DISCOVERING PARTONIC RESCATTERING IN LIGHT NUCLEUS COLLISIONS

Alexander Huss

- based on: [2007.13754, 2007.13758]

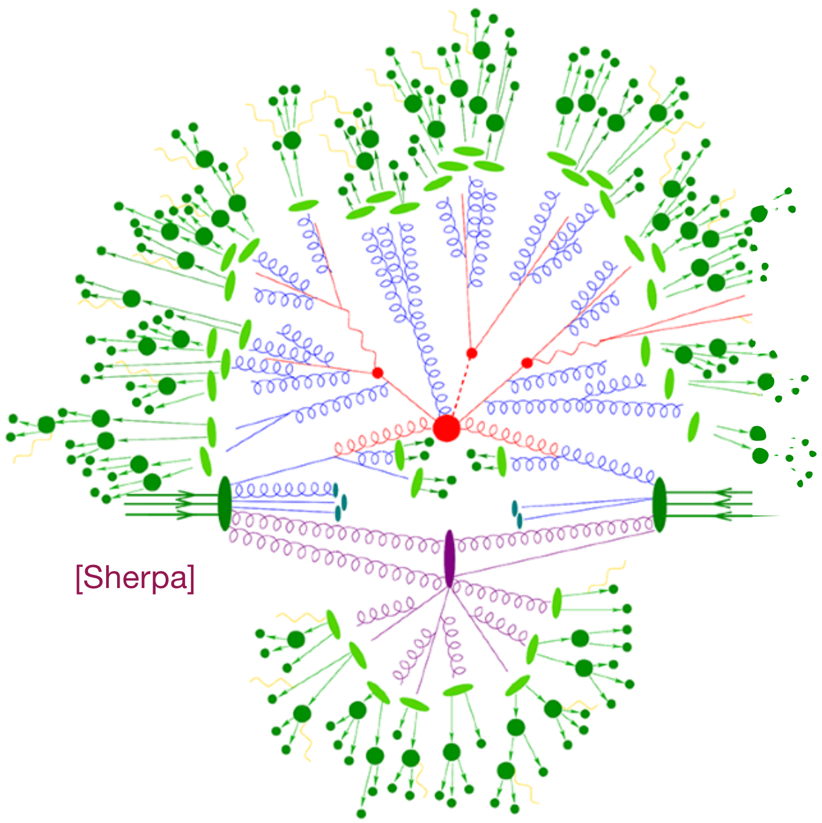
AH, A. Kurkela, A. Mazeliauskas, R. Paatelainen, W. van der Schee, U. Wiedemann

OppOrtunities of OO and pO collisions at the LHC — CERN, 8th Feb. 2021

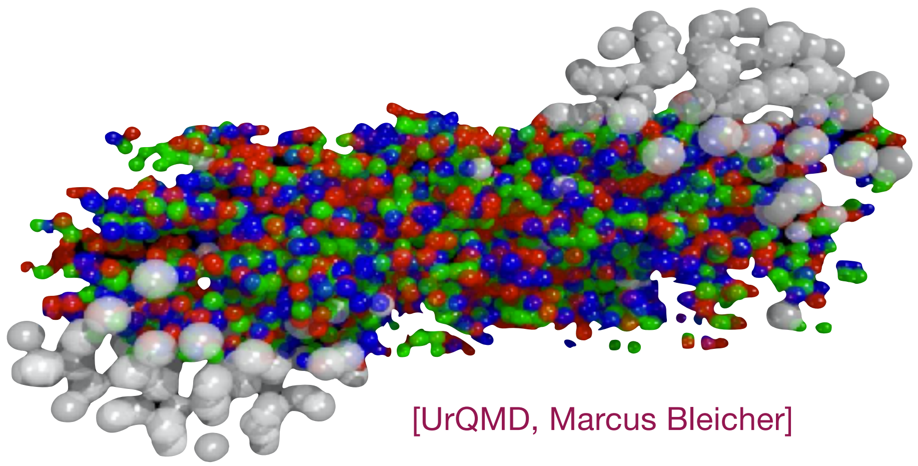
CERN

Describing Hadron Collisions — The two Paradigms

HEP



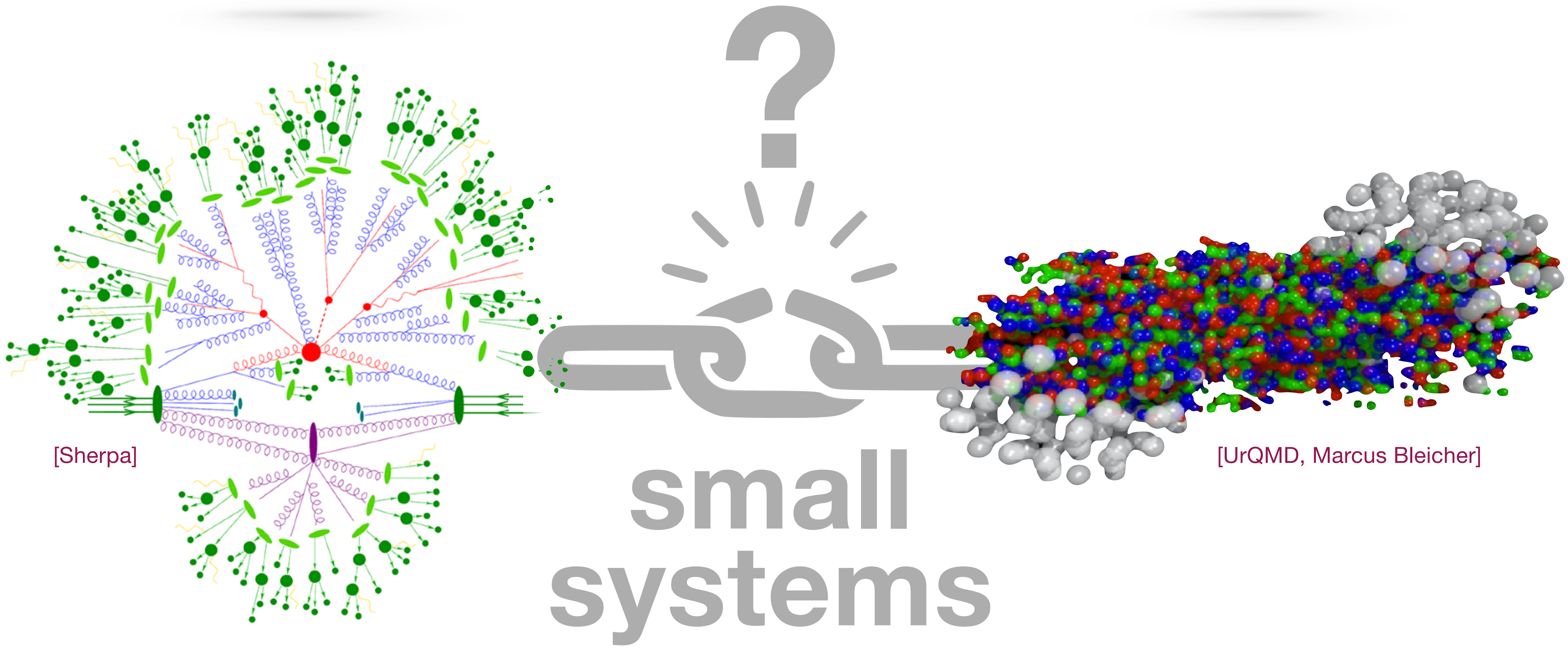
HIP



- proton-proton
  - ↭ no re-scattering
  - "free streaming"
- nucleus-nucleus (AA)
  - ↭ many re-scatterings
  - nearly perfect fluid

Describing Hadron Collisions — The two Paradigms

HEP | *HIP*



- proton-proton
  - ↭ no re-scattering
  - "free streaming"

- nucleus-nucleus (AA)
  - ↭ many re-scatterings
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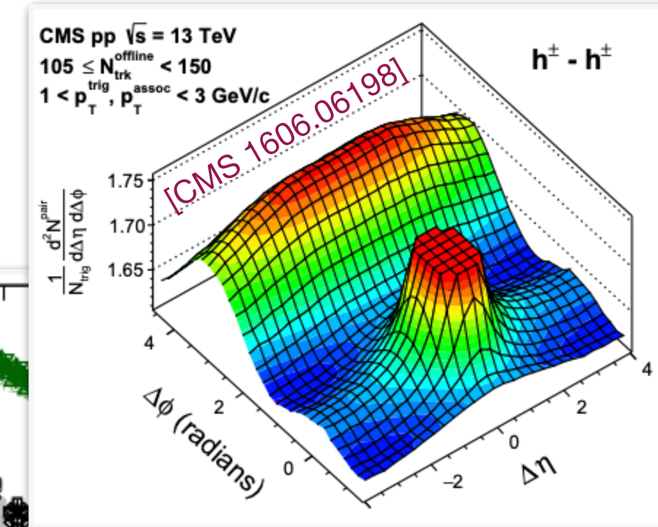
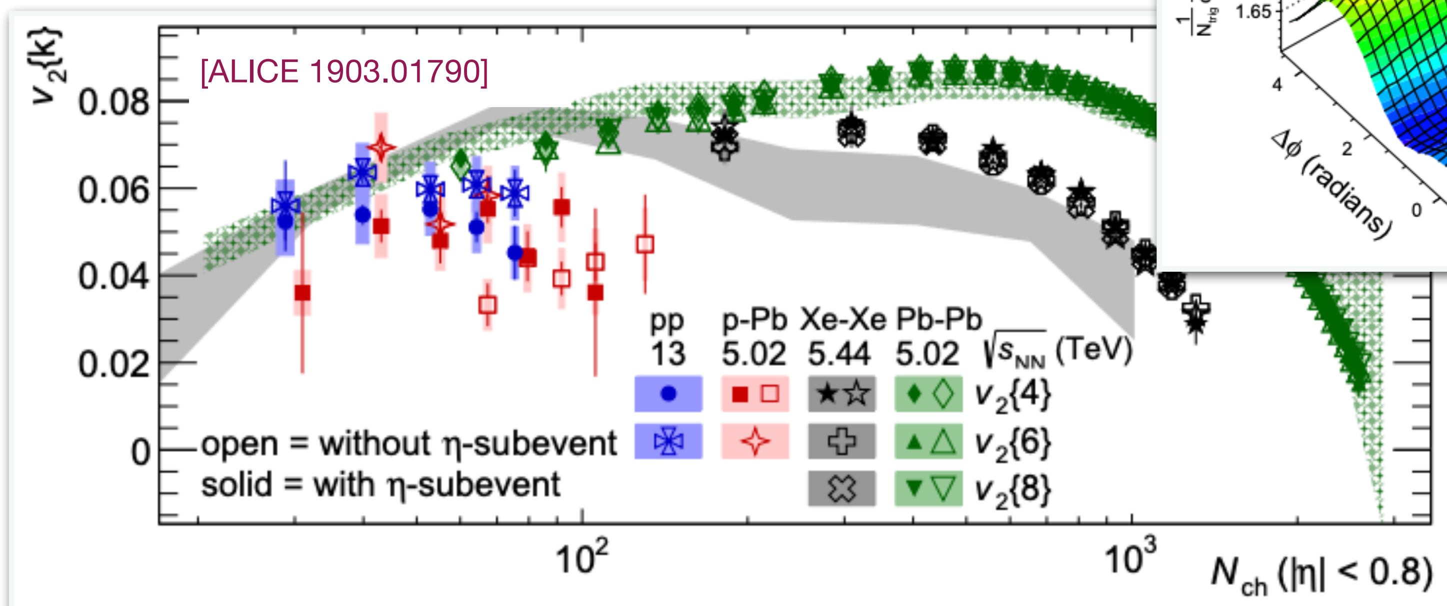
SMALL SYSTEMS — CHALLENGING THE TWO PARADIGMS

(talk by Jacquelyn Noronha-Hostler)

✓ observation of collectivity in small systems:

(collective flow v_n's)





✗ no sign of parton energy loss!

collectivity ⇜⇝ parton rescattering

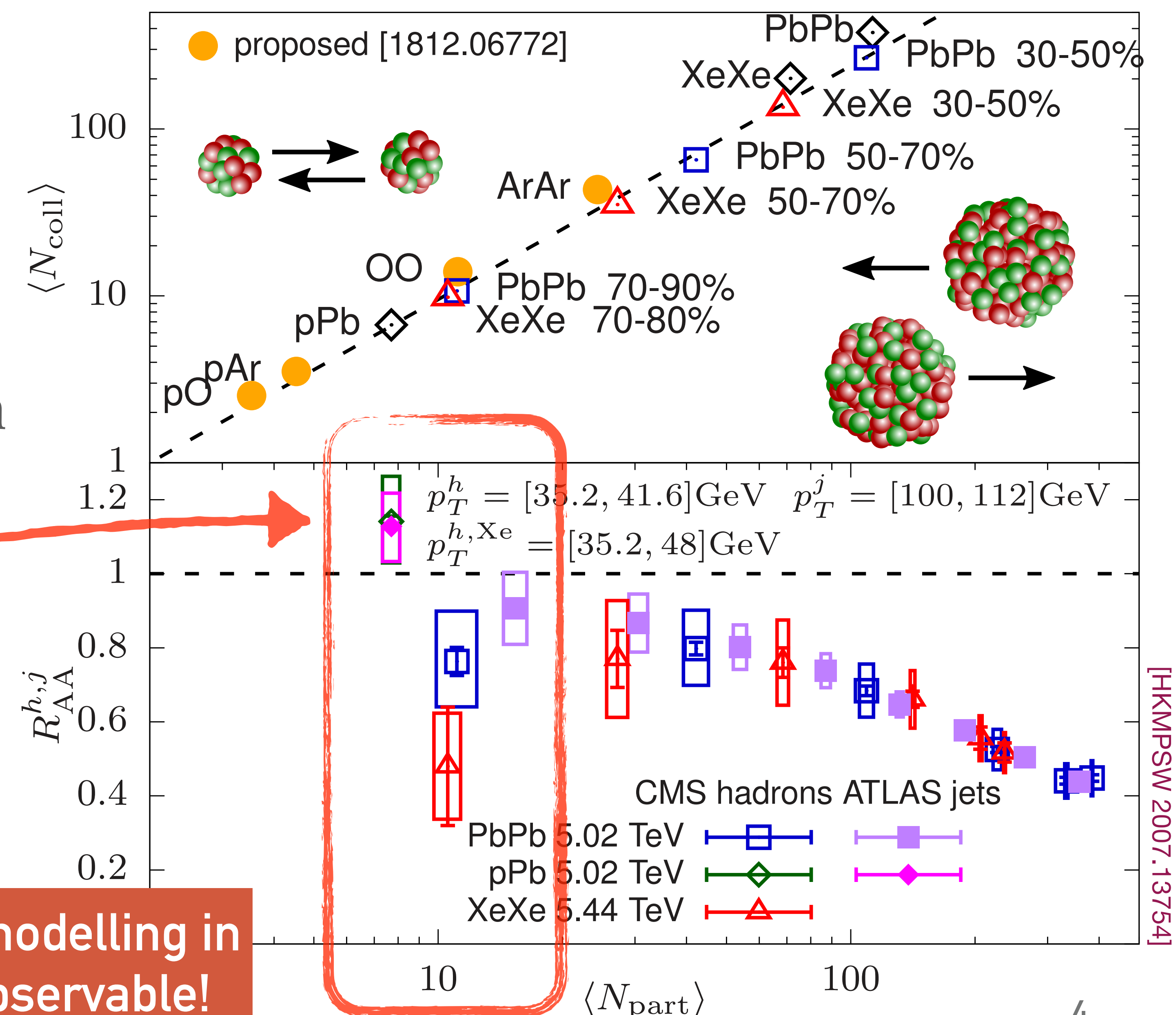
- some parton energy loss must also be present in small systems!

THE NUCLEAR MODIFICATION FACTOR $R_{AA}^{j,h}$

compare differential yield in AA collisions
to an equivalent number of pp collisions

$$R_{AA}^{j,h}(p_T) = \frac{(1/N_{ev})}{\langle T_{AA}\rangle}\frac{dN_{AA}^{j,h}/dp_T}{d\sigma_{pp}^{j,h}/dp_T}$$

- system size
  ↭ centrality selection
- $\langle T_{AA}\rangle$: nuclear overlap function (from model calculations)
- $\langle N_{part}\rangle \sim 10$
  systematics (boxes)
  dominated by $\langle T_{AA}\rangle$



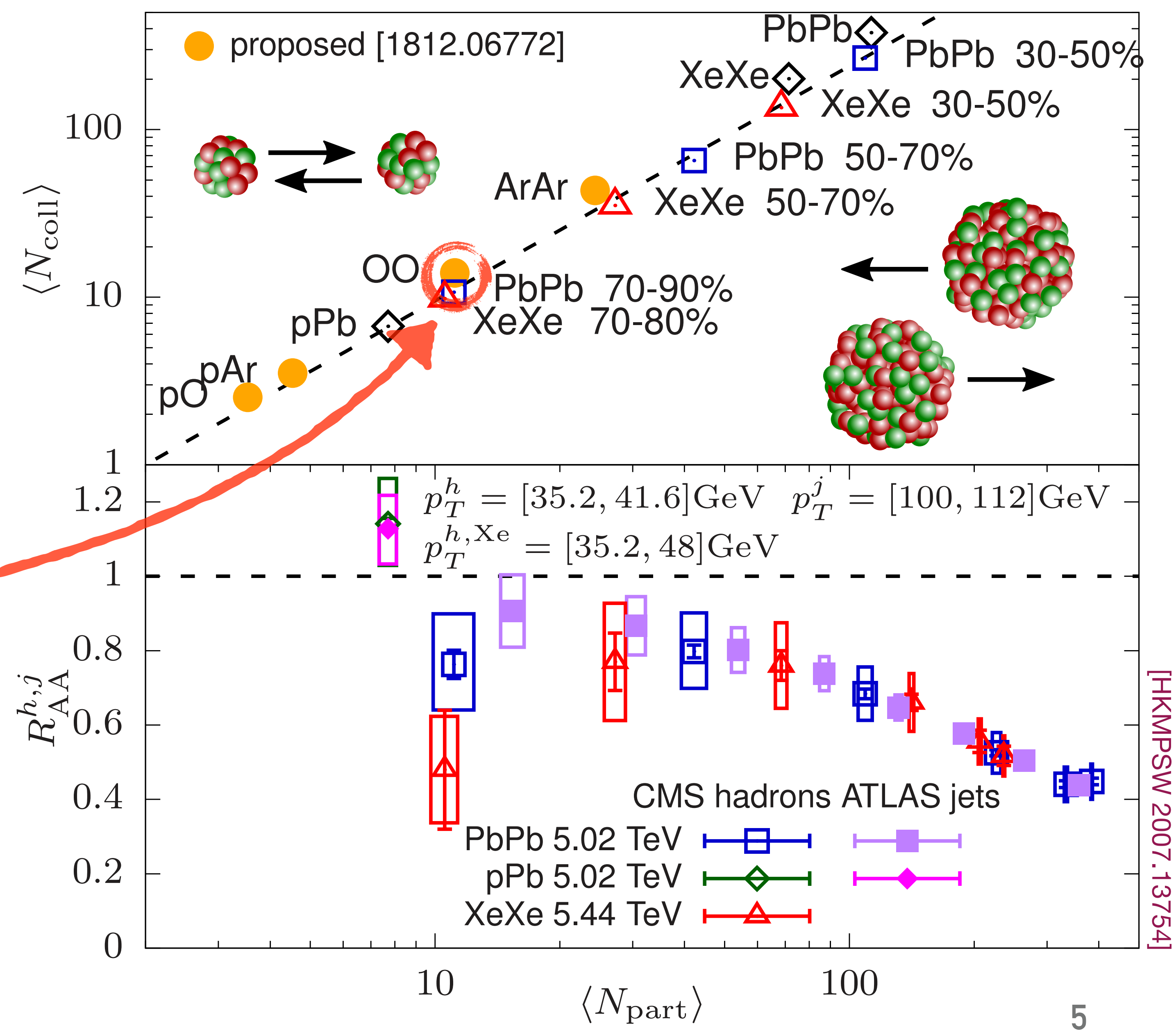
need to get rid of soft modelling in our nominally hard observable!

THE NUCLEAR MODIFICATION FACTOR $R_{AA}^{j,h}$

only in minimum-bias collisions

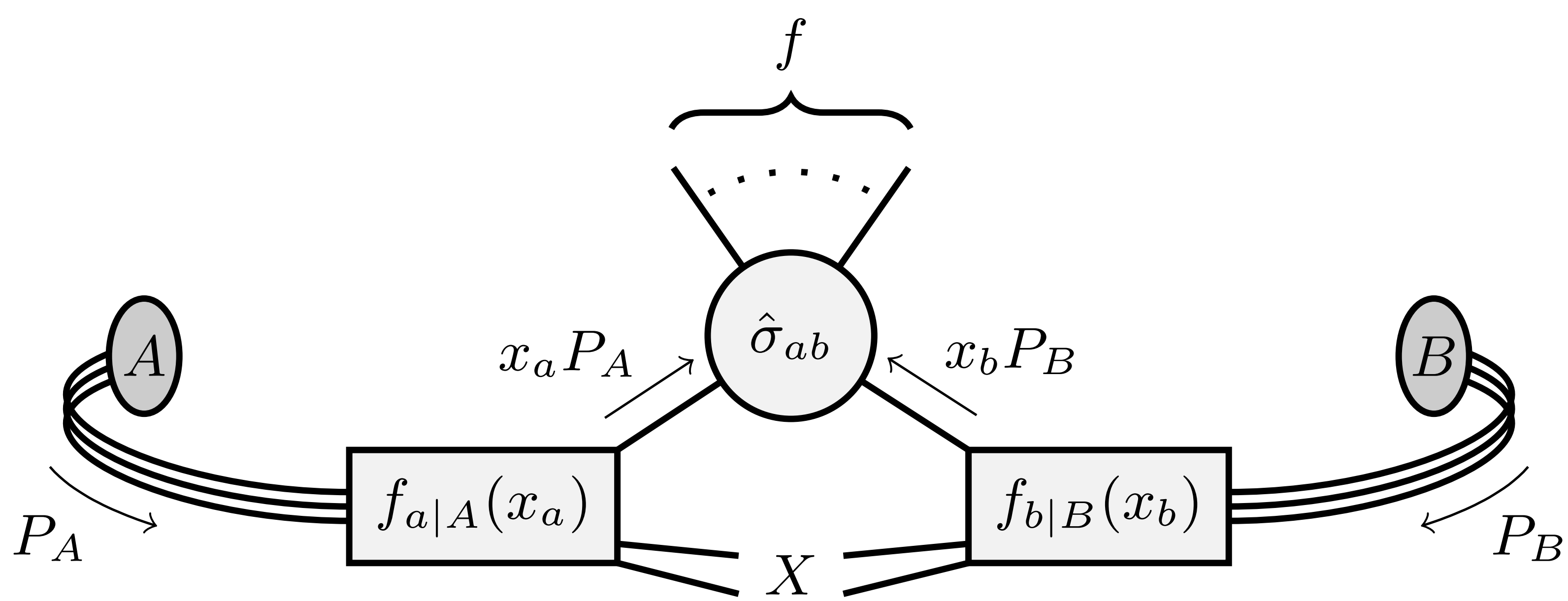
$$R^{j,h}_{AA,\text{min bias}}(p_T) = \frac{1}{A^2}\frac{d\sigma^{j,h}_{AA}/dp_T}{d\sigma^{j,h}_{pp}/dp_T}$$

- system size
  ↭ A: nucleon number
- $\langle T_{AA}\rangle$ replaced by:
  beam luminosity
- $\langle N_{\text{part}}\rangle \sim 10$
  collide light nuclei: OO



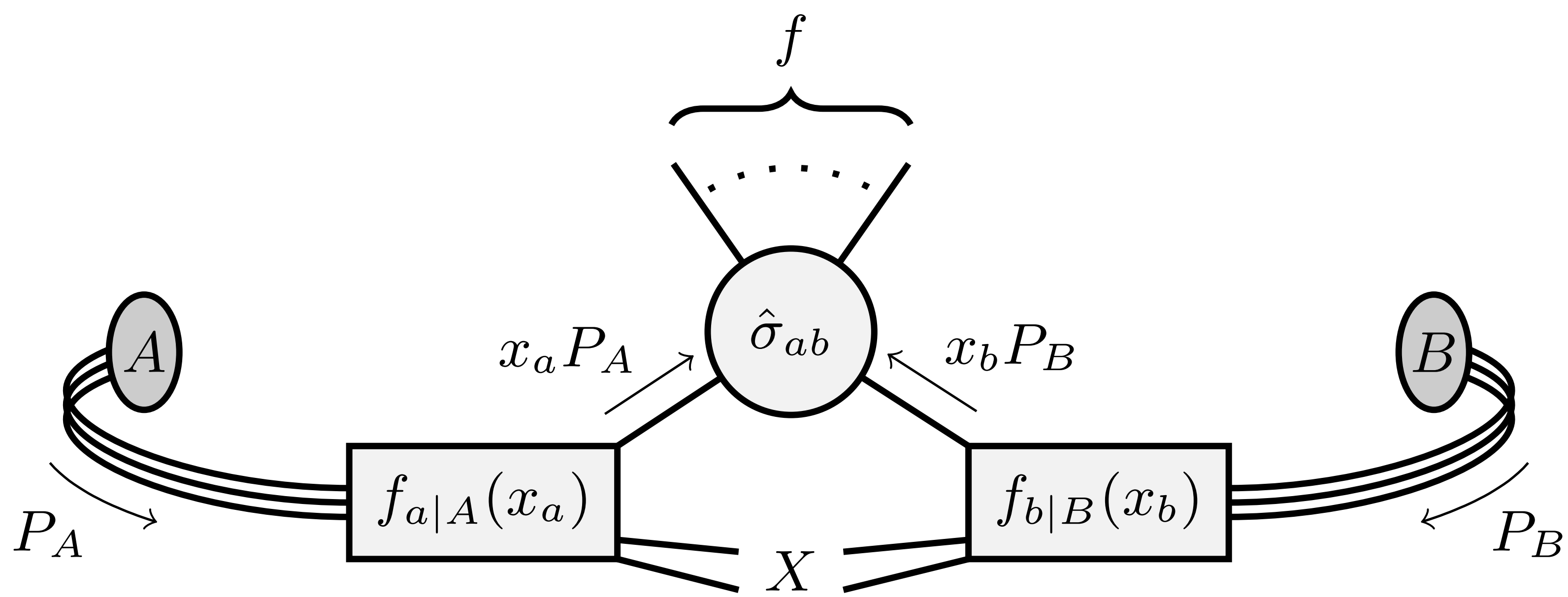
THE NULL HYPOTHESIS

- discovering a small energy loss signal requires a precise theoretical baseline (`null` = "no energy loss")
- can compute $R^{j,h}_{AA,\text{min bias}}$ (`null`) using QCD factorization ($Q \gg \Lambda_{\text{QCD}}$):



$$\sigma_{AB} = \sum_{ab} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \; f_{a|A}(x_a)\; f_{b|B}(x_b)\; \hat{\sigma}_{ab}(x_a, x_b)\; \left(1 + \mathcal{O}(\Lambda_{\text{QCD}}/Q)\right)$$

QCD Factorization

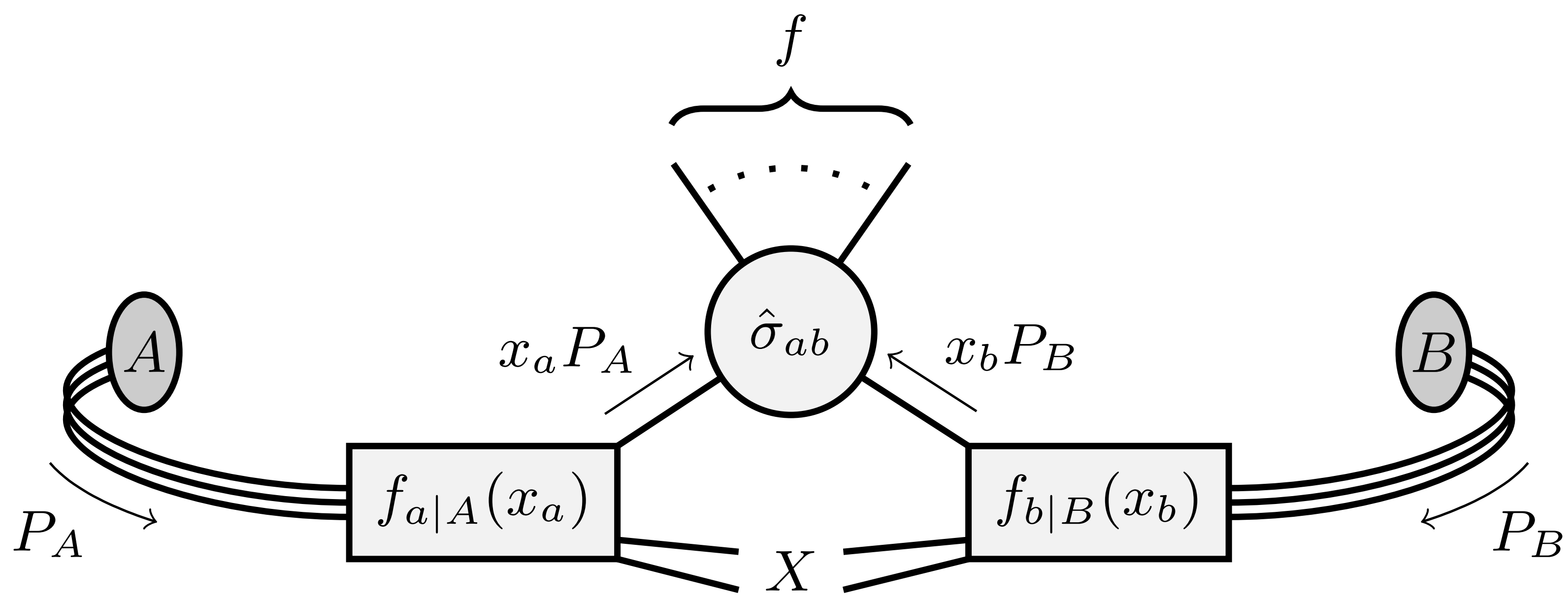


$$\sigma_{AB} = \sum_{ab} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \, f_{a|A}(x_a)\, f_{b|B}(x_b)\, \hat{\sigma}_{ab}(x_a, x_b)\, \left(1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)\right)$$

(nuclear) parton distribution functions
(non-perturbative, universal)

hard scattering
(perturbation theory)

QCD Factorisation



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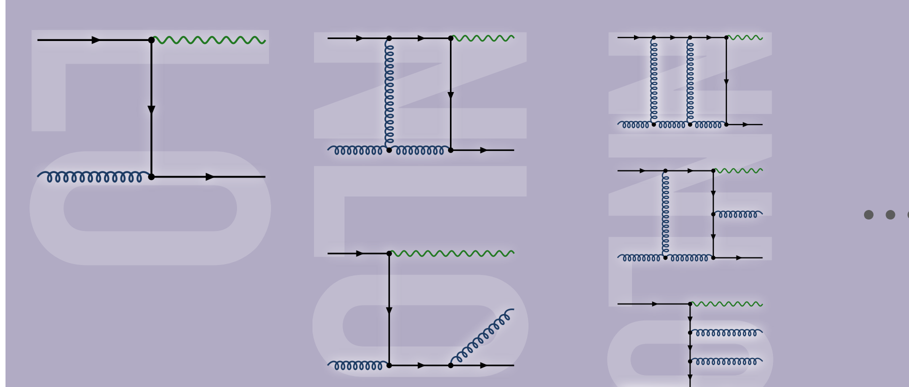
(n)PDFs
(in principle, improvable)
(talk by Petja Paakkinen)

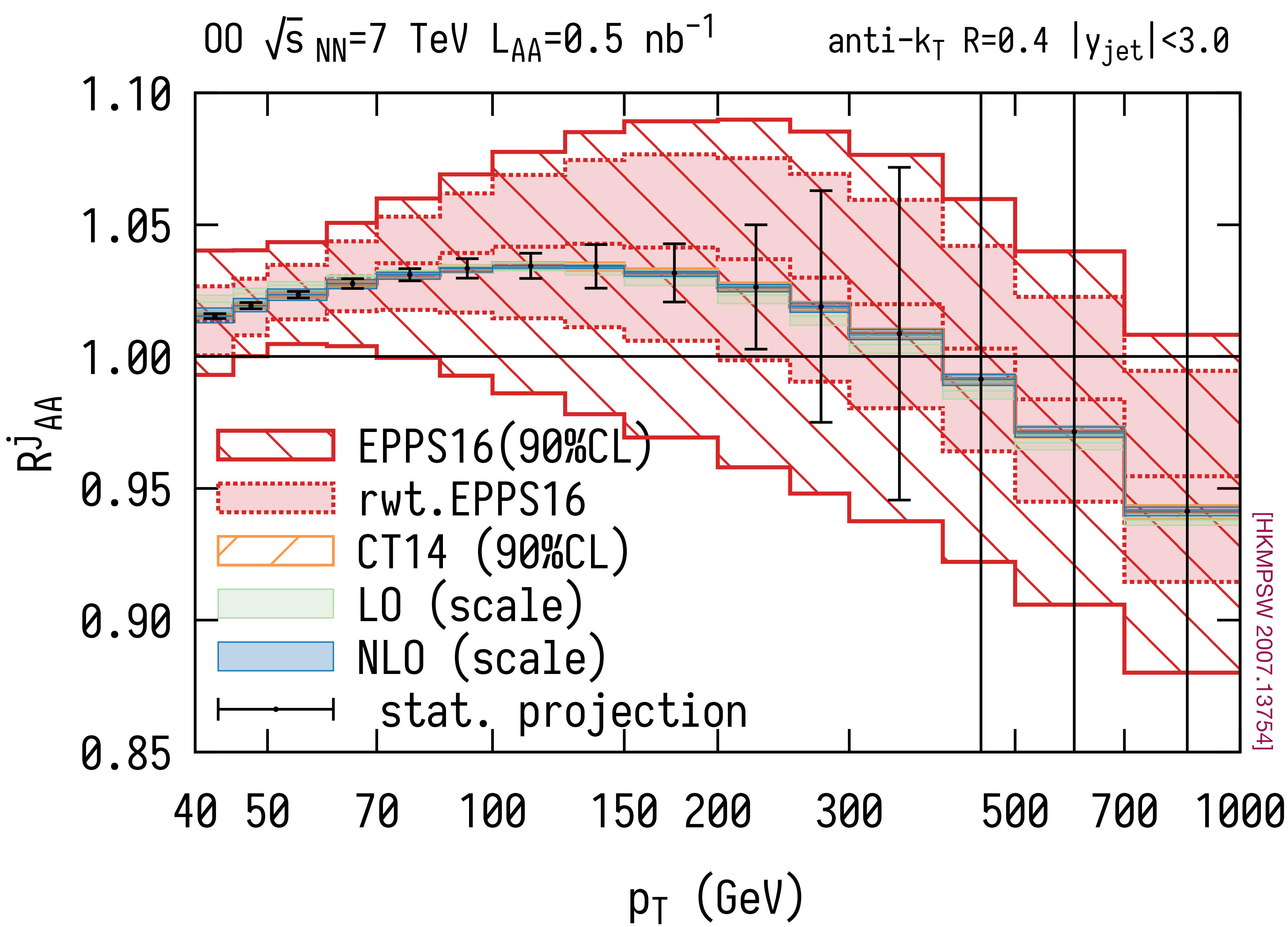
hard scattering
(systematically improvable)



Minimum-Bias R^j_{AA} (null)

2. nPDFs

1. pQCD



Minimum-Bias R^j_{AA} (null) — Scale Uncertainties

- truncation of series:
  - ⇝ scale-dependence: μ_R & μ_F *(unphysical)*

$$\sigma^{\mathrm{N^kLO}}(\mu) - \sigma^{\mathrm{N^kLO}}(\mu') = \mathcal{O}(\mathrm{N^{k+1}LO})$$

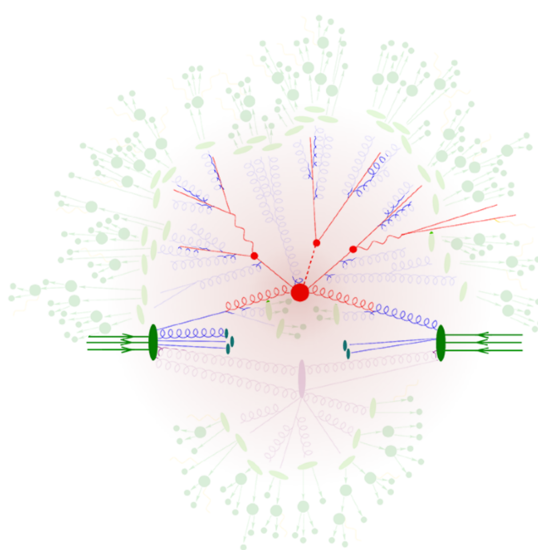
- estimate size of missing higher-order terms:
  - ⇝ vary μ_R & μ_F by factors (½, 2) $(1/2 \leq \mu_R/\mu_F \leq 2)$

- estimate for ratios:
  - ⇝ same process ⇒ assume correlated μ_R & μ_F
  - ⇝ test prescription by inspecting perturbative series

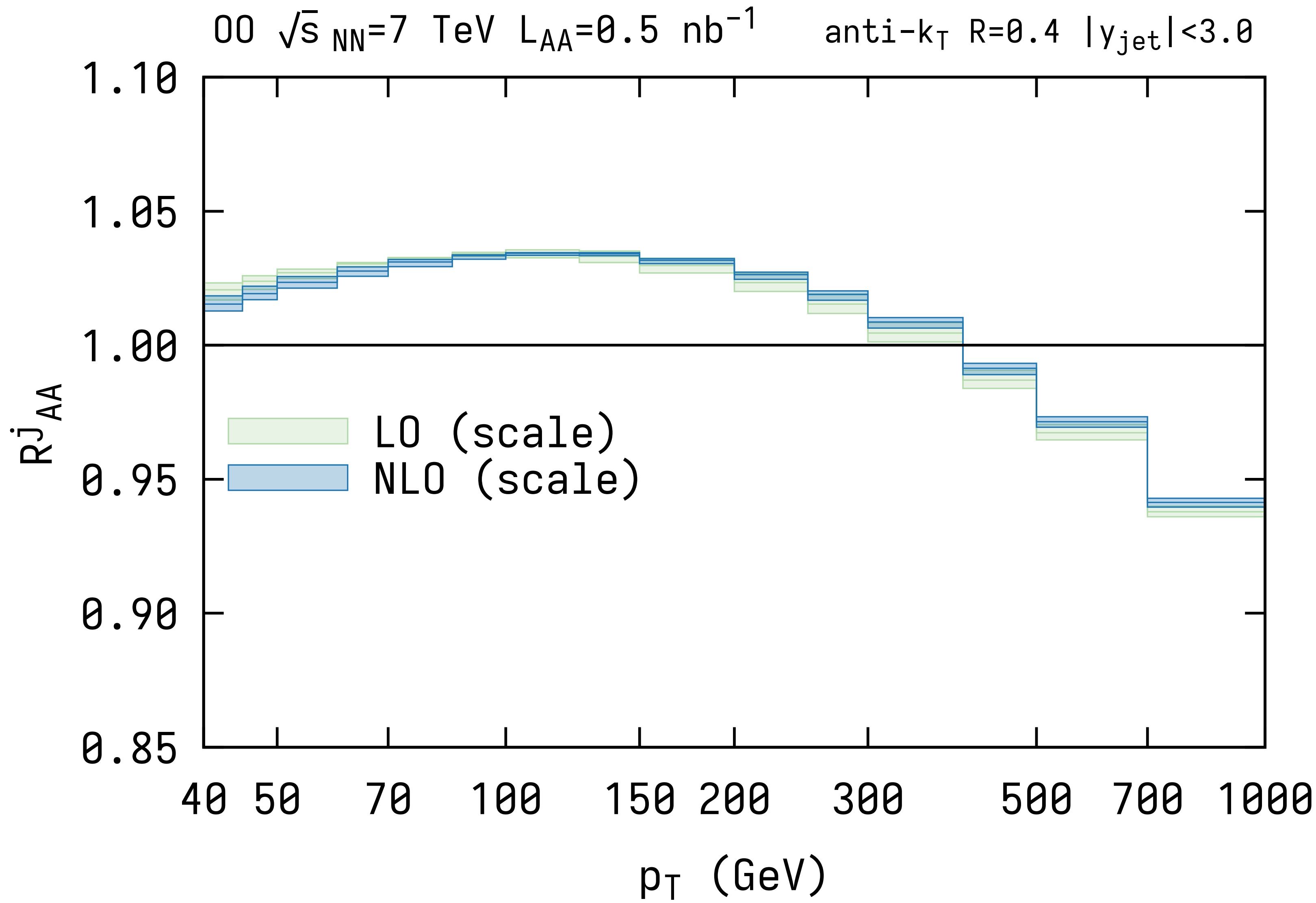
$$R^{A/B}(\mu_R, \mu_F) = \frac{\sigma^A(\mu_R, \mu_F)}{\sigma^B(\mu_R, \mu_F)}$$

"7-point variation"

Minimum-Bias R^j_{AA} (null) — Scale Uncertainties

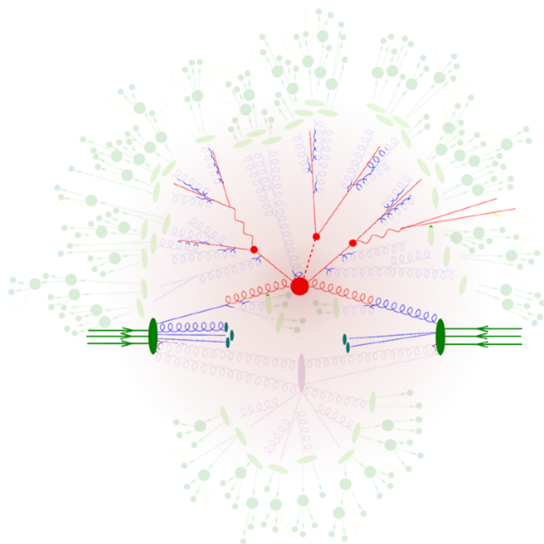


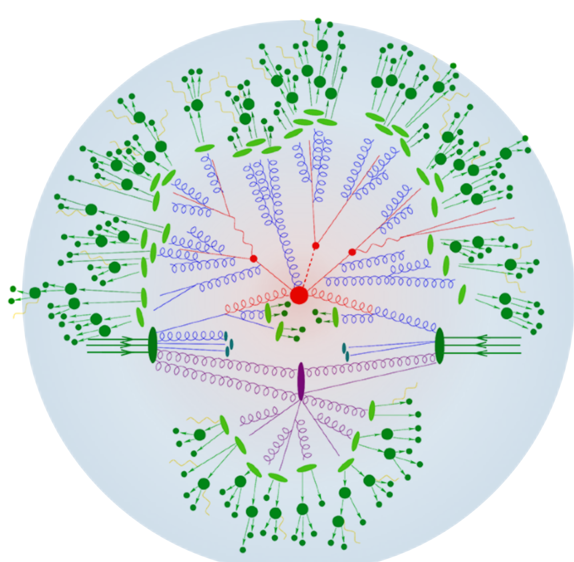
fixed-order hard scattering

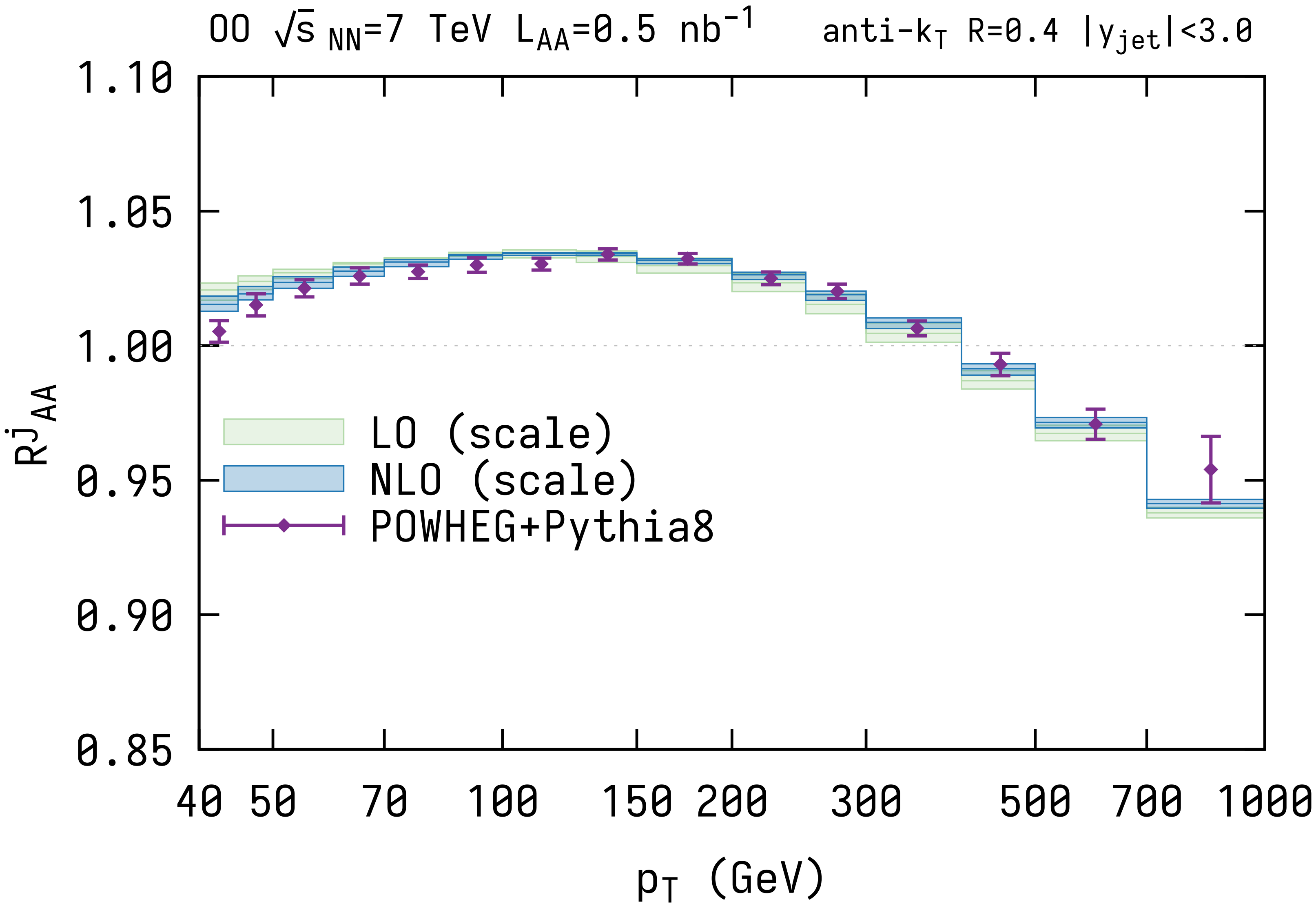


- observable under good perturbative control.

MINIMUM-BIAS R^j_{AA} (null) — PARTON SHOWER & HADRONIZATION







- observable under good perturbative control.
- parton shower and hadronization effects largely cancel in the ratio

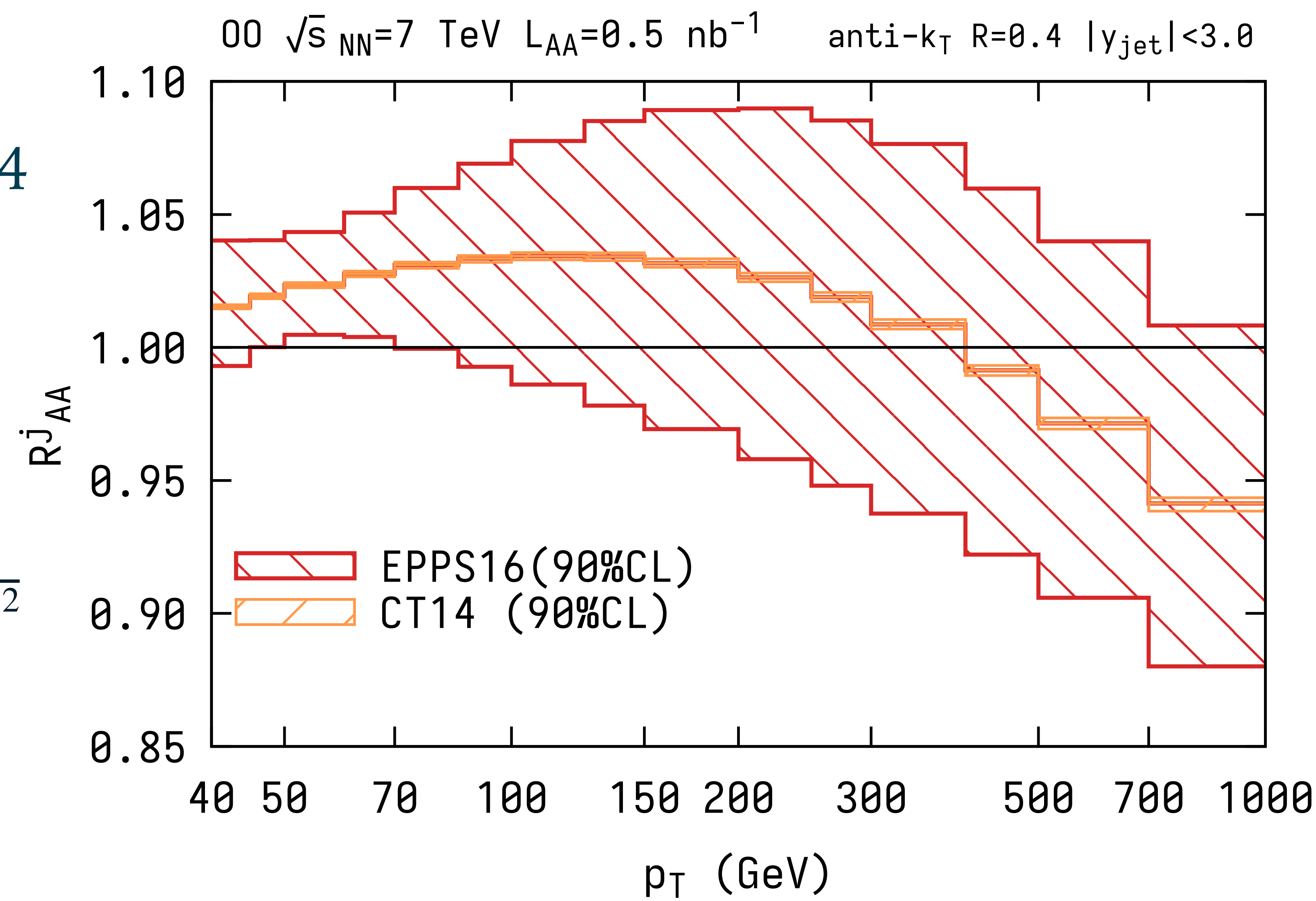
Minimum-Bias R^j_{AA} (null) — (n)PDF Uncertainties

- EPPS16 for ^{16}O
  - ⇝ proton baseline: CT14

    (56 members: $S^{\pm}_{i=21,\ldots,48}$)
  - ⇝ nuclear modification

    (40 members: $S^{\pm}_{i=1,\ldots,20}$)
  - ⇝ errors: (90% CL)

$$\Delta\mathcal{O} = \frac{1}{2}\sqrt{\sum_i \left[\mathcal{O}(S_i^+) - \mathcal{O}(S_i^-)\right]^2}$$



- proton variation cancel
- nPDF uncertainties remain

can be improved by including more data!

$$R_{AA} = \frac{d\sigma_{AA}}{d\sigma_{pp}}$$

← EPPS16 (+CT14)

← CT14

Minimum-Bias R^j_{AA} (null) — (n)PDF Uncertainties

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  - proton baseline: CT14

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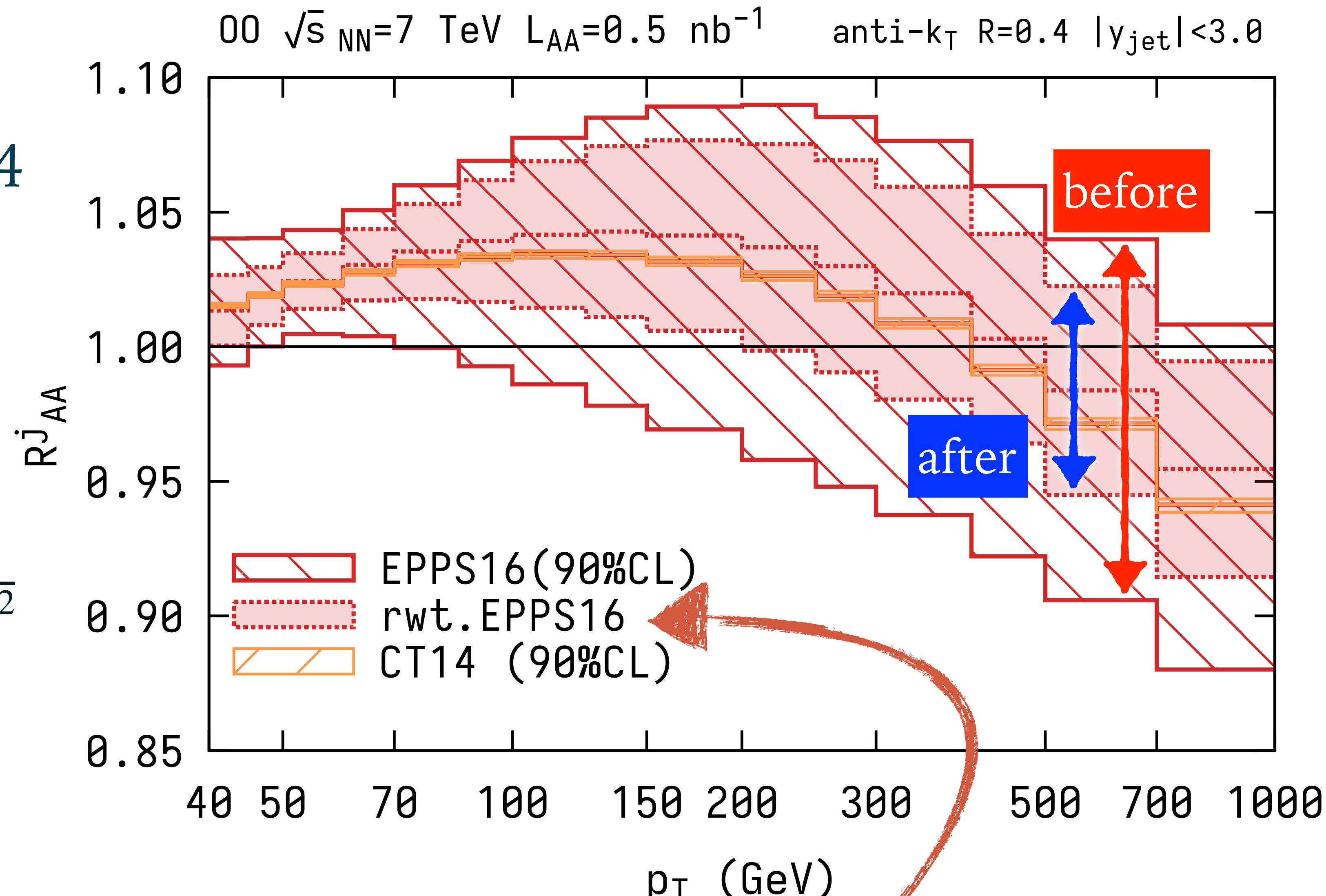
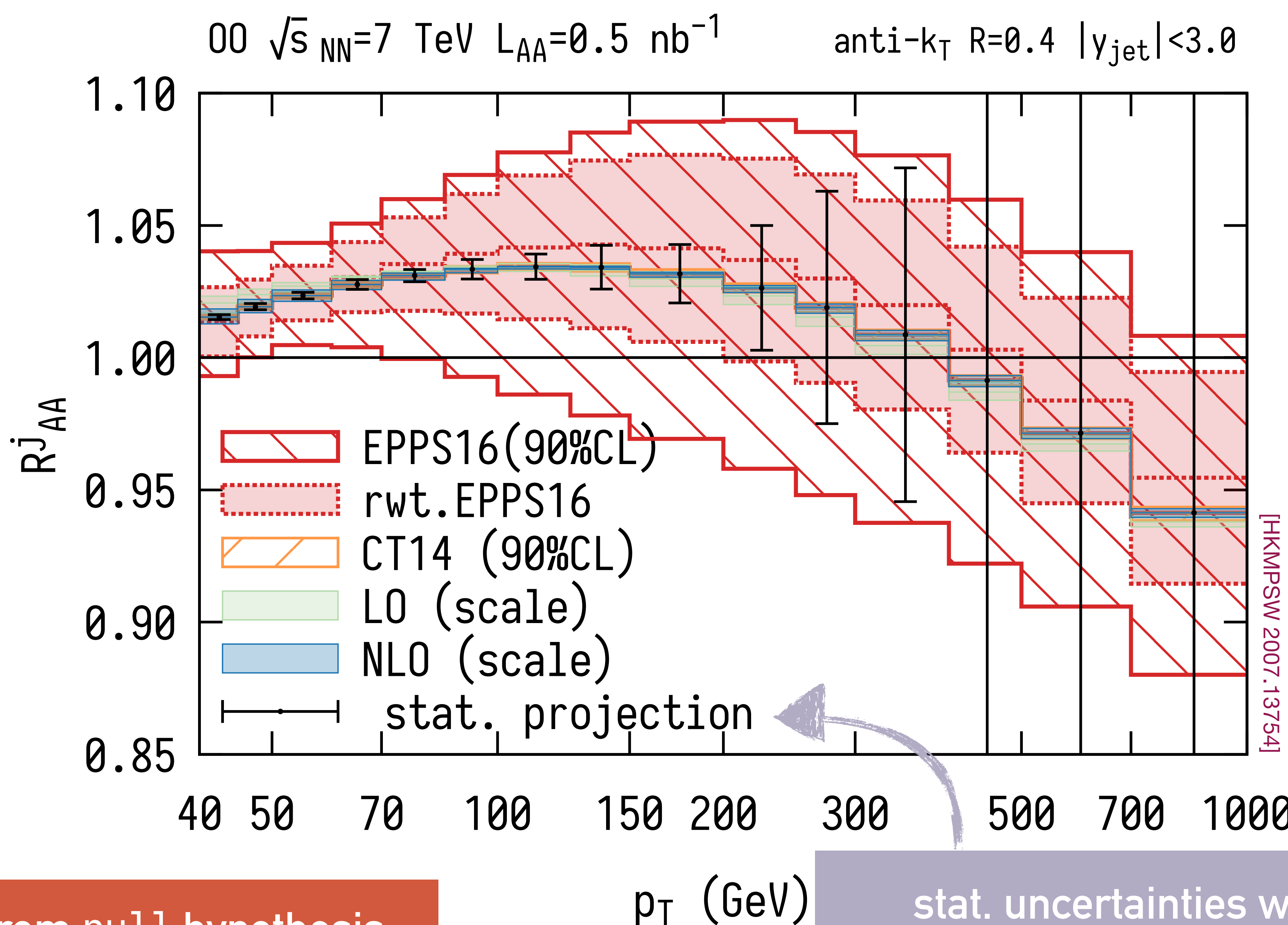


- proton variation cancel
- nPDF uncertainties remain

reweight nPDFs using CMS pPb dijet data

[Eskola, Paakkinen, Paukkunen '19] [CMS 1805.04736]

Minimum-Bias R^j_{AA} (null)



deviation from `null` **hypothesis**
$\Rightarrow$ *discovery of energy loss!*

stat. uncertainties with $0.5\ \text{nb}^{-1}$
few hours "moderately optimistic" scenario

[CERN Yellow Rep.Monogr. 7 (2019)]

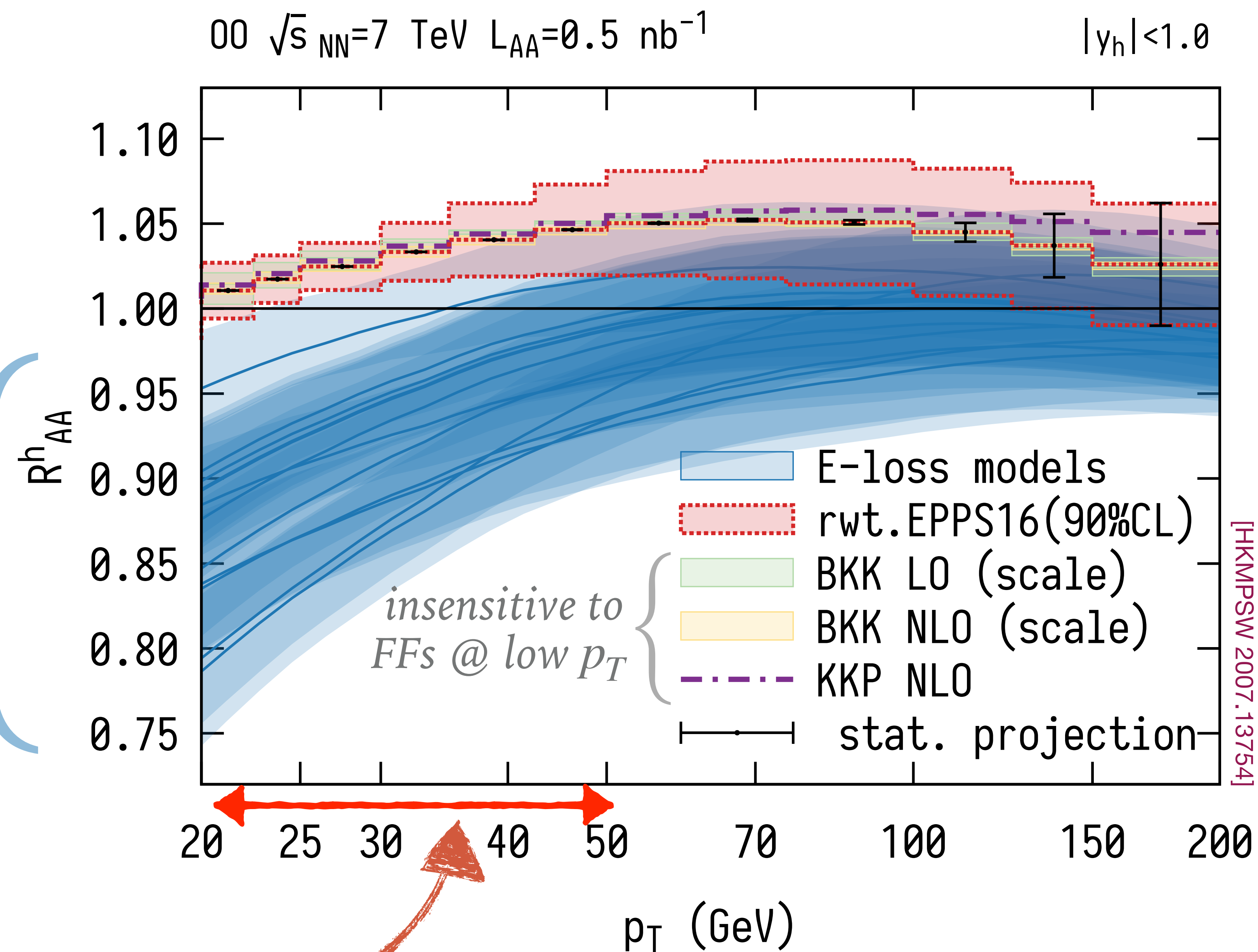
Minimum-Bias R^h_{AA} (null) v.s. Energy-Loss Models

$\sigma^h \sim$ (n)PDFs $\otimes\, \hat{\sigma}_{q,g} \otimes$ FFs

fragmentation functions

- energy-loss models
  - ⇝ extrapolate to OO
  - ⇝ estimate for signal

[HKMPSW 2007.13758]



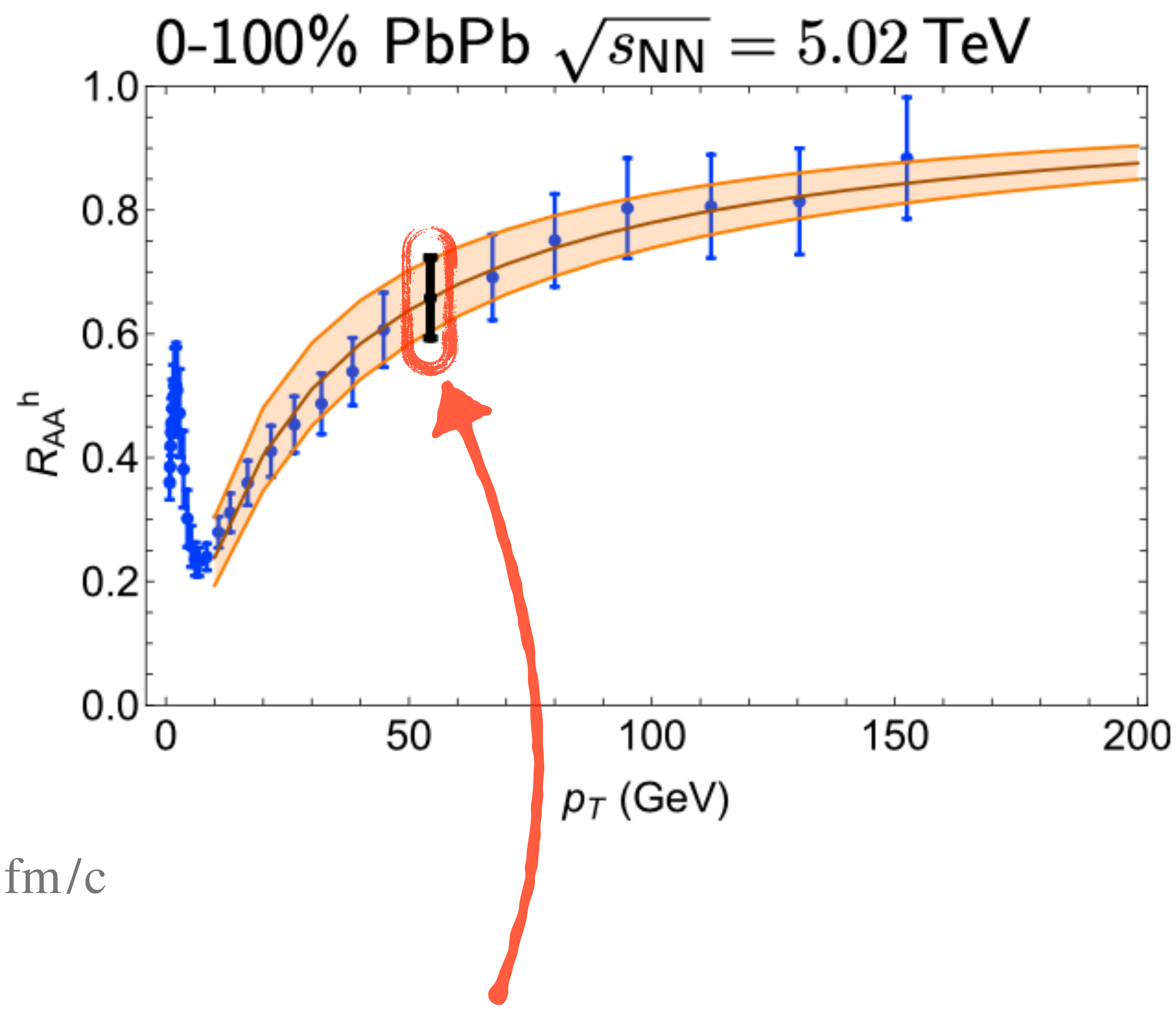
potentially measurable signal in $20\text{ GeV} \lesssim p_T \lesssim 50\text{ GeV}$

* *no signal ⇒ rule out models / scenarios*

Hadron Energy-Loss in Light-Ion Collisions

[HKMPSW 2007.13758]

- simple & modular framework to explore different model setups
  - ⇝ background $T(\tau, r)$ profile:
    - from hydro-like to free streaming
    - conformal EoS v.s. lattice EoS
    - dynamical geometry v.s. Bjorken $\tau^{-1/3}$
    - isotropic geometry v.s. azimuthal anisotropy ϵ_2
  - ⇝ energy-loss models:
    - BDMPS-Z [Arnold 0808.2767]
    - v.s. AdS/CFT inspired
    - v.s. $\mathrm{d}E/\mathrm{d}L \sim L^{0.4}T^{1.2}$
    - v.s. $\mathrm{d}E/\mathrm{d}L \sim LT^3$
    - varying starting time of energy loss $\tau_0 = 0.05 - 0.5$ fm/c
    - with or without nPDFs and FFs

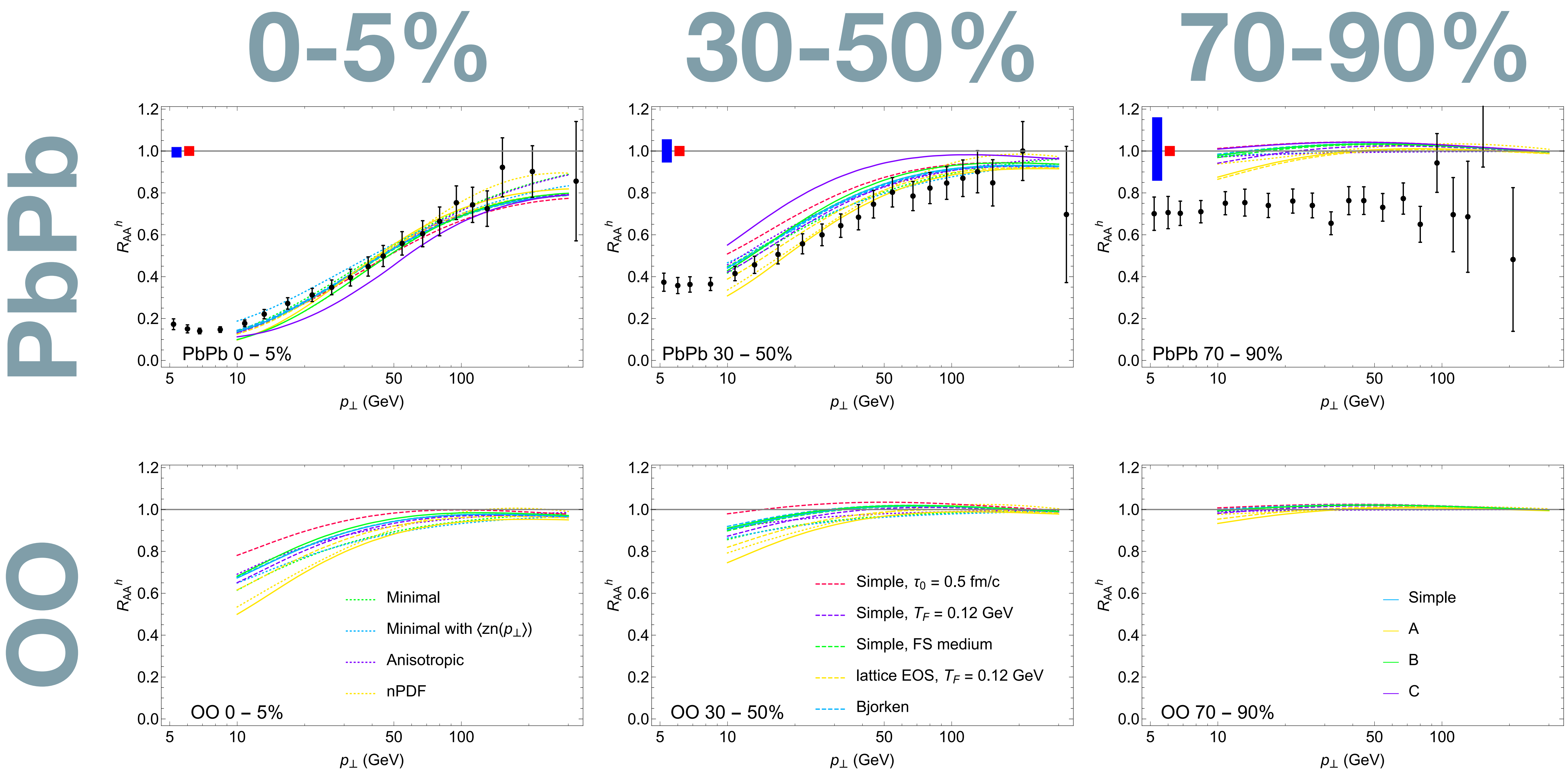


  - ⇝ model parameter ($\hat{q}$) fitted to single data point @ $R^h_{\mathrm{Pb\,Pb}}(p_T = 54.4\ \mathrm{GeV})$

- dependence on p_T & system size are predictions of the model

Hadron Energy-Loss in Light-Ion Collisions

[HKMPSW 2007.13758]



- good mid-central description
- theory uncertainty (conservative) — spread of different scenarios

Z - Bosons as a Standard Candle

- $\langle T_{AA} \rangle$ replaced by beam luminosity in $R^{j,h}_{AA,\text{min bias}}$
  ⇝ requires van der Meer scan (session on Thursday)
- use Drell-Yan as luminosity meter
  ⇝ cancel luminosity uncertainties in cross-ratio:

$$R^{j,h}_{AA,Z}(p_T) = \frac{\sigma^Z_{pp}}{\sigma^Z_{AA}} \frac{\mathrm{d}\sigma^{j,h}_{AA}/\mathrm{d}p_T}{\mathrm{d}\sigma^{j,h}_{pp}/\mathrm{d}p_T}$$

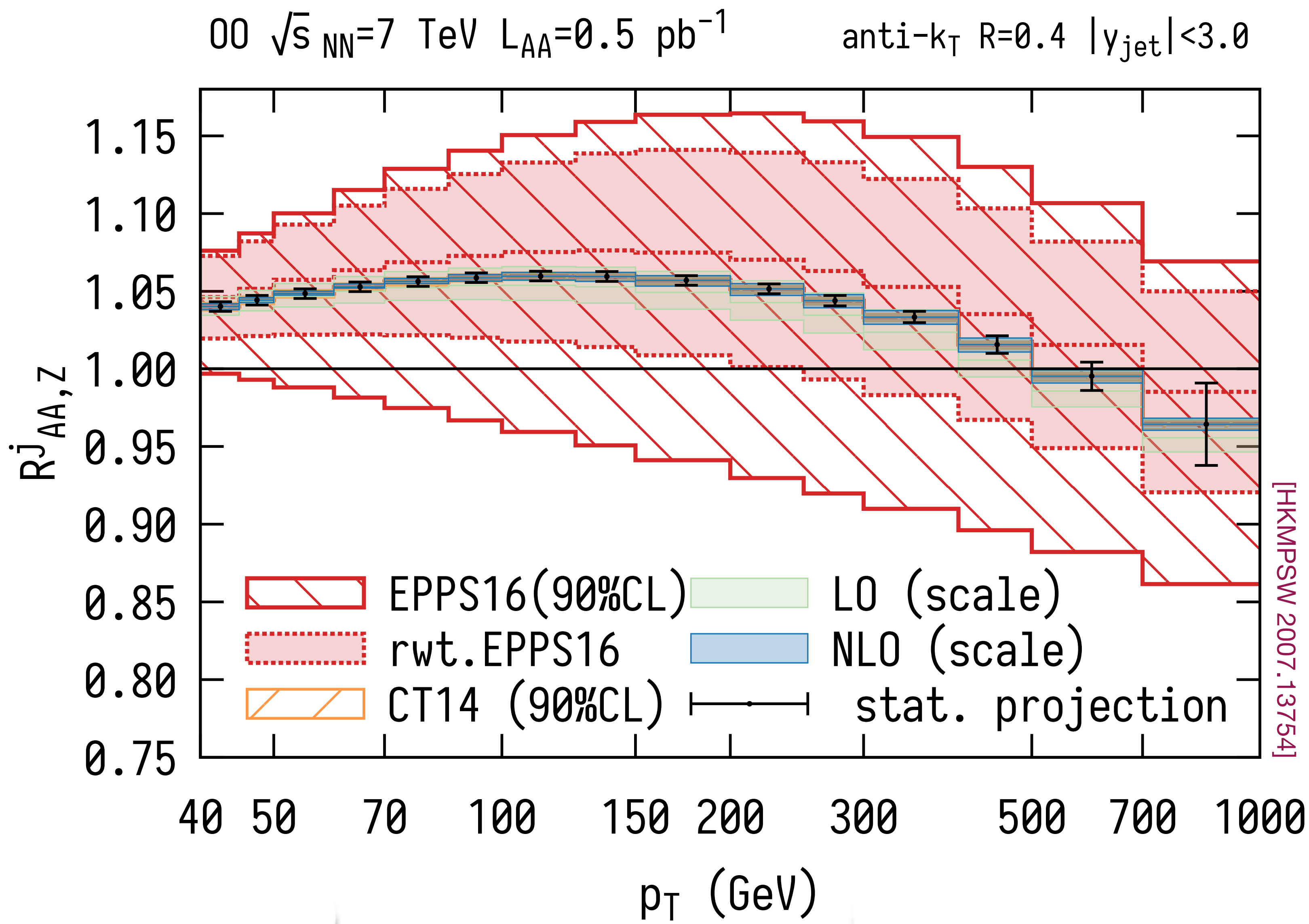
? maybe even get some cancellation of nPDF uncertainties…

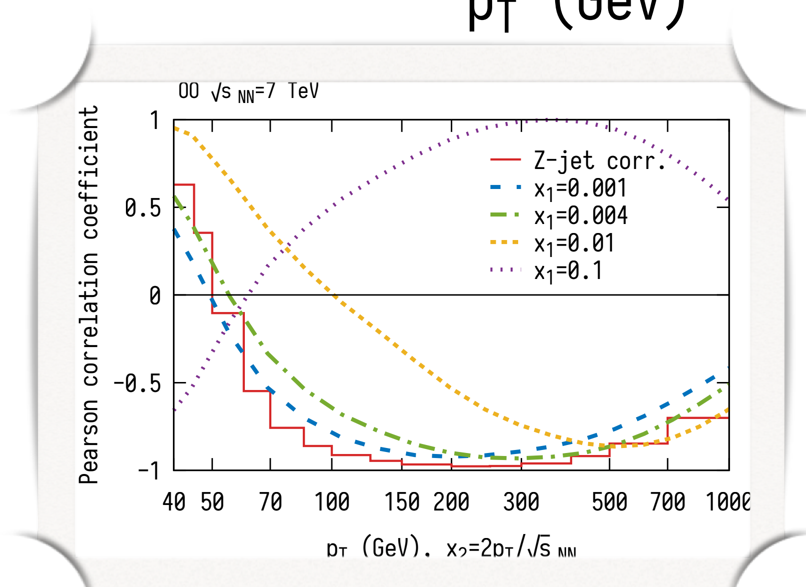
Z - Boson Normalised $R^j_{AA,Z}$ (null)

…nope ;(

- luminosity uncertainties cancel
- requires larger statistics $\mathcal{O}(1\ \mathrm{pb}^{-1})$
- nPDF uncertainties larger than for R^j_{AA}

⇝ anti-correlation in Bjorken-x between Z- & jet-production:





TRIGGERED JET SPECTRUM

- trigger on Z-boson:
  ⇝ $p_T^Z > 30$ GeV (⇒ also inclusive case, effectively "Z+jets")
  ⇝ $m_{\ell\ell} \in [76, 106]$ GeV, $p_T^{\ell^\pm} > 20$ GeV, $|y^{\ell^\pm}| < 2.5$

- measure inclusive jet p_T^j spectrum in triggered events
  & normalize w.r.t. $N_Z \sim \sigma^Z(p_T^Z > 30\text{ GeV})$

$$I_{AA}^{Z\text{+jets}}(p_T^j) \equiv \left.\frac{R_{AA}^{Z\text{+jets}}(p_T^j)}{R_{AA}^Z}\right|_{Z\text{-trig.}} = \left.\frac{\sigma_{pp}^Z}{\sigma_{AA}^Z}\,\frac{\mathrm{d}\sigma_{AA}^{Z\text{+jets}}/\mathrm{d}p_T^j}{\mathrm{d}\sigma_{pp}^{Z\text{+jets}}/\mathrm{d}p_T^j}\right|_{Z\text{-trig.}}$$

! surely, nPDF uncertainties cancel in this case…

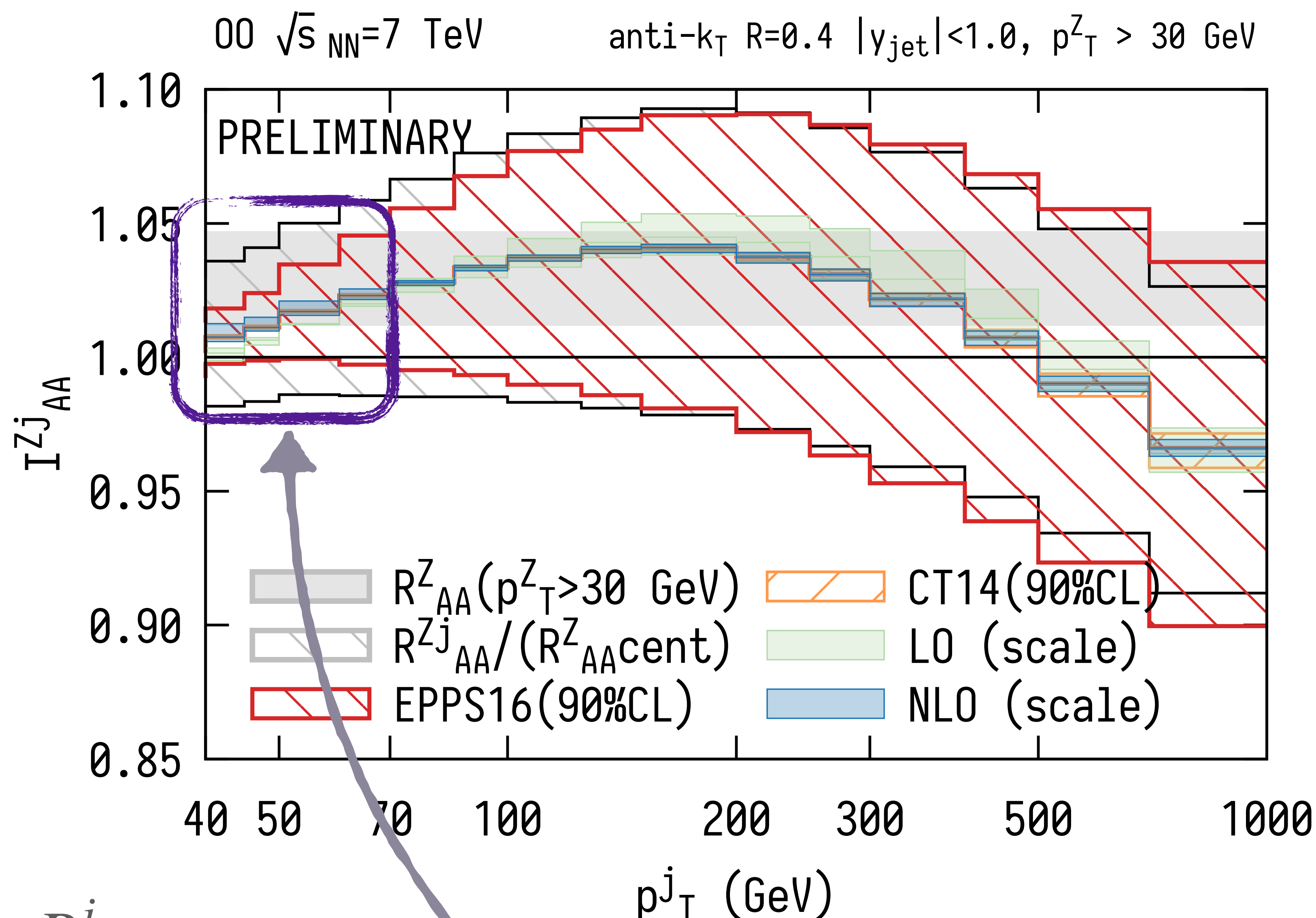
Z - Boson Triggered $I_{AA}^{Z+\text{jets}}$

…still no :|

- luminosity uncertainties cancel
- higher luminosity required
- nPDF uncertainties

  $p_T > 100$ GeV: similar to R_{AA}^{j}

  ⇝ denominator inclusive in jet(s) smears out x-dependence



some cancellation $p_T^j \simeq p_T^Z$

maybe better observables?!

* *hadron+jets, work in progress: smearing due to FFs*

Conclusions & Outlook

- OO — explore the intersection between HEP & HIP
  - inclusive measurement (minimum bias) for R_{AA}
    ⇝ eliminates soft-physics dependence
    (source of large uncertainties)
    ⇝ accurate theoretical baseline possible
    ⇝ main residual uncertainties from nPDFs (improvable)
  - opportunity to establish:
    collectivity ⇜⇝ parton rescattering ⇜⇝ energy loss
- possibility to eliminate/reduce luminosity/nPDF uncertainties
  - ❖ Drell-Yan as luminosity meter: nPDF anti-correlations
  - ❖ triggered observables: still sizeable residual nPDF uncertainties

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  - ❖ triggered observables: still sizeable residual nPDF uncertainties

Thank you!

Backup.

Scale Dependence

$$\sigma(\mu_0, \alpha_s(\mu_0)) = \left(\frac{\alpha_s(\mu_0)}{2\pi}\right)^n \sigma^{(0)} + \left(\frac{\alpha_s(\mu_0)}{2\pi}\right)^{n+1} \sigma^{(1)} + \left(\frac{\alpha_s(\mu_0)}{2\pi}\right)^{n+2} \sigma^{(2)} + \left(\frac{\alpha_s(\mu_0)}{2\pi}\right)^{n+3} \sigma^{(3)} + \mathcal{O}(\alpha_s^{n+4})\,.$$

$$\begin{aligned}
&\sigma(\mu_R, \mu_F, \alpha_s(\mu_R), L_R, L_F) = \\
&\quad \left(\frac{\alpha_s(\mu_R)}{2\pi}\right)^n \hat{\sigma}_{ij}^{(0)} \otimes f_i(\mu_F) \otimes f_j(\mu_F) \\
&\quad + \left(\frac{\alpha_s(\mu_R)}{2\pi}\right)^{n+1} \hat{\sigma}_{ij}^{(1)} \otimes f_i(\mu_F) \otimes f_j(\mu_F) \\
&\quad + L_R \left(\frac{\alpha_s(\mu_R)}{2\pi}\right)^{n+1} n\,\beta_0\, \hat{\sigma}_{ij}^{(0)} \otimes f_i(\mu_F) \otimes f_j(\mu_F) \\
&\quad + L_F \left(\frac{\alpha_s(\mu_R)}{2\pi}\right)^{n+1} \Big[- \hat{\sigma}_{ij}^{(0)} \otimes f_i(\mu_F) \otimes \left(P_{jk}^{(0)} \otimes f_k(\mu_F)\right) \\
&\qquad - \hat{\sigma}_{ij}^{(0)} \otimes \left(P_{ik}^{(0)} \otimes f_k(\mu_F)\right) \otimes f_j(\mu_F) \Big]
\end{aligned}$$

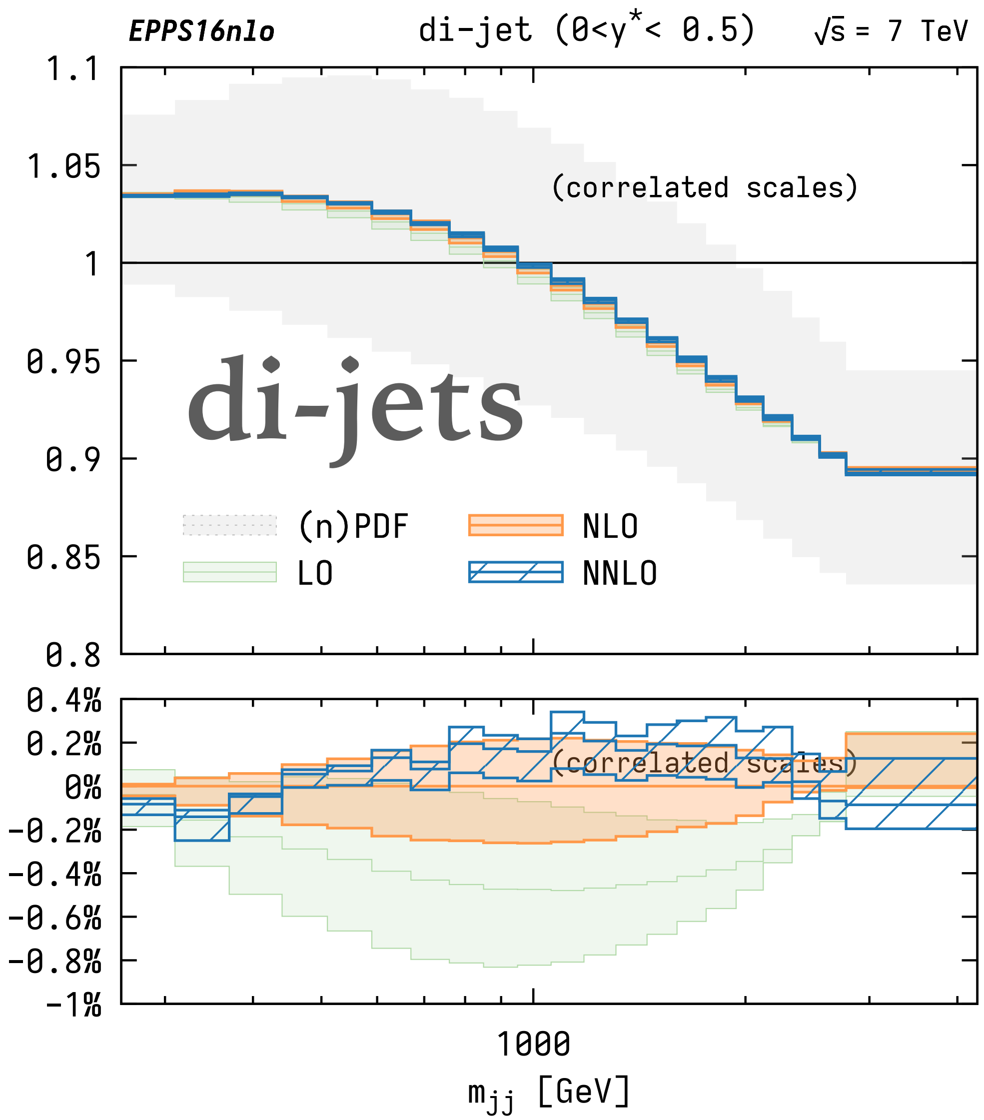
Renormalization group equation

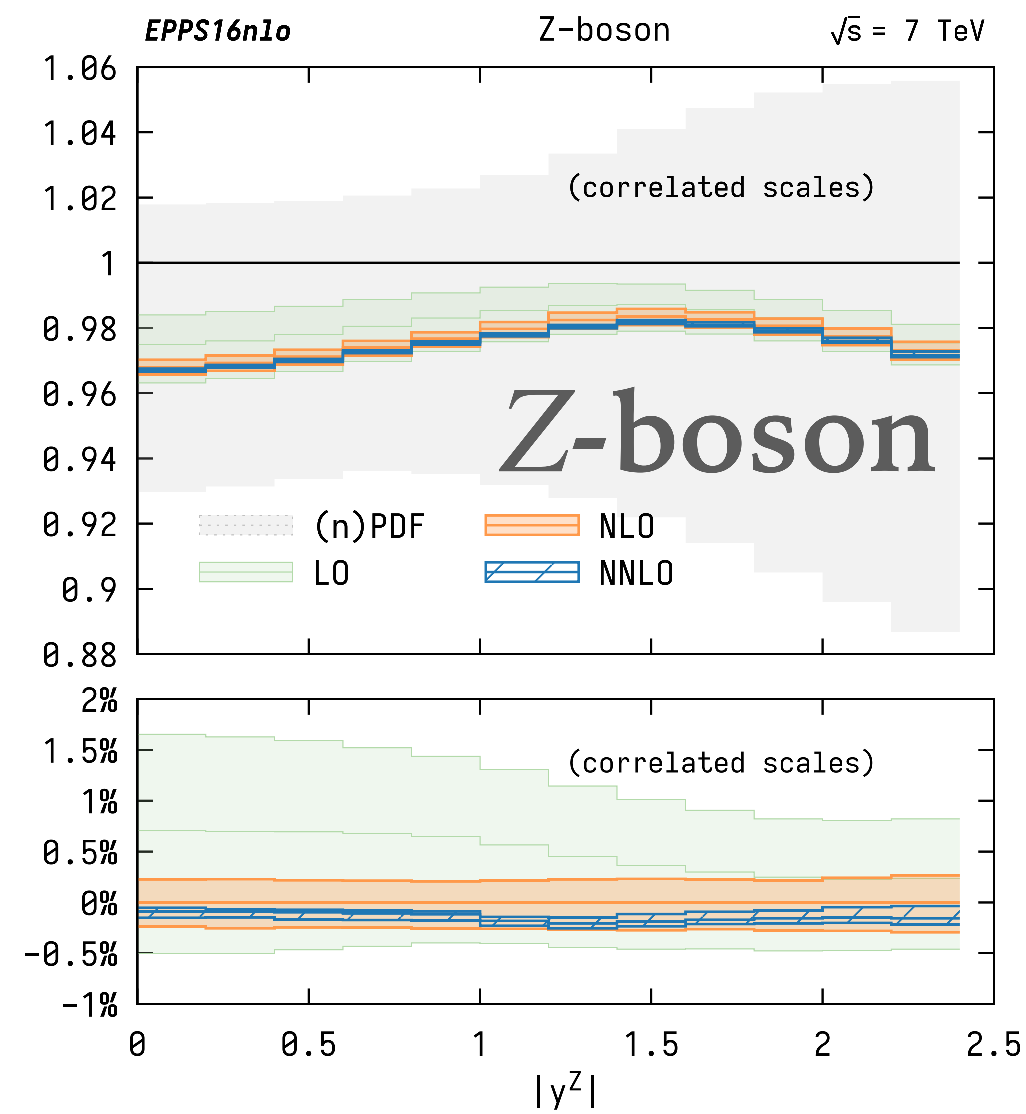
DLAGP evolution

SCALE UNCERTAINTIES — CORRELATED

$$R^{A/B}(\mu_R,\mu_F) = \frac{\sigma^A(\mu_R,\mu_F)}{\sigma^B(\mu_R,\mu_F)}$$

7-point



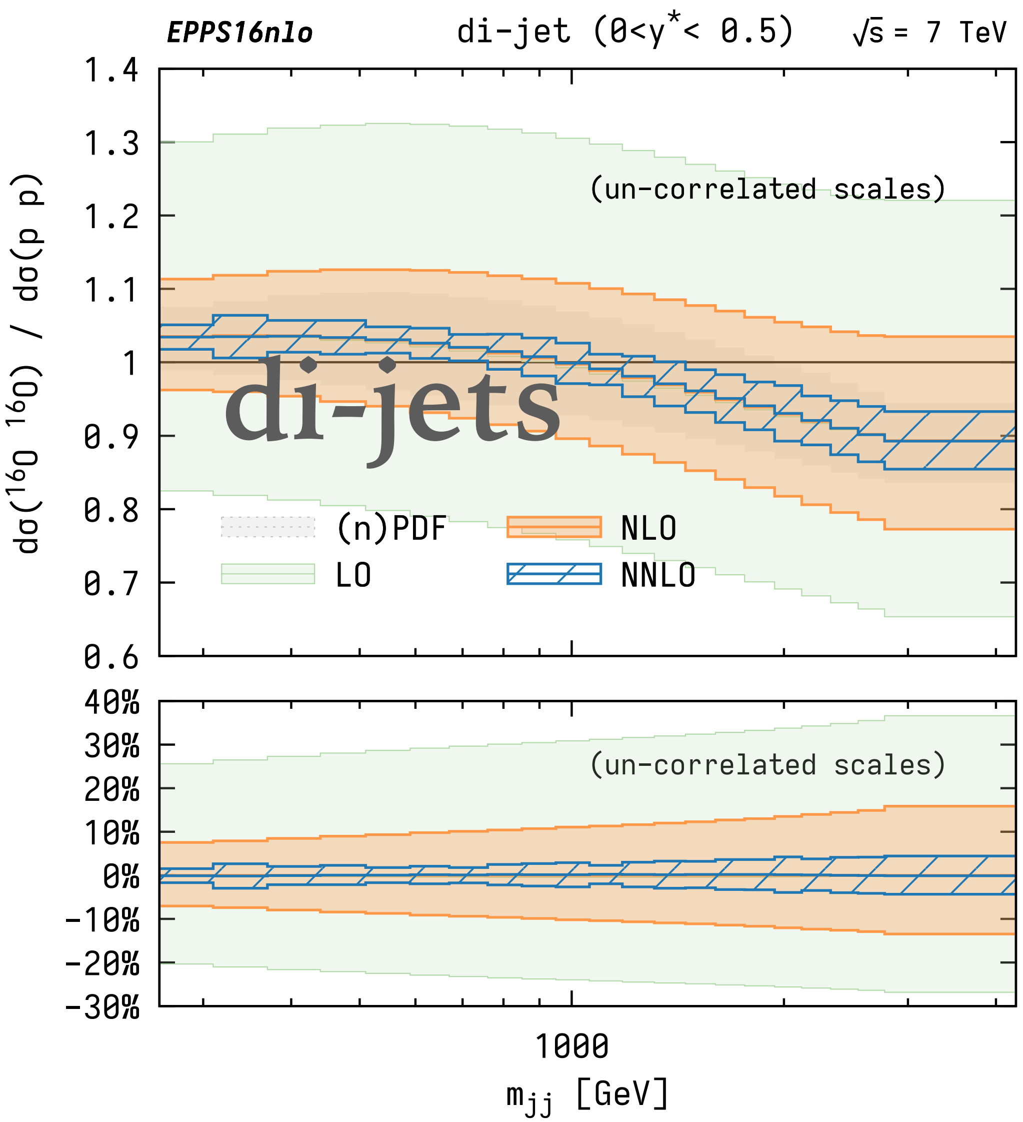


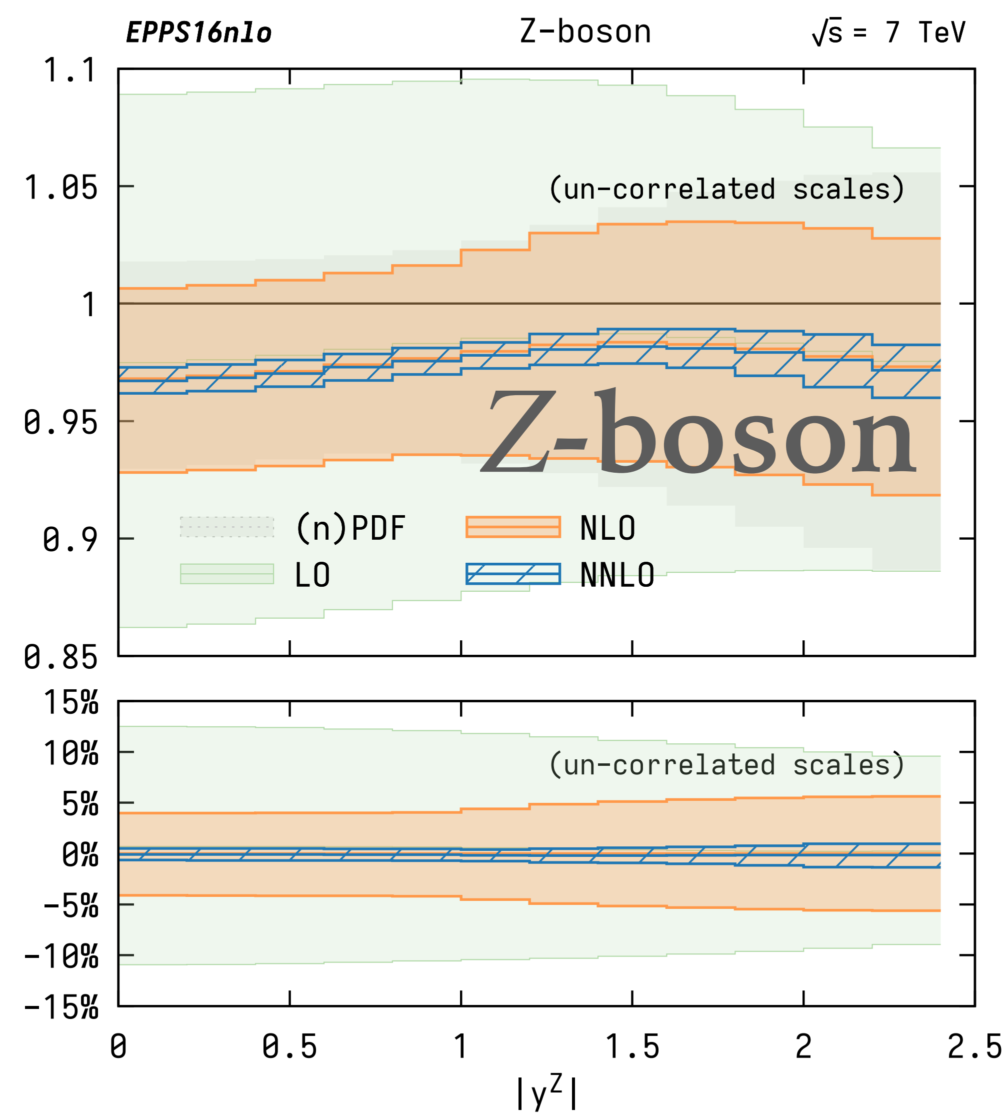
- higher-order corrections $< 1\,\%$
- realistically captured by uncertainty estimates

SCALE UNCERTAINTIES — UN-CORRELATED

$$R^{A/B}(\mu_R^A, \mu_R^B, \mu_F^A, \mu_F^B) = \frac{\sigma^A(\mu_R^A, \mu_F^A)}{\sigma^B(\mu_R^B, \mu_F^B)}$$

31-point

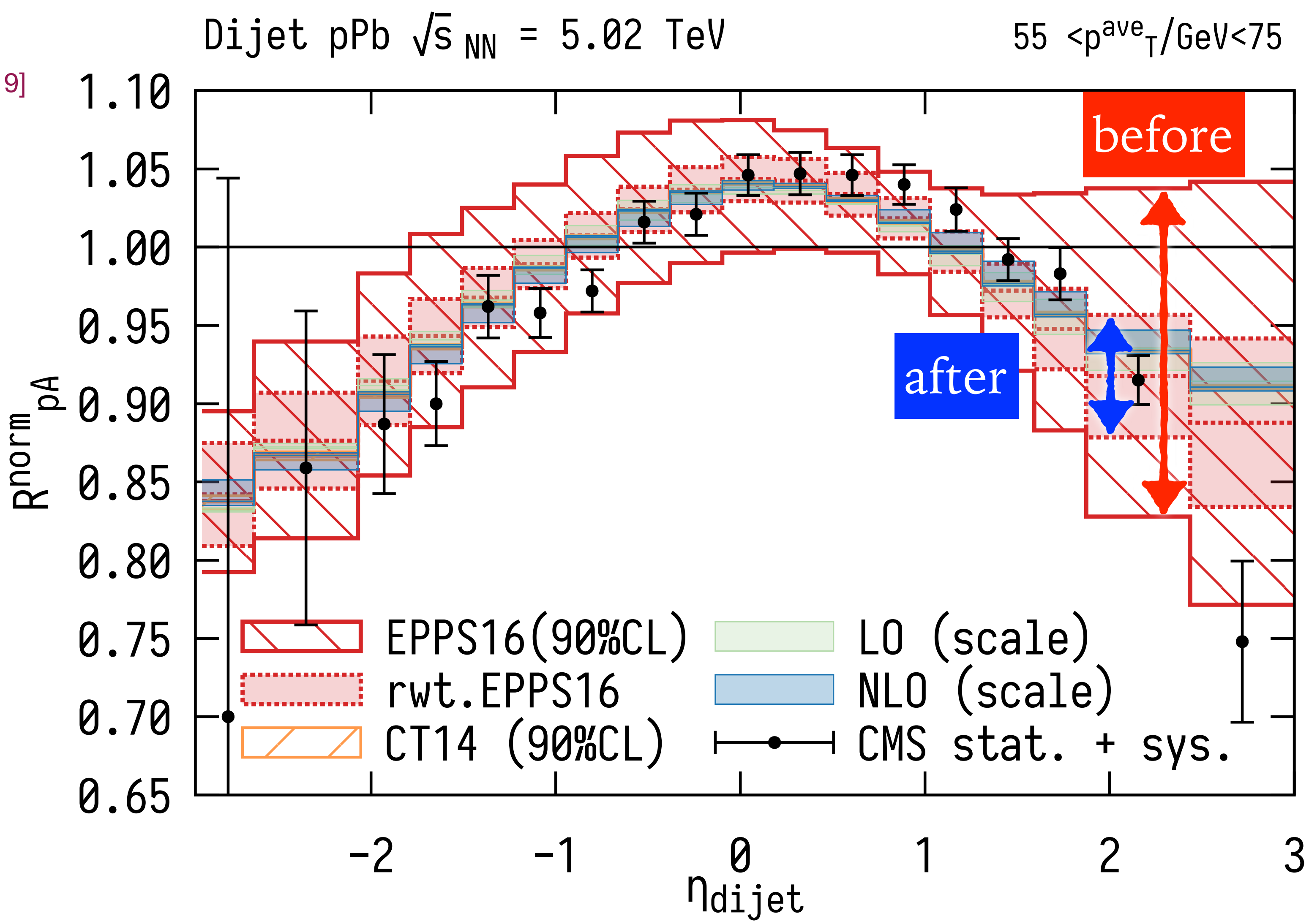




- higher-order corrections $< 1\,\%$
- over-estimated uncertainties: $\pm\mathcal{O}(10\%)$

nPDFs — Impact of new Data

- following [Eskola, Paakkinen, Paukkunen '19]
  - ⇝ reweight nPDFs using CMS pPb dijet data ⇝ [CMS 1805.04736]
  - ⇝ substantial reduction in uncertainties!



- danger of "fitting away" energy loss effects?!
  - ⇝ observable insensitive:

$$R^{\text{norm}}_{\text{p Pb}} = \left(\frac{1}{d\sigma_{\text{p Pb}}/dp_T} \frac{d\sigma_{\text{p Pb}}}{dp_T d\eta} \right) \Big/ \left(\frac{1}{d\sigma_{\text{pp}}/dp_T} \frac{d\sigma_{\text{pp}}}{dp_T d\eta} \right)$$