Interpreting inclusive jet and gamma-jet suppression in heavy-ion collisions at the LHC

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Introduction - how can one model jet suppression?

- Jet suppression is not trivial to predict
  - energy loss depends on the flavour, parton shower shapes, path length etc.
- Trying to keep the model **simple**
  - one could identify which component plays the major role
  - using parametric modelling of parton energy loss

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- Jet suppression is not trivial to predict
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- Trying to keep the model **simple**
  - one could identify which component plays the major role
  - using parametric modelling of parton energy loss
- This approach was discussed in several papers
  - Eur.Phys.J. C76 (2016) no.2, 50
  - Phys.Lett B767 (2017) 10
  - Nucl.Part.Phys.Proc. 289-290 (2017) 53-58
  - arXiv:2407.11234 ← focus of this talk
- Goal: extract basic properties of jet quenching with **minimal assumptions** on the quenching physics

The parametric modeling of parton energy loss

- **Jet spectra** are parameterized by power law

$$\frac{dN}{dp_{\mathrm{T}}^{\mathrm{jet}}} = A\left[f_{q0}\left(\frac{p_{T0}}{p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n_q} + (1-f_{q0})\left(\frac{p_{T0}}{p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n_g}\right]$$

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where the exponent is $p_{\mathrm{T}}^{\mathrm{jet}}$-dependent:

up to 2

$$n_i(p_{\mathrm{T}}^{\mathrm{jet}}) = \sum_{j=0}^{j_{\max}} \beta_j \log^j\left(\frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}0}}\right)$$

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- Average jet transverse momentum loss modelled using **three parameters**

$$\langle \Delta p_{\mathrm{T}}^{\mathrm{jet}} \rangle_i = c_{F,i}\ s\left(\frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}0}}\right)^{\alpha}$$

Including fluctuations

- Energy loss has a **distribution** $w(p_{\mathrm{T}}^{\mathrm{jet}}, \Delta p_{\mathrm{T}}^{\mathrm{jet}})$ which dictates quenched jet spectra, $$\frac{dN_Q}{dp_{\mathrm{T}}^{\mathrm{jet}}} = \int d\Delta p_{\mathrm{T}}^{\mathrm{jet}} \frac{dN}{dp_{\mathrm{T}}^{\mathrm{jet}}} w(p_{\mathrm{T}}^{\mathrm{jet}}, \Delta p_{\mathrm{T}}^{\mathrm{jet}})$$

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- Assume that energy loss distribution depends only on self-normalized fluctuations (c.f. [Phys. Rev. Lett. 122, 252302 (2019)]), $x \equiv p_{\mathrm{T}}^{\mathrm{jet}} / \langle \Delta p_{\mathrm{T}}^{\mathrm{jet}} \rangle$
- Energy loss distribution **parameterized** by generalized integrand of gamma function: $w(x) = \frac{c_1^{c_0}}{\Gamma(c_0)} x^{c_0 - 1} e^{-c_1 x}$

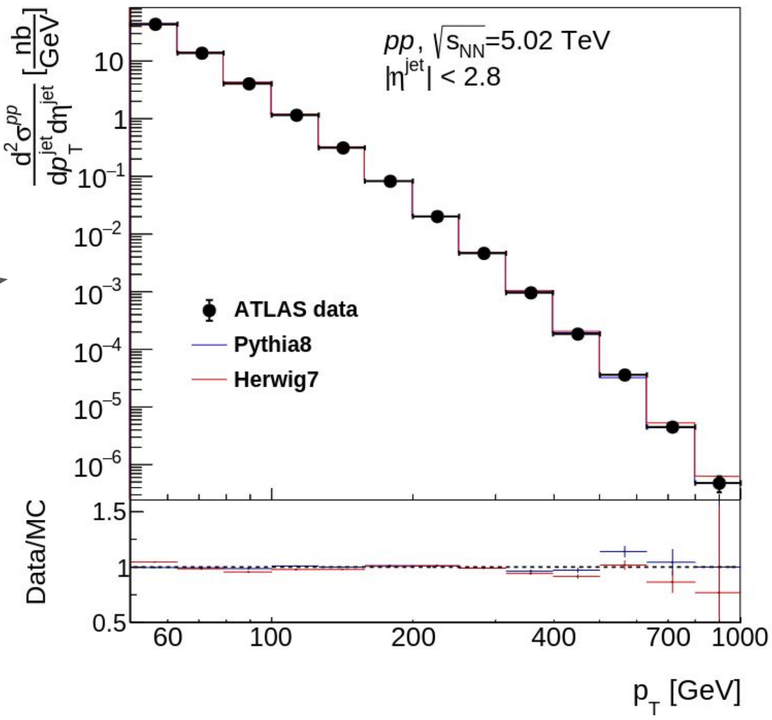
Including more complex parameterizations

- **Logarithmic** dependence of energy loss used e.g. in LBT model also included as an option,

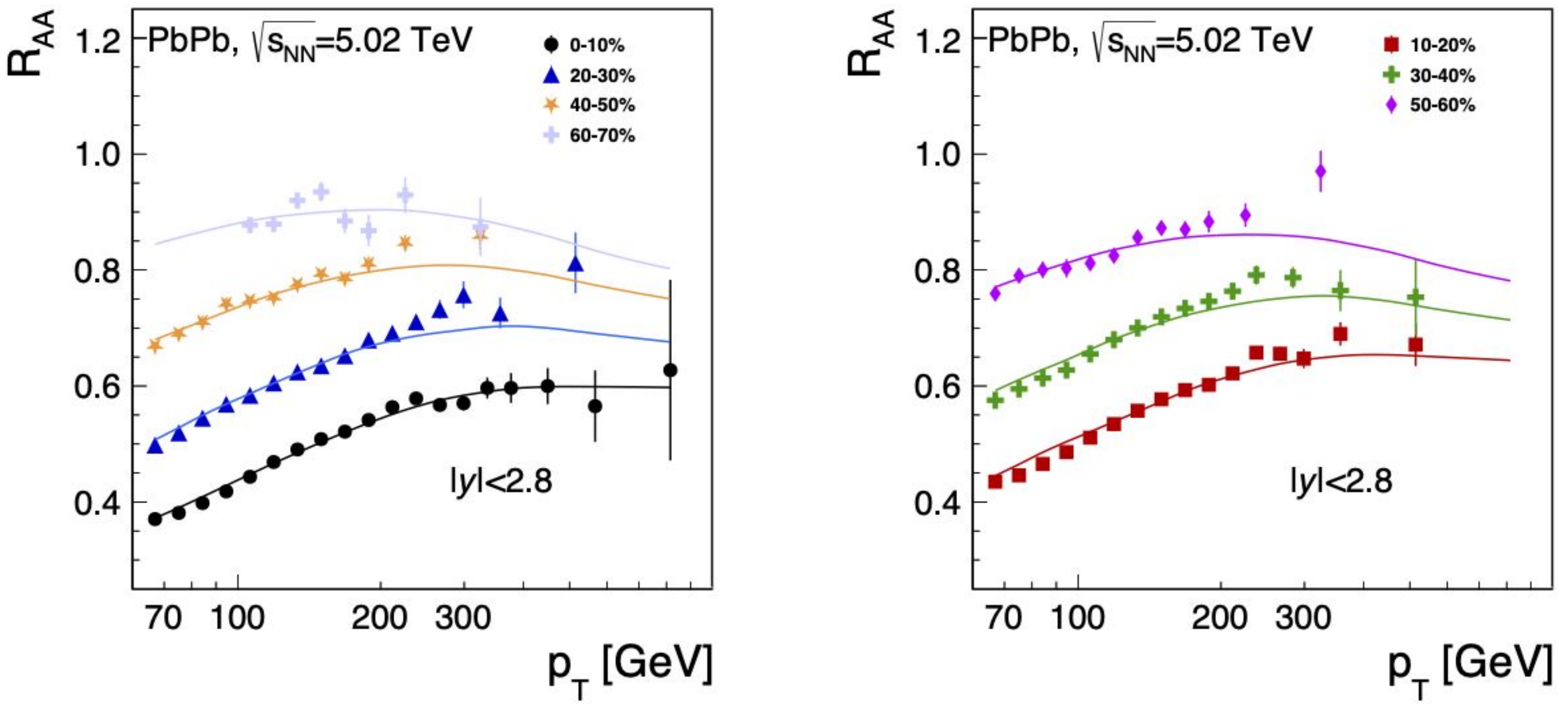
$$\langle \Delta p_{\mathrm{T}}^{\mathrm{jet}} \rangle = c_F \; s \; \left(\frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}0}} \right)^{\alpha} \log \left(\frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}0}} \right)$$

Methodology

- **Pythia8** (w/ & w/o nPDF effects) and **Herwig 7** used to obtain parameterized quark-and gluon-initiated **jet spectra**.
- Spectra reweighted to fit the data.
- Energy loss **parameters** (s, α) from χ^2 minimization wrt to 5 TeV jet R_{AA} data [Phys. Lett. B 790, 108 (2019)] for various c_F parameters.
- Energy loss parameters then used to model **other observables**.



Best parameterization



Can describe all centrality bins **with single power α=0.27**, c_F=1.78, when including **nPDF** effects and **fluctuations**.

Systematic comparison of parameterizations

Label	Spectra	Parameters	$\chi^2\|_{0-10\%}$	$\chi^2\|_{\text{all}}$	
p1	P8, nPDF	$\alpha_{\text{min}} = 0.27, c_{\text{F}} = 1.78$	0.51	1.06	Configuration w/ nPDFs, w/ fluctuations, insensitive to c_F
p2	P8, nPDF	$\alpha_{\text{min}} = 0.24, c_{\text{F}} = (9/4)^{1/3}$	0.53	1.05	
p3	P8, nPDF	$\alpha_{\text{min}} = 0.29, c_{\text{F}} = 9/4$	0.50	1.09	
p4	P8	$\alpha_{\text{min}} = 0.33, c_{\text{F}} = 1.78$	0.70	1.06	
p5	H7	$\alpha_{\text{min}} = 0.30, c_{\text{F}} = 1.78$	0.88	1.18	
p6	P8, nPDF	$\alpha_{\text{min}} = 0.40, c_{\text{F}} = 1.78$	0.62	1.53	no fluctuations
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Significantly worse description without fluctuations

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Significantly worse description when using log-term

Path-length dependence of energy loss

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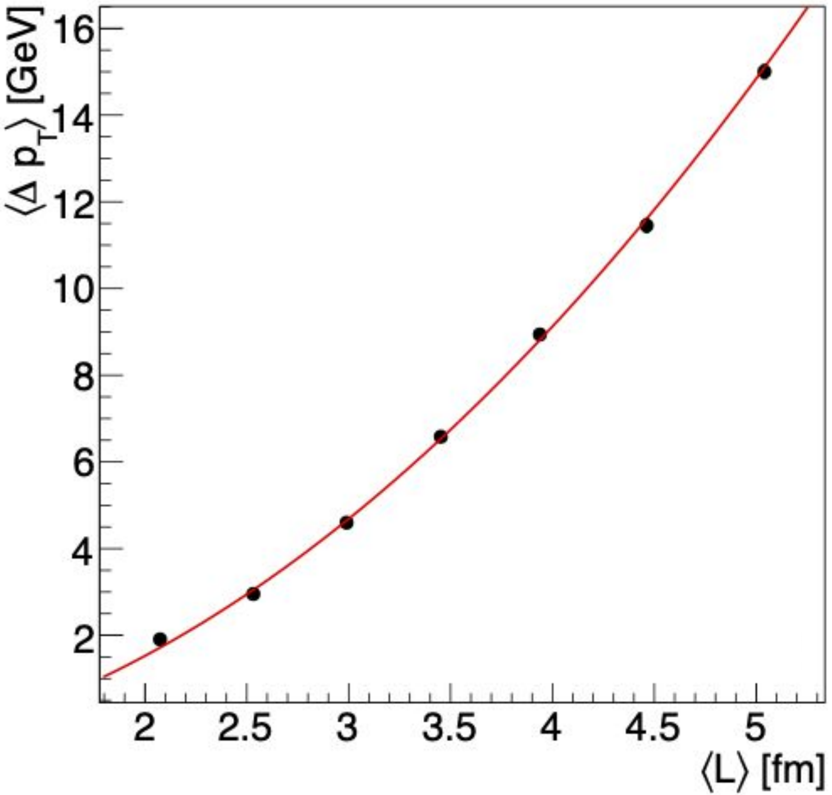
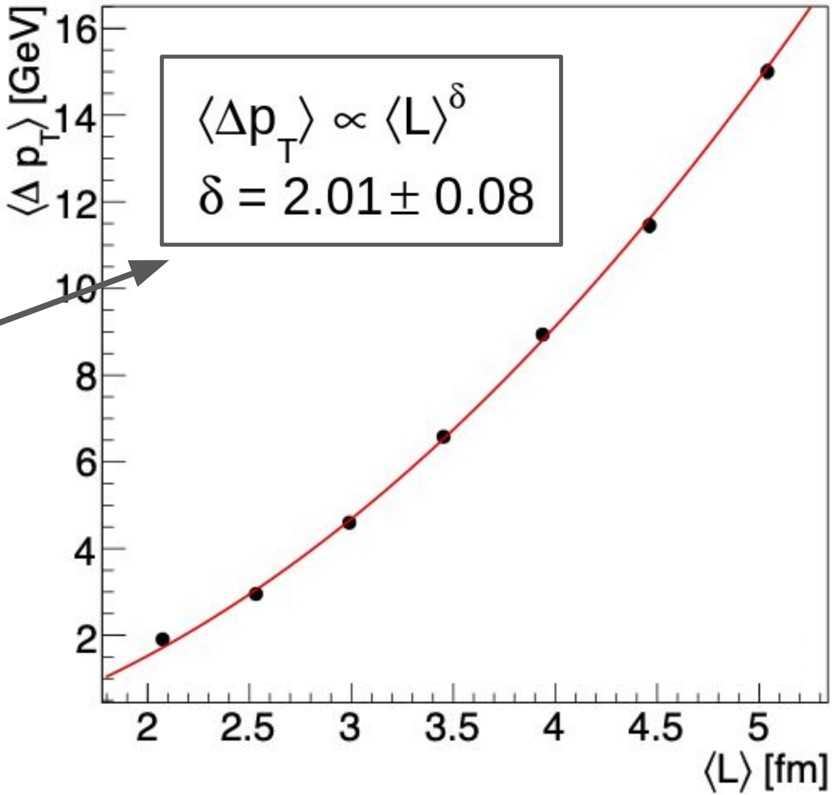
- Assumption: path-length proportional to **Glauber model** initial conditions.



Path-length dependence of energy loss

- Fitted $\langle \Delta p_T \rangle$ can be used to **extract path-length** dependence of energy loss.
- Assumption: path-length proportional to **Glauber model** initial conditions.
- Fitted exponent strongly supports **quadratic dependence**.
- Confirming **radiative nature** of energy loss with minimal model assumptions.



Jet v_2

$$v_2 \approx \frac{1}{2}\frac{R_{\mathrm{AA}}(L_{in}) - R_{\mathrm{AA}}(L_{out})}{R_{\mathrm{AA}}(L_{in}) + R_{\mathrm{AA}}(L_{out})}$$

$$L_{in} = \langle L \rangle - c \cdot \Delta L_{in}$$
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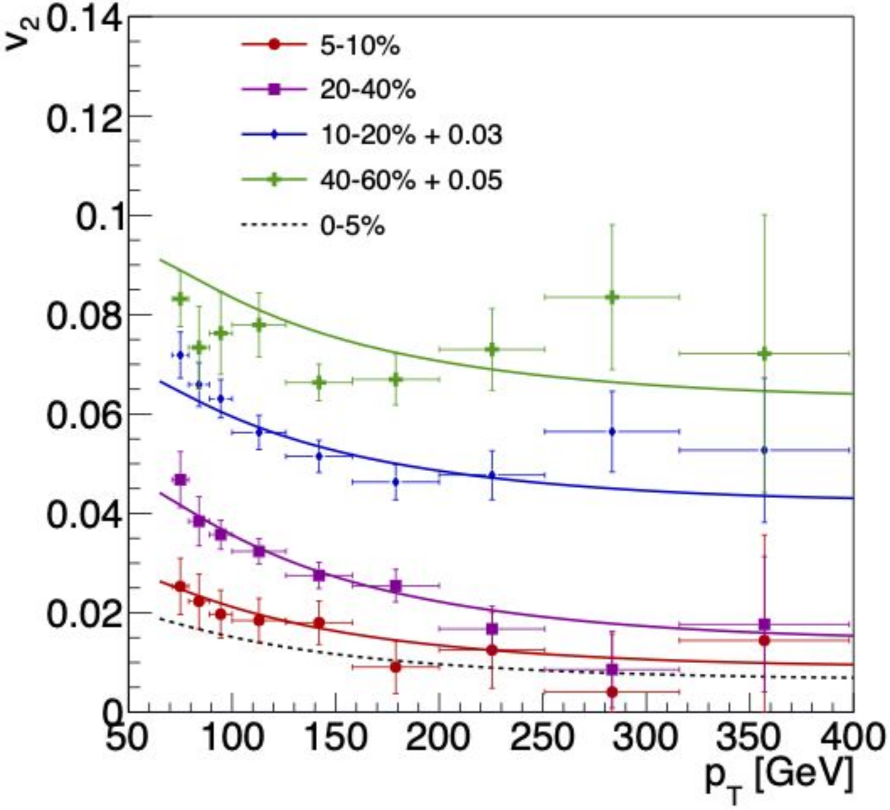


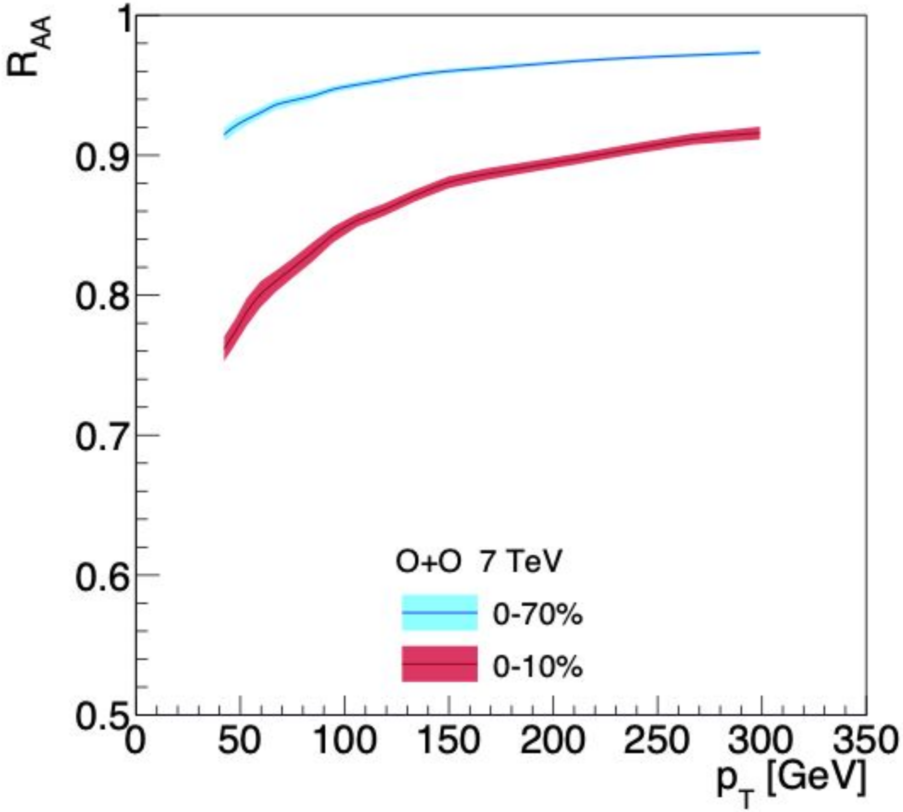
$$L_{in} = \langle L \rangle - c \cdot \Delta L_{in}$$
$$L_{out} = \langle L \rangle + c \cdot \Delta L_{out}$$

- Good **agreement with** ATLAS **data** [Phys. Rev. C 105, 064903 (2022)] found for

$$c = 0.35$$

- This supports **validity of L^2** dependence

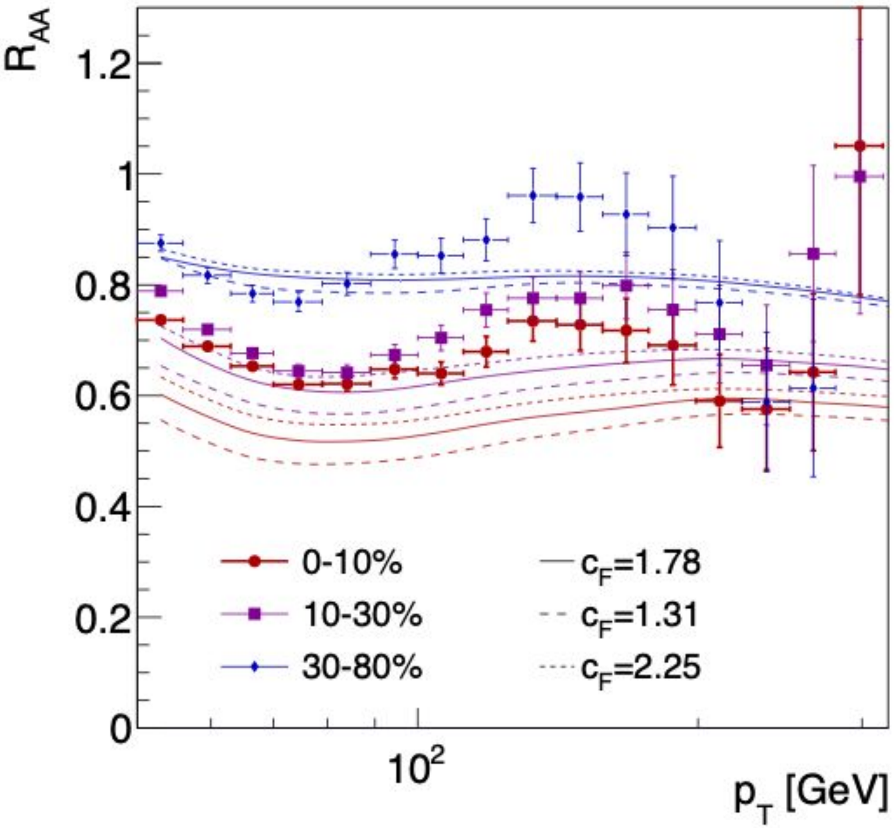
Jet R_{AA} for Oxygen-Oxygen



- Extracted energy loss in **2.76 TeV and 5.02 TeV** Pb+Pb extrapolated to 7 TeV
- Extracted path-length dependence allows extrapolating from Pb+Pb to O+O using **Glauber model**.
- Jet **R_{AA} of 0.8** at 50 GeV in central O+O collisions – energy loss is expected to be be significant.

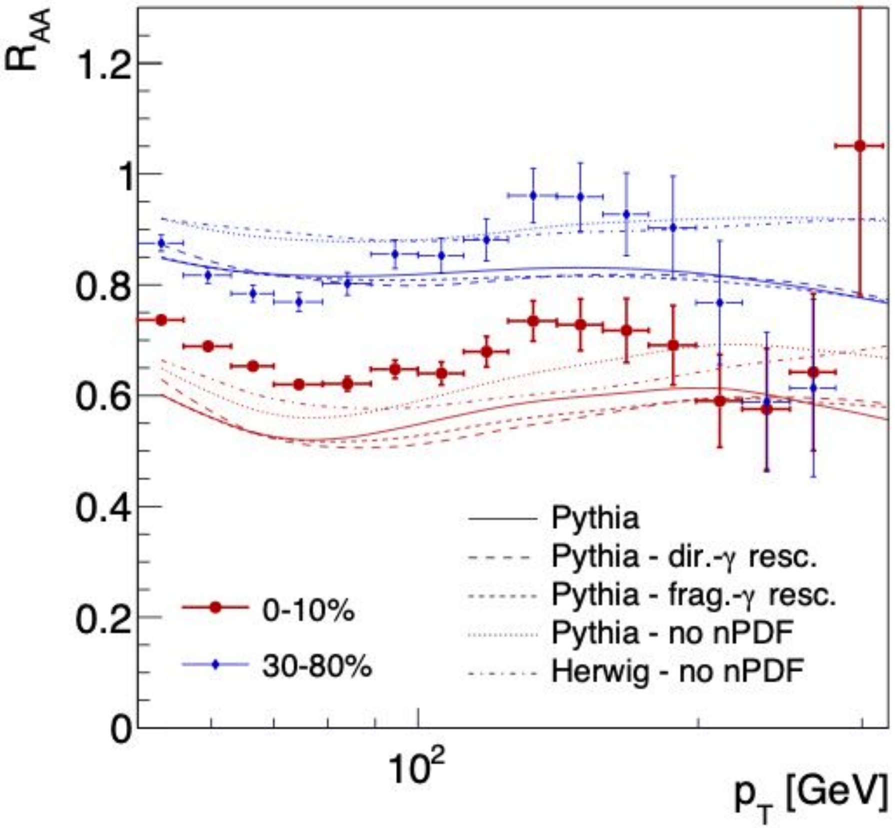
Gamma-jet R_{AA} - c_F dependence

- Quenching parametrizations (p1-p3) from inclusive jet R_{AA} were used
- **Rather large differences** in R_{AA} between **different** c_F values
  - role of flavor in the jet quenching can be constrained with gamma-jet measurement
- **Shape qualitatively reproduced** below 120 GeV
- Local maximum around 150 GeV not reproduced



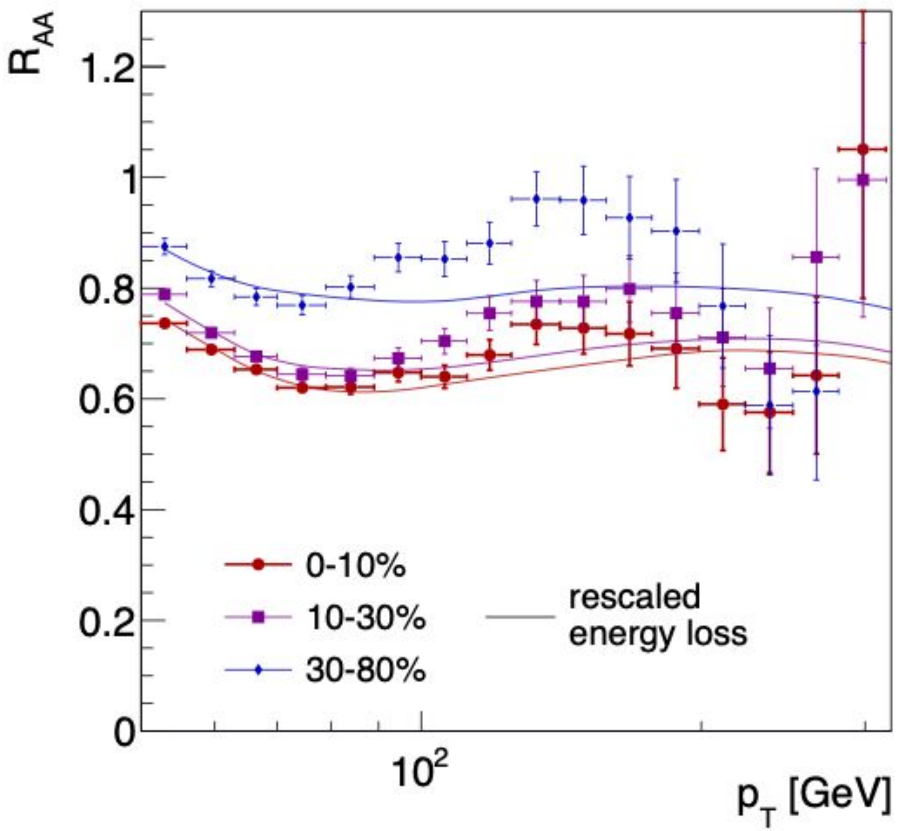
Gamma-jet R_{AA} - impact of initial spectra

- Baseline quenching parametrization (p1) used
- Substantial differences in the magnitude of R_{AA}:
  - **Different input spectra reweighting** have less than 10% effect
  - **Implementation of nPDF effects** influences R_{AA} by 15-20%
  - **The choice of MC generator** changes R_{AA} by another ~10%
- Precise **knowledge of input parton spectra crucial** to determine the exact shape of R_{AA}



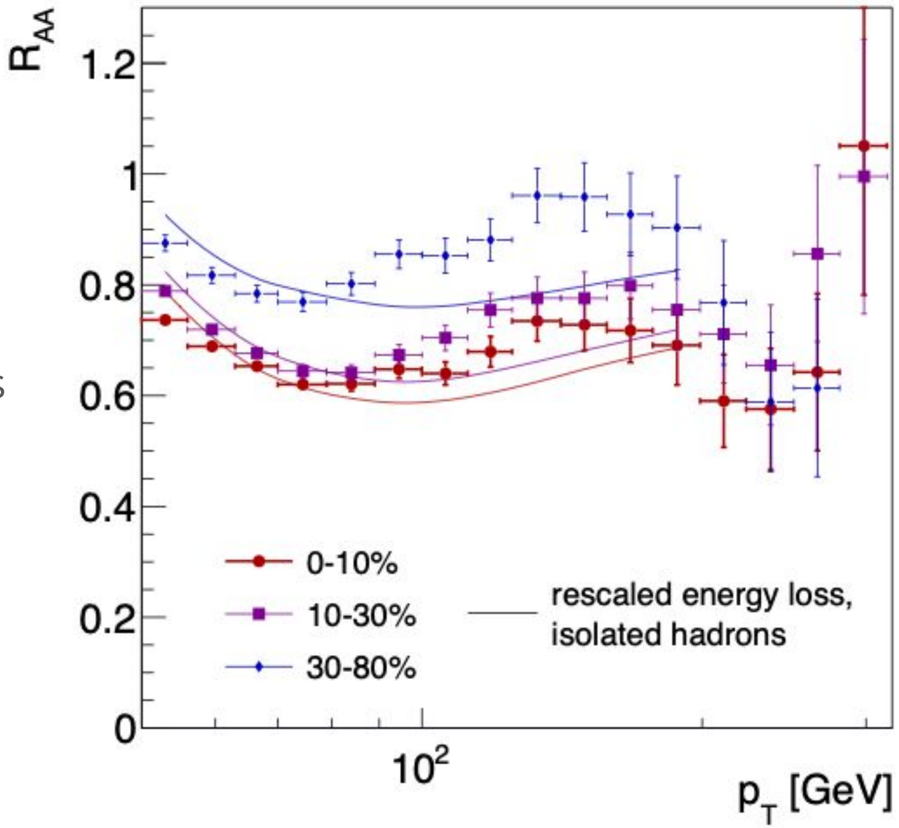
Gamma-jet R_{AA} - rescaled energy loss

- **Selection bias** may cause **difference** in energy loss suffered by jets **between gamma-jet and inclusive jet** systems
- Quenching parameter s refitted to match gamma-jet R_{AA}
- This is translated to **change in average path-length**
- Ratio between $\langle L_\gamma \rangle / \langle L \rangle$ is 0.80±0.02, 0.9±0.03, and 1.07±0.03 for 0-10%, 10-30%, and 30-80% centrality bins



Gamma-jet R_{AA}- isolated hadrons background

- **Possible contamination** by isolated, predominantly neutral hadrons considered
- The **cross-section** for such process is of **similar order of magnitude** as gamma-jet production
- Large uncertainty in modeling of the very end of the fragmentation spectrum
- The **shape of R_{AA}** strikingly **similar to gamma-jet** result



Summary

- Energy loss **fluctuations** are crucial for describing jet quenching.
- $\langle \Delta p_T \rangle \sim p_T^{\mathbf{0.3}}$ and **single power** can describe all centrality bins
- $\langle \Delta p_T \rangle \sim \langle L \rangle^{\mathbf{2}}$, i.e. data strongly supports **radiative energy loss**.
- **No RAA-v2 puzzle** present in jet data.
- Expecting jet R_{AA} of ~ **0.8** in central **O+O collisions.**
- Energy loss of jets in **gamma-jet system is different** from energy loss of inclusive jets – provided quantifications may help understanding biases
- Details and more can be found in arXiv:2407.11234

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