Minimum bias and underlying event measurements with the ATLAS detector
Soft QCD - why bother?

- Phenomenological models of sQCD need experimental constraint
  - perturbation theory not possible
  - needs well described sQCD for understanding pile-up and underlying event activity in all LHC measurements
  - measurement done as differential distributions

\[
\frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d\eta}, \quad \frac{1}{N_{ev}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2 N_{ch}}{d\eta dp_T}, \quad \frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}} \quad \text{and} \quad \langle p_T \rangle \text{ vs. } n_{ch}
\]

- Long standing history & improvements in ATLAS

<table>
<thead>
<tr>
<th>analysis differences</th>
<th>0.9 TeV</th>
<th>7 TeV</th>
<th>8 TeV</th>
<th>13 TeV</th>
<th>benefits @ 8+13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>remove strange baryons</td>
<td></td>
<td></td>
<td>yes</td>
<td>yes</td>
<td>reduces model dependence</td>
</tr>
<tr>
<td>high-n_{ch} phase spaces</td>
<td></td>
<td></td>
<td>yes</td>
<td></td>
<td>paper scope + MC tuning</td>
</tr>
<tr>
<td>final Run-1 geometry</td>
<td></td>
<td></td>
<td>yes</td>
<td>yes (IBL)</td>
<td>reduces material uncertainty</td>
</tr>
<tr>
<td>baseline MC tune for analysis</td>
<td>Pythia 6</td>
<td>Pythia 6</td>
<td>Pythia 8 A2</td>
<td>Pythia 8 A2</td>
<td>reduces systematics (e.g. pt-spectrum)</td>
</tr>
<tr>
<td>Geant4 physics list</td>
<td>QGSP_BERT</td>
<td>QGSP_BERT</td>
<td>FTFP_BERT</td>
<td>FTFP_BERT</td>
<td>improves simulation of antiprotons</td>
</tr>
</tbody>
</table>
Charged particle distribution measurement

- **Track counting** measurement with correction to particle level
  - attempt to minimally bias your trigger selection
  - understanding the detector effects is biggest experimental challenge
    
    *track reconstruction efficiency/systematics needs to be well understood (dominant)*
    
    *additionally corrections to trigger efficiency, vertex efficiency and phase space needed*

- Typically first measurements at "new" collision energy
  - need dedicated run with minimal pile-up
  - very beneficial for detector understanding
Analysis procedure | Selection

- Event selection
  - MBTS trigger selection
  - $\mu < 0.01$ to suppress pile-up track counting
  - require reconstructed vertex with minimum 2 tracks (veto event with additional vertex with > 4 tracks)
  - require a minimum number of selected tracks ($n_{\text{sel}}$)

- Track selection
  - $|d_0^{\text{PV}}| < 1.5$ mm \ $|z_0^{\text{PV}} \sin(\theta)| < 1.5$ mm
  - fit $\chi^2$ probability $> 0.01$ for $p_T > 10$ GeV
  - innermost pixel hit if module active/crossed, minimum 1 hit in the pixel detector
  - minimum 2/4/6 hits in the strip detector for $p_T > 0.1/0.2/0.3$ GeV

MBTS = Minimum Bias Trigger Scintillators
(2.08 < |eta| < 3.75)
32 scintillation counters
Analysis procedure | Correction

- Event weights

\[ \omega_{ev}(n_{\text{BS}}^\text{sel}) = \frac{1}{\epsilon_{\text{trig}}(n_{\text{BS}}^\text{sel})} \cdot \frac{1}{\epsilon_{\text{vtx}}(n_{\text{BS}}^\text{sel}, x)} \cdot \omega_{\text{zvrtx}} \]

- Track weights

\[ \omega_{trk}(p_T, \eta) = \frac{1}{\epsilon_{\text{trk}}(p_T, \eta)} \cdot (1 - f_{\text{nonp}}(p_T, \eta) - f_{\text{SB}}(p_T, \eta) - f_{\text{okr}}(p_T, \eta)) \]

1. Track reconstruction efficiency
2. Non-primary fraction
3. Strange baryon fraction
4. Out of phase space

(resolution effects)
**Event weights**

**trigger efficiency**
- measured from data using a random space point trigger
- parameterised as $n_{\text{sel}}^{\text{BS}}$
  analysis track selection w/o PV (uses beam spot instead)

**vertex reconstruction efficiency**
- probability to find a vertex on a triggered event
  measured from data
- parameterised as $n_{\text{sel}}^{\text{BS}}$
  $n_{\text{sel}}^{\text{BS}} \geq 2$ for $p_T > 0.1$ GeV analysis
  $n_{\text{sel}}^{\text{BS}} \geq 1$ for $p_T > 0.5$ GeV analysis
Track weights

**track reconstruction efficiency**

- estimated from MC simulation, binned in $\tau_a$ and $p_T$
- relies on correct modelling of the tracker material
- dominant systematic uncertainty for these analyses
- assumes material modelling of the inner tracker to 5% accuracy
- supported by many studies of the tracker material budget
  hadron interaction rates (vertexing)
  photon conversion
  track length requirements
- in general excellent modelling of the data by full simulation
Track weights

**Track reconstruction efficiency**

- estimated from MC simulation, binned in $\eta$ and $p_T$
  relies on correct modelling of the tracker material
- dominant systematic uncertainty for these analyses
  assumes material modelling of the inner tracker to 5% accuracy
- supported by many studies of the tracker material budget
  hadron interaction rates (vertexing)
  photon conversion
  track length requirements
- in general excellent modelling of the data by full simulation

JINST 7 (2012) P01013
Track weights

**non-primary fraction**

- for analysis no distinction between fakes and secondaries done
- estimated via a template fit to the impact parameter distribution
  
  *done w.r.t beam line to avoid event biases*

**strange baryon fraction**

- updated stable particle definitions: $\tau > 300$ ps
- includes many strange baryons
  very low tracking efficiency,
  strongly varies with transverse momentum
- generators predict very different fractions
- removed for 8/13 TeV from fiducial definition
  decreases generator dependency, EPOS LHC
  extrapolation for comparison with older analyses

![Graph showing the number of tracks vs. d_0^{BL} [mm] for different particle types: Primaries, Electrons, Non-electrons, and Fakes.](image)

![Graph showing the generated fraction of strange baryons vs. p_T [GeV] for different particle types: PYTHIA 8 A2, PYTHIA 8 Monash, EPOS LHC.](image)
Charged particle multiplicities | Result History

- Fairly good shape modelling by most generators
  - measurements are continuously used for tuning
  - EPOS (LHC tune) very good modelling at 8 TeV
Charged particle multiplicities | Results 8 TeV

- 8 TeV analysis extended to high multiplicity phase-spaces
  - event selections with $n_{\text{ch}} = 1, 6, 20, 50$
  - most generators have seen limited tuning in this corner
  - deviations from data start getting bigger
Charged particle multiplicities | Results 13 TeV

- 13 TeV result gives a new tuning point with large lever arm
  - high precision measurements for two phase space definitions
  - good description of data through EPOS for event quantities
Set of ATLAS measurements (0.9/7/13 TeV) used for PYTHIA tuning

- new ATLAS Pythia tune A3 starting from Monash tune, using NNPDF 2.3LO PDF

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [TeV]</th>
<th>used measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>charged particle distribution</td>
</tr>
<tr>
<td>7</td>
<td>charged particle distribution, transverse energy flow, fiducial inelastic cross-section, rapidity gap analysis</td>
</tr>
<tr>
<td>13</td>
<td>charged particle distribution, fiducial inelastic cross-section</td>
</tr>
</tbody>
</table>

- better description at 7/8/13 TeV but worse at lower s
without strange baryon removal

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [TeV]</th>
<th>$dN_{ch}/d\eta$</th>
<th>$\eta=0$</th>
<th>$\pm$ stat</th>
<th>$\pm$ sys</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>1.343*</td>
<td>0.004</td>
<td>0.027</td>
<td></td>
<td>NJP 13 (2011) 053033</td>
</tr>
<tr>
<td>2.36</td>
<td>1.74*</td>
<td>0.019</td>
<td>0.058</td>
<td></td>
<td>Eur. Phys. J. C (2016) 76:403</td>
</tr>
<tr>
<td>7</td>
<td>2.43*</td>
<td>0.001</td>
<td>0.050</td>
<td></td>
<td>PLB (2016), Vol. 758, pp. 67-88</td>
</tr>
<tr>
<td>8</td>
<td>2.477</td>
<td>0.001</td>
<td>0.031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2.874</td>
<td>0.001</td>
<td>0.033</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$p_T > 0.5$ GeV, $n_{ch} \geq 1$

$p_T > 0.1$ GeV, $n_{ch} \geq 2$

Charged particle multiplicities

| Result Summary |
Underlying event analyses

- Charged particle measurement* accompanying hard scatter
  - partons not included in hard scatter (beam remnants)
  - additional scatters in same p-p collision (multi parton interactions, MPI)
  - contributions from initial (ISR) and final (FSR) gluon radiation

- phase space definition for the underlying event

<table>
<thead>
<tr>
<th>Observable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle d^2 N_{\text{ch}} / d\eta d\phi \rangle$</td>
<td>Number of tracks per unit $\eta-\phi$</td>
</tr>
<tr>
<td>$\langle d^2 \sum p_T / d\eta d\phi \rangle$</td>
<td>Scalar sum of track $p_T$ per unit $\eta-\phi$</td>
</tr>
</tbody>
</table>

*very similar/identical experimental technique and systematics as slides 3-8
Underlying event | Results

- Leading track analysis
  - analysis separated into 3 regions
  - requirement on $p_T > 1 \text{ GeV}$

- Good modelling by Pythia 8 tunes
  - shapes generally well modelled
Conclusion

‣ ATLAS has a full set of minimum bias and underlying event analyses
  - covering different centre of mass energies and phase space definitions

‣ Recent 8 TeV and 13 TeV improved sys. uncertainties significantly
  - mainly due to better understanding of the tracker material
    description after IBL insertion can still improve w.r.t. Run-1 description
    helps many other precision measurements
  - better understanding of strange baryon handling

‣ Rich dataset for generator tuning available
  - data only corrected for detector effects, no model corrections/extrapolations
  - data available as HepData

‣ Underlying event results of similar quality and importance
  - give confidence in current UE simulation
Track reconstruction performance

- Track reconstruction performance evaluation is essential
  - excellent modelling of track parameters and properties by simulation puts confidence in estimating key parameters from simulation
  - result of years of detailed detector modelling in the full simulation
### Systematic uncertainties

- **13 TeV low pt**

| Distribution          | $\frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d|\eta|}$ | $\frac{1}{N_{ev}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2N_{ch}}{d\eta dp_T}$ | $\frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}}$ | $\langle p_T \rangle$ vs. $n_{ch}$ |
|-----------------------|--------------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------|
| **Range**             | 0–2.5                                            | 0.1–50 GeV                                    | 2–250                                         | 0–160 GeV                         |
| Track reconstruction  | 1%–7%                                            | 1%–6%                                         | 0%–38%                                        | 0%–0.7%                           |
| Track background      | 0.5%                                             | 0.5%–1%                                       | 0%–7%                                         | 0%–0.1%                           |
| $p_T$ spectrum        | –                                                | –                                             | 0%–3%                                         | 0%–+0.3%                          |
| Non-closure           | 0.4%–1%                                          | 1%–3%                                         | 0%–4%                                         | 0.5%–2%                           |