Precision Simulation of Photoproduction and Diffractive Jets for the EIC and HERA

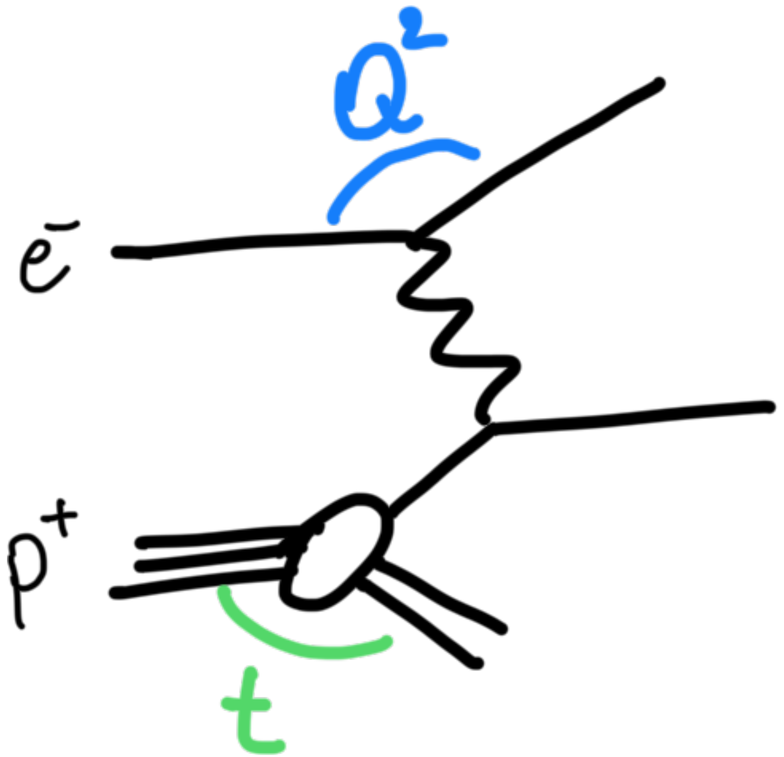
based on Eur.Phys.J.C 84 (2024) 2, 178,
Phys.Rev.D 109 (2024) 3, 034037, and
Eur.Phys.J.C 84 (2024) 9, 894

Peter Meinzinger, University of Zurich

Universität Zürich[UZH]

Large spectrum of lepton-hadron physics

Preparing for the EIC



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

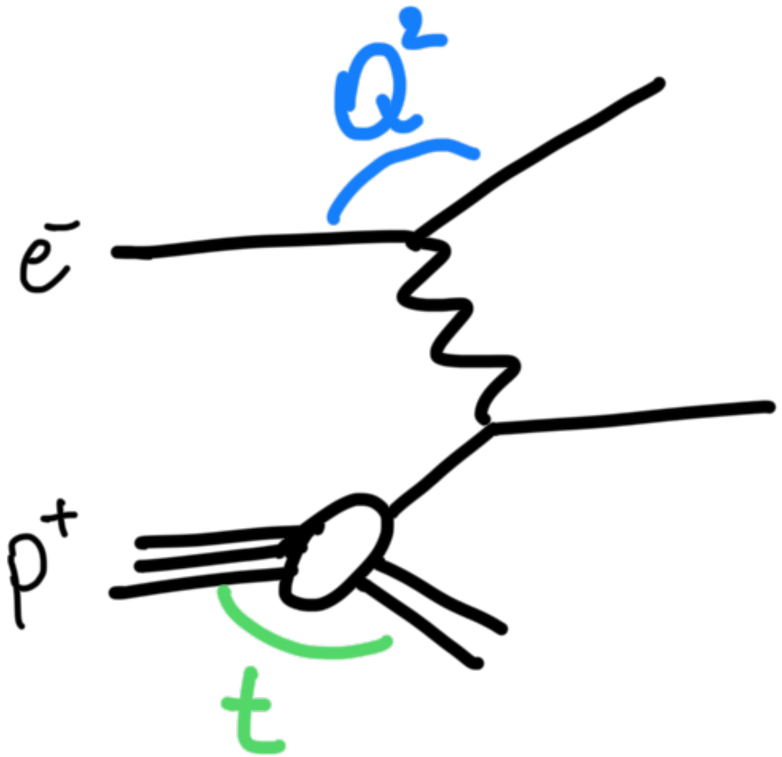
high-Q^2, "deep" ↓ low-Q^2

DIS e.g. Daniel Reichelt's talk	**Diffractive DIS**
Photoproduction	**Diffractive Photoproduction**

Large spectrum of lepton-hadron physics

Preparing for the EIC

Most times we focus on DIS



high-$|t|$, inelastic

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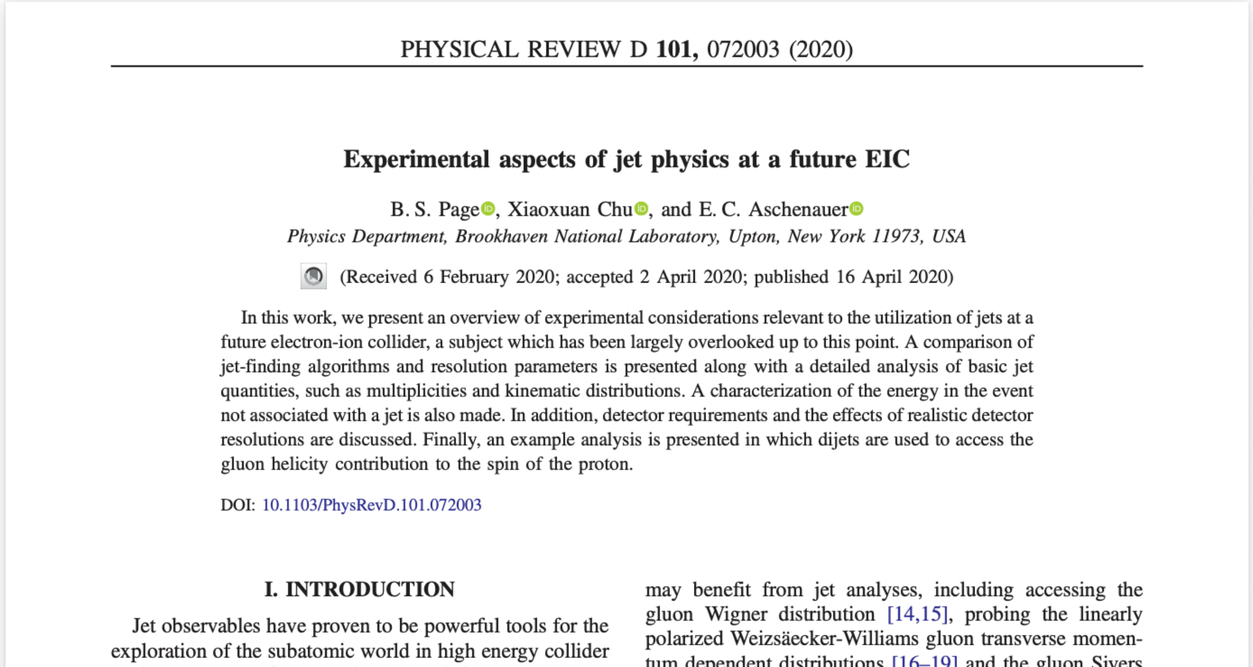
high-Q^2, "deep"		
	DIS e.g. Daniel Reichelt's talk	**Diffractive DIS**
low-Q^2	**Photoproduction**	**Diffractive Photoproduction**

Large spectrum of lepton-hadron physics

Preparing for the EIC

Preparing for measurements of the hadronic final state,

for example with jets of $p_T > 5$ GeV



PHYSICAL REVIEW D **101,** 072003 (2020)

Experimental aspects of jet physics at a future EIC

B. S. Page, Xiaoxuan Chu, and E. C. Aschenauer
Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA

(Received 6 February 2020; accepted 2 April 2020; published 16 April 2020)

In this work, we present an overview of experimental considerations relevant to the utilization of jets at a future electron-ion collider, a subject which has been largely overlooked up to this point. A comparison of jet-finding algorithms and resolution parameters is presented along with a detailed analysis of basic jet quantities, such as multiplicities and kinematic distributions. A characterization of the energy in the event not associated with a jet is also made. In addition, detector requirements and the effects of realistic detector resolutions are discussed. Finally, an example analysis is presented in which dijets are used to access the gluon helicity contribution to the spin of the proton.

DOI: 10.1103/PhysRevD.101.072003

I. INTRODUCTION

Jet observables have proven to be powerful tools for the exploration of the subatomic world in high energy collider

may benefit from jet analyses, including accessing the gluon Wigner distribution [14,15], probing the linearly polarized Weizsäecker-Williams gluon transverse momen-

high-$|t|$, inelastic

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Large spectrum of lepton-hadron physics

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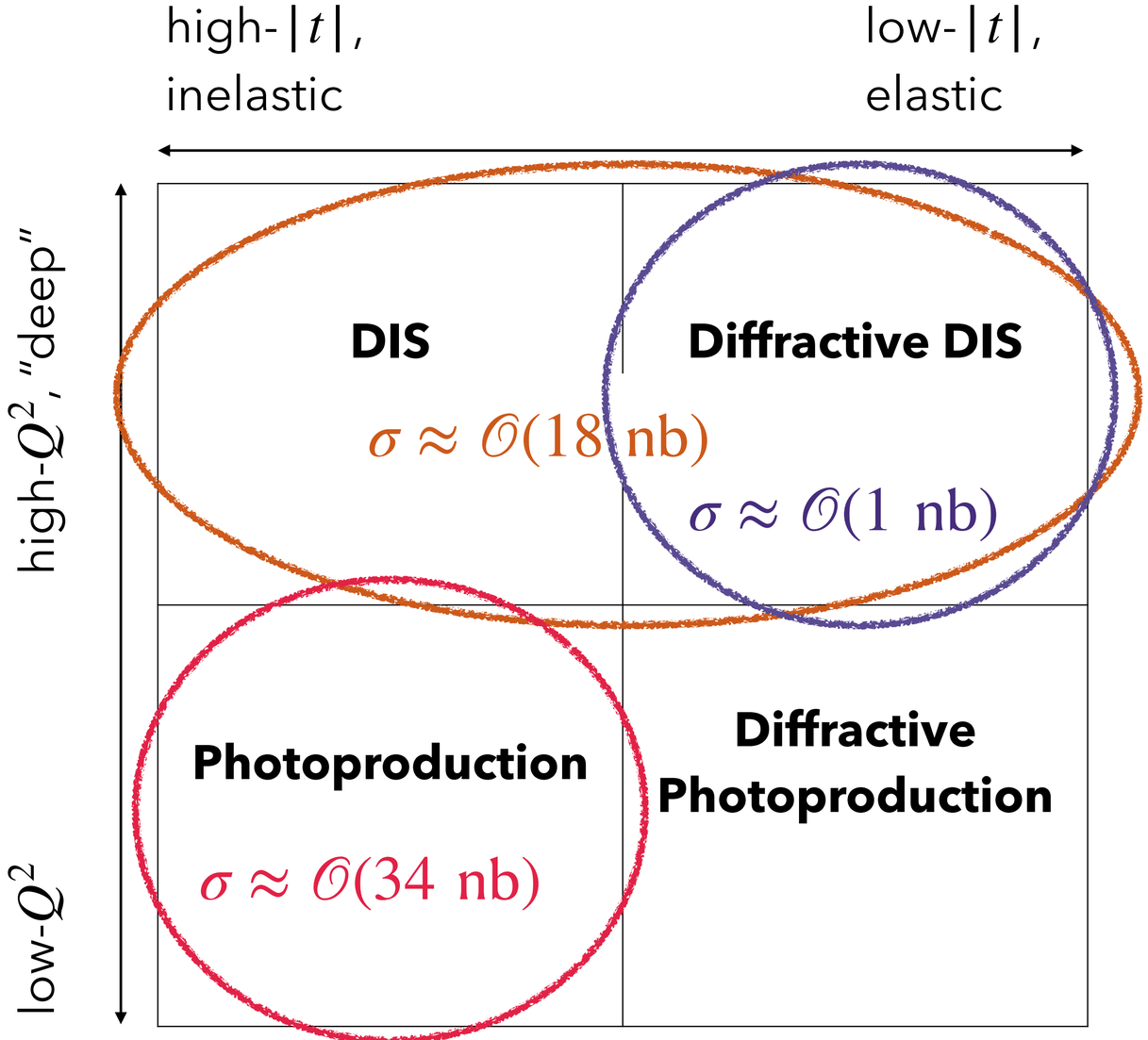

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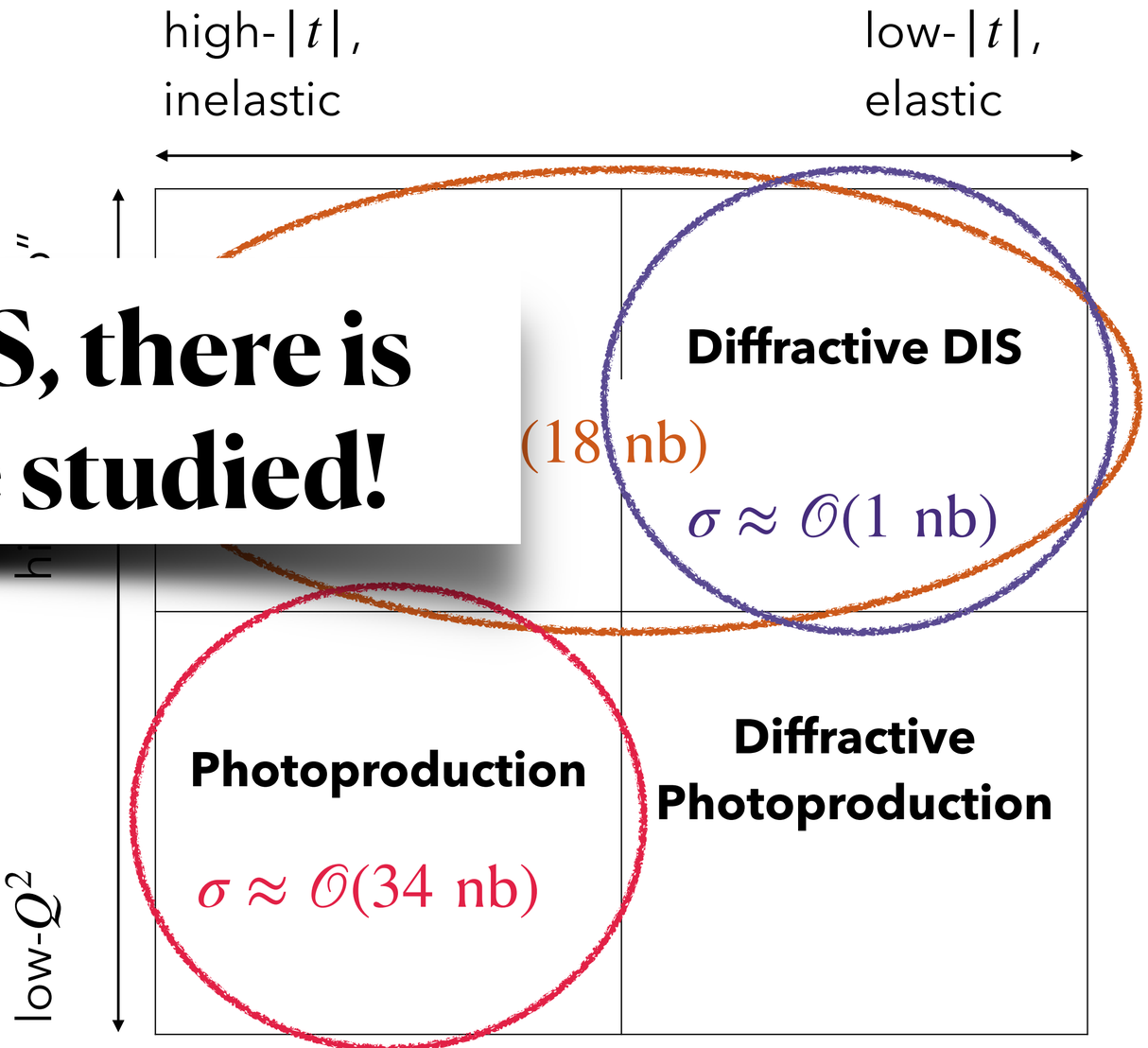
Large spectrum of lepton-hadron physics

Preparing for the EIC

Preparing for measurements of the hadronic final state,

for example with jet

Beyond DIS, there is more to be studied!



PHYSICAL REVIEW D 1

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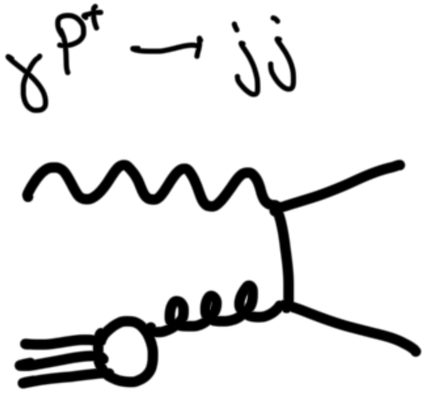
This talk

- provide an introduction to two significant jet production channels at EIC and HERA beyond DIS
- present the phenomenology of these channels at hadron-level, matched NLO

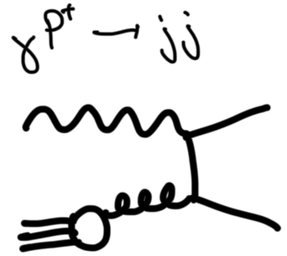
Content

1. Photoproduction
    1. Motivation and introduction
    2. Phenomenology at NLO
    3. PDF quality for photons
2. Diffractive Jets
    1. Motivation and introduction
    2. Phenomenology at NLO
3. Conclusions

Photoproduction



Primer on photoproduction



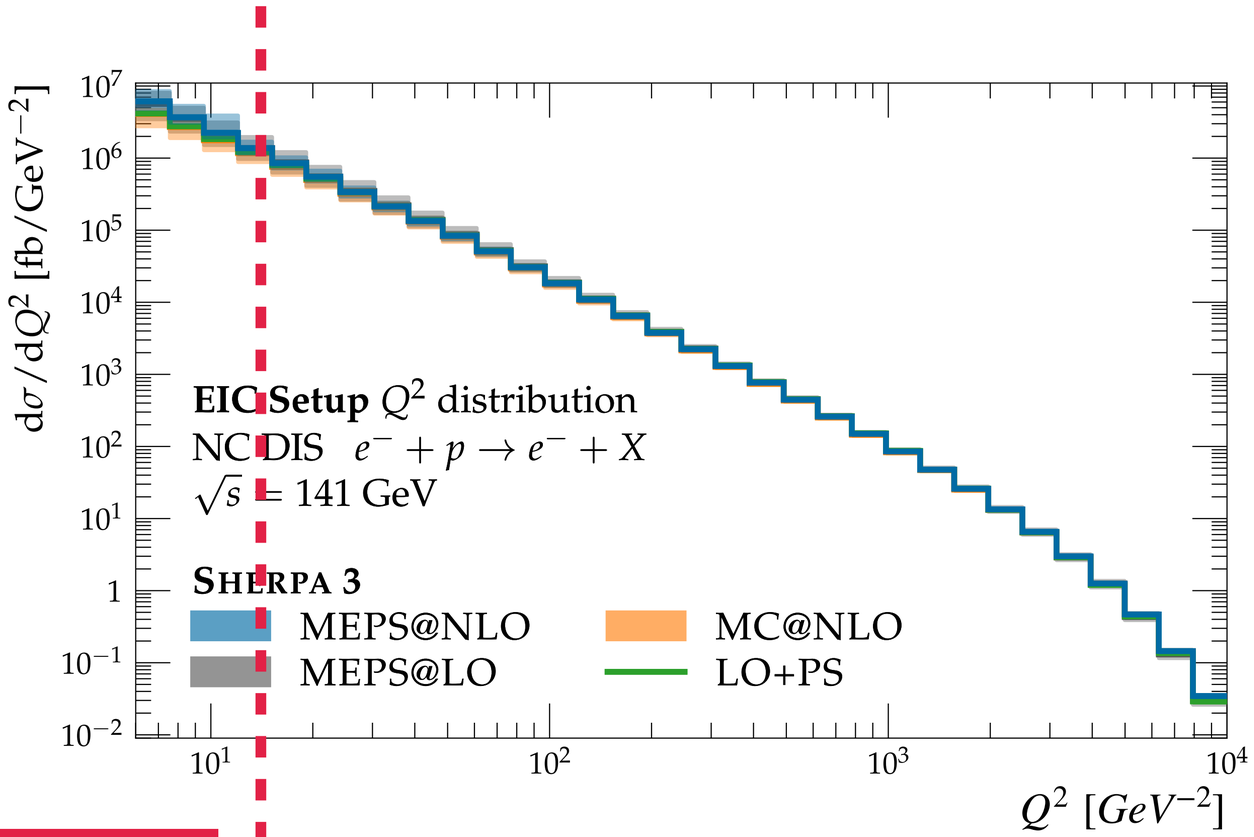
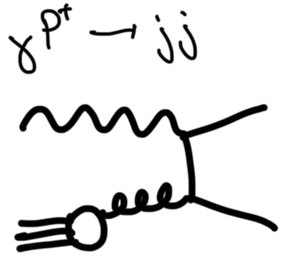


Photo-production

DIS

- photoproduction is the $Q^2 \to 0$ limit in lepton-hadron collisions
- $\sigma \propto Q^{-4}$, hence significant contributions to hadronic final state

Primer on photoproduction



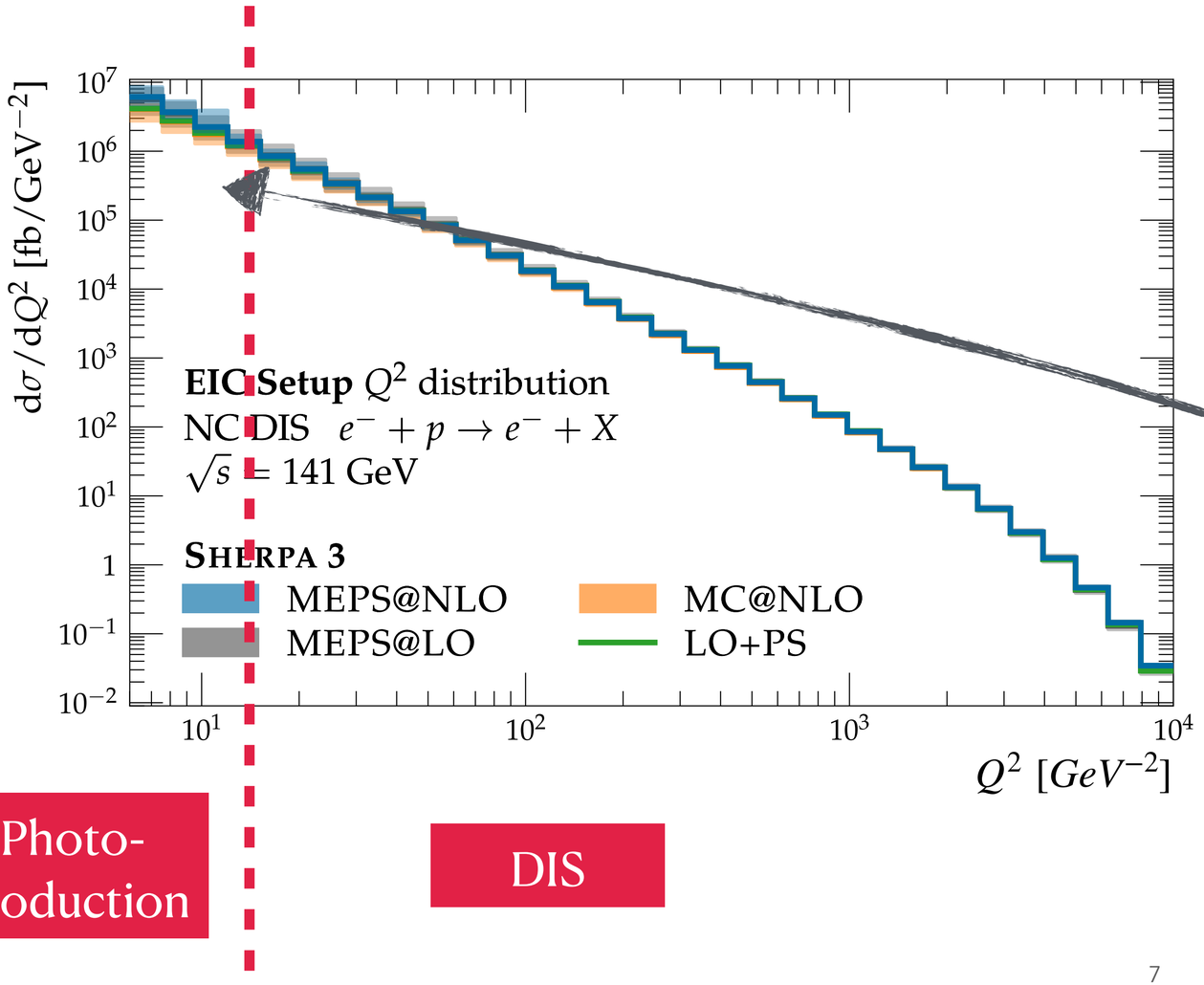


Photo-production

DIS

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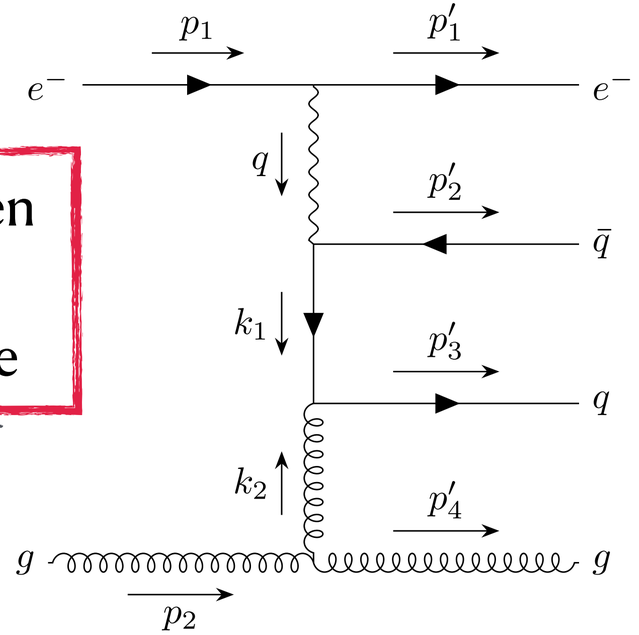
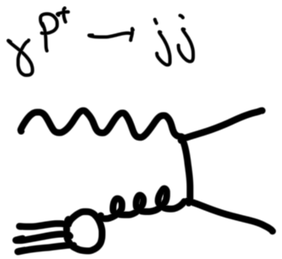
Largest scale is given by jets, **not** by Q^2 anymore



Factorisation in photoproduction



- Put the photon on-shell with the **Equivalent Photon Approximation**
- The photon mixes with neutral vector mesons, c.f. Vector Meson Dominance (VMD) model
- Introduces the concept of partons inside the photon, so (parton-in-)**photon PDF**

See review from the 1978 …

… and talk by Madhav Chithirasreemadam at this conference!

The Hadronic Properties of the Photon in High-Energy Interactions

T.H. Bauer (Cornell U., LNS), R.D. Spital (Cornell U., LNS), D.R. Yennie (Cornell U., LNS), F.M. Pipkin (Harvard U.)
Jul, 1977

377 pages
Published in: *Rev.Mod.Phys.* 50 (1978) 261, *Rev.Mod.Phys.* 51 (1979) 2, 407 (erratum)
Published: Apr 1, 1979
DOI: 10.1103/RevModPhys.50.261, 10.1103/RevModPhys.51.407 (erratum)
Report number: PRINT-77-0549 (HARVARD)
View in: OSTI.GOV, ADS Abstract Service

cite claim reference search 1,053 citations

New parton distributions of the real photon

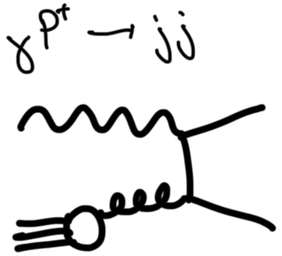
5 May 2026, 15:30
20m
Sala IMPERIALE A, First Floor (Hotel Carlton)

Talk WG1 Structure Func… WG1 Structure functio…

Speaker

Madhav Chithirasreemadam (University of Jyväskylä)

Factorisation in photoproduction



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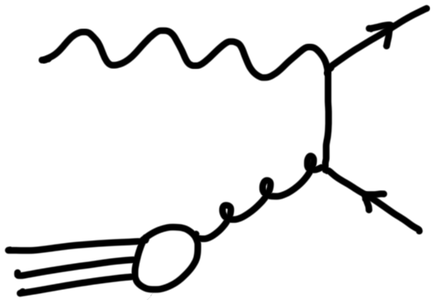
- The photon mixes with neutral vector mesons, c.f. Vector Meson Dominance (VMD) model
- Introduces the concept of partons inside the photon, so (parton-in-)**photon PDF**
- We need to sum the direct and resolved component



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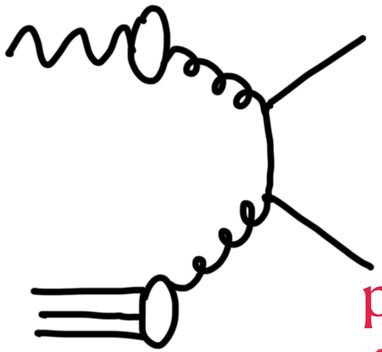


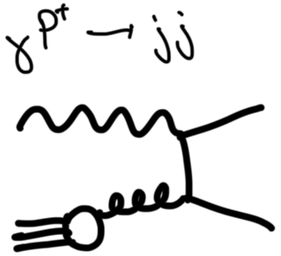
photon PDF

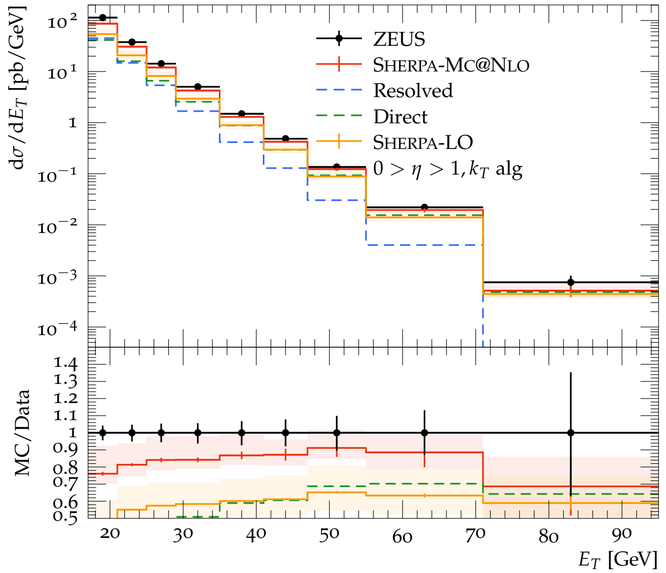
$$\mathrm{d}\sigma^{(\mathrm{direct})}_{\gamma P\to X} = \sum_i \int \mathrm{d}x\, f_{i/P}\left(x, \mu_F^{(P)}\right)\, \mathrm{d}\hat{\sigma}_{\gamma i}$$

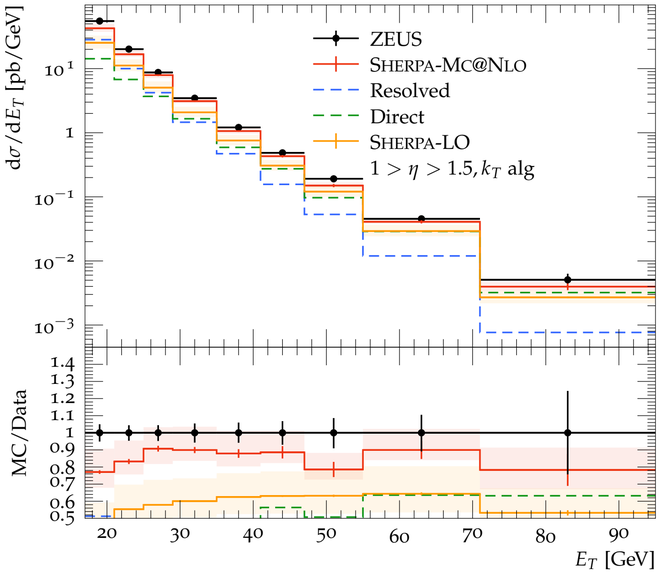
$$\mathrm{d}\sigma^{(\mathrm{hadr})}_{\gamma P\to X} = \sum_{ij} \int\int \mathrm{d}x_1\, \mathrm{d}x_2\, f_{i/P}\left(x_1, \mu_F^{(P)}\right) f_{j/\gamma}\left(x_2, \mu_F^{(\gamma)}\right)\, \mathrm{d}\hat{\sigma}_{ij}$$

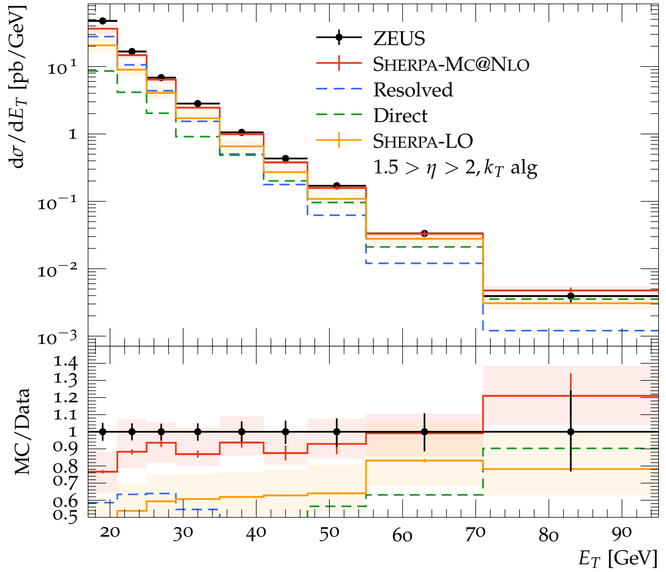
so the total cross section is $\sigma^{\mathrm{pho}}_{eP\to X} = \int \mathrm{d}x\, f_{\gamma/e}(x)\, \mathrm{d}\sigma_{\gamma P\to X} = \int \mathrm{d}x\, f_{\gamma/e}(x)\, \left(\mathrm{d}\sigma^{(\mathrm{point})}_{\gamma P\to X} + \mathrm{d}\sigma^{(\mathrm{hadr})}_{\gamma P\to X}\right)$

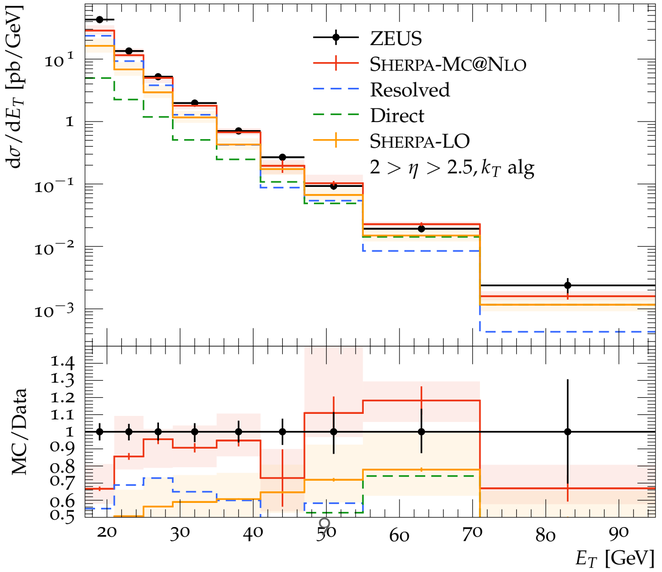
Phenomenology at matched NLO









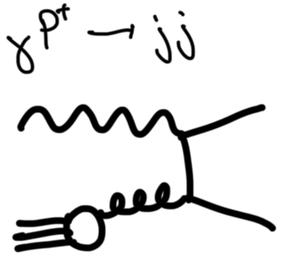


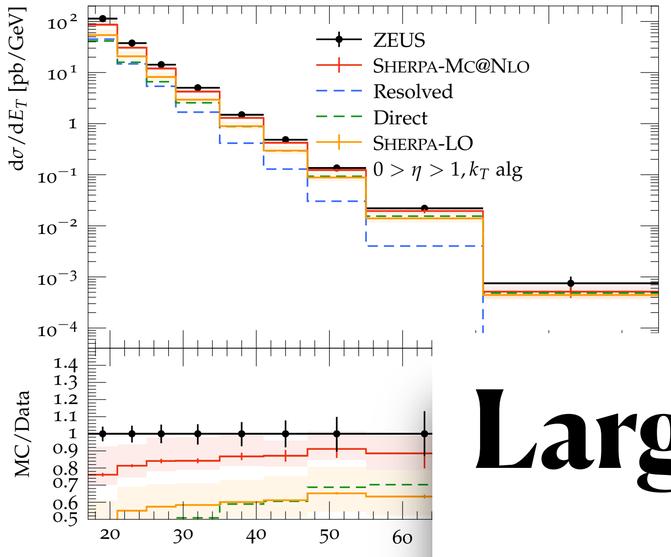
Jets clustered
using the k_T-algorithm with
$R = 1.0$ and
with cuts

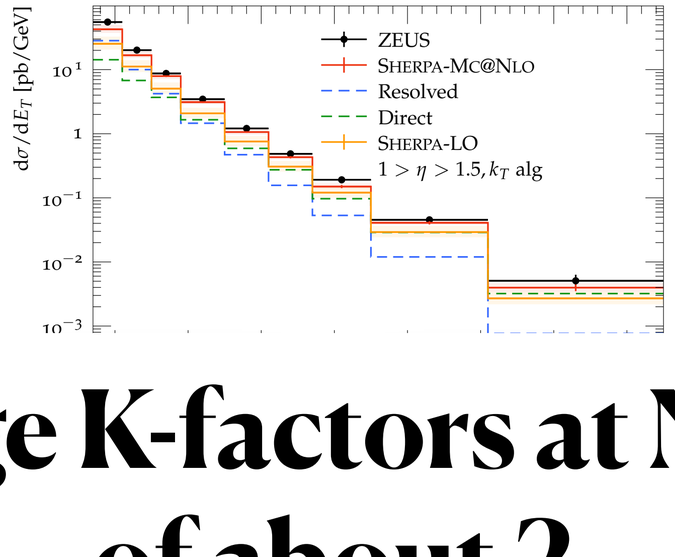
- $142\ \text{GeV} < W < 293\ \text{GeV}$
- $E_T^{(1)} > 17\ \text{GeV}$
- $-1 < \eta^{(1)} < 2.5$
- $Q^2 < 1\ \text{GeV}^2$

[ZEUS, *Nucl.Phys.B* 864 (2012) 1-37]

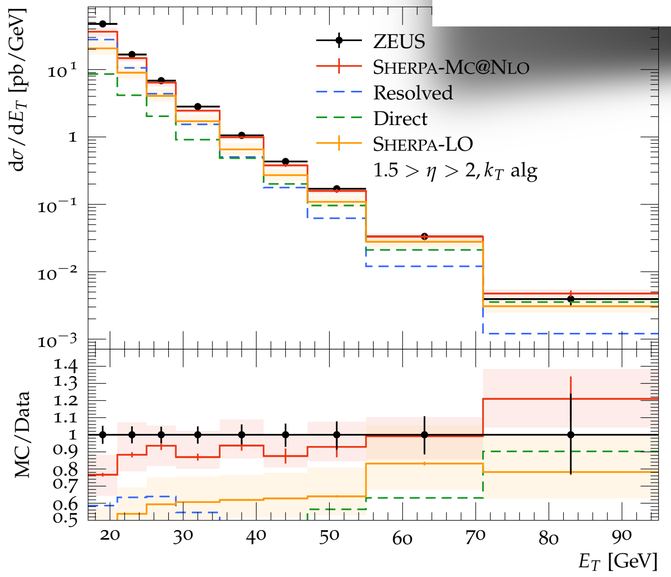
Phenomenology at matched NLO

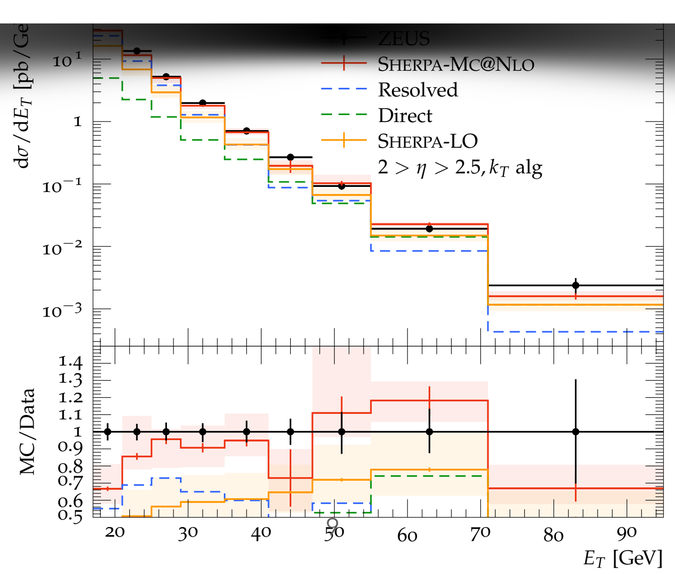






Large K-factors at NLO of about 2





Jets clustered using the k_T-algorithm with 1.0 and cuts

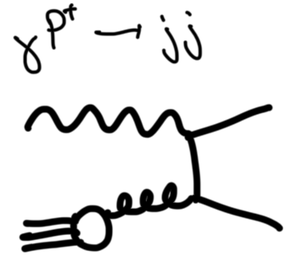
$2 \text{ GeV} < W < 293 \text{ GeV}$

- $E_T^{(1)} > 17 \text{ GeV}$
- $-1 < \eta^{(1)} < 2.5$
- $Q^2 < 1 \text{ GeV}^2$

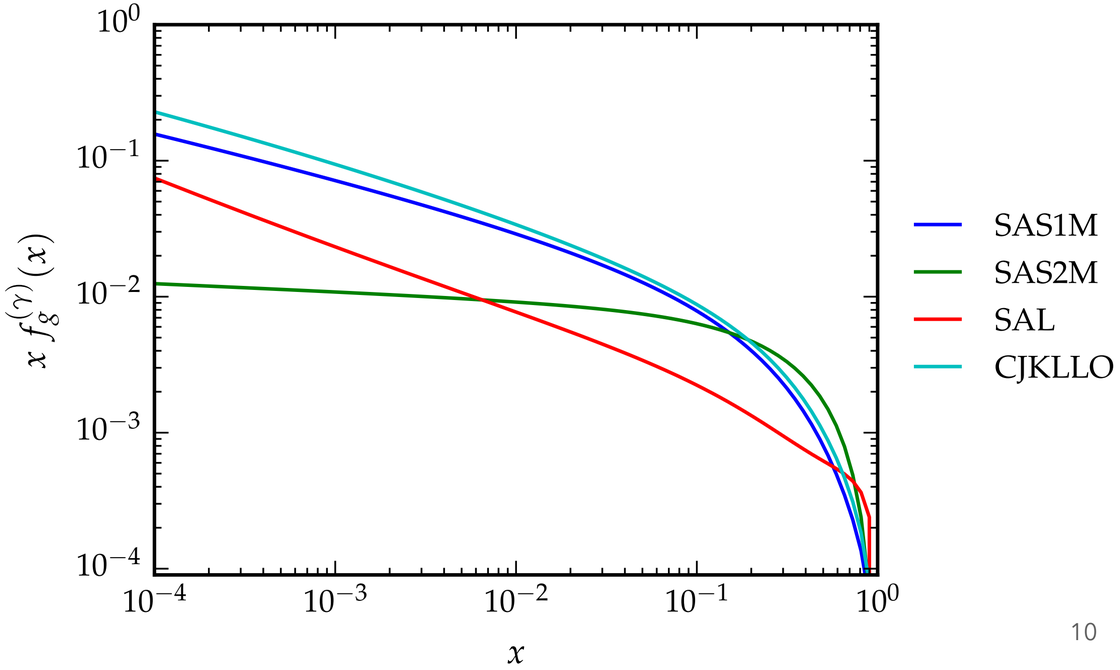
[ZEUS, *Nucl.Phys.B* 864 (2012) 1-37]

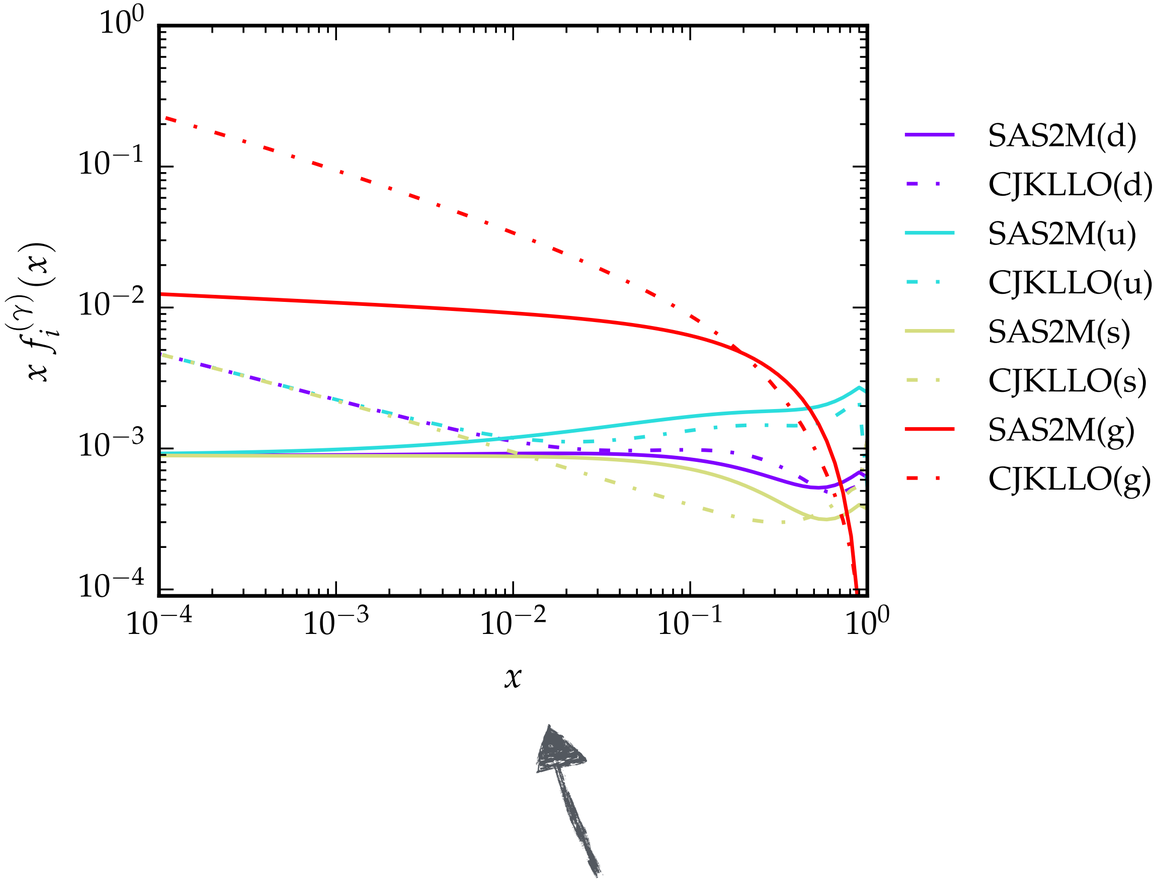
Photon PDF quality

Currently available fits are from the 90s



Gluon PDFs dominant channel,
but poorly constrained

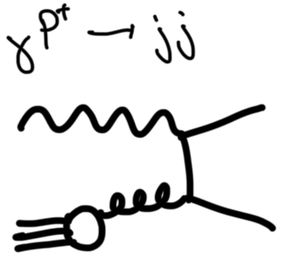


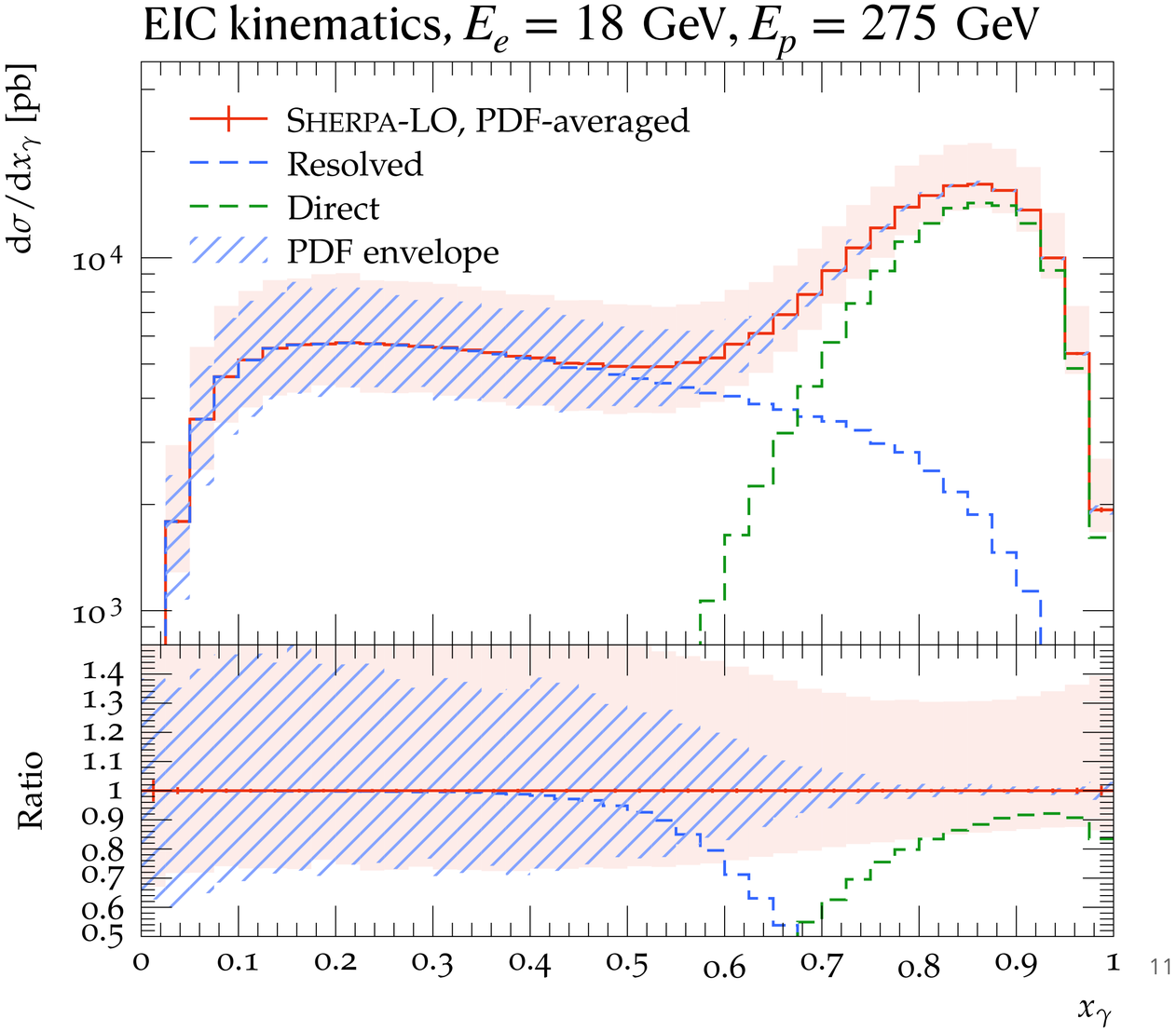


Small-x behaviour differs significantly
between different sets

Photon PDF quality

PDF envelope from 11 photon PDF sets





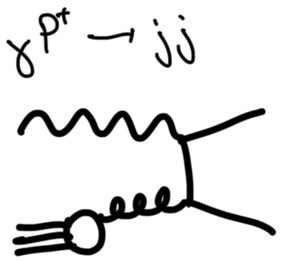
x_γ is a proxy for momentum ratio of parton to photon, defined as

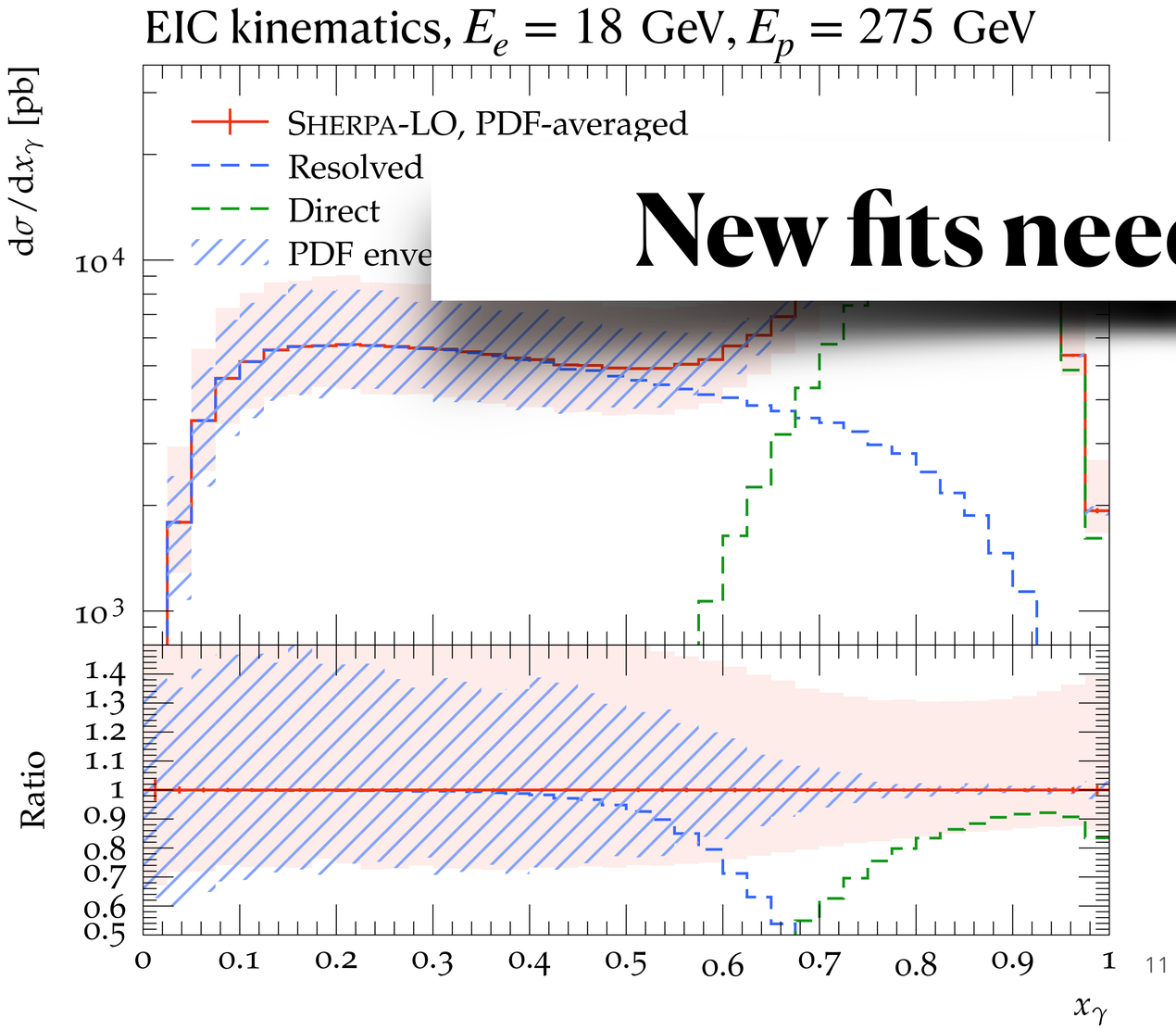
$$x_\gamma = \frac{\sum_{j=1,2} E^{(j)} + p_z^{(j)}}{\sum_{i \in \text{hfs}} E^{(i)} + p_z^{(i)}}$$

- Deviations up to 40%
- α_S value inconsistent with modern proton PDFs
- No error estimates

Photon PDF quality

PDF envelope from 11 photon PDF sets





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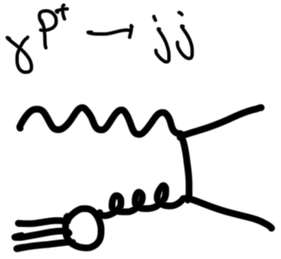
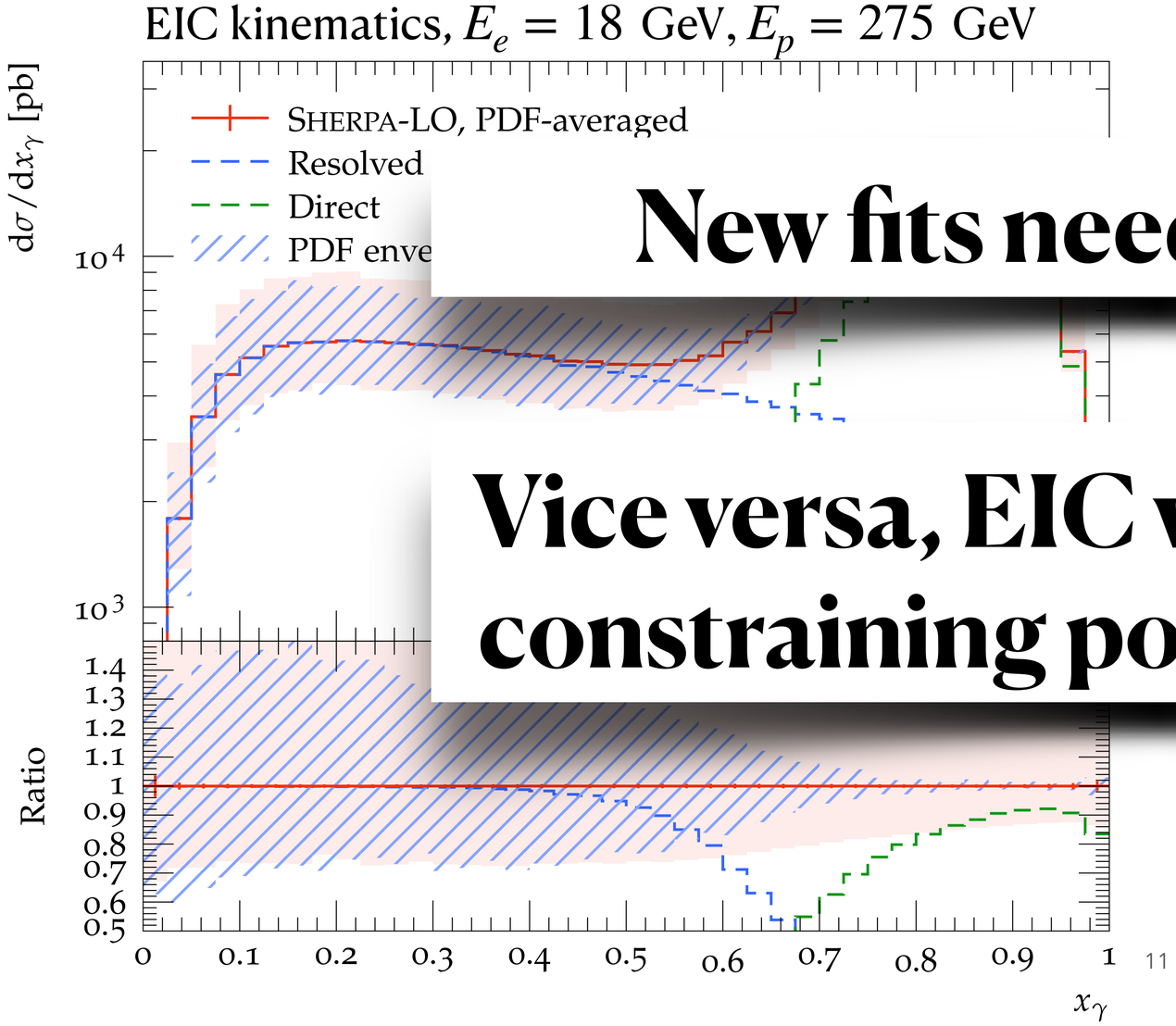
New fits needed for EIC

- Deviations up to 40%
- α_S value inconsistent with modern proton PDFs
- No error estimates

Photon PDF quality

PDF envelope from 11 photon PDF sets





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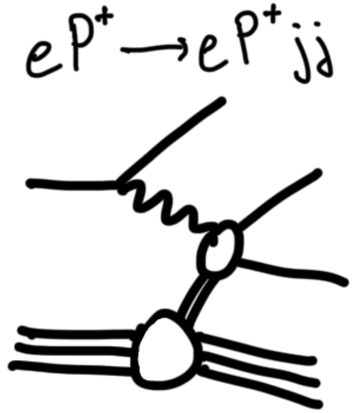
New fits needed for EIC

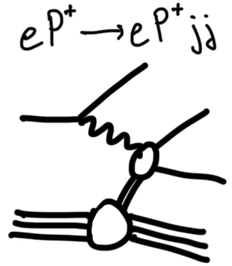
Vice versa, EIC will have strong constraining power on new fits

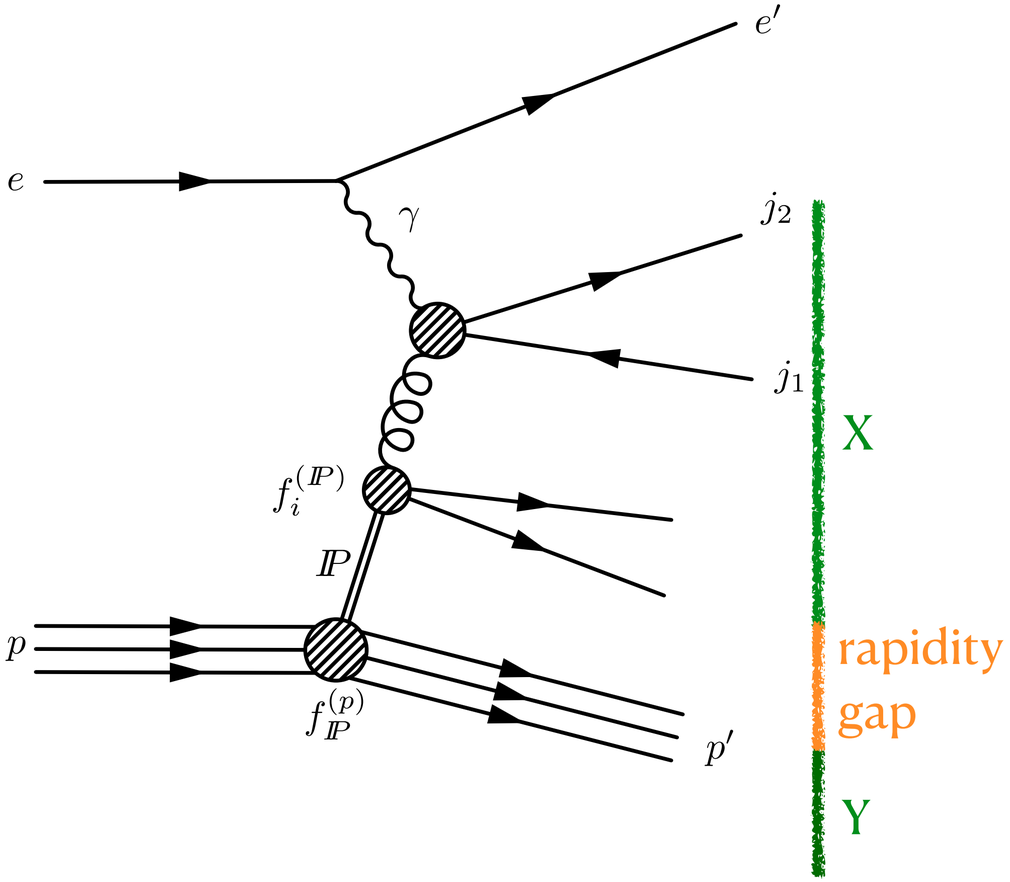
- α_S value inconsistent with modern proton PDFs
- No error estimates

Diffraction in DIS



Diffraction in ep



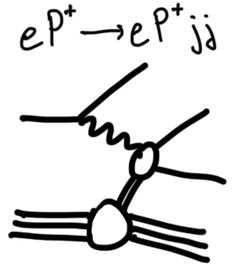


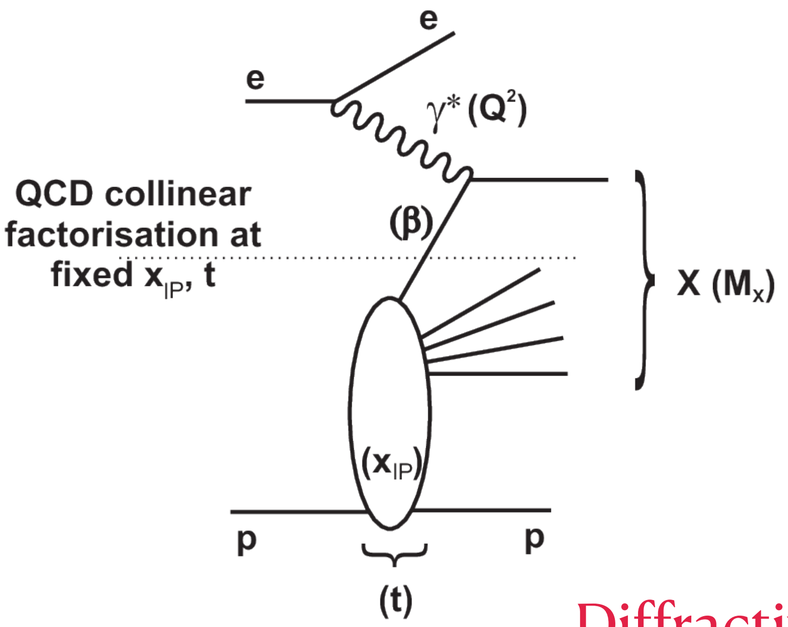
- Presence of rapidity gap, $eP \to eX + Y$
- Colourless exchange, proton stays intact

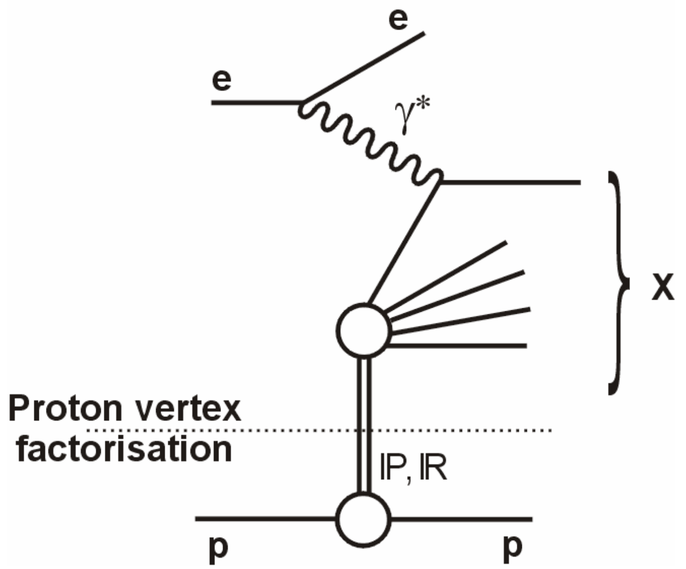
Questions:

- Nature of the Pomeron and Reggeon
- Relation to higher twist, small-x and saturation
- Dependence on energy scales and momentum transfer
- Background for DVCS

Factorisation for Diffractive DIS







Diffractive PDF

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

[Phys. Rev. D 57, 3051]

- Analogous factorisation formula to usual DIS, introducing a **Diffractive PDF**
- Factorise also at the proton vertex into „Pomeron“ flux

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

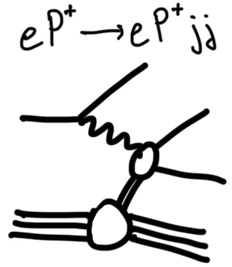
- Needs fits to data as usual
- Analogous formulae for Reggeon contribution

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

[Phys. Lett. 152B, 256]

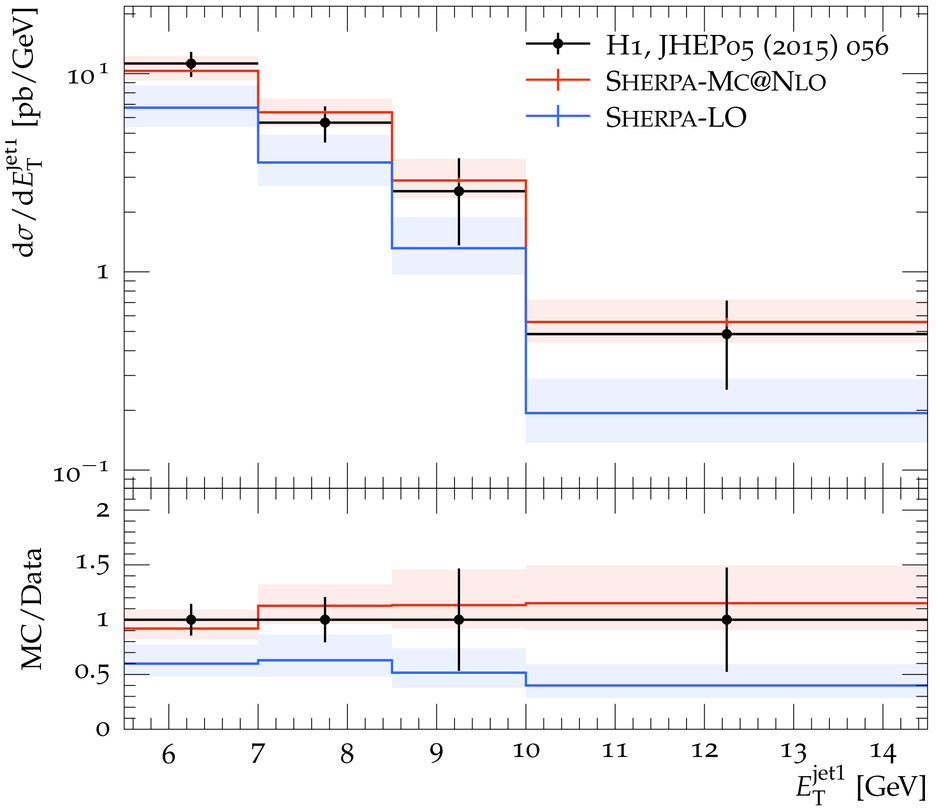
Phenomenology at matched NLO

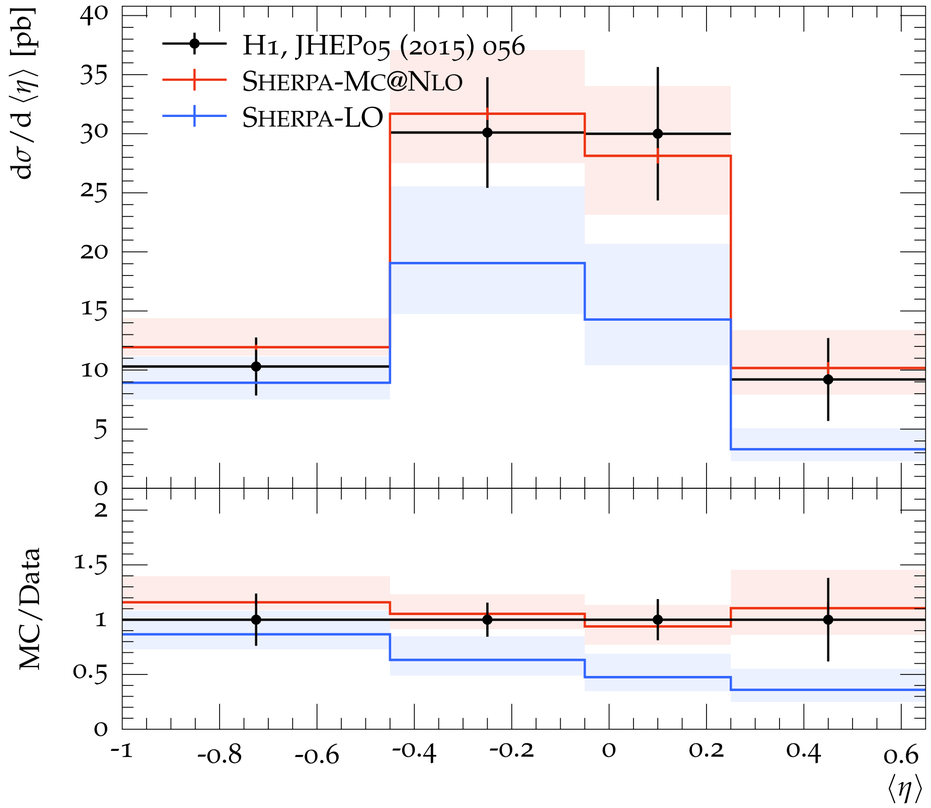
Diffractive dijet production in DIS measured by H1



Jets clustered in the $\gamma^* p$ frame using the k_T-algorithm with $R = 1.0$ and with cuts

- $E_T^{(1)} > 5.5$ GeV
- $E_T^{(2)} > 4.0$ GeV
- $-1 < \eta^{(1,2)} < 2.5$
- $4\ \text{GeV}^2 < Q^2 < 80\ \text{GeV}^2$





[H1, *JHEP* 05 (2015) 056]

Phenomenology at matched NLO

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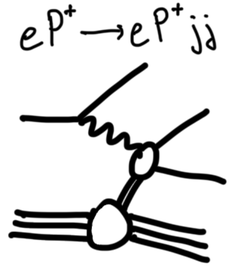

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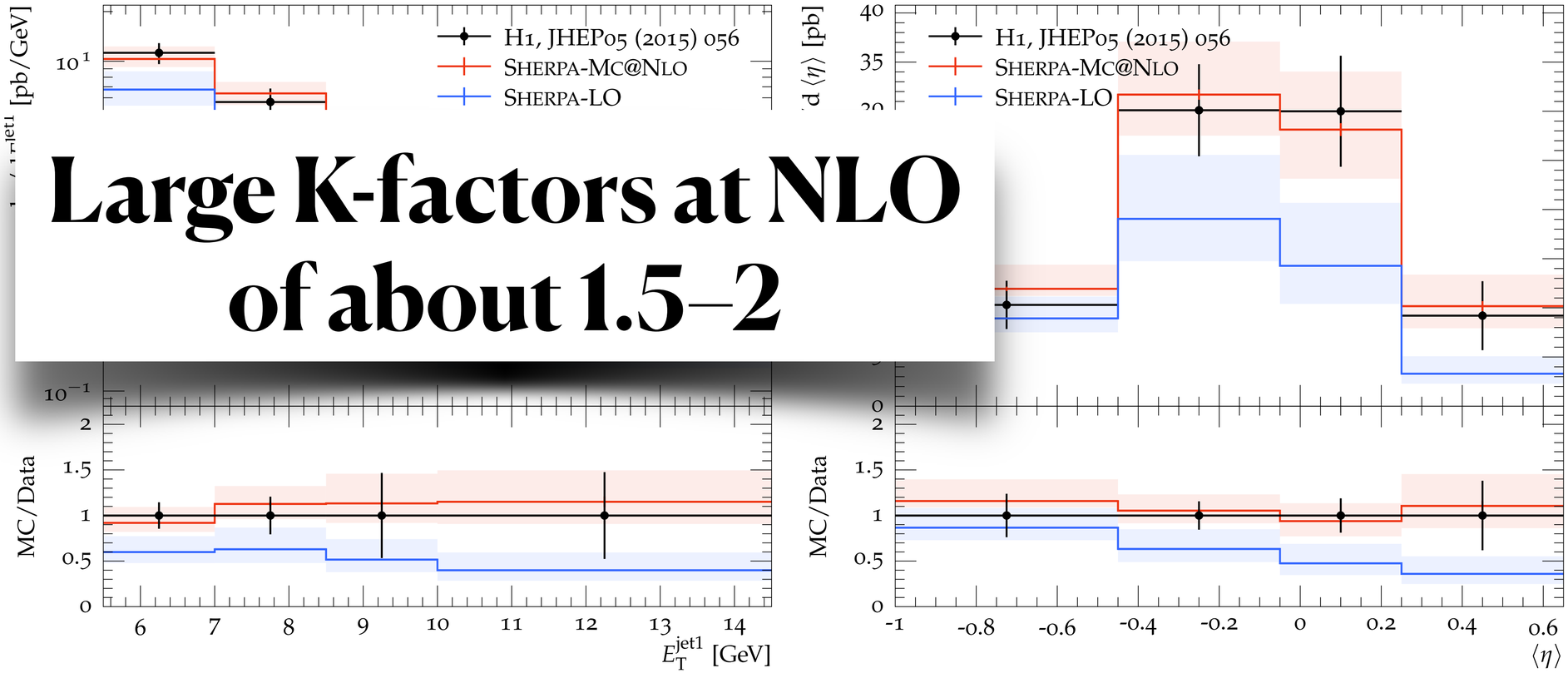
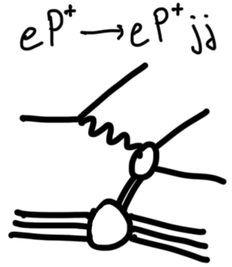


Large K-factors at NLO of about 1.5–2

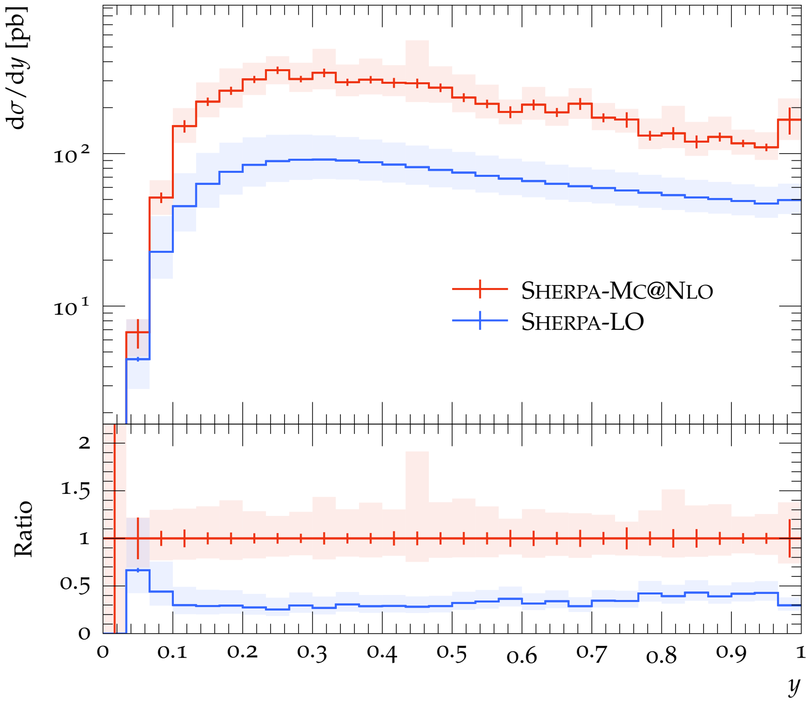
[H1, *JHEP* 05 (2015) 056]



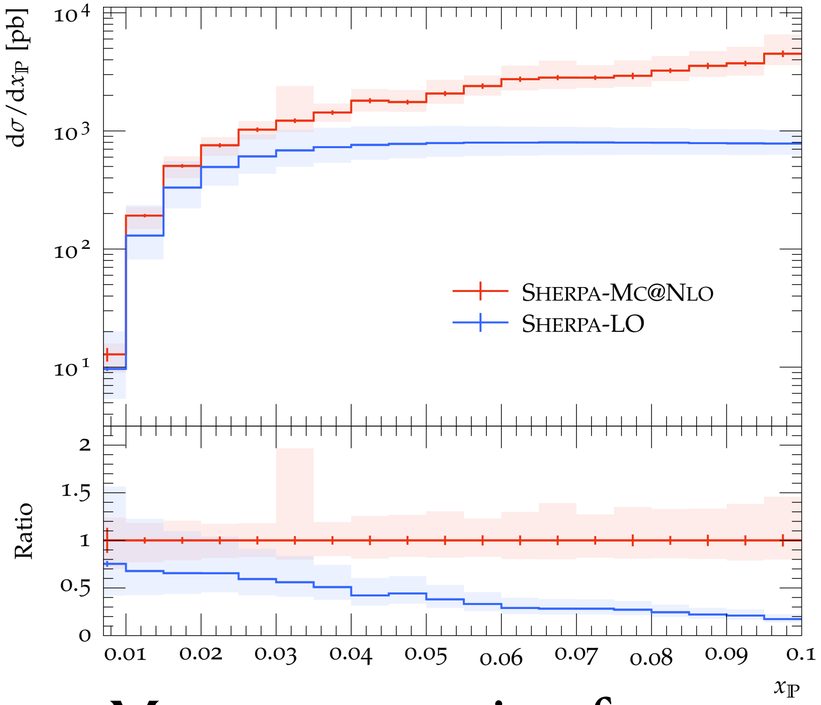
Predictions for EIC

Inspired by [H1, JHEP 05 (2015) 056]:

$4\ \text{GeV}^2 < Q^2 < 110\ \text{GeV}^2,\ x_{I\!P} < 0.1,\ |t| < 0.6\ \text{GeV}^2,\ E_T^{(1)} > 5.5\ \text{GeV},\ E_T^{(2)} > 4.0\ \text{GeV}$

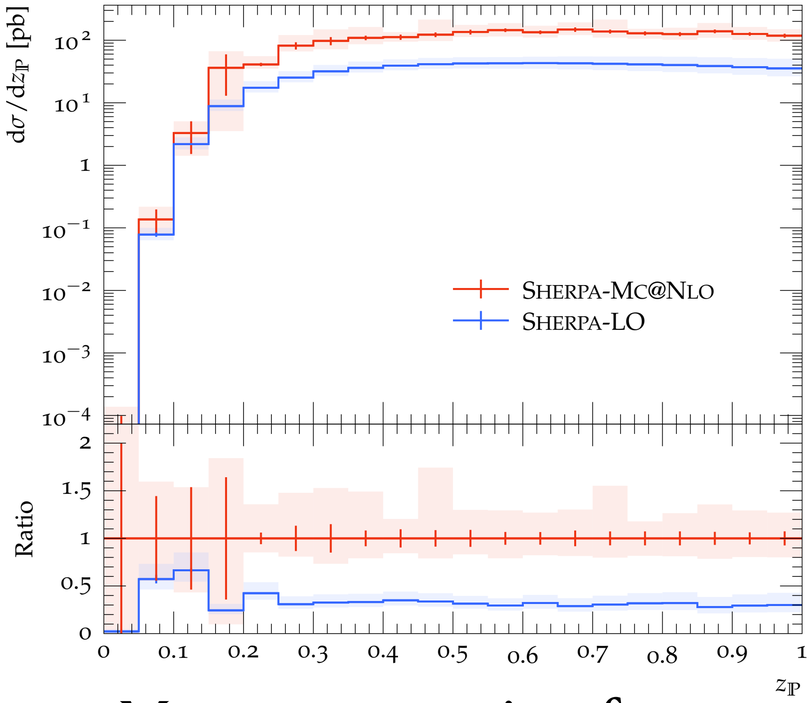


Inelasticity y,
analogous to DIS



Momentum ratio of
„Pomeron“ to proton

$$x_{I\!P} = 1 - \frac{E'_p}{E_p}$$



Momentum ratio of parton
to „Pomeron“

$$z_{I\!P} = \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$$

Announcement

Workshop on Monte Carlo event generation for the EIC
at University of Zurich,
16-28 August 2026

Registration is open at
https://indico.cern.ch/e/mc4eic2026

Conclusions

First matched NLO for two key jet production channels for the EIC

Photoproduction at NLO+PS accuracy in Sherpa

- Large K-factors for past HERA measurements
- Photon PDF deviations between different sets of up to 40%, new fits needed for EIC phenomenology
- EIC data impactful for future fits

Diffraction at NLO+PS accuracy in Sherpa

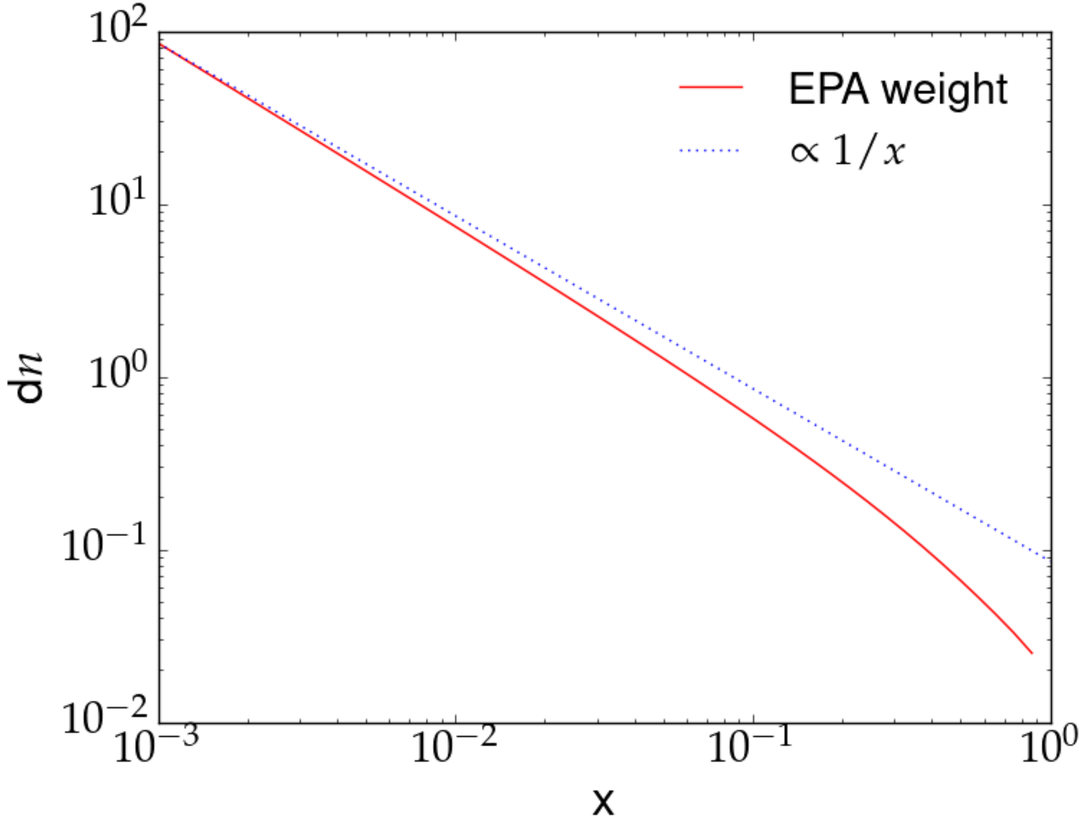
- Impact on Diffractive PDF and nature of the Pomeron
- Large K-factors for past HERA and similar EIC measurements

Backup

Equivalent Photon Approximation

a.k.a. Weizsäcker-Williams approximation

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



Integrated in Q^2,

$Q^2_{\text{min}} = m_e^2x^2/(1-x)$ given by kinematics,

Q^2_{max} by experimental cuts

Equivalent Photon Approximation

a.k.a. Weizsäcker-Williams approximation

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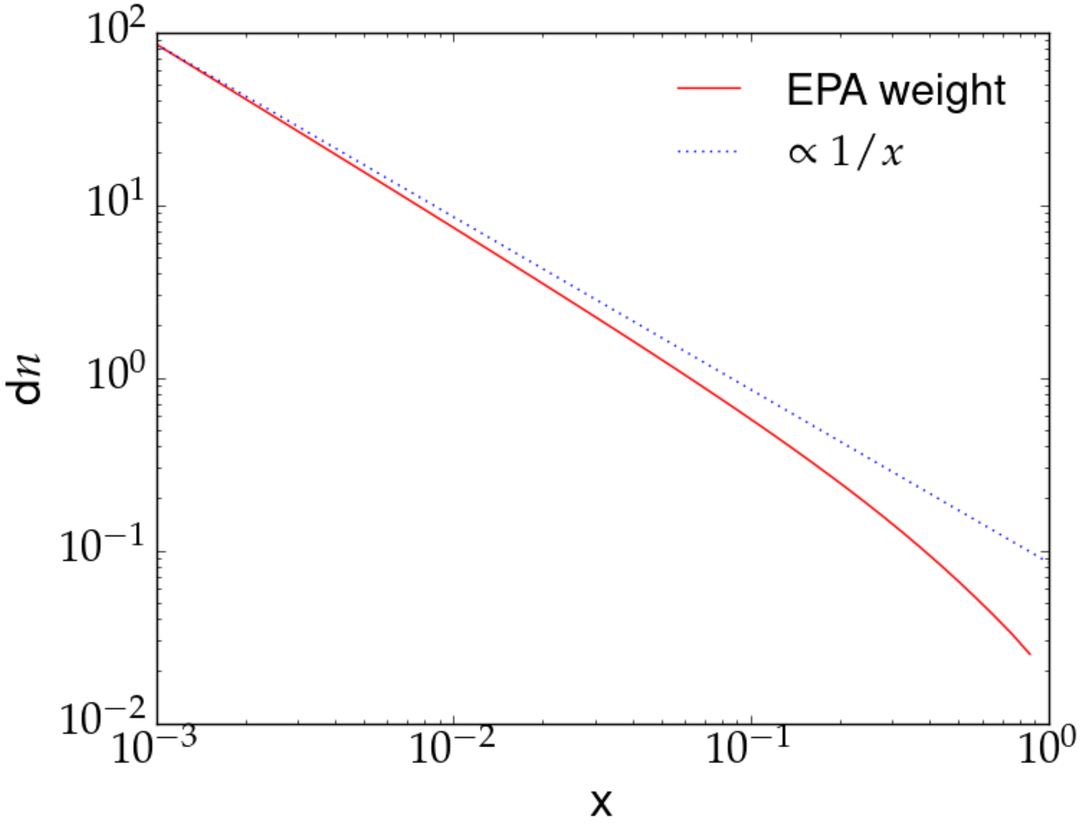
dominated by this term

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



Integrated in Q^2,

$Q^2_{\text{min}} = m_e^2x^2/(1-x)$ given by kinematics,

Q^2_{max} by experimental cuts

Predictions for photoproduction at the 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

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
- including fragmentation, MPIs, beam remnants,...

Predictions for diffractive DIS at the EIC

Loosely inspired by [H1, JHEP 05 (2015) 056]

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 $E_T > 5.5\ (4)$ GeV for (sub-)leading jet

For event generation in SHERPA

- Matched with S-MC@NLO
- scales chosen as $\mu_R = \mu_F = \frac{1}{2}\sqrt{Q^2 + H_T^2}$, incl. 7-point variation
- H1 DPDF fit for pomeron, GRVP1o PDF for reggeon
- fragmentation, beam remnants, primordial-k_T, ...