Photoproduction and Diffraction at NLO in Sherpa

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

Outline

1. Introduction and motivation
2. Photoproduction
    1. Theory
    2. Photon PDFs and NLO matching
    3. Validation and predictions
3. Diffraction
    1. Theory
    2. Factorisation breaking
    3. Validation and predictions
4. Conclusion

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

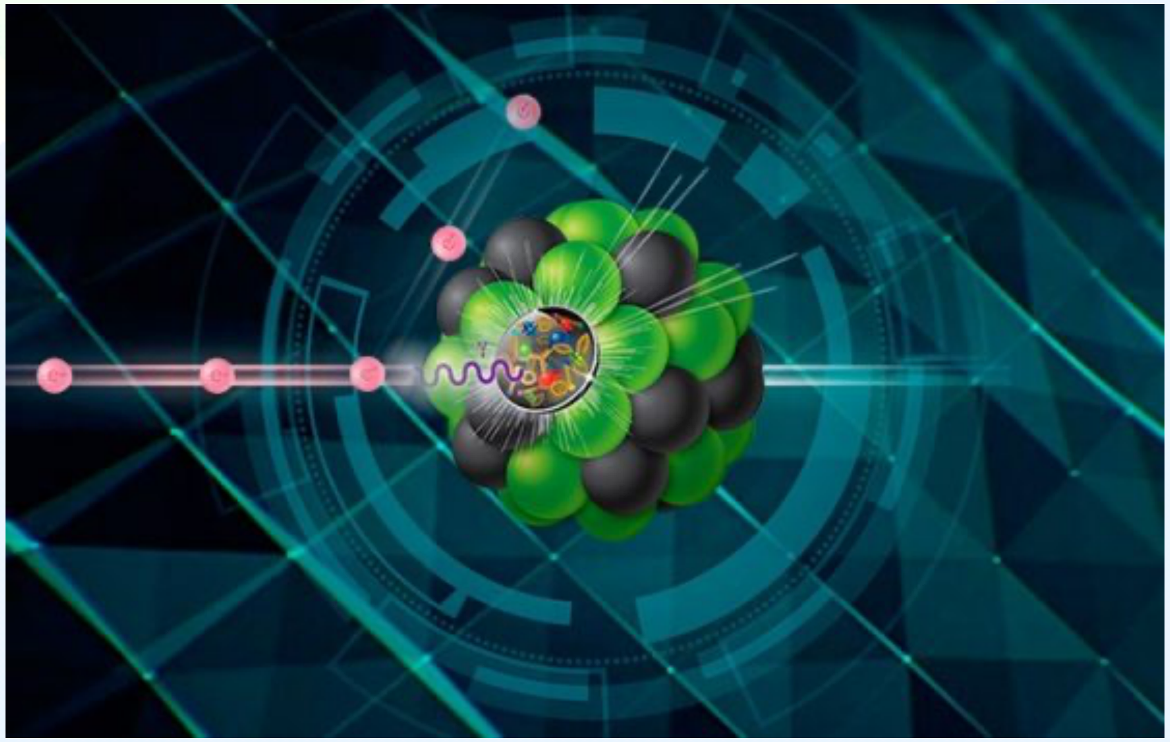
Soft photon resummation in production
- YFS-based resummation
- matched up to $O(\alpha^3 L^3)$
- QCD+QED parton shower
- Electron structure function

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

Lepton—hadron colliders

Window to parton content and non-perturbative physics

- Decades long interest; played important role in discoveries
- Simple kinematics and clean environment, fully described by Q^2, y, x and s
- Upcoming Electron-Ion Collider at BNL, programme is "understanding the glue that binds us all"
- Allows to measure properties of nuclei, e.g. spin distribution, spatial distribution and transverse momenta of partons

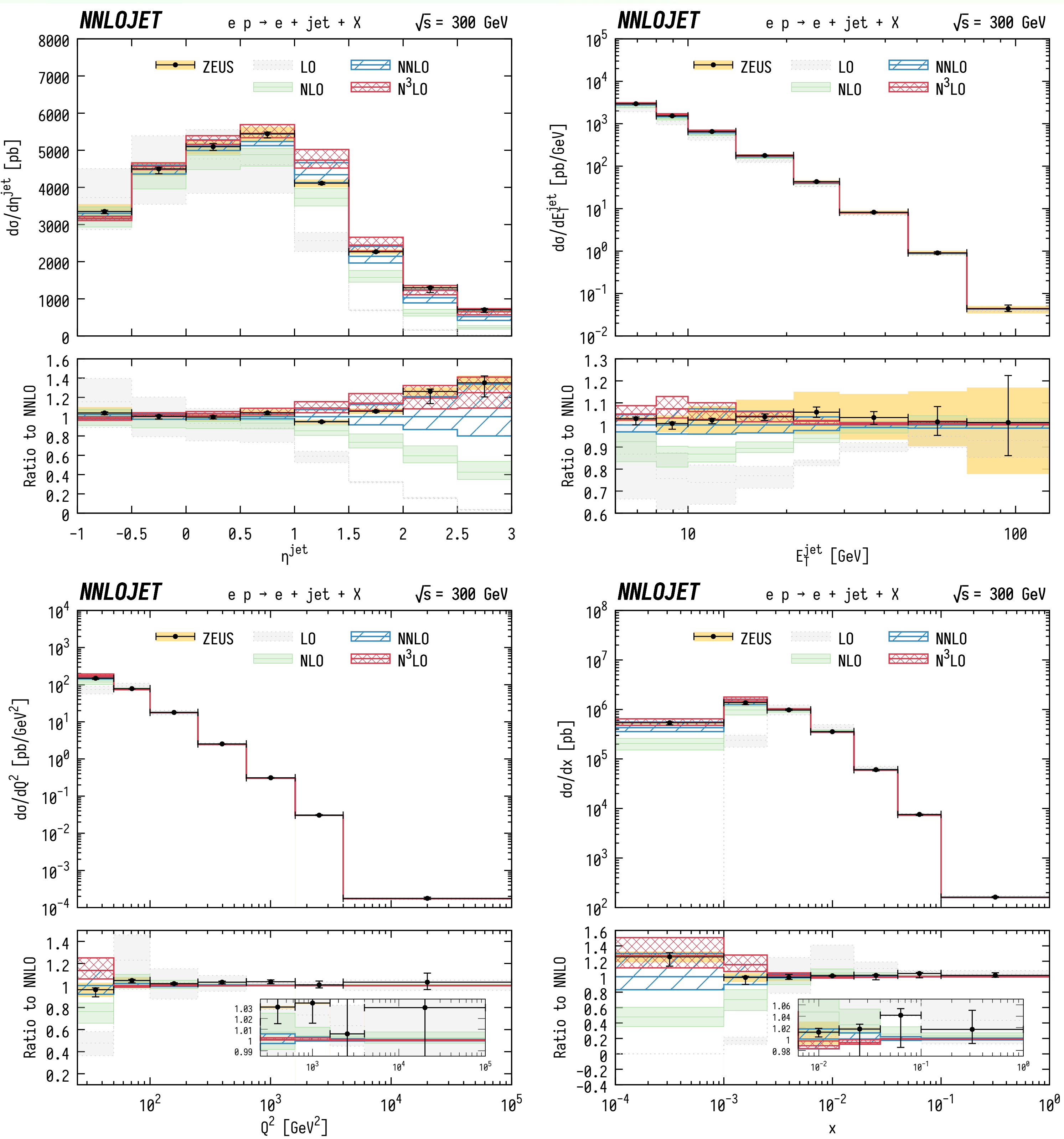


(Image courtesy of Brookhaven National Laboratory)

> *Continuing interest has lead to excellent theoretical understanding and highly accurate predictions for DIS*

Lepton—hadron colliders

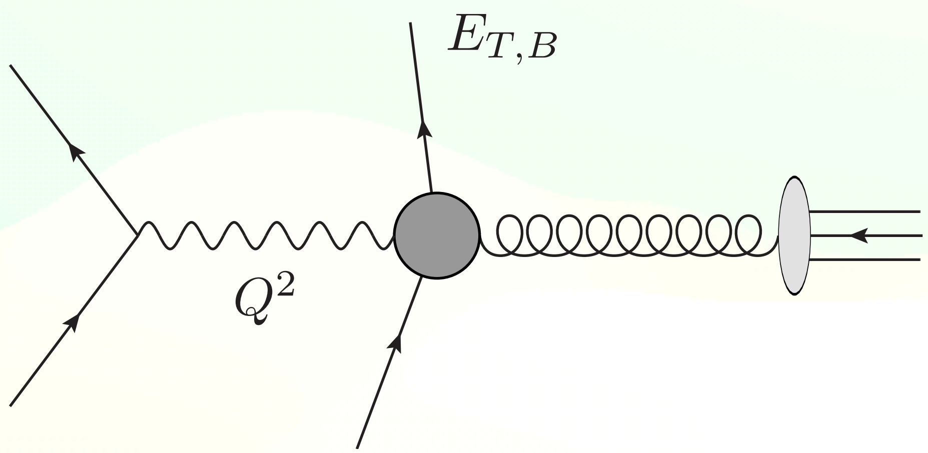
State of the art calculations



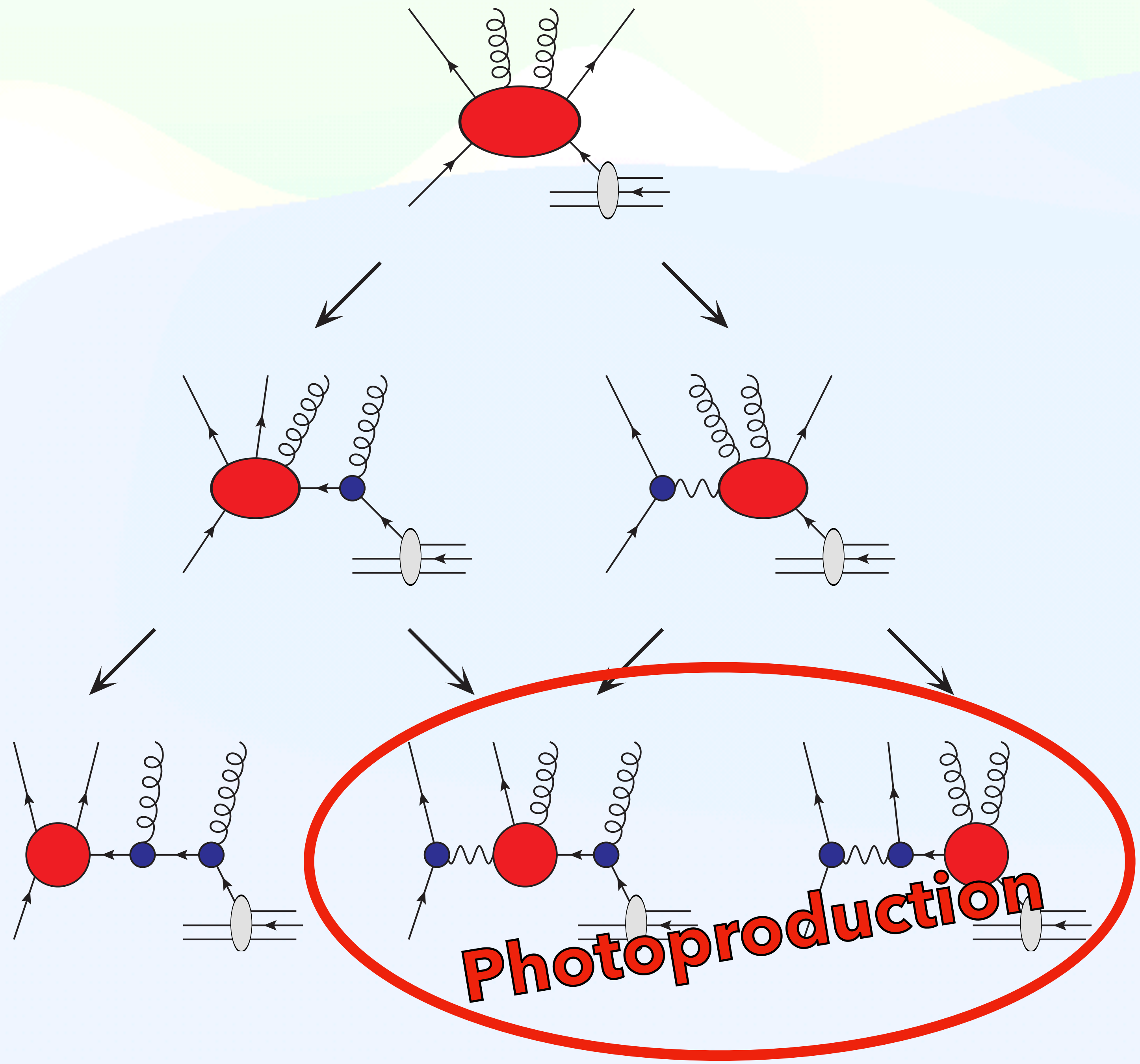
- [*JHEP 05 (2018) 209*] achieved N3LO QCD, fully differential, at Fixed Order using Antenna subtraction and Projection-to-Born
- [*PRD 98 (2018) 11, 114013*] achieved N2LO QCD, fully exclusive with UN2LOPS matching
- Data from ZEUS with $Q^2 > 25$ GeV^2, $y > 0.04$, $E'_e > 10$ GeV, $E_{T,j} > 6$ GeV, $-1 < \eta_j < 3$

Choosing the correct scale

Competition between Q^2 and $E_{T,B}$



- Need to take into account additional emissions
- Merging or Higher Order Corrections can fix it partially
- Correct clustering of scale hierarchies is the key to correct computation



Photoproduction

Motivation

Photoproduction

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

Photoproduction is the dominant channel for jet production!

What is the status-quo in hep-ph for lepton–hadron colliders?

- For $Q^2 \gg 0$, predictions available fully-exclusive at NNLO or Fixed Order N^3LO
- For $Q^2 \gtrsim 0$, only Leading Order + Parton Shower or Fixed Order NLO

Missing full and accurate simulations for a large part of the total cross-section

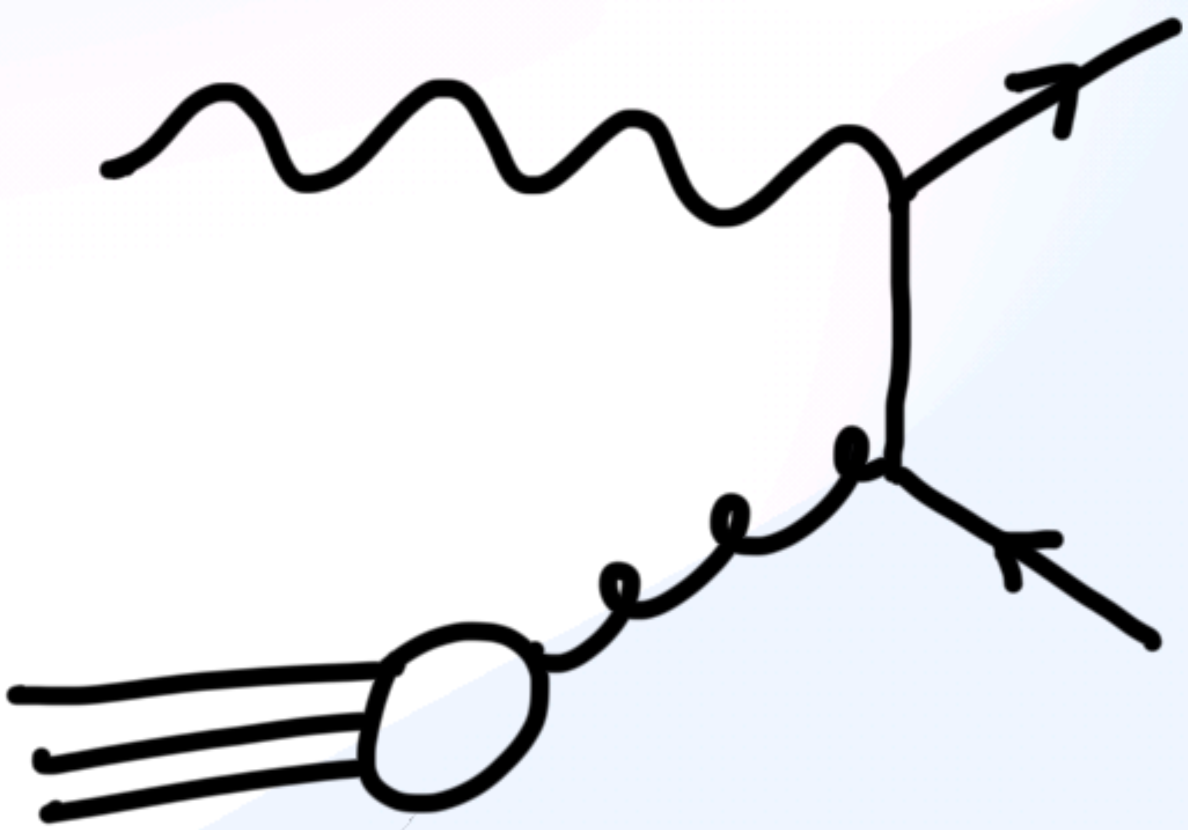
Necessary e.g. for precise α_S extraction and jet physics at the EIC

Photoproduction

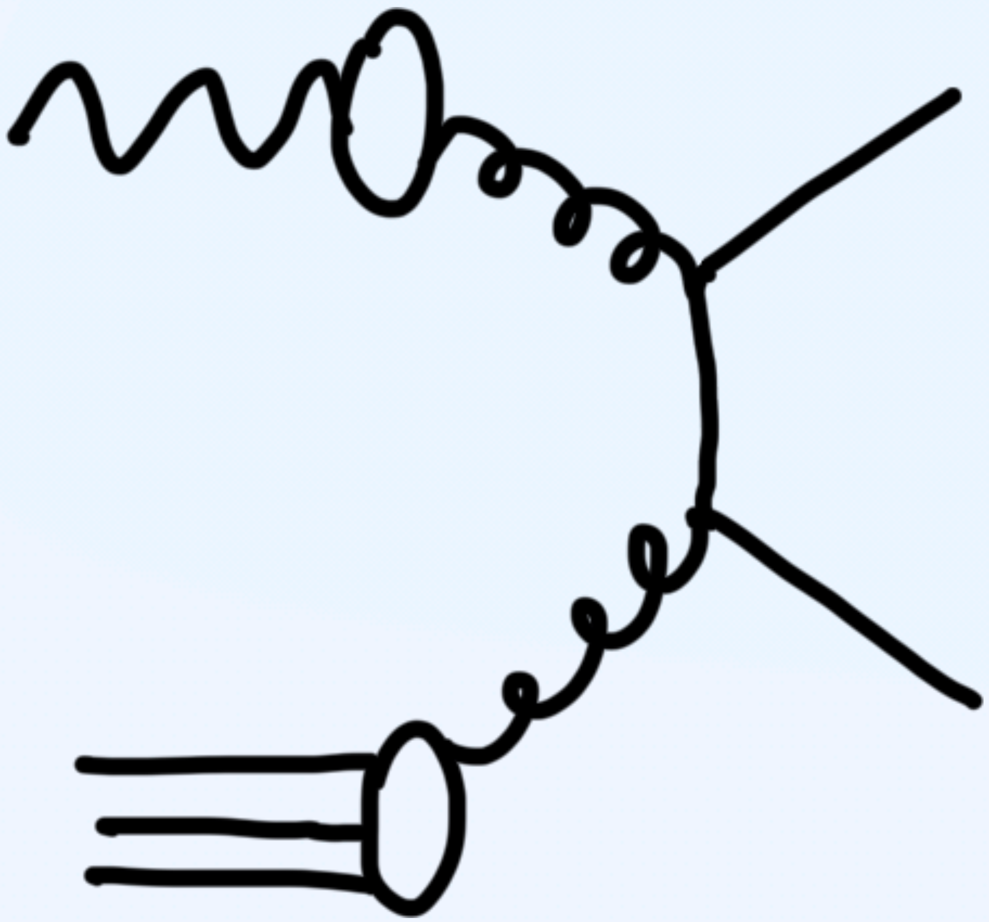
Clarifying the jargon

Photons can also look like hadrons!

Direct (aka. point-like) photoproduction



Resolved (aka. hadron-like) photoproduction



The total cross-section

In photoproduction, it is

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

where

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

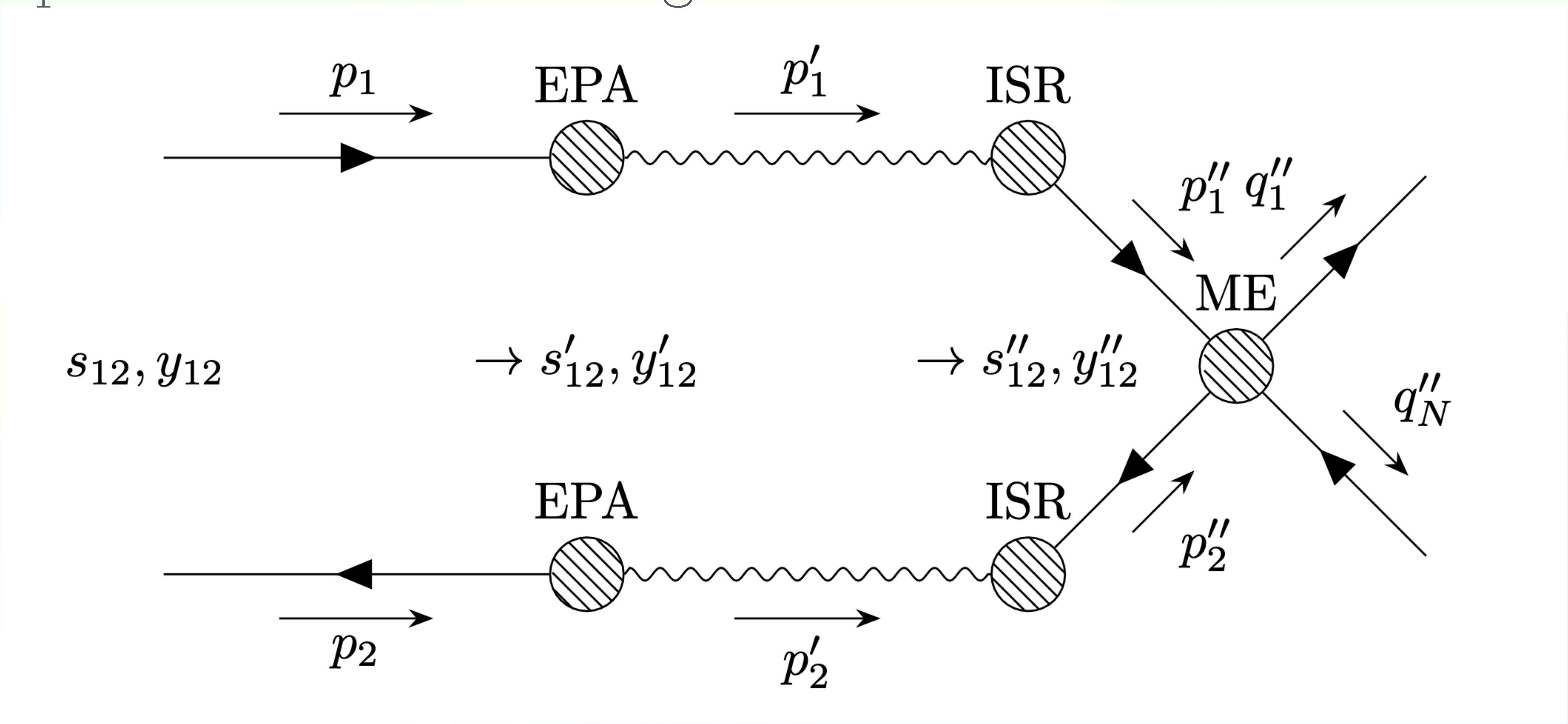
$$\mathrm{d}\sigma^{(\text{hadr})}_{\gamma P\to X} = \sum_{ij} \int\int \mathrm{d}x_1\, \mathrm{d}x_2\, f_{i/P}\left(x_1, \mu_F^{(P)}\right) f_{j/\gamma}\left(x_2, \mu_F^{(\gamma)}\right)\, \mathrm{d}\hat{\sigma}_{ij}\left(\{p_k\}, \alpha_S(\mu_R), \mu_F^{(P)}, \mu_F^{(\gamma)}\right)$$

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

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

Phase Space Setup

Exemplified with the most general case



- Additional phase space integration using multi-channeling and Vegas optimization
- Calculate Initial State Radiation wrt. the “bunch” energies, i.e. the photon
- Any other case simplifies this setup

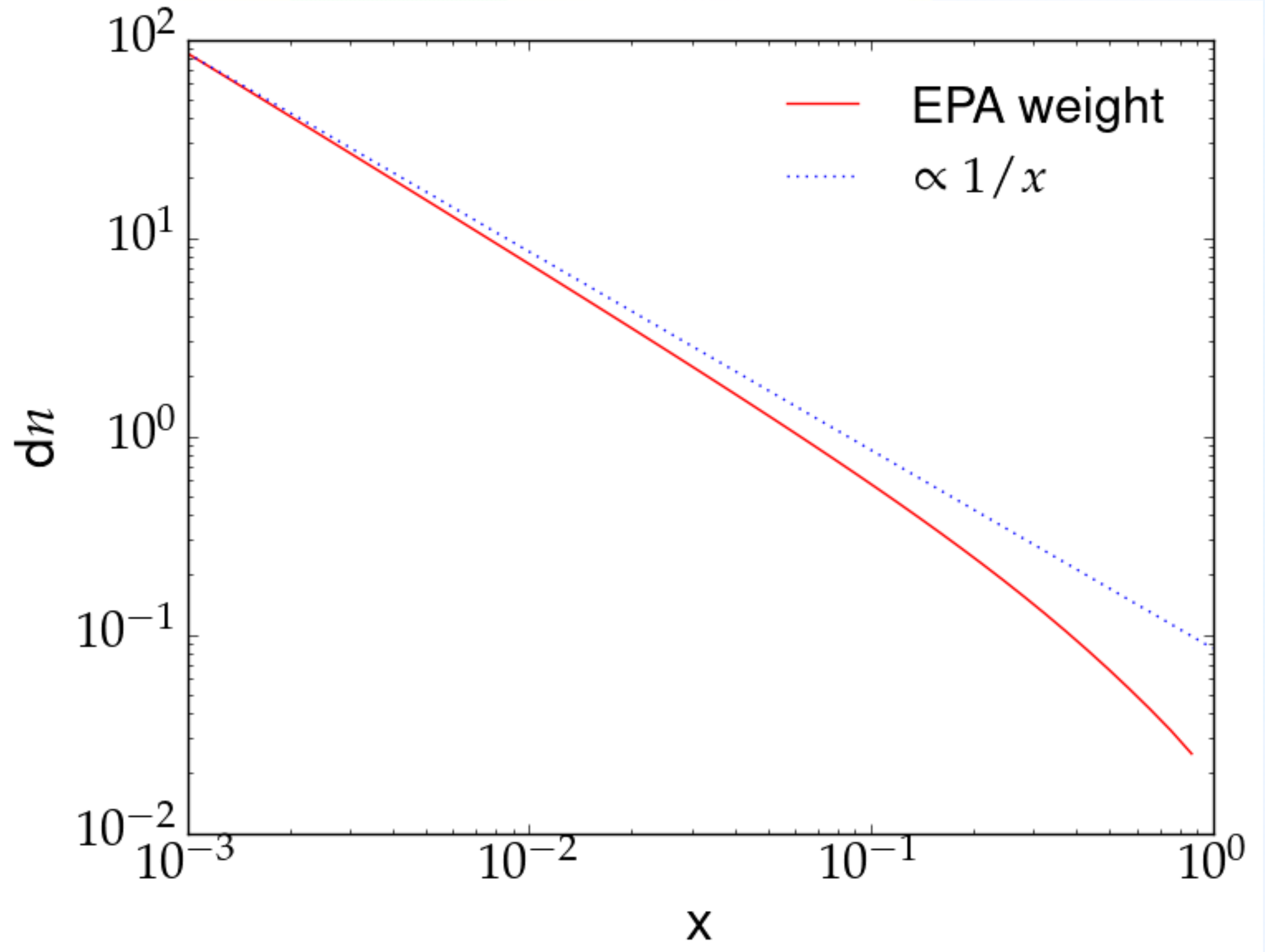
Equivalent Photon Approximation

a.k.a. Weizsäcker-Williams approximation

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

dominated by this term

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



Photon PDFs

The photon PDF obeys the evolution

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

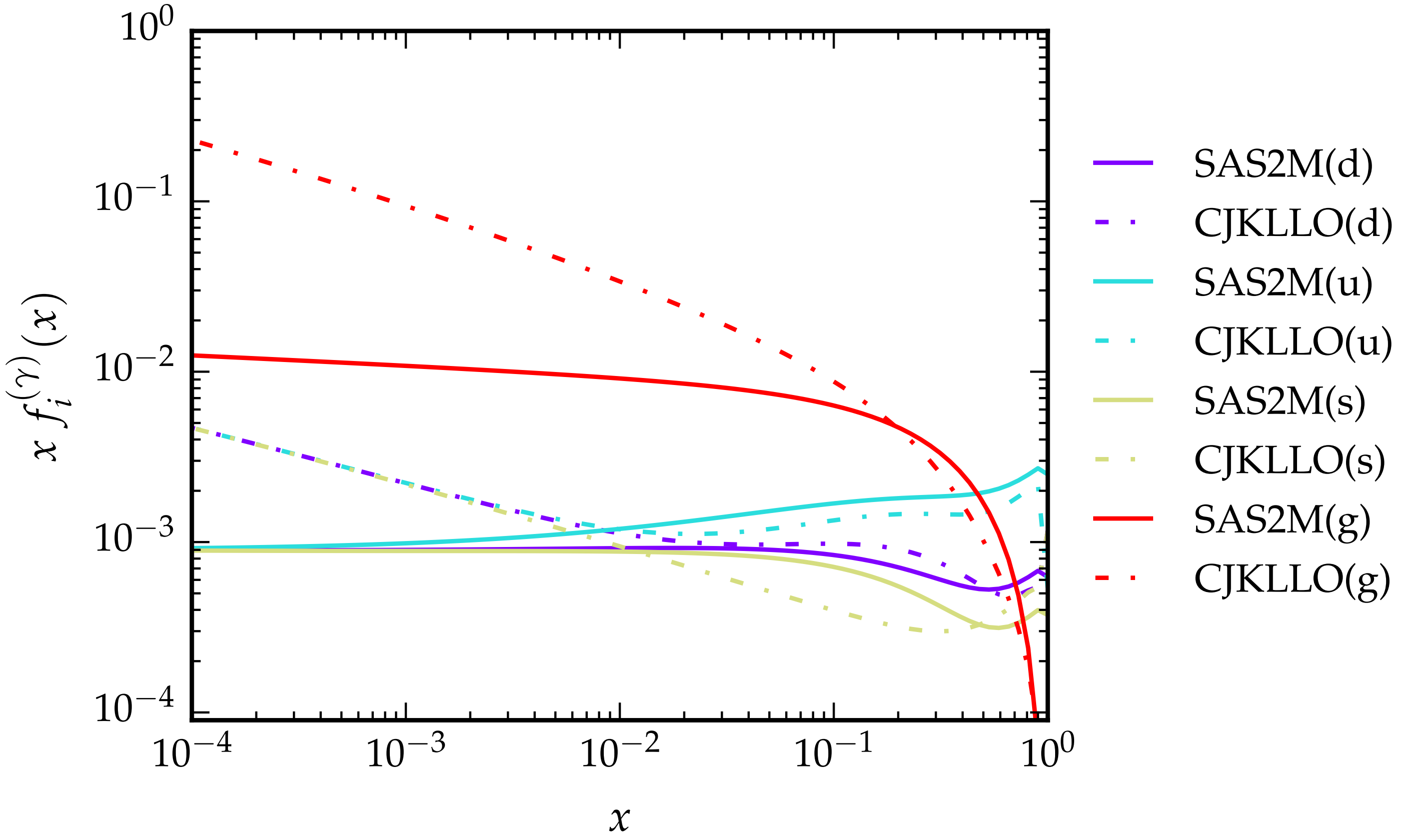
hence, the solution is of the form

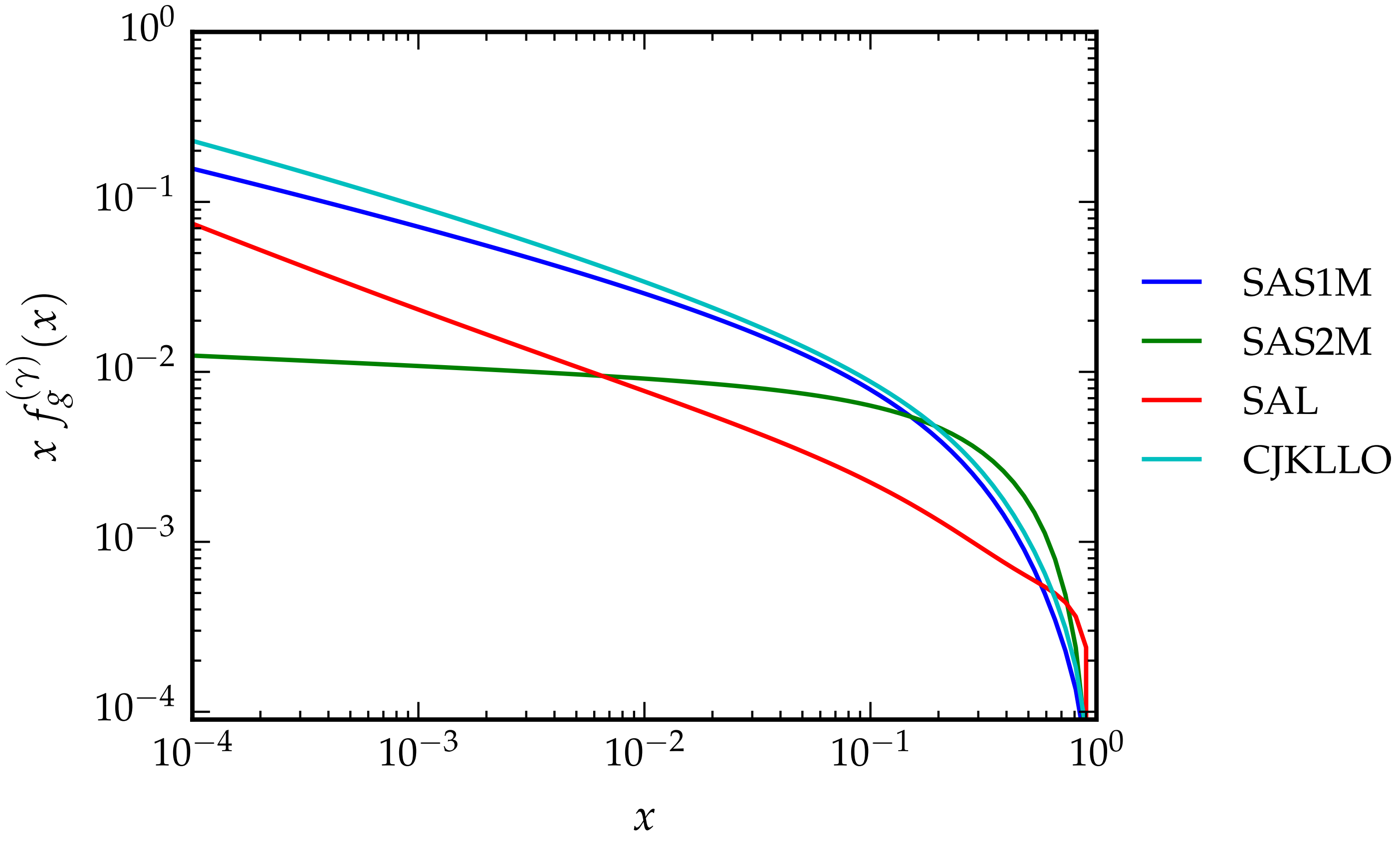
$$f_{i/\gamma}(x, \mu_F^2) = f_{i/\gamma}^{(\text{point}-\text{l.})}(x, \mu_F^2) + f_{i/\gamma}^{(\text{hadron}-\text{l.})}(x, \mu_F^2)$$

- Four libraries interfaced to Sherpa
- $f^\gamma_{\rm had}$ is fitted from non-perturbative input, c.f. Vector-Meson Dominance
- many available, but hard to find; mostly outdated
- differences of factor $\mathcal{O}(10)$

Photon PDFs

Gluon PDFs dominant channel, but poorly constrained



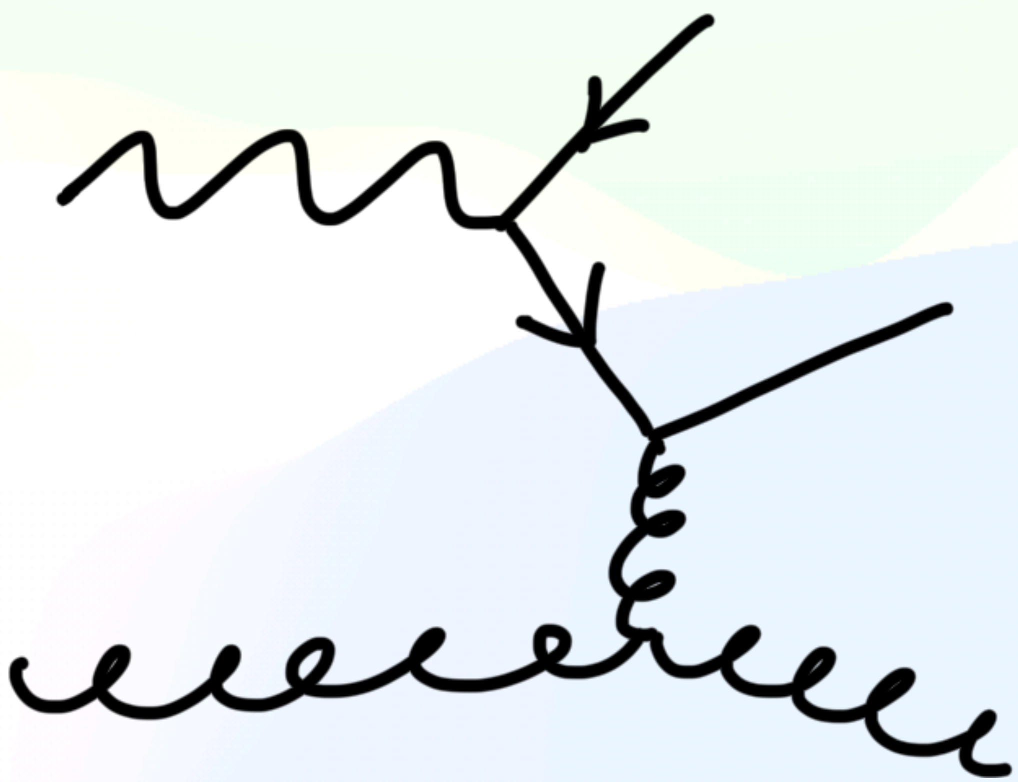


Small-x behaviour differs significantly between different sets

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?

Photon PDF and PS matching

Collinear divergences in the intial state

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, respecting the varying beam energies
- $\sigma^{(\text{point})}_{\gamma P \to X}$ has QCD **and** collinear QED divergences; the latter do **not** cancel against virtual corrections

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

Photon PDF and PS matching

The photon PDF obeys the evolution

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

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

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

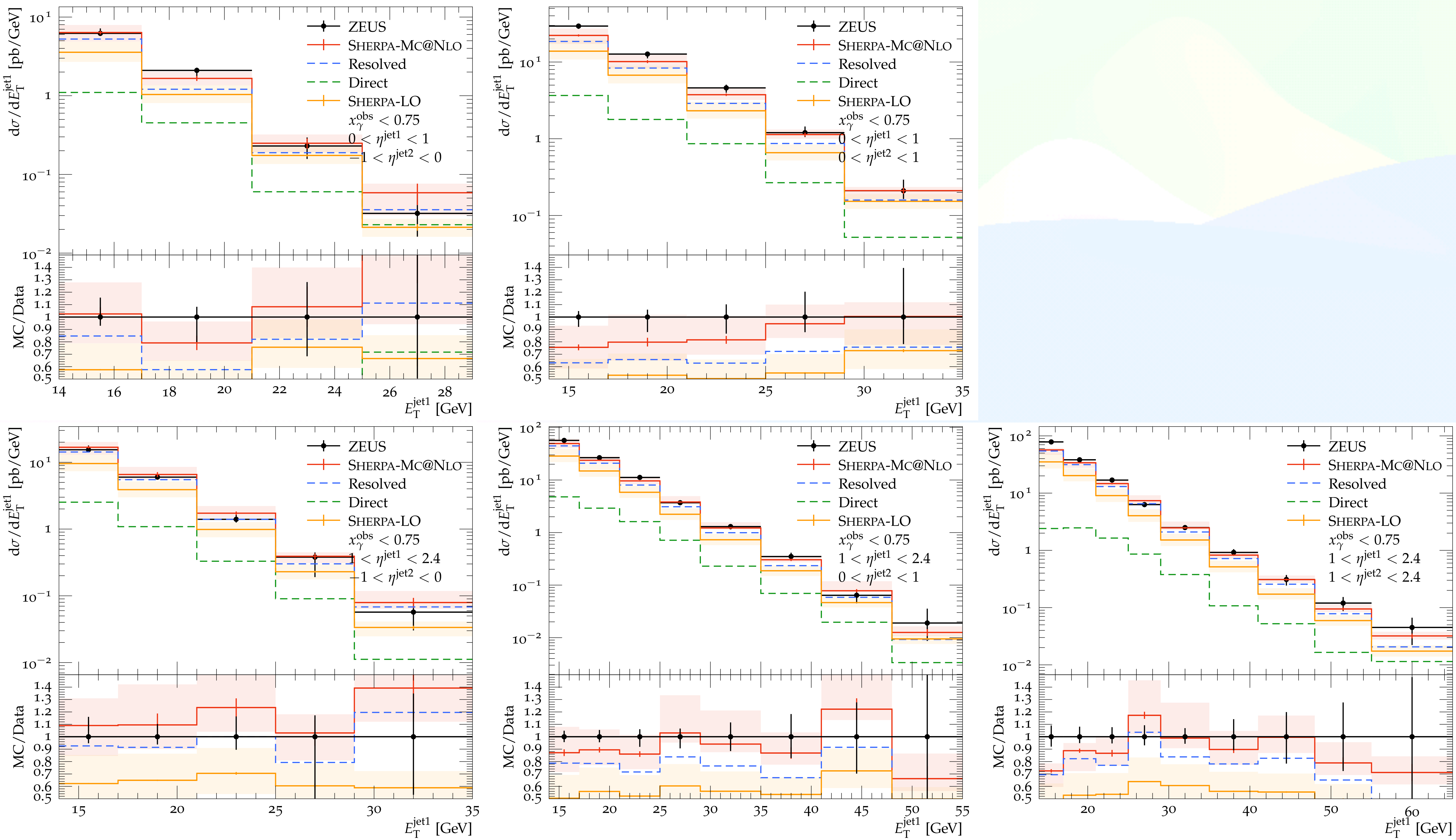
Caveats:

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

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

Validation against HERA

Jet transverse energy in different pseudorapidity bins



Predictions for EIC

Implemented Rivet analysis

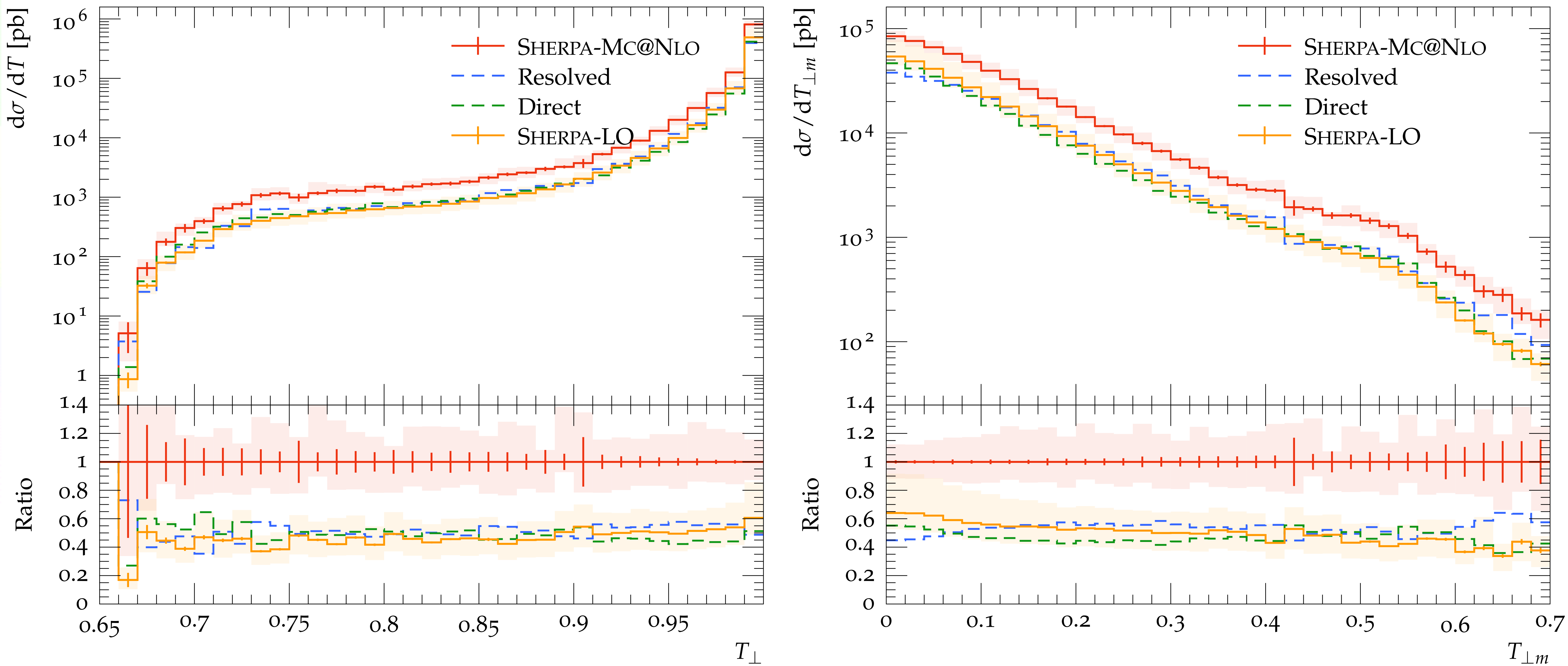
- electron-proton beam with 18 and 275 GeV, respectively
- anti-k_T jet clustering with $R = 1.0$ and $E_T > 6$ GeV
- at least one jet

For event generation in SHERPA

- Matched with S-MC@NLO
- 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,…

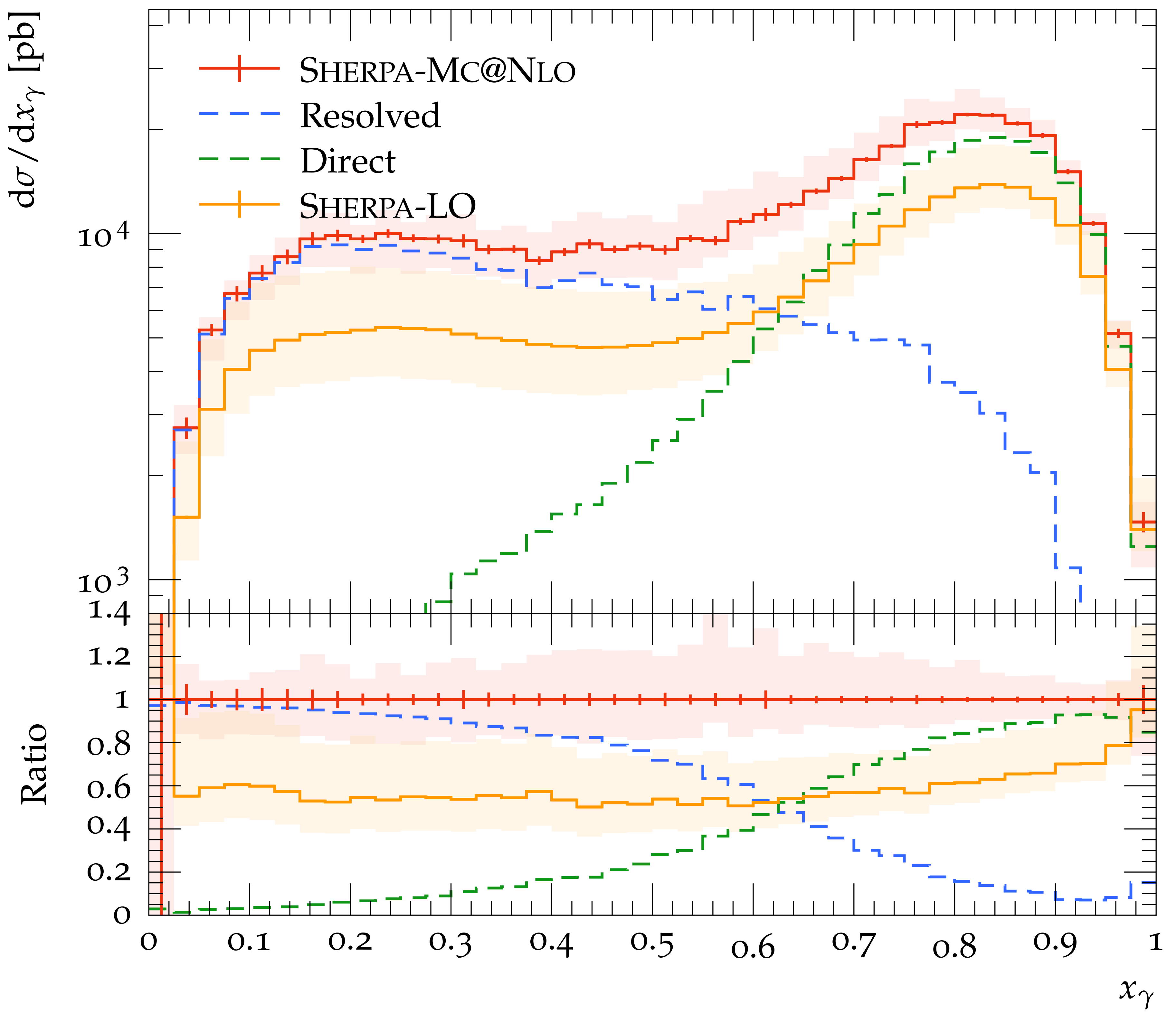
Predictions for EIC

Transverse thrust and transverse thrust minor



Predictions for EIC

Distribution of x_γ



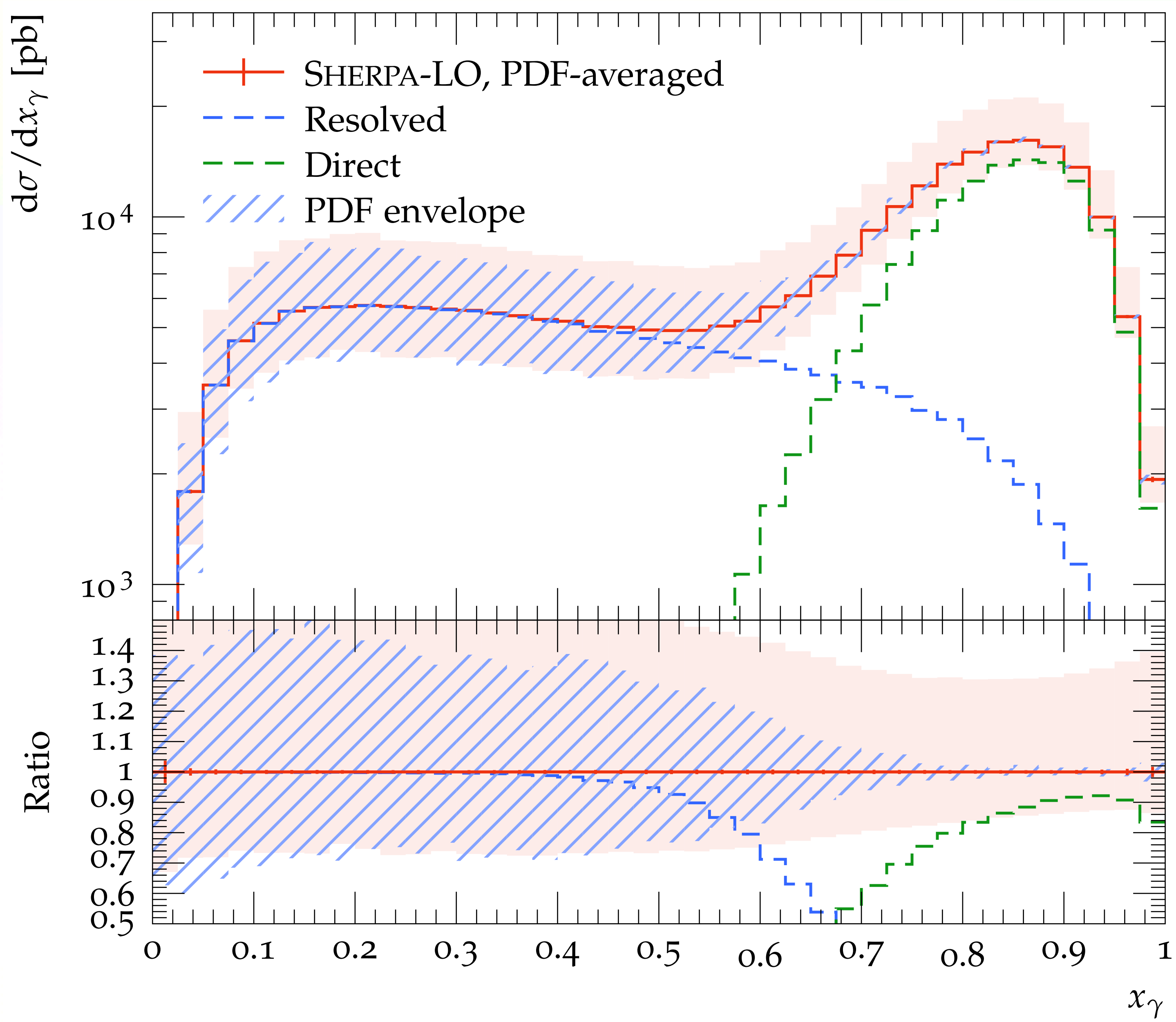
x_γ is a proxy for momentum ratio of parton to photon, defined as

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

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

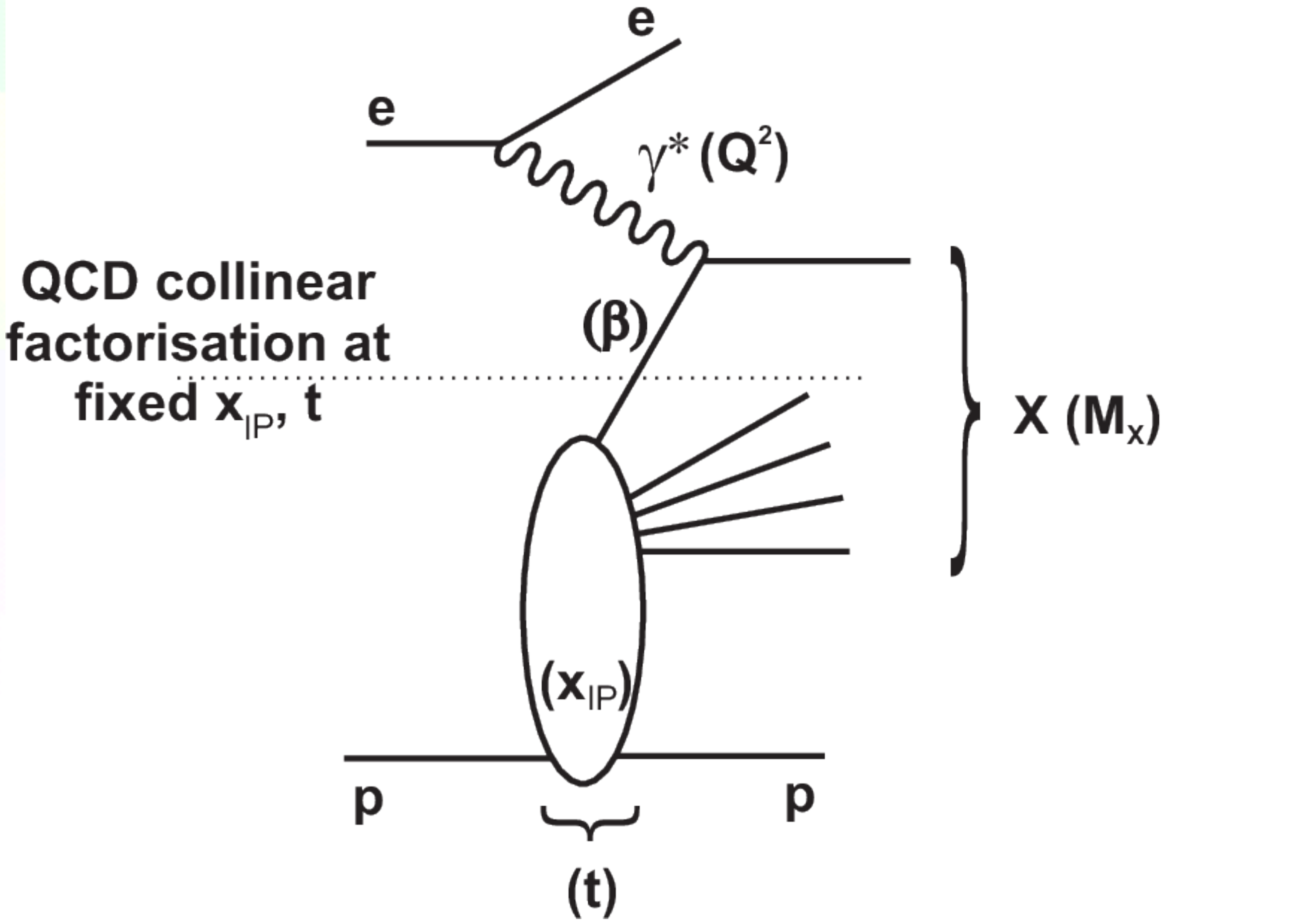
- Process of type $ep \to eX + Y$, where $+$ denotes a separation in rapidity
- Y is an intact proton or a low-mass excitation
- Experimental identification relies on either large rapidity gaps or proton tagging

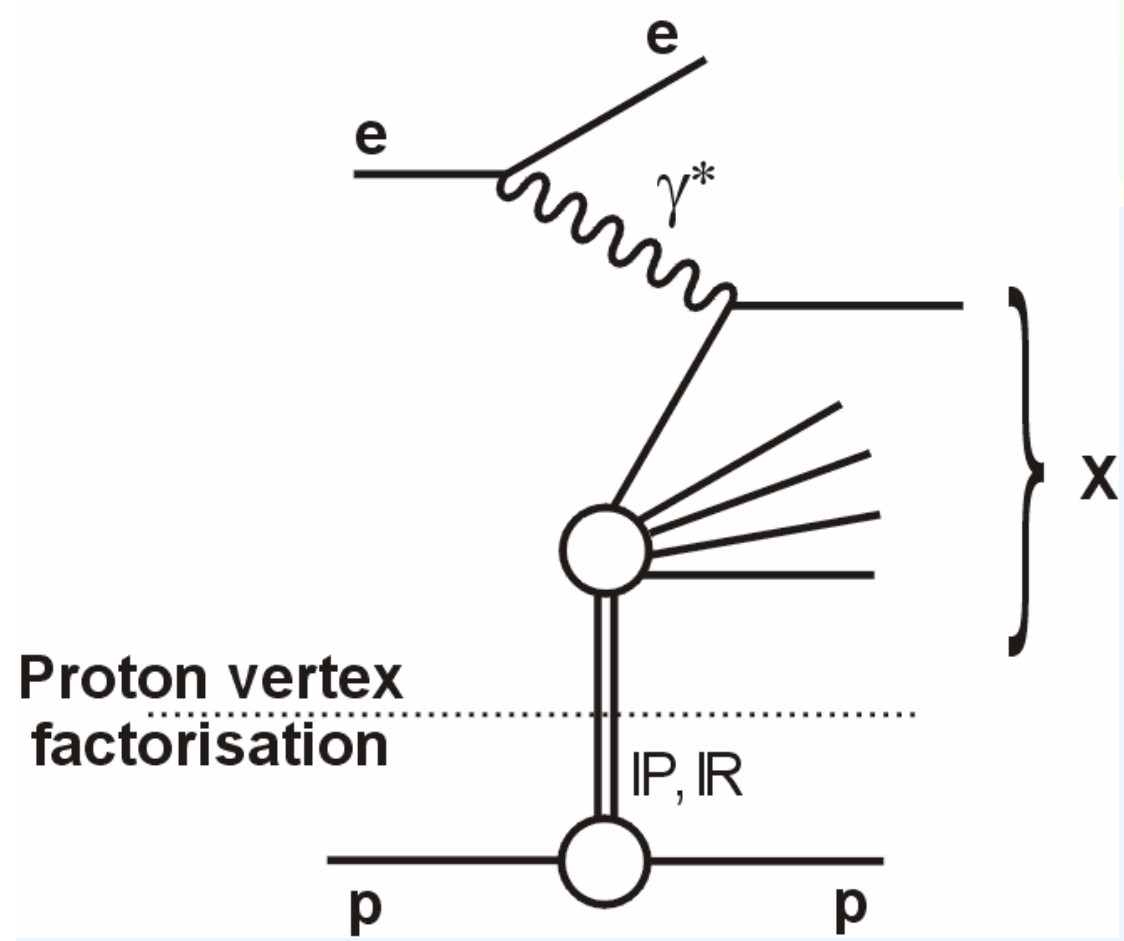
> Diffractive processes make up 10% of the total cross-section!
>
> Probing the hadron at low-scales, insights of transition into the non-perturbative region
>
> Background to GPD measurements

- Current state of the art is NNLO QCD Fixed Order in [*EPJC 78 (2018) 7, 538*] for Diffractive DIS and NLO QCD Fixed Order in [*Eur.Phys.J.C 38 (2004) 93-104*] for Diffractive Photoproduction; no matching to parton showers yet beyond LO

Factorisation of diffraction

Introduction of Diffractive PDFs





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

[Phys. Rev. D 57, 3051]

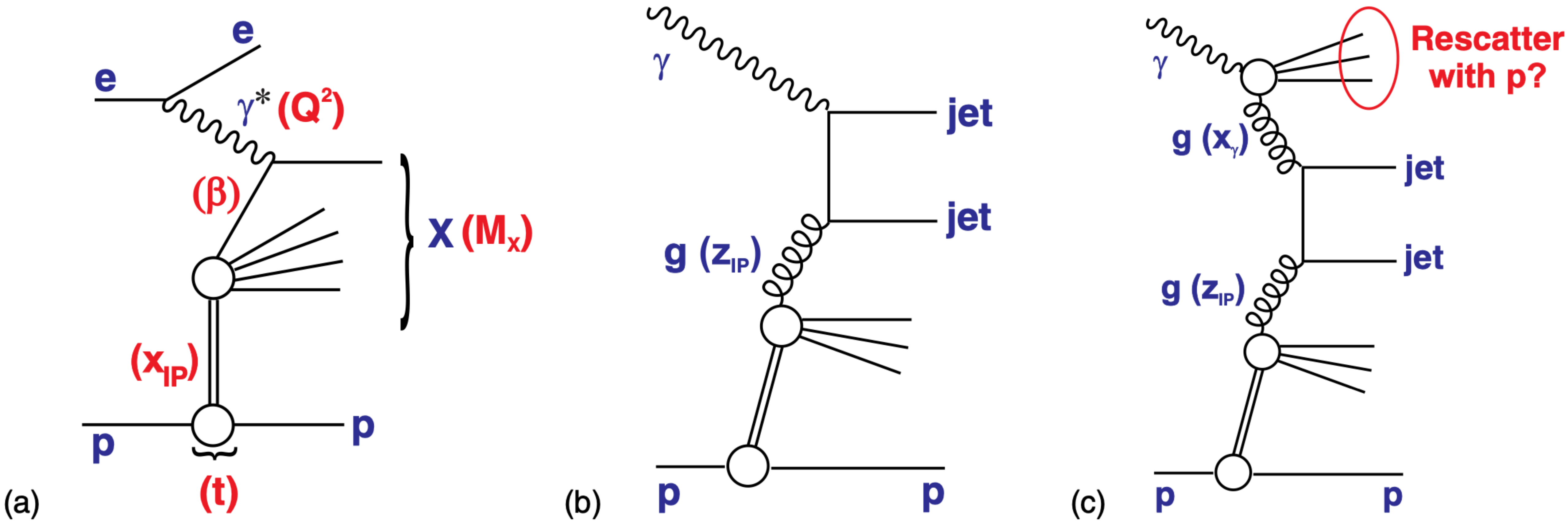
$$f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) f_i(\beta = x/x_{IP}, Q^2)$$

[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

Factorisation formula

- Including the sub-leading Reggeon term, the factorisation is

$$f_i^D(x, \mu_F, x_{\mathbb{P}}, t) = f_{\mathbb{P}/P}(x_{\mathbb{P}}, t)\, f_{i/\mathbb{P}}(x, \mu_F) + n_{\mathbb{R}} f_{\mathbb{R}/P}(x_{\mathbb{P}}, t)\, f_{i/\mathbb{R}}(x, \mu_F)$$

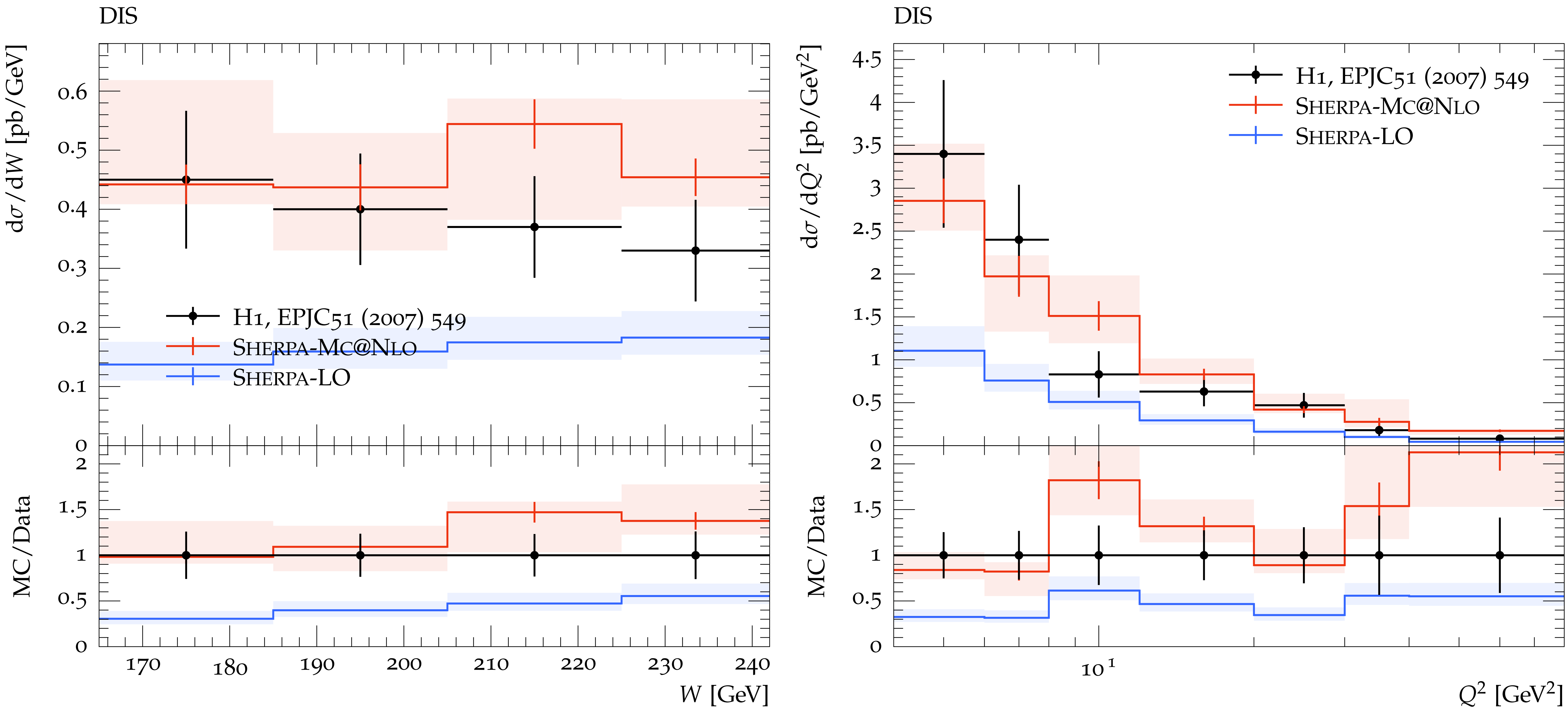
- The Pomeron and Reggeon flux can be fitted with

$$f_{\mathbb{P}/P}(x_{\mathbb{P}}, t) = A_{\mathbb{P}} \frac{e^{B_{\mathbb{P}} t}}{x_{\mathbb{P}}^{2\alpha_{\mathbb{P}}(t)-1}}$$

- Pomeron PDF needs fitting to data; Reggeon PDF can be approximated by pion PDF
- Builds upon the same phase space setup as photoproduction

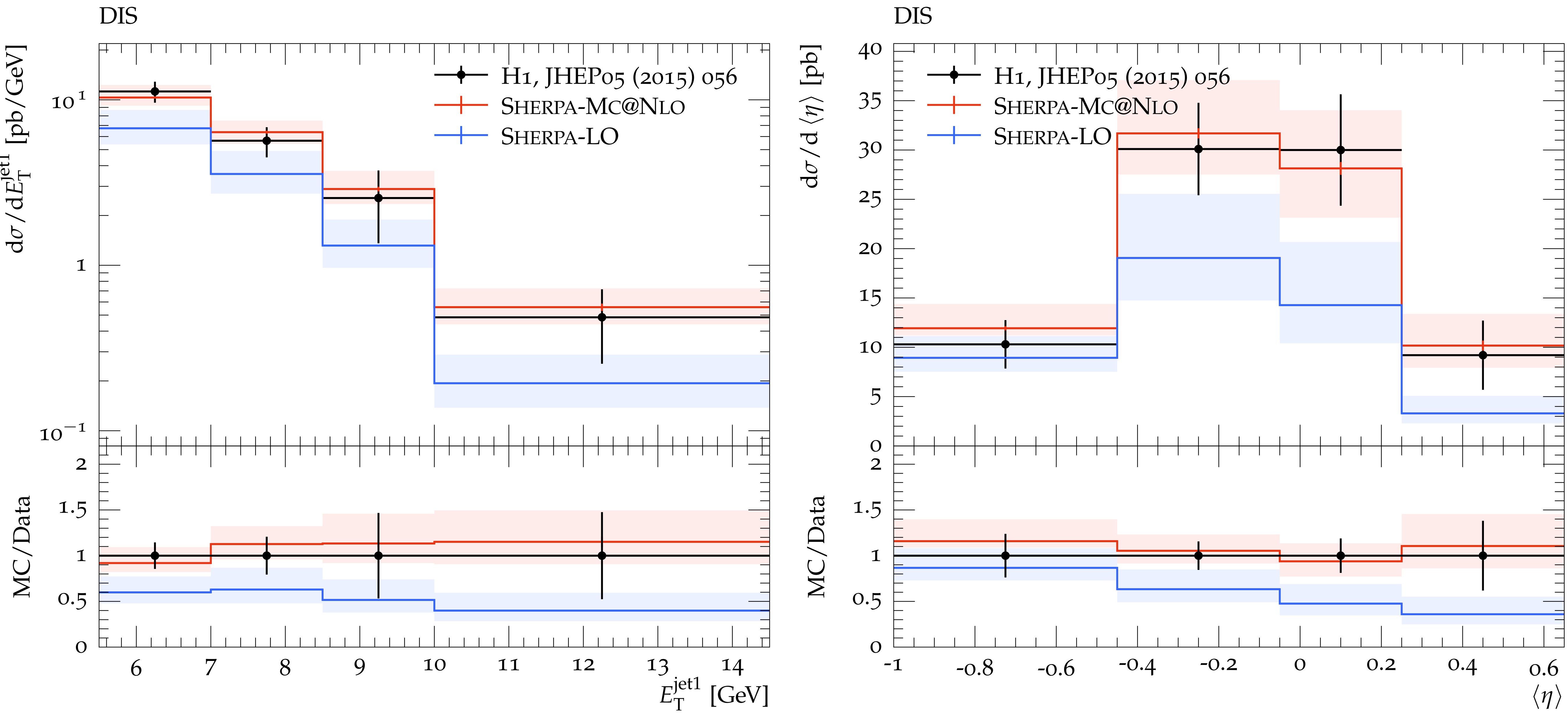
Validation against HERA data

Diffractive DIS



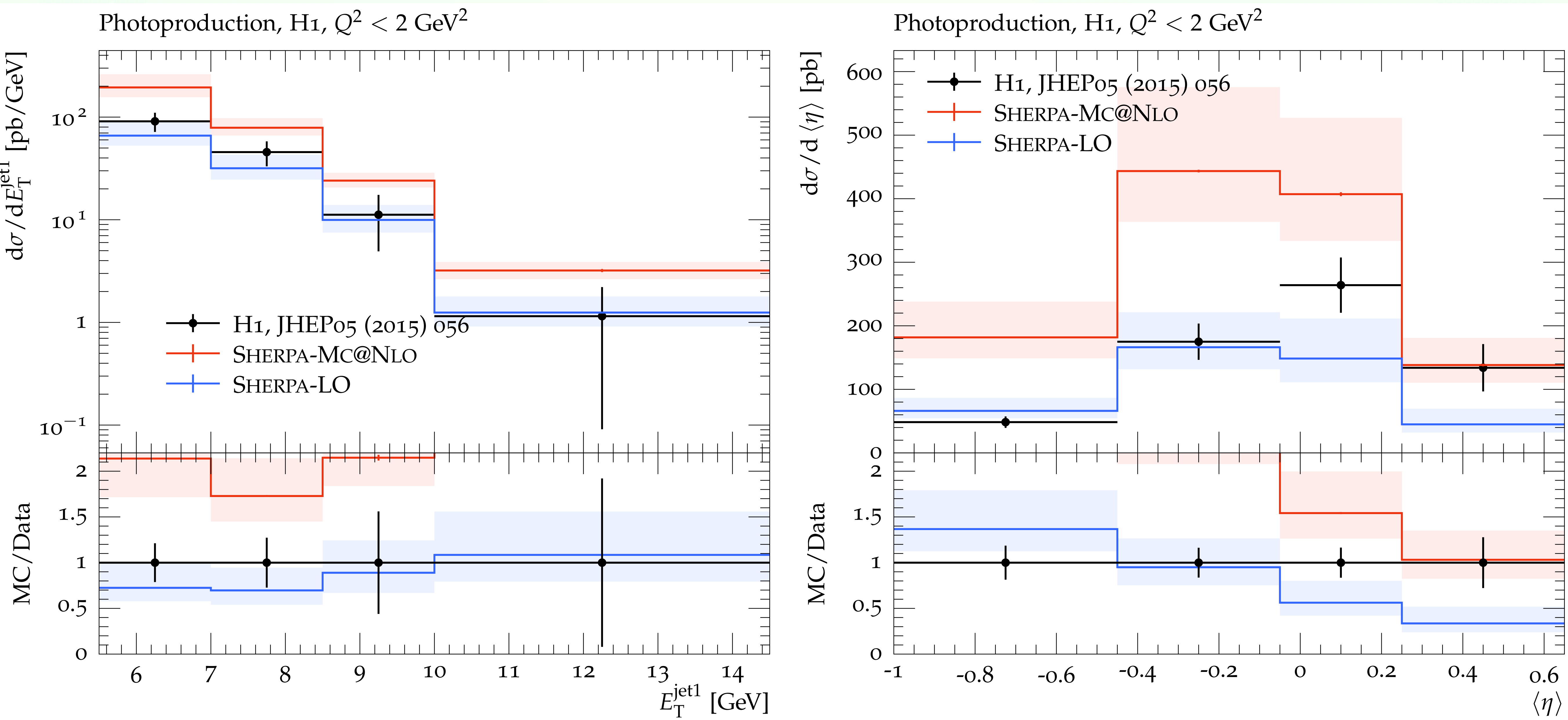
Validation against HERA data

Diffractive DIS



Validation against HERA data

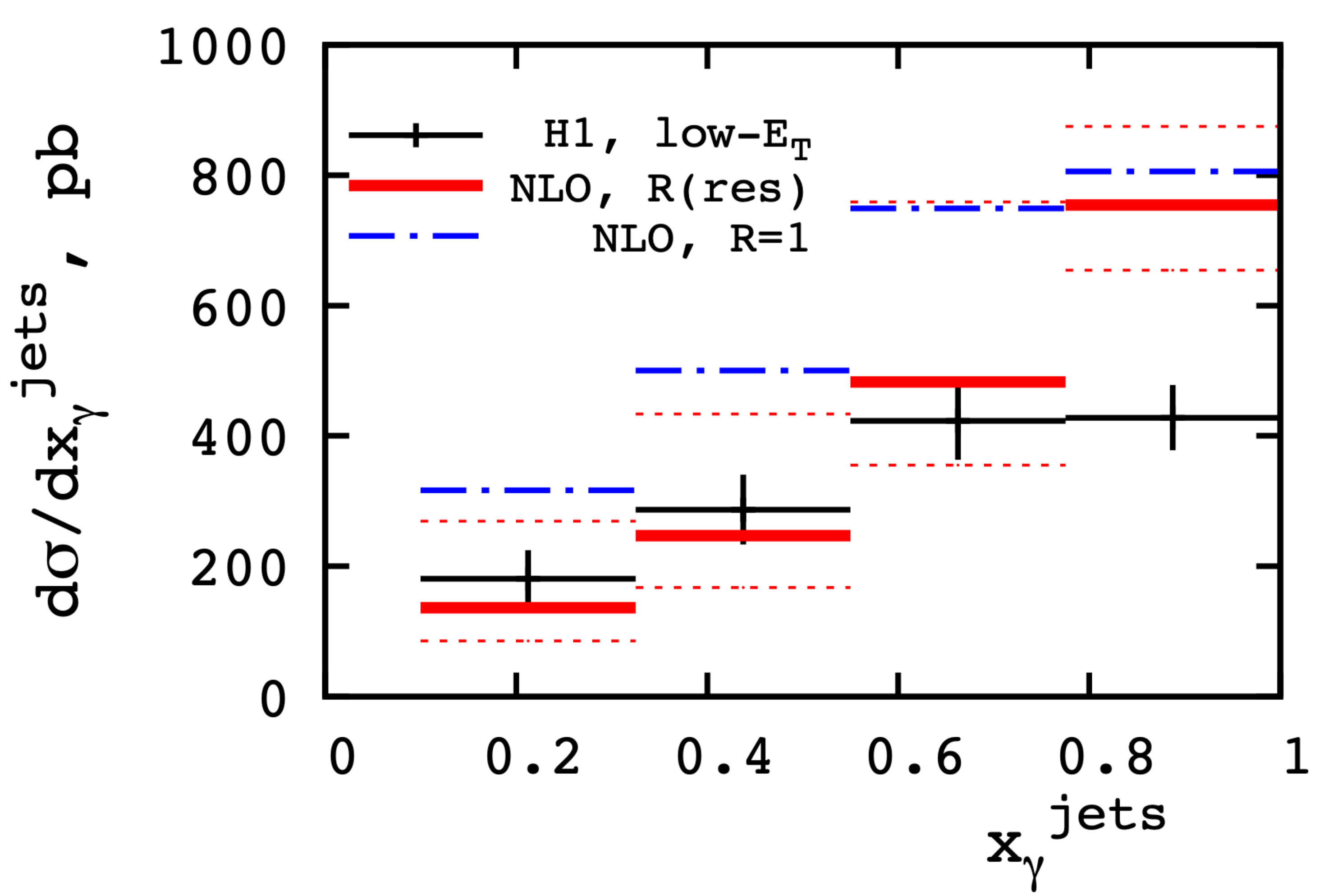
Diffractive Photoproduction



Validation against HERA data

Also seen in previous calculations

- Published in [*Eur.Phys.J.C 38 (2004) 93-104]* and [*Mod.Phys.Lett.A 23 (2008) 1885-1907]*
- Follow-up study by Guzey and Klasen for the EIC in [*JHEP 05 (2020) 074]*



taken from Guzey and Klasen, [*Eur.Phys.J.C 76 (2016) 8, 467]*

Validation against HERA data

Is a veto of rescattering the solution?

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?

Let's do a brief and incomplete review of some approaches…

Validation against HERA data

Is a veto of rescattering the solution?

The suppression of the NLO cross-section has been modelled with

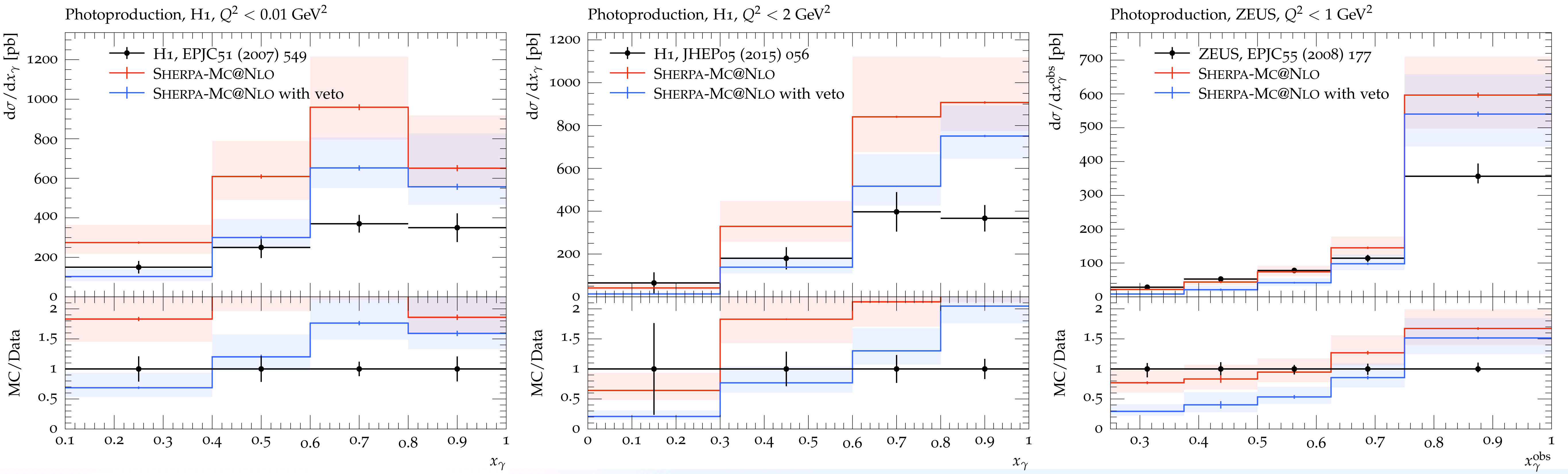
- global factors, $R_{\text{glob}} = 0.5$
- scaling of the resolved component, $R_{\text{res.}} = 0.34$, [Phys.Lett.B 567 (2003) 61-68]
- in [Eur.Phys.J.C 76 (2016) 8, 467], an interpolation between the regimes with

$$S_i^2(x_\gamma) \to \begin{cases} 1\,, & i = c\,, \\ A_q\, x_\gamma + 0.34\,, & i = u, d, s\,, \\ A_g\, x_\gamma + 0.34\,, & i = g\,, \end{cases}$$

All approaches are somewhat ad-hoc empirical models

Validation against HERA data

Is a veto of rescattering the solution?



Implementation of interactions between photon and intact beam proton

- Three measurements of x_γ as a discriminator between direct and resolved photoproduction
- Largest bin shows deviation but is dominated by direct component, smallest bin suppressed too far in ZEUS measurement

Validation against HERA data

Eur.Phys.J.C 66 (2010) 373-376

Factorisation breaking in diffractive dijet photoproduction at HERA

A.B. Kaidalov[1], V.A. Khoze[2,3,a], A.D. Martin[2], M.G. Ryskin[2,3]

Abstract We discuss the factorisation breaking observed in diffractive dijet photoproduction by the H1 and ZEUS collaborations at HERA. By considering the effects of rapidity gap survival, hadronisation, migration and NLO contributions, we find that the observed data are compatible with theoretical expectations.

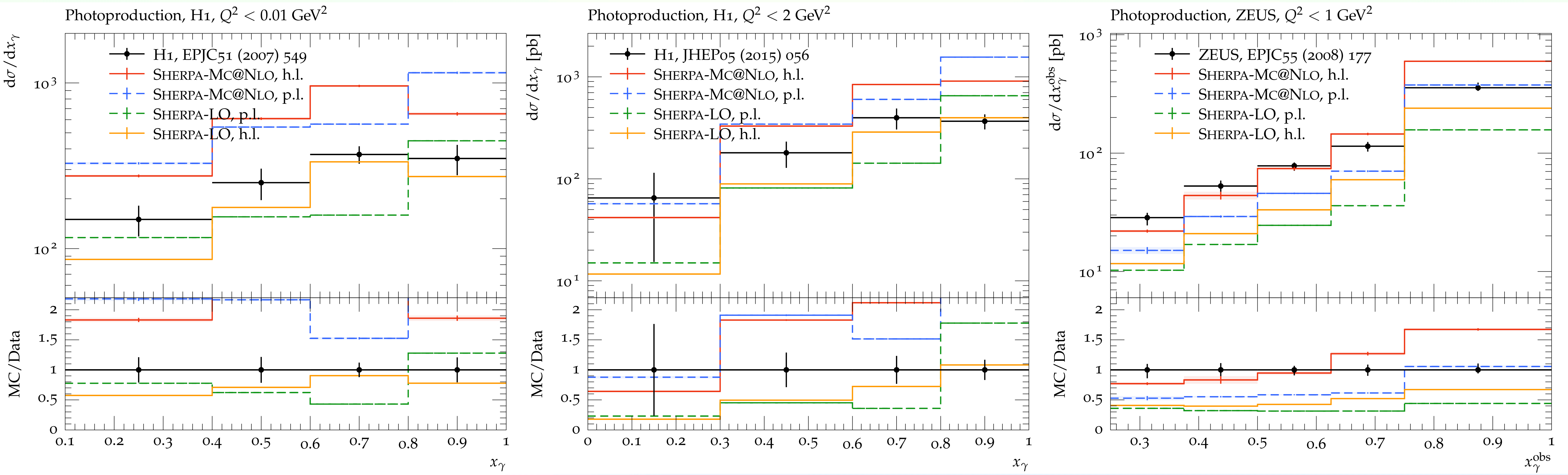
- Different suppression for point-like and hadron-like photon component
- Also argue against inclusion of dijet data in DPDF fits

Our findings:

While these play a non-negligible role, they do **not** resolve the factorisation breaking

Validation against HERA data

Eur.Phys.J.C 66 (2010) 373-376



- Hadronisation corrections are indeed large, up to 50%
- More significant at large x_γ
- In H1 measurements, they shift the cross-section to smaller x_γ
- In ZEUS measurement, they lower the total cross-section

Validation against HERA data

Eur.Phys.J.C 71 (2011) 1741

Factorisation breaking in diffractive dijet photoproduction at HERA?

Radek Žlebčík, Karel Černý, Alice Valkárová[a]

Abstract Recent experimental data on dijet cross sections in diffractive photoproduction at HERA collider are analysed with an emphasis on QCD factorisation breaking effects. The possible sources of the different conclusions of H1 and ZEUS collaborations are studied.

Three-fold comparison between ZEUS and H1 data:

- Hadronisation corrections
- Alternative photon distribution function
- Matching the different phase space

Their conclusion: these effects play only a minor role in the discrepancy

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

Implemented Rivet analysis

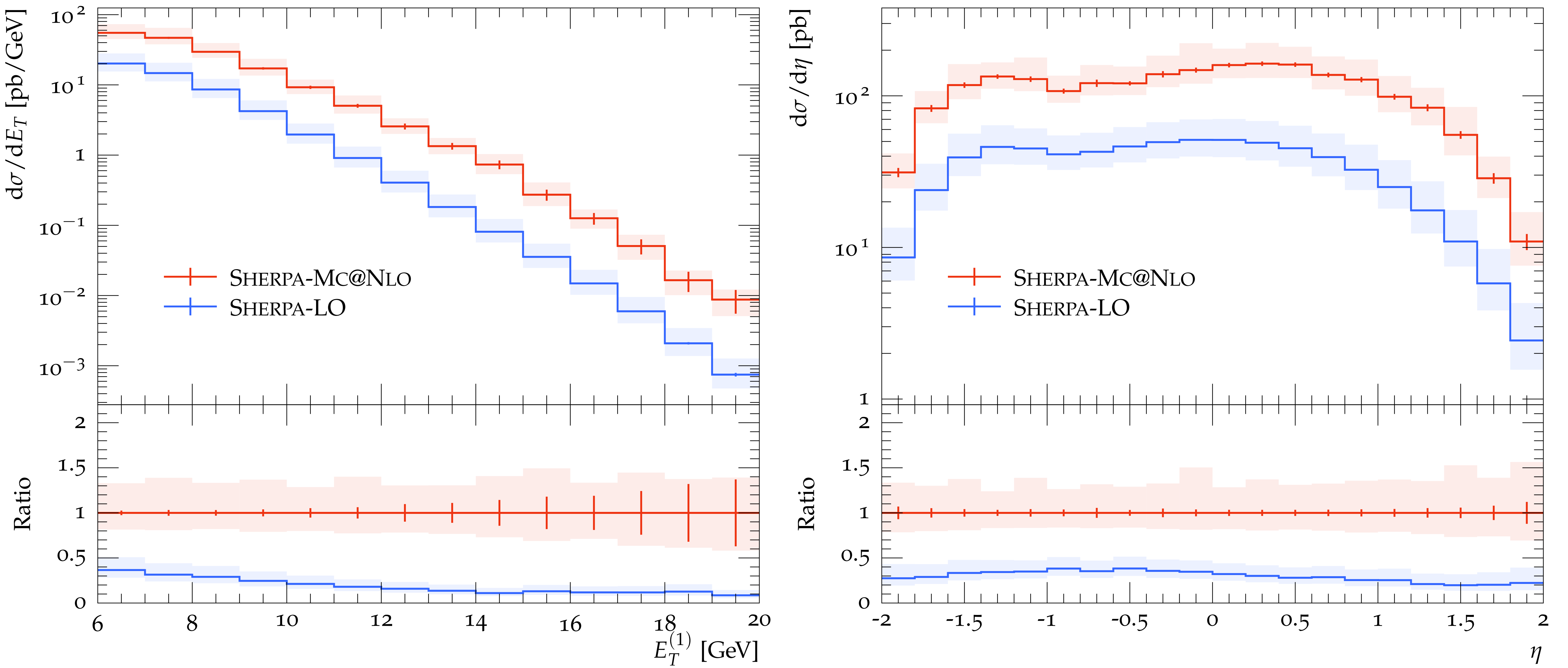
- electron-proton beam with 18 and 275 GeV, respectively
- anti-k_T jet clustering with $R = 1.0$
- at least two jets and $E_T > 6\ (4)\ \mathrm{GeV}$ for (sub-)leading jet

For event generation in SHERPA

- Matched with S-MC@NLO
- scales chosen as $\mu_R = \mu_F = H_T/2$ and $\frac{1}{2}\sqrt{Q^2 + H_T^2}$, incl. 7-point variation
- H1 DPDF fit for pomeron, GRVPI0 PDF for reggeon, SAS1M PDF for photon
- fragmentation, beam remnants, primordial-k_T, …

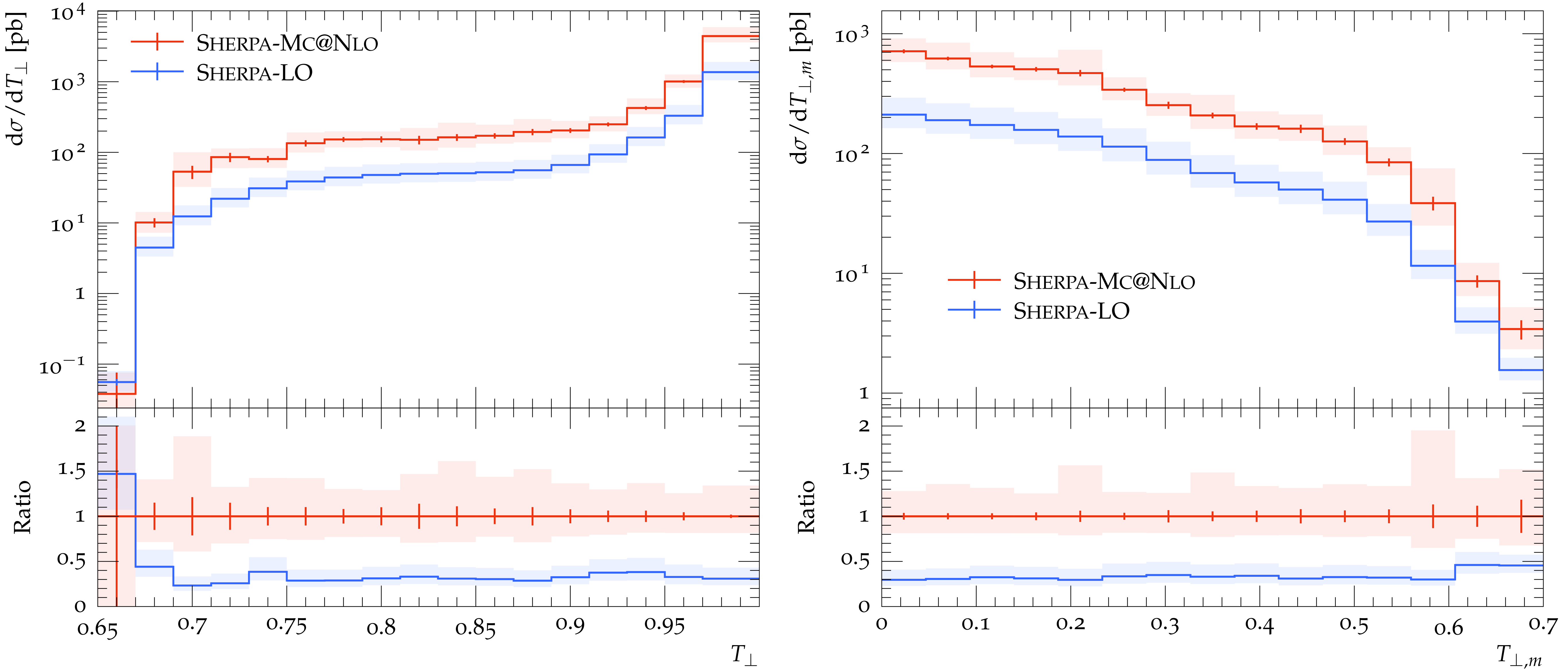
Predictions for EIC

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



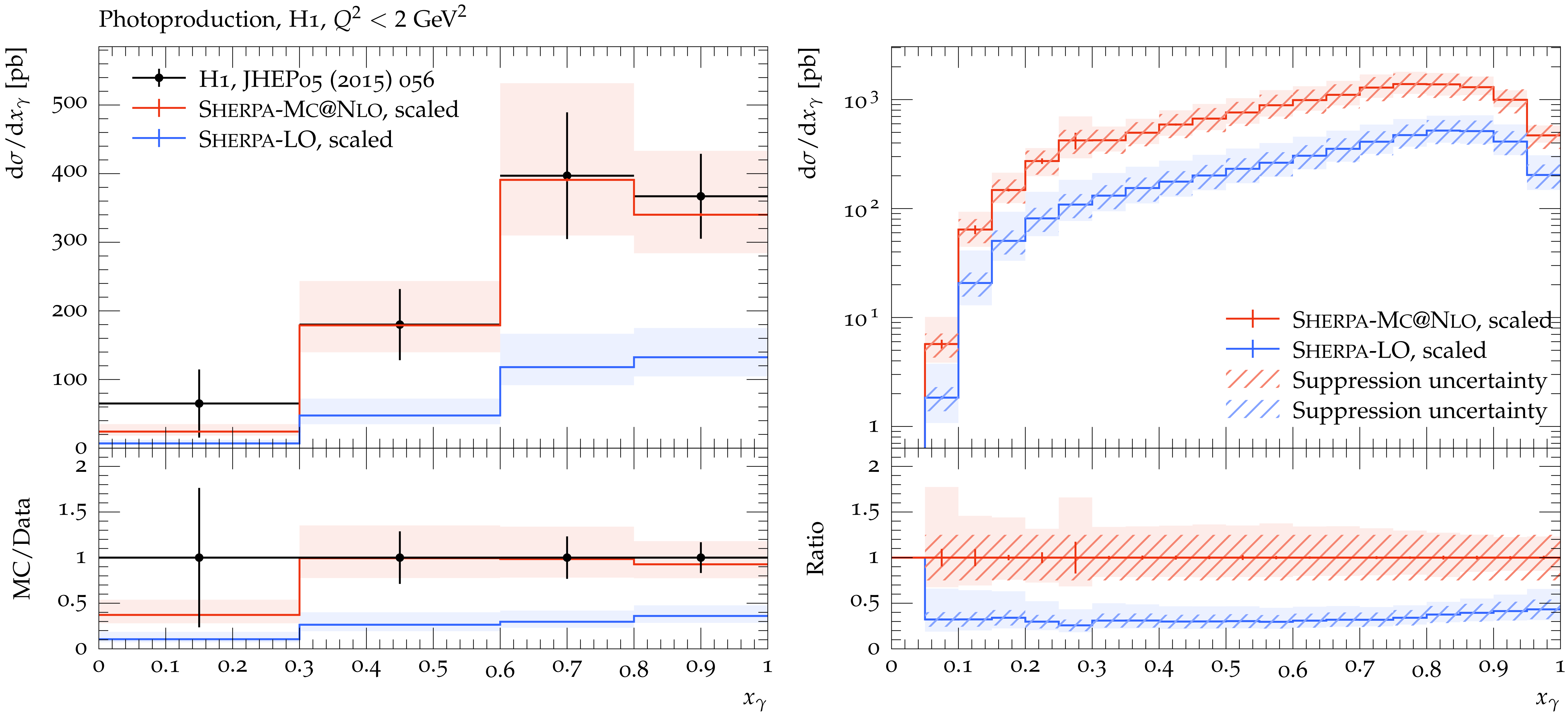
Predictions for EIC

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

- DIS has been well understood
- Photoproduction and Diffraction have not seen the same interest – despite significant contributions to the total cross-section
- Both are crucial for background studies and inclusive QCD observables at the EIC, for example in α_S extraction and jet physics
- First hadron-level matched NLO predictions for Photoproduction, Diffractive DIS and Diffractive Photoproduction in Sherpa
- 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