Energy loss in small systems (theory overview)

Aleksas Mazeliauskas

CERN Theoretical Physics Department

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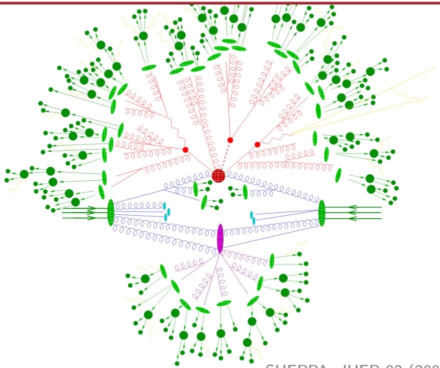
2022-2028

Motivation

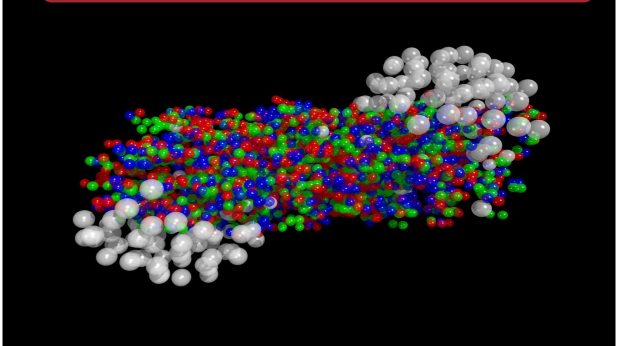
High-energy (HEP) and heavy-ion (HIP) physics paradigms of hadron collisions

(HEP) free-streaming final state in pp



SHERPA, JHEP 02 (2009)

(HIP) abundant parton re-scatterings in AA



UrQMD, Marcus Bleicher

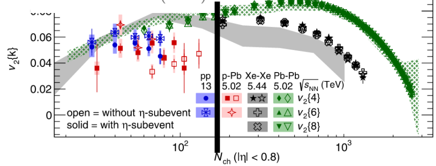
Core hypothesis: partonic rescattering $\Leftrightarrow$ HIP phenomena.

But many QCD medium signals have been observed also in small systems.

Evidence for medium induced pheonomena in small systems

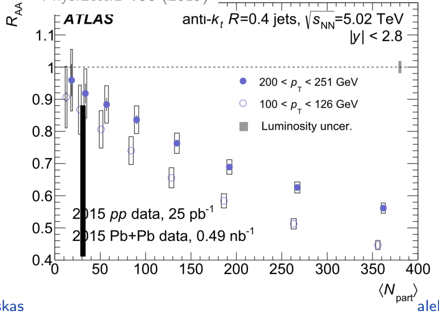
Collective flow

ALICE PRL 123 (2019)



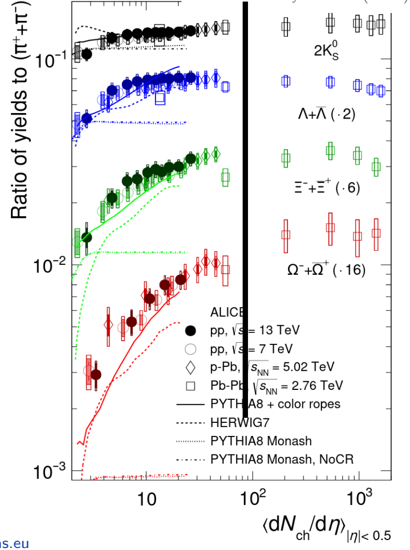
BUT no jet quenching

Phys.Lett.B 790 (2019)



Strangeness enhancement

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



Challenge for the heavy-ion community

- Partonic rescattering is a *prerequisite* for Quark-Gluon Plasma formation.
- Azimuthal anisotropies *implies*[1] final state interactions.
- Partonic energy loss is *necessary* for consistency of HIP phenomenology.

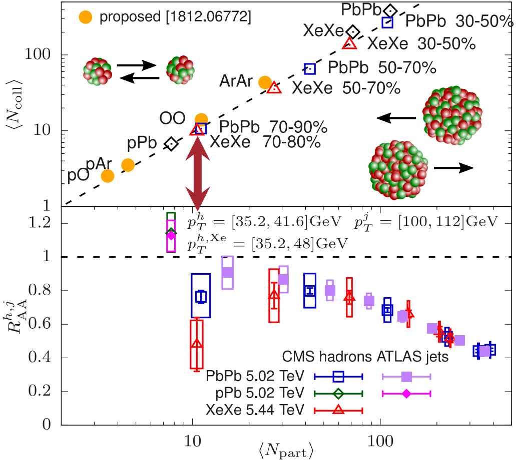
We must either validate or disprove HIP picture in small systems.

Necessary ingredients for the discovery of medium-induced energy loss:

1. Accurate measurement (reduce systematics, maximize statistics).
2. Precise theoretical baseline (what to expect if no energy-loss).
3. Sufficiently large medium effect compared to 1 and 2.

[1] Standard interpretation that is well tested in large collision systems.

System size scan with light ions at the LHC



Huss et al. (2020) [1, 2]

$\sqrt{s_{NN}} \sim 7$ TeV OO at LHC in 2024

STAR collected $\mathcal{L}_{\rm OO} = 32\,{\rm nb}^{-1}$ at $\sqrt{s_{NN}} = 200$ GeV

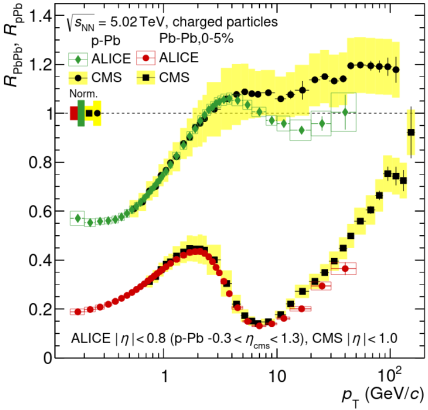
Brewer, AM, van der Schee (2021) [3]

- Measurements with peripheral PbPb and pPb collisions are inconclusive.
- *Minimum bias oxygen-oxygen collisions probe the relevant size regime!*

Hadron (jet) nuclear modification factor R_{AA}

Ratio of spectrum in AA to an *equivalent number* N_{coll} of pp collisions.

$$R_{\text{AA}}(p_T) = \frac{1}{\underbrace{\langle N_{\text{coll}} \rangle / \sigma_{nn}^{\text{inel}}}_{\langle T_{\text{AA}} \rangle}} \frac{1/N_{\text{ev}}^{AA} dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$



ALICE JHEP 11 (2018)

R_{AA} can deviate from unity because:

- nPDF effects (different quark/gluon abundances).
- Parton rescattering (medium-induced energy loss).
- Geometry and event selection bias. Loizides, Morsch (2017) [4]
- Systematics in extrapolation of pp reference spectrum. ATLAS (2016) [5]

Inclusive hadron (jet) nuclear modification factor R_{AA}

$\langle T_{AA} \rangle$ can be replaced with *experimentally measurable* beam luminosity.

$$R^{h,j}_{\text{AA, min bias}}(p_T) = \frac{1}{A^2} \frac{d\sigma^{h,j}_{\text{AA}}/dp_T}{d\sigma^{h,j}_{pp}/dp_T}, \quad A \text{ – the nucleon number}$$

- Only applicable to minimum bias AA measurements[2].
- Requires van der Meer scan to determine absolute AA luminosity.
- System size (multiplicity) controlled by nuclei species and collision energy.
- *Light nuclei collisions $\Longrightarrow$ precision studies of system size dependence.*

Unique opportunity of complementary measurements of $^{16}_{8}$O at the LHC and RHIC.

[2] Theoretically can do pA, but worse cancellation of experimental uncertainties due to shifted rapidities in pp and pA.

The null hypothesis—no medium-induced energy loss

The null baseline of R_{AA} can be computed with HEP precision techniques

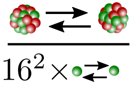
- Factorization of jet cross-section in perturbative QCD:

$$\sigma({}^{16}_{8}\mathrm{O} + {}^{16}_{8}\mathrm{O} \to j + X) = \underbrace{\mathrm{nPDF}({}^{16}_{8}\mathrm{O})}_{\text{parton distribution functions}} \otimes \underbrace{\hat{\sigma}^{j}_{ab}}_{\text{hard partonic cross section}}$$

- (n)PDF – process-independent, non-perturbative, fixed by data.
- $\hat{\sigma}_{ab}$ – universal, perturbative and systematically improvable (LO, NLO, . . .).

We will calculate jet and hadron no-energy-loss baseline at next-to-leading order

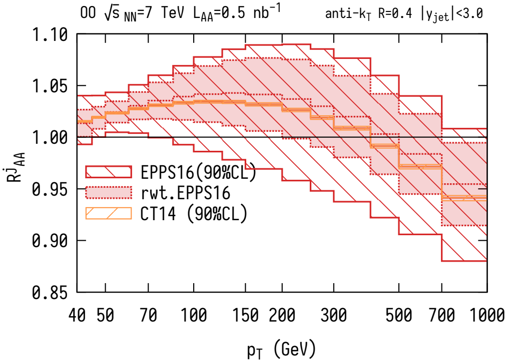
$$R^{h,j}_{\mathrm{AA,\ min\ bias}}(p_T) = \frac{1}{A^2}\frac{d\sigma^{h,j}_{\mathrm{AA}}/dp_T}{d\sigma^{h,j}_{pp}/dp_T} =$$



Deviation from the baseline $\Longrightarrow$ medium induced energy loss.

Minimum-bias jet R^j_{AA} (no energy loss) in OO at $\sqrt{s_{\mathrm{NN}}} = 7\,\mathrm{TeV}$

1. Overlap of LO, NLO scale "uncertainties" ⇒ perturbative convergence.
2. Propagate uncertainties in proton and nuclear modified PDFs.
3. Hadronization, showering and fragmentation uncertainties.



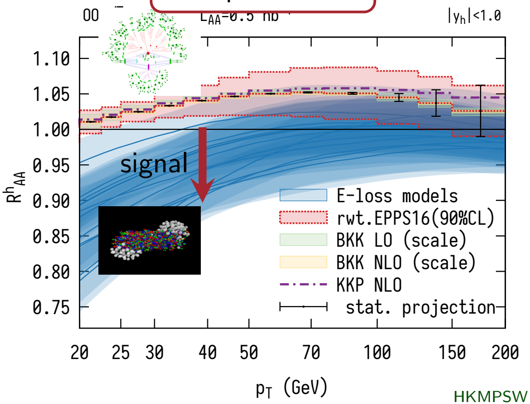
We achieved $\mathcal{O}(1\text{–}4\%)$ accuracy in the no-energy-loss jet baseline.

We also performed NLO calculations of inclusive hadron R_{AA} with INCNLO code.

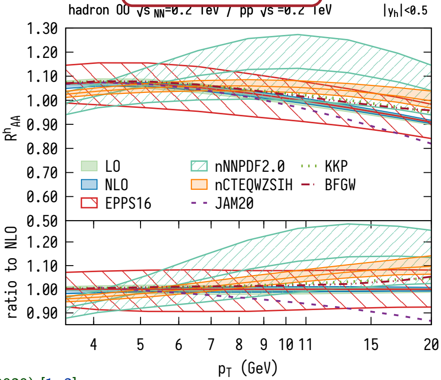
Minimum-bias hadron R^h_{AA} in OO at $\sqrt{s_{NN}} = 7$ TeV and $\sqrt{s_{NN}} = 200$ GeV

The envelope of model predictions $\Rightarrow$ conservative estimate of the signal.

LHC predictions



RHIC baseline



HKMPSW (2020) [1, 2]

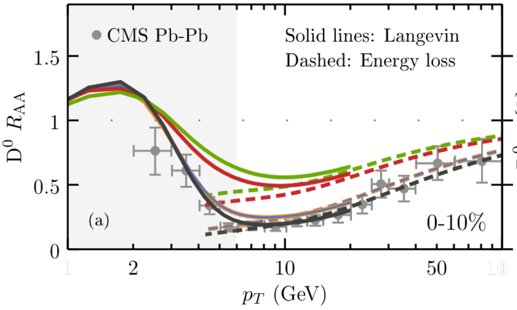
Measurable energy loss signal in 10 GeV $< p_T <$ 50 GeV region at the LHC.

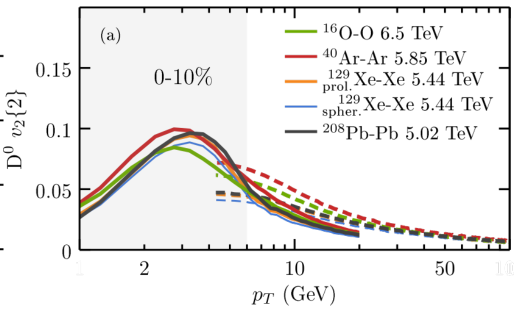
See also Zakharov *JHEP* (2021)

Heavy meson quenching and flow in small systems

Heavy quarks probe the entire evolution of QGP:

- At low momentum: random motion modelled by Langevin
- At high momentum: radiative energy loss.



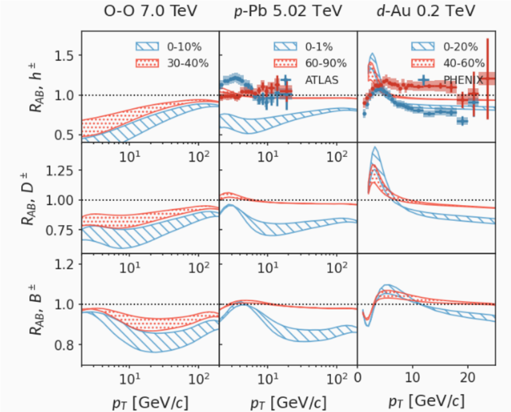


Katz, Prado, Noronha-Hostler, Suaide *PRD*, 2020

Similar elliptic flow, but reduced energy loss in small systems.

Simultaneous description of light and heavy meson quenching in small systems

- Include dynamical nuclear matter effects to better understand the baseline.
- QGP-modified splitting functions from SCETG + modified DGLAP evolution.
- Collisional energy loss (more important in small systems)



Ke, Vitev (2022), 2204.00634

System size scan ⇒ opportunity to separate different effects.

Strategies for constructing reference jet and hadron spectra

The ratio of spectra cancels large theoretical and experimental uncertainties.

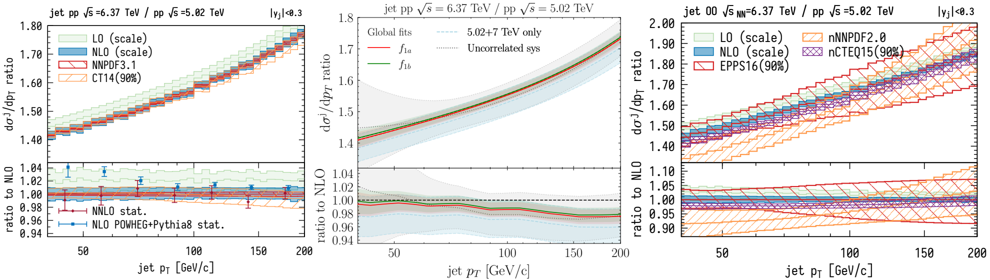
$$R^{h,j}_{\text{AA, min bias}}(p_T) = \frac{1}{A^2} \frac{d\sigma^{h,j}_{\text{AA}}/dp_T(6.37\,\text{TeV})}{\underbrace{d\sigma^{h,j}_{pp}/dp_T(5.02\,\text{TeV})}_{\text{measured}} \times \underbrace{\frac{d\sigma^{h,j}_{pp}/dp_T(6.37\,\text{TeV})}{d\sigma^{h,j}_{pp}/dp_T(5.02\,\text{TeV})}}_{\text{scaling factor}}}$$

Brewer, Huss, AM, van der Schee [2108.13434]

1. Use perturbative QCD to calculate scaling factor theoretically.
2. Interpolate measured pp spectra at nearby energies.
3. Consider hadron and jet spectra ratios at different collision energies.

Perturbative QCD baseline for jet and hadron spectra

1. We calculated NNLO jet and NLO hadron spectra.
2. We performed 3-energy interpolation with uncertainty propagation.
3. We calculated NLO baseline of jet and hadron R_{AA} at mixed energies.



- $\mathcal{O}(1-4\%)$ accuracy in scaling factor for the considered momentum range.
- *Uncertainty in oxygen nPDF is the limiting factor for mixed-energy ratio ⇒ motivation for pO.*

See also Paakkinen, 2111.05368 [6]

Conclusions

Motivation:

- Suppression of high momentum particles is one of key signals of QGP.
- Jet quenching has so far escaped experimental detection in small systems.
- Upcoming oxygen collisions at LHC provide unique discovery opportunities.

Outlook:

- State-of-the-art HEP techniques $\Rightarrow$ precise null-hypothesis baseline for R_{AA}
- Jet energy loss also in heavy quark sector
- Significant medium-induced signal extrapoled from existing data.
- Feasible to do accurate R_{AA} measurements even without without pp reference.

If observed in OO, jet quenching will be clear signal of high-p_T partonic rescattering affecting high momentum observables in a system just a few times larger than pp.

We need a unified picture of hadron collisions of all sizes.

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[15] Claude Duhr, Alexander Huss, Aleksas Mazeliauskas, and Robert Szafron. An analysis of Bayesian estimates for missing higher orders in perturbative calculations. *JHEP*, 09:122, 2021, 2106.04585.

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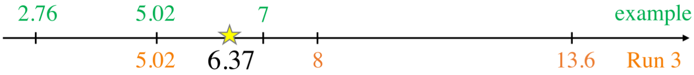
Backup

Interpolating using global fits of pp spectra

As a proof of principle we used existing jet and hadron data for interpolation:



We maximize the log-likelihood function

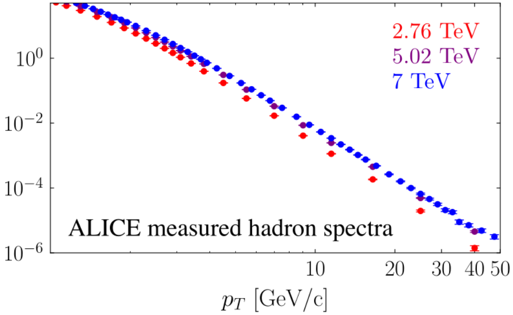
$$\log \mathcal{L} = -\frac{1}{2} \sum \Delta y_i (C^{-1})_{ij} \Delta y_j,$$

Covariance matrix (for each $\sqrt{s}$)

$$C_{ij} = \underbrace{\sigma^2_{\text{statistical}}}_{\text{uncorrelated}} \delta_{ij} + \underbrace{\sigma^2_{\text{luminosity}}}_{\text{correlated}}$$

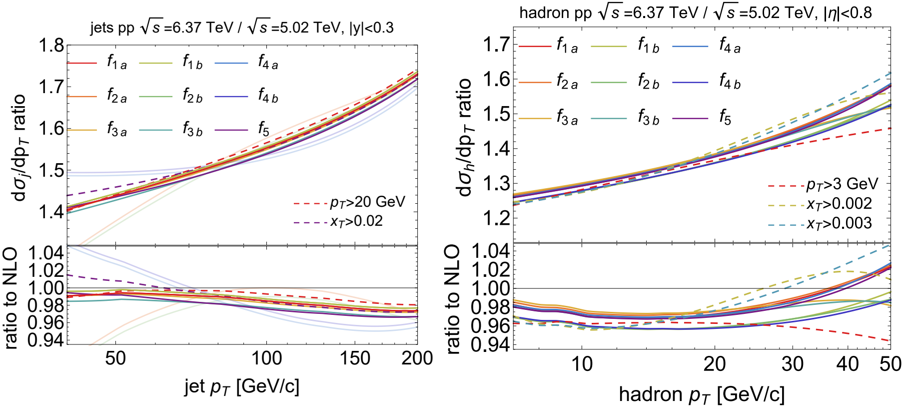
We also considered the case of uncorrelated systematic uncertainties.

$$\frac{d\sigma}{dp_T} \equiv y = A\sqrt{s}^{\beta} \left(\frac{2p_T}{\sqrt{s}} \right)^{n(2p_T/\sqrt{s}, \sqrt{s})}$$



Sensitivity to interpolation forms and assumptions

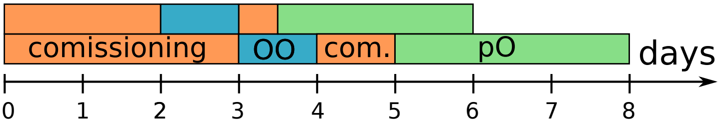
We used 9 fitting forms and varied the p_T^{min} cut off.



Up to $\mathcal{O}(4\%)$ uncertainty from functional form, but larger sensitivity to p_T^{min}

$\mathcal{O}(2\%)$ systematic discrepancy from pQCD.

Oxygen run in LHC Run 3



- Short ∼ 1 week run (new ion species for the LHC).
- Tentatively planned in 2024.
- Precise collision energy to be decided.

	pp	pPb, pp	PbPb, pp	OO	pO
$\sqrt{s}$	13.6 TeV	8 TeV	5.02 TeV	6.37 TeV	9 TeV

- *Currently no corresponding pp reference planned for OO and pO.*

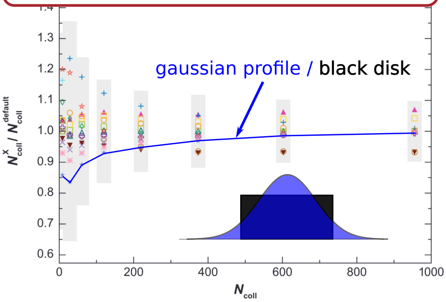
How to make accurate R_{AA} measurements without a pp reference?

Soft physics assumptions in R_{AA} normalization

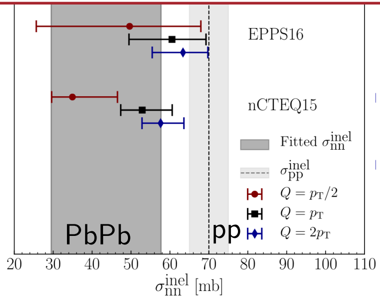
Nuclear overlap function $\langle T_{AA} \rangle = \frac{\langle N_{coll} \rangle}{\sigma_{nn}^{inel}}$ is the ratio of *model-dependent quantities*

number of binary collisions $\langle N_{coll} \rangle$

inelastic nucleon-nucleon cross-section σ_{nn}^{inel}



Miller, Reygers, Sanders, Steinberg (2007) [7]



Eskola, Helenius, Kuha, Paukkunen (2020)[8], see also Jonas, Loizides (2021) [9]

This way nominally high-p_T observable R_{AA} depends on soft physics assumptions.

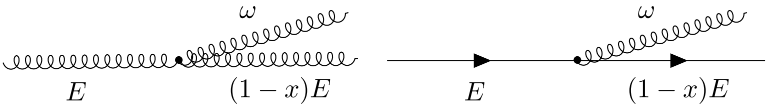
Predicting energy loss in small systems

Energy loss model predictions in light ion collisions

- Estimation of expected signal is important for the feasibility of the discovery.
- We will use a simple framework to explore various ideas from $>$20 years of energy loss modelling in heavy-ion collisions.
- We then extrapolate predictions to OO collisions.
- *The goal: conservative theory prediction of energy loss.*
- For simplicity, we study energy loss only for charged hadron spectra (not jets).

Medium induced gluon radiation

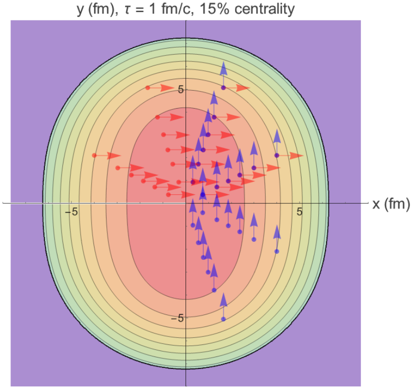
The presence of background QCD medium modifies the parton shower



Simple BDMPS-Z reformulation due to Arnold [10]

$$\omega\frac{dI^s}{d\omega} - \omega\frac{dI^s_{\text{vac}}}{d\omega} = \frac{\alpha_s}{\pi} x P_{s\to g}(x) \ln\left|c[\hat{\hat{q}}]\right|.$$

- Medium modelling enters through quenching parameter $\hat{\hat{q}}(t, \vec{x}(t))$
- $d = \hat{\hat{q}}/T^3$ – free-model parameter

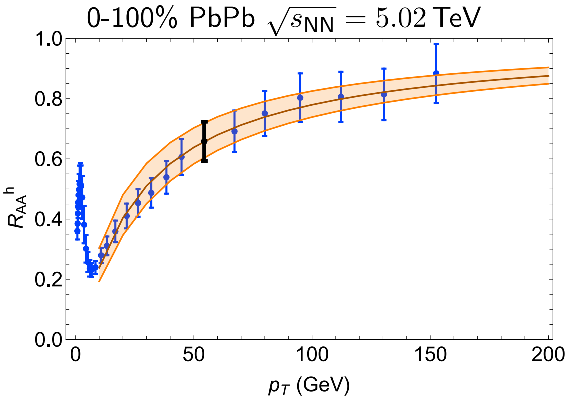


Predicting hadron energy loss in light-ion collisions

HKMPSW (2020) [1, 2]

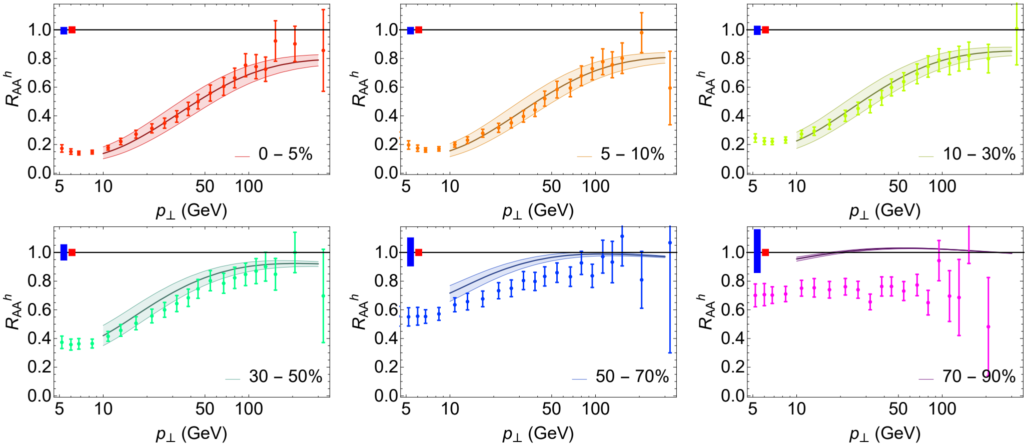
1. Background medium
   - Smooth $T(\tau, r)$ profile.
   - Width rescaled to $\langle R^2 \rangle$
   - Hydro-like and free-streaming expansions
2. Energy loss models
   - BDMPS-Z à la Arnold [10]
   - $dE/dx \sim \tau^{0.4} T^{1.2}$
   - $dE/dx \sim \tau T^3$
   - stopping à la holography

Models fitted to a single data point $R^h_{\mathrm{AA}}(p_T = 54.4\,\mathrm{GeV})$ CMS [11].



Dependence on system size and momentum are then model predictions.

Validation of a simple model centrality dependence in PbPb



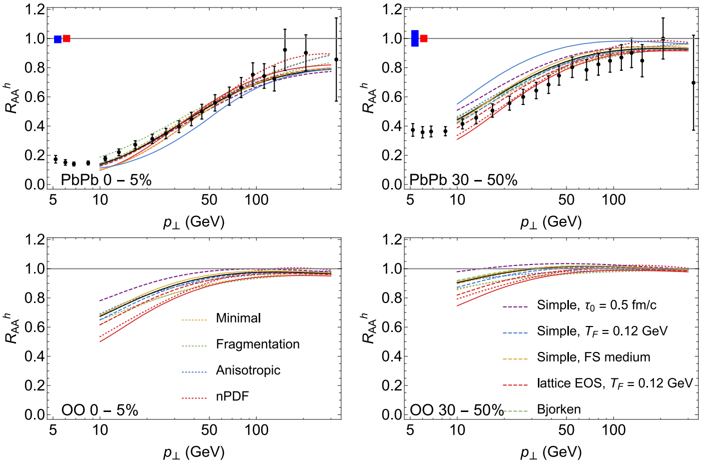
Good central to mid-central description of hadron energy loss.

Modelling uncertainties in PbPb and OO

We drastically varied background medium evolution and energy loss formulas.

PbPb comparison to data

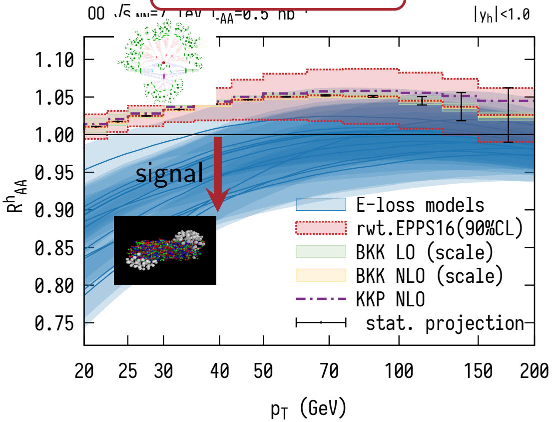
OO prediction



The spread of different scenarios—theoretical model uncertainty.

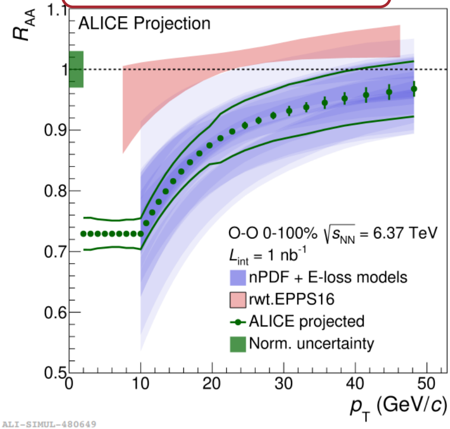
Minimum-bias hadron R^h_{AA} in OO at $\sqrt{s_{NN}} = 7$ TeV

Theory predictions



HKMPSW (2020) [1, 2]

Experimental projections

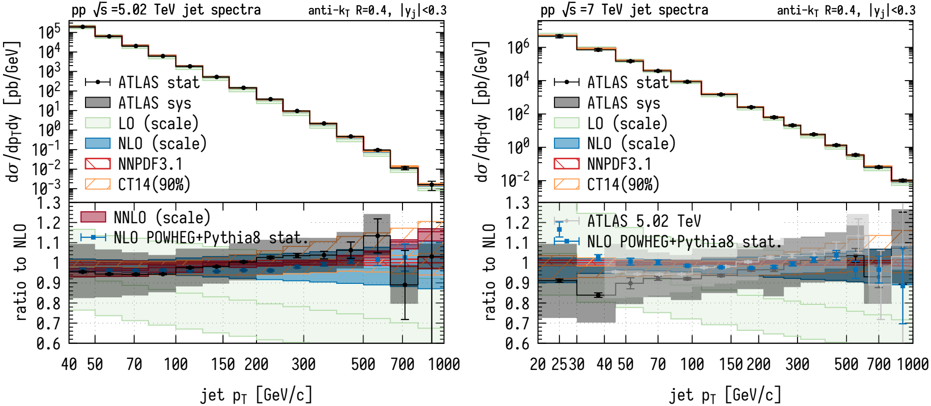


ALICE (2021) [12]

Measurable energy loss signal in 10 GeV $< p_T < 50$ GeV!

pQCD comparison to measured data

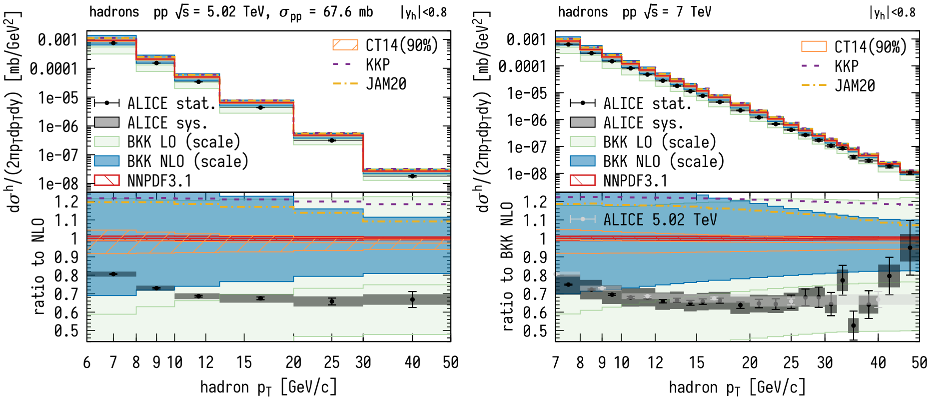
NNLO jet spectra ant 5.02 and 7 TeV.



Good NNLO agreement with data. Some systematic deviations at NLO.

pQCD comparison to measured data

NLO hadron spectra ant 5.02 and 7 TeV.

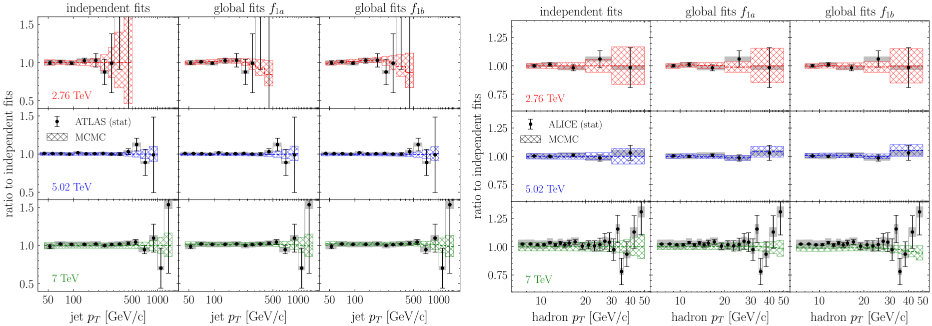


Large systematic deivations of absolute spectra, but constant with energy.

known problem of fragmentation functions. see d'Enterria et al. [13]

MCMC fits to anchor energy spectra

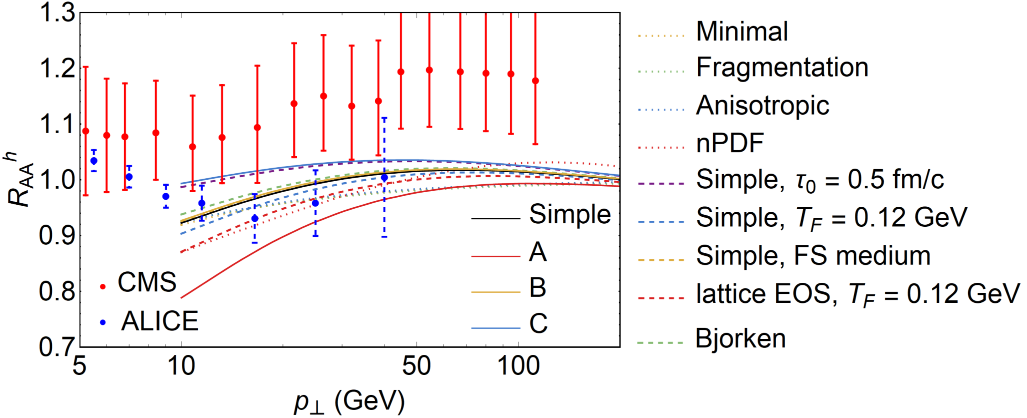
Compare the confidence intervals of MCMC fits to experimental uncertainties.



MCMC confidence intervals reproduce statistical uncertainties.

Modification in pPb

None of the models can explain $R^h_{p\text{Pb}} \sim 1.1$



Estimating Missing Higher Order (MHO) terms

What is the accuracy of the truncated perturbative series?

- Unphysical dependence on renormalization (μ_R) and factorization scales (μ_F)

$$\sigma = \sigma^{\mathsf{N}^n\mathsf{LO}}(\mu_R, \mu_F) + \mathcal{O}\left(\mathsf{N}^{n+1}\mathsf{LO}\right).$$

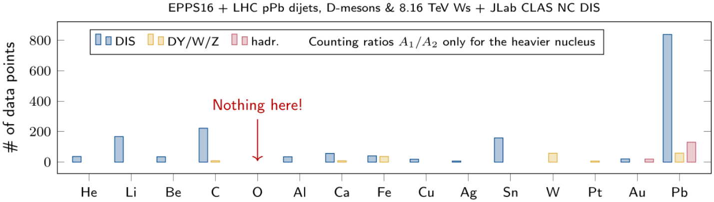
- Central scale μ_0 – typical Q for the hard process, e.g., jet p_T
- Estimate MHO by varying μ_R, μ_F by factors $k_i = 1/2, 1, 2$ around μ_0
- Scale "uncertainty" is defined as the envelope of scale variation

$$[\sigma_{\mathsf{min}}, \sigma_{\mathsf{max}}]^{\mathsf{N}^n\mathsf{LO}} = [\min_{i,j} \sigma^{\mathsf{N}^n\mathsf{LO}}(k_i\mu_0, k_j\mu_0), \max_{i,j} \sigma^{\mathsf{N}^n\mathsf{LO}}(k_i\mu_0, k_j\mu_0)].$$

- Nested scale bands at LO, NLO,... $\Longrightarrow$ "good" perturbative convergence

For Bayesian approach to estimating MHO, see Bonvini (2020) [14], Duhr, Huss, AM, Szafron (2021) [15]

Estimating PDF and nPDF uncertainties



Paakkinen, OppOatLHC 2021

We use oxygen nPDF from EPPS16 [16] with CT14 proton PDF reference.

- Central observable value is computed with the central PDF set.
- PDF error = the spread of values evaluated over ~ 100 PDF error sets.
- Expect partial cancellation of PDF uncertainties in the ratio.

$$R^{h,j}_{\mathrm{AA,\ min\ bias}}(p_T) = \frac{1}{A^2}\frac{d\sigma^{h,j}_{\mathrm{AA}}/dp_T}{d\sigma^{h,j}_{pp}/dp_T}$$

$\longleftarrow$ oxygen nPDF (EPPS16+CT14)

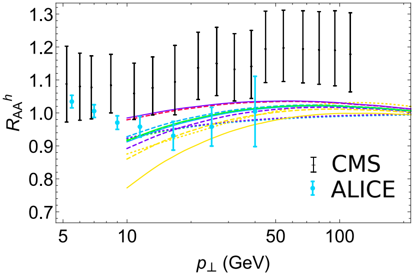
$\longleftarrow$ proton PDF (CT14)

Importance of nPDF effects in small and large systems

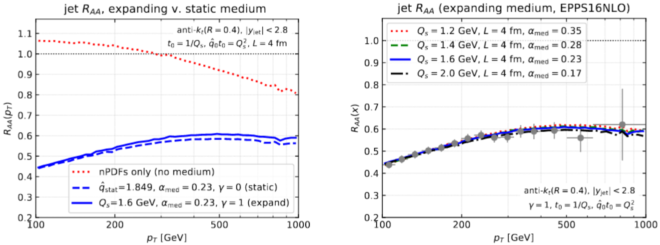
- Small systems (pA) provide valuable information on nPDFs

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) [1, 2]



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

Even in large systems nPDF effects (and their uncertainties) can be relevant.

Different pA measurements will help to constrain A-dependence.

Z-bosons as a hard parton luminosity meter

Can we construct more precise observables for detecting energy loss?

- Z-bosons – experimentally clean observable unaffected by the medium
- Requires large $\mathcal{O}\left(1\text{pb}^{-1}\right)$ statistics (long run, not planned in Run 3).
- Ratio of Z boson cross-section – partonic luminosity meter $\sigma^Z_{pp}/\sigma^Z_{AA} \sim 1/A^2$.
- Use Z bosons to normalize jet R^j_{AA}:

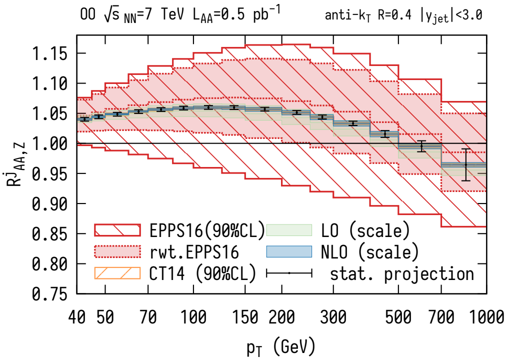
$$R^{h,j}_{\text{AA},Z}(p_T) = \frac{\sigma^Z_{pp}(\text{CT14})}{\sigma^Z_{\text{AA}}(\text{EPPS16+CT14})} \times \frac{d\sigma^j_{\text{AA}}/dp_T(\text{EPPS16+CT14})}{d\sigma^j_{pp}/dp_T(\text{CT14})}.$$

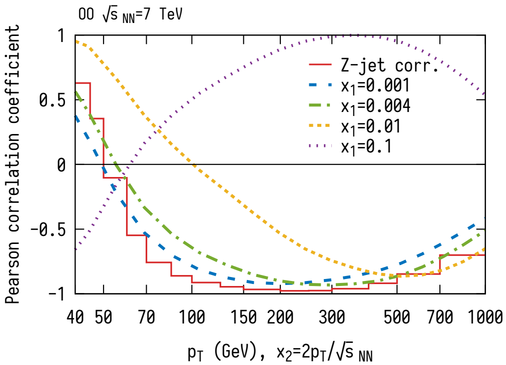
- Luminosity uncertainties cancel.
- *Expect the nPDF uncertainties to cancel too.*

Z boson weighted nuclear modification factor

Large nPDF uncertainties in the double ratio!

$$\langle f_g(x_1, Q) f_g(x_2, Q)\rangle$$





Surprising nPDF uncertainty *anticorrelation* between Z-boson and jet Bjorken-x.

Light-ion collisions are different from heavy-ion collisions!

	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
γ	3760.	3390.	3760.	3470.	3150.	2960.
$\sqrt{s_{NN}}$/TeV	7.	6.3	7.	6.46	5.86	5.52
σ_{had}/b	1.41	2.6	2.6	4.06	5.67	7.8
σ_{BFPP}/b	2.36×10^{-5}	0.00688	0.0144	0.88	15.	280.
σ_{EMD}/b	0.0738	1.24	1.57	12.2	51.8	220.
σ_{tot}/b	1.48	3.85	4.18	17.1	72.5	508.
N_b	1.58×10^{10}	3.39×10^{9}	2.77×10^{9}	9.08×10^{8}	4.2×10^{8}	1.9×10^{8}
ϵ_{xn}/μm	2.	1.8	2.	1.85	1.67	1.58
f_{IBS}/(m Hz)	0.168	0.164	0.184	0.18	0.17	0.167
W_b/MJ	175.	84.3	76.6	45.2	31.4	21.5
$L_{AA0}/cm^{-2}s^{-1}$	9.43×10^{31}	4.33×10^{30}	2.9×10^{30}	3.11×10^{29}	6.66×10^{28}	1.36×10^{28}
$L_{NN0}/cm^{-2}s^{-1}$	2.41×10^{34}	6.93×10^{33}	4.64×10^{33}	1.89×10^{33}	1.11×10^{33}	5.88×10^{32}
P_{BFPP}/W	0.0199	0.601	0.935	11.	60.6	350.
P_{EMD1}/W	32.	55.6	52.2	78.3	107.	141.
τ_{L0}/h	6.45	11.6	13.1	9.74	4.96	1.57
T_{opt}/h	5.68	7.62	8.08	6.98	4.98	2.8
$\langle L_{AA} \rangle$ cm^{-2}s^{-1}	4.54×10^{31}	2.45×10^{30}	1.69×10^{30}	1.68×10^{29}	2.95×10^{28}	3.8×10^{27}
$\langle L_{NN} \rangle$ cm^{-2}s^{-1}	1.16×10^{34}	3.93×10^{33}	2.71×10^{33}	1.02×10^{33}	4.91×10^{32}	1.64×10^{32}
$\int_{month} L_{AA}$ dt/nb^{-1}	5.89×10^{4}	3180.	2190.	218.	38.2	4.92
$\int_{month} L_{NN}$ dt/pb^{-1}	1.51×10^{4}	5090.	3510.	1330.	636.	213.
R_{had}/kHz	1.33×10^{5}	1.12×10^{4}	7540.	1260.	378.	106.
μ	10.6	0.893	0.598	0.1	0.03	0.00842

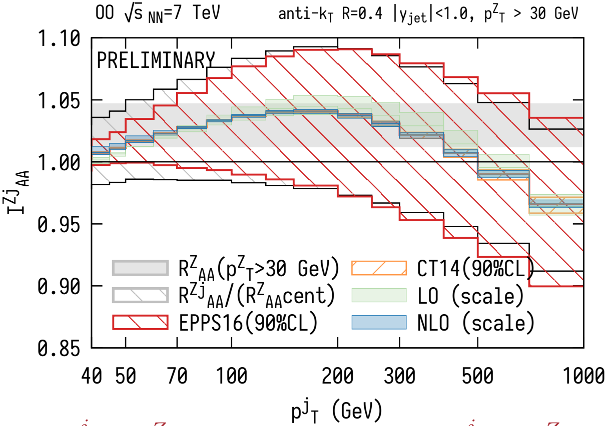
Beam loss cross-section subdominant to hadronic cross-section

Machine	Ion	Beam Energy	Design Luminosity	σ (e^- capture)	$\sigma(GDR)$
RHIC	gold	100 GeV/n	$2 \times 10^{26} cm^{-2}s^{-1}$	45 b	58 b
RHIC	iodine	104 GeV/n	$2.7 \times 10^{27} cm^{-2}s^{-1}$	6.5 b	15 b
RHIC	silicon	125 GeV/n	$4.4 \times 10^{28} cm^{-2}s^{-1}$	1.8 mb	150 mb
LHC	lead	2.76 TeV/n	$1 \times 10^{27} cm^{-2}s^{-1}$	102 b	113 b
LHC	niobium	3.1 TeV/n	$6.5 \times 10^{28} cm^{-2}s^{-1}$	3.1 b	10 b
LHC	calcium	3.5 TeV/n	$2 \times 10^{30} cm^{-2}s^{-1}$	36 mb	800 mb
LHC	oxygen	3.5 TeV/n	$3 \times 10^{31} cm^{-2}s^{-1}$	81 μb	37 mb

Light-ion collisions are different from heavy-ion collisions!

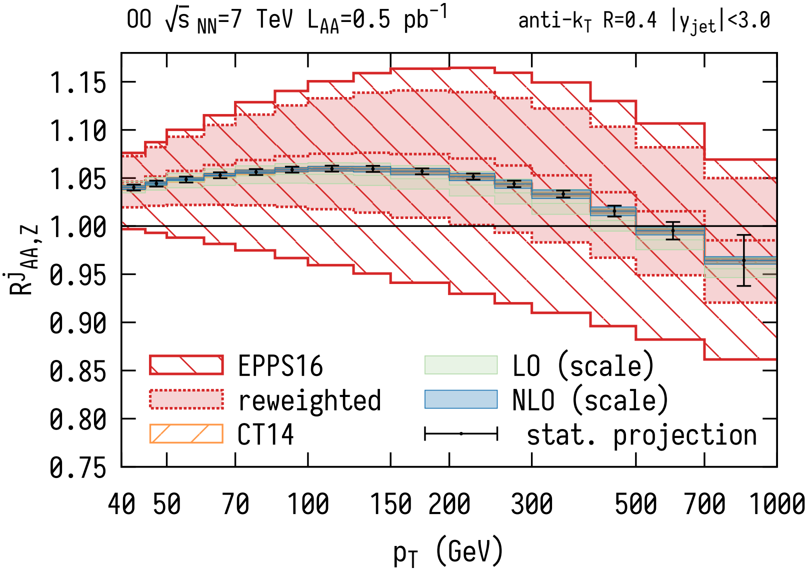
Coincidence measurement of $Z + j$

$$R^{h,j}_{\mathrm{AA},Z}(p_T) = \frac{\sigma_{pp}^{Z,p_T^Z>30\,\mathrm{GeV}}(\mathrm{CT14})}{\sigma_{\mathrm{AA}}^{Z,p_T^Z>30\,\mathrm{GeV}}(\mathrm{EPPS16+CT14})} \times \frac{d\sigma^{j+Z}_{\mathrm{AA}}/dp_T(\mathrm{EPPS16+CT14})}{d\sigma^{j+Z}_{pp}/dp_T(\mathrm{CT14})}.$$

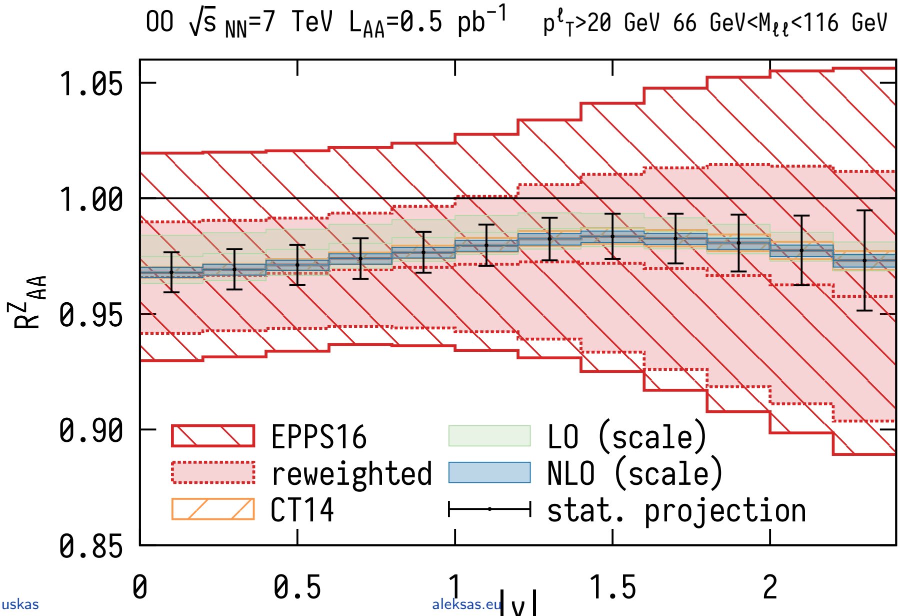


Some cancellation for $p_T^j \sim p_T^Z$, but no advantage for $p_T^j \gg p_T^Z$.

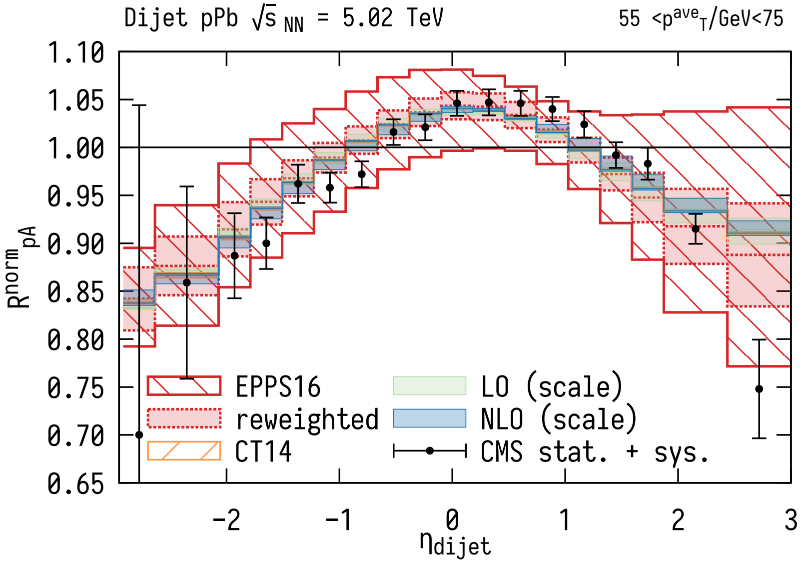
Z boson normalized



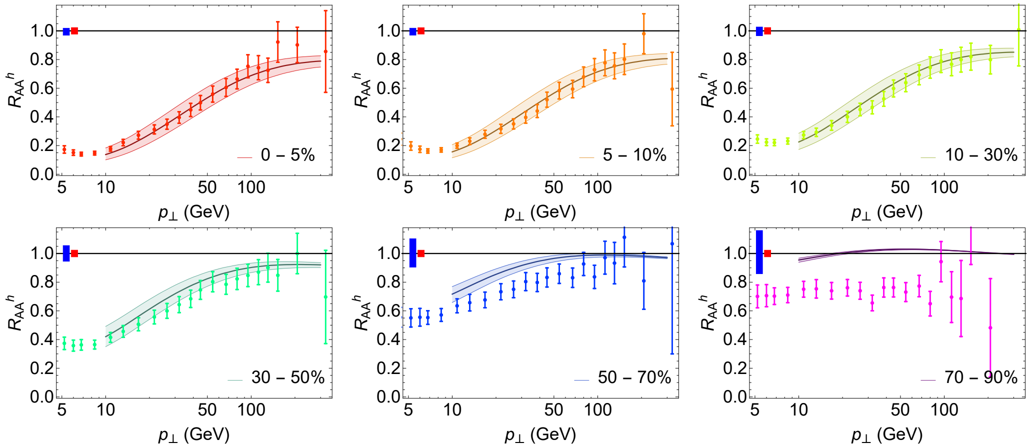
Z boson nuclear modification



Reweighting with CMS di-jet data

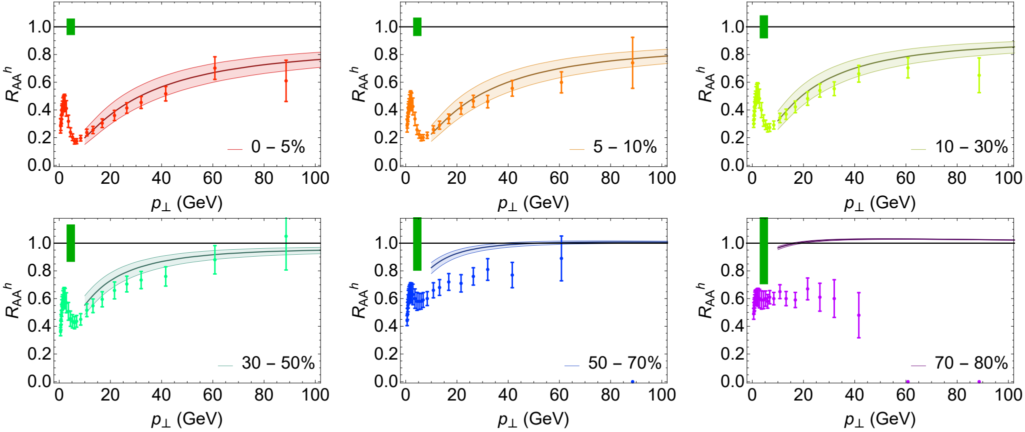


Validation of simple model centrality dependence in PbPb



Good central to mid-central description of hadron energy loss.

Validation of simple model centrality dependence in PbPb



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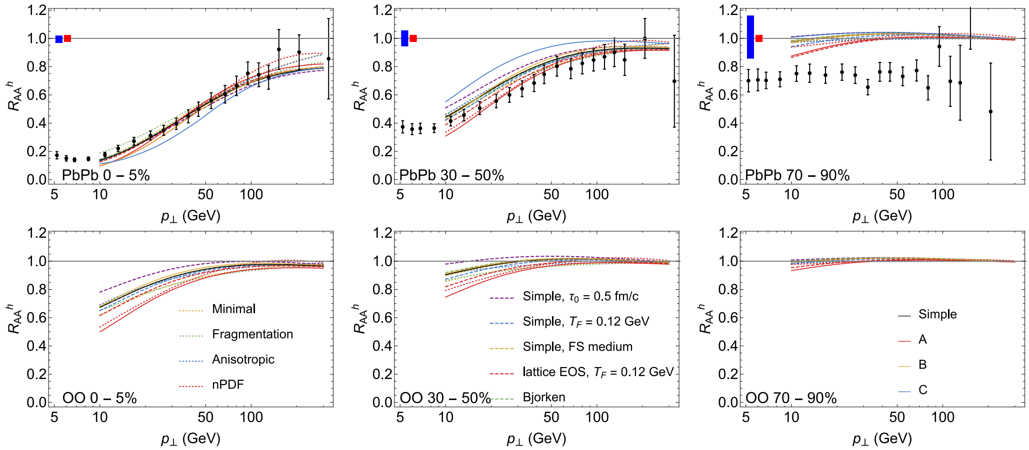

Good central to mid-central description of hadron energy loss.