Simulations of photo-nuclear dijets with Pythia 8 and their sensitivity to nuclear PDFs

DIS 2018

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April 17th, 2018

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Motivation & Outline

Why study photoproduction?

- Monte-Carlo event generators essential to study the potential of future experiments (EIC)
  $\Rightarrow$ Photoproduction implemented into Pythia 8
- Photo-nuclear processes in ultra-peripheral collisions can be used to probe the structure of nucleons (nuclear PDFs)

Outline

1. Photoproduction in Pythia 8
2. Comparisons to HERA photoproduction data
3. Ultra-peripheral heavy-ion collisions
4. Summary & Outlook

Photoproduction in Pythia 8

Pythia 8

- A general-purpose Monte-Carlo event generator
- Current version 8.235, released a couple of weeks ago
- Main focus has been in pp, now extensions to ee, ep, pA, AA

Team:

- Christian Bierlich — Lund University
- Nishita Desai — CNRS-Universite de Montpellier
- Nadine Fischer — Monash University
- Ilkka Helenius — Tübingen University
- Philip Ilten — University of Birmingham
- Leif Lönnblad — Lund University
- Stephen Mrenna — Fermi National Accelerator Laboratory
- Stefan Prestel — Fermi National Accelerator Laboratory
- Christine O. Rasmussen — Lund University
- Torbjörn Sjöstrand — Lund University
- Peter Skands — Monash University

Event generation in PYTHIA 8

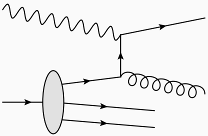
1. Hard process generation
   - Generate according to LO partonic cross section and PDFs (or feed in processes from external matrix element generator)
2. Parton showers
   - Generate Initial and Final State Radiation (ISR & FSR) according to DGLAP evolution equations
3. Multiparton interactions (MPIs)
   - Use regularized QCD $2 \to 2$ cross sections finite also at $p_T \to 0$
4. Add beam remnants
   - Minimal number of partons to conserve colour and flavour
   - Fix momenta so that total momentum is conserved
5. Hadronization
   - Using Lund string model with color reconnection
   - Decays into stable hadrons

Photoproduction in ep

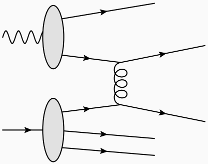
Photoproduction: Small photon virtuality $Q_\gamma^2 \lesssim 1\ \mathrm{GeV}^2$ (cf. DIS)

- Factorize the flux of photons from the hard scattering (Weizsäcker-Williams)

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



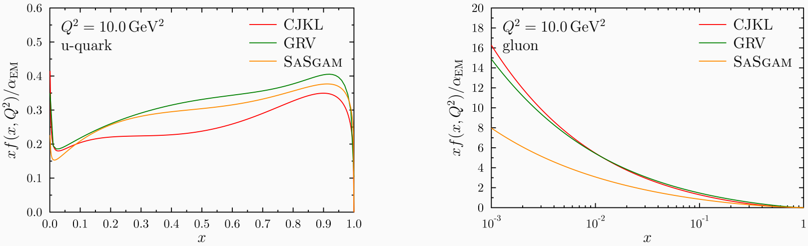
- Direct processes
  - Photon initiator of the hard process
  - No MPIs but FSR and ISR for hadron



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

PDFs for resolved photons

Obtained through global DGLAP analysis (LEP data mainly)



- Some differences between analyses, especially for gluon
  $\Rightarrow$ Theoretical uncertainty for resolved processes
- CJKL used as a default in Pythia 8, others via LHAPDF5 but only for hard-process generation

MPIs in PYTHIA 8

- Probability for MPIs from $2 \to 2$ QCD processes
- Partonic cross section diverges at $p_\mathrm{T} \to 0$

  $\Rightarrow$ Regulate the divergence with parameter $p_{\mathrm{T}0}$

$$\frac{\mathrm{d}\sigma^{2\to2}}{\mathrm{d}p_\mathrm{T}^2} \propto \frac{\alpha_\mathrm{s}(p_\mathrm{T}^2)}{p_\mathrm{T}^4} \to \frac{\alpha_\mathrm{s}(p_{\mathrm{T}0}^2 + p_\mathrm{T}^2)}{(p_{\mathrm{T}0}^2 + p_\mathrm{T}^2)^2}$$

- pp: Power-law in $\sqrt{s}$

  $p_{\mathrm{T}0}(\sqrt{s}) = p_{\mathrm{T}0}^{\mathrm{ref}}(\sqrt{s}/7\ \mathrm{TeV})^{\alpha}$

  $p_{\mathrm{T}0}^{\mathrm{ref}} = 2.28$ GeV/c, $\alpha = 0.215$

  (Monash tune)

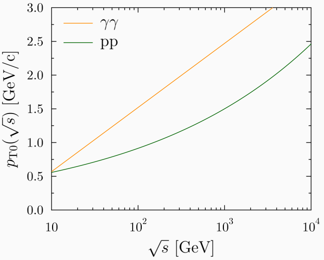
- $\gamma\gamma$: Logarithmic in $\sqrt{s}$

  $p_{\mathrm{T}0}(\sqrt{s}) = p_{\mathrm{T}0}^{\mathrm{ref}} + \alpha \log\left(\sqrt{s}/100\ \mathrm{GeV}\right)$

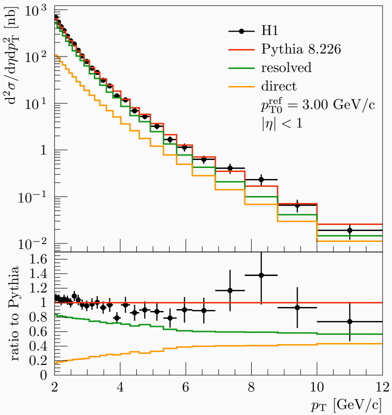
  $p_{\mathrm{T}0}^{\mathrm{ref}} = 1.52$ GeV/c, $\alpha = 0.413$

  (I.H., T. Sjöstrand, *in prep.*)

- Parametrization for γp?



Comparisons to HERA data



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

H1 measurement

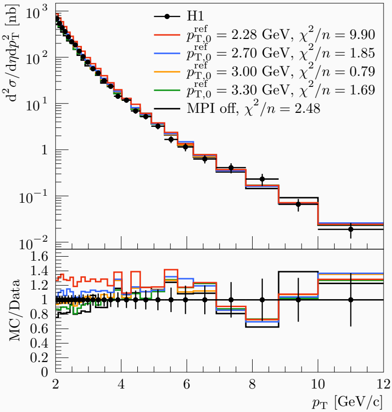
- $E_\mathrm{p} = 820$ GeV, $E_\mathrm{e} = 27.5$ GeV
- $< W_{\gamma\mathrm{p}} > \quad \approx 200$ GeV
- $Q^2_\gamma < 0.01\ \mathrm{GeV}^2$

Comparison to Pythia 8

- Resolved contribution dominates
- Good agreement with the data using $p_{\mathrm{T0}}^{\mathrm{ref}} = 3.00$ GeV/c

$\Rightarrow$ MPI probability between pp and $\gamma\gamma$

Charged particle p_T spectra in ep collisions at HERA



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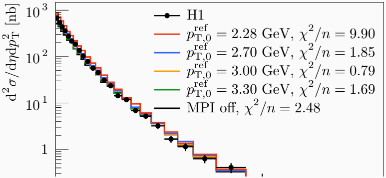

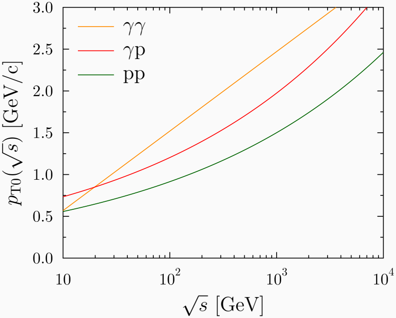

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$\Rightarrow$ MPI probability between pp and $\gamma\gamma$

Dijet photoproduction in ep collisions at HERA

ZEUS dijet measurement

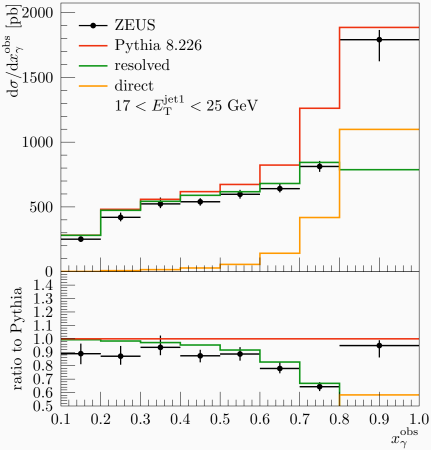
- $Q^2_\gamma < 1.0$ GeV^2
- $134 < W_{\gamma p} < 277$ GeV
- $E_T^{\text{jet1}} > 14$ GeV,
  $E_T^{\text{jet2}} > 11$ GeV
- $-1 < \eta^{\text{jet1,2}} < 2.4$

Different contributions

- Define

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

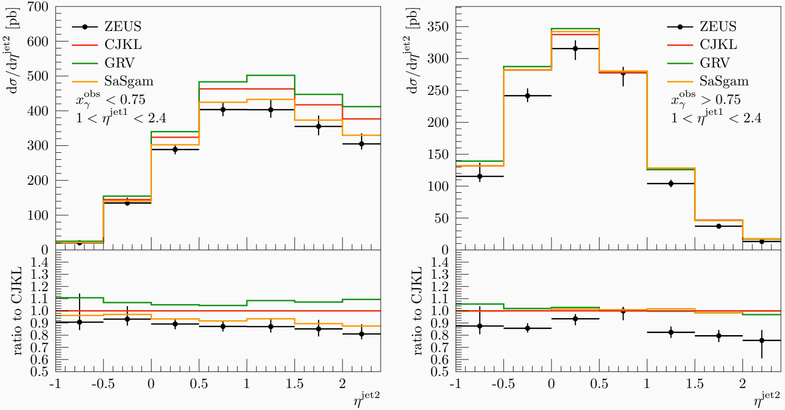
  to discriminate direct and resolved processes (=x in γ at LO parton level)
- At high-x_γ^{obs} direct processes dominate



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

Dijet in ep collisions at HERA

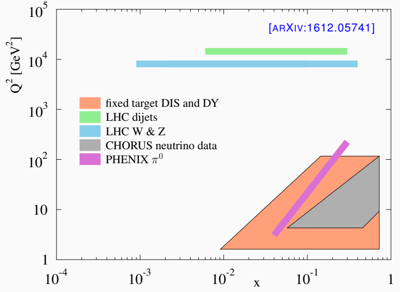
Pseudorapidity dependence of dijets [Eur.Phys.J. C23 (2002) 615-631]



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

Ultraperipheral heavy-ion collisions

Motivation: Nuclear parton distribution functions (nPDFs)



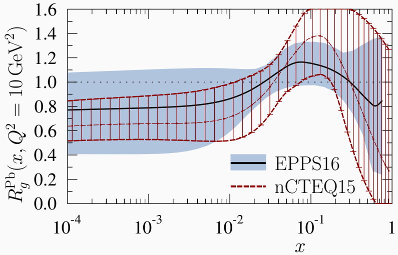
Data available for nPDF fits

- Fixed-target (ν)DIS and DY
- Pions in dAu at RHIC
- Dijets in pPb at the LHC
- EW bosons at the LHC

⇒ Limited kinematic reach

⇒ Large uncertainties especially for gluon nPDFs

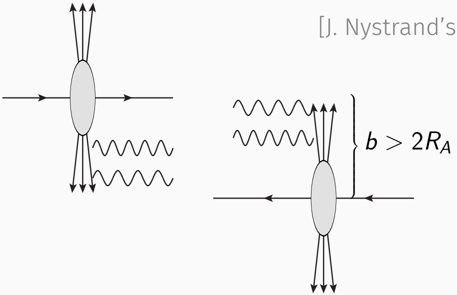
⇒ Uncertainty in the pQCD baseline for heavy-ion physics at the LHC



[Figures from EPPS16: Eur.Phys.J. C77 (2017) no.3, 163]

Ultra-peripheral heavy-ion collisions

[J. Nystrand's talk on Monday]



- Large impact parameter b ⇒ No strong interaction
- EM-field of nuclei described with quasi-real photons (EPA)

⇒ Flux of photons with low virtuality (= Photoproduction)

  - Photon-photon (dileptons, light-by-light)

    ⇒ Useful to calibrate the photon flux
  - Photon-nucleus (dijets, incl. hadrons, heavy flavours, ...)

    ⇒ Can be used to probe nuclear PDFs

Proposed by M. Strikman, R. Vogt and S. White [PRL 96 (2006) 082001]

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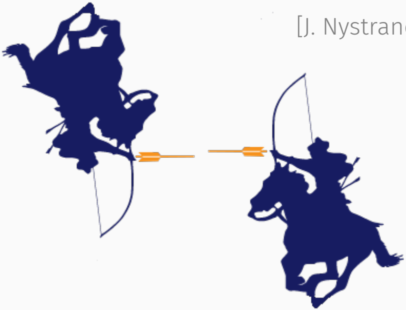

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Photon-photon interactions

Photon flux from nuclei in impact-parameter b space

- Obtained by a Fourier transformation of the time-dependent EM-field

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

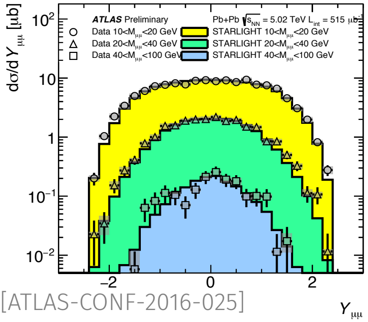
  where Z is nuclear charge, m (per-nucleon) mass and K_1 modified Bessel function [Jackson, Classical Electrodyn., 2nd ed.]

Effective photon-photon luminosity

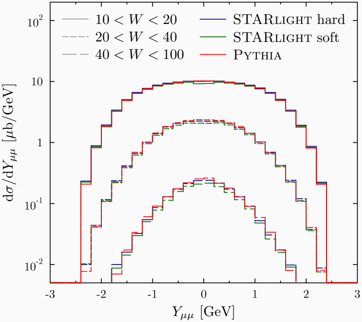
- Need to reject events with hadronic interactions
  - Reject events based on hard-sphere approximation
    $\Rightarrow$ Possible to set up in Pythia 8
  - Use hadronic interaction probabilities based on nuclear overlap, e.g. STARLight [Comput.Phys.Commun. 212 (2017) 258-268]

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

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})

Photon-nucleus interactions

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 $\xi = 2R_A x_\gamma m / \hbar c$

- Maximum $W_{\gamma\mathrm{Pb}} \approx 2\sqrt{s}$ in HERA

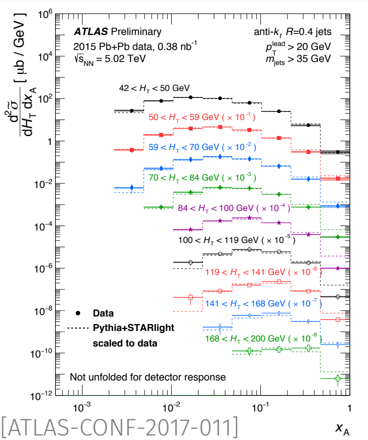
Photo-nuclear dijet production

- Preliminary ATLAS analysis [ATLAS-CONF-2017-011]
  anti-k_T, $R = 0.4$, $p_\mathrm{T}^{\mathrm{lead}} > 20$ GeV, $p_\mathrm{T}^{\mathrm{jets}} > 15$ GeV, $|\eta| < 4.4$
- Event-level variables:

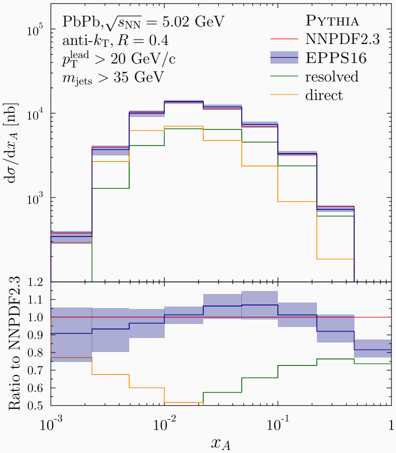
$$m_{\mathrm{jets}} = \sqrt{(\Sigma_i E_i)^2 - \left|\Sigma_i \vec{p}_i\right|^2}, \qquad H_\mathrm{T} = \Sigma_i p_{\mathrm{T}i}$$

$$y_{\mathrm{jets}} = \frac{1}{2} \log \left(\frac{\Sigma_i E_i + \Sigma_i p_{zi}}{\Sigma_i E_i - \Sigma_i p_{zi}} \right) \qquad x_A = \frac{m_{\mathrm{jets}}}{\sqrt{s}} \mathrm{e}^{-y_{\mathrm{jets}}}$$

Differential photo-nuclear dijet distributions (Preliminary)

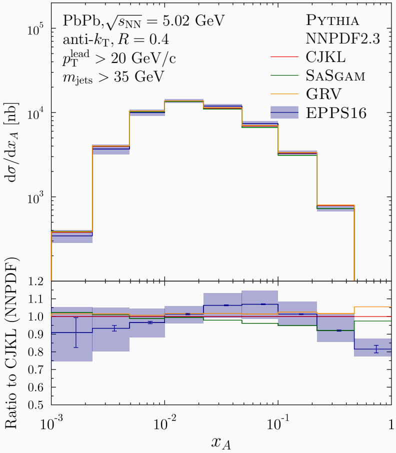


[ATLAS-CONF-2017-011]



- Preliminary data well described with γp from PYTHIA 6 and photon flux from STARLIGHT
- Nuclear PDFs and photon flux now included in PYTHIA 8
- Direct processes dominate at $x_A \lesssim 10^{-2}$

Expected potential of the dijet data with ATLAS cuts



Photon PDF dependence

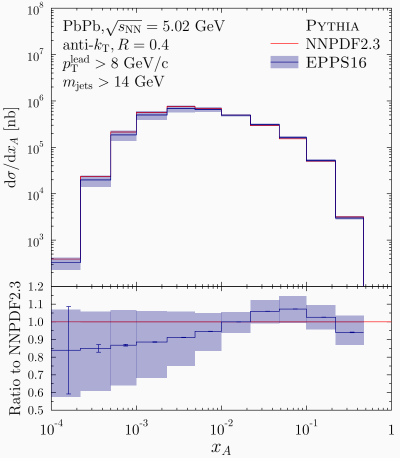
- Largest sensitivity (~ 10 %) at $x_A > 0.1$
- Negligible effect at $x_A < 0.02$

Expected statistical error

- Assume $L = 1$ nb^{-1} for the measurement
- Clearly smaller than nPDF uncertainty

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

Dijets at lower p_T



Lower the jet p_T

- $p_T^{jet1} > 8$ GeV
- $p_T^{jet2} > 6$ GeV
- Similar cuts as in HERA
- Increase cross section and x_A reach

Expected statistical error

- Sufficient statistics at $x_A > 2 \cdot 10^{-4}$ ($L = 1\,\mathrm{nb}^{-1}$)

- Larger nPDF uncertainties due to smaller Q^2 and x_A
  $\Rightarrow$ Enhanced potential to constrain nPDFs
- Possible to use other observables at lower p_T (e.g. γ+jet)

Summary & Outlook

Summary

Photoproduction implemented into Pythia 8

- Automatic mixing of direct and resolved processes
- Full parton-level evolution (parton showers, MPIs)
- Agreement with HERA data, support for MPIs
- Can simulate UPCs by using heavy-ion specific photon flux (though not yet with nuclear targer but with nPDFs)

Ultra-peripheral heavy-ion collisions

- Use dilepton production to calibrate the photon flux
- Can study photo-nuclear processes with LHC before EIC
- ATLAS dijets can provide nPDF constraints down to $x \sim 10^{-3}$
- Number of potential observables, increased low-x_A reach with lower p_T

Outlook

Ongoing work for UPCs and *eA* simulations in PYTHIA 8

- Improve UPC sampling efficiency (optimized for ep)
- Merge with new heavy-ion machinery (Angantyr) recently introduced to PYTHIA 8 [by L. Lönnblad and C. Bierlich]
- Study hard diffraction in γA using new implementation for photoproduction in ep [I.H., C. O. Rasmussesn, T. Sjöstrand]
  - Based on diffractive PDFs and dynamical rapidity gap survival from MPIs
    [originally implemented for pp by C. O. Rasmussesn, T. Sjöstrand]
- Smooth merging of photoproduction and DIS events

Backup slides

MPI and parton shower generation

Common evolution scale (p_T) for FSR, ISR and MPIs

- Probability for something to happen at given p_T

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\mathrm{T}} = \left(\frac{\mathrm{d}\mathcal{P}_\mathrm{MPI}}{\mathrm{d}p_\mathrm{T}} + \sum \frac{\mathrm{d}\mathcal{P}_\mathrm{ISR}}{\mathrm{d}p_\mathrm{T}} + \sum \frac{\mathrm{d}\mathcal{P}_\mathrm{FSR}}{\mathrm{d}p_\mathrm{T}} \right) \times \exp\left[- \int_{p_\mathrm{T}}^{p_\mathrm{T}^\mathrm{max}} \mathrm{d}p'_\mathrm{T} \left(\frac{\mathrm{d}\mathcal{P}_\mathrm{MPI}}{\mathrm{d}p'_\mathrm{T}} + \sum \frac{\mathrm{d}\mathcal{P}_\mathrm{ISR}}{\mathrm{d}p'_\mathrm{T}} + \sum \frac{\mathrm{d}\mathcal{P}_\mathrm{FSR}}{\mathrm{d}p'_\mathrm{T}} \right) \right]$$

  where $\exp[\dots]$ is a Sudakov factor
  (probability that nothing else has happened before p_T)

Simultaneous partonic evolution

1. Start the evolution from a scale related to the hard process
2. Sample p_T values for each $\mathcal{P}_i$, pick one with highest p_T
3. Continue from the sampled p_T until reach $p_\mathrm{Tmin} \sim \Lambda_\mathrm{QCD}$

Partonic evolution for resolved photons

DGLAP equations for photons

- Additional term due to $\gamma \to q\bar{q}$ splittings

$$\frac{\partial f_i^\gamma(x,Q^2)}{\partial \log(Q^2)} = \frac{\alpha_{\mathrm{em}}}{2\pi} e_i^2 P_{i\gamma}(x) + \frac{\alpha_s(Q^2)}{2\pi} \sum_j \int_x^1 \frac{dz}{z} P_{ij}(z) f_j(x/z, Q^2)$$

  where $P_{i\gamma}(x) = 3(x^2 + (1-x)^2)$ for quarks, 0 for gluons (LO)
- Solution has two components:

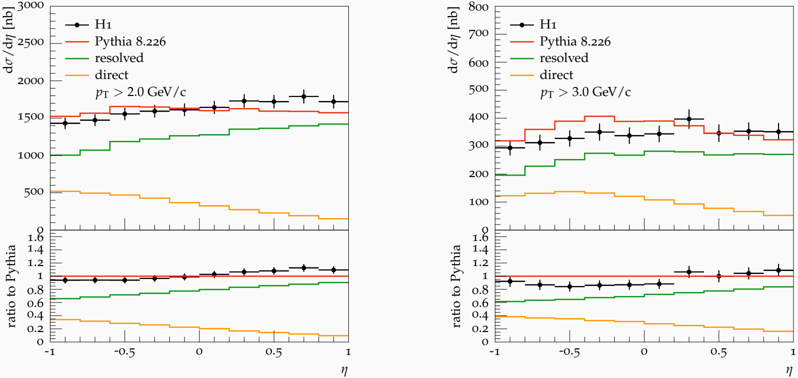
$$f_i^\gamma(x,Q^2) = f_i^{\gamma,\mathrm{pl}}(x,Q^2) + f_i^{\gamma,\mathrm{had}}(x,Q^2)$$

  - Point-like part from perturbative QCD
  - Non-perturbative input required for the hadron-like part

$$f_i^{\gamma,\mathrm{had}}(x,Q_0^2) = N_i x^{a_i}(1-x)^{b_i}$$

    Parameter fixed in a global analysis

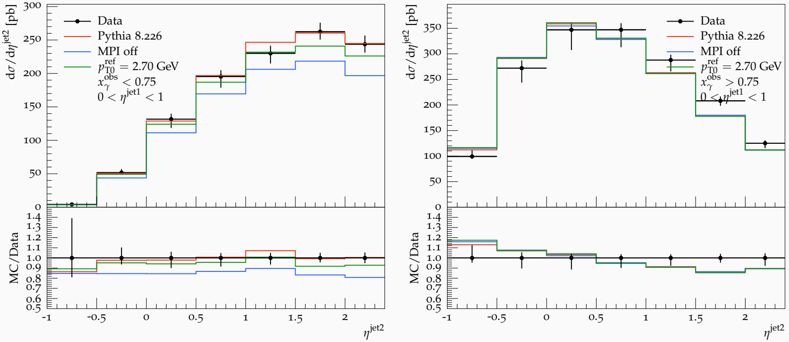
Charged particle η dependence in ep collisions at HERA



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

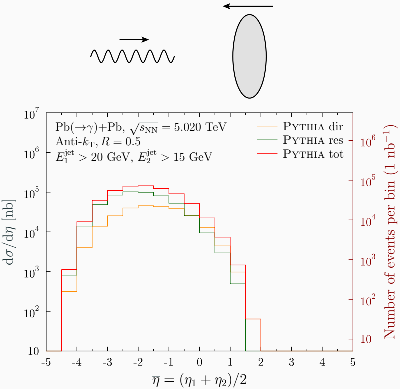
Dijet in ep collisions at HERA

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



- Good agreement with the data
- Some sensitivity to MPIs with $x_\gamma^{obs} < 0.75$

Dijet η distribution



Dijet kinematics

- Due to soft γ spektrum jets asymmetrically distributed in η
- No need to push for large η to gain sensitivity to small x

Quantifying the impact of the data to nPDFs requires

- Finalized data
- NLO calculation for photoproduction of dijets
- Accurate description of photon flux from nuclei