Minimum Bias Measurements at the LHC

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On behalf of ATLAS and CMS collaborations

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Minimum Bias?

- Events selected with a minimally biased trigger selection
- Measurements performed with both tracks and clusters
- Complementary information

Not to be confused with Underlying Event or Pileup
Why important?

• Pedestal activity to all physics processes
• Not perturbative processes
• Cant subtract the contribution on an event-by-event basis
• Modelled in Monte Carlo Generators
# Monte Carlo Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td><strong>Pythia8 4C</strong></td>
<td>(Author) MB+UE tune with CTEQ6L1</td>
</tr>
<tr>
<td><strong>Pythia8 Monash</strong></td>
<td>(Author) MB+UE tune with NNPDF2.3LO</td>
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<tr>
<td><strong>Pythia8 CUETP8S1</strong></td>
<td>(CMS) UE tune based on 4C</td>
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<tr>
<td><strong>Pythia8 CUETP8M1</strong></td>
<td>(CMS) UE tune based on Monash</td>
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<tr>
<td><strong>Pythia8 A2</strong></td>
<td>(ATLAS) Minbias/Central ET flow tune based on 4C</td>
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<tr>
<td><strong>Herwig++ UE-EE-5C</strong></td>
<td>(Author) UE tune with energy scaling using CTEQ6L1</td>
</tr>
<tr>
<td><strong>Epos LHC</strong></td>
<td>Based on Gribov’s Pomeron exchange/collective flow approach, use LHC and fixed target experiment data to describe hadron and nuclear collisions.</td>
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<tr>
<td><strong>QGSJET-II</strong></td>
<td>Cosmic Ray/Air Shower</td>
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<td><strong>Sibyll</strong></td>
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Looking back ...

- Measurements at the beginning of Run 1 showed bad description of data by then-existing (mostly from Tevatron) Monte Carlo models and tunes.

- Significant effort went in both theory and experimental communities to improve the modelling, using LHC Run 1 data.

- Big question we had at the beginning of Run 2: can these models describe the 13 TeV data?
Overall Epos is the best, stark difference in A2 predictions going from 100 to 500 MeV
Charged Particle Transverse Momentum

Higher transverse momentum threshold

Epos is best for both A2 and Monash are competitive but not over the full range

arXiv:1606.01133

Charged Particle Multiplicity

Higher transverse momentum threshold

Similar trends

None of the models do well over the whole range
Mean Transverse Momentum against Multiplicity Correlation

Higher transverse momentum threshold

Correlation depends on colour reconnection

Better modelled at 500 MeV, QGSJETII has no CR
• Models show discriminating power
• Results available for different phase spaces
Dependence on E.C.M

About 20% increase from going from 7 to 13 TeV

Most models get the energy extrapolation trend right
Pythia8 A3 Tune

Using Donnachie-Landshoff diffractive model and NNPDF2.3LO

Much improved total inelastic cross section prediction

Mostly similar level of agreement with Minbias observables
**Pythia8 A3 Tune**

Using Donnachie-Landshoff diffractive model and NNPDF2.3LO

<table>
<thead>
<tr>
<th>ATLAS data (mb)</th>
<th>SS (mb)</th>
<th>A3 (mb)</th>
</tr>
</thead>
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<tr>
<td>At $\sqrt{s} = 13$ TeV</td>
<td>68.1 ± 1.4</td>
<td>74.4</td>
</tr>
<tr>
<td>At $\sqrt{s} = 7$ TeV</td>
<td>60.3 ± 2.1</td>
<td>66.1</td>
</tr>
</tbody>
</table>

Mostly similar level of agreement with Minbias observables
Forward Energy Flow

Measured in $3.15 < |\eta| < 6.6$

Models in general perform worse in more forward region

Large spread in predictions

Also measured in non-single diffractive events, where models tend to do better.
Forward Energy Flow

Measured in $3.15 < |\eta| < 6.6$

Transverse energy flow as a function of shifted pseudorapidity (longitudinal scaling behaviour)

Consistent across wide range of collision energies, and becomes independent of $\sqrt{s}$ at beam fragmentation region

At least two charged particles in the range $3.9 < |\eta| < 4.4$
At least one on each side with respect to the interaction point

CMS-PAS-FSQ-15-006
Very Forward Energy Flow

Bump at \( \sim 200 \text{ GeV} \), then steeply falling

Castor
\[-5.2 < \eta < -6.6\]

Discriminating power between the models

Generally worse at the soft part of the spectrum
Very Forward Energy Flow

Electromagnetic

Models overall perform better

Sensitive to MPI

Hadronic

The bump comes from hadronic spectrum

Cosmic shower models better, but none predicts the entire shape well
Summary

• A wide range of minimum bias measurements, both with charged and neutral particles have been performed with LHC Run 2 data

• While none of the models considered is perfect for all observables and full ranges, many do a reasonable job

• Energy evolution of Multiple Parton Interactions is historically a poorly understood parametrisation, but most models seem to perform well at this new highest collision energy

• Important for pileup modelling, and constraining the Monte Carlo event generators
References

• ATLAS A3 Tune: ATL-PHYS-PUB-2016-017
• CMS forward energy flow: CMS-PAS-FSQ-15-006
• CMS/Totem very forward energy flow: CMS-PAS-FSQ-16-002
Supporting Material
NEW PREDICTIONS (10 years)

1. QCD tests & applications will greatly improve, incorporating NLO, NNLO,... and a theory of fragmentation and hadronization.
2. Atlas and CMS will discover a candidate Higgs particle.
3. There will be convincing evidence for Susy particles.
4. Plans will be underway to build a LC (at Cern) to explore the superworld and the US will join CERN.
5. There will be direct detection of the Dark Matter wind.
6. Alice will see a crossover to the perturbative quark-gluon plasma.
7. Some new Z mesons will be discovered.
8. Gravitational waves and B modes will be observed.
9. String theory will start to be a **theory** with predictions.
10. We will have a plausible explanation of why \( \Lambda \) is so small.

David Gross at EPS 2011
Detour: Event Generators

- We want realistic simulation of the collision events. To devise analysis strategy, background model, study/remove detector effect, etc.

- The hard scattering part can be calculated theoretically (in some order).

- The soft part is not calculable, so we use phenomenological models implemented in Monte Carlo.

Actually two step process, but not going to discuss detector simulation!
Hard Process
Parton Shower
Hadronization
Decays
Multi Parton Interaction

From Frank Krauss
Monte Carlo Models

- Leading order/Parton shower models: Trying to build up a complex 2->N final state by showers.

- Pieces of a Parton-Shower MC Generator: (2->2 hard scattering), ISR, FSR, MPI, Fragmentation, Hadronization.

- Examples: Pythia, Herwig family.

- Higher order/Multileg generators: Sherpa, Alpgen, MC@NLO, Madgraph, Powheg ...

- Generators used mostly for a specific process: Phojet (diffraction), HIJING (heavy ion), AcerMC (top), JHU (spin and polarization information)...

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Tuning

• Ultimate goal: models need to describe real data.

• “Free” parameters control all these aspects of the models, which cannot be derived analytically.

• A bunch of correlated (or anti-correlated) parameters describe one aspect, so have to change them simultaneously.

Tune: A particular optimized parameter setting in a particular MC generator to match the simulation with available data. Differ according to which datasets are included.
A Note on the Models

“The predictions of the model are reasonable enough physically that we expect it may be close enough to reality to be useful in designing future experiments and to serve as a reasonable approximation to compare to data. We do not think of the model as a sound physical theory . . .”

– Richard Feynman and Rick Field, 1978
Charged Particle Distributions

About 10M events, using low $\mu$ run

Tracks with $p_T > 0.5$ GeV and $|\eta| < 2.5$

Remove primary charged particles with $30 < \tau < 300$ ps (strange baryons)
Glossary

- **Minimum-bias (MB):** Pretty much everything, exact definition trigger dependent.

- **Underlying event (UE):** background to events with an identified hard scatter (more like the actual interesting events we want to look at).

- **Pileup (PU):** (uncorrelated) separate collisions within the same/different bunch crossing we can’t differentiate because of our finite detector resolution (more like “isotropic” min-bias events).