Perspectives on Physics and on CMS at Very High Luminosity

Are the QCD MC Models Ready for High Luminosity?

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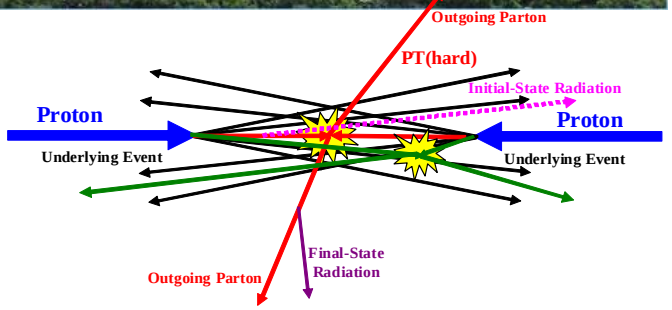
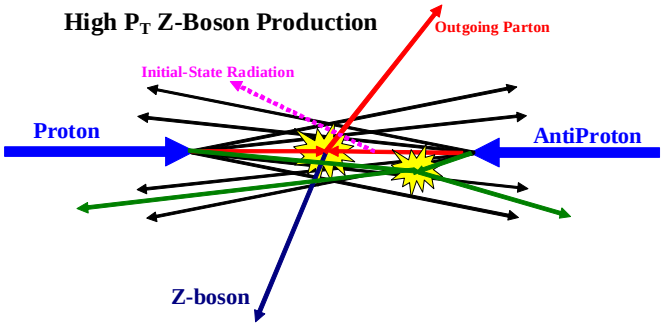
Outline

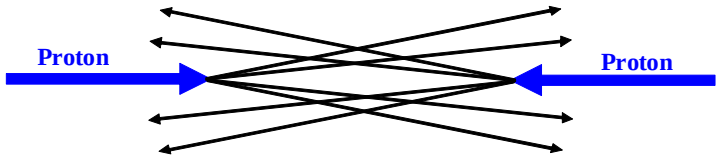
- How Universal are the QCD MC Model Tunes?
  - Do we need a separate tune for each center-of-mass energy? 900 GeV, 1.96 TeV, 7 TeV, etc.
  - Do we need a separate tune for each hard QCD subprocess? Jet Production, Drell-Yan Production, etc.
  - Do we need separate tunes for "Min-Bias" (MB) and the "underlying event" (UE) in a hard scattering process?
- A close look at two PYTHIA tunes:
  - PYTHIA 6.2 Tune DW (CDF UE tune).
  - PYTHIA 6.4 Tune Z1 (CMS UE tune).
- Pile-Up: A quick look at the fluctuations in pile-up.
- New CDF UE Data: The Tevatron Energy Scan (300 GeV, 900 GeV, 1.96 TeV).



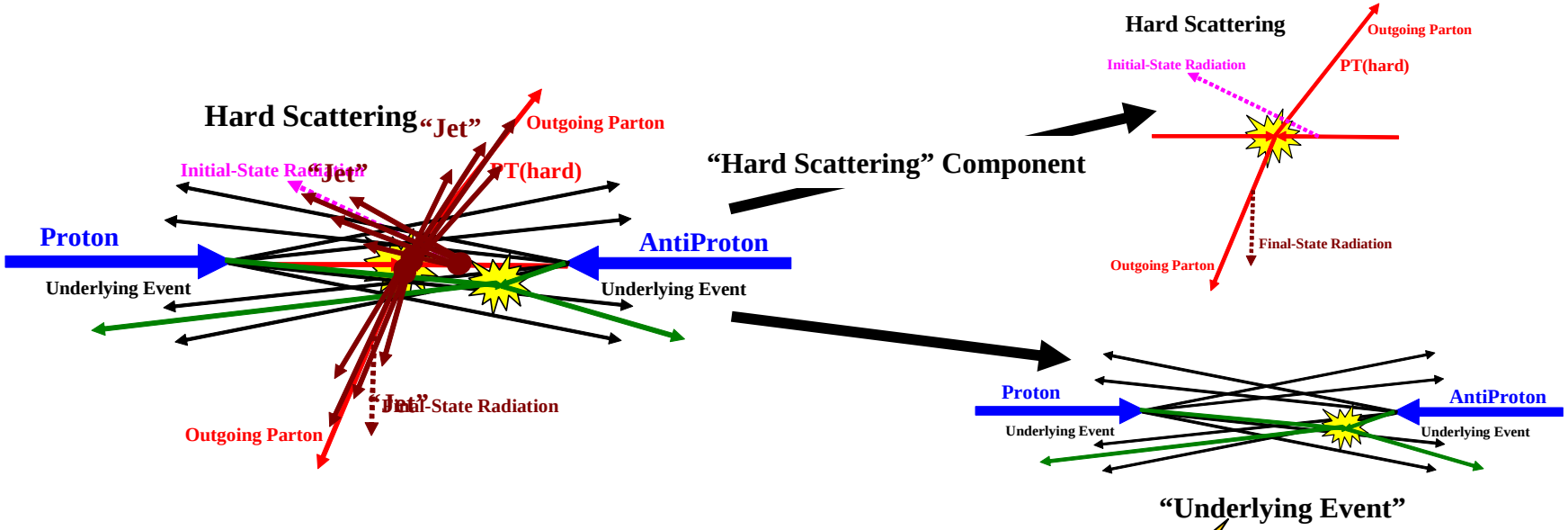
High P_T Z-Boson Production



"Minimum Bias" Collisions



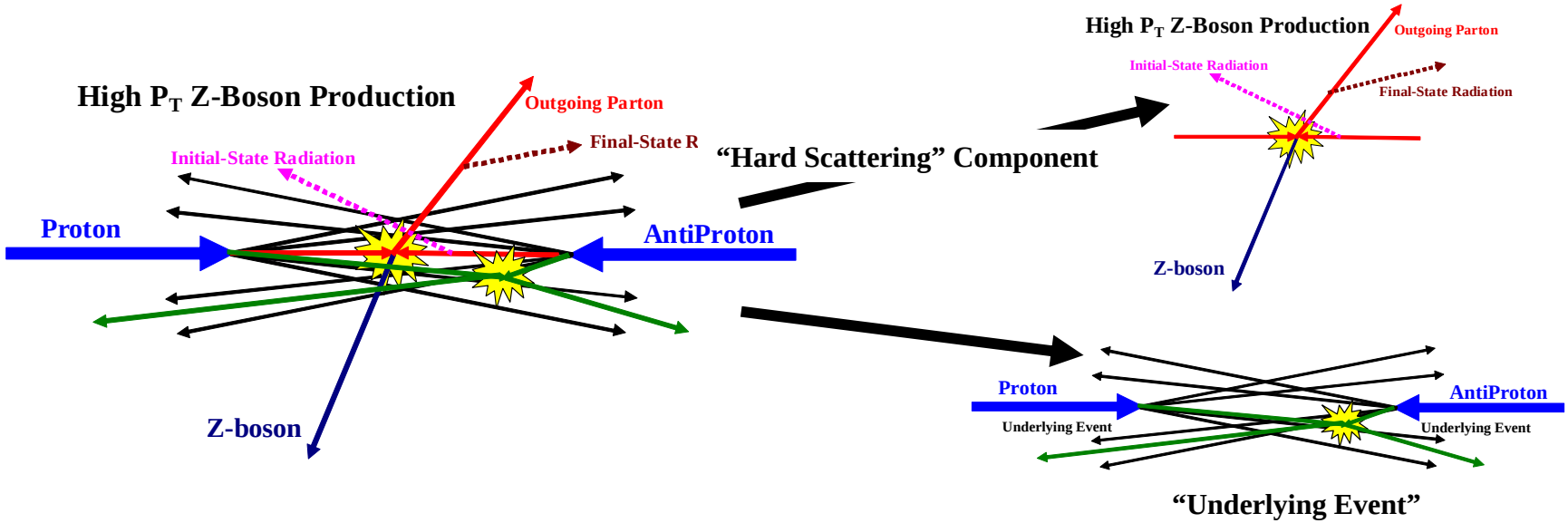
QCD Monte-Carlo Models: High Transverse Momentum Jets



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

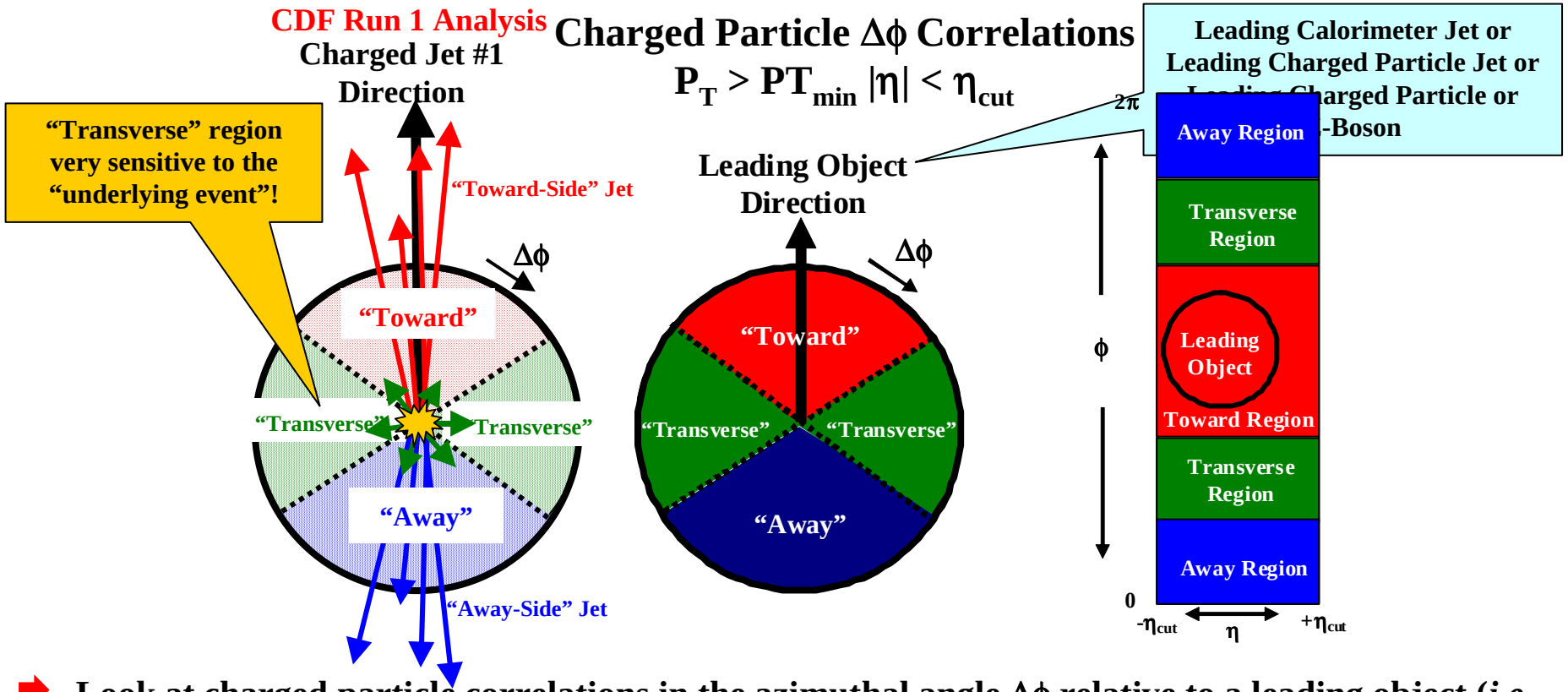
The "underlying event" is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!

QCD Monte-Carlo Models: Lepton-Pair Production



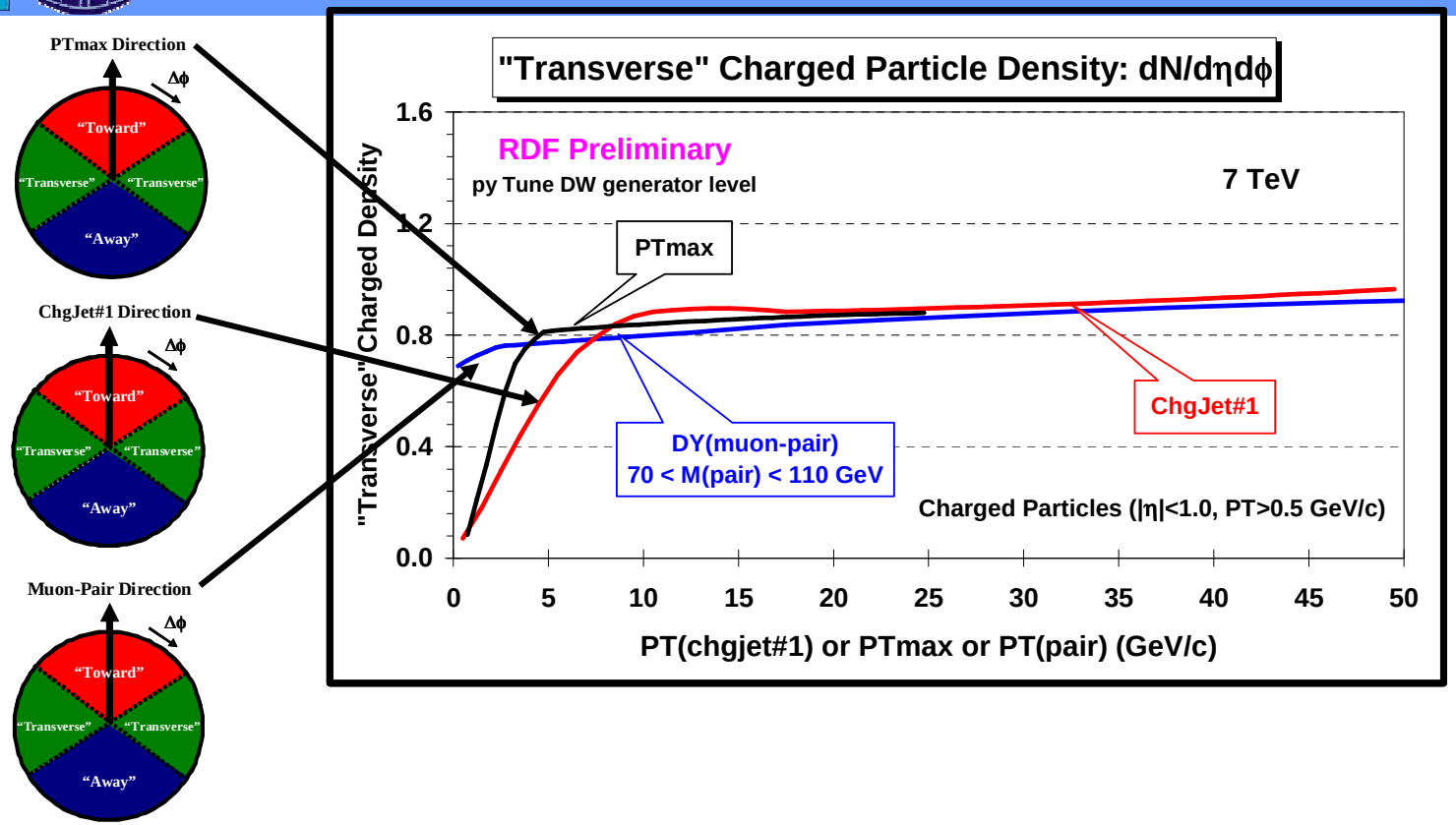
- Start with the perturbative Drell-Yan muon pair production and add initial-state gluon radiation (in the leading log approximation or modified leading log approximation).
- The "underlying event" consists of the "beam-beam remnants" and from particles arising from soft or semi-soft multiple parton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

Traditional Approach



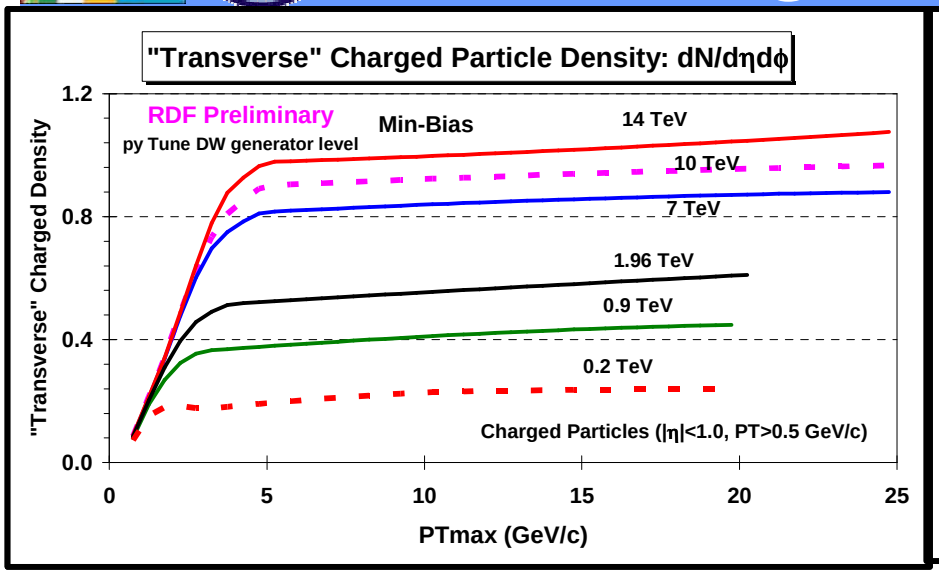
- Look at charged particle correlations in the azimuthal angle Δϕ relative to a leading object (*i.e.* CaloJet#1, ChgJet#1, PTmax, Z-boson). For CDF PTmin = 0.5 GeV/c η_{cut} = 1.
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as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

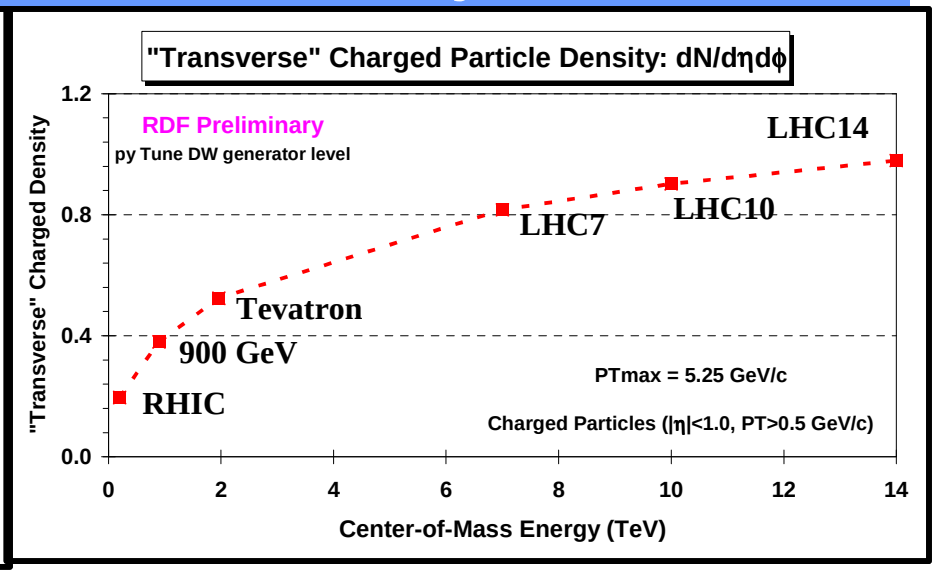
"Transverse" Charged Density

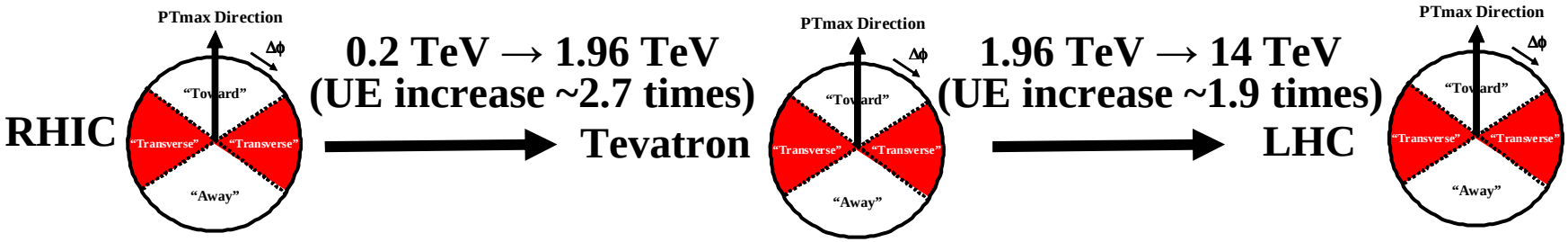


- **Shows the charged particle density in the "transverse" region for charged particles (p_T > 0.5 GeV/c, |η| < 1) at 7 TeV as defined by PTmax, PT(chgjet#1), and PT(muon-pair) from PYTHIA Tune DW at the particle level (*i.e.* generator level). Charged particle jets are constructed using the Anti-KT algorithm with d = 0.5.**

Min-Bias "Associated" Charged Particle Density

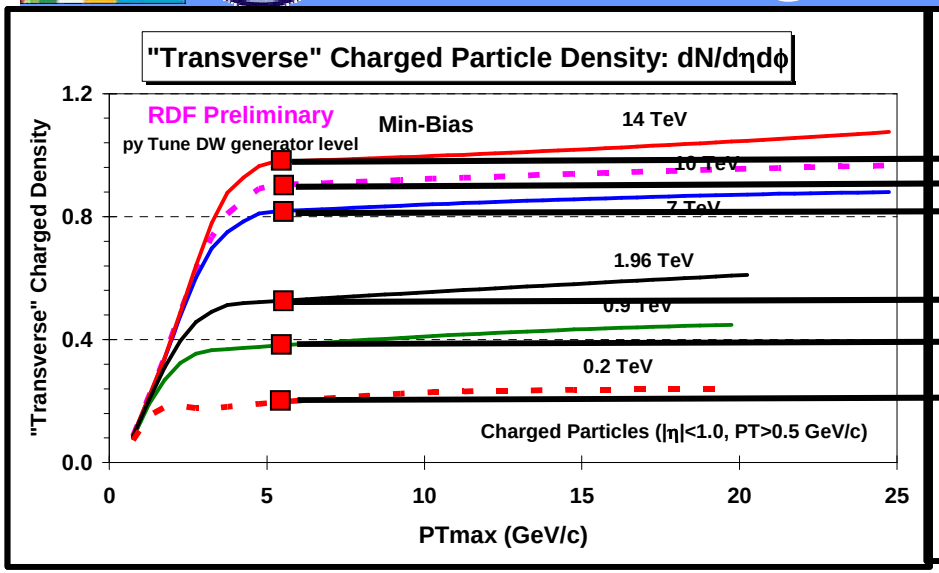


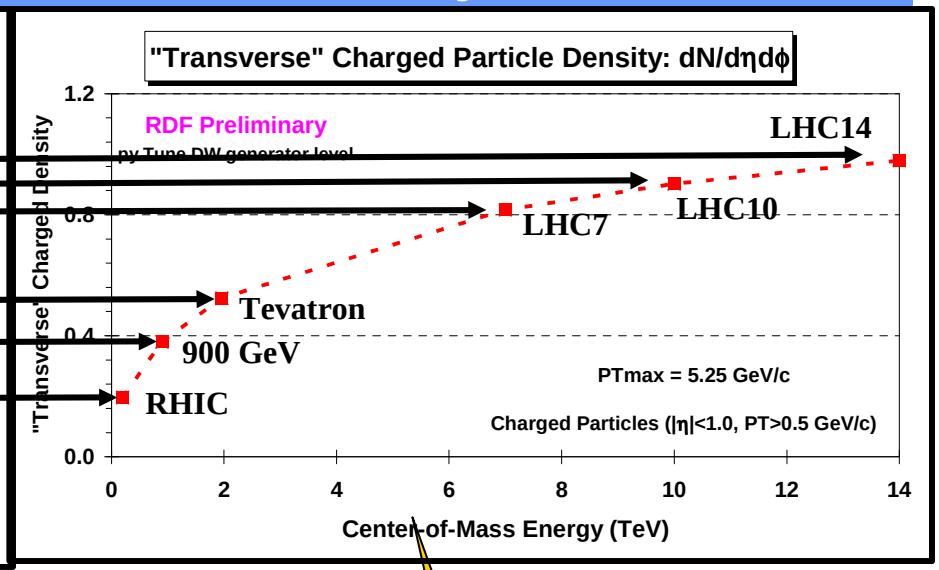




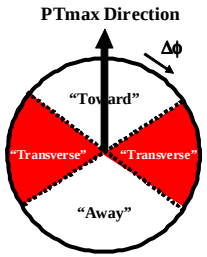
- **Shows the "associated" charged particle density in the "transverse" region as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min-bias" events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tune DW at the particle level (*i.e.*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

Min-Bias "Associated" Charged Particle Density

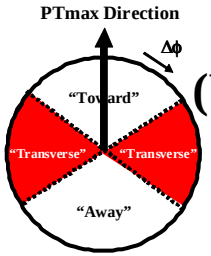




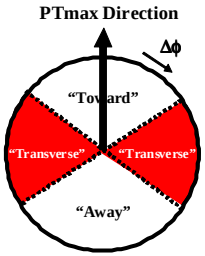
RHIC



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



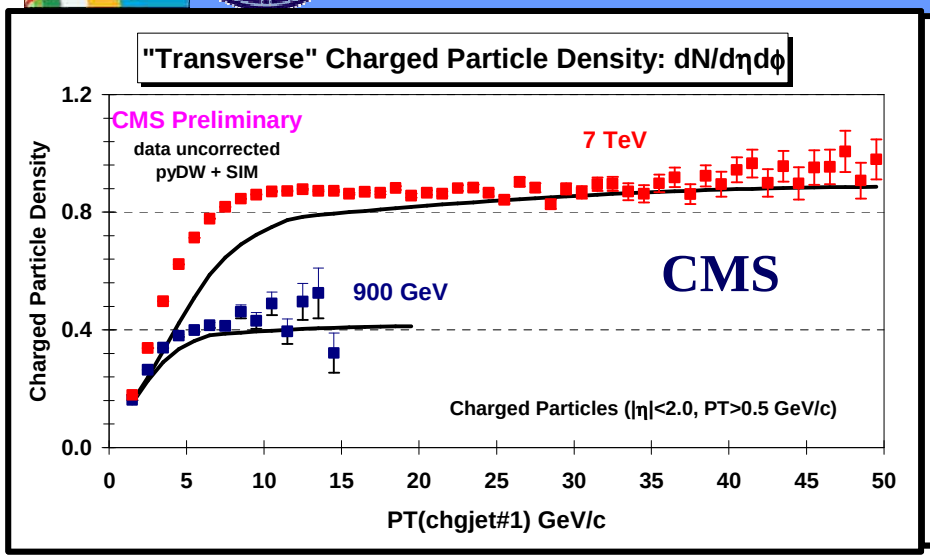
1.96 TeV → 14 TeV (UE increase ~1.9 times) → **LHC**

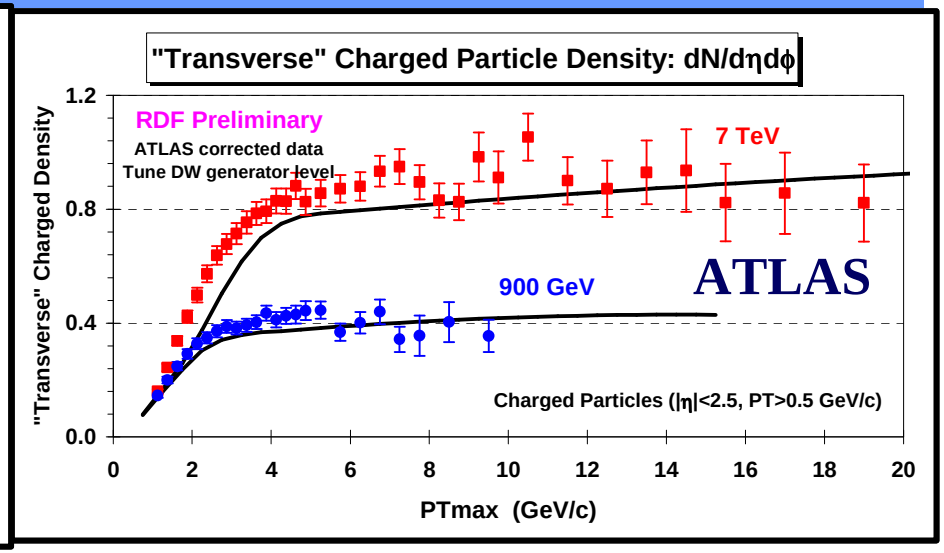


Linear scale!

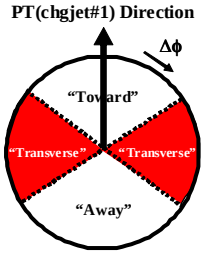
- **Shows the "associated" charged particle density in the "transverse" region as a function of PTmax for charged particles (p_T > 0.5 GeV/c, |η| < 1, *not including PTmax*) for "min-bias" events at 0.2 TeV, 0.9 TeV, 1.96 TeV, 7 TeV, 10 TeV, 14 TeV predicted by PYTHIA Tune DW at the particle level (*i.e.*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

PYTHIA Tune DW

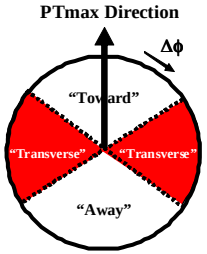




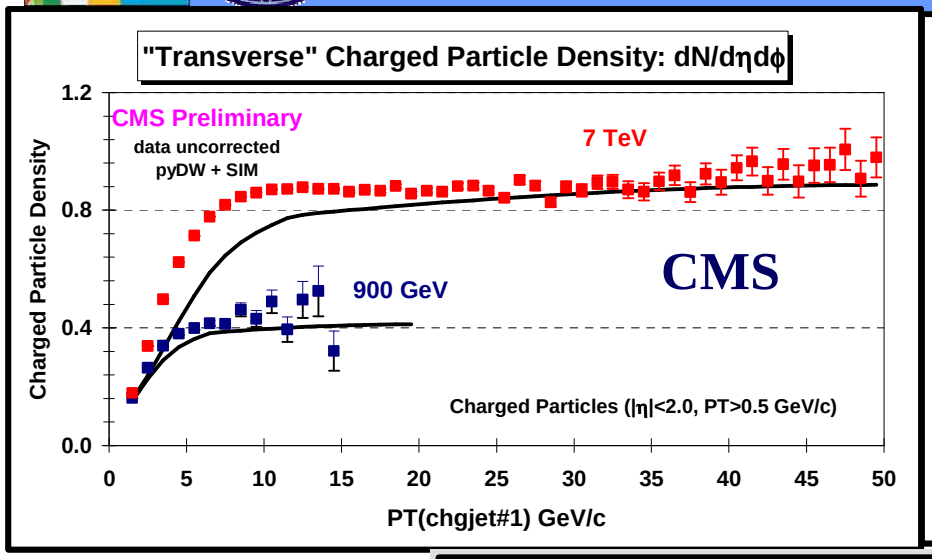
➡ **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.**

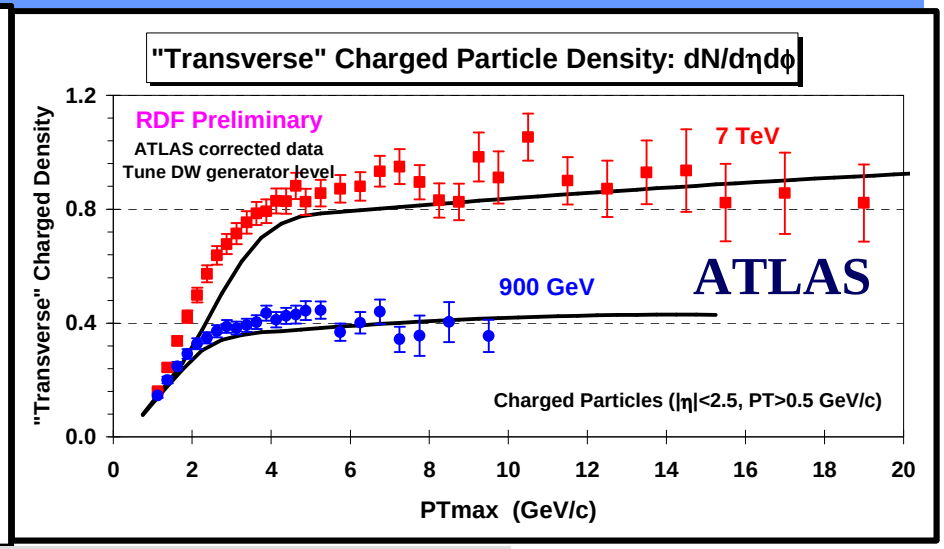


➡ **ATLAS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune DW at the generator level.**

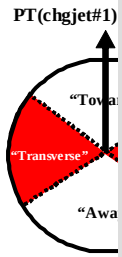


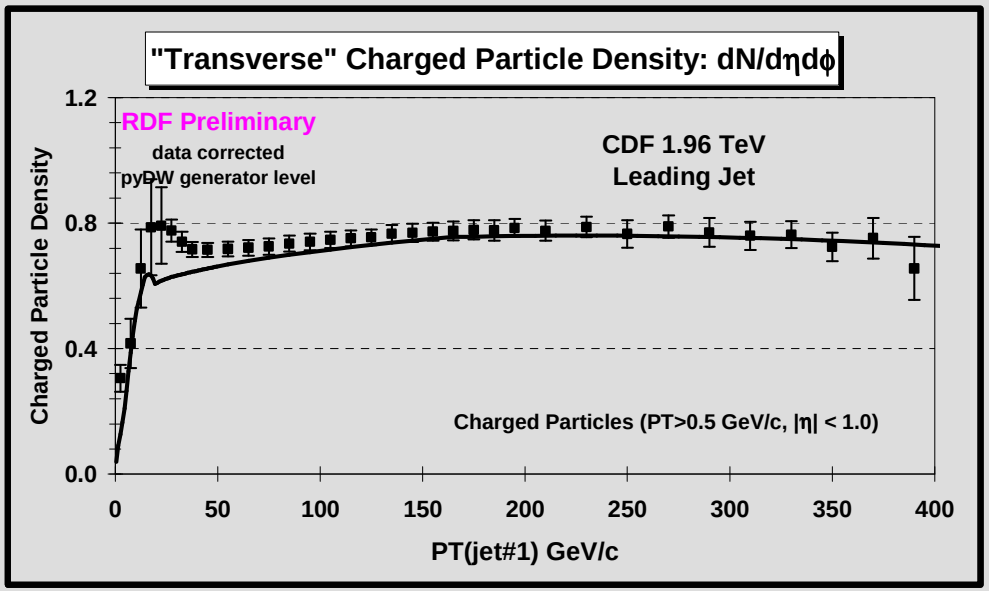
PYTHIA Tune DW





➡ **CMS preliminary d ta at 900 GeV and 7 on the "transverse" ' charged particle dN/dηdϕ, as defined fined by the leading particle jet (chgjet# x) for charged particles with p_T > 0.5 GeV/c | |η| < 2.5. The data are uncorrected and co l with PYTHIA Tune Tune DW after dete el.**





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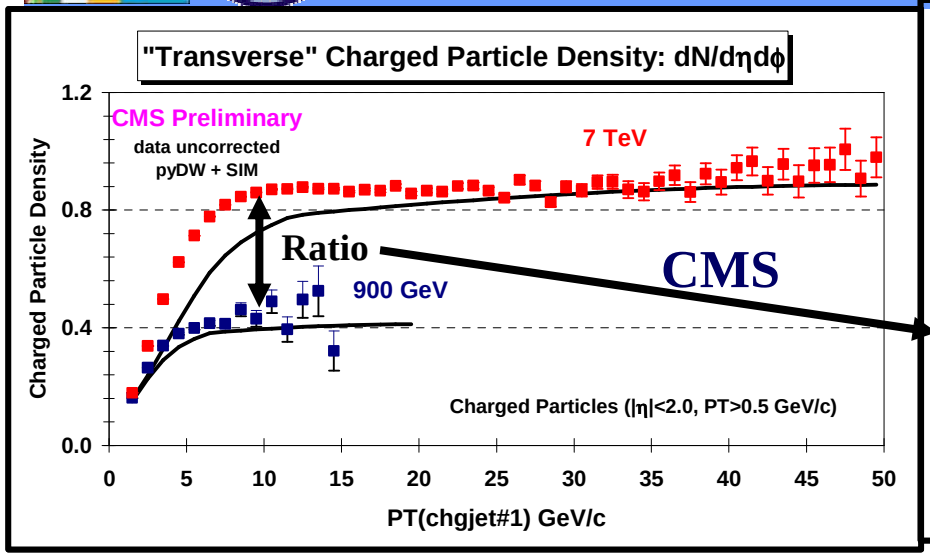
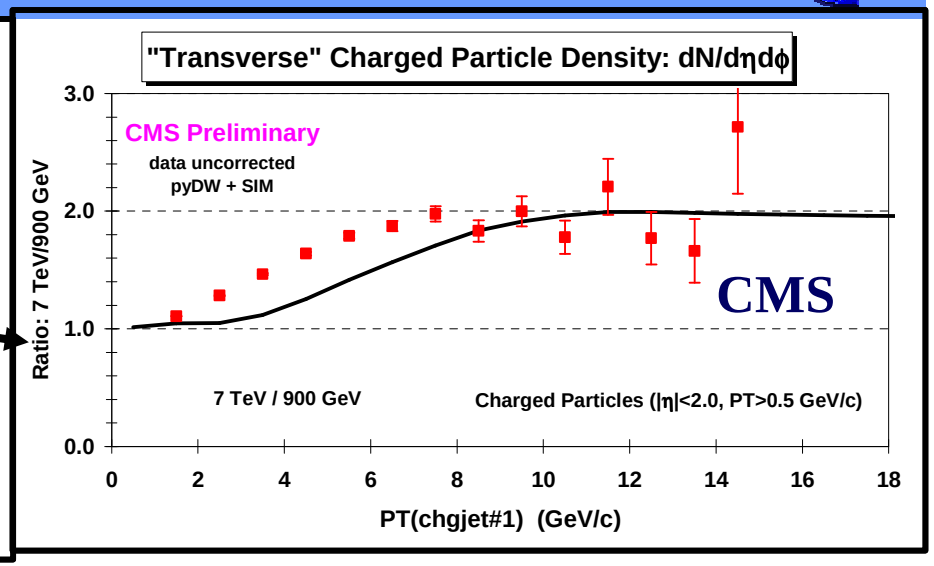
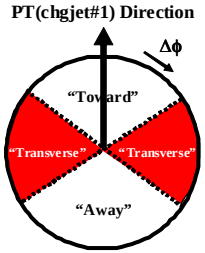
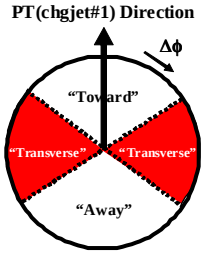




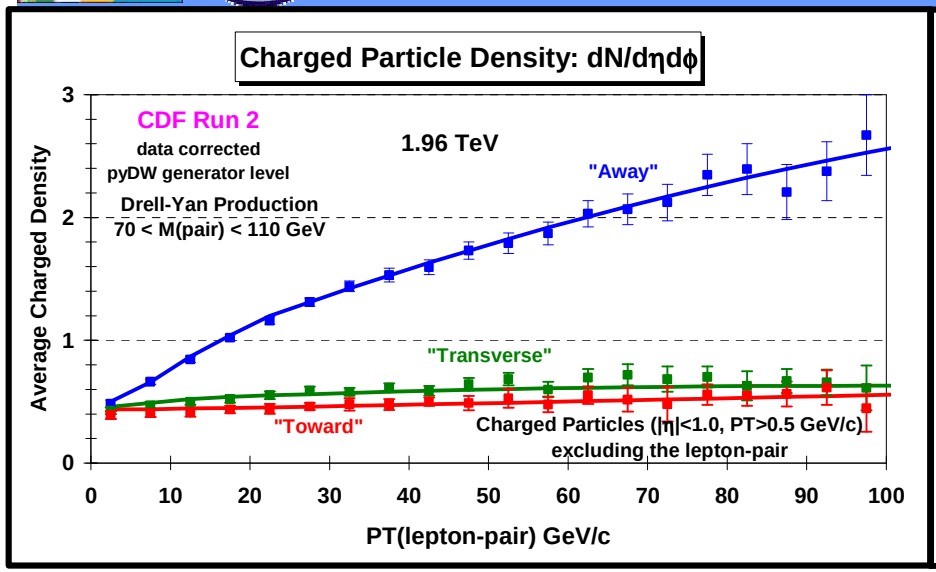
- **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.**

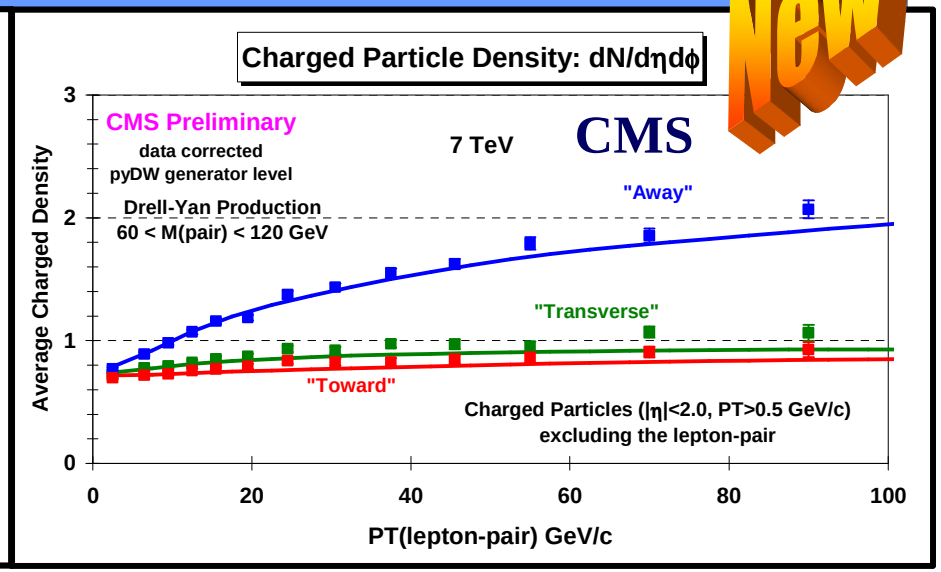
- **Ratio of CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector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

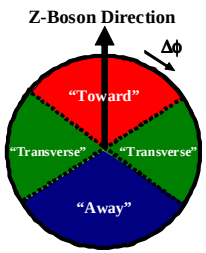


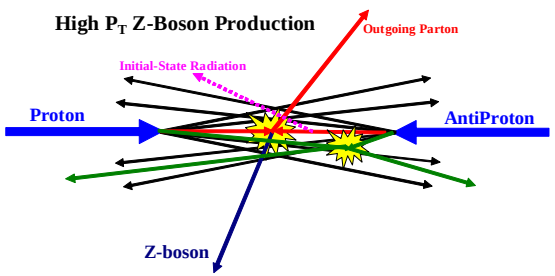


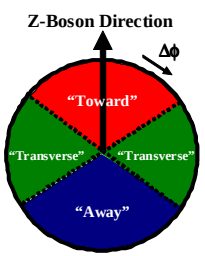
Charged Particle Density

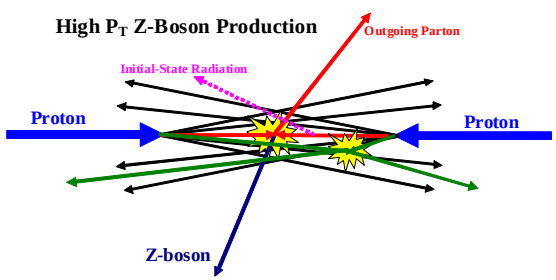






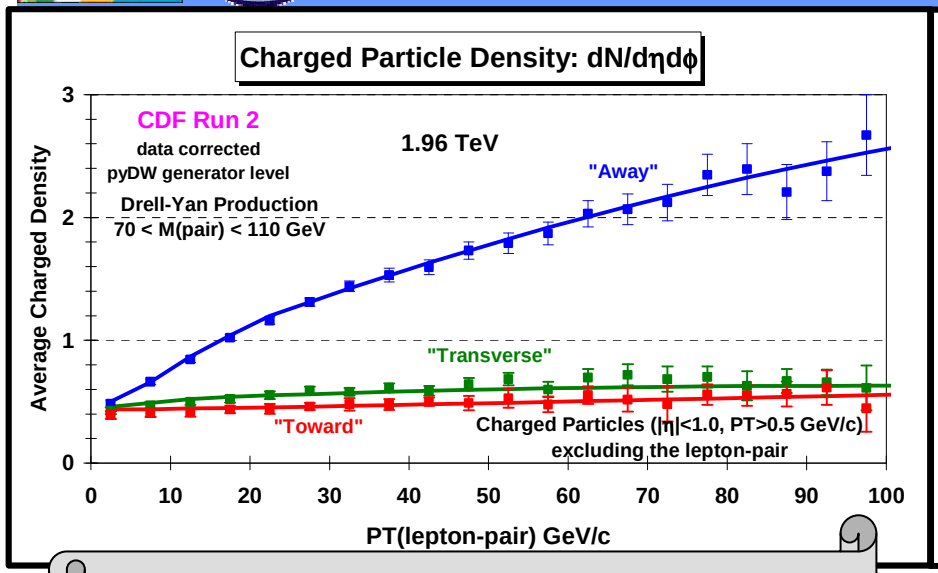


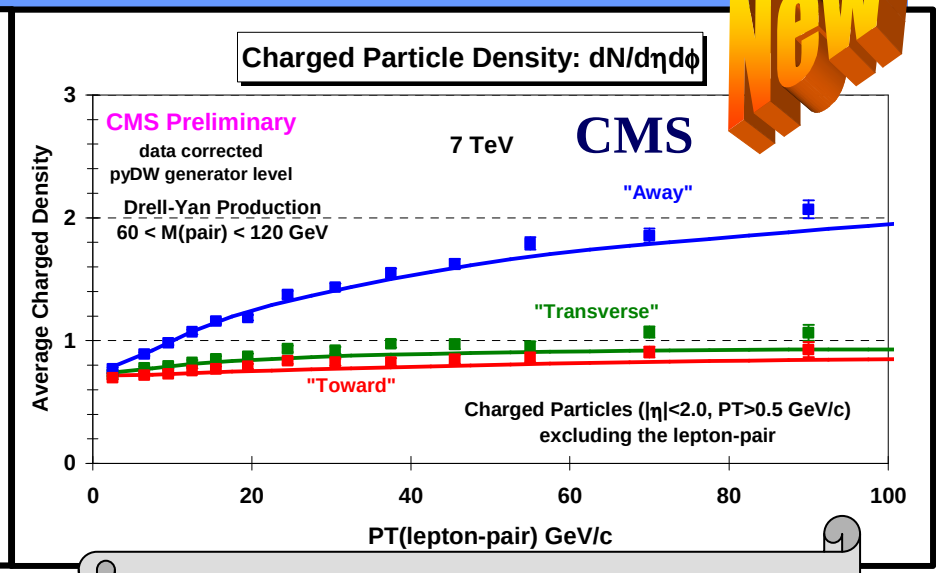




- **CDF data at 1.96 TeV on the density of charged particles, dN/dηdϕ, with p_T > 0.5 GeV/c and |η| < 1 for Drell-Yan production as a function of P_T(Z) for the "toward", "away", and "transverse" regions compared with PYTHIA Tune DW.**
- **CMS data at 7 TeV on the density of charged particles, dN/dηdϕ, with p_T > 0.5 GeV/c and |η| < 2 for Drell-Yan production as a function of P_T(Z) for the "toward", "away", and "transverse" regions compared with PYTHIA Tune DW.**

Charged Particle Density





CDF: Proton-Antiproton Collisions at 1.96 GeV
Lepton Cuts: $p_T > 20$ GeV $|\eta| < 1.0$
Mass Cut: 70 < M(lepton-pair) < 110 GeV
Charged Particles: $p_T > 0.5$ GeV/c $|\eta| < 1.0$

CMS: Proton-Proton Collisions at 7 GeV
Lepton Cuts: $p_T > 20$ GeV $|\eta| < 2.4$
Mass Cut: 60 < M(lepton-pair) < 120 GeV
Charged Particles: $p_T > 0.5$ GeV/c $|\eta| < 2.0$

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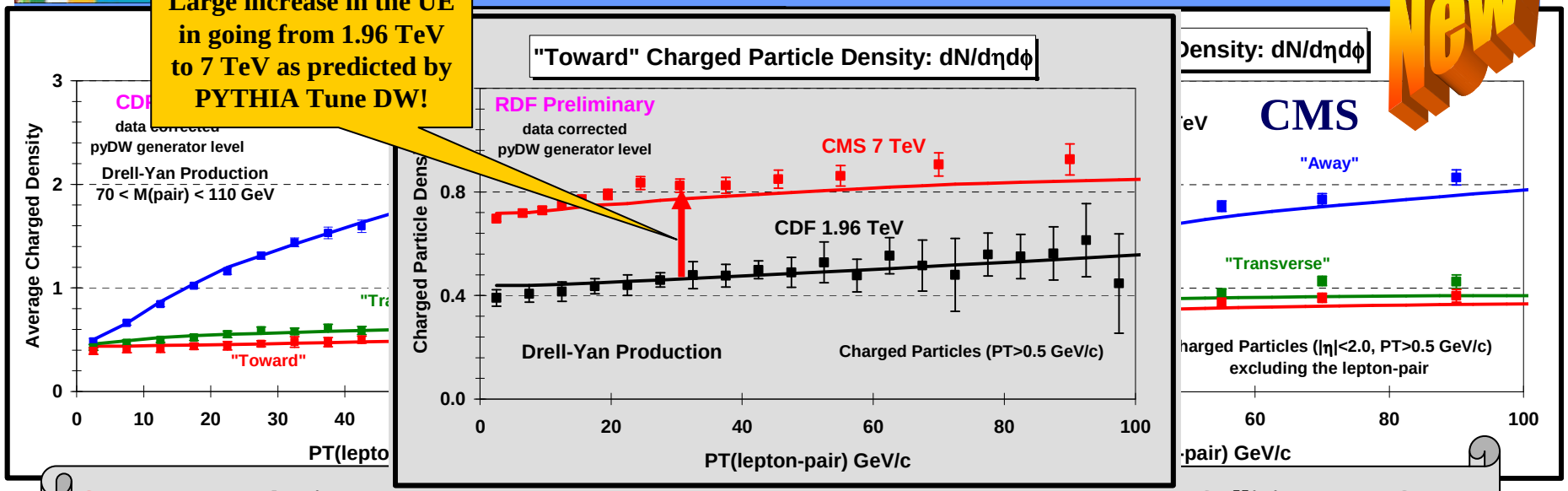
Charged Particle Density



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Z-boson

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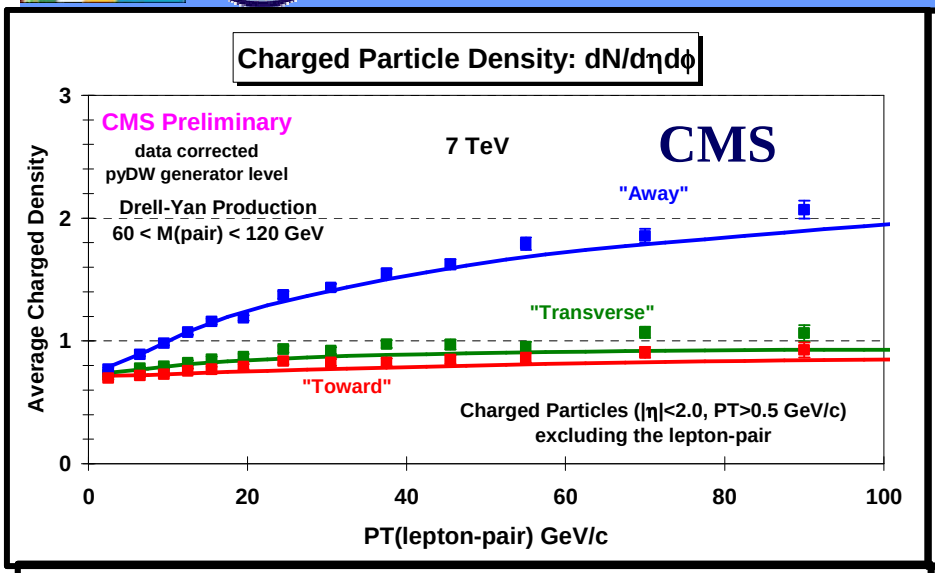
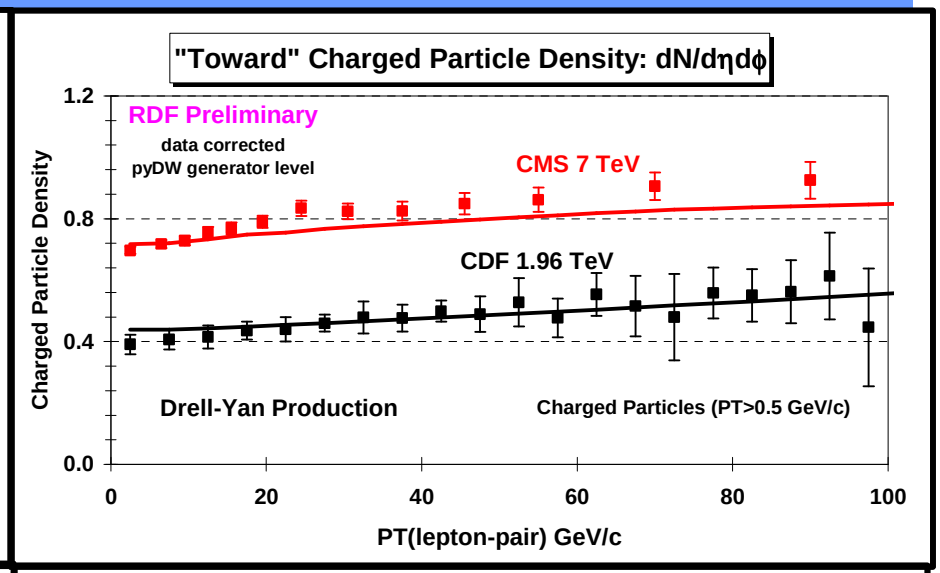
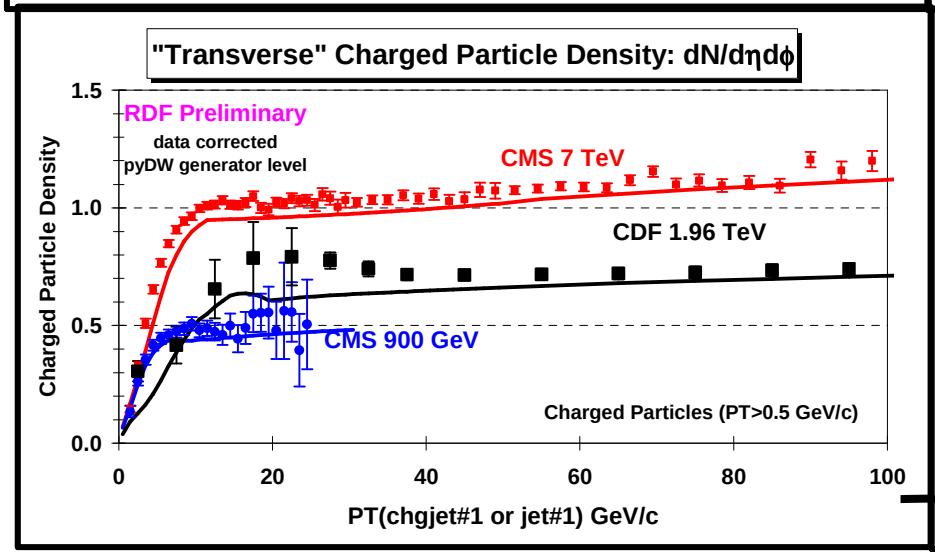
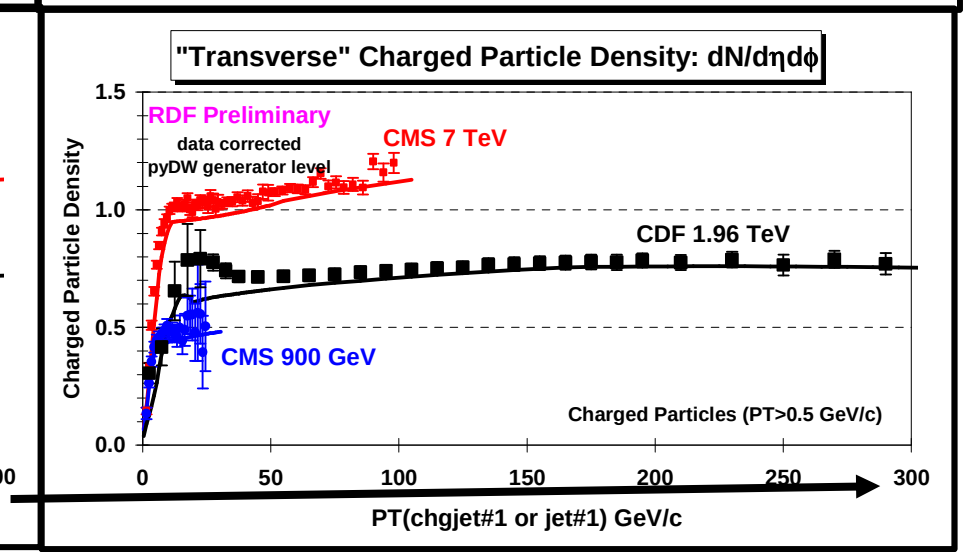
PYTHIA Tune DW

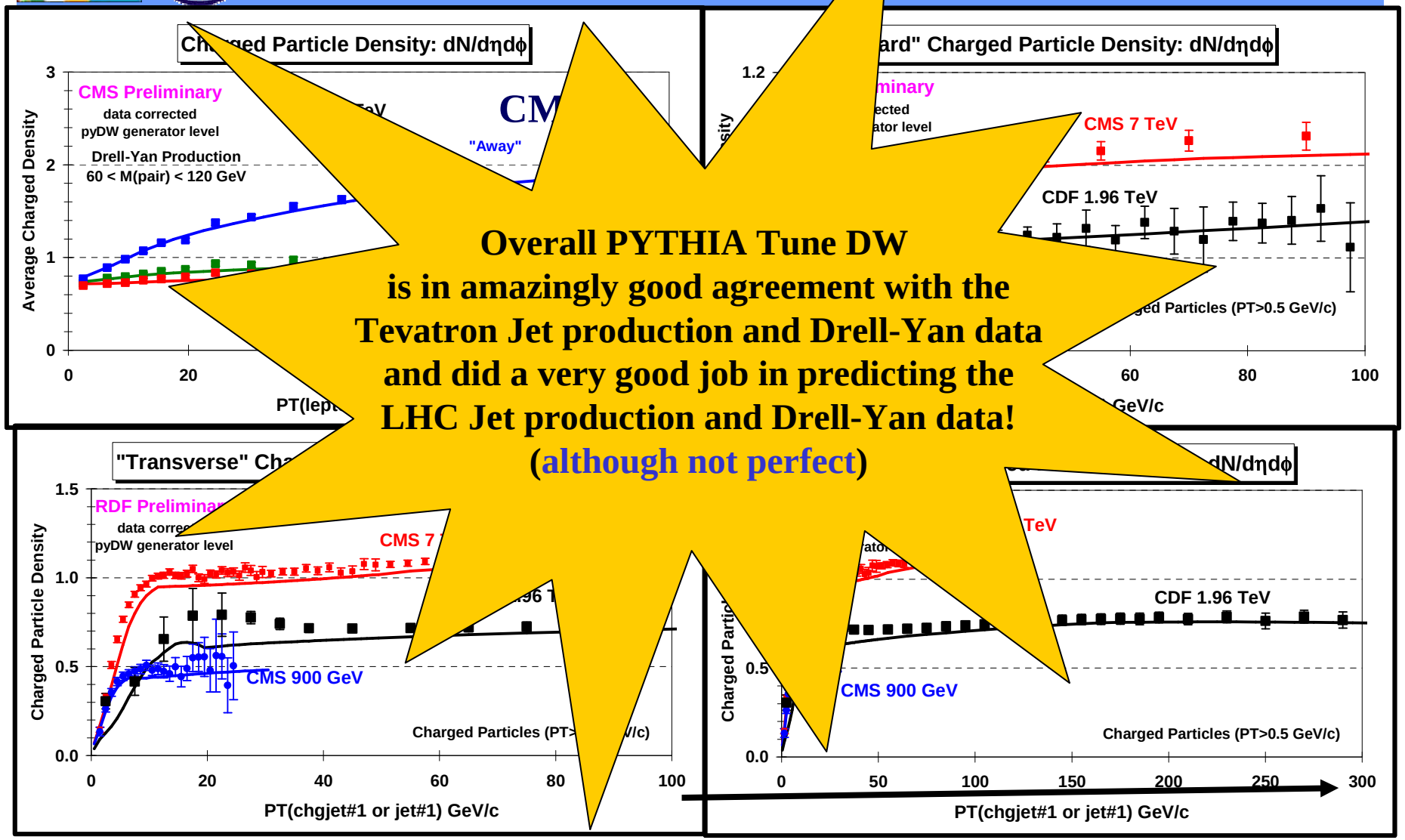








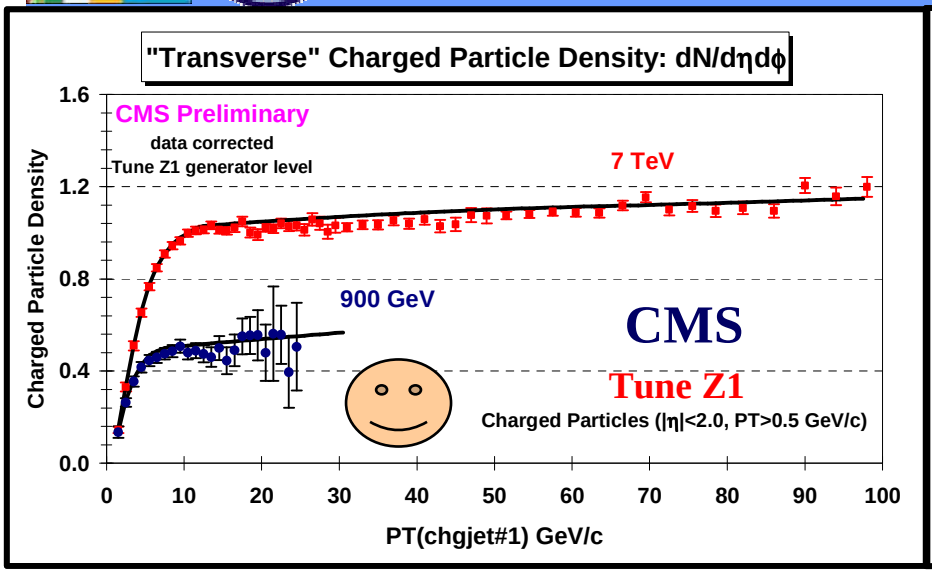
PYTHIA Tune DW

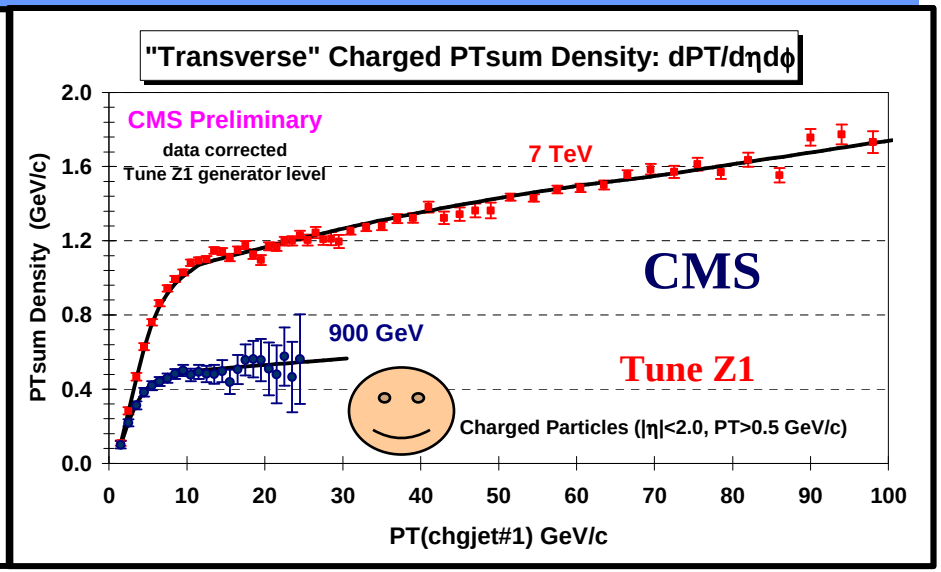


Overall PYTHIA Tune DW is in amazingly good agreement with the Tevatron Jet production and Drell-Yan data and did a very good job in predicting the LHC Jet production and Drell-Yan data!

(although not perfect)

CMS UE Data





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

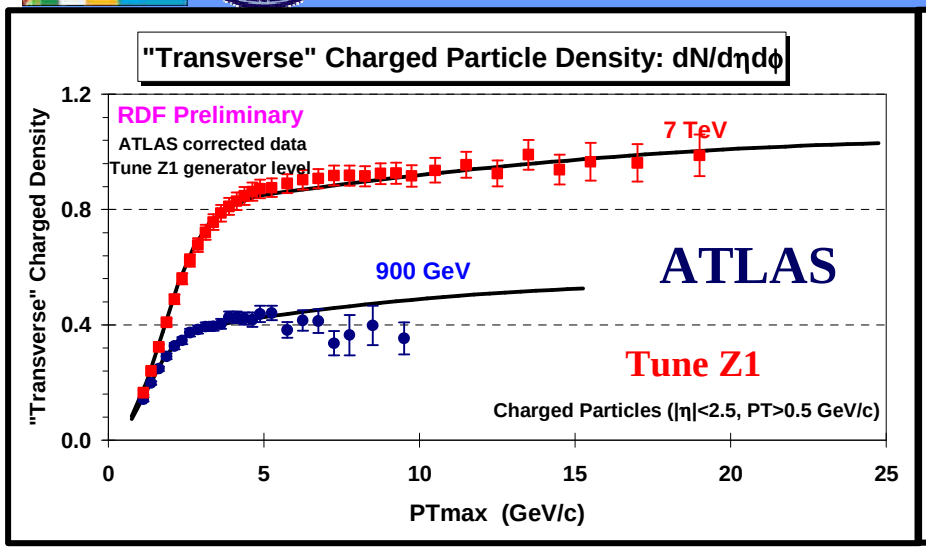
- **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged PTsum density, dPT/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$. The data are corrected and compared with PYTHIA Tune Z1 at the generator level.**

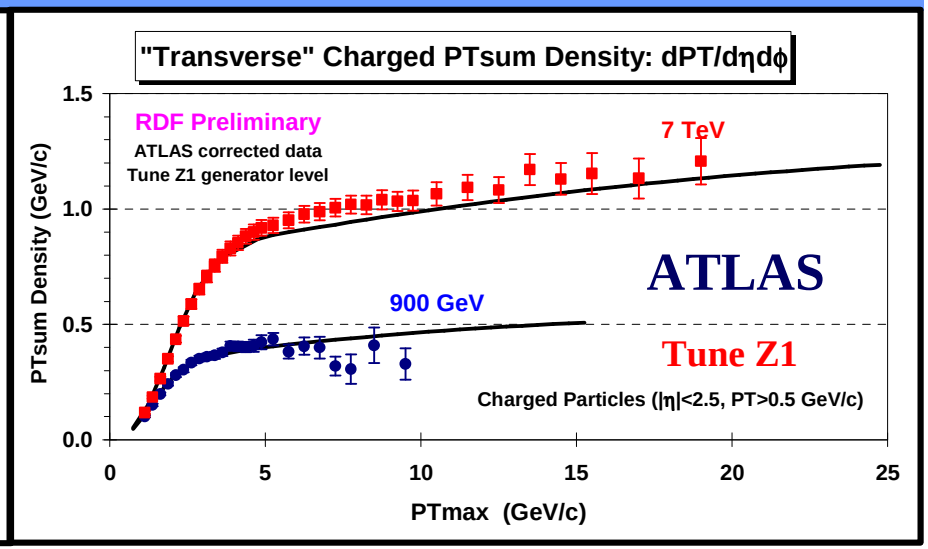
CMS corrected data!

Very nice agreement!

CMS corrected data!

ATLAS UE Data



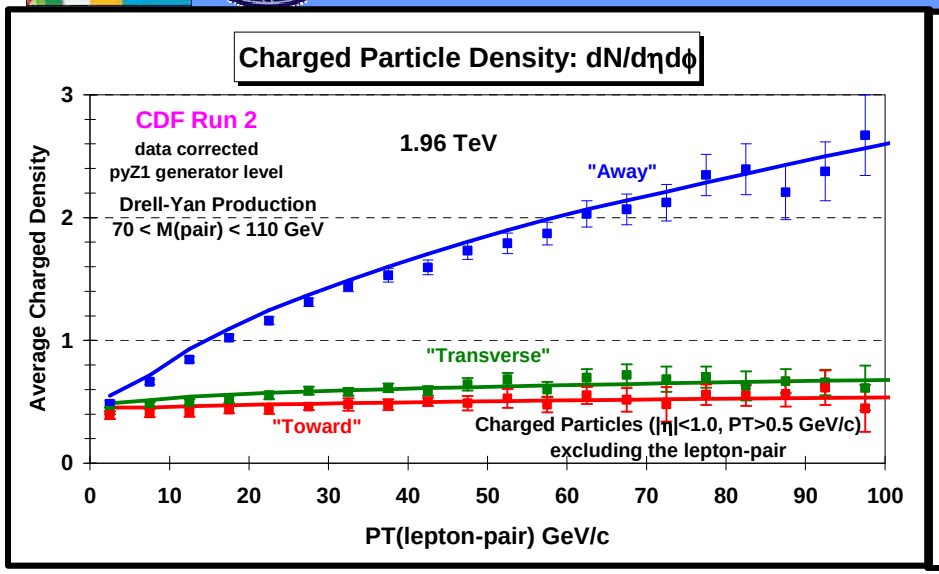


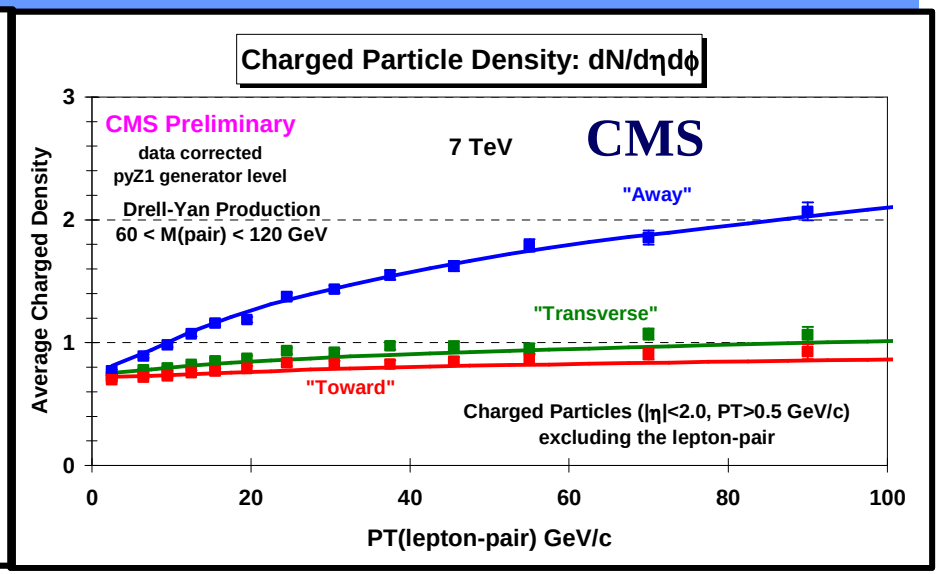
- **ATLAS published data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune Z1 at the generator level.**

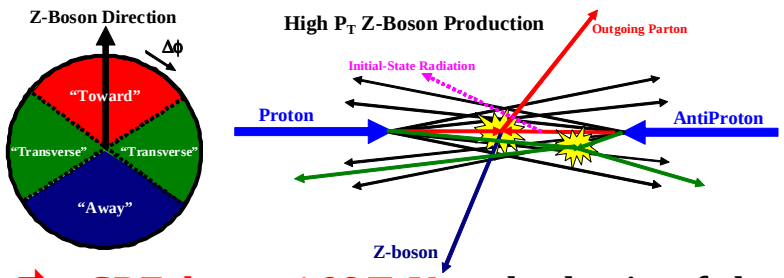
- **ATLAS published data at 900 GeV and 7 TeV on the "transverse" charged PTsum density, dPT/dηdϕ, as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune Z1 at the generrator level.**

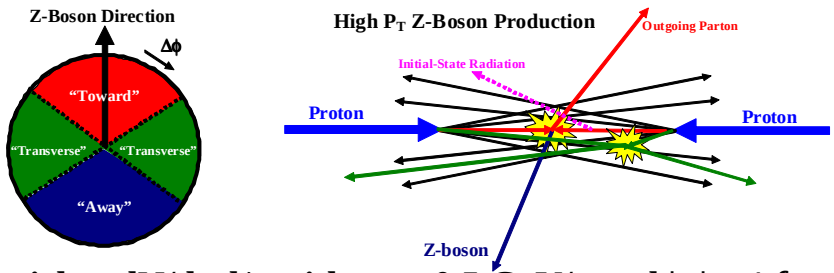
ATLAS publication – arXiv:1012.0791
December 3, 2010

PYTHIA Tune Z1



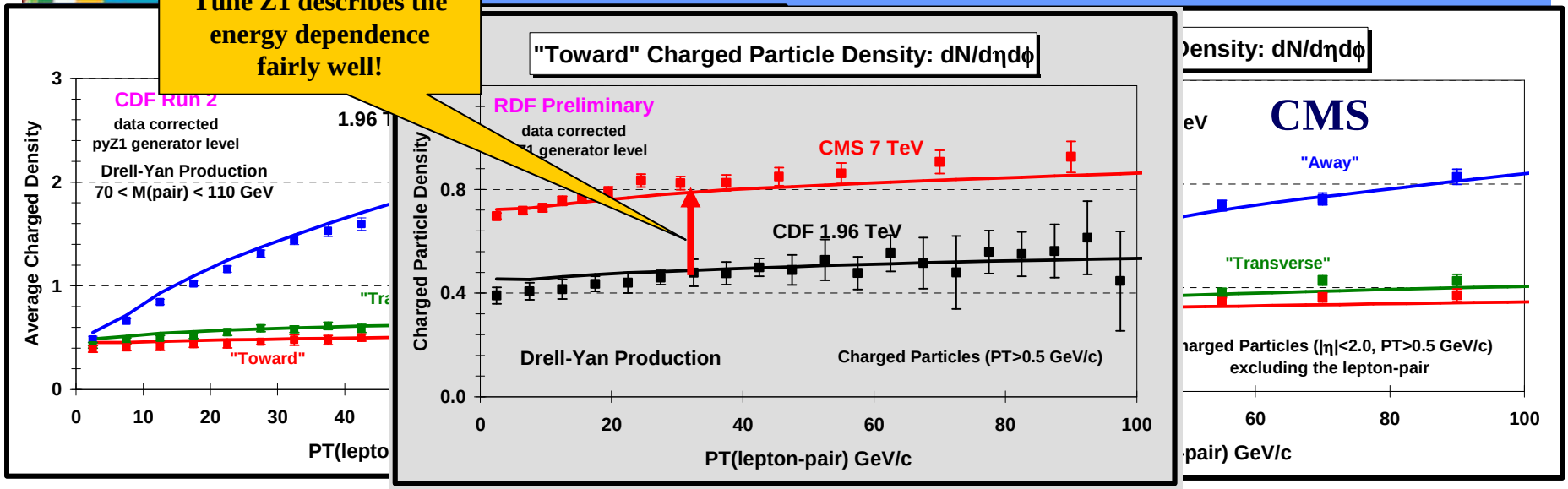


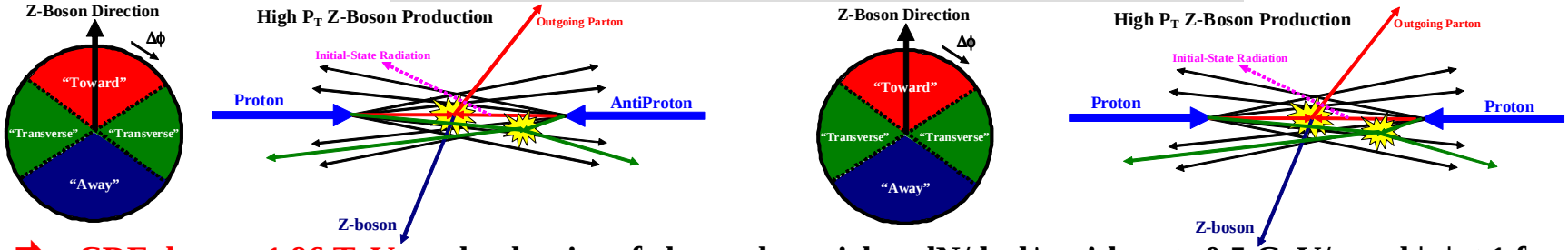




- **CDF data at 1.96 TeV on the density of charged particles, dN/dηdϕ, with p_T > 0.5 GeV/c and |η| < 1 for Drell-Yan production as a function of P_T(Z) for the "toward", "away", and "transverse" regions compared with PYTHIA Tune Z1.**
- **CMS data at 7 TeV on the density of charged particles, dN/dηdϕ, with p_T > 0.5 GeV/c and |η| < 2 for Drell-Yan production as a function of P_T(Z) for the "toward", "away", and "transverse" regions compared with PYTHIA Tune Z1.**

PYTHIA Tune Z1





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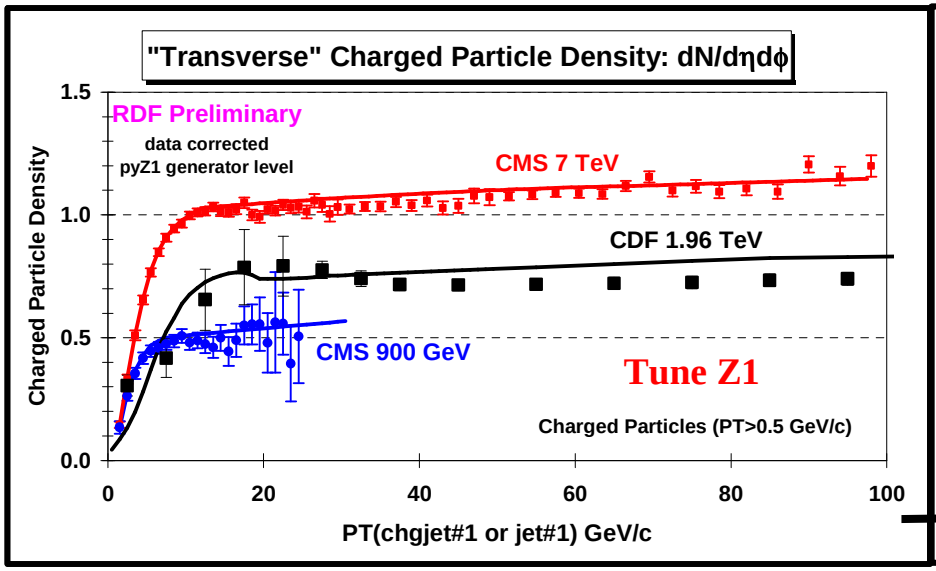
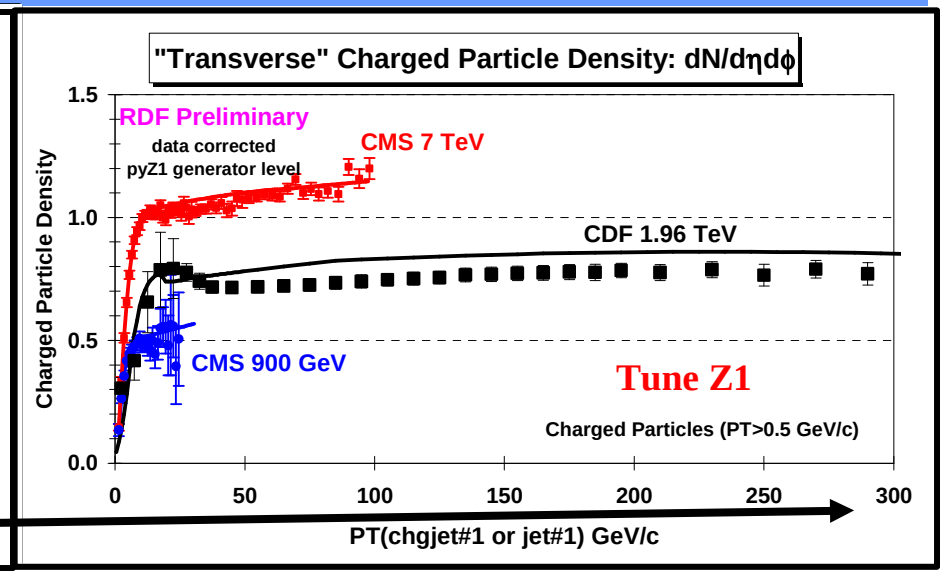
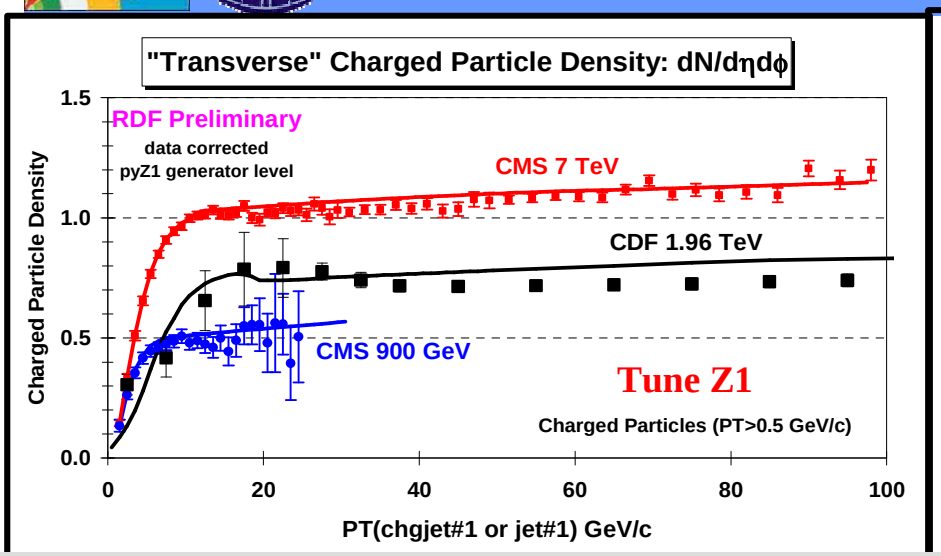


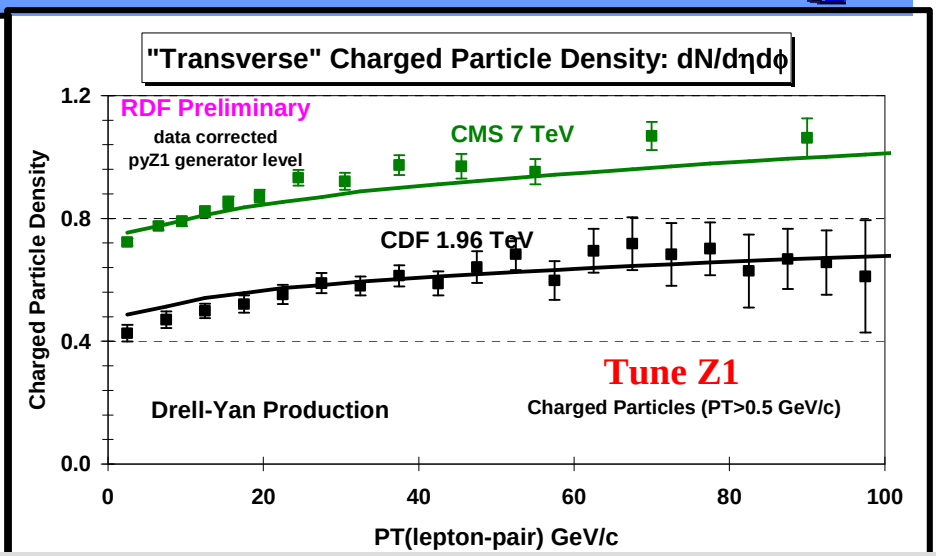


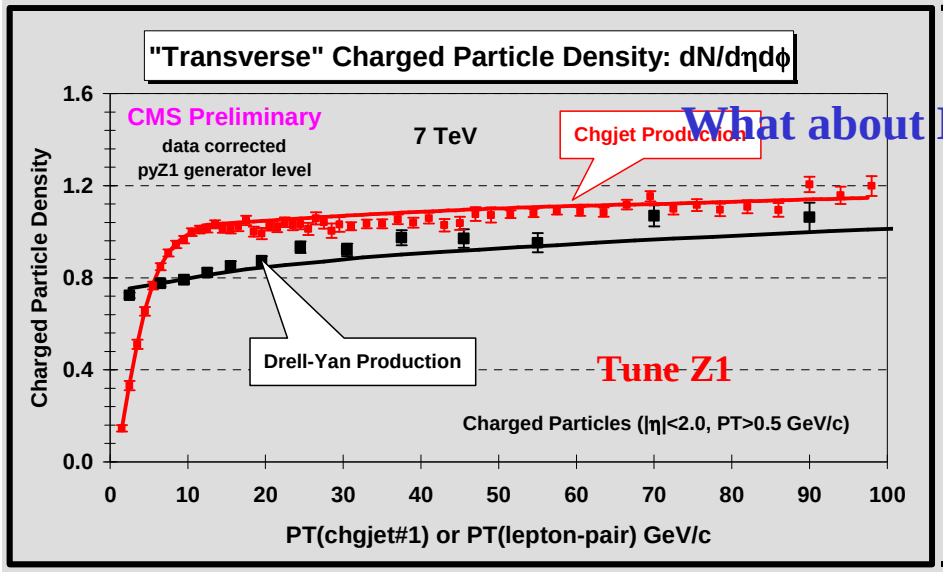
- **CMS data at 900 GeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with p_T > 0.5 GeV/c and |η| < 2.0. The data are corrected and compared with PYTHIA Tune Z1 at the generator level.**

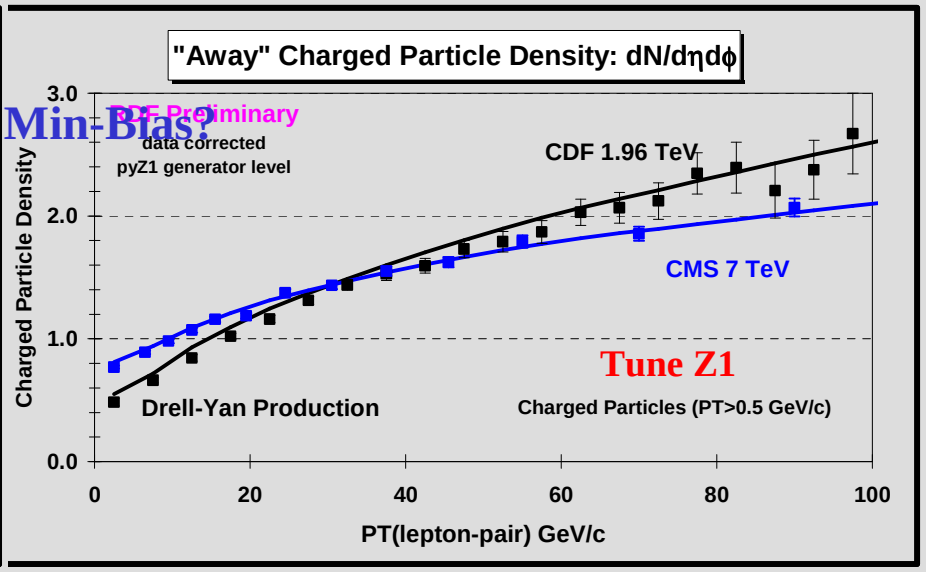
- **CDF data at 1.96 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading calorimeter jet (jet#1) for charged particles with p_T > 0.5 GeV/c and |η| < 1.0. The data are corrected and compared with PYTHIA Tune Z1 at the generator level.**

PYTHIA Tune Z1



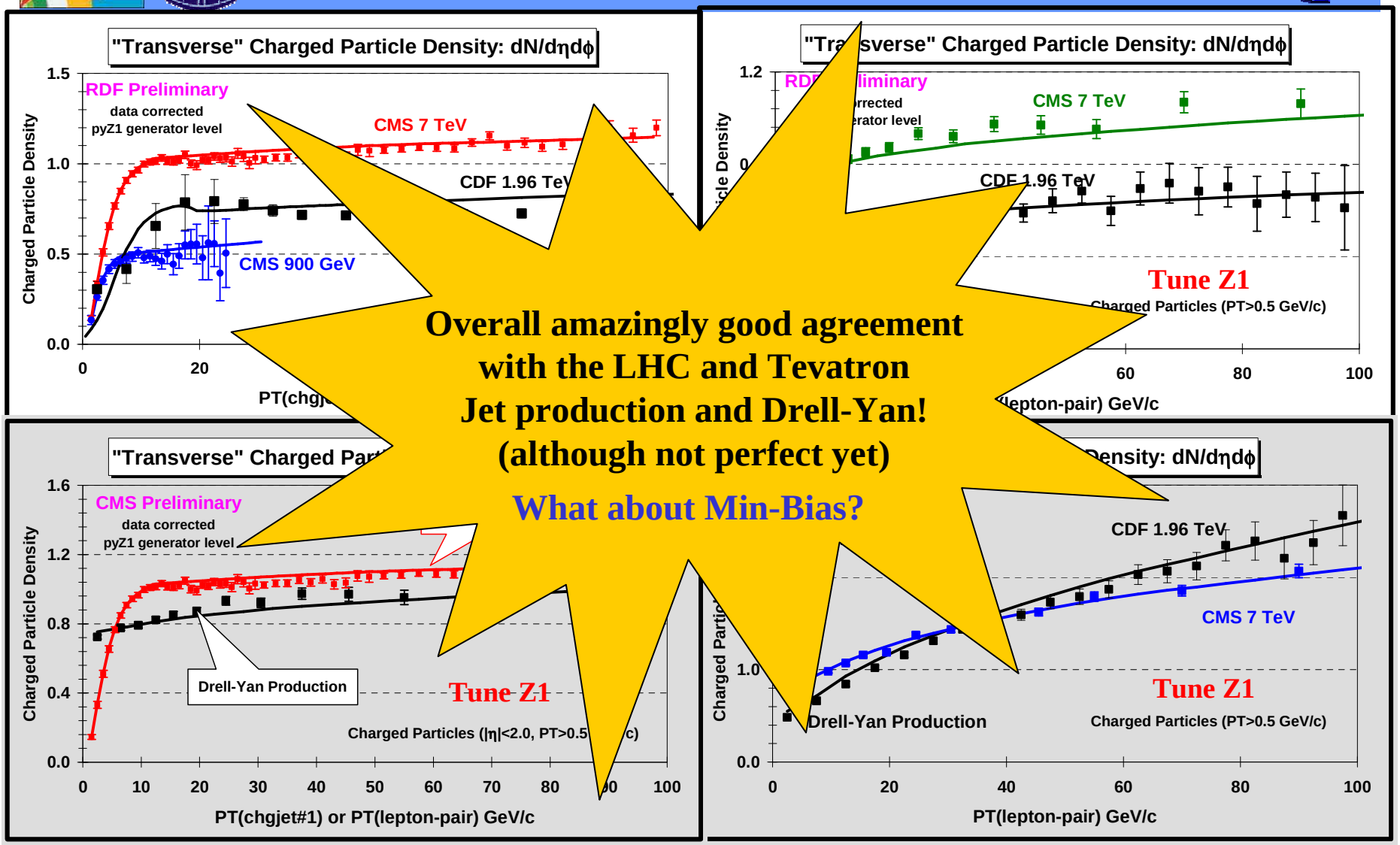






What about Min-Bias?

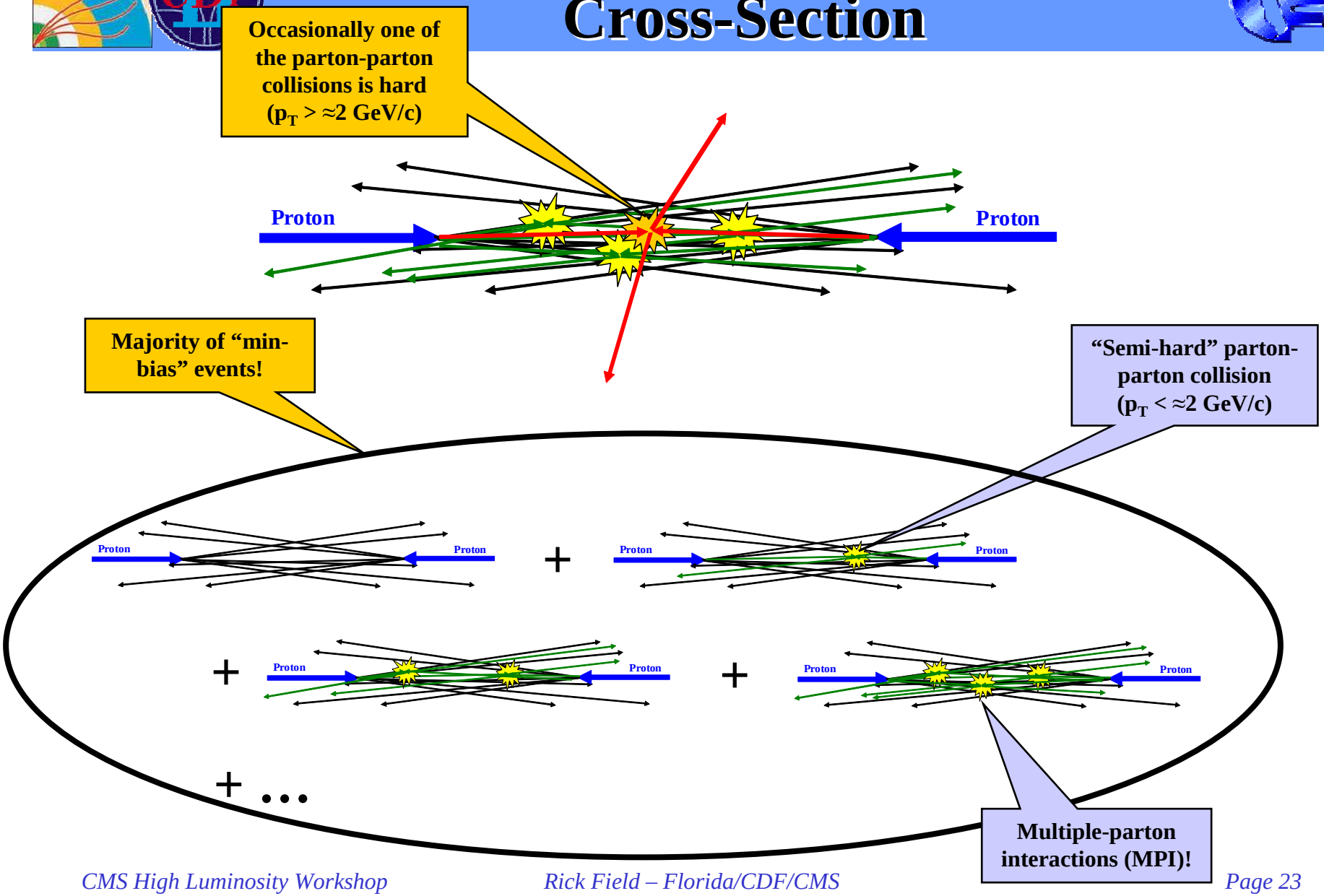
PYTHIA Tune Z1



Overall amazingly good agreement with the LHC and Tevatron Jet production and Drell-Yan! (although not perfect yet)

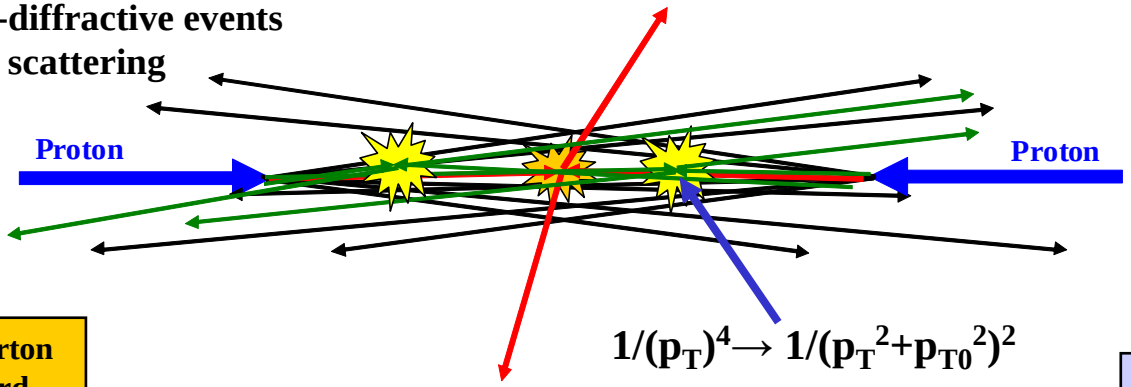
What about Min-Bias?

The Inelastic Non-Diffractive Cross-Section



The "Underlying Event"

Select inelastic non-diffractive events that contain a hard scattering

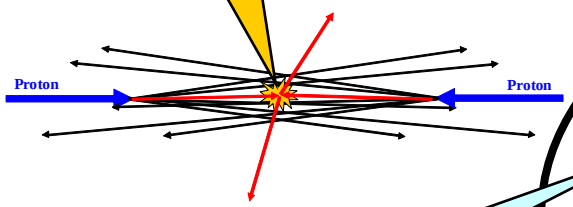


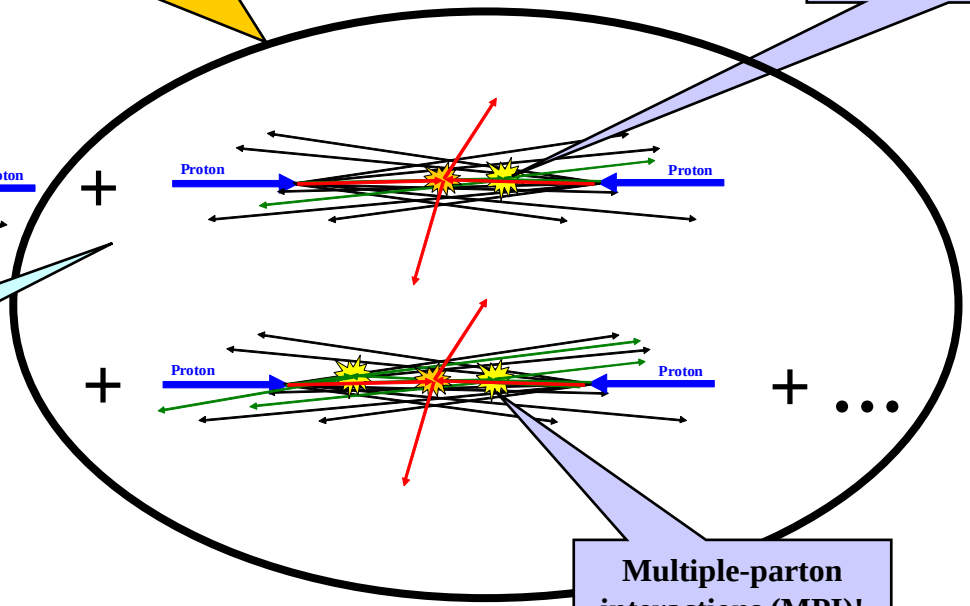
$1/(p_T)^4 \rightarrow 1/(p_T^2+p_{T0}^2)^2$

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)



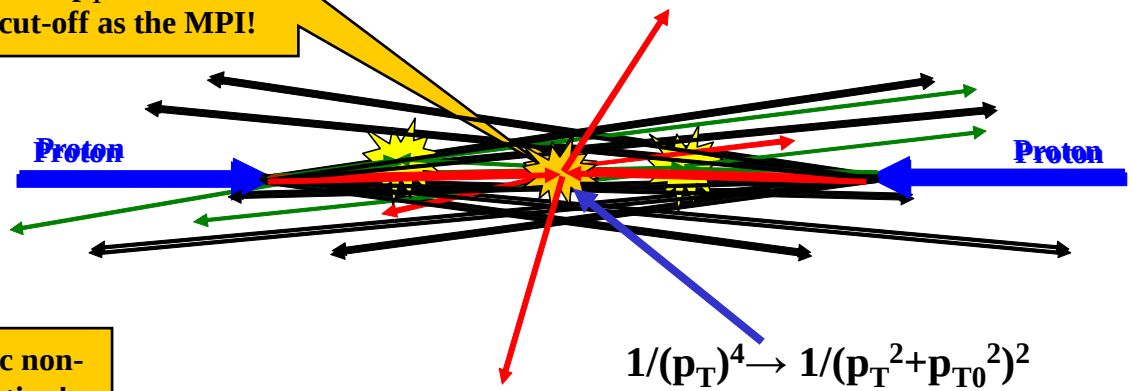


Given that you have one hard scattering it is more probable to have MPI! Hence, the UE has more activity than "min-bias".

Multiple-parton interactions (MPI)!

Model of σ_{ND}

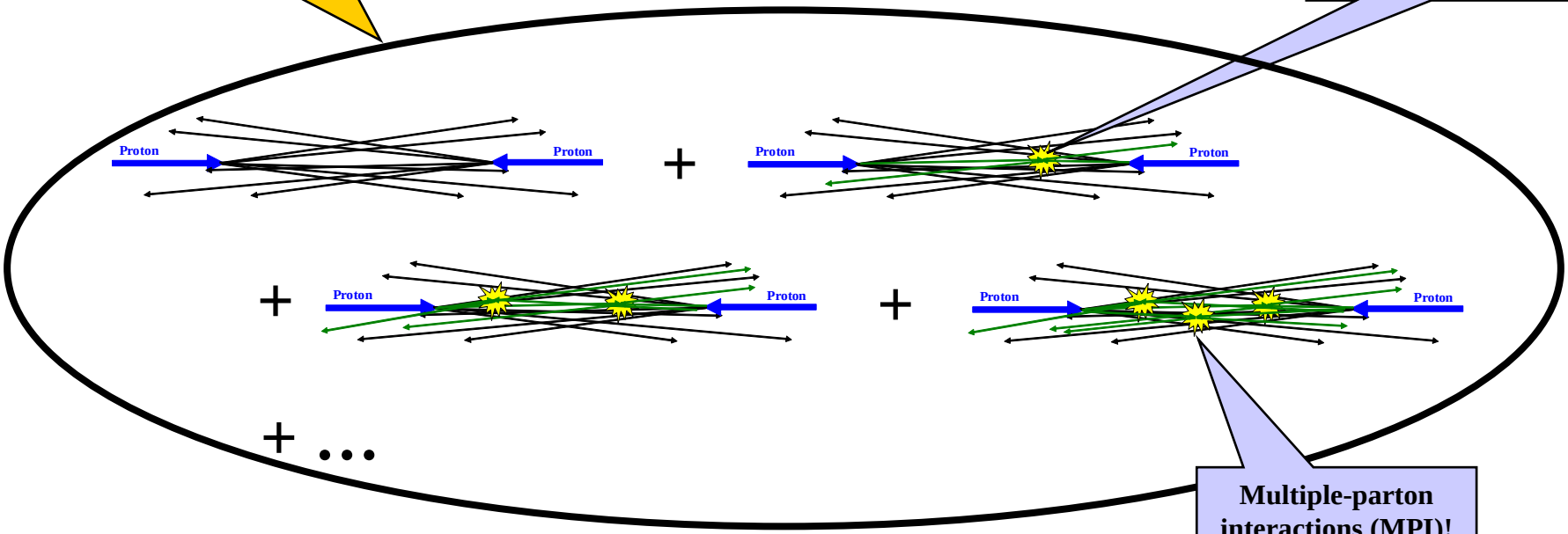
Allow leading hard scattering to go to zero p_T with same cut-off as the MPI!



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

Model of the inelastic non-diffractive cross section!

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



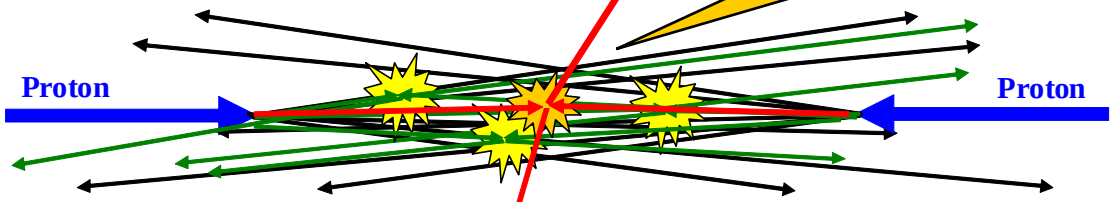
Multiple-parton interactions (MPI)!

UE Tunes

"Underlying Event"

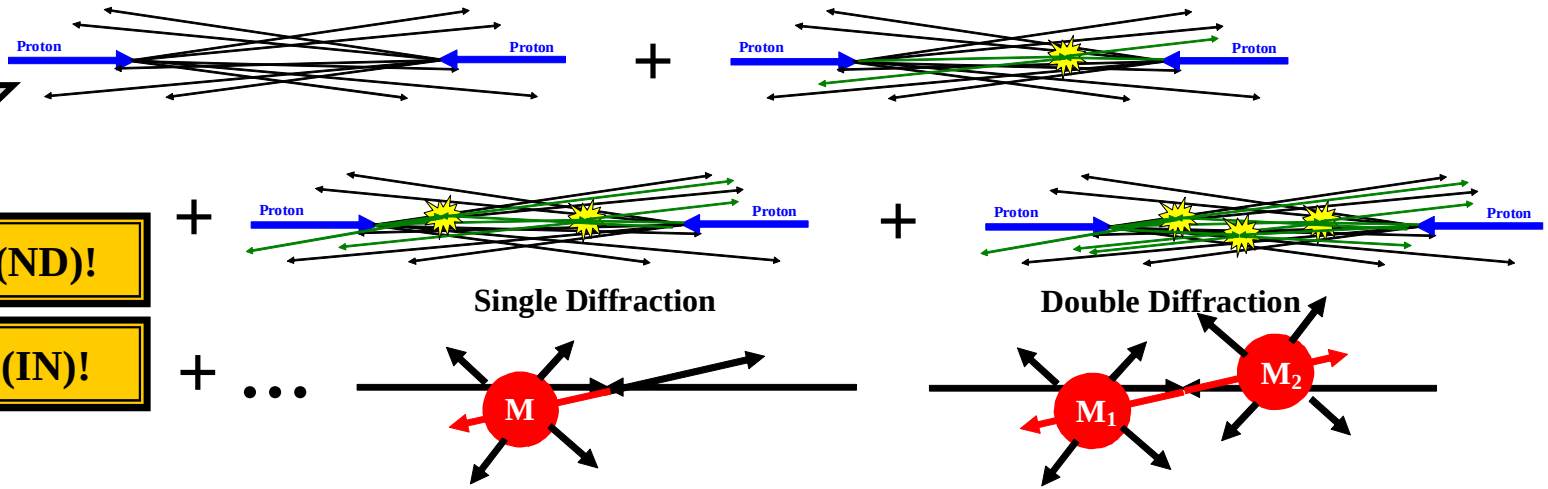
Allow primary hard-scattering to go to $p_T = 0$ with same cut-off!

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



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

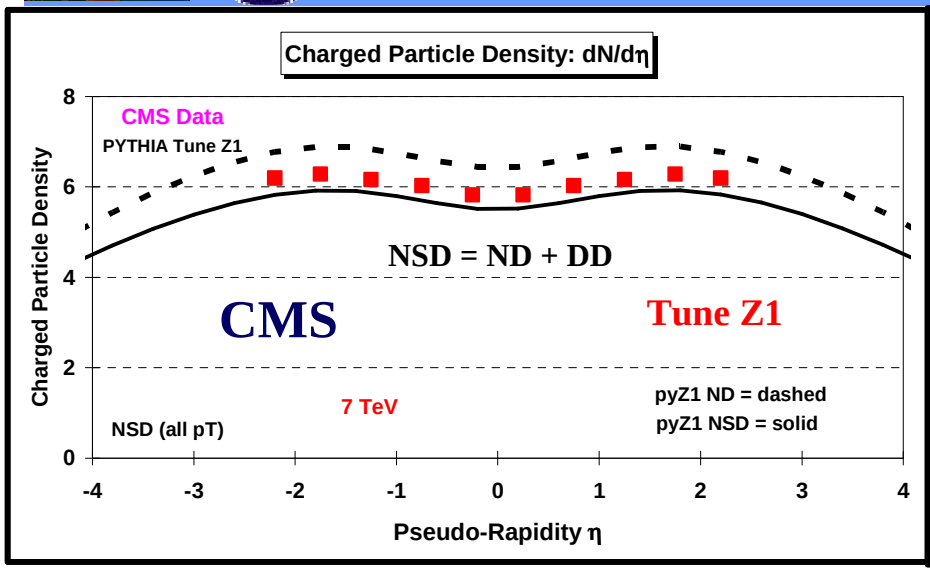
"Min-Bias" (add single & double diffraction)

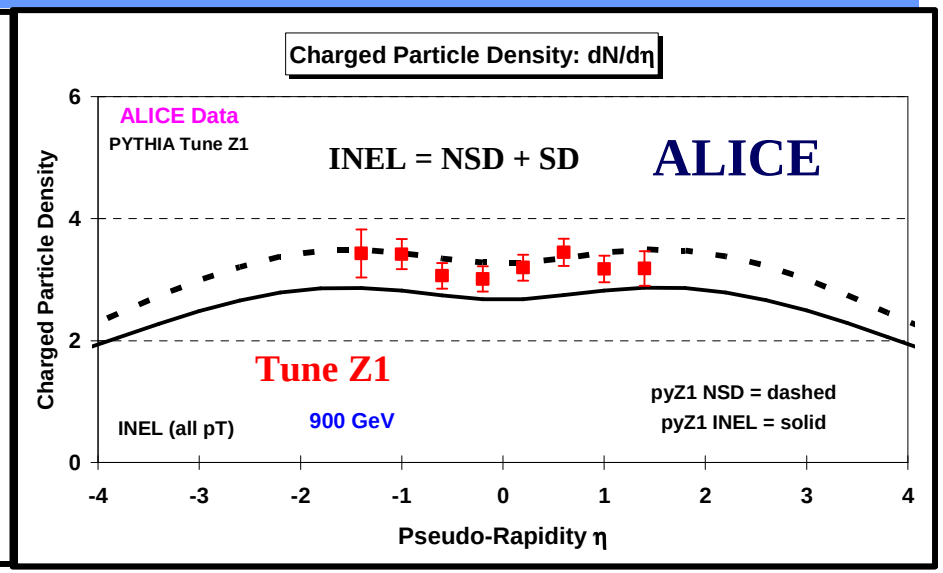


Predict MB (ND)!

Predict MB (IN)!

Min-Bias Collisions

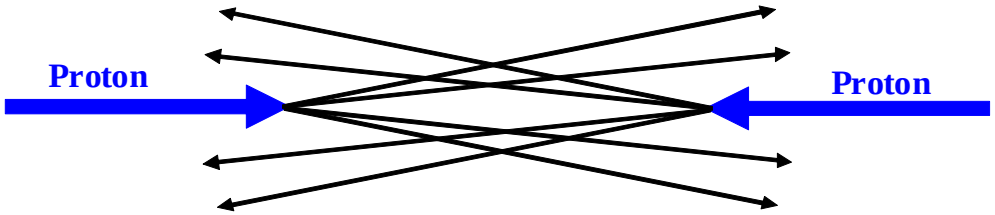




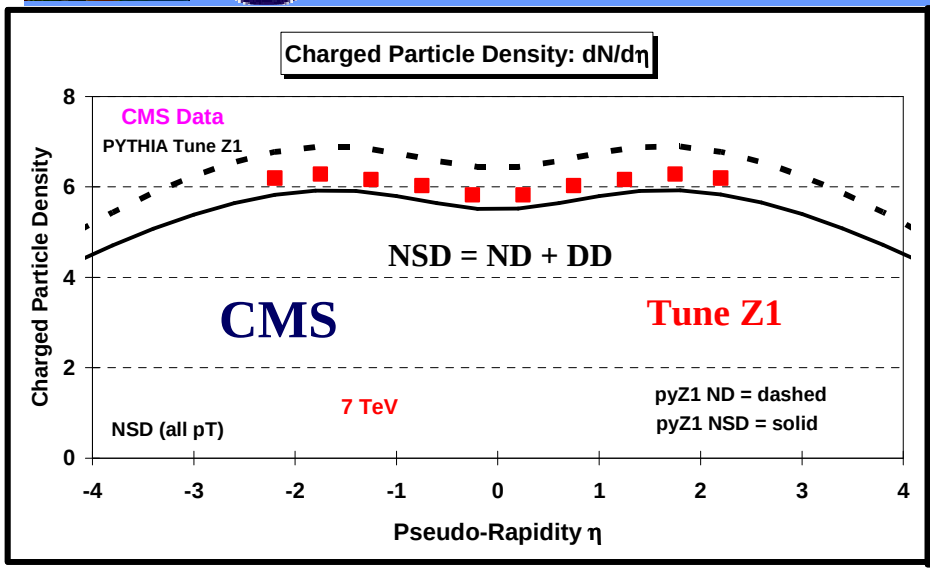
- **CMS NSD data on the charged particle rapidity distribution at 7 TeV compared with PYTHIA Tune Z1. The plot shows the average number of particles per NSD collision per unit η, $(1/N_{NSD})\ dN/d\eta$.**

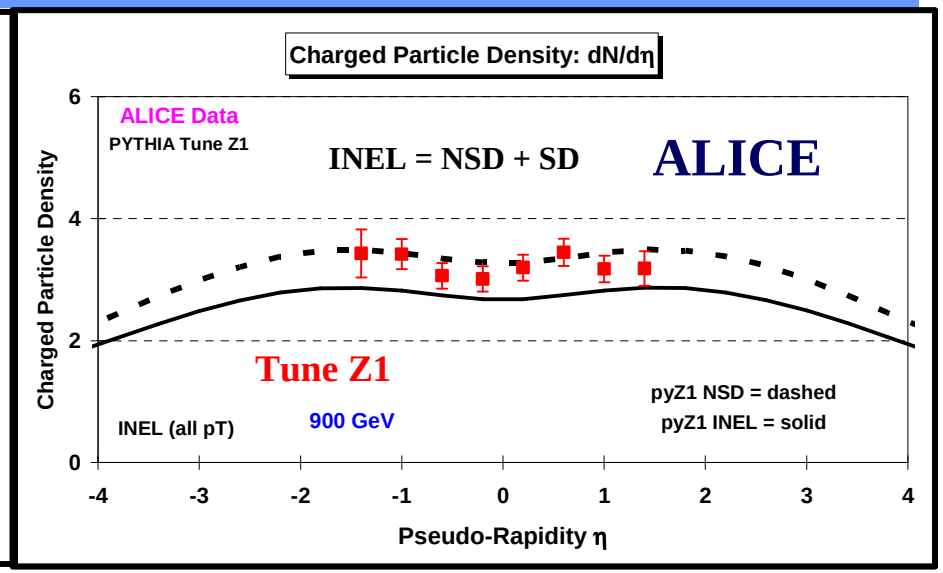
- **ALICE NSD data on the charged particle rapidity distribution at 900 GeV compared with PYTHIA Tune Z1. The plot shows the average number of particles per INEL collision per unit η, $(1/N_{INEL})\ dN/d\eta$.**

"Minimum Bias" Collisions



Min-Bias Collisions





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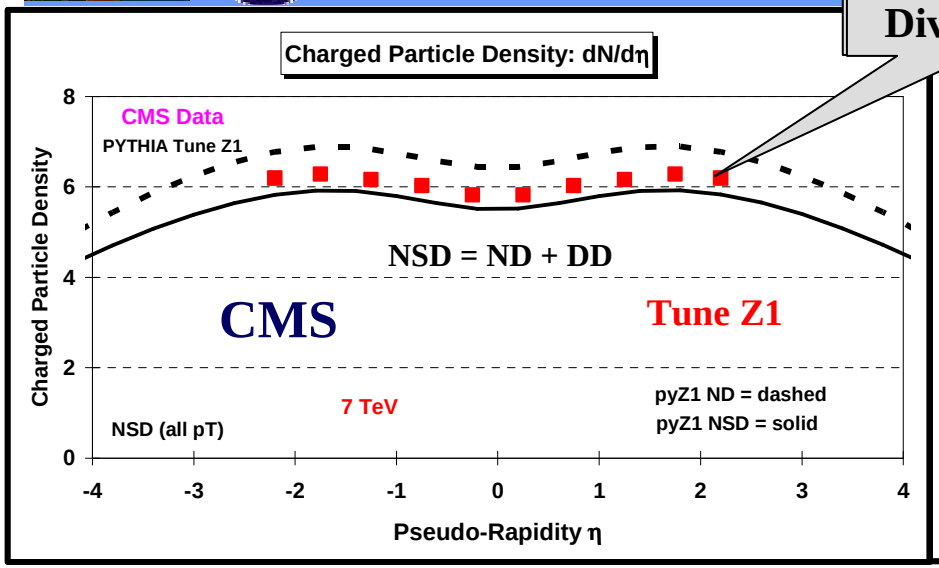
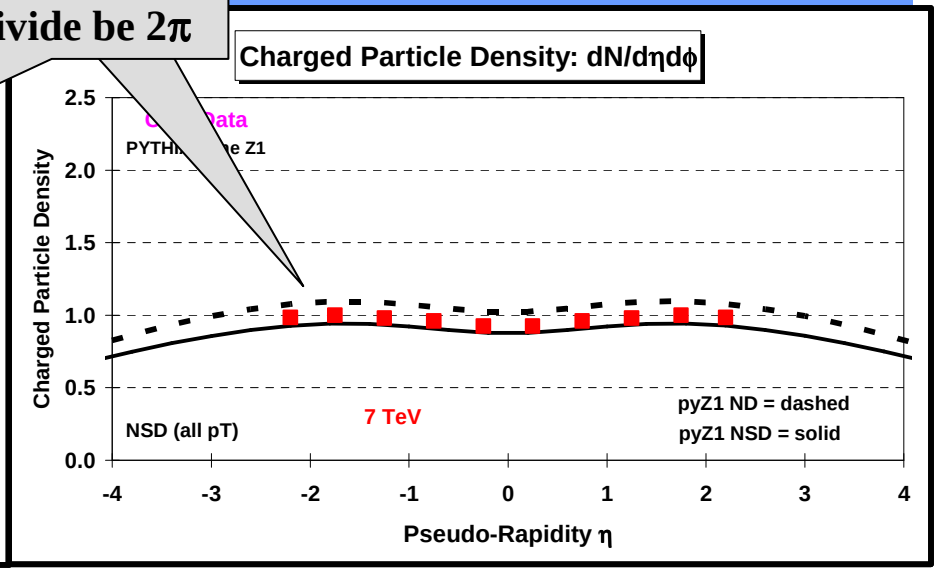
"Minimum Bias" Collisions

Okay not perfect, but remember we know that SD and DD are not modeled well!

MB versus UE

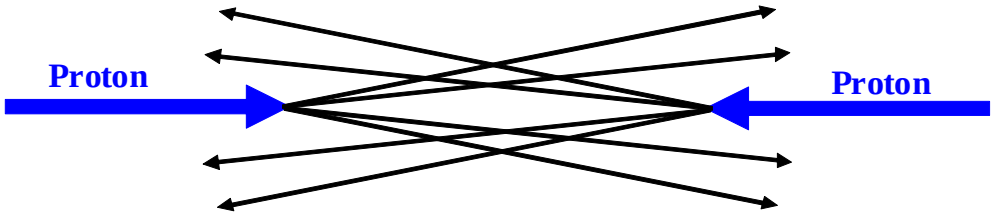


Divide be 2π

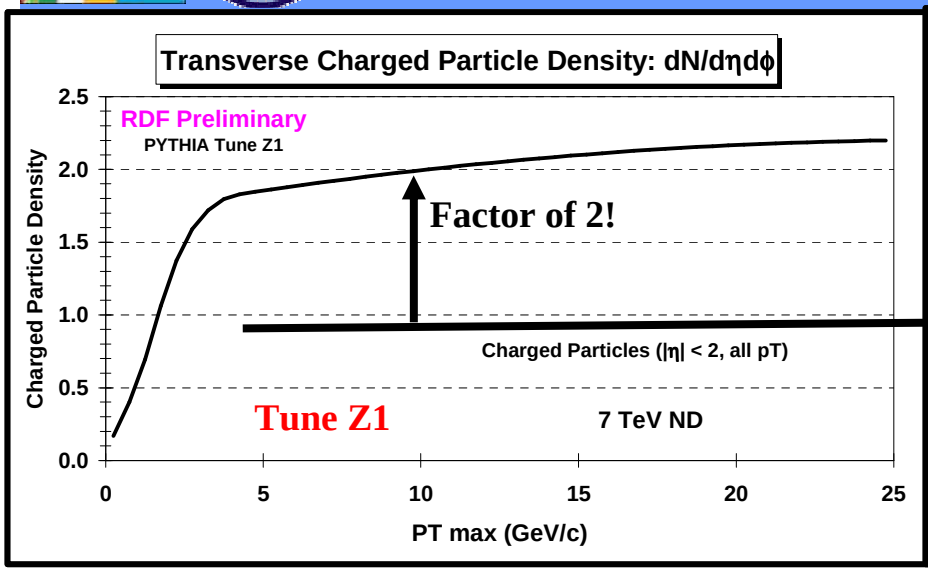


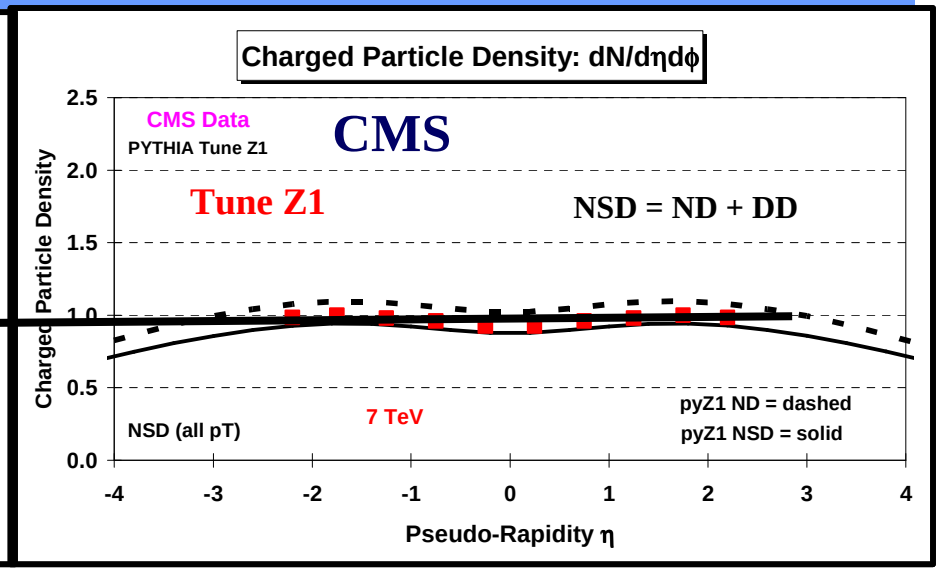
- **CMS NSD data on the charged particle rapidity distribution at 7 TeV compared with PYTHIA Tune Z1. The plot shows the average number of charged particles per NSD collision per unit η, $(1/N_{NSD})$ dN/dη.**
- **CMS NSD data on the charged particle rapidity distribution at 7 TeV compared with PYTHIA Tune Z1. The plot shows the average number of charged particles per NSD collision per unit η–φ, $(1/N_{NSD})$ dN/dηdφ.**

"Minimum Bias" Collisions

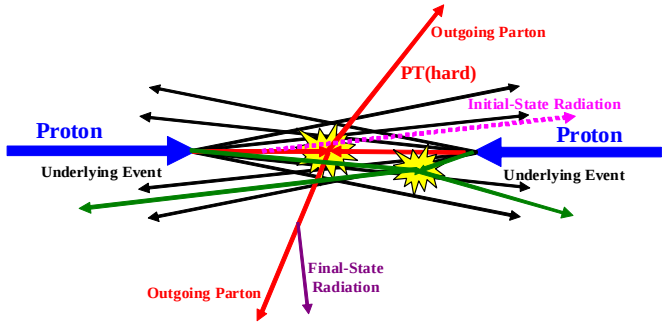


MB versus UE

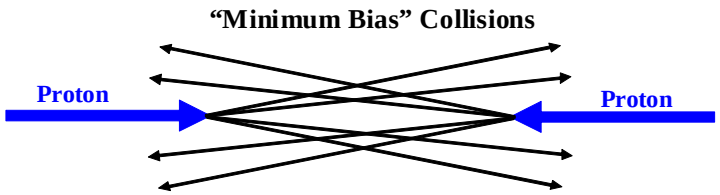




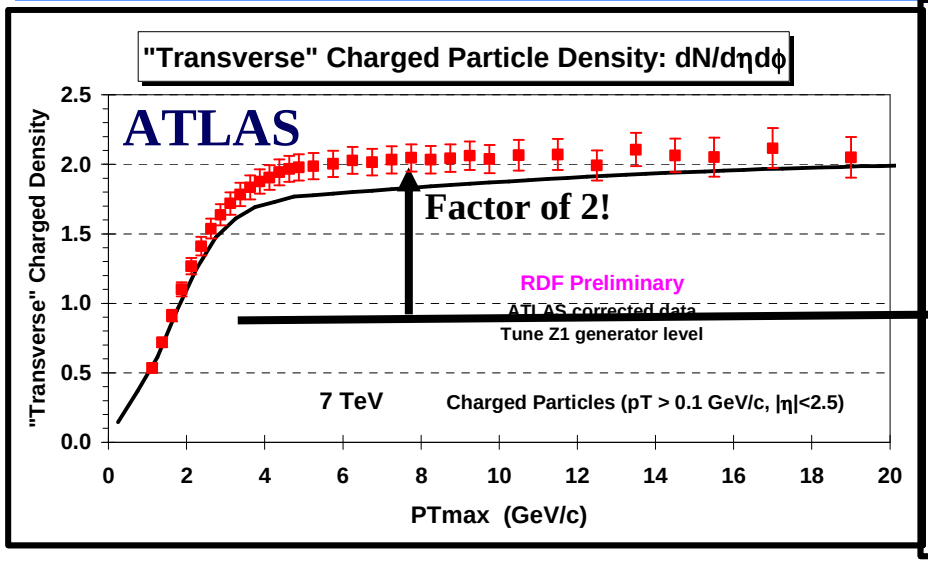
- **Shows the density of charged particles in the "transverse" region as a function of PTmax for charged particles (All p_T, $|\eta| < 2$) at 7 TeV from PYTHIA Tune Z1.**

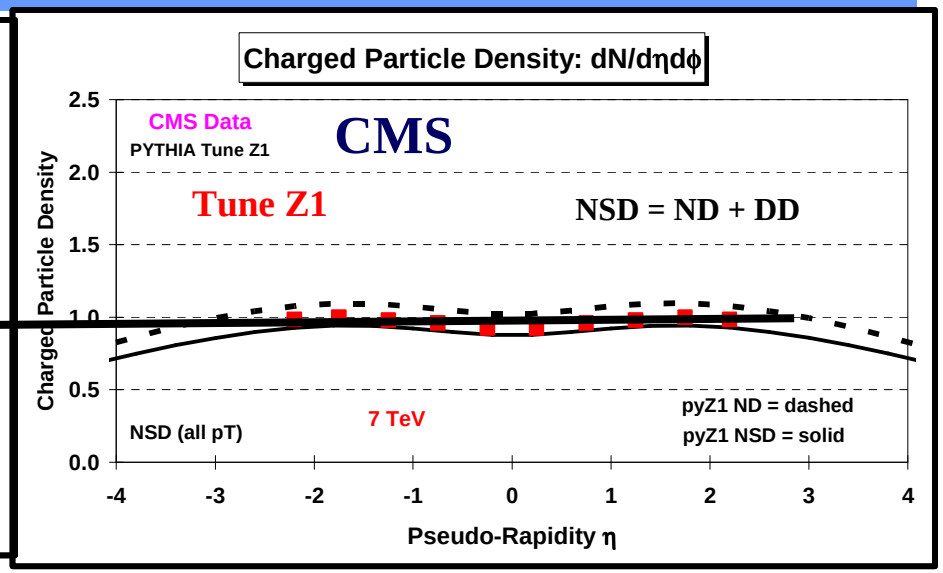


- **CMS NSD data on the charged particle rapidity distribution at 7 TeV compared with PYTHIA Tune Z1. The plot shows the average number of charged particles per NSD collision per unit $\eta-\phi$, $(1/N_{NSD})\ dN/d\eta d\phi$.**

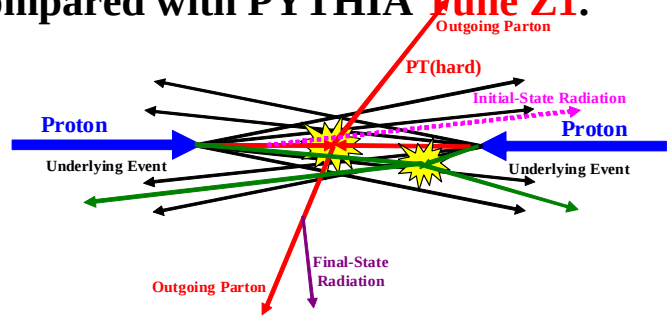


MB versus UE





- **ATLAS data on the density of charged particles in the "transverse" region as a function of PTmax for charged particles (p_T > 0.1 GeV/c, |η| < 2.5) at 7 TeV compared with PYTHIA Tune Z1.**



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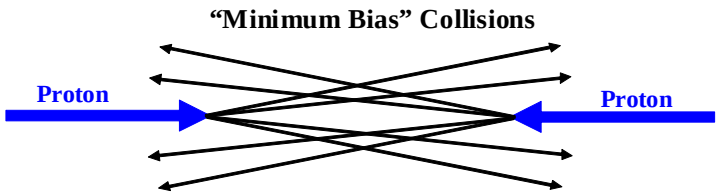
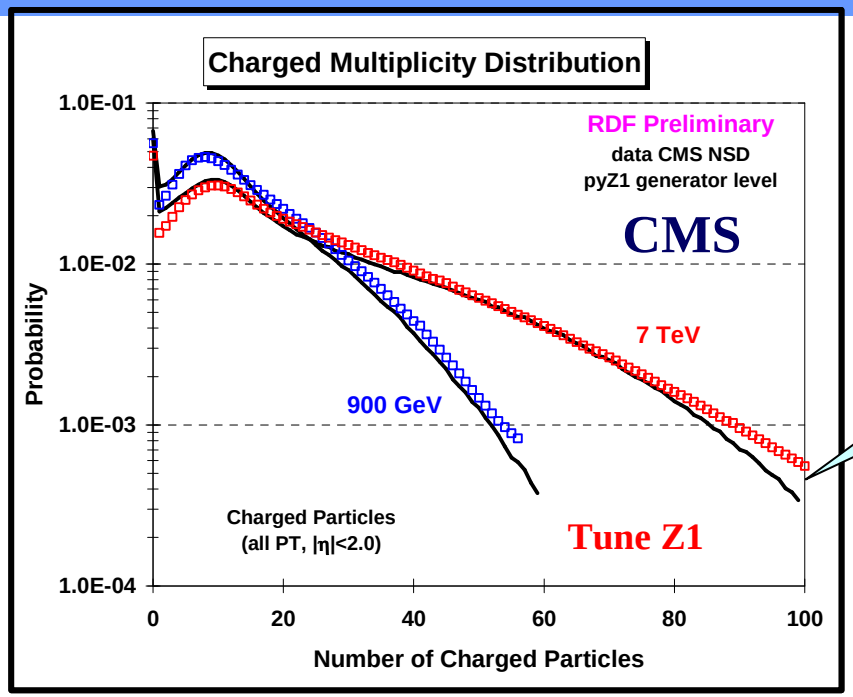
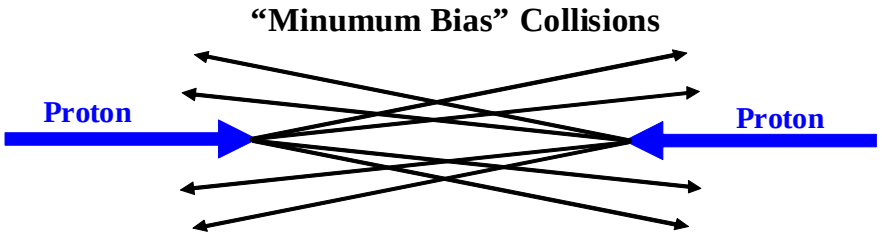


NSD Multiplicity Distribution

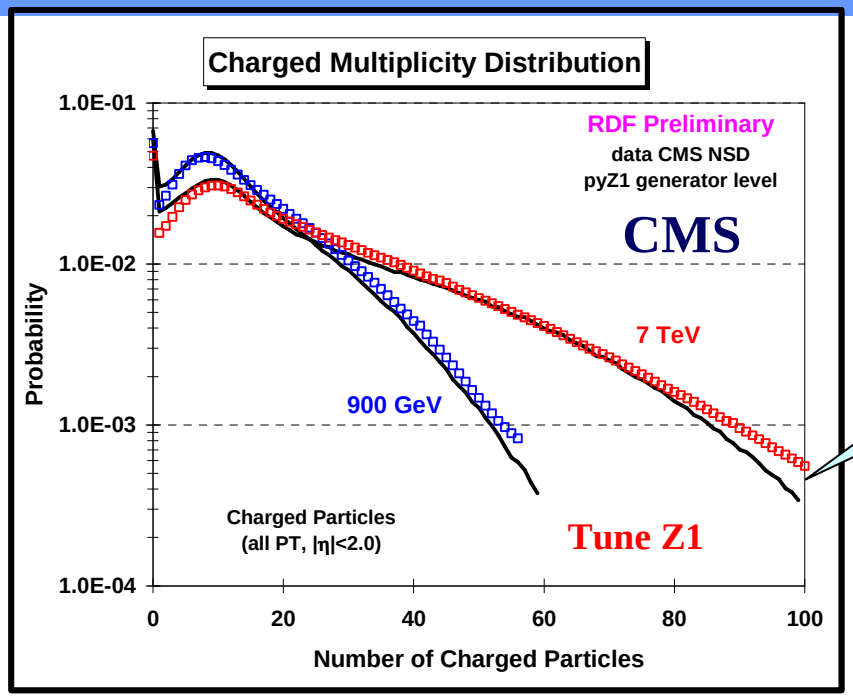


Difficult to produce enough events with large multiplicity!

- **Generator level charged multiplicity distribution (all pT, |η| < 2) at 900 GeV and 7 TeV. Shows the NSD = HC + DD prediction for Tune Z1. Also shows the CMS NSD data.**



NSD Multiplicity Distribution



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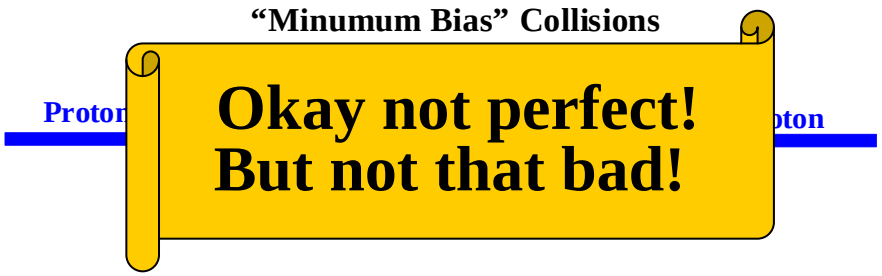
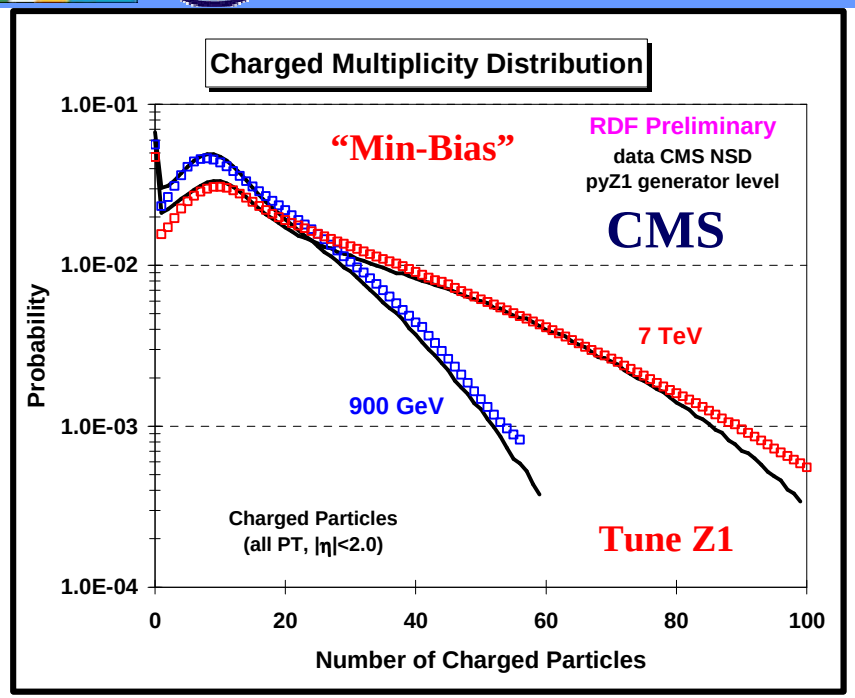
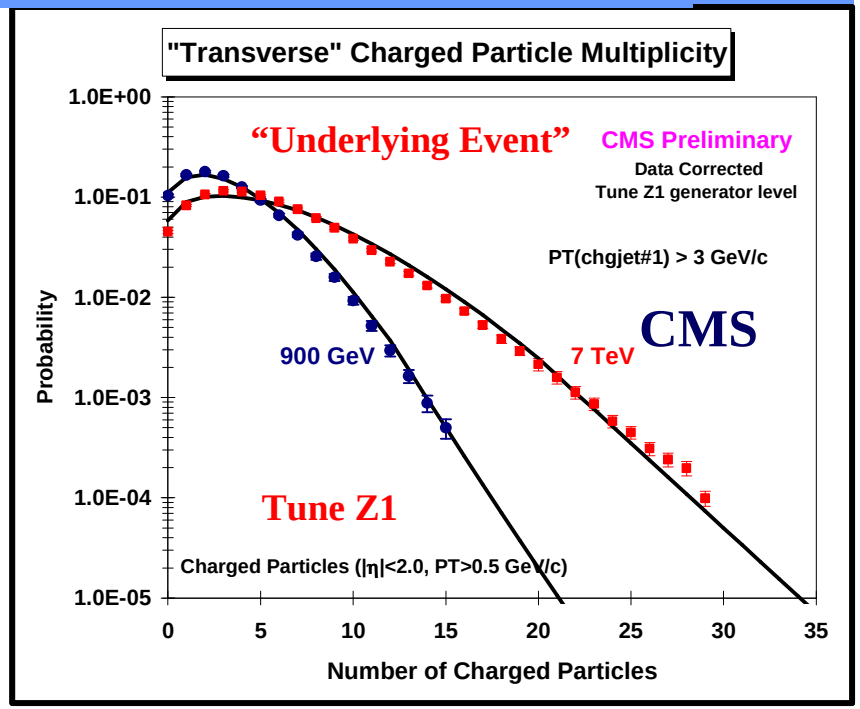


MB & UE

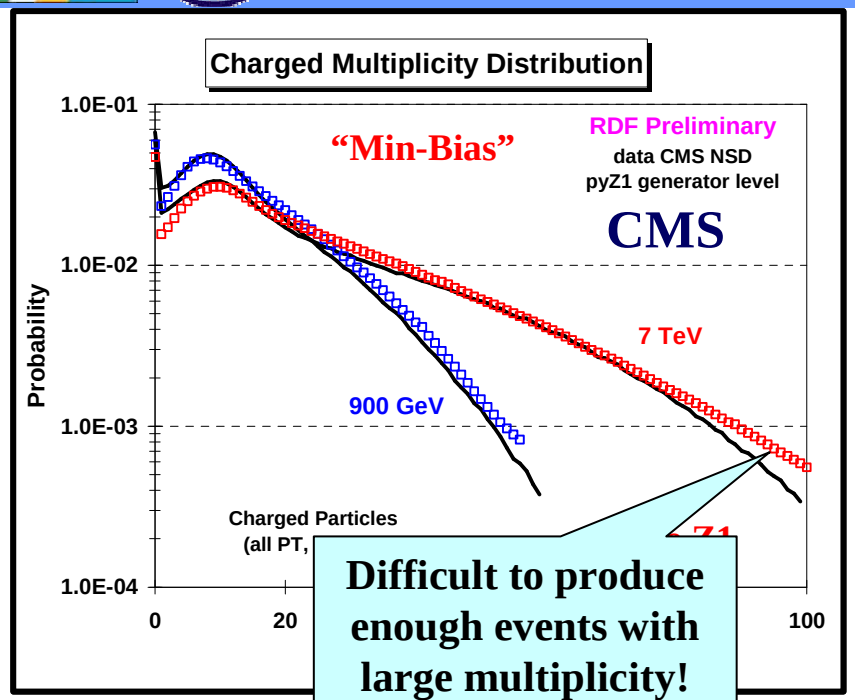




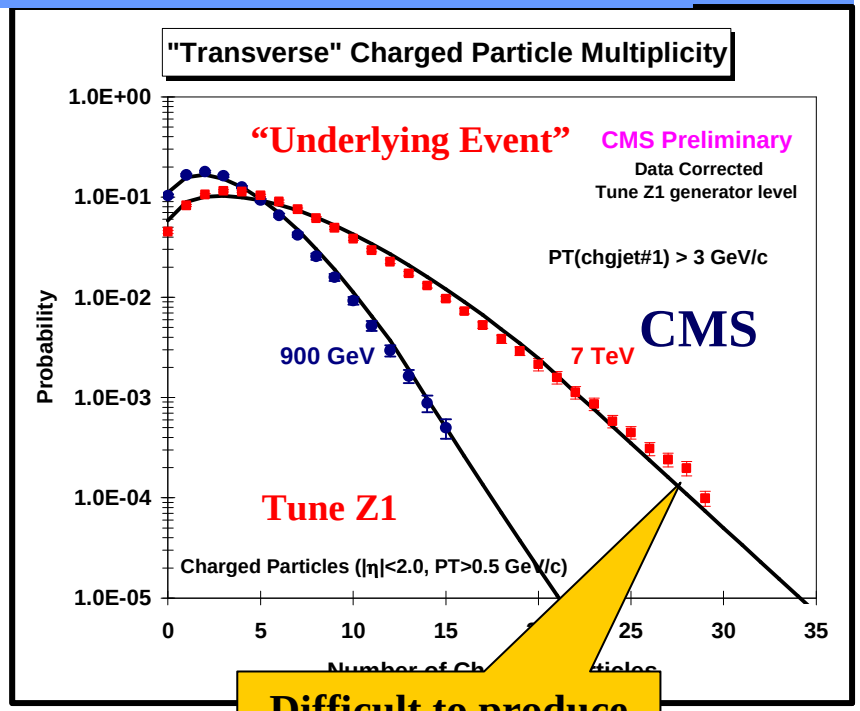
- **Generator level charged multiplicity distribution (all pT, |η| < 2) at 900 GeV and 7 TeV. Shows the NSD = HC + DD prediction for Tune Z1. Also shows the CMS NSD data.**

- **CMS corrected data at 900 GeV and 7 TeV on the charged particle multiplicity distribution in the "transverse" region for charged particles (p_T > 0.5 GeV/c, |η| < 2) as defined by the leading charged particle jet with PT(chgjet#1) > 3 GeV/c compared with PYTHIA Tune Z1 at the generator level.**

MB & UE



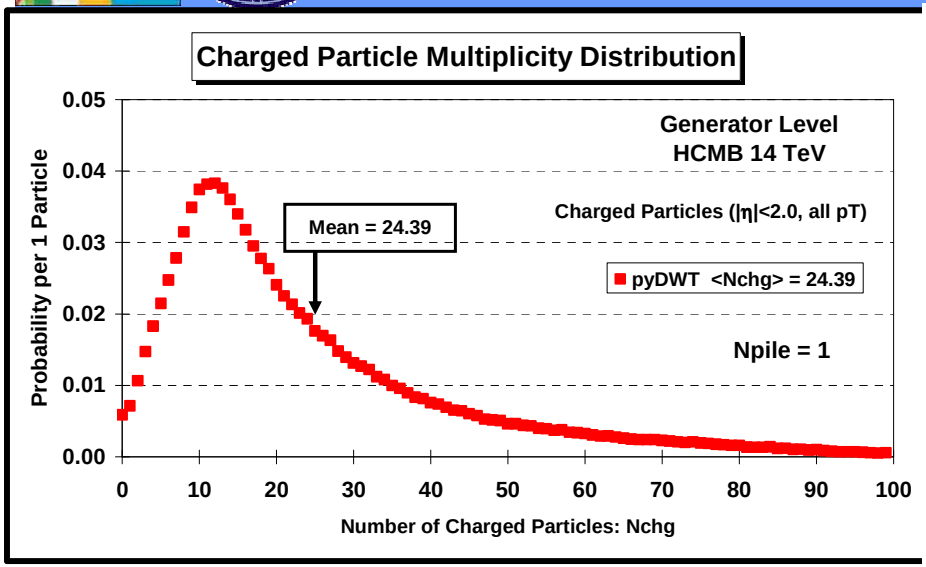
Difficult to produce enough events with large multiplicity!

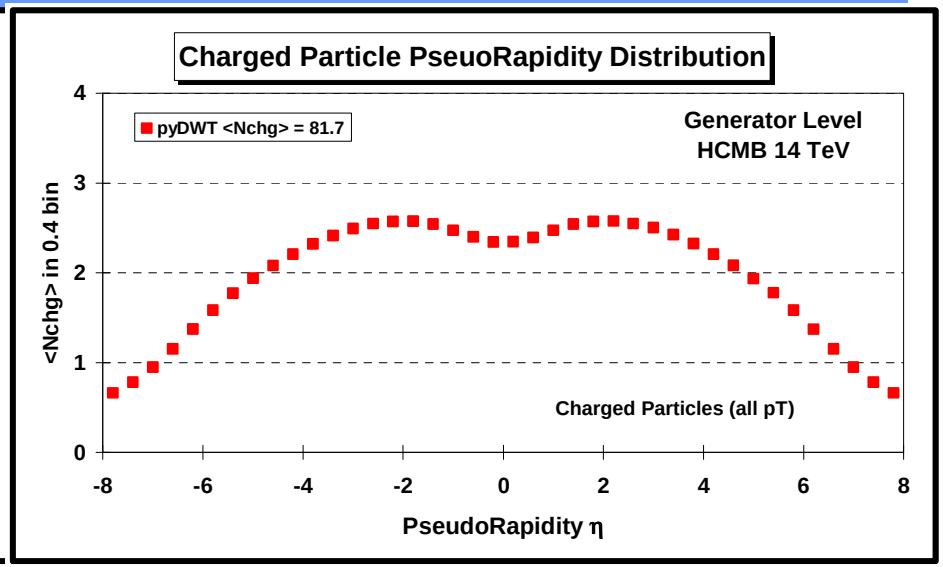


Difficult to produce enough events with large "transverse" multiplicity at low hard scale!

- **Generator level charged multiplicity distribution (all pT, |η| < 2) at 900 GeV and 7 TeV. Shows the NSD = HC + DD prediction for Tune Z1. Also shows the CMS NSD data.**
- **CMS corr and 7 TeV on th iplicity distributi egion for charged p , |η| < 2) as defined particle jet with PT(chgjet#1) > 3 GeV/c compared with PYTHIA Tune Z1 at the generator level.**

Pile-Up at the LHC



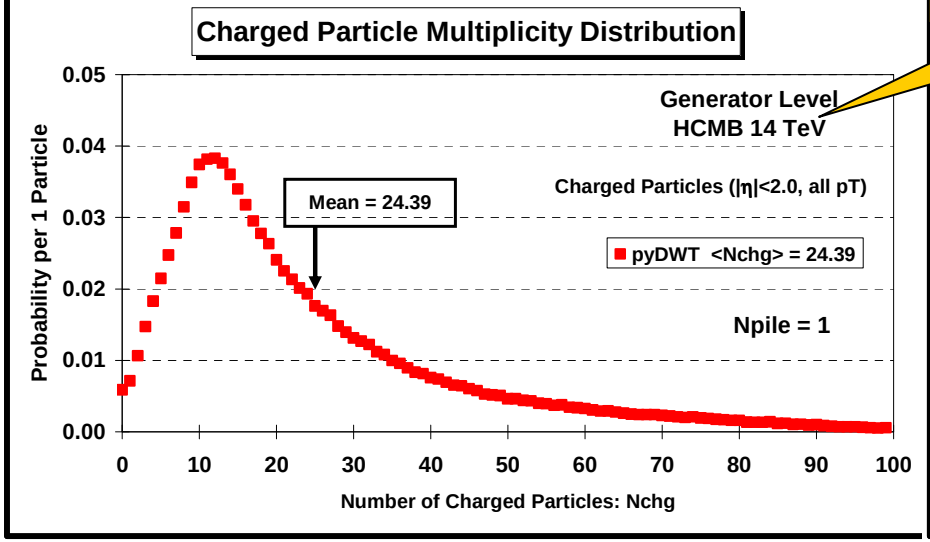


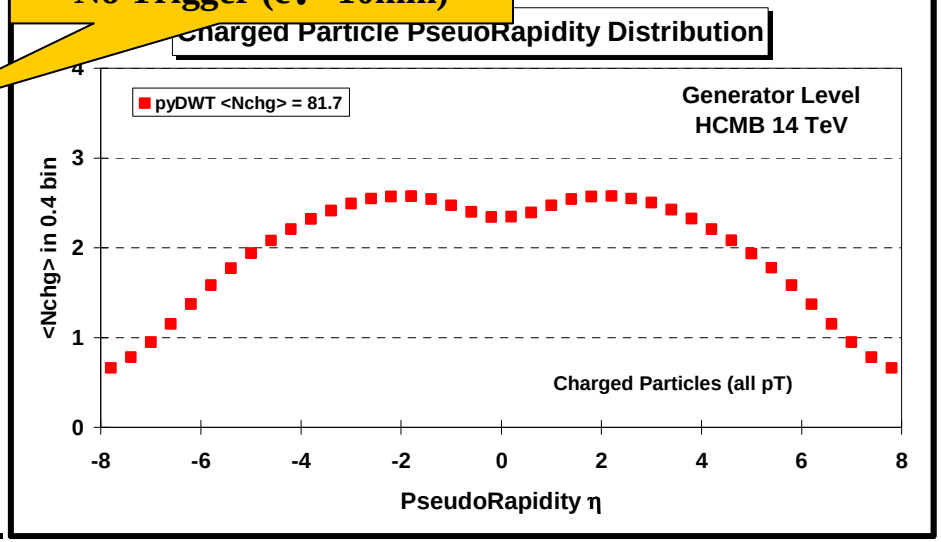
- **Shows the charged multiplicity distribution ($|\eta| < 2$, all p_T) for Npile = 1 (*i.e.* shows, on the average, what one event looks like). The plot shows the probability of finding 0, 1, 2, … etc. charged particles. The sum of the points is equal to one. The mean is 24.39 charged particles and $\sigma = 19.7$.**

- **Shows the charged particle pseudo-rapidity distribution (all p_T) for Npile = 1 (*i.e.* shows, on the average, what one event looks like). The plot shows the <Nchg> in a 0.4 bin (*i.e.* not divided by bin size). The sum of the points with $|\eta| < 2$ is 24.39.**

Pile-Up at the LHC

Tune DWT "Hard-Core"
No Trigger (cτ =10mm)





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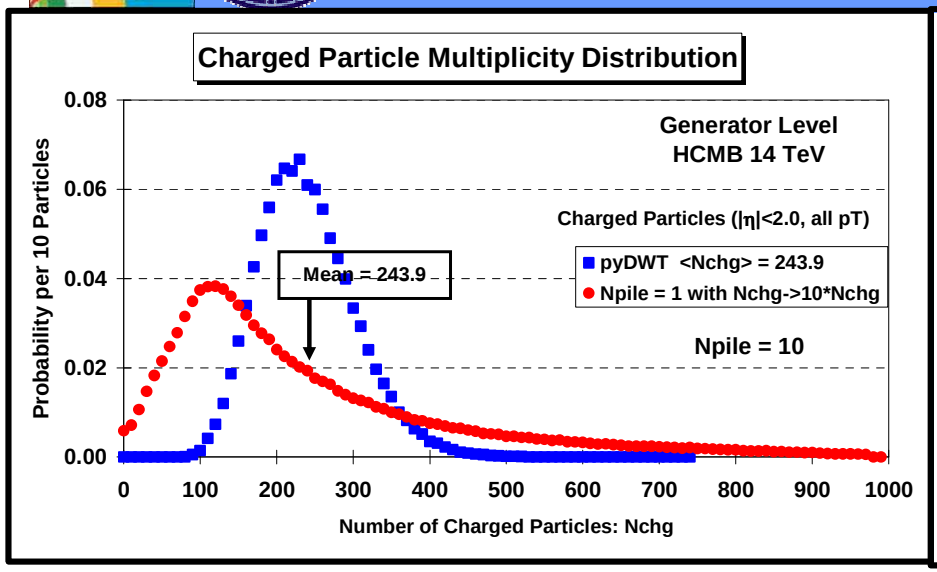
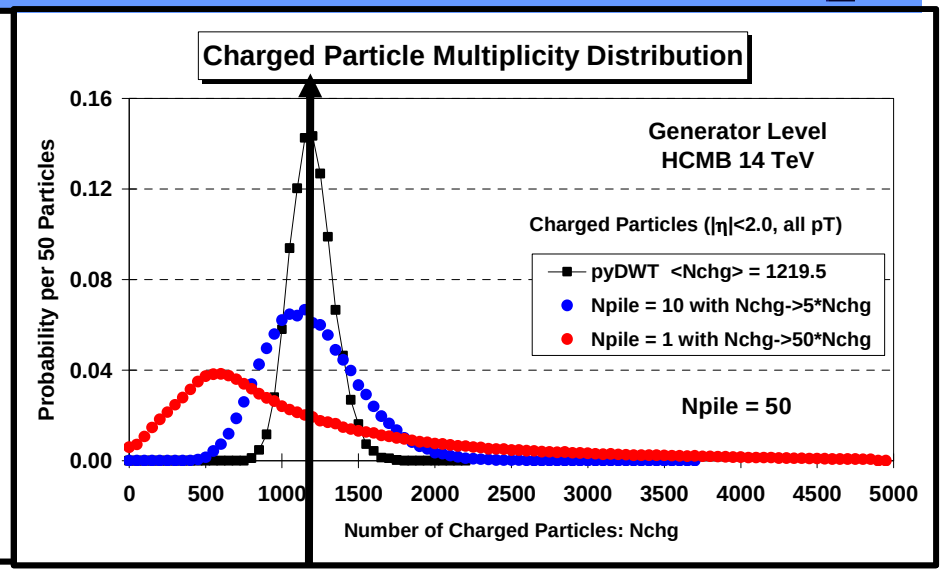
Pile-Up at the LHC

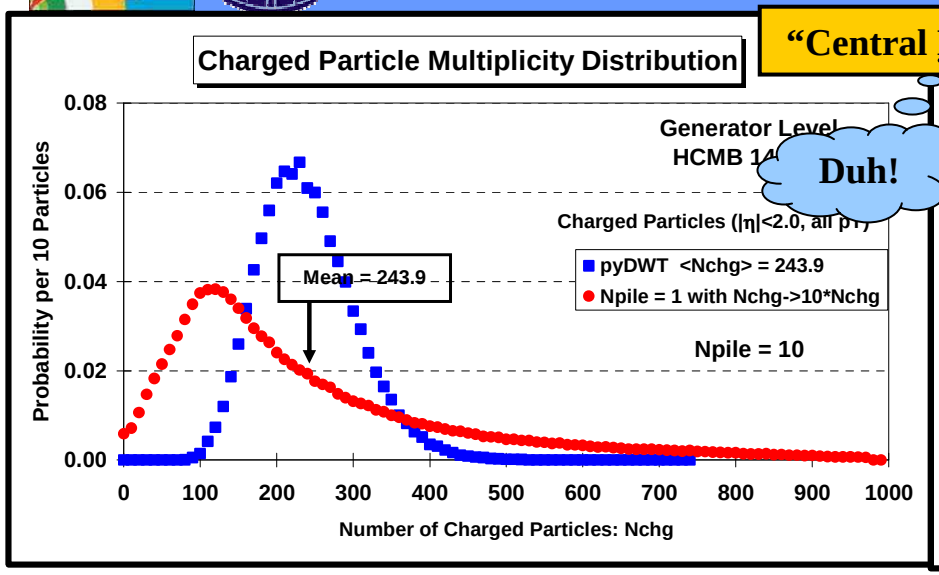


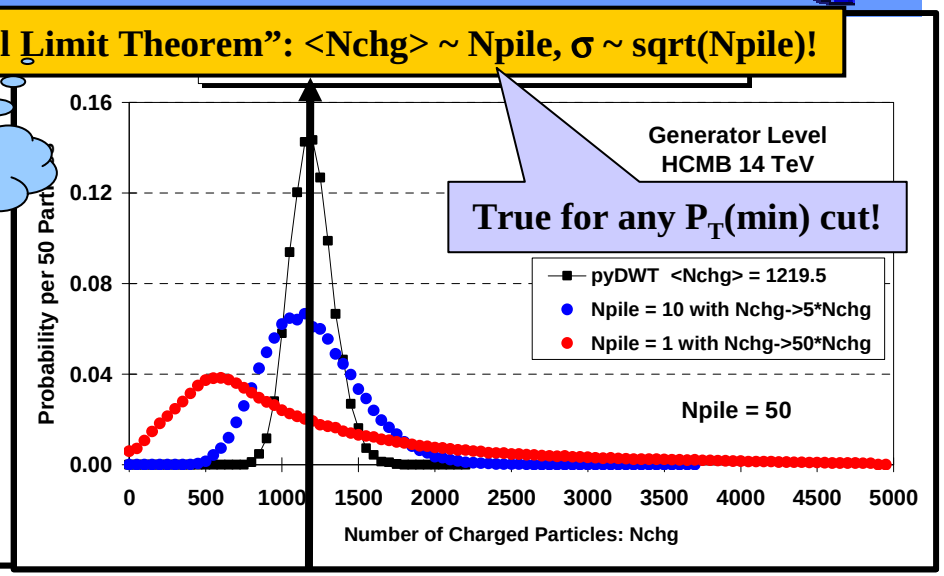


- **Shows the charged multiplicity distribution ($|\eta| < 2$, all p_T) for Npile = 10 (*i.e.* shows, on the average, what 10 events looks like). The plot shows the probability of finding 0, 10, 20, … etc. charged particles. The sum of the points is equal to one. The mean is 243.9 charged particles and $\sigma = 62.3$. Also shown is the Npile = 1 distribution scaled by a factor of 10 (*i.e.* Nchg → 10 × Nchg).**

- **Shows the charged multiplicity distribution ($|\eta| < 2$, all p_T) for Npile = 50 (*i.e.* shows, on the average, what 50 events looks like). The plot shows the probability of finding 0, 50, 100, … etc. charged particles. The sum of the points is equal to one. The mean is 1219.5 charged particles and $\sigma = 138.9$. Also shown is the Npile = 1 distribution scaled by a factor of 50 (*i.e.* Nchg → 50 × Nchg) and the Npile = 10 distribution scaled by a factor of 5 (*i.e.* Nchg → 5 × Nchg).**

Pile-Up at the LHC





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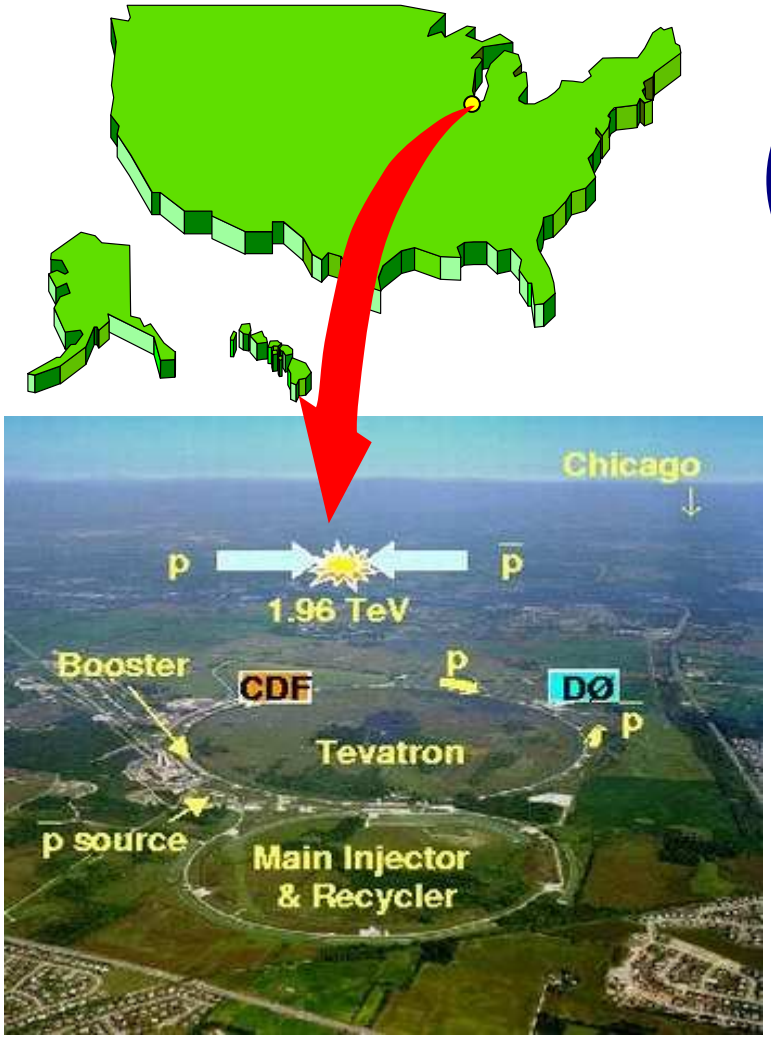
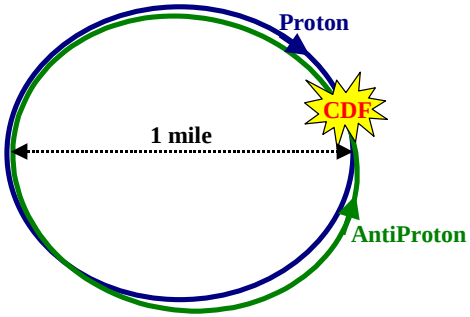
Tevatron Energy Scan



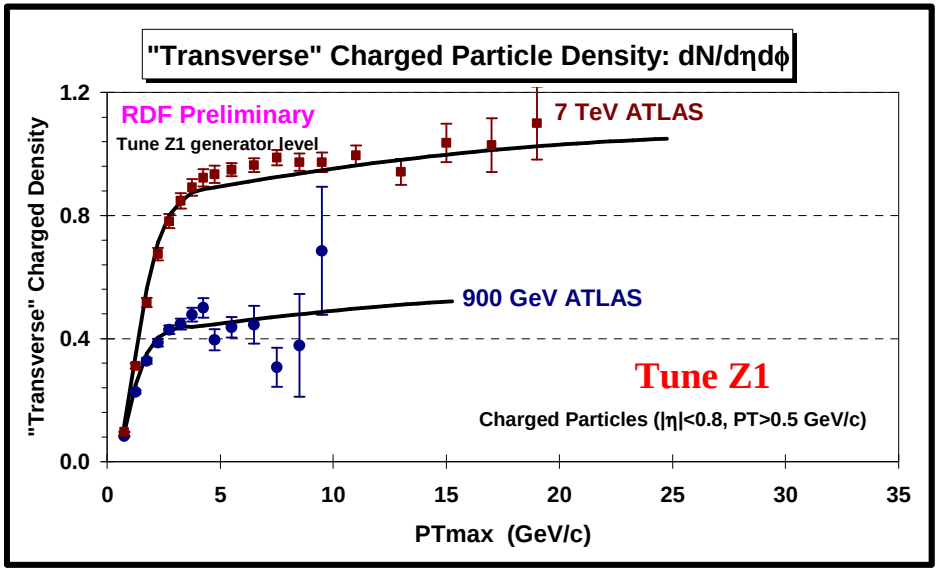


- **Just before the shutdown of the Tevatron CDF has collected more than 10M "min-bias" events at several center-of-mass energies!**

300 GeV 12.1M MB Events

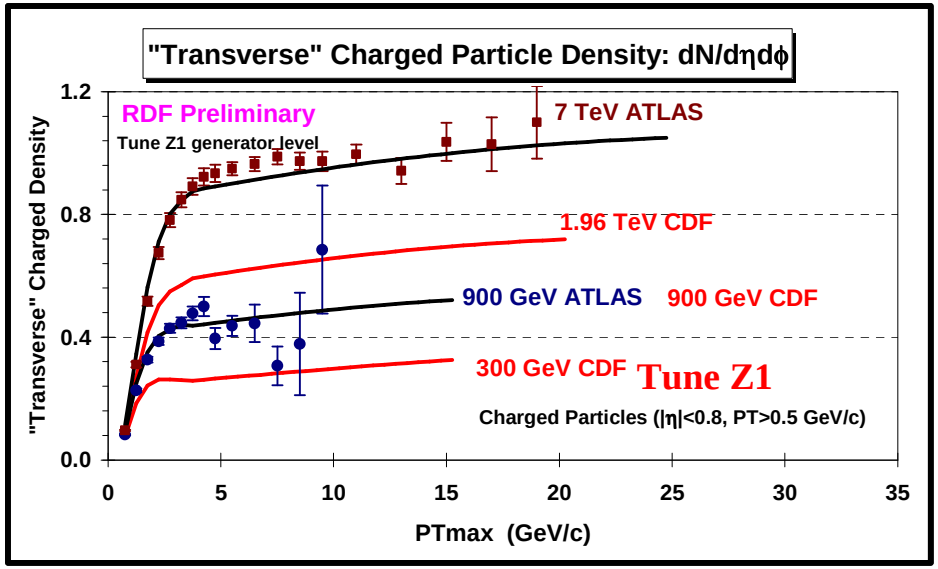
900 GeV 54.3M MB Events

New CDF Energies



- **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 |η| < 0.8. The data are corrected and compared with PYTHIA Tune Z1 at the generator level.**
- **Predictions for CDF 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 |η| < 0.8 from PYTHIA Tune Z1 at the generator level.**

New CDF Energies



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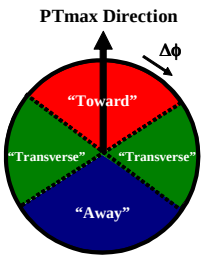
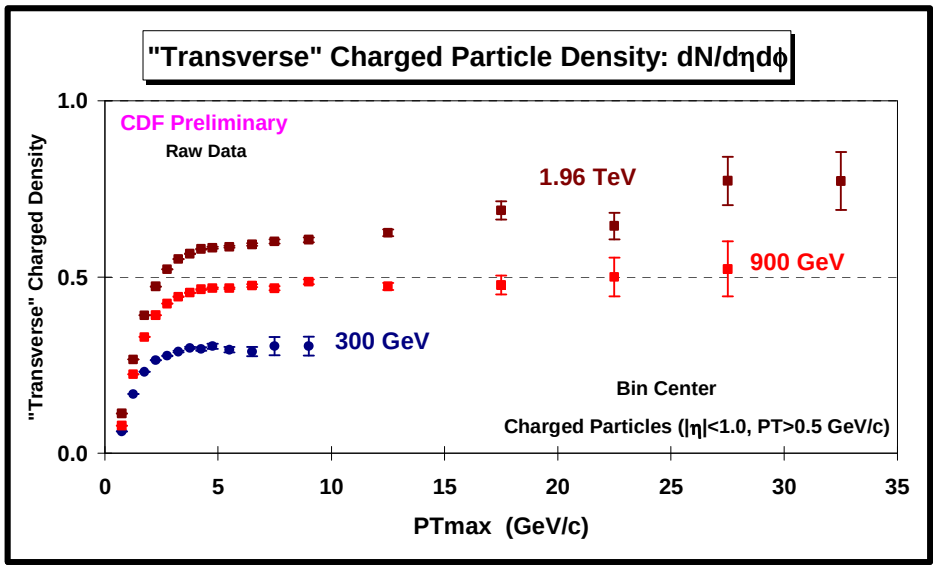
gmbsar

Files = 273 Events = 66,374,130
Size = 803,837,367 KB

Runs	Events	Energy
311581	801,635	300 GeV
311583	579,395	300 GeV
311597	140,241	300 GeV
311604	2,456,067	300 GeV
311610	2,608,939	300 GeV
311620	2,351,053	300 GeV
311629	3,062,960	300 GeV
Total =	12,000,290	300 GeV
311661	91,463	900 GeV
311662	2,243,884	900 GeV
311664	384,775	900 GeV
311665	108,831	900 GeV
311666	3,737,978	900 GeV
311683	2,078,901	900 GeV
311698	1,518,750	900 GeV
311699	1,454,421	900 GeV
311712	302,108	900 GeV
311713	1,541,439	900 GeV
311714	869,983	900 GeV
311730	2,945,609	900 GeV
311825	2,418,224	900 GeV
311833	533,085	900 GeV
311835	5,188,204	900 GeV
311910	11,209,632	900 GeV
311923	732,652	900 GeV
311956	9,163,307	900 GeV
311976	7,538,044	900 GeV
Total =	54,061,290	900 GeV





➡ **Raw CDF data at 300 GeV, 900 GeV, and 1.96 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 |η| < 1.0.**

gmbsar

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Size = 803,837,367 KB

Runs	Events	Energy
311581	801,635	300 GeV
311583	579,395	300 GeV
311597	140,241	300 GeV
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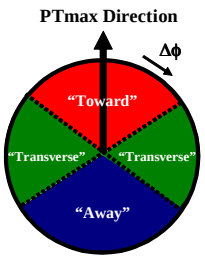
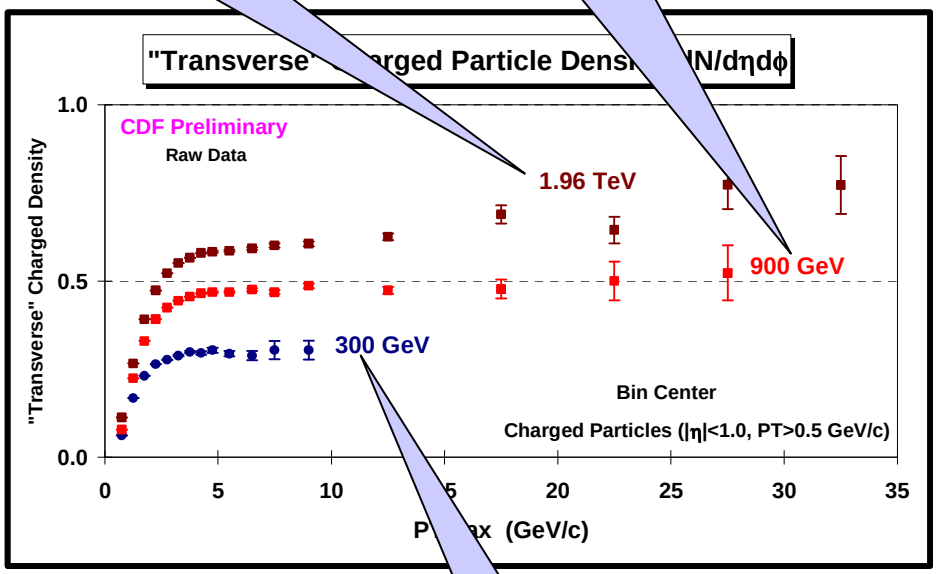
311910	11,209,632	900 GeV
311923	732,652	900 GeV
311956	9,163,307	900 GeV
311976	7,538,044	900 GeV
Total =	54,061,290	900 GeV

1.96 TeV
1 and only 1 Q12 Vertex
P0-5 19,420,876 Events

900 GeV
0 or 1 Q12 Vertex
38,306,169 Events





➡ **Raw CDF data at 300 GeV, 900 Ge nd 1.96 TeV on the "transverse" charged particle densit N/dηdϕ, as defined by the leading charged particle (PTma or charged particles with p_T > 0.5 GeV/c and |η**

300 GeV
0 or 1 Q12 Vertex
7,484,514 Events

How Universal are the Tunes?

- Do we need a separate tune for each center-of-mass energy? 900 GeV, 1.96 TeV, 7 TeV, etc.

PYTHIA Tune DW did a nice (although not perfect) job predicting the LHC Jet Production and Drell-Yan UE data. I am still hoping for a single tune that will describe all energies! Tune Z1 also very good!

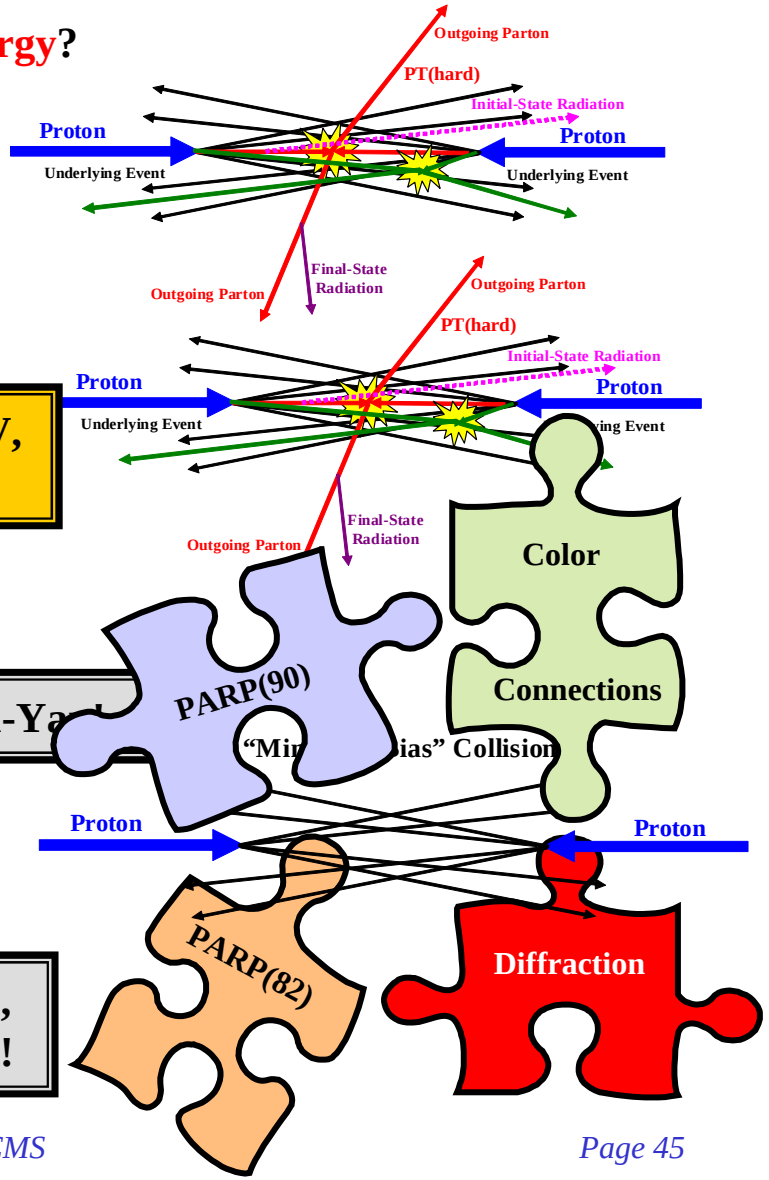
Soon we will have UE data at 300 GeV, 900 GeV, 1.96 TeV, 7 TeV, & 8 TeV and can map out the energy dependence!

- Do we need a separate tune for each hard QCD subprocess? Jet Production, Drell-Yan Production, etc.

The same tune can describe both Jet Production and Drell-Ya

- Do we need separate tunes for "Min-Bias" (MB) and the "underlying event" (UE) in a hard scattering process?

PHTHIA Tune Z1 does fairly well at both the UE and MB, but you cannot expect such a naïve approach to be perfect!



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  "underlying event" (UE) in a hard sca g process

PHTHIA Tune Z1 does fairly well at bo the UE and MB
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What we are learning should allow for more precise predictions at future LHC energies (10 TeV, 13 TeV)!