ALICE results
on system-size dependence of
charged-particle multiplicity density
in p-Pb, Pb-Pb and Xe-Xe collisions

Beomkyu Kim
For the ALICE Collaboration

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Charged-particle multiplicity density

- Study interplay between soft and hard QCD

**AA collisions**
- Direct relation to the initial $\epsilon$ of QGP\(^1\)
  \[ \epsilon = \frac{dE_T/dy}{\tau_0 \pi R^2} \approx \frac{3}{2} \langle m_T \rangle \frac{dN_{ch}/d\eta}{\tau_0 \pi R^2} > 1\, \text{GeV}/\text{fm}^3 \]

**pp collisions**
- Reference data for nuclear effect
- Study MPI in high $N_{ch}$ collisions

**p–Pb collisions**
- Discriminate between FSR in AA and ISR of nuclei themselves

- QGP-like effects even in pp and p–Pb collisions at LHC energies
  proton (A=1) → p–Pb ———- Xe (A=129) ——— Pb (A=208)

- System size and $\langle dN_{ch}/d\eta \rangle \rightarrow$ starting of the story

\(^1\)See the discussion: system-size dependence of $\langle dN_{ch}/d\eta \rangle$ at $\sqrt{s_{NN}} = 5.02$ TeV at QM 2017 by Christian Holm Christensen
A Large Ion Collider Experiment

V0 (Scintillator hodoscopes)
- triggers forward activity
- $-3.7 < \eta < -1.7$, $2.8 < \eta < 5.1$

SPD (Silicon Pixel Detector)
- Two-layer silicon detector
- counting tracklets at mid rapidity
- $-2 < \eta < 2$

FMD (Forward Mult. Detector)
- three sets of Si strip sensors
- counting $N_{ch}$ at forward rapidity
- $-3.7 < \eta < -1.7$, $1.7 < \eta < 5.1$

ZDC (Zero Degree Calorimeter)
- measuring $E$ of spectator nucleons
- $\eta \sim \pm 10$

- 18 detectors, sensitivity at low $p_T$, excellent PID
\[ \langle dN_{\text{ch}}/d\eta \rangle \text{ in pp collisions} \]

- Inclusive study: \( \text{INEL} \propto s^{0.102}, \text{NSD} \propto s^{0.114} \) and \( \text{INEL}_{>0} \propto s^{0.114} \)
- Multiplicity dependence study\(^2\)
  - \( \langle dN_{\text{ch}}/d\eta \rangle \) for different multiplicity classes
  - The evolution of \( \langle dN_{\text{ch}}/d\eta \rangle \) with \( \sqrt{s} \): steeper for higher multiplicity class (MPI)

\(^1\)INEL requiring at least one charged particle in \( |\eta| = 1 \)
\(^2\)“Multiplicity dependence study of the \( \eta \)-density distribution of charged particles in pp collisions with ALICE” by Prabhakar Palni
\[ \langle dN_{ch}/d\eta \rangle \text{ in } p - \text{Pb collisions} \]

All models lie within 15\% of data

  - strong \( b \) dependence of parton shadowing
  - combines pQCD and soft QCD
  - reproduces magnitude and shape for Pb-going side

  - collective effects like flow included
  - reproduces Pb-going side

- **EPOS 3** (Phys. Rev. C89 (2014) 064903)
  - includes a full viscous hydrodynamical simulation
  - only the most forward part in the Pb-going side

  - saturation based models
  - perform better in \( \eta_{lab} > -1.3 \)
Impact parameter ($b$)

- The degree of geometrical overlap
- Centrality: fraction of geometrical cross-section
- $N_{\text{part}}, N_{\text{coll}}$

Centrality estimation for Xe–Xe

- Deformation of the nuclear density considered
- Multiplicity with the V0 detector
- NBD Glauber fit coupled to a two component model
\[ \langle \frac{dN_{\text{ch}}}{d\eta} \rangle \text{ AND } N_{\text{ch}}^{\text{tot}} \text{ IN Pb – Pb AND Xe – Xe COLLISIONS} \]

**arXiv:1805.04432**

\[ \frac{\langle dN_{\text{ch}}/d\eta \rangle}{\langle N_{\text{part}} \rangle} \text{ and } \frac{2}{\langle N_{\text{part}} \rangle} N_{\text{ch}}^{\text{tot}} \]

- for the most 5% central collisions
- Xe–Xe result is in agreement with the trend
- A stronger rise w.r.t. \( \sqrt{s_{\text{NN}}} \) than for pp
- At \(|\eta| < 0.5\) p–Pb fits with INEL pp points
\[ \frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}}/d\eta \rangle \text{ AND } \frac{2}{\langle N_{\text{part}} \rangle} N_{\text{ch}}^{\text{tot}} \text{ AS A FUNCTION OF } \langle N_{\text{part}} \rangle \]

Data are scaled to $\sqrt{s}$, $\sqrt{s_{NN}} = 5.44$ TeV (prev.) to match with Xe–Xe results.

- ALICE data decreasing by 2 from the most central to the peripheral
- smoothly connect to pp and p–Pb
- Xe–Xe shapes exceed Pb–Pb at similar $\langle N_{\text{part}} \rangle$ for the top 10% central collisions
- RHIC data show hint of same behaviour
Scaling of $\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}} / d\eta \rangle$

Different scalings for particle production

1. Power law function

2. Two component model

3. Core and corona model

4. Quark-Glauber parametrisation

- using wounded constituent quarks
- $N_q = 3$ and 5
- A scaling violation for the 0–5% centrality range in Xe–Xe collisions
  (0-1-2-3-4-5% binning)
$\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}} / d\eta \rangle$ AND MODELS IN Xe – Xe COLLISIONS

ALICE
- initial state by HIJING
- and then hydrodynamical evolution

PYTHIA/Angantyr (JHEP 10 (2016) 139)
- performing each nucleon-pair (parton level)
- Lund strings hadronised as an ensemble

- viscous hydrodynamics coupled to a hadronic cascade model

rc-BK, KLN, ASW$^1$, IP-Glasma$^2$ and EKRT$^3$
- saturation-inspired models to limit $N_{\text{parton}}$

All models describe data within ±20%

\( dN_{\text{ch}}/d\eta \) vs \( \eta \) and models for 0–5\% central Xe–Xe collisions

### Models Compared

**HIJING**
- Good match in mid, overestimate at forward \( \eta \)
- (due to large value of \( s_g \))

**AMPT and PYTHIA/Angantyr**
- fairly good, slight overestimate at forward \( \eta \)

**EPOS LHC**
- underestimate data overall

**rcBK-MC**
- overall overestimation

**KLN**
- matches in mid \( \eta \), not true for forward \( \eta \)

**IP-Glasma**
- wider than data

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**Graph Details**

- **Graph Title**: \( Xe-Xe, \sqrt{s_{\text{NN}}} = 5.44 \text{ TeV} \)
- **Axes**: \( \eta \) vs \( dN_{\text{ch}}/d\eta \)
- **Models Shown**:
  - ALICE
  - HIJING 2.1, \( s_g = 0.28 \)
  - AMPT
  - PYTHIA/Angantyr
  - EPOS-LHC
  - rcBK-MC
  - KLN, \( \lambda = 0.252 \)
  - IP-Glasma + subnucleon fluct.

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**Legend**

- **Legend Entries**:
  - ALICE
  - HIJING 2.1, \( s_g = 0.28 \)
  - AMPT
  - PYTHIA/Angantyr
  - EPOS-LHC
  - rcBK-MC
  - KLN, \( \lambda = 0.252 \)
  - IP-Glasma + subnucleon fluct.
Charged-particle multiplicity density studies on various collision systems and energies in centre of mass

**pp and p–Pb collisions**

- Compared to various theoretical models: for p-Pb better agreement with saturation based models
- $|\eta| < 0.5 \langle dN_{ch}/d\eta \rangle (|\eta| < 0.5)$ in p–Pb fits with INEL pp points

**Pb–Pb and Xe–Xe collisions**

- The high statistics distributions are useful to constrain the available models
- $\frac{2}{\langle N_{part} \rangle} \langle dN_{ch}/d\eta \rangle$ and $\frac{2}{\langle N_{part} \rangle} N_{ch}^{\text{tot}}$ for the top 5% central Xe–Xe collisions in agreement with the previous AA power-law trend
- Steep rise of $\frac{2}{\langle N_{part} \rangle} \langle dN_{ch}/d\eta \rangle$ and $\frac{2}{\langle N_{part} \rangle} N_{ch}^{\text{tot}}$, and $N_{part}$-scaling violation for the 0–5% central Xe-Xe
Backup
Woods-Saxon distributions

**Xe ion (deformed)**

\[ \rho(r, \vartheta) = \rho_0 \frac{1}{1 + \exp \left( \frac{r - R(\vartheta)}{a} \right)} \]

- \( \rho_0 \): the nucleon density
- The nuclear skin thickness \( a = 0.59 \pm 0.07 \) fm \(^1\)
- Nuclear radius \( R(\vartheta) = R_0 \left[ 1 + \beta_2 \, Y_{20}(\vartheta) \right] \)

**Pb ion (spherical)**

\[ \rho(r, \vartheta) = \rho_0 \frac{1}{1 + \exp \left( \frac{r - R}{a} \right)} \]

- \( \rho_0 \): the nucleon density
- The nuclear skin thickness \( a = 0.546 \pm 0.01 \) fm
- Nuclear radius \( R = 6.62 \pm 0.06 \) fm

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When the squared momentum transfer is much less than $\sqrt{s}$

$$t = (p_a - p_c)^2 \ll \sqrt{s}$$

- Help us understand QCD in the non-perturbative regime
  ($t \sim 0$ or $q^2 < \Lambda^2_{\text{QCD}}$)
- By Regge theory $^{1,2,3}$, diffraction proceeds via the exchange of Pomerons
  ($gg$ leading order + $ggg$ next leading order + $\cdots$)

SD, DD and ND

SD

DD

ND
$N_{ch}$ in $pp$ collisions

\[ \langle dN_{ch} / d\eta \rangle \propto s^{0.103} \]  

\[ \langle dN_{ch} / d\eta \rangle_{>0} \propto s^{0.111} \]
\( N_{\text{ch}} \) in Xe – Xe collisions

- HIJING using gluon shadowing parameter \( s_g = 0.28 \)
- EPOS based on Gribov-Regge theory incorporated with collected effect
- Saturation-inspired models: rcBK-MC, Armesto, Kharzeev and EKRT
$N_{\text{ch}}$ in pp collisions

- Published multiplicity papers

<table>
<thead>
<tr>
<th>Type</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>paper</th>
</tr>
</thead>
</table>

- Reference data to study nuclear effect
  - in nucleus–nucleus
  - in proton–nucleus collisions

- Big contribution from non-perturbative QCD processes
  - INEL$^1$ : ND + SD + DD + CD ...
  - NSD : ND + DD (to ignore large uncertainty from SD)
  - $\text{INEL}_{>0}$ : INEL + at least one activity in $|\eta| = 1$
    (effective filter for SD and DD events)

$^1$INEL = ND($\sim$ 70 %) + SD ($\sim$ 20 %) + DD ($\sim$ 10 %) + CD ($< 1$ %) arXiv:1208.4968
Published (ongoing) multiplicity papers

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<thead>
<tr>
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<th>paper</th>
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<tbody>
<tr>
<td>p-Pb</td>
<td>5.02</td>
<td>PRL 110 (2013) 032301</td>
</tr>
<tr>
<td></td>
<td>8.16</td>
<td>preliminary</td>
</tr>
</tbody>
</table>

Valuable tool to discriminate between
- final state effects in nucleus–nucleus
- initial state effect of nuclei themselves

$N_{ch}$
- Discriminate the initial and final state effects
- A tool to study the various models of gluon saturation\(^1\)
- Providing constraints to the initial state and small Bjorken-$x$ modeling

\(^1\) Different descriptions of the upper limit in growth of the parton density
\[ \langle dN_{\text{ch}}d\eta \rangle \text{ in Pb – Pb and Xe – Xe collisions} \]

- Published (and ongoing) multiplicity papers

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<th>paper</th>
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<tr>
<td>Xe-Xe</td>
<td>5.44</td>
<td></td>
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- \( N_{\text{ch}} \): A key observable in the QGP (initial energy density)
- Impact parameter \( (b) \): The degree of geometrical overlap
- Centrality: Experimental proxy of \( b \)
- \( N_{\text{part}} \): the number of nucleons participating in the collision
- \( N_{\text{coll}} \): the number of binary nucleon-nucleon collisions among the participant nucleons
A Large Ion Collider Experiment

- 17 different detectors, Low $p_T$ sensitivity, excellent PID

<table>
<thead>
<tr>
<th>Trigger detectors</th>
<th>$\eta_{\text{min}} / \eta_{\text{max}}$</th>
</tr>
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<tbody>
<tr>
<td>SPD</td>
<td>-2/2</td>
</tr>
<tr>
<td>V0</td>
<td>2.8/5.1 -3.7/-1.7</td>
</tr>
<tr>
<td>AD</td>
<td>4.8/6.3 -7/-4.9</td>
</tr>
<tr>
<td>ZDC</td>
<td>$\sim \pm 10$</td>
</tr>
</tbody>
</table>

**SPD (Silicon Pixel Detector)**
- Innermost two-layer silicon detector
- $r = 3.9, 7.6$ cm
- Triggers central activity

**V0 (Scintillator hodoscopes)**
- Triggers forward activity
- $z = -0.9, 3.3$ m

**AD (Alice Diffraction)**
- Scintillation counters
- $z = -19.5, 17$ m

**ZDC:**
A Large Ion Collider Experiment

- 17 different detectors, Low $p_T$ sensitivity, excellent PID

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<tr>
<th>Data taking detectors</th>
<th>$\eta_{\text{min}} / \eta_{\text{max}}$</th>
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<tbody>
<tr>
<td>A side</td>
<td>C side</td>
</tr>
<tr>
<td>ITS</td>
<td>$-1.4 / 1.4$</td>
</tr>
<tr>
<td>TPC</td>
<td>$-0.9 / 0.9$</td>
</tr>
<tr>
<td>FMD</td>
<td>$1.7 / 5.1$</td>
</tr>
<tr>
<td></td>
<td>$-3.4 / -1.7$</td>
</tr>
</tbody>
</table>

- ITS (Inner Tracking System)
  - 6 layers of Si detectors
  - Containing SPD

- TPC (Time Projection Chamber)
  - Large cylindrical detector
  - $-250 < z < 250$ cm
  - $86 < r < 250$ cm
  - 558 k readout channels

- FMD (Forward Multiplicity Detector)
  - Two sets of Si strip sensors
  - close to V0 detectors

ITS = SPD + SDD + SSD
\[
\frac{2}{\langle N_{\text{part}} \rangle} \langle dN_{\text{ch}}/d\eta \rangle \text{ AND } \frac{2}{\langle N_{\text{part}} \rangle} N_{\text{ch}}^{\text{tot}} \text{ AS A FUNCTION OF CENTRALITY}
\]

Data are scaled to \( \sqrt{s} \), \( \sqrt{s_{\text{NN}}} = 5.44 \text{ TeV (prev.)} \) to match with Xe–Xe results.

- ALICE data decreasing by 2 from the most central to the peripheral
- smoothly connect to pp and p–Pb