Photoproduction simulations (and other advances) in Sherpa

MC4EIC 2022 workshop @ BNL

Peter Meinzinger on behalf of the Sherpa collaboration

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IPPP, Durham University

Outline

Recent progress in SHERPA

Photoproduction simulation

Validation

Notes on EIC physics

Discussion of going NLO_{QCD}

Next steps and outlook

Conclusion

Recent progress in SHERPA

The SHERPA General Purpose Event Generator

SHERPA homepage

Analytic calculations: CAESAR framework in SHERPA

- CAESAR formalism [Banfi, Salam, Zanderighi '04]
- implemented in SHERPA

  [Gerwick, Höche, Marzani, Schumann '15]

  [Baberuxki, Preuss, DR, Schumann '19]
- extended for jet observables...
  - modified wide angle behaviour

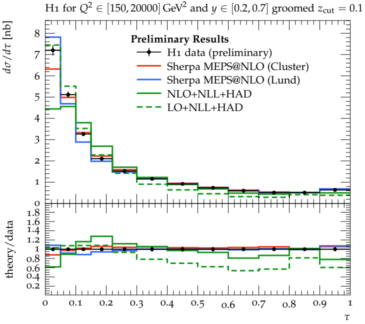
    [Dasgupta, Khelifa-Kerfa, Marzani, Spannowski '12]

    [Caletti, Fedkevych, Marzani, DR, Schumann '21]
  - non-global logs [Dasgupta, Salam, '01]
- ...and soft drop grooming
  - CAESAR-style formulas available

    [Baron, DR, Schumann, Schwanemann, Theeuwes '20]
- + non-perturbative transfer matrices

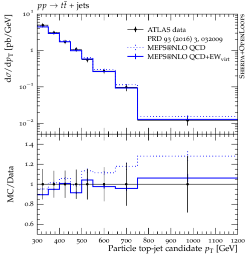
  [DR, Caletti, Fedkevych, Marzani, Schumann, Soyez]

- General framework, ready for DIS



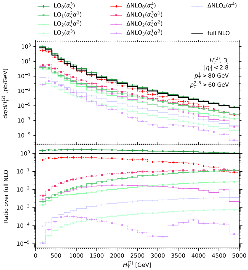
preliminary data from [H1 / Klest (Talk at DIS '22)]

EW corrections in SHERPA



SHERPA-2.2

- particle-level event generation
  - approximate NLO EW corrections in multijet-merged calculations MEPS@NLO QCD+EW$_{\rm virt}$

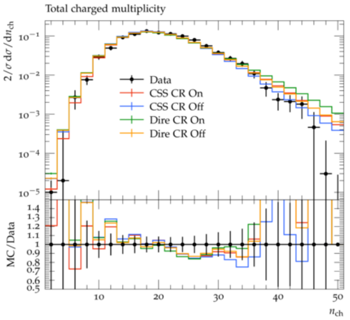


SHERPA-3.0

- parton-level calculations
  - exact NLO EW fixed-order
  - (resummed) EW Sudakov corrections
- particle-level event generation
  - MEPS@NLO QCD+EW$_{\rm virt}$
  - MEPS@NLO QCD+EW$_{\rm sud}$ (NLO and resummed)

A word on Tuning [Slide adapted from Steffen Schumann]

- Modelling of non-perturbative phenomena corner stone of HEP MCs
  → lack of first-principle ansatz, e.g. Lund- & Cluster models, MPI etc
- Need to calibrate $\mathcal{O}(10-100)$ model parameters with experimental data
- very costly to evaluate for different energies, colliders, lots of measurements
  → grid search not feasible, parametrize/model MC response
  → Professor [Hoeth et al.] & Apprentice [Krishnamoorthy et al.] tools
  → Based on analyses available in RIVET
- fast turn-overs desirable, less resource intense, uncertainty estimates



[Chahal and Krauss, SciPost Phys. 13 (2022) no.2]

New ALARIC shower

- Use partial fraction matrix element & match to collinear sectors NPB178(1981)421, hep-ph/9605323

$$\frac{W_{ik,j}}{E_j^2} \quad \to \quad \frac{1}{p_i p_j}\frac{p_i p_k}{(p_i + p_k)p_j} + \frac{1}{p_k p_j}\frac{p_i p_k}{(p_i + p_k)p_j}$$

- ALARIC: Separate into energy & angle first arXiv:2208.06057
  Partial fraction angular radiator only: $W_{ik,j} = \bar{W}^i_{ik,j} + \bar{W}^k_{ki,j}$

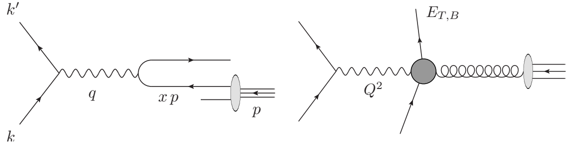
$$\bar{W}^i_{ik,j} = \frac{1 - \cos\theta_{ik}}{(1 - \cos\theta_{ij})(2 - \cos\theta_{ij} - \cos\theta_{kj})}$$

  - Bounded by $\bar{W}^i_{ik,j} < 2$
  - Strictly positive
- NLL accuracy analytically and numerically proven
- Intuitive understanding & connection to angular ordering

Matching at NNLO accuracy

[Kuttimalai,Li,SH] arXiv:1809.04192

- New Sherpa module for computation of inclusive DIS at NNLO QCD
- Projection-to-Born method for fully differential fixed order predictions
  [Zijlstra,vanNeerven] NPB383(1992)525, PLB297(1992)377 [Moch,Vermaseren,Vogt] hep-ph/0504242
  [Bern,Dixon,Kosower] hep-ph/9708239, [Berger et al.] arXiv:0803.4180
- UN^{2}LOPS matching to parton shower for particle-level simulations
  [Lönnblad,Prestel] arXiv:1211.7278, [Li,Prestel,SH] arXiv:1405.3607
- Scale choice appropriate for simultaneous description of inclusive DIS and inclusive jet / di-jet / tri-jet production $\rightarrow \mu^2_{R/F} = (Q^2 + (H_T/2)^2)/2$



- Good agreement with H1 measurements in both high-Q^2 and low-Q^2 region [Andreev et al.] arXiv:1406.4709, arXiv:1611.03421

Photoproduction simulation

Why do we need photoproduction?

Complementary to high-virtuality photon exchange
⇒ **get coherent picture of QCD production**
⇒ **measure non-perturbative QCD effects**

Significant QCD background
⇒ **improves signal-to-background ratio**

Window into photon physics
⇒ **transition from real to virtual photons**
⇒ **get data for photon PDFs**
⇒ **sensitive for New Phyics signals**

production mode at every collider
⇒ **can be applied to very different settings**

The Equivalent Photon Approximation [1–3]

Observe that

- for photon virtuality $Q^2 < \Lambda^2_{\text{cut}}$, the photo-absorption cross-section can be approximated by its mass-shell value
- the same domain gives the dominant contribution in photoproduction

$\Rightarrow$ approximate the cross-section by $\mathrm{d}\sigma_{eX} = \sigma_{\gamma X}(Q^2 = 0)\mathrm{d}n$, with $\mathrm{d}n$ the photon spectrum

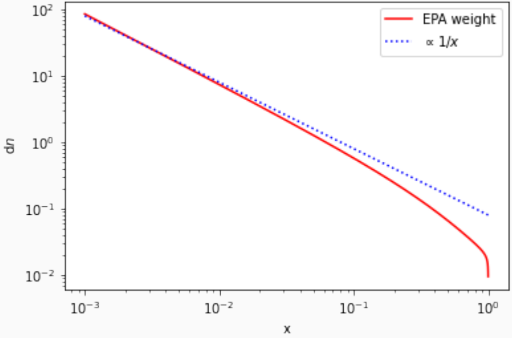
$\Rightarrow$ Calculate $\mathrm{d}n$ from DIS matrix element in approximation $Q^2 \to 0$.

- form factors available for protons
- also extendible for ions (validation is work in progress)
- corresponds to elastic production modes

Plotting the spectrum for electrons

$$\mathrm{d}n = \frac{\alpha_{\rm em}}{2\pi}\frac{\mathrm{d}x}{x}\left[\left(1+(1-x)^2\right)\log\left(\frac{Q^2_{\rm max}}{Q^2_{\rm min}}\right) + 2m_e^2x^2\left(\frac{1}{Q^2_{\rm min}} - \frac{1}{Q^2_{\rm max}}\right)\right]$$

with x the energy fraction, Q^2 the virtualities.

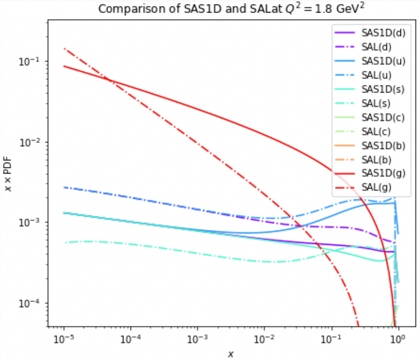


Photon PDFs

(Quasi-)real photons need parton distribution functions!

The following photon PDF libraries have been included in SHERPA:
Glück-Reya-Vogt [4], Glück-Reya-Schienbein [5],
Slominski-Abramowicz-Levy [6], Schuler-Sjöstrand [7, 8]

- All librarys at least for the real photon in LO
- Some additionally in NLO
- GRS and SaS also for virtual photon



The phase space setup

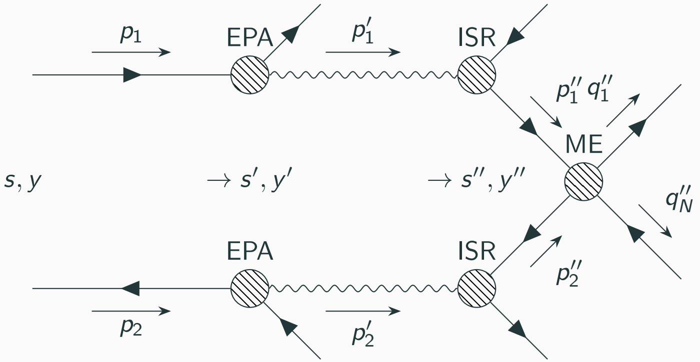


Figure 1: Schematic sketch of the phase space mappings between the Equivalent Photon Approximation (EPA) and the Initial State Radiation (ISR), and the Matrix Element (ME).

Validation

Some technical remarks

Typical observables are:

- (average) jet transverse energy E_T
- pseudo-rapidity η
- $\cos\Theta^*$, the angle between the two jets (approximately)
- $x_\gamma^\pm$, which is defined as

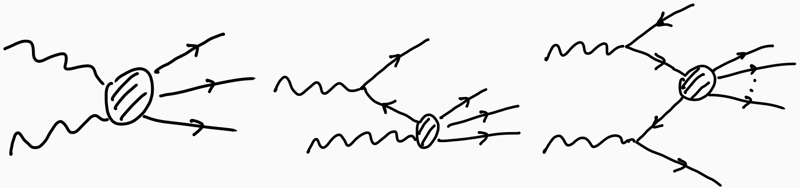
$$x_\gamma^\pm = \frac{\sum\limits_{j=1,2} E^{(j)} \pm p_z^{(j)}}{\sum\limits_{i\in \mathrm{hfs}} E^{(i)} \pm p_z^{(i)}} \tag{1}$$

Setup:

- MEPS@LO for 2(+2) jets for LEP data and LO for HERA data
- 1M weighted events including 7-point scale variation
- c- and b-quarks are massive
- averaged over the available PDF sets
- Disclaimer: preliminary results

Photoproduction cross-section, exemplified for LEP

Three different hard processes: direct, single-resolved and double-resolved: $\sigma_{\text{tot}} = \sigma_{\gamma\gamma} + 2\sigma_{j\gamma} + \sigma_{jj}$



Validated against data from ZEUS, OPAL and L3.

SHERPA calculations for LEP – preliminary

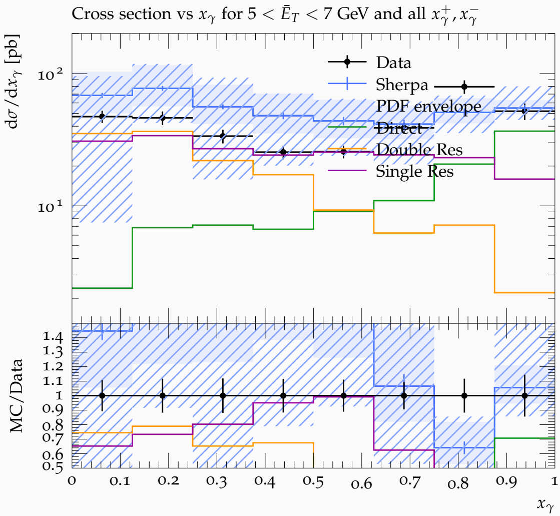


Figure 2: Distributions x_γ for average transverse jet energy $\bar{E}_T \in [11\,\mathrm{GeV}, 25\,\mathrm{GeV}]$ at $\sqrt{s} = 198$ GeV.

SHERPA calculations for LEP – preliminary

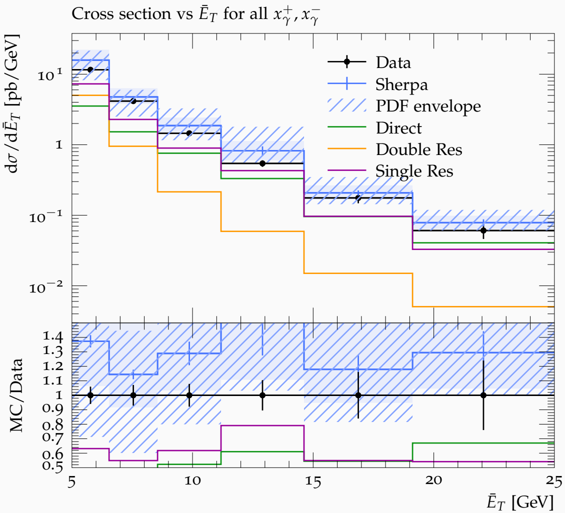


Figure 3: Distribution for average jet transverse energy $\bar{E}_T$ for LEP at $\sqrt{s} = 198$ GeV.

SHERPA calculations for LEP – preliminary

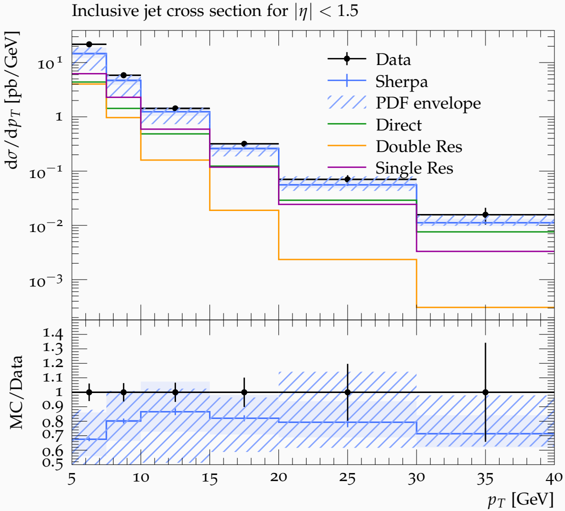


Figure 4: Distribution for jet transverse momentum p_T for LEP at $\sqrt{s} = 206$ GeV.

SHERPA calculations for HERA at LO – preliminary

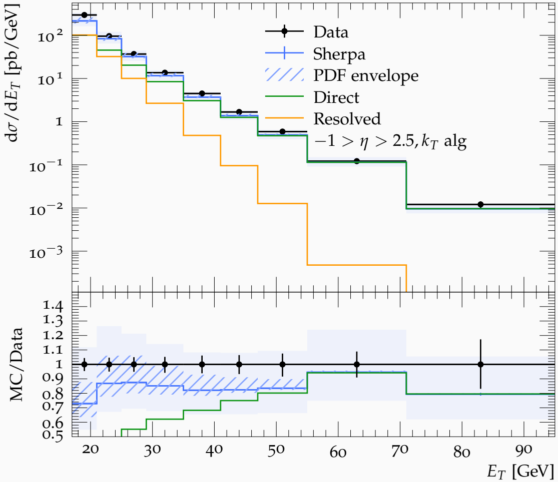


Figure 5: Distribution for jet transverse energy E_T for HERA.

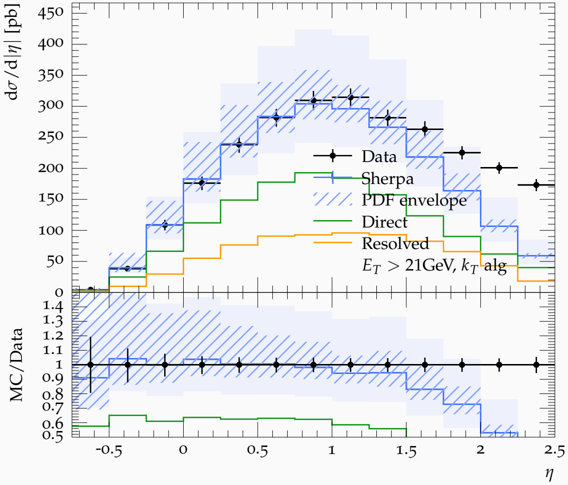


Figure 6: Distribution for jet pseudo-rapidity η for HERA. The drop at $\eta > 1.5$ is due to the missing underlying event [9].

Notes on EIC physics

EIC physics

Big step towards complete description of events over full Q^2 region:

- photon flux for proton beams is implemented, too
- factorized phase space allows calculation combined with, e.g., LUXqed PDF sets
- Full Final-State spectrum available from the ME generators, incl. photon PDFs, with hadronisation, fragmentation, etc.
- QED already works at NLO
- tuning of UE, MinBias in progress
- diffractive and semi-inclusive production would need form factors for proton diffraction and $\gamma \to V$ transition probability
- ... and what about matched $\mathrm{NLO}_{\mathrm{QCD}}$?

Discussion of going $\mathrm{NLO}_{\mathrm{QCD}}$

SHERPA calculations for LEP at MC@NLO accuracy – preliminary

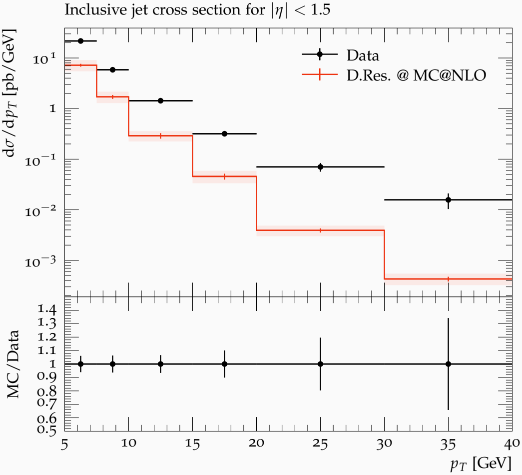


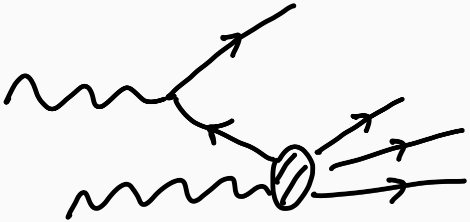
Figure 7: Distribution for jet transverse momentum p_T for LEP at $\sqrt{s} = 206$ GeV. SHERPA simulation is at $\mathrm{NLO_{QCD}}$ accuracy using MC@NLO where both photons are resolved.

The difficulty of defining NLO_{QCD}

Photons in the initial state show collinear divergences

$\Rightarrow$ introduces ambiguity and double-counting

Example:



Is a collinear parton the real correction to $\gamma\gamma \to X$?
Or remnant of the PDF in $j\gamma \to X$?

The difficulty of defining NLO$_{\text{QCD}}$

Cancel the divergences with QED subtraction terms

Pros:

- Would allow fixed order calculation
- builds up on known subtraction schemes

Cons:

- needs PDF to construct underlying Born process
- needs shower with QED splittings to allow matching in Mc@Nlo

Create "subtraction by PDF", i.e. make cut at shower cut-off scale

Pros:

- does not need the PDF
- extendible to Mc@Nlo with standard shower
- start point for consistent matching between the three modes

Cons:

- is very setup-specific
- also needs PDF, implicitly

Next steps and outlook

Next steps

- **Multiple-parton interaction for photons**
  $\Rightarrow$ work in progress
- **Extension to Minimum Bias events**
- **Include Proton–Pomeron vertex**
- **Extend for A**
  $\Rightarrow$ Needs form factors for each nucleus
- **$Q^2 > 0$ and non-collinear kinematics**
  leave the Weizsäcker-Williams $Q^2 \rightarrow 0$ approximation
  $\Rightarrow$ interpolation to virtual photons?
  $\Rightarrow$ extend to a generalized VMD model?
- . . . any other suggestions?

Next step: extension to virtual photons: VMD-type model [10, 11]

Vector-Meson Dominance model – needed for stringent description of event characteristics

Photonic interaction can be either **bare** or through fermionic fluctuations:

- $\rightarrow$ negligible for jet production
- **'hard' quarks** $\rightarrow$ $p_{\perp}^2 \sim Q^2 > 0$ $\rightarrow$ short-lived and perturbatively calculable
- **'soft' quarks** $\rightarrow$ $p_{\perp}^2 \sim Q^2 \approx 0$ $\rightarrow$ long-lived and non-perturbative $\rightarrow$ meson production and non-perturbative hadron physics

(Q^2 – virtuality)

Conclusion

Conclusion

- Photoproduction is an important ingredient for phenomenology at the EIC
- Simulation in SHERPA validated against LEP and HERA data
- Uncertainties in QCD observables dominated by photon PDFs
- Underlying Event and Ion Form Factors (soon) to be included
- Efforts are going towards achieving $\mathrm{NLO}_{\mathrm{QCD}}$ accuracy
- **How do we achieve a coherent picture between electro- and photo-production?**

Thank you for the attention!

References

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