P^3 : Precision in Polarized Pdfs

Daniel de Florian

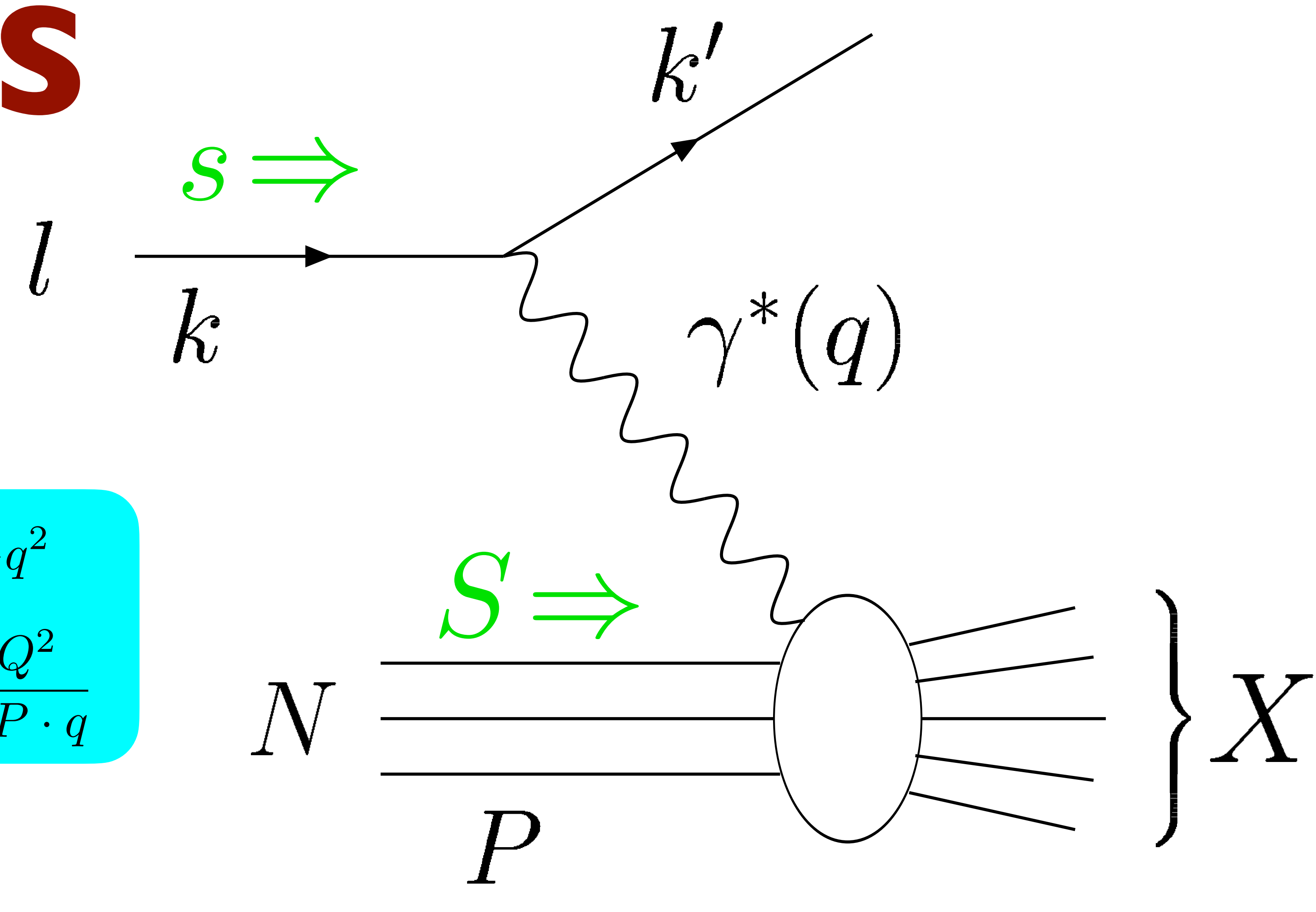
Instituto de
Ciencias Físicas
ICIFI-ECYT_UNSAM-CONICET

Summary

- Brief intro to polarized pdfs/DIS
- Why Global and why NNLO
- BDSSV24 NNLO global fit — Borsa, deF, Sassot, Stratmann, Vogelsang (2024)
- QED and photon pdfs — deF. , Palma, Volonnino (2024)
- Conclusions

Brief intro polarized DIS

cross section $$\frac{d\sigma}{dE'\,d\Omega} = \frac{\alpha^2}{Q^4}\frac{E'}{E}\underbrace{\mathcal{L}_{\mu\nu}(k,q,s)}_{\text{leptonic}} \cdot \underbrace{\mathcal{W}^{\mu\nu}(P,q,S)}_{\text{hadronic}}$$



$Q^2 \equiv -q^2$

$x \equiv \frac{Q^2}{2P\cdot q}$

- Hadronic tensor in terms of Structure Functions (non-perturbative)

$$\mathcal{W}^{\mu\nu}(P,q,S) = \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right)F_1(x,Q^2) + \left(P^\mu - \frac{P\cdot q}{q^2}q^\mu\right)\left(P^\nu - \frac{P\cdot q}{q^2}q^\nu\right)F_2(x,Q^2)$$

$$+\, i\, M\, \varepsilon^{\mu\nu\rho\sigma} q_\rho \left[\frac{S_\sigma}{P\cdot q}\, g_1(x,Q^2) + \frac{S_\sigma(P\cdot q) - P_\sigma(S\cdot q)}{(P\cdot q)^2}\, g_2(x,Q^2)\right]$$

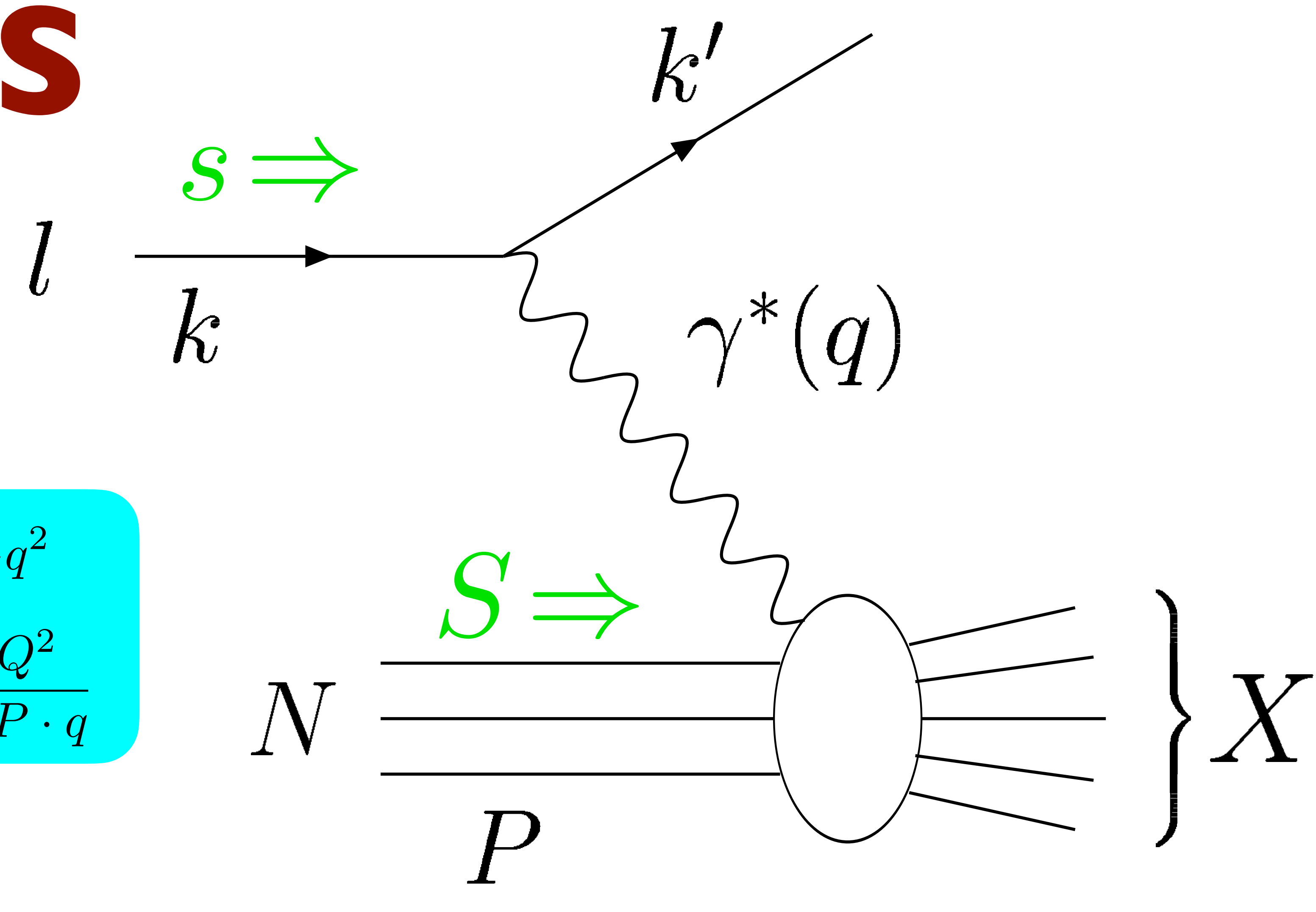
F_i : unpolarized structure functions

g_i : polarized structure functions

Asymmetry $A_1(x,Q^2)$

$$A_\parallel = \frac{d\sigma^{(\rightarrow\Leftarrow)} - d\sigma^{(\rightarrow\Rightarrow)}}{d\sigma^{(\rightarrow\Leftarrow)} + d\sigma^{(\rightarrow\Rightarrow)}} = D(y)\,\frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$

Brief intro polarized DIS



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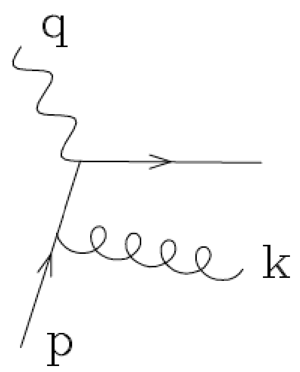
$$g_1(x,Q^2) = \sum_i \frac{e_i^2}{2}\Delta q_i(x,Q^2)$$ LO

$$+\frac{\alpha_s}{2\pi}\sum_i \frac{e_i^2}{2}\int_x^1 \frac{dz}{z}\Delta C_i^q(z)\Delta q_i(x/z,Q^2)$$



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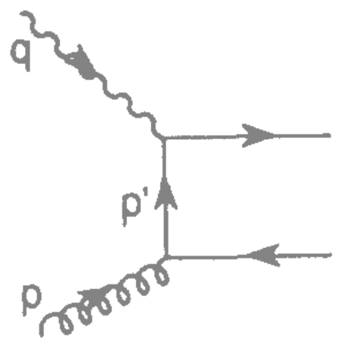

NLO

Brief intro polarized DIS

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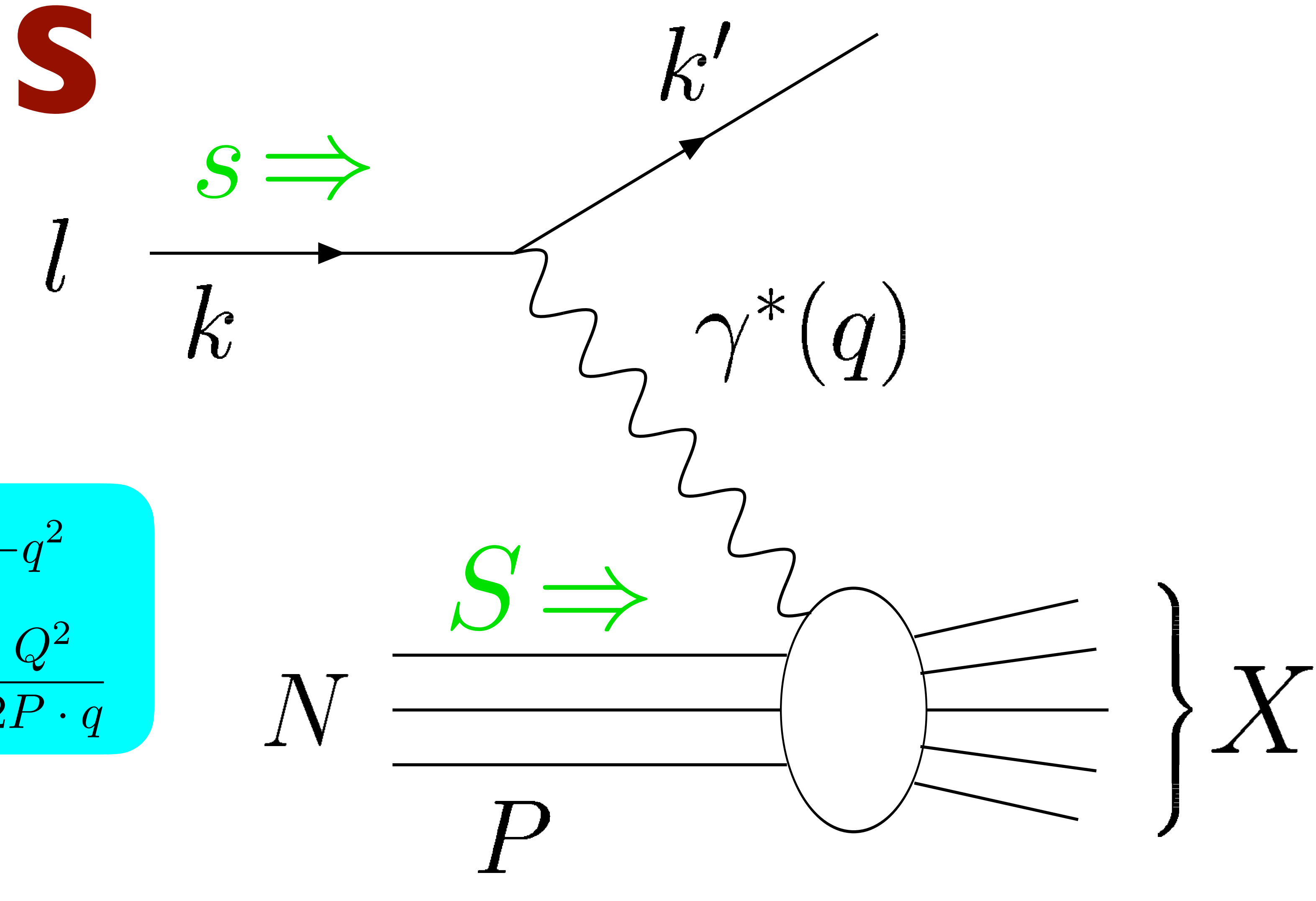

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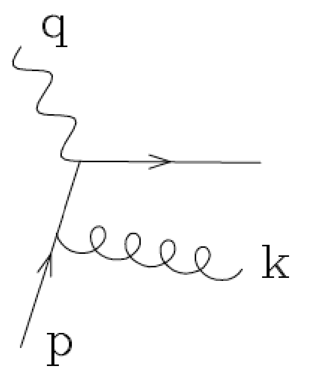

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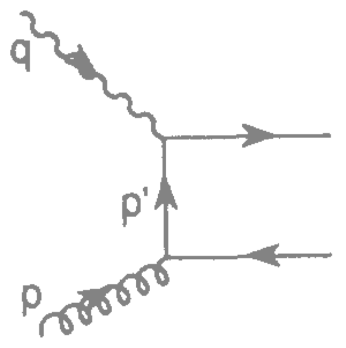


NLO

- quark and gluon contribution to proton spin

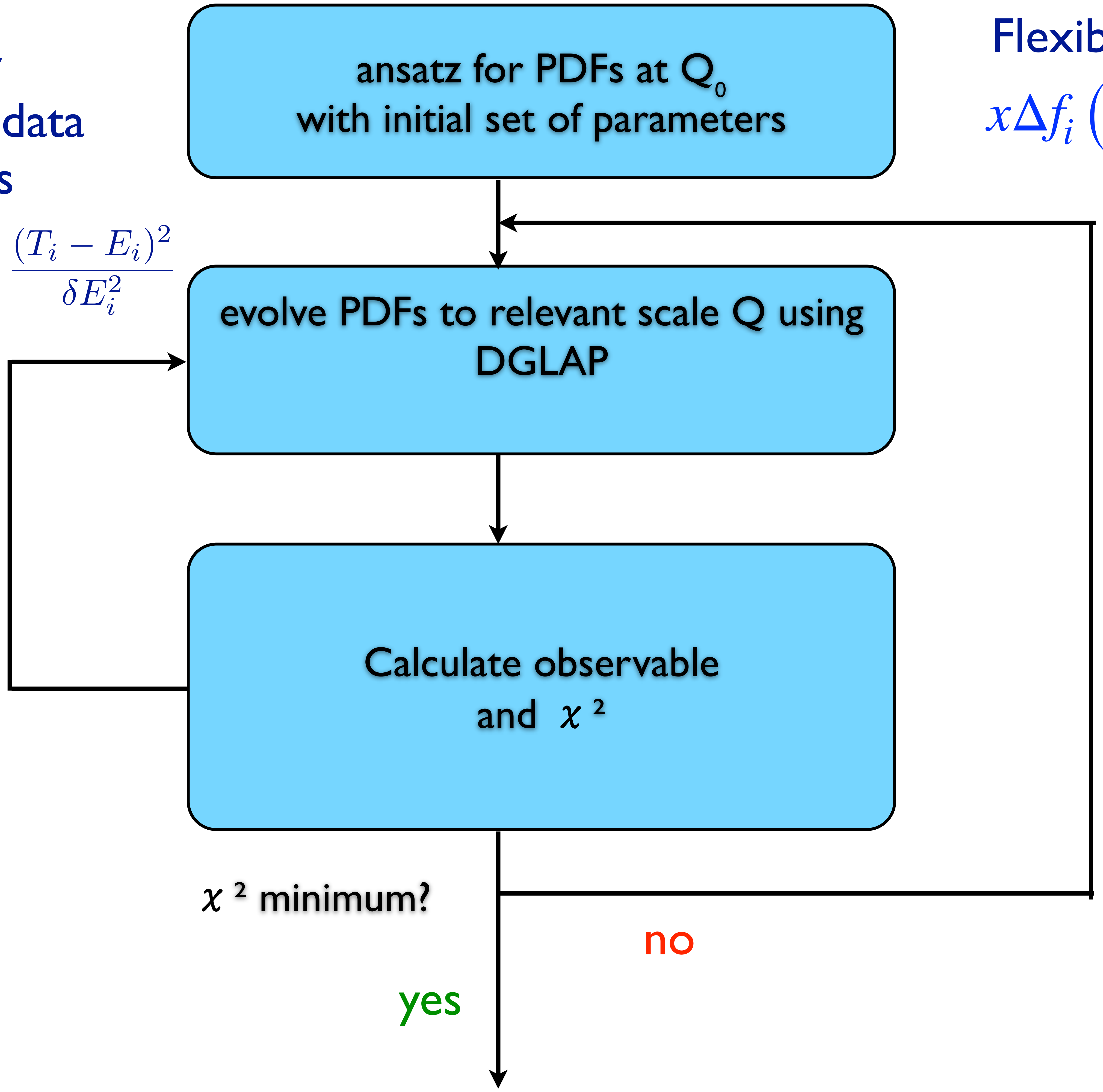
$$\Delta\Sigma = \sum_i \int_0^1 \Delta q_i(x,Q^2)\,dx \qquad \Delta G = \int_0^1 \Delta g(x,Q^2)\,dx$$

needs extrapolation to 0

PDFs obtained by **global** fit : χ^2 minimization

~few hundred data points

$$\chi^2 = \sum_{i=1}^{N} \frac{(T_i - E_i)^2}{\delta E_i^2}$$



result : best fit + uncertainties
(many fits)

Flexible parametrization at Q_0

$$x\Delta f_i\left(x, Q_0^2\right) = N_i x^{\alpha_i}(1-x)^{\beta_i}\left(1 + \gamma_i x + \eta_i x^{\kappa_i}\right)$$

change parameters ~ few thousand times

several NLO analyses

DSSV
NNPDF
JAM

"partial" NNLO

MAP Bertone, Chiefa, Nocera (2024)

NNPDF coming: talk by Juan

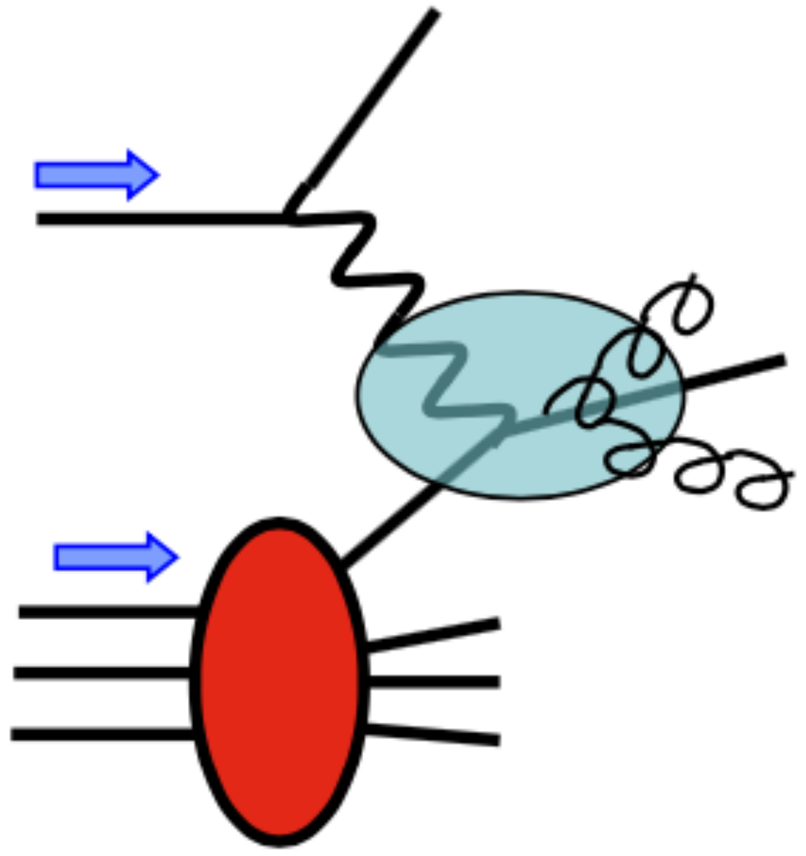
first global NNLO

BDSSV24

Borsa, deF, Sassot, Stratmann, Vogelsang (2024)

Why global?

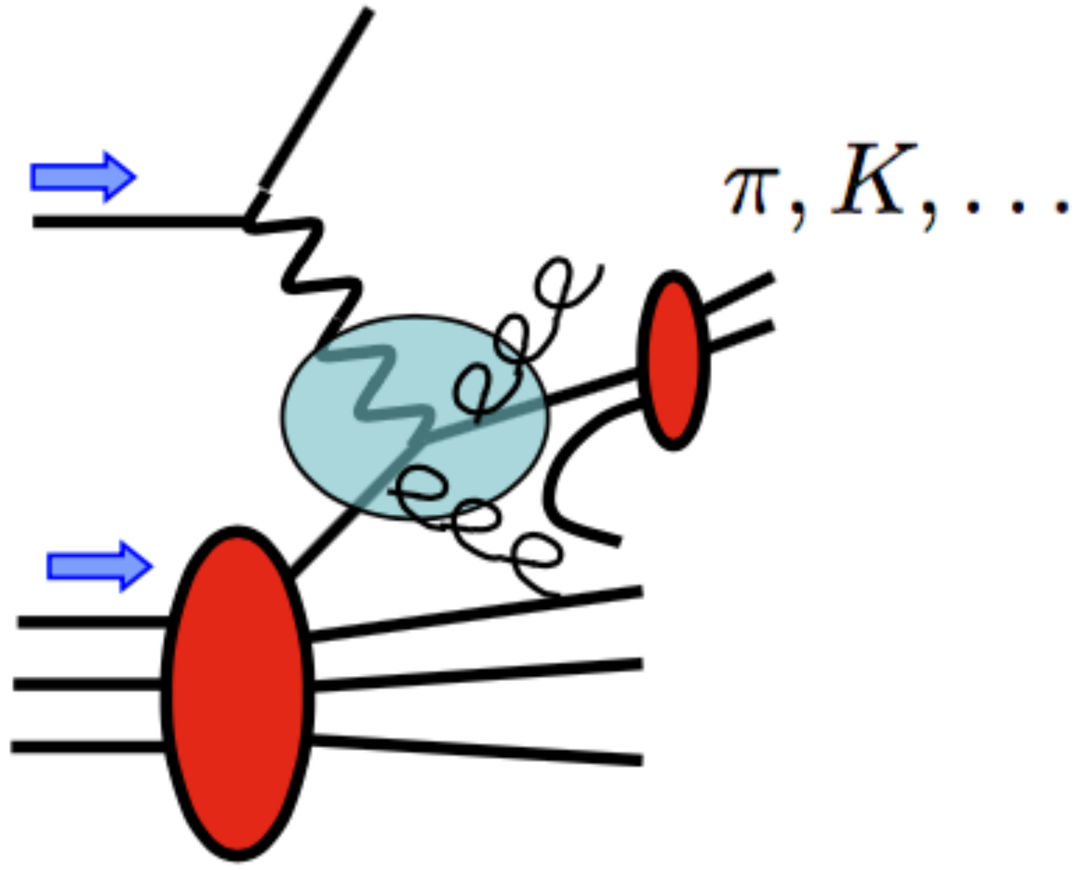
- Observables provide sensitivity on different pdfs



DIS

$\Delta\Sigma\,,(\Delta q+\Delta\bar{q})\,,\Delta g$

$q=u\,,d\,,\;s$



SIDIS

$\Delta q\,,\Delta\bar{q}$

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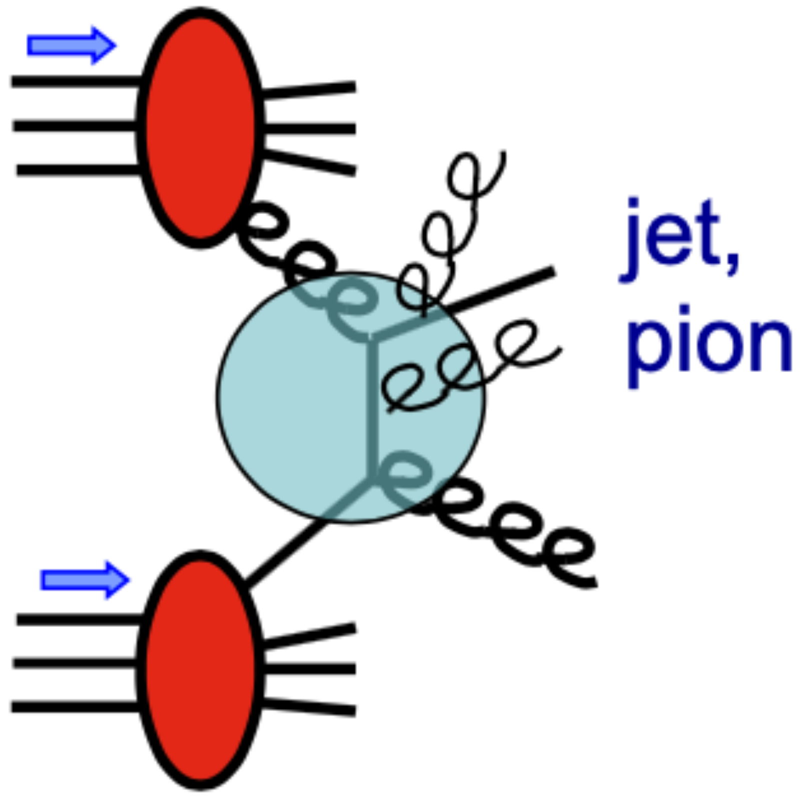
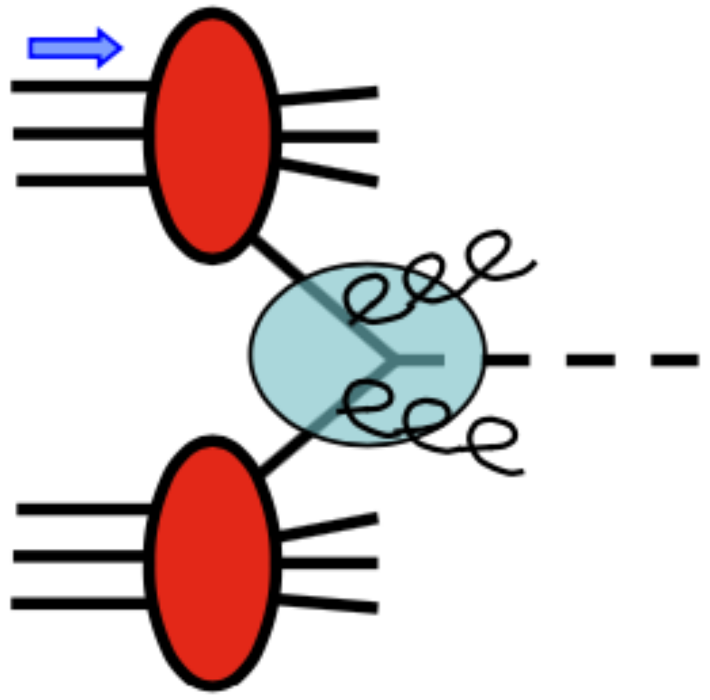


pp high-p_T

$\Delta g\,,\Delta q\,,\Delta\bar{q}$



W bosons

$\Delta q\,,\Delta\bar{q}$

Why NNLO?

talk by Shohini

TH needed to match experimental accuracy/understanding

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70's, 80's LO
(Born Level)

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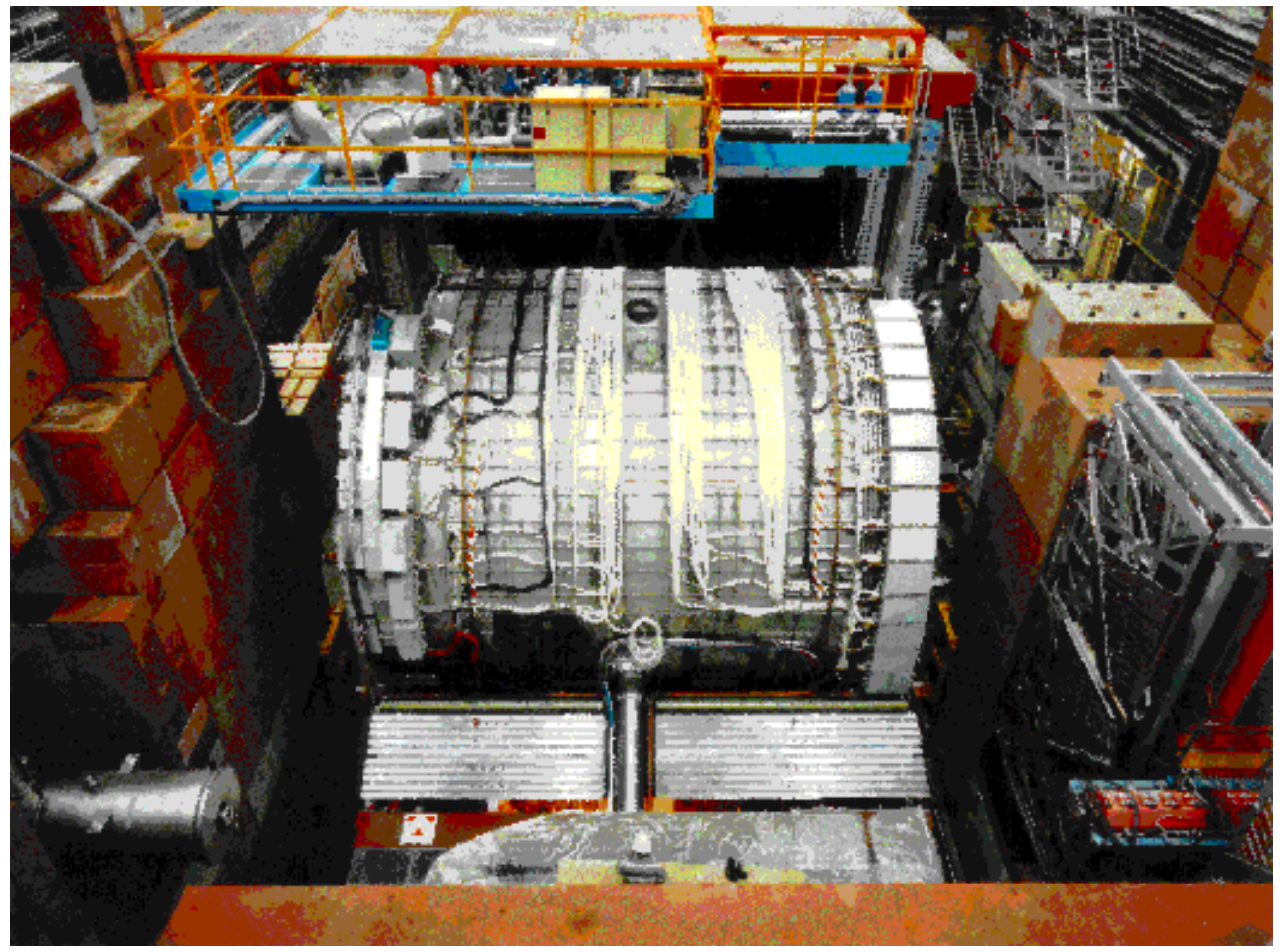

LEP- HERA 90's -00's NLO+

talk by Shohini

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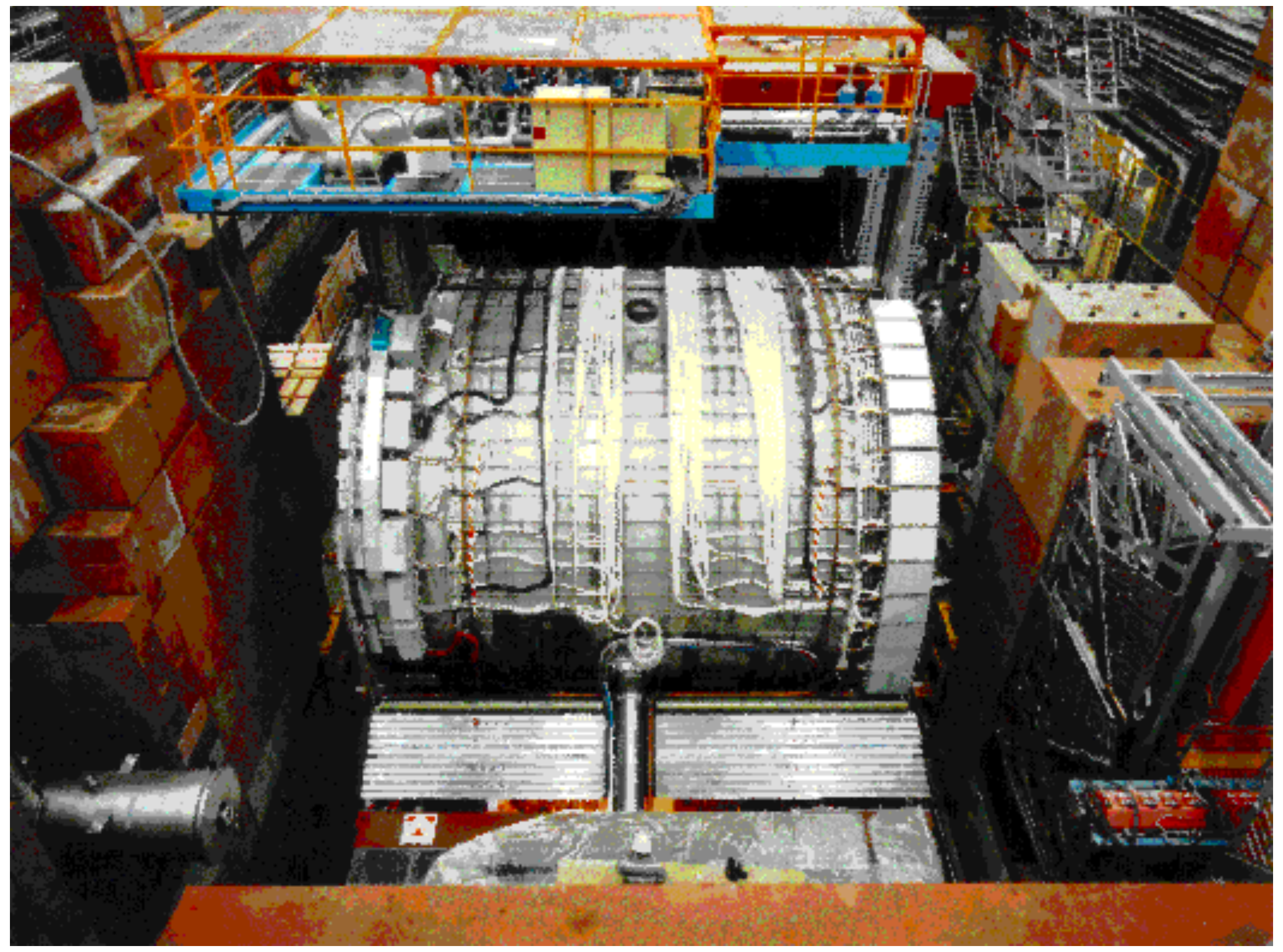
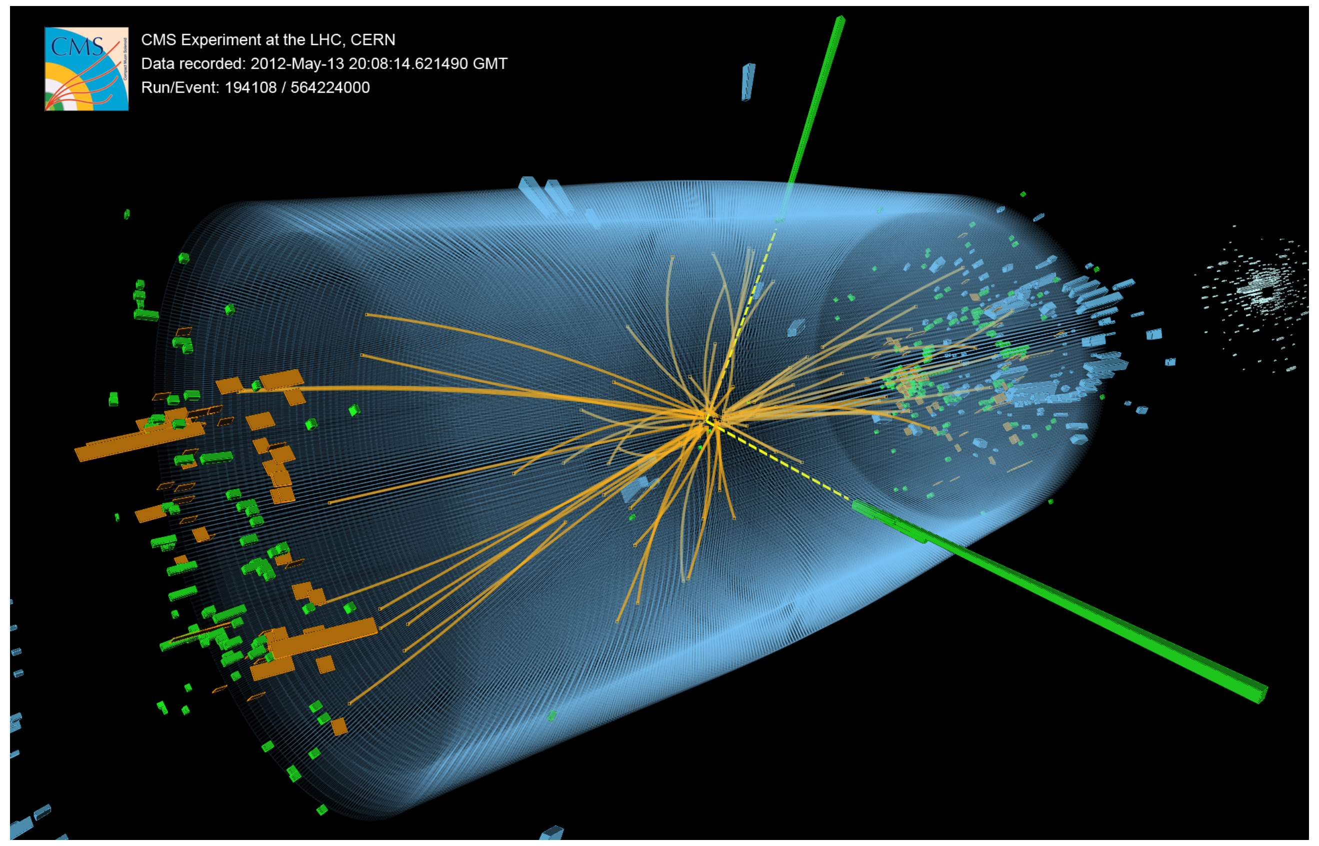


LEP- HERA 90’s -00’s
NLO+

LHC 10’s-20’s-
NLO+PS
NNLO and beyond



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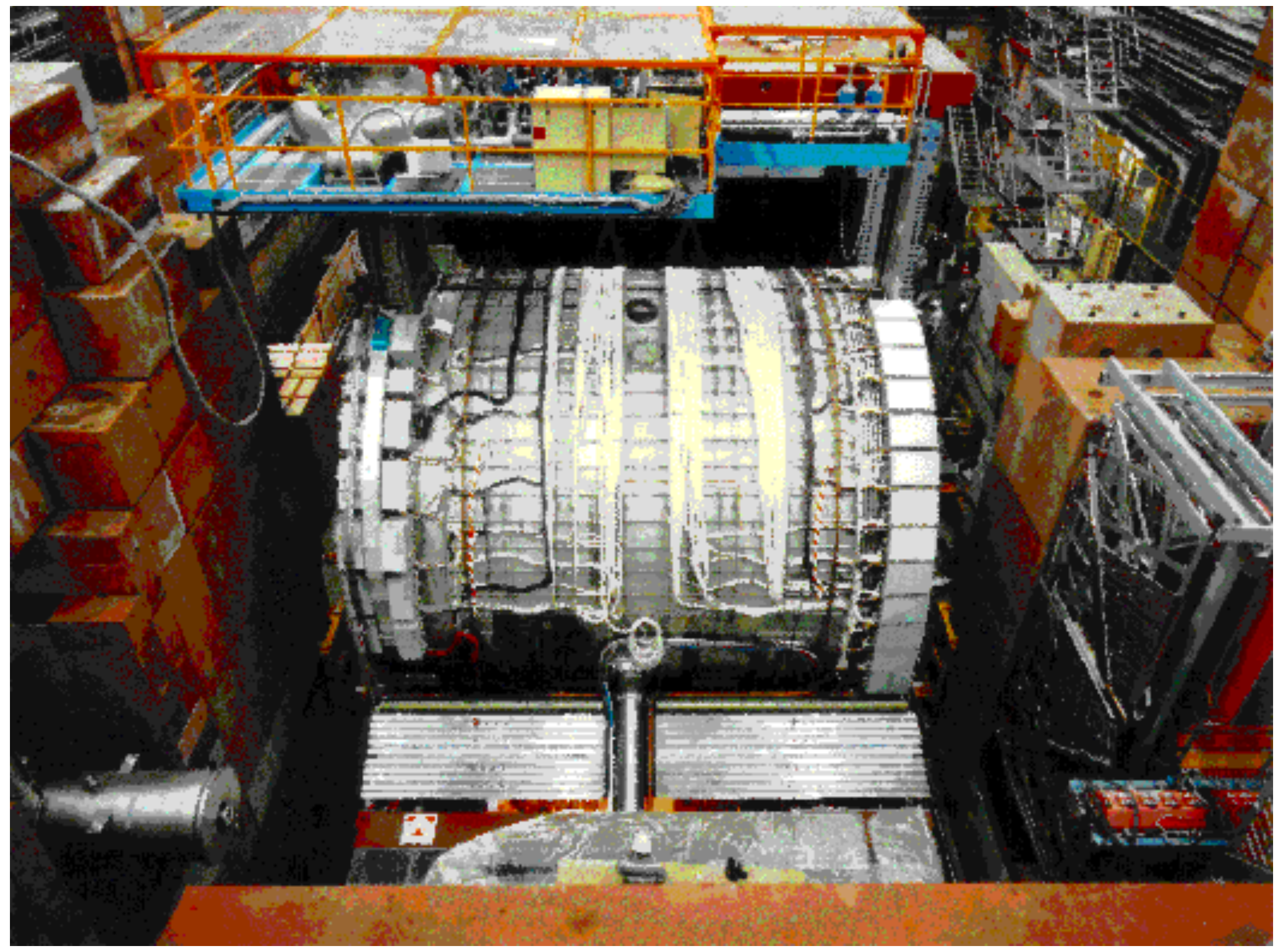

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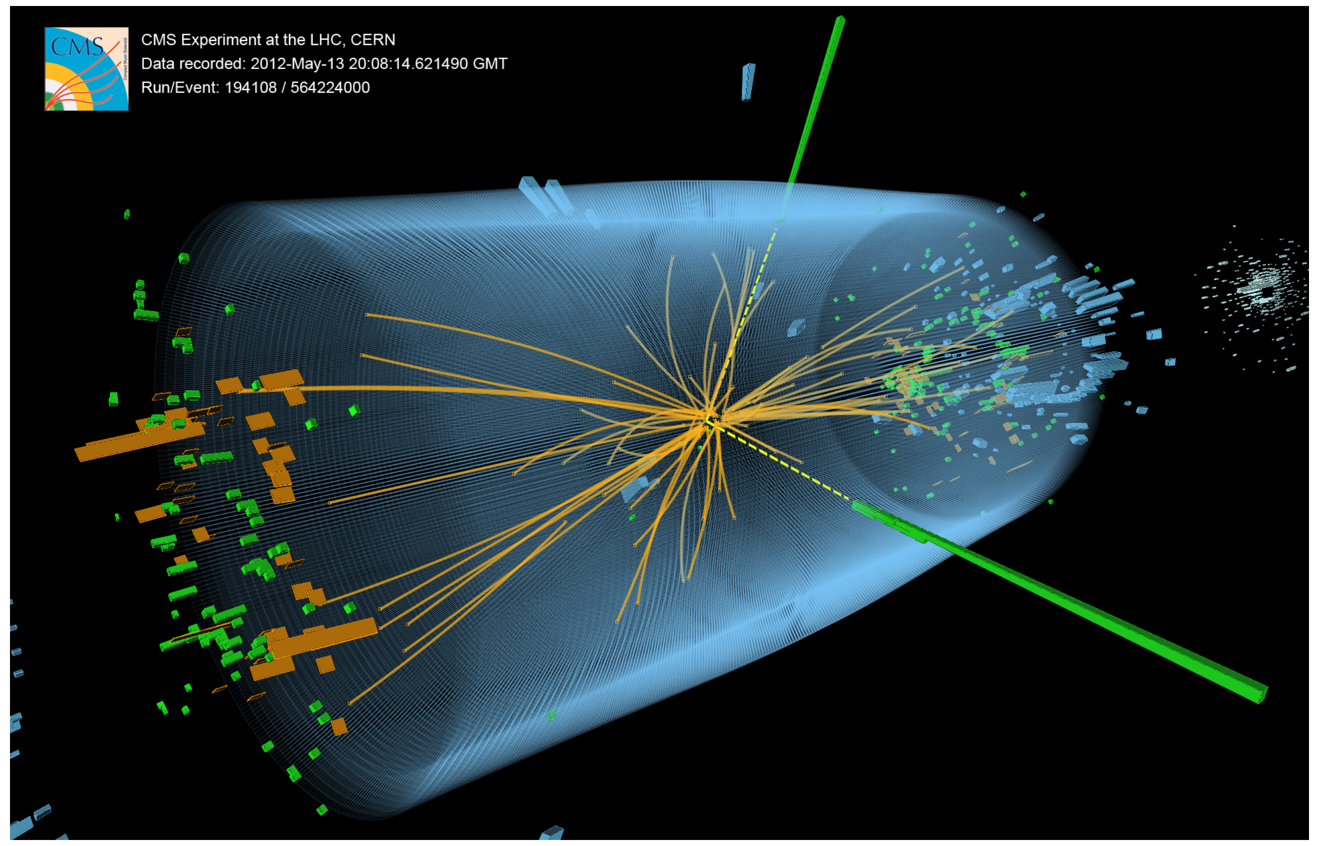

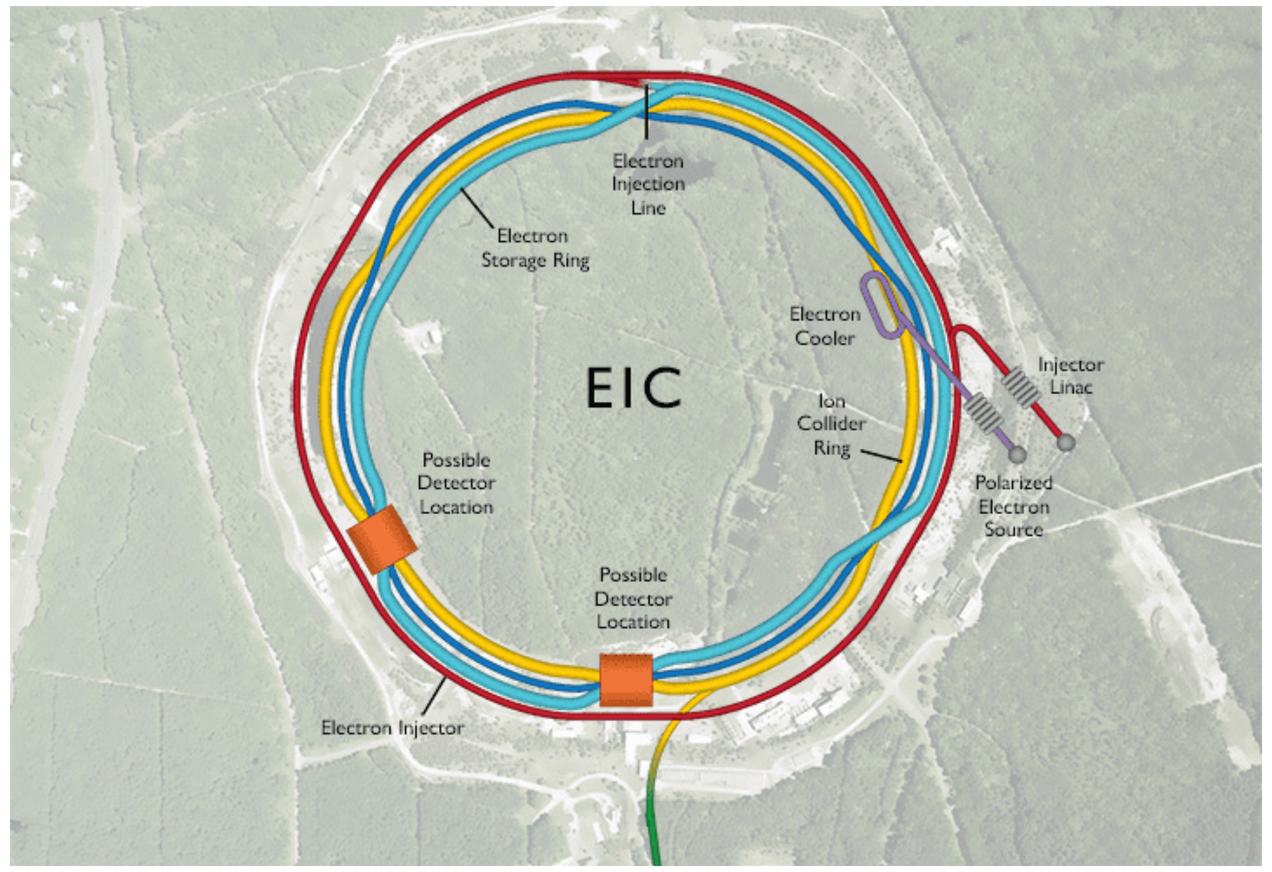

EIC 30's-
≥NNLO+ and beyond

Why NNLO?

talk by Shohini

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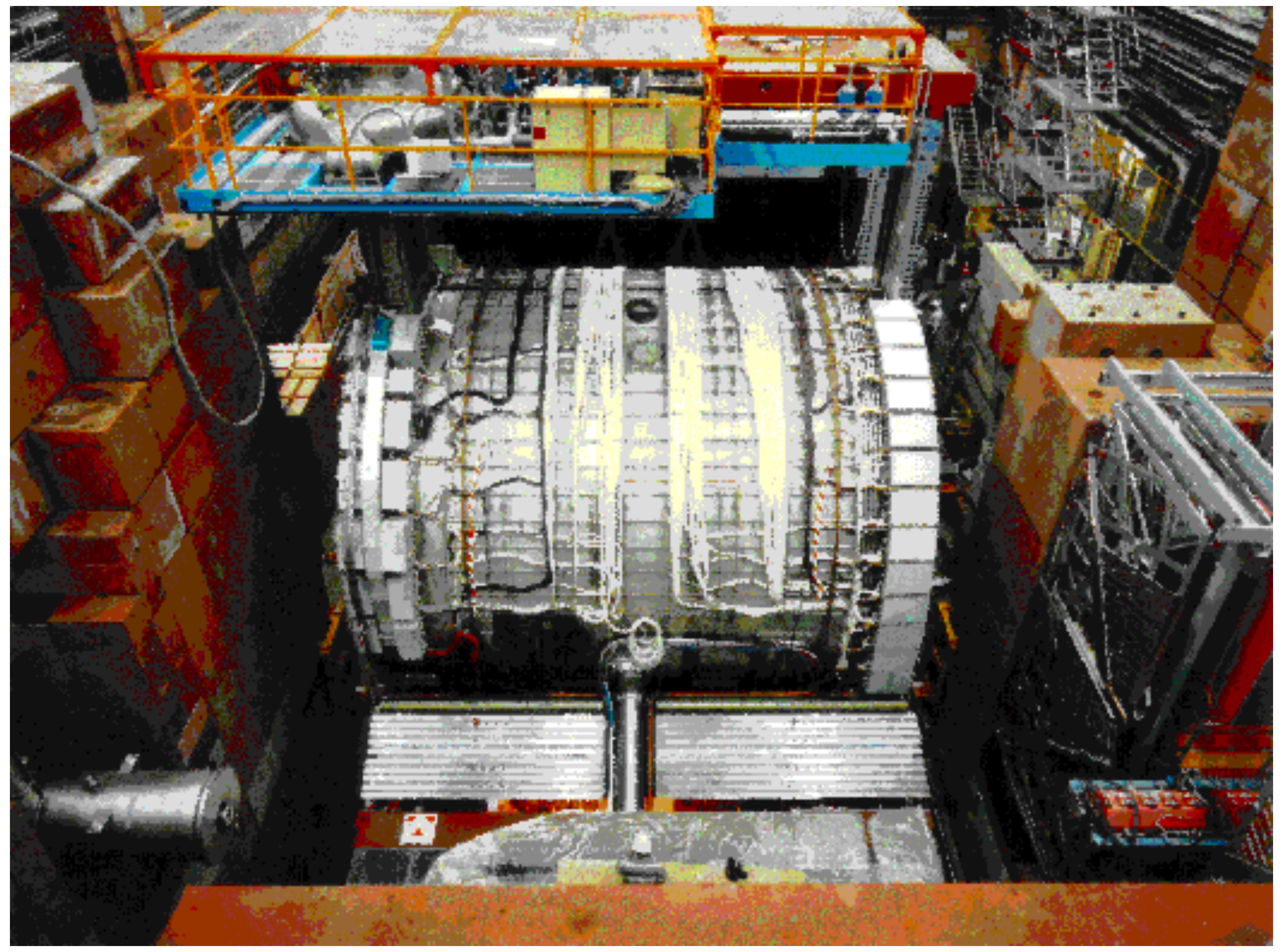

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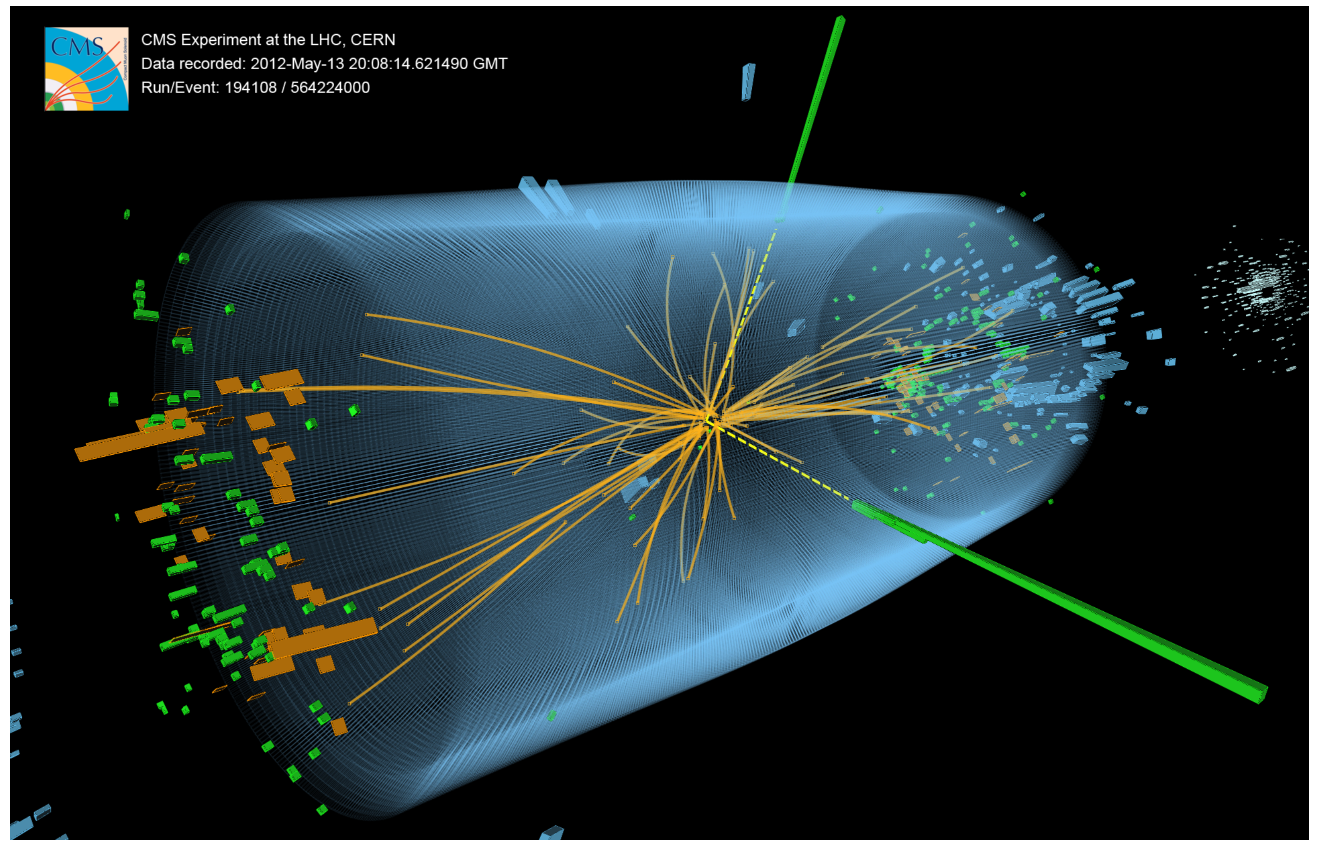
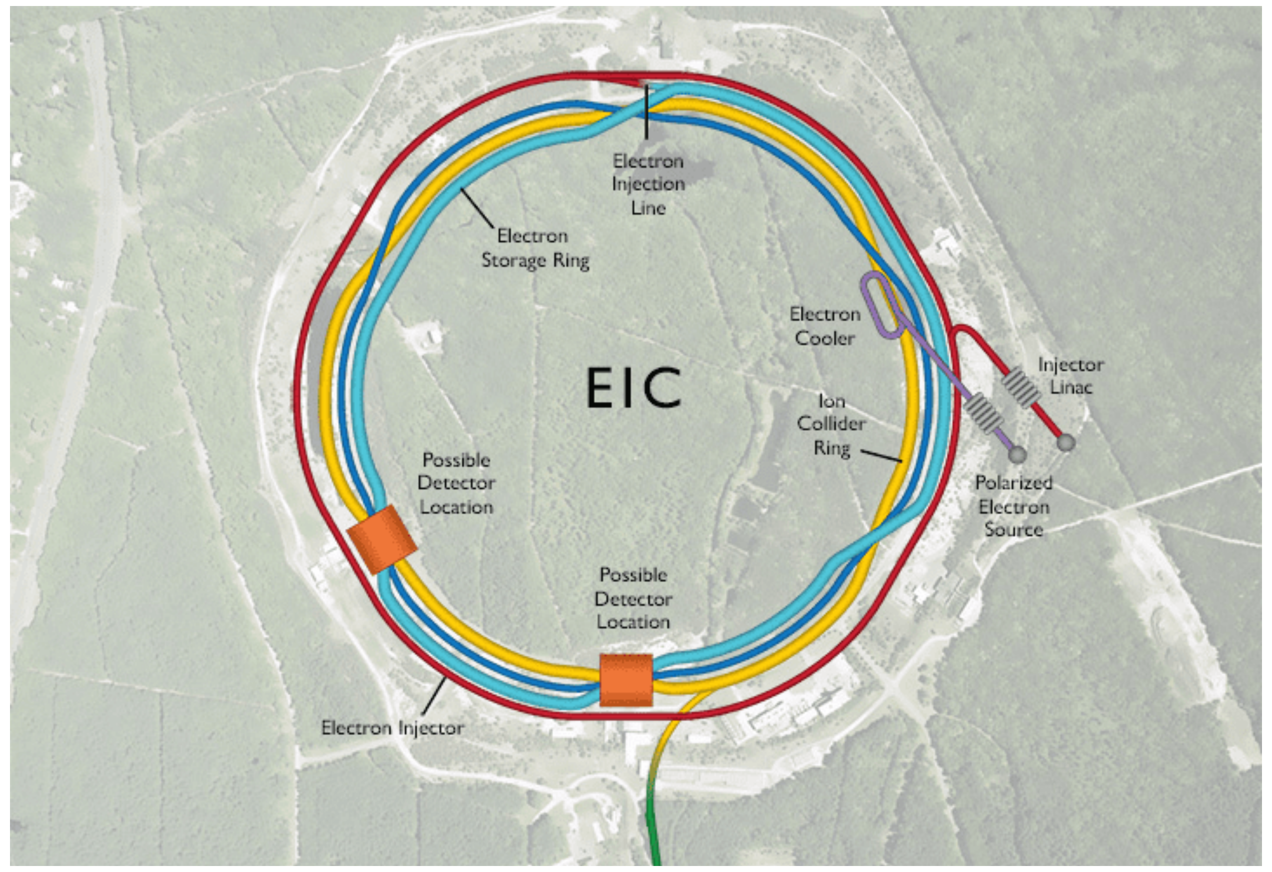


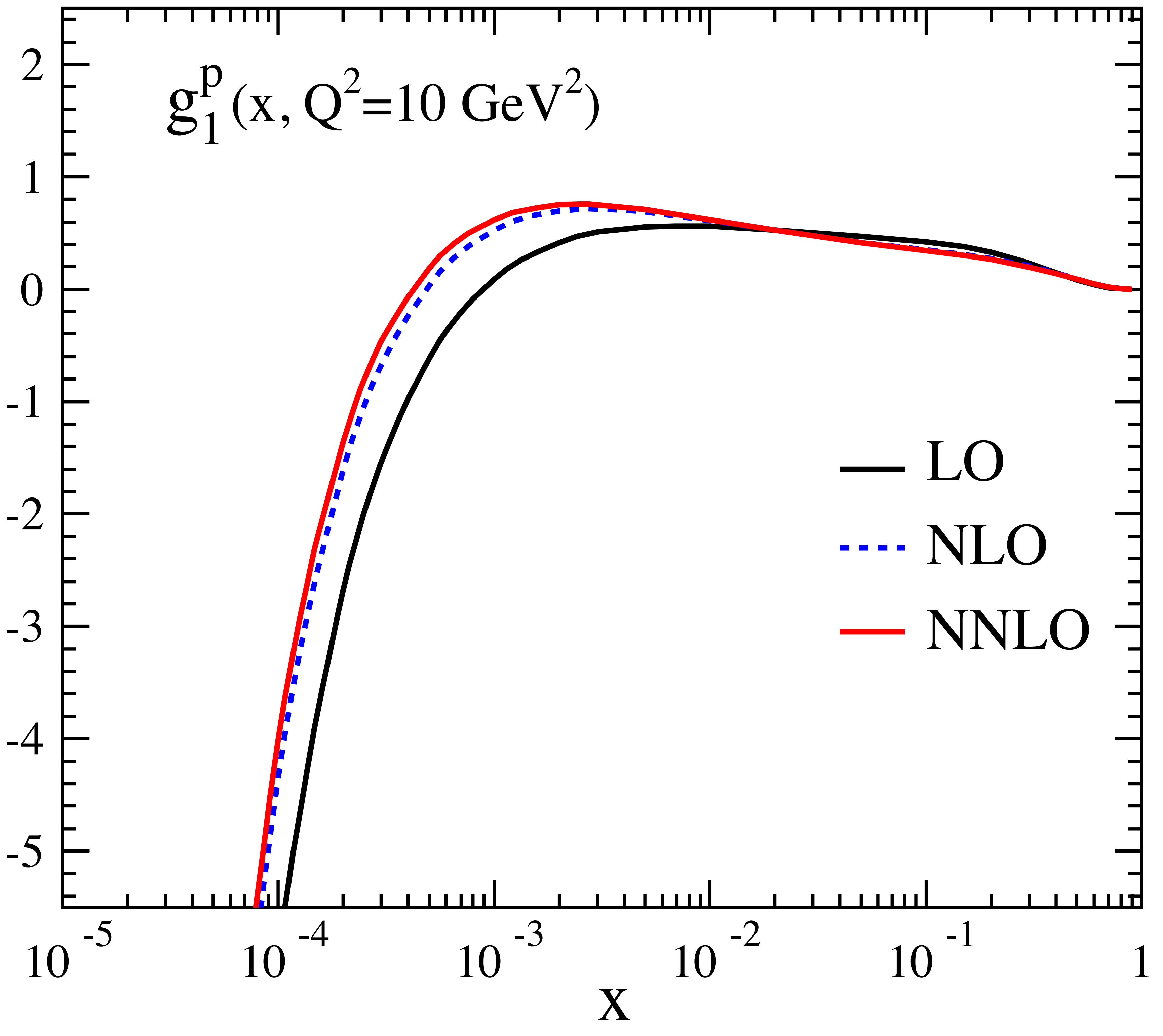


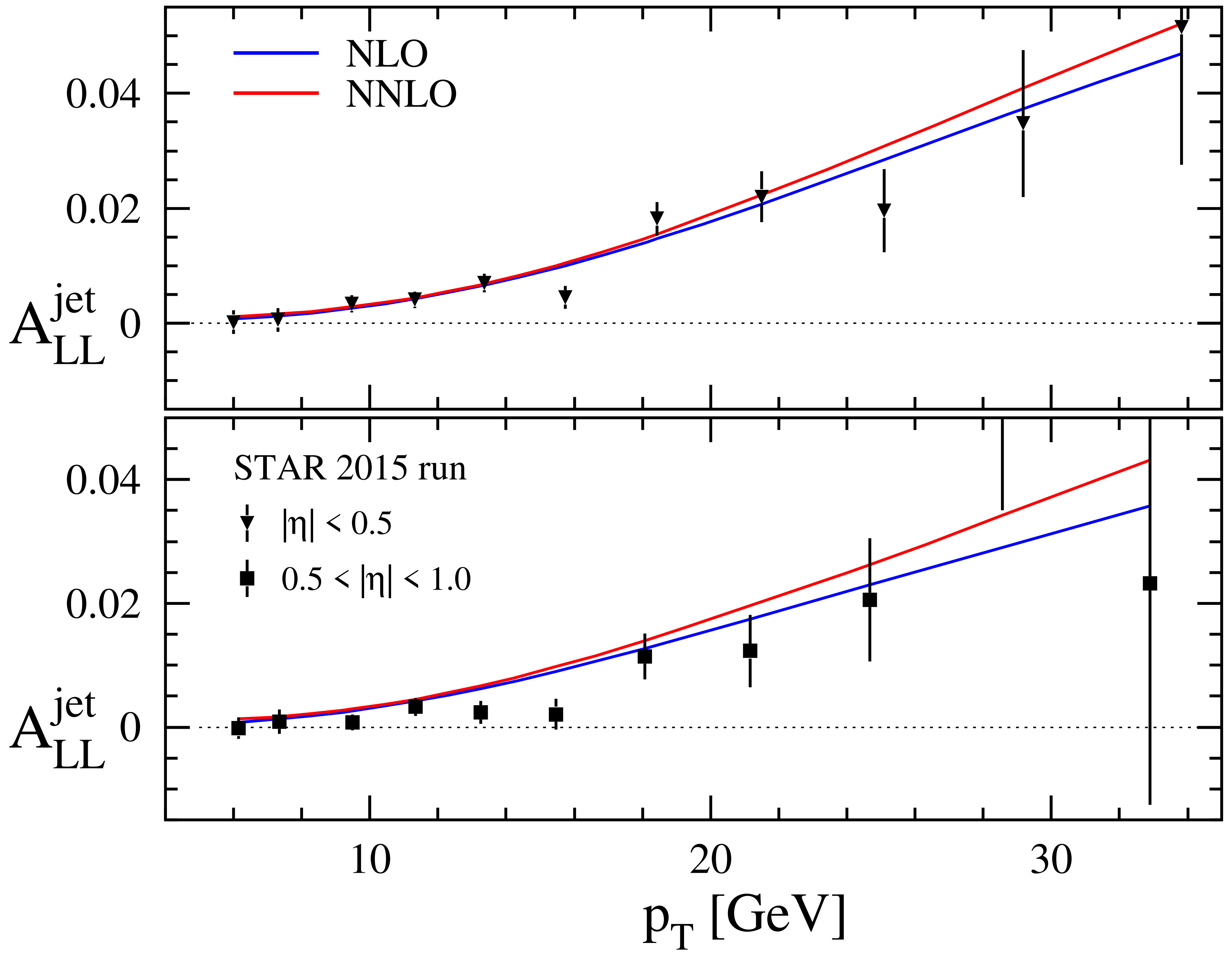
EIC 30's-
≥NNLO+ and beyond

TH effort driven by experimental possibilities!

Why NNLO?

- Precision!





- Not all observables known at NNLO accuracy yet in polarized case

✔	DIS	NNLO g_1 coefficients	E. B. Zijlstra and W. L. van Neerven (1994)
✔	DY	NNLO pp → W → $e^{\pm}\,\nu^{(-)}$	R. Boughezal, Hai Tao Li, F. Petriello (2021)
✔	Evolution	NNLO evolution kernels	S. Moch, J.A.M. Vermaseren, A. Vogt (2014, 2015) A. Vogt , S. Moch, M. Rogal, J.A.M. Vermaseren (2008)
✔	HQ	Heavy quark matching coefficients	Bierenbaum et al. (2022)
✔ ▲	SIDIS	NNLO SIDIS coefficients	not ready for use in global fit

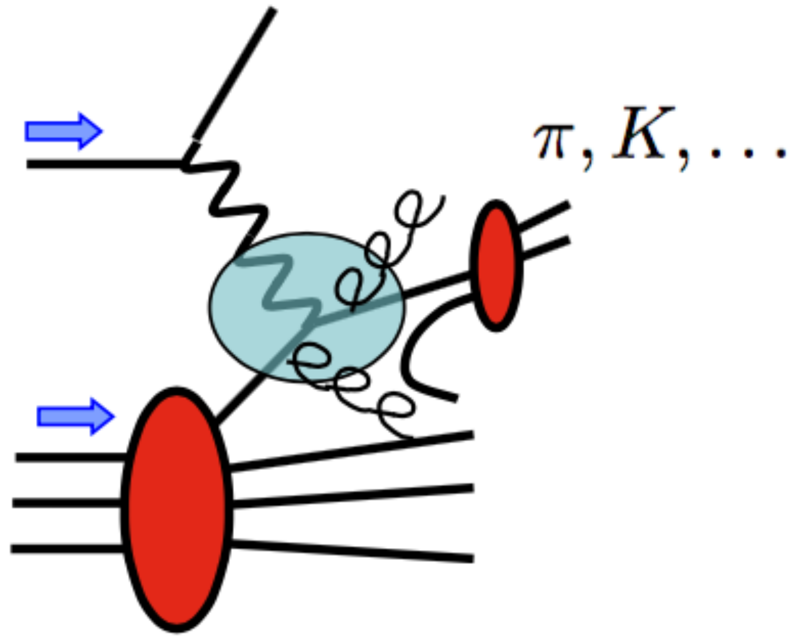
L.Bonino, T.Gehrmann, M.Löchner, K.Schonwald (2024)
S.Goyal, R.Lee, S.Moch, V.Pathak, N.Rana, V.Ravindran (2024)

hard to implement in Mellin space
(became available while performing fit)

▲ RHIC jets, dijets, hadrons $pp \to$ jets, $\pi^{\pm,0}$ only NLO known

- Rely on Soft approximation at NNLO : dominant terms in the threshold limit (on top of full NLO)

Use threshold resummation at NNLL to obtain the leading terms in the perturbative expansion



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$$\alpha_s^k \left(\frac{\ln^m(1-\hat{x})}{1-\hat{x}}\right)_+ \left(\frac{\ln^n(1-\hat{z})}{1-\hat{z}}\right)_+ \; \text{with } m+n \leq 2k-2.$$

$$\hat{x} = \frac{Q^2}{2p_a \cdot q}$$

$$\hat{z} = \frac{p_a \cdot p_b}{p_a \cdot q}$$

All distributions known (up to N3LO), missing regular terms

M. Abele, D. de Florian, W. Vogelsang (2022,2023)

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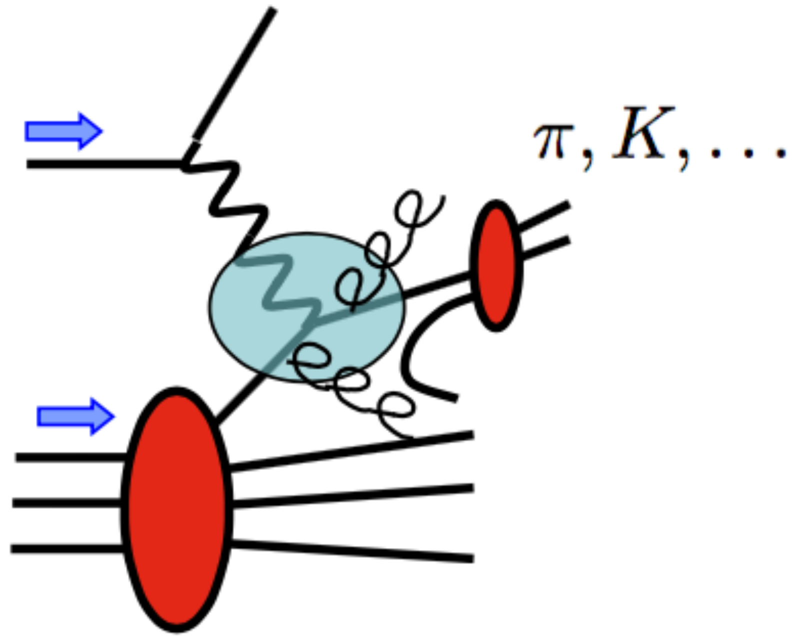

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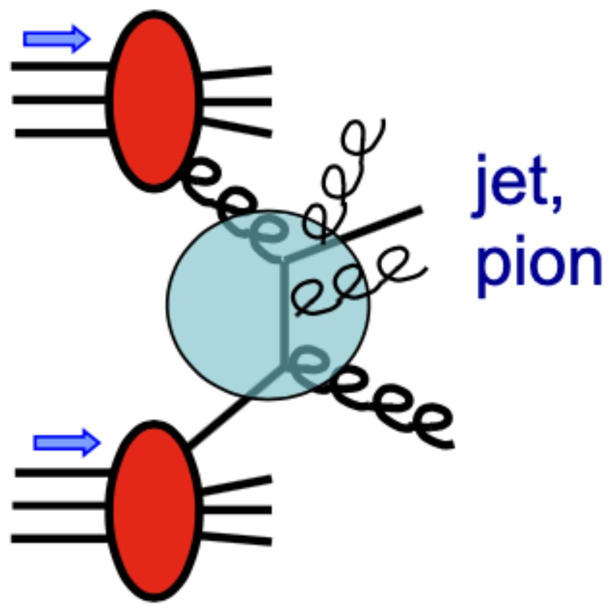

pp high-p_T

All ( )+ distributions known

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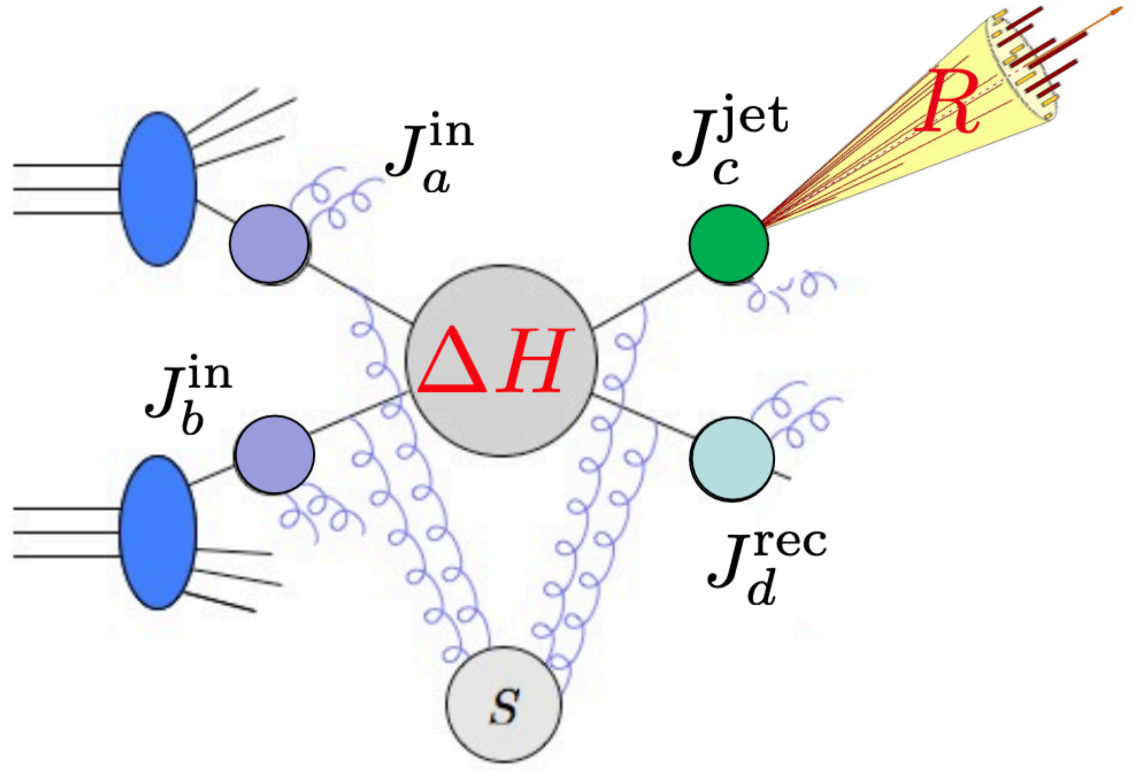
D. deF, W. Vogelsang (in preparation)



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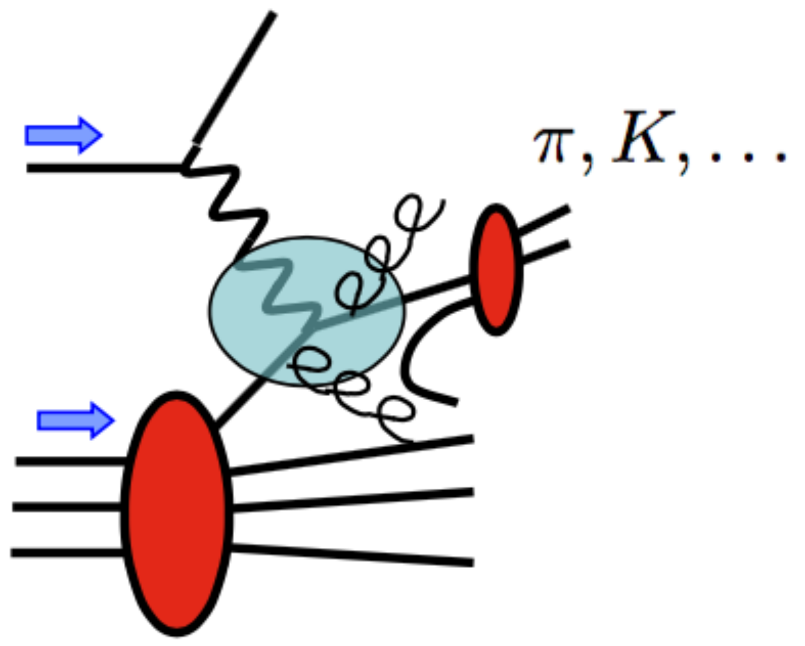

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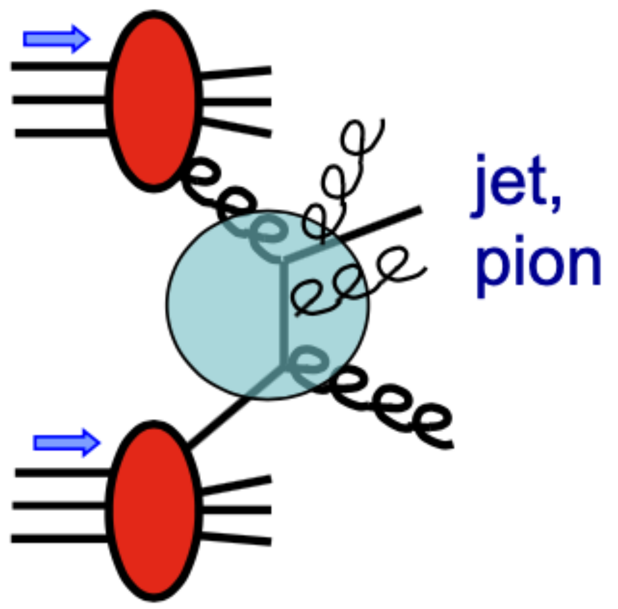

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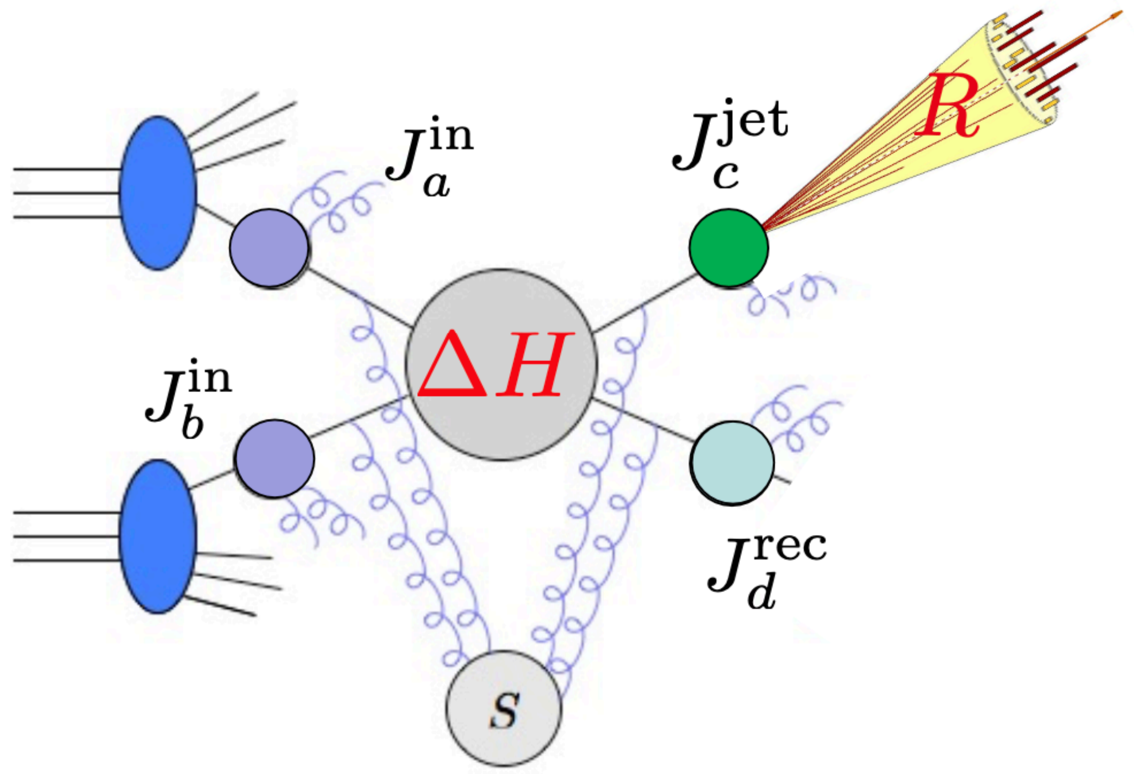

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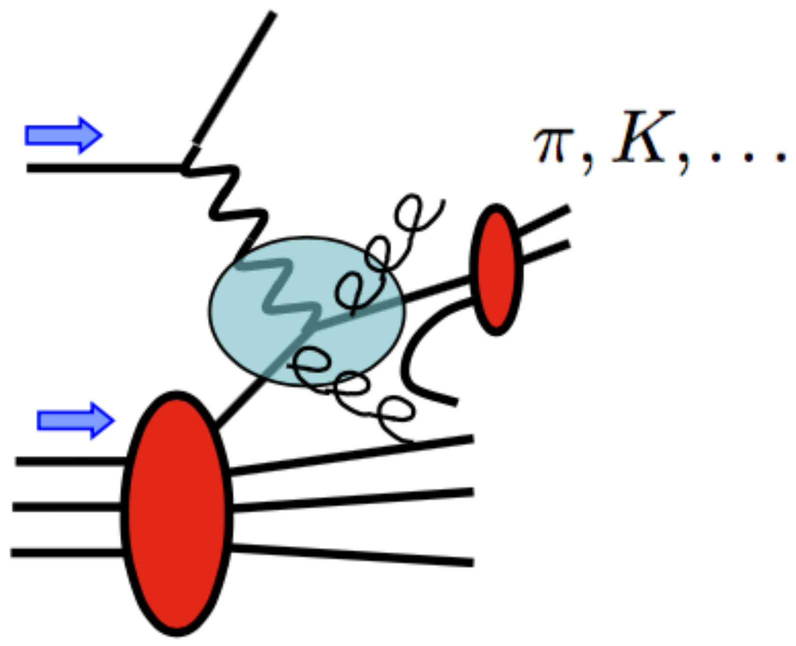

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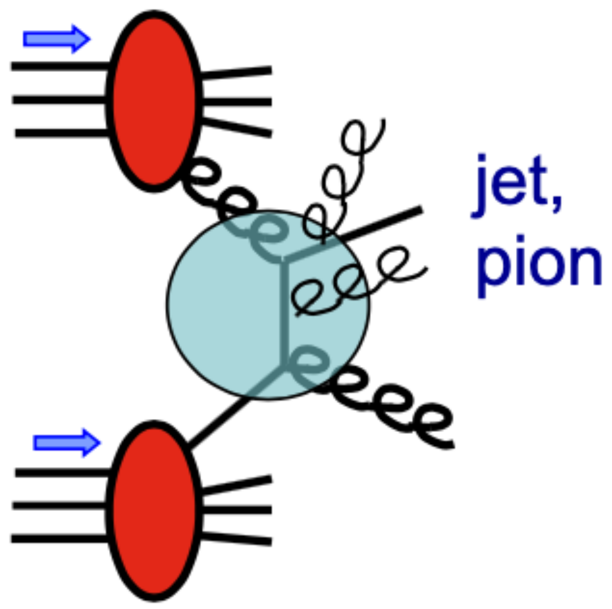

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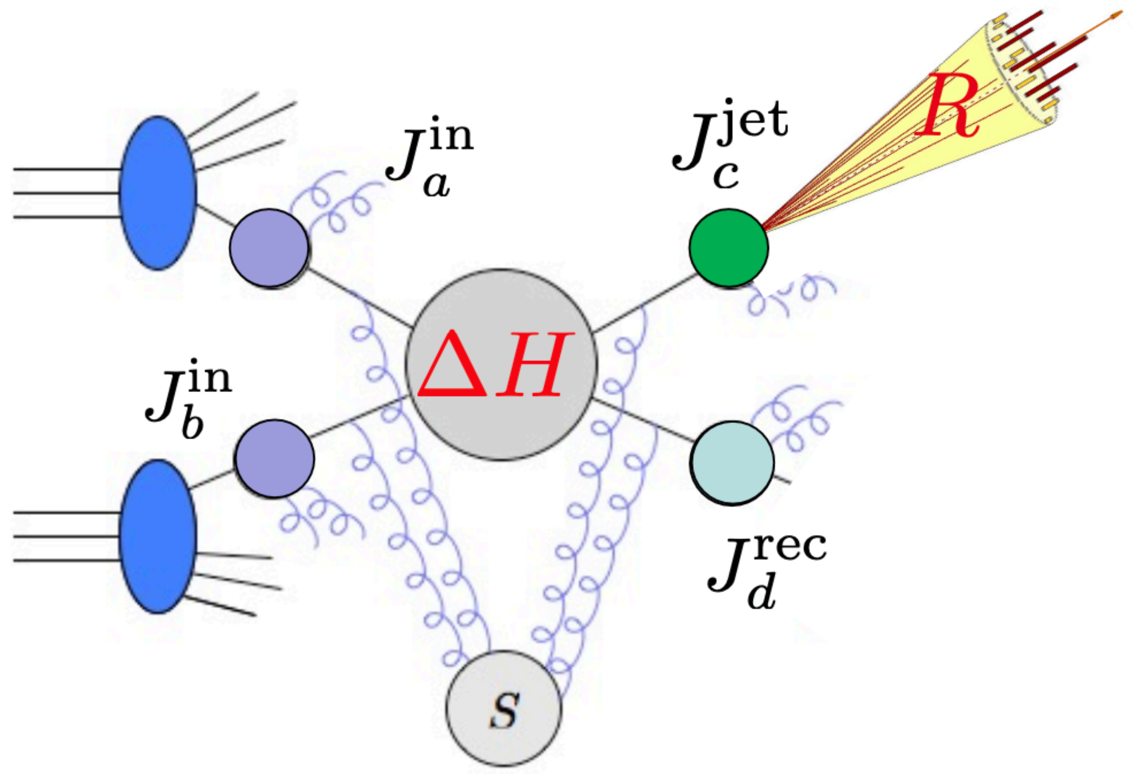

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- To be safe: select data in a restricted region of phase space (cuts in $x_{SIDIS} > 0.12$ and $p_T > 1.5$ GeV)

Ingredients

- Parameterizations:

$$(\Delta q + \Delta\bar{q})(x, Q_0^2) = N_q\, x^{\alpha_q}(1-x)^{\beta_q}\left(1 + \gamma_q x^{\delta_q} + \eta_q x\right) \quad (u,d) \qquad Q_0^2 = 1\, GeV^2$$

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(32 **parameters**)

- Evolution: ZMVFNS HQ matching coefficients QCD-PEGASUS framework checked EKO and APFEL
  A.Vogt (2004)

- Assumptions: no $SU(2)/SU(3)$ constraints positivity relative to MSHT20 S. Bailey et al.

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  data replicas → 600 PDFs replicas
  → error propagation
  → reweighting

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Data Selection:

		#data	NLO	NNLO
DIS:	EMC,SMC,E142,E143,E154,E155, HERMES, COMPASS, HALL-A,CLAS (p,n,d,He)	368	302.7	294.3
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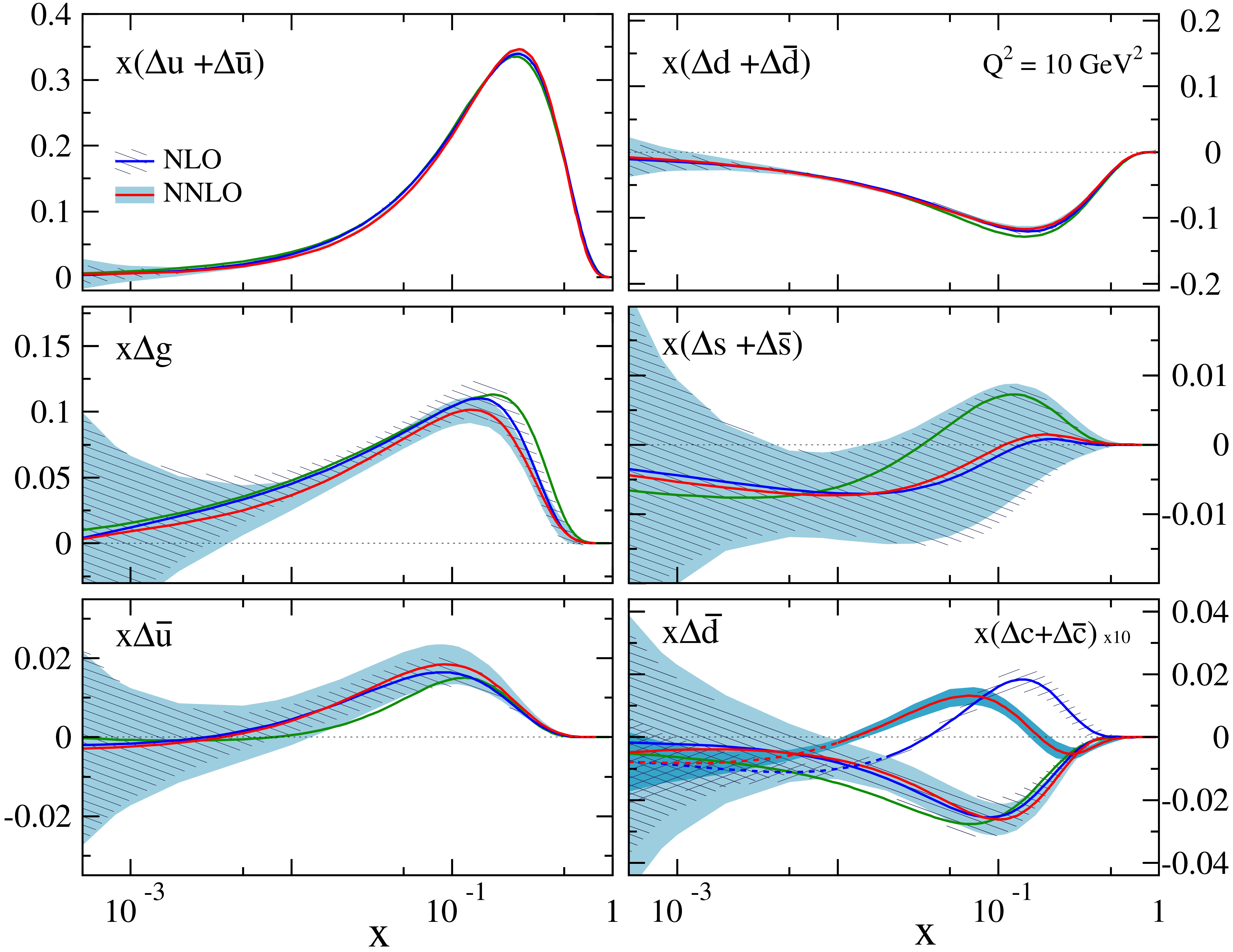
PP-$\pi^0/\pi^{\pm}$:	PHENIX, STAR	78	63.5	66.0
PP $W^{\pm}$:	PHENIX, STAR	22	22.3	20.3
Total:		673	627.2	607.5

$x_{SIDIS} > 0.12$ $p_T > 1.5$ GeV

Distributions



BDSSV22: NLO with dijets and no cuts on sidis

$(\Delta u + \Delta \overline{u})$ and $(\Delta d + \Delta \overline{d})$ well constrained

no significant NNLO/NLO differences

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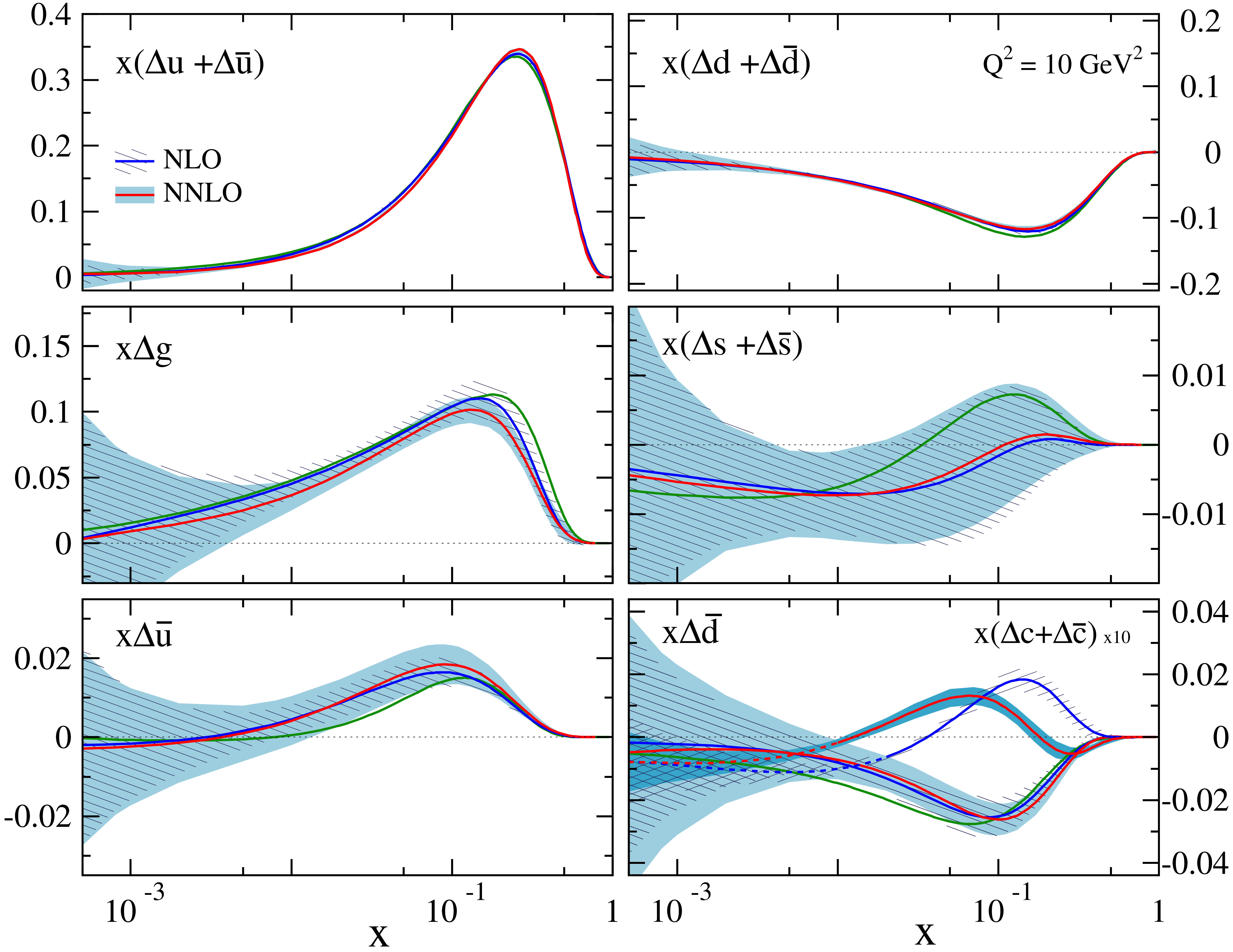

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NNLO/NLO differences within uncertainties

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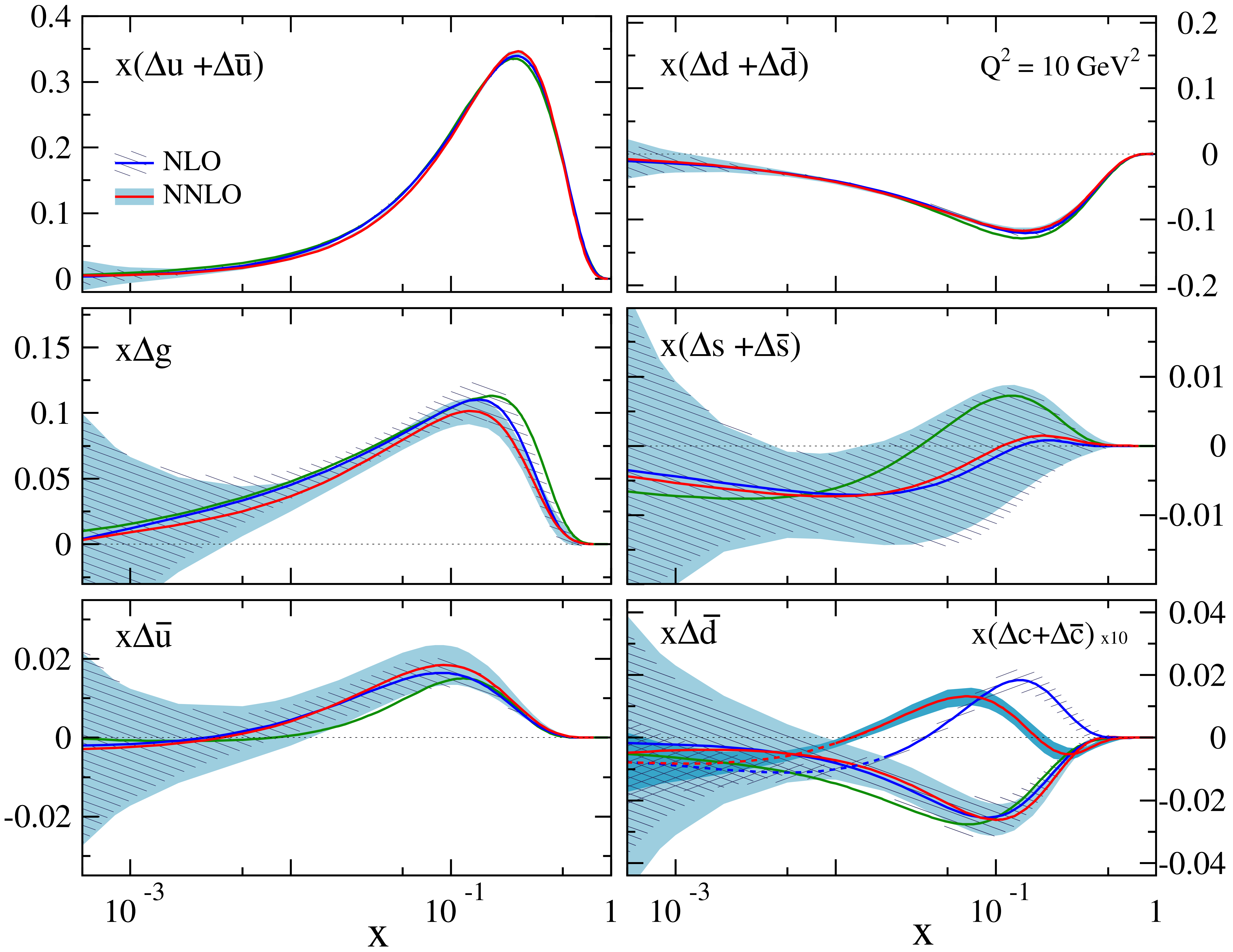

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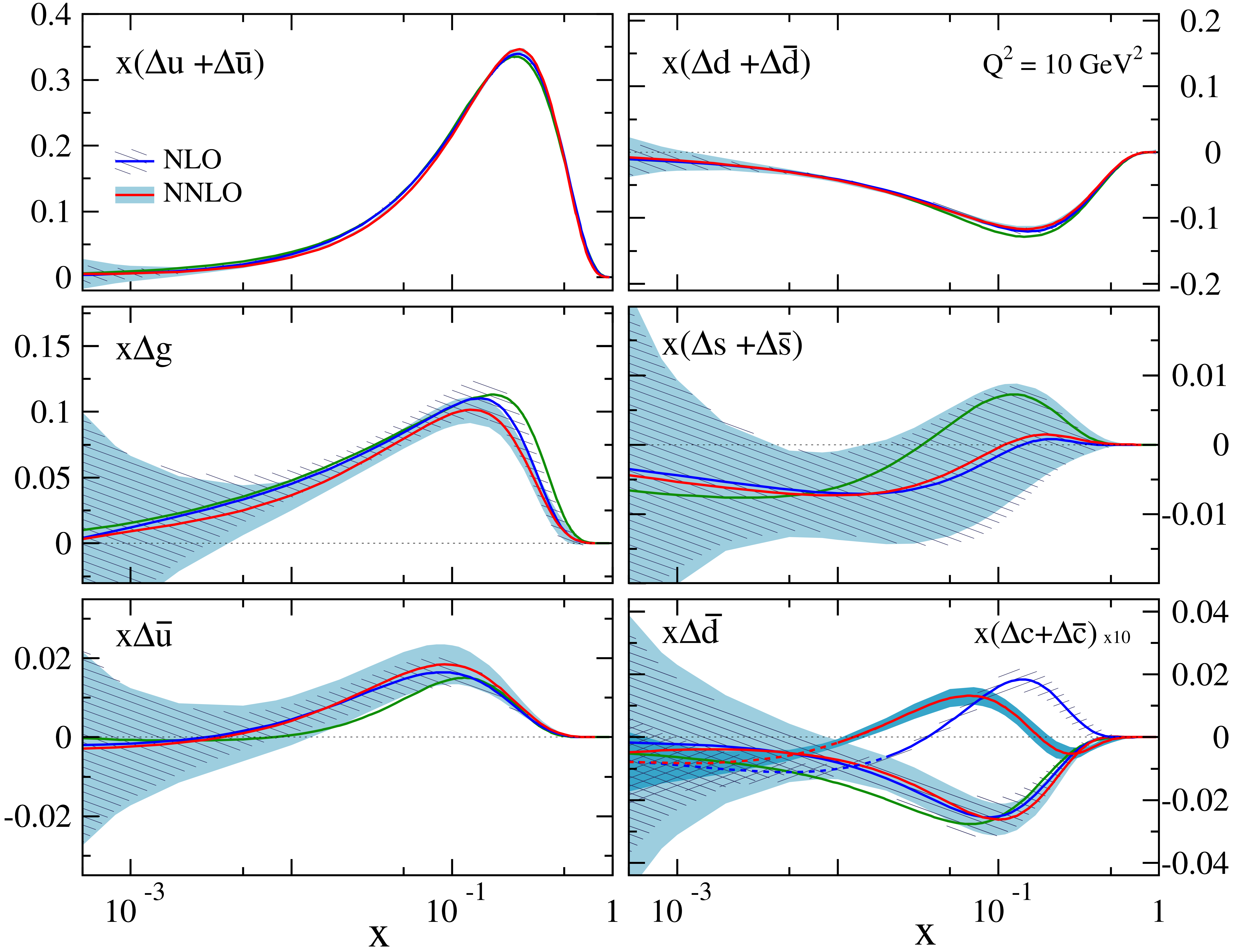

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NNLO/NLO differences within uncertainties

$(\Delta s + \Delta \overline{s})$ consistent with zero

suffers the cut and lack of F, D constraints

$\Delta \overline{u}$ and $\Delta \overline{d}$ opposite signs

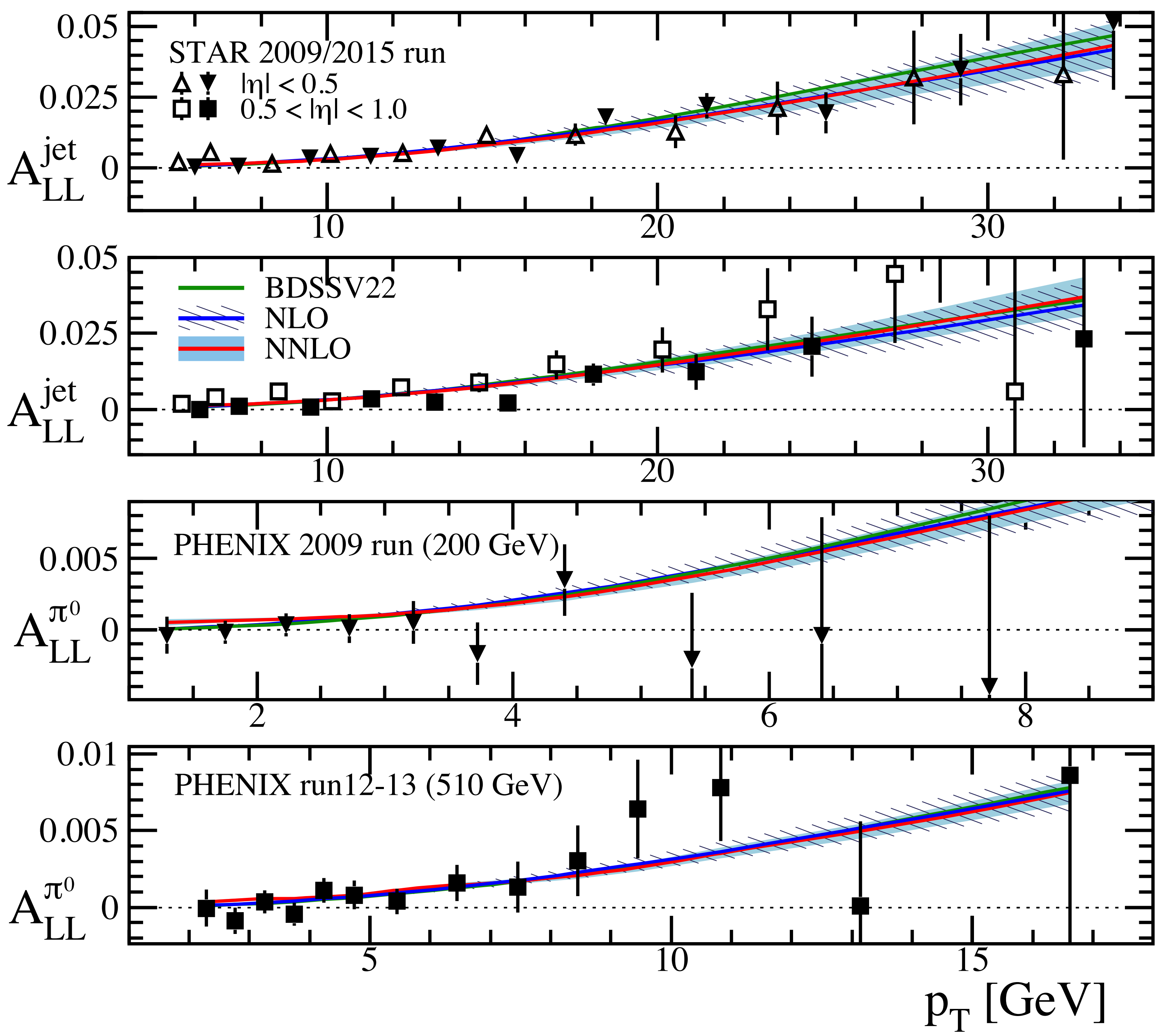
constrained by W

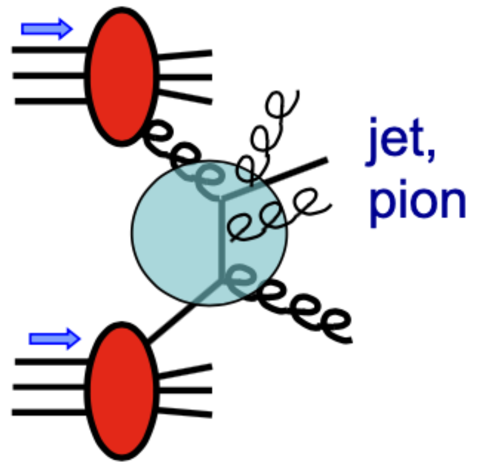
$(\Delta c + \Delta \overline{c})$ small!

inherits the gluon uncertainties

strongly dependent on perturbative order

Selected Data Sets





pp high-p_T

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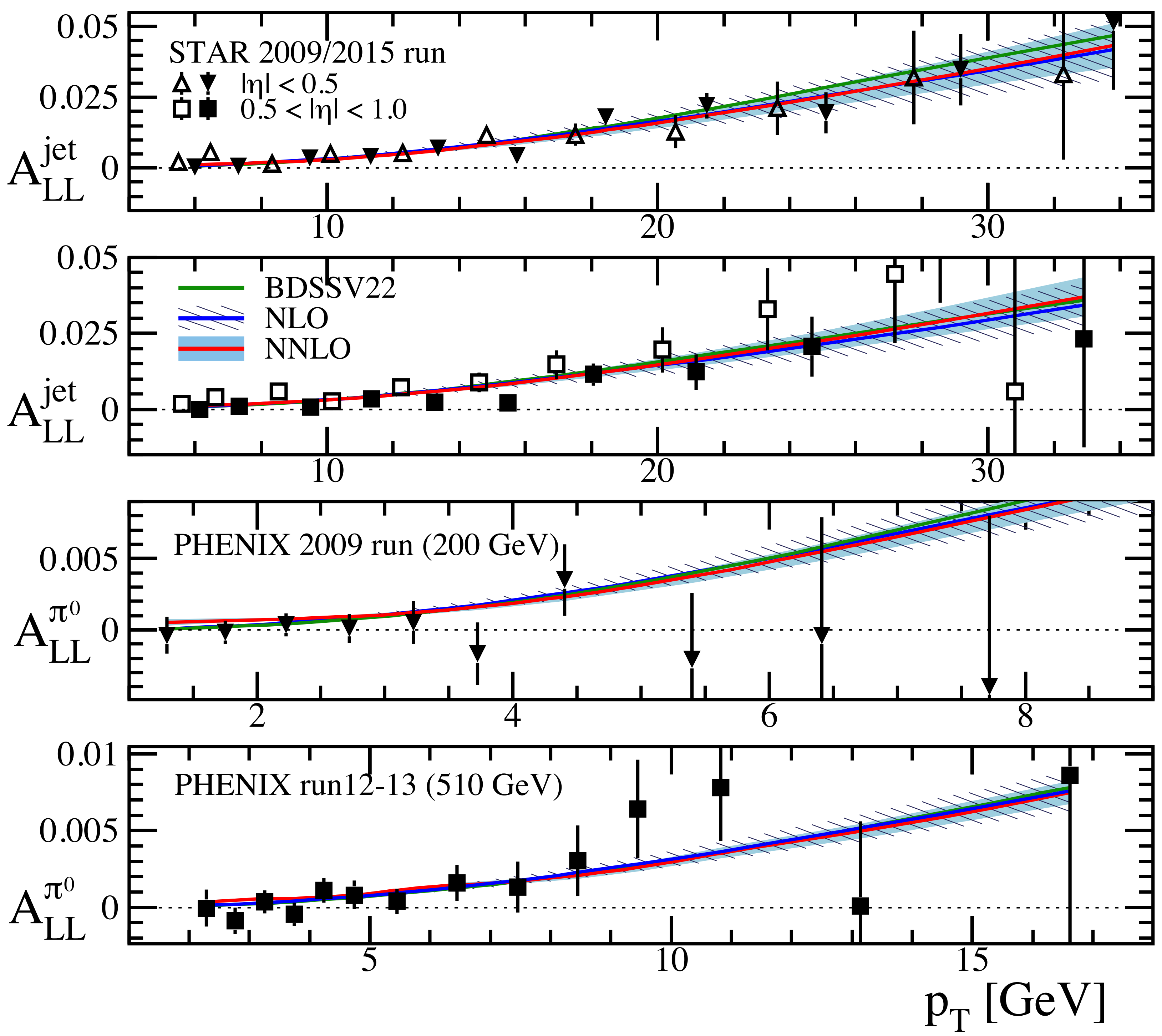

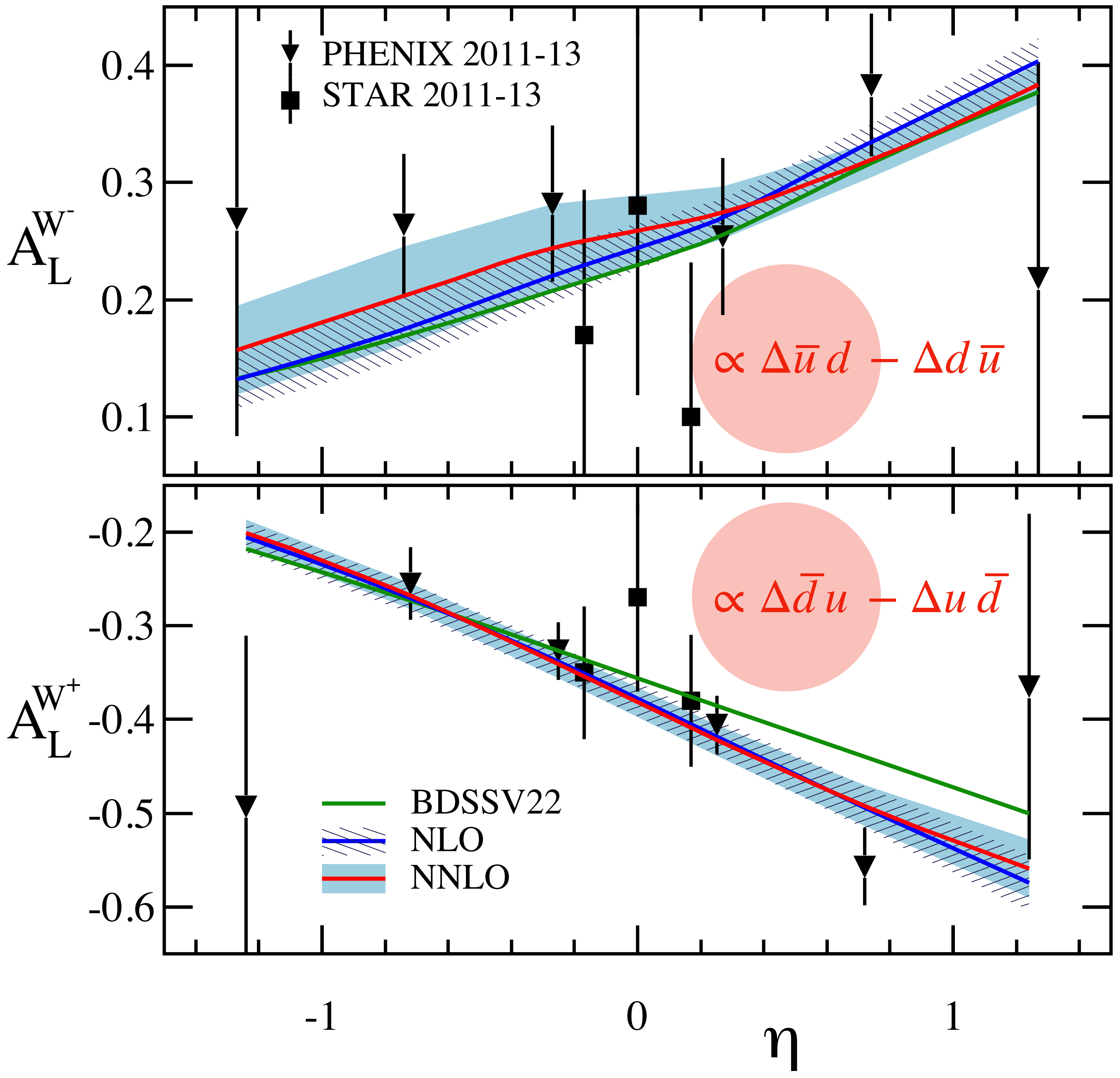

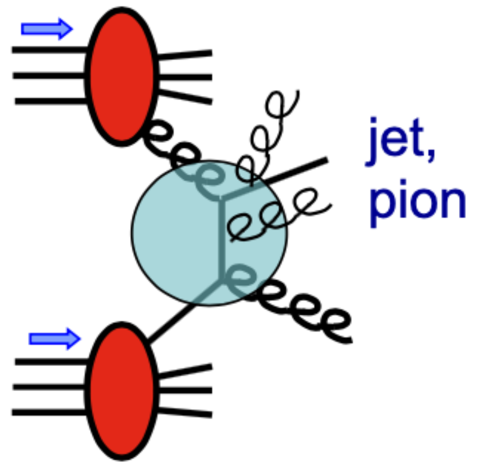

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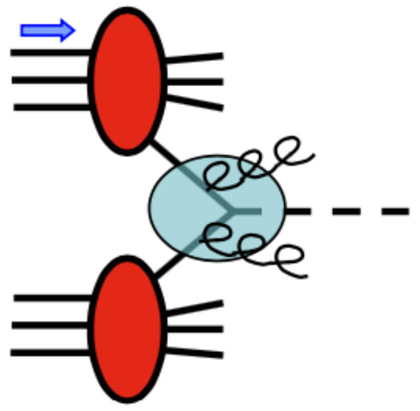

W bosons

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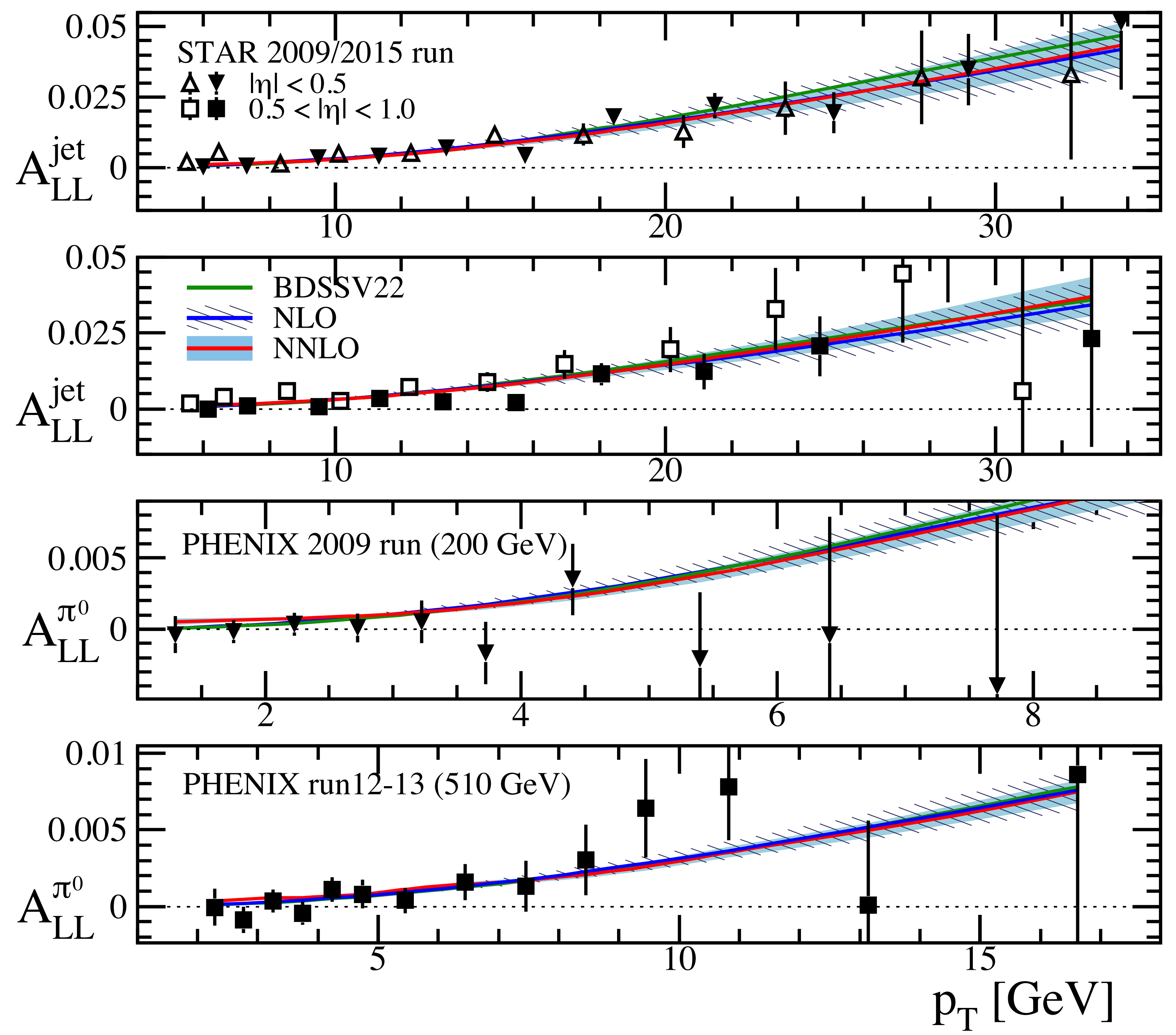

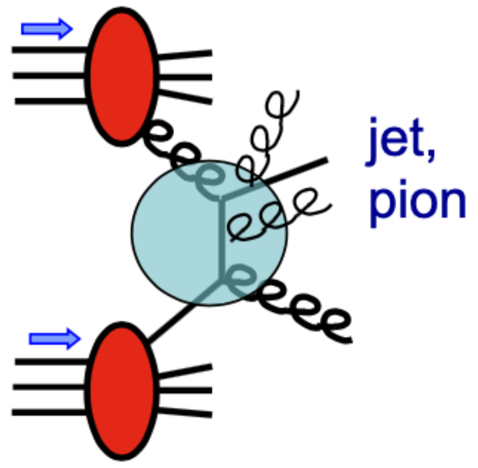

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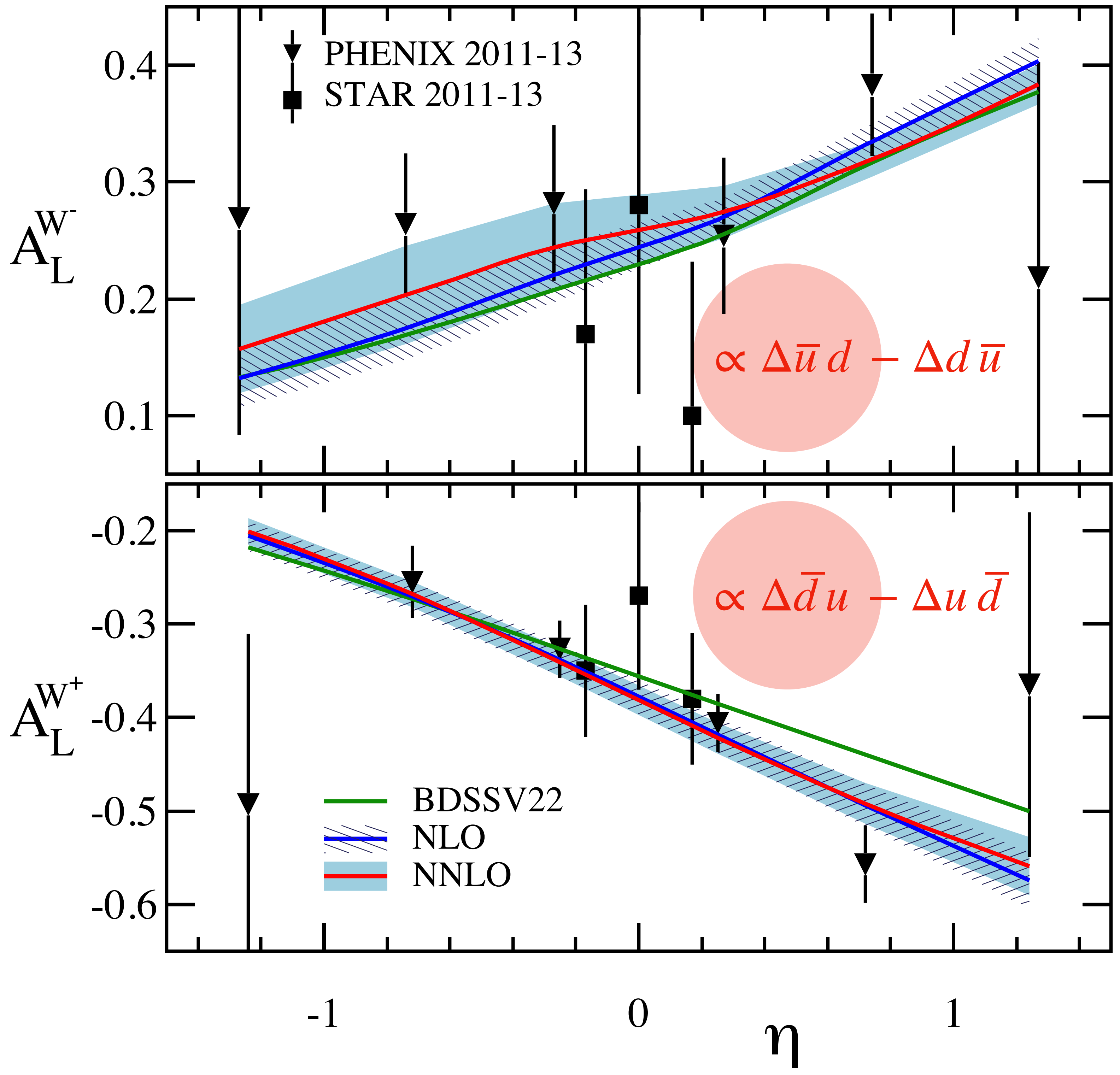

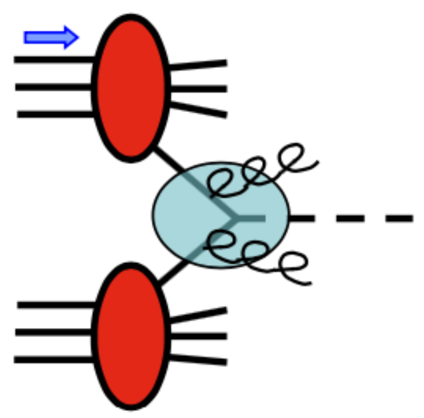

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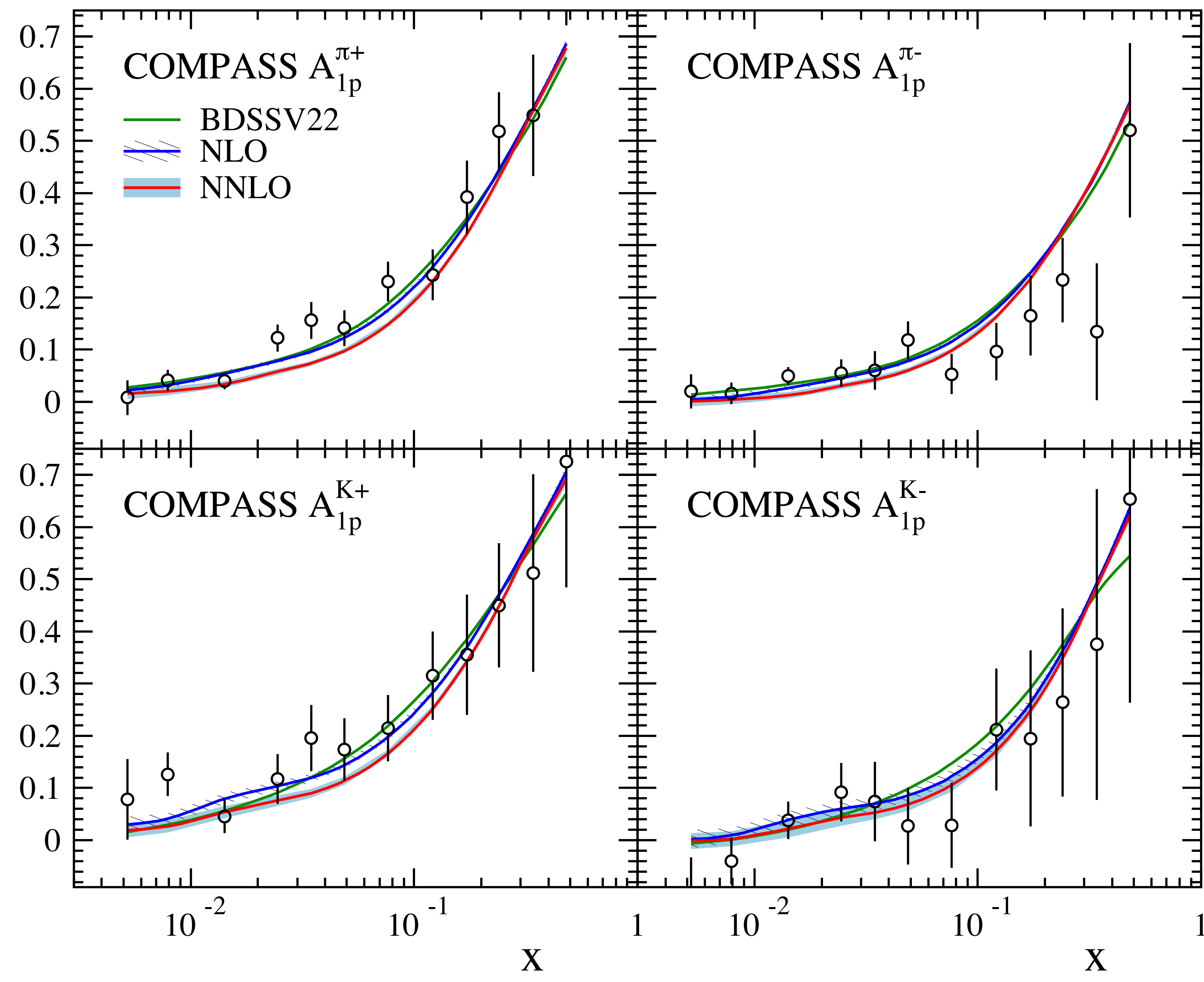
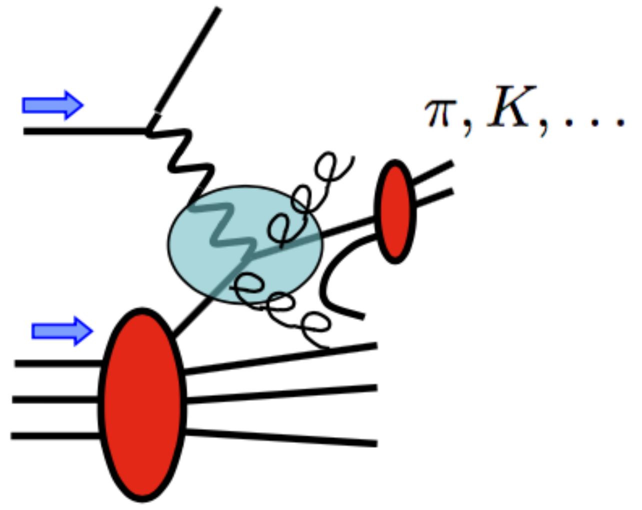
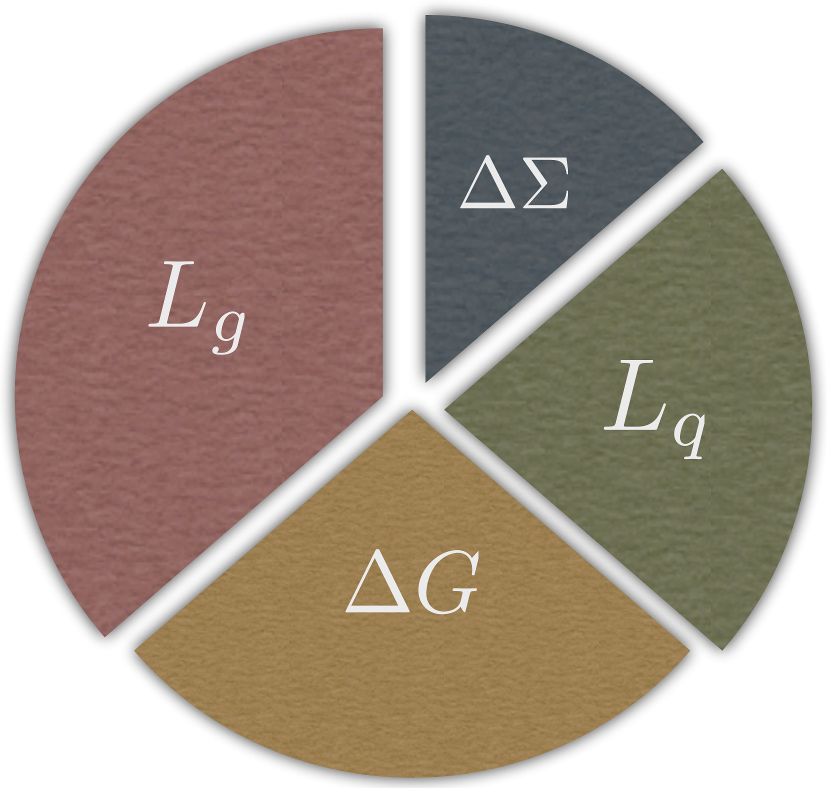




SIDIS

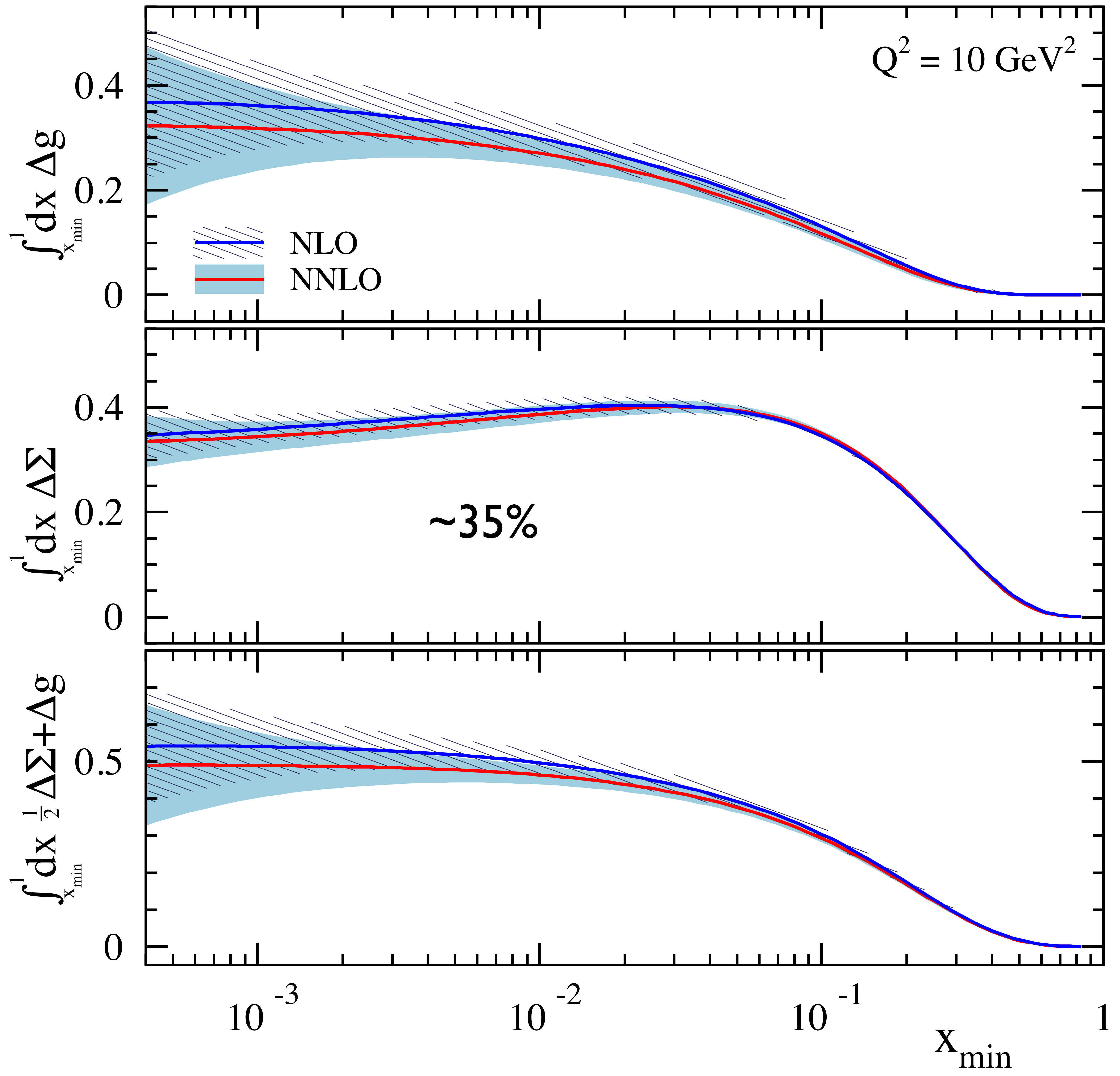
Spin Sum Rule



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

Extrapolation at small x very uncertain…

but might saturate the spin sum rule just from spin of quarks and gluons (no orbital angular momentum)



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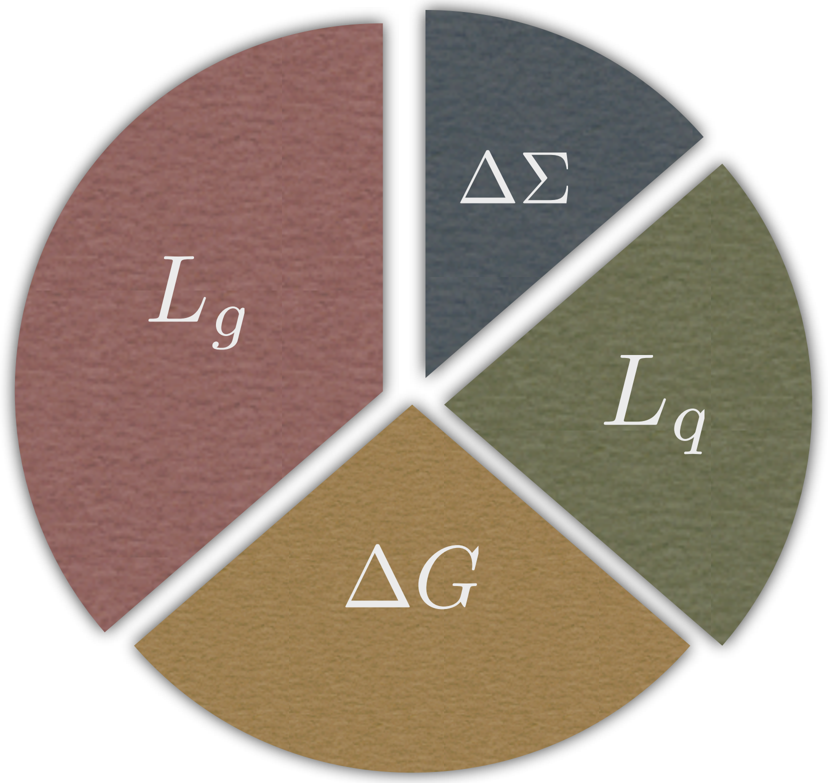

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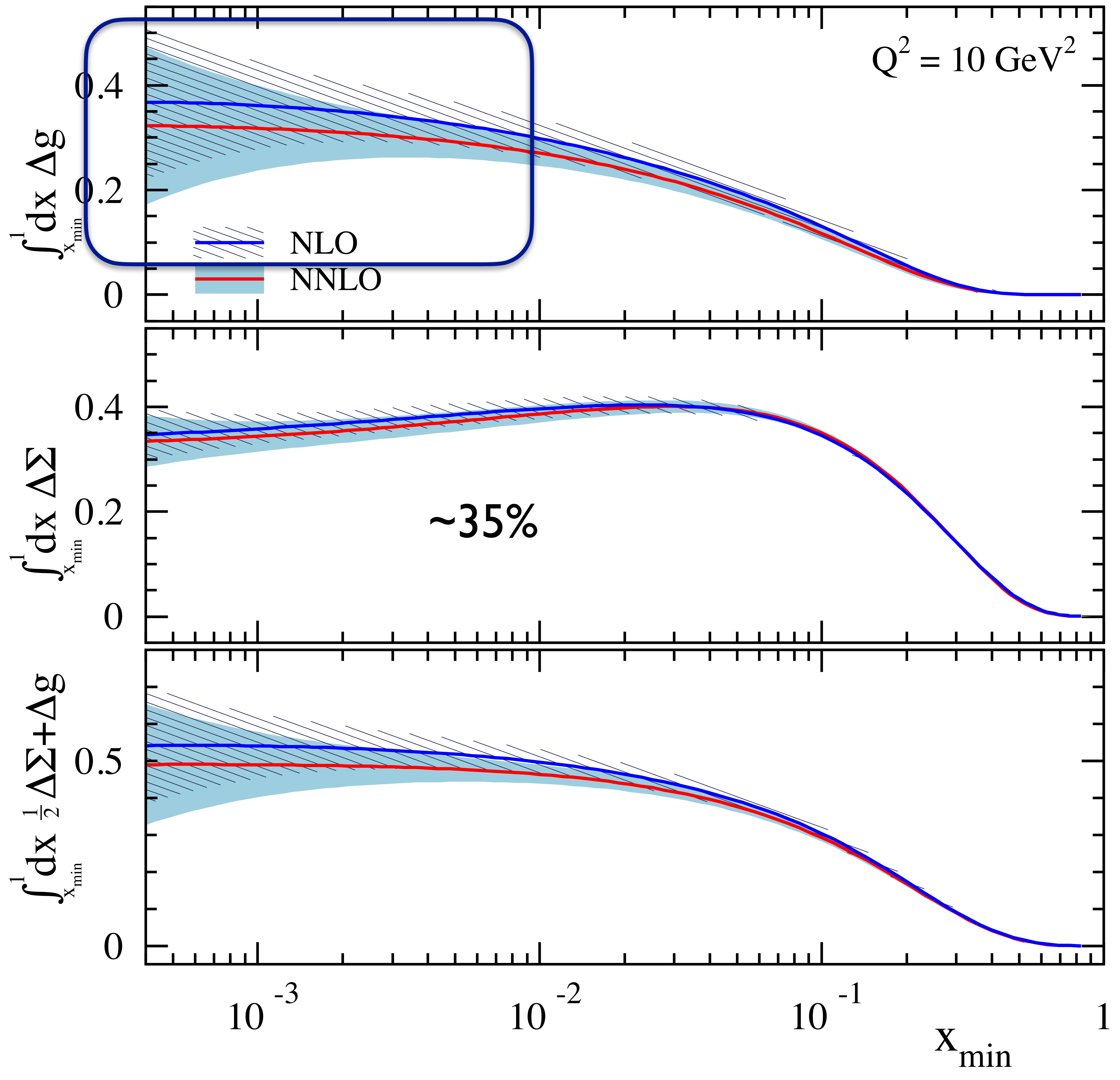

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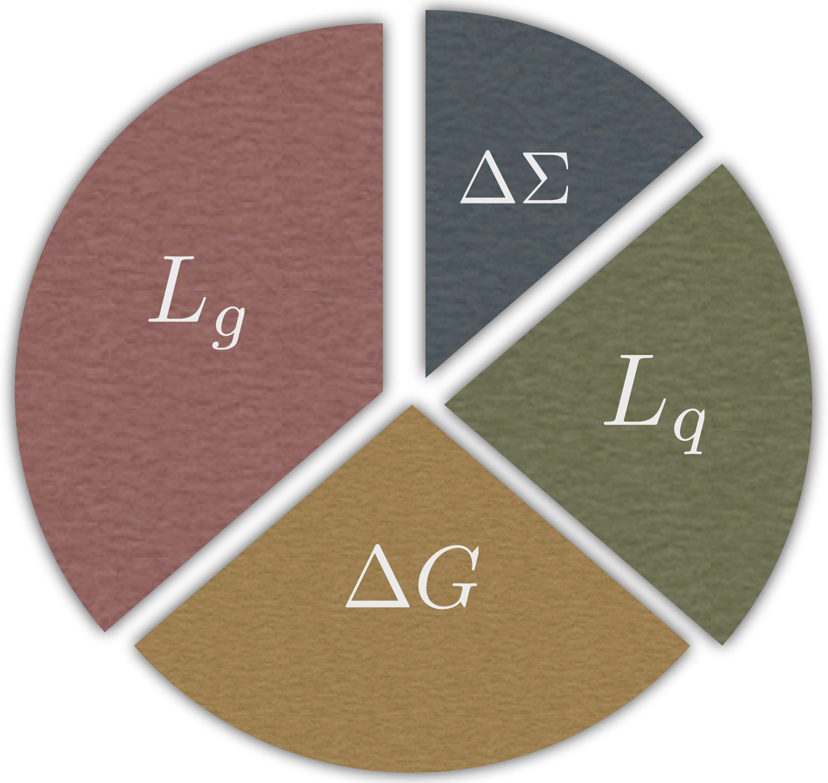

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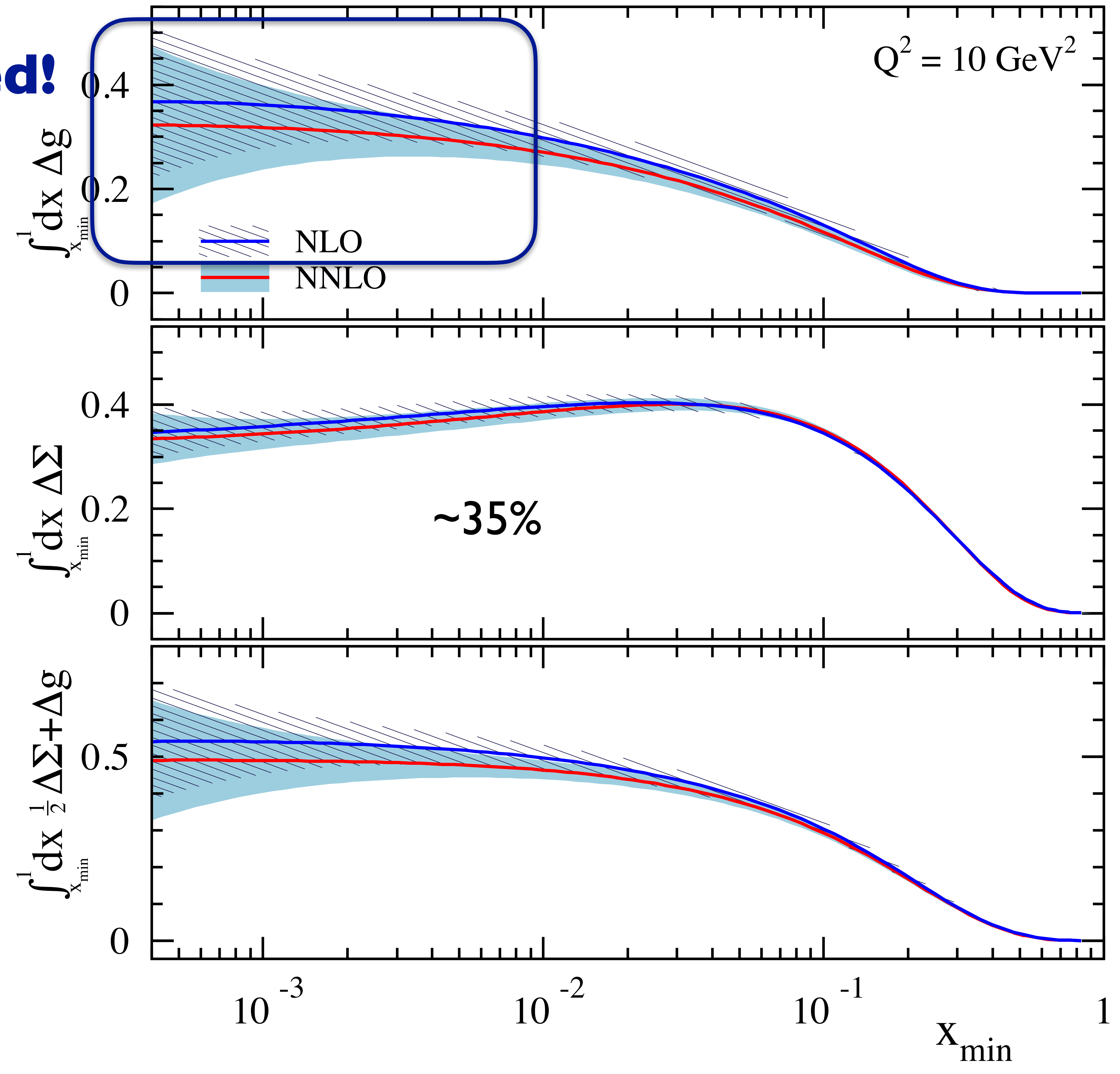
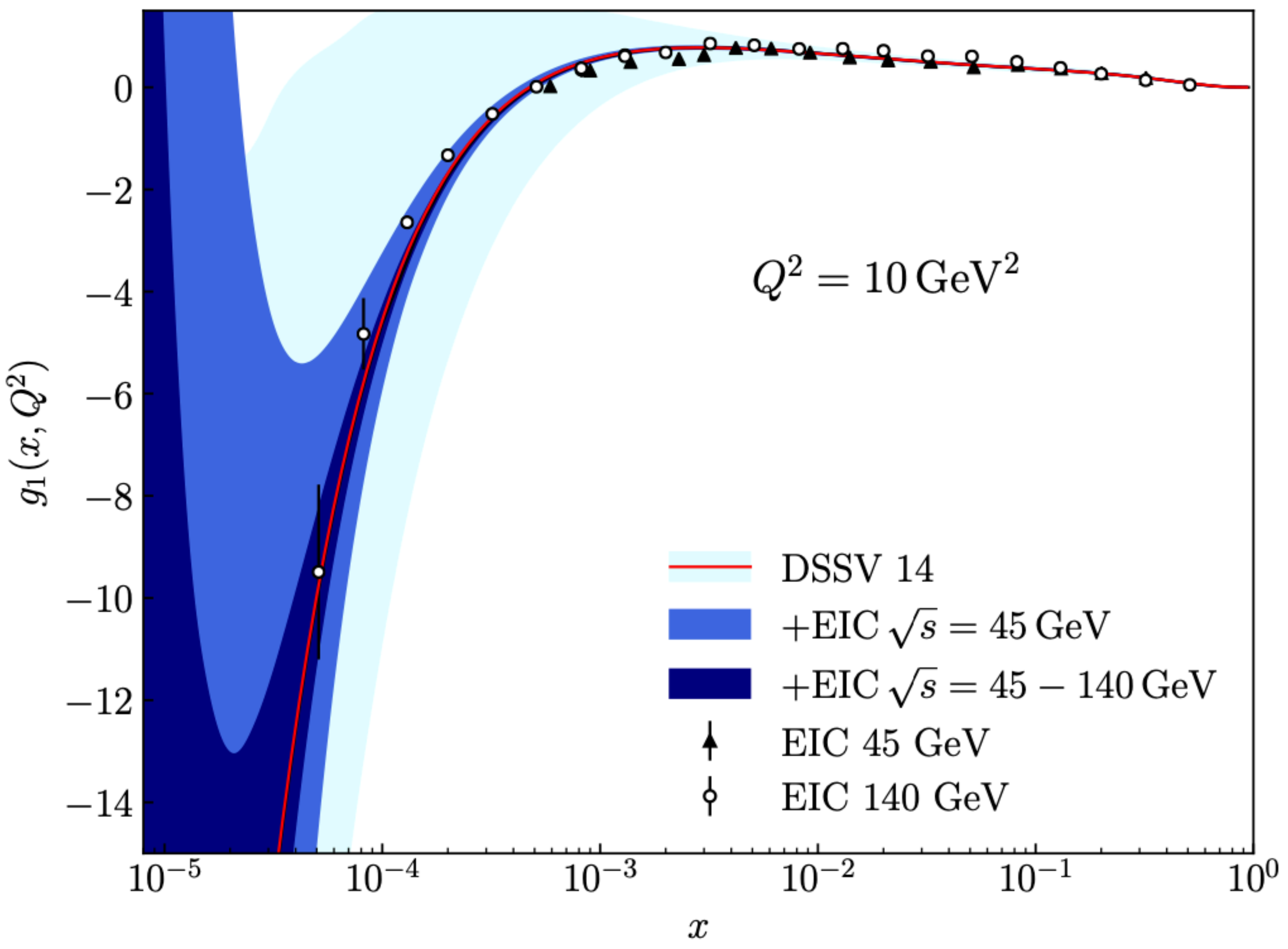
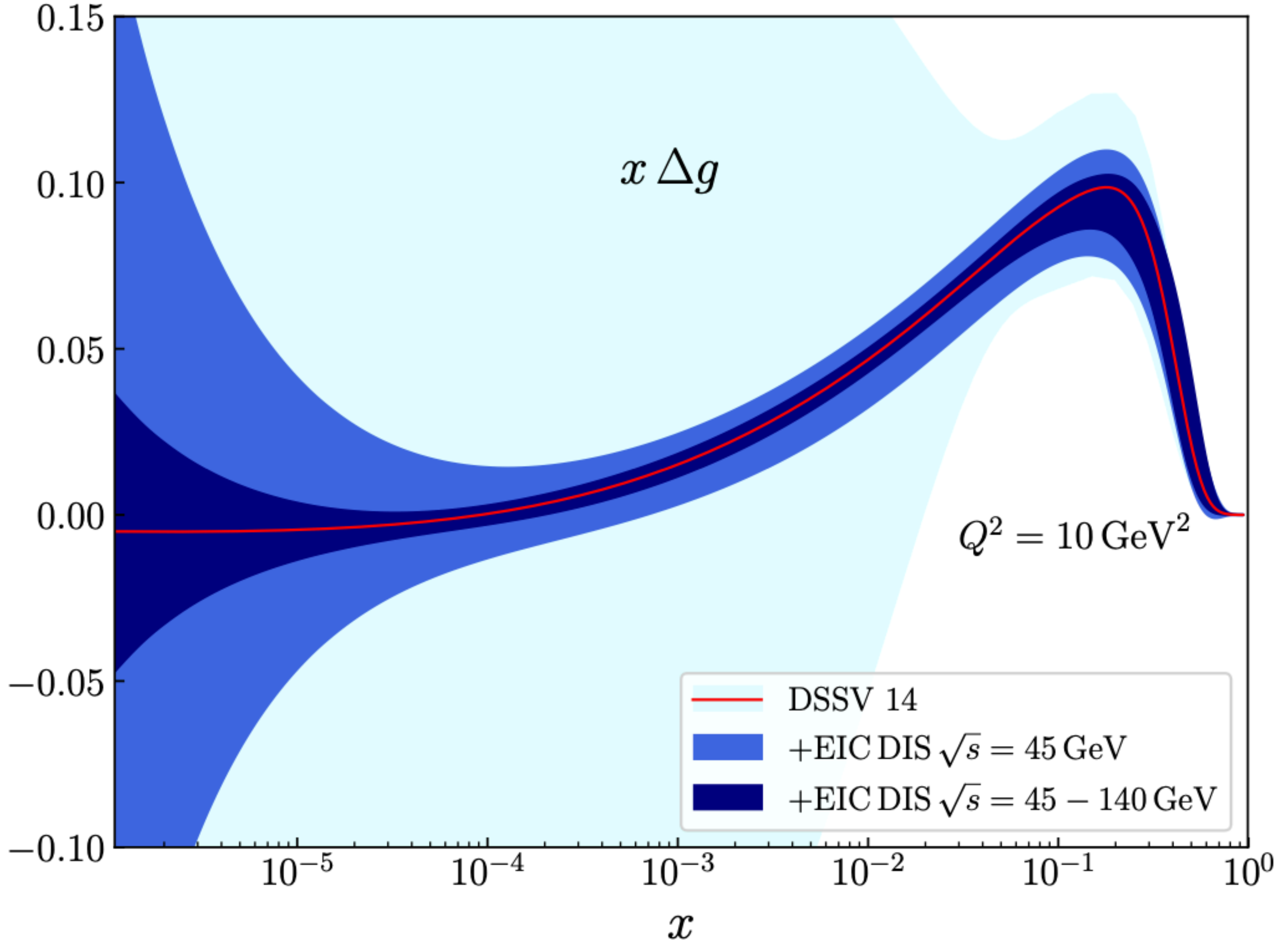
EIC needed!



Key measurement for polarized gluon distribution : $g_1(x, Q^2)$ at small x at EIC (coefficient + evolution)





at small x $\quad \dfrac{\partial g_1(x, Q^2)}{\partial \ln Q^2} \approx -\Delta g(x, Q^2)$.

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

QCD+QED/EW effects

Notice that $\alpha_s^2 \sim \alpha \sim 0.01$ and EW effects can be enhanced..

$$\sigma(\alpha_s, \alpha) = \sigma^{(0,0)} + \alpha_s\,\sigma^{(1,0)} + \alpha_s^2\,\sigma^{(2,0)} + \ldots + \alpha\,\sigma^{(0,1)} + \ldots + \alpha_s\,\alpha\,\sigma^{(1,1)} + \ldots$$

LO NLO QCD NNLO QCD NLO EW NNLO mixed QCD-EW

- mixed QCD-QED splitting functions known

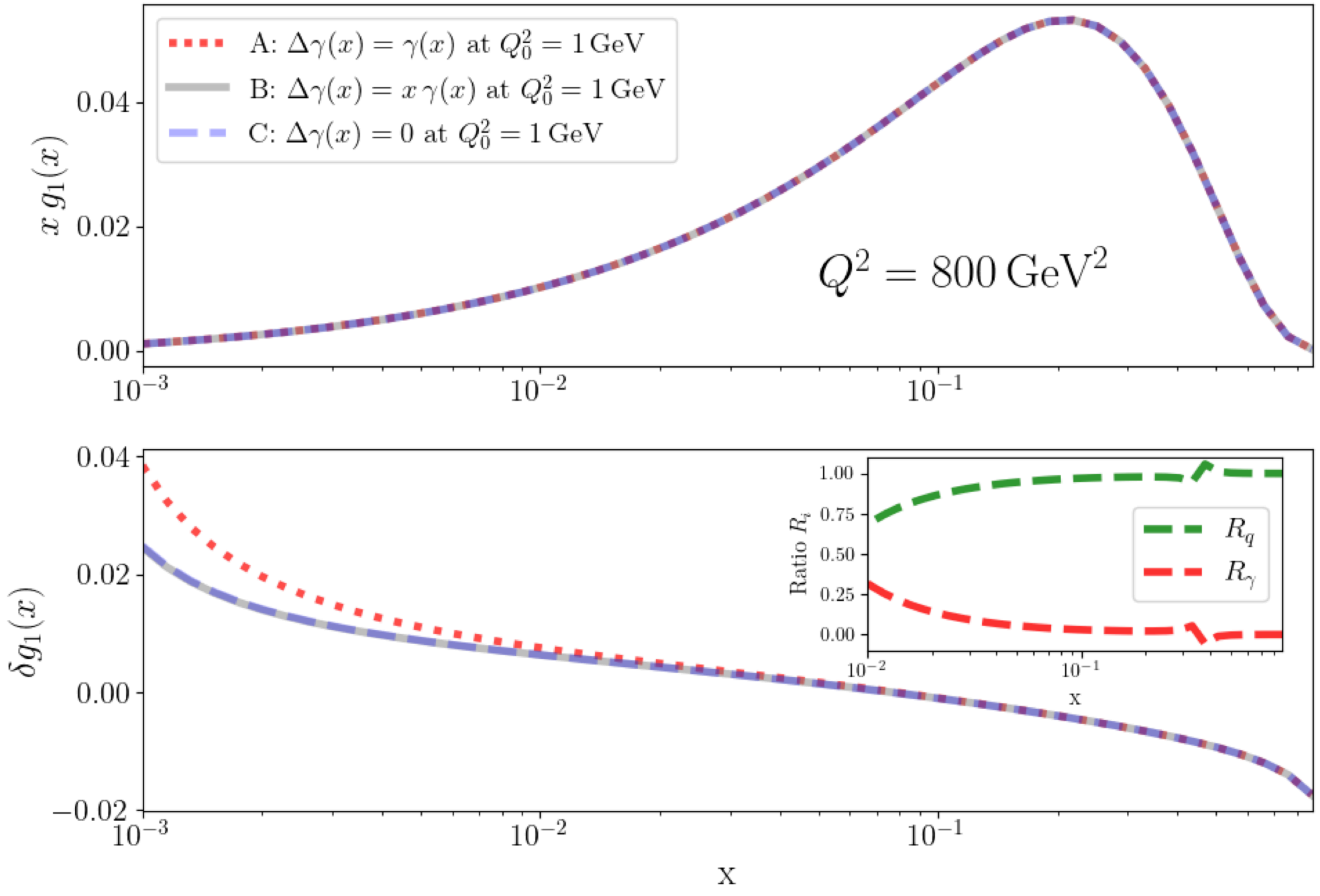
unpolarized deF. Rodrigo, Sborlini (2016)

polarized deF. , Palma (2023)

- QED corrections to $g_1(x, Q^2)$ deF. , Palma (2023)

‣ Corrections typically ~1% but can be enhanced in certain kinematical regions

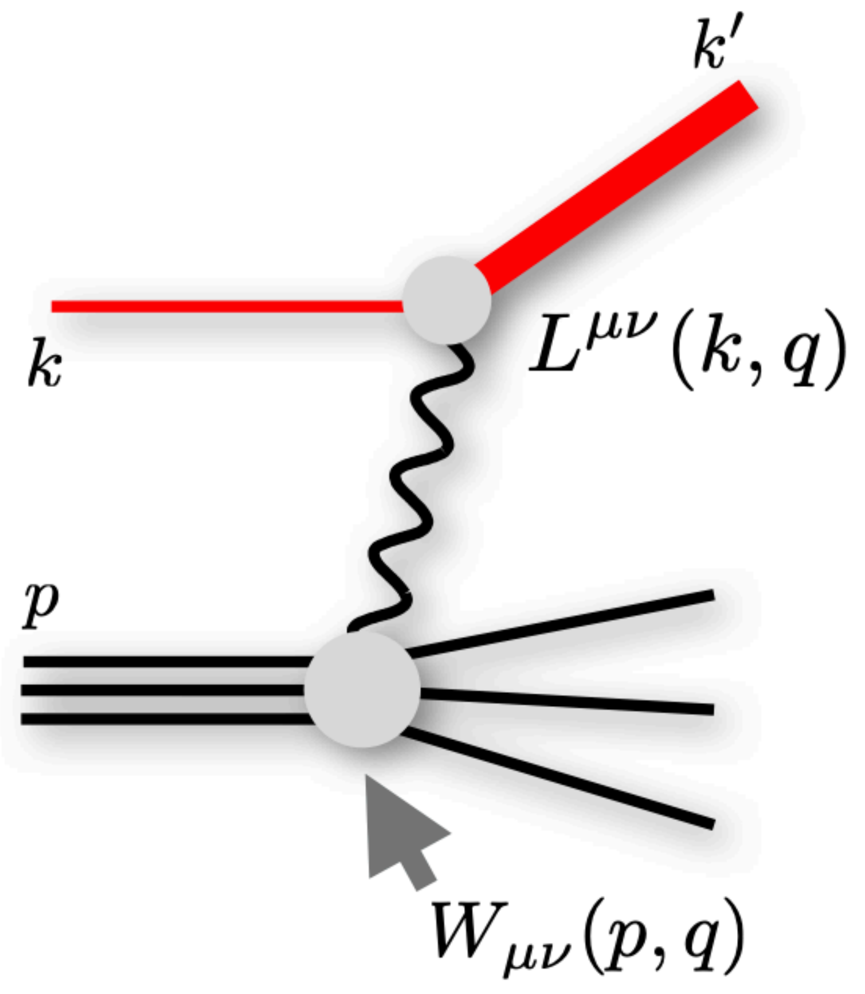
new distributions: photon and lepton in the proton



photon distribution :LUXQED

"Hypothetical DIS process" $l + p \to L + X$ calculated in two ways Manohar, Nason, Salam, Zanderighi (2016)

1. total cross section in terms of structure functions



$$\Delta\sigma_{lp}(p) = \frac{1}{2\pi\alpha\left(\mu^2\right)}\sigma_0 \int_x^1 \frac{dz}{z}\int_{Q^2_{\rm min}}^{Q^2_{\rm max}} \frac{dQ^2}{Q^2}\alpha^2_{\rm ph}\left(-Q^2\right)$$

$$\left\{ H\left(4 - 2z - \frac{4m_p^2x^2}{Q^2} - \frac{4m_p^2x^2Q^2}{M^4} - \frac{8m_p^2x^2}{M^2} - \frac{2zQ^2}{M^2}\right) x\, g_1\left(x/z, Q^2\right) \right.$$

$$\left. -H\left(\frac{8m_p^2x^2}{zM^2} + \frac{8m_p^2x^2}{zQ^2}\right) x\, g_2\left(x/z, Q^2\right) \right\}$$

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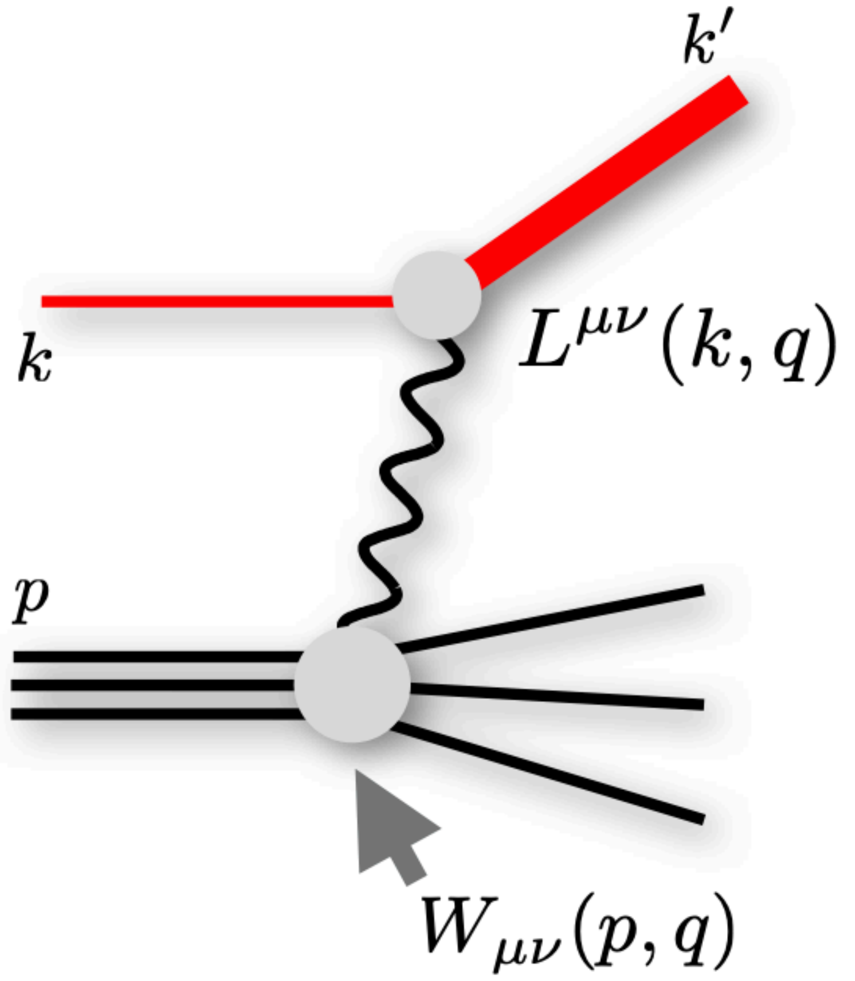

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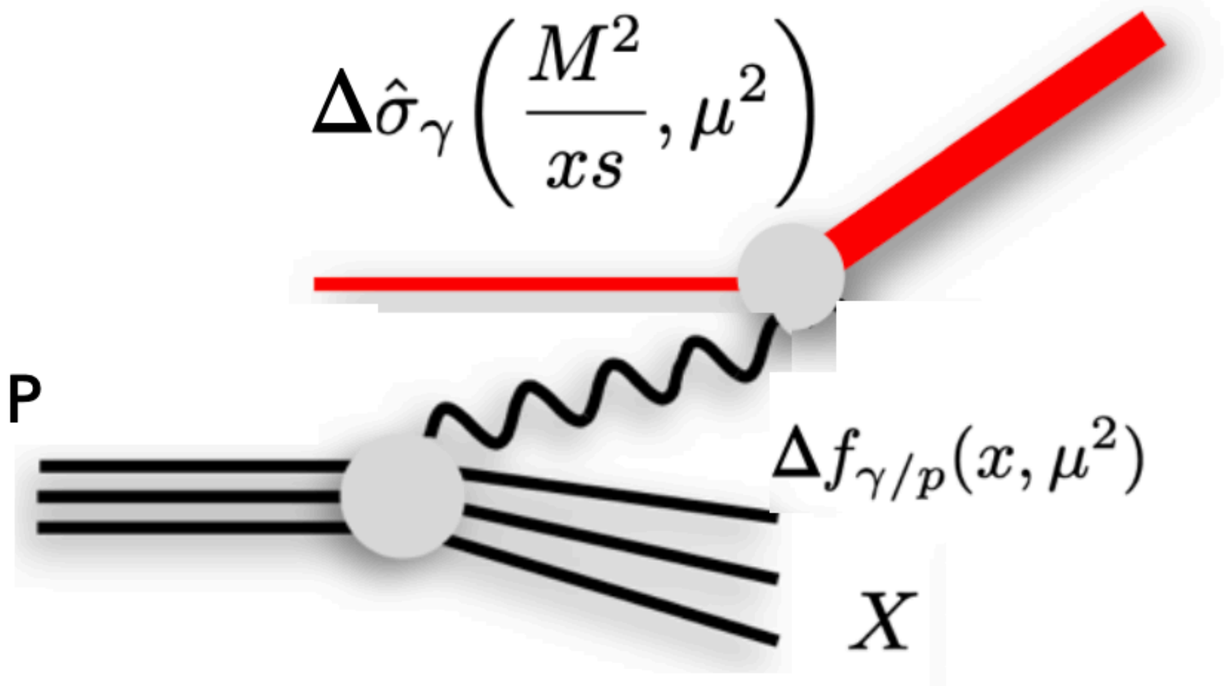
2. from collinear factorization in terms of photon distribution



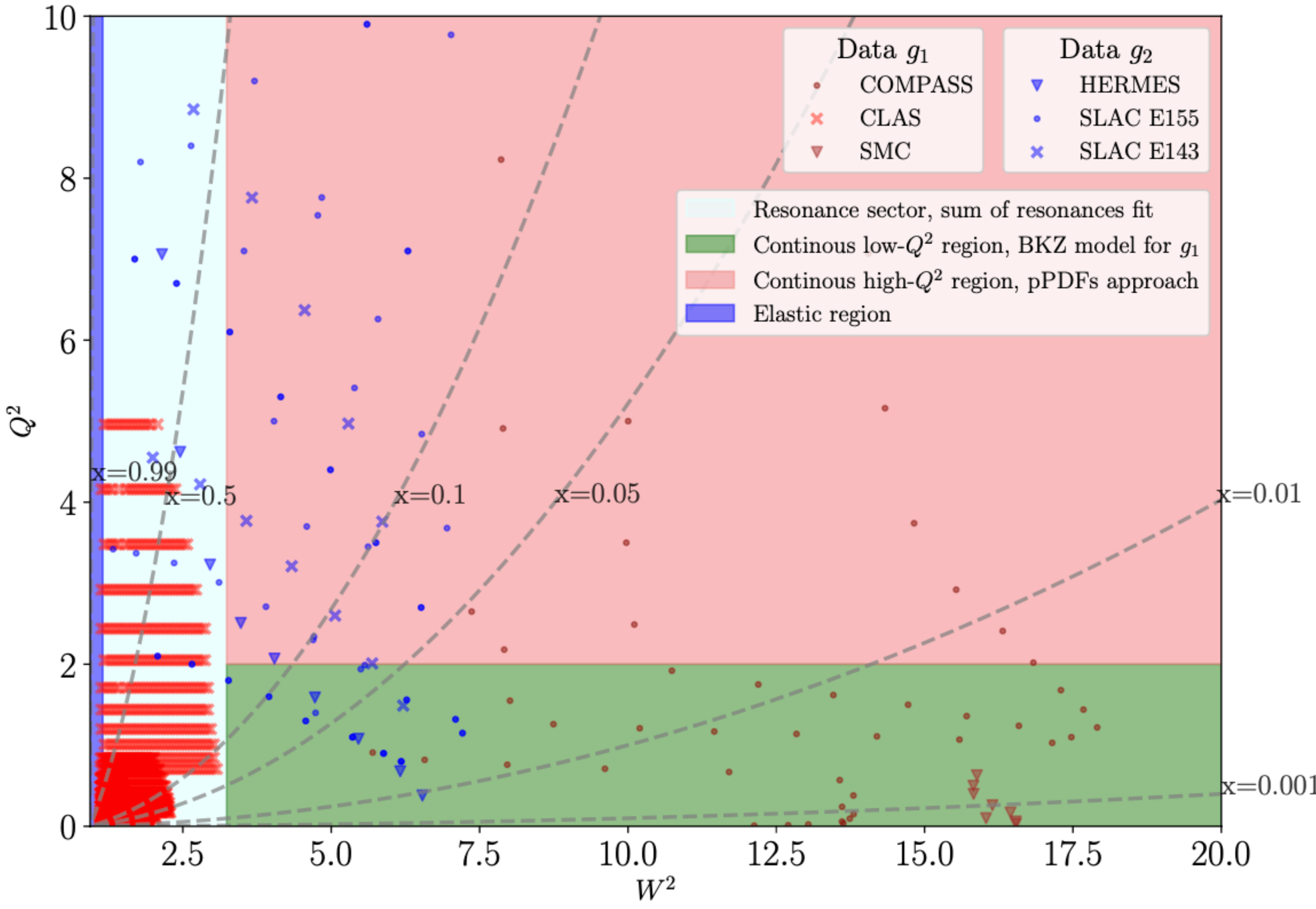
$$\Delta\sigma_{lp}(p) = \int dy\, \Delta\hat{\sigma}^{(0,0)}_{l\gamma}(yp)\ \Delta f_\gamma\left(x, \mu^2\right) + \cdot$$

equate and deduce photon distribution

Polarized photon pdf

Allows to compute the polarized photon distribution

$$\Delta f_\gamma\left(x,\mu^2\right) = \frac{1}{2\pi\alpha\left(\mu^2\right)} \int_x^1 \frac{dz}{z} \left\{ \int_{Q^2_{\rm min}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\, \alpha^2_{\rm ph}\left(Q^2\right) \left[\left(4-2z-\frac{4m_p^2x^2}{Q^2}\right) g_1\left(x/z,Q^2\right) - \left(\frac{8m_p^2x^2}{zQ^2}\right) g_2\left(x/z,Q^2\right)\right] + \alpha^2\left(\mu^2\right) 4(1-z)\, g_1\left(x/z,\mu^2\right) \right\}$$



Requires knowledge of structure functions over full kinematical regime : Elastic, Resonance, Continuum

deF. , Palma, Volonnino (2024)

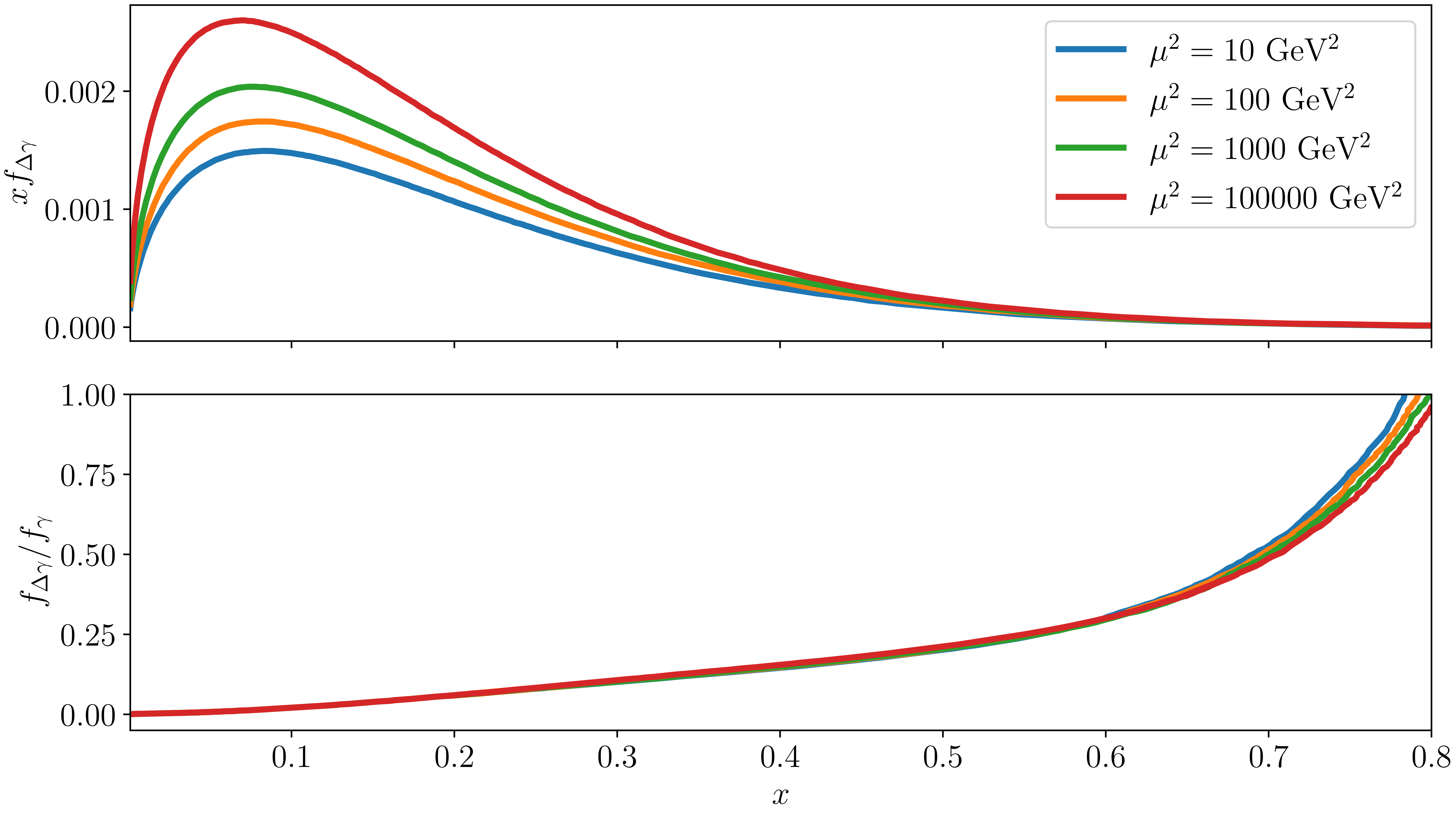
Elastic: E/M Sach Form factors

Low Q continuum: VMD model/Fits

Resonance: Fits CLAS data

High Q continuum: Perturbative QCD

several sources of uncertainties…



deF. , Palma, Volonnino (2024)

proton spin carried by photons (~1%)

shape consistent with x*f

- Uncertainties on distribution (10-20% level)

$$\int_{0.001}^{1} \Delta\gamma\, dx \simeq 0.0049 \pm 0.0008$$

Conclusions

- First 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.

- Percent level accuracy required both for EXP and TH (even QED can contribute)

- 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.


Who carries the spin of the proton?

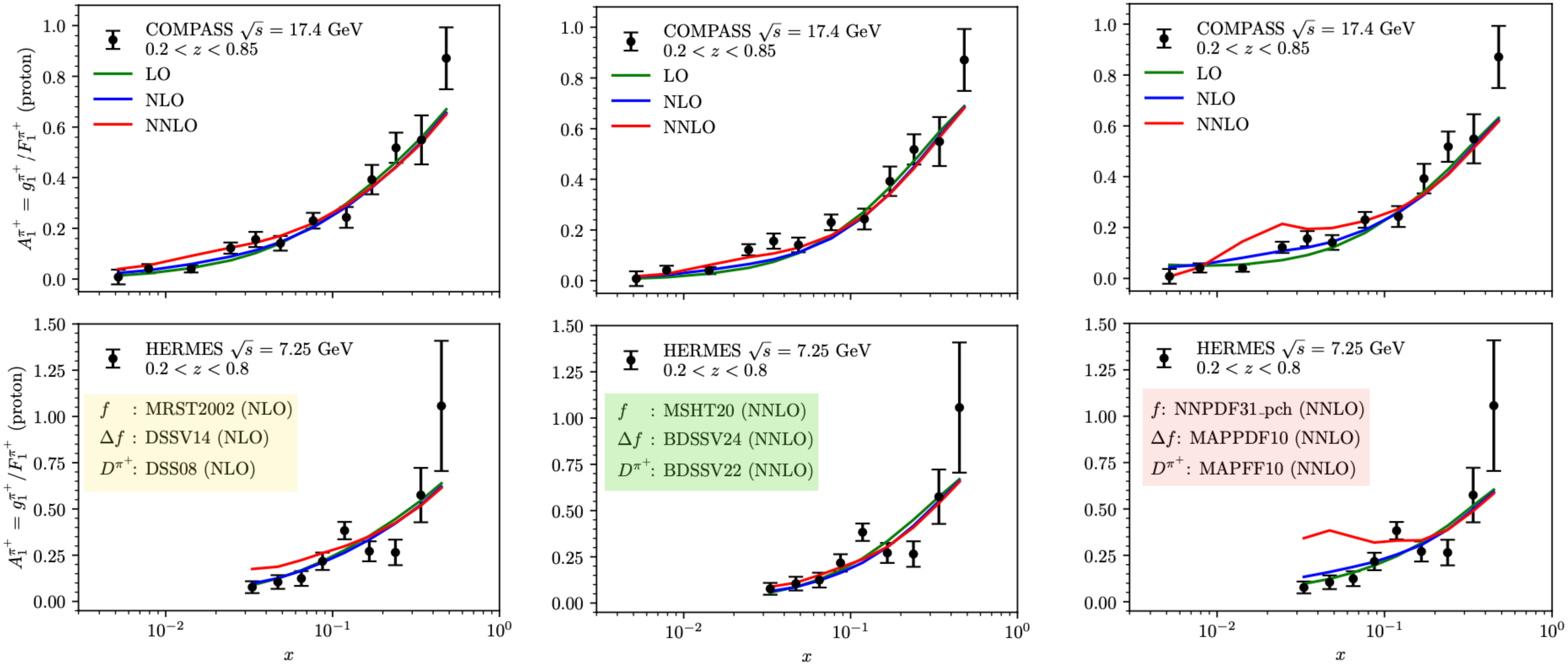

Who carries the spin of the proton?
I don’t know, ask the americans, they are building a new collider

THANKS

Backup

Post validation: # Exact NNLO SIDIS coefficients

L.Bonino, T.Gehrmann, M.Löchner, K.Schonwald (2024)



NNLO matter for SIDIS
NNLO matter for EIC

FFs matter for SIDIS
No NNLO FFS for RHIC yet

Ingredients and Results

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Total:		673	627.2	607.5			

$x_{SIDIS} > 0.12$ $p_T > 1.5$ GeV

no cuts

~ **MAP findings**
V. Bertone et al. (2024)