Study of the Underlying Event at LHC

Markus Lichtnecker

LMU Munich, LS Schaile

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Outline

- Introduction
  - ATLAS
  - Minimum Bias
  - Underlying Event
- Analysis Tools
- Studies of the UE
  - Characteristics
  - Subtraction Method
- Summary
The ATLAS Experiment at the LHC

- Universal Detector
- Width: 44 m
- Diameter: 22 m
- Weight: 7000 t
What happens at a bunch crossing?

- bunch crossing every 25 ns
- usually no hard interaction, but soft interactions between the hadrons:
  - no big change of the direction of the outgoing particles in comparison to the initial hadrons
  - small momentum transfer
  - soft inelastic interactions are called **Minimum Bias** (MB)
- about 23 MB events per bunch crossing are expected!
Hard scattering

- particles from hard $2 \text{ Parton} \rightarrow 2 \text{ Parton}$ collision
- Initial and Final State Radiation
- additional, soft contributions - the Underlying Event (UE)
  - Beam remnants
  - Multiple Interactions
MC Generator PYTHIA (6.4.10) was used for this analysis. Perturbation theory can’t be applied at low $p_T$. Models are needed to describe the Underlying Event. Different Tunes (set of parameters) which fit UE-data of previous collider experiments (at Tevatron) have been set up (by Rick Field) and extrapolated to LHC. Tunes were obtained from "transverse region" in respect to leading jets at CDF run1 and run2.
Shape of the jets

- hard scattering of $p_{T\text{min}} = 20$ GeV
- Hard and Tune A simulated at same time (Hard+Tune A)
- take single event
- assign particles to jets (same colour = same jet)

$k_T$ exclusive, $d_{\text{cut}} = 400$ GeV$^2$
Number of jets

Hard alone has on average $2.1 \pm 0.4$ jets, (Hard+Tune A) $2.9 \pm 1.3$ and (Hard+ATLAS Tune) $3.2 \pm 1.7$ jets
Jet-$p_T$

Cone 0.4

$k_T$ exclusive

UE leads to higher $p_T$(jets)
Influence of UE decreases in comparison to generator-level
$p_T$ (constituents)

<table>
<thead>
<tr>
<th></th>
<th>$&lt; p_T &gt;$ (GeV)</th>
<th>$p_T$ sum (GeV)</th>
<th>$p_T$ fraction of UE/event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard</td>
<td>1.208</td>
<td>57.9</td>
<td>0</td>
</tr>
<tr>
<td>Hard + Tune A</td>
<td>1.011</td>
<td>88.9</td>
<td>0.35</td>
</tr>
<tr>
<td>Hard + ATLAS</td>
<td>0.7672</td>
<td>97.2</td>
<td>0.40</td>
</tr>
</tbody>
</table>
Subtraction of UE: low-$p_T$-method

(Hard+Tune A) – Hard approximates the fraction of UE in a hard process

How to describe the UE in a real event, when no possibility to get solely particles from hard scattering (without contribution of UE)?

idea: $\text{UE} \approx \text{soft collision} \rightarrow \text{low-}p_T\text{ jets}$

select low-$p_T$ jets in hard collision:

- if only 2 jets in an event $\rightarrow$ force 3 jets
- jet with lowest $p_T$ is called low-$p_T$ jet
comparision: “low-$p_T$ jets” to “UE $\approx (\text{Hard+Tune A}) - \text{Hard}$”
scalefactor needed: $\text{low-}p_T \times 1.7$ (ATLAS Tune: $\times 2.75$)

UE can be approximated by low-$p_T$-jet!
comparison: “(Hard+TuneA) – (1.7×low-\(p_T\))” to “Hard”

UE can be approximated by low-\(p_T\)-jet!
How to correct $k_T$ jets for UE?

- weight each particle in jet by probability not to come from UE
- weighing-factors from

$$\frac{[(\text{Hard}+\text{Tune A})-(1.7 \times \text{low-} p_T)]}{(\text{Hard}+\text{Tune A})}$$

$$\chi^2/\text{ndf} = 32.78/96$$

$p_0 = 0.483 \pm 0.001$

$p_1 = 0.07338 \pm 0.00113$

$p_2 = -0.003298 \pm 0.000160$

$p_3 = 3.945e-05 \pm 3.597e-06$

→ perfect correction up to $\sim 20$ GeV!
characteristics of the UE for $k_T$ algorithm:

- $p_{T\text{sum}}$ of UE per event: 30-40 GeV
- increase of jet-$p_T$ (about 10 GeV) and number of jets (about 1 additional jet) due to UE

- low-$p_T$-jets describe UE
- weighting method corrects $k_T$-jets for UE
- $k_T$-jets can be used at hadron collider experiments
Backup
Exclusive $k_T$-algorithm, $\Delta R$-scheme

$$d_{kl} = \min(p_{tk}^2, p_{tl}^2)R_{kl}^2 \quad d_{kB} = p_{tk}^2$$

- $d_{min}$: smallest value among $d_{kB}$ and $d_{kl}$
- $d_{Cut}$: cut-off parameter until jets are merged (here: $d_{Cut}=400$ GeV)
- $d_{min} > d_{Cut}$: all remaining objects are classified as jets
  - if $d_{kl}$ is smallest, k and l are combined
  - if $d_{kB}$ is smallest, k is included in beam jet
  - jet-size is dynamic, no overlapping jets

$$R = \sqrt{\Delta \eta^2 + \Delta \Phi^2}$$
### Simulated processes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUB (53,1)</td>
<td>$g + g \rightarrow f + f$</td>
</tr>
<tr>
<td>MSUB (11,1)</td>
<td>$f + f' \rightarrow f + f'$ (QCD)</td>
</tr>
<tr>
<td>MSUB (12,1)</td>
<td>$f + f \rightarrow f' + f'$</td>
</tr>
<tr>
<td>MSUB (13,1)</td>
<td>$f + f \rightarrow g + g$</td>
</tr>
<tr>
<td>MSUB (28,1)</td>
<td>$f + g \rightarrow f + g$</td>
</tr>
<tr>
<td>MSUB (68,1)</td>
<td>$g + g \rightarrow g + g$</td>
</tr>
<tr>
<td>CKIN(3,20)</td>
<td>$p_{T\text{min}}$ in hard 2 → 2 scattering (20 GeV)</td>
</tr>
<tr>
<td><strong>PARAMETER</strong></td>
<td><strong>TUNE A</strong></td>
</tr>
<tr>
<td>---------------</td>
<td>------------</td>
</tr>
<tr>
<td>PARP 82</td>
<td>2.0</td>
</tr>
<tr>
<td>PARP 83</td>
<td>0.5</td>
</tr>
<tr>
<td>PARP 84</td>
<td>0.4</td>
</tr>
<tr>
<td>PARP 85</td>
<td>0.9</td>
</tr>
<tr>
<td>PARP 86</td>
<td>0.95</td>
</tr>
<tr>
<td>PARP 89</td>
<td>1800</td>
</tr>
<tr>
<td>PARP 90</td>
<td>0.25</td>
</tr>
<tr>
<td>PARP 62</td>
<td>1.0</td>
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<tr>
<td>PARP 64</td>
<td>1.0</td>
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<tr>
<td>PARP 67</td>
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<tr>
<td>MSTP 91</td>
<td>1</td>
</tr>
<tr>
<td>PARP 91</td>
<td>1.0</td>
</tr>
<tr>
<td>PARP 93</td>
<td>5.0</td>
</tr>
</tbody>
</table>

- **MSTP(51,1):** chosen PDF (CETEQ 5L)
- **MSTP(81,1):** MPI on
- **MSTP(82,4):** further MPI switches on

**UE-Parameter**

**ISR-Parameter**

**intrinsic \( k_T \)**
Explanation of some parameters

double Gaussian matter distribution inside proton:
\[ \rho(r) \propto \frac{1-\beta}{a_1^3} \exp\left(-\frac{r^2}{a_1^2}\right) + \frac{\beta}{a_2^3} \exp\left(-\frac{r^2}{a_2^2}\right) \]

\[ \beta = \text{PARP}(83) \]
\[ \frac{a_2}{a_1} = \text{PARP}(84) \]

Energy-dependency of \( p_{T0} \)
\[ p_{T0}(E_{cm}) = p_{T0}\left(\frac{E_{cm}}{E_0}\right)^\epsilon \]
with \( p_{T0} = \text{PARP}(82), \]
\[ E_0 = \text{PARP}(89), \]
\[ \epsilon = \text{PARP}(90) \]
How does the UE in a hard process look like?

→ assumption: UE in a hard process fits (Hard+Tune A) - Hard
- check: backtrack final particles to find out origin
- method works until string
- problem: information about mother particle of "first particle after string" gets lost due to hadronisation
idea: associate “first particle after string” with particle in string via certain criteria:

\[(\Delta R \ast (\Delta p_T)^2)_{min} \leq 25\]

→ subtraction of UE-particles from \((\text{Hard}+\text{TuneA})\) and comparison to \(\text{Hard}\):

![Graph 1](image1)

![Graph 2](image2)
UE-particles are in good agreement with (Hard+Tune A) - Hard

UE adds on average 11.4 GeV to a jet!