Measurements of Particle Production, Underlying Event and Double Parton Interactions at the LHC

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Introduction

Measurements of Particle Production, Underlying Event and Double Parton Interactions at the LHC

- LHC – high profile searches and measurements
  - Higgs, precision measurements, new physics
- crucial part of precision: soft QCD effects
  - pile-up, underlying event, multiple parton interactions, (radiation)
- only phenomenological models
  - free parameters have to be tuned
  - diverse measurements as inputs
Many results...

**Particle Production**

- Charged-particle distributions at low transverse momentum in $\sqrt{s} = 13$ TeV $pp$ interactions measured with the ATLAS detector at the LHC – arXiv:1606.01133
- Strangeness production as a function of charged particle multiplicity in proton-proton collisions – ALI-PREL-98750
Many many results...

Underlying Event

- Detector level leading track underlying event distributions at 13 TeV measured in ATLAS – ATL-PHYS-PUB-2015-019
- Underlying event measurements with leading particles and jets in $pp$ collisions at $\sqrt{s} = 13$ TeV – CMS-PAS-FSQ-15-0070
- Measurement of event-shape observables in $Z \rightarrow \ell^+\ell^-$ events in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC – arXiv:1602.08980

Double Parton Interaction

- Double Parton Scattering cross section limit from same-sign $W$ bosons pair production in di-muon final state at LHC – CMS-PAS-FSQ-13-001
- Studies of 2 b-jet + 2 jet production in proton-proton collisions at 7 TeV – CMS-PAS-FSQ-13-010
- Study of hard double parton scattering in four-jet events in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS experiment at the LHC – ATLAS-CONF-2015-058
Particle production – Minimum Bias

- **First measurements** at $\sqrt{s} = 13$ TeV
- **Important input for pile-up modeling**


**Very good results** from EPOS LHC tune – based on hydrodynamic model

**Herwig tunes for UE, don’t expect good min. bias description**
Particle production – Minimum Bias

\[ \frac{1}{N_{\text{ev}} \cdot dN_{\text{ch}} / d\eta} |_{|\eta| < 0.2} \]

\[ p_T > 100 \text{ MeV}, n_{\text{ch}} \geq 2 \]
\[ p_T > 500 \text{ MeV}, n_{\text{ch}} \geq 6 \]
\[ \tau > 30 \text{ ps (extrapolated)} \]

Data
ATLAS
PYTHIA8 A2
PYTHIA8 Monash
EPOS LHC
QGSJET II-04

- energy scaling overall well described in simulations

arXiv:1606.01133
Strange particle production

- measurement of the strange particle production vs. multiplicity
- strong increase in rates – up to the level of Pb-Pb collisions
- incompatible with Pythia6 and Pythia8 predictions

ALI-PREL-98750

Jan Küchler (BUW)
underlying event: activity in addition to hard scattering
- initial/final state radiation
- multiple (soft) parton interactions

non-pertubative QCD – **only models**
- measurements important for **tuning**

many measurements: require hard object, split event into three regions
- **toward**: close to leading object
- **away**: recoil of leading object
- **transverse**: sensitive to UE

alternative method: colour-neutral leading object, e.g. $Z \rightarrow \ell\ell$
- less interaction between hard scatter and underlying event
Underlying Event at 13 TeV

- leading track UE measurements from ATLAS at $\sqrt{s} = 13 \text{ TeV}$
- detector level measurement – closely following the min. bias analysis

- simulation reproduces measurement within ~10% in transverse region

ATL-PHYS-PUB-2015-019
Underlying event at 13 TeV

- measurement for 13 TeV low-$\mu$ data in leading track and jet events
  - $p_T > 0.5$ (1.0) GeV for tracks (jets)
- two observables: particle density $\langle N_{\text{chg}} \rangle / [\Delta \eta \Delta (\Delta \phi)]$
  and energy density $\langle \sum p_T \rangle / [\Delta \eta \Delta (\Delta \phi)]$
- four configurations
  - transMAX/MIN – transverse region with higher/lower density
  - transAVE – average of both transverse regions
  - transDIF – difference of both transverse regions
- full correction for detector effects
  - charged particles: $p_T > 0.5$ GeV, $|\eta| < 2.0$
some discrepancies between data and simulation

best description: Pythia8 Monash

- EPOS worse (as expected), CUE tunes generally better

CMS-PAS-FSQ-15-0070
event shape measurement in leptonic Z boson events at 7 TeV

all charged particles excluding Z decay products

corrected for pile-up and detector effects

good agreement at high $p_T$ and in inclusive observables

discrepancies at low Z boson $p_T$ especially in $N_{ch}$ and correlated variables

arXiv:1602.08980
Double Parton Interactions – Introduction

- **only phenomenological description**

\[ \sigma_{A+B}^{\text{DPI}} = \frac{1}{1 + \delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \]

- assume processes A and B to be uncorrelated

- parameter \( \sigma_{\text{eff}} \)
  - characterizes the transverse area of interaction
  - assumed to be process independent
  - no \( \sqrt{s} \) dependence observed
  - \( \sigma_{\text{eff}} \sim 15 \text{ mb} \sim 0.2 \sim 0.3 \times \sigma_{\text{inel.}} \)
DPI in same-sign \(WW\) events

- measurement of DPI in leptonic same-sign \(WW\) events
  - \(\sigma_{\text{DPI}}\) nearly as large as \(\sigma_{\text{SPI}}\)

- select events with exactly two muons
- BDT to separate SPI and DPI
  - angular correlation of leptons
  - lower boost in DPI events
- 95\% CL limits on DPI signal strength using \(CL_s\) method
  - systematic uncertainties via nuisance parameters
  - \(\sigma_{\text{DPI}}^{\text{WW}} < 1.12\text{ pb} \ (1.18\text{ pb exp.})\)
  - \(\rightarrow \sigma_{\text{eff}} > 5.91\text{ mb}\)
DPI in four jet events

- measurement of DPI in four jet events
  - complete-DPI: \(2j \oplus 2j\) events ("cDPS")
  - semi-DPI: \(3j \oplus 1j\) events ("sDPS")
- based on low-pileup data at 7 TeV (2010)

classify events using **neural network**

- three outputs \(\rightarrow\) Dalitz plot
  \[ \xi_{SPS} + \xi_{cDPS} + \xi_{sDPS} = 1 \]
- model cDPS events using **di-jet** events from data
- observables: \(p_T\) balance, angular separation, rapidity difference

\[ \Delta_{34}^{p_T} \]
DPI in four jet events

- NN important to isolate DPI contribution
- extract $\sigma_{4j}^{\text{DPI}}$ and $\sigma_{\text{eff}}$ with a template fit

\[ \sigma_{\text{eff}} = 16.1^{+2.0}_{-1.5} \text{ (stat.)} +^{6.1}_{-6.8} \text{ (syst.)} \text{ mb} \]

- agreement with prev. measurements

ATLAS-CONF-2015-058
Studies of 2 $b$-jet + 2 jet production

- measurement of 2 $b$-jet + 2 light jet events
- part of the phase-space sensitive to DPI
- based on low-pileup data at 7 TeV (2010)

- good agreement in differential $p_T$ and $\eta$ distributions
- mean $p_T$ balance not well reproduced any models
- difficult description of soft MPI (→UE) and hard DPI in the same model

$$\Delta^{rel}p_T = \frac{|\vec{p}_T^{jet1} + \vec{p}_T^{jet2}|}{|\vec{p}_T^{jet1}| + |\vec{p}_T^{jet2}|}$$
Conclusion and summary

- many, diverse results, important measurements
  - understanding of soft, non-pertubative region of QCD
  - tuning of models for pileup simulation, underlying event
  - background to measurements and new physics searches

- overall summary
  - fair general agreement of existing models
  - much room for improvement
    - refinement of phenomenological models
    - further tuning needed
  - some discrepancies:
    - strange baryon production vs. multiplicity
    - hard DPI
Minimum Bias – Energy Scaling

Yield ratio 13 TeV to 7 TeV

- Data
- EPOS LHC
- PYTHIA 8 (Monash-2013)
- PYTHIA 6 (Perugia-2011)

ALICE, pp, INEL>0, charged particles, |η| < 0.8

Underlying event at 13 TeV

281 nb$^{-1}$ (13 TeV)

CMS Preliminary

transMAX

transDIF

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Particle Production, UE and DPI

LHCP – QCD Parallel 1