Jet Production in Polarized Deep Inelastic Scattering

Ivan Pedron

in collaboration with Ignacio Borsa and Daniel de Florian
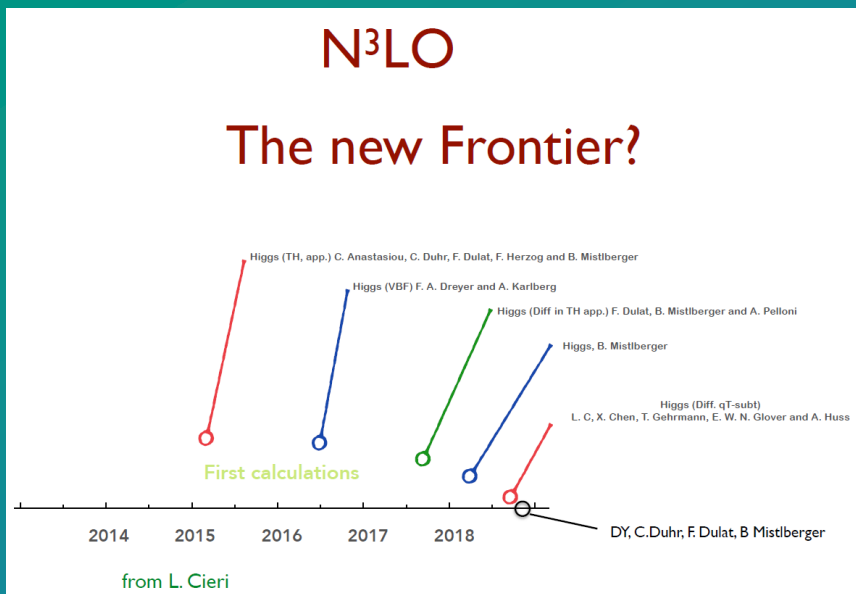
EINN2023

QCD analysis of nucleon structure

01.11.2023

www.kit.edu

The status of precision QCD (not so long ago)

UNPOLARIZED SECTOR

N³LO

The new Frontier?

Higgs (TH, app.) C. Anastasiou, C. Duhr, F. Dulat, F. Herzog and B. Mistlberger

Higgs (VBF) F. A. Dreyer and A. Karlberg

Higgs (Diff in TH app.) F. Dulat, B. Mistlberger and A. Pelloni

Higgs, B. Mistlberger

Higgs (Diff. qT-subt)
L. C, X. Chen, T. Gehrmann, E. W. N. Glover and A. Huss

First calculations

2014   2015   2016   2017   2018

DY, C.Duhr, F. Dulat, B Mistlberger

from L. Cieri
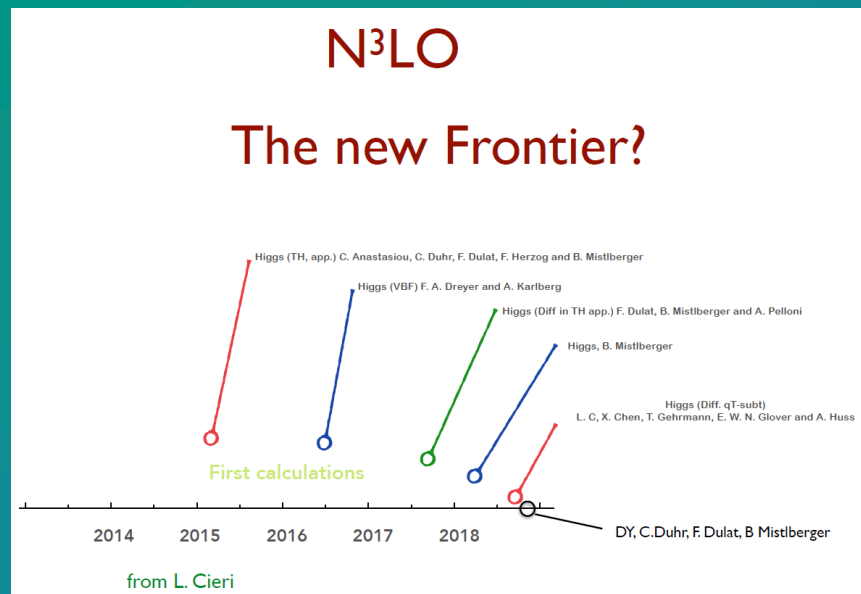
And it still keeps going...

POLARIZED SECTOR

- g1 NNLO - van Neerven, Zijlstra ('94)

- NNLO splittings – Moch, Vermaseren, Vogt ('14)

...

The status of precision QCD (not so long ago)

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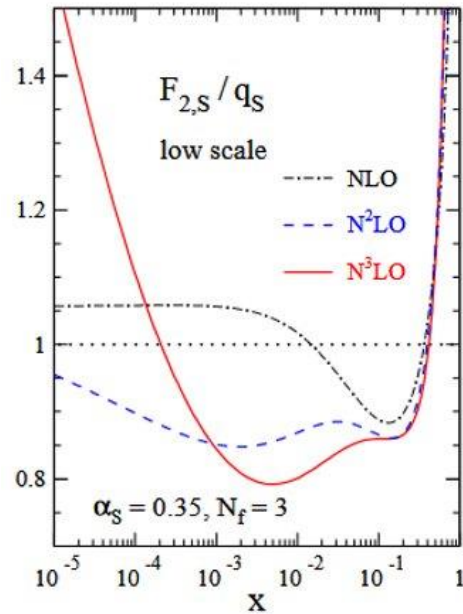And it still keeps going...

POLARIZED SECTOR

- g1 NNLO - van Neerven, Zijlstra ('94)

- NNLO splittings – Moch, Vermaseren, Vogt ('14)

- NNLO singlejet DIS - Borsa, de Florian, **IP** ('20)

- NNLO W production - Boughezal, Li, Petriello ('21)

- NNLO+ SIDIS (approx.) - Abele, de Florian, Vogelsang ('22)

- N3LO g1 - Blumlein, Marquard, Schneider, Schönwald ('22)

The need of higher order corrections

Significant correctios even in inclusive observables!!!
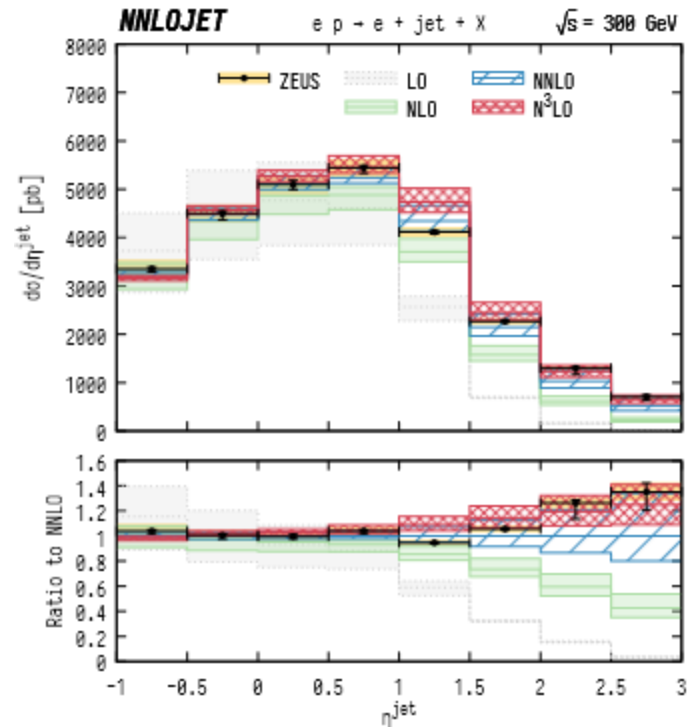
Vermaseren, Vogt, Moch ('05)

$$\sigma_a = \sigma_a^{(0)} + \frac{\alpha_s}{2\pi}\sigma_a^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma_a^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma_a^{(3)} + \cdots$$

LO   NLO   NNLO   N3LO
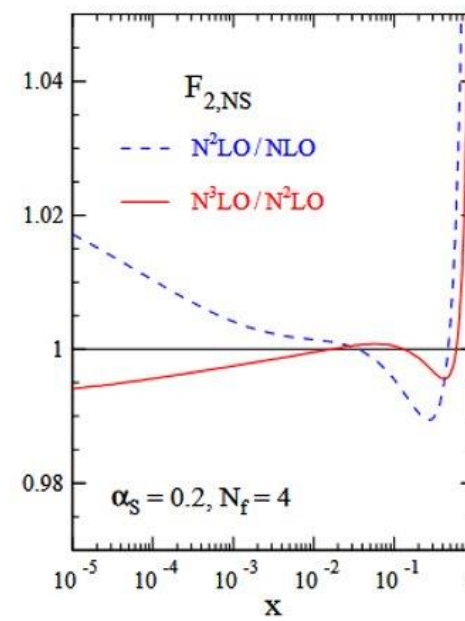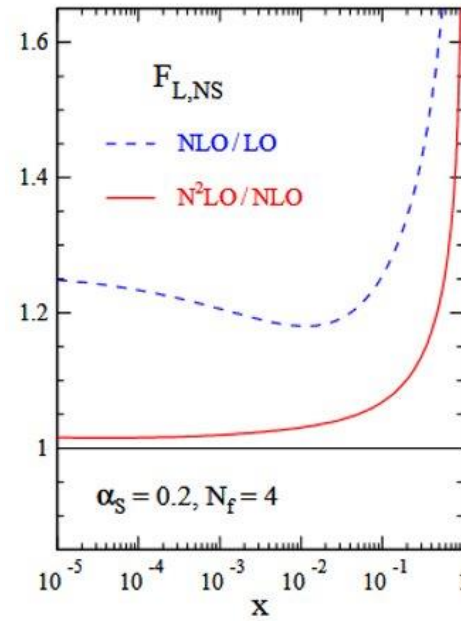
DIS structure functions

$$W_{\mu\nu}^i = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right)\left[F_1^i(x,Q^2) - \frac{h}{2}\,g_5^i(x,Q^2)\right]$$
$$+ \frac{\left(p_\mu - \frac{p\cdot q}{q^2}q_\mu\right)\left(p_\nu - \frac{p\cdot q}{q^2}q_\nu\right)}{p\cdot q}\left[F_2^i(x,Q^2) - \frac{h}{2}\,g_4^i(x,Q^2)\right]$$
$$- i\epsilon_{\mu\nu\alpha\beta}\frac{q^\alpha p^\beta}{2p\cdot q}\left[F_3^i(x,Q^2) + h\,g_1^i(x,Q^2)\right],$$
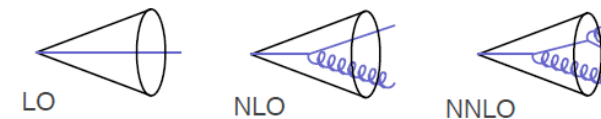
The need of higher order corrections

- New partonic channels at higher orders (e.g. gluons in DIS)
- Parton luminosities can produce sizable corrections (interrelation with PDFs)

- QCD jets acquiree internal structure
- Better matching of jets with experiments

Currie, Gehrmann, Glover, Huss, Niehues, Vogt ('18)

Current status of jets in polarized DIS

Status on jet production in polarized DIS:

- Not much interest in fixed-target
- 1jet at NLO (N-jetiness)

    Boughezal, Petriello, Xing ('18)

- 2jets at NLO (dipoles)

    Photon - Borsa, de Florian, **IP** ('20)
    NC & CC - Borsa, de Florian, **IP** ('21)

- 1jet at NNLO (dipoles + P2B)

    Photon - Borsa, de Florian, **IP** ('20)
    NC & CC - Borsa, de Florian, **IP** ('23)

Status on polarized inclusive DIS:

Structure function coefficients available at

- NNLO (photon - g1)

    van Neerven, Zijlstra ('94)

- NNLO (NC & CC - g1, g4, g5)

    Borsa, de Florian, **IP** ('22)

- N3LO (photon – g1)*

- Blumlein, Marquard, Schneider, Schönwald ('22)

Dipole subtraction (NLO)

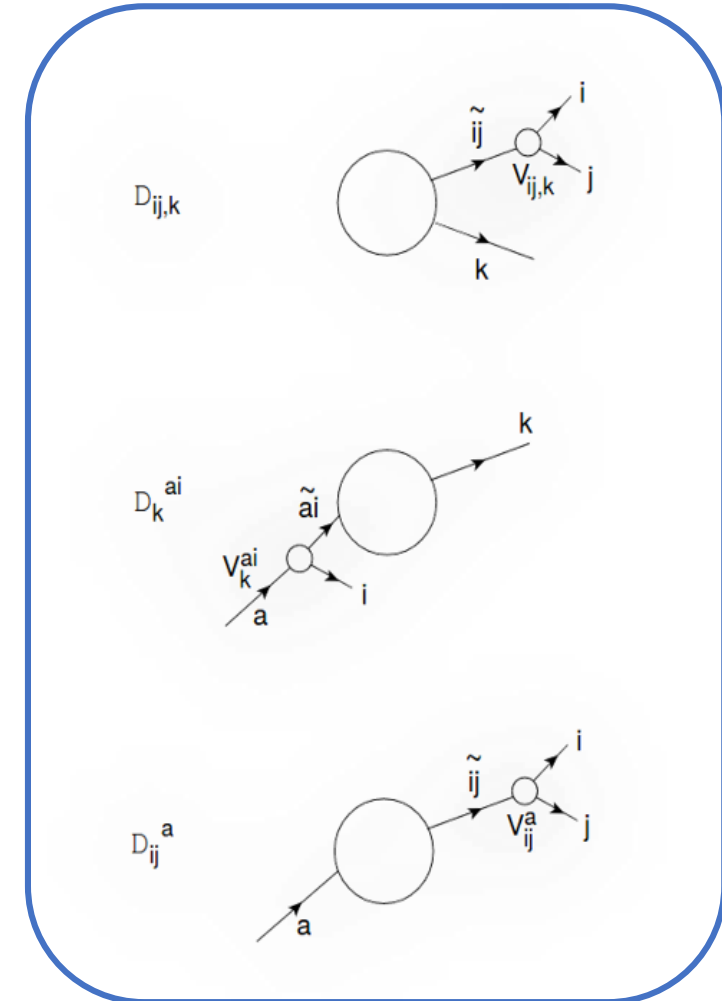As in any subtraction method, we build a counterterm **A** that

- Matches the IR behavior of real emission
- Is easily integrated to cancel IR divergences of virtual piece

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

They are **process independent**, and they are based on the factorization formula:

$$d\sigma^A = \sum_{\text{dipoles}} d\sigma^B \otimes dV_{\text{dipole}}$$

Catani, Seymour ('96)

Polarized dipole subtraction (NLO)

$$d\Delta\sigma \equiv \frac{1}{4}\left(d\sigma^{++} - d\sigma^{+-} - d\sigma^{-+} + d\sigma^{--}\right)$$

As in any subtraction method, we build a counterterm A that

- Matches the IR behavior of real emission
- Is easily integrated to cancel IR divergences of virtual piece

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

Differences only in
initial state
dipoles!!

They are **process independent**, and they are ba
factorization formula:

$$d\sigma^A = \sum_{\text{dipoles}} d\sigma^B \otimes dV_{\text{dipole}}$$

Catani, Seymour ('96) - Borsa, de Florian, **IP** ('20)
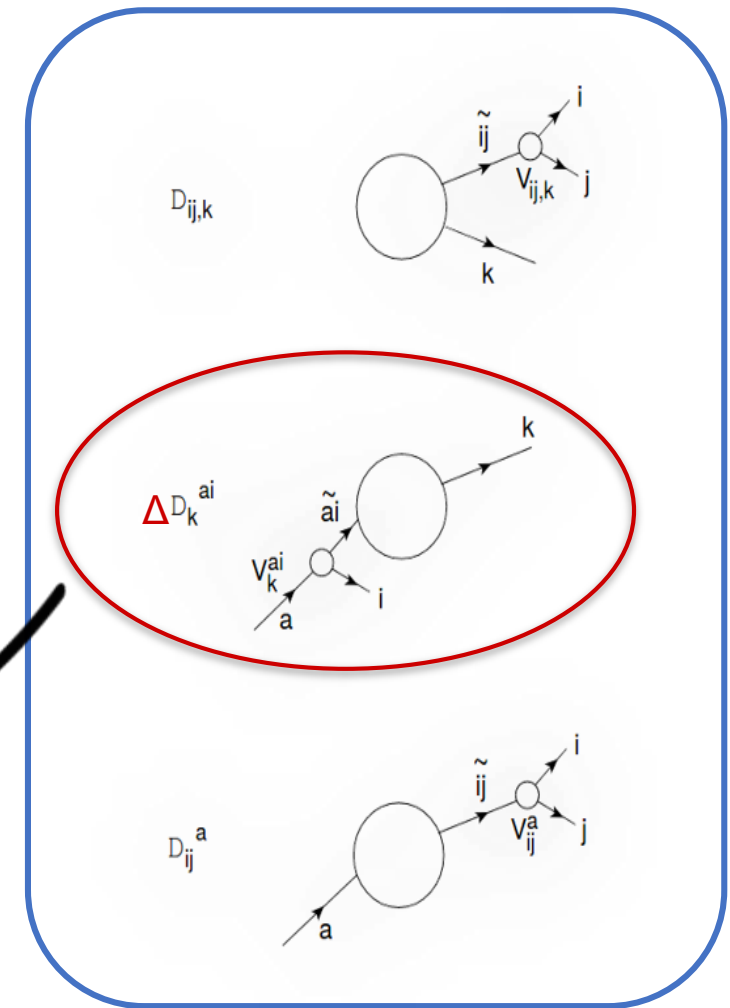
NNLO – Projection-to-Born method (P2B)

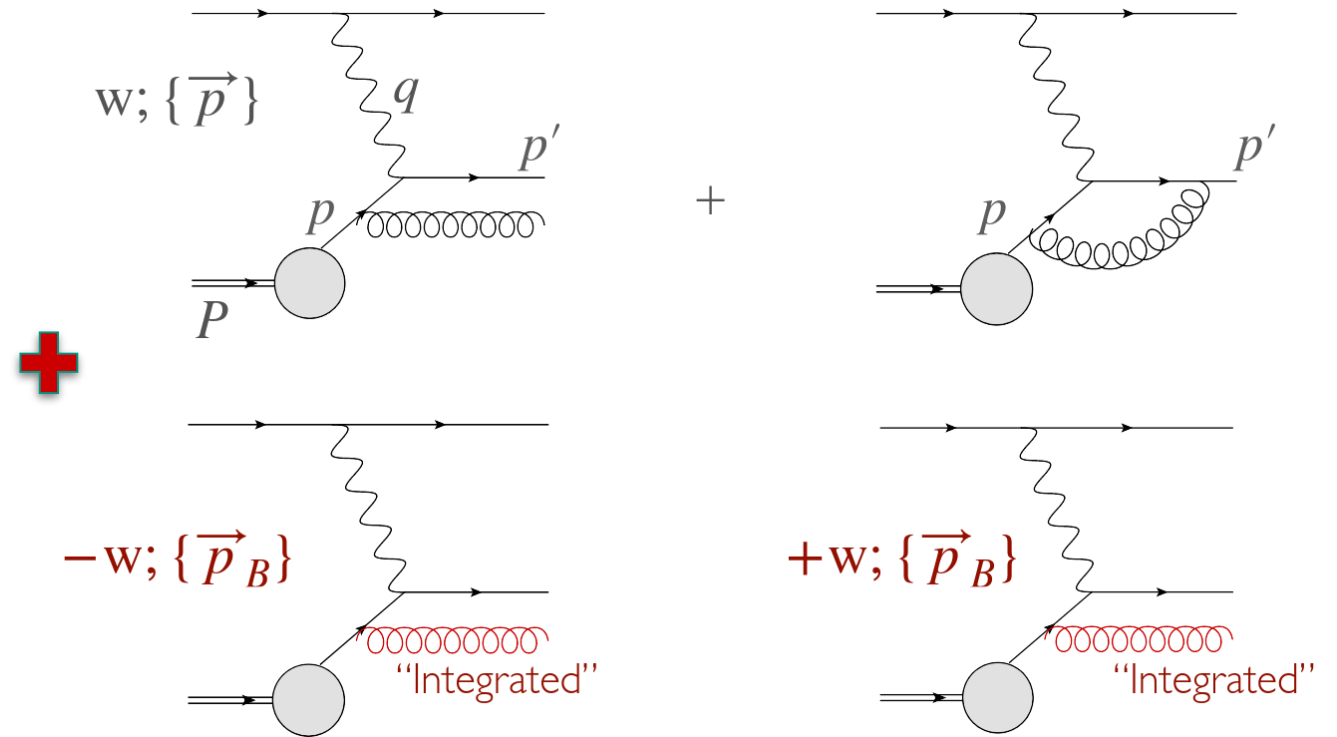Obtain the **fully differential** cross section from

- The **inclusive** cross section at the desired order
- The exclusive cross section of the **observable + 1 jet at one lower order**

Born kinematics mapping:

$$p_B = xP$$
$$p'_B = p_B + q$$

Not possible in the Breit-frame!!

$$d\sigma_{\mathcal{O}}^{\mathrm{NLO}} = d\sigma_{\mathcal{O}+jet}^{\mathrm{LO}} - d\sigma_{\mathcal{O}+jet,\mathrm{P2B}}^{\mathrm{LO}} + d\sigma_{\mathcal{O}}^{\mathrm{NLO,\ incl}}$$

NNLO – Projection-to-Born method (P2B)

Obtain the **fully differential** cross section from

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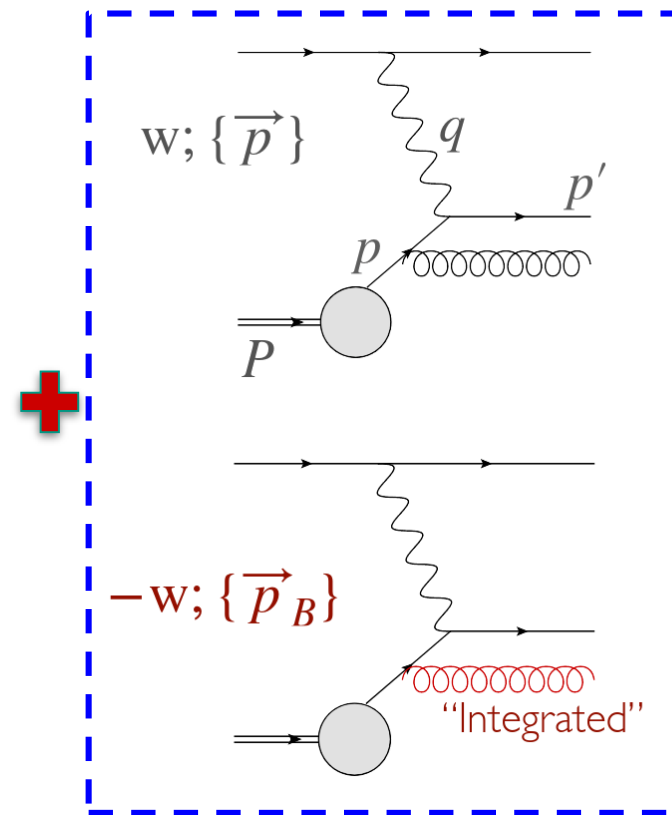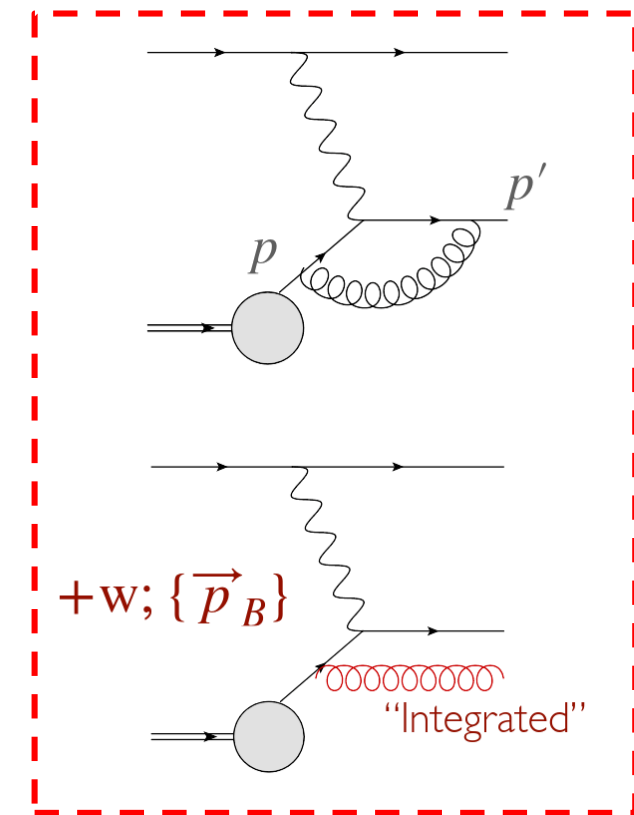
Born kinematics mapping:

$$p_B = xP$$
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Not possible in the Breit-frame!!

Finite/integrable in 4-dimensions

Inclusive cross section

$$d\sigma_{\mathcal{O}}^{\mathrm{NLO}} = d\sigma_{\mathcal{O}+jet}^{\mathrm{LO}} - d\sigma_{\mathcal{O}+jet,\mathrm{P2B}}^{\mathrm{LO}} + d\sigma_{\mathcal{O}}^{\mathrm{NLO,\ incl}}$$

NNLO – Projection-to-Born method (P2B)

Obtain the **fully differential** cross section from

- The **inclusive** cross section at the desired order
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In our case…

Born kinematics mapping:

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Not possible in the Breit-frame!!
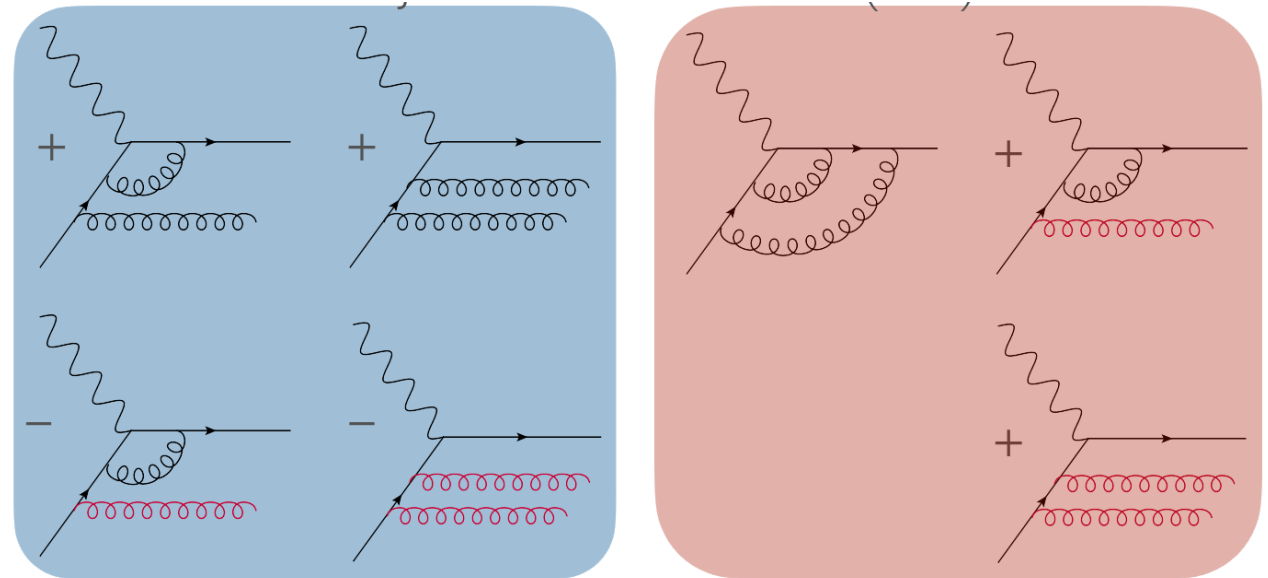
$$d\sigma_{1jet}^{\mathrm{NNLO}} = d\sigma_{2jet}^{\mathrm{NLO}} - d\sigma_{2jet,\mathrm{P2B}}^{\mathrm{NLO}} + d\sigma_{1jet}^{\mathrm{NNLO, incl}}$$

Dipoles   Structure Functions

Parity violating (PV) contributions to DIS

Links between polarized and parity violating processes

$$\sigma^{\mathrm{PV}} \longleftrightarrow \Delta\sigma^{\mathrm{NPV}}$$
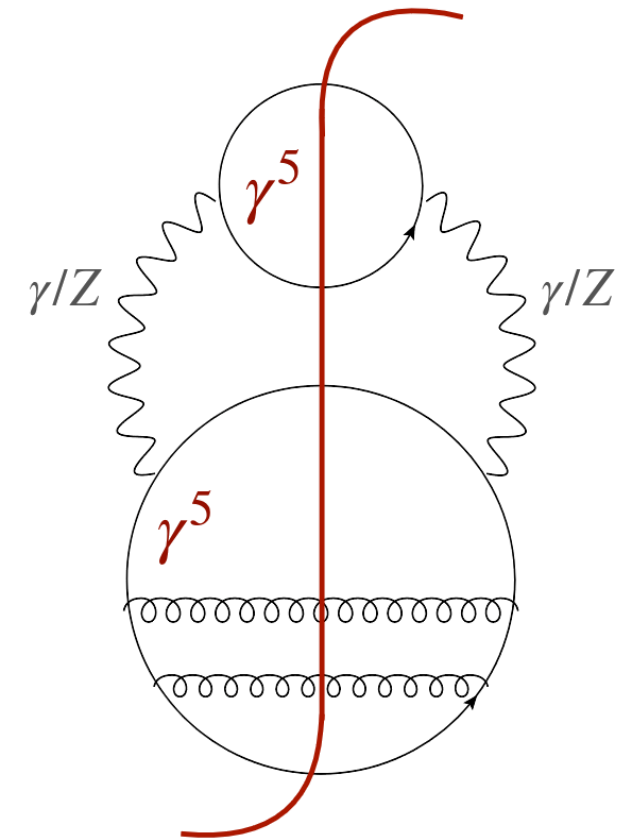
$$\Delta\sigma^{\mathrm{PV}} \longleftrightarrow \sigma^{\mathrm{NPV}}$$

- Trivial in **real contributions** (4-dimensional)
- Only valid in **virtual** ones after vertex simmetrization and finite renormalization (d-dimensional)

$$-ie\left(C_V + C_A\,\gamma^5\right) \rightarrow -ie\left(C_V\,\gamma^\mu + C_A\,\tilde{\gamma}^\mu\gamma^5\right)$$

$$(\Delta)C_T = \alpha_s\,4C_F\,d(\Delta)\hat{\sigma}^{\mathrm{LO}}_{\mathrm{axial}}$$

(restauration of axial Ward identity)

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

Parity violating (PV) contributions to DIS

Quark channel

Gluon channel

γ^5 EVEN

- Unpolarized NPV
- Polarized PV

$$\text{“}\Delta\hat{\sigma}_q^{PV} = \hat{\sigma}_q^{NPV}\text{”}$$

γ^5 ODD

- Unpolarized PV
- Polarized NPV

$$\text{“}\hat{\sigma}_q^{PV} = \Delta\hat{\sigma}_q^{NPV}\text{”}$$

γ^5 EVEN

No analog relation!

γ^5 ODD

- Unpolarized PV
- Polarized NPV

$$\text{“}\hat{\sigma}_g^{PV} = -\Delta\hat{\sigma}_q^{NPV}\text{”}$$

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

VALID FOR

$$q + W/Z \to q, \; q + W/Z \to q + g \text{ and } q + W/Z \to q + g + g$$

However, PV contributions with initial gluons cancel due to charge conjugation arguments!

Parity violating (PV) Structure Functions

The unpolarized F_3 was known at NNLO (van Neerven, Zijlstra ('92)), but it's polarized equivalents g_4 y g_5 not
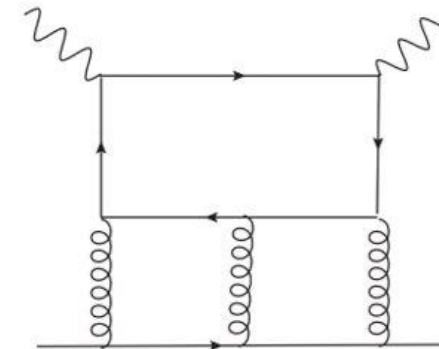
We get g_4 & g_5 at NNLO out of F_2 y F_1 by the axial Ward identities since

- Initial gluon contributions vanish

- Ignore triangle terms in NC

$$W^i_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right)\left[F^i_1(x, Q^2) - \frac{h}{2}\, g^i_5(x, Q^2)\right]$$
$$+ \frac{\left(p_\mu - \frac{p\cdot q}{q^2}q_\mu\right)\left(p_\nu - \frac{p\cdot q}{q^2}q_\nu\right)}{p\cdot q}\left[F^i_2(x, Q^2) - \frac{h}{2}\, g^i_4(x, Q^2)\right]$$
$$- i\epsilon_{\mu\nu\alpha\beta}\frac{q^\alpha p^\beta}{2p\cdot q}\left[F^i_3(x, Q^2) + h\, g^i_1(x, Q^2)\right],$$

$$L^{\mu\nu}_\gamma = 2\left(-k\cdot k' g^{\mu\nu} + k^\mu k'^\nu + k'^\mu k^\nu - i\lambda\epsilon^{\mu\nu\alpha\beta}k_\alpha k'_\beta\right),$$
$$L^{\mu\nu}_z = (g^e_V + e\lambda g^e_A)^2\, L^{\mu\nu}_\gamma,$$
$$L^{\mu\nu}_{\gamma/z} = (g^e_V + e\lambda g^e_A)\, L^{\mu\nu}_\gamma,$$
$$L^{\mu\nu}_W = (1 + e\lambda)^2\, L^{\mu\nu}_\gamma,$$

Borsa, de Florian, **IP** ('22)

Parity violating (PV) Structure Functions

The unpolarized F_3 was known at NNLO (van Neerven, Zijlstra ('92)), but it's polarized equivalents g_4 y g_5 not

$$\Delta C_4^{j,g,(2)} = \Delta C_L^{j,g,(2)} = 0,$$
$$\Delta C_4^{j,\mathrm{NS},(2)} = \Delta C_4^{j,\mathrm{S},(2)} = C_2^{j,\mathrm{NS},(2)},$$
$$\Delta C_L^{j,\mathrm{NS},(2)} = \Delta C_L^{j,\mathrm{S},(2)} = C_L^{j,\mathrm{NS},(2)}.$$

(Pure-singlet PV cancels at NNLO)

We get g_4 & g_5 at NNLO out of F_2 y F_1 by the axial Ward identities since

- Initial gluon contributions vanish

- Ignore triangle terms in NC

No longer valid at N3LO!

POLDIS

```
################################################################
# #                                                        # #
# #         __    __    _                                  # #
# #        |  \/  |   (_)                                  # #
# #        | |_) | ___| |  _____                           # #
# #        |  _ \ / _ \ |/  / _ \                          # #
# #        | |_) | (_) |   <(_) |                          # #
# #        |_____/ \___/|_|\_\___/                         # #
# #                                                        # #
################################################################
# #       by  I. Borsa, D.de Florian & I. Pedron (2020)    # #
################################################################
# Significant extension of DISENT v0.1 by Mike Seymour, with   #
# minor modifications by Gavin Salam. It includes polarization #
# of initial estate particles and the Projection-to-Born method #
# to obtain exclusive NNLO results.                            #
#                                                              #
# NOTE: a bug was found in one of the dipoles of the gluon     #
#       channel in DISENT v0.1!!! This accounts for the        #
#       discrepancies observed with respect to DISASTER++ in   #
#       G. McCance, DESY-PROC-1999-02, also hep-ph/9912481, and #
#       V. Antonelli, M. Dasgupta and G.P. Salam,              #
#       JHEP 0002 (2000) 001, among others.                    #
################################################################
```

Calculation implemented in our Monte Carlo code POLDIS

- (un)polarized NNLO singlejet in lab frame, for NC and CC

- (un)polarized dijets at NLO in lab frame or Breit frame, for NC and CC

NNLO Jet production at EIC

UNPOLARIZED
NEUTRAL CURRENTS

- Small Z contribution (photon interference mostly)
- Good perturbative convergence

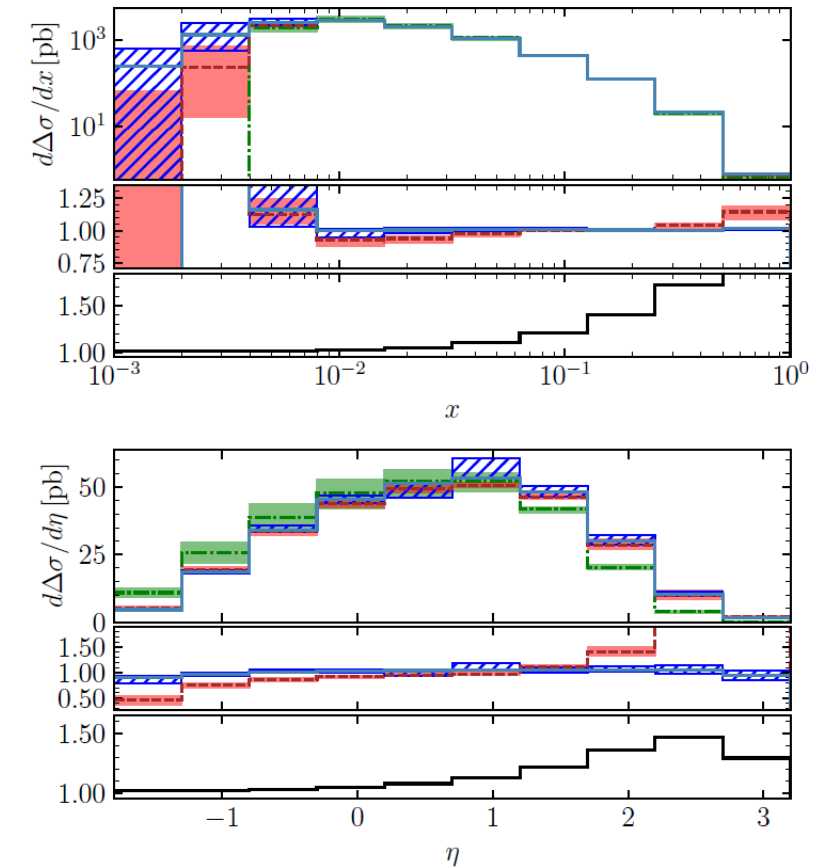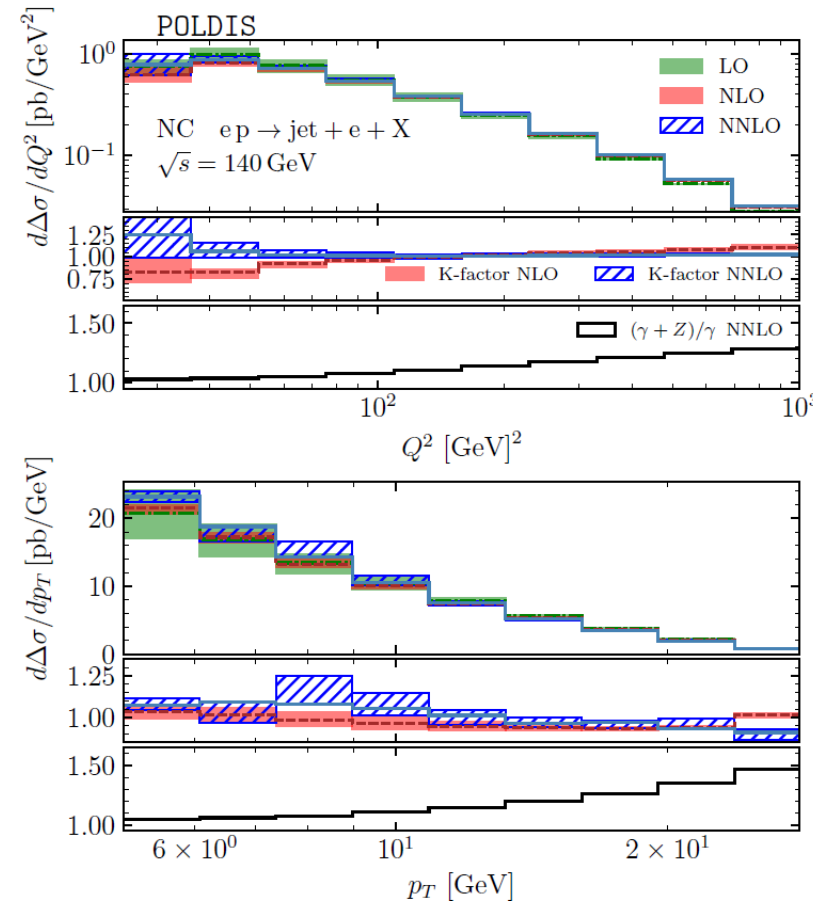Borsa, de Florian, **IP** ('23)
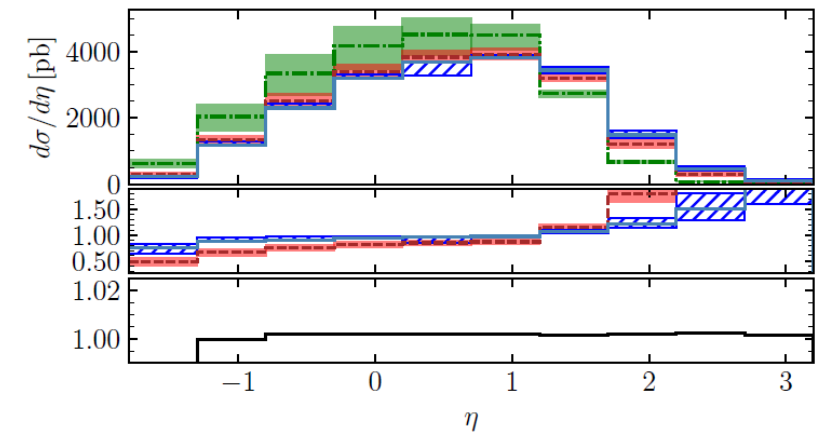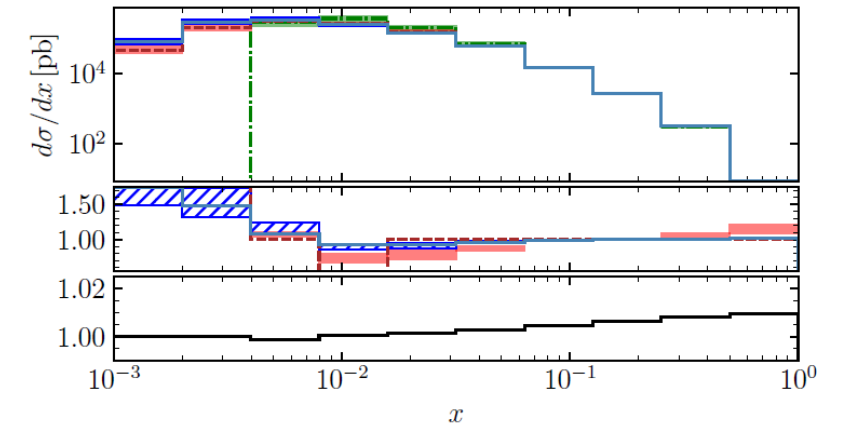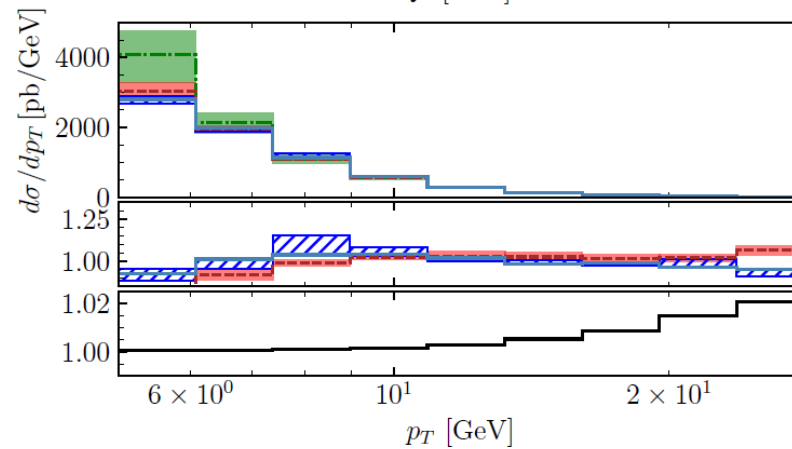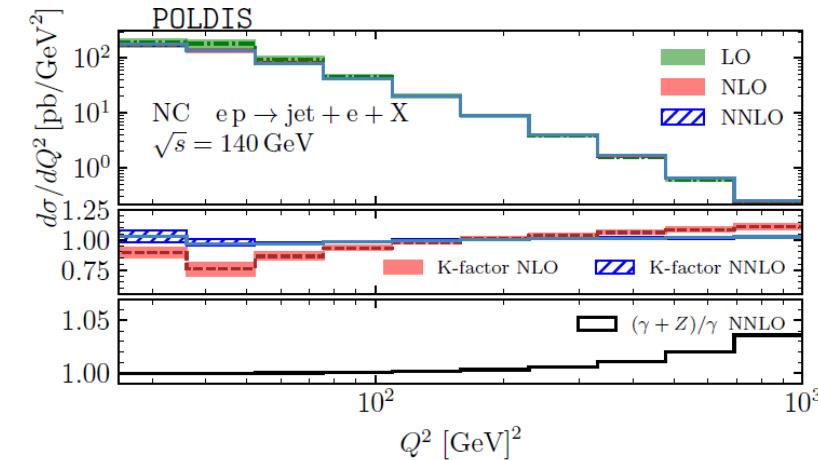
NNLO Jet production at EIC

***POLARIZED* NEUTRAL CURRENTS**

- Enhanced contribution at high Q2, x and pt (PV terms and cancelations)
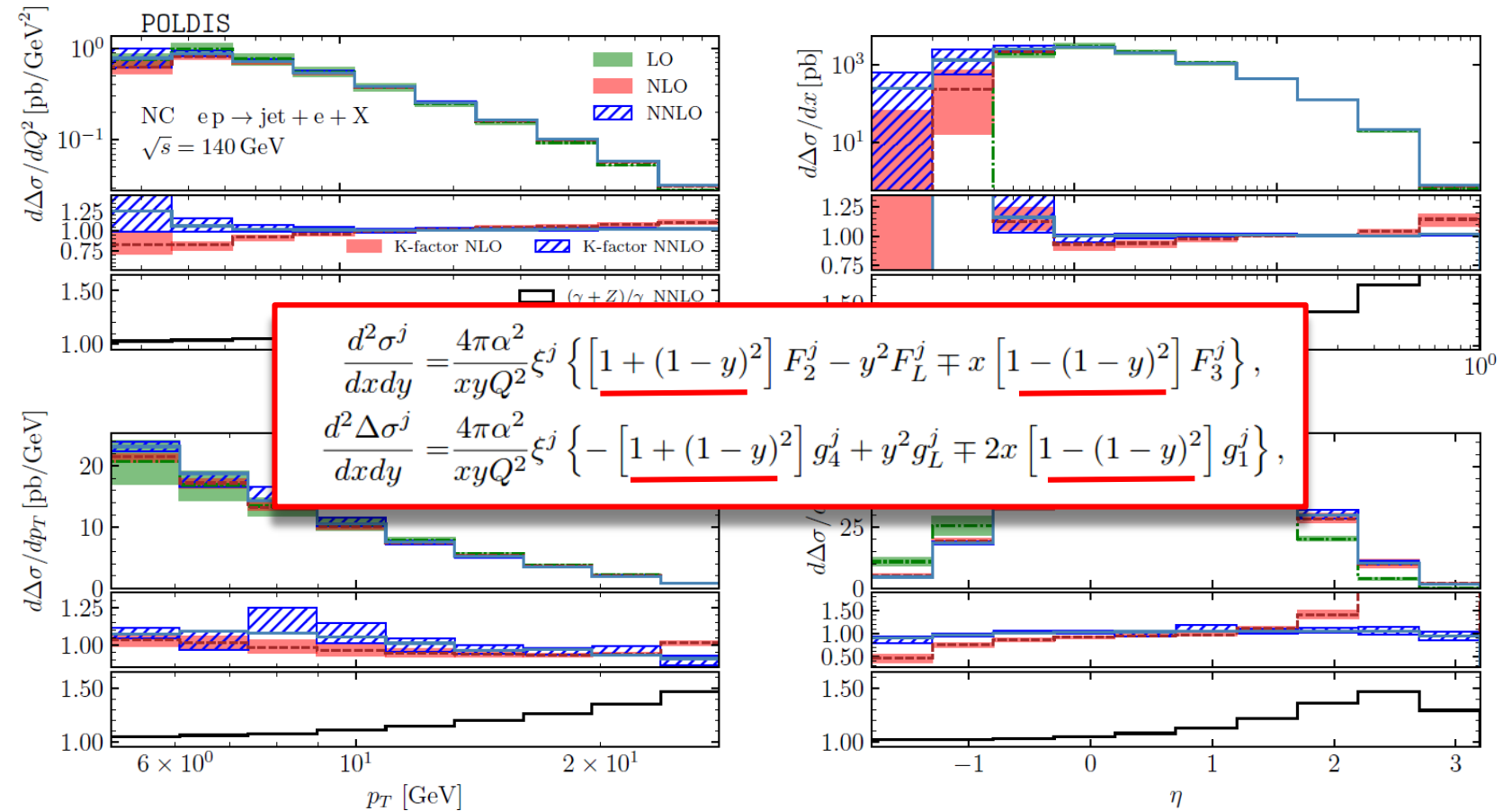- Sizable effect on spin asymmetries!

Borsa, de Florian, **IP** ('23)

NNLO Jet production at EIC

POLARIZED NEUTRAL
CURRENTS

- Enhanced contribution at high Q2, x and pt (PV terms and cancelations)
- Sizable effect on spin asymmetries!

Borsa, de Florian, **IP** ('23)

$$\frac{d^2\sigma^j}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\xi^j \left\{ \left[1 + (1-y)^2\right] F_2^j - y^2 F_L^j \mp x \left[1 - (1-y)^2\right] F_3^j \right\},$$

$$\frac{d^2\Delta\sigma^j}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\xi^j \left\{ -\left[1 + (1-y)^2\right] g_4^j + y^2 g_L^j \mp 2x \left[1 - (1-y)^2\right] g_1^j \right\},$$

NNLO Jet production at EIC

SPIN ASYMMETRIES NEUTRAL CURRENTS

- Enhanced contribution at high Q2, x and pt (PV terms and cancelations)
- Sizable effect on spin asymmetries!

Borsa, de Florian, **IP** ('23)
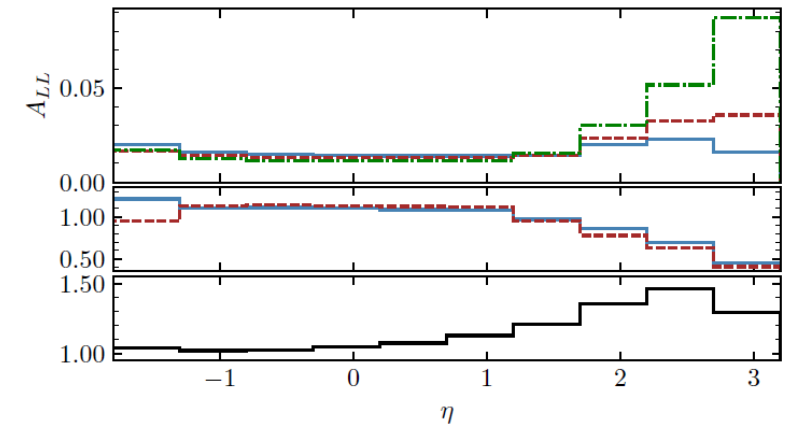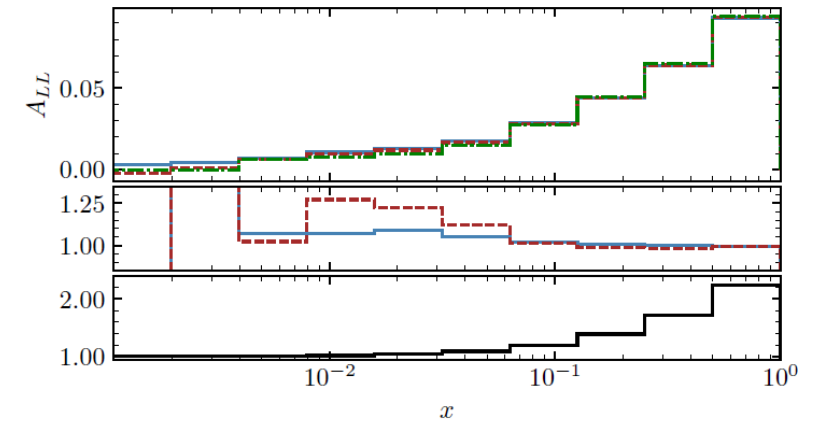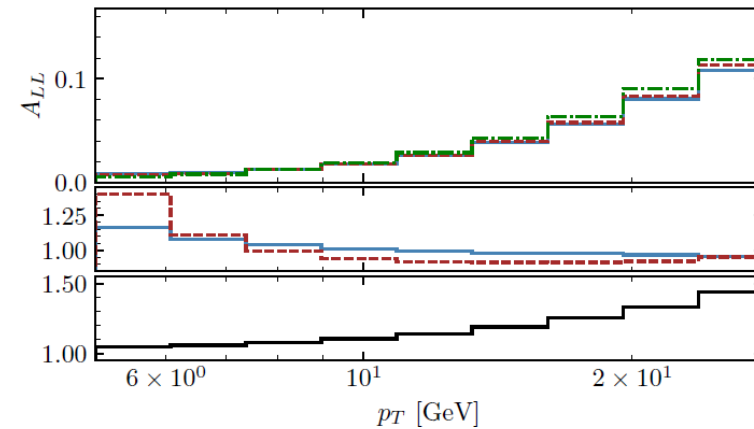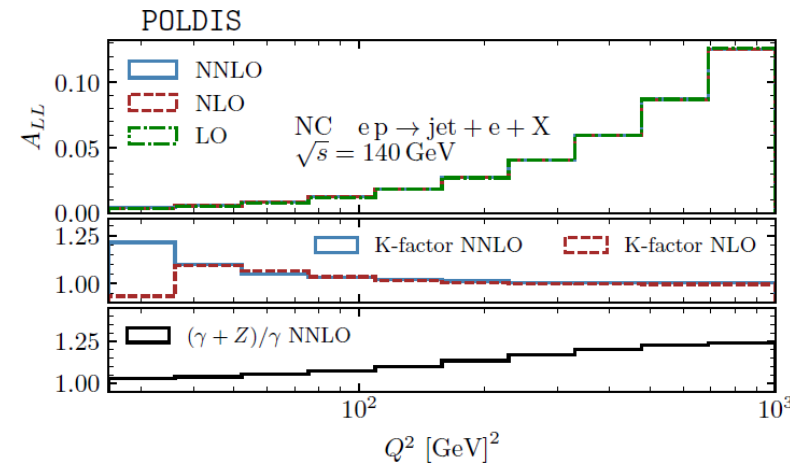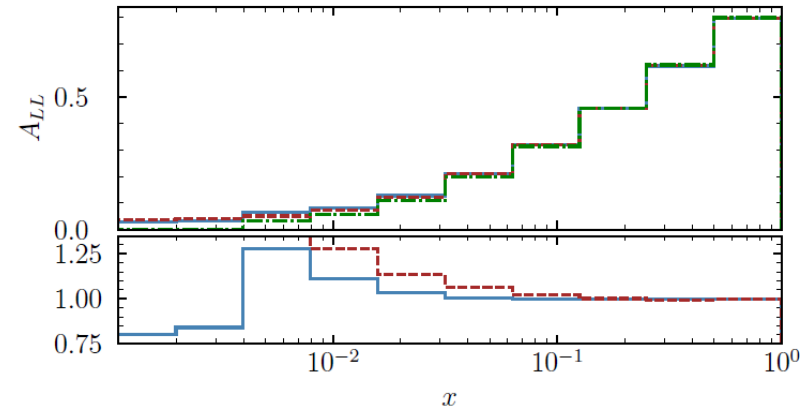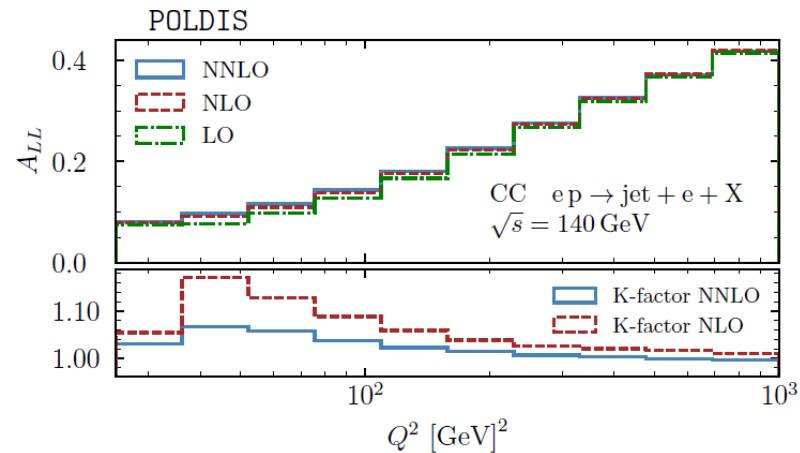
NNLO Jet production at EIC
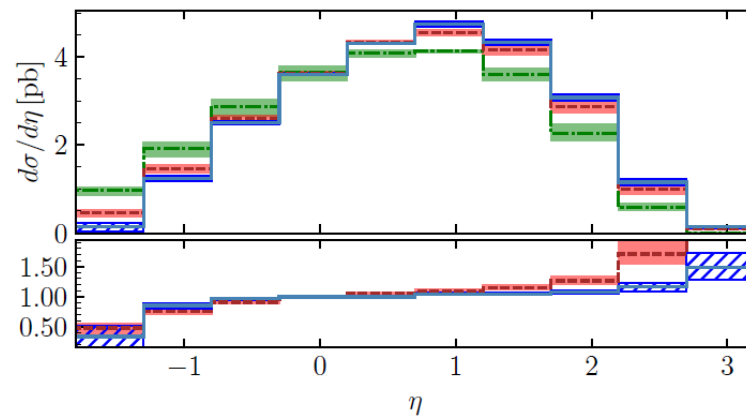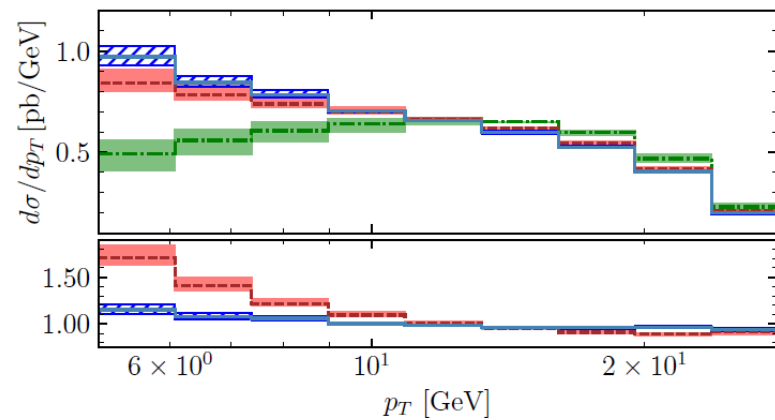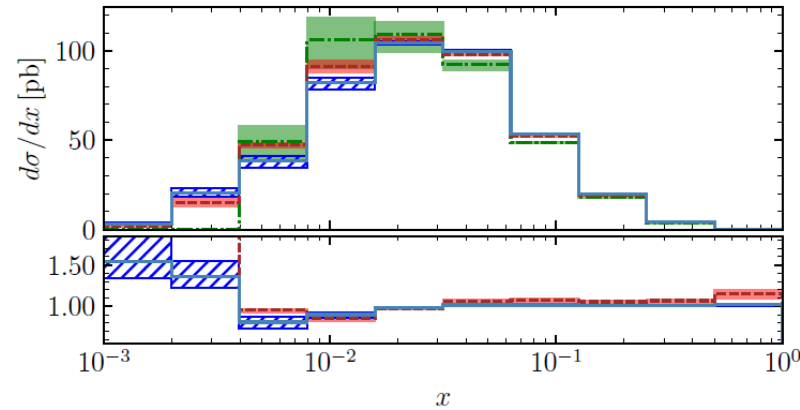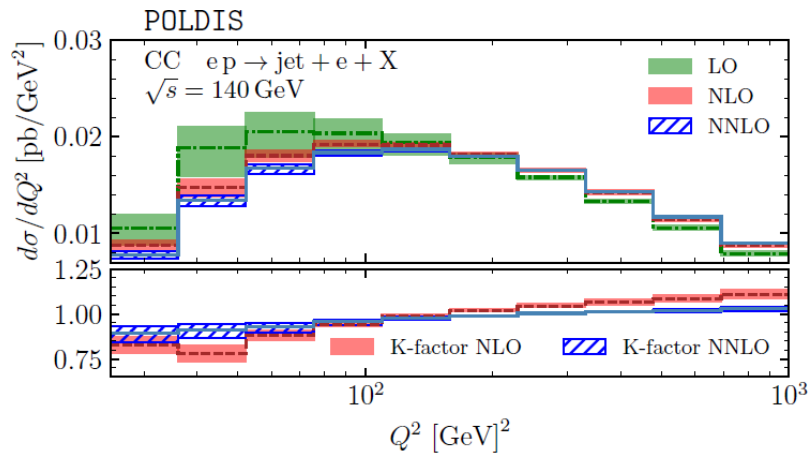
UNPOLARIZED
CHARGED CURRENTS

- Greatly suppressed by W mass
- At LO pt and Q2 are related, leading to large corrections

Borsa, de Florian, **IP** ('23)

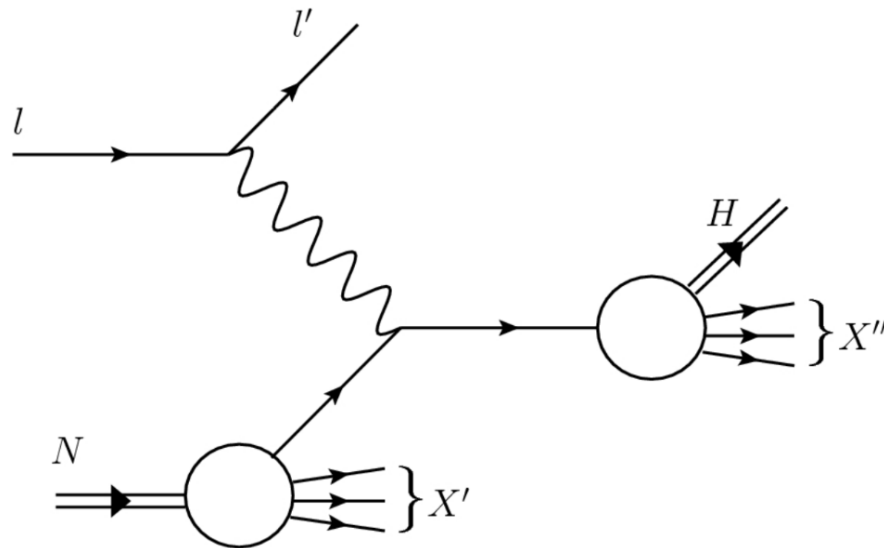# NNLO Jet production at EIC
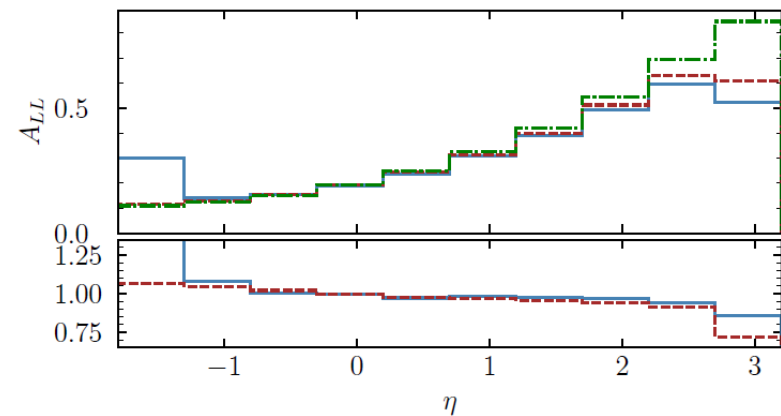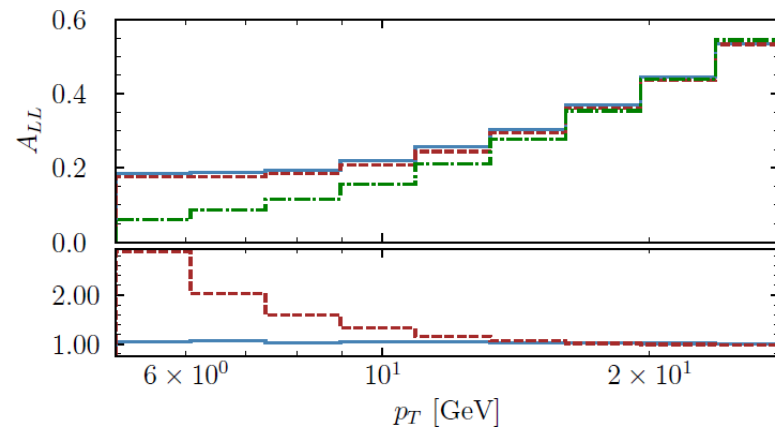
ASYMMETRIES CHARGED CURRENTS

- Higher than NCs
- At LO pt and Q2 are related, leading to large corrections

Borsa, de Florian, **IP** ('23)

What's next?

Possibilities:

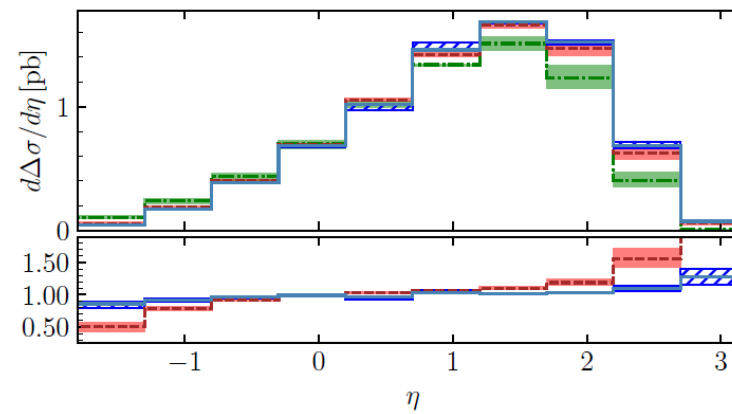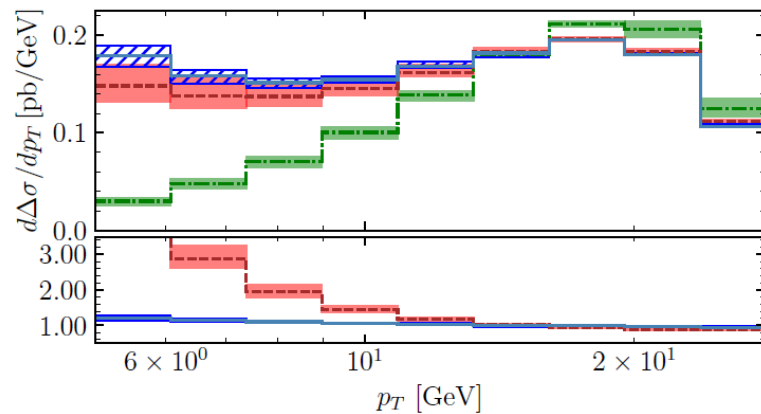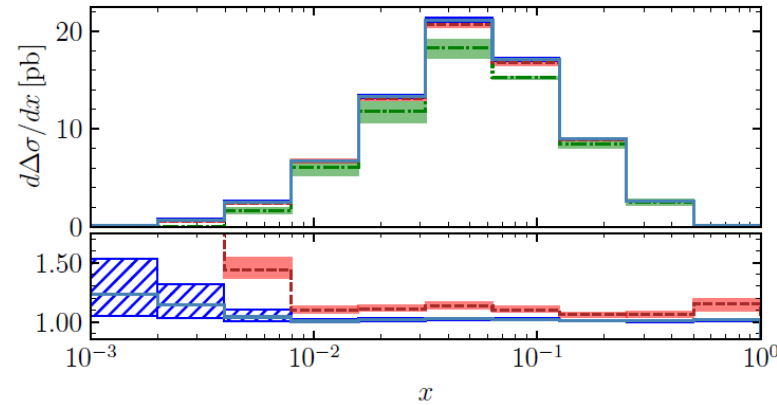- ❖ **Extend code to calculate SIDIS**
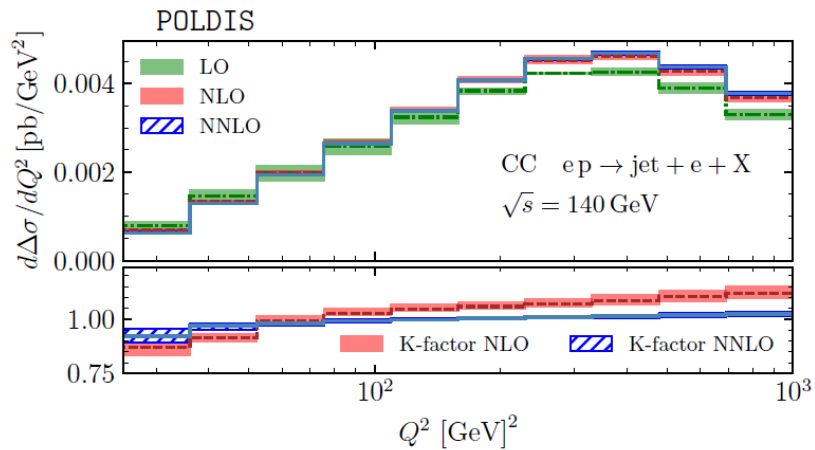- ❖ **Add quark mass effects**

In conclusion...

- ✓ Higher order **QCD** corrections are fundamental for the precise description of observables, and they will be instrumental in the description of the proton's spin (**EIC underway!**)

- ✓ We presented Polarized NNLO 1-jet production for neutral & charged current DIS

- ✓ Better perturbative convergence, but still with sizable corrections

- ✓ Significant corrections to double spin asymmetries

1 November 2023   Ivan Pedron - Jet Production in Polarized Deep Inelastic Scattering   IAP - TTP, KIT

Thank you!!

NNLO Jet production at EIC

POLARIZED CHARGED CURRENTS

- Greatly suppressed by W mass
- At LO pt and Q2 are related, leading to large corrections

Borsa, de Florian, **IP** ('23)