Charged-particle pseudorapidity density

N_{part} versus N_{coll}

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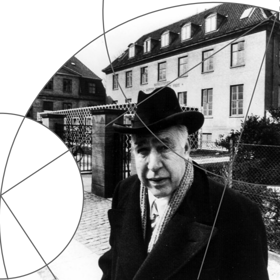
Niels Bohr Institute

COST Workshop on interplay of hard and soft QCD probes for collectivity in heavy–ion collisions — 27th of February, 2019



Disclaimer

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

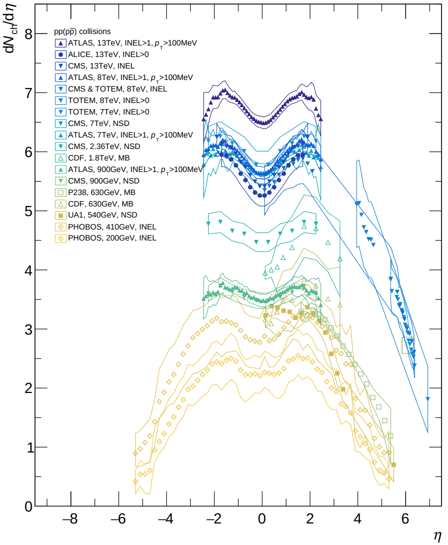
Overview

1. Measurements of $\frac{dN_{ch}}{d\eta}$
   - Other measurements of interest
   - Take-away
2. Scaling
   - Midrapidity $\frac{dN_{ch}}{d\eta}$ and total N_{ch}
   - Natural Centrality
   - Glauber modelling
3. Summary

Wealth of measurements

pp($\bar{\text{p}}$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 $|\eta| < 2$



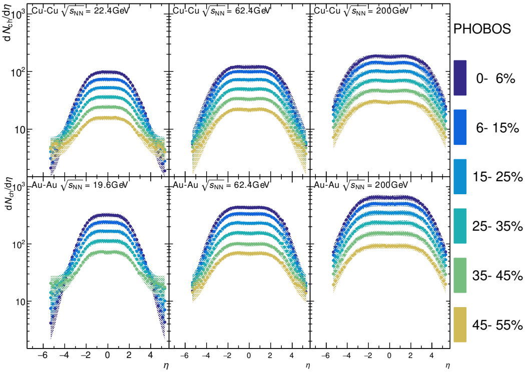
HepData

Wealth of measurements

AA at RHIC energies

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

  Also results from BRAHMS, STAR



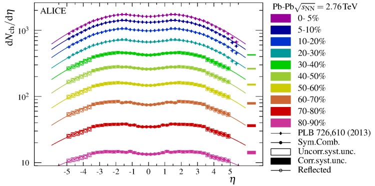
PRC83(2011)024913

Wealth of measurements

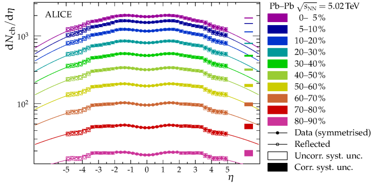
AA at LHC energies

- 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

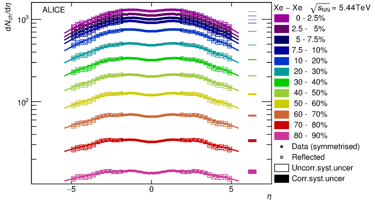
Pb–Pb, $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV
PLB754(2016)373-385



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



Xe–Xe, $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV
PLB790(2019)35

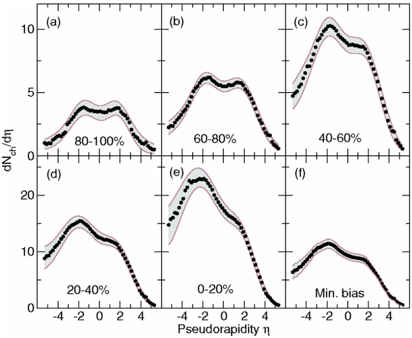


Wealth of measurements

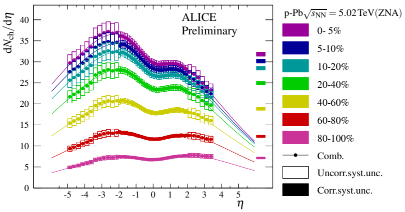
d–Au & p–Pb results

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



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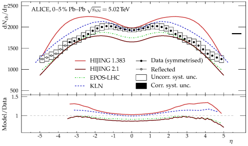
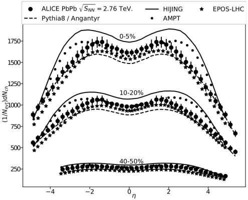
Models have room for improvement

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

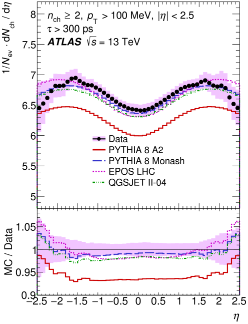
PLB754(2016)373-385



JHEP10(2018)134



EPJC76(2016)502



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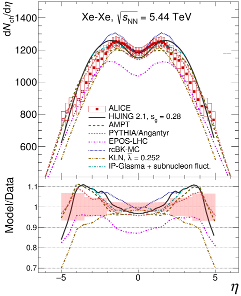
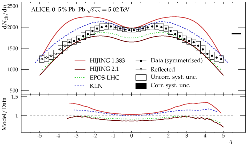


Models have room for improvement

- Generally OK near $\eta = 0$
- Most deviate for $|\eta| > 0$
- Good news for Lund: Pythia/Angantyr not the worst

PLB754(2016)373-385



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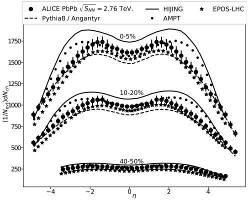

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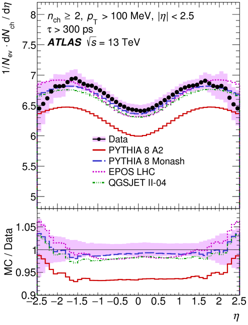

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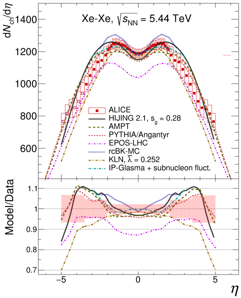
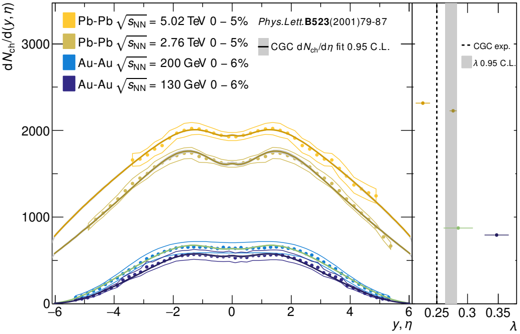


The (not-so) transparent glass

- Fit CGC expression
  PLB523(2001)79-87
- Good fit of $\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}$
- λ parameter off

However ...



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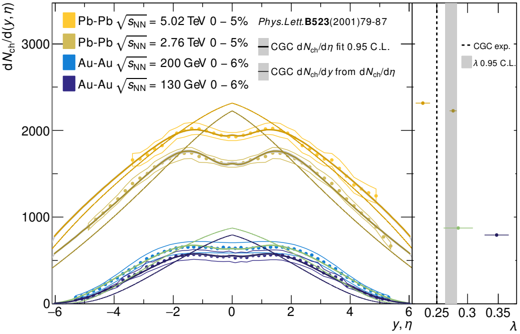


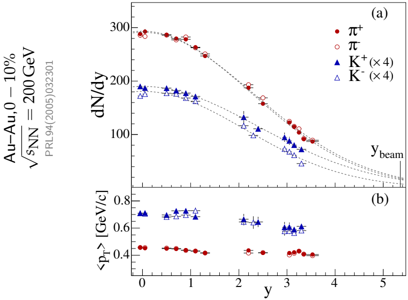
However . . .

- Sharp peak in $\frac{dN_{ch}}{dy}$ at $y = 0$
  Caveat: older paper, but mechanism the same AFAIK

Normality and transparency

BRAHMS Results:

- $\frac{dN_{\pi,K}}{dy} \sim N[0,\sigma]$
  similar for $\overline{p}$
- Small decrease in $\langle p_T \rangle$ over y
  similar for $p,\overline{p}$



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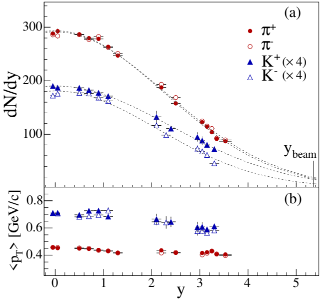
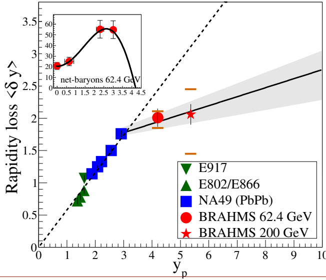
- *Small* rapidity loss $\langle \delta y \rangle$ over SPS energies
  Increased *transparency* for $\sqrt{s_{NN}} \gtrsim 17\,\mathrm{GeV}$

Au–Au, 0 − 10% $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$
PRL94(2005)032301



Au–Au,Pb–Pb, central
PLB677(2009)267-271



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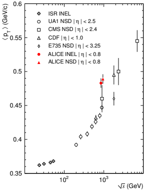
- Slow $\langle p_T \rangle$ increase with $\sqrt{s}$



PLB693(2010)53-68

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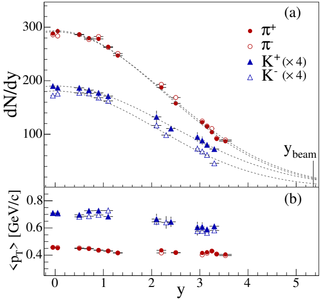
PRL94(2005)032301



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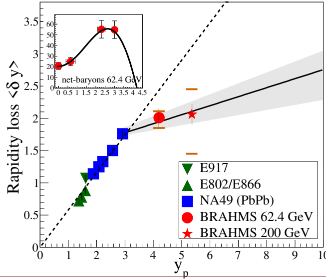
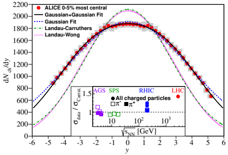


Transforming to rapidity

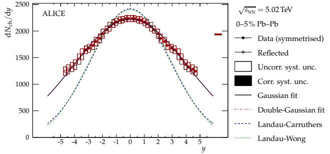
ALICE Results:

- $\frac{dN_{ch}}{dy} \sim N[0, \sigma]$ in Pb–Pb
  - For $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$
  - and $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$
- Landau-like hydrodynamics *not* consistent
  "Extended longitudinal scaling"

Pb–Pb, 0 – 5% $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ PLB726(2013)610-622

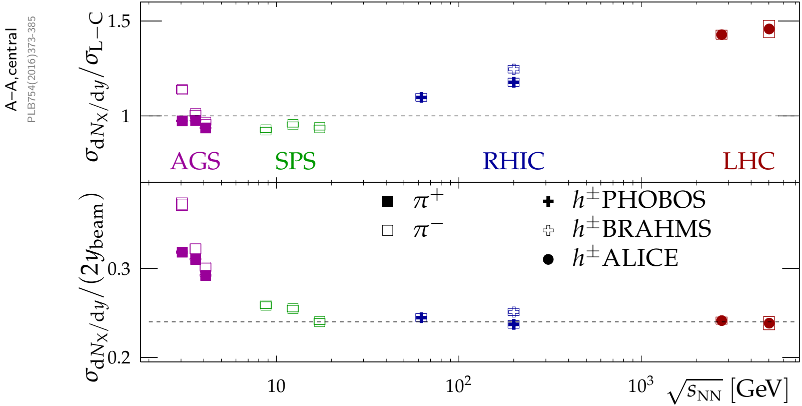


Pb–Pb, 0 – 5% $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$ PLB754(2016)373-385



- Landau-Carruthers: $\frac{dN_{ch}}{dy} \sim N\left[0, \log\sqrt{s_{NN}}/(2m_p)\right]$
- Landau-Wong: $\frac{dN_{ch}}{dy} \propto e^{\sqrt{y_{beam}^2 - y^2}}$

Fill up phase-space



- N_{ch} production fill phase-space for $\sqrt{s_{\mathrm{NN}}} \gtrsim 17\,\mathrm{GeV}$

Take-away from these results

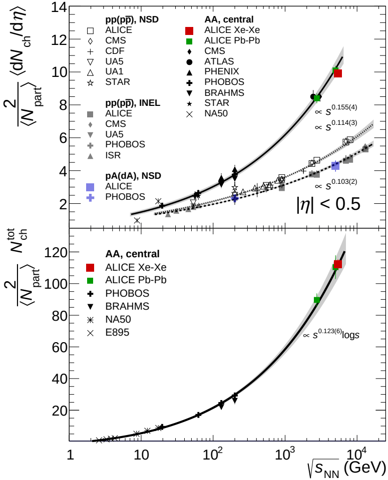
- Lots of $\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}$ measurements
  - Au–Au, Pb–Pb, Xe–Xe
  - d–Au, p–Pb
  - pp, $\overline{\mathrm{p}}$p
  - $\sqrt{s}, \sqrt{s_{\mathrm{NN}}} \in \{0.9, 2.76, 5.02, 5.44\}$ TeV
  - Challenge for theory

Take-away from these results

- Lots of $\frac{dN_{ch}}{d\eta}$ measurements
  - Au–Au, Pb–Pb, Xe–Xe
  - d–Au, p–Pb
  - pp, $\overline{\text{p}}$p
  - $\sqrt{s}, \sqrt{s_{NN}} \in \{0.9, 2.76, 5.02, 5.44\}$ TeV
  - Challenge for theory
- Shift at end of SPS ($\sqrt{s_{NN}} \gtrsim 17$ TeV)
  - (Almost) Net-baryon free over extended rapidity does *not* imply flat $\frac{dN_{ch}}{d\eta}$
  - N_{ch} fill up phase-space
    Particles more spread-out
  - AFAICT: Easier for theory?

Power-law systematic of N_{ch} production

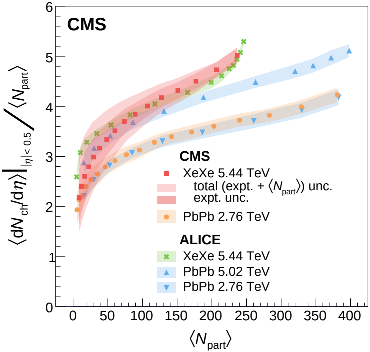
- Mid rapidity $\frac{dN_{\mathrm{ch}}}{d\eta}$ vs $\sqrt{s_{\mathrm{NN}}}$
- Total N_{ch} vs $\sqrt{s_{\mathrm{NN}}}$
- $N_{\mathrm{ch}}^{\mathrm{total}}$ increase faster than $\left\langle\frac{dN_{\mathrm{ch}}}{d\eta}\right\rangle\Big|_{|\eta|<0.5}$
- Both faster than pp($\overline{\mathrm{p}}$p)



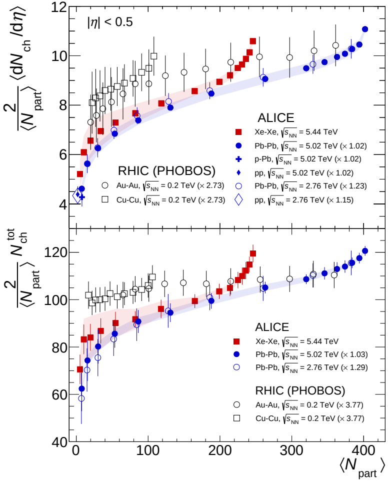
PLB790(2019)35

Per participant production

- Consistent increase from pp to most central *ALICE*: $\left\langle\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}\right\rangle\Big|_{|\eta|<0.5}$ and $N_{\mathrm{ch}}^{\mathrm{total}}$ scaled by $s^{0.155}$ and $s^{0.123}\log(s)$ to match Xe–Xe



arXiv:1902.03603



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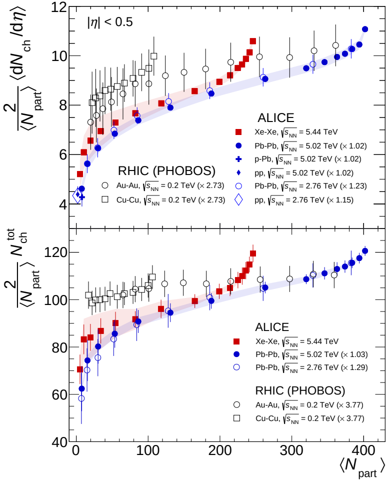
- However, “rapid” increase for most central $(N_{\mathrm{part}} \approx 2A)$.
- Also “up-tick” in total N_{ch}



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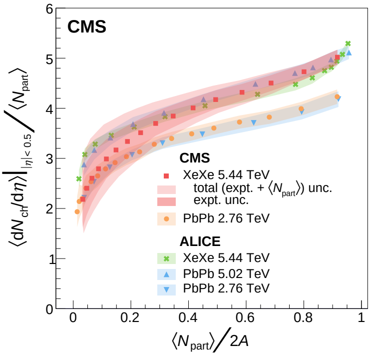
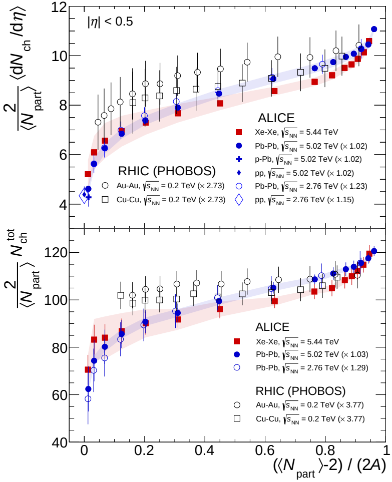
Production versus "natural centrality"

- Scale abscissa by
  $\max\left(N_{\mathrm{part}}\right) = 2A$
  ALICE: Subtract 2 to line up pp



arXiv:1902.03603



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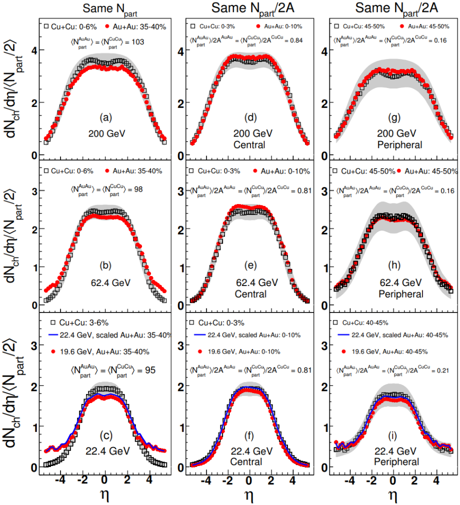
$\frac{dN_{ch}}{d\eta}$ versus “natural centrality”

PHOBOS Result:

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



PRL102(2009)142301

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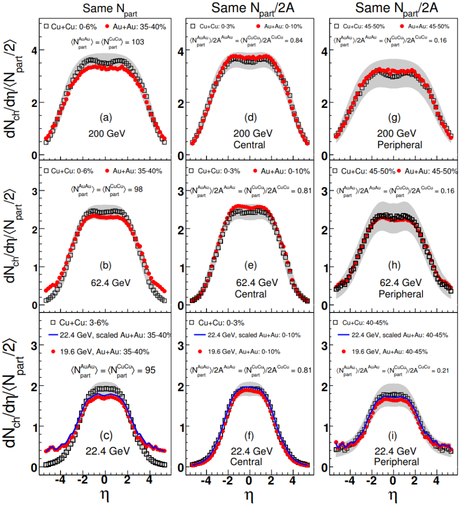
How can that be?

participants do not know "natural centrality"



PRL102(2009)142301

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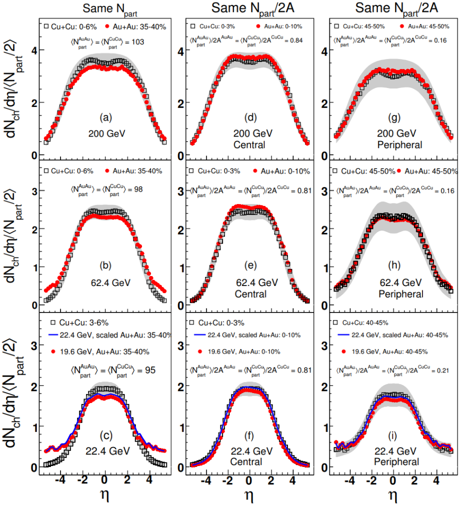
Important: N_{part} from Glauber i.e., Model



PRL102(2009)142301

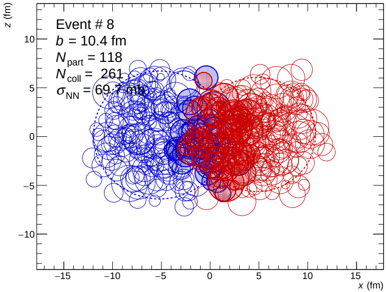
Glauber and Glauber–Gribov

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, 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`

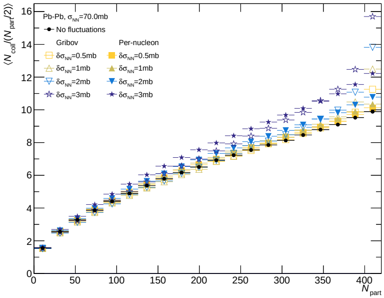
PRC97(2017)054910

Work-in-progress: Apply skepticism here

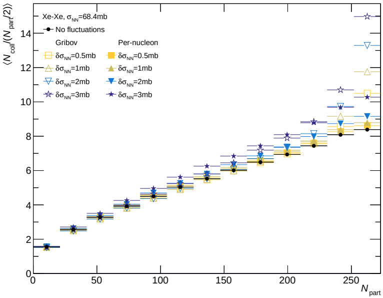
"Up-tick" in AA collisions

Ansatz: Take N_{coll} as proxy for $\frac{dN_{\text{ch}}}{d\eta}$ or total N_{ch}

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



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



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

  Fluctuations *a la* p–A

So where are we?

- Lots of result on N_{ch} production
  - Cu–Cu,Xe–Xe,Au–Au,Pb–Pb,d–Au,p–Pb,pp
  - $\sqrt{s}, \sqrt{s_{\mathrm{NN}}} \in \{0.9, 2.76, 5.02, 5.44, 7, 8, 13\}$ TeV

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- Above top SPS
  - Normal distributed in measured range
  - Fill up phase space (wide $\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}y}$)
  - $\sqrt{s_{\mathrm{NN}}}$-scaling pretty solid

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- N_{ch} fluctuate up in central A–A
  - Significant σ_{NN} fluctuations at small b?
    Similar to p–Pb
  - "Up-tick" *not* centrality bias
    Probably need better Glauber or Core-Corona approach?
  - N_{part} "scaling" not necessarily broken
    But N_{coll} strongly dependent on N_{part}, so hard to tell

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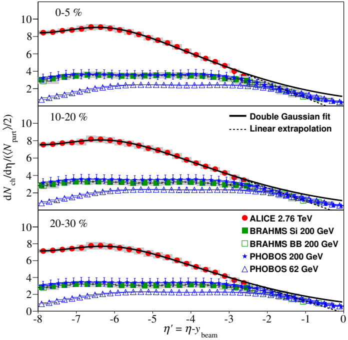
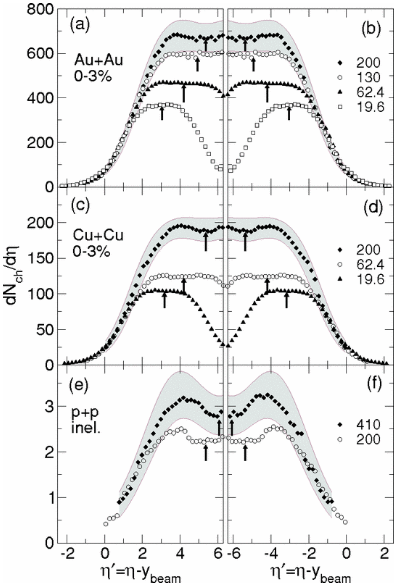
N_{ch} production still a challenge

Back-ups

Limiting fragmentation

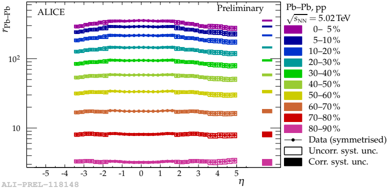
- $\frac{dN_{ch}}{d\eta}$ at large $|\eta|$ independent of $\sqrt{s_{NN}}$.
- Holds in pp and Cu–Cu
- Study not feasible for $\sqrt{s_{NN}} > 2.76\,\mathrm{TeV}$





Comparing to pp

$$r_X = \left.\frac{dN_{ch}}{d\eta}\right|_X \Big/ \left.\frac{dN_{ch}}{d\eta}\right|_{pp}$$

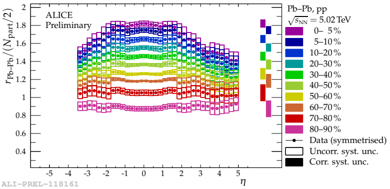


Pb–Pb

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

Comparing to pp

$$\frac{2r_X}{N_\mathrm{part}} = \frac{2}{N_\mathrm{part}} \left.\frac{\mathrm{d}N_\mathrm{ch}}{\mathrm{d}\eta}\right|_X \Big/ \left.\frac{\mathrm{d}N_\mathrm{ch}}{\mathrm{d}\eta}\right|_\mathrm{pp}$$

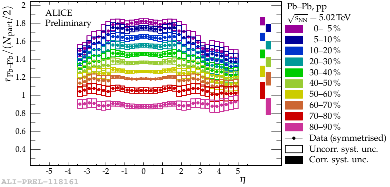


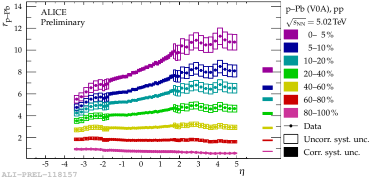
Pb–Pb

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

Comparing to pp

$$\frac{2r_X}{N_{\rm part}} = \frac{2}{N_{\rm part}} \left.\frac{dN_{\rm ch}}{d\eta}\right|_X \Big/ \left.\frac{dN_{\rm ch}}{d\eta}\right|_{\rm pp}$$





Pb–Pb

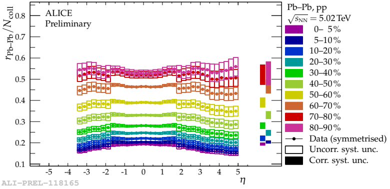
- $\times 10^2$ over pp
- Increase as $\eta \to 0$
- Scale by $2/N_{\rm part}$ (Glauber)
- Collimation near $\eta = 0$

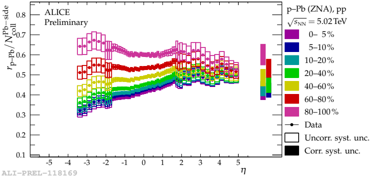
p–Pb

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

Nuclear modification

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





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

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

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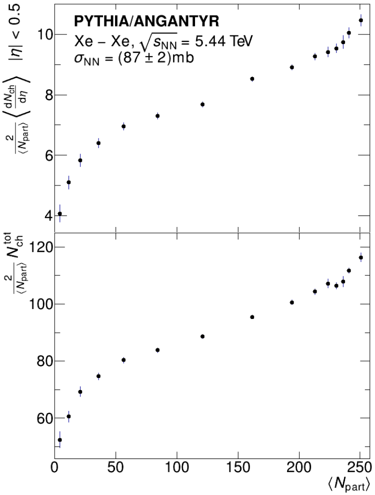
- Similar level in ion for most central Pb–Pb events.

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

Angantyr results

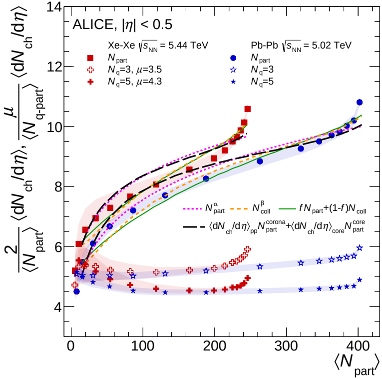
- Same trends as data for both $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle|_{|\eta|<0.5}$ and $N_{\mathrm{ch}}^{\mathrm{total}}$
- Sophisticated σ_{NN} fluctuations

  "Up-tick" *not* centrality bias



Quark participants and component models

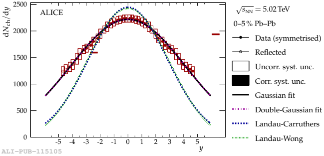
- $N^{\alpha}_{\mathrm{part}}$ over-shoots, no "up-tick"
- $N^{\beta}_{\mathrm{coll}}$ over- and under-shoots, no "up-tick"
- $fN_{\mathrm{part}} + (1-f)N_{\mathrm{coll}}$ over- and under-shoots, no "up-tick"
- Core-Corona over-shoots, no "up-tick"



- Quark participant scaling not much clear than N_{part}
- Rise at low N_{part}?
- Still rise at high N_{part}

  σ_{qq} fluctuations?

Express $\frac{dN_{ch}}{d\eta}$ in terms of $\frac{dN_{ch}}{dy}$



PLB772(2017)567-577

- Direct measurement of $\frac{dN_{ch}}{dy}$: Gaussian in measured region
- Via mean Jacobian: Gaussian in measured region

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

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

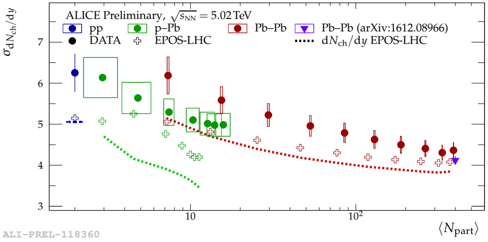
$$\langle\beta\rangle \approx \frac{1}{\sqrt{1+1/(a^2\cosh^2\eta)}}$$

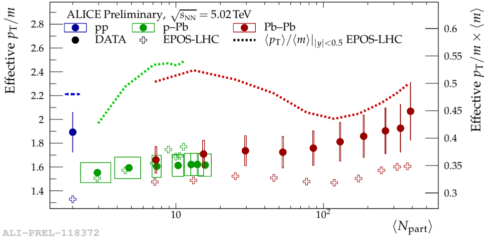
a: effective p_T/m

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

Fit $\frac{dN_{ch}}{d\eta}$ to extract σ, effective p_T/m

σ_y and effective p_T/m



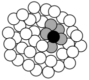


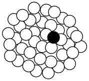
- σ decrease
  Collimation of production
- Peripheral similar σ to pp
  Limiting fragmentation
- Effective p_T/m increase for Pb–Pb
  consistent with pp

Back-of-the-envelope initial energy density

- Bjorken formula:

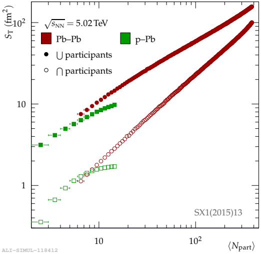
$$\varepsilon_{\mathrm{Bj}}\tau = 1/S_{\mathrm{T}}\,\mathrm{d}E_{\mathrm{T}}/\mathrm{d}y$$

$\bigcup$ part.: 

$\bigcap$ part.: 

- with

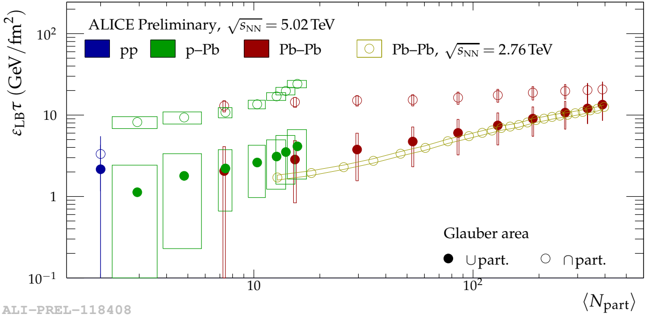
$$\mathrm{d}E_{\mathrm{T}}/\mathrm{d}y \approx 2\langle m_{\mathrm{T}}\rangle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$$
$$\gtrsim 2\langle m\rangle \sqrt{1+(p_{\mathrm{T}}/m)^2}\,\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$$



- 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 ∪part, large increase over pp
- If same initial ε in systems, then similar final state effects?