Prospectives of the Hadron Program in ATLAS

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on behalf of
the ATLAS-Collaboration

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Outline

• Introduction

• From soft to hard hadron Physics in ATLAS
  – Minimum Bias Physics
    • Motivation for soft hadron physics
    • Minimum Bias Trigger
    • Track reconstruction performance
    • Results of the studies
  – Underlying Event studies
    • Definition and impact of UE to high-$p_T$ studies

• Analysis Plan with Early Data

• Summary and Outlook
Introduction

- ATLAS is one of the 4 major experiments at the Large Hadron Collider (LHC) at CERN
- It covers a wide physics program and is prepared for
  - Higgs discovery at different masses
  - measurements of deviations from the Standard Model
  - unknown signatures
- Good understanding of soft hadron physics is also necessary for any high-$p_T$ analysis

→ First measurements will analyse properties of inelastic pp-collisions
- Will be able to measure quantities which are only known with large uncertainties at LHC energies, even at initial energies of $\sqrt{s} = 7$ and 10 TeV

ATLAS has ca. 25 m diameter, is 46 m long and weighs ~7000 t.

Inner Tracker system:
$\varnothing = 2.1$ m, 6.2 m length, consists of silicon pixel, silicon strip detector (SCT), transition radiation detector (TRT) in a 2 T solenoid homogenous magnetic field
Motivation for Soft Hadron Analyses

- There are 2 main hadron studies for soft interactions
  - Minimum Bias (MB)
  - Underlying Event (UE)
- Why is soft physics relevant for LHC?
  With design parameters LHC runs at
  - $\sqrt{s} = 14$ TeV
  - bunch crossing rate at 25 ns
  - luminosity $L = 10^{34}$/cm$^2$s

  → high interaction rate
  10$^9$ pp-interactions/second
  → expect pile-up
  ~ 25 pp-collisions overlapping in one bunch-crossing
  → high gluon density
  gives rise to any QCD-cross-section

<table>
<thead>
<tr>
<th>soft interactions at LHC</th>
</tr>
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<tbody>
<tr>
<td>- can improve knowledge about</td>
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<tr>
<td>- inelastic scattering processes</td>
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<td>- multi-parton interactions</td>
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<tr>
<td>→ ultimate goal: fundamental description of soft physics in QCD</td>
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<td>- represent detector occupancies</td>
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<td>- QCD-background in high-$p_T$ analyses</td>
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<td>- influence</td>
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<td>- jet energy-/missing $E_T$-scale</td>
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<td>- lepton isolation</td>
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<td>- vertex determination</td>
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<td>- Higgs-searches in VBF</td>
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</table>

Analyses of soft interactions can pin-down inelastic cross-sections and are the base for any high-$p_T$-physics analysis
Multiple Parton Interactions

• The concept of multiple parton interactions (MPI) was introduced to describe that \( \sigma_{\text{int}}(\text{parton-parton}) \) exceeded \( \sigma_{\text{tot}}(\text{proton-proton}) \)

\[
\frac{\sigma_{\text{int}}(p_{\perp \text{min}})}{\sigma_{\text{tot}}} = \langle n \rangle (p_{\perp \text{min}})
\]

• UA5 data were well fitted to models based on MPI, MPI has been directly measured at CDF

• UE and KNO-scaling variables are very sensitive to MPI, typically
  – mean \( p_T \) or mean sum \( p_T \) vs #particles
  – probability distributions for multiple particle production as a function of \( z = n/\langle n \rangle \), \( n = \#\text{particles} \)

• Cannot apply perturbative QCD for low \( Q^2 \) as

\[
\int_{p_{\perp \text{min}}}^{(\sqrt{s}/2)^2} \frac{d\sigma}{dp_{\perp}^2} dp_{\perp}^2 \propto \frac{1}{p_{\perp \text{min}}^2} \quad p_{\perp \text{min}} \to 0 \quad \infty
\]

• several models exist to describe MPI
  • dual parton model
  • geometrical model
  • stochastic models
  • models in QCD framework

→ measurements will improve understanding, tune MC
Definition of Minimum Bias

- Minimum Bias events comprise contributions from inelastic interactions, here shown for \( \sqrt{s} = 14 \text{ TeV} \) for Pythia6.4 20 (Phojet1.12):

  \[
  \sigma_{\text{ndiff}} \approx 55 \ (68) \text{ mb} \quad \sigma_{\text{sdiff}} \approx 14 \ (11) \text{ mb} \quad \sigma_{\text{ddiff}} \approx 10 \ (4) \text{ mb} \quad \sigma_{\text{cdiff}} \approx -/\ - \ (1) \text{ mb}
  \]

- In previous studies minimum bias events are associated to ND and DD events (NSD, non-single diffractive e.g. as at CDF)
- Exact definition is defined by the trigger system
- At ATLAS we have non- and both-diffractive events, but \( \to \) ND events strongly dominate
- Will also study NSD distributions at ATLAS to compare with previous results
Predictions for Soft Hadron Activities

- Predictions from different models have large variations, e.g. in Pythia 6.420 (+ATLAS mc08 tune) and Phojet 1.12 on
  - inclusive cross-sections
  - charged particle densities
- variations in $\sqrt{s}$ from 10 TeV to 14 TeV is not very large

At LHC energies the properties of inelastic interactions are highly uncertain.

$\eta = -\ln(\tan(\theta/2))$
Predictions for Soft Hadron Activities

• Predictions from different models have large variations, e.g. in Pythia 6.420 (+ATLAS mc08 tune) and Phojet 1.12 on
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  – charged particle densities
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At LHC energies the properties of inelastic interactions are highly uncertain.
### Minimum Bias Physics

#### Strategy at ATLAS

- Investigate pp-collisions at the beginning of data-taking
  - have a clean signal of a single pp-collision
- pp-interaction rate is still very small in the initial phase
  - $L = 10^{28}/\text{cm}^2\text{s}$
  - 43 bunches
  - 2021 ns bunch spacing
- expect in 10% of the bunch-crossings a pp-collision
  - Minimum-Bias Trigger
    - at higher pp-interaction rate → use pure random trigger

#### Minimum Bias Observables

- charged particle densities
  - $p_T$-spectrum
  - $\eta$-spectrum
- KNO-variables; multiplicity scaled variables
- $<p_T>$ vs charged particle multiplicity

#### Analysis Requirements

- introduce as little trigger bias as possible
- perform efficiently track reconstruction for low $-p_T$ particles (standard tracking starts at 500 MeV)
Minimum Bias Triggers

• At initial low pp-interaction rate ATLAS uses 2 main Minimum Bias Triggers:
  – **Minimum Bias Trigger Scintillators (MBTS)**
    • consist of 16 counters per side
    • 32 read-out channels
    • covers $2.1 < |\eta| < 3.8$
  – **Inner Tracking Detector (ID) based Minimum Bias Trigger**
    • Level 1 Trigger (L1): random trigger
    • Level 2/Level 3 Trigger (L2/EF): use hits/tacks from silicon detector
      (≈ 86 million read-out channels)
    • covers ID-region: $|\eta| < 2.5$
• Additional **support triggers** are available eg. Zero-Degree-Calorimeter: triggering only on neutrals at +-140 m away from interaction point (good for diffractive events)
MBTS Trigger Efficiency

- Trigger efficiencies for different configurations of MBTS
- both configuration highly suppress all empty bunch-brossing events and are very efficient for ND
- MBTS_2: 2-hit-multiplicity trigger performs overall better
• L2 requires a certain number of detector hits (SpacePoints)
  – forms spacepoints in pixel and SCT detector
  – operates just above noise level

• EF requires a certain number of tracks close to the IP
  • # tracks with $|z_0| < 200$ mm
  • $p_{\text{min}} = 200$ MeV

very good efficiency for ND events
high suppression of noise events
Define trigger bias as a *change* in generated distribution, introduced by the trigger conditions.

\[ \text{bias} = \frac{\text{distribution with trigger conditions}}{\text{plain generated distribution}} \]

- **no bias** in the relevant region (ID coverage) in \( \eta \) expected for MBTS_2 and ID Minbias Trigger
- **strong bias** for diffractive for MBTS_1_1 expected (won't use as physics trigger)
Standard-track reconstruction improved for low-$p_T$ tracks

$\rightarrow p_{T\text{min}} = 100 \text{ MeV}$ (default: 500 MeV)

Low-$p_T$ track reconstruction in 2 steps:

- Tracking efficiency = number of matched rec. primary tracks/
  number of generated primary tracks
Event Selection and Corrections

• Offline-selection criterium
  – event contains one primary reconstructed vertex

• Corrections for
  – trigger (bias, efficiencies)
  – primary vertex reconstruction
  – track reconstruction
  → corrections are functions of primary charged particle multiplicity, $p_T$ and $\eta$

• Estimate of total uncertainties is 
  $\sim 8\%$ including mainly contributions from [see CERN-OPEN-2008-020] :
  – misalignment
  – diffractive cross-section (NSD sample)
• Show NSD distributions with $p_T \geq 150$ MeV for $\sqrt{s} = 14$ TeV
• Reconstructed and generated distributions (pythia 6.420+ATLAS tune mc08) are in good agreement
  → consistency check for the analysis method
Underlying Event

• UE in hadron-hadron interactions is defined to *all particles produced accompanying the hard scattering component of the collision*

• Experimentally such separation is impossible
  → define regions *sensitive* to the UE
    – divide transverse plane into 3 regions based on the leading jet or leading track

• Contributions to particle production in UE
  – convolution of initial and final state radiation
  – beam remnants and their interactions
  – multiple parton scattering

• Predictions highly uncertain
  → Measurements will probe the sum of these effects and are needed to improve soft models and for tuning Monte Carlo models
Underlying Event Analysis Goals

• Measure UE at different energies,
  - $\sqrt{s} = 7$ TeV, 10 TeV
    (14 TeV in ~ 4-5 yrs)
  $\rightarrow 1 < \int L dt < 10 \text{ pb}^{-1}$ already useful for UE studies, but need to understand the systematics first

Underlying Event Observables

• typically quantities in transverse region:
  • charged particle density
  • $p_T$, $<p_T>$, $<\Sigma p_T>$ of tracks and jets

Measurement of UE helps distinguishing different physics models
Analysis Plan with Early Data

Should collect enough tracks very quickly, depending on beam and detector stability.

Limitation is not set by statistics but by systematics
Tracking and trigger performance need to be understood

Day 1 data:
focus on $p_T > 500$ MeV and barrel region:
- 😞 lose events
- 😊 gain confidence on systematics

Prepare for low-$p_T$ tracking at 7 TeV

R.Kwee
QNP 2009, IHEP Beijing 19
Summary and Outlook

• Base for a successful ATLAS physics programme is to understand as good as possible soft QCD physics in LHC environment
  – Minimum Bias studies → particles densities, origin of KNO-scaling violations, inelastic cross-sections, pile-up description
  – Underlying events studies → determine constituents of UE, reduce systematic uncertainties (jet energy, missing $E_T$ and lepton isolation,...)
→ both studies valuable to improve theory and MC models

• ATLAS provides a detailed strategy for trigger and early data analyses
  – analysis method is in good shape
  – tools have been much improved since 14 TeV studies

• MB and UE studies are just the beginning of an exciting physics program! For more on early hadron physics analyses, see talk by K.Hara
backup
Plan for LHC Scenarios

Staged commissioning of high luminosity operation of LHC at points 1 and 5

\[ L = \frac{N^2 k_p f^2 r^4}{4 \pi s_n^2 \beta^2} \]

\[ \text{Event rate/Cross} = \frac{L \sigma_{TOT}}{k_b f} \]

"Thus, to achieve high luminosity, all one has to do is make high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible." PDG 2006, chapter 25

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</table>
Impact of UE to Physics Analyses

- The uncertainty of the jet energy scale (JES) is a principal uncertainty to all analyses with jet $E_T$-measurements, e.g.
  - top quark mass
  - Higgs production in VBF
  - lepton isolation

- more significant impact of UE for low-$P_T$ jets

### Determination of JES for high $P_T$ Jets

- Method: Jet-balancing, e.g.:
  - take 1-jet events as $\Sigma E_T = 0$:
    - $1 \text{ jet} + Z \rightarrow 2\mu$: $Z$ mass is very well known
      - balance jet $E_T$/jet $P_T$
      - determine JES for $10 \text{ GeV} < P_T < \text{ca. 200 GeV}$
    - $1 \text{ jet} + \gamma$ for $\text{ca. 100 GeV} < P_T < \text{ca. 200 GeV}$

- uncertainties [arXiv.0901.0512] from JES for
  - $P_T < 100 \text{ GeV}: \sim 10 \%$
  - $P_T > 100 - 500 \text{ GeV}: \sim 1-2 \%$

- statistical error [arXiv.0901.0512] on JES for $100\text{pb}^{-1}$ is 1-2 \%
Trigger provides inelastic pp-collisions

Offline-Software

reconstruct tracks and vertices

compare to MC
improve MC+detectorsimulation
(alignment, material)

Monte-Carlo-models
e.g. Pythia, Phojet

Offline-Software

\( \sigma_{\text{ndiff}}, \sigma_{\text{sdiff}}, \sigma_{\text{ddiff}} \)
with systematic uncertainties

Offline-Software

study: bias and effizienies
reconstruct: tracks and vertices

Measurement with data

Analysis with MC

QNP 2009, IHEP Beijing
MPI Models

- **dual parton model**
  - assume hadron separates after collision into 2 colored systems: quark and di-quark
  - gluons mediate interaction, produce quark-antiquark pairs
  \(\rightarrow\) increase re-scattering component
  \(\rightarrow\) MPI

- **geometrical model**
  - probability distribution (in KNO-scaling) is a superposition of many Poisson-distributions, characterised by impact parameter \(b\).
  \(\rightarrow\) the higher the energy, the more forward-backward multiplicity

- **stochastic model**
  - scaling relates to general statistical and dynamical properties of MPI
  - describe probability distribution e.g. with negative binominal model (Fourier-Transform of Poissonian) \(\rightarrow\) fits well UA5 data
  or
  - use Fokker-Planck eq. to describe MPI as a stochastic-dissipative process

- **models in QCD**
  - MPI have contributions from quark and gluon bremsstrahlung (parton-branching)
<table>
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<tr>
<th>Physics process</th>
<th>Cross section (mb)</th>
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<td>$\sqrt{s} = 14$ TeV</td>
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<td><strong>Total</strong></td>
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<td>96.2</td>
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</table>
• Trigger bias for L1 MBTS_1_1

• strong bias for diffractive for MBTS_1_1 expected (won’t use as physics trigger)