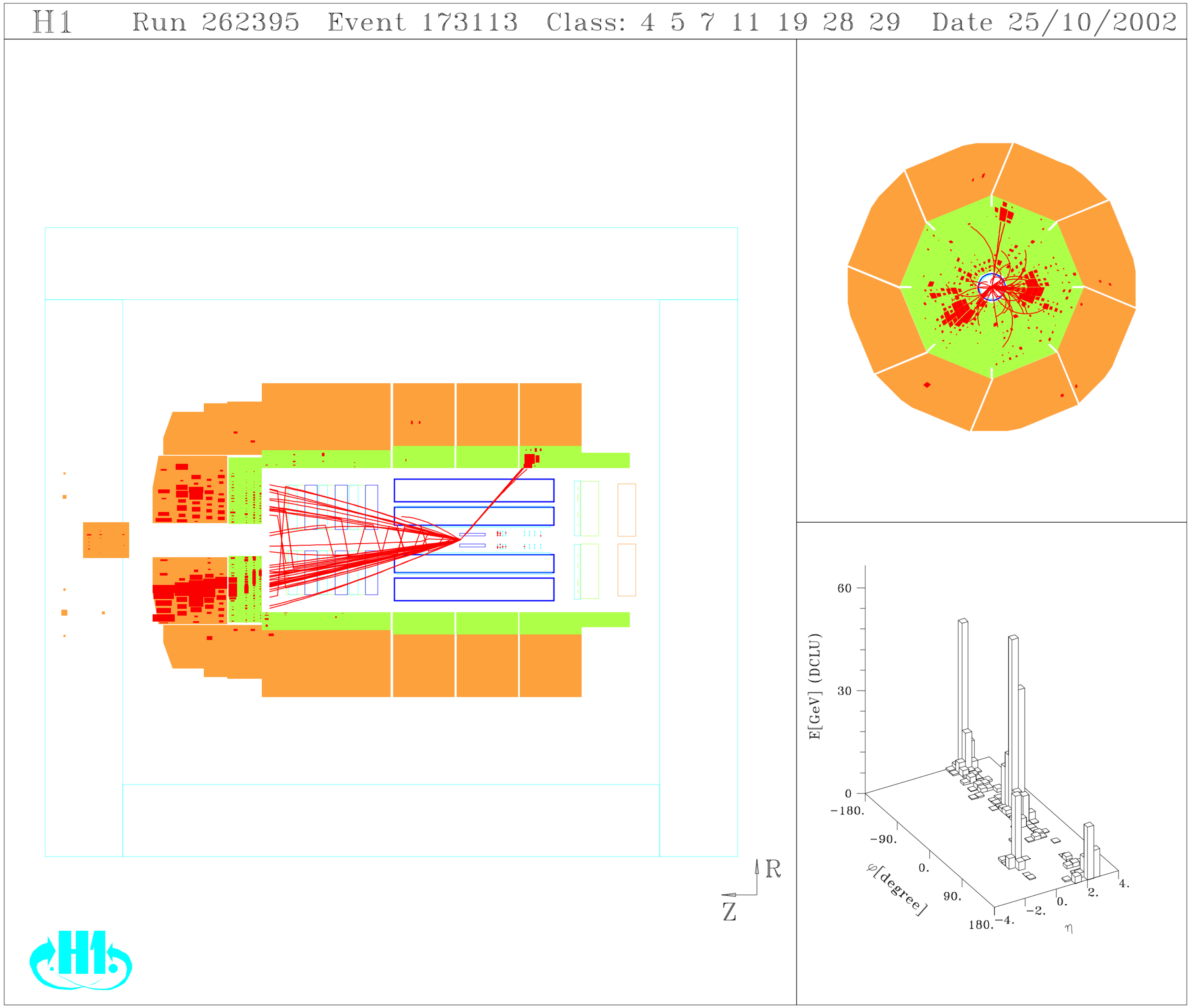
EIC jet phenomenology in Sherpa and NNLOJET

Bridging Theory and Experiment at the Electron-Ion Collider workshop @ INT, Seattle

Peter Meinzinger, Universität Zürich, 3rd June 2025

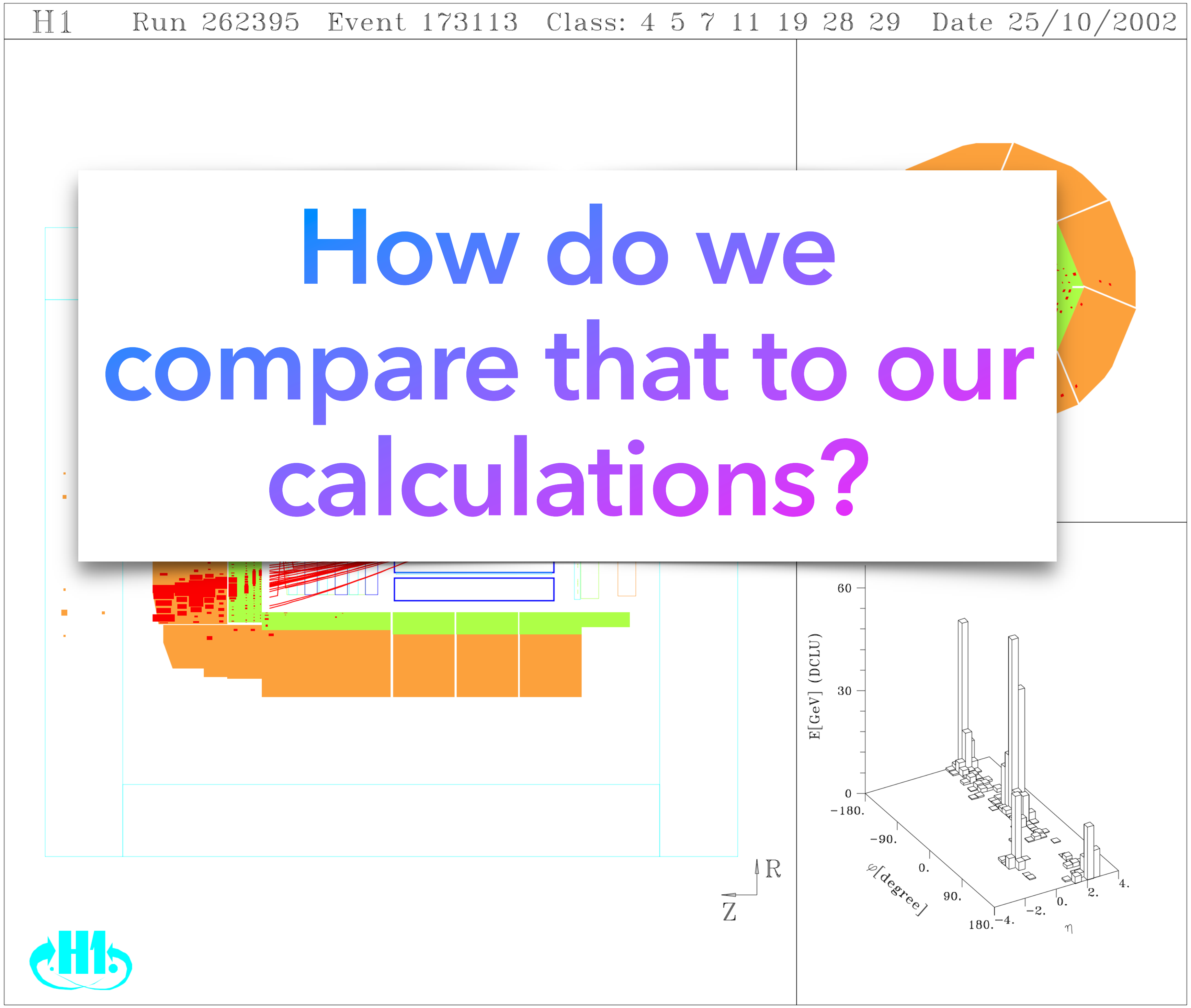
Introduction

What we measure



[taken from H1 website]

What we measure

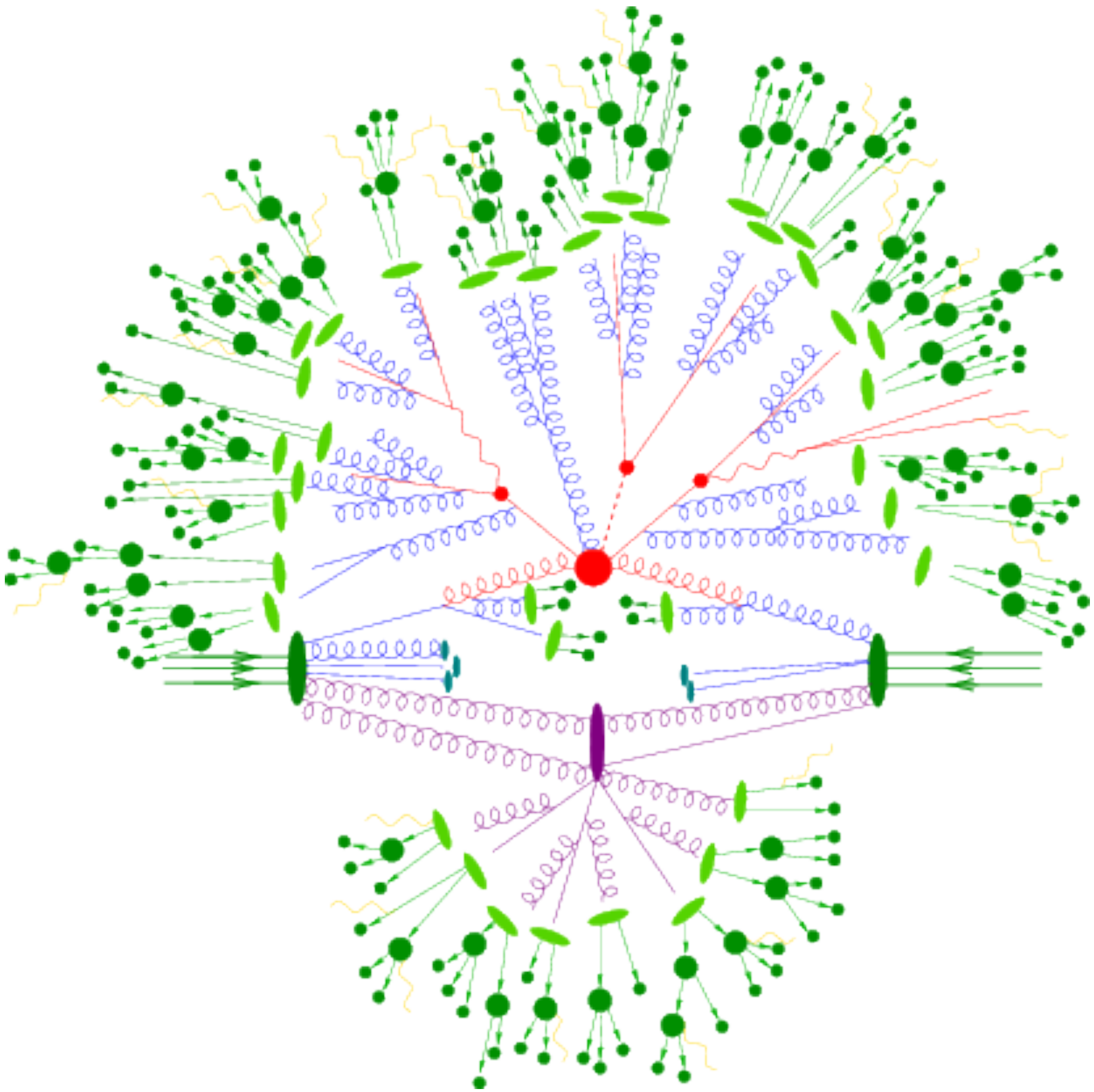


How do we compare that to our calculations?

[taken from H1 website]

What we compute

theorists' tool for phenomenology

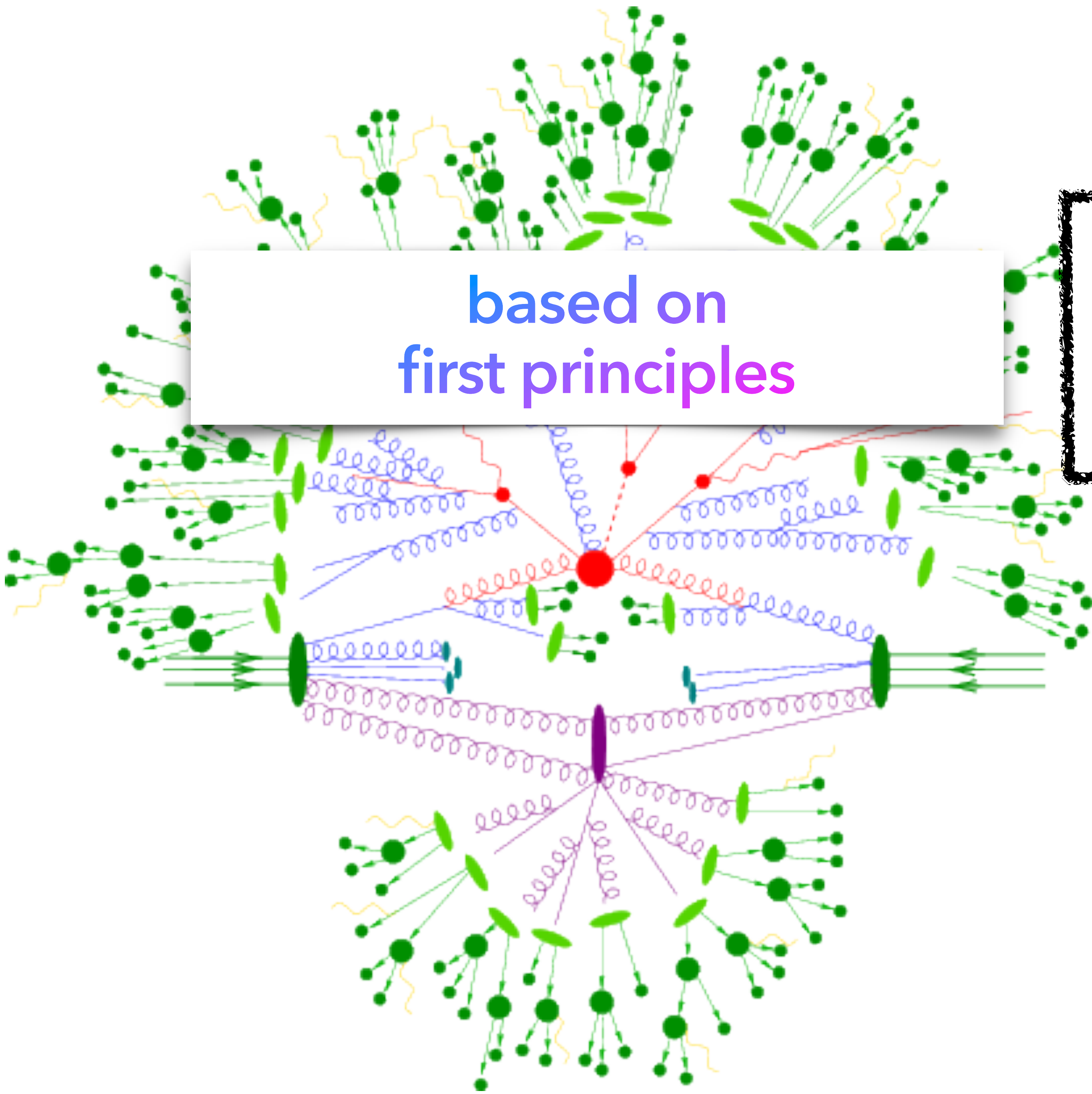


Event generators compute

- matrix element
- parton shower/ resummation
- multiple interactions
- hadronisation
- hadron decays
- beam remnants

What we compute

theorists' tool for phenomenology



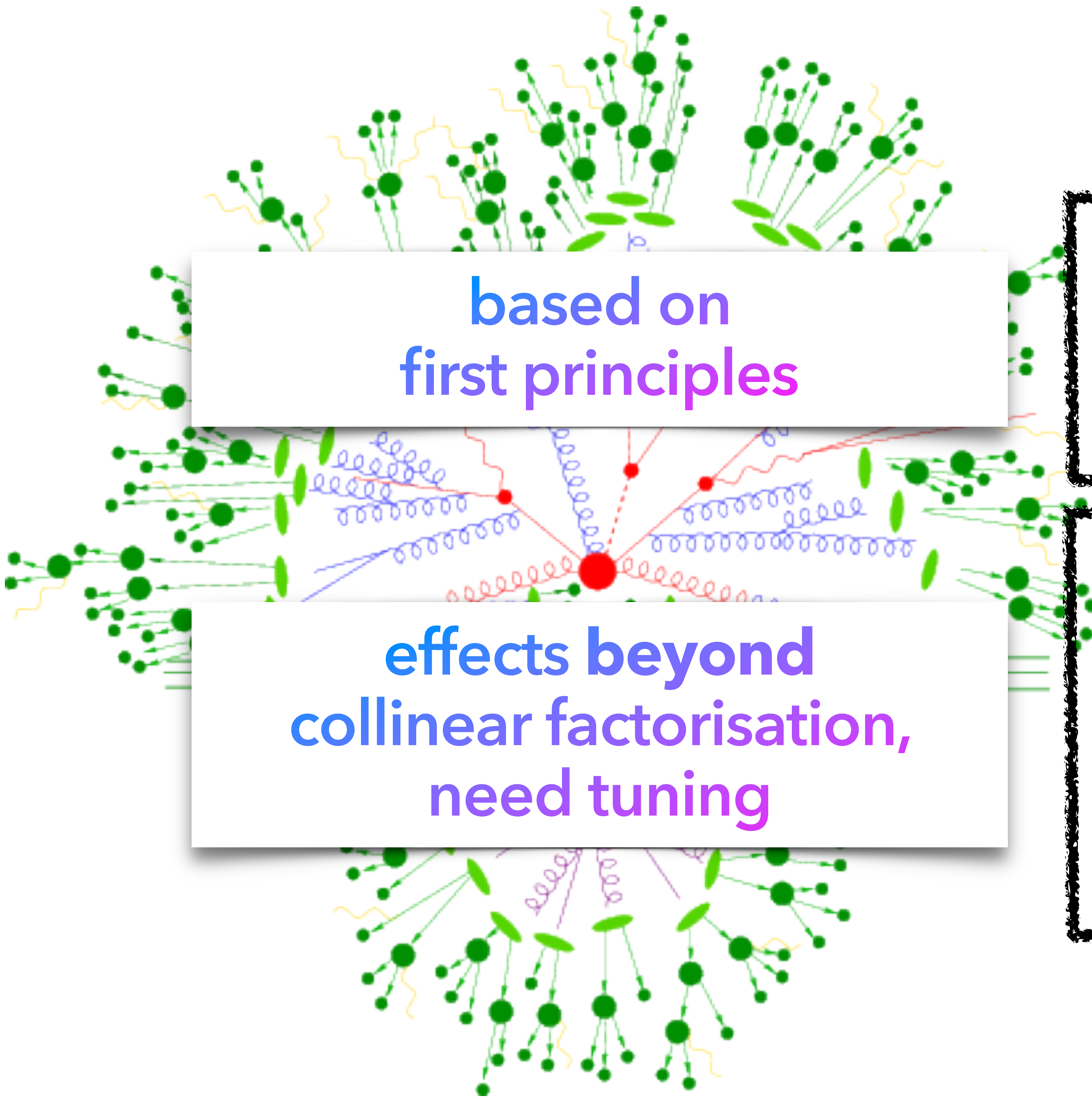
based on
first principles

Event generators compute

- matrix element
- parton shower/ resummation
- multiple interactions
- hadronisation
- hadron decays
- beam remnants

What we compute

theorists' tool for phenomenology



Event generators compute

- matrix element
- parton shower/ resummation
- multiple interactions
- hadronisation
- hadron decays
- beam remnants

Event generation for the EIC

Jet measurements, α_S extractions, background studies etc

- **need fully exclusive perturbative calculations**
- **need to use correct fiducial cross-section**
- **need to be fully inclusive in phase space**

e.g. inclusive measurements of jets would need to cover full range of virtuality, consider the detector acceptance region and allow analysis of arbitrary observables

Event generation for the EIC

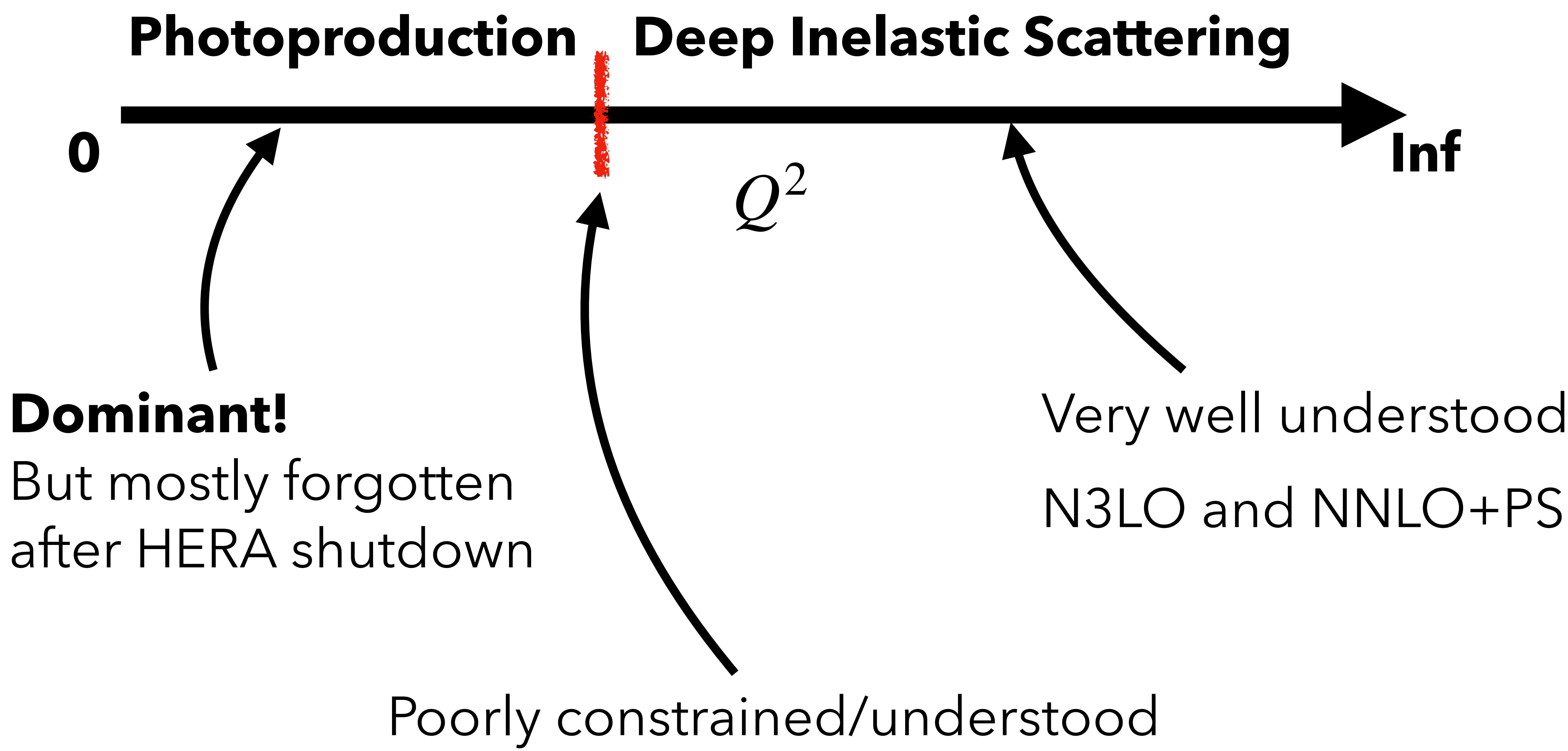
Jet measurements, α_s extractions, background studies etc

- **need**
- **need**
- **need**

The precision goals at the EIC mandate an accuracy of NLO or higher

e.g. inclusive measurements of jets would need to cover full range of virtuality, consider the detector acceptance region and allow analysis of arbitrary observables

Event generation for the EIC



Event generators

for DIS and more, considered here

NNLOJET

parton-level event generator

NNLO and beyond

Antenna subtraction

Sherpa

hadron-level event generator

NLO, matched to parton showers

multi-leg merging of matrix elements

SciPost Physics Codebases Submission

CERN-TH-2025-012, IPPP/25/09, ZU-TH 11/25

NNLOJET: a parton-level event generator for jet cross sections at NNLO QCD accuracy

NNLOJET

NNLOJET Collaboration

A. Huss[1,*], L. Bonino[2], O. Braun-White[3], S. Caletti[4], X. Chen[5], J. Cruz–Martinez[1], J. Currie[3], W. Feng[2], G. Fontana[2], E. Fox[3], R. Gauld[6], A. Gehrmann–De Ridder[2,4], T. Gehrmann[2], E.W.N. Glover[3], M. Höfer[7], P. Jakubčík[2], M. Jaquier[8], M. Löchner[2], F. Lorkowski[2], I. Majer[4], M. Marcoli[3], P. Meinzinger[2], J. Mo[2], T. Morgan[3], J. Niehues[3,9], J. Pires[10,11], C. T. Preuss[12,13], A. Rodriguez Garcia[4], K. Schönwald[2], R. Schürmann[2], V. Sotnikov[2], G. Stagnitto[14], D. Walker[3], S. Wells[3], J. Whitehead[15], T.Z. Yang[2] and H. Zhang[16]

JHEP PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: November 13, 2024
ACCEPTED: December 3, 2024
PUBLISHED: December 20, 2024

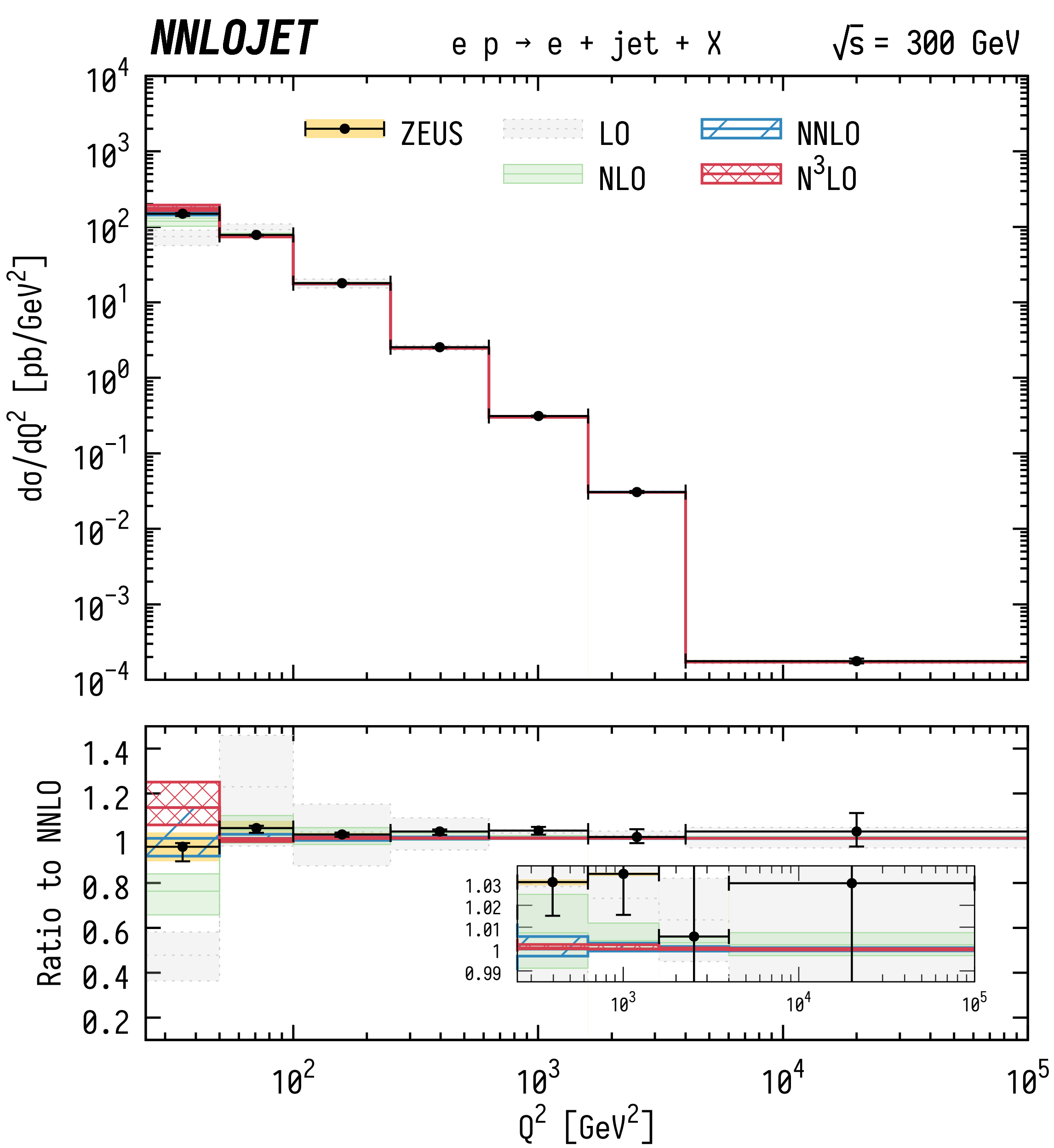
Event generation with SHERPA 3

Enrico Bothmann[a], Lois Flower[b,c] Christian Gütschow[d,e] Stefan Höche[f], Mareen Hoppe[g] Joshua Isaacson[f] Max Knobbe[a,f] Frank Krauss[b], Peter Meinzinger[b,h] Davide Napoletano[i] Alan Price[j] Daniel Reichelt[b,k], Marek Schönherr[b,*] Steffen Schumann[a] and Frank Siegert[g]

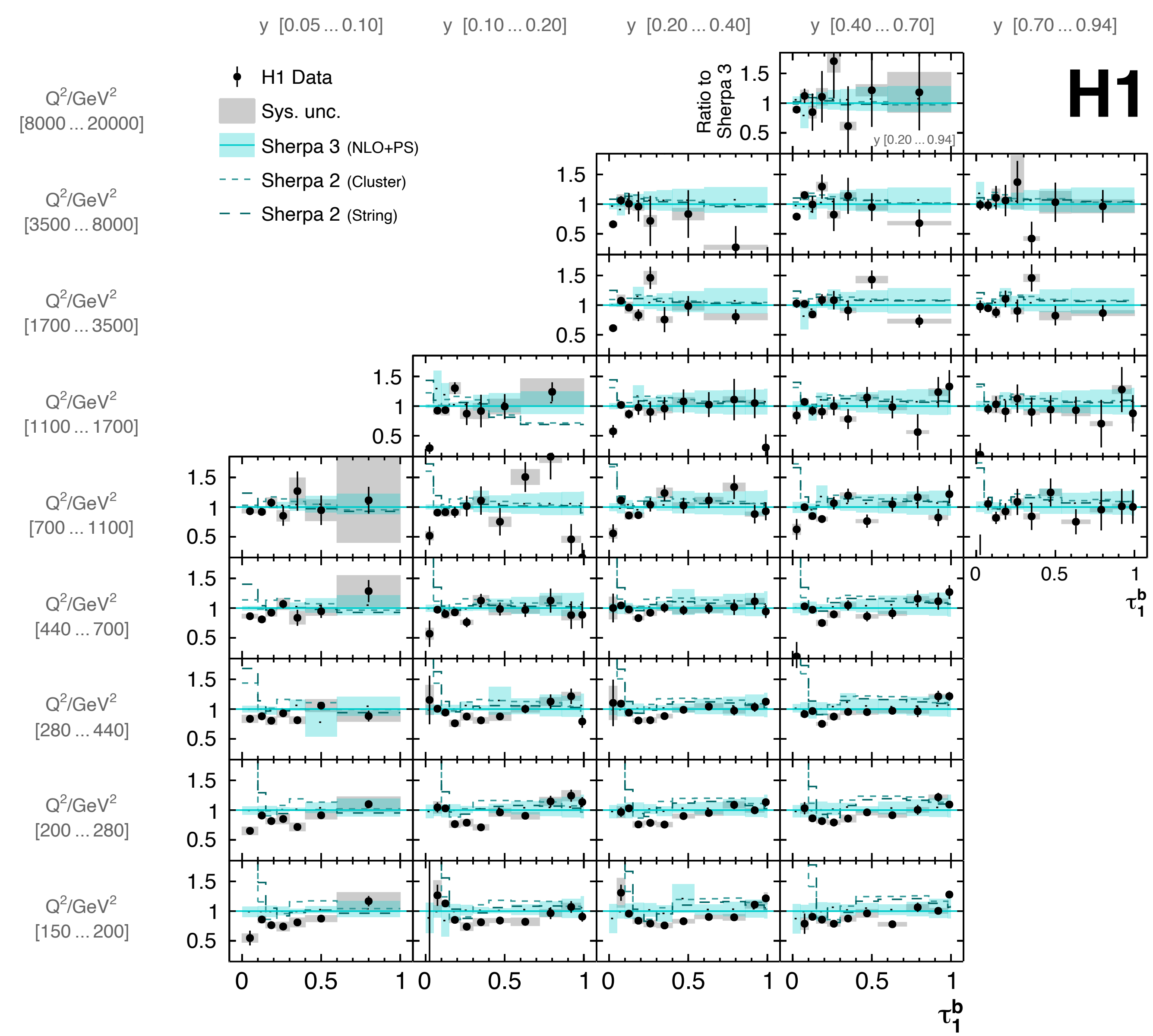
[a]Institut für Theoretische Physik, Georg-August-Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany

[b]Institute for Particle Physics Phenomenology, Department of Physics, Durham University,

Applications in DIS



[J. Currie, Th. Gehrmann, E. Glover, A. Huss, J. Niehues, A. Vogt, 1803.09973]



measurement of 1-jettiness, [H1, 2403.10109]

Glossary

Matrix elements and techniques used throughout

- **LO**
  $e^-p \to e^- + 1j$ @ LO
- **MC@NLO**, "matched"
  $e^-p \to e^- + 1j$ @ NLO
- **MEPS@LO**, "merged"
  $e^-p \to e^- + 1,2,3,4j$ @ LO
- **MEPS@NLO**, "merged and matched"
  $e^-p \to e^- + 1,2j$ @ NLO $+\ 3,4j$ @ LO

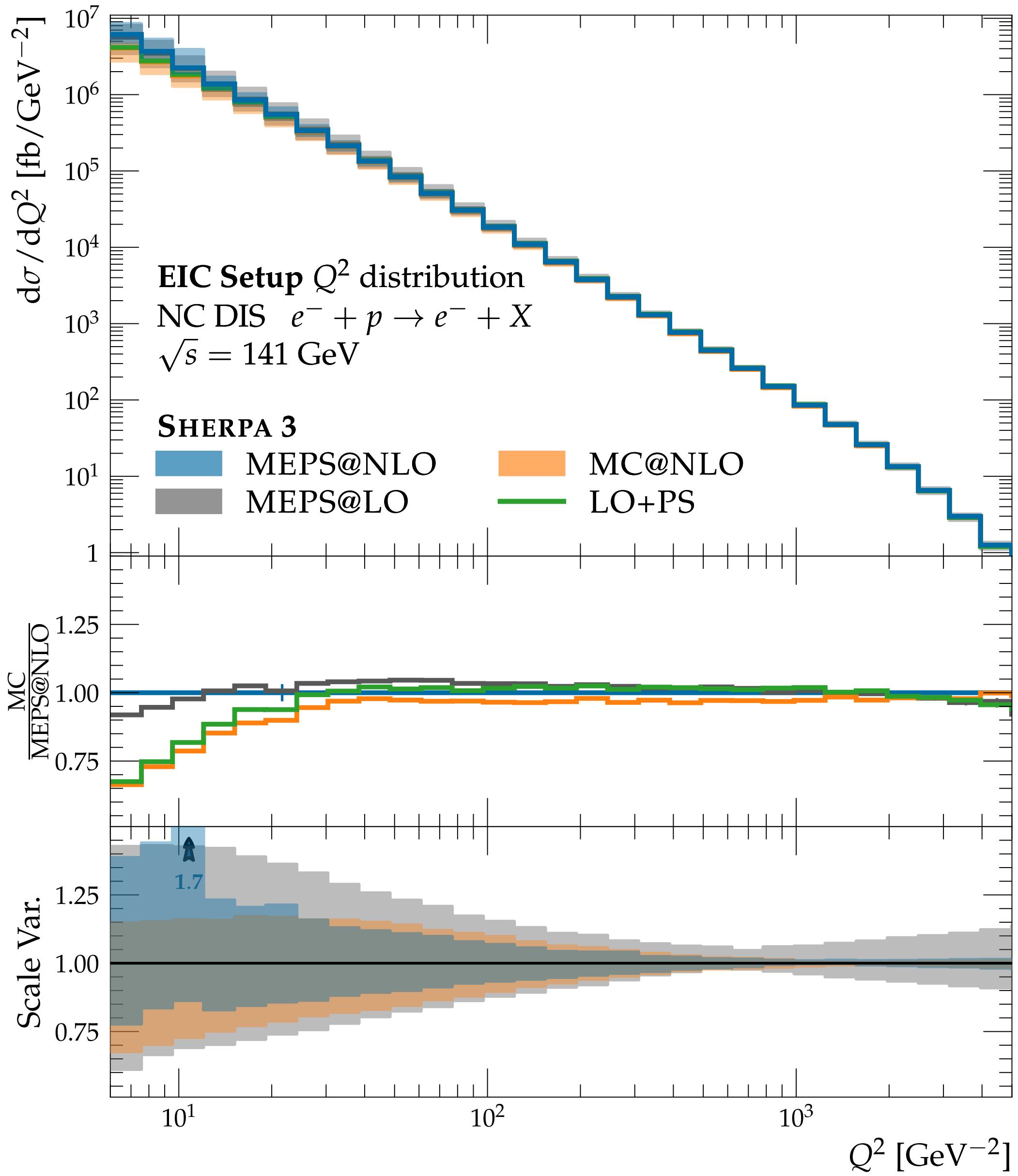
EIC phenomenology

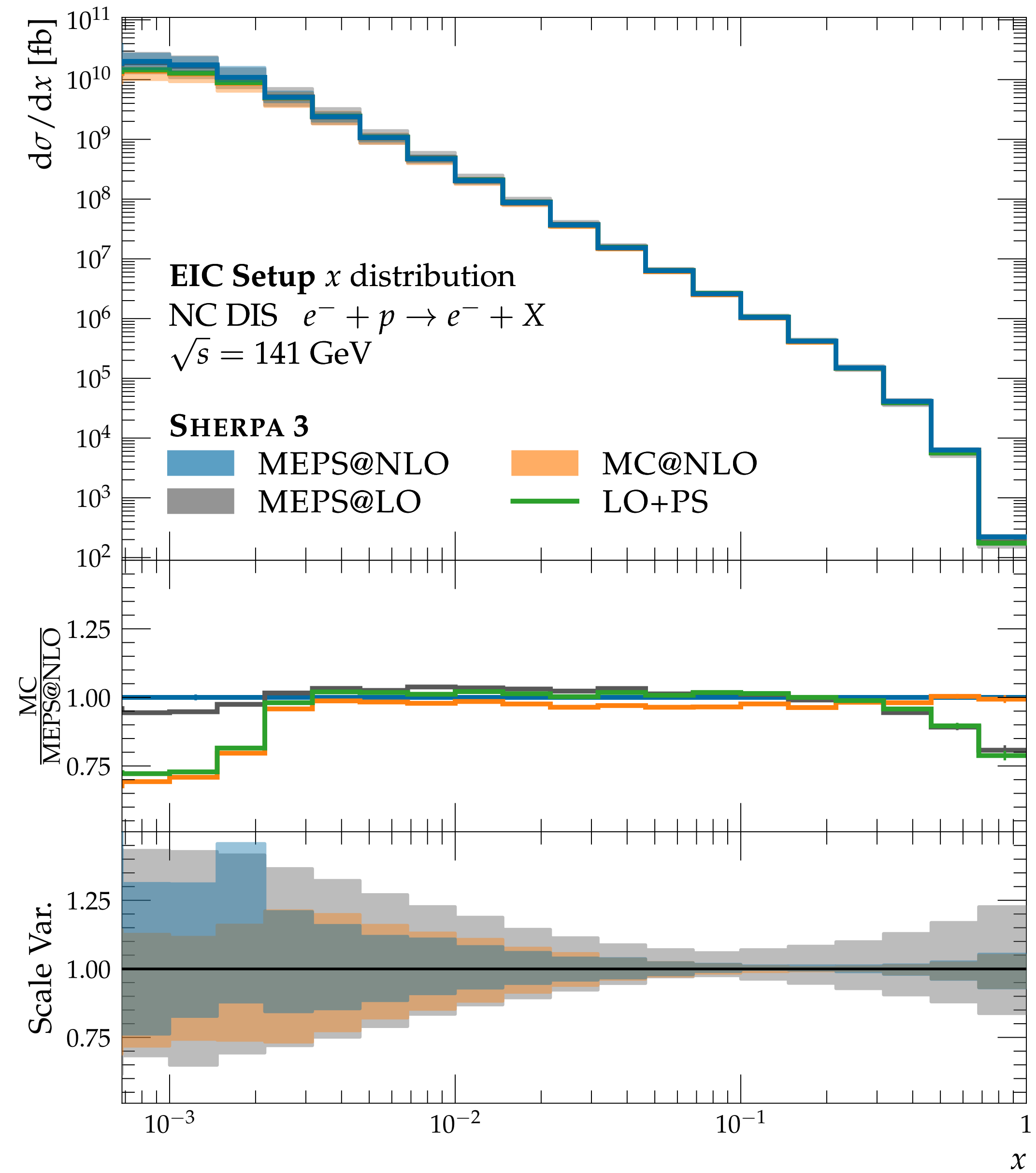
Analysis for DIS

- Assuming 18x275 ep beams
- Event-/hadron-level analysis in Rivet
- Detector acceptance of $|\eta| < 4$
- Phase space cuts of $Q^2 > 6\ (10)\ \mathrm{GeV}^2$ and $0.2 < y < 0.9$ for NC (CC)
- Using merging, matching to the parton shower, hadronisation, beam remnants,…
- Both, charged current and neutral current
- 7-point scale variations to estimate HO uncertainties

Predictions for DIS

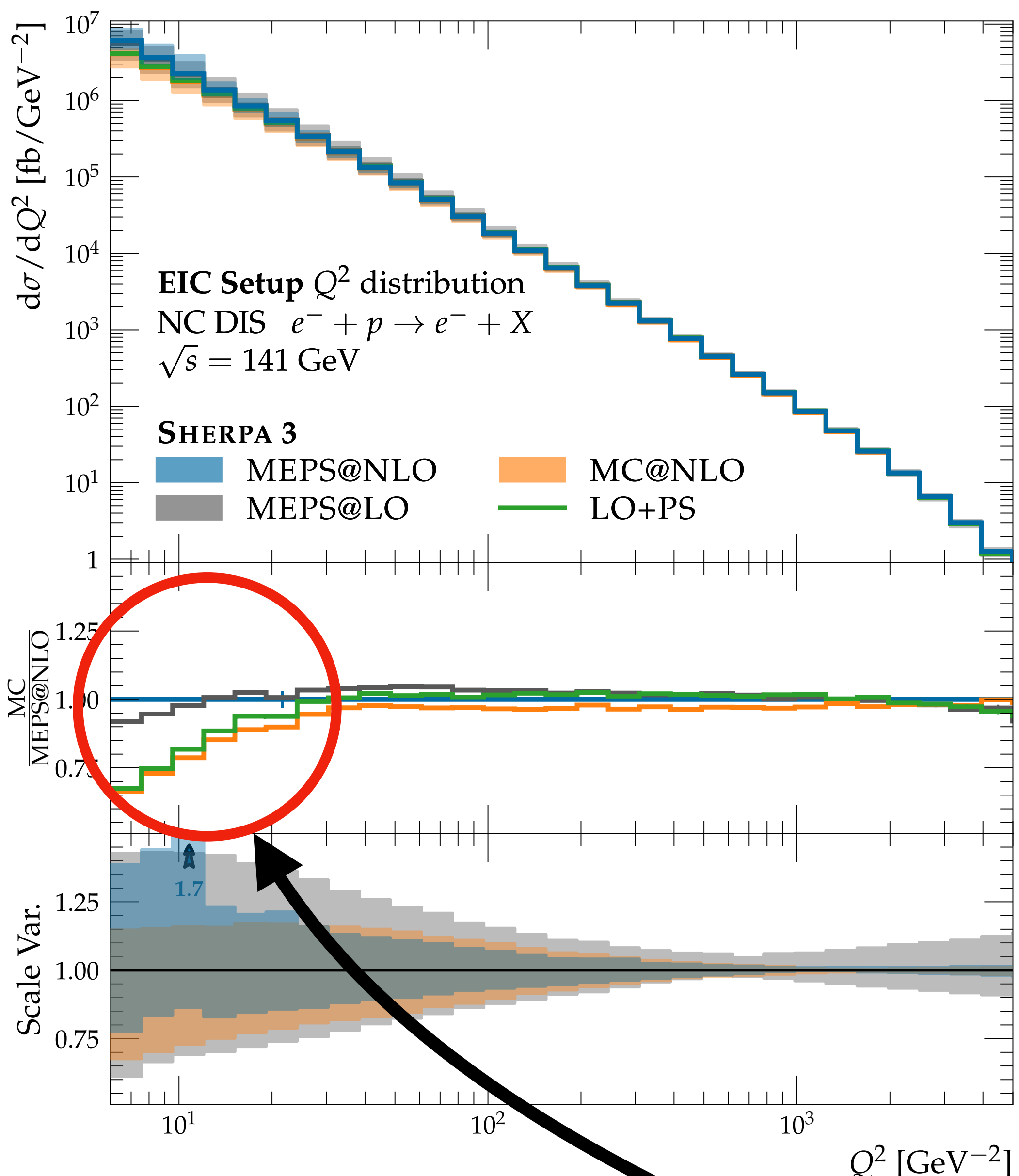
Why use multi-leg merging?

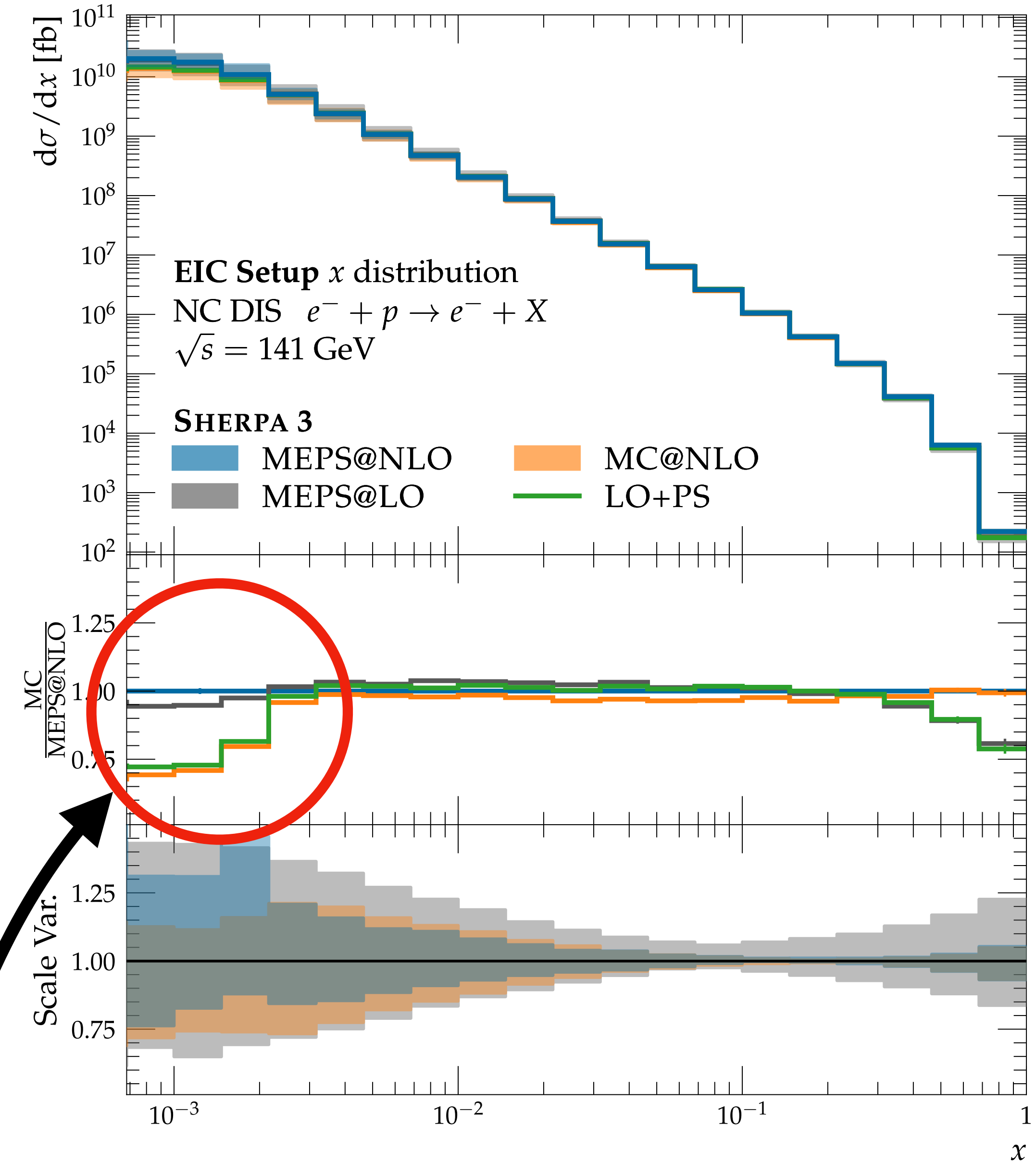




Predictions for DIS

Why use multi-leg merging?



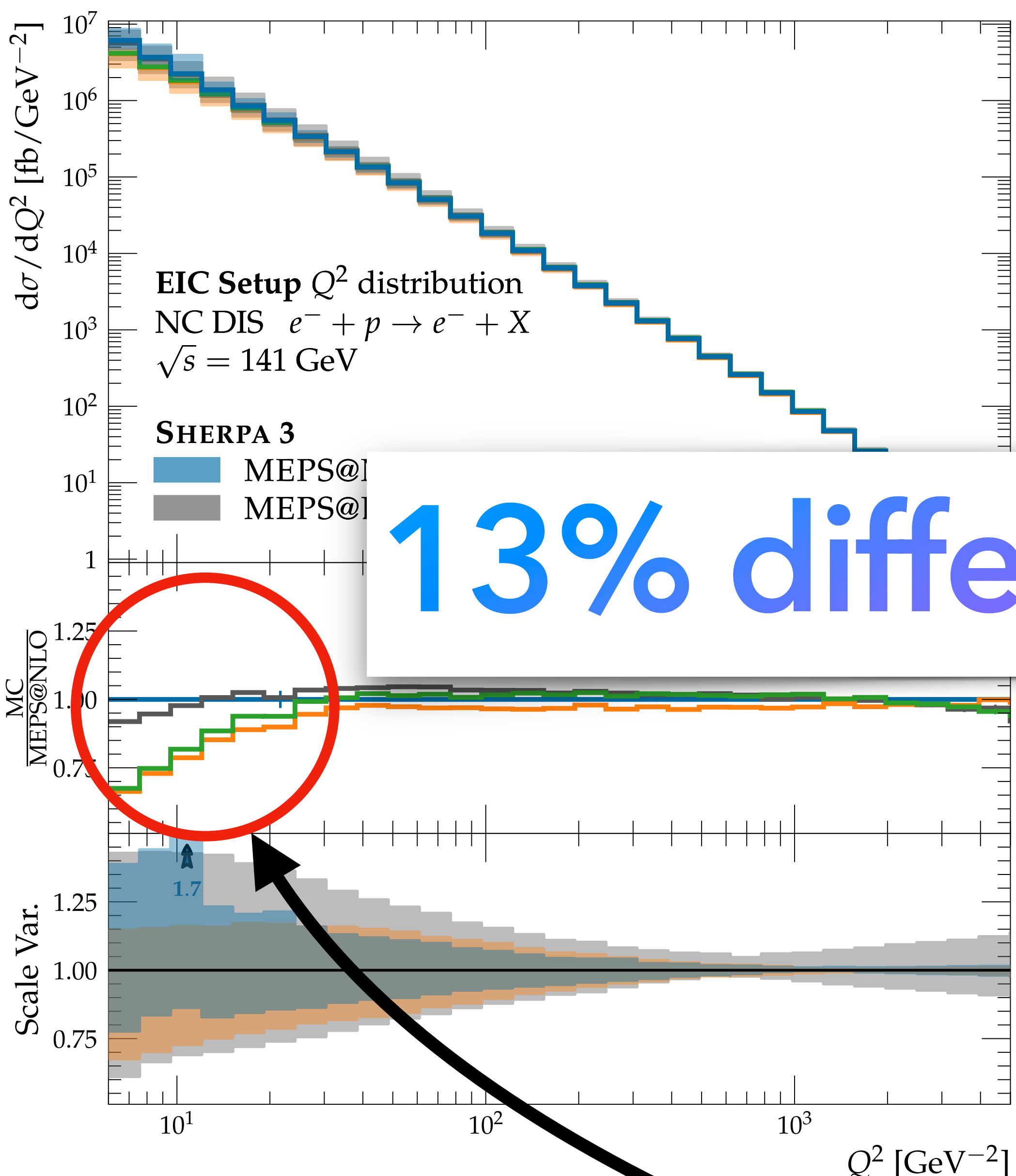


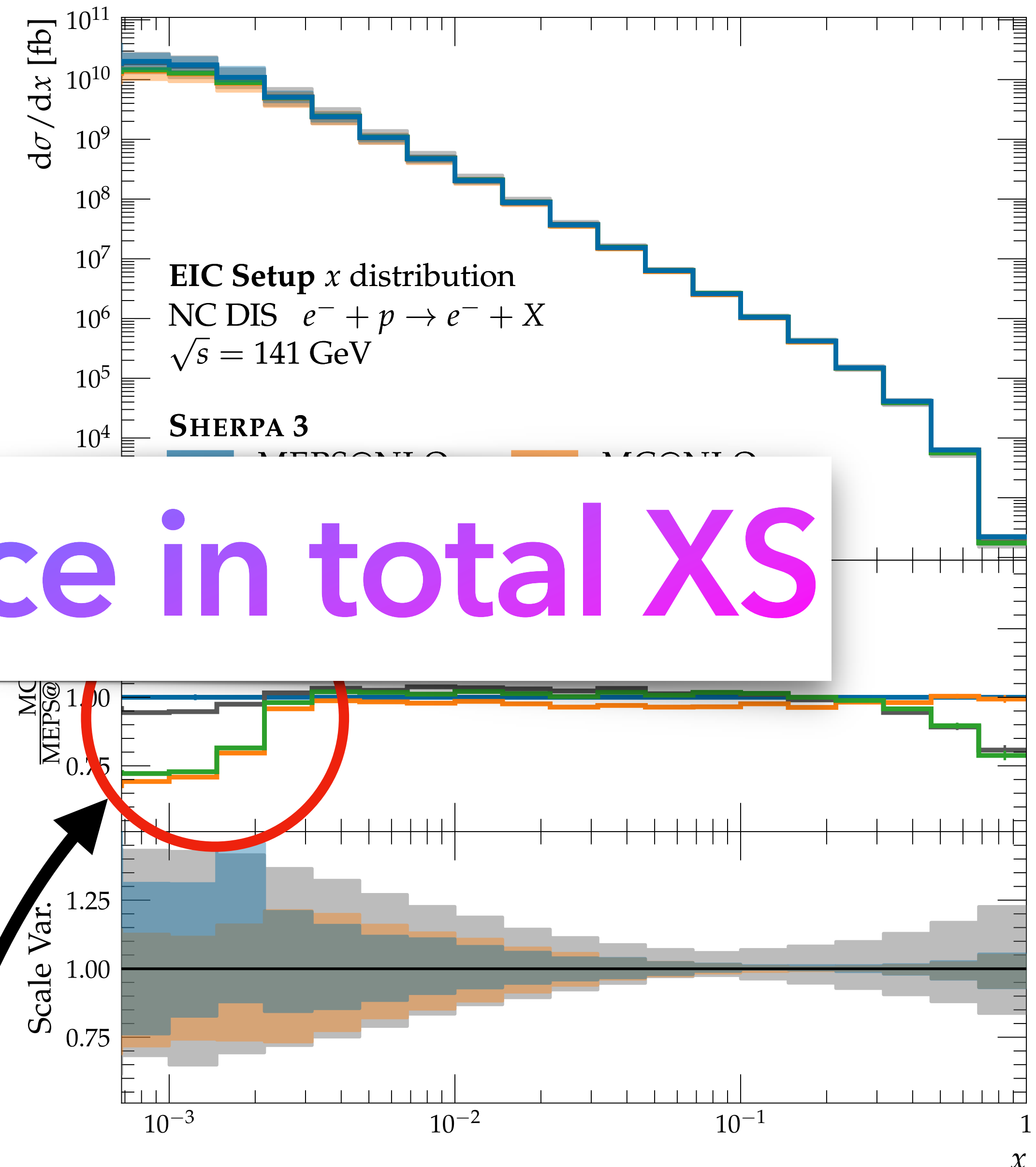
Low Q^2 and x needs real corrections,

interpolates to photoproduction!

Predictions for DIS

Why use multi-leg merging?





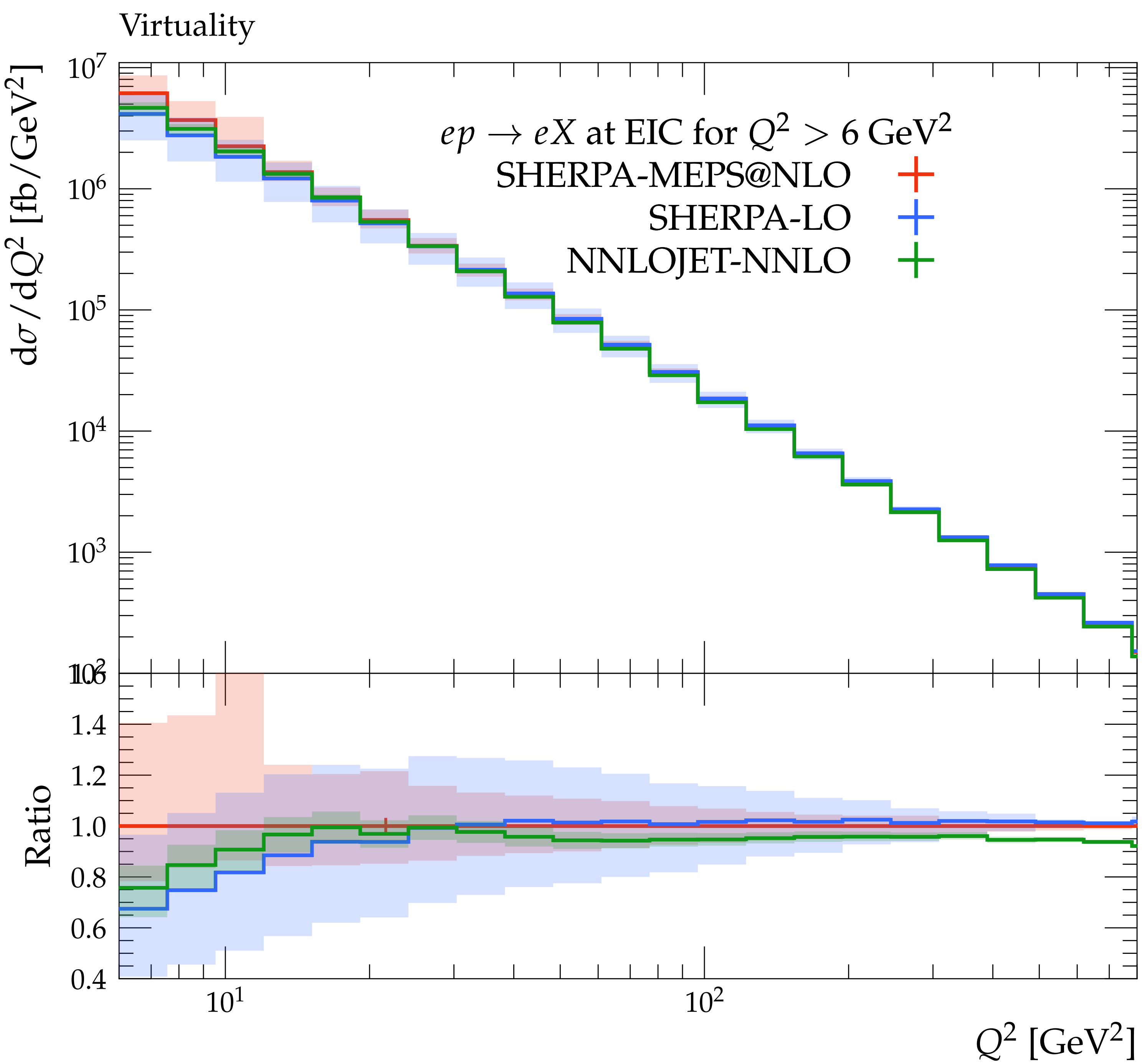
13% difference in total XS

Low Q^2 and x needs real corrections,

interpolates to photoproduction!

Predictions for DIS

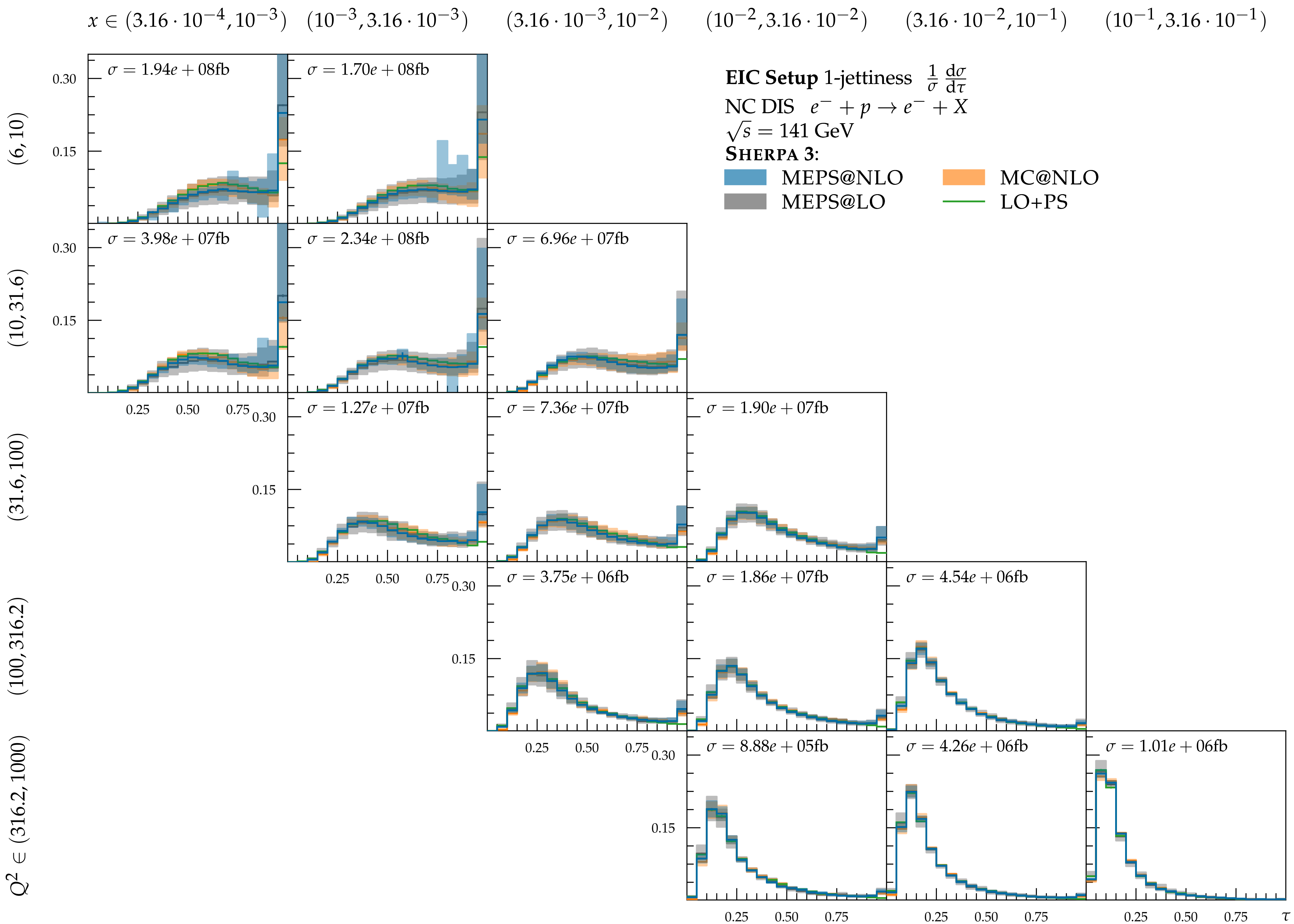
Multi-leg merging vs. NNLO



- Merging of legs for interpolation to photoproduction
- NNLO for precision targets, e.g., α_S extraction

Predictions for DIS

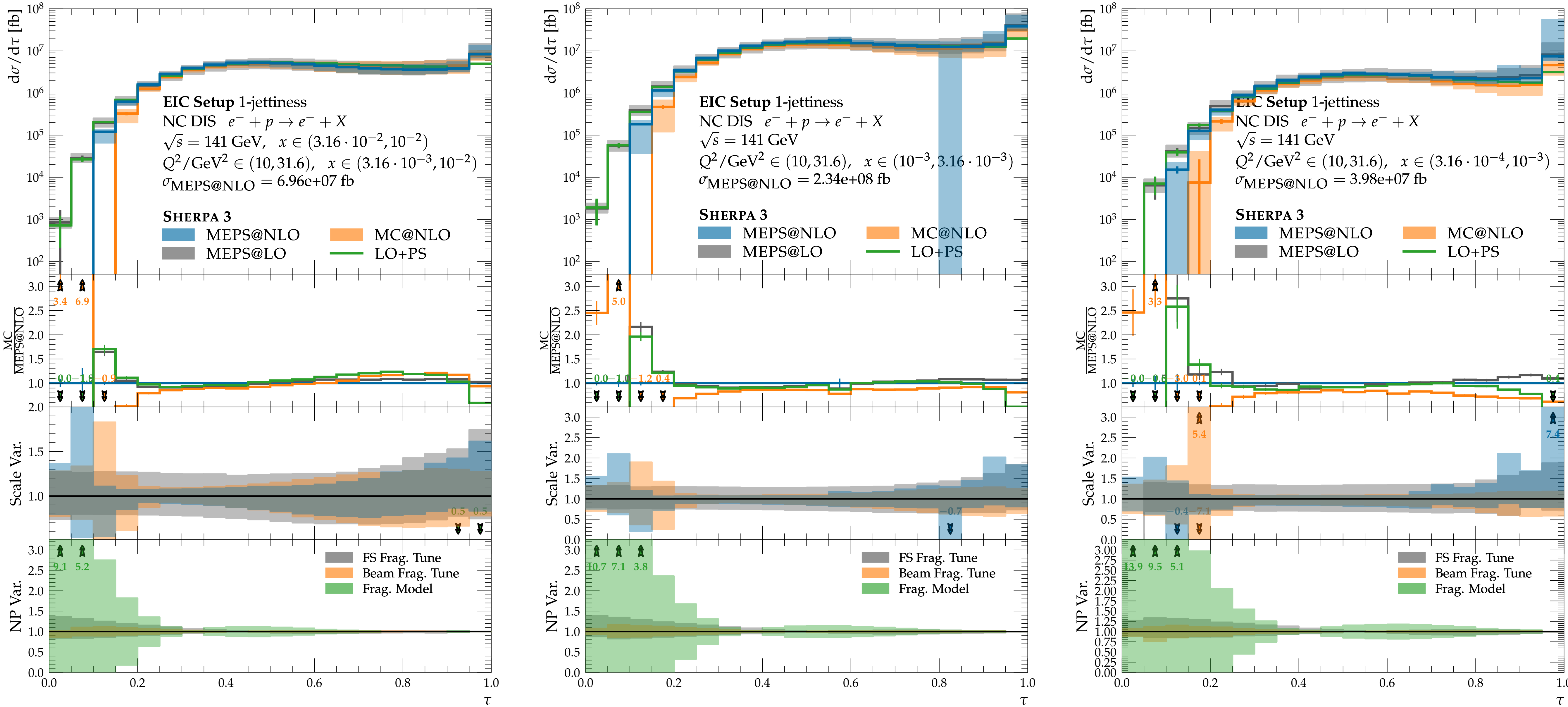
1-jettiness in bins of x and Q^2 in Neutral Current



[PM, D. Reichelt, F. Silvetti, 2506.xxxxx]

Predictions for DIS

1-jettiness: assessment of leading uncertainties

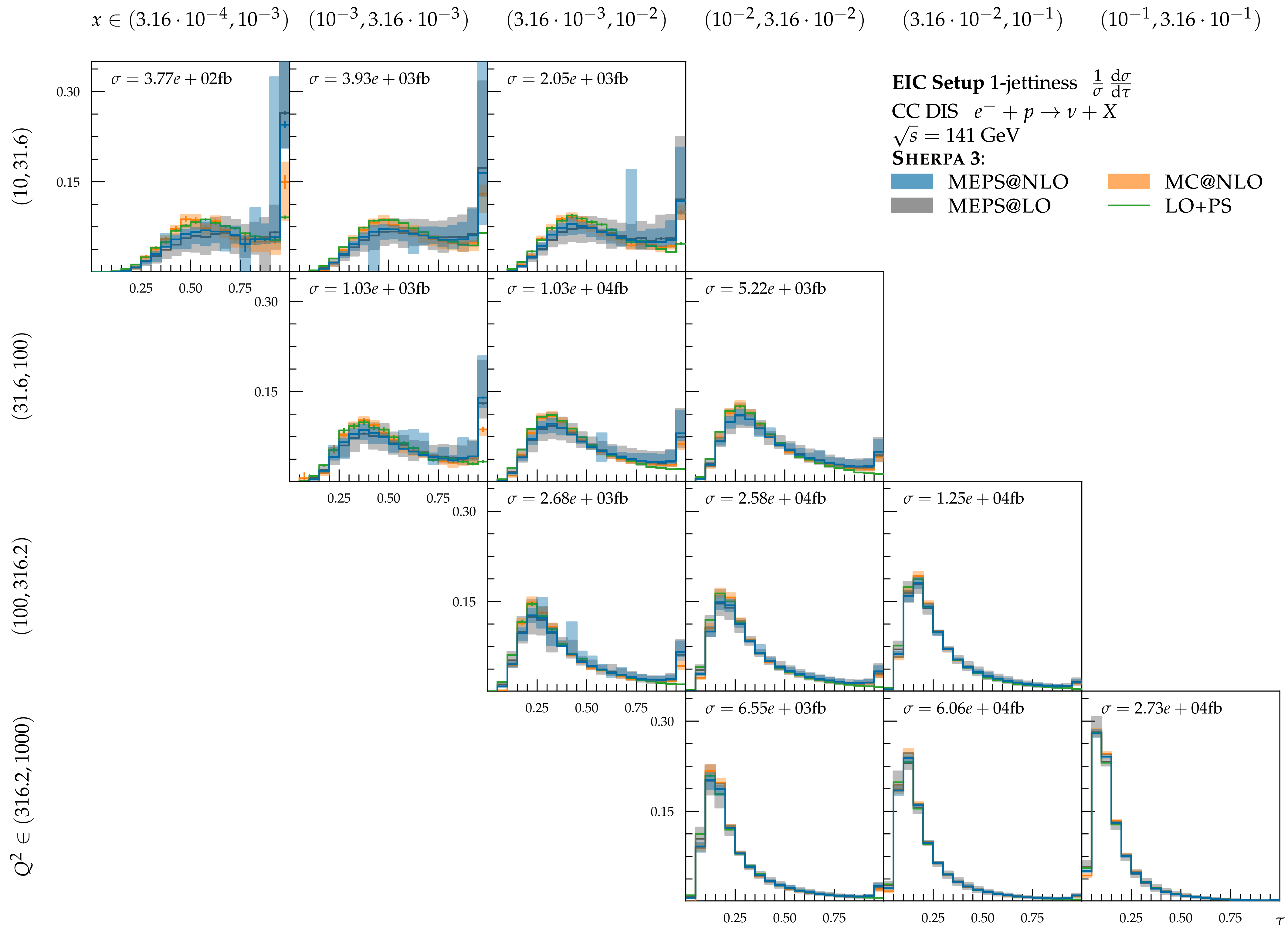


Hadronisation uncertainties generally smaller than perturbative uncertainties

[PM, D. Reichelt, F. Silvetti, 2506.xxxxx]

Predictions for DIS

1-jettiness in bins of x and Q^2 in Charged Current



[PM, D. Reichelt, F. Silvetti, 2506.xxxxx]

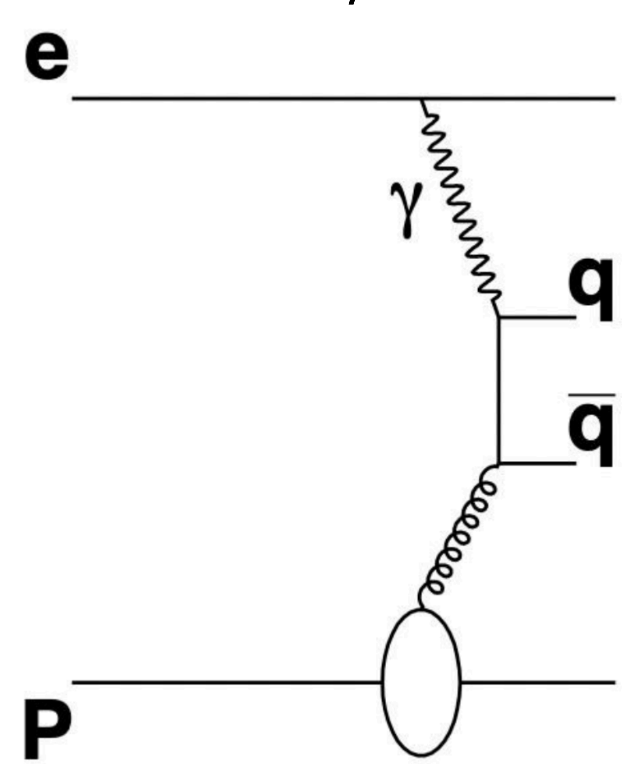
Conclusion for DIS

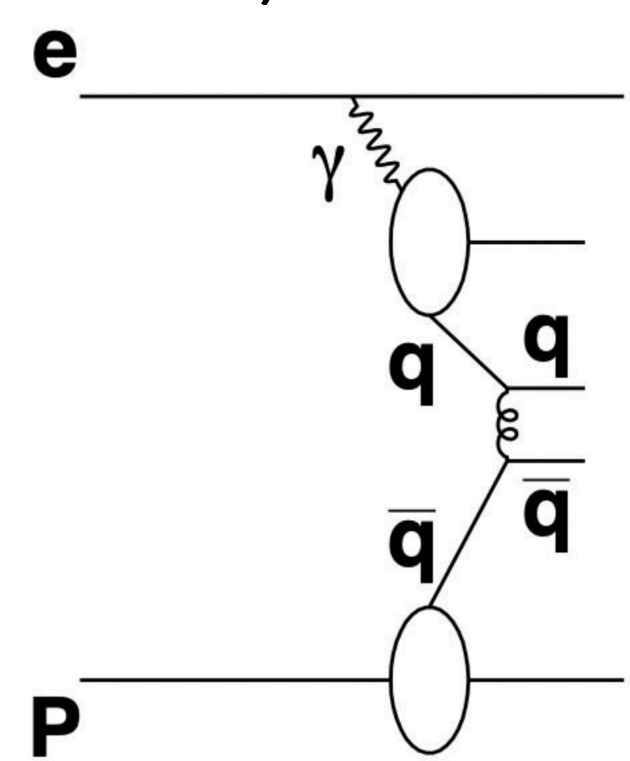
- NNLO and even N3LO available in Fixed Order
- NLO+PS with multi-leg merging, study using Sherpa
- small x and Q^2 phase space get large corrections from real emissions and merging, respectively
- scale uncertainties reduced significantly with Higher Orders

Photoproduction

a quick introduction

- In DIS, $Q^2 \gtrapprox \mu_{\text{jet}}$; in photoproduction, $Q^2 < \mu_{\text{jet}}$
- in that regime, the electron can be decoupled with Weizsäcker-Williams approximation
- the photon either interacts **directly** or acquires a **hadron-like** structure ("resolved", DGLAP evolved)





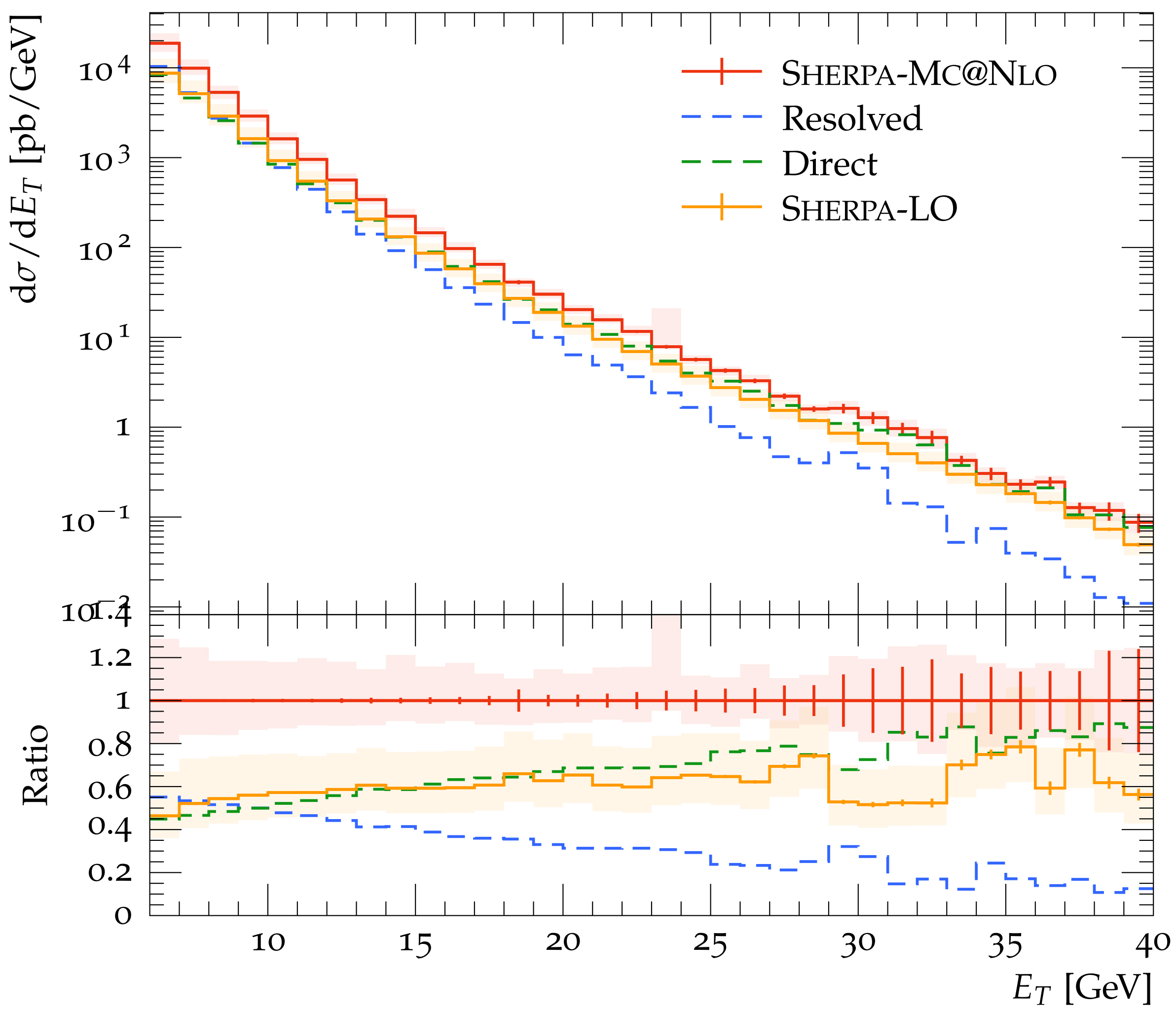
Analysis for Photoproduction

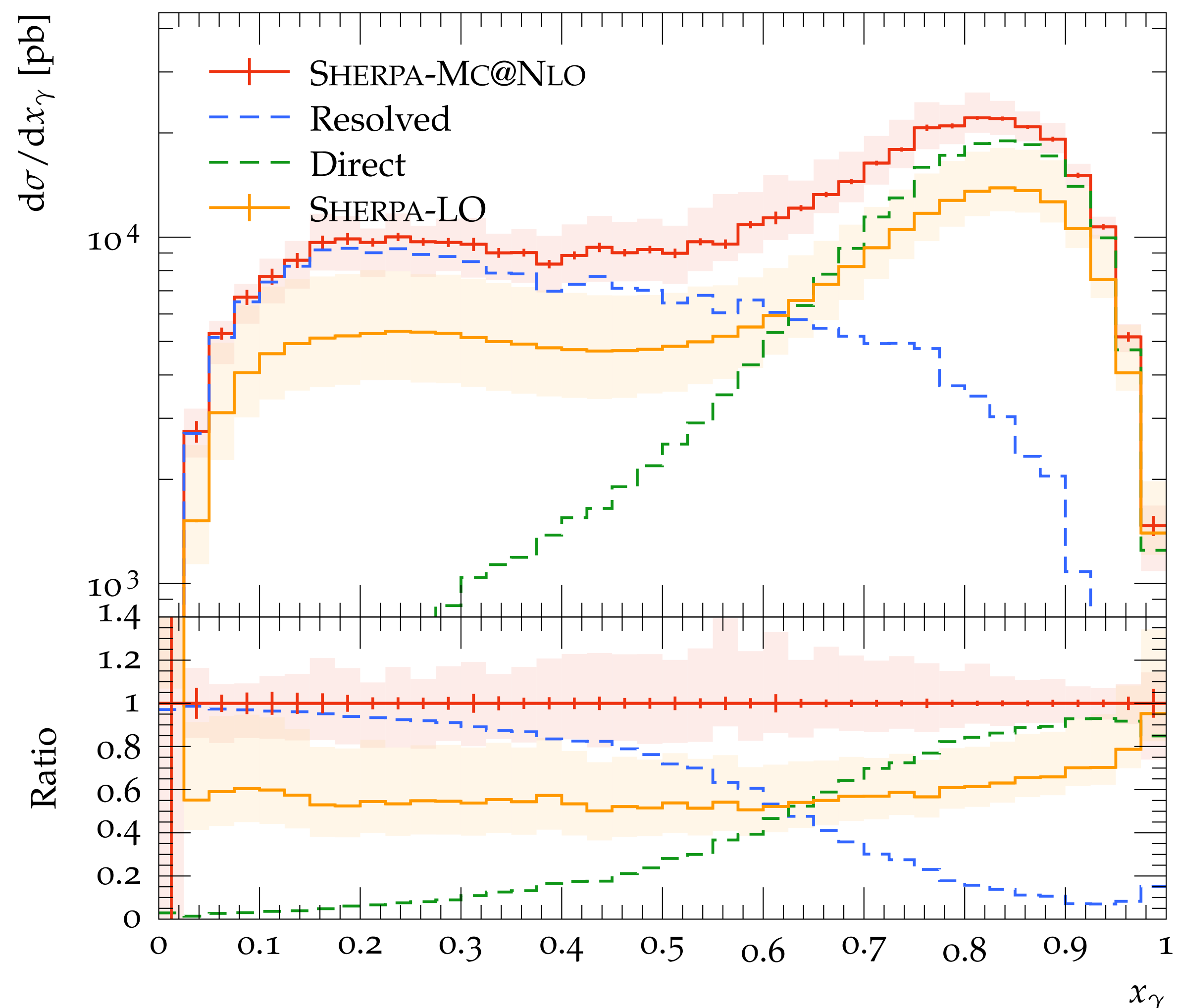
- Assuming 18x275 ep beams
- Event-/hadron-level analysis in Rivet
- Detector acceptance of $|\eta| < 4$
- anti-k_T jet clustering with $R = 1.0$ and $E_T > 6$ GeV
- Computing
  $\gamma_{\mathrm{dir+had}}\, p \to j\, j$ @ NLO
  including parton shower, hadronisation, beam remnants, multiple interactions,…
- 7-point scale variations to estimate HO uncertainties

[PM, F. Krauss, 2311.14571]

Predictions for Photoproduction

Inclusive jet E_T and x_γ





$$x_\gamma = \frac{E_T^{(1)}\exp(-\eta^{(1)}) + E_T^{(2)}\exp(-\eta^{(2)})}{2yE_e}$$

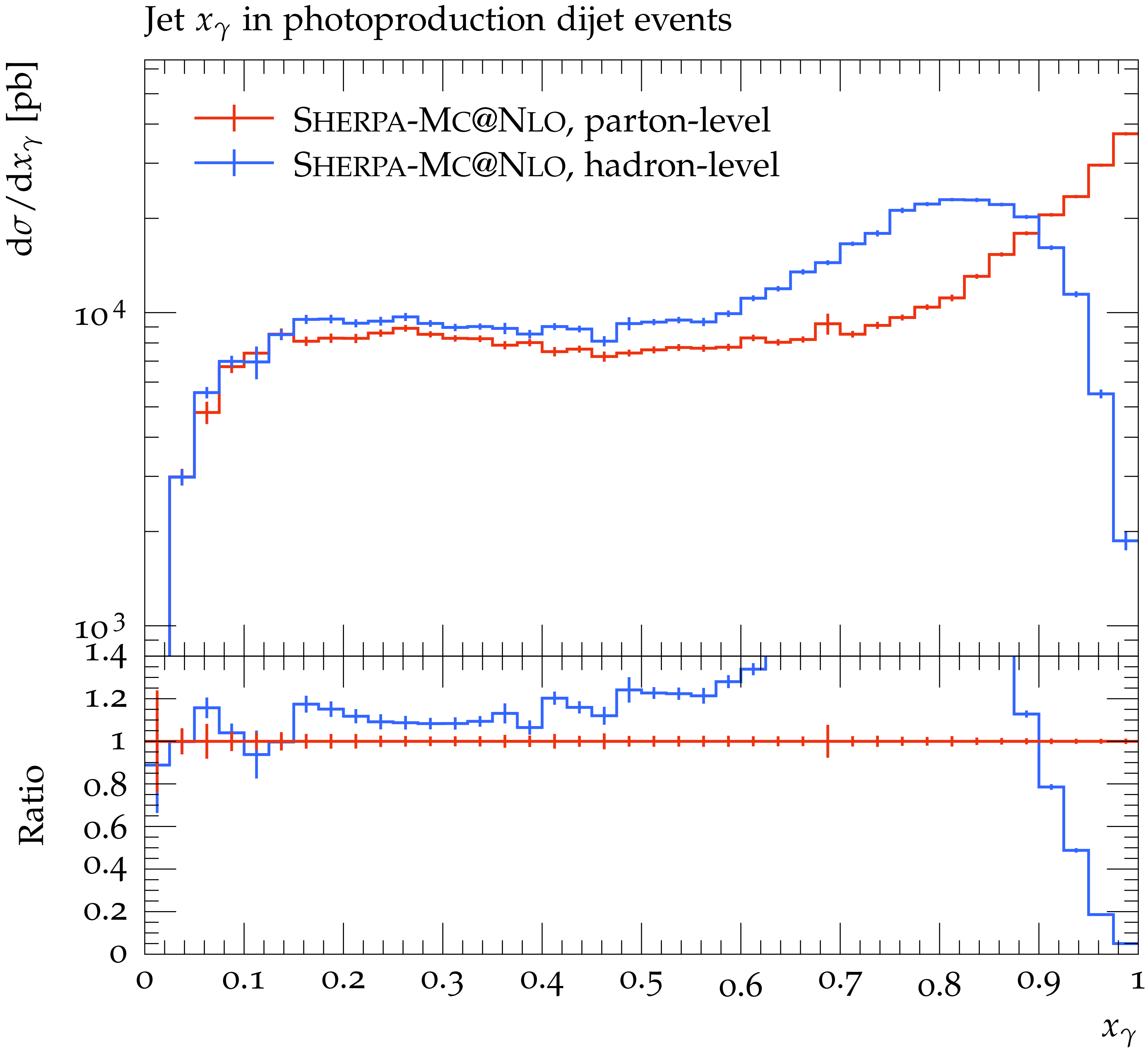
commonly used at HERA for photoproduction

especially useful for photon PDF fitting

[PM, F. Krauss, 2311.14571]

Predictions for Photoproduction

Effect of hadronisation



Significant non-perturbative corrections in x_γ

Conclusion for Photoproduction

- NLO+PS studied in Sherpa
- hadronisation corrections are quite large in x_γ
- NNLO is work-in-progress in NNLOJET
- NLO corrections are large,
  depending on phase space cuts

- what about the uncertainties?

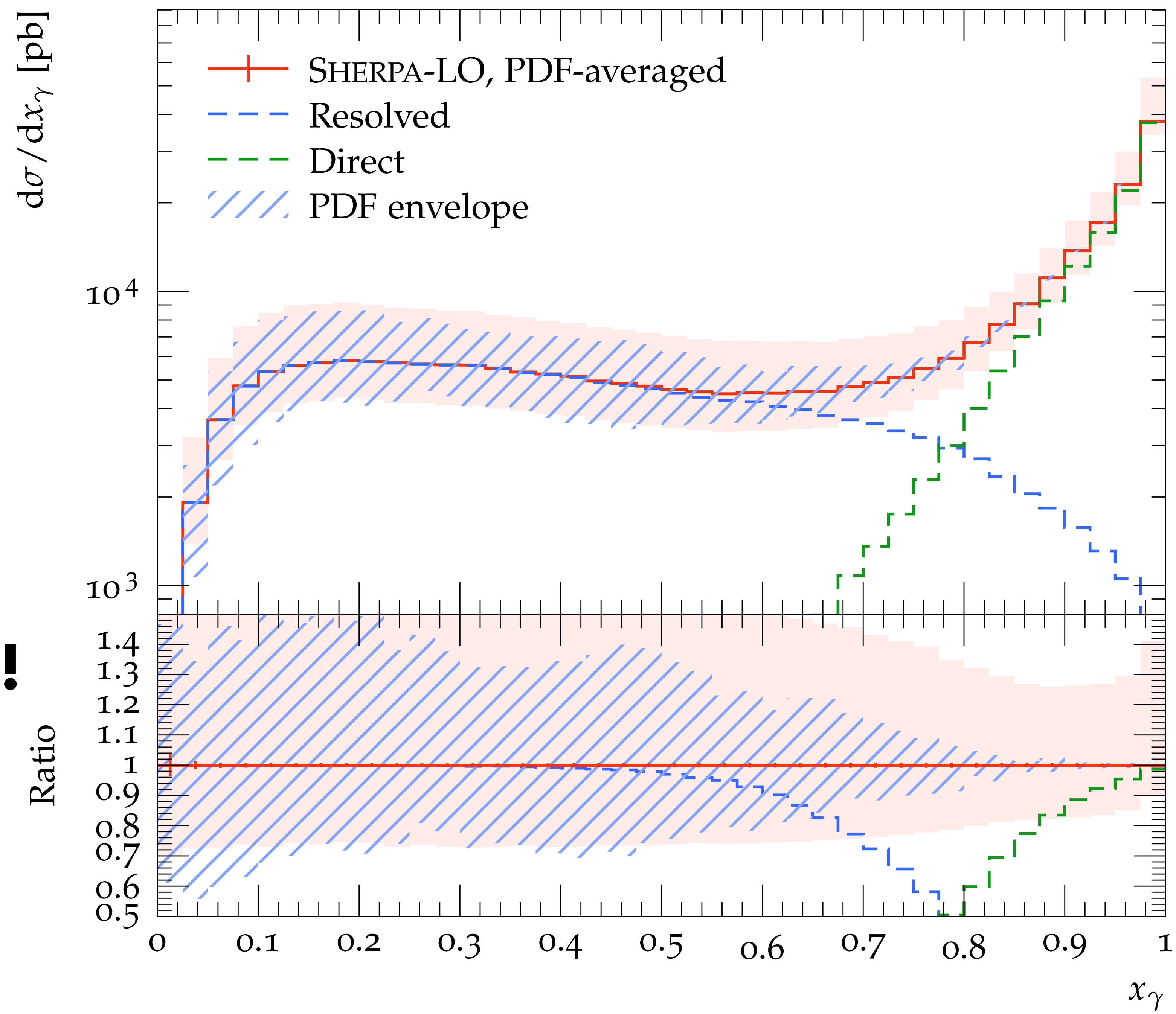
Photon PDFs

Bottleneck for precision calculations

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

PDF variation as large as LO scale uncertainty!

Last fit from 2004!



PDF fitting

an alternative approach

Current Photon PDFs have

- no error estimates
- unclear running of strong coupling
- large variations between each other

PDF fitting

an alternative approach

Current Photon PDFs have

- no error esti
- unclear runn
- large variations between each other

For EIC, we need to do better!

PDF fitting

an alternative approach

Current Photon PDFs have

- no error esti
- unclear runn
- large variations between each other

For EIC, we need to do better!

Problems:

- small scales, e.g. jet transverse momentum
- large hadronisation corrections
- multiple interactions between photon and proton?

PDF fitting

an alternative approach

Current Photon PDFs have

- no error esti
- unclear runn
- large variations between each other

For EIC, we need to do better!

Problems:

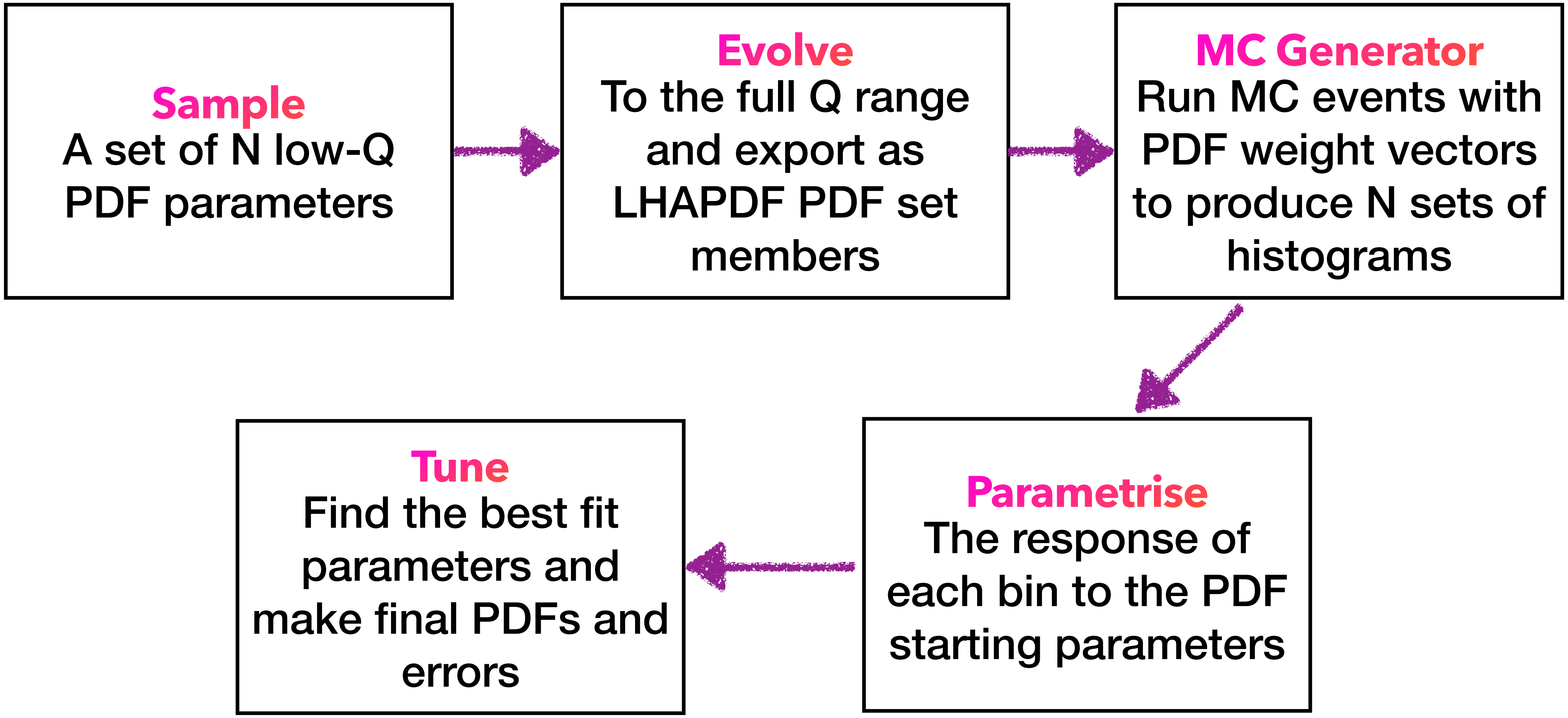
- small sca
- large ha
- multiple interactions between photon and proton?

Use hadron-level calculations for fitting?

PDF fitting

an alternative approach

Leveraging modern MC tools and technology developed for the LHC like PDF multi-weights and parton shower matching

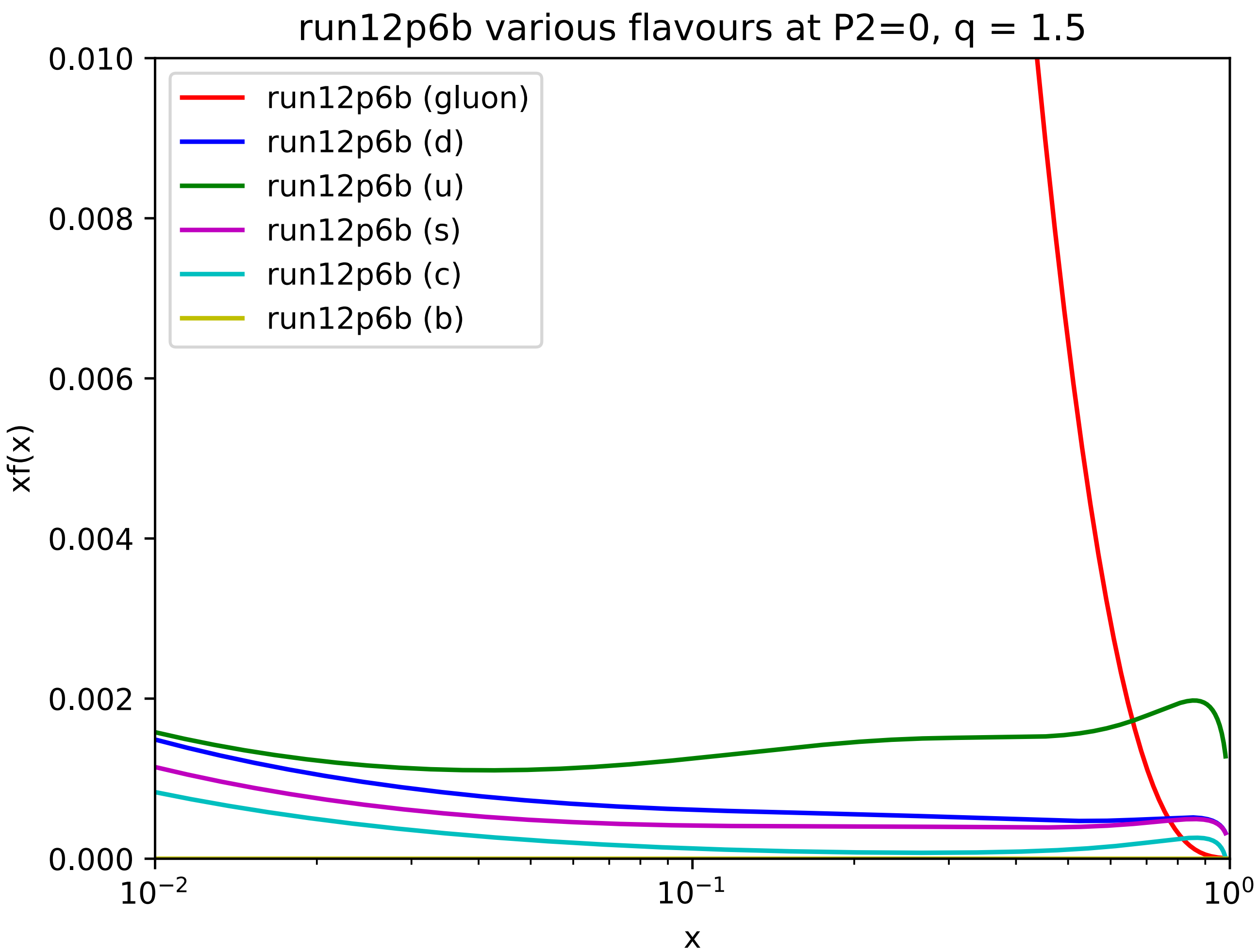


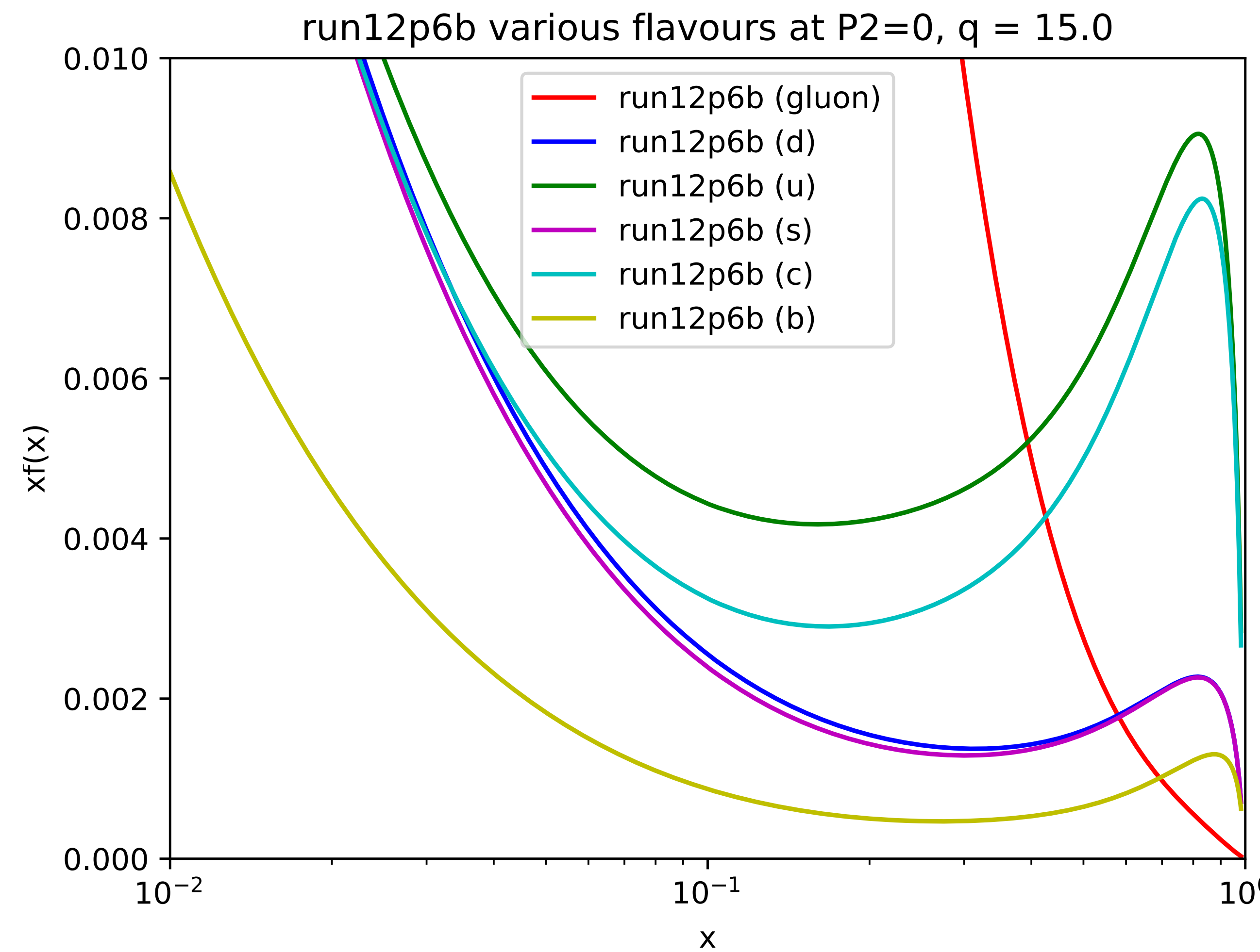
[A. Buckley, V.A. Narendran, 25xx.xxxx]

PDF fitting

an alternative approach

Preliminary!





Disclaimer: not final, pending a bugfix in the evolution in APFEL

[A. Buckley, V.A. Narendran, 25xx.xxxx]

Summary

Summary

- Strong efforts to move established event generators from LHC to the EIC
- will allow fully differential predictions at NLO and NNLO (and N3LO for DIS) in collinear factorisation
  - DIS can be considered a precision domain
  - Photoproduction needs modern NLO (and NNLO) PDFs
- Interpolation between DIS and Photoproduction is an open question
- Important for jet measurements, global fits and background studies at the EIC

Summary

- Strong efforts to move established event generators from LHC to the EIC
- will allow fully differential predictions at NLO and NNLO (and N3L
  - DI
  - Photoproduction needs modern NLO (and NNLO) PDFs

Thank you for the attention!

- Interpolation between DIS and Photoproduction is an open question
- Important for jet measurements, global fits and background studies at the EIC