Universität
Münster

Event generation of dijet photoproduction in POWHEG BOX

EMMI Workshop: Mining for gluon saturation at the LHC and the future EIC

Alexander Feike, Tomáš Ježo and Michael Klasen

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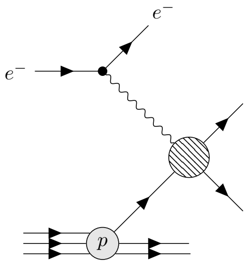
Introduction

Motivation

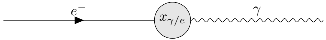
- dijet photoproduction yields wide range applicability
  - key process at ep and ee colliders (HERA, LEP, EIC)
  - important for LHC via ultra-peripheral collisions (UPCs)
  - renewed interest Sherpa [Höche, Krauss, Meinzinger 2310.18674] Pythia [Helenius, Rasmussen 1901.05261]
- precision calculations to test the Standard Model
  - interplay of QED and QCD
  - complementary to DIS
  - tool to measure structure functions of photons and nuclei
  - large hadronisation effects (complicated structure)
- current status not satisfactory
  - process disregarded for approx. 20 yrs.
  - γ-PDFs not well known (recent efforts)
  - precision up to NLO available

Photoproduction of Dijets

- lepton radiates photon with low virtuality $Q^2 = -q^2$ (high virtuality $\rightarrow$ DIS-type process)
- *quasi-real* photon interacts with hadron producing 2 jets at LO
  - **direct photoproduction** ($\gamma j \rightarrow jj$)
  - resolved photoproduction ($jj \rightarrow jj$)
- additional spectator jets from beam remnants and MPIs



(a) Direct Photoproduction Diagram



(b) Direct Photoproduction Spectrum

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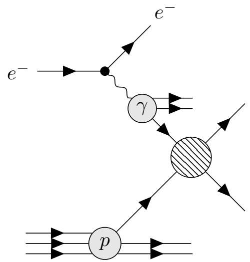
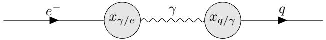


(a) Resolved Photoproduction Diagram



(b) Resolved Photoproduction Spectra

Photon Spectrum in the Electron

- for a small difference between incoming and outgoing e^--momentum the cross section factorizes as

$$\sigma_{eP}(eP \to eX) = \int_0^1 dx F_{\gamma/e}(x)\sigma_{\gamma P}(\gamma P \to X) \text{ with } x = x_{\gamma/e}$$

$$F_{\gamma/e}(x) = \frac{\alpha}{2\pi}\left[\frac{1+(1-x)^2}{x}\ln\frac{Q^2_{\max}}{Q^2_{\min}} + 2m_e^2 x\left(\frac{1}{Q^2_{\max}} - \frac{1}{Q^2_{\min}}\right)\right]$$

- improved **Weizsäcker-Williams Approximation** (WWA) or **Equivalent Photon Approximation** (EPA) [Frixione, Mangano, Nason, Ridolfi 1993]
- $Q^2_{\min} = \frac{m_e^2 x^2}{1-x}$ given by kinematical restrictions
- $Q^2_{\max} = E_e^2(1-x)\theta^2_{\max}$ depending on experimental setup

Photon Spectrum in the Electron

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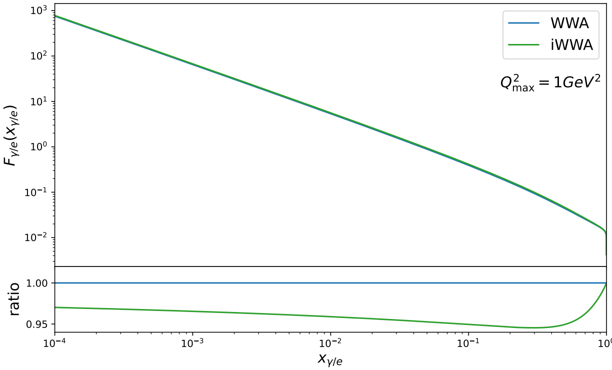
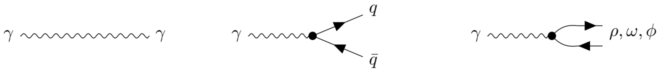


Parton Spectrum in the Photon



- direct
- point-like (perturbative)
- hadronic (non-perturbative), vector meson dominance (VMD)

- PDFs fulfill evolution equation
- inhomogeneous $\mathcal{O}(\alpha)$ term differs from hadronic case

$$\frac{d f^{i/\gamma}(x,Q^2)}{d \ln Q^2} = \frac{\alpha}{2\pi} P_{i\leftarrow\gamma} \otimes f^{\gamma/\gamma} + \frac{\alpha_s}{2\pi} \sum_j P_{i\leftarrow j} \otimes f^{j/\gamma}$$

$$f^{\gamma/\gamma}(x) = \delta(1-x)$$

- at NLO, collinear singularities absorbed into photon PDF $\rightarrow$ factorization scheme dependence

- use $\overline{\text{MS}}$ scheme, *i.e.* PDFs in DIS$_\gamma$ scheme are converted

Parton Spectrum in the Photon

- GRV ($\mathrm{DIS}_\gamma \to \overline{\mathrm{MS}}$)
  [Glück, Reya, Vogt 1992]
- CJKL [Cornet, Jankowski, Krawczyk, Lorca 2002], regulate $x \to 1$ divergence
- SaS [Schuler, Sjostrand 1995]
- VALO1.0 [Chithirasreemadam, Guzey, Hekhorn, Helenius, Paukkunen 06.2026]

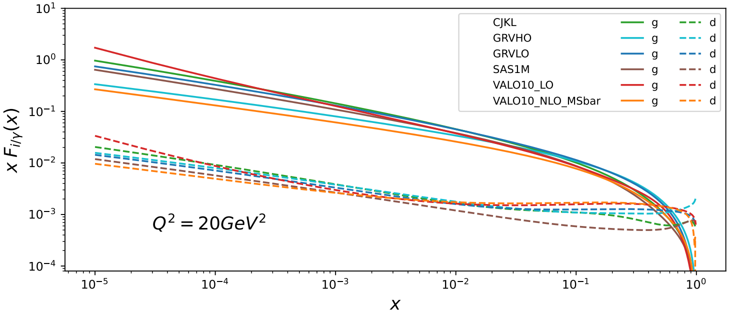
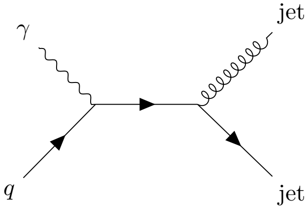


Figure: Photon PDF

POWHEG

POWHEG

[Nason 2004; Frixione, Nason, Oleari 2007; Alioli, Nason, Oleari, Re 2010]

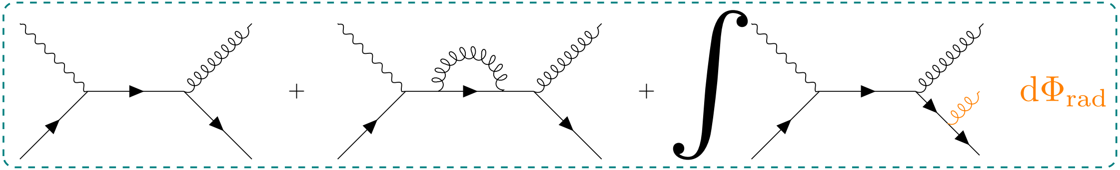


$$\mathrm{d}\sigma = \overline{B}(\Phi_n)\mathrm{d}\Phi_n \left[\Delta(p_T^{\min}) + \sum_\alpha \Delta(k_T^\alpha)\theta(k_T - p_t^{\min})\frac{R_\alpha(\Phi_\alpha(\Phi_{n+1}))}{B(\Phi_n)}\mathrm{d}\Phi_{\mathrm{rad}}\right]$$

with Sudakov form factor: $\Delta(k_T^\alpha) = \exp\left\{-\int \frac{R_\alpha(\Phi_\alpha(\Phi_{n+1}))}{B(\Phi_n)}\mathrm{d}\Phi_{\mathrm{rad}}\right\}$

POWHEG

[hep-ph/0409146, arXiv:0709.2092, arXiv:1002.2581]



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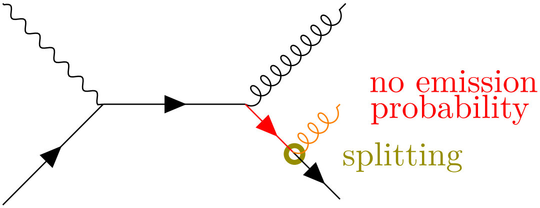

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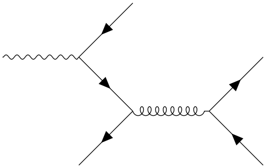
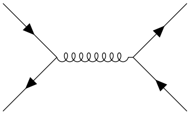
Dijet Photoproduction in POWHEG BOX

Challenges

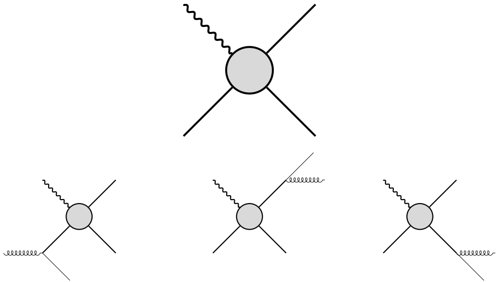
- analytically calculate direct photon contribution (LO, virtuals, reals)
  - cross checked with automated tools MadGraph5 and Recola
  - cross checked with existing analytic calculations [Klasen, Kleinwort, Kramer 1997]
  - resolved cross sections taken from POWHEG-Box/dijet
    [Alioli, Hamilton, Nason, Oleari, Re 1012.3380]
- resolving the beam twice
  - handle resolved and direct case separately
  - constructing the real phase space



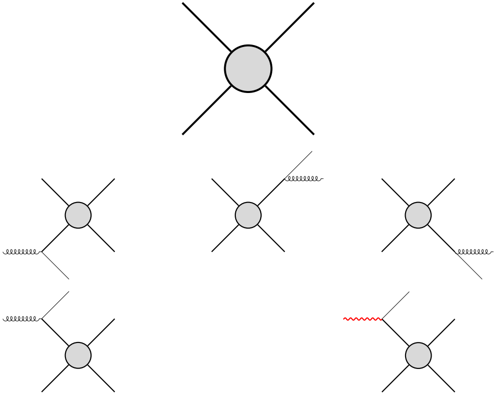


Division of direct and resolved contributions

direct



resolved



- competing QED and QCD emissions possible [Barze, Chiesa, Montagna, Nason, Nicrosini, Piccinini, Prosperi 1408.5766]

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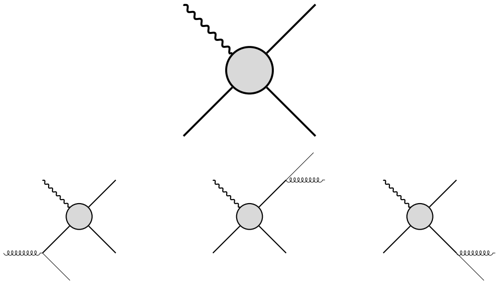

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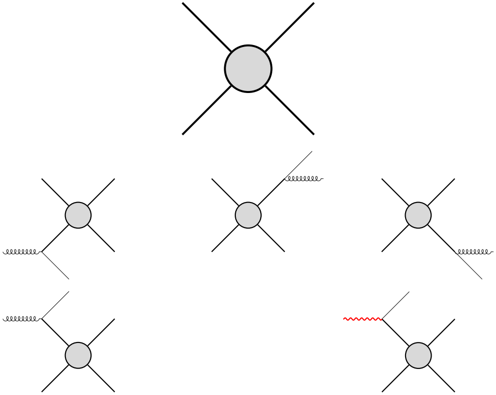

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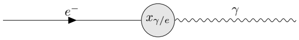
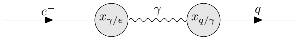
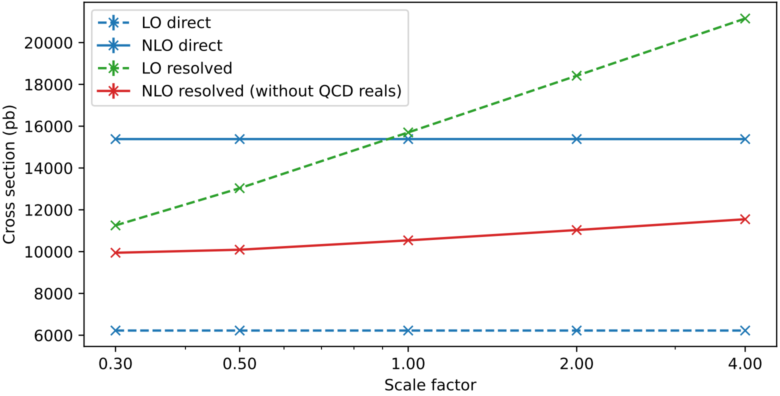
  - resolved cross sections taken from `POWHEG-Box/dijet` [Alioli, Hamilton, Nason, Oleari, Re 1012.3380]
- resolving the beam twice
  - handle resolved and direct case separately
  - constructing the real phase space
- using appropriate integrated counter terms
- `Pythia` doesn't support external resolved photon processes yet
  - implemented sampling photon momentum fraction $x_{\gamma/e}$ in `Pythia`
  - alternatively: POWHEG BOX hands over $x_{\gamma/e}$ to `Pythia`



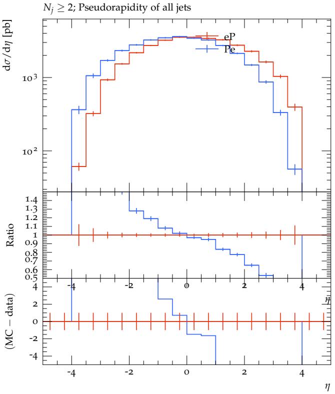


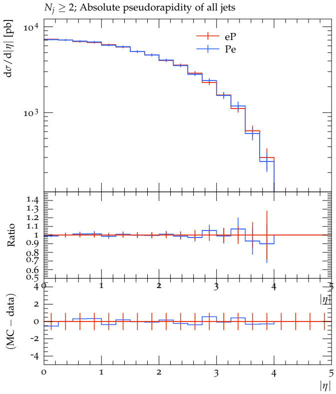
Photon factorization scale dependence

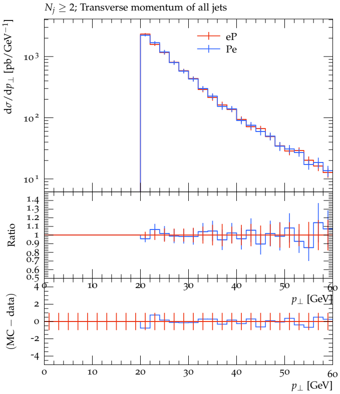


Consistency check

resolved case: compare eP- with Pe-collisions (fixed order NLO)







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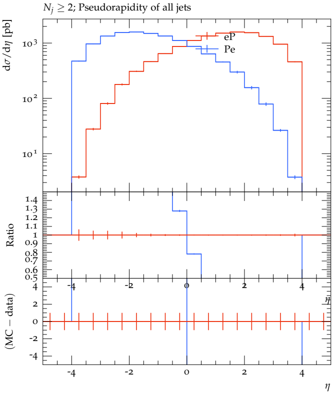
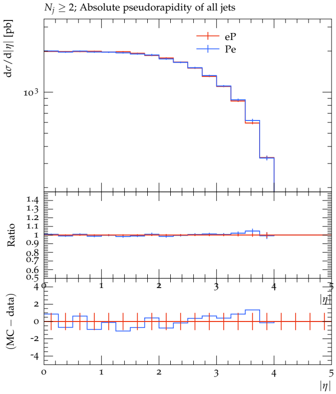
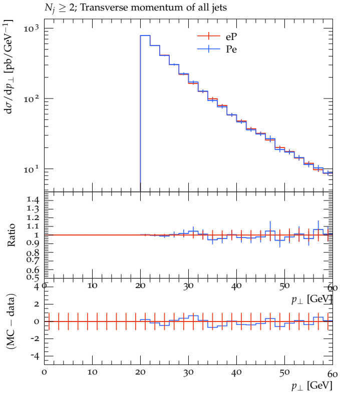
direct case: compare eP- with Pe-collisions (fixed order NLO)



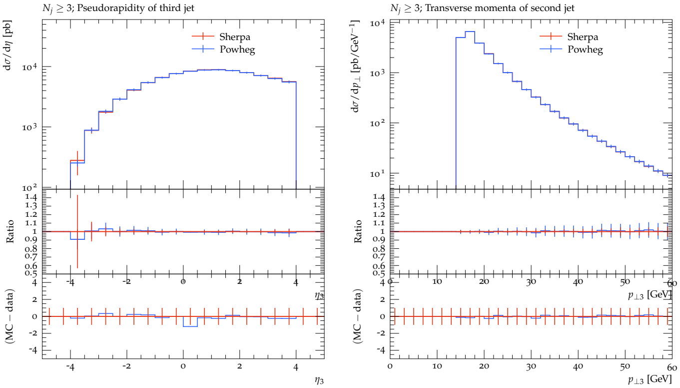




Fixed order comparison at NLO

- resolved γP-collision (no QED splitting $\gamma \to q\bar{q}$)
- $\mu_f^2 = \mu_r^2 = 100\,\mathrm{GeV}^2$; $E_P = E_\gamma = 800\,\mathrm{GeV}$
- agreement for 3rd jet observables
- disagreement 1st and 2nd jet observables

  $\to$ work in progress



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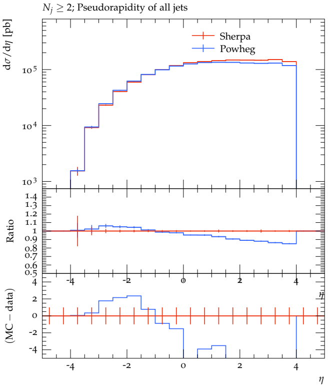
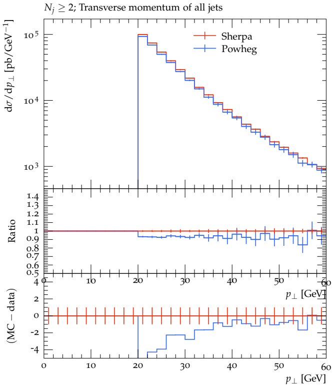




LO in HERA - Preliminary

e^+p-collision data from ZEUS [Chekanov et al 2002]

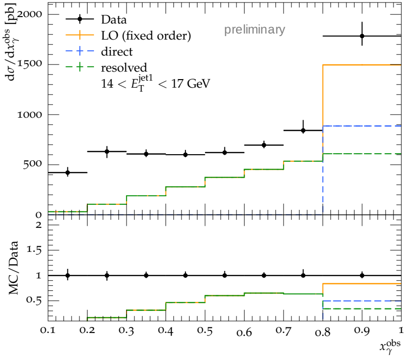
$E_e = 27.5$ GeV and $E_p = 820$ GeV

$-1 < \eta < 2.4$

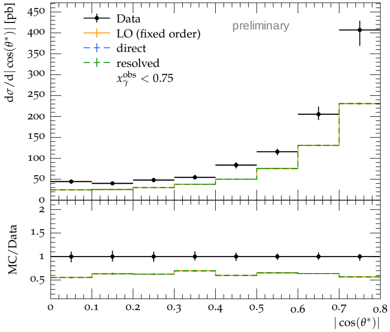
$p_T^{(1)} > 14$ GeV and $p_T^{(2)} > 11$ GeV

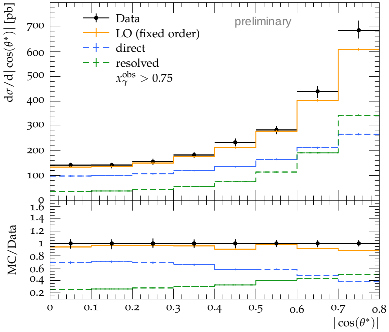
$$x_\gamma^{\text{obs}} = \frac{E_T^{\text{jet1}} e^{-\eta^{\text{jet1}}} + E_T^{\text{jet2}} e^{-\eta^{\text{jet2}}}}{2 x_{\gamma/e} E_e}$$

$$\cos\theta^* = \tanh\left(\frac{\eta^{\text{jet1}} - \eta^{\text{jet2}}}{2}\right)$$



LO in HERA - Preliminary





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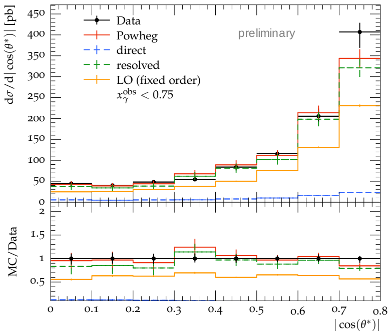

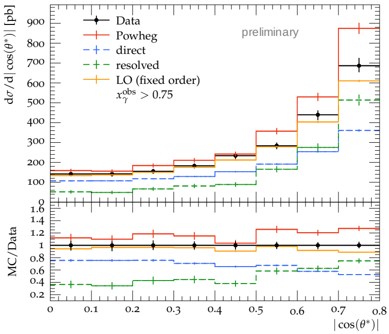

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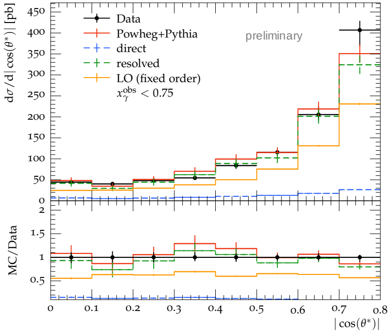

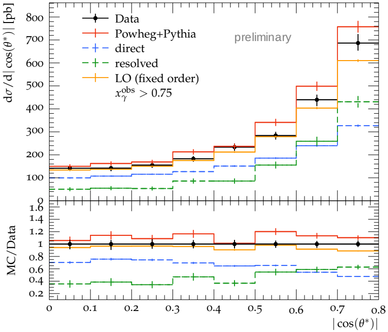

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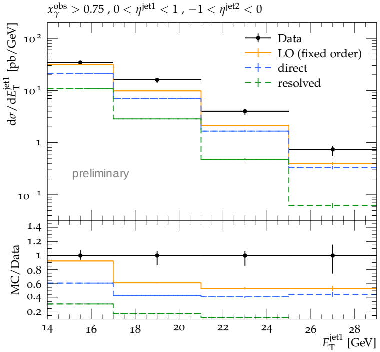

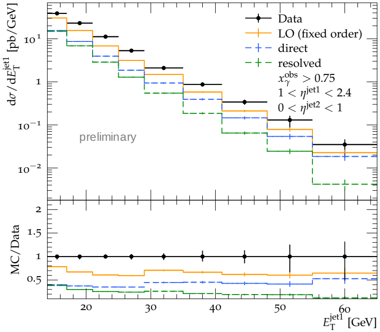

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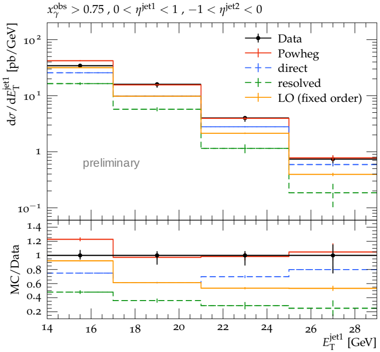

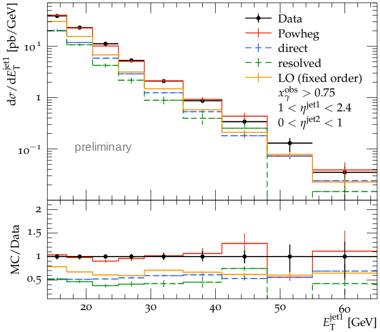

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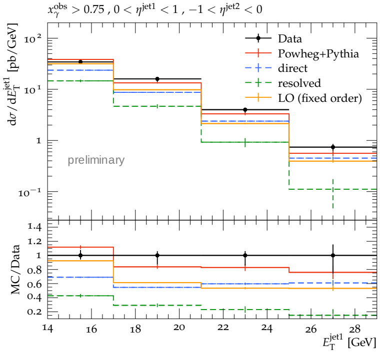

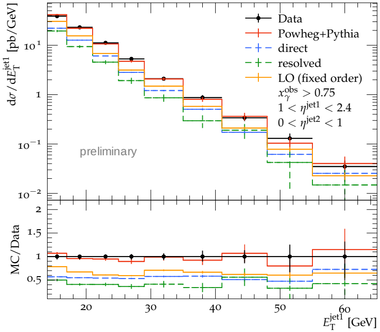

Outlook

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- finalize NLO fixed order comparison
- compare and validate NLO+PS using photoproduction data from HERA and LEP
- implement photon fluxes and analyze with UPC settings

  $\rightarrow$ compare to up-to-date data from LHC (ATLAS) [Aad et al 2409.11060]
- use wide-range applicability for making EIC relevant predictions
- provide public access to this POWHEG BOX process