Soft QCD at the LHC: Findings & Surprises

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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) inspired by the ATLAS Tune AMBT1.

- Strange particle production. A problem for the models?

PYTHIA 6.4 Tune Z1:

- Underlying Event
- Final State Radiation
- Initial-State Radiation
- Outgoing Parton
CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged particle density, \(\frac{dN}{d\eta d\phi}\), 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, \( dN/d\eta d\phi \), 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.
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CDF published data at 1.96 TeV on the “transverse” charged particle density, $dN/d\eta d\phi$, as defined by the leading calorimeter jet (jet#1) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 1.0$. The data are corrected and compared with PYTHIA Tune DW at the generator level.
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“Transverse” Charge Density

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

~0.4 → ~0.8

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

RDF Preliminary
by Tune DW generator level

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

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Shows the growth of the “underlying event” as the center-of-mass energy increases.
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, $|\eta| < 2$) 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.
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!
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!
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!
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.

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“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!
“Leading Jet”
Jet #1 Direction
“Toward”
“TransMAX”
“Away”
“TransMIN”
Jet #2 Direction
“Toward”
“TransMAX”
“ Away”
“TransMIN”

“Back-to-Back”
Jet #1 Direction
“Toward”
“TransMAX”
“ Away”
“TransMIN”

Shows the data on the tower ETsum density, dET_sum/d\eta d\phi, in the “transMAX” and “transMIN” region (E_T > 100 MeV, |\eta| < 1) versus P_T(jet#1) for “Leading Jet” and “Back-to-Back” events.

Compares the (corrected) data with PYTHIA Tune A (with MPI) and HERWIG (without MPI) at the particle level (all particles, |\eta| < 1).
Shows the data on the tower ETsum density, \( d\text{ET}_{\text{sum}}/d\eta d\phi \), in the “transMAX” and “transMIN” region (\( E_T > 100 \text{ MeV} \), \( |\eta| < 1 \)) versus \( P_T(\text{jet#1}) \) for “Leading Jet” and “Back-to-Back” events.

Compares the (corrected) data with PYTHIA Tune A (with MPI) and HERWIG (without MPI) at the particle level (all particles, \( |\eta| < 1 \)).

Neither PY Tune A or HERWIG fits the ETsum density in the “transferse” region! HERWIG does slightly better than Tune A!
Use the leading jet to define the MAX and MIN "transverse" regions on an event-by-event basis with MAX (MIN) having the largest (smallest) charged PTsum density.

Shows the "transDIF" = MAX-MIN ETsum density, dET\text{sum}/d\eta d\phi, for all particles (|\eta| < 1) versus \text{P}_T(jet#1) for "Leading Jet" and "Back-to-Back" events.
Possible Scenario??

PYTHIA Tune A fits the charged particle PTsum density for $p_T > 0.5$ GeV/c, but it does not produce enough ETsum for towers with $E_T > 0.1$ GeV.

It is possible that there is a sharp rise in the number of particles in the “underlying event” at low $p_T$ (i.e. $p_T < 0.5$ GeV/c).

Perhaps there are two components, a vary “soft” beam-beam remnant component (Gaussian or exponential) and a “hard” multiple interaction component.
Compared 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 $dN/d\eta$ for the region $|\eta| < 0.6$.
LHC MB Predictions: 900 GeV

• Compares the 900 GeV Proton Proton "Minimum Bias" Collisions 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 |η| < 0.6.
None of the tunes fit the ATLAS INEL $dN/d\eta$ data with $PT > 100$ MeV! They all predict too few particles.

The ATLAS Tune AMBT1 was designed to fit the inelastic data for $N_{ch}g \geq 6$ with $p_T > 0.5$ GeV/c!
ALICE inelastic data at 900 GeV on the $dN/d\eta$ distribution for charged particles ($p_T > PT_{\text{min}}$) for events with at least one charged particle with $p_T > PT_{\text{min}}$ and $|\eta| < 0.8$ for $PT_{\text{min}} = 0.15$ 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.
ALICE inelastic data at 900 GeV on the dN/d\(\eta\) distribution for charged particles (\(p_T > PT_{\text{min}}\)) for events with at least one charged particle with \(p_T > PT_{\text{min}}\) and |\(\eta| < 0.8\) for \(PT_{\text{min}} = 0.15 \text{ GeV/c}, 0.5 \text{ GeV/c},\) and 1.0 GeV/c compared with PYTHIA Tune Z1 at the generator level (dashed = ND, solid = INEL).

Diffraction contributes less at harder scales!

Cannot trust PYTHIA 6.2 modeling of diffraction!
Generator level $dN/d\eta$ (all $p_T$). Shows the NSD = HC + DD and the HC = ND contributions for Tune DW. Also shows the CMS NSD data.

Off by 50%!
Okay if the Monte-Carlo does not fit the data what do we do?

We tune the Monte-Carlo to fit the data!

Charged Particle Density: \( \frac{dN}{d\eta} \)

- \( \eta \) varies from -3.0 to 3.0
- PseudoRapidity

- 7 TeV
- RDF Preliminary
- CMS NSD data pyDW generator level
- dashed = ND  solid = NSD

- CMS

- \( \frac{dN}{d\eta} \) (all pT)

- Shows the NSD = HC + DD and the HC = ND contributions for Tune DW.

- Also shows the CMS NSD data.

- Off by 50%!
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!
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 $N_{ch} \geq 6$ and to fit the $p_T^{\text{max}}$ UE data with $p_T^{\text{max}} > 10$ GeV/c. Tune AMBT1 is primarily a min-bias tune, while Tune Z1 is a UE tune!
## PYTHIA Tune Z1

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

Parameters not shown are the PYTHIA 6.4 defaults!
CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged particle density, $dN/d\eta d\phi$, 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).

Tune Z1 (CTEQ5L)
- $\text{PARP}(82) = 1.932$
- $\text{PARP}(90) = 0.275$
- $\text{PARP}(77) = 1.016$
- $\text{PARP}(78) = 0.538$

Color reconnection suppression. Color reconnection strength.

Tune Z1 is a PYTHIA 6.4 using $p_T$-ordered parton showers and the new MPI model!
 CMS preliminary data at 900 GeV and 7 TeV on the “transverse” charged PTsum density, \(dPT/d\eta d\phi\), 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.
"Transverse" Charged Particle Density: \( \frac{dN}{d \eta d \phi} \)

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 \( p_T > 0.5 \text{ GeV/c} \) and \( |\eta| < 2.0 \). The data are uncorrected and compared with PYTHIA Tune DW, D6T, CW, and P0 after detector simulation (SIM).

- **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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Ratio of the ATLAS preliminary data on the charged particle density in the “transverse” region for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 2.5$) at 900 GeV and 7 TeV as defined by $P_T_{max}$ compared with PYTHIA Tune Z1 at the generator level.

Ratio of the ATLAS preliminary data on the charged PTsum density in the “transverse” region for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 2.5$) at 900 GeV and 7 TeV as defined by $P_T_{max}$ compared with PYTHIA Tune Z1 at the generator level.
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MPI Cut-Off versus the Center-of-Mass Energy $W_{cm}$: PYTHIA Tune Z1 was determined by fitting $p_T^0$ independently at 900 GeV and 7 TeV and calculating $\varepsilon = \text{PARP}(90)$. The best fit to $p_T^0$ at CDF is slightly higher than the Tune Z1 curve. This is very preliminary! Perhaps with a global fit to all three energies (i.e. “Professor” tune) one can get a simultaneous fit to all three??

$p_T^0(W)=p_T^0(W/W_0)^\varepsilon \quad \varepsilon = \text{PARP}(90) \quad p_T^0 = \text{PARP}(82) \quad W = E_{cm}$
MPI Cut-Off versus the Center-of Mass Energy $W_{cm}$: PYTHIA Tune Z1 was determined by fitting $p_{T0}$ independently at 900 GeV and 7 TeV and calculating $\varepsilon = \text{PARP}(90)$. The best fit to $p_{T0}$ at CDF is slightly higher than the Tune Z1 curve. This is very preliminary! Perhaps with a global fit to all three energies (i.e. “Professor” tune) one can get a simultaneous fit to all three?*

$$p_{T0}(W) = p_{T0}(W/W_0)^\varepsilon \quad \varepsilon = \text{PARP}(90) \quad p_{T0} = \text{PARP}(82) \quad W = E_{cm}$$
In PYTHIA 6.4 the “color reconnection” strength, PARP(78), is a constant. However, if you find the best value (“min-bias” tune) at each energy independently it seems to have an energy dependence!
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, $|\eta| < 2$) as defined by the leading charged particle jet with $\text{PT}(\text{chgjet#1}) > 3$ GeV/c compared with PYTHIA Tune DW, and Tune D6T at the detector level (i.e. Theory + SIM).

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Difficult to produce enough events with large “transverse” multiplicity at low hard scale!
CMS uncorrected data at 7 TeV on the charged PTsum distribution in the "transverse" region for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 2$) as defined by the leading charged particle jet with $PT(chgjet#1) > 3$ GeV/c and $PT(chgjet#1) > 20$ GeV/c compared with PYTHIA Tune DW and Tune D6T at the detector level (i.e. Theory + SIM).

CMS Preliminary data uncorrected Theory + SIM

CMS Preliminary data uncorrected pyZ1 + SIM

Normalized to 1

Charged Particles ($|\eta|<2.0$, $PT>0.5$ GeV/c)

Charged Particles ($|\eta|<2.0$, $PT>0.5$ GeV/c)

7 TeV

7 TeV

CMS

CMS

"Transverse" Charged PTsum Distribution

"Transverse" Charged PTsum Distribution
CMS uncorrected data at 7 TeV on the charged PTsum distribution in the “transverse” region for charged particles ($p_T > 0.5$ GeV/c, $|\eta| < 2$) 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).

Difficult to produce enough events with large “transverse” PTsum at low hard scale!
Generator level $dN/d\eta$ (all pT). Shows the NSD = HC + DD and the HC = ND contributions for Tune Z1. Also shows the CMS NSD data.

Generator level $dN/d\eta$ (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!
ALICE inelastic data at 900 GeV on the $dN/d\eta$ distribution for charged particles ($p_T > PT_{\text{min}}$) for events with at least one charged particle with $p_T > PT_{\text{min}}$ and $|\eta| < 0.8$ for $PT_{\text{min}} = 0.15$ 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!
Generator level charged multiplicity distribution (all pT, |η| < 2) at 7 TeV. Shows the NSD = HC + DD and the HC = ND contributions for Tune Z1. Also shows the CMS NSD data.

Okay not perfect! But not that bad!
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!
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 uncorrected data at 900 GeV and 7 TeV on the charged particle multiplicity distribution in the “transverse” region for charged particles (pT > 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).
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, $|\eta| < 2$) as defined by the leading charged particle jet with $p_T(chgjet#1) > 20$ GeV/c compared with PYTHIA Tune Z1 at the detector level (i.e. Theory + SIM). Also shows the CMS corrected NSD multiplicity distribution (all $p_T$, $|\eta| < 2$) compared with Tune Z1 at the generator.

Amazing what we are asking the Monte-Carlo models to fit!
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, $|\eta| < 2$) as defined by the leading charged particle jet with $PT(chgjet#1) > 20$ GeV/c compared with PYTHIA Tune Z1 at the detector level (i.e. Theory + SIM). Also shows the CMS corrected NSD multiplicity distribution (all $p_T$, $|\eta| < 2$) compared with Tune Z1 at the generator.

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!

$K/\pi$ ratio fairly independent of the center-of-mass energy.
More strange baryons than expected!
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 than 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.
We need a better understanding and modeling of diffraction!

Explore by defining “diffractive enhanced” data samples!

See the talk by Lauren Tompkins at the LPCC MB&UE@LHC Meeting September 6, 2010,
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!

Explore by using a high multiplicity trigger!

Fired chips in first pixel detector layer
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!

Explore by using a high multiplicity trigger!

CMS also has a high multiplicity trigger and will report on their early findings soon!

Fired chips in first pixel detector layer
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.

Here it is important to study the ratios K/π or K/(all charged) etc.!