# HIGHER ORDER CORRECTIONS FOR JET OBSERVABLES IN POLARIZED DIS

**Ignacio Borsa**
Tübingen University

Loops and Legs in Quantum Field Theory
Wittenberg - April 18th 2024

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

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## Introduction
Why polarized processes?

## Jet production in polarized DIS at NNLO
In collaboration with D. de Florian and I. Pedron

## NLO+PS implementation for polarized DIS
In collaboration with B. Jäger

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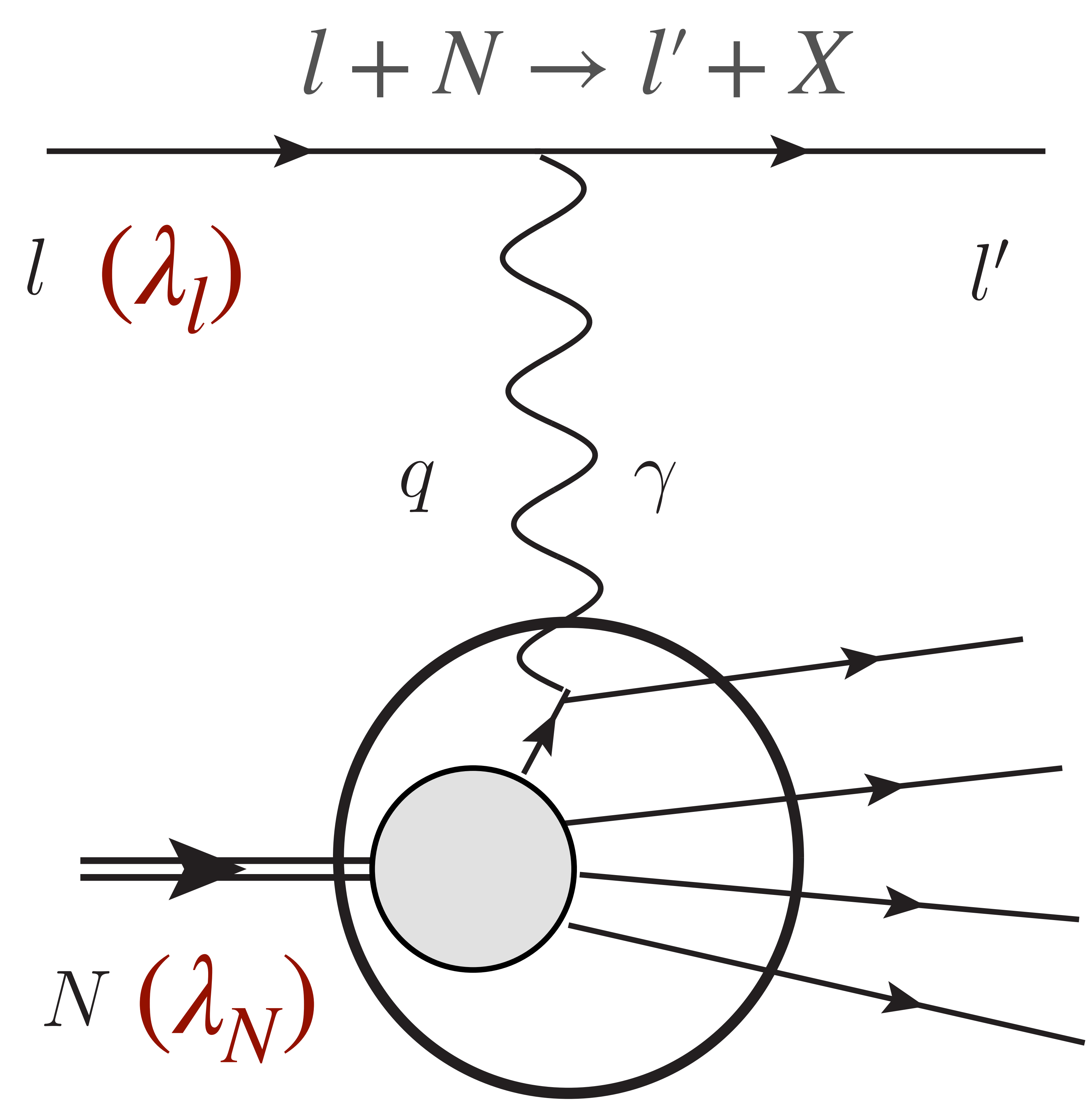
# MOTIVATION - THE PROTON'S SPIN STRUCTURE




$$\Delta\sigma \equiv \sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}$$
$$\Delta\sigma = (\sigma^{++} + \sigma^{--}) - (\sigma^{+-} + \sigma^{-+})$$

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

Helicity PDFs

$$\Delta f_a \equiv f_a^{\uparrow} - f_a^{\downarrow}$$

Polarized Partonic Cross-Section

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

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

Contribution of parton $a$ to the proton's spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + \mathscr{L}$$

$$\Delta\Sigma \sim 0.25$$

European Muon Collaboration (1989) -"Proton spin crisis"

Evidence for positive contribution from $\Delta g$

De Florian, Sassot, Stratmann, Vogelsang (2014)

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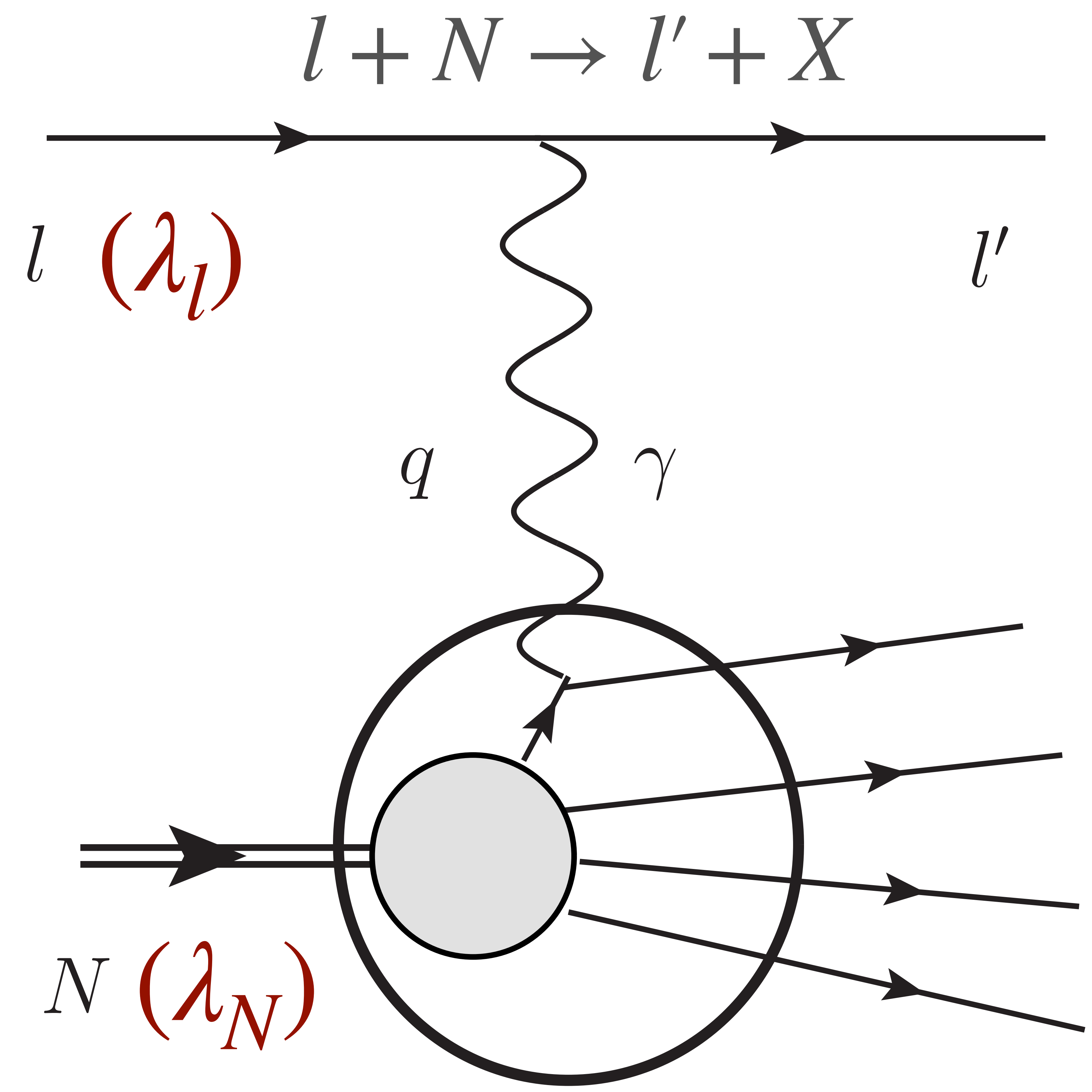


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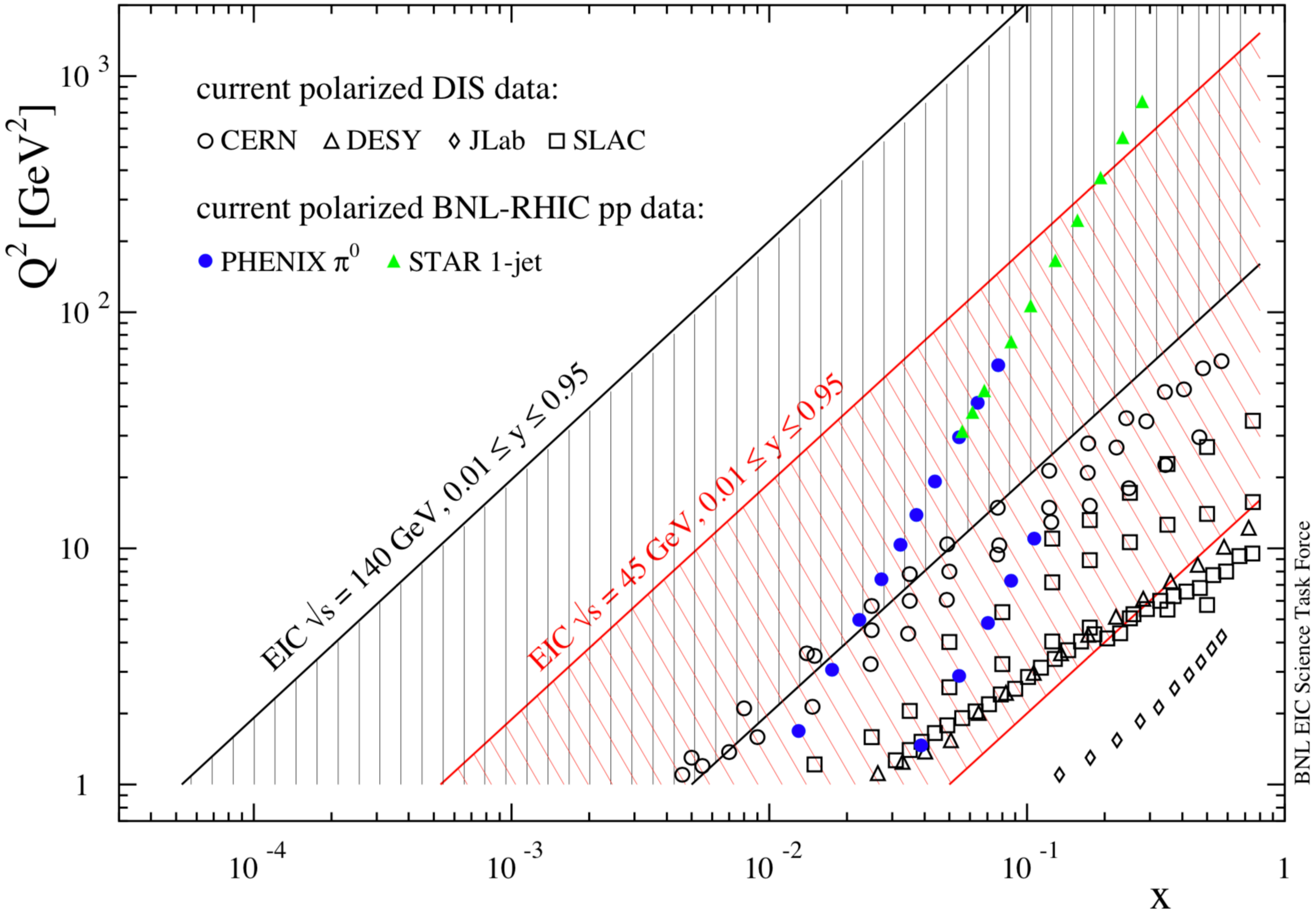
New constraints coming from the future Electron-Ion Collider (EIC)



# STATUS - HIGHER ORDER CALCULATIONS FOR POLARIZED DIS

- NNLO structure functions $g_1$ (photon exchange)
  van Neerven, Zijlstra (1994)
- NLO Photoproduction single-jet (small-cone approximation)
  Jäger (2008)
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  Hinderer, Schlegel, Vogelsang (2017)
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  Boughezal, Petriello, Xing (2018)
- NNLO Single-Jet production (polarized Catani-Seymour Dipoles+Projection to Born)
  Photon- IB, de Florian, Pedron (2020)
- NNLO NC & CC structure functions $g_1, g_4, g_5$
  IB, de Florian, Pedron (2022)
- NNLO Single-Jet production (polarized Catani-Seymour Dipoles+Projection to Born)
  NC and CC- IB, de Florian, Pedron (2023)
- (approx. N3LO) Semi-Inclusive DIS
  Abele, de Florian, Vogelsang (2022)
- N3LO structure function $g_1$ (photon exchange)
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  [See J. Blümlein talk for HF corrections]

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- NNLO Semi-Inclusive DIS

  Bonino, Gehrmann, Löchner, Schönwald, Stagnitto (2024)
  Goyal, Moch, Pathak, Rana, Ravindran (2024)

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# IMPLEMENTATION - NLO: DIPOLE SUBRTACTION

Based on the construction of counter-terms $d\sigma^A$, that satisfy:

- **Exactly** reproduce the divergent behavior of the real emission part
- Simple enough to be **integrated analytically** over the divergent part of the phase space

$$\sigma^{NLO} = \int_{m+1} \left[ \left(d\sigma^R\right)_{\epsilon=0} - \left(d\sigma^A\right)_{\epsilon=0} \right] + \int_m \left[ \int_1 d\sigma^A + d\sigma^V \right]_{\epsilon=0}$$

**Polarized Dipole subtraction**

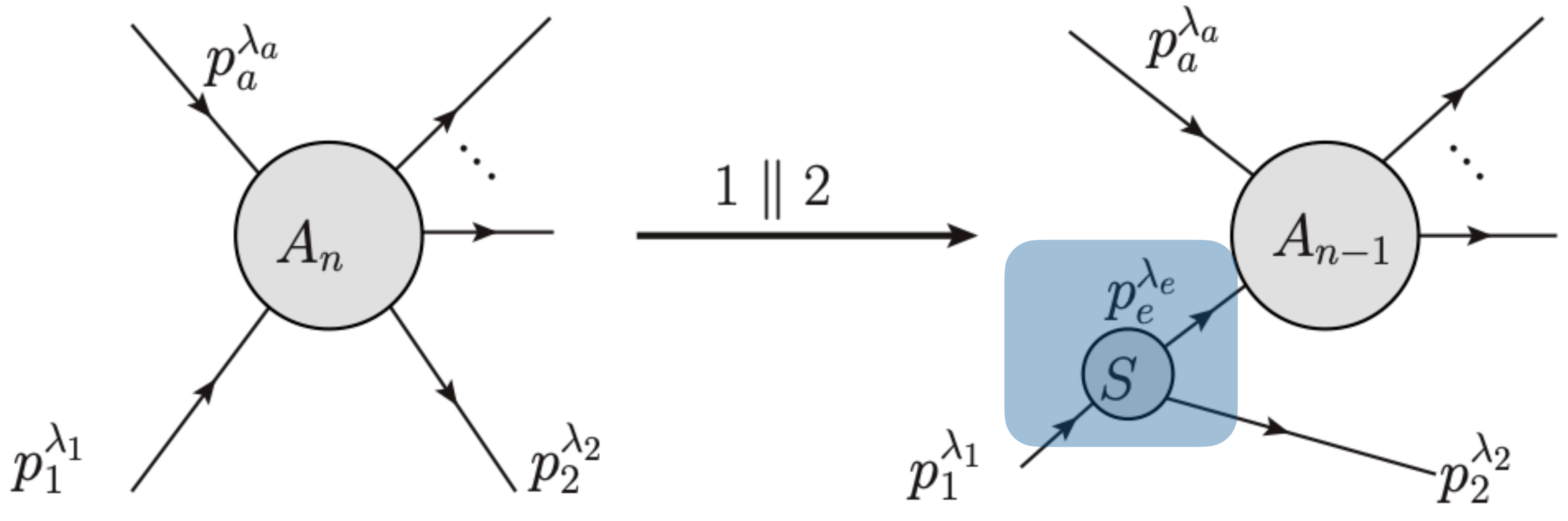
Based on the **polarized** dipole factorization formula

$$d\Delta\hat{\sigma}^{\text{NLO}}_{(m+1)} = d\Delta\hat{\sigma}^{\text{Born}}_{(m)} \otimes d\Delta V_{\text{dipole}}$$

Universal dipole factor ; Interpolates between collinear AP splittings and soft eikonal factor

IB, de Florian, Pedron. Phys.Rev.Lett. 125 (2020)

IB, de Florian, Pedron. *Phys.Rev.D* 103 (2021)

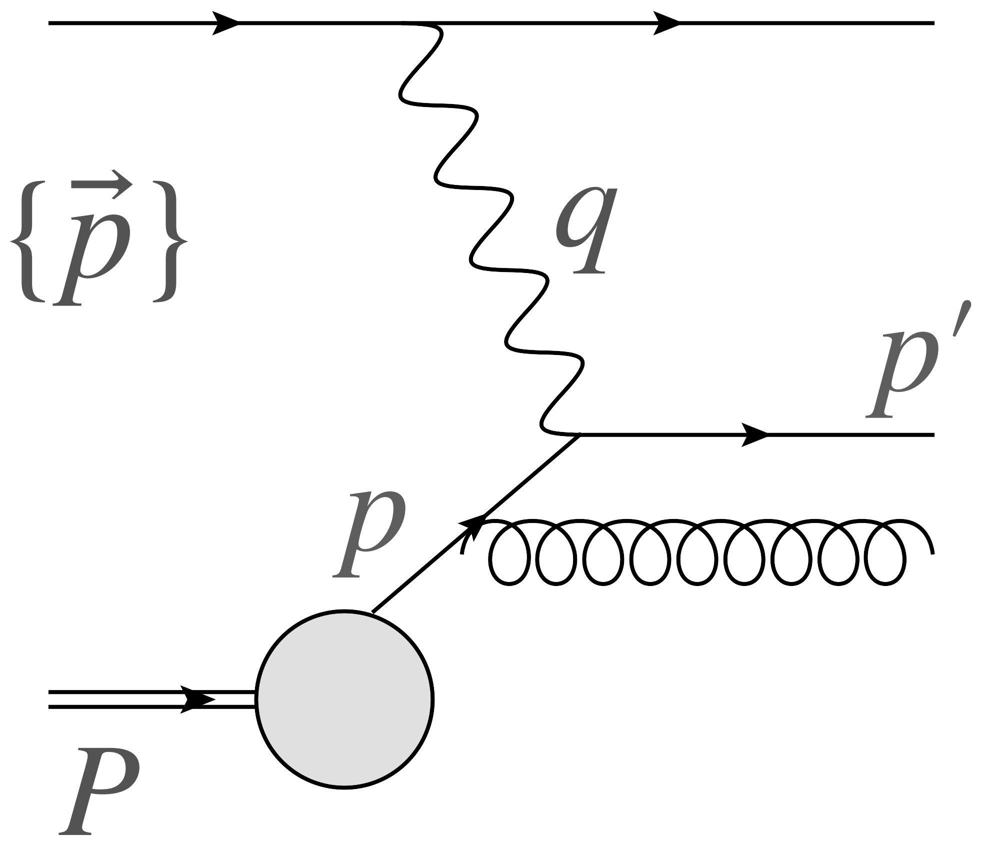



$$dA = \sum d\Delta\hat{\sigma}^{\text{Born}} \otimes d\Delta V_{\text{dipole}}$$ → **General NLO subtraction scheme for (initially) polarized processes**

# IMPLEMENTATION - NNLO: PROJECTION TO BORN (P2B)

Allows to obtained fully differential cross section for $\mathcal{O}$ if the **inclusive cross section for $\mathcal{O}$ at that order** and for **$\mathcal{O}$+jet at the previous order** are known

$\mathrm{w}; \{\vec{p}\}$

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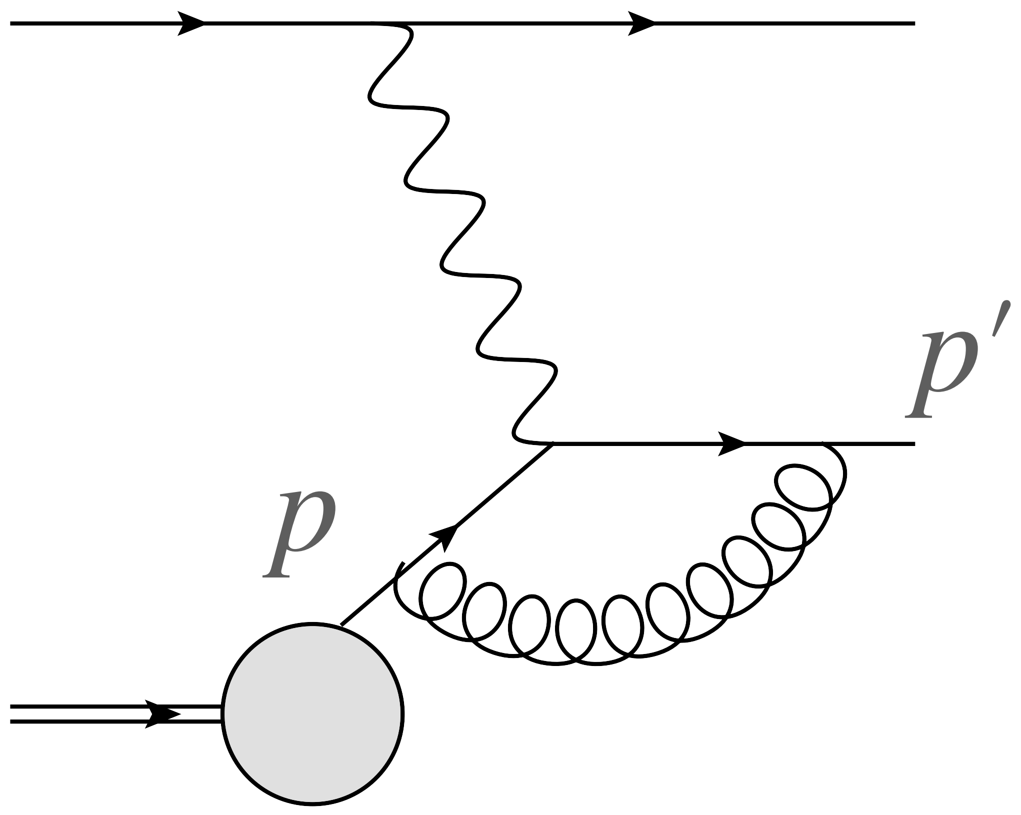


Born kinematic can be inferred from non-QCD particles

$p_B = x\,P$

$p'_B = x\,P + q$

Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2015)

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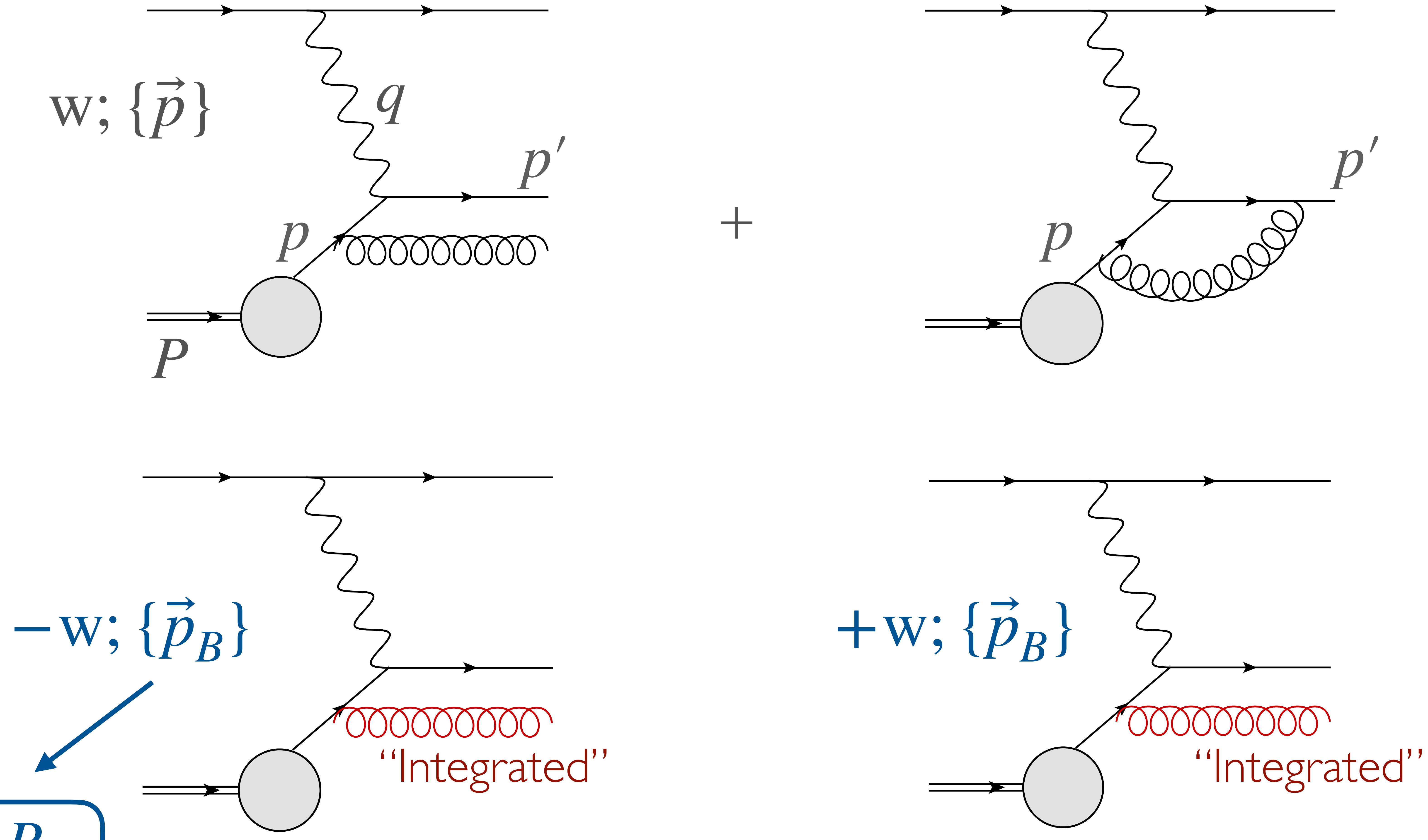


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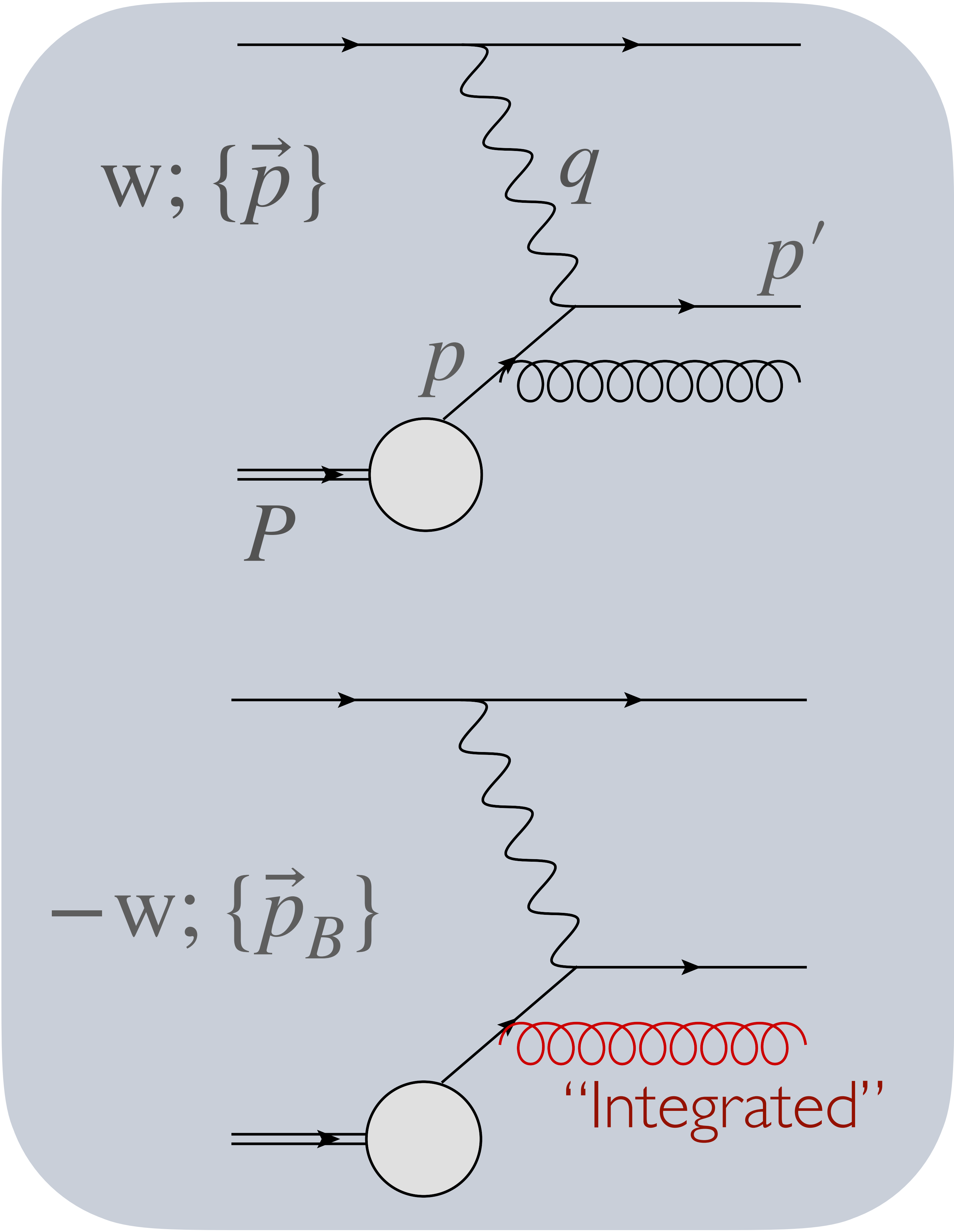
# IMPLEMENTATION - NNLO: PROJECTION TO BORN (P2B)

Finite & Integrable in 4D

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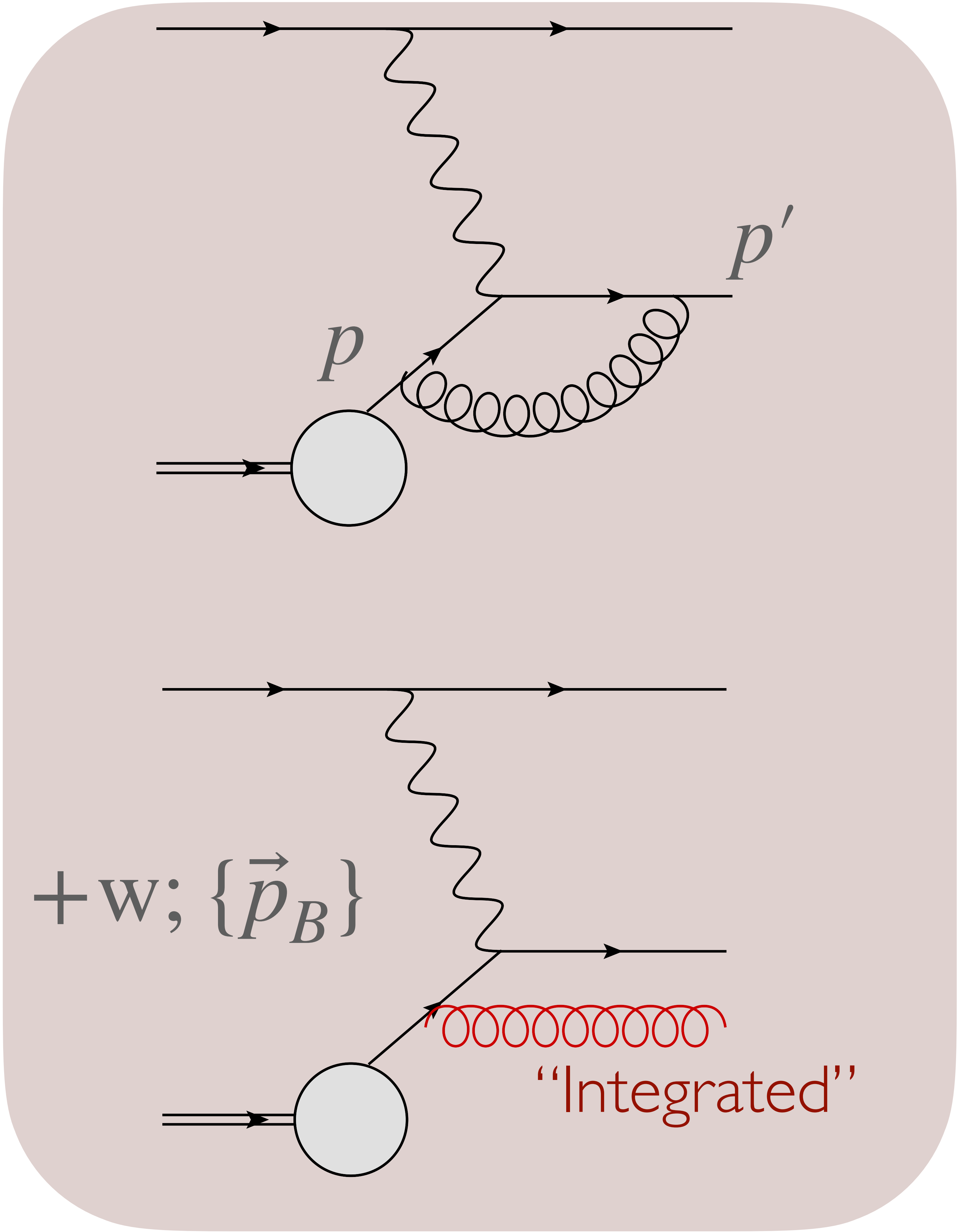
Contribution to the inclusive cross section

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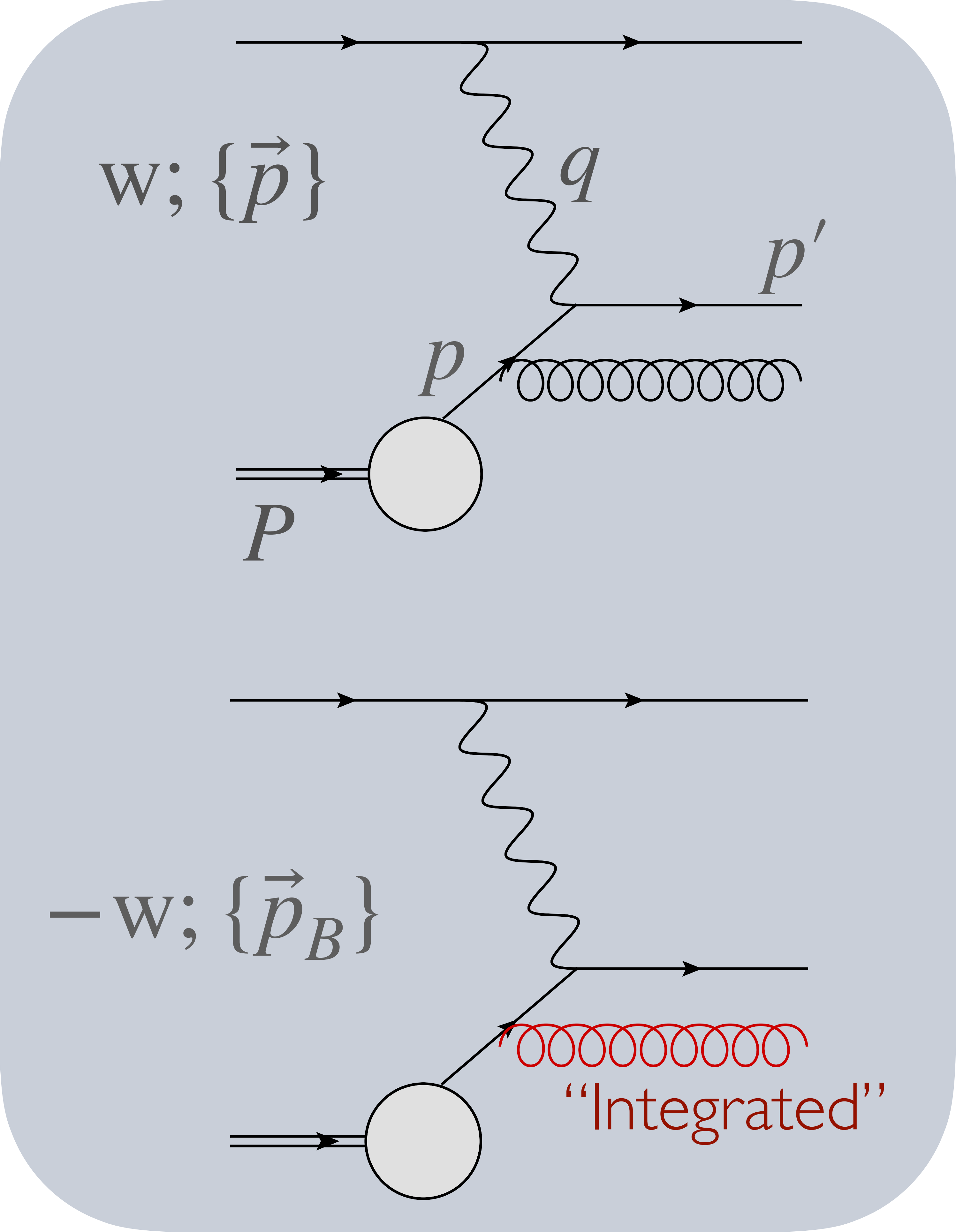


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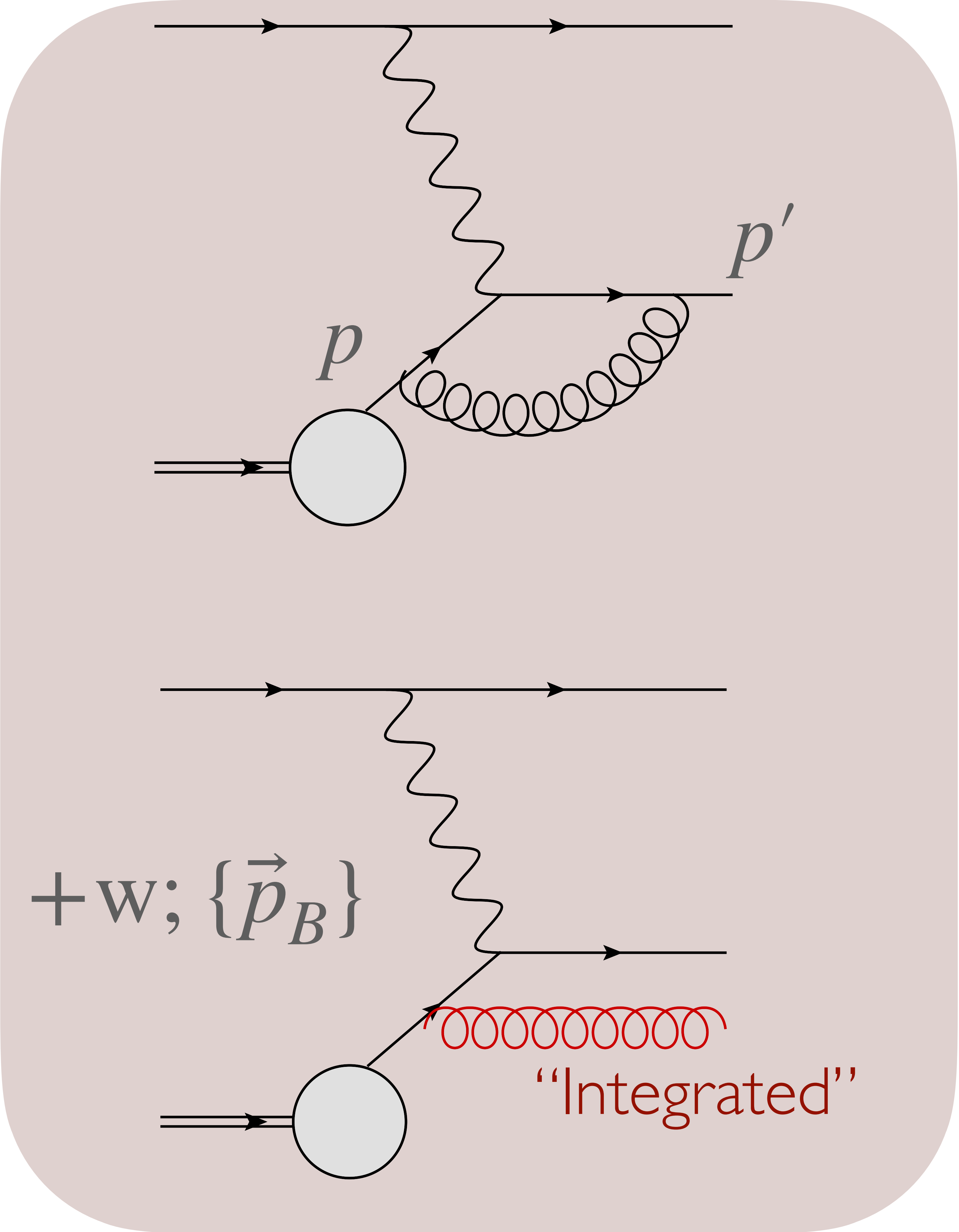
Contribution to the inclusive cross section

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$$d\sigma^{\rm NLO}_{\rm 1jet} = d\sigma^{\rm LO}_{\rm 2jets} - d\sigma^{\rm LO}_{\rm 2jets\,P2B} + d\sigma^{\rm NLO,incl}_{\rm 1jet\,P2B}$$

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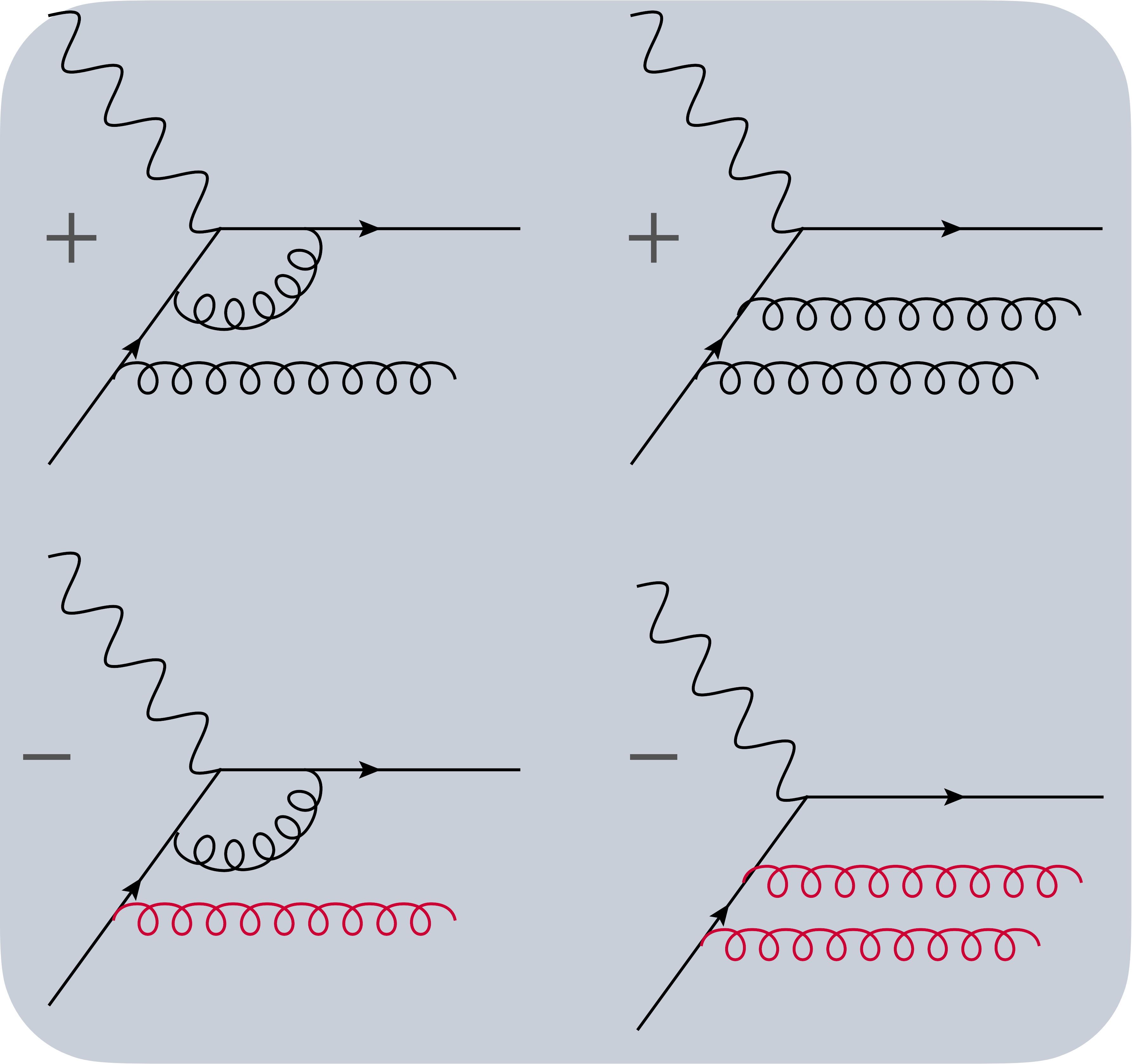

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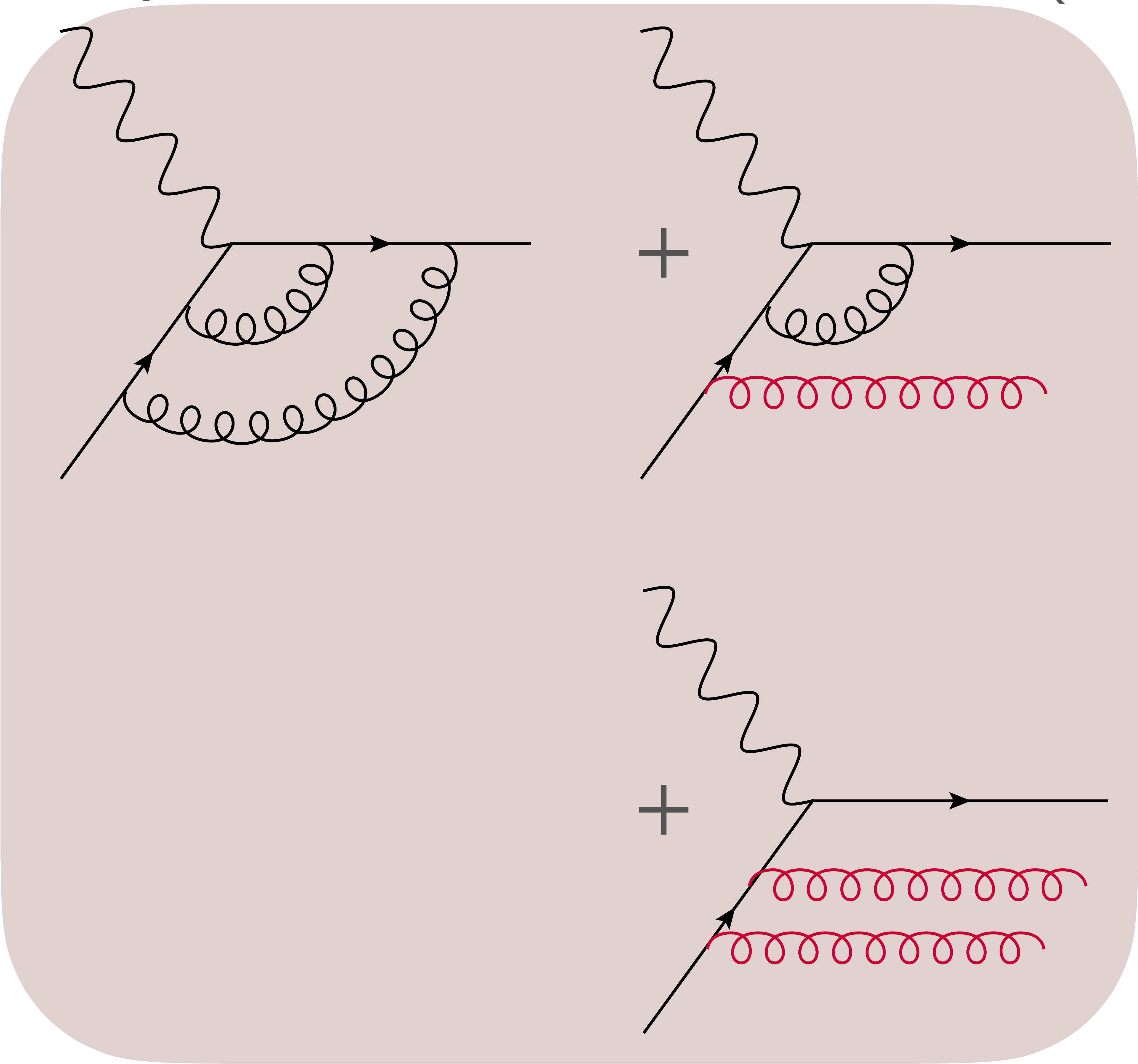

Contribution to the inclusive cross section

$$d\sigma^{\mathrm{NNLO}}_{\mathrm{1jet}} = d\sigma^{\mathrm{NLO}}_{\mathrm{2jets}} - d\sigma^{\mathrm{NLO}}_{\mathrm{2jets\,P2B}} + d\sigma^{\mathrm{NNLO,incl}}_{\mathrm{1jet\,P2B}}$$

Can compute the **NNLO cross section for 1-jet,** given that the **NLO calculation for 2-jets** and the **NNLO inclusive cross** sections are available

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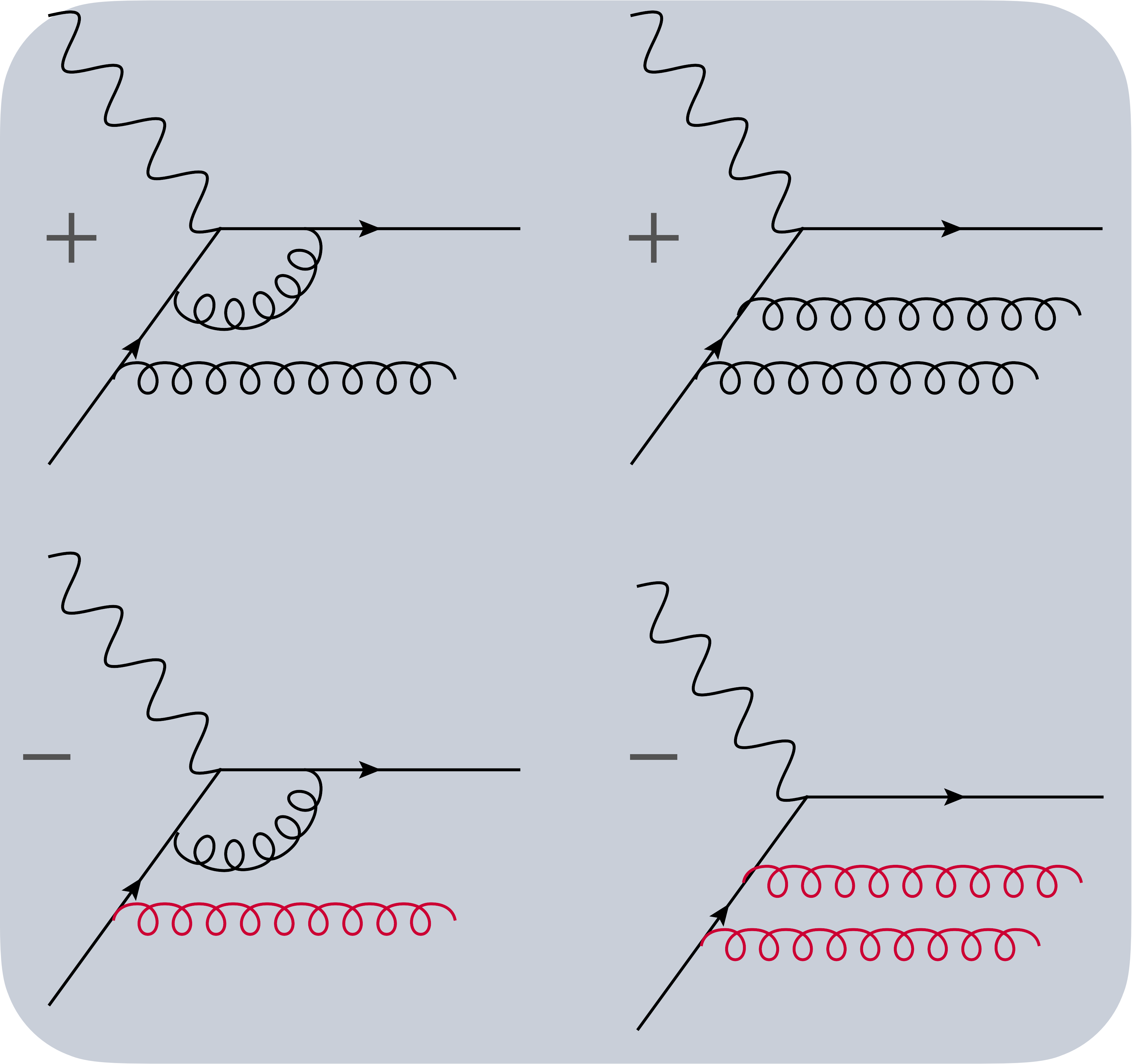


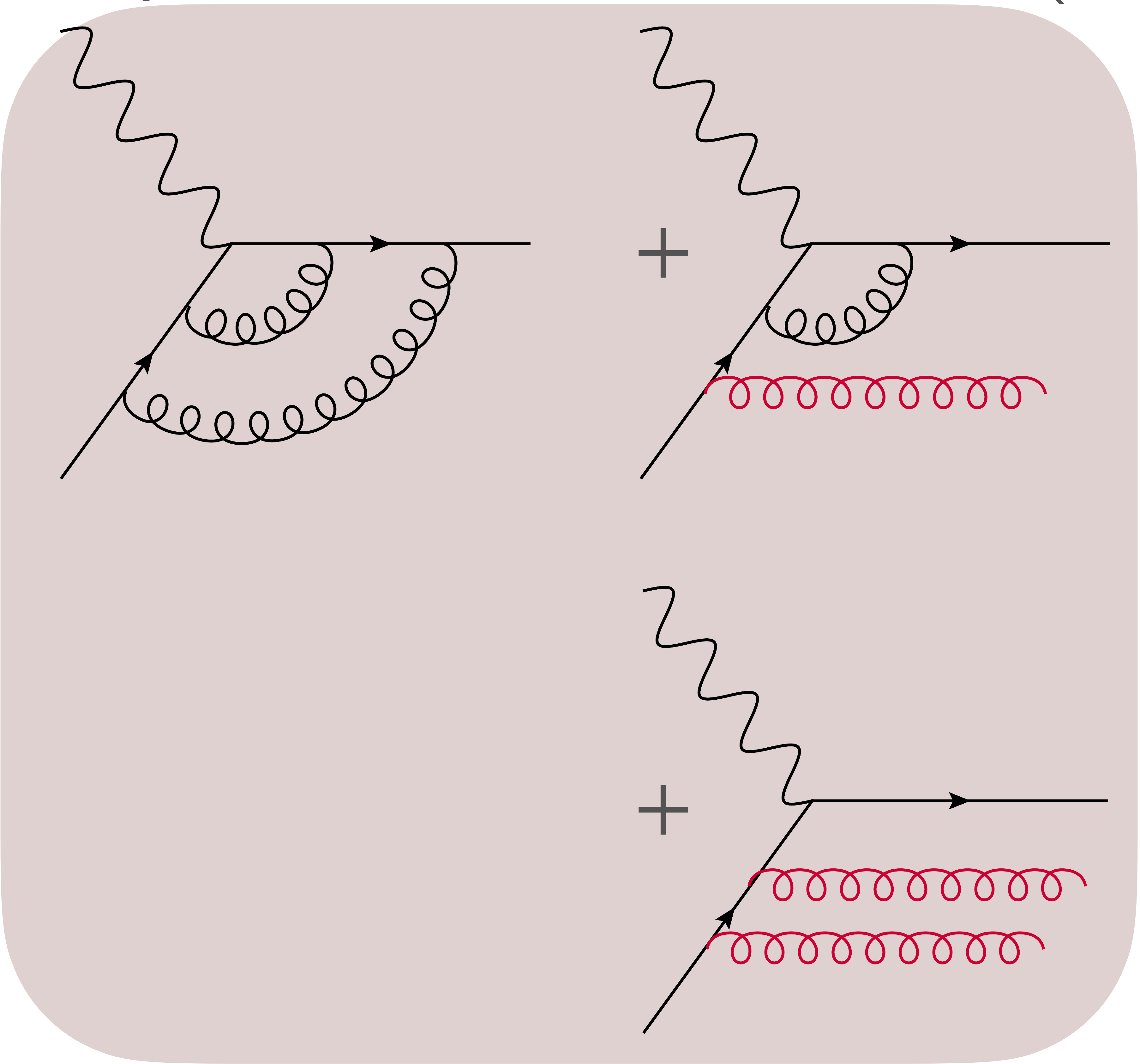


Finite & Integrable in 4D

Contribution to the inclusive cross section

Calculated using polarized dipoles

$$d\sigma^{\mathrm{NNLO}}_{\mathrm{1jet}} = d\sigma^{\mathrm{NLO}}_{\mathrm{2jets}} - d\sigma^{\mathrm{NLO}}_{\mathrm{2jets\,P2B}} + d\sigma^{\mathrm{NNLO,incl}}_{\mathrm{1jet\,P2B}}$$

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# IMPLEMENTATION - POLDIS CODE

- NLO calculation for di-jet production in polarized DIS using polarized dipoles
- NNLO cross section for single-jet production in pol DIS using P2B + dipoles
- Implementation in (soon-to-be-public …hopefully) in Fortran code POLDIS/POLDIZ

**Based on `DISENT` → Fixed bug in the gluon channel**

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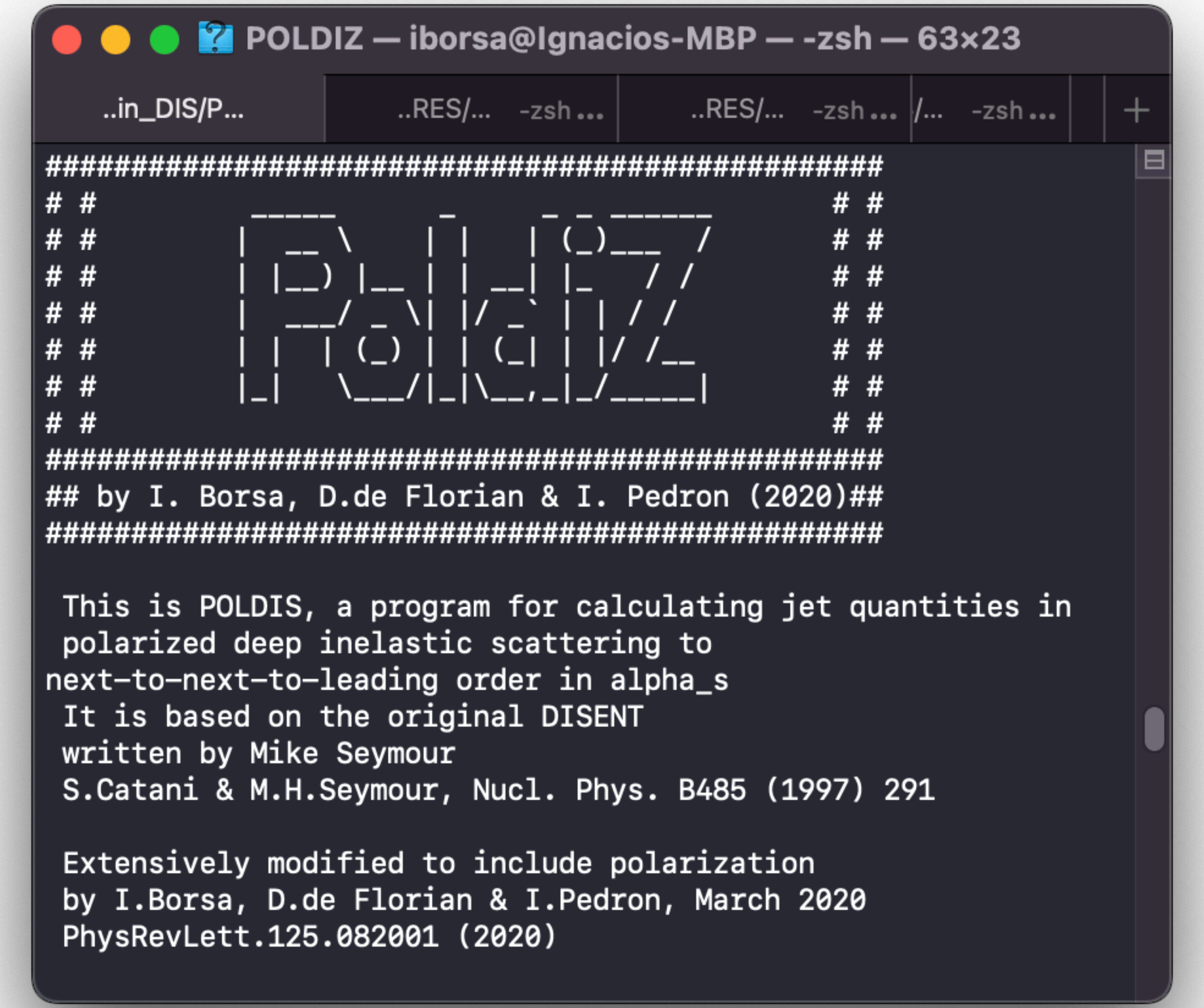


**POLDIS: Photon exchange**

- Completely differential 1-jet observables up to NNLO
- Completely differential 2-jet observables up to NLO

IB, de Florian, Pedron. Phys.Rev.Lett. 125 (2020)
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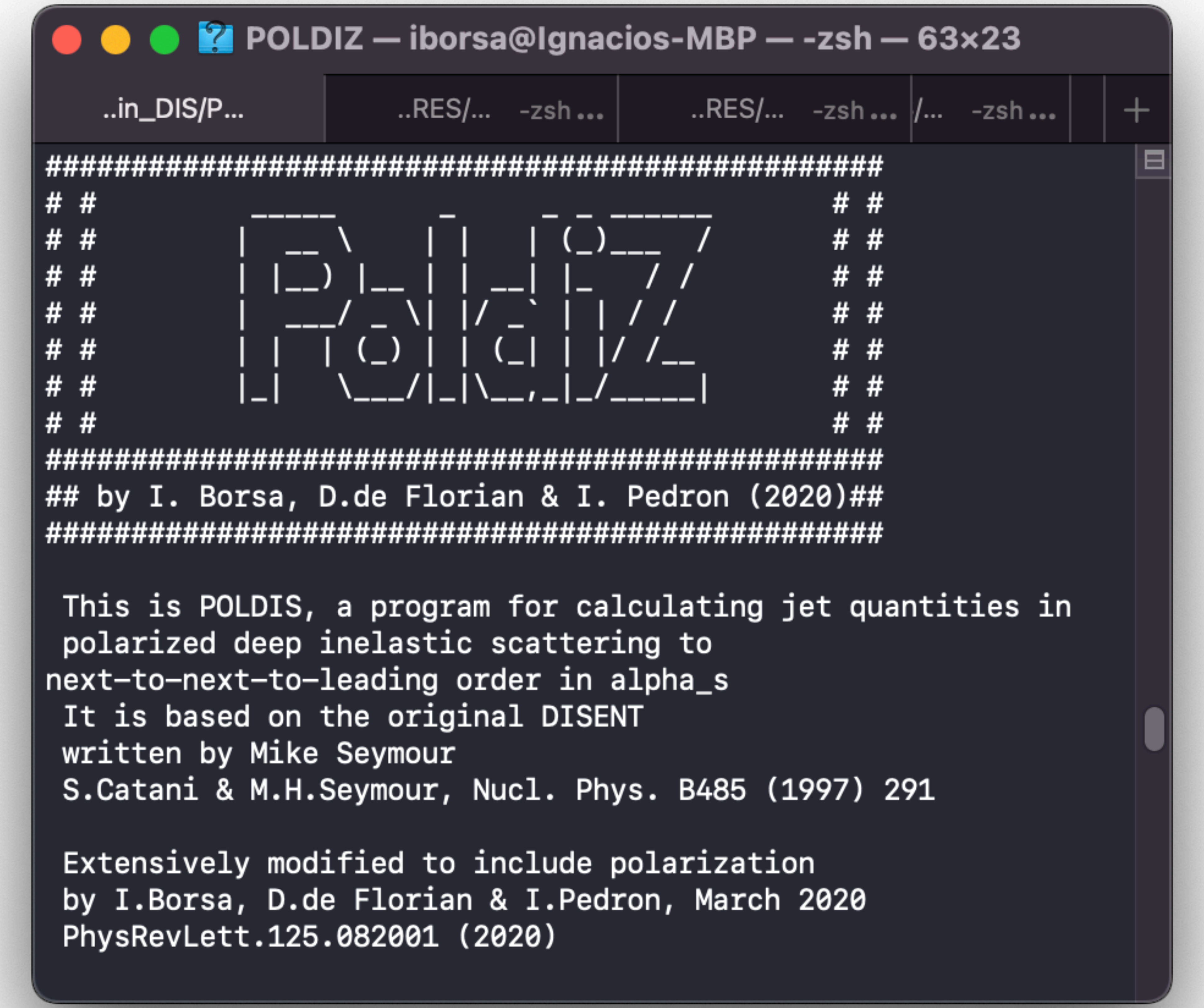


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IB, de Florian, Pedron. Phys.Rev.Lett. 125 (2020)
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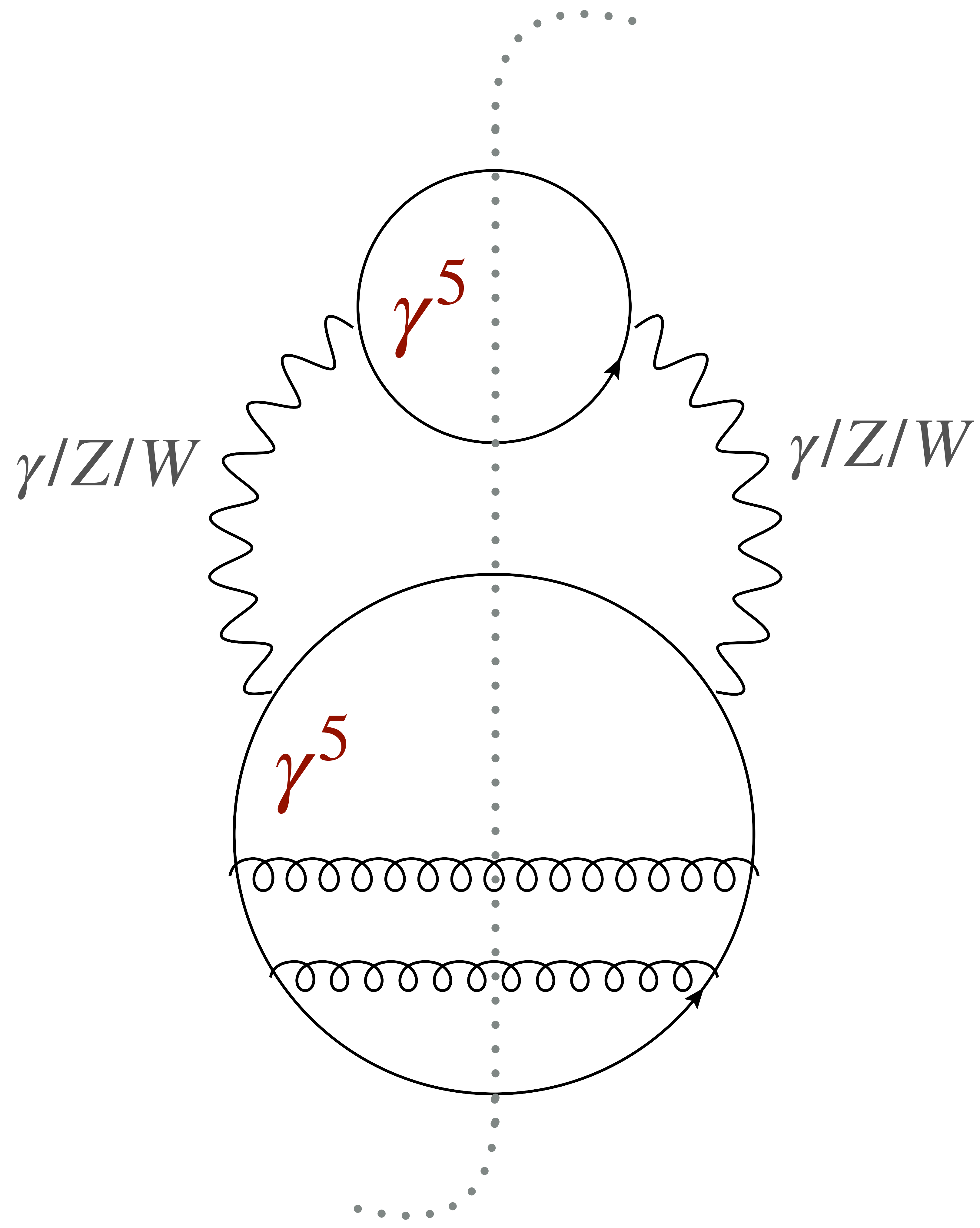
\+ Full Neutral current
\+ Charged current

IB, de Florian, Pedron. *Phys.Rev.D* 105 (2022)
IB, de Florian, Pedron. Phys.Rev.D 107 (2023)

# IMPLEMENTATION - INCLUSION OF EW CURRENTS




$$-ie\gamma^\mu(C_V + C_A\gamma^5)$$

HVBM scheme

't Hooft, Veltman (1972); Breitenlohner, Maison (1977)

$$\hat{\sigma}_q = \hat{\sigma}_q^{\mathrm{PV}} + \hat{\sigma}_q^{\mathrm{NPV}}$$

- **Quark channel**: Relations between polarized and unpolarized contributions

$$\text{ODD } \gamma^5: \quad \hat{\sigma}_q^{\mathrm{PV}} \Leftrightarrow \Delta\hat{\sigma}_q^{\mathrm{NPV}}$$
$$\text{EVEN } \gamma^5: \quad \Delta\hat{\sigma}_q^{\mathrm{PV}} \Leftrightarrow \hat{\sigma}_q^{\mathrm{NPV}}$$

  - Easy to see for real emission contributions (4 dimensional)
  - Virtual contributions require additional finite renormalization from HVBM

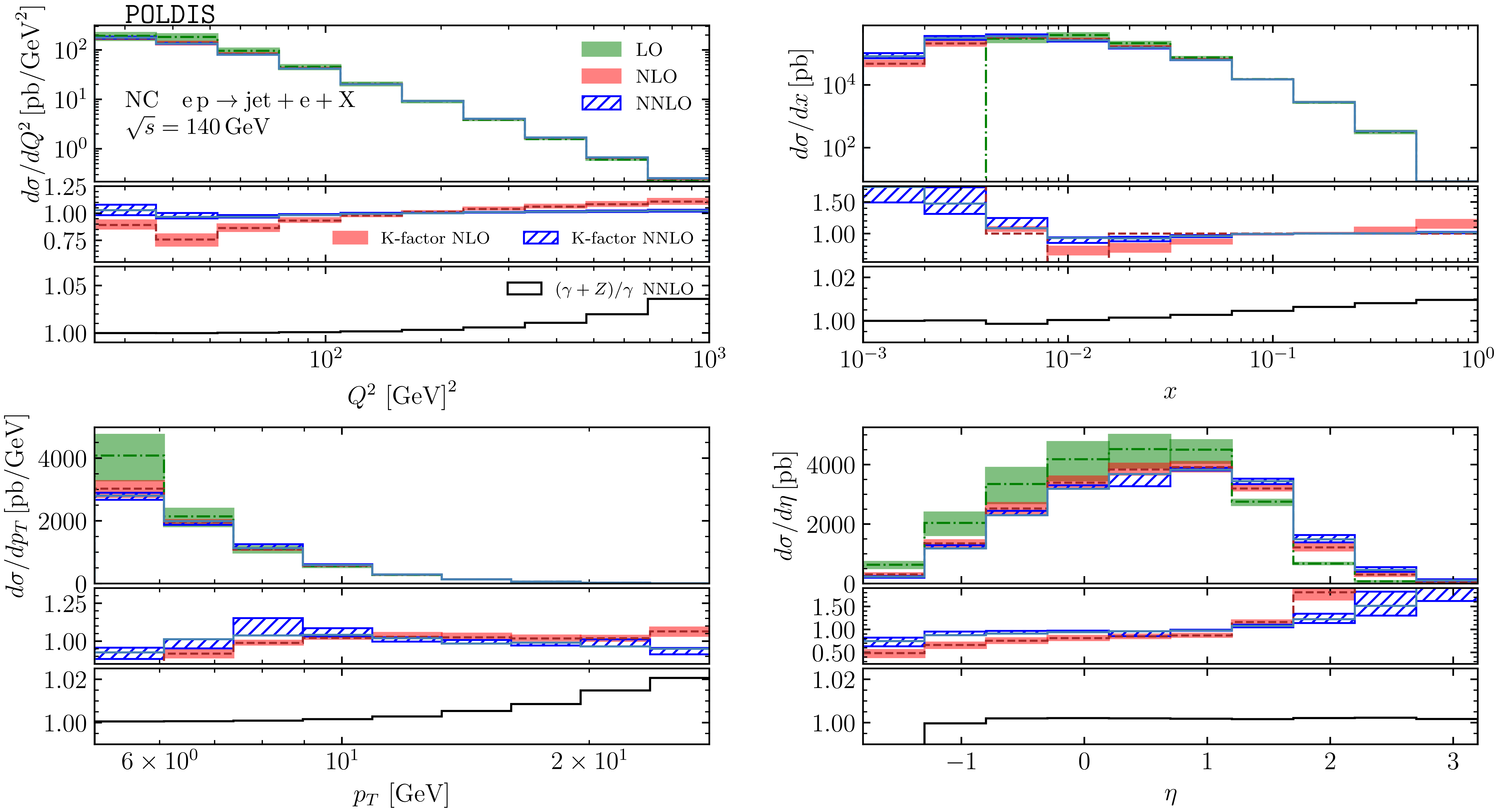
- **Gluon channel:** Contribution cancels if the charged of the jet is not identified

Parity-violating structure functions $g_4, g_5$

IB, de Florian, Pedron (2022)

# PHENOMENOLOGY - NNLO SINGLE-JET PRODUCTION IN DIS

## Neutral Current DIS




- Improved perturbative convergence
- Small contribution from Z-boson exchange

IB, de Florian, Pedron. Phys.Rev.D 107 (2023)

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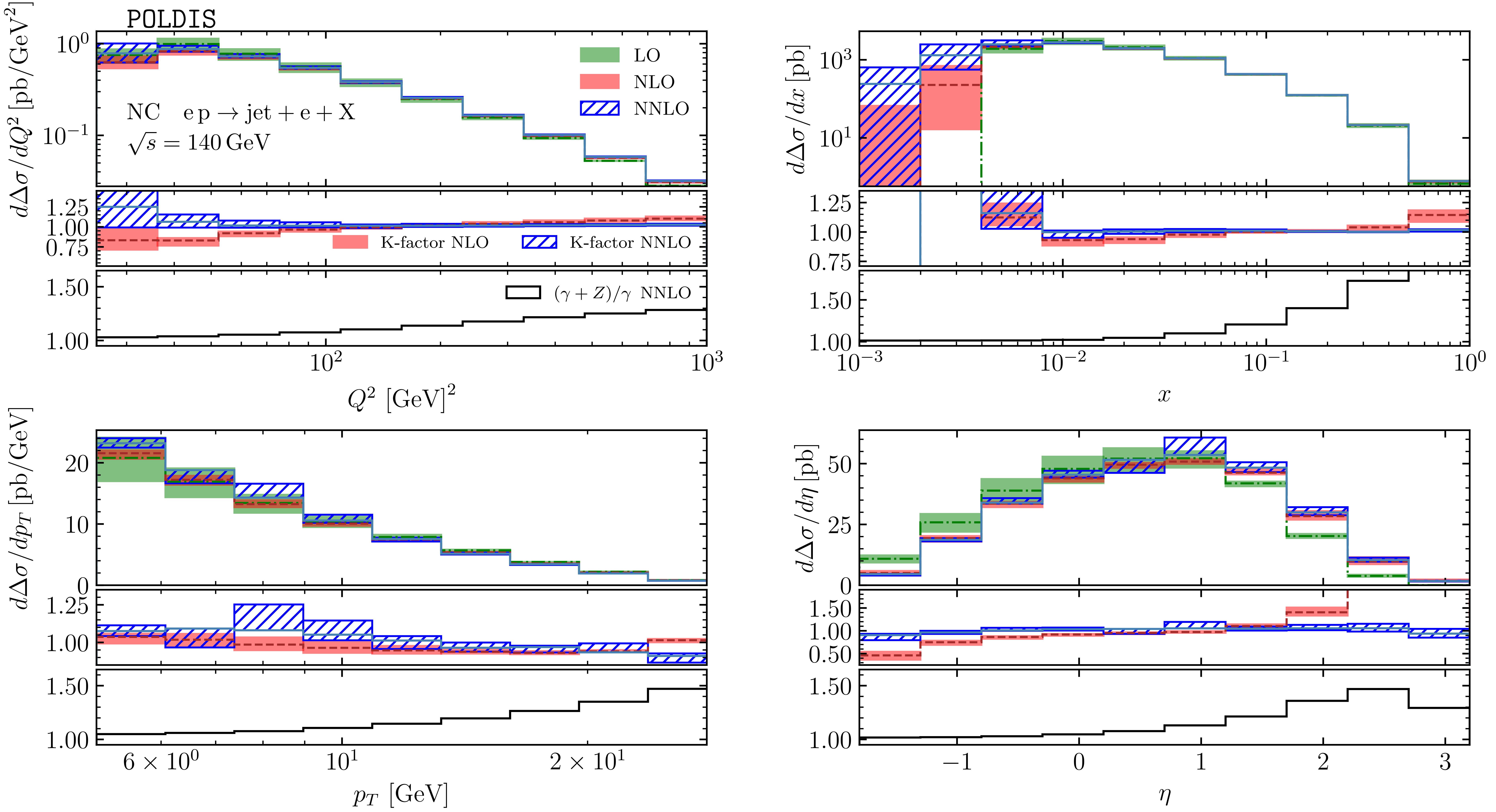


IB, de Florian, Pedron. Phys.Rev.D 107 (2023)

- Enhanced contributions at high $Q^2, x,$ and $p_T$ compared to the unpolarized case (unsuppressed parity-violating terms for Z exchange)
- Enhancement is translated to increased spin asymmetries

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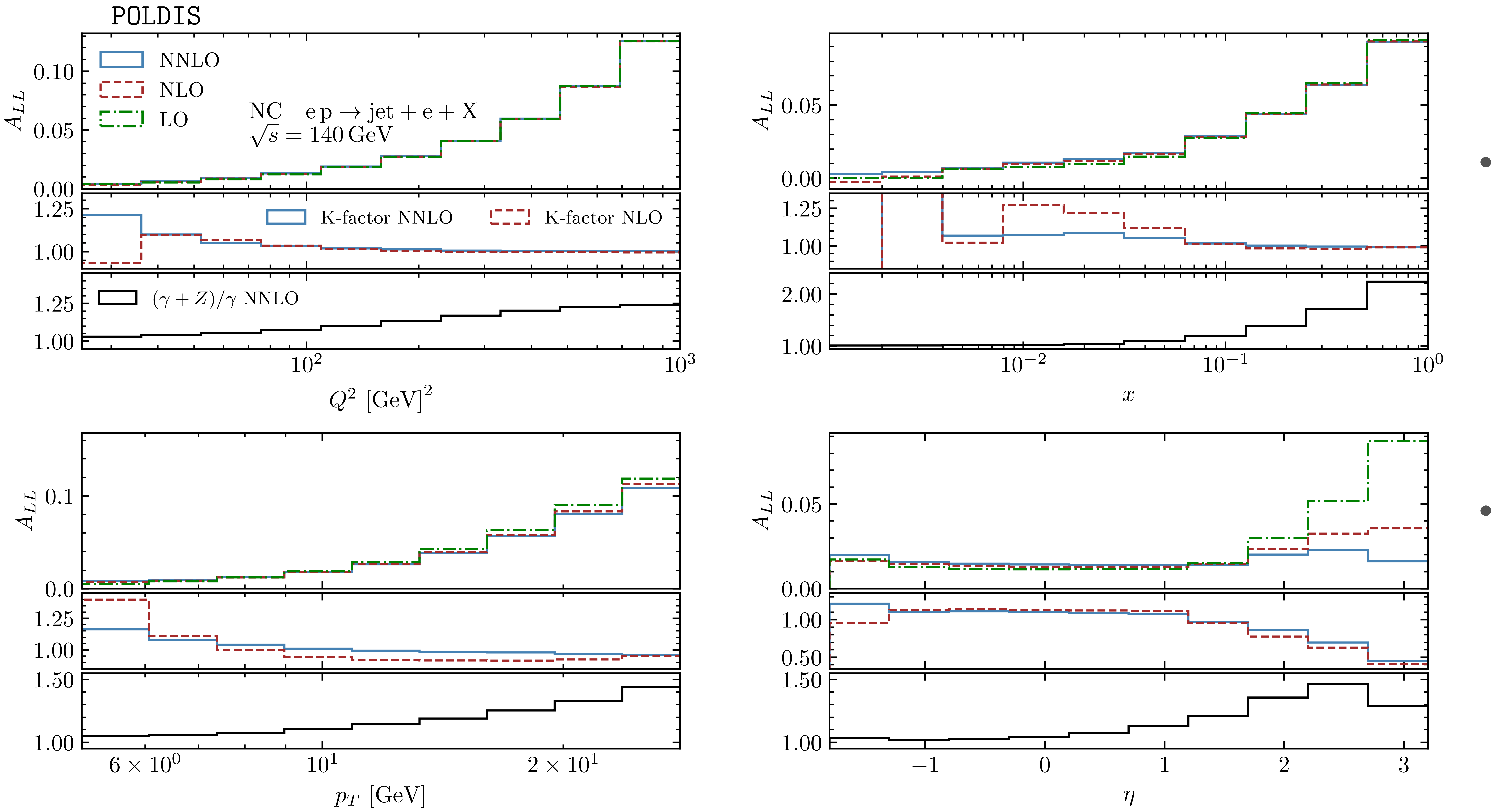


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# HIGHER ORDER CORRECTIONS FOR JET OBSERVABLES IN POLARIZED DIS

**Introduction**

What can we learn from polarized processes?
Why do we need higher order corrections?

**Fixed-order approach to jet observables**

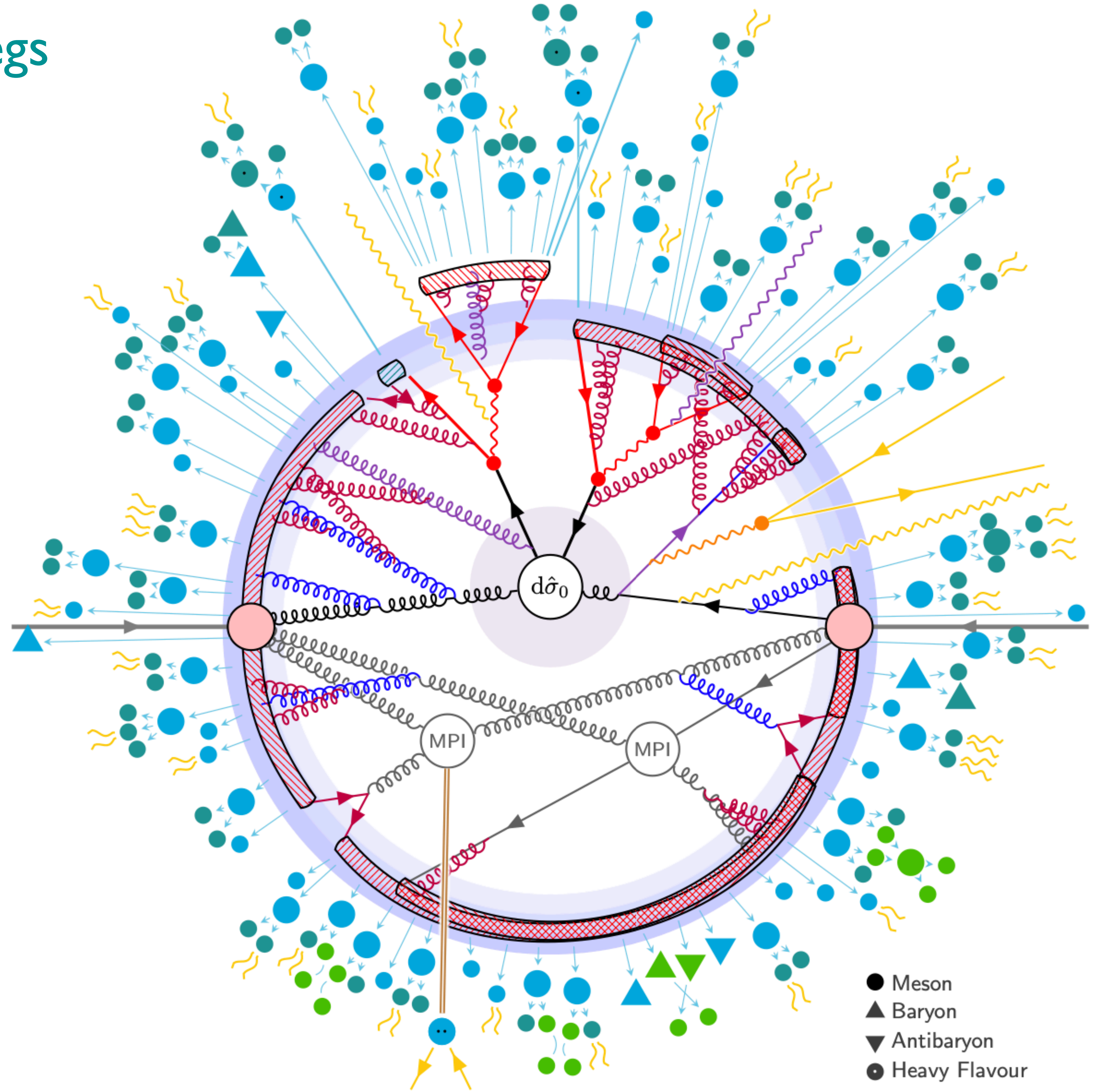
Jet production in polarized DIS at NNLO

**Beyond fixed order calculations**

NLO+PS for polarized DIS

**(In collaboration with B. Jäger)**

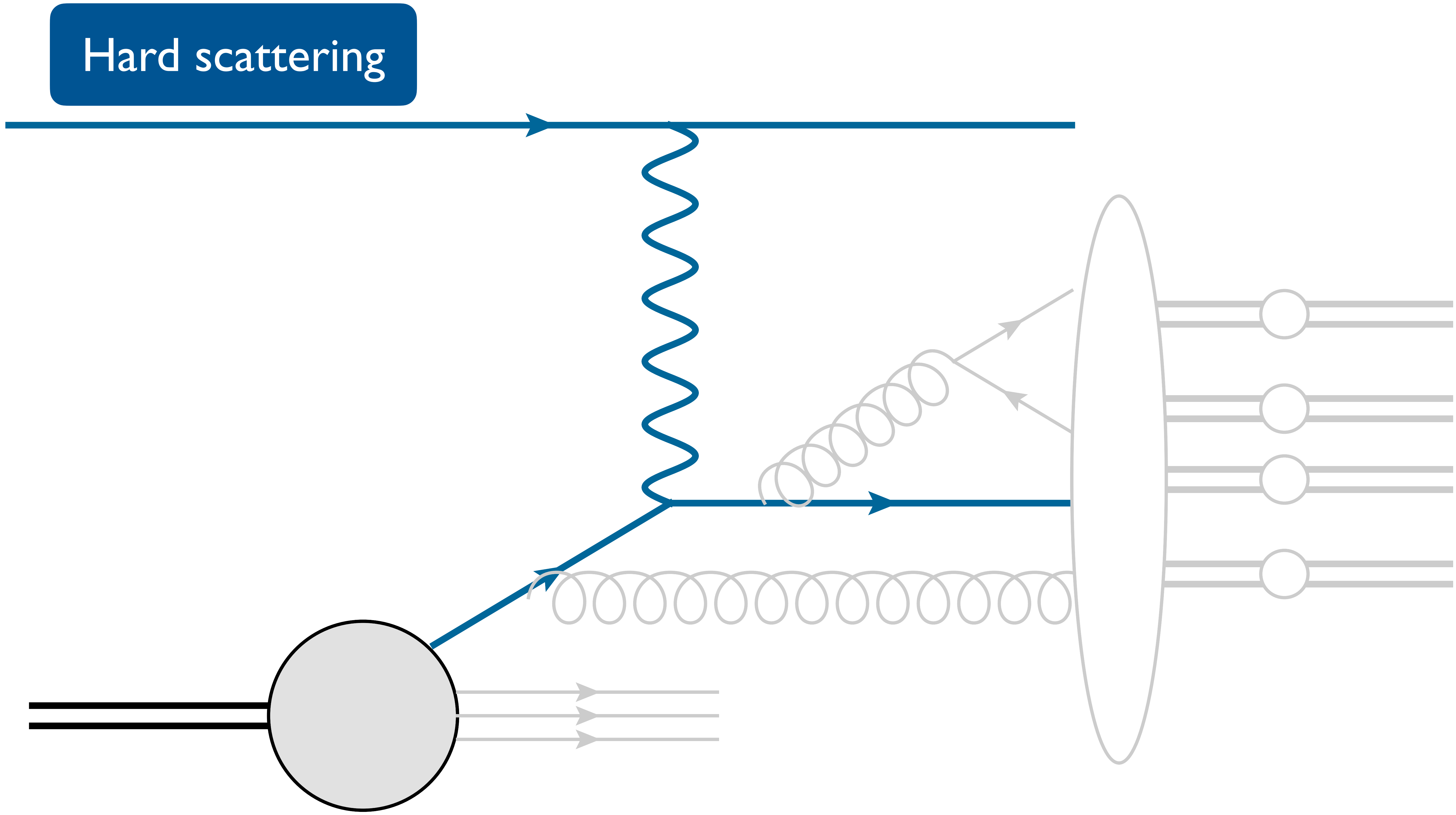
# Loops << Legs




Plot from Pythia manual arXiv:2203.11601 [hep-ph]

# MONTE CARLO EVENT GENERATORS

[See Florian Herren's talk]



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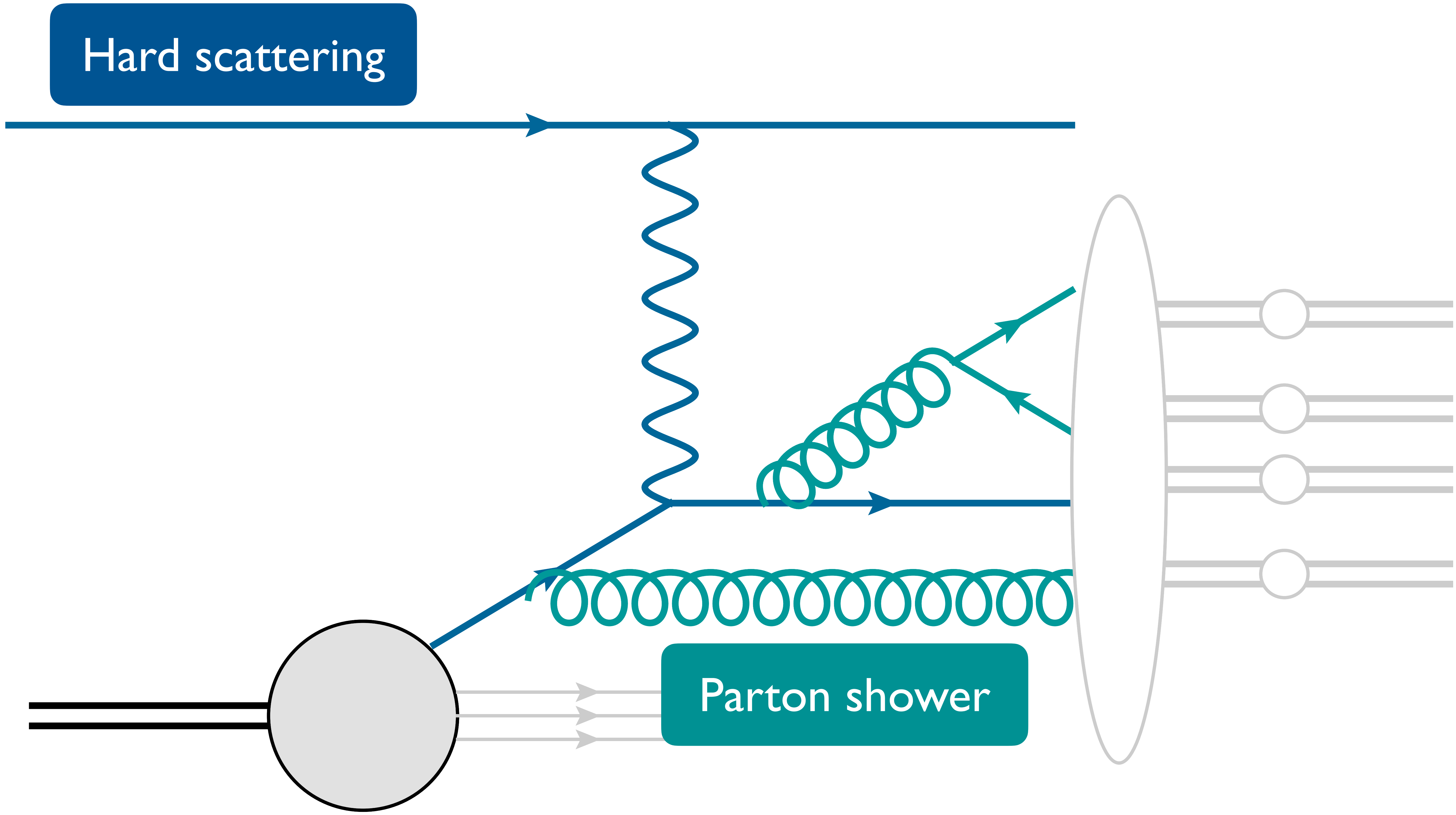


[See Florian Herren's talk]

Leading Log accurate

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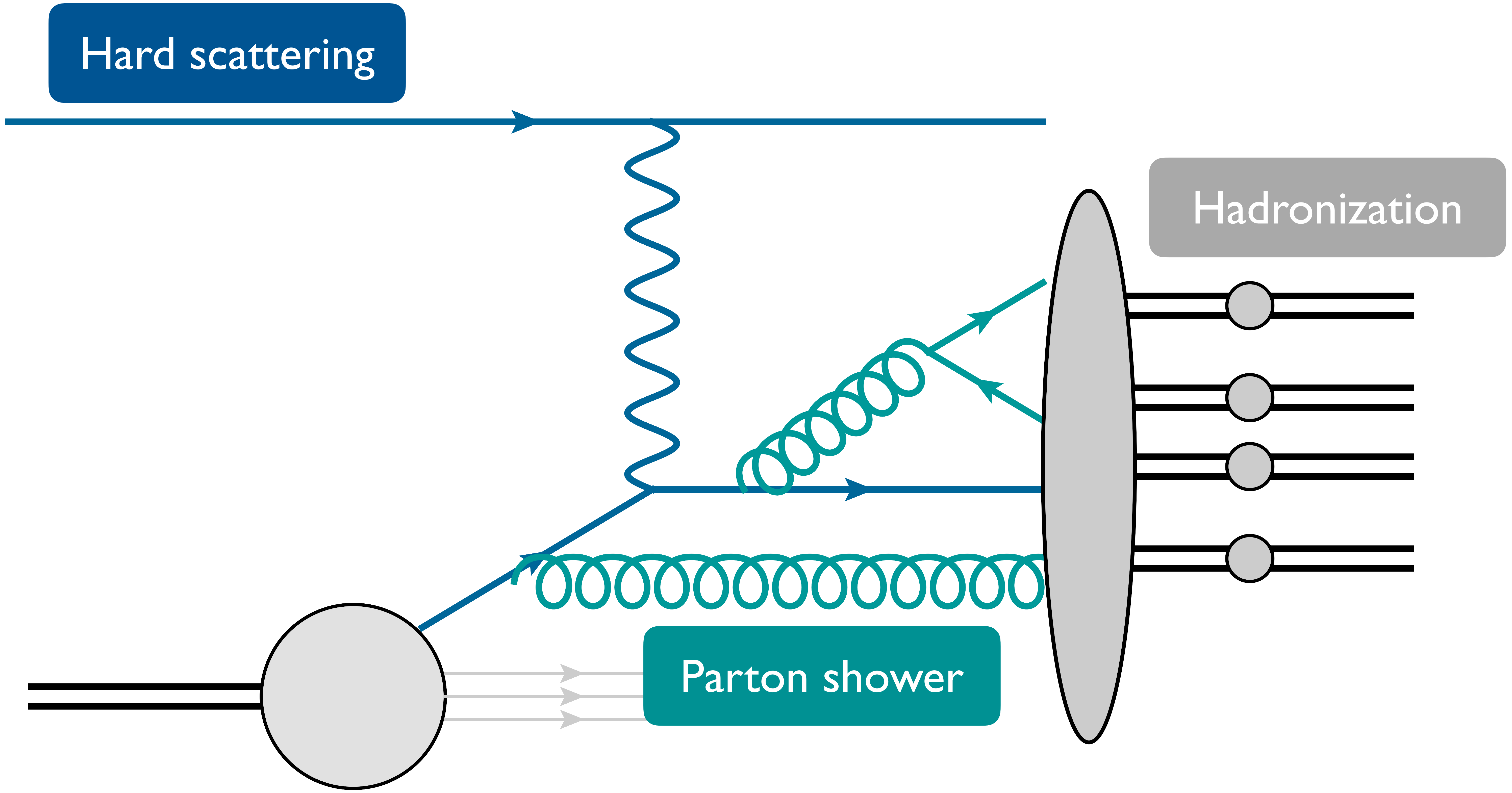


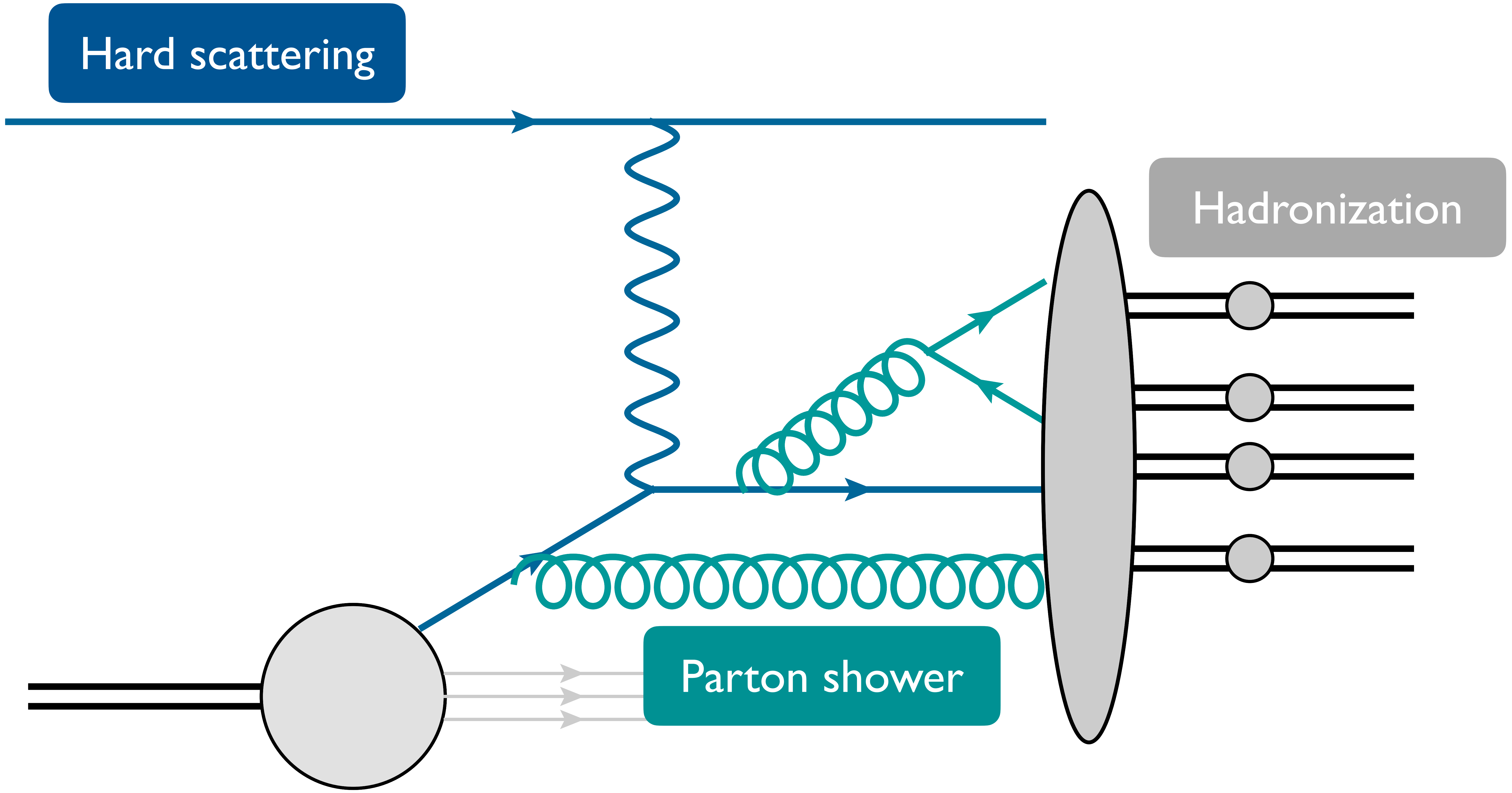

[See Florian Herren's talk]

Leading Log accurate

- Hadronization
- Hadron decays
- EW radiation

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

# MONTE CARLO EVENT GENERATORS

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…

**Polarized event generators** (unpolarized parton shower)
PEPSI Mankiewicz, Schafer, Veltri (1992)
DJANGOH Charchula, Schuler, Spiesberger (1994)

# FIXED-ORDER VS SMC

## NLO

- Accurate distributions at high $p_T$
- Normalization accurate at NLO

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

## SMC (LO + Parton Shower)

- Incorrect distributions at high $p_T$
- Normalization accurate at LO

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

Try to merge the two approaches, trying to keeps the desirable features of both
**potential problems with double counting of real emission!**

MC@NLO - Frixione, Webber (2001)
POWHEG - Nason(2004)
MiNNLOPS - Monni, Nason, Re, Wiesemann, Zanderighi (2020)

[See talk by Vasily Sotnikov]

# NLO + PARTON SHOWER - POWHEG SCHEME

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

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

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

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

POWHEG SUDAKOV

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

# NLO + PARTON SHOWER - POWHEG SCHEME

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

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

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

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

POWHEG SUDAKOV

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

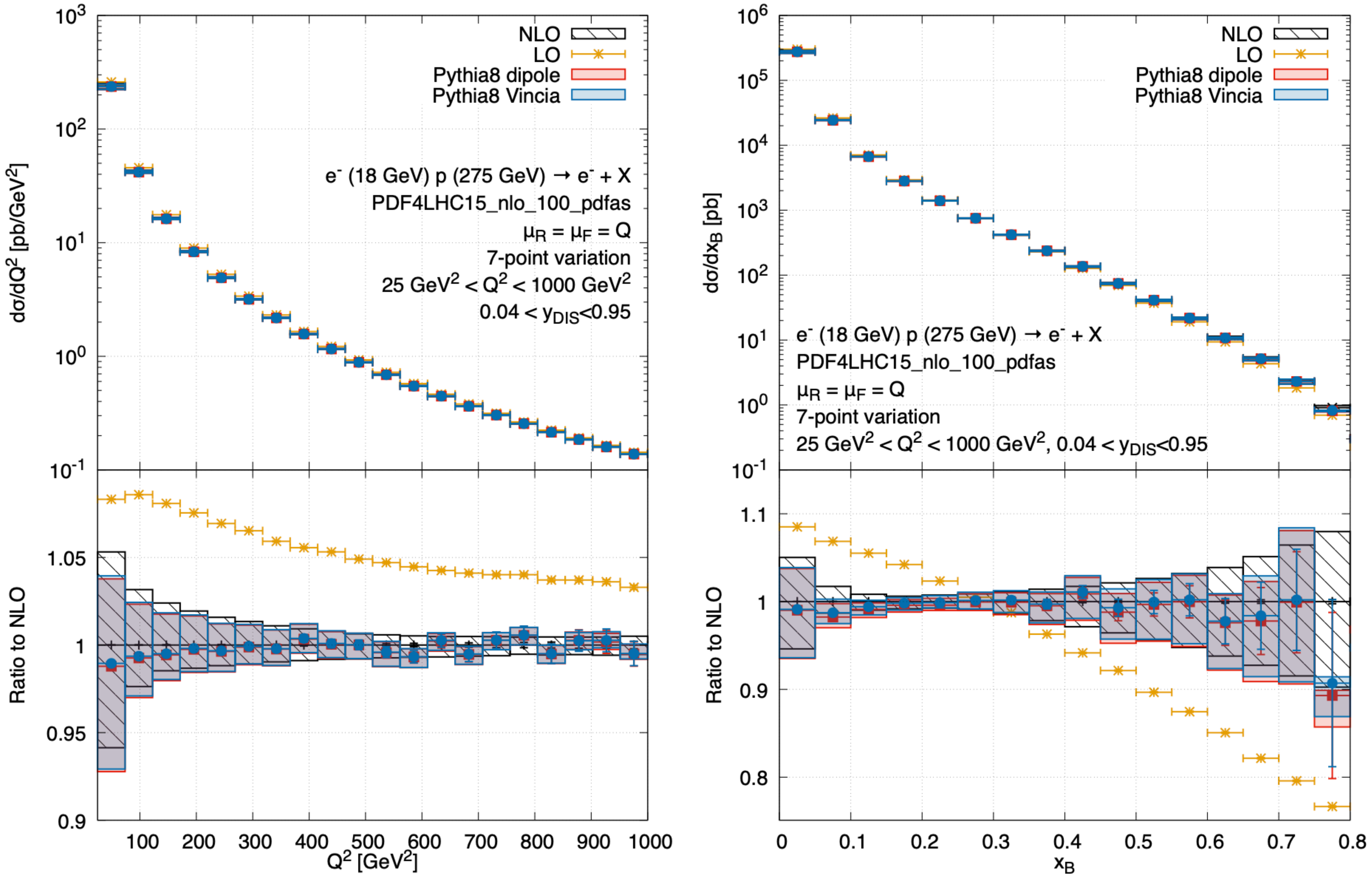
- Hardest emission generated according to the POWHEG Sudakov and $\overline{B}(\Phi_n)$
- Subsequent (less hard)radiation generated using parton-shower programs ($p_T$ veto)

☑ NLO accuracy on integrated quantities

☑ Leading log accurate

# NLO + PARTON SHOWER - POWHEG SCHEME

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




Unpolarized DIS (NC and CC) in POWHEG
Banfi, Ferraro Ravasio, Jäger, Karlberg, Reichenbach, Zanderighi (2023)

# NLO + PARTON SHOWER - POLARIZED POWHEG SCHEME

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

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

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

**Modifications to handle polarized DIS**

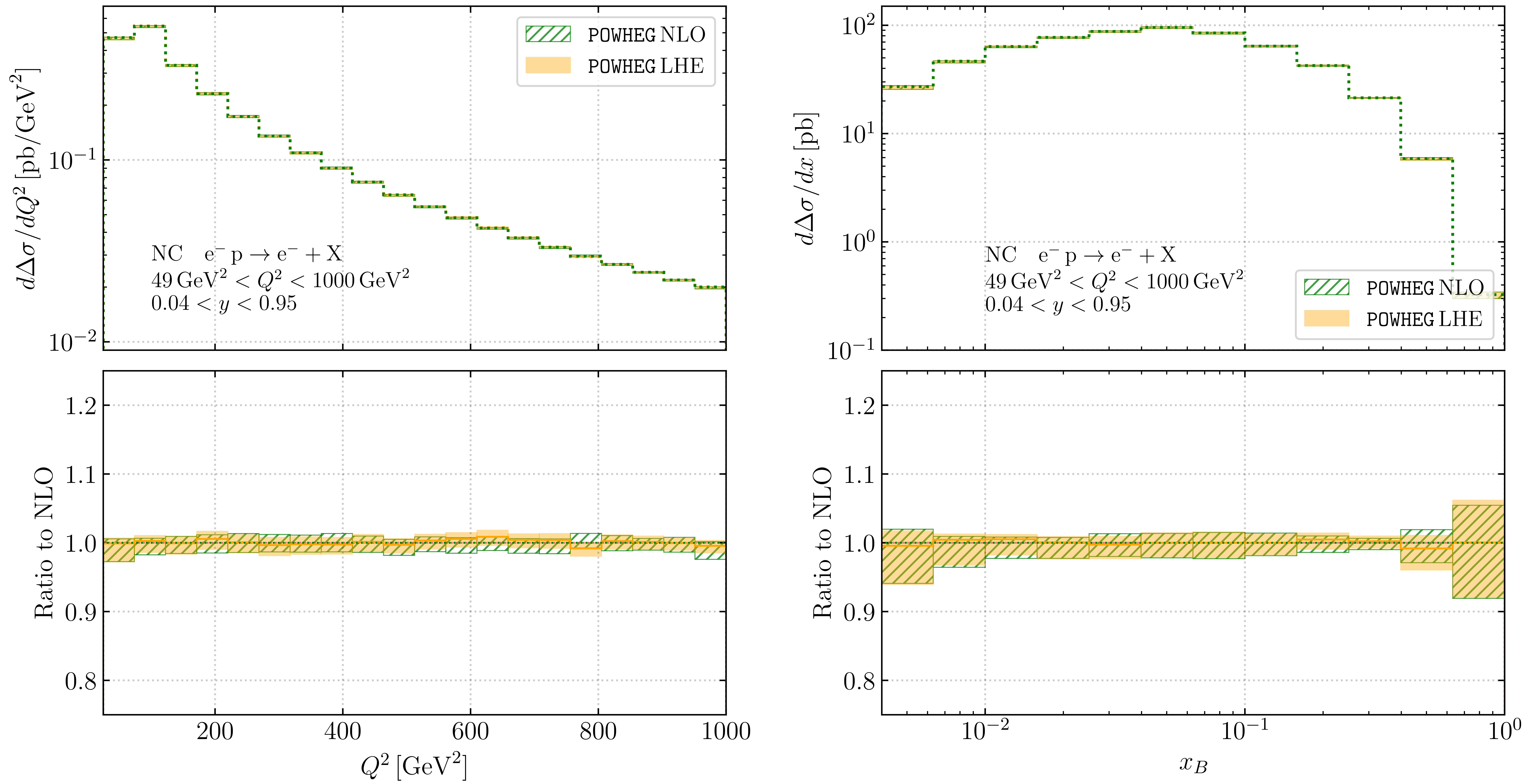
- Polarized Matrix elements & PDFs
- NLO Subtraction scheme → implementation of polarized FKS subtraction

  Frixione, Kunszt, Signer(1996)

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

IB, Jäger arXiv 2404.07702

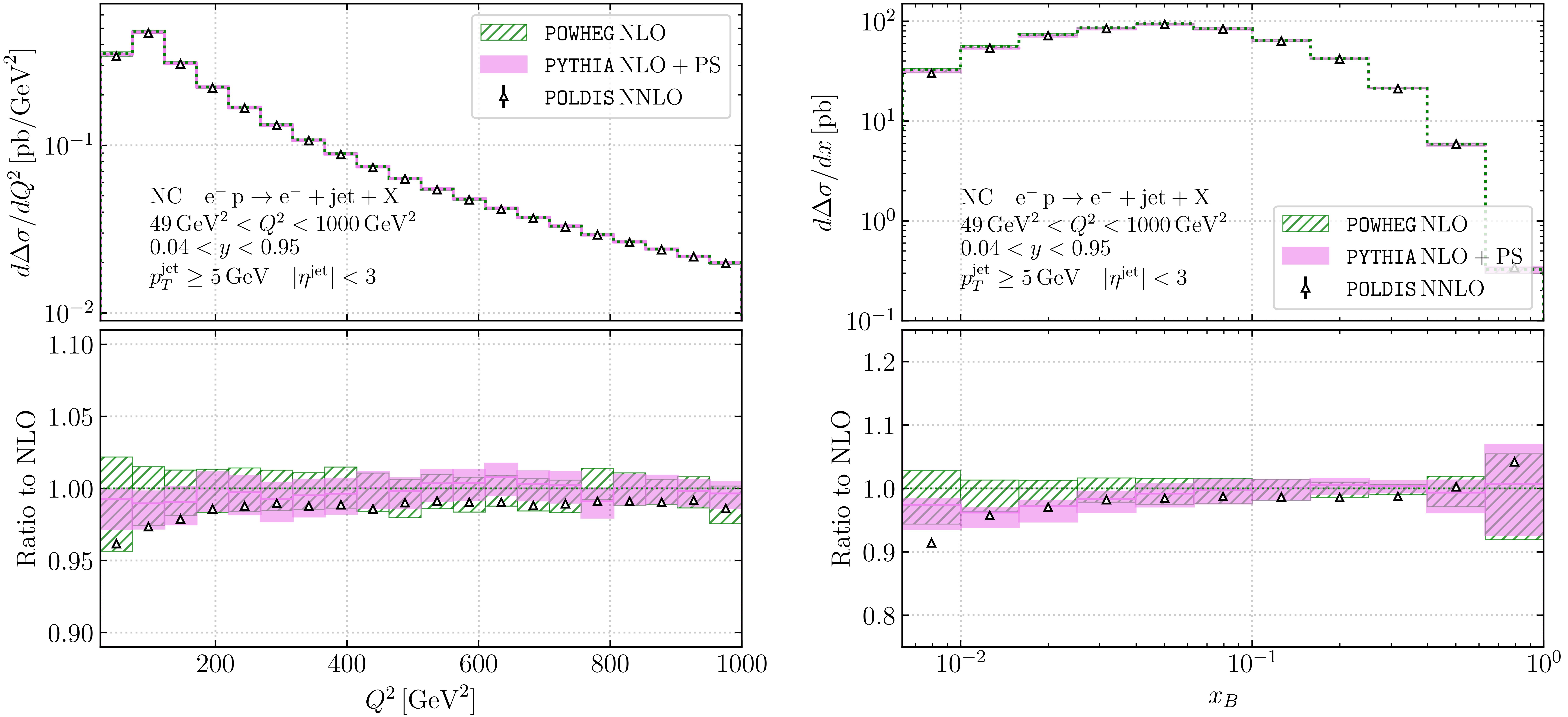
# PHENOMENOLOGY




- Small corrections from the PS to more inclusive observables
- Slight improvement in the agreement with NNLO results

IB, Jäger arXiv 2404.07702

# PHENOMENOLOGY

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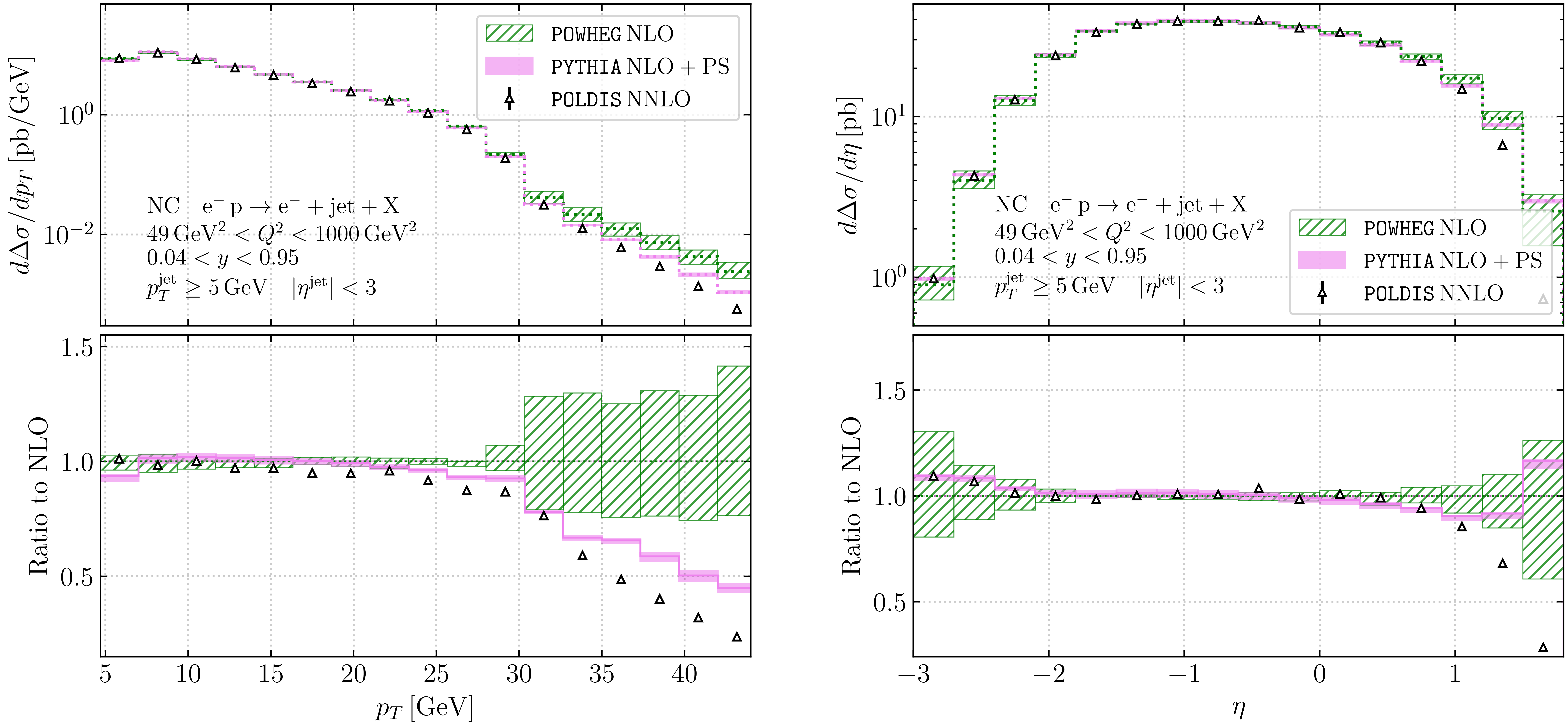



- Sizable corrections in the kinematical suppressed regions
- Slight improvement in the agreement with NNLO results

IB, Jäger arXiv 2404.07702

# SUMMARY

- Higher order corrections instrumental for a precise description of polarized jet observables, and will play a central role in the improvement of our picture of the proton's spin.

**NNLO calculation for jet production in Polarized DIS - full NC & CC**

- Numerical implementation in code POLDIS (also allows NLO calculation for di-jet production in pol DIS).
- For EIC kinematics, Increased perturbative stability is observed, but corrections are still sizable.
- Significant corrections in double spin asymmetries.

**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

# BACK-UP SLIDES

# NNLO SINGLE-JET PRODUCTION IN DIS

EIC kinematics: $E_p = 275$ GeV $E_e = 18$ GeV

Laboratory Frame (Needed for the P2B mapping)

Kinematical cuts:

$$0.04 < y < 0.95, \qquad 5\,\text{GeV} < p_T^L < 36\,\text{GeV},$$
$$25\,\text{GeV}^2 < Q^2 < 1000\,\text{GeV}^2 \qquad |\eta^L| < 3,$$

NLO PDFS:
DSSV14 MC (polarized case)/PDF4LHC15 (unpolarized case)

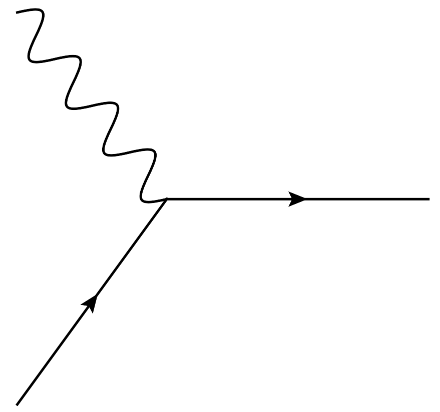
Central Scale: $\mu_F^2 = \mu_R^2 = Q^2 \equiv \mu_0$

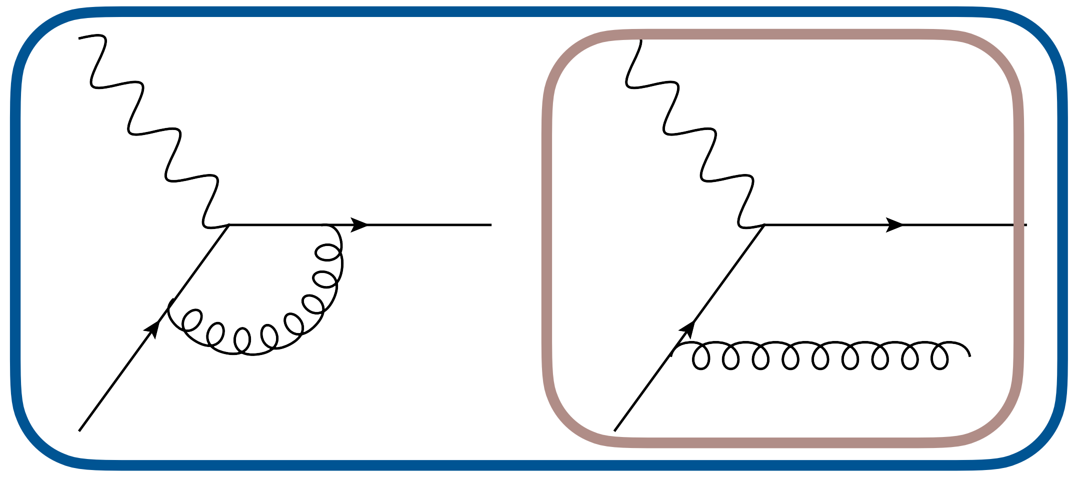
$k_T$ jet algorithm (R=0.8)

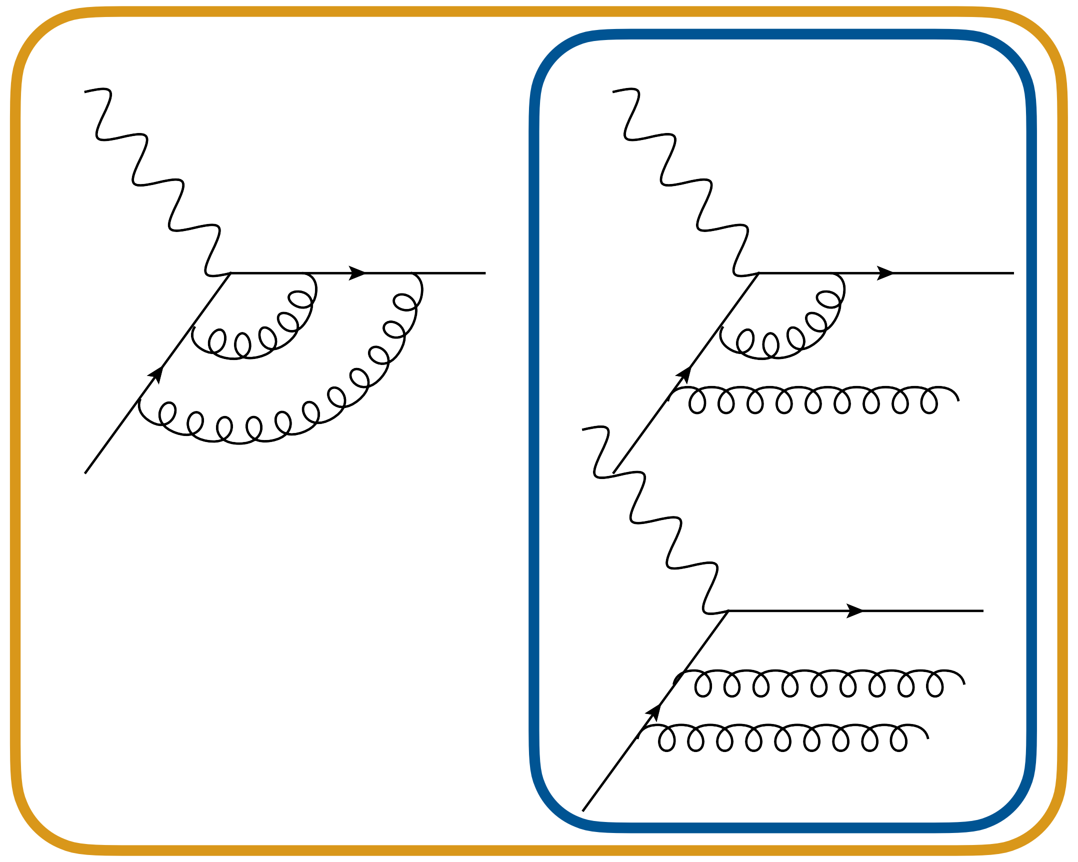
Seven-Point independent variation to estimate theoretical uncertainty

# IMPLEMENTATION - PROJECTION TO BORN (P2B)

| | Inclusive cross section | Single-Jet | Di-jet |
|---|---|---|---|
| $\alpha_S^0$ | $q\gamma^* \to q$ LO | $q\gamma^* \to q$ | |
| $\alpha_S^1$ | $q\gamma^* \to q$ 1 loop<br>$q\gamma^* \to qg$<br>$g\gamma^* \to q\bar{q}$ NLO | $q\gamma^* \to q$ 1 loop<br>$q\gamma^* \to qg$<br>$g\gamma^* \to q\bar{q}$ | $q\gamma^* \to qg$<br>$g\gamma^* \to q\bar{q}$ LO |
| $\alpha_S^2$ | $q\gamma^* \to q$ 2 loops<br>$q\gamma^* \to qg$ 1 loop<br>$g\gamma^* \to q\bar{q}$ 1 loop<br>$q\gamma^* \to qgg$<br>$q\gamma^* \to qq\bar{q}$<br>$g\gamma^* \to q\bar{q}g$ NNLO | $q\gamma^* \to q$ 2 loops<br>$q\gamma^* \to qg$ 1 loop<br>$g\gamma^* \to q\bar{q}$ 1 loop<br>$q\gamma^* \to qgg$<br>$q\gamma^* \to qq\bar{q}$<br>$g\gamma^* \to q\bar{q}g$ | $q\gamma^* \to qg$ 1 loop<br>$g\gamma^* \to q\bar{q}$ 1 loop<br>$q\gamma^* \to qgg$<br>$q\gamma^* \to qq\bar{q}$<br>$g\gamma^* \to q\bar{q}g$ NLO |

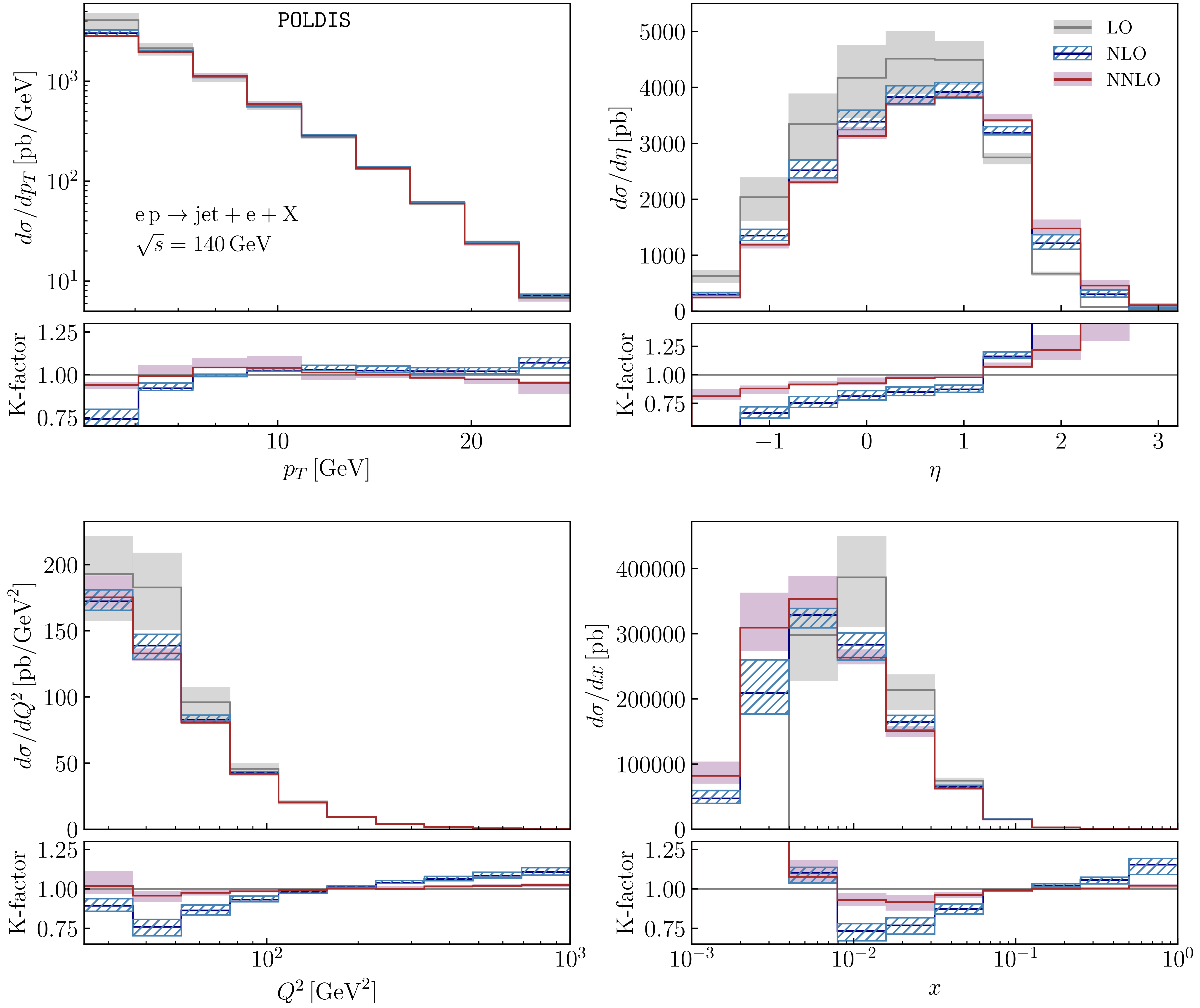






# NNLO SINGLE-JET PRODUCTION IN DIS

## Unpolarized distributions

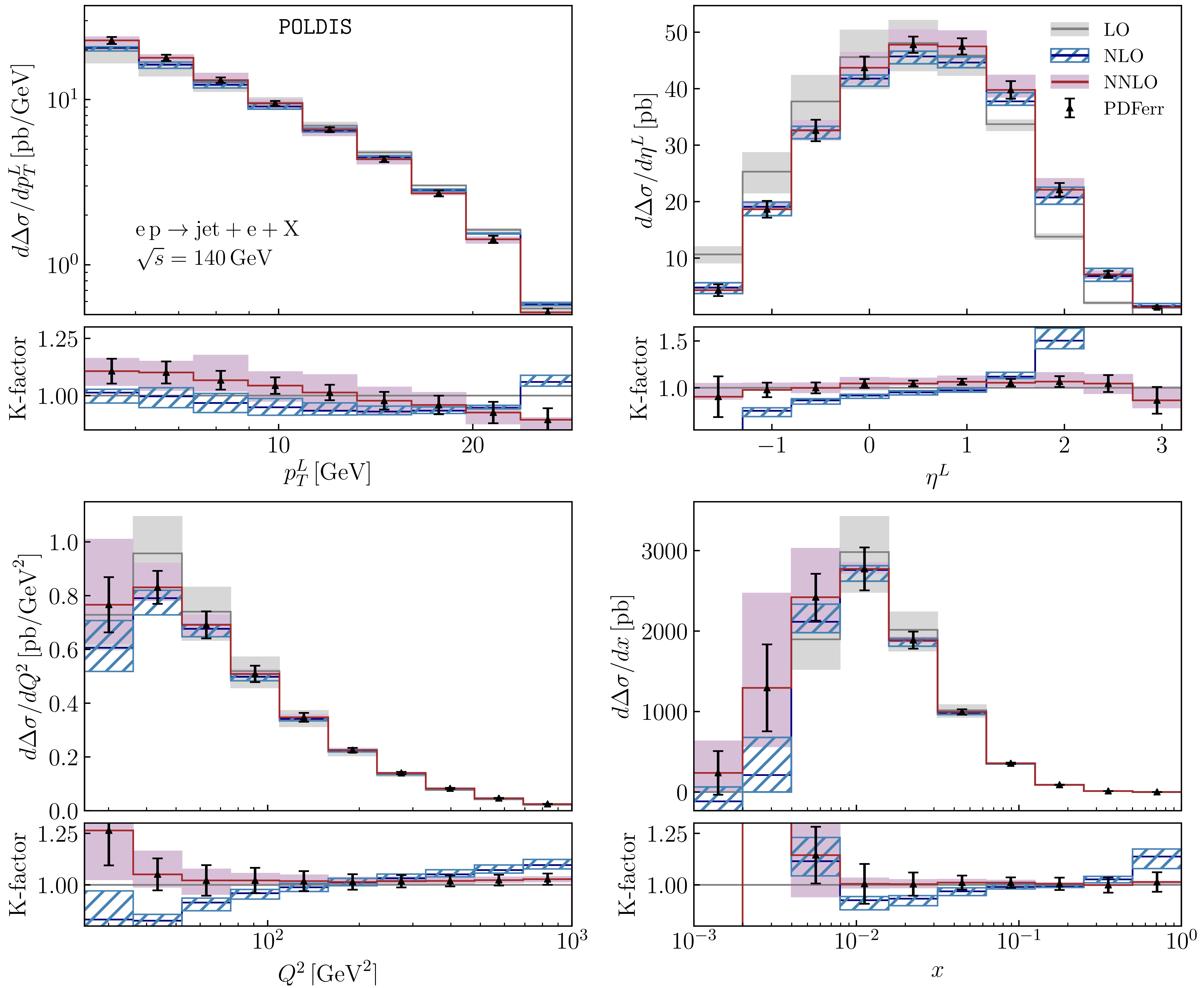



- Improved convergence at NNLO: reduced NNLO/NLO K-factor
- Shift towards larger rapidities and lower $p_T$, as the emission of extra partons populates those regions
- Larger NLO and NNLO corrections for the forward and backward regions
- Milder corrections for central rapidity bins

IB, de Florian, Pedron. Phys.Rev.Lett. 125 (2020)
IB, de Florian, Pedron. Phys.Rev.D 103 (2021)

# NNLO SINGLE-JET PRODUCTION IN DIS

## Polarized distributions

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Stronger scale dependence because of cancellations between partonic channels

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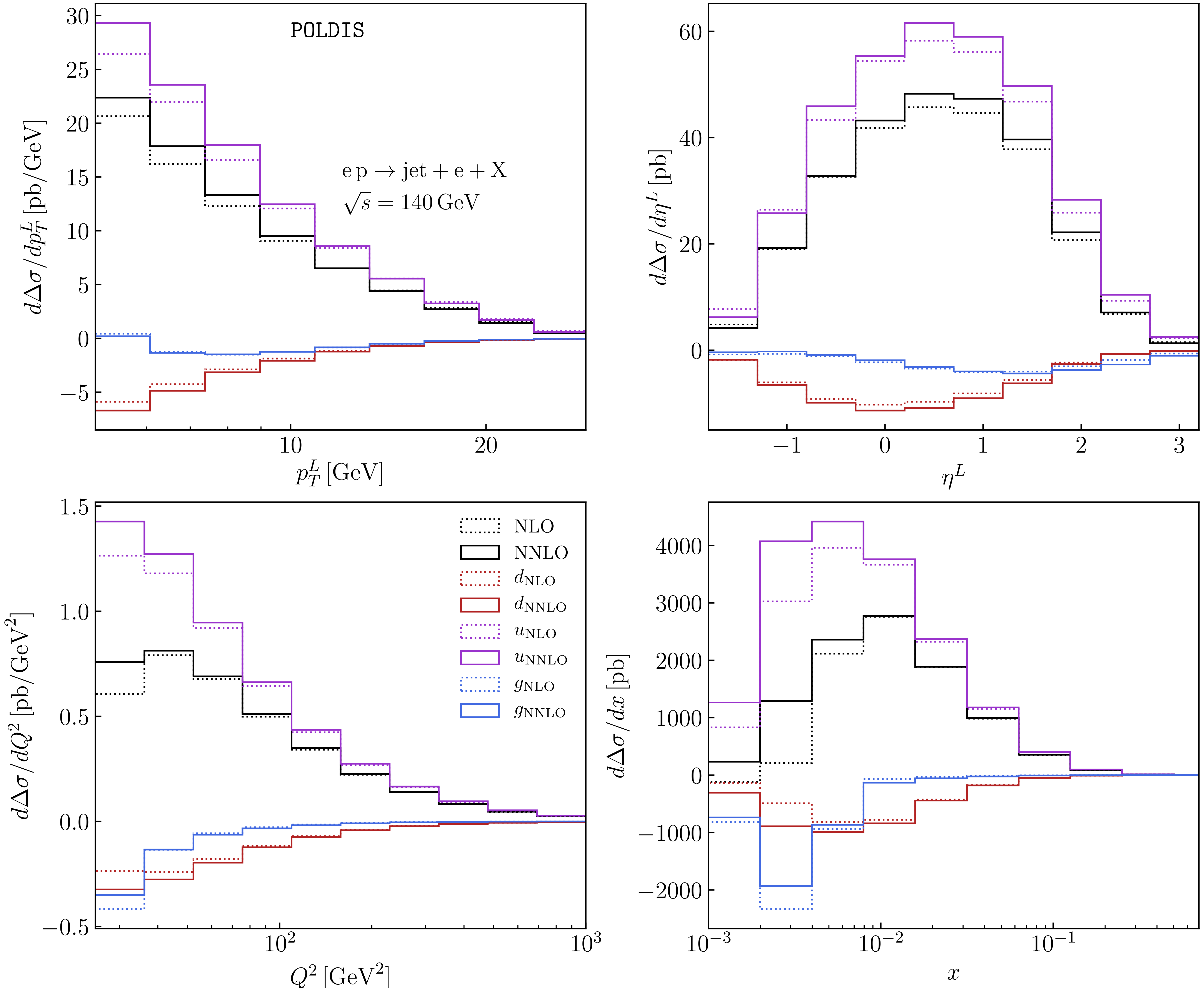


IB, de Florian, Pedron. Phys.Rev.Lett. 125 (2020)
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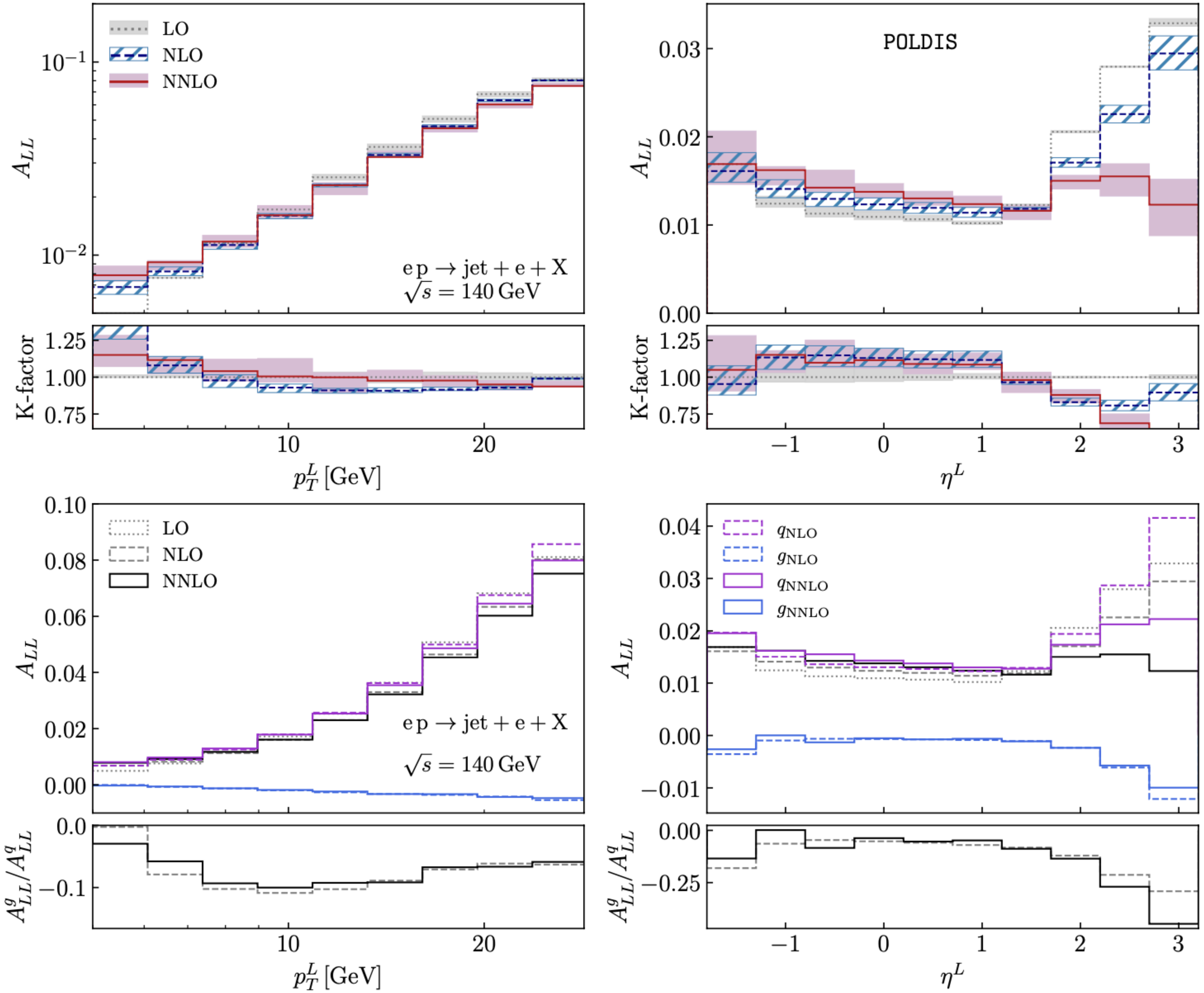
# NNLO SINGLE-JET PRODUCTION IN DIS

## Double spin asymmetries $\rightarrow A_{LL} = \dfrac{\Delta\sigma}{\sigma}$

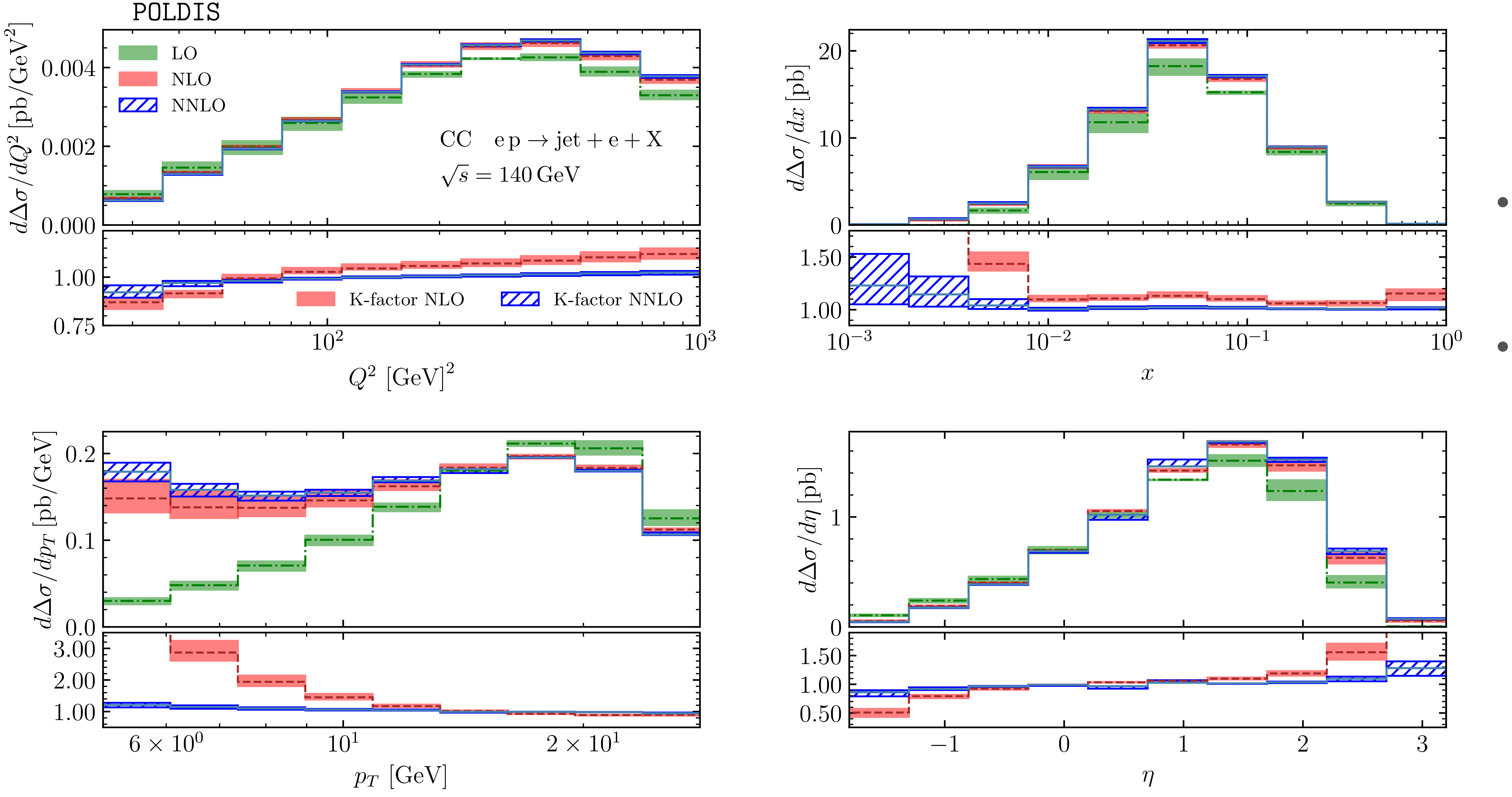



- Cancellations in the polarized cross section lead to small asymmetries $\mathcal{O} \sim 2\,\%$
- Different behavior between polarized and unpolarized leads to significant corrections in the asymmetries, even at NNLO

IB, de Florian, Pedron. Phys.Rev.Lett. 125 (2020)
IB, de Florian, Pedron. Phys.Rev.D 103 (2021)

# PHENOMENOLOGY - NNLO SINGLE-JET PRODUCTION IN DIS

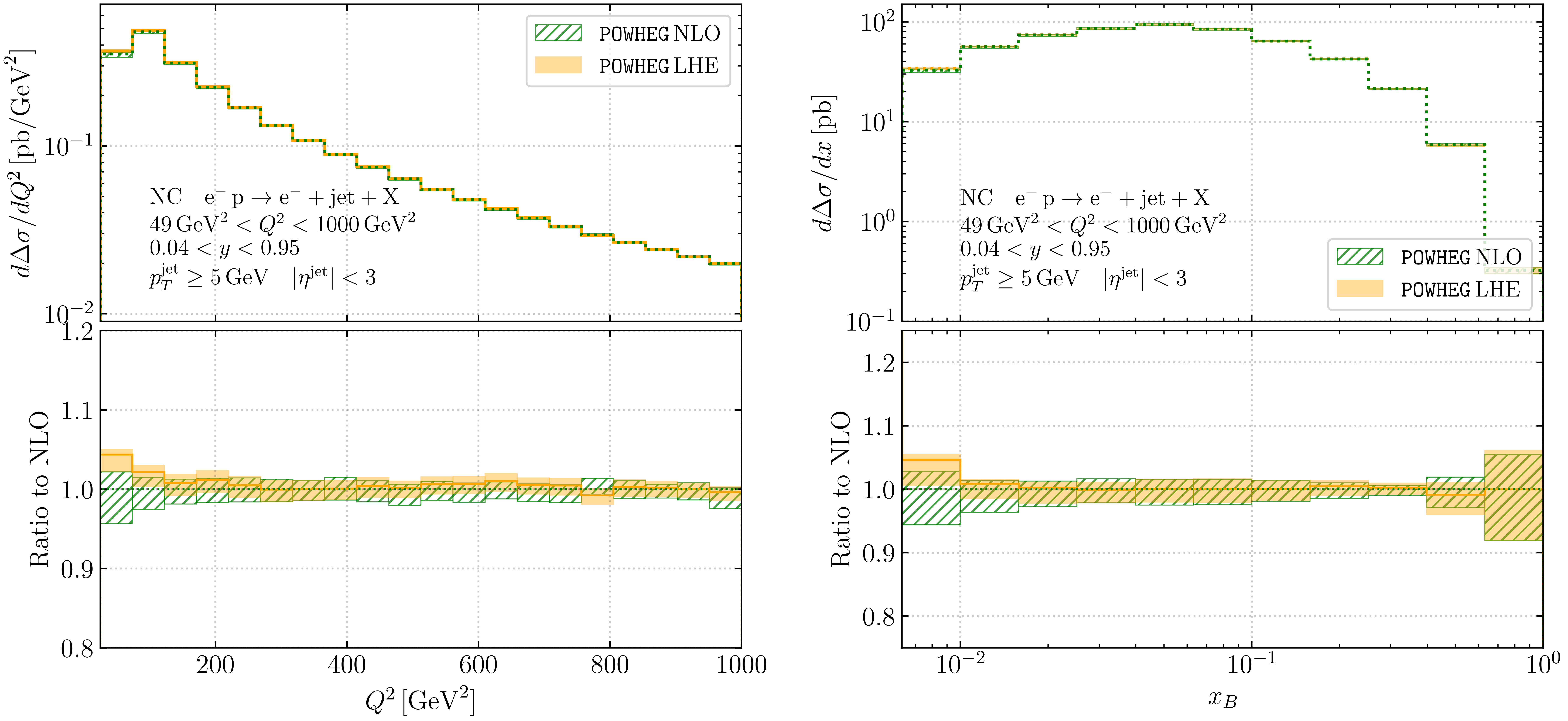
## Charged Current DIS



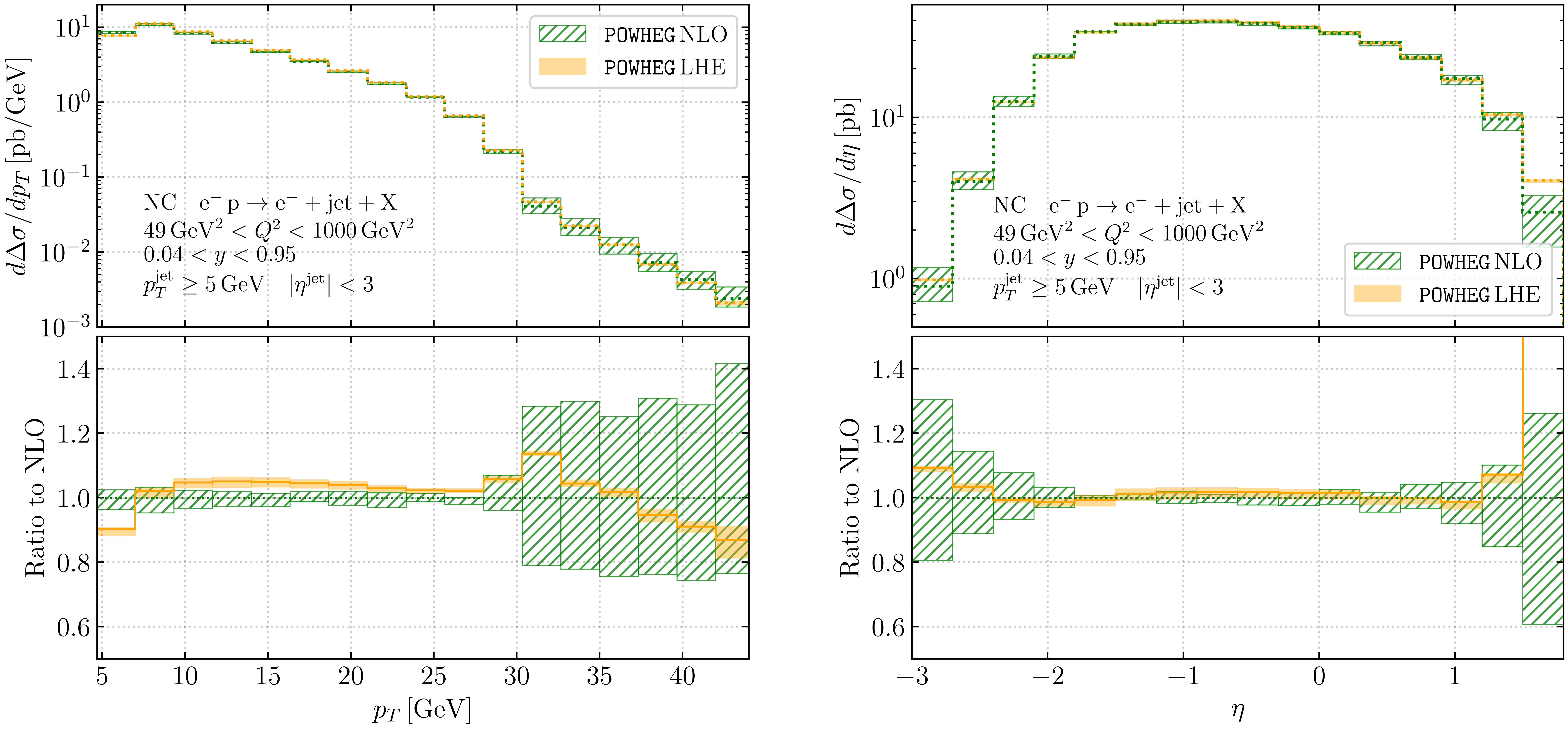

IB, de Florian, Pedron. Phys.Rev.D 107 (2023)

- Suppression at low $Q^2$ due to the massive propagator.
- LO distribution suppressed at low $p_T$, since at that order $p_T$ is proportional to $Q^2$. Sizable corrections at higher orders.

# NLO + PARTON SHOWER - POWHEG



# NLO + PARTON SHOWER - POWHEG



# NLO + PARTON SHOWER - POWHEG