Jet and charged hadron production in heavy-ion collisions in the ATLAS detector

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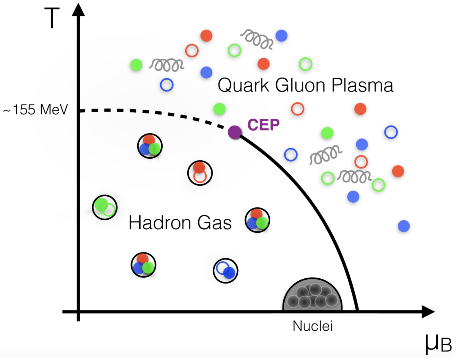
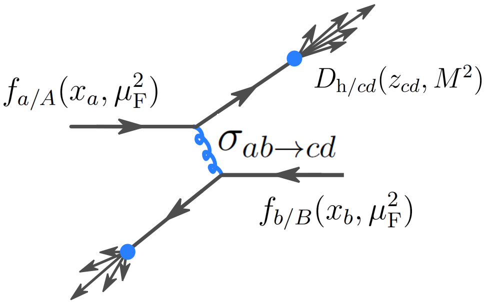
introduction

- in collisions of heavy ions, quark-gluon plasma is created
- interacts strongly
- consist of free quarks and gluons
- somewhat distinguishable from hadron gas
- has cross-over at lower μ_B, second order critical end point
- we would like to study it



arXiv:1504.05274

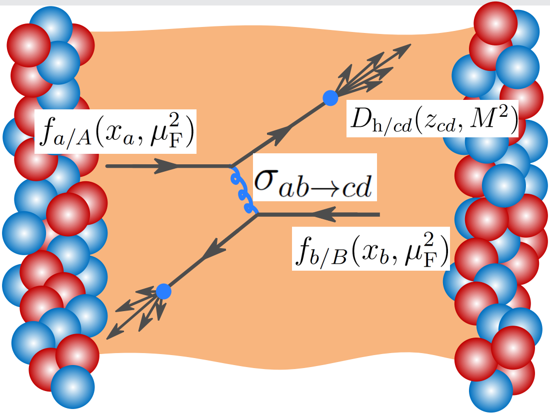
interaction in vacuum



- in order not to be surprised by the result of a *pp* collision, we should know:
  - parton distribution functions ($f_{a/A}$, $f_{b/B}$)
  - cross section (σ)
  - fragmentation functions ($D_{h/cd}$, ...)

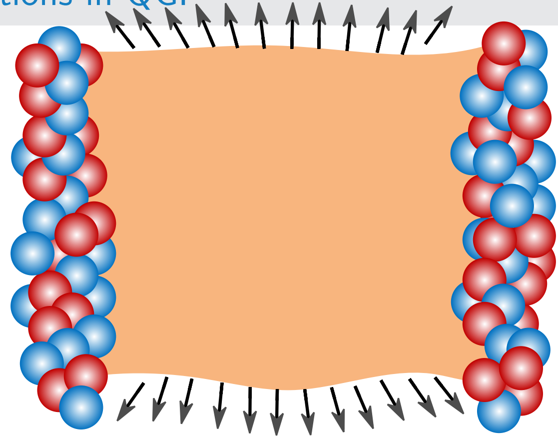
this a similar cartoons by Martin Rybář

hard interaction in QGP



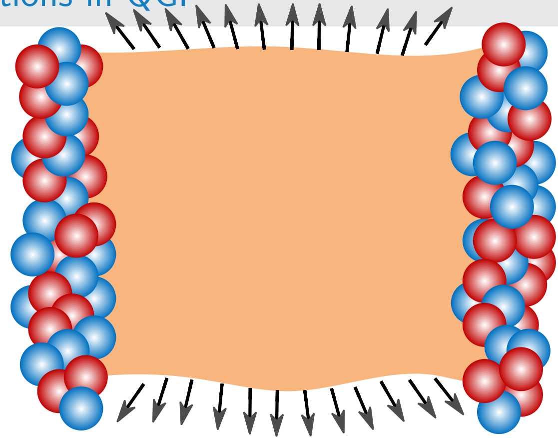
- in order not to be surprised by the result of a heavy-ion collision, we should know:
  - parton distribution functions *in a nuclei* ($f_{a/A}$, $f_{b/B}$)
  - cross section (σ)
  - fragmentation functions *in QGP* ($D_{h/cd}$, ...)
    and interactions in QGP in general

soft interactions in QGP



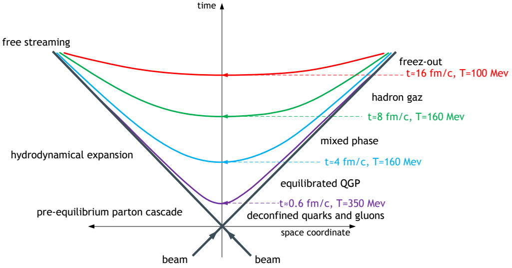
- in order not to be surprised by the result of a heavy-ion collision, we should *in addition* know:
  - all the parton interactions, fragmentation functions, ...

soft interactions in QGP



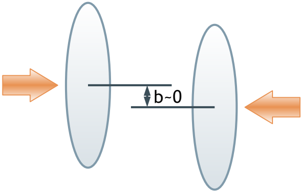
- in order not to be surprised by the result of a heavy-ion collision, we should *in addition* know:
  - ~~all the parton interactions, fragmentation functions, ...~~
  - how the medium expands and cool down
  - how the partons lose their energy in the medium
  - what are the global properties of the outcome, as such v_2, v_3, ...

quark-gluon plasma

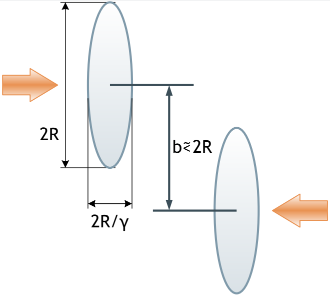


- a typical life experience of a heavy-ion collision consist of:
  - initial collision of ions large enough to create QGP
  - deconfined quarks and gluons create *film czeski*
  - termal equilibrium
  - creation of hadrons
  - freeze-out
  - a curious physicist poking its nose uncomfortably close to it

centrality in HI collisions



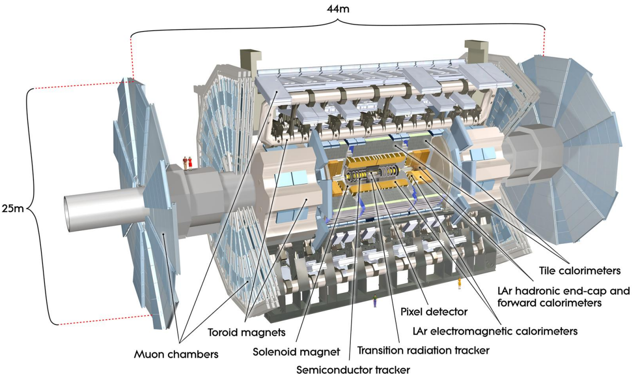
Central collision



Peripheral collision

- small impact factor ⇒ central collision
  - large overlap
  - large number of interacting nucleons ("participants")
  - large deposited energy in forward calorimeter
- large impact factor ⇒ peripheral collision
  - small overlap
  - small number of interacting nucleons ("participants")
  - small deposited energy in forward calorimeter

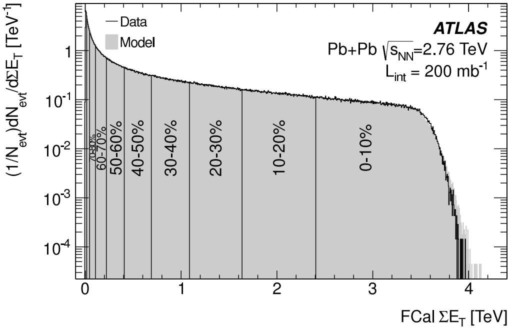
ATLAS detector



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

centrality in HI collisions

- instead of impact factor, we measure energy deposited in FCal
- it is not exactly one-to-one correspondence but there's a strong correlation
- we don't want observables (hadrons, jets, ...) to bias the centrality measurement



nuclear modification factor R_{AA}

- observables measured in HI collisions are usually compared to the same observables in pp collisions
- modification of various observables is typically studied in ratios
- not specific for jets or hadrons; one can do the same for W, Z, H, ...

- nuclear modification factor R_{AA}:

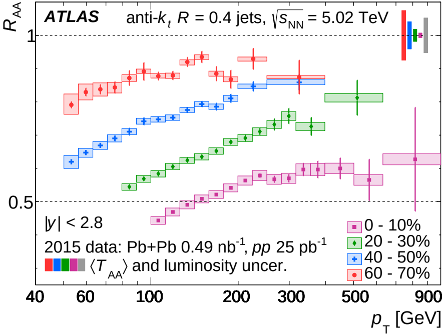
$$R_{\mathrm{AA}} = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{1/N_{evt}\ \mathrm{d}^2 N_{ch}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}{\mathrm{d}\sigma^2_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}$$

$$R_{\mathrm{AA}} = \frac{1}{\{geometry\}} \frac{\{heavy\text{-}ion\ collisions\}}{\{pp\ collisions\}}$$

- we have to account for a larger size of an ion
  $\rightarrow$ no free credits out of that

jet R_{AA}

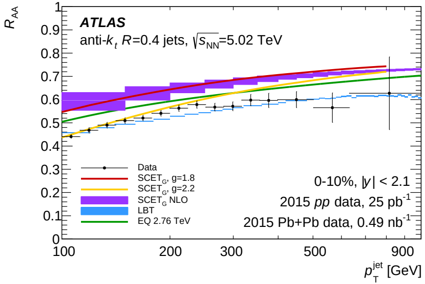
- every hard parton traversing QGP eventually fragments and form a jet
- very similar statement is true for pp collisions
  - "every hard parton ... eventually fragments and form a jet"
- partons also lose energy in QGP
- thus, they create jets with *somewhat* smaller energy than they would have in a vacuum



arXiv:1805.05635

jet R_{AA}

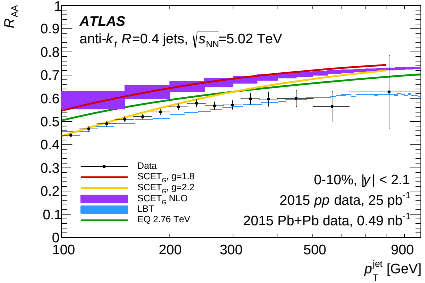
- what does exactly mean 'somewhat smaller'?
  - very good question but it's not easy to answer



- SCET$_G$
  - Soft Collinear Effective Theory
  - uses modified splitting functions and generalized DGLAP evolution
  - partons lose energy via soft gluon emissions
  - g is a coupling between a jet and the medium

jet R_{AA}

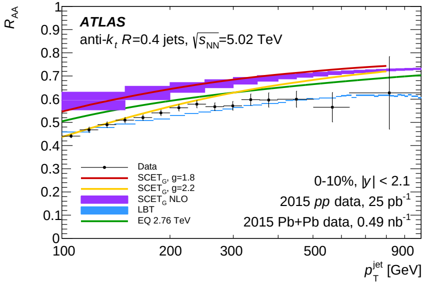
- what does exactly mean 'somewhat smaller'?
  - very good question but it's not easy to answer



- LBT
  - Linear Boltzmann Transport model
  - kinetic description of parton propagation
  - hydrodynamic description of the medium evolution
  - also keeps track of thermal recoil partons from each scattering and their further propagation in the medium

jet R_{AA}

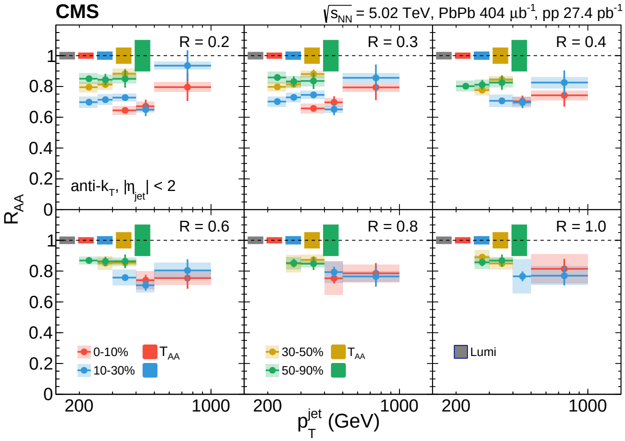
- what does exactly mean ‘somewhat smaller’?
  - very good question but it’s not easy to answer



- EQ
  - Effective Quenching
  - a semi-empirical parameterisation of jet quenching effect, applies shifts in p_{T} spectrum
  - larger for gluon-initiated jet, smaller for quark-initiated jet
  - jets fragments as in vacuum
  - requires experimental data to extract the parameters of the energy loss

large jet R_{AA}

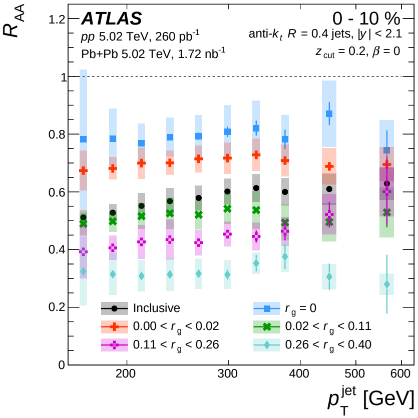
- the lost energy may be recovered in a larger cone
- partially true for central collisions, not so much for peripheral ones
- unclear what happens at lower p_T



arXiv:2102.13080

grooming of jets & R_{AA}

- one can study energy loss and the radiation in the medium
- it's possible to drop the soft contributions of a jet
- the angle between the first hard splitting is r_g
- at large angles, the medium is able to recognize two partons
- not at small angles



arXiv:2211.11470

nuclear modification & fragmentation functions

- fragmentation of a jet often estimated in term of longitudinal momentum fraction relative to the jet:

$$z = \frac{p_{\mathrm{T}}}{p_{\mathrm{T}}^{jet}} \cos \Delta R$$

- fragmentation function:

$$D(p_{\mathrm{T}}) = \frac{1}{N_{jet}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}p_{\mathrm{T}}} \qquad D(z) = \frac{1}{N_{jet}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}z}$$

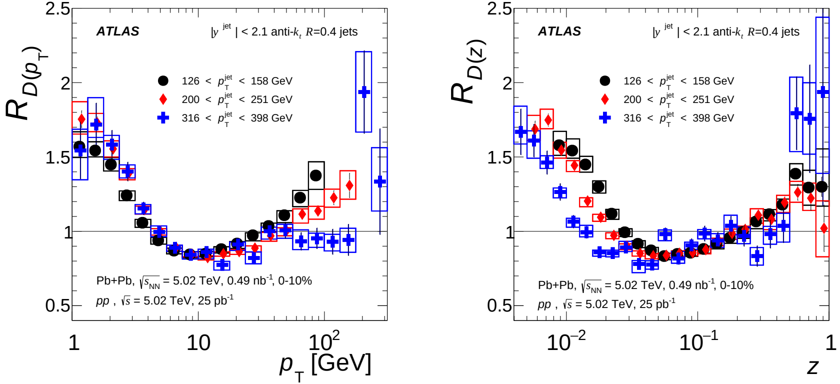
- ratios of fragmentation function:

$$R_D(p_{\mathrm{T}}) = \frac{D(p_{\mathrm{T}})_{PbPb}}{D(p_{\mathrm{T}})_{pp}} \qquad R_D(z) = \frac{D(z)_{PbPb}}{D(z)_{pp}}$$

- *per-jet* distributions, thus accounting for a larger size of ion by definition $\rightarrow$ no free credits here either

fragmentation functions

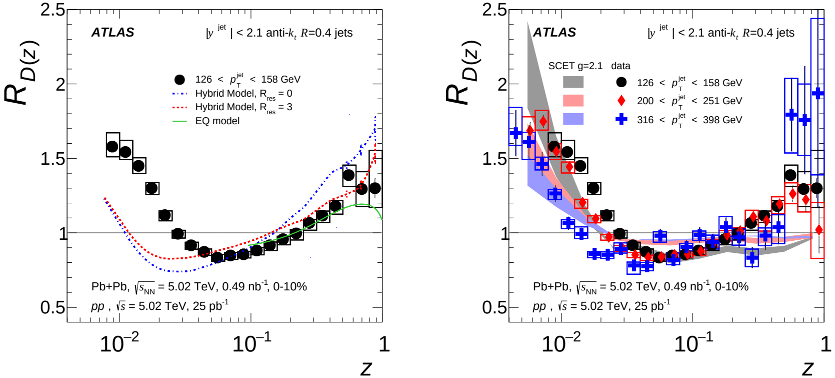
- we have more particles with low p_{T} and with high p_{T} in jets in heavy ions
- and we have less particles with intermediate p_{T}
- we can same something similar for z as well



arXiv:1805.05424

fragmentation functions

- why is it so?
  - very good question but it's not easy to answer



- Hybrid Model
  - uses perturbation for high-Q^2 processes
  - strong coupling for low-q^2 processes
  - R_{res} is a length parameters that distinguishes these two

charged hadron R_{AA}

- nuclear modification factor R_{AA}:

$$R_{\mathrm{AA}} = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{1/N_{evt}\ \mathrm{d}^2 N_{ch}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}{\mathrm{d}\sigma^2_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}$$

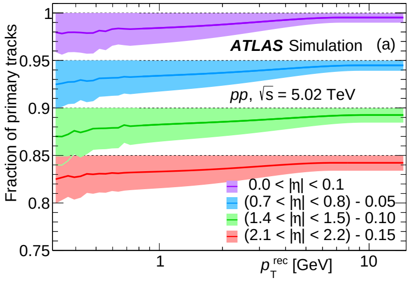
- same definition as for jets
- accounts for a large size of an ion
- at high p_{T}, the production of charged hadrons is driven by jets and their fragmentation
- at low p_{T}, the production is driven by bulk production of the medium

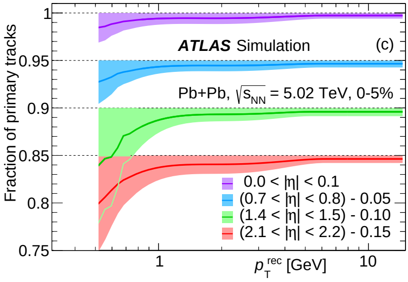
analysis overview

- the distributions are always corrected to the particle-level, i.e. independent on the detector
  - easy for theorists to compare with their models
  - easy for experimentalists to compare with other collaborations
  - tricky for experimentalists to work it out
- using several data sets:
  - pp, $\sqrt{s_{NN}} = 5.02$TeV, 25pb^{-1}
  - PbPb, $\sqrt{s_{NN}} = 5.02$TeV, 0.50nb^{-1}
  - XeXe, $\sqrt{s_{NN}} = 5.44$TeV, 3μb^{-1}
- to get particle-level distributions, we correct for:
  - fake and secondary track
  - p_{T} and η resolutions
  - track reconstruction efficiency
  - interpolation to the same $\sqrt{s_{NN}}$

fake and secondary track

- same reconstructed tracks are better than others
- tracks may be linked to:
  - primary particles (our interest, $\tau > 0.3 \times 10^{-10}$ s)
  - secondary particles, from decays of Σ, Ξ, ... (not our interest)
  - no particles, just a spurious combination of hits (not our interest)

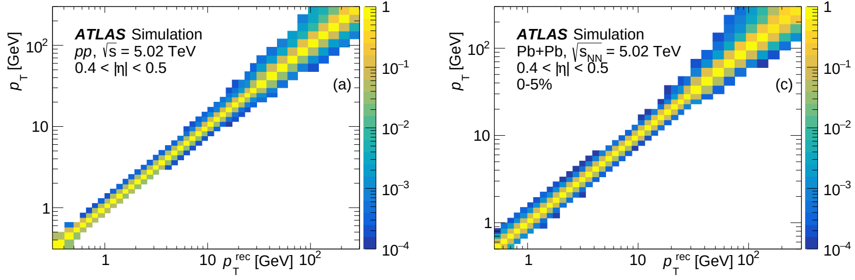




arXiv:2211.15257

p_{T} and η resolution correction

- measured p_{T} is not the real p_{T}
- $\sigma_{p_{\mathrm{T}}} \approx c_0 + c_1 \cdot p_{\mathrm{T}}$
- migration to other p_{T} bin is very common
- problem more pronounced at higher p_{T}
- corrected for by Bayesian unfolding

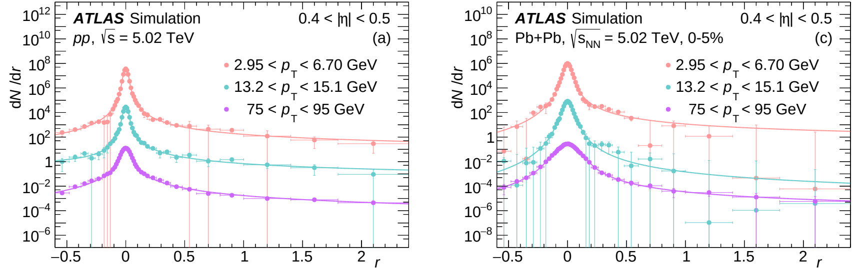


- analogically for η resolution, although that one is more diagonal

p_{T} resolution

- off-diagonal elements susceptible to the statistical fluctuations
- thus, we first fit distributions of resolution:

$$r = (p_{\mathrm{T}}/p_{\mathrm{T}}^{rec}) - 1$$

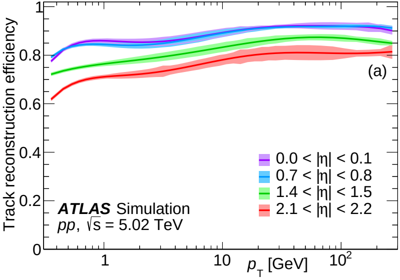


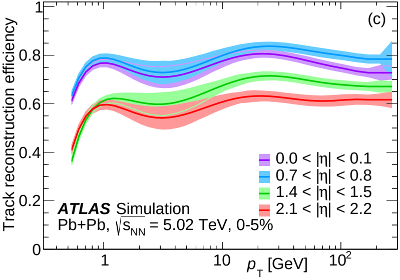
- the fits are used to fill the migration matrices for the Bayesian unfolding

$\Rightarrow$ this approach lead to a large reduction of systematic uncertainties

track reconstruction efficiency

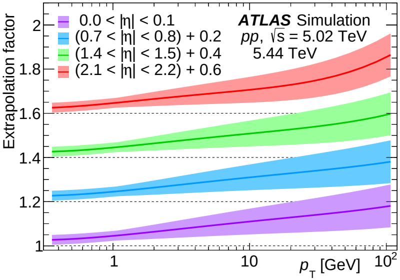
- some particles pass through the detector undetected
- the reconstruction efficiency depends on the type of a particle
  - π, K, p
    - ★ reconstructed from low p_{T}; small differences
  - strange baryons (Σ, Ξ, Ω)
    - ★ at low p_{T}, decay before reaching the detector $\rightarrow$ truly unsportsmanlike
    - ★ possible to reconstruct only at $p_{\mathrm{T}} \gtrsim 10$GeV
  - simulations reweighted to reflect the particle composition as in data
  - at p_{T} 3-4GeV, there is a "bitter spot" where it hurts the most



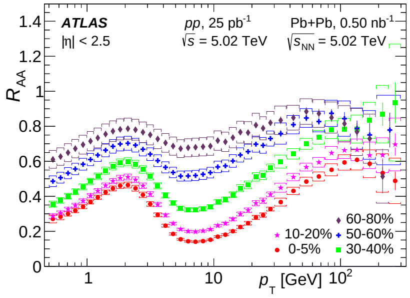


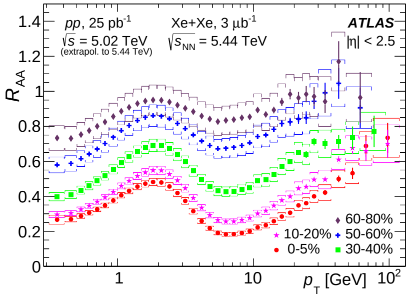
extrapolation to the same $\sqrt{s_{NN}}$

- to mitigate differences between samples due to different $\sqrt{s_{NN}}$
- pp cross-section measured only at $\sqrt{s} = 5.02$TeV
- to use it for comparison of XeXe collision, using Pythia for extrapolation to $\sqrt{s} = 5.44$TeV



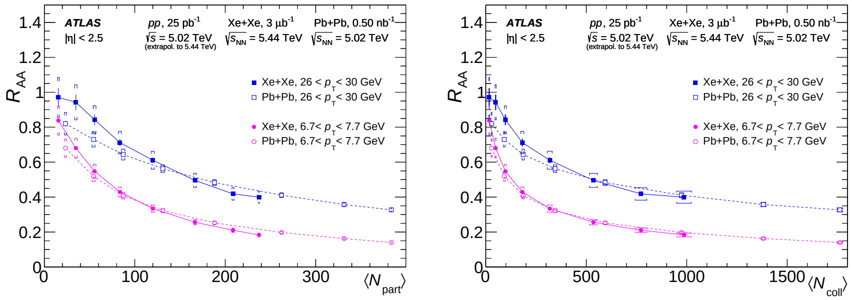
- larger suppression in more central collisions
- milder suppression in more peripheral collisions
- "shouldn't there be no suppression when the collisions are peripheral enough?"
  - good question, uncertain answer
  - problem with ultra-peripheral collisions, not clear what is a collision and what is not





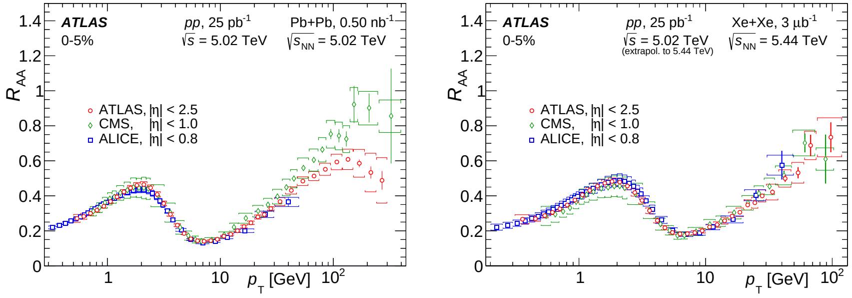
charged hadron R_{AA}

- we can compare suppression in PbPb and XeXe
- both follow the same trend but the magnitude is different
- not only size of the fireball matters but probably something else as well

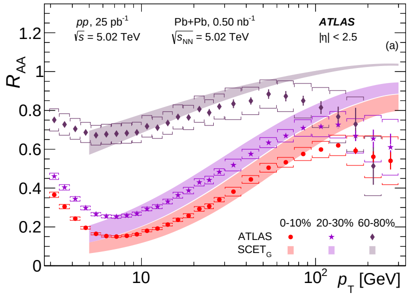


charged hadron R_{AA}

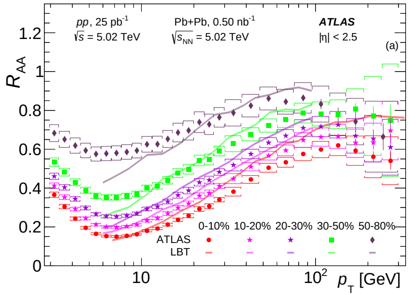
- all 3 experiments are consistent
- anything else would be worrisome
- all of them use the same definition for primary particles, correct to particle-level, ... etc.

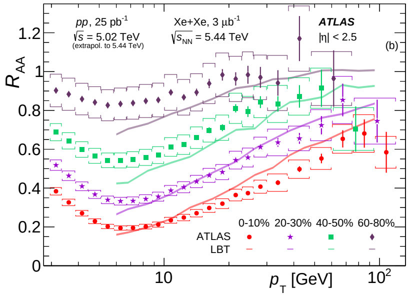


- Soft Collinear Effective Theory

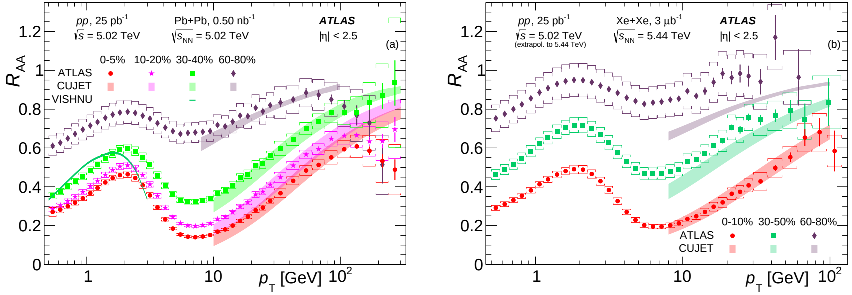


- Linear Boltzmann Transport model





- VUSHNU is a (2+1)D viscous hydrodynamic model
- CUJET describes high-p_{T} energy loss



summary

- quark-gluon plasma affects partons traversing it
- the energy loss is well documented
- the partons' interactions with QGP is also documented
- all this affect production of jets, hadrons, ...

- there are still many white spots on the map
- with upcoming data-taking during Run 3, we may fill some gaps