Event simulation of ep collisions: a theory introduction to electro- vs photoproduction

Jefferson Lab Theory seminar

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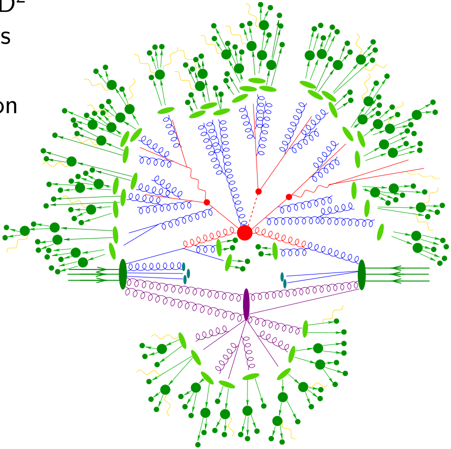
Precision QCD vs event generators

Anatomy of MC simulations

- **Hard interaction**
  LO, NLO QCD/EW[1], NNLO QCD[2]
  Generic matrix-element generators
- **Radiative corrections**
  Parton Showers, YFS resummation
- **Hadronization** & **Decays**
  Cluster / String model
  Phase space or EFTs + YFS



Comparison to fixed order (FO)

- **Hard interaction**
  Lower precision than FO
- **Radiative corrections**
  Resummed & matched to FO
- **Hadronization** & **Decays**
  Not accessible at FO

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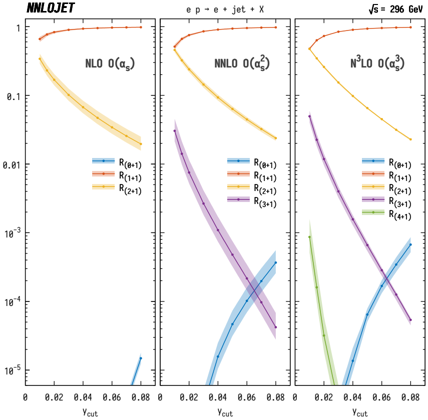
[1]via interfaces to 1-loop generators
[2]for selected processes

Precision QCD calculations available to date

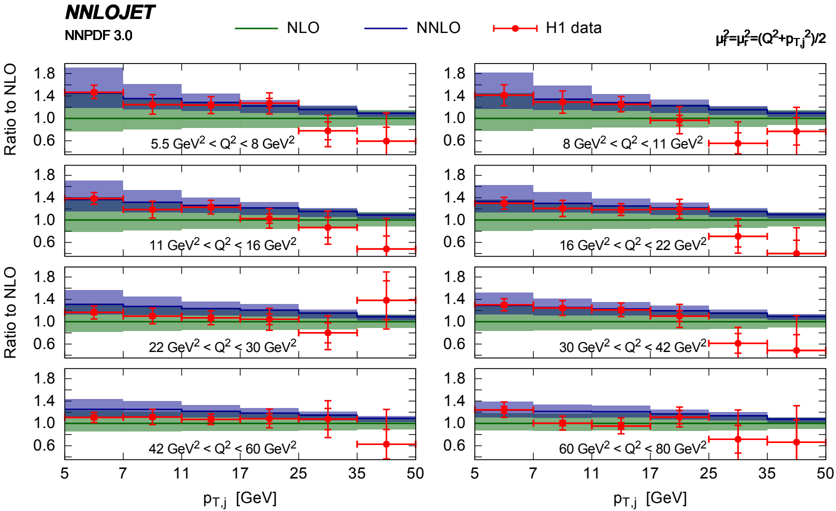
- Inclusive DIS at NLO QCD
  [PRD18(1978)3998]
  [NPB143(1978)521]
  [NPB184(1981)225]
- ... at N^{2}LO QCD [NPB383(1992)525],
  [PLB297(1992)377]
  [hep-ph/9912355]
- ... at N^{3}LO QCD [hep-ph/0504242],
  [NPB813(2009)220-258]
- Di-jet production at NLO QCD
  [hep-ph/9511448]
  [hep-ph/9710244]
  [hep-ph/0104315]
- ... at N^{2}LO QCD
  [arXiv:1607.04921]
  [arXiv:1606.03991]
  [arXiv:1703.05977]
- DIS at N^{3}LO QCD, fully exclusive
  [JHEP 05 (2018) 209]

[JHEP 05 (2018) 209]



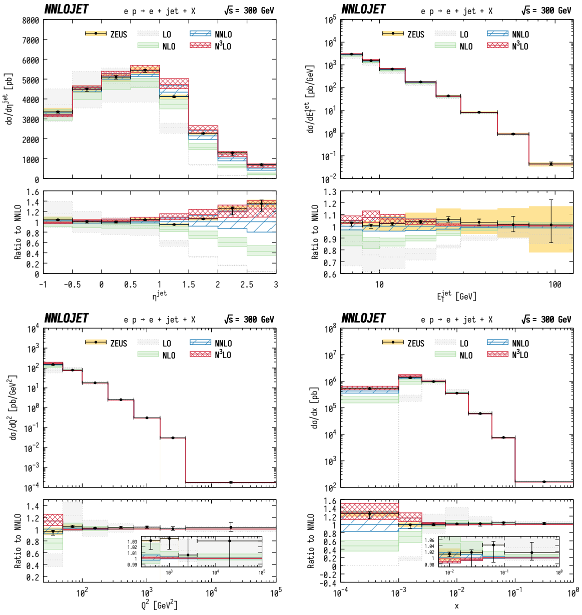
Highest precision for di-jet production

[Currie, Gehrmann, Huss, Niehues] [arXiv:1703.05977]



- H1 data from arXiv:1611.03421

Highest precision for inclusive DIS



[arXiv:1803.09973]

- N^3LO QCD, fully differential

  Projection-to-Born Antenna subtraction

- ZEUS data from hep-ex/0502029

$Q^2 > 25\ \mathrm{GeV}^2$

$y > 0.04$

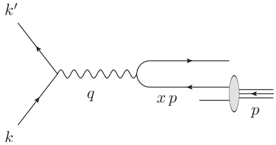
$E'_e > 10\ \mathrm{GeV}$

$E_{T,j} > 6\ \mathrm{GeV}$

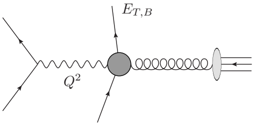
$-1 < \eta_j < 3$

Peculiarities of DIS

- Leading order $e^{\pm}p$ - scattering in collinear factorization
  - No jets, sole kinematical variables are
    $$Q^2 = q^2 = (k' - k)^2 \text{ and } x = \frac{Q^2}{2\, q \cdot p}$$
  - Hadronic cm energy
    $W = Q\sqrt{(1-x)/x}$

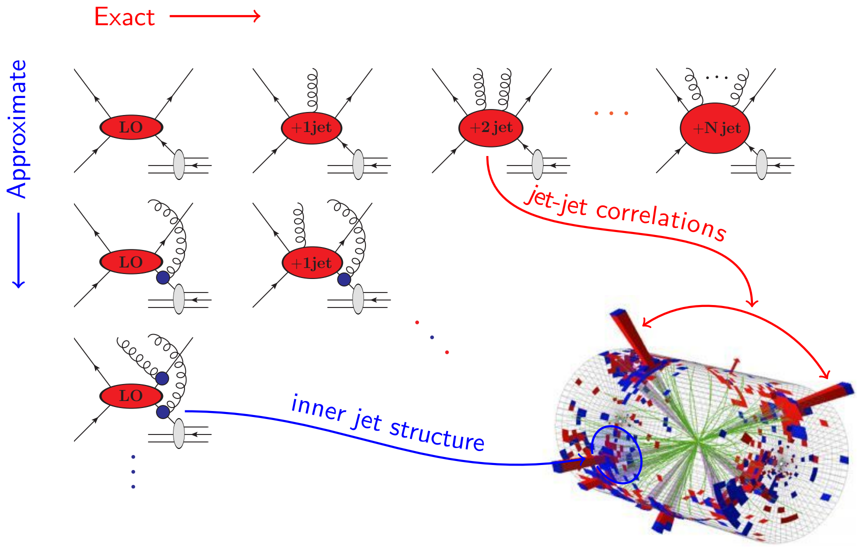


- QCD dynamics at higher orders



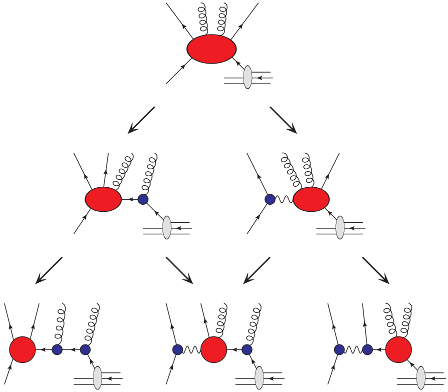
  - Multiple scales, e.g. $E^2_{T,B}$
  - $e^{\pm} q \to e^{\pm} q$ if $E^2_{T,B} \lesssim Q^2$
    $\gamma^* g \to jets$ if $Q^2 \lesssim E^2_{T,B}$
- What makes DIS different from $e^+e^- \to jj$ and $pp \to e^+e^-$ is that the virtuality of the exchanged photon tends to be close to zero
- Also the case in low-mass Drell-Yan $pp \to e^+e^-$,
  but recent experimental studies usually focus on $m_{l\bar{l}} \approx m_Z$

Merging fixed-order calculations and parton-showers



Merging fixed-order calculations and parton-showers

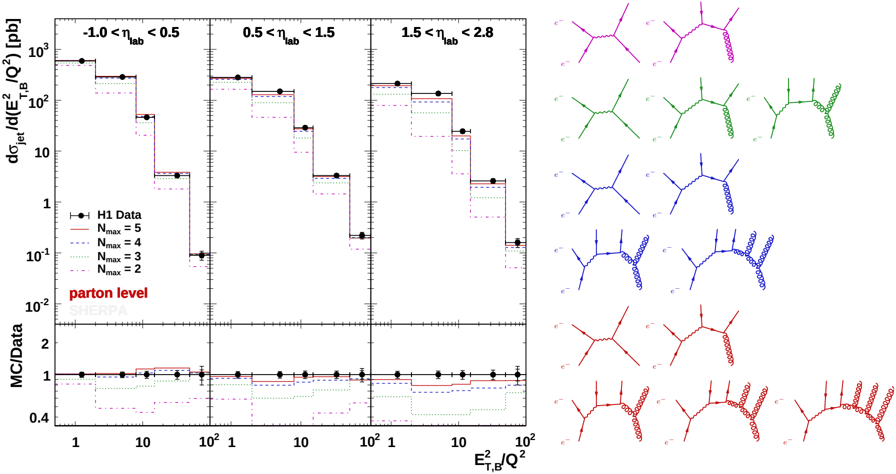
- QCD dynamics of the multi-jet final state must be reflected accurately when identifying parton-shower branching history
  [arXiv:0912.3715]
  - $e^{\pm} q \to e^{\pm} q$ if $E_{T,B}^2 \lesssim Q^2$
  - $\gamma^* g \to$ jets if $Q^2 \lesssim E_{T,B}^2$
  - $qg \to$ jets if $Q^2 \ll E_{T,B}^2$
- Similar to taking direct and fragmentation component into account in hard photon production at hadron colliders
  [arXiv:0912.3501]



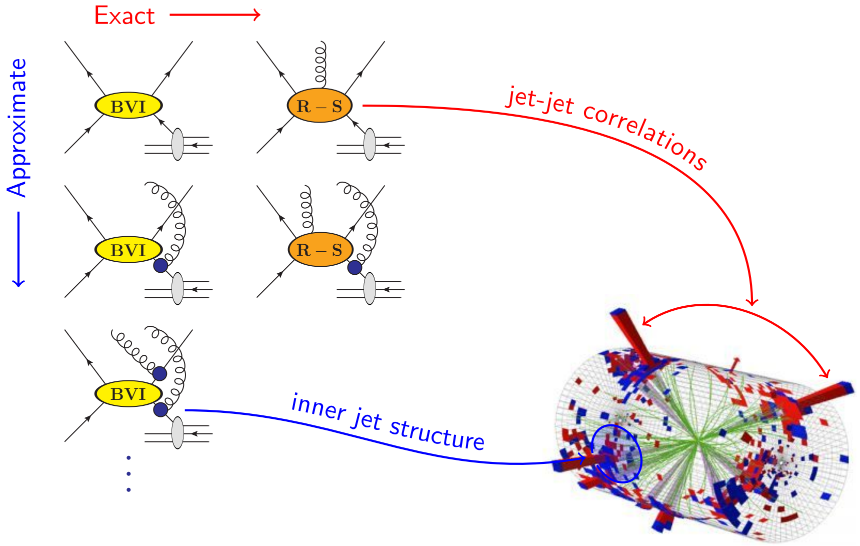
Comparison to HERA data

[arXiv:0912.3715]

Variation of maximum matrix-element multiplicity, $N_{\max}$



Matching fixed-order NLO calculations to parton-showers



Matching fixed-order NLO calculations to parton-showers

Two possible ways to match NLO calculations and parton showers

MC@NLO

[Frixione,Webber] [JHEP 06 (2002) 029]

- Use parton-shower splitting kernel as infrared subtraction term
- Multiply LO event weight by Born-local K-factor including integrated subtraction term and virtual corrections
- Add hard remainder function consisting of subtracted real-emission correction

POWHEG

[Nason] [JHEP 11 (2004) 040]

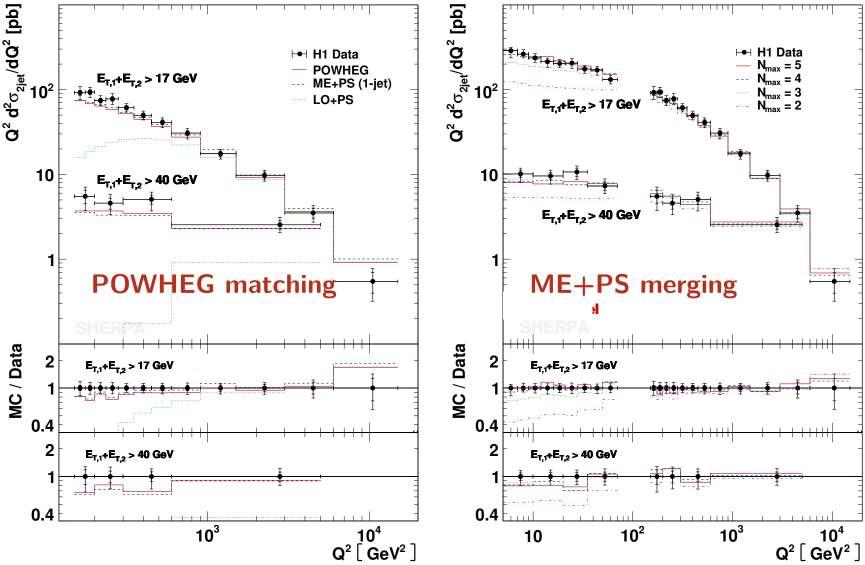
- Use matrix-element corrections to replace parton-shower splitting kernel by full real-emission matrix element in first shower branching
- Multiply LO event weight by Born-local NLO K-factor (integrated over real corrections that can be mapped to Born according to parton-shower kinematics)

Both cases: Beware of sub-leading color terms and spin correlations!

Matching vs Merging

[Krauss,Schönherr,Siegert,Höche] [arXiv:1008.5399]

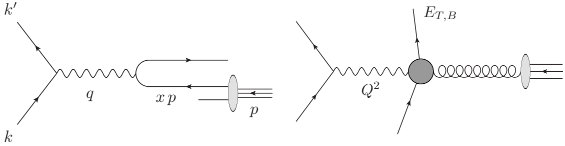
[Carli,Gehrmann,Höche] [arXiv:0912.3715]



Matching at NNLO accuracy

[Kuttimalai,Li,SH] [Phys.Rev.D 98 (2018) 11]

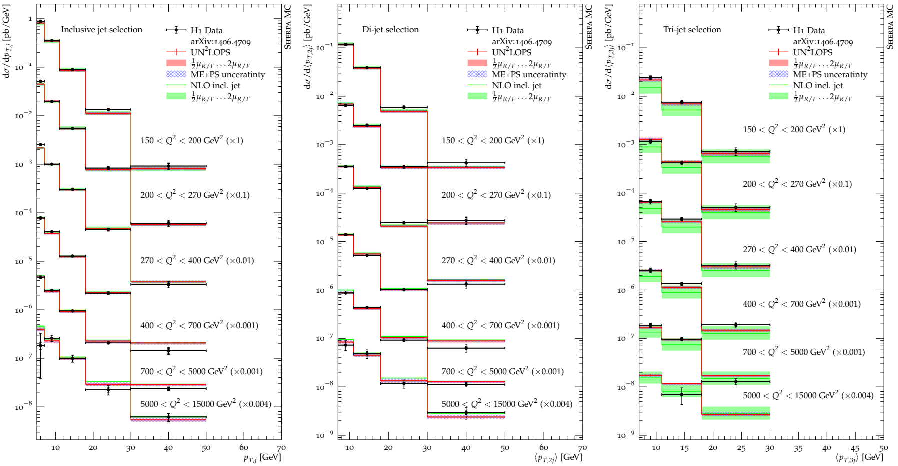
- New Sherpa module for computation of inclusive DIS at NNLO QCD
- Projection-to-Born method for fully differential fixed order predictions
  [Zijlstra,vanNeerven] [NPB383(1992)525], [PLB297(1992)377] [Moch,Vermaseren,Vogt] [hep-ph/0504242]
  [Bern,Dixon,Kosower] [hep-ph/9708239], [Berger et al.] [arXiv:0803.4180]
- UN^{2}LOPS matching to parton shower for particle-level simulations
  [Lönnblad,Prestel] [arXiv:1211.7278], [Li,Prestel,Höche] [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]

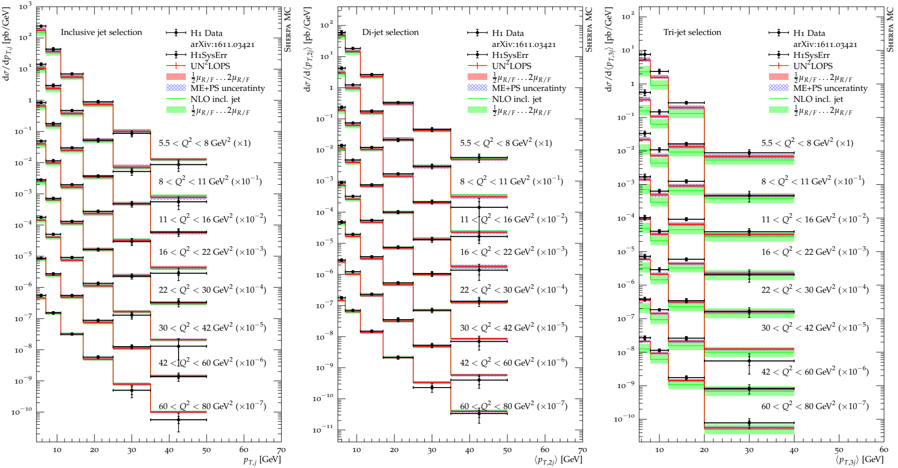
NNLO particle-level simulation vs. H1 high-Q^2 data

[Kuttimalai,Li,Höche] [arXiv:1809.04192]



NNLO particle-level simulation vs. H1 low-Q^2 data

[Kuttimalai,Li,Höche] [arXiv:1809.04192]



DIS is not the end of the story

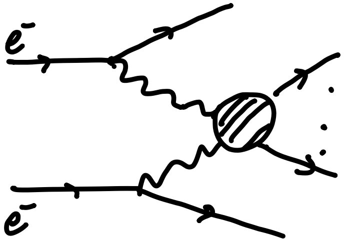
It works well in the perturbative regime of high-Q^2, but ...

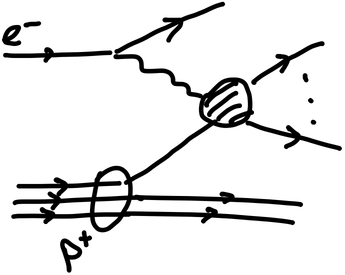
- misses non-perturbative effects
- breaks down at low-Q^2 and in the forward region
- scale hierarchies need special care

This regime needs separate modelling
at NLO accuracy

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?

For jet production at e^+e^- and ep, but also

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

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

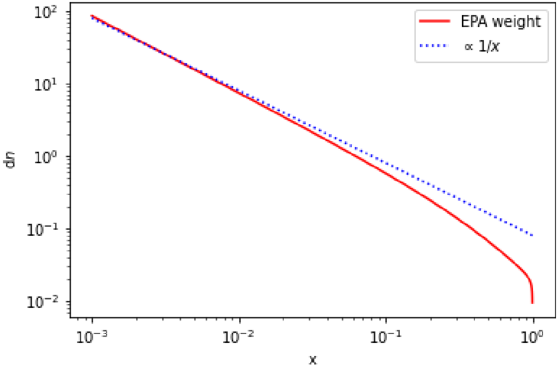
$\Rightarrow$ Q^2_{max} is process-/experiment-dependent

- 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

$$d\sigma^{(\gamma H)}_{\text{point}}(P_\gamma, P_H) = \sum_j \int dx f_j^{(H)}(x, \mu_F) d\hat{\sigma}_{\gamma j}(P_\gamma, xP_H, \alpha_S(\mu_R), \mu_R, \mu_F, \mu_\gamma)$$

$$d\sigma^{(\gamma H)}_{\text{hadr}}(P_\gamma, P_H) = \sum_{ij} \int dx dy f_i^{(\gamma)}(x, \mu_\gamma) f_j^{(H)}(y, \mu'_F)$$

$$\times\, d\hat{\sigma}_{ij}(xP_\gamma, yP_H, \alpha_S(\mu'_R), \mu'_R, \mu'_F, \mu_\gamma)$$

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

Solution must look like

$$f^\gamma(x, Q^2) = f^\gamma_{pl}(x, Q^2) + f^\gamma_{\mathrm{had}}(x, Q^2)$$

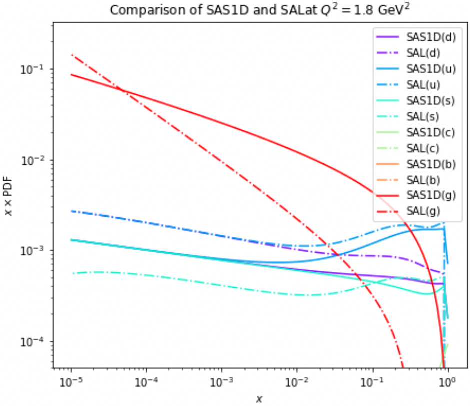
Ansatz

choose Q_0 with $f^\gamma_{pl}(x, Q_0^2) \equiv 0$
set f^γ_{had} from non-perturbative input, c.f. VMD
evolve up to higher scales

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: $\gamma\gamma \to$ 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

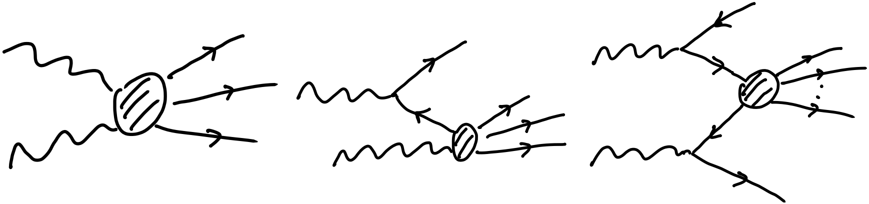
$$x_\gamma^\pm = \frac{\sum_{j=1,2} E^{(j)} \pm p_z^{(j)}}{\sum_{i\in\text{hfs}} E^{(i)} \pm p_z^{(i)}} \tag{1}$$

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

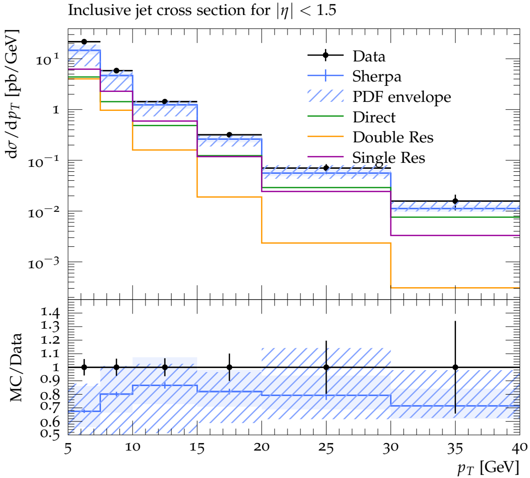


Figure: Distribution for jet transverse momentum p_T for LEP at $\sqrt{s} = 206$ GeV, averaged over all 10 PDF sets.

SHERPA calculations for LEP at MC@NLO – preliminary

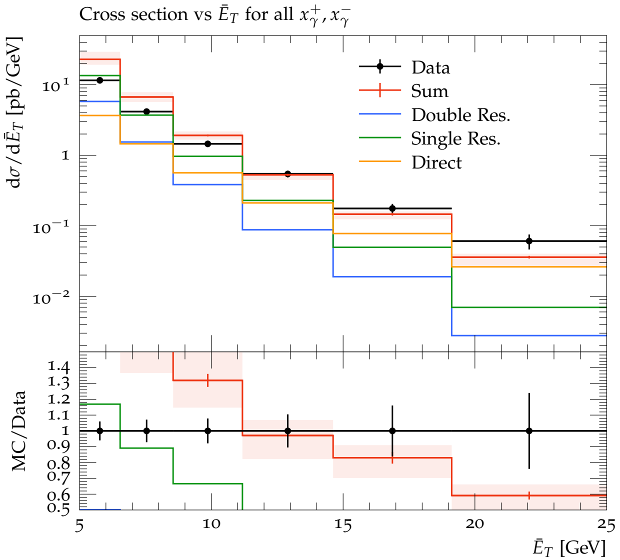


Figure: Distribution for average jet transverse energy $\bar{E}_T$ for LEP at $\sqrt{s} = 198$ GeV.

SHERPA calculations for HERA at MC@NLO – preliminary

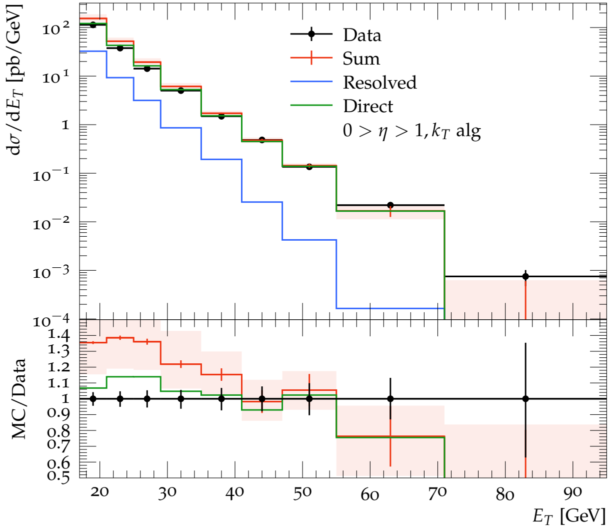


Figure: Distribution for jet transverse energy E_T for HERA.

Extension to inclusive modes

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

Implementation based on [Phys.Rev.D 36 (1987) 2019]

But why stop there?

- EPA combinable with LUXqed PDFs for inclusive 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

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 transition into ρ, ω or ϕ and non-perturbative hadron physics

(Q^2 – virtuality)

Parton content needs more study: resonances when evolving virtuality?

Conclusion

- ep show an interesting physics case
- electroproduction, i.e. DIS, is purely perturbative and well understood
- photoproduction is the complementary mode for jet production
- ...however it shows interesting interplay with non-perturbative physics
- Simulation in SHERPA validated against LEP and HERA data
- Uncertainties in QCD observables dominated by photon PDFs
- $\mathrm{NLO}_{\mathrm{QCD}}$ matching, validation is WIP
- interpolation between electro- and photoproduction important unsolved puzzle

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.

[5] M. Glück, E. Reya, and I. Schienbein. "Radiatively Generated Parton Distributions of Real and Virtual Photons". In: *Phys.Rev.D60:054019,1999; Erratum-ibid.D62:019902,2000* 60 (Mar. 1999).

[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.

[7] Gerhard A. Schuler and Torbjörn Sjöstrand. “Low- and high-mass components of the photon distribution functions”. In: *Z. Phys. C* 68.4 (Dec. 1995), pp. 607–623.

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

[9] Gerhard A. Schuler and Torbjörn Sjöstrand. “Towards a Complete Description of High-Energy Photoproduction”. In: *Nuclear Physics B* 407.3 (Oct. 1993), pp. 539–605.

[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

SHERPA calculations for LEP – preliminary

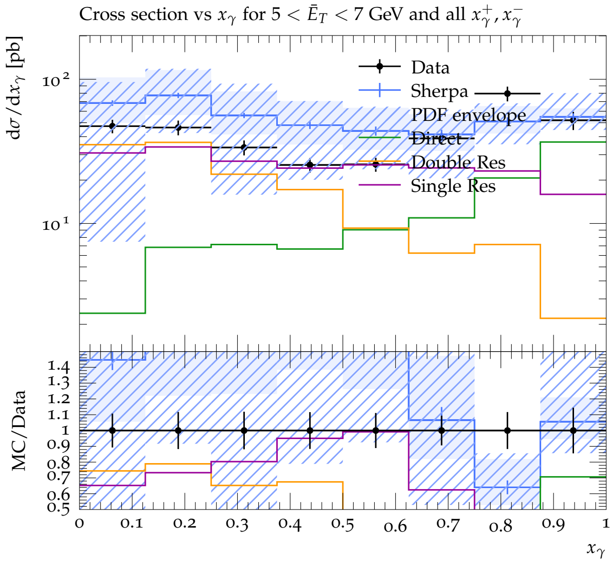


Figure: Distributions x_γ for average transverse jet energy $\bar{E}_T \in [11\,\mathrm{GeV}, 25\,\mathrm{GeV}]$ at $\sqrt{s} = 198$ GeV.

SHERPA calculations for LEP

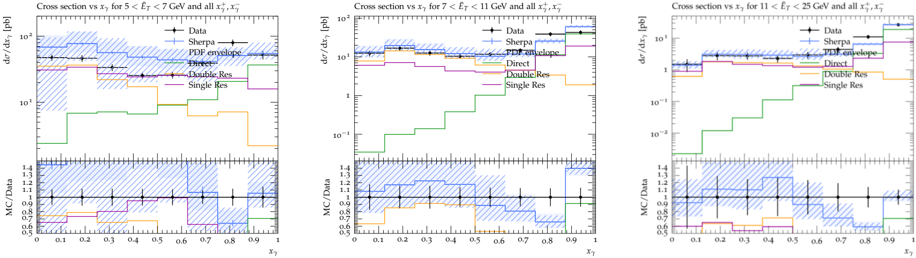


Figure: Distributions $x_\gamma^\pm$, collectively denoted as x_γ in different bins of average transverse jet energy: $\bar{E}_T \in [5\,\mathrm{GeV}, 7\,\mathrm{GeV}]$ (left), $\bar{E}_T \in [7\,\mathrm{GeV}, 11\,\mathrm{GeV}]$ (middle), $\bar{E}_T \in [11\,\mathrm{GeV}, 25\,\mathrm{GeV}]$ (right). 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

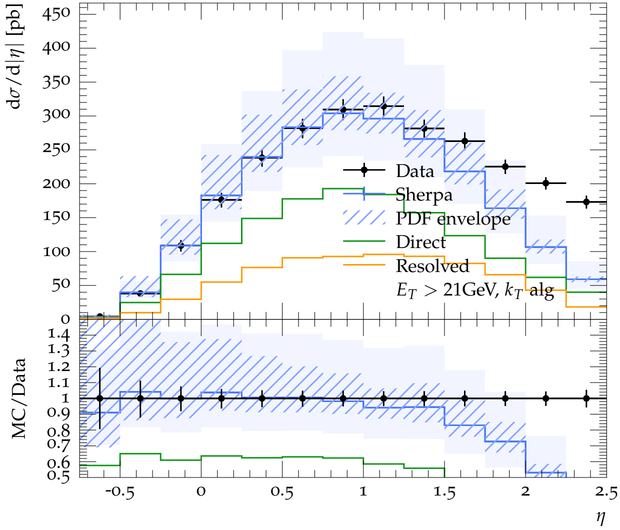


Figure: Distribution for jet pseudo-rapidity η for HERA. The drop at $\eta > 1.5$ is due to the missing underlying event [11].