Early LHC Data

Findings & Surprises

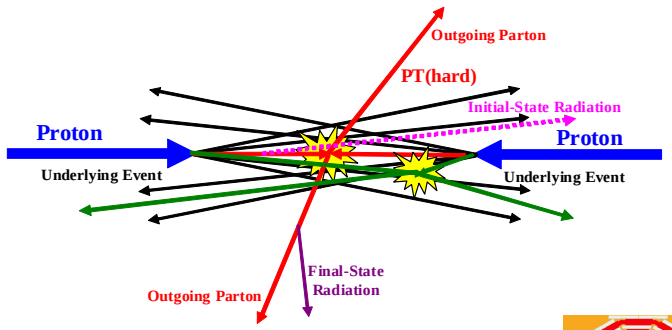
Rick Field
University of Florida

SESAPS 2010

APS physics

Outline of Talk

- How well did we do at predicting the LHC UE data at 900 GeV and 7 TeV? A careful look.
- How well did we do at predicting the LHC MB data at 900 GeV and 7 TeV? A careful look.
- **PYTHIA 6.4 Tune Z1:** New CMS 6.4 tune (pT-ordered parton showers and new MPI).
- **Strange particle production:** A problem for the models?
- **New physics in min-bias??:** Observation of long-range same-side correlations at 7 TeV.

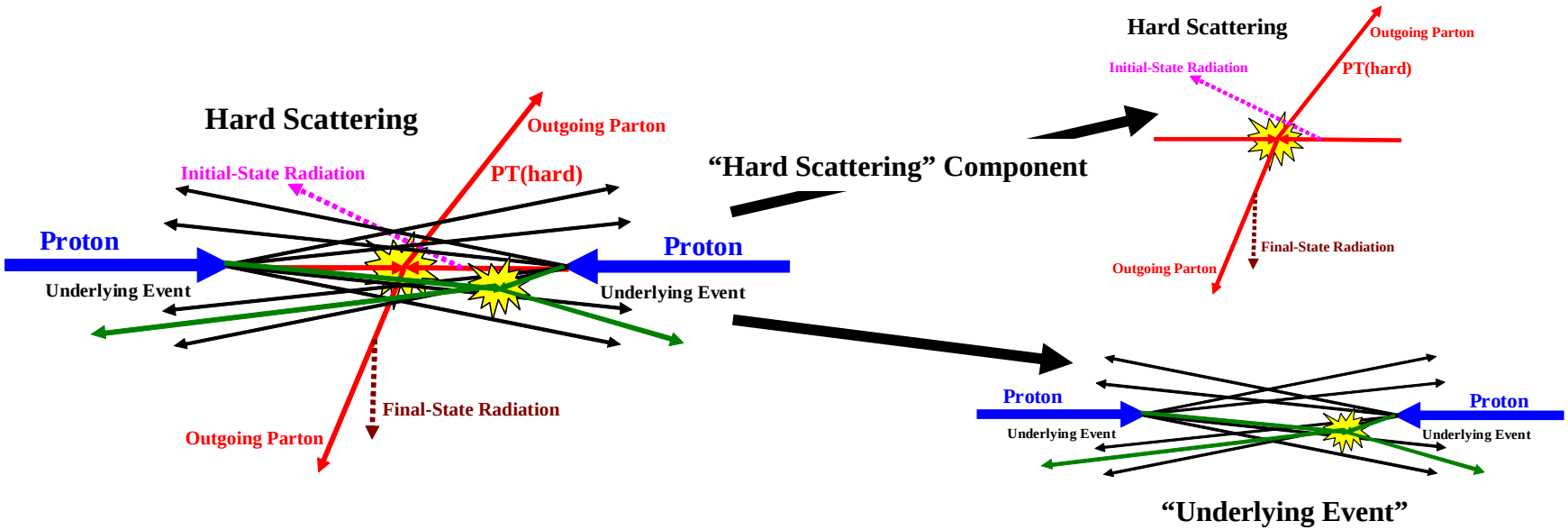


UE&MB@CMS

Quantum Chromo-Dynamics

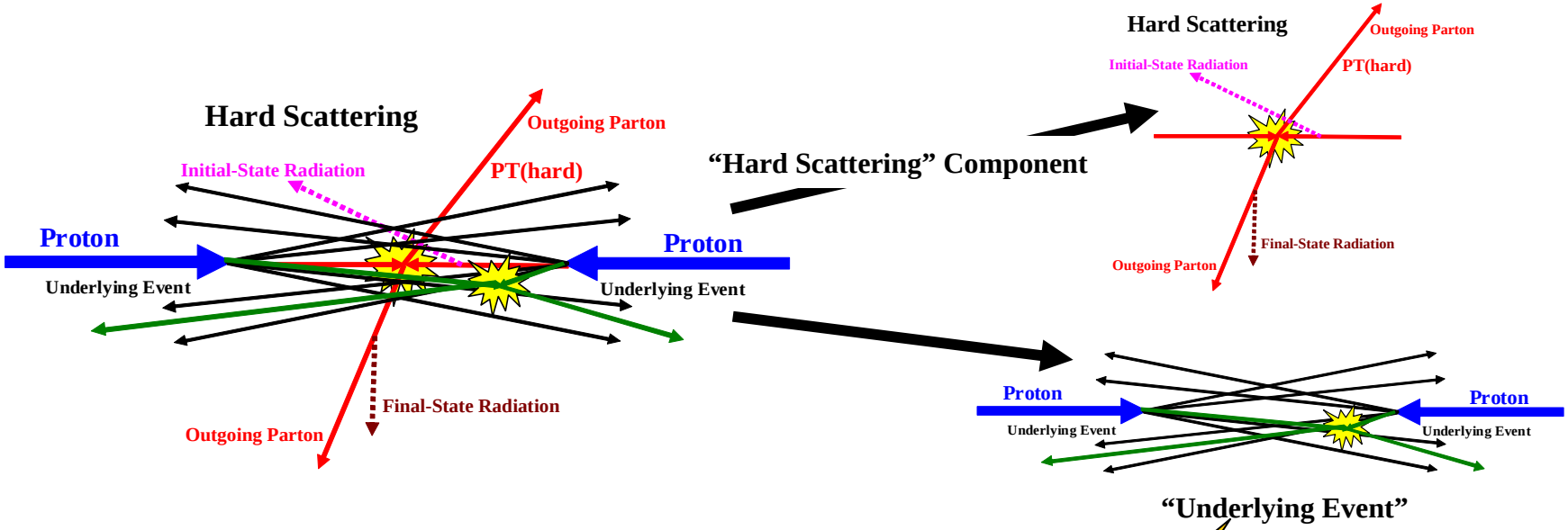
LSU LOUISIANA STATE UNIVERSITY

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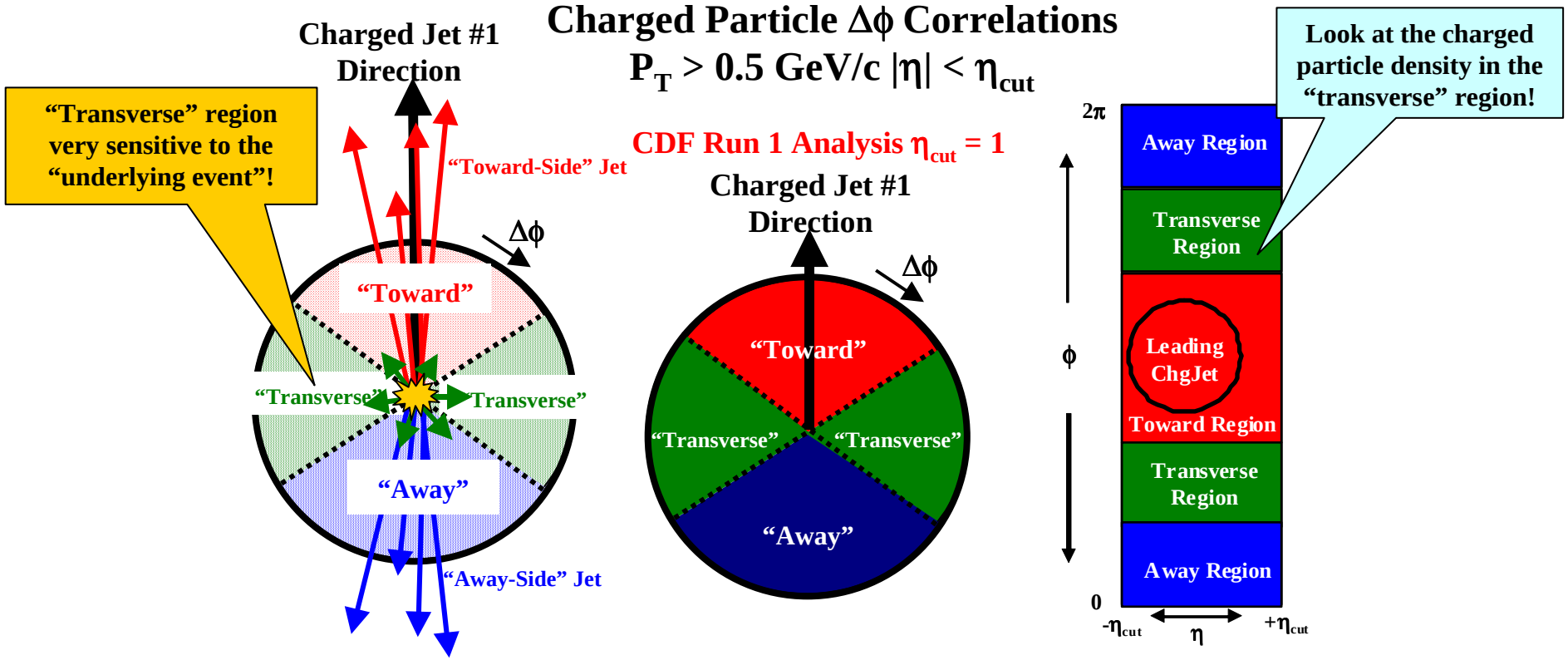
The "underlying event" is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!

The "Transverse" Region



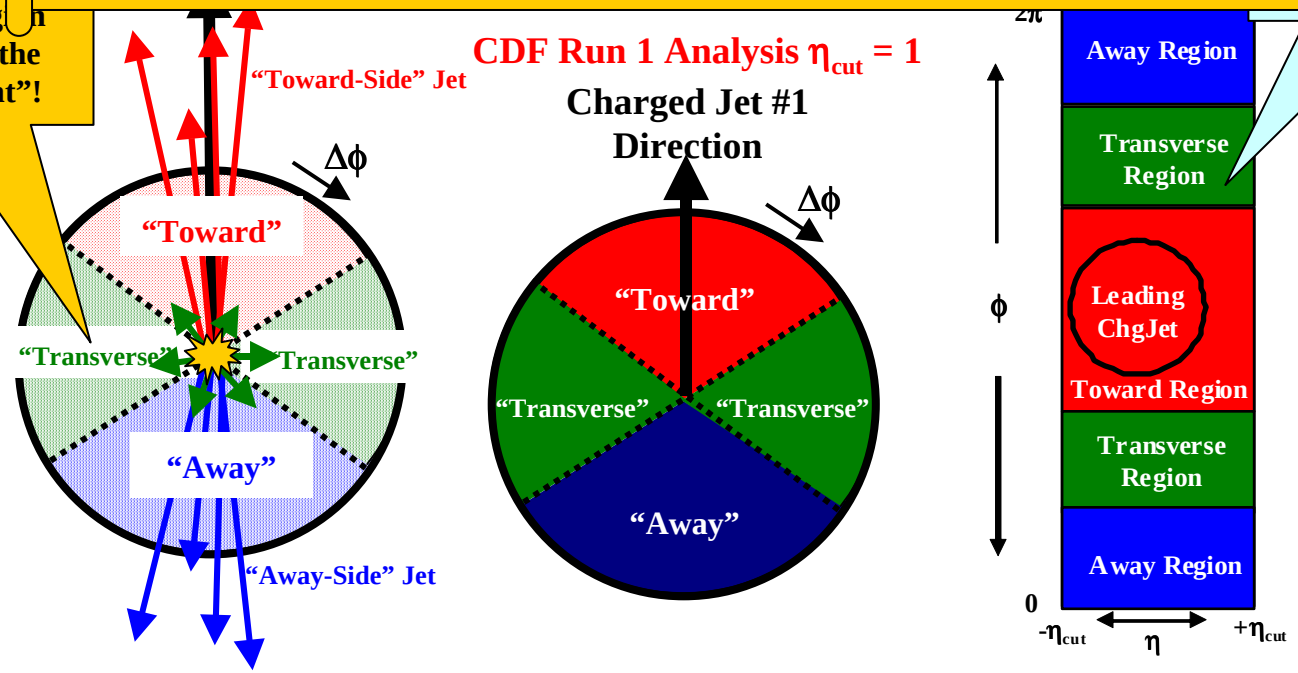
- Look at charged particle correlations in the azimuthal angle Δϕ relative to the leading charged particle jet.
- Define |Δϕ| < 60° as "Toward", 60° < |Δϕ| < 120° as "Transverse", and |Δϕ| > 120° as "Away".
- All three regions have the same area in η-ϕ space, $\Delta\eta \times \Delta\phi = 2\eta_{cut} \times 120^{o} = 2\eta_{cut} \times 2\pi/3$.
- Construct densities by dividing by the area in η-ϕ space.

The "Transverse" Region

Traditional Approach!

"Transverse" region very sensitive to the "underlying event"!

k at the charged cle density in the nsverse" region!



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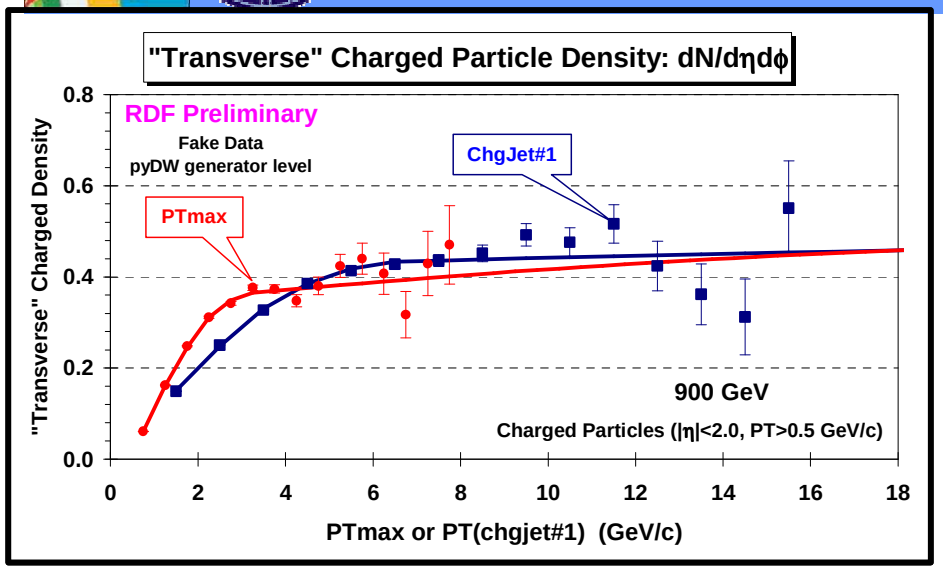
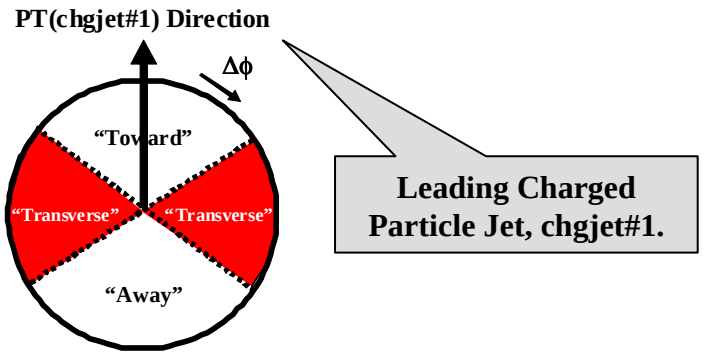
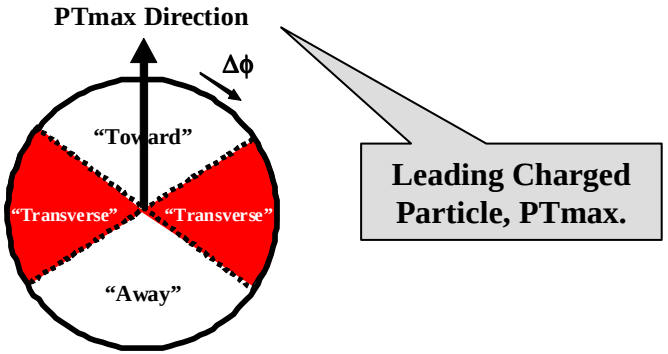
"Transverse" Charged Particle Density



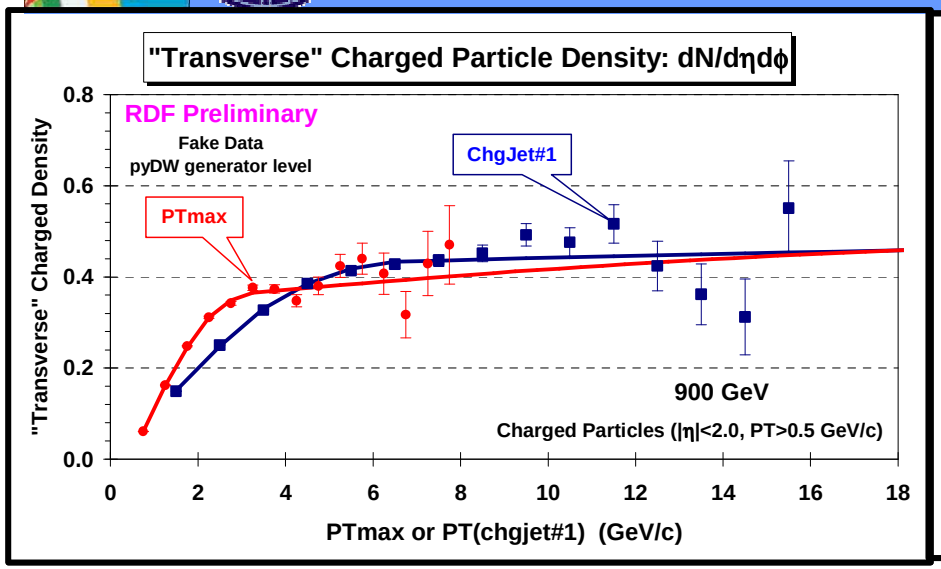


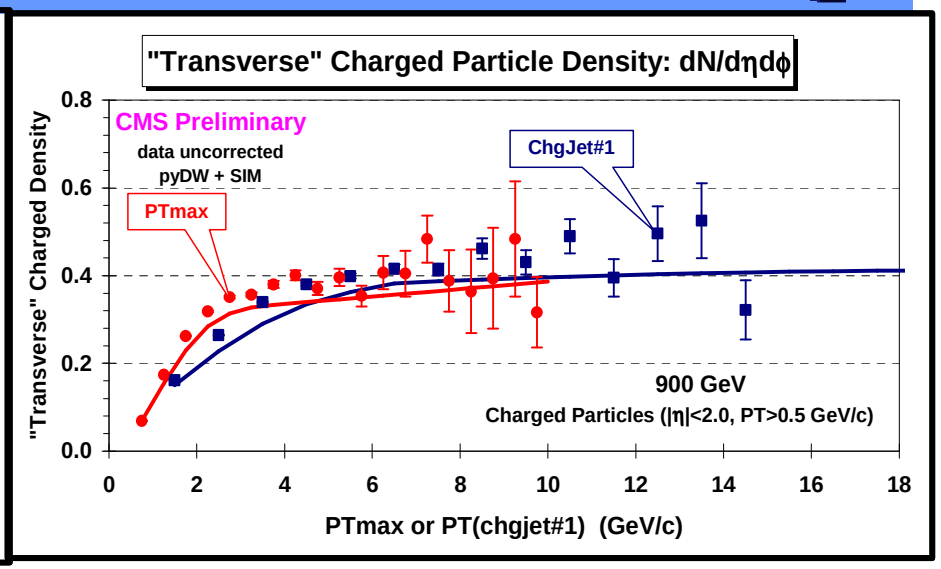


- **Fake data (from MC) at 900 GeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) and the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The fake data (from PYTHIA Tune DW) are generated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





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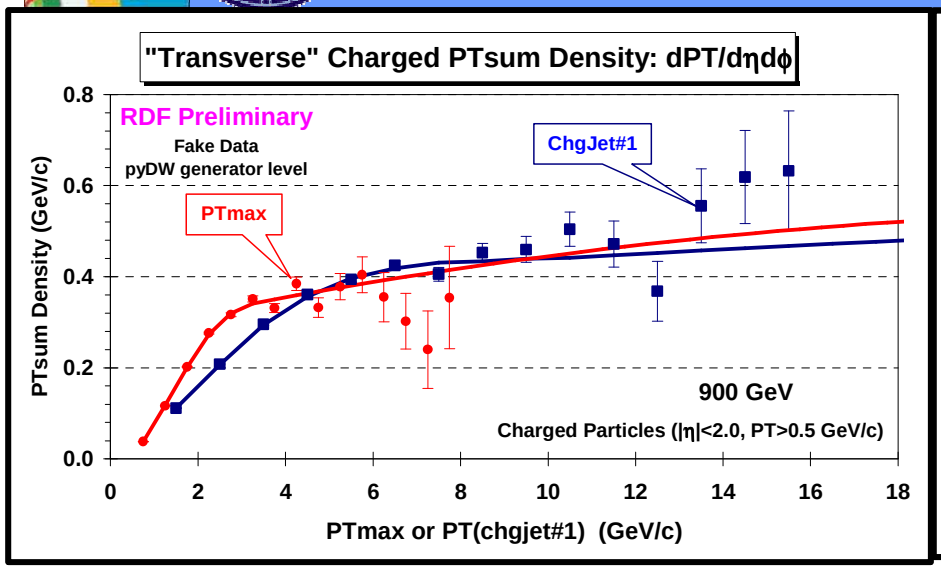
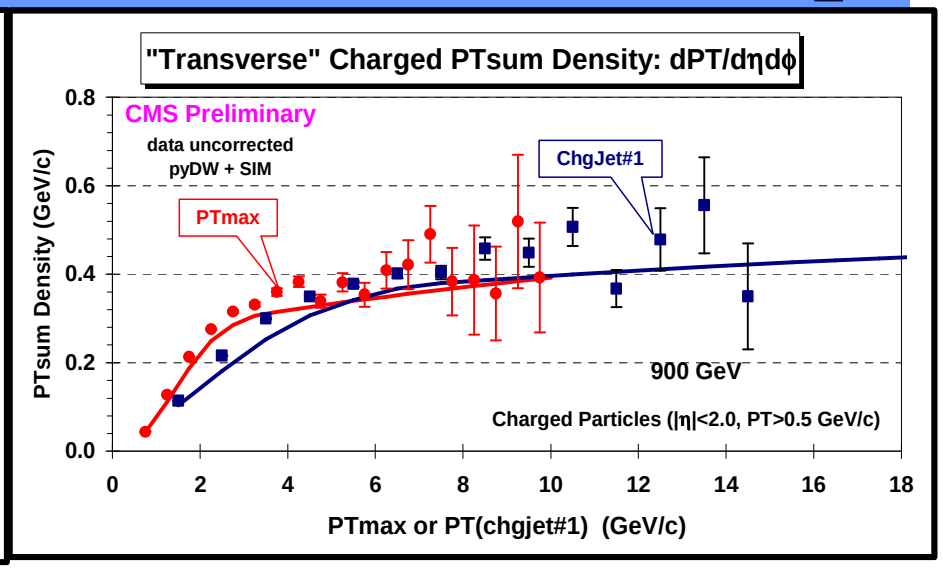
"Transverse" Charged PTsum Density





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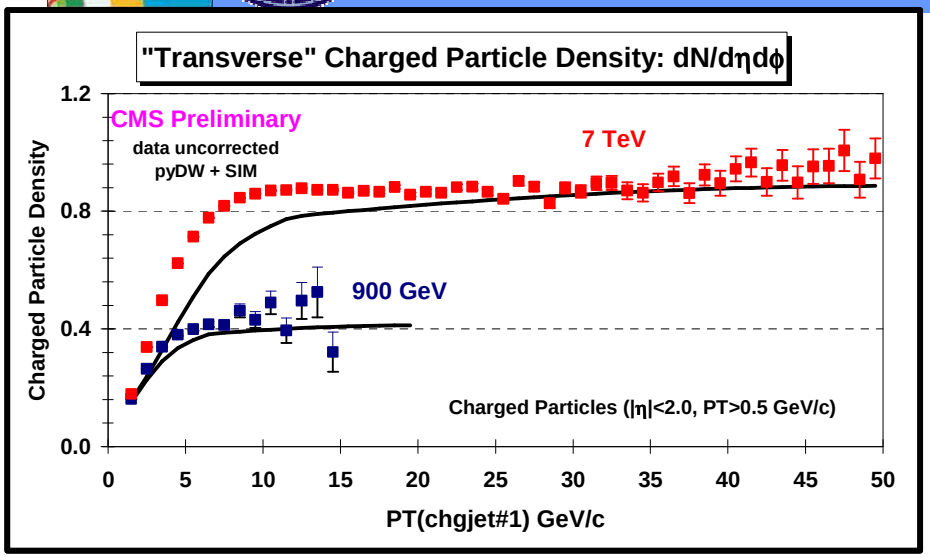
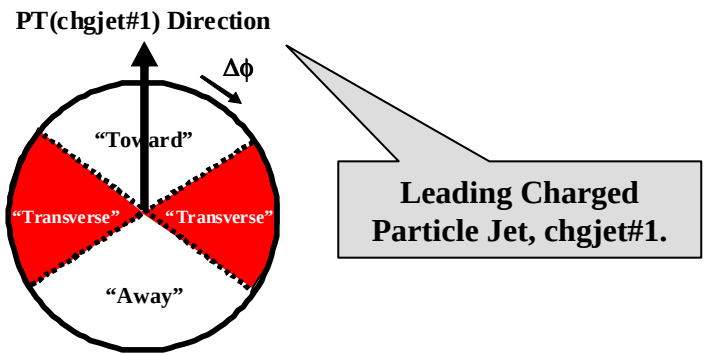
PYTHIA Tune DW





➡ **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 |η| < 2. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation.**

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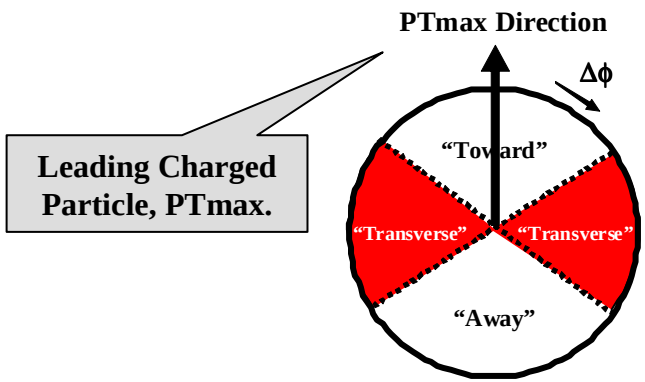

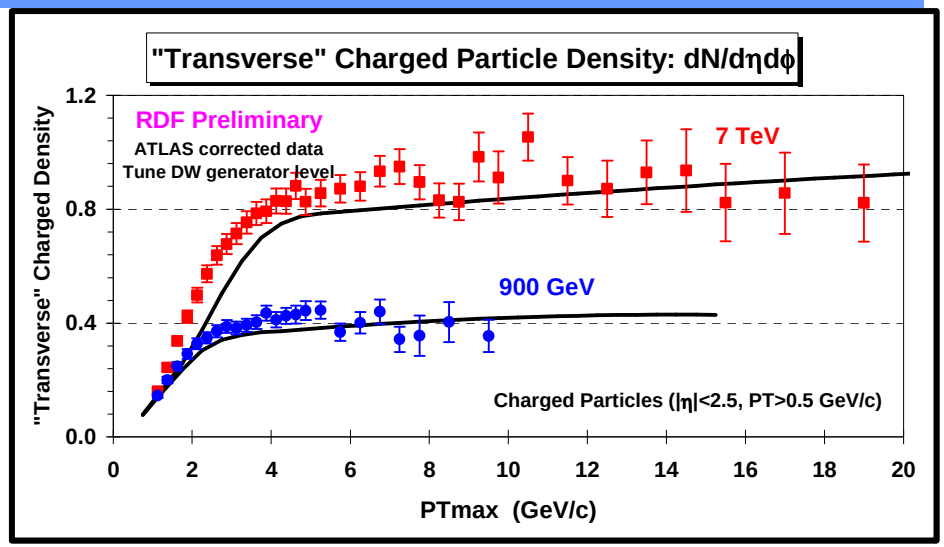

- **ATLAS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 2.5. The data are corrected and compared with PYTHIA Tune DW at the generator level.**

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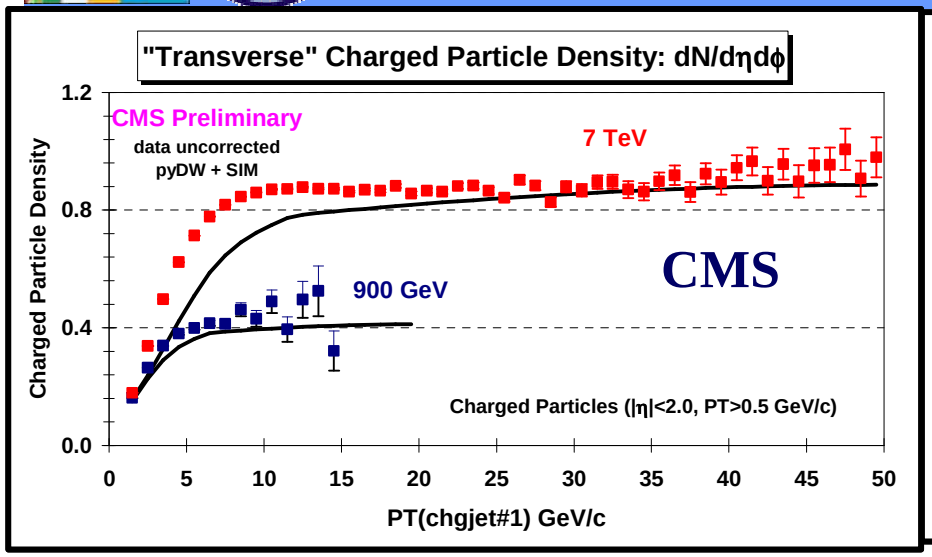

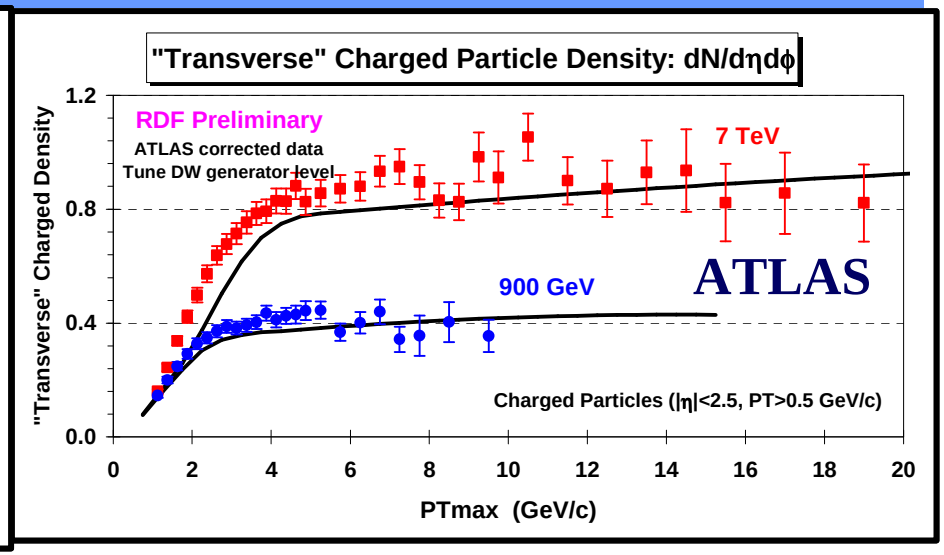

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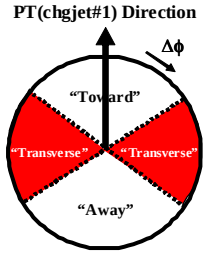

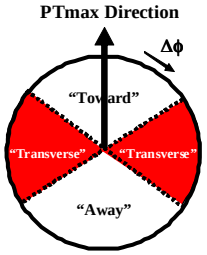

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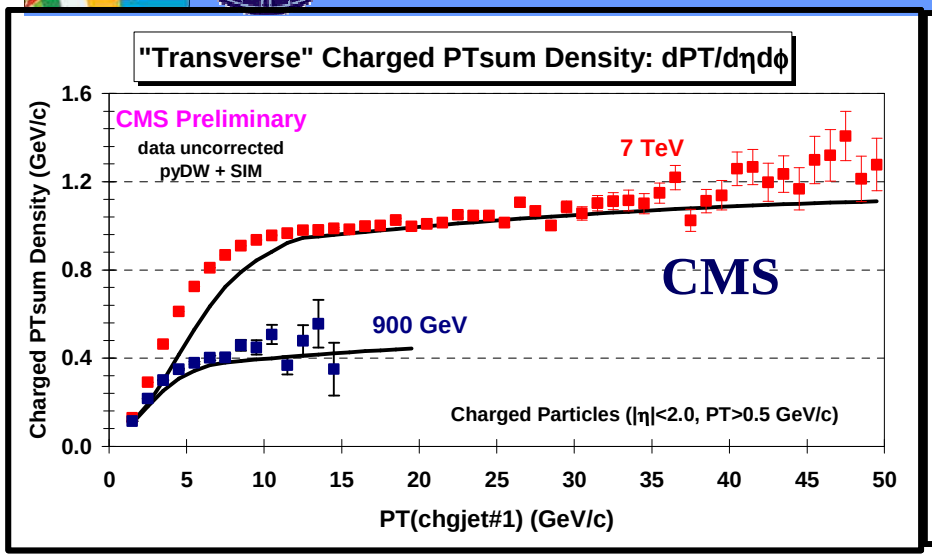

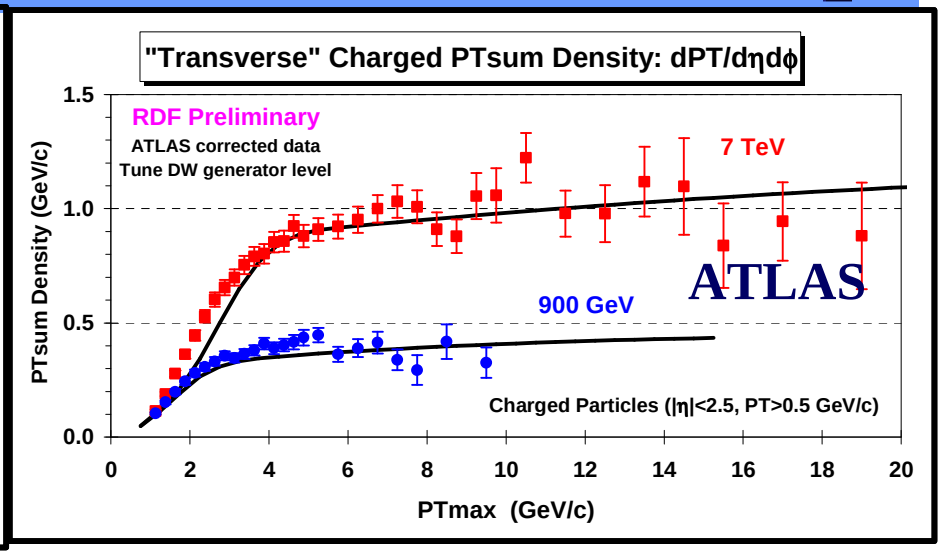

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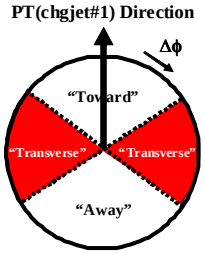

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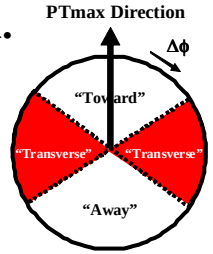
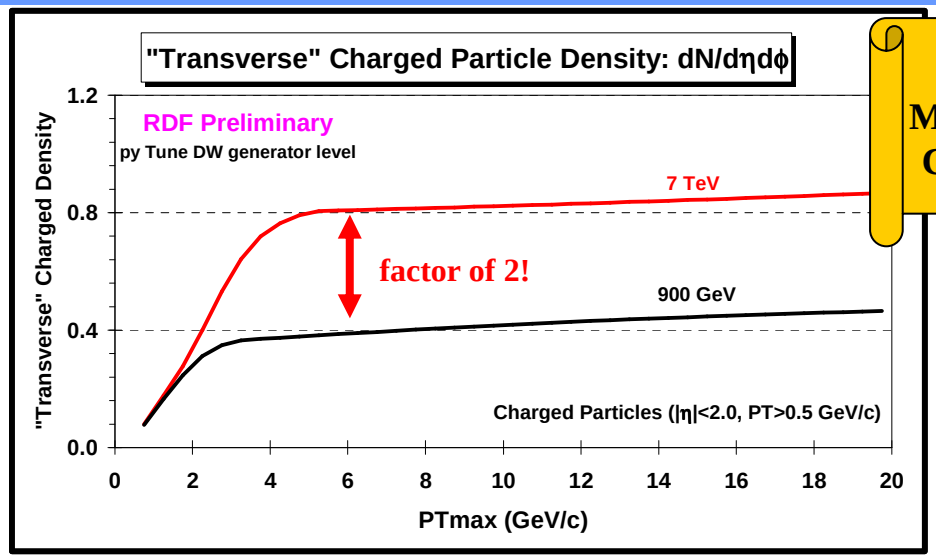


"Transverse" Charge Density



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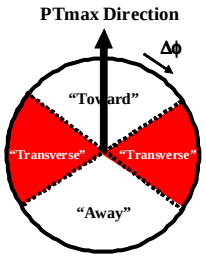
MB&UE@CMS Workshop
CERN, November 6, 2009

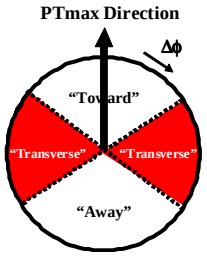
LHC 900 GeV



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

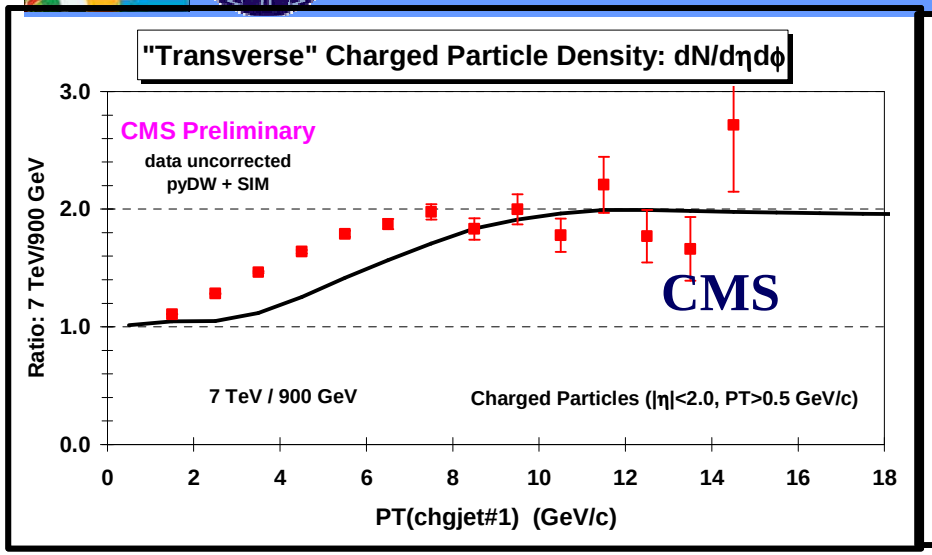
~0.4 → ~0.8

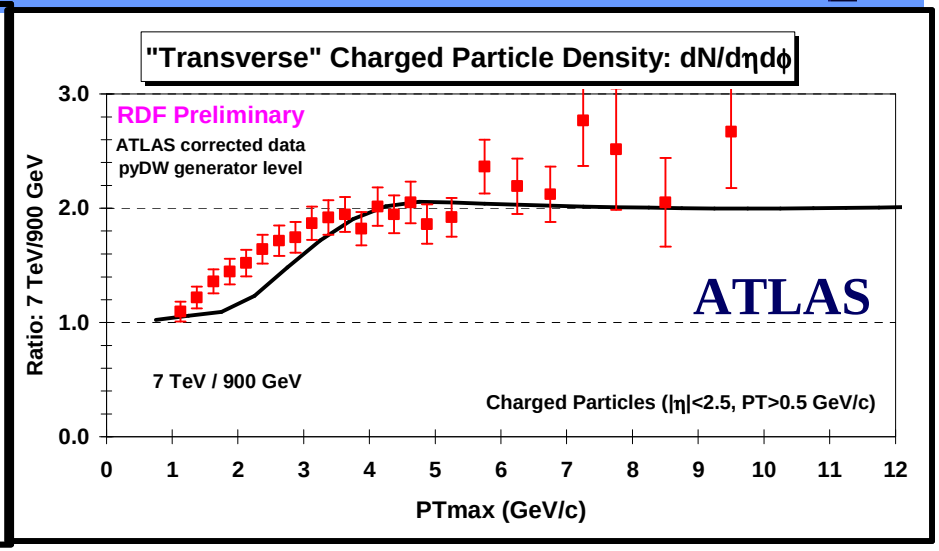
LHC 7 TeV



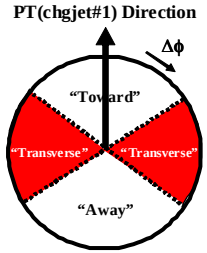
➡ **Shows the charged particle density in the "transverse" region for charged particles (p_T > 0.5 GeV/c, |η| < 2) at 900 GeV and 7 TeV as defined by PTmax from PYTHIA Tune DW and at the particle level (*i.e.* generator level).**

PYTHIA Tune DW

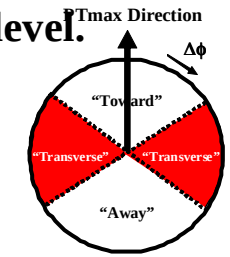




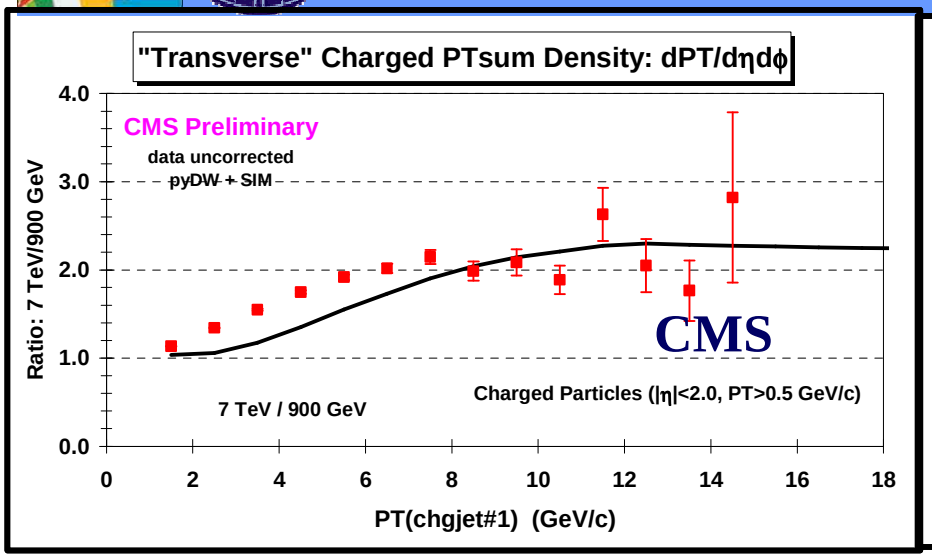
- **Ratio of CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2$. The data are uncorrected and compared with PYTHIA Tune DW after detector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

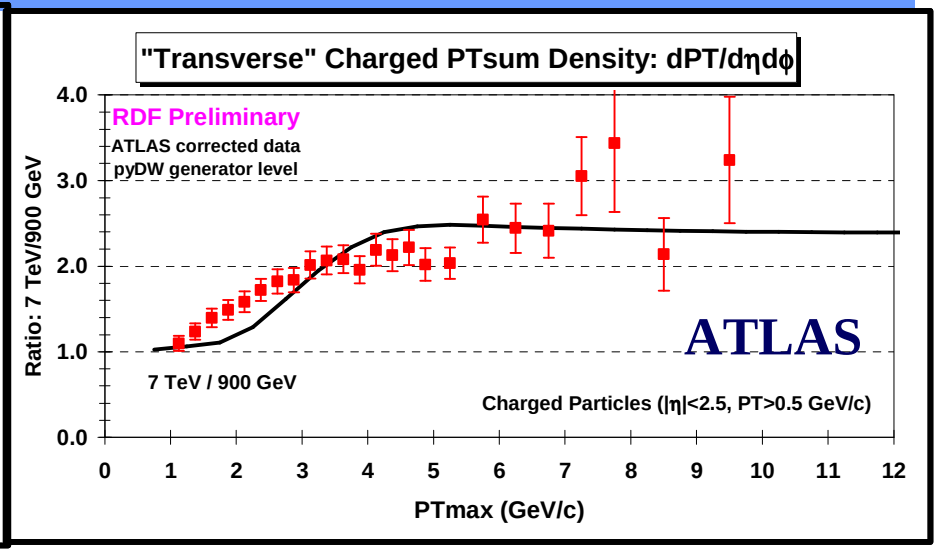


- **Ratio of the ATLAS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune DW at the generator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



PYTHIA Tune DW





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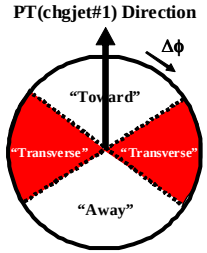

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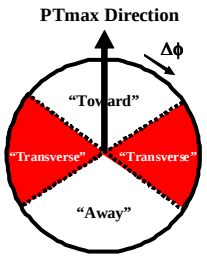
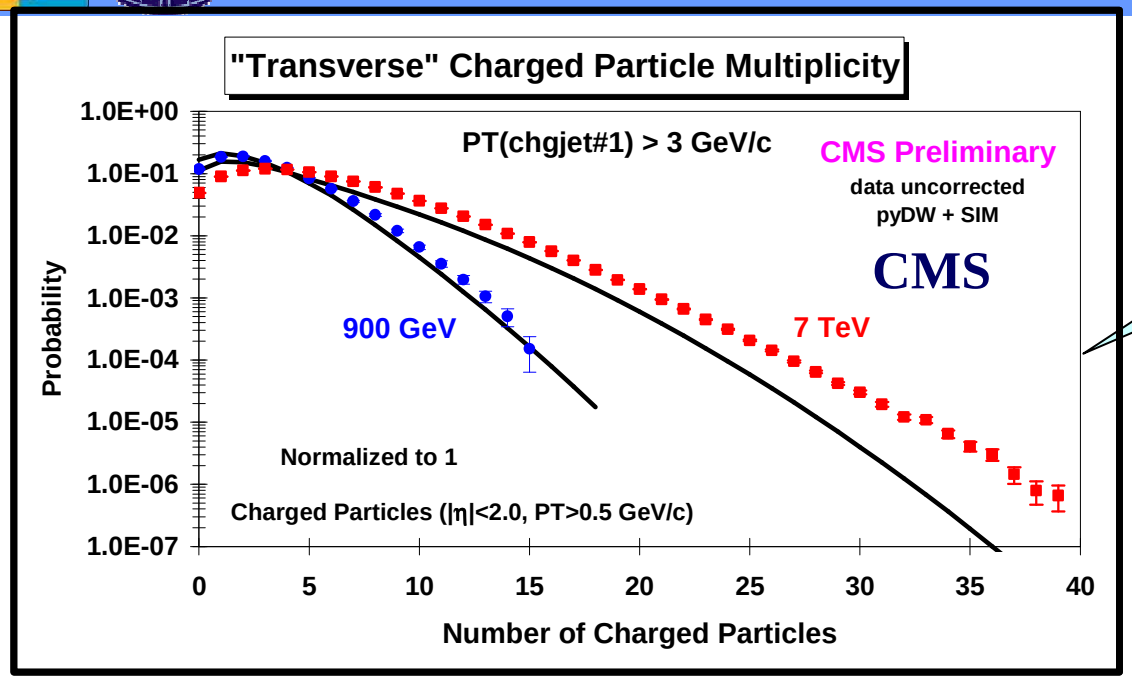
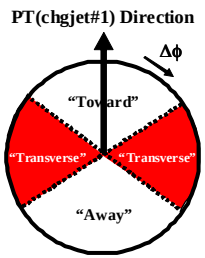


"Transverse" Multiplicity Distribution



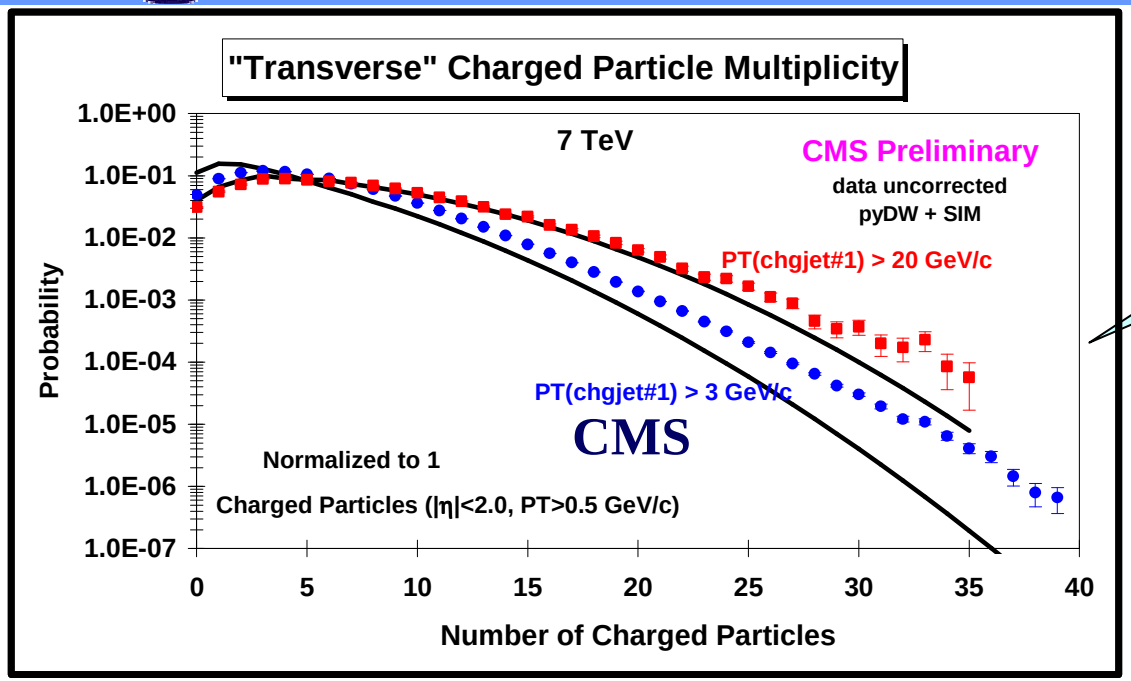
Same hard scale at two different center-of-mass energies!



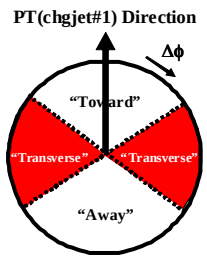
- **CMS uncorrected data at 900 GeV and 7 TeV on the charged particle multiplicity distribution in the "transverse" region for charged particles (p_T > 0.5 GeV/c, |η| < 2) as defined by the leading charged particle jet, chgjet#1, with PT(chgjet#1) > 3 GeV/c compared with PYTHIA Tune DW at the detector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

Shows the growth of the "underlying event" as the center-of-mass energy increases.

"Transverse" Multiplicity Distribution



Same center-of-mass energy at two different hard scales!

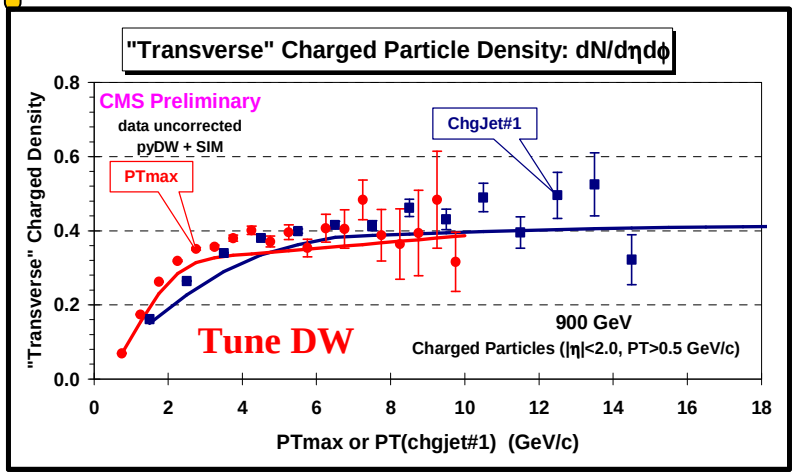


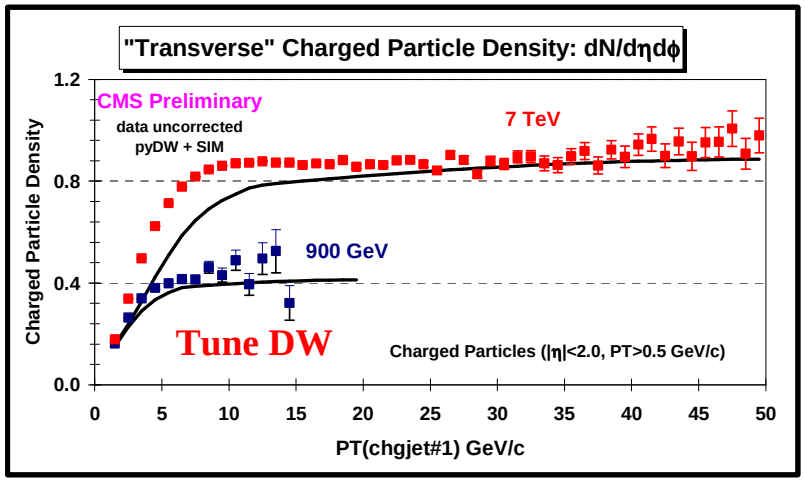
- **CMS uncorrected data at 7 TeV on the charged particle multiplicity distribution in the "transverse" region for charged particles (p_T > 0.5 GeV/c, |η| < 2) as defined by the leading charged particle jet, chgjet#1, with PT(chgjet#1) > 3 GeV/c and PT(chgjet#1) > 20 GeV/c compared with PYTHIA Tune DW at the detector level (*i.e.* Theory + SIM).**

Shows the growth of the "underlying event" as the hard scale increases.

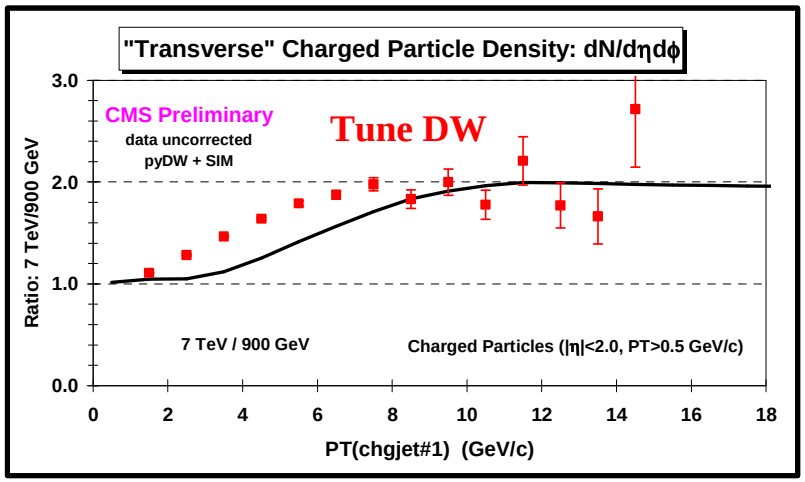
PYTHIA Tune DW

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



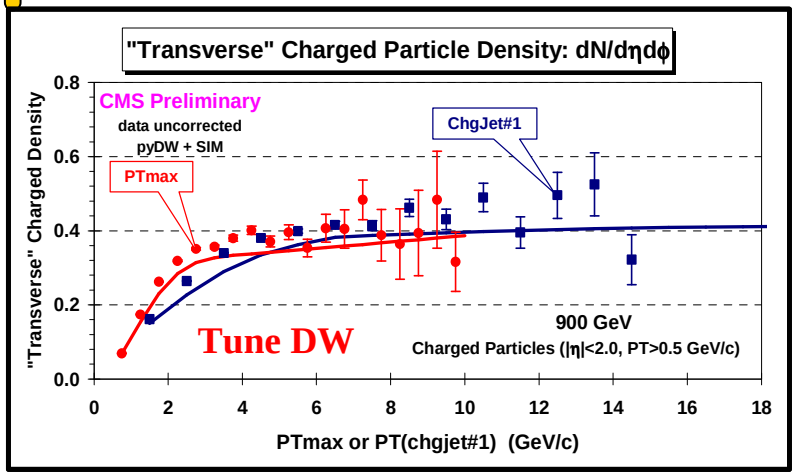


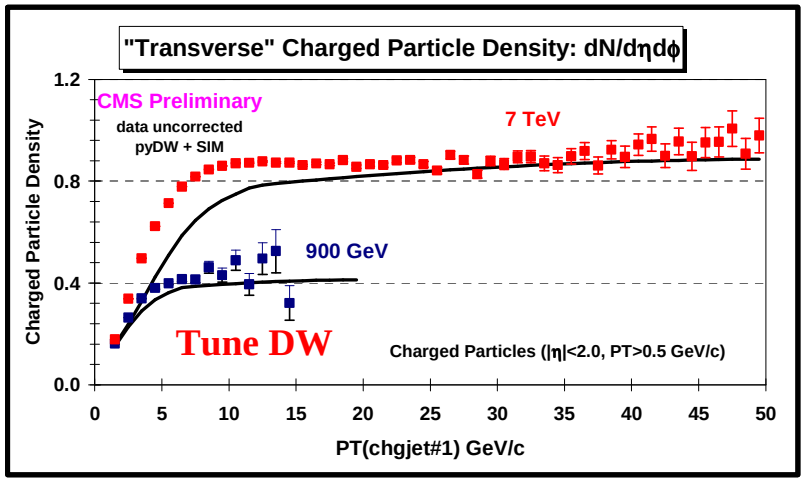
➡ **I am surprised that the Tunes did not do a better job of predicting the behavior of the "underlying event" at 900 GeV and 7 TeV!**



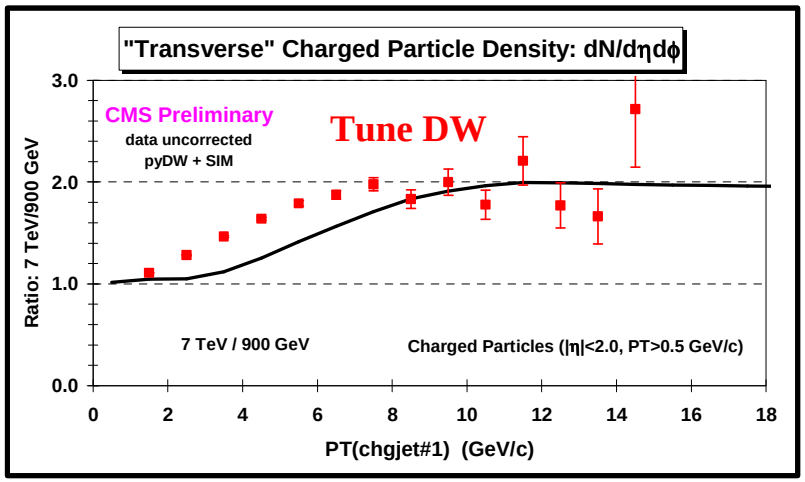
PYTHIA Tune DW

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



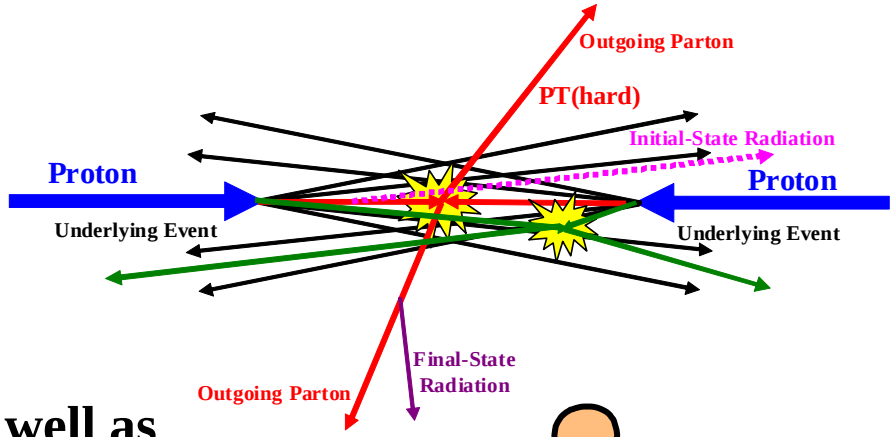


➡ **I am surprised that the Tunes did as well as they did at predicting the behavior of the "underlying event" at 900 GeV and 7 TeV!**

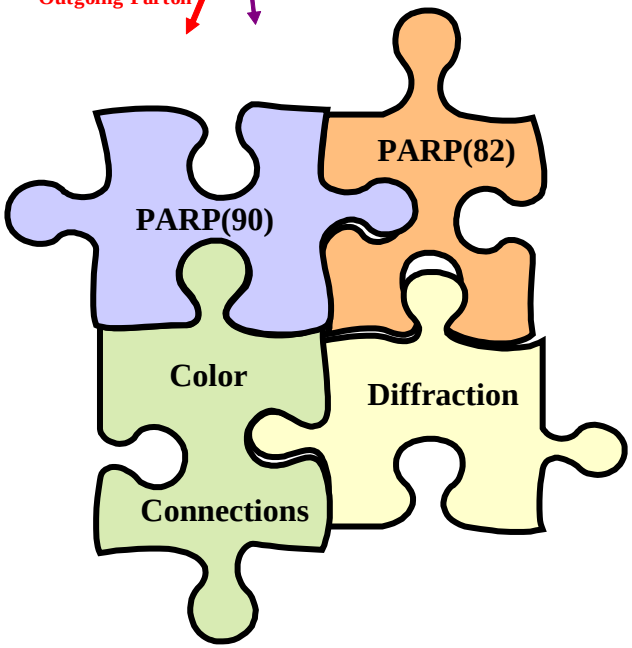


UE Summary

- The "underlying event" at 7 TeV and 900 GeV is almost what we expected! With a little tuning we should be able to describe the data very well (see Tune Z1 later in this talk).



- I am surprised that the Tunes did as well as they did at predicting the behavior of the "underlying event" at 900 GeV and 7 TeV! Remember this is "soft" QCD!

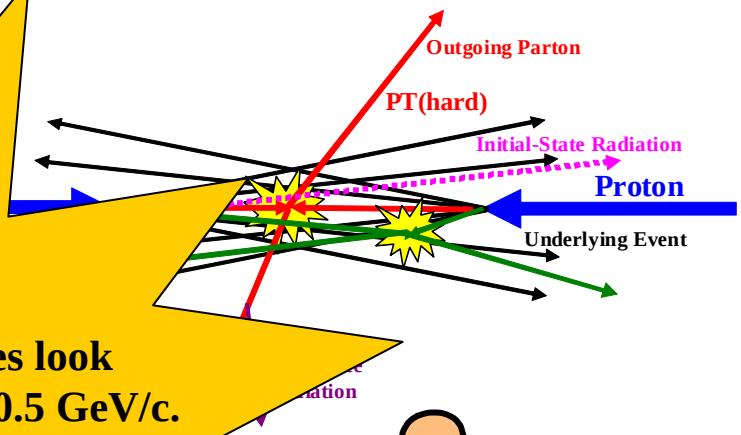


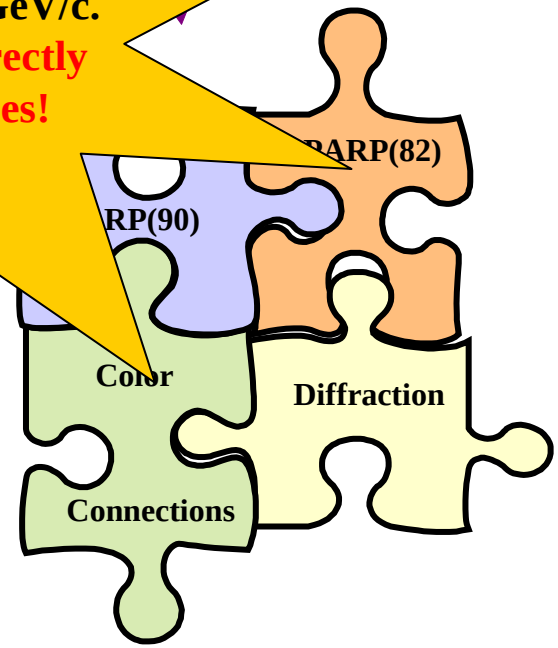
- "Min-Bias" is a whole different story! Much more complicated due to diffraction!

UE Summary

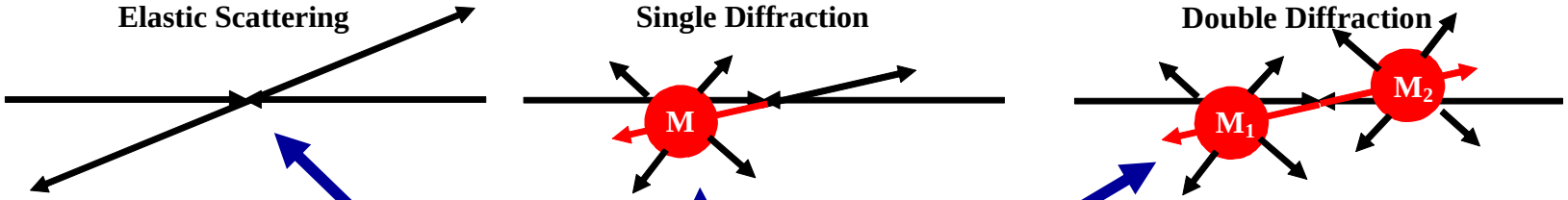
- The "underlying event" at 7 TeV and 900 GeV is almost what we expected! With little tuning we should be able to describe it very well.
- I am surprised how well they did at predicting the "underlying event". Remember this is "soft".
- "Min-Bias" is a whole different story! Much more complicated due to diffraction!

Warning! All the UE studies look at charged particles with $p_T > 0.5$ GeV/c.
We do not know if the models correctly describe the UE at lower p_T values!





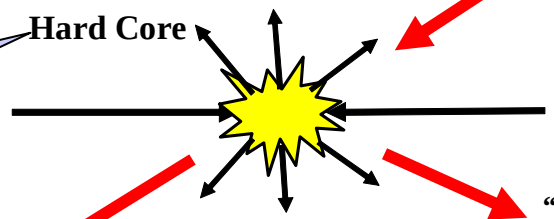
Proton-Proton Collisions

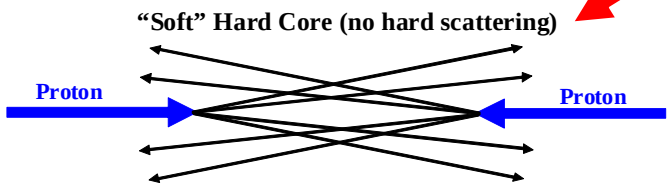


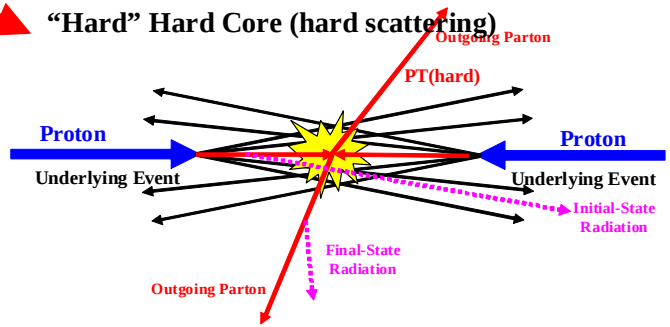
$$\sigma_{tot} = \sigma_{EL} + \sigma_{SD} + \sigma_{DD} + \sigma_{ND}$$

"Inelastic Non-Diffractive Component"

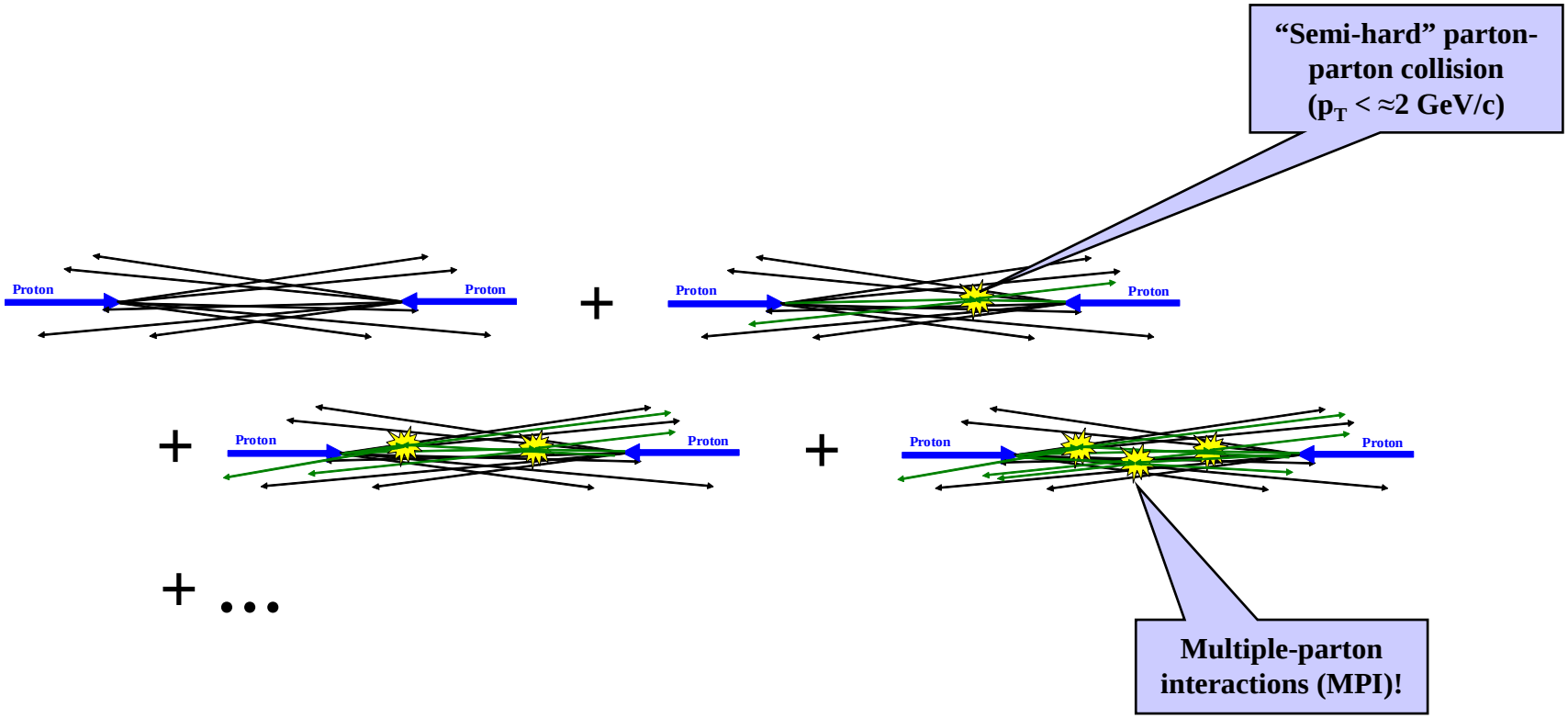
The "hard core" component contains both "hard" and "soft" collisions.



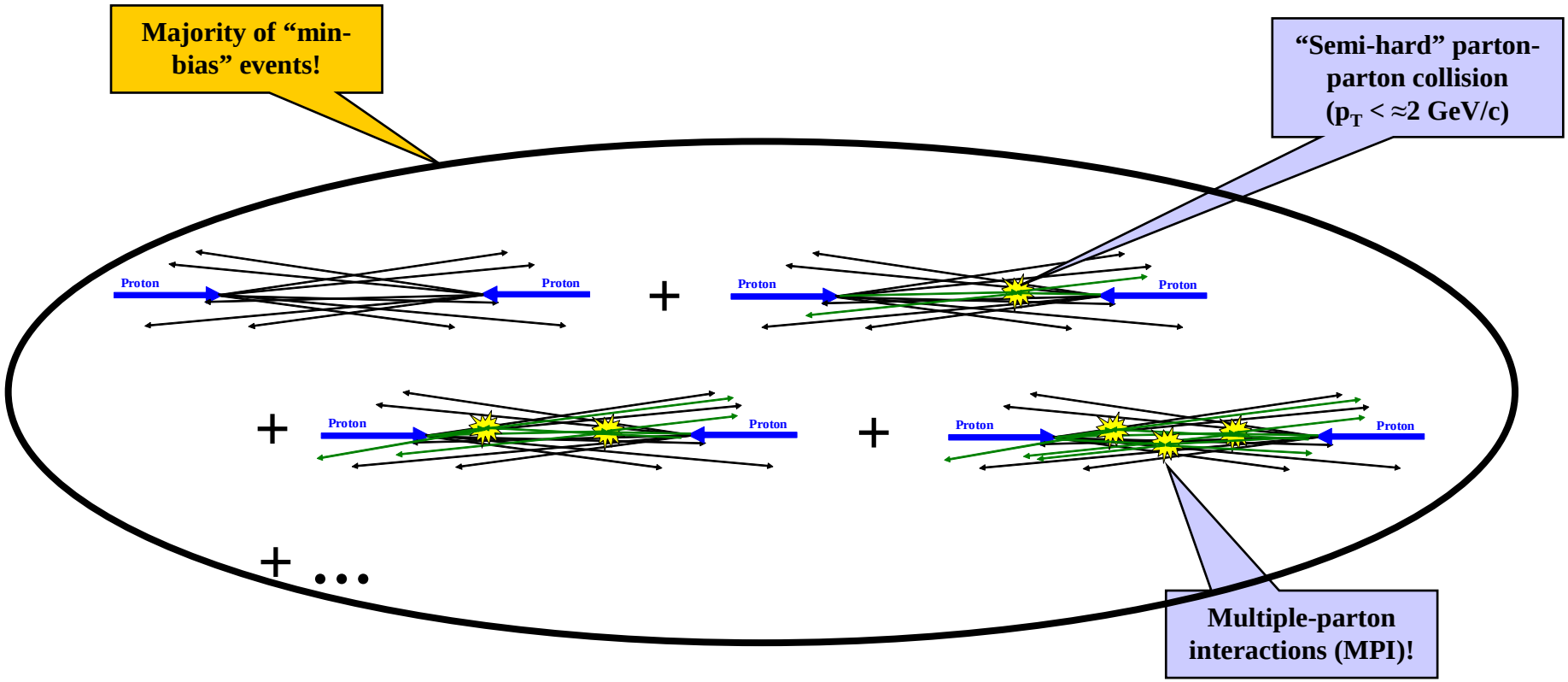




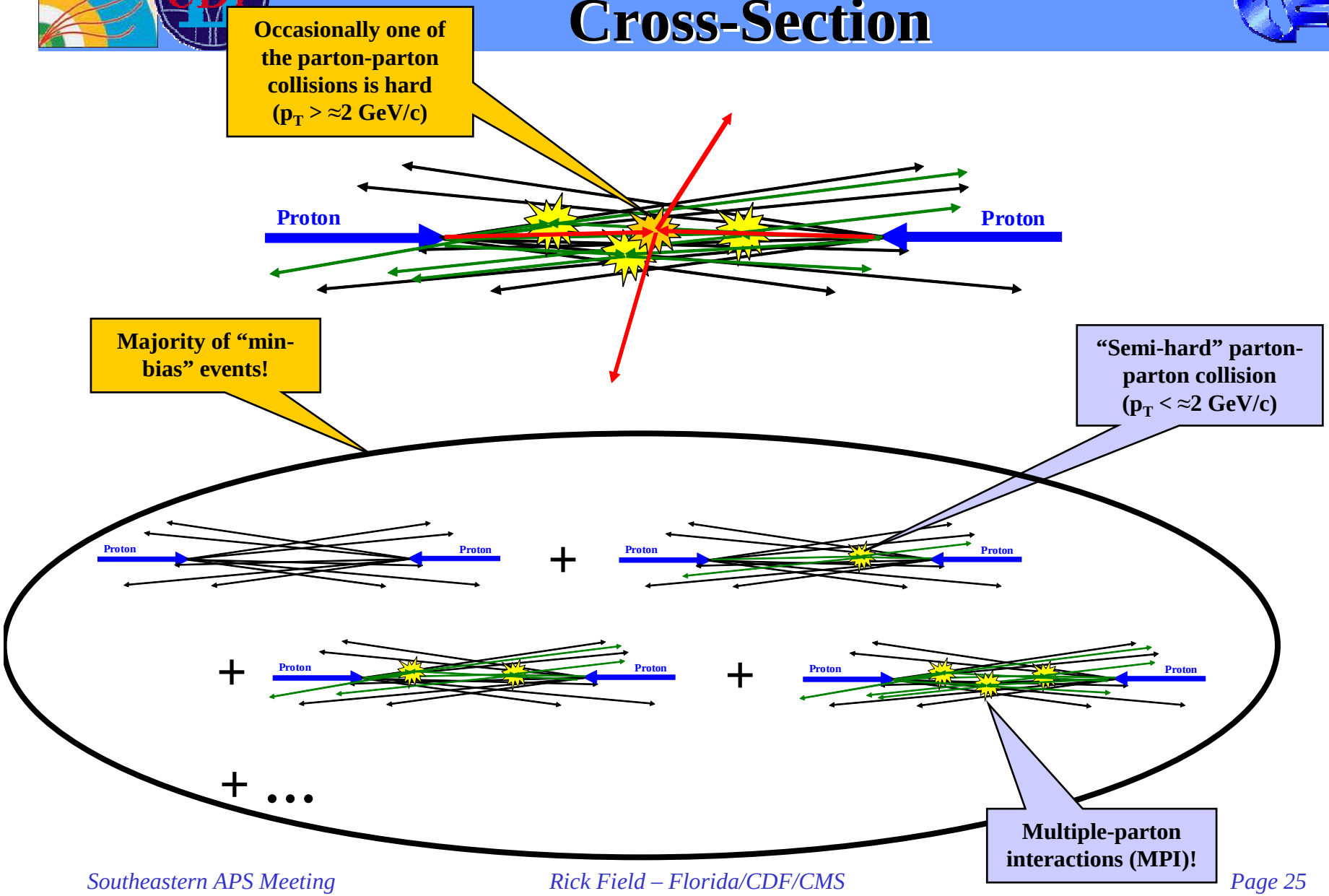
The Inelastic Non-Diffractive Cross-Section



The Inelastic Non-Diffractive Cross-Section

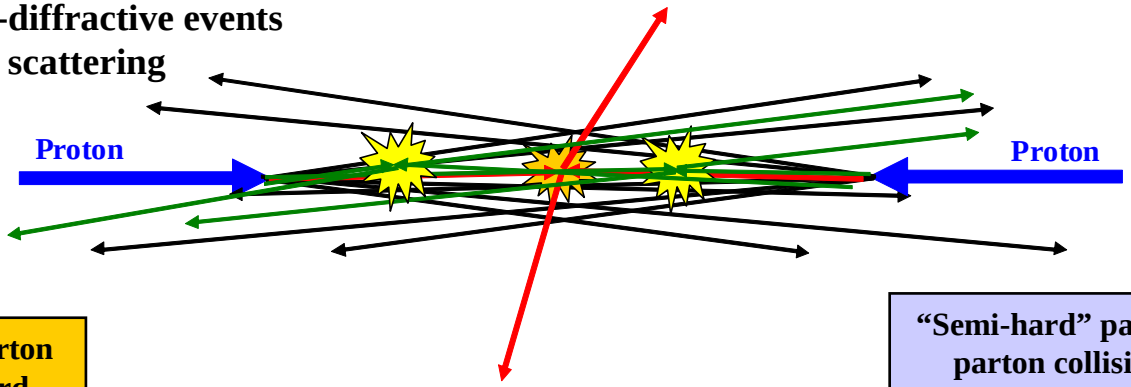


The Inelastic Non-Diffractive Cross-Section



The "Underlying Event"

Select inelastic non-diffractive events that contain a hard scattering

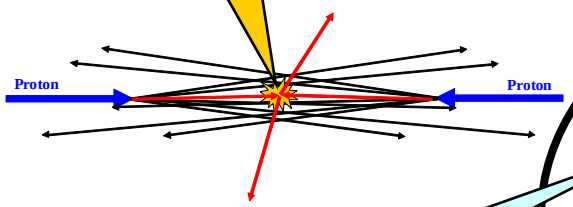


Hard parton-parton collisions is hard ($p_T > \approx 2$ GeV/c)

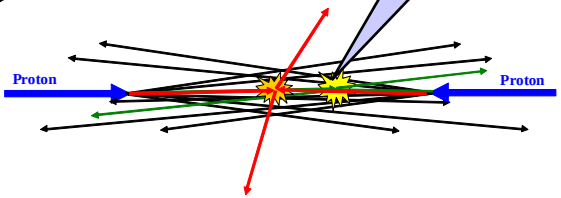
The "underlying-event" (UE)!

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

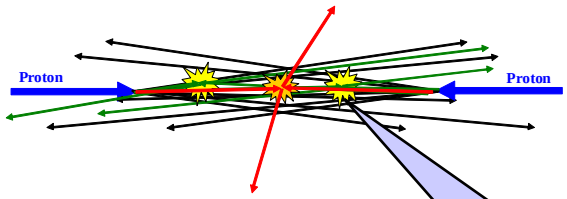
$$1/(p_T)^4 \rightarrow 1/(p_T^2+p_{T0}^2)^2$$



+



+



+ …

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

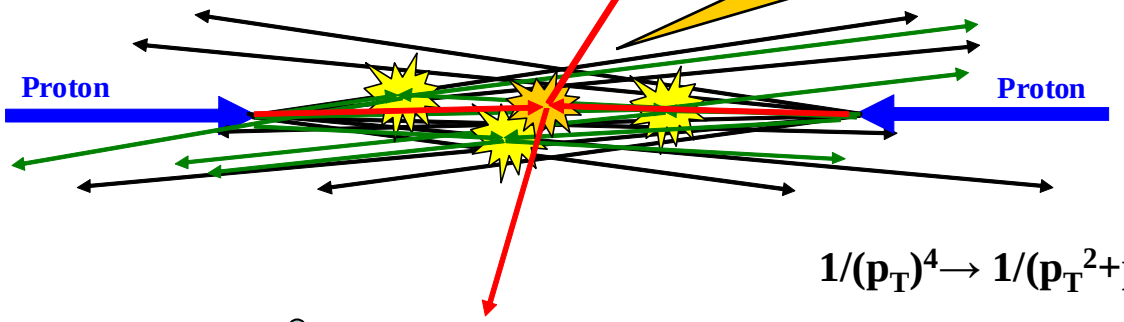
Multiple-parton interactions (MPI)!

UE Tunes

"Underlying Event"

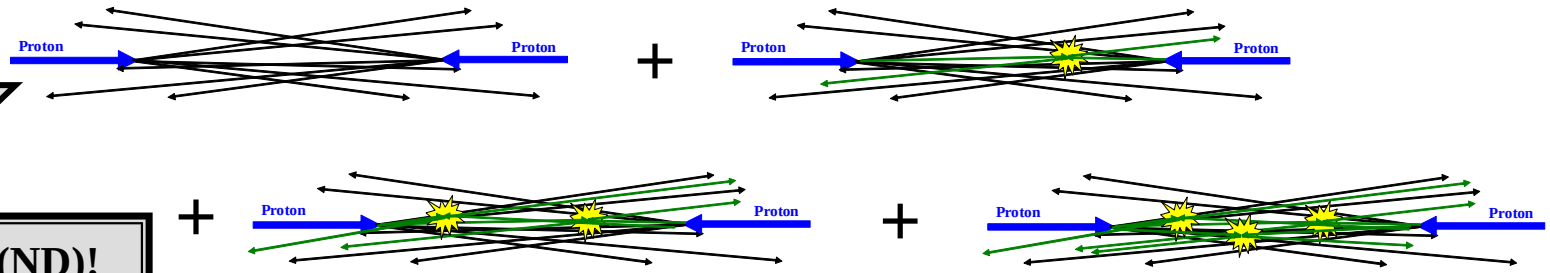
Allow primary hard-scattering to go to $p_T = 0$ with same cut-off!

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



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

"Min-Bias" (ND)



Predict MB (ND)!

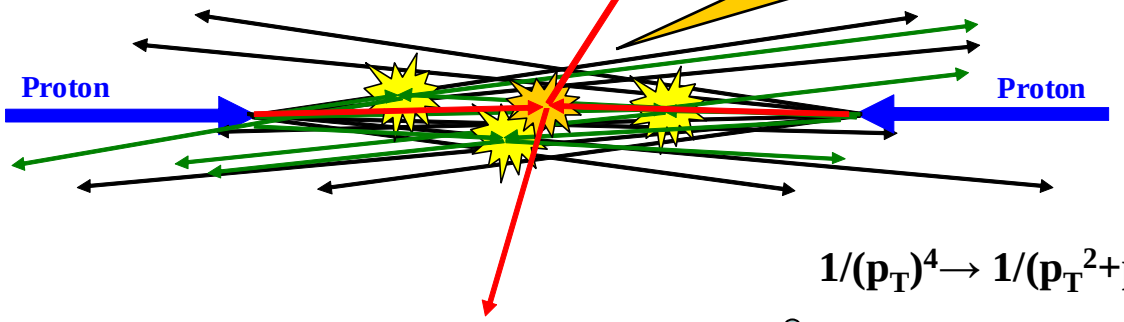
+ …

UE Tunes

"Underlying Event"

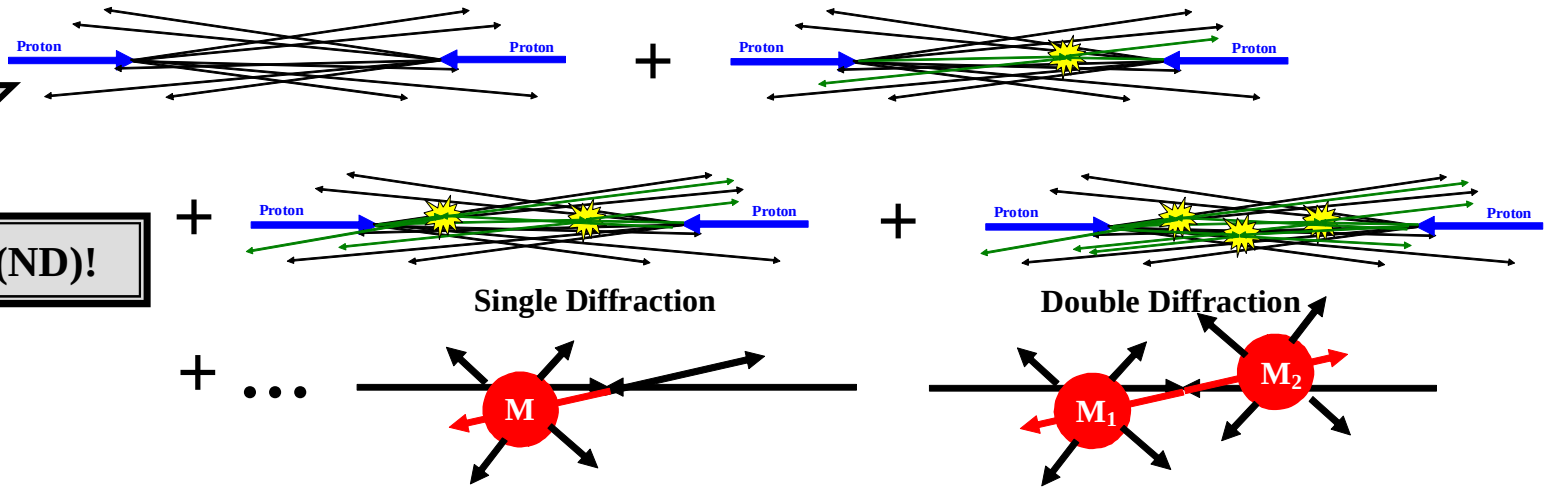
Allow primary hard-scattering to go to $p_T = 0$ with same cut-off!

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



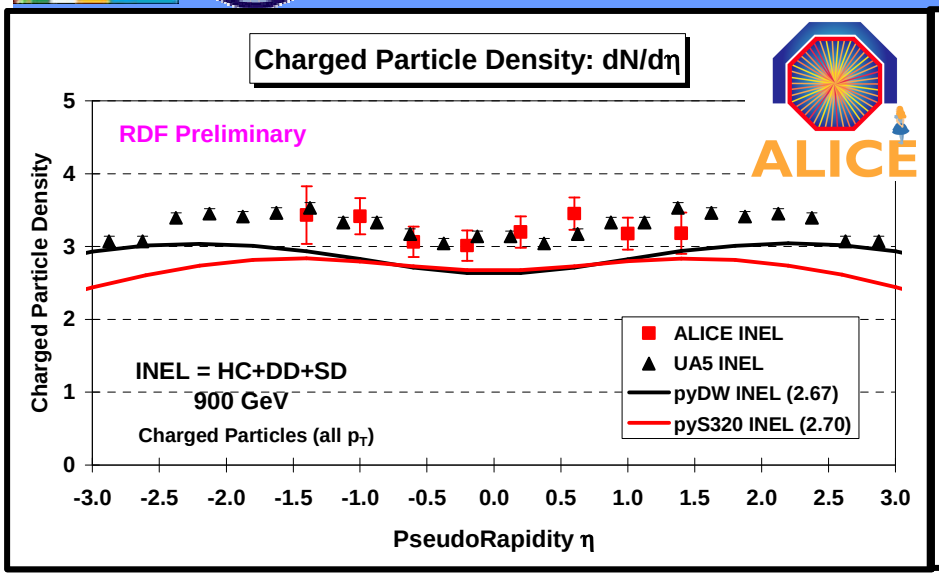
$$1/(p_T)^4 \rightarrow 1/(p_T^2+p_{T0}^2)^2$$

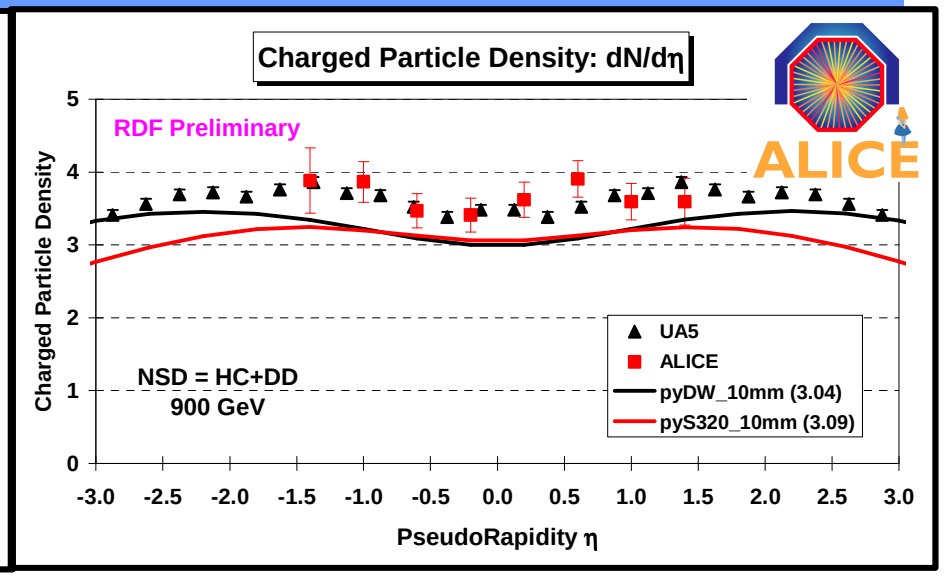
"Min-Bias" (add single & double diffraction)

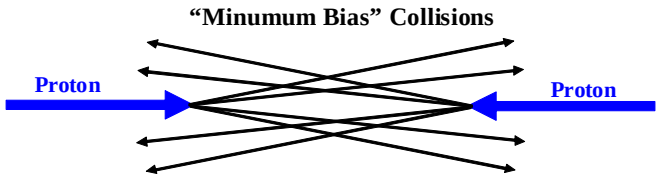


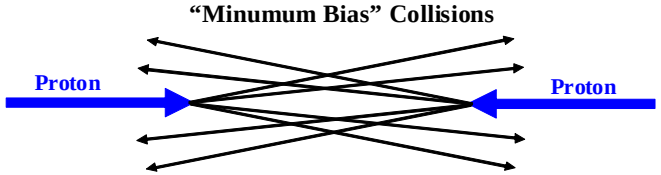
Predict MB (ND)!

LHC MB Predictions: 900 GeV



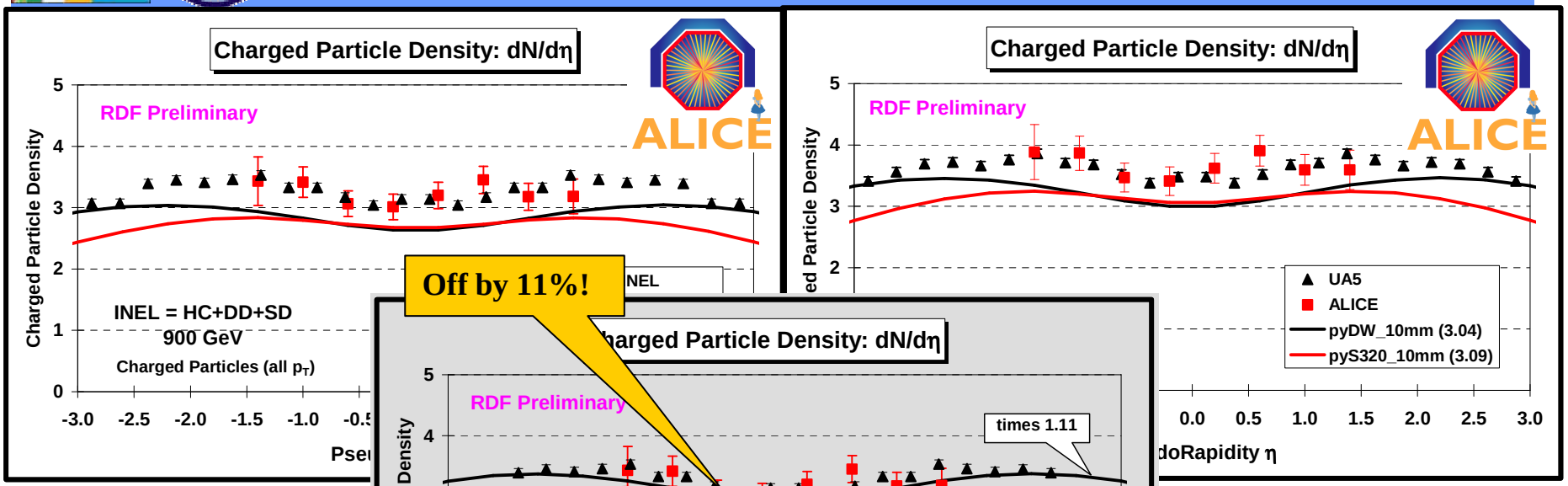


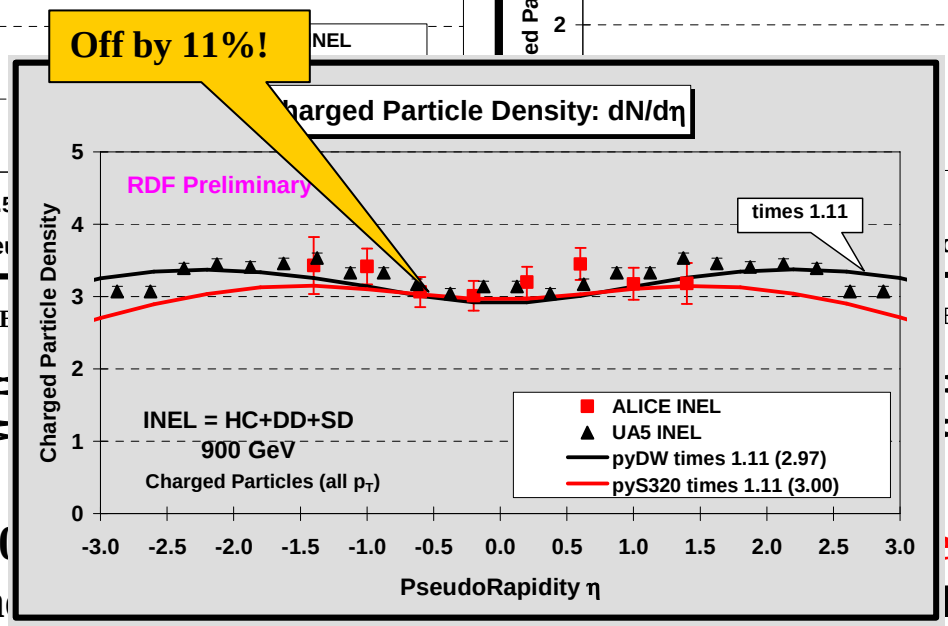


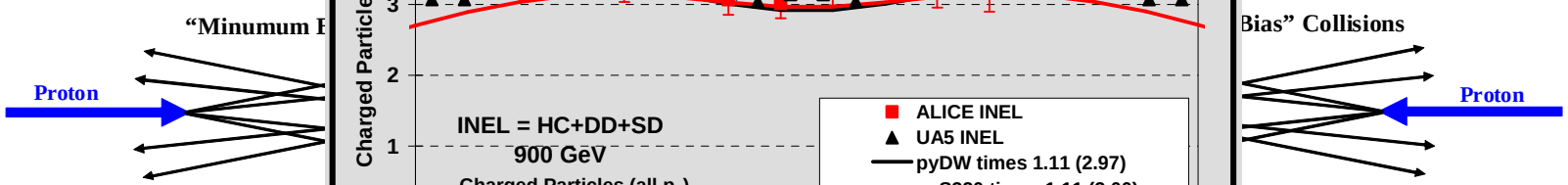


➡ **Compares the 900 GeV ALICE data with PYTHIA Tune DW and Tune S320 Perugia 0. Tune DW uses the old Q^2-ordered parton shower and the old MPI model. Tune S320 uses the new p_T-ordered parton shower and the new MPI model. The numbers in parentheses are the average value of dN/dη for the region $|\eta| < 0.6$.**

LHC MB Predictions: 900 GeV





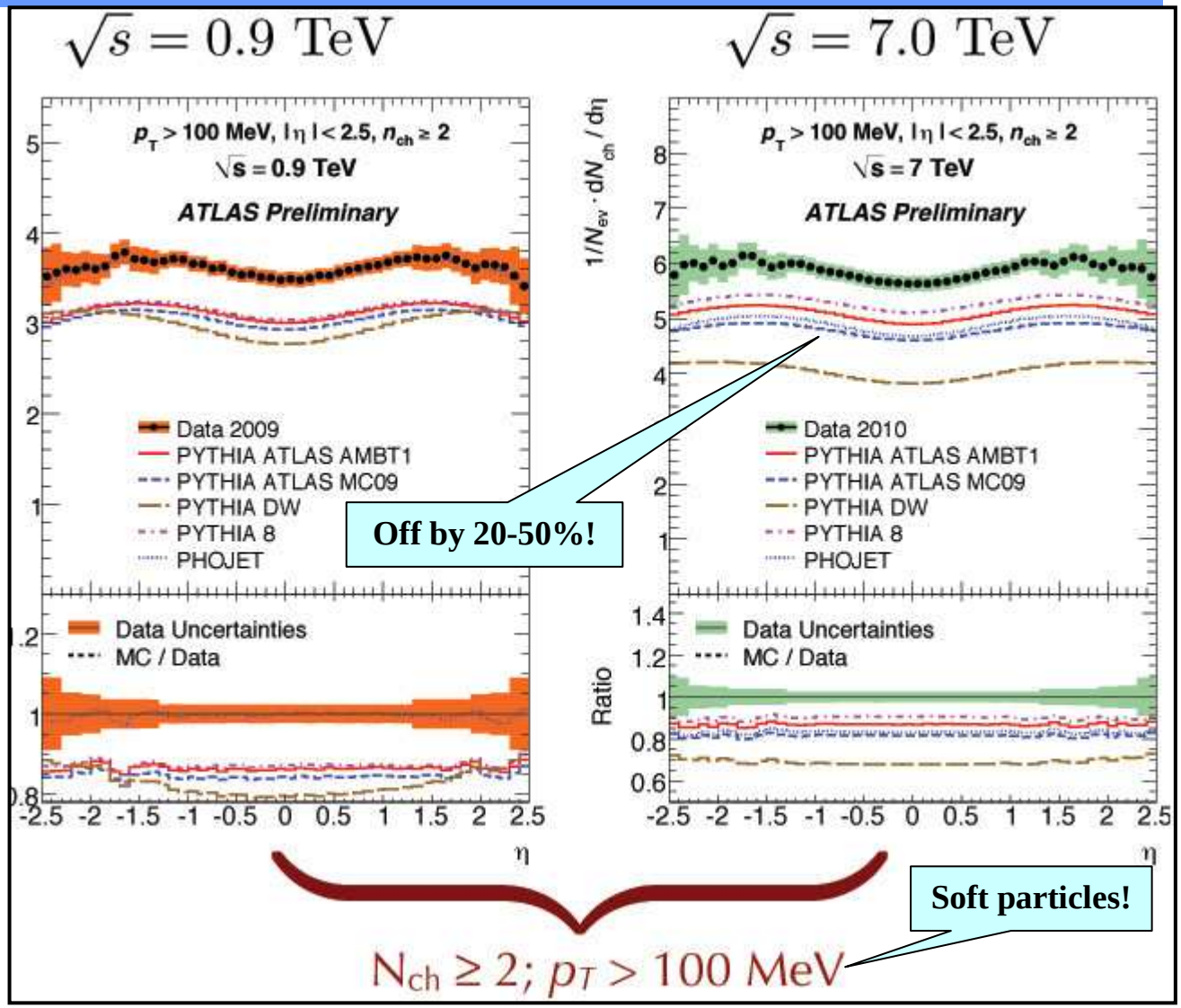


➡ **Compares the 90(… e S320 Perugia 0. Tune DW uses th… IPI model. Tune S320 uses the new p_T-ordered parton shower and the new MPI model. The numbers in parentheses are the average value of dN/dη for the region |η| < 0.6.**

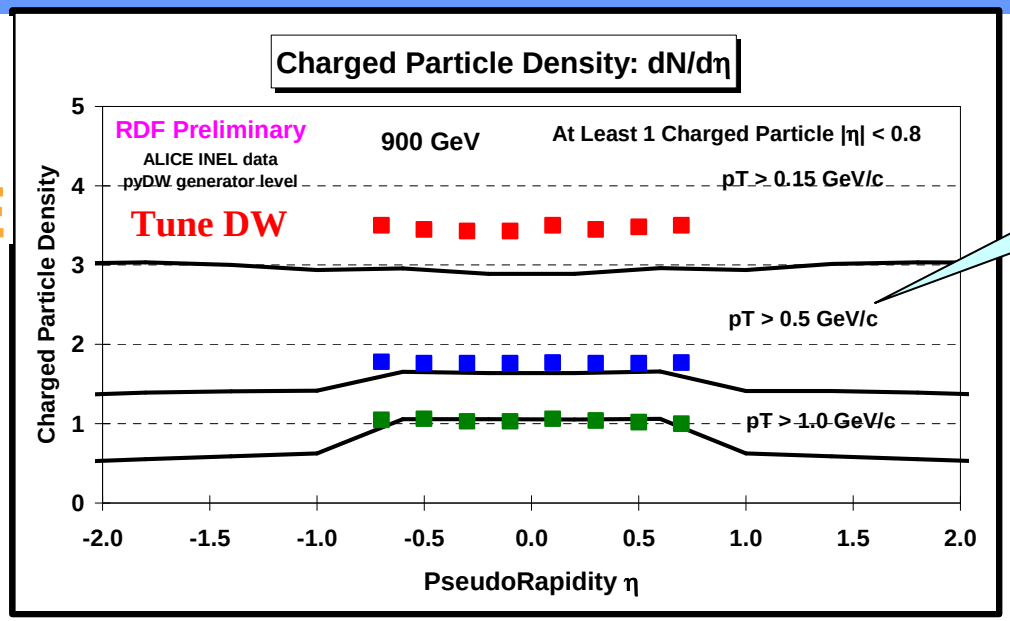
ATLAS INEL dN/dη

- None of the tunes fit the ATLAS INEL dN/dη data with PT > 100 MeV! They all predict too few particles.

- The ATLAS Tune AMBT1 was designed to fit the inelastic data for Nchg ≥ 6 with p_T > 0.5 GeV/c!



PYTHIA Tune DW

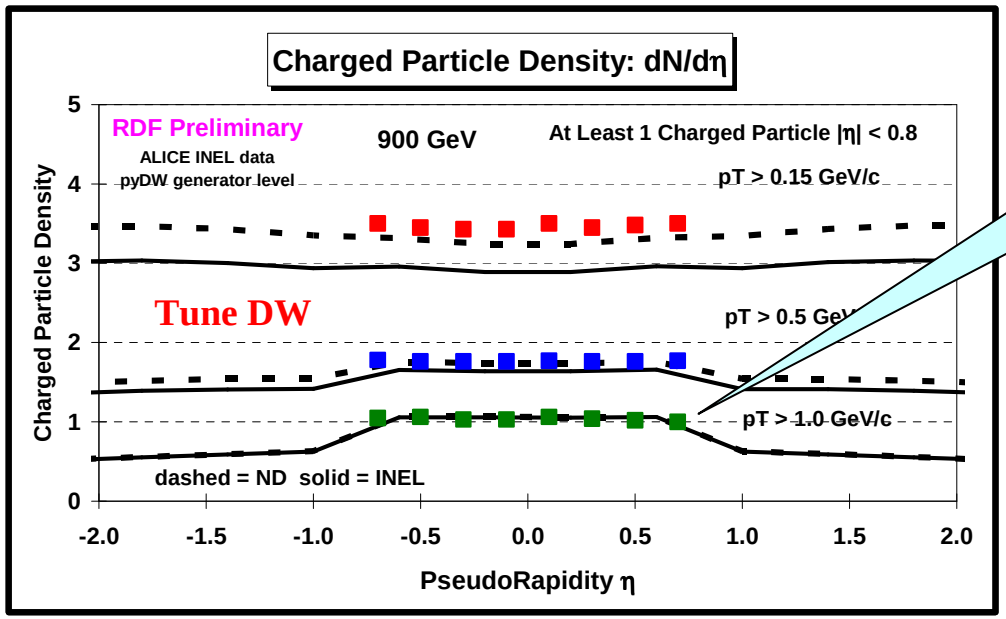


If one increases the hard scale the agreement improves!

- **ALICE inelastic data at 900 GeV on the dN/dη distribution for charged particles (p_T > PTmin) for events with at least one charged particle with p_T > PTmin and |η| < 0.8 for PTmin = 0.15 GeV/c, 0.5 GeV/c, and 1.0 GeV/c compared with PYTHIA Tune DW at the generator level.**

The same thing occurs at 7 TeV!
ALICE, ATLAS, and CMS data coming soon.

PYTHIA Tune DW

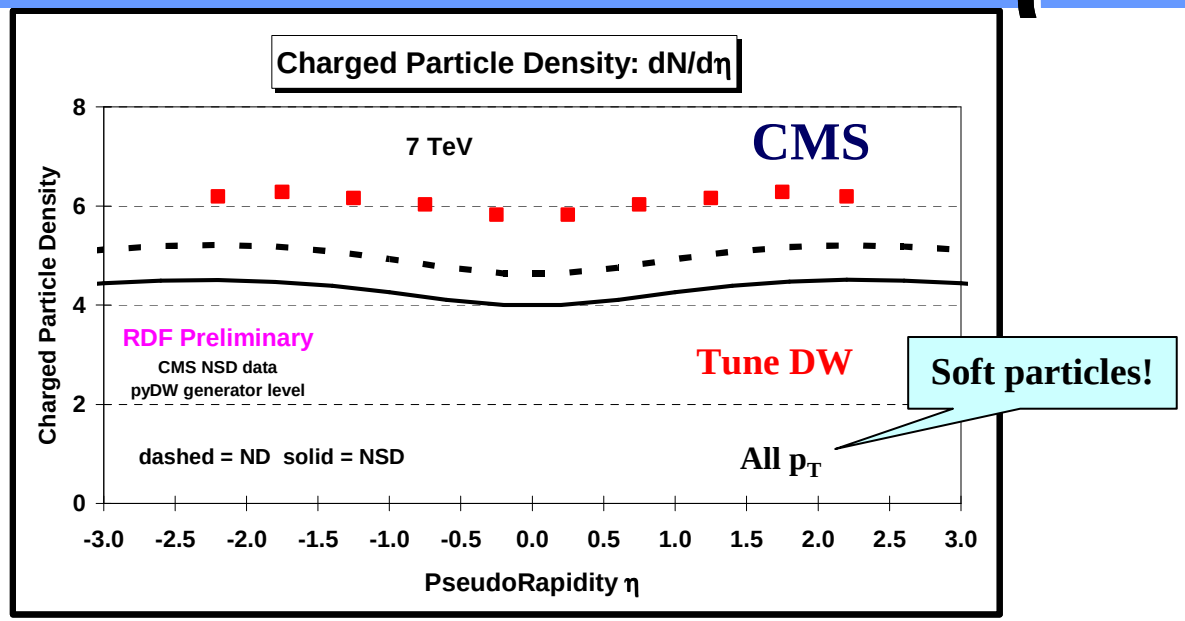


Diffraction contributes less at harder scales!

- **ALICE inelastic data at 900 GeV on the dN/dη distribution for charged particles (p_T > PTmin) for events with at least one charged particle with p_T > PTmin and |η| < 0.8 for PTmin = 0.15 GeV/c, 0.5 GeV/c, and 1.0 GeV/c compared with PYTHIA Tune Z1 at the generator level (dashed = ND, solid = INEL).**

Cannot trust PYTHIA 6.2 modeling of diffraction!

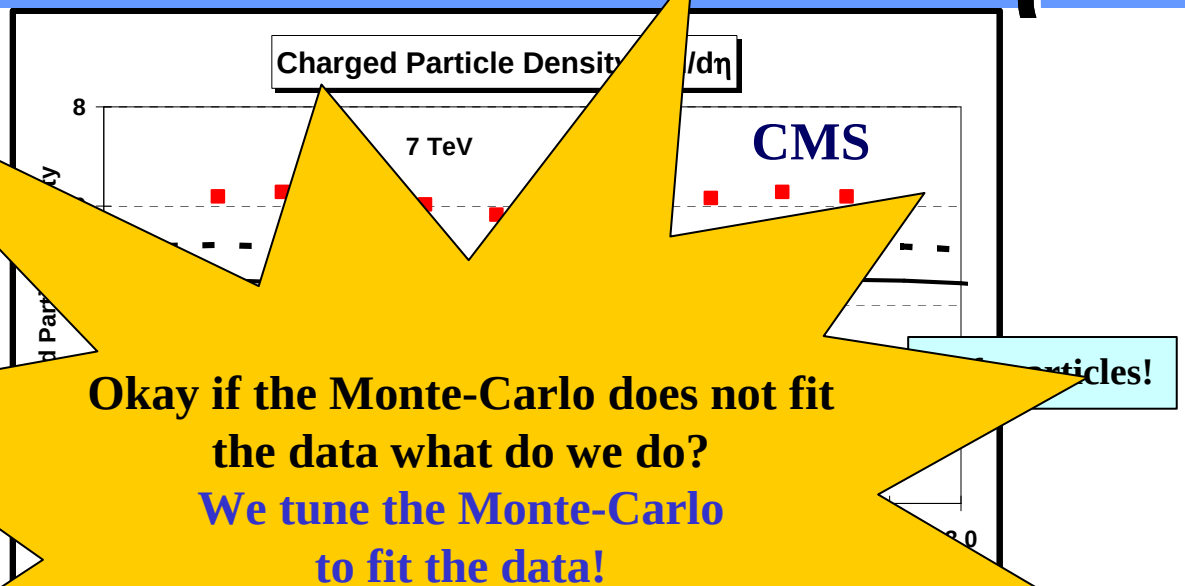
CMS dN/dη



➡ **Generator level dN/dη (all pT). Shows the NSD = HC + DD and the HC = ND contributions for Tune DW. Also shows the CMS NSD data.**

Off by 50%!

CMS dN/dη

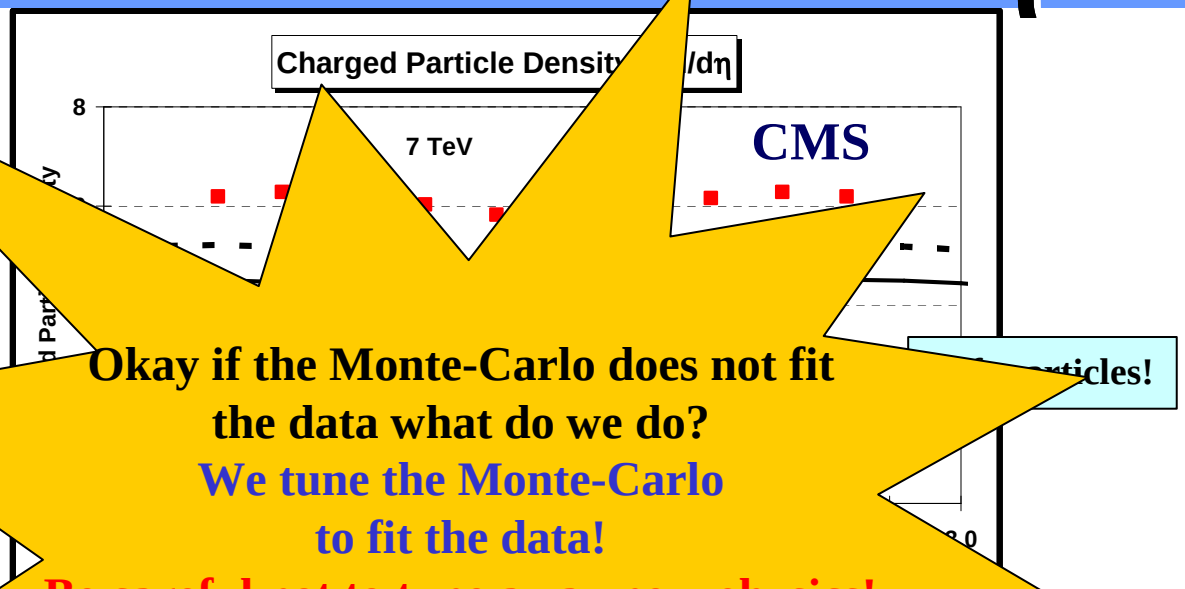


Okay if the Monte-Carlo does not fit the data what do we do?
We tune the Monte-Carlo to fit the data!

➡ **Generator** [illegible] **DD and the HC = ND contributions for Tune** [illegible] **S** [illegible] **ta.**

O [illegible] **by 50** [illegible] **%!**

CMS dN/dη



Okay if the Monte-Carlo does not fit the data what do we do?

We tune the Monte-Carlo to fit the data!

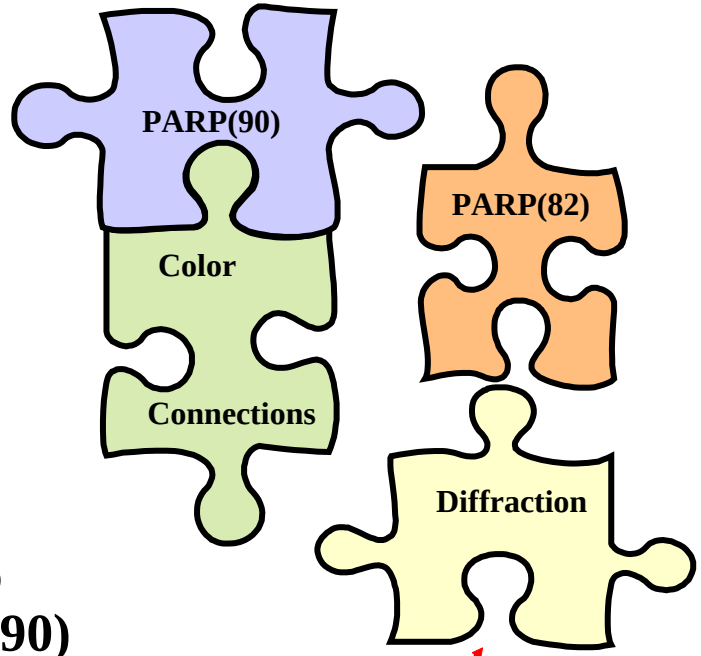
Be careful not to tune away new physics!

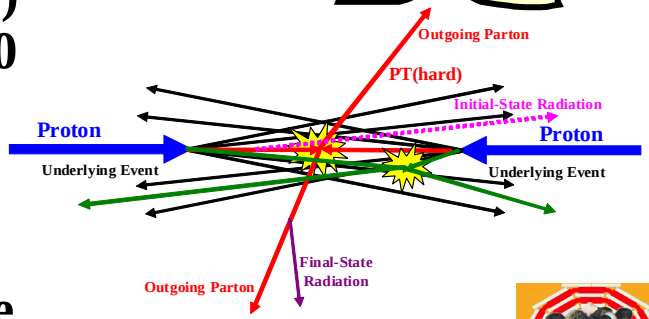
➡ **Generator** [illegible] **DD and the HC = ND contributions for Tune** [illegible] **S** [illegible] **ta.**

O [illegible] **by 50** [illegible] **%!**

PYTHIA Tune Z1

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





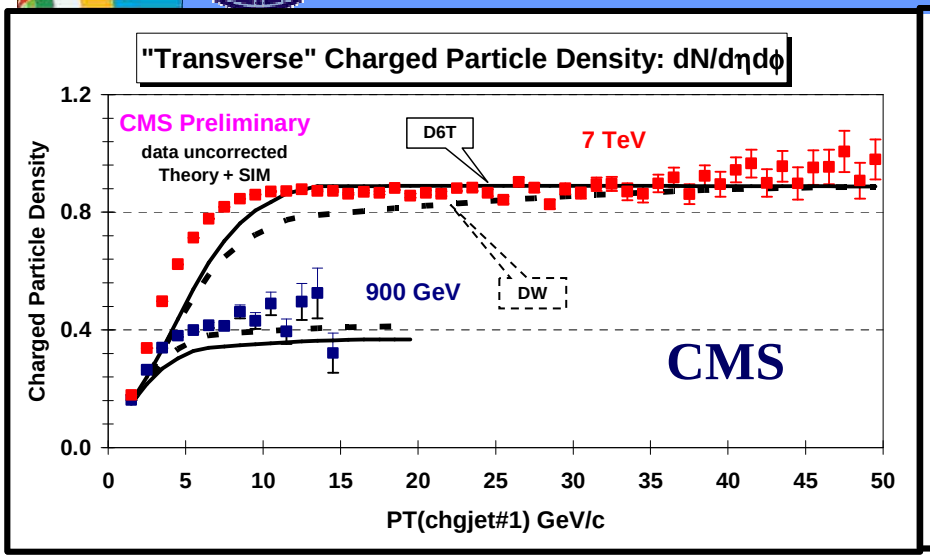
UE&MB@CMS

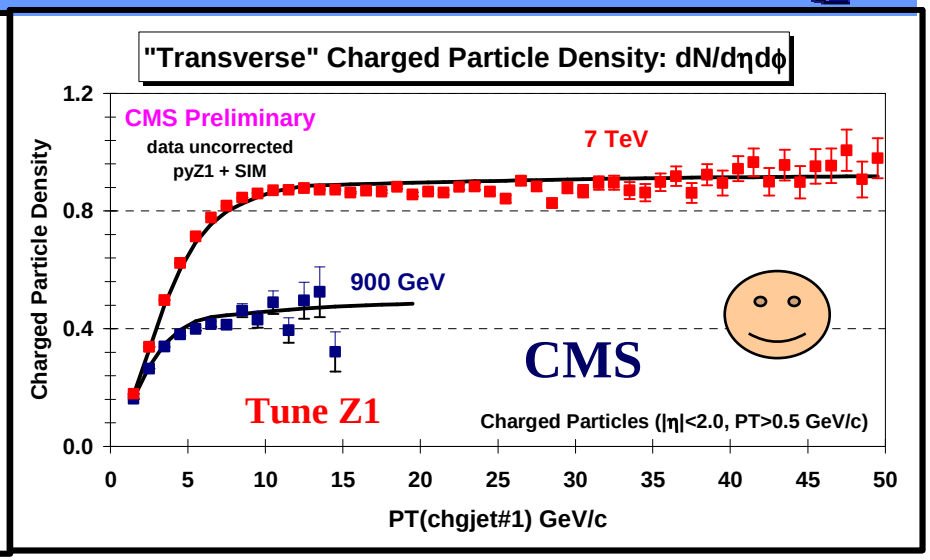
PYTHIA Tune Z1

Parameters not shown are the PYTHIA 6.4 defaults!

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

PYTHIA Tune Z1





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

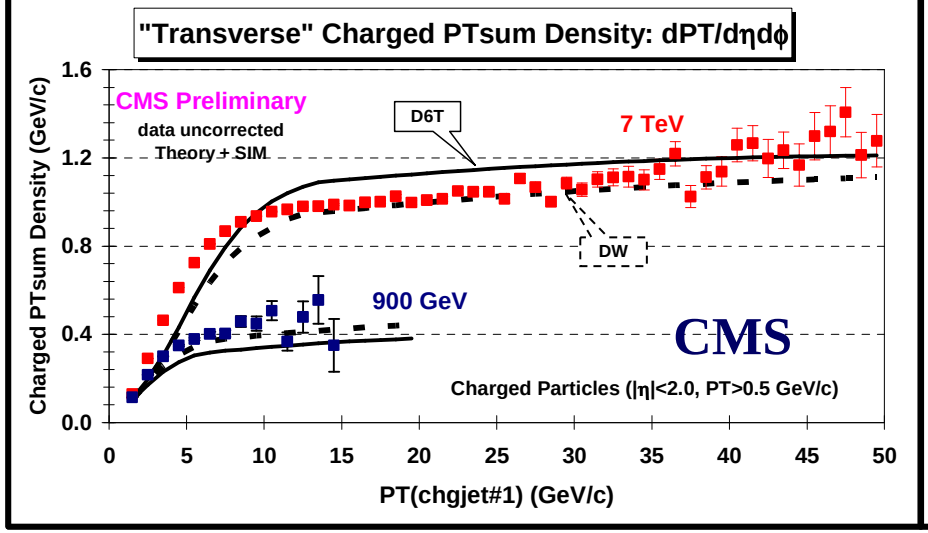
- **CMS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdϕ, as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$. The data are uncorrected and compared with PYTHIA Tune Z1 after detector simulation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

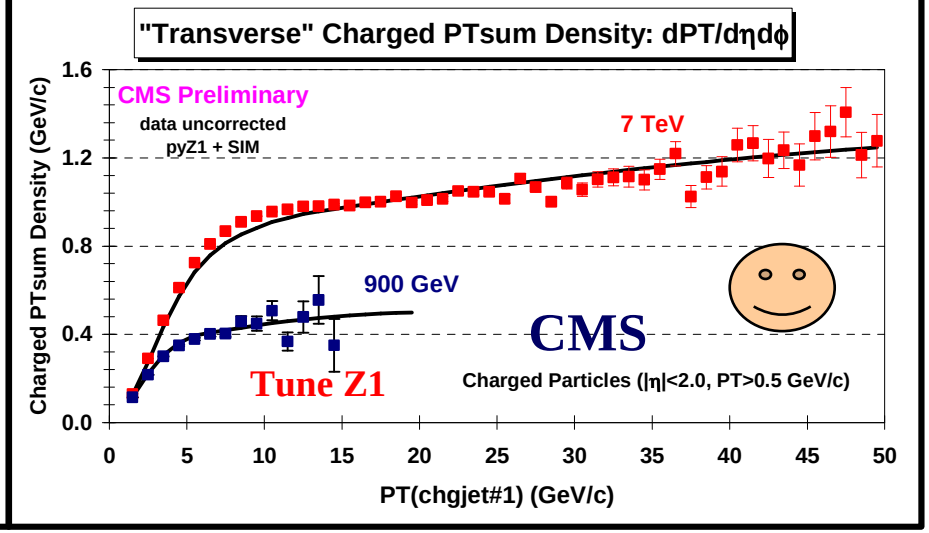
Color reconnection suppression.
Color reconnection strength.

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

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

PYTHIA Tune Z1





- **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 uncorrected and compared with PYTHIA Tune DW and D6T after detector simulation (SIM).**

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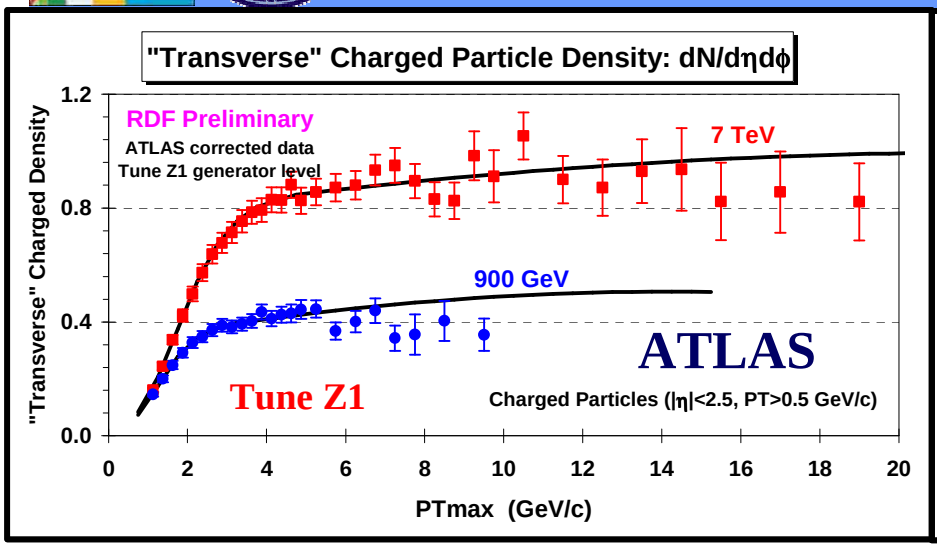
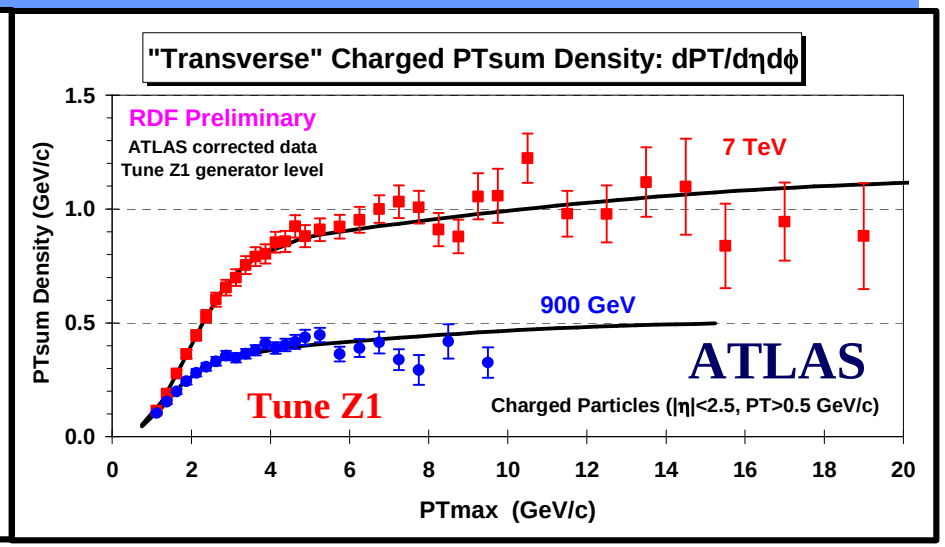
Color reconnection suppression.
Color reconnection strength.

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





- **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| < 2.5. The data are corrected and compared with PYTHIA Tune Z1 at the generator level.**

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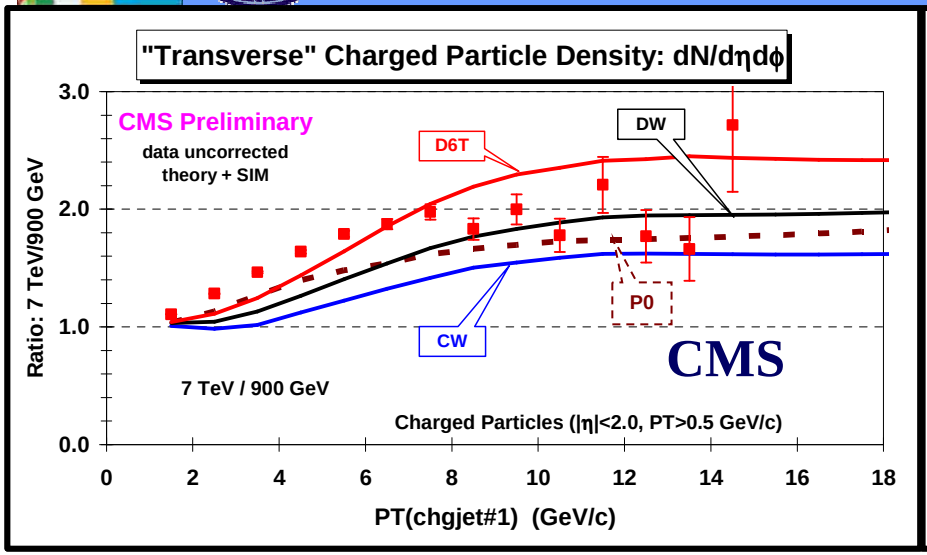

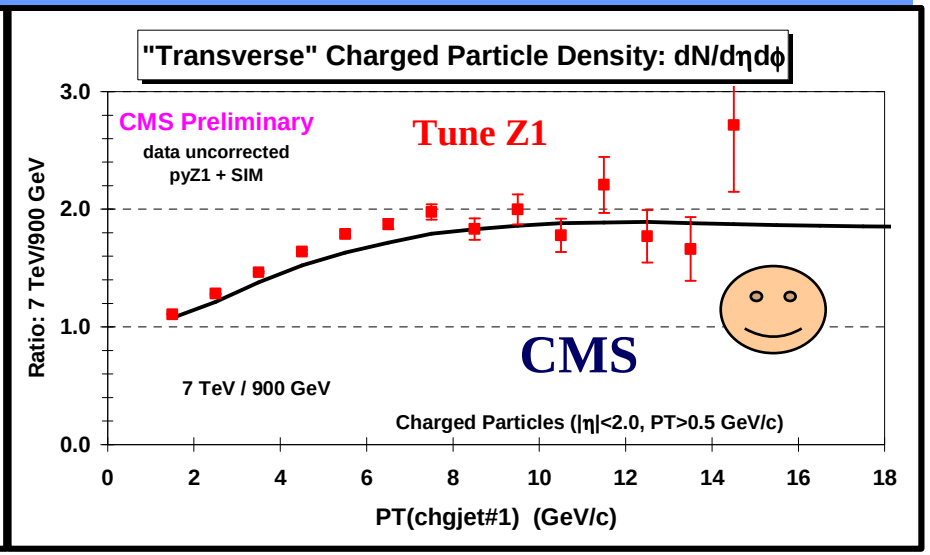

- **Ratio of CMS preliminary data at 900 GeV and 7 TeV (7 TeV divided by 900 GeV) on the "transverse" charged particle density as defined by the leading charged particle jet (chgjet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.0$. The data are uncorrected and compared with PYTHIA Tune DW, D6T, CW, and P0 after detector simulation (SIM).**

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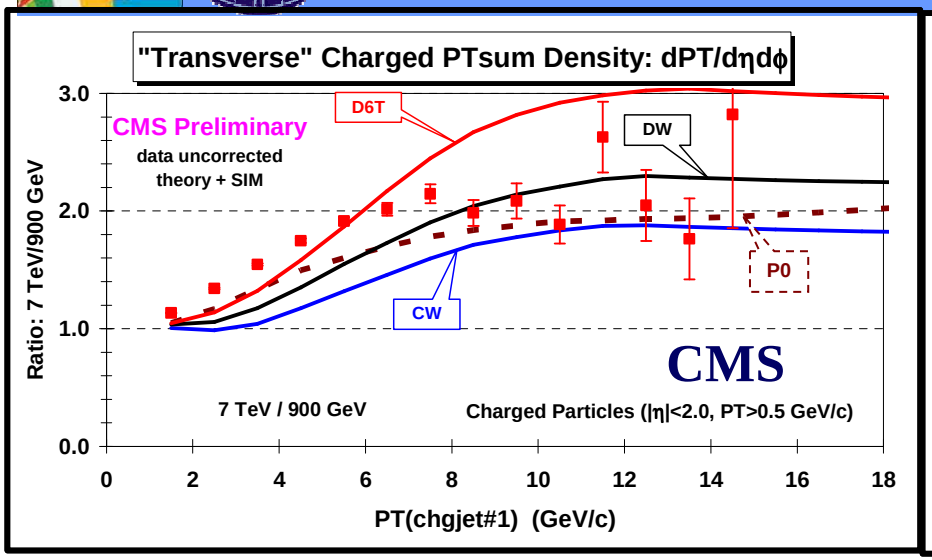

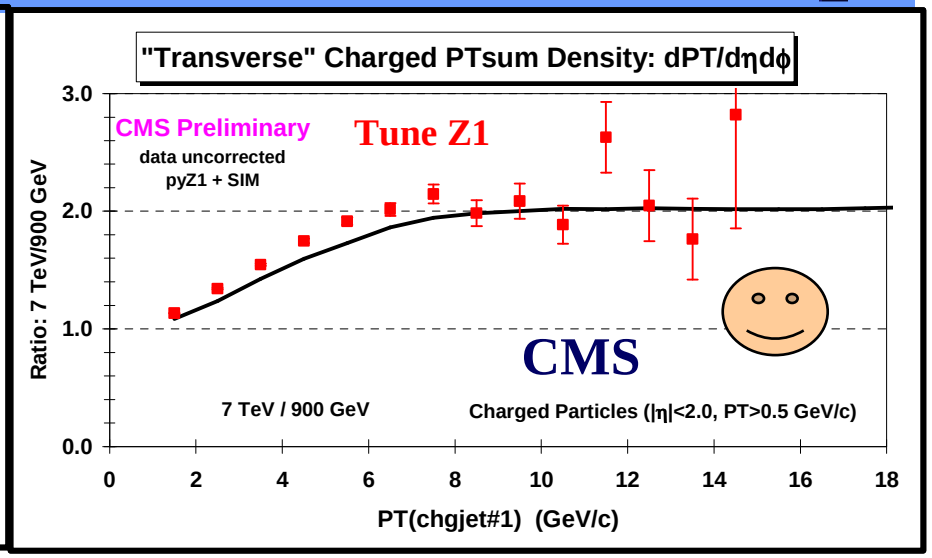

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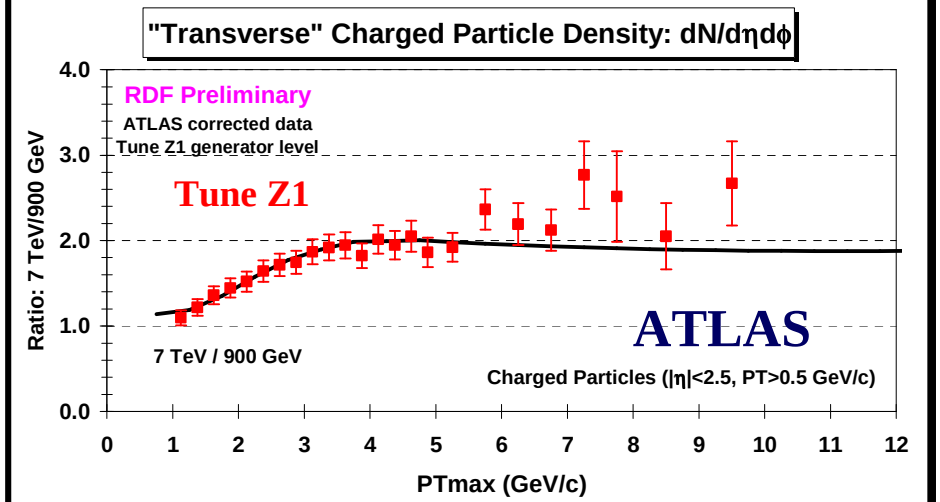

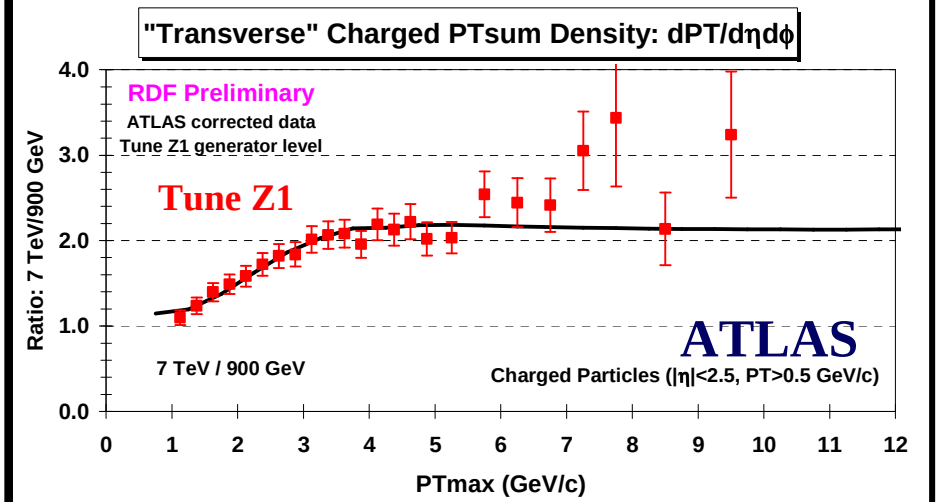

- **Ratio of the ATLAS preliminary data on the charged particle density in the "transverse" region for charged particles (p_T > 0.5 GeV/c, |η| < 2.5) at 900 GeV and 7 TeV as defined by PTmax compared with PYTHIA Tune Z1 at the generator level.**

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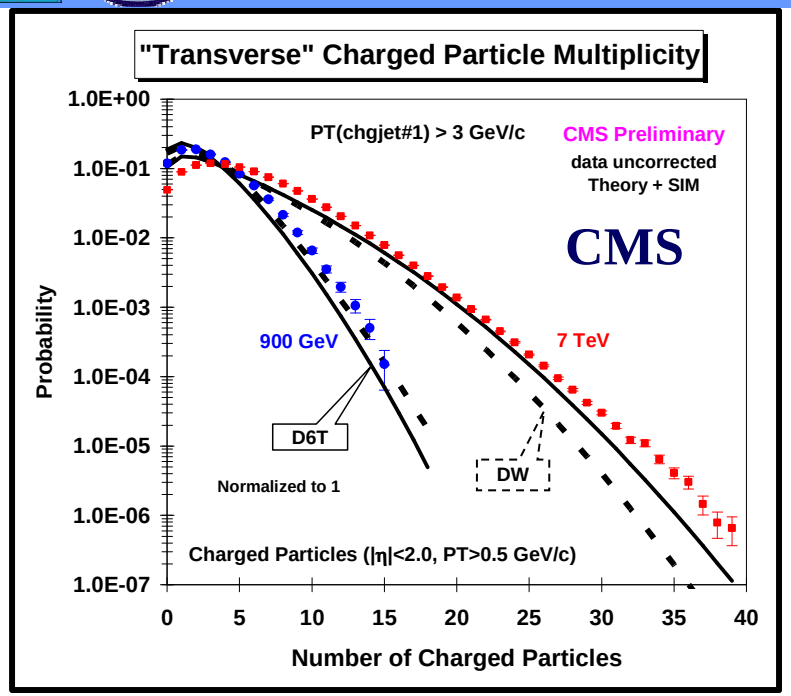
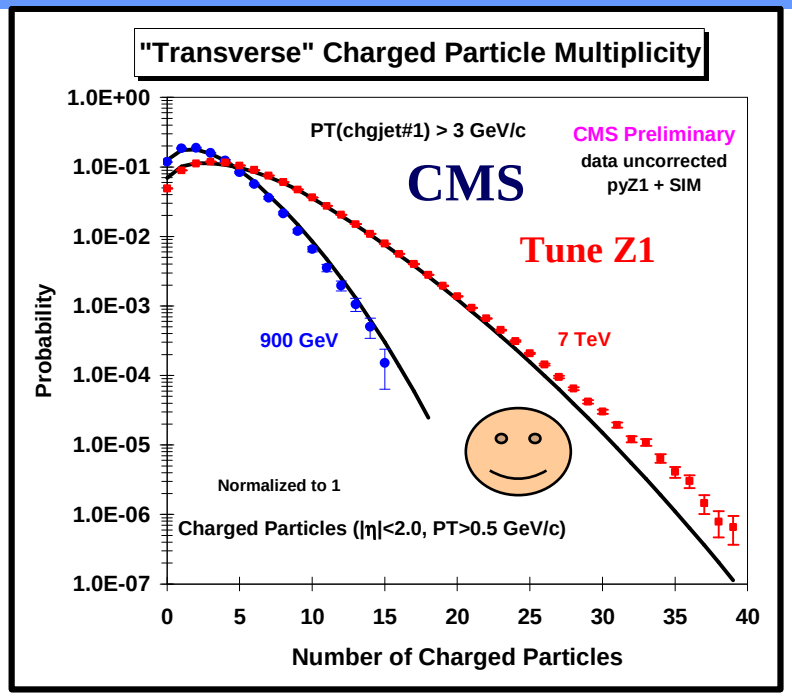
"Transverse" Multiplicity Distribution





- **CMS uncorrected 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 DW and Tune D6T at the detector level (*i.e.* Theory + SIM).**

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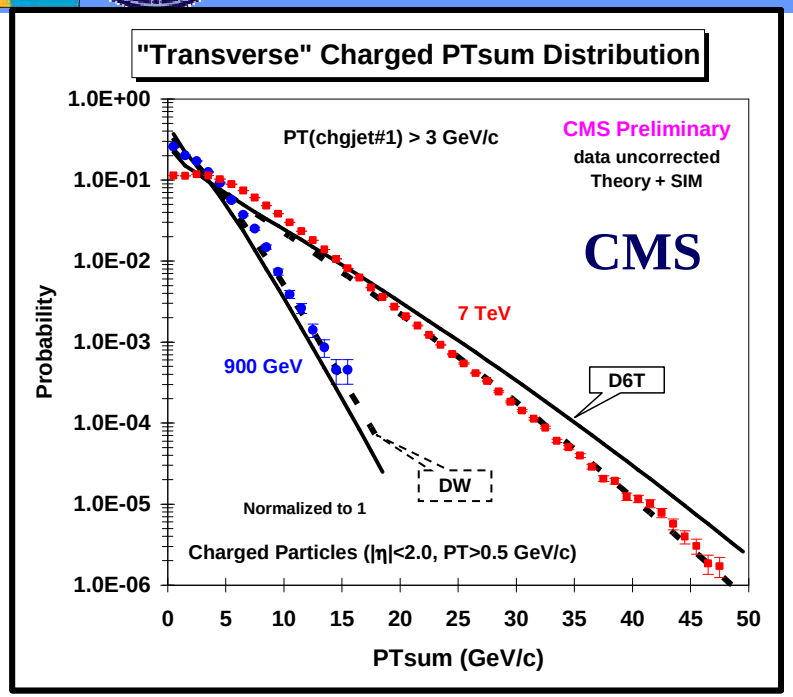

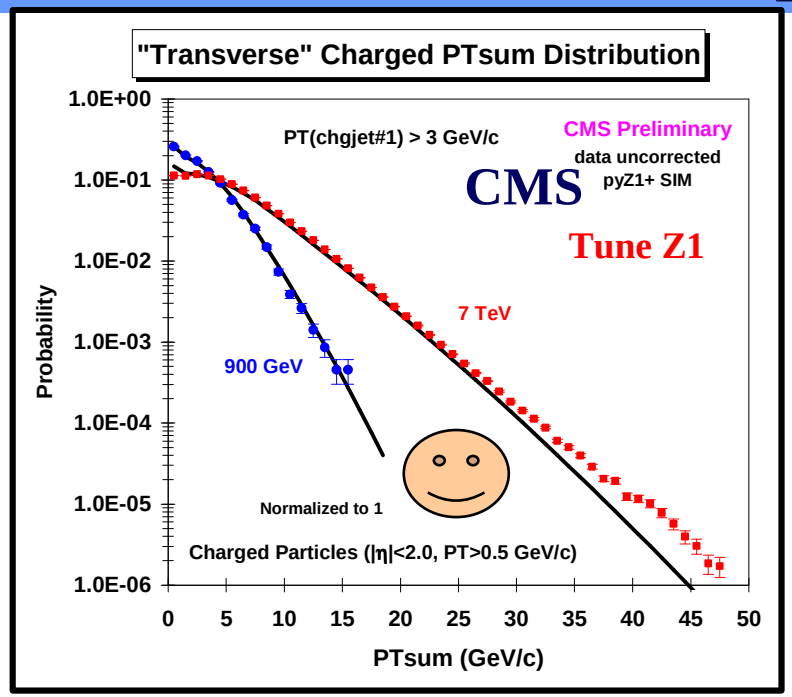

- **CMS uncorrected data at 900 GeV and 7 TeV on the charged scalar PTsum distribution in the "transverse" region for charged particles (p_T > 0.5 GeV/c, |η| < 2) as defined by the leading charged particle jet with PT(chgjet#1) > 3 GeV/c compared with PYTHIA Tune DW, and Tune D6T at the detector level (*i.e.* Theory + SIM).**

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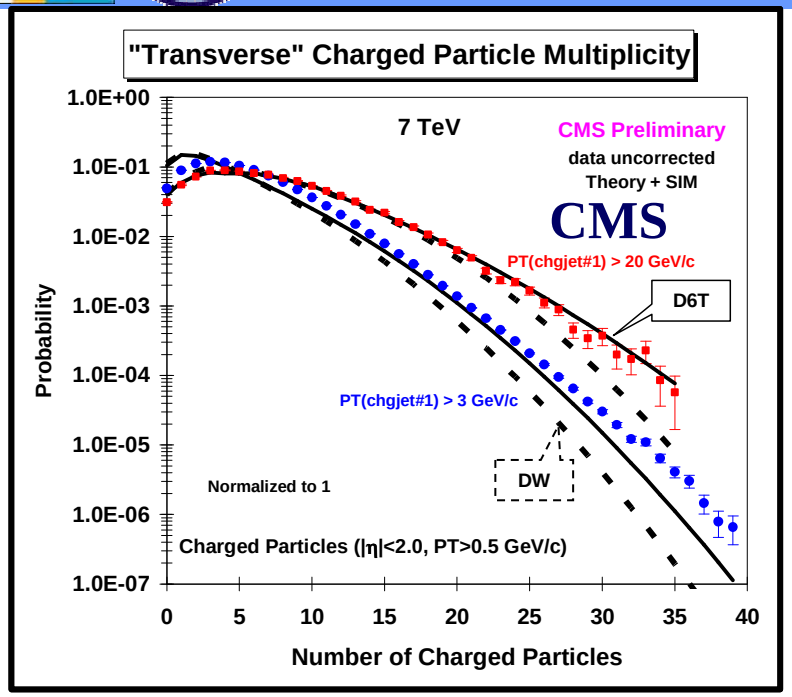

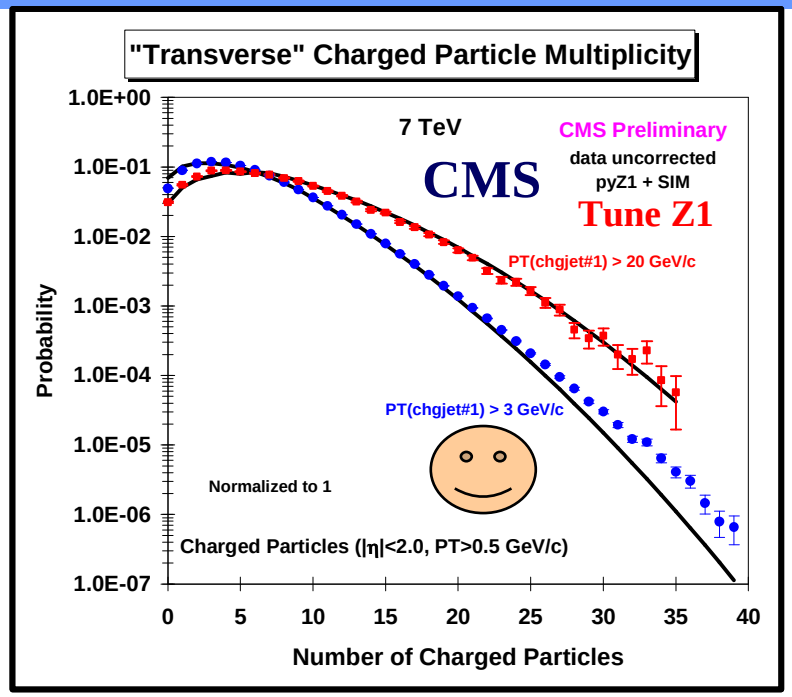

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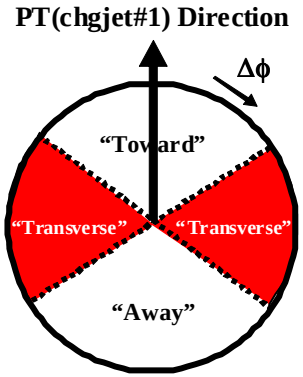
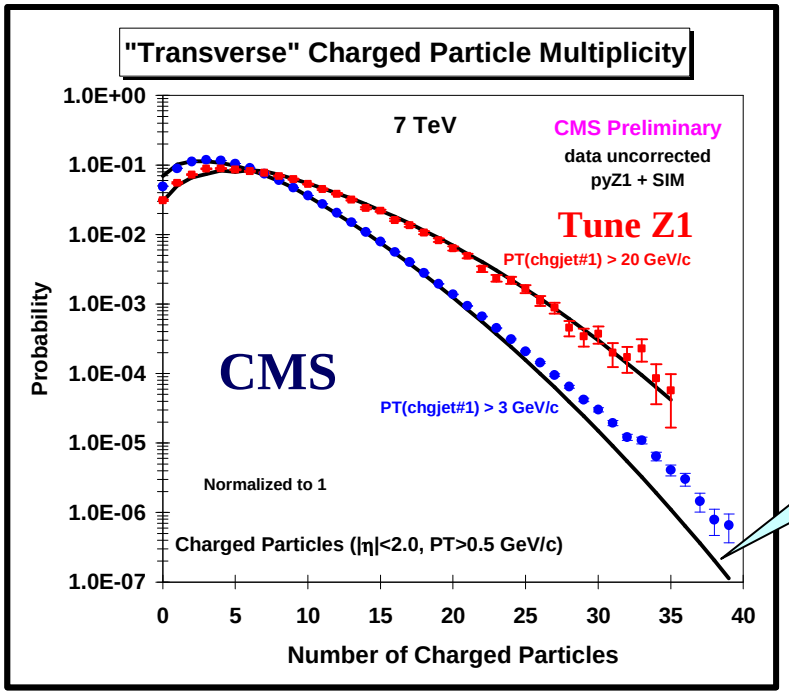
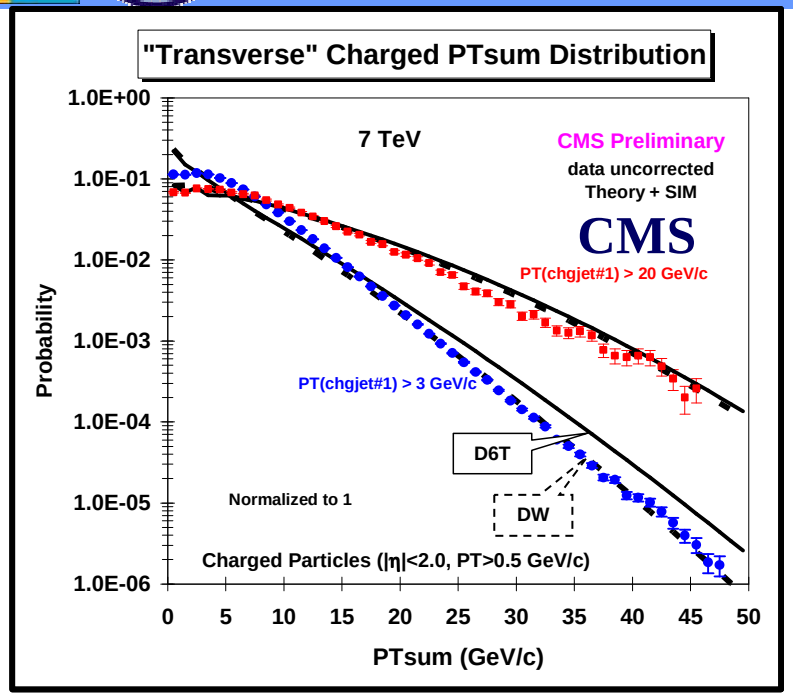


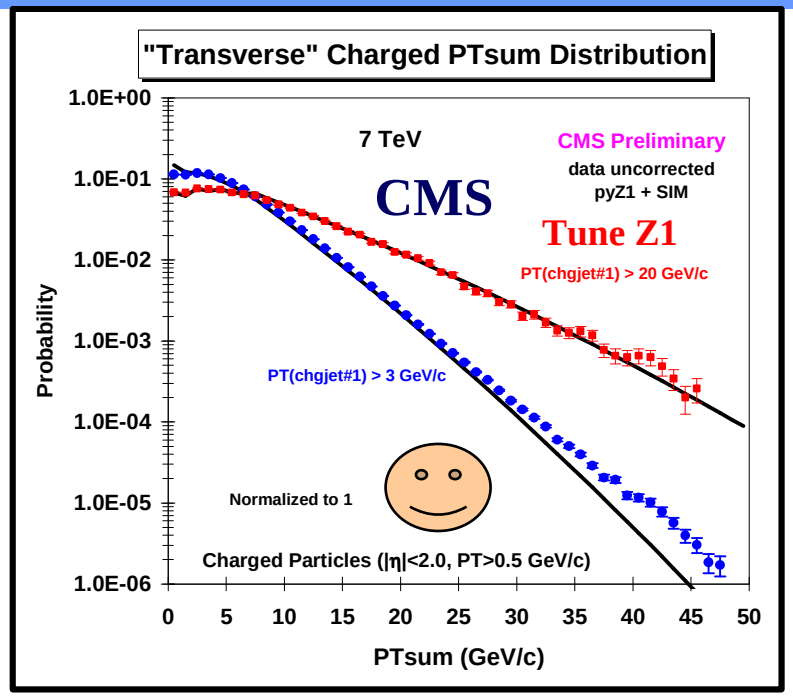


Difficult to produce enough events with large "transverse" multiplicity at low hard scale!

- **CMS uncorrected data at 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, chgjet#1, with PT(chgjet#1) > 3 GeV/c and PT(chgjet#1) > 20 GeV/c compared with PYTHIA Tune Z1 at the detector level (*i.e.* Theory + SIM).**

"Transverse" PTsum Distribution





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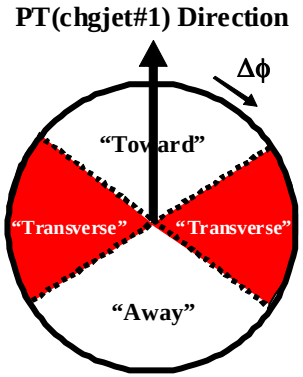

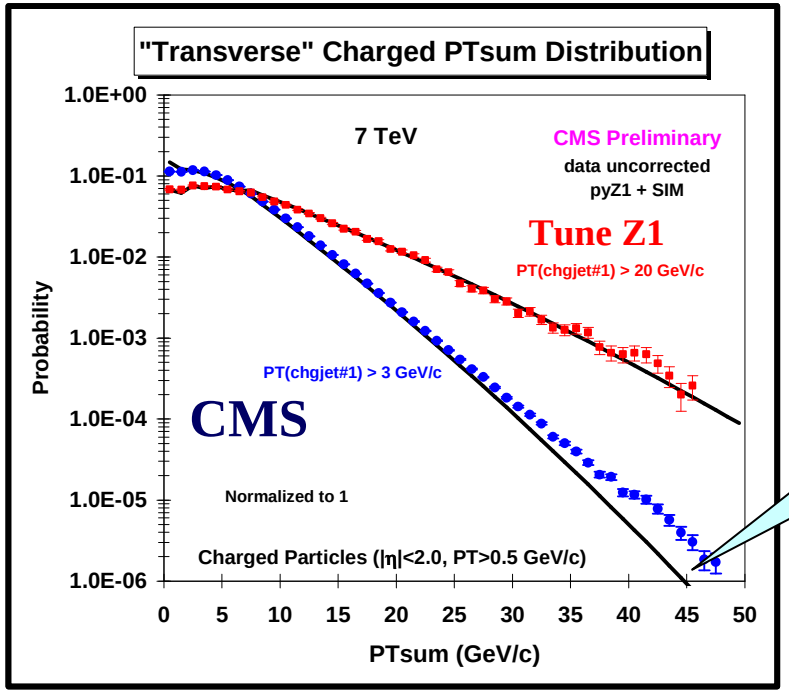

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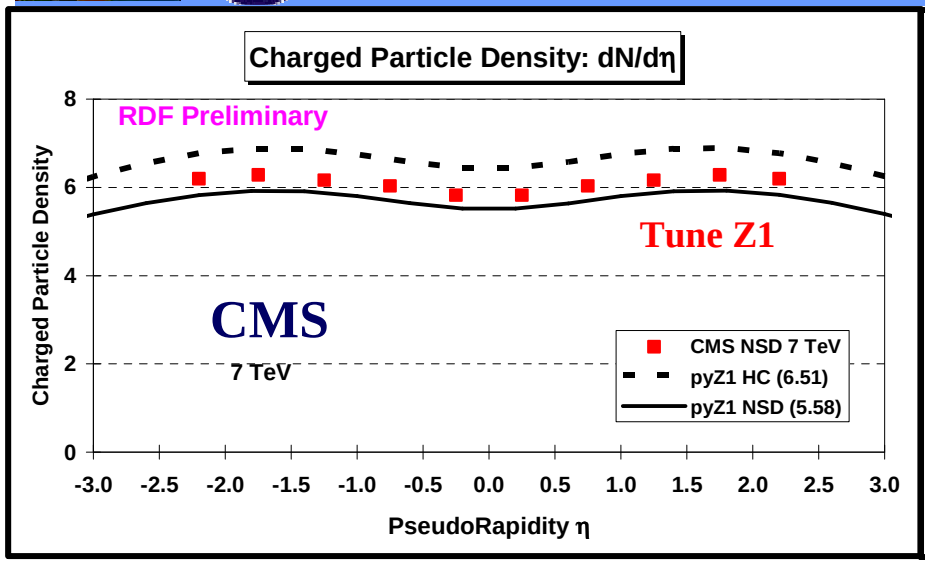
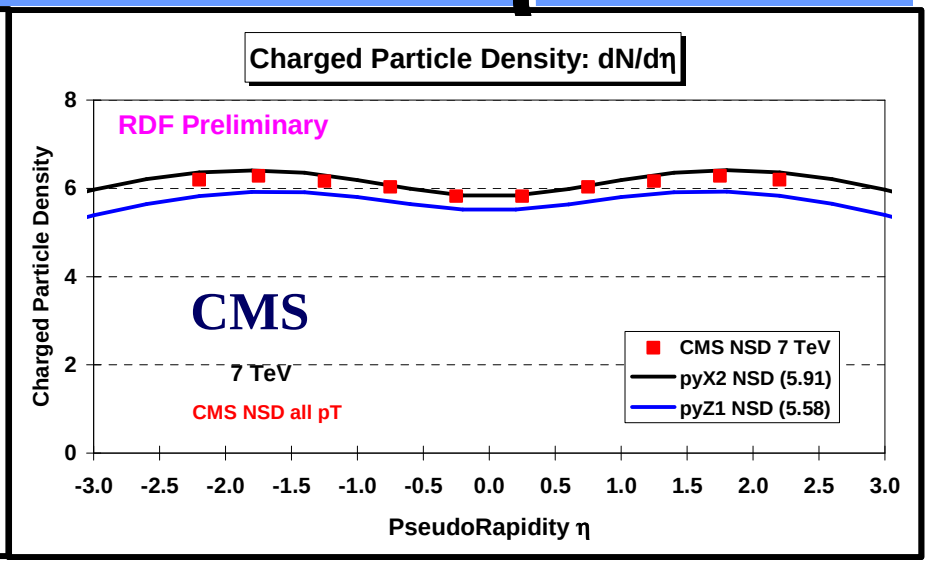
CMS dN/dη

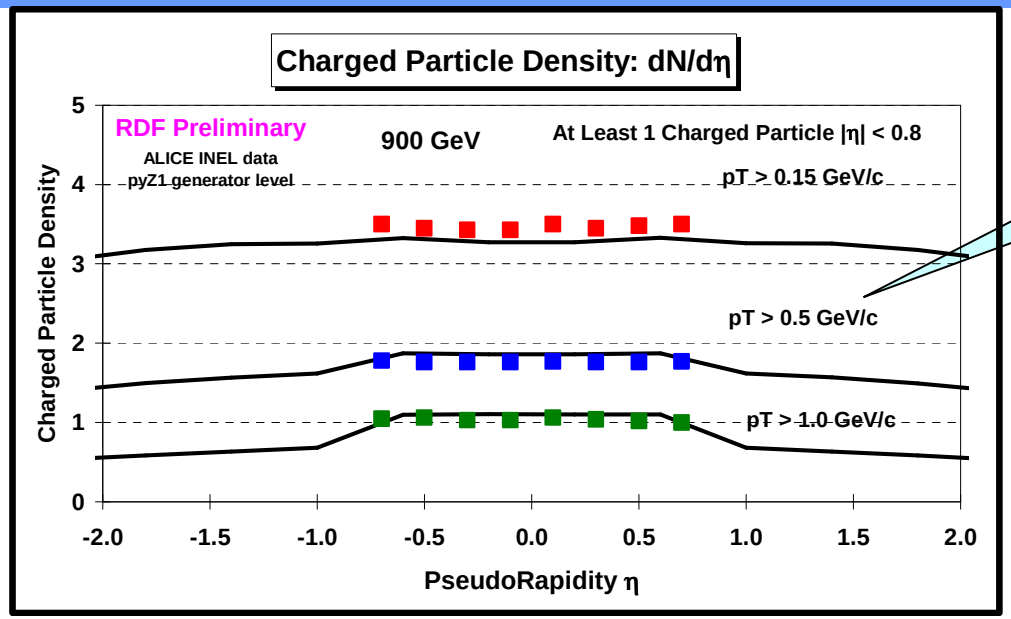




- **Generator level dN/dη (all pT). Shows the NSD = HC + DD and the HC = ND contributions for Tune Z1. Also shows the CMS NSD data.**
- **Generator level dN/dη (all pT). Shows the NSD = HC + DD prediction for Tune Z1 and Tune X2. Also shows the CMS NSD data.**

Okay not perfect, but remember we do not know if the DD is correct!

PYTHIA Tune Z1

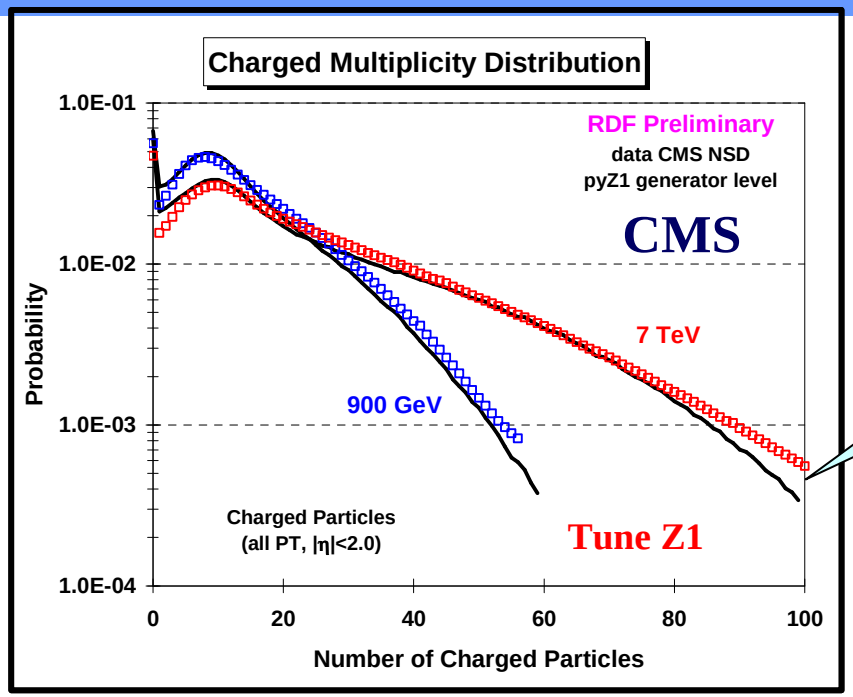


If one increases the hard scale the agreement improves!

- **ALICE inelastic data at 900 GeV on the dN/dη distribution for charged particles (p_T > PTmin) for events with at least one charged particle with p_T > PTmin and |η| < 0.8 for PTmin = 0.15 GeV/c, 0.5 GeV/c, and 1.0 GeV/c compared with PYTHIA Tune Z1 at the generator level.**

Okay not perfect, but remember we do not know if the SD & DD are correct!

NSD Multiplicity Distribution

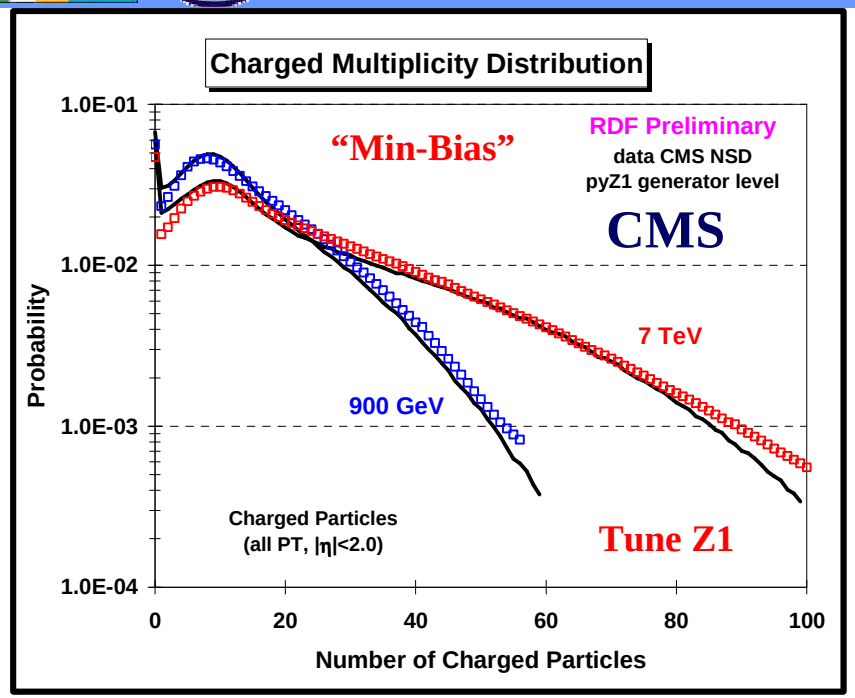


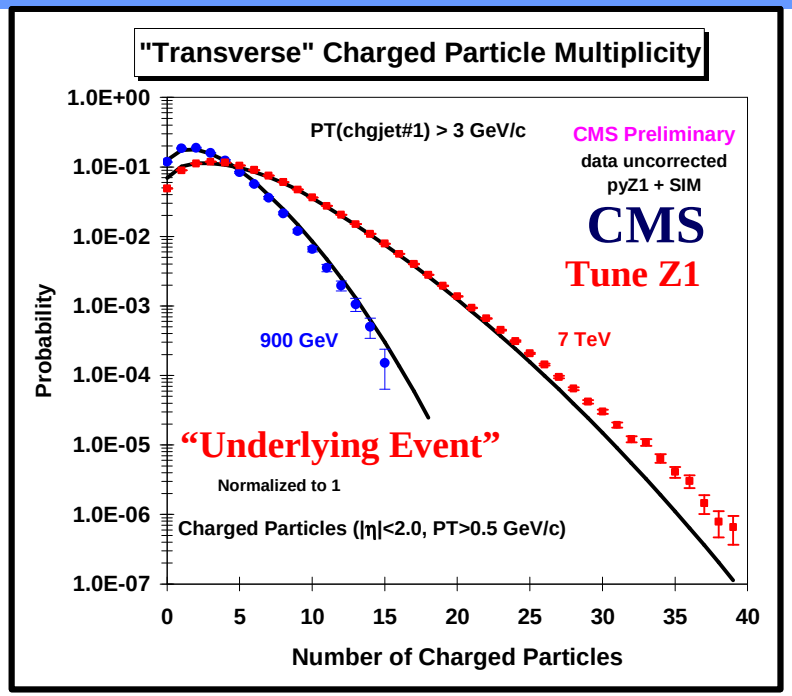
Difficult to produce enough events with large multiplicity!

- **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.**

Okay not perfect!
But not that bad!

MB & UE





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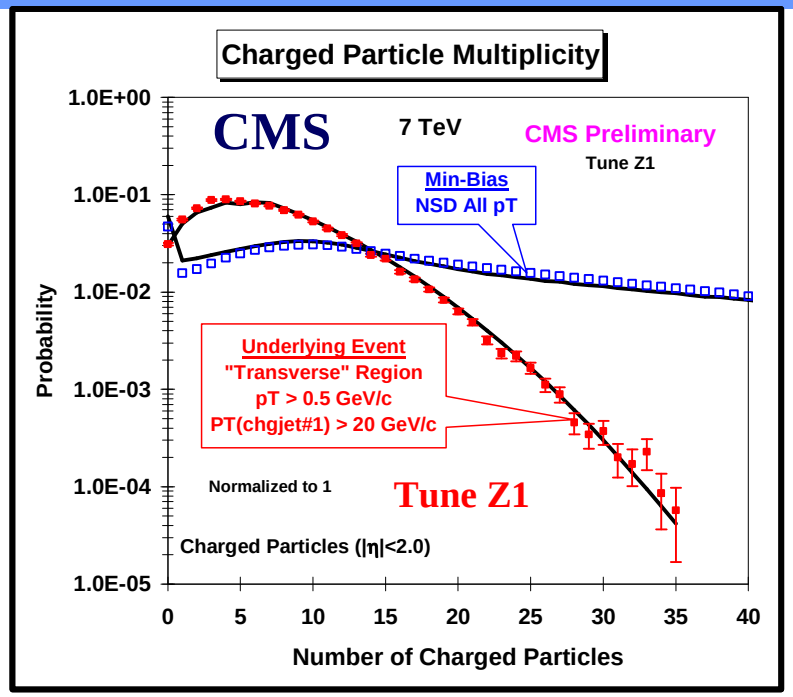
- **CMS uncorrected data at 900 GeV and 7 TeV on the charged particle multiplicity distribution in the "transverse" region for charged particles (p_T > 0.5 GeV/c, |η| < 2) as defined by the leading charged particle jet with PT(chgjet#1) > 3 GeV/c compared with PYTHIA Tune Z1 at the detector level (*i.e.*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

MB & UE



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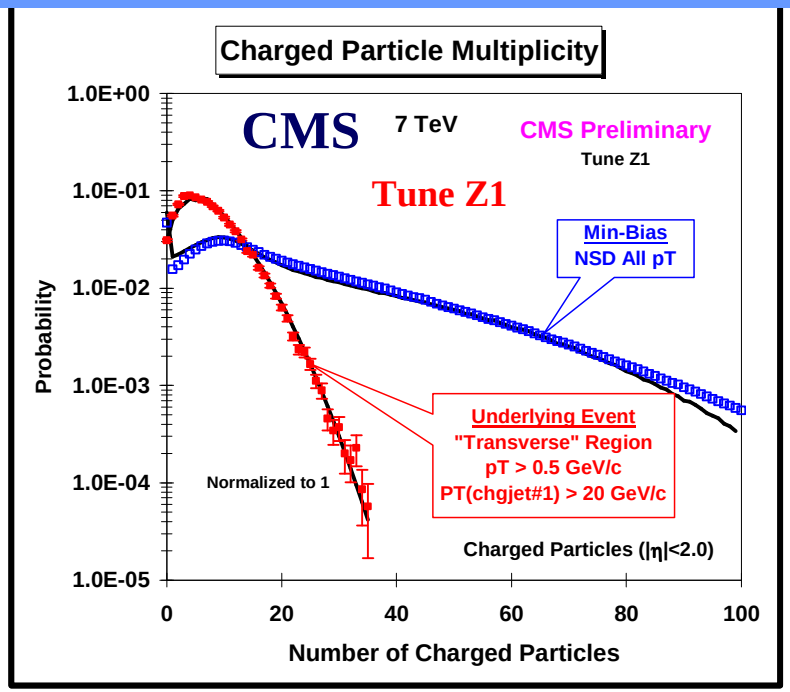
Amazing what we are asking the Monte-Carlo models to fit!

MB & UE



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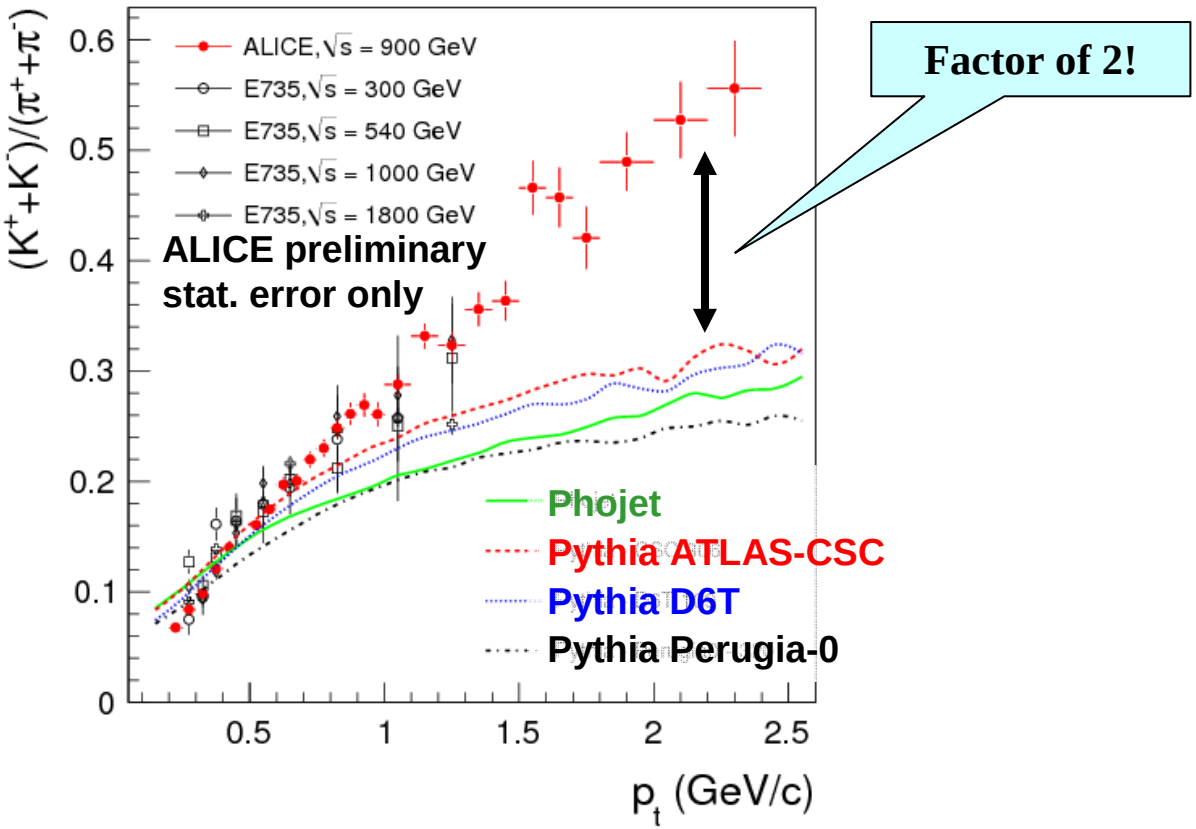
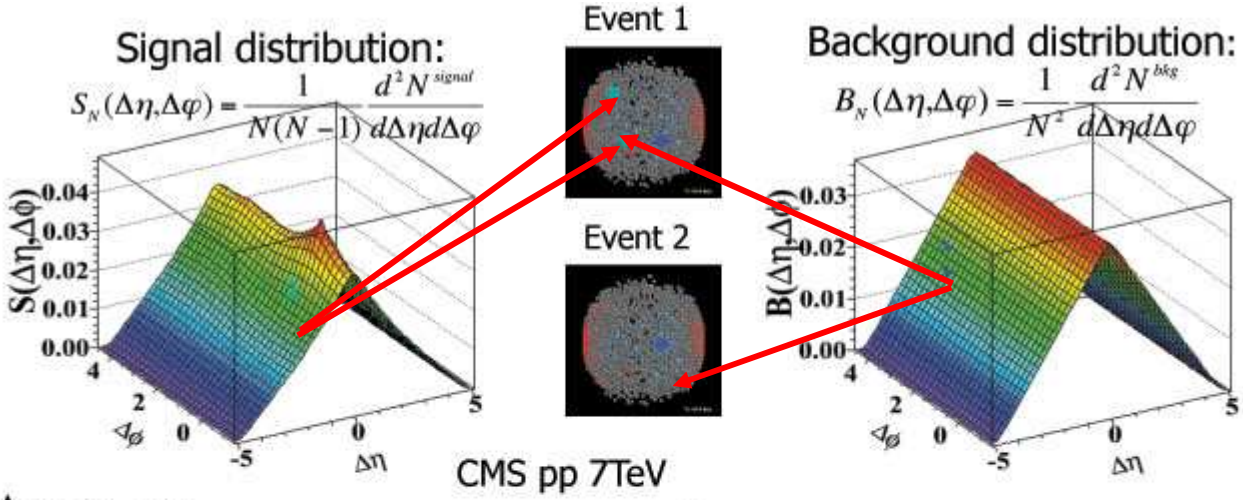
Amazing what we are asking the Monte-Carlo models to fit!

Strange Particle Production



- A lot more strange mesons at large p_T than predicted by the Monte-Carlo Models!
- K/π ratio fairly independent of the center-of-mass energy.

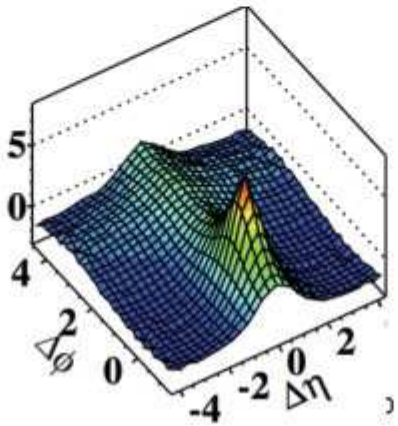
Two Particle Angular Correlations



$\Delta\eta = \eta_1 - \eta_2$

$\Delta\varphi = \varphi_1 - \varphi_2$

CMS pp 7TeV



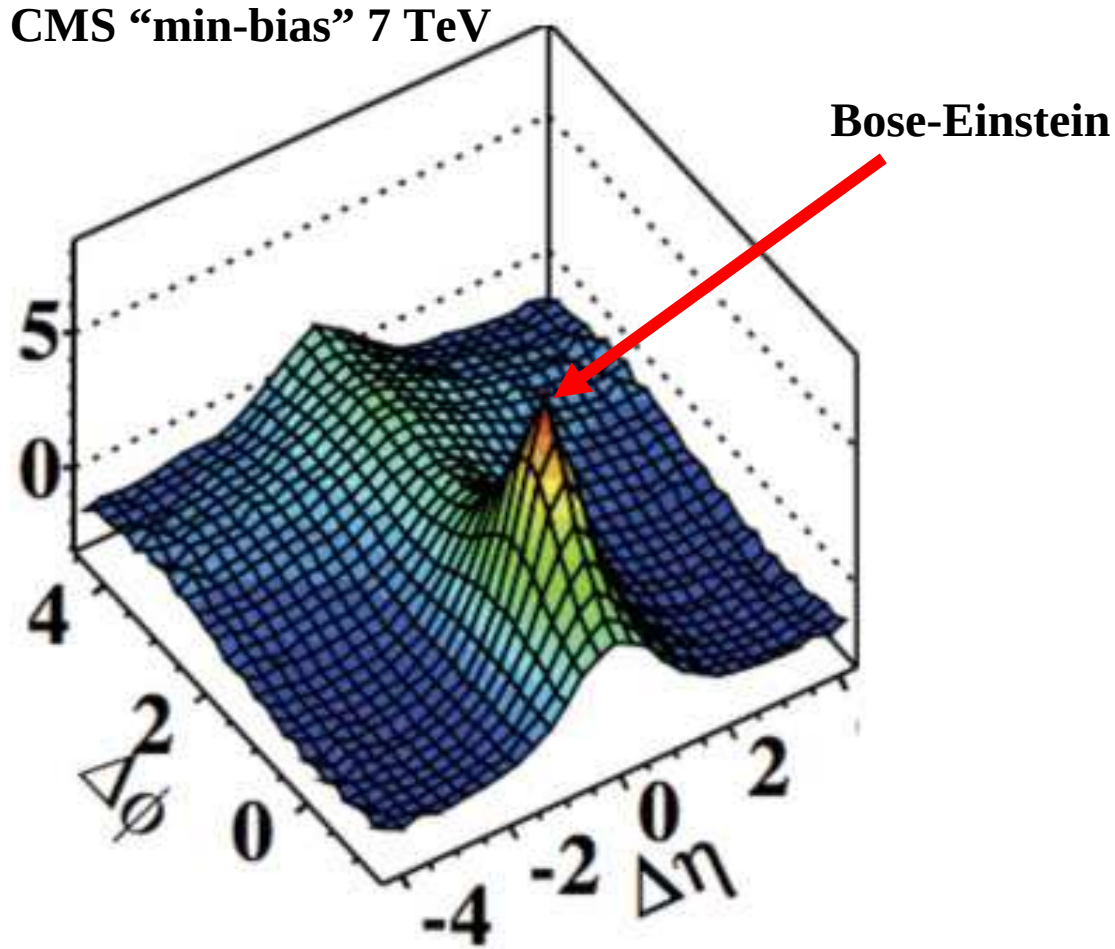
$$R(\Delta\eta,\Delta\varphi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right)\right\rangle,$$

p_T-inclusive two-particle angular correlations in MinBias collisions

- **Signal, S, is two particles in the same event. Background, B, is two particles in two different events.**
- **Correlation, R, is ~(S-B)/B.**

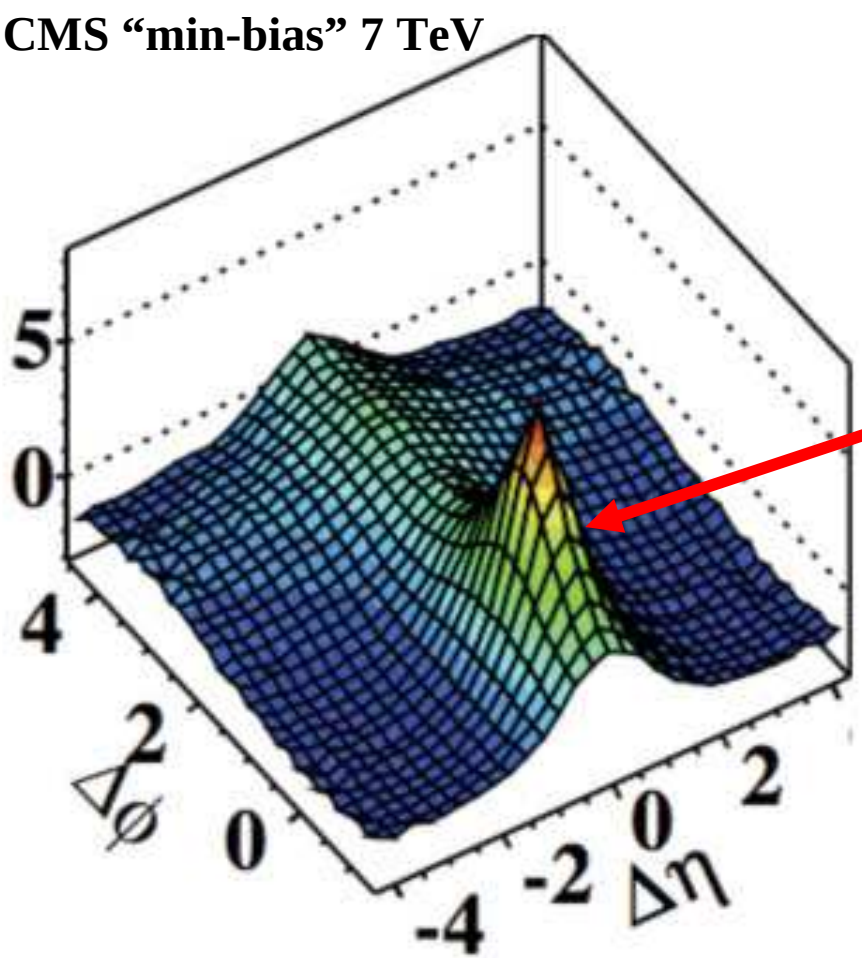
Two Particle Angular Correlations

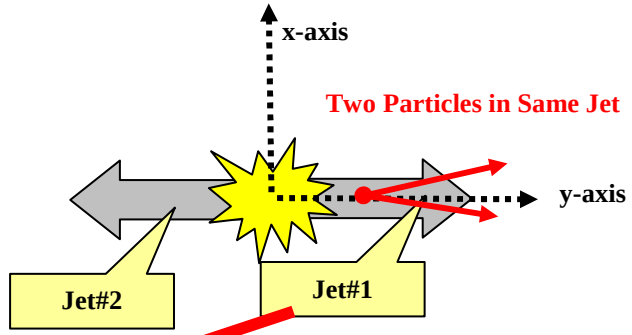
CMS "min-bias" 7 TeV



Two Particle Angular Correlations

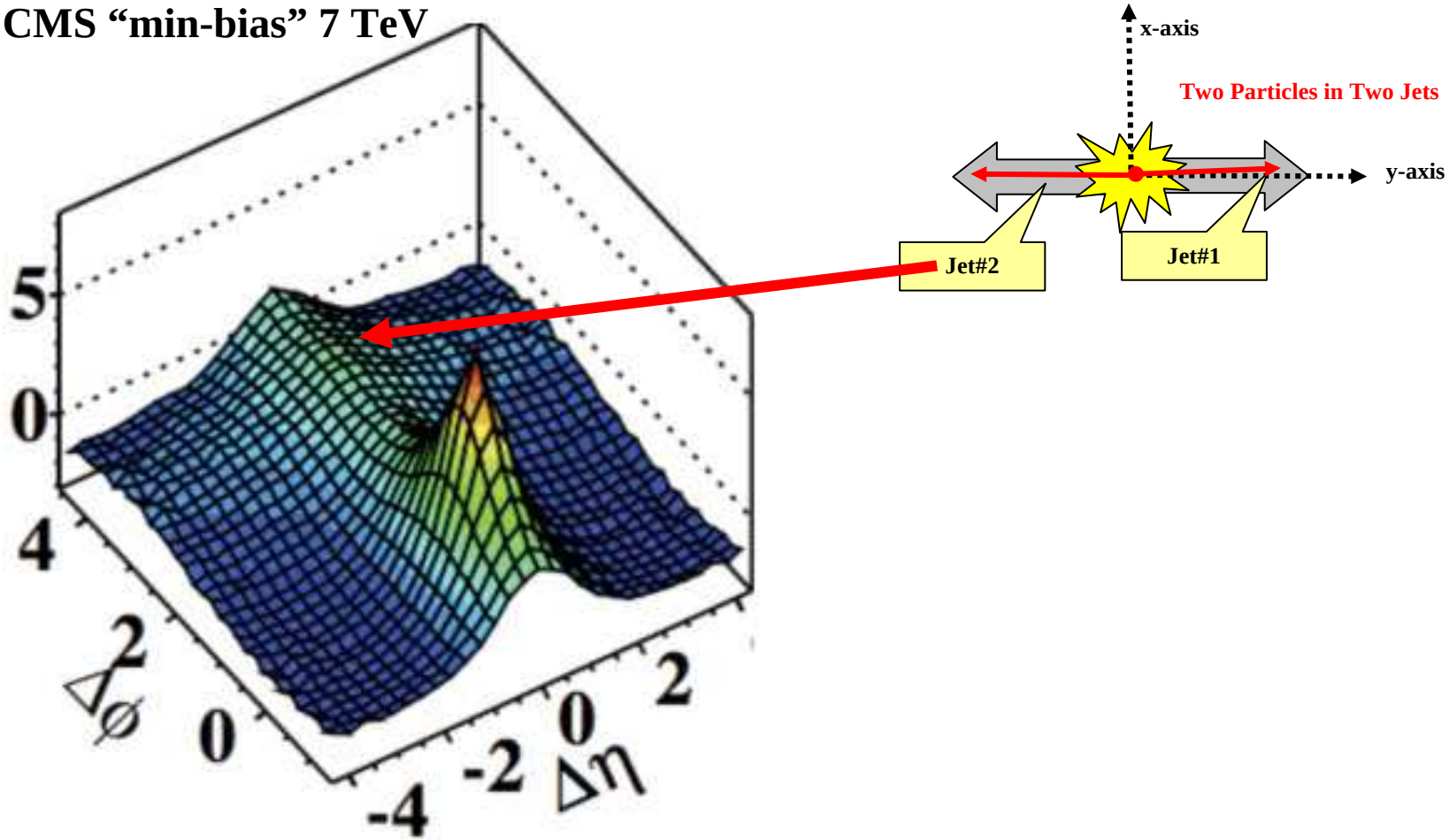
CMS "min-bias" 7 TeV



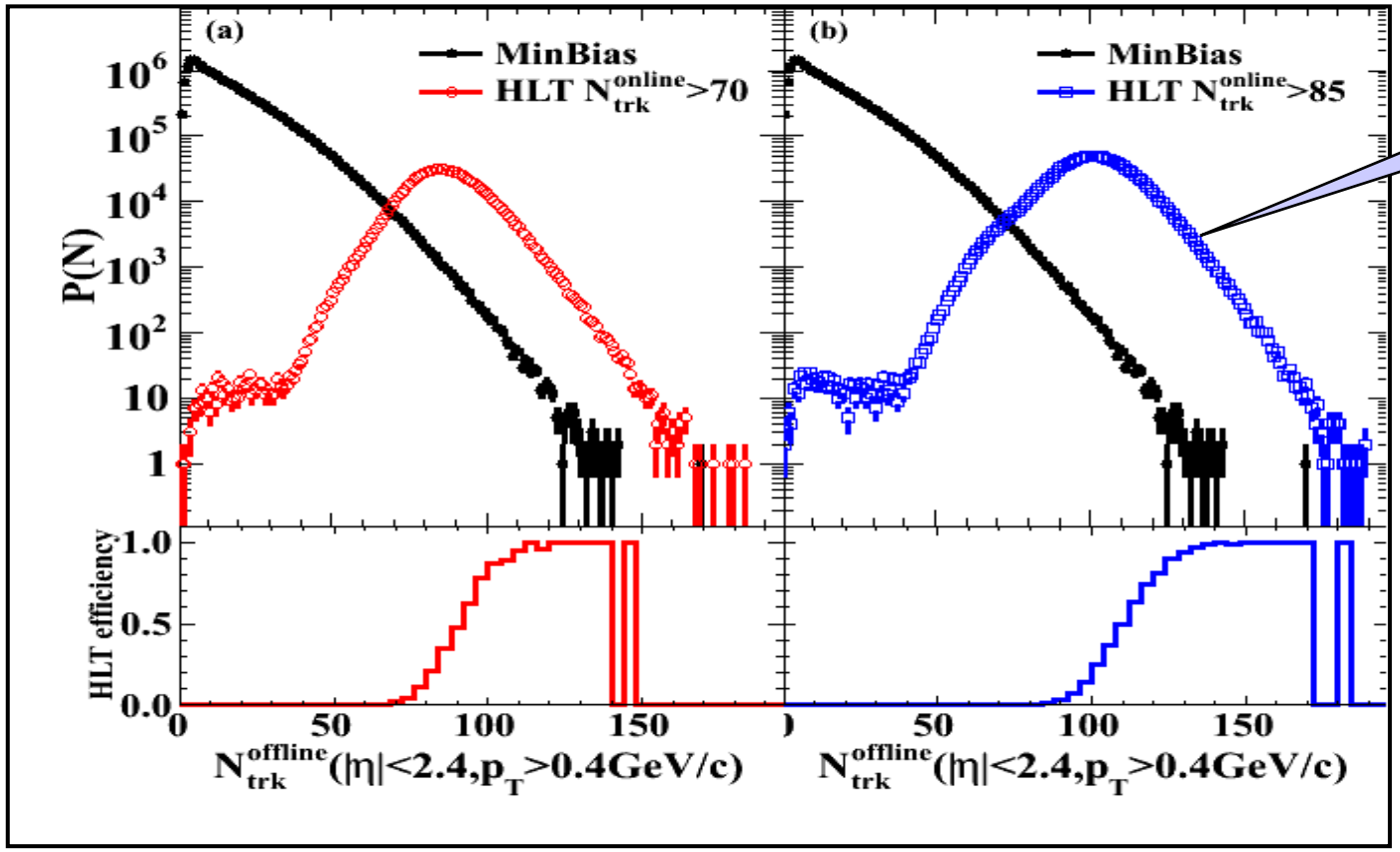


Two Particle Angular Correlations

CMS "min-bias" 7 TeV



CMS High Multiplicity Trigger

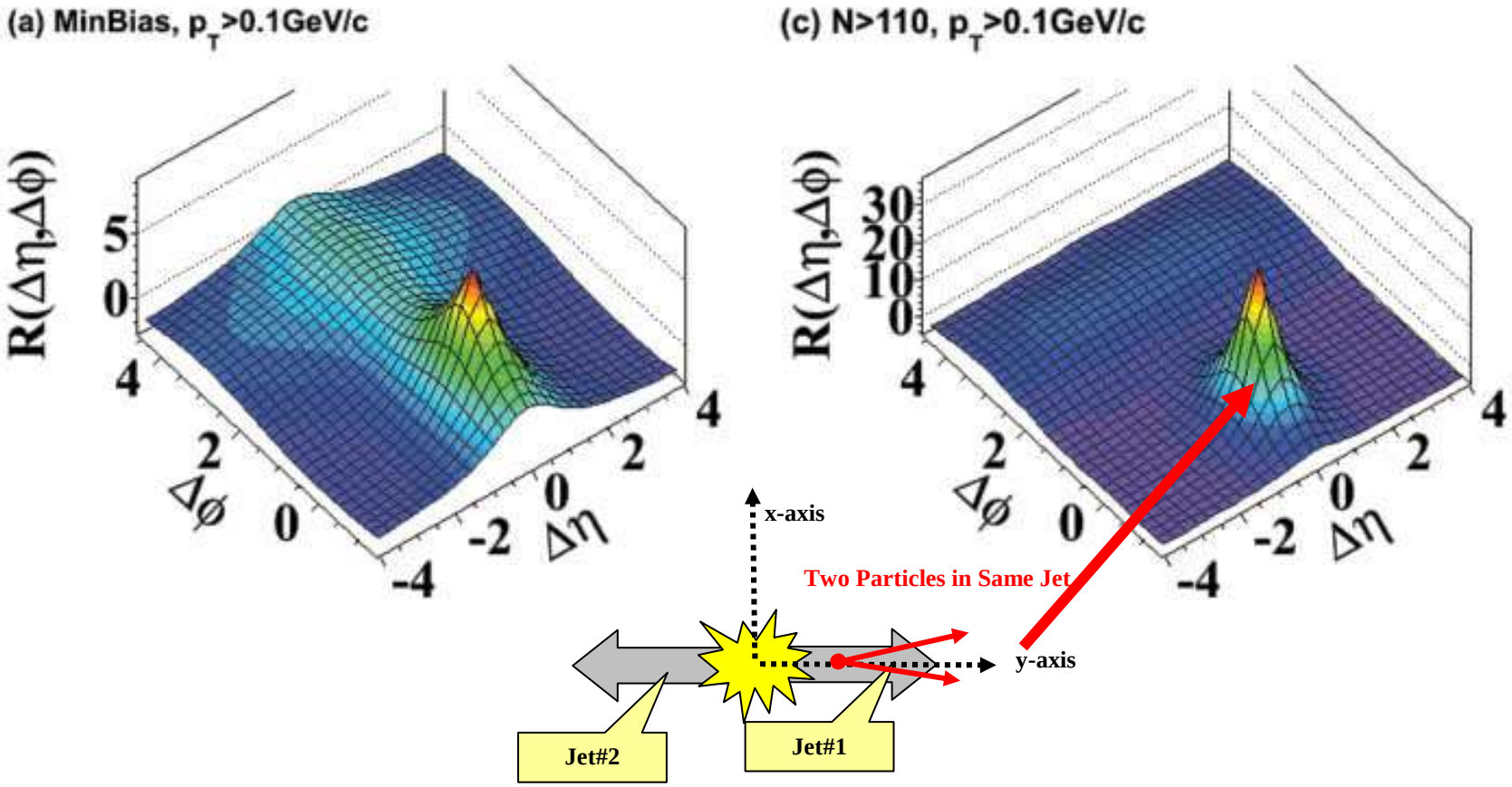


Statistics for high multiplicity enhanced by ~1,000!

- A dedicated high multiplicity trigger was implemented in the two levels of the CMS trigger system. Level 1 (L1): Sum of the total ET (ECAL, HCAL, and HF) > 60 GeV.
- High-level trigger (HLT): number of online tracks built from the three layers of pixel detectors >70 (85).

Two Particle Angular Correlations

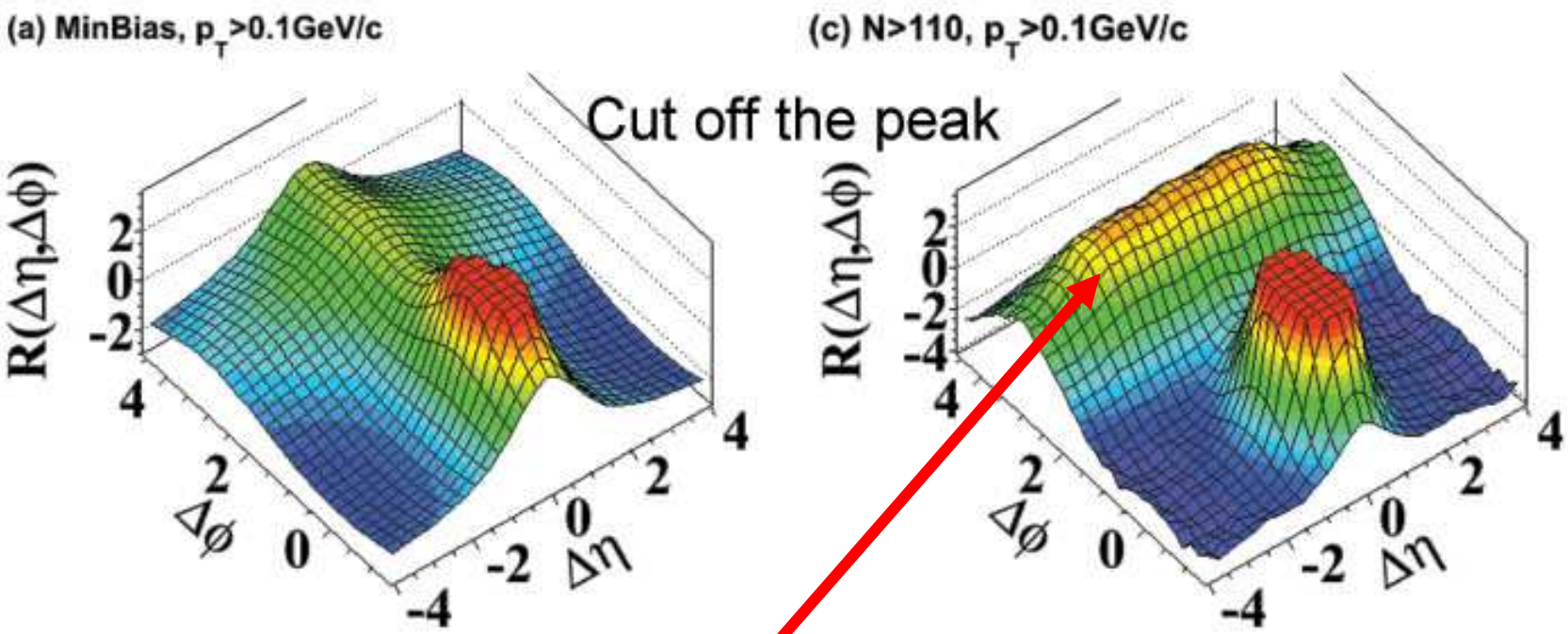
Average "Min-Bias" | **High Multiplicity "Min-Bias"**



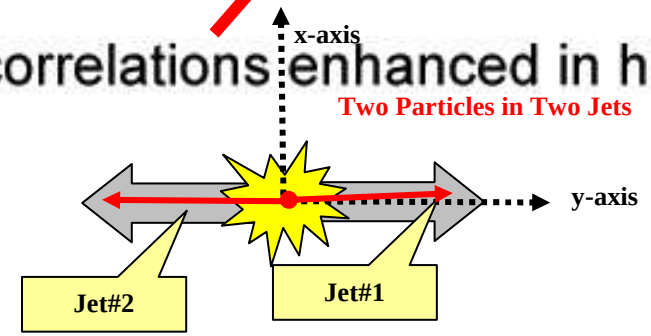
➡ **Lots of jets at high multiplicity!**

Two Particle Angular Correlations

Average "Min-Bias" | **High Multiplicity "Min-Bias"**



Back-to-back jet correlations enhanced in high multiplicity



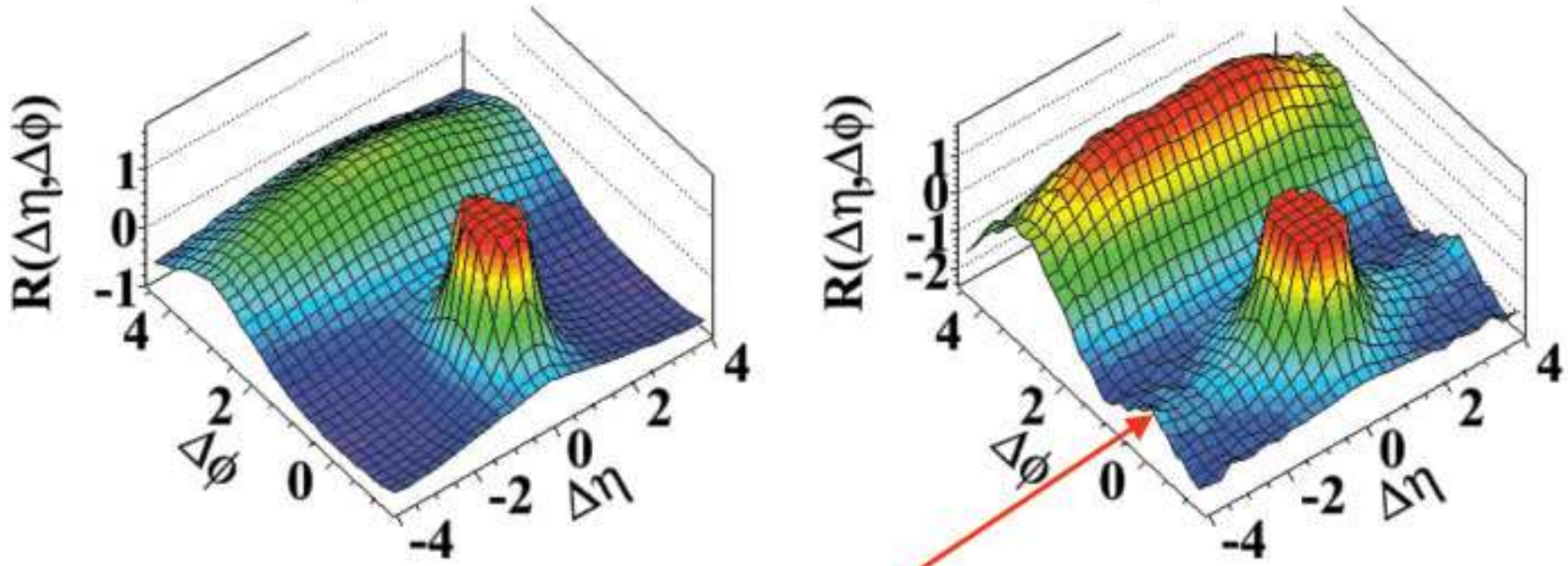
Two Particle Angular Correlations

Average "Min-Bias"

(b) MinBias, 1.0GeV/c<p_T<3.0GeV/c

High Multiplicity "Min-Bias"

(d) N>110, 1.0GeV/c<p_T<3.0GeV/c

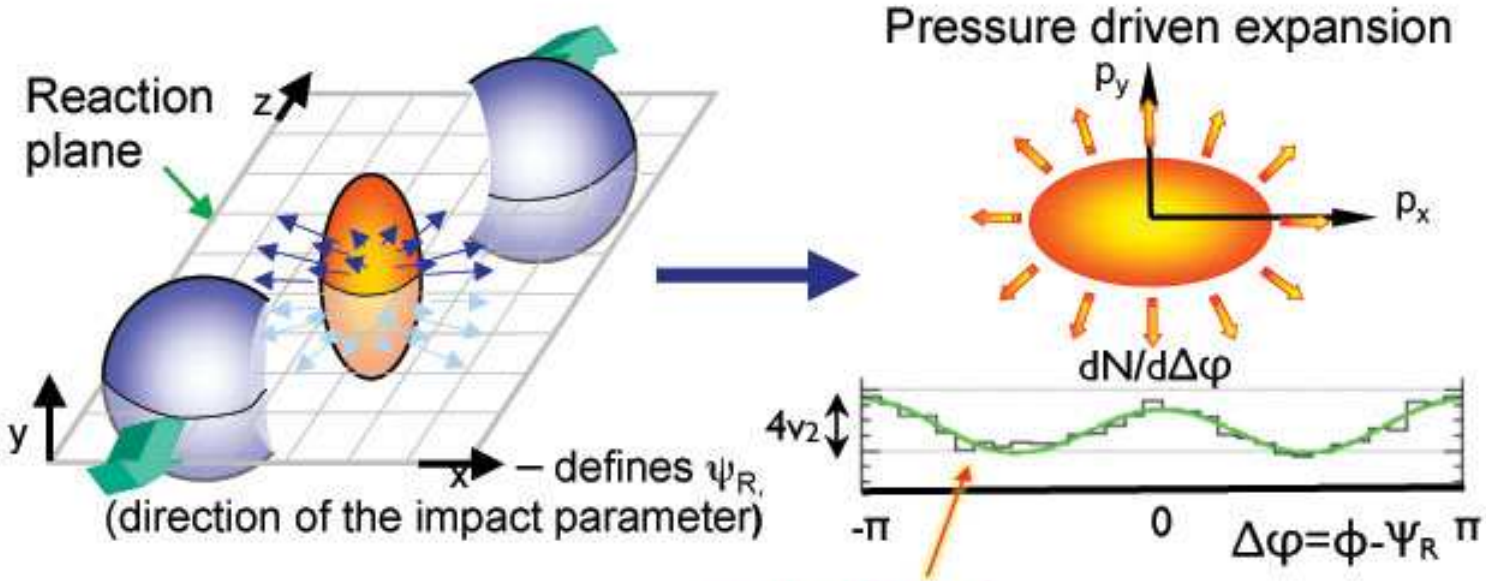


Striking "ridge" structure extending to large Δη at Δφ ~ 0

➡**Long range (in Δη) same side correlations! What is this?**

Correlation in Heavy Ion Collisions

Collective flow phenomena:



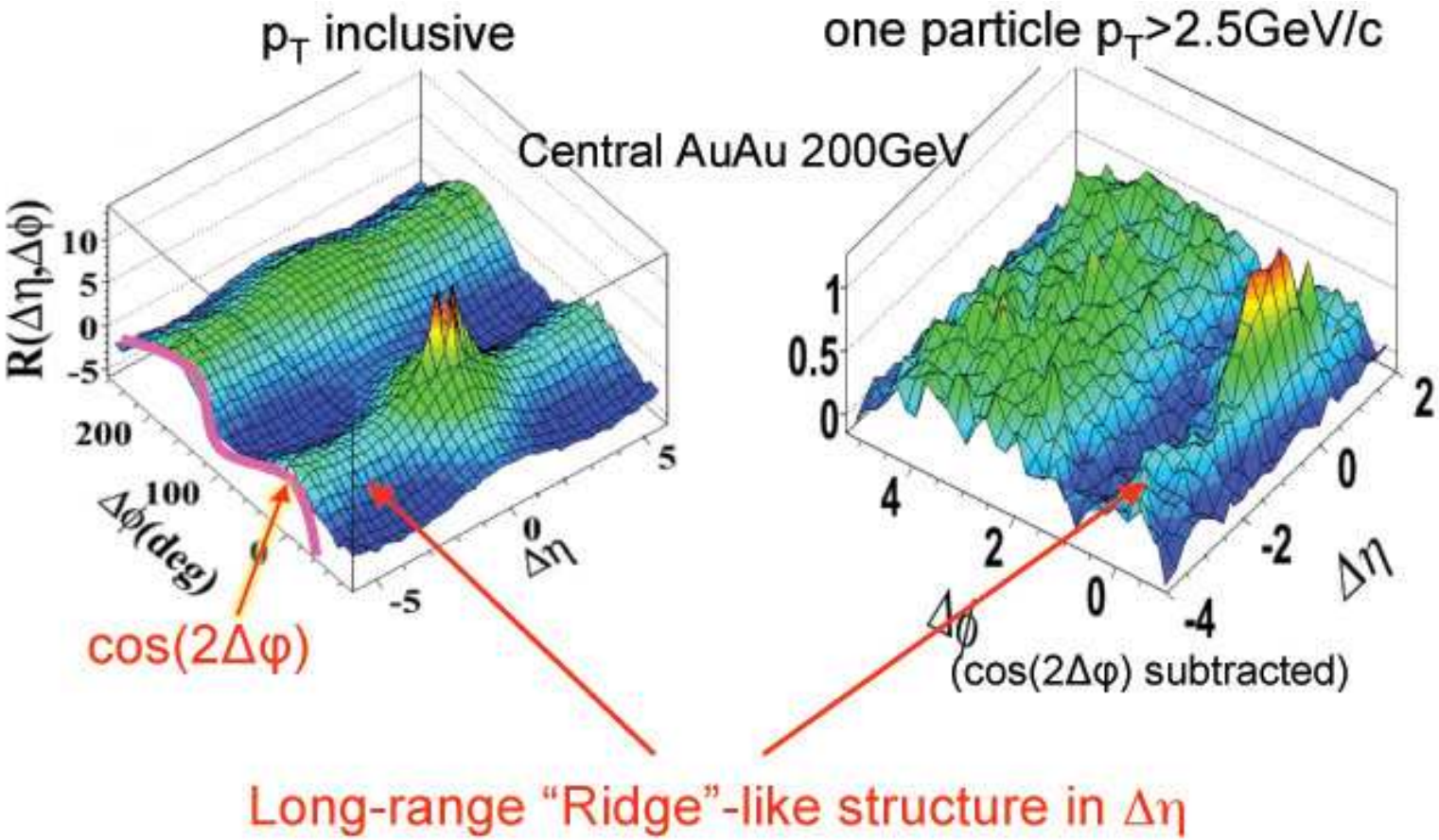
~ cos(2Δφ) (long-range in η)

Extracted shear viscosity of the medium found to be close to theoretical lower bound 1/4π

Most convincing evidence of "Perfect liquid" at RHIC!

➡ **Long range correlations expected in "collective flow" in heavy ion collisions.**

Correlation in Heavy Ion Collisions

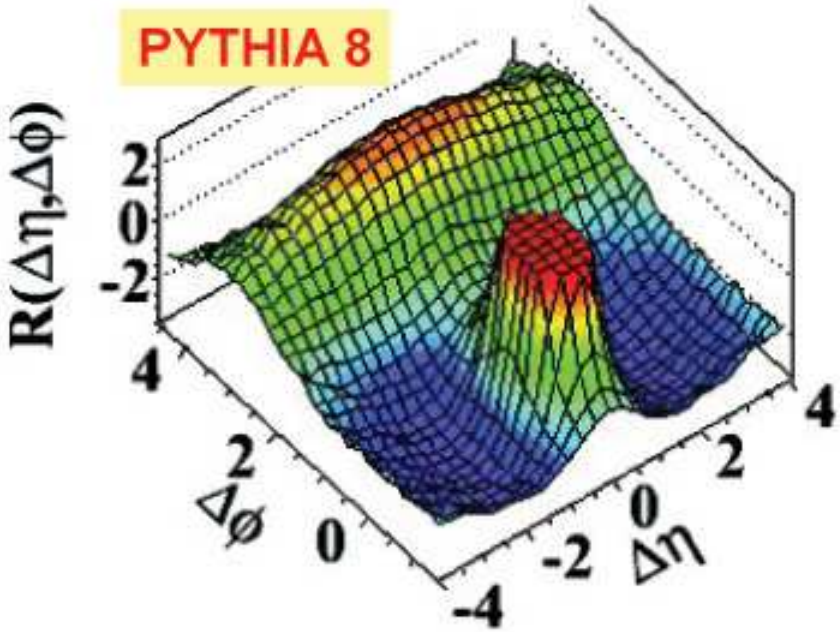


➡ **Long-range "Ridge"-like structure in Δη at Δφ ≈ 0!**

Long-Range Same-Side Correlations

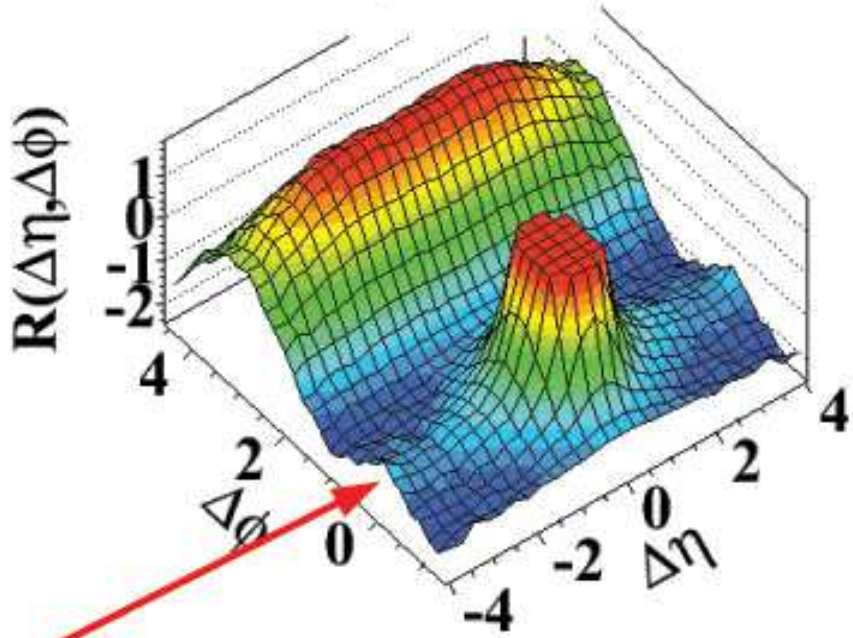
High Multiplicity "Min-Bias"

(d) N>110, 1.0GeV/c<p_T<3.0GeV/c



High Multiplicity "Min-Bias"

(d) N>110, 1.0GeV/c<p_T<3.0GeV/c

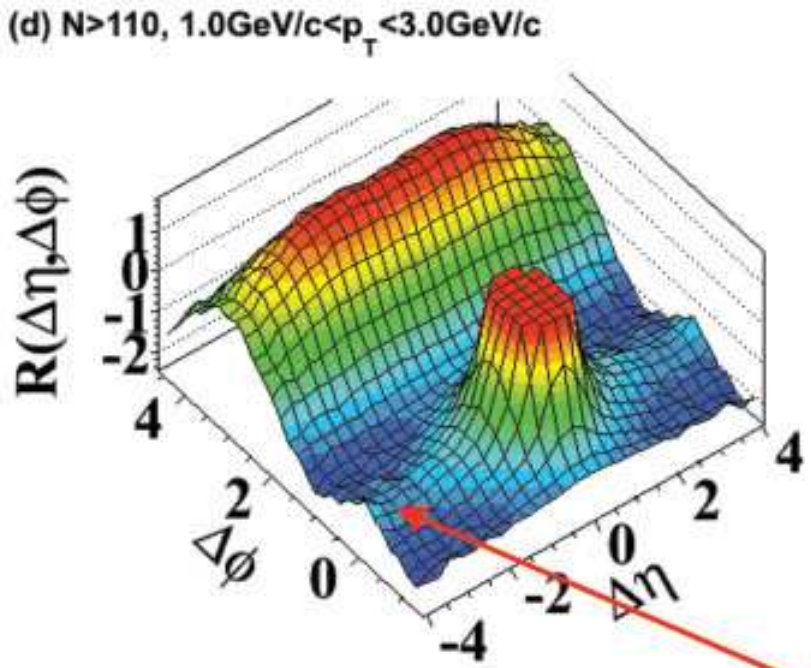


→ Observation of a Long-Range, Near-Side angular correlations at high multiplicity in pp events at intermediate p_T (Ridge at $\Delta\phi \sim 0$)

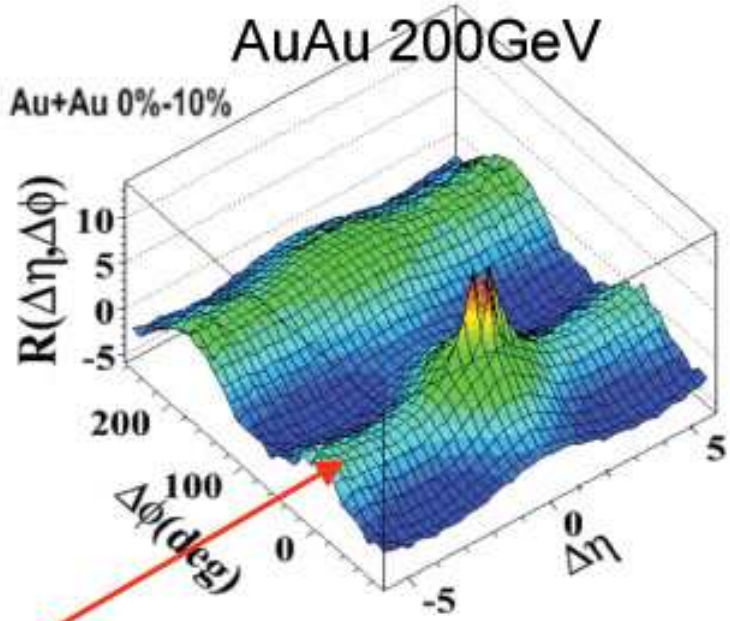
Not there in PYTHIA8! Also not there in PYTHIA 6 and HERWIG++!

Proton-Proton vs Au-Au

Proton-Proton Collisions 7 TeV



Gold-Gold Collisions 200 GeV



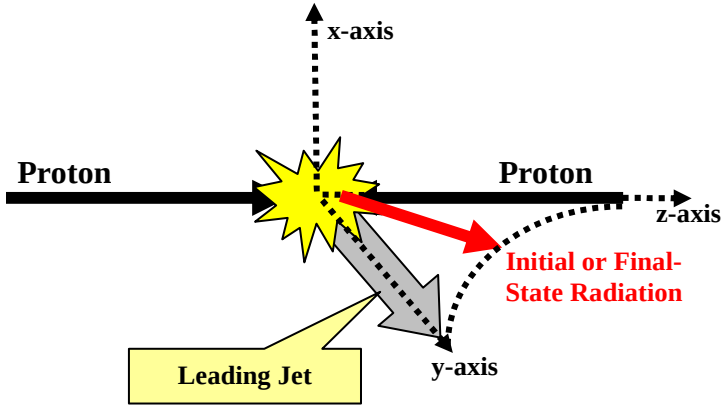
Similar "ridge" in high multiplicity pp
(even similar p_T dependence)

➡ **I am not ready to jump on the quark-gluon plasma bandwagon quite yet!**

Jet-Jet Correlations

- Are the "leading-log" or "modified leading-log" QCD Monte-Carlo Models missing an important QCD correlation?

- The leading jet and the incident protons form a plane (yz-plane in the figure). This is the plane of the hard scattering.

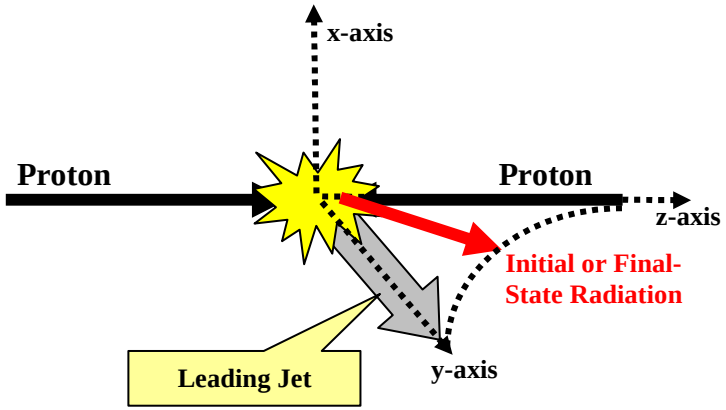


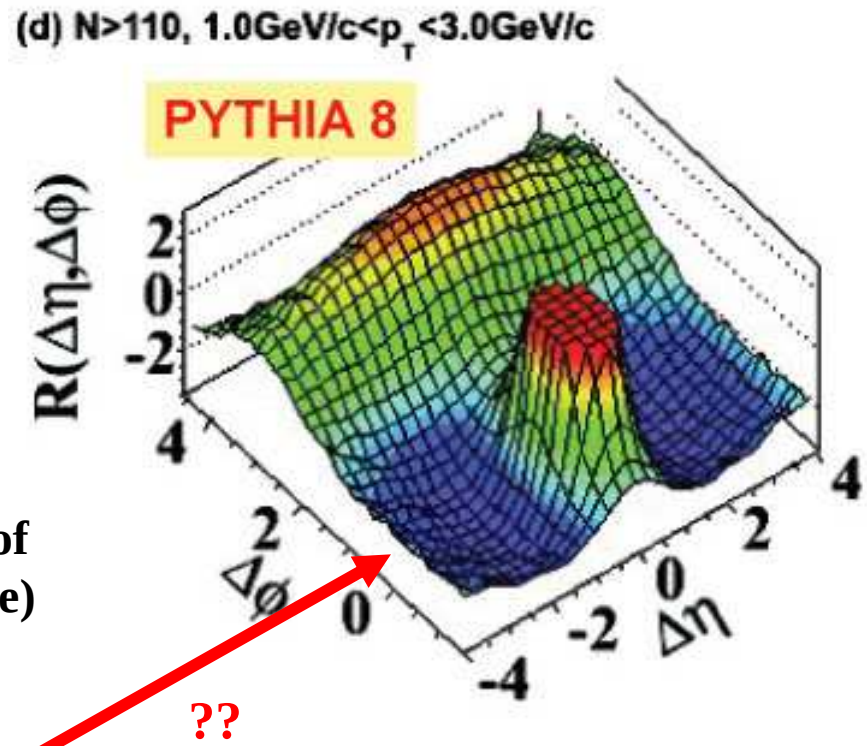
- Initial & final-state radiation prefers to lie in this plane. This is a higher order effect that you can see in the 2→3 or 2→4 matrix elements, but it is not there if you do 2→2 matrix elements and then add radiation using a naïve leading log approximation (*i.e.* independent emission).

- I do not know to what extent this higher order jet-jet correlation is incorporated in the QCD Monte-Carlo models.

- I would think that this jet-jet correlation would produce a long range (in $\Delta\eta$) correlation with $\Delta\phi \approx 0$ from two particles with one in the leading jet and one in the radiated jet. Why don't we see this in the Monte-Carlo models?

Jet-Jet Correlations





- **Initial & Final-State Radiation:** **There should be more particles "in-the-plane" of the hard scattering (yz-plane in the figure) than "out-of –the-plane".**

- **I do not understand why this does not result in a long-range same-side correlation?**

Min-Bias Summary

- **We are a long way from having a Monte-Carlo model that will fit all the features of the LHC min-bias data! There are more soft particles that expected!**
- **We need a better understanding and modeling of diffraction!**
- **It is difficult for the Monte-Carlo models to produce a soft event (*i.e.* no large hard scale) with a large multiplicity. There seems to be more "min-bias" high multiplicity soft events at 7 TeV than predicted by the models!**
- **The models do not produce enough strange particles! I have no idea what is going on here! The Monte-Carlo models are constrained by LEP data.**