No-quenching baseline for energy-loss signals in oxygen-oxygen collisions

Aleksas Mazeliauskas, aleksas.eu
Institute for Theoretical Physics, Heidelberg University

September 29, 2024 SoftJet 2024, Tokyo

- Huss, Kurkela, AM, Paatelainen, van der Schee, Wiedemann,
  PRL (2021) arXiv:2007.13754
  PRC (2021) arXiv:2007.13758
- Brewer, Huss, AM, van der Schee
  PRD (2022), arXiv:2108.13434
- Belmont et al. NPA (2024), 2305.15491

- Gebhard, AM, Takacs, arXiv:2410.xxxx


Jannis Gebhard

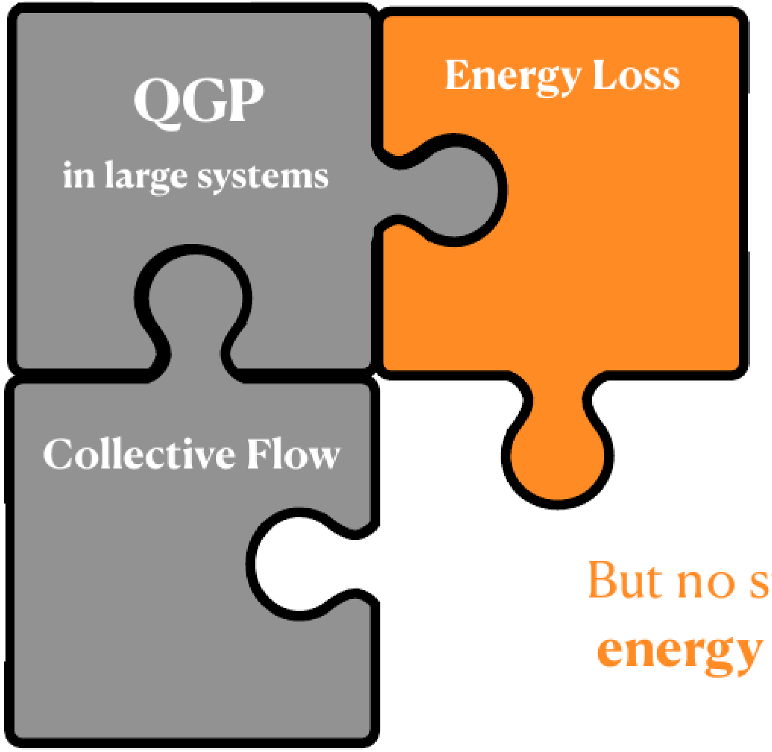

Adam Takacs

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

UNIVERSITÄT HEIDELBERG
ZUKUNFT
SEIT 1386

isoQuant
SFB1225
www.isoquant-heidelberg.de

Small system puzzle



QGP

in large systems

Energy Loss

Collective Flow

Observation of **collective flow** in proton-nucleus, peripheral nucleus-nucleus and even proton-proton!

But no sign of **energy loss?**

QGP

in small systems

?

Thanks to Jannis Gebhard for help preparing these slides

Motivation for light-ion collisions

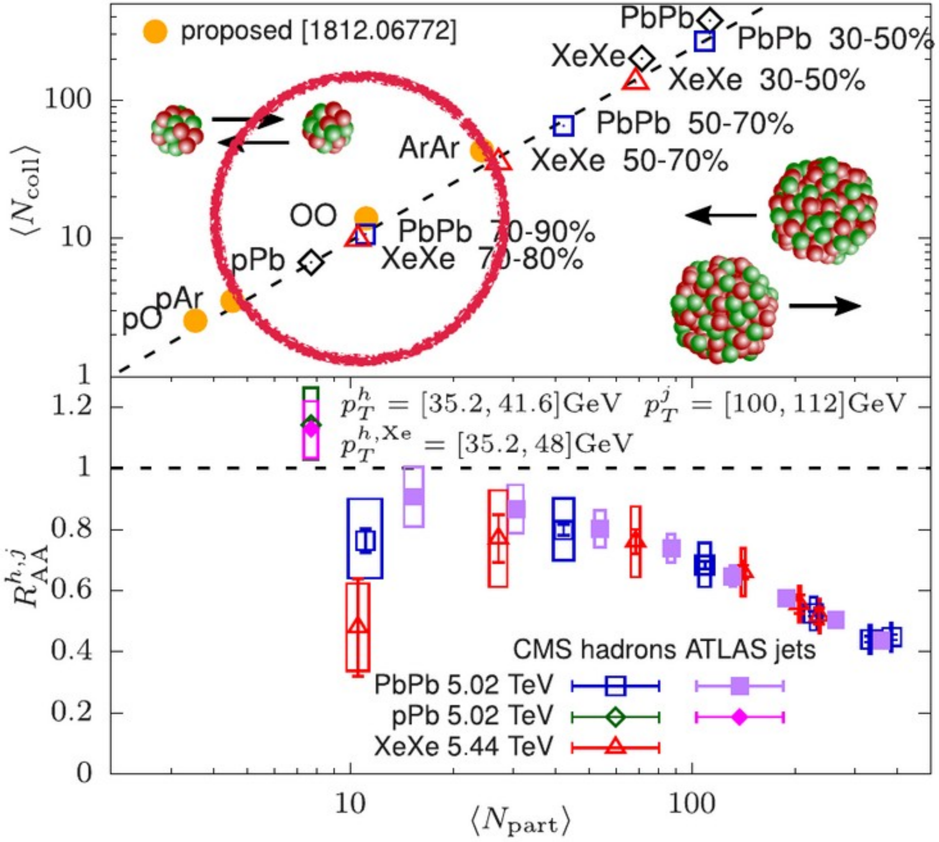
Inconclusive energy loss signals in pA and peripheral AA collisions

→ OO probes similar size

- symmetric collision system
- better understood geometry
- LHC → at 6.8 TeV in 2025
- STAR took data at 200 GeV in 2021

oppOrtunities
at the LHC

Feb 4-5&8-10, 2021
cern.ch/OppOatLHC



Huss et al. PRL (2021)

How to detect energy loss phenomena?

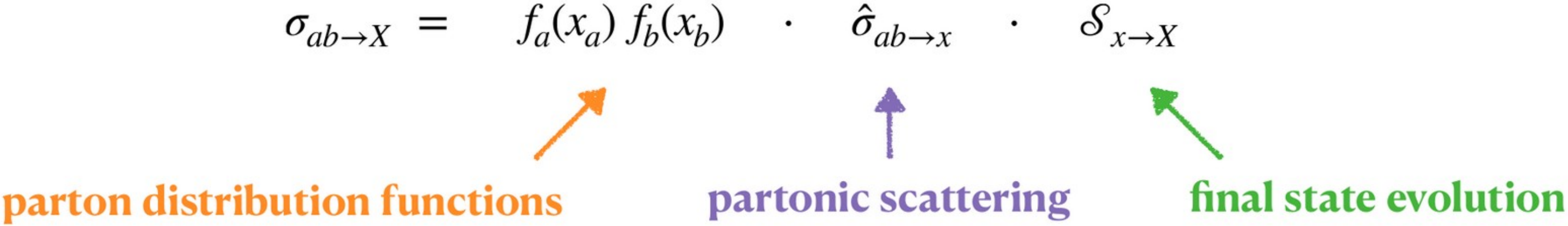
No-quenching baseline

a prediction **excluding** medium effects

Measure deviation from the baseline.

Perturbative QCD baseline

For high-momentum-exchange processes can use QCD factorization



$$\sigma_{ab\to X} = f_a(x_a)\, f_b(x_b) \cdot \hat{\sigma}_{ab\to x} \cdot \mathcal{S}_{x\to X}$$

- systematically improvable (LO, NLO,…) baseline predictions
- quantifiable uncertainty (scale, nPDF,…)

We will compute NLO pQCD baseline for R_{AA} and I_{AA} in OO

Conclusions (in the interest of time)

- OO collisions → opportunity to understand energy loss in small systems
- Discovery of small effects needs precise no-quenching baseline
- Uncertainties in nPDFs is the dominant baseline uncertainty
- Semi-inclusive observables are not free of nPDF uncertainties but few percent uncertainty can be achieved for jet-triggered hadron I_{AA}

Inclusive
nuclear modification factor
R_{AA}

Sources of uncertainties in the baseline

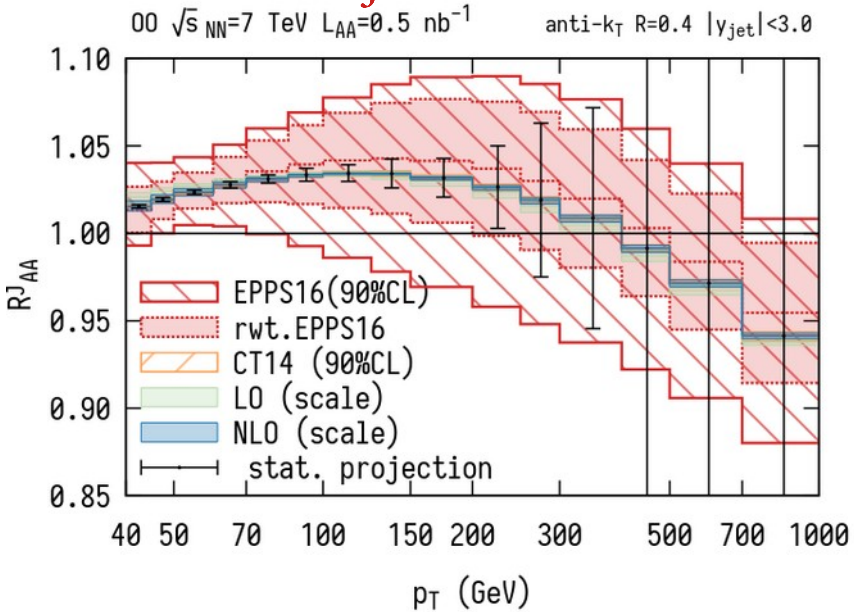
$$R^{h,j}_{\text{AA, min bias}}(p_T) = \frac{1}{A^2}\frac{d\sigma^{h,j}_{\text{AA}}/dp_T(\mu_R,\mu_F)}{d\sigma^{h,j}_{pp}/dp_T(\underbrace{\mu_R,\mu_F}_{\text{renormalization, factorization scales}})} \begin{array}{l} \leftarrow \text{oxygen nPDF} \\ \leftarrow \text{proton PDF} \end{array}$$

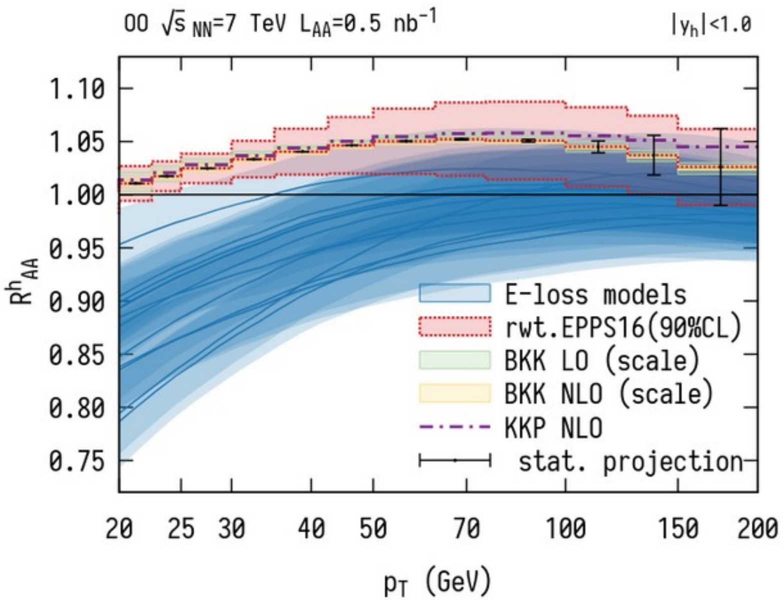
- Overlap of LO, NLO scale “uncertainties” ⟶ perturbative convergence.
  ⟶ Expect cancellation of scale dependence in the ratio.
- Propagate uncertainties in proton and nuclear modified PDFs.
  ⟶ Expect partial cancellation in the ratio.
- Hadronization, showering and fragmentation uncertainties.
  ⟶ Independent of the collision system and should cancel.

Jet and hadron R_{AA} @ 7TeV in 2020

- NLO partonic jets with NNLOJET
- NLO hadrons with INCNLO
- Extrapolation of hadron energy loss to minimum bias OO

Huss et al., PRL (2021), PRC (2021)


jets

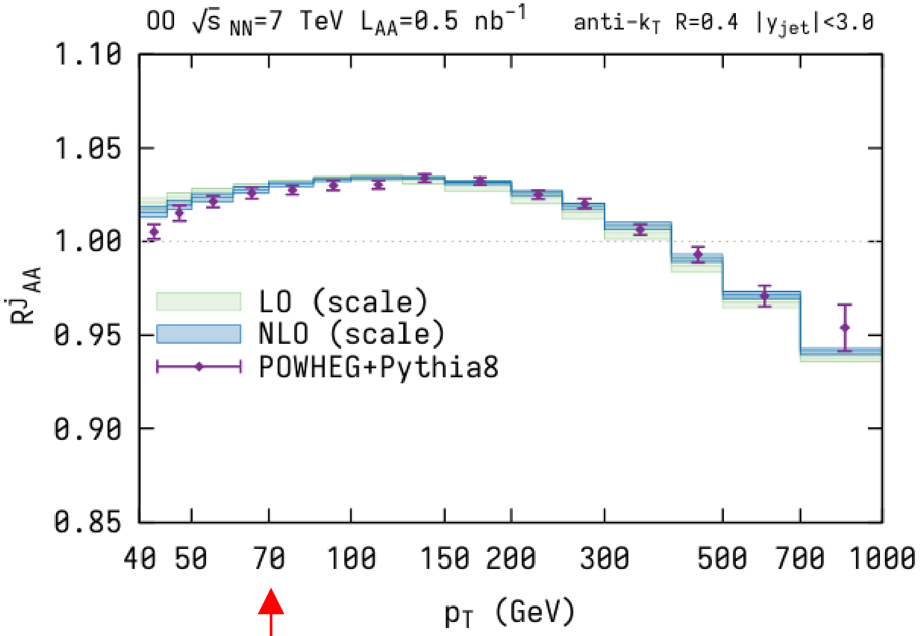

hadrons

Measurable energy loss signal in 20 GeV < p_T < 50 GeV region at the LHC

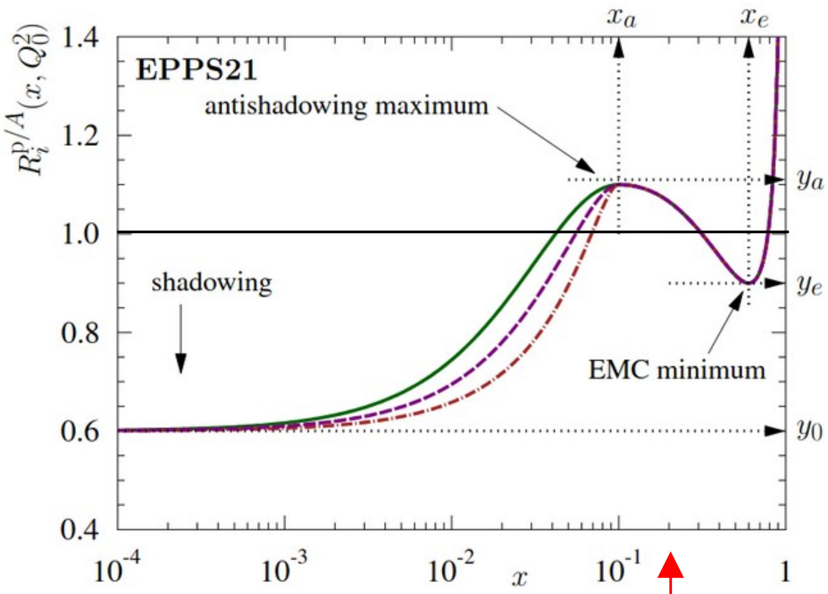
Hadronization and parton shower effects

- NLO hadronic jets with POWHEG+Pythia8

jets



nuclear modification of PDF



$$x \sim 2p_T/\sqrt{s}$$

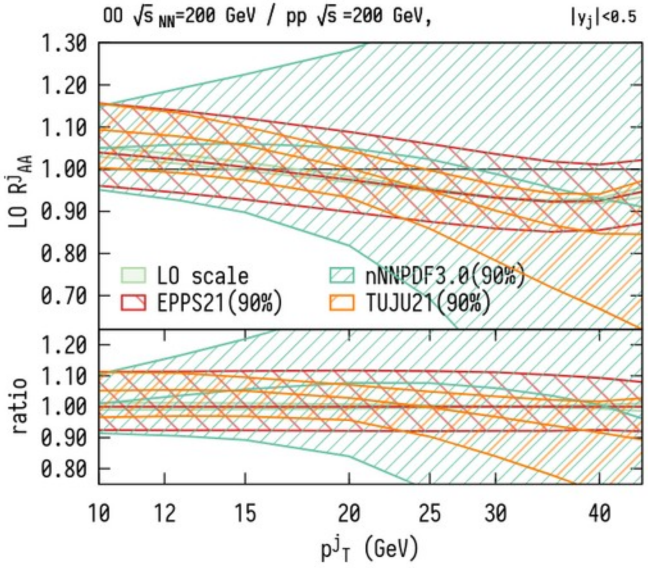
Scale, shower and hadronization uncertainties cancel

Jet and hadron R_{AA} @ 200TeV in 2023

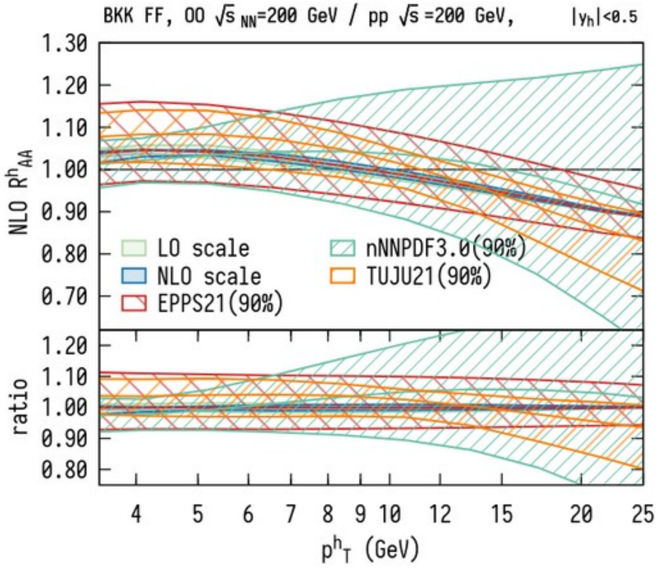
- LO partonic jets
- NLO hadrons with INCNLO
- New sets of nPDFs (2021)

Predictions for sPHENIX, Belmont et al. NPA (2024)

jets



hadrons



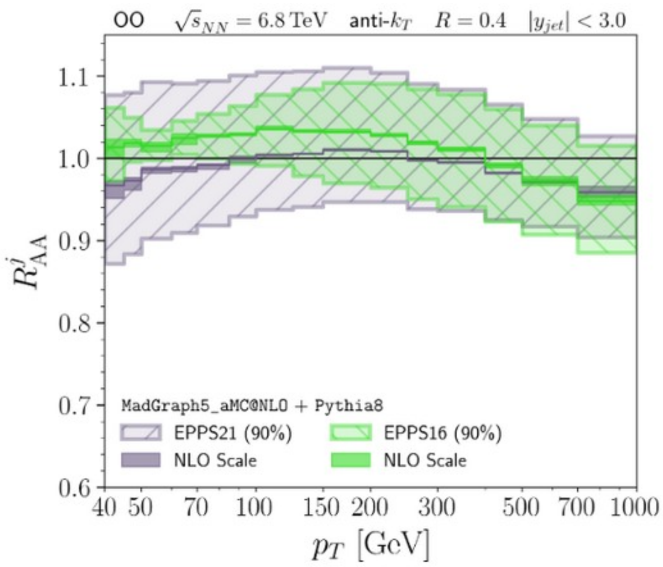
Sizable nPDF uncertainties for oxygen-oxygen → unconstrained A-dependence

Jet R_{AA} @ 6.8TeV in 2024

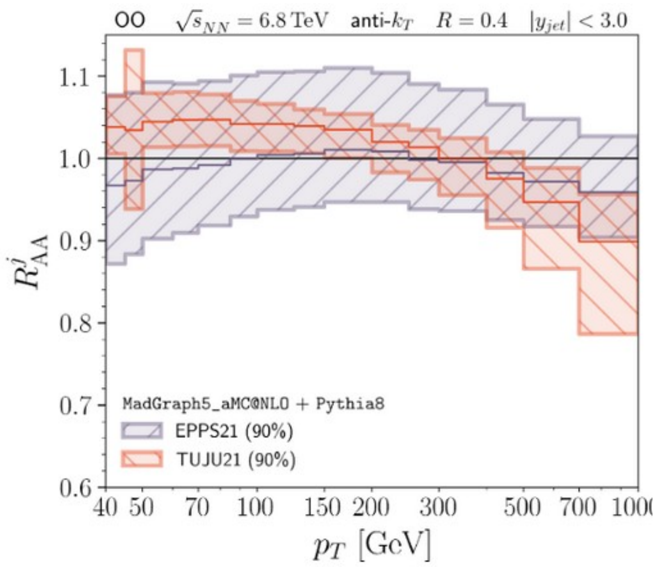
- NLO jets with MadGraph@NLO + Pythia8

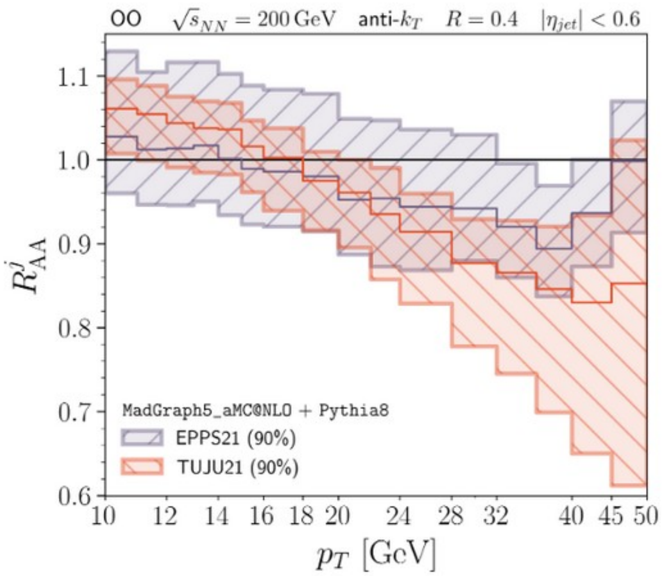
Gebhard, AM, Takacs, in preparation

EPPS16 vs 21



EPPS21 vs TUJU21 at 6.8 TeV and 200 GeV





~ 10 % uncertainty in the baseline with non-trivial behaviour

Semi-inclusive
nuclear modification factor
I_{AA}

Coincidence measurement

- Trigger particle (e.g. jet with $p_T^j > p_{T,\min}$) → $\sigma^j|_{p_T^j > p_{T,\min}}$
- Probe correlated with the trigger (e.g. hadrons opposite to the jet) → $\frac{d\sigma^{h+j}}{dp_T}$

adapted from Nagle (2023)

$$
\boxed{Y_{\mathrm{AA}}(p_T) = \frac{1}{\sigma^j}\frac{d\sigma^{h+j}}{dp_T} \quad \text{(per-trigger yield)} \qquad I_{\mathrm{AA}}(p_T) = \frac{Y_{\mathrm{AA}}}{Y_{pp}}}
$$

Self-normalising observable → uncertainty cancellations

Jet-triggered hadron I_{AA} @ 6.8 TeV

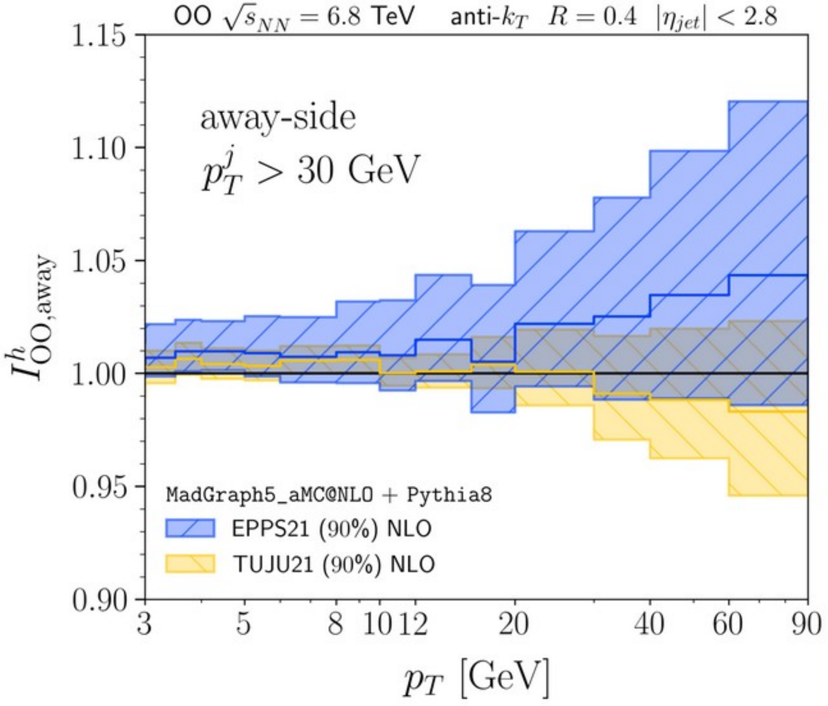
- NLO jets with MadGraph@NLO + Pythia8

Gebhard, AM, Takacs, in preparation

- Jet-Trigger: $p^j_{T,\mathrm{min}} = 30$ GeV
- Hadrons with transverse momentum p_T opposite to jet

observe ..

- Differences among different nPDFs
- $I_{AA} \neq 1$
- Increasing nPDF uncertainties!

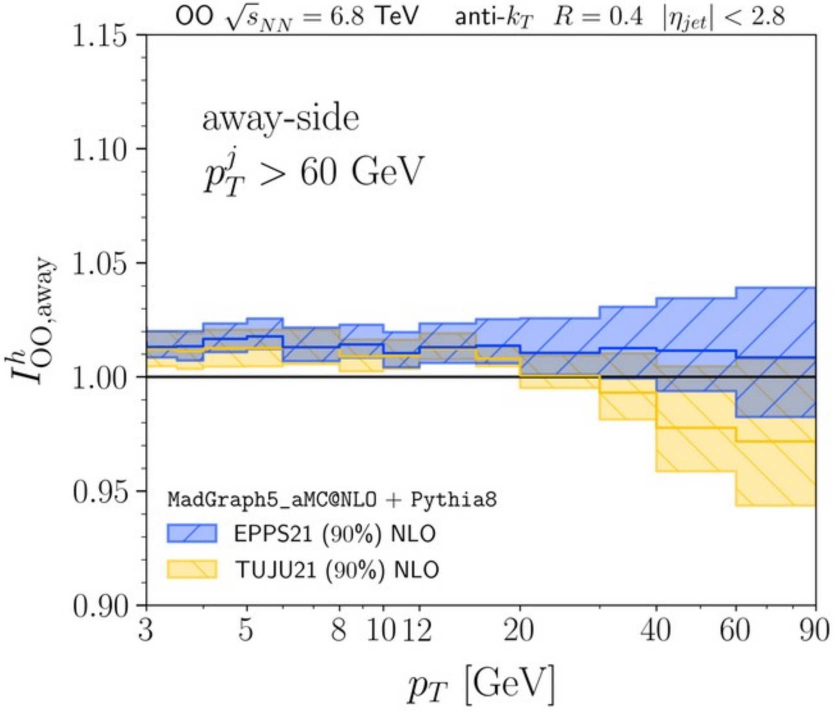


Jet-triggered hadron I_{AA} @ 6.8 TeV

- NLO jets with MadGraph@NLO + Pythia8

Gebhard, AM, Takacs, in preparation

- Jet-Trigger: $p^j_{T,\mathrm{min}} = 60$ GeV
- Otherwise identical



observe ..

- nPDF uncertainties still growing!
- But overall smaller and increase at larger p_T

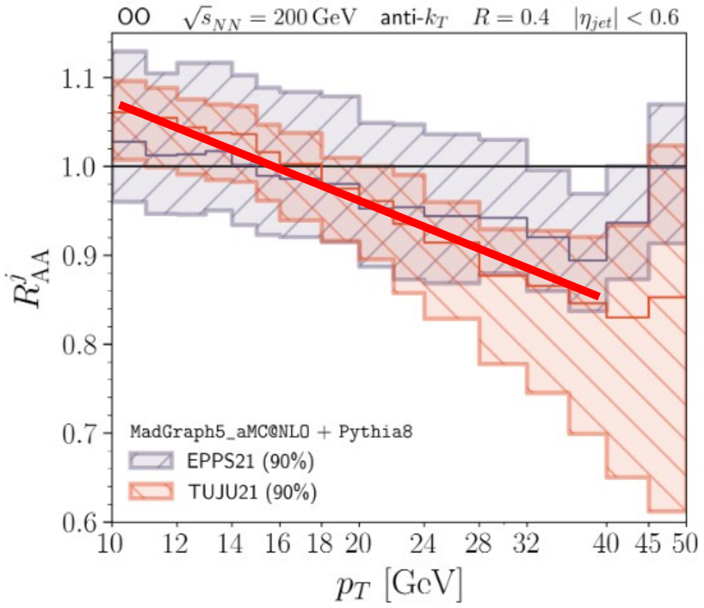
~2% percent uncertainty in low momentum region

Jet-triggered hadron I_{AA} @ 200 GeV

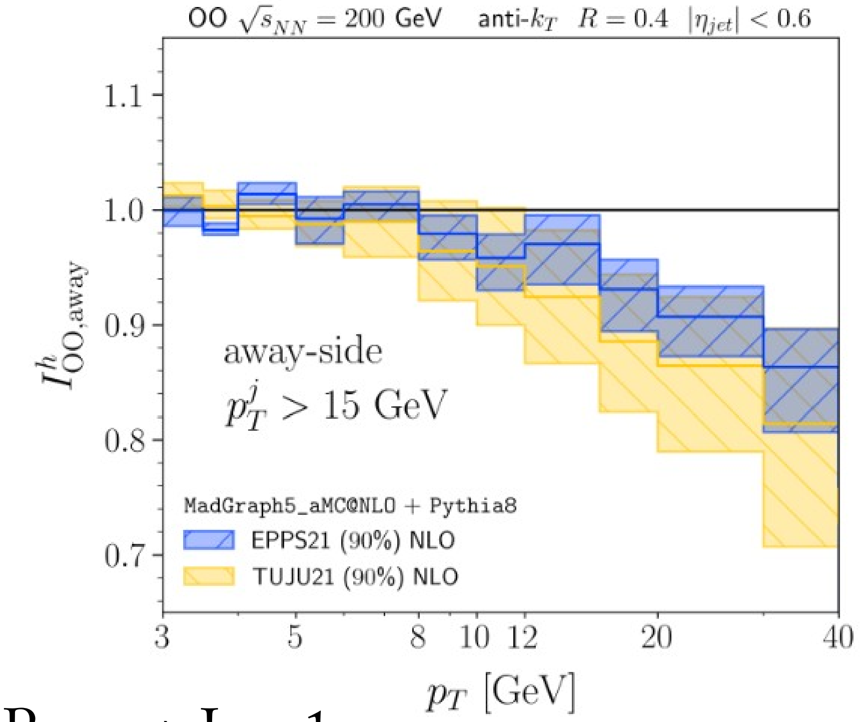
- NLO jets with MadGraph@NLO + Pythia8

Gebhard, AM, Takacs, in preparation

R_{AA}



I_{AA}



Handwavy argument: negative slope of $R_{AA} \longrightarrow I_{AA}<1$

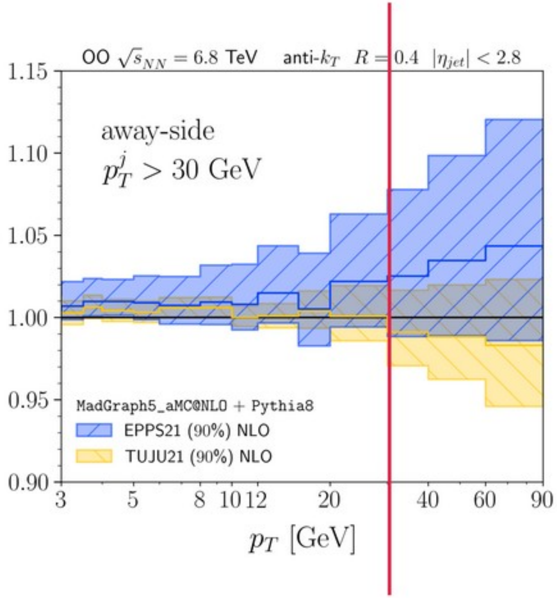
Uncertainty (non)-cancellation

Why do uncertainties stop canceling? →

$$\Delta\left(\frac{X}{Y}\right) = \frac{X}{Y}\sqrt{\left(\frac{\Delta X}{X}\right)^2 + \left(\frac{\Delta Y}{Y}\right)^2 - \underline{2\rho(X,Y)}\frac{\Delta X}{X}\frac{\Delta Y}{Y}}$$

check correlation of

$$Y_{\mathrm{AA}}(p_T) = \frac{1}{\sigma^j}\frac{d\sigma^{h+j}}{dp_T}$$



$p_{T,\min}$

low p_T high p_T

Uncertainty (non)-cancellation

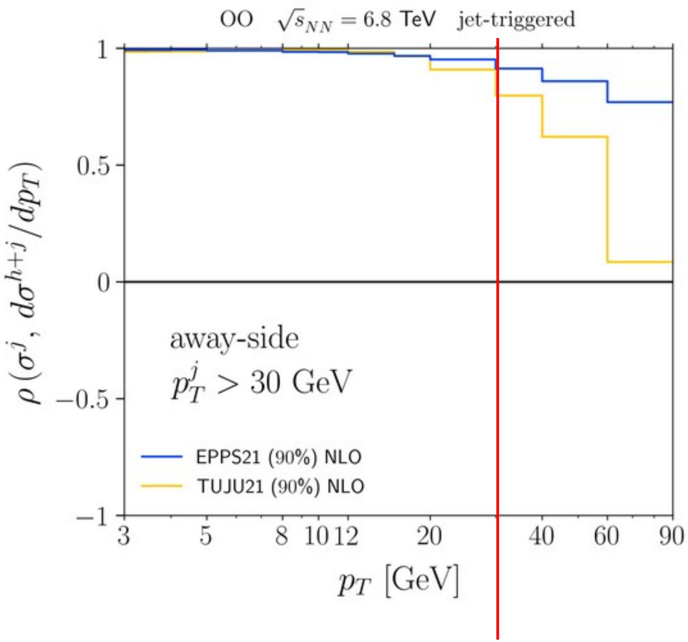
Why do uncertainties stop canceling? →

$$\Delta\left(\frac{X}{Y}\right) = \frac{X}{Y}\sqrt{\left(\frac{\Delta X}{X}\right)^2 + \left(\frac{\Delta Y}{Y}\right)^2 - \underline{2\rho(X,Y)}\frac{\Delta X}{X}\frac{\Delta Y}{Y}}$$

check correlation of

$$Y_{\mathrm{AA}}(p_T) = \frac{1}{\sigma^j}\frac{d\sigma^{h+j}}{dp_T}$$

→ Loss of correlation for $p_T \gtrsim p_{T,\mathrm{min}}$



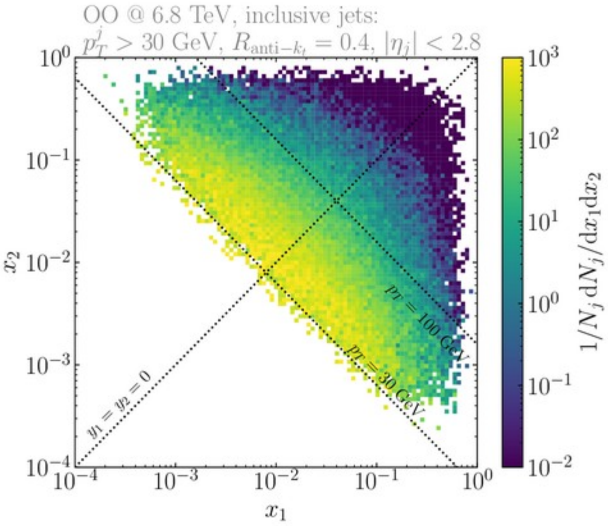
Bjorken x dependence

- LO jets with Pythia8

$$x_{a,b} = \frac{p_T}{\sqrt{s}} \left[\exp(\pm y_a) + \exp(\pm y_b)\right]$$

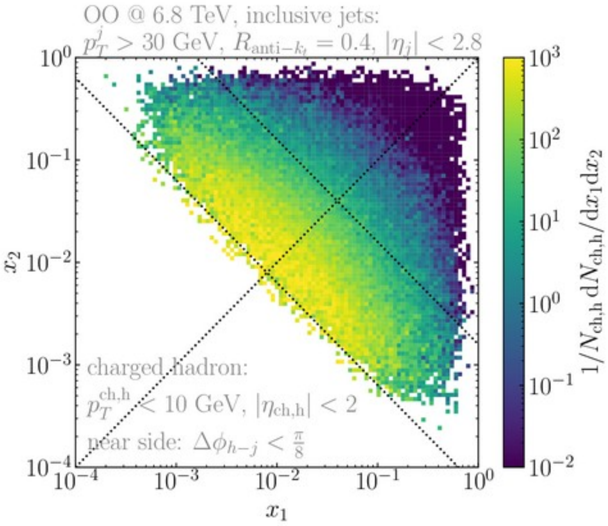
$$x_a\, x_b = \frac{2p_T^2}{s}\left[1 + \cosh(y_a - y_b)\right] \geq \frac{4p_T^2}{s}$$

inclusive



$$\sigma^j \big|_{p_T^j > p_{T,\min}}$$

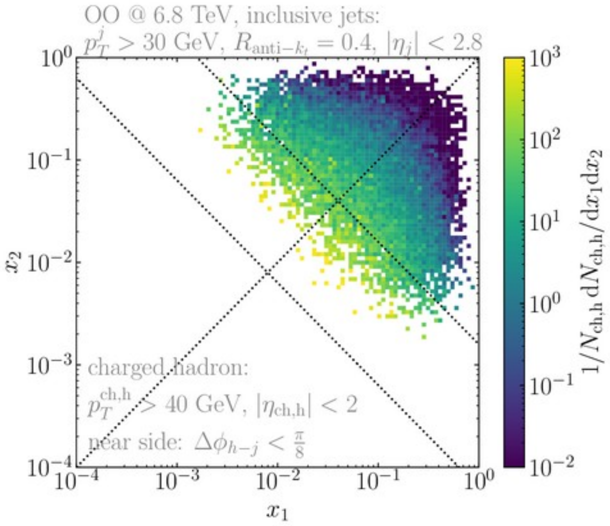
h+j low p_T



$$d\sigma^{h+j}/dp_T$$

$p_T < p_{T,min}$

h+j high p_T



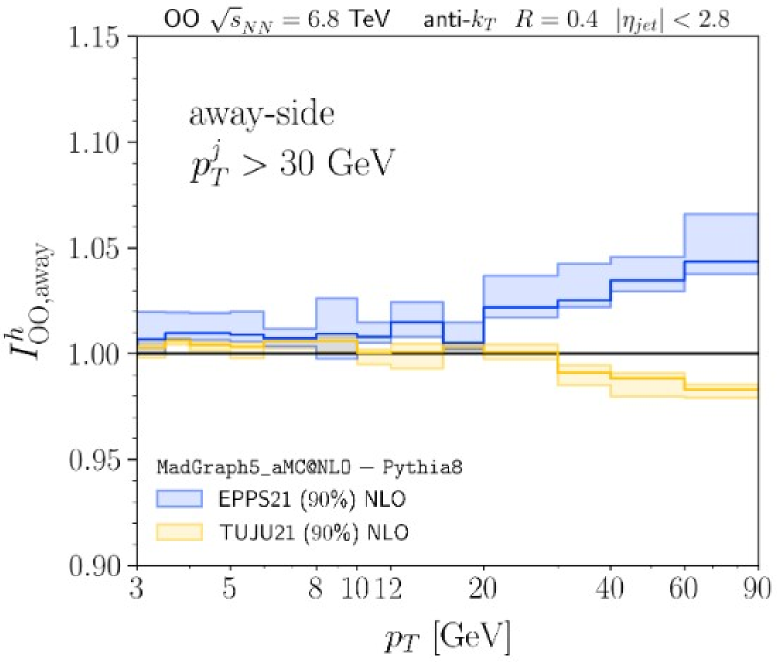
$$d\sigma^{h+j}/dp_T$$

$p_T > p_{T,min}$

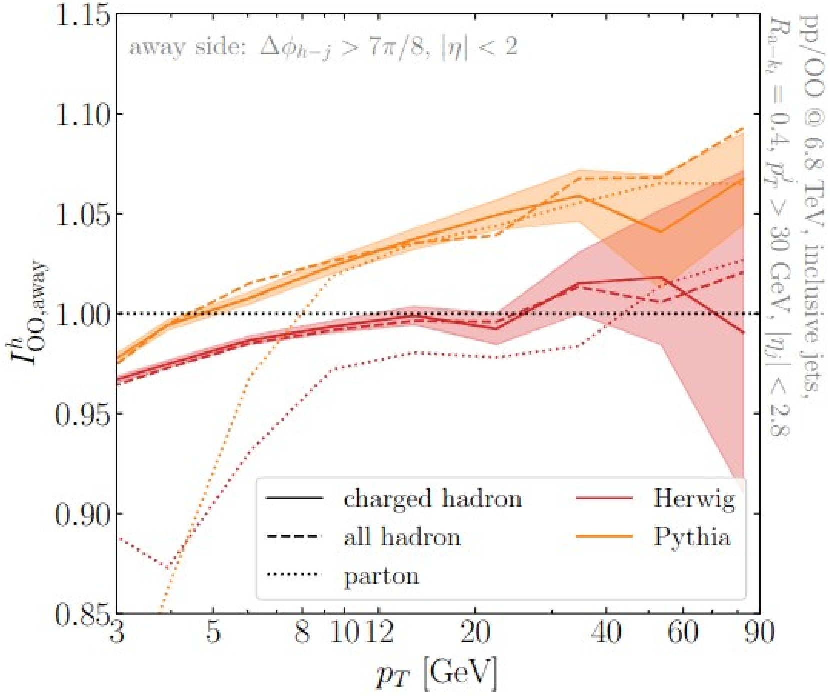
Trigger and coincidence cross-sections probe different Bjorken x

Scale and hadronization uncertainties

μ_F and μ_R scale variation



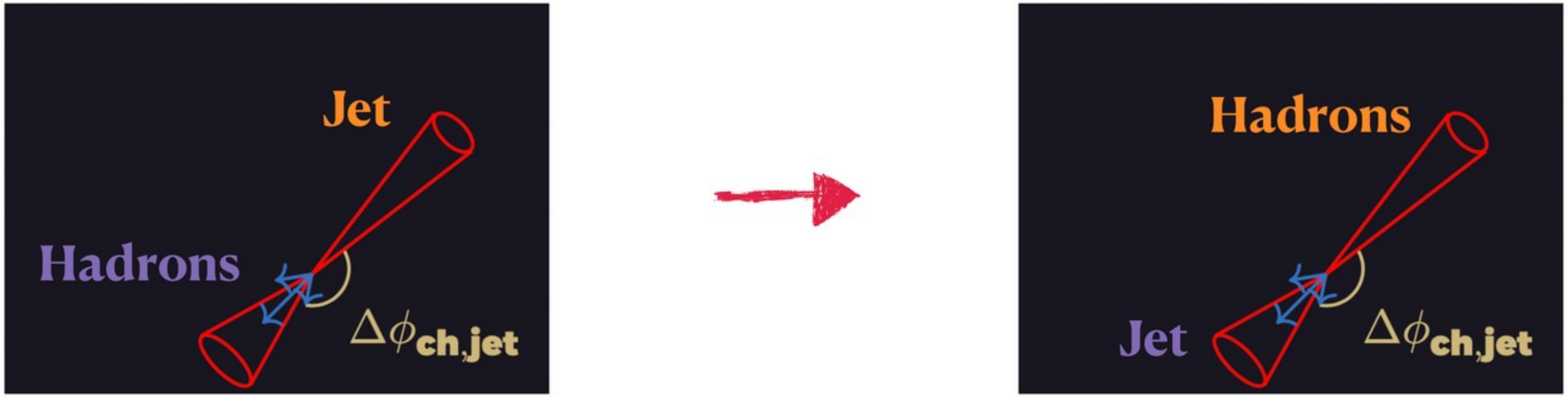
Pythia vs Herwig at LO



Additional few percent differences in low momentum region

Hadron-triggered jet I_{AA}

trigger on hadrons ($p_T^h > p_{T,\min}^h$) and measure away-side jets



adapted from Nagle (2023)

$$Y_{\mathrm{AA}}(p_T) = \frac{1}{\sigma^h}\frac{d\sigma^{j+h}}{dp_T} \quad \text{(per-trigger yield)} \qquad I_{\mathrm{AA}}(p_T) = \frac{Y_{\mathrm{AA}}}{Y_{pp}}$$

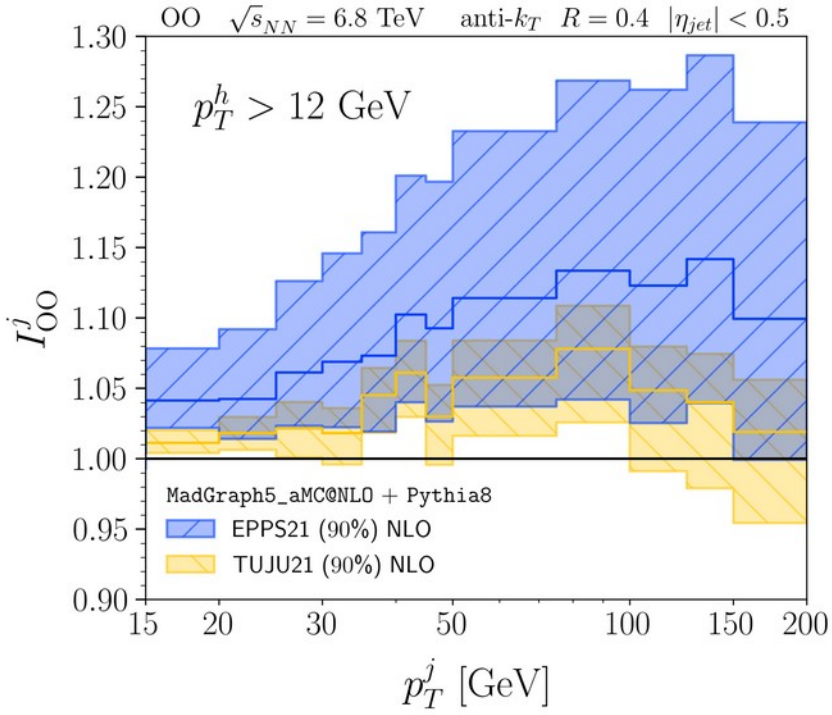
Note that we do not subtract different trigger yields, c.f., ALICE

Hadron-triggered jet I$_{\text{AA}}$ @ 6.8TeV

- Hadron-Trigger: $p^h_{T,\text{min}} = 12\,\text{GeV}$
- Jets with transverse momentum p_T opposite to trigger hadron

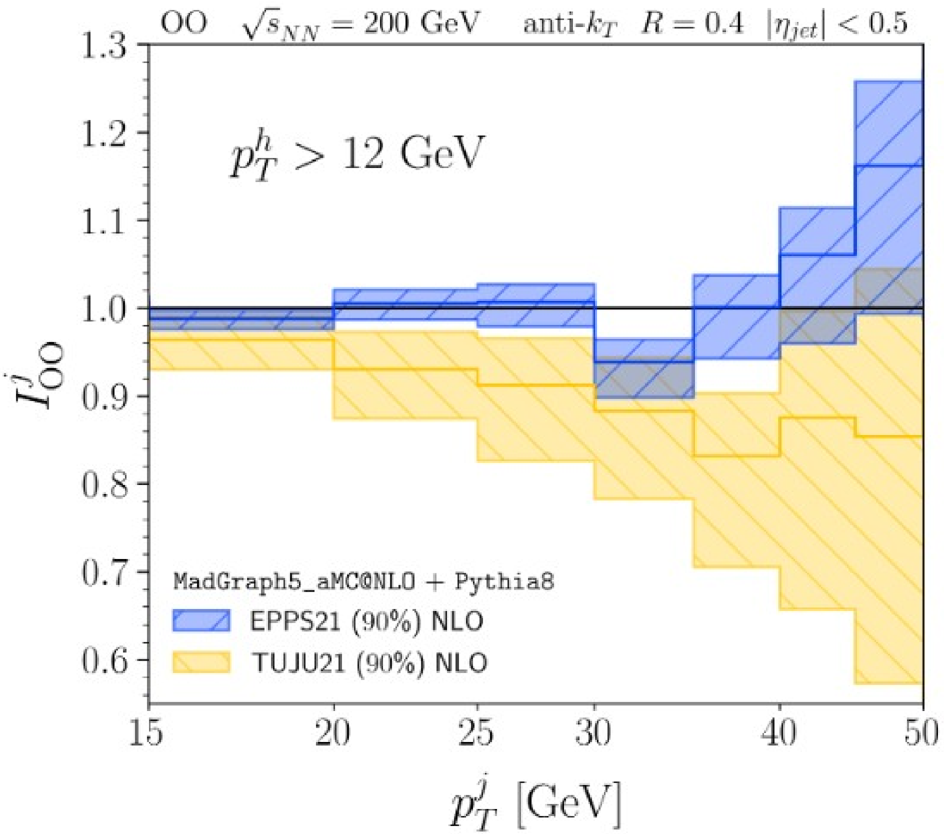
observe ..

- Differences among different nPDFs
- $I_{\text{AA}} \neq 1$
- Increasing nPDF uncertainties!



Hadron-triggered jet I_{AA} @ 200 GeV

- Significant differences between nPDFs



Proton baseline

Strategies for constructing reference spectra

The ratio of spectra cancels large theoretical and experimental uncertainties.

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

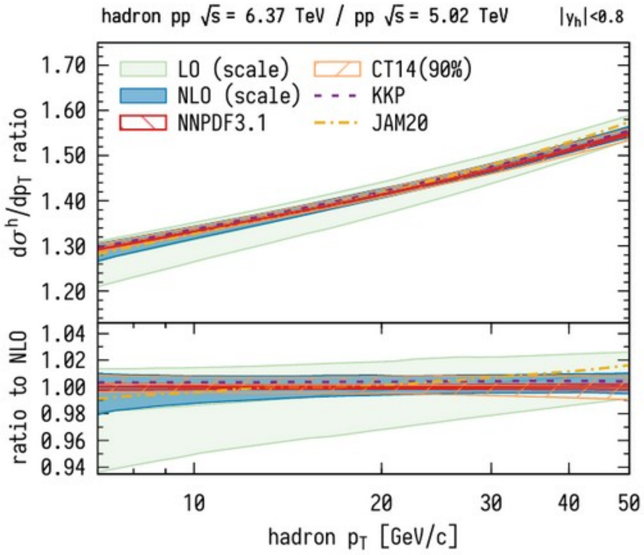
1) Use perturbative QCD to calculate scaling factor theoretically.
2) Interpolate measured pp spectra at nearby energies.
3) Consider hadron and jet spectra ratios at different collision energies.

Brewer, Huss, AM, van der Schee, PRD (2022)

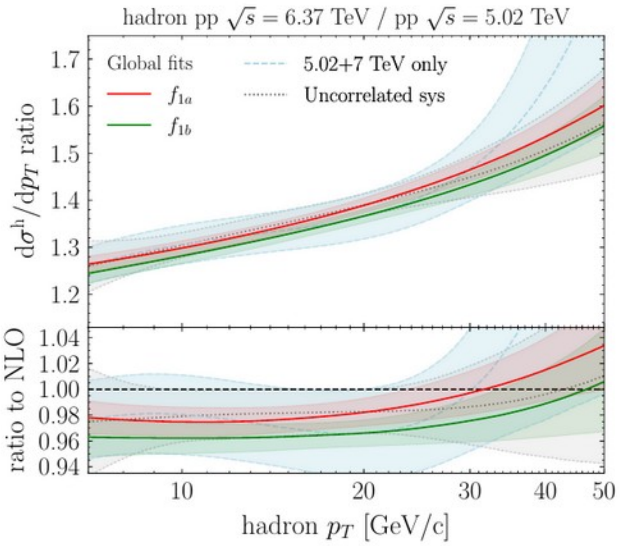
Ratios of hadron spectra @ 6.37 TeV/5.02 TeV in 2021

Brewer, Huss, AM, van der Schee, PRD (2022)

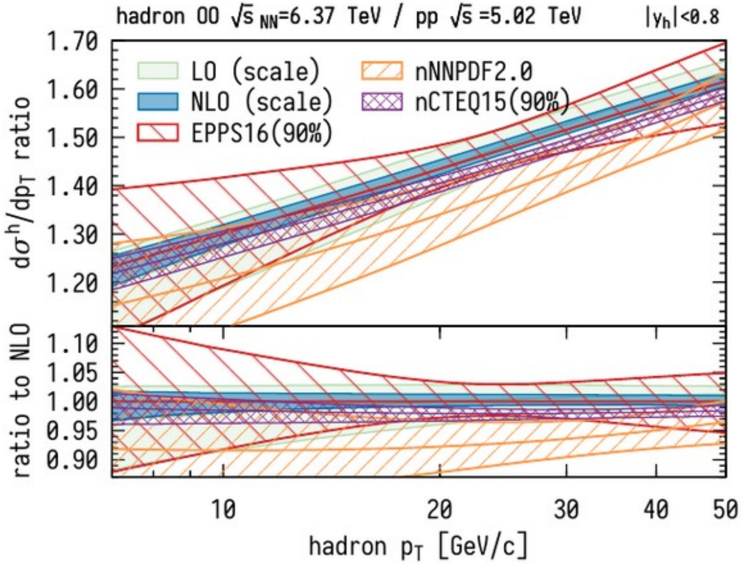
NLO pQCD



data interpolation



OO(6.37TeV)/pp(5.02TeV)

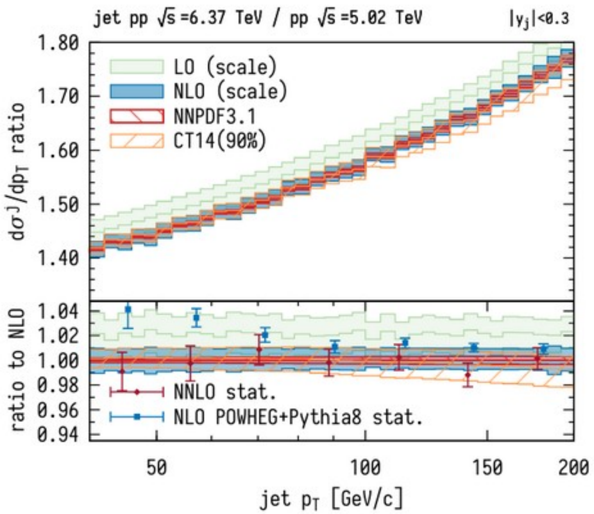


Different mitigation strategies possible if no pp reference available

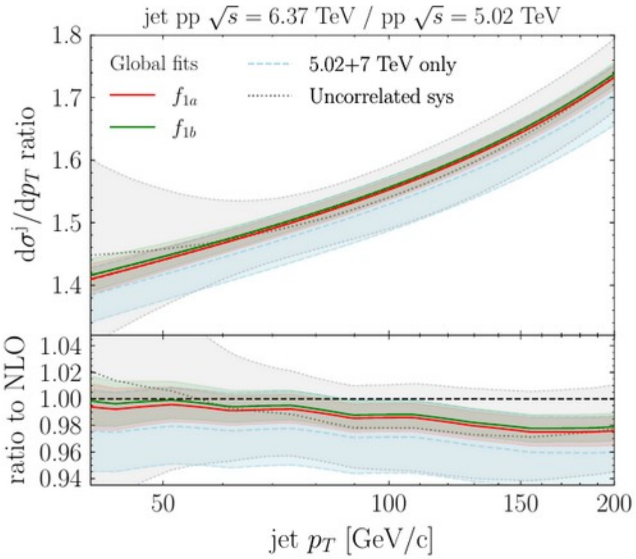
Ratios of jet spectra @ 6.37 TeV/5.02 TeV in 2021

Brewer, Huss, AM, van der Schee, PRD (2022)

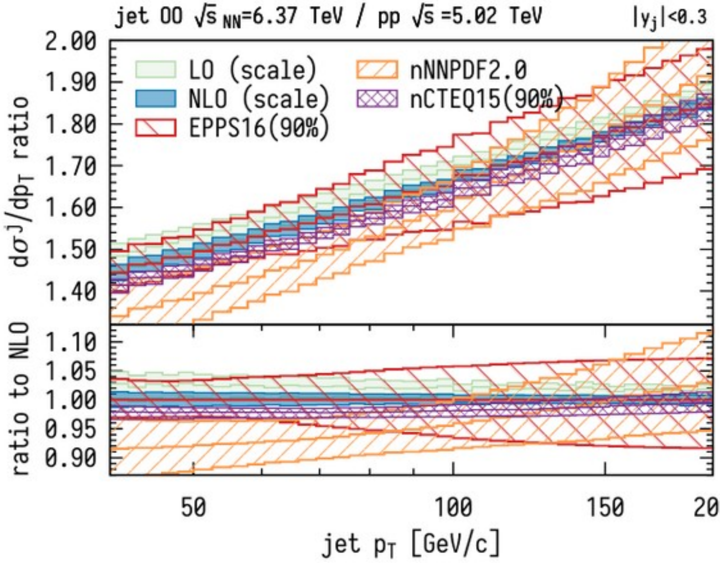
NNLO pQCD



data interpolation



OO(6.37TeV)/pp(5.02TeV)



Different mitigation strategies possible if no pp reference available

Conclusions

Conclusions

- OO collisions ⟶ opportunity to understand energy loss in small systems
- Discovery of small effects needs precise no-quenching baseline
- Uncertainties in nPDFs is the dominant baseline uncertainty
- Semi-inclusive observables are not free of nPDF uncertainties
  but few percent uncertainty can be achieved for jet-triggered hadron I_{AA}

Outlook

- OO and pO collisions at LHC in 2025
- The same energy baseline would be helpful
- Longer pO run would help constrain nPDFs
- Other opportunities with light ions, e.g., neon

Light ion collisions at the LHC

Location: 4/3-006, CERN
Website: cern.ch/lightions

Date: Nov. 11-15, 2024

Topics covered in relation to small systems:

Experimental highlights and projections
Heavy flavour
Hydrodynamics
Initial conditions
Jets
Ultraperipheral collisions
Nuclear parton distribution functions
Nuclear structure
LHC accelerator opportunities

Organisers:

Reyes Alemany Fernandez
Giuliano Giacalone
Qipeng Hu
Govert Hugo Nijs
Saverio Mariani
Wilke van der Schee
Huichao Song
Jing Wang
Urs Wiedemann
You Zhou

cern.ch/lightions

Light ion collision at the LHC

Organisers
Reyes Alemany Fernandez
Giuliano Giacalone
Qipeng Hu
Govert Hugo Nijs
Saverio Mariani
Wilke van der Schee
Huichao Song
Jing Wang
Urs Wiedemann
You Zhou

cern.ch/lightions

Light ion collisions at the LHC

Location: 4/3-006, CERN
Website: cern.ch/lightions

Date: Nov. 11-15, 2024

Topics covered in relation to small systems:
Experimental highlights and projections
Heavy flavour
Hydrodynamics
Initial conditions
Jets
Ultraperipheral collisions
Nuclear parton distribution functions
Nuclear structure
LHC accelerator opportunities

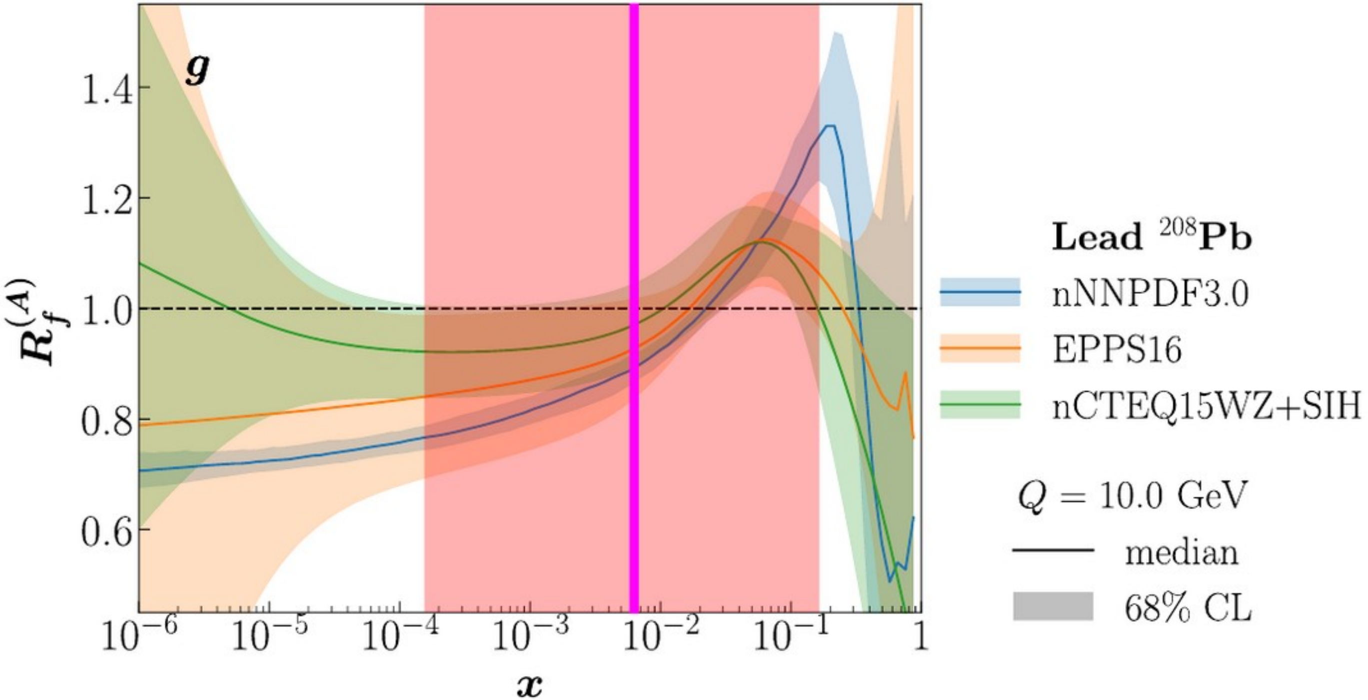
Organisers:
Reyes Alemany Fernandez
Giuliano Giacalone
Qipeng Hu
Govert Hugo Nijs
Saverio Mariani
Wilke van der Schee
Huichao Song
Jing Wang
Urs Wiedemann
You Zhou

Bjorken x dependence of cross-sections

$$\frac{1}{\mathrm{N}_{\mathrm{trig}}^{\mathrm{AA}}}\frac{\mathrm{d}^2\mathrm{N}_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}}\mathrm{d}\eta_{\mathrm{jet}}}\bigg|_{p_{\mathrm{T,trig}}\in\mathrm{TT}} = \left(\boxed{\frac{1}{\sigma^{\mathrm{AA}\to\mathrm{h+X}}}}\cdot\boxed{\frac{\mathrm{d}^2\sigma^{\mathrm{AA}\to\mathrm{h+jet+X}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}}\mathrm{d}\eta_{\mathrm{jet}}}}\right)\bigg|_{p_{\mathrm{T,h}}\in\mathrm{TT}}$$

$$x_A = \frac{p_T}{\sqrt{s}}(e^{y_j} + e^{y_h})$$

$$x_B = \frac{p_T}{\sqrt{s}}(e^{-y_j} + e^{-y_h})$$



Inclusive σ depends on different x range than coincidence σ