Photo-production of jets at NLO in Sherpa

EIC-UG Inclusive PWG meeting, 6th Nov 2023

Based on arXiv:2310.18674 and arXiv:2311.xxxxx

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Outline

1. Motivation
2. Theory
3. Validation
4. Predictions for the EIC
5. Photon PDF quality
6. Conclusions

Motivation

The total cross-section in ep collision is $\sigma_{\text{tot}} \propto \frac{1}{\left(Q^2\right)^2}$

- For $Q^2 \gg 0$, predictions available fully-differentially at NNLO, e.g. [Höche, 2018]
- For $Q^2 \gtrsim 0$, only Leading Order event generation or Fixed Order NLO

➡ **Missing out on full simulations for a large part of the cross section**

This region also interplays with Semi-Inclusive DIS, Exclusive DIS and Diffraction

Equivalent Photon Approximation

[Budnev, 1978]

Observe that

- photo-absorption for $Q^2 < \Lambda^2_{\text{cut}}$ can be approximated by on-shell value
- the same low-virtuality domain dominates photo-production

$\Rightarrow$ **approximate photo-production by** $\mathrm{d}\sigma_{eX} = \mathrm{d}\sigma_{\gamma X}\ _{Q^2=0} f_{\gamma/e}(x)$

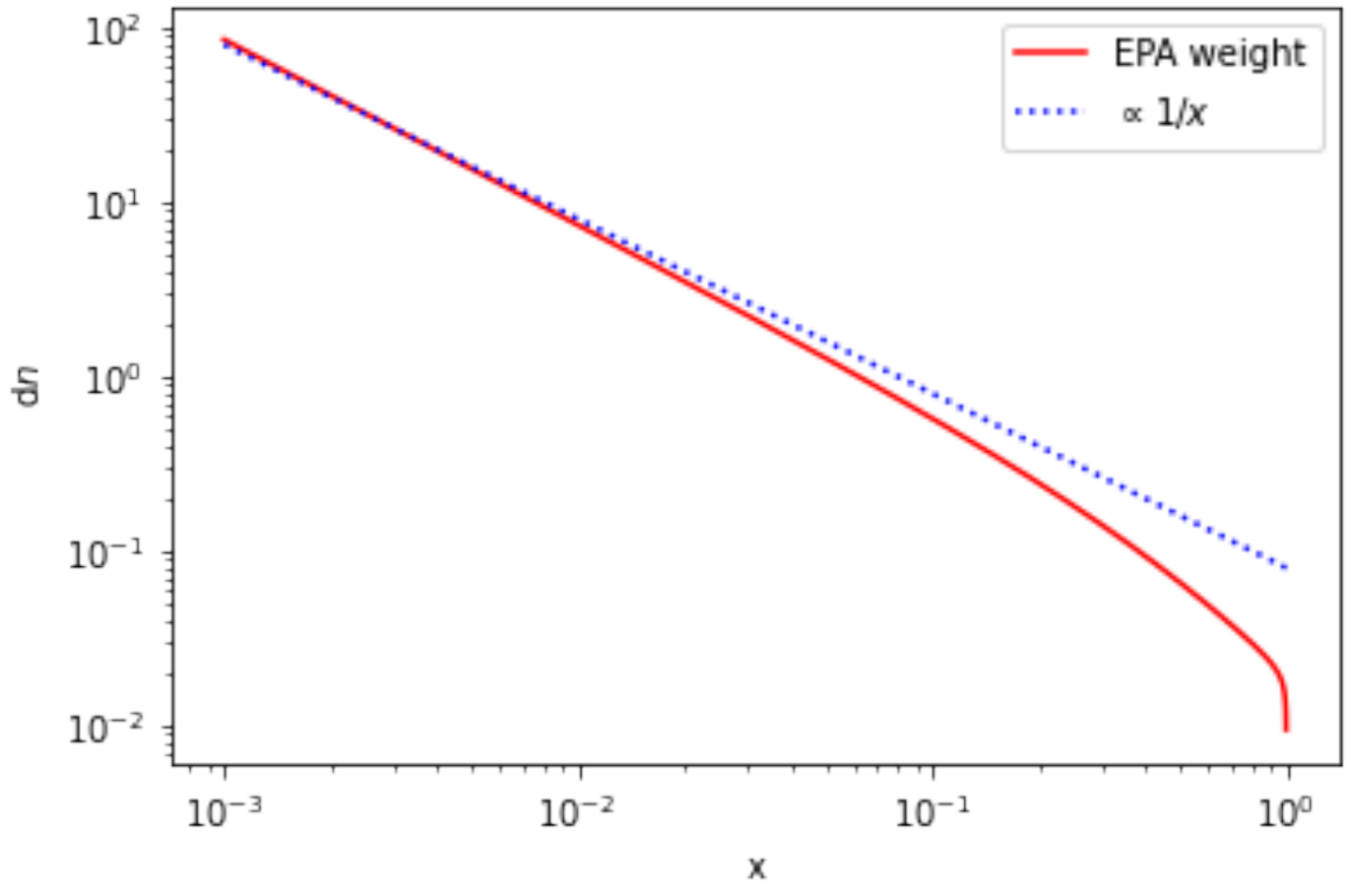
x is the photon to electron momentum ratio

Q^2 is integrated out in $f_{\gamma/e}(x)$, so need to set the limits

collinear kinematics

The EPA spectrum

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



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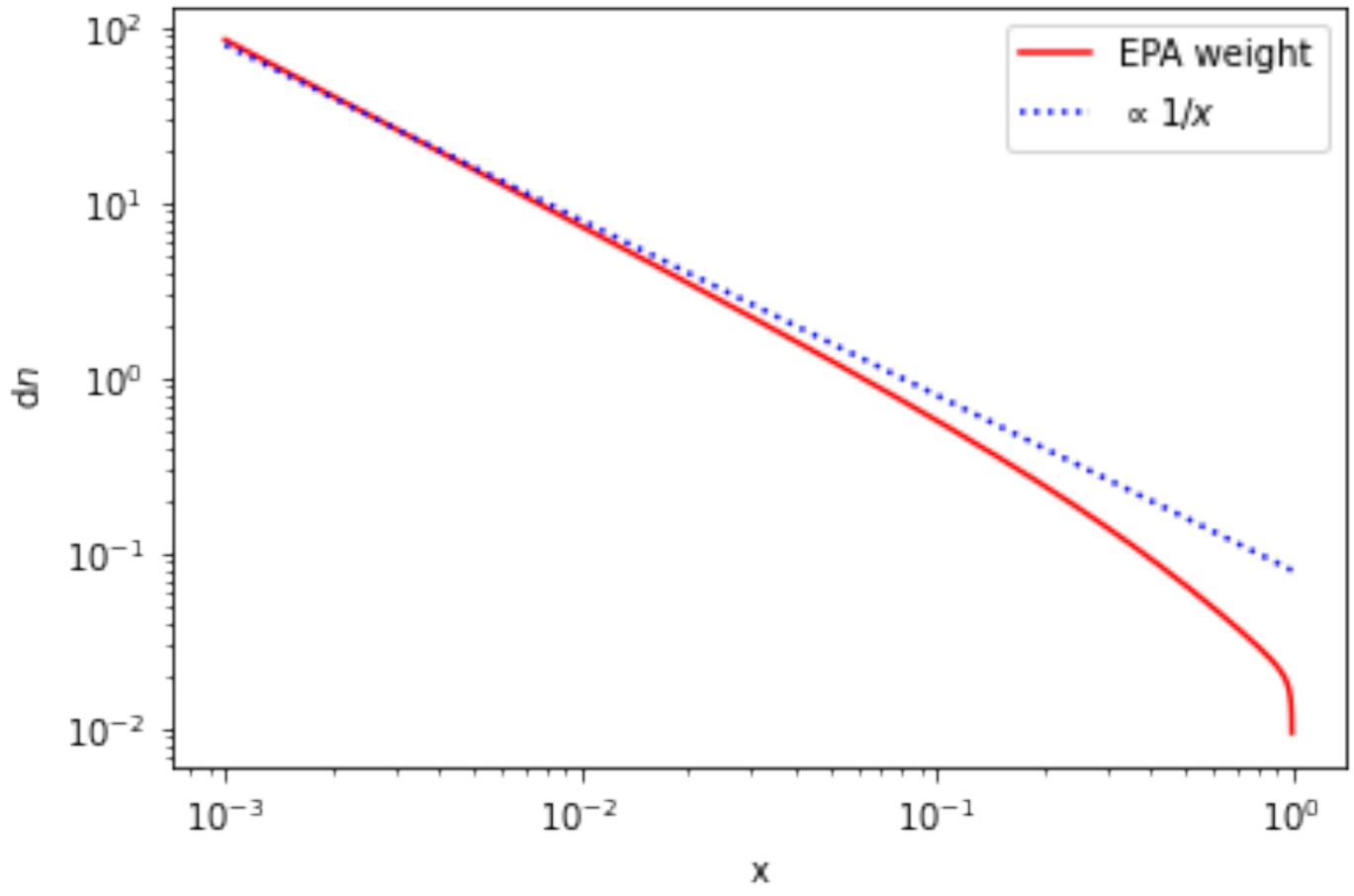
dominated by this term



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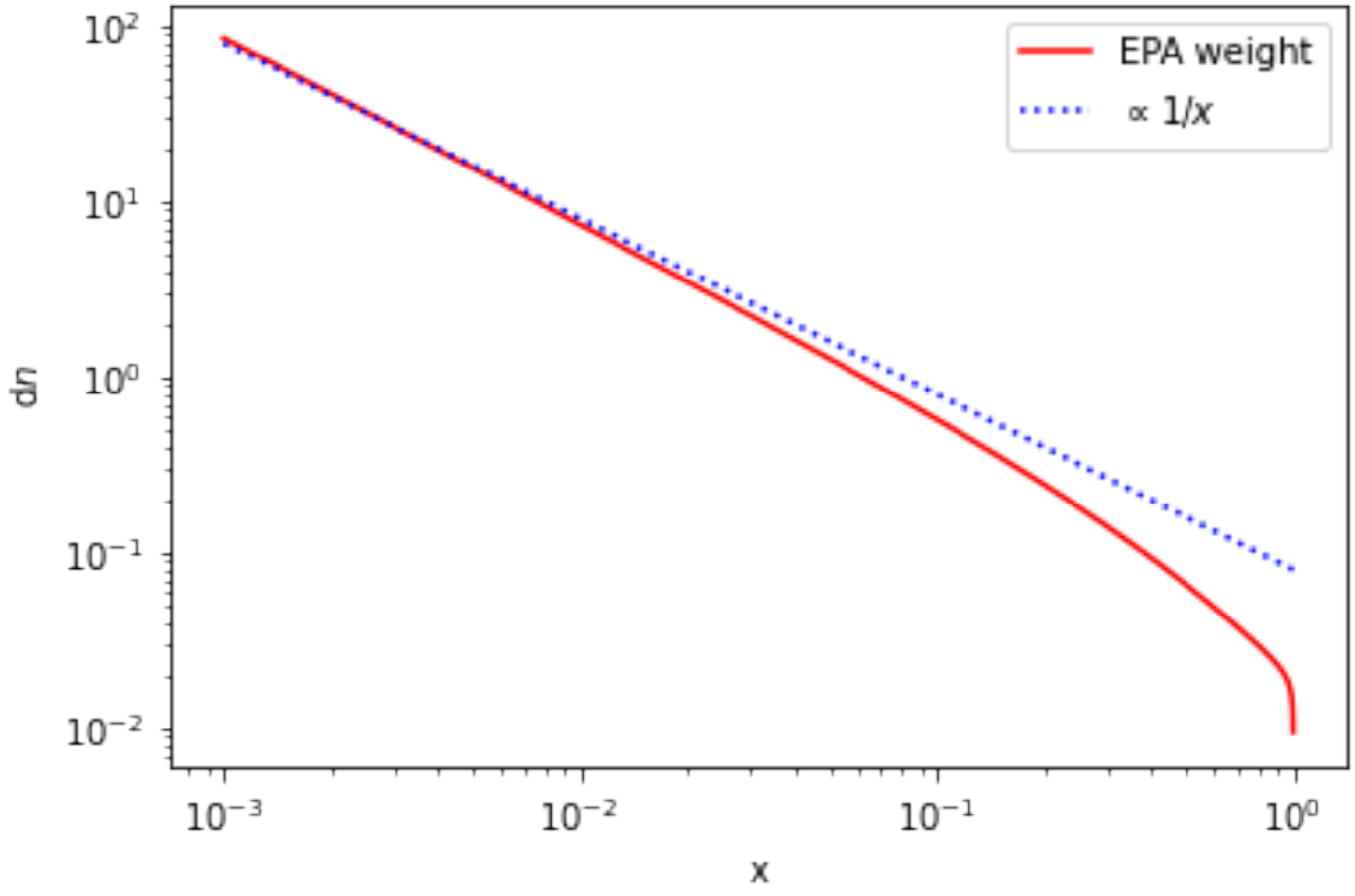
correction for $x \to 1$ as in [Frixione, 1993] and [Schuler, 1996]



The total cross-section

[Frixione, 1994]

In photo-production, it is

$$\sigma_{eP\to X} = \int \mathrm{d}x\; f_{\gamma/e}(x)\; \mathrm{d}\sigma_{\gamma P\to X} = \int \mathrm{d}x\; f_{\gamma/e}(x)\;\; \left(\mathrm{d}\sigma^{(\mathrm{point})}_{\gamma P\to X} + \mathrm{d}\sigma^{(\mathrm{hadr})}_{\gamma P\to X}\right)$$

where

$$\mathrm{d}\sigma^{(\mathrm{point})}_{\gamma P\to X} = \sum_i \int \mathrm{d}x\; f_{i/P}\left(x, \mu_F^{(P)}\right)\;\; \mathrm{d}\hat{\sigma}_{\gamma i}\left(\{p_k\}, \alpha_S(\mu_R), \mu_F^{(P)}, \mu_F^{(\gamma)}\right)$$

$$\mathrm{d}\sigma^{(\mathrm{hadr})}_{\gamma P\to X} = \sum_{ij} \int\int \mathrm{d}x_1\; \mathrm{d}x_2\;\; f_{i/P}\left(x_1, \mu_F^{(P)}\right)\;\; f_{j/\gamma}\left(x_2, \mu_F^{(\gamma)}\right)\;\; \mathrm{d}\hat{\sigma}_{ij}\left(\{p_k\}, \alpha_S(\mu_R), \mu_F^{(P)}, \mu_F^{(\gamma)}\right)$$

NB: The dependence on $\mu_F^{(\gamma)}$ cancels only in the total cross-section!

Photon PDF and PS matching

[Frixione, 1994]

The photon PDF obeys the evolution

$$\frac{\partial f_{i/\gamma}}{\partial \log \mu_F^2} = \frac{\alpha_{\text{em}}}{2\pi} P_{i\gamma} + \frac{\alpha_S}{2\pi} \sum_j P_{ij} \otimes f_{j/\gamma}$$

How can we match FO NLO to the parton shower?

- $\sigma^{(\text{hadr})}_{\gamma P \to X}$ is pure QCD ⇒ matching analogous to LHC jet-production
- $\sigma^{(\text{point})}_{\gamma P \to X}$ has QCD **and** QED divergences — no implementation for QED available yet

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Collinear singularities stemming from $\gamma \to q\bar{q}$ are part of the PDF evolution!

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Matching to the parton shower by matching QCD terms and subtracting any collinear QED divergences in $\sigma^{(\text{point})}_{\gamma P \to X}$ as they're included in the PDF in $\sigma^{(\text{hadr})}_{\gamma P \to X}$

Caveats:

- needs PDFs with $\overline{\text{MS}}$ scheme
- neglecting $\gamma \to q\bar{q}$ in ISR shower evolution

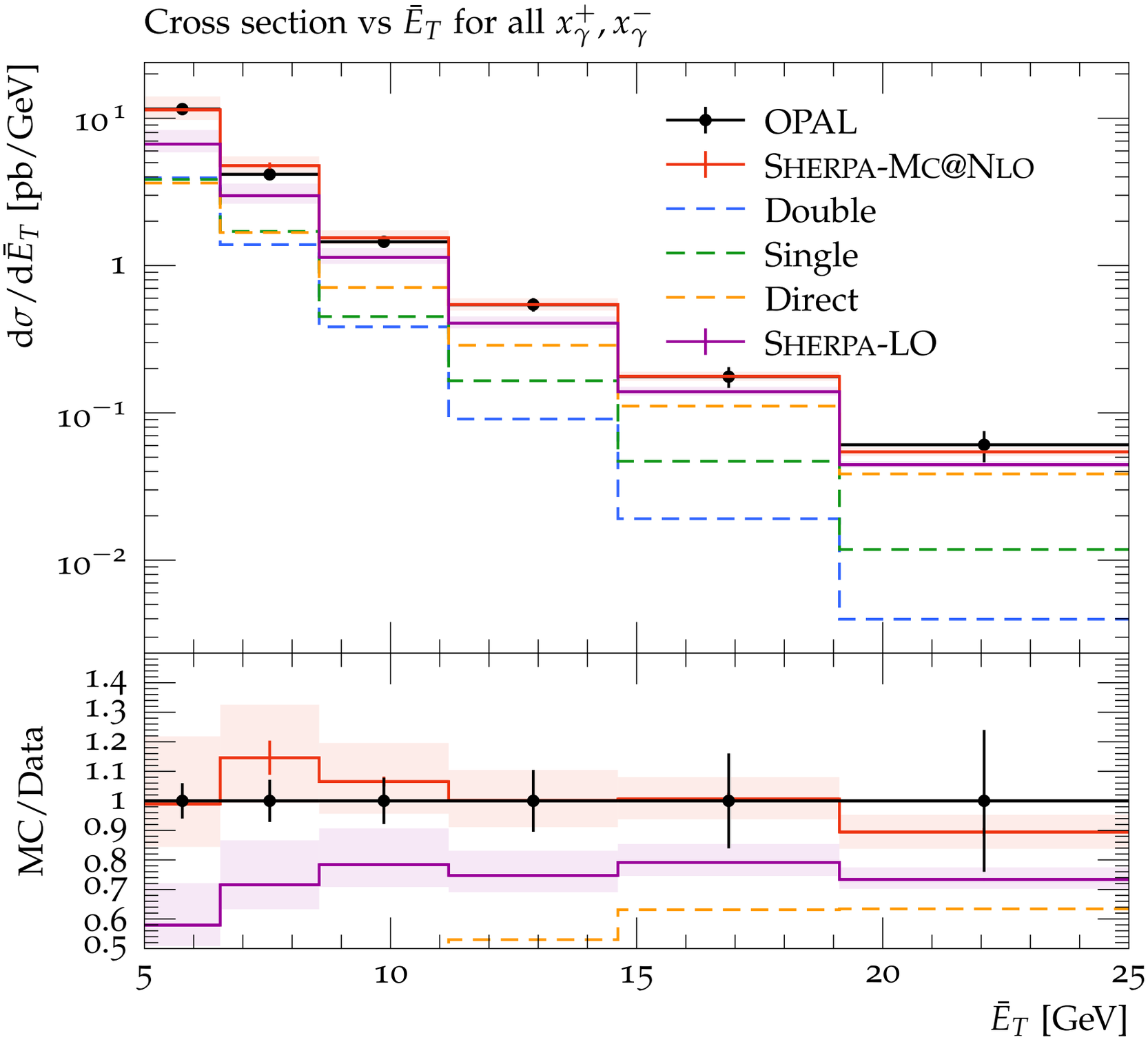
Event generation

- Compared Leading Order vs MC@NLO results
- (di-)jet production at OPAL and ZEUS
- Observables are
  - pseudo-rapidity η
  - jet transverse energy E_T
  - $\cos\,\theta^*$, for the angle between the jets
  - $x_\gamma^\pm$ as proxy for momentum ratio of parton to photon, defined by

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

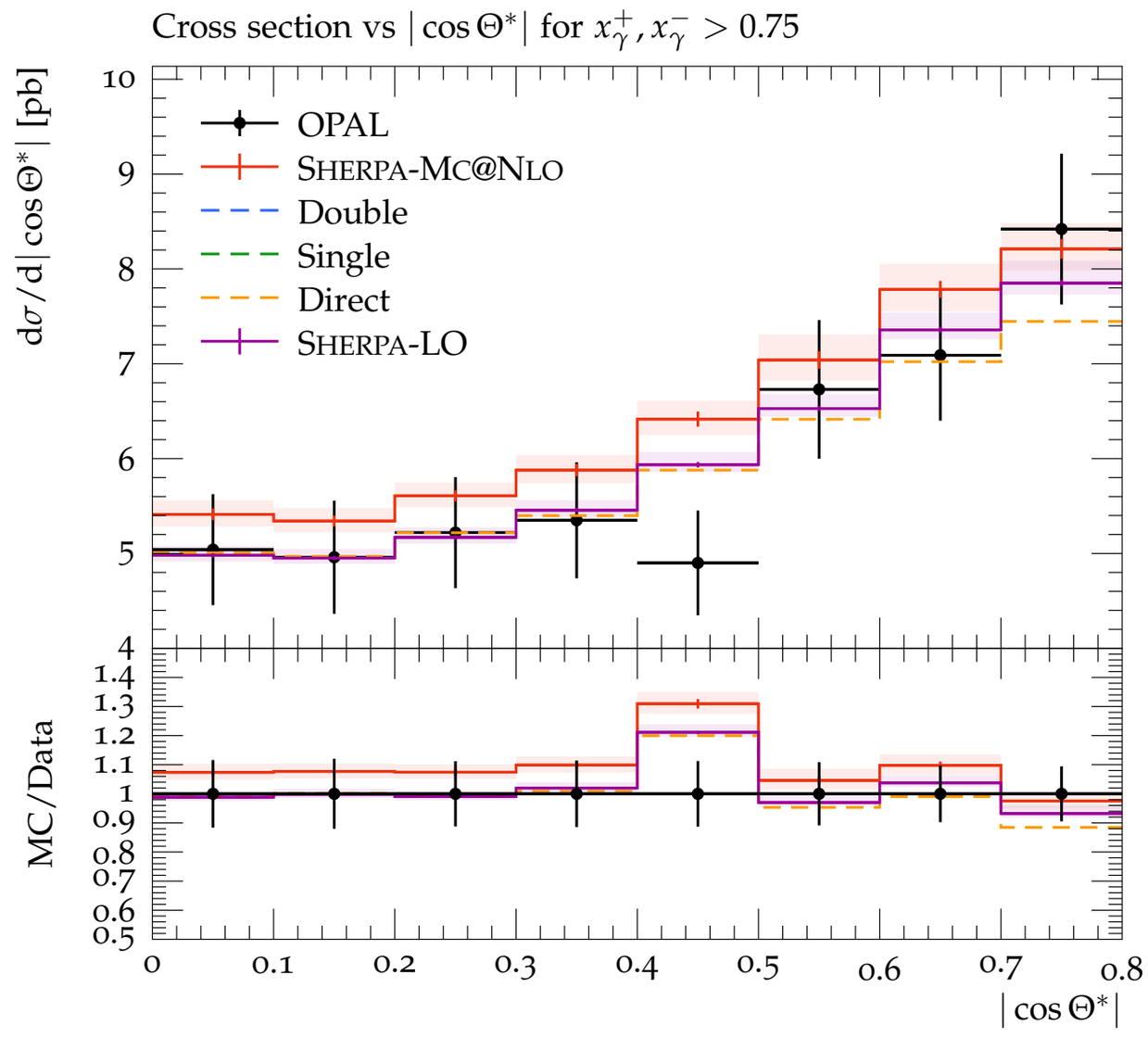
Validation against LEP

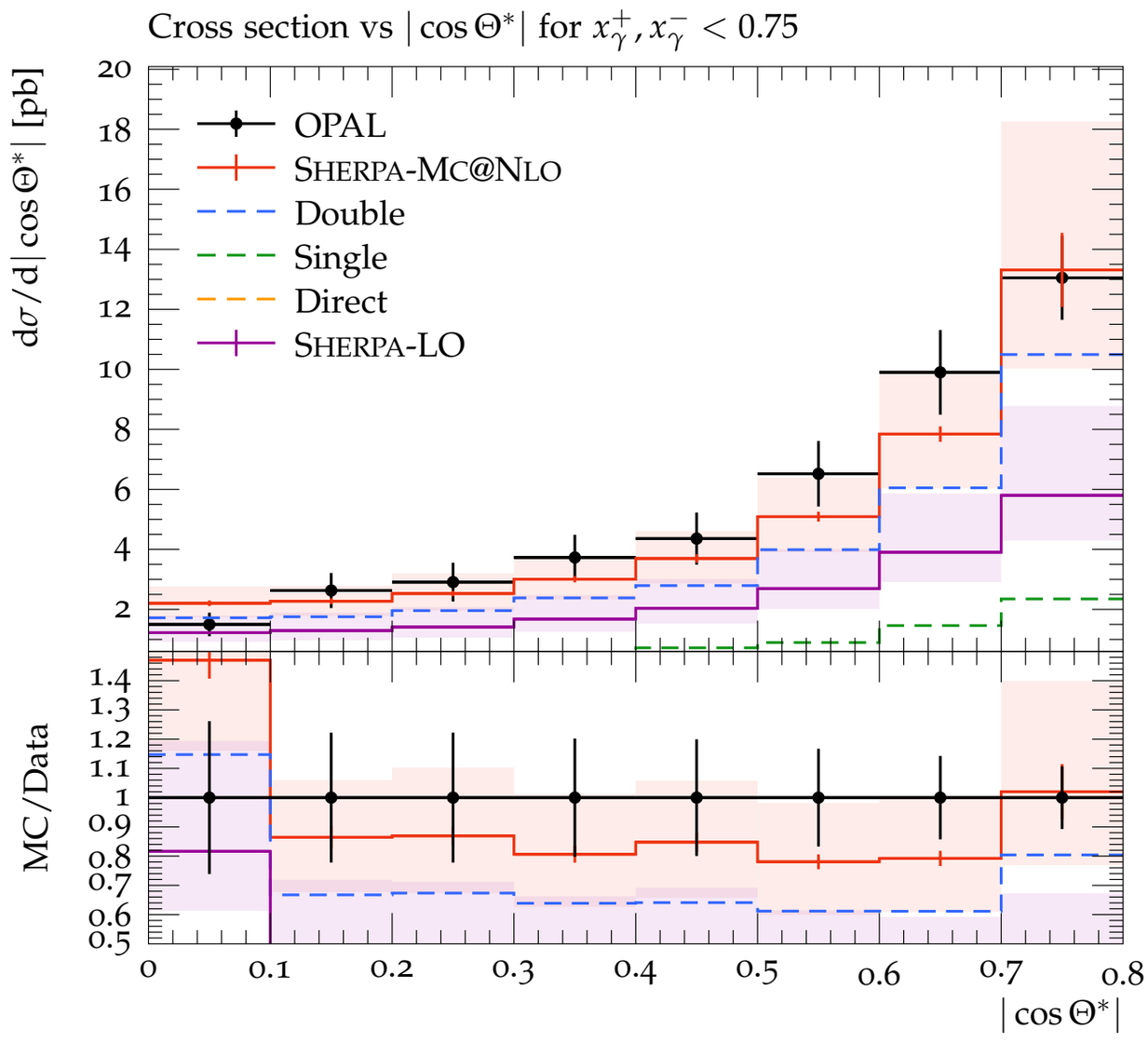
Average jet transverse energy



Validation against LEP

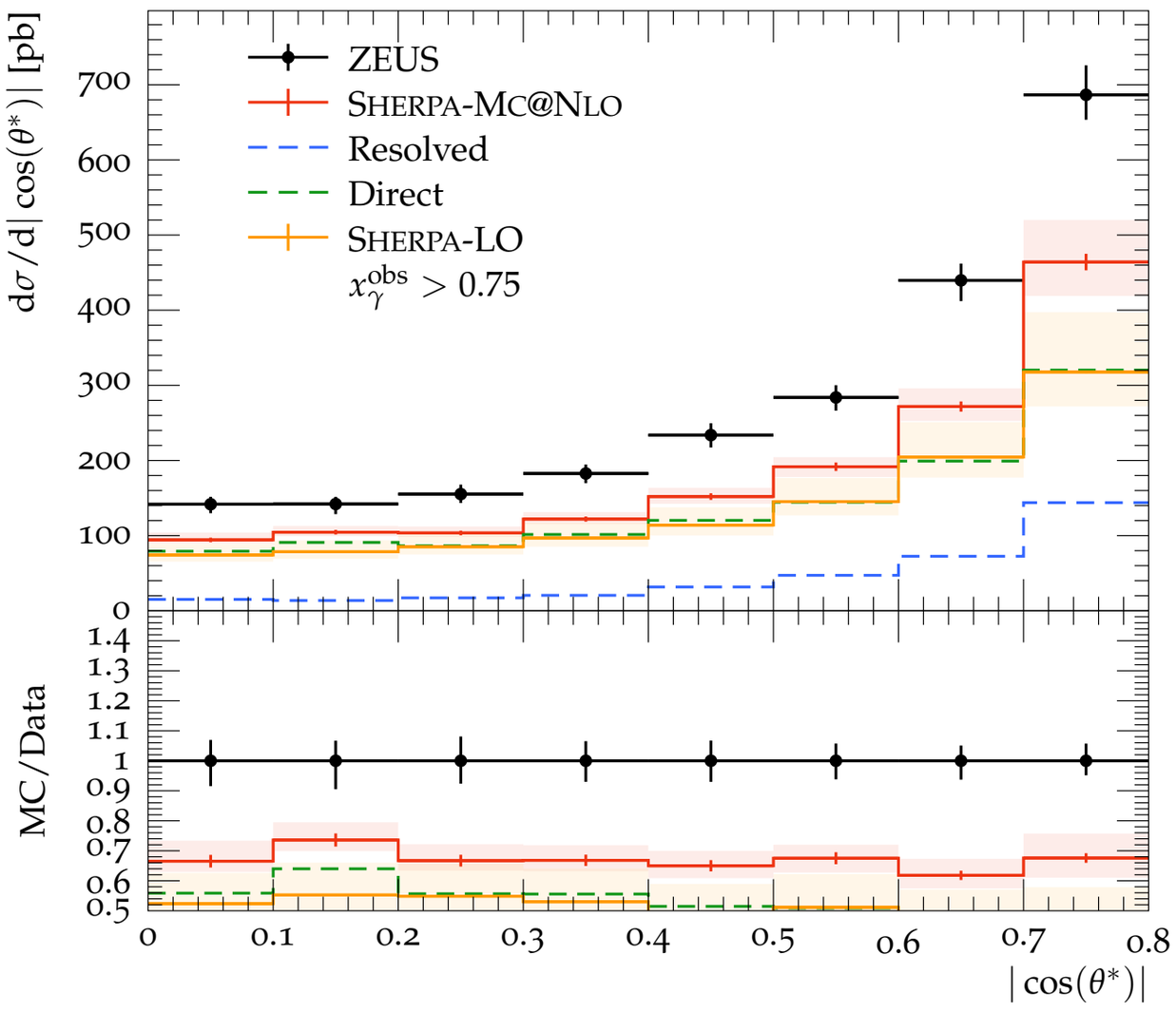
$cos\theta^*$ for angle between dijet system

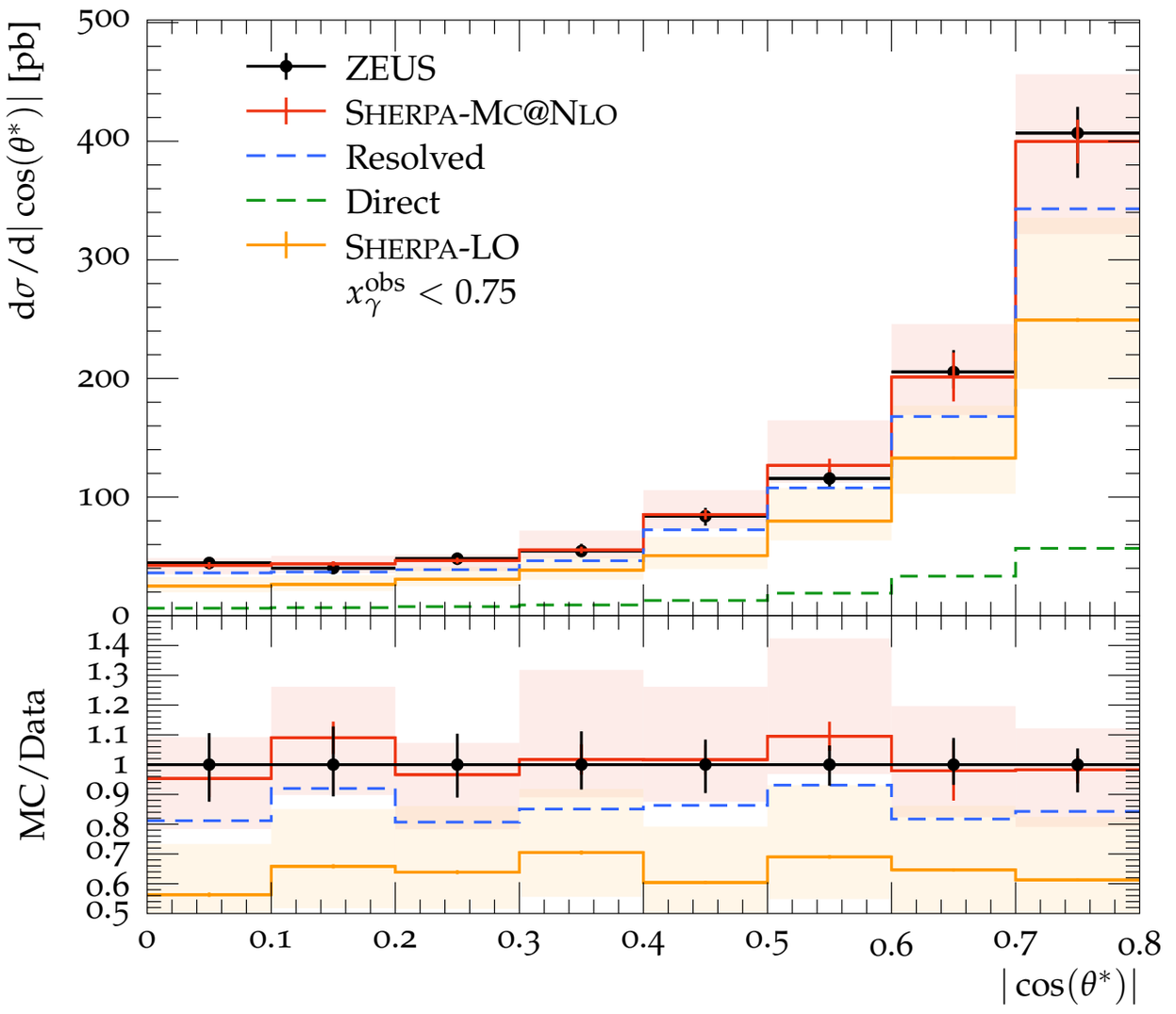




Validation against HERA

$cos\theta^*$ for angle between dijet system



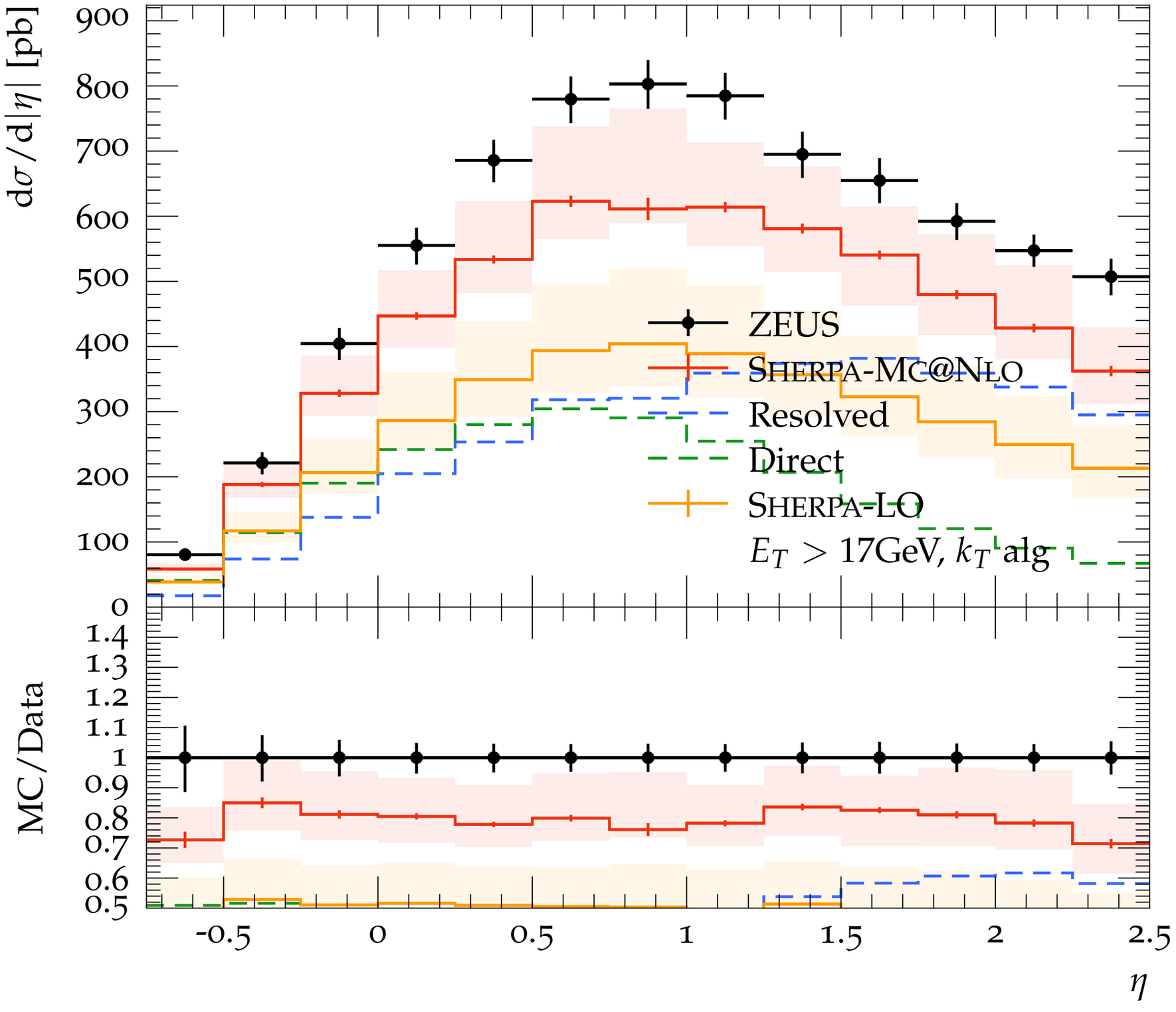


Undershoot the cross-section in direct component, potential reasons:

- fragmentation and MPIs have been seen to shift the events towards larger x_γ
- inclusion of photon splitting in Initial State Radiation
- contamination through DIS events

Validation against HERA

Jet pseudo-rapidity



Predictions for EIC

Implemented Rivet analysis

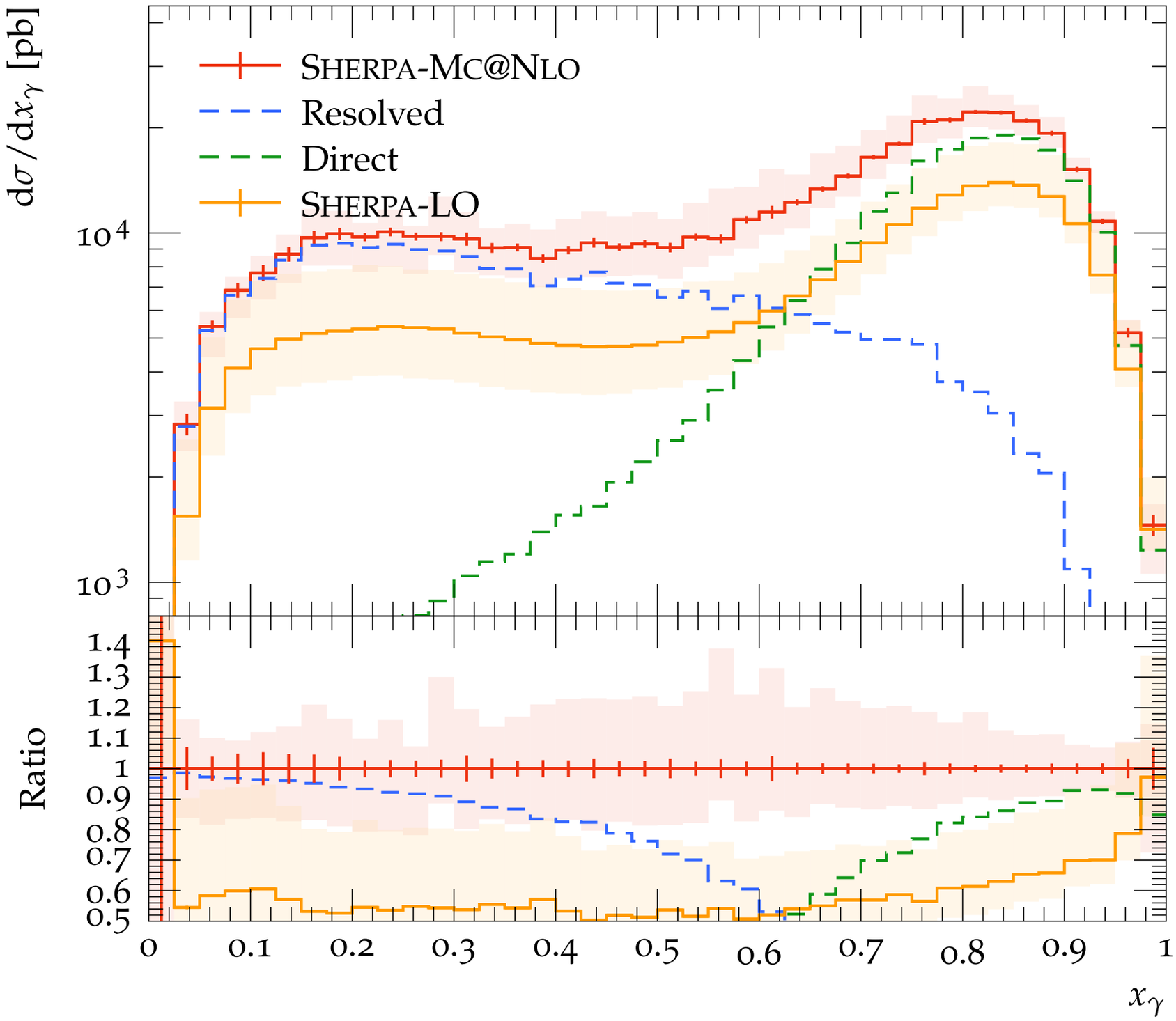
- electron-proton beam with 18 and 275 GeV, respectively
- anti-k_T jet clustering with $R = 1.0$ and $E_T > 6$ GeV
- at least one jet

Generated 10 million MC@NLO events per component with SHERPA

- scales chosen as $\mu_R = \mu_F = H_T/2$, incl. 7-point variation
- averaged over SAS1M and SAS2M photon PDF sets
- fragmentation, MPIs, beam remnants,…

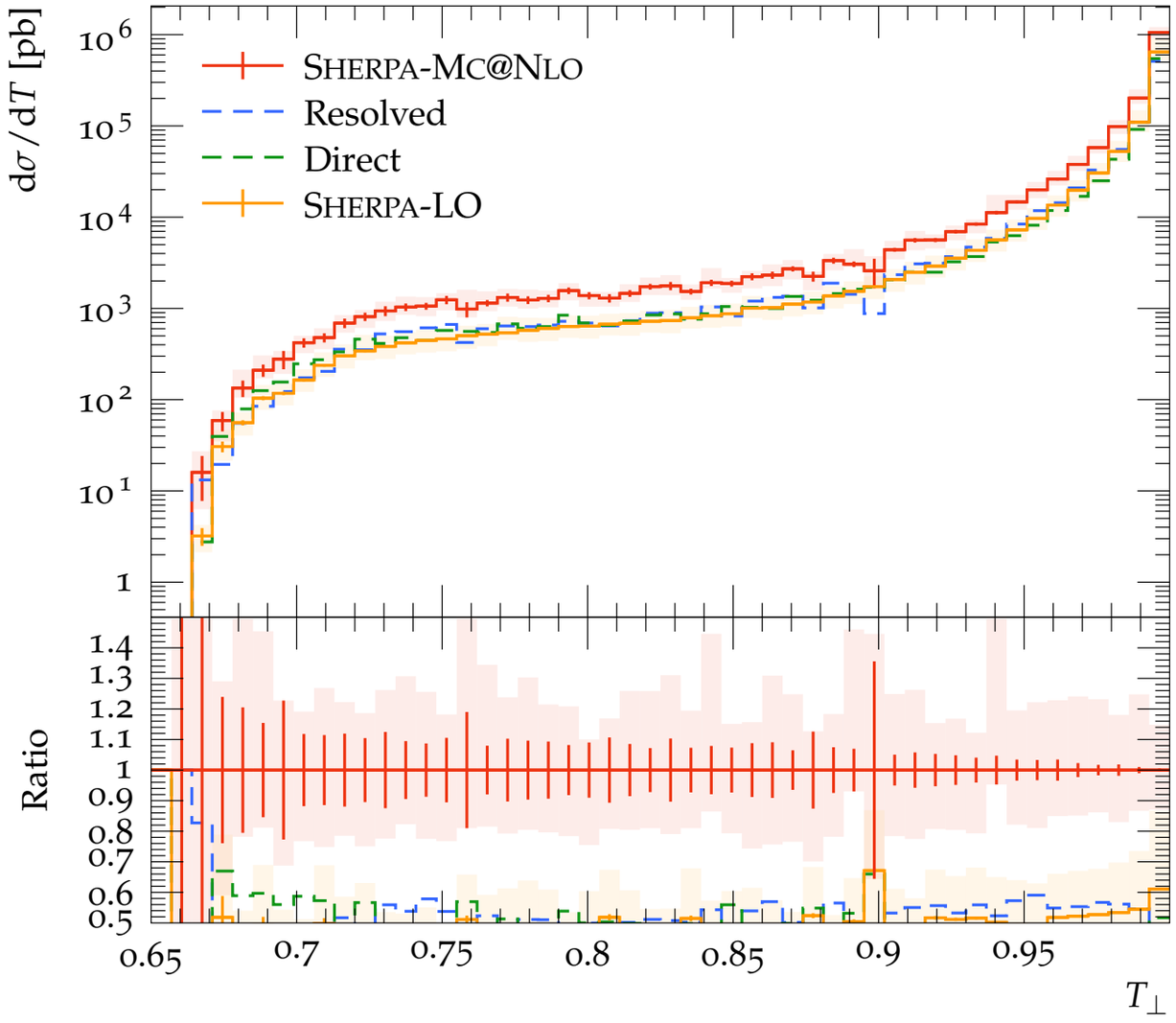
Predictions for EIC

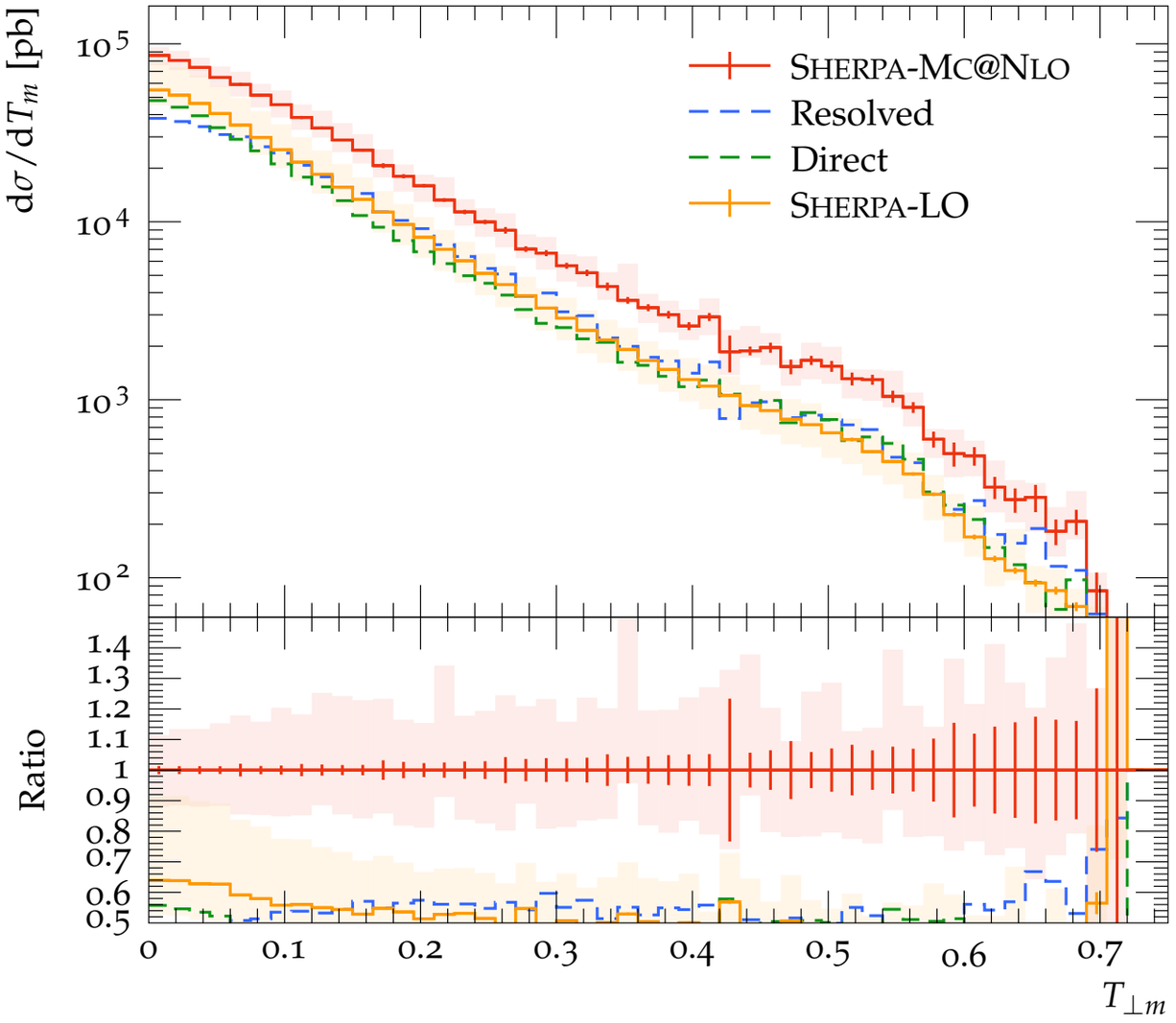
Distribution of x_γ



Predictions for EIC

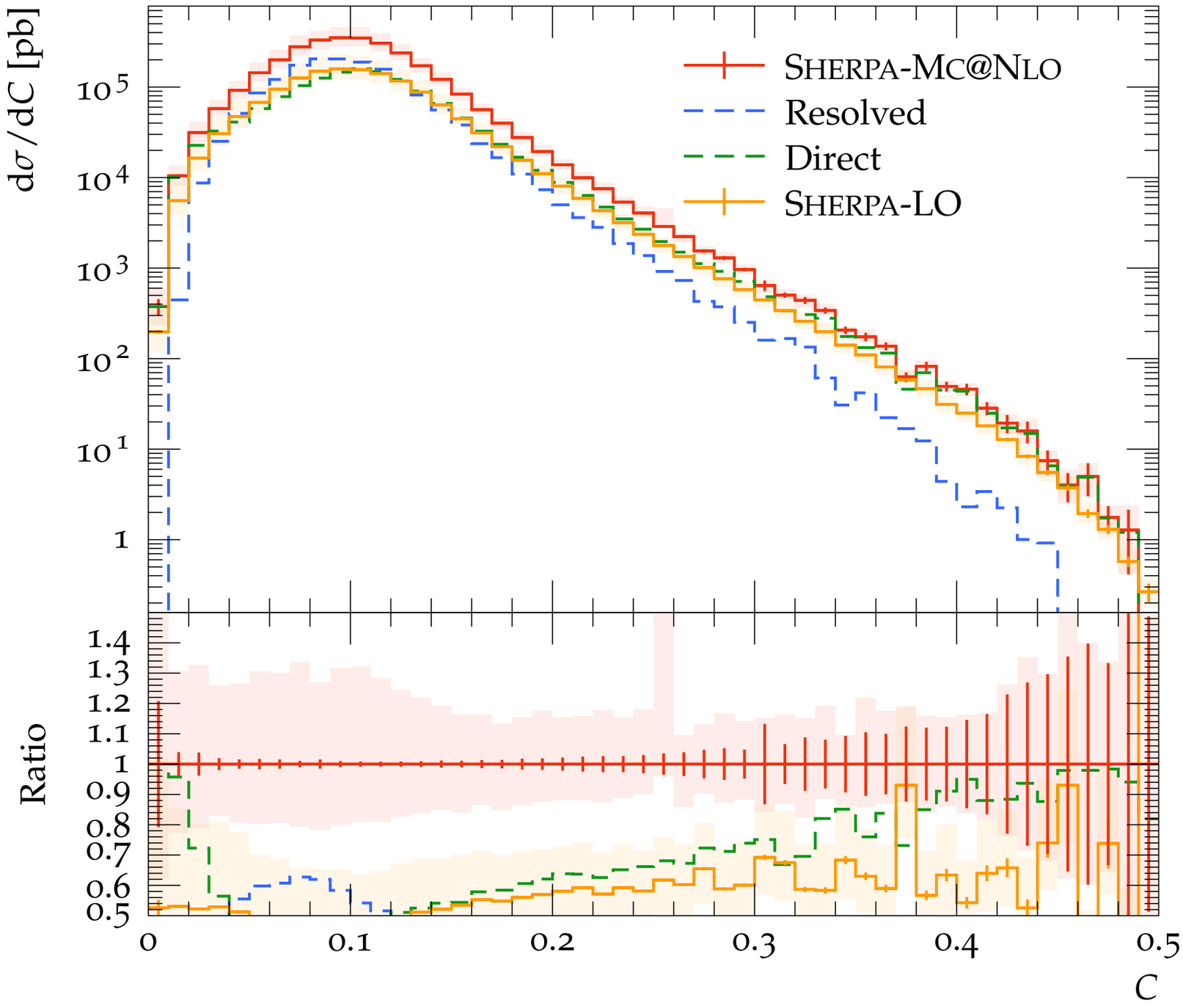
Transverse thrust and transverse thrust minor





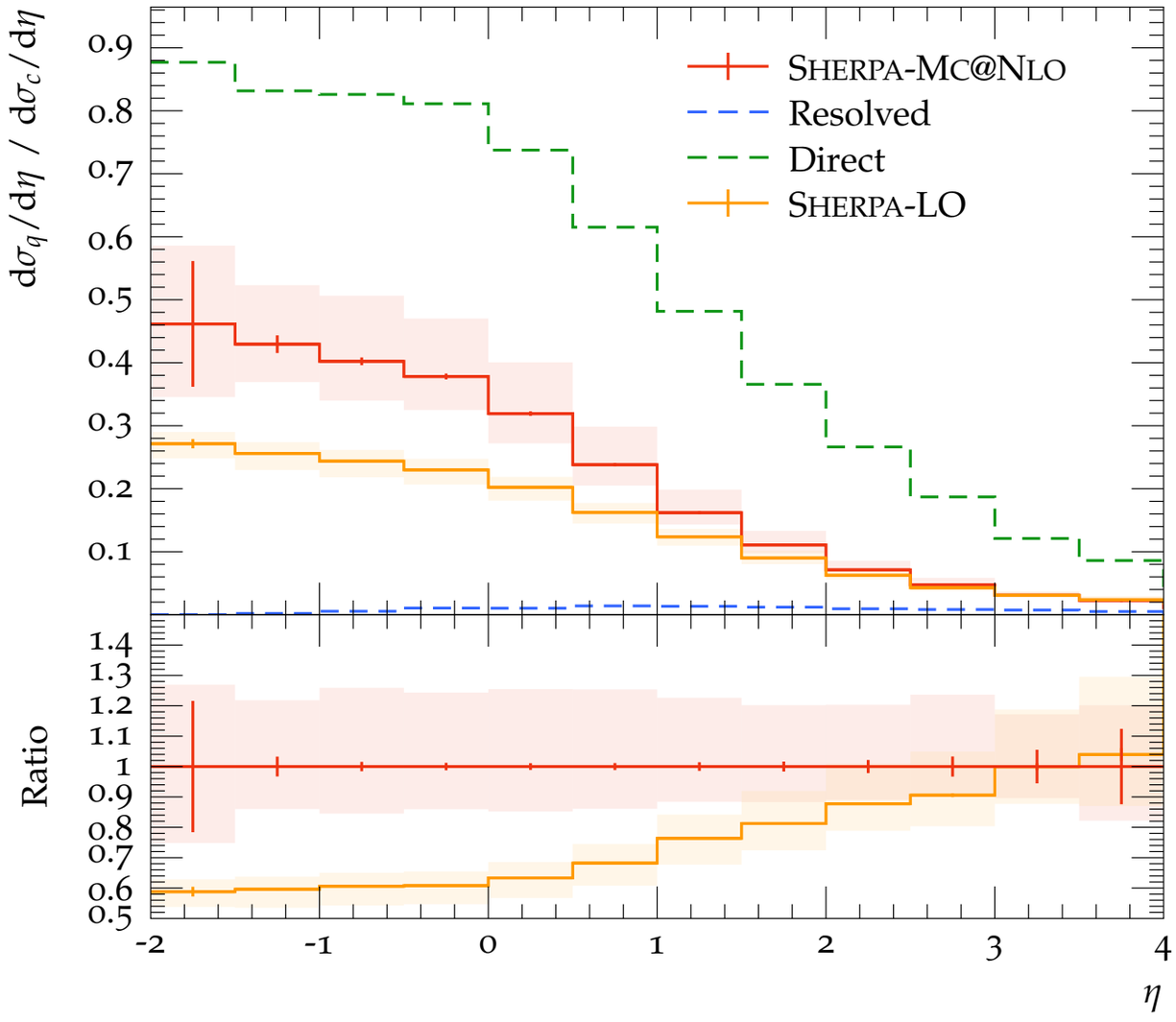
Predictions for EIC

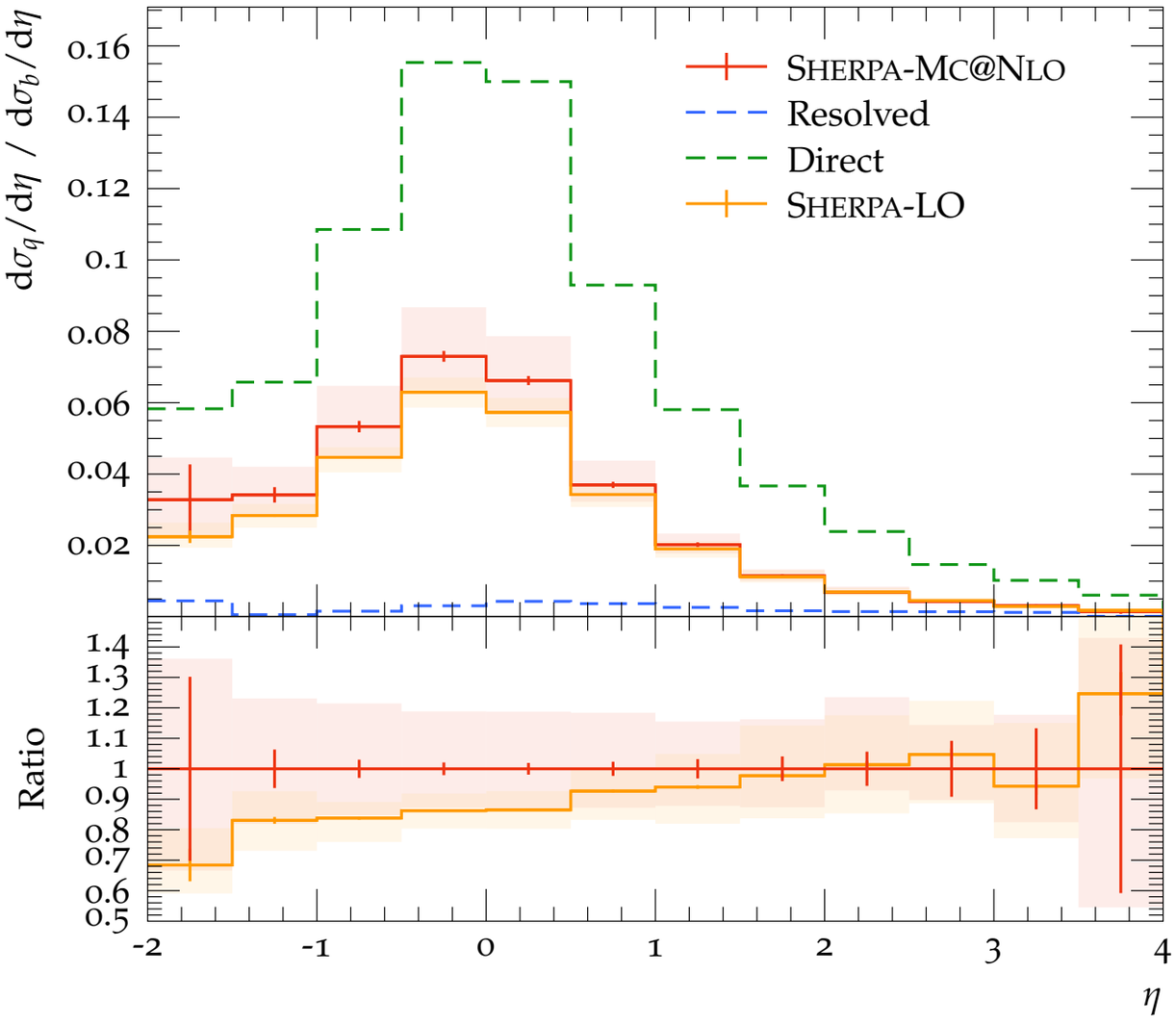
Distribution of C parameter



Predictions for EIC

Ratio of c/b- to light-quark jets in pseudo-rapidity



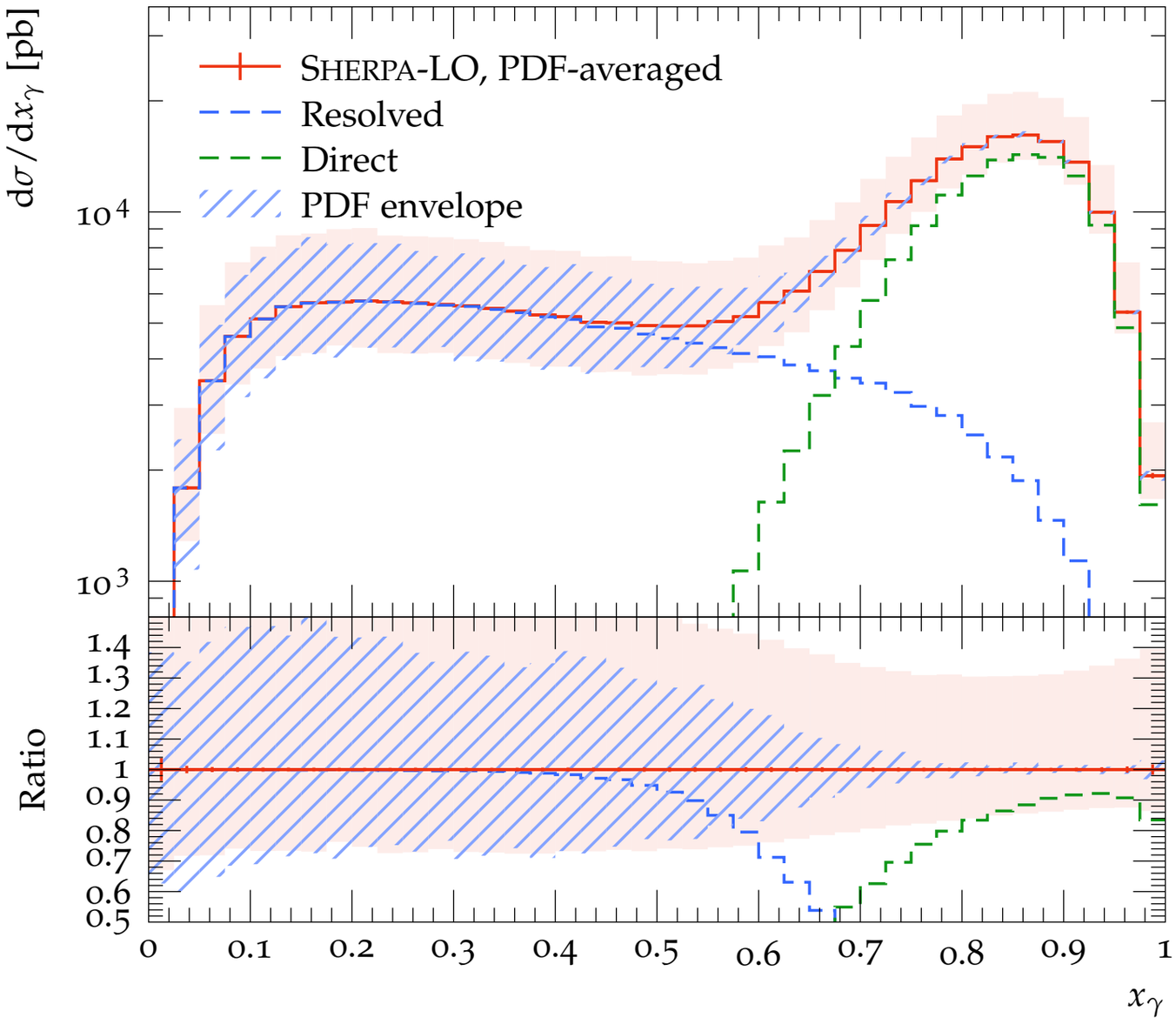


Events generated at parton-level for these observable

Photon PDF quality

The bottleneck in photo-production phenomenology

- interfaced 11 photon PDF sets to SHERPA
- 1 million Leading Order events, scale and PDF varied independently



- Deviations up to 50%
- α_S value inconsistent with modern proton PDFs
- No error estimates

Conclusion

- Photo-production is an important, but poorly examined domain
- Fully-differential event simulation within SHERPA now available at MC@NLO accuracy
- Validated against LEP and HERA data
- Predictions of inclusive jet observables, event shapes and heavy-quark jets for the EIC at NLO
- Photon PDFs are the bottleneck for precision phenomenology