Charged-Particle Multiplicity Distributions over a Wide Pseudorapidity Range in Proton-Proton Collisions with ALICE

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Motivation and Outline

Data from the Silicon Pixel Detector (SPD) and the Forward Multiplicity Detector (FMD) in ALICE are used to access a uniquely wide pseudorapidity range at the LHC of more than eight $\eta$ units, from $-3.4 < \eta < 5.0$

The results presented here for pp collisions from $\sqrt{s} = 0.9$ TeV to 8 TeV extend:

i. the pseudorapidity range of the earlier results published by ALICE and CMS around midrapidity,

ii. the high-multiplicity reach.
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1. ALICE Detector

2. Analysis Procedure

3. Results

4. Summary and Outlook
A Large Ion Collider Experiment

Trigger
Detectors

V0 A

SPD

V0 C
Detectors Used

- SPD
- FMD 1
- FMD 2 & 3

A Large Ion Collider Experiment

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Forward Multiplicity Detector

- Silicon strip detector in 5 rings
- Full azimuthal coverage
- Pseudorapidity coverage: 
  $+5.0 < \eta < +1.7$ and $-1.7 < \eta < -3.4$

**Outer rings**
20 sensors with 256 silicon strips each

**Total of 51200 silicon strips**
Forward Multiplicity Detector

- Silicon strip detector in 5 rings
- Full azimuthal coverage
- Pseudorapidity coverage: $+5.0 < \eta < +1.7$ and $-1.7 < \eta < -3.4$

+ Silicon Pixel Detector Inner Layer $-2 < \eta < +2$
Event Display for a pp Collision

Raw Data

Disentangle the Primary Spectrum (*) of Charged Particles

(*) Primary particles are defined in ALICE as particles produced in the collision except decay products from weak decays of light flavour hadrons and muons.

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Unfolding

Bayes’ theorem [1]

\[ P(A|B) = \frac{P(B|A)P(A)}{P(B)} \]

\[ \tilde{R}_{tm} = \frac{R_{mt}P_t}{\sum_{t'} R_{mt'}P_{t'}} \quad \rightarrow \quad U_t = \sum_{m} \tilde{R}_{tm}M_m \]

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Trigger and Vertex Efficiency

**Event class:**
- **INEL** = Diff + Non-Diff
- **NSD** = (Diff – Single-Diff) + Non-Diff

**Triggering Criteria:**
- **MB$_{OR}$** = V0A || SPD || V0C
- **MB$_{AND}$** = V0A && V0C
Trigger and Vertex Efficiency

event class: \( \text{INEL} = \text{Diff} + \text{Non-Diff} \)

\( \text{NSD} = (\text{Diff} - \text{Single-Diff}) + \text{Non-Diff} \)

\[ \epsilon_{\text{trig}} = \frac{N_{\text{ch, reco}}(\text{trig} \& |v_{z, \text{reco}}| < 4\text{cm})}{N_{\text{ch, gen}}(\text{trig} \& |v_{z, \text{gen}}| < 4\text{cm})} \]

\[ U_t = \frac{U^*_t}{\epsilon_{\text{trig}}} \]

Diffraction tuned [2] generators used: PYTHIA 6 (Perugia 0) and PHOJET.

Double Negative Binomial Distribution

\[ P(n) = \lambda \alpha P_{NBD}(n, \langle n \rangle_1, k_1) + (1 - \alpha) P_{NBD}(n, \langle n \rangle_2, k_2) \]
Results for $\sqrt{s} = 0.9$ TeV

Fit with a **Double Negative Binomial Distribution**:

$$P(n) = \lambda [\alpha P_{NBD}(n, \langle n \rangle_1, k_1) + (1 - \alpha) P_{NBD}(n, \langle n \rangle_2, k_2)]$$

**ALICE SPD only: on arXiv today [3]**

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ALICE Preliminary, INEL \( pp, \sqrt{s} = 0.9 \) TeV

ALICE Preliminary, NSD \( pp, \sqrt{s} = 0.9 \) TeV

ALICE SPD only: on arXiv today [3]
Results for $\sqrt{s} = 7$ TeV

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$pp, \sqrt{s} = 8$ TeV

ALICE Preliminary, NSD
$pp, \sqrt{s} = 8$ TeV

ALICE SPD only: on arXiv today [3]

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Comparisons with CMS Results

Difference with CMS for $\sqrt{s} = 0.9$ TeV

CMS: JHEP 1101,079 [4]

ALICE SPD only: on arXiv today [3]

no diffraction tuning in CMS
different cut in diffractive mass
Comparisons with CMS Results

Difference with CMS for $\sqrt{s} = 0.9$ TeV

Good agreement for $\sqrt{s} = 7$ TeV

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Comparisons with Monte Carlo

✓ PHOJET tuned to $\sqrt{s} = 0.9$ TeV
Comparisons with Monte Carlo

- **PHOJET** tuned to $\sqrt{s} = 0.9$ TeV
- **EPOS LHC**
- **PYTHIA 8 Monash**
Comparison with IP-Glasma Model

Color Glass Condensate based
1. Color-Charge Fluctuations
2. Glasma fields

- **green**: no fluctuations of color charge [5]
- **blue**: includes Gaussian fluctuations [5]
- **black**: includes asymmetric fluctuations [6]

Summary and Outlook

\( P(N_{\text{ch}}) \) vs \( N_{\text{ch}} \) from ALICE analyzed:
- \( \sqrt{s} = 0.9, 7, \) and \( 8 \) TeV
- INEL and NSD

A uniquely wide pseudorapidity coverage at the LHC of more the eight \( \eta \) units, from \(-3.4 < \eta < 5.0 \) → extend high-multiplicity reach

• Multiplicity distributions for 7 TeV collisions measured for NSD events agree with CMS. For 0.9 TeV, the results are systematically higher in the high multiplicity tails with respect to CMS → different definition of the diffractive mass.

• Monte Carlo models and the Color Glass Condensate based IP–Glasma model underestimate the fraction of high multiplicity events. Exceptions are EPOS LHC for 7 TeV and IP-Glasma model with color-charge fluctuations, which model better the tails of the distributions.

13 TeV multiplicity distributions over wide rapidity coming soon!

Thank you!
References


Backup
Systematic Uncertainties Overview

1. Efficiency Correction
   • derived from the difference between diffractive tuned PYTHIA 6 and PHOJET
   • influences the first bins of the distributions

2. Run-to-run Fluctuations
   • derived analyzing different runs to study the effect of run conditions

3. Unfolding
   • covariance matrix obtained from Bayesian Unfolding procedure

4. Counting Methods
   • variation of 5% of the cuts used in the FMD for counting the particles and performing the energy loss fits

5. Material Budget
   • derived from the missing information of the material in front of the FMD
   • major source of systematics

On average, the systematics are of around:
- 25% in the first bins
- 7% around the mean value
- 40-50% in the last bins.

In general, they increase increasing the pseudorapidity range and the collision energy.
Koba-Nielsen-Olesen Scaling

1. Feynman Scaling
\[ \langle N \rangle \propto \ln W \propto \ln \sqrt{s} \]

2. Moments define uniquely the distribution
\[ c_q = \frac{\langle n^q \rangle}{\langle n \rangle^q} \]

\[ P_n(s) = \frac{1}{\langle n \rangle} \psi \left( \frac{n}{\langle n \rangle} \right) \]

KNO scaling is violated
for all the pseudorapidity ranges probed  \( \rightarrow \)  More violated for wider ranges
(spectrum of the events is harder)
Chapter 4. Multiplicity of Charged-Particles

Negative Binomial Distributions

The KNO scaling is not valid as a description of multiplicity distributions above 30 GeV, in fact, it was found by the UA5 experiment in 1985, that the Negative Binomial Distributions (NBD), instead, can describe the data at 540 GeV [47, 48]. If one of the parameters of the NBD is kept free, the KNO scaling is obtained.

The NBD is the probability distribution of the successes before a specified number of failures \( k \), when Bernoulli trials are performed, and it is defined as

\[
P(n; p; k) = \binom{n + k - 1}{k - 1} \left( \frac{1}{1 + \langle n \rangle / k} \right)^k \left( \frac{\langle n \rangle / k}{1 + \langle n \rangle / k} \right)^n
\]

where the binomial coefficient can be rewritten like

\[
\binom{n + k - 1}{k - 1} = \frac{(n + k - 1)!}{n! (k - 1)!} = \frac{(n + k - 1)(n + k - 2)\cdots(n + 1)}{(k - 1)!}
\]

In particular, the probability for every specific sequence of \( n \) successes and \( k \) failures is

\[
(1 - p)^k p^n,
\]

because the outcomes of the \( n + k \) trials are independent. The \( k \)th failure comes in the end, therefore, the \( n \) trials with successes are free to choose out of the remaining \( n + k - 1 \) trials. The above binomial coefficient gives the number of all these sequences of length \( n + k - 1 \).

If \( k = 1 \) the NBD is a geometrical distribution, while if \( k \not= 1 \), it is the Poisson distribution.

The UA5 observed a violation of the KNO scaling [47, 48] in their multiplicity distributions. Namely the scaling implies that, if \( P(n) \) is the probability of finding \( n \) particles in the final state of the interaction, and \( \langle n \rangle \) is the mean multiplicity,

\[
\langle n \rangle P(n) = \left( \frac{n}{\langle n \rangle} \right)
\]

is energy independent at very high energy. UA5 found, instead, that the distributions were following a NBD of the form

\[
P(n; \langle n \rangle; k) = \binom{n + k - 1}{k - 1} \left( \frac{1}{1 + \langle n \rangle / k} \right)^k \left( \frac{\langle n \rangle / k}{1 + \langle n \rangle / k} \right)^n
\]

where the \( k \) parameter affects the shape. If \( k \) is constant and does not depend on the energy, the KNO scaling is valid.

In the past years, several trials to understand why the NBD approximates the multiplicity distribution have been done, e.g. by Giovannini and Van Hove in [49], right after UA5's publication. They tried to interpret the NBD behavior in terms of a simple form of cascade process, which leads to the concept of clusters, that will be explained in the following paragraphs. Other models, like e.g. [50], aimed to explain the NBD assuming stimulated emission of identical bosons by identical cells, but those models would produce an integer value of \( k \), which is not in agreement with the UA5 results.

Ancestor + daughters

\((n+1)\)th particle

1. ancestor \( \rightarrow \) constant term
2. emitted by preexisting cluster \( \rightarrow \) proportional to \( n \)

\[
P(n; \langle n \rangle; k) = \binom{n + k - 1}{k - 1} \left( \frac{1}{1 + \langle n \rangle / k} \right)^k \left( \frac{\langle n \rangle / k}{1 + \langle n \rangle / k} \right)^n
\]
Double Negative Binomial Distributions

1. $w$ mini-jets
2. $\langle n_{\text{semi-hard}} \rangle \approx 2 \langle n_{\text{soft}} \rangle$
3. soft obeys KNO!

$$P_{n}^{\text{total}}(w, \langle n_{\text{soft}} \rangle, k_{\text{soft}}, \langle n_{\text{semi-hard}} \rangle, k_{\text{semi-hard}}) =$$

$$= (1 - w)P_{NBD}^{\text{soft}}(n; \langle n_{\text{soft}} \rangle, k_{\text{soft}}) + wP_{NBD}^{\text{semi-hard}}(n; \langle n_{\text{semi-hard}} \rangle, k_{\text{semi-hard}})$$

$\chi^2 > 2$

$\chi^2 = 1.16$

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