Light-ion collisions in the ATLAS detector

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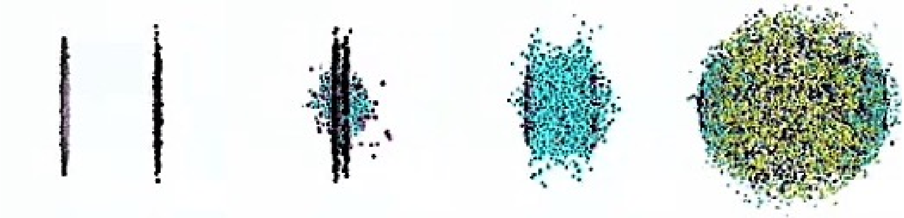
10 October 2025

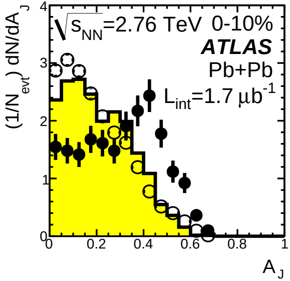
introduction

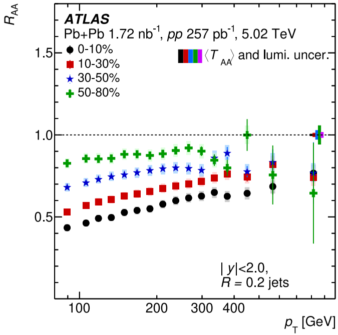


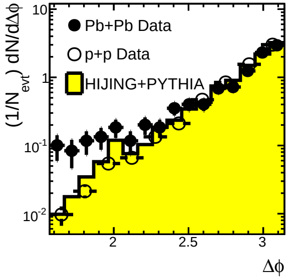
- a life of a typical heavy-ion collision:
  - initial collision of heavy ions
  - quarks and gluons become deconfined
  - termal equilibrium
  - creation of hadrons
  - freeze-out

- collisions of Pb+Pb ions:
  - clear signs of energy loss
  - clear signs of collective behaviour

$\Rightarrow$ signs of quark-gluon plasma







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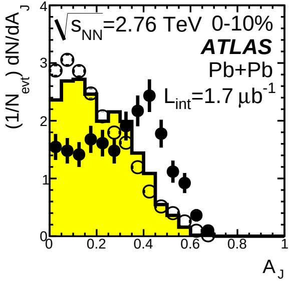

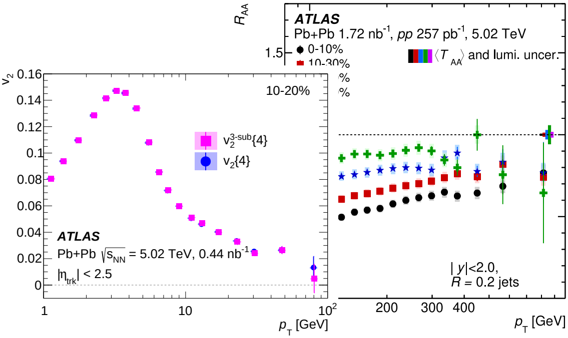

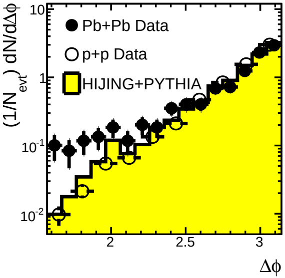

- collisions of Xe+Xe ions:
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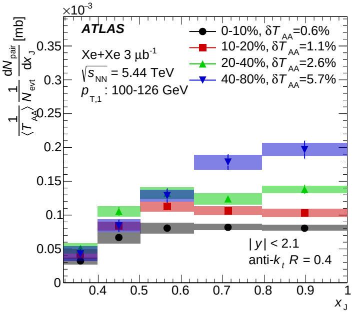

introduction (real)

- collisions of Xe+Xe ions:
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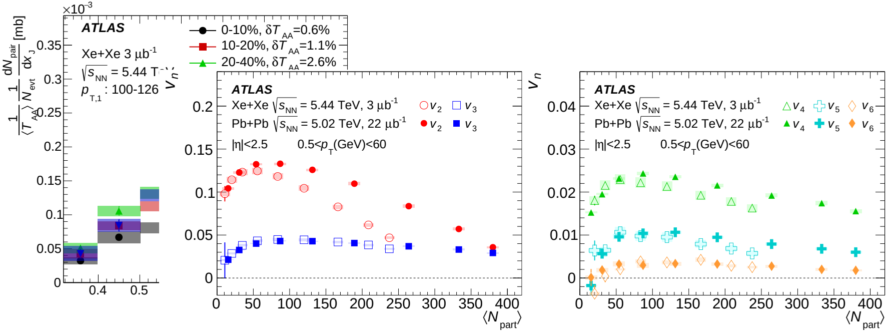
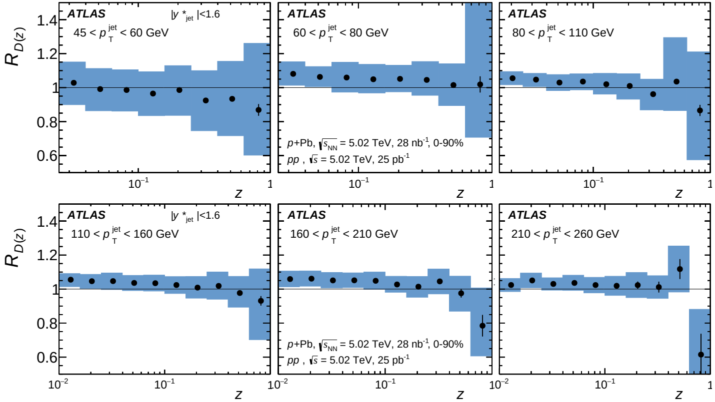
⇒ signs of quark-gluon plasma



- collisions of p+Pb ions:
  - no clear signs of energy loss
  - signs of collective behaviour

$\Rightarrow$ quark-gluon plasma? or initial state effects?



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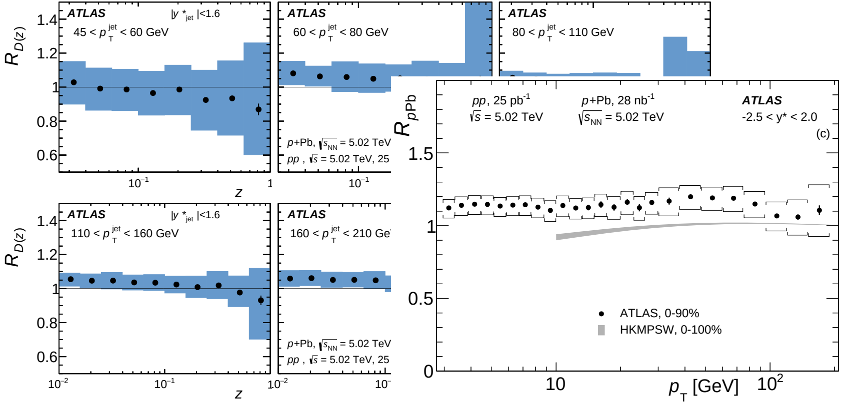

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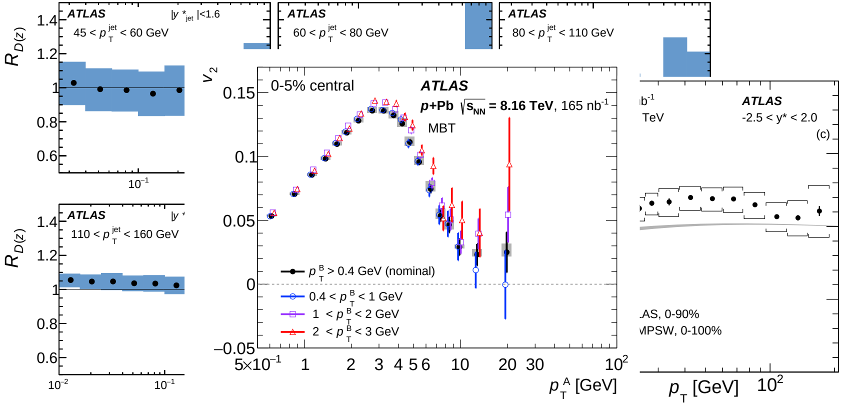
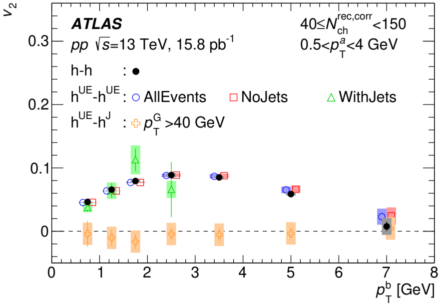


introduction (real)

- collisions of p+p:
  - how to even look for energy loss?
  - signs of collective behaviour[1]

$\Rightarrow$???



[1]terms and conditions apply; available only for tracks from underlying events

- is there some minimum size of a system where we will start seeing energy loss?
- can we see collectivity in all systems?

- ^{208}Pb
- ^{129}Xe

- ^{1}p

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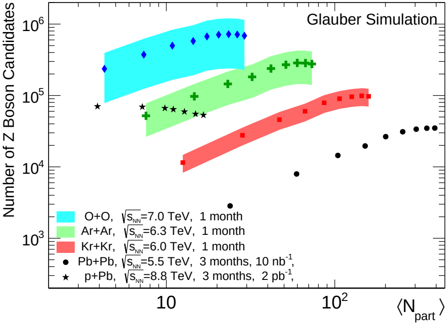
- ^{208}Pb
- ^{129}Xe
- ^{20}**Ne**
- ^{16}**O**
- ^{1}p



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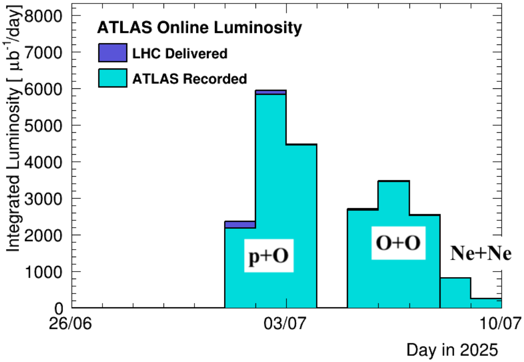
p+O, O+O and Ne+Ne data-taking

- in July 2025, only 10 days
- expected about:
  - 1.5/nb of p+O
  - 0.8/nb of O+O
  - 0.1/nb of Ne+Ne

p+O, O+O and Ne+Ne data-taking

- in July 2025, only 10 days
- expected about:
  - 1.5/nb of p+O
  - 0.8/nb of O+O
  - 0.1/nb of Ne+Ne
- actually got:
  - 7.8/nb of p+O
  - 8.1/nb of O+O
  - 1.0/nb of Ne+Ne



transmutation of beams

- colliding nuclei do not need to be completely destroyed
- remnants typically hit the beampipe

- if the remnants have the same charge/mass ratio as colliding ions, they may stay in the beampipe
- for ^{208}Pb, that's only ^{104}Nb
- for ^{129}Xe, that's only ^{43}Ar

- for ^{16}O, that's ^{14}N, ^{12}C, ^{10}B, ^{8}Be, ^{6}Li, ^{4}He, ^{2}H
- for ^{20}Ne, that's the same and ^{18}F

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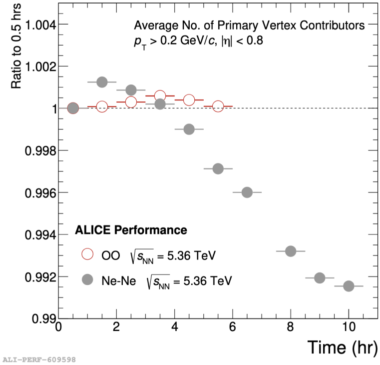
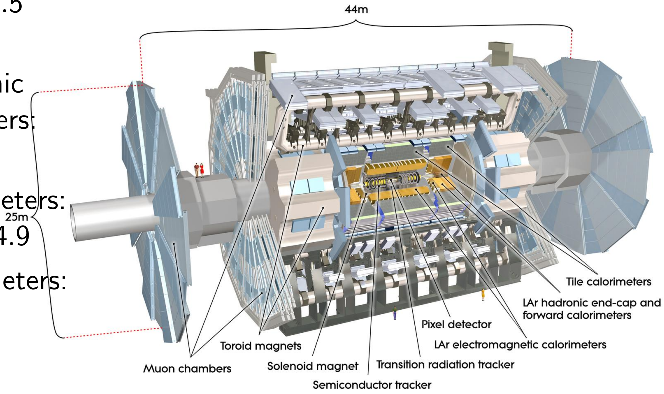
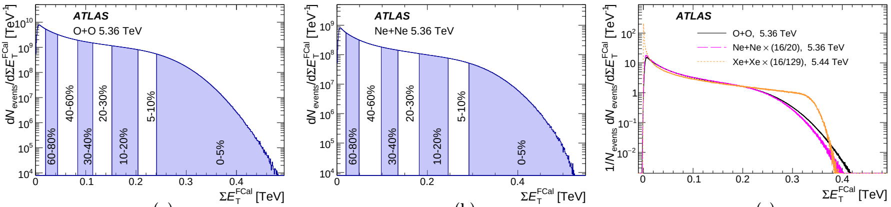


ATLAS detector

- tracker: $|\eta| < 2.5$
- EM and hadronic calorimeters: $|\eta| < 3.2$
- forward calorimeters: $3.1 < |\eta| < 4.9$
- muon spectrometers: $|\eta| < 2.7$



- similarly to heavy-ion collisions, *centrality* is based on the energy deposited in FCal ($3.2 < |\eta| < 4.9$)

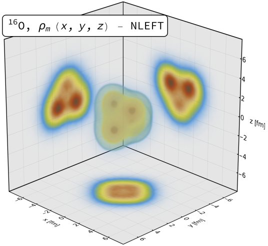


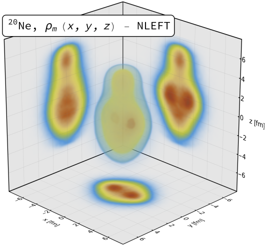
(a) (b) (c)

- longer tail for O+O and Ne+Ne
- corresponds to larger relative event-by-event fluctuations in particle production in the smaller systems

azimuthal anisotropies in O+O and Ne+Ne

- while oxygen nucleus is round (like a bowling ball), neon nucleus resembles a bowling pin
- can compare O+O and Ne+Ne v_2 to see the influence of the initial state geometry
- use 2 methods to get v_n:
  - 2 particle correlations
  - multi-particle cumulants





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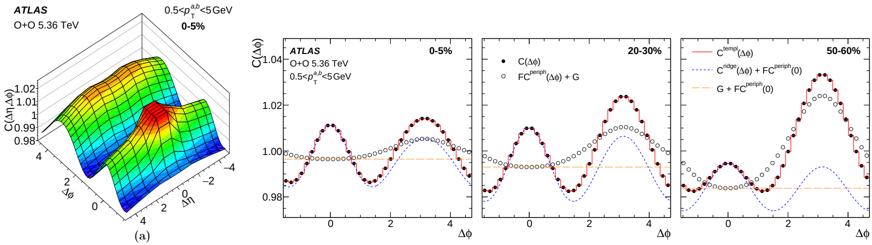
azimuthal anisotropies in O+O and Ne+Ne

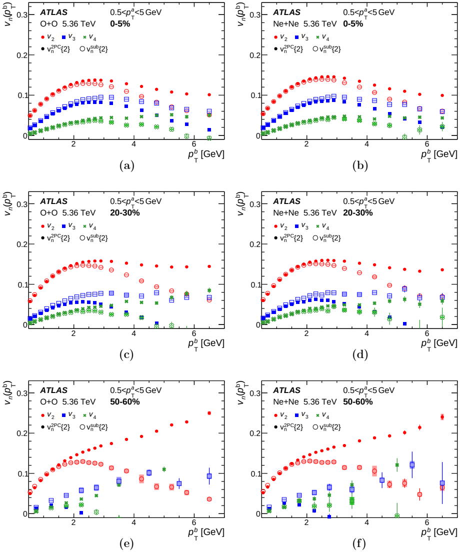
- 2PC method measures ratio of "signal" over "background":
$$C(\Delta\eta,\Delta\phi) = S(\Delta\eta,\Delta\phi)/B(\Delta\eta,\Delta\phi)$$
- S and B are distributions of particles pairs from the same (S) or different (B) events
- integrated over $2 < |\Delta\eta| < 5$ and parametrized with a Fourier series:
$$C(\Delta\phi) = FC^{periph}(\Delta\phi) + C^{ridge}(\Delta\phi)$$
$$C^{ridge}(\Delta\phi) = G\left[1 + \sum_{n=2}^{5} v_{n,n}(p_\mathrm{T}^a, p_\mathrm{T}^b)\cos(n\Delta\phi)\right]$$



azimuthal anisotropies in O+O and Ne+Ne

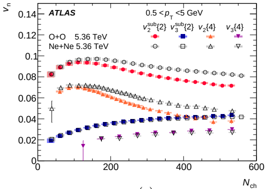
- v_n for 2PC:
  $$v_n(p_\mathrm{T}^b) = \frac{v_{n,n}(p_\mathrm{T}^a, p_\mathrm{T}^b)}{\sqrt{v_{n,n}(p_\mathrm{T}^a, p_\mathrm{T}^a)}}$$
- multi-particle cumulants use two- or four-particle correlations:
  $$\langle\{2\}_n\rangle = \langle e^{in(\phi_1 - \phi_2)}\rangle$$
  $$\langle\{4\}_n\rangle = \langle e^{in(\phi_1 + \phi_2 - \phi_1 - \phi_2)}\rangle$$
- uses 2 sub-events ($\eta < 0$, $\eta > 0$)
- two- or four-particle cumulant use averages over all events:
  $$c_n\{2\} = \langle\langle\{2\}_n\rangle\rangle$$
  $$c_n\{4\} = \langle\langle\{4\}_n\rangle\rangle - 2\langle\langle\{2\}_n\rangle\rangle^2$$
- v_n for cumulants:
  $$v_n\{2\} = \sqrt{c_n\{2\}}$$
  $$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

- behaviour comparable to other collision systems:
  - rise till 2-3 GeV, then decrease
  - ordering $v_2 > v_3 > v_4$
- larger non-flow contribution in 2PC method
  - particularly at higher p_T and peripheral collisions

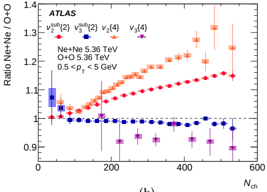


azimuthal anisotropies in O+O and Ne+Ne

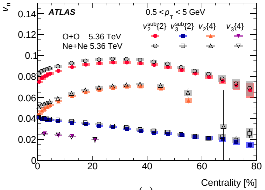
- $v_2\{2\}$ more susceptible to event-by-event fluctuations than $v_2\{4\}$
- more central collisions more susceptible than peripheral



(a)



(b)



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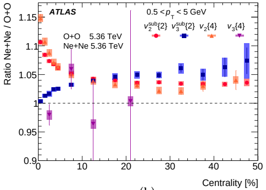
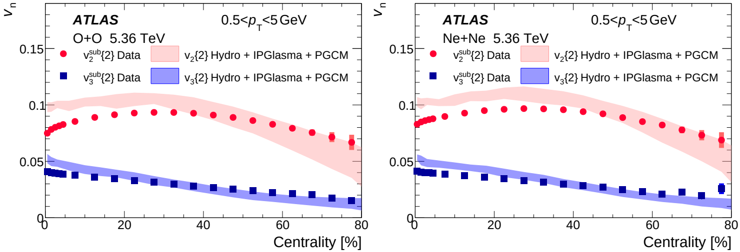


(b)

- higher v_2 in central collisions for neon due to its deformed nucleus

azimuthal anisotropies in O+O and Ne+Ne

- PGCM calculates nuclear structure from the first principles
- IPGlasma calculates the initial energy densities
- energy densities evolved using viscous relativistic hydrodynamic

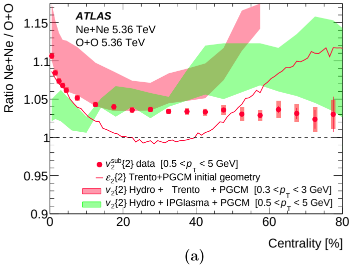


(a) (b)

- over-predicts in central collisions
- agrees with data in more peripheral collisions

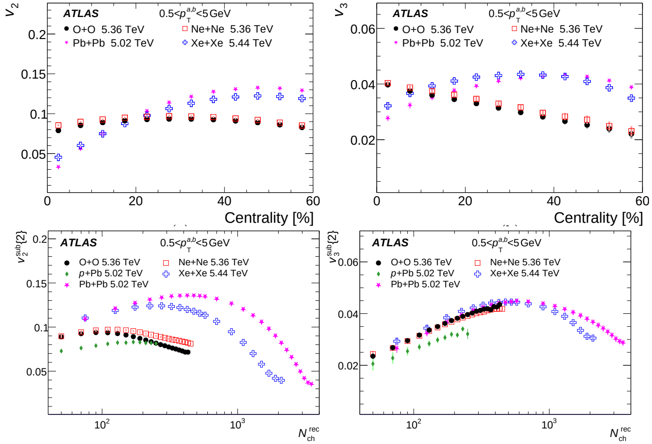
azimuthal anisotropies in O+O and Ne+Ne

- PGCM calculates nuclear structure from the first principles
- Trento provides the initial energy densities
- Trajectum hydrodynamic framework is used to simulate the event



azimuthal anisotropies in O+O and Ne+Ne

- v_2 has weaker centrality dependence for light ions than heavy ions
  - dominant role of event-by-event fluctuations
- very similar v_3 for the same multiplicity in all systems
  - while very different as a function of centrality

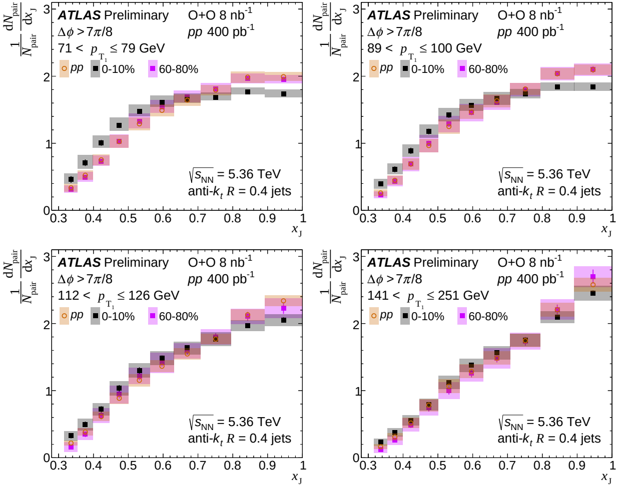


jet quenching in O+O

- jet quenching studied via dijet momentum balance:
  $$x_J = p_{\mathrm{T},2}/p_{\mathrm{T},1}$$
  - uses 2 jets with the highest p_{T} in an event;
    leading jet has "$p_{\mathrm{T},1}$", sub-leading has "$p_{\mathrm{T},2}$"
  - they need to be back-to-back
    $$\Delta\phi = |\phi_1 - \phi_2| > 7\pi/8$$
  - uncorrelated jets would have flat $\Delta\phi$ distribution
  - jets p_{T} is corrected for the detector effects

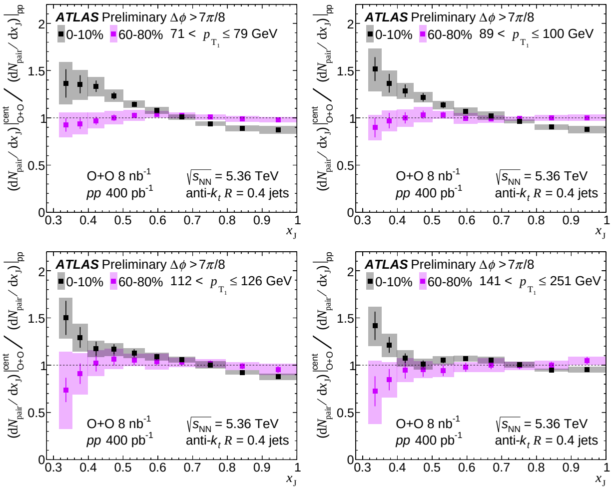
jet quenching in O+O

- lower-p_{T} jets are not so well balanced due to jet energy resolution
- however, very similar trend in both p+p and O+O



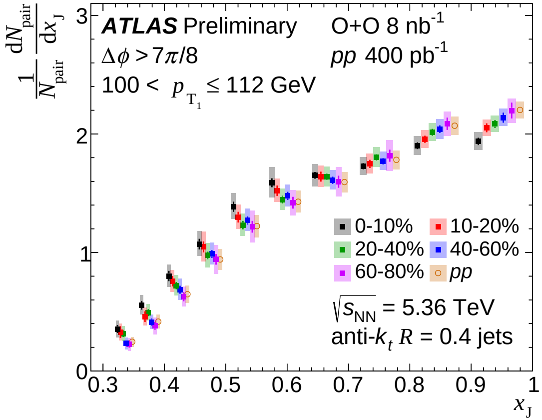
jet quenching in O+O

- cancelation of systematic uncertainties in ratios of x_J
- more imbalanced jets in O+O, less nearly-balanced jets



jet quenching in O+O and Ne+Ne

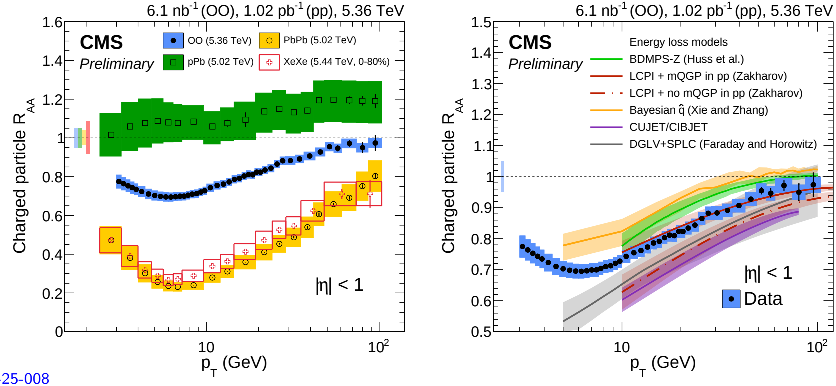
- more imbalanced jets in central collisions
- more balanced jets in peripheral collisions



other experiments?

- other experiments also took light-ion data!
- and they also analysed them!

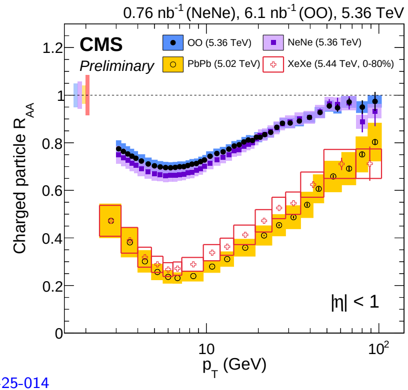
- measured nuclear modification factor R_{AA} for charged hadrons:
$$R_{\mathrm{AA}} = \frac{1}{A^2}\frac{\mathrm{d}\sigma^{AA}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma^{pp}/\mathrm{d}p_{\mathrm{T}}}$$
- did not measure centrality
  - neatly avoiding problems with pile-up and centrality
- corrected for track reconstruction efficiency

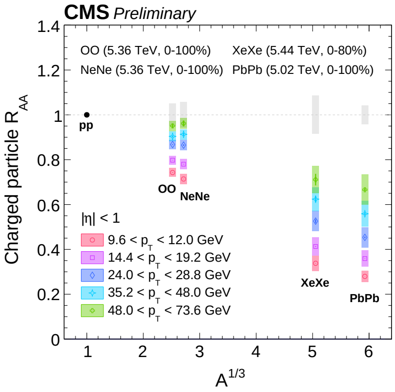


HIN-25-008

CMS: charged hadrons in Ne+Ne

- measured nuclear modification factor R_{AA}
$$R_{\mathrm{AA}} = \frac{1}{A^2} \frac{\mathrm{d}\sigma^{AA}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma^{pp}/\mathrm{d}p_{\mathrm{T}}}$$
- similar measurement as for O+O
- slightly larger suppression for Ne+Ne

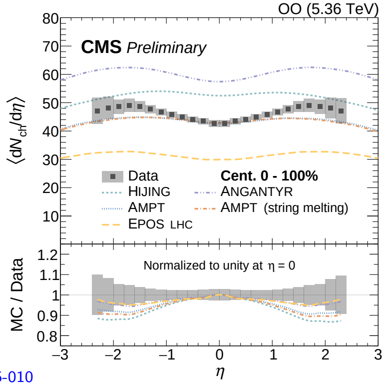


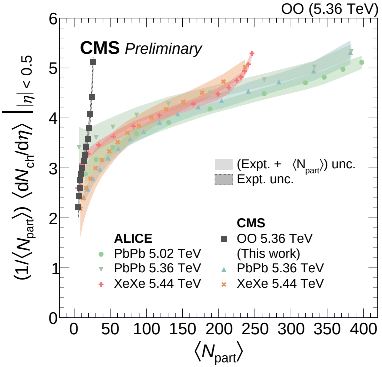


HIN-25-014

CMS: charged hadrons dN/dη in O+O

- charged hadrons dN/dη for Pb+Pb is O(1000)
- for collisions with similar N_{part}, number of produced particles is much higher in O+O
- approximately similar maxima for the most central collisions in different systems





HIN-25-010

outline – what else is there?

- light ions are hot topic in heavy-ion community
  - should we call it just "ion community"?
- these were just the first results, made in the last 2-3 months!
- many results will come

- there is definitely some collective behaviour in light-ion collision
- and there are also signs of energy loss
  - is there some universal scaling across systems?

- there will be a "heavy"-ion data-taking in November (Pb+Pb)
- also planned data-taking in June-July 2026 – maybe with light ions?