The spin structure of the proton beyond NLO

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In collaboration with Daniel de Florian, Rodolfo Sassot, Marco Stratmann and Werner Vogelsang

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Zürich- October 15th

EBERHARD KARLS
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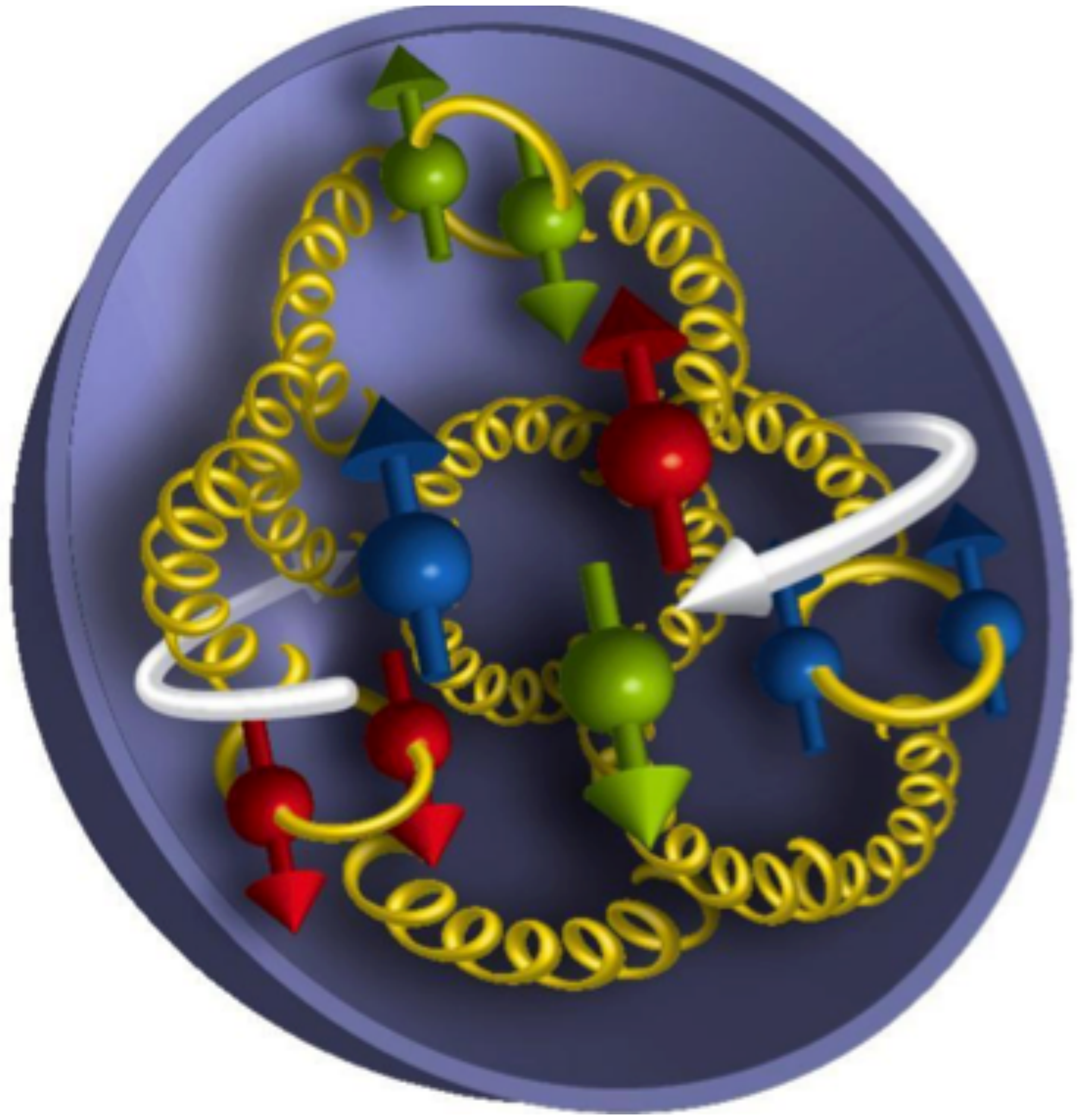
Introduction

Motivation - 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)] → "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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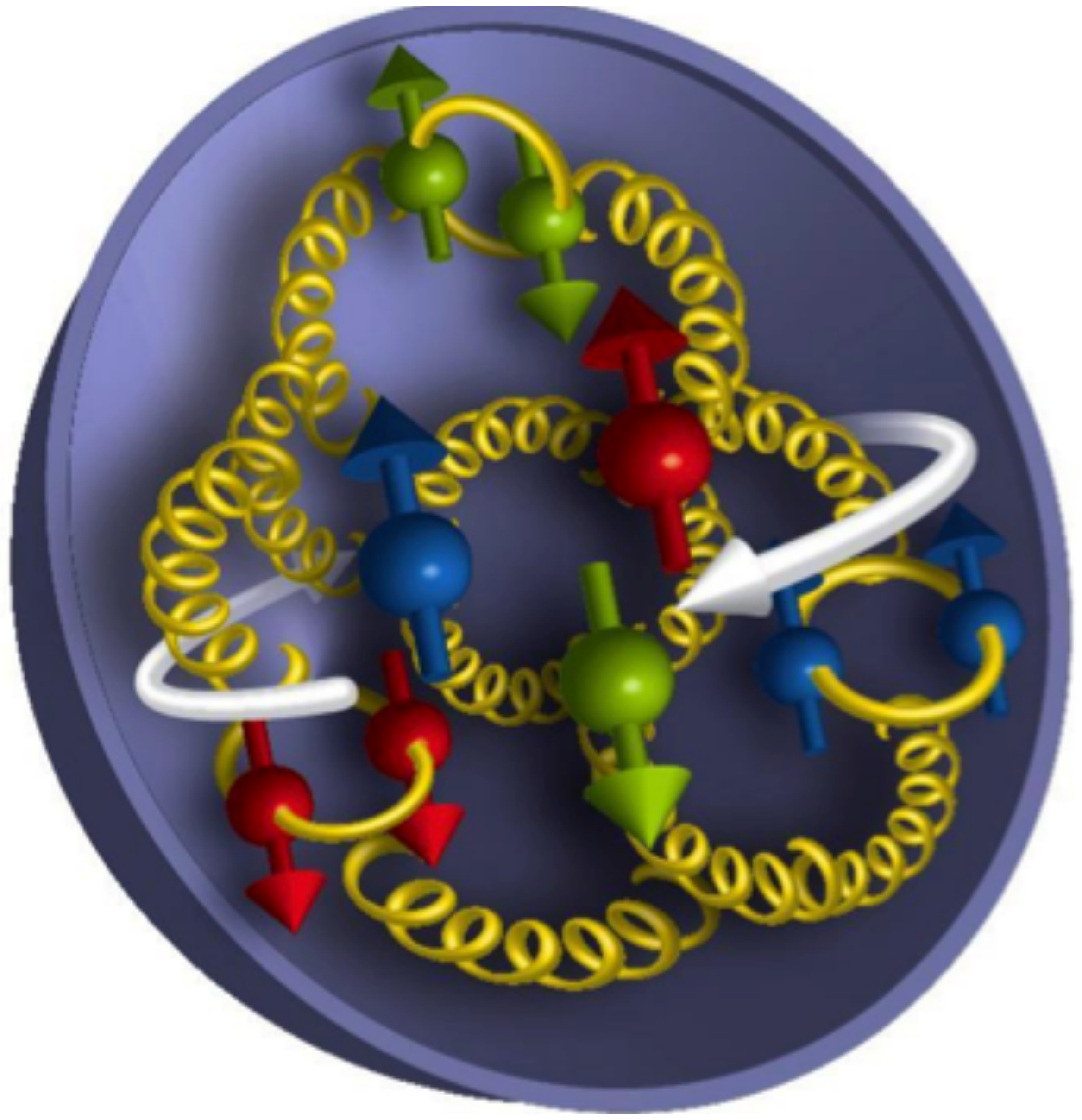

Quark's spin Gluon's spin OAM

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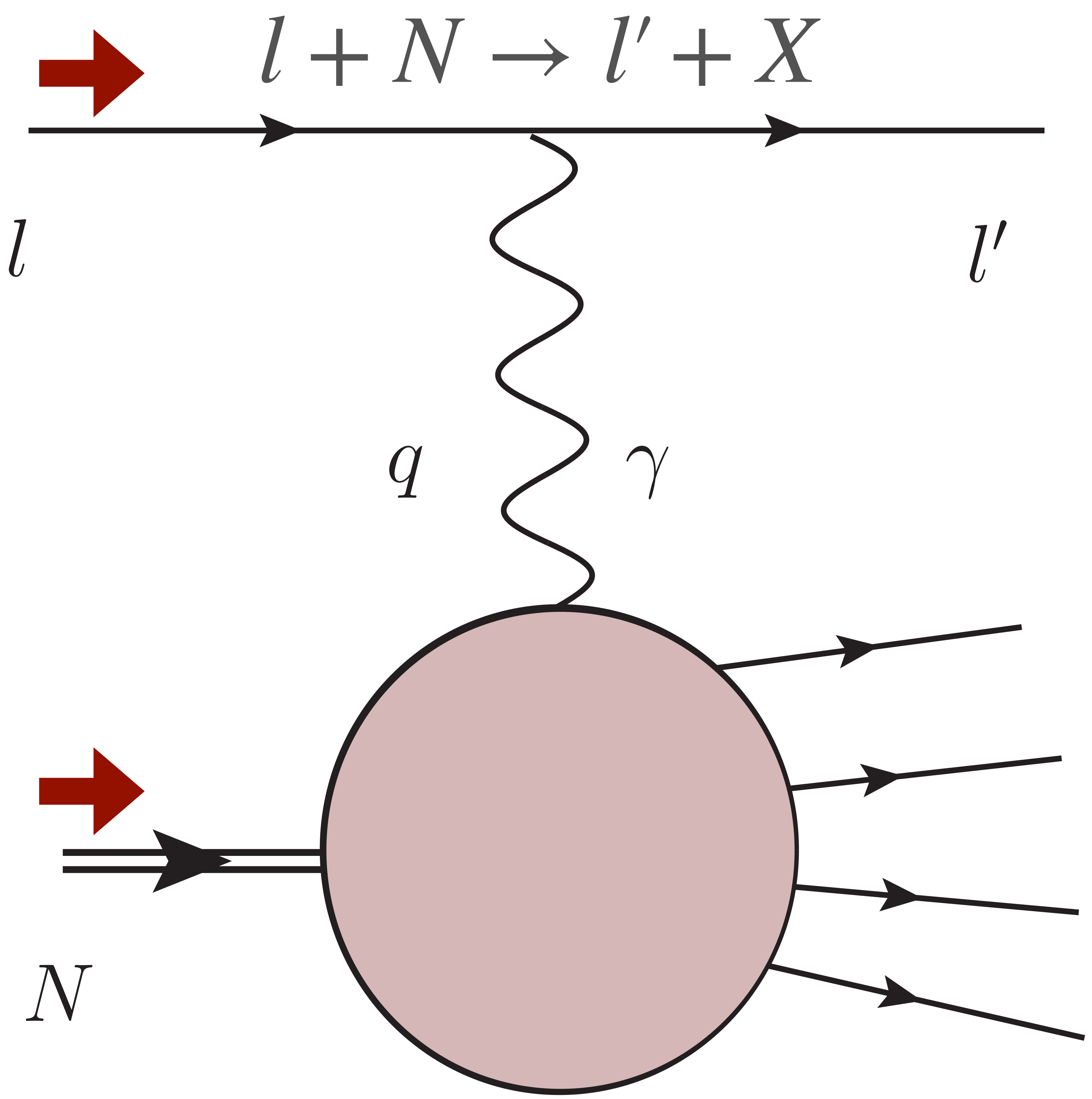

$$\Delta\sigma \equiv \frac{1}{2}\left[\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}\right]$$

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

Polarized PDFs

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

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

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

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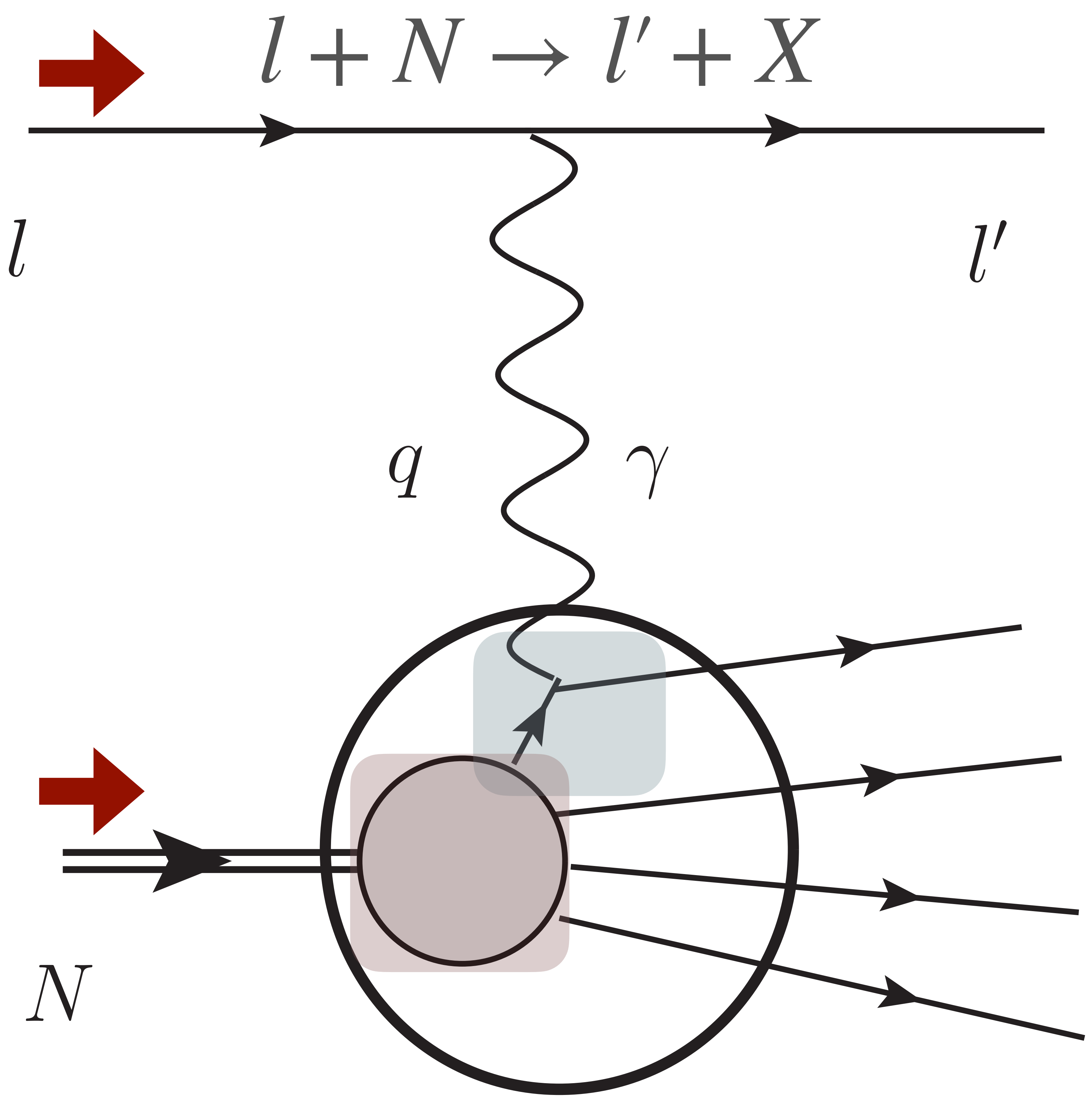

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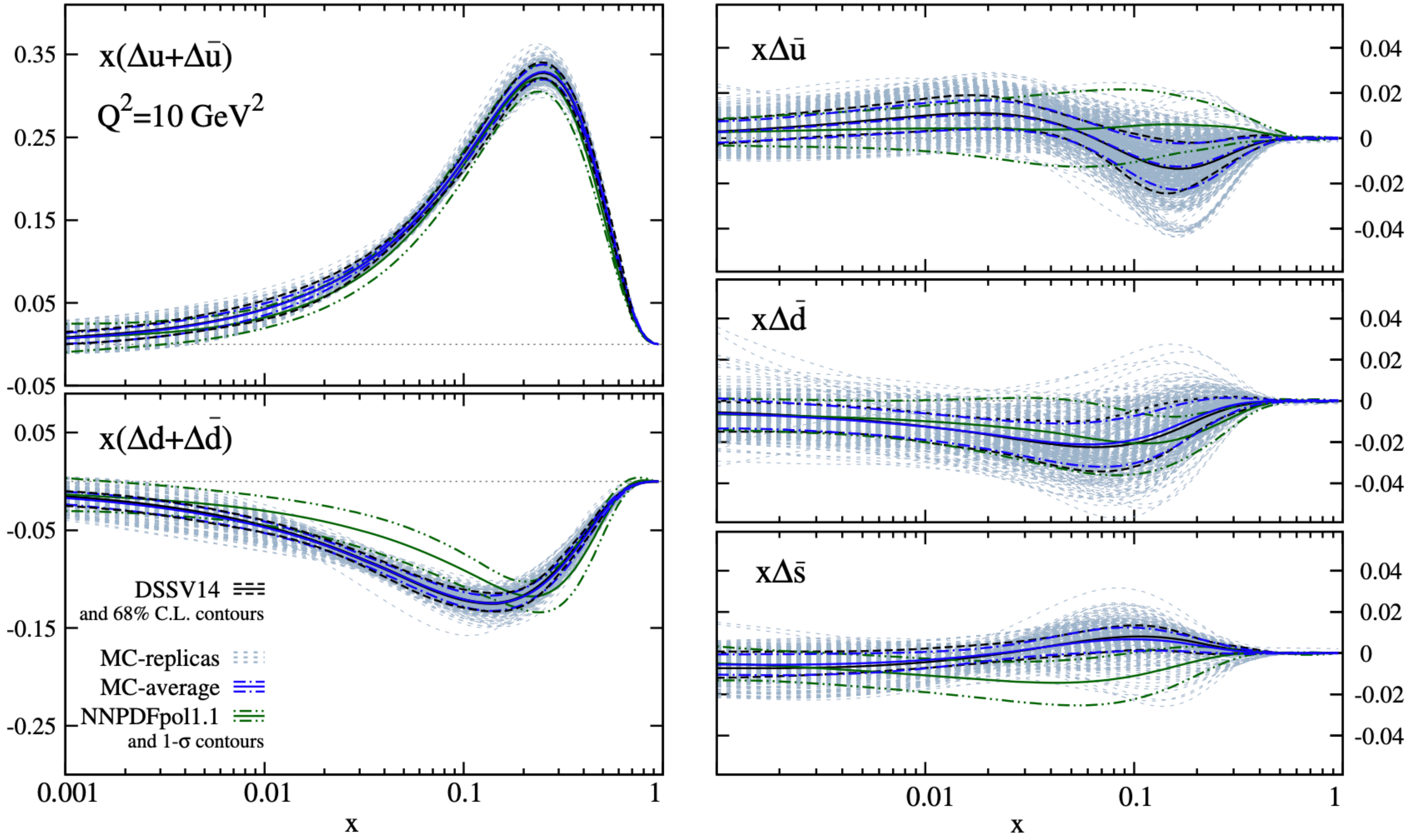
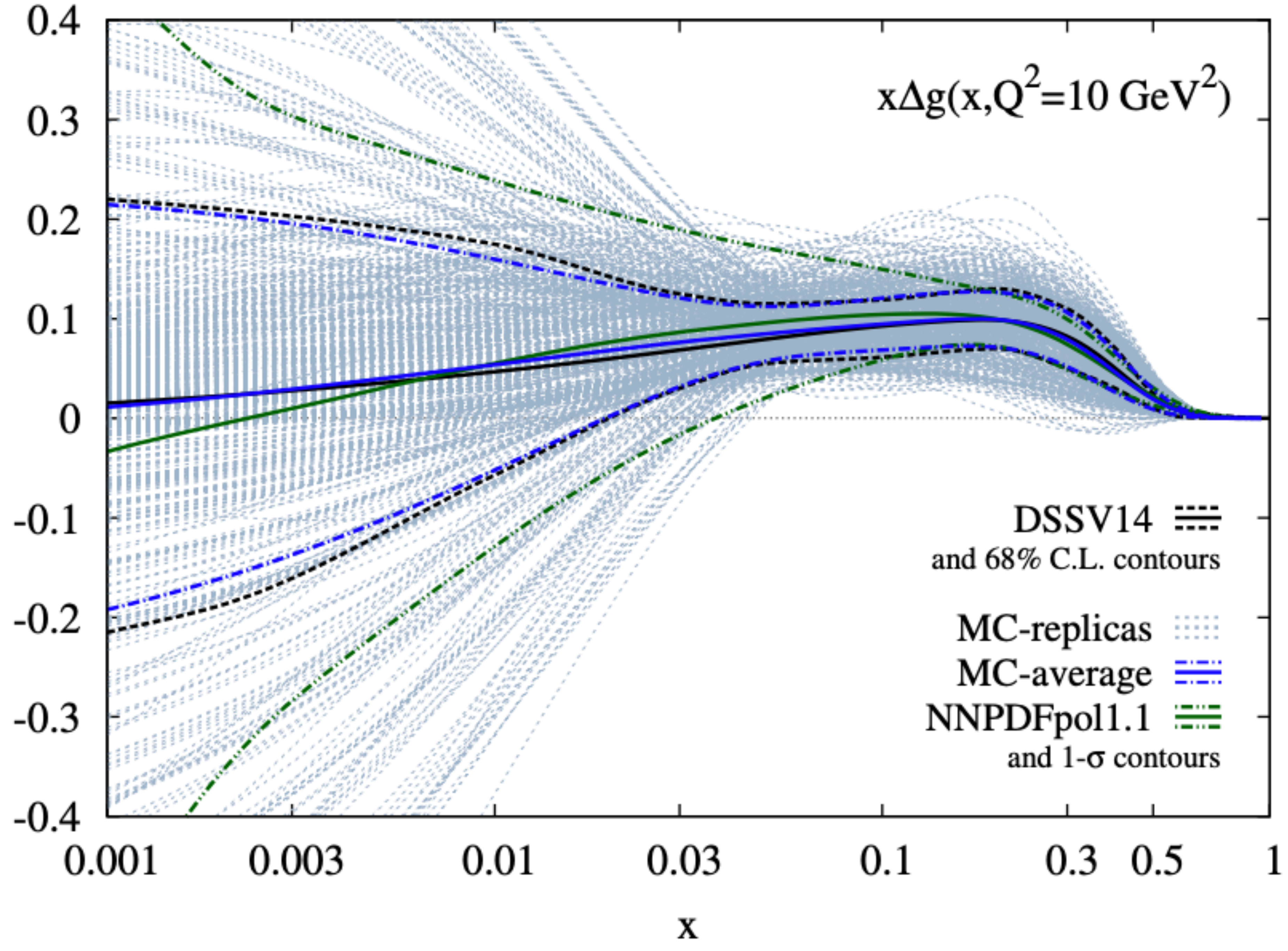
Introduction - The proton's spin structure

How well do we know polarized PDFs?





de Florian, Lucero, Sassot, Stratmann, Vogelsang (2019)

- Well constrained singlet combination
- Still incomplete picture in terms of flavor separation and contribution from gluons

Introduction - The proton's spin structure

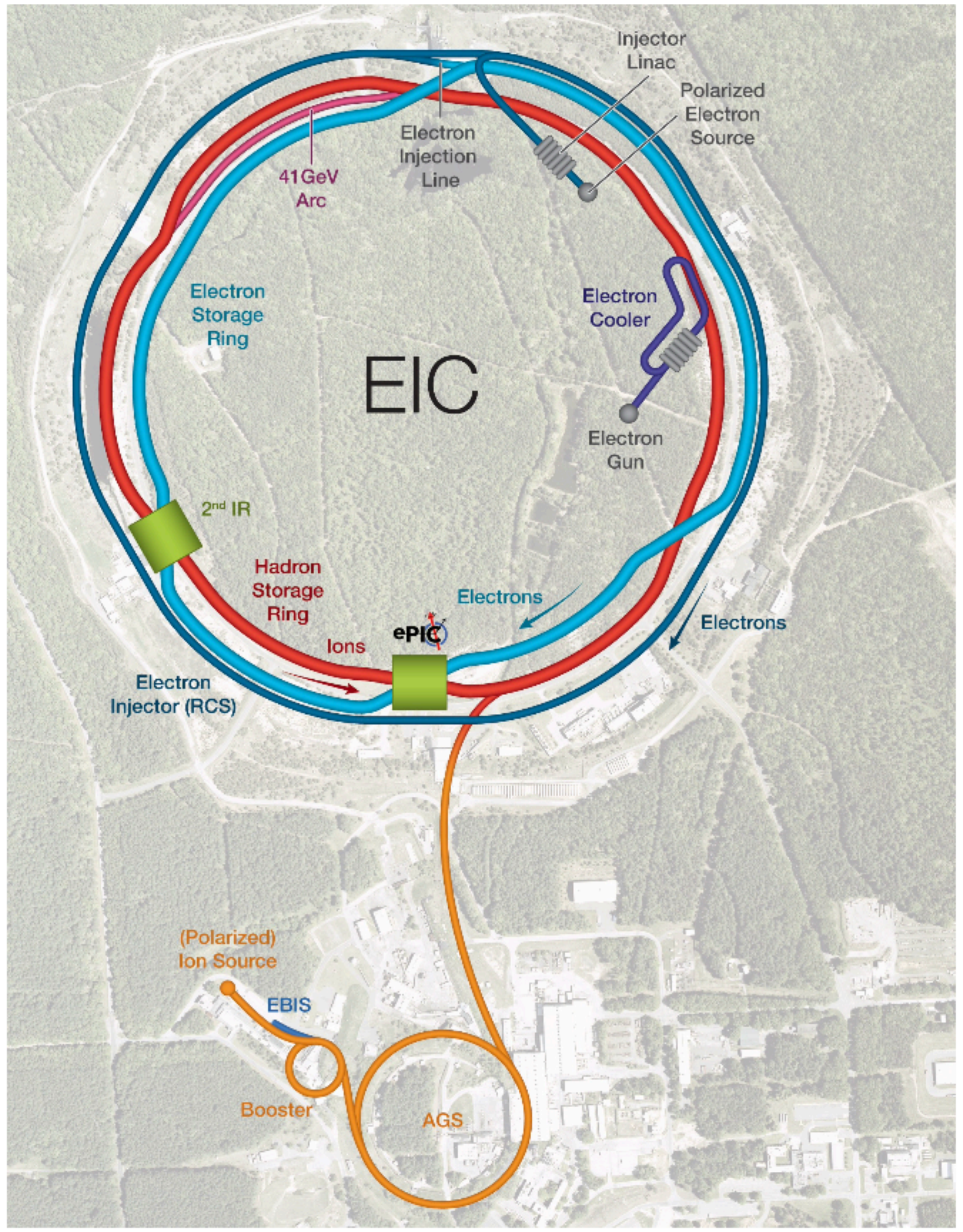
Why NNLO? - Precision physics at the Electron-Ion Collider

BNL-based EIC on its path towards construction

- High Luminosity: $\mathscr{L} = 10^{33} - 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$
- 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!

Physical interpretation of EIC data will require an increased precision of theory predictions



EIC Yellow Report. Nucl.Phys.A 1026 (2022)

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

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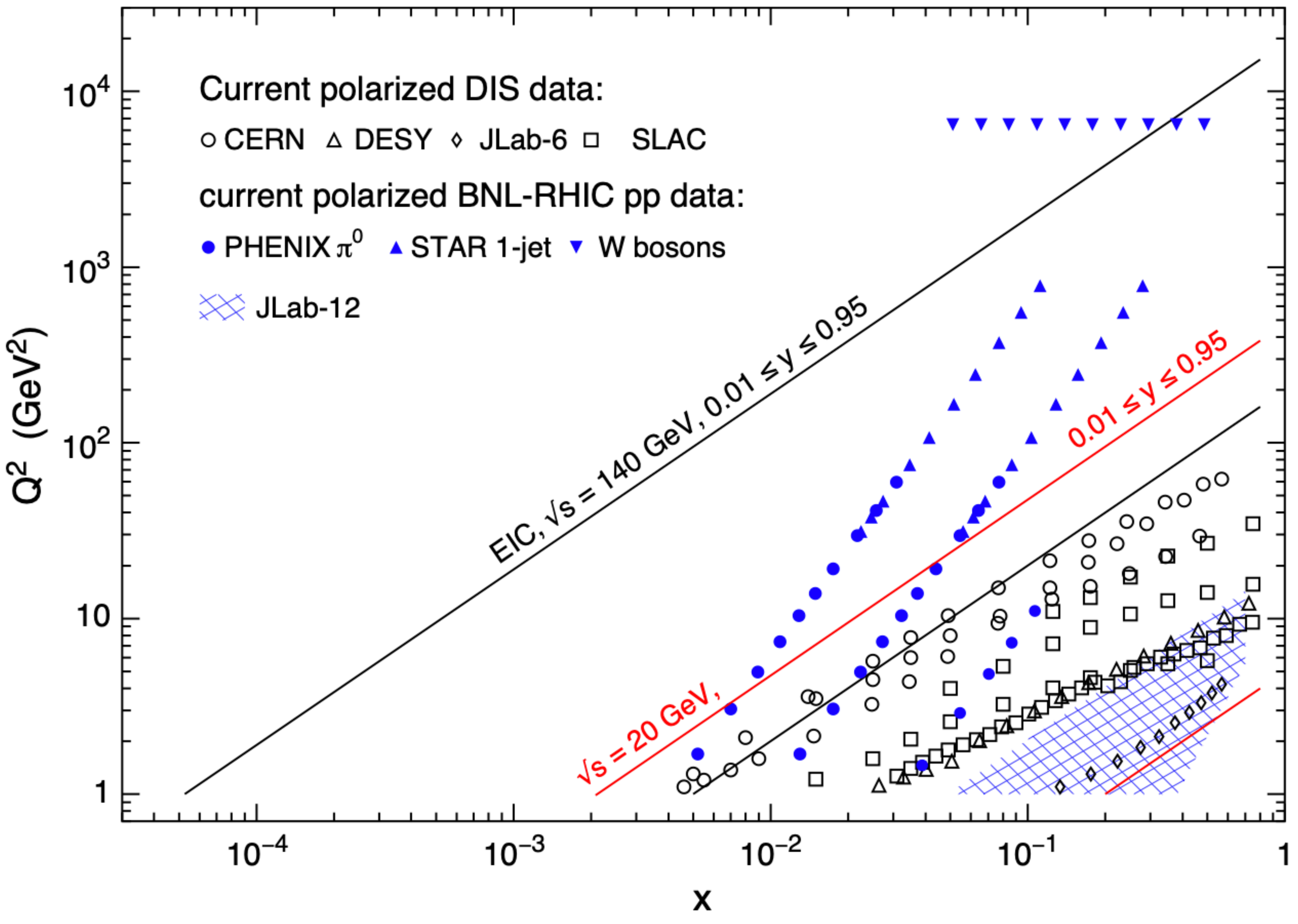

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Calculations for polarized eP observables beyond NLO:

- 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)

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This talk

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Parton distribution functions:

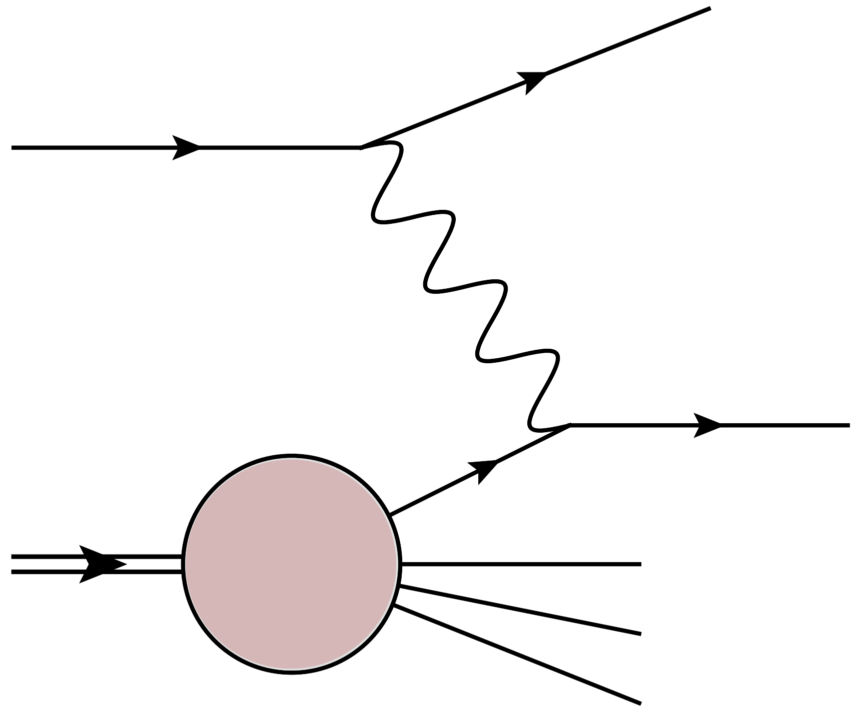
- NNLO polarized PDFs
  Taghavi-Shahri, Khanpour, Atashbar Tehrani, Alizadeh Yazdi (2016)
  Bertone, Chiefa, Nocera (2024)
  IB, de Florian, Sassot, Stratmann, Vogelsang (2024)

Global analysis of pPDFS

Global analysis of helicity PDFs

Accessing pPDFs in polarized high-energy scattering processes

DIS



- Mainly constrains
  $\Delta\Sigma \sim (\Delta q + \Delta\bar{q})$
- Only indirect constraints on
  $\Delta g, \Delta s$

First NLO QCD analyses based on DIS data:

[Gehrmann, Stirling; Glück, Reya, Stratmann, Vogelsang; Blümlein, Böttcher; Leader, Sidorov, Stamenov; Hirai, Kumano, Saito; Bourrely, Soffer, Bucella]

Global analysis of helicity PDFs

Accessing pPDFs in polarized high-energy scattering processes

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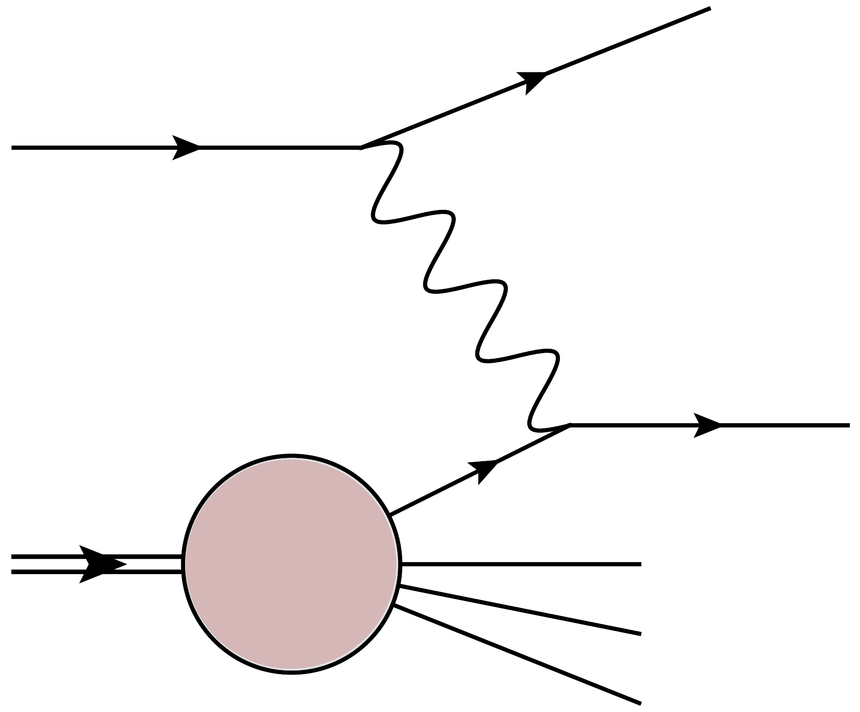

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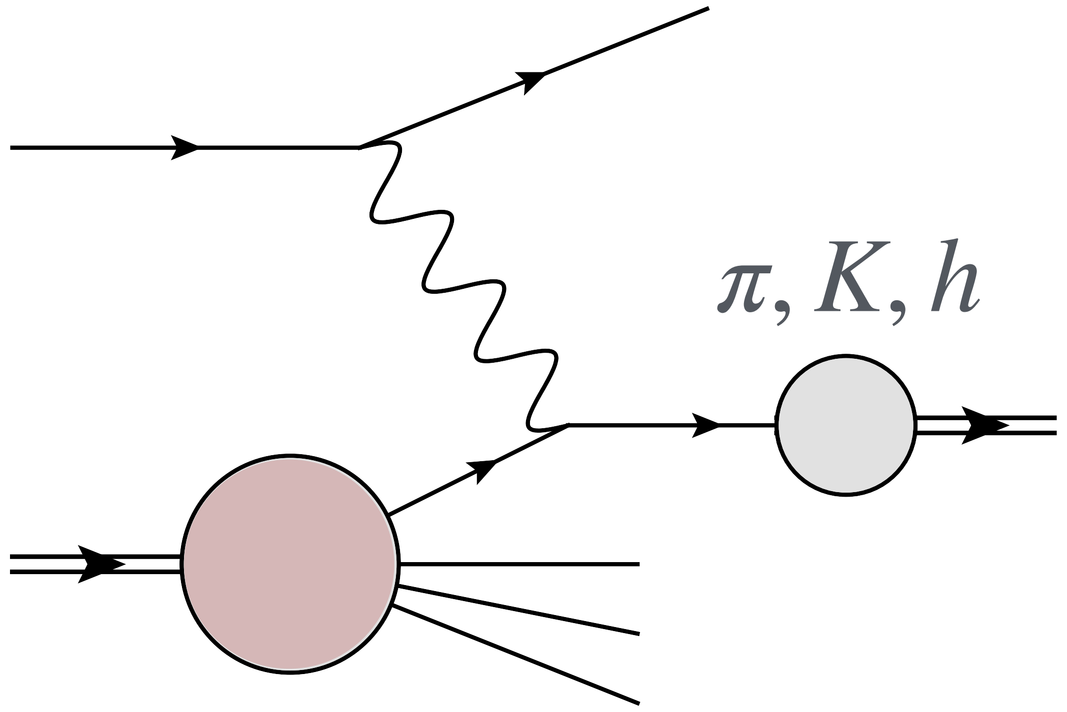
SIDIS



- Improved flavor discrimination
- Only indirect constraints on Δg

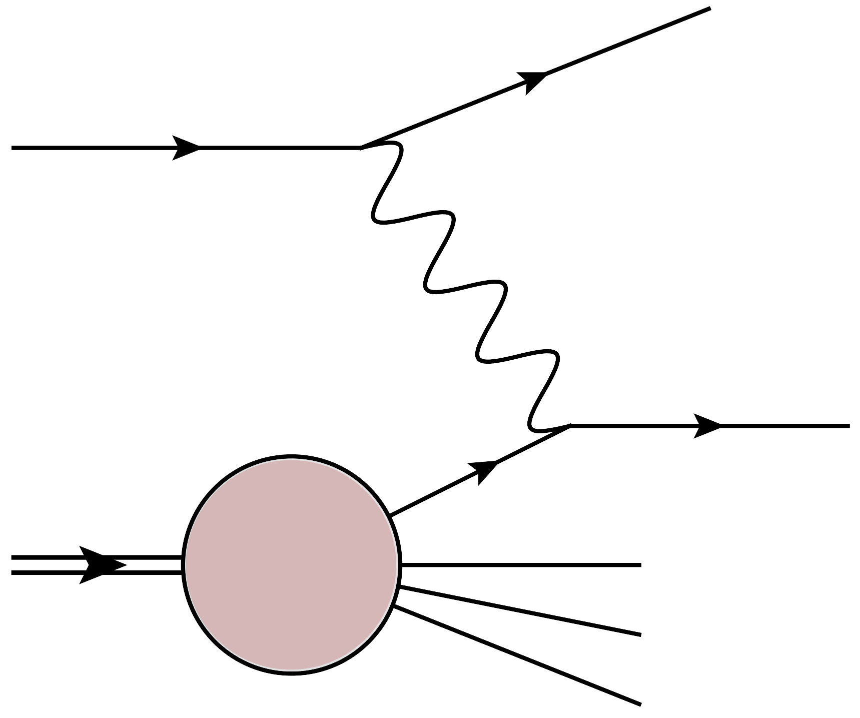
NLO QCD analyses based on combined DIS+SIDIS: data:

[de Florian, Sampayo, Sassot; de Florian, Navarro, Sassot]

Global analysis of helicity PDFs

Accessing pPDFs in polarized high-energy scattering processes

DIS



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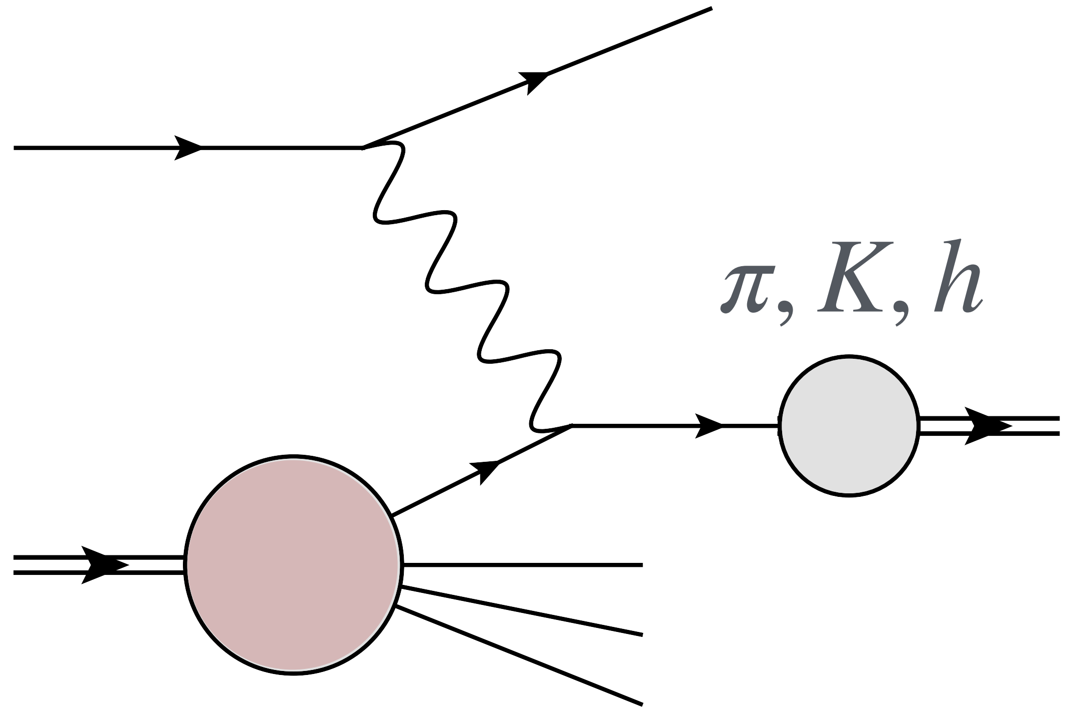
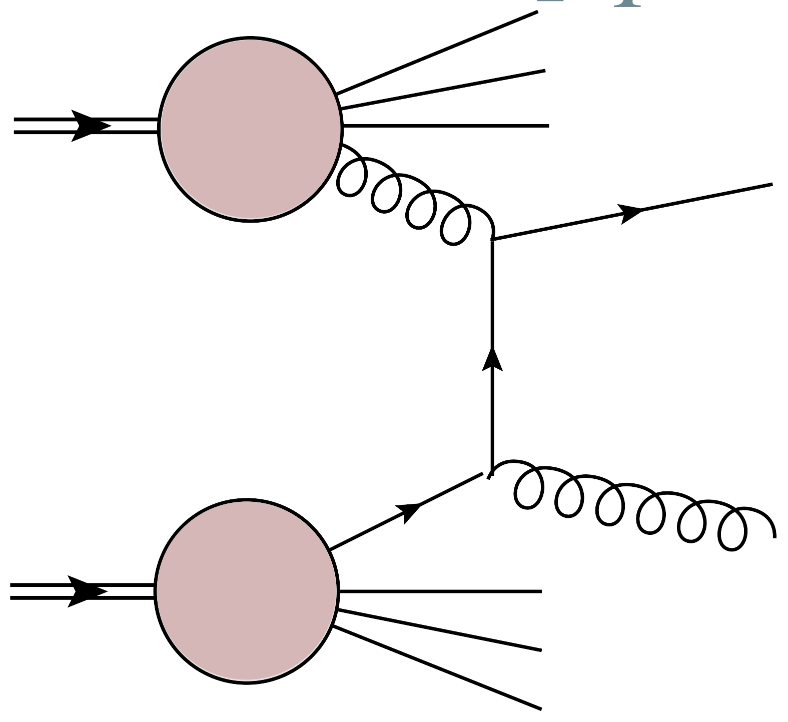
SIDIS



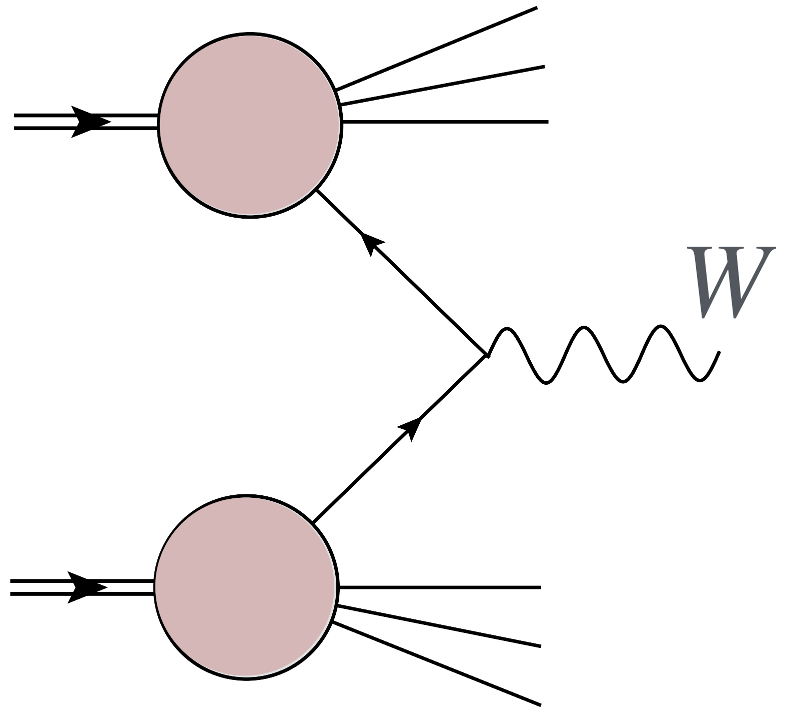
- Improved flavor discrimination
- Only indirect constraints on Δg

pp high-p_T



- Constraints on Δg
- Improved flavor discrimination

pp W boson



- Improved flavor discrimination

Fully global NLO analyses:
[de Florian, Sassot, Stratmann, Vogelsang (2008-); Nocera, Ball Forte, Ridolfi, Rojo (2013-); Cocuzza, Ethier, Melnitchouk, Sato (2013-)] $\Rightarrow$ Mature analysis frameworks with robust estimation of uncertainties

Global analysis of helicity PDFs

Workflow

Parametrization for $\Delta f(x, Q_0)$ at input scale Q_0, e.g:

$$\Delta q(z, Q_0) = N_q\, x^{\alpha_q}(1-x)^{\beta_q}(1+\gamma_q x^{\delta_q})$$

Change parameters

Evolve to the relevant scale using DGLAP Equations

Evaluate cross section and calculate χ^2

χ^2 minimum?

No

Yes

Optimum set of parameters

+ Prescription for uncertainties

Global analysis of helicity PDFs

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No → Change parameters

Yes →

Optimum set of parameters

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"Time-consuming" convolution integrals:

$$\frac{\partial}{\partial \ln \mu^2}\Delta f_i(x,\mu^2) = \Delta P_{ij} \otimes \Delta f_j(x,\mu^2)$$

Eg:

$$\Delta\sigma_{pp} = \sum_{a,b} \Delta f_a(x_a,\mu) \otimes \Delta f_b(x_b,\mu) \otimes \Delta\hat{\sigma}_{ab}$$

$$a(x) \otimes b(x) \equiv \int_0^1 dy \int_0^1 dz\, \delta(x-yz)\, a(y)\, b(z)$$

$\Rightarrow$ Switch to Mellin space

Global analysis of helicity PDFs

Mellin Technique

- Fast evaluation in Mellin N-space ⇒ Convolutions become simple products

$$\tilde{a}\,(N) = \int_0^1 dx\, x^{N-1}\, a\,(x) \qquad \left[a \otimes b\right](N) = \tilde{a}(N) \cdot \tilde{b}(N)$$

- Simple Gaussian integral for each convolution in the cross-section
- If analytical coefficients are known in Mellin space (e.g: DIS) ⇒ Direct application
- "Trick" if coefficients not known in N-space (e.g: $pp \to \pi X$) ⇒ write PDFs in terms of their Mellin inverse $\Delta f_i(x) = \frac{1}{2\pi i}\int_{\mathscr{C}_N} dN\, x^{-N} \Delta\tilde{f}_i(N)$

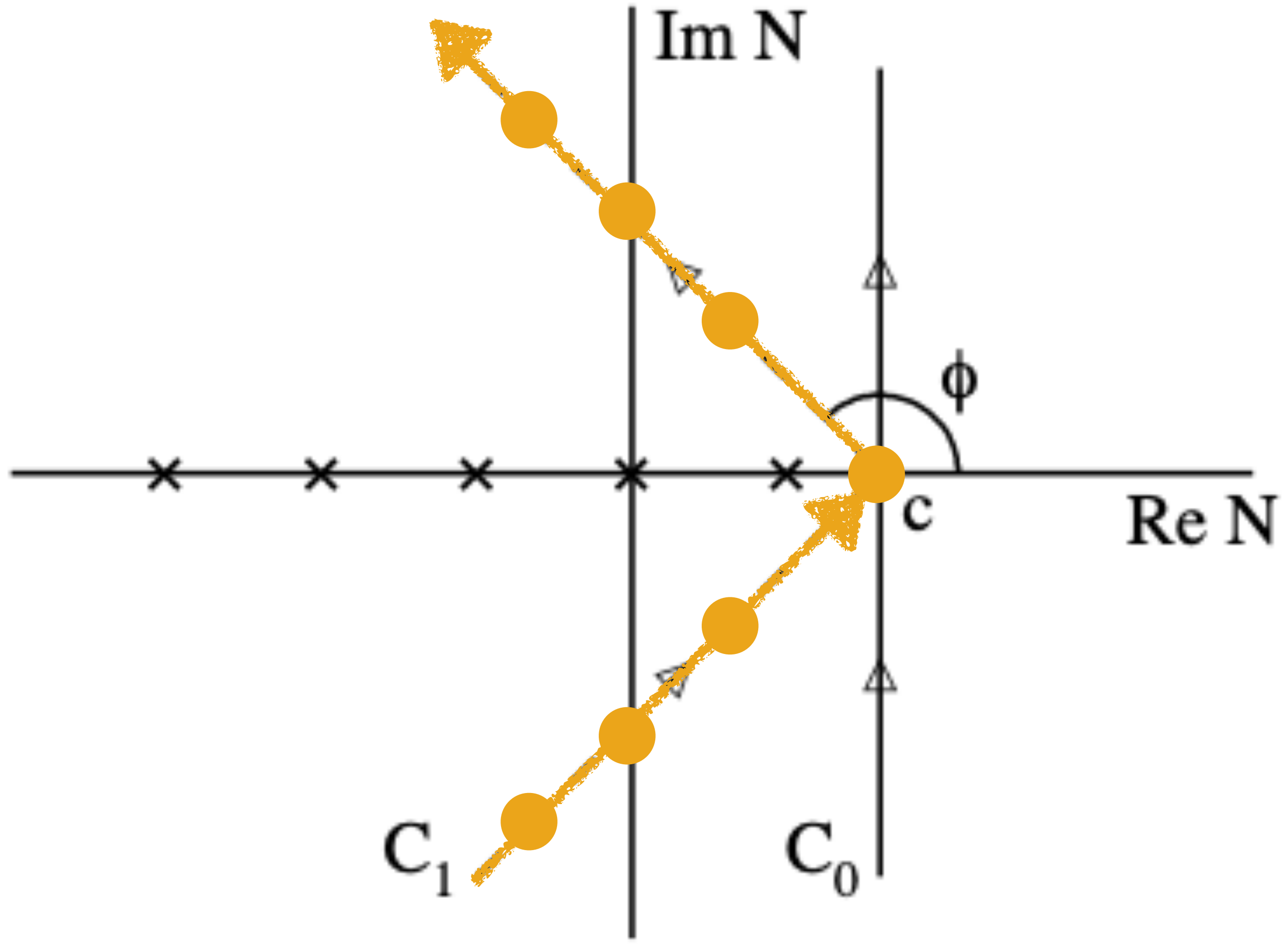
Mellin inversion

$$\frac{d\Delta\sigma}{dO} = \sum_{ab} \int_{\mathscr{C}_N}\int_{\mathscr{C}_M} \Delta\tilde{f}_a(N)\,\Delta\tilde{f}_b(M)\; \Delta\tilde{\sigma}^h_{ab}(N, M, O)$$

Fit

Precomputed grid

$$a(x) = \frac{1}{2\pi i}\int_{\mathscr{C}_N} dN\, x^{-N}\tilde{a}(N)$$



From NLO to NNLO

Global analysis of helicity PDFs

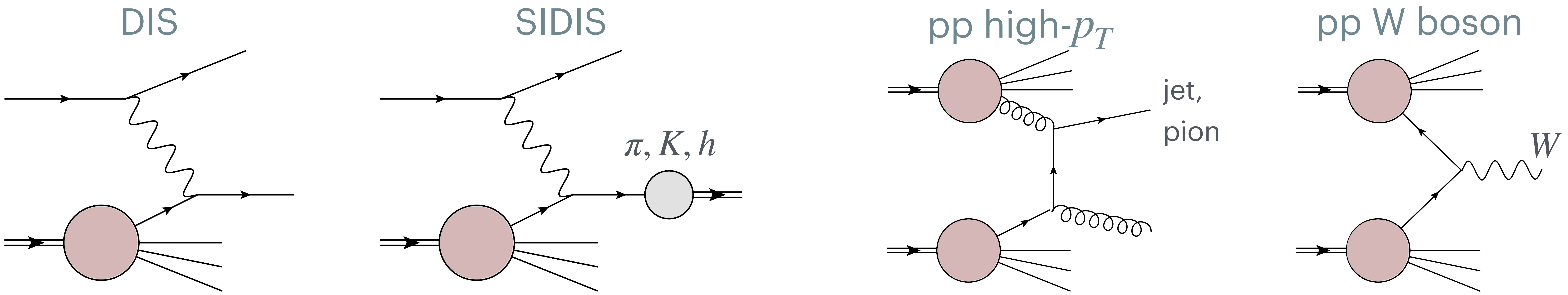
Ingredients for NNLO

- PDF evolution kernels

$$\Delta P_{ij} = \frac{\alpha_s}{2\pi}\Delta P_{ij}^{\mathrm{LO}} + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta P_{ij}^{\mathrm{NLO}} + \left(\frac{\alpha_s}{2\pi}\right)^3 \Delta P_{ij}^{\mathrm{NNLO}} + \ldots$$

- Partonic hard scattering:

$$\Delta\hat{\sigma}_{ab} = \Delta\hat{\sigma}_{ab}^{\mathrm{LO}} + \frac{\alpha_s}{\pi}\Delta\hat{\sigma}_{ab}^{\mathrm{NLO}} + \left(\frac{\alpha_s}{\pi}\right)^2 \Delta\hat{\sigma}_{ab}^{\mathrm{NNLO}} + \ldots$$



Global analysis of helicity PDFs

Ingredients for NNLO

NNLO helicity PDFs:

- DIS-only analysis [Taghavi-Shahri, Khanpour, Atashbar Tehrani, Alizadeh Yazdi (2016)]
- DIS and (approximate) SIDIS [MAP: Bertone, Chiefa, Nocera (2024)]
- Fully global analysis with approximate NNLO for SIDIS and pp [BDSSV: IB, de Florian, Sassot, Stratmann, Vogelsang (2024)]

Global analysis of helicity PDFs

NNLO PDF evolution

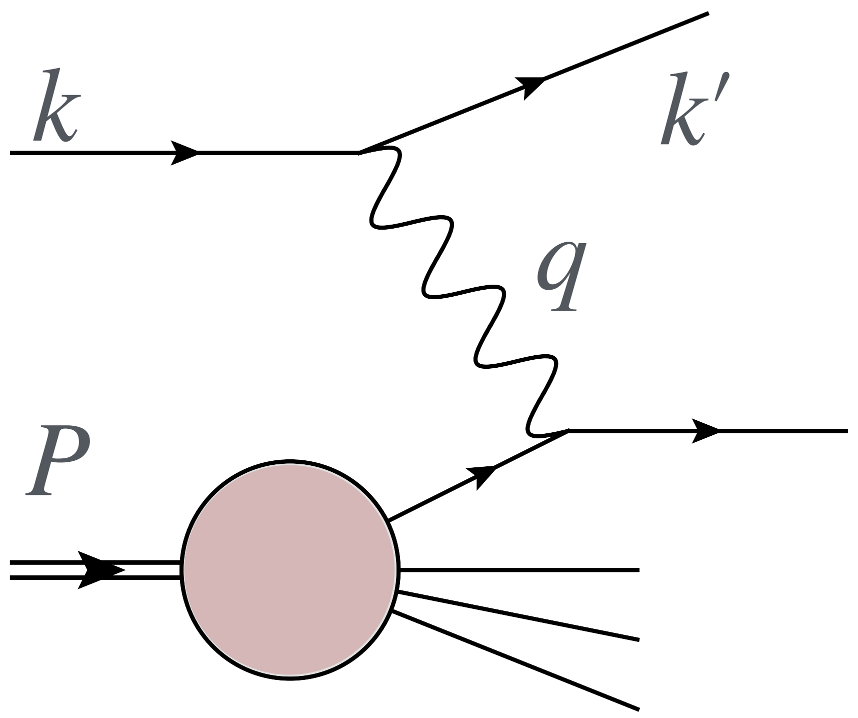
$$\frac{\partial}{\partial \ln \mu^2} \Delta f_i(x,\mu^2) = \Delta P_{ji} \otimes \Delta f_j(x,\mu^2) \qquad \Delta P_{ij} = \frac{\alpha_s}{2\pi} \Delta P_{ij}^{\mathrm{LO}} + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta P_{ij}^{\mathrm{NLO}} + \left(\frac{\alpha_s}{2\pi}\right)^3 \Delta P_{ij}^{\mathrm{NNLO}} + \ldots$$

- NNLO polarized evolution kernels known [Moch, Vermaseren, Vogt (2008, 2014, 2015)]; [Blümlein, Marquard, Schneider, Schönwald (2022)].
- NNLO evolution of pPDFs implemented in extended PEGASUS library [Vogt (2004)].
  - Evolution equations solved in Mellin space ⇒ direct interface.
  - Included missing NNLO polarized kernels
  - Included OMEs for matching conditions [Bierenbaum, Blümlein, De Freitas, Goedicke, Klein (2022)].
- Evolution benchmarked against libraries EKO [Candido, Hekhorn, Magni (2022)] and APFEL [Bertone, Carrazza, Rojo (2013)]; [Bertone (2017)].

Global analysis of helicity PDFs

NNLO Coefficient functions for DIS

DIS



$$\frac{d^2\Delta\sigma}{dx\,dy} = \frac{8\pi\alpha^2}{Q^2}\left[(2-y)\,g_1(x,Q^2)\right] \qquad g_1(x,Q^2) = \sum_{f=q,g} \Delta C^f(x,Q^2) \otimes \Delta f(x,Q^2)$$

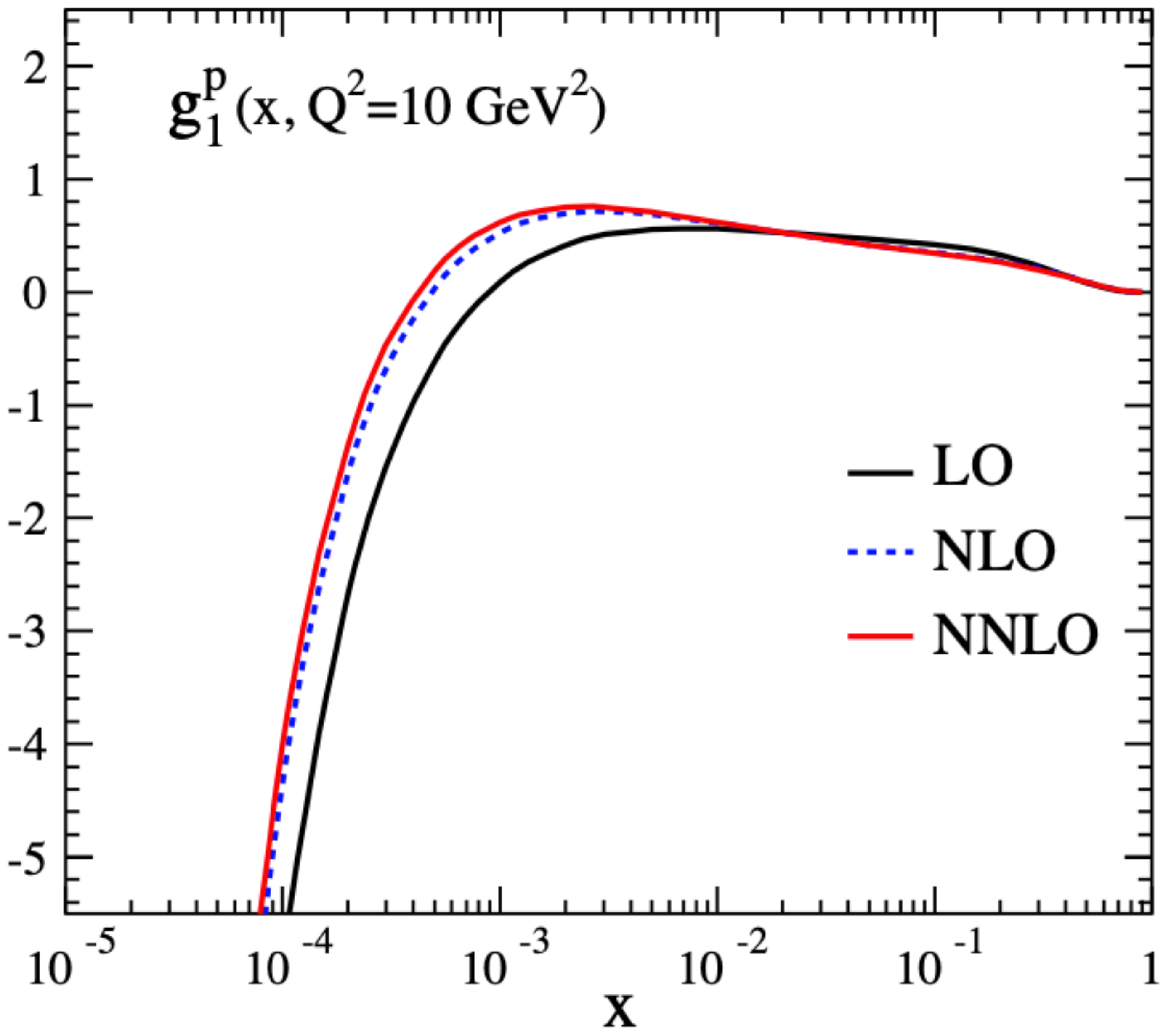
$$\Delta C^f = \Delta C^{f,(0)} + \frac{\alpha_s}{2\pi}\Delta C^{f,(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta C^{f,(2)} + \ldots$$

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

- NNLO corrections to $g_1(x,Q^2)$ known [van Neerven, Zijlstra (1994)] (N3LO corrections recently obtained for Larin scheme [Blümlein, Marquard, Schneider, Schönwald (2023)]).

- Possible to obtain analytical expression in Mellin space (MT package [Höschele, Hoff, Oak, Steinhauser, Ueda (2013)]; ANCONT program [Blümlein (2000)]).

- Already used in DIS-only analysis [Taghavi-Shahri, Khanpour, Tehran, Yazdi (2023)].



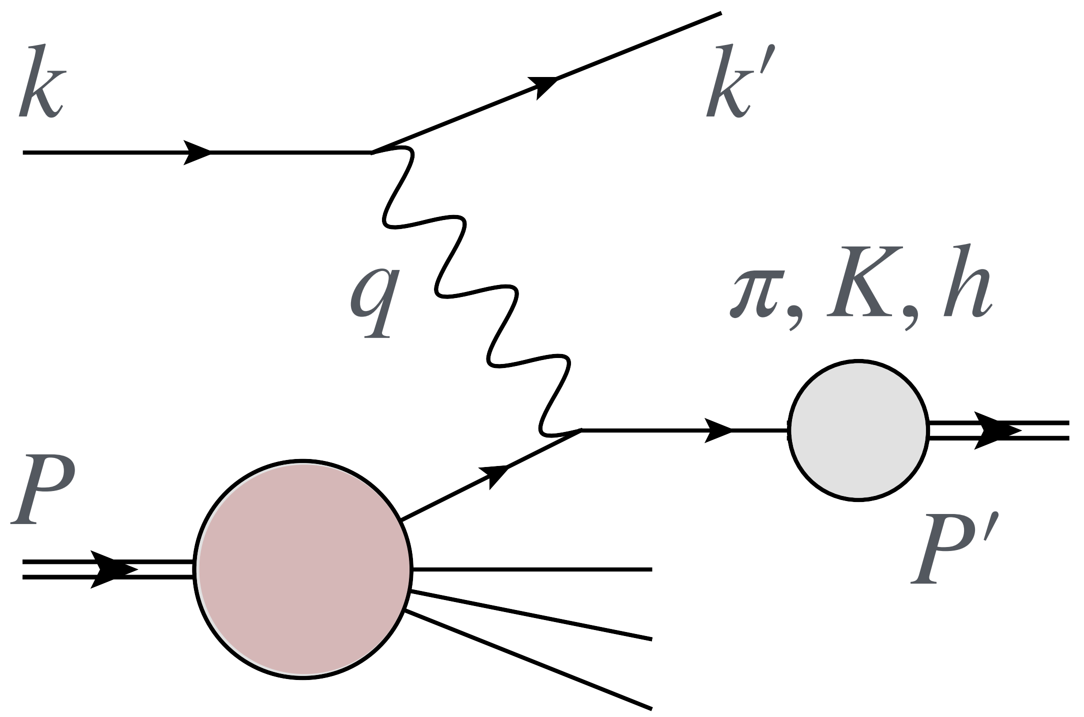
Global analysis of helicity PDFs

NNLO Coefficient functions for SIDIS

$$\frac{d^3\Delta\sigma^h}{dx\,dy\,dz} = \frac{4\pi\alpha^2}{Q^2}\left[(2-y)\,g_1^h(x,z,Q^2)\right] \qquad g_1^h(x,z,Q^2) = \sum_{f,f'} \Delta f(x,Q^2) \otimes \Delta C_{ff'}(x,z,Q^2) \otimes D_{f'}^h$$

$$\Delta C_{ff'} = \Delta C_{ff'}^{(0)} + \frac{\alpha_s}{2\pi}\Delta C_{ff'}^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta C_{ff'}^{(2)} + \dots$$

SIDIS

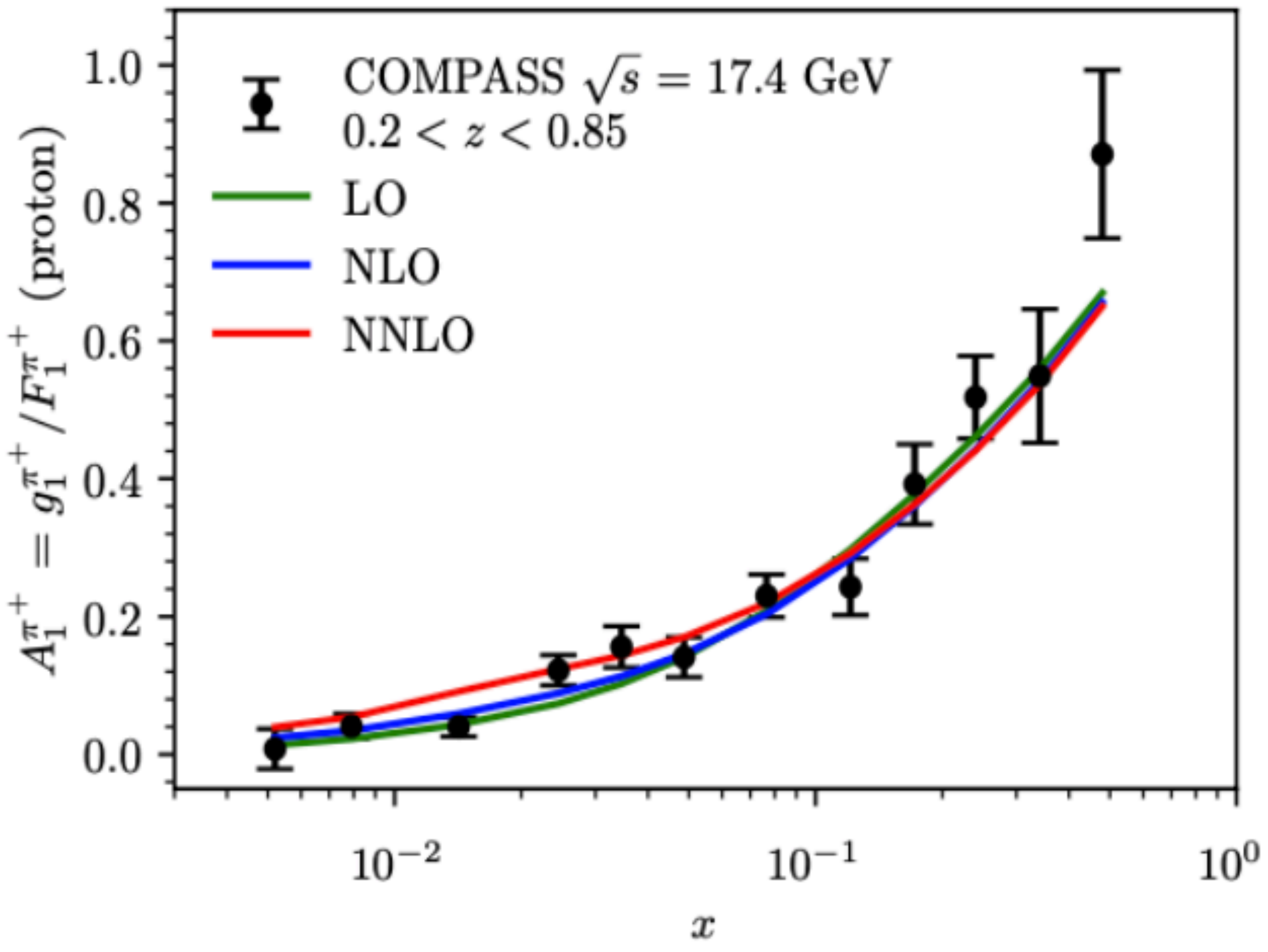


$$Q^2 = -q^2 \quad x = \frac{Q^2}{2P\cdot q} \quad z = \frac{P\cdot P_h}{P\cdot q}$$

- NNLO coefficients recently obtained [Bonino, Gehrmann, Löchner, Schönwald, Stagnitto (2024)]; [Goyal, Lee, Much, Pathak, Rana, Ravindran (2024)]) ⇒ Soon to be included in global analyses of FFs and pPDFs.

- Soft gluon approximate NNLO [Anderle, Ringer, Vogelsang (2012)]; [Abelde, de Florian, Vogelsang (2021)].

- NNLO FFs available, but ... based only on SIA [Anderle, Ringer, Stratmann (2015)]; [Bertone, Carrazza, Hartland, Nocera, Rojo (2017)], or SIA+approx. SIDIS [IB, de Florian, Sassot, Stratmann, Vogelsang (2021)], [Abdul-Khalek, Bertone, Khoudii, Nocera (2021)].

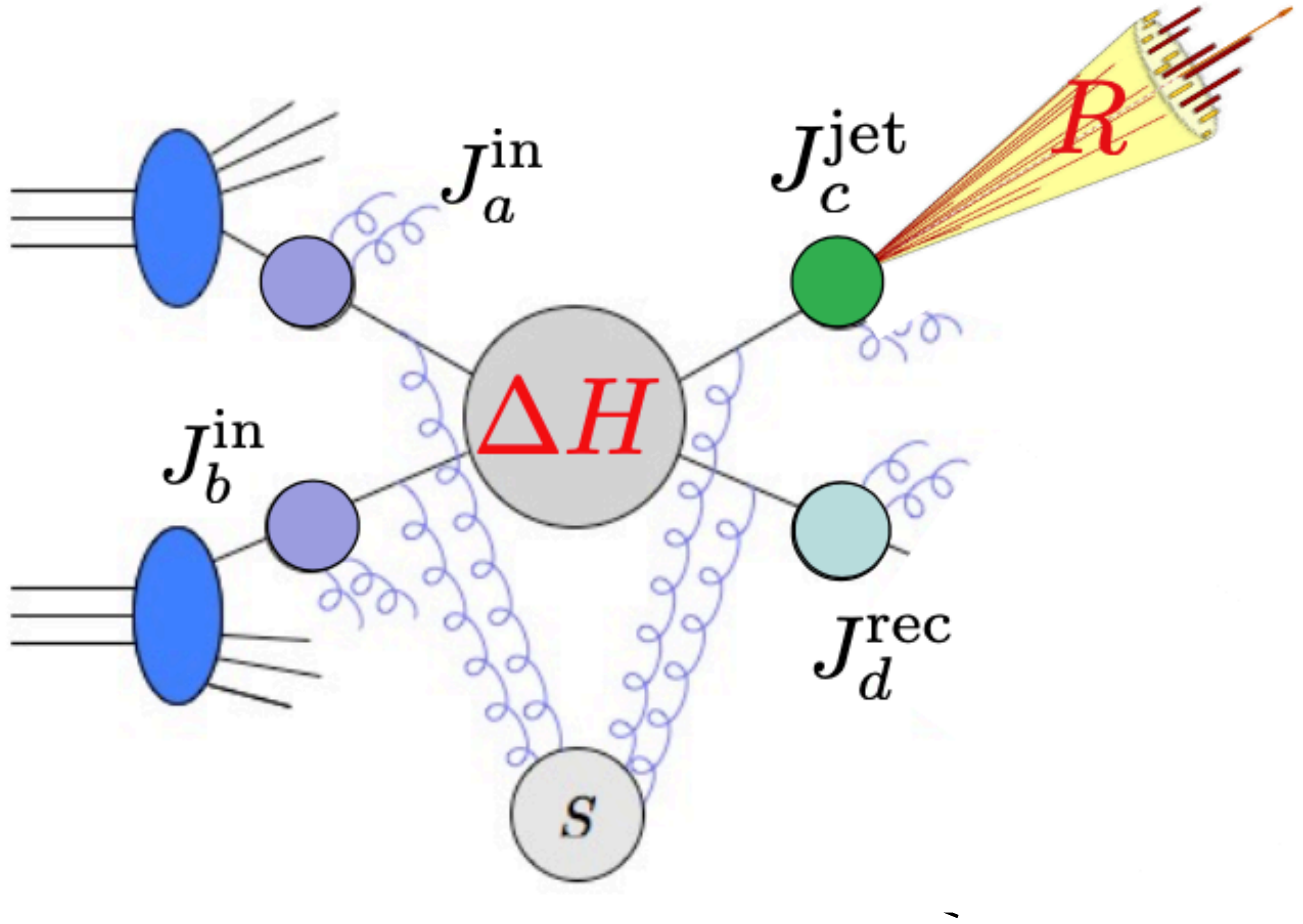


Global analysis of helicity PDFs

NNLO Coefficient functions for pp observables

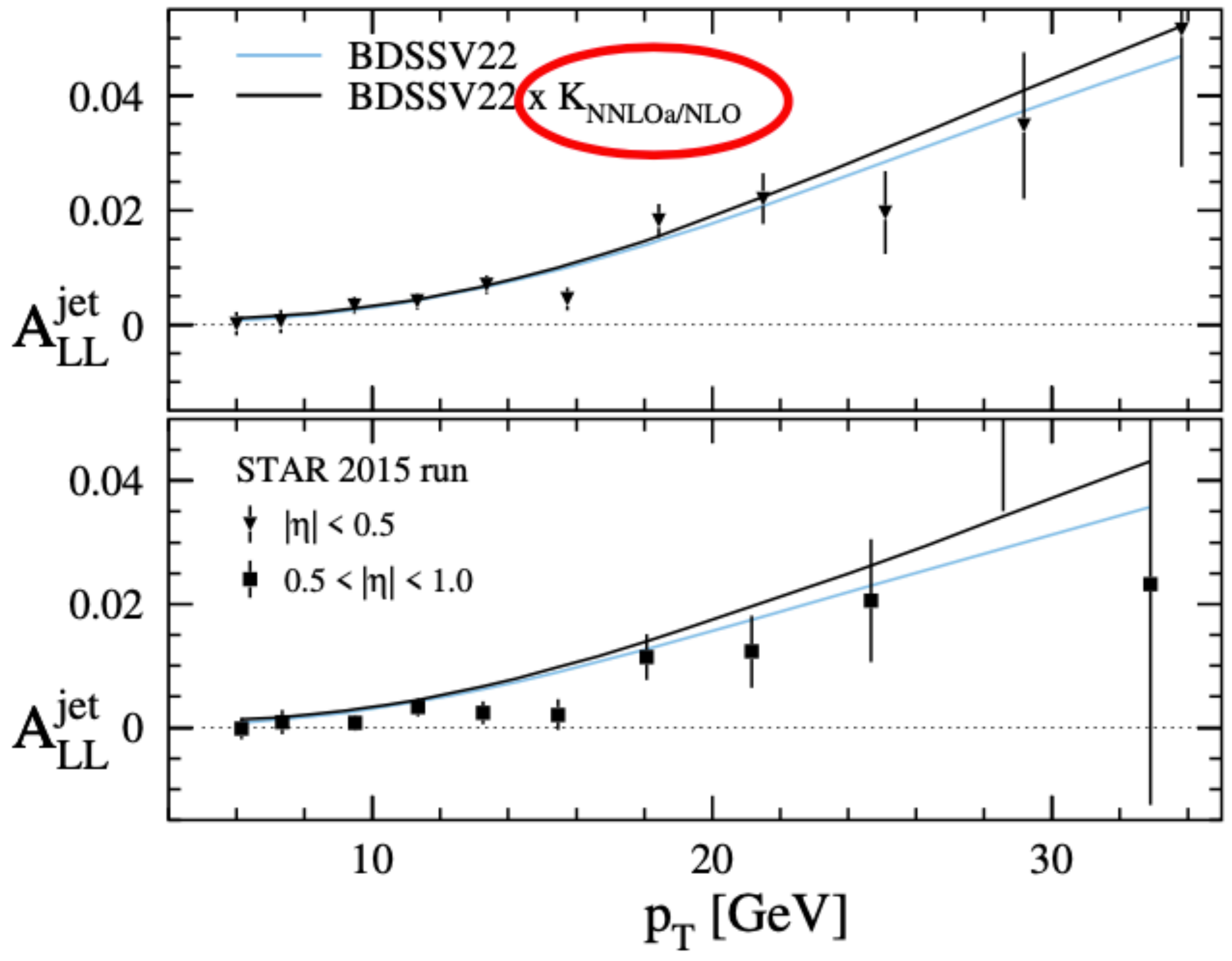
$$\Delta\sigma^{ab\to cd} \sim J_a^{in} \times J_b^{in} \times J_c^{\rm jet} \times J_d^{\rm rec} \times {\rm Tr}[\Delta H\, S]_{ab\to cd}$$

Threshold logarithms $\ln\left(1 - \frac{s_{\rm rad}}{s}\right)$



- NNLO corrections not known for jet nor pion production.

- Still possible to derive approximate NNLO corrections based on the resummation of threshold logs [Kidonakis, Oderda, Sterman, (1998); de Florian, Vogelsang (2005); Hinderer, Ringer, Sterman, Vogelsang (2019)].



Global analysis of helicity PDFs

NNLO Coefficient functions for pp observables

$$\Delta\sigma = \sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes \Delta\hat{\sigma}_{ab}$$

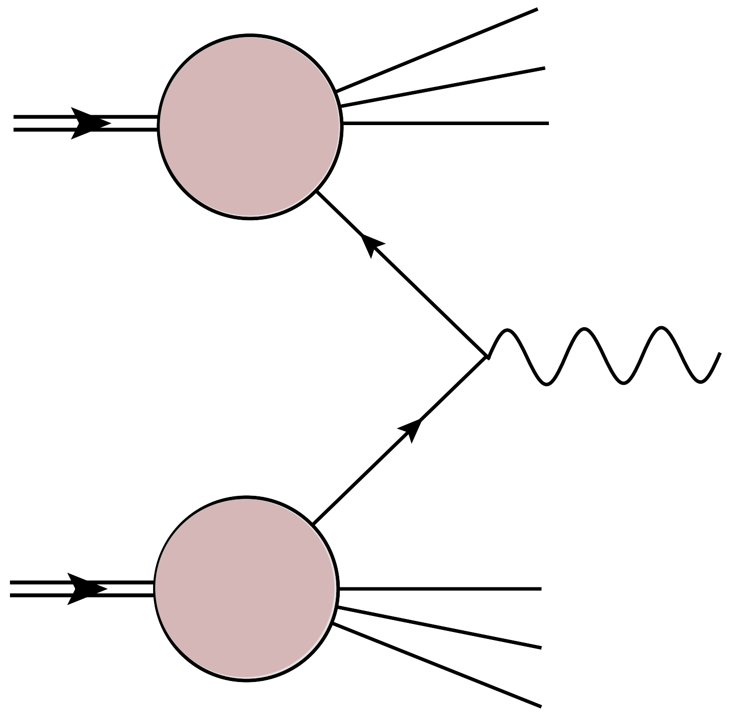
At LO :

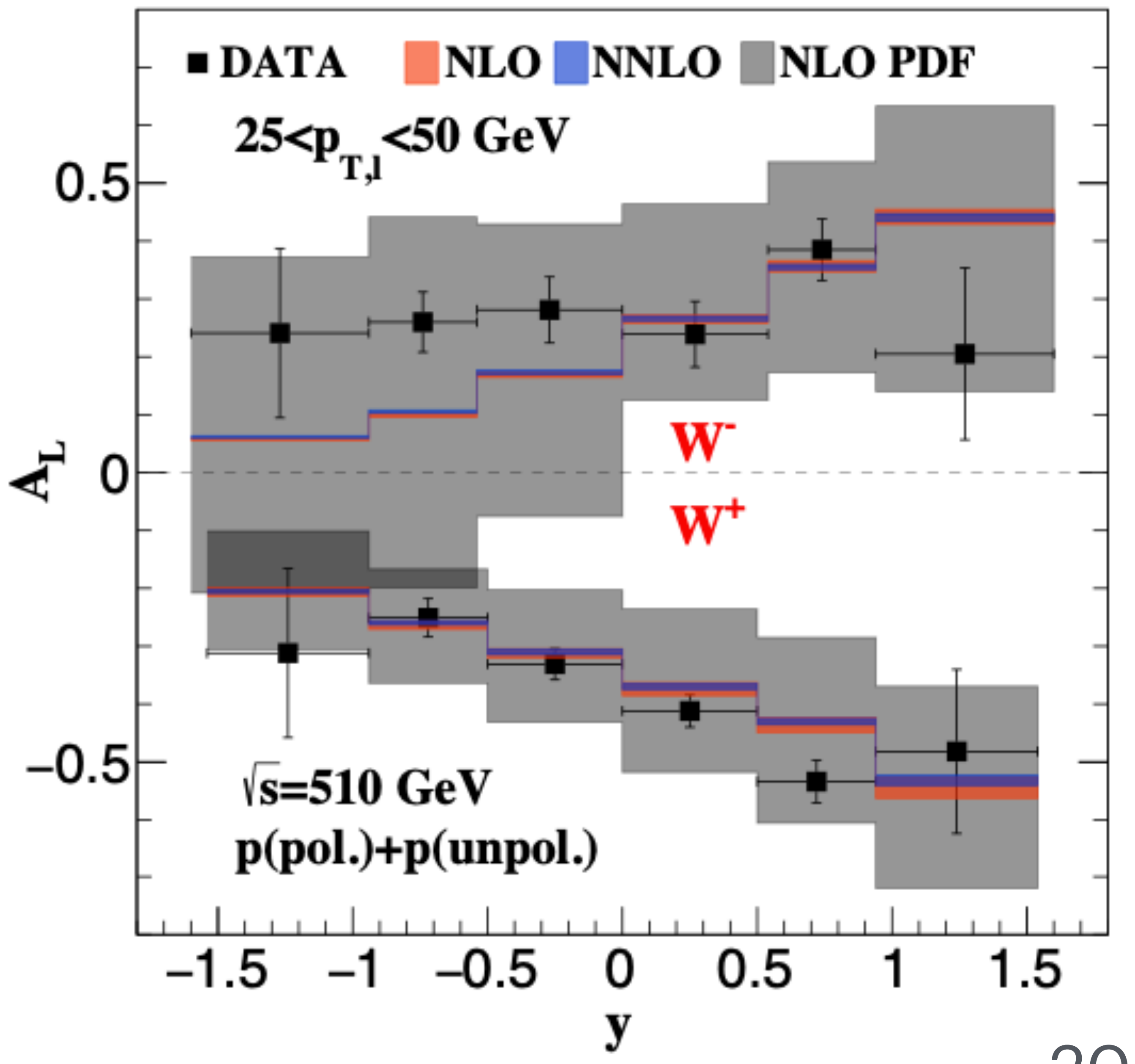
$$A_L^{W^+} \propto \Delta\bar{d}\,u - \Delta u\,\bar{d}$$

$$A_L^{W^-} \propto \Delta\bar{u}\,d - \Delta d\,\bar{u}$$

- NNLO corrections for $W^{\pm}$ known [Boughezal, Li, Petriello (2021)].
- NNLO implemented with K-factors in the analysis.

pp W boson





Global analysis of helicity PDFs

Technical specifications & data selection

- Parameterizations (at $Q_0^2 = 1\,\mathrm{GeV}^2$):
  - $(\Delta q + \Delta\bar{q})(x, Q_0^2) = N_q\, x^{\alpha_q}(1 - x^{\beta_q})(1 + \gamma_q x^{\delta_q} + \eta_q x)$ for (u, d)
  - $\Delta\bar{q}(x, Q_0^2) = N_{\bar{q}}\, x^{\alpha_{\bar{q}}}(1 - x^{\beta_{\bar{q}}})(1 + \gamma_{\bar{q}} x^{\delta_{\bar{q}}})$ for (u, d, s)
  - $\Delta g(x, Q_0^2) = N_g\, x^{\alpha_g}(1 - x^{\beta_g})(1 + \gamma_g x^{\delta_g})$
- Evolution:
  - Zero-Mass Variable Flavor Number Scheme (ZMVFNS). HQ Matching coefficients from [Bierenbaum et al.]
  - Extended QCD-PEGASUS library [Vogt]
- Assumptions
  - No SU(2)/SU(3) constraints
  - Positivity enforced (with respect to MSHT20 [Bailey, Cridge, Harland-Lang, Martin, Thorne (2020)])
- NLO FFs [IB, de Florian, Sassot, Stratmann (2021, 2024)]
- Uncertainties
  - Monte Carlo Sampling [de Florian, Lucero, Sassot, Stratmann , Vogelsang (2019)]

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  - ~~Monte Carlo Sampling~~ Montecarlo Error Sampling Systematic Implementation

Global analysis of helicity PDFs

Technical specifications & data selection

Data:	data-points
DIS: EMC, SMC, E142, E143, E154, E155, HERMES, COMPASS, HALL-A, CLAS (p, n, d, He targets)	378
SIDIS: HERMES, COMPASS (p, n, targets; identified $\pi^{\pm}, K^{\pm}, h^{\pm}$)	277
PP-JETS: STAR run 5, 6, 9, 12, 13, 15 ($\sqrt{s} = 200, 510$ GeV)	91
PP-$\pi^0/\pi^{\pm}$: PHENIX, STAR	78
PP-$W^{\pm}$: PHENIX, STAR	22
TOTAL:	850

Global analysis of helicity PDFs

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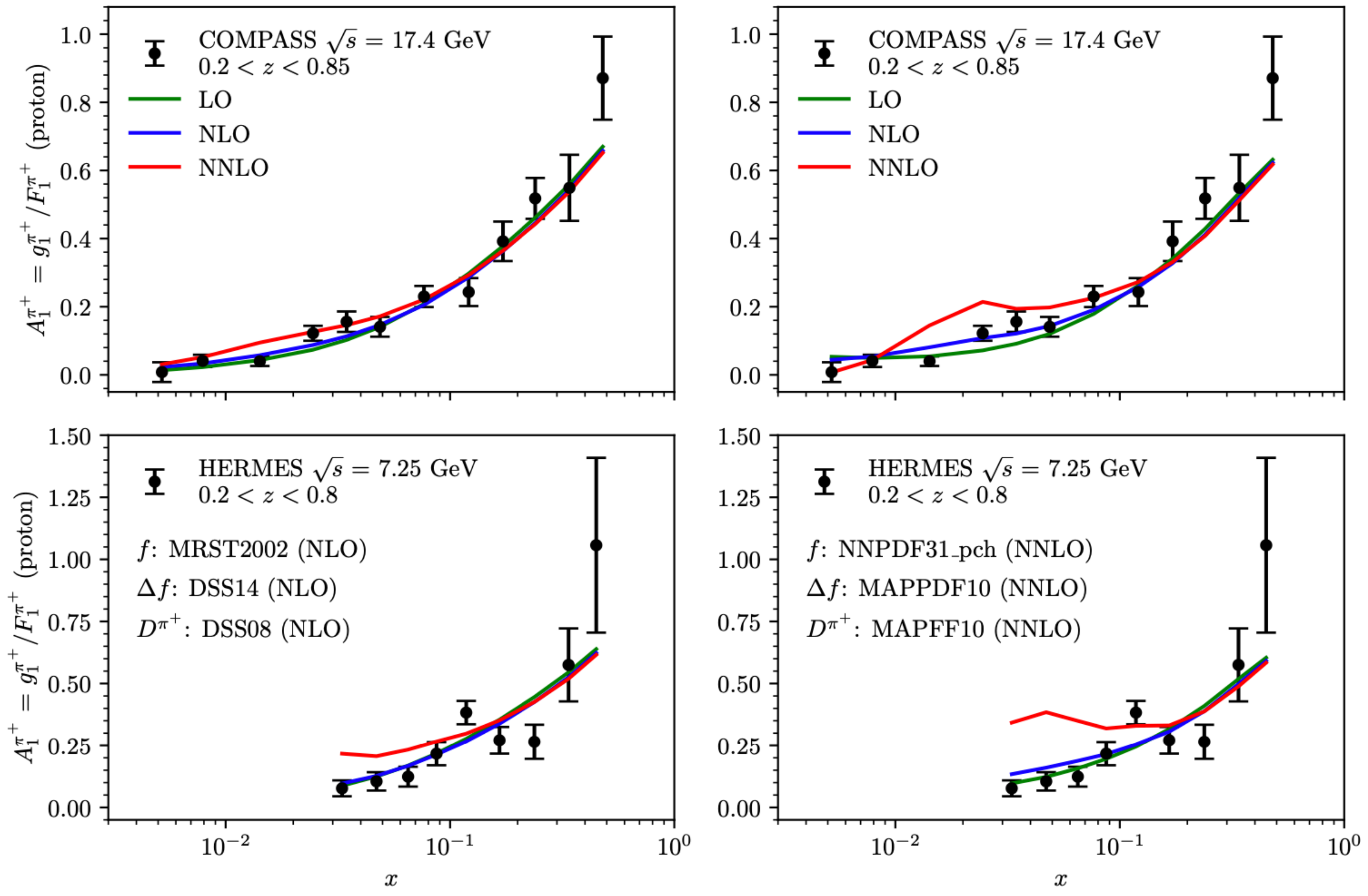
But

Bonino, Gehrmann, Löchner, Schönwald, Stagnitto (2024)



- Bump in the asymmetry not captured by the threshold approximation

Global analysis of helicity PDFs

Technical specifications & data selection

Data:	data-points	χ^2-NLO	χ^2-NNLO
DIS: EMC, SMC, E142, E143, E154, E155, HERMES, COMPASS, HALL-A, CLAS (p, n, d, He targets)	378	304.7	308.74
SIDIS: HERMES, COMPASS (p, n, targets; identified $\pi^{\pm}, K^{\pm}, h^{\pm}$)	277	276.1	322.5
PP-JETS: STAR run 5, 6, 9, 12, 13, 15 ($\sqrt{s} = 200, 510$ GeV)	91		
PP-$\pi^0/\pi^{\pm}$: PHENIX, STAR	78		
PP-$W^{\pm}$: PHENIX, STAR	22		
TOTAL:	850		

Similar observations:

- MAP analysis [Bertone et al. (2024)]
- NNLO FFs fits [IB et al. (2022); Abdul-Khalek et al. (2022)]

$\Rightarrow$ Conservative cut of $x_{\text{SIDIS}} > 0.12$ imposed on SIDIS data

Results

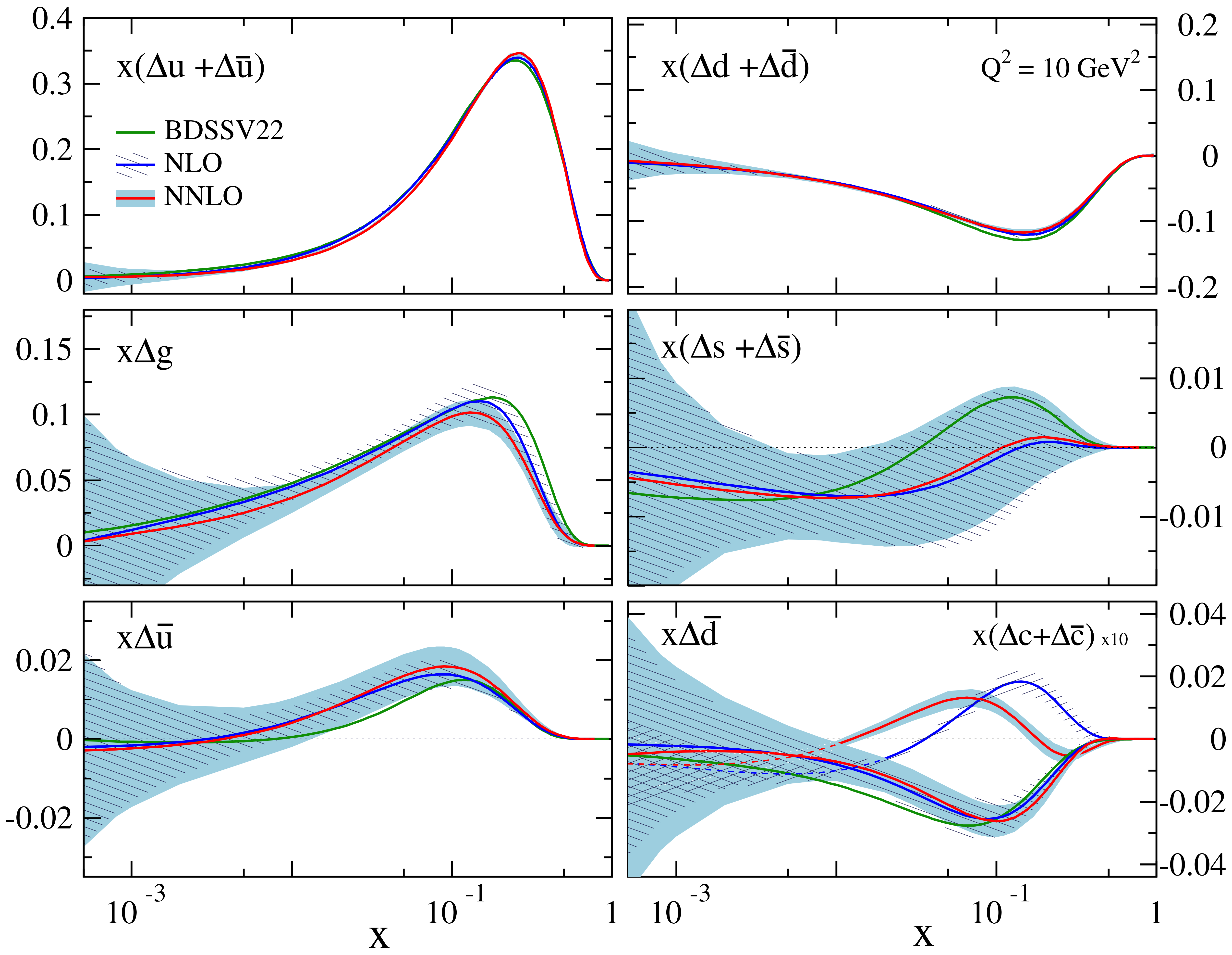
Results

χ^2-numerology

Data:	data-points	No cut on x_{SIDIS}: χ^2-NLO	No cut on x_{SIDIS}: χ^2-NNLO	$x_{SIDIS} > 0.12$: χ^2-NLO	$x_{SIDIS} > 0.12$: χ^2-NNLO
DIS: EMC, SMC, E142, E143, E154, E155, HERMES, COMPASS, HALL-A, CLAS (p, n, d, He targets)	378	304.7	308.7	302.8	294.5
SIDIS: HERMES, COMPASS (p, n, targets; identified $\pi^\pm, K^\pm, h^\pm$)	114 (277)	276.1	322.5	127.6	122.9
PP-JETS: STAR run 5, 6, 9, 12, 13, 15 ($\sqrt{s} = 200, 510$ GeV)	91			111.1	104.7
PP-$\pi^0/\pi^\pm$: PHENIX, STAR	78			63.5	66.0
PP-$W^\pm$: PHENIX, STAR	22			22.3	20.3
TOTAL:	673			627.2	607.5

Results

NNLO polarized distributions



BDSSV22: NLO including dijets, $W^{\pm}$ data and no cuts on SIDIS

- $(\Delta u + \Delta \bar{u})$ and $(\Delta d + \Delta \bar{d})$ well constrained. No significant differences between NLO & NNLO.
- Δg positive, and constrained for RHIC kinematics. NLO/NNLO differences well within uncertainties.
- $(\Delta s + \Delta \bar{s})$ consistent with zero → Reduced number of data-points from SIDIS & lack of F, D constraints.
- $\Delta \bar{u}$ and $\Delta \bar{d}$ constrained by $W^{\pm}$ data.
- $(\Delta c + \Delta \bar{c})$ small, and strongly dependent on perturbative order (no intrinsic-charm).

Results

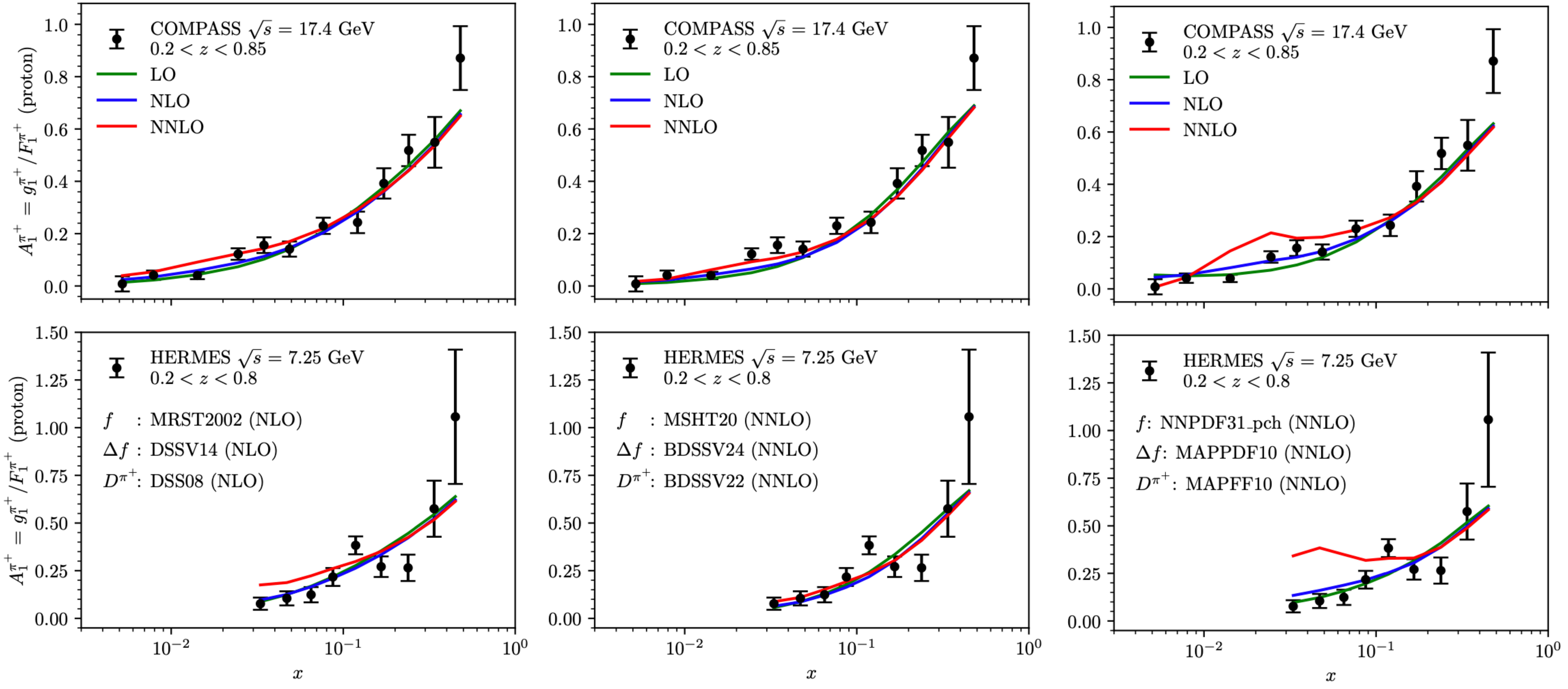
Selected data sets

- In general, good description of data; similar results for NLO and NNLO
- For SIDIS, slight suppression of the NNLO asymmetry for low-x

Results

Revisiting SIDIS data

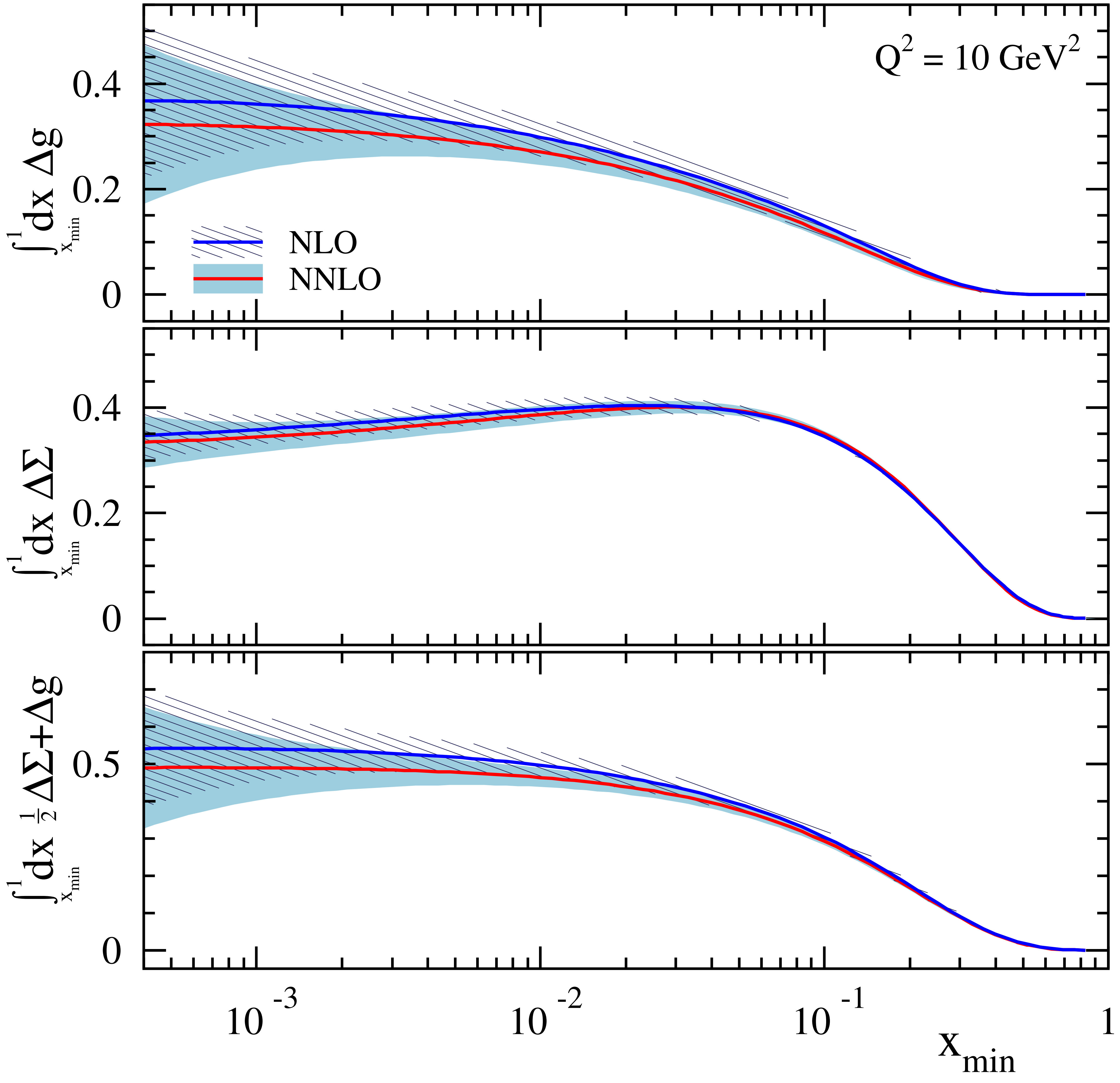
Bonino, Gehrmann, Löchner, Schönwald, Stagnitto (2024)



- Good description of the asymmetries even at low values of x
- NNLO corrections seem to solve some of the tension between HERMES and COMPASS data

Results

Revisiting the spin sum rule



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

- Room for OAM?
- Improved picture with EIC low-x data

Summary

Summary

- Still rather incomplete picture of the proton's spin in terms of the contribution from quarks, anti-quarks and gluons.
- The spin program at the future EIC expected to give unique access to the proton's spin structure.

- First "proof-of-principle" NNLO global analysis of polarized PDFs:
  - Good perturbative stability going from NLO to NNLO
  - Slight improvement in the description of data (after imposing cut on x_{SIDIS})

- Outlook:
  - Include full NNLO SIDIS results → First stage: new NNLO analysis of FFs.

Thank you

Global analysis of helicity PDFs

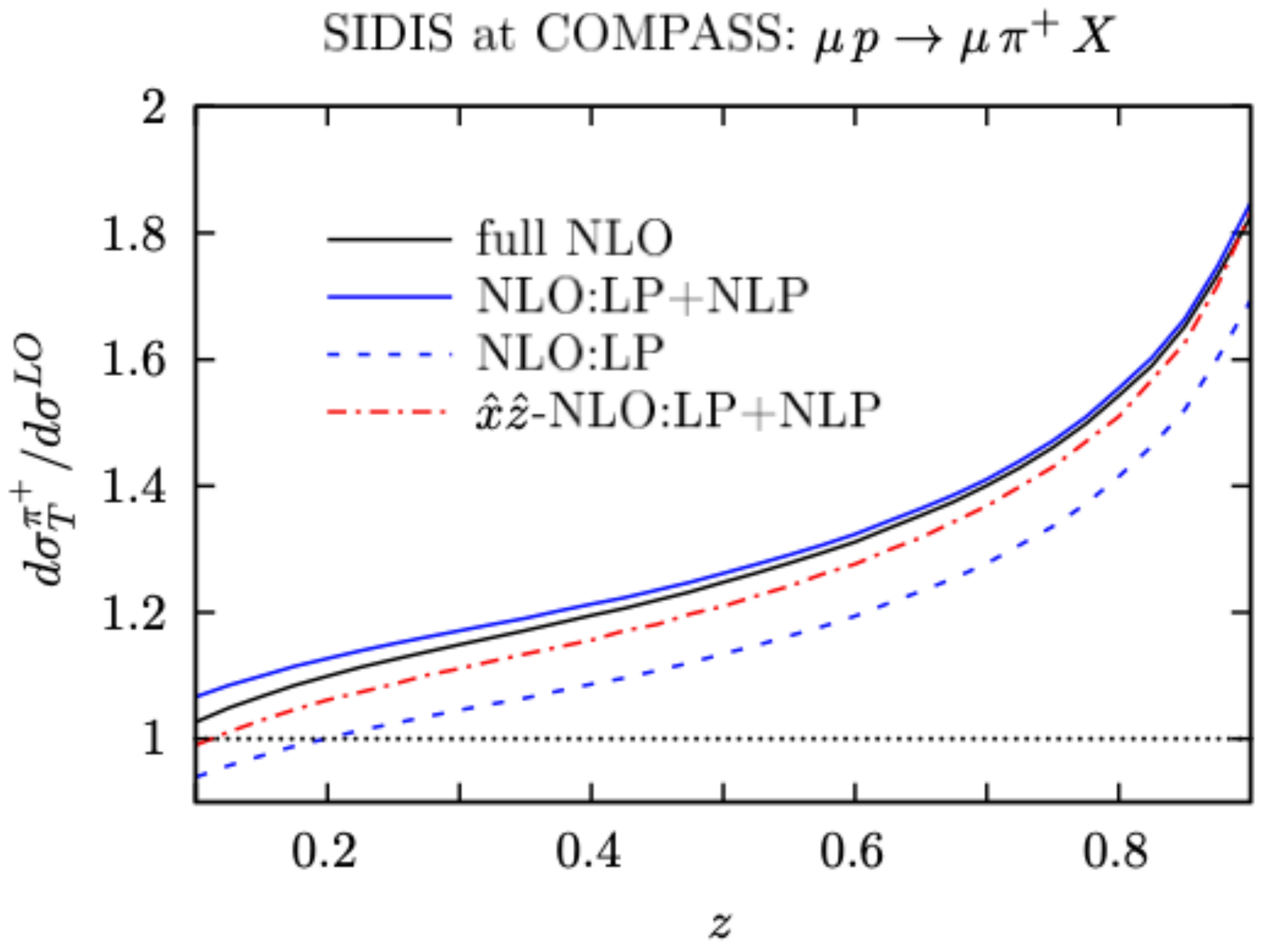
Approximate NNLO Coefficient functions for SIDIS

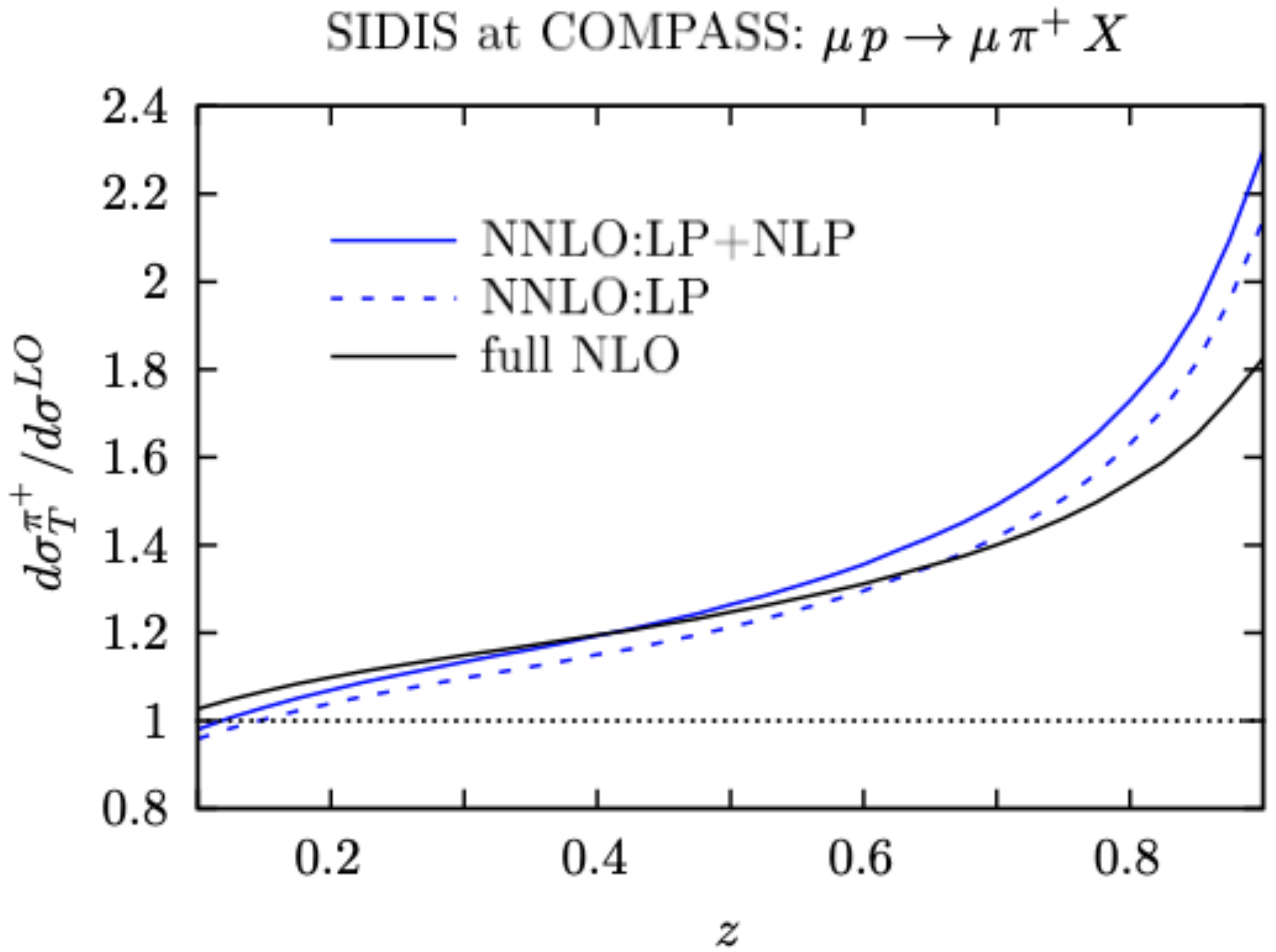
k^{th} order of perturbation theory:

$$\Delta\hat{\sigma}_{qq}^{\mathrm{N}^k\mathrm{LO}}(\hat{x},\hat{z}) \sim \alpha_s^k \Bigg[\delta(1-\hat{x})\left(\frac{\ln^{2k-1}(1-\hat{z})}{1-\hat{z}}\right)_+ + \delta(1-\hat{z})\left(\frac{\ln^{2k-1}(1-\hat{x})}{1-\hat{x}}\right)_+ + \frac{1}{(1-\hat{x})_+}\left(\frac{\ln^{2k-2}(1-\hat{z})}{1-\hat{z}}\right)_+ + \frac{1}{(1-\hat{z})_+}\left(\frac{\ln^{2k-2}(1-\hat{x})}{1-\hat{x}}\right)_+ + \dots\Bigg]$$

- Near the threshold for hadronic production $x, z \to 1$, logs can be resumed to all orders: **threshold resummation** [Anderle, Ringer, Vogelsang (2012)]; [Abelde, de Florian, Vogelsang (2021)].

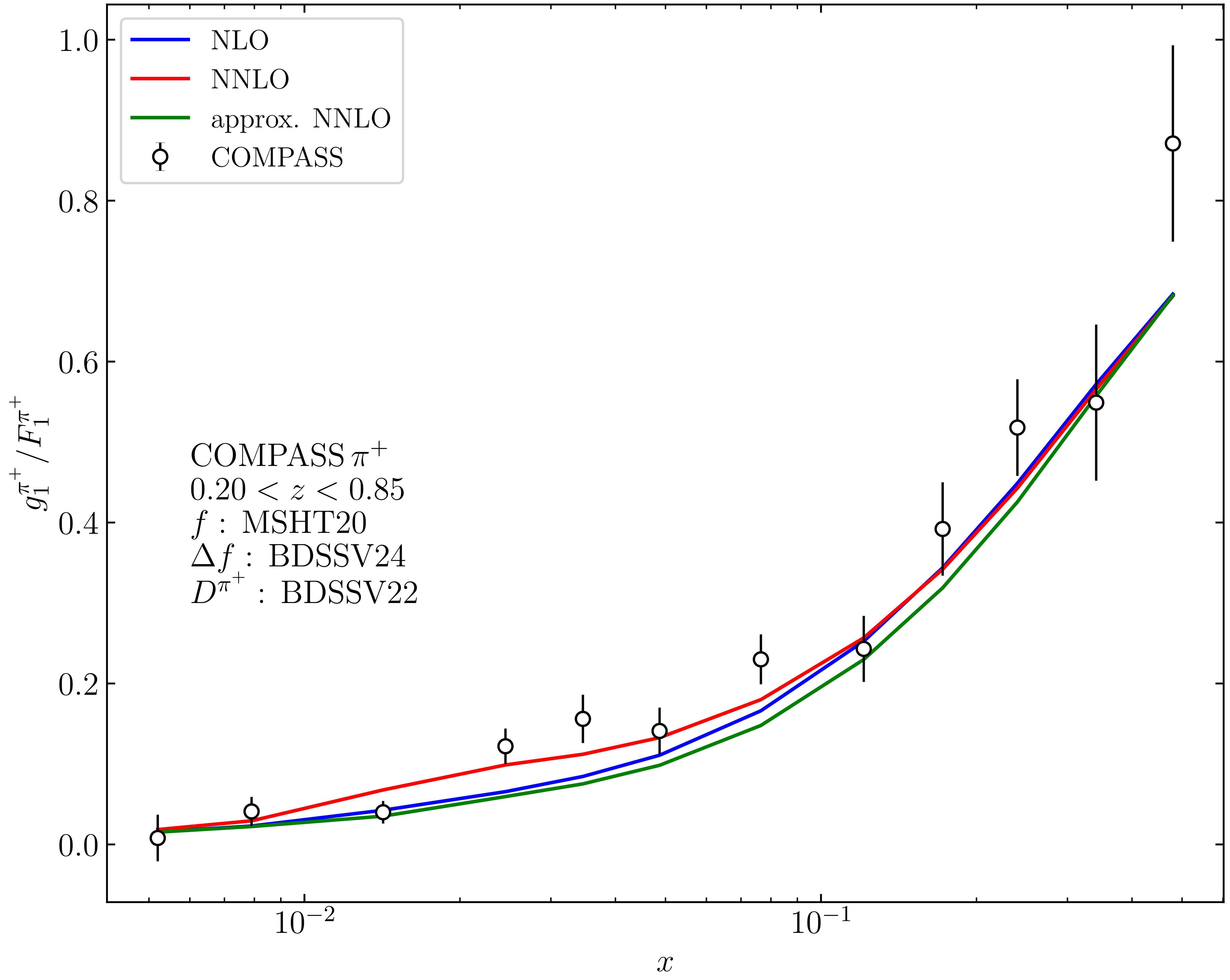
- Approximate NNLO coefficients derived for the $q \to q$ channel.





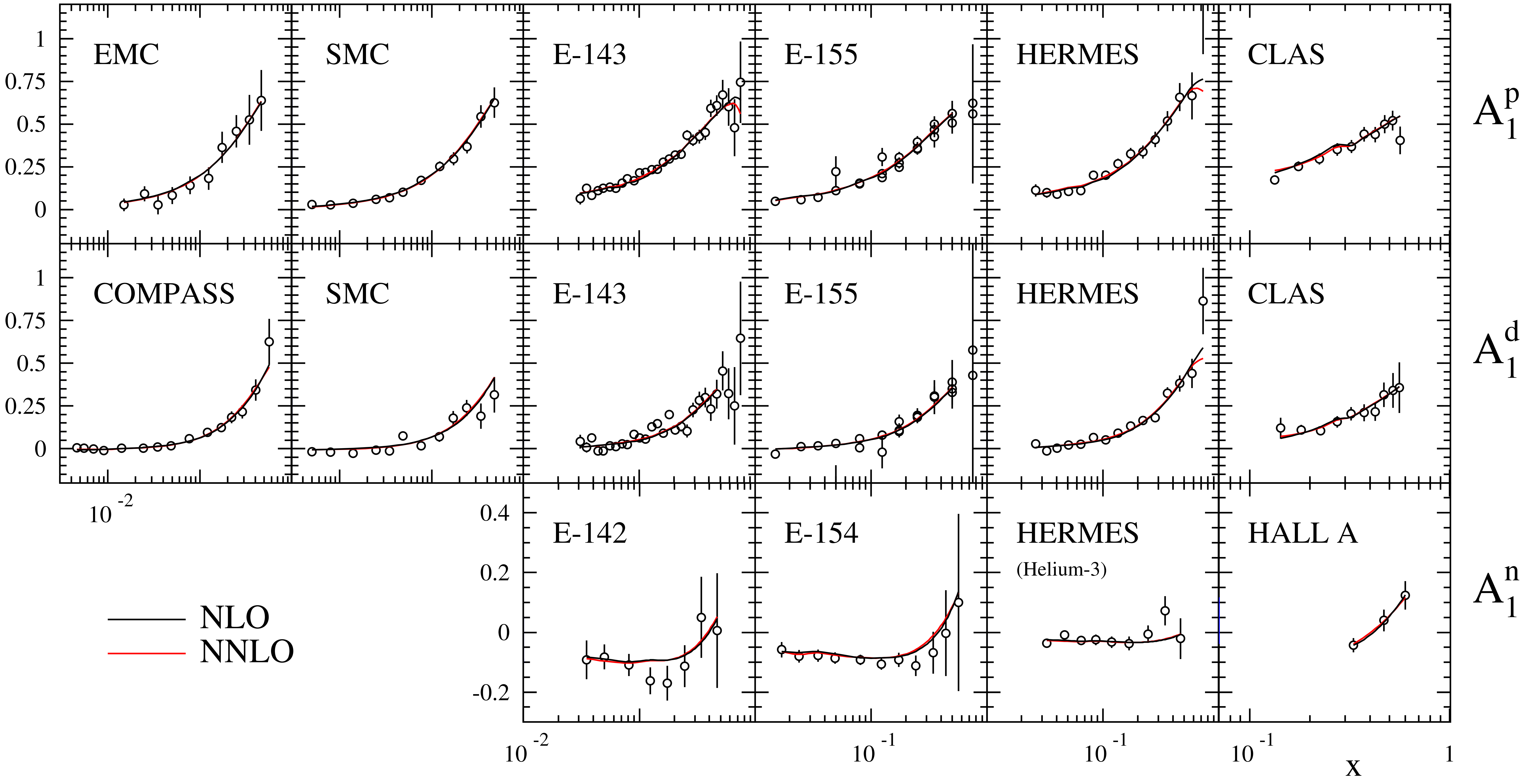
Results

Post validation



Results

Other data sets : DIS



Results

Other data sets : Full SIDIS