PARTON SHOWER EFFECTS IN POLARIZED DEEP-INELASTIC SCATTERING

Ignacio Borsa
University of Tübingen

Summer meeting FOR2926
Regensburg - July 2024

EBERHARD KARLS
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HRT

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Ignacio Borsa
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In collaboration with B. Jäger. *JHEP* 07 (2024) 177

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Introduction

Shower Monte Carlo event generators
Fixed Order vs. Parton Showers

POWHEG

NLO + PS matching
Extension to polarized DIS

EIC Phenomenology

Jet production in polarized DIS @ EIC

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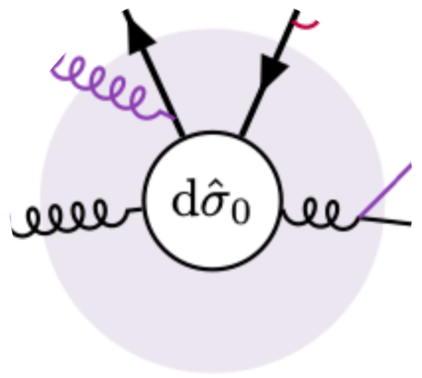
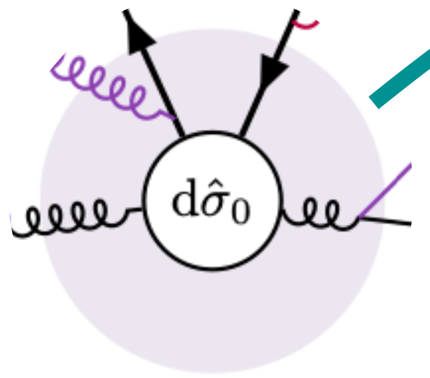
SHOWER MONTE CARLO EVENT GENERATORS



SHOWER MONTE CARLO EVENT GENERATORS

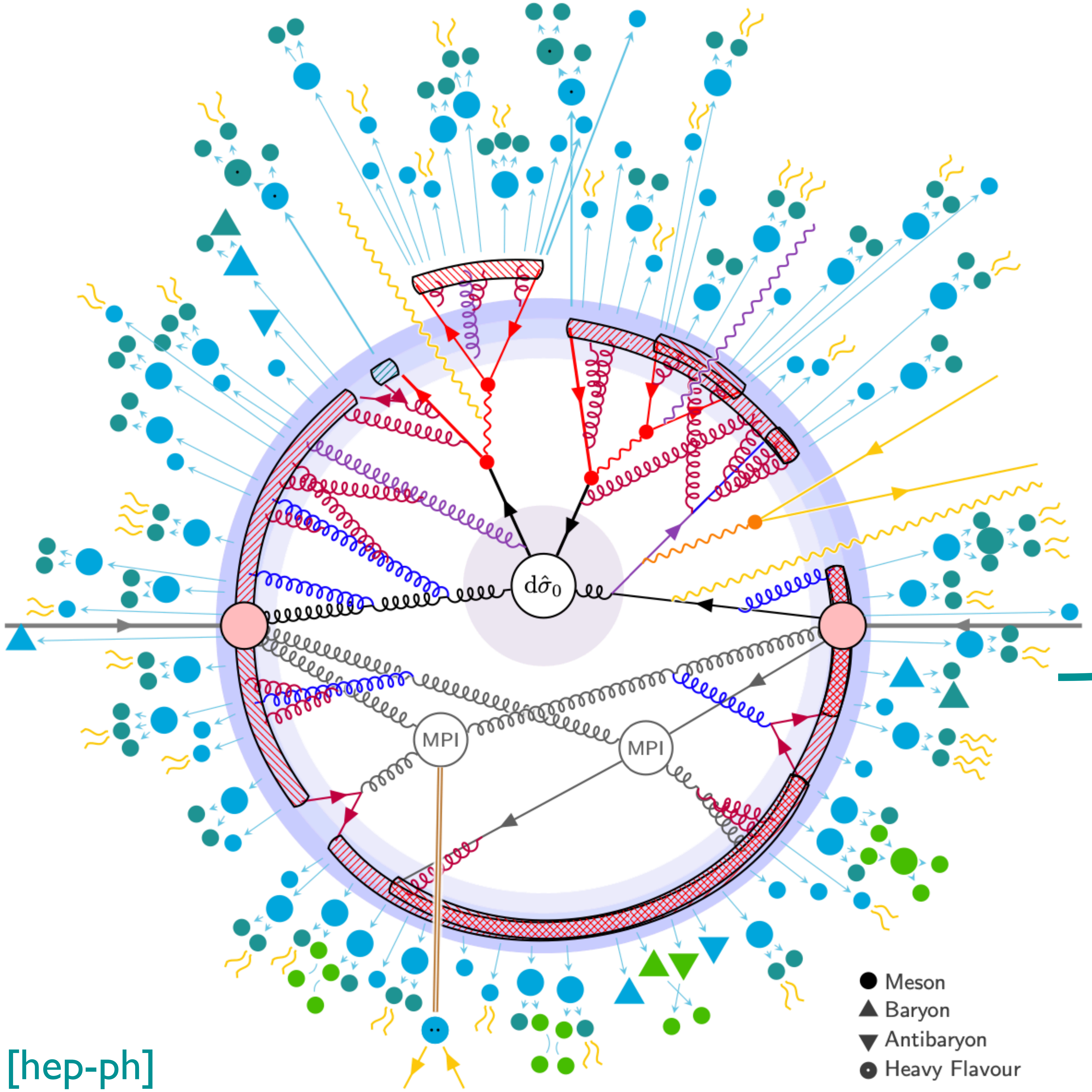
How do we go from this…?



Hard scattering

SHOWER MONTE CARLO EVENT GENERATORS

…to this?



Experimental measurement

Pythia manual arXiv:2203.11601 [hep-ph]

SHOWER MONTE CARLO EVENT GENERATORS

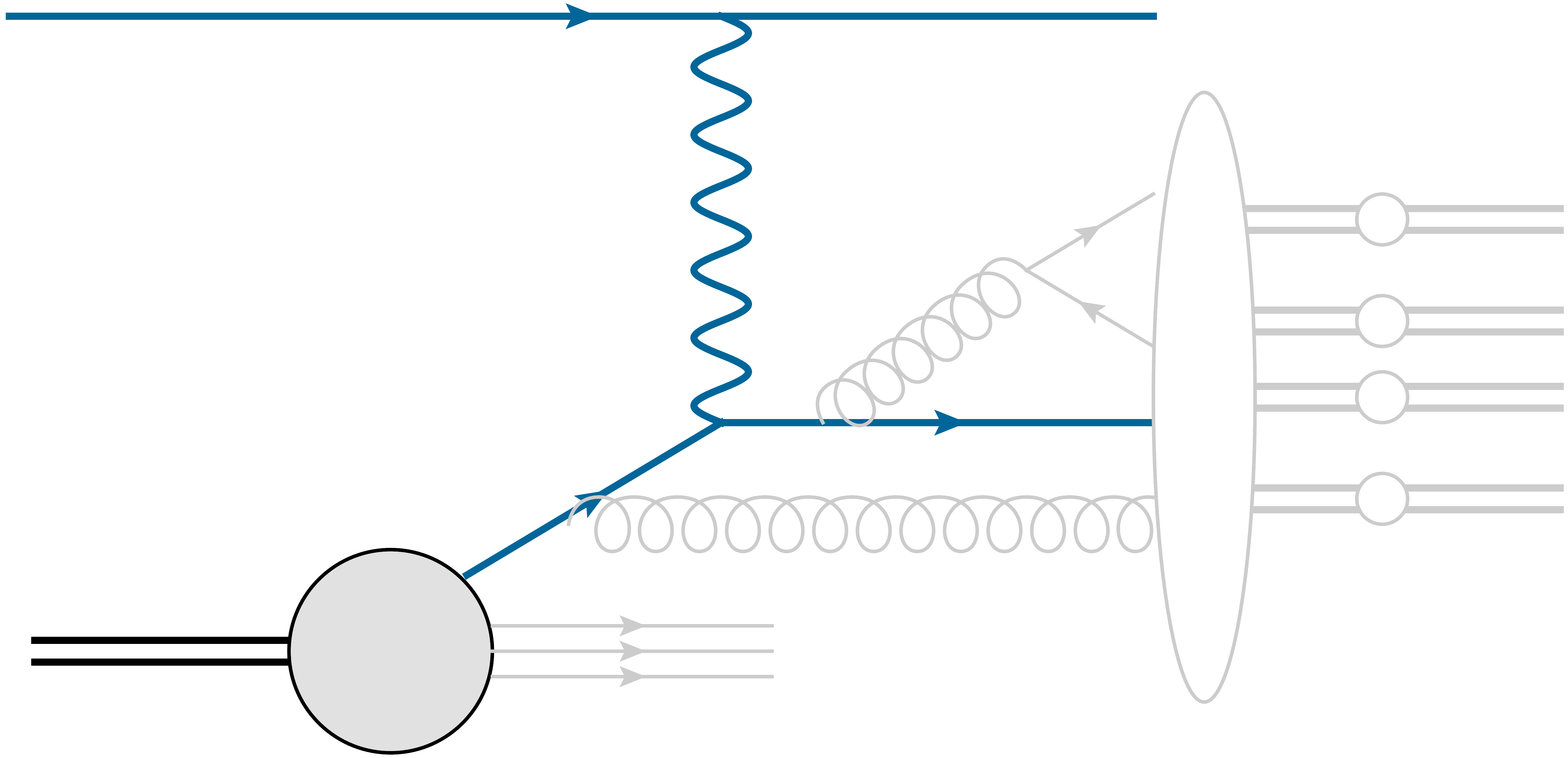
Resummation of enhanced contributions in the collinear limit

$$d\sigma_{\text{SMC}} = B(\Phi_n)\, d\Phi_n \left\{ \Delta_{t_0} + \frac{\alpha_S}{2\pi} P(z) \frac{1}{t} \Delta_t \, d\Phi_r \right\}$$

Sudakov factor

$$\Delta_t = \exp \left[- \int d\Phi'_r \frac{\alpha_s}{2\pi} P(z') \frac{1}{t'} \theta(t - t') \right]$$

Hard scattering



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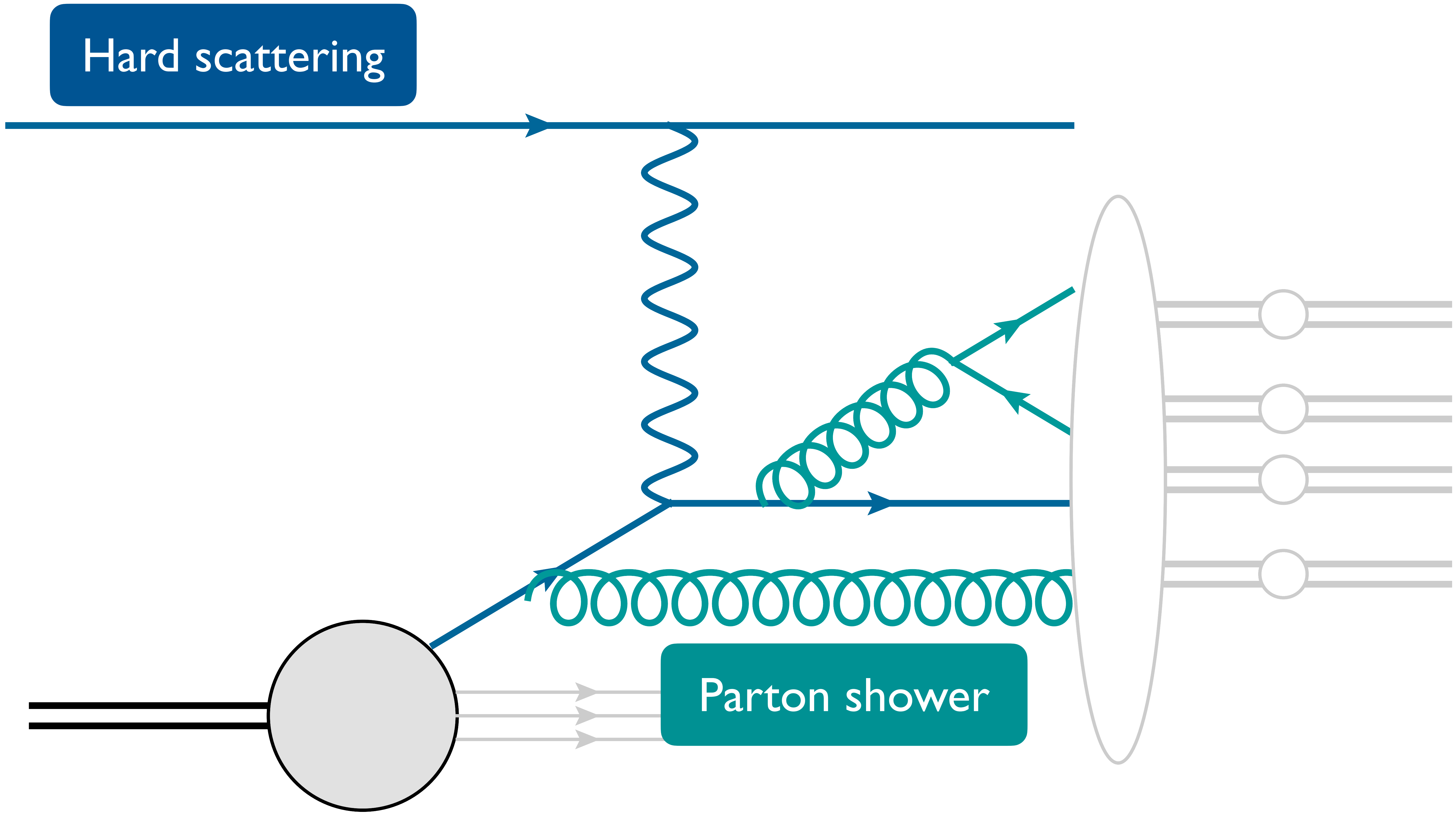

- Leading Log accurate
- Correct description in the collinear limit

SHOWER MONTE CARLO EVENT GENERATORS

Resummation of enhanced contributions in the collinear limit

$$d\sigma_{\text{SMC}} = B(\Phi_n)\, d\Phi_n \left\{ \Delta_{t_0} + \frac{\alpha_S}{2\pi} P(z) \frac{1}{t} \Delta_t \, d\Phi_r \right\}$$

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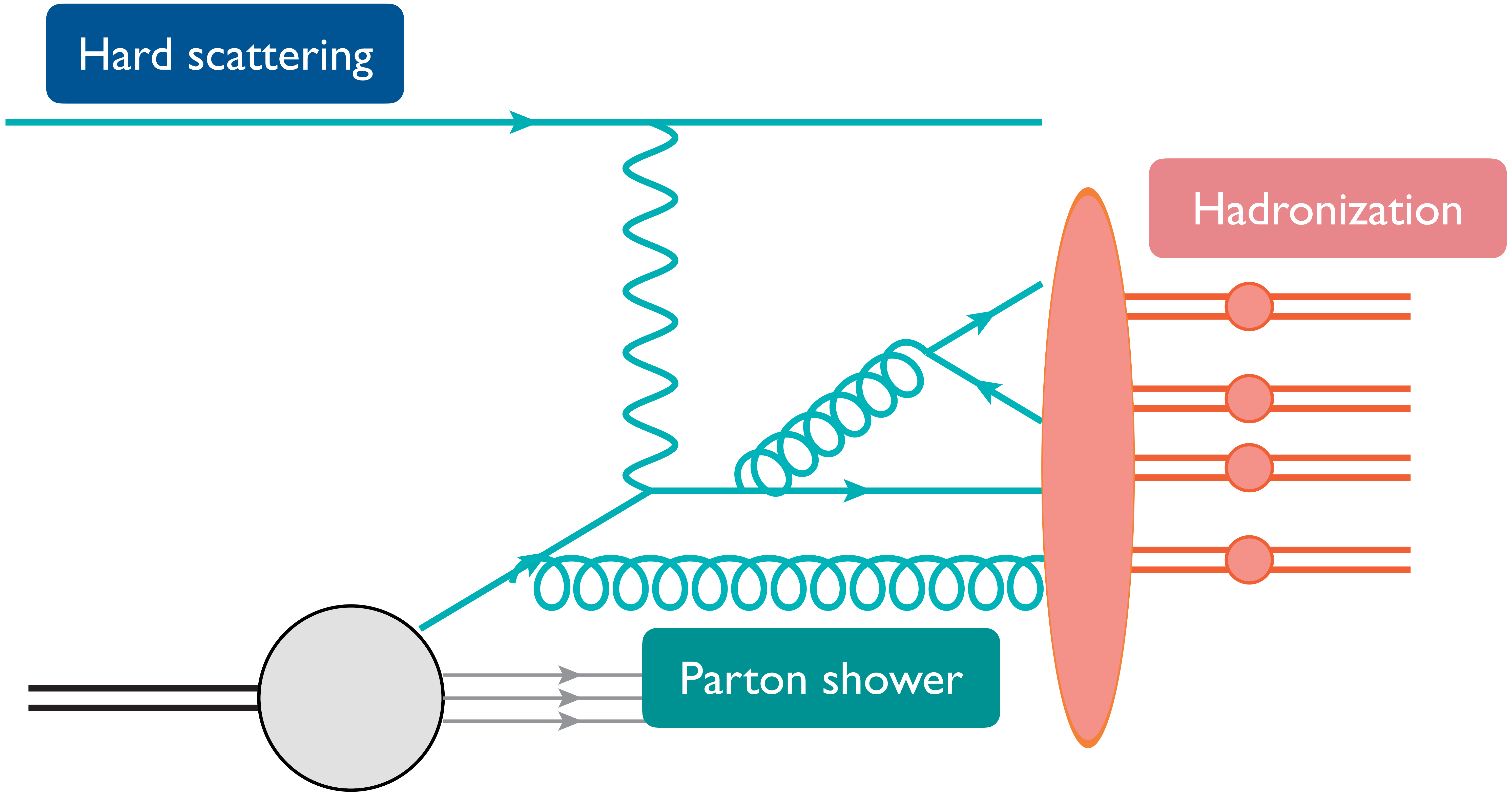

- Leading Log accurate
- Correct description in the collinear limit

- Hadronization
- Hadron decays
- EW radiation

…
PYTHIA - Bengtsson, Sjöstrand (1987)
HERWIG - Marchesini, Webber (1988)
ARIADNE - Lönnblad (1992)
SHERPA - Gleisberg, Höhe, Krauss, Schlicke, Schumann, Winter (2004)
…

HIGHER ORDER CORRECTIONS + PS

SMC (LO + Parton Shower)

- Correct Sudakov suppression at small p_T
- Possible to simulate events at the hadron level

- Incorrect distributions at high p_T
- Normalization accurate at LO

Fixed Order

- Accurate distributions at high p_T
- Normalization accurate at N^k LO

- Wrong distributions at small p_T
- Description only at the parton level

Try to merge the two approaches, trying to keep the desirable features of both

Potential problems with double counting of real emission!

- Consistent matching of NLO+PS

  MC@NLO - Frixione, Webber (2001)

  POWHEG - Nason(2004)

- Matching of NNLO+PS

  MiNNLOPS - Monni, Nason, Re, Wiesemann, Zanderighi (2020)

EVENT GENERATORS FOR EIC

- The EIC science program will require precise simulations of electron-ion collisions

- Development of event generators that include QCD and QED higher order corrections and polarization in all stages of simulation.

- Update on older polarized lepton-hadron event generators:

PEPSI Mankiewicz, Schäfer, Veltri (1992)
DJANGOH Charchula, Schuler, Spiesberger (1994)
(Both with unpolarized PS)

arXiv:2203.11110v3 [hep-ph] 23 Jan 2024

Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Event Generators for High-Energy Physics Experiments

We provide an overview of the status of Monte-Carlo event generators for high-energy particle physics. Guided by the experimental needs and requirements, we highlight areas of active development, and opportunities for future improvements. Particular emphasis is given to physics models and algorithms that are employed across a variety of experiments. These common themes in event generator development lead to a more comprehensive understanding of physics at the highest energies and intensities, and allow models to be tested against a wealth of data that have been accumulated over the past decades. A cohesive approach to event generator development will allow these models to be further improved and systematic uncertainties to be reduced, directly contributing to future experimental success. Event generators are part of a much larger ecosystem of computational tools. They typically involve a number of unknown model parameters that must be tuned to experimental data, while maintaining the integrity of the underlying physics models. Making both these data, and the analyses with which they have been obtained accessible to future users is an essential aspect of open science and data preservation. It ensures the consistency of physics models across a variety of experiments.

CP3-22-12 DESY-22-042 FERMILAB-PUB-22-116-SCD-T IPPP/21/51
JLAB-PHY-22-3576 KA-TP-04-2022 LA-UR-22-22126 LU-TP-22-12
MCNET-22-04 OUTP-22-03P P3H-22-024 PITT-PACC 2207 UCI-TR-2022-02

MCEG Requirements for EIC
arXiv:2203.11110

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NLO + PARTON SHOWER - POWHEG

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$$d\sigma_{\mathrm{NLO}} = d\Phi_n \left\{ B(\Phi_n) + \left[V(\Phi_n) + \int d\Phi_r\, C(\Phi_n, \Phi_r) \right] + \left[R(\Phi_n, \Phi_r) - C(\Phi_n, \Phi_r) \right] d\Phi_r \right\}$$

POWHEG - Frixione, Nason, Oleari (2007)
POWHEG-BOX - Alioli, Nason, Oleari, Re (2010)

NLO + PARTON SHOWER - POWHEG

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$$d\sigma_{\mathrm{POWHEG}} = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta(\Phi_n, p_{Tmin}) + \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} \Delta(\Phi_n, p_T)\, d\Phi_r \right\}$$

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NLO + PARTON SHOWER - POWHEG

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POWHEG SUDAKOV

$$\Delta(\Phi_n, p_T) \sim \exp\left[- \int d\Phi'_r \frac{R(\Phi_n, \Phi'_r)}{B(\Phi_n)} \right]$$

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$$\Delta(\Phi_n, p_T) \sim \exp\left[-\int d\Phi'_r \frac{R(\Phi_n, \Phi'_r)}{B(\Phi_n)} \right]$$

- Hardest emission generated according to the POWHEG Sudakov and $\overline{B}(\Phi_n)$ → **Positive weight**
- Subsequent radiation generated using parton-shower programs + p_T-veto → **avoids double counting**

☑ NLO accuracy on integrated quantities

☑ Leading log accurate

NLO + PARTON SHOWER - POWHEG

$$d\sigma_{\rm SMC} = B(\Phi_n)\, d\Phi_n \left\{ \Delta_{t_0} + \frac{\alpha_S}{2\pi} P(z) \frac{1}{t} \Delta_t\, d\Phi_r \right\}$$

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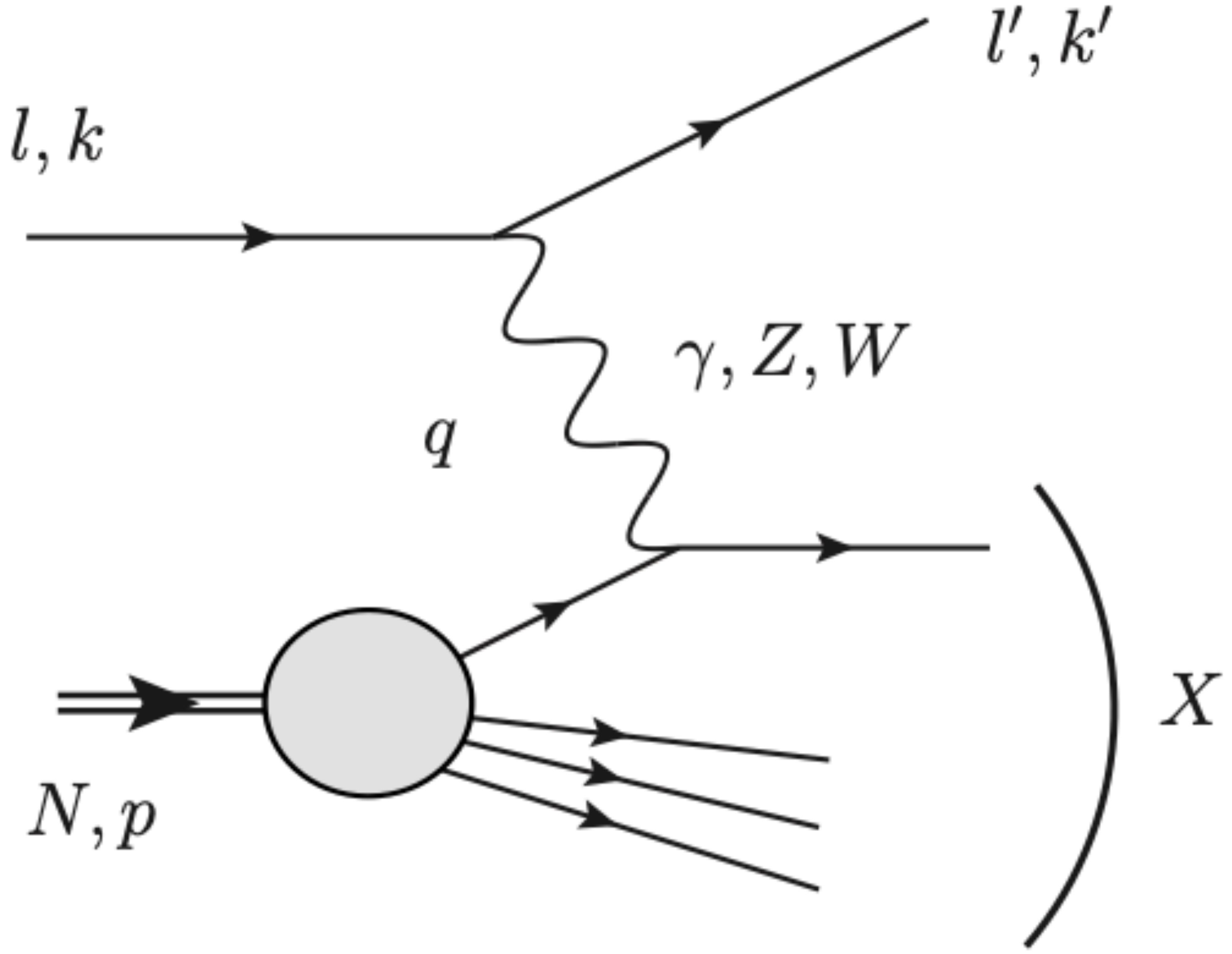
NLO + PARTON SHOWER - DIS

DIS kinematics

$$l(k) + N(P) \to l'(k') + X$$

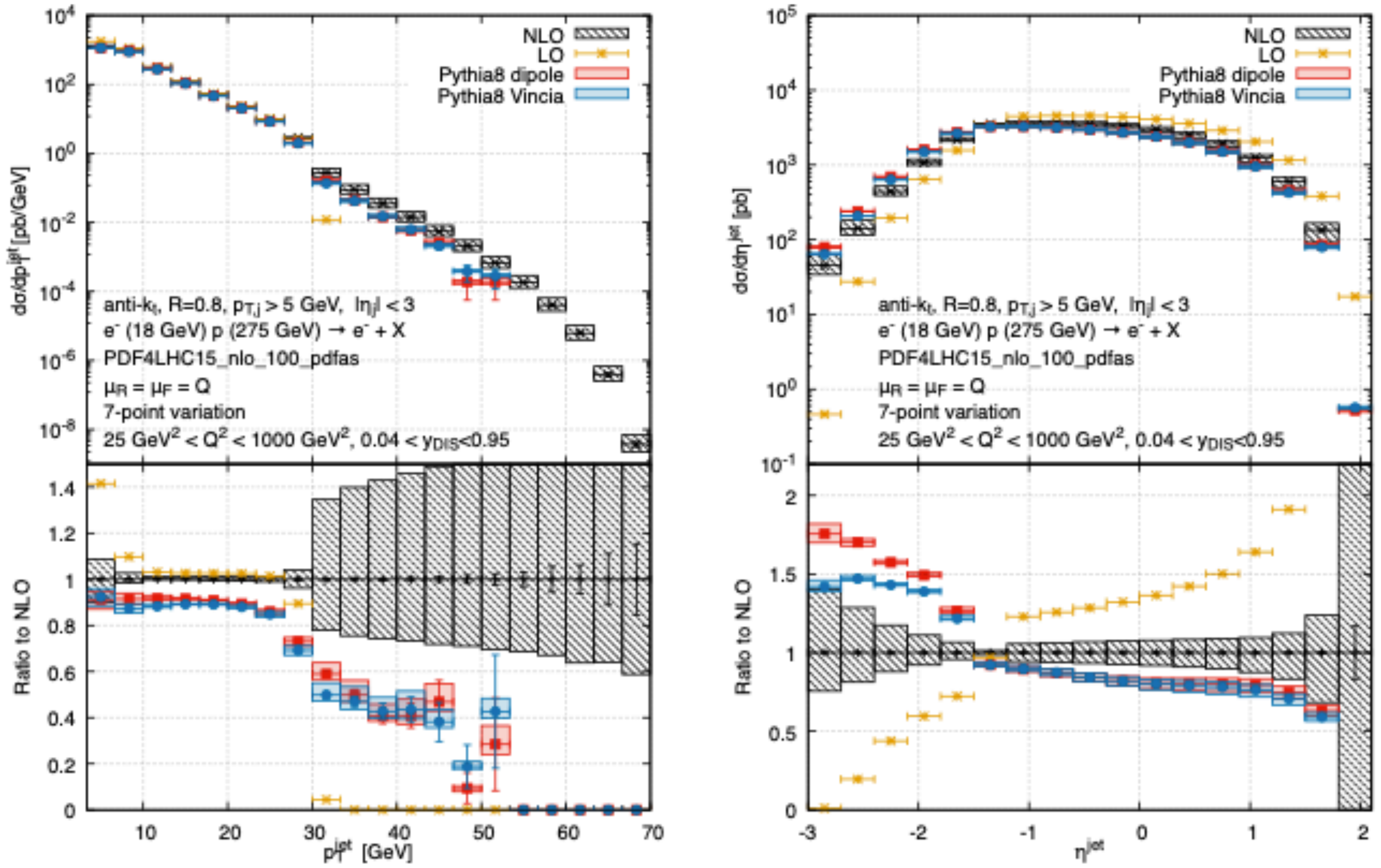


Kinematical invariants

$$Q^2 = -q^2 \qquad x = \frac{Q^2}{2P \cdot q} \qquad y = \frac{q \cdot P}{k \cdot p}$$

NLO + PS implementation of DIS in POWHEG

Banfi, Ferraro Ravasio, Jäger, Karlberg, Reichenbach, Zanderighi (2023)



- Modified mappings for radiation phase-space
$$d\Phi^{\alpha}_{n+1} = d\overline{\Phi}_n \, d\Phi^{\alpha}_{\text{rad}}$$
- The modifications allow to preserve DIS variables x_B, Q^2, y
- Sizable PS effects for EIC kinematics

NLO + PARTON SHOWER - POLARIZED POWHEG

$$d\sigma_{\text{POWHEG}} = \Delta\bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta^{\text{pol}}(\Phi_n, p_{Tmin}) + \frac{\Delta R(\Phi_n, \Phi_r)}{\Delta B(\Phi_n)} \Delta^{\text{pol}}(\Phi_n, p_T)\, d\Phi_r \right\}$$

$$\Delta\bar{B}(\Phi_n) = \Delta B(\Phi_n) + \left[\Delta V(\Phi_n) + \int d\Phi_r\, \Delta C(\Phi_n, \Phi_r)\right] + \int d\Phi_r \left[\Delta R(\Phi_n, \Phi_r) - \Delta C(\Phi_n, \Phi_r)\right] d\Phi_r$$

$$\Delta(\Phi_n, p_T) \sim \exp\left[-\int d\Phi'_r \frac{\Delta R(\Phi_n, \Phi'_r)}{\Delta B(\Phi_n)}\right]$$

Modifications to handle polarized DIS

- Polarized Matrix elements & PDFs
- NLO Subtraction scheme → implementation of polarized FKS subtraction

  Frixione, Kunszt, Signer(1996)

  de Florian, Frixione, Signer, Vogelsang (1999)
- Modifications to handle negative weights
- ~~Polarized shower~~

IB, Jäger *JHEP* 07 (2024) 177

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PHENOMENOLOGY

JET production in polarized DIS @ EIC (NC +CC)

$$e^- + p \to \ell + \text{jet} + X$$

- $E_e = 18\,\text{GeV}$ and $E_p = 275\,\text{GeV}$ $(\sqrt{s} = 140\,\text{GeV})$
- $49\,\text{GeV}^2 \leq Q^2 \leq 1000\,\text{GeV}^2$ and $0.04 \leq y \leq 0.95$
- $5\,\text{GeV} \leq p_T^{\text{jet}}$ and $|\eta^{\text{jet}}| < 3$
- anti-k_T algorithm with $R = 0.8$ and E-recombination
- Polarized PDFs: DSSV14 [de Florian, Sassot, Stratmann, Vogelsang (2014)]
- PS: Antenna shower from VINCIA, as implemented in PYTHIA8
- Theoretical uncertainty from 7-poin scale variation

PHENOMENOLOGY - NC

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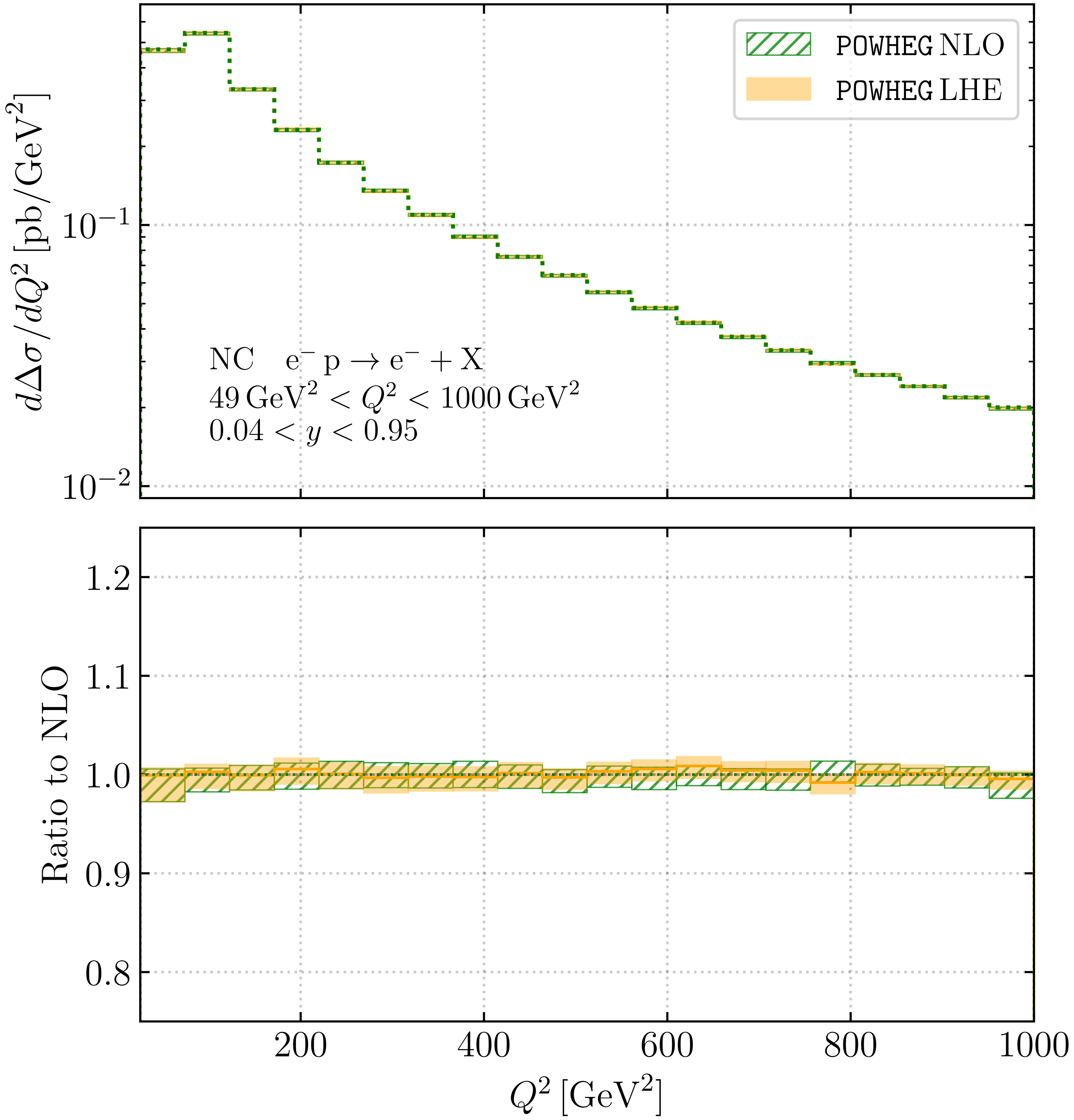

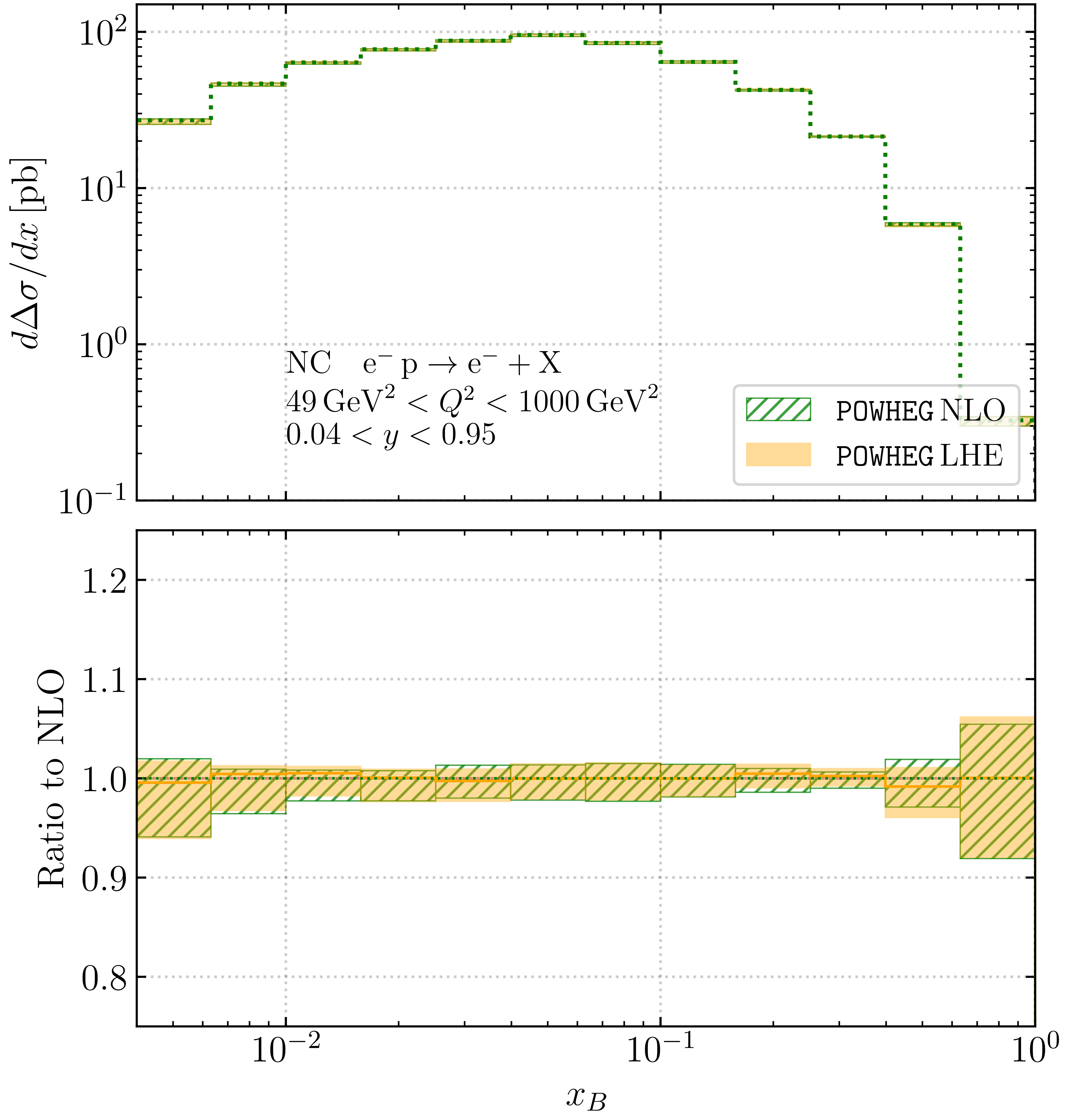

- NLO accuracy for observables inclusive in the additional radiation

PHENOMENOLOGY - NC

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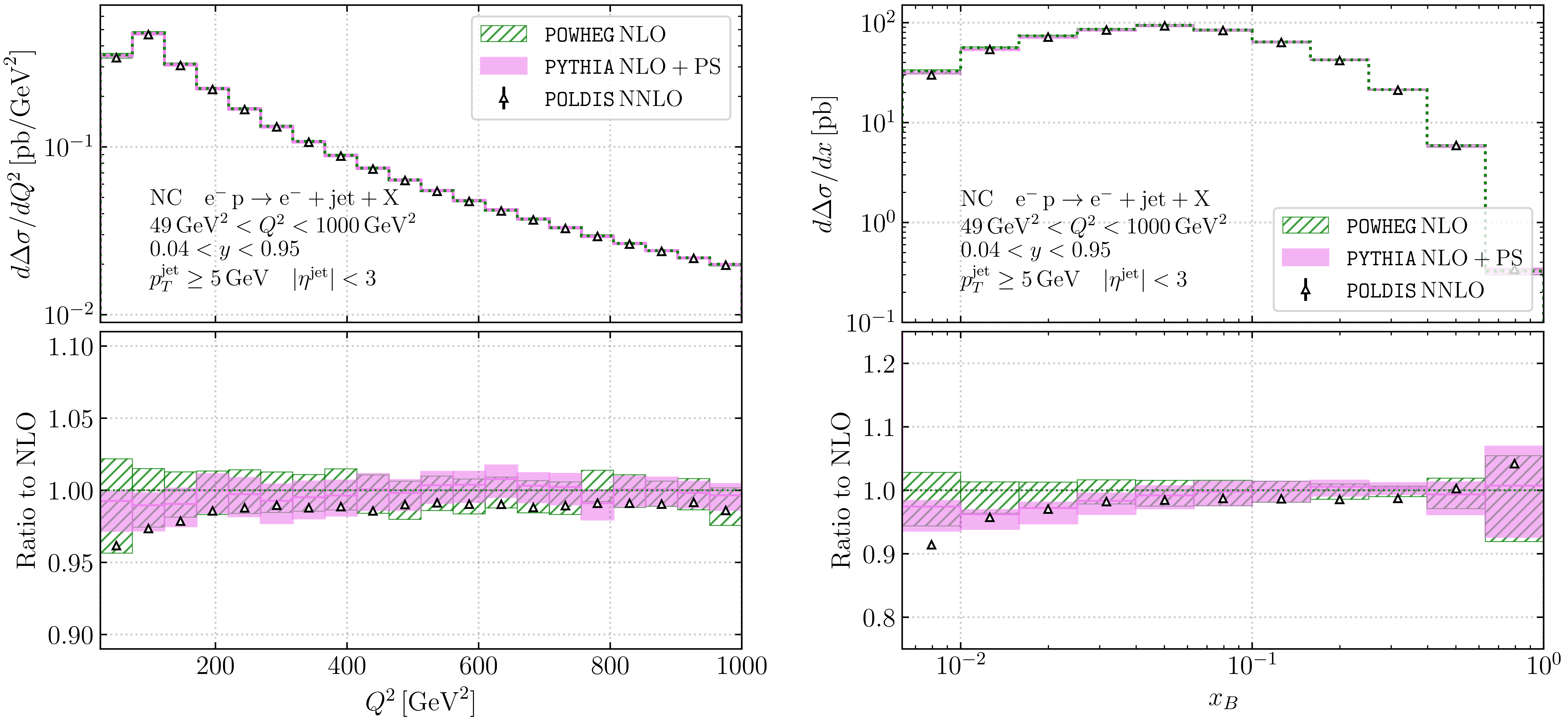
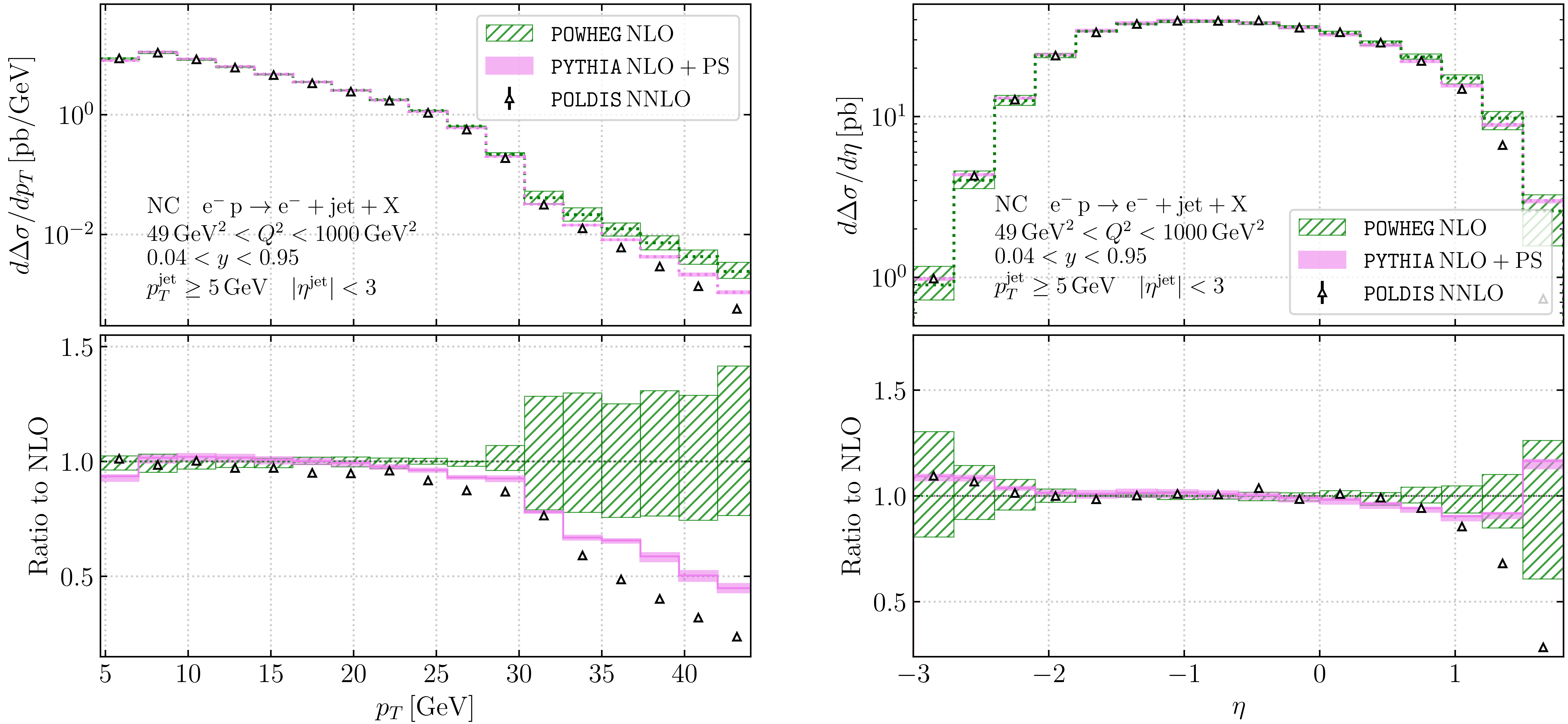


- Small corrections from the PS to more inclusive observables
- Slight improvement in the agreement with NNLO results [IB, D. de Florian, I. Pedron]

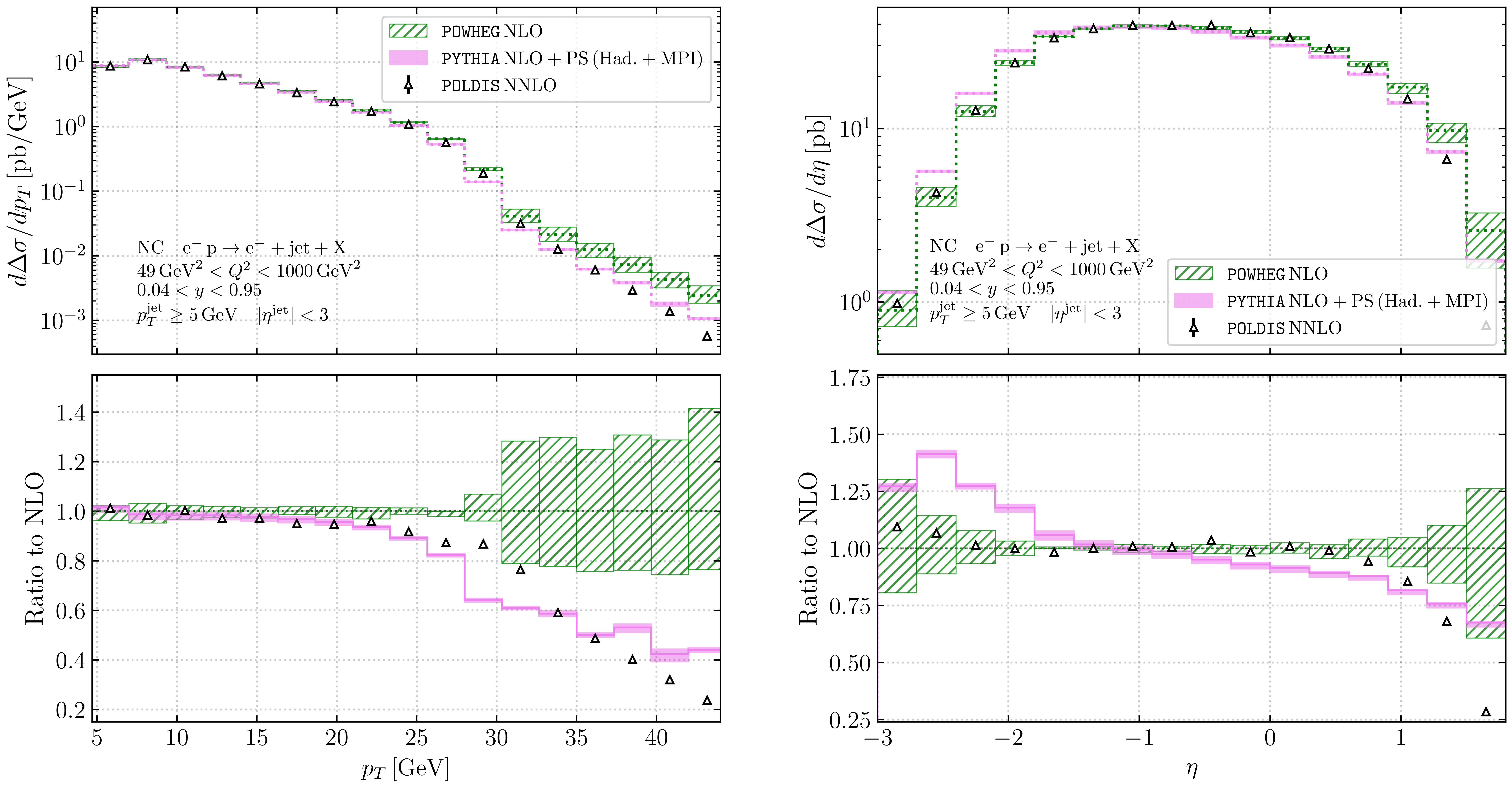
PHENOMENOLOGY - NC

IB, Jäger *JHEP* 07 (2024) 177



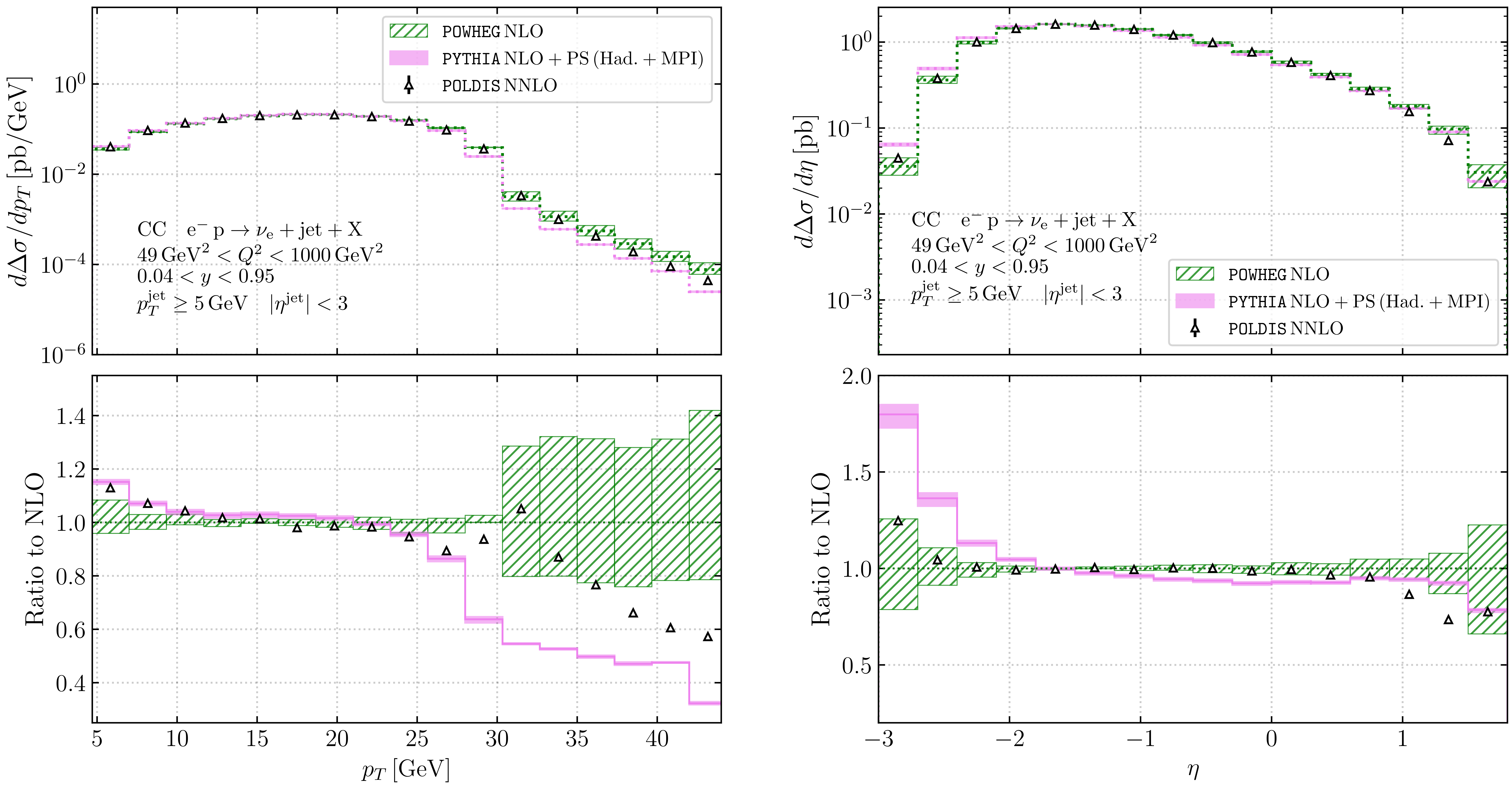
- Sizable corrections in the kinematical suppressed regions
- Improvement in the agreement with NNLO results [IB, D. de Florian, I. Pedron]

PHENOMENOLOGY - NC



PHENOMENOLOGY - CC

IB, Jäger *JHEP* 07 (2024) 177



SUMMARY

- Monte Carlo Generators for eH scattering crucial to fully realize the EIC physics program.
- Spin program will require matching of higher order corrections with parton showers that consistently account for polarized beams.

NLO+PS implementation of polarized DIS in POWHEG

- Extended POWHEG scheme to account for the helicities of the initial-state particles.
- Sizable PS effects in selected regions of phase space for EIC kinematics.
- Important step towards the development of polarized parton-shower generators for EIC, with polarization included in all stages of simulation.

THANK YOU

EXTRA SLIDES

NLO + PARTON SHOWER - POLARIZED POWHEG

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de Florian, Frixione, Signer, Vogelsang (1999)

$P^{<}_{ab}(z, \epsilon) \rightarrow \Delta P^{<}_{ab}$ for ISR

$dM \rightarrow \Delta M$

- Modifications to handle negative weights

$$n_+ = \frac{\sigma(+)}{\sigma(+) + |\sigma(-)|} \qquad n_- = \frac{\sigma(-)}{\sigma(+) + |\sigma(-)|}$$

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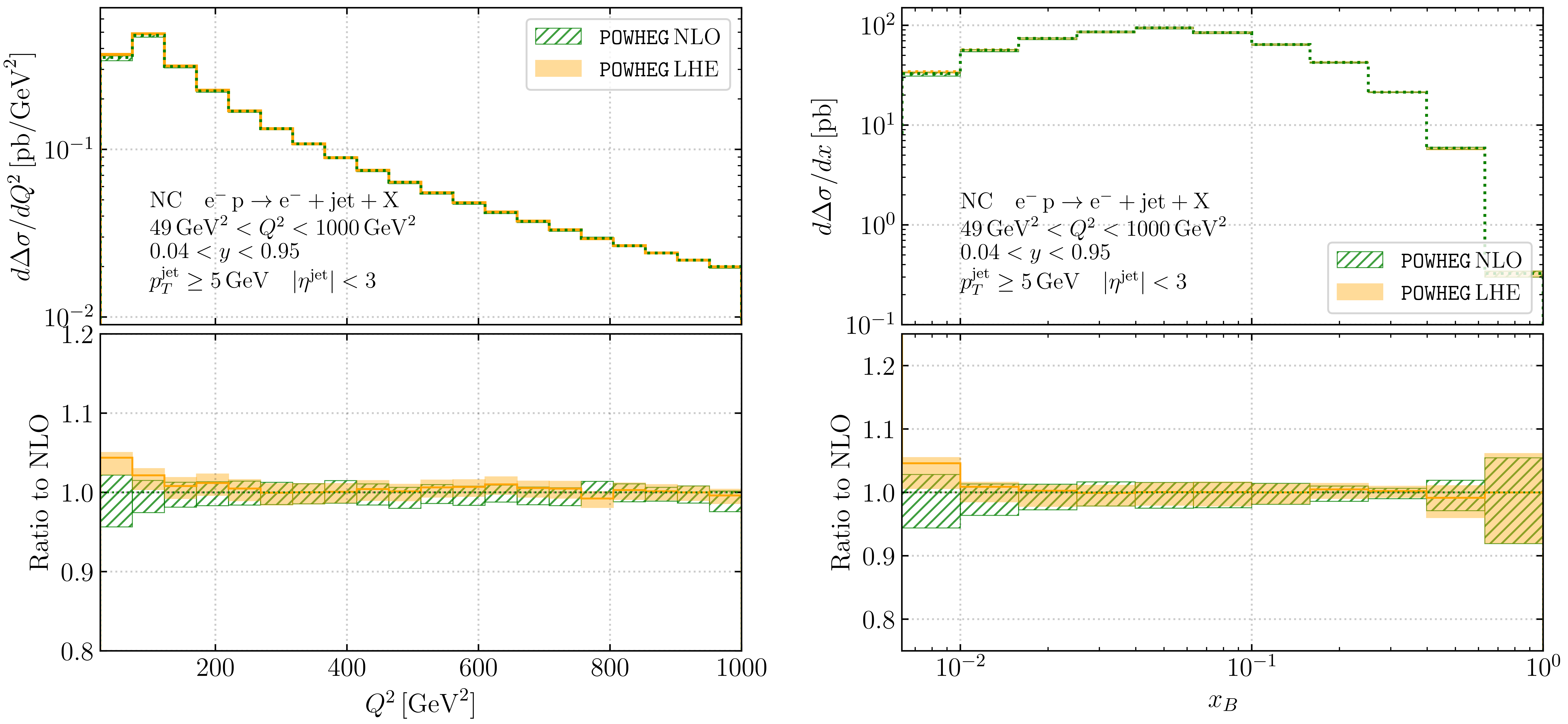
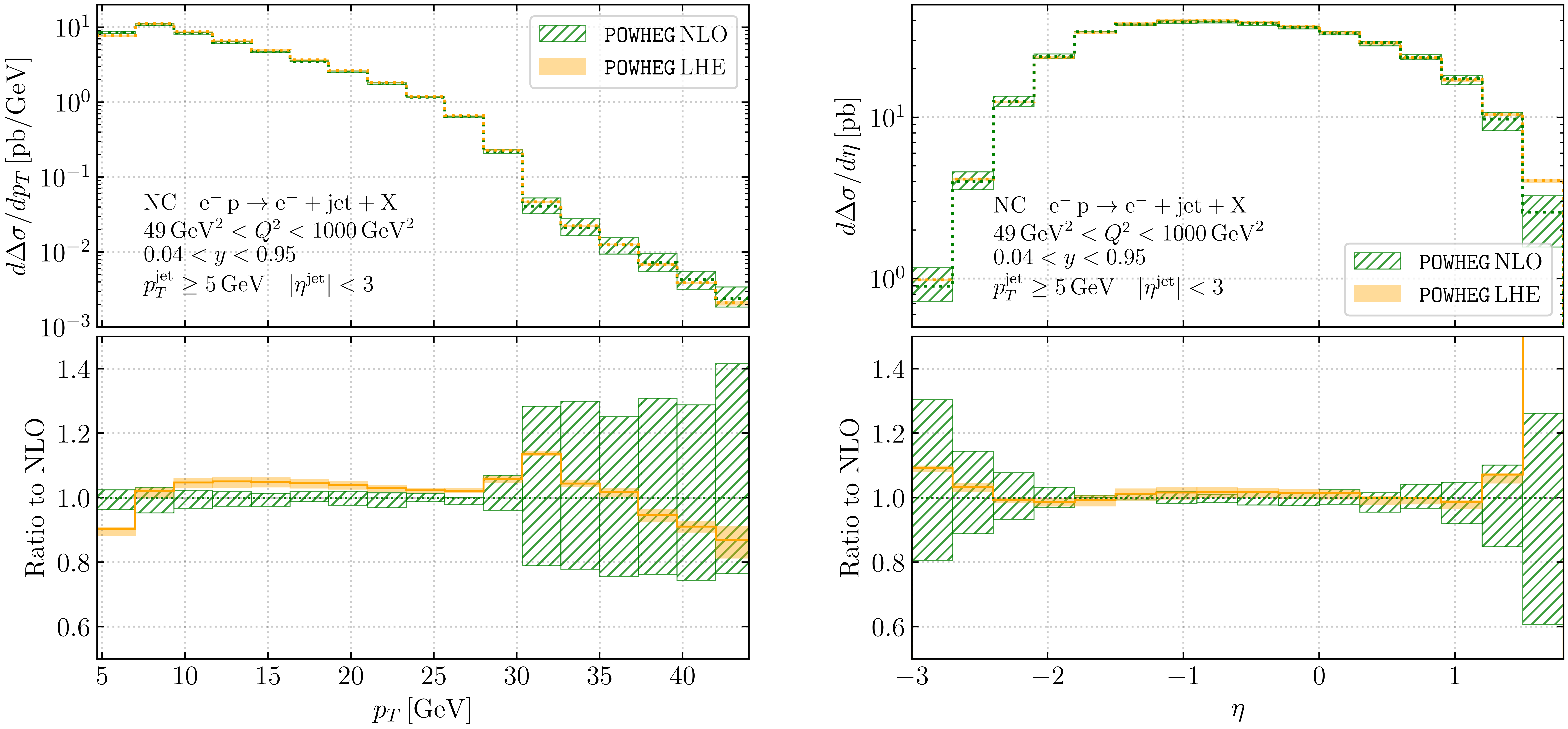
NLO + PARTON SHOWER - POWHEG



NLO + PARTON SHOWER - POWHEG



NLO + PARTON SHOWER - POWHEG