Probing the saturation regime with forward photon+jet production in pp and pPb

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Outline

- Motivation
- Hybrid factorization
- Monte Carlo KaTie
- Results
- Summary

High gluon densities and EIC

- One of the main goals of EIC is to study the collective behavior of gluons under conditions where self-interactions dominate;
- Not only the onset of saturation, but also to study the properties and dynamics of saturation;
- While a direct study of saturation phenomena in proton may not be possible, it will be possible to study saturation in large nuclei.

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(γ), 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.)
- The process under consideration here is:

$$p(P_B) + A(P_A) \to \gamma(k_1) + J(k_2) + X$$

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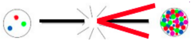
Dilute-dense collisions

Our interest:



with:

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

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

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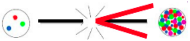

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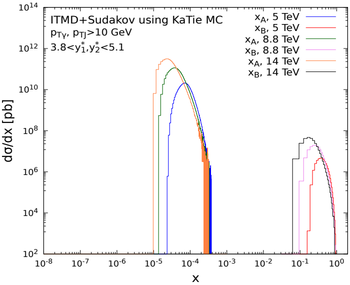

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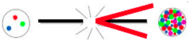

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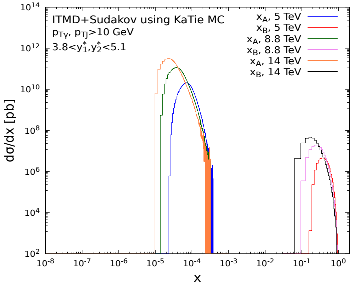

Spectra of longitudinal fractions probed in the PDF for different CMS energies and transverse momentum cut of 10 GeV. Both k_1 and k_2 are large giving $x_A << x_B$. arxiv:2306.04706.

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Improved Transverse Momentum Dependent(ITMD) factorization

ITMD accounts for:

- complete kinematics with off-shell gluons,
- gauge invariant TMD gluon densities,
- recovers the high energy factorization in the limit of large off-shellness of the initial-state gluon.

It can be obtained from CGC:
T. Altinoluk, R. Boussarie, Piotr Kotko JHEP 1905 (2019) 156

Hybrid factorization

The leading order factorization formula reads:

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

with incoming momenta:

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

and,

- 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 $d\sigma_{qg^*\to q\gamma}$

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ITMD with KaTie

- When provided with k_T -dependent PDFs KaTie(van Hameren Comput.Phys.Commun. 224 (2018) 371-380) automatically generates the necessary matrix elements,
- The PDFs can be provided using TMDLib or independent grid files,
- Key features of KaTie:
  - Adaptive importance sampling: KaTie optimizes adaptable probability densities iteratively, using the events generated so far in each iterative step,
  - Rejection: to mimic detector acceptance KaTie makes the weight function zero outside the phase space cuts,
  - Unweighting: taking out events with very low weight.

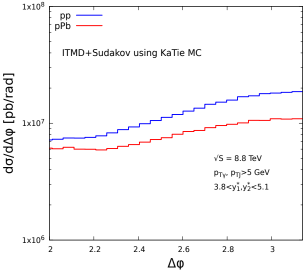
Saturation in forward γ + jet

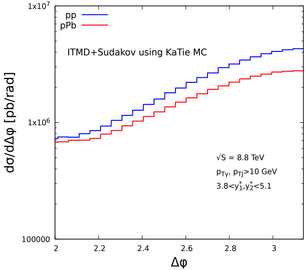
- For this study: final states were recorded in the pseudorapidity range $3.8 < \eta < 5.1$, for different CMS energies and p_T thresholds.
- Highly asymmetric kinematics; $x_A << x_B$, and $x_A \sim 10^{-4} - 10^{-5}$.
- The collinear PDF was provided via LHAPDF and set to CT18NLO and for the target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

Results based on arxiv:2306.04706

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)

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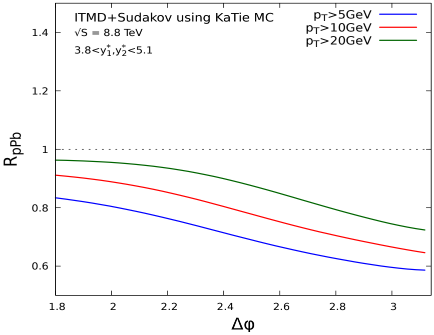
Saturation in forward γ + jet

Nuclear modification factor:

$$R_{pPb} = \frac{\left(\frac{d\sigma}{d\Delta\phi}\right)_{pPb}}{\left(\frac{d\sigma}{d\Delta\phi}\right)_{pp}}$$



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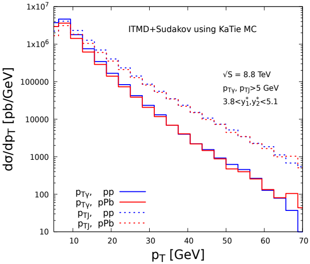
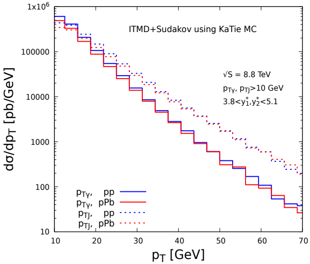
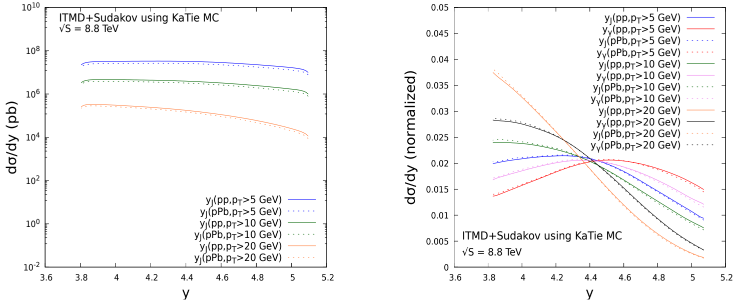
Saturation in forward $\gamma + \text{jet}$

p_T distribution

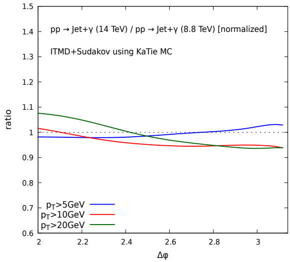


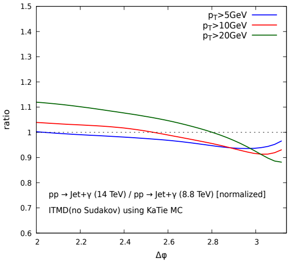


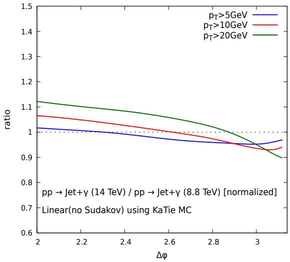
Saturation in forward γ + jet: Rapidity



Ratio of pp cross sections at different energies







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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 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!