Full event simulation of Photoproduction at NLO QCD in SHERPA

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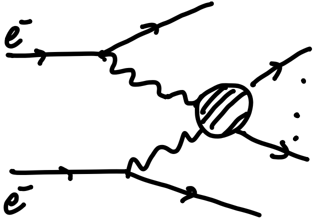
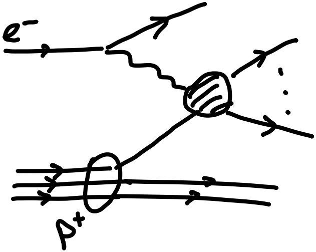
Outline

- Motivation
- Photoproduction simulation
- NLO calculation
- Validation
- Outlook: "All-inclusive" minimum bias
- Notes on LHC and EIC physics
- Conclusion

What is photoproduction?

Consider electromagnetic interaction in lepton-lepton and lepton-hadron collisions





Discern two types of electromagnetic interaction:

Electroproduction ⇒ high virtuality (→ e.g. DIS)
Photoproduction ⇒ low virtuality ⇒ "quasi-real photons"

Why do we need photoproduction?

1. Direct measurements, e.g.
    - quartic gauge couplings, electromagnetic fluxes, Onium-states
    - QCD observables
    - BSM signals, e.g. ALPs
2. Background measurement
    - Dominant contribution for QCD at e^+e^- and e^-p^+ colliders
    - complementary picture to DIS
3. Interplay of perturbative and non-perturbative QCD
    - evolution from real to virtual photons
    - parton content of photon and relation to vector meson states

see also talks by F. Staszewski and F. Krauss yesterday

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

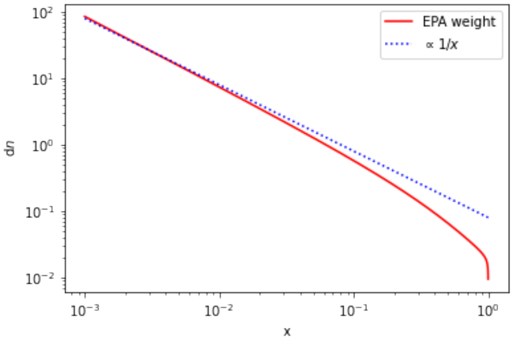
$\Rightarrow$ Q^2_{max} is process-/experiment-dependent

- form factors for protons implemented, too
- also extendible for ions (WIP)
- corresponds to elastic production modes

Plotting the spectrum for electrons

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

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



Photon PDFs

The total physical cross-section is given by [hep-ph/9702287]

$$d\sigma^{(\gamma H)}(P_\gamma, P_H) = d\sigma^{(\gamma H)}_{\text{point}}(P_\gamma, P_H) + d\sigma^{(\gamma H)}_{\text{hadr}}(P_\gamma, P_H)$$

with

$$\begin{aligned} d\sigma^{(\gamma H)}_{\text{point}}(P_\gamma, P_H) &= \sum_j \int dx f_j^{(H)}(x, \mu_F) d\hat{\sigma}_{\gamma j}(P_\gamma, xP_H, \alpha_S(\mu_R), \mu_R, \mu_F, \mu_\gamma) \\ d\sigma^{(\gamma H)}_{\text{hadr}}(P_\gamma, P_H) &= \sum_{ij} \int dx dy f_i^{(\gamma)}(x, \mu_\gamma) f_j^{(H)}(y, \mu'_F) \\ &\quad \times d\hat{\sigma}_{ij}(xP_\gamma, yP_H, \alpha_S(\mu'_R), \mu'_R, \mu'_F, \mu_\gamma) \end{aligned}$$

and the evolution obeys

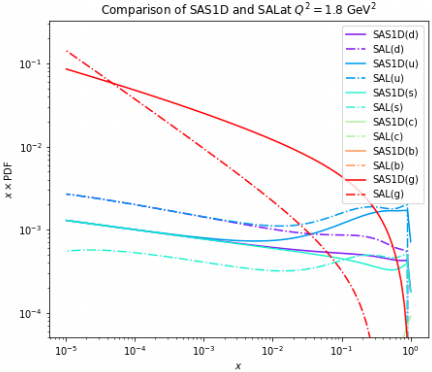
$$\frac{\partial f_i^{(\gamma)}}{\partial \log \mu^2} = \frac{\alpha_{\text{em}}}{2\pi} P_{i\gamma} + \frac{\alpha_S}{2\pi} \sum_j P_{ij} \otimes f_j^{(\gamma)}$$

Dependence on μ_γ only cancels in the physical cross-section!

Photon PDFs

Included in SHERPA: Glück-Reya-Vogt [4], Glück-Reya-Schienbein [5], Slominski-Abramowicz-Levy [6], Schuler-Sjöstrand [7, 8]

- need non-perturbative input from ρ^0, ω and ϕ
- GRS and SaS also for virtual photon
- many more available, but rather hard to find
- uncertainties of factor $\mathcal{O}(10)$
- *new fit to data possible?*



NLO matching

[hep-ph/9306337]

- collinear singularities of the photon can be subtracted
  $\Rightarrow$ cancel against PDF
- all the (factorisation) scales can be chosen equal
- MC@NLO matching possible under neglection of inhomogenous term in DGLAP and for PDFs with $\overline{\mathrm{MS}}$ scheme

$\Rightarrow$ update photoproduction phenomenology with the LHC machinery

(Note: $\gamma\gamma \rightarrow$ QED FS is already available in SHERPA)

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

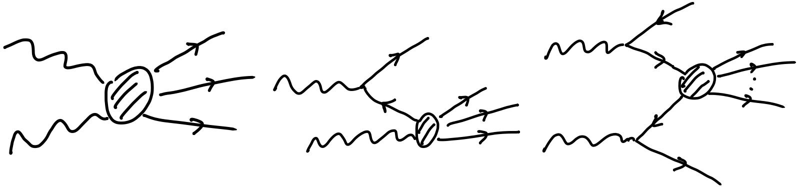
$$x_\gamma^\pm = \frac{\sum_{j=1,2} E^{(j)} \pm p_z^{(j)}}{\sum_{i\in\mathrm{hfs}} E^{(i)} \pm p_z^{(i)}} \quad (1)$$

Setup:

- MC@NLO (di-)jet production for LEP data and HERA data
- 1M weighted events including 7-point scale variation
- c- and b-quarks are massive
- 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 at LO – preliminary

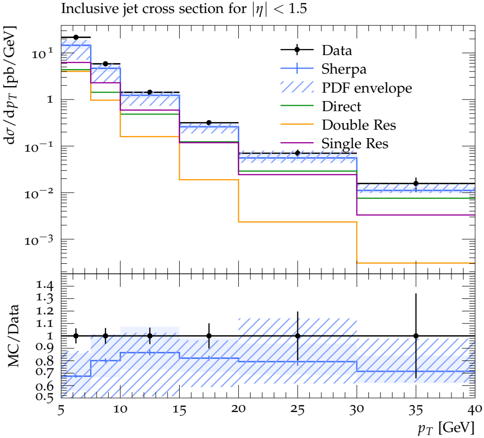


Figure: Distribution for jet transverse momentum p_T for LEP at $\sqrt{s} = 206$ GeV, averaged over all 10 PDF sets.

SHERPA calculations for LEP at MC@NLO – preliminary

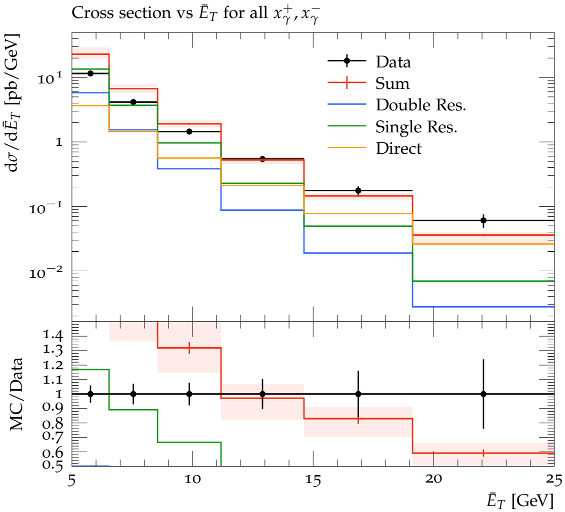


Figure: Distribution for average jet transverse energy $\bar{E}_T$ for LEP at $\sqrt{s} = 198$

SHERPA calculations for HERA at MC@NLO – preliminary

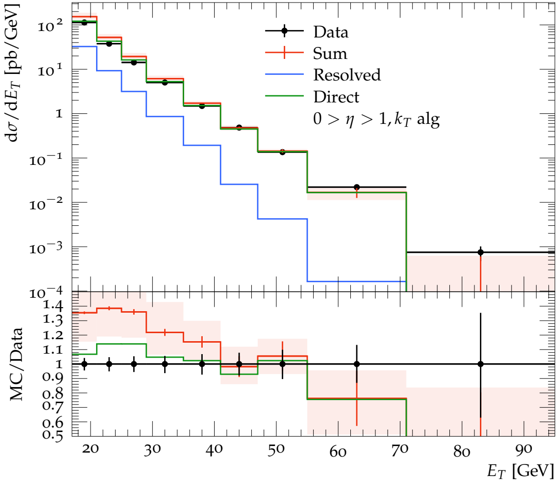


Figure: Distribution for jet transverse energy E_T for HERA.

Extension to inclusive modes

Multiple-parton interactions are non-negligible in photoproduction [Z.Phys.C 72 (1996) 637-646]

Implementation based on [Sjostrand:1987su]

But why stop there?

- EPA combinable with (non-)elastic LUXqed PDFs for semi-diffractive production
- Same framework can be used for Pomeron flux
- Factorise the multi-parton interaction model
- Allow MPIs for photon–photon, photon–proton and proton–proton interactions
- Model includes diffractive and elastic modes
- Tuning in progress

Arrive at a fullly-inclusive picture of the interaction in proton–proton and proton–electron collisions

Interesting starting point for study of non-perturbative collider physics

LHC and EIC physics

LHC:

- Pomeron flux allows for, e.g., Instanton search, c.f. [Eur.Phys.J.C 83 (2023) 1, 35]
- Study of forward physics without Sudakov on impact parameter

EIC:

- Step towards complete description of events over full Q^2 region
- diffractive and semi-inclusive production would need form factors for proton diffraction and $\gamma \to V$ transition probability

Conclusion

- wealth of physics there to explore
- Simulation in SHERPA validated against LEP and HERA data
- Uncertainties in QCD observables dominated by photon PDFs
- $\mathrm{NLO}_{\mathrm{QCD}}$ matching achieved, validation is WIP
- Generalized mulitple interaction model will allow new perspective on inclusive measurements

Step towards updating photon physics onto state-of-the-art machinery

Thank you for the attention!

[1] C. F. v. Weizsäcker. 'Ausstrahlung bei Stössen sehr schneller Elektronen'. In: *Z. Phys.* 88.9-10 (1934), pp. 612–625.

[2] E. J. Williams. 'Nature of the High Energy Particles of Penetrating Radiation and Status of Ionization and Radiation Formulae'. In: *Phys. Rev.* 45.10 (May 1934), pp. 729–730.

[3] V. M. Budnev et al. 'The two-photon particle production mechanism. Physical problems. Applications. Equivalent photon approximation'. In: *Physics Reports* 15.4 (Jan. 1975), pp. 181–282.

[4] M. Glück, E. Reya and A. Vogt. 'Photonic parton distributions'. In: *Phys. Rev. D* 46.5 (Sept. 1992), pp. 1973–1979.

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[6] W. Slominski, H. Abramowicz and A. Levy. 'NLO photon parton parametrization using ee and ep data'. In: *Eur. Phys. J. C* 45 (Apr. 2006), pp. 633–641.

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[8] Gerhard A. Schuler and Torbjörn Sjöstrand. 'Parton Distributions of the Virtual Photon'. In: *Phys. Lett. B* 376 (Jan. 1996), pp. 193–200.

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[10] T. H. Bauer et al. 'The hadronic properties of the photon in high-energy interactions'. In: *Reviews of Modern Physics* 50.2 (Apr. 1978). [Erratum: Rev.Mod.Phys. 51, 407 (1979)], pp. 261–436.

[11] J. M. Butterworth, J. R. Forshaw and M. H. Seymour. 'Multiparton Interactions in Photoproduction at HERA'. In: *Z. Phys. C* 72 (Jan. 1996), pp. 637–646.

Backup

Extension to virtual photons: VMD-type model [9, 10]

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

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

- leptonic $\rightarrow$ 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)

The phase space setup

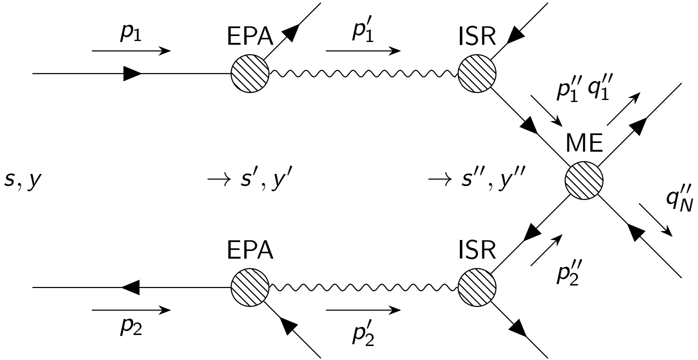

Figure: Schematic sketch of the phase space mappings between the Equivalent Photon Approximation (EPA) and the Initial State Radiation (ISR), and the Matrix Element (ME).

SHERPA calculations for LEP – preliminary

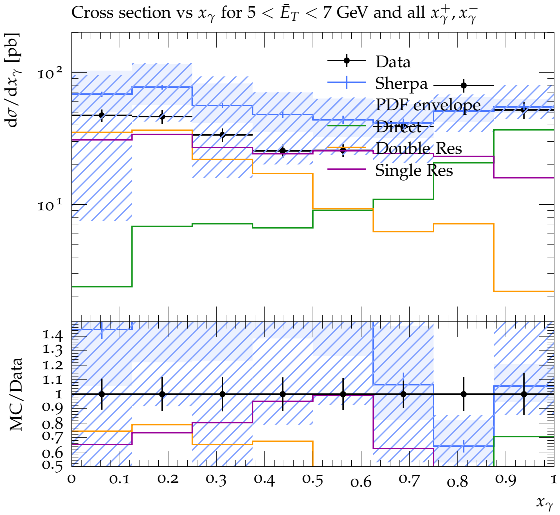

Figure: Distributions x_γ for average transverse jet energy

SHERPA calculations for LEP

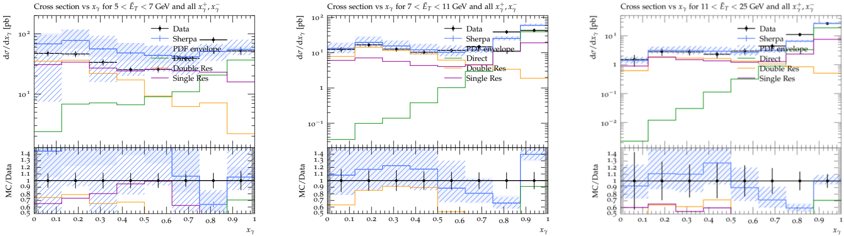

Figure: Distributions $x_\gamma^\pm$, collectively denoted as x_γ in different bins of average transverse jet energy: $\bar{E}_T \in [5\,\mathrm{GeV}, 7\,\mathrm{GeV}]$ (left), $\bar{E}_T \in [7\,\mathrm{GeV}, 11\,\mathrm{GeV}]$ (middle), $\bar{E}_T \in [11\,\mathrm{GeV}, 25\,\mathrm{GeV}]$ (right). Results of the SHERPA simulation are compared with results from OPAL at an e^-e^+ c.m.-energy of 198 GeV.

SHERPA calculations for HERA at LO – preliminary

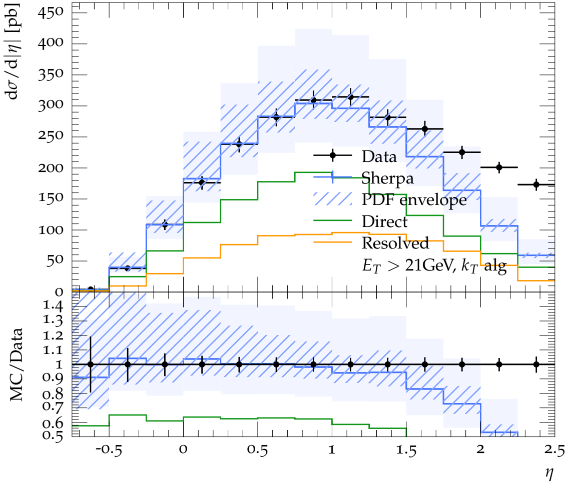

Figure: Distribution for jet pseudo-rapidity η for HERA. The drop at $\eta > 1.5$ is