FACULTY OF SCIENCE

Charged-particle pseudorapidity density

and the initial state

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Disclaimer

I am an ALICE collaborator, so many results will be from the ALICE collaboration

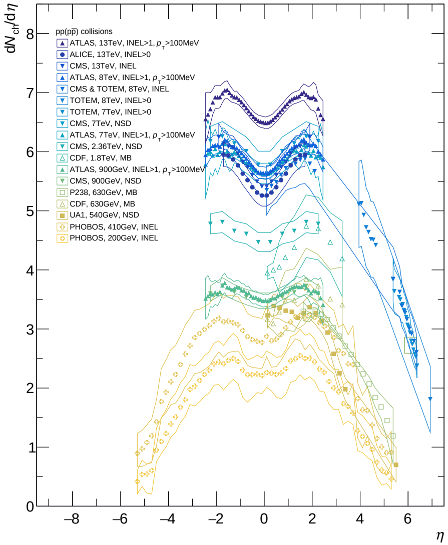
Overview

1. Measurements of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$
2. Theoretical expectations
3. Interlude
4. Experimental conclusions
   - Limiting fragmentation and ratios
   - Midrapidity $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ and total N_{ch}
   - Gaussianity of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$
5. Summary

Wealth of measurements

pp($\overline{\text{p}}$p) results

- From $\sqrt{s} = 200\,\text{GeV}$ to $13\,\text{TeV}$
- Inelastic
  - with $N_{\text{ch}} > 0$
  - with $N_{\text{ch}} > 1$
- Non-single diffractive
- Mostly $|\eta| < 2$



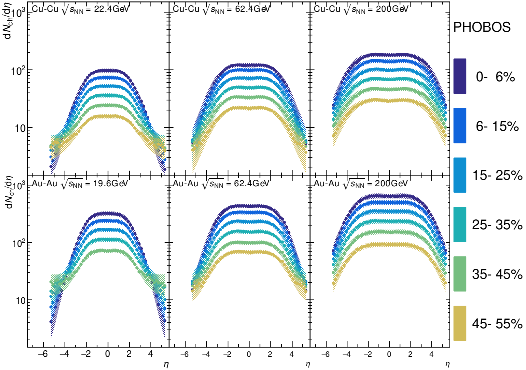
HepData

Wealth of measurements

AA at RHIC energies

- Au–Au & Cu–Cu
- From $\sqrt{s_{NN}} = 20\,\mathrm{GeV}$ to $200\,\mathrm{GeV}$
- Mostly PHOBOS

  Also results from BRAHMS, STAR



PRC83(2011)024913

Wealth of measurements

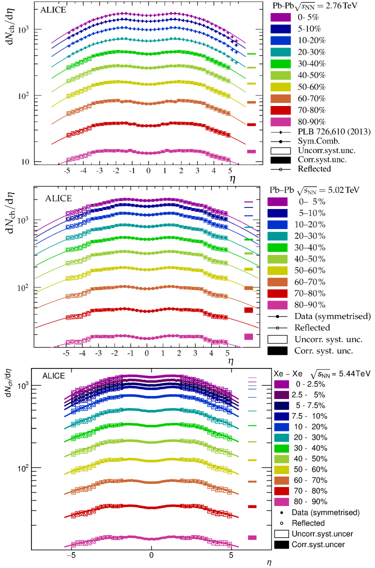
AA at LHC energies

- Xe–Xe & Pb–Pb
- From $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ to $5.44\,\mathrm{TeV}$
- Here ALICE $-3.5 < \eta < 5$
- Also ATLAS, CMS

Pb–Pb, $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ PLB754(2016)373-385

Pb–Pb, $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ PLB772(2017)567-577

Xe–Xe, $\sqrt{s_{\mathrm{NN}}} = 5.44\,\mathrm{TeV}$ arXiv:1805.04432

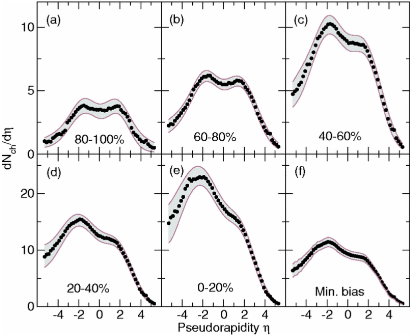


Wealth of measurements

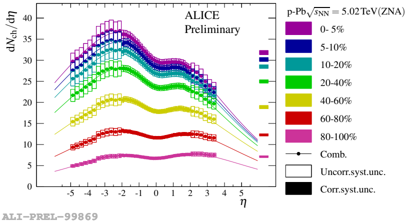
d–Au & p–Pb results

- From $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ to $5.02\,\mathrm{TeV}$
- Here, PHOBOS & ALICE $|\eta| < 5.3$ $-5 < \eta < 3.5$, resp.
- Also BRAHMS, ALTAS, CMS

d–Au, $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$
PRC83(2011)024913



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



What to expect

Large range of expectations

- Microscopic models
  - Glauber-based
  - Core-corona
  - ...
- Calculations
  - Landau-Carruthers

    $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y \propto 1/(\sqrt{2\pi}\sigma)e^{-y^2/(2\sigma^2)}$ with $\sigma = \log\sqrt{s_{\mathrm{NN}}}/(2m_p)$
  - Landau-Wong

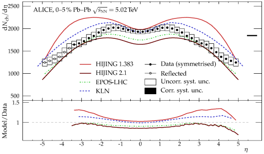
    $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y \propto e^{\sqrt{y_{\mathrm{beam}}^2 - y^2}}$
  - 3-source models

    2 fragmentation Gaussians plus one production Gaussian
  - Colour-Glass-Condensate
  - ...

Models have room for improvement

- Generally OK near $\eta = 0$
- Most deviate for $|\eta| > 0$

PLB772(2017)567-577



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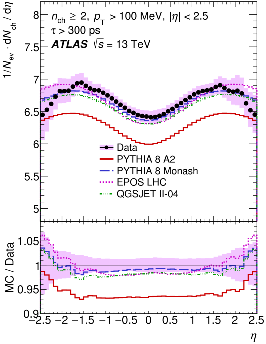

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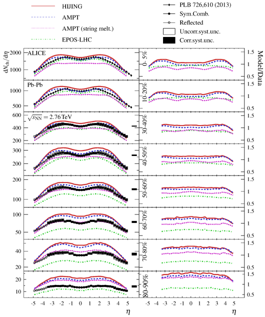

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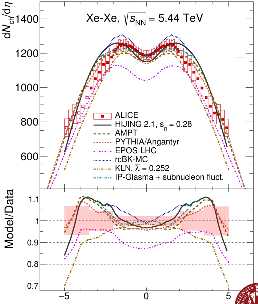
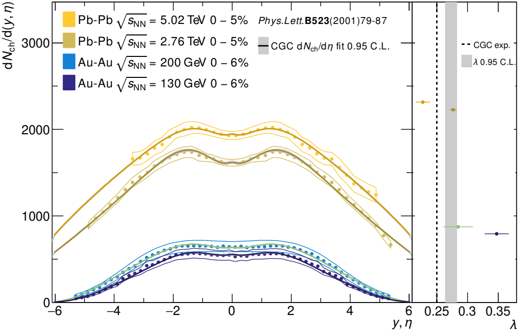


The (not-so) transparent glass

- Fit CGC expression
- Good fit of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$
- λ parameter off

However . . .



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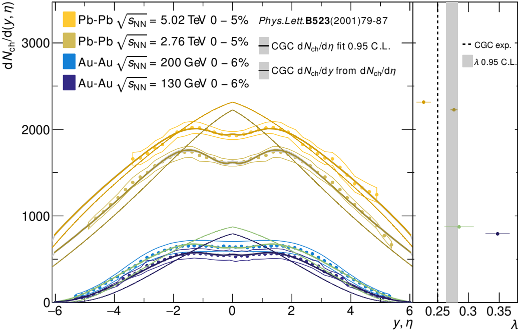
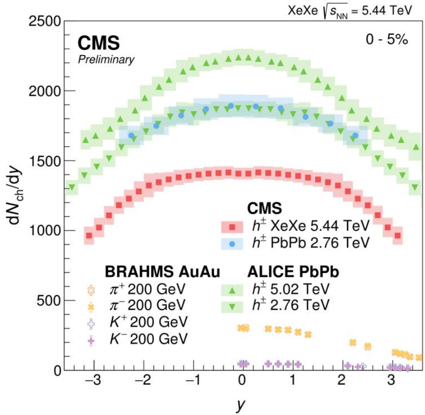


However . . .

- Sharp peak in $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$ at $y = 0$

Calculations via $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$ estimates

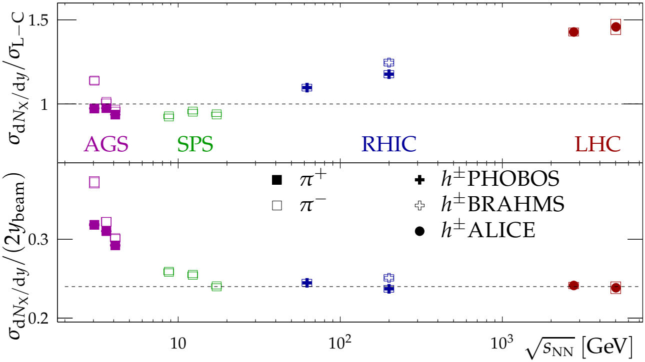
Landau-Carruthers et al prescribe width of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$



- BRAHMS: Direct measurement $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$
- CMS: $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \xrightarrow{J} \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$ Simulated Jacobian J
- ALICE: $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \xrightarrow{J} \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$ Calculated Jacobian J from identified $\mathrm{d}N/\mathrm{d}p_{\mathrm{T}}$

All (except CMS) Gaussian, extract σ

Data wider than expectation



- From top SPS, wider than Landau hydrodynamics
- Same range, follow y_{beam}
- Final state fill up phase-space

Interlude — theory & experiment

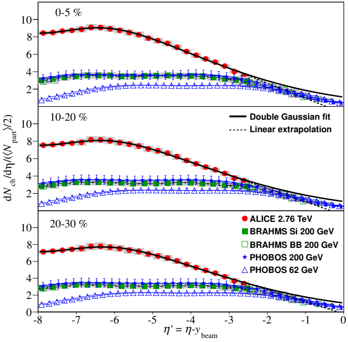
- Microscopic models have room for improvement
- Landau-Hydro good up to top SPS

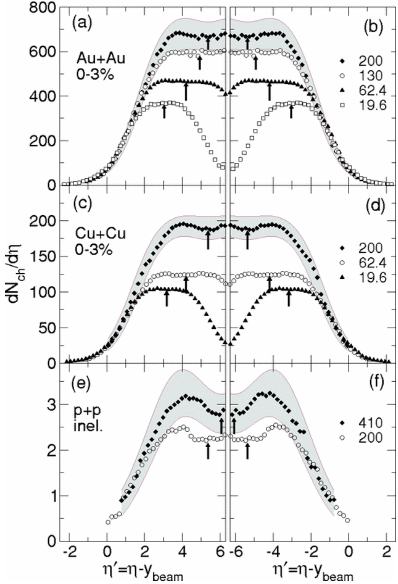
- Roughly Gaussian $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$
- Incoherent particle production

How to make sense of it all?

Limiting fragmentation

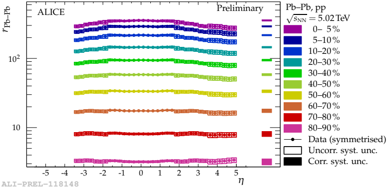
- $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ at large $|\eta|$ independent of $\sqrt{s_{\mathrm{NN}}}$.
- Holds in pp and Cu–Cu
- Study not feasible for $\sqrt{s_{\mathrm{NN}}} > 2.76\,\mathrm{TeV}$





Comparing to pp

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

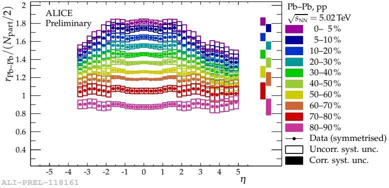


Pb–Pb

- $\times 10^2$ over pp
- Increase as $\eta \to 0$

Comparing to pp

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

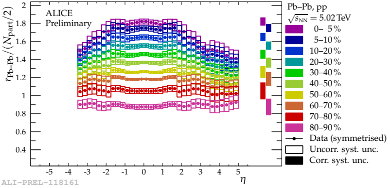


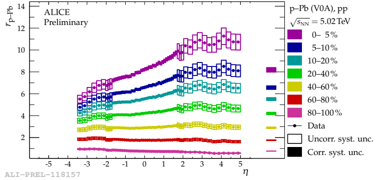
Pb–Pb

- $\times 10^2$ over pp
- Increase as $\eta \to 0$
- Scale by $2/N_{\mathrm{part}}$ (Glauber)
- Collimation near $\eta = 0$

Comparing to pp

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





Pb–Pb

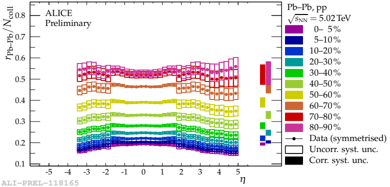
- $\times 10^2$ over pp
- Increase as $\eta \to 0$
- Scale by $2/N_{\mathrm{part}}$ (Glauber)
- Collimation near $\eta = 0$

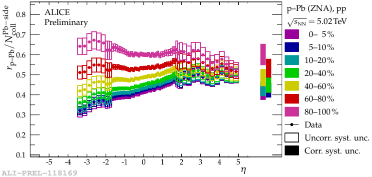
p–Pb

- Centrality: V0A
- $\times 10$ over pp
- Near-linear increase from p- to Pb-going side

Nuclear modification

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





- $\nearrow$ as $\eta \to 0$

- N.B.: Centrality ZNA
- Independent proton-nucleon scattering

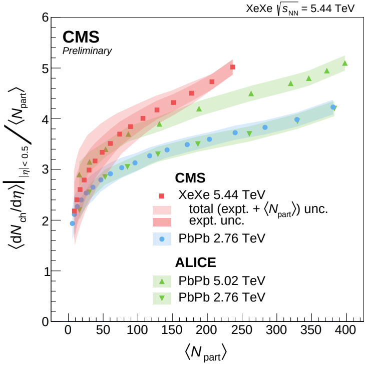
PRC72(2005)034907 PRL39(1977)1120

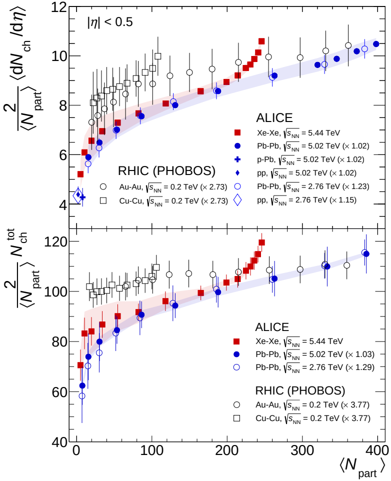
- Similar level in ion for most central Pb–Pb events.

  similar fluctuations in central Pb–Pb as in p–Pb?

Per participant production

- Consistent increase from pp to most central
- However, “rapid” increase for most central smaller systems.



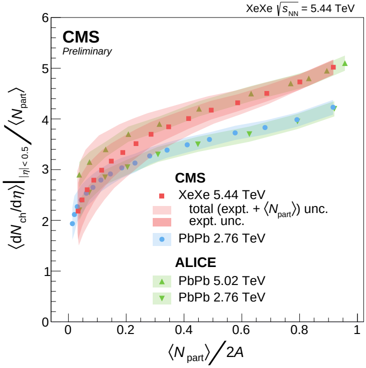


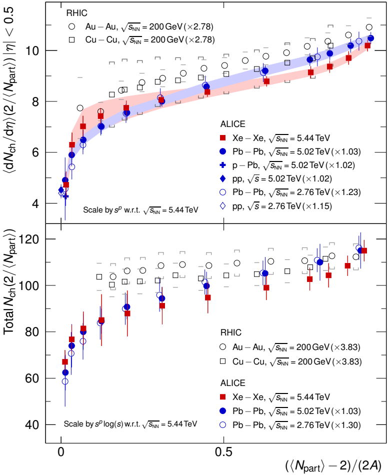
arXiv:1805.04432

- Also “up-tick” in total N_{ch}

Production versus "natural centrality"

- Scale abscissa by max $\left(N_{\text{part}}\right)$

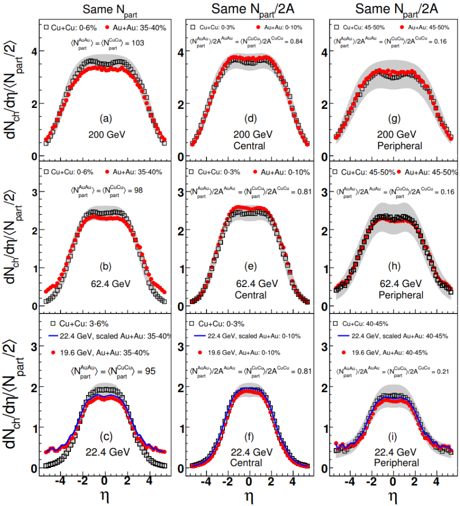




"Up-tick" also present in larger systems

$dN_{ch}/d\eta$ versus "natural centrality"

- Constant N_{part} show deviations
- Constant $N_{part}/(2A)$ show scaling

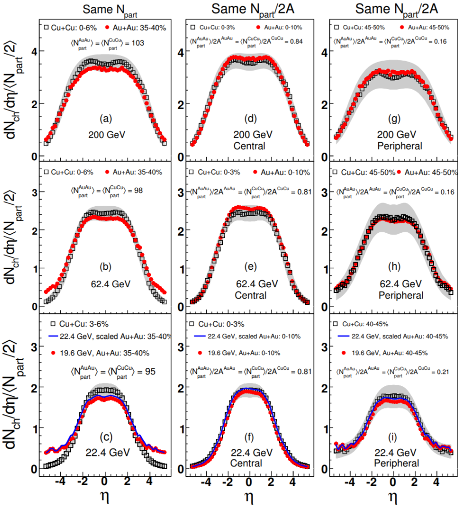


$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ versus "natural centrality"

- Constant N_{part} show deviations
- Constant $N_{\mathrm{part}}/(2A)$ show scaling

How can that be?

participants do not know "natural centrality"



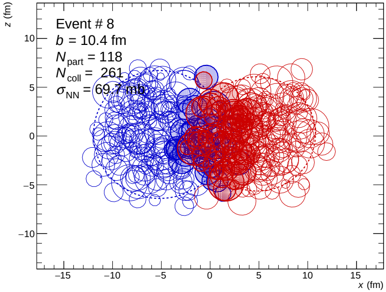
Glauber and Glauber–Gribov

Glauber:

- Inputs:
  - Charge-distribution (e.g., 3pF or 3pG)
  - Nucleon–nucleon cross-section σ_{NN}
  - Black-disc: $P(b_{\mathrm{NN}}) = \Theta(2r - b_{\mathrm{NN}})$
  - Impact parameter b
- Outputs:
  - $N_{\mathrm{part}}, N_{\mathrm{coll}}, \ldots$
  - Nucleon distribution

Glauber–Gribov

- Colour-state fluctuations Fluctuation of σ_{NN} ($\delta\sigma_{\mathrm{NN}}$)



Normal Gribov:

- Sample σ_{NN} *once* per event
- OK for p–A, but tricky for A–A

Individual nucleon fluctuations

- Allow each nucleon to fluctuate in "size"
  Simple approach, Angantyr/PYTHIA more evolved
- Calculate σ_{AB} for any two nucleons A and B
- Fix to reproduce $\langle\sigma_{\mathrm{NN}}\rangle = \langle\langle\sigma_{AB}\rangle\rangle$
  not necessarily $P(\sigma_{\mathrm{NN}})$
- Nucleon "sizes" fixed throughout
  Frozen colour state
- Based on `TGlauberMC`

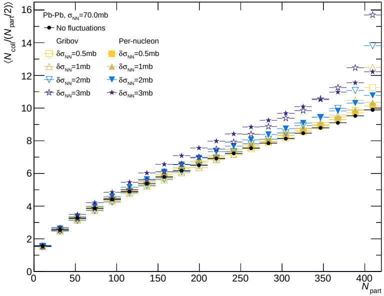
  PRC97(2017)054910

Work-in-progress: Apply skepticism here

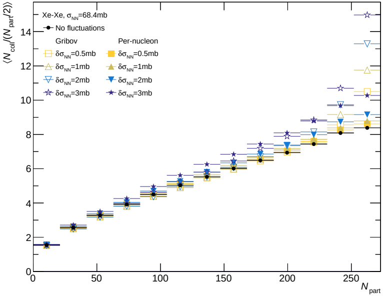
“Up-tick” in AA collisions

Ansatz: Take N_{coll} as proxy for $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ or total N_{ch}

Pb–Pb, $\sigma_{\mathrm{NN}} = 70\mathrm{mb}$ ($\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$)



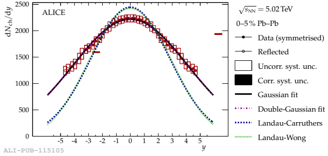
Xe–Xe, $\sigma_{\mathrm{NN}} = 68.4\mathrm{mb}$ ($\sqrt{s_{\mathrm{NN}}} = 5.44\,\mathrm{TeV}$)



- Glauber–Gribov: “up-tick”
- individual nucleon fluctuation: More smooth increase
- “Up-tick” possible sign of σ_{NN} fluctuations

  Fluctuations *a la* p–A

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



PLB772(2017)567-577

- Direct measurement of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$: Gaussian in measured region
- Via mean Jacobian: Gaussian in measured region

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

$$y \approx \eta - \frac{\cos\vartheta}{2a^2}$$

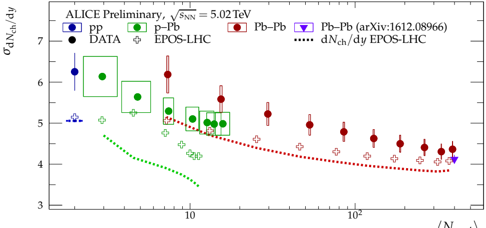
$$\langle\beta\rangle \approx \frac{1}{\sqrt{1+1/(a^2\cosh^2\eta)}}$$

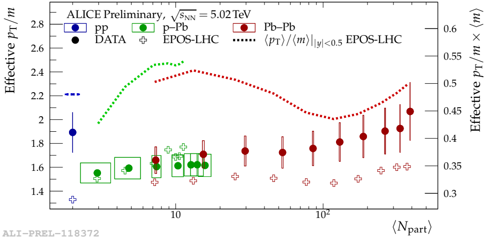
a: effective p_{T}/m

- pp and Pb–Pb Ansatz:
  $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta = \langle\beta\rangle A/(\sqrt{2\pi}\sigma)e^{-y^2/(2\sigma)}$
- p–Pb Ansatz: $A \rightarrow (\alpha y + a)$
  $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta = \langle\beta\rangle(\alpha y + A)/(\sqrt{2\pi}\sigma)e^{-y^2/(2\sigma)}$

Fit $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ to extract σ, effective p_{T}/m

σ_y and effective p_T/m



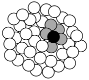


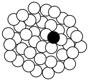
- σ decrease
  Collimation of production
- Peripheral similar σ to pp
  Limiting fragmentation
- Effective p_T/m increase for Pb–Pb
  consistent with pp

Back-of-the-envelope initial energy density

- Bjorken formula:

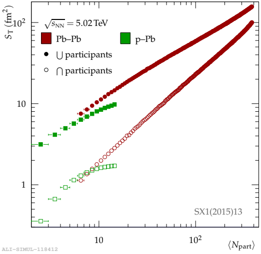
$$\varepsilon_{\mathrm{Bj}}\tau = 1/S_{\mathrm{T}}\,\mathrm{d}E_{\mathrm{T}}/\mathrm{d}y$$

$\bigcup$ part.: 

$\bigcap$ part.: 

- with

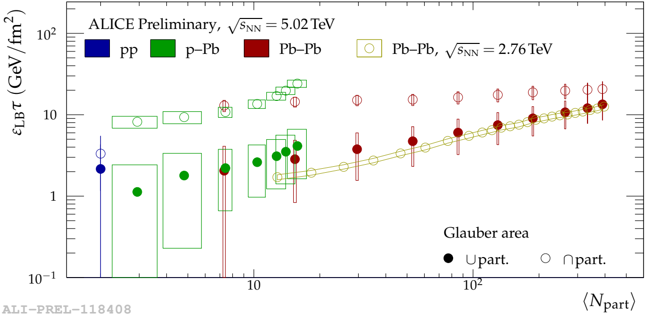
$$\mathrm{d}E_{\mathrm{T}}/\mathrm{d}y \approx 2\langle m_{\mathrm{T}}\rangle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$$
$$\gtrsim 2\langle m\rangle\sqrt{1+(p_{\mathrm{T}}/m)^2}\,\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$$



- S_{T} from Glauber
  - $\bigcup$ part. Full area
  - $\bigcap$ part. Overlap

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

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



PRC94(2016)034903

- Fixed energy density at fixed N_{part}
  Except for central p–Pb
- For $\cup$ part, large increase over pp
- If same initial ε in systems, then similar final state effects?

So where are we?

- Lots of results on N_{ch} production
- Models has room for improvements

- From top SPS, fill-up phase-space
- Central AA fluctuations
  Similar to p–Pb
  Possibly σ_{NN} fluctuations

- pp, p–Pb, Pb–Pb similar initial ε

N_{ch} production still a challenge

Back-ups