System-size dependence of \( \frac{dN_{\text{ch}}}{d\eta} \) at
\( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \)
Over a wide \( \eta \) range
A Large Ion Collider Experiment

System-size dependence of $\frac{dN_{\text{ch}}}{d\eta}$ at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Over a wide $\eta$ range
Example of reasons to look forward

- Large $\eta$ acceptance
- Width of $dN_{ch}/dy$ in A–A collisions

- Clear deviation from Landau–Hydro ($\sigma_{L-C}$) from top SPS and up
- Clear scaling with beam rapidity from top SPS and up
ALICE

Results

- $dN_{ch}/d\eta$ over $-3.5 < \eta < 5$ in
  - pp
  - p–Pb
  - Pb–Pb

- Ratios
- $dN_{ch}/dy$
ALICE

Results

- $dN_{ch}/d\eta$ over $-3.5 < \eta < 5$ in
  - pp
  - p–Pb
  - Pb–Pb

- Ratios
- $dN_{ch}/dy$

Detectors:

- V0
  trigger, centrality

- ZDC
  (note, at $z = \pm 112.5\,m$)
  centrality

- SPD
  $N_{ch} (|\eta| < 2)$

- FMD
  $N_{ch} (-3.5 < \eta < -1.8 \text{ and } 1.8 < \eta < 5)$
ALICE

Results

- $dN_{\text{ch}}/d\eta$ over $-3.5 < \eta < 5$ in
  - pp
  - p–Pb
  - Pb–Pb
- Ratios
- $dN_{\text{ch}}/dy$

Detectors:

- V0
  - trigger, centrality
- ZDC
  - (note, at $z = \pm 112.5m$)
  - centrality
- SPD
  - $N_{\text{ch}} (|\eta| < 2)$
- FMD
  - $N_{\text{ch}} (-3.5 < \eta < -1.8 \text{ and } 1.8 < \eta < 5)$
Results

- $dN_{ch}/d\eta$ over $-3.5 < \eta < 5$ in
  - pp
  - p–Pb
  - Pb–Pb
- Ratios
- $dN_{ch}/dy$

Detectors:

- V0
  - trigger, centrality
- ZDC
  - (note, at $z = \pm 112.5 m$)
  - centrality
- SPD
  - $N_{ch}$ ($|\eta| < 2$)
- FMD
  - $N_{ch}$ ($-3.5 < \eta < -1.8$ and $1.8 < \eta < 5$)
ALICE

Results
▶ \( dN_{\text{ch}}/d\eta \) over \(-3.5 < \eta < 5\) in
   ▶ pp
   ▶ p–Pb
   ▶ Pb–Pb
▶ Ratios
▶ \( dN_{\text{ch}}/dy \)

Detectors:
▶ V0
trigger, centrality
▶ ZDC
  (note, at \( z = \pm 112.5 m \))
centrality
▶ SPD
  \( N_{\text{ch}} (|\eta| < 2) \)
▶ FMD
  \( N_{\text{ch}} (-3.5 < \eta < -1.8 \text{ and } 1.8 < \eta < 5) \)
A wealth of data

Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- 3 weeks of data taking in 2015
- $\approx 150$ M events
- Here, only low-intensity beams
  - Small pile-up background
  - Analysis not statistics limited
A wealth of data

- Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
  - 3 weeks of data taking in 2015
  - $\approx 150$ M events
  - Here, only low-intensity beams
    - Small pile-up background
    - Analysis not statistics limited

- p–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
  - 11 days of data taking in 2013
  - $\approx 130$ M events (MB)
A wealth of data

Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- 3 weeks of data taking in 2015
- $\approx 150$ M events
- Here, only low-intensity beams
  - Small pile-up background
  - Analysis not statistics limited

p–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- 11 days of data taking in 2013
- $\approx 130$ M events (MB)

pp, $\sqrt{s} = 5.02$ TeV
- 5 days of data taking in 2015
- $\approx 130$ M events
Collision classification

**Pb–Pb**
- Centrality classes from sum V0 amplitudes (V0M)
- Fractions of hadronic cross section

**p–Pb**
- Centrality classes from Pb–side V0 (V0A) and neutrons on same side (ZNA)
- Fractions of hadronic cross section

**pp**
- Inelastic cross-section and $N_{\text{ch}} |\eta| < 1 \geq 1$

![Graphs and plots showing data analysis results.](ALICE-PUBLIC-2015-008, PRC91(2015)064905)
A Large Ion Collider Experiment

Pb–Pb collisions

\[ \frac{dN\text{ch}}{d\eta} \]

\[ \eta \]

ALICE

Data (symmetrised)

Reflected

Uncorr. syst. unc.

Corr. syst. unc.

Pb–Pb \( \sqrt{s_{NN}} = 5.02 \) TeV

0– 5 %

5–10 %

10–20 %

20–30 %

30–40 %

40–50 %

50–60 %

60–70 %

70–80 %

80–90 %

ALI-PUB-115086

10 centrality classes from 0% to 90% [arXiv:1612.08966]

Selection based on sum signal in V0 (V0M)
p–Pb collisions

Laboratory pseudorapidity
7 centrality classes from 0% to 100%
Pb-going: +\( \eta \), p-going: −\( \eta \), \( \gamma_{CM} = 0.465 \)
Selection based on signal in V0 on Pb-going side (V0A)
Inelastic collisions with at least one charged particle in $|\eta| < 1$

- Minimize systematic uncertainties due to normalisation

$pp \sqrt{s} = 5.02$ TeV

INEL > 0

- Data (symmetrised)
- Reflected
- Uncorr. syst. unc.
Dividing by pp baseline

\[ r_X = \frac{dN_{ch}/d\eta|_X}{dN_{ch}/d\eta|_{pp}} \]

Pb–Pb

- 2 orders of magnitude over pp
- Increase as \( \eta \to 0 \)
Dividing by pp baseline

\[ r_X = \frac{dN_{ch}/d\eta|_X}{dN_{ch}/d\eta|_{pp}} \]

Pb–Pb

- 2 orders of magnitude over pp
- Increase as \( \eta \to 0 \)
- Scale by \( 2/N_{\text{part}} \) (Glauber)
Dividing by pp baseline

\[ r_X = \frac{dN_{ch}/d\eta|_X}{dN_{ch}/d\eta|_{pp}} \]

Pb–Pb
- 2 orders of magnitude over pp
- Increase as \( \eta \to 0 \)
- Scale by \( 2/N_{\text{part}} \) (Glauber)

p–Pb
- Centrality: V0A
- 1 order of magnitude over pp
- Near-linear increase from p-going to Pb-going side
Nuclear modification per binary collision versus $\eta$

$$\frac{1}{N_{\text{coll}}} \left( \frac{dN_{\text{ch}}}{d\eta} \right)_{X} \left/ \left( \frac{dN_{\text{ch}}}{d\eta} \right)_{\text{pp}} \right.$$ 

Pb–Pb
- $N_{\text{coll}}$: Glauber
- $\uparrow$ as $\eta \to 0$

p–Pb
- $N_{\text{coll}}$: Hybrid model
- Centrality: ZNA
- Near-linear $\uparrow$ from p- to Pb-going side
- Consistent with independent proton-nucleon scatterings
  (see PRC72(2005)034907, PRL39(1977)1120)
Model’s change in particle production

\[ r_X = \frac{dN_{ch}/d\eta|_X}{dN_{ch}/d\eta|_{pp}} \]

pp, p–Pb, & Pb–Pb from same model

HIJING
- Pb–Pb/pp far flatter
- p–Pb/pp non-linear
Model’s change in particle production

\[ r_X = \frac{dN_{ch}/d\eta|_X}{dN_{ch}/d\eta|_{pp}} \]

pp, p–Pb, & Pb–Pb from same model

**HIJING**
- Pb–Pb/pp far flatter
- p–Pb/pp non-linear

**EPOS-LHC**
- Pb–Pb/pp more curved
- p–Pb/pp non-linear
Model’s change in particle production

\[ r_X = \frac{dN_{ch}/d\eta|_X}{dN_{ch}/d\eta|_{pp}} \]

pp, p–Pb, & Pb–Pb from same model

**HIJING**
- Pb–Pb/pp far flatter
- p–Pb/pp non-linear

**EPOS-LHC**
- Pb–Pb/pp more curved
- p–Pb/pp non-linear

- HIJING, EPOS-LHC does not reproduce data
Express $dN_{\text{ch}}/d\eta$ in terms of $dN_{\text{ch}}/dy$

\[
dN/dy = \frac{1}{\langle \beta \rangle} dN_{\text{ch}}/d\eta
\]

\[
y \approx \eta - \cos \vartheta/(2a^2)
\]

\[
\langle \beta \rangle \approx \frac{1}{\sqrt{1 + 1/(a^2 \cosh^2 \eta)}}
\]

$a$: effective $p_T/m$

(assumed $da/d\eta$ = constant, equal for all particle species)

Ansatz: For symmetric: $dN_{\text{ch}}/dy$ Gaussian

\[
\frac{dN_{\text{ch}}}{d\eta} = \langle \beta \rangle A/(\sqrt{2\pi}\sigma)e^{-y^2/(2\sigma^2)}
\]

[arXiv:1612.08966]
Express $dN_{\text{ch}}/d\eta$ in terms of $dN_{\text{ch}}/dy$

$$dN/dy = \frac{1}{\langle \beta \rangle} dN_{\text{ch}}/d\eta$$

$$y \approx \eta - \cos \vartheta / (2a^2)$$

$$\langle \beta \rangle \approx \frac{1}{\sqrt{1 + 1/(a^2 \cosh^2 \eta)}}$$

$a$: effective $p_T/m$

(assumed $da/d\eta = \text{constant}$, equal for all particle species)

Ansatz: For symmetric: $dN_{\text{ch}}/dy$ Gaussian

$$\frac{dN_{\text{ch}}}{d\eta} = \langle \beta \rangle A / (\sqrt{2\pi} \sigma) e^{-y^2/(2\sigma^2)}$$
Express $dN_{\text{ch}}/d\eta$ in terms of $dN_{\text{ch}}/dy$

$$dN/dy = \frac{1}{\langle \beta \rangle} dN_{\text{ch}}/d\eta$$

$$y \approx \eta - \cos \vartheta/(2a^2)$$

$$\langle \beta \rangle \approx \frac{1}{\sqrt{1 + 1/(a^2 \cosh^2 \eta)}}$$

$a$: effective $p_T/m$

(assumed $da/d\eta =$ constant, equal for all particle species)

Ansatz: For symmetric: $dN_{\text{ch}}/dy$ Gaussian

$$\frac{dN_{\text{ch}}}{d\eta} = \langle \beta \rangle A/(\sqrt{2\pi}\sigma)e^{-y^2/(2\sigma^2)}$$
Express $dN_{ch}/d\eta$ in terms of $dN_{ch}/dy$

$$dN/dy = \frac{1}{\langle \beta \rangle} dN_{ch}/d\eta$$

$$y \approx \eta - \cos \vartheta/(2a^2)$$

$$\langle \beta \rangle \approx \frac{1}{\sqrt{1 + 1/(a^2 \cosh^2 \eta)}}$$

$a$: effective $p_T/m$

(assumed $da/d\eta = \text{constant, equal for all particle species}$)

**Ansatz:** For symmetric: $dN_{ch}/dy$ Gaussian

$$\frac{dN_{ch}}{d\eta} = \langle \beta \rangle A/(\sqrt{2\pi\sigma}) e^{-y^2/(2\sigma^2)}$$

**Ansatz:** For asymmetric $A \to (\alpha y + A)$

$$\frac{dN_{ch}}{d\eta} = \langle \beta \rangle (\alpha y + A)/(\sqrt{2\pi\sigma}) e^{-y^2/(2\sigma^2)}$$

Here, $y$ in centre-of-mass
Express $dN_{\text{ch}}/d\eta$ in terms of $dN_{\text{ch}}/dy$

$$dN/dy = \frac{1}{\langle \beta \rangle} dN_{\text{ch}}/d\eta$$

$$y \approx \eta - \cos \vartheta/(2a^2)$$

$$\langle \beta \rangle \approx \frac{1}{\sqrt{1 + 1/(a^2 \cosh^2 \eta)}}$$

$a$: effective $p_T/m$ 
(assumed $da/d\eta =$ constant, equal for all particle species)

Ansatz: For symmetric: $dN_{\text{ch}}/dy$ Gaussian

$$\frac{dN_{\text{ch}}}{d\eta} = \langle \beta \rangle A/(\sqrt{2\pi}\sigma)e^{-y^2/(2\sigma^2)}$$

Ansatz: For asymmetric $A \rightarrow (\alpha y + A)$

$$\frac{dN_{\text{ch}}}{d\eta} = \langle \beta \rangle (\alpha y + A)/(\sqrt{2\pi}\sigma)e^{-y^2/(2\sigma^2)}$$

Here, $y$ in centre-of-mass
Width in $y$ and lower-bound $p_T/m$ estimate

Fit parameters
Also for EPOS-LHC

- $\sigma$ consistent with estimate from $p_T$ spectra and $dN_{ch}/d\eta$ [arXiv:1612.08966]
Width in $y$ and lower-bound $p_T/m$ estimate

Fit parameters
Also for EPOS-LHC

- **Width**
  - $\sigma$ consistent with estimate from $p_T$ spectra and $dN_{ch}/dy$ \cite{arXiv:1612.08966}

- **Effective $p_T/m = a$**
  - Hint of moderate increase
  - $\langle m \rangle$ from Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV particle ratios
    (see PRC88,044910)
  - **Note** $a < \langle p_T \rangle / \langle m \rangle$
    Illustrated by EPOS-LHC w/open markers and lines
Back-of-the-envelope estimate of energy density

Bjorken formula

\[ \varepsilon_{\text{Bj}} \tau = \frac{1}{S_T} \frac{dE_T}{dy} \]

Approximations

\[ \frac{dE_T}{dy} \approx 2 \langle m_T \rangle \frac{dN_{\text{ch}}}{dy} \]

\[ \gtrsim 2 \langle m \rangle \sqrt{1 + (p_T / m)^2} \frac{dN_{\text{ch}}}{dy} \]

\( S_T \) from Glauber
Back-of-the-envelope estimate of energy density

Bjorken formula

\[ \varepsilon_{\text{Bj}} = \frac{1}{S_T} \frac{dE_T}{dy} \]

Approximations

\[ \frac{dE_T}{dy} \approx 2 \langle m_T \rangle \frac{dN_{\text{ch}}}{dy} \]

\[ \gtrsim 2 \langle m \rangle \sqrt{1 + \left(\frac{p_T}{m} \right)^2} \frac{dN_{\text{ch}}}{dy} \]

\( S_T \) from Glauber

Transverse area – Two extremes

\[ \bigcup \text{part.} \]

Union of participant areas

\[ \bigcap \text{part.} \]

Intersect of participant areas

- \( \sigma_{NN} = 70 \text{ mb} \)
- Black-disc protons
- Spatial overlap resolution 0.1 fm
- SX1(2015)13

\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

\( \text{Pb-Pb} \quad \bigcup \text{participants} \)

\( \bigcap \text{participants} \)

SX1(2015)13
Back-of-the-envelope estimate of energy density

Bjorken formula

\[
\varepsilon_{\text{Bj}} = \frac{1}{S_T} \frac{dE_T}{dy}
\]

\[
\gtrsim \varepsilon_{\text{LB}} \equiv \frac{1}{S_T} \sqrt{1 + \left(\frac{p_T}{m}\right)^2} \frac{dN_{\text{ch}}}{dy}
\]

Approximations

\[
\frac{dE_T}{dy} \approx 2 \langle m_T \rangle \frac{dN_{\text{ch}}}{dy}
\]

\[
\gtrsim 2 \langle m \rangle \sqrt{1 + \left(\frac{p_T}{m}\right)^2} \frac{dN_{\text{ch}}}{dy}
\]

\[S_T \text{ from Glauber}\]

Transverse area – Two extremes

\[\bigcup \text{part.}\]

Union of participant areas

\[\bigcap \text{part.}\]

Intersect of participant areas

- \(\sigma_{\text{NN}} = 70 \text{ mb}\)
- Black-disc protons
- Spatial overlap resolution 0.1 fm
- SX1(2015)13
The lower-bound of $\varepsilon_{\text{Bj}}$

Large level variation depending on area model, but features constant:
- Fixed energy density at fixed $N_{\text{part}}$
  - Except for central $p$–$Pb$
- For $\cup \text{part}$, large increase over $pp$

ALICE Preliminary, $\sqrt{s_{\text{NN}}} = 5.02$ TeV

$\langle N_{\text{part}} \rangle$

$\varepsilon_{\text{LB}\tau}$ (GeV/fm$^2$)
The lower-bound of $\varepsilon_{Bj}$

- Large *level* variation depending on area model, but features constant:
  - Fixed energy density at fixed $N_{\text{part}}$
    - Except for central p–Pb
  - For $\cup\text{part}$, large increase over pp
  - Same trend as $\varepsilon_{Bj}\tau$ in Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV (PRC94(2016)034903)

\[ \varepsilon_{LB}(\text{GeV}/\text{fm}^2) \]

- ALICE Preliminary, $\sqrt{s_{NN}} = 5.02$ TeV
- pp, p–Pb, Pb–Pb, Pb–Pb, $\sqrt{s_{NN}} = 2.76$ TeV

Glauber area

$\langle N_{\text{part}} \rangle$

- $\cup\text{part.}$
- $\cap\text{part.}$
The lower-bound of $\varepsilon_{Bj}$

- Large level variation depending on area model, but features constant:
  - Fixed energy density at fixed $N_{\text{part}}$
    - Except for central $p$–$Pb$
  - For $\cup_{\text{part}}$, large increase over $pp$
- Same trend as $\varepsilon_{Bj}\tau$ in Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV (PRC94(2016)034903)
- If same initial $\varepsilon$ in systems, then similar final state effects?
Summary

Charged-particle pseudorapidity density
▶ Measured in $\sqrt{s_{NN}} = 5.02$ TeV collisions over a wide $\eta$ range for 3 systems
  ▶ Pb–Pb versus centrality
  ▶ p–Pb versus centrality
  ▶ pp w.r.t. INEL>0 visible cross-section

Ratios of Pb–Pb, p–Pb to pp
▶ Pb–Pb peaked near $\eta = 0$ than pp, increase in $N_{ch}$
▶ p–Pb exhibit triangular shape, consistent with independent nucleon-nucleon scatterings
▶ HIJING, EPOS-LHC cannot reproduce data

Charged-particle rapidity density
▶ Pb–Pb, pp Gaussian
▶ p–Pb modified by linear factor in $y$
▶ Lower-bound estimates of energy density show $\times 10$ increase in Pb–Pb over pp, p–Pb more moderate
Backups
\[
\frac{dN_{\text{ch}}}{dy} \text{ in Pb–Pb at } \sqrt{s_{NN}} = 5.02 \text{ TeV}
\]

Direct evaluation of \( \langle J \rangle = \langle \beta \rangle \) from \( p_T \)-spectra in Pb–Pb at \( \sqrt{s_{NN}} = 2.76 \) TeV

[arXiv:1612.08966]
Fit of $dN_{\text{ch}}/d\eta$ distributions

ALICE

$\sqrt{s_{\text{NN}}} = 5.02$ TeV

0–5%
5–10%
10–20%
20–30%
30–40%
40–50%
50–60%
60–70%
70–80%
80–90%

Preliminary

ALI–PREL–118212
Fit of $dN_{ch}/d\eta$ distributions

p–Pb $\sqrt{s_{NN}} = 5.02$ TeV

V0A
0–5%
5–10%
10–20%
20–40%
40–60%
60–80%
80–100%

Data
Uncorr. syst. unc.
Corr. syst. unc.
Fit of $dN_{\text{ch}}/d\eta$ distributions

ALICE Preliminary

$pp \sqrt{s} = 5.02 \text{ TeV}$

$\text{INEL}>0$

- Data (symmetrised)
- Reflected
- Uncorr. syst. unc.

ALICE® | QM'17 | 7. Feb, 2017 | C.H.Christensen
Fit of EPOS-LHC $dN_{ch}/d\eta$ distributions

Pb–Pb $\sqrt{s_{NN}} = 5.02$ TeV

ALICE

Simulation

EPOS-LHC
Fit of EPOS-LHC $dN_{\text{ch}}/d\eta$ distributions

$\text{p--Pb } \sqrt{s_{\text{NN}}} = 5.02\ \text{TeV}$

V0A
0– 5%
5–10%
10–20%
20–40%
40–60%
60–80%
80–100%

ALICE Simulation

\[ \begin{align*}
\text{dN}_{\text{ch}}/\text{d}\eta \\
\eta \\
\text{p--Pb } \sqrt{s_{\text{NN}}} = 5.02\ \text{TeV} \\
\text{V0A} \\
0– 5\% \\
5–10\% \\
10–20\% \\
20–40\% \\
40–60\% \\
60–80\% \\
80–100\% \\
\end{align*} \]
Fit of EPOS-LHC $dN_{\text{ch}}/d\eta$ distributions

$pp \sqrt{s} = 5.02 \text{ TeV}$

INEL $>$ 0

ALICE Simulation

EPOS-LHC