Parton-shower effects in polarized DIS

Ignacio Borsa

In collaboration with Barbara Jäger

Based on JHEP 07 (2024) 177

TUM-MPP Collider Phenomenology Seminar Series

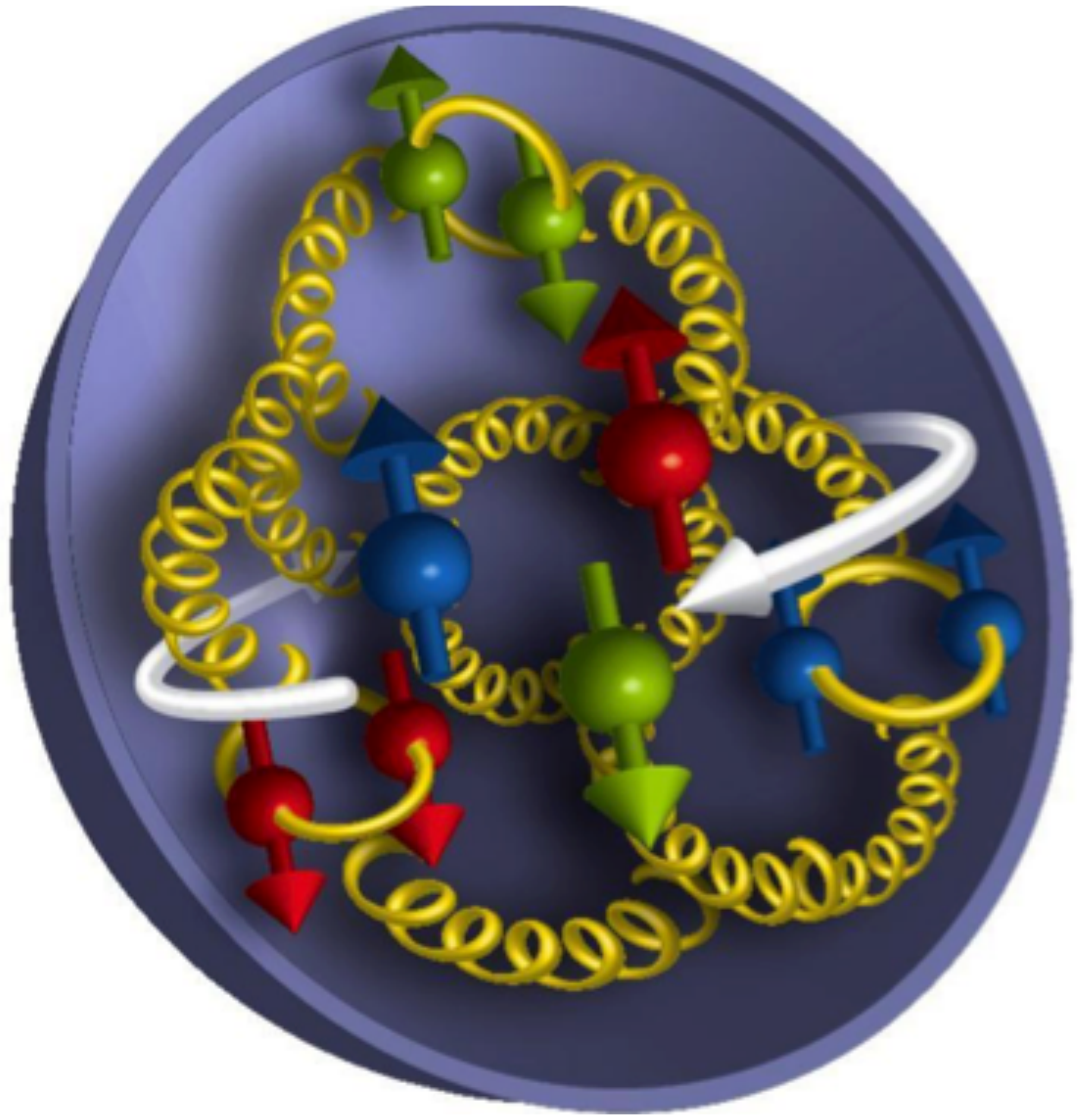
München- October 29th 2024

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Introduction

Introduction - The proton's spin structure

How is the proton's spin distributed among its constituents?



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$$

Jaffe, Manohar (1990)

- Surprisingly low amount of spin carried by intrinsic quarks, $\Delta\Sigma \sim 0.25 \ll 1$ [European Muon Collaboration (1989)] $\rightarrow$ "Proton spin crisis".

- Significant progress both from experiment and theory [for a review: Aidala, Bass, Hasch, Mallot (2013)]. First evidence of positive polarization of gluons from polarized proton-proton collisions at RHIC [de Florian, Sassot, Stratmann, Vogelsang (2014); Nocera, Ball Forte, Ridolfi, Rojo (2014)].

- Still, rather incomplete picture of the spin structure in terms of the contribution from gluons or flavor decomposition.

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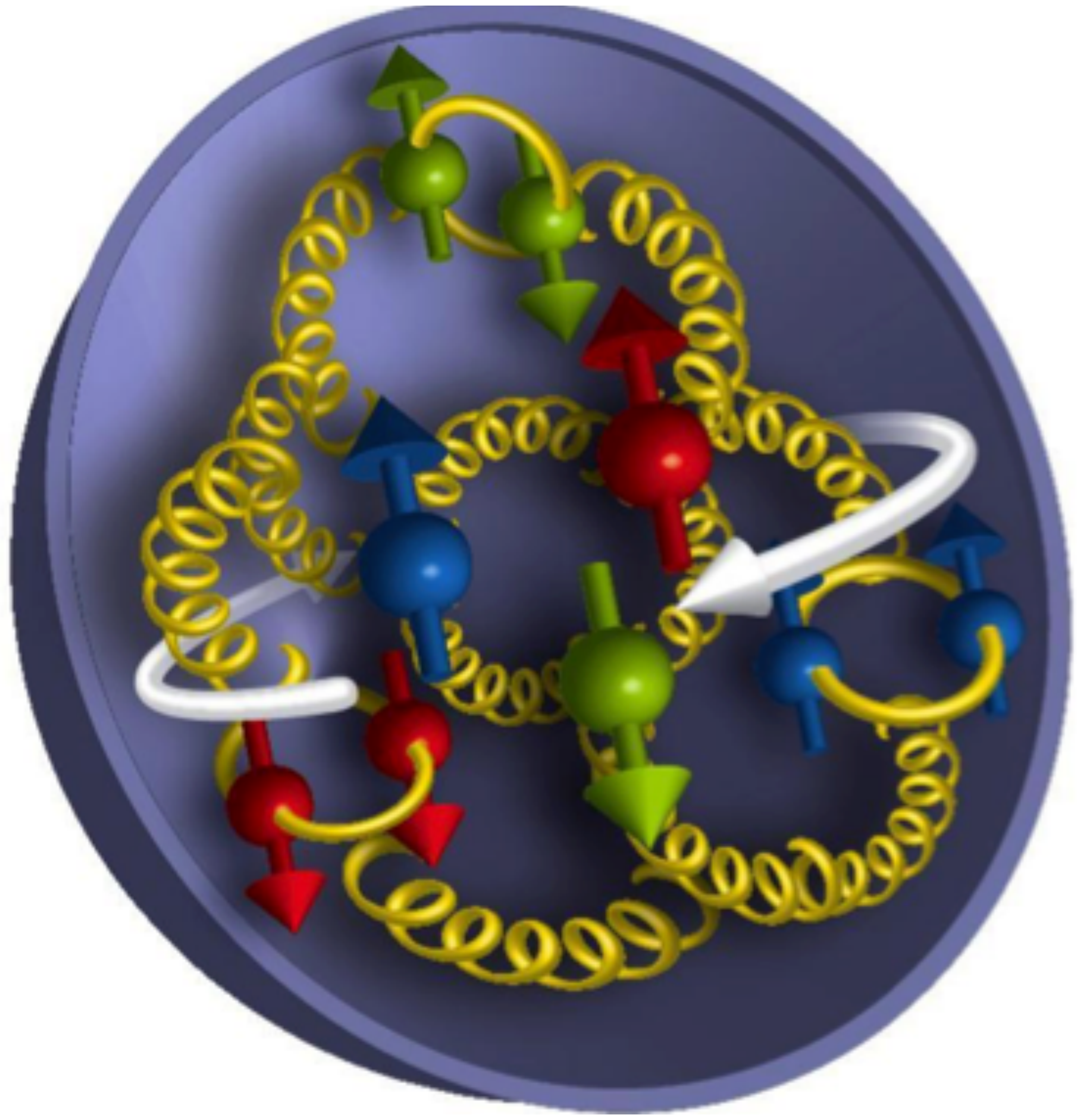

Quark's spin Gluon's spin OAM

$$\frac{1}{2} = \boxed{\frac{1}{2}\Delta\Sigma} + \boxed{\Delta g} + \boxed{L_q + L_g}$$

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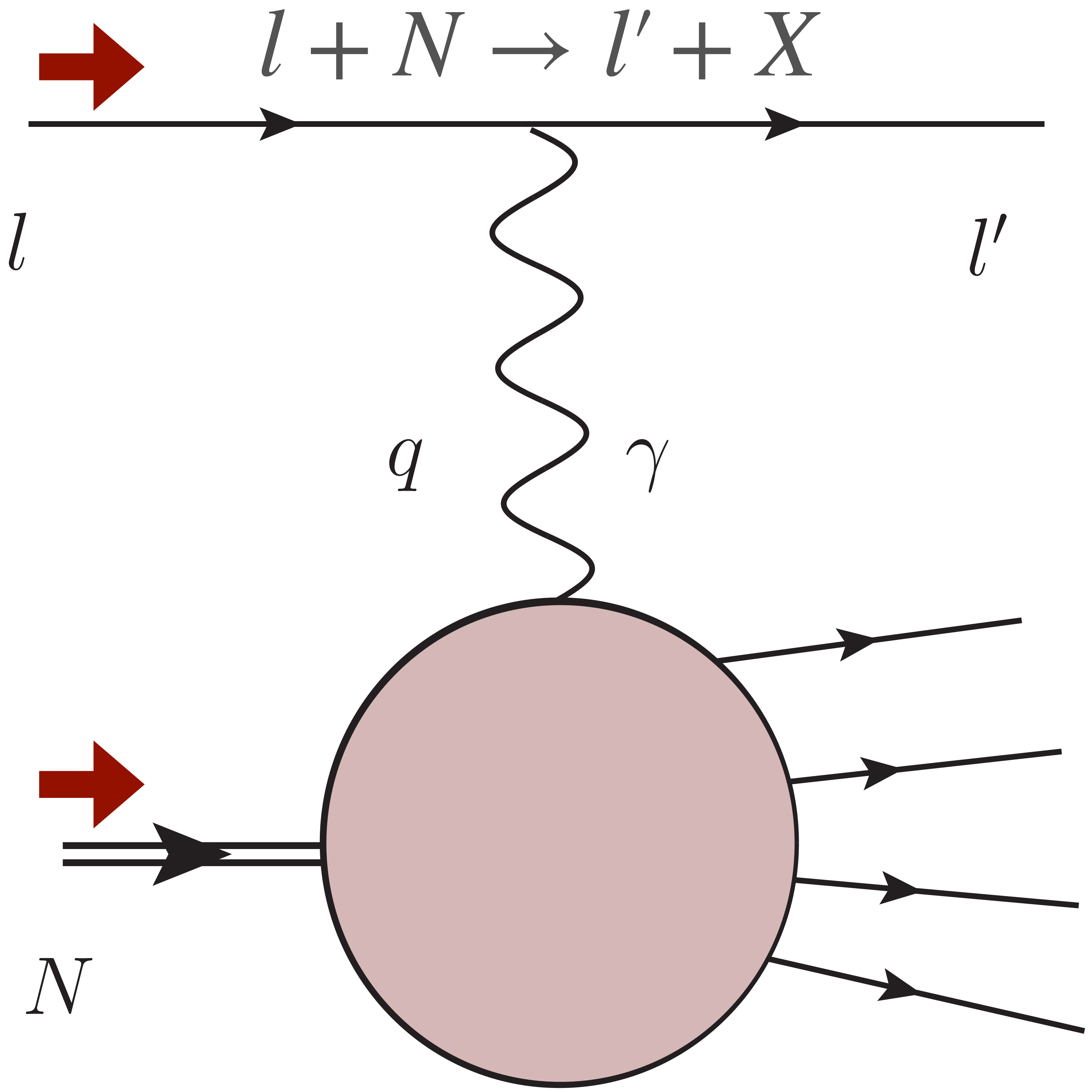

Longitudinally polarized cross section

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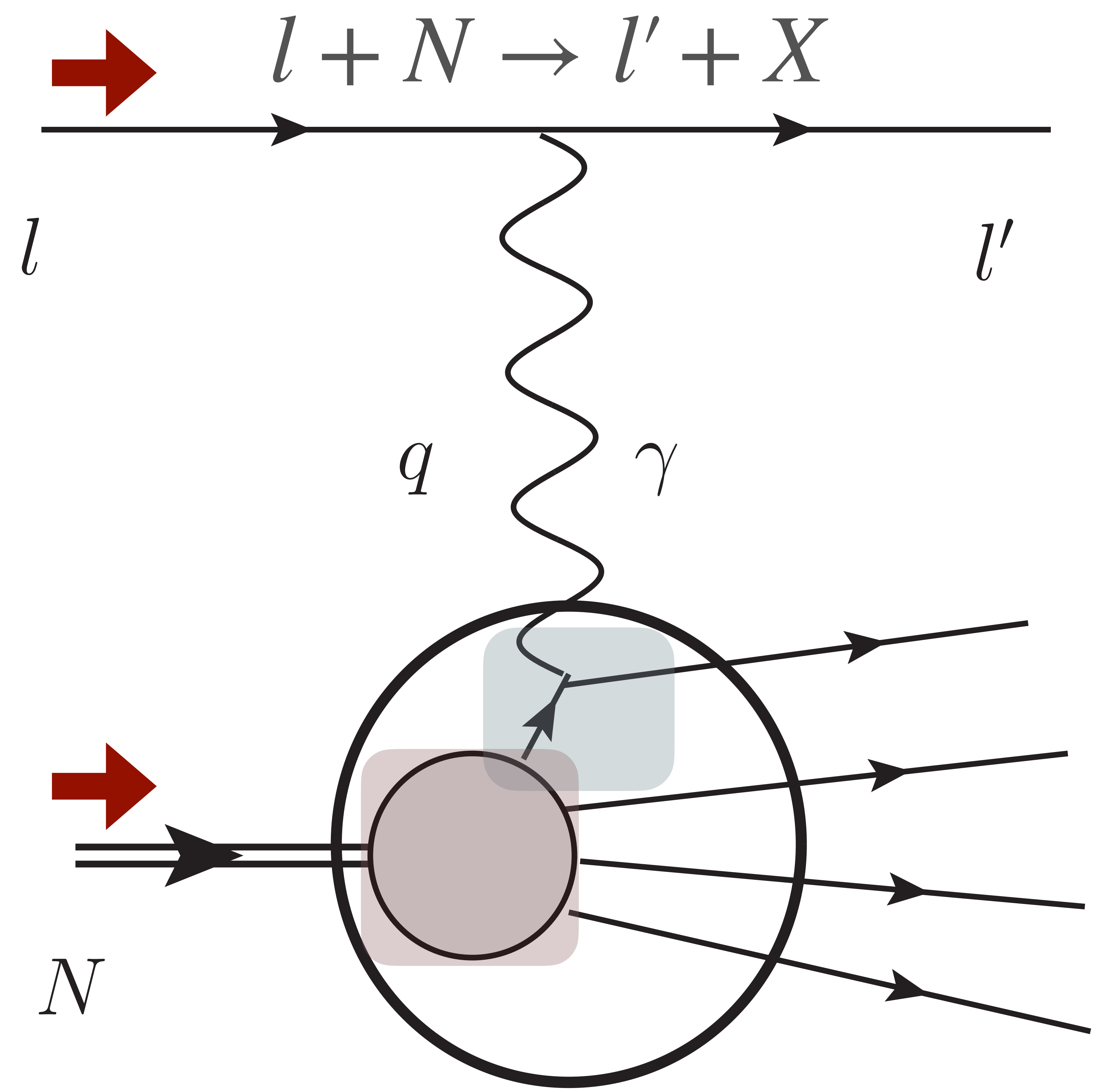

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$$\Delta\sigma = \sum_a \int dz\, \Delta f_a(z, \mu_F^2)\, \Delta\hat{\sigma}_i(\alpha_S(\mu_R), \mu_F^2, \mu_R^2)$$

Polarized PDFs

$$\Delta f_a \equiv f_a^+ - f_a^-$$

Polarized Partonic cross-section

$$\Delta\hat{\sigma} \equiv \frac{1}{2}[\hat{\sigma}^{++} - \hat{\sigma}^{+-}]$$

$$\Delta f_a(\mu_F^2) = \int_0^1 \Delta f_a(x, \mu_F^2)\, dx$$

Contribution of parton a to the proton's spin

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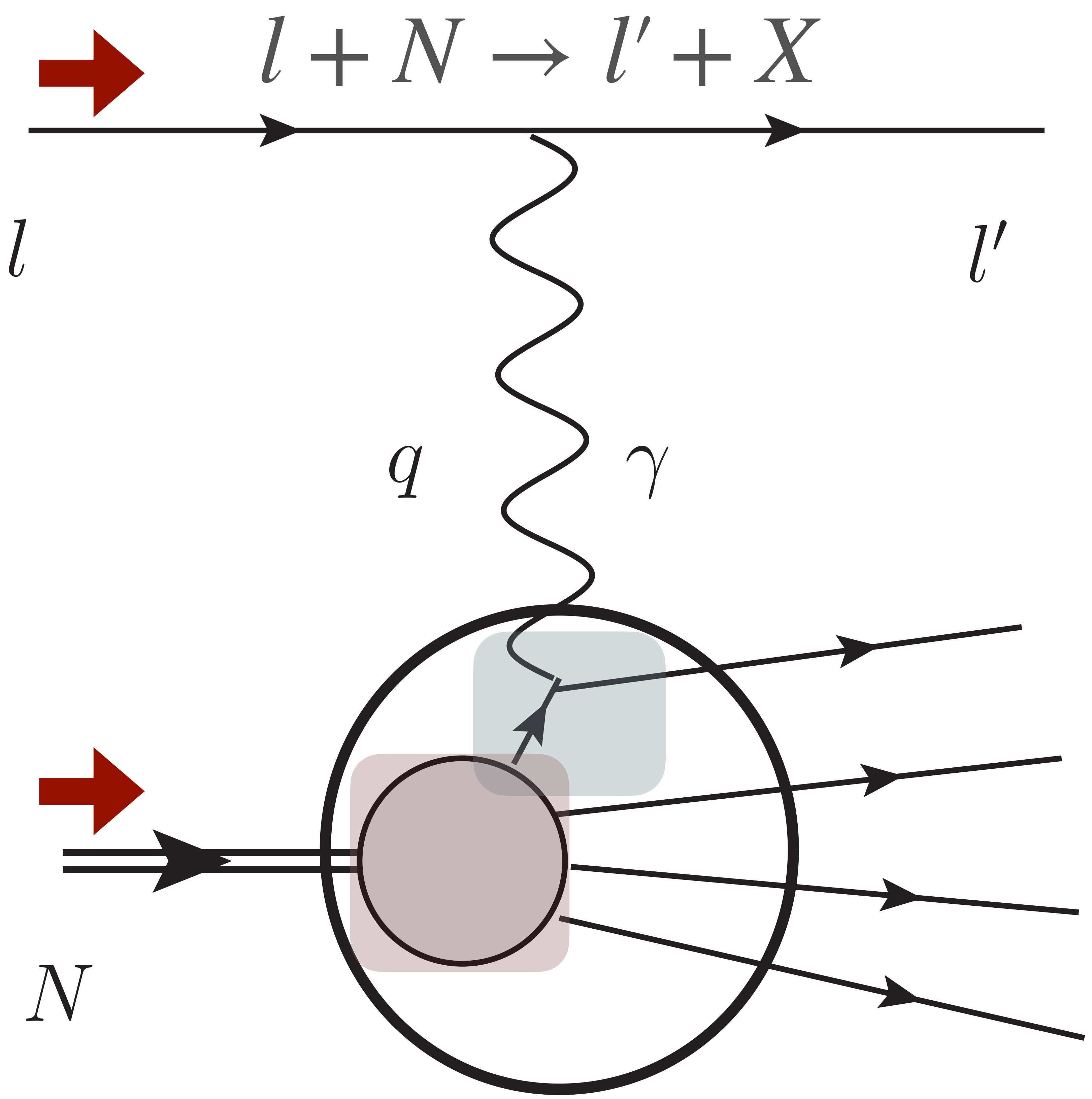

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Contribution of parton a to the proton's spin

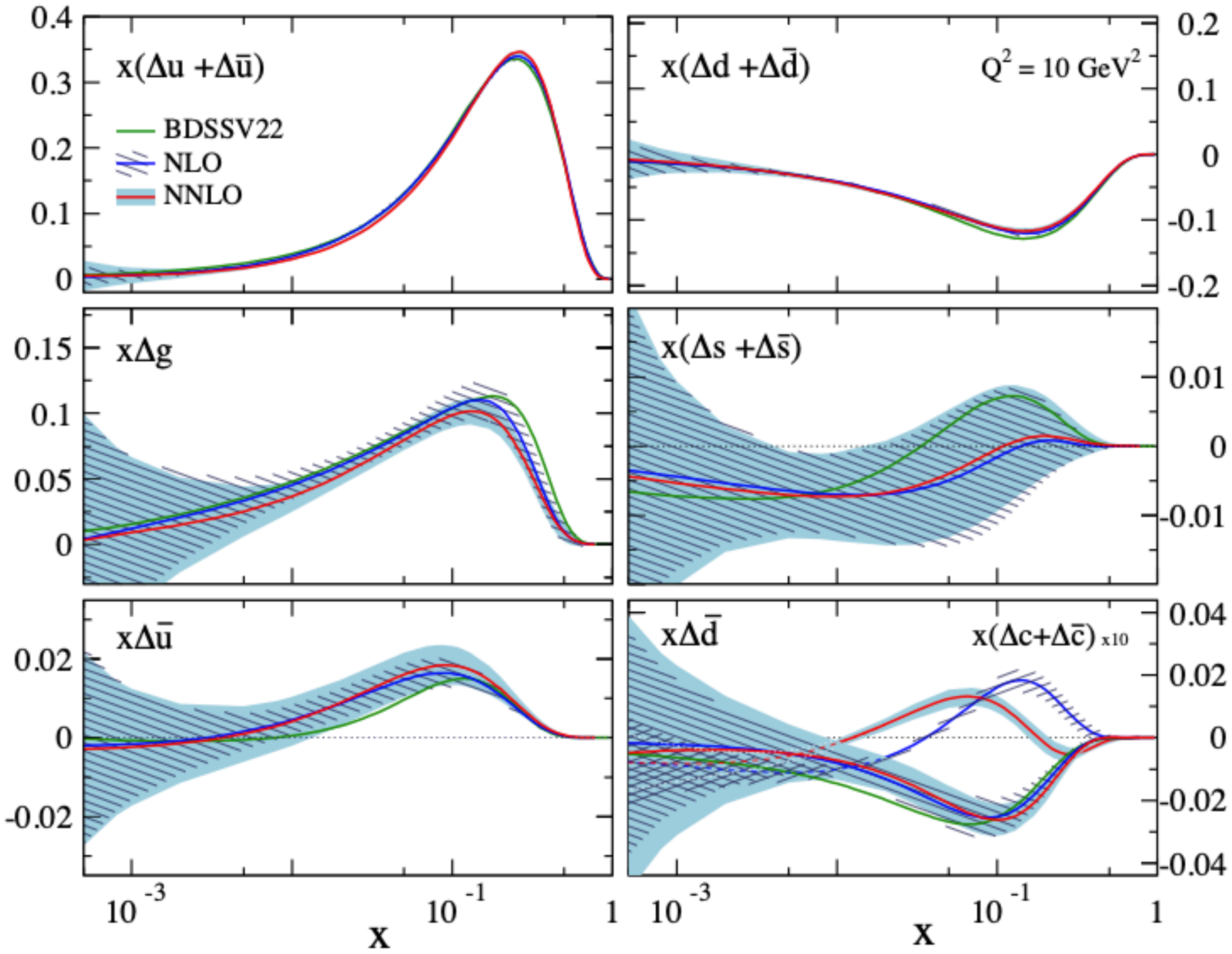
PDFs' scale dependence can be calculated perturbatively in QCD

$$\frac{\partial}{\partial \ln \mu^2} \Delta f_i(z, \mu^2) = \sum_j \int_z^1 \frac{dy}{y} \Delta P_{ji}(y, \alpha_S(\mu^2))\, \Delta f_j(\frac{z}{y}, \mu^2)$$

They can be determined at some input scale from a set of experimental measurements → QCD global analyses

Introduction - The proton's spin structure

How well do we know polarized PDFs?



- Recently NNLO global analyses of polarized PDFs based on DIS, SIDIS and pp data [MAP: V. Bertone, E.Chiefa, E.Nocera; BDSSV: IB, de Florian, Sassot, Stratmann, Vogelsang]
- Well constrained singlet combination
- Still incomplete picture in terms of flavor separation and contribution from gluons

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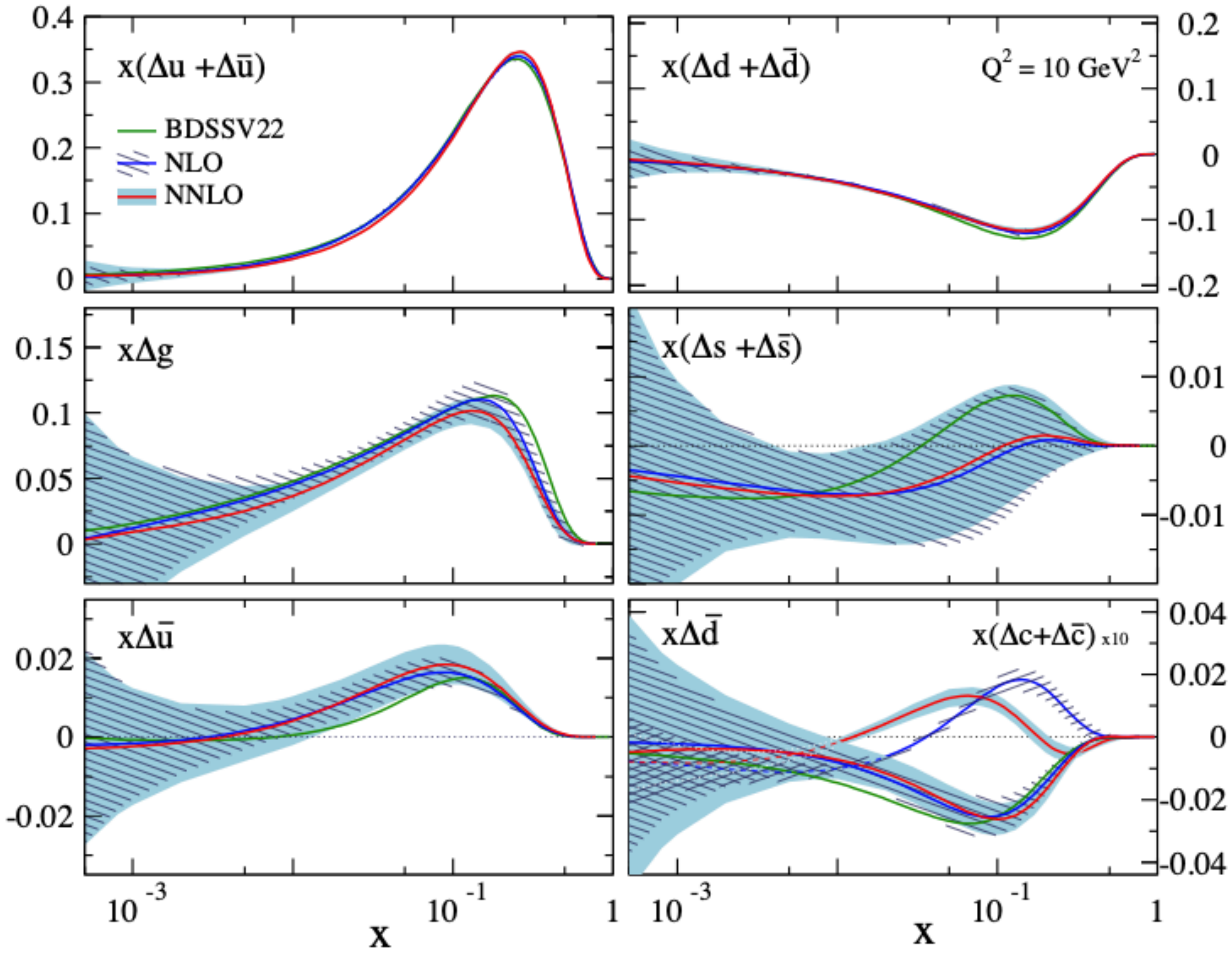

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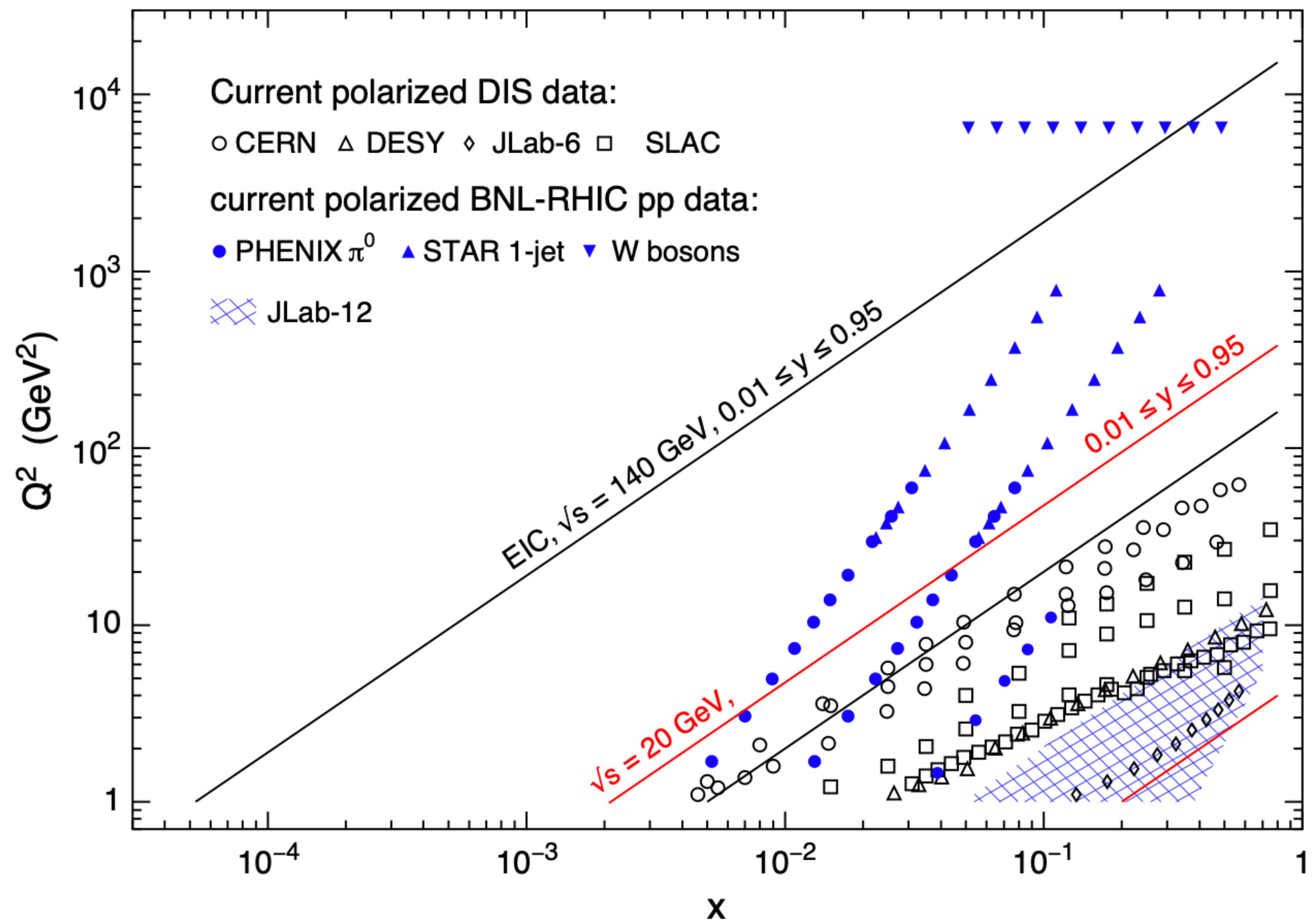


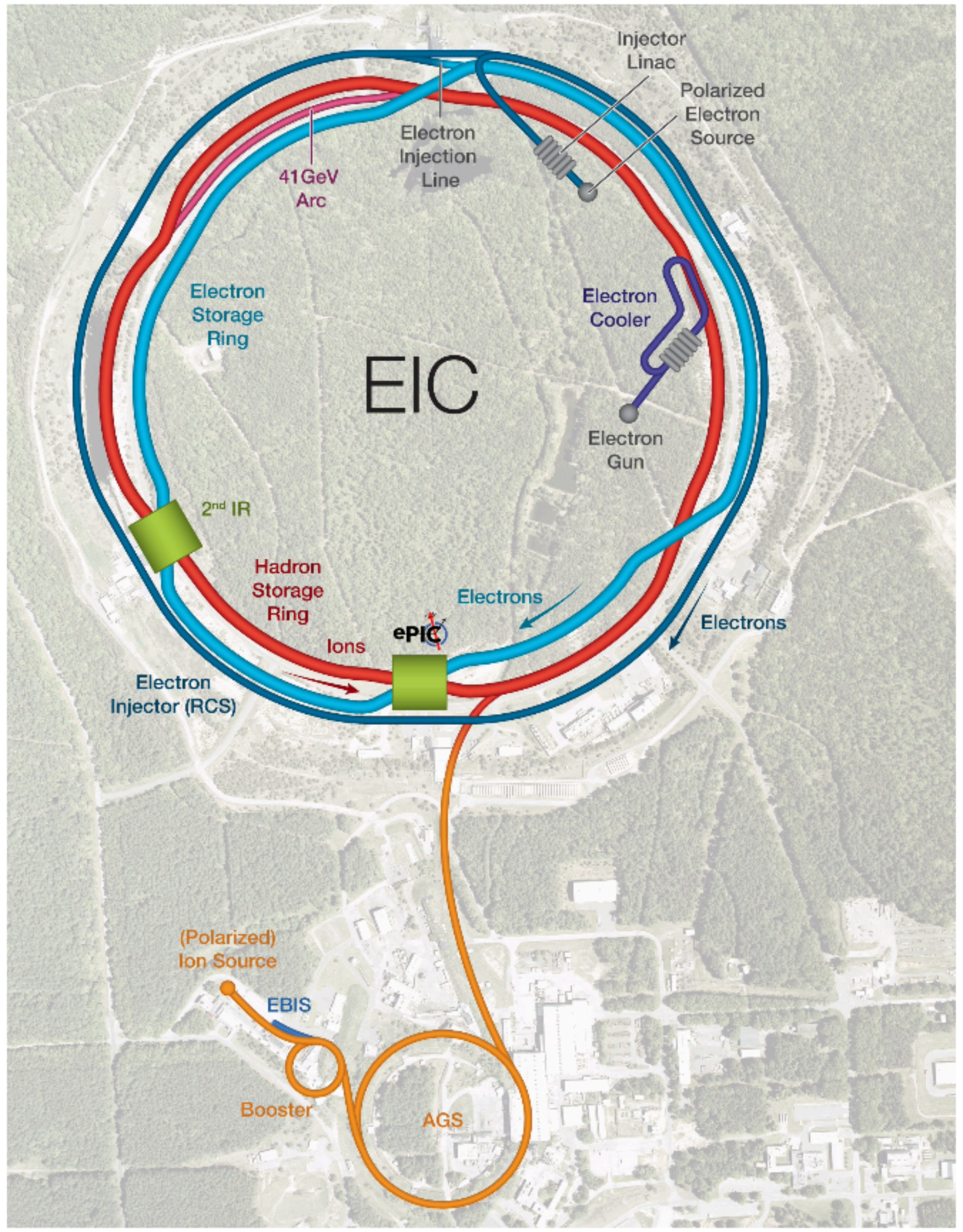
Introduction - The proton's spin structure

Spin physics at the future Electron-Ion Collider (EIC)

BNL-based EIC on its path towards construction

- High Luminosity: $\mathscr{L} = 10^{33} - 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$
- Large center-of-mass energy range: $20 - 140\,\mathrm{GeV}$
- Highly polarized electron & light hadron beams

Unique access to the proton's spin structure in terms of helicity parton distributions!



Electron Ion Collider: The Next QCD Frontier : Understanding the glue that binds us all. Eur.Phys.J.A 52 (2016)

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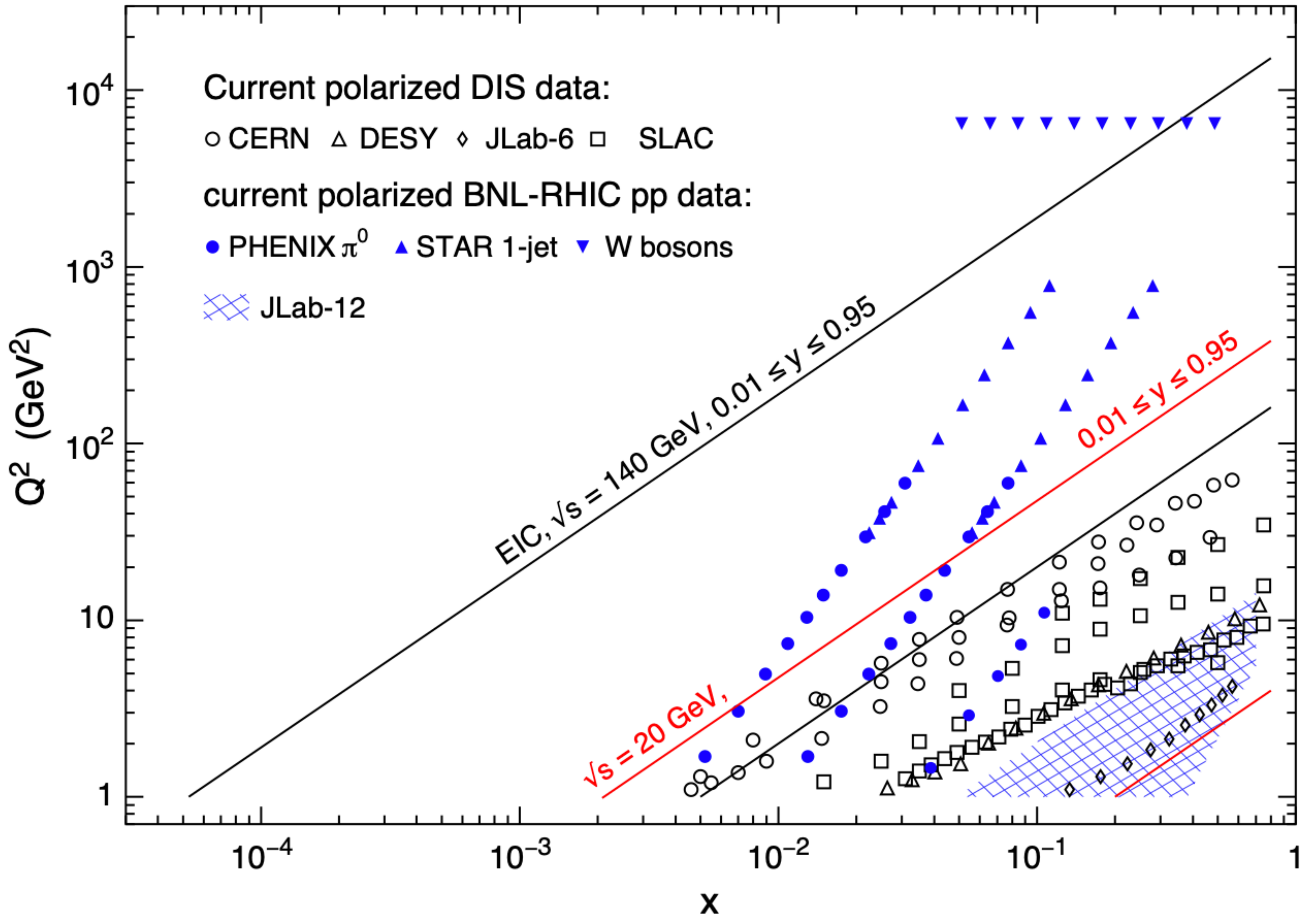

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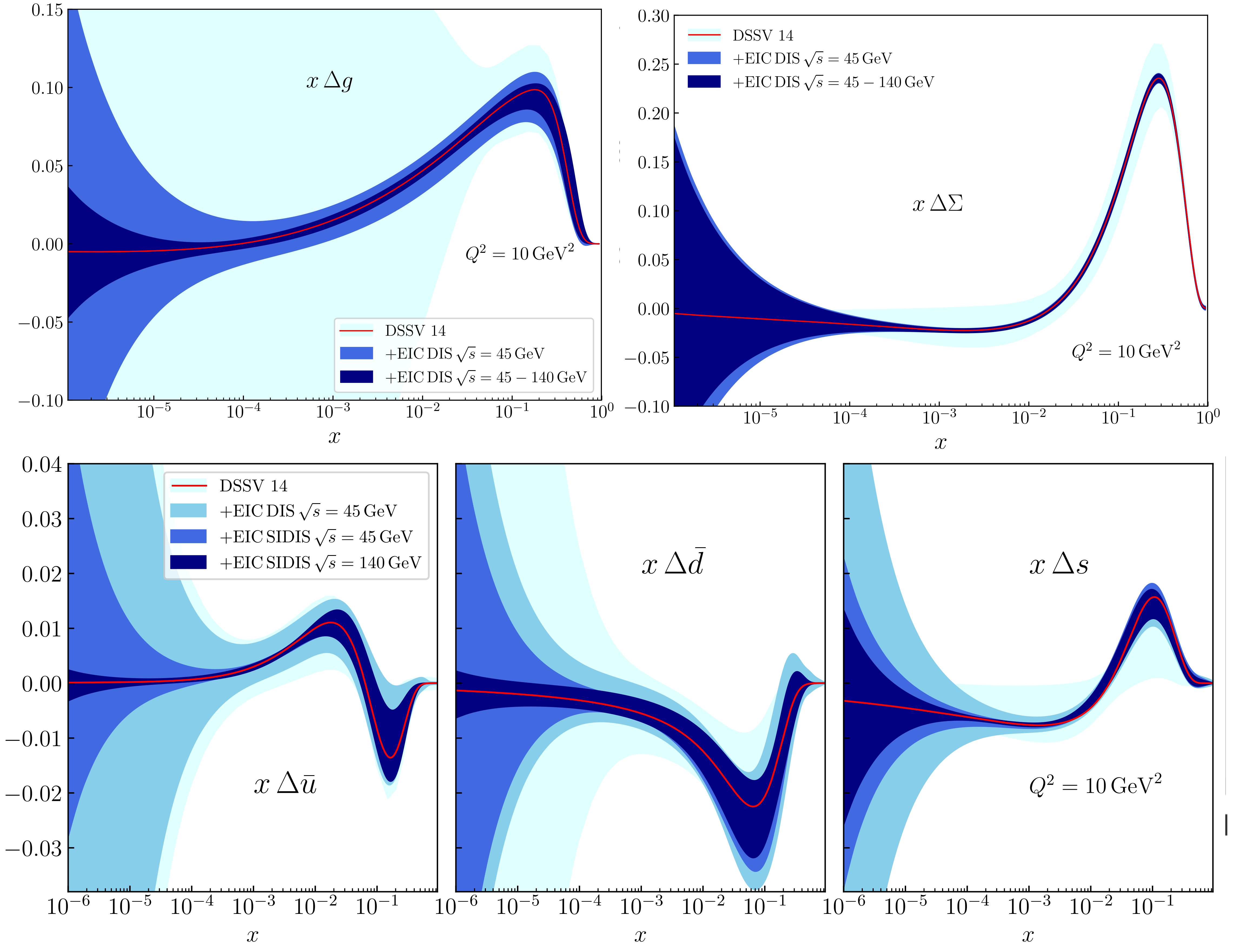

Aschenauer, IB, Lucero, Nunes, Sassot (2020)

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- Increased theoretical accuracy (NNLO)
- Precise MC event generators

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Calculations for polarized eP observables beyond NLO:

- NNLO structure functions g_1 (photon exchange)
  van Neerven, Zijlstra (1994)
- NNLO NC & CC structure functions g_1, g_4, g_5
  IB, de Florian, Pedron (2022)
- Approx. NNLO and N3LO Semi-Inclusive DIS
  Abele, de Florian, Vogelsang (2022)
- NNLO Single-Jet production
  NC and CC- IB, de Florian, Pedron (2023)
- NNLO Semi-Inclusive DIS
  Bonino, Gehrmann, Löchner, Schönwald, Stagnitto (2024)
  Goyal, Moch, Pathak, Rana, Ravindran (2024)
- N3LO structure function g_1 (photon exchange)
  Blümlein, Marquard, Schneider, Schönwald (2023)

Parton distribution functions

- NNLO polarized PDFs
  Taghavi-Shahri, Khanpour, Atashbar Tehrani, Alizadeh Yazdi (2016)
  Bertone, Chiefa, Nocera (2024)
  IB, de Florian, Sassot, Stratmann, Vogelsang (2024)

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This talk

MC event generators for eN scattering including higher order corrections

- SHERPA & HERWIG7

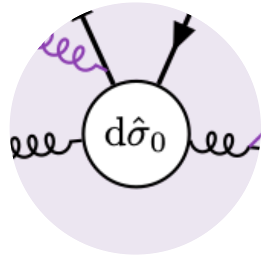
Carli, Gehrmann, Höhe (2009)
Höche, Kuttimalai, Li (2018)

- POWHEG

Banfi, Ferrario Ravasio, Jäger, Karlberg, Reichenbach, Zanderighi (2024)
Buonocuore, Limatola, Nason, Tramontano, (2024)
Polarized - IB, Jäger (2024)

Introduction - The proton's spin structure

Event generators for polarized DIS: What do we have? What do we need?



Pythia manual arXiv:2203.11601 [hep-ph]

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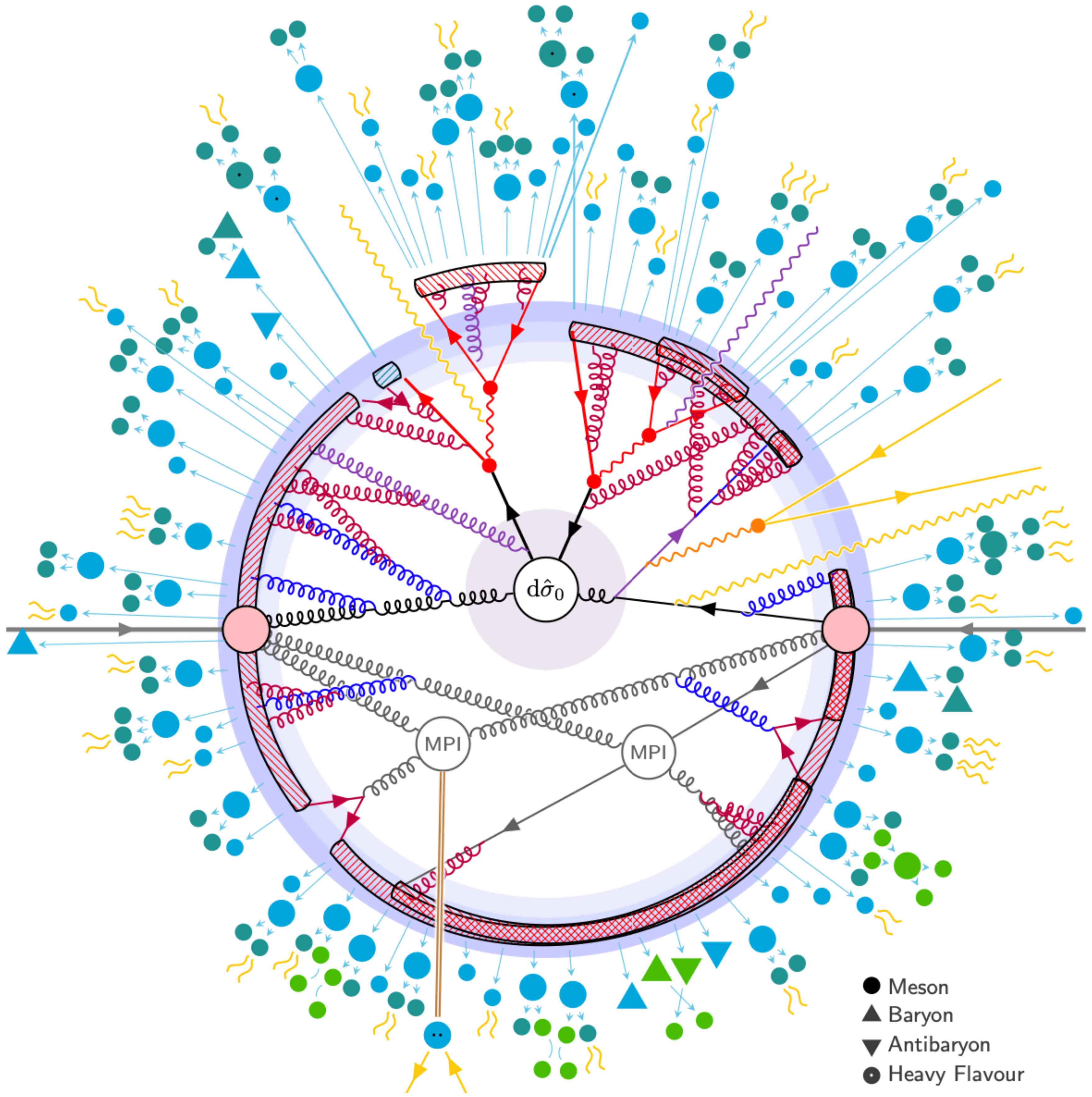

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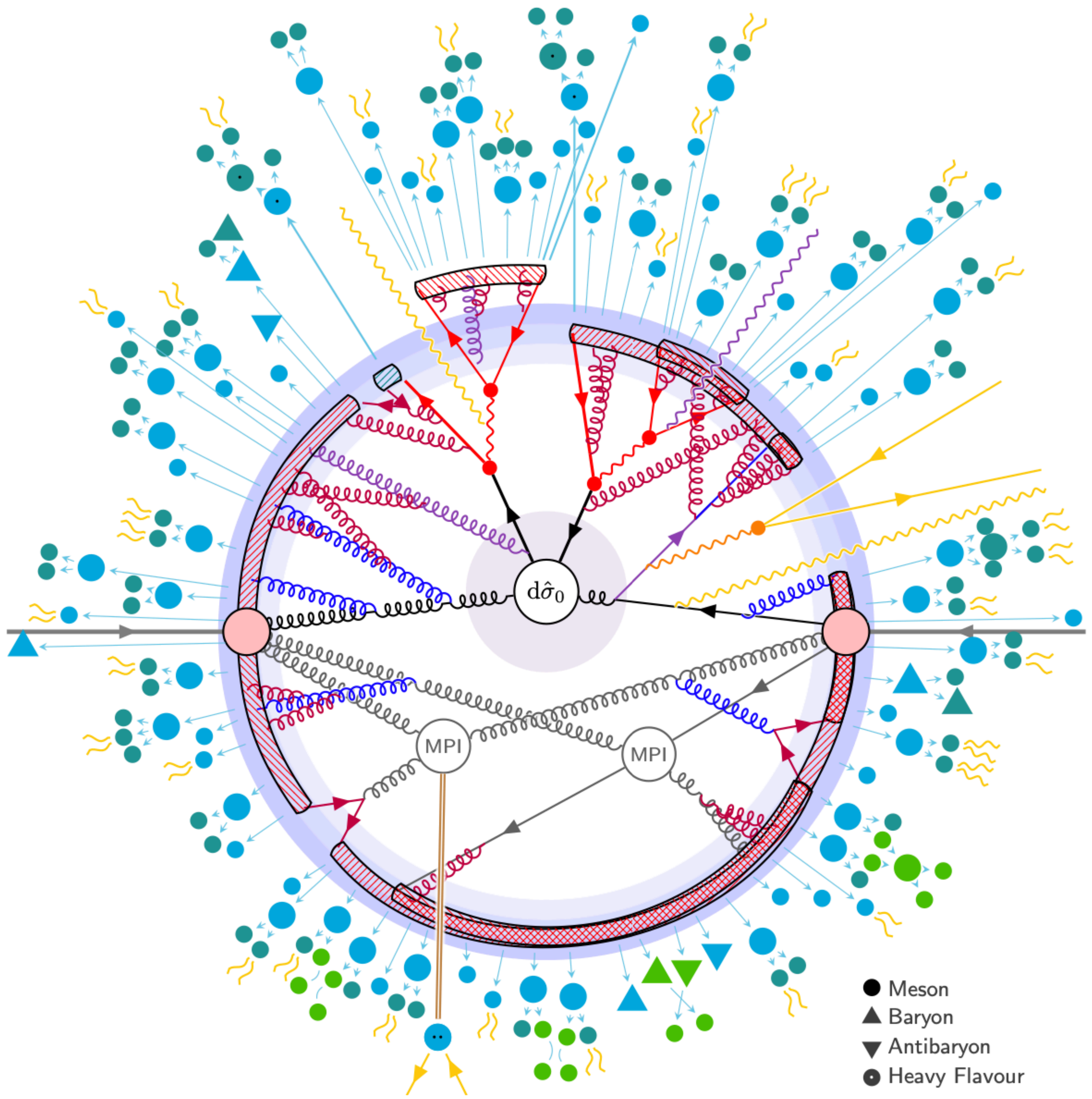

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Requirements for MC for spin physics:

- NLO description of polarized inclusive and semi-inclusive NC and CC
- Polarized and unpolarized PS and radiative corrections
- Polarization included in all stages of simulation: Initial state, hard-scattering, parton showers, QED corrections

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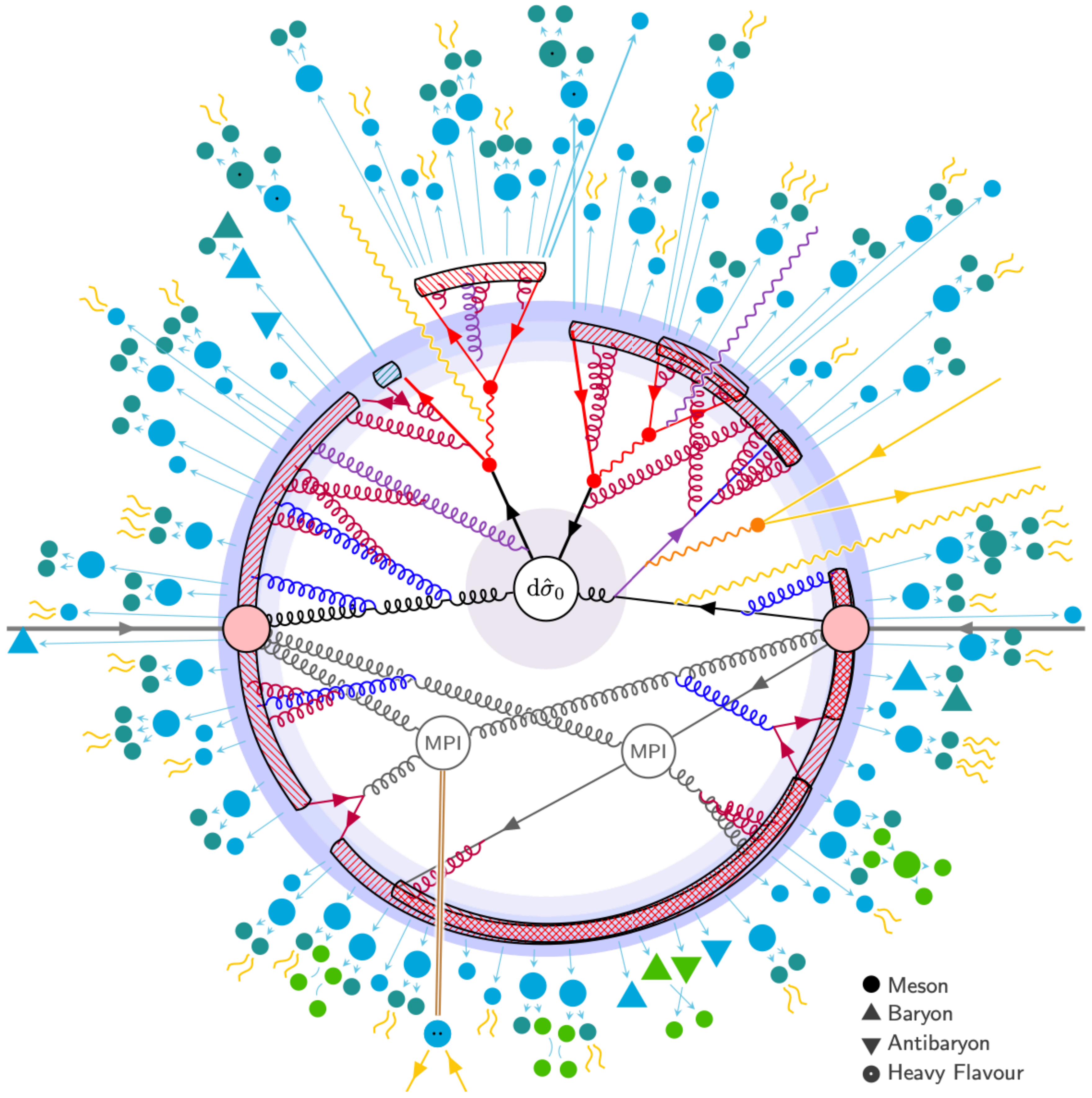

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Update older LO polarized eN event generators

PEPSI

Mankiewicz, Schäfer, Veltri (1992)

DJANGOH

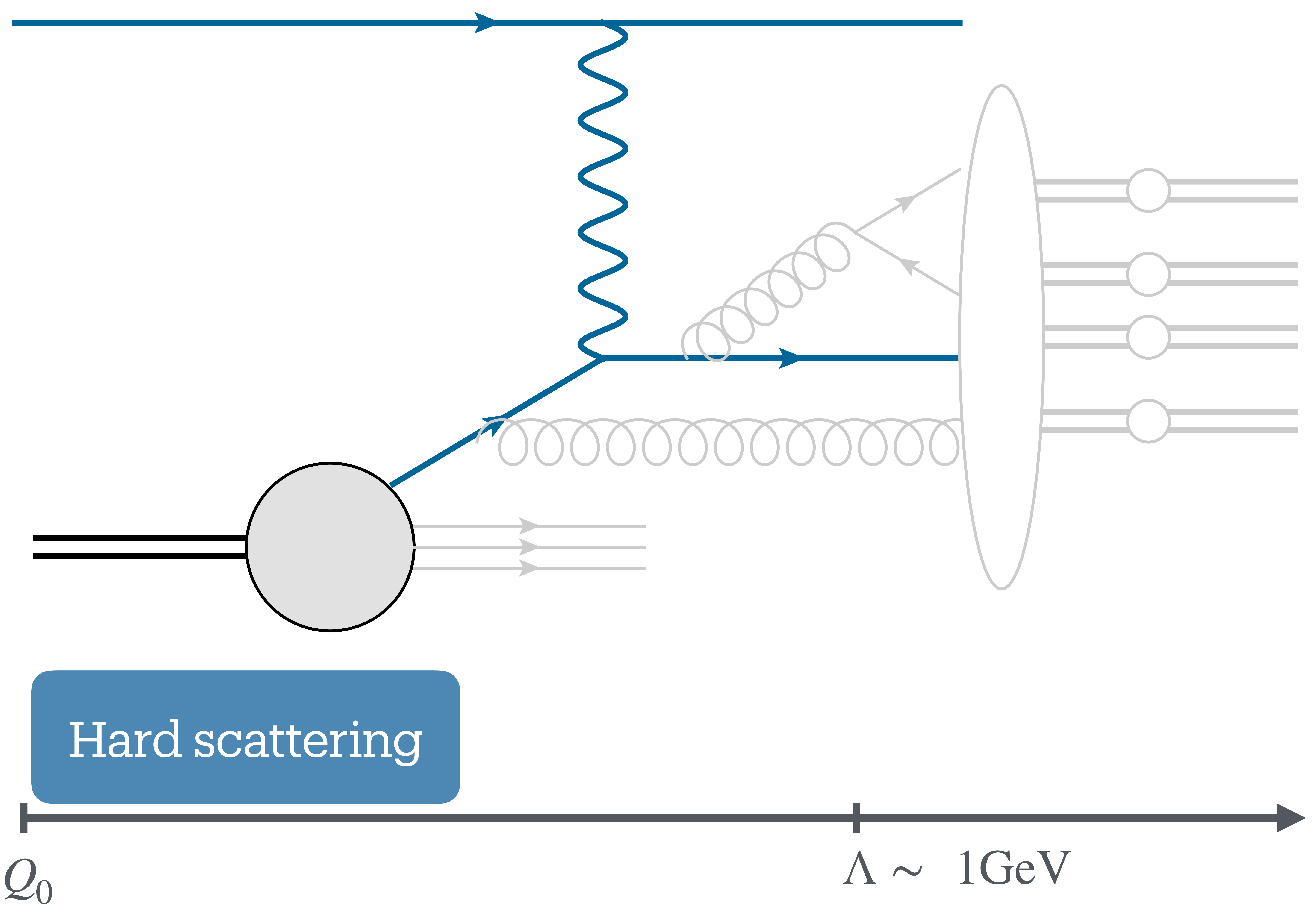
Charchula, Schuler, Spiesberger (1994)

Aschenauer, Burton, Martini, Spiesberger, Stratmann (2013)

Matching higher order corrections to Parton Showers

Shower Monte Carlo event generators

SMC in a nutshell



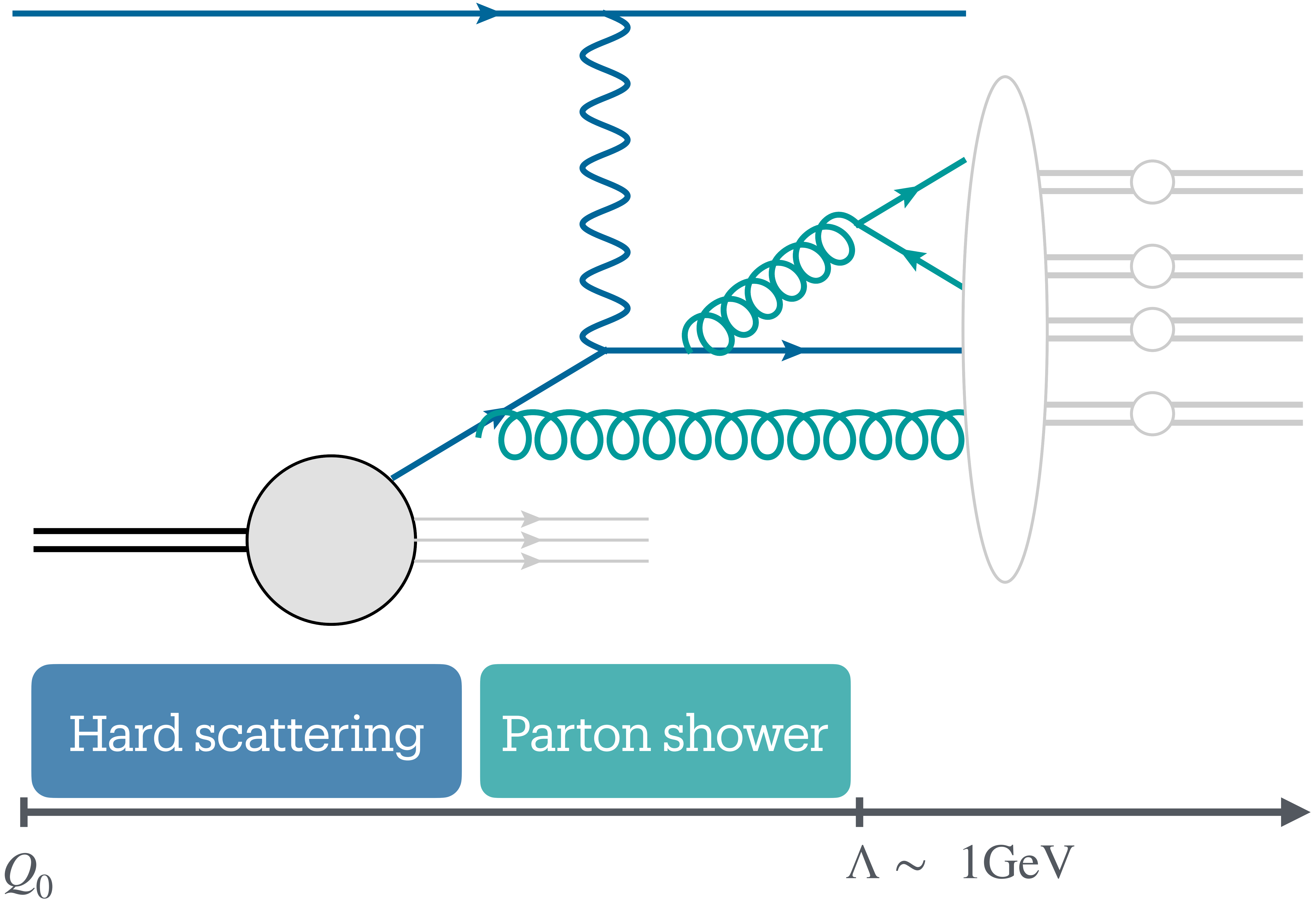
Resummation of enhanced contributions in the collinear limit

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

- Iterated simulation of softer and softer emissions from hard scale down to hadronization scale
- Leading logarithmic accuracy (correct behavior in the collinear limit)
- Simulate hadronization and hadronic decays

Shower Monte Carlo event generators

SMC in a nutshell



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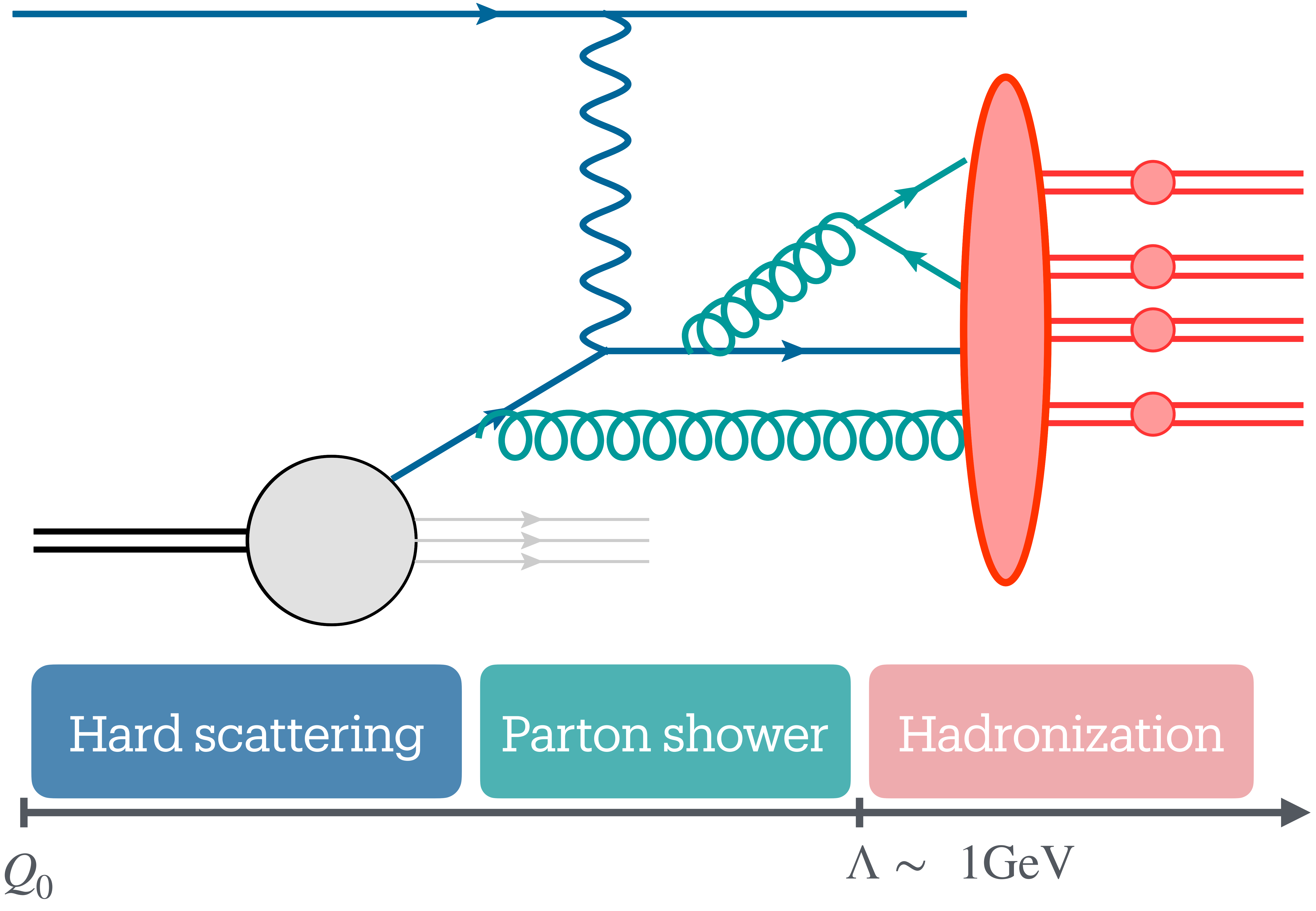

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Matching higher order corrections to PS

SMC (LO + Parton Shower)

- Correct behavior 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

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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) ; Frixione, Nason, Oleari (2007)

Matching of NNLO+PS

UNNLOPS - Höhe, Pressten (2014, 2015)

GENEVA - Alioli, Bauer, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi (2013)

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

Matching higher order corrections to PS

POsitive-Weight Hardest Event Generator (POWHEG)

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

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

POWHEG - Nason (2004);
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$$d\sigma_{\mathrm{POWHEG}} = \overline{B}(\Phi_n)\, d\Phi_n \left\{ \Delta(\Phi_n, p_{Tmin}) + \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} \Delta(\Phi_n, p_T)\, d\Phi_r \right\}$$

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POWHEG SUDAKOV

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

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

POWHEG - Nason (2004); Frixione, Nason, Oleari (2007)

Matching higher order corrections to PS

POsitive-Weight Hardest Event Generator (POWHEG)

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

POWHEG SUDAKOV

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

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

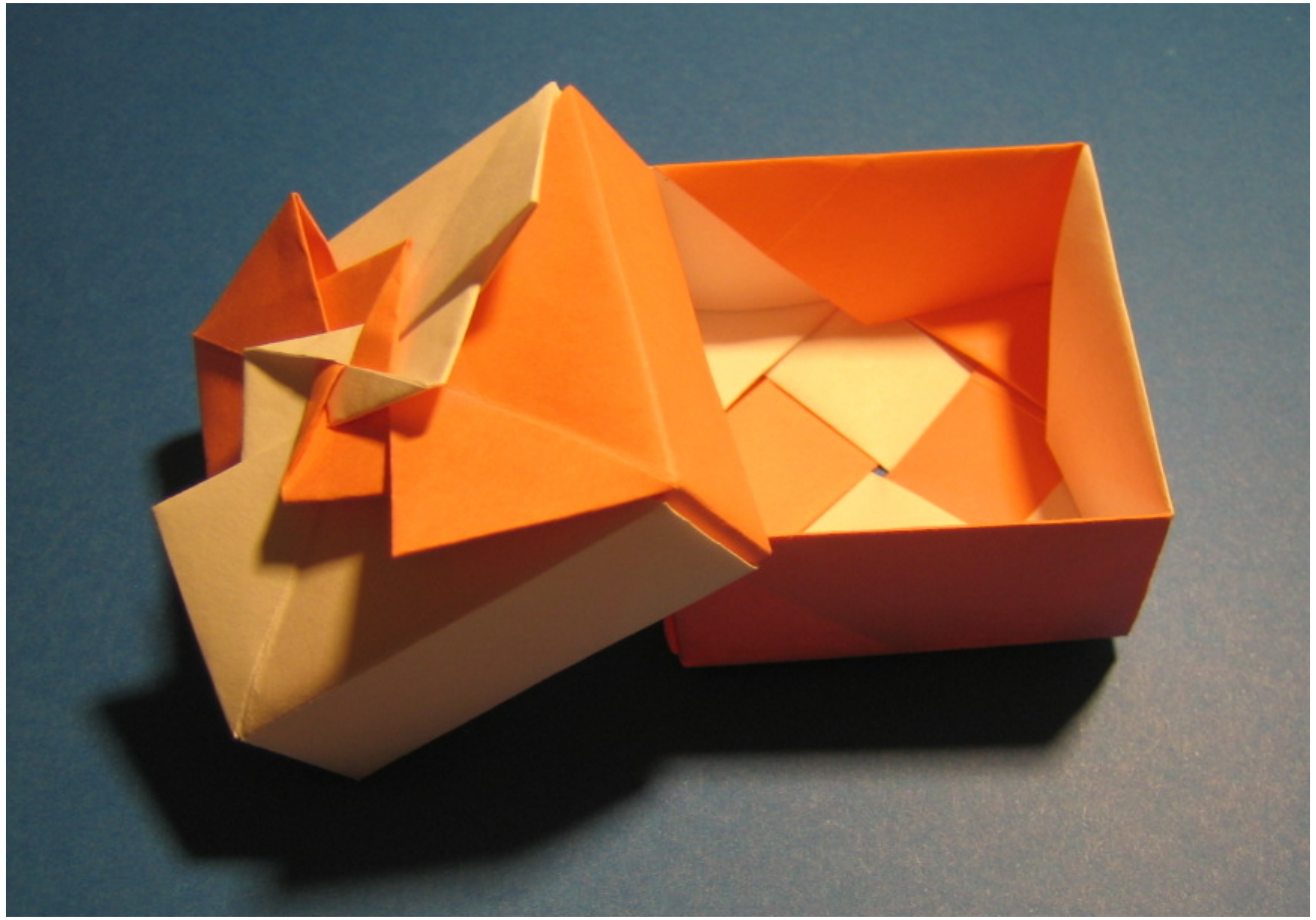
- Hardest emission generated according to the POWHEG Sudakov and $\bar{B}(\Phi_n)$ → **Positive weight**
- Subsequent radiation generated using parton-shower programs + p_T-veto → **avoids double counting**

☑ **NLO accuracy on integrated quantities**
☑ (At least) **Leading log accurate**

POWHEG - Nason (2004);
Frixione, Nason, Oleari (2007)

Matching higher order corrections to PS

POWHEG-BOX



https://powhegbox.mib.infn.it/
POWHEG - Frixione, Nason, Oleari (2007)
POWHEG-BOX - Alioli, Nason, Oleari, Re (2010)

Public computer framework that implements the POWHEG formalism for generic NLO processes.

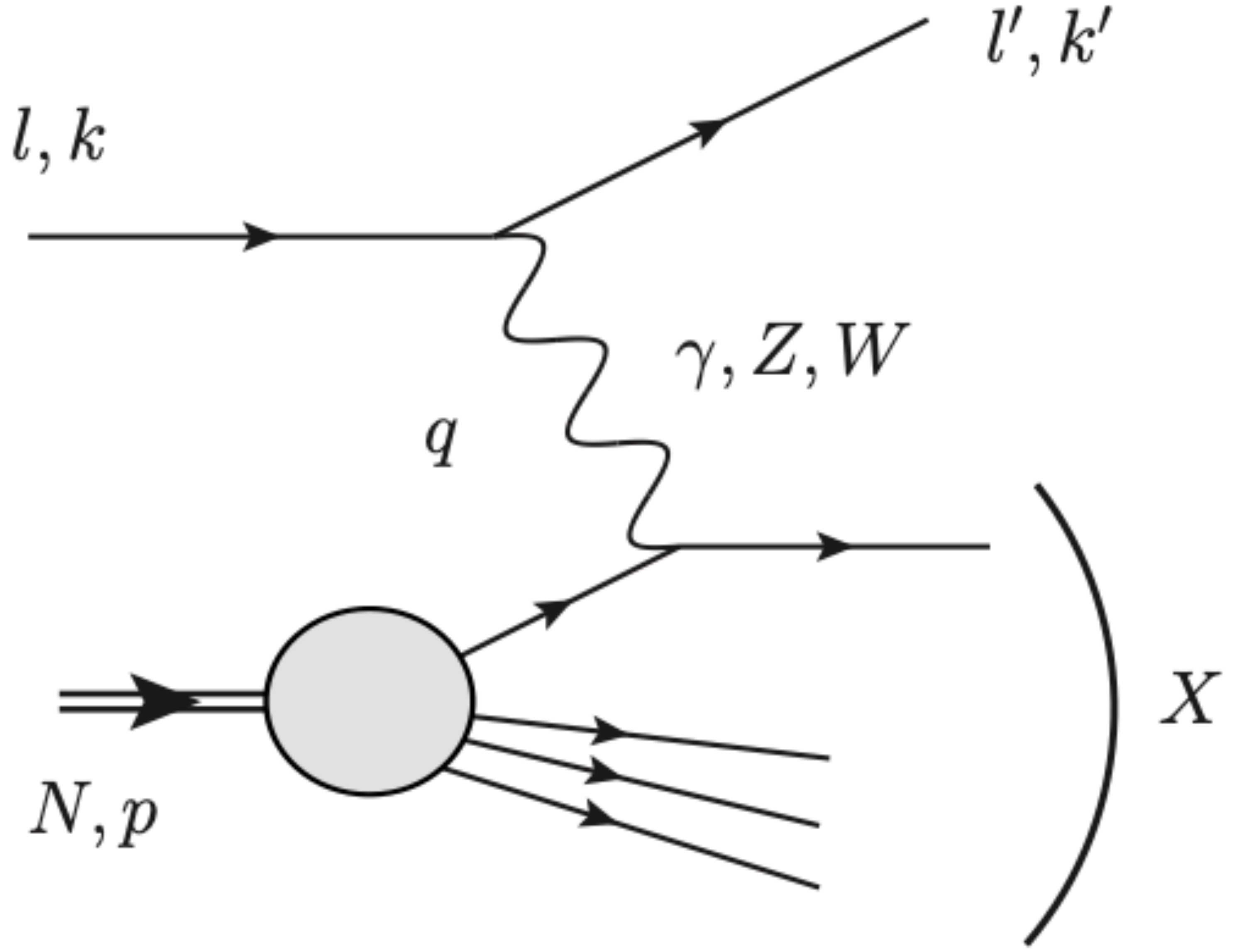
- Only necessary to provide a few standard elements:
  - List of Born and Real partonic processes
  - Born phase space
  - Born squared amplitudes, spin- and color-correlated amplitudes
  - Real squared amplitude
  - Finite part of virtual corrections
- The code handles the NLO calculation (FKS subtraction scheme [Frixione, Kunszt, Signer(1996)]), and the generation of the hardest radiation.
- Events written into the Les Houches interface, to be treated by the LO PS.

Matching higher order corrections to PS

DIS in the POWHEG-BOX

DIS kinematics

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



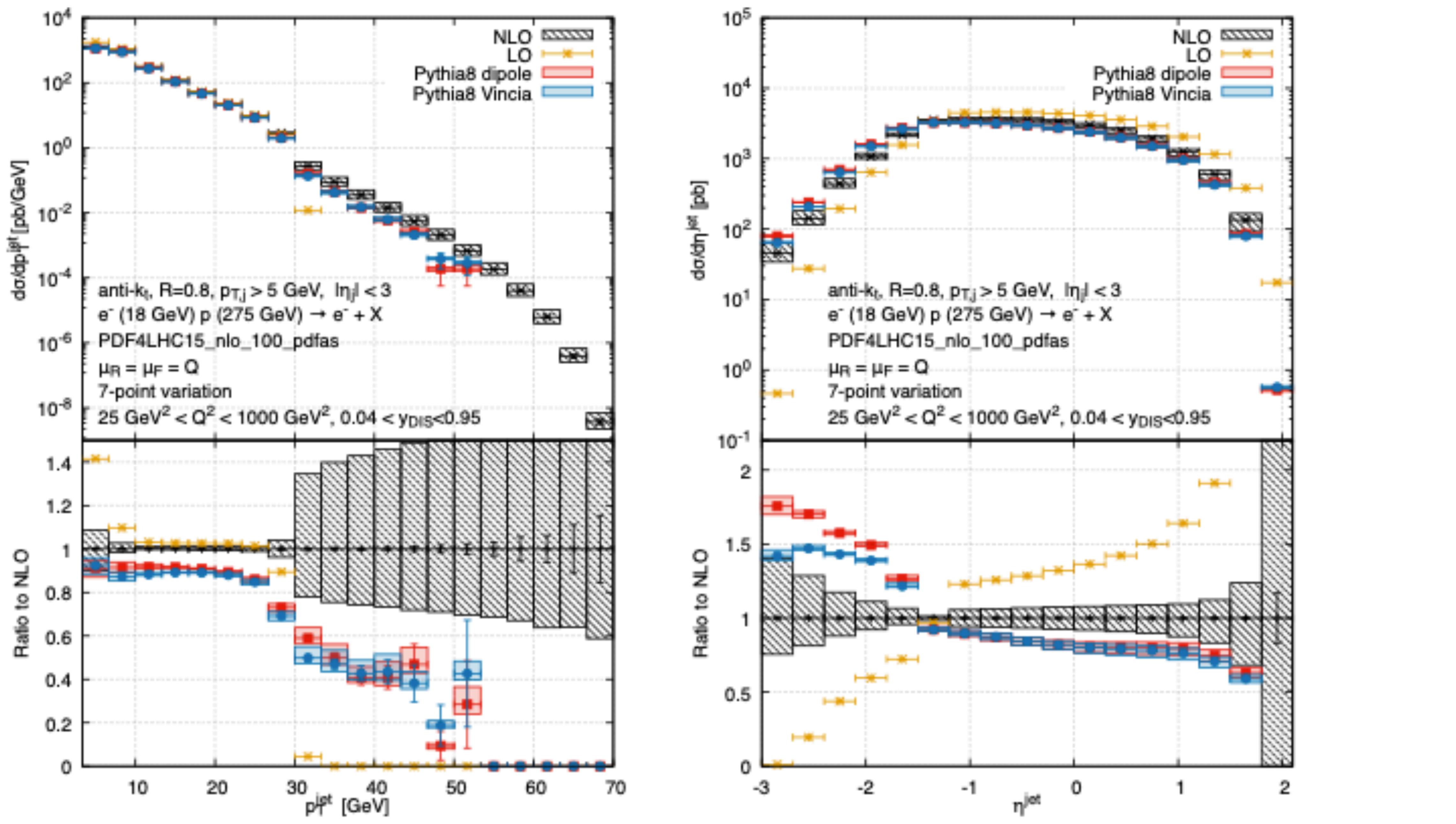
Kinematical invariants

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

NLO + PS implementation of DIS in POWHEG-BOX

Banfi, Ferraro Ravasio, Jäger, Karlberg, Reichenbach, Zanderighi (2024)

(massive quark & lepton) Buonocore, Limatola, Nason, Tramontano (2024)



- Modified mappings for radiation phase-space $d\Phi^{\alpha}_{n+1} = d\overline{\Phi}_n d\Phi^{\alpha}_{\mathrm{rad}'}$ allowing to preserve DIS variables x_B, Q^2, y

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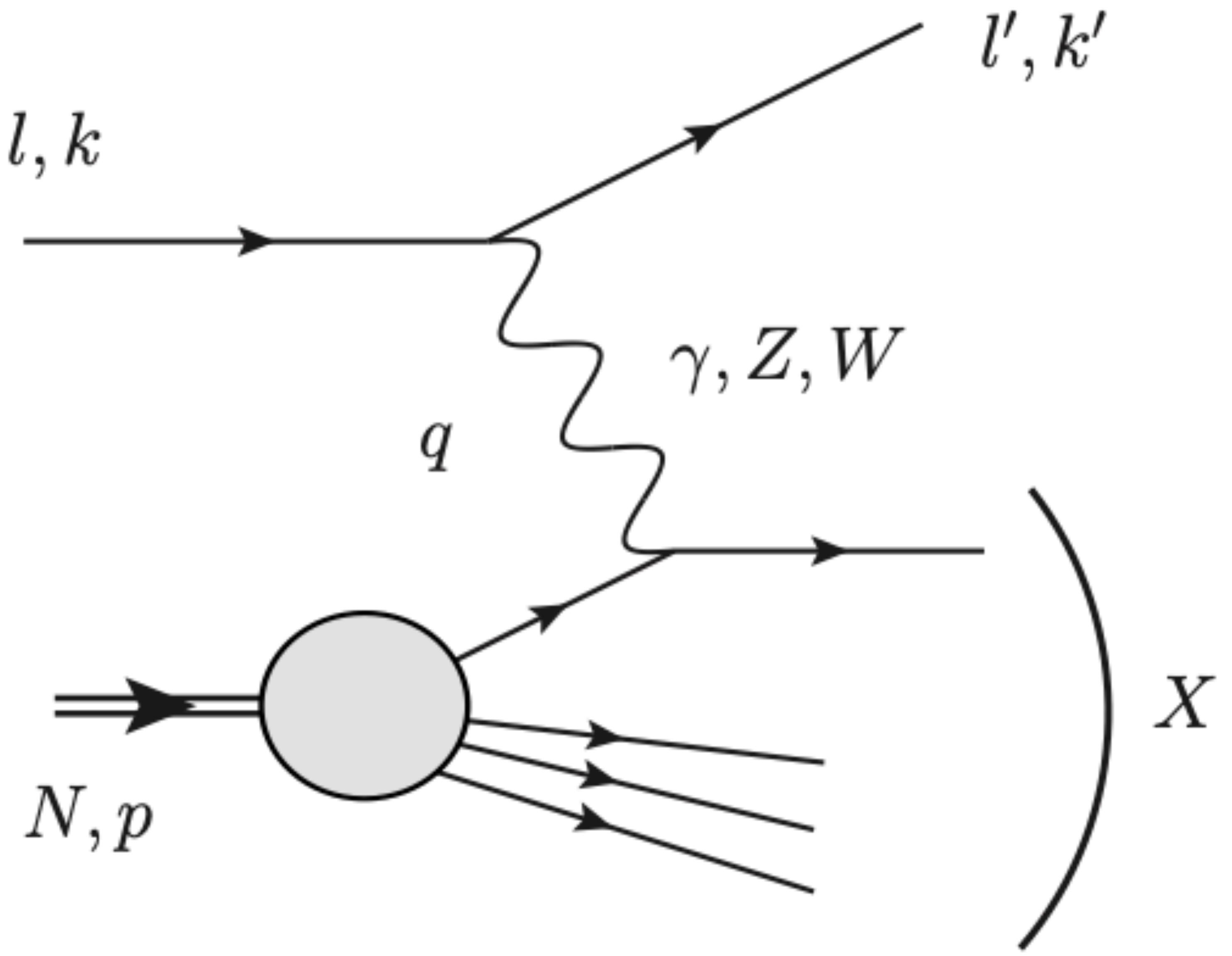
DIS kinematics

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



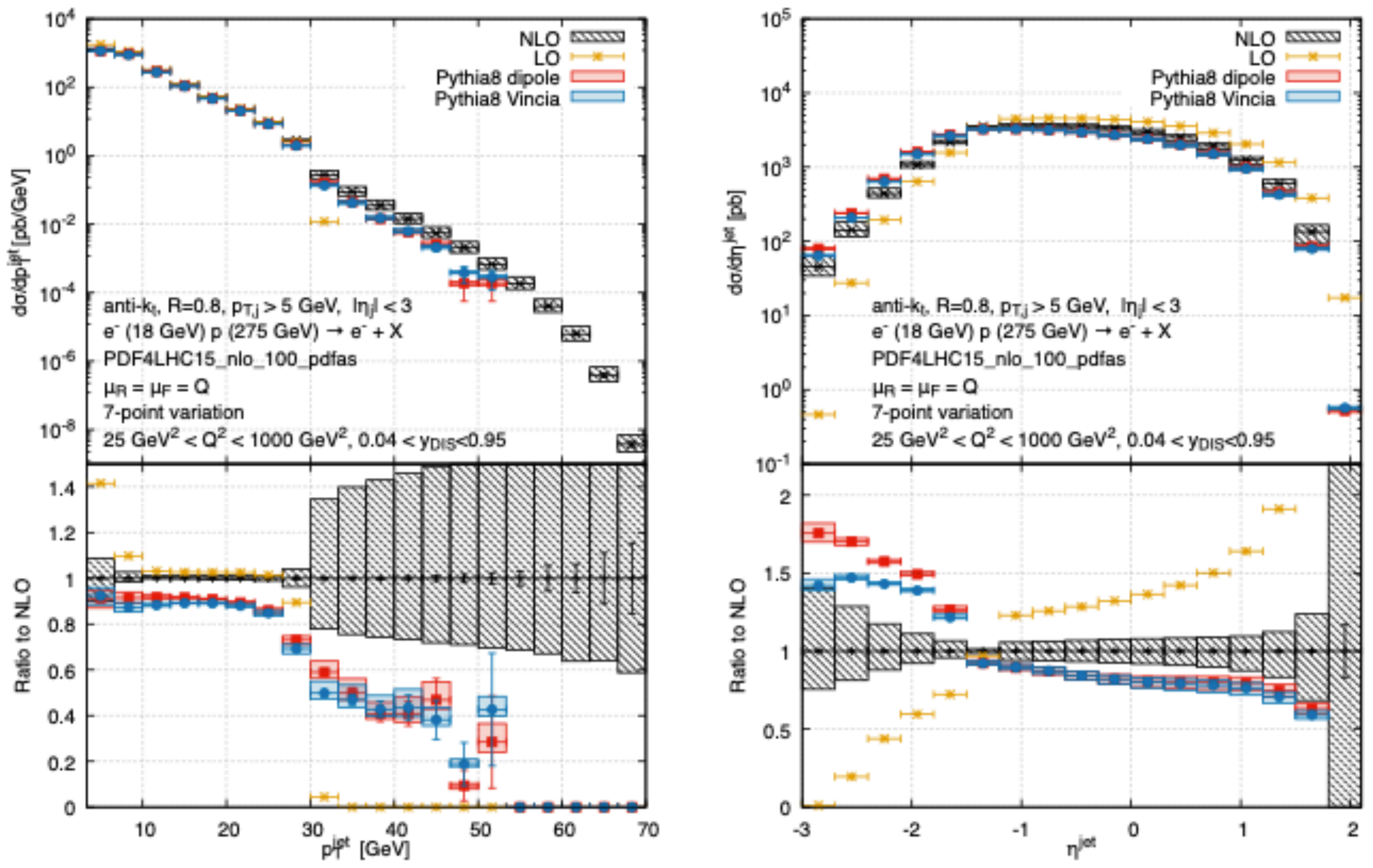
Polarized scattering

$$\Delta\sigma \equiv \frac{1}{2}(\sigma^{++} - \sigma^{+-})$$

NLO + PS implementation of DIS in POWHEG-BOX

Banfi, Ferraro Ravasio, Jäger, Karlberg, Reichenbach, Zanderighi (2024)

(massive quark & lepton) Buonocore, Limatola, Nason, Tramontano (2024)



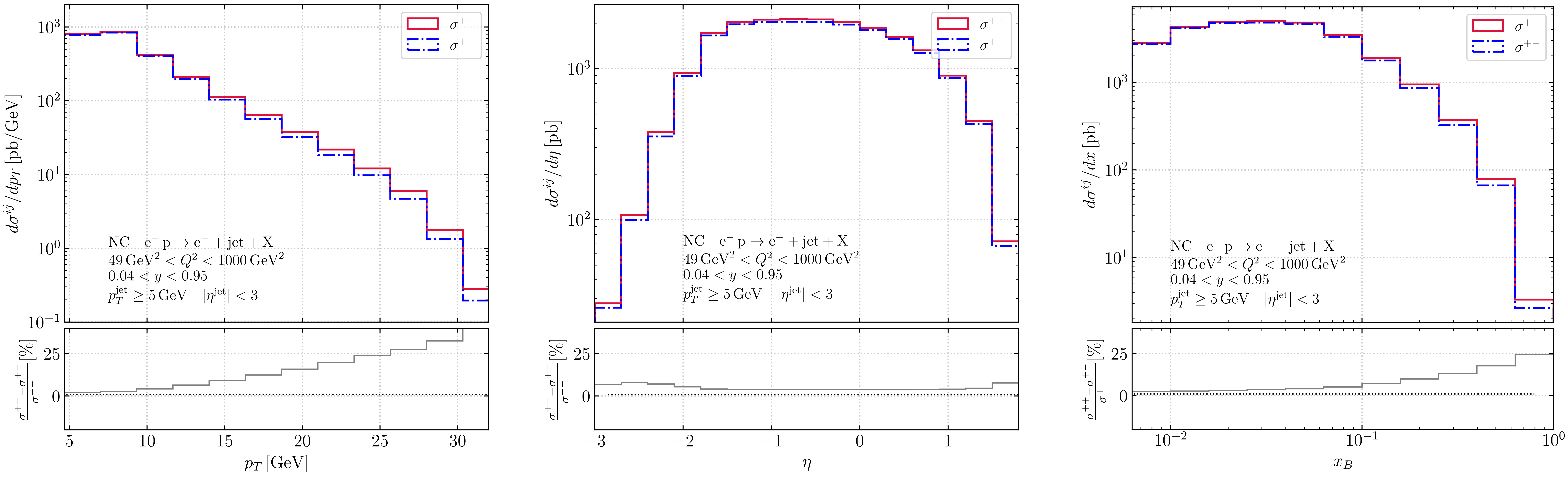
- Modified mappings for radiation phase-space $d\Phi^{\alpha}_{n+1} = d\overline{\Phi}_n \, d\Phi^{\alpha}_{\text{rad}}$, allowing to preserve DIS variables x_B, Q^2, y

Matching higher order corrections to PS

POLARIZED DIS in the POWHEG-BOX

$\Delta\sigma \equiv \frac{1}{2}\left[\sigma^{++} - \sigma^{+-}\right] \Rightarrow$ Why not generating events for $\boldsymbol{\sigma}^{++}$ and $\boldsymbol{\sigma}^{+-}$ separately?

- Large cancellation between helicity configurations



Matching higher order corrections to PS

POLARIZED DIS in the POWHEG-BOX

$\Delta\sigma \equiv \frac{1}{2}\left[\sigma^{++} - \sigma^{+-}\right]$ $\Rightarrow$Why not generating events for σ^{++} and σ^{+-} separately?

- Large cancellation between helicity configurations
- Use of non-standard "fixed-helicity" PDFs

$$\sigma^{++} = \sum_a \left(f_a^+ \otimes \hat{\sigma}_a^{++} + f_a^- \otimes \hat{\sigma}_a^{+-}\right)$$

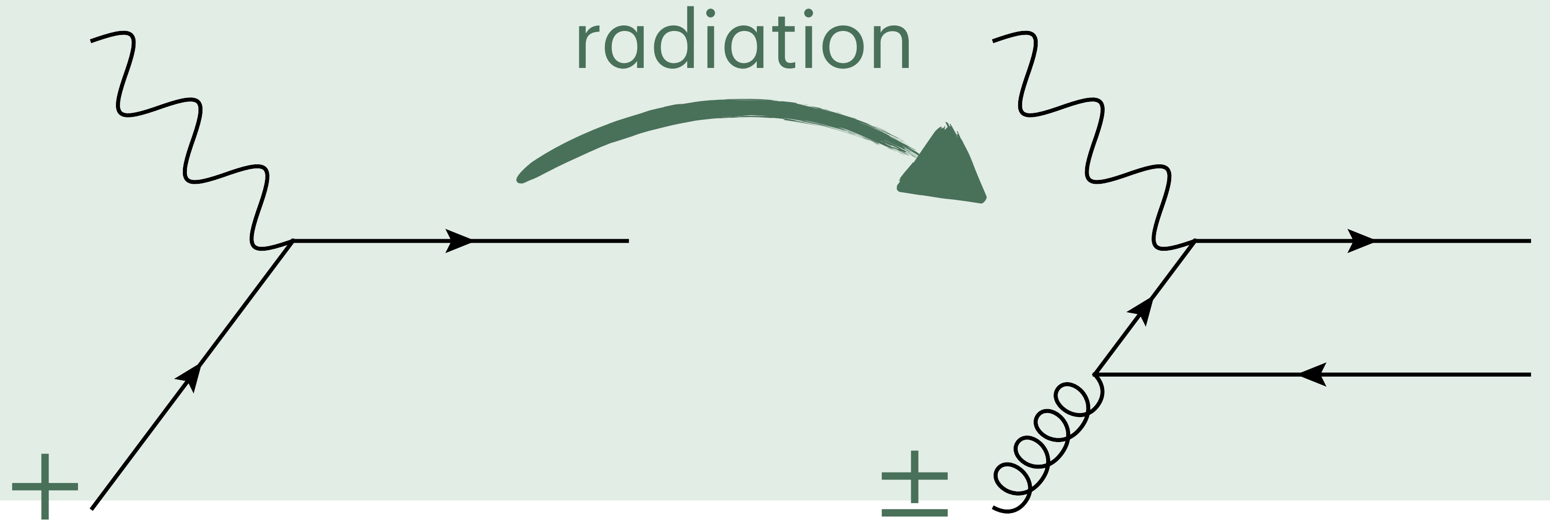
$$f_a^{\pm} = \frac{1}{2}\left(f_a \pm \Delta f_a\right)$$

Matching higher order corrections to PS

POLARIZED DIS in the POWHEG-BOX

$\Delta\sigma \equiv \frac{1}{2}\left[\sigma^{++} - \sigma^{+-}\right]$ $\Rightarrow$ Why not generating events for $\boldsymbol{\sigma}^{++}$ and $\boldsymbol{\sigma}^{+-}$ separately?

- Large cancellation between helicity configurations
- Use of non-standard "fixed-helicity" PDFs
- Potential changes in the helicity of the incoming parton



Instead, use

$$\sigma^{+\pm} = \sum_a \left(f_a \otimes \hat{\sigma}_a \pm \Delta f_a \otimes \Delta\hat{\sigma}_a\right)$$

Matching higher order corrections to PS

POLARIZED DIS in the POWHEG-BOX

IB, Jäger *JHEP* 07 (2024) 177

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

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

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

Modifications to handle processes with polarized initial-state hadrons

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

de Florian, Frixione, Signer, Vogelsang (1999)

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

$$dM \rightarrow \Delta M$$

Matching higher order corrections to PS

POLARIZED DIS in the ~~P~~OWHEG-BOX

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

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

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

Modifications to handle processes with polarized initial-state hadrons

- ☑ Polarized Matrix elements & PDFs
- ☑ NLO Subtraction scheme → implementation of polarized FKS subtraction
- ☑ Handle negative-valued Born cross sections. Positive-weight events not guaranteed. Positive- and negative-weight events generated according to

$$n_+ = \frac{\sigma(+)}{\sigma(+) + |\sigma(-)|} \qquad n_- = \frac{\sigma(-)}{\sigma(+) + |\sigma(-)|}, \text{ with } w_+ = (\sigma(+) + |\sigma(-)|),\ w_- = -(\sigma(+) + |\sigma(-)|)$$

Matching higher order corrections to PS

POLARIZED DIS in the POWHEG-BOX

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

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

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

Modifications to handle processes with polarized initial-state hadrons

- [x] Polarized Matrix elements & PDFs
- [x] NLO Subtraction scheme → implementation of polarized FKS subtraction
- [x] Handle negative-valued Born cross sections. Positive-weight events not guaranteed.
- [ ] ~~Polarized~~ Unpolarized Parton shower, but dominant logarithmic contributions correctly reproduced:
    - Since $\Delta P_{qq} = P_{qq}$, emission of gluons from an initial-state quark line described correctly.
    - Since $\Delta P_{ij}(z \to 1) = P_{ij}(z \to 1)$, Initial-state soft-collinear behavior correctly captured.
    - No polarization effects for final state-radiation.

EIC Phenomenology

Phenomenology

Single jet production in the EIC (NC & CC)

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

- $$E_e = 18\,\text{GeV} \qquad \text{and} \qquad E_p = 275\,\text{GeV}$$
  $$(\sqrt{s} = 140\,\text{GeV})$$
- $$49\,\text{GeV}^2 \leq Q^2 \leq 1000\,\text{GeV}^2 \qquad \text{and} \qquad 0.04 \leq y \leq 0.95$$
- $$5\,\text{GeV} \leq p_T^{\text{jet}} \qquad \text{and} \qquad |\eta^{\text{jet}}| < 3$$
- 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-point scale variation

Phenomenology

Single jet production in NC DIS

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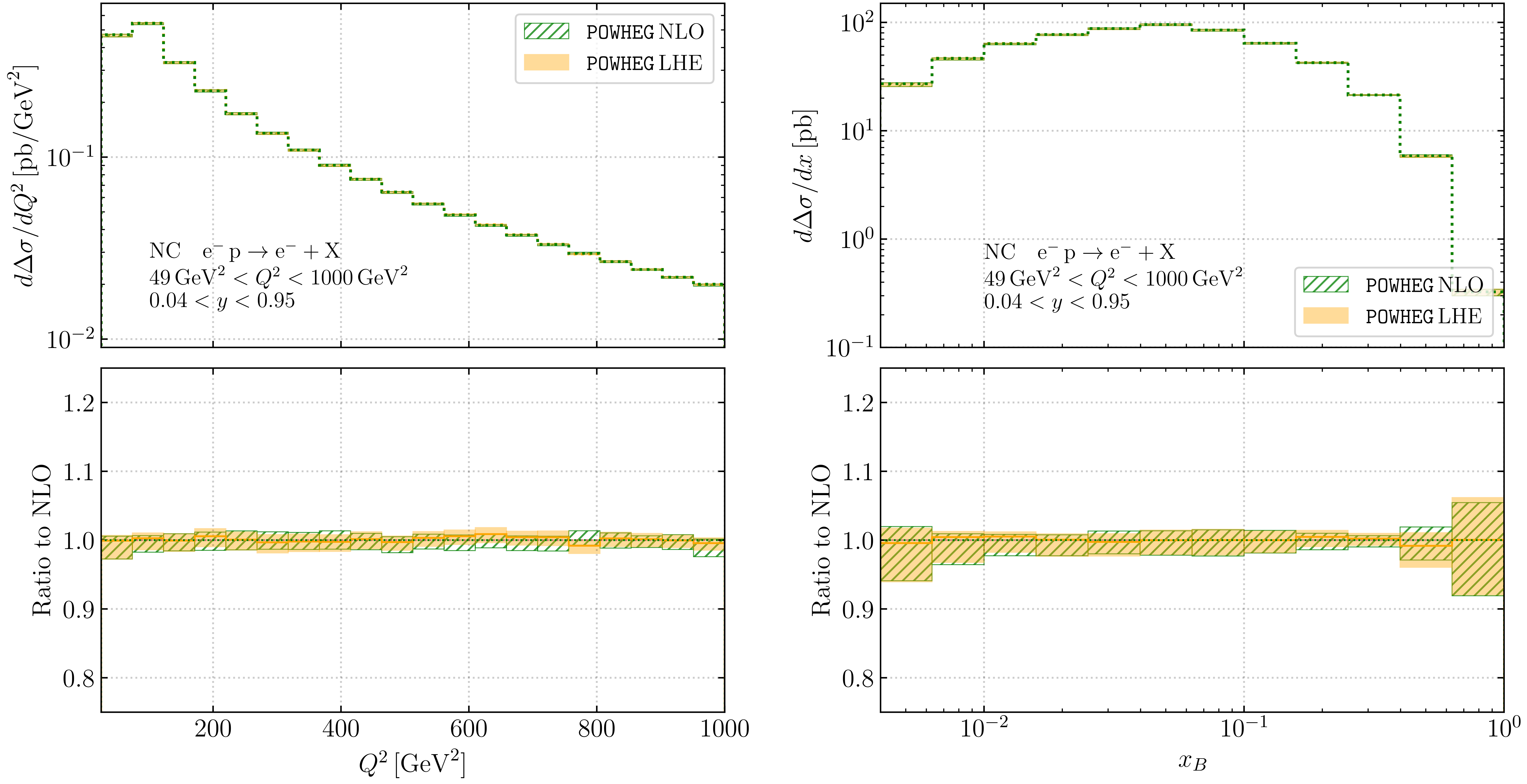

Some checks:

Cross section differential in Q^2, x_B
(No cuts on the outgoing partons)

☑ NLO accuracy for observables inclusive in the additional radiation

Phenomenology

Single jet production in NC DIS

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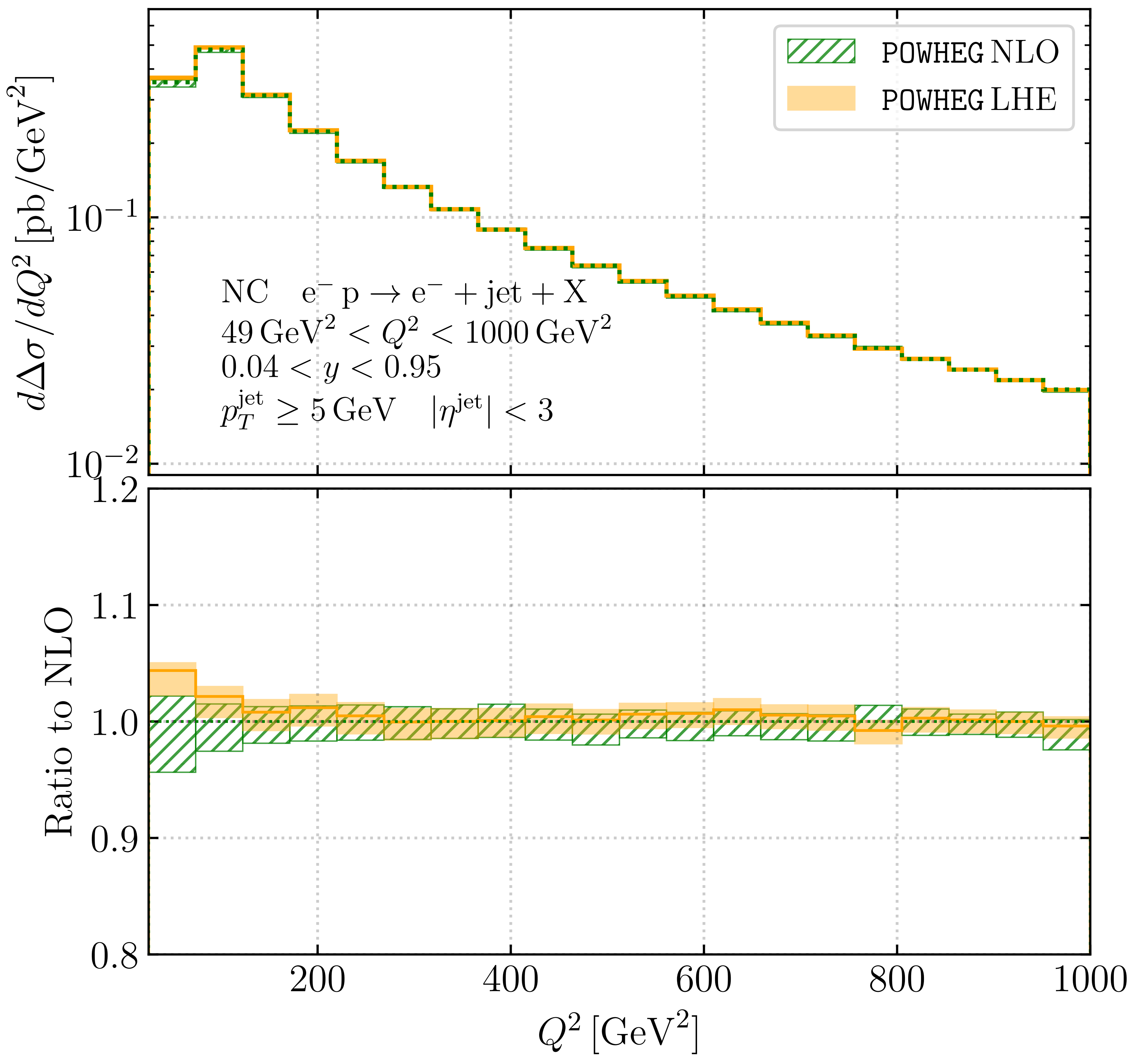

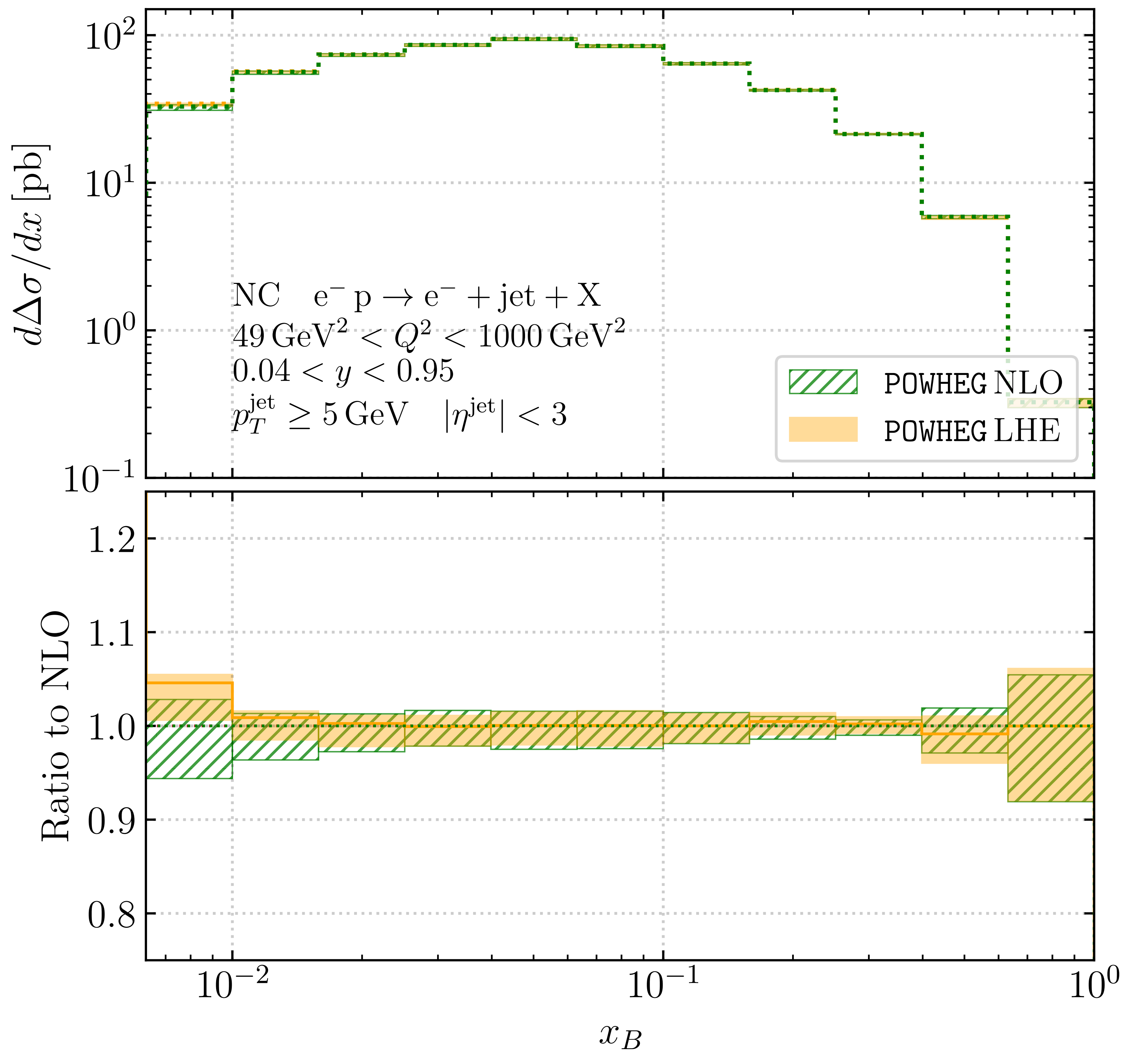

Some checks:

Cross section differential in $p_T^{\text{jet}}, \eta^{\text{jet}}$ for jet production

☑ POWHEG events (LHE) distributed according to the NLO cross section in regions where enhanced-logs not expected

Phenomenology

Single jet production in NC DIS

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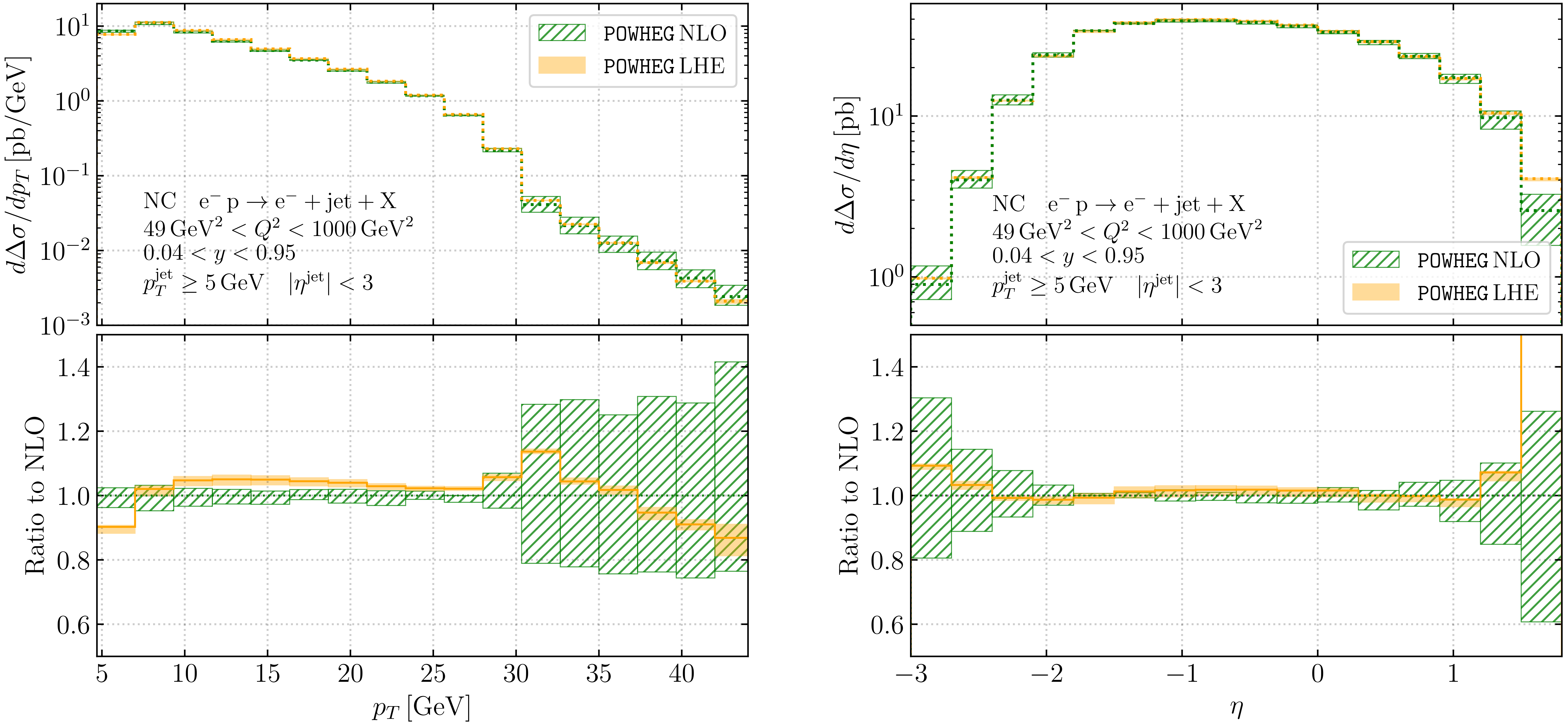

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Cross section differential in $p_T^{\mathrm{jet}}, \eta^{\mathrm{jet}}$ for jet production

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Phenomenology

Single jet production in NC DIS

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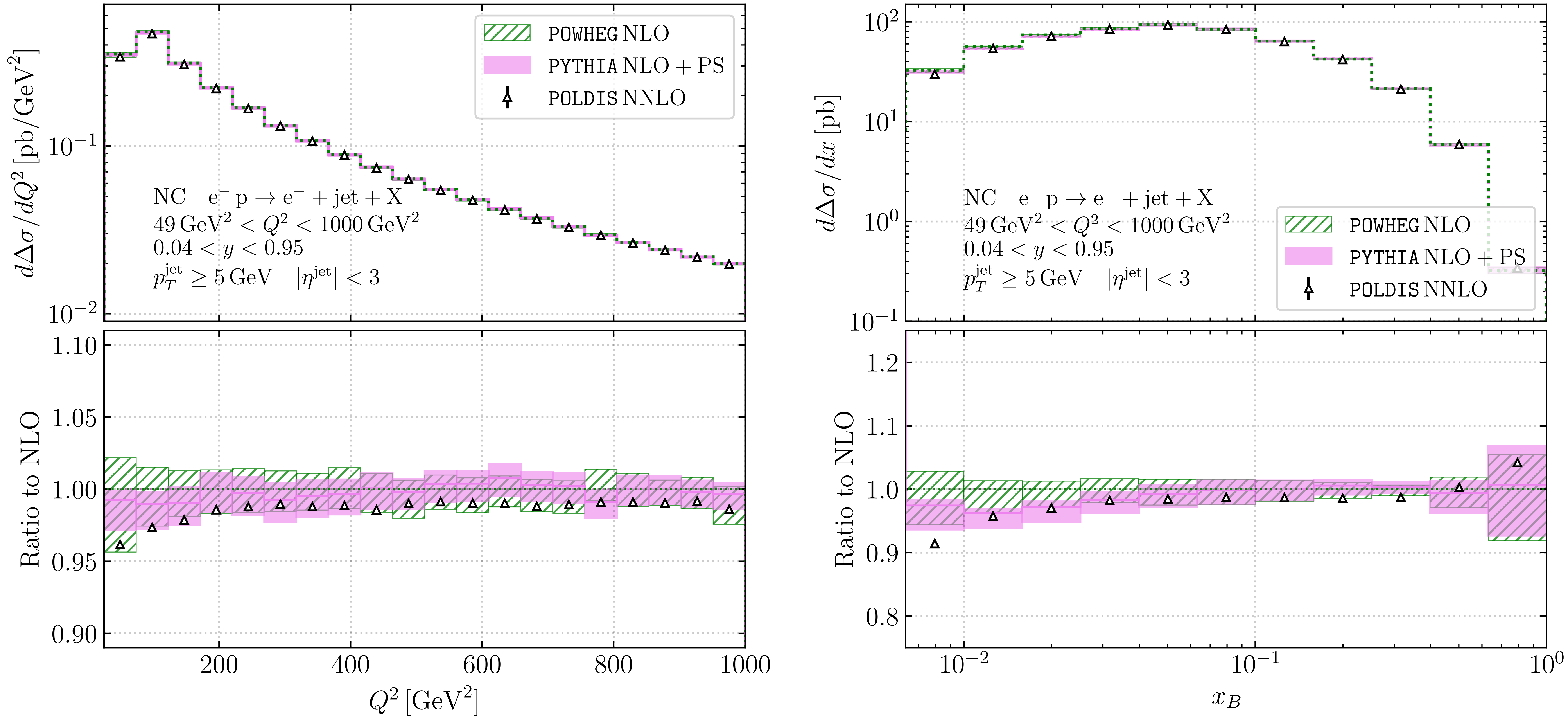

Some checks:

☑ Improvement in the agreement with NNLO results (small corrections from the PS to more inclusive observables)

Phenomenology

Single jet production in NC DIS

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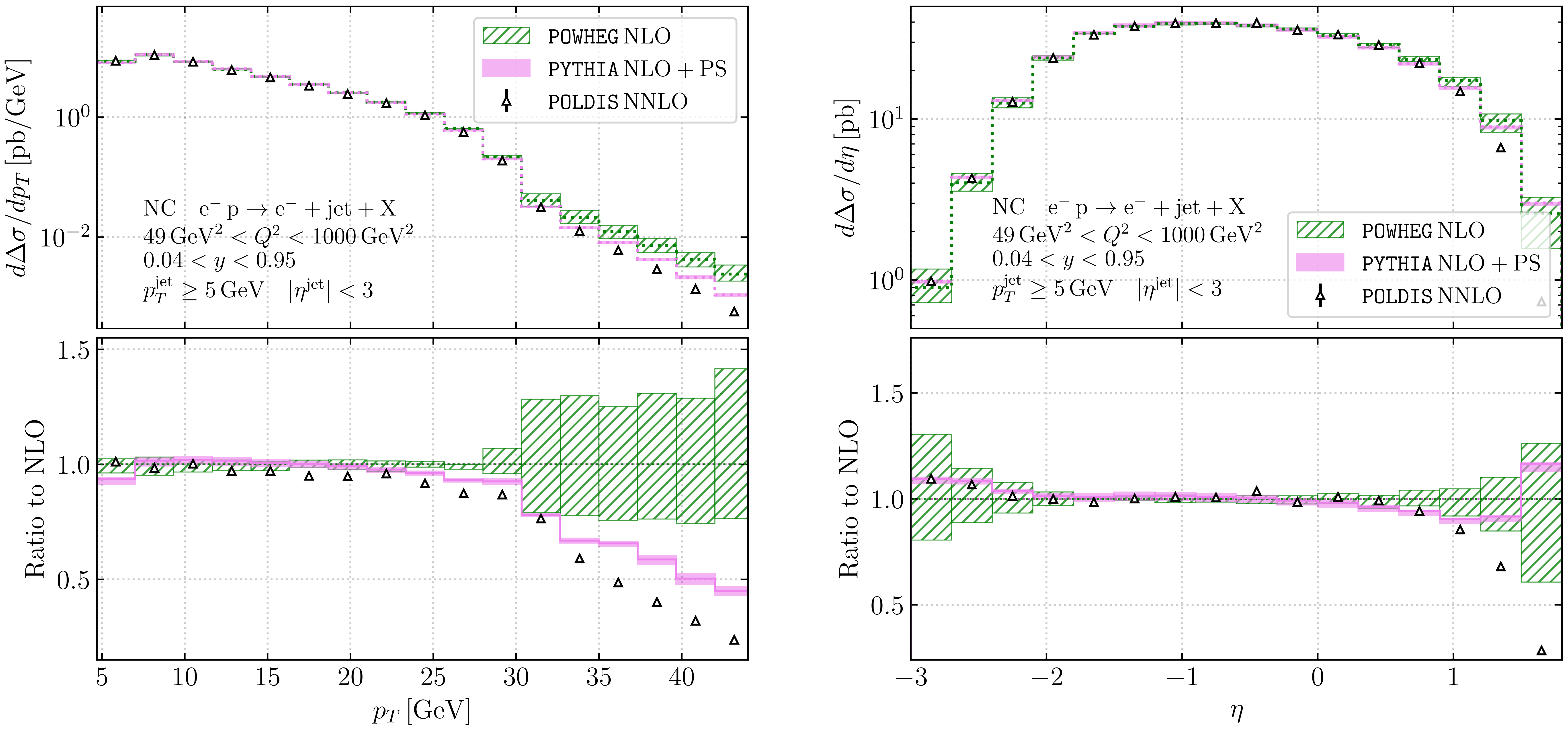
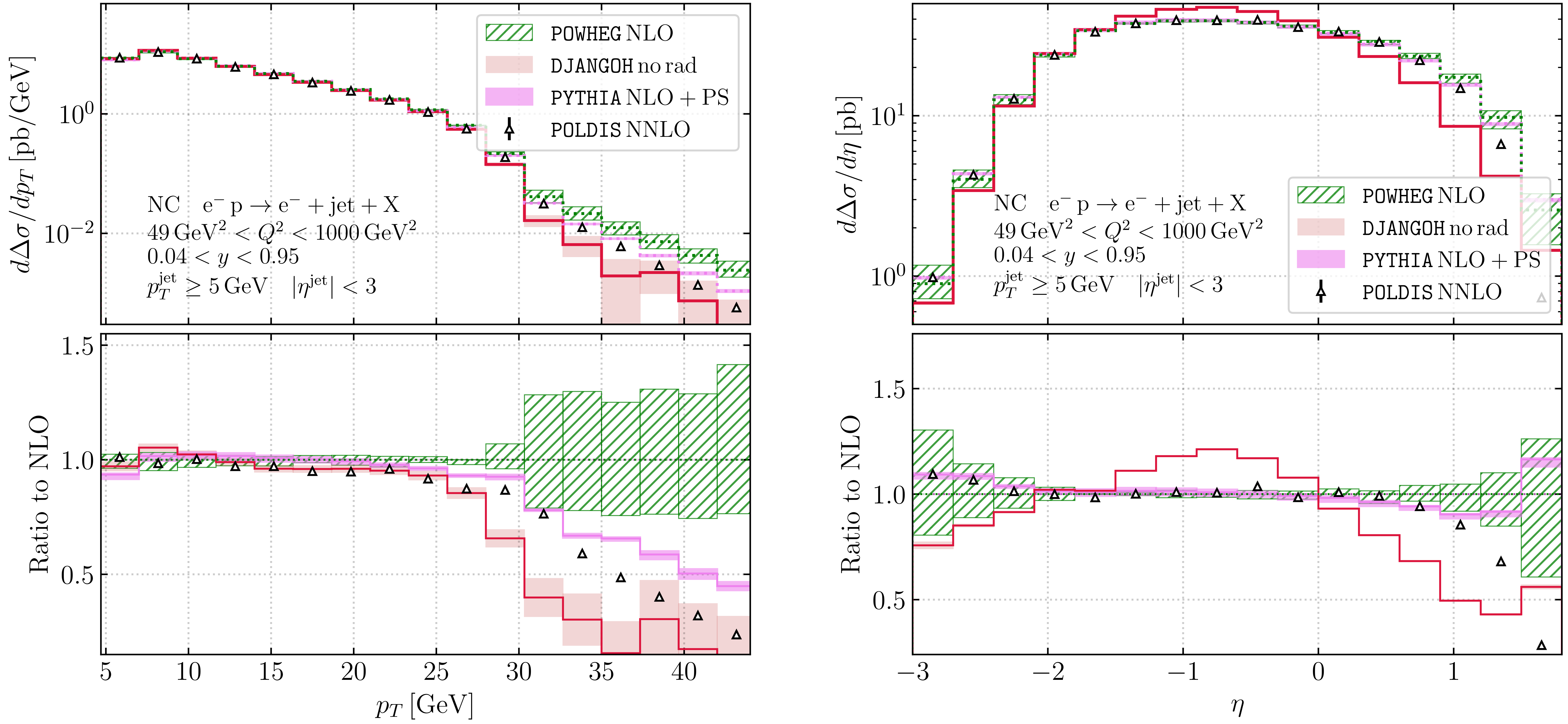


Some checks:

- Improvement in the agreement with NNLO results (sizable corrections in the kinematically-suppressed regions)

Phenomenology

Single jet production in NC DIS



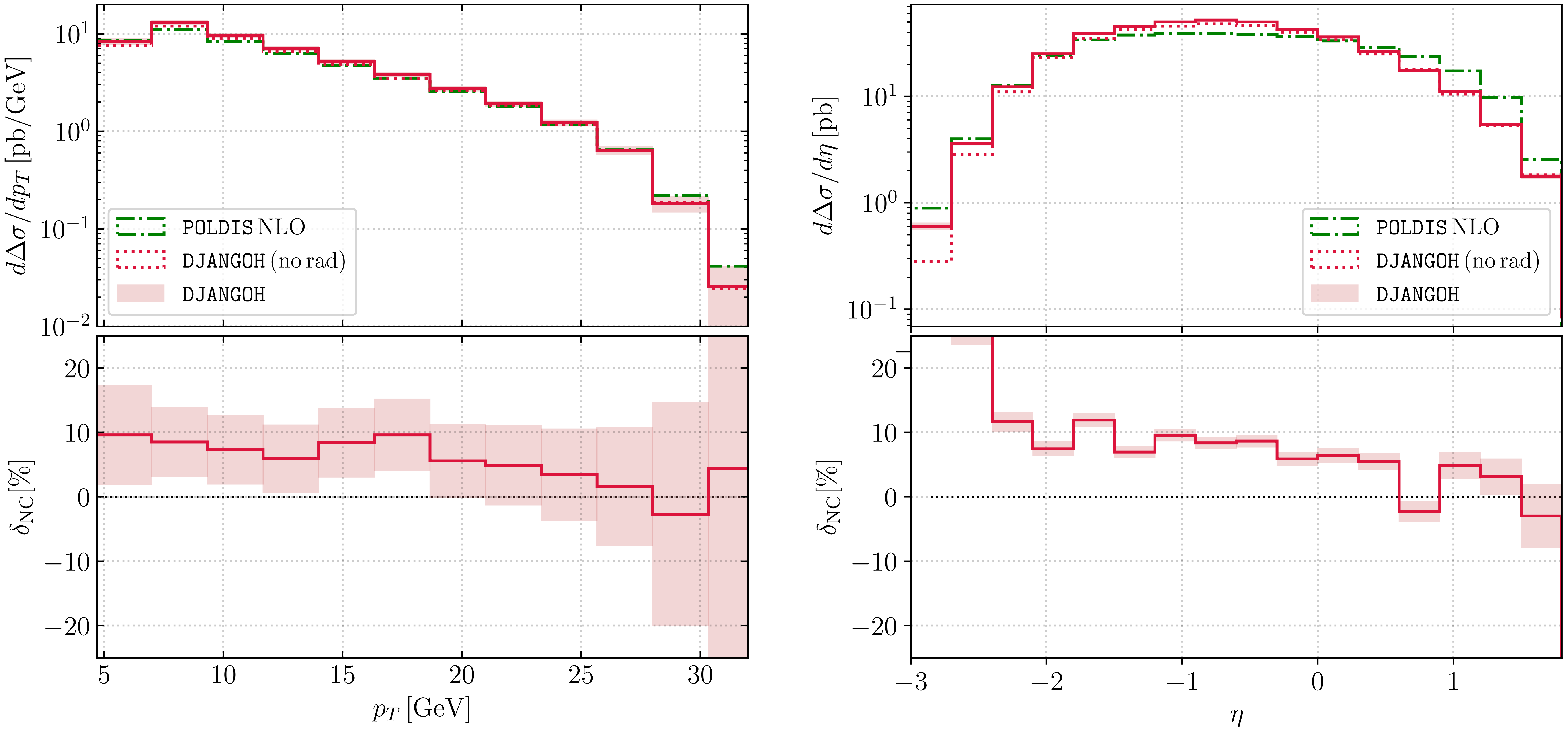
Some checks:

☑ Improvement in the agreement with NNLO results (sizable corrections in the kinematically-suppressed regions)

▶ Potentially large differences with LO codes in those regions

Phenomenology

Single jet production in NC DIS



Some checks:

☑ Improvement in the agreement with NNLO results (sizable corrections in the kinematically-suppressed regions).

No proper estimation of EW radiative corrections, which can also be sizable.

Phenomenology

Single jet production in NC DIS

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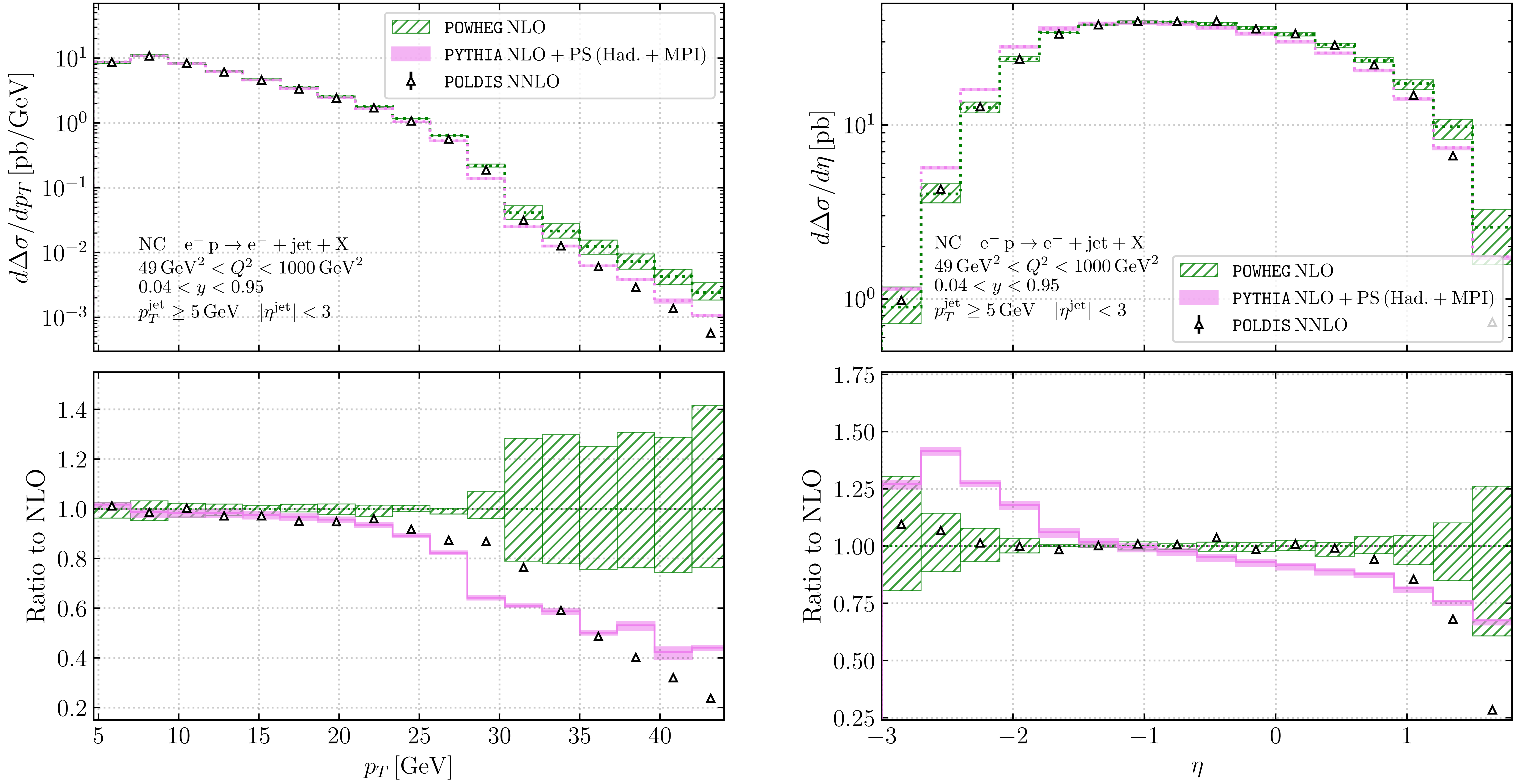


- Sizable PS effects in kinematically-suppressed regions
- Hadronization effects further suppress the high-p_T region, while low-η is enhanced

Summary

- Monte Carlo Generators for eN scattering crucial to fully realize the EIC physics program.
- The EIC spin program, in particular, will require matching of higher order corrections with parton showers that consistently account for polarized beams.

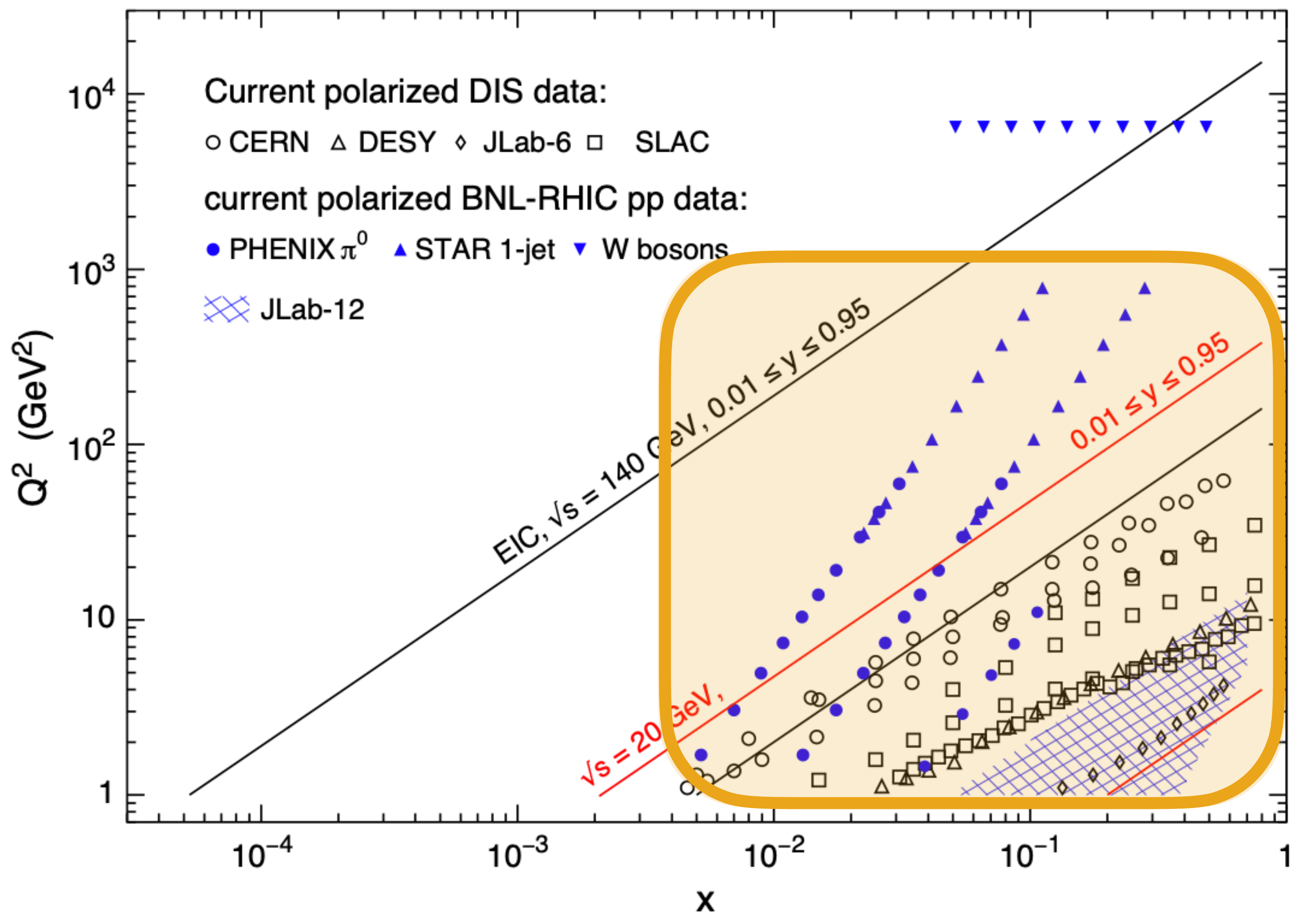
NLO+PS implementation of polarized DIS in the POWHEG-BOX
(publicly available in https://powhegbox.mib.infn.it/)

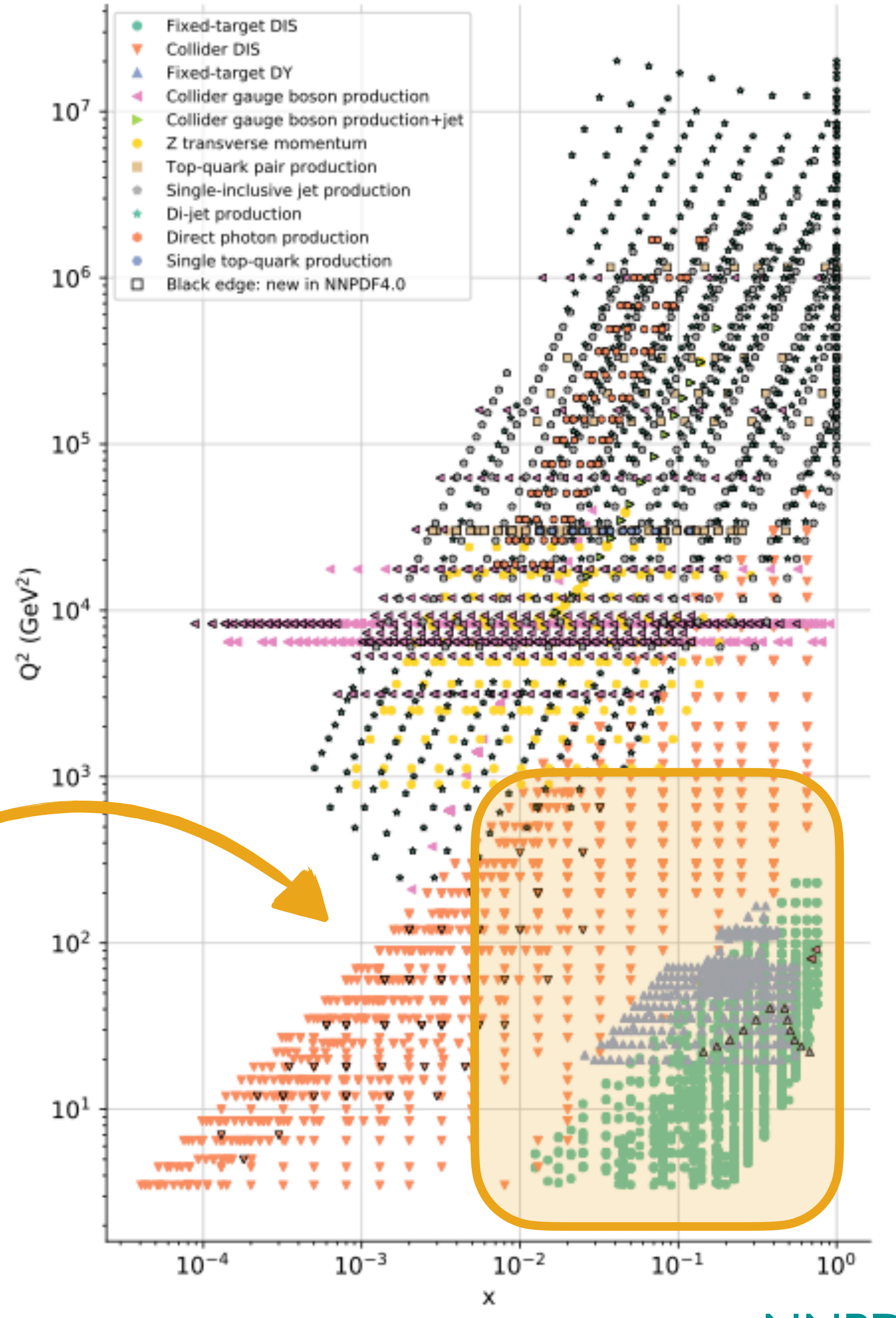
- Extended POWHEG scheme to account for the helicities of the initial-state particles.
- Events generated according to the NLO cross section, with PS effects bringing the distributions closer to the NNLO results.
- Sizable PS effects in selected regions of phase space for EIC kinematics.
- Important step towards the development of polarized parton-shower generators for EIC, with polarization included in all stages of simulation.

Thank you

Some extra slides

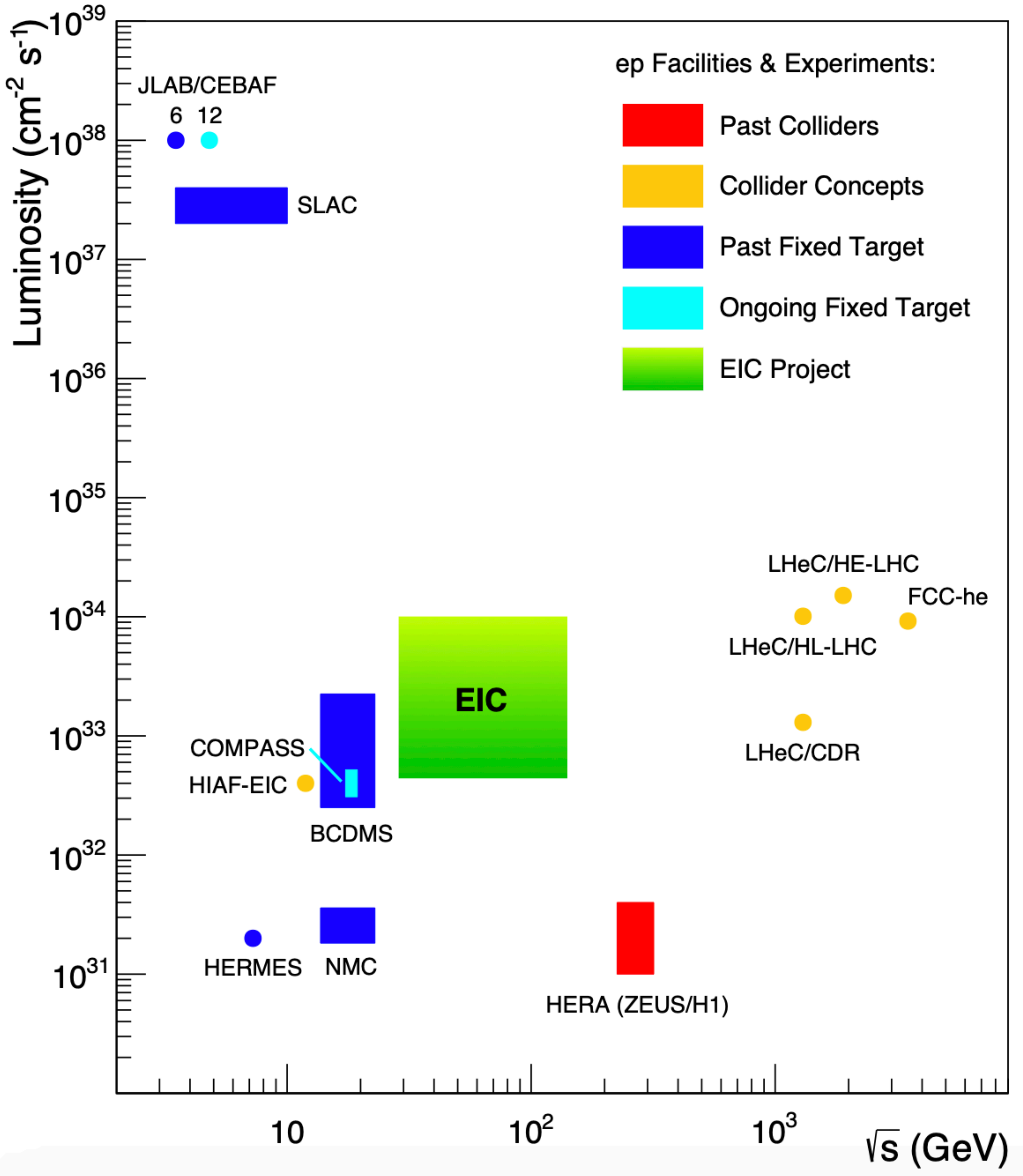
Kinematical coverage of unpolarized and polarized observables

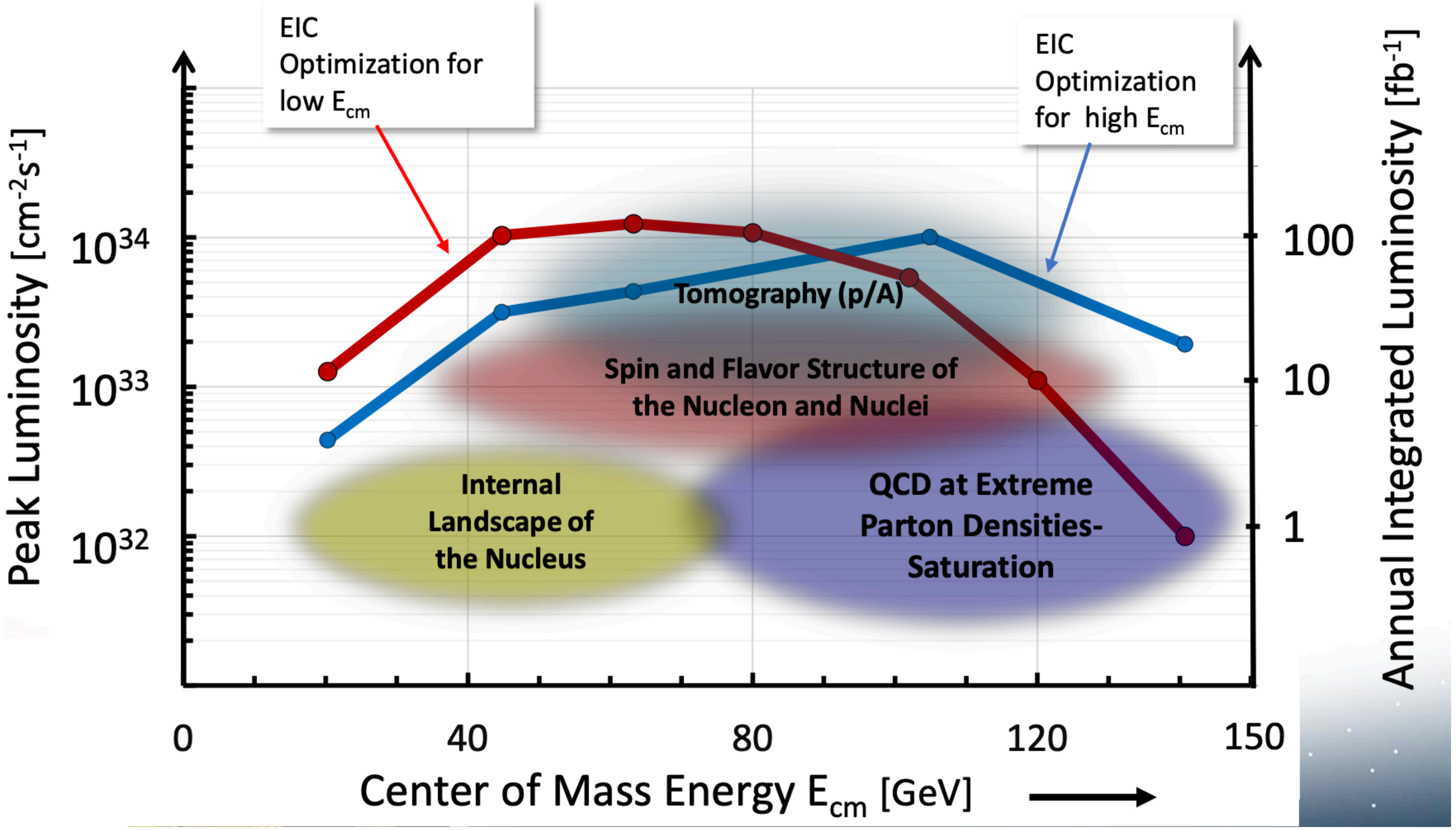




NNPDF4.0 EPJC 82 (2022)

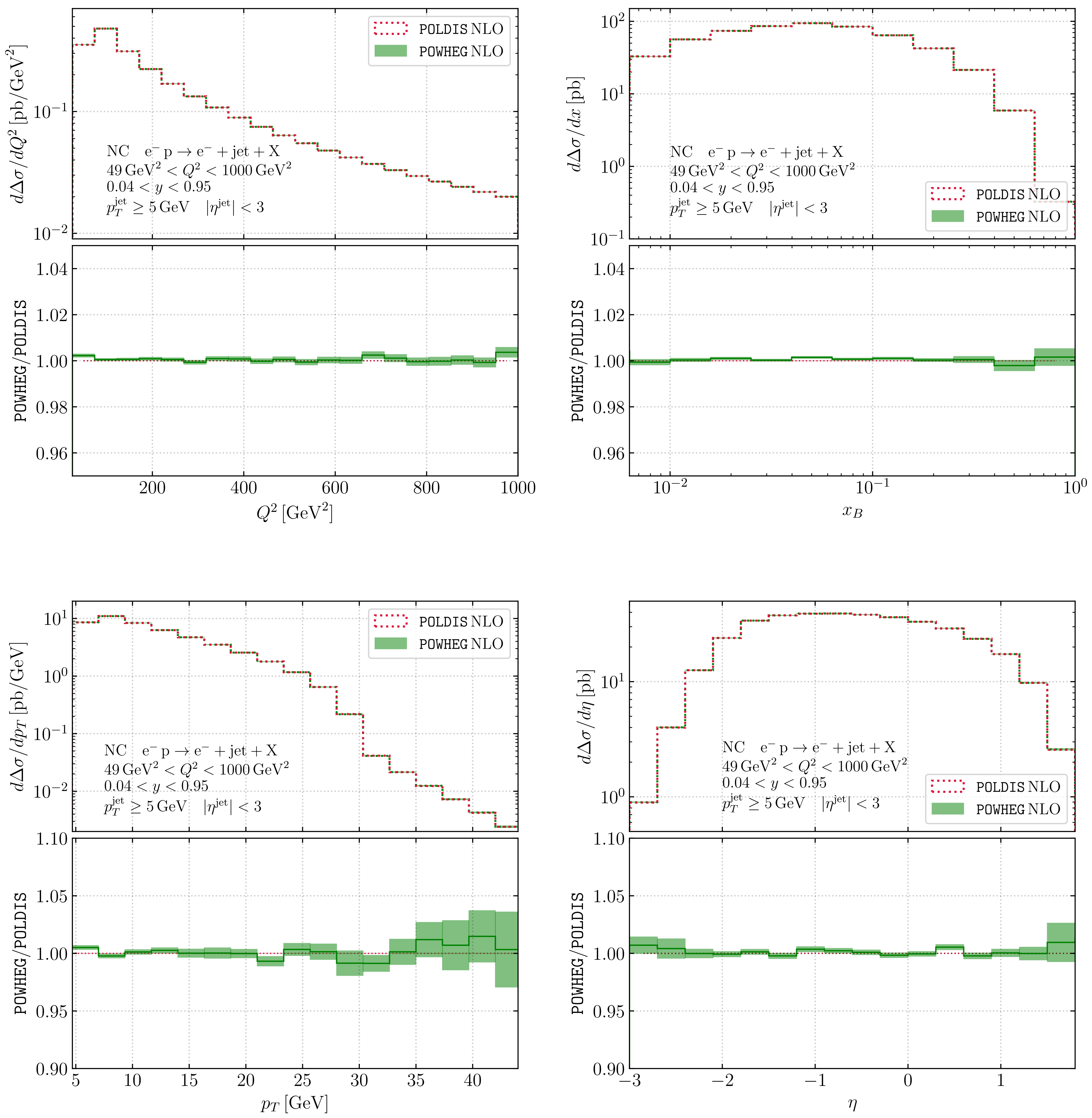
Spin physics at the future EIC



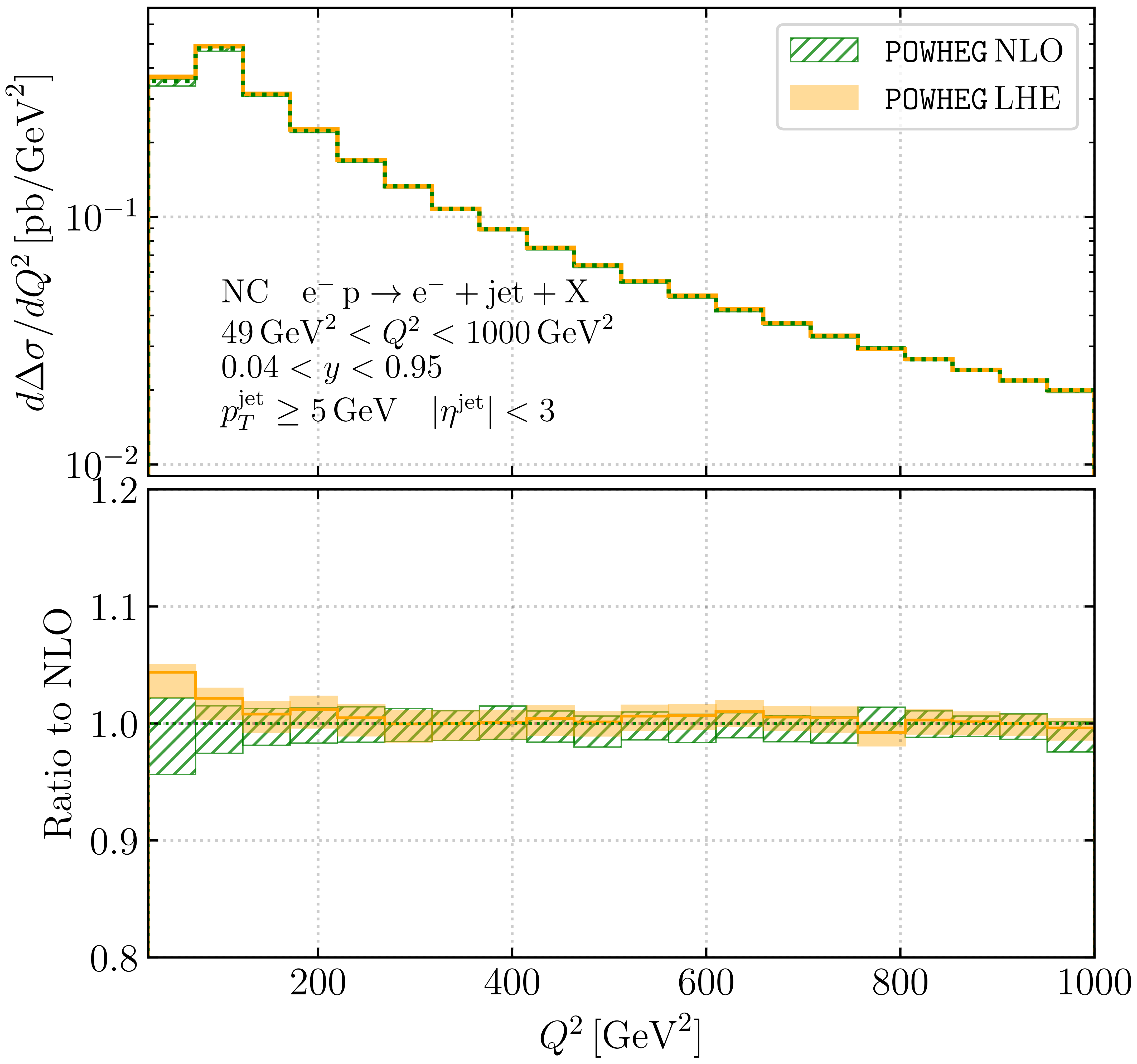


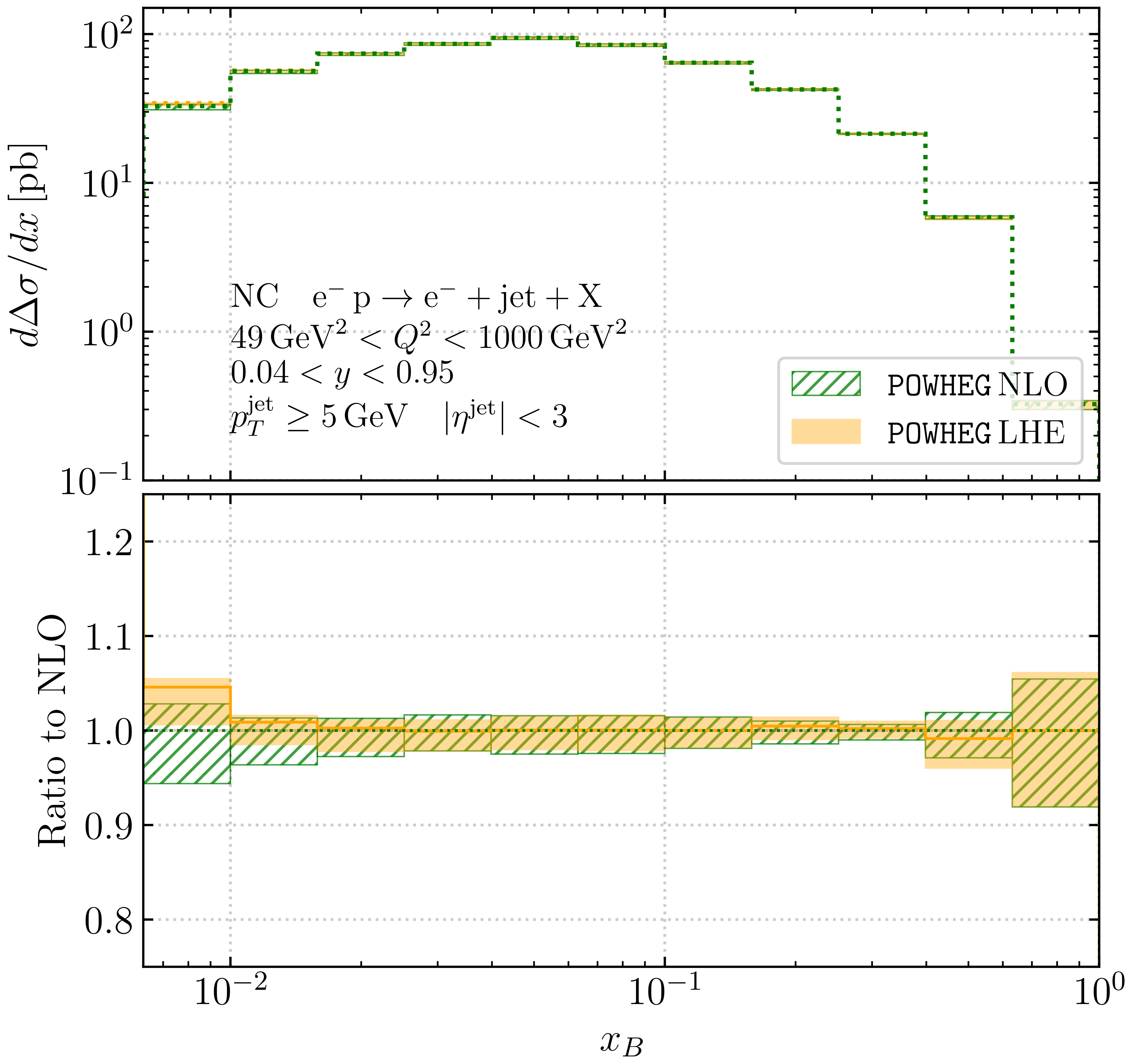
NNPDF4.0 EPJC 82 (2022)

Phenomenology

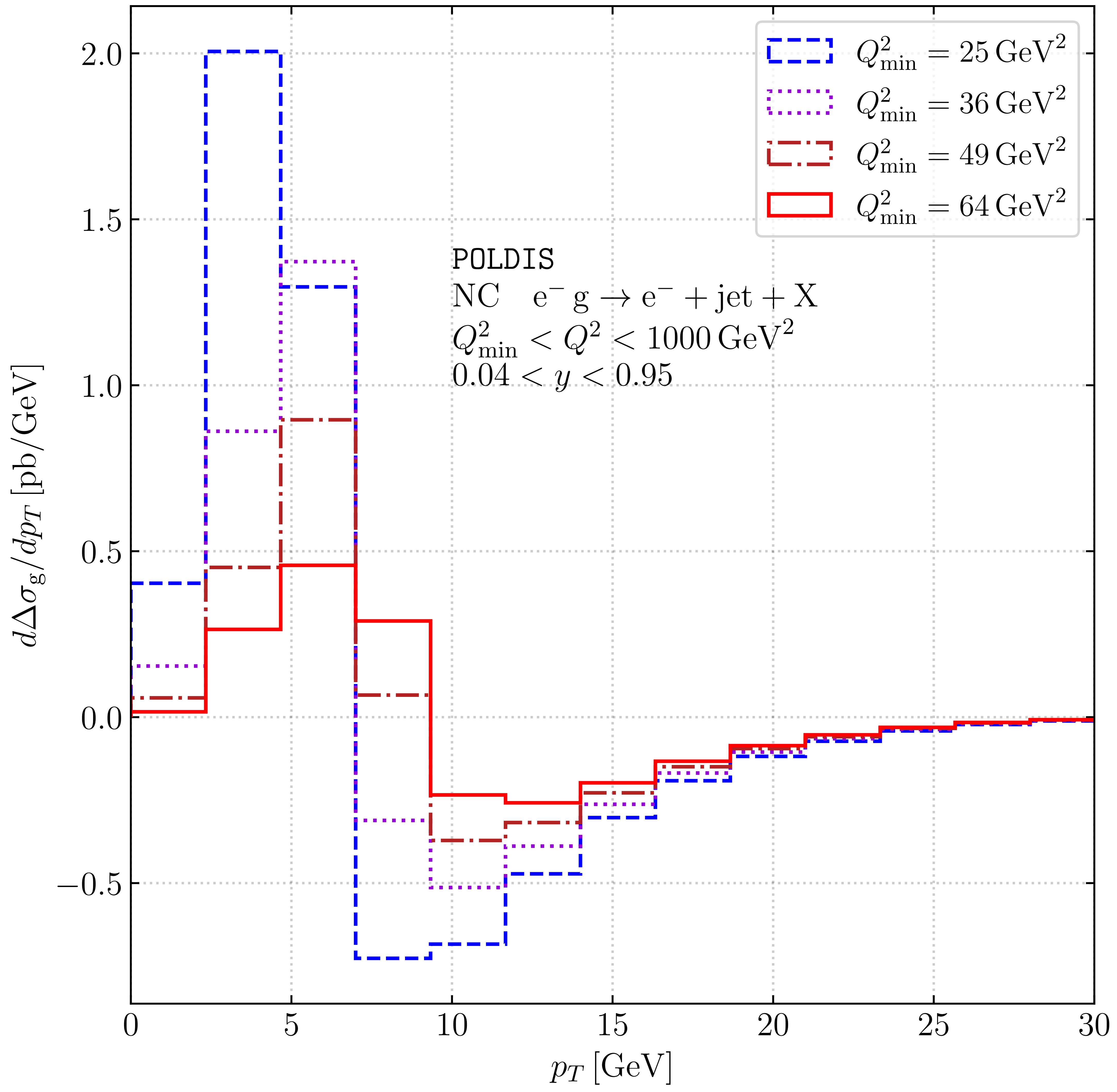


Phenomenology





Phenomenology



Phenomenology

Single jet production in CC DIS

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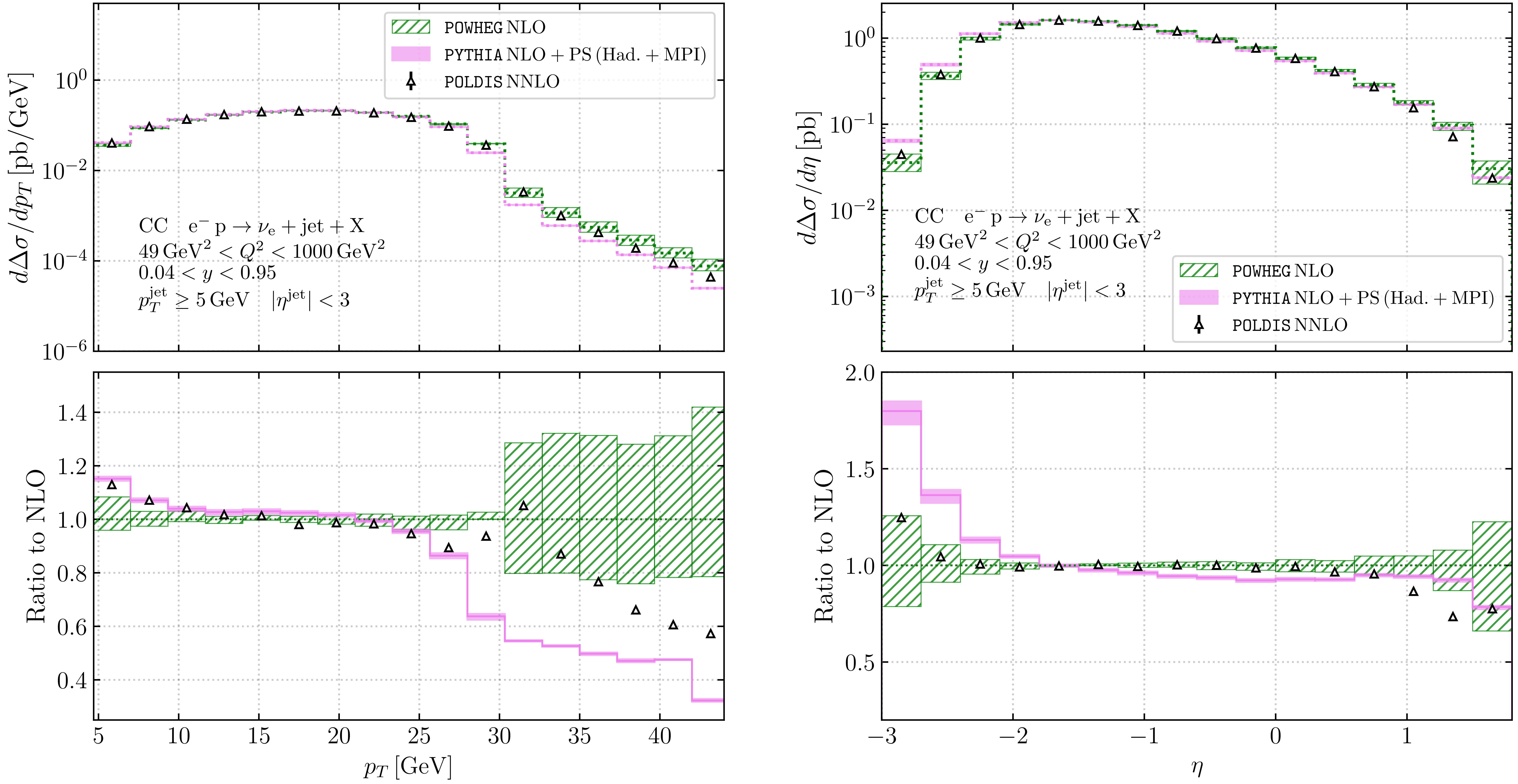

- Sizable PS effects in kinematically-suppressed regions
- Hadronization effects further suppress the high-p_T region, while low-η is enhanced

Phenomenology