NNLO jets in in polarized DIS

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WHY DO WE NEED HIGHER ORDER CORRECTIONS?

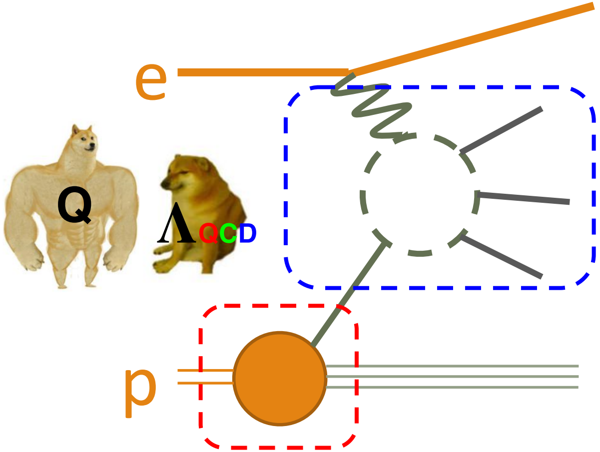
Factorization theorem

$$\sigma = \sum_a \int f_a(z, \mu_F^2)\, \hat{\sigma}_a\left(\alpha_s(\mu_R), \mu_F, \mu_R\right) dz + \mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)$$

Power corrections

PDFs
(non-perturbative)

Partonic cross section
(perturbative)



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

LO **NLO** **NNLO** **N3LO**

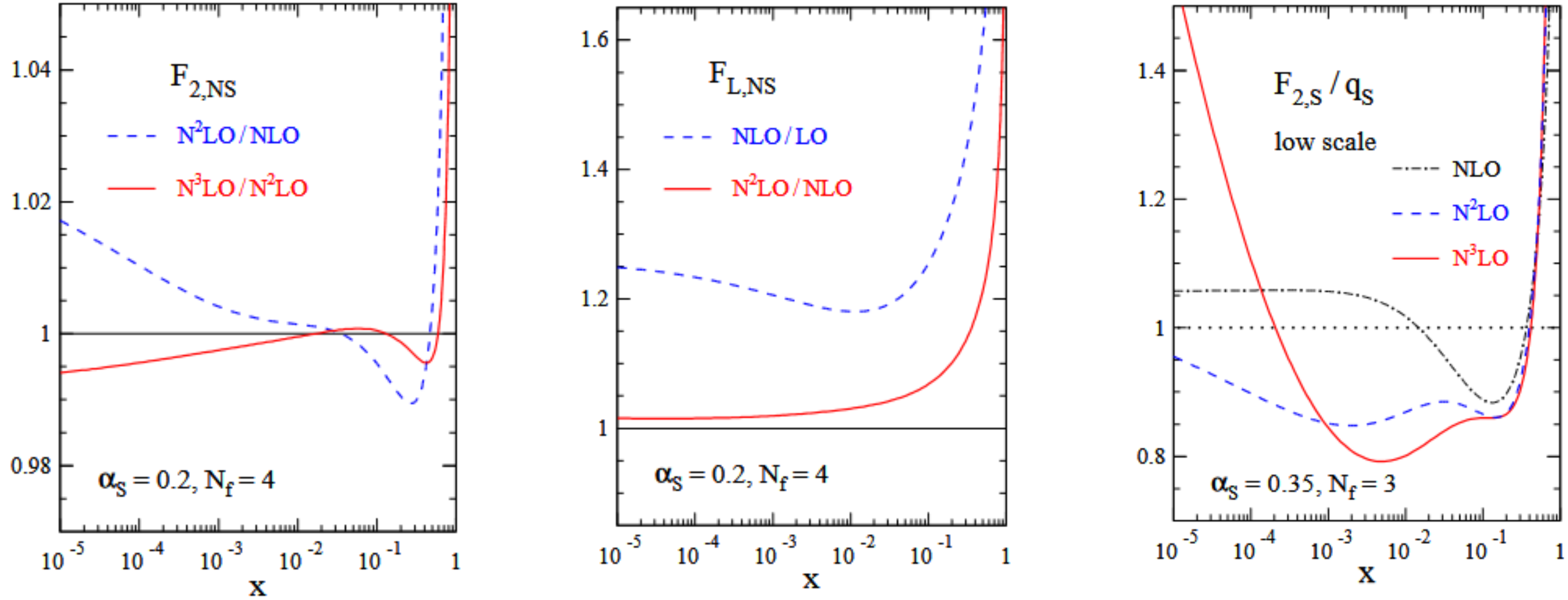
- Accurate predictions require refinement of both perturbative and non-perturbative pieces
- Perturbative convergence depends on scale, observable, phase space region, etc.

WHY DO WE NEED HIGHER ORDER CORRECTIONS?

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

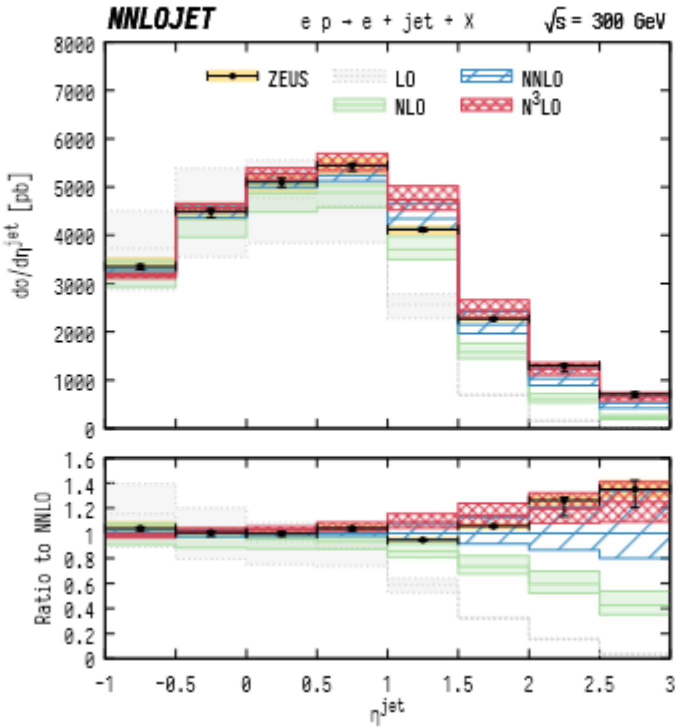
LO **NLO** **NNLO** **N3LO**

Vermaseren, Vogt, Moch (2005)



Inclusive observables!!

WHY DO WE NEED HIGHER ORDER CORRECTIONS?

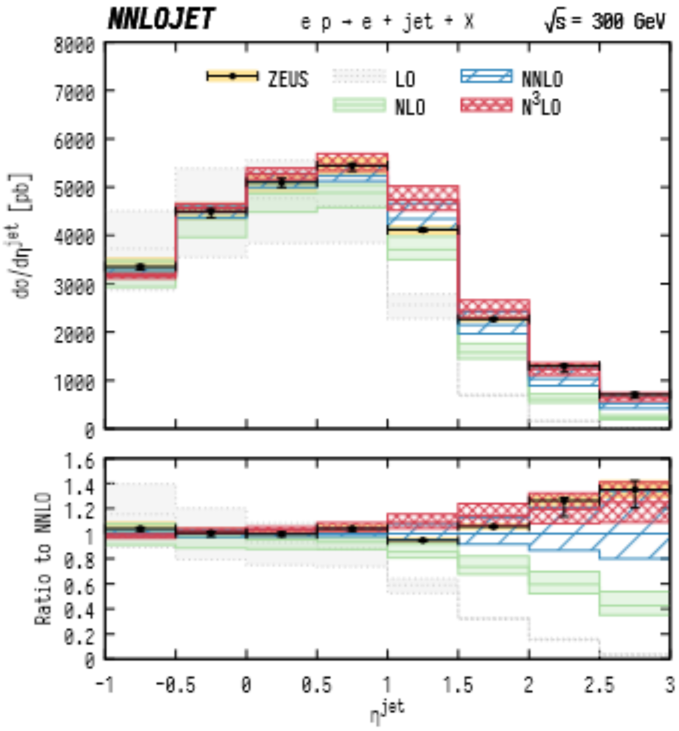


- Important corrections in differential observables as new regions of phase space become available
- At higher orders uncertainties can still be larger than experimental errors (HERA)

- Reduced scale dependence
- Residual dependence on μ_R and μ_F provides an estimate of the missing higher order corrections
- Reliable predictions in regions where there is good convergence

Currie, Gehrmann, Glover, Huss, Niehues, Vogt (2018)

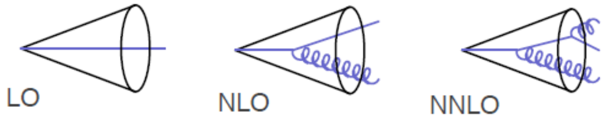
WHY DO WE NEED HIGHER ORDER CORRECTIONS?



Currie, Gehrmann, Glover, Huss, Niehues, Vogt (2018)

- New channels may become available at higher orders (e.g, gluons in DIS)
- Parton luminosity can provide large correction (interplay with non-perturbative PDFs)

- QCD jet acquire structure at higher orders
- Better matching with experiments as more partons are considered



HIGH ORDER JET CALCULATIONS IN POLARIZED DIS

Theory status for polarized jet production in DIS:

- Not much interest in fixed-target experiments
- NLO single jet production (polarized N-jetiness)

Boughezal, Petriello, Xing (2018)

- NLO dijet production (polarized dipole subtraction)

Photon - Borsa, De Florian, IP (2020)

NC and CC - Borsa, De Florian, IP (2021)

- NNLO single jet production (polarized dipoles + P2B)

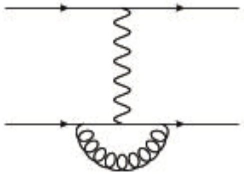
Photon - Borsa, De Florian, IP (2020)

NC and CC - Borsa, De Florian, IP (in preparation)

SUBTRACTION METHODS

Beyond LO, IR singularities that arise in virtual contributions are cancelled against those from real emission diagrams (KNL Theorem)

Divergence cancel each other, but in different phase spaces. This is problematic for numerical implementations!



Virtual $\int_m d\hat{\sigma}_a^V$

Real $\int_{m+1} d\hat{\sigma}_a^R$

This only gets worse beyond NLO due to overlapping singularities and mixed real-virtual contributions!

The main idea of **subtraction methods** is to extract the singularities without performing the full integration over the phase space of the real emission processes

DIPOLE SUBTRACTION (NLO)

One of the **general** NLO subtraction methods. The goal is to use a counterterm A that both

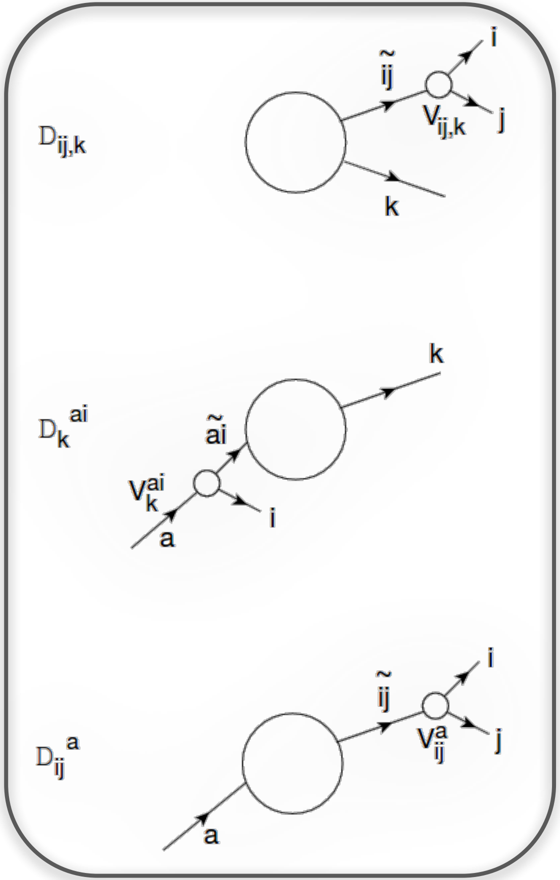
- Reproduces IR divergent behaviour of the real emission
- Is simple enough to be analytically integrated to cancel the IR divergences of the virtual contribution

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

The counterms are **process independent**, and are based on the factorization formulae:

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

Catani, Seymour (1996)



POLARIZED DIPOLE SUBTRACTION (NLO)

One of the **general** NLO subtraction methods. The goal is to use a counterterm A that both

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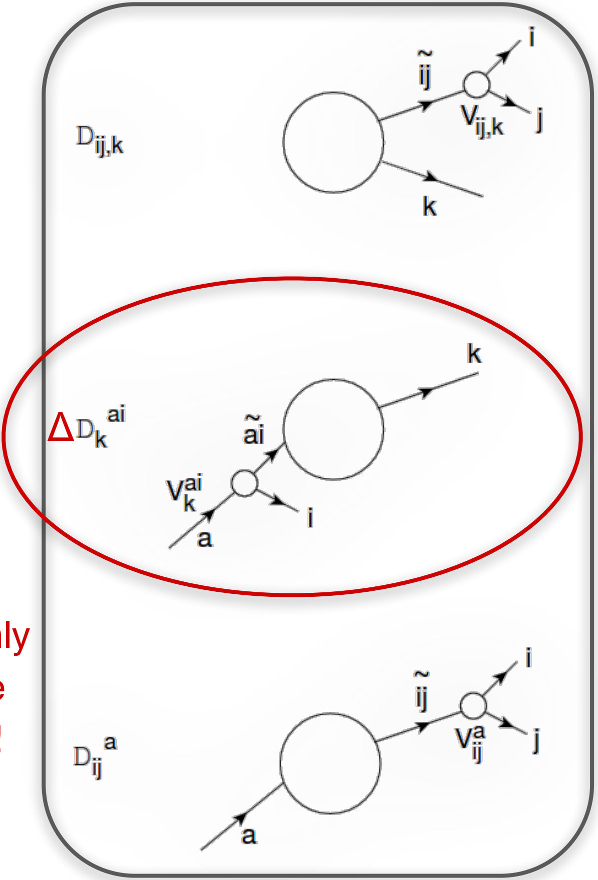
$$\sigma^{NLO} = \int_{m+1} \left[\left(d\sigma^R\right)_{\epsilon=0} - \left(d\sigma^A\right)_{\epsilon=0} \right] + \int_m \left[d\sigma^V + \int_1 d\sigma^A \right]_{\epsilon=0}$$

The counterterms are **process independent**, and are based on the factorization formulae:

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

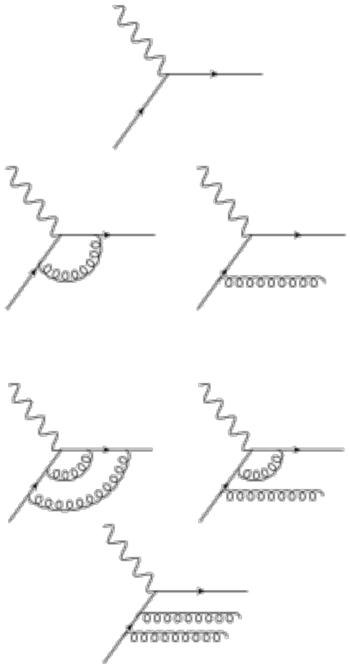
Differences only in initial-state factorization!



Catani, Seymour (1996) - Borsa, De Florian, IP (2020)

HIGH ORDER JET CALCULATIONS IN POLARIZED DIS

	Inclusive cross section	Single-Jet (Lab Frame)	Di-jet (Breit Frame)
α_S^0	$q\gamma^* \to q$ LO	$q\gamma^* \to q$	
α_S^1	$q\gamma^* \to q$ 1 loop $q\gamma^* \to qg$ $g\gamma^* \to q\bar{q}$ NLO	$q\gamma^* \to q$ 1 loop $q\gamma^* \to qg$ $g\gamma^* \to q\bar{q}$	$q\gamma^* \to qg$ $g\gamma^* \to q\bar{q}$ LO
α_S^2	$q\gamma^* \to q$ 2 loops $q\gamma^* \to qg$ 1 loop $g\gamma^* \to q\bar{q}$ 1 loop $q\gamma^* \to qgg$ $q\gamma^* \to qq\bar{q}$ $g\gamma^* \to q\bar{q}g$ NNLO	$q\gamma^* \to q$ 2 loops $q\gamma^* \to qg$ 1 loop $g\gamma^* \to q\bar{q}$ 1 loop $q\gamma^* \to qgg$ $q\gamma^* \to qq\bar{q}$ $g\gamma^* \to q\bar{q}g$	$q\gamma^* \to qg$ 1 loop $g\gamma^* \to q\bar{q}$ 1 loop $q\gamma^* \to qgg$ $q\gamma^* \to qq\bar{q}$ $g\gamma^* \to q\bar{q}g$ NLO



(From Borsa)

HIGH ORDER JET CALCULATIONS IN POLARIZED DIS

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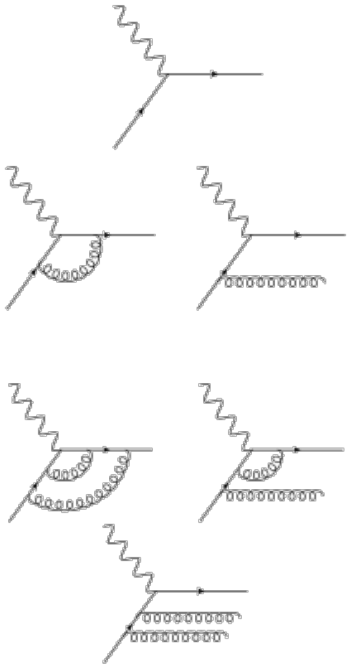
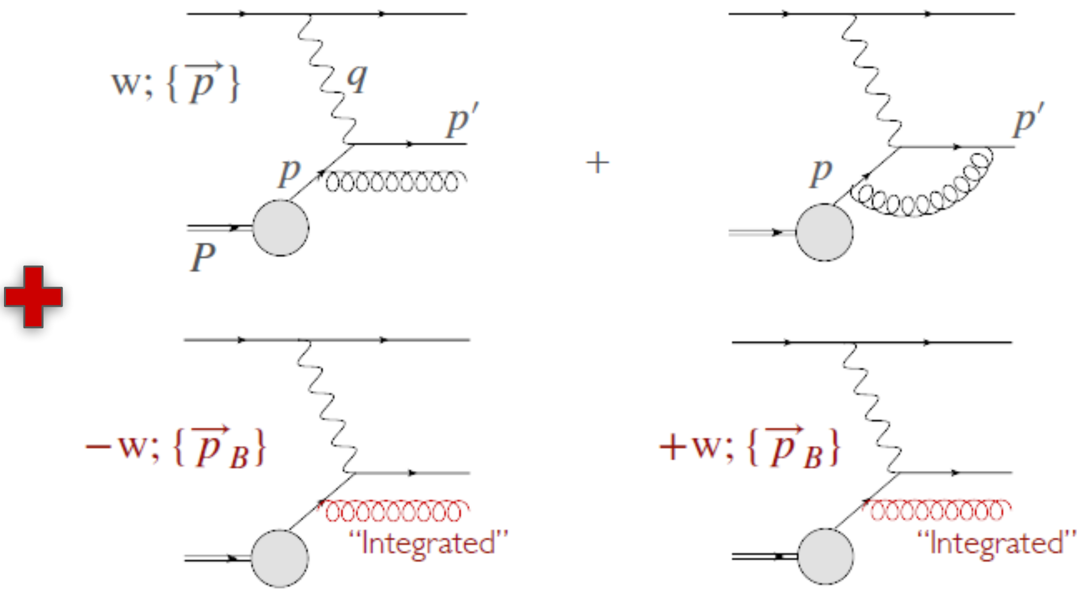


(From Borsa)

NNLO - PROJECTION TO BORN (P2B)

P2B provides the **fully differential** cross section of an observable given that we know

- The **inclusive** cross section at that order
- The exclusive cross section of that **observable + 1 jet at one order below**



We need to be able to map all event to *Born kinematics*

$$p_B = xP$$

$$p'_B = p_B + q$$

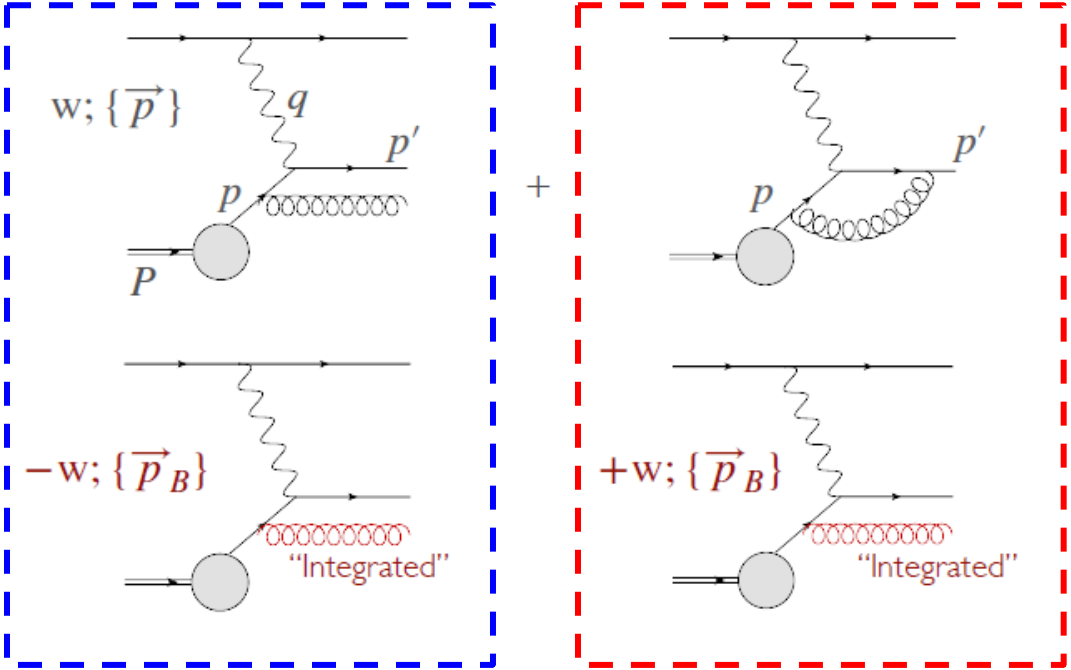
Not possible in Breit Frame!

The same real emission weight is subtracted, but in Born kinematics

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

NNLO - PROJECTION TO BORN (P2B)

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



Finite/integrable in 4-dimensions

Inclusive x-sec

We need to be able to map all event to *Born kinematics*

$$p_B = xP$$

$$p'_B = p_B + q$$

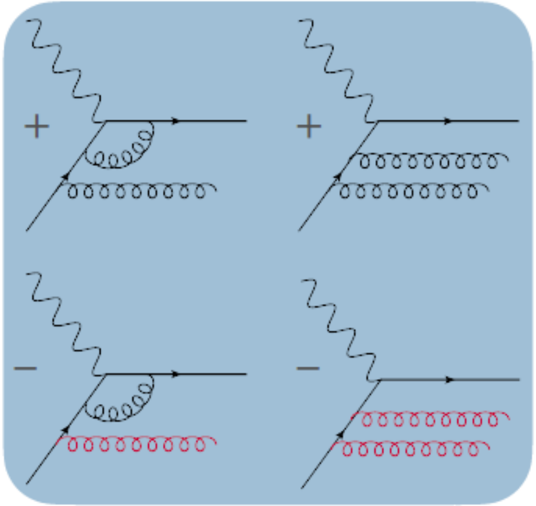
Not possible in Breit Frame!

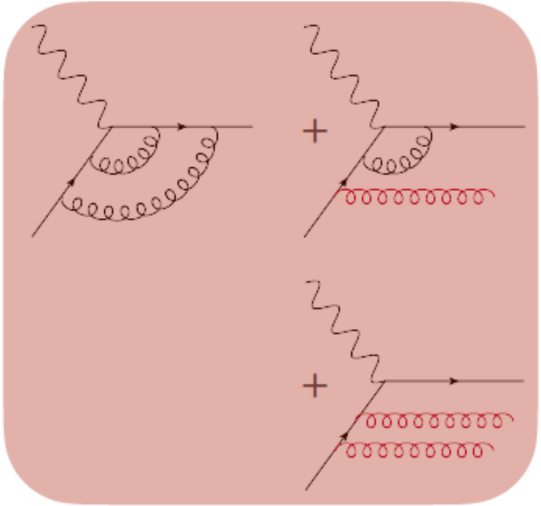
Be careful with scales!

NNLO - PROJECTION TO BORN (P2B)

IN OUR CASE:

We compute the polarized **NNLO cross section for 1-jet**, using our NLO calculation for 2-jets (dipoles) and the NNLO inclusive cross sections that are already available



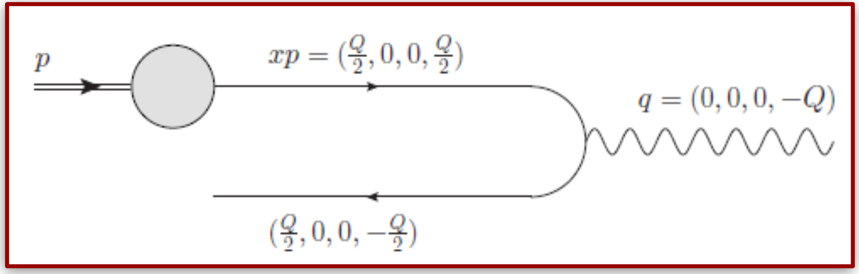


$$d\sigma^{\text{NNLO}}_{1jet} = d\sigma^{\text{NLO}}_{2jet} - d\sigma^{\text{NLO}}_{2jet,\text{P2B}} + d\sigma^{\text{NNLO, incl}}_{1jet}$$

Dipoles

van Neerven, Zijlstra (1994)

NLO DIJETS IN POLARIZED DIS (BREIT FRAME)



EIC KINEMATICS: Ep = 275 GeV

Ee = 18 GeV

KINEMATICAL CUTS:

$$p^B_{T,1} > 5 \text{ GeV}, \quad p^B_{T,2} > 4 \text{ GeV}, \quad |\eta^L| < 3.5,$$

$$0.2 < y < 0.6, \quad 25\,\text{GeV}^2 < Q^2 < 2500\,\text{GeV}^2$$

NLO PDFs: DSSV14 MC (polarized) - PDF4LHC15 (unpolarized)

SCALES: $\mu_F^2 = \mu_R^2 = \frac{1}{2}(Q^2 + \langle p_T^B \rangle_2^2) \equiv \mu_0^2$ (dynamical)

JET ALGORITHM: anti-Kt, R = 0.8

Asymmetrical Pt cuts to improve perturbative stability!

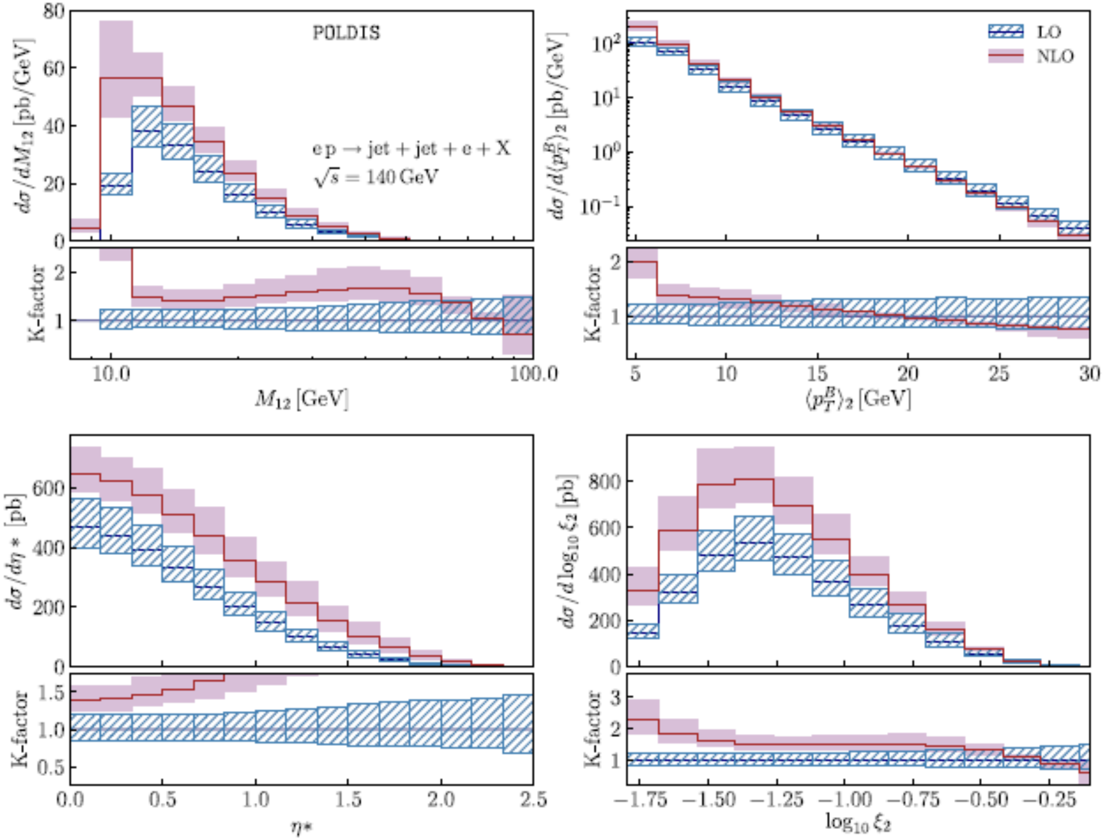
NLO DIJETS IN DIS (PHOTON)

$$M_{12} = \sqrt{(p_1 + p_2)^2} \qquad \eta^* = \frac{1}{2}|\eta_1^B - \eta_2^B|$$

$$\langle p_T \rangle_2 = \frac{1}{2}(p_{T,1}^B + p_{T,2}^B) \qquad \xi_2 = x(1 + \frac{M_{12}^2}{Q^2})$$

UNPOLARIZED CASE

- Significant NLO corrections (K factors above 1.5)
- Strong scale dependence (7-point variation)
- Perturbative instabilities due to regions of phase space forbidden at LO (M12 > 10 GeV)



NLO DIJETS IN DIS (PHOTON)

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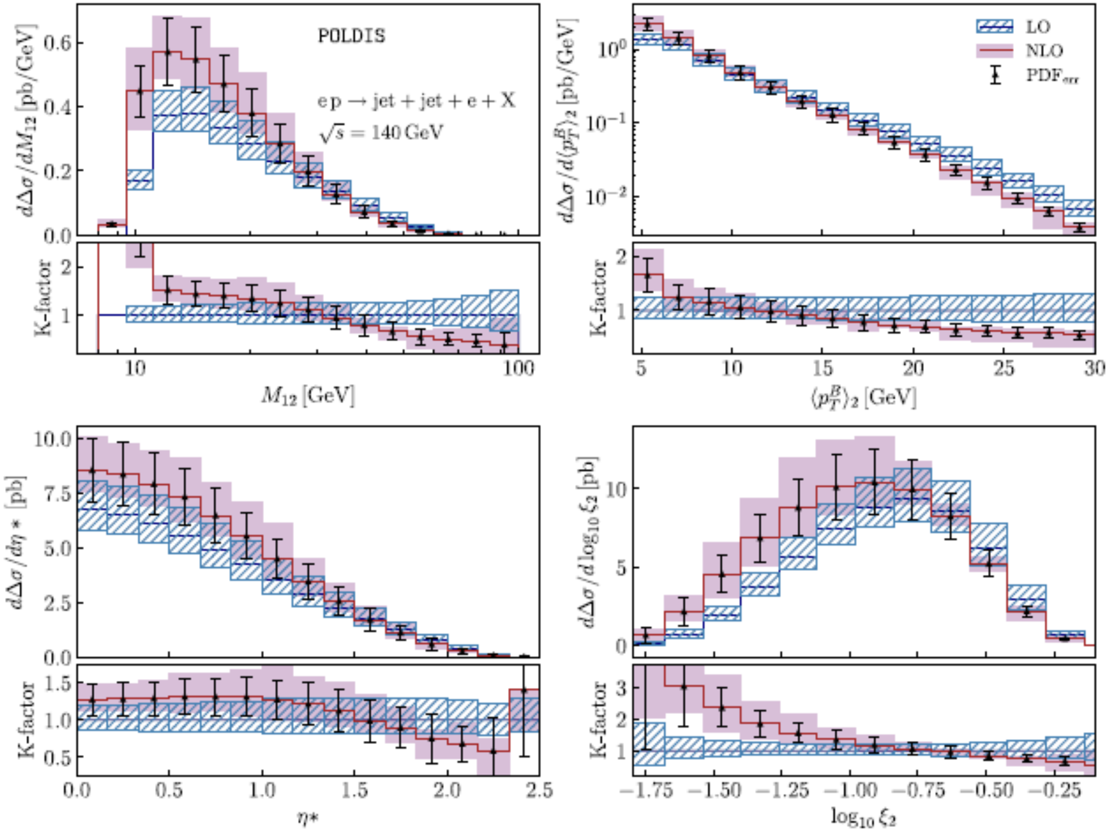


POLARIZED CASE

- Significant NLO corrections
- Strong scale dependence (can be bigger than PDFs errors!)
- Perturbative instabilities due to forbidden regions at LO
- Different shape/size of corrections respect to the unpol case (see asymmetries)
- Shift in dijet momentum fraction

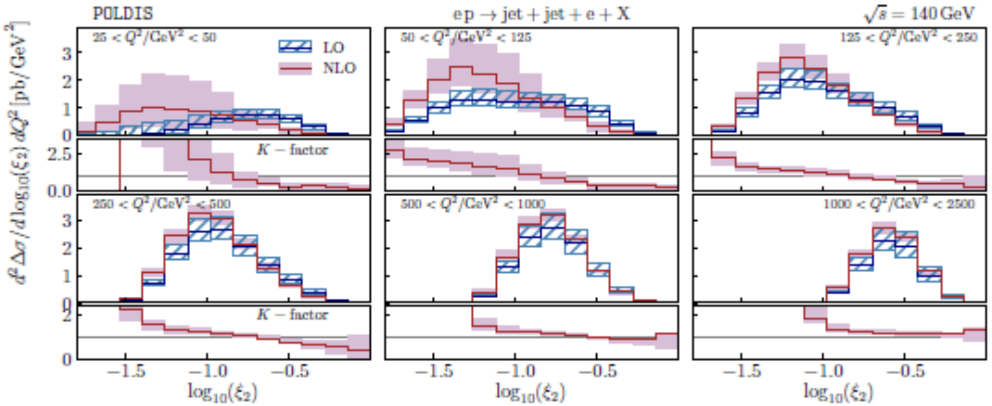
NLO DIJETS IN DIS (PHOTON)

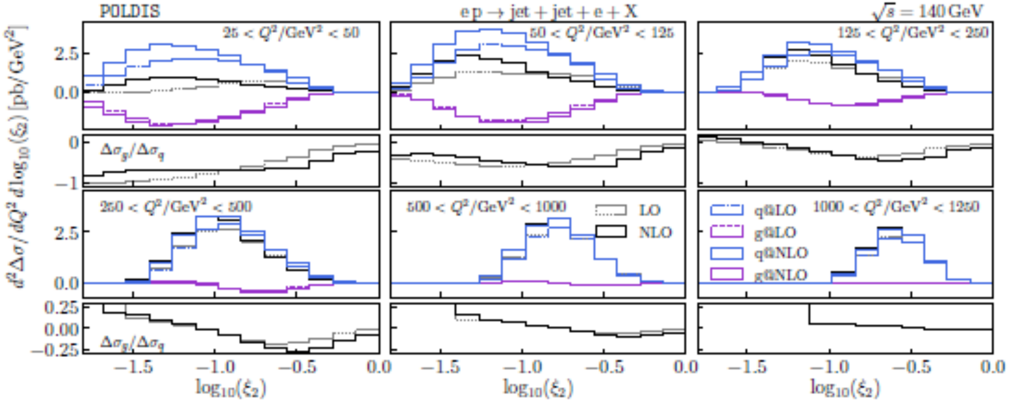
$$M_{12} = \sqrt{(p_1 + p_2)^2} \qquad \eta^* = \frac{1}{2}|\eta_1^B - \eta_2^B|$$

$$\langle p_T \rangle_2 = \frac{1}{2}(p_{T,1}^B + p_{T,2}^B) \qquad \xi_2 = x(1 + \frac{M_{12}^2}{Q^2})$$

POLARIZED CASE

- Cancellation between quark and gluon channels at low Q2
- Also, there is a shift in the quark contribution at low Q2
- Good perturbative convergence at high Q2





NLO DIJETS IN DIS (PHOTON)

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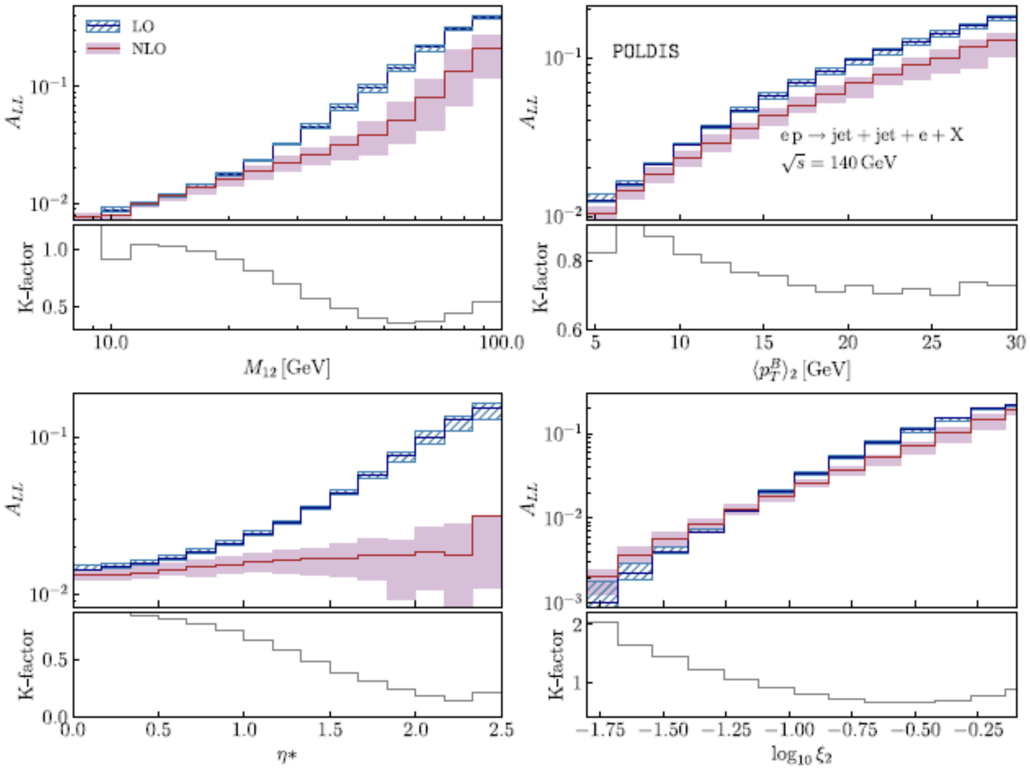
$$\langle p_T \rangle_2 = \frac{1}{2}(p_{T,1}^B + p_{T,2}^B) \qquad \xi_2 = x(1 + \frac{M_{12}^2}{Q^2})$$

ASYMMETRIES

- Reduction in double spin asymmetries due to quark-gluon channel cancellation, particularly in pseudorapidity distribution
- Shift in dijet momentum fraction



EW CONTRIBUTION TO DIS

- EW boson introduce **vector** and **axial** couplings

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

- In the case of neutral currents, we also have Z/photon interference

The presence of γ^5 in the HVBM scheme of dimensional regularization adds further complications:

VERTEX SYMMETRIZATION IN D-DIMENSIONS

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

FINITE SUBTRACTION DUE TO UV DIVERGENCES

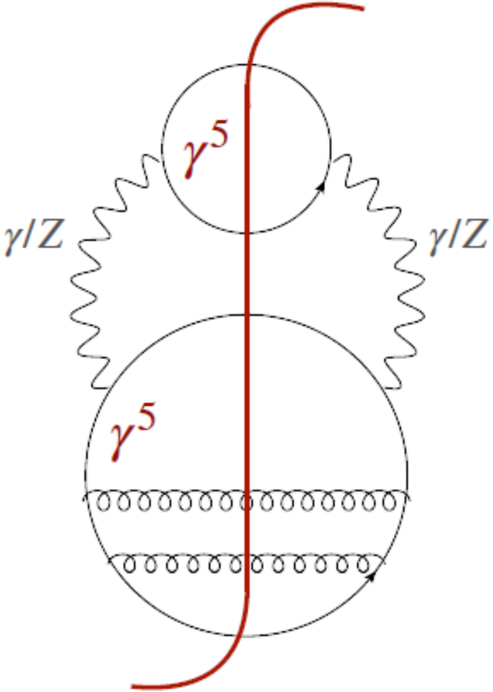
$$(\Delta)C_T = \alpha_s\,4C_F\,d(\Delta)\hat{\sigma}^{\mathrm{LO}}_{\mathrm{axial}}$$

EW CONTRIBUTION TO DIS

The possible results of the differents fermion traces depend only on whether there is an odd or even number of γ^5.

- Trivial in real emission diagrams (4-dimensional)
- Only valid in virtual diagrams after symmetrization and finite subtraction (d-dimensional)

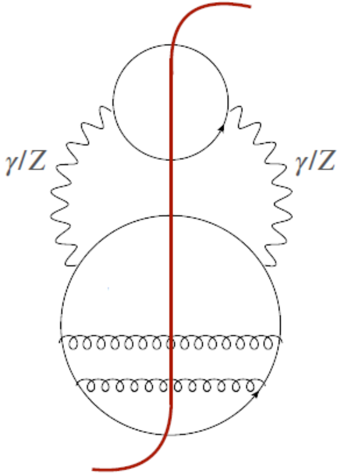
Since spin projectors also add γ^5, we can reuse polarized matrix elements for unpolarized parity violating pieces (PV), and vice versa!



EW CONTRIBUTION TO DIS

EVEN γ^5

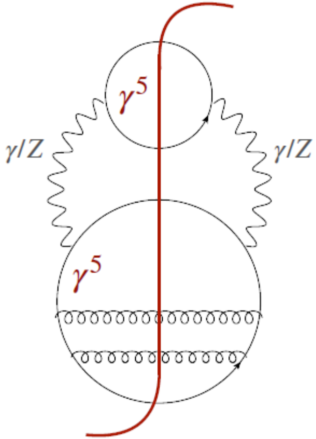
- Unpolarized NPV
- Polarized PV



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

ODD γ^5

- Unpolarized PV
- Polarized NPV



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

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

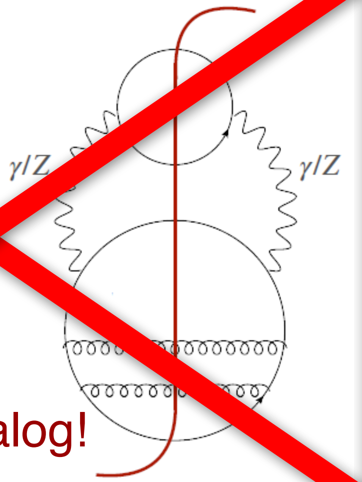
VALID FOR $q+W/Z \rightarrow q$, $q+W/Z \rightarrow q+g$ and $q+W/Z \rightarrow q+g+g$

(up to NNLO)

EW CONTRIBUTION TO DIS

AND THE GLUON CHANNELS?

EVEN γ^5



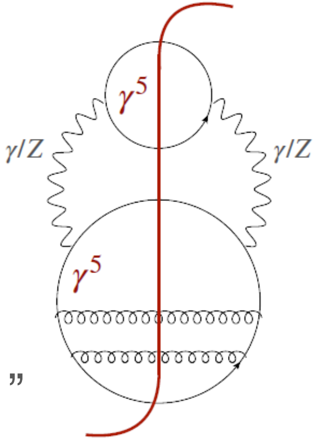
No analog!

ODD γ^5

- Unpolarized PV
- Polarized quark NPV

" $\hat{\sigma}_g^{PV} = -\Delta\hat{\sigma}_q^{NPV}$ "

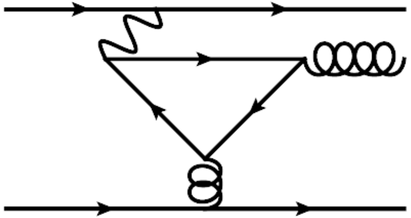
(minus from crossing)



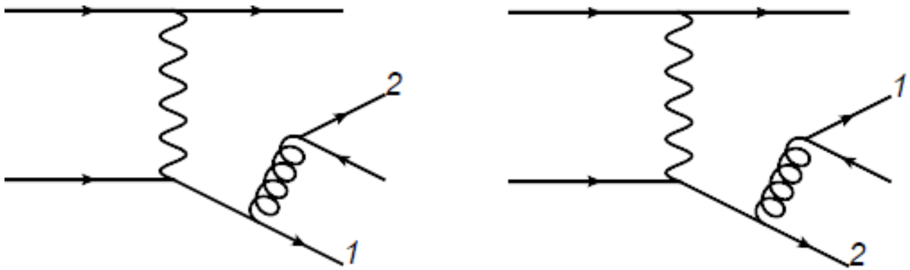
No analogous relation for polarized NPV gluon channel. **However, PV terms with initial gluon cancel due to charge conjugation arguments** (antisymmetric in quark-antiquark crossing)

SPECIAL CASE - TRIANGLE DIAGRAMS

Virtual



Real (interference)



Triangles only in Z exchange, but they cancel out if the two members of each weak isospin doublet are considered

Also, in the particular 4 quark channel we can use properties similar to those of the previous slides, depending on each particular case

$$q + W/Z \to q + q' + \bar{q}'$$

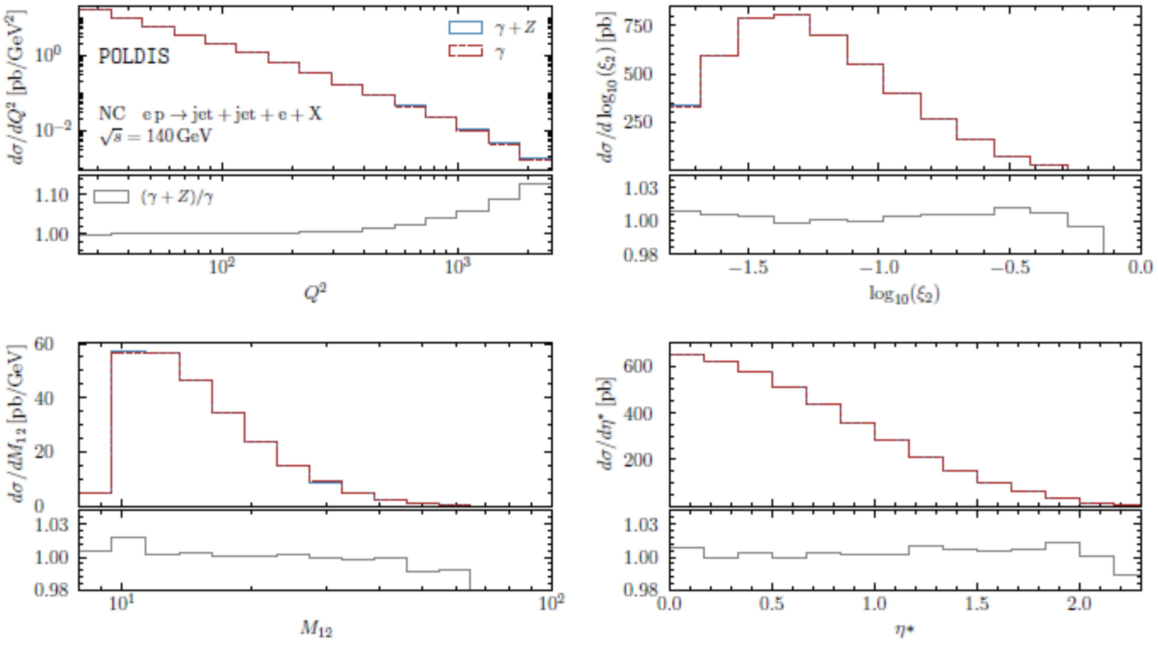
NLO DIJETS IN DIS (NEUTRAL CURRENTS)

$$M_{12} = \sqrt{(p_1 + p_2)^2} \qquad \eta^* = \frac{1}{2}|\eta_1^B - \eta_2^B|$$

$$\langle p_T \rangle_2 = \frac{1}{2}(p_{T,1}^B + p_{T,2}^B) \qquad \xi_2 = x(1 + \frac{M_{12}^2}{Q^2})$$

UNPOLARIZED CASE

- Contribution of the Z boson in very small, and comes mainly due to interference with photon
- 10% only at Q2 ~ 2000 GeV
- Q2 does not reach high enough values at EIC for Z



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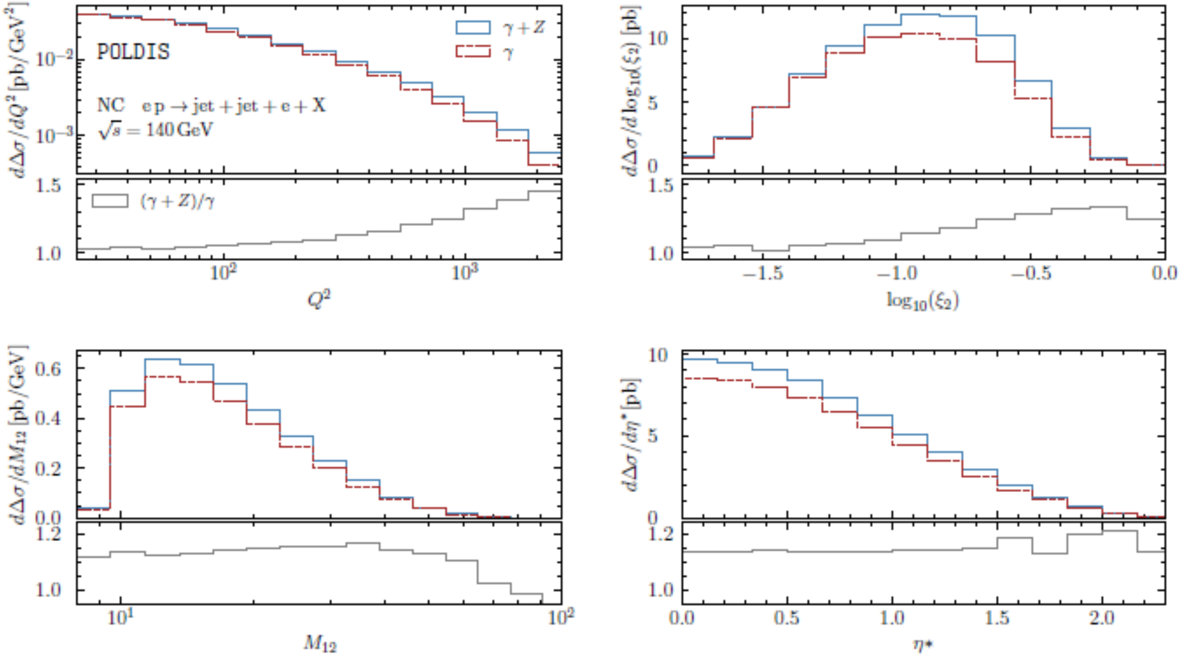
POLARIZED CASE

- Stronger contribution in polarized cross section due to channel cancellation
- Parity violating pieces only in quark channel
- This overall improves the asymmetries (~10%), but mainly at high Q2 and



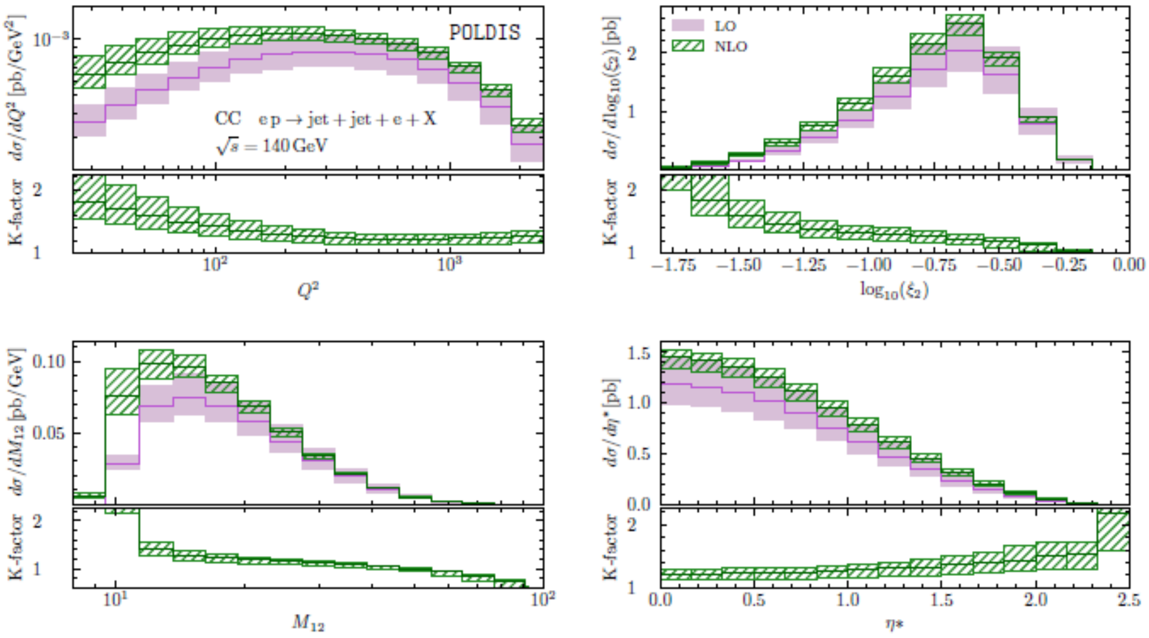
NLO DIJETS IN DIS (CHARGED CURRENTS)

$$M_{12} = \sqrt{(p_1 + p_2)^2} \qquad \eta^* = \frac{1}{2}|\eta_1^B - \eta_2^B|$$

$$\langle p_T \rangle_2 = \frac{1}{2}(p_{T,1}^B + p_{T,2}^B) \qquad \xi_2 = x\left(1 + \frac{M_{12}^2}{Q^2}\right)$$

UNPOLARIZED CASE

- Massive propagator suppression at low Q2
- Q2 and dijet momentum fraction are related
- Same perturbative instabilities as in photon exchange



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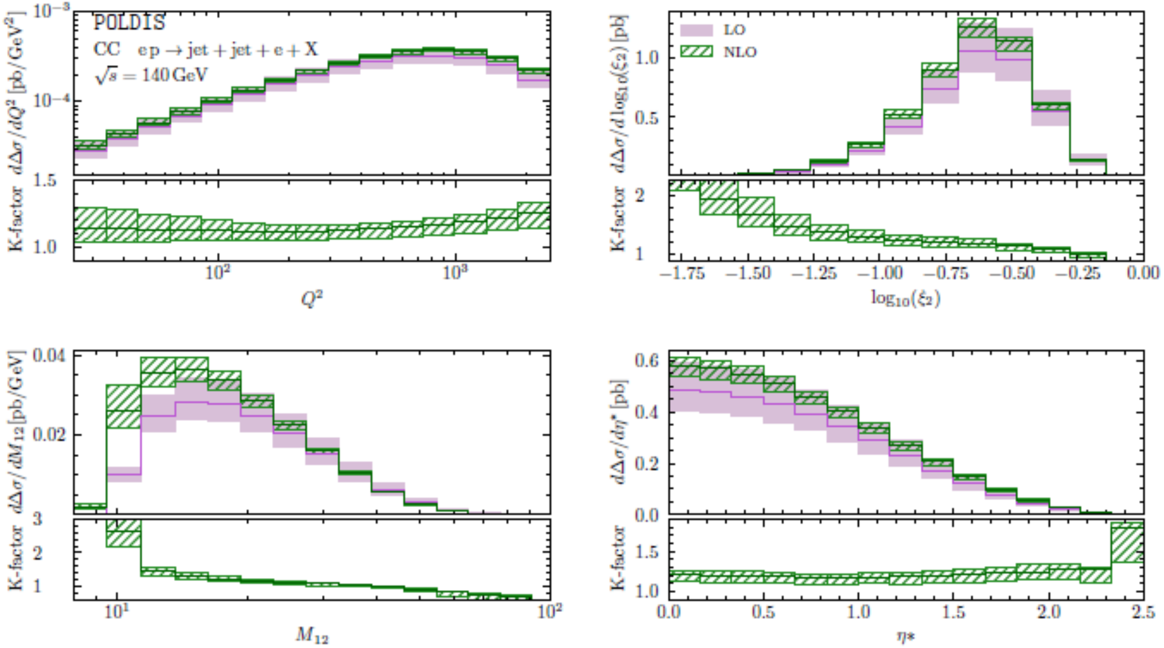
$$M_{12} = \sqrt{(p_1 + p_2)^2} \qquad \eta^* = \frac{1}{2}|\eta_1^B - \eta_2^B|$$

$$\langle p_T \rangle_2 = \frac{1}{2}(p_{T,1}^B + p_{T,2}^B) \qquad \xi_2 = x(1 + \frac{M_{12}^2}{Q^2})$$

POLARIZED CASE

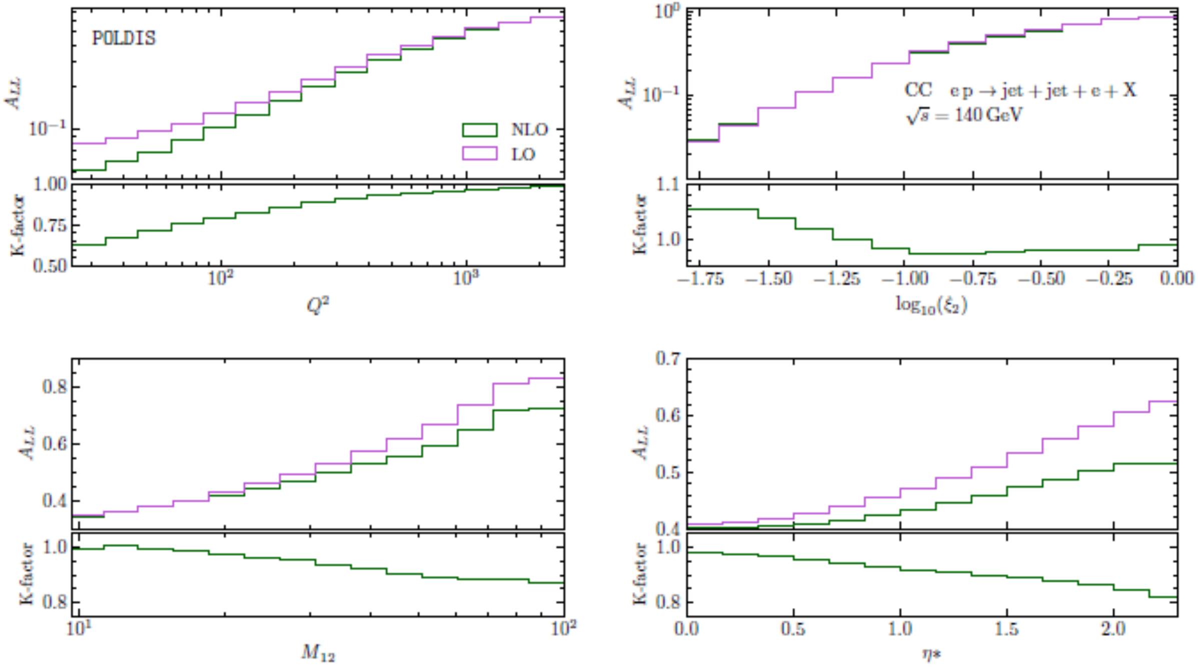
- Polarized x-sec not as suppressed compared to NC
- Parity-violating piece of x-sec is more relevant (due to couplings)



NLO DIJETS IN DIS (CHARGED CURRENTS)

$$M_{12} = \sqrt{(p_1 + p_2)^2} \qquad \eta^* = \frac{1}{2}|\eta_1^B - \eta_2^B|$$

$$\langle p_T \rangle_2 = \frac{1}{2}(p_{T,1}^B + p_{T,2}^B) \qquad \xi_2 = x(1 + \frac{M_{12}^2}{Q^2})$$



ASYMMETRIES

- Bigger double spin asymmetries, specially at high Q2
- 10% at Q2 ~ 100 GeV

NNLO SINGLE JET IN POLARIZED DIS (LAB FRAME)

EIC KINEMATICS: Ep = 275 GeV

Ee = 18 GeV

Lab Frame needed for P2B!

KINEMATICAL CUTS:

$$0.04 < y < 0.95,$$
$$25\,\mathrm{GeV}^2 < Q^2 < 1000\,\mathrm{GeV}^2$$

$$5\,\mathrm{GeV} < p_T^L < 36\,\mathrm{GeV},$$
$$|\eta^L| < 3,$$

NLO PDFs: DSSV14 MC (polarized) - PDF4LHC15 (unpolarized)

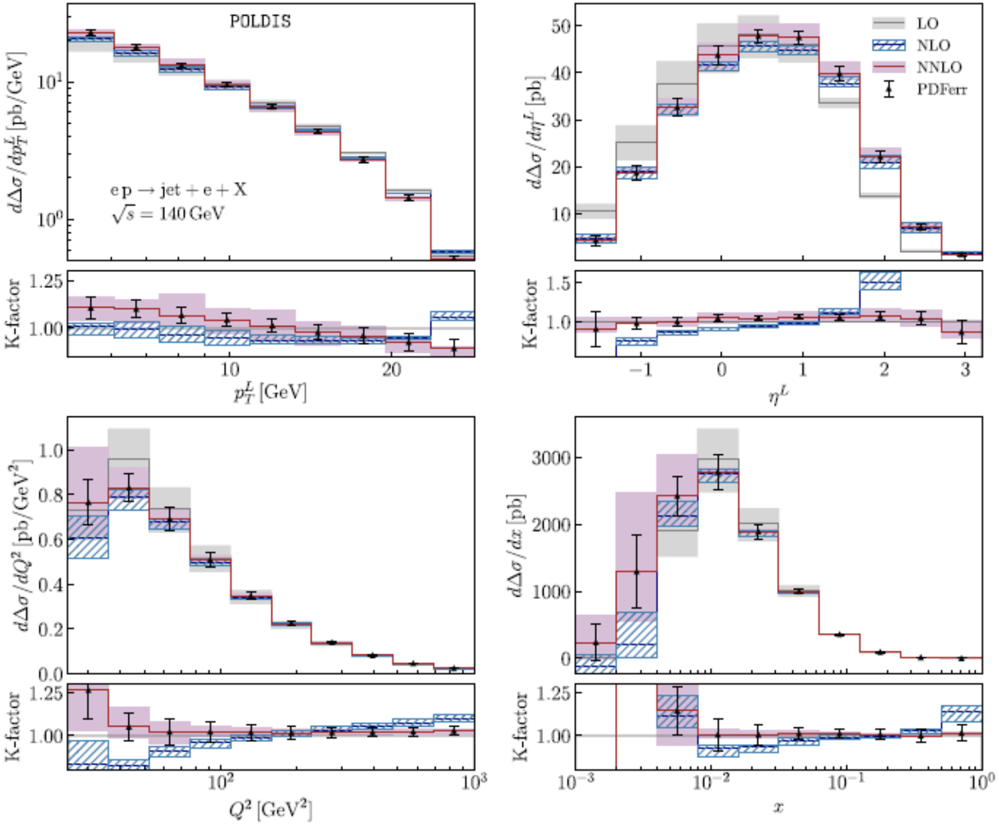
SCALES: $\mu_F^2 = \mu_R^2 = Q^2 \equiv \mu_0$

JET ALGORITHM: anti-Kt, R = 0.8

NLO SINGLE JET IN DIS (PHOTON)

POLARIZED CASE

- Improved convergence at NNLO (K-factors)
- Shift towards larger rapidities and lower Pt, as the emission of extra partons populates those regions
- Strong scale dependence at low Q2 and x due to kinematical cuts in Pt and y
- This is further enhanced in the polarized case due to channel cancellations

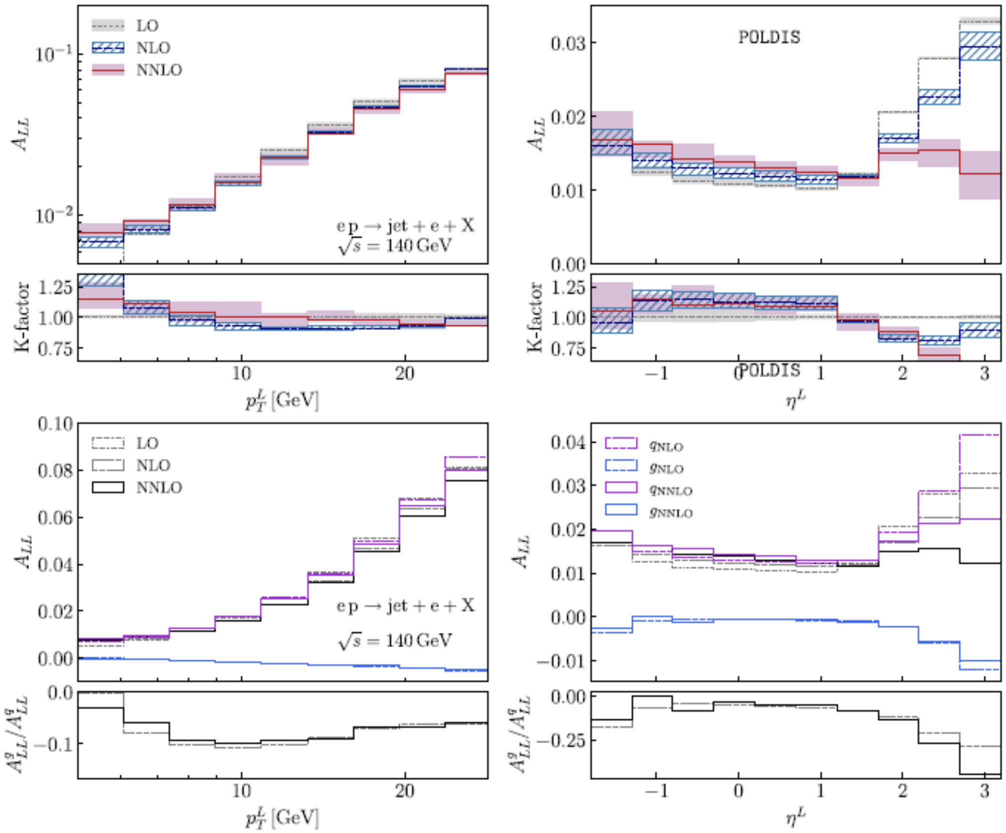


NLO SINGLE JET IN DIS (PHOTON)

Asymmetries

- Cancellations in the polarized cross section lead to small asymmetries (~ 2%)
- Significant corrections in the asymmetries, even at NNLO

$$A_{LL} = \frac{\Delta\sigma}{\sigma}$$



PARITY VIOLATING STRUCTURE FUNCTION (P2B)

The F_3 unpolarized structure functions is known to NNLO (van Neerven, Zijlstra (1992)), but the polarized equivalent g_4 and g_5 are not available

We get the NNLO g_4 and g_5 from F_2 and F_1 due to the previous arguments. Initial gluon contributions are not a problem since they cancel out, and we can safely ignore Z triangle terms

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

$$L^{\mu\nu}_\gamma = 2\left(-k\cdot k' g^{\mu\nu} + k^\mu k'^\nu + k'^\mu k^\nu - i\lambda\epsilon^{\mu\nu\alpha\beta} k_\alpha k'_\beta\right),$$

$$L^{\mu\nu}_Z = (g^e_V + e\lambda g^e_A)^2\, L^{\mu\nu}_\gamma,$$

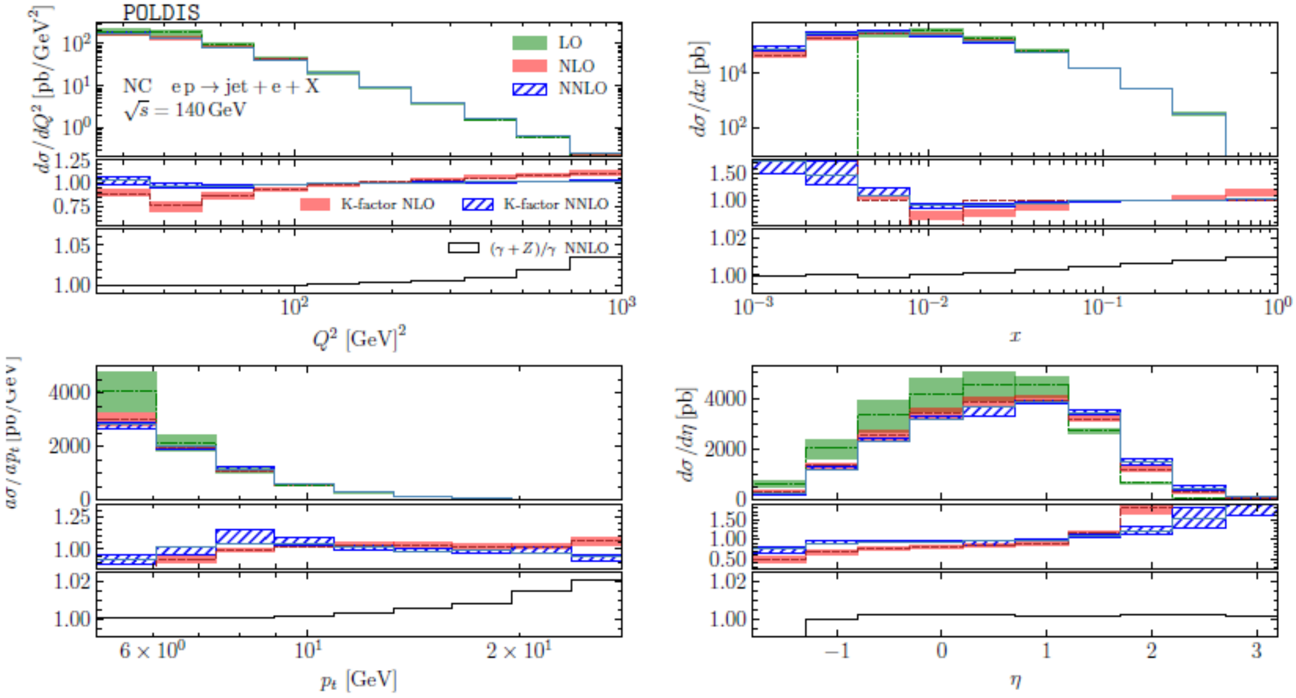
$$L^{\mu\nu}_{\gamma/Z} = (g^e_V + e\lambda g^e_A)\, L^{\mu\nu}_\gamma,$$

$$L^{\mu\nu}_W = (1 + e\lambda)^2\, L^{\mu\nu}_\gamma,$$

NNLO SINGLE JET IN DIS (NEUTRAL CURRENTS)

UNPOLARIZED CASE

- Contribution of the Z boson in very small, and comes mainly due to interference with photon
- Overall good convergence of the perturbative series

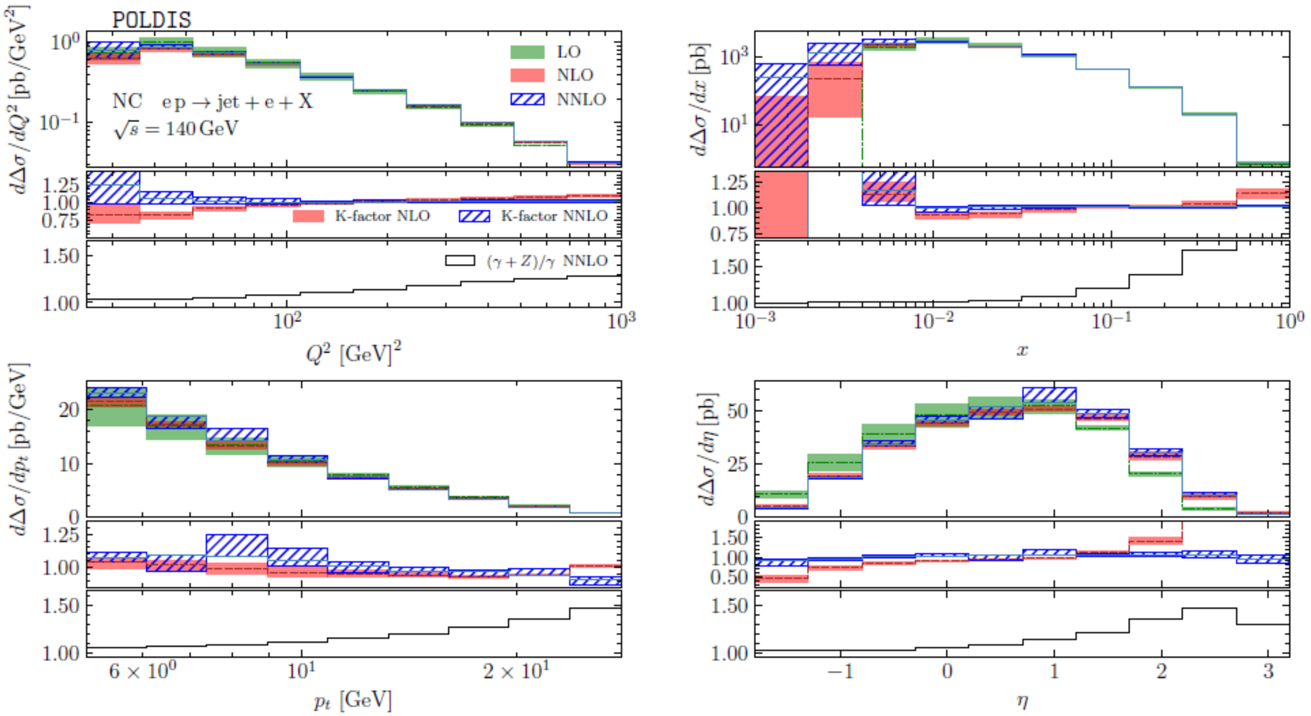


SENSITIVE BUT UNCLASSIFIED

NNLO SINGLE JET IN DIS (NEUTRAL CURRENTS)

POLARIZED CASE

- Enhanced contribution at high Q2, x and pt
- This enhancement translated into spin asymmetries

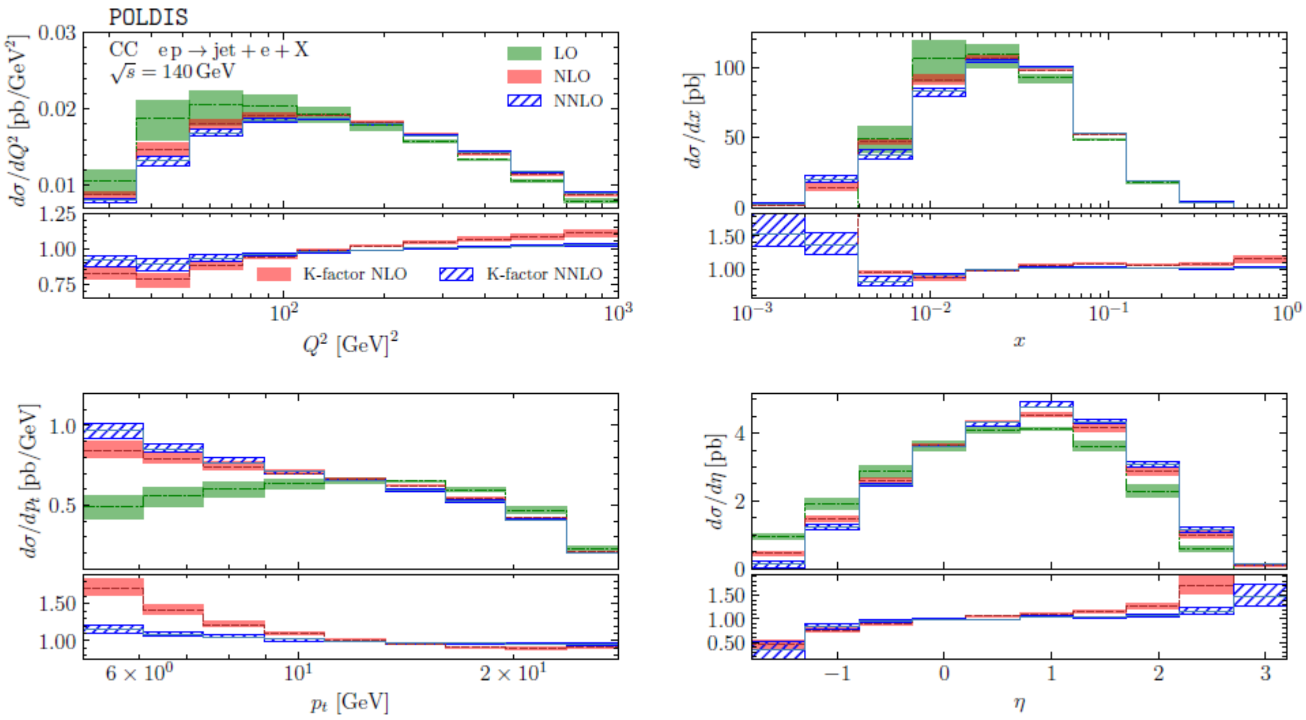


SENSITIVE BUT UNCLASSIFIED

NNLO SINGLE JET IN DIS (CHARGED CURRENTS)

UNPOLARIZED CASE

- Massive propagator suppression at low Q2
- Pt^2 in proportional to Q2 at LO, leading to large corrections
- Shifted towards higher x and Q2

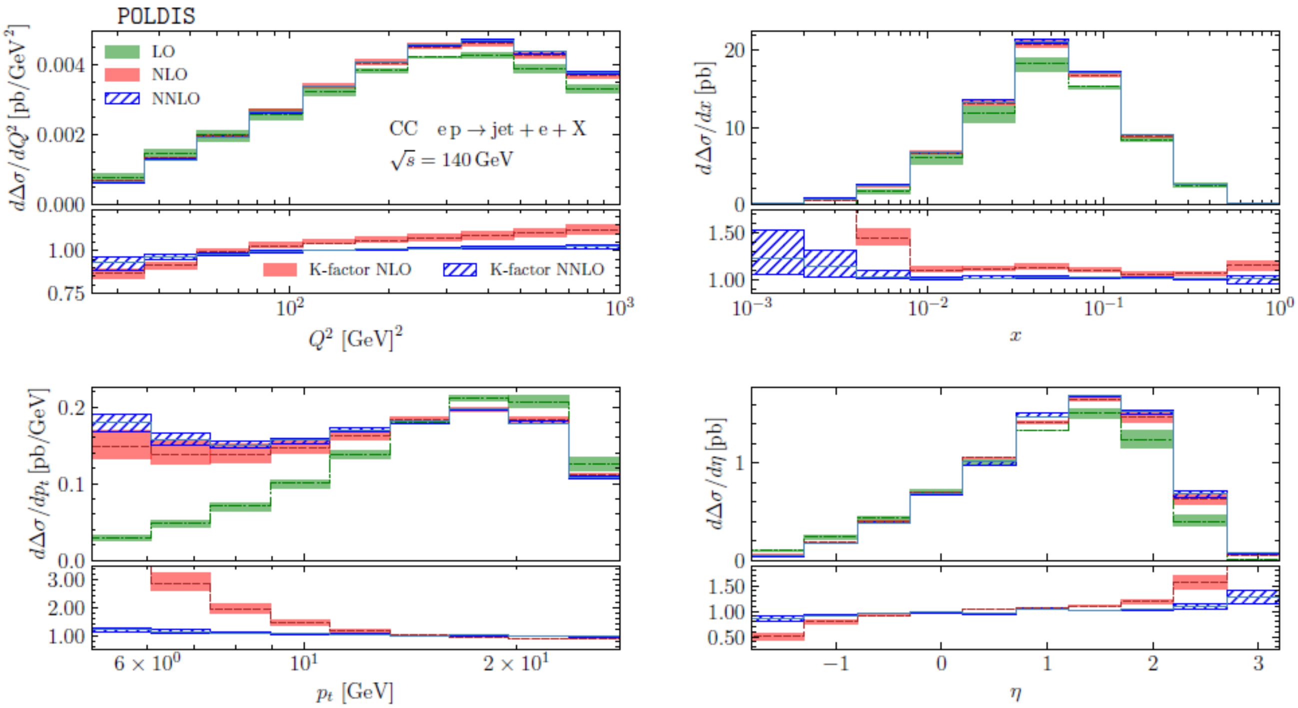


SENSITIVE BUT UNCLASSIFIED

NNLO SINGLE JET IN DIS (CHARGED CURRENTS)

POLARIZED CASE

- Massive propagator suppression at low Q2
- Pt^2 in proportional to Q2 at LO, leading to large corrections
- Shift towards higher values of Q2, x, pt and rapidity when compared to unpolarized case



SENSITIVE BUT UNCLASSIFIED

SUMMARY

- Higher order corrections are fundamental piece in the high precision description of observables, and they will be instrumental in the description of proton spin.

We presented:

- NNLO calculation of polarized single-jet production, in both Neutral and Charged Current DIS.
- As an ingredient of the P2B method, we also calculated the NLO dijet production in both processes.
- Increased perturbative convergence, but still showing sizable corrections and scale dependance.
- Sizable correction to asymmetries (no cancellation of higher order effects)

YOU CAN NOW GO GRAB A COFFEE

Back Up

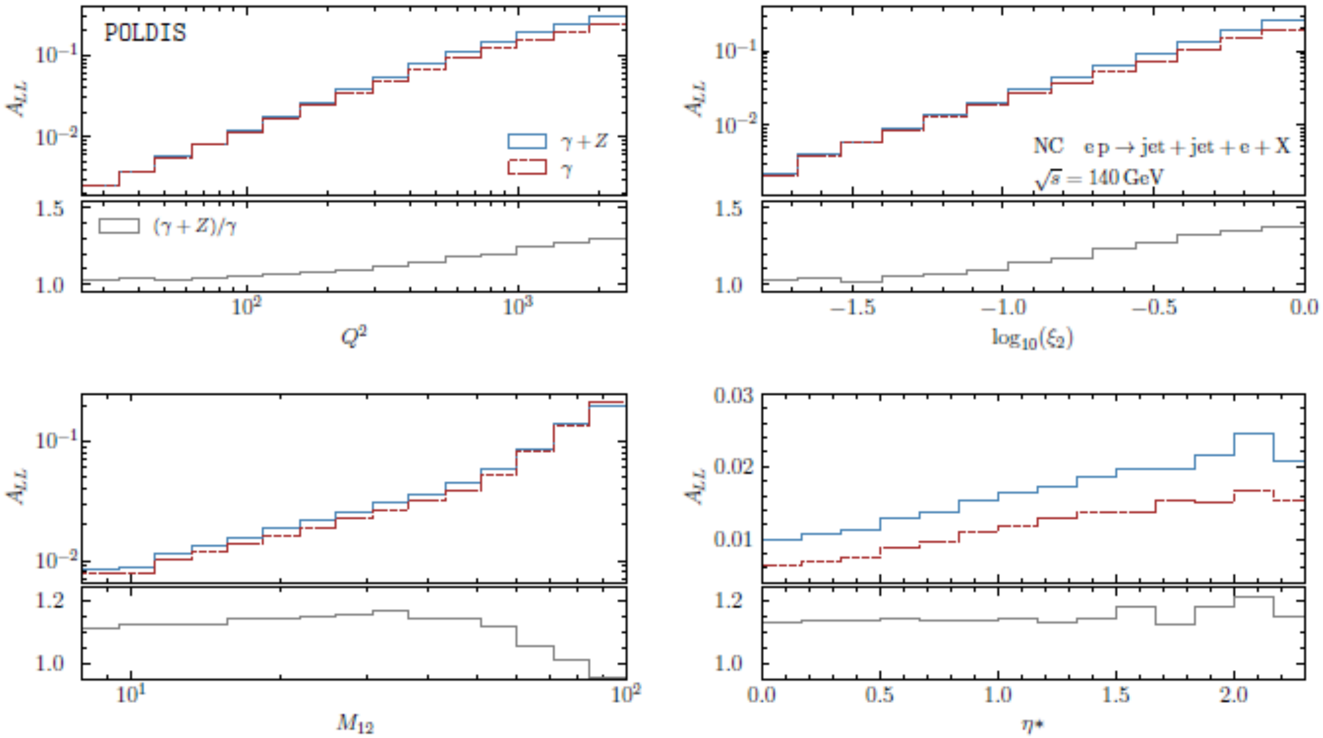
NLO DIJETS IN DIS (NEUTRAL CURRENTS)

$$M_{12} = \sqrt{(p_1 + p_2)^2}$$

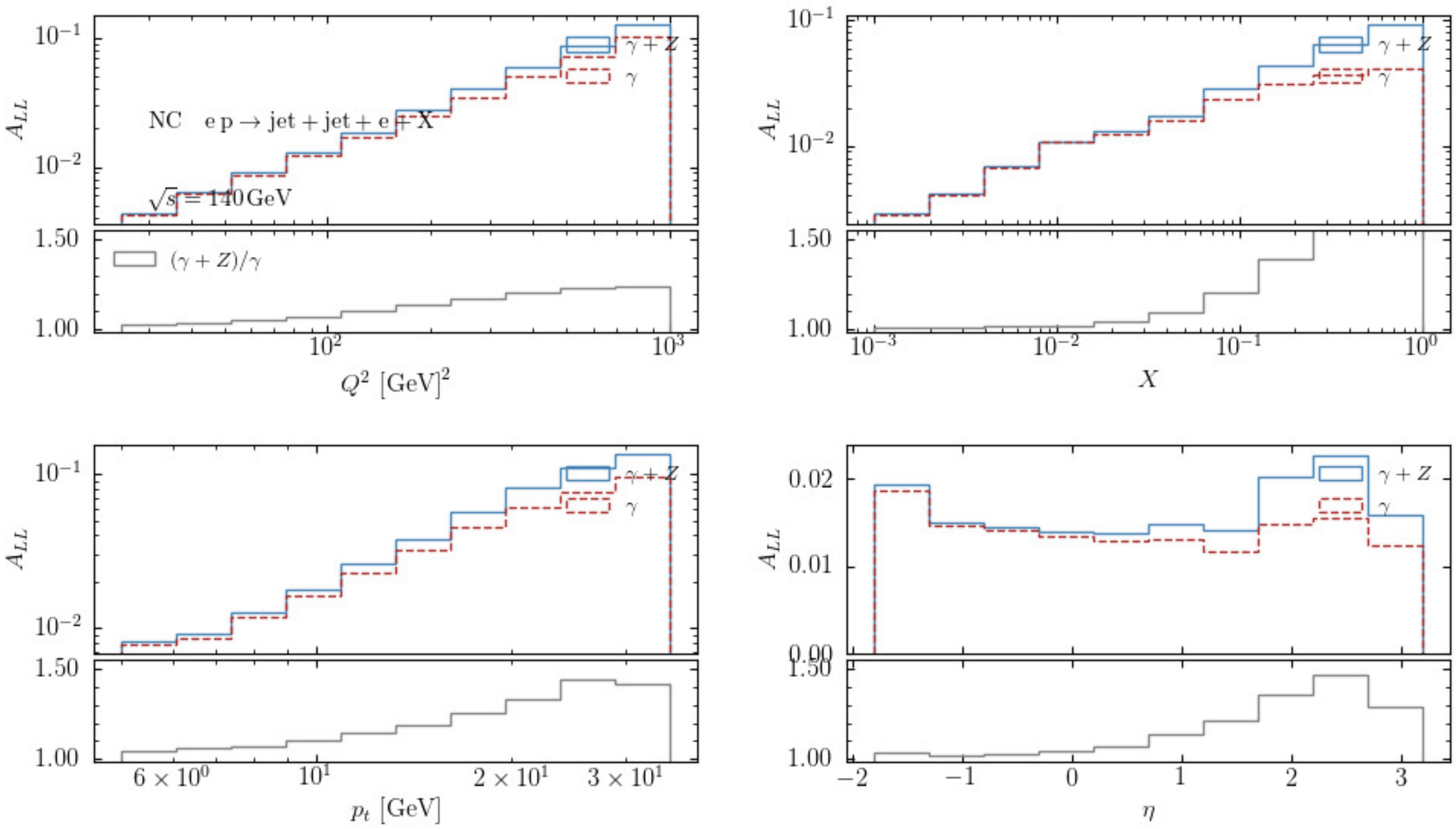
$$\langle p_T \rangle_2 = \frac{1}{2}(p^B_{T,1} + p^B_{T,2})$$

$$\eta^* = \frac{1}{2}|\eta^B_1 - \eta^B_2|$$

$$\xi_2 = x(1 + \frac{M^2_{12}}{Q^2})$$



Asymmetries



Asymmetries