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Studying Gluon Saturation Effects in Forward Photon-Hadron Transverse Energy-Energy and Azimuthal Correlations in Proton-Proton and Proton-Lead Collisions at the LHC

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Based on: Phys. Rev. D 112, 114020, in collaboration with P. Kotko

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Forward particle production in pA

- We compare γ-hadron Transverse Energy-Energy Correlation (TEEC) and Azimuthal correlation in pp and pPb collisions following the detector upgrades planned for high-luminosity LHC.

- Saturation predicts a suppression in forward particle production in pA as compared to pp. This type of suppression was already observed at RHIC, both for inclusive hadron production and two-particle correlations [1] and at the LHC in the inclusive hadron p_T spectra measured by LHCb [2]. But it is important to discriminate saturation from other competing mechanisms that can be at play.

We need...

$\rightarrow$ Extended coverage in x and Q^2, broad range of observables and complementary measurements: e-A DIS and diffractive processes at EIC, forward particle production in p-A collisions at RHIC and LHC

[1] BRAHMS Collaboration, I. Arsene et al. 2004; STAR Collaboration, J. Adams et al. 2006; PHENIX Collaboration, A. Adare et al. 2011; STAR Collaboration, M. S. Abdallah et al. 2022; STAR Collaboration, X. Chu 2022

[2] LHCb Collaboration, R. Aaij et al. 2023; 2024

Photon-Hadron/Photon-Jet in pA Collisions

- The photon does not interact with the medium
- Unlike in the case of di-jet observables only a single gluon TMD distribution contributes to the cross-section: the dipole TMD distribution
- Choosing a hadron trigger and hadrons, instead of jets helps probe smaller p_T

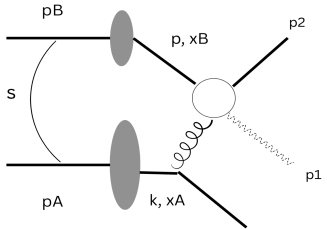
Production of photons has been computed in pp and pA collisions: Rezaeian, 2012; Jalilian-Marian, Rezaeian, 2012; Ducloue, Lappi, Mantysaari, 2018; Goncalves, Lima, Pasechnik, Sumbera, 2020; Santos, Silveira, Machado, 2020; Golec-Biernat, Motyka, Stebel, 2020; Santos, Silveira, Machado, 2022; Benic, Garcia-Montero, Perkov, 2022;

And in eA collisions: Roy, Venugopalan, 2018; 2020; Kolbe, Roy, Salazar, Schenke and Venugopalan, 2021;

Measured by: ALICE collaboration, S. Acharya et al. 2020; 2025; ATLAS collaboration, G. Aad et al. 2012; ATLAS collaboration, M. Aaboud et al. 2018;

In processes like: $p(P_B) + A(P_A) \to \gamma(p_1) + h(p_2) + X$,

$\langle k_{\mathrm{A}t} \rangle \sim Q_s(x_2)$



$\langle k_{\mathrm{B}t} \rangle \sim \Lambda_{\mathrm{QCD}}$

$$x_{\mathrm{target}} \equiv x_A = \frac{1}{\sqrt{s}}(|p_{1t}|e^{-\eta_1} + |p_{2t}|e^{-\eta_2}) \ll 1$$

$$x_{\mathrm{proj}} \equiv x_B = \frac{1}{\sqrt{s}}(|p_{1t}|e^{\eta_1} + |p_{2t}|e^{\eta_2}) \sim 1$$

- The parton originating from the dilute projectile is described in terms of collinear PDFs.
- The parton from the target is described using transverse momentum dependent (TMD) PDFs.

Gluon transverse momenta $|k_t|^2 = |p_{1t} + p_{2t}|^2 = |p_{1t}|^2 + |p_{2t}|^2 + 2|p_{1t}||p_{2t}|\cos\Delta\phi$

Dilute-dense Collision and Improved TMD (ITMD) Factorization [3]

For the partonic process:

- Collinear PDF

$$d\sigma = \int dx_A dx_B \int d^2k_T \quad f_{q(\bar{q})/B}(x_B;\mu) \quad F(x_A,k_T;\mu) \quad d\sigma_{q(\bar{q})g^*\to q(\bar{q})\gamma}(x_A,x_B,k_T;\mu)$$

- Small x gluon TMD
- Hard scattering involving off-shell gluon

Small-x limit of TMD gluon distribution has beem intensively studied: Kharzeev, Kovchegov, Tuchin, 2003; Dominguez, Marquet, Xiao, Yuan, 2011; Bury, Kotko, Kutak, 2018; Altinoluk, Boussarie, 2019 and more...

[3] P. Kotko, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. v Hameren 2015; T. Altinoluk, R. Boussarie, P. Kotko 2019

Transverse Energy-Energy Correlators (TEEC)

An extension of Energy-Energy Correlators (EEC) in the context of hadron colliders [4]. Both TEEC and Asymmetry of TEEC (ATEEC) have been measured by ATLAS [5] and used in α_s determination.

$$\textbf{TEEC} \equiv \frac{d\Sigma}{d\phi} = \sum_h \int d\sigma \frac{E_{T_\gamma} E_{T_h}}{E_{T_\gamma} \sum_{h'} E_{T_{h'}}} \delta(\phi_{\gamma h} - \phi)$$

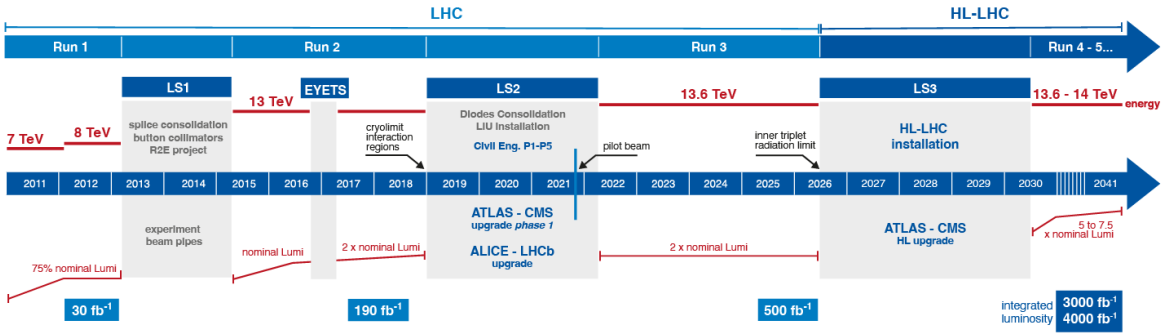
- E_{T_γ}, E_{T_h}: Transverse energy of the photon and the hadron,
- $\phi_{\gamma h}$: Angular separation between the photon and each hadron.

IR and collinear safe, easy to compare with experiments, soft radiations suppressed.

[4] Ali, Pietarinen, Stirling 1984

[5] ATLAS Collaboration: Phys. Lett. B 750 (2015) 427; Eur. Phys. J. C 77 (2017) 872; JHEP 07 (2023) 85

High-luminosity LHC



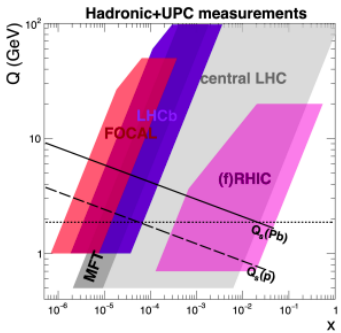
Upgrades relevant for our study:

1. FoCal or Forward Calorimeter (ALICE), $3.4 < \eta < 5.8$.

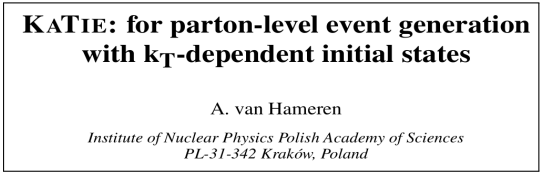
   - Multi-messenger approach:

     Prompt photon, γ-hadron/jet correlations, dijet production, vector meson photo-production in UPC etc.

2. Extended ATLAS acceptance, $|\eta| < 4$.



ALICE-PUBLIC-2023-001
ALICE-TDR-022



KaTie: for parton-level event generation with k_T-dependent initial states

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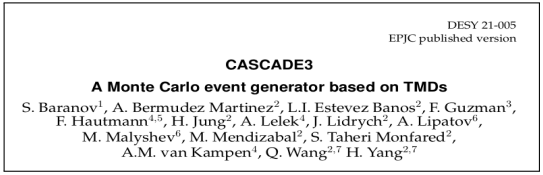


DESY 21-005
EPJC published version

CASCADE3

A Monte Carlo event generator based on TMDs

S. Baranov[1], A. Bermudez Martinez[2], L.I. Estevez Banos[2], F. Guzman[3], F. Hautmann[4,5], H. Jung[2], A. Lelek[4], J. Lidrych[2], A. Lipatov[6], M. Malyshev[6], M. Mendizabal[2], S. Taheri Monfared[2], A.M. van Kampen[4], Q. Wang[2,7] H. Yang[2,7]

- When provided with transverse momentum dependent PDFs KaTie[6] generates the phasespace points and the necessary matrix elements.
- KaTie's color-connection decomposition guarantees gauge-invariant partial amplitudes and systematic bookkeeping of color, making it naturally extensible to more complex QCD processes.
- The output from KaTie is then provided to CASCADE[7]. CASCADE performs initial and final state showers, including full hadronization using modules from PYTHIA. The initial-state shower follows the TMD PDFs.

[6] Hameren Comput.Phys.Commun. 224 (2018) 371-380
[7] European Physical Journal C 81 (May, 2021)

Kinematics

Parton-level:

$\sqrt{s} = 8.16$ TeV for ATLAS and 8.8 TeV for FoCal.

Quantity	ATLAS	FoCal
$p_{T_{\gamma,P}}$	> 5 GeV	> 7 GeV
η_γ	$2.7 < \eta_\gamma < 4.0$	$3.8 < \eta_\gamma < 5.1$
η_P	$1.7 < \eta_P < 5.0$	$2.8 < \eta_P < 6.1$

P: Parton

Hadron-level:

At least one hadron with $p_{T\text{Trig}} > 5$ GeV.

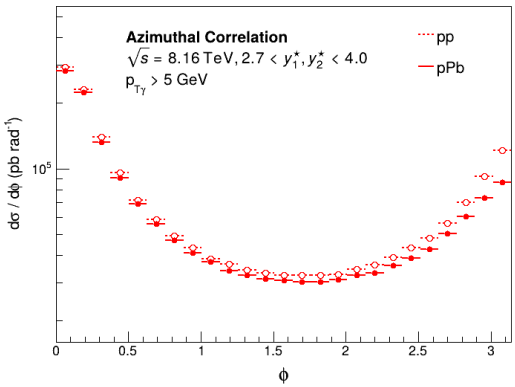
Quantity	ATLAS	FoCal
p_{T_γ}	> 5 GeV	> 5 GeV
η_γ	$2.7 < \eta_\gamma < 4.0$	$3.8 < \eta_\gamma < 5.1$
η_h	$2.7 < \eta_h < 4.0$	$3.8 < \eta_h < 5.1$

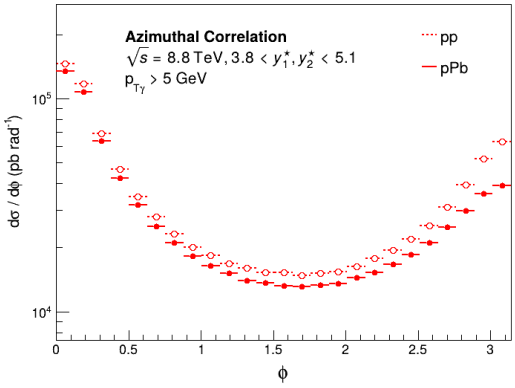
h: Hadron

- Collinear PDF: set to CT18NLO,
- Small x dipole gluon TMD: Based on KS non-linear fit to HERA data [a]

[a] K. Kutak, S. Sapeta; Phys. Rev. D 86, 094043 (2012)

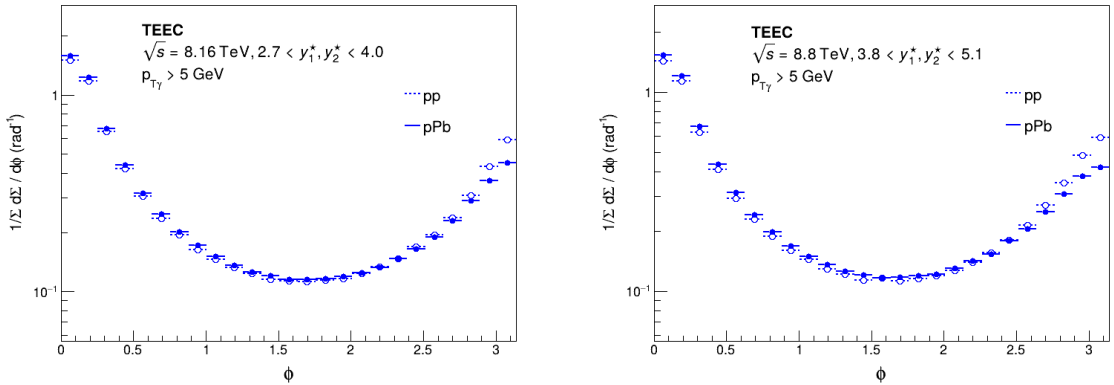
Hadron Level Azimuthal Correlation





- γ-hadron azimuthal correlation in pp and pPb collisions at CM energy 8.16 TeV, $2.7 < y_1^*, y_2^* < 4.0$ (on the left) and at CM energy 8.8 TeV, $3.8 < y_1^*, y_2^* < 5.1$ (on the right).
- Significant suppression in pPb compared to pp, more pronounced towards $\Delta\phi \sim \pi$.

TEEC Distributions

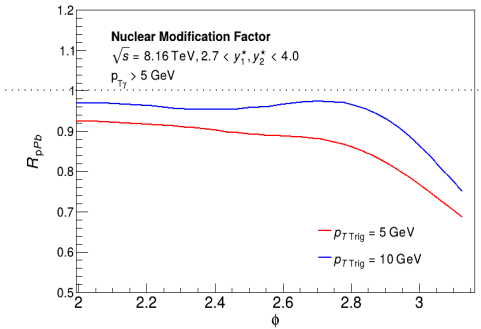


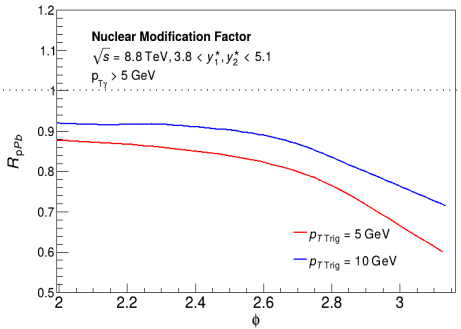
- Normalized γ-hadron TEEC in pp and pPb collisions at CM energy 8.16 TeV, $2.7 < y_1^*, y_2^* < 4.0$ (on the left) and at CM energy 8.8 TeV, $3.8 < y_1^*, y_2^* < 5.1$ (on the right).

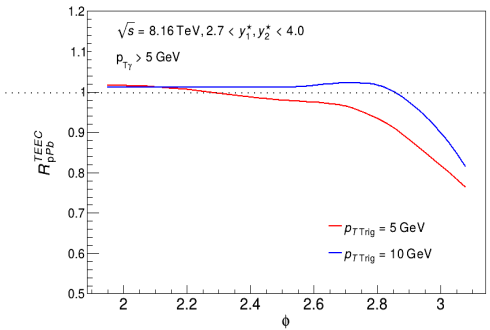
Nuclear Modification Factor

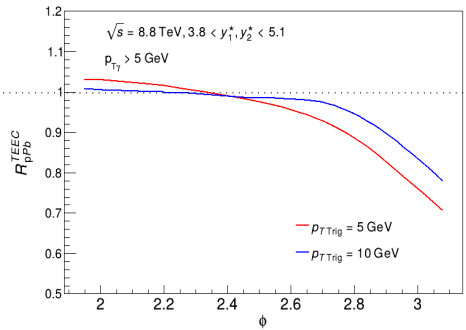
$$R_{\mathrm{p}Pb} = \frac{1}{A}\frac{(\frac{d\sigma}{d\phi})_{\mathrm{p}Pb}}{(\frac{d\sigma}{d\phi})_{\mathrm{pp}}}$$

$$R_{\mathrm{p}Pb}^{\mathrm{TEEC}} = \frac{(\frac{1}{\Sigma}\frac{d\Sigma}{d\phi})_{\mathrm{p}Pb}}{(\frac{1}{\Sigma}\frac{d\Sigma}{d\phi})_{\mathrm{pp}}}$$

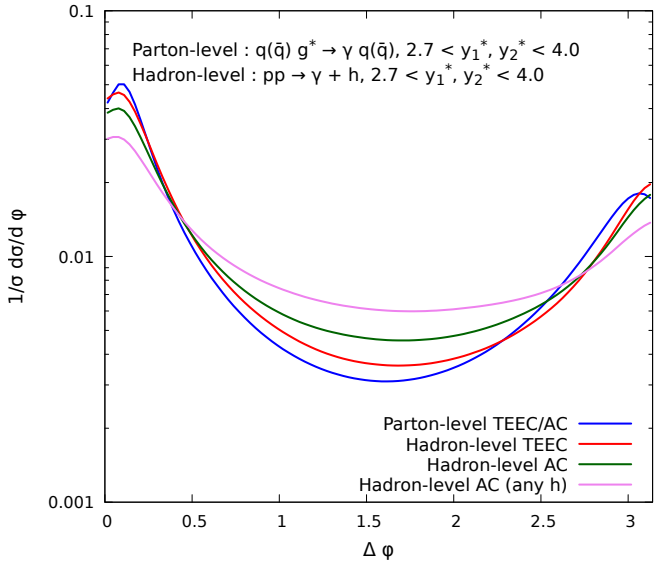






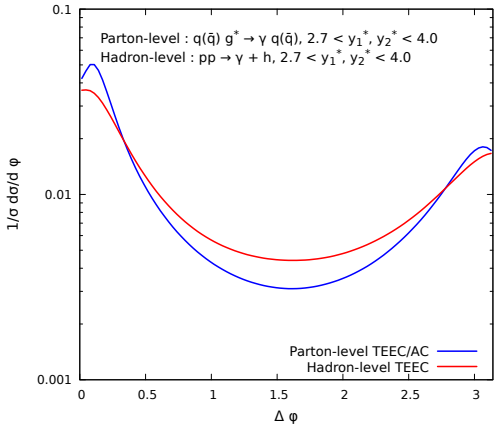


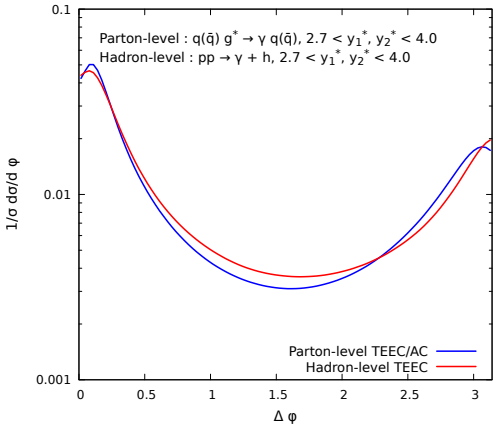
Comparison of Observables



- Comparison of parton level azimuthal correlation from KaTie, with γ-hadron TEEC and azimuthal correlation in pp collisions at CM energy 8.16 TeV, with $2.7 < y_1^*, y_2^* < 4.0$ (all normalized).
- The partons were generated with a minimum transverse momentum of 5 GeV in KaTie.

Comparison of Observables (Contd.)



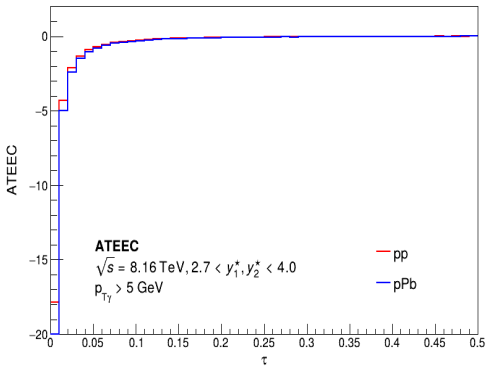


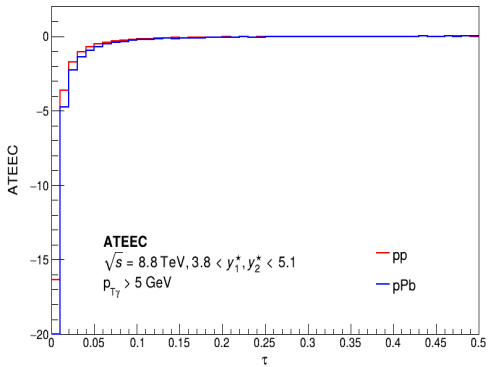
- Comparison of the parton-level result, with the hadron-level simulation with two choices of the hadronic trigger p_T : 1 GeV and 5 GeV. The photon was required to have a minimum p_T of 5 GeV.
- The "parton-level" here refers to the off-shell hard matrix element convoluted with the dipole gluon TMD evaluated in KaTie, with a p_T cut of 5 GeV for both the parton and the photon.

Asymmetry of TEEC

ATEEC or the asymmetry of TEEC is defined as the difference:

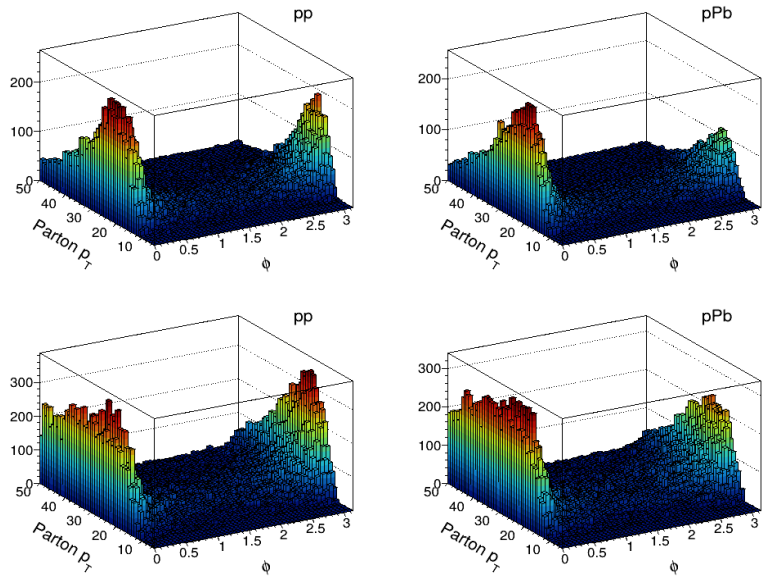
$$\textbf{ATEEC} = \frac{1}{\Sigma}\frac{d\Sigma}{d\tau}|_{\tau} - \frac{1}{\Sigma}\frac{d\Sigma}{d\tau}|_{1-\tau}\,, \text{ where } \tau = \frac{1+\cos\phi}{2}.$$





- γ-hadron ATEEC in pp and pPb collisions at CM energy 8.16 TeV, $2.7 < y_1^*, y_2^* < 4.0$ (on the left) and at CM energy 8.8 TeV, $3.8 < y_1^*, y_2^* < 5.1$ (on the right).

Effect of Parton-Level Constraints



γ-hadron counts in pp and pPb collisions at CM Energy 8.16 TeV, $2.7 < y_1^*, y_2^* < 4.0$ (bottom row) and CM energy 8.8 TeV, $3.8 < y_1^*, y_2^* < 5.1$ (top row) w.r.t. their azimuthal separation (ϕ) and the p_T of hardest parton.

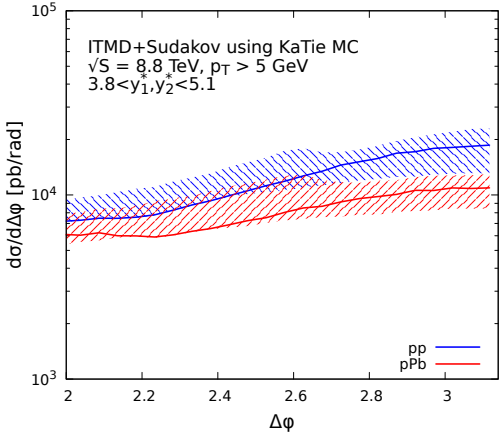
Summary

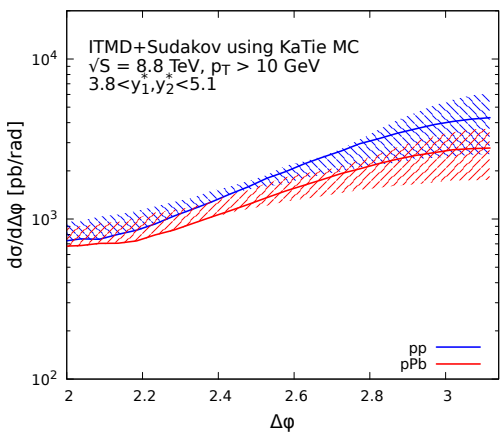
- Measurements of the nuclear modification factor $R_{\mathrm{p}A}$ as a function of different kinematic observables is indispensable to identifying gluon saturation effects. We study the nature of a similar ratio defined for the TEEC and observe a significant suppression near the back-to-back region.
- By using different $p_{T\mathrm{Trig}}$ values we notice a lower $p_{T\mathrm{Trig}}$ corresponds to a stronger suppression for both TEEC and the azimuthal correlation.
- For this computation we used hybrid k_T factorization, with the gluon TMD PDF incorporating saturation effects, with full shower and hadronization via CASCADE. This is a parallel study to [a] from the Monte-Carlo perspective.
- Although this computation does incorporate the nonlinear gluon dynamics, there is no explicit parton-recombination implemented.

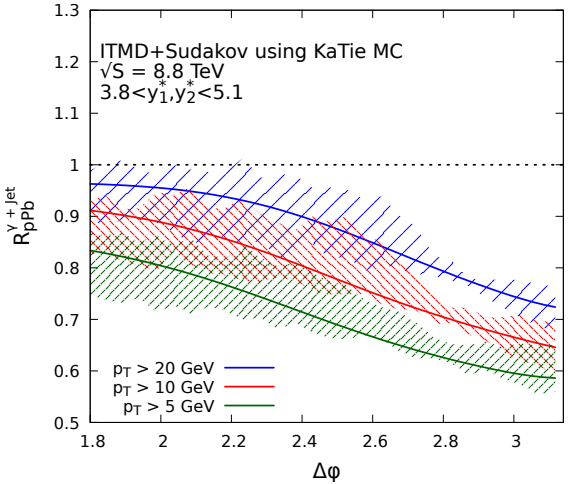
[a] Kang, Kao, Li, Penttala 2025

Thank you

Backup...





Parton level correlations in pp and pPb collisions at 8.8 TeV, within the FoCal acceptance: the minimum transverse momentum was varied between 5 and 20 GeV.

- The uncertainty was computed by varying the hard scale by a factor of two and including the statistical errors due to Monte Carlo integration.
- The suppression of the pPb cross section is up to 40% for the lowest p_T cut, and about 20% for $p_T > 20$ GeV.