Event Generation for Photoproduction and Diffraction in *ep*

Electron-Ion Collider UK gathering
19th November 2024

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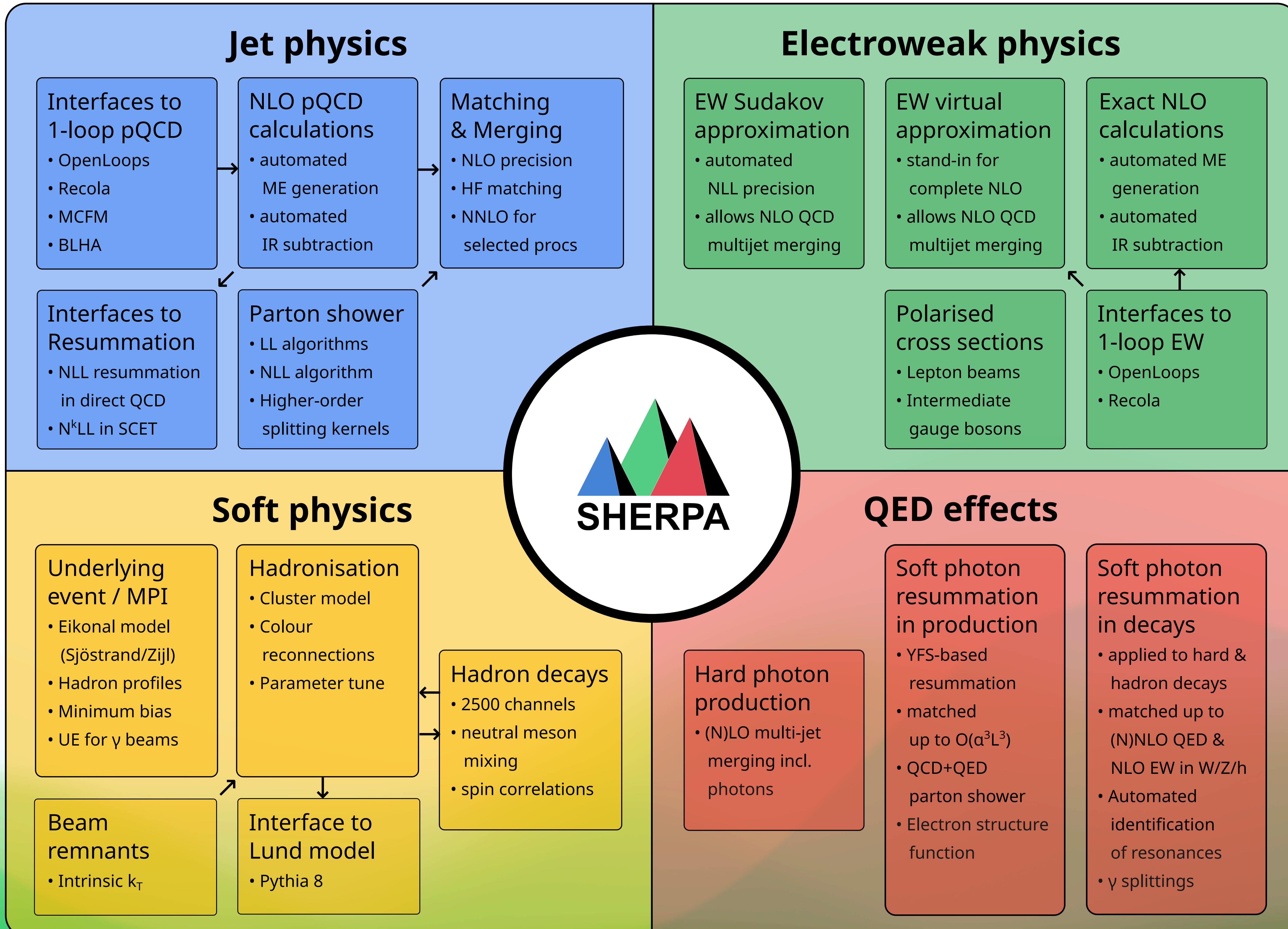
based on [*Eur.Phys.J.C 84 (2024) 2, 178*],
[*Phys.Rev.D 109 (2024) 3, 034037*],
[*Eur.Phys.J.C* 84 (2024) 9, 894]

Sherpa v3


Jet physics
Interfaces to 1-loop pQCD
• OpenLoops
• Recola
• MCFM
• BLHA
NLO pQCD calculations
• automated ME generation
• automated IR subtraction
Matching & Merging
• NLO precision
• HF matching
• NNLO for selected procs
Interfaces to Resummation
• NLL resummation in direct QCD
• N^kLL in SCET
Parton shower
• LL algorithms
• NLL algorithm
• Higher-order splitting kernels
Electroweak physics
EW Sudakov approximation
• automated NLL precision
• allows NLO QCD multijet merging
EW virtual approximation
• stand-in for complete NLO
• allows NLO QCD multijet merging
Exact NLO calculations
• automated ME generation
• automated IR subtraction
Polarised cross sections
• Lepton beams
• Intermediate gauge bosons
Interfaces to 1-loop EW
• OpenLoops
• Recola
SHERPA
Soft physics
Underlying event / MPI
• Eikonal model (Sjöstrand/Zijl)
• Hadron profiles
• Minimum bias
• UE for γ beams
Hadronisation
• Cluster model
• Colour reconnections
• Parameter tune
Hadron decays
• 2500 channels
• neutral meson mixing
• spin correlations
Beam remnants
• Intrinsic k_T
Interface to Lund model
• Pythia 8
QED effects
Hard photon production
• (N)LO multi-jet merging incl. photons
Soft photon resummation in production
• YFS-based resummation
• matched up to $O(\alpha^3 L^3)$
• QCD+QED parton shower
• Electron structure function
Soft photon resummation in decays
• applied to hard & hadron decays
• matched up to (N)NLO QED & NLO EW in W/Z/h
• Automated identification of resonances
• γ splittings

Motivation

The different regimes in *ep*

$$Q^2 = -(p_e - p_e')^2\,,$$
$$t = (p_p - p_Y')^2$$

high-$|t|$, inelastic ⟷ low-$|t|$, elastic

high-Q^2, "deep" ↕ low-Q^2

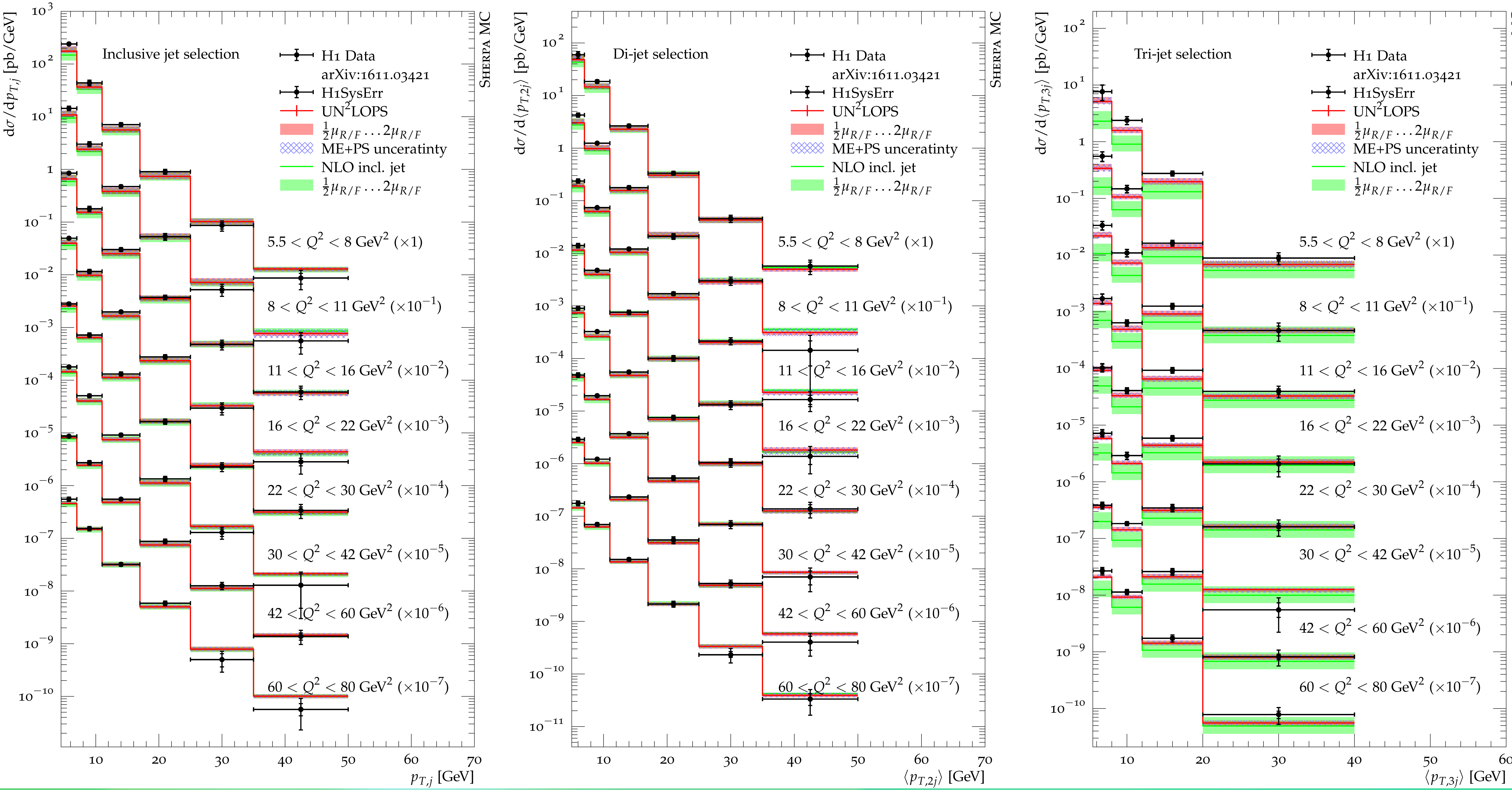
high-$|t|$, inelastic	low-$|t|$, elastic
DIS NNLO matched	**Diffractive DIS** Only Fixed Order
Photoproduction LO+PS	**Diffractive Photoproduction** LO+PS

With respect to the total cross-section

- Photoproduction is dominant
- Diffraction was 10% at HERA, more at EIC

DIS event generation

Matched at NNLO accuracy



[Phys.Rev.D 98 (2018) 11, 114013] using UN2LOPS matching

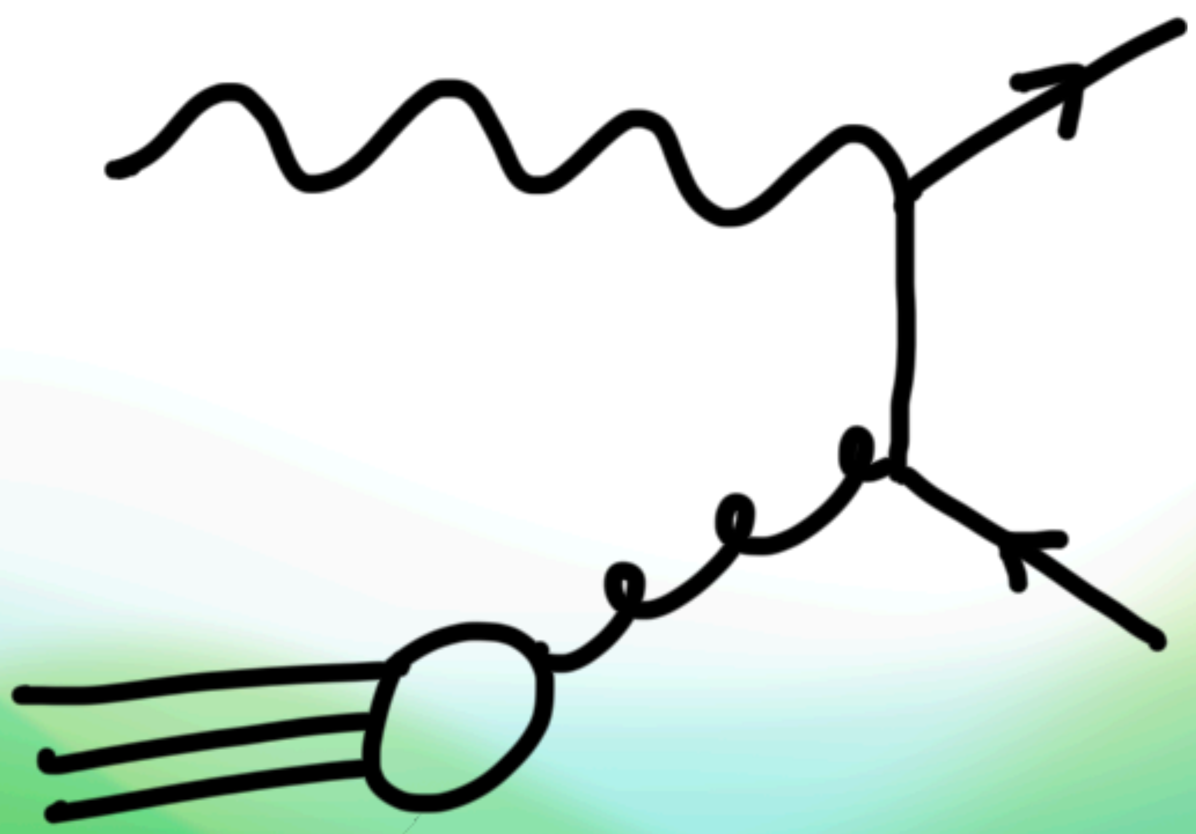
Photoproduction

Photoproduction

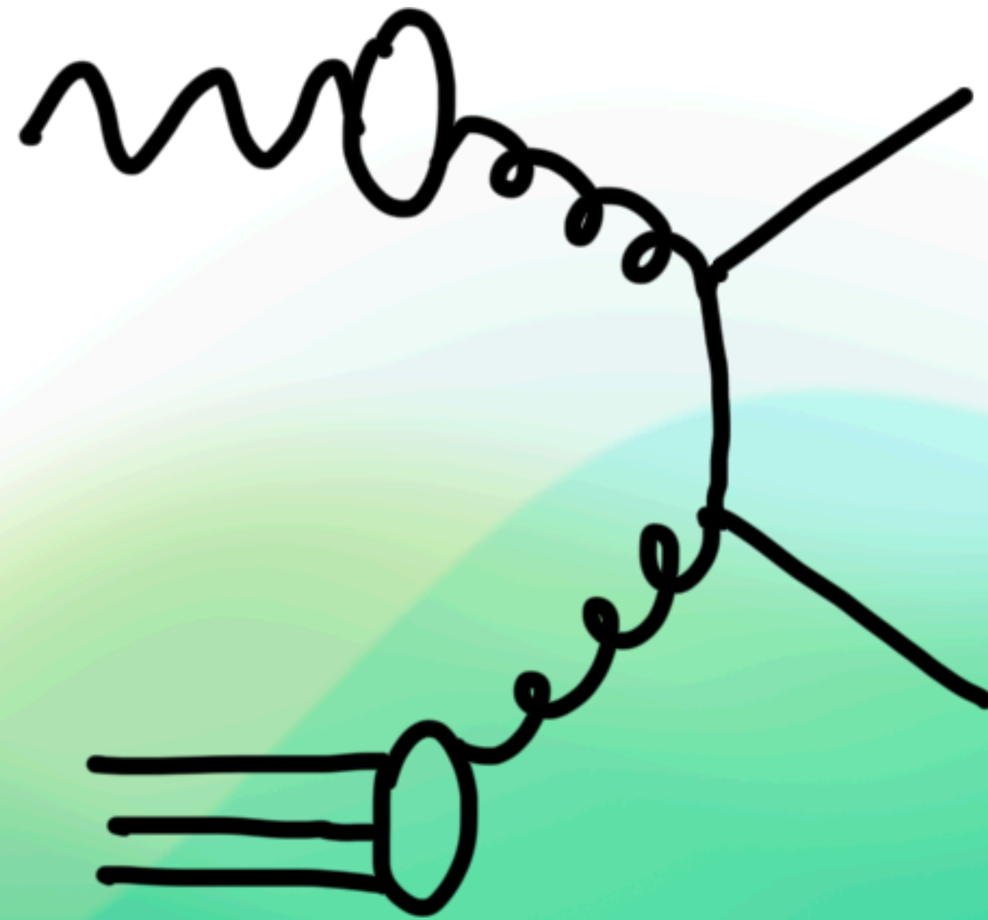
Clarifying the jargon

Photons can also look like hadrons!

Direct photoproduction



Resolved photoproduction



The total cross-section

Weizsäcker-Williams a.k.a
Equivalent Photon spectrum

In photoproduction, it is

$$\sigma_{eP\to X} = \int \mathrm{d}x\, f_{\gamma/e}(x)\, \mathrm{d}\sigma_{\gamma P\to X} = \int \mathrm{d}x\, f_{\gamma/e}(x) \left(\mathrm{d}\sigma^{(\text{direct})}_{\gamma P\to X} + \mathrm{d}\sigma^{(\text{resolved})}_{\gamma P\to X} \right)$$

where

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

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

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

[Nucl.Phys.B Proc.Suppl. 79 (1999) 399-402]

Photon PDFs

The photon PDF obeys the evolution

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

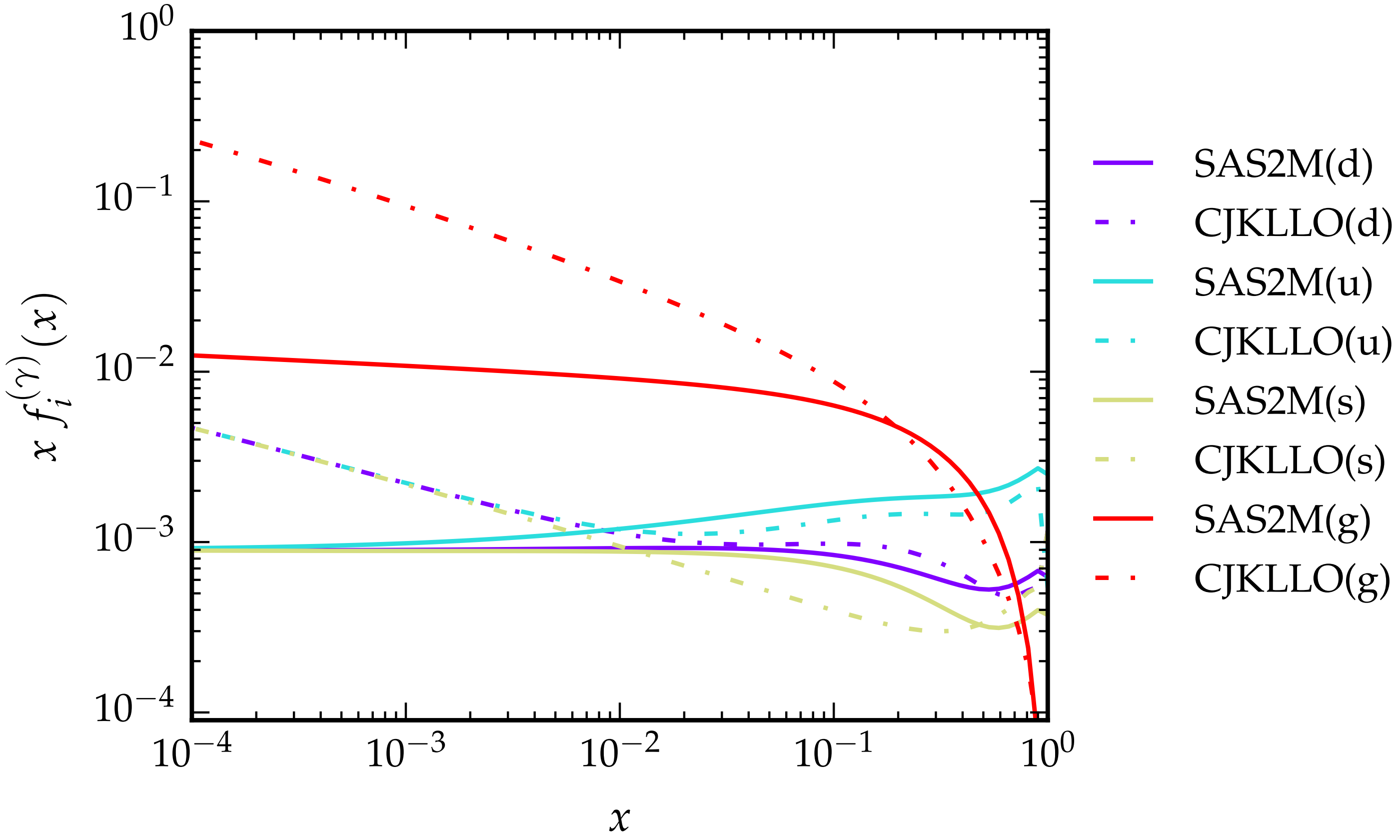
hence, the solution is of the form

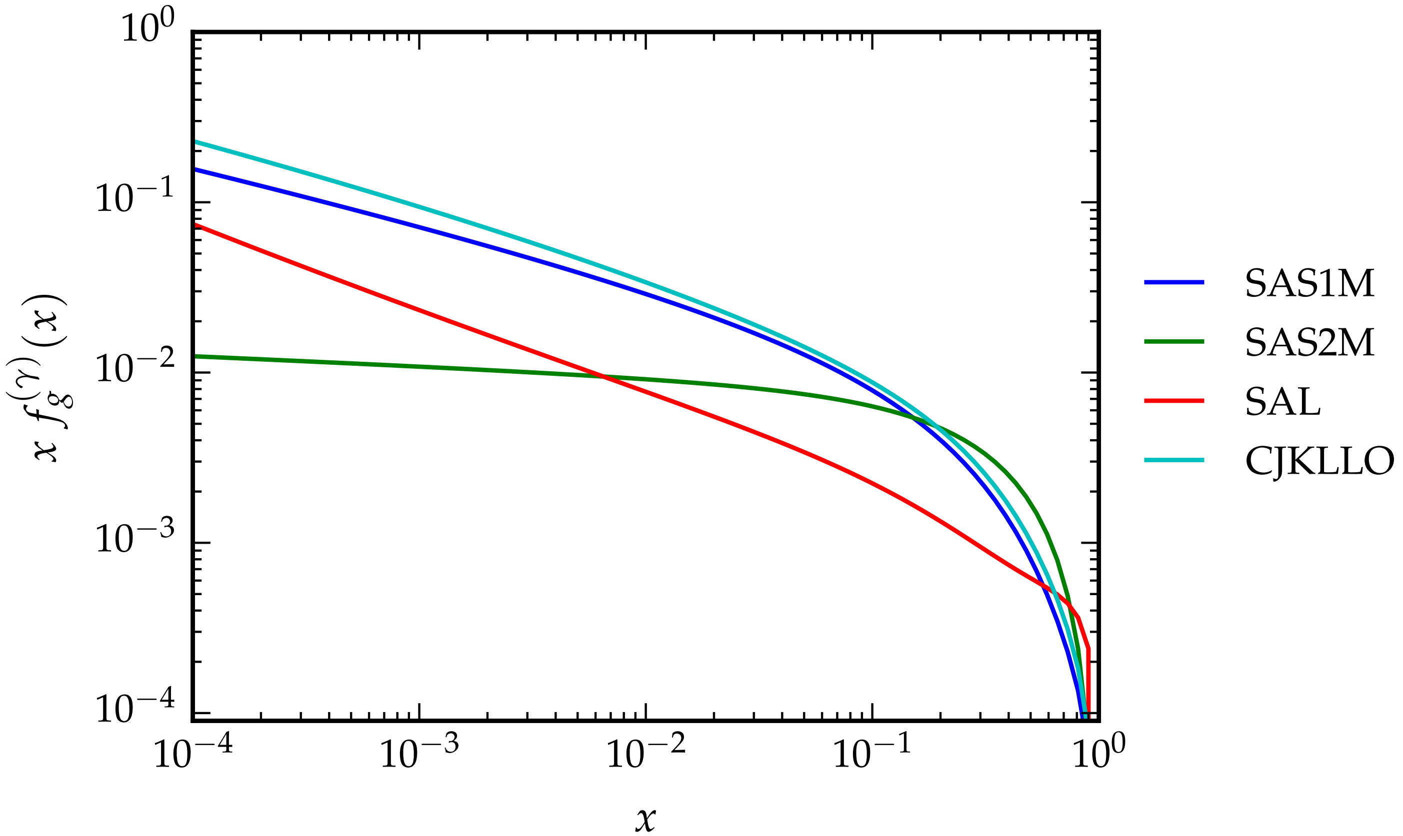
$$f_{i/\gamma}(x, \mu_F^2) = f_{i/\gamma}^{(\rm point-l.)}(x, \mu_F^2) + f_{i/\gamma}^{(\rm hadron-l.)}(x, \mu_F^2)$$

- Four libraries interfaced to Sherpa
- $f_{i/\gamma}^{(\rm hadron-l.)}$ is fitted from non-perturbative input, c.f. Vector-Meson Dominance
- many available, but hard to find; mostly outdated
- differences of factor $\mathcal{O}(10)$
- including Multiple-Parton-Interactions between photon and proton

Photon PDFs

Gluon PDFs dominant channel, but poorly constrained



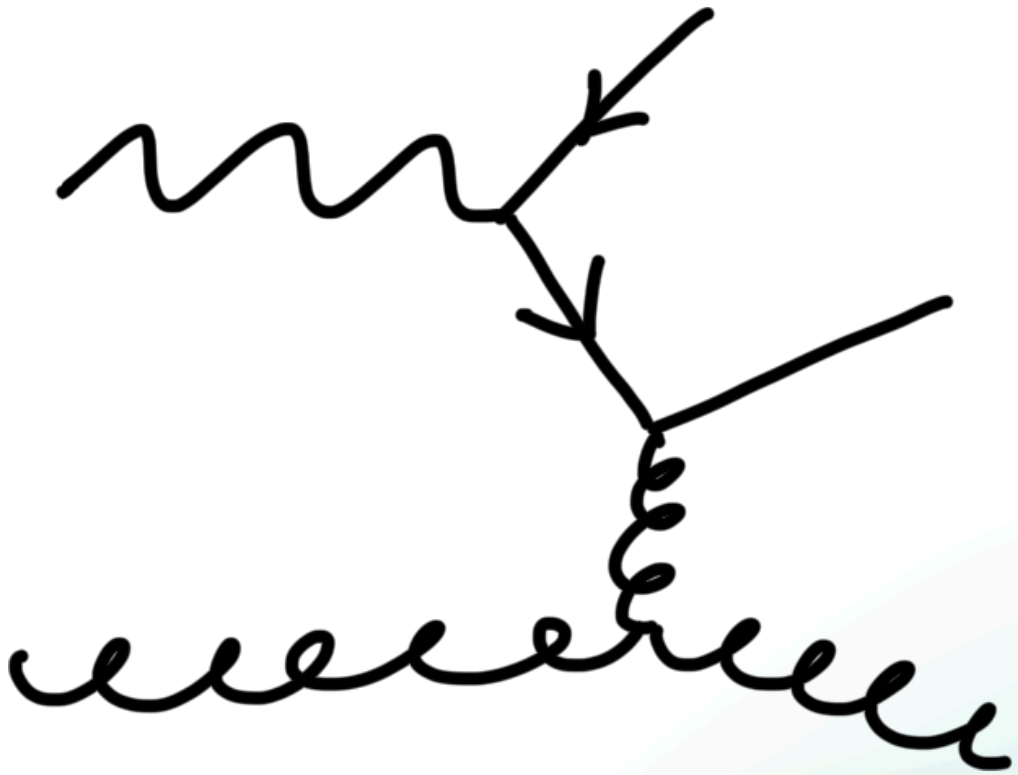


Small-x behaviour differs significantly between different sets

Going to NLO

Conceptual difference to protons

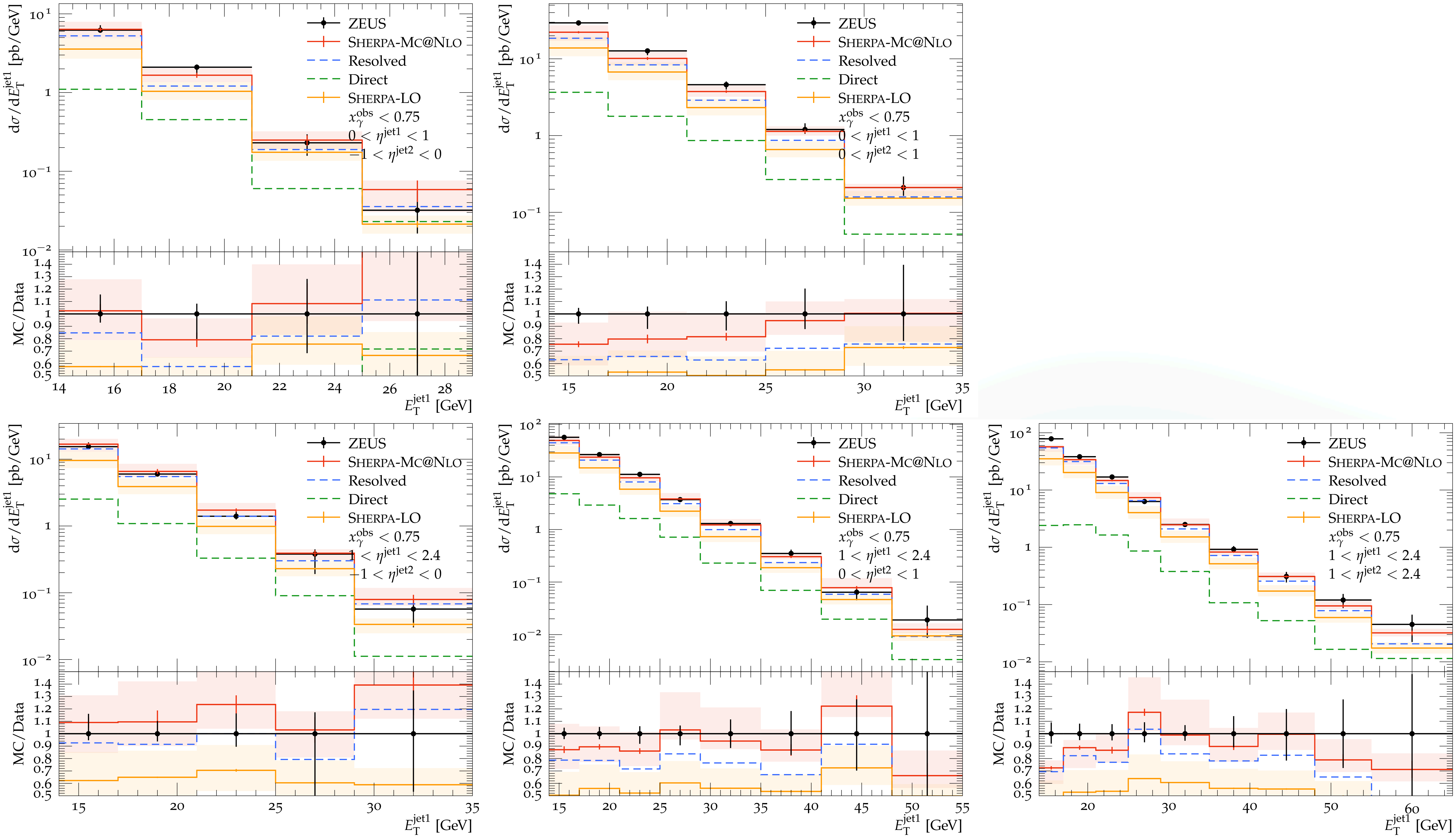
At NLO, the distinction between Direct and Resolved breaks down



Is that a resolved photon? Or a real correction to a direct process?

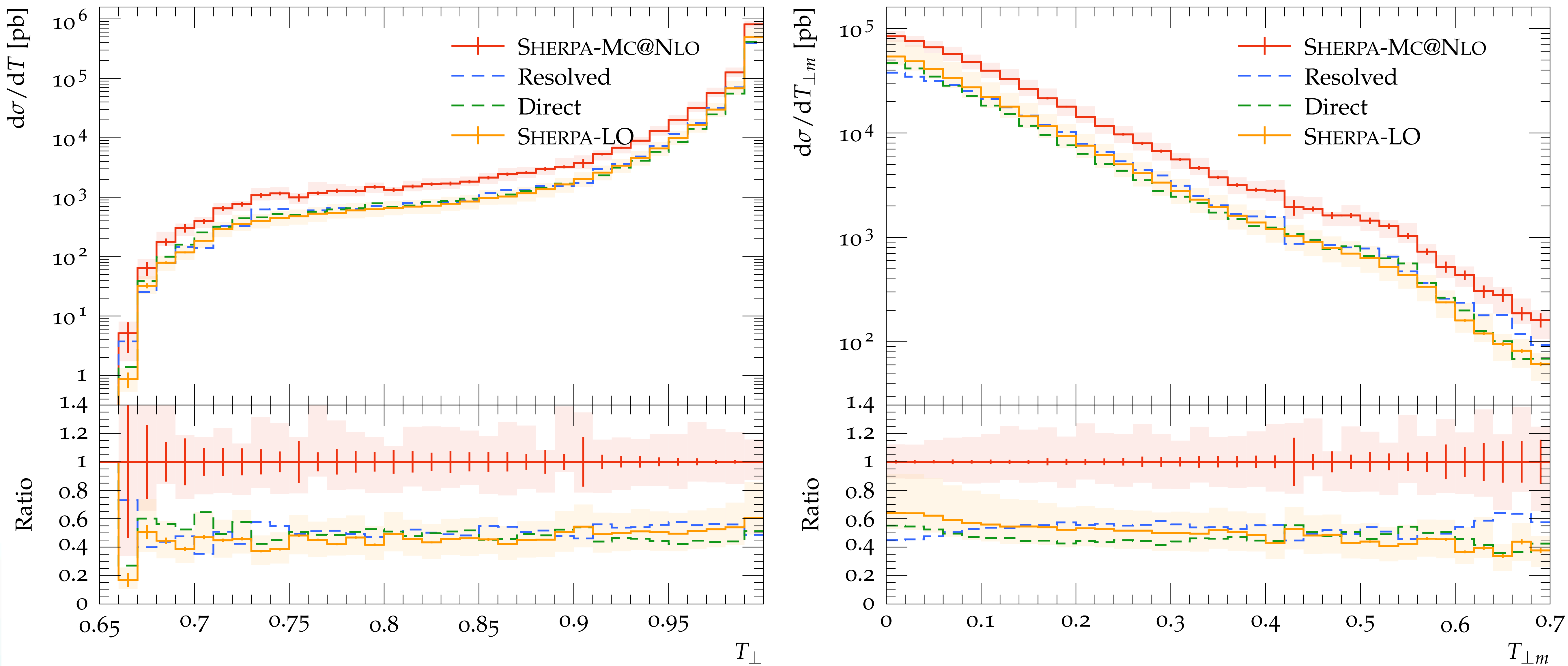
Validation against HERA

Jet transverse energy in different pseudorapidity bins



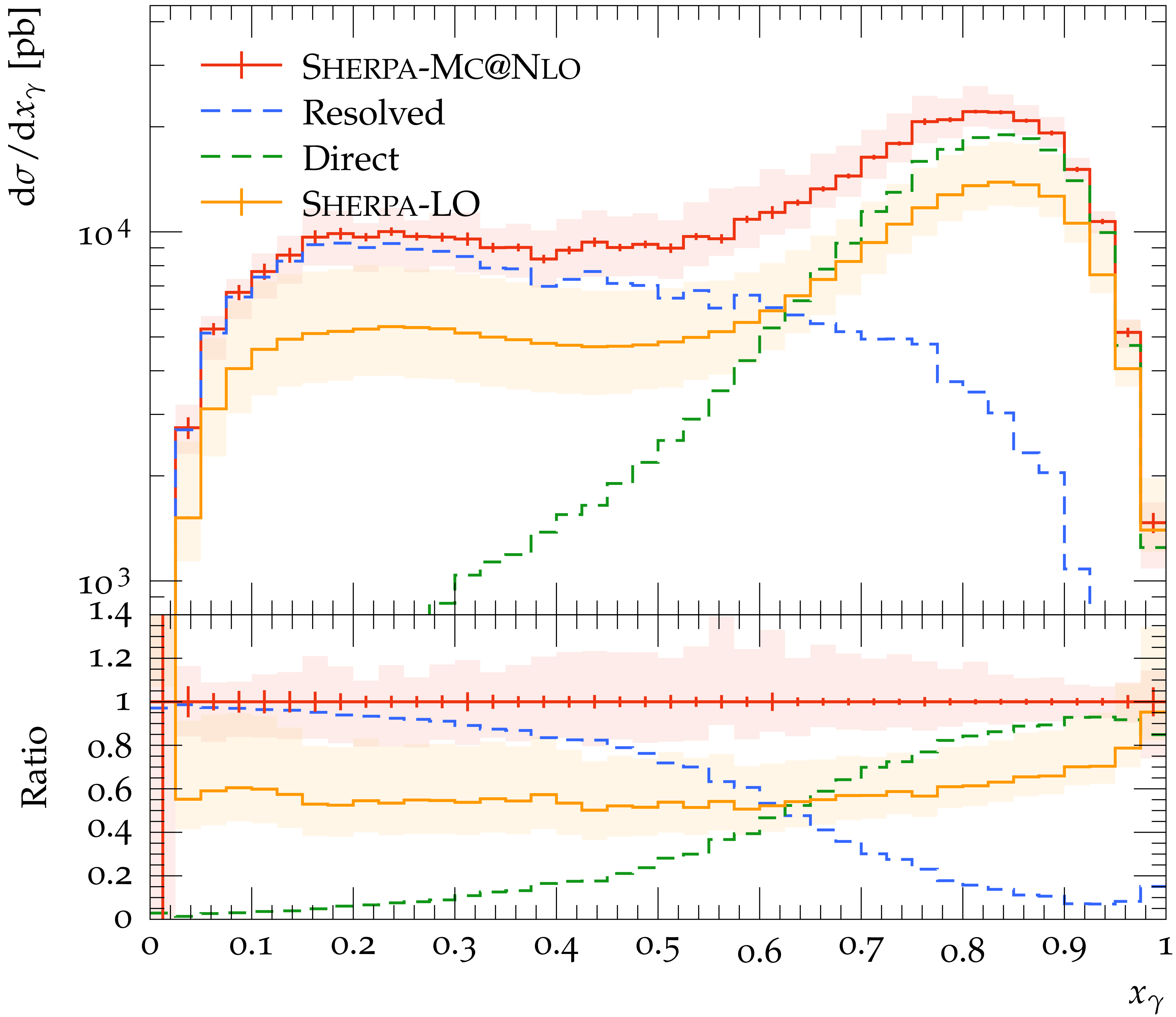
Predictions for EIC

Transverse thrust and transverse thrust minor



Predictions for EIC

Distribution of x_γ



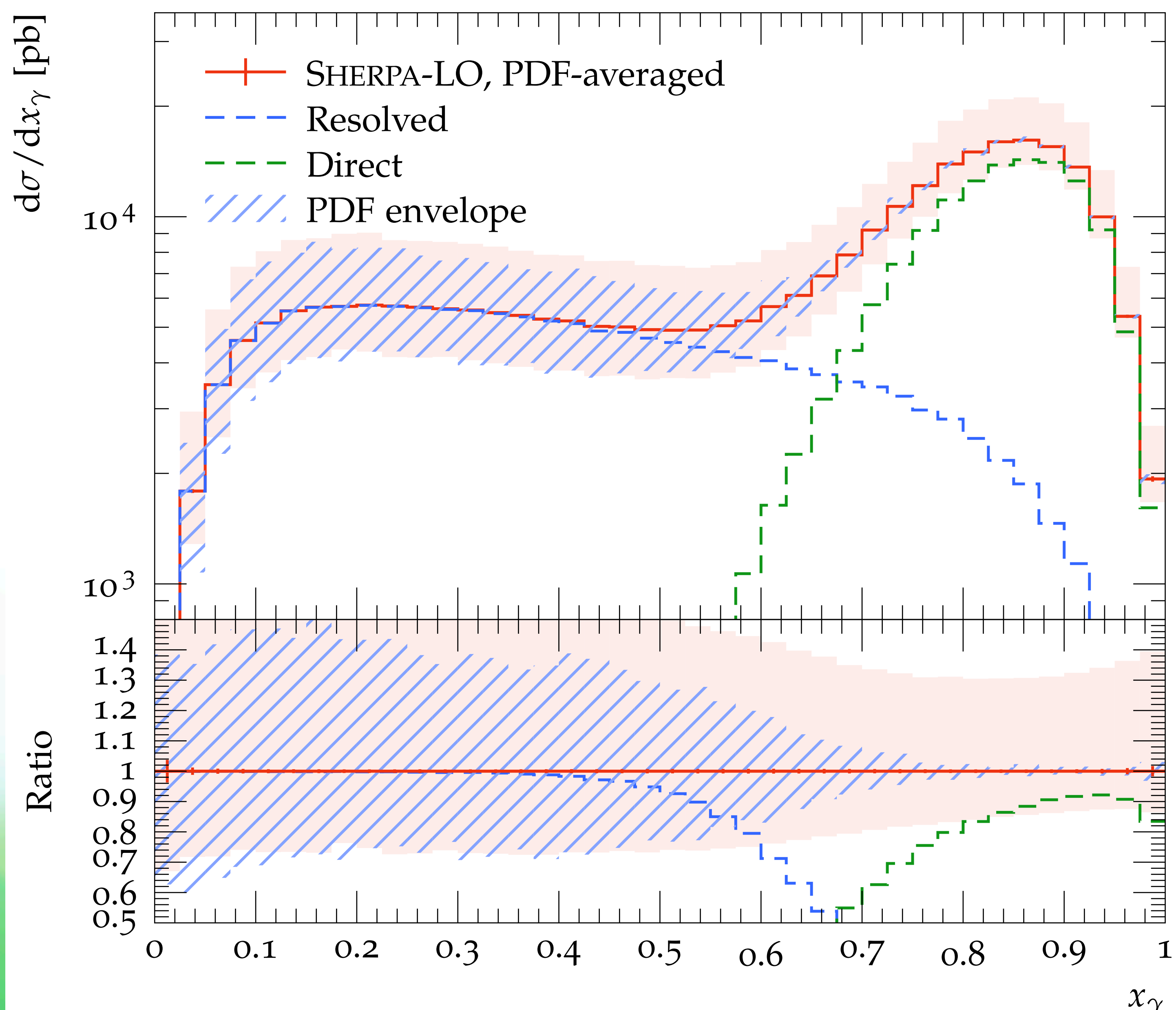
x_γ is a proxy for momentum ratio of parton to photon, defined as

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

Photon PDF quality

The bottleneck in photoproduction 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

New fits are needed!

Diffraction

Diffraction

What we learned at HERA

- Process of type $ep \to eX + Y$, where $+$ denotes a separation in rapidity
- Y is an intact proton or a low-mass excitation
- Experimental identification relies on either large rapidity gaps or proton tagging

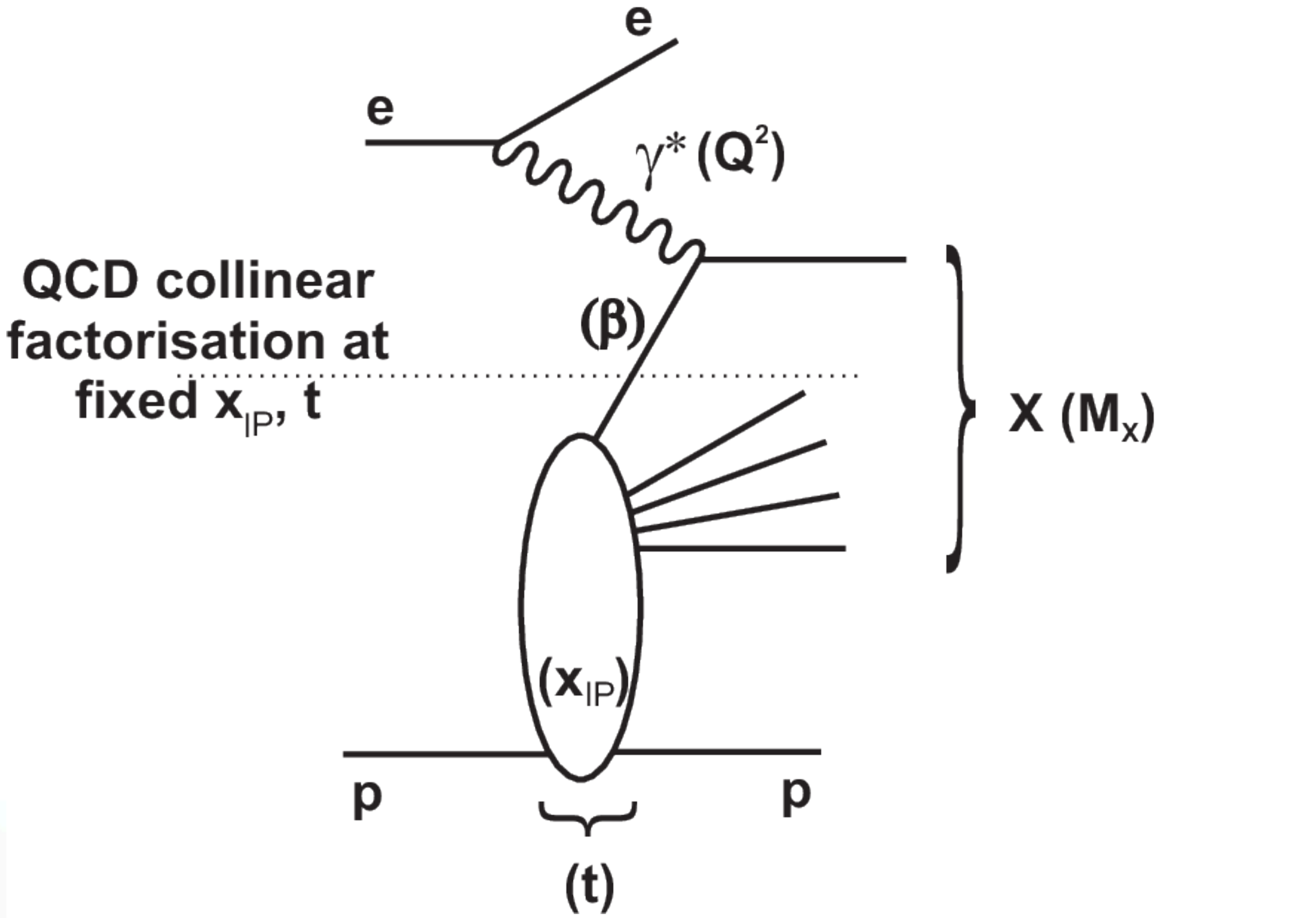
Diffractive processes made up 10% of the total cross-section at HERA

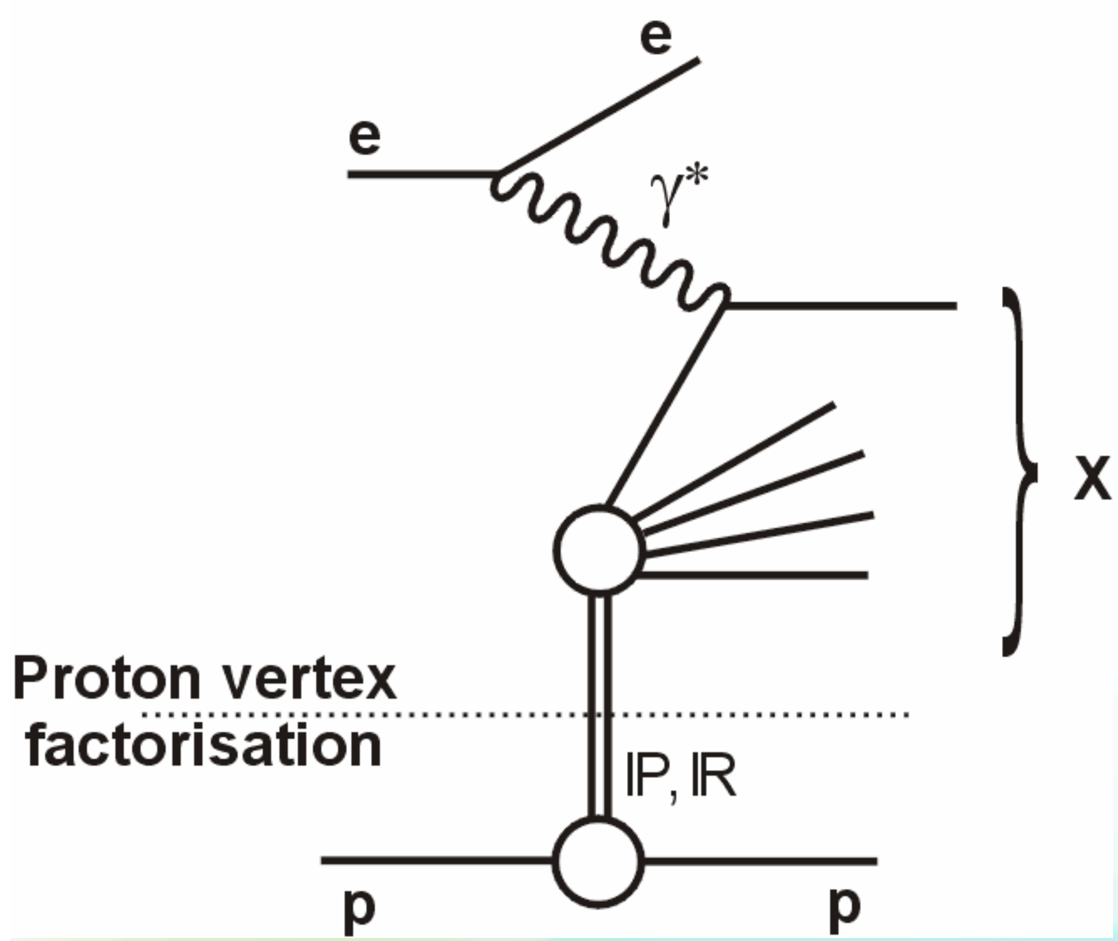
Probing the hadron at low-scales, insights of transition into the non-perturbative region

Background to GPD measurements

Factorisation of diffraction

Introduction of Diffractive PDFs





$$d\sigma^{ep\to eXY}(x,Q^2,x_{IP},t) = \sum_i f_i^D(x,Q^2,x_{IP},t) \otimes d\hat{\sigma}^{ei}(x,Q^2)$$

[*Phys. Rev. D 57, 3051*]

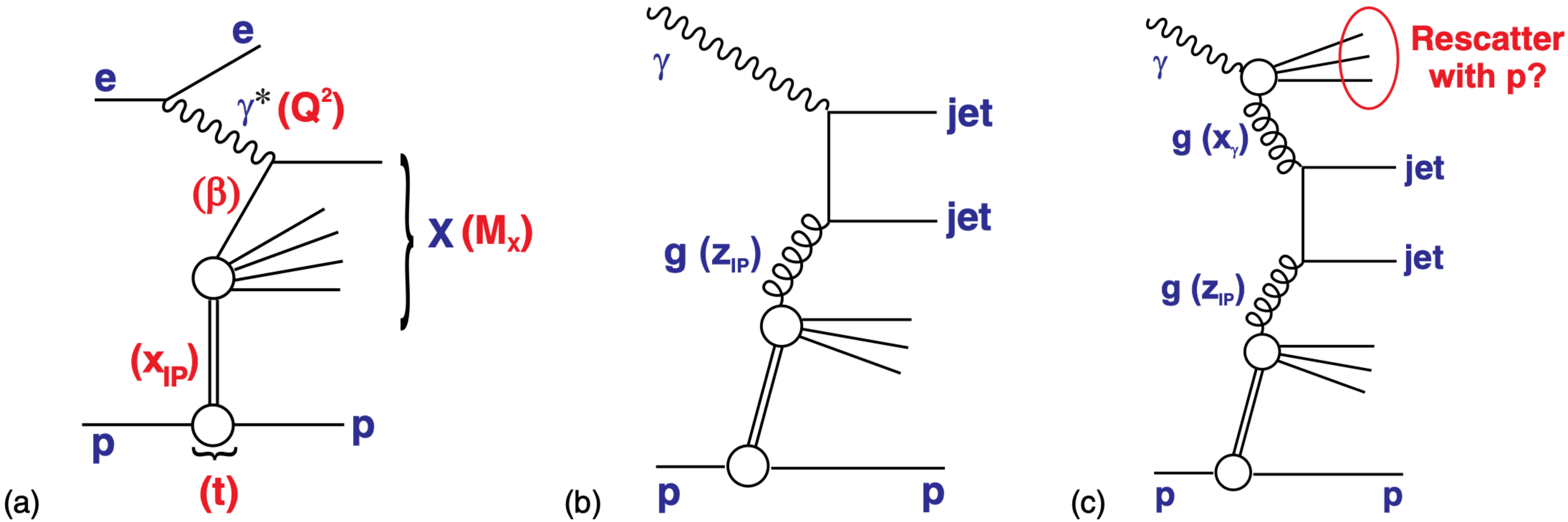
$$f_i^D(x,Q^2,x_{IP},t) = f_{IP/p}(x_{IP},t) f_i(\beta = x/x_{IP}, Q^2)$$

[*Phys. Lett. 152B, 256*]

Diffraction

Contributions to the cross-section

taken from [*Rev.Mod.Phys. 86 (2014) 3, 1037*]



Diffractive DIS

factorisation proven to hold

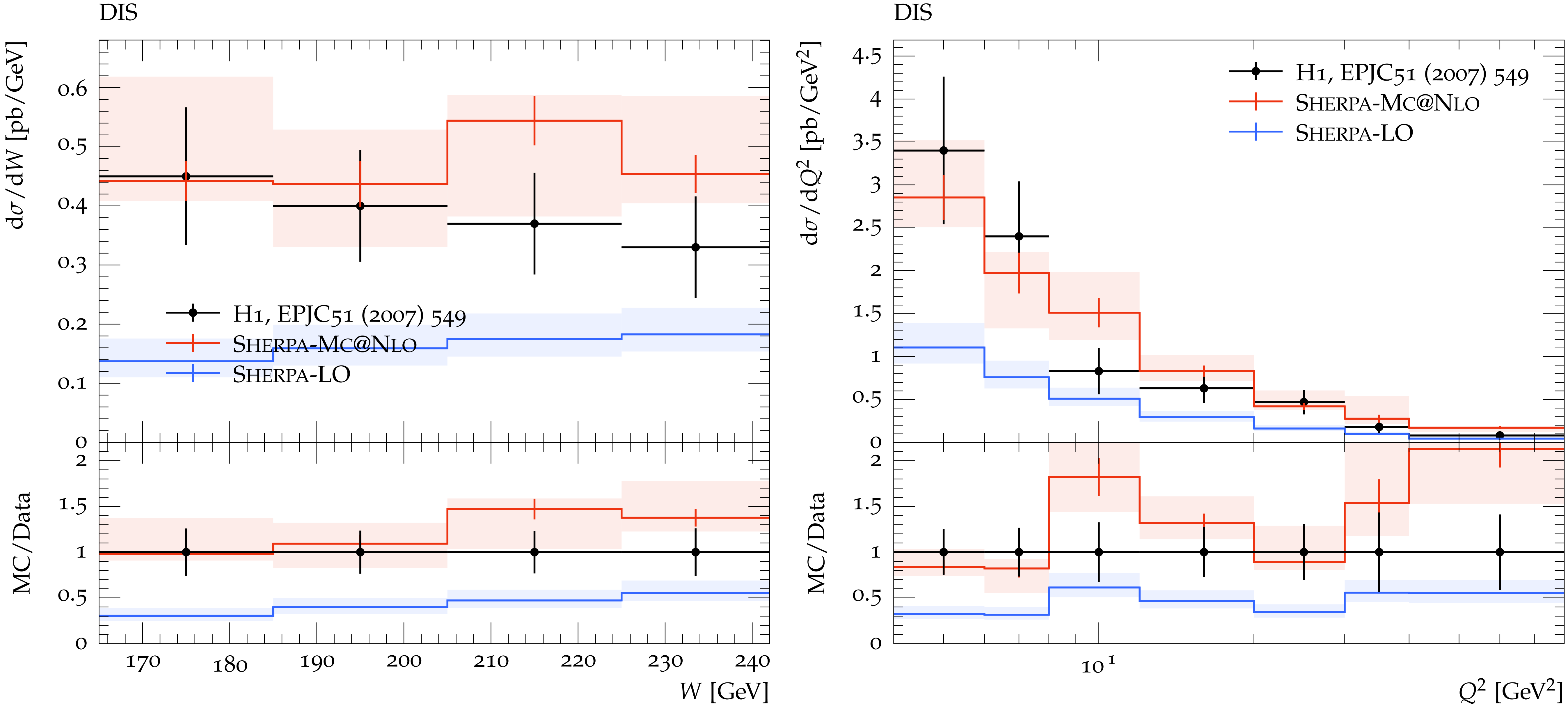
Diffractive Photoproduction

factorisation breaks down

window to diffraction at hadron colliders

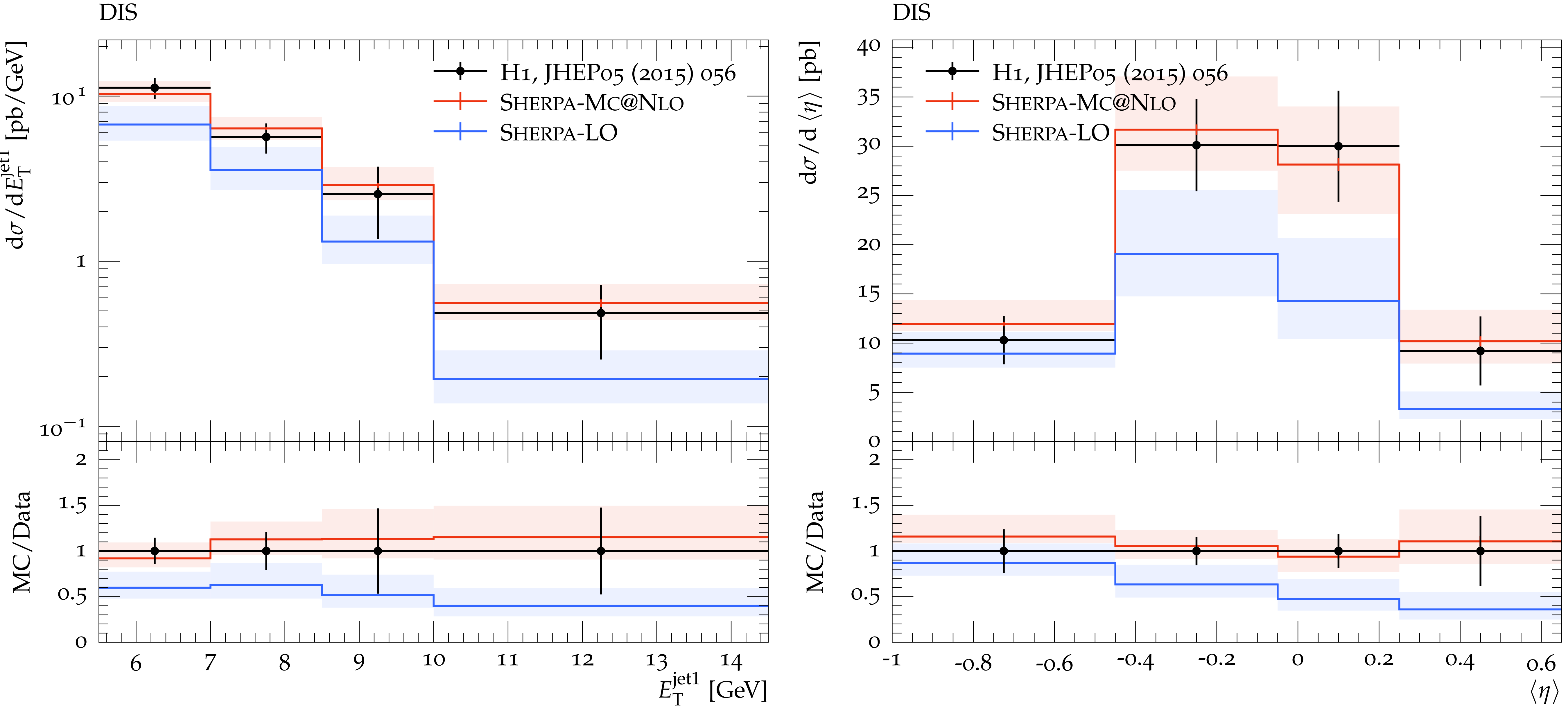
Validation against HERA data

Diffractive DIS



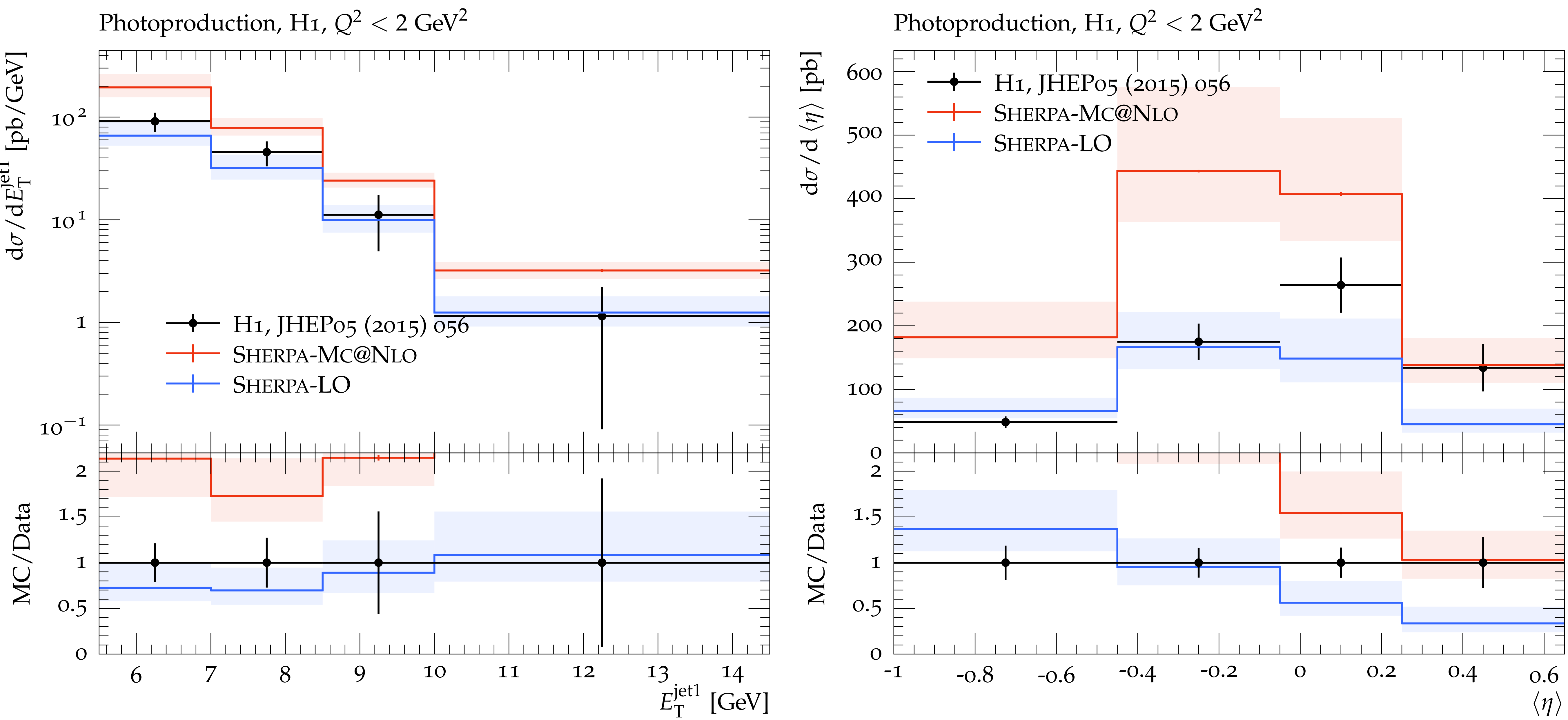
Validation against HERA data

Diffractive DIS



Validation against HERA data

Diffractive Photoproduction



Validation against HERA data

Factorisation breaking has been observed at H1

ZEUS however does **not** support the evidence

Common explanations include:

- Soft rescattering, i.e. MPIs, between the photon and the proton
- Hadronisation effects
- Different phase space cuts
- DPDFs and their applicability; dependence on used data?
- Photon PDF and its $x_\gamma \to 1$ behaviour?

See, for example, [*Eur.Phys.J.C 66 (2010) 373-376*] and [*Eur.Phys.J.C 71 (2011) 1741*]

All these do not suffice to explain the differences and the factorisation breaking

Factorisation breaking

Fit of the data in diffractive photoproduction

Is the assumption of factorisation breaking only in resolved photoproduction valid?

Testing the hypothesis:

Fit direct and resolved component to data separately using full event simulation

This is accounting for 1.) NLO corrections, 2.) parton shower, 4.) hadronisation and 5.) bin migration

	H1, EPJC51 (2007) 549 [72]	H1, JHEP05 (2015) 056 [136]	ZEUS, EPJC55 (2008) 177 [137]
R_{res}	0.4 ± 0.1	0.6 ± 0.3	1.3 ± 0.1
R_{dir}	0.4 ± 0.1	0.3 ± 0.2	0.5 ± 0.1

Factorisation breaking

Fit of the data in diffractive photoproduction

Is the assumption of factorisation breaking only in resolved photoproduction valid?

Conclusion: probably not! ZEUS actually in agreement with H1 in that factorisation breaking also in direct component!

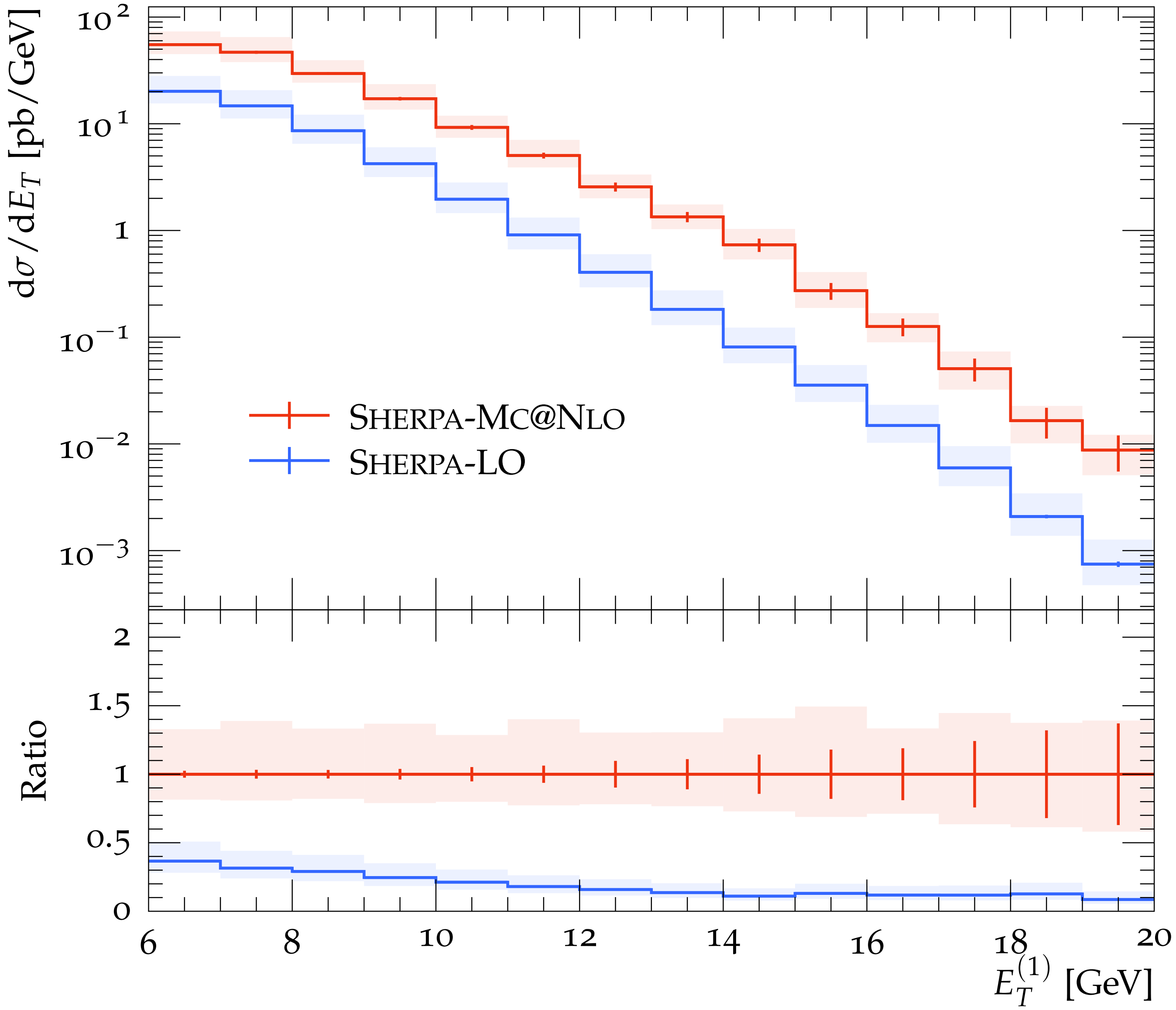
Direct and resolved photons are indistinguishable at NLO

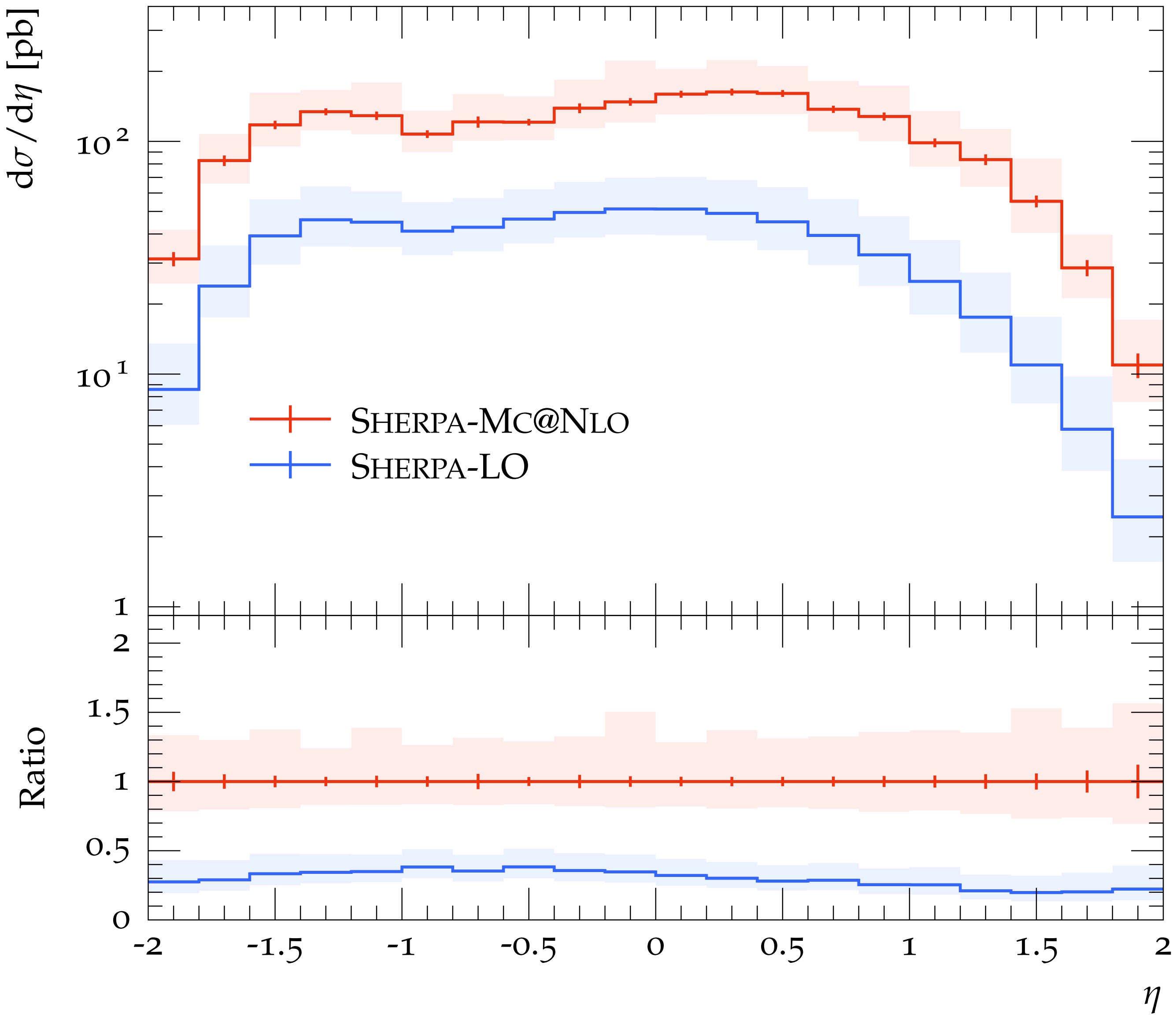
Suppression based on additional interactions between the photon and the proton might be the underlying reason for factorisation breaking

But multiple interactions for "direct" photons poses a conceptual problem

Predictions for EIC

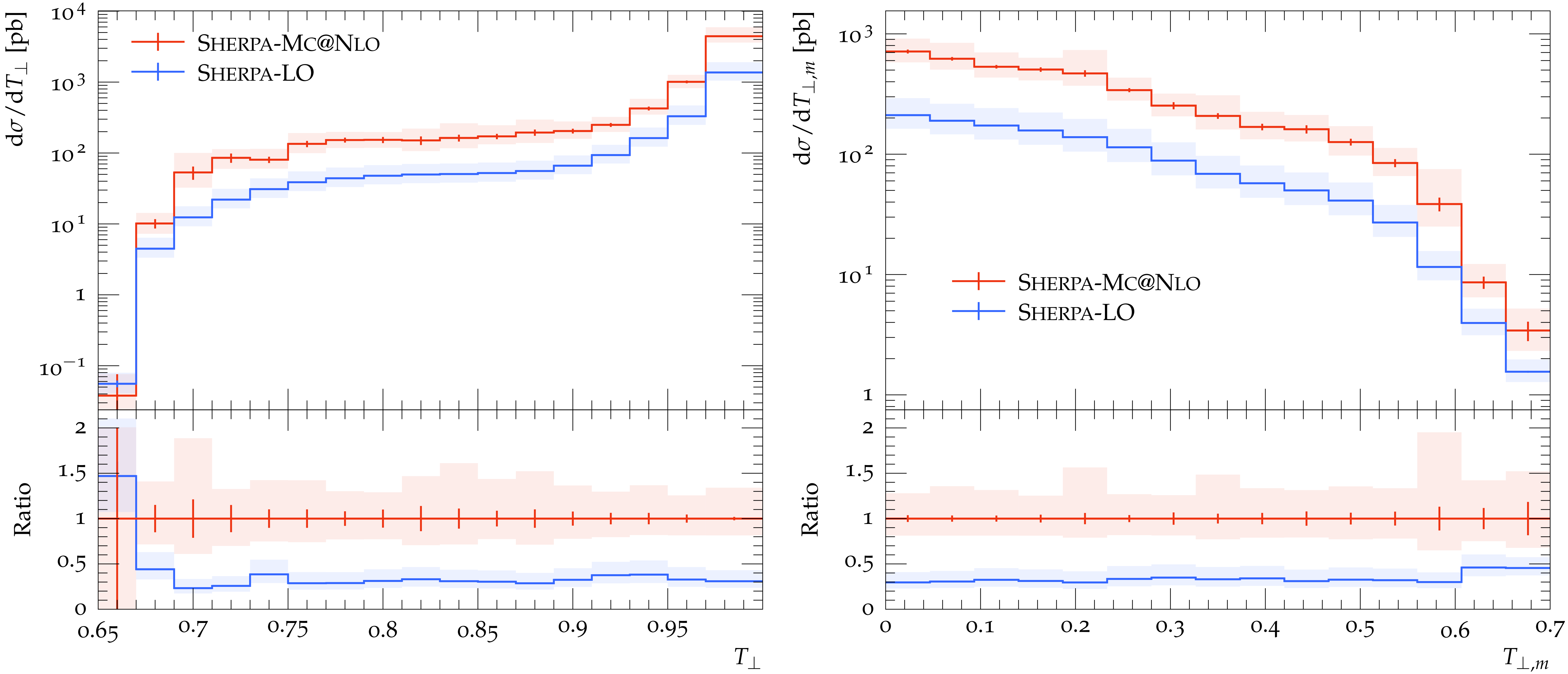
Leading-jet E_T and inclusive jet pseudo-rapidity in diffractive DIS





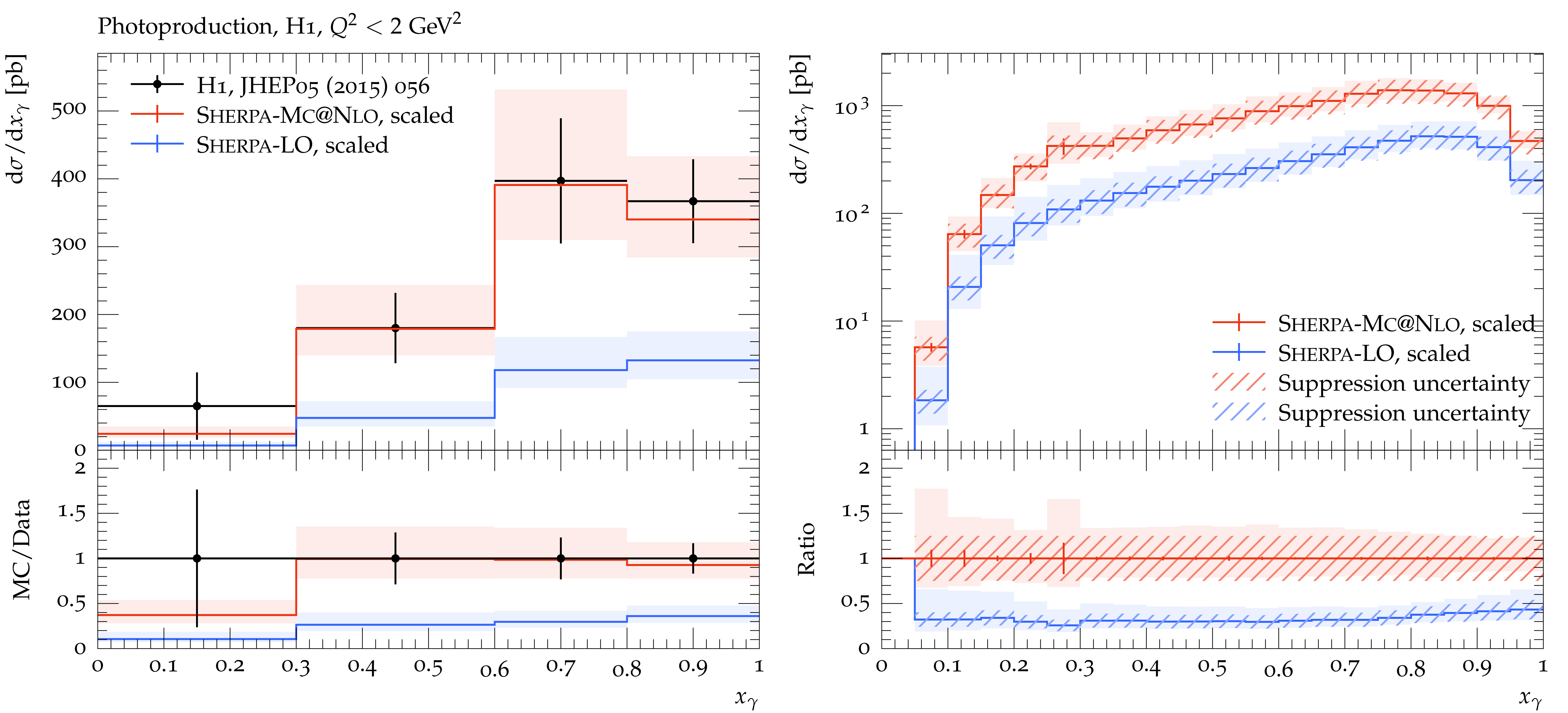
Predictions for EIC

Transverse thrust and thrust-minor in diffractive DIS



Predictions for EIC

Fitted simulation for H1 (left) and EIC (right)



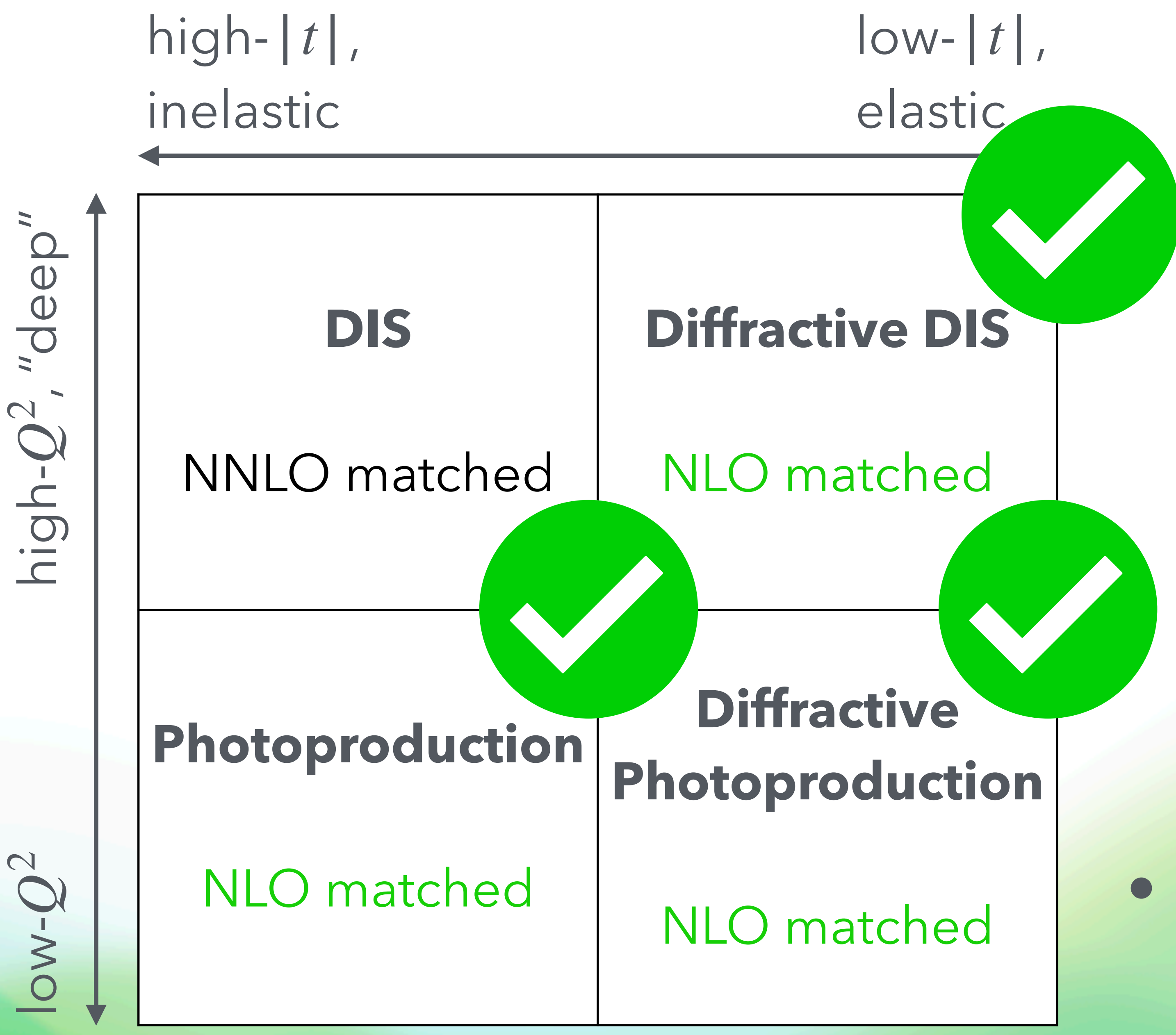
Conclusion

Event generation for the EIC

	high-$|t|$, inelastic	low-$|t|$, elastic
high-Q^2, "deep"	**DIS** NNLO matched	**Diffractive DIS** Only Fixed Order
low-Q^2	**Photoproduction** LO+PS	**Diffractive Photoproduction** LO+PS

Conclusion

Event generation for the EIC



- First hadron-level matched NLO predictions for Photoproduction, Diffractive DIS and Diffractive Photoproduction in Sherpa
  Crucial for background studies and inclusive QCD observables at the EIC, for example in α_s extraction and jet physics
  Photon PDFs are a bottleneck for precision photoproduction phenomenology
- Diffractive jet production and its factorisation breaking not yet understood, predictions/models need confrontation with data

Backup