Overview of Charged–Particle Multiplicities with ALICE

Valentina Zaccolo
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for the ALICE Collaboration
Motivation and outline

Multiplicity measurements:
1. $dN_{ch}/d\eta$
2. $P(N_{ch})$

measured at the **beginning** of the data taking, or when the detector is known **better** and with better analysis techniques

LHC energies $\rightarrow$ particle production dominated by soft QCD processes
Colliding energy grows $\rightarrow$ increased contributions from hard processes
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Colliding energy grows \(\rightarrow\) increased contributions from hard processes

✓ ALICE Detector
✓ Results

✓ Models and dependence on initial conditions
✓ Summary and outlook
A Large Ion Collider Experiment

Trigger Detectors

Run 1
years: 2009 - 2014

pp $\sqrt{s} = 0.9$ to 8 TeV
p-Pb $\sqrt{s_{NN}} = 5.02$ TeV
Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
A Large Ion Collider Experiment

Trigger
Detectors
Run 2
years: 2015 - now
\( pp \sqrt{s} = 13 \text{ TeV} \)
\( Pb-Pb \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
A Large Ion Collider Experiment

Detectors Used

Central rapidity

ITS

TPC
A Large Ion Collider Experiment

Detectors Used
Forward rapidity

TPC
ITS
FMD 1
FMD 2 & 3
Sub-detectors used

Central rapidity

1. Global tracks
   TPC
   • $|\eta| < 0.9$
   • $70 < \text{points} \leq 159$

   ITS
   • $|\eta| < 1.3$
   • $2 < \text{points} \leq 6$
   ✓ $p_T$ information

2. SPD tracklets
   SPD alone
   • expand the range to $|\eta| < 2.0$
   ✓ no $p_T$ information
Sub-detectors used

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Forward rapidity

Silicon strip detector in 5 rings
• Full azimuthal coverage
• Pseudorapidity coverage:
  $+5.0 < \eta < +1.7$ and $-1.7 < \eta < -3.4$
Run 1
Charged-particle multiplicities in proton–proton collisions at $\sqrt{s} = 0.9$ to 8 TeV [1]

- Global tracks
- three event classes: INEL, INEL>0 (at least one particle in $|\eta|<1$) and NSD
- Monte Carlo adjusted to reproduce: 1) measured diffraction cross-sections
  2) diffractive mass system distribution

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Power-fit extrapolation from lower energy:

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>INEL</th>
<th>NSD</th>
<th>INEL&gt;0</th>
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<tbody>
<tr>
<td>13</td>
<td>5.30 ± 0.24</td>
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Pseudorapidity density in pp

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Procedure:
1. Unfolding: disentangle the primary spectrum of charged particles
   • $\chi^2$ minimization or Bayesian method
2. Trigger + vertex efficiency

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

Multiplicity distributions in pp

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Run 1
Charged-particle multiplicities in proton–proton collisions at $\sqrt{s} = 0.9$ to 8 TeV [1]

- fit with double NBD successful

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

Multiplicity distributions in pp

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Run 1

Charged-particle multiplicities in proton–proton collisions at $\sqrt{s} = 0.9$ to 8 TeV [1]

- Koba-Nielen-Olesen scaling test

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


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Multiplicities distributions in pp

Run 1

Charged-particle multiplicity distributions over a wide pseudorapidity range in proton-proton collisions with ALICE [3]

- SPD and FMD
  $-3.4 < \eta < 5.0$

- fit with a double NBD

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

### Multiplicity distributions in pp

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---

*ALICE Preliminary, INEL pp, \( \sqrt{s} = 8 \text{ TeV} \)*

*ALICE Preliminary, NSD pp, \( \sqrt{s} = 8 \text{ TeV} \)*


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Run 1
Charged-particle multiplicity distributions over a wide pseudorapidity range in proton-proton collisions with ALICE [3]

- SPD and FMD 
  $-3.4 < \eta < 5.0$

- comparisons with Monte Carlo:
  ✓ PHOJET
tuned to $\sqrt{s} = 0.9$ TeV
  ✓ EPOS LHC
  ✓ PYTHIA 8 Monash

Pseudorapidity density in pp

Run 2

Pseudorapidity and transverse-momentum distribution of charged particles in proton-proton collisions at √s = 13 TeV [4]

measurement in |η| < 1.8

\[
\int_{-0.5}^{+0.5} \frac{dN_{ch}}{d\eta} d\eta
\]

<table>
<thead>
<tr>
<th></th>
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<tr>
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### Run 2

**Pseudorapidity density in pp**

### Pseudorapidity and transverse-momentum distribution of charged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV

Measurement in $|\eta| < 1.8$

$$\int_{-0.5}^{+0.5} \frac{dN_{ch}}{d\eta} \, d\eta$$

**INEL**

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Power-fit extrapolation from lower energy:

$$\sqrt{s} = 9/16 \quad \rho_{pp}$$

---

**Run 2**

**Pseudorapidity density of charged particles with $p_T$ thresholds in proton-proton collisions at $\sqrt{s} = 13$ TeV**


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Pseudorapidity density in p-Pb

Run 1

Pseudorapidity density of charged particles in p–Pb collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) [6]

\[
\frac{dN_{\text{ch}}}{d\eta_{\text{cms}}}/\langle N_{\text{part}} \rangle = 2.14 \pm 0.17 \text{ (syst.)}.
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Pseudorapidity density in p-Pb

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Centrality slicing using ZNA estimator: energy deposited in the neutron calorimeter on the Pb fragmentation side

1. Define stochastically the position of the nucleons

nuclear density function (Fermi distribution)

\[ \rho(r) = \rho_0 \frac{1 + w(r/R)^2}{1 + \exp \left( \frac{r-R}{a} \right)} \]
**Centrality Slicing:**

**The Glauber MC model [7]**

1. Define stochastically the position of the nucleons nuclear density function (Fermi distribution)
   \[ \rho(r) = \rho_0 \frac{1 + w(r/R)^2}{1 + \exp \left( \frac{r-R}{a} \right)} \]

2. Simulate a nuclear collision
   - sequence of independent binary nucleon-nucleon collisions
   - eikonal approximation
   - same cross section is used for all successive collisions
   - “ball diameter”
   \[ d < \sqrt{\frac{\sigma_{NN}^{\text{inel}}}{\pi}}. \]

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3. Hadronic cross section
   - Glauber MC + fit with NBD → multiplicity distribution

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3. Hadronic cross section
   Glauber MC + fit with NBD \rightarrow multiplicity distribution

4. Anchor Point [8]
   location of the discrepancy between the data and simulation

---


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Pseudorapidity density in Pb-Pb

Run 2

Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [9]

- Confirmation of the trend established by lower energy data

In pp collisions, $\sim \frac{1}{2}$ of energy (*) used for particle production, the rest is for leading nucleons.

Nucleons bound in nuclei seem to be more effective in particle production.


(*) if inelasticity coefficient $K \approx 0.5$ for pp
Run 2

Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [9]

- Decrease by 1.8 from the most central $<N_{\text{part}}>$ to the most peripheral
- Ratio between 5.02 TeV and 2.76 TeV is flat within the uncorrelated uncertainties

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Glauber MC with quark scaling [10]

Single quark position determined with proton density:

$$\rho(r) = \rho_0^{\text{proton}} \exp(-a \cdot r)$$

Particle multiplicity density scales linearly with the number of constituent quark participants [8]

---

Comparison with IP-Glasma Model

1. "IP-Glasma" initial conditions **IP-Sat model** with classical evolution of the glasma gluon fields. Contains fluctuations of color charge.

![Graph showing comparisons with ALICE]({})

**Red**
- ALICE [3]
  - no fluctuations of color charge [12]

**Green**
- no fluctuations of color charge [12]

**Blue**
- includes Gaussian fluctuations [12]

**Black**
- includes asymmetric fluctuations [13]

---

Other saturation based models

2. Armesto model [14] geometrical scaling model with no pre-thermal evolution of the produced gluons
3. EKRT model [15]
   - dominance of minijets in high energy nuclear collisions
   - saturation of gluon production
   - no fluctuations of color charge
4. Several others (rcBK [16], MC-KLN [17] …)

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Challenges:
- implementation of glasma
- distributions: additional fluctuations
- complications at forward rapidities

Summary and Outlook

Detailed studies published for Run 1 + papers for Run2:

- Fair predictions from extrapolation to higher energies

Waiting for new $\sqrt{s_{NN}} = 5$ and 8 TeV data at the end of the year

- Solid method for centrality estimation

Paper published in December

- No surprises going from $\sqrt{s_{NN}} = 2.76$ to 5.02 TeV
Summary and Outlook

Next paper in the pipeline:
Pseudorapidity dependence of the charged–particle density in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Detailed studies published for Run 1 + papers for Run2:
✓ fair predictions from extrapolation to higher energies

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...Stay Tuned!
References I

[1] ALICE Collaboration, “Charged-particle multiplicities in proton-proton collisions at $s\sqrt{s} = 0.9$ to $8$ TeV”, arXiv: 1509.07541 [nucl-ex]


[8] ALICE Collaboration, “Centrality dependence of the charged-particle multiplicity density at midrapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV ”, ALICE-PUBLIC-2015-008


Backup
Soft diffraction and IPomerons

**IPomeron**

Multiple gluon, colorless and flavorless.

**Single diffraction**

- Proton $p_i$ interacts with a Pomeron $P$
- Quasi-elastic outcoming proton $p_i'$
- Large rapidity gap (LRG)
- Invariant mass $x_F$

**Double diffraction**

- Two protons $p_1$ and $p_2$
- Pomeron $P$
- Diffractive system $X$
- Non-Single Diffractive & INEL $> 0$

**Non-Single Diffractive & INEL $> 0$**

- V0A
- V0C

**Diagram**

- One exchange mediator called the Reggeon $I_R$
- Needed to reproduce diffractive dissociation [9]

**Figure 1.5**

- Double Diffractive diagram
- Further in this thesis, together with other multiple Pomeron exchange processes
- Very low cross section at the LHC (around 1 mb [10]), and therefore, is not considered

**Chapter 1. High-Energy Physics**

- Elastic Interaction
  - When the Pomeron interacts with the proton
  - Single, double or central diffractive
  - Diffraction is described in terms of exchange of a Pomeron $(IP)$

- Inelastic Interaction
  - Non-dissociated pomeron is characterized by its diffractive mass $x_F$
  - The Pomeron's momentum carried by its constituent gluon $x_F$

**Soft Diffraction**

- Soft diffraction is a process in which both the colliding protons dissociate
- Central Diffraction (CD) occurs
- This process has a very low cross section at the LHC

**Equations**

- $p_i$ and $p_j$ are the incoming protons
- $x_F$ is the fraction of the proton's momentum carried by the Pomeron
- $X$ is the diffractive system
- $\phi$, $\eta$, $X_1$, $X_2$, $p_1$, $p_2$, $p_i$, $p_i'$

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Glauber MC + Negative Binomial Distribution $\rightarrow$ simulate a multiplicity distribution

- Two-components model [18], which decompose nucleus–nucleus collisions into soft interactions (proportional to $N_{\text{part}}$) and hard interactions (prop to $N_{\text{coll}}$)

\[ N_{\text{ancestors}} = f \cdot N_{\text{part}} + (1 - f) \cdot N_{\text{coll}} \]

- NBD function: particles produced per interaction

\[ P_{\mu,k}(n) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \cdot \frac{(\mu/k)^n}{(\mu/k+1)^{n+k}}, \]

- Anchor Point [8] location of the divergence between the data and simulation

---


Analysis procedure for pseudorapidity density in Pb-Pb

- Tracklet candidates are formed using the position of the reconstructed primary vertex and two hits, one on each SPD layer.
- $p_T$ cut-off is approximately 50 MeV/c (particle absorption in detector material)

The charged-particle pseudorapidity density is obtained from the measured distribution of tracklets $dN_{\text{tracklets}}/d\eta$ as $dN_{\text{ch}}/d\eta = \alpha (1 - \beta) dN_{\text{tracklets}}/d\eta$

1. $\alpha$: acceptance and efficiency for a primary particle to produce a tracklet
2. $\beta$: contamination of reconstructed tracklets from combinations of hits not produced by the same primary particle.

All corrections are calculated using Monte Carlo data from HIJING through a GEANT3 simulation of ALICE.

**Uncertainties of [9]**

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>70–80%</th>
<th>0–2.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background events and pileup</td>
<td>negligible</td>
<td></td>
</tr>
<tr>
<td>Material budget</td>
<td>negligible</td>
<td></td>
</tr>
<tr>
<td>Tracklet selection criteria</td>
<td>negligible</td>
<td></td>
</tr>
<tr>
<td>Detector acceptance and efficiency</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>Centrality determination</td>
<td>7.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>0.2%</td>
<td>2%</td>
</tr>
<tr>
<td>Particle composition</td>
<td>negligible</td>
<td></td>
</tr>
<tr>
<td>Weak-decay contamination</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>Zero-$p_T$ extrapolation</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>TOTAL ($N_{\text{part}}$-dependent)</td>
<td>7.5%</td>
<td>2.1%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>7.7%</td>
<td>2.7%</td>
</tr>
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</table>

**Bayes’ theorem** [19] \( P(A|B) = \frac{P(B|A)P(A)}{P(B)} \)

\[
\tilde{R}_{tm} = \frac{R_{mt}P_t}{\sum_{t'} R_{mt'}P_{t'}}
\]

\[
U_t = \sum_m \tilde{R}_{tm}M_m
\]

Trigger and Vertex Efficiency

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

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

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

\( \text{V0C} \)

\( \text{V0A} \)

\( \text{U}^* = \frac{\text{U}_t}{\varepsilon_{\text{trig}}} \)

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

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


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\[ \langle N \rangle \propto \ln W \propto \ln \sqrt{s} \]


1. Feynman Scaling
2. Moments define uniquely the distribution

\[ c_q = \frac{\langle n^q \rangle}{\langle n \rangle^q} \]

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

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 \cite{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 \cite{4}, 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

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

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 \( n + k \) trials. The above binomial coefficient gives the number of all these sequences of length \( n + k \).

If \( k = 1 \) the NBD is a geometrical distribution, while if \( k \to 1 \), it is the Poisson distribution.

The UA5 observed a violation of the KNO scaling \cite{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 \cite{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. \cite{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

1. ancestor \( \longrightarrow \) constant term
2. emitted by preexisting cluster \( \longrightarrow \) proportional to \( n \)
1. $w$ mini-jets
2. $\langle n_{\text{semi-hard}} \rangle \approx 2 \langle n_{\text{soft}} \rangle$
3. soft obeys KNO!

\[
P_n^{\text{total}}(w, \langle n_{\text{soft}} \rangle, k_{\text{soft}}, \langle n_{\text{semi-hard}} \rangle, k_{\text{semi-hard}}) =
\]
\[
= (1 - w)P_{\text{NBD}}^{\text{soft}}(n; \langle n_{\text{soft}} \rangle, k_{\text{soft}}) + wP_{\text{NBD}}^{\text{semi-hard}}(n; \langle n_{\text{semi-hard}} \rangle, k_{\text{semi-hard}})
\]
Results for $\sqrt{s} = 0.9$ TeV [3]

Fit with a Double Negative Binomial Distribution: ALICE SPD only

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


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Fit with a Double NBD:

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


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Comparisons with CMS Results [3]

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

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


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Initial Conditions: 
Partons and Their Evolution

In Deep Inelastic Scattering: Bjorken-$x$

\[ x \equiv \frac{Q^2}{2(P \cdot q)} = \frac{Q^2}{s + Q^2 - M^2} \]

Parton Area \( 1/Q^2 \)

1. \( Q^2 \)-evolution \( Q^2 \) grows
In Deep Inelastic Scattering: Bjorken-x

\[ x \equiv \frac{Q^2}{2(P \cdot q)} = \frac{Q^2}{s + Q^2 - M^2} \]

Parton Area \( 1/Q^2 \)

1. \( Q^2 \)-evolution \( Q^2 \) grows
2. \( Y \)-evolution \( x \) decreases at fixed \( Q^2 \)

Gluon density:

\[ xg(x, Q^2) \equiv x \frac{dN_g}{dx} \]

occupation number increases

\[ n(x, Q^2) \sim xg(x, Q^2)/Q^2 R^2 \]

formation of Color Glass Condensate [11]

1. pre-equilibrium $\rightarrow$ Glasma: Colored flux tubes

2. Distributions $\rightarrow$ additional fluctuations
   - gluon distribution inside a proton at a given rapidity $Y$ can be thought of as a distribution of dipoles
   - in the saturation regime, the dipole picture breaks down
   - with the evolution in rapidity, individual dipoles inside the target start to split into new dipoles stochastically.

3. Forward rapidities $\rightarrow$ rapidity dependence of color charge fluctuations