# Radiative corrections in MC Event Generators
# From QCD to QED


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# Introduction and disclaimer

**This talk is inspired by work in the LHC event generator community**

- Much of it will focus on QCD radiative corrections
- It will summarize a unified approach to QCD+QED evolution . . .
- . . . and a technique to match this resummation to fixed-order NLO
- There will be some results on QED radiative corrections in ep also
  These are courtesy of Stefan Prestel, who is the expert on this

**The aim is to show how existing methods and codes can be useful**

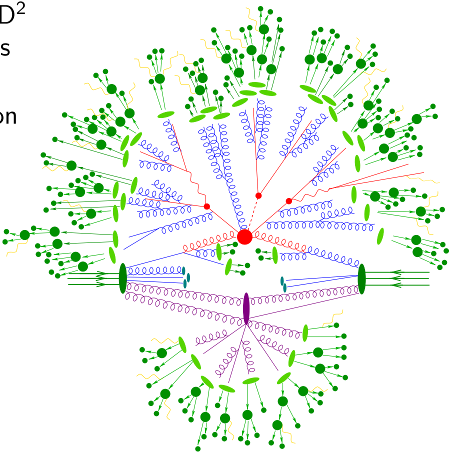
- Computational techniques developed for the LHC are *generic*
  - QCD+QED resummation in the form of parton showers
  - Matching to fixed-order calculations at NLO
  - Incorporation of NLO electroweak corrections
  - No difference between neutral and charged current
- Tools developed for the LHC are *highly automated*
  - Parton showers are validated against $e^+e^-$, DIS and pp data
  - Matching to fixed order NLO is now a push-button operation
  - One-loop corrections are computed fully automatically

# Conceptual design of general-purpose event generators

[Buckley at al.] arXiv:1101.2599

**Modular structure of physics simulation**

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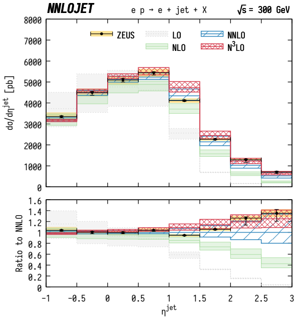
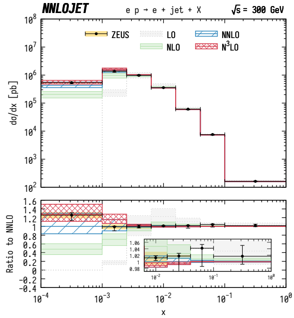
[1]via interfaces to 1-loop generators
[2]for selected processes

# QCD radiative corrections in DIS

# Precision QCD calculations

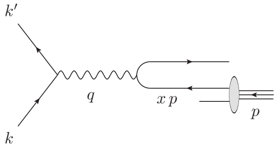
- Inclusive DIS at NLO QCD
  [Bardeen,Buras,Duke,Muta] PRD18(1978)3998
  [Altarelli,Ellis,Martinelli] NPB143(1978)521
  [Humpert,van Neerven] NPB184(1981)225
- ... at N$^2$LO QCD [Zijlstra,vanNeerven]
  NPB383(1992)525, PLB297(1992)377
  [Moch,Vermaseren] hep-ph/9912355
- ... at N$^3$LO QCD [Moch,Vermaseren,Vogt]
  hep-ph/0504242, arXiv:0812.4168
- Di-jet production at NLO QCD
  [Mirkes,Zeppenfeld] hep-ph/9511448
  [Graudenz] hep-ph/9710244
  [Nagy,Trocsanyi] hep-ph/0104315
- ... at N$^2$LO QCD
  [Abelof,Boughezal,Liu,Petriello] arXiv:1607.04921
  [Currie,Gehrmann,Niehues] arXiv:1606.03991
  [Currie,Gehrmann,Huss,Niehues] arXiv:1703.05977
- DIS at N$^3$LO QCD, fully exclusive
  [Currie,Gehrmann,Glover,Huss,Niehues,Vogt]
  arXiv:1803.09973



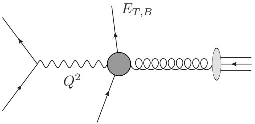



# Peculiarities of DIS

- Leading order $e^{\pm}p$ - scattering in collinear factorization
  - Only one scale! Kinematical variables:
    $$Q^2 = q^2 = (k' - k)^2 \text{ and } x = \frac{Q^2}{2\,q \cdot p}$$
  - Hadronic cm energy $W = Q\sqrt{(1-x)/x}$



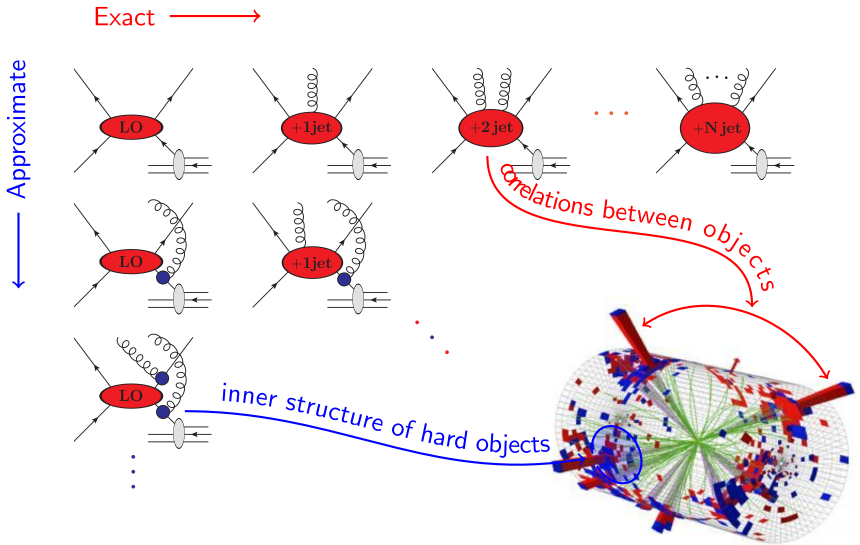

- Dynamics at higher orders




  - Multiple scales, e.g. $E_{T,B}^2$
  - $e^{\pm}q \to e^{\pm}q$ if $E_{T,B}^2 \lesssim Q^2$
    $\gamma^* g \to jets$ if $Q^2 \lesssim E_{T,B}^2$

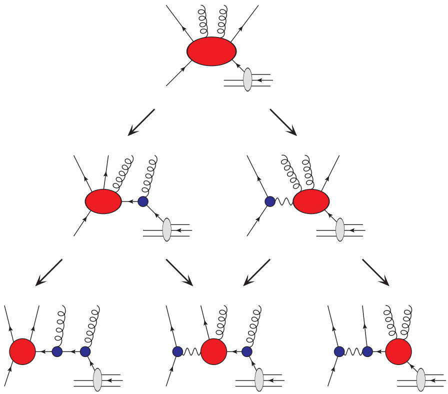
- What makes DIS different from $e^+e^- \to jj$ and $pp \to e^+e^-$ is that the virtuality of the exchanged photon tends to be close to zero
- This necessitates are more sophisticated aproach to radiative corrections which is not specific to QCD but applies to all massless gauge theories

# Combining fixed-order calculations and resummation



# Combining fixed-order calculations and resummation

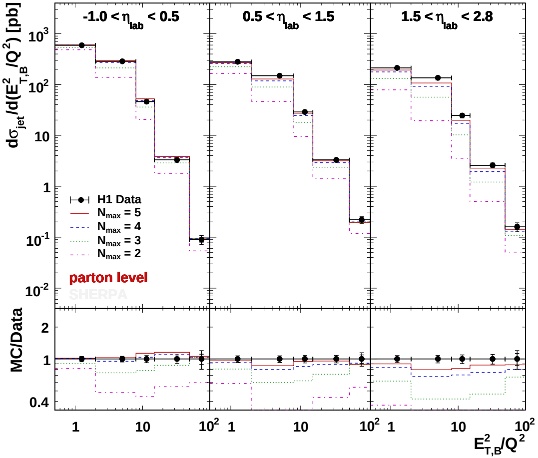
- Dynamics of the QCD multi-jet final state must be reflected accurately when matching fixed-order to the resummation
  [Carli,Gehrmann,SH] arXiv:0912.3715
  - $e^{\pm}q \to e^{\pm}q$ if $E_{T,B}^2 \lesssim Q^2$
  - $\gamma^* g \to$ jets if $Q^2 \lesssim E_{T,B}^2$
  - $qg \to$ jets if $Q^2 \ll E_{T,B}^2$
- Similar to taking direct and fragmentation component into account in hard photon production at hadron colliders
  [Schumann,Siegert,SH] arXiv:0912.3501

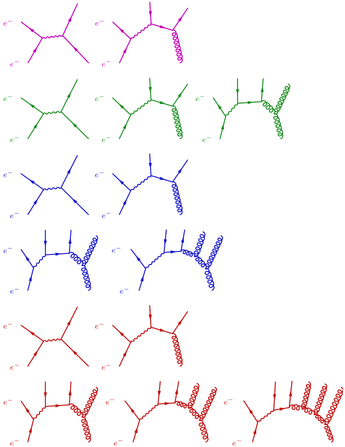


# Comparison to HERA data

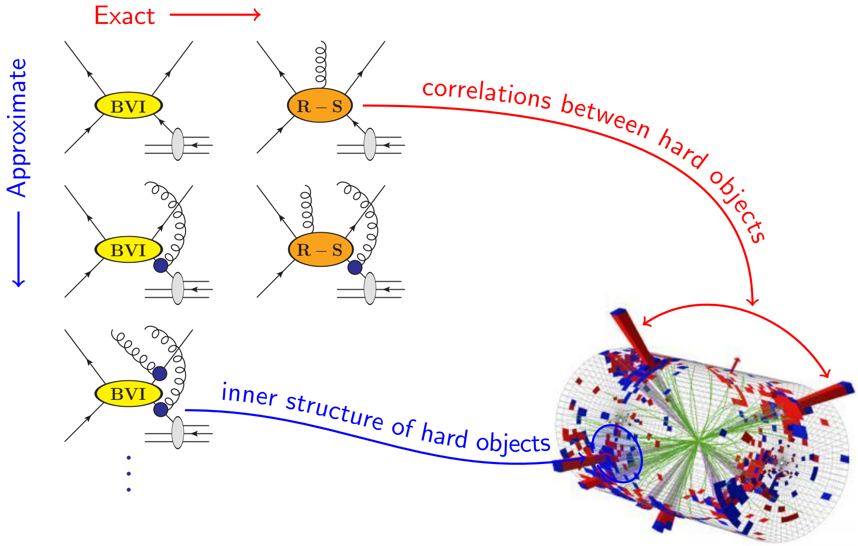
[Carli,Gehrmann,SH] arXiv:0912.3715

Variation of highest multiplicity in fixed-order calculation, $N_{\max}$



# Matching fixed-order NLO calculations to resummation



# Matching fixed-order NLO calculations to parton-showers

Two possible ways to match NLO calculations and parton showers

### MC@NLO

[Frixione,Webber] hep-ph/0204244

- 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

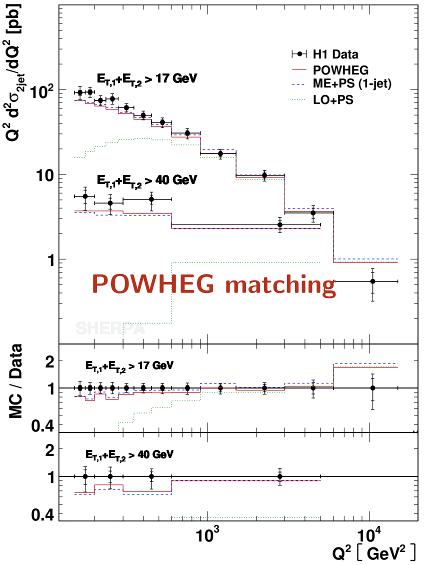
[Nason] hep-ph/0409146

- 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)

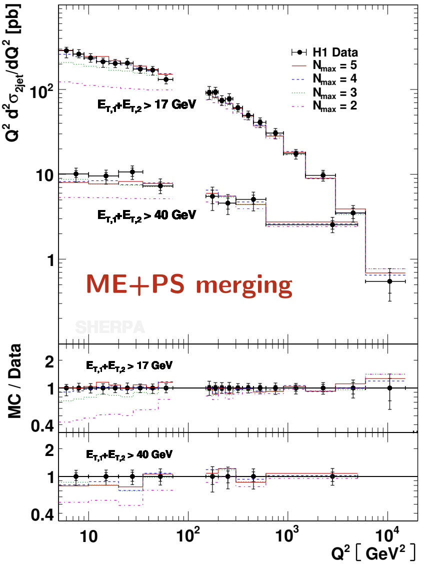
Both cases: Beware of sub-leading color terms and spin correlations!

# Matching vs Merging

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



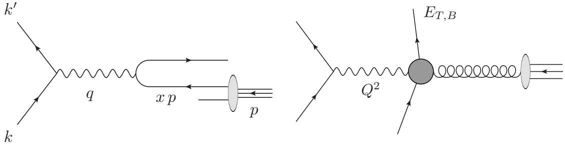

[Carli,Gehrmann,SH] arXiv:0912.3715



# Matching at NNLO accuracy

[Kuttimalai,Li,SH] arXiv:1809.04192

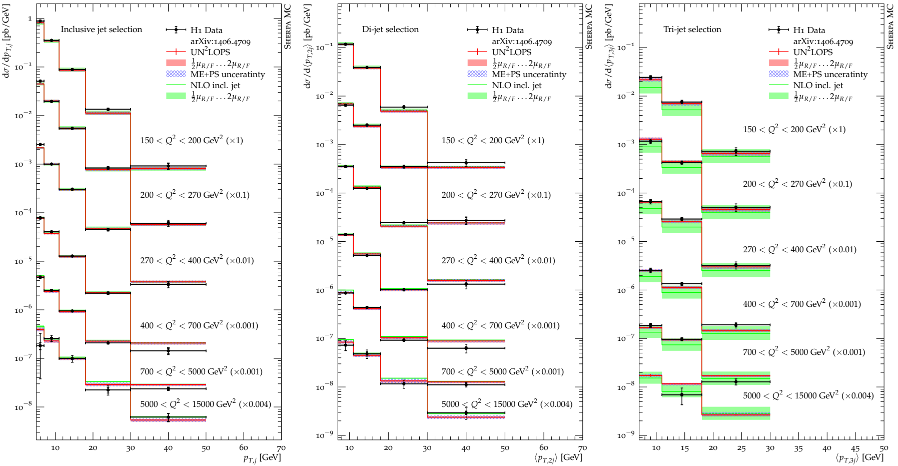
- Highest QCD accuracy in the simulation of inclusive DIS
- Projection-to-Born method for fully differential fixed order predictions
  [Zijlstra,vanNeerven] NPB383(1992)525, PLB297(1992)377 [Moch,Vermaseren,Vogt] hep-ph/0504242
  [Bern,Dixon,Kosower] hep-ph/9708239, [Berger et al.] arXiv:0803.4180
- 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

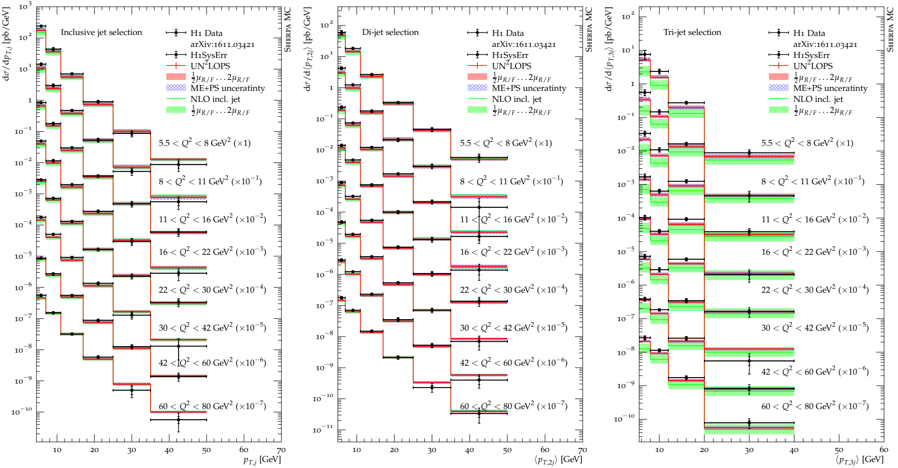
# NNLO particle-level simulation vs. H1 high-$Q^2$ data

[Kuttimalai,Li,SH] arXiv:1809.04192



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

[Kuttimalai,Li,SH] arXiv:1809.04192



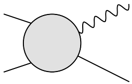
# Availability of simulations

- **Herwig**
  - Matching fully automated [Gieseke,Plätzer] arXiv:1109.6256
  - External 1-loop providers & builtin loop library
  - Merging in modified unitarized approach
    [Plätzer] arXiv:1211.5467, [Bellm,Gieseke,Plätzer] arXiv:1705.06700
  - QED & mixed higher-order corrections work in progress
- **Pythia**
  - New parton shower Dire [Prestel,SH] arXiv:1506.05057
  - QED radiative corrections in preparation [Giele,Prestel]
  - Unitarized merging under development [Prestel,Lönnblad] arXiv:1211.4827
  - NLO QCD Matching via interface to POWHEG / MC@NLO
- **Sherpa**
  - Matching fully automated [Krauss,Schönherr,Siegert,SH] arXiv:1008.5399, arXiv:1111.1220
  - External 1-loop providers & builtin loop library
  - Merging in non-unitarized approach [Krauss,Schönherr,Siegert,SH] arXiv:1207.5030
  - NNLO matching [Kuttimalai,Li,SH] arXiv:1809.04192

# QCD+QED radiative corrections in pp collisions

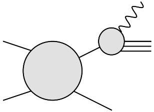
# The standard perturbative QCD approach

**"Direct" component**
fixed-order calculation with isolated $\gamma$



- $\gamma$+jet hep-ph/0602133
- $\gamma\gamma$ hep-ph/9911340
- $\gamma\gamma$+jet hep-ph/0303012
- $gg \to \gamma\gamma g$ hep-ph/9905283

**"Fragmentation" component**
factorization of $q\gamma$ collinear singularity



- Gives rise to $\gamma$ fragmentation function PLB79(1978)83
- Contribution depends on photon isolation criterion

- Based on assumption that dominant higher-order corrections of QCD type
- Direct and fragmentation component both needed for a complete prediction
- Fragmentation function depends on nonperturbative input

# The democratic approach used in MC event generators

**Procedure**

- Treat partons and photons fully democratically
- Combine fixed-order results of varying $\gamma$/parton multiplicity ...
- ... with interleaved QCD+QED parton shower evolution

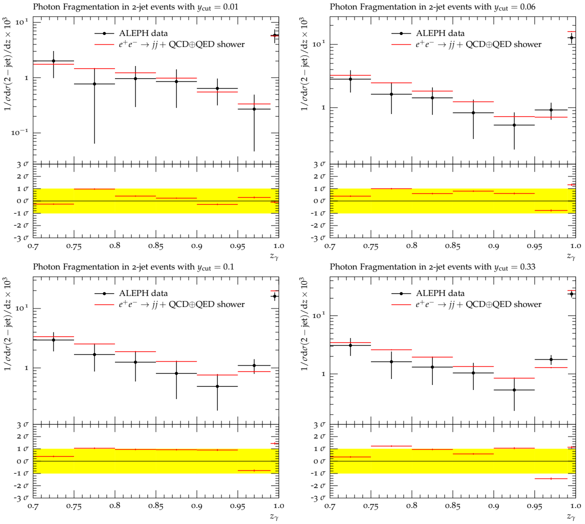
**Advantages**

- Parton-to-hadron transition via fragmentation models
- No new parameters related to $\gamma$ fragmentation
- Unified treatment of QCD & QED radiative corrections
- Non-prompt $\gamma$-production comes for free

Corresponding parton shower modifications available
in all major LHC generators (Herwig, Pythia, Sherpa)

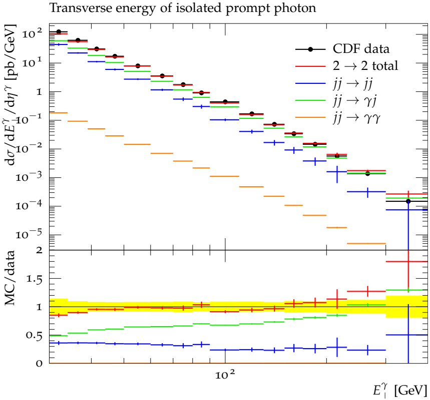
# Performance of QED parton showers in $e^+e^- \to$ hadrons

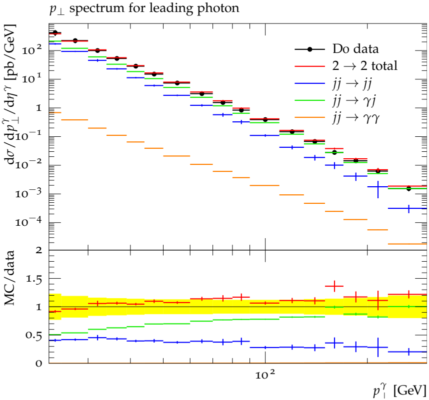
[Schumann,Siegert,SH] arXiv:0912.3501



# Example result: Prompt photon production at the Tevatron

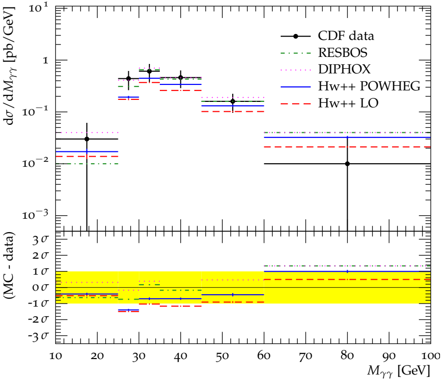
[Schumann,Siegert,SH] arXiv:0912.3501

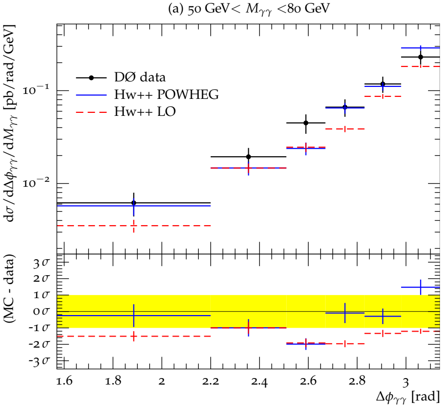


# Matching to fixed-order NLO calculations

[d'Errico,Richardson] arXiv:1106.3939



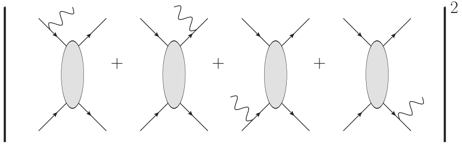



## QED radiative corrections DIS

## Plots & figures courtesy of Stefan Prestel

# Simulation in Pythia

- Soft radiation pattern emerges from semi-classical soft current



$$\mathcal{M}_{X+\gamma} \propto \mathcal{M}_{X,\mu} \sum_i \eta_i Q_i \frac{2p_i^\mu}{2p_i q}$$

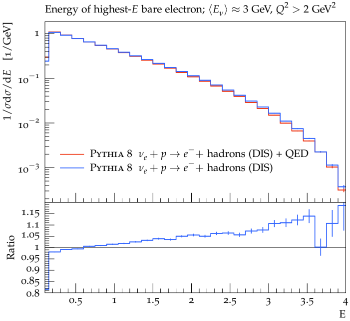
$$\rightarrow |\mathcal{M}_{X+\gamma}|^2 \propto |\mathcal{M}_X|^2 \sum_{i,j} \eta_i Q_i \eta_j Q_j \frac{4(p_i p_j)}{2(p_i q) 2(p_j q)}$$

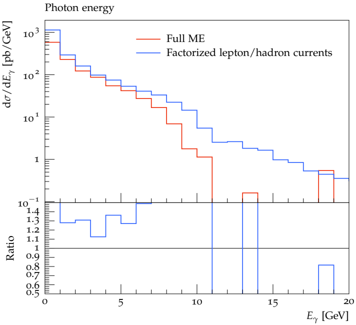
Individual contributions can be negative, but sum is positive

- Resummed calculation implemented as a parton shower with matrix-element corrections $\rightarrow$ recovers all interferences

# Simulation in Pythia

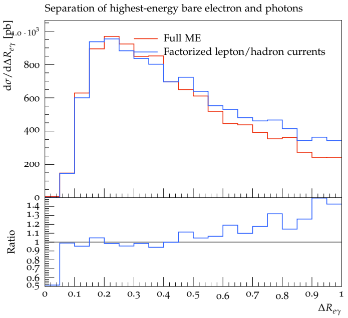
- Example: $ep$ collisions at $E_e = E_p = 10$ GeV, $Q > 2$ GeV

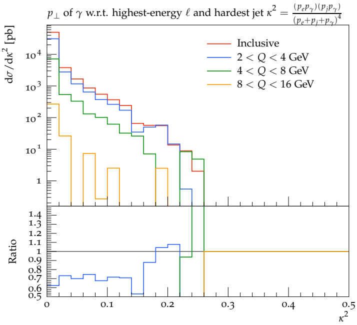


# Interference effects

- Even in neutral current reactions at low $Q^2$ factorization does not work
- Naively: At small $Q^2$ the reconfiguration of the EM radiation field occurs at longer distances $\rightarrow$ interferences more important




- Angular spearation between lepton and photon
- Lepton and $\gamma$ closer to each other when including interferences

- Relative $\gamma$ transverse momentum w.r.t. axis defined by hardest electron and hardest jet
- At low $Q^2$ more radiation between l and j, interferences of $\mathcal{O}(10\%)$

# Summary

- DIS simulations available in all major event generation frameworks
- QCD NLO matching & merging of fixed-order and resummation standard
- QED matching & merging being developed in Pythia (S. Prestel)
  - Offers unified treatment of radiative corrections in QCD+QED
  - Includes interferences between radiation off leptons & quarks
  - Works for both charged an neutral current interactions