System-size dependence of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$

Over a wide η range

System-size dependence of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$

Over a wide η range

Overview

ALICE, data, conditions

Charged-particle pseudorapidity density

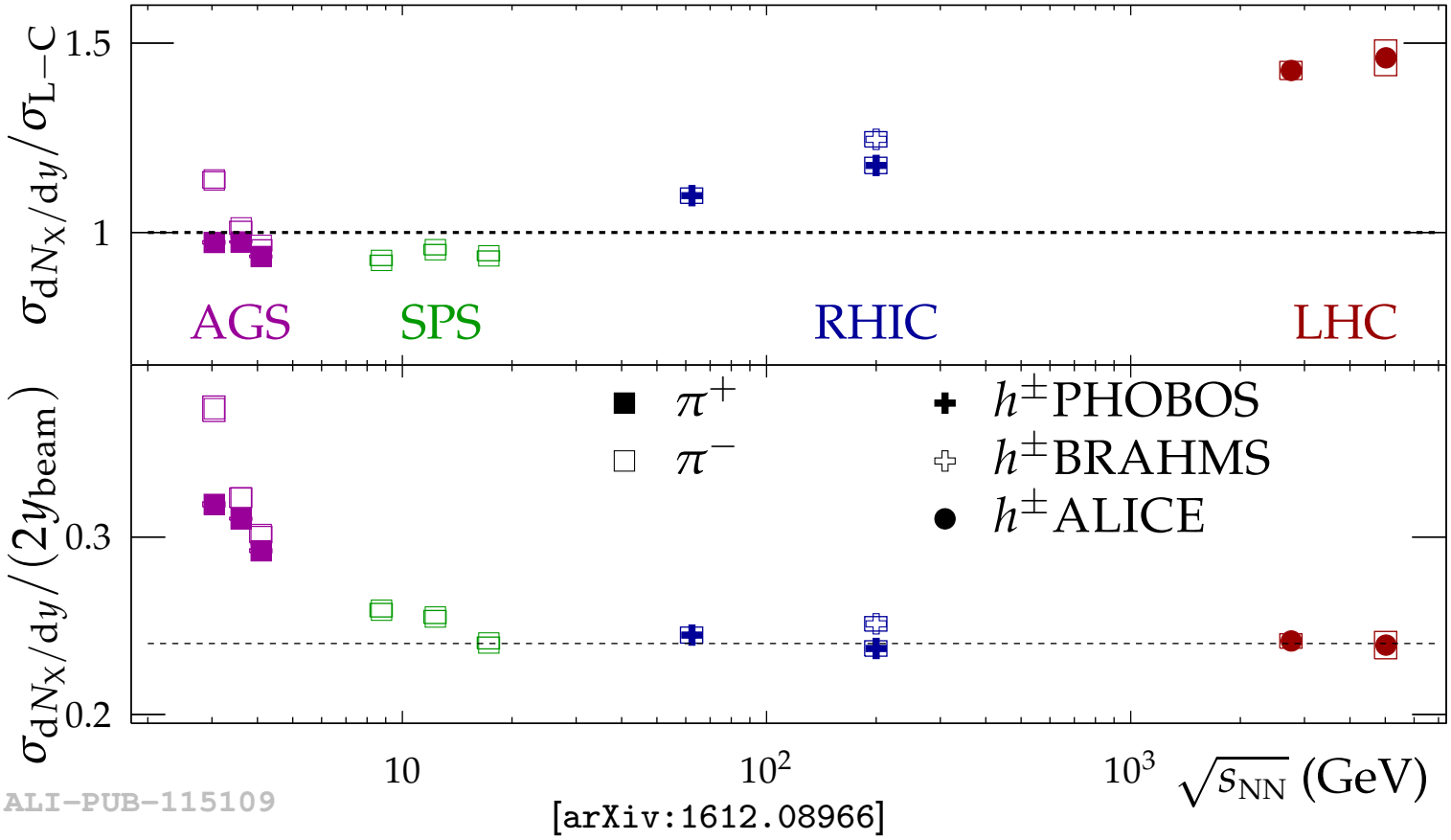
Comparison of systems

Model comparisons

Unified parameterisation of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$

Example of reasons to look forward

- Large η acceptance
- Width of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$ in A–A collisions



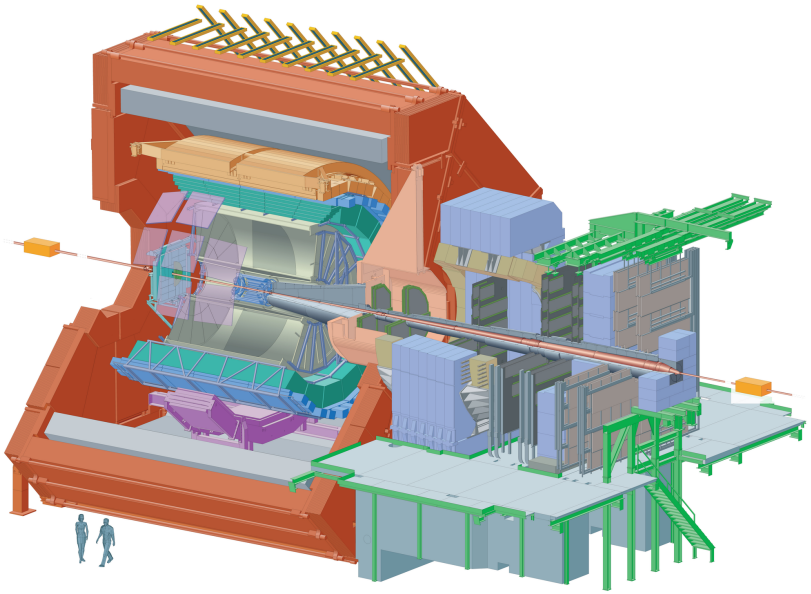
[arXiv:1612.08966]

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

ALICE

Results

- $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ over $-3.5 < \eta < 5$ in
  - pp
  - p–Pb
  - Pb–Pb
- Ratios
- $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$



ALICE

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  - pp
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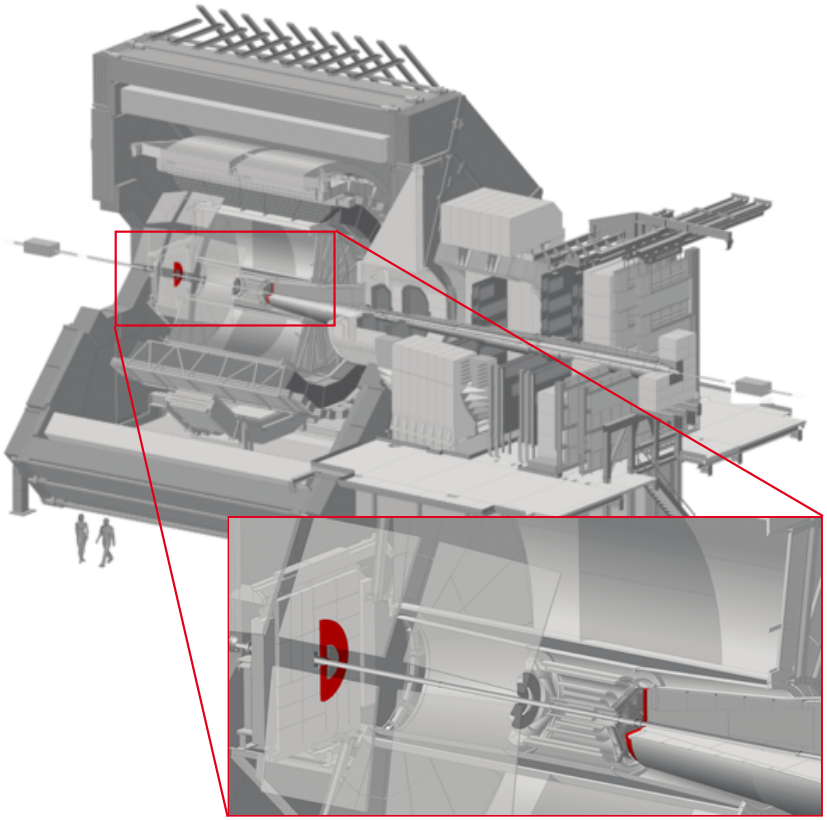
- $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$

Detectors:

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



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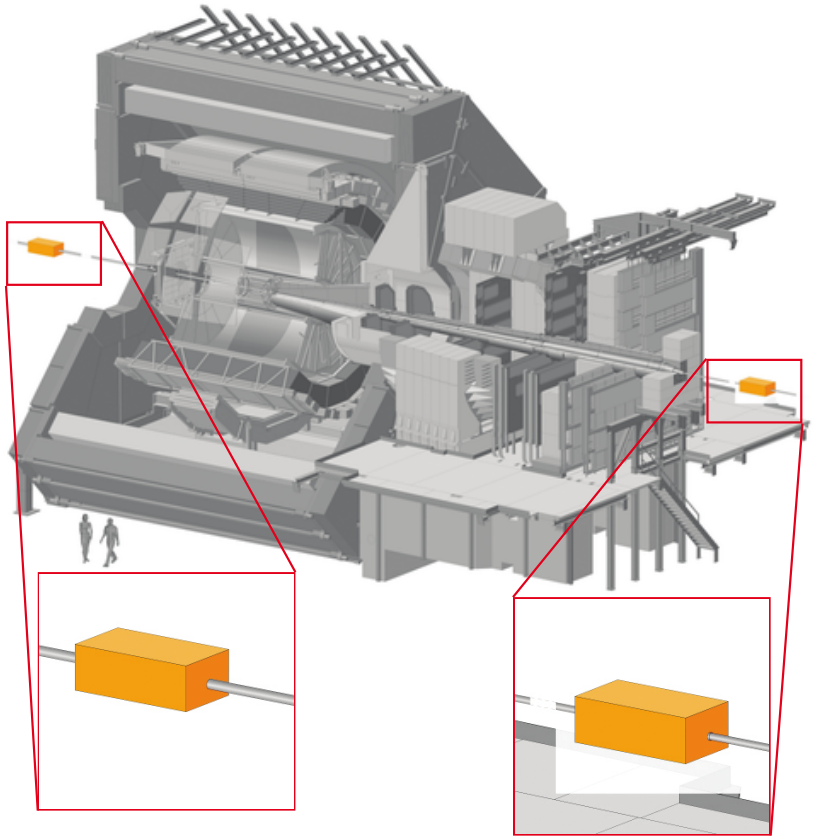

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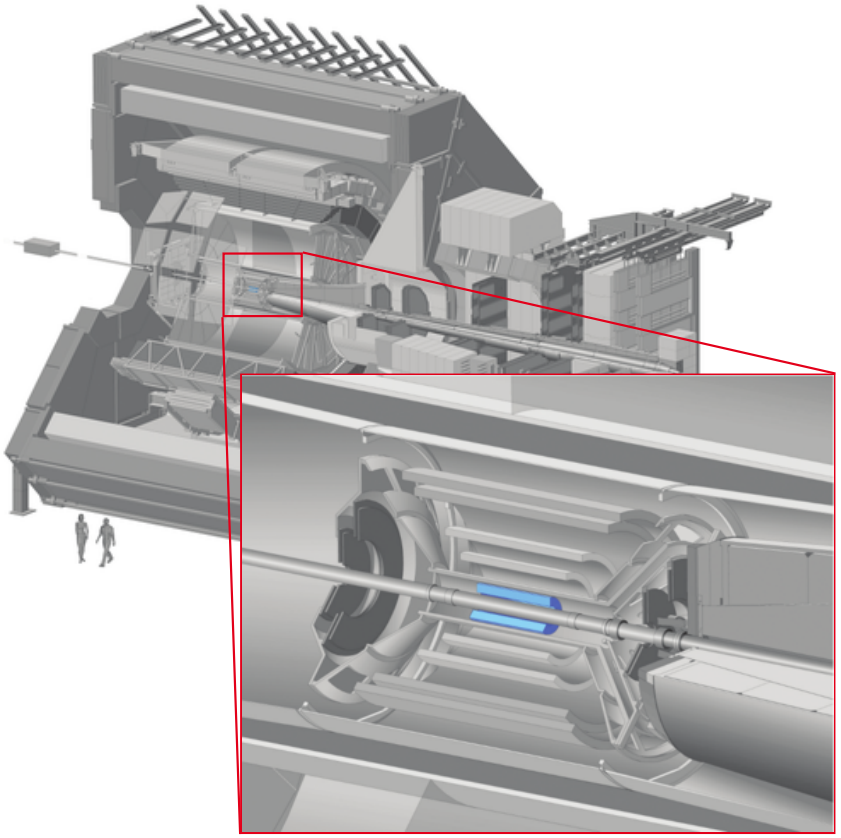

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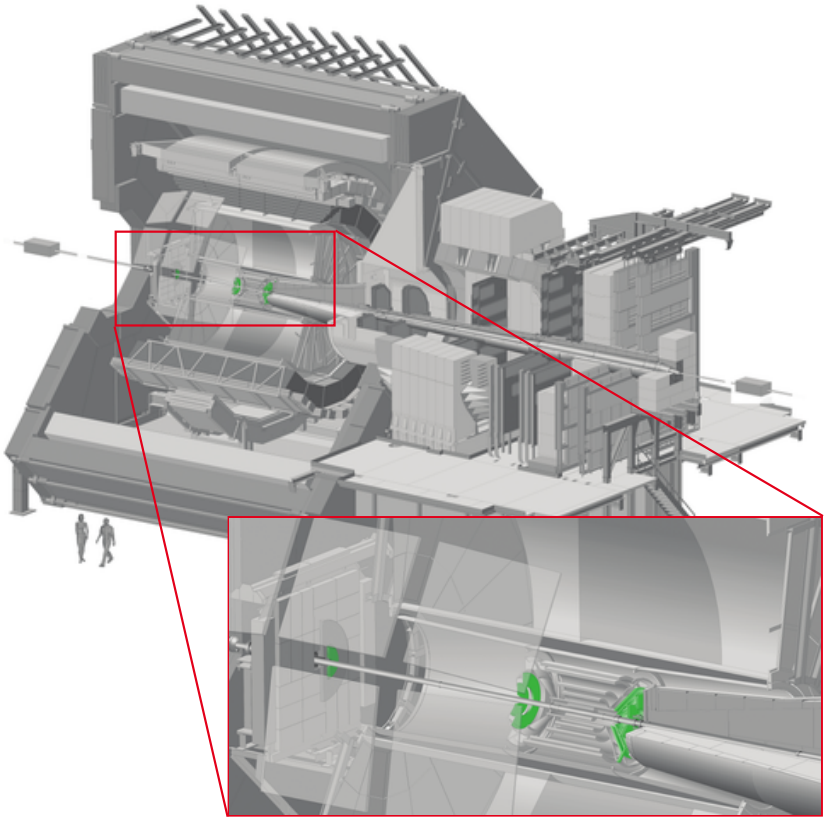
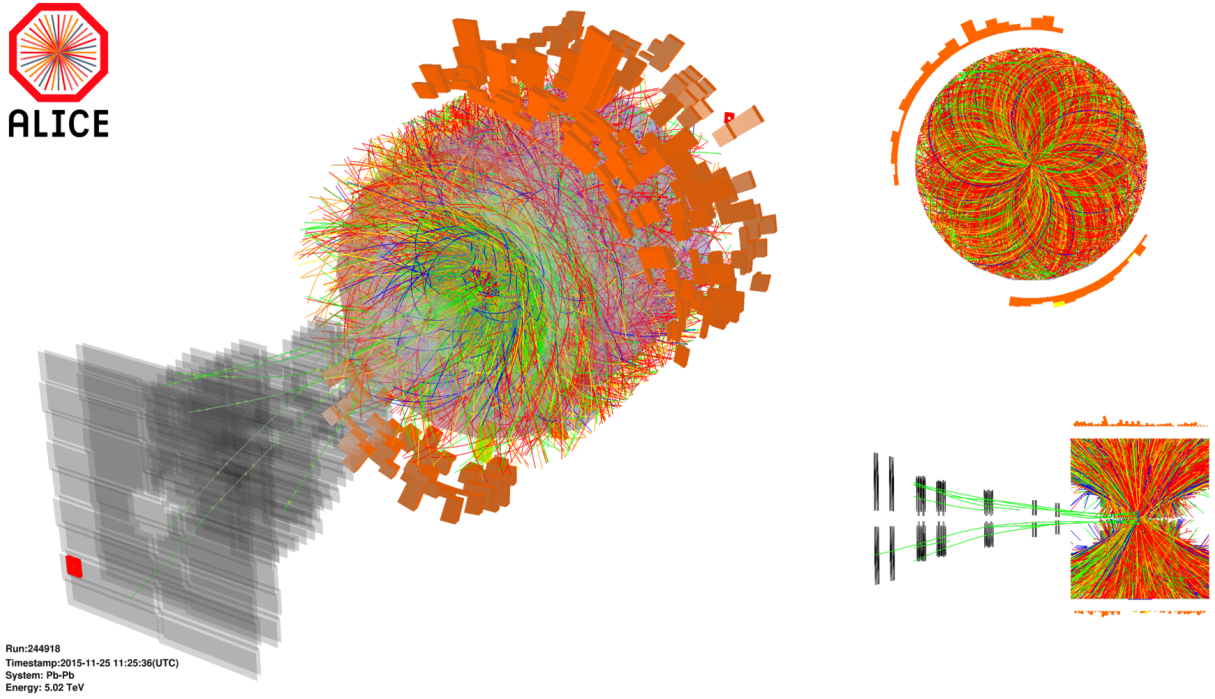


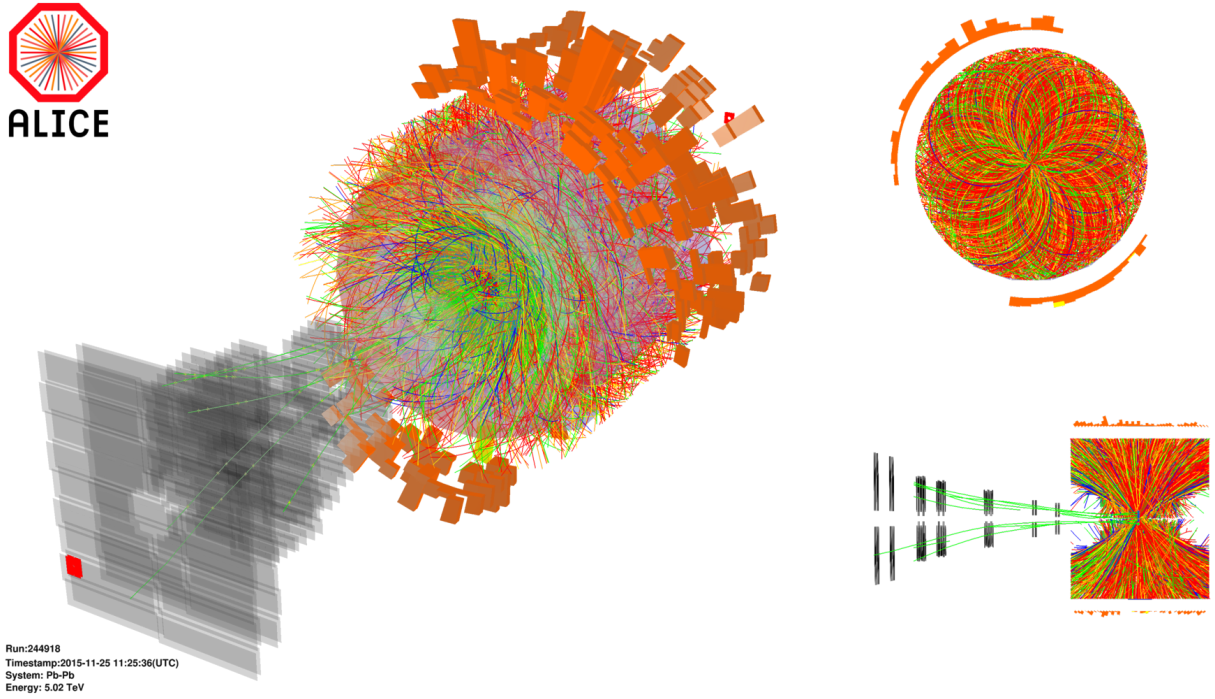
A wealth of data



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

- 3 weeks of data taking in 2015
- $\approx 150\,\mathrm{M}$ events
- Here, only low-intensity beams
  - Small pile-up background
  - Analysis not statistics limited

A wealth of data



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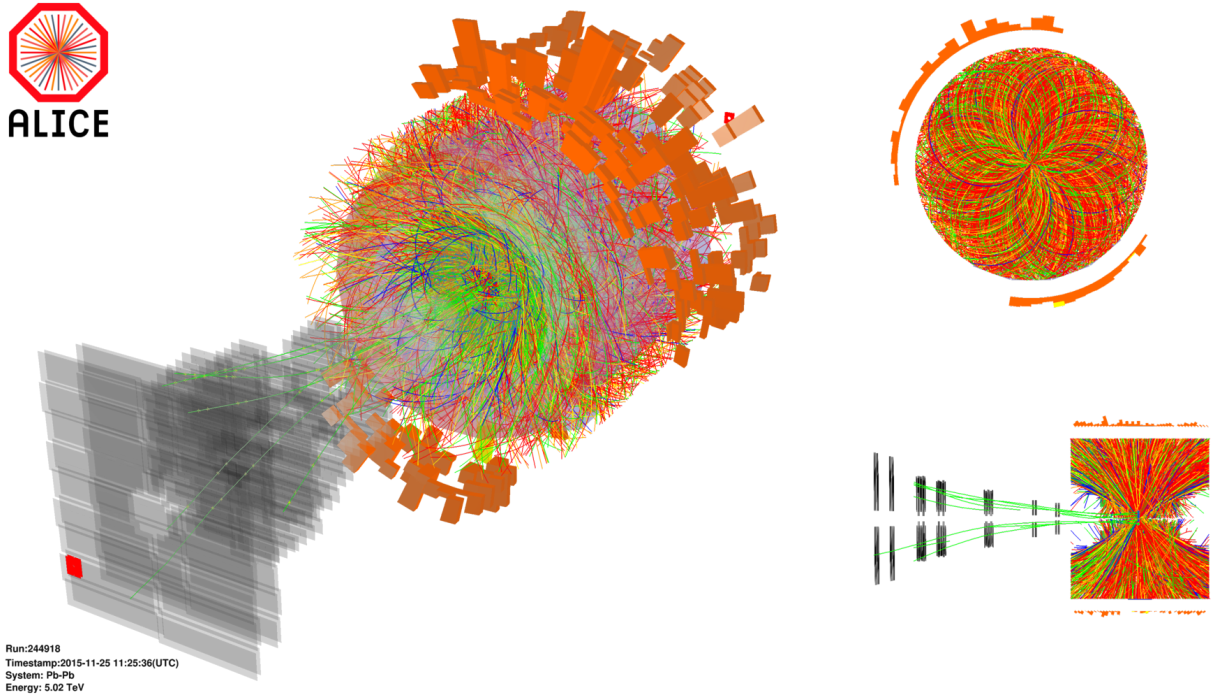
- 11 days of data taking in 2013
- $\approx 130\,\mathrm{M}$ events (MB)

A wealth of data



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

- 3 weeks of data taking in 2015
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p–Pb, $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$

- 11 days of data taking in 2013
- $\approx 130\,\mathrm{M}$ events (MB)

pp, $\sqrt{s} = 5.02\,\mathrm{TeV}$

- 5 days of data taking in 2015
- $\approx 130\,\mathrm{M}$ events

Collision classification

Pb–Pb

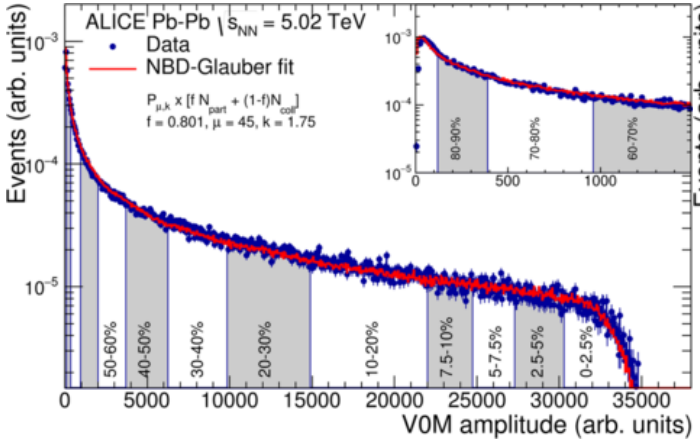
- Centrality classes from sum V0 amplitudes (V0M)
- Fractions of hadronic cross section

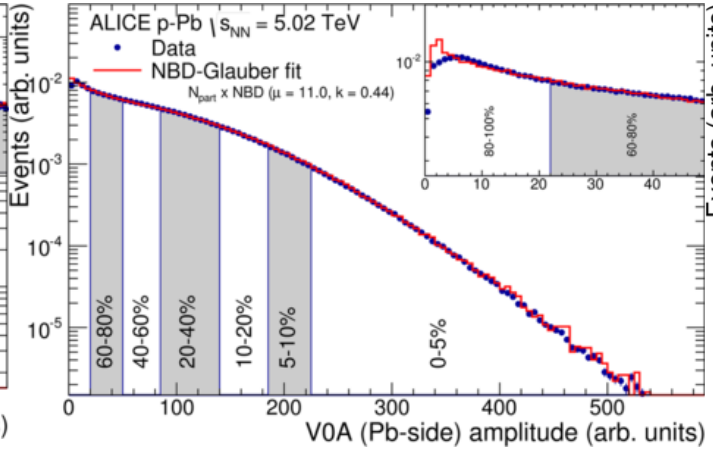
p–Pb

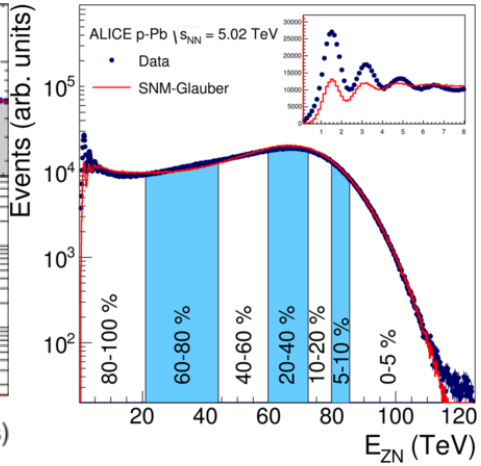
- Centrality classes from Pb–side V0 (V0A) and neutrons on same side (ZNA)
- Fractions of hadronic cross section

pp

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







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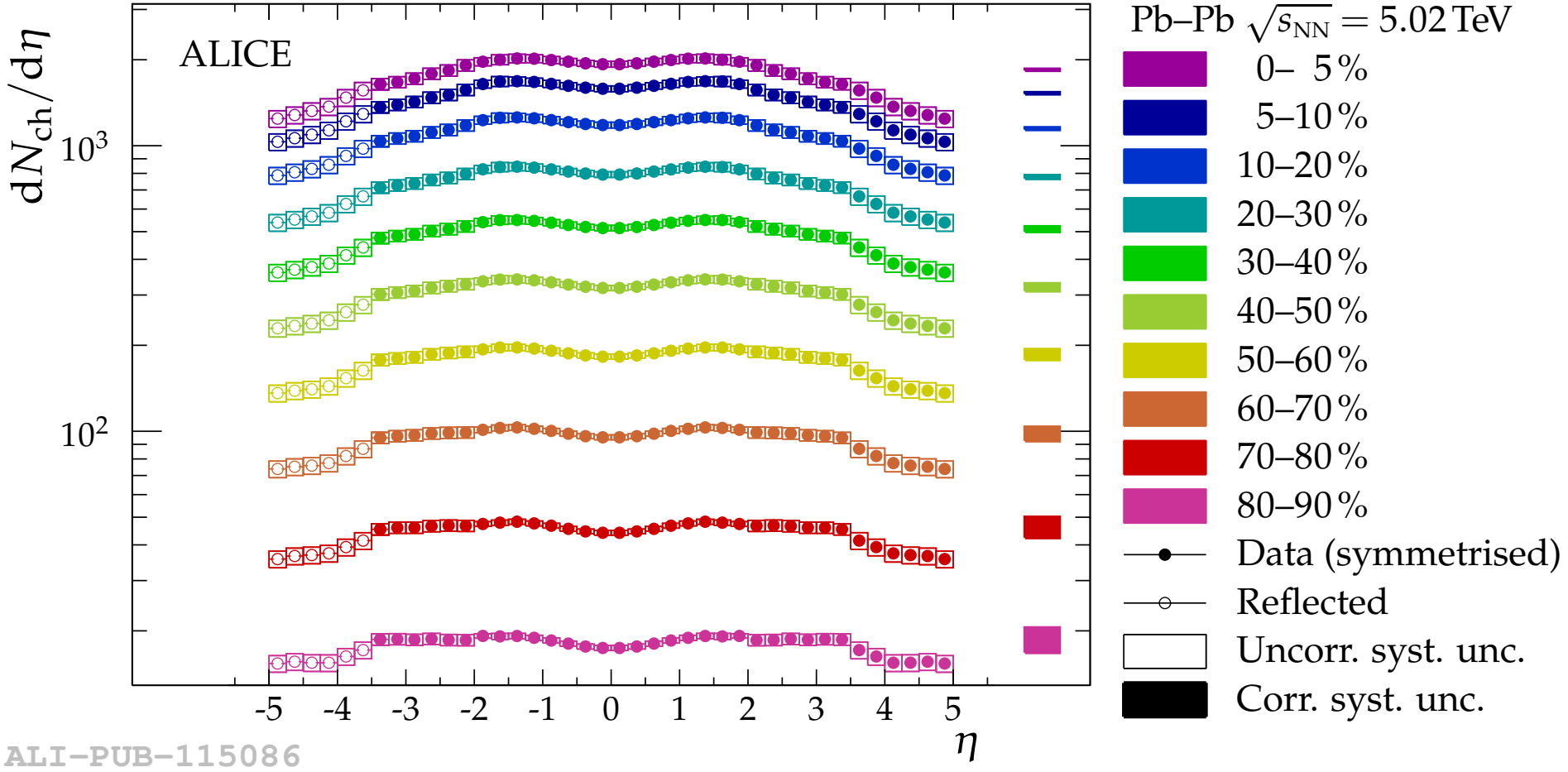
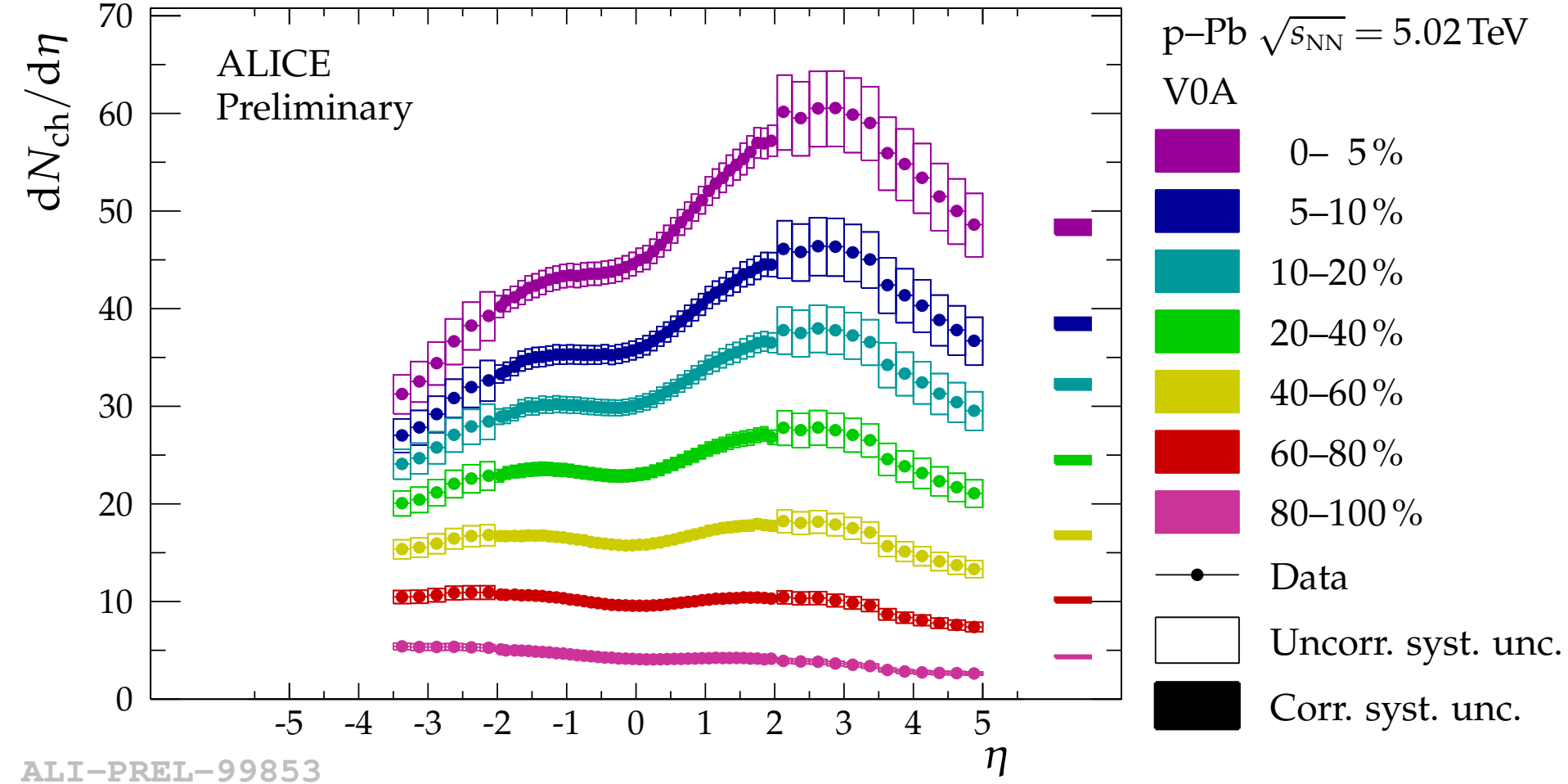
PRC91(2015)064905

Pb–Pb collisions



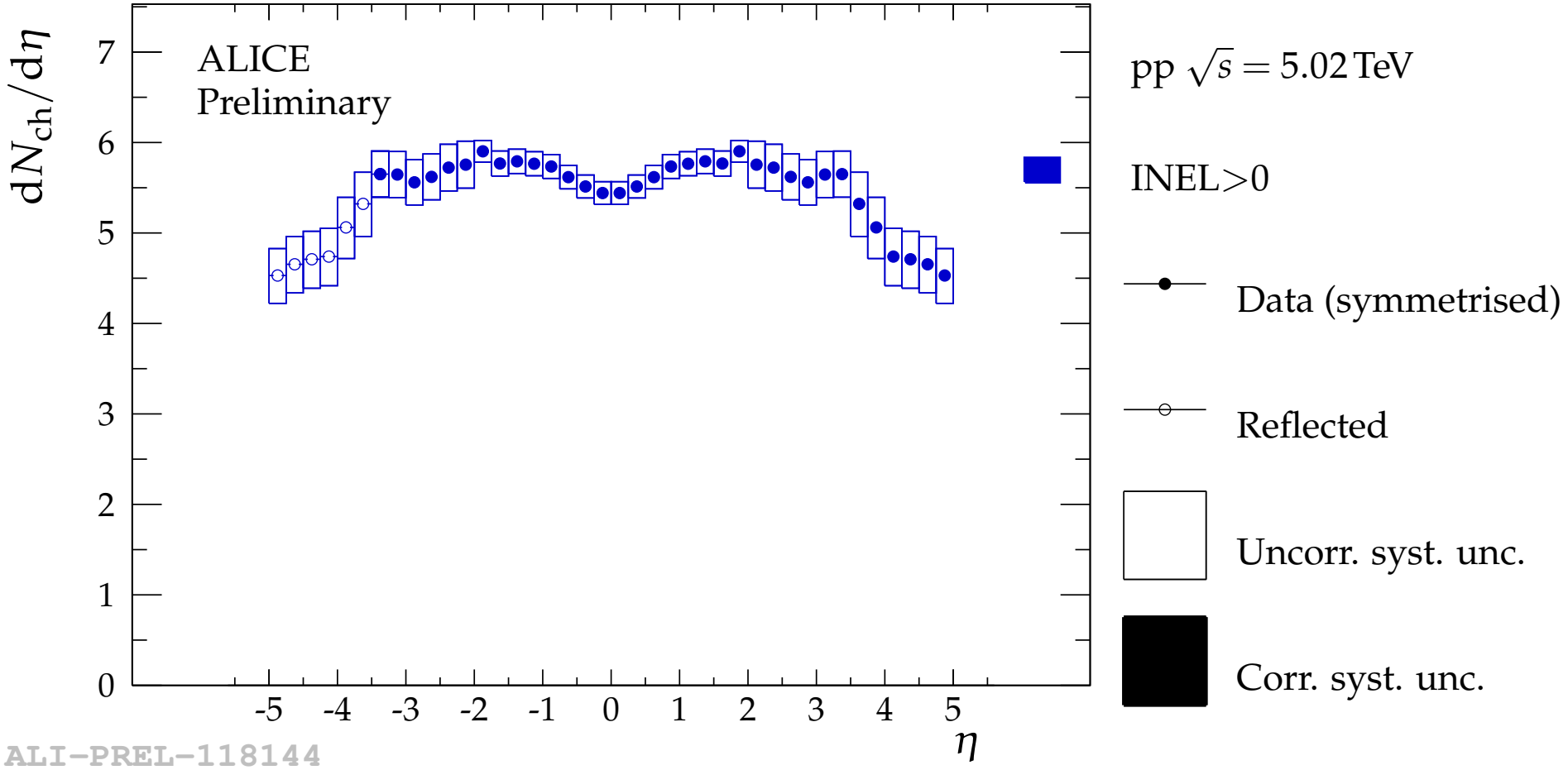
- 10 centrality classes from 0% to 90% [arXiv:1612.08966]
- Selection based on sum signal in V0 (V0M)

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)

pp collisions



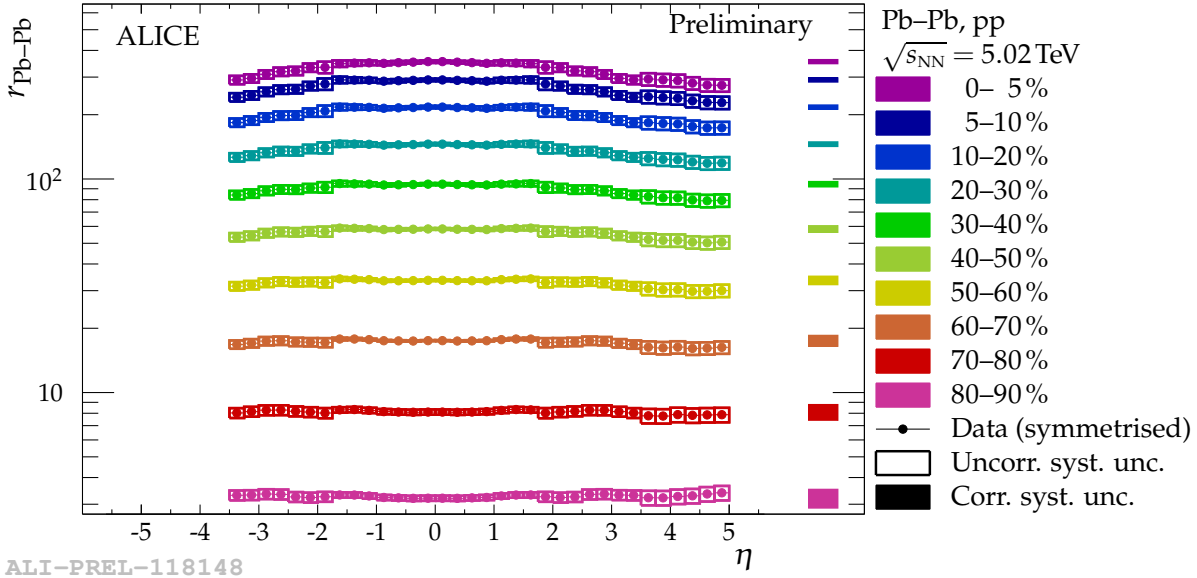
- Inelastic collisions with at least one charged particle in $|\eta| < 1$
  - Minimize systematic uncertainties due to normalisation

Dividing by pp baseline

$$r_X = \frac{\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_X}{\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{\mathrm{pp}}}$$

Pb–Pb

- 2 orders of magnitude over pp
- Increase as $\eta \to 0$



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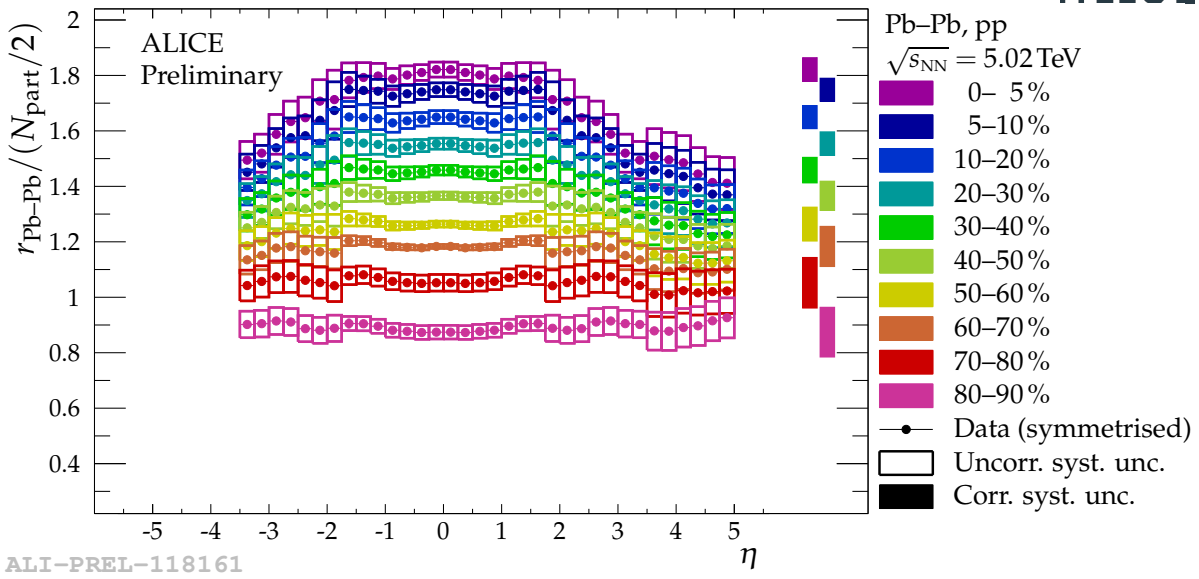
Pb–Pb

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



Dividing by pp baseline

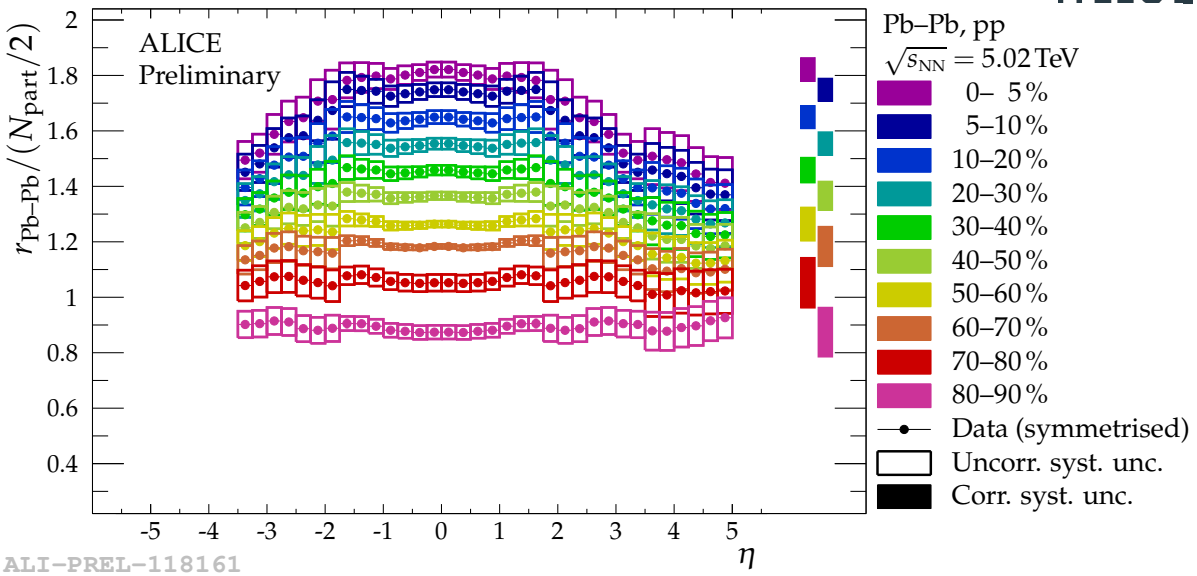
$$r_X = \frac{\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_X}{\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{\mathrm{pp}}}$$

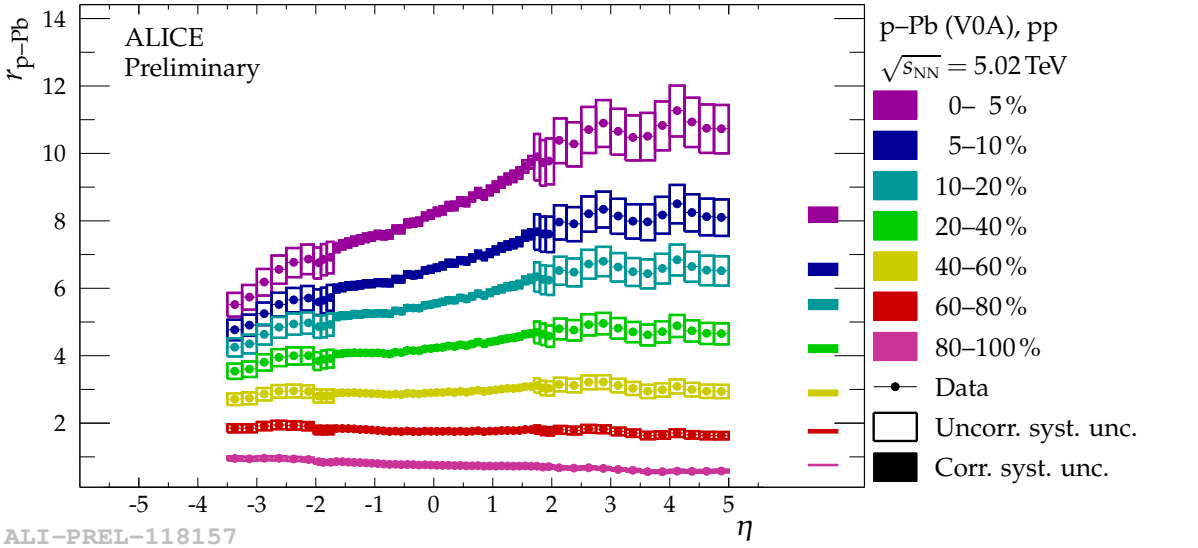
Pb–Pb

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

p–Pb

- Centrality: V0A
- 1 order of magnitude over pp
- Near-linear increase from p-going to Pb-going side





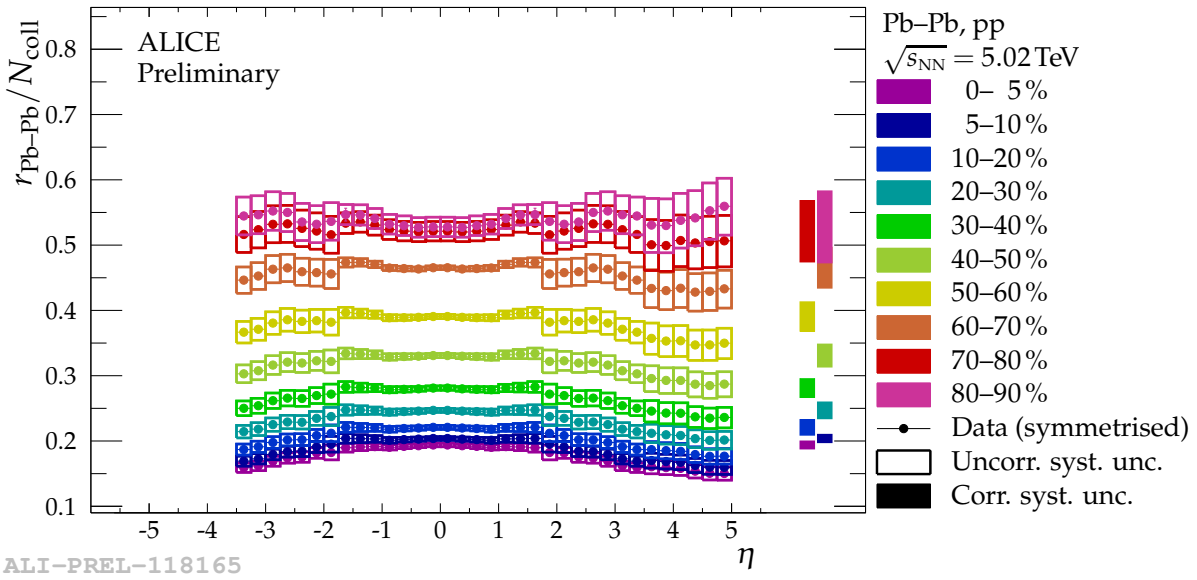
Nuclear modification per binary collision versus η

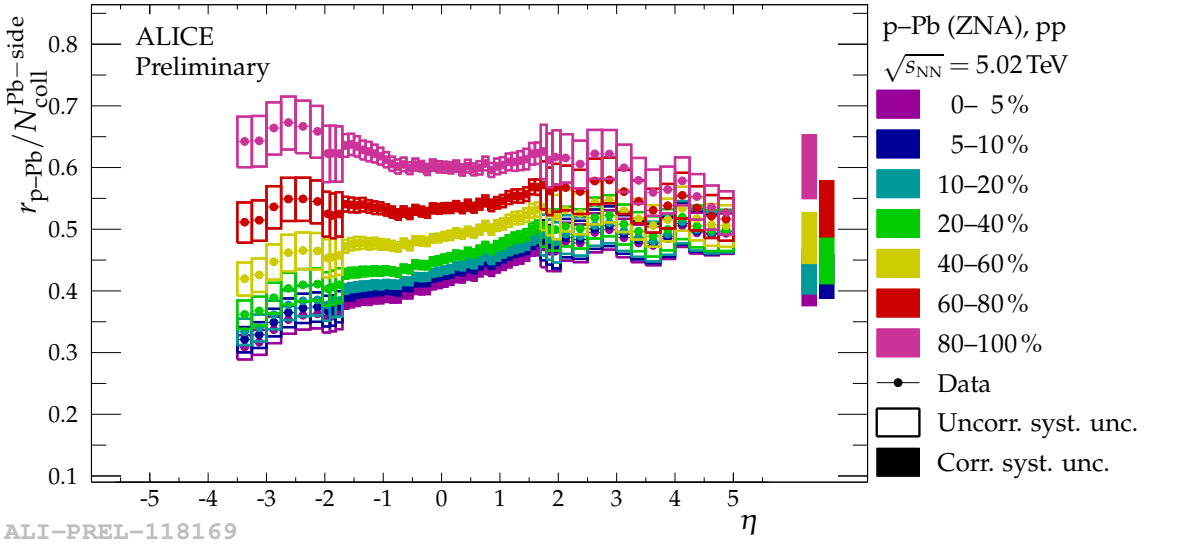
$$\frac{1}{N_{\mathrm{coll}}}\frac{\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_X}{\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{\mathrm{pp}}}$$

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

p–Pb
- N_{coll}: Hybrid model
- Centrality: ZNA
- Near-linear $\nearrow$ from p- to Pb-going side
- Consistent with independent proton-nucleon scatterings

(see PRC72(2005)034907, PRL39(1977)1120)





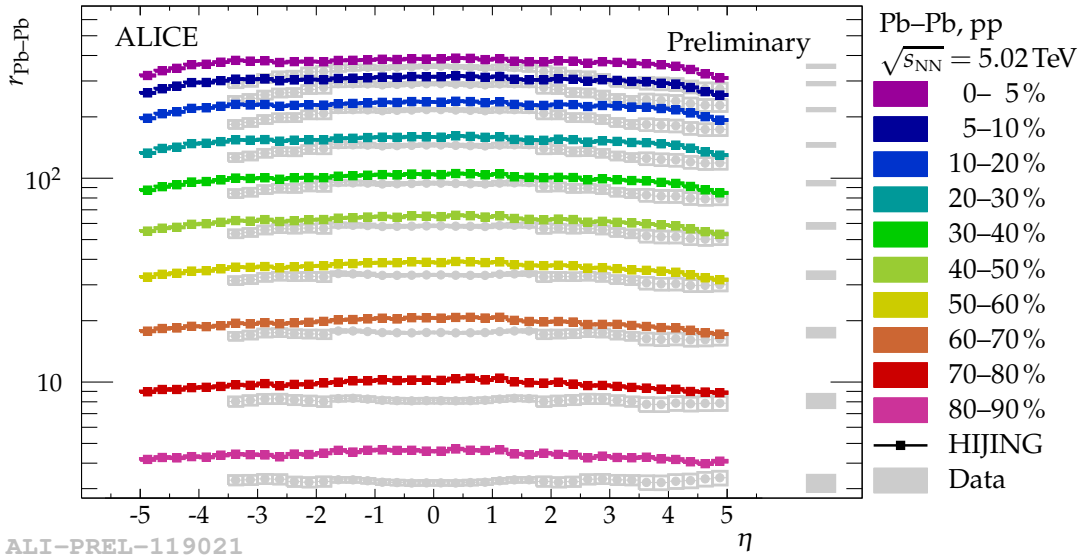
Model's change in particle production

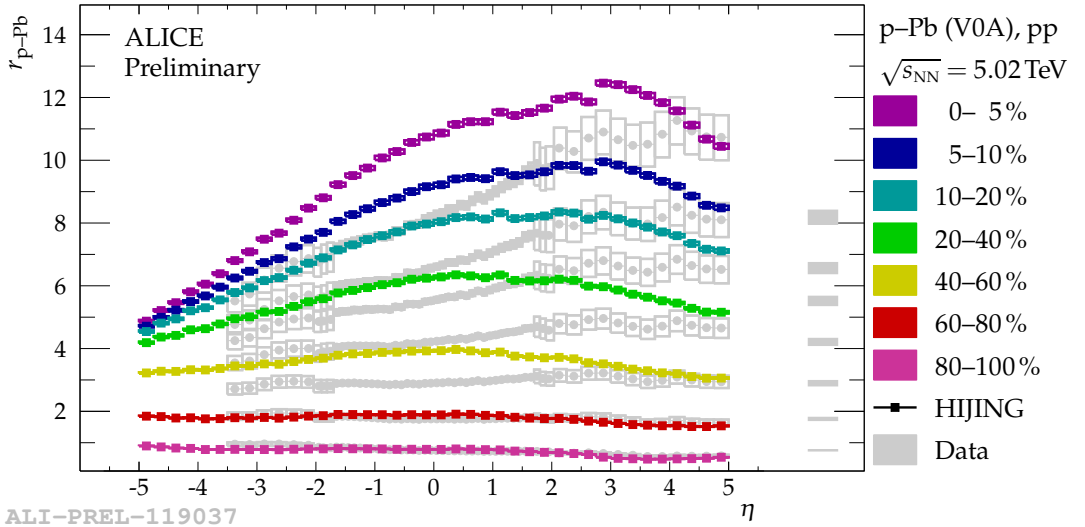
$$r_X = \frac{\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_X}{\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{\mathrm{pp}}}$$

pp, p–Pb, & Pb–Pb from same model

HIJING

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





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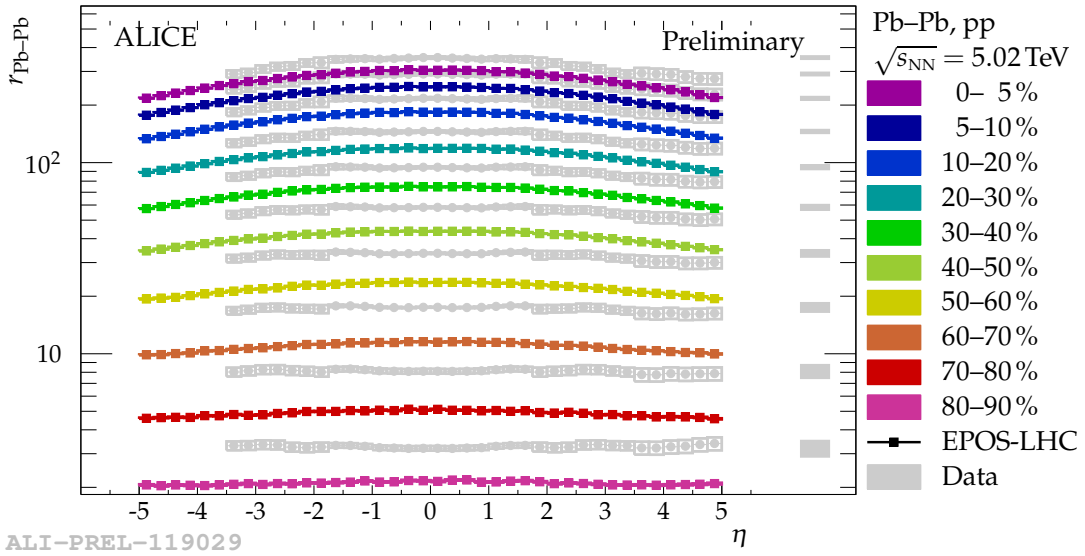
pp, p–Pb, & Pb–Pb from same model

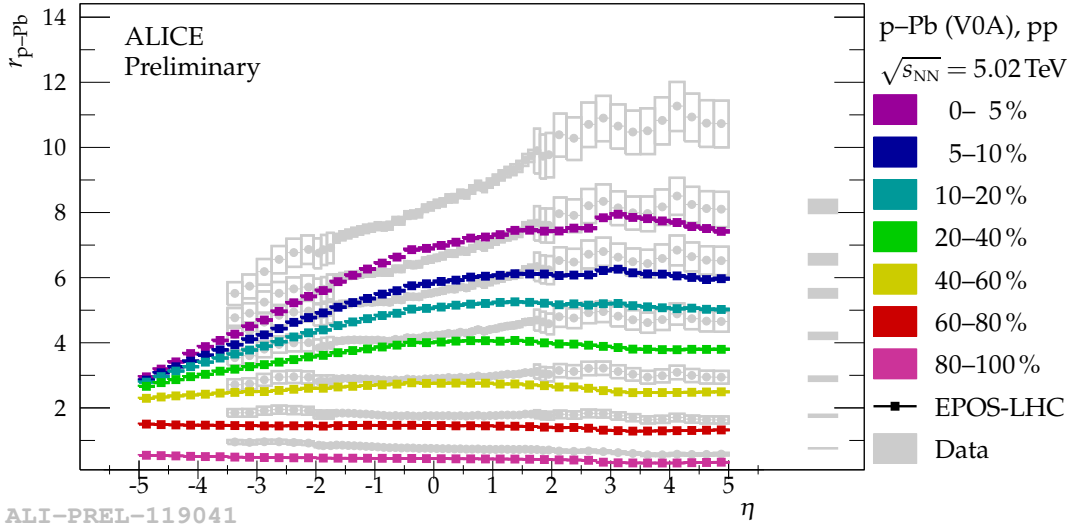
HIJING

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

EPOS-LHC

- Pb–Pb/pp more curved
- p–Pb/pp non-linear





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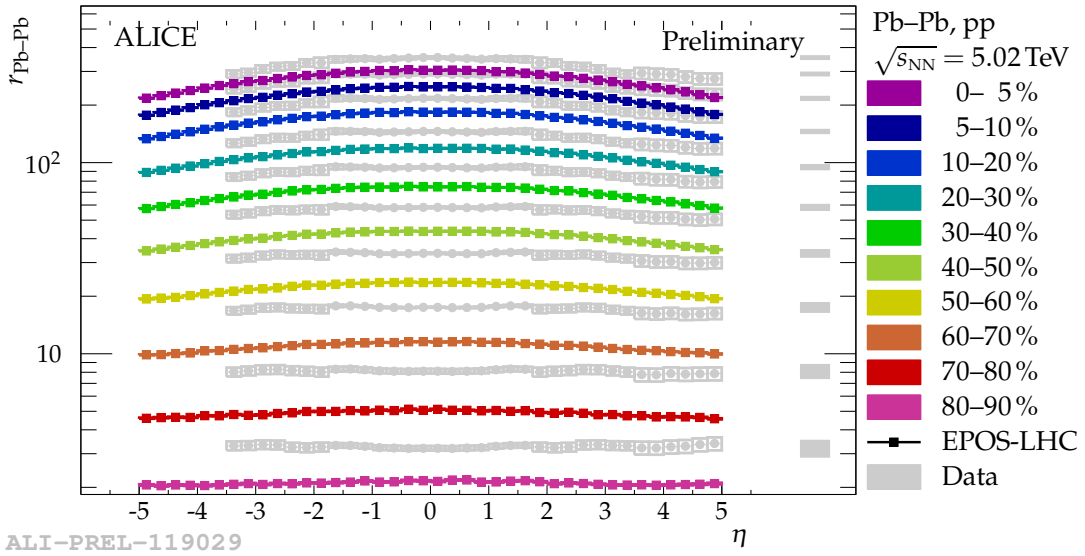
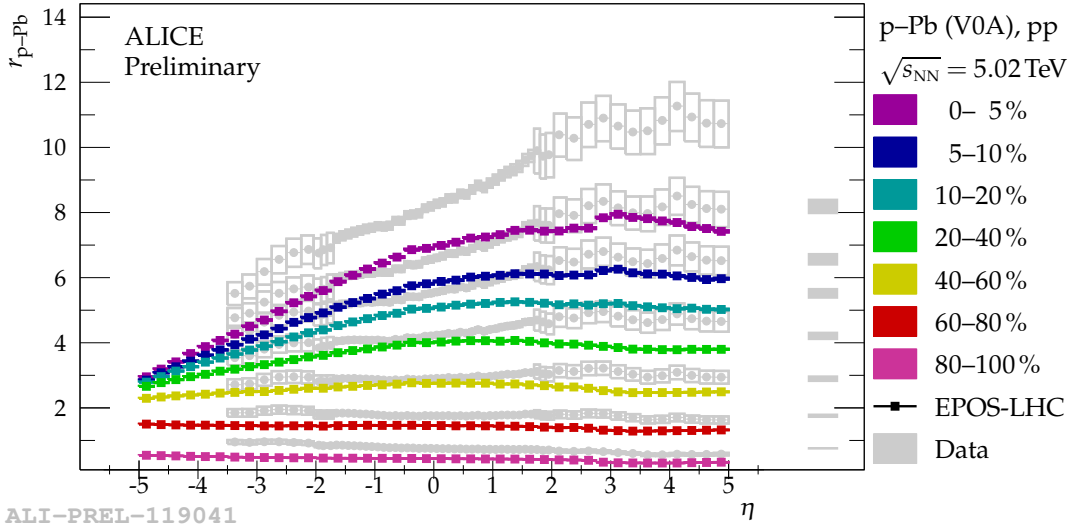
- HIJING, EPOS-LHC does not reproduce data





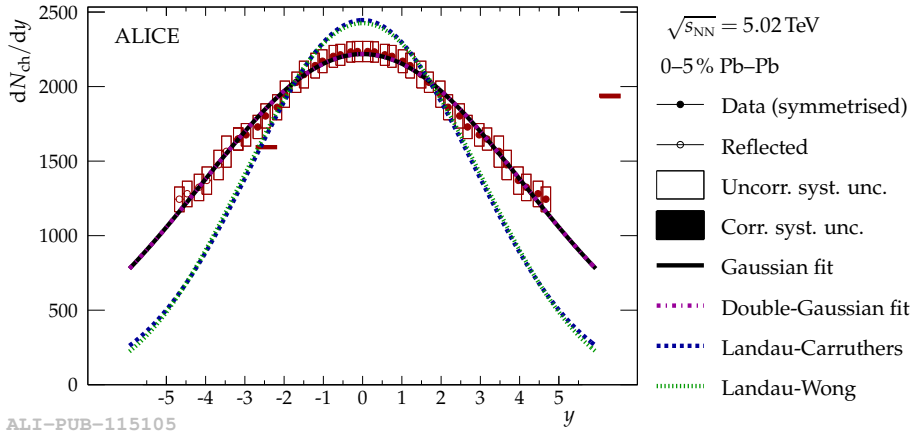
Express $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ in terms of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$

$$\mathrm{d}N/\mathrm{d}y = \frac{1}{\langle\beta\rangle}\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$$

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

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

a: effective p_{T}/m
(assumed $\mathrm{d}a/\mathrm{d}\eta = \mathrm{constant}$, equal for all particle species)



[arXiv:1612.08966]

Ansatz: For symmetric: $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$ Gaussian

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

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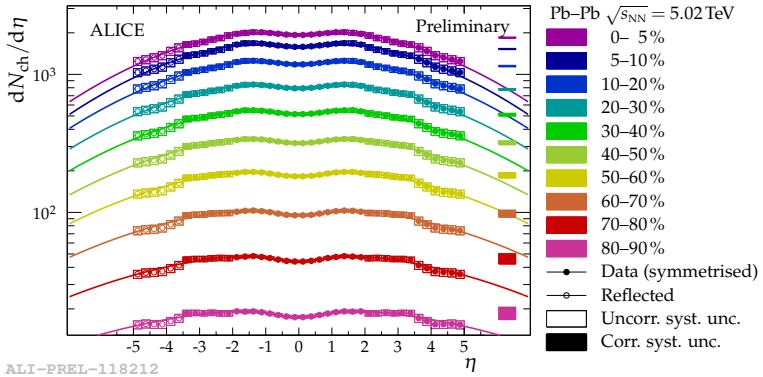
Pb–Pb



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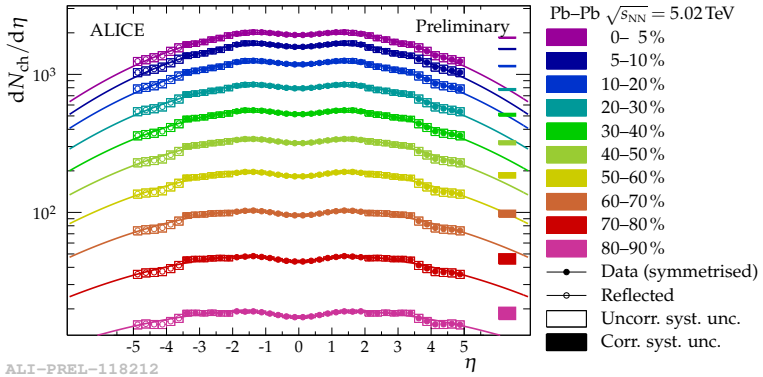

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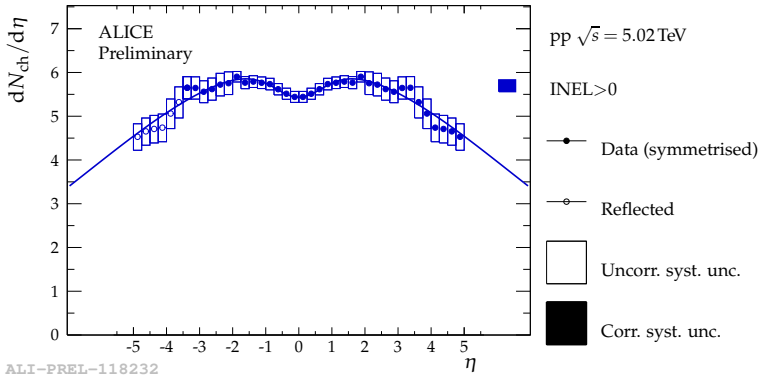
pp



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a: effective p_{T}/m
(assumed $\mathrm{d}a/\mathrm{d}\eta = \mathrm{constant}$, equal for all particle species)

Ansatz: For symmetric: $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$ Gaussian

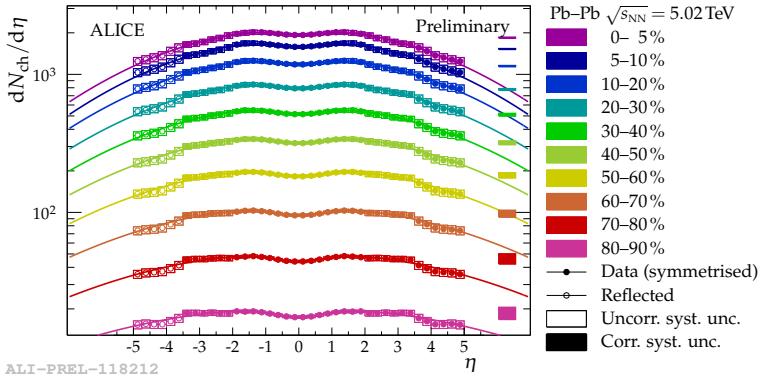
$$\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta} = \langle\beta\rangle\, A/(\sqrt{2\pi}\sigma)e^{-y^2/(2\sigma^2)}$$

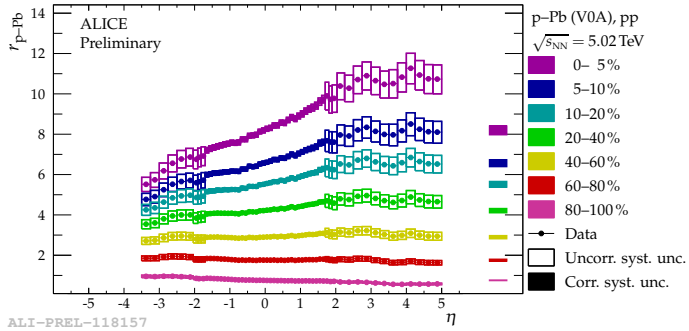
Ansatz: For asymmetric $A \to (\alpha y + A)$

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

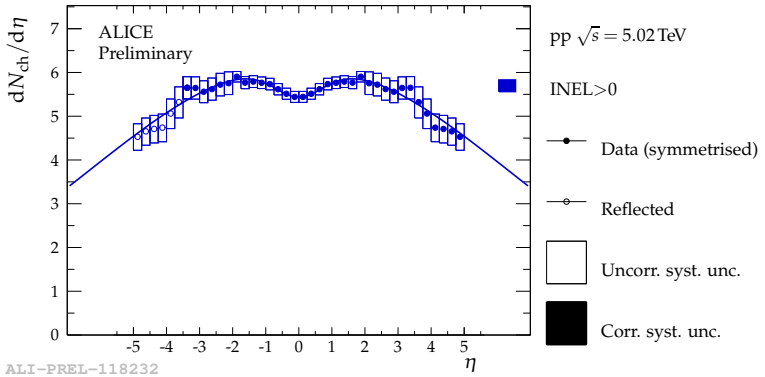
Here, y in centre-of-mass

Pb–Pb





pp



Express $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ in terms of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$

$$\mathrm{d}N/\mathrm{d}y = \frac{1}{\langle\beta\rangle}\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$$

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

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

a: effective p_{T}/m
(assumed $\mathrm{d}a/\mathrm{d}\eta = \mathrm{constant}$, equal for all particle species)

Ansatz: For symmetric: $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$ Gaussian

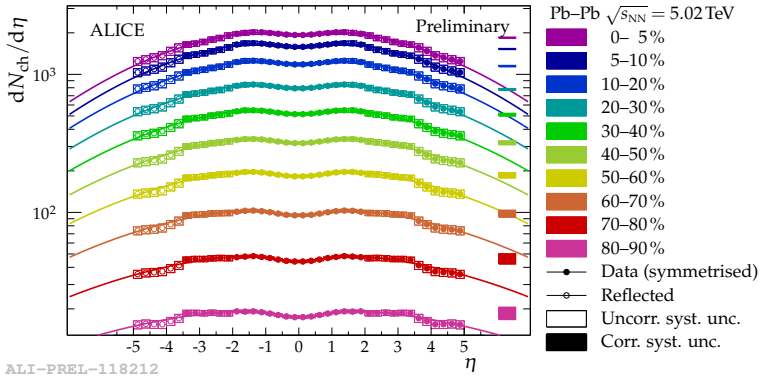
$$\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta} = \langle\beta\rangle\, A/(\sqrt{2\pi}\sigma)e^{-y^2/(2\sigma^2)}$$

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

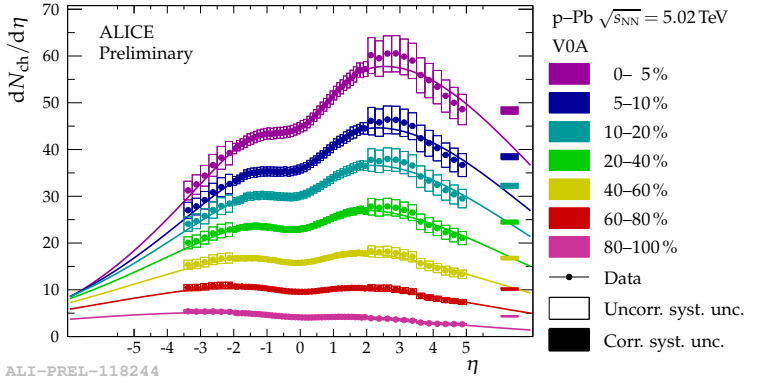
$$\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta} = \langle\beta\rangle\,(\alpha y + A)/(\sqrt{2\pi}\sigma)e^{-y^2/(2\sigma^2)}$$

Here, y in centre-of-mass

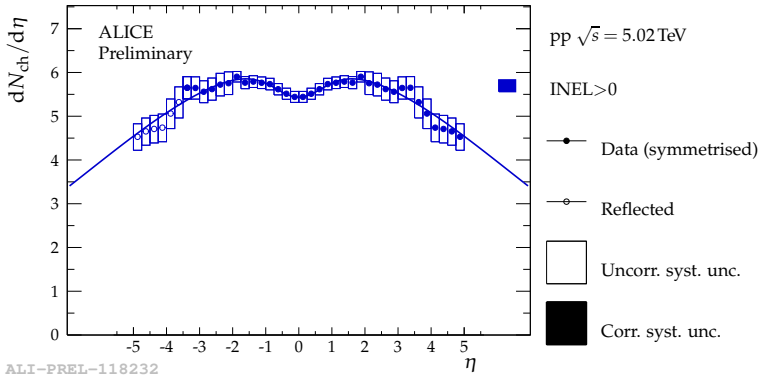
Pb–Pb



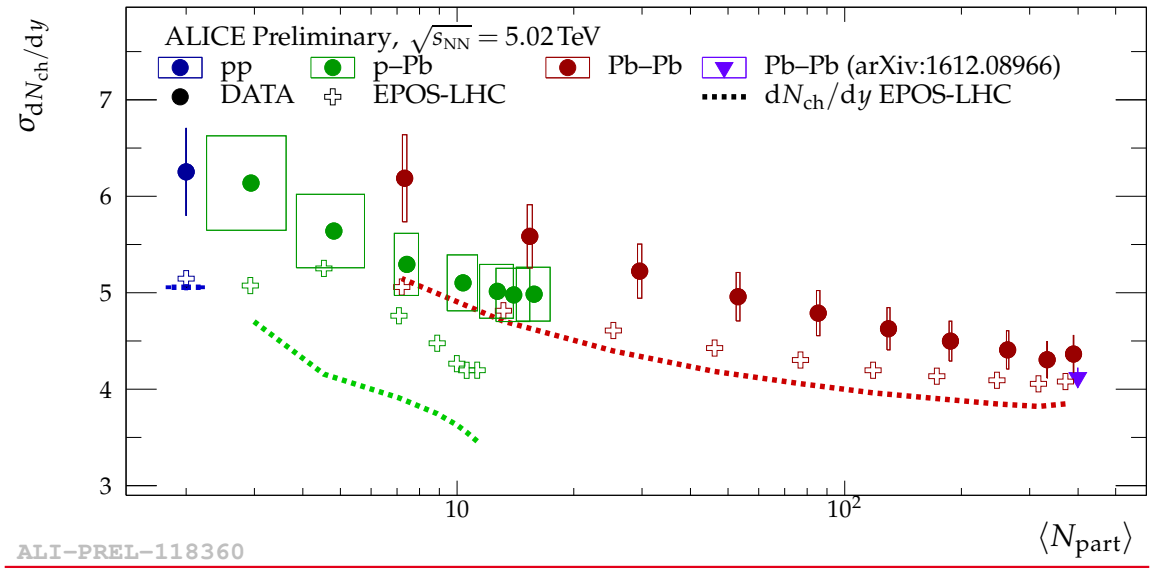
p–Pb



pp



Width in y and lower-bound p_{T}/m estimate



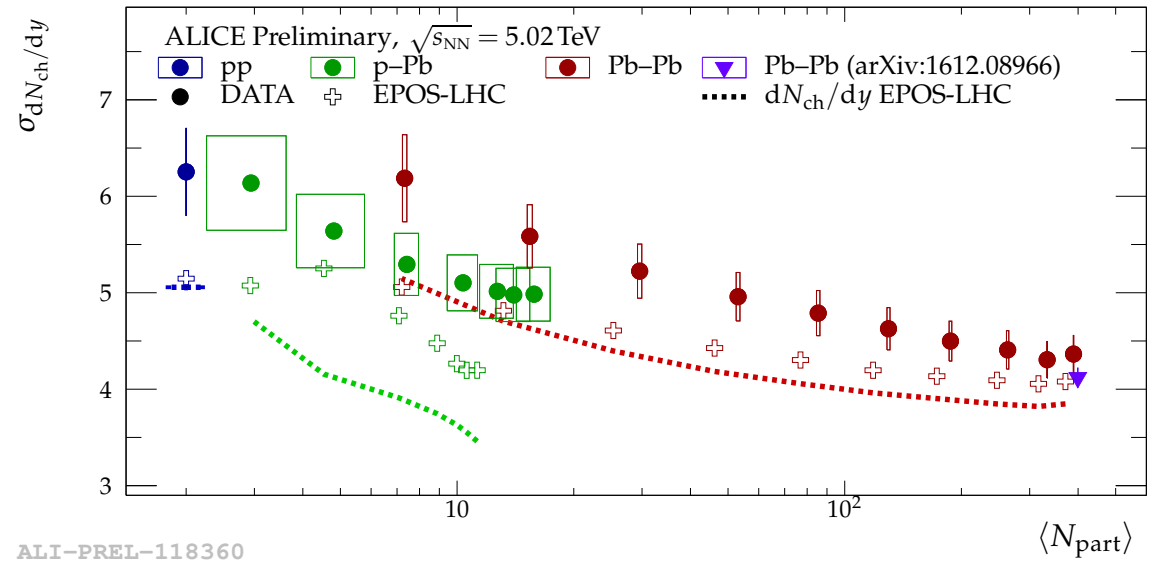
Fit parameters

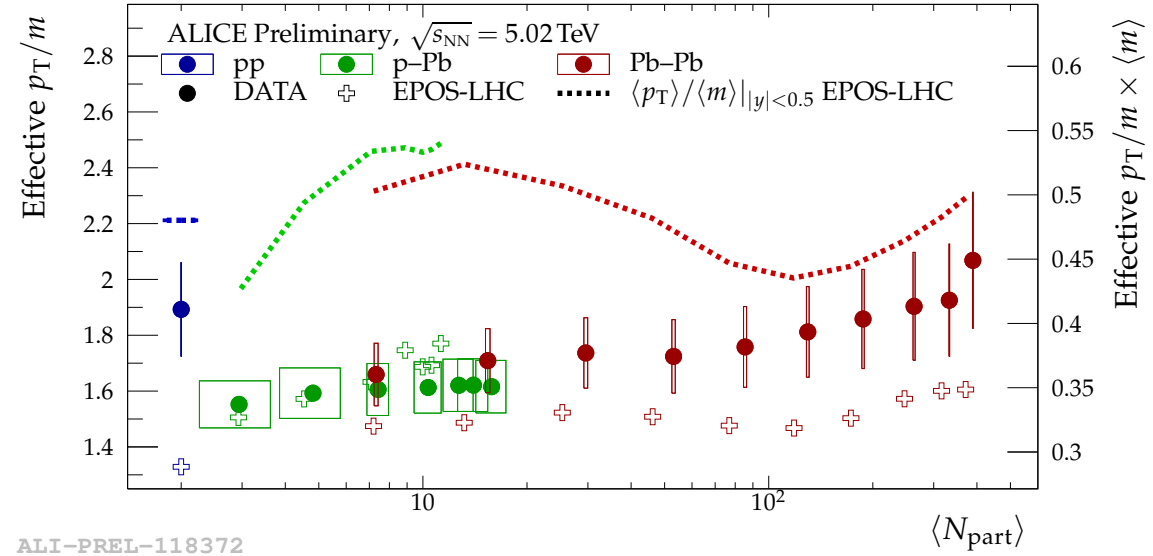
Also for EPOS-LHC

Width

- σ consistent with estimate from p_{T} spectra and $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ [arXiv:1612.08966]

Width in y and lower-bound p_{T}/m estimate





Fit parameters

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Width

- σ consistent with estimate from p_{T} spectra and $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ [arXiv:1612.08966]

Effective $p_{\mathrm{T}}/m = a$

- Hint of moderate increase
- $\langle m \rangle$ from Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ particle ratios (see PRC88,044910)
- Note $a < \langle p_{\mathrm{T}} \rangle / \langle m \rangle$ Illustrated by EPOS-LHC w/open markers and lines

Back-of-the-envelope estimate of energy density

Bjorken formula

$$\varepsilon_{\mathrm{Bj}}\tau = \frac{1}{S_{\mathrm{T}}}\frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}y}$$

Approximations

$$\frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}y} \approx 2\left\langle m_{\mathrm{T}}\right\rangle \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}y}$$

$$\gtrsim 2\left\langle m\right\rangle \sqrt{1+(p_{\mathrm{T}}/m)^2}\,\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}y}$$

S_{T} from Glauber

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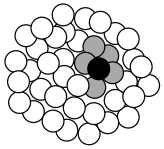
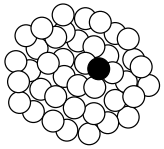
S_{T} from Glauber

Transverse area – Two extremes

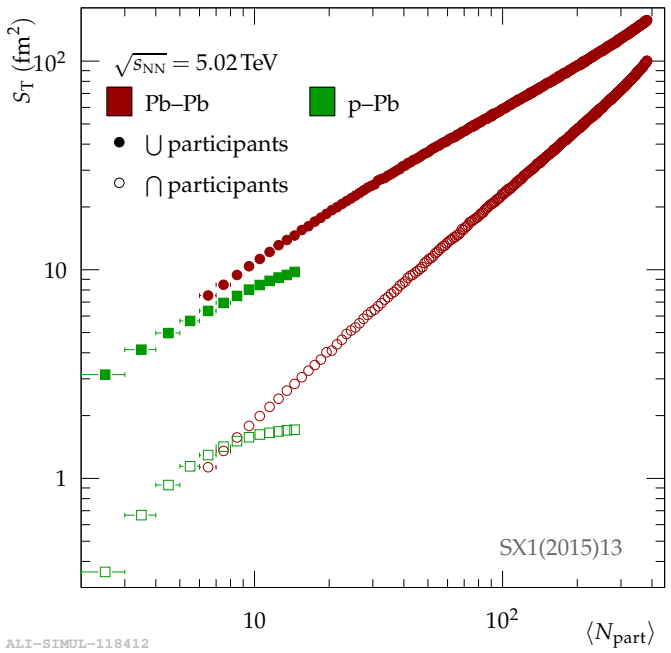


$\bigcup$ part.
Union of participant areas



$\bigcap$ part.
Intersect of participant areas

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



Back-of-the-envelope estimate of energy density

Bjorken formula

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$$\gtrsim \varepsilon_{\mathrm{LB}}\tau \equiv \frac{1}{S_{\mathrm{T}}^{\cap,\cup}} 2\sqrt{1+(p_{\mathrm{T}}/m)^2}\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}y}$$

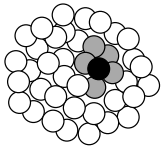
Approximations

$$\frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}y} \approx 2\langle m_{\mathrm{T}}\rangle \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}y}$$

$$\gtrsim 2\langle m\rangle \sqrt{1+(p_{\mathrm{T}}/m)^2}\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}y}$$

S_{T} from Glauber

Transverse area – Two extremes



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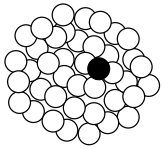

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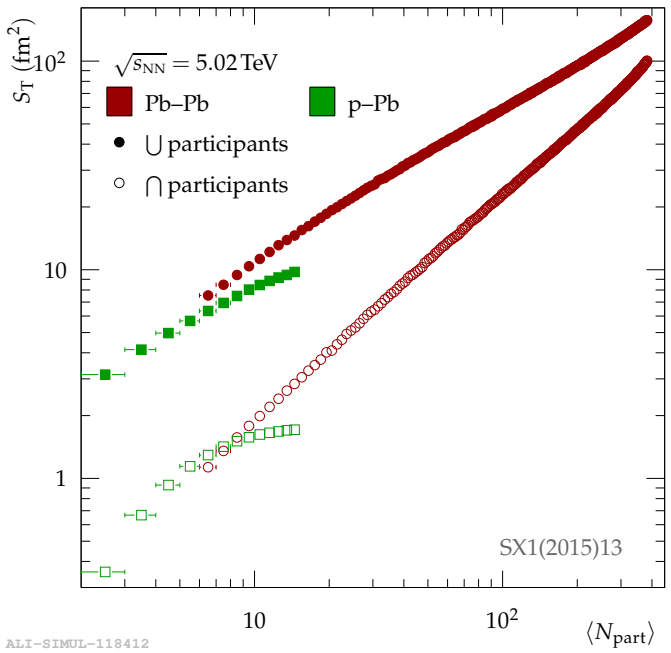
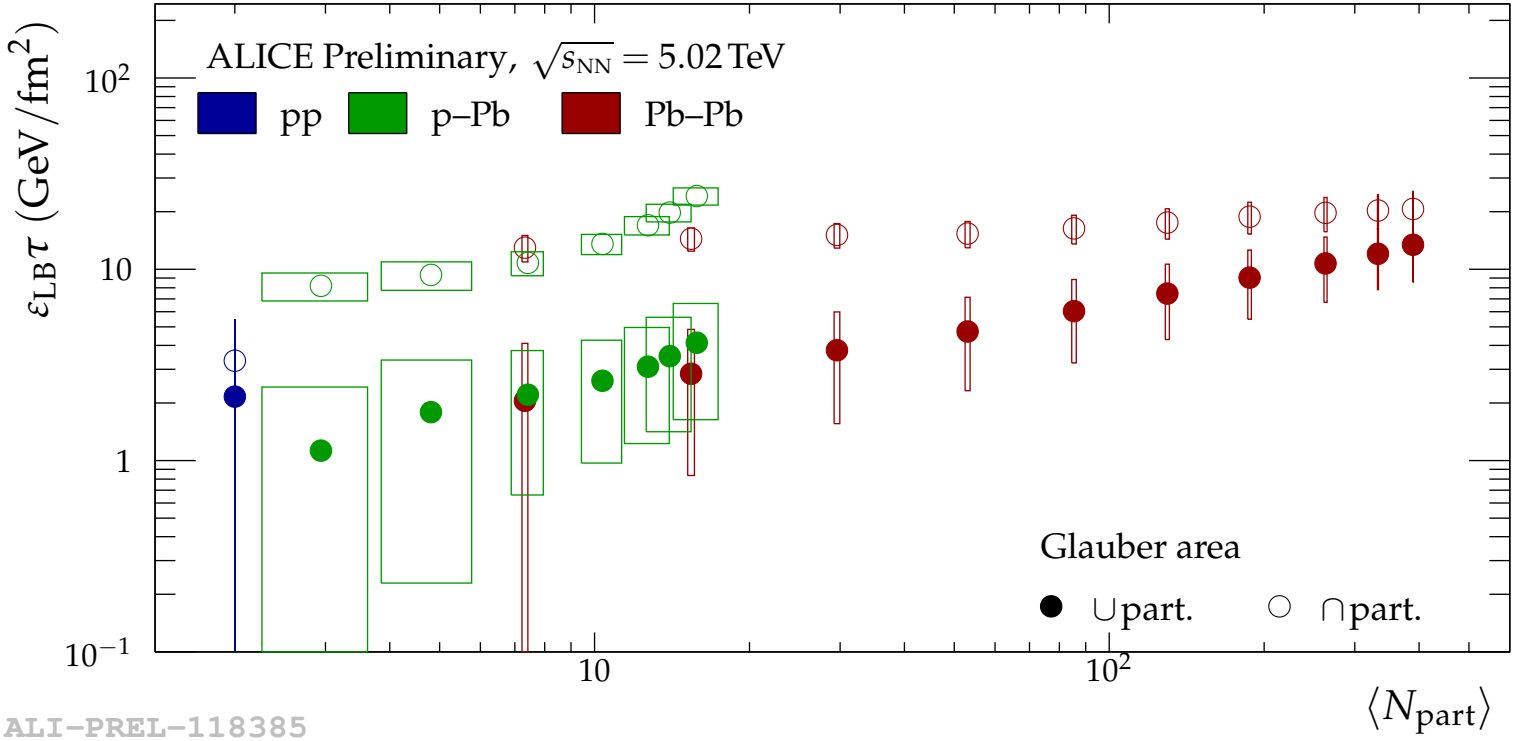
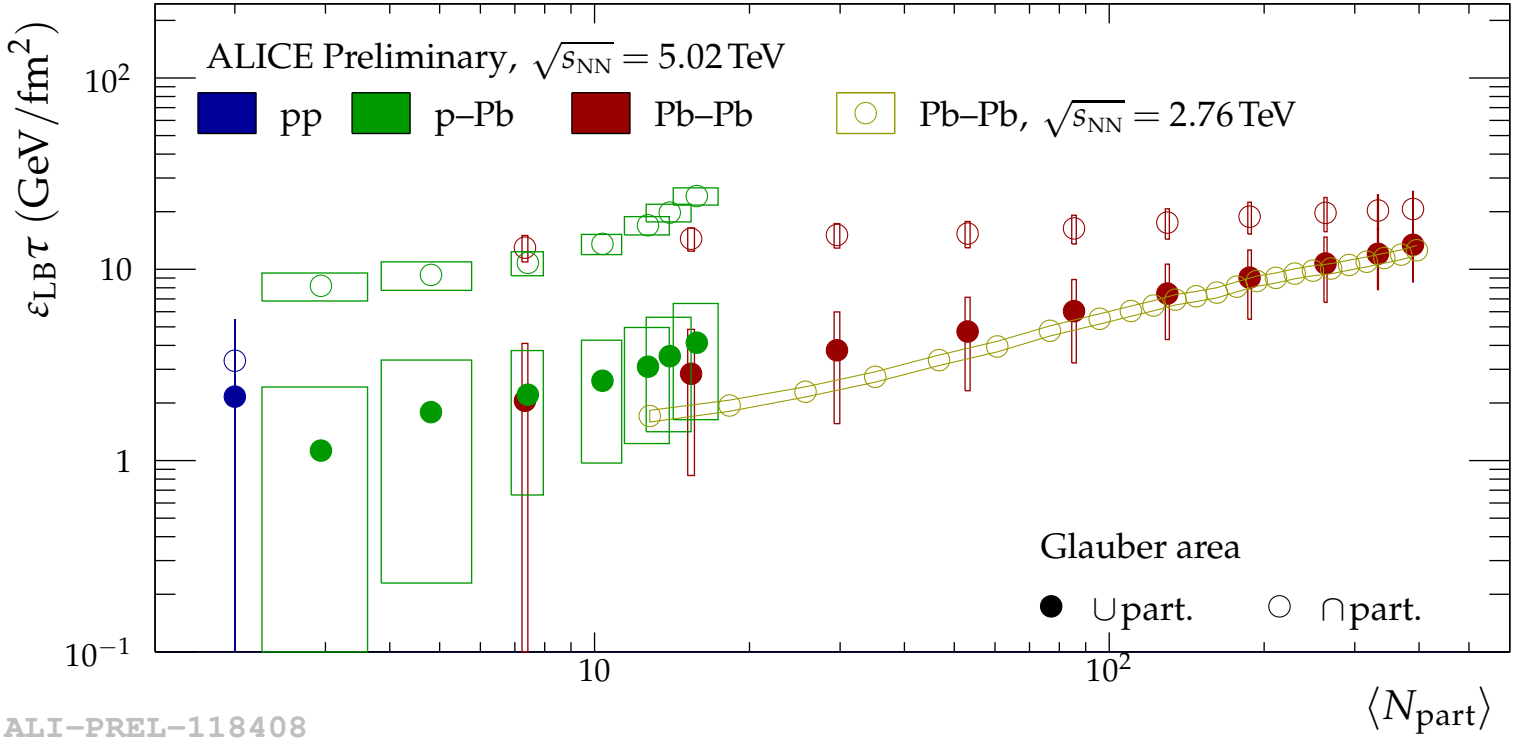


The lower-bound of $\varepsilon_{\mathrm{Bj}}$



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

The lower-bound of $\varepsilon_{\mathrm{Bj}}$



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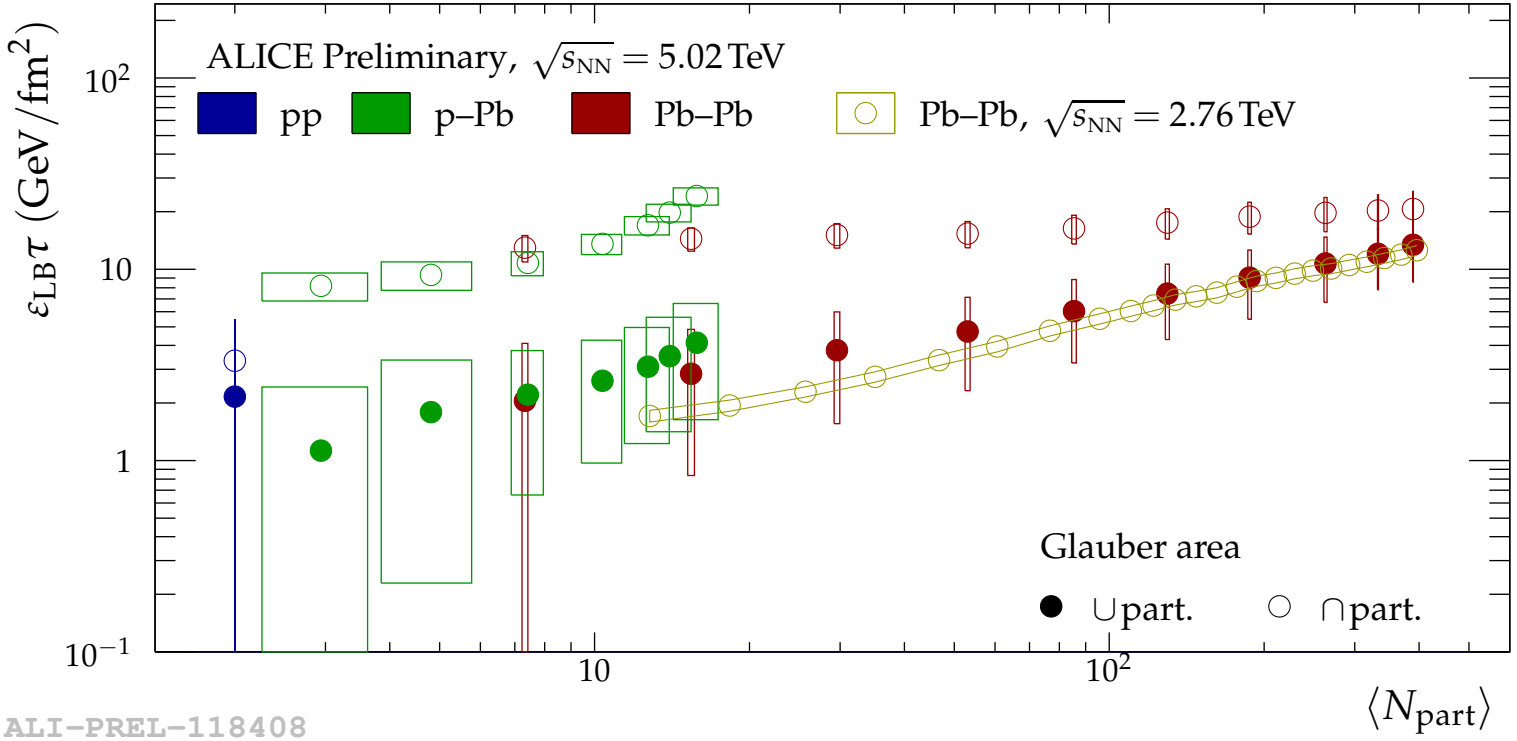
- Same trend as $\varepsilon_{\mathrm{Bj}}\tau$ in Pb–Pb $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ (PRC94(2016)034903)

The lower-bound of $\varepsilon_{\mathrm{Bj}}$



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- Same trend as $\varepsilon_{\mathrm{Bj}}\tau$ in Pb–Pb $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ (PRC94(2016)034903)
- If same initial ε in systems, then similar final state effects?

Summary

Charged-particle pseudorapidity density

- Measured in $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ collisions over a wide η 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

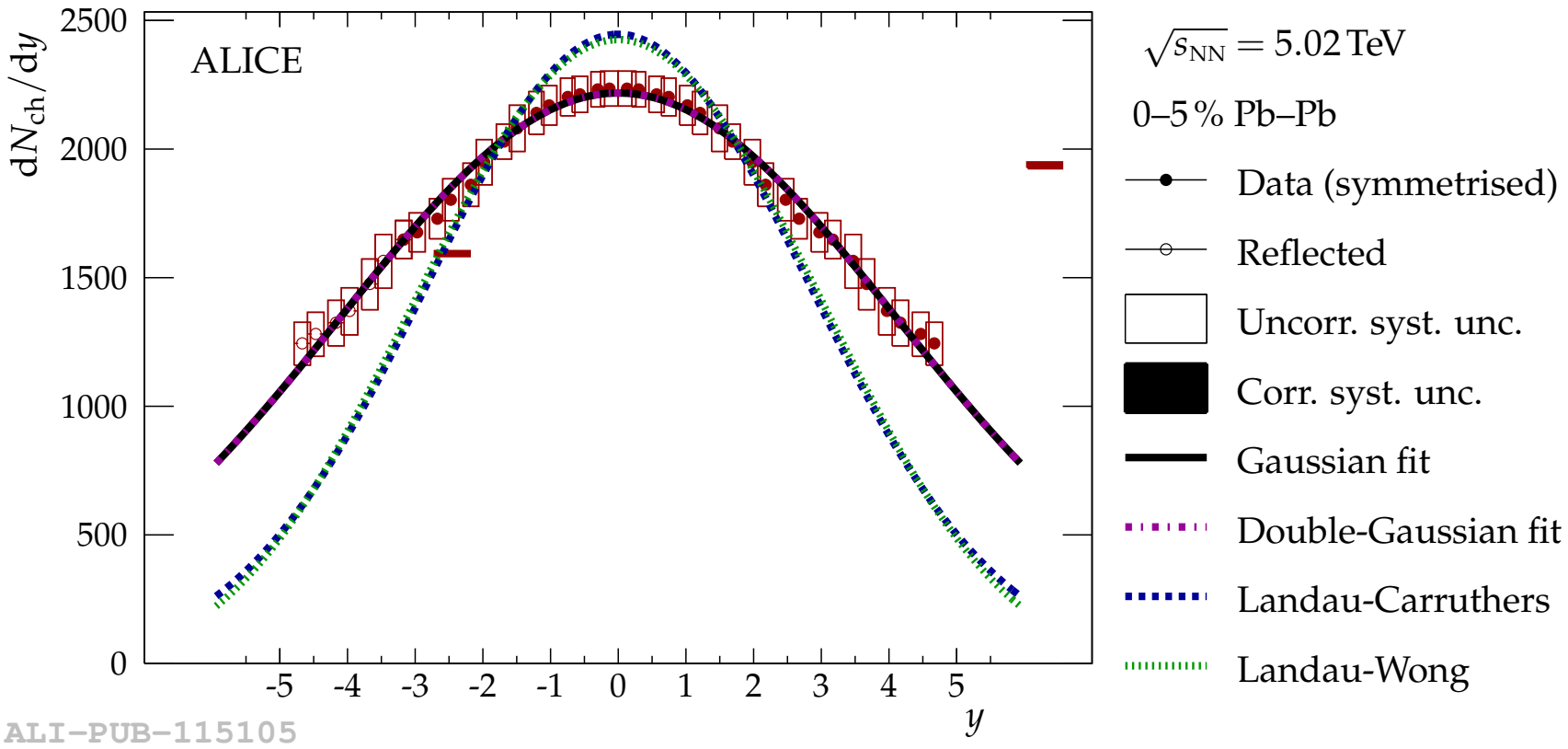
- Pb–Pb peaked near $\eta = 0$ than pp, increase in N_{ch}
- p–Pb exhibit triangular shape, consistent with independent nucleon-nucleon scatterings
- HIJING, EPOS-LHC cannot reproduce data

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

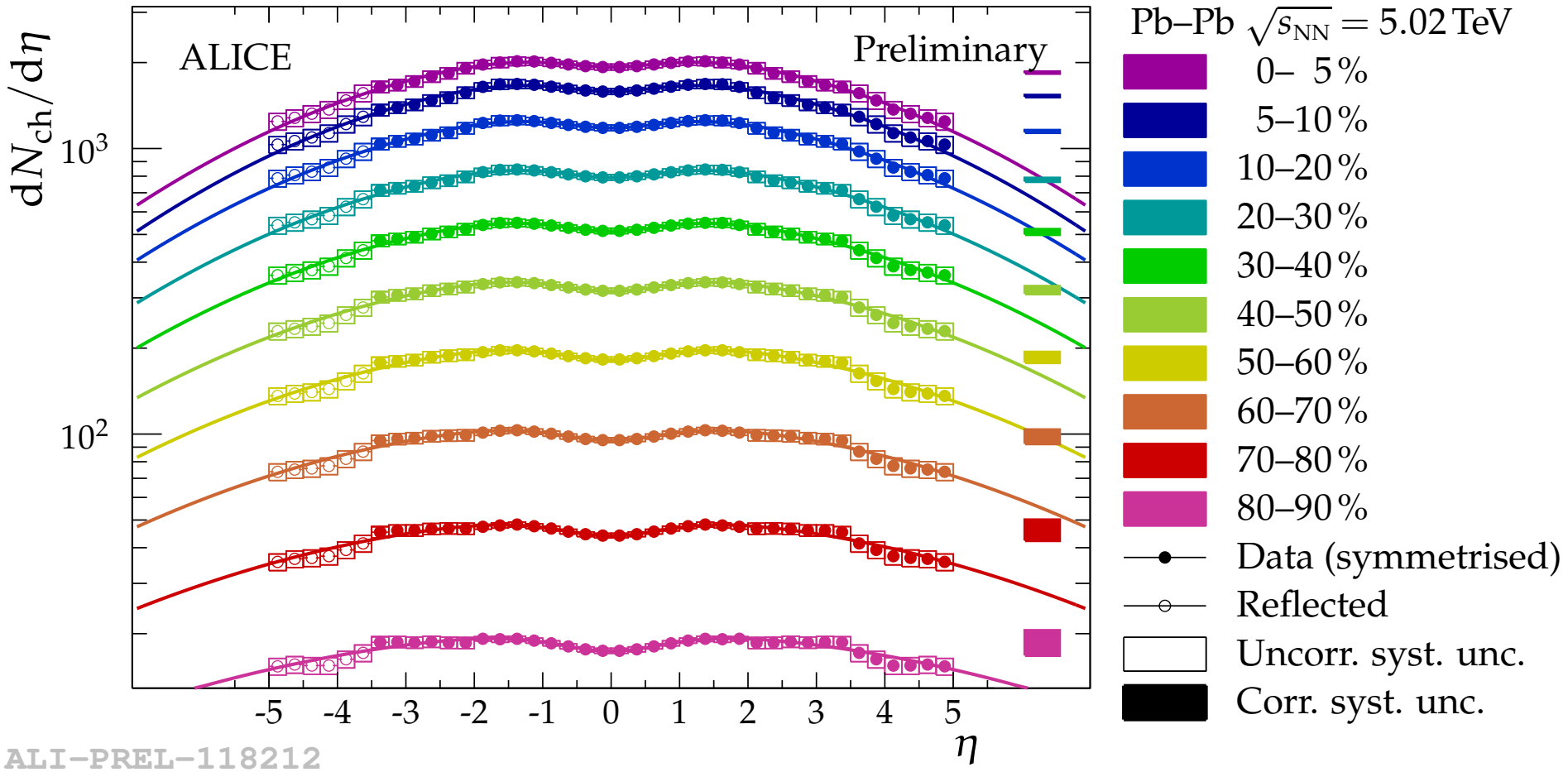
Backups

$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$ in Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$



- [arXiv:1612.08966]
- Direct evaluation of $\langle J \rangle = \langle \beta \rangle$ from p_{T}-spectra in Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$

Fit of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ distributions



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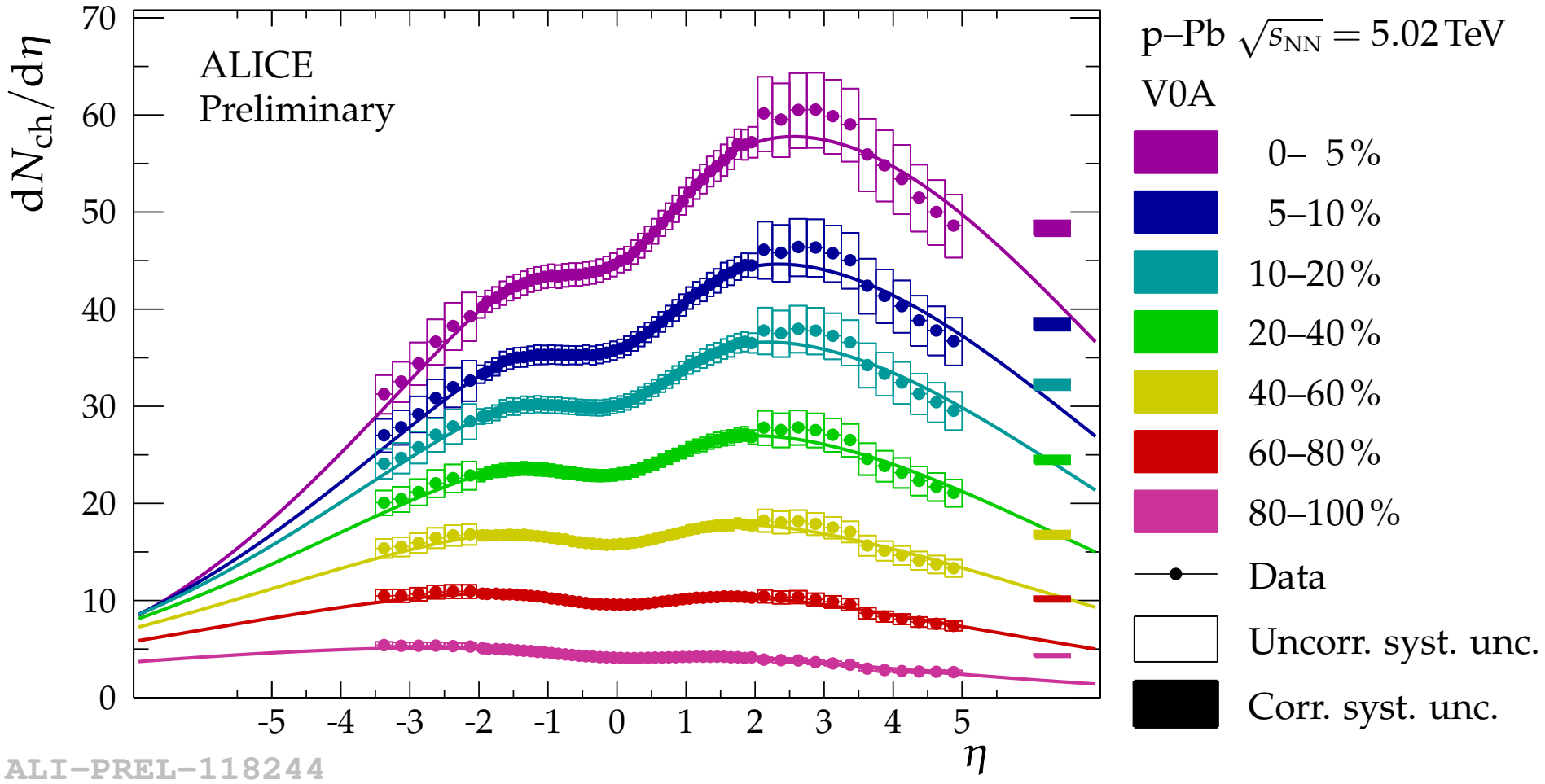

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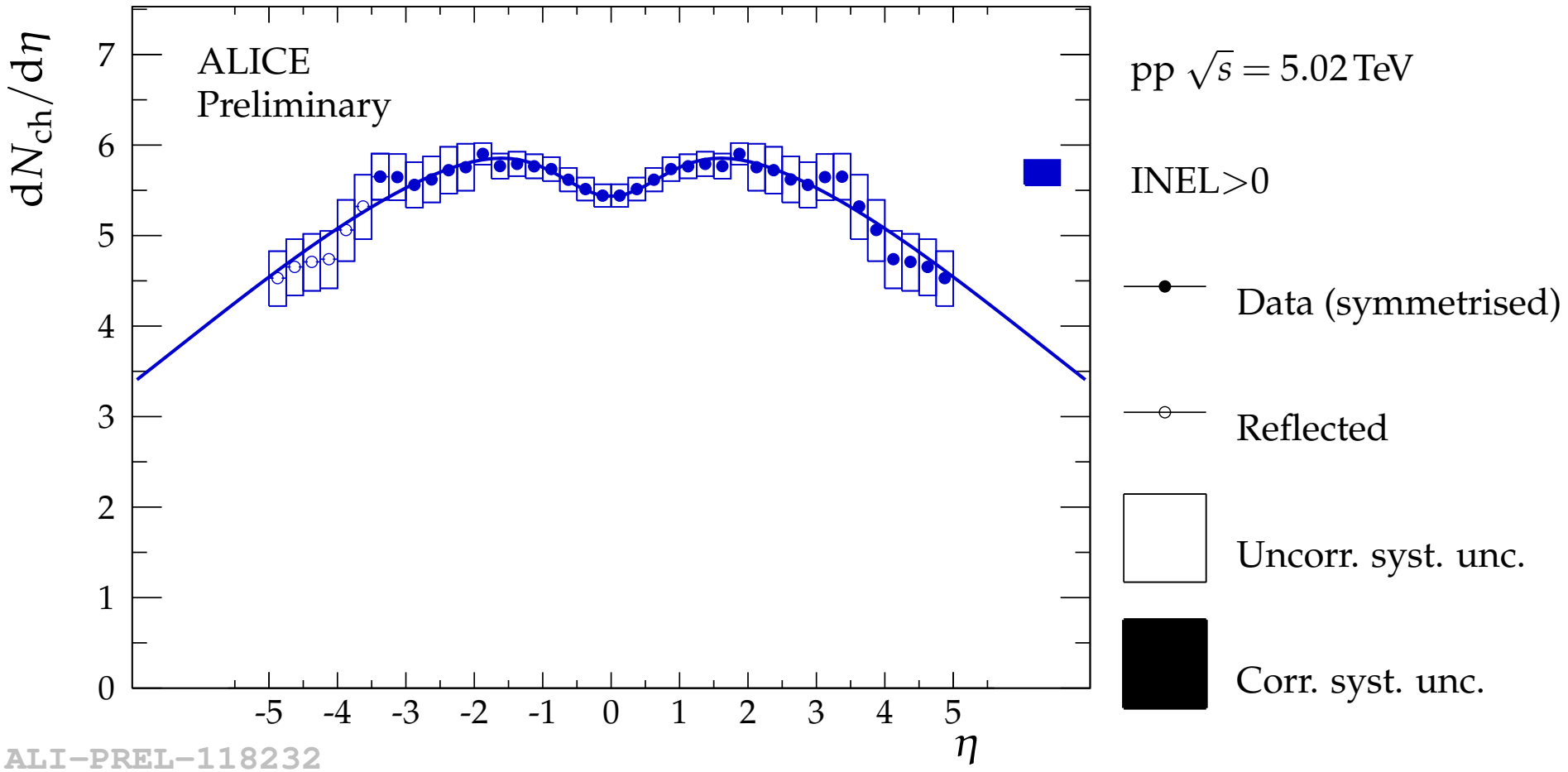
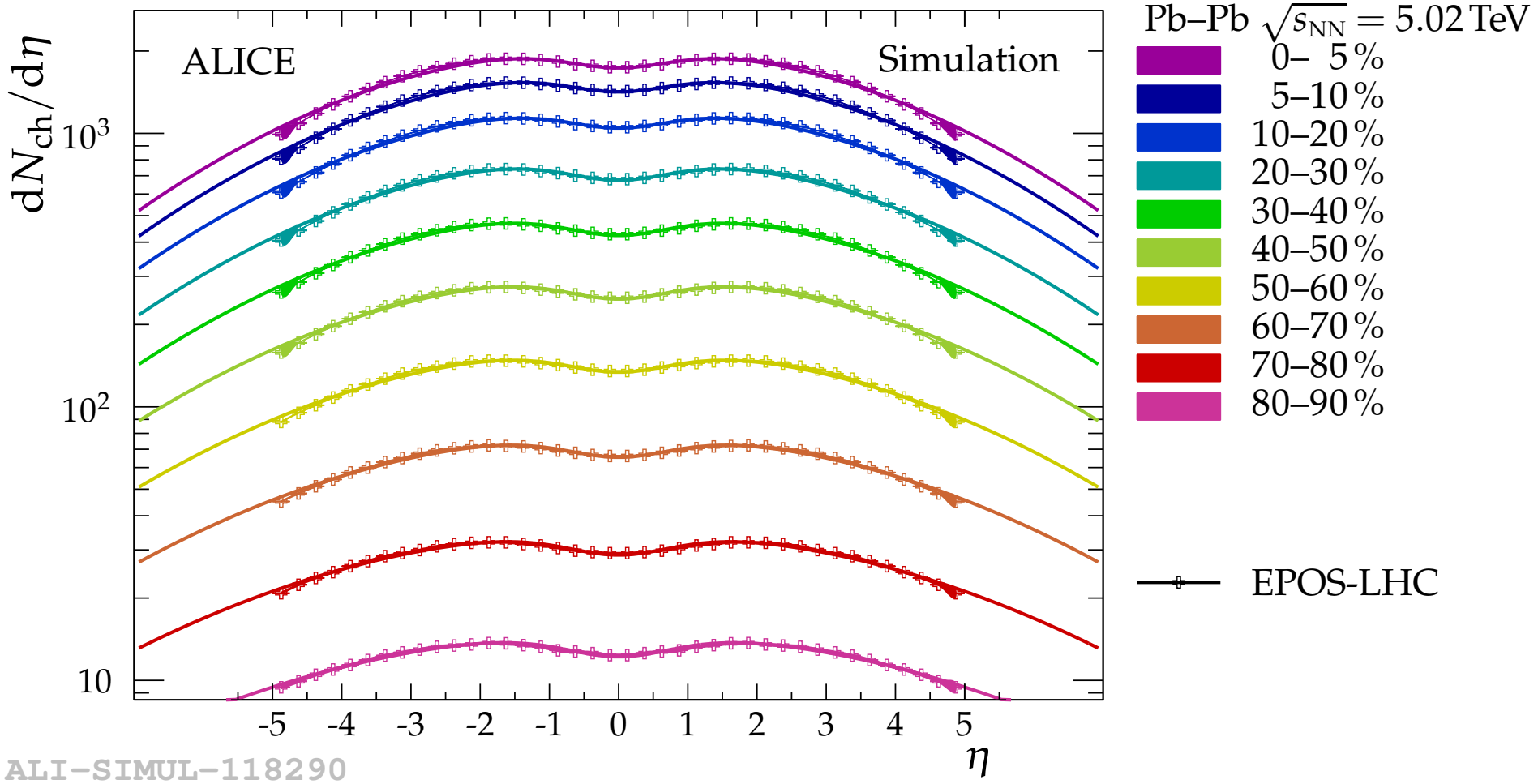
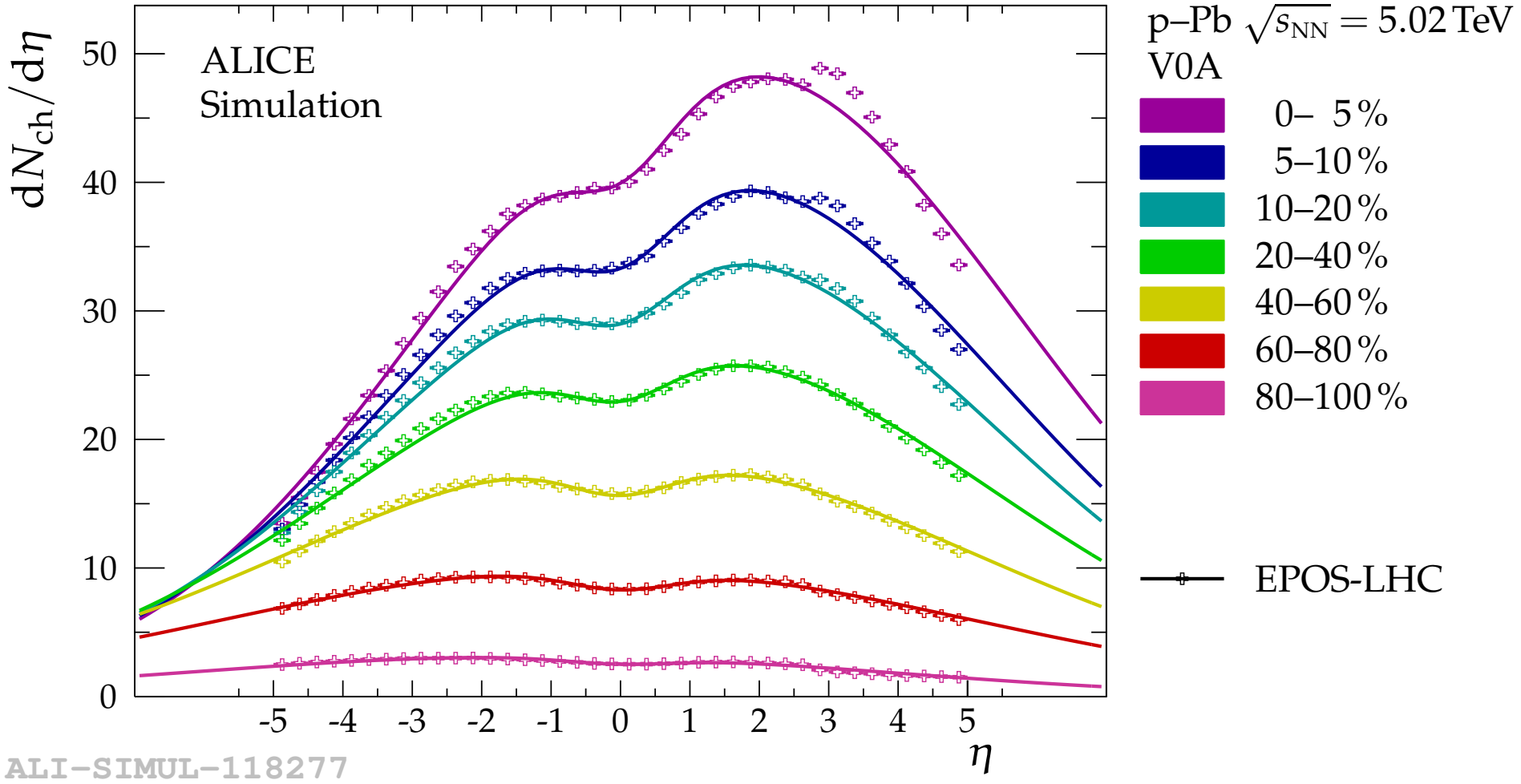


Fit of EPOS-LHC $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ distributions



Fit of EPOS-LHC $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ distributions



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