

Dijet Photoproduction in POWHEG-Box

MC4EIC 2025

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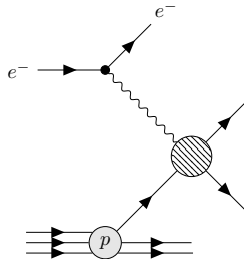
Introduction

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 [arXiv:2310.18674], Pythia [arXiv: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
 - 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



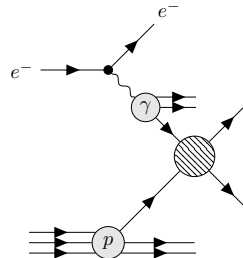
(a) Direct Photoproduction Diagram



(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

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

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

- ▶ improved **Weizsäcker-Williams Approximation** (WWA) or **Equivalent Photon Approximation** (EPA) [hep-ph/9310350]

- ▶ $Q_{\min}^2 = \frac{m_e^2 x^2}{1-x}$ given by kinematical restrictions

- ▶ $Q_{\max}^2 = E_e^2(1-x)\theta_{\max}^2$ depending on experimental setup

Photon Spectrum in the Electron

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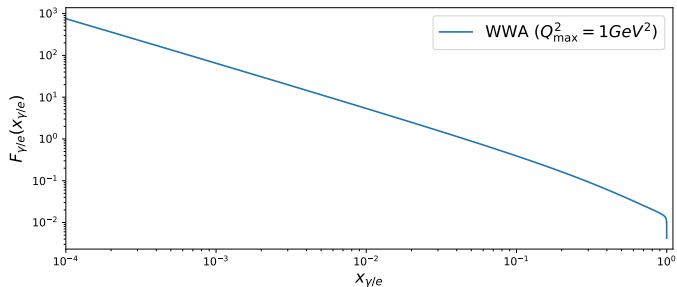
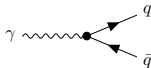
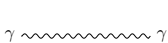


Figure: Weizsäcker-Williams Approximation

Parton Spectrum in the Photon



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

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

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

- ▶ at NLO, collinear singularities absorbed into photon PDF
→ factorization scheme dependence
- ▶ use $\overline{\text{MS}}$ scheme, *i.e.* PDFs in DIS_γ scheme are converted

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

Parton Spectrum in the Photon

► GRV ($\text{DIS}_\gamma \rightarrow \overline{\text{MS}}$)

[10.1103/PhysRevD.45.3986]

► CJKL [hep-ph/0212160], regulate
 $x \rightarrow 1$ divergence

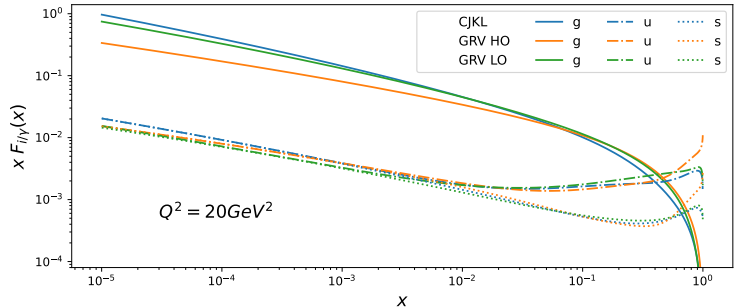
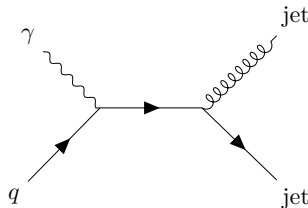


Figure: Photon PDF

POWHEG

POWHEG

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

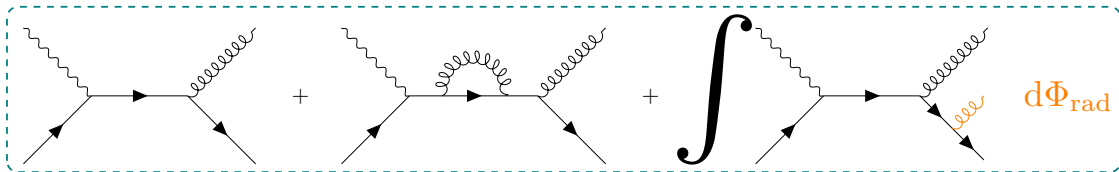


$$d\sigma = \overline{B}(\Phi_n) d\Phi_n \left[\Delta(p_T^{\min}) + \sum_{\alpha} \Delta(k_T^{\alpha}) \theta(k_T - p_t^{\min}) \frac{R_{\alpha}(\Phi_{\alpha}(\Phi_{n+1}))}{B(\Phi_n)} d\Phi_{\text{rad}} \right]$$

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

POWHEG

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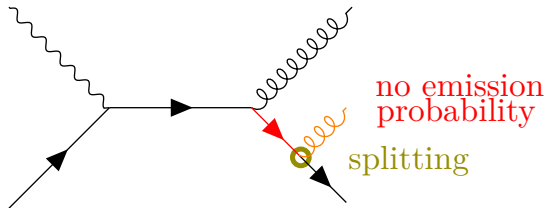


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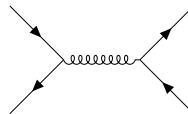
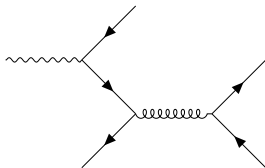
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Dijet Photoproduction in POWHEG-Box

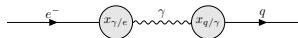
Challenges

- ▶ analytically calculate direct photon contribution (LO, virtuals, reals)
 - cross checked with automated tools MadGraph5 and RecoLa
 - cross checked with existing analytic calculations [hep-ph/9712256]
 - resolved cross sections taken from POWHEG-Box/dijet [arXiv 1012.3380]
- ▶ resolving the beam twice
 - handle resolved and direct case separately
 - constructing the real phase space



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- ▶ resolving the beam twice
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 - 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



LO in HERA - Preliminary

e^+p -collision data from ZEUS [hep-ex/0112029]

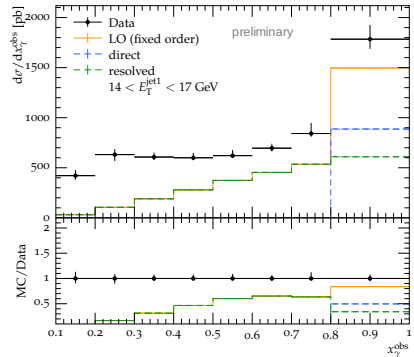
$E_e = 27.5$ GeV and $E_p = 820$ GeV

$-1 < \eta < 2.4$

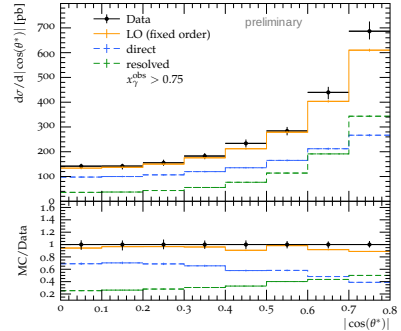
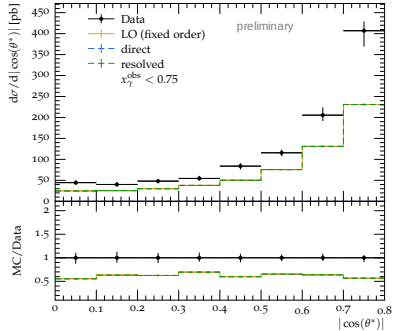
$p_T^{(1)} > 14$ GeV and $p_T^{(2)} > 11$ GeV

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

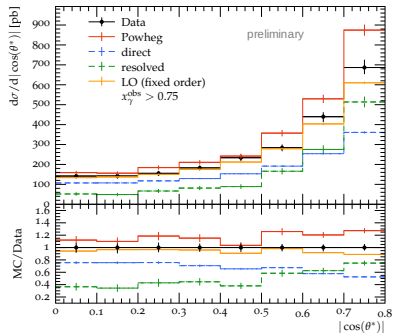
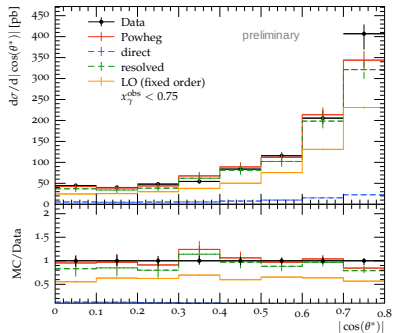
$$\cos \theta^* = \tanh \left(\frac{\eta^{\text{jet1}} - \eta^{\text{jet2}}}{2} \right)$$



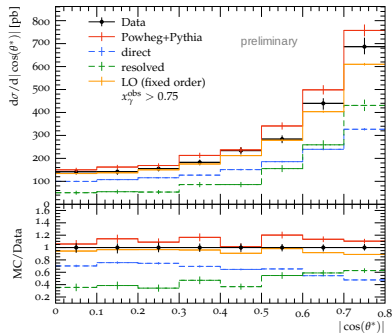
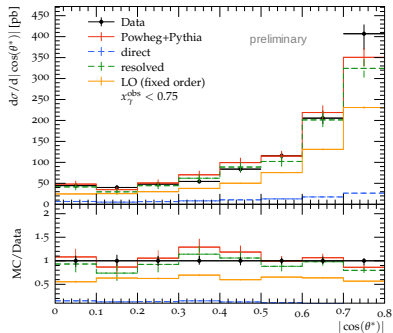
LO in HERA - Preliminary



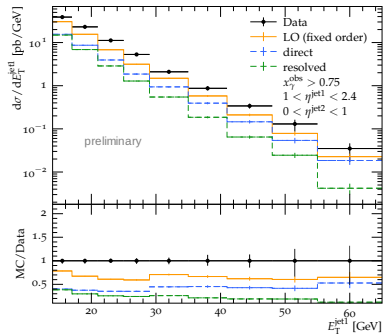
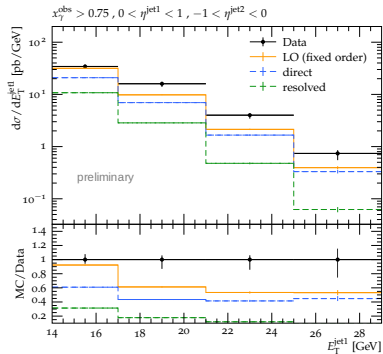
NLO in HERA - Preliminary



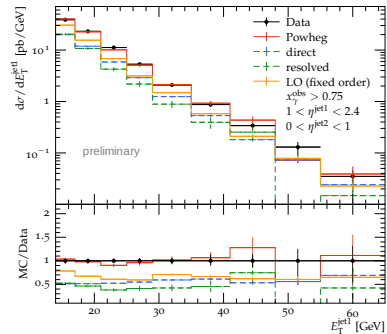
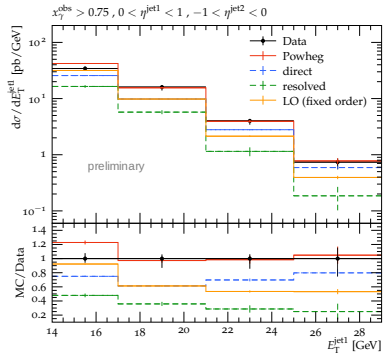
NLO in HERA - Preliminary



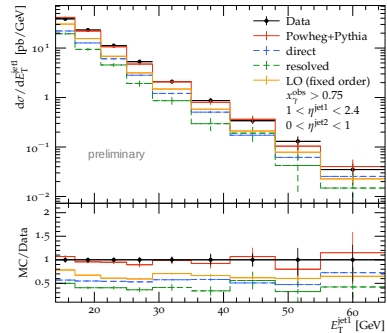
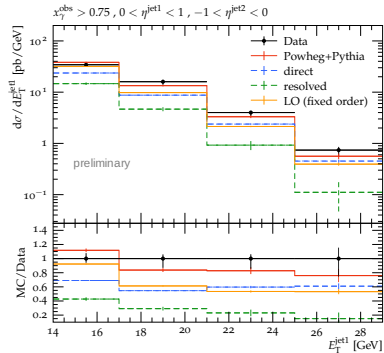
LO in HERA - Preliminary



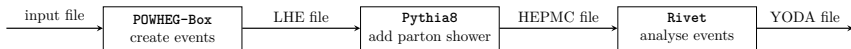
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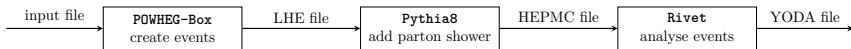


Toolchain



- ▶ supply process details via input file in POWHEG-Box
- ▶ supply shower details via Pythia8 main file (eg. `main343.cc`)
- ▶ use PowhegHooks for POWHEG matching

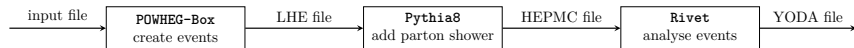
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```
numevts 1000  
ih1 -11  
ih2 1  
ebeam1 27.5  
ebeam2 820  
bornktmin 10  
...
```

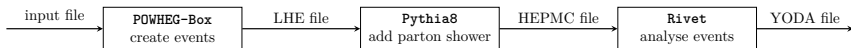
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```
Beams:frameType = 4
Beams:LHEF = pwgevents.lhe
Photon:ProcessType = 3
PartonLevel:FSR= on
PartonLevel:MPI = off
PartonLevel:ISR = off
...
```

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```
POWHEG:nFinal = 2
POWHEG:veto = 1
POWHEG:vetoCount = 50
POWHEG:pThard = 2
POWHEG:pTdef = 1
POWHEG:emitted = 0
...
```

Outlook

Outlook

- ▶ finalize NLO implementation
 - validate using old photoproduction data from HERA and LEP
- ▶ run and analyze with UPC settings
 - compare to up-to-date data from LHC (ATLAS) [arXiv:2409.11060]
- ▶ use wide-range applicability for making EIC relevant predictions
- ▶ provide public access to this POWHEG-Box process