Theoretical status of helicity-dependent parton densities

The 21st International Symposium on Spin Physics

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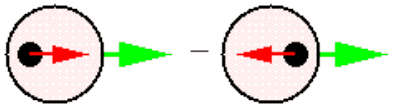
Foreword



$$\Delta f(x, Q^2) = f^{\Rightarrow\rightarrow}(x, Q^2) - f^{\Rightarrow\leftarrow}(x, Q^2)$$

How do quarks (including sea quarks) and gluons carry the proton spin

$$\mathcal{S}(\mu) = \frac{1}{2} = \sum_f \left\langle P; S|\hat{J}_f^z(\mu)|P; S\right\rangle = \frac{1}{2}\int_0^1 dx\Delta\Sigma(x,\mu) + \int_0^1 dx\Delta g(x,\mu) + L_z$$

All quantities depend on factorization scheme and scale μ

Spin decomposition is not unique (Y. Hatta, S1)

Very little of the proton spin is carried by quarks

$$\int_0^1 dx\Delta\Sigma = \int_0^1 dx \sum_{q=u,d,s} (\Delta q + \Delta\bar{q}) \sim 30\%$$

Quark and gluon longitudinal contributions $\Longleftrightarrow$ longitudinal spin-dependent PDFs

Outline

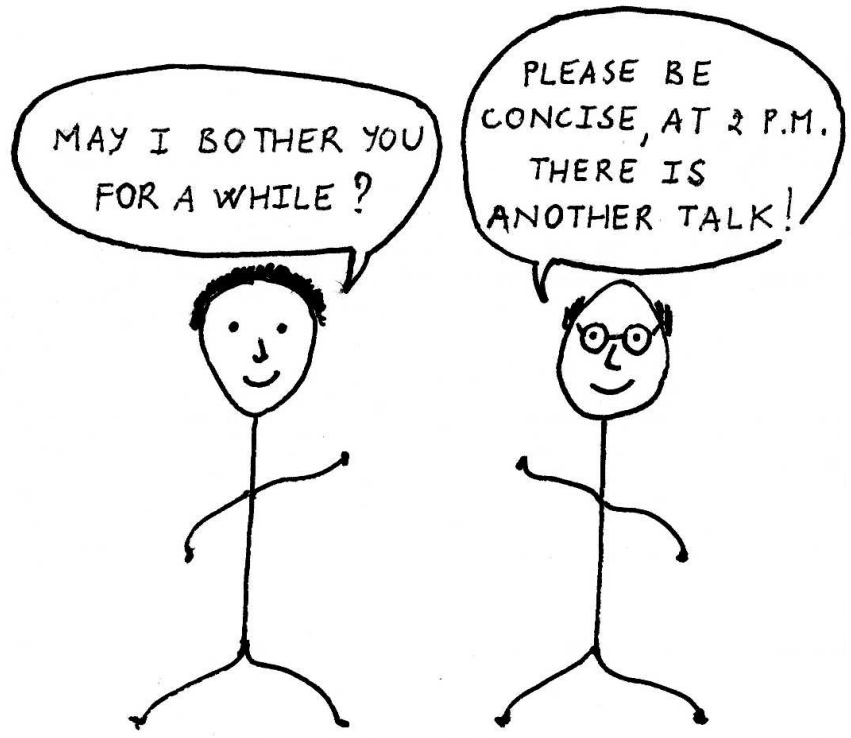
1. Introduction
2. Impact of latest experimental results
   - pp collisions at RHICH: $W^{\pm}$, π and jet production
   - inclusive DIS: COMPASS and JLAB
3. Recent theoretical progress
   - higher-twist corrections
   - all-order resummation, higher-order computations
4. Summary and outlook

DISCLAIMER

Emphasis on recent achievements in our knowledge of polarized PDFs in global QCD analyses

Apologies in advance for not discussing your favourite subject

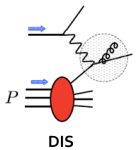
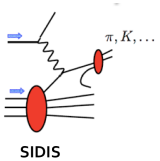
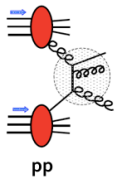
1. Introduction



Probes of nucleon helicity structure

Guiding principle: FACTORIZATION

e.g. DIS $\quad d\Delta\sigma = \sum_{q,\bar{q},g} \Delta f(x,Q^2) \otimes d\Delta\hat{\sigma}_{\gamma^* f}(xP, \alpha_s(Q^2)) \quad d\Delta\hat{\sigma}_{\gamma^* f} = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{4\pi}\right)^n d\Delta\hat{\sigma}^{(n)}_{\gamma^* f}$

	Reaction	Partonic subprocess	PDF probed	x	Q^2 [GeV^2]
	$\ell^\pm\{p,d,n\} \to \ell^\pm X$	$\gamma^* q \to q$	$\Delta q + \Delta\bar{q}$ Δg	$0.003 \lesssim x \lesssim 0.8$	$1 \lesssim Q^2 \lesssim 70$
	$\ell^\pm\{p,d\} \to \ell^\pm hX$	$\gamma^* q \to q$	$\Delta u\ \Delta\bar{u}$ $\Delta d\ \Delta\bar{d}$ Δg	$0.005 \lesssim x \lesssim 0.5$	$1 \lesssim Q^2 \lesssim 60$
	$\ell^\pm\{p,d\} \to \ell^\pm DX$	$\gamma^* g \to c\bar{c}$	Δg	$0.06 \lesssim x \lesssim 0.2$	~ 10
	$\overrightarrow{p}\,\overrightarrow{p} \to jet(s)X$	$gg \to qg$ $qg \to qg$	Δg	$0.05 \lesssim x \lesssim 0.2$	$30 \lesssim p_T^2 \lesssim 800$
	$\overrightarrow{p}\,p \to W^\pm X$	$u_L\bar{d}_R \to W^+$ $d_L\bar{u}_R \to W^-$	$\Delta u\ \Delta\bar{u}$ $\Delta d\ \Delta\bar{d}$	$0.05 \lesssim x \lesssim 0.4$	$\sim M_W^2$
	$\overrightarrow{p}\,\overrightarrow{p} \to \pi X$	$gg \to qg$ $qg \to qg$	Δg	$0.05 \lesssim x \lesssim 0.4$	$1 \lesssim p_T^2 \lesssim 200$

Different processes constrain different PDFs, factorization is successful

Polarized vs unpolarized PDF determinations

1. Limited (x, Q^2) kinematic coverage
   - difficult to get Δg from scaling violations in DIS and SIDIS
     $\rightarrow$ additional *direct* probes of Δg are needed (jets, open-charm)
   - need to use data down to $Q^2 = 1$ GeV^2
     $\rightarrow$ is perturbative QCD reliable?
     $\rightarrow$ how much higher twists affect the perturbative description of observables?
2. No neutrino DIS data
   - no quark-antiquark separation from inclusive DIS
     $\rightarrow$ limited set of $W^{\pm}$ production data in pp collisions
     $\rightarrow$ SIDIS data require knowledge of fragmentation functions (extra uncertainties)
3. Sum rules on shaky (?) grounds
   - first moments of nonsinglet distributions $\Longleftrightarrow$ hyperon decay constants
     $\rightarrow$ some constraints on Δs and $\Delta\Sigma$ at small-x values
     $\rightarrow$ is SU(3) symmetry broken?

Recent determinations of polarized PDFs @ NLO

Fit	Data sets	Parton Distributions	Uncertainties	Latest update
AAC08	DIS, π^0	Δu^+, Δd^+, Δs^+, Δg	Hessian $\Delta\chi^2 = 12.95$	[arXiv:0808.0413]
BB10	DIS	Δu^-, Δd^-, $\Delta \bar{q}$, Δg	Hessian $\Delta\chi^2 = 1$	[arXiv:1005.3113]
LSS10	DIS, SIDIS	Δu^+, Δd^+, $\Delta \bar{u}$, $\Delta \bar{d}$, $\Delta \bar{s}$, Δg	Hessian $\Delta\chi^2 = 1$	[arXiv:1010.0574]
JAM13	DIS	Δu^+, Δd^+, $\Delta \bar{u}$, $\Delta \bar{d}$, $\Delta \bar{s}$, Δg	Hessian $\Delta\chi^2 = 1$	[arXiv:1310.3734]
DSSV++	DIS, SIDIS, π^0, jets	Δu^+, Δd^+, $\Delta \bar{u}$, $\Delta \bar{d}$, $\Delta \bar{s}$, Δg	Hessian $\Delta\chi^2 = 1$ Lagr. mult. $\Delta\chi^2/\chi^2 = 2\%$	[arXiv:1404.4293]
NNPDFpol1.1	DIS, OC, $W^\pm$, jets	Δu^+, Δd^+, $\Delta \bar{u}$, $\Delta \bar{d}$, $\Delta \bar{s}$, Δg	Monte Carlo	[arXiv:1406.5539]

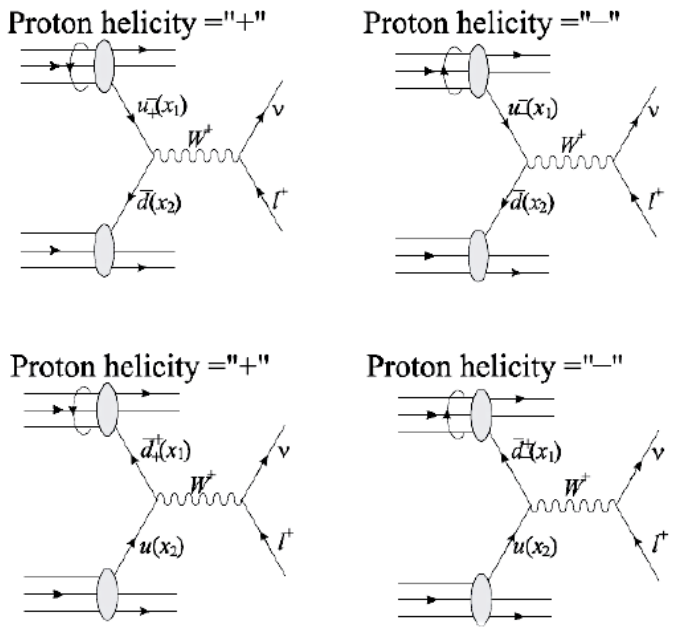
PDF uncertainties stem from three sources

1. the underlying data, affected by statistical and (correlated) systematic errors
2. the theory used to describe them, based on the truncation of a perturbative series
3. the procedure used to extract PDFs from data

Available PDF sets are all based on item 2, but may differ significantly for items 1 and 3

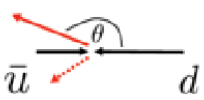
2. Impact of latest experimental results

1) pp collisions at RHIC: $W^{\pm}$ production

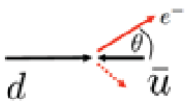


$$A_L^{W^-} \sim$$

$$\frac{\Delta\bar{u}_{x_1}\, d_{x_2}\,(1-\cos\theta)^2 - \Delta d_{x_1}\,\bar{u}_{x_2}\,(1+\cos\theta)^2}{\bar{u}_{x_1}\, d_{x_2}\,(1-\cos\theta)^2 - d_{x_1}\,\bar{u}_{x_2}\,(1+\cos\theta)^2}$$



backward lepton rapidity



forward lepton rapidity

Longitudinal single- and double-spin asymmetries

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \qquad A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

FEATURES

- quark/antiquark separation at $Q \sim M_W$
- no need of fragmentation functions
- at RHIC, $\langle x_{1,2} \rangle \simeq \frac{M_W}{\sqrt{s}} e^{-\eta_l/2} \approx [0.04, 0.4]$
- for W^+, $d \longleftrightarrow d$ and $\Delta d \longleftrightarrow \Delta u$
- non-trivial positivity bound [arXiv:1104.2920]

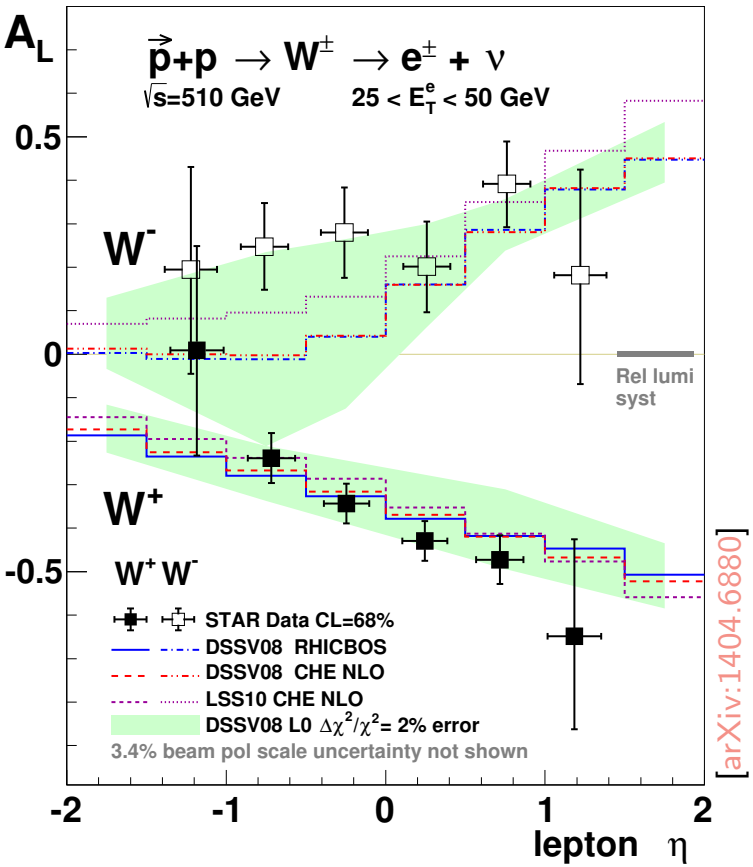
$$1 \pm A_{LL}(y_W) > |A_L(y_W) \pm A_L(-y_W)|$$

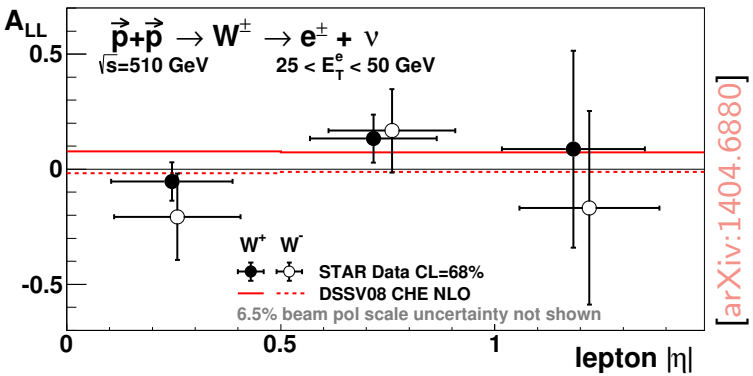
- no access to strangeness ($W^{\pm}$ + c required)

MEASUREMENTS

- STAR + PHENIX (Z. Jinlong & F. Giordano)
- much more to come from ongoing RHIC run

1) *pp* collisions at RHIC: $W^{\pm}$ production





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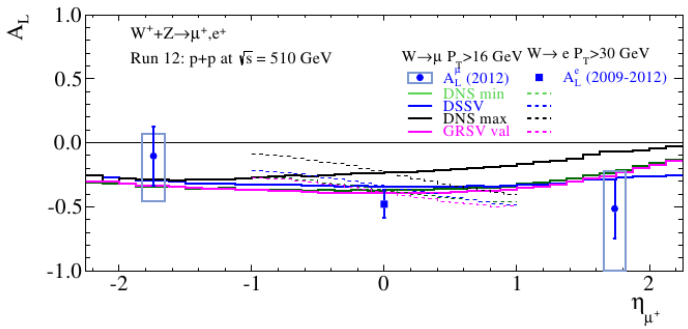
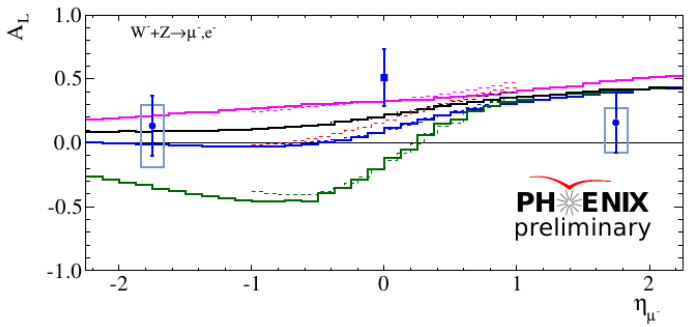
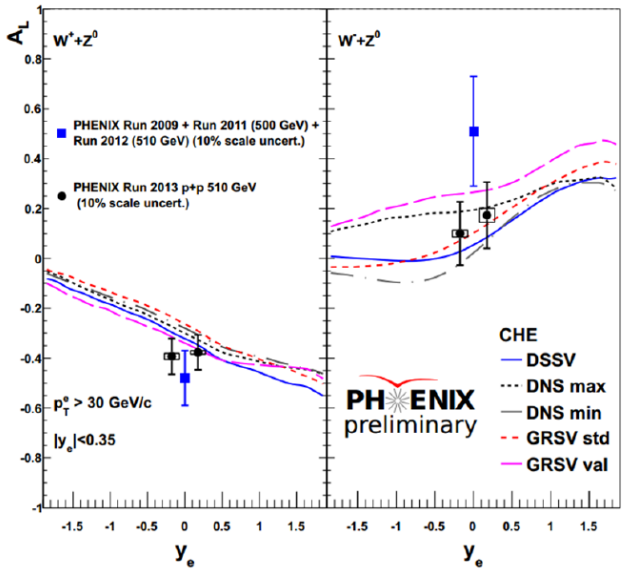




[PoS(DIS2014)205]



[PoS(DIS2014)219]

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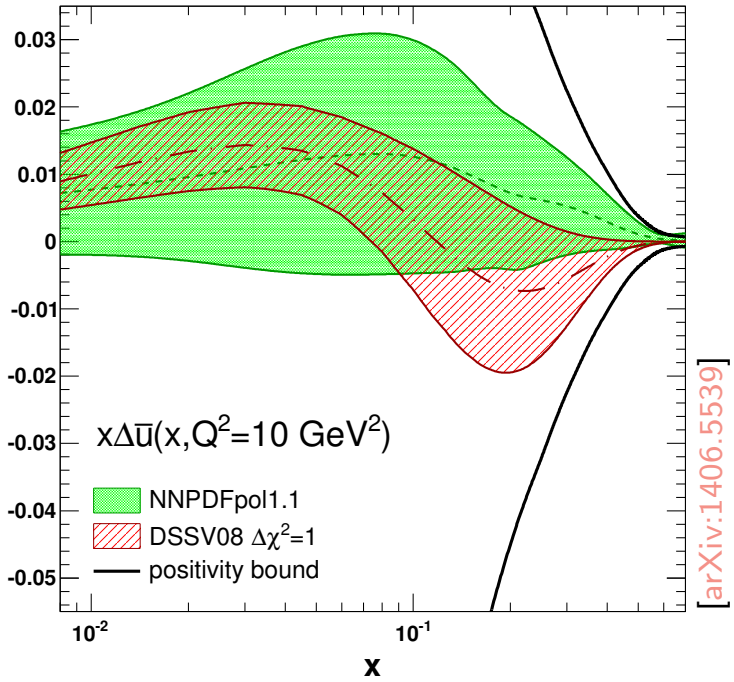
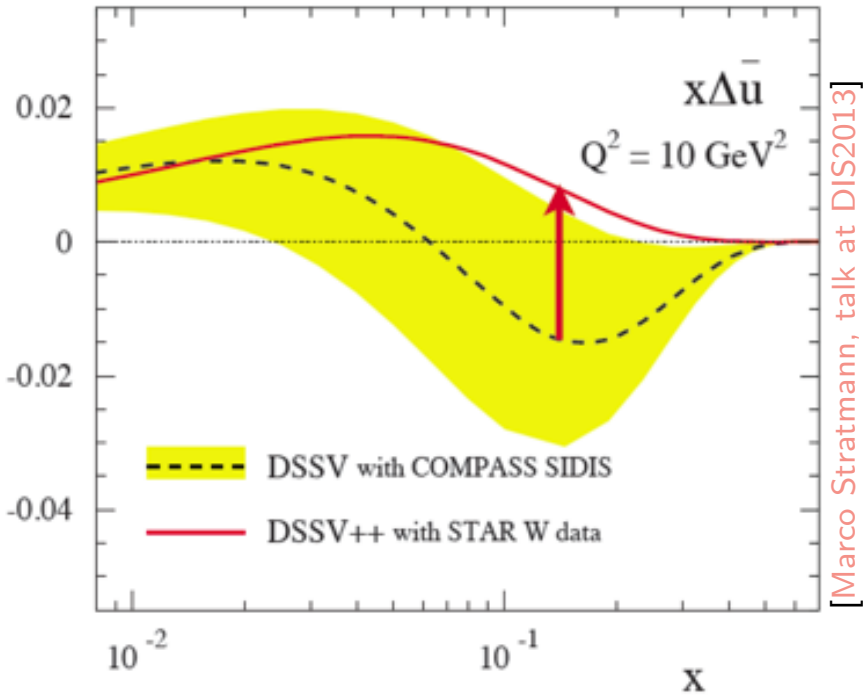
EFFECTS ON $\Delta\bar{u}$ AND $\Delta\bar{d}$ DISTRIBUTIONS



NNPDFpol1.1: $W^{\pm}$ ☑, SIDIS ☒

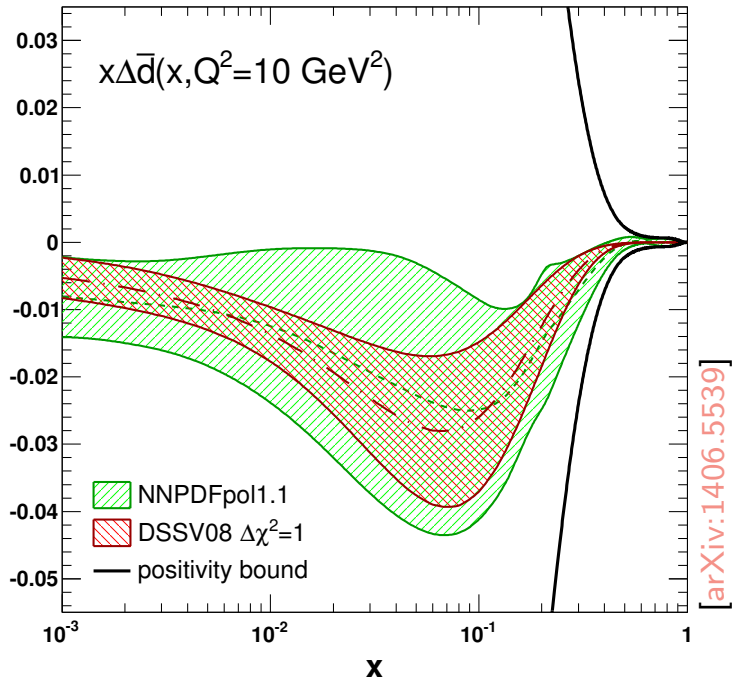


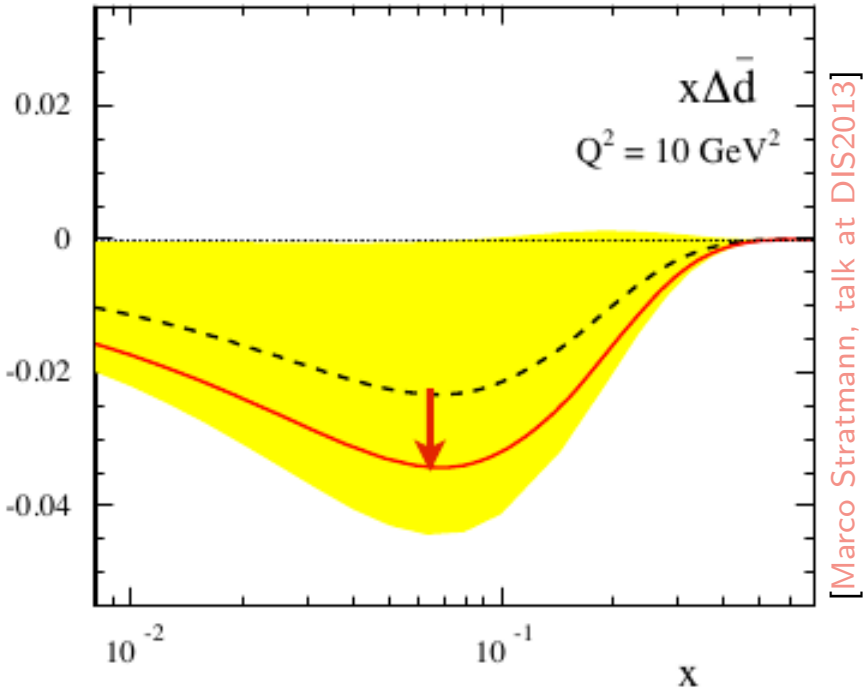
DSSV08/++ : $W^{\pm}$ ☒ , SIDIS ☑

- start to test of what we know about light sea quarks from SIDIS with pions
- looming (mild) tension between $W^{\pm}$ and SIDIS data?
- are fragmentation function uncertainties underestimated?

1) pp collisions at RHIC: $W^{\pm}$ production

EFFECTS ON $\Delta\bar{u}$ AND $\Delta\bar{d}$ DISTRIBUTIONS





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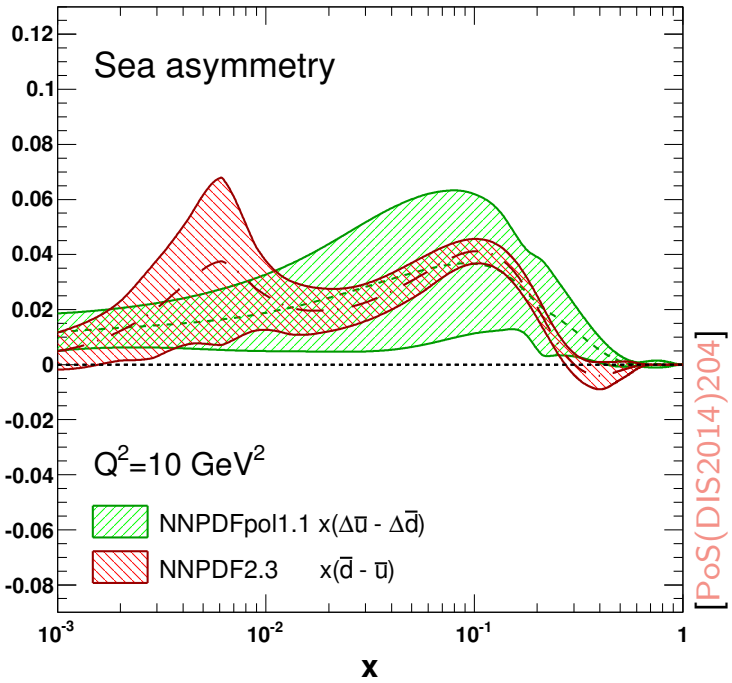
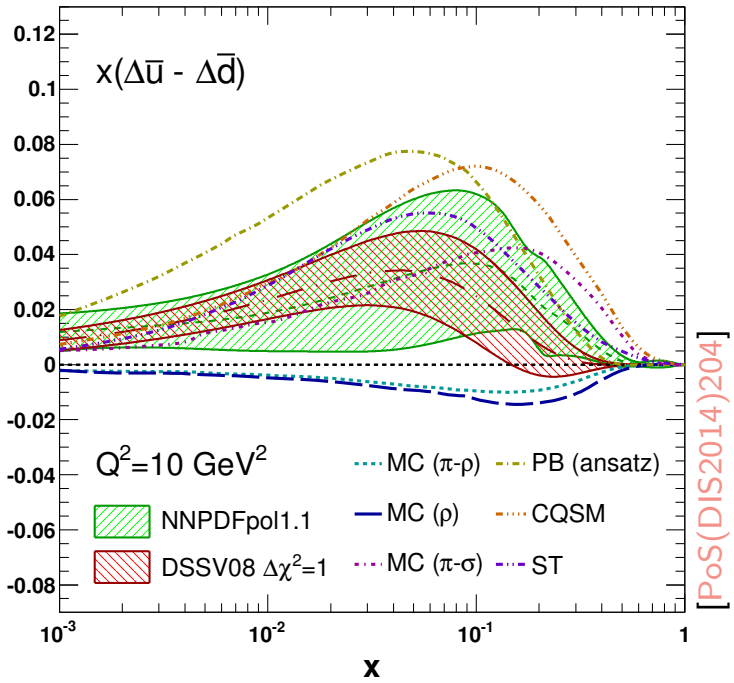
1) pp collisions at RHIC: $W^{\pm}$ production

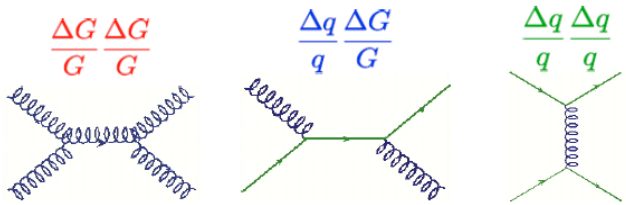
EFFECTS ON FLAVOR ASYMMETRY $\Delta\bar{u} - \Delta\bar{d}$



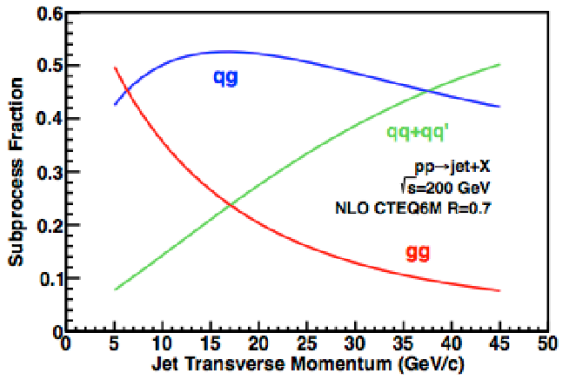


- the polarized asymmetry is sizable and comparable to the unpolarized asymmetry
- polarized and unpolarized asymmetries have opposite sign
  $\rightarrow$ large uncertainties, difficult to determine whether $|\Delta\bar{u} - \Delta\bar{d}| > |\bar{u} - \bar{d}|$
- the polarized asymmetry is positive, hence some models are likely to be disfavored
  $\rightarrow$ more data are needed to discriminate between models

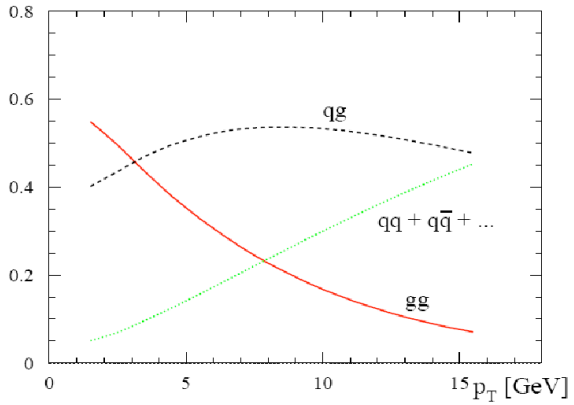
2) *pp* collisions at RHIC: jet and π production



Jet production



π production



Longitudinal double-spin asymmetry

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

FEATURES

- at RHIC, $\langle x_{1,2} \rangle \simeq \frac{2p_T}{\sqrt{s}} e^{-\eta/2} \approx [0.05, 0.2]$
- qg and gg initiated subprocesses dominate (for most of the RHIC kinematics)
- A_{LL} sensitive to gluon polarization
- cross sections are well described at NLO in pQCD

MEASUREMENTS

- STAR (mainly jets) (Z. Chang & C. Dilk)
- PHENIX (π production) (A. Manion & I. Yoon)
- much more to come from ongoing RHIC run
  $\rightarrow$ gaining precision
  $\rightarrow$ di-jet measurements

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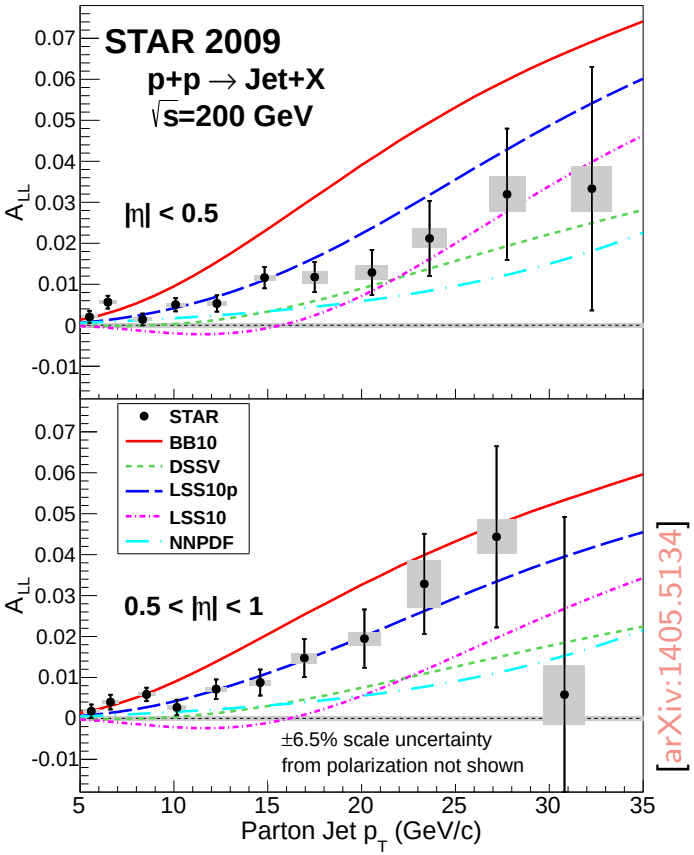

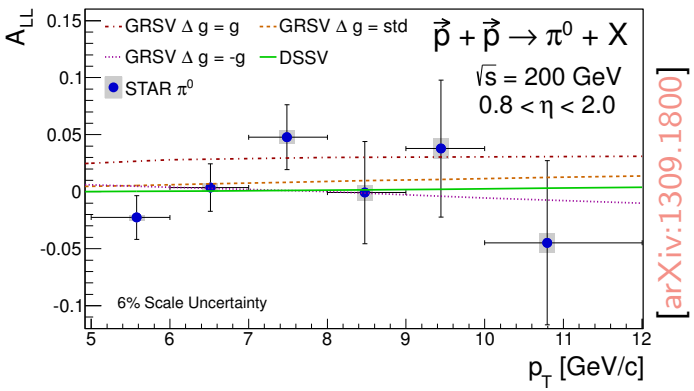

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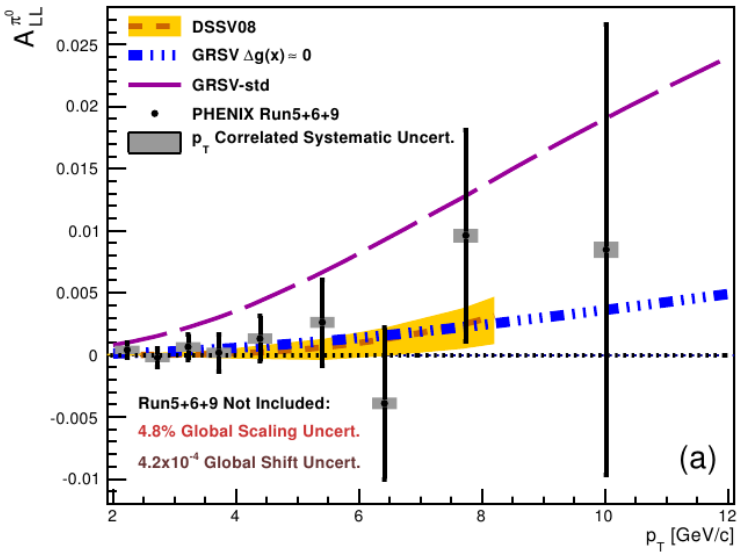
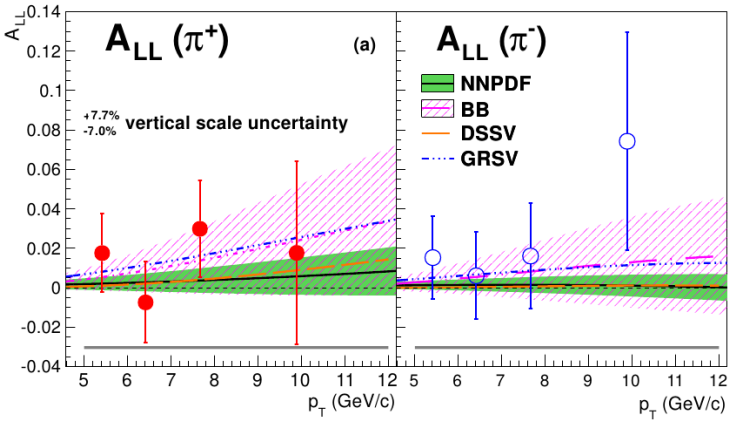


[arXiv:1402.6296]



[arXiv:1409.1907]

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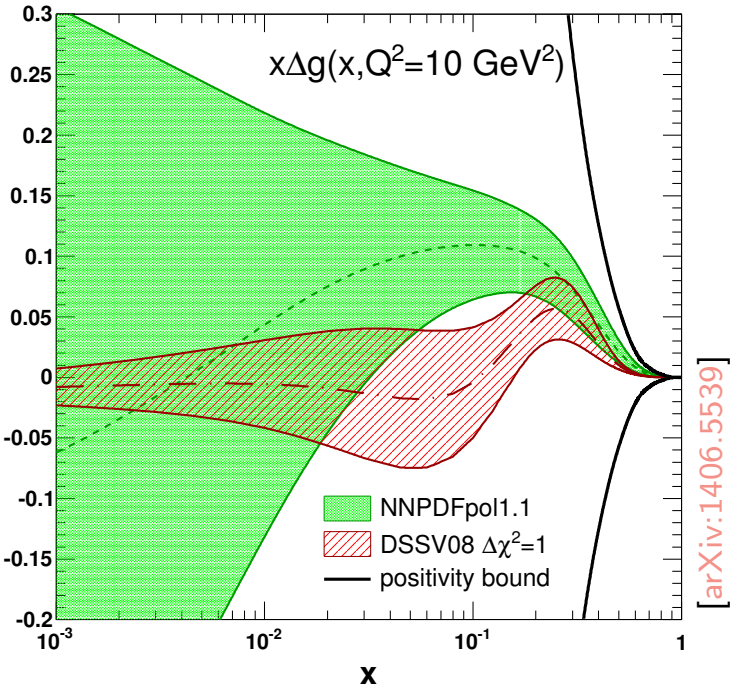
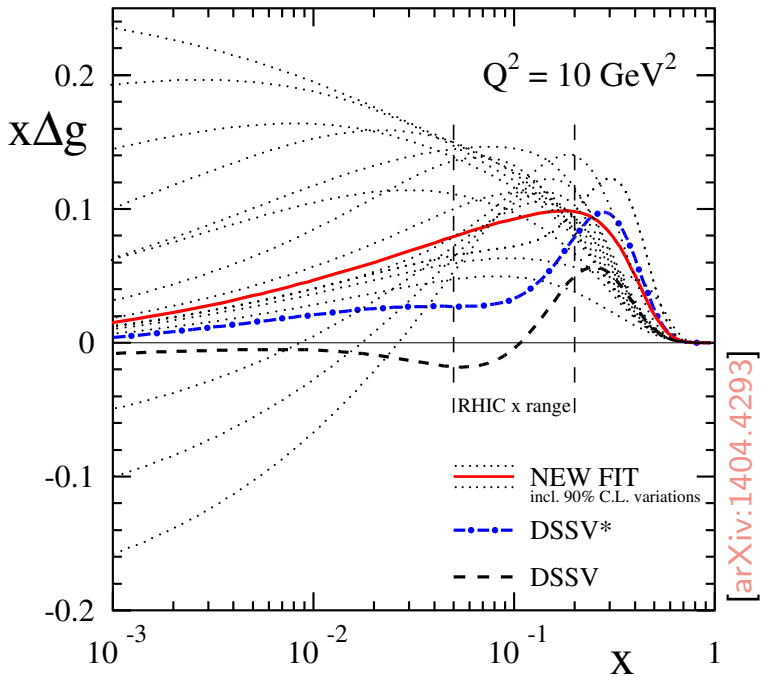
EFFECTS ON Δg DISTRIBUTION





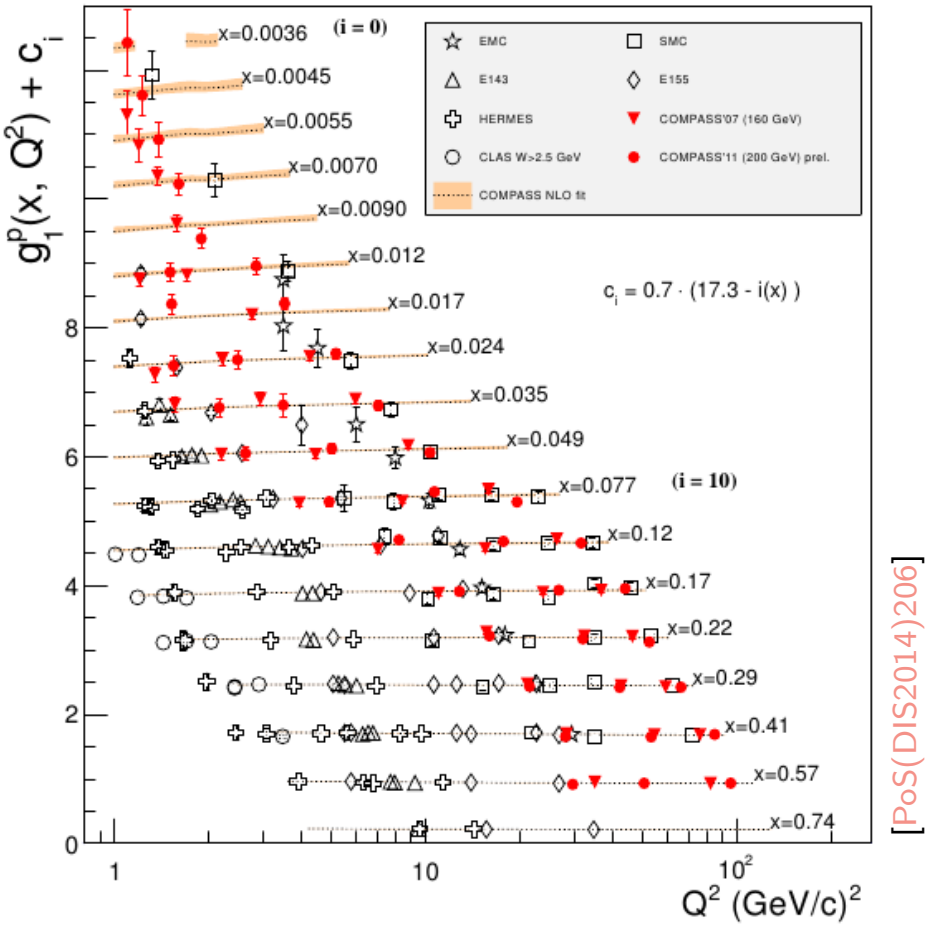
NNPDFpol1.1: jet data ☑, π data ☒ DSSV++: jet data ☑, π ☑

- first evidence of sizable gluon polarization
- NNPDFpol1.1 and DSSV++ results in perfect agreement
- most significant constraints come from STAR jet data from 2009 run
- the gluon polarization remains largely uncertain outside the x-range probed by RHIC

3) More DIS data: COMPASS

INCLUSIVE DIS (F. Kunne)

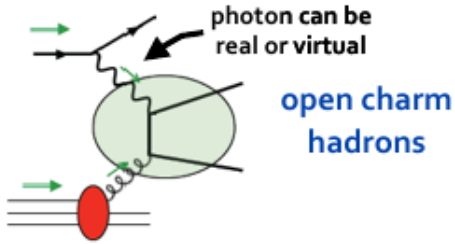
- new measurement of A_1^p and g_1^p (2011)
- beam energy increased to 200 GeV
- lower values of x and higher values of Q^2



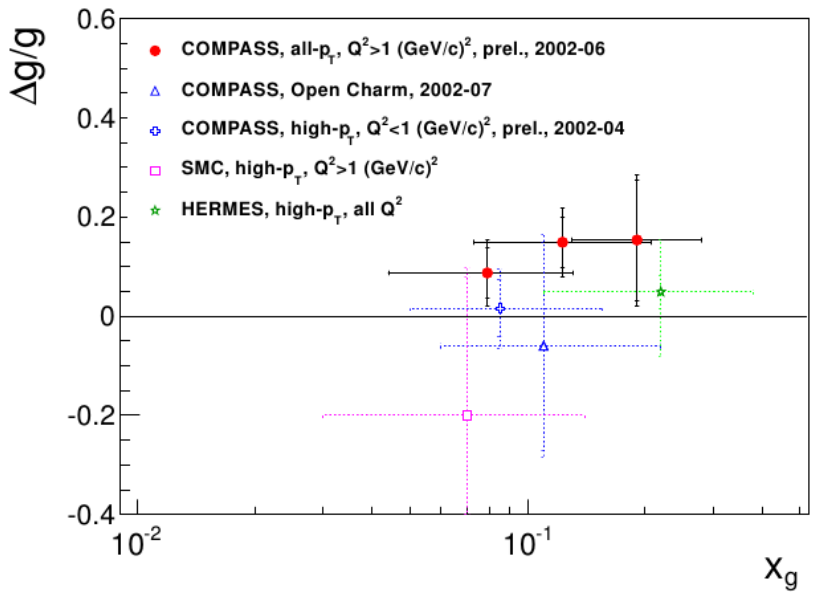
[PoS(DIS2014)206]

OPEN-CHARM PRODUCTION (K.Kurek)

- idea: process receiving (dominant) contributions from $\gamma^* g$ fusion



- new evaluation of gluon polarization at LO with a neural network approach

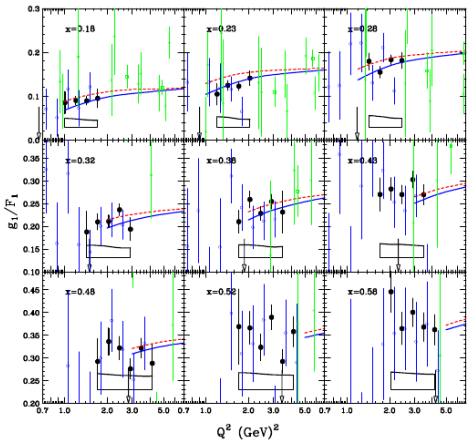


[PoS(DIS2014)211]

3) More DIS data: JLAB

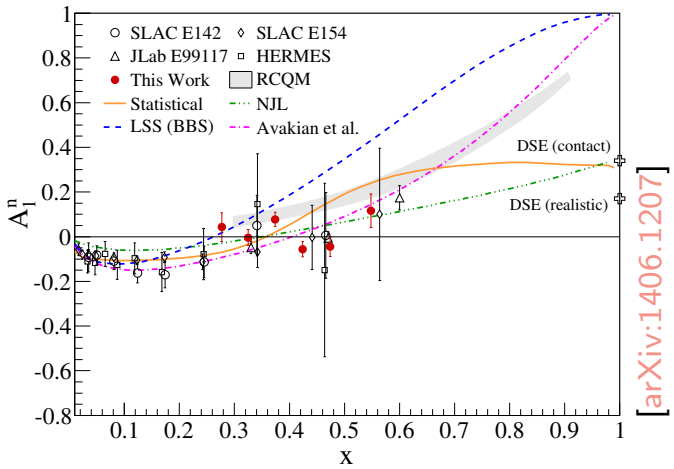
INCLUSIVE DIS: g_1 AT LARGE x (P. Bosted)

- new data on $g_1^{p,d}/F_1^{p,d}$ from CLAS



[arXiv:1404.6231]

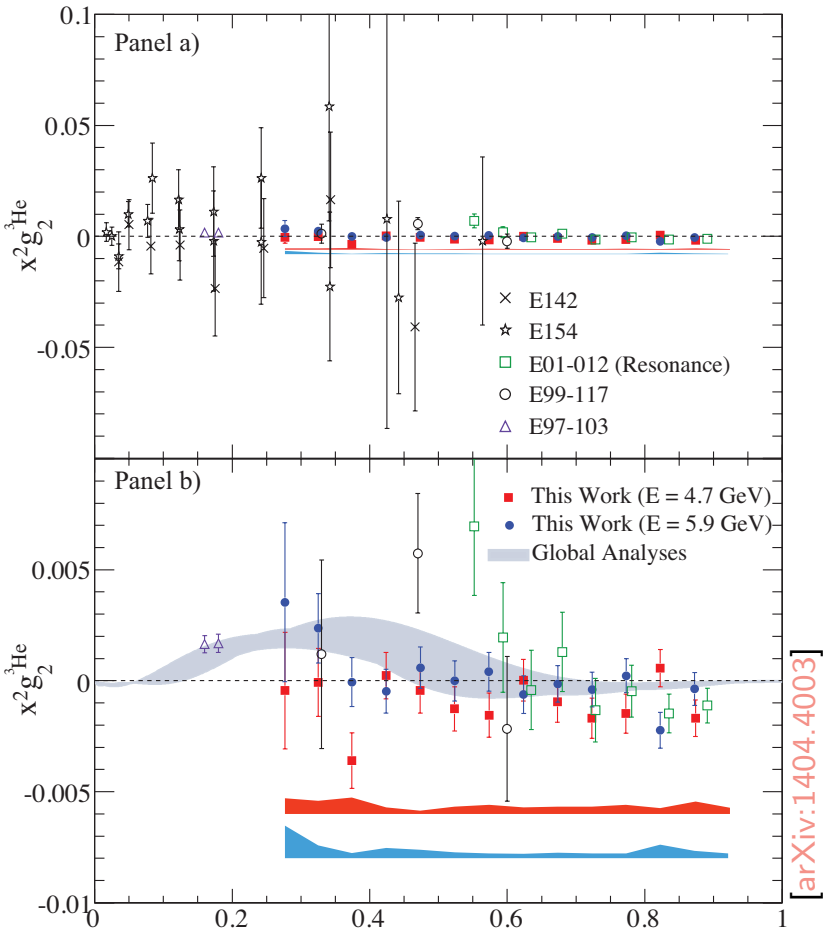
- new data on A_1^n from Hall A



[arXiv:1406.1207]

INCLUSIVE DIS: g_2 (S. Choi & M. Cummings)

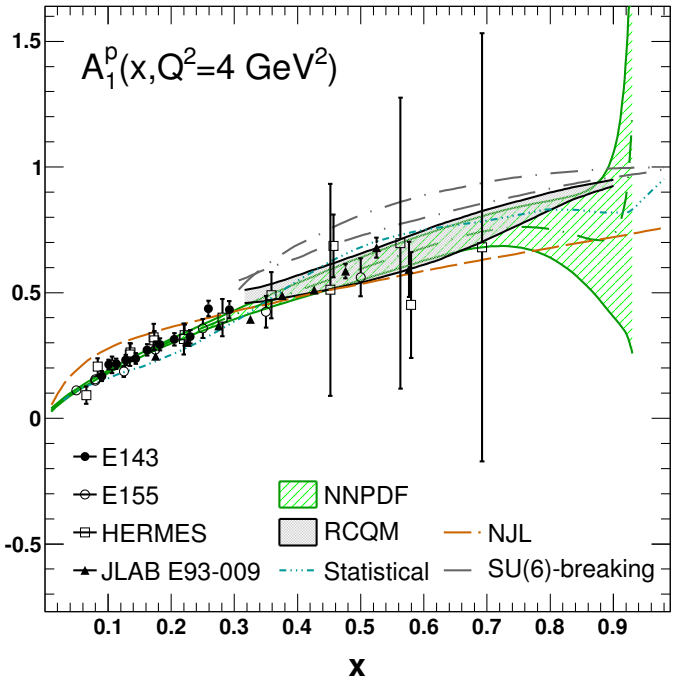
- measurement of $g_2^{^3He}$ by JLAB Hall A
- much more to come from JLAB Hall C

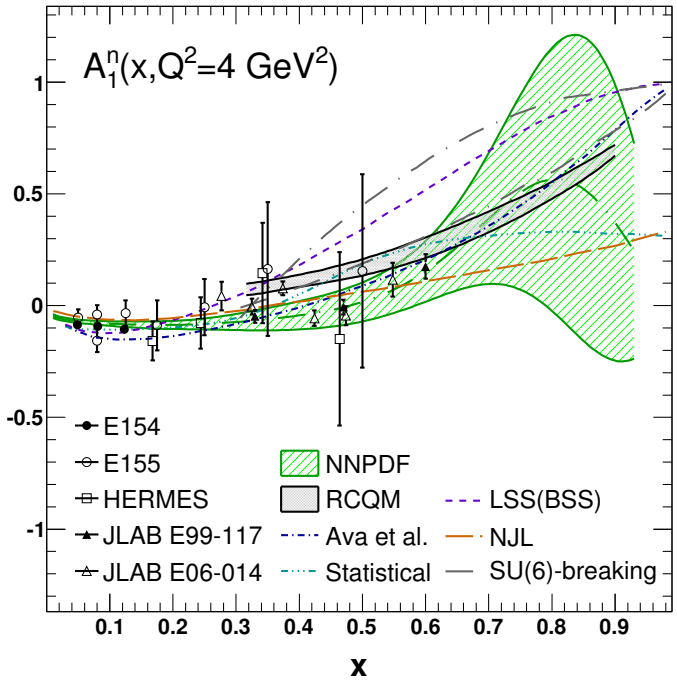


[arXiv:1404.4003]

3) More DIS data: JLAB

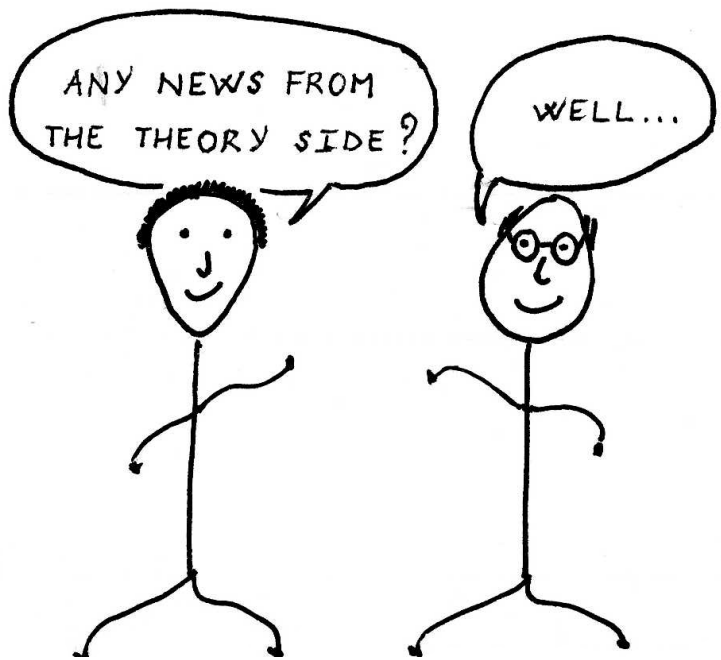
POTENTIAL IMPACT OF JLAB DATA ON LONGITUDINAL ASYMMETRIES



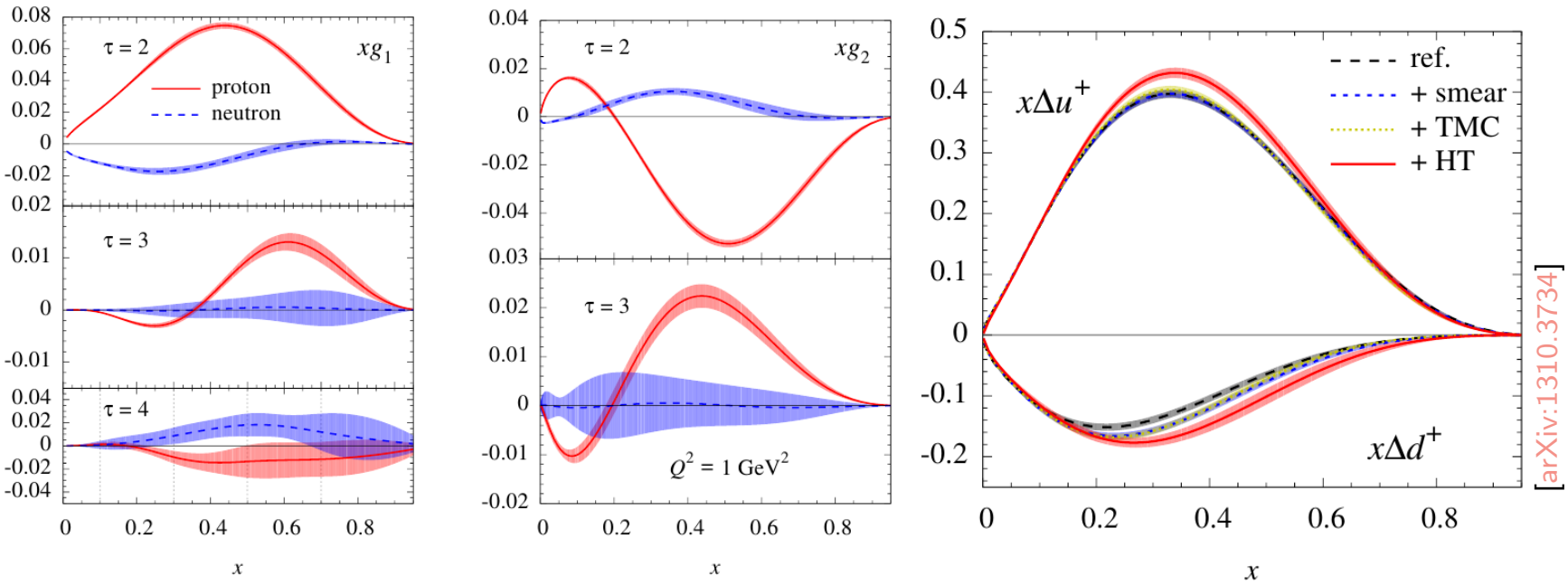


- JLAB data are much more precise than previous measurement
- JLAB data cover the large-x region, up to $x \sim 0.7$
- JLAB data are expected to have significant impact in narrowing PDF uncertainties
  $\rightarrow$ better determination of total up and down distributions
  $\rightarrow$ possibility to test different models of nucleon structure in the valence region

3. Recent theoretical progress



1) Progress on inclusion of higher-twist corrections: JAM13



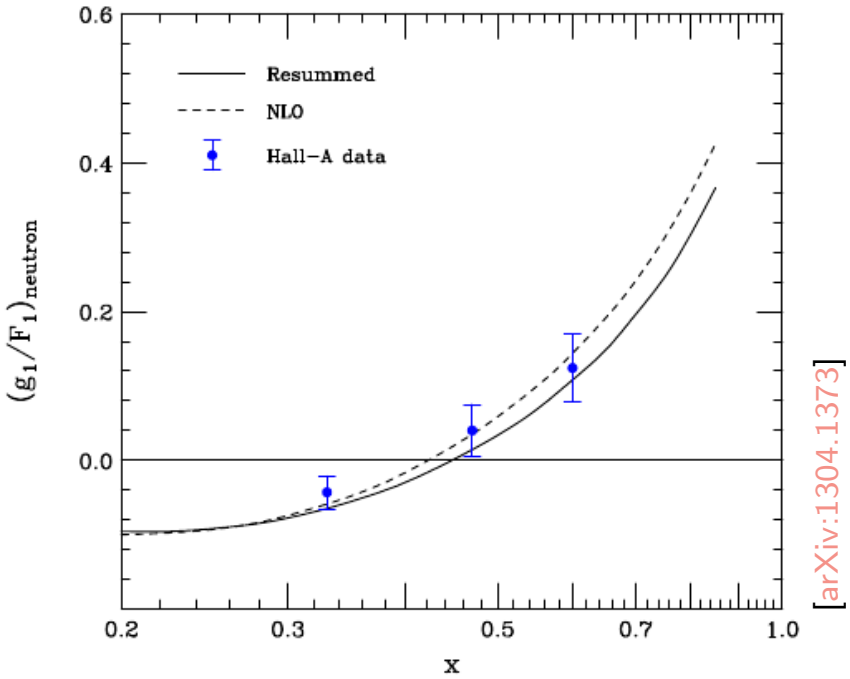
- leading-twist factorization of g_1 and g_2 receives contributions from higher-twist terms

$$g_1 = g_1^{\tau=2} + g_1^{\tau=3} + g_1^{\tau=4} \qquad g_2 = g_2^{\tau=2} + g_2^{\tau=3}$$

  - $\rightarrow$ $g_2^{\tau=2}$ can be related to $g_1^{\tau=2}$ via Wandzura-Wilckzek relation [PLB,72,195]
  - $\rightarrow$ $g_2^{\tau=3}$ can be related to $g_1^{\tau=3}$ via Blümlein-Tkablaze identity [arXiv:hep-ph/9812478]
  - $\rightarrow$ $g_2^{\tau=3}$ can be parametrized (using *e.g.* the form by Braun *et al.*) [arXiv:1103.1269]
  - $\rightarrow$ $g_1^{\tau=4}$ can be parametrized as $g_1^{\tau=4}(x, Q^2) = h(x)/Q^2$ (D. Hui)
- higher twists to both g_1 and g_2 are included in JAM13
- higher twist contributions are sizable and are needed for describing JLAB data properly

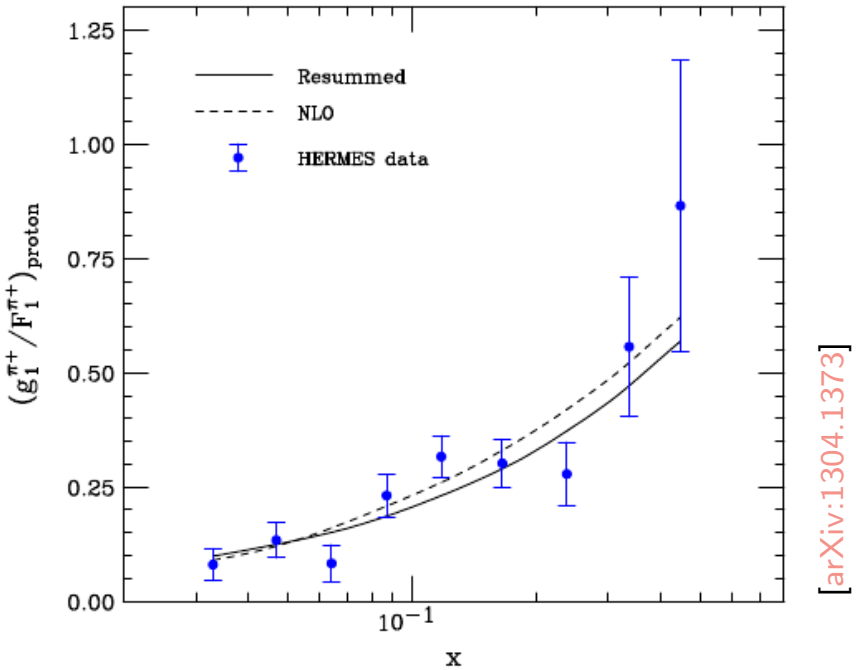
2) Progress on all-order resummation

DIS: Hall A data [arXiv:nucl-ex/0405006]



[arXiv:1304.1373]

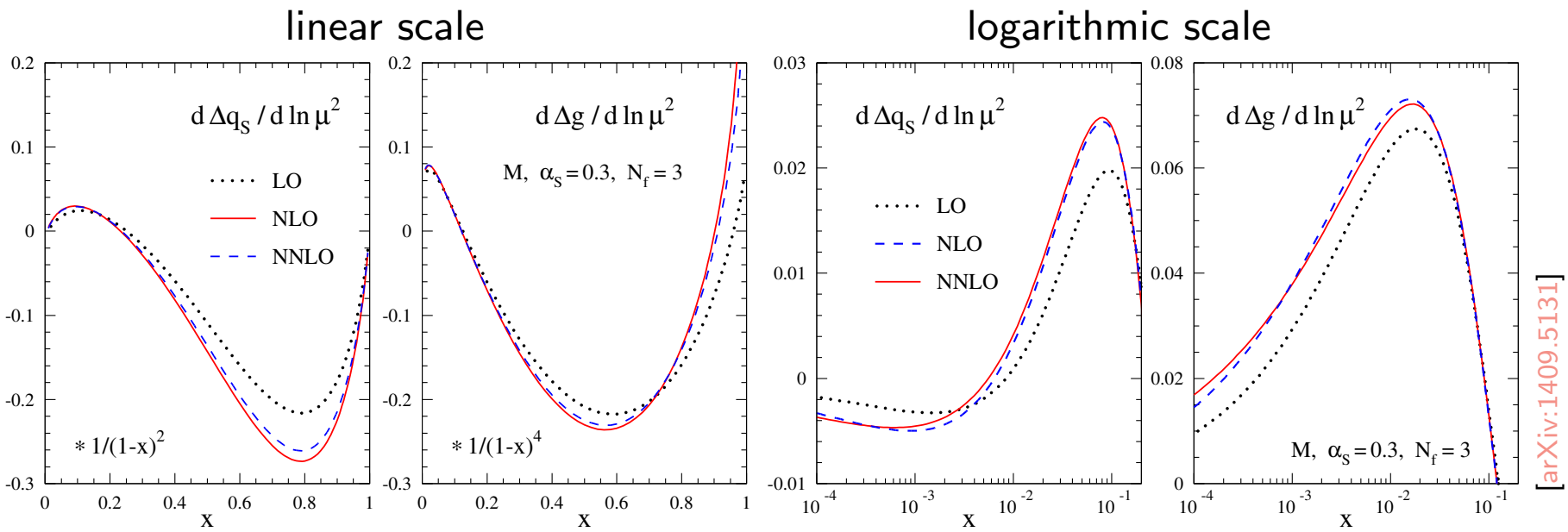
SIDIS: G. Karayan data [arXiv:hep-ex/0407032]



[arXiv:1304.1373]

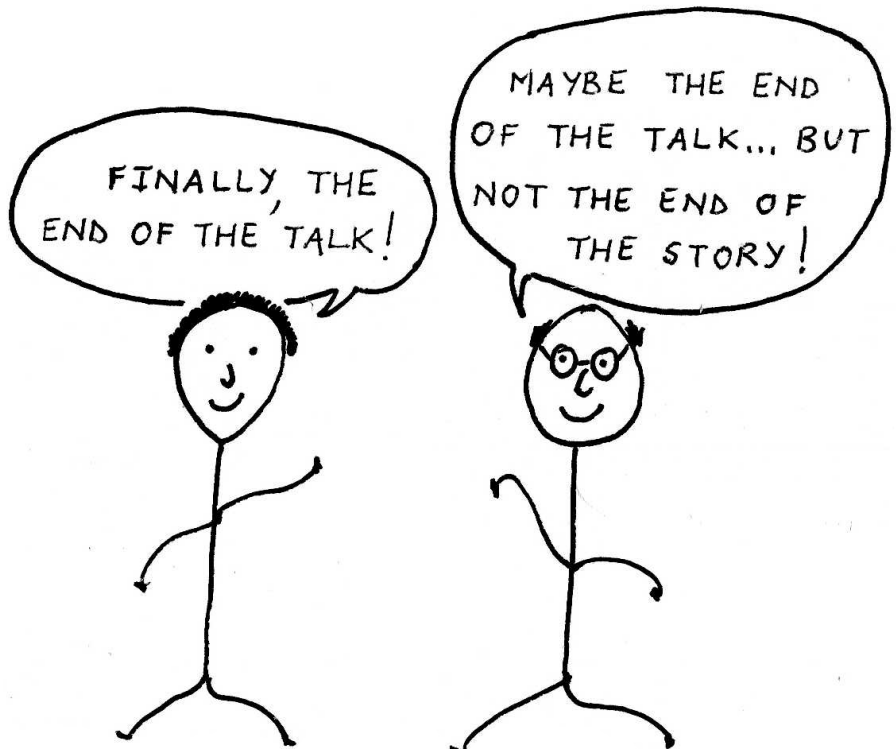
- resummation of large logarithm corrections to spin asymmetries in DIS and SIDIS
- asymmetries are rather insensitive to the inclusion of resummed higher-order terms
- modest decrease of spin asymmetries at fairly high x values, more pronounced for SIDIS
- most relevant for JLAB kinematics, important for future high statistic JLAB12

3) Progress on higher-order computations ($\overline{\text{MS}}$ scheme)



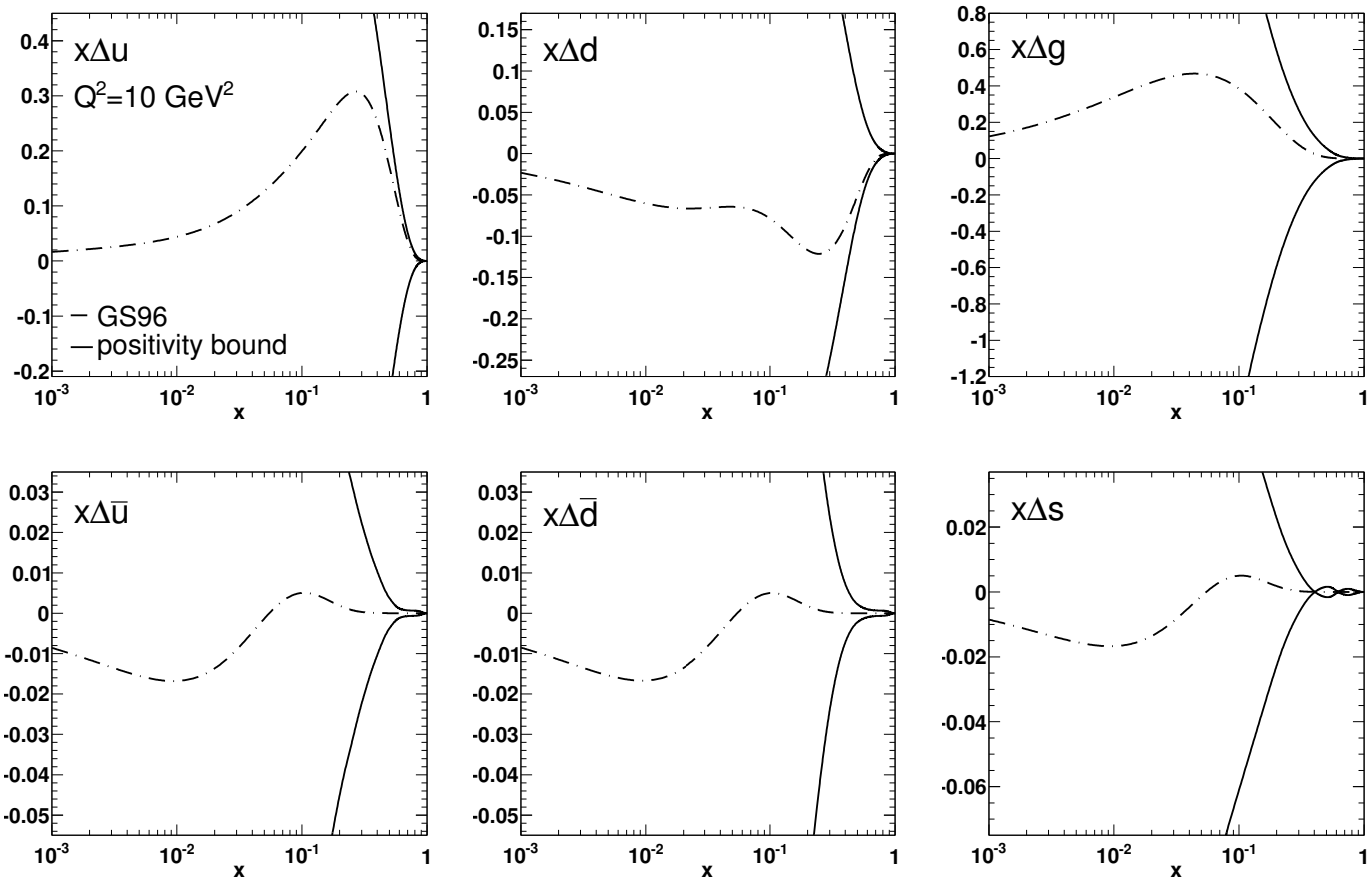
- NNLO (three-loop) corrections to spin-dependent splitting functions have been computed
- NNLO corrections to the splitting functions are small outside the region of small x
- corrections to the evolution of the PDFs can be unproblematic down to $x \approx 10^{-4}$
- QCD analyses of polarized PDFs are now feasible up to NNLO accuracy
  $\rightarrow$ only in a FFN scheme (VFN would require non-trivial unknown matching conditions)
  $\rightarrow$ only including DIS data (coefficient functions are know at NNLO only for DIS)

4. Summary and outlook



A new standard of spin-dependent PDF

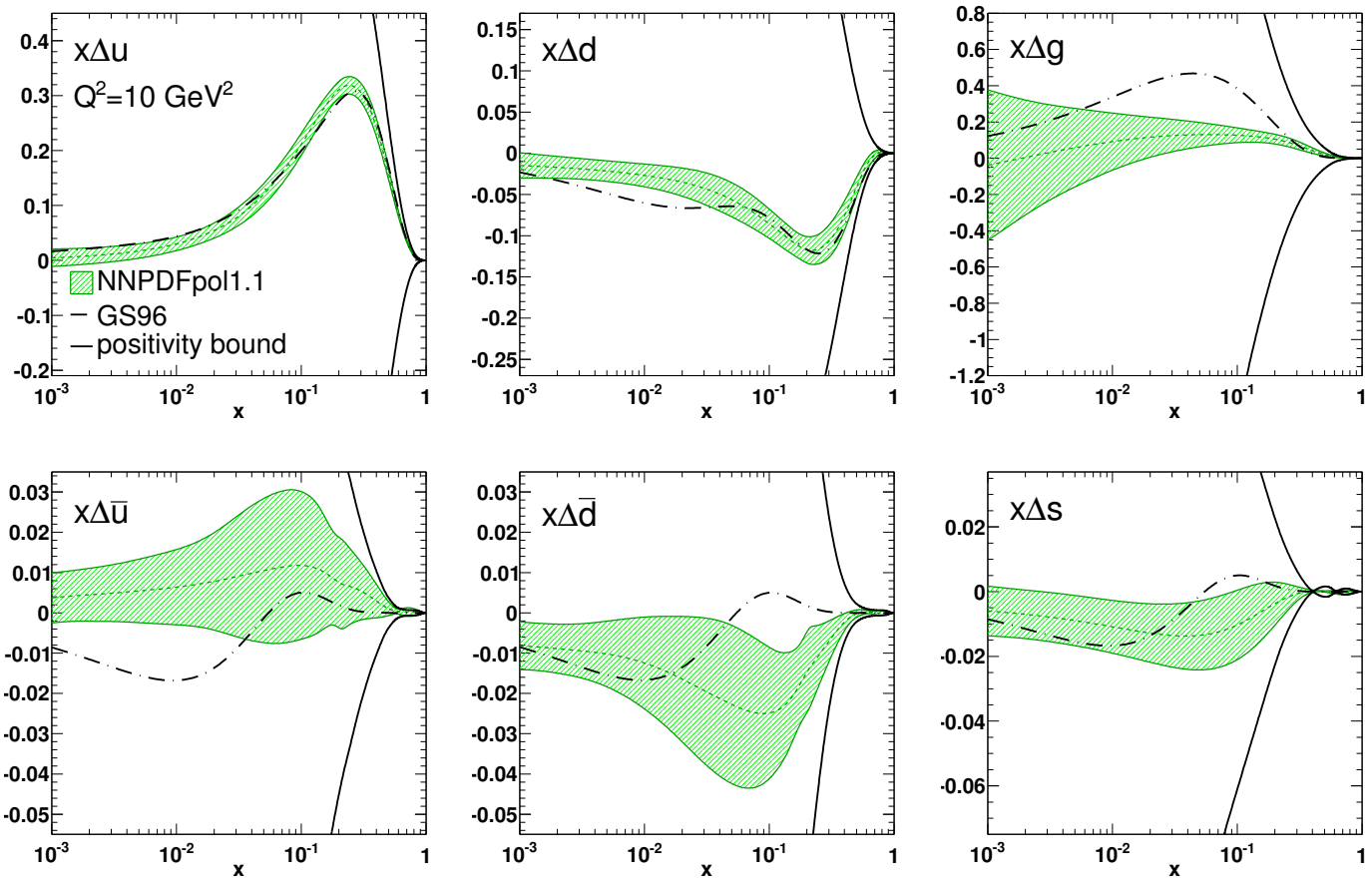
1996 [arXiv:hep-ph/9512406]



Polarized PDFs took the first steps

A new standard of spin-dependent PDF

2014 [arXiv:1406.5539]



Polarized PDFs are coming of *adult age* now

Achievements & open issues

ACHIEVEMENTS

- new data are improving the accuracy of PDFs determined in global QCD analyses
- there is evidence for a positive gluon polarization in the x region covered by RHIC data
- a determination of $\Delta\bar{u}$ and $\Delta\bar{d}$ distributions from W data is now possible

$$\int_{10^{-3}}^{1} dx\Delta\Sigma(x, 10\,\mathrm{GeV}^2) = 0.25 \pm 0.10 \qquad \int_{0.05}^{0.5} dx\Delta g(x, 10\,\mathrm{GeV}^2) = 0.23 \pm 0.07$$

OPEN ISSUES

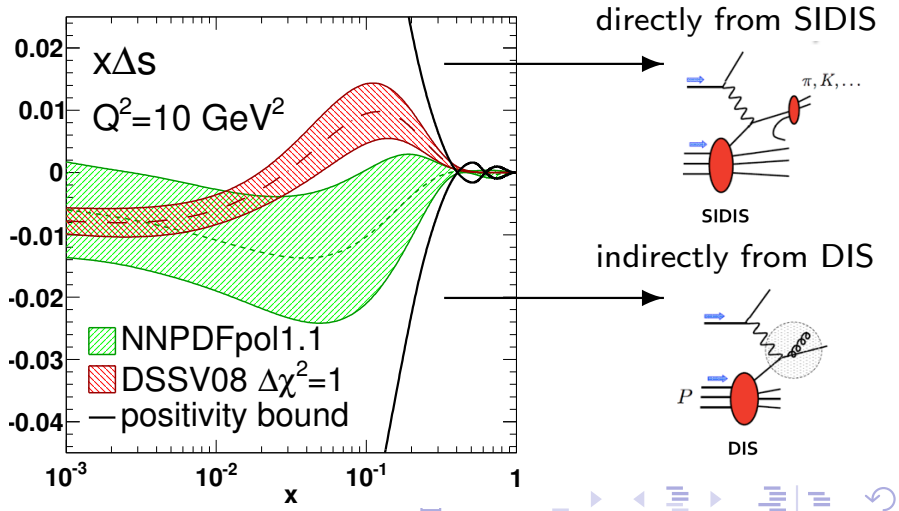
- uncertainties coming from the small-x unmeasured region dominate

$$\int_{0}^{1} dx\Delta\Sigma(x, 10\,\mathrm{GeV}^2) = 0.18 \pm 0.21 \qquad \int_{0}^{1} dx\Delta g(x, 10\,\mathrm{GeV}^2) = 0.03 \pm 3.24$$

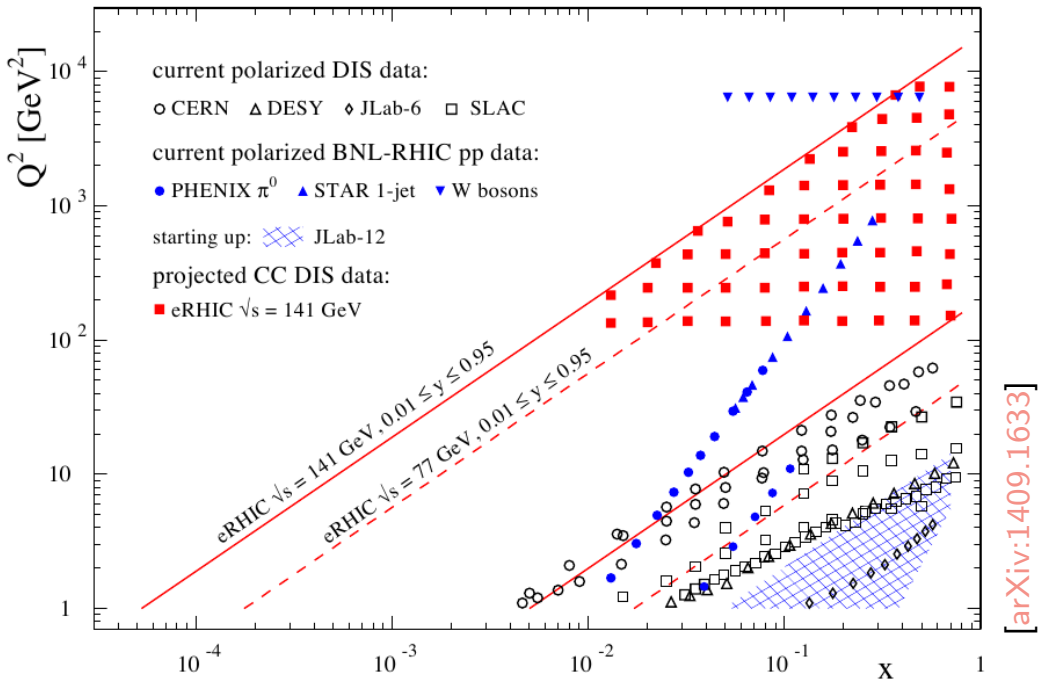
- is there mounting tension between inclusive DIS and (kaon) SIDIS data?

  $\rightarrow$ DIS data $\Rightarrow$ negative $x\Delta s$
  $\rightarrow$ SIDIS data $\Rightarrow$ changing sign $x\Delta s$
  $\rightarrow$ new, very precise, JLAB data (DIS) point to negative $x\Delta s$ [arXiv:14101657]
  $\rightarrow$ simmetry breaking? (F.-C. Cao)

- need for a better knowledge of FF
  $\rightarrow$ new data are now available (F. Kunne, G. Karayan)
  $\rightarrow$ global QCD analyses are ongoing



Opportunities at a future EIC



[arXiv:1409.1633]

REQUIREMENTS & FEATURES

- large kinematic reach
  $\rightarrow$ high-energy collider
- precision of electromagnetic probes
  $\rightarrow$ electron beams
- spin
  $\rightarrow$ polarized hadron beams
- versatility
  $\rightarrow$ heavy ion beams

DELIVERABLES	OBSERVABLES	WHAT WE LEARN
Δg	scaling violations in DIS	gluon contribution to proton spin
Δq, $\Delta \bar{q}$	SIDIS for pions and kaons	quark contribution to proton spin; flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$; strangeness Δs
$g_1^{W^-}$, $g_5^{W^-}$	inclusive CC DIS at high Q^2	flavor separation at medium x and high Q^2

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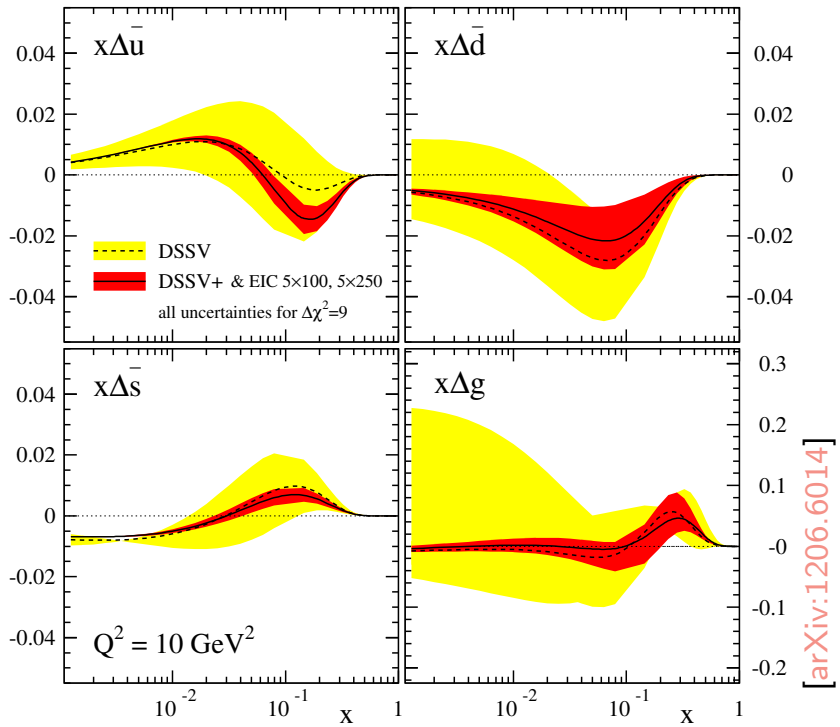

EXPECTED IMPACT OF EIC DATA

- dramatic reduction of uncertainties of both PDFs and their moments
- accurate determination of Δg via scaling violations in DIS
- accurate determination of $\Delta\bar{u}$, $\Delta\bar{d}$ via SIDIS and CC DIS
- access to unknown electroweak structure functions via CC DIS

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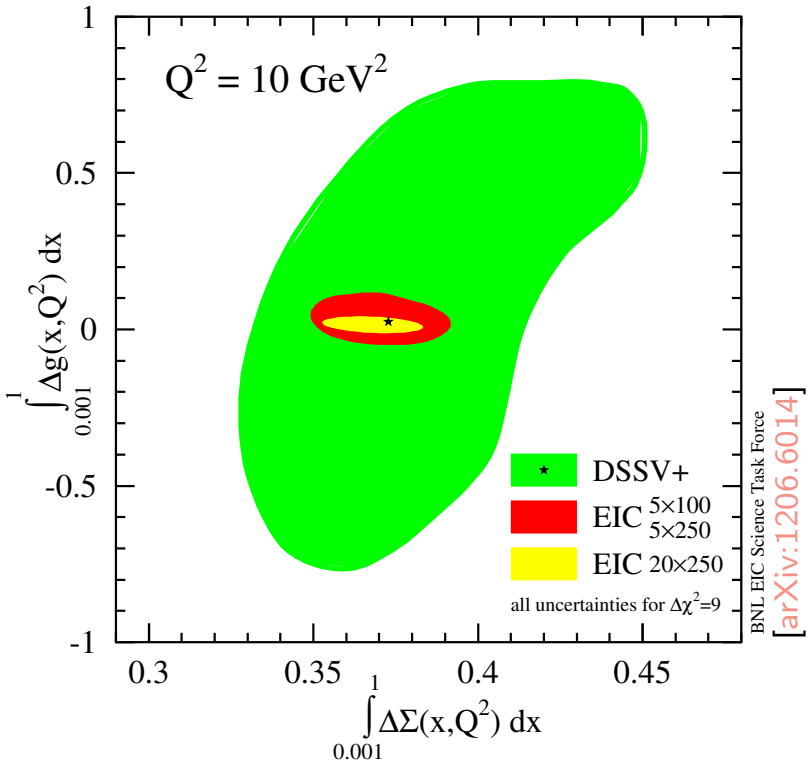

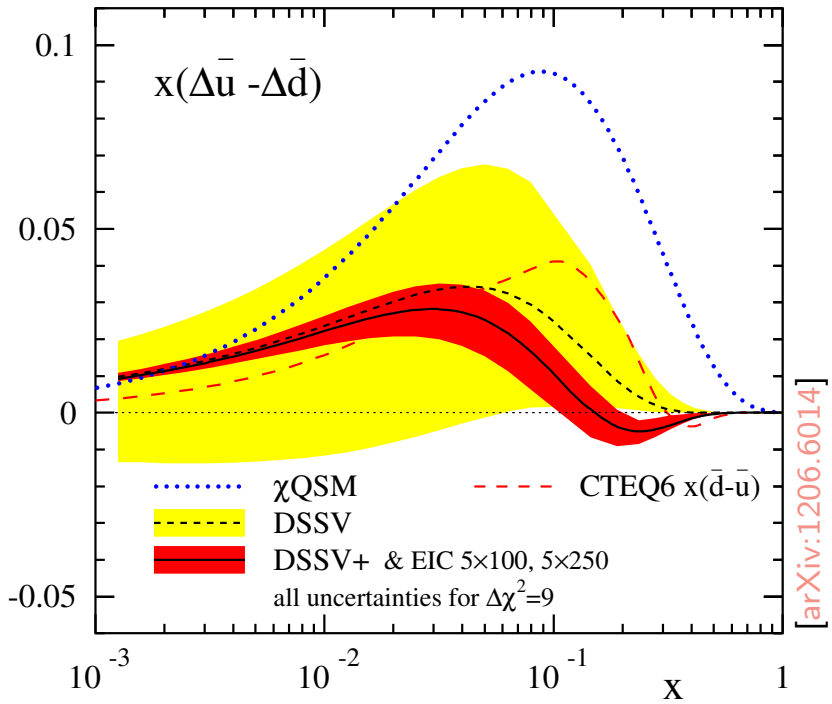

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(X. Jiang)

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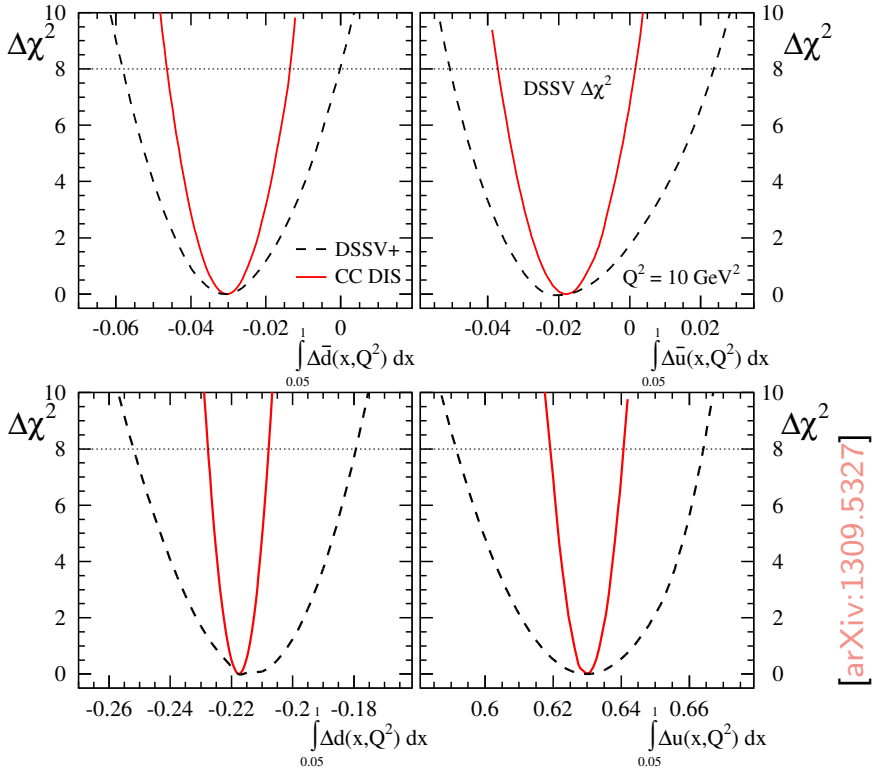

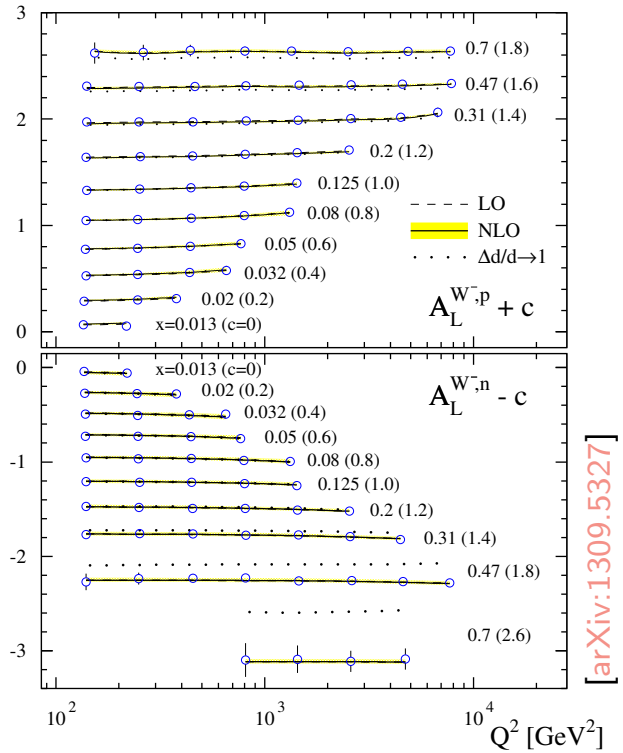

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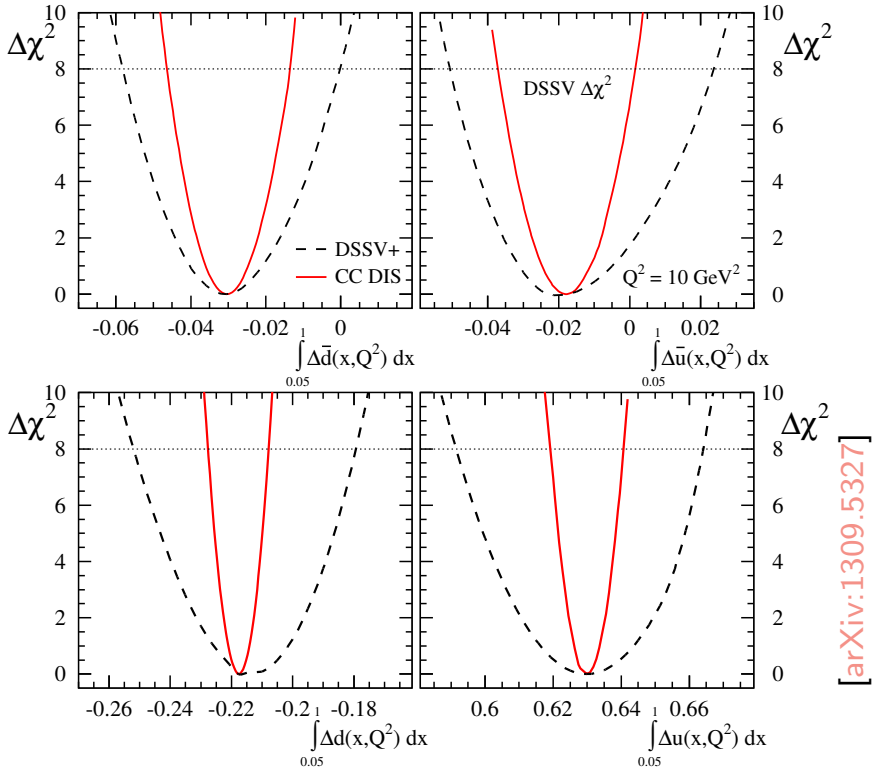

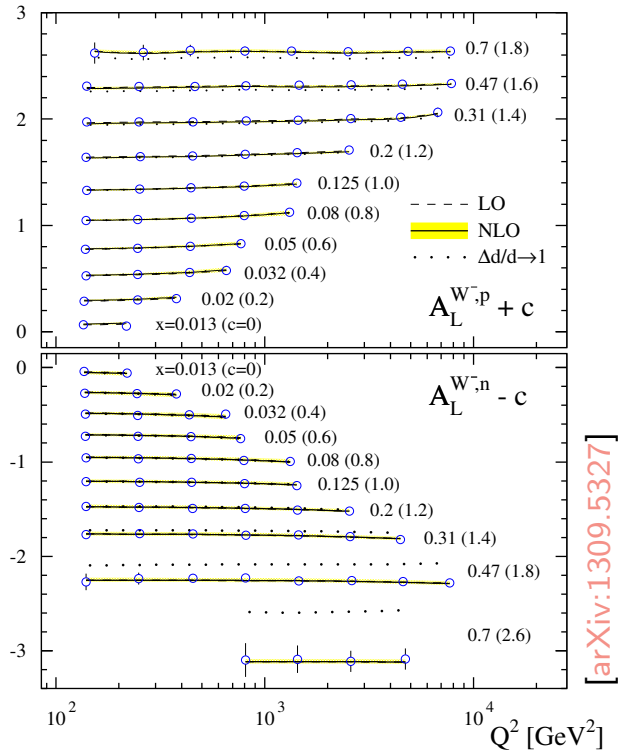

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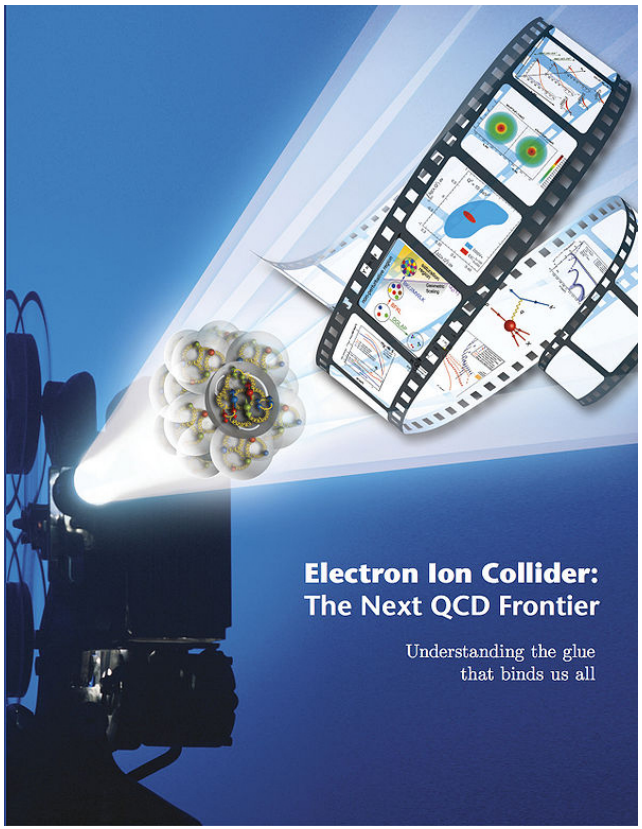
More in S11 parallel session

Take away message

Spin experiments continue to produce high impact results
(STAR, PHENIX, COMPASS, JLAB)

Theory efforts and global QCD fits try to keep up interesting physics questions in gluon/sea quark regime

The next (last?) chapter in the tale of the proton spin will begin with an EIC



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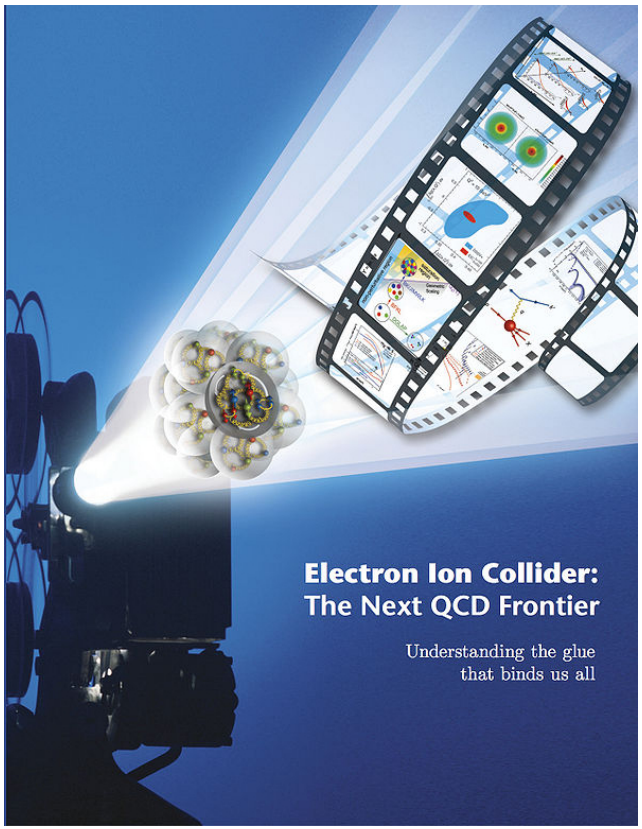
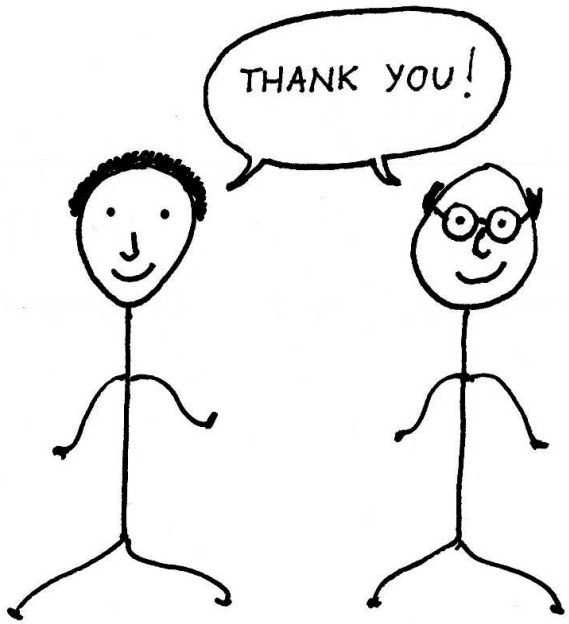


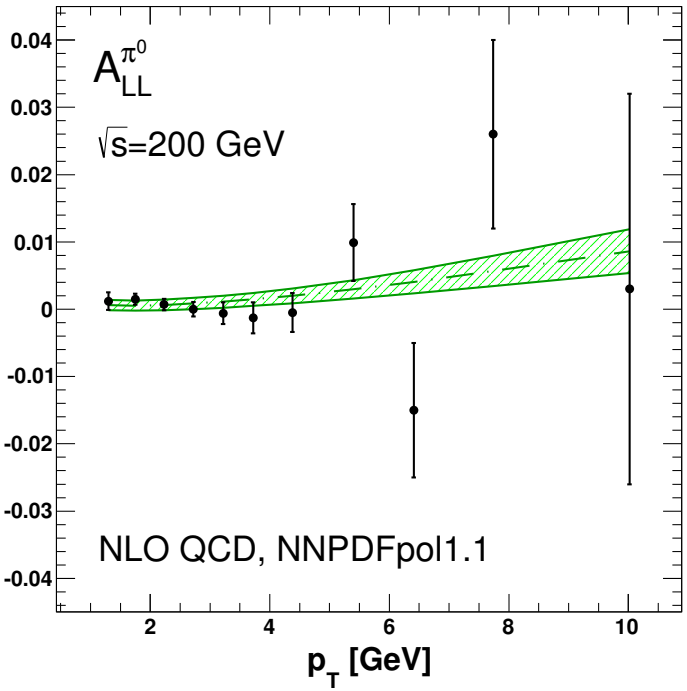


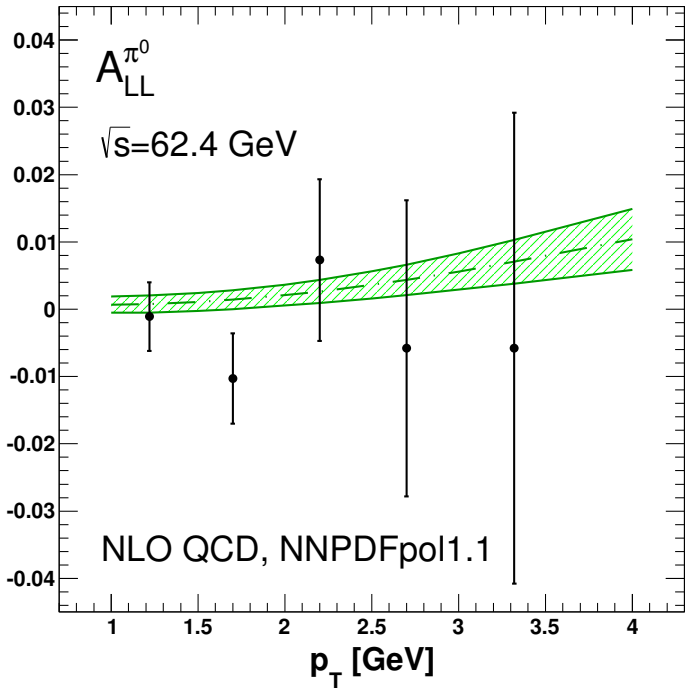
5. Backup

Predictions for single-hadron production asymmetry

$$A_{LL}^{H} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes D_c^H \otimes \Delta\hat{\sigma}_{ab}^c}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes D_c^H \otimes \hat{\sigma}_{ab}^c}$$

PHENIX [arXiv:0810.0701] [arXiv:0810.0694] [arXiv:1402.6296] STAR [arXiv:1309.1800]





- Good agreement between experimental data and theoretical predictions
- Experimental uncertainties are larger than than those of the corresponding predictions
- We expect a slight impact on the gluon PDF from these data

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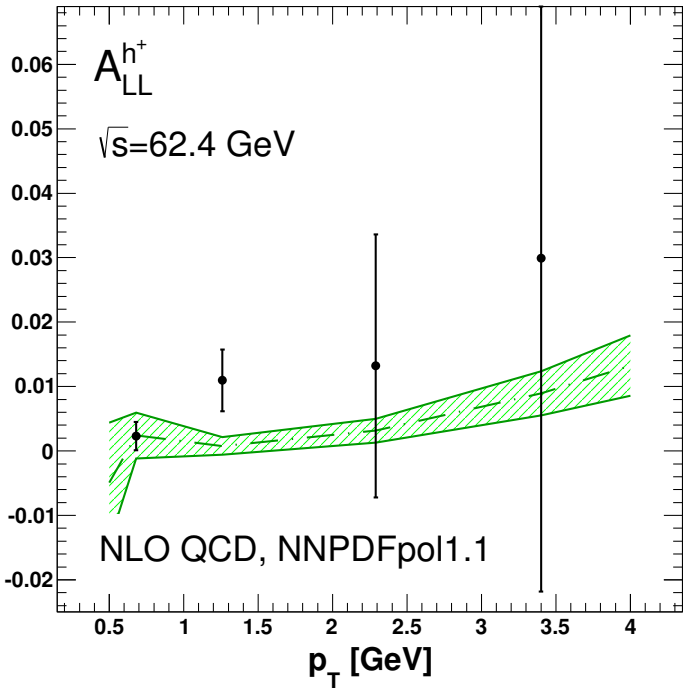

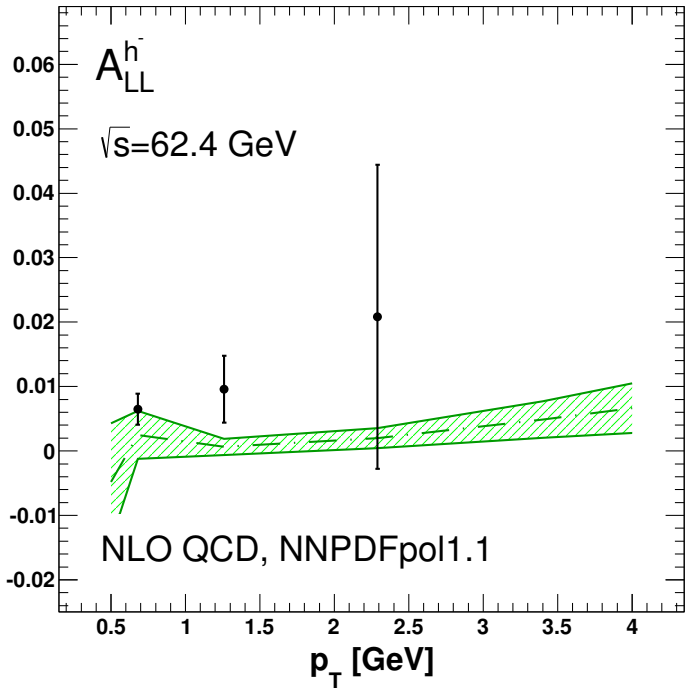

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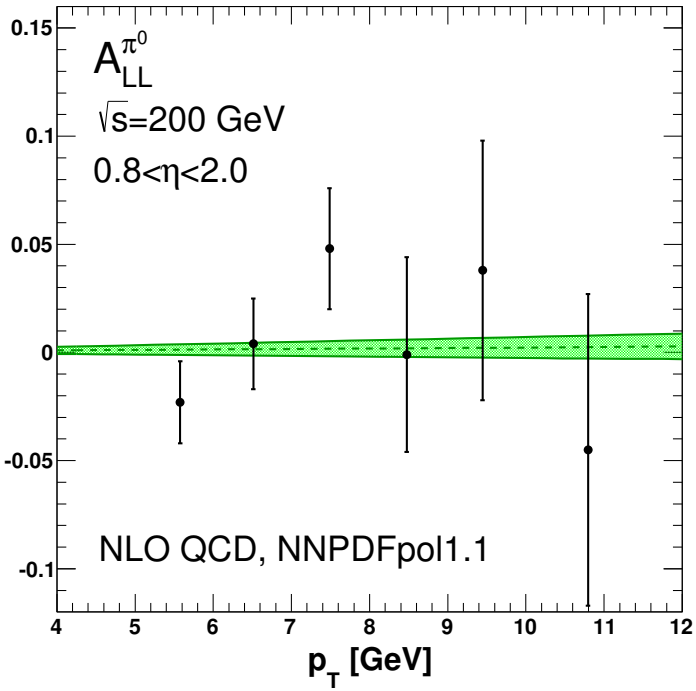

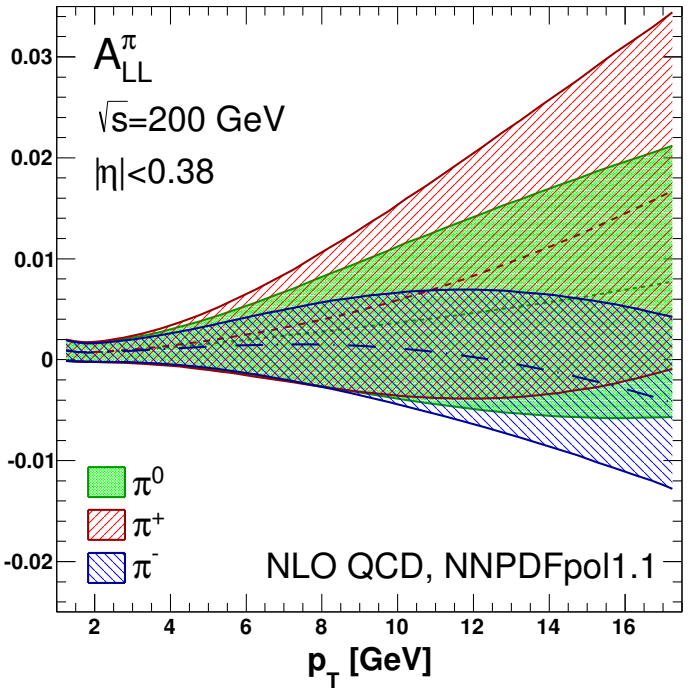

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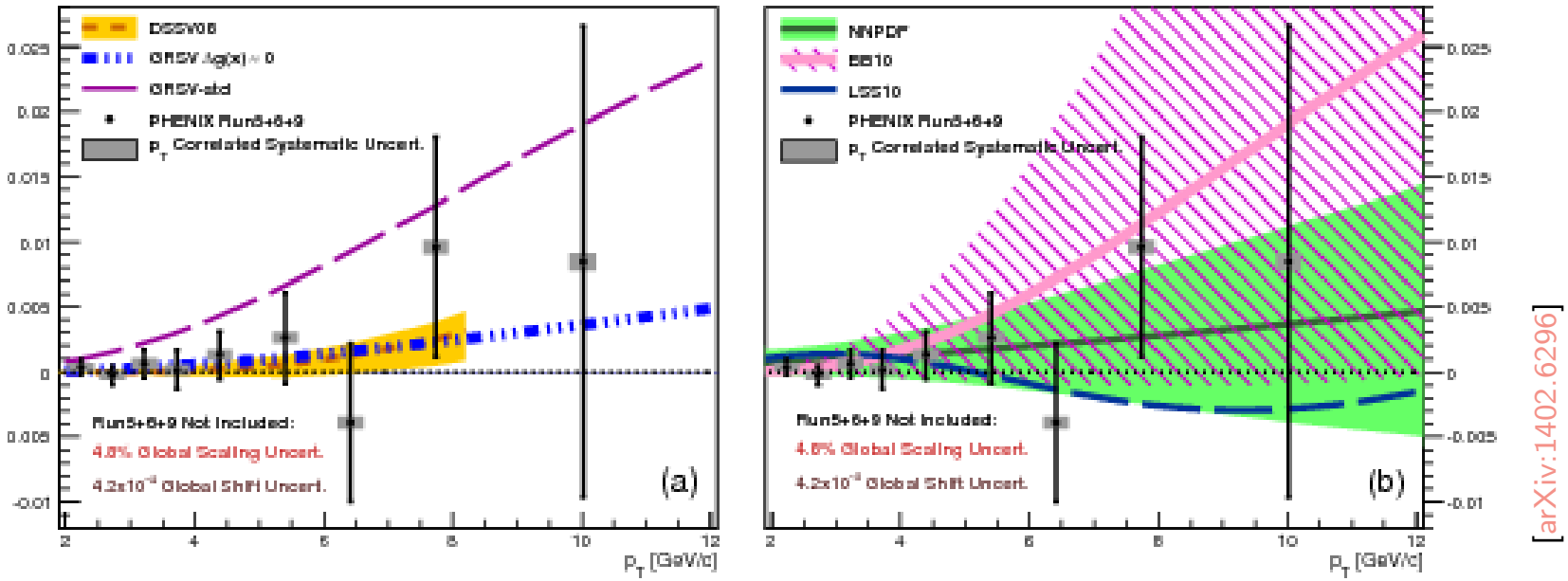

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Effects of open-charm production at COMPASS

Virtual photon-nucleon asymmetry for open-charm production

[arXiv:1212.1319]

$$A^{\gamma N \to D^0 X} = \frac{\Delta g \otimes \Delta\hat{\sigma}_{\gamma g} \otimes D_c^H}{g \otimes \hat{\sigma}_{\gamma g} \otimes D_c^H}$$

FEATURES

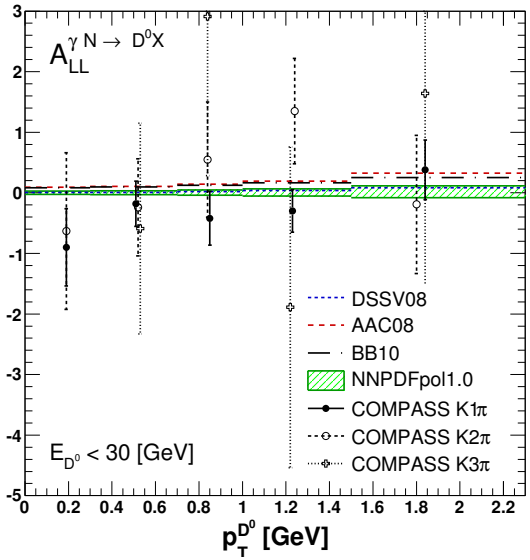
- Δg is probed *directly* through the photon-gluon fusion process
  (in DIS Δg is mostly probed through scaling violations instead)
- the fragmentation functions for heavy quarks are computable in perturbation theory
  (and only introduce a very moderate uncertainty in the fit)

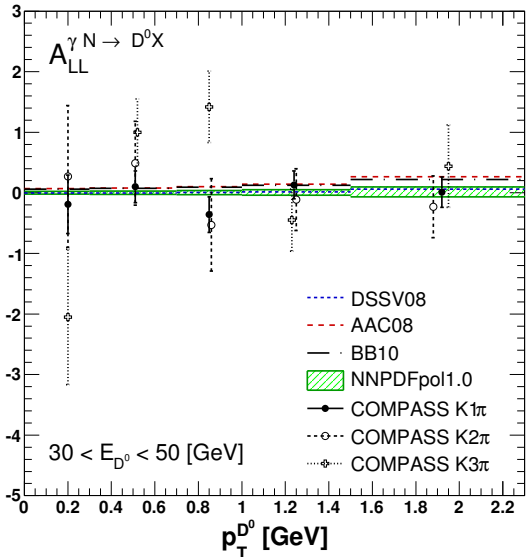
EXPERIMENTAL MEASUREMENT

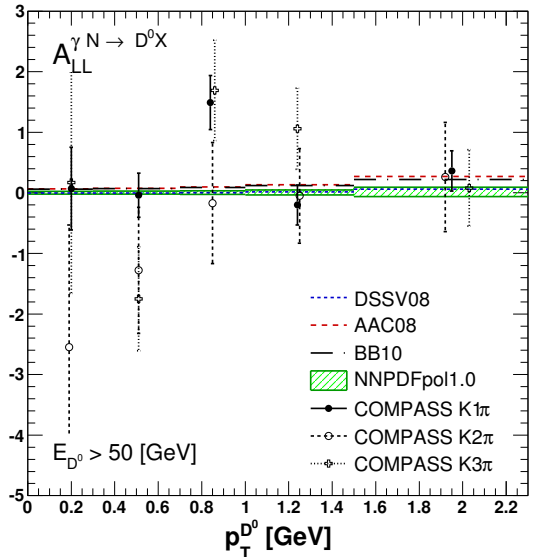
- COMPASS (2002-2007) [arXiv:1211.6849]

Experiment	Set	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$ NNPDFpol1.0	DSSV08	AAC08	BB10
COMPASS		45	1.23	1.23	1.27	1.25
	COMPASS $K1\pi$	15	1.27	1.27	1.43	1.38
	COMPASS $K2\pi$	15	0.51	0.51	0.56	0.55
	COMPASS $K3\pi$	15	1.90	1.90	1.81	1.82

Effects of open-charm production at COMPASS



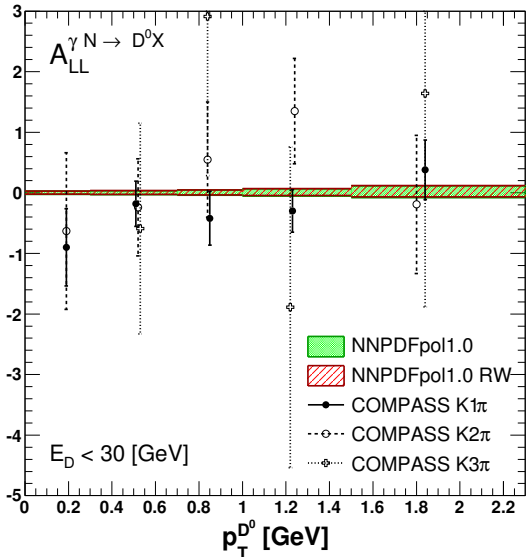


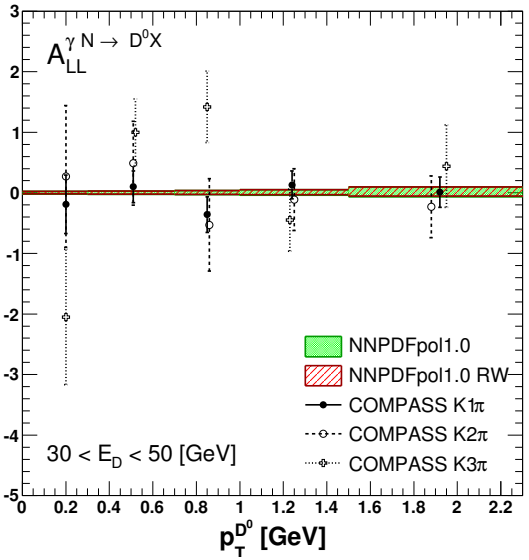


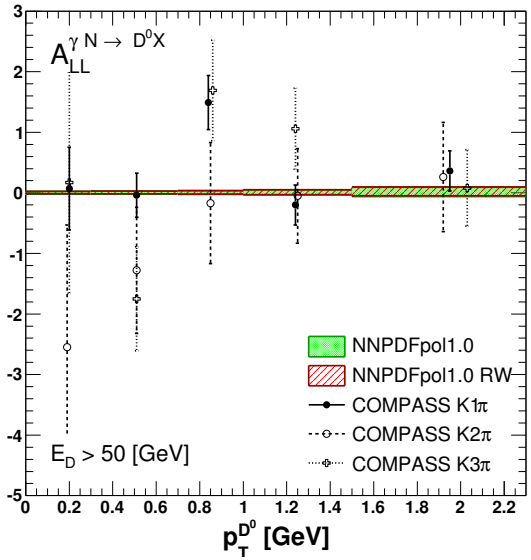
Data are affected by large uncertainties w.r.t. the uncertainty due to PDFs
They do not show a clear trend

Experiment	Set	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$ NNPDFpol1.0	DSSV08	AAC08	BB10
COMPASS		45	1.23	1.23	1.27	1.25
	COMPASS $K1\pi$	15	1.27	1.27	1.43	1.38
	COMPASS $K2\pi$	15	0.51	0.51	0.56	0.55
	COMPASS $K3\pi$	15	1.90	1.90	1.81	1.82

Effects of open-charm production at COMPASS







The impact of open-charm data from COMPASS is mostly negligible, as we notice from the value of the $\chi^2/N_{\rm ndat}$ and the reweighted observable

Experiment	Set	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$	$\chi^2_{\rm rw}/N_{\rm dat}$
COMPASS		45	1.23	1.23
	COMPASS $K1\pi$	15	1.27	1.27
	COMPASS $K2\pi$	15	0.51	0.51
	COMPASS $K3\pi$	15	1.90	1.89