

New Monte Carlo Samples for Inclusive QCD Final States

Frank Krauss

Institute for Particle Physics Phenomenology
Durham University

14.7.2026 - ePIC/EICUG Meeting - Glasgow



- introduction
- inclusive QCD results @ HERA
- plans for future samples
- outlook

instead of an introduction

inclusive event topologies

electro- vs. photo-production & diffraction

- consider (inclusive) $ep \rightarrow eX$ processes in QCD
- parton level: resolve proton's structure
process reads $eq_0 \rightarrow eq_1 q_2 q_3 \dots q_n$ (where $q_i = \text{partons}$)
- however: intermediate photon can fluctuate into hadrons

($q\bar{q}$ -pairs: $\rho^0, \omega, \phi, J/\psi, \dots$, simple quantum mechanics at work : **vector meson dominance model!**) $\Rightarrow$

effectively hadron scattering, involves photon PDF

- diffraction: proton gets excited (or not: $p \rightarrow p'$)
 $\Rightarrow$ parton level: $ep \rightarrow eq_1 q_2 q_3 \dots q_n + p'$
 $\Rightarrow$ add "pomeron + pdf: $ep \rightarrow e\mathbf{P}p' \rightarrow eq_1 q_2 q_3 \dots q_n + p'$

a quick word on technology and technical terms

- traditionally, MC's at HERA were mainly leading order in QCD:
parton level: $eq \rightarrow eq \otimes$ parton showers (multiple emissions)
- usually large scale uncertainties
(and usually underestimated as well!)
- modern MC's (HERWIG 7, PYTHIA 8, SHERPA):
 - mostly NLO accuracy in simulation (MC@NLO) of DIS
 - for multijets: MEPS@NLO ("towers of MC@NLO's")
 - NLO or LO in photoproduction
- below some "propaganda" for higher accuracy

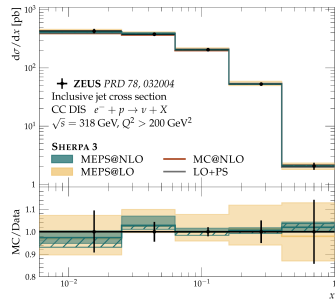
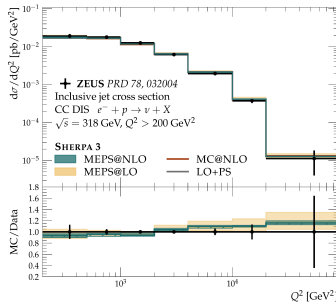
inclusive QCD @ HERA

(validating the MC)

neutral and charged current DIS

(see also Meinzinger, Reichelt, Silvetti, 2506.08994)

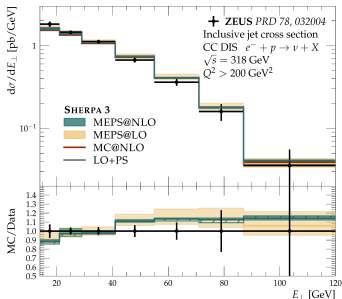
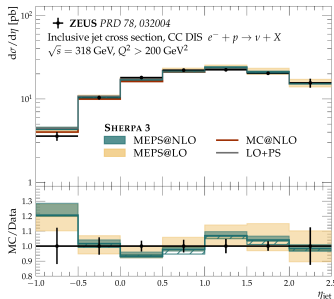
- consider charged current at HERA
- compare LO with NLO (as well as merged samples)
- Q^2 and x in different MC settings



neutral and charged current DIS

(see also Meininger, Reichelt, Silveti, 2506.08994)

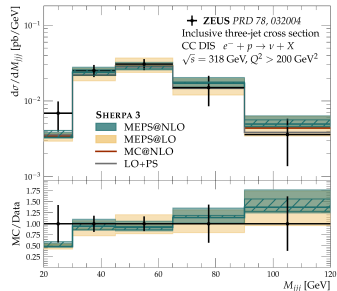
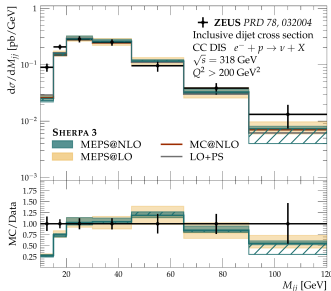
- consider charged current at HERA
- compare LO with NLO (as well as merged samples)
- jet- η and $-E_T$



neutral and charged current DIS

(see also Meinzinger, Reichelt, Silvetti, 2506.08994)

- consider charged current at HERA
- compare LO with NLO (as well as merged samples)
- M_{jj} and M_{jjj}



electro- vs. photo-production: an MC perspective

- suggestion: use trick out of the MC box
- using the notion of “jet measure” and cluster partons backwards:
 - ① calculate distance between any two partons i and j and between any parton i and proton p according to k_T measure:

$$d_{ij} = \min\{E_i^2, E_j^2\}(1 - \cos \theta_{ij})$$

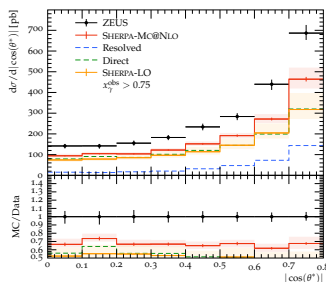
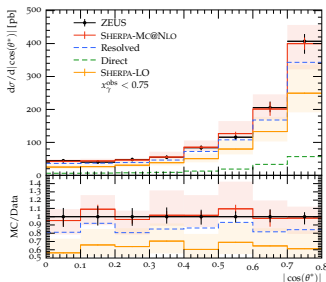
$$d_i = E_i^2(1 - \cos \theta_{ip})$$

- ② cluster smallest distance pair, to a new parton $[ij]$ or absorb i in beam
 - ③ repeat with step 1 until $2 \rightarrow 2$ configuration
- three possible outcomes:
 - $eq_0 \rightarrow eq_1$: electro-production, usually at $Q^2 \gg m_p^2$
 - $\gamma q_0 \rightarrow q_1 q_2$: (direct) photo-production, usually at $Q^2 \approx 0$
 - $q_0 q_1 \rightarrow q_2 q_3$: (resolved) photo-production, usually at $Q^2 \approx 0$

resolved photon production

(see also Hoche, FK, Meinzinger, 2310.18674)

- “resolve” photons (i.e. with hadronic structure) at LEP & HERA:
- use x_γ with a cut at $x_\gamma \gtrless 0.75$
- $\cos\theta^* = \tanh \frac{\eta_1 - \eta_2}{2}$ (vs. ZEUS hep-ex/0112029)

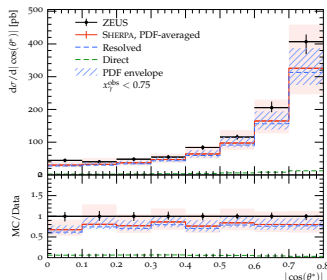
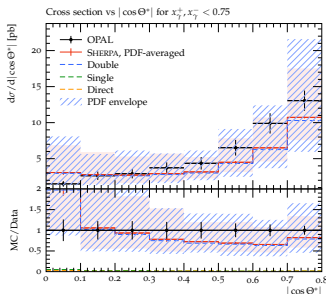


resolved photon production

(see also Hoche, FK, Meinzinger, 2310.18674)

- “resolve” photons (i.e. with hadronic structure) at LEP & HERA:
- use x_γ with a cut at $x_\gamma \gtrsim 0.75$
- impact of photon PDFs

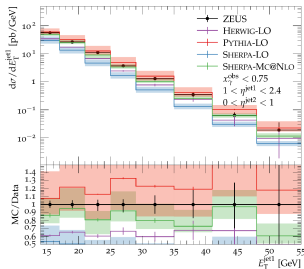
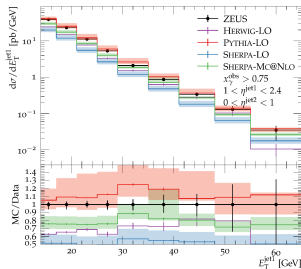
data from OPAL, hep-ex/0301013 ZEUS, hep-ex/0112029



resolved photon production

(see also Helenius, Meinzinger, Platzer, Richardson, 2406.08026)

- $E_T^{\text{jet}1}$, unresolved (left) vs. resolved (right)

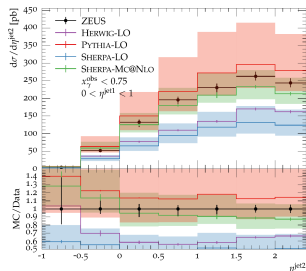
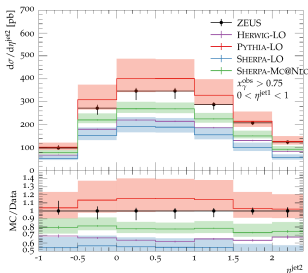


ZEUS, 1205.6153

resolved photon production

(see also Helenius, Meizinger, Platzer, Richardson, 2406.08026)

- $\eta^{\text{jet}2}$, unresolved (left) vs. resolved (right)

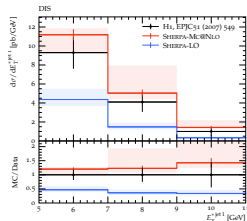
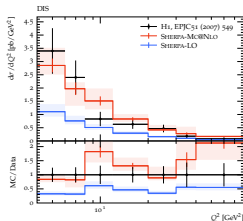
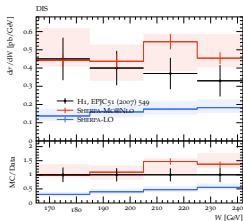


ZEUS, 1205.6153

a quick peak to diffraction

(FK Meininger, 2407.02133)

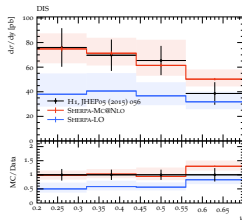
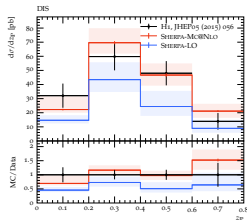
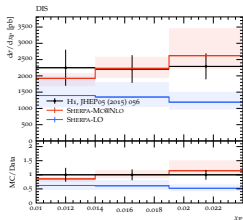
- diffraction modelled with pomeron PDF
- compare with data from HERA
- c.m.energy W , Q^2 , E_T^{jet1}



a quick peak to diffraction

(FK Meininger, 2407.02133)

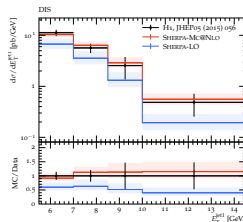
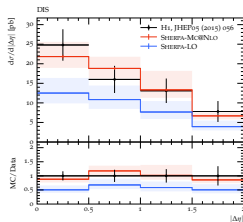
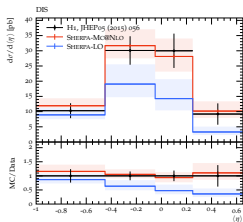
- diffraction modelled with pomeron PDF
- compare with data from HERA
- x_p , z_p , y



a quick peak to diffraction

(FK Meininger, 2407.02133)

- diffraction modelled with pomeron PDF
- compare with data from HERA
- jet η , $\Delta\eta$, $E_T^{\text{jet}1}$



future samples

(maybe with some input?)

plans

- every sample with HepMC3 output files, 1M unweighted events
(all at LO, Mc@NLO, MEPS@NLO, where available in MC)
- track MC versions + run cards (guarantee reproducibility - somewhat important, isn't it?)
- (cross-)validation with RIVET analyses (see A.Buckley's talk)
- will produce samples with HERWIG 7, PYTHIA 8 and SHERPA for
 - *ep* DIS NC & CC for $5 \otimes 41$, $5 \otimes 100$, $10 \otimes 100$, $10 \otimes 275$, $18 \otimes 275$
(questions: Q^2 -binning? preferred PDFs? PDF-weights?)
 - photo-production in *ep* for $10 \otimes 100$, $10 \otimes 275$, $18 \otimes 275$
(questions: Q^2 -binning? preferred PDFs? PDF-weights (γ and p)?)
 - diffractive DIS NC in *ep* for $5 \otimes 100$, $10 \otimes 100$, $10 \otimes 275$, $18 \otimes 275$
(questions: Q^2 -binning? which pomeron-PDF?)
 - can produce $\gamma\gamma \rightarrow \text{QCD}$ events in *ep*/ eA ?
- before burning a few 10k CPU hours: **is this relevant/wanted?**

summary & outlook

(the now and the future)

summary

- slowly upgrading DIS MC tools to industrial standard:
 - MC@NLO and MEPS@NLO becoming available
 - added photo-production @ NLO to the capabilities
 - verified/validated vs. HERA data
 - next steps: QED/EW corrections, MC@NNLO, MPIs
- opportunities for improvement beyond pert. theory:
 - eA collisions (the big one)
 - needed: updated photon PDFs
 - (re-)tuning of soft QCD models to exp. data
(beam and FS fragmentation, nuclear fission, ...)
(add hist. data to HEPDATA + RIVET)
- personal prediction (unlimited youthful optimism):
MCs will be ready for EIC
- start playing now!

announcement of MC4EIC in Zurich, August 26th-28th



EICUG-ePIC workshop on MC event simulation for the EIC

August 26-28, 2026 <https://indico.cern.ch/event/1667909/>

MC4EIC 2026

Ilkka, Peter, Thomas, and I are looking forward to seeing some/many of you there!

(it will be fun, I promise!)



LIMITATIONS

UNTIL YOU SPREAD YOUR WINGS,
YOU'LL HAVE NO IDEA HOW FAR YOU CAN WALK.