Probing nuclear PDFs with dijets in ultra-peripheral Pb+Pb collisions

Hard Probes 2018

Ilkka Helenius

October 3rd, 2018

University of Jyväskylä
Department of Physics

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

Motivation & Outline

Motivation

- Nuclear PDFs not well constrained by current data in kinematic region relevant for heavy-ion physics at the LHC
- Ideally measured in a lepton-ion collider
- Ultra-peripheral collisions (UPC) provide possibility to study γA collisions at the LHC

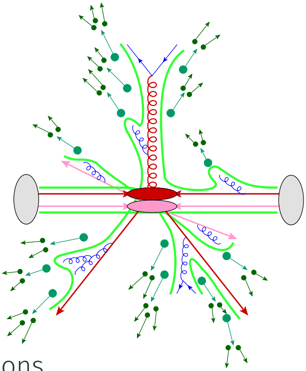
  $\Rightarrow$ Apply photoproduction framework recently introduced in Pythia 8 [I.H., T. Sjöstrand] to study potential of UPC dijets

Outline

1. Photoproduction in Pythia 8
2. Ultra-peripheral collisions
3. Dijet production in UPCs at the LHC
4. Summary

Event generation in PYTHIA 8

1. Hard scattering
   - Convolution of LO partonic cross sections and PDFs
2. Parton showers
   - Generate Initial and Final State Radiation (ISR & FSR) using DGLAP evolution
3. Multiparton interactions (MPIs)
   - Use regularized QCD $2 \to 2$ cross sections



[Figure: S. Prestel]

4. Beam remnants
   - Minimal number of partons to conserve colour and flavour
5. Hadronization
   - Using Lund string model with color reconnection
   - Decays into stable hadrons

Event classification in electron-proton (ep) collisions

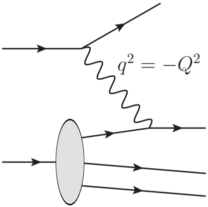
Virtuality of photon related to scattering angle of the lepton

$$Q^2 \approx 2E_l^2(1 - x_\gamma)(1 - \cos\theta)$$

where x_γ is fraction of photon momentum wrt. to the lepton

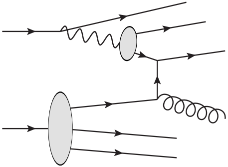
Deep inelastic scattering

- High virtuality, $Q^2 >$ a few GeV^2
- Lepton scatters off from a parton



Photoproduction

- Low virtuality, $Q^2 \lesssim 1$ GeV^2
- Can factorize the photon flux from partonic cross section
- Hard scale provided by the scattering (Jets, high-p_T hadron, ...)

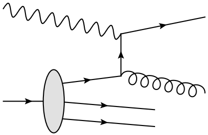


Photoproduction in ep

Photon flux from leptons (Weizsäcker-Williams)

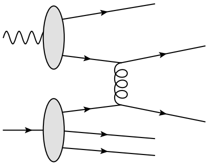
$$f_{\gamma}^{l}(x_{\gamma}) = \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{(1 + (1 - x_{\gamma})^2)}{x_{\gamma}} \log \left[\frac{Q^2_{\mathrm{max}}}{Q^2_{\mathrm{min}}(x_{\gamma})} \right]$$

$\Rightarrow$ Sample photon kinematics (x_{γ}, Q^2) and set up γp sub-collision with $W_{\gamma \mathrm{p}}$



Direct processes

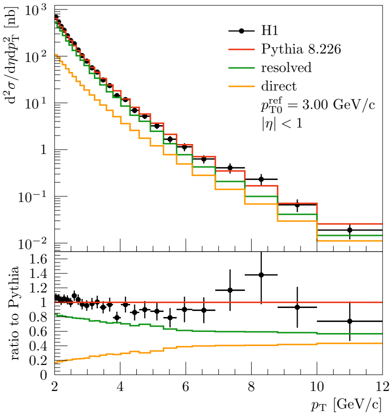
- Photon initiator of the hard process
- No MPIs but FSR and ISR for hadron



Resolved processes

- Photon fluctuates into a hadronic state
- Partonic structure described with PDFs
- FSR and ISR for both sides, also MPIs

Charged particle p_T spectra in ep collisions at HERA



[H1: Eur.Phys.J. C10 (1999) 363-372]

H1 measurement

- $E_p = 820$ GeV, $E_e = 27.5$ GeV
- $< W_{\gamma p} > \approx 200$ GeV
- $Q^2_{max} = 0.01$ GeV^2

Comparison to Pythia 8

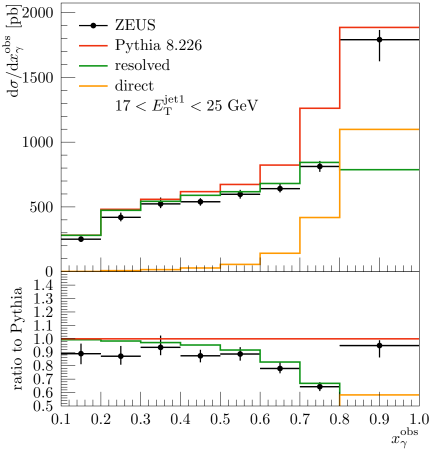
- Resolved contribution dominates
- Good agreement with the data using $p_{T0}^{ref} = 3.00$ GeV/c
  - p_{T0}^{ref} controls $\mathcal{P}_{MPI}$

$\Rightarrow$ Less MPIs in γp than in pp (Only retuned parameter when pp $\to \gamma$p)

Dijet photoproduction in ep collisions at HERA

ZEUS dijet measurement

- $Q^2_\gamma < 1.0$ GeV^2
- $134 < W_{\gamma p} < 277$ GeV
- $E_T^{\text{jet1}} > 14$ GeV,
  $E_T^{\text{jet2}} > 11$ GeV
- $-1 < \eta^{\text{jet1,2}} < 2.4$



[ZEUS: Eur.Phys.J. C23 (2002) 615-631]

Different contributions

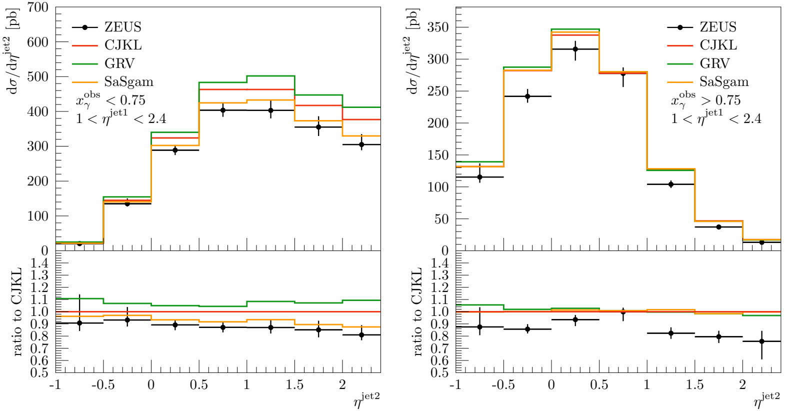
- Define

$$x_\gamma^{\text{obs}} = \frac{E_T^{\text{jet1}} e^{\eta^{\text{jet1}}} + E_T^{\text{jet2}} e^{\eta^{\text{jet2}}}}{2yE_e}$$

  to discriminate direct and resolved processes
- Corresponds to x of partons from γ in LO (=1 for direct)

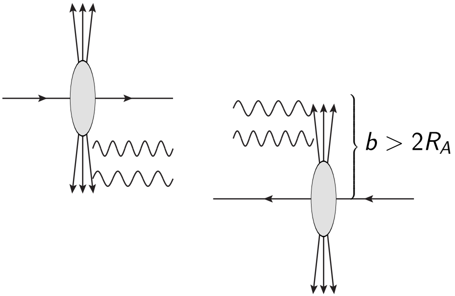
Dijet in ep collisions at HERA

Pseudorapidity dependence of dijets [Eur.Phys.J. C23 (2002) 615-631]



- Simulations tend to overshoot the dijet data by ∼10 %
- ∼ 10 % uncertainty from photon PDFs for $x_\gamma^{obs} < 0.75$

Ultra-peripheral heavy-ion collisions



- Large impact parameter $b \Rightarrow$ No strong interactions
- EM-field of nuclei described with quasi-real photons (EPA)

$\Rightarrow$ Flux of photons with low virtuality (= Photoproduction)

$$x_\gamma f_\gamma^A(x_\gamma, b) = \frac{\alpha_{\text{EM}} Z^2}{\pi^2} \left[\frac{x_\gamma m}{\hbar c} K_1 \left(\frac{x_\gamma b m}{\hbar c} \right) \right]^2$$

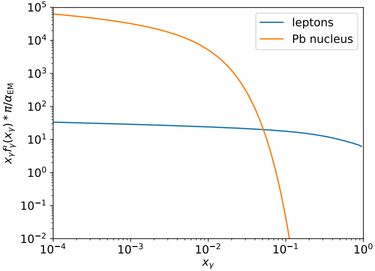
where Z is nuclear charge, m (per-nucleon) mass and K_1 modified Bessel function

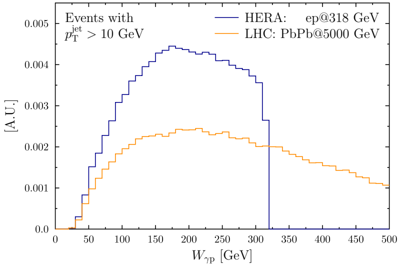
Effective photon flux for photon-nucleus interactions

- Integrate over $b > 2R_A$ to reject hadronic interactions

$$x_\gamma f_\gamma^A(x_\gamma) = \frac{2\alpha_{\mathrm{EM}} Z^2}{\pi} \left[\xi K_1(\xi) K_0(\xi) - \frac{\xi^2}{2} \left(K_1^2(\xi) - K_0^2(\xi) \right) \right],$$

where $\xi = 2R_A x_\gamma m/\hbar c$, some uncertainty from R_A





- Larger flux from Pb due to Z, exponential fall at $x_\gamma \gtrsim 10^{-2}$
- Can reach ~ 2 times larger $W_{\gamma A}$ than in ep at HERA

$\Rightarrow$ Possible to study nuclear PDFs in γPb at the LHC

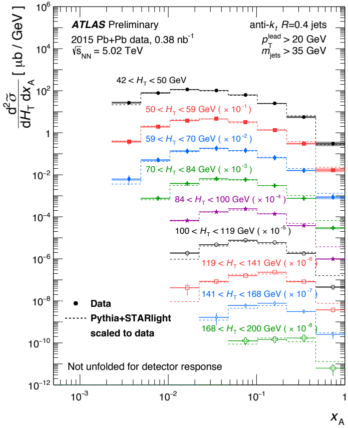
Photo-nuclear dijets from ATLAS

Preliminary ATLAS analysis

[ATLAS-CONF-2017-011]

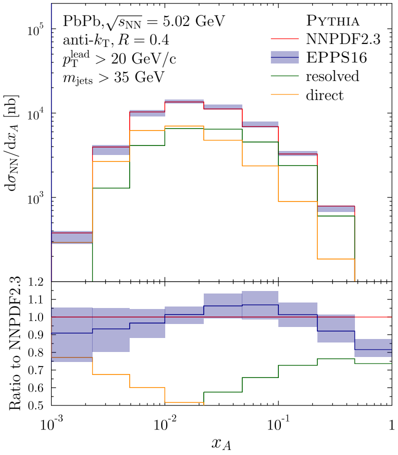
- Jet selection:
  - Anti-k_T, $R = 0.4$, $|\eta| < 4.4$
  - $p_T^{\text{lead}} > 20$ GeV, $p_T^{\text{jets}} > 15$ GeV
- Event-level variables:
  - $H_T = \Sigma_i p_{Ti}$
  - $m_{\text{jets}} = \sqrt{(\Sigma_i E_i)^2 - |\Sigma_i \vec{p}_i|^2}$
  - $y_{\text{jets}} = \frac{1}{2} \log\left(\frac{\Sigma_i E_i + \Sigma_i p_{zi}}{\Sigma_i E_i - \Sigma_i p_{zi}}\right)$
  - $x_A = \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}}$

  where x_A corresponds to x of partons in nucleus



- Reasonable agreement with ep from Pythia 6 reweighted with photon flux from STARLIGHT (normalized to data)

Photo-nuclear dijets in Pythia 8



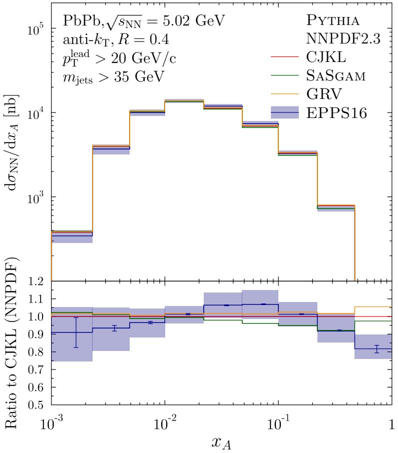
Pythia 8 implementation

- b-integrated γ flux
- Nuclear PDFs for hard scattering
- Identical jet selection with ATLAS study

Dijet cross section

- Direct processes dominate at $x_A < 10^{-2}$
- Sensitive to nuclear PDF modifications

Expected potential of the dijet data with ATLAS cuts



Photon PDF dependence

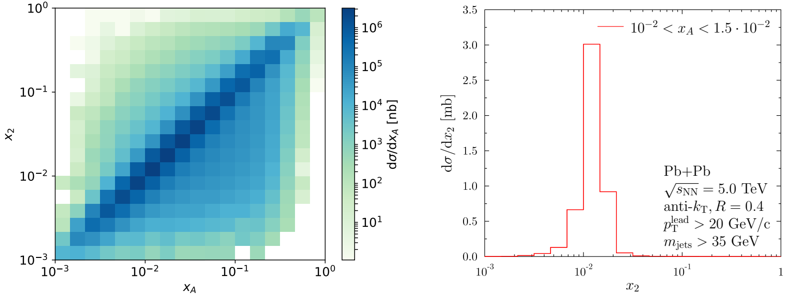
- Largest sensitivity (~ 10 %) at $x_A > 0.1$
- Negligible effect at $x_A < 0.02$

Expected statistical error

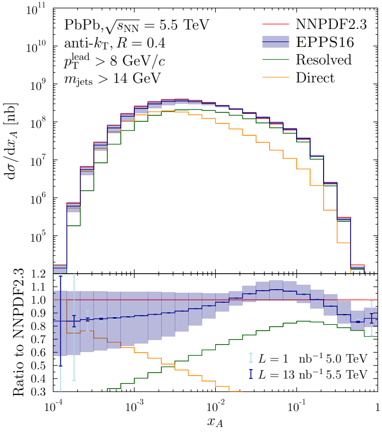
- Assume $L = 1\ \text{nb}^{-1}$ for the measurement
- Smaller than nPDF uncertainty

$\Rightarrow$ Potential to provide constraints for nPDFs down to $x \approx 10^{-3}$ with the ATLAS cuts on jet kinematics

Correlation of x_A and x_2



- x_A matches well with x_2 after MPIs, parton shower, hadronization and jet reconstruction
- Here MPIs generated as for γp system, presumably somewhat more underlying event with γA



Lower jet p_T cuts

- $p_T^{lead} > 8$ GeV, $p_T^{jets} > 6$ GeV (Similar to HERA analyses)
- Larger cross section
- Extended small-x_A reach
- Larger nPDF uncertainties due to lower scale

Expected statistical error

- LHC with $L = 1$ nb^{-1}
- HL-LHC with $L = 10$ nb^{-1}
- Negligible statistical errors down to $x_A \sim 2 \cdot 10^{-4}$

Diffractive dijets in UPCs (preliminary)

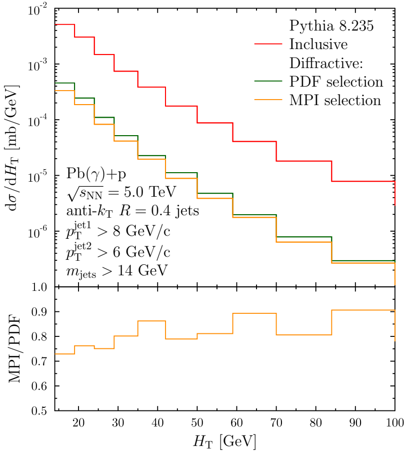
PDF selection

[I.H., C.O. Rasmussen, T. Sjöstrand]

- Use diffractive PDFs to select diffractive events
- Some uncertainties from diffractive PDFs

MPI selection

- Rapidity gap survival: Reject evets where additional MPIs would shroud the diffractive signal (rapidity gap)
- Sensitive to $p_{\mathrm{T0}}^{\mathrm{ref}}$



Summary

Photoproduction in Pythia 8

- Automatic mixing of direct and resolved processes
- Full parton-level evolution (parton showers, MPIs)
- Hard diffraction with dynamical rapidity gap survival
- Validated against HERA data
- Can be applied for UPCs with appropriate photon flux

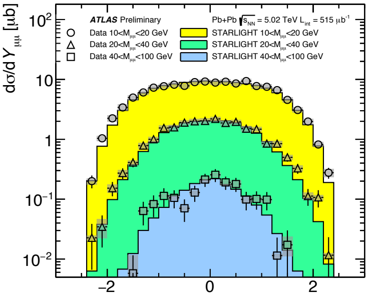
Photo-nuclear dijets in UPCs

- Can use dijets to study nuclear PDFs in γA processes
- Some theoretical uncertainty from γPDFs, mainly at high-x_A
- With preliminary ATLAS jet cuts constraints at $x_A \gtrsim 10^{-3}$
- Decreasing jet p_{T} would increase the small-x_A reach

Backup slides

High-mass dimuons in ultraperipheral Pb+Pb at the LHC

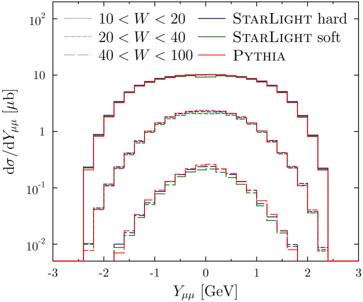
$\text{Pb+Pb} \rightarrow \mu^{+} + \mu^{-} + \text{Pb}^{*} + \text{Pb}^{*}$



[ATLAS-CONF-2016-025]

- Data well described by STARLIGHT MC

⇒ Confirms EPA for Pb+Pb at the LHC



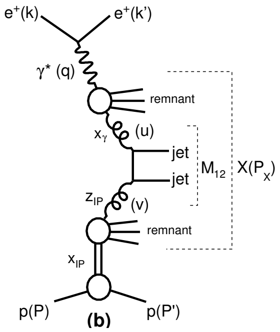
- PYTHIA hard-sphere flux agrees with STARLIGHT
- Small difference at high-W from nuclear density ($\sim$ high-x_{γ})

Hard diffraction in Pythia 8

Dynamical rapidity gap survival

- Originally introduced for pp

  C. O. Rasmussen and T. Sjöstrand [JHEP 1602 (2016) 142]



[Figure: H1: JHEP 1505 (2015) 056]

ep implementation

I.H., C. O. Rasmussen and T. Sjöstrand

- Select diffractive events based on dPDFs (γ or proton)

  (PDF selection)
- Check whether MPIs between (resolved) photon and proton
- Reject events where MPIs shroud the diffractive signature

  (MPI selection)

Comparison to ZEUS measurement (preliminary)

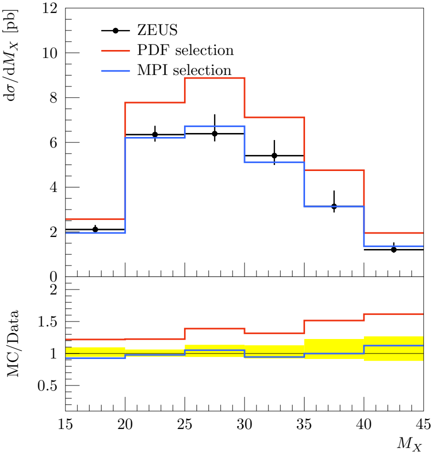
ZEUS diffractive dijets

- $Q^2_\gamma < 1.0$ GeV^2
- $0.2 < y < 0.85$
- $E_T^{\text{jet1}} > 7.5$ GeV, $E_T^{\text{jet2}} > 6.5$ GeV
- $-1.5 < \eta^{\text{jet1,2}} < 1.5$

Pythia setup

- Pomeron flux: H1 Fit B
- Diffractive PDF: H1 Fit B LO
- PDF selection overshoots the data by $\sim 40\%$
- Good agreement with MPI selection

Mass of the hadronic system



[ZEUS: Eur.Phys.J. C55, 177–191 (2008)]