Probing gluon saturation in forward photon+jet production in pp and pPb

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Gluon saturation

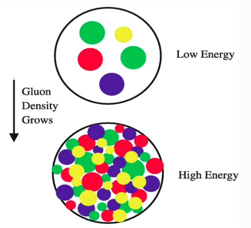
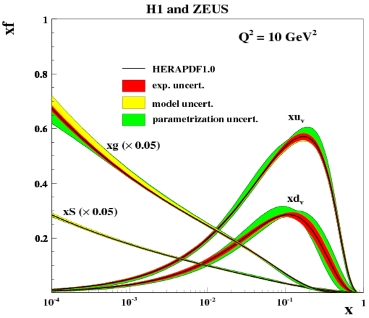


Figure: From hep-ph/0402137



High momentum gluons split into small momentum gluons, but at sufficiently high gluon density this splitting is balanced by recombination.

Figure: Parton distribution functions from HERAPDF1.0, published in JHEP 01 (2010) 109.

High gluon densities and EIC

- One of the main goals of EIC is to study the collective behavior of gluons under conditions where recombination dominates;
- Not only the onset of saturation, but also to study the properties and dynamics of saturation;
- Q_s^2 increases with increasing gluon density, and:

$$Q_s^2(x) \propto A^{1/3} \cdot x^{-\lambda},$$

- While a direct study of saturation phenomenon in proton may not be possible, it will be possible to study saturation in large nuclei due to this enhancement.

Motivation

- Before EIC starts operating, there is still an enormous potential to study saturation in the LHC program.
- FoCal will cover the pseudorapidity range $3.4 < \eta < 5.8$ for measurements of prompt and isolated photons, identified π^0s and other neutral mesons, J/ψ and its excited states, W and Z bosons, inclusive jets, correlations (di-hadron, di-jet, γ+hadron, γ+jet, etc.)

About FoCal:

A forward high-granularity electromagnetic calorimeter combined with conventional hadronic calorimeter aiming to study:

- Gluon saturation in pA: at very small x, since it has large forward coverage for identified particle production. Sensitive observables:
  - J/ψ
  - Di-jet/di-hadron production
  - Direct(Isolated) photons: large cross section
- Long-range correlations.

Dilute-dense collisions

The process here is: $p(P_B) + A(P_A) \rightarrow \gamma(k_1) + J(k_2) + X$,

with the longitudinal momentum fractions:

$$x_A = \sum_i \frac{|\vec{k}_{T_i}|}{\sqrt{s}} e^{-\eta_i},$$

$$x_B = \sum_i \frac{|\vec{k}_{T_i}|}{\sqrt{s}} e^{\eta_i}$$

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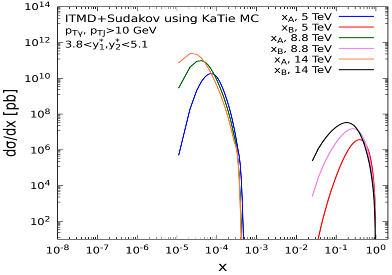


Spectra of longitudinal fractions probed in the PDF for different CM energies and transverse momentum cut of 10 GeV. Showing $x_A << x_B$.
*Eur.Phys.J.C*83(2023)9, 868 .

Improved Transverse Momentum Dependent(ITMD) factorization

ITMD accounts for complete kinematics with off-shell gluons. The leading order ITMD factorization formula for our process of interest reads:

$$d\sigma_{pA\to j+\gamma} = \int dx_A dx_B \int d^2 k_T f_{q/B}(x_B;\mu) F_{qg}^{(1)}(x_A, k_T;\mu) d\sigma_{qg^*\to q\gamma}(x_A, x_B, k_T;\mu)$$

with incoming momenta:

$$k_A^\mu = x_A P_A^\mu + k_T^\mu \, , k_B^\mu = x_B P_B^\mu$$

- collinear PDFs: $f_{q/B}(x_B;\mu)$,
- unintegrated gluon PDFs: $F(x_A, k_{T_A};\mu)$,
- off-shell gauge invariant tree-level matrix elements reside in $d\sigma_{qg^*\to q\gamma}$

S. Catani, M. Ciafaloni, F. Hautmann, 1991;
P. Kotko, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren, 2015;
T. Altinoluk, R. Boussarie, P. Kotko, 2019.

ITMD with KaTie

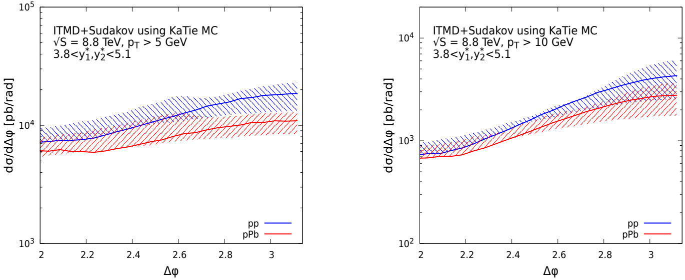
- It is a parton level event generator,
- When provided with k_T -dependent PDFs KaTie (van Hameren Comput.Phys.Commun. 224 (2018) 371-380) generates the phasespace points and the necessary matrix elements through AVHLIB,
- The PDFs can be provided using TMDLib or independent grid files,

Saturation in forward γ + jet

- For this study: final states were recorded in the pseudorapidity range $3.8 < \eta < 5.1$,
- For different CM energies: 5 TeV, 8.8 TeV and 14 TeV for pp and 8.8 TeV for pPb and p_T thresholds: 5, 10 and 20 GeV.
- Highly asymmetric kinematics; $x_A << x_B$, and $x_A \sim 10^{-4} - 10^{-5}$.
- The collinear PDF was provided via LHAPDF and set to CT18NLO and for the target we have used the KS non-linear gluon TMD PDF K. Kutak, S. Sapeta, Phys.Rev. D86, 094043 (2012).

Saturation in forward γ + jet

Azimuthal Correlations:

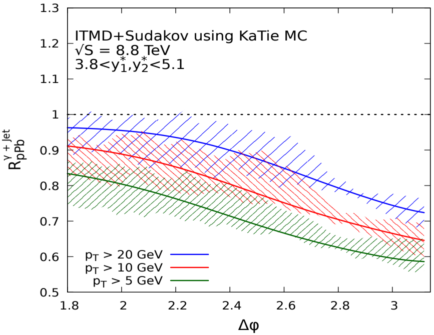


Similar results were obtained for di-jets in: Al-Mashad, M.A., van Hameren, A., Kakkad, H. et al. Dijet azimuthal correlations in p-p and p-Pb collisions at forward LHC calorimeters. J. High Energ. Phys. 2022, 131 (2022)

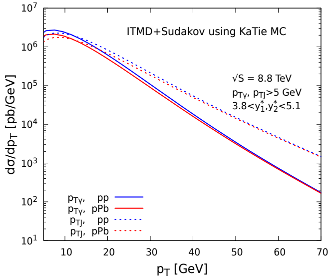
Saturation in forward γ + jet

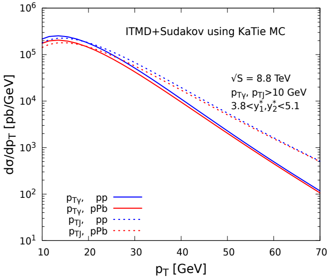
Nuclear modification factor:

$$R_{\rm pPb}^{\gamma+jet} = \frac{\left(\frac{d\sigma}{d\Delta\phi}\right)_{\rm pPb}}{\left(\frac{d\sigma}{d\Delta\phi}\right)_{\rm pp}}$$



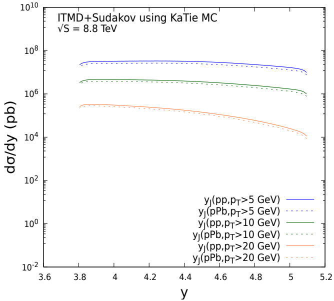
p_T distribution:

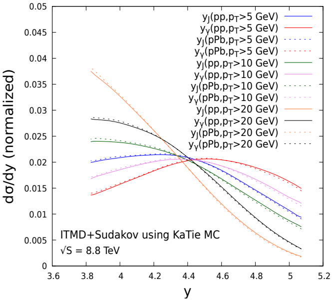




Saturation in forward γ + jet

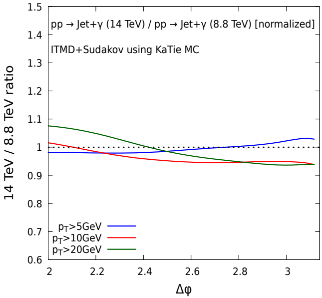
Rapidity:



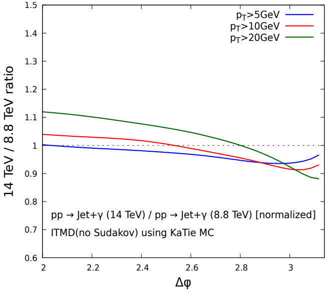


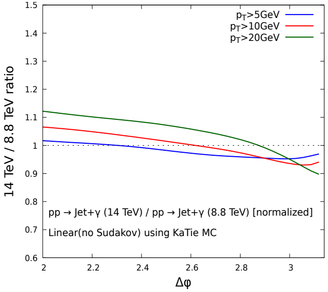
Ratio of pp cross sections at different energies

- In the saturation formalism both nuclei and protons have to be treated within non-linear evolution,
- We now try to see the dependence of pp cross sections on different CM energies as it changes x.



Ratio of pp cross sections at different energies





Ratio of pp cross-sections at different energies

- For moderate p_T cuts we observe a growing suppression in the large $\Delta\varphi$ region and enhancement for smaller $\Delta\varphi$;
- We see that without Sudakov resummation the trend is similar for all p_T cuts, indicating that the Sudakov resummation gives a nontrivial interplay between the shape of the distribution and the cutoff;
- We plot the same observable using the linear version of the KS TMD gluon distribution, and observe very similar shape of the curves, except they cross unity at different points for different energy.

Summary

- The proton-lead cross section (per nucleon) is highly suppressed compared to proton-proton cross section, indicating significant saturation effects;
- The suppression is strongest in the back-to-back region of azimuthal angles;
- The saturation signal, which is the suppression of p-Pb with respect to p-p, is not washed away even after including the Sudakov resummation.
- We also studied the ratios of proton-proton differential cross-sections at different energies for different TMD PDF evolution equations. We observed signatures of different methods in the observables.

Thank you!