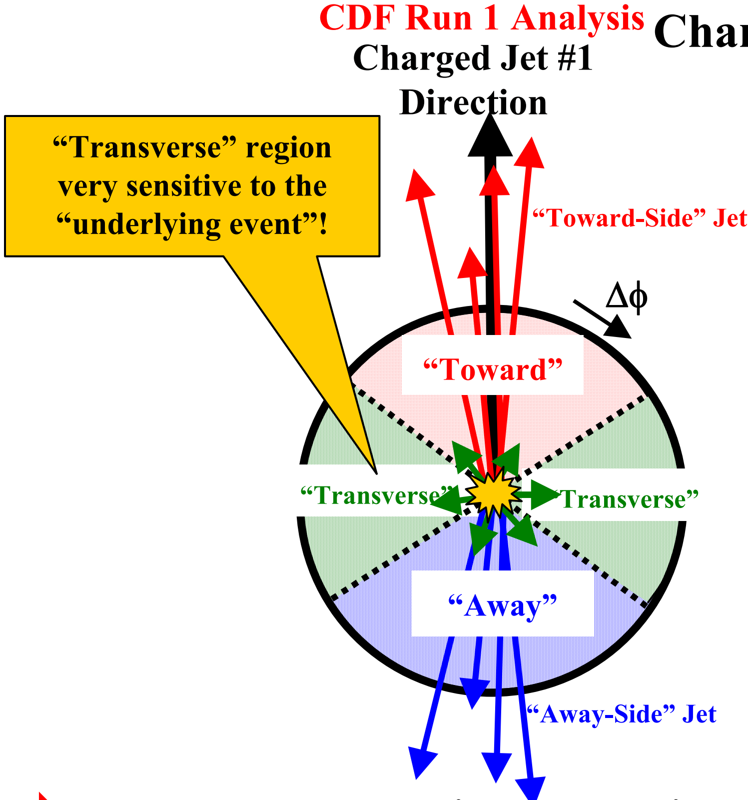


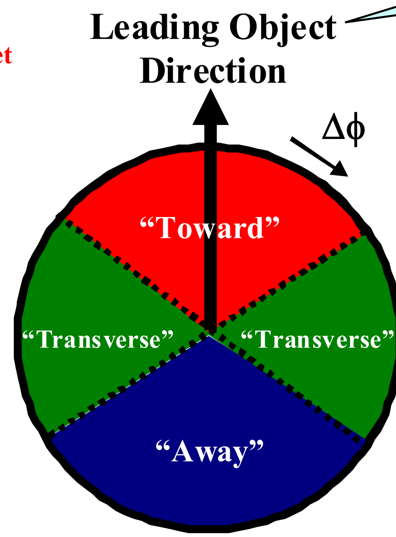
- Look at charged particle correlations in the azimuthal angle Δϕ relative to a leading object (*i.e.* CaloJet#1, ChgJet#1, PTmax, Z-boson). For CDF PTmin = 0.5 GeV/c η_{cut} = 1.0 or 0.8.
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$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

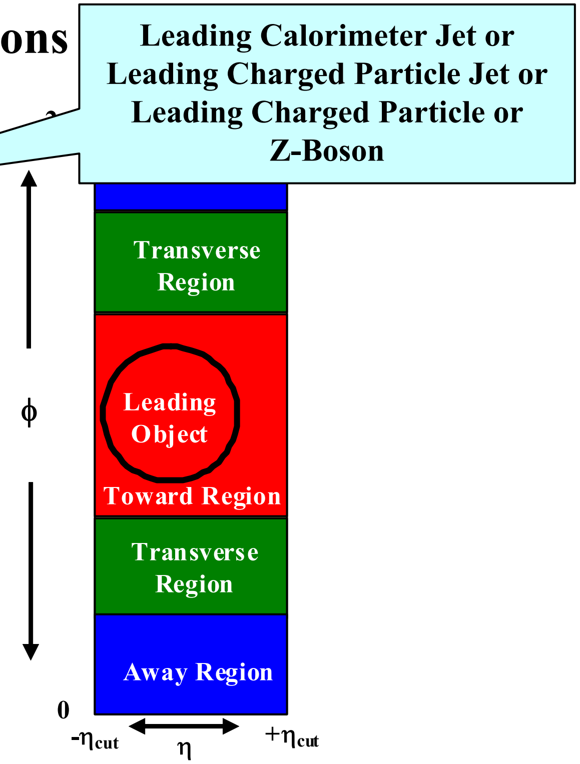
Traditional Approach

Charged Particle $\Delta\phi$ Correlations

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



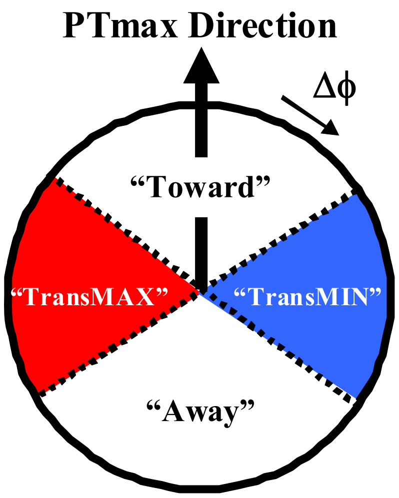




- Look at charged particle correlations in the azimuthal angle $\Delta\phi$ relative to a leading object (*i.e.* CaloJet#1, ChgJet#1, PTmax, Z-boson). For CDF PTmin = 0.5 GeV/c η_{cut} = 1.0 or 0.8.
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ 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.

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, $2\eta_{cut}\times2\pi/6$, 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, $2\eta_{cut}\times2\pi/6$, averaged over all events with at least one particle with p_T > 0.5 GeV/c, $|\eta| < \eta_{cut}$.

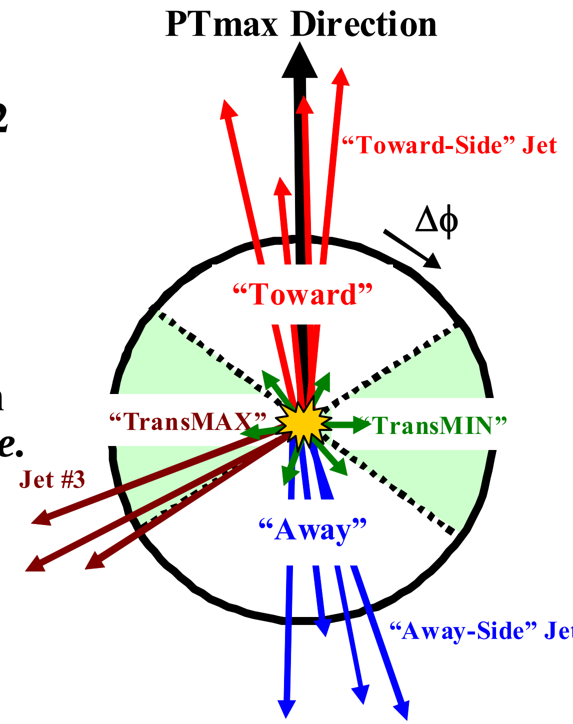
Note: The overall "transverse" density is equal to the average of the "transMAX" and "TransMIN" densities. The "TransDIF" Density is the "transMAX" Density minus the "transMIN" Density

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

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

"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).



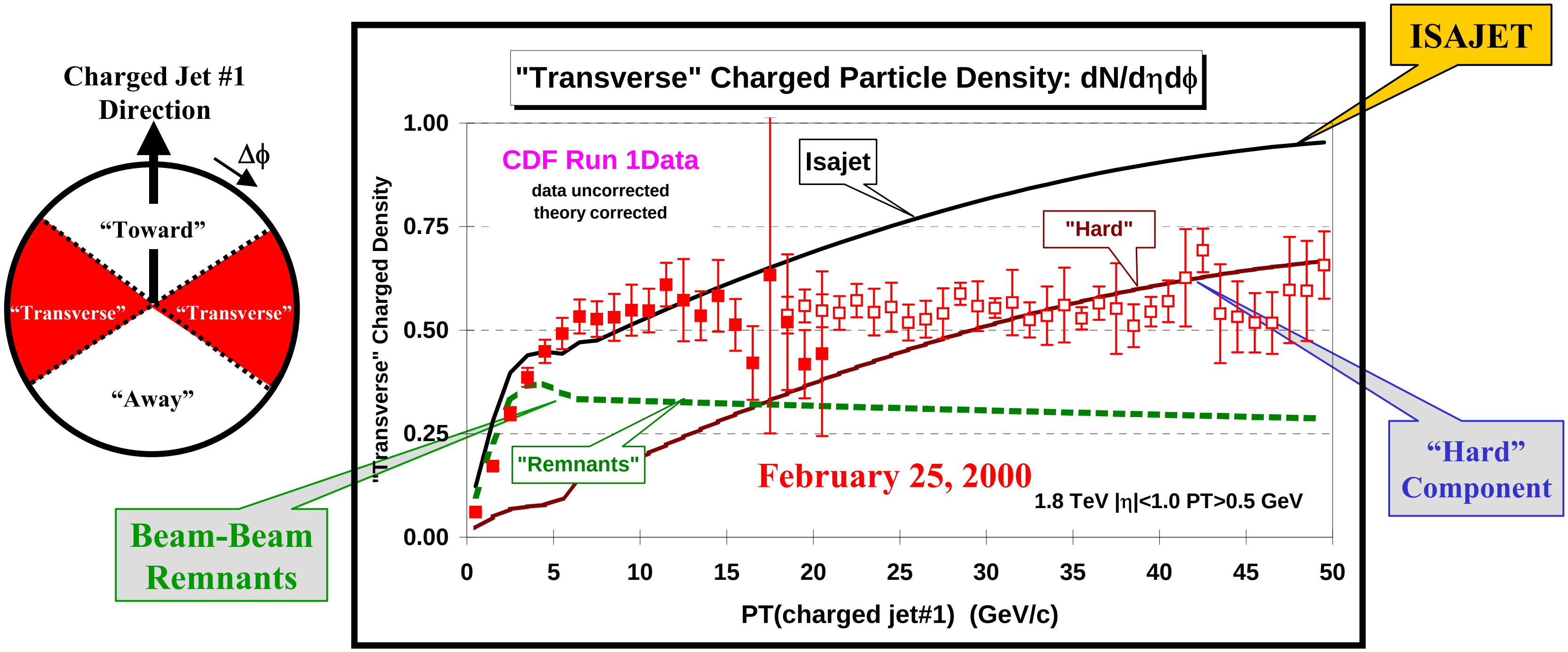
"TransMIN" density more sensitive to MPI & BBR.

"TransDIF" density more sensitive to ISR & FSR.

0 ≤ "TransDIF" ≤ 2×"TransAVE"

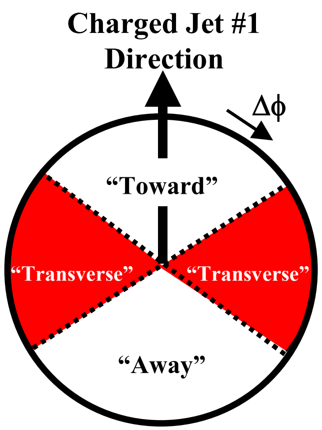
"TransDIF" = "TransAVE" if "TransMIX" = 3×"TransMIN"

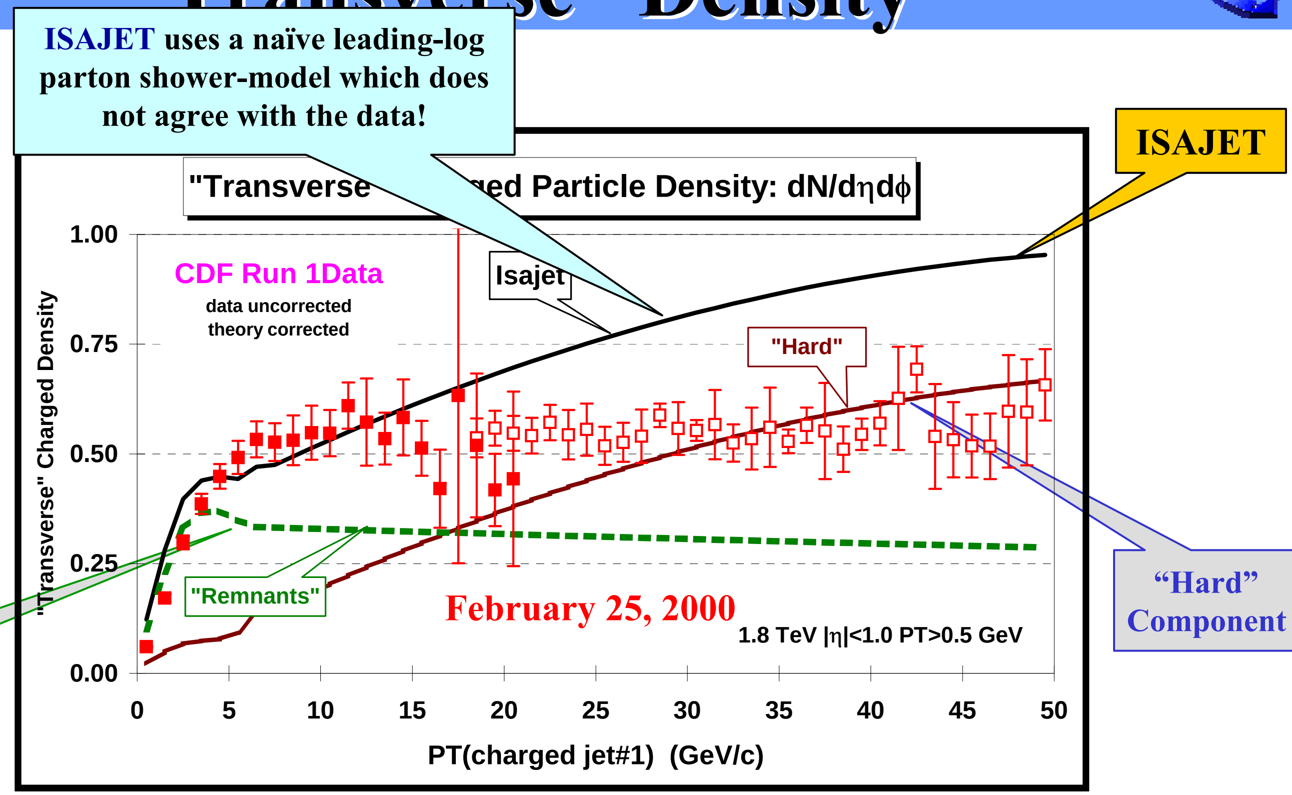
ISATJET 7.32 (without MPI) "Transverse" Density



- 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).

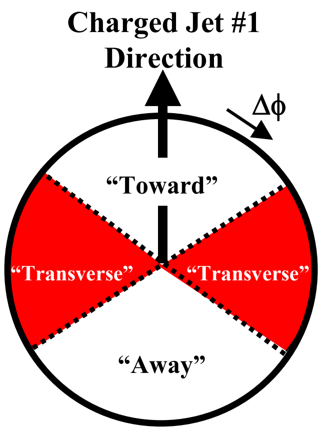
ISAJET 7.32 (without MPI) "Transverse" Density



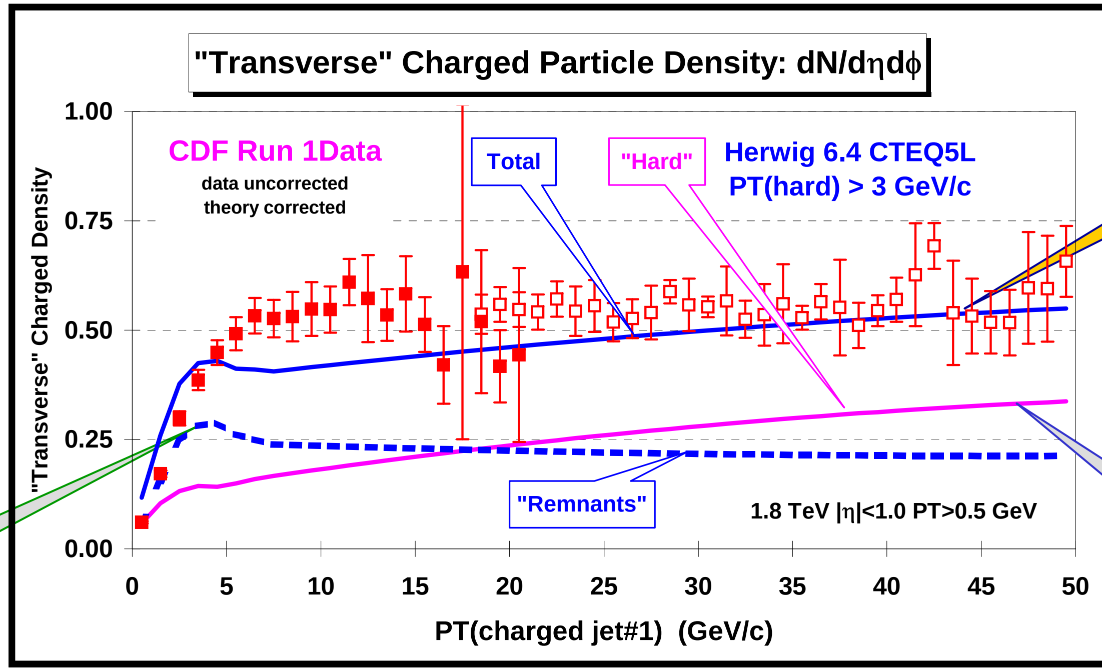


- Plot shows average "transverse" charge particle density ($|\eta|<1$, $p_T>0.5$ GeV) versus P_T(charged jet#1) compared to the QCD hard scattering predictions of ISAJET 7.32 (default parameters with P_T(hard)>3 GeV/c) .
- The predictions of ISAJET are divided into two categories: charged particles that 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



Beam-Beam Remnants



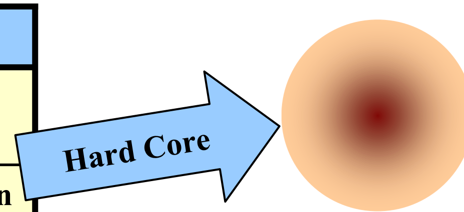
HERWIG

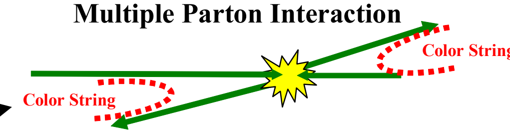
"Hard" Component

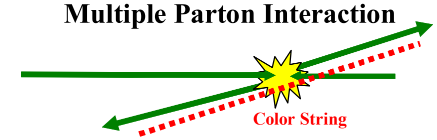
- Plot shows average "transverse" charge particle density (|η|<1, p_T>0.5 GeV) versus P_T(charged jet#1) compared to the QCD hard scattering predictions of HERWIG 5.9 (default parameters with P_T(hard)>3 GeV/c without MPI).
- The predictions of HERWIG are divided into two categories: charged particles 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).

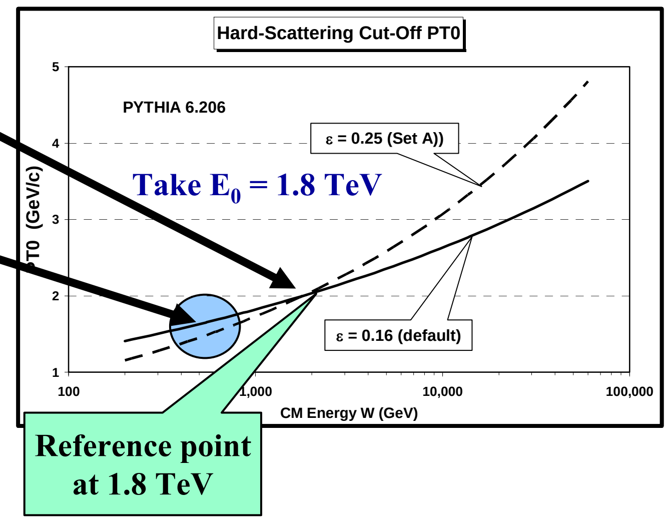
Tuning PYTHIA 6.2:
Multiple Parton Interaction Parameters

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.







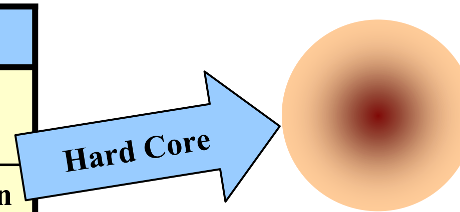


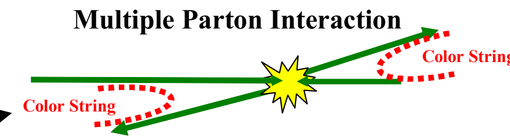
Tuning PYTHIA 6.2:
Multiple Parton Interaction Parameters

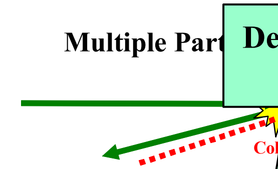
Parameter	Default	Description
PARP(83)	0.5	Double-Gaussian: Fraction of total hadronic matter within PARP(84)
PARP(84)	0.2	Double-Gaussian: Fraction of the overall hadron radius containing the fraction PARP(83) of the total hadronic matter.
PARP(85)	0.33	Pr… uces two gluons w… nearest neighbors.
PARP(86)	0.66	Prob…y t… luons eit…s des… closed …l loop. … ists of …ark-antiqua…s.
PARP(89)	1 Te…	Determin… reference energy E_0.
PARP(82)	…9 GeV/c	The c…off P_{T0} that regulates the 2-to-2 sc…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!

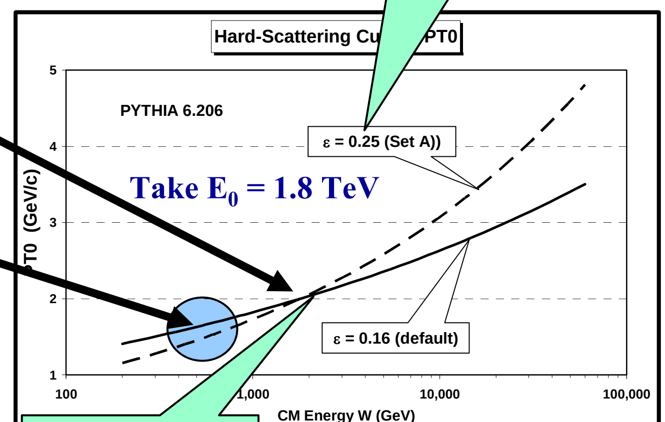
Affects the amount of initial-state radiation!







Determine by comparing with 630 GeV data!



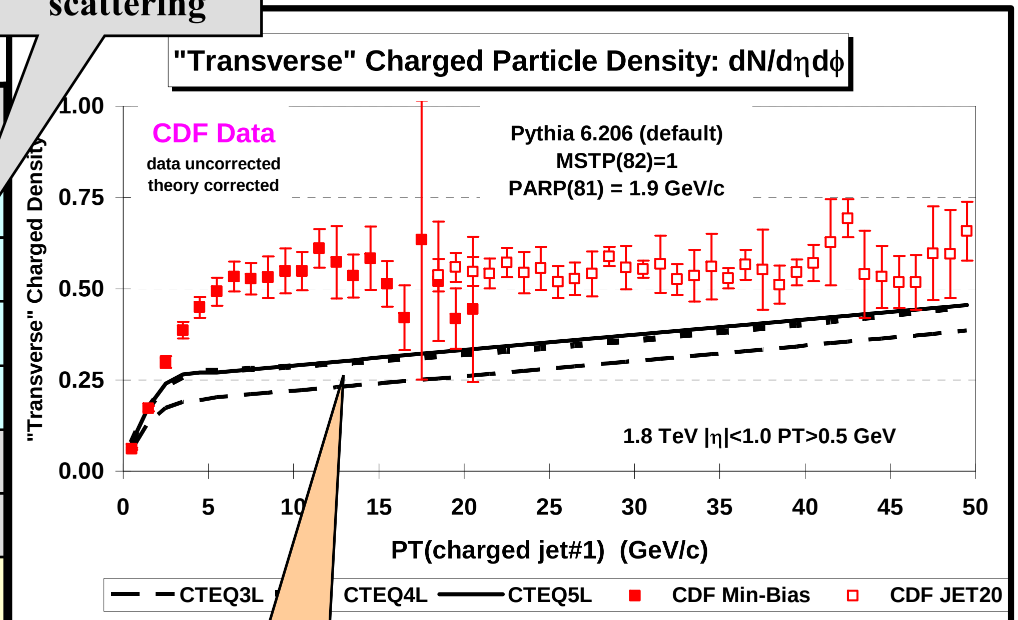
Reference point at 1.8 TeV

PYTHIA 6.206 Defaults

MPI constant probability scattering

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



- 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)

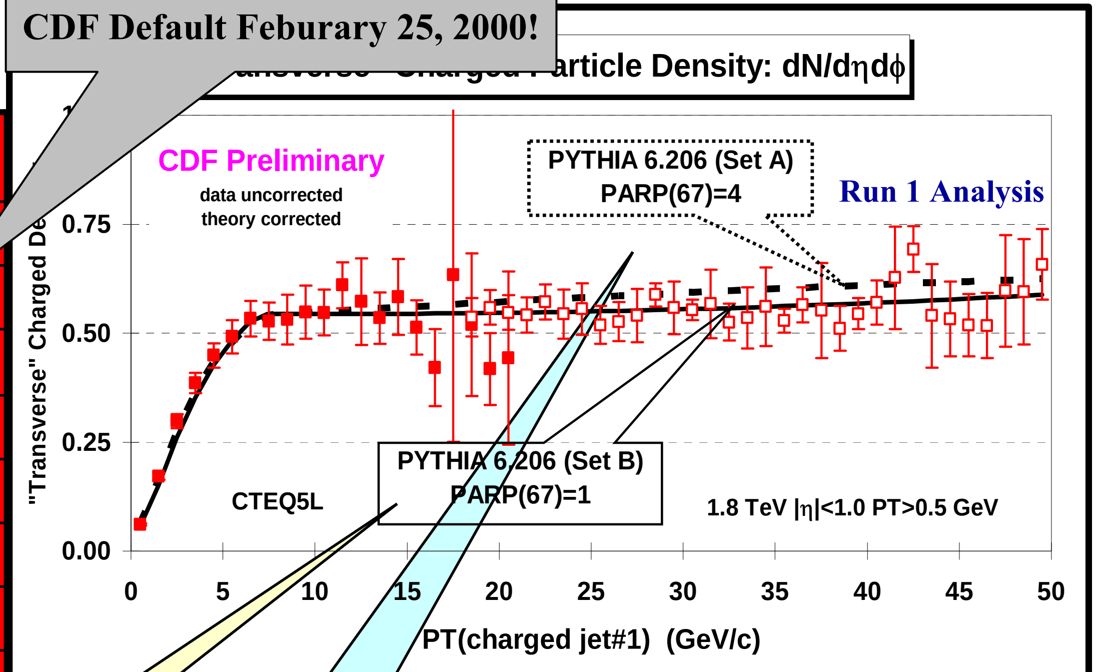
Default parameters give very poor description of the "underlying event"!

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

CDF Default Feburary 25, 2000!

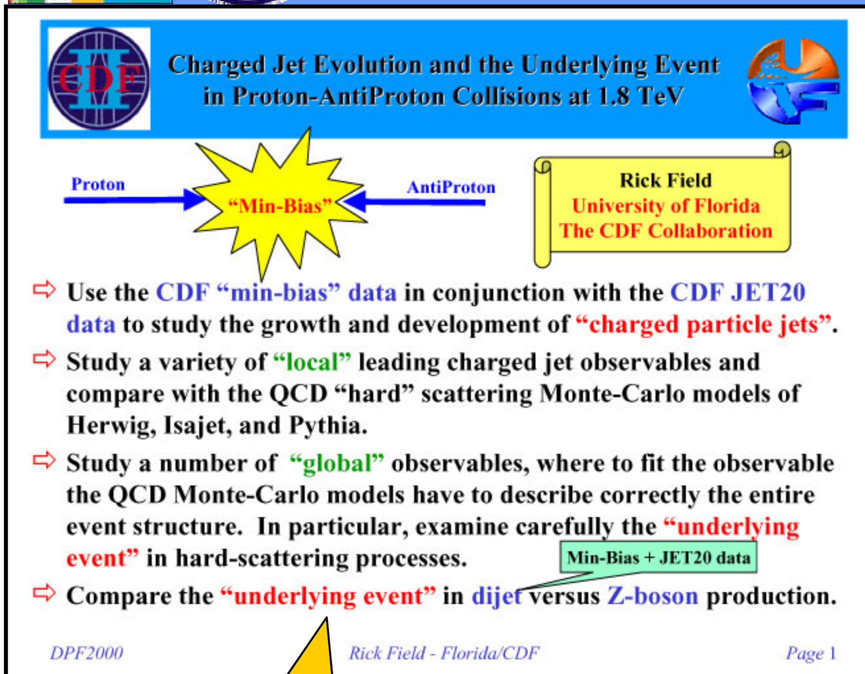


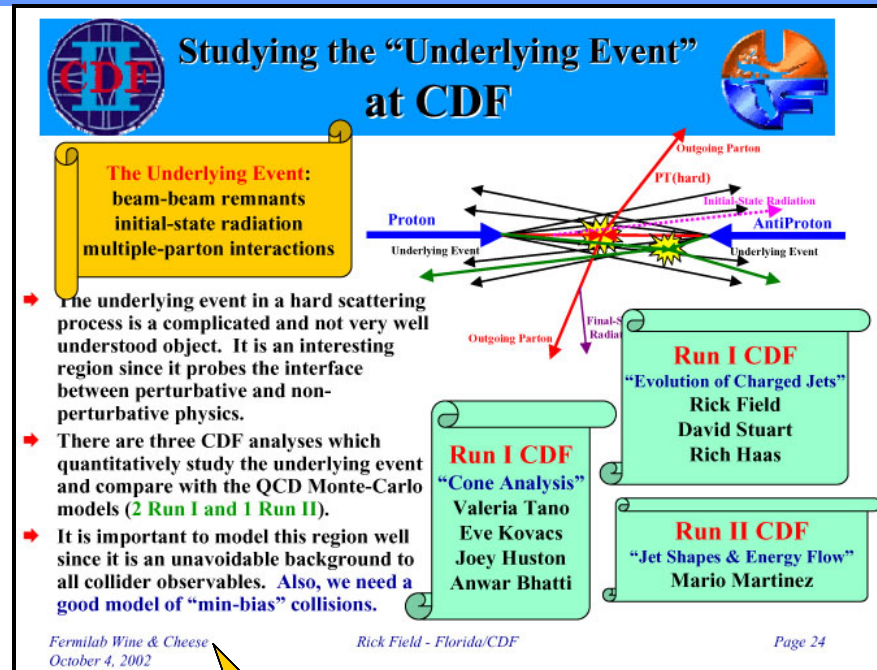
- Plot shows the "transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

Early Studies of the UE

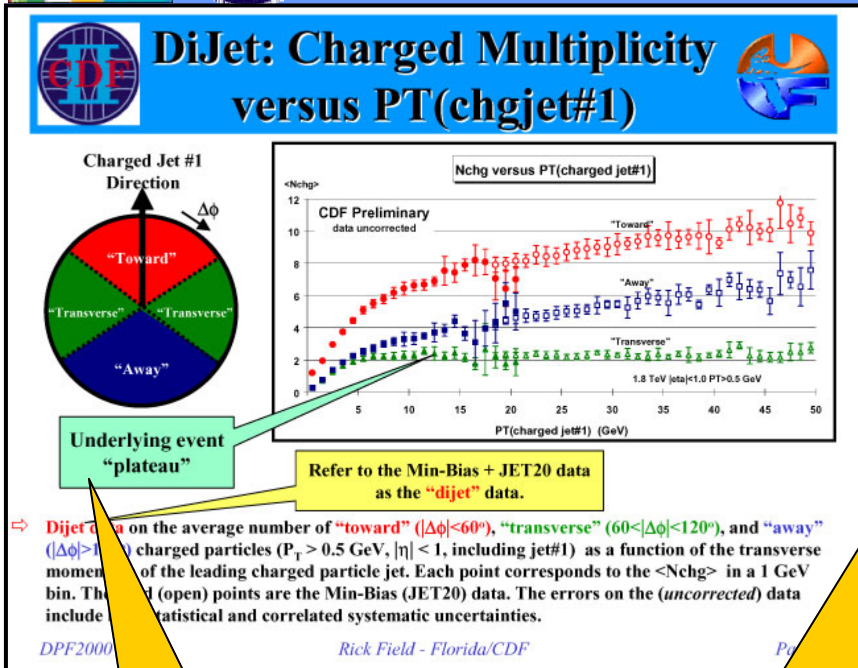


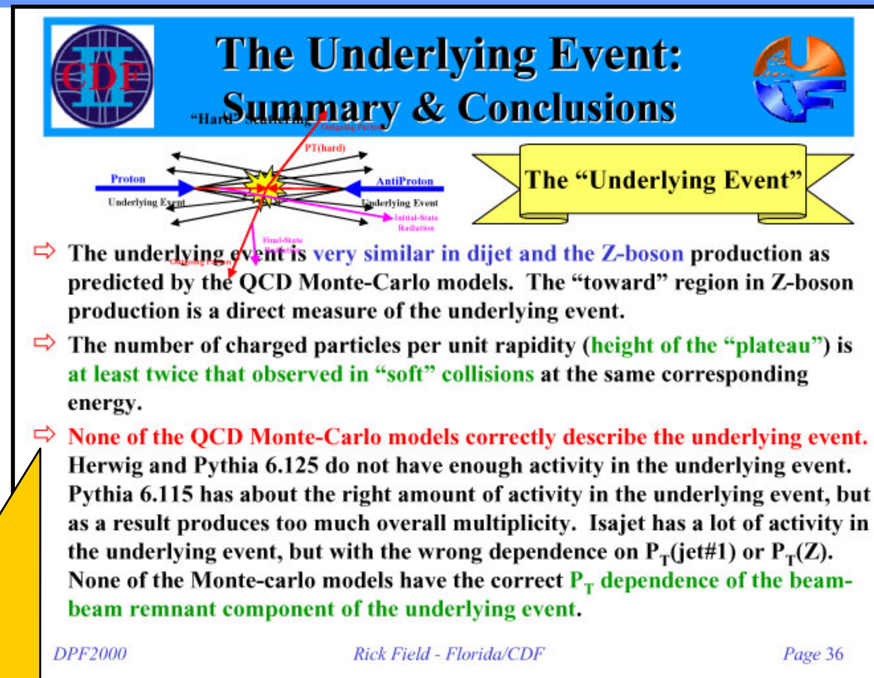


DPF 2000: My first presentation on the "underlying event"!

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

My First Talk on the UE



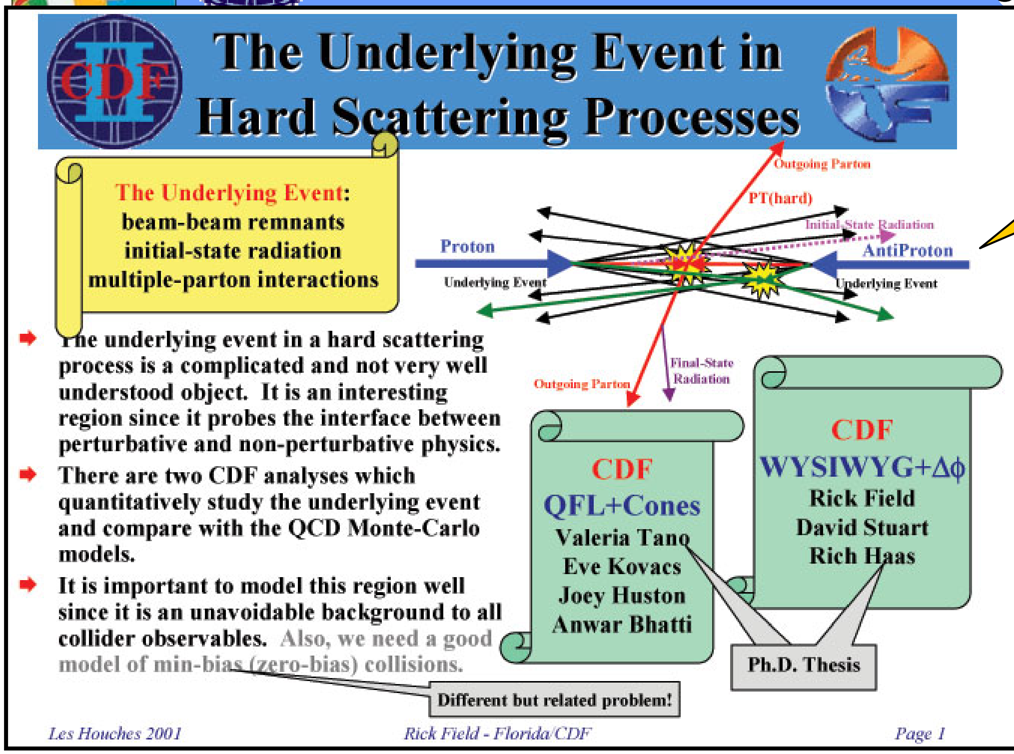


Need to "tune" the QCD MC models!

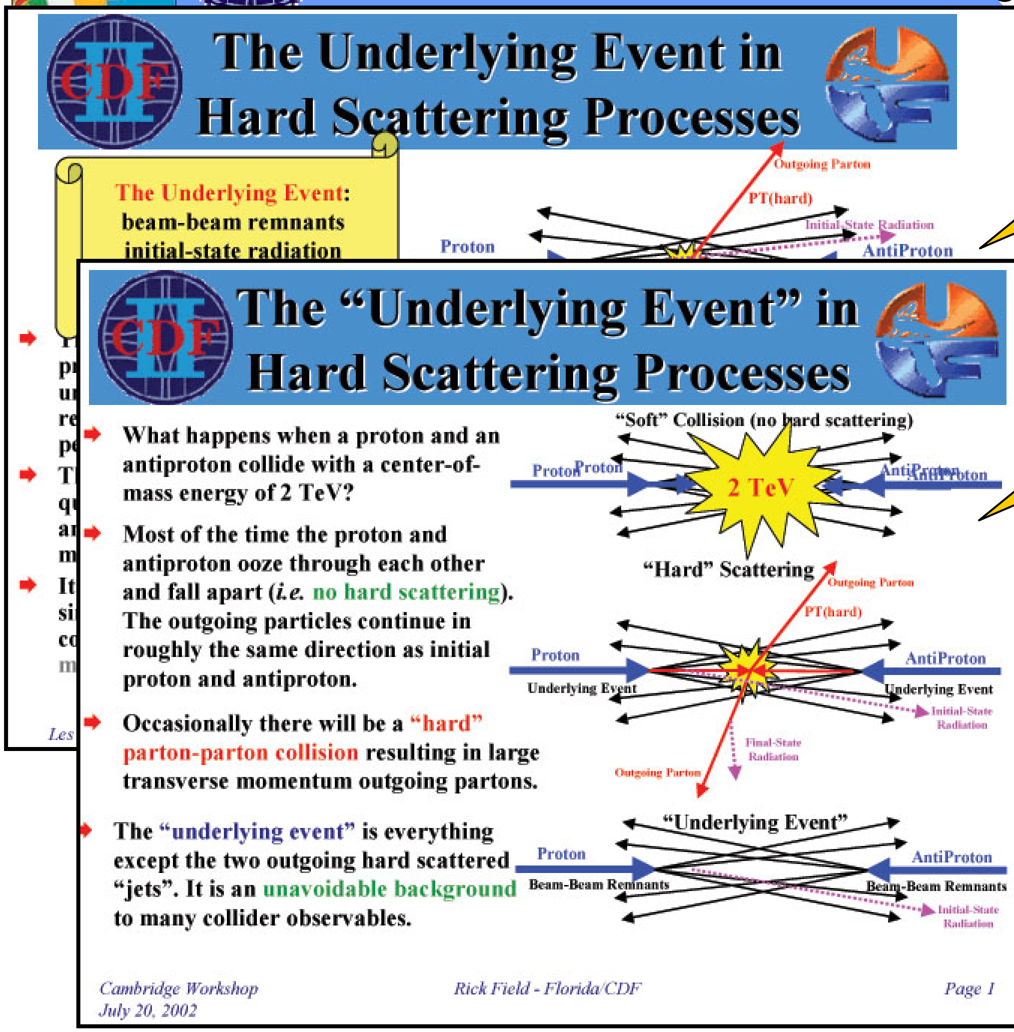
My first look at the "underlying event plateau"!

Other Early UE Talks

Workshop on Physics at TeV Colliders,
Les Houches, *May 30, 2001*.



Other Early UE Talks



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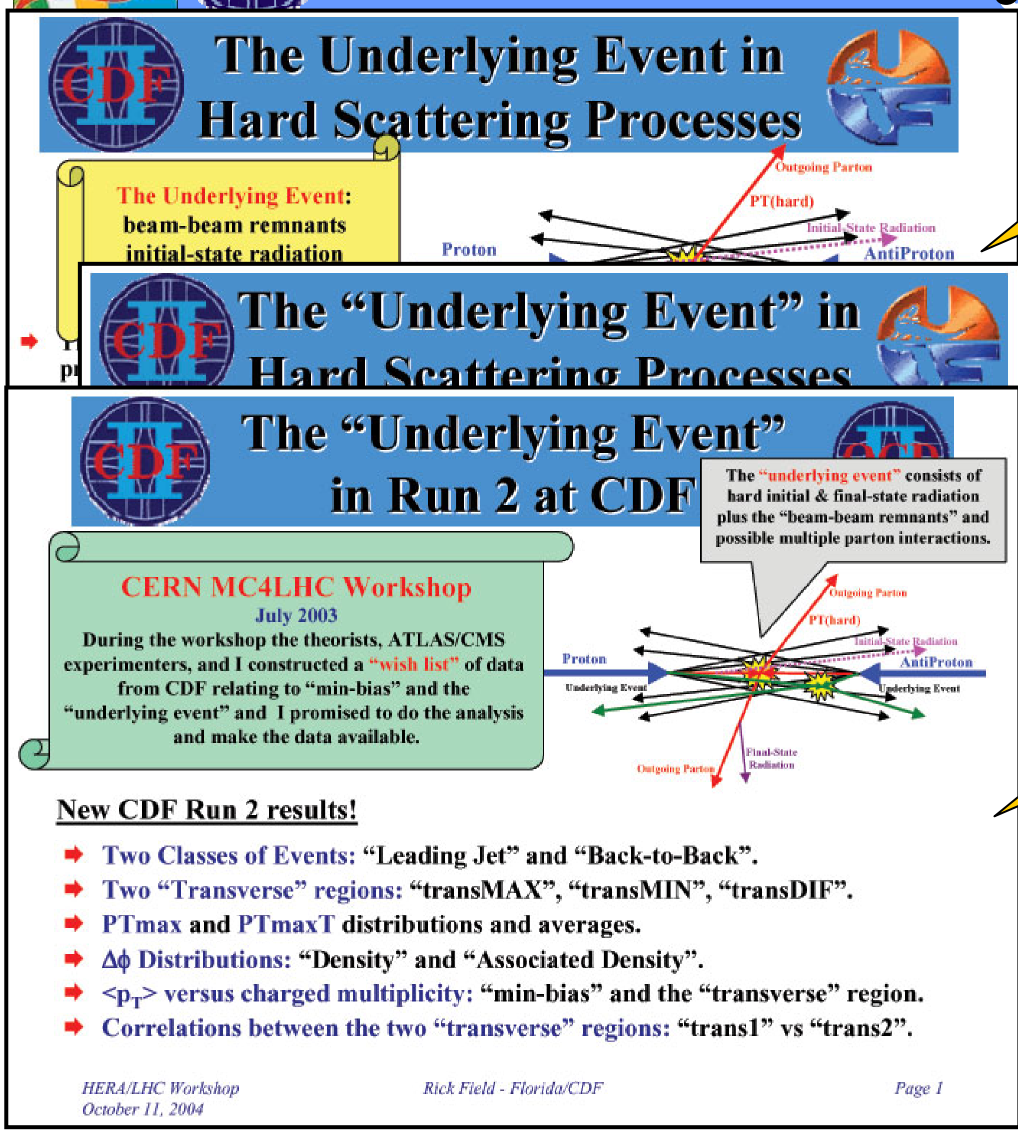
Other Early UE Talks



Workshop on Physics at TeV Colliders, Les Houches, *May 30, 2001*.

Cambridge Workshop on TeV-Scale Physics, *July 20, 2002*.

HERA and the LHC Workshop, CERN, *October 11, 2004*.

KITP Collider Workshop 2004

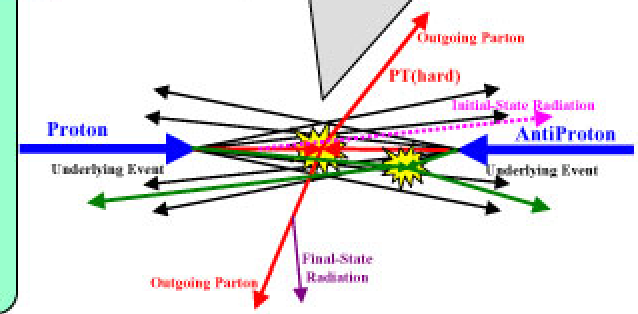
A Closer Look at the Underlying Event in Run 2 a…

CERN MC4LHC Workshop

July 2003

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

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



New CDF Run 2 results!

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

KITP Collider Workshop
February 17, 2004
Rick Field - Florida/CDF
Page 1

KITP Collider Workshop 2004

Together with Torbjörn Sjöstrand and his graduate student Peter Skands!

A Closer Look at the
nderlying Event in Run 2 a

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

CERN M LHC Workshop

July 2 3

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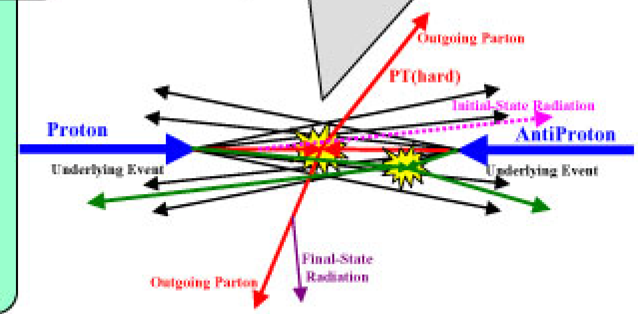

New CDF Run 2 results!

- **Two Classes of Events:** "Leading Jet" and "Back-to-Back".
- **Two "Transverse" regions:** "transMAX", "transMIN", "transDIF".
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- **$\Delta\phi$ Distributions:** "Density" and "Associated Density".
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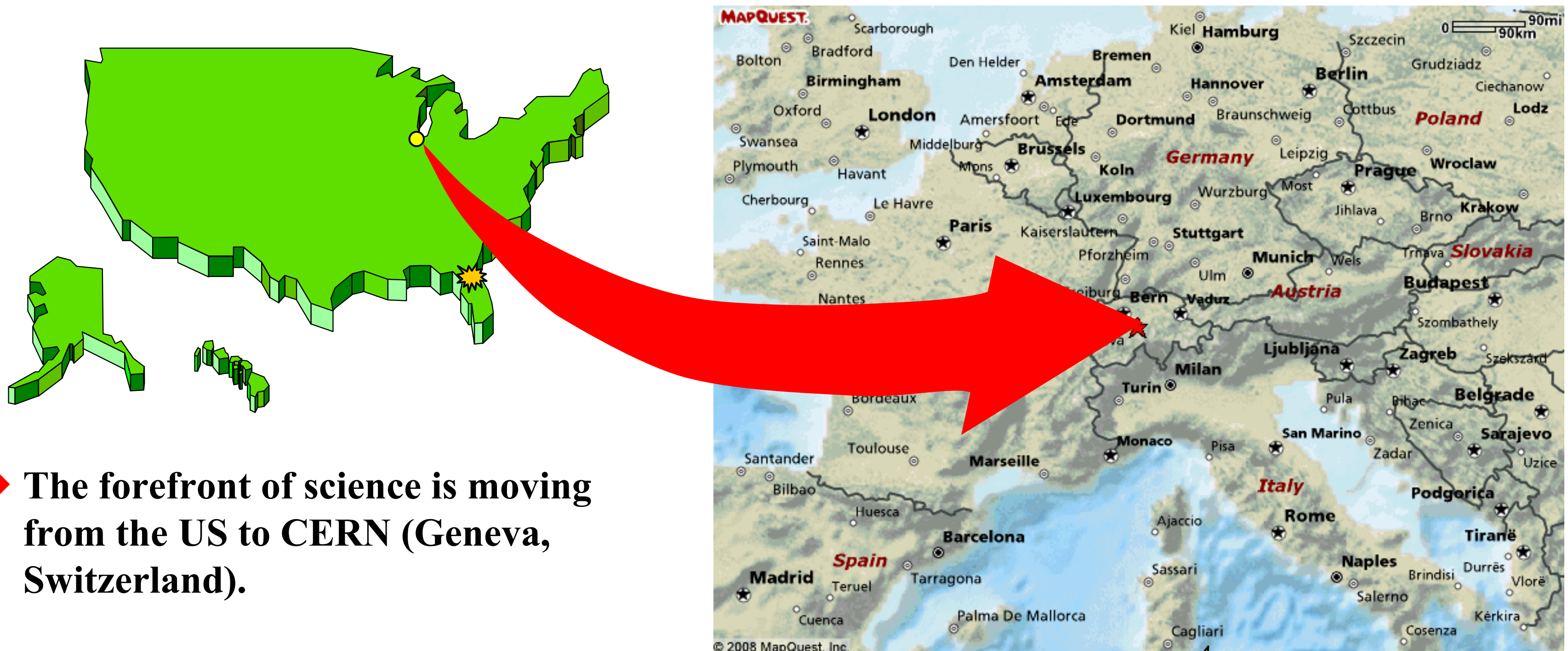
- **Correlations between the two "transverse" regions:** "trans1" vs "trans2".

KITP Collider Workshop
February 17, 2004 *Rick Field - Florida/CDF* *Page 1*

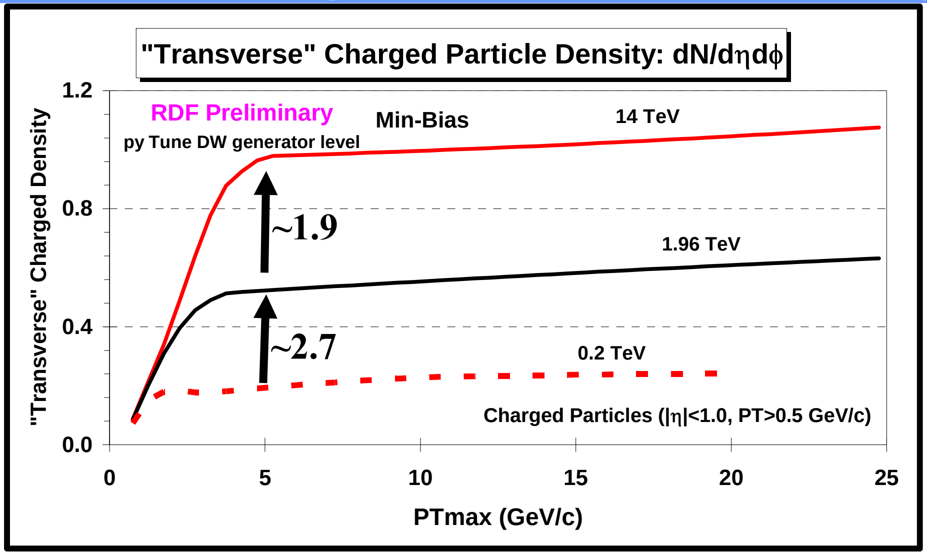
The New Forefront



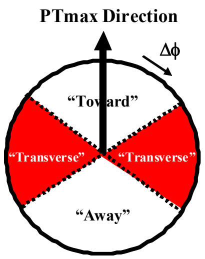
- The forefront of science is moving from the US to CERN (Geneva, Switzerland).

- The LHC is designed to collide protons with protons at a center-of-mass energy of 14 TeV (seven times greater energy than Fermilab)!

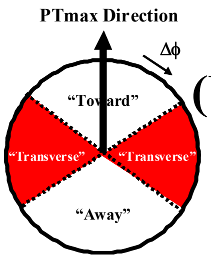
Min-Bias "Associated" Charged Particle Density



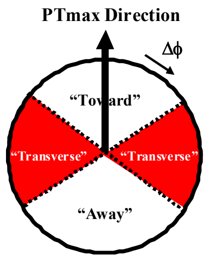
RHIC



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

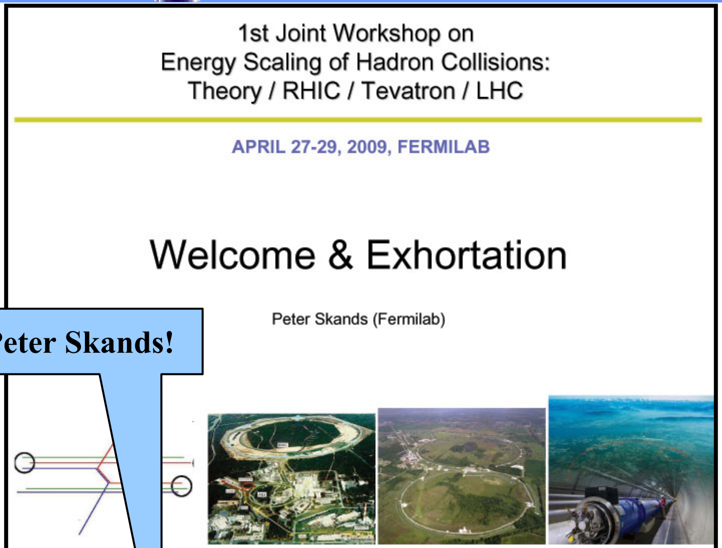


1.96 TeV → 14 TeV (UE increase ~1.9 times) → LHC



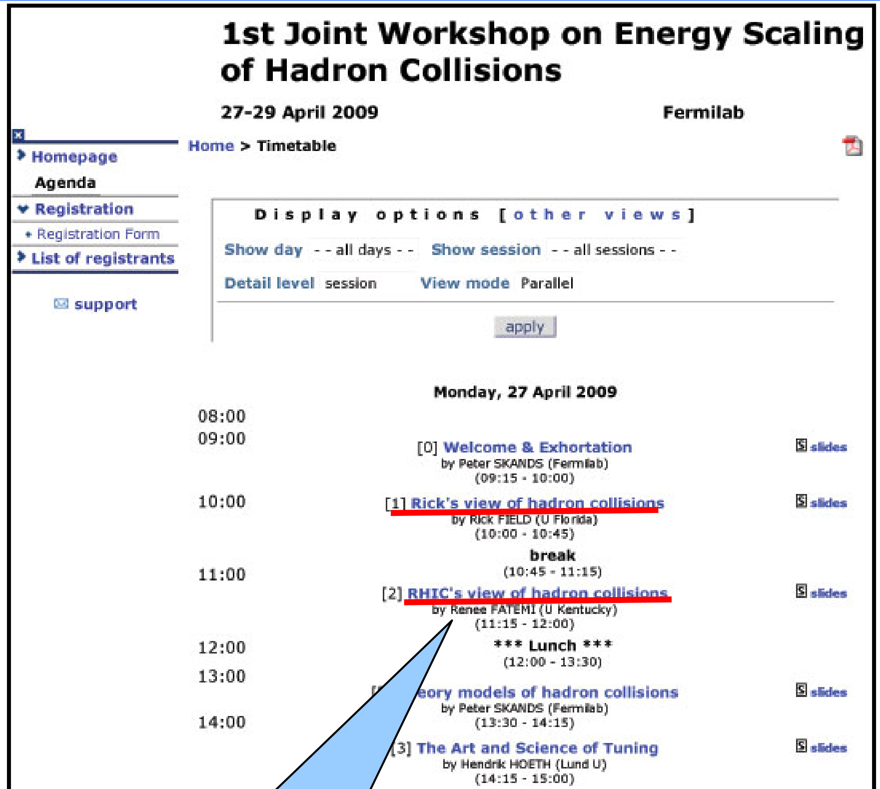
- **Shows the "associated" charged particle density in the "transverse" region as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min-bias" events at 0.2 TeV, 1.96 TeV and 14 TeV predicted by PYTHIA Tune DW at the particle level (*i.e.* generator level).**

1st Workshop on Energy Scaling in Hadron-Hadron Collisions



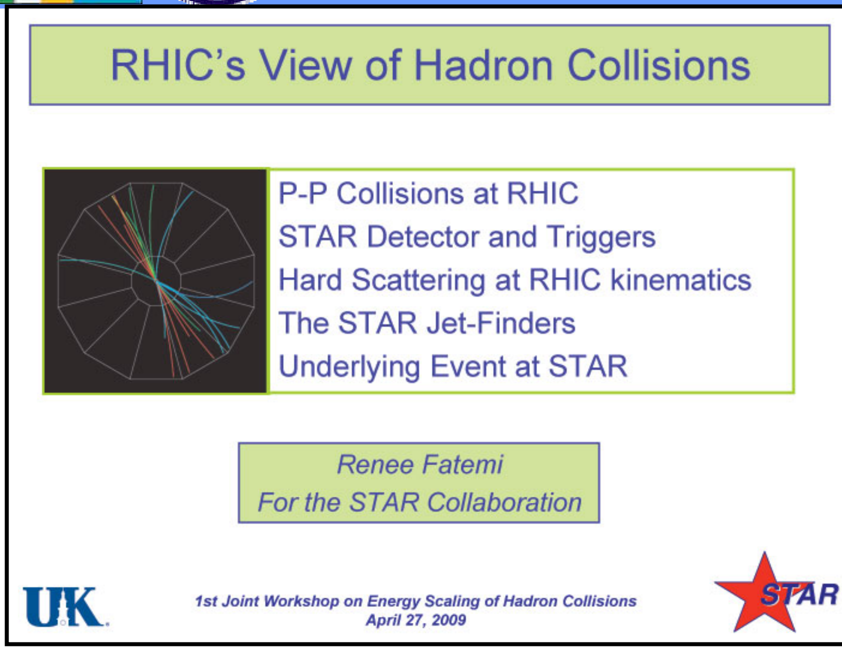
Peter Skands!

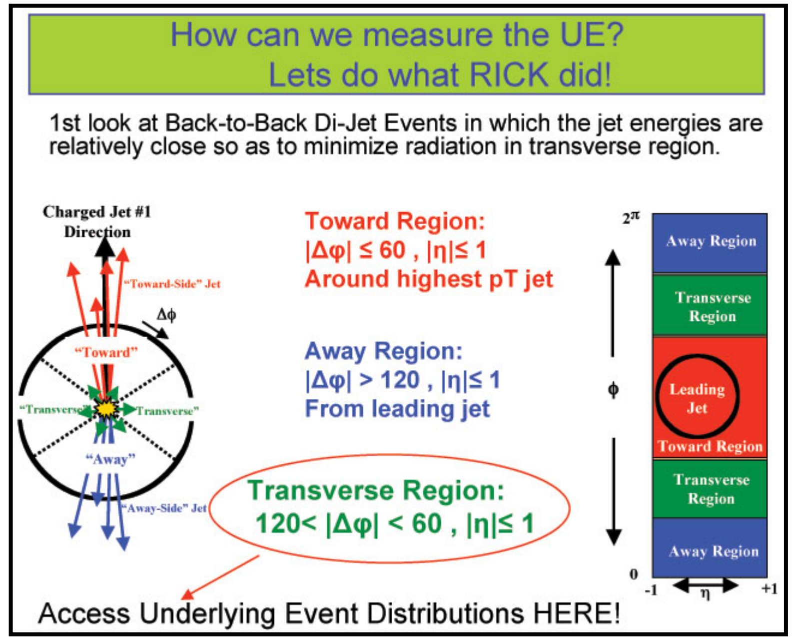
"On the Boarder" restaurant, Aurora, IL
April 27, 2009



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

The “Underlying Event” at STAR

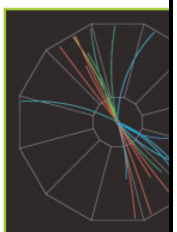




- At STAR they have measured the “underlying event at W = 200 GeV ($|\eta| < 1$, $p_T > 0.2$ GeV) and compared their uncorrected data with PYTHIA Tune A + STAR-SIM.

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.

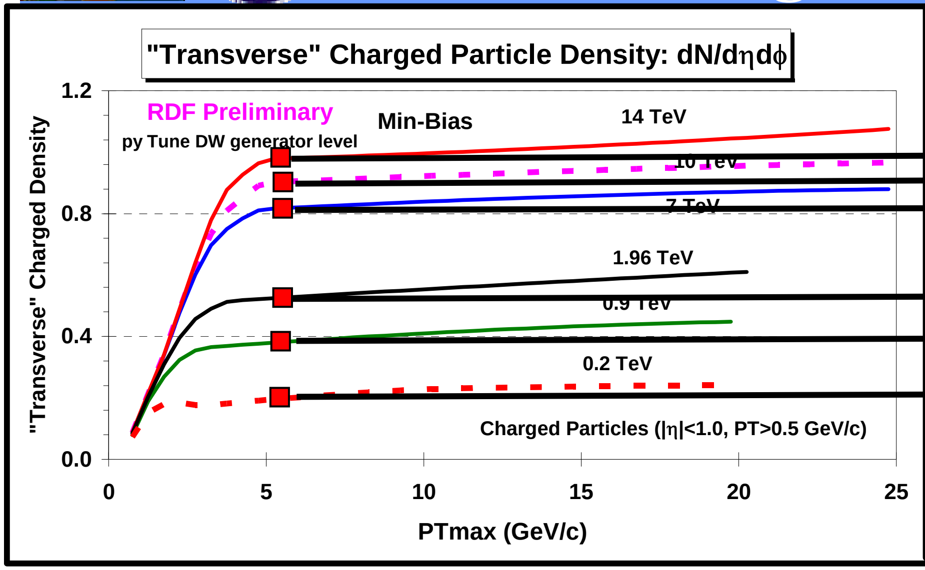
VII. For a cone jet with R=0.7 UE contributes 0.5-0.9 GeV.

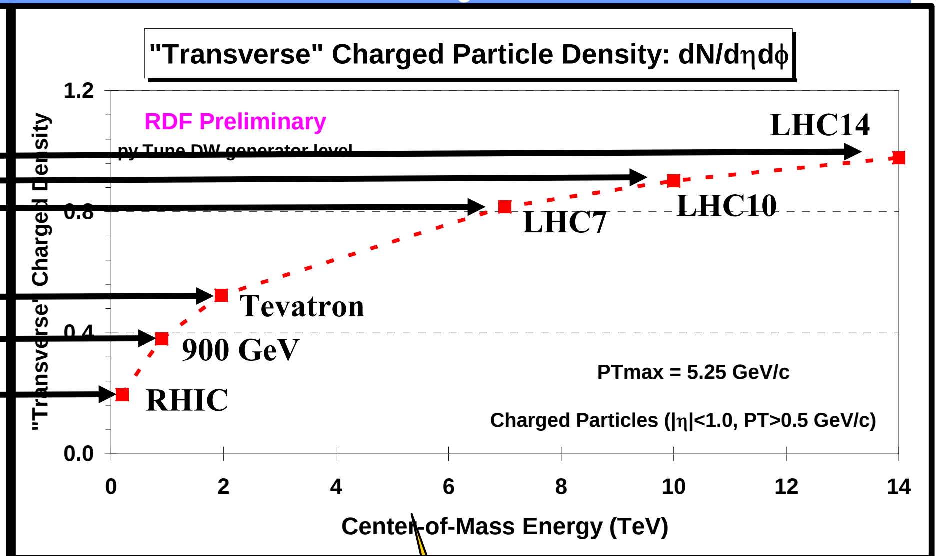
VIII. Comparison of Leading Jet and Back-to-Back distributions indicate that large angle radiation contributions are small at RHIC energies.

UK

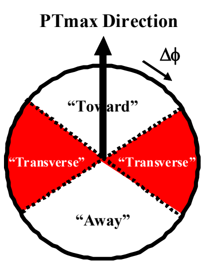
➡ **At STAR** ... **2 GeV)**
and comp

Min-Bias "Associated" Charged Particle Density



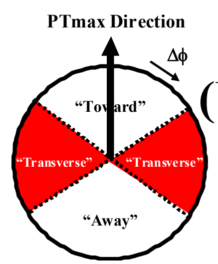


RHIC



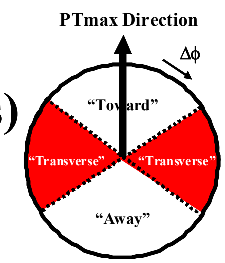
0.2 TeV → 1.96 TeV (UE increase ~2.7 times)

Tevatron



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

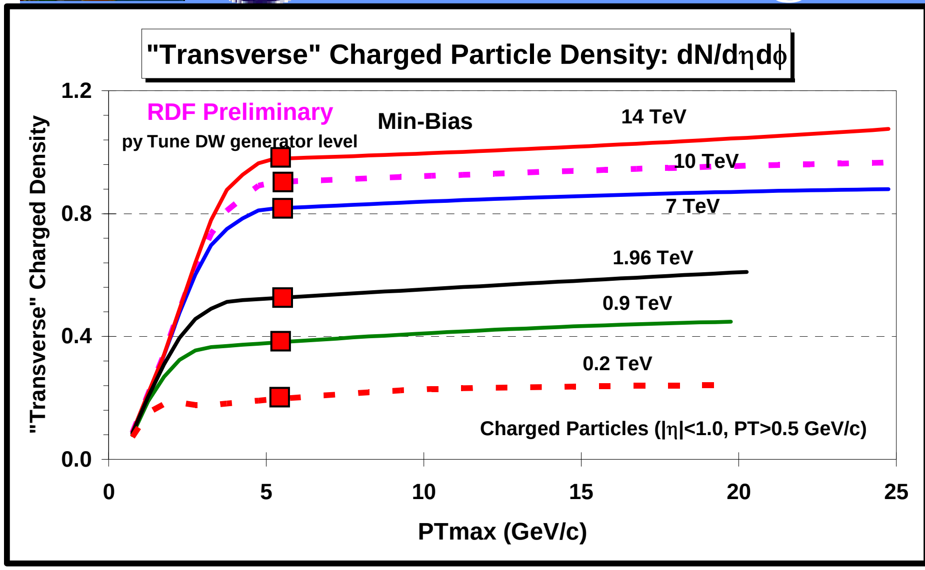
LHC

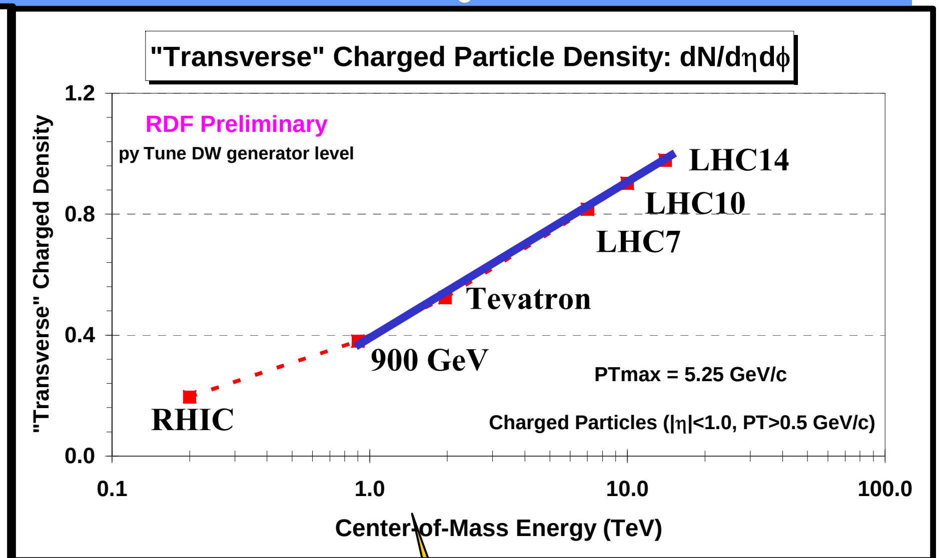


- **Shows the "associated" charged particle density in the "transverse" region as a function of PTmax for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 1$, *not including PTmax*) for "min-bias" events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tune DW at the particle level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

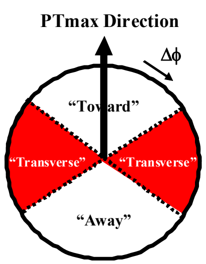
Linear scale!

Min-Bias "Associated" Charged Particle Density





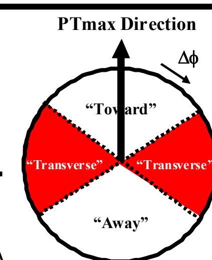
LHC7



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 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).

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

UE&MB@CMS

Florida-Perugia-CERN

- **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.**

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).

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

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Florida-Perugia-CERN

University of Perugia

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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.

INFN

QCD contribution to the Joint QCD/HI 2007 paper

Pre-approval talk

Authors:
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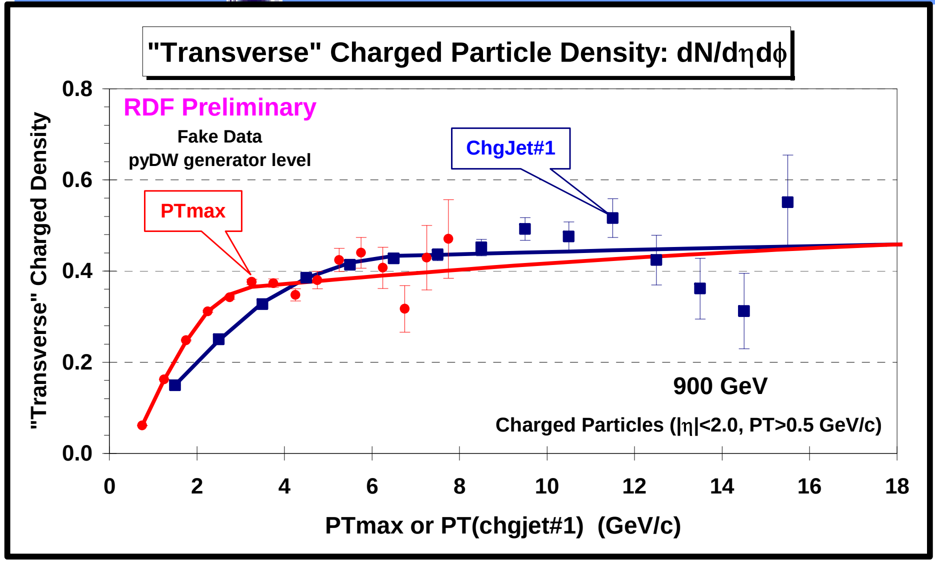
L. Fano', R. Field

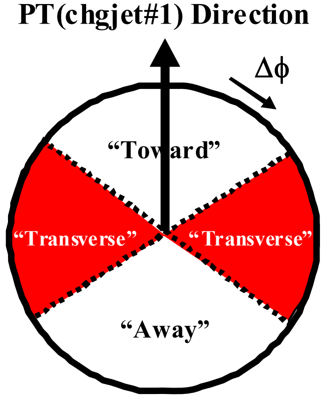
Institutions:
INFN and Universita' di Perugia
National Taiwan University
University of Florida

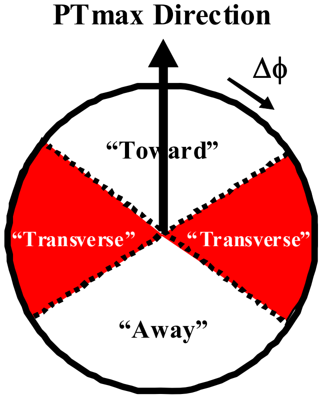
Referees:
W. Adam
C. Lourenco
P. Marage

University of Perugia

"Transverse" Charged Particle Density



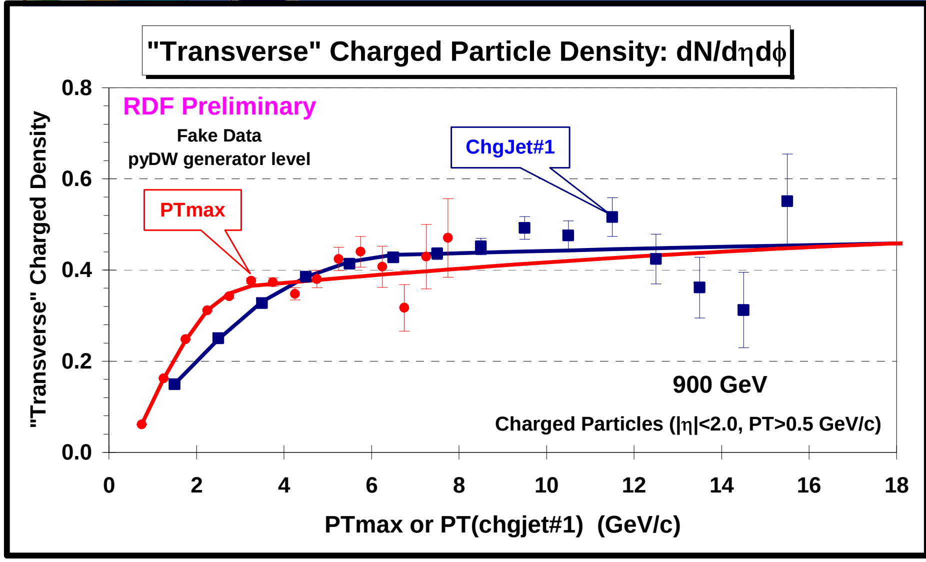


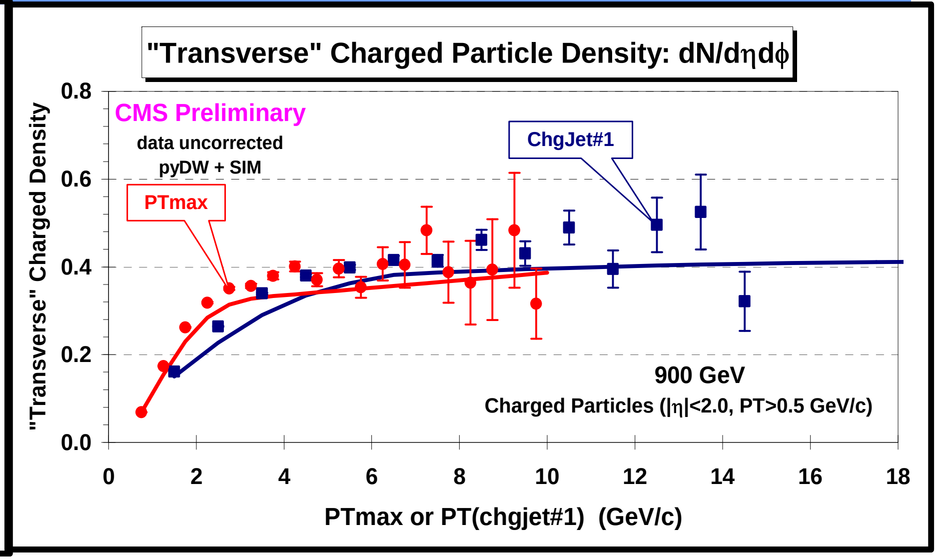


- **Fake data (from MC) at 900 GeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The fake data (from PYTHIA Tune DW) are generated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

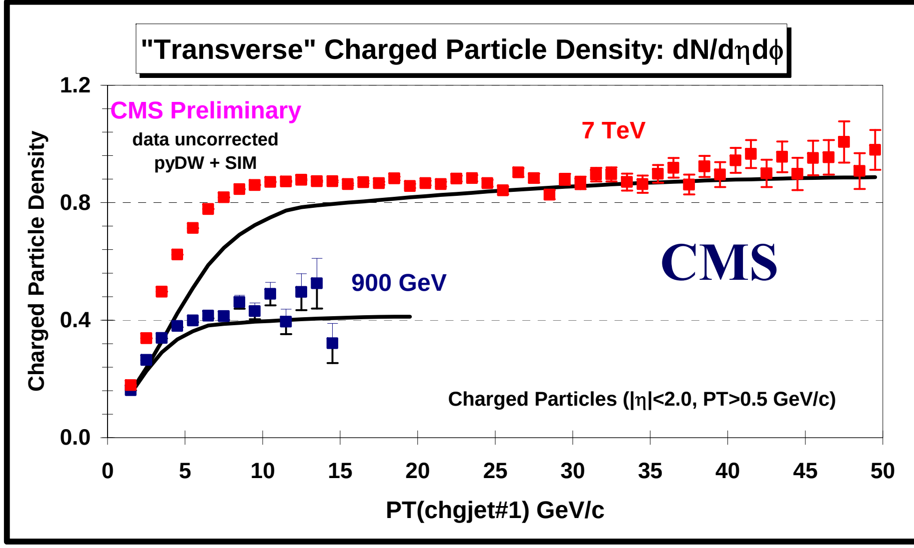
"Transverse" Charged Particle Density

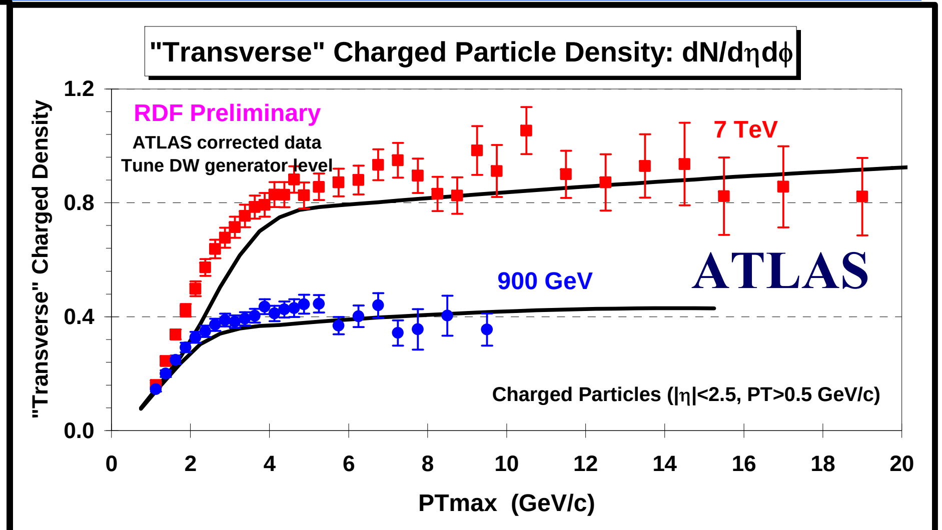




- Fake data (from MC) at 900 GeV on the "transverse" charged particle density, dN/dηdφ, as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The fake data (from PYTHIA Tune DW) are generated at 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).

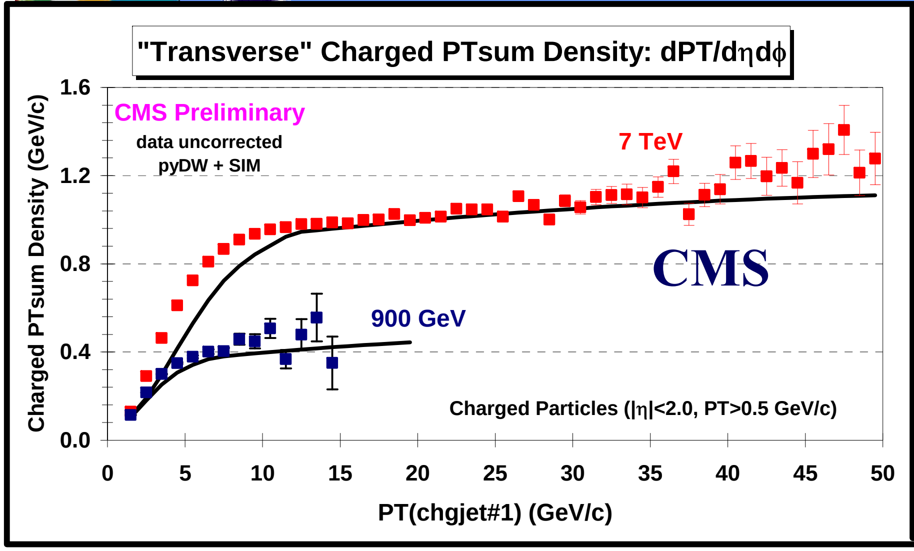
PYTHIA Tune DW

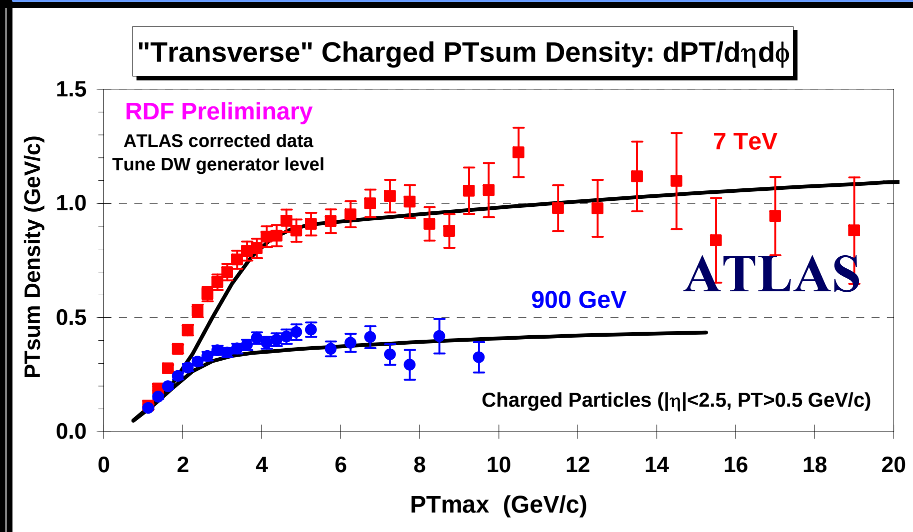




- **CMS preliminary data at 900 GeV and 7 TeV** on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA **Tune DW** after detector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

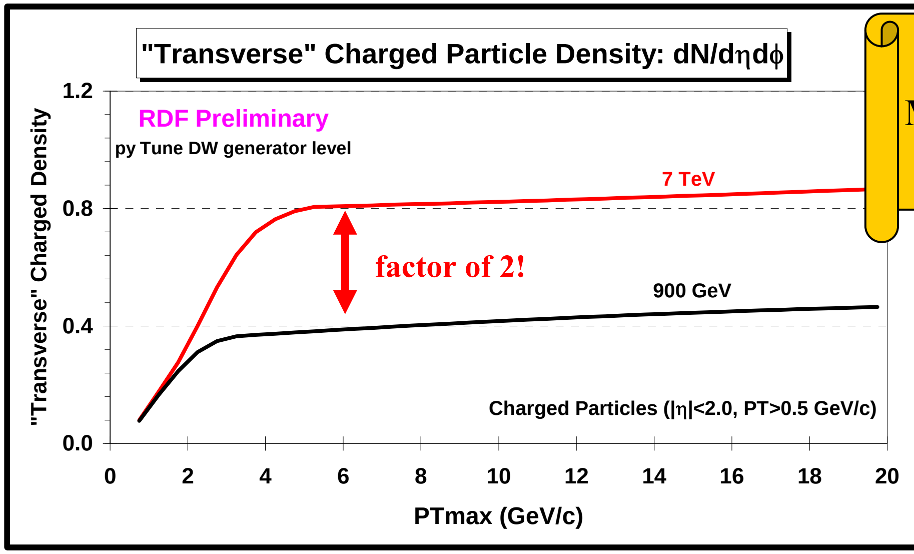




- **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged PTsum density, dPT/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.**

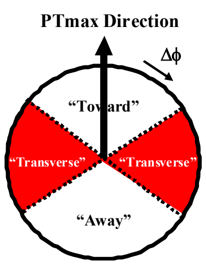
- **ATLAS preliminary data at 900 GeV and 7 TeV on the "transverse" charged PTsum density, dPT/dηdϕ, as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune DW at the generator level.**

“Transverse” Charge Density



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

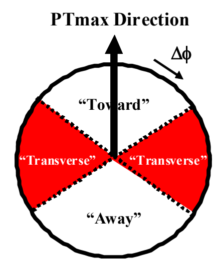
LHC
900 GeV



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

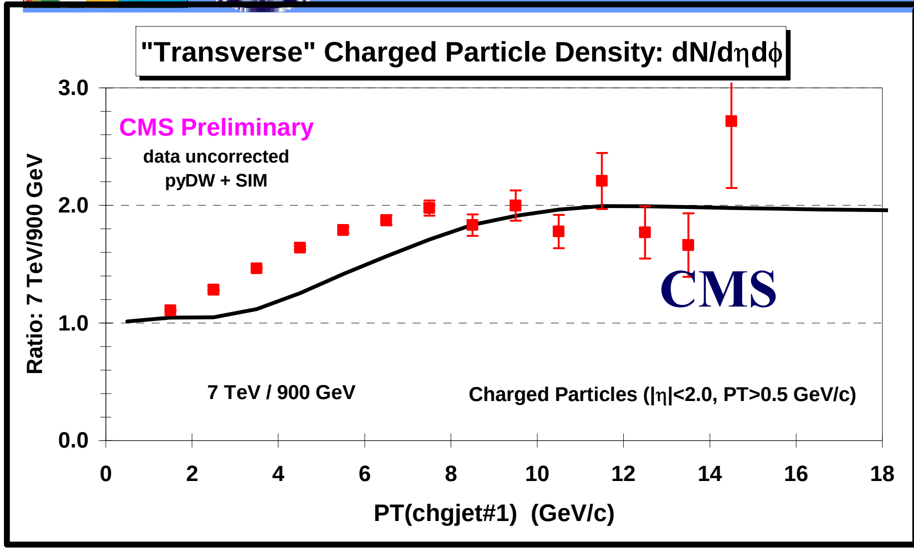
~0.4 → ~0.8

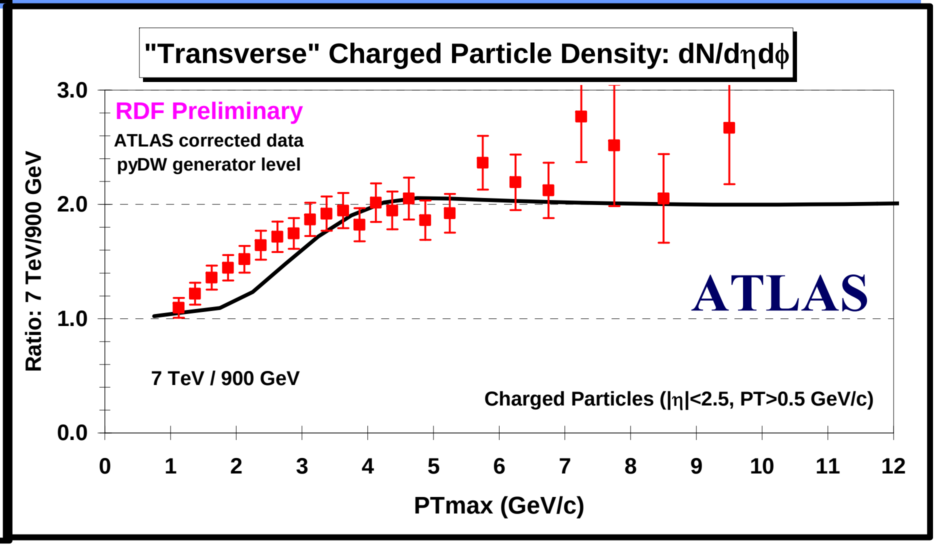
LHC
7 TeV



- **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.**
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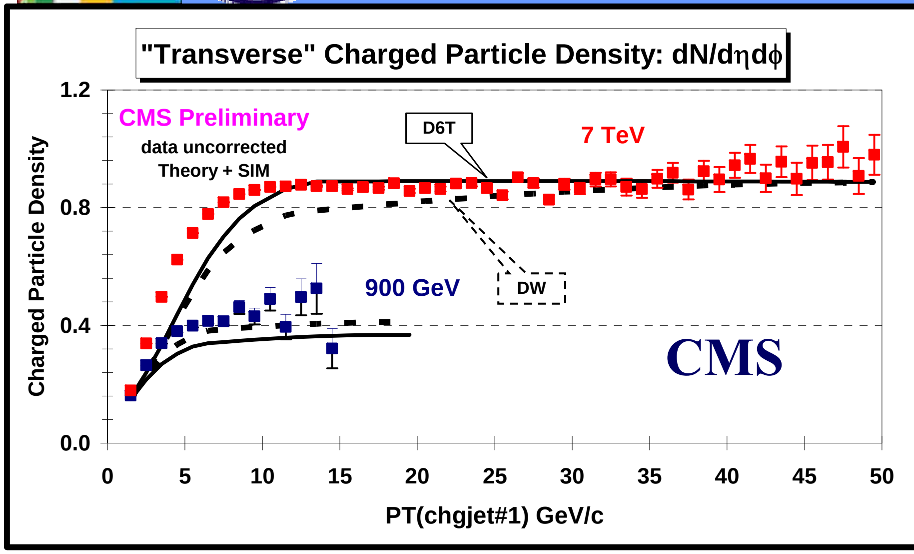
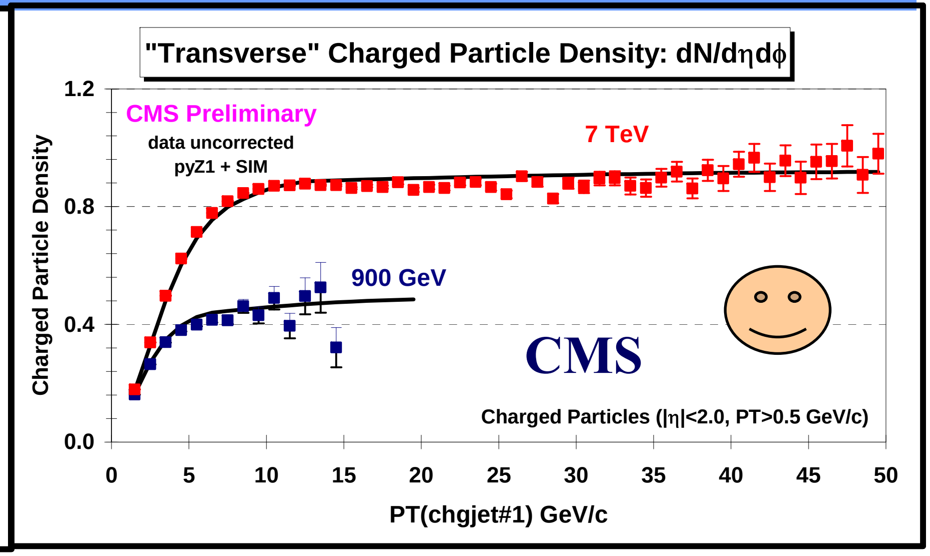
PYTHIA Tune Z1





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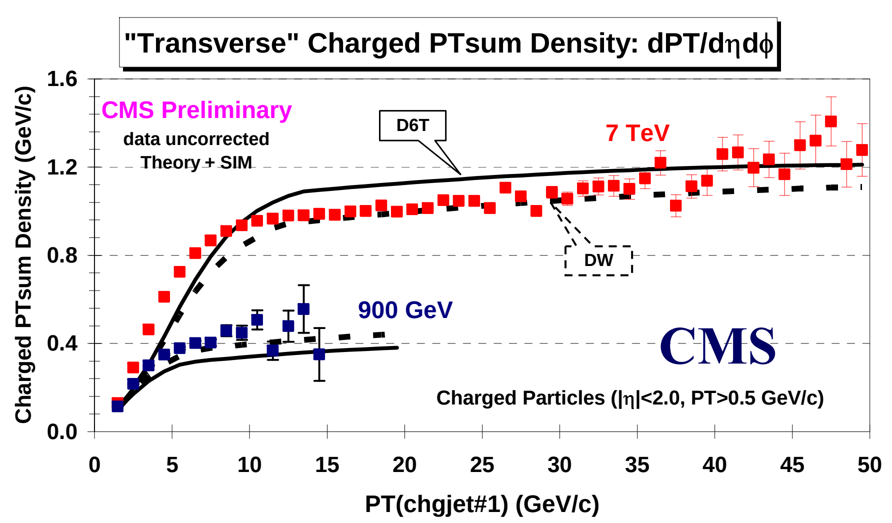
- **CMS preliminary data at 900 GeV and 7 TeV** on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with p_T > 0.5 GeV/c and |η| < 2.0. The data are uncorrected and compared with **PYTHIA Tune Z1** after detector simulation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

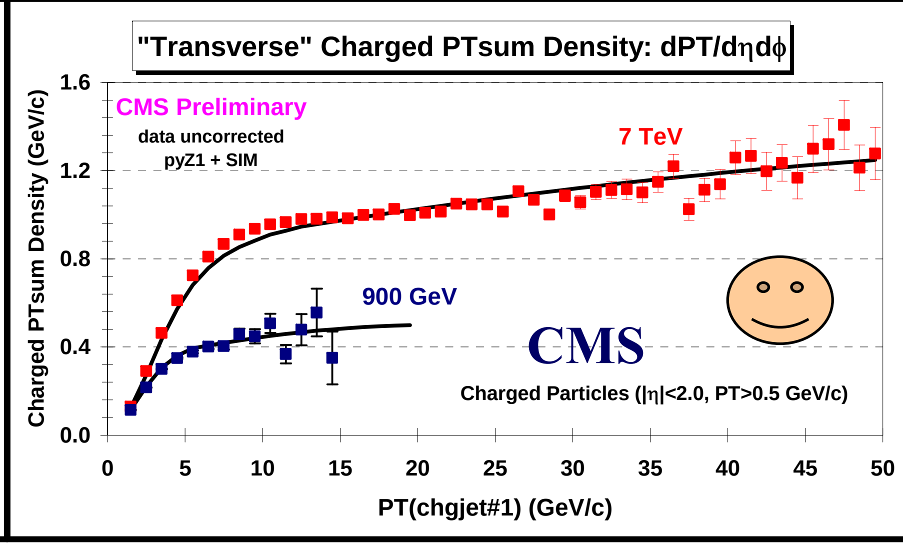
Color reconnection suppression.
Color reconnection strength.

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 Z1





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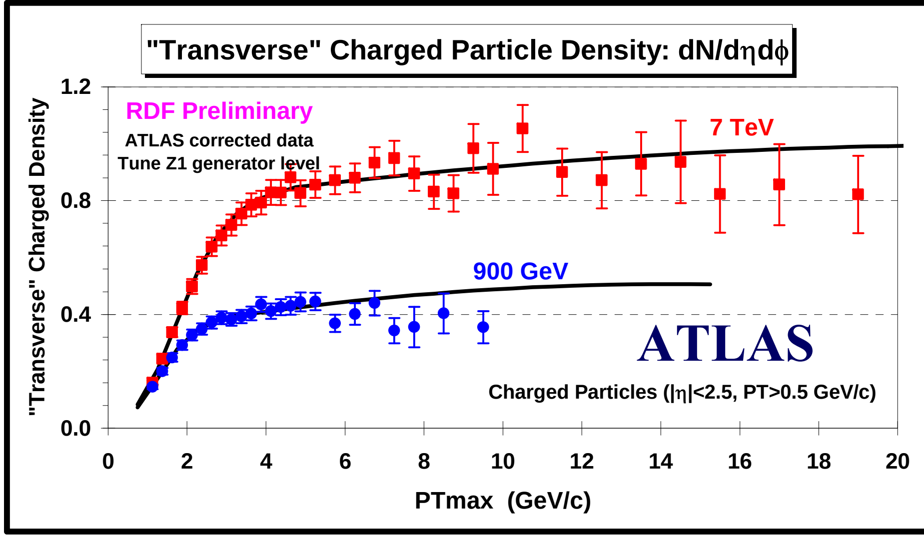

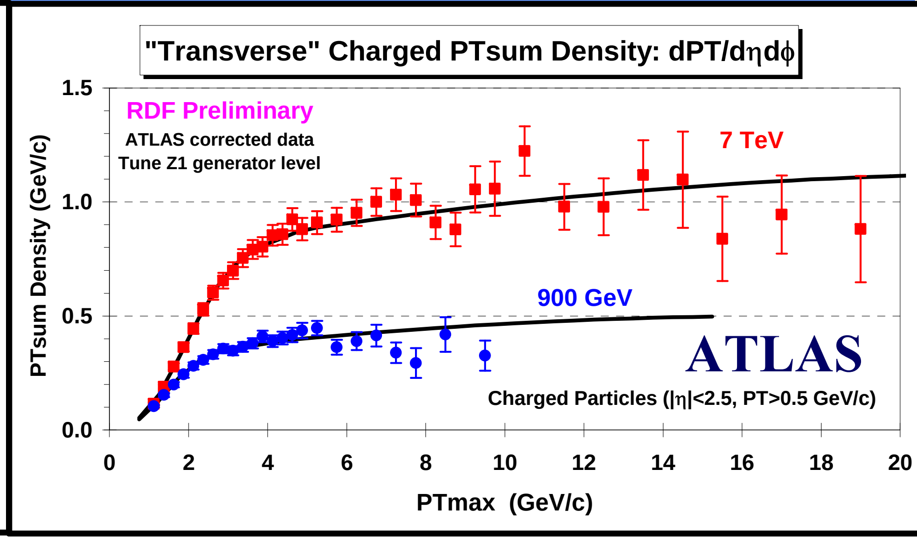

- ATLAS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune Z1 at the generator level.

- 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 Z1 at the generrator level.

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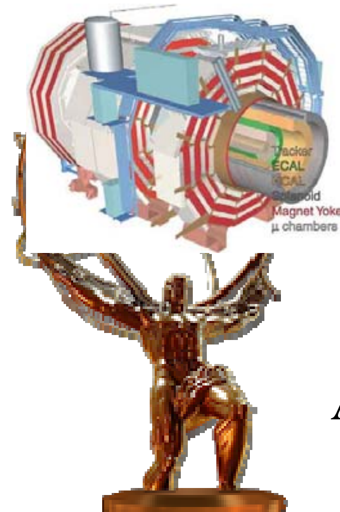
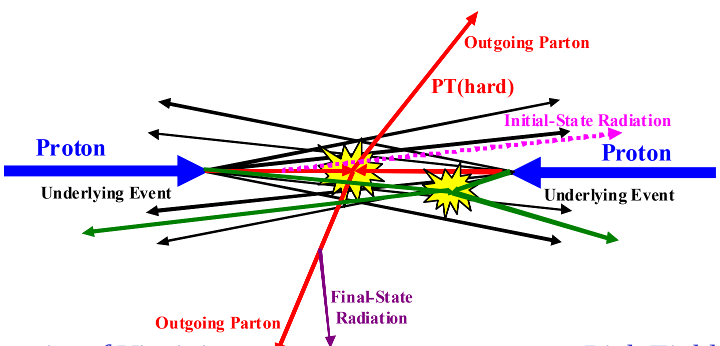
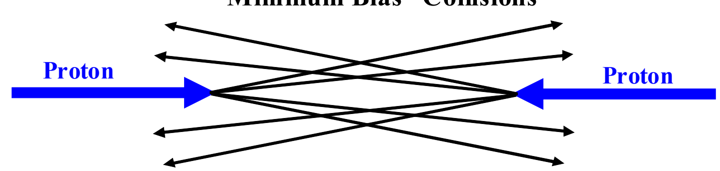
MB & UE Common Plots

Quantum Chromo-Dynamics



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





CMS Common Plots

Observable	900 GeV	7 TeV
MB1: $dN_{chg}/d\eta$ $N_{chg} \geq 1$ $\|\eta\| < 0.8$ $p_T > 0.5$ Gev/c & 1.0 GeV/c	Done QCD-10-024	Done QCD-10-024
MB2: dN_{chg}/dp_T $N_{chg} \geq 1$ $\|\eta\| < 0.8$	Stalled	Stalled
MB3: Multiplicity Distribution $\|\eta\| < 0.8$ $p_T > 0.5$ GeV/c & 1.0 GeV/c	Stalled	Stalled
MB4: $<p_T>$ versus Nchg $\|\eta\| < 0.8$ $p_T > 0.5$ GeV/c & 1.0 GeV/c	Stalled	Stalled
UE1: Transverse Nchg & PTsum as defined by the leading charged particle, PTmax $\|\eta\| < 0.8$ $p_T > 0.5$ GeV/c & 1.0 GeV/c	Done FSQ-12-020	Done FSQ-12-020

Direct charged particles (including leptons) corrected to the particle level with no corrections for SD or DD.

CMS Common Plots

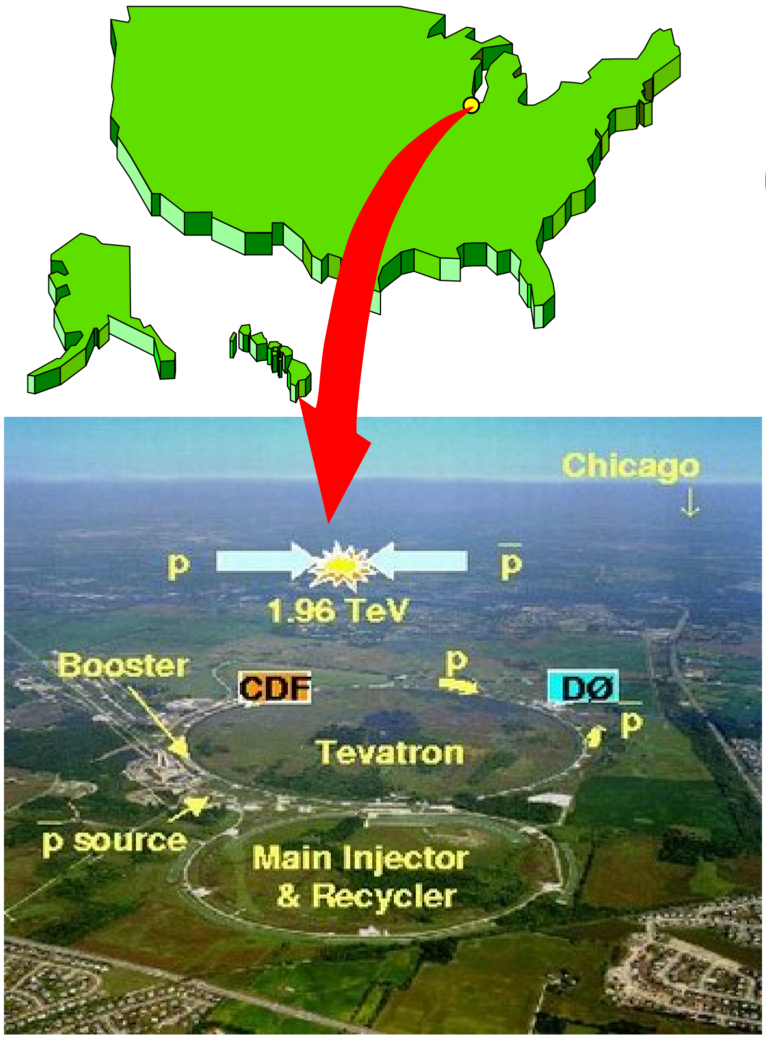
Observable	900 GeV	7 TeV
MB1: dN... /dη $N_{chg} \geq 1$ $|\eta| < 0.8$ $p_T >$ ... /c & 1.0 G...	Do... QC...	Done ... 0-024
MB2: dN_{chg}/dp_T ...		...talled
MB3 ... $|\eta| < 0.8$ p...		
MB4: $<p_T>$ ver... $|\eta| < 0.8$ p_T ...		
UE1: ...ansverse Nchg defined by the leading... particle, PTmax $|\eta| < 0.8$ $p_T > 0.5$ GeV/c & 1.0 G...	FSQ...	...one F... 2-020

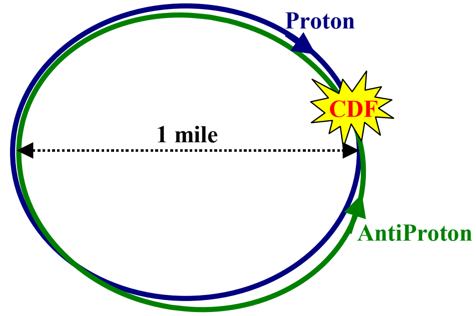
Note that all the "common plots" require at least one charged particle with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$!

This was done so that the plots are less sensitive to SD and DD.

Direct charged partic... (including leptons) corrected to the particle level with ...o corrections for SD or DD.

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

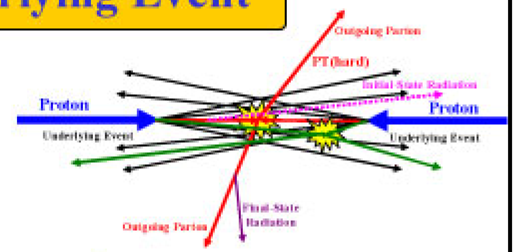
900 GeV 54.3M MB Events

PHYSICS at the UNIVERSITY of VIRGINIA

The Energy Dependence of the Underlying Event

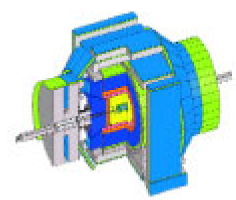
Rick Field
University of Florida

Quantum Chromo-Dynamics

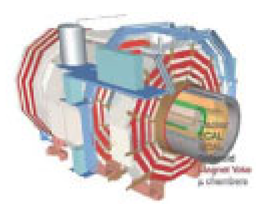


Outline

- **Review:** The CDF Tevatron "underlying event" tunes (Tune A, B, D, AW, DW, D6, DWT, D6T).
- How **Universal** are the QCD MC Model Tunes?
  - Do we need a separate tune for each center-of-mass energy? 900 GeV, 1.96 TeV, 7 TeV, etc.
  - Do we need a separate tune for each hard QCD subprocess? Jet Production, Drell-Yan Production, etc.
- A close look at two PYTHIA tunes:
  - PYTHIA 6.2 Tune DW (CDF UE tune).
  - PYTHIA 6.4 Tune Z1 (CMS UE tune).
- **New CDF UE Data:** The Tevatron Energy Scan (300 GeV, 900 GeV, 1.96 TeV)



CDF Run 2
300 GeV, 900 GeV, 1.96 TeV



CMS
900 GeV, 7 TeV & 8 TeV

University of Virginia
April 10, 2012
Rick Field – Florida/CDF/CMS
Page 1

UVA Seminar April 10, 2012

Physics at the University of Virginia

The Energy D

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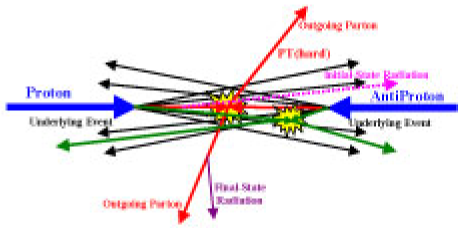
Univer

- **Review:** The CDF Tevat (Tune A, B, D, AW, DW,
- How **Universal** are the Q
  - Do we need a separ **energy**? 900 GeV,
  - Do we need a separ **subprocess**? Jet Pr
- A close look at two PYTI
  - PYTHIA 6.2 **Tune**
  - PYTHIA 6.4 **Tune**
- **New CDF UE Data:** The (**300 GeV**, **900 GeV**, 1.96

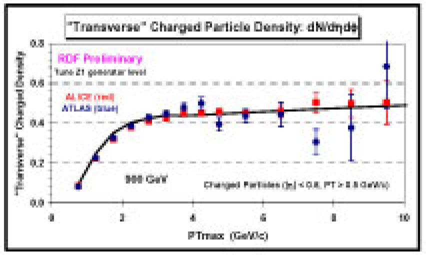
University of Virginia
April 10, 2012

My CDF UE Plan



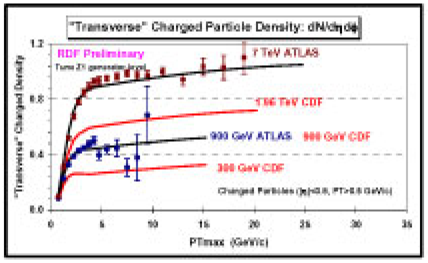
- **Produce the CDF PTmax UE "common plots" at 900 GeV to compare with ALICE-ATLAS-CMS.**

Must correct the data to the particle level!



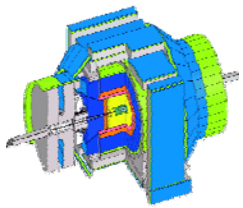
- **Study the energy dependence of the PTmax UE (300 GeV, 900 GeV, 1.96 TeV) at CDF.**

Must correct the data to the particle level!



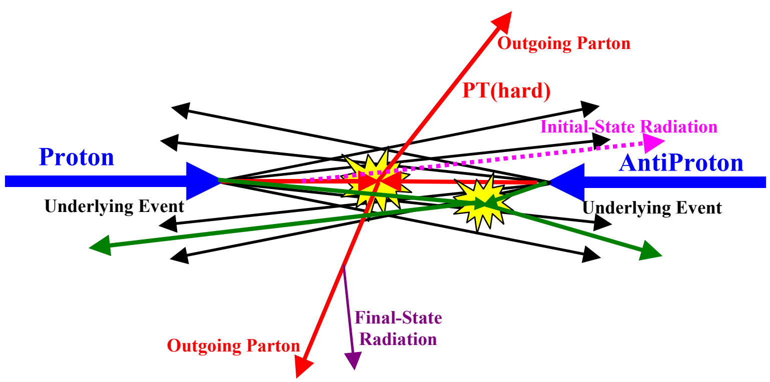
University of Virginia *Rick Field – Florida/CDF/CMS* *Page 52*
April 10, 2012

Latest CDF UE Publication



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

Sorry to be so slow!!



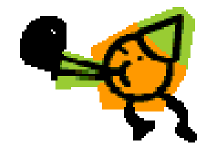
Draft PRD Version 6

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



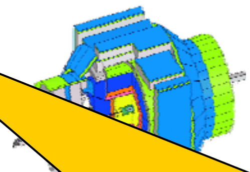
Abstract

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

Latest CDF UE Publication



CDF
Tevatron Ener
300 GeV

Sorry t

The CDF “Tevatron Energy Scan” UE analysis and publication could not have been done without the help from Craig Group!

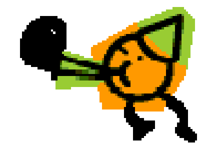
Draft PRD Version 6

Phys. Re , 092009 – Published 23 November 2015

A Stud nergy Dependence of the Underlying Event
Proton-Antiproton Collisions

oration

, 2015



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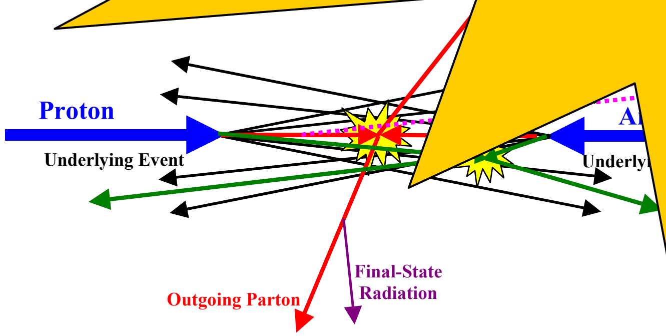


ta (corrected to the el) tha used by the theorists to t mprove the Monte-Carlo models tha sed to simulate h dron-hadron collisi .

http://arxiv.org/abs/1508.05340

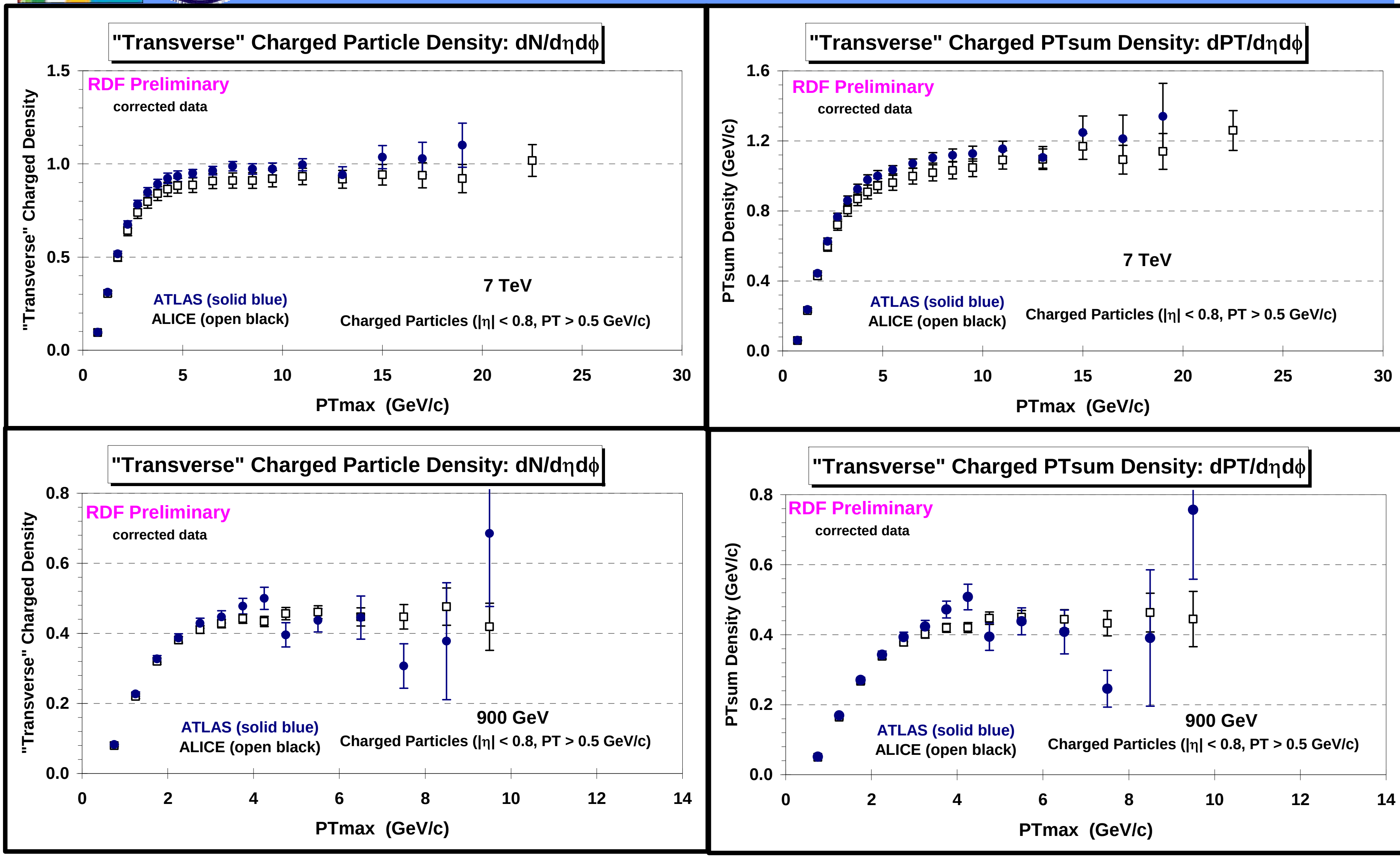
CDF Common Plots

Observable	300 GeV	900 GeV	1.96 TeV
MB1: $dN_{chg}/d\eta$ $N_{chg} \geq 1$ $\|\eta\| < 0.8$ $p_T > 0.5$ Gev/c & 1.0 GeV/c	Done	Done	Done
MB2: dN_{chg}/dp_T $N_{chg} \geq 1$ $\|\eta\| < 0.8$	Stalled	Stalled	Stalled
MB3: Multiplicity Distribution $\|\eta\| < 0.8$ $p_T > 0.5$ GeV/c & 1.0 GeV/c	Stalled	Stalled	Stalled
MB4: $\langle p_T \rangle$ versus Nchg $\|\eta\| < 0.8$ $p_T > 0.5$ GeV/c & 1.0 GeV/c	Stalled	Stalled	Stalled
UE1: Transverse Nchg & PTsum as defined by the leading charged particle, PTmax $\|\eta\| < 0.8$ $p_T > 0.5$ GeV/c & 1.0 GeV/c	$p_T > 0.5$ GeV/c Done	$p_T > 0.5$ GeV/c Done	$p_T > 0.5$ GeV/c Done

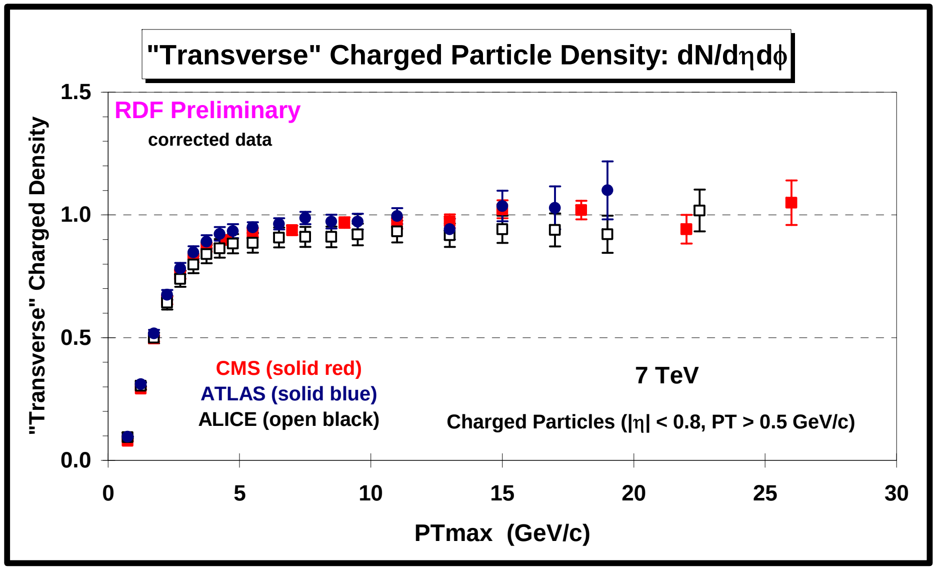
Direct charged particles (including leptons) corrected to the particle level with no corrections for SD or DD.

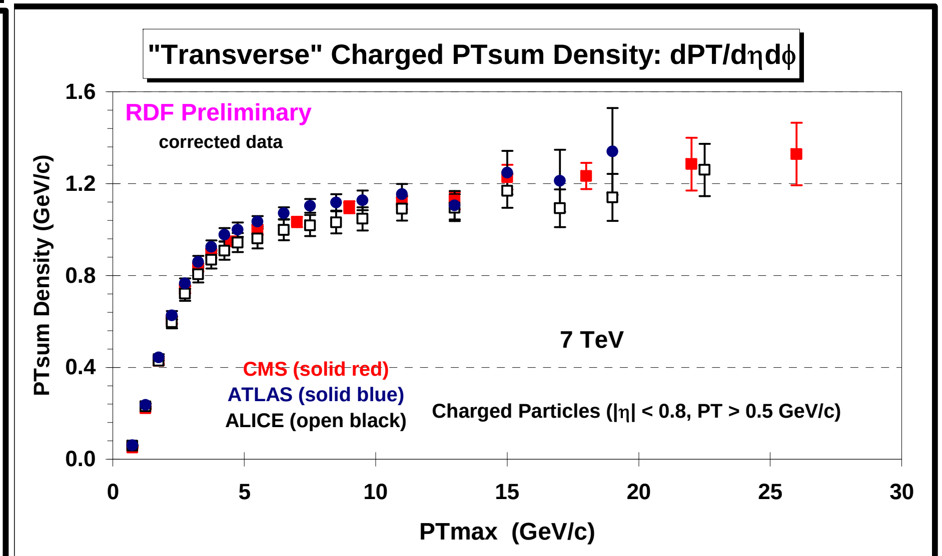
R. Field, C. Group, and D. Wilson.

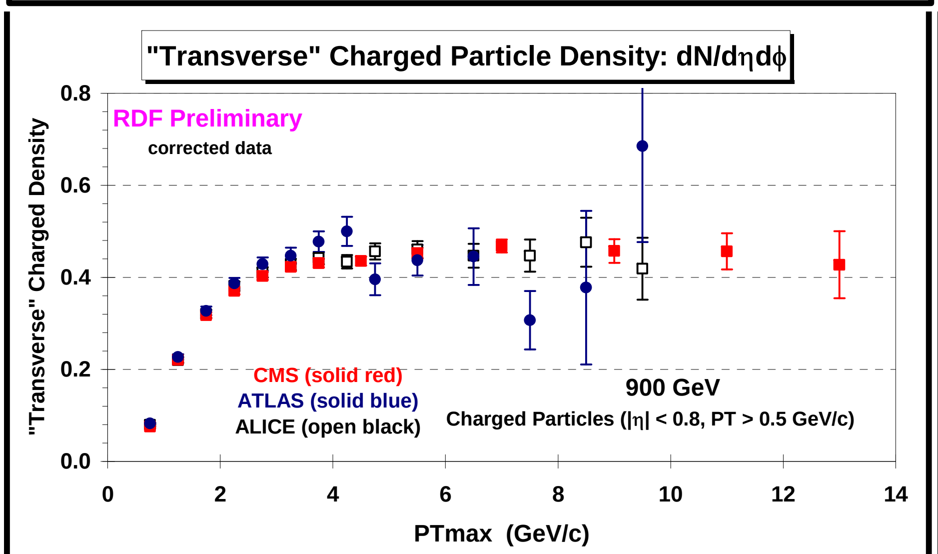
UE Common Plots

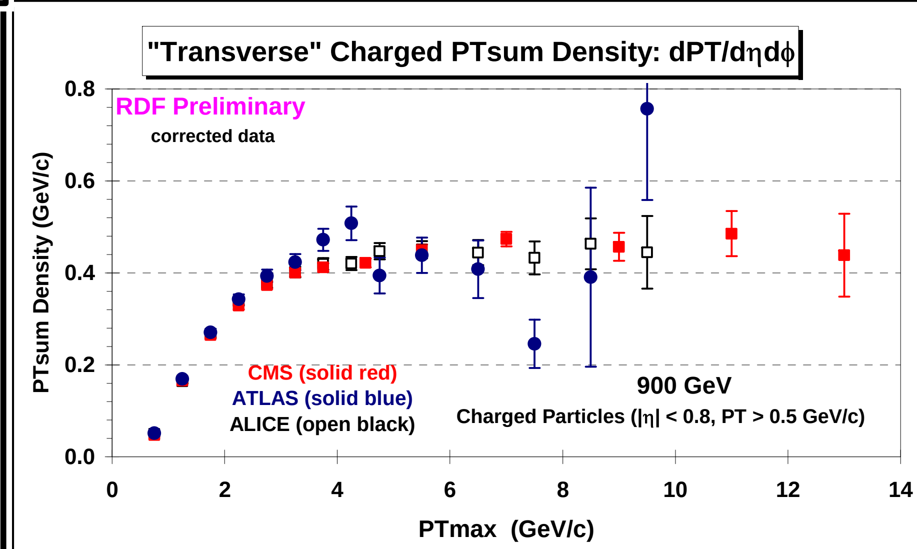


UE Common Plots

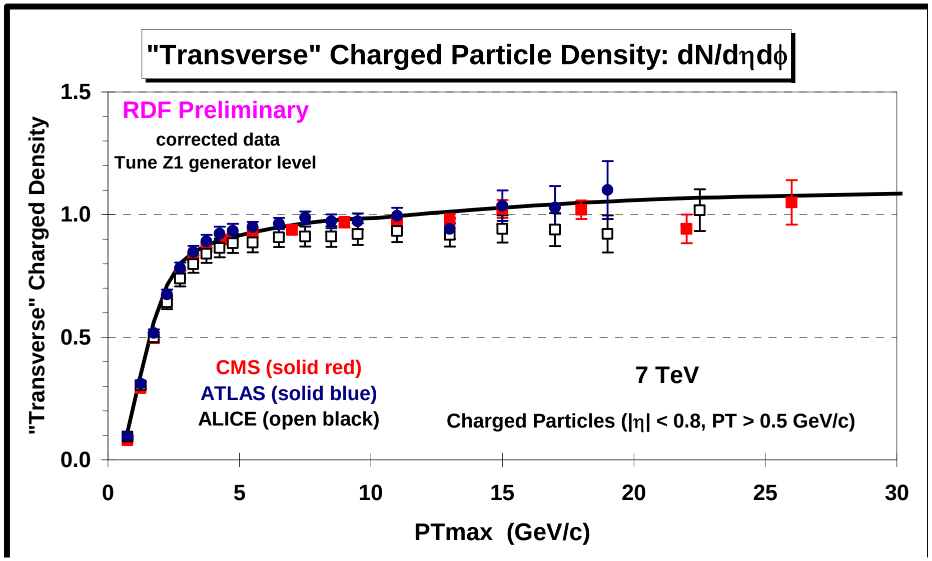


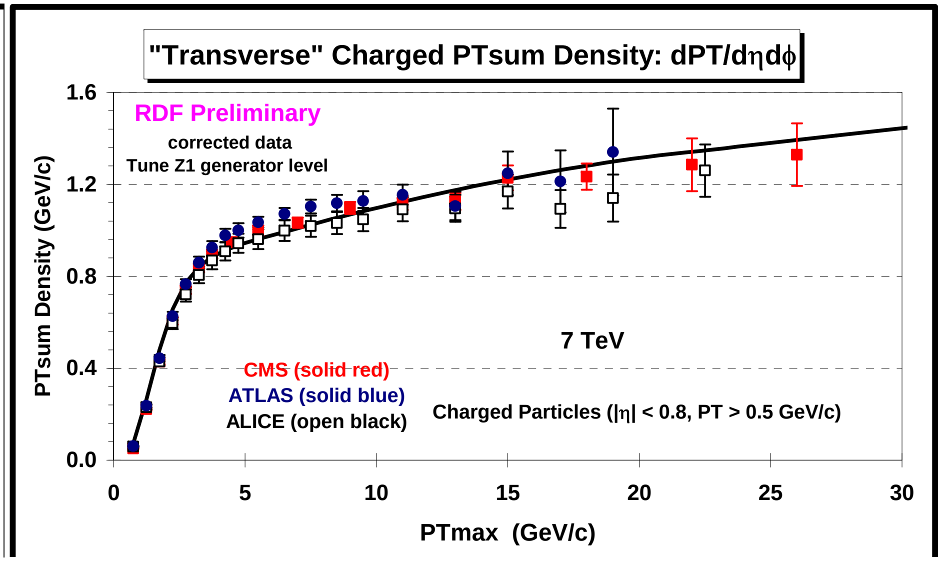


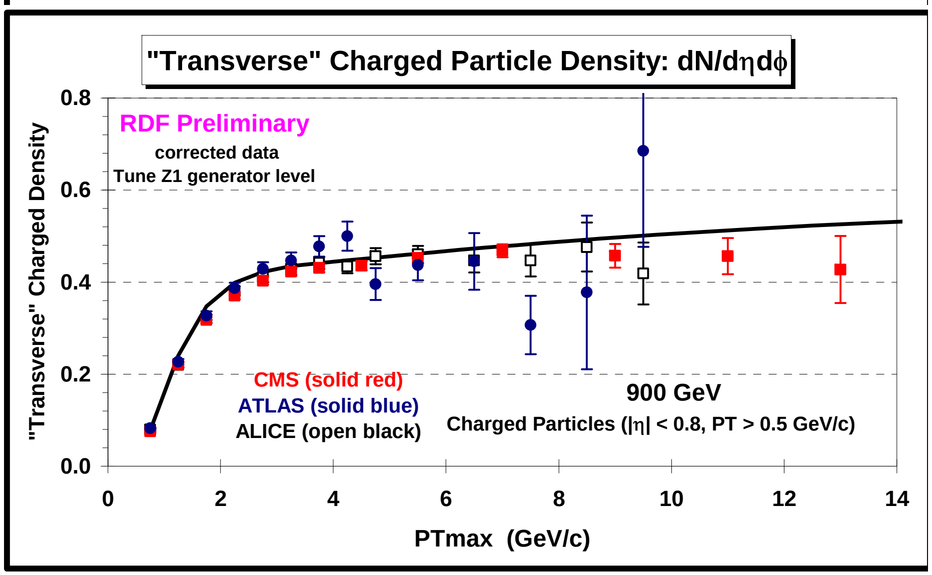


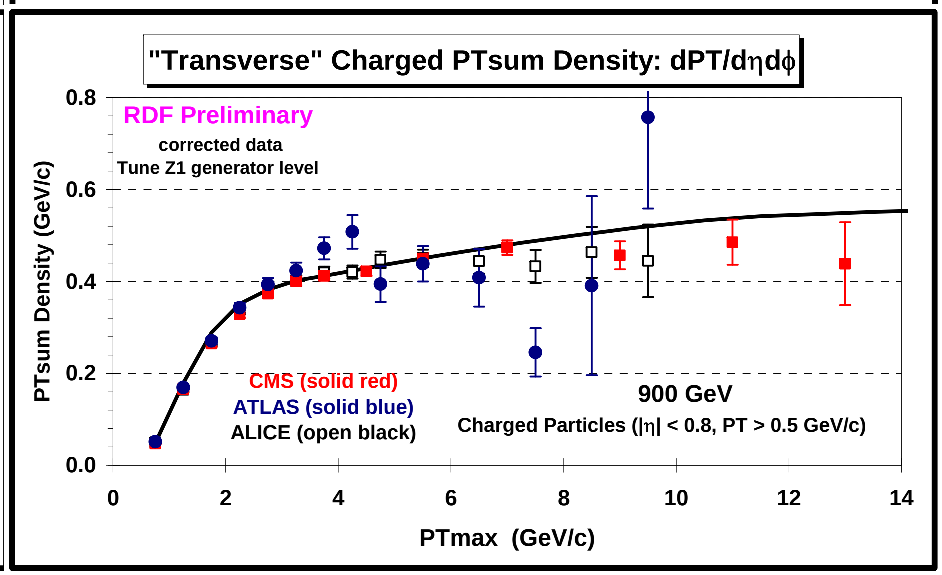


UE Common Plots

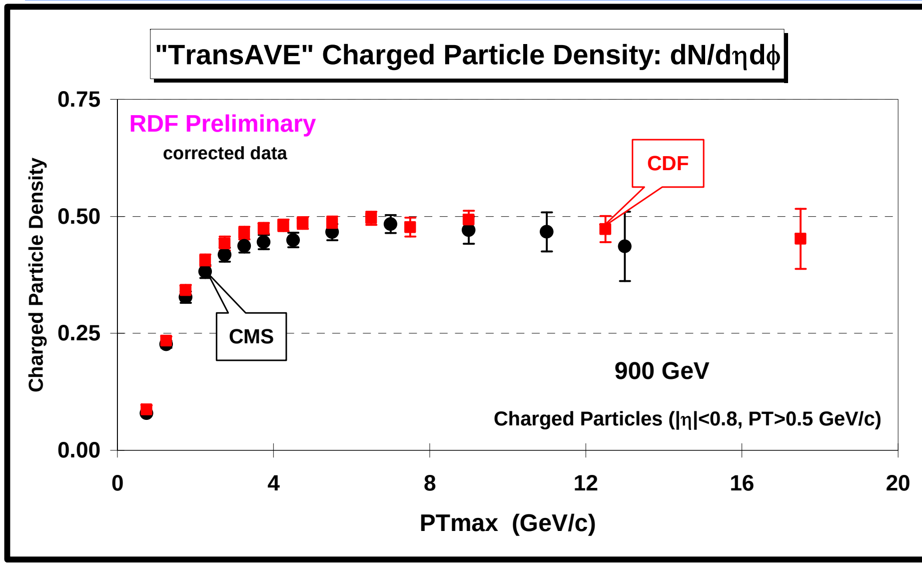


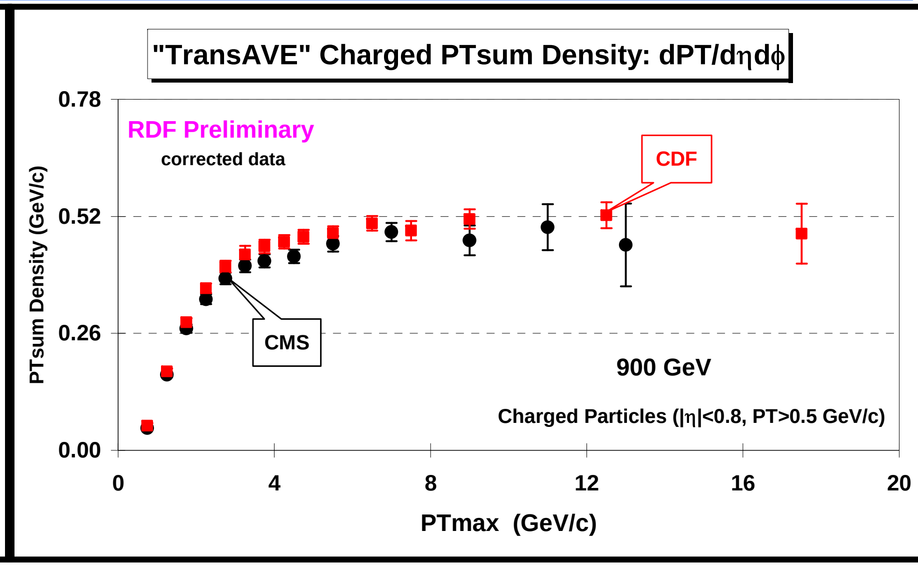






CDF versus LHC

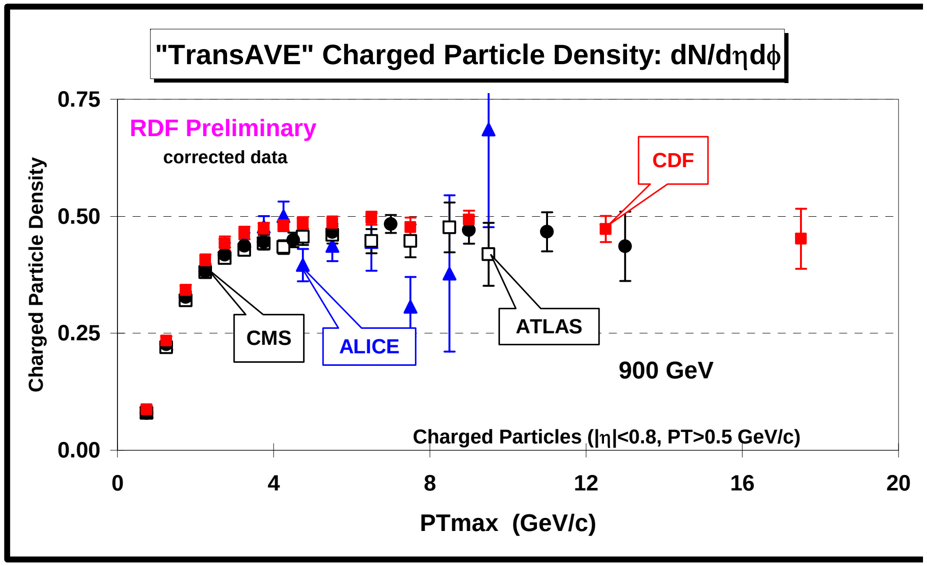


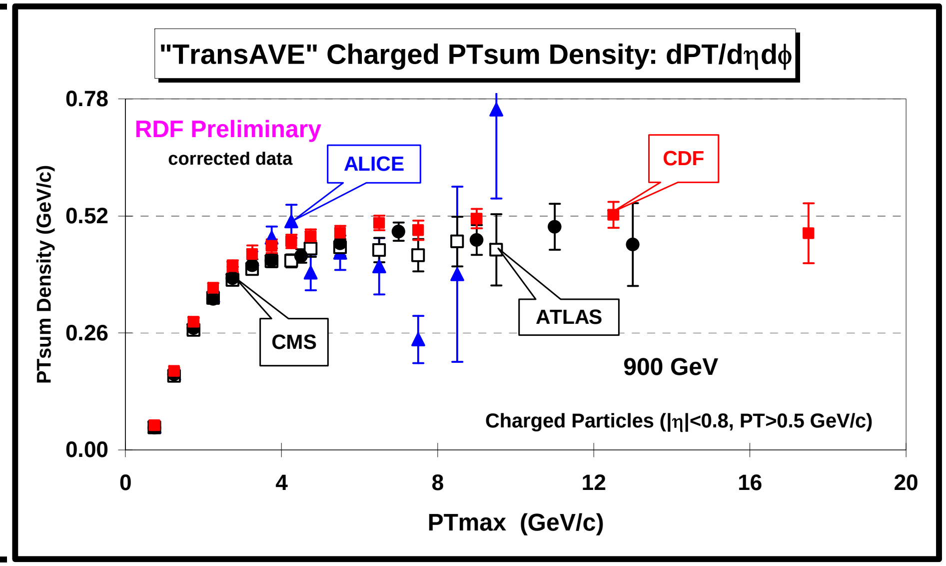


- **CDF and CMS data at 900 GeV/c on the charged particle density in the "transverse" region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$. The data are corrected to the particle level with errors that include both the statistical error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





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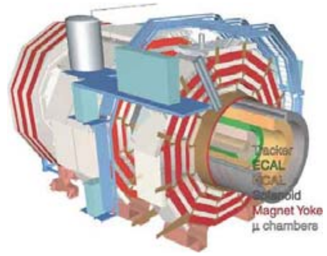
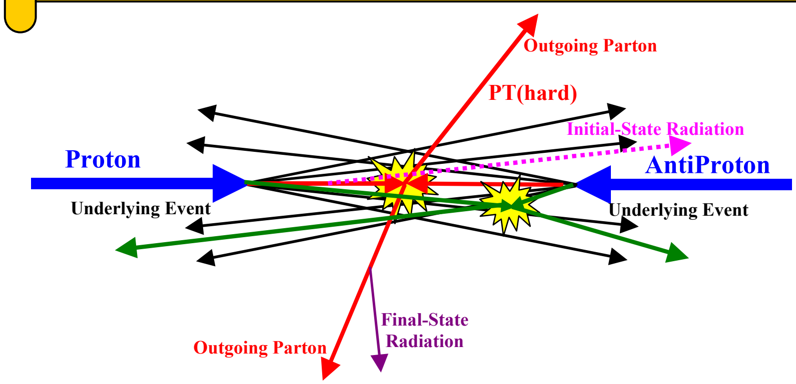
CMS Tuning Publication



CMS at the LHC

900 GeV, 2.96 TeV, 7 TeV, 8 TeV, 13 TeV

Physics Comparisons & Generstor Tunes



Hannes Jung, Paolo Gunnellini, Rick Field

To appear soon!

CMS PAPER GEN-14-001

DRAFT
CMS Paper

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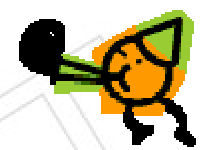
2015/08/12
Head Id: 234706
Archive Id: 299863P
Archive Date: 2014/04/01
Archive Tag: trunk

CMS underlying event and double parton scattering tunes

The CMS Collaboration

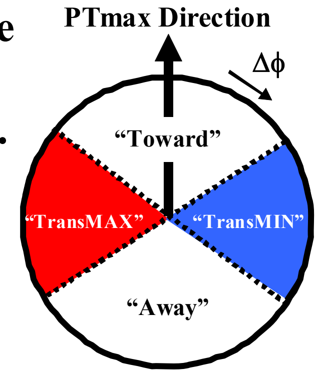


Abstract

Three new PYTHIA-8 underlying event (UE) tunes are constructed, one using the CTEQ6L1 parton distribution function (PDF), one using HERAPDF 1.5 leading order (LO), and one using the NNPDF2.3LO PDF; two new PYTHIA-6 UE tunes, one for the CTEQ6L PDF and one for the HERAPDF 1.5 LO, and one new HERWIG ++ UE tune for the CTEQ6L1 PDF are also available. Simultaneous fits to CDF UE data at 300 GeV, 900 GeV, and 1.96 TeV, together with CMS UE data at 7 TeV, check the UE models and constrain their parameters, providing thereby more precise predictions for proton-proton collisions at 13 TeV. In addition, several new double-parton scattering (DPS) tunes are investigated when the values of the UE parameters from fits to observables are consistent with the values determined from fitting DPS-sensitive observables. Also examined is how well the new UE tunes predict "minimum bias" (MB) events, jet and Drell–Yan ($q\bar{q} \to Z/\gamma^* \to$lepton-antilepton+jets) observables, as well as the MB and UE observables at 13 TeV.

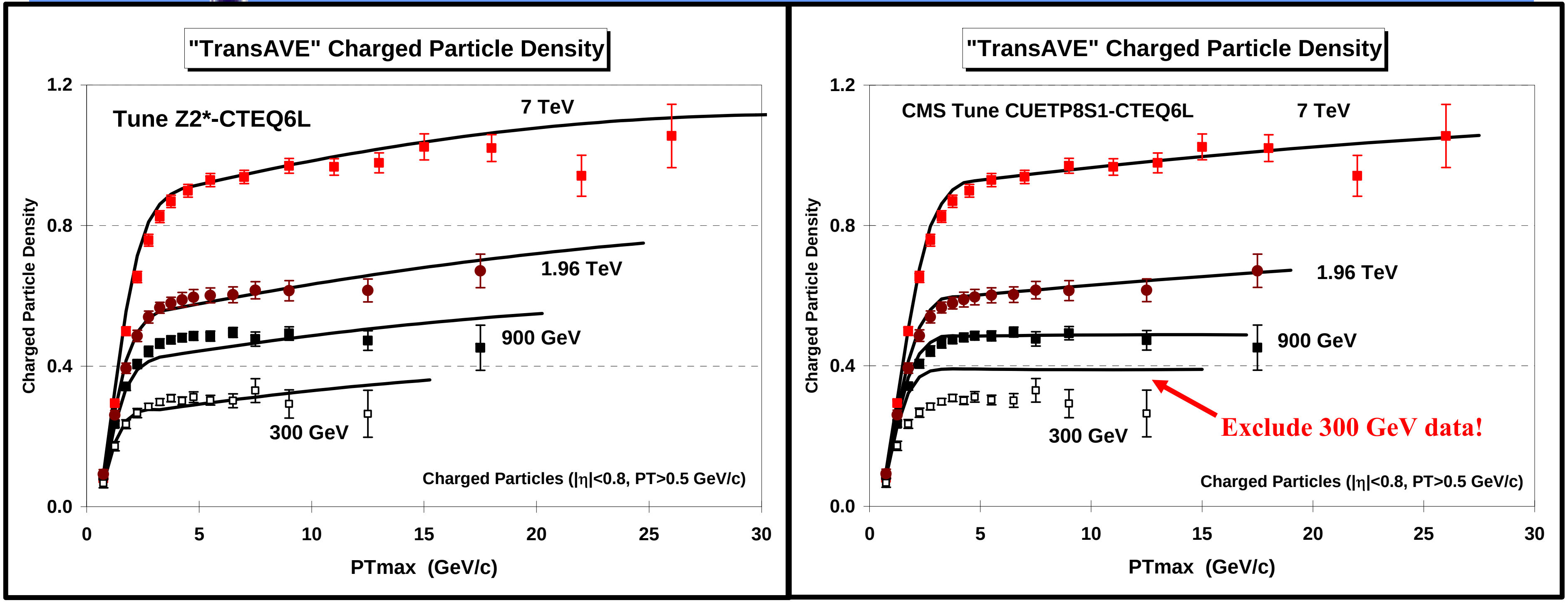
CMS UE Tunes

- **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.



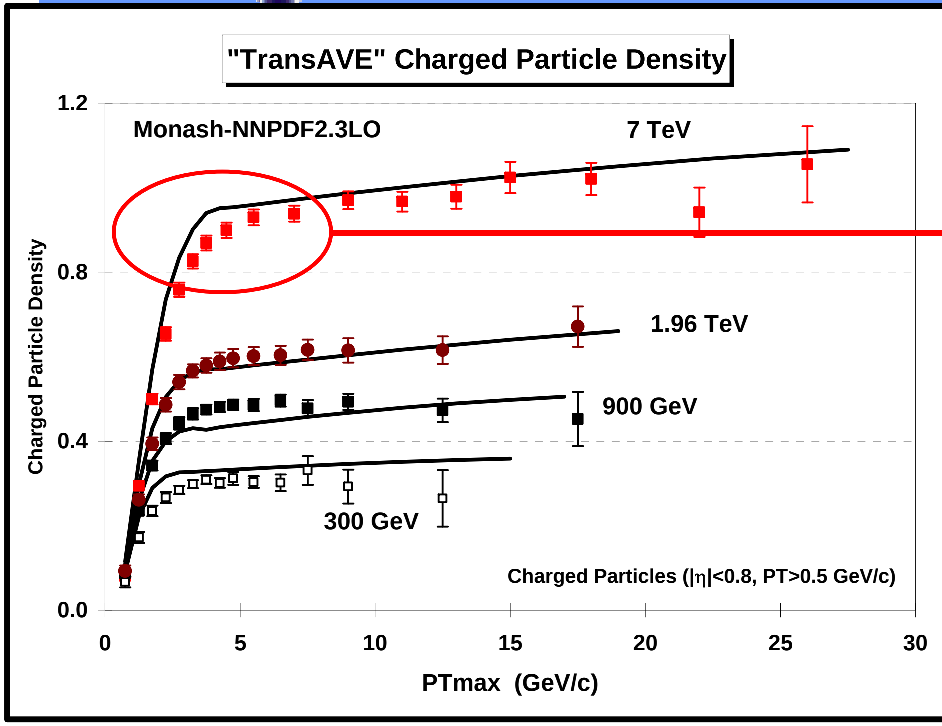
- **PYTHIA 8 Tune CUETP8S1-CTEQ6L:** Start with Corke & Sjöstrand Tune 4C and tune to the CDF PTmax "transMAX" and "transMIN" UE data at 900 GeV, and 1.96 TeV and the CMS PTmax "transMAX" and "transMIN" UE data at 7 TeV. Exclude 300 GeV data.
- **PYTHIA 8 Tune CUETP8S1-HERAPDF1.5LO:** Start with Corke & 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.

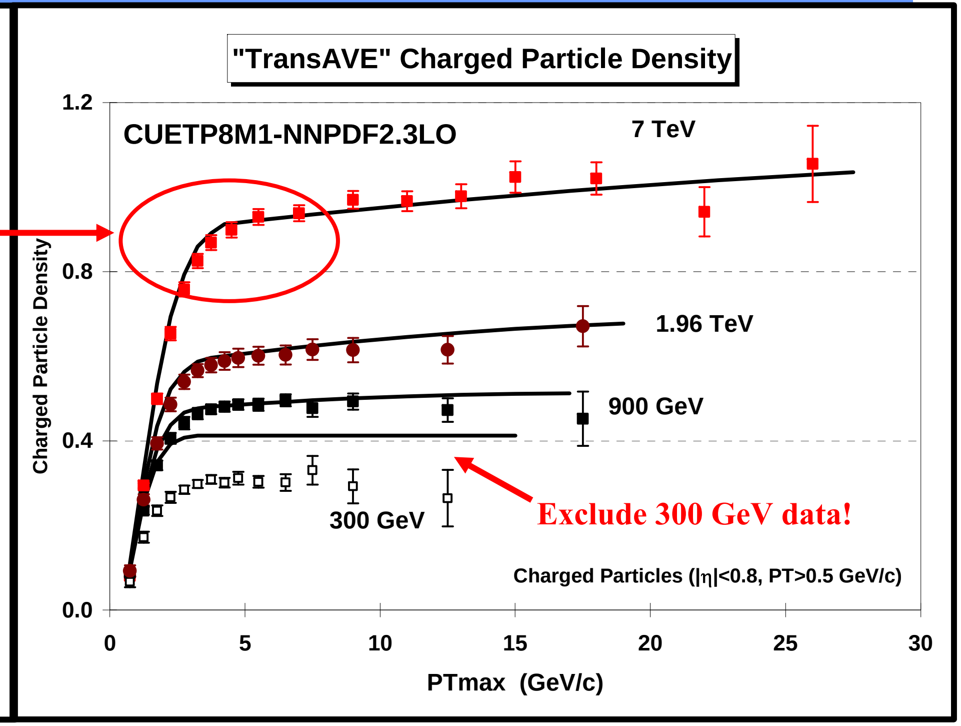
CUETP8S1-CTEQ6L



- **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**).

CUETP8M1-NNPDF2.3LO





- **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 the PYTHIA 8 Tune Monash-NNPDF2.3LO.

- **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 the PYTHIA 8 Tune CUETP8M1-NNPDF2.3LO (**excludes 300 GeV in fit**).

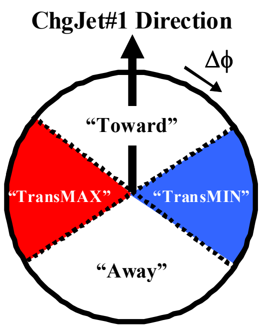
UE@CMS 13 TeV

UE@13TeV

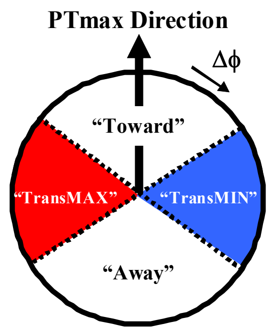
Livio Fano' (University of Perugia)
Diego Ciangottini (University of Perugia)
Rick Field (University of Florida)
Doug Rank (University of Florida)
Sunil Bansal (Panjab University Chandigarh)
Wei Yang Wang (National University of Singapore)

University of Perugia

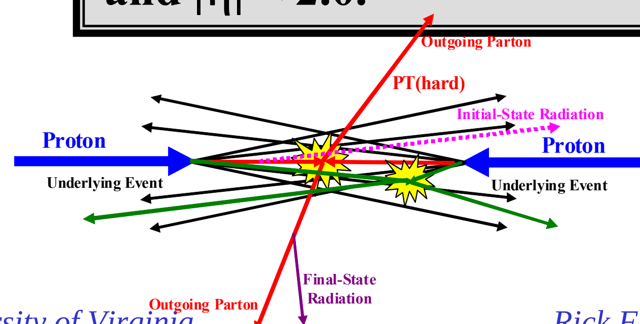
➡ **Measure the "Underlying Event" at 13 TeV at CMS**



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 $|\eta| < 2.0$.



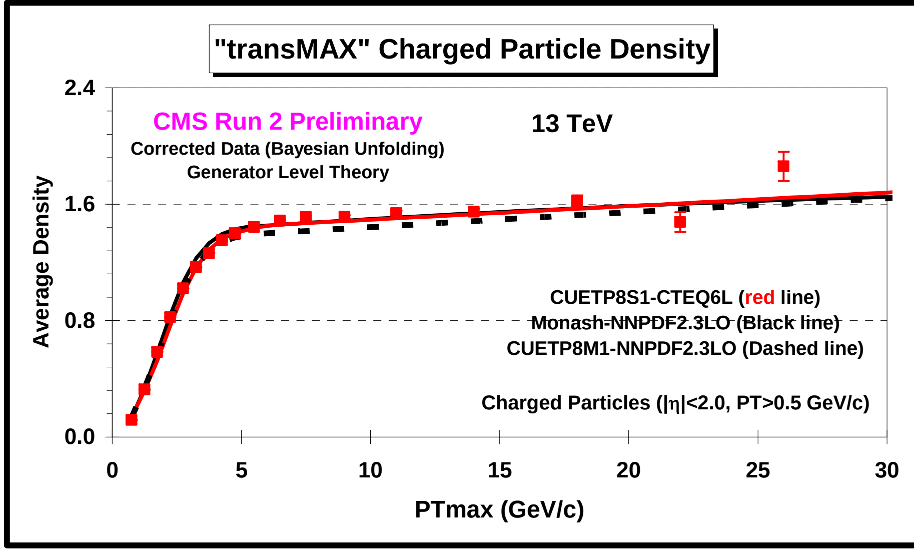
Measure the UE observables as defined by the leading charged particle, PTmax, for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$ and $|\eta| < 0.8$.

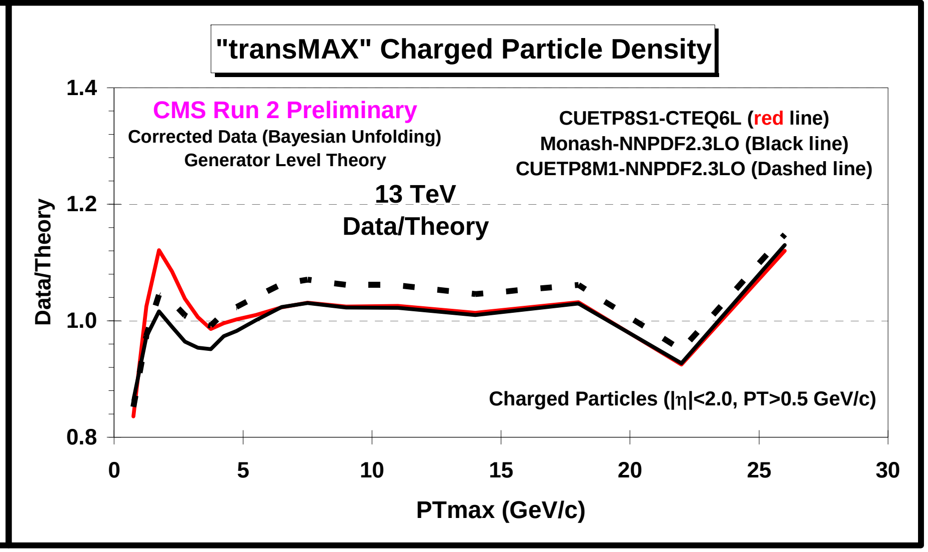


UE&MB@CMS

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

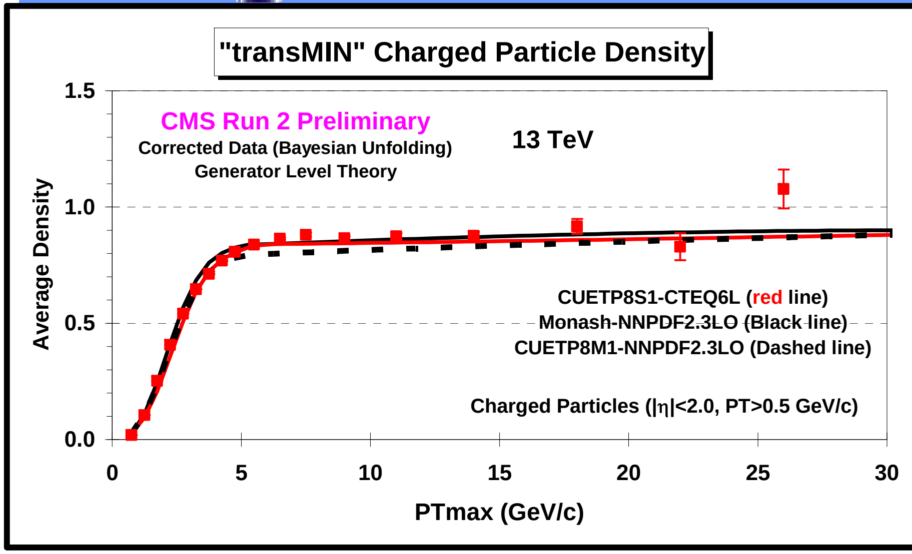
"transMAX" NchgDen

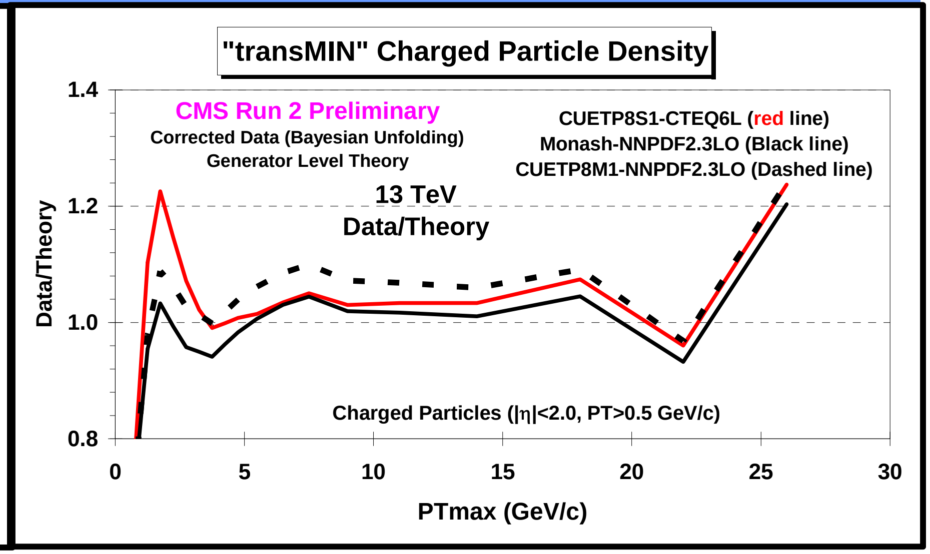




- **Corrected data (Bayesian unfolding) on the "transMAX" charged particle density with p_T > 0.5 GeV/c and |η| < 2.0 as defined by the leading charged particle, as a function of the transverse momentum of the leading charged particle, PTmax. The data are compared with PYTHIA 8 tune CUETP8S1-CTEQ6L, CUETP8M1-NNPDF2.3LO, and tune Monash at the generator level.**
- **The data divided by theory for PYTHIA 8 tune CUETP8S1-CTEQ6L, CUETP8M1-NNPDF2.3LO, and tune Monash.**

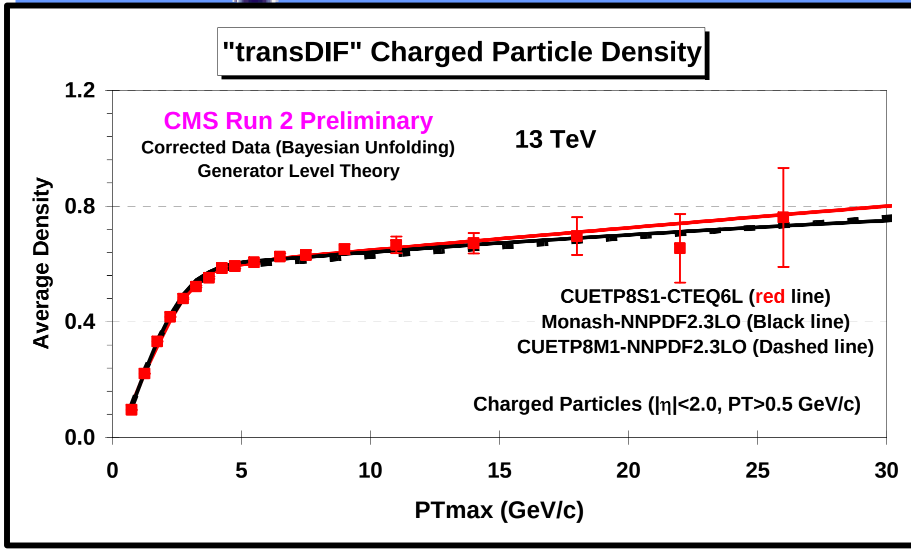
"transMIN" NchgDen

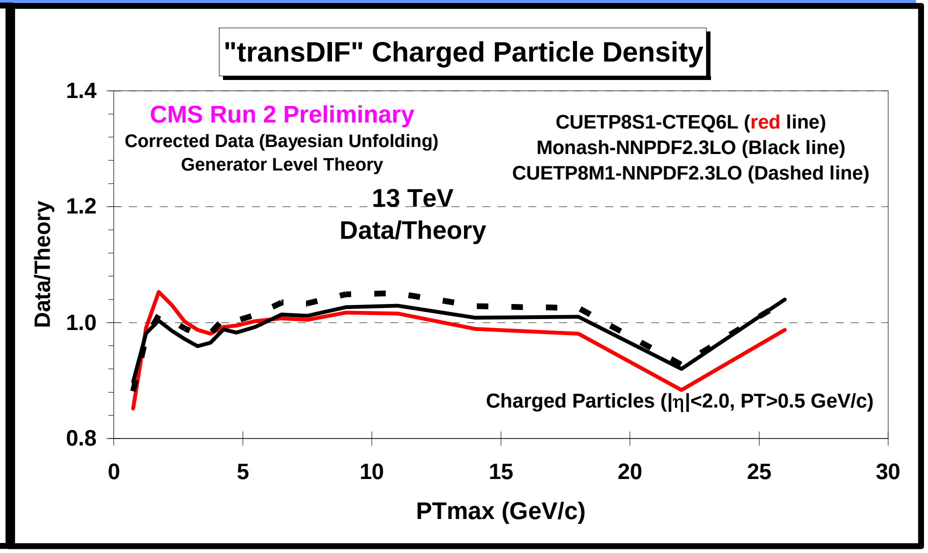




- Corrected data (Bayesian unfolding) on the "transMIN" charged particle density with p_T > 0.5 GeV/c and |η| < 2.0 as defined by the leading charged particle, as a function of the transverse momentum of the leading charged particle, PTmax. The data are compared with PYTHIA 8 tune CUETP8S1-CTEQ6L, CUETP8M1-NNPDF2.3LO, and tune Monash at the generator level.
- The data divided by theory for PYTHIA 8 tune CUETP8S1-CTEQ6L, CUETP8M1-NNPDF2.3LO, and tune Monash.

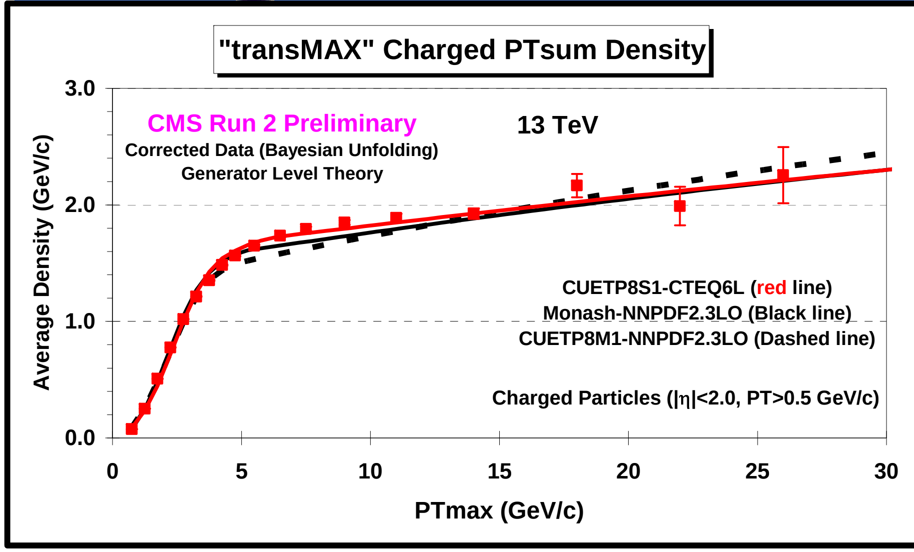
“transDIF” NchgDen

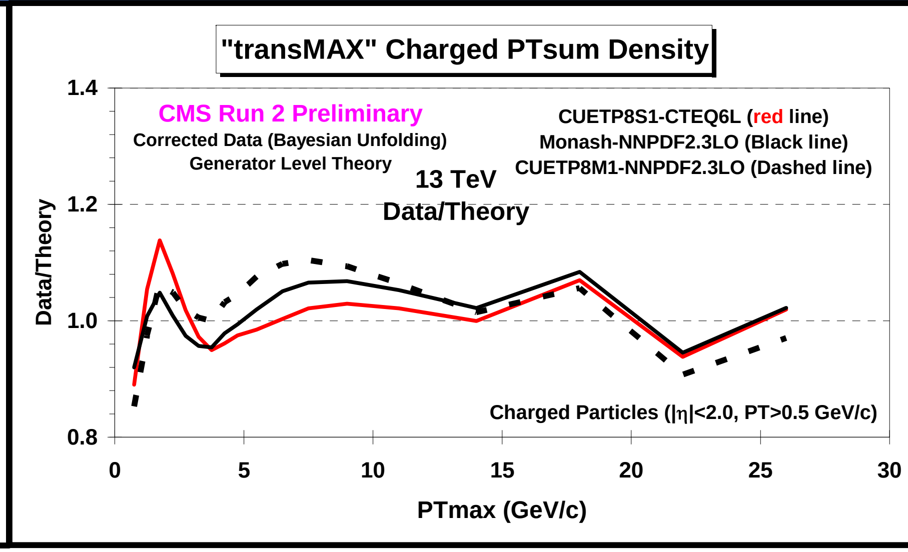




- **Corrected data (Bayesian unfolding) on the “transDIF” charged particle density with p_T > 0.5 GeV/c and |η| < 2.0 as defined by the leading charged particle, as a function of the transverse momentum of the leading charged particle, PTmax. The data are compared with PYTHIA 8 tune CUETP8S1-CTEQ6L, CUETP8M1-NNPDF2.3LO, and tune Monash at the generator level.**
- **The data divided by theory for PYTHIA 8 tune CUETP8S1-CTEQ6L, CUETP8M1-NNPDF2.3LO, and tune Monash.**

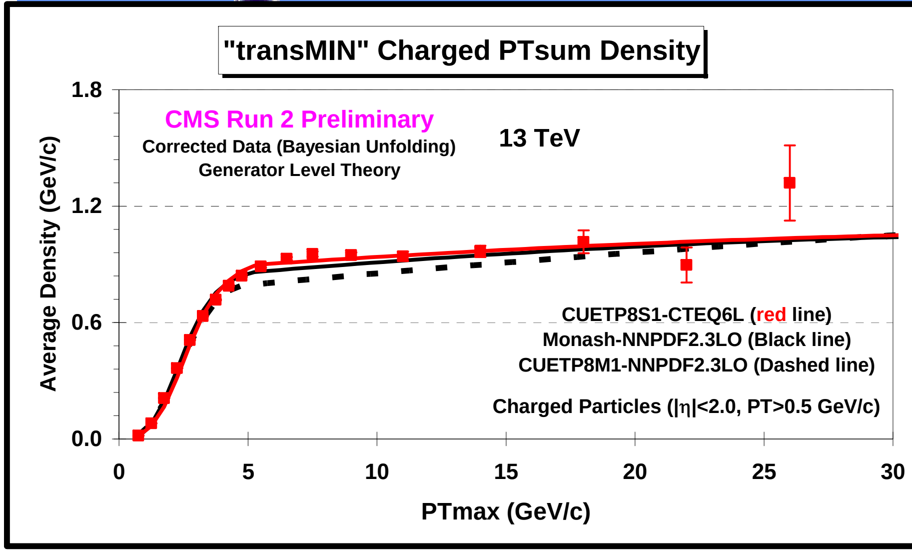
“transMAX” PTsumDen

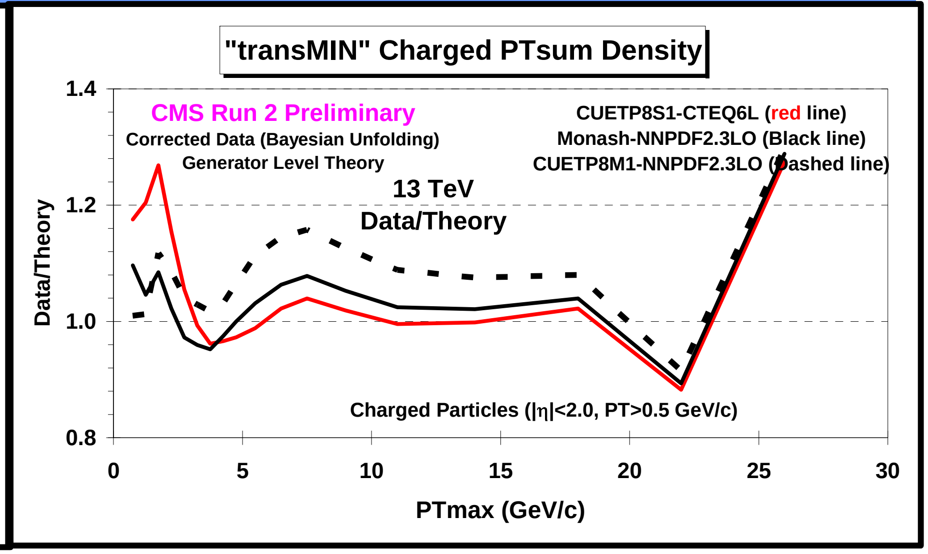




- **Corrected data (Bayesian unfolding) on the “transMAX” charged PTsum density with p_T > 0.5 GeV/c and |η| < 2.0 as defined by the leading charged particle, as a function of the transverse momentum of the leading charged particle, PTmax. The data are compared with PYTHIA 8 tune CUETP8S1-CTEQ6L, CUETP8M1-NNPDF2.3LO, and tune Monash at the generator level.**
- **The data divided by theory for PYTHIA 8 tune CUETP8S1-CTEQ6L, CUETP8M1-NNPDF2.3LO, and tune Monash.**

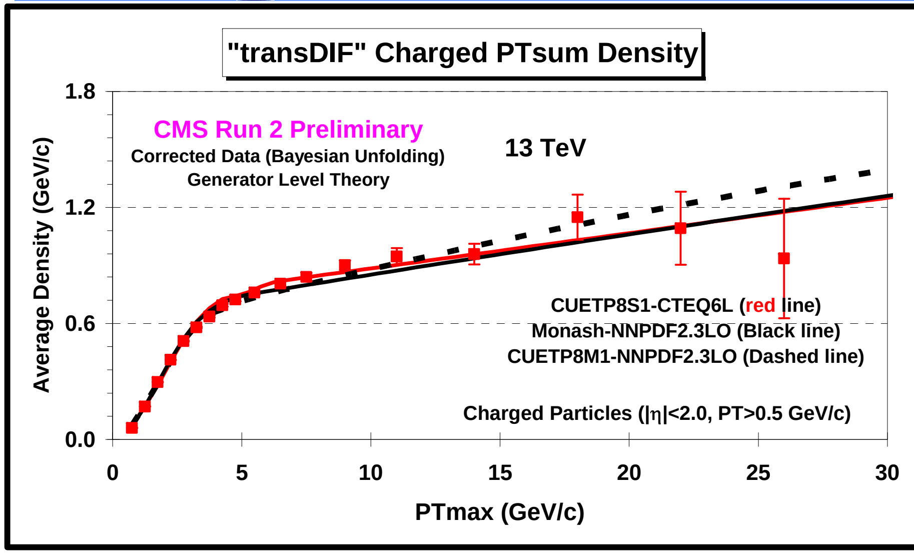
“transMIN” PTsumDen

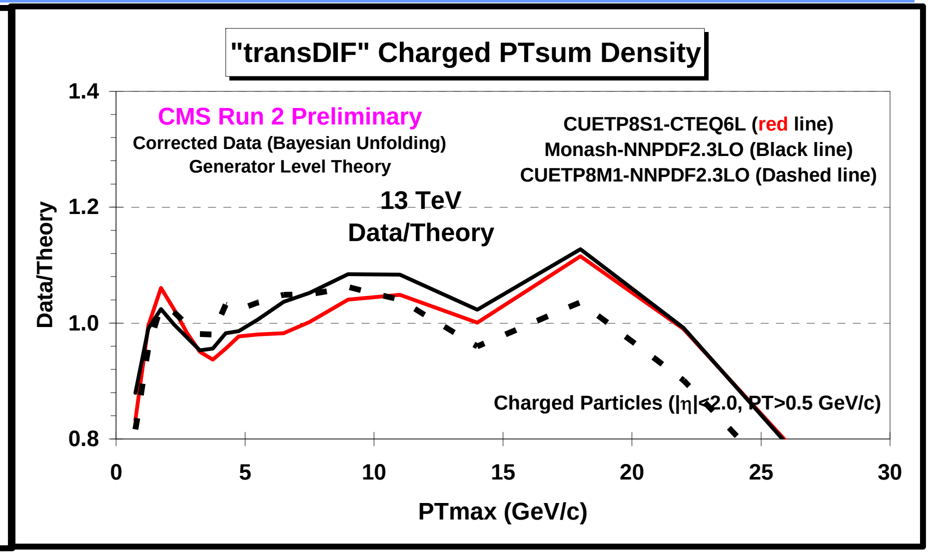




- **Corrected data (Bayesian unfolding) on the “transMIN” charged PTsum density with p_T > 0.5 GeV/c and |η| < 2.0 as defined by the leading charged particle, as a function of the transverse momentum of the leading charged particle, PTmax. The data are compared with PYTHIA 8 tune CUETP8S1-CTEQ6L, CUETP8M1-NNPDF2.3LO, and tune Monash at the generator level.**
- **The data divided by theory for PYTHIA 8 tune CUETP8S1-CTEQ6L, CUETP8M1-NNPDF2.3LO, and tune Monash.**

“transDIF” PTsumDen





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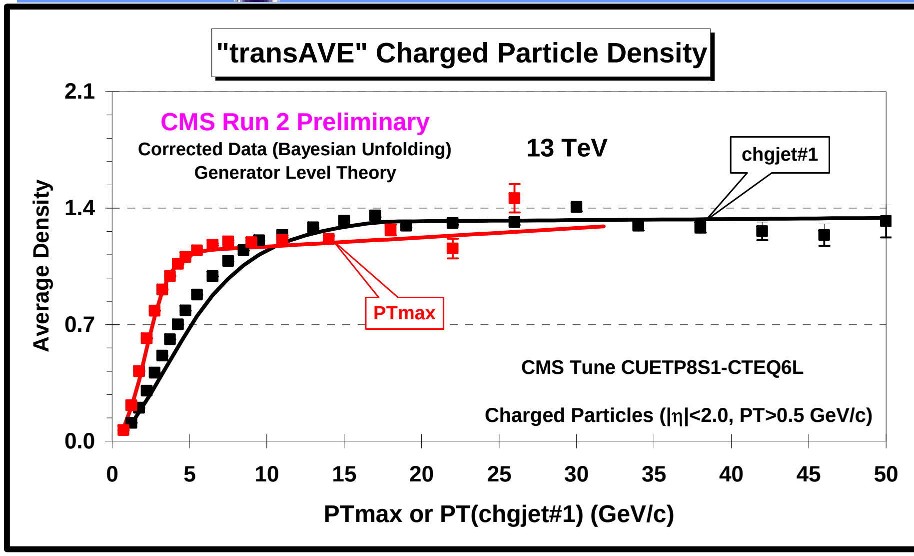
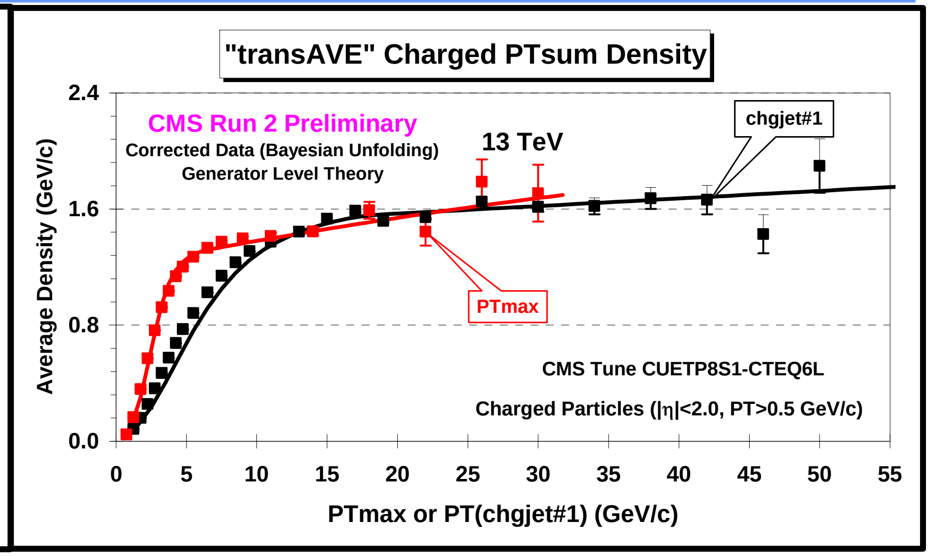
ChgJet#1 vs PTmax





- **Corrected data (Bayesian unfolding) on the "transAVE" charged particle density with p_T > 0.5 GeV/c and |η| < 2.0 as defined by the leading charged particle, PTmax, and as defined by the leading charged particle jet, chgjet#1. The data are compared with PYTHIA 8 tune CUETP8S1-CTEQ6L at the generator level.**

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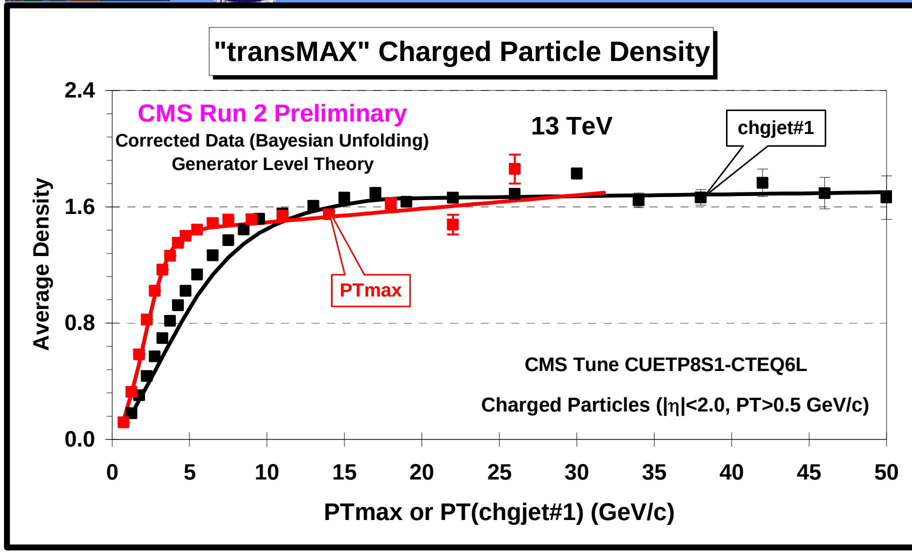
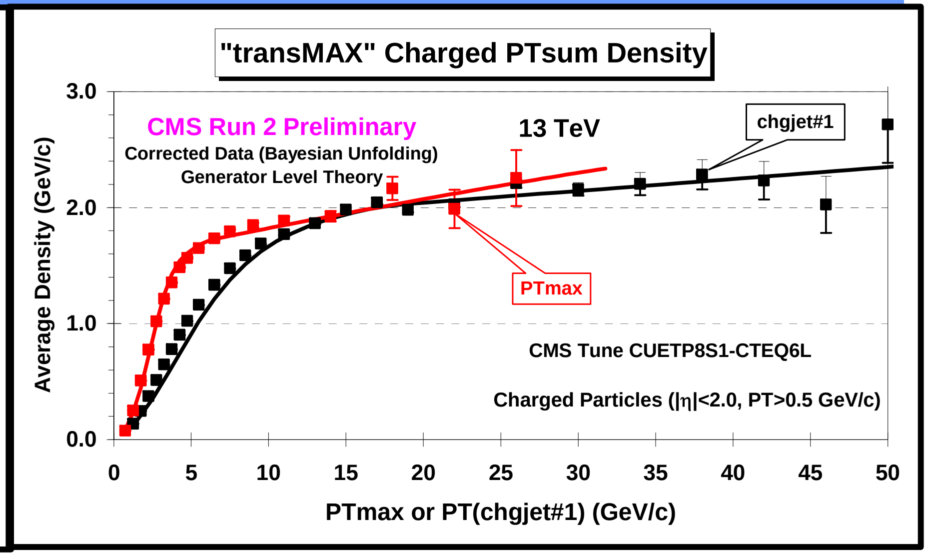
ChgJet#1 vs PTmax





- **Corrected data (Bayesian unfolding) on the "transMAX" charged particle density with p_T > 0.5 GeV/c and |η| < 2.0 as defined by the leading charged particle, PTmax, and as defined by the leading charged particle jet, chgjet#1. The data are compared with PYTHIA 8 tune CUETP8S1-CTEQ6L at the generator level.**

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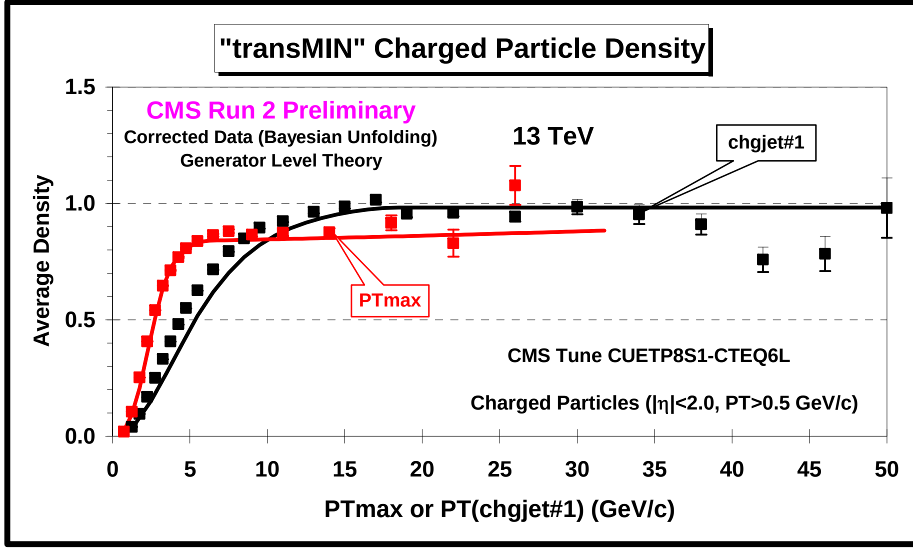

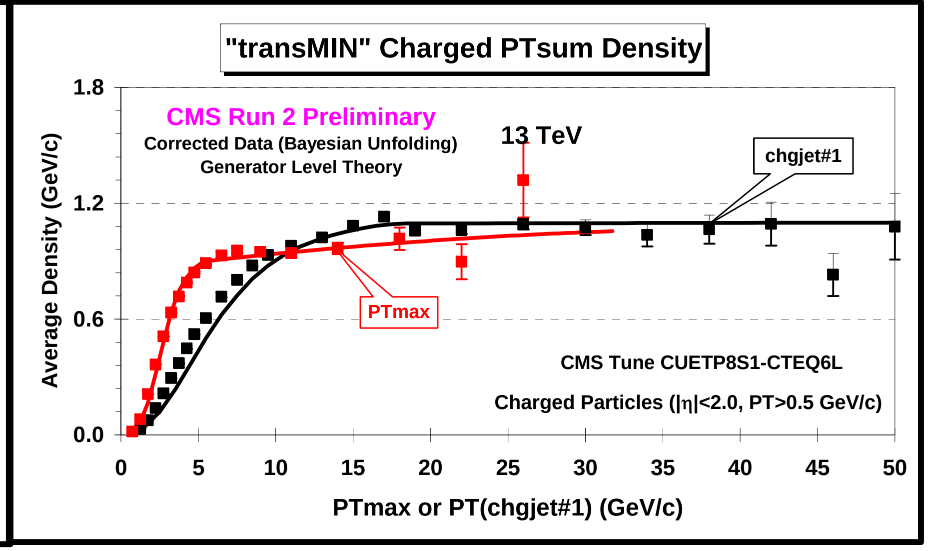

- **Corrected data (Bayesian unfolding) on the "transMIN" charged particle density with p_T > 0.5 GeV/c and |η| < 2.0 as defined by the leading charged particle, PTmax, and as defined by the leading charged particle jet, chgjet#1. The data are compared with PYTHIA 8 tune CUETP8S1-CTEQ6L at the generator level.**
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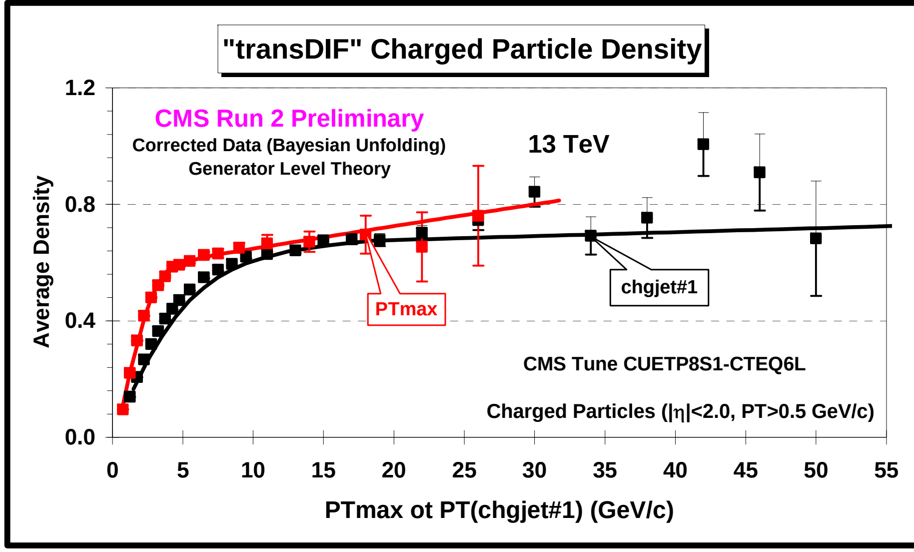
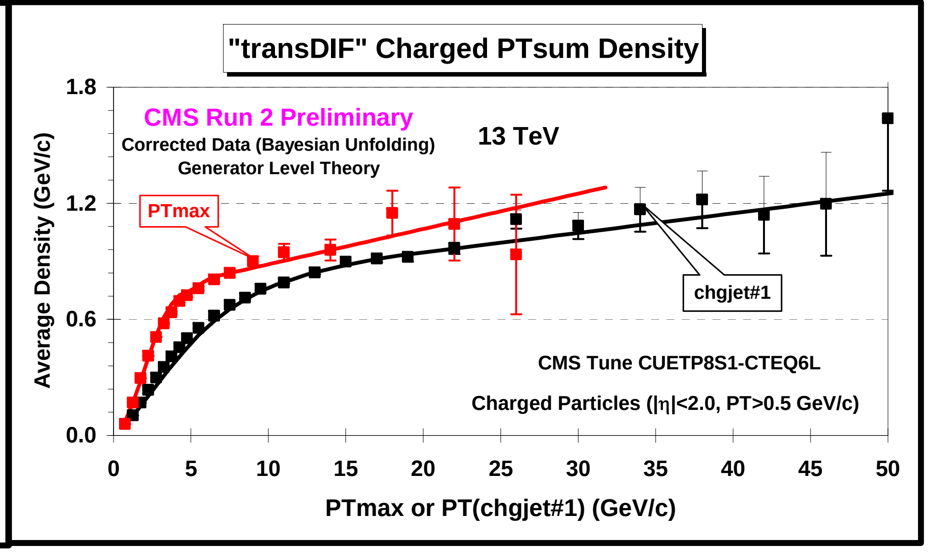
ChgJet#1 vs PTmax



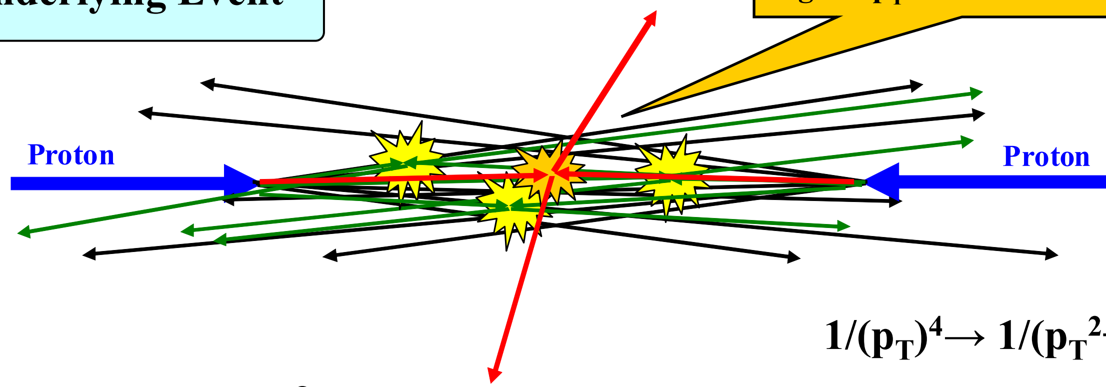


- **Corrected data (Bayesian unfolding) on the "transDIF" charged particle density with p_T > 0.5 GeV/c and |η| < 2.0 as defined by the leading charged particle, PTmax, and as defined by the leading charged particle jet, chgjet#1. The data are compared with PYTHIA 8 tune CUETP8S1-CTEQ6L at the generator level.**
- **Corrected data (Bayesian unfolding) on the "transDIF" charged PTsum density with p_T > 0.5 GeV/c and |η| < 2.0 as defined by the leading charged particle, PTmax, and as defined by the leading charged particle jet, chgjet#1. The data are compared with PYTHIA 8 tune CUETP8S1-CTEQ6L at the generator level.**

UE Tunes and MB

"Underlying Event"

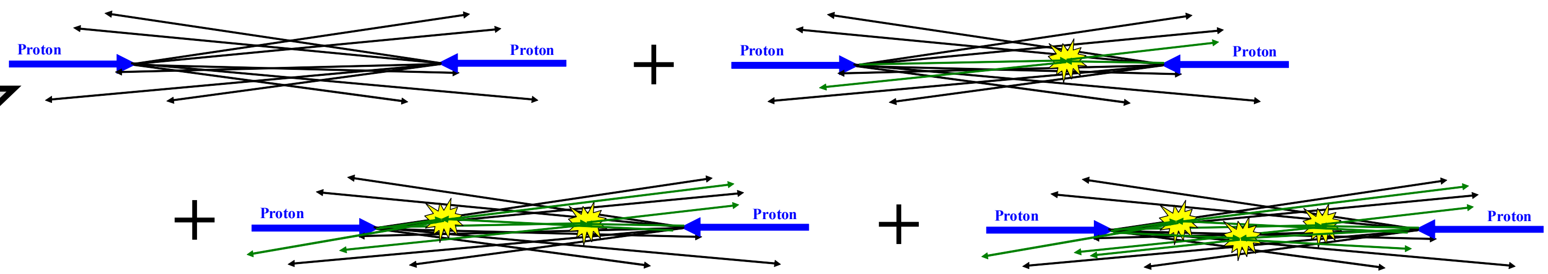
Allow primary hard-scattering to go to $p_T = 0$ with same cut-off!



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

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

"Min-Bias" (ND)

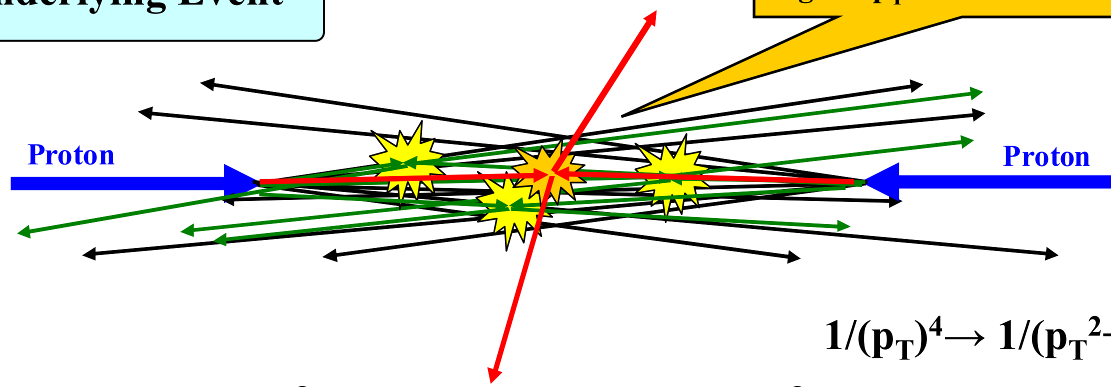


+ …

UE Tunes and MB

"Underlying Event"

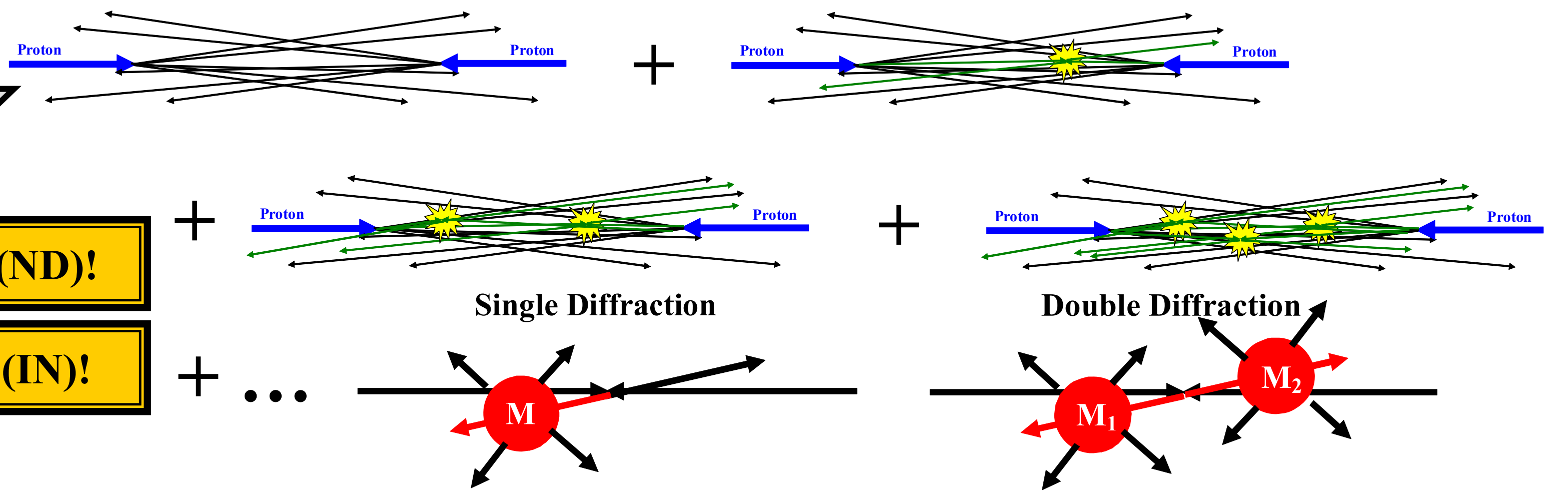
Allow primary hard-scattering to go to $p_T = 0$ with same cut-off!



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

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

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

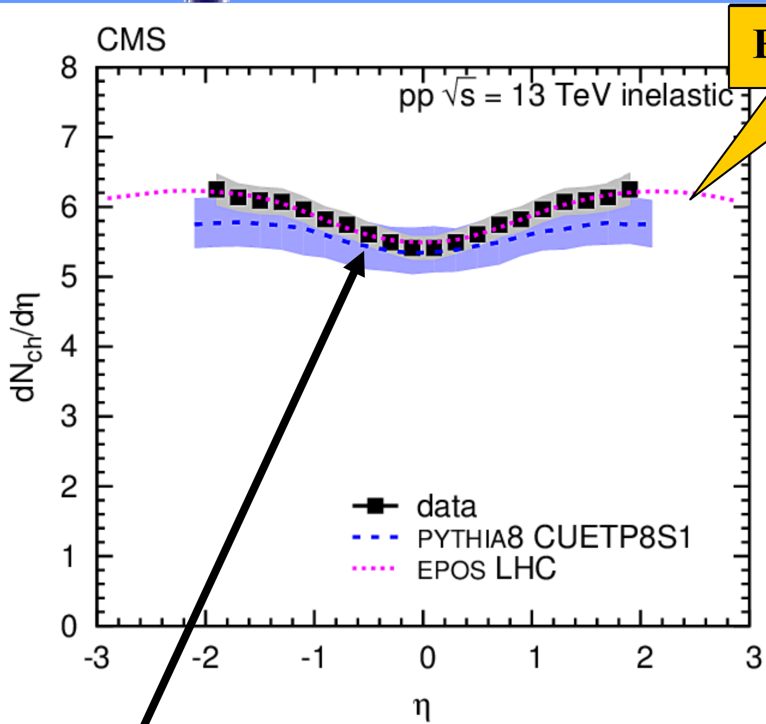


Predict MB (ND)!

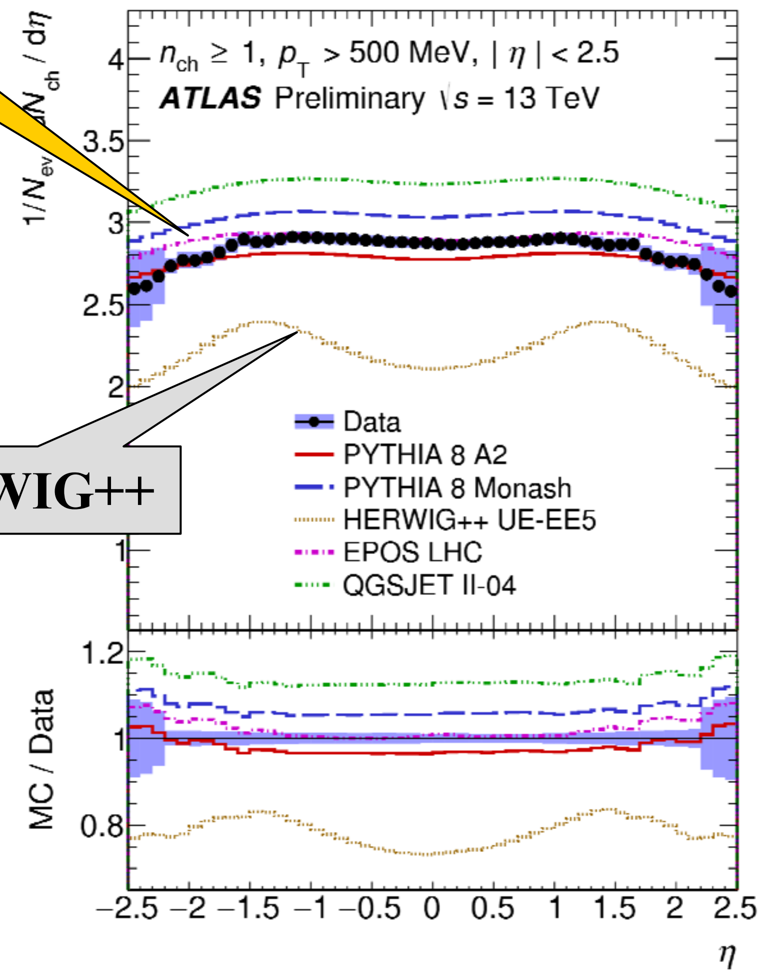
Predict MB (IN)!

+ …

MB at 13 TeV: dN/dη



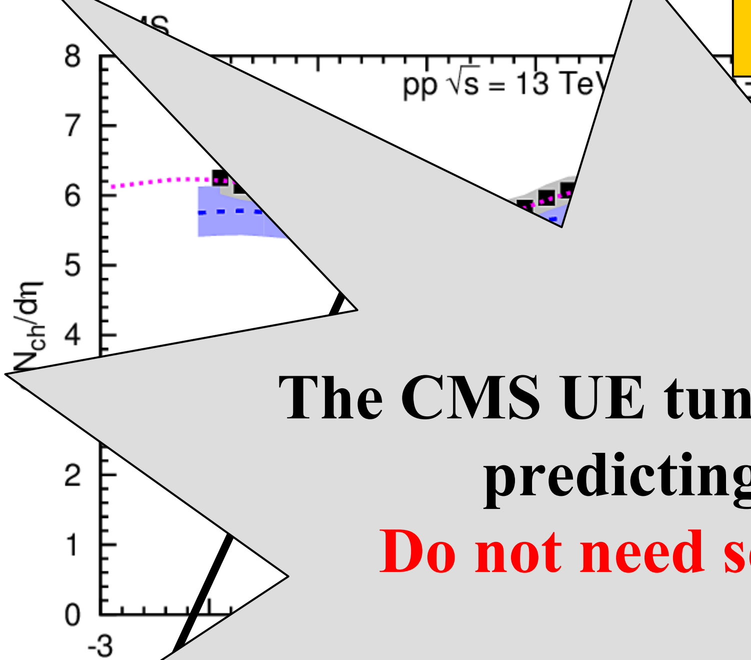
EPOS LHC

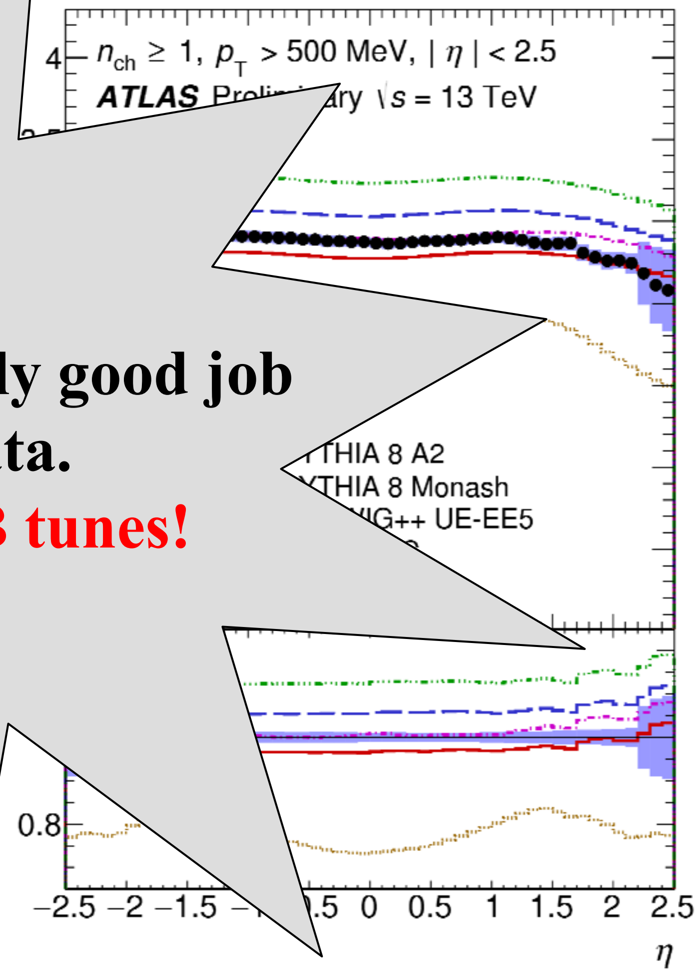


HERWIG++

CMS UE Tune CUETP8S1-HERAPDF1.5LO.

MB at 13 TeV: dN/dη



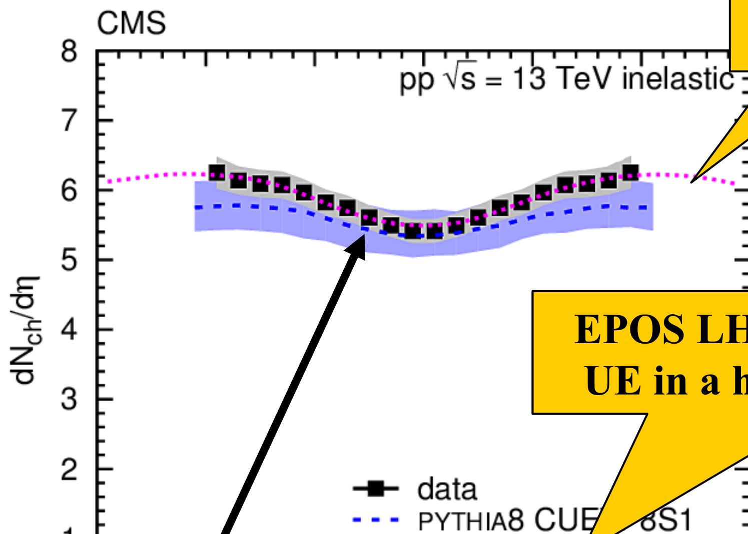


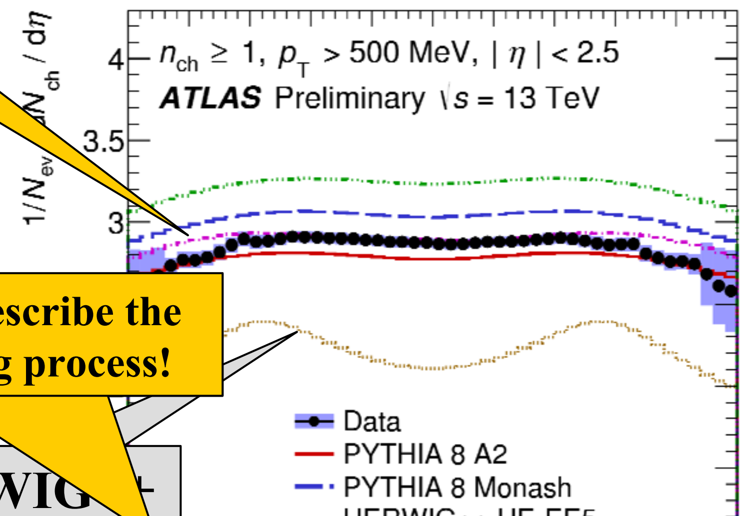
The CMS UE tunes do a fairly good job predicting the MB data.

Do not need separate MB tunes!

CMS UE Tune CUET

MB at 13 TeV: dN/dη

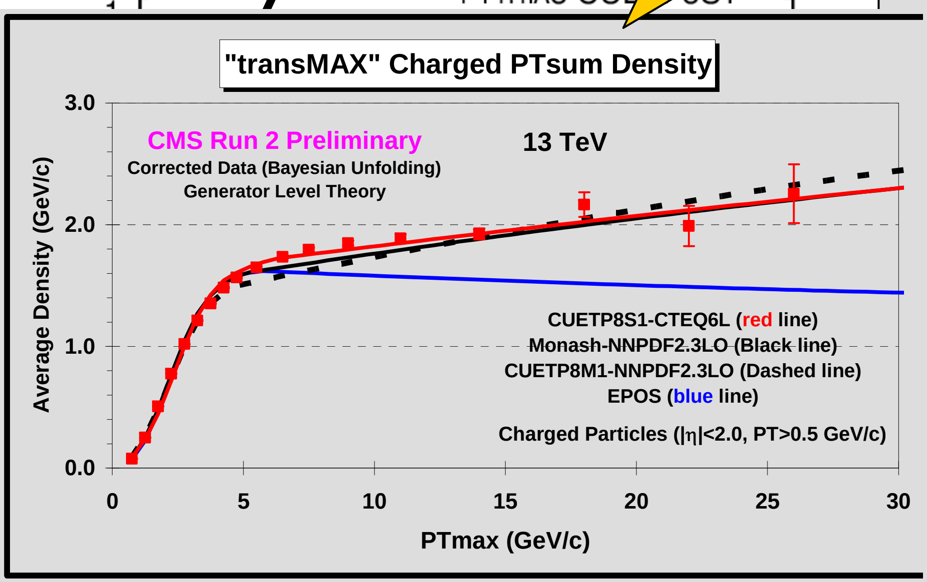


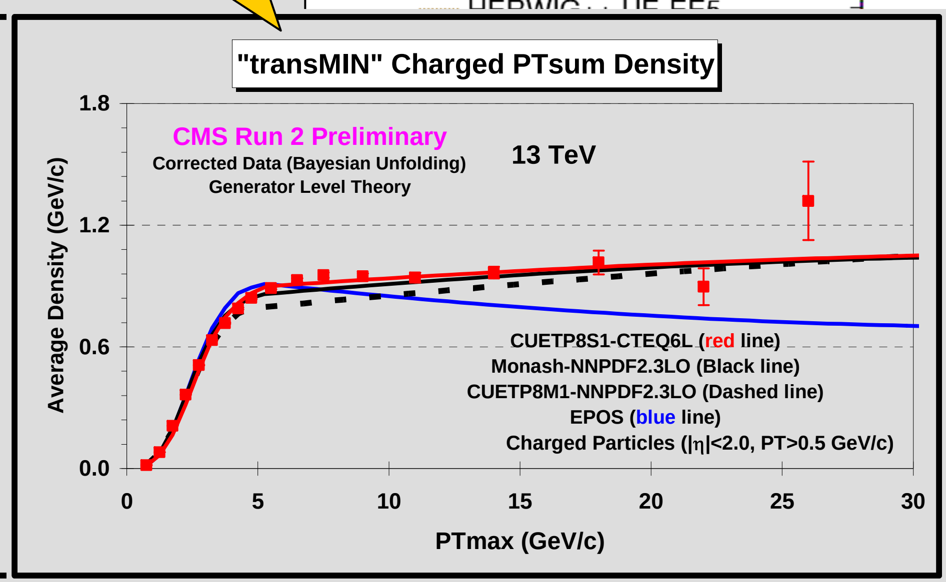


EPOS LHC

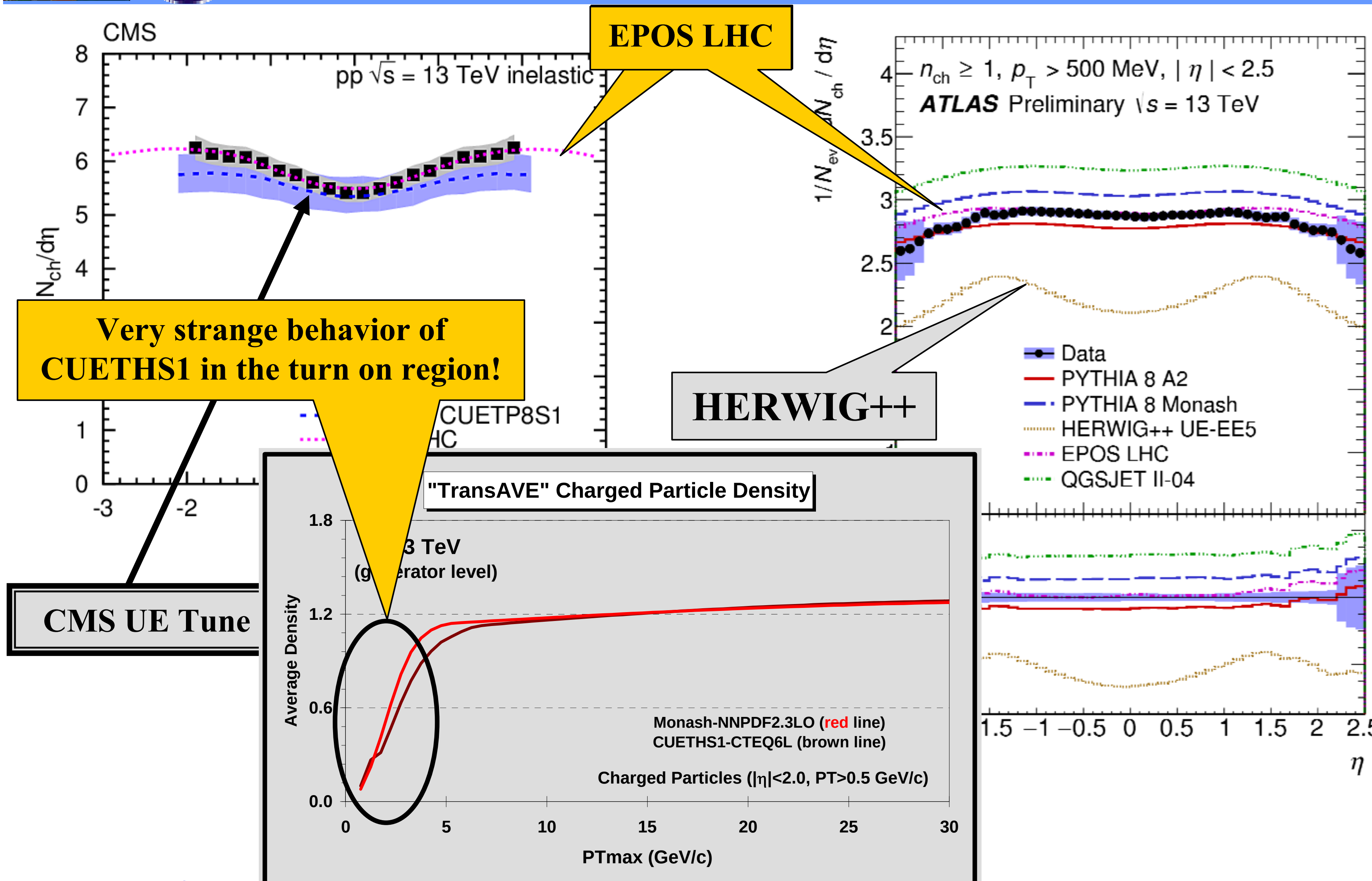
EPOS LHC does not describe the UE in a hard scattering process!

HERWIG++

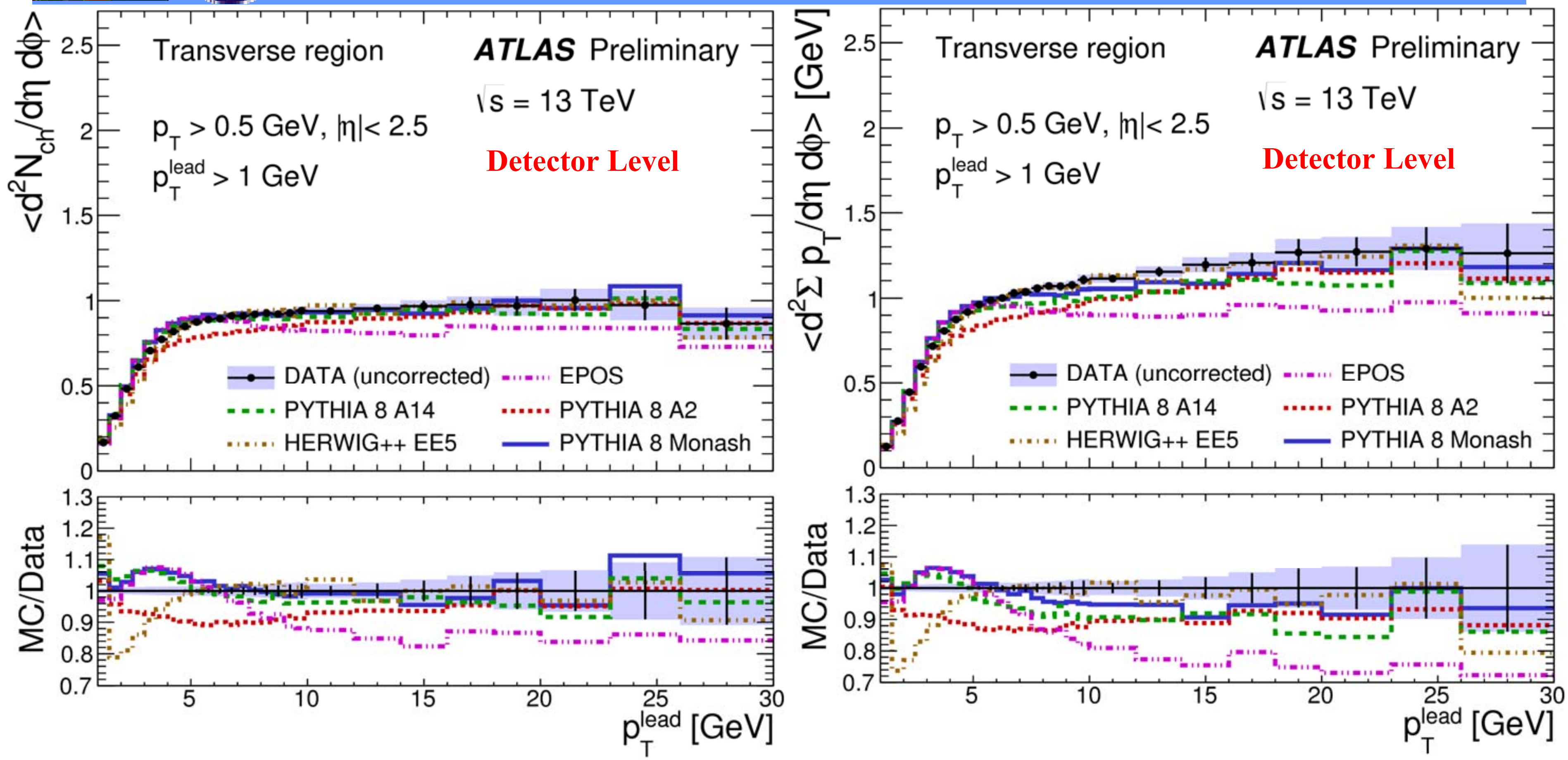




MB at 13 TeV: dN/dη

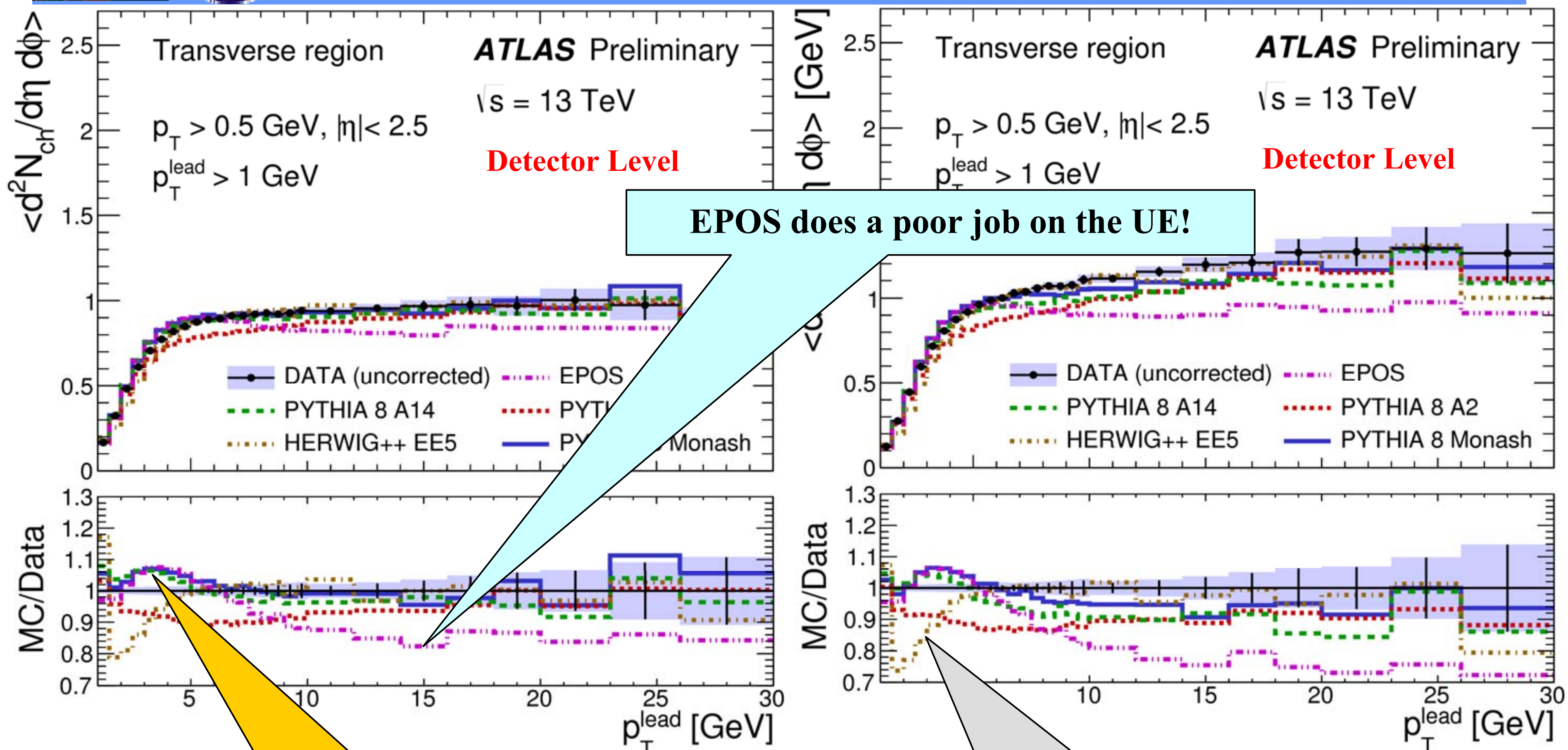


ATLAS 13 TeV UE Data



➡ **ATLAS data at 13 TeV on the charged particle density (keft) and charged PTsum density in the "transAVE" region as defined by the leading charged particle for charged particles with $p_T > 0.5$ GeV/c and |η| < 2.5. The data are uncorrected and compared with the MC models after detector simulation.**

ATLAS 13 TeV UE Data



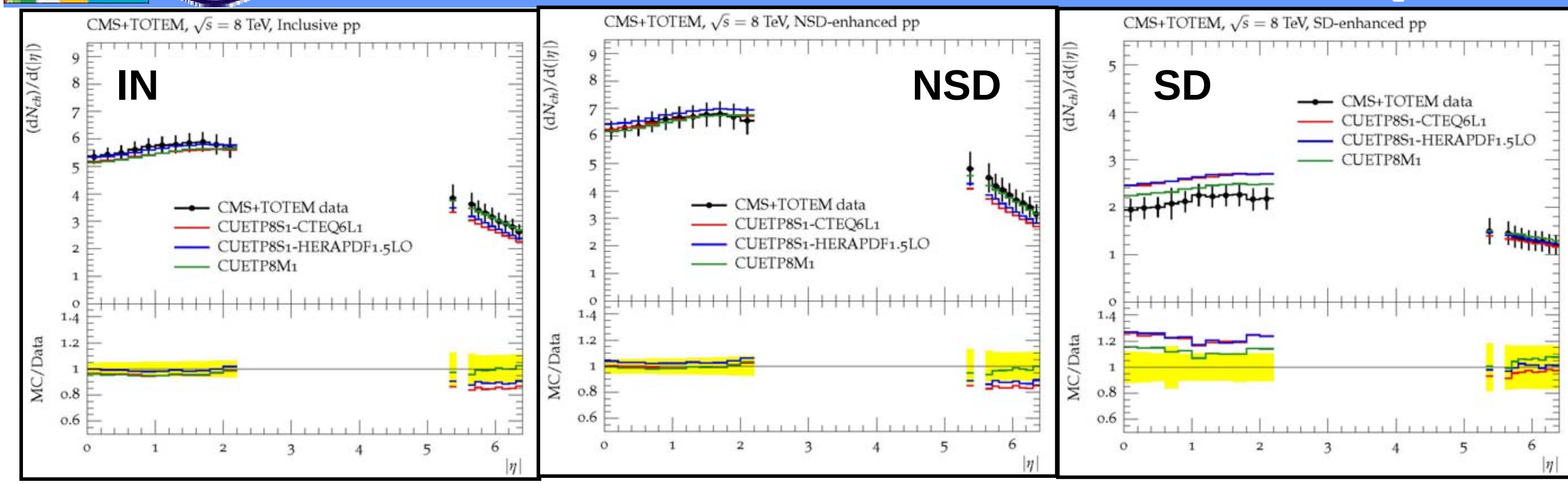
EPOS does a poor job on the UE!

Monash doing well except the turn on region!

Very strange behavior by HERWIG++ in the turn on region!

➡ ATLAS data ... eV on the charged particle density (keft) ... rged PTsum density in the "transA... ading charged p... GeV/c a... rected and com... simulation.

CMS+TOTEM dN/dη

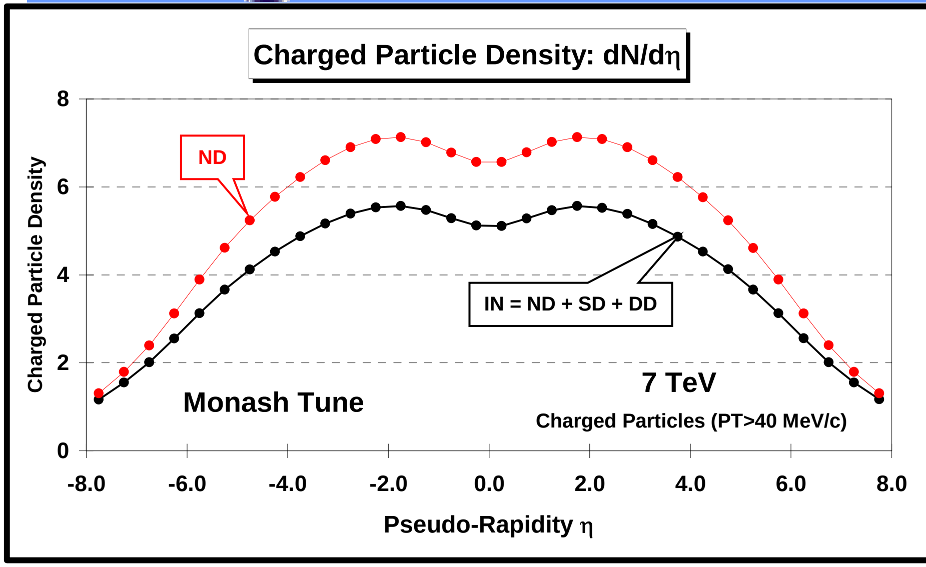


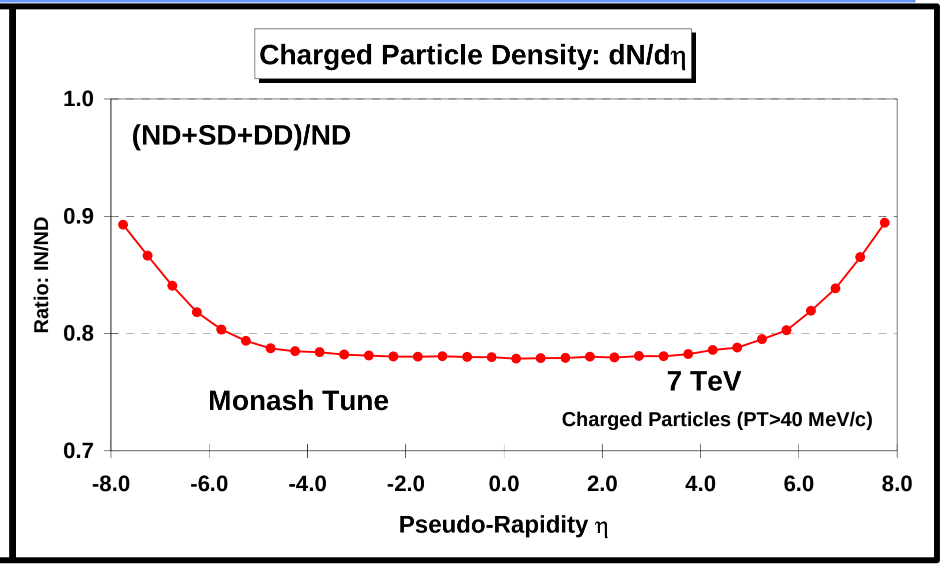
- **Compares the CMS CUEP8M1-NNPDF2.3LO (Mstar) tune with the CMS+TOTEM dN/dη data at 8 TeV.**

The CMS UE tunes do a fairly good job (although not perfect) describing the MB data! No need for a separate MB tune.

The CMS UE tune CUEP8M1-NNPDF2.3LO (Mstar) does a better job in the forward region due to the PDF!.

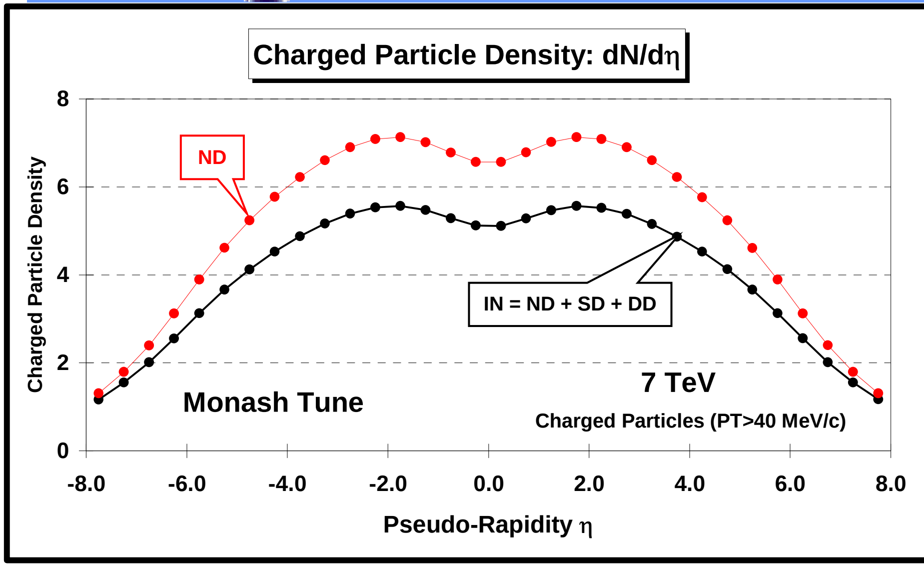
Charged Particle Density

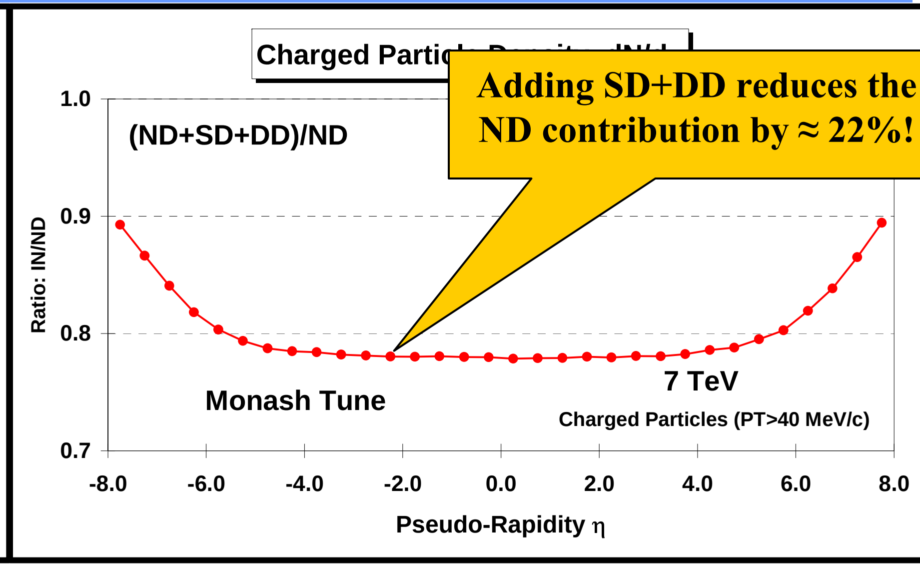




- **The charged particle density, dN/dη, for charged particles with p_T > 40 MeV/c at 7 TeV predicted by the Monash tune for the non-diffractive component (ND) and the inelastic component (IN = ND+SD+DD).**
- **The ratio on the inelastic component (IN = ND+SD+DD) and the non-diffractive component (ND) for the charged particle density, dN/dη, for charged particles with p_T > 40 MeV/c as predicted by the Monash tune at 7 TeV.**

Charged Particle Density





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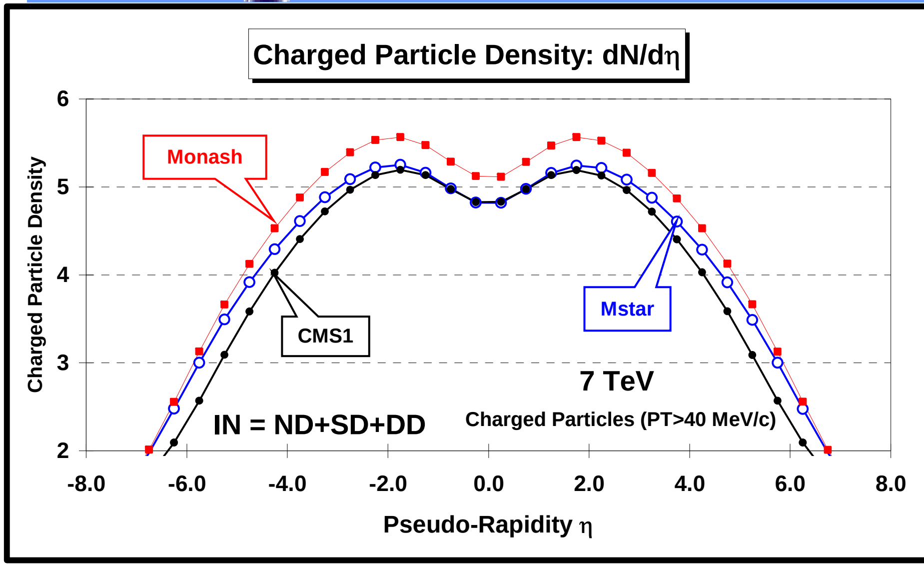
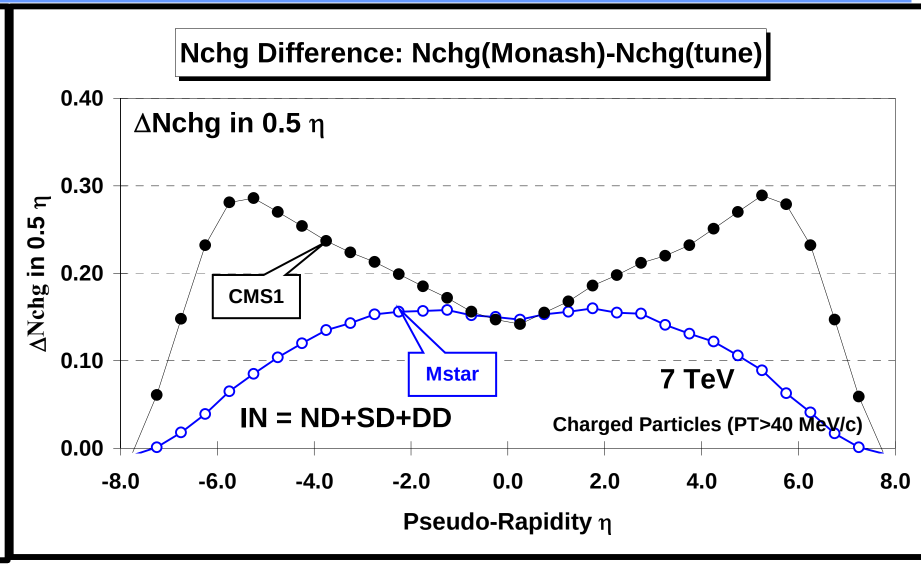
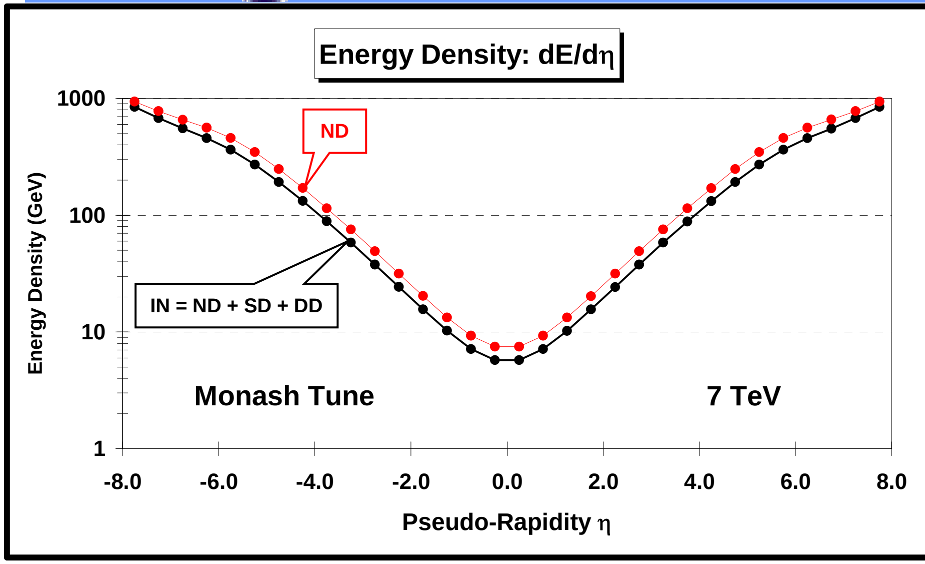
Charged Particle Density

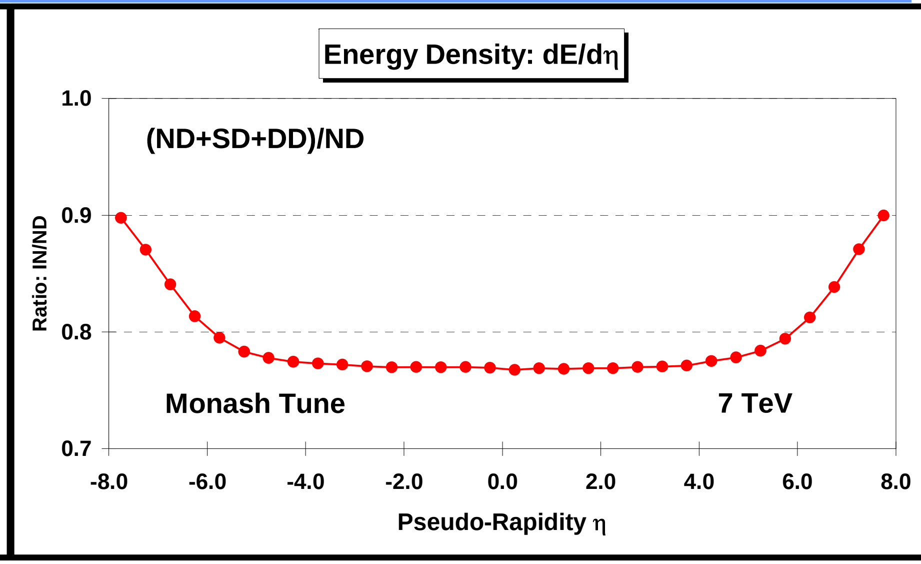




- **The charged particle density, dN/dη, for charged particles with p_T > 40 MeV/c at 7 TeV predicted by the Monash-NNPDF2.3LO tune, the tune CUETP8S1-CTEQ6L (CMS1), and tune CUEP8M1-NNPDF2.3LO (Mstar) for the inelastic component (IN = ND+SD+DD).**
- **Shows the charged particle difference, ΔN_{chg}, for charged particles with p_T > 40 MeV/c at 7 TeV between the Monash-NNPDF2.3LO tune and tune CUETP8S1-CTEQ6L (CMS1), and tune CUEP8M1-NNPDF2.3LO (Mstar) for the inelastic component (IN = ND+SD+DD), where $\Delta N_{chg} = N_{chg}$(Monash)-N_{chg}(tune) and corresponds to the number of charged particles in 0.5 η.**

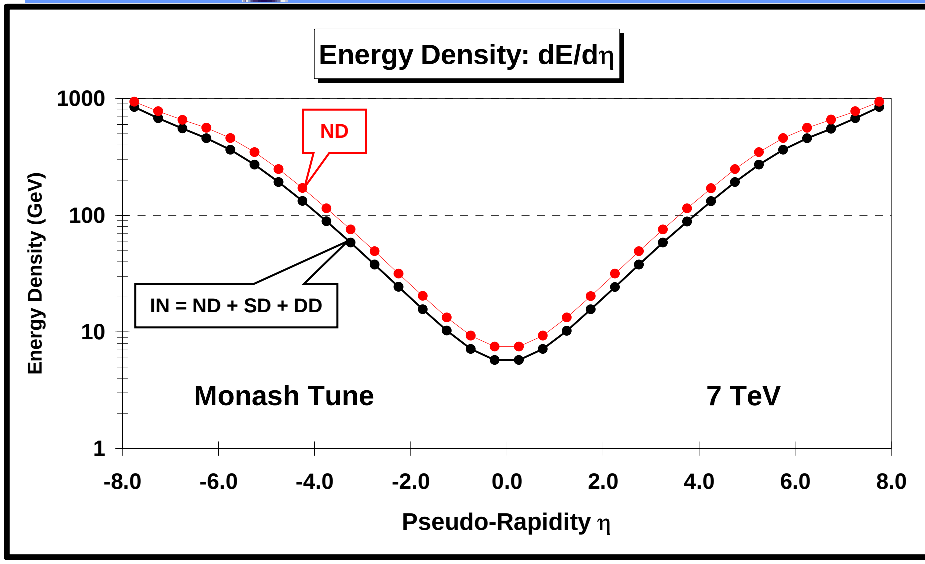
Energy Flow: dE/dη

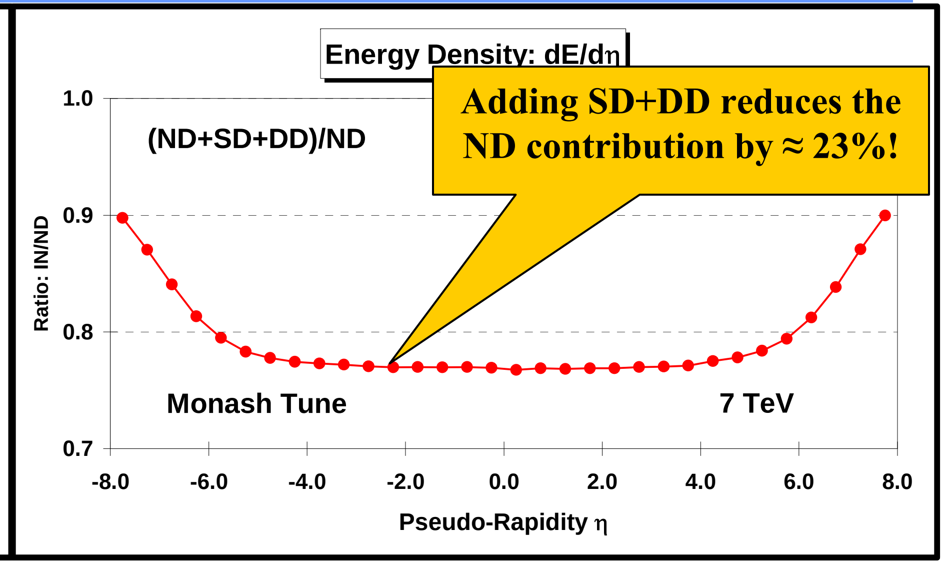




- **The energy density, dE/dη, at 7 TeV predicted by the Monash tune for the non-diffractive component (ND) and the inelastic component (IN = ND+SD+DD).**
- **The ratio on the inelastic component (IN = ND+SD+DD) and the non-diffractive component (ND) energy density, dE/dη, predicted by the Monash tune at 7 TeV.**

Energy Flow: dE/dη





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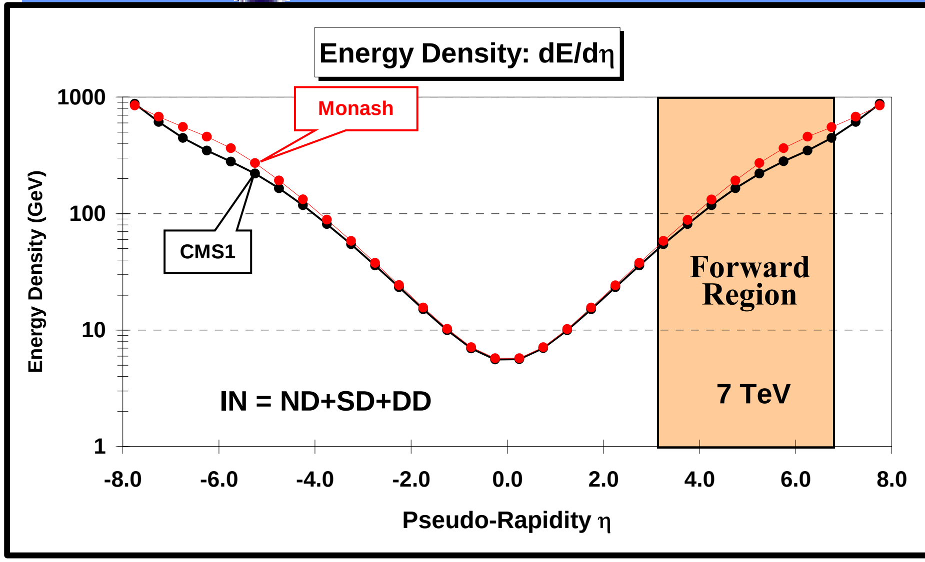
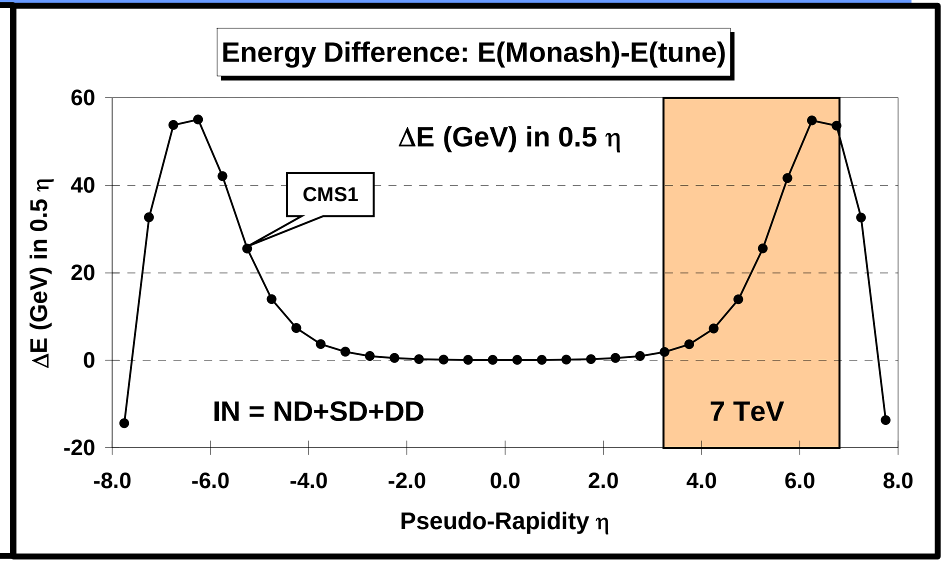
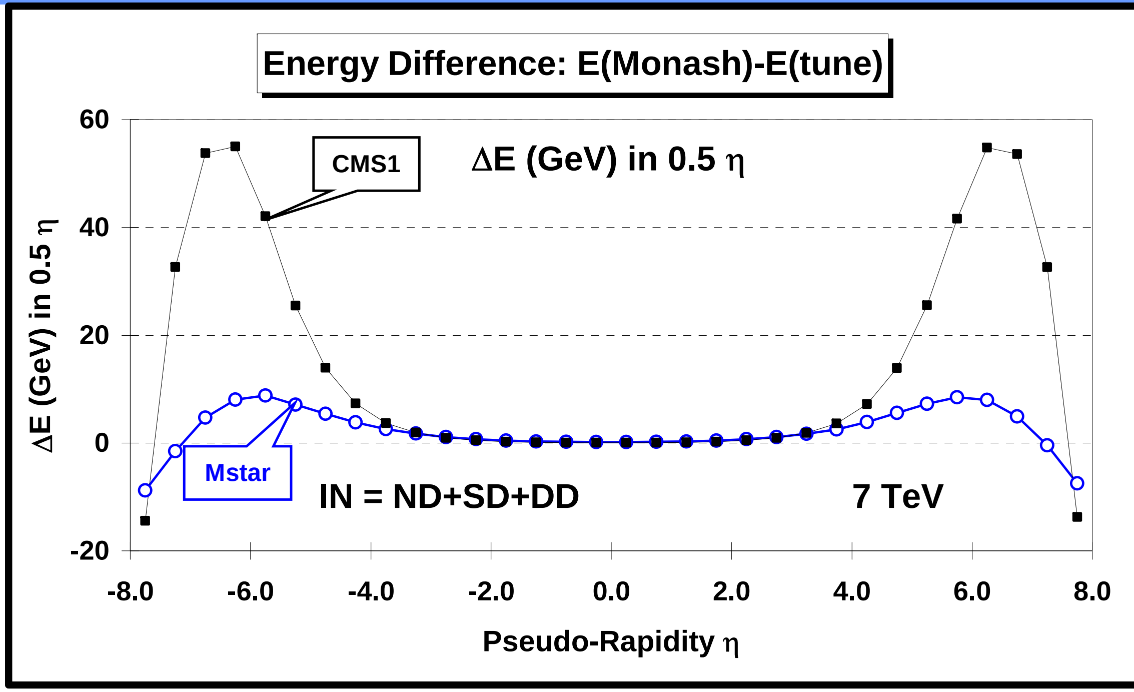
Energy Flow: dE/dη





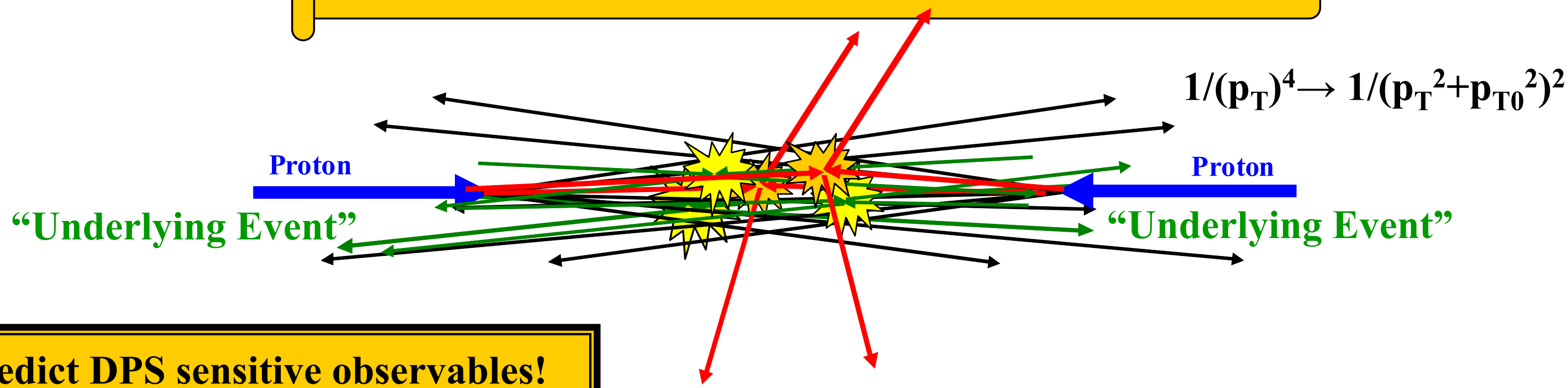
- **The energy density, dE/dη, at 7 TeV predicted by the Monash-NNPDF2.3LO tune and the tune CUETP8S1-CTEQ6L (CMS1) for the inelastic component (IN = ND+SD+DD).**
- **The energy difference, ΔE, at 7 TeV between the Monash-NNPDF2.3LO and tune CUETP8S1-CTEQ6L (CMS1) for the inelastic component (IN = ND+SD+DD), where ΔE = E(Monash)-E(CMS1) and corresponds to the amount of energy in GeV in 0.5 η.**

Energy Flow: dE/dη



- **Shows the energy density difference, ΔE, at 7 TeV between the Monash-NNPDF2.3LO tune, and tune CUETP8S1-CTEQ6L (CMS1), and tune CUEP8M1-NNPDF2.3LO (Mstar) for the inelastic component (IN = ND+SD+DD), where ΔE = E(Monash)-E(tune) and corresponds to the amount of energy in GeV in 0.5 η.**

DPS: Double Parton Scattering

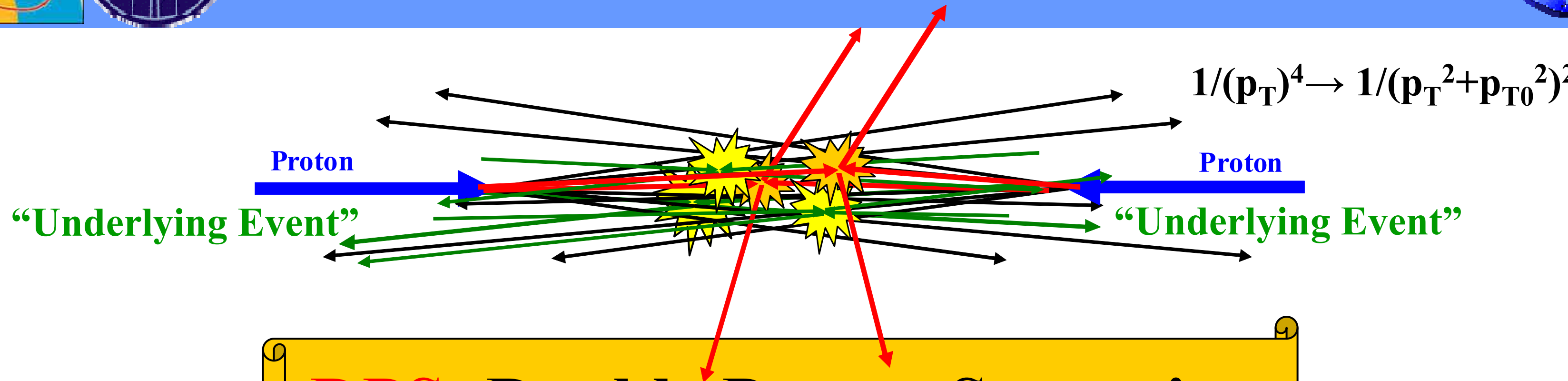


Predict DPS sensitive observables!

Most of the time MPI are much "softer" than the primary "hard" scattering, however, occasionally two "hard" 2-to-2 parton scatterings can occur within the same hadron-hadron. This is referred to as double parton scattering (DPS).

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

DPS and the "Underlying Event"



DPS: Double Parton Scattering

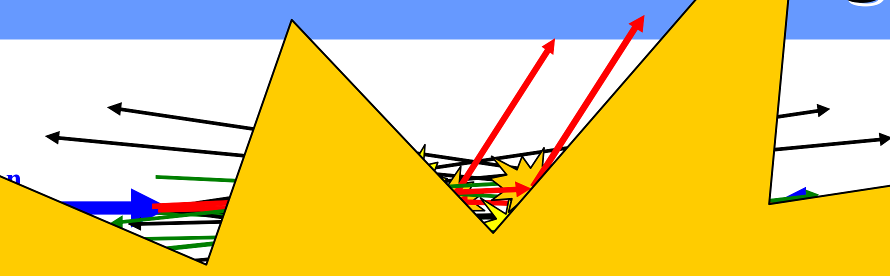
Most of the time MPI are much "softer" than the primary "hard" scattering, however, occasionally two "hard" 2-to-2 parton scatterings can occur within the same hadron-hadron. This is referred to as double parton scattering (DPS) and is typically described in terms of an effective cross section parameter, σ_{eff}, defined as follows:

$$\sigma_{AB} = \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

Independent of A and B

where σ_A and σ_B are the inclusive cross sections for individual hard scatterings of type A and B, respectively, and σ_{AB} is the cross section for producing both scatterings in the same hadron-hardon collision. If A and B are indistinguishable, as in 4-jet production, a statistical factor of ½ must be inserted.

DPS and the “Underl ing Event”



Having determined the parameters of an MPI model, one can make an unambiguous prediction of σ_{eff}. In PYTHIA 8 σ_{eff} depends primarily on the matter overlap function, which for bProfile = 3 is determined by the exponential shape parameter, expPow, and the MPI cross section determined by p_{T0} and the PDF.

Most of the tim … however, occasionally two … n- hadron. Th … pically described in terms … cross

σ_{eff}

…ndependen… nd B

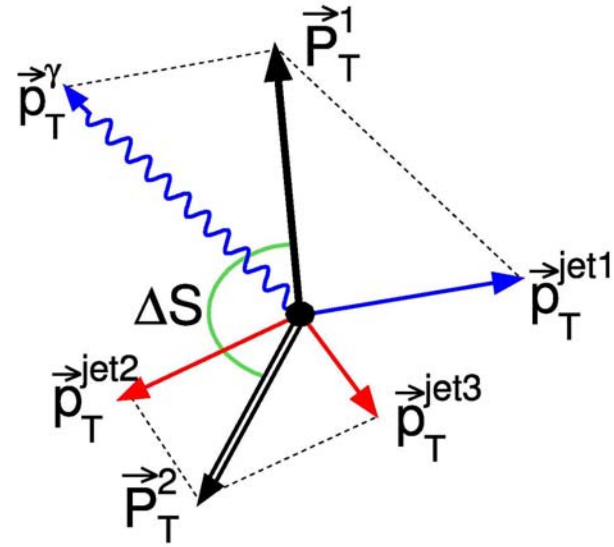
where σ_A and σ_B are the inclusive … ections fo … vidual hard scatte ings of type A and B, respectively, and σ_{AB} is the … section for pr … ducing both scatterings in the same hadron-hardon collision. If A … d B are indistinguishable, as in 4-jet production, a statistical factor of ½ must be inser … d.

DPS Observables

- Direct measurements of σ_{eff} are performed by studying correlations between the outgoing objects in hadron-hadron collision. Two correlation observables that are sensitive to DPS are ΔS and $\Delta^{rel}p_T$ defined as follows:

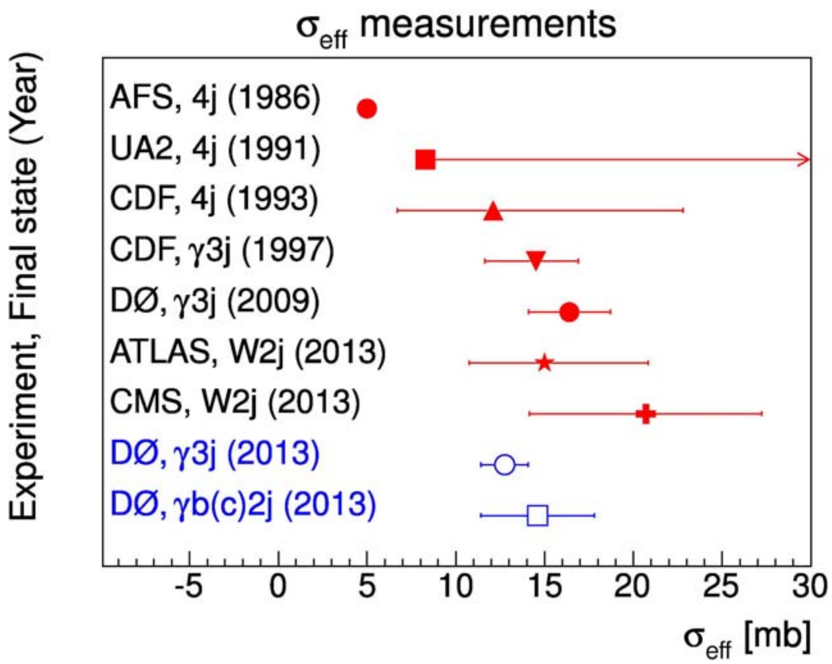
$$\Delta S = \arccos\left(\frac{\vec{p}_T(object\#1)\cdot\vec{p}_T(object\#2)}{|\vec{p}_T(object\#1)|\times|\vec{p}_T(object\#2)|}\right)$$

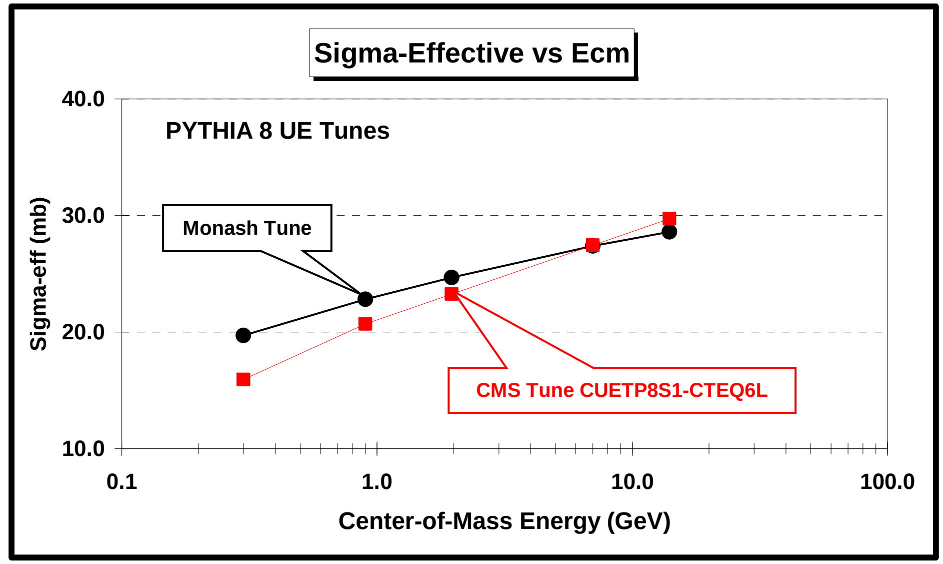
$$\Delta^{rel}p_T = \frac{|\vec{p}_T^{\,jet\#1}+\vec{p}_T^{\,jet\#2}|}{|\vec{p}_T^{\,jet\#1}|+|\vec{p}_T^{\,jet\#2})|}$$



For γ+3jets object#1 is the photon and the leading jet (jet1) and object#2 is jet2 and jet3. For W+dijet production object#1 is the W-boson and object#2 dijet. For 4-jet production object#1 is hard-jet pair and object#2 is the soft-jet pair. For $\Delta^{rel}p_T$ in W+dijet production jet#1 and jet#2 are the two dijets, while in 4-jet production jet#1 and jet#2 are the softer two jets.

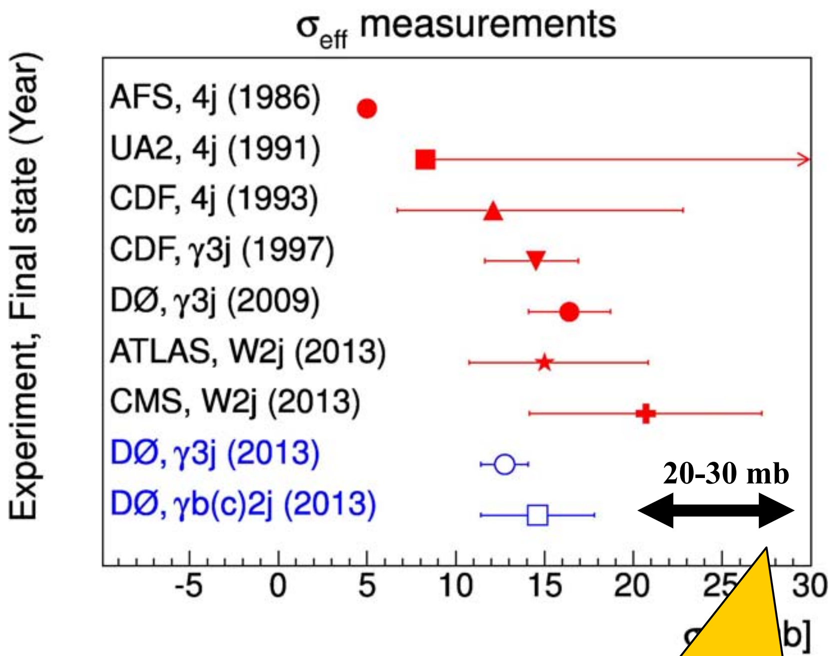
Sigma-Effective

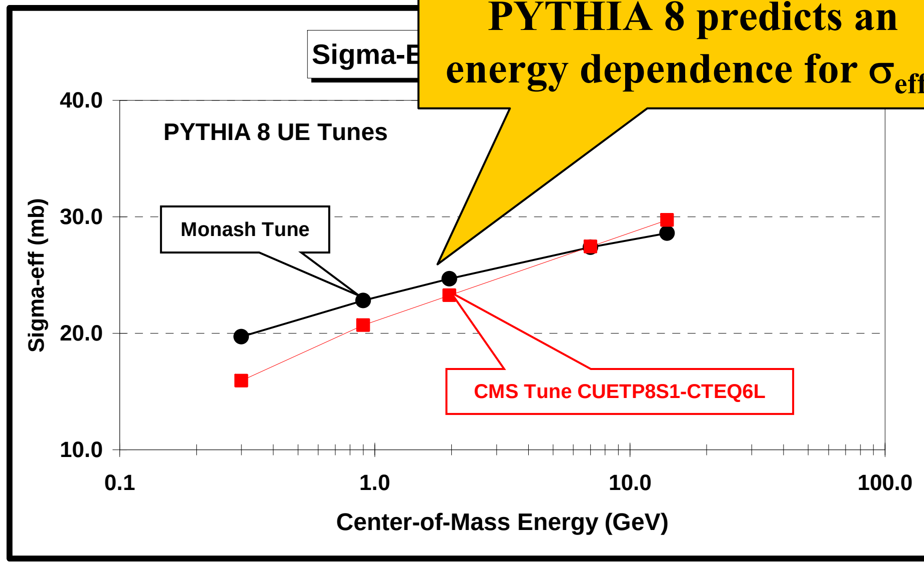




- **Shows the σ_{eff} values caluclated from the PYTHIA 8 Monash and CMS tune CUETP8S1-CTEQ6L.**

Sigma-Effective





PYTHIA 8 predicts an energy dependence for σ_{eff}!

- **Shows the σ_{eff} values caluclated from the PYTHIA 8 Monash and CMS tune CUETP8S1-CTEQ6L.**

The σ_{eff} predicted from the PYTHIA 8 UE tunes is slightly larger than the direct measurements!

Sigma-Effective

Constraining MPI models using σ_{eff} and recent Tevatron and LHC Underlying Event data

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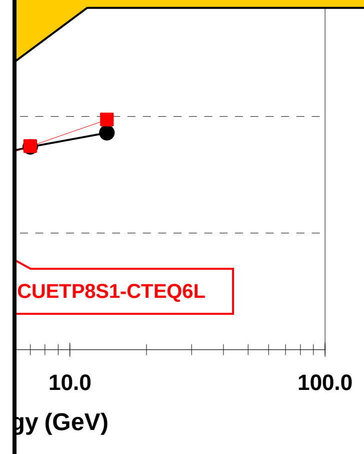
E-mail: michael.seymour@manchester.ac.uk, andrzej.siodmok@manchester.ac.uk

ABSTRACT: We review the modelling of multiple interactions in the event generator HERWIG++ and study implications of recent tuning efforts to Tevatron and LHC data. It is often said that measurements of the effective cross section for double-parton scattering, σ_{eff}, are in contradiction with models of the final state of multi-parton interactions, but we show that the HERWIG++ model is consistent with both and gives stable predictions for underlying event observables at 14 TeV.

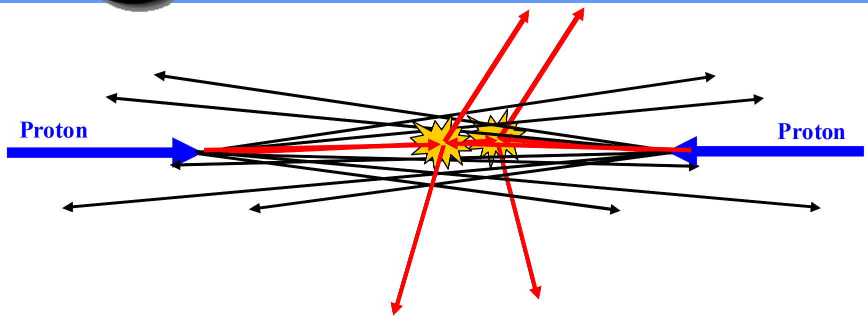
HIA 8 predicts an dependence for σ_{eff}!



ed from the PYTHIA 8 TP8S1-CTEQ6L.

The σ_{eff} predicted from the PYTHIA 8 UE tunes is slightly larger than the direct measurements!

CMS DPS Tunes



CMS W+DiJet Measurement

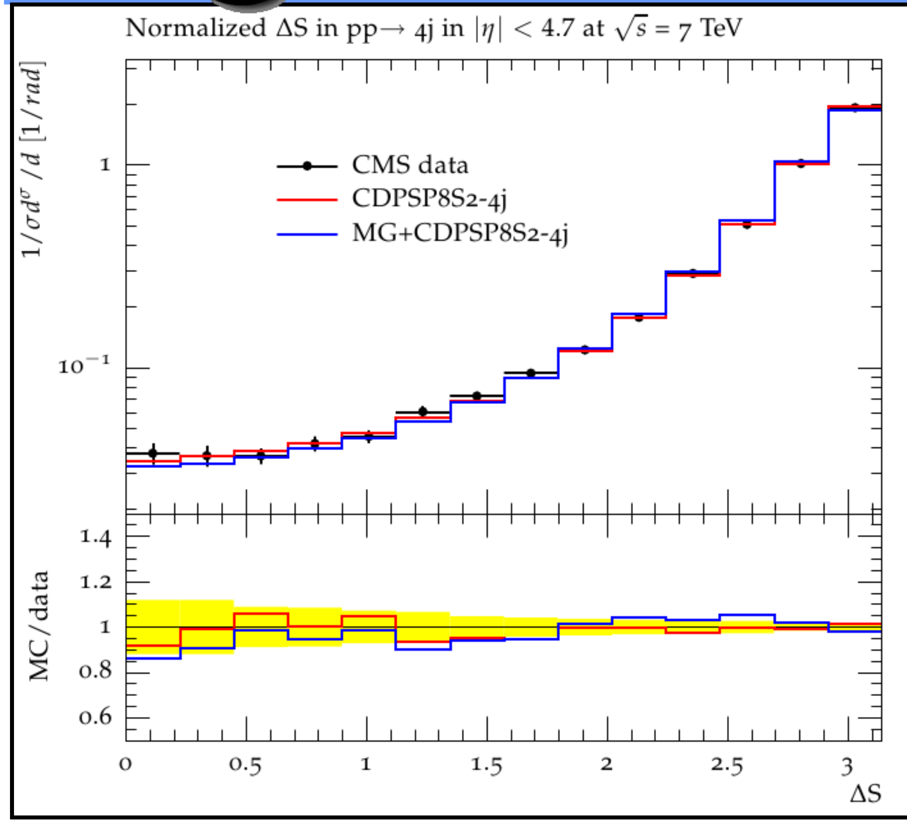
σ_{eff} = 20.7 ± 0.8 (stat) ± 6.6 (sys)

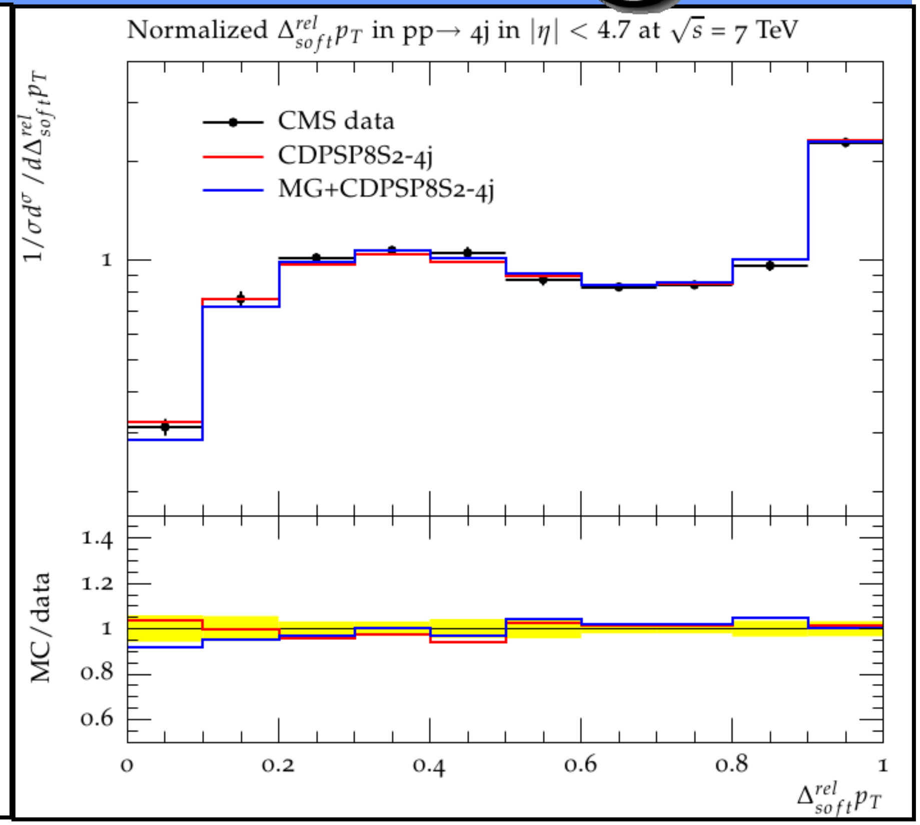
- **PYTHIA 8 Tune CDPSTP8S2-Wj:** Start with Tune 4C (CTEQ6L) and tune to the DPS sensitive observables in W + DiJet production by varying the 4 UE parameters.
- **PYTHIA 8 Tune CDPSTP8S2-4j:** Start with Tune 4C (CTEQ6L) and tune to the DPS sensitive observables in 4 Jet production by varying the 4 UE parameters.

Tune	σ_{eff}(mb)
4C	30.3
CUETP8S1-CTEQ6L1	27.8
CUETP8S1-HERAPDF1.5LO	29.1
CDPSTP8S2-Wj	25.8+8.2-4.2
CDPSTP8S2-4j	19.0+4.7-3.0

7 TeV

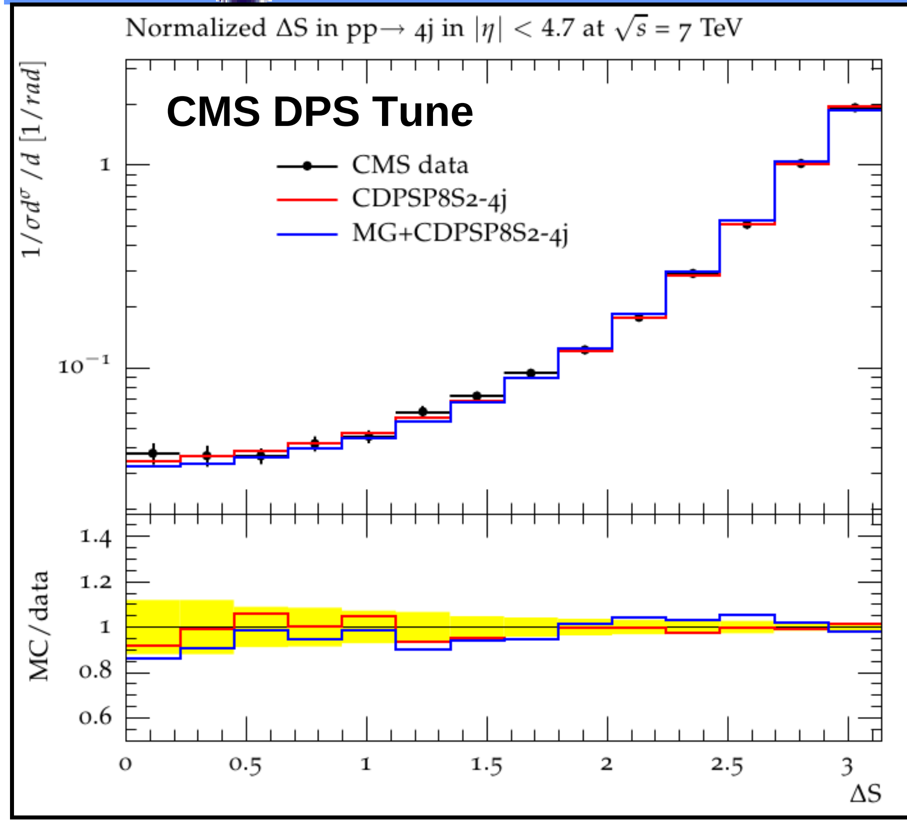
CMS DPS Tunes

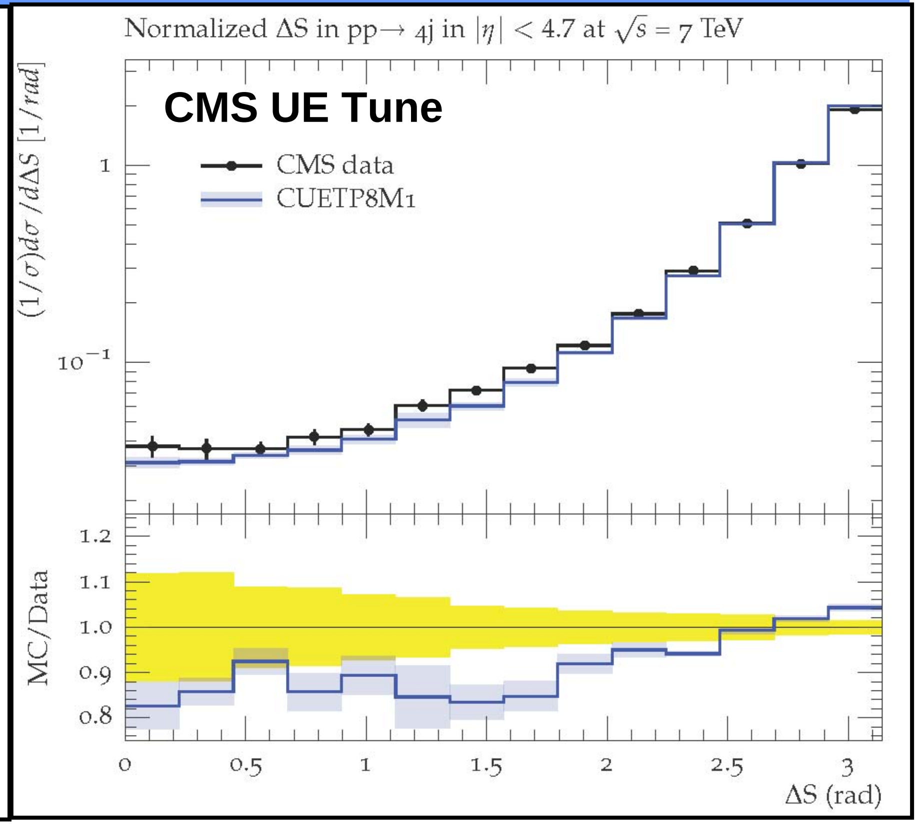




- **Compares the CMS DPS tune CDPSTP8S2-4j with the DPS sensitive observables in 4 Jet production at 7 TeV.**

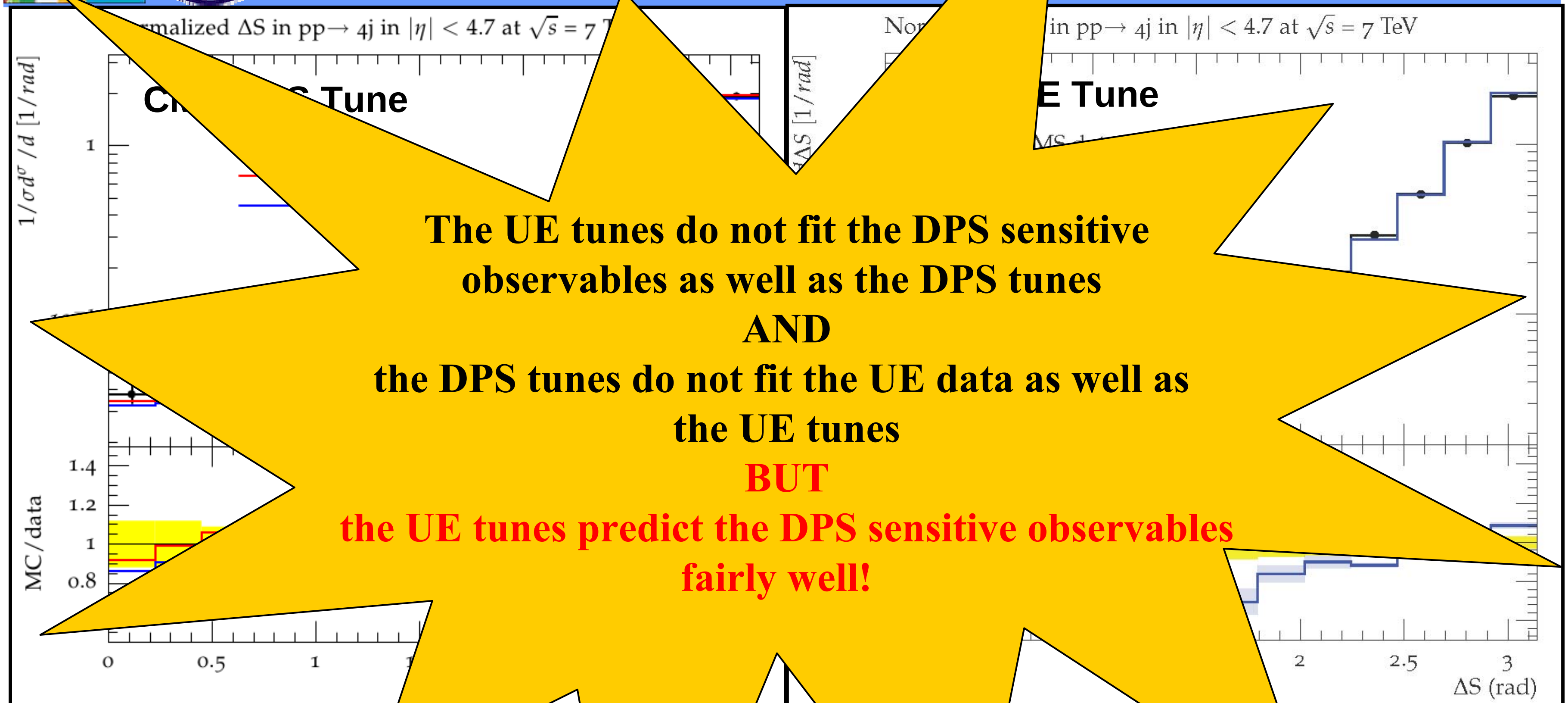
DPS versus UE Tunes





- **Compares the CMS DPS tune CDPSTP8S2-4j and the CMS UE tune CUETP8M1 with the DPS sensitive observable ΔS in 4 Jet production at 7 TeV.**

DPS versus UE Tunes



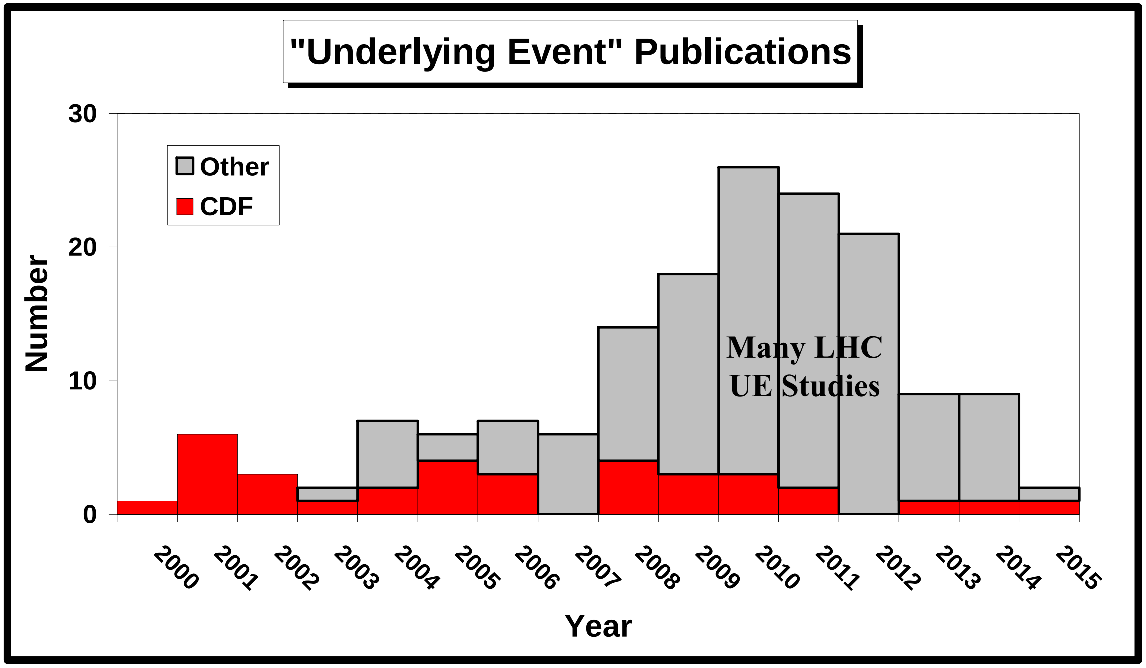
The UE tunes do not fit the DPS sensitive observables as well as the DPS tunes
AND
the DPS tunes do not fit the UE data as well as the UE tunes
BUT
the UE tunes predict the DPS sensitive observables fairly well!

- **Compares the CMS D tune CD 4j and UE tune CUE M1 with the DPS sensitive observable ΔS in 4 Je ction at 7**

CMS Tuning Summary

- **PDF Dependence:** If you change the PDF you must re-tune to fit the UE. We have several nice CMS PYTHIA 8 UE tunes with different PDF's (CTEQ6L, HERALOPDF, and NNPDF2.3LO. THE CMS Tune CUETP8M1-NNPDF2.3LO (Mstar) does better in the forward region due to the PDF!
- **Predicting the UE at 13 TeV:** The CMS PYTHIA 8 UE tunes and the HERWIG++ Tune EE5 fit the energy dependence of the UE and give similar UE predictions at 13 TeV! The new CMS HERWIG++ tune is similar to Tune EE5, but comes with the "eigentunes". Found a "bug" in the HERWIG++ UE model which has now been fixed!
- **Predicting MB Observables:** The CMS PYTHIA 8 UE tunes do a fairly good (although not perfect) job in predicting MB observables. We do not need separate MB tunes!
- **DPS Tunes:** The UE tunes do not fit the DPS sensitive observables as well as the DPS tunes AND the DPS tunes do not fit the UE data as well as the UE tunes. The UE tunes do a fairly good (although not perfect) job in predicting the DPS sensitive observables.
- **ME Tunes:** The CMS UE tunes do a good job when interfaced with POWHEG or MADGRAPH! We do not need separate ME tunes!

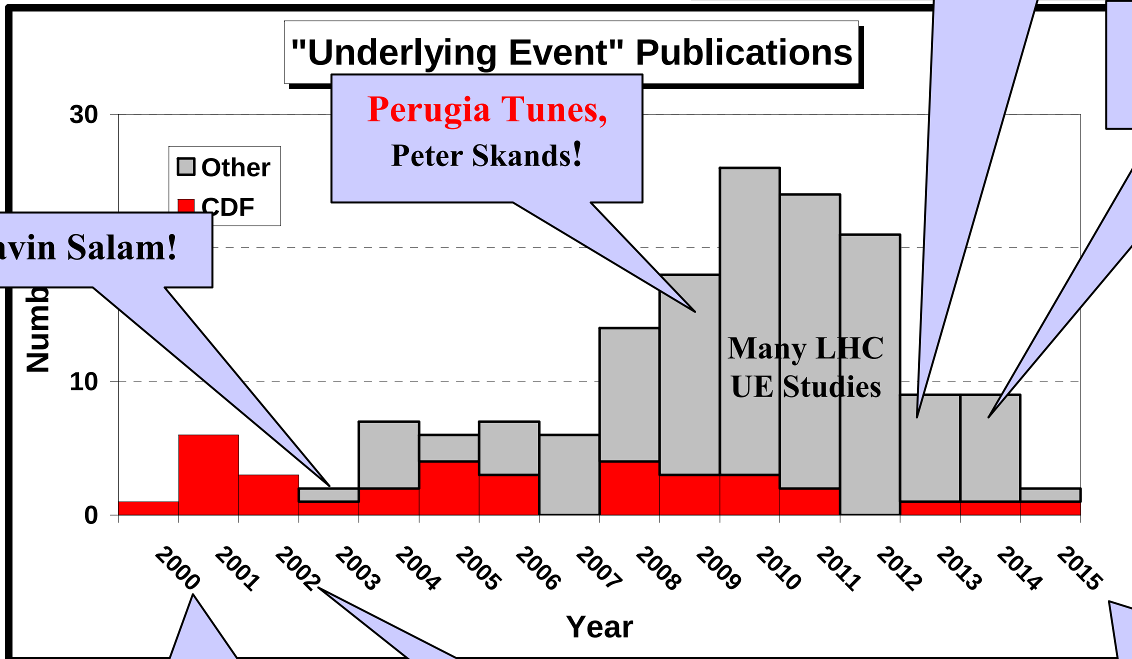
UE Publications



- **Publications on the "underlying event" (2000-2015).**

UE Publications

HERWIG++ UE Tune, M. Seymour and A. Siódmok!



Monash Tune, Peter Skands!

Perugia Tunes, Peter Skands!

Gavin Salam!

➡ Publications on t… derlying ev… "

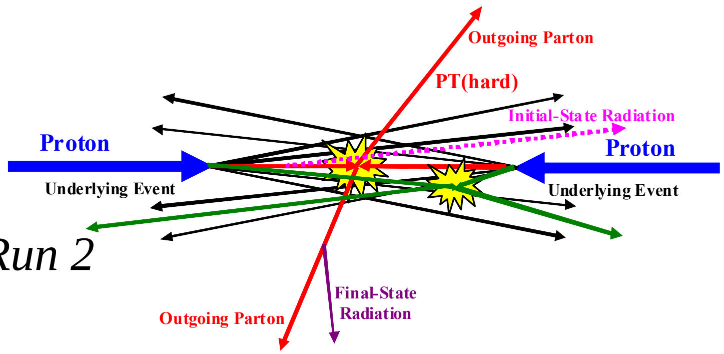
The Underlying Event in Large Transverse Momentum Charged Jet and Z−boson Production at CDF, R. Field, published in the proceedings of DPF 2000.

A Study of the Energy Dependence of the Underlying Event in Proton-Antiproton Collisions, CDF Collaboration, Phys. Rev. D92, 092009, Published 23 November 2015!

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

Rick's UE Graduate Students

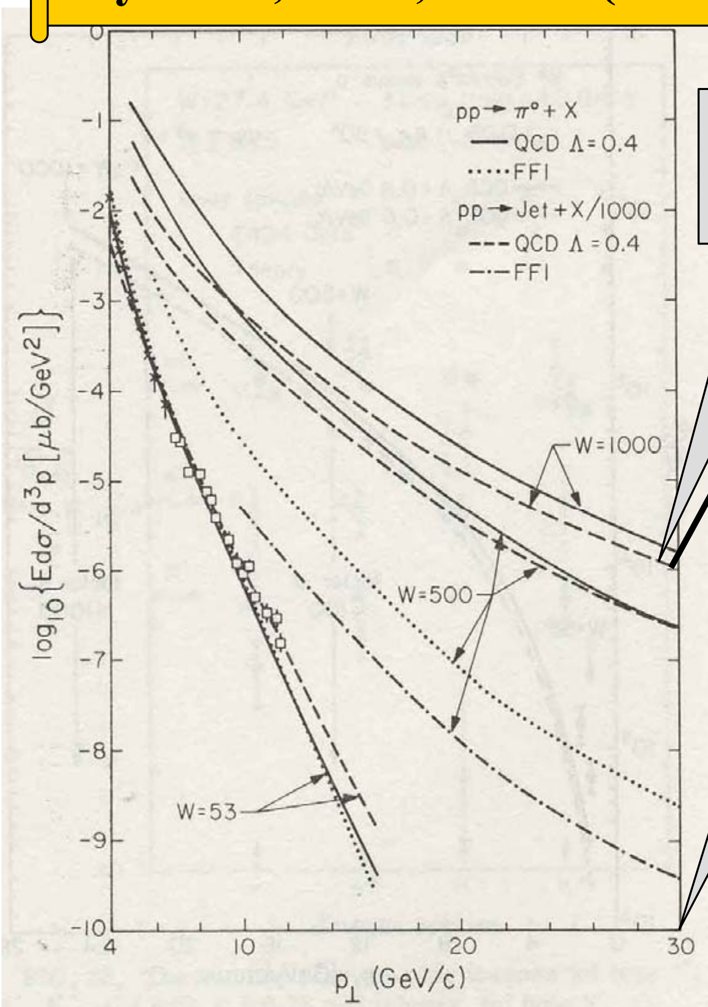
- **Richard Haas (CDF Ph.D. 2001):** *The Underlying Event in Hard Scattering Collisions of Proton and Antiproton at 1.8 TeV.*
- **Alberto Cruz (CDF Ph.D. 2005):** *Using MAX/MIN Transverse Regions to Study the Underlying Event in Run 2 at the Tevatron.*



- **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. Expected 2016):** *The Underlying Evant via Leading Track and Track Jet at 13 TeV.*

High P_T Jets

Feynman, Field, & Fox (1978)

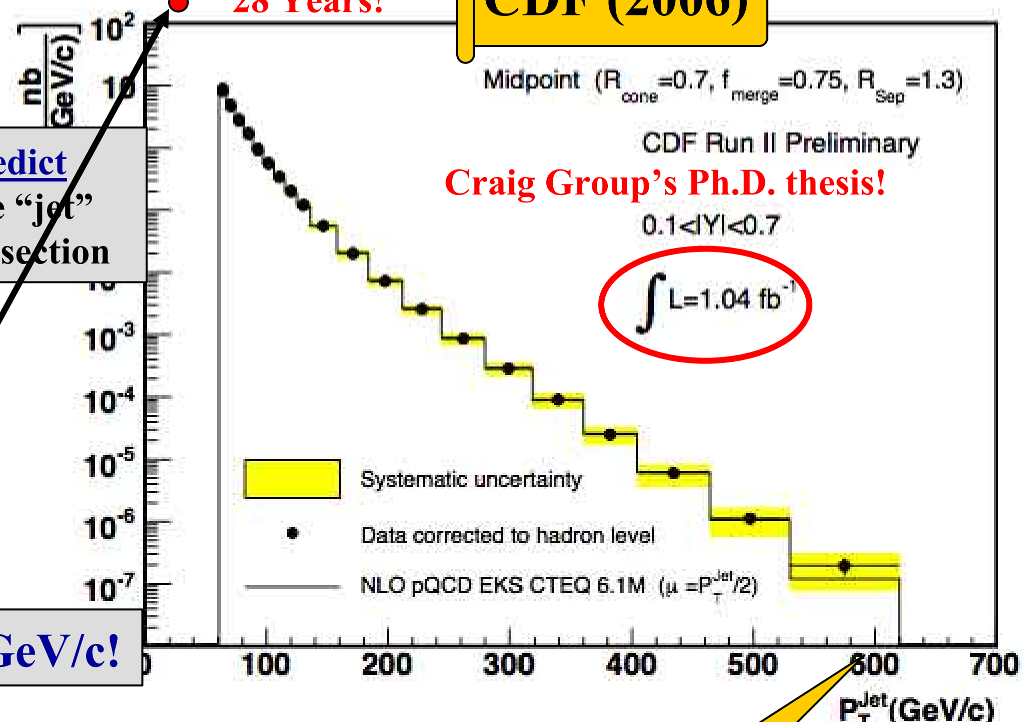


Predict large "jet" cross-section

30 GeV/c!

28 Years!

CDF (2006)



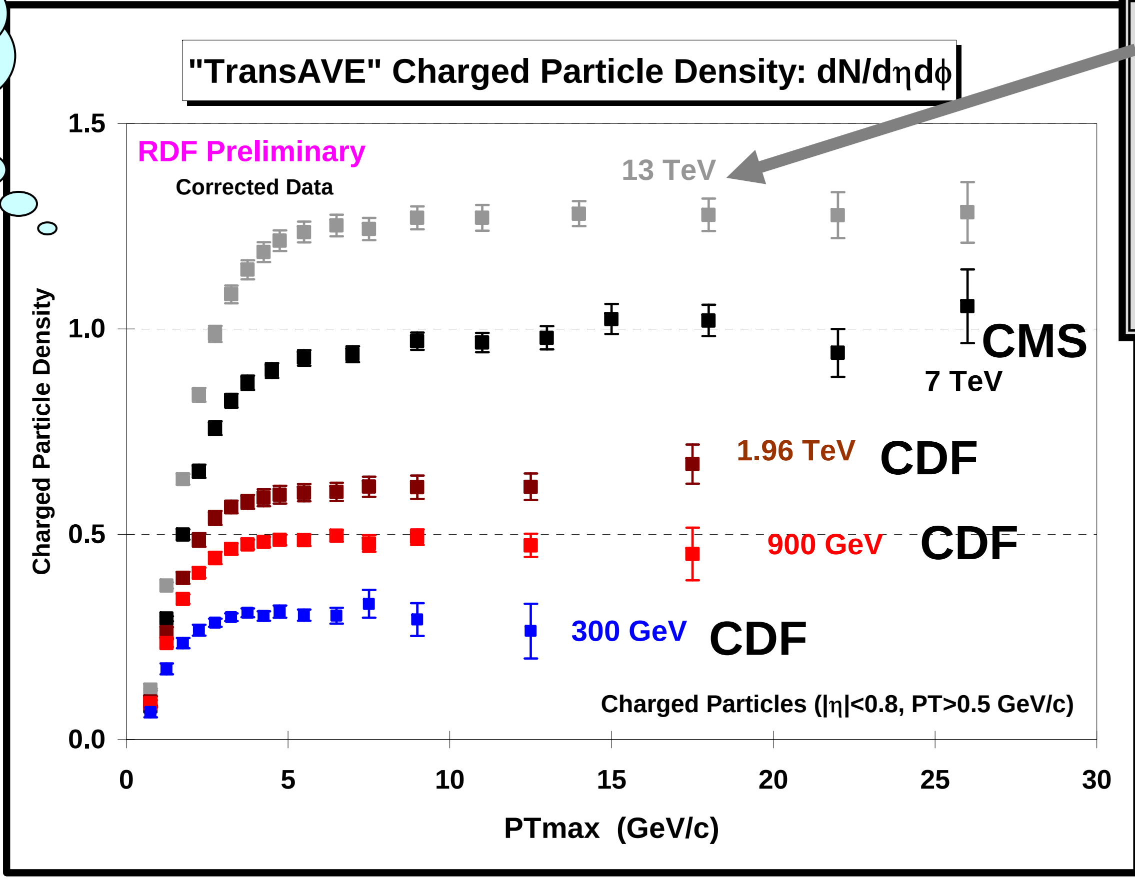
Craig Group's Ph.D. thesis!

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."

“Tevatron” to the LHC

My dream!



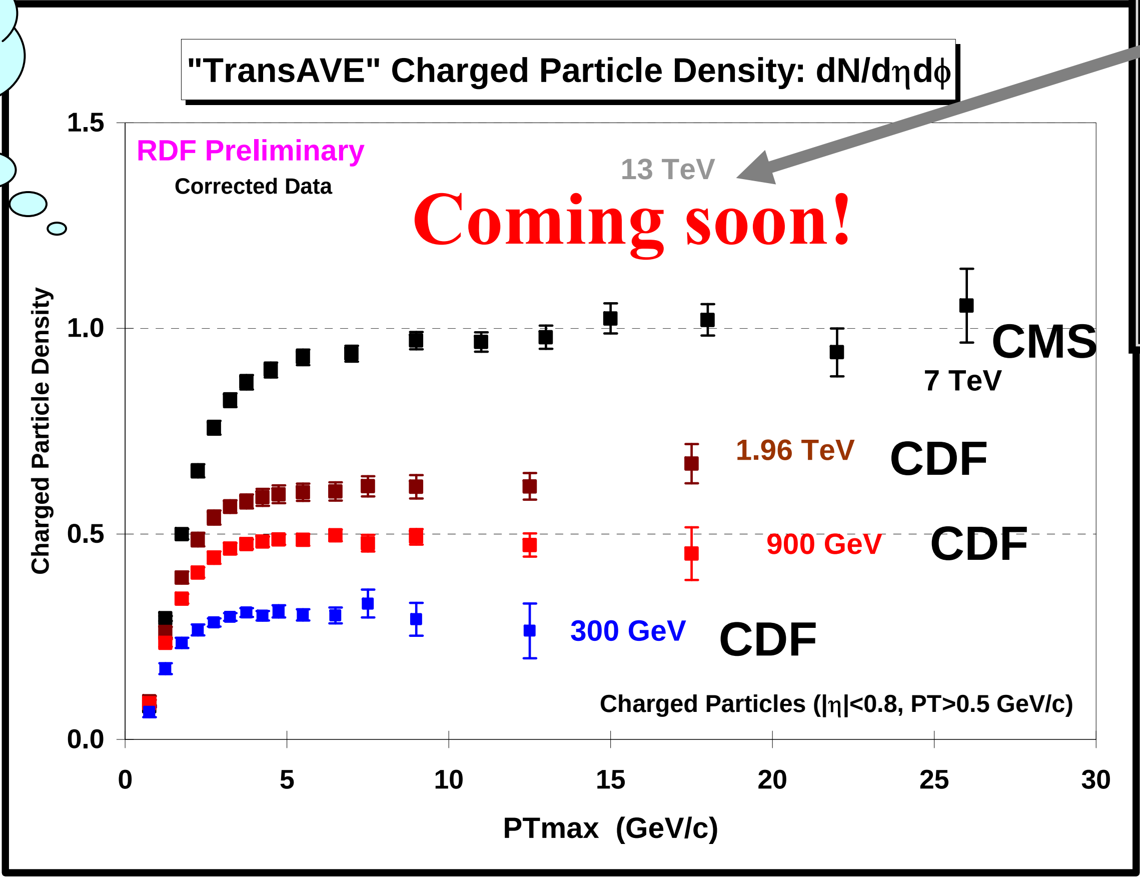
Fake data generated by Rick using the Monash tune with the statistics we currently have at CMS!

<u>**Mapping out the Energy Dependence of the UE**</u>

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

“Tevatron” to the LHC

My dream!

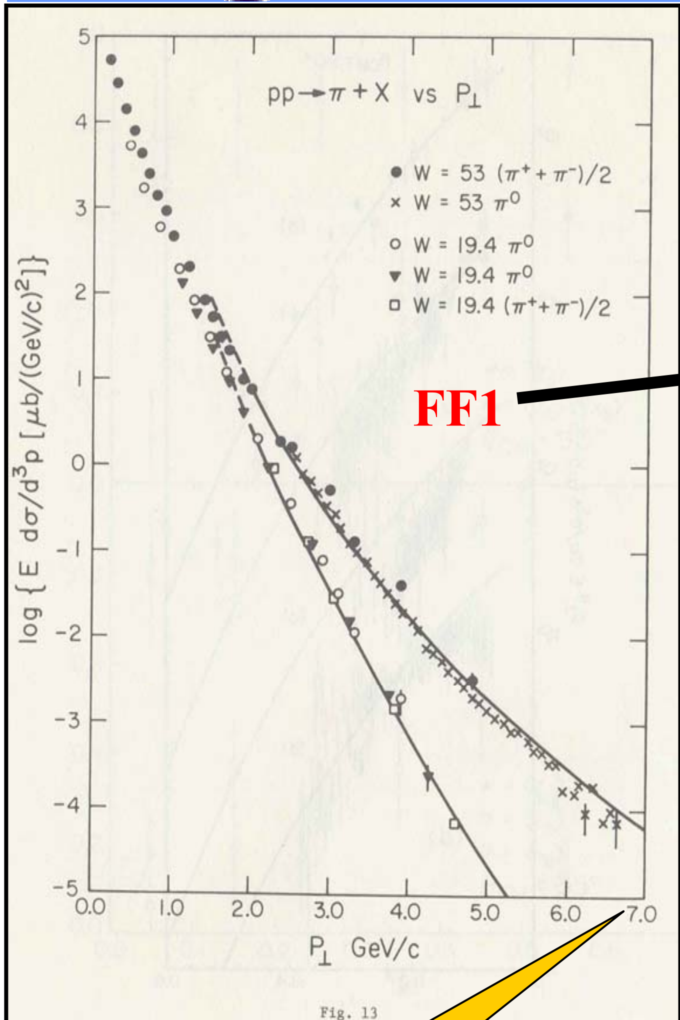


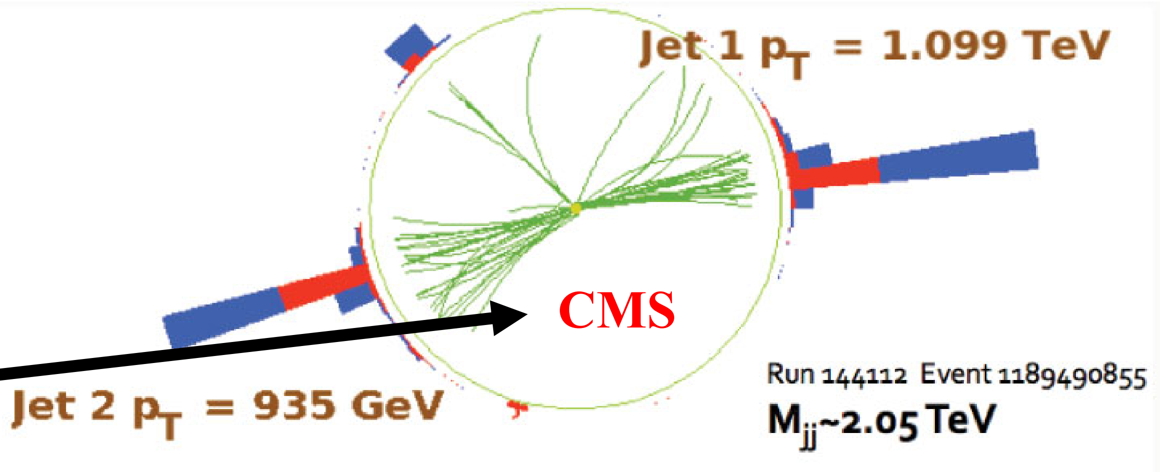
13 TeV UE data coming soon from both ATLAS and CMS!

<u>Mapping out the Energy Dependence of the UE</u>

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

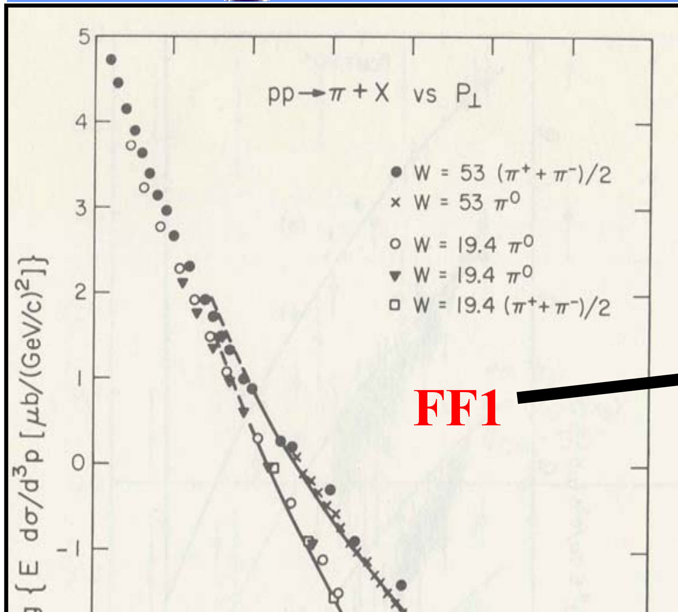
7 GeV π^0's → 1 TeV Jets



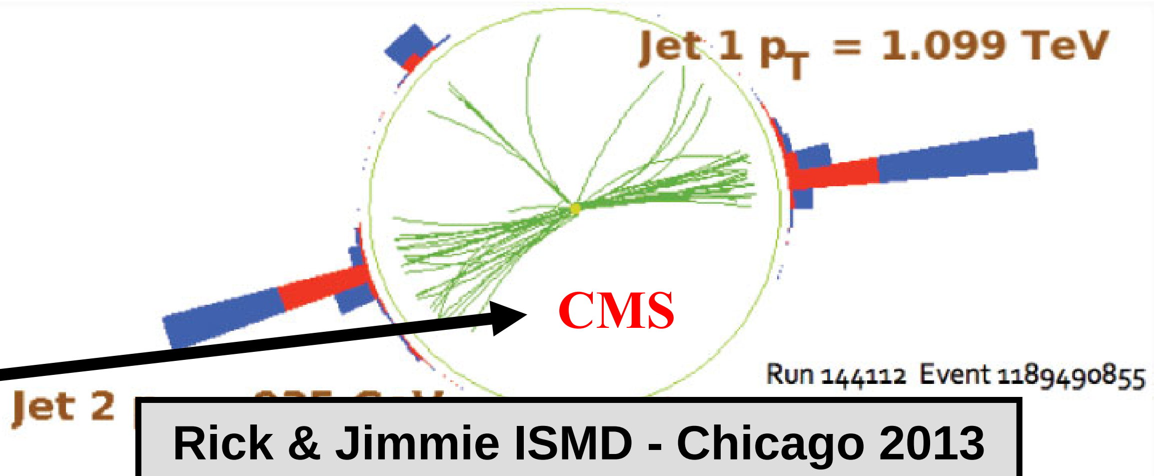


7 GeV/c π^0's!

7 GeV π^0's → 1 TeV Jets



FF1 → CMS



Rick & Jimmie ISMD - Chicago 2013

Rick & Jimmie CALTECH 1973

I will retire from the University of Florida on June 1, 2016. I hope I can keep doing physics!