Photoproduction: towards NLO accuracy

Electrons for the LHC workshop @ IJCLab, Orsay

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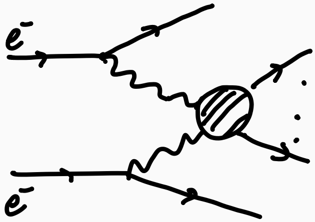
IPPP, Durham University

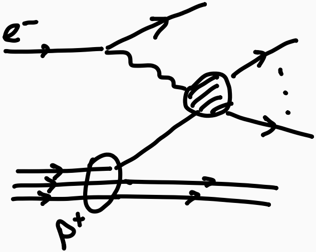
Outline

Intro and motivation

What is photoproduction?

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





Discern two types of electromagnetic interaction:

Electroproduction $\Rightarrow$ high virtuality ($\rightarrow$ e.g. DIS)
Photoproduction $\Rightarrow$ low virtuality $\Rightarrow$ "quasi-real photons"

Why do we need photoproduction?

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

Significant QCD background
$\Rightarrow$ **improves signal-to-background ratio**

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

ee, *eA*, *AA* collisions show photoproduction, too
$\Rightarrow$ **Create understanding for different colliders**

(See also talks by Felix Ringer & Paul Newman)

Components of photoproduction simulation

The Weizsäcker-Williams formula [1]

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 $d\sigma_{eX} = \sigma_{\gamma X}(Q^2 = 0)dn$, with dn the photon spectrum

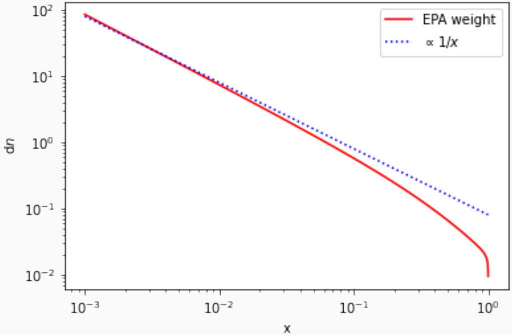
$\Rightarrow$ Calculate dn from DIS matrix element in approximation $Q^2 \to 0$.

[1]formulated in 1934 [1, 2], see [3] for review

Plotting the spectrum

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

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

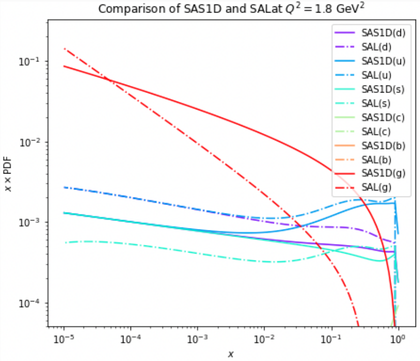


Photon PDFs

(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

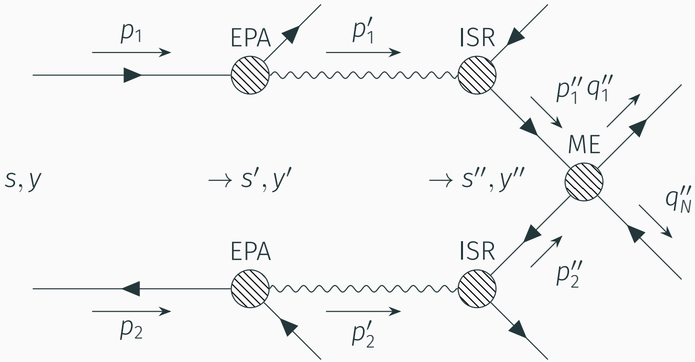


Figure 1: Schematic sketch of the phase space mappings between the Equivalent Photon Approximation (EPA) and the Initial State Radiation (ISR), and the Matrix Element (ME).

Validation

Results: 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

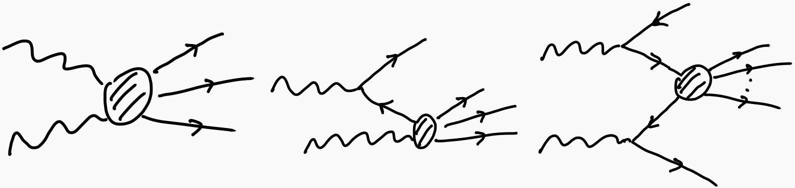
$$x_\gamma^\pm = \frac{\sum\limits_{j=1,2} E^{(j)} \pm p_z^{(j)}}{\sum\limits_{i\in\mathrm{hfs}} E^{(i)} \pm p_z^{(i)}} \tag{2}$$

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 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

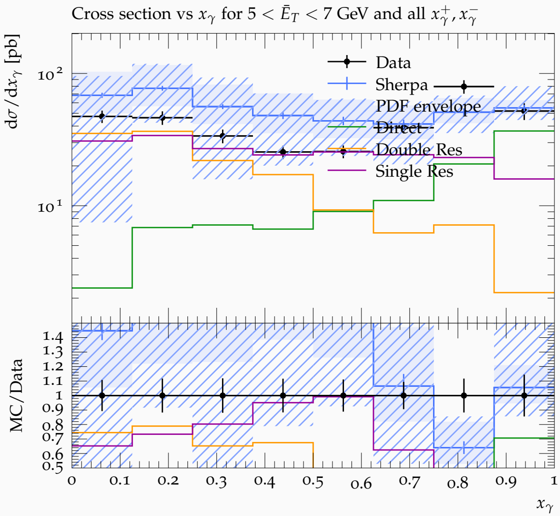


Figure 2: Distributions x_γ for average transverse jet energy $\bar{E}_T \in [11\,\mathrm{GeV}, 25\,\mathrm{GeV}]$ at $\sqrt{s} = 198$ GeV.

Sherpa calculations for LEP – preliminary

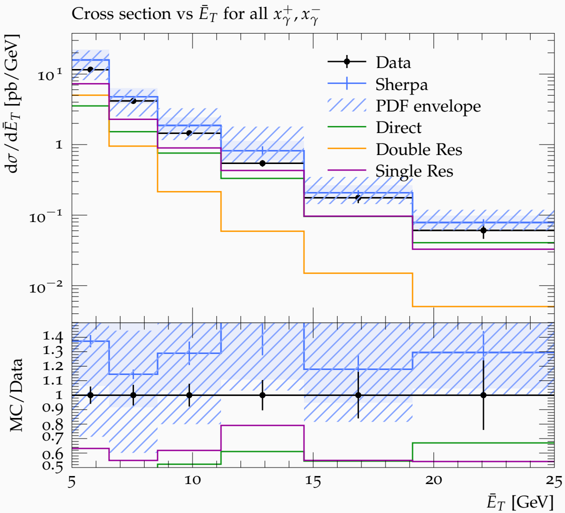


Figure 3: Distribution for average jet transverse energy $\bar{E}_T$ for LEP at $\sqrt{s} = 198$ GeV.

Sherpa calculations for LEP – preliminary

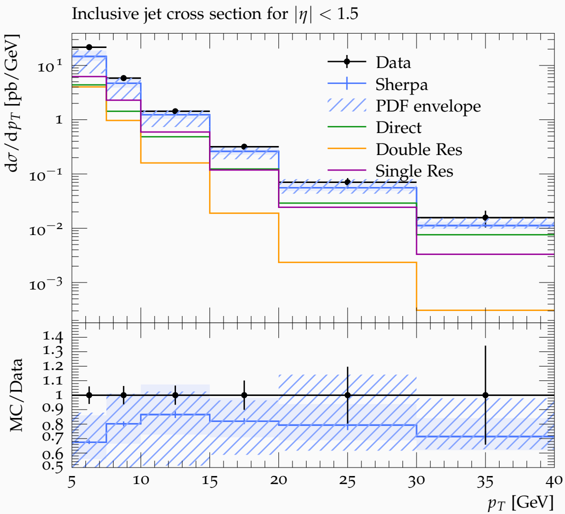


Figure 4: Distribution for jet transverse momentum p_T for LEP at $\sqrt{s} = 206$ GeV.

Sherpa calculations for HERA at LO – preliminary

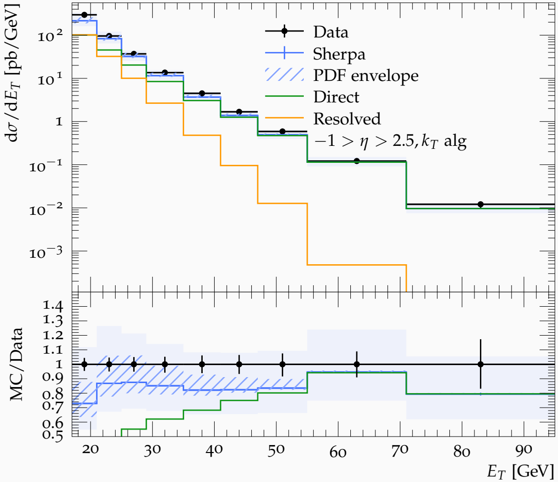


Figure 5: Distribution for jet transverse energy E_T for HERA2.

Sherpa calculations for HERA at LO – preliminary

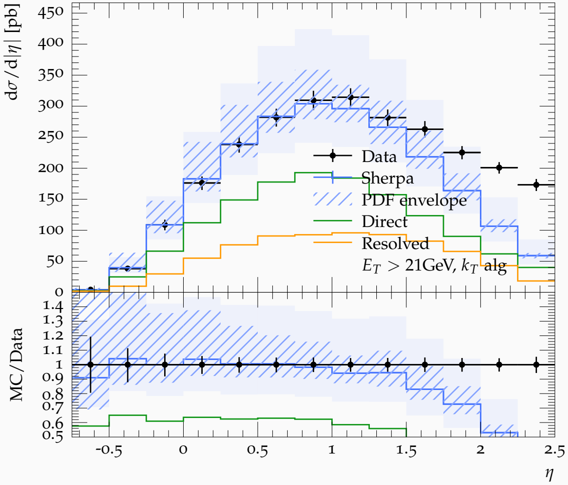


Figure 6: Distribution for jet pseudo-rapidity η for HERA2. The drop at $\eta > 1.5$ is due to the missing underlying event [9].

Discussion of going NLO

Sherpa calculations for LEP at MC@NLO accuracy – preliminary

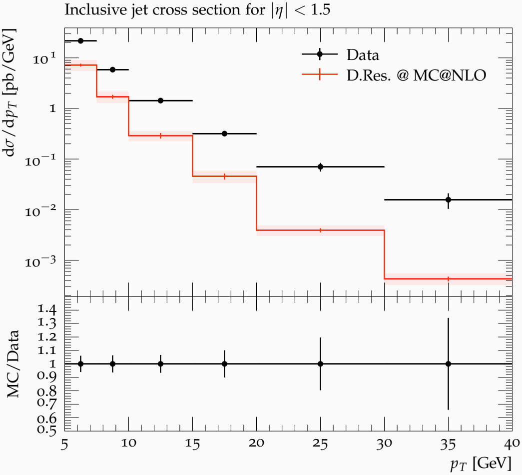


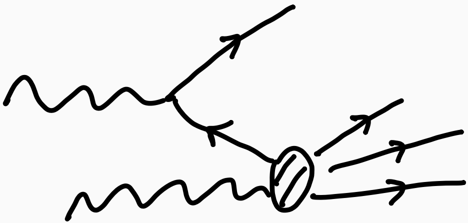
Figure 7: Distribution for jet transverse momentum p_T for LEP at $\sqrt{s} = 206$ GeV. Sherpa simulation is at NLO QCD accuracy using MC@NLO where both photons are resolved.

The difficulty of defining NLO

Photons in the initial state show collinear divergences

$\Rightarrow$ introduces ambiguity and double-counting

Example:



Is it the real correction to $\gamma P^{+} - > X$? Or remnant of the PDF?

The difficulty of defining NLO

Cancel the divergences with QED subtraction terms

Pros:

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

Cons:

- needs QED shower to allow matching in MC@NLO
- is very involved
- needs PDF to construct underlying Born process

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

Next steps and outlook

Next steps

1. **Multiple-parton interaction (MPI)**

The data (and literature [9]) suggests that multi-parton interaction are non-negligible!

$\Rightarrow$ need to include an estimator for the number of multiple interaction

2. **Extend for p and A**

$\Rightarrow$ Needs form factors for each nucleus

3. **$Q^2 > 0$ and non-collinear kinematics**

leave the Weizsäcker-Williams $Q^2 \to 0$ approximation

$\Rightarrow$ extend VMD model?

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:

- 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 $\rightarrow$ hadron-hadron physics

(Q^2 – virtuality)

Conclusion

Conclusion

- Photoproduction is an important ingredient for lepton–lepton collider phenomenology, especially for QCD observables
- Simulation in Sherpa validated against LEP and HERA data
- Uncertainties dominated by photon PDFs
- Deviations from data can be attributed to missing MPI model for the photon
- Extension to NLO QCD needs some attention, but is feasible

Thank you for the attention!

References

[1] C. F. v. Weizsäcker. ‘Ausstrahlung bei Stößen sehr schneller Elektronen’. In: *Zeitschrift für Physik* 88.9-10 (Sept. 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: *Physical Review* 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.

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[8] Gerhard A. Schuler and Torbjörn Sjöstrand. 'Parton Distributions of the Virtual Photon'. In: *Phys.Lett.B376:193-200,1996* (Jan. 1996).

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