Baseline calculations for oxygen and neon isotopes

Adam Takacs (Heidelberg)

Based on: 2410.22405


Jannis Gebhard

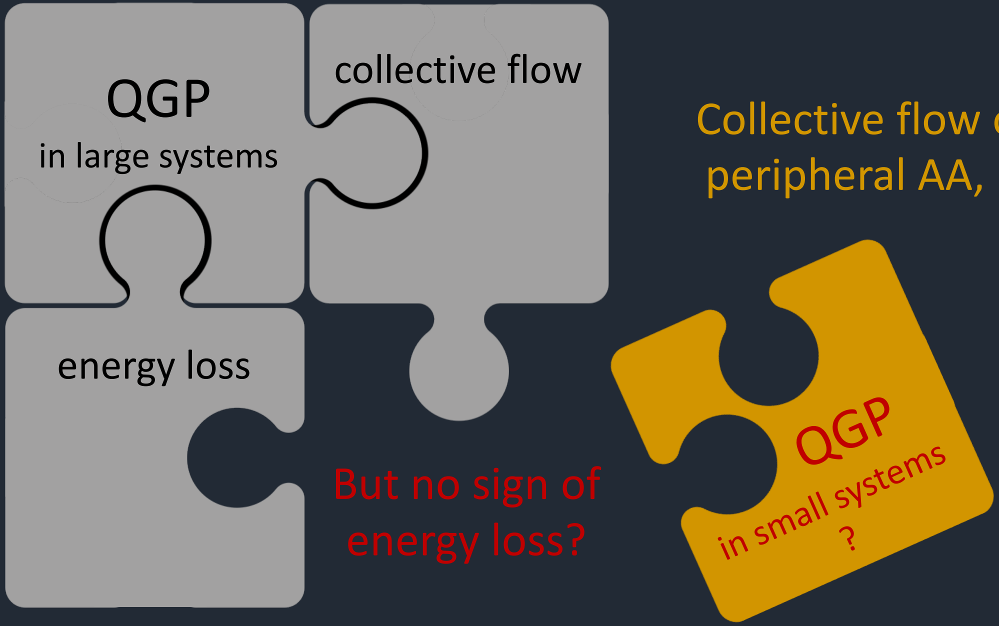

Aleksas Mazeliauskas

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

DFG Deutsche Forschungsgemeinschaft

Light ion collisions at the LHC, CERN 2024

Small system puzzle



QGP

in large systems

collective flow

energy loss

Collective flow observed in peripheral AA, pA and pp!

But no sign of energy loss?

QGP

in small systems

?

Small system puzzle

troubles with quenching in
pp, pA, peripheral AA

(*e.g. small system* R_{AA} *vs.* v_2 *puzzle*)

Challenges:

- Path lengths are short
- Understanding the geometry
- Soft and hard sector overlaps

Small system puzzle

troubles with quenching in
pp, pA, peripheral AA

(e.g. small system R_{AA} vs. v_2 puzzle)

Challenges:

- Path lengths are short
- Understanding the geometry
- Soft and hard sector overlaps

A NEW
HOPE

light-ion collisions

- $Pb^{208} > Xe^{129} > Ar^{40} > Ne^{20} > O^{16} > p^{1}$
- geometry is more controlled
- centrality is less of an issue
- OO collisions at LHC and RHIC 2103.01939

Detecting energy loss in OO

1. No-quenching baseline
2. Measure deviation from baseline
3. Interpret results (model predictions)

Observables:

- Jet suppression
- Hadron suppression
- Semi-inclusive jet and hadron observables

Master formula of no-quenching baseline

$$\sigma_n = \int dx_i dx_j \, f_i^{h_1}(x_i)\, f_j^{h_2}(x_j) \otimes \hat{\sigma}_{ij\to n} \otimes \left[1 + \mathcal{O}\left(\frac{\Lambda}{Q}\right)\right]$$

(n)pdf

LO $\lesssim 20\%$
NLO $\lesssim 10\%$
N^{2}LO $\lesssim 5\%$

$ij \to n$

LO $\lesssim 40\%$	LL $\lesssim 100\%$
NLO $\lesssim 20\%$	NLL $\lesssim 20\%$
N^{2}LO $\lesssim 5\%$	N^{2}LL $\lesssim 5\%$

pow. corr.

hadronization,
MPI,
centrality, etc.

Master formula of no-quenching baseline

$$\sigma_n = \int dx_i dx_j \, f_i^{h_1}(x_i) \, f_j^{h_2}(x_j) \otimes \hat{\sigma}_{ij\to n} \otimes \left[1 + \mathcal{O}\left(\frac{\Lambda}{Q}\right)\right]$$

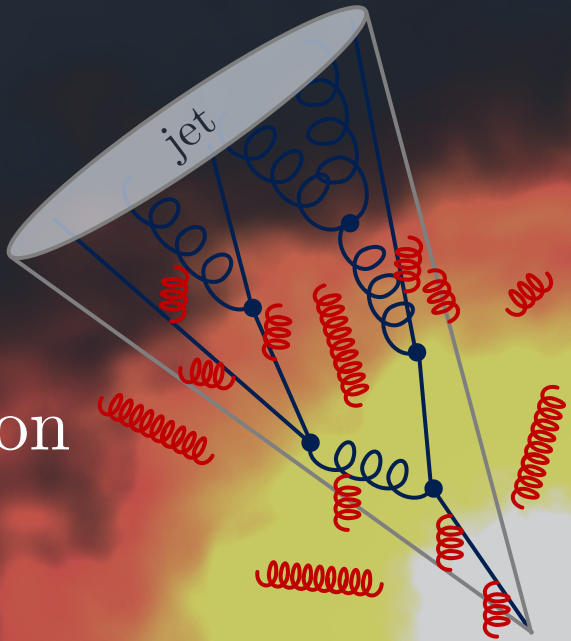
Use state-of-the-art for evaluation:

EPPS16,21,
TUJU21,
etc.

NLO MadGraph5 + Pythia8

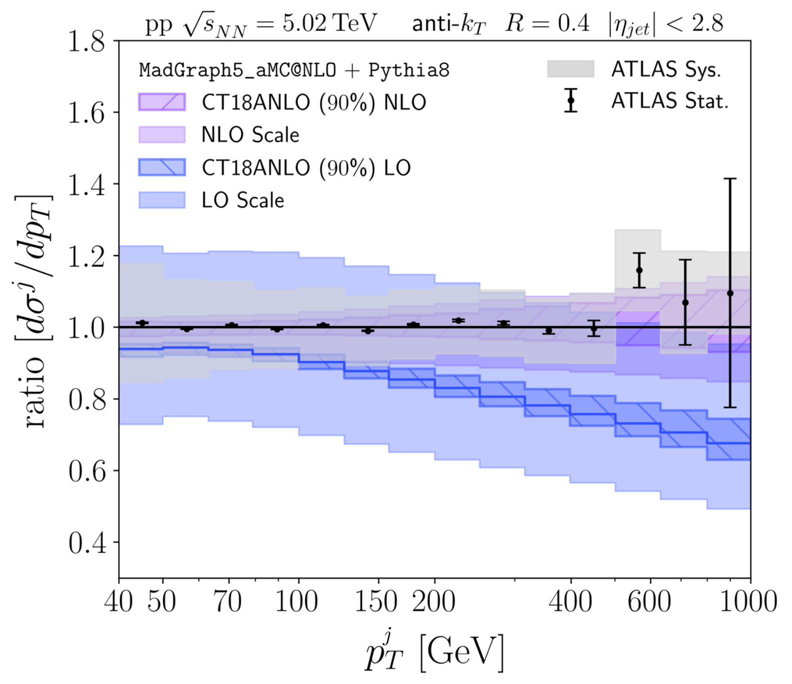
hadronization,
MPI,
MC tunes

1. Jet suppression



Jet spectrum at NLO in pp

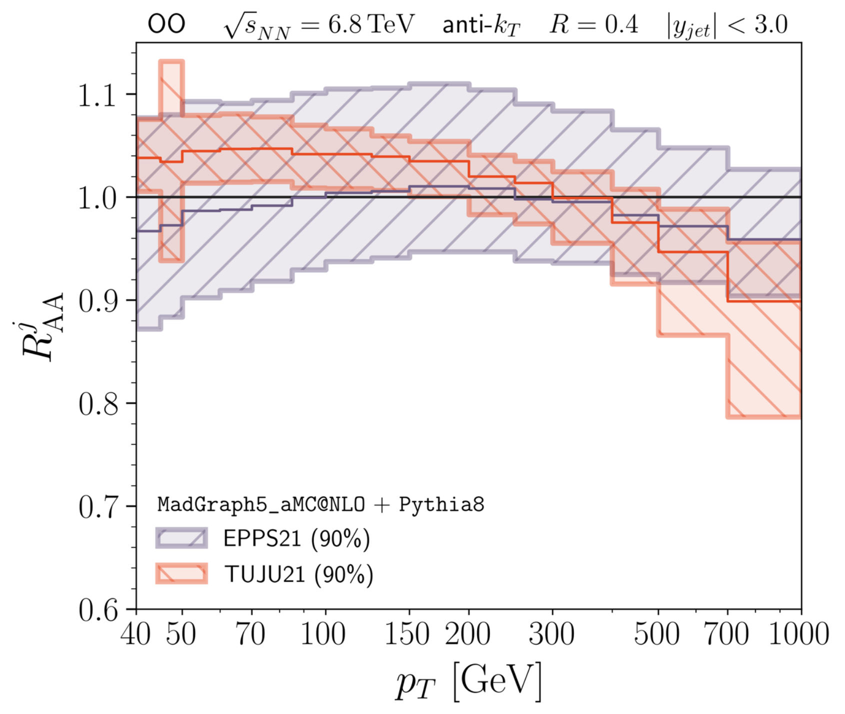
- NLO is better with data in pp
- scale uncertainty: LO 20% → NLO 10%
- pdf uncertainty: 5%



Jet suppression in OO

$$R^{j}_{AA}(p_T, y) = \frac{1}{A^2}\frac{d\sigma^{j}_{AA}/dp_T dy}{d\sigma^{j}_{pp}/dp_T dy}$$

- Baseline is not 1! (nPDF effects)

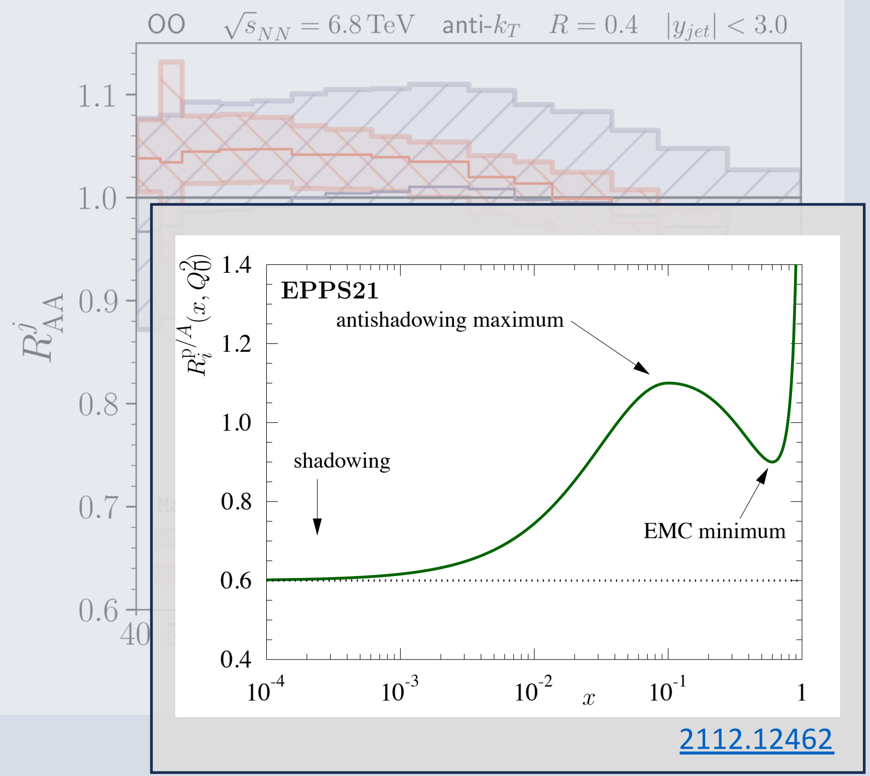


nNNPDF30 is in the backup.

Jet suppression in OO

$$R^{j}_{AA}(p_T, y) = \frac{1}{A^2}\frac{d\sigma^{j}_{AA}/dp_T dy}{d\sigma^{j}_{pp}/dp_T dy}$$

- Baseline is not 1! (nPDF effects)

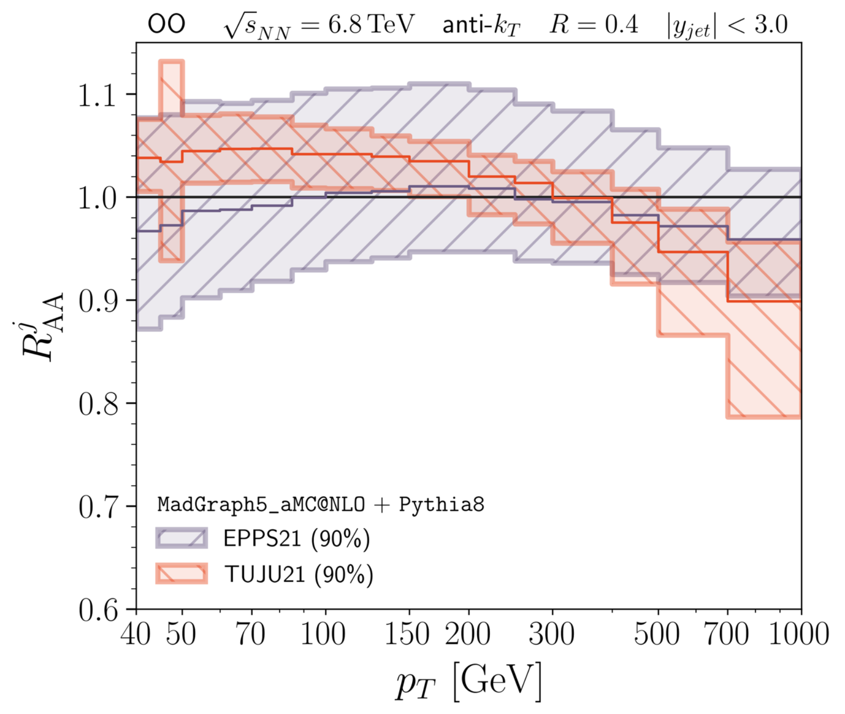


2112.12462

Jet suppression in OO

$$R^{j}_{AA}(p_T, y) = \frac{1}{A^2}\frac{d\sigma^{j}_{AA}/dp_T dy}{d\sigma^{j}_{pp}/dp_T dy}$$

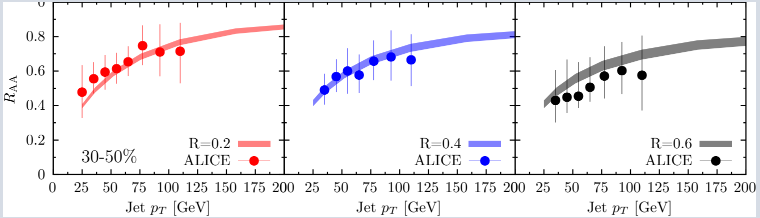
- Baseline is not 1! (nPDF effects)
- nPDF uncertainty is 10%
- difference between nPDF fits
- scale and hadr. uncertainty is small

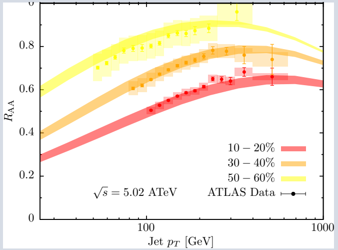


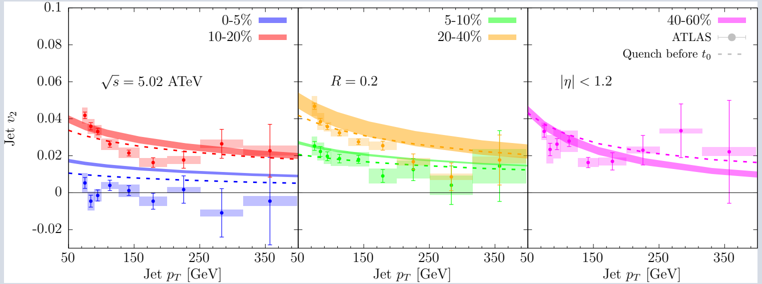
nNNPDF30 is in the backup.

Jet suppression prediction

- ✓ R_{AA} cone size dependence in PbPb
- ✓ R_{AA} centrality dependence in PbPb
- ✓ jet v_2 and R_{AA} in PbPb







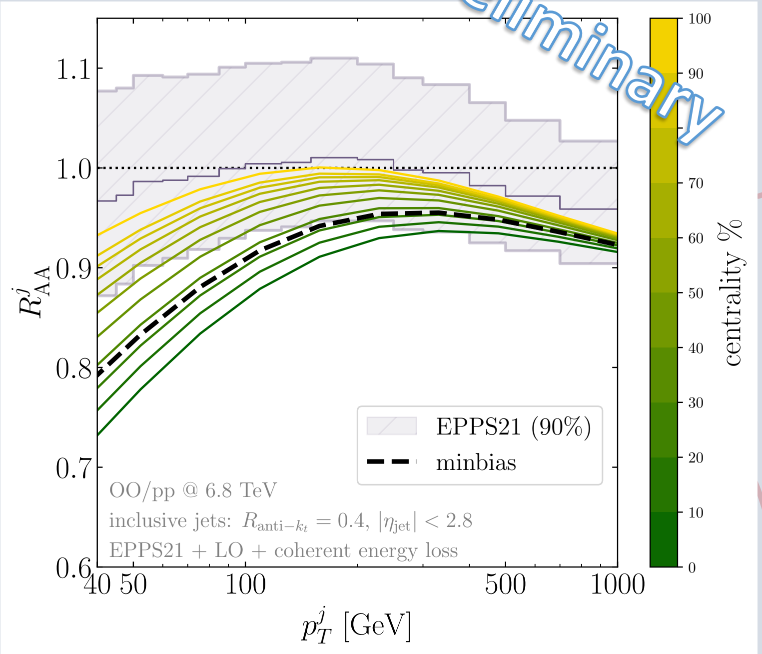
Model ingredients

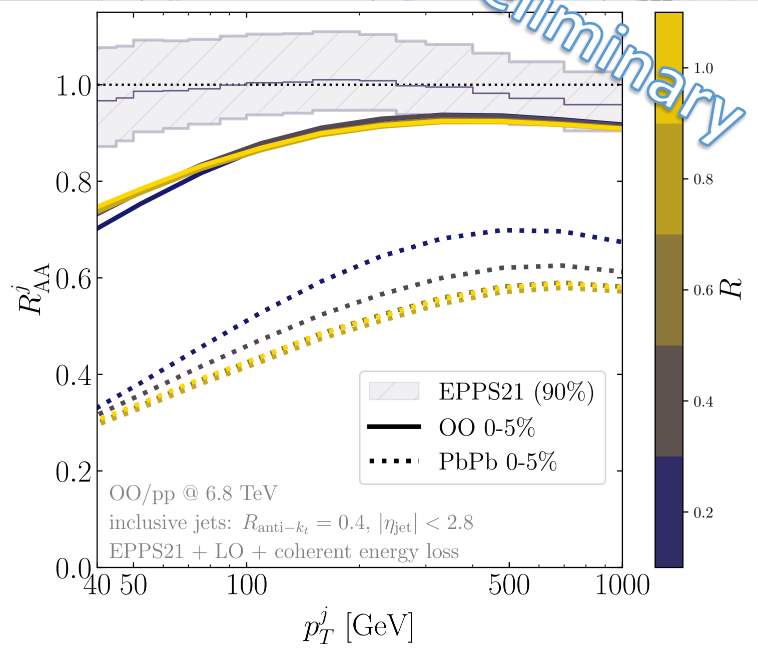
- Quenching weights
- Improved opacity expansion
- Coherent energy loss (collimator)
- Event-by-event IPGlasma+MUSIC

Mehtar-Tani, Pablos, Takacs, Tywoniuk: 2101.01742, 2103.14676, 2402.07869

In collab. with D. Pablos.

Jet suppression prediction





✓

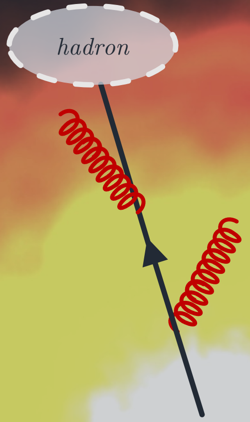
✓

✓

- Coherent energy loss (collimator)
- Event-by-event IPGlasma + MUSIC

- best signal at 50 GeV
- new cone-size behavior!

Mehtar-Tani, Pablos, Takacs, Tywoniuk: 2101.01742, 2103.14676, 2402.07869

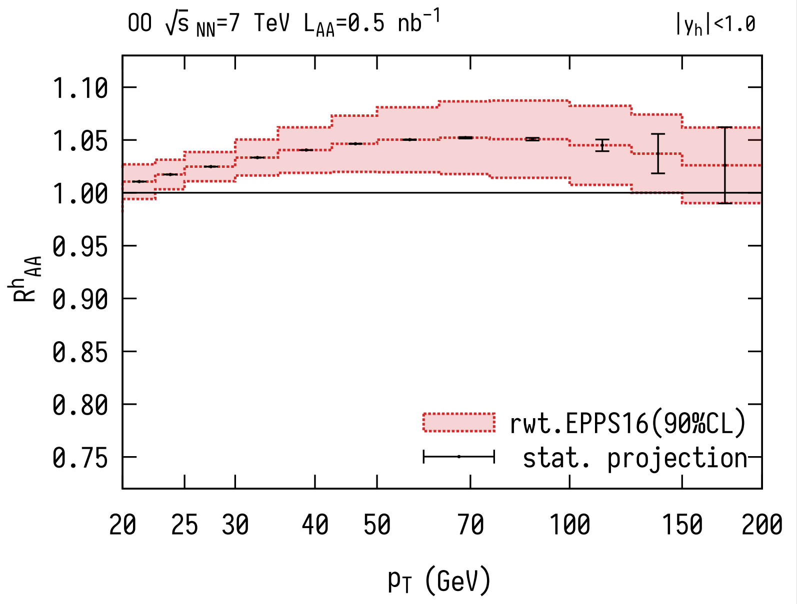


2. Charged hadron suppression

Charged hadron suppression

$$R^{h}_{AA}(p_T, y) = \frac{1}{A^2}\frac{d\sigma^h_{AA}/dp_T dy}{d\sigma^h_{pp}/dp_T dy}$$

- nPDF + NLO + FF baseline is not 1!
- nPDF uncertainty ~5%



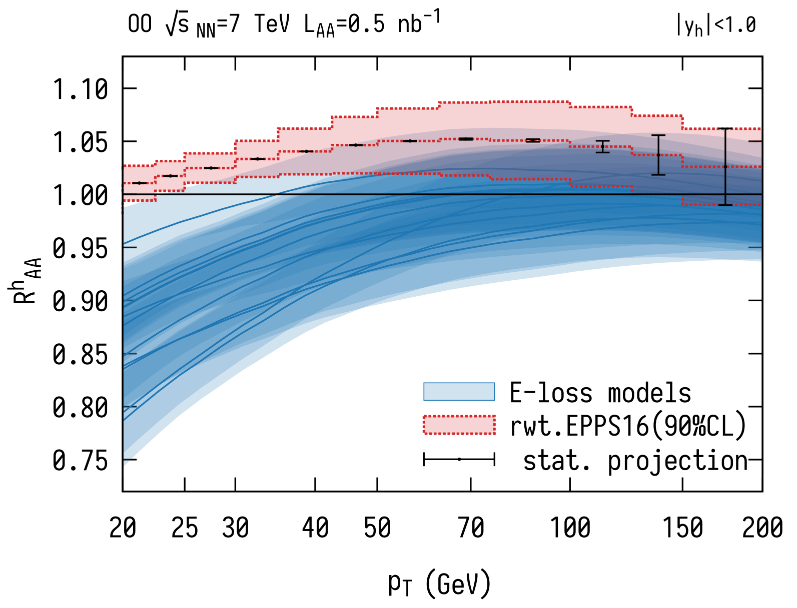
Huss, Kurkela, Mazeliauskas, Paatelainen, van der Schee, Wiedemann 2007.13754, 2007.13758

Many more works on hadron suppression, see in the references.

Charged hadron suppression

$$R^h_{AA}(p_T, y) = \frac{1}{A^2} \frac{d\sigma^h_{AA}/dp_T dy}{d\sigma^h_{pp}/dp_T dy}$$

- nPDF + NLO + FF baseline is not 1!
- nPDF uncertainty ~5%
- model predictions vary



Huss, Kurkela, Mazeliauskas, Paatelainen, van der Schee, Wiedemann 2007.13754, 2007.13758

Many more works on hadron suppression, see in the references.

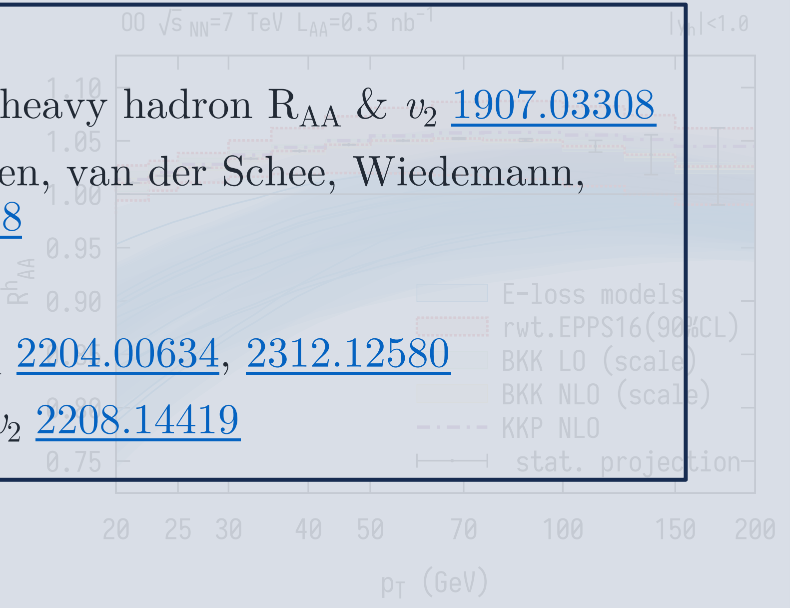
Charged hadron suppression

Hadron energy loss in OO:

- Katz, Prado, Noronha-Hostler, Suaide, heavy hadron R_{AA} & v_2 1907.03308
- Huss, Kurkela, Mazeliauskas, Paatelainen, van der Schee, Wiedemann, hadron R_{AA} & v_2 2007.13754, 2007.13758
- Zakharov, hadron R_{AA} & v_2 2105.09350
- Ke, Vitev, hadron & heavy hadron R_{AA} 2204.00634, 2312.12580
- Xie, Ke, Zhang, Wang, hadron R_{AA} & v_2 2208.14419

$$R^h_{AA}(p_T, y) = \frac{1}{A^2}\frac{d\sigma^h_{AA}/dp_T dy}{d\sigma^h_{pp}/dp_T dy}$$

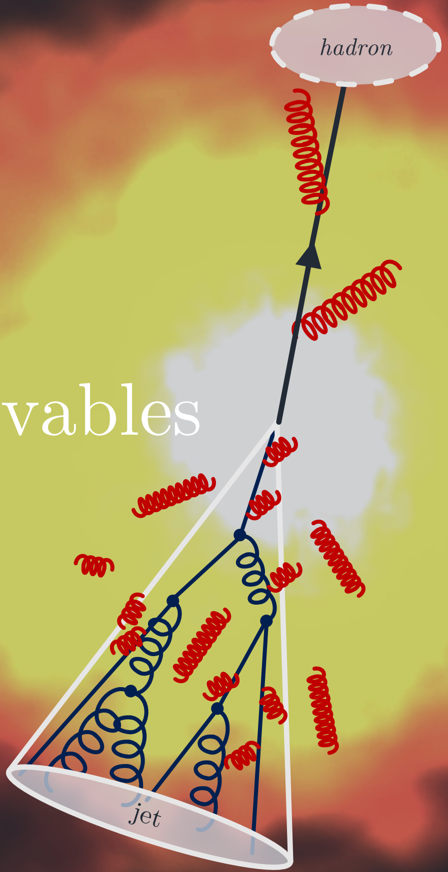
- nPDF + NLO + FF baseline is not 1!
- nPDF uncertainty ~10%
- model predictions vary



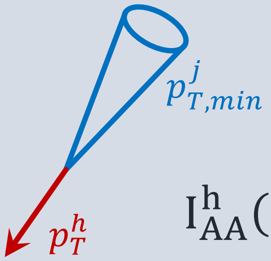
2007.13754, 2007.13758

Many more works on heavy hadron suppression, see in the references.

3. Semi-inclusive observables

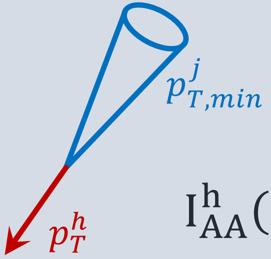


Jet triggered hadrons (ATLAS)



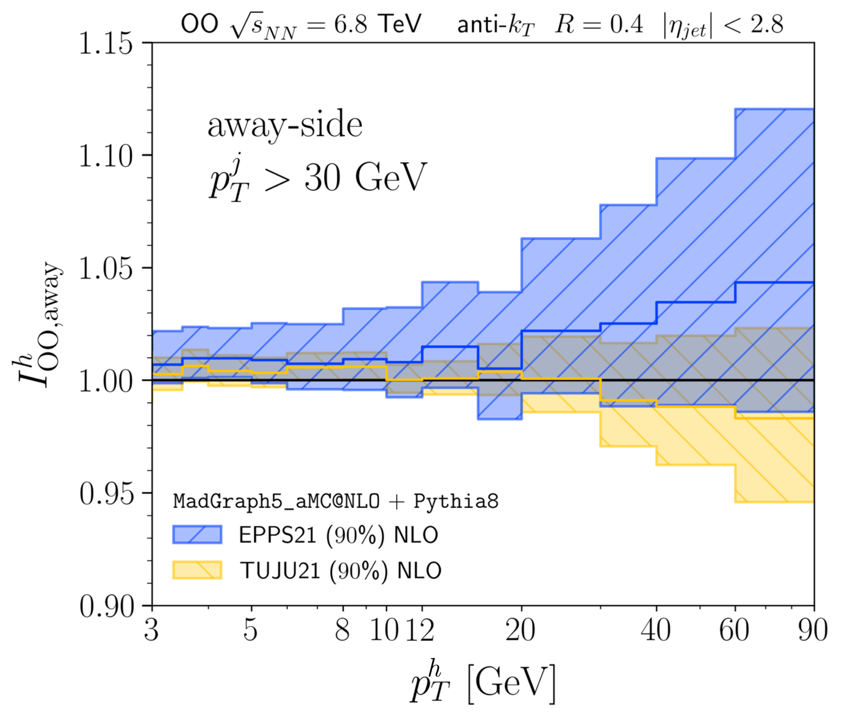
$$I^h_{AA}(p_T) = \frac{1/\sigma^j_{AA}}{1/\sigma^j_{pp}} \frac{d\sigma^{h+j}_{AA}/dp_T}{d\sigma^{h+j}_{pp}/dp_T}$$

Jet triggered hadrons

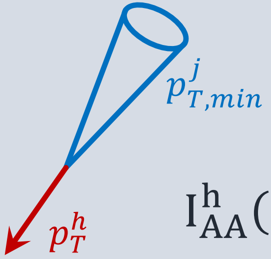


$$I^h_{AA}(p_T) = \frac{1/\sigma^j_{AA}}{1/\sigma^j_{pp}} \frac{d\sigma^{h+j}_{AA}/dp_T}{d\sigma^{h+j}_{pp}/dp_T}$$

- Baseline is not 1!

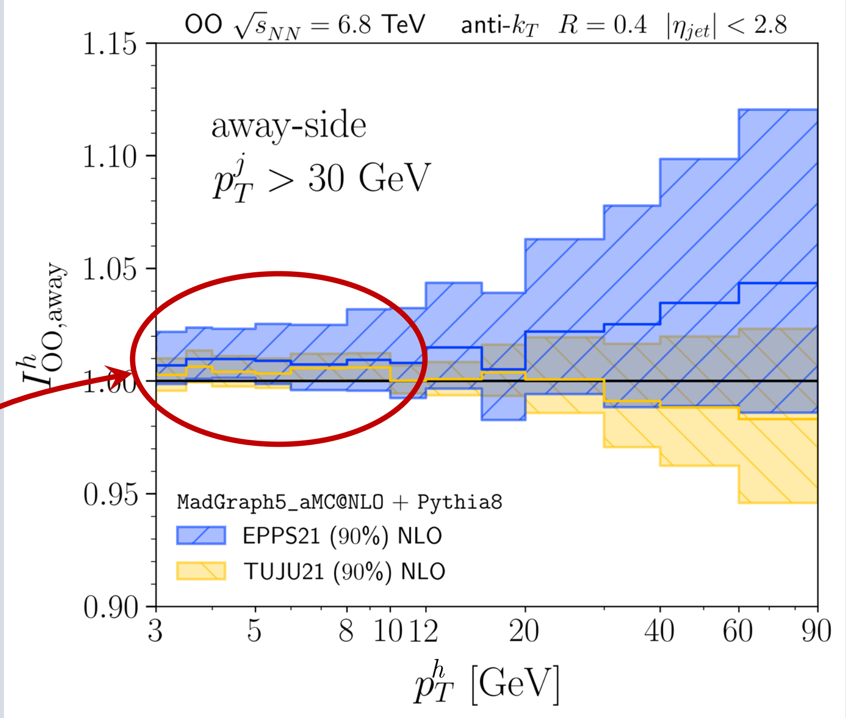


Jet triggered hadrons



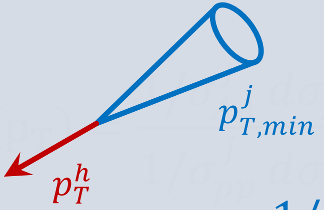
$$I^{h}_{AA}(p_T) = \frac{1/\sigma^{j}_{AA}\; d\sigma^{h+j}_{AA}/dp_T}{1/\sigma^{j}_{pp}\; d\sigma^{h+j}_{pp}/dp_T}$$

- Baseline is not 1!
- nPDF err. cancellation

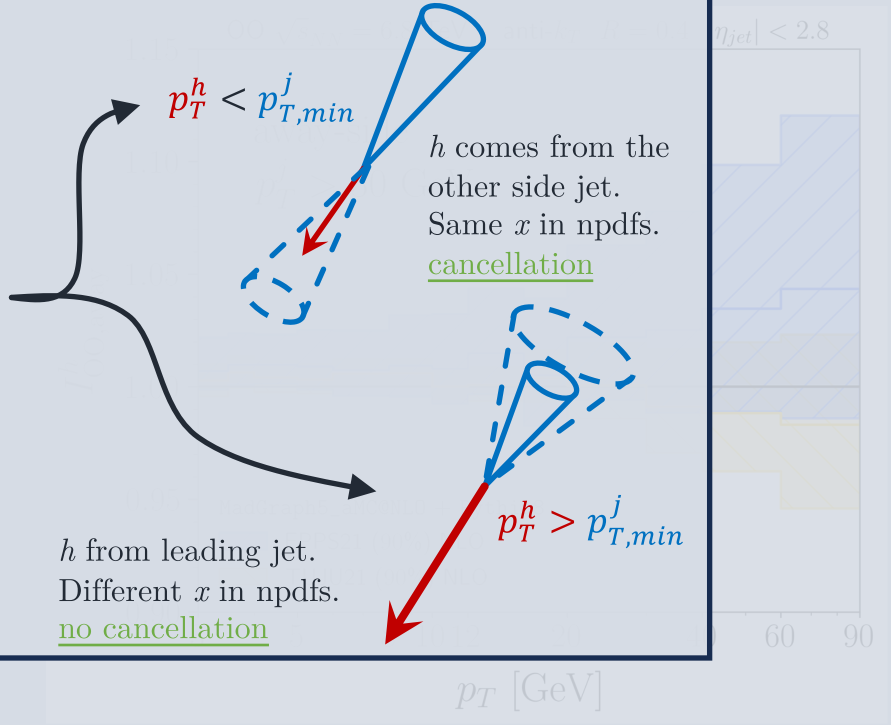


Semi-inclusive observables

Why nPDF uncertainties cancel?



$$I^h_{AA}(p_T) = \frac{1/\sigma^j_{AA}\, d\sigma^{h+j}_{AA}/dp_T}{1/\sigma^j_{pp}\, d\sigma^{h+j}_{pp}/dp_T}$$



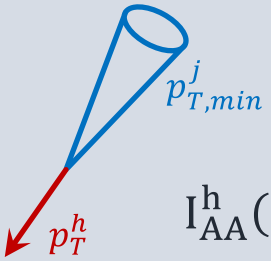
h comes from the other side jet. Same x in npdfs. cancellation

h from leading jet. Different x in npdfs. no cancellation

- The ratio is not strictly 1
- nPDF fits are slightly different
- nPDF uncertainties sometimes cancel to 3%

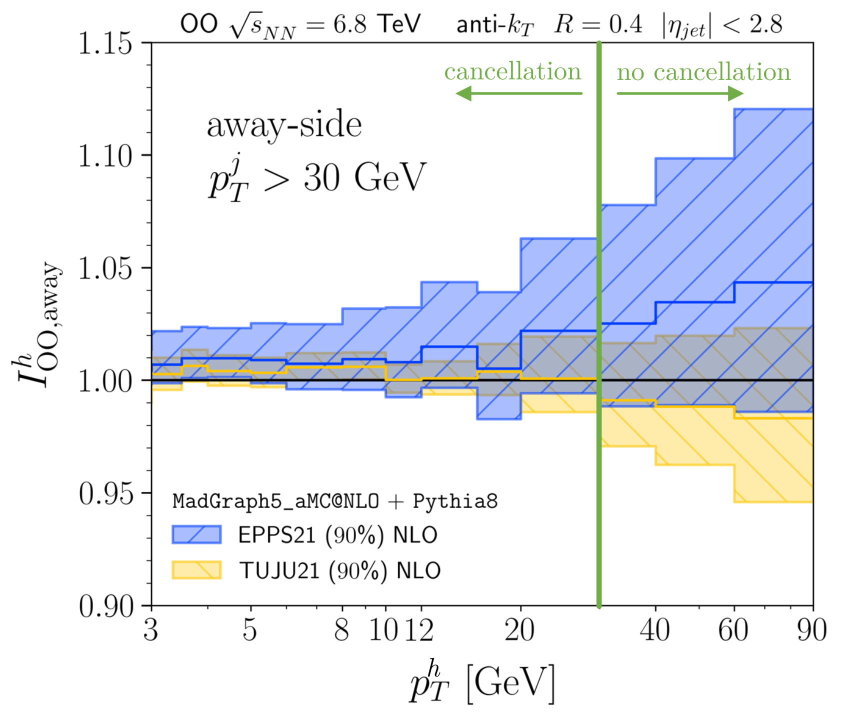
- scale uncertainty 2%
- hadronization uncertainty 5%

Jet triggered hadrons

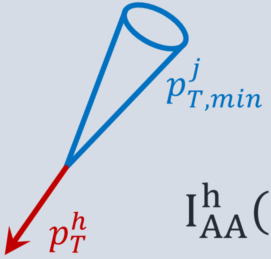


$$I^h_{AA}(p_T) = \frac{1/\sigma^j_{AA}\; d\sigma^{h+j}_{AA}/dp_T}{1/\sigma^j_{pp}\; d\sigma^{h+j}_{pp}/dp_T}$$

- Baseline is not 1!
- nPDF err. cancellation

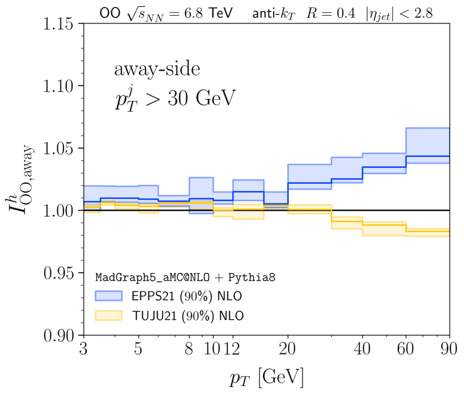


Jet triggered hadrons

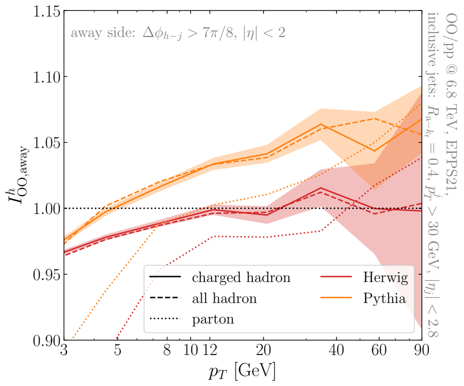


$$I_{AA}^{h}(p_T) = \frac{1/\sigma_{AA}^{j}\, d\sigma_{AA}^{h+j}/dp_T}{1/\sigma_{pp}^{j}\, d\sigma_{pp}^{h+j}/dp_T}$$

- Baseline is not 1!
- nPDF err. cancellation
- small scale & hadr. uncertainty

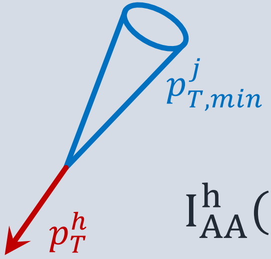


scale unc.



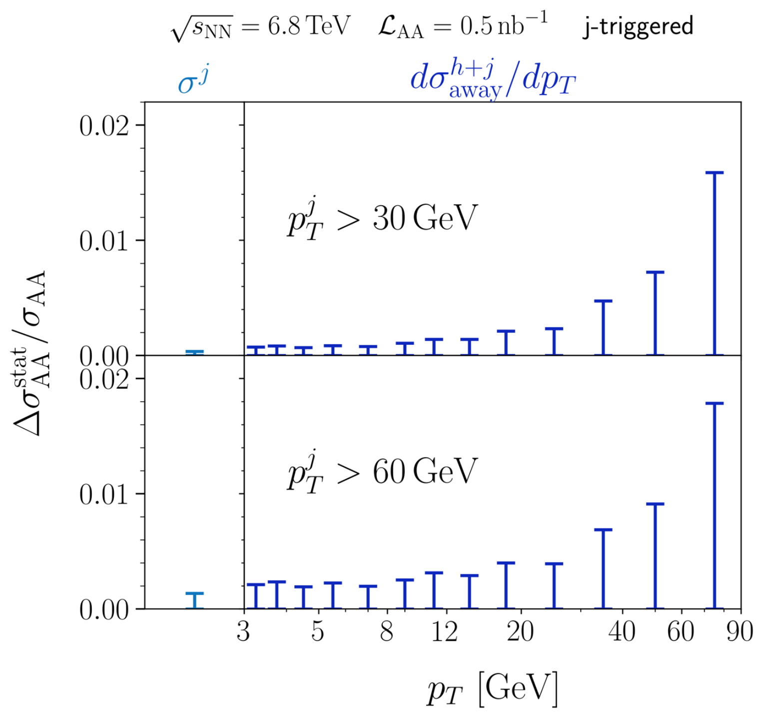
hadr and tune unc.

Jet triggered hadrons

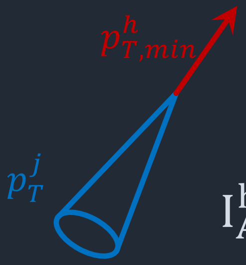


$$I^h_{AA}(p_T) = \frac{1/\sigma^j_{AA}\, d\sigma^{h+j}_{AA}/dp_T}{1/\sigma^j_{pp}\, d\sigma^{h+j}_{pp}/dp_T}$$

- Baseline is not 1!
- nPDF err. cancellation
- small scale & hadr. uncertainty
- small stat err.

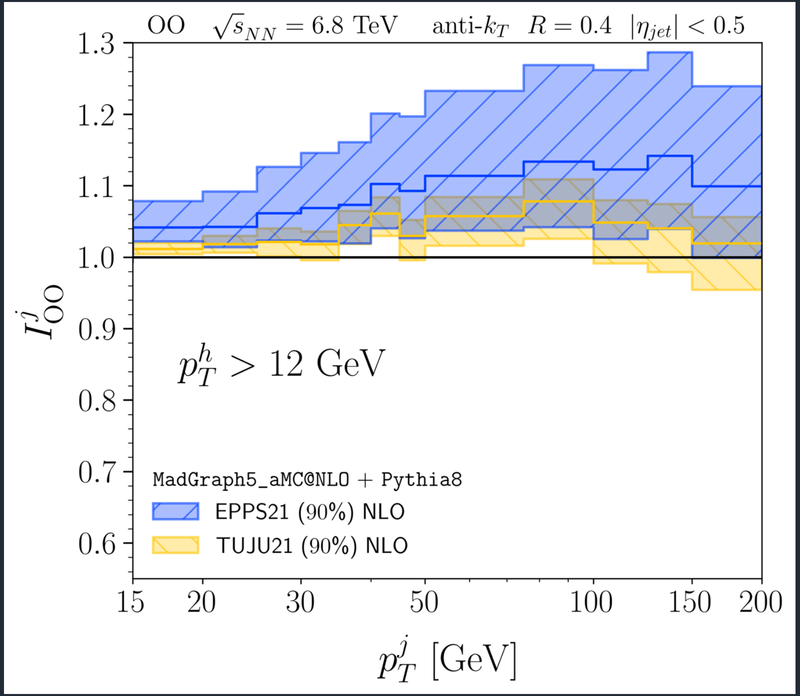


Hadron triggered jets (ALICE)



$$I^h_{AA}(p_T) = \frac{1/\sigma^h_{AA}}{1/\sigma^h_{pp}} \frac{d\sigma^{j+h}_{AA}/dp_T}{d\sigma^{j+h}_{pp}/dp_T}$$

- nPDF uncertainties cancel less.
- scale and hadr. unc. is larger
- Hadron trigger is less robust.



Summary: energy loss in small systems

1. hadrons and jets:
   - the baseline is not 1!
   - nPDF uncertainty is dominant
2. semi-inclusive observables:
   - baseline is not 1!
   - nPDF uncertainty is reduced

+1. alternative observable: v_2

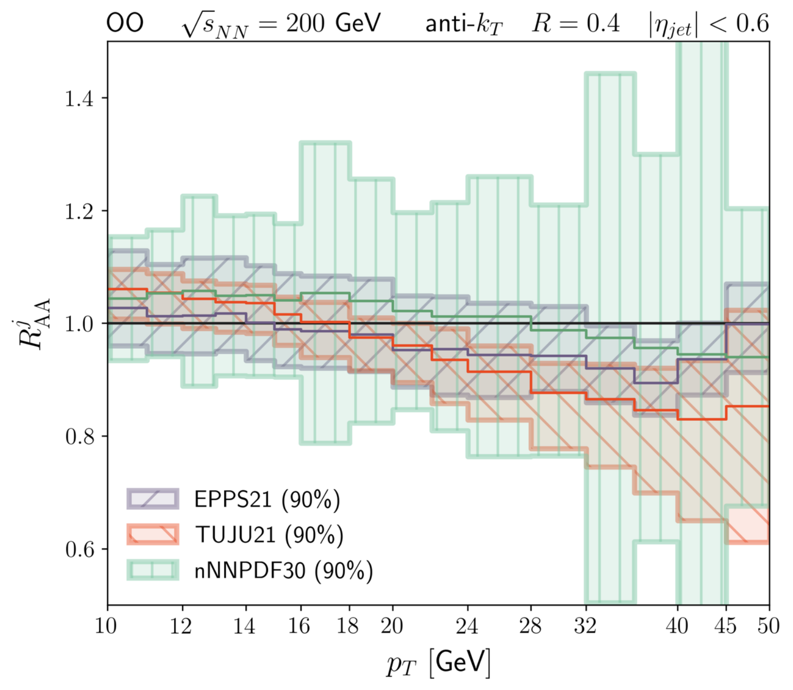
More OO energy loss references:

- Katz, Prado, Noronha-Hostler, Suaide, heavy hadron R_{AA} & v_2 1907.03308
- Huss, Kurkela, Mazeliauskas, Paatelainen, van der Schee, Wiedemann, hadron R_{AA} & v_2 2007.13754, 2007.13758
- Zakharov, hadron R_{AA} & v_2 2105.09350
- Brewer, Huss, Mazeliauskas, van der Schee, missing pp reference strategies in OO 2108.13434
- Ke, Vitev, hadron & heavy hadron R_{AA} 2204.00634, 2312.12580
- Xie, Ke, Zhang, Wang, hadron R_{AA} & v_2 2208.14419
- Ogrodnik, Rybář, Spousta, jet R_{AA} extrapolation 2407.11234
- Gebhard, Mazeliauskas, Takacs, hadron & jet R_{AA}, I_{AA} 2410.22405

Thank you for your attention!

Jet suppression

- The nNNPDF30 uncertainties are largely fluctuating.
- Possible LHAPDF6/MG5 issue.



Without pp reference

$$R_{AA} = \frac{1}{A^2} \frac{d\sigma_{AA}(7\ TeV)/dp_T}{\underbrace{d\sigma_{pp}(5\ TeV)/dp_T}_{\text{measured}} \cdot \underbrace{\frac{\sigma_{AA}}{\sigma_{pp}}}_{\text{scaling}}}$$

0. Can you measure the spectrum directly?
1. Calculate the scaling in pQCD.
2. Interpolate the measurements.
3. Take ratios of different energies.

Brewer, Huss, Mazeliauskas, van der Schee, 2108.13434