News on polarized PDFs

Werner Vogelsang
Univ. of Tübingen

EINN 2023, 10/31/2023

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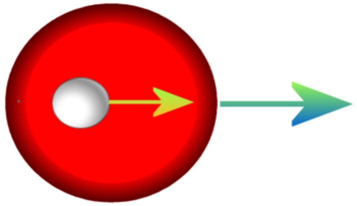
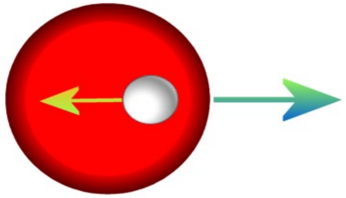
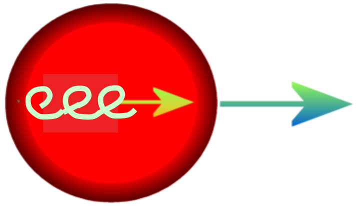
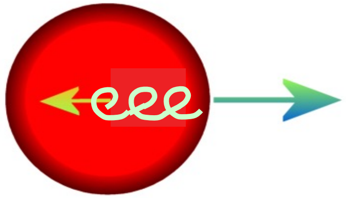
* thanks to my collaborators

I. Borsa, D. de Florian, R. Sassot, M. Stratmann

$\Delta q(x) =$  $-$ 

$\Delta g(x) =$  $-$ 

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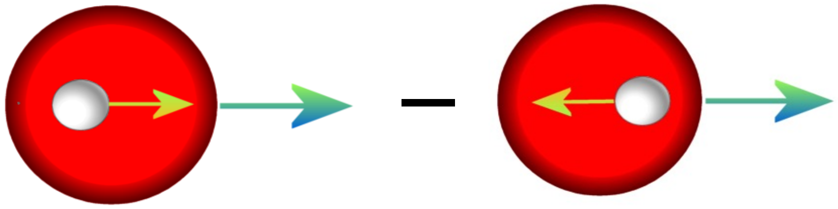

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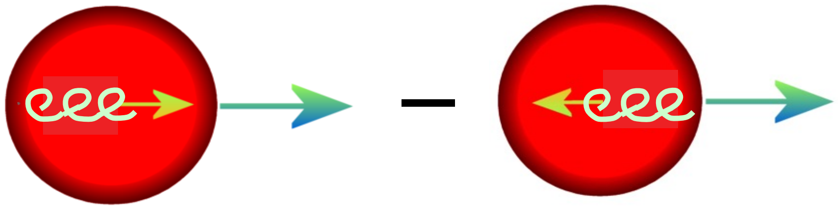
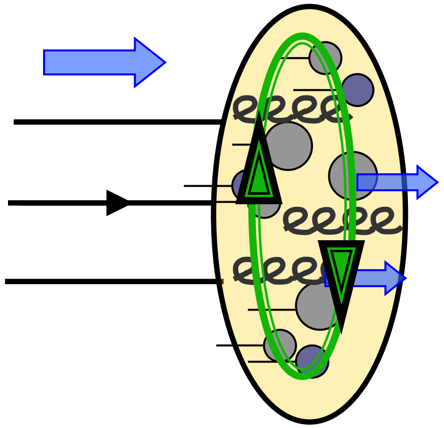


- in QCD: dependence on “resolution” scale μ

proton spin:

Jaffe, Manohar; Chen et al; Wakamatsu; Hatta; …



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

$$\Delta\Sigma = \int_0^1 dx\, [\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}](x)$$

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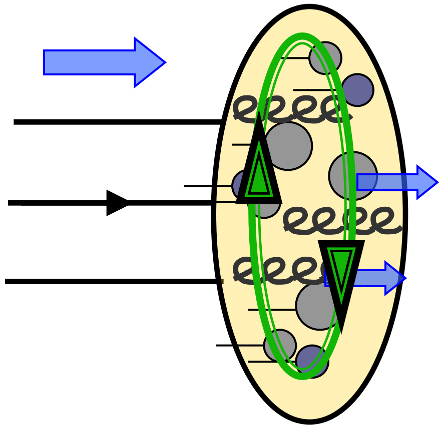

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$$\Delta G = \int_0^1 dx\,\Delta g(x)$$

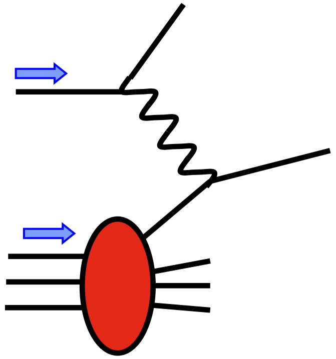
Outline:

- Global analysis of helicity PDFs: status
- Theory advances
- Conclusions

Global analysis: status

Helicity PDFs accessible in polarized high-energy scattering:

EMC, SMC,
COMPASS,
E142, E143, E154,
E155, HERMES,
CLAS, HALL-A



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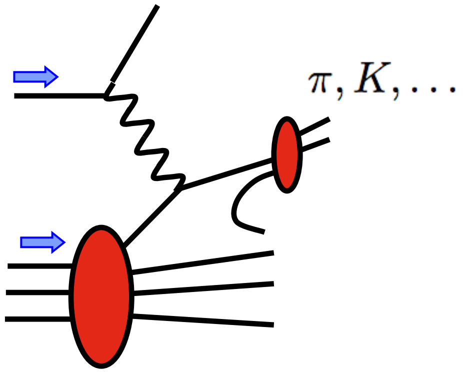

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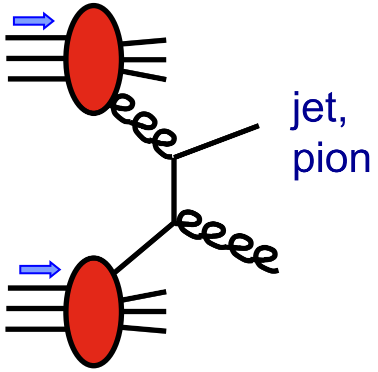
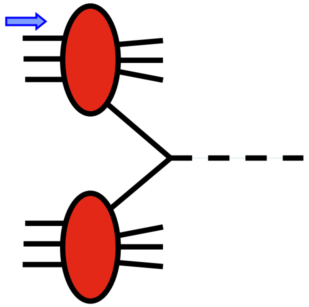


high-p_T



W bosons

RHIC:
PHENIX,
STAR

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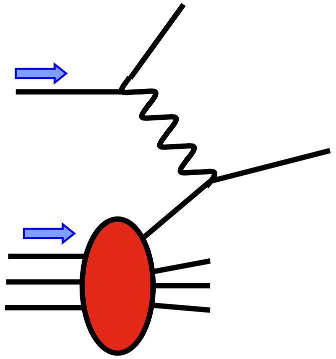

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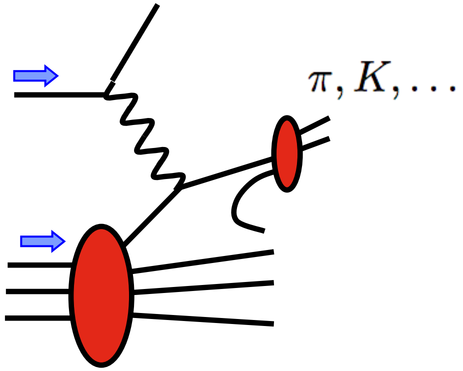

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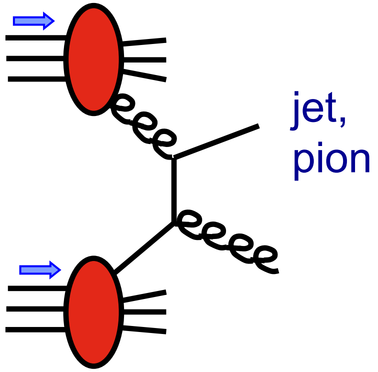

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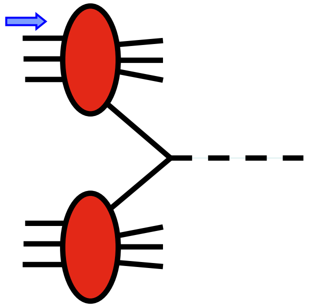

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e.g.

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

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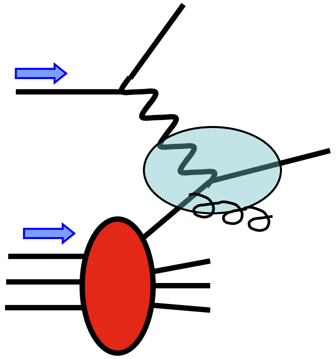

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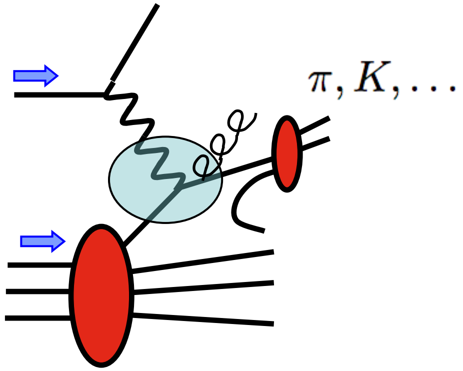

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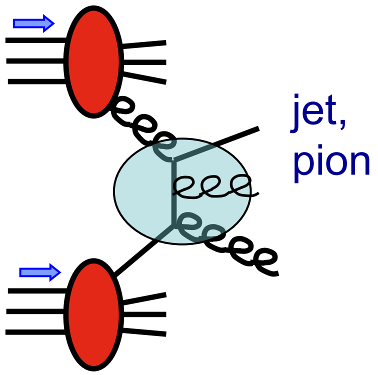

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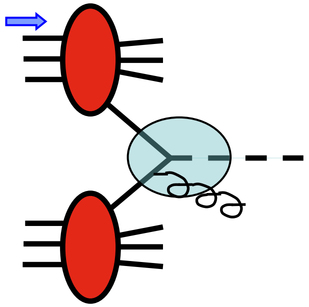

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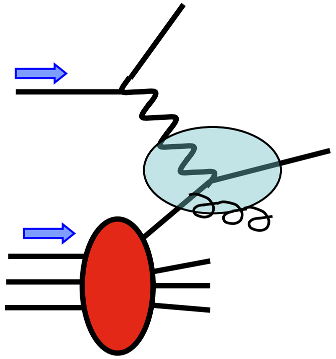

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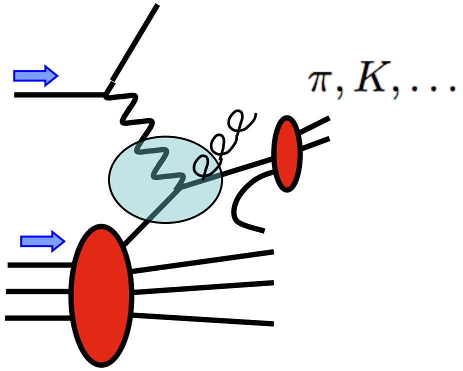

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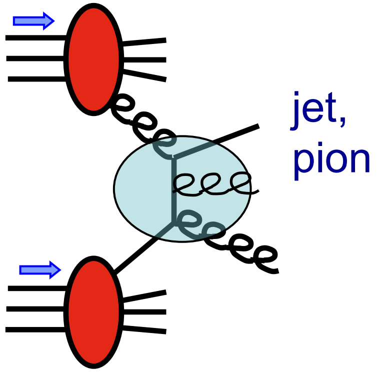

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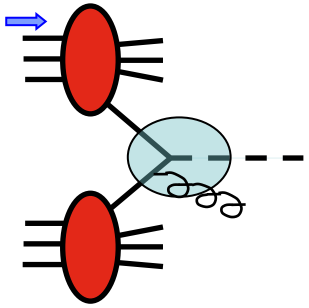

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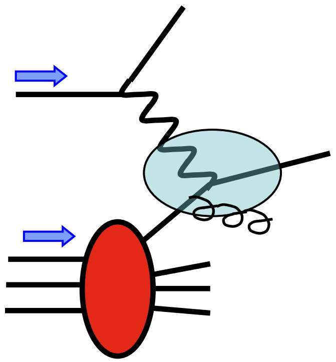

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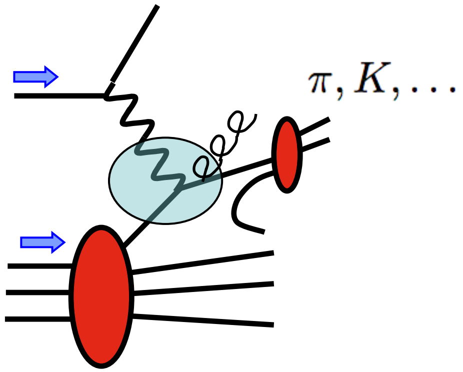

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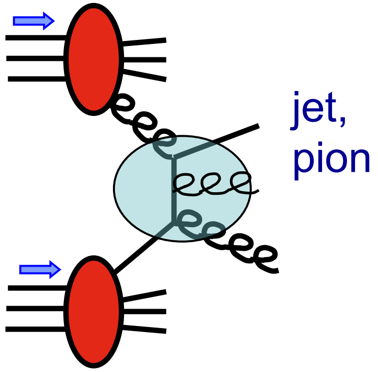

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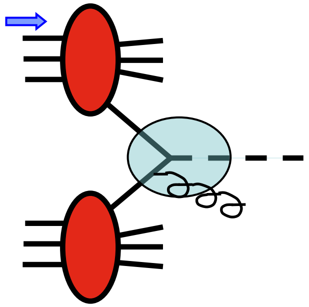

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Key players over recent years (all at NLO ($\overline{\mathrm{MS}}$)):

DSSV (2008 –)

de Florian, Sassot,
Stratmann, WV

NNPDF (2013 –)

Nocera, Ball, Forte,
Ridolfi, Rojo, …

JAM (2013 –)

Sato, Cocuzza, Ethier,
Melnitchouk, …

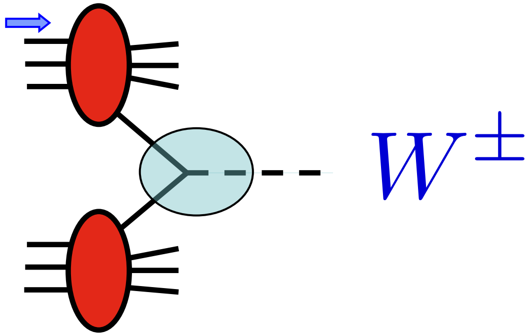
- differences in methodology:

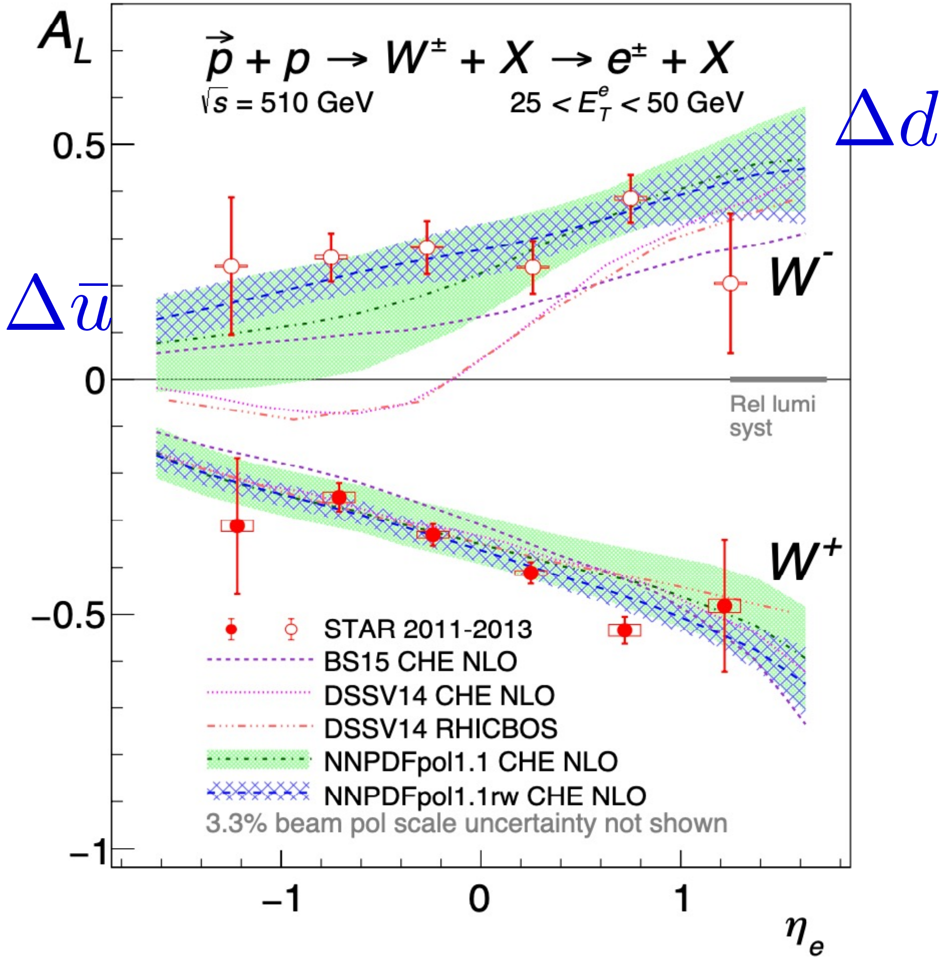
  DSSV and JAM: Mellin moment techniques

  NNPDF: neural-network technique, x-space

- mature analysis frameworks with robust assessment of uncertainties

Light sea quarks:





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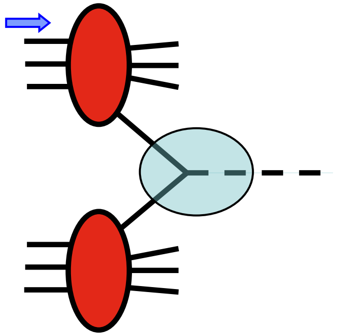
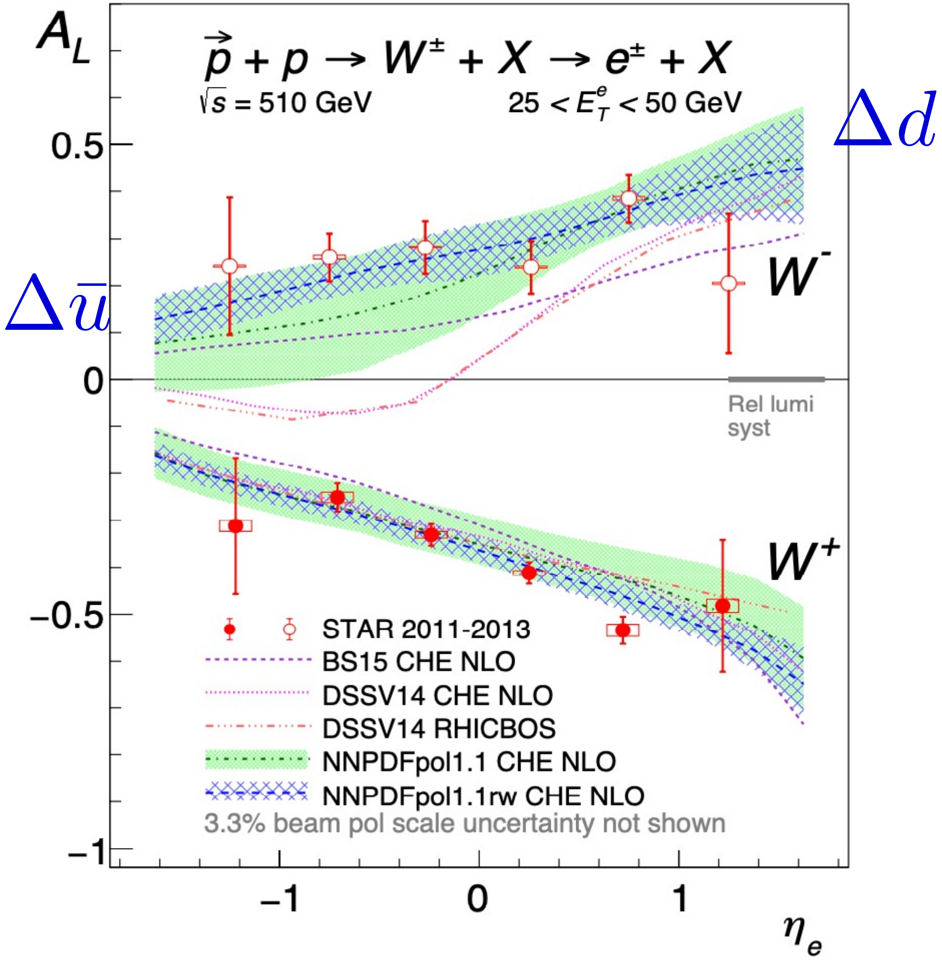
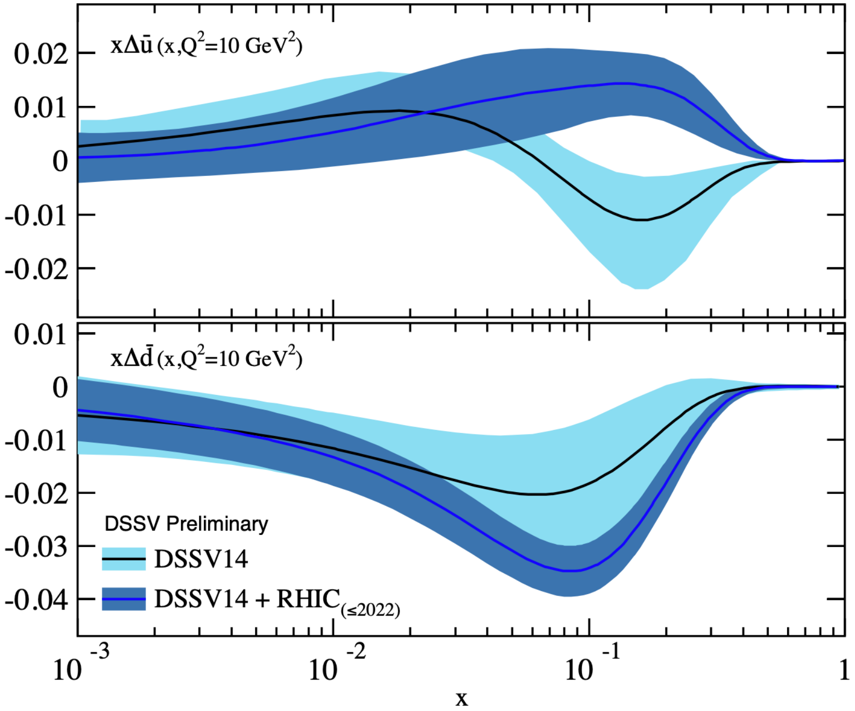


(from 2302.00605)





(consistent w/ SIDIS)

also NNPDF, JAM
(Cocuzza, Melnitchouk, Metz, Sato)

Gluon polarization: 2014 RHIC-discovery that $\Delta g > 0$

→ improvement and consolidation !

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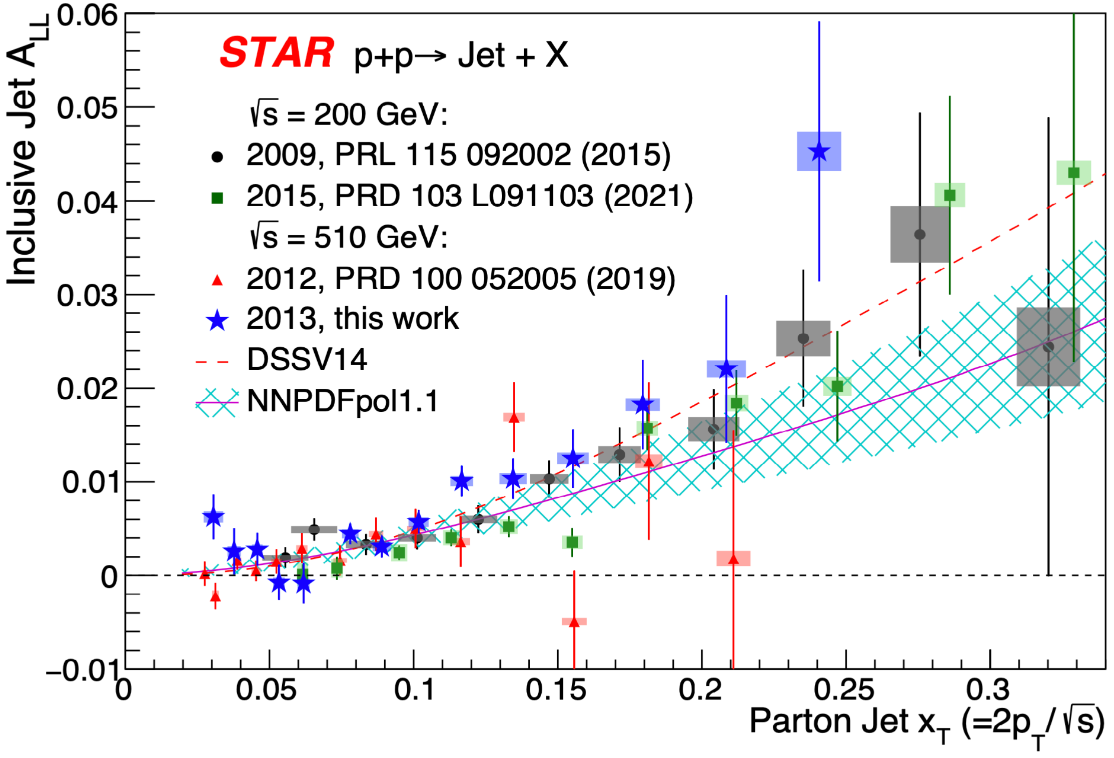

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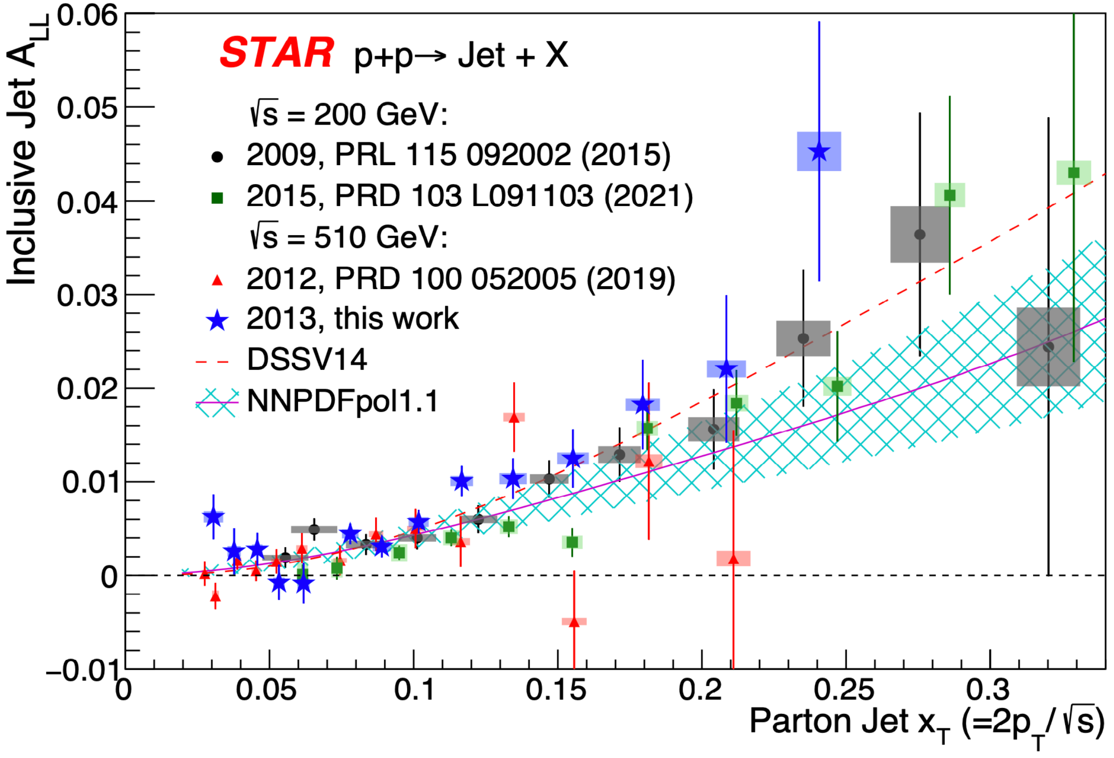

+ Phenix $\pi^{0,\pm}$

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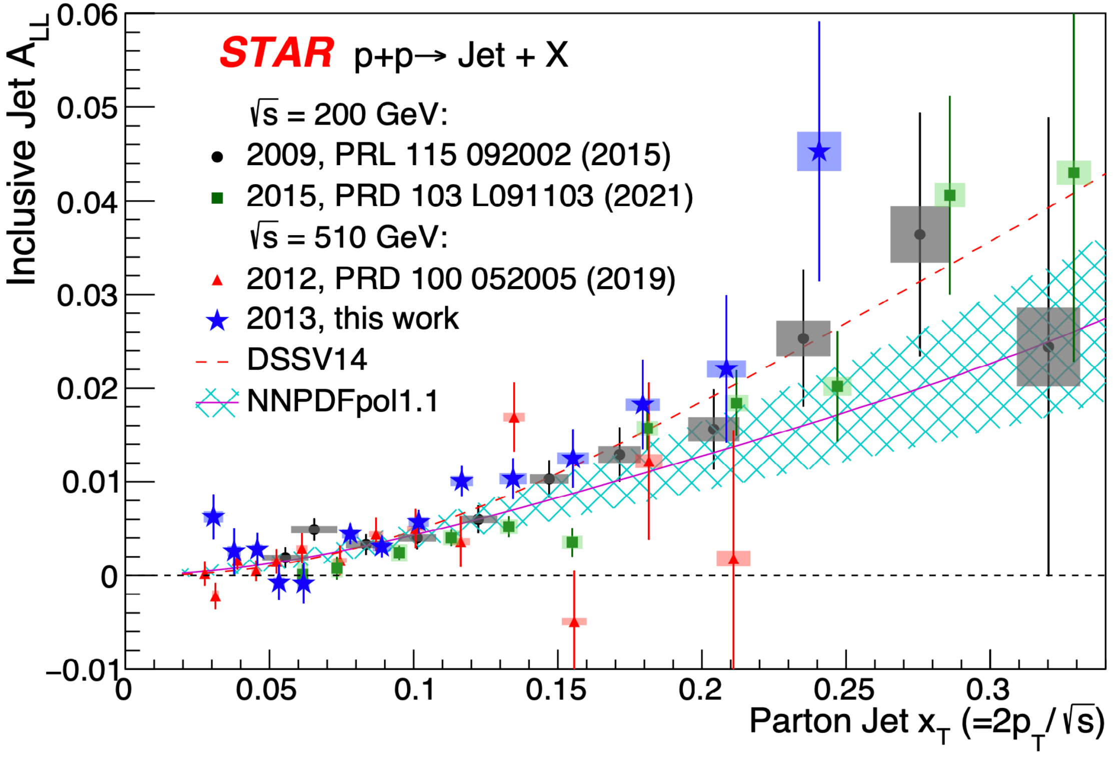

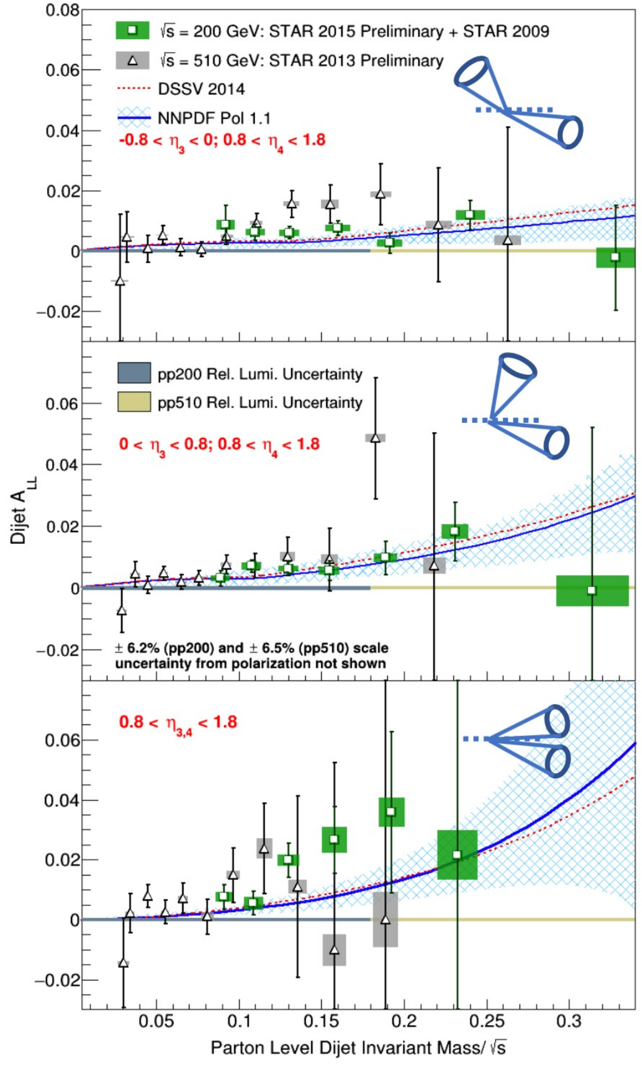

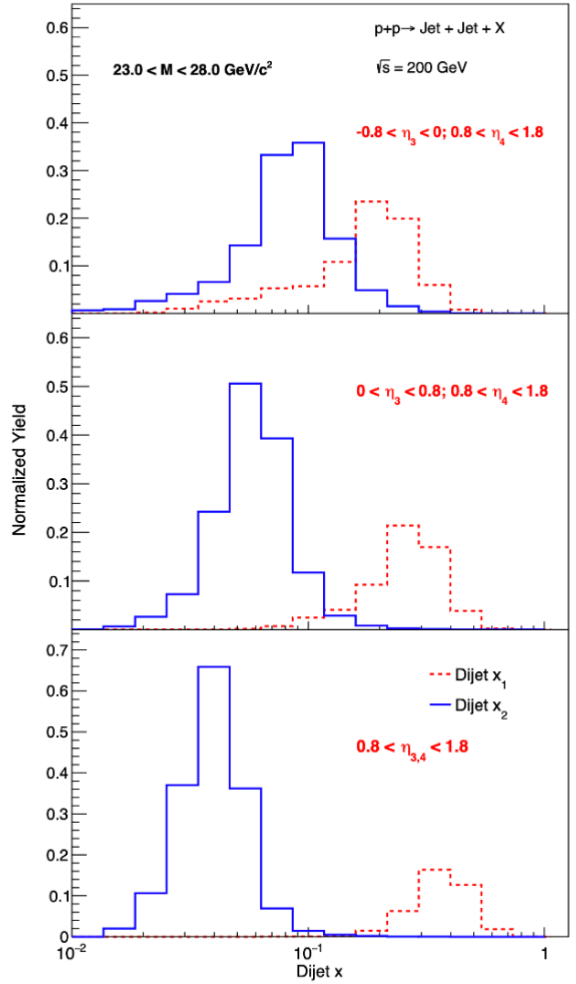

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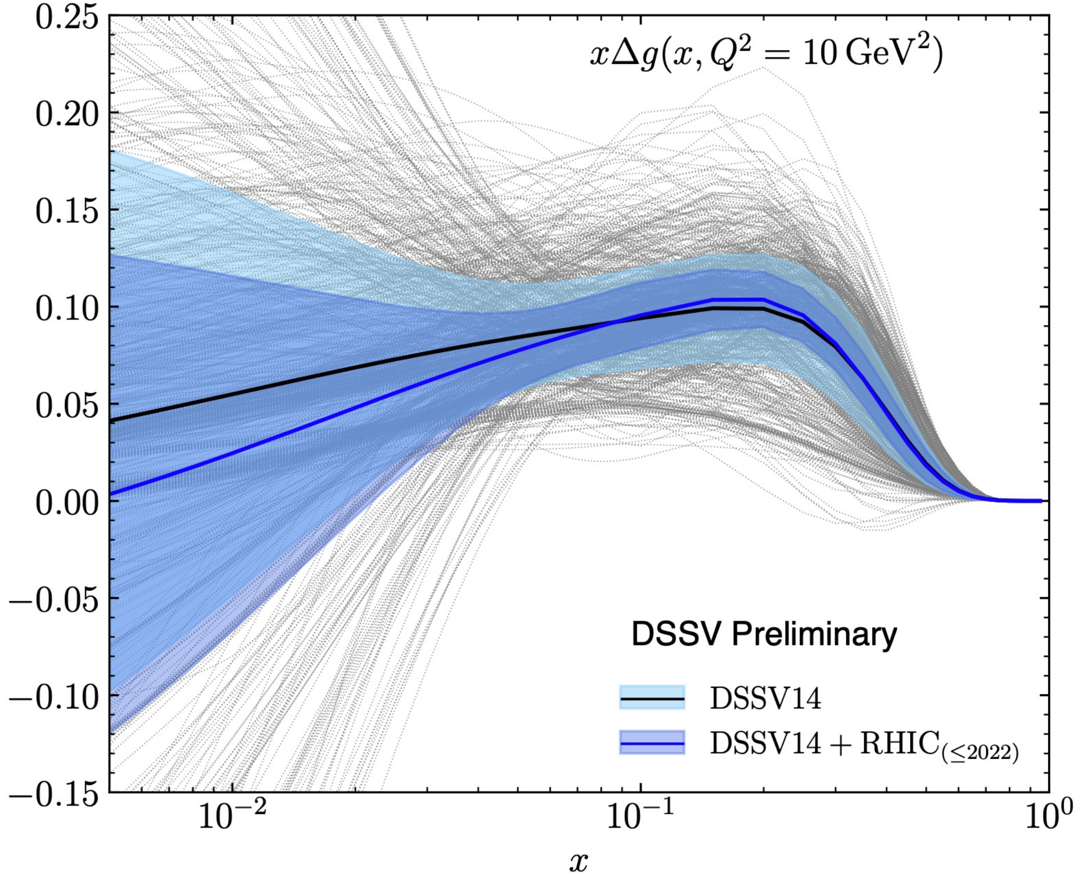

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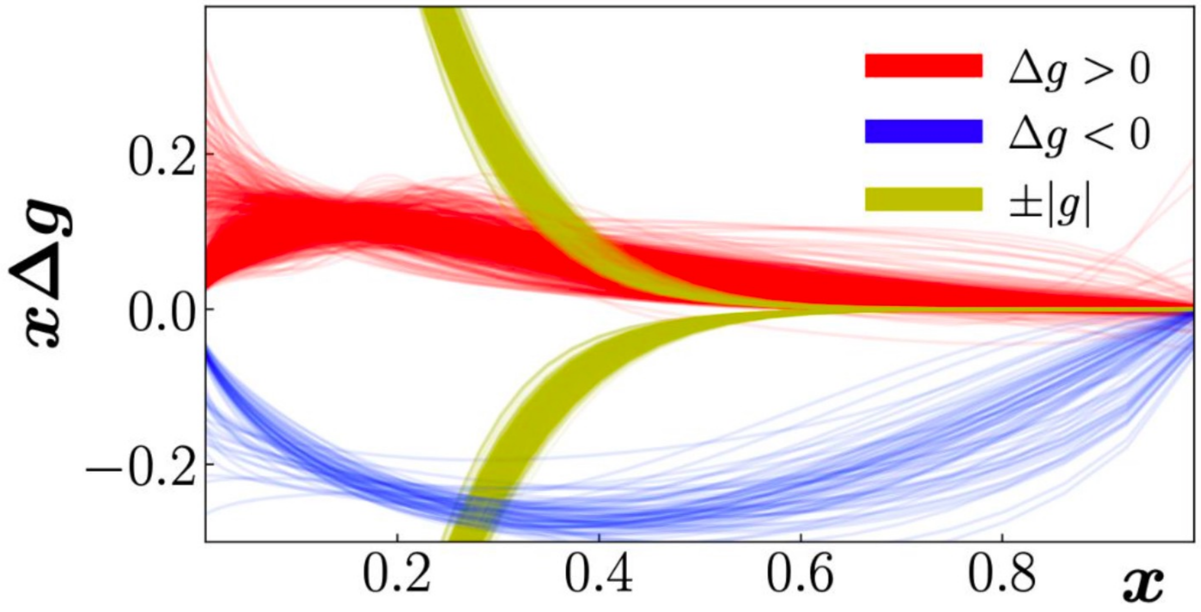
JAM 2022



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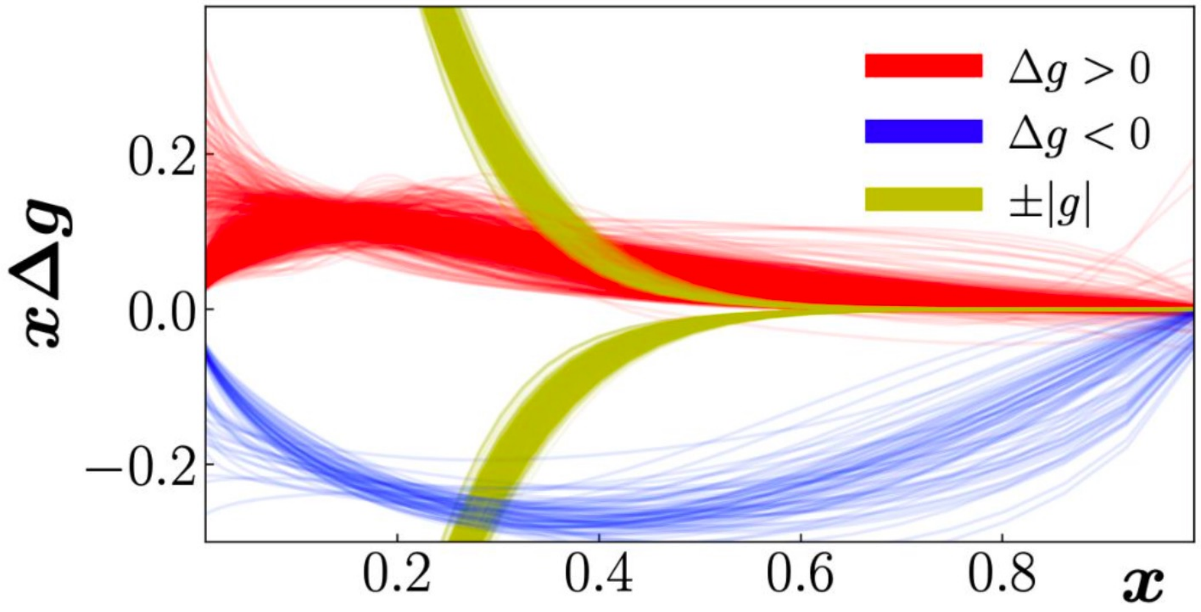
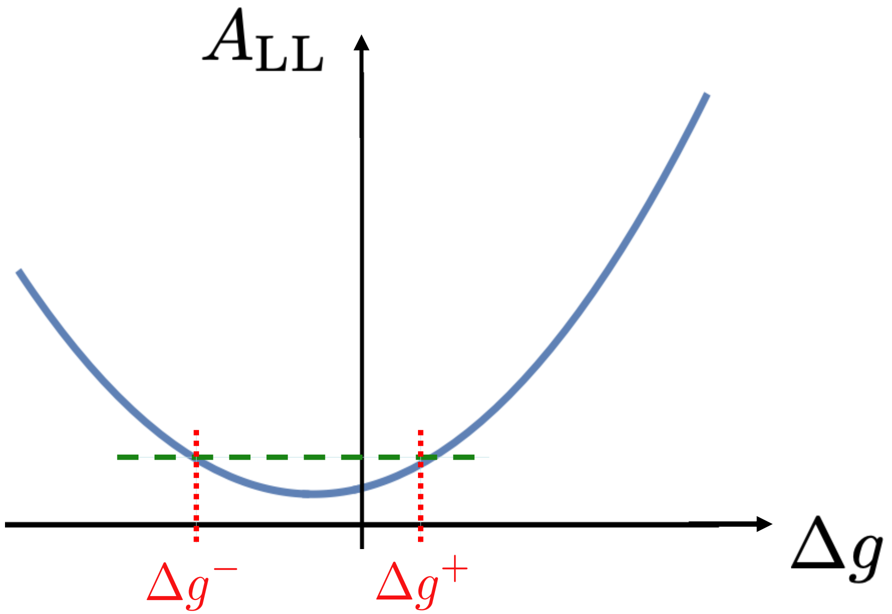


$$\text{“}\, A_{\rm LL} = a_{gg}\,(\Delta g)^2 + a_{qg}\,\Delta g + a_{qq}\,\text{“}$$

Jäger, Kretzer, Stratmann, WV 2004



JAM 2022

“ $A_{\mathrm{LL}} = a_{gg}\,(\Delta g)^2 + a_{qg}\,\Delta g + a_{qq}$ “

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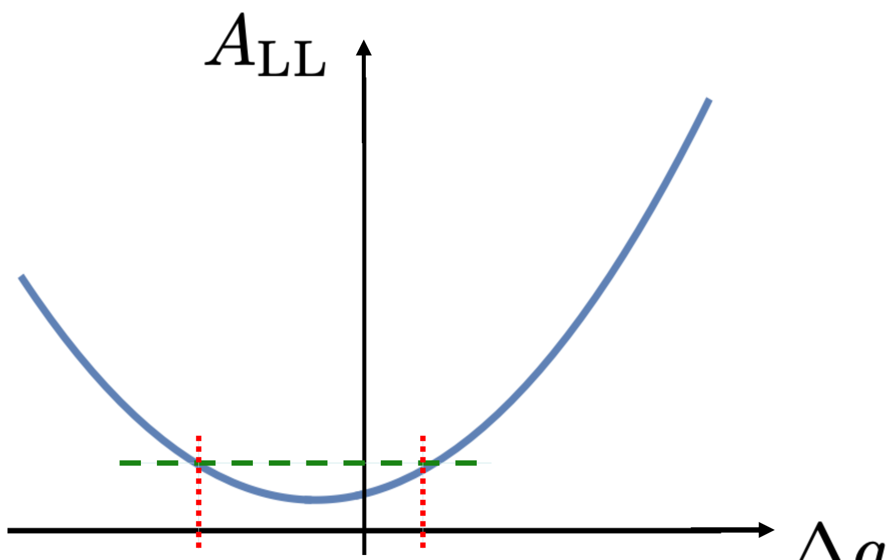
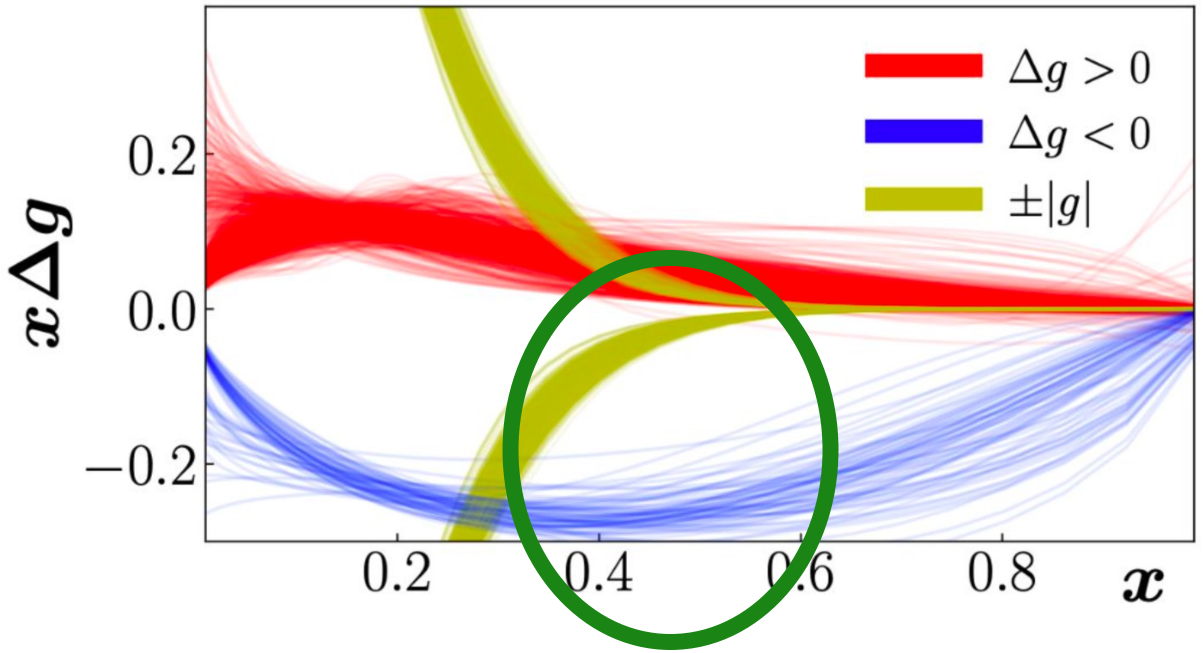




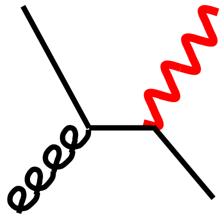
$$|\Delta g| > g \quad !?$$

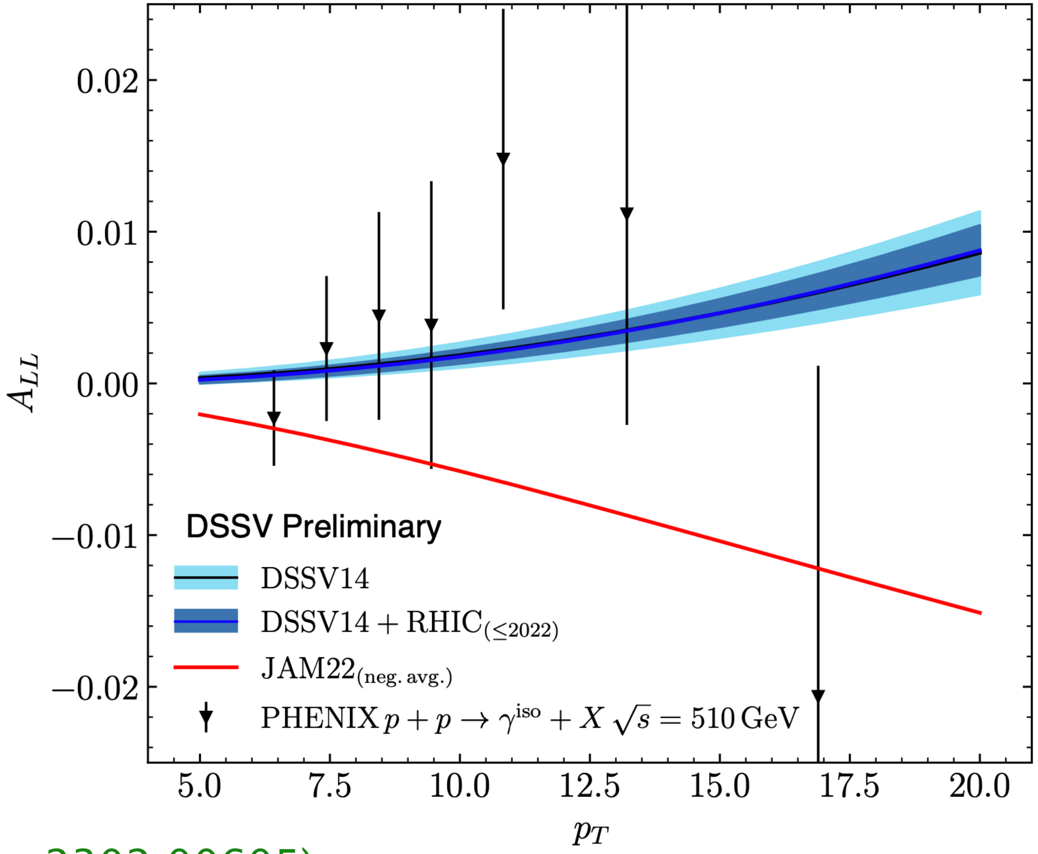
$$\Delta g = g^+ - g^-$$

$$g = g^+ + g^-$$

In any case, not favored by data:

Phenix direct photons:





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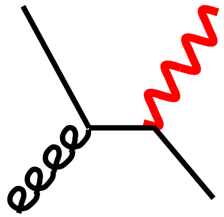

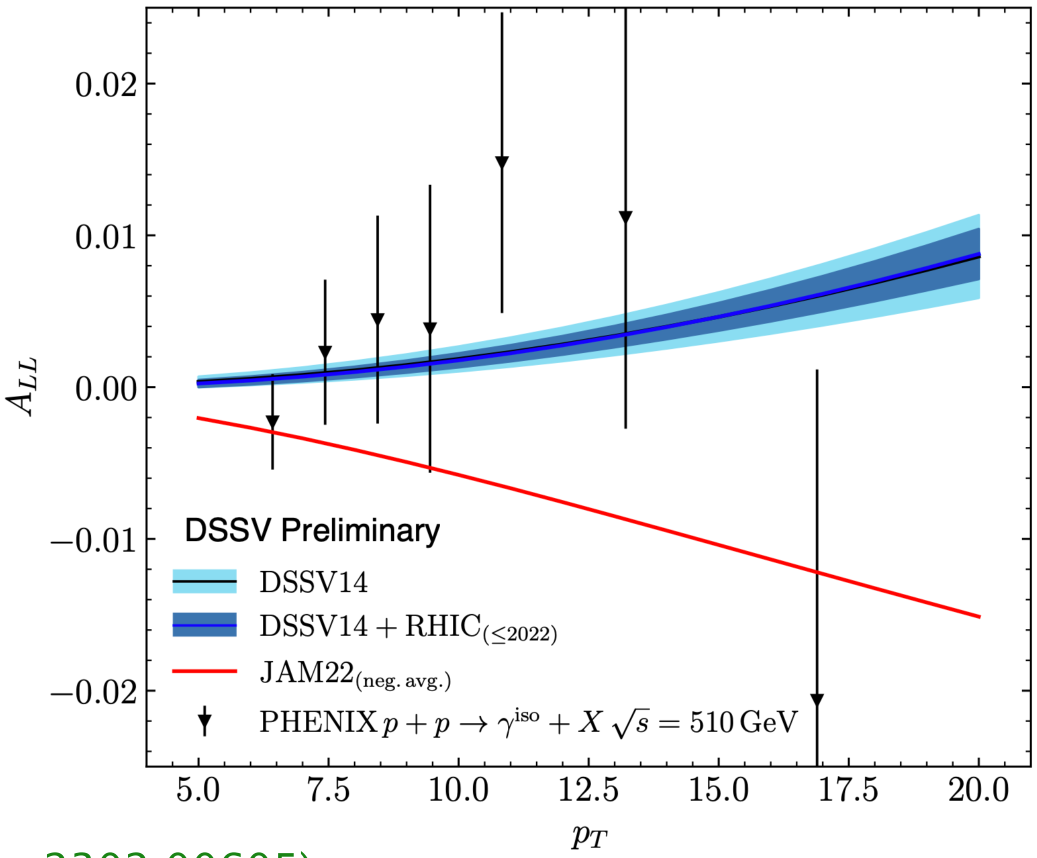

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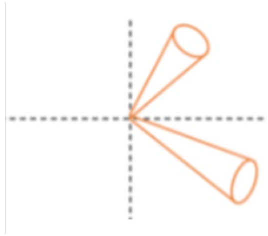
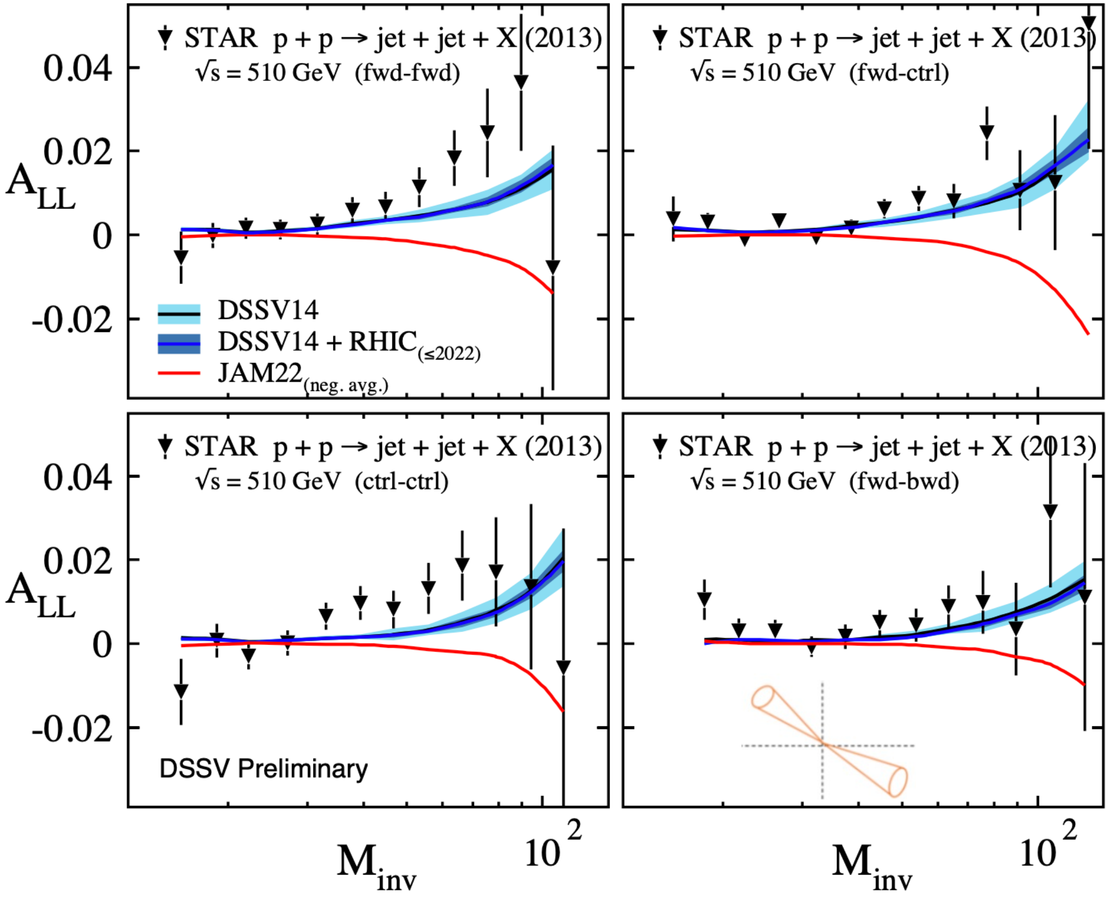


STAR dijets



First ever NLO "global" analysis of nucleon helicity (GRSV, 1996)

PHYSICAL REVIEW D VOLUME 53, NUMBER 9 1 MAY 1996

Next-to-leading-order radiative parton model analysis of polarized deep inelastic lepton-nucleon scattering

M. Glück, E. Reya, and M. Stratmann
Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany

W. Vogelsang
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, England

(Received 28 August 1995; revised manuscript received 10 January 1996)

A next-to-leading-order QCD analysis of spin asymmetries and structure functions in polarized deep inelastic lepton-nucleon scattering is presented within the framework of the radiative parton model. A consistent NLO formulation of the Q^2 evolution of polarized parton distributions yields two sets of plausible NLO spin-dependent parton distributions in the conventional $\overline{\mathrm{MS}}$ factorization scheme. They respect the fundamental positivity constraints down to the low resolution scale $Q^2=\mu^2_{\mathrm{NLO}}=0.34$ GeV^2. The Q^2 dependence of the spin asymmetries $A_1^{p,n,d}(x,Q^2)$ is similar to the leading-order (LO) one in the range $1\leqslant Q^2\leqslant 20$ GeV^2 and is

Nucleon helicity structure at NNLO

NEW

Borsa, de Florian, Sassot,Stratmann, WV

BDSSV

Why NNLO ?

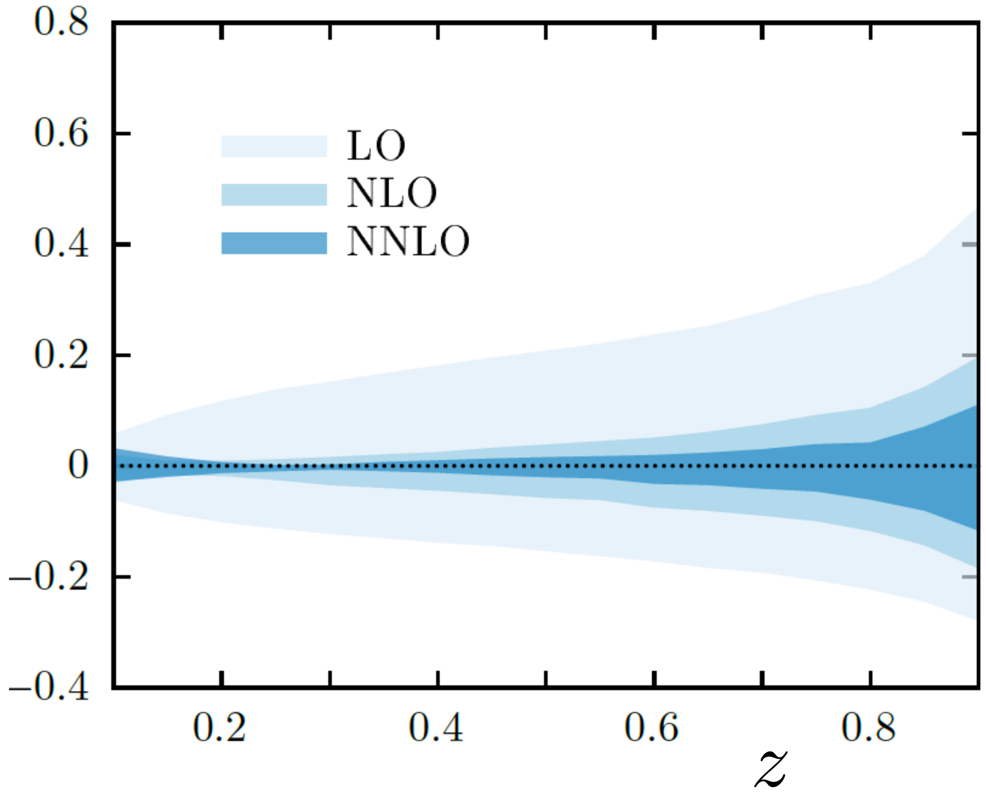
- need per cent accuracy for EIC and JLab (cf. LHC experience)

Why NNLO ?

- need per cent accuracy for EIC and JLab (cf. LHC experience)
- reduce theory uncertainty

$$\frac{\sigma(\mu) - \sigma(Q)}{\sigma(Q)}$$

$$Q/2 \leq \mu_{R,F} \leq 2Q$$



$$Q^2 > 5\,\mathrm{GeV}^2$$

SIDIS@EIC

Abele, De Florian, WV

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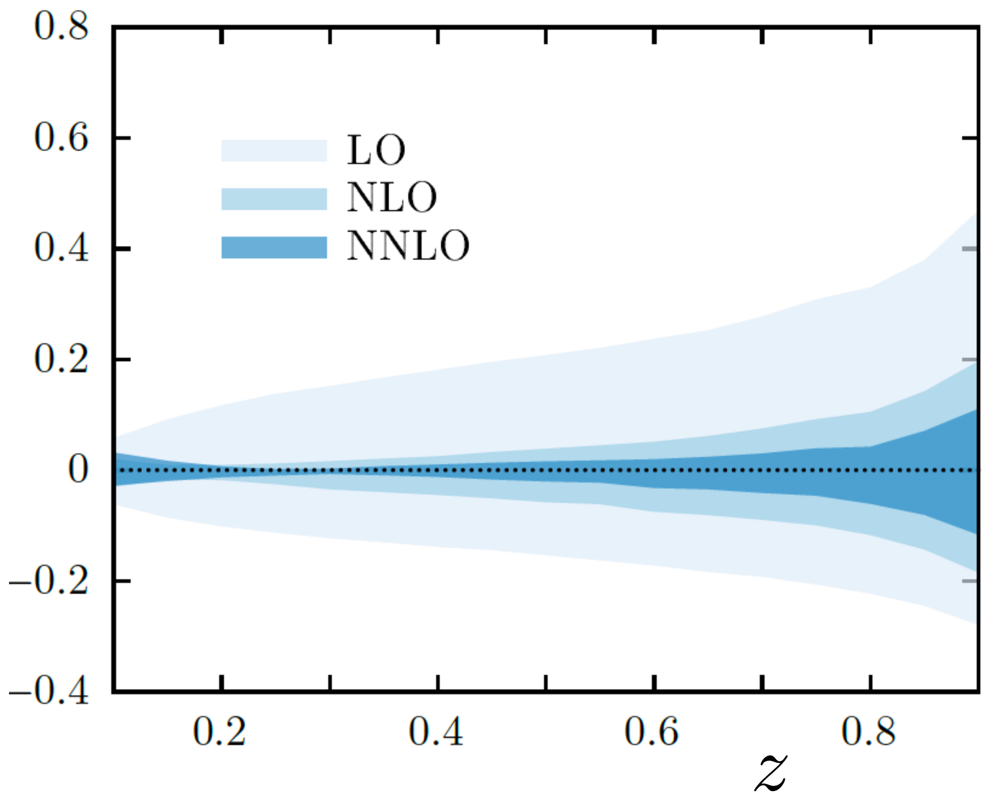

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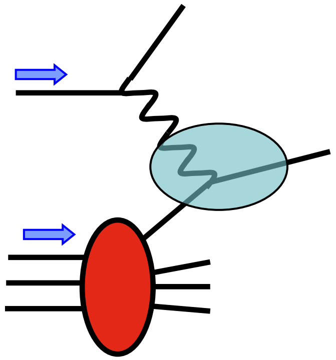
SIDIS@EIC

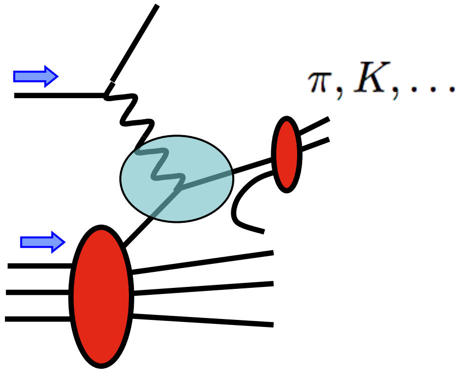
Abele, De Florian, WV

- progress in lattice computations

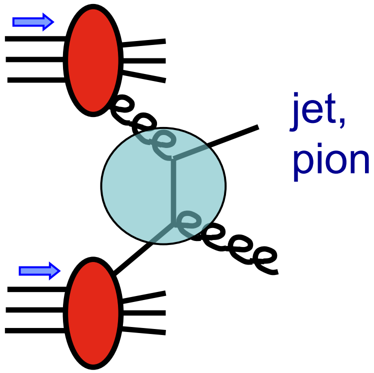
How to get to NNLO ?



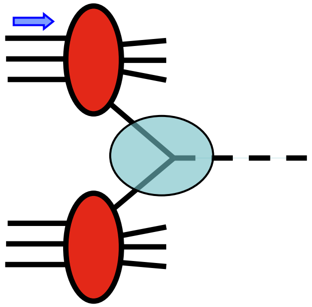
DIS



SIDIS

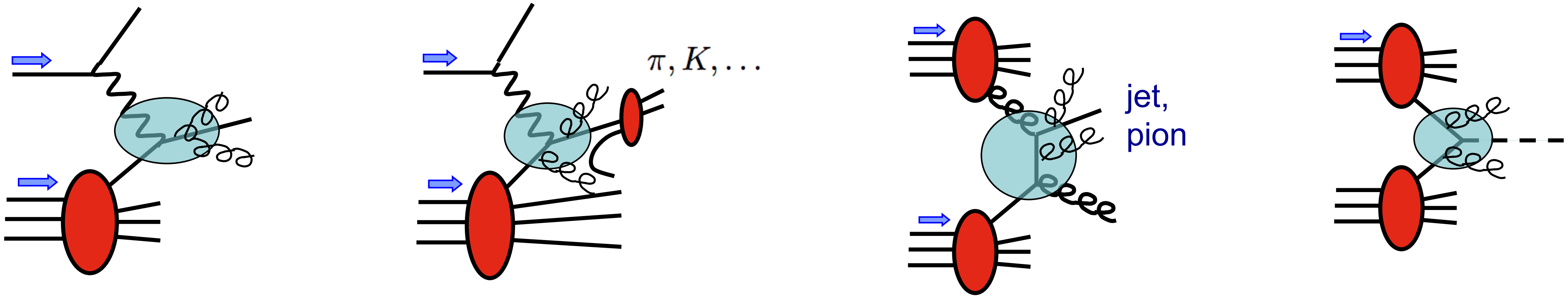


pp high-p_T



W bosons

How to get to NNLO ?



DIS SIDIS pp high-p_T W bosons

Ingredients for NNLO:

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

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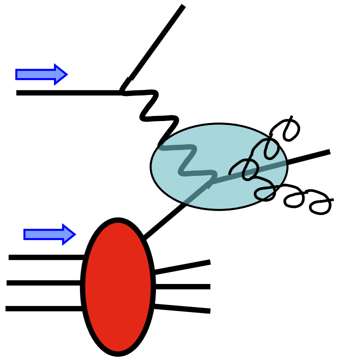
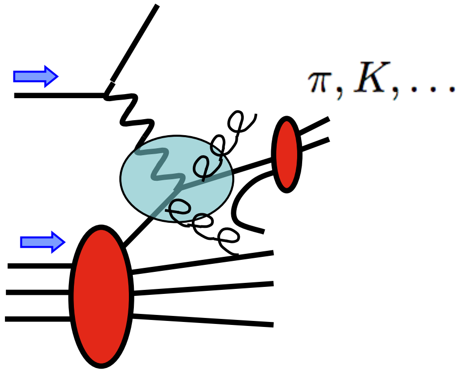


DIS



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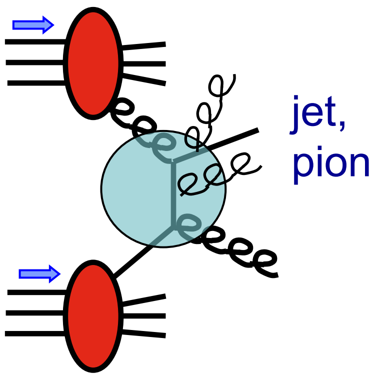

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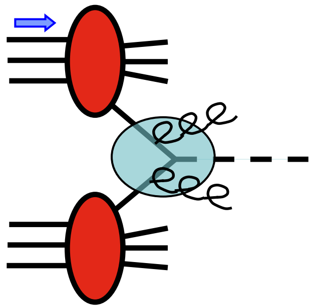

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- PDF evolution: $\Delta\mathcal{P}_{ij} = \frac{\alpha_s}{2\pi}\Delta P_{ij}^{\mathrm{LO}} + \left(\frac{\alpha_s}{2\pi}\right)^2\Delta P_{ij}^{\mathrm{NLO}} + \left(\frac{\alpha_s}{2\pi}\right)^3\Delta P_{ij}^{\mathrm{NNLO}} + \ldots$

NNLO PDF evolution known:

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

Moch, Vogt, Vermaseren 2008, 2014, 2015
Blümlein, Marquard, Schneider, Schönwald 2022

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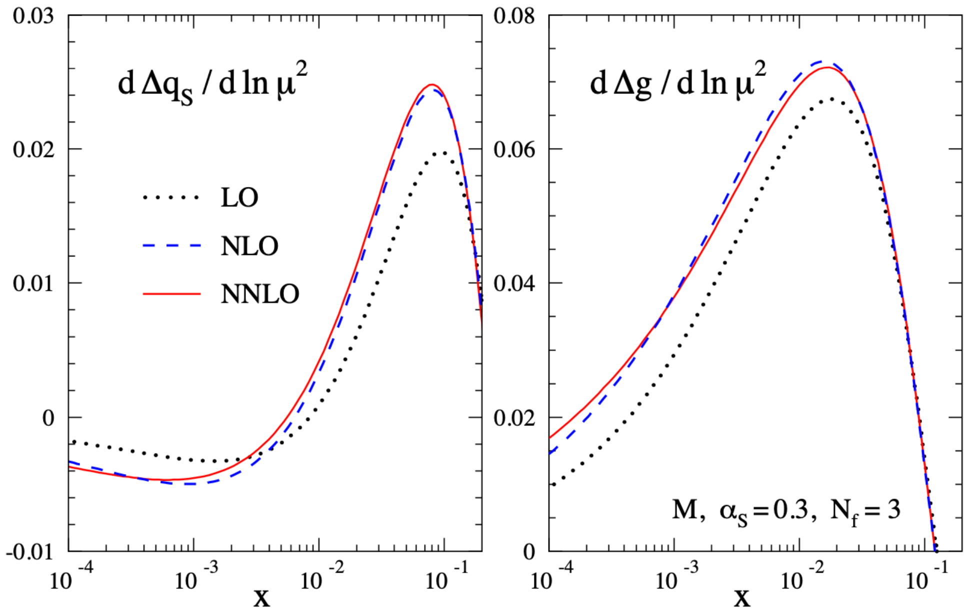

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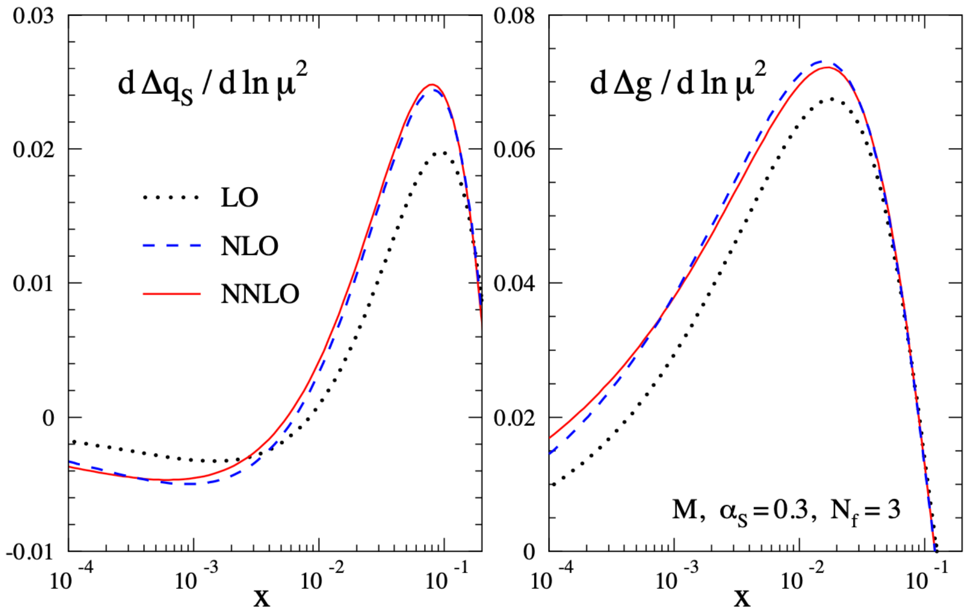
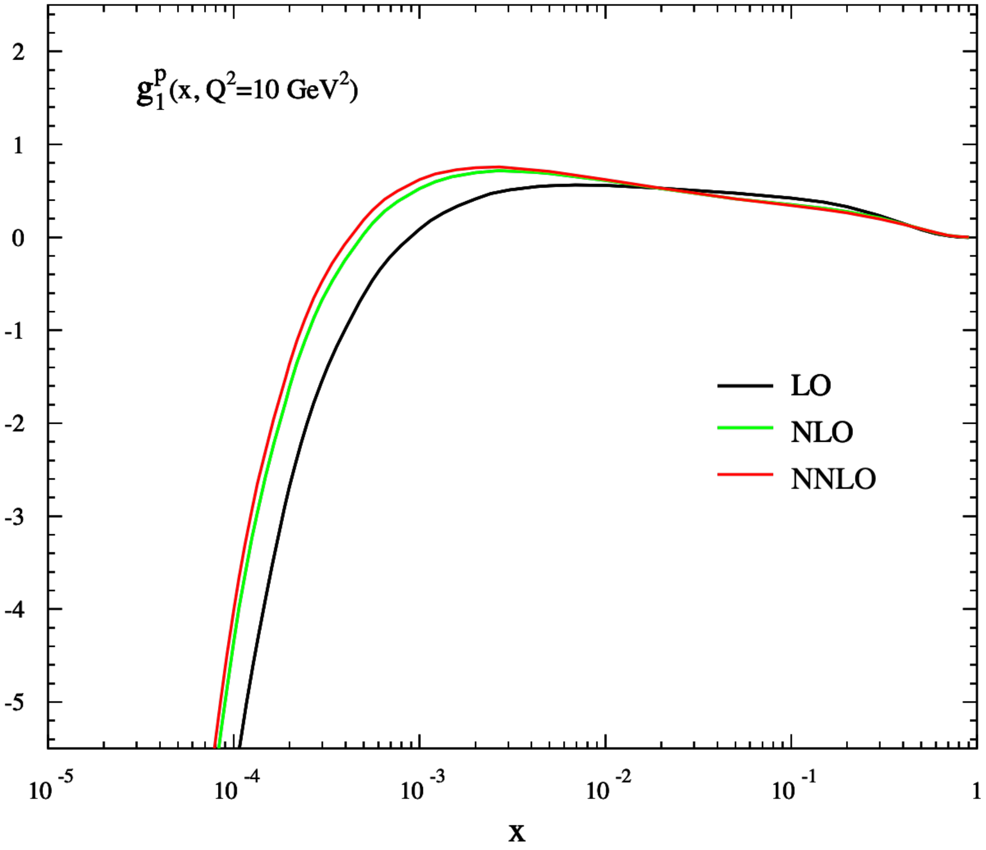


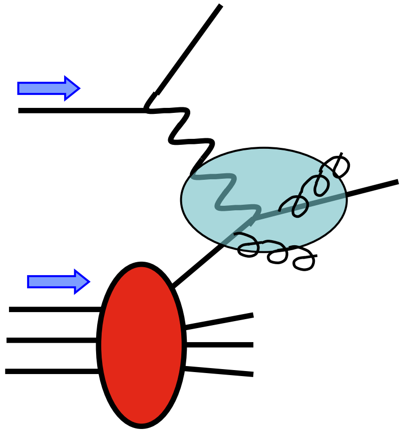
implemented in QCD–PEGASUS framework

A. Vogt

NNLO corrections to DIS (g_1 structure function):

Zijlstra, van Neerven 1994





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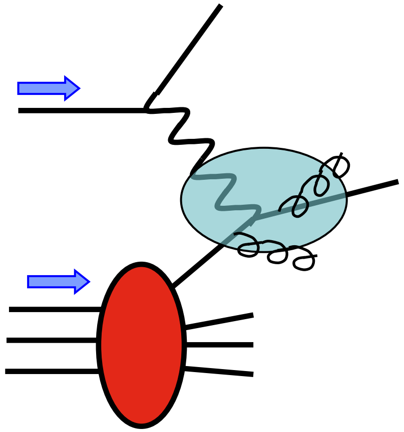

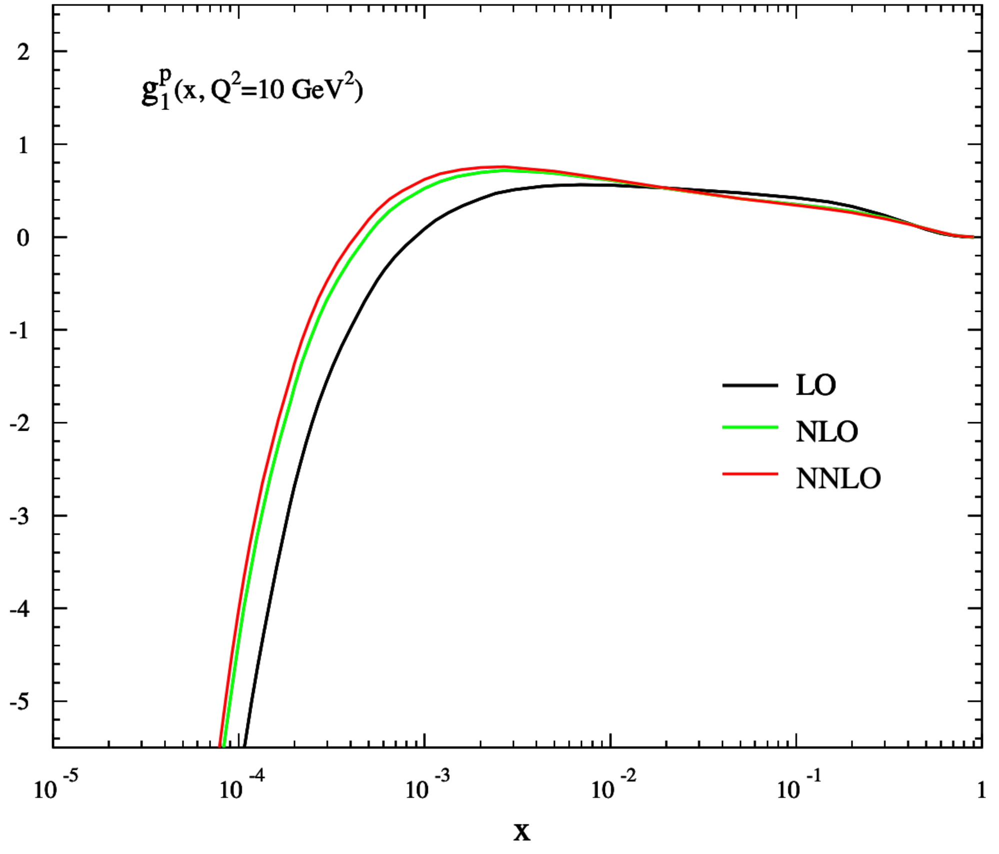

We use Mellin moments:

program MT:
Höschele, Hoff, Pak, Steinhauser, Ueda 2013

program ANCONT: Blümlein 2000

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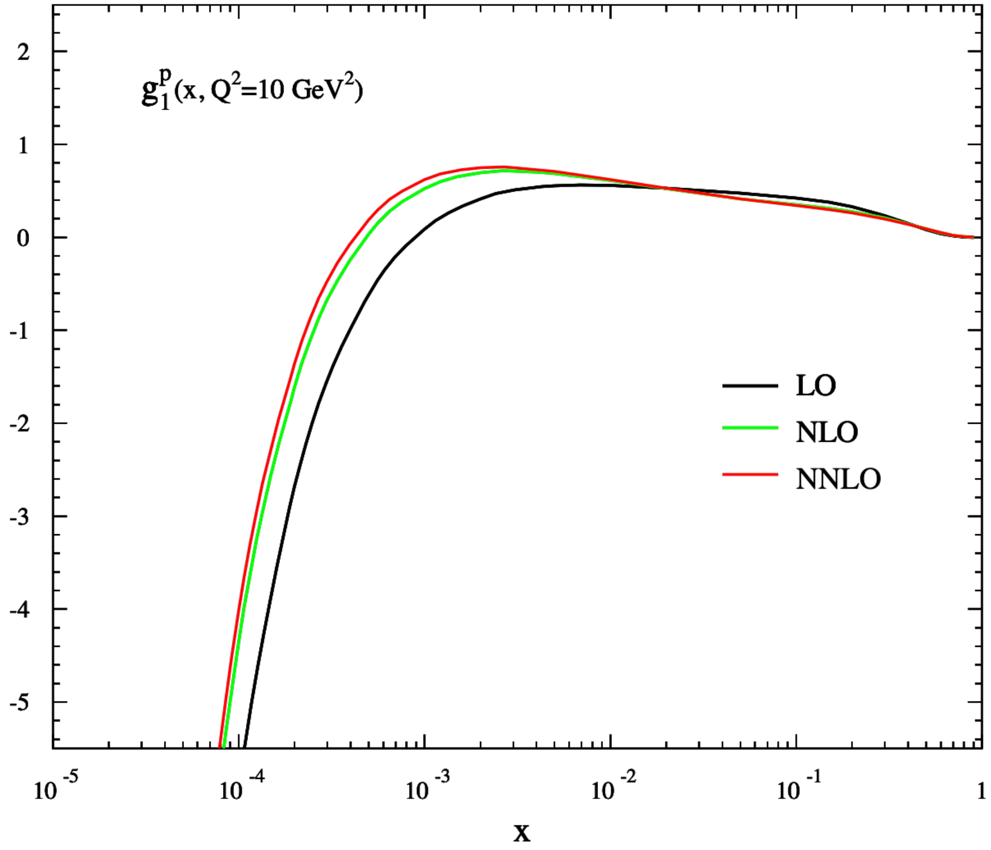

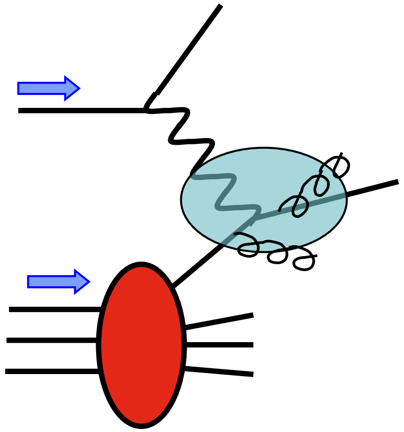

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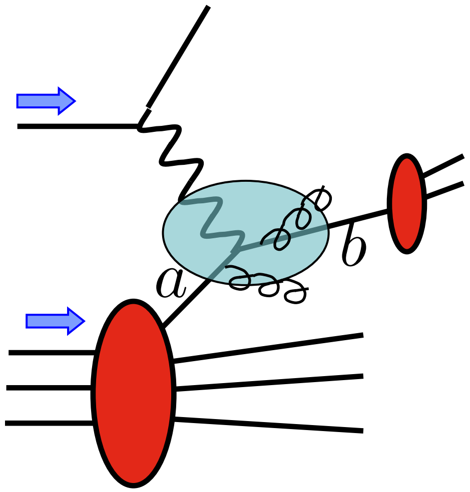
- DIS-only analysis: Taghavi-Shahri et al., 2016

NNLO corrections to SIDIS:
not fully available yet…



NNLO corrections to SIDIS:
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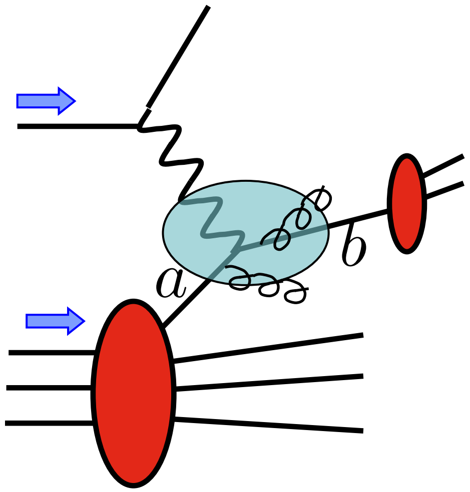
…however: can use powerful techniques to obtain approximate NNLO



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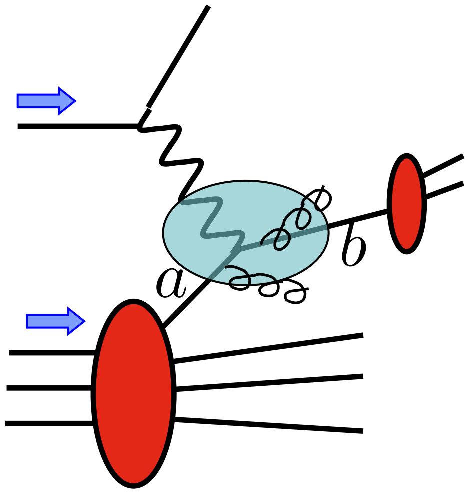


…however: can use powerful techniques to obtain approximate NNLO

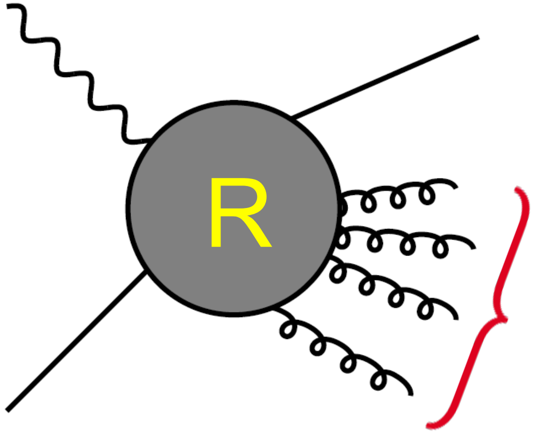
$$\hat{x} = \frac{Q^2}{2p_a \cdot q}$$

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

k^{th} order of perturbation theory:

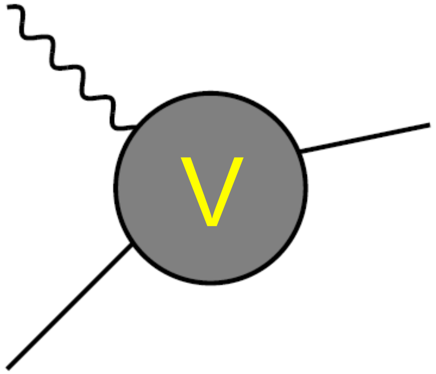
$$\Delta\hat{\sigma}_{qq}^{\mathrm{N}^k\mathrm{LO}}(\hat{x},\hat{z}) \sim \alpha_s^k \left[\delta(1-\hat{x}) \left(\frac{\ln^{2k-1}(1-\hat{z})}{1-\hat{z}} \right)_+ + \delta(1-\hat{z}) \left(\frac{\ln^{2k-1}(1-\hat{x})}{1-\hat{x}} \right)_+ \right.$$

$$\left. + \frac{1}{(1-\hat{x})_+} \left(\frac{\ln^{2k-2}(1-\hat{z})}{1-\hat{z}} \right)_+ + \frac{1}{(1-\hat{z})_+} \left(\frac{\ln^{2k-2}(1-\hat{x})}{1-\hat{x}} \right)_+ + \ldots \right]$$

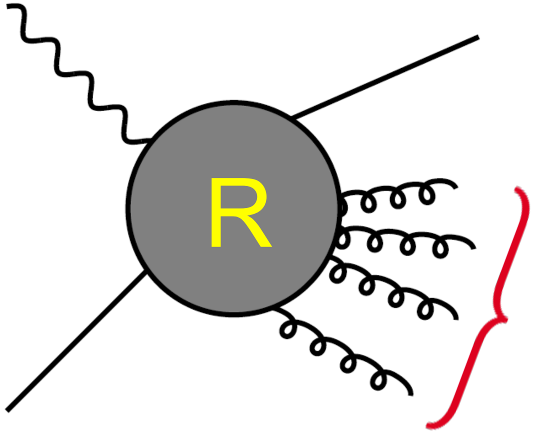


k

($k = 2$ for NNLO)



$\hat{x} = \hat{z} = 1$



k

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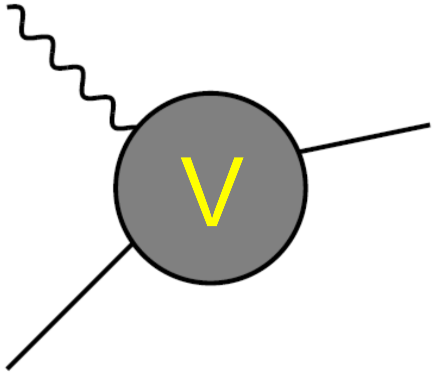


$\hat{x} = \hat{z} = 1$

- logs can be resummed to all orders: threshold resummation

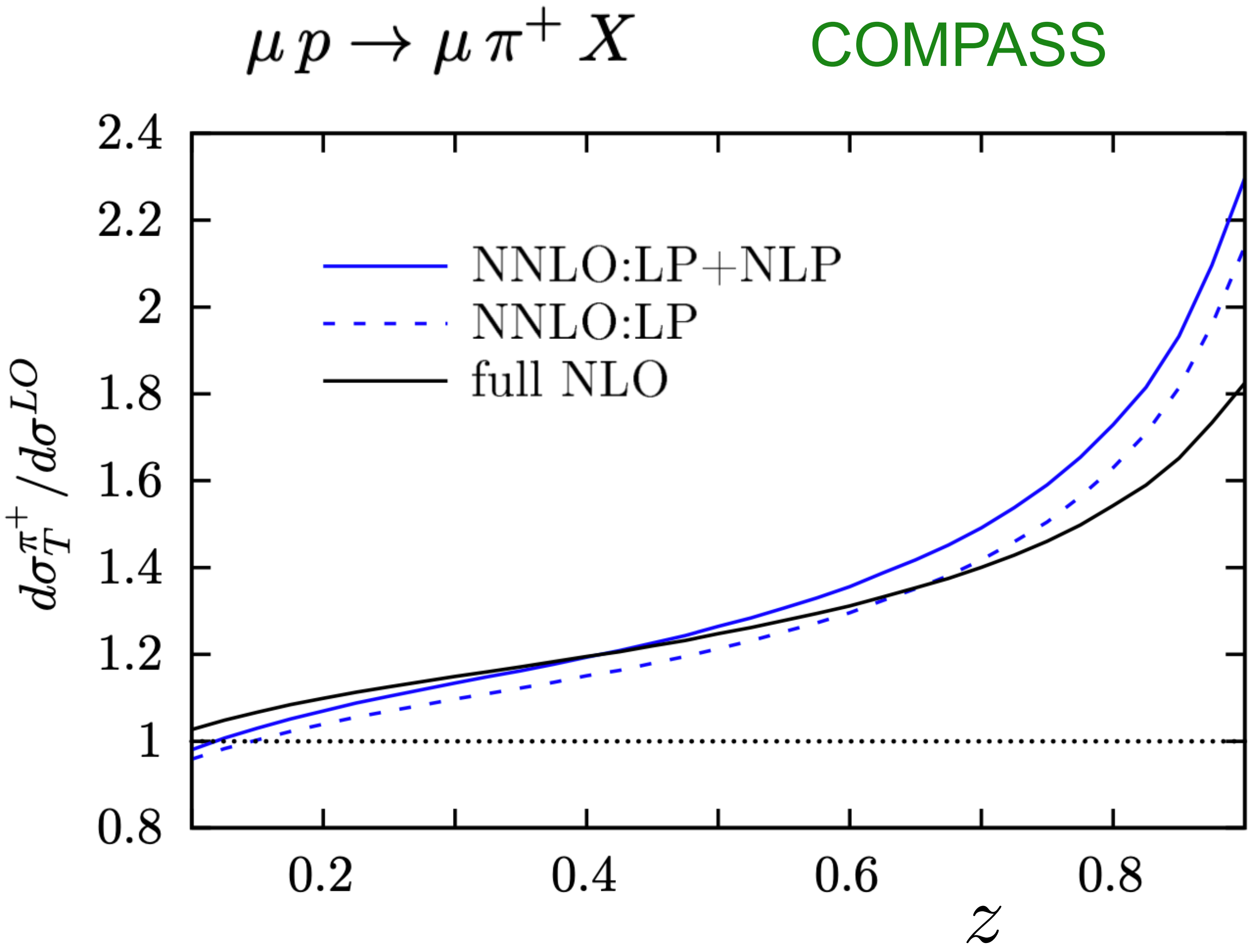
Anderle, Ringer, WV
Abele, de Florian, WV

Fixed Order

Resummation

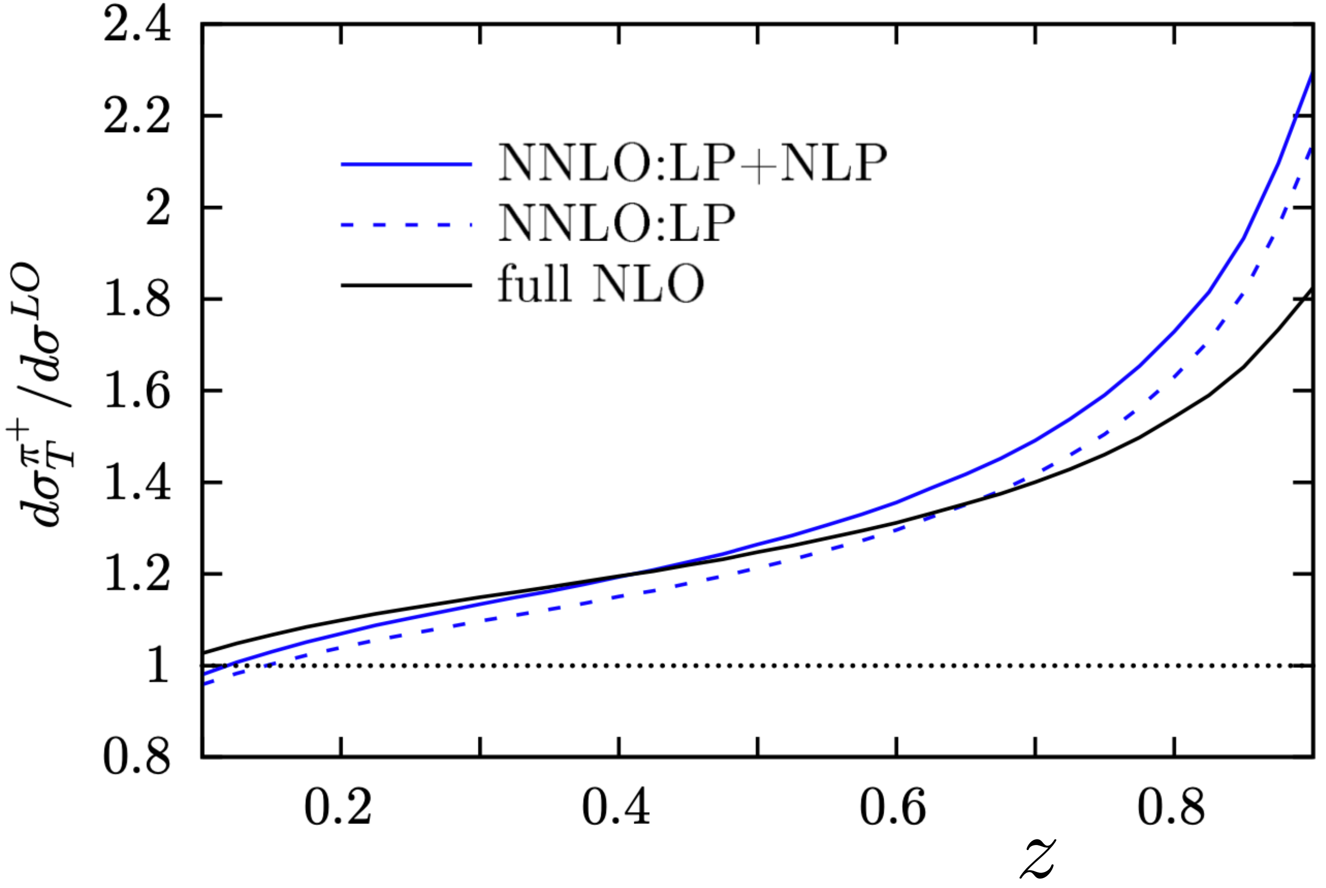
LO	1					
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s			
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	α_s^2	
...	...	...	...	...	...	
N^{k}LO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$	$\alpha_s^k L^{2k-2}$	$\alpha_s^k L^{2k-3}$	$\alpha_s^k L^{2k-4}$	...

LL NLL NNLL



$\mu\, p \to \mu\, \pi^+ X$
COMPASS
NNLO:LP+NLP
NNLO:LP
full NLO
$d\sigma_T^{\pi^+}/d\sigma^{LO}$
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.2
0.4
0.6
0.8
z

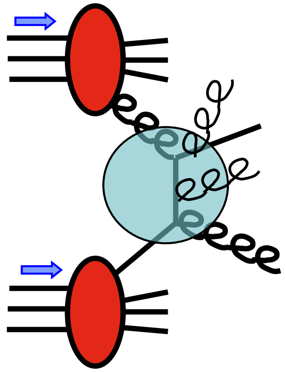
$\mu\, p \to \mu\, \pi^+ X$ COMPASS

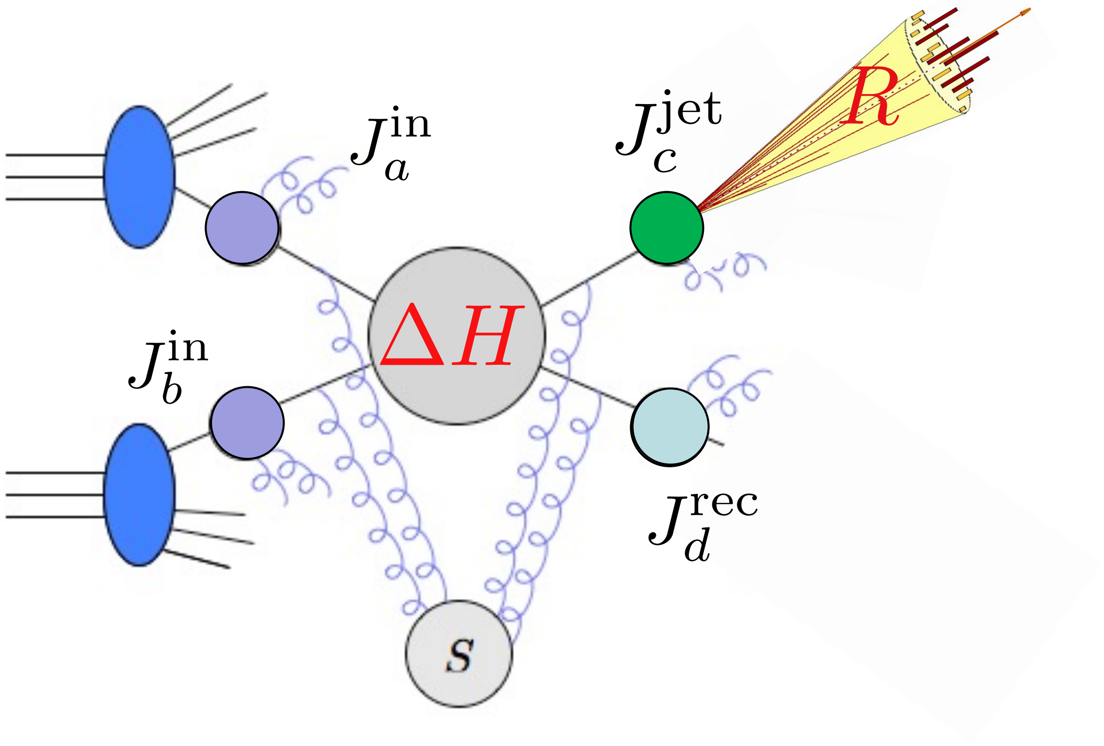


Framework used for first global NNLO analysis of fragm. fcts.

Borsa, de Florian, Sassot,Stratmann, WV

Approximate NNLO corrections for pp → jet+X at RHIC:

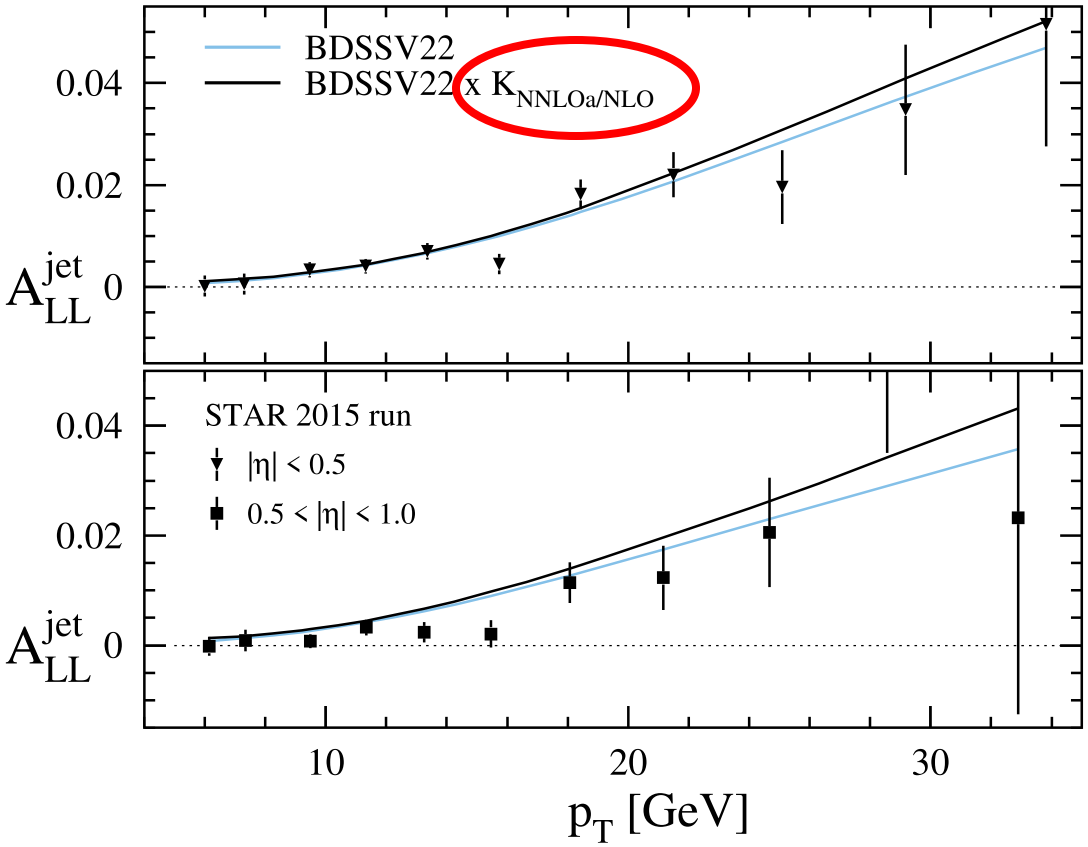




Kidonakis, Oderda, Sterman
de Florian, WV
Hinderer, Ringer, Sterman, WV, ….

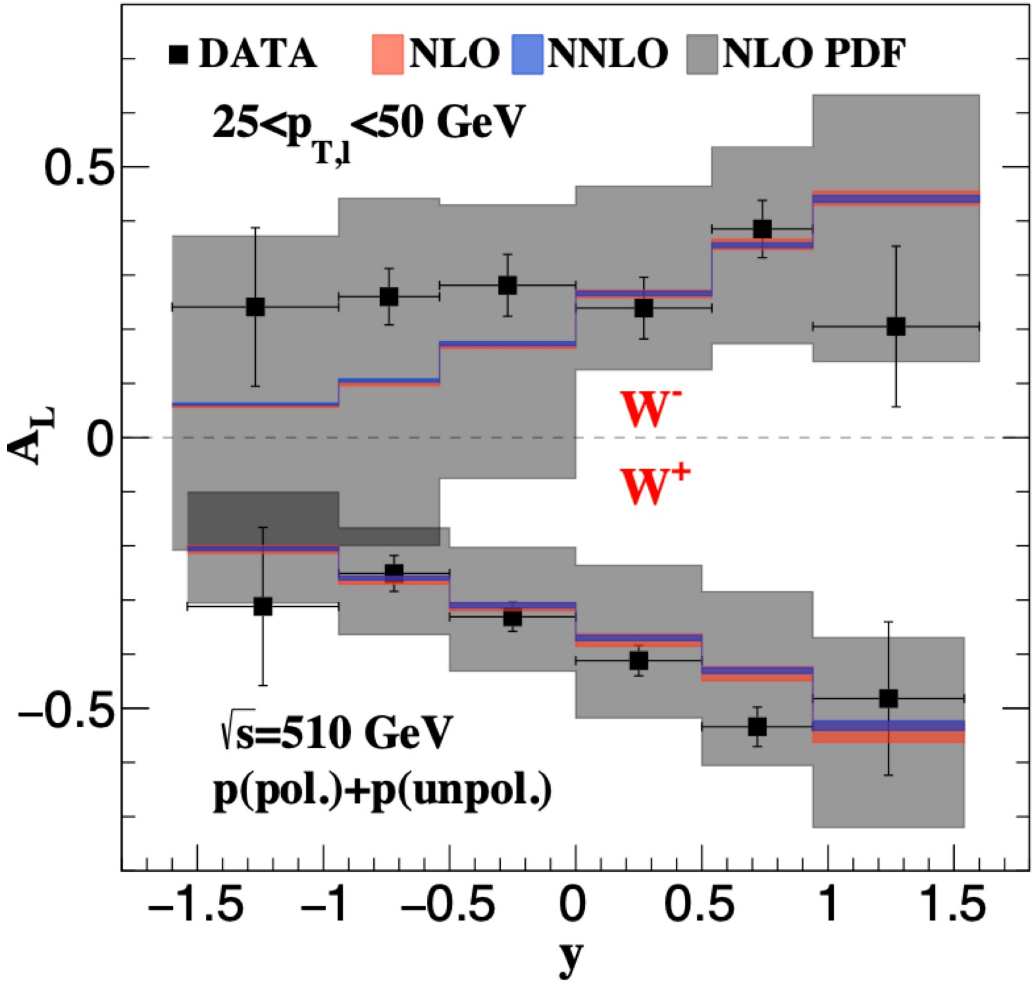
threshold logs $\ln\left(1 - \frac{s_{\mathrm{rad}}}{s}\right)$

$$\Delta\hat{\sigma}^{ab\to cd} \sim J_a^{\mathrm{in}} \times J_b^{\mathrm{in}} \times J_c^{\mathrm{jet}} \times J_d^{\mathrm{rec}} \times \mathrm{Tr}\left[\Delta H\, \mathcal{S}^\dagger S \mathcal{S}\right]_{ab\to cd}$$



BDSSV22
BDSSV22 x K$_{NNLOa/NLO}$
0.04
0.02
0
A_{LL}^{jet}
STAR 2015 run
$|\eta| < 0.5$
$0.5 < |\eta| < 1.0$
10
20
30
p_T [GeV]

NNLO corrections for W bosons at RHIC:



Boughezal, Li, Petriello

Our 1st global NNLO fit !

Data:

DIS:	EMC,SMC,E142,E143,E154,E155, HERMES, COMPASS, HALL-A,CLAS (p,n,d,He)	**378**
SIDIS:	HERMES, COMPASS (p-$\pi^{\pm}$,d-$\pi^{\pm}$)	**80**
PP-JETS:	STAR run 5,6,9,12,13,15 $(\sqrt{s} = 200, 510\, GeV)$ (no dijets yet)	**91**
PP-$\pi^0/\pi^{\pm}$:	PHENIX, STAR	**82**
PP $W^{\pm}$:	PHENIX, STAR	**22**
Total:		**653**

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Total:		**653**

Parameterizations:

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

$$\Delta\bar{q}(x, Q_0^2) = N_{\bar{q}}\, x^{\alpha_{\bar{q}}}(1-x)^{\beta_{\bar{q}}}\left(1 + \gamma_{\bar{q}} x^{\delta_{\bar{q}}}\right)$$

$$\Delta g(x, Q_0^2) = N_g\, x^{\alpha_g}(1-x)^{\beta_g}\left(1 + \gamma_g x^{\delta_g}\right)$$

$Q_0^2 = 1\, GeV^2$ (32 **parameters**)

χ^2

	NNLO	*NLO*
DIS (378)	302	298
SIDIS (80)	99	93
JETS (91)	103	111
$\pi^{0,\pm}$ (82)	65	65
$W^{\pm}$ (22)	22	21

χ^2

	NNLO	*NLO*
DIS (378)	302	298
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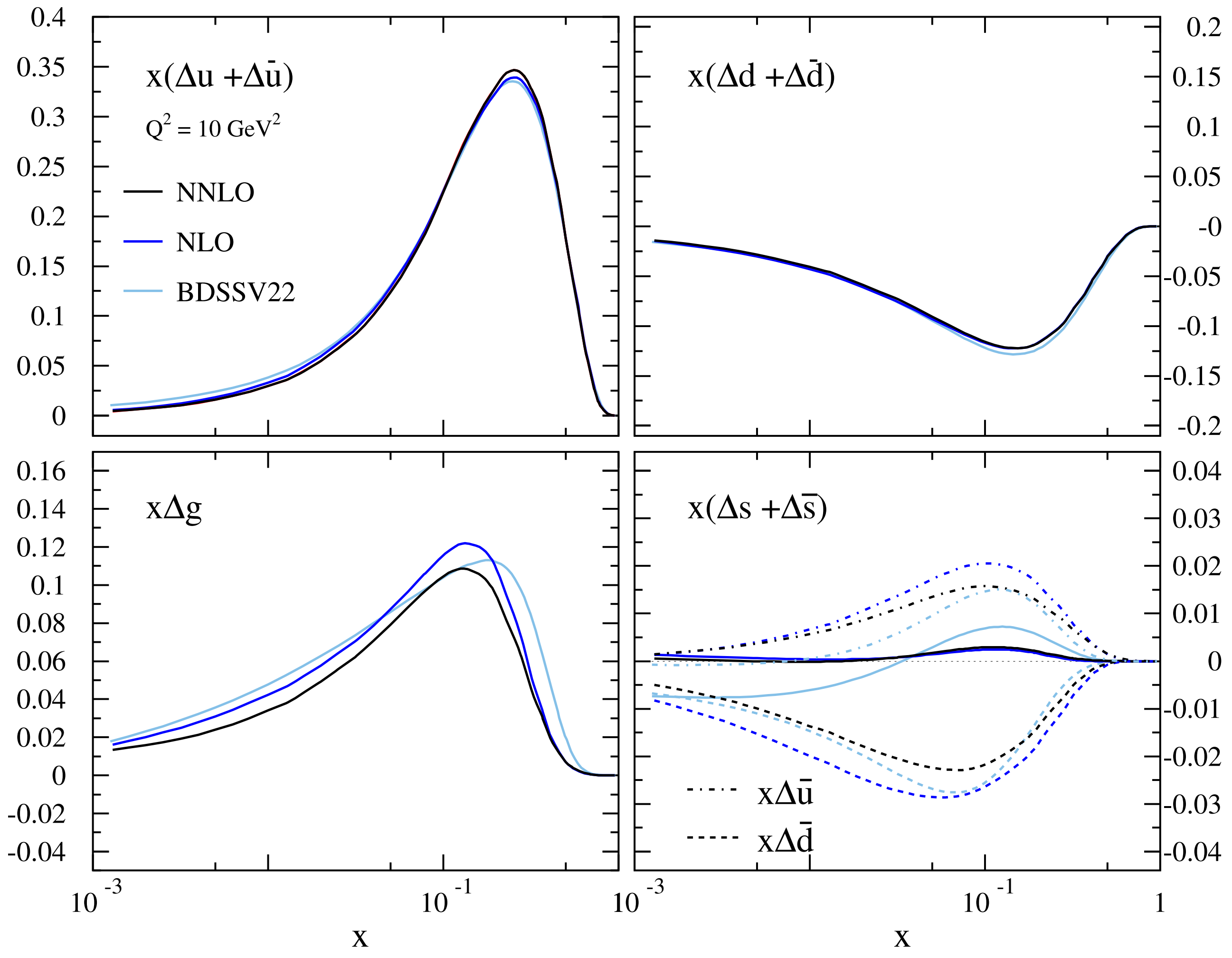
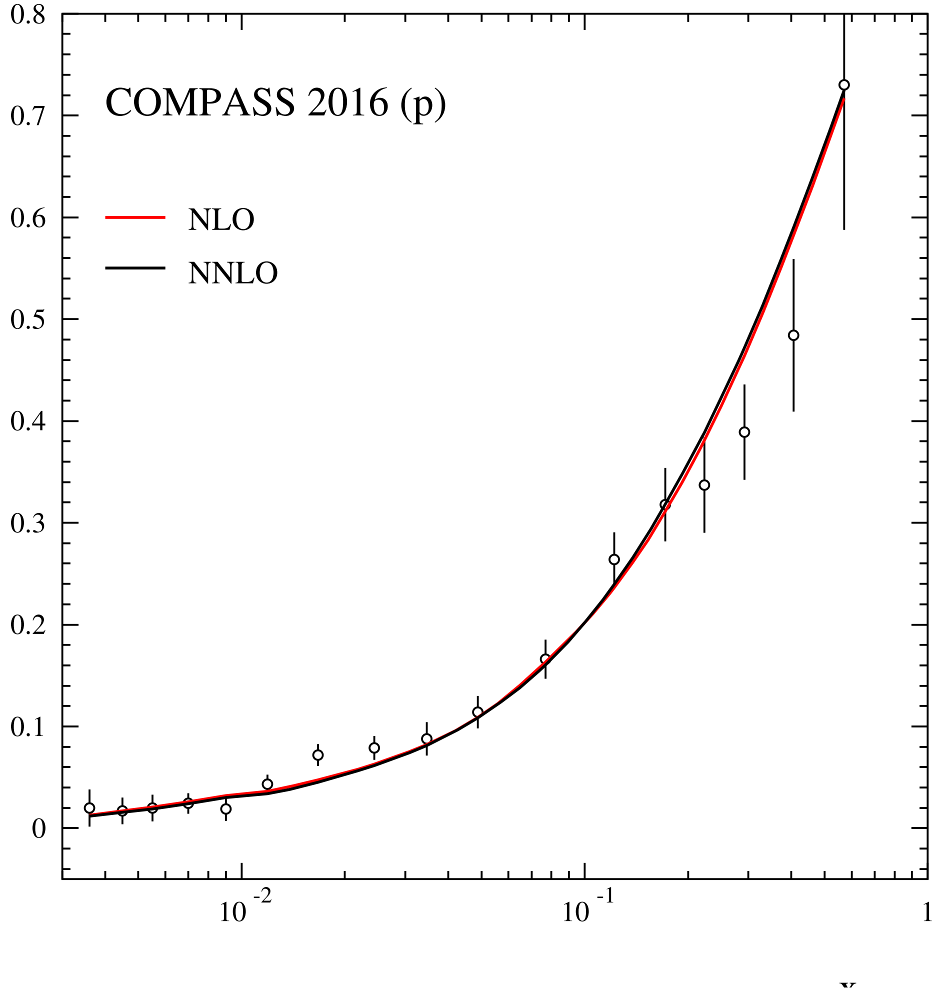
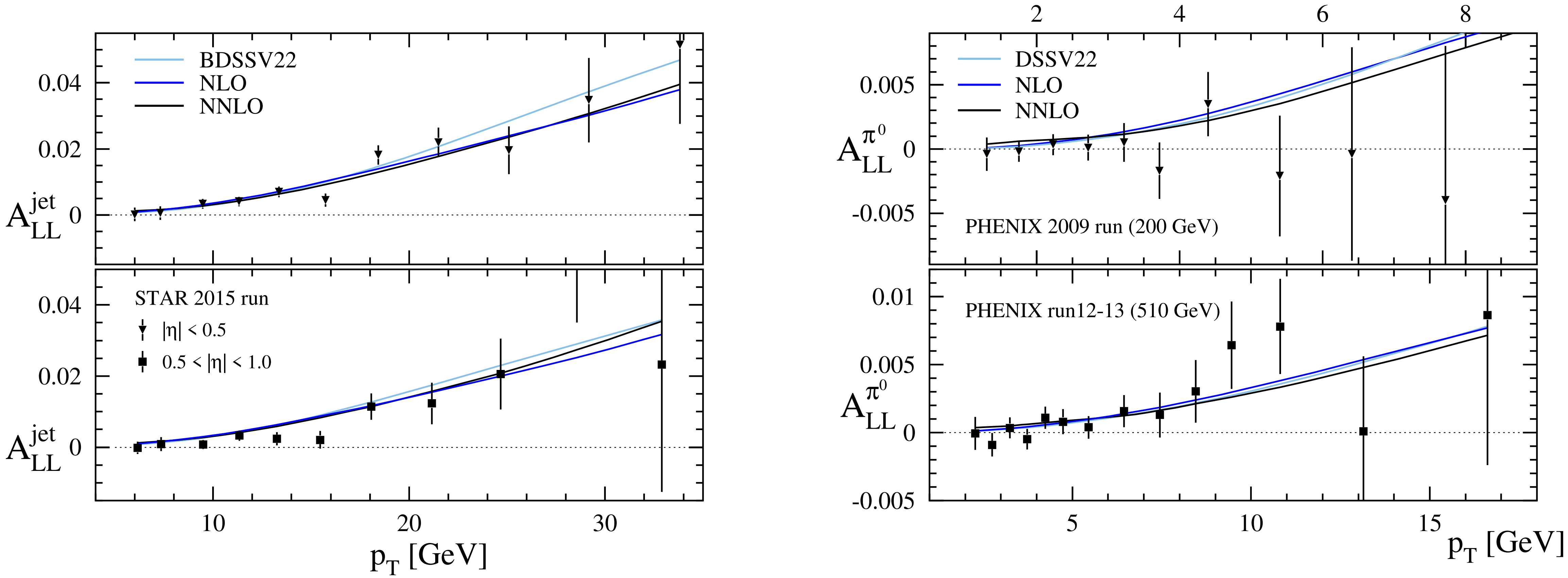




COMPASS 2016 (p)
NLO
NNLO
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^{-2}
10^{-1}
1

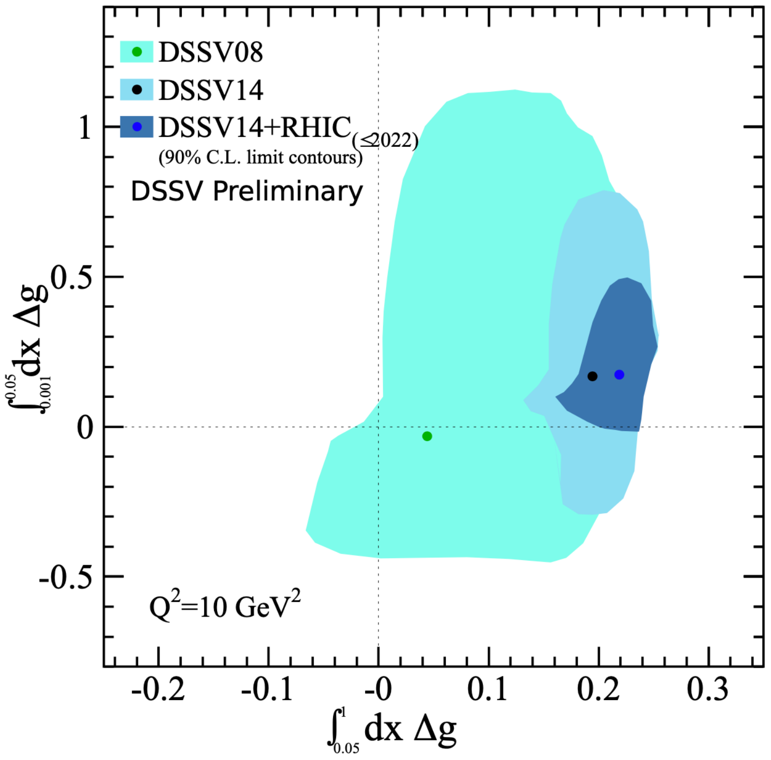

BDSSV22
NLO
NNLO
STAR 2015 run
|η| < 0.5
0.5 < |η| < 1.0
A_{LL}^{jet}
p_T [GeV]
DSSV22
NLO
NNLO
PHENIX 2009 run (200 GeV)
PHENIX run12-13 (510 GeV)
$A_{LL}^{\pi^0}$
p_T [GeV]

Concluding remarks:

- enormous recent progress on helicity PDFs

$$\int_{0.01}^{1} dx\, \Delta\Sigma(x, Q^2) \;=\; 0.43 \pm 0.08$$

$$\int_{0.01}^{1} dx\, \Delta g(x, Q^2) \;=\; 0.3 \pm 0.1$$



- qualitative step forward to NNLO: pQCD analysis "in good shape"

- work on improving NNLO analysis ongoing

- numerous outstanding issues: low-x, power corrections, synergies with lattice