System-size dependence of $dN_{\text{ch}}/d\eta$ at
$\sqrt{s_{\text{NN}}} = 5.02$ TeV
Over a wide $\eta$ range
System-size dependence of $dN_{ch}/d\eta$ at $\sqrt{s_{NN}} = 5.02$ TeV
Over a wide $\eta$ range

Overview
ALICE, data, conditions
Charged-particle pseudorapidity density
Comparison of systems
Model comparisons
Unified parameterisation of $dN_{ch}/d\eta$
Example of reasons to look forward

- Large $\eta$ acceptance
- Width of $dN_{\text{ch}}/dy$ 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
- \( dN_{ch}/dy \)
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
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  - $N_{\text{ch}}$ ($|\eta| < 2$)
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  - $N_{\text{ch}}$ ($-3.5 < \eta < -1.8$ 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

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  - (note, at $z = \pm 112.5\,\text{m}$)
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  - $N_{\text{ch}} (|\eta| < 2)$

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

Results

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

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 Large Ion Collider Experiment

A wealth of data

Pb–Pb, $\sqrt{s_{\text{NN}}} = 5.02$ 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, $\sqrt{s_{\text{NN}}} = 5.02$ 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 $N_{ch}|\eta|<1 \geq 1$
Pb–Pb collisions

\[
\frac{dN_{\text{ch}}}{d\eta} \quad \text{ALICE}
\]

\[
10^3
\]

\[
10^2
\]

\[
\eta \quad \text{0– 5 %}
\]

\[
5–10 %
\]

\[
10–20 %
\]

\[
20–30 %
\]

\[
30–40 %
\]

\[
40–50 %
\]

\[
50–60 %
\]

\[
60–70 %
\]

\[
70–80 %
\]

\[
80–90 %
\]

\[
Pb–Pb \quad \sqrt{s_{NN}} = 5.02 \text{ TeV}
\]

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: -\(\eta\), \(y_{CM} = 0.465\)
- Selection based on signal in V0 on Pb-going side (V0A)

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

ALI-PREL-99853
pp collisions

Inelastic collisions with at least one charged particle in $|\eta| < 1$

- Minimize systematic uncertainties due to normalisation

**ALI-PREL-118144**

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

**ALICE**

Preliminary Data (symmetrised)

Reflected

Uncorr. syst. unc.

Corr. syst. unc.

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

**INEL > 0**

**ALICEdNch/d\eta**

- $dN_{ch}/d\eta$
- $\eta$
- $\eta = -5 -4 -3 -2 -1 0 1 2 3 4 5$

**ALICE© | QM’17 | 7. Feb, 2017 | C.H.Christensen**
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 $\eta$

\[
\frac{1}{N_{\text{coll}}} \frac{dN_{\text{ch}}/d\eta}{dN_{\text{ch}}/d\eta}_{\text{pp}}
\]

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

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

pp, p–Pb, & Pb–Pb from same model

HIJING

► Pb–Pb/pp far flatter
► p–Pb/pp non-linear

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

ALICE

Preliminary

Pb–Pb, pp

P–Pb, pp

p–Pb (V0A), pp

Data

HIJING
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 $dN_{\text{ch}}/dy$

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

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

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

$a$: effective $p_T/m$

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

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

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

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

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

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

$a$: effective $p_T/m$

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

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

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

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

0– 5 %

5–10 %

10–20 %

20–30 %

30–40 %

40–50 %

50–60 %

60–70 %

70–80 %

80–90 %

Data (symmetrised)

Reflected

Uncorr. syst. unc.

Corr. syst. unc.
Express \( \frac{dN_{\text{ch}}}{d\eta} \) in terms of \( \frac{dN_{\text{ch}}}{dy} \)

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

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

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

\( a \): effective \( p_T/m \)

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

Ansatz: For symmetric: \( \frac{dN_{\text{ch}}}{dy} \) 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 $A \rightarrow (\alpha y + A)$

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

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

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

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

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

$a$: 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 $A \to (\alpha y + A)$

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

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

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

$\sigma dN_{\text{ch}}/dy$

Fit parameters
Also for EPOS-LHC

Width

- $\sigma$ consistent with estimate from $p_T$ spectra and $dN_{\text{ch}}/d\eta$ [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 $dN_{ch}/d\eta$ [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

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

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

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

Bjorken formula

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

Approximations

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

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

\[ S_T \text{ from Glauber} \]

Transverse area – Two extremes

- Union of participant areas
- Intersect of participant areas

- \( \sigma_{NN} = 70 \text{ mb} \)
- Black-disc protons
- Spatial overlap resolution 0.1 fm
- SX1(2015)13
Back-of-the-envelope estimate of energy density

Bjorken formula

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

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

Approximations

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

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

\( S_T \) 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
The lower-bound of $\varepsilon_{Bj}$

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

- pp
- p–Pb
- Pb–Pb

Glauber area
- $\cup_{\text{part.}}$
- $\cap_{\text{part.}}$

ALI-PREL-118385

- 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

$\langle N_{\text{part}} \rangle$
The lower-bound of $\varepsilon_{Bj}$

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

- **ALICE Preliminary, $\sqrt{s_{NN}} = 5.02$ TeV**
  - $\varepsilon_{LB} \tau$ (GeV/fm$^2$)
  - $10^2$ 
  - $10^1$ 
  - $10^{-1}$ 
  - $10^{-2}$

- Glauber area
  - $\cup$ part. 
  - $\cap$ part.

- **ALI-PREL-118408**
  - Large *level* variation depending on area model, but features constant:
    - Fixed energy density at fixed $N_{\text{part}}$
      - Except for central p–Pb
    - For $\cup$ 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
dN_{ch}/dy in Pb–Pb at \( \sqrt{s_{NN}} = 5.02 \) TeV

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

0–5% Pb–Pb

ALICE

Data (symmetrised)

Reflected

Uncorr. syst. unc.

Corr. syst. unc.

Gaussian fit

Double-Gaussian fit

Landau-Carruthers

Landau-Wong

▷ [arXiv:1612.08966]

▷ Direct evaluation of \( \langle J \rangle = \langle \beta \rangle \) from \( p_T \)-spectra in Pb–Pb at \( \sqrt{s_{NN}} = 2.76 \) TeV
Fit of $dN_{ch}/d\eta$ distributions

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%

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

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

ALICE
Preliminary

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

INEL > 0

Data (symmetrised)

Reflected

Uncorr. syst. unc.

Corr. syst. unc.
Fit of EPOS-LHC $dN_{ch}/d\eta$ distributions

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 %

ALICE
Simulation

$\eta$

$10^3$
$10^2$
$10$

EPOS-LHC

ALI-SIMUL-118290
Fit of EPOS-LHC $dN_{\text{ch}}/d\eta$ distributions

$p$–$Pb$ $\sqrt{s_{NN}} = 5.02$ TeV

V0A

0–5%

5–10%

10–20%

20–40%

40–60%

60–80%

80–100%

ALICE Simulation

EPOS-LHC

ALI-SIMUL-118277
Fit of EPOS-LHC $dN_{ch}/d\eta$ distributions

ALICE Simulation

pp $\sqrt{s} = 5.02$ TeV

INEL > 0

EPOS-LHC