What do we learn from small systems about the physics of heavy ion collisions?

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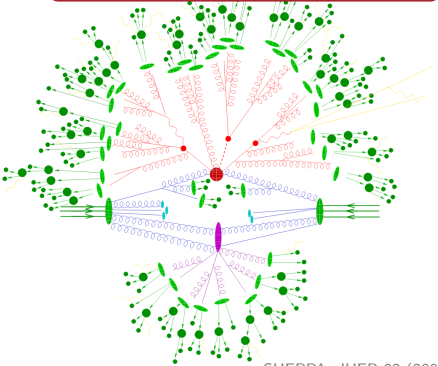
January 15, 2021

Thanks to Chun, Giuliano, Jasmine, Sören, Urs, Wilke and all the speakers at the conference.

Why study small systems?

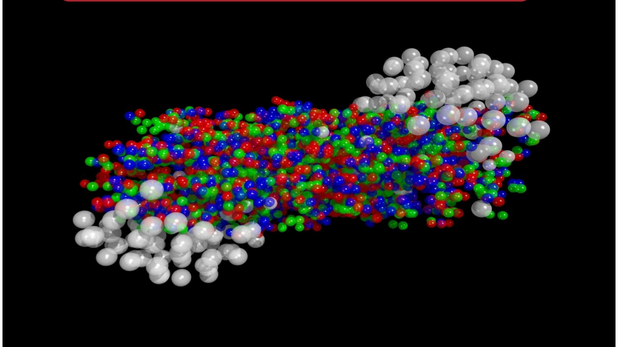
Two successful paradigms of hadron collisions

free-streaming final state in pp



SHERPA, JHEP 02 (2009)

abundant parton re-scatterings in AA

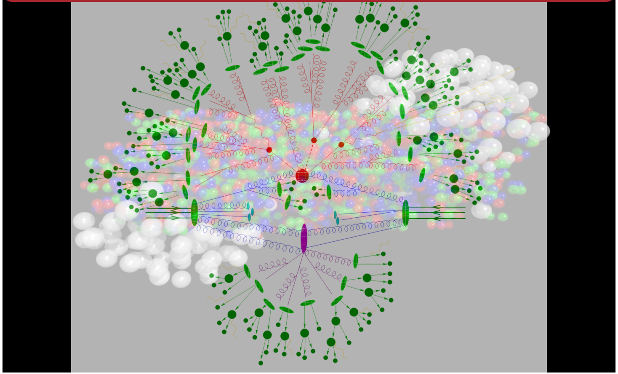


UrQMD, Marcus Bleicher

- Understanding small systems closes the disconnect between HEP and HIP.
- Small systems can teach us when the physics of heavy-ions is applicable.

Two successful paradigms of hadron collisions

How to reconcile both pictures in small systems?

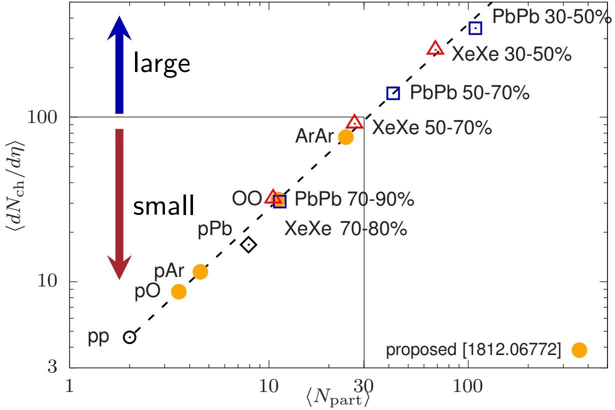


- Understanding small systems closes the disconnect between HEP and HIP.
- Small systems can teach us when the physics of heavy-ions is applicable.

Multiplicity as a measure of system size

- RHIC: pp, pAl, pAu, dAu, ^{3}HeAu, CuCu, CuAu, AuAu, UU (RuRu, ZrZr, OO)
- LHC: pp, pPb, XeXe, PbPb (OO, ArAr)

Exotics: e^+e^-, γ^*Pb or γ^*p.

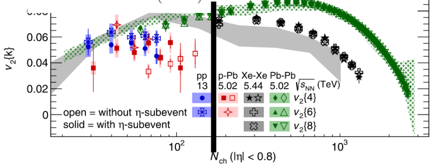


Are small systems ($dN_{ch}/d\eta < 100$ and $N_{part} < 30$) different from the large ones?

Small systems show new features in observables

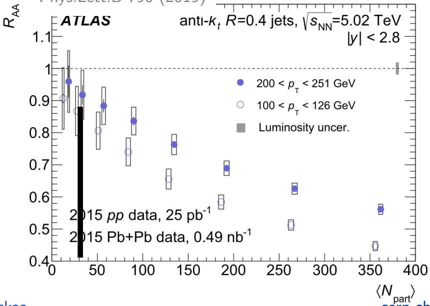
"Flattening" of v_n

ALICE PRL 123 (2019)



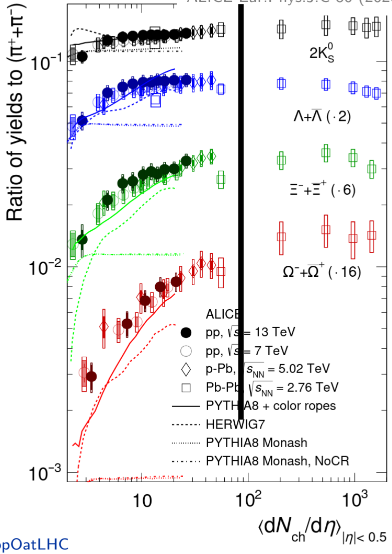
Disapearence of jet quenching

Phys.Lett.B 790 (2019)



Change in strangeness enhancement

ALICE Eur.Phys.J.C 80 (2020)



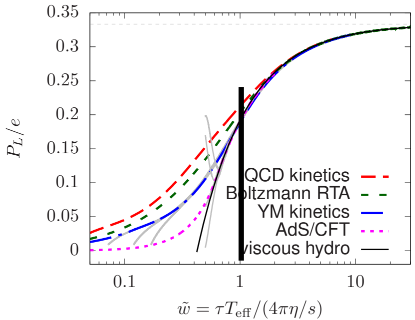
Is the medium evolution the same in large and small systems?

Small systems $\Longrightarrow$ out-of-equilibrium dynamics

Compare system life-time to equilibration times in QCD kinetic theory

Kurkela, AM, Paquet, Schlichting and Teaney (2018)[1] Kurkela, AM (2018)[2]

hydrodynamization $\frac{dN_{\text{ch}}}{d\eta} \gtrsim 63 \left(\frac{\eta/s}{0.16}\right)^3$, chemical equilibration $\frac{dN_{\text{ch}}}{d\eta} \gtrsim 110 \left(\frac{\eta/s}{0.16}\right)^3$



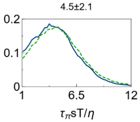
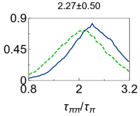
Giacalone, AM, Schlichting (2019)[3]

Which new features of macroscopic description (beyond lattice EoS, η/s, ζ/s) can be tested with "hydro" in small systems?

Same code $\neq$ same (relevant) physics for different size systems

Need to understand relative importance to

- Higher order-transport coefficients. *Can we see different hydro attractor?*
- Physical constraints in small systems. *Causality? Pressure positivity?*
  Plumberg Sun 19:45, Noronha, Mon 19:20, Nunes, Wed 16:30
- Non-equilibrium equation of state. *Extensions to lattice EoS?*
  Mrozcek, Mon 18:40, Dore, Thu 15:20
- Hadronization. *Cooper-Frye? Coalescence? Fragmentation functions?*
  see talks by Paquet, Monday 15:30, Almaalol, Fri 16:55, Zhao Sun 19:45, Song, Wed 18:10

	Trajectum	AdS/CFT	kinetic theory
$\frac{\tau_\pi sT}{\eta}$		$4-\log(4)\approx 2.61$	5
$\frac{\tau_{\pi\pi}}{\tau_\pi}$		$\frac{88}{35(2-\log 2)}\approx 1.92$	$\frac{10}{7}\approx 1.43$

Second order transport coefficients fitted to pPb and PbPb data

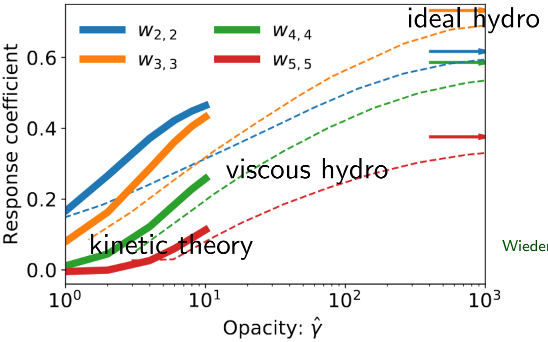
Talk by van der Schee, Tue 18:20

Beyond hydrodynamic descriptions

Many new developments on flow from kinetic descriptions.

See talks/posters by Almaalol, Brewer, Kersting, Yin, Roch, Werthmann, Wiedemann ...

$$v_n = w_{n,m}\,(\text{system size} \sim \hat{\gamma})\,\epsilon_m + \ldots.$$



Wiedemann, Wed 16:30

Response to initial geometry changes with system size (interaction strength).

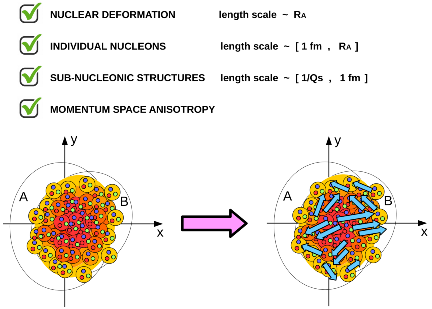
For different ways of complementing hydro description see also Song, Wed 18:10

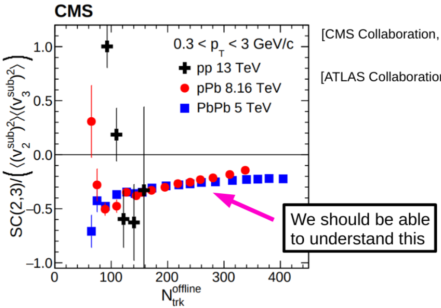
What new features of initial state can we see in small systems?

The relevant degrees of freedom in the initial state

Sources of initial state fluctuations can be constrained by a variety of observables.

See the detailed plenary talks by Giacalone, Tue, 15:30 and Soto-Ontoso 17:20





[CMS Collaboration, 1709.09189, 1905.09935]

[ATLAS Collaboration, 1807.02012]

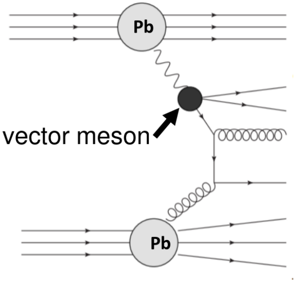
Subnucleonic structures are especially relevant for small systems, e.g. p-, d-, ^{3}He-Au.

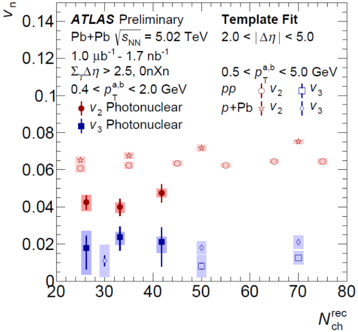
Small systems test the finer details of initial state modelling.

See also Schee, Tue 18:20, Song, Wed 18:10

Collectivity in exotic systems: γ^*Pb collisions

$$|\gamma\rangle = |\gamma_0\rangle + \sum_{m,n} |mq\bar{q} + ng\rangle + \sum_{\rho,\omega} |V\rangle + \ldots .$$





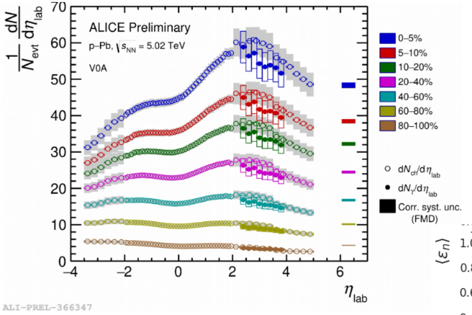
talk by Seidlitz, Mon 18:40

CGC based predictions for v_2 Shi et al. [4], but none for v_3 and final state interactions.

Can we probe nuclear wavefunction in γ^*Pb collisions?

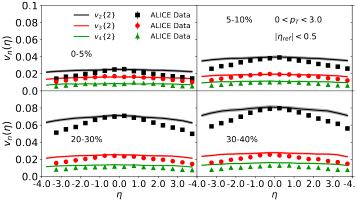
Going beyond boost-invariance

Often we make comparisons between 2D models and 3D measurement.



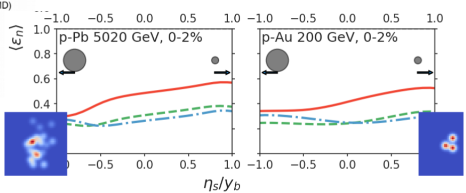
Particle production in ALICE

Modak, Wed 15:50



3D IP-Glasma

Sangyong, Tue 17:40



3D Trento

Ke, Wed 19:20

Observables in small systems can be particularly sensitive to rapidity fluctuations.

see plenaries by Hu and Belmont, Tue 15:55,16:20

Further theoretical developments and studies are needed! see also Singh, Fri 18:40

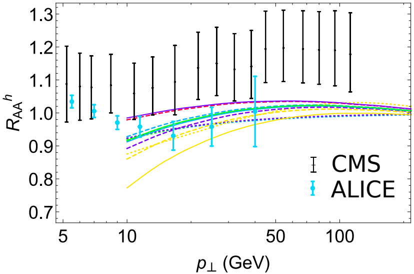
High-p_T observables in small systems

Importance of nPDF effects in small and large systems

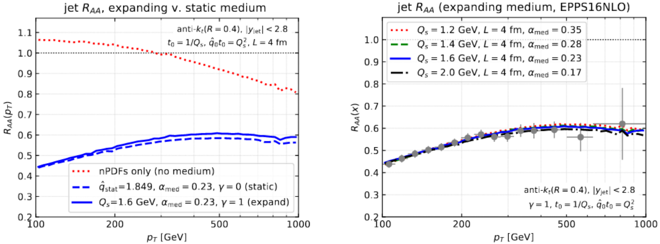
- Small systems (pA) provide valuable information on nPDFs

  See plenary by Paakkinen, Fri, 18:50

- If negligible jet-quenching in pPb $\Longrightarrow$ jet observables can be used in nPDF fits.



Energy loss in pPb, Huss et al. (2020) [5, 6]

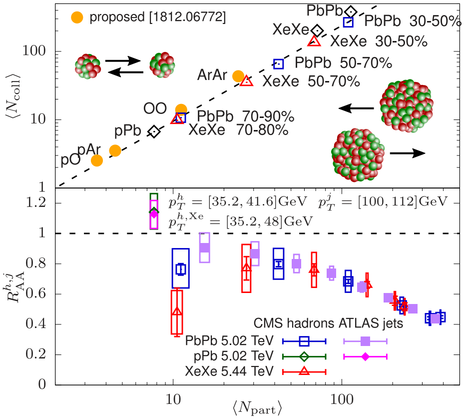


Jet quenching in large systems, Caucal et al. [7]

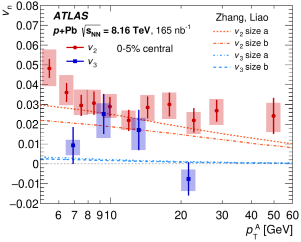
Even in large systems nPDF effects (and their uncertainties) can be relevant.
Different pA measurements will help to constrain A-dependence.

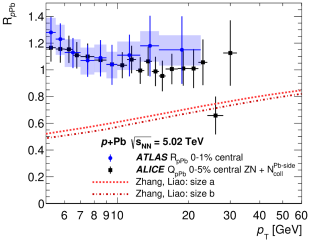
$R_{AA} - v_2$ puzzle in small systems

Persistent high-p_T flow in the absence of significant energy loss.



Huss et al. (2020) [5, 6]





Mohapatra, Wed 17:40

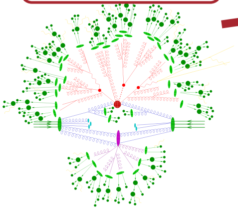
How to measure small high-p_T energy loss signal in small systems with precision?

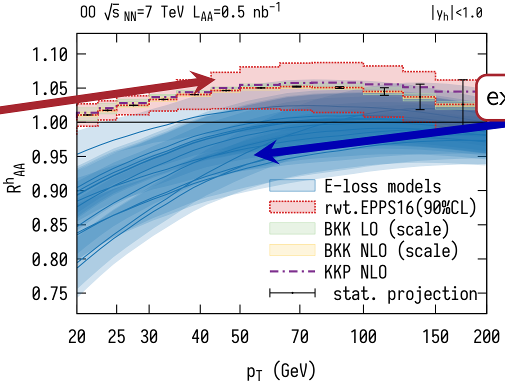
Minimum-bias hadron R^h_{AA} in OO at $\sqrt{s_{NN}} = 7$ TeV

- System size comparable to peripheral AA ($\langle N_{npart} \rangle \approx 10$)
- Luminosity measurement – no modeling of T_{AA} needed
- Symmetric system – measurement uncertainty cancellation with pp.

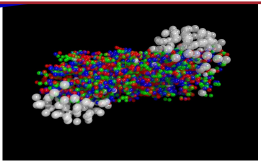
Minimum-bias measurement crucial to establish HEP baseline. See Kurkela, Wed 15:30

no-rescattering





extrapolated AA energy loss



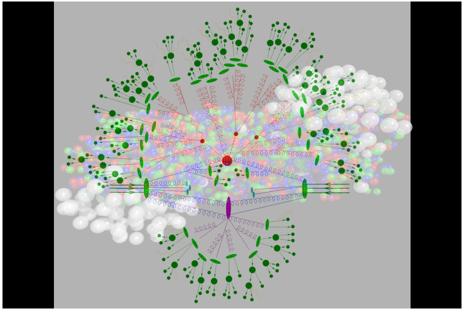
Huss et al. (2020) [5, 6]

Great opportunity for a short run of oxygen-oxygen at RHIC and LHC!

What do we learn from small systems about the physics of heavy ion collisions?

Tentative answers:

- The requirements of macroscopic descriptions to apply.
- Fine details of the initial state physics.
- The nuclear modifications (and A-dependence) of PDF.
- The challenge for high-p_T energy-loss models.



Opportunities of oxygen-oxygen and proton-oxygen collisions at LHC

- Co-organisers: **Jasmine Brewer**, **Wilke van der Schee**
- 5-day virtual workshop (afternoons Geneva time)
- Physics opportunities during LHC Run 3.
  - Initial state
  - Soft dynamics of small systems
  - Hard probes in OO and pO
  - Experimental opportunities with OO and pO
  - Machine development
  - pO for cosmic-ray physics

Please register!

4 Feb 2021 (AM: –)

PM	
14:25	Opening (Zoom)
14:30	**Machine development** (until 15:50) (Zoom)
14:30	Talk - Reyes Alemany Fernandez (CERN) (Zoom)
15:00	LHC machine scenario for a short oxygen run - Dr Roderik Bruce (CERN) (Zoom)
15:30	Luminosity determination with heavy-ion beams at the LHC - Martino Gagliardi (Universita e INFN Torino (IT)) (Zoom)
15:50	**Discussion** (until 16:15) (Zoom)
16:15	--- Coffee break ---
16:30	**Initial state** (until 18:05) (Zoom)
16:30	Eccentricities in collisions with 16O and 12C - Wojciech Broniowski (IFJ PAN) (Zoom)
17:10	Talk - Prof. Soeren Schlichting (Universität Bielefeld) (Zoom)
17:50	--- Coffee break ---
18:05	**Discussion** (until 18:30) (Zoom)

5 Feb 2021

14:30	**Soft dynamics of small systems** (until 15:50) (Zoom)
14:30	Collectivity and QGP signals in Large and Small systems - Wenbin Zhao (Peking University) (Zoom)
15:10	Dynamical Modeling of the Collectivity in pO and OO Collisions - Dr Chun Shen (Wayne State University) (Zoom)
15:50	--- Coffee break ---
16:05	**Soft dynamics of small systems** (until 17:25) (Zoom)
16:05	Talk - Harri Niemi (Johann Wolfgang Goethe-Universität) (Zoom)
16:35	Bayesian Analysis of Oxygen-Oxygen Collisions - Govert Nijs (Massachusetts Institute of Technology) (Zoom)
17:05	Hadron yield ratios in dynamical core-corona initialization from small to large systems - Yuuka Kanakubo (Sophia Univ.) (Zoom)
17:25	--- Coffee break ---
17:40	**Discussion** (until 18:30) (Zoom)

8 Feb 2021

14:30	**Hard probes in pO and OO** (until 15:40) (Zoom)
14:30	Talk - Petja Paakkinen (IGFAE - Universidade de Santiago de Compostela) (Zoom)
15:10	Talk - Alexander Yohei Huss (CERN) (Zoom)
15:40	--- Coffee break ---
15:55	**Hard probes in pO and OO** (until 17:05) (Zoom)
15:55	Jet Quenching from light to dense systems - Liliana Apolinario (LIP (PT)) (Zoom)
16:25	The elusive energy loss signal of the Quark Gluon Plasma in OO collisions - Prof. Jacquelyn Noronha-Hostler (University of Illinois Urbana Champaign) (Zoom)
17:05	--- Coffee break ---
17:20	**Discussion** (until 18:10) (Zoom)

9 Feb 2021

14:30	**Experimental opportunities with OO and pO** (until 15:50) (Zoom)
14:30	ALICE contribution (Zoom)
15:10	ATLAS contribution - Anne Marie Sickles (Univ. Illinois at Urbana Champaign (US)) (Zoom)
15:50	--- Coffee break ---
16:05	**Experimental opportunities with OO and pO** (until 17:25) (Zoom)
16:05	CMS contribution - Michael Murray (The University of Kansas (US)) (Zoom)
16:45	Oxygen beams and LHCb: prospects of pO and OO collisions for nuclear and astroparticle physics - Dr Hans Peter Dembinski (TU Dortmund) (Zoom)
17:05	Oxygen beams and LHCb: prospects of collisions with fixed-targets - Giacomo Graziani (INFN, Sezione di Firenze (IT)) (Zoom)
17:25	--- Coffee break ---
17:40	**Discussion** (until 18:30) (Zoom)

10 Feb 2021

14:30	**pO for cosmic-ray physics** (until 15:50) (Zoom)
14:30	LHCf contribution (Zoom)
15:10	Talk - Dr Tanguy Pierog (KIT) (Zoom)
15:50	**Discussion** (until 16:10) (Zoom)
16:10	--- Coffee break ---
16:25	**Experimental opportunities with OO and pO** (until 17:05) (Zoom)
16:25	sPHENIX contribution - Dennis Perepelitsa (University of Colorado Boulder) (Zoom)
16:45	STAR contribution - Wei Li (Rice University (US)) (Zoom)
17:05	**Soft dynamics of small systems** (until 17:45) (Zoom)
17:05	A Pythia/Angantyr perspective on OO and pO collisions - Christian Bierlich (Lund University (SE)) (Zoom)
17:45	**Discussion** (until 18:05) (Zoom)
18:05	--- Coffee break ---
18:20	**Discussion** (until 18:50) (Zoom)
18:50	Closing (Zoom)

Bibliography I

[1] Aleksi Kurkela, Aleksas Mazeliauskas, Jean-François Paquet, Sören Schlichting, and Derek Teaney. Matching the Nonequilibrium Initial Stage of Heavy Ion Collisions to Hydrodynamics with QCD Kinetic Theory. *Phys. Rev. Lett.*, 122(12):122302, 2019, 1805.01604.

[2] Aleksi Kurkela and Aleksas Mazeliauskas. Chemical equilibration in hadronic collisions. *Phys. Rev. Lett.*, 122:142301, 2019, 1811.03040.

[3] Giuliano Giacalone, Aleksas Mazeliauskas, and Sören Schlichting. Hydrodynamic attractors, initial state energy and particle production in relativistic nuclear collisions. *Phys. Rev. Lett.*, 123(26):262301, 2019, 1908.02866.

[4] Yu Shi, Lei Wang, Shu-Yi Wei, Bo-Wen Xiao, and Liang Zheng. Exploring the Collective Phenomenon at the Electron-Ion Collider. 2020, 2008.03569.

[5] Alexander Huss, Aleksi Kurkela, Aleksas Mazeliauskas, Risto Paatelainen, Wilke van der Schee, and Urs Achim Wiedemann. Discovering partonic rescattering in light nucleus collisions. 2020, 2007.13754.

[6] Alexander Huss, Aleksi Kurkela, Aleksas Mazeliauskas, Risto Paatelainen, Wilke van der Schee, and Urs Achim Wiedemann. Predicting parton energy loss in small collision systems. 2020, 2007.13758.

[7] P. Caucal, E. Iancu, A. H. Mueller, and G. Soyez. Nuclear modification factors for jet fragmentation. *JHEP*, 10:204, 2020, 2005.05852.

Backup