

Nucleon Helicity Structure: Experimental Overview

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Spin'16

Parton Distribution Functions (PDF)

Partons \equiv (anti)quarks and gluons

Helicity distribution

$$\Delta f(x) =$$

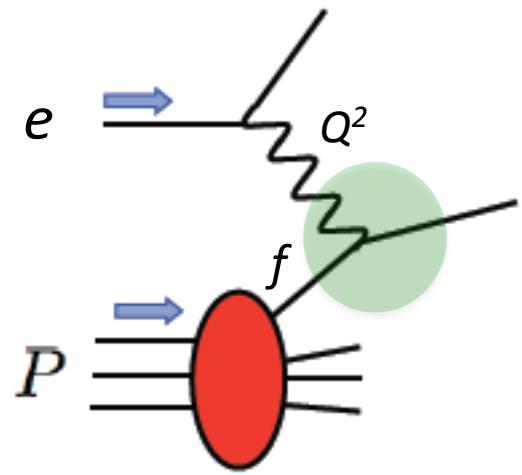


Unpolarized distribution

$$f(x) =$$



PDF and pQCD



Factorization:

$$\Delta\sigma \sim \sum_{f=q,\bar{q},g} \int dx \cdot \Delta f(x) \cdot \hat{\Delta\sigma}^f(\hat{s})$$

$\Delta f(x)$, $f(x)$ – Universal between DIS and pp

Scale dependence: $\Delta f(x)$, $f(x) \Rightarrow \Delta f(x, Q^2)$, $f(x, Q^2)$

- Different Q^2 probe PDF differently
- Higher Q^2 - better resolution
- DGLAP evolution: $\Delta f(x, Q_0^2) \Rightarrow \Delta f(x, Q^2)$
- Gluon and quark PDF mix up

$$\frac{d}{d \ln Q^2} \begin{pmatrix} \Delta q \\ \Delta g \end{pmatrix} = \begin{pmatrix} \Delta P_{qq} & \Delta P_{qg} \\ \Delta P_{gq} & \Delta P_{gg} \end{pmatrix} \otimes \begin{pmatrix} \Delta q \\ \Delta g \end{pmatrix}$$

ΔP_{ij} – splitting functions, calculable in pQCD

Helicity PDF and Proton Spin

Jaffe – Manohar Spin Sum rule

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

$$\Delta\Sigma(Q^2) = \int_0^1 dx [\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}] (x, Q^2)$$

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

=> Need to know $\Delta f(x)$ in wide x range

Helicity PDF: other applications

- Valence region:
Testing ground for models
- Sea quarks: $\Delta\bar{u}$ vs $\Delta\bar{d}$
Asymmetry in pol. sea?
- Strange quarks: Δs , $\Delta\bar{s}$
 $SU(3)_f$ breaking?
- Bjorken sum rule:
A fundamental pQCD prediction

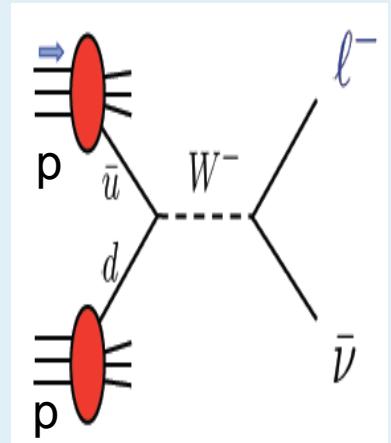
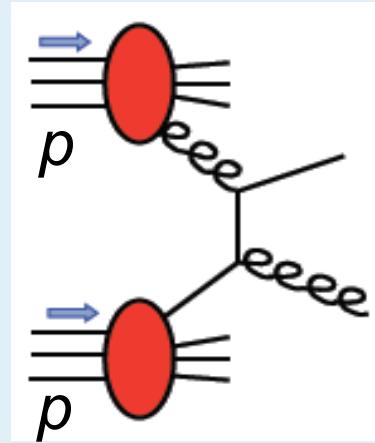
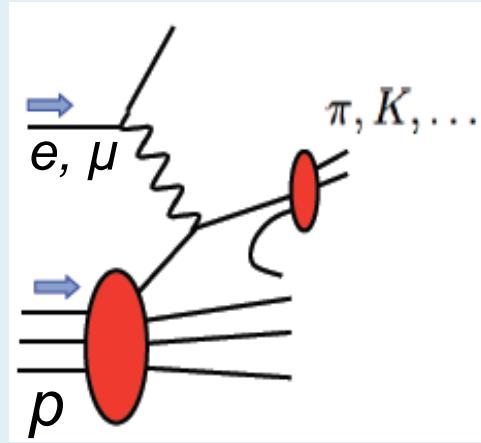
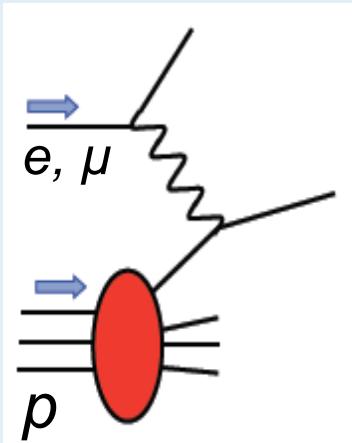
$$\frac{\Delta d}{d} \xrightarrow{x \rightarrow 1} \begin{cases} 1 & \text{Counting rules/pQCD} \\ -1/3 & \text{Constituent quark model} \end{cases}$$

Variety of models:
meson cloud, chiral quark, Pauli blocking, ...

$$\Delta\Sigma = (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s}) = \\ 3F - D + 3(\Delta s + \Delta\bar{s})$$

$$\int_0^1 [g_1^p(x, Q^2) - g_1^n(x, Q^2)] dx = \frac{1}{6} \frac{g_A}{g_V} C^{NS}(\alpha_s(Q^2))$$

Access to Helicity PDF



DIS:

$$\Delta q + \Delta \bar{q}$$

Δg (From Q^2 evolution of g_1)

SIDIS:

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

Δg

pp:

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

Δg

Complementarity:

Different reaction – different aspects and kinematics

Test for Factorization&Universality

Experiments

Tremendous efforts over ~30 years



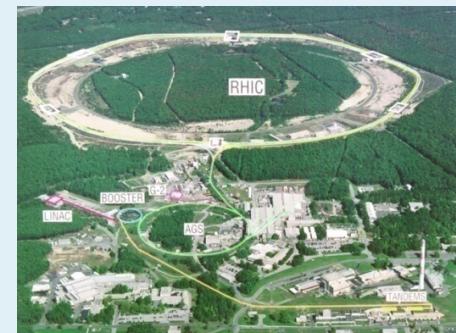
SLAC:
E80 – 155
 $e+p, d, {}^3He$

HERA:
HERMES
 $e+p, d, {}^3He$



CERN:
EMC, SMC,
COMPASS
 $\mu+p, d$

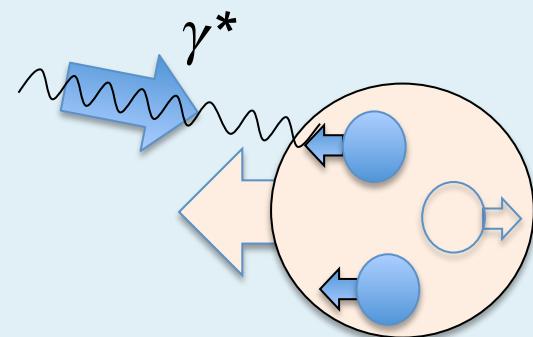
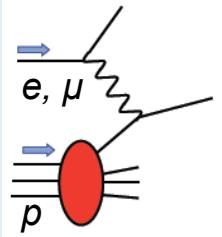
JLab:
Hall A, B, C
 $e+p, d, {}^3He$



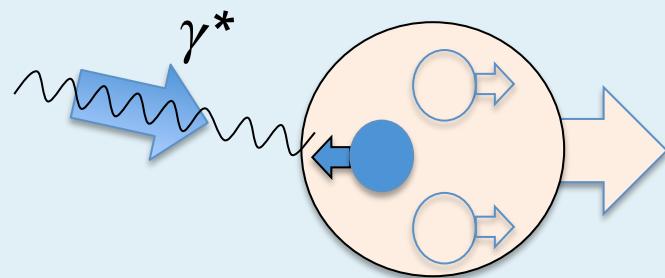
RHIC:
PHENIX,
STAR
 $p+p$ collider

Δq

DIS: Δq



$$\sigma_{1/2} \sim \sum_q e_q^2 q^+$$



$$\sigma_{3/2} \sim \sum_q e_q^2 q^-$$

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{g_1}{F_1} \approx \frac{\sum_q e_q^2 \Delta q}{\sum_q e_q^2 q}$$

From unpolarized DIS

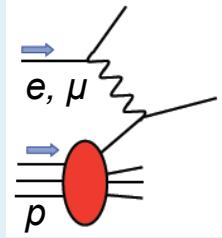
Spin independent

$$\frac{d^2\sigma}{d\Omega dE'} \sim c_1 F_1(x, Q^2) + c_2 F_2(x, Q^2) + c_3 g_1(x, Q^2) + c_4 g_2(x, Q^2)$$

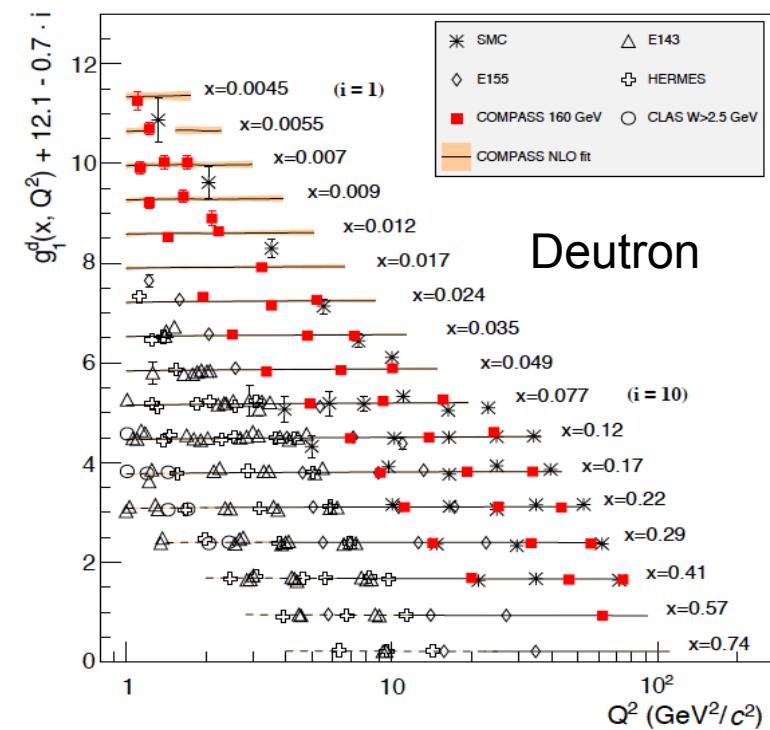
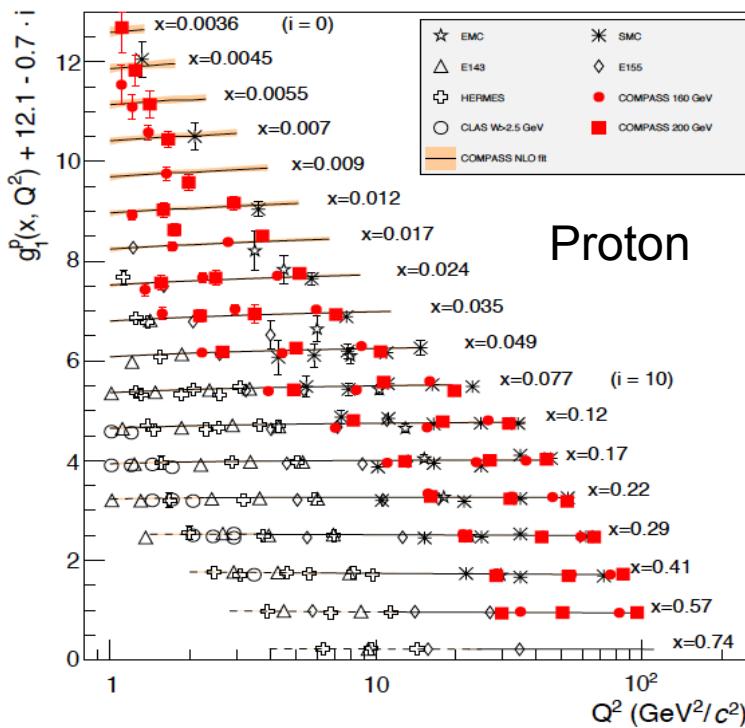
Spin dependent

DIS: g_1

$$g_1 \approx \sum_q e_q^2 \Delta q$$

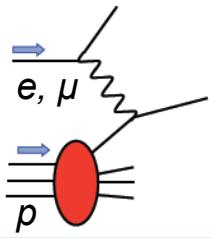


COMPASS: M.Wilfert, Parallel II

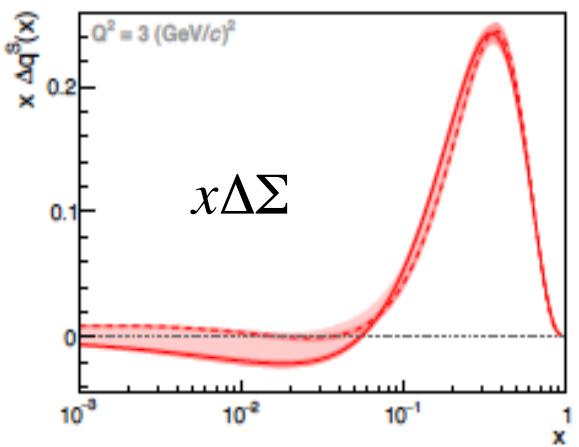


Precise recent data from COMPASS:
Extended x&Q² coverage

DIS: Δq fit



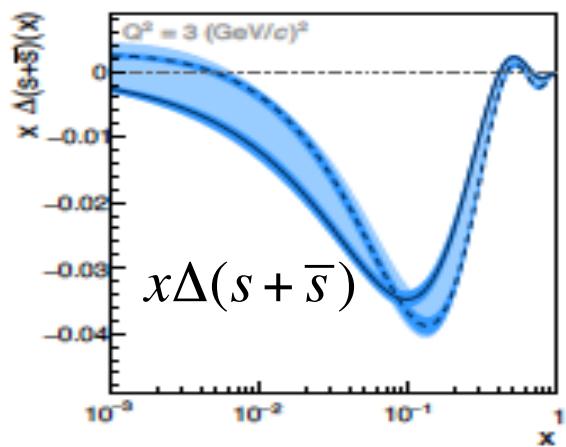
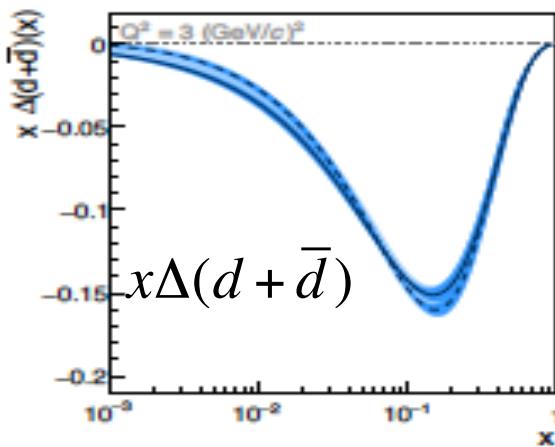
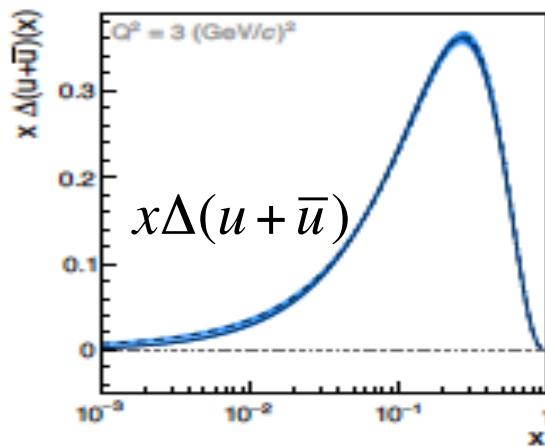
COMPASS: PLB 753 (2016), 18



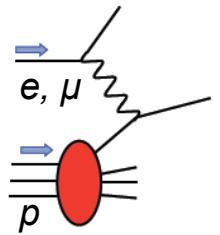
NLO pQCD fit of p, d and n (${}^3\text{He}$) data

- $0.26 < \Delta\Sigma < 0.36$ ($\sim 1/3$ of the proton spin)
(extrapolated to $x=0$ and $x=1$)
- p/n iso-symmetry \Rightarrow u/d separation
- Strange quark polarization is negative
Assumes SU(3)_f flavor symmetry:

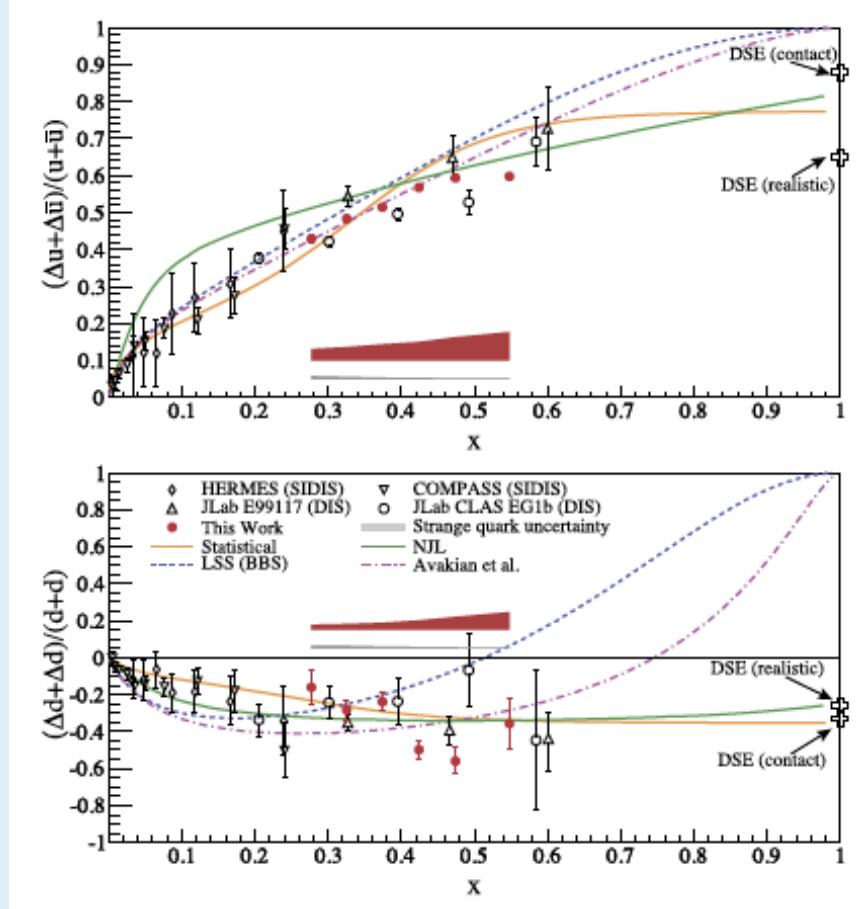
$$\Delta\Sigma = 3F - D + 3(\Delta s + \Delta \bar{s})$$



DIS: valence Δq



JLab-Hall A: Phys.Lett.B744 (2015), 309



Also new data from JLab-SANE

$\Delta u/u > 0$
 $\Delta u/u \rightarrow 1$ for $x \rightarrow 1$

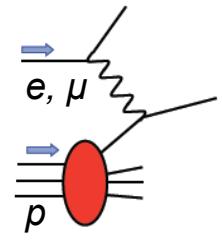
$\Delta d/d < 0$
 Up to $x \sim 0.6$

Test models on nucleon structure in valence region (with different OAM assumptions)

More precise data with extended x range expected from JLab-12GeV

DIS: Bjorken Sum Rule

A fundamental pQCD prediction



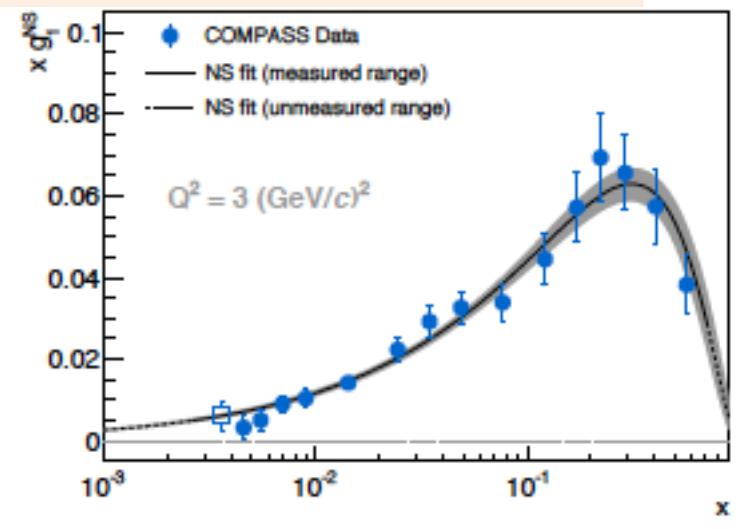
J.D.Bjorken, Phys. Rev. 148, 1467 (1966)

Current algebra, Isospin symmetry between u and d quarks

$$\Gamma_1^{NS}(Q^2) = \int_0^1 [g_1^p(x, Q^2) - g_1^n(x, Q^2)] dx = \frac{1}{6} \frac{g_A}{g_V} C^{NS}(\alpha_s(Q^2))$$

DIS data From neutron β decay Calculated to $O(\alpha_s^4)$

COMPASS: PLB 753 (2016), 18



COMPASS:

$$g_A/g_V = 1.22 \pm 0.05(\text{stat}) \pm 0.10(\text{syst})$$

Neutron β decay and C^{NS}

$$g_A/g_V = 1.2701 \pm 0.0020$$

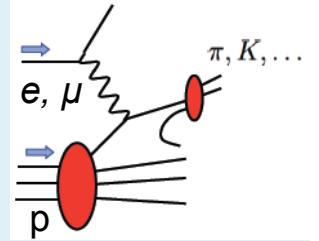
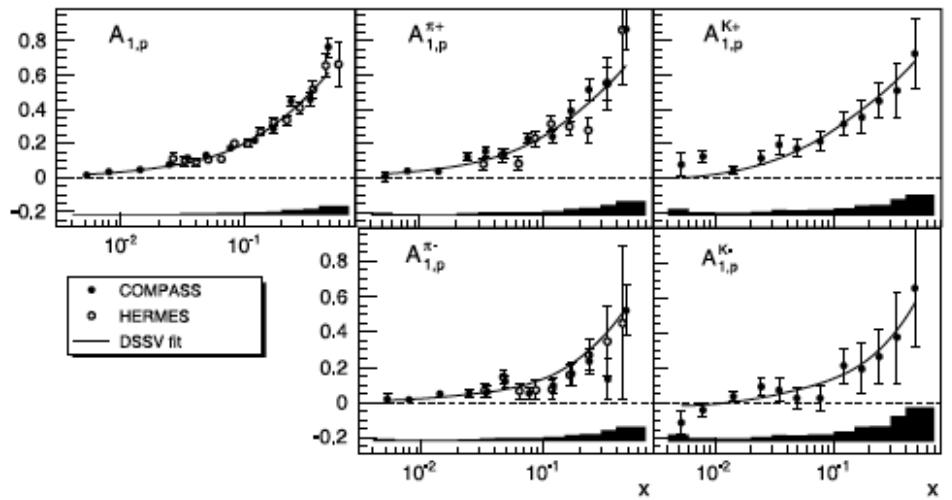
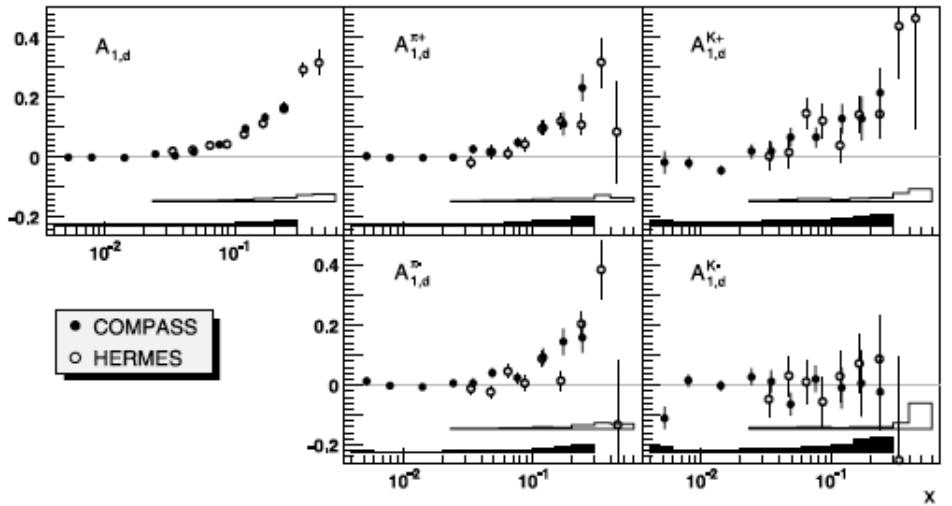
Verified to ~10%

~20% in NNPDF

(no functional form assumed for extrapolation to $x \sim 0$)

COMPASS: PLB680, 217; PLB693, 227
HERMES: PRD71, 012003

SIDIS: A_1



Measure:

$$A_{1d}, A_{1d}^{K^\pm}, A_{1d}^{\pi^\pm}, A_{1p}, A_{1p}^{K^\pm}, A_{1p}^{\pi^\pm}$$

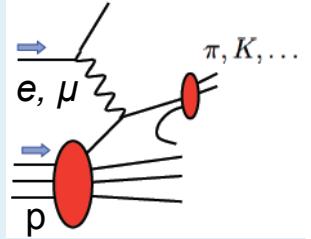
Extract:

$$\Delta u, \Delta \bar{u}, \Delta d, \Delta \bar{d}, \Delta s = \Delta \bar{s}$$

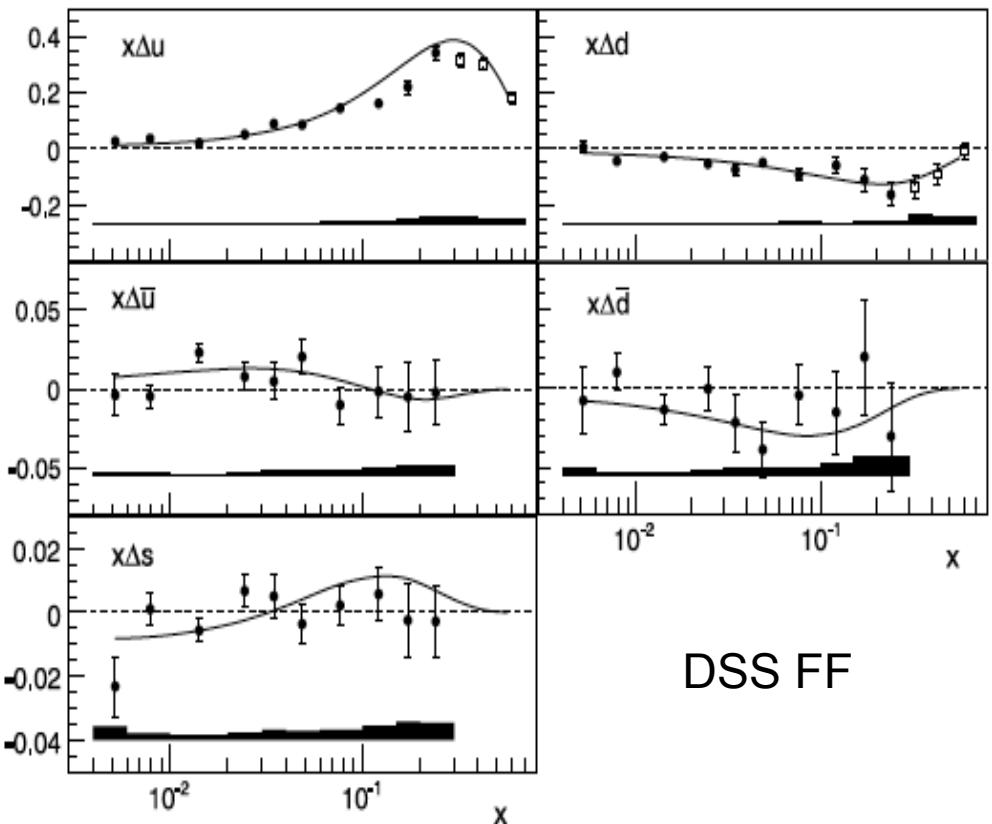
$$A_1^h = \frac{\sum_q e_q^2 \Delta q(x) \int D_q^h(z) dz}{\sum_q e_q^2 q(x) \int D_q^h(z) dz}$$

Depends on Fragmentation Func !

SIDIS: Δq



COMPASS: PLB693, 227



COMPASS LO extraction:

- Sea quarks pol. consistent with 0
Hint on $\Delta\bar{u} > 0$ and $\Delta\bar{d} < 0$
Flavor symmetry breaking?
- $\Delta s \sim 0$
Disagree with DIS extraction?
DIS: $\Delta s + \Delta\bar{s} \approx -0.1$
SU(3)_f broken?
Sensitive to kaon FF !

E.Leader, Parallel V

Similar results from other fits
(with larger variations for Δs)

Δs Puzzle

Tension between DIS and (kaon) SIDIS?

DIS => $\Delta s < 0$

Even more precise fit from LSS, PRD91, 054017 (2015)

SIDIS => $\Delta s \sim 0$, changing sign vs x

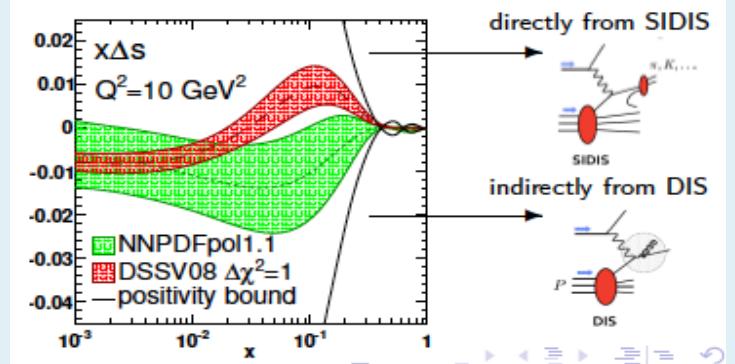
$\Delta s \sim 0$ also in Lattice: QCDSF Coll., PRL108, 222001

Resolution Path(s):

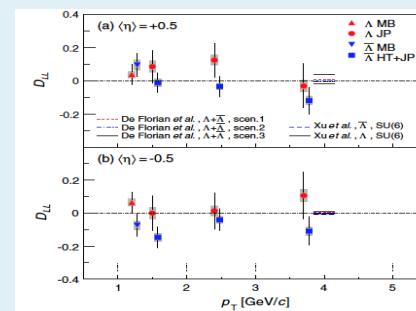
- SIDIS: improve (kaon) FF
 - From LHC, COMPASS, HERMES, BELLE, BaBar
- $\vec{p}p \rightarrow \vec{\Lambda}X$
 - Λ polarization sensitive to Δs
 - Need more theoretical work
 - Exp. data coming
- DIS CC charm production or $p\bar{p} \rightarrow W+c$
 - Charm-tagging to probe Δs
 - Requires a lot of $L \Rightarrow$ EIC
- NC $v p$
 - $\Delta s = G_A^s(Q^2=0)$, trend to $\Delta s < 0$
 - New data coming from μ BooNE

K.Woodruff, Parallel V

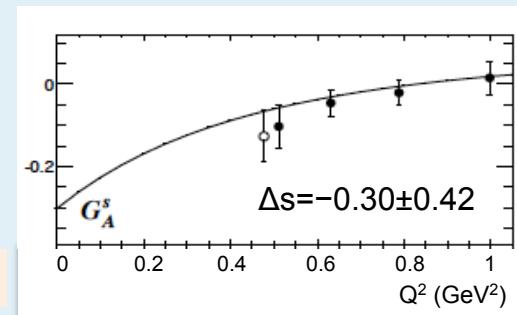
E.Nocera at SPIN2014



STAR
PRD80,111102



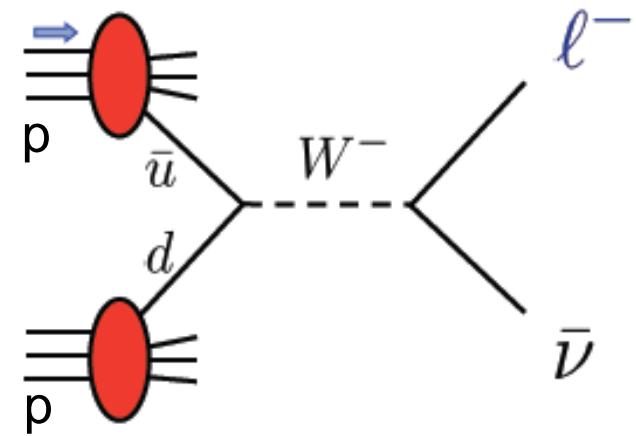
S.Pate
At INPC-2013



pp: $\Delta q(\text{bar})$

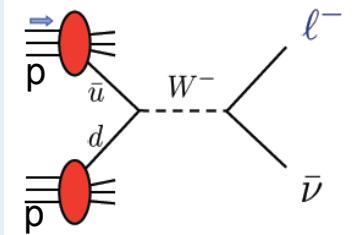
$$p+p \rightarrow W^\pm \rightarrow (e/\mu)^\pm + \nu$$

- Parity violating W production:
Fixes quark helicity and flavor:
 $d_L \bar{u}_R \rightarrow W^- \quad u_L \bar{d}_R \rightarrow W^+$
- No fragmentation involved
- High Q^2 (set by W mass)

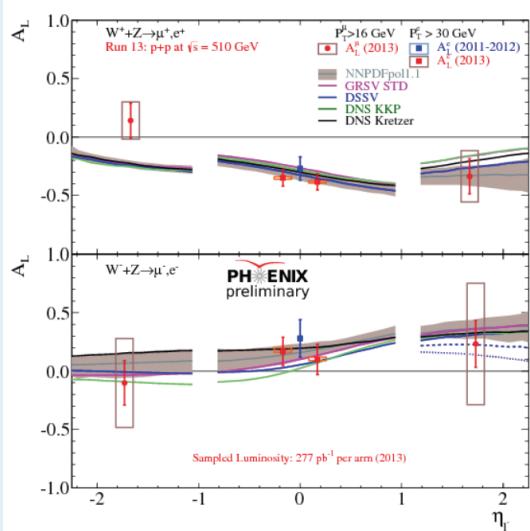


$$A_{L^{\pm}} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \sim \frac{\Delta \bar{u}(x_1) d(x_2)(1 - \cos\theta)^2 - \Delta d(x_1) \bar{u}(x_2)(1 + \cos\theta)^2}{\bar{u}(x_1) d(x_2)(1 - \cos\theta)^2 - d(x_1) \bar{u}(x_2)(1 + \cos\theta)^2}$$

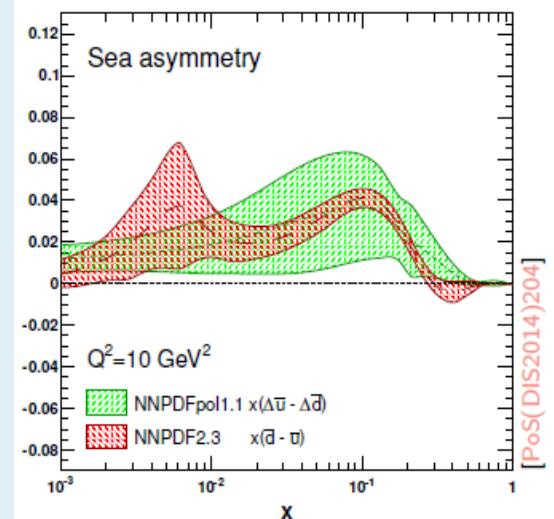
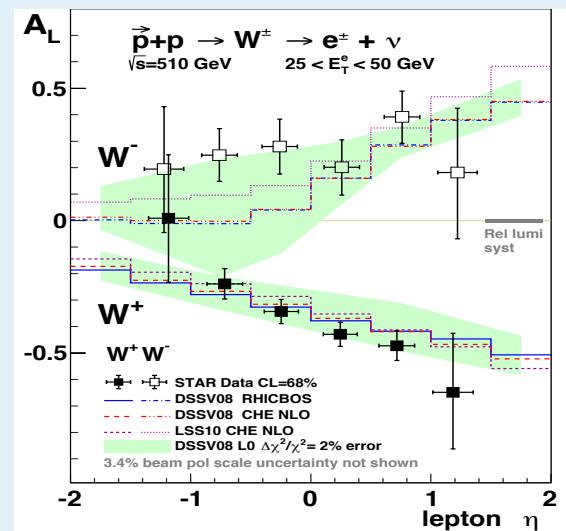
$p\bar{p} \rightarrow W^\pm \rightarrow l^\pm$



PHENIX: $W \rightarrow e$, PRD93, 051103 (2016)
 $W \rightarrow \mu$, Preliminary

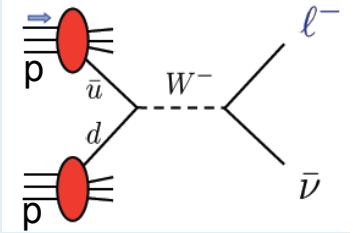


STAR: $W \rightarrow e$, PRL113, 072301 (2014)



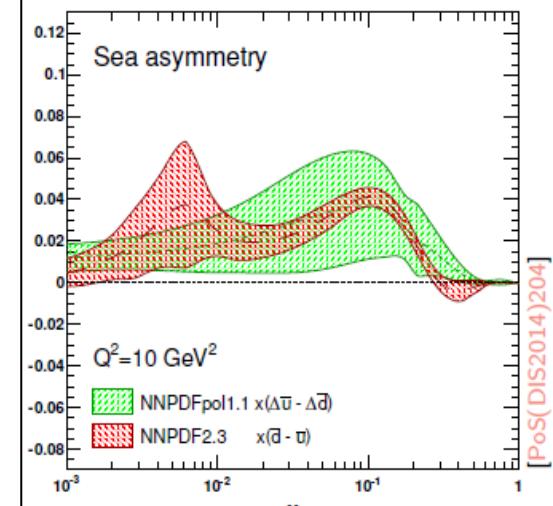
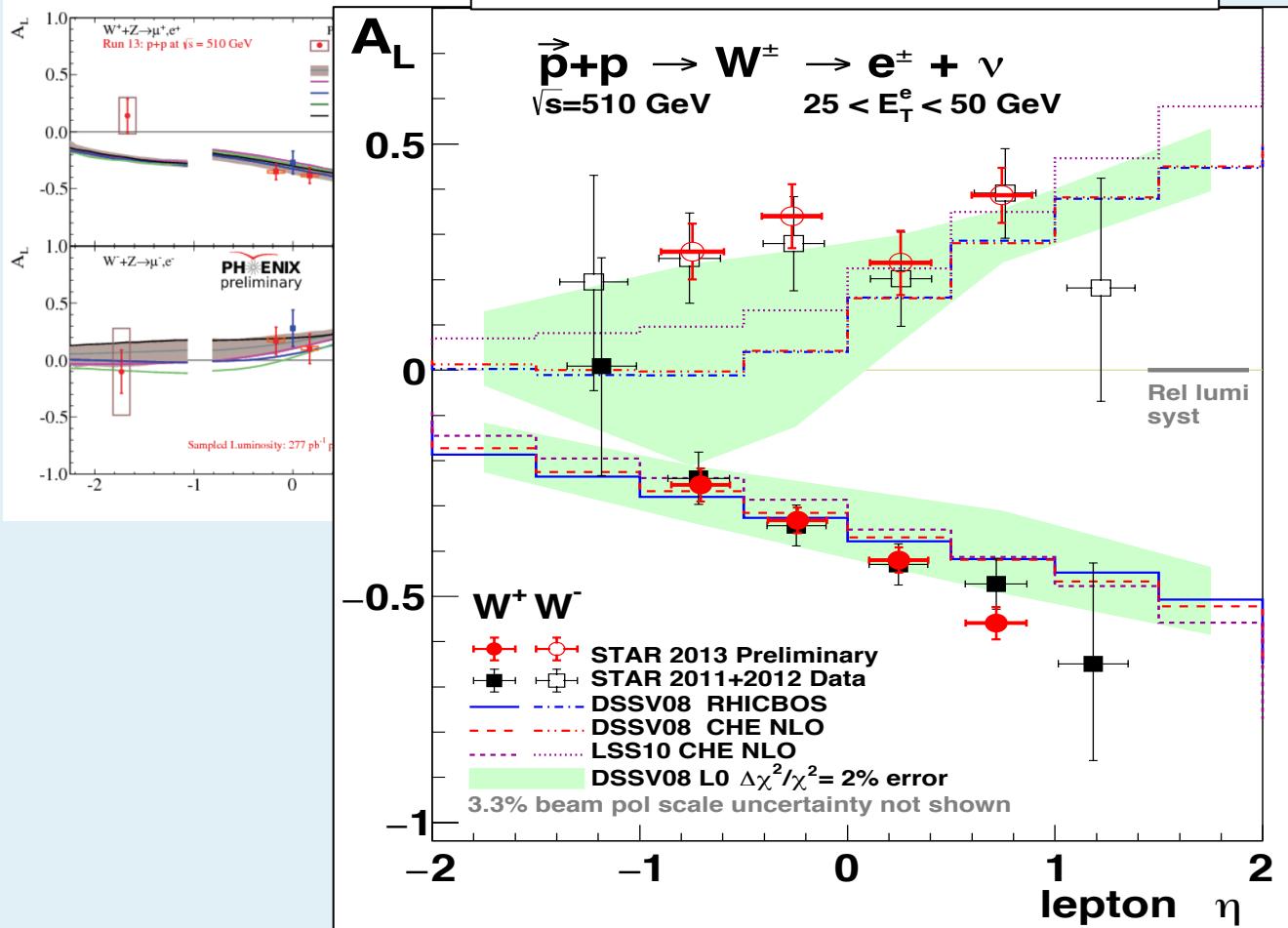
$\Delta u\bar{u}$ tends to be more positive
 ⇒ Symmetry breaking in polarized sea?
 ⇒ Opposite sign asymmetry compared to unpol case

$p\bar{p} \rightarrow W^\pm \rightarrow l^\pm$



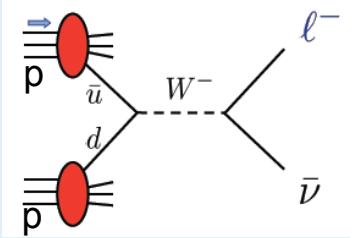
PHENIX: $W \rightarrow e$, PRD93, 051103
 $W \rightarrow \mu$, Preliminary

New data from STAR!
D.Gunarathne, Parallel V



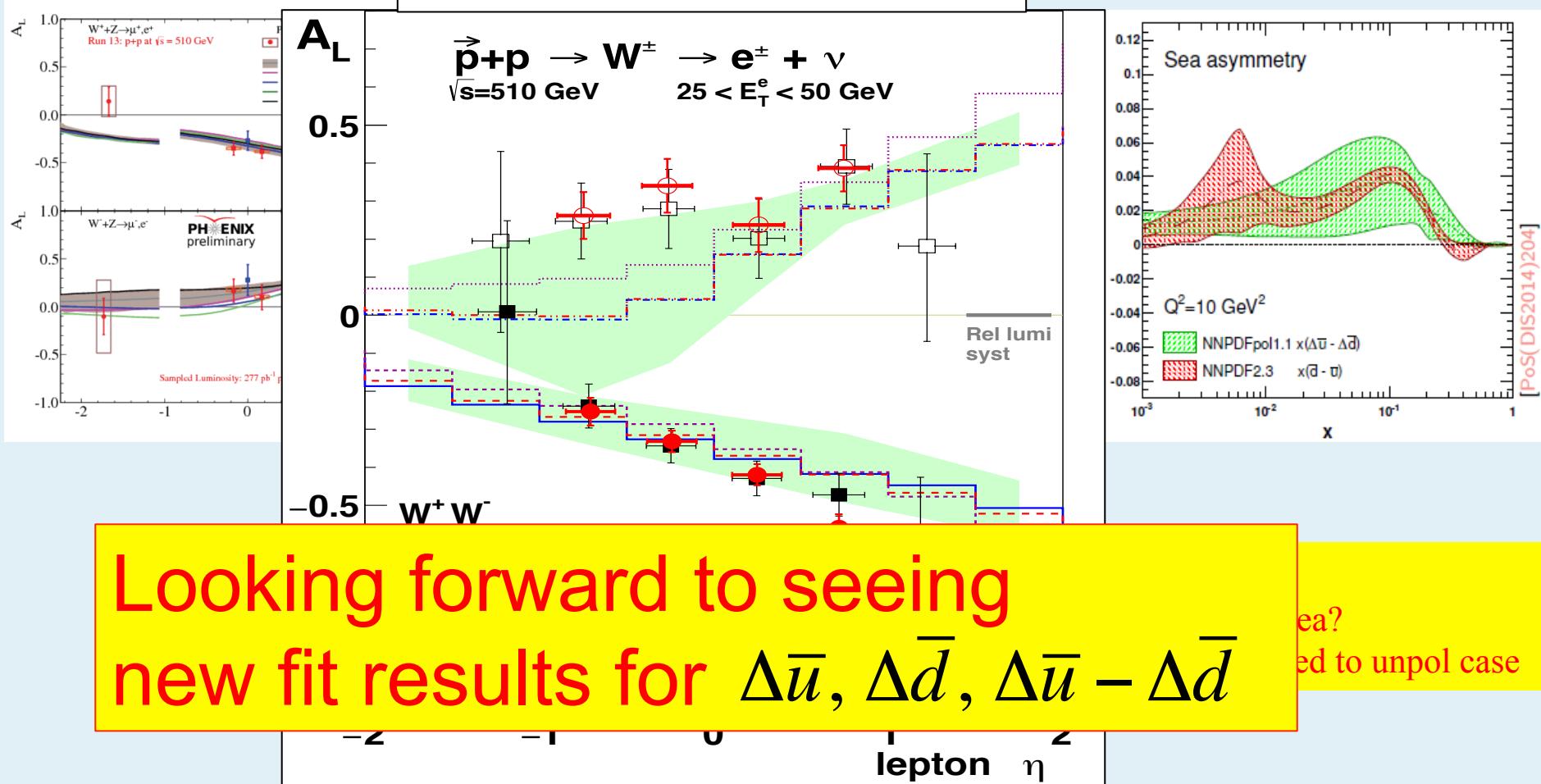
positive
in polarized sea?
asymmetry compared to unpol case

$p\bar{p} \rightarrow W^\pm \rightarrow l^\pm$



PHENIX: $W \rightarrow e$, PRD93, 051103
 $W \rightarrow \mu$, Preliminary

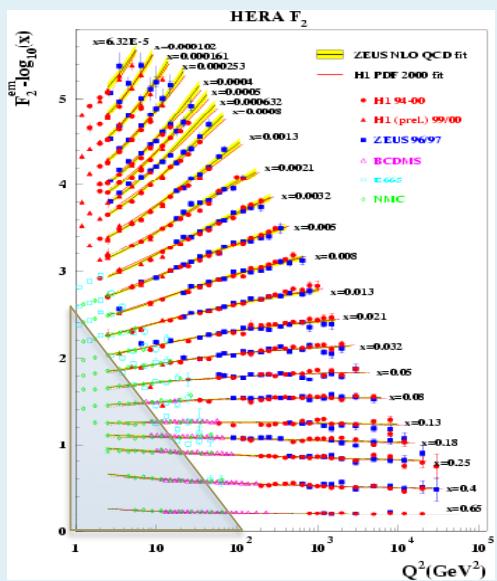
New data from STAR!
D.Gunarathne, Parallel V



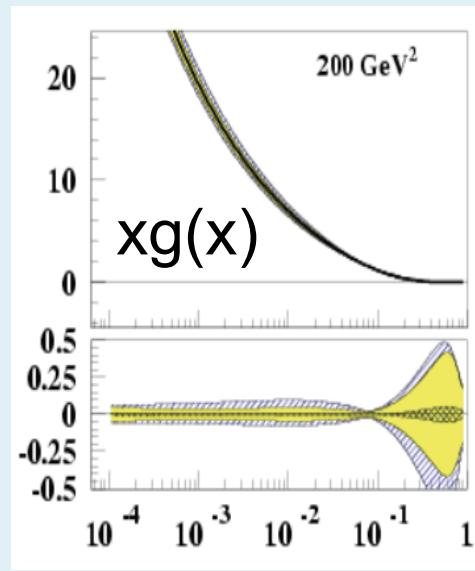
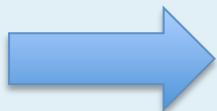
Δg

DIS: ΔG

F_2

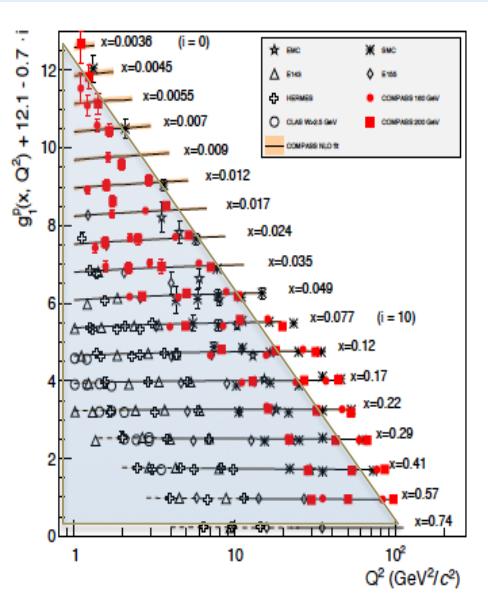


$$\frac{dF_2(x, Q^2)}{d \ln Q^2} \propto x g(x, Q^2)$$

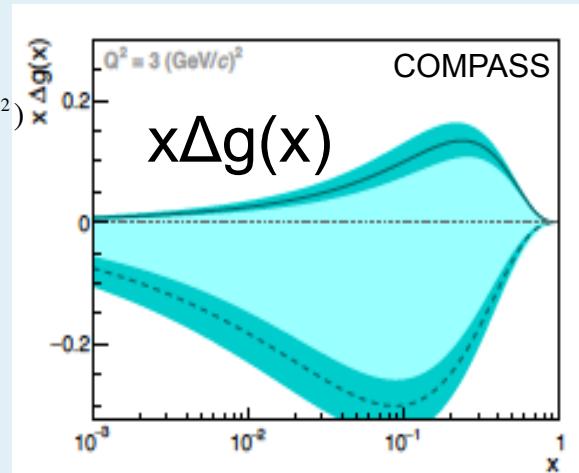
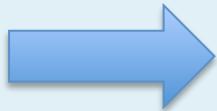


Works well
for $g(x)$
With HERA data

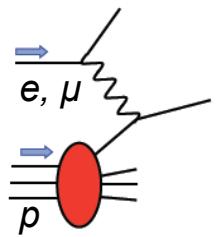
g_1



$$\frac{dg_1(x, Q^2)}{d \ln Q^2} \propto -\Delta g(x, Q^2)$$

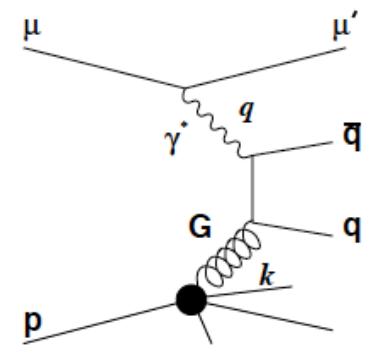


Doesn't
constrain
 $\Delta g(x)$
(small Q^2
lever arm)



SIDIS: ΔG

Photon gluon fusion



$$A_{\gamma N}^{PGF} \approx \langle \alpha_{LL}^{PGF} \rangle \frac{\Delta G}{G}$$

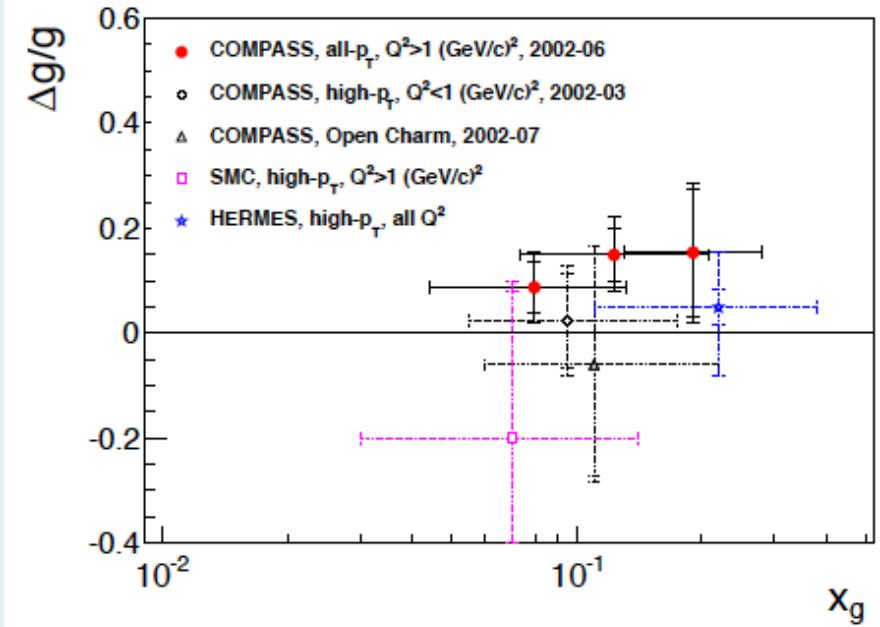
$$\gamma g \rightarrow c\bar{c} \rightarrow D^0, D^*$$

Low stat.
Theoretically clean

$$\gamma g \rightarrow q\bar{q} \rightarrow h^+h^-, h$$

High stat.
Background
Low Q^2 ?

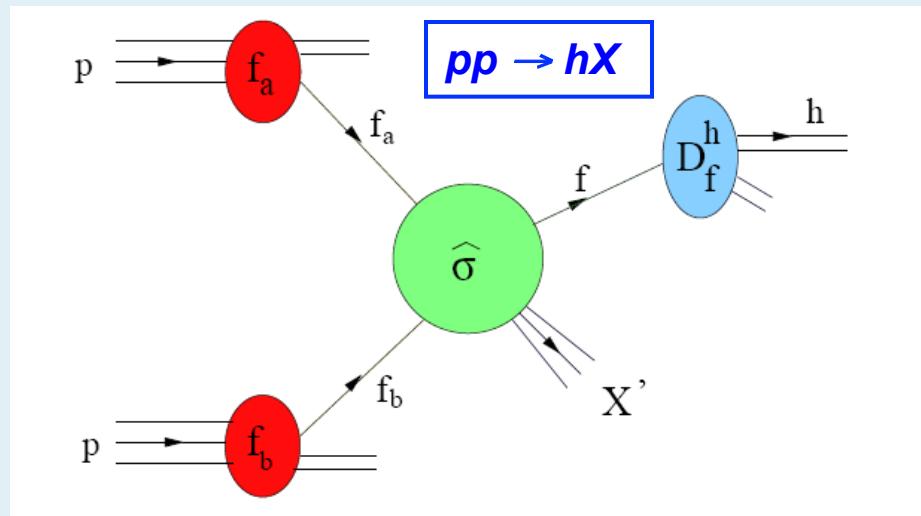
COMPASS: arXiv: 1512.05053
K.Klimaszewski, Parallel IV



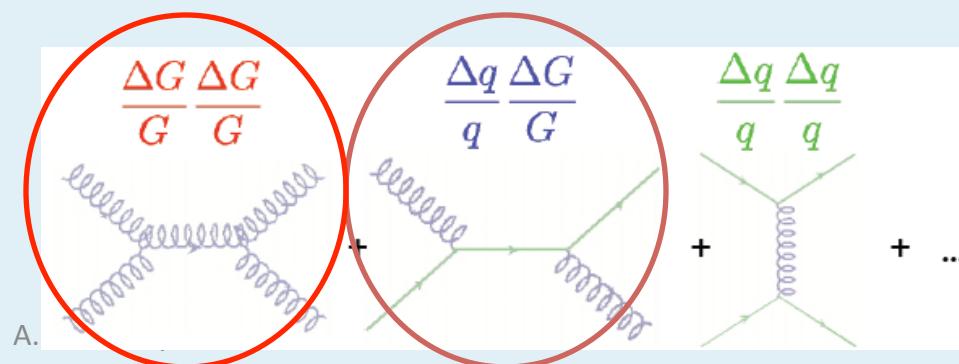
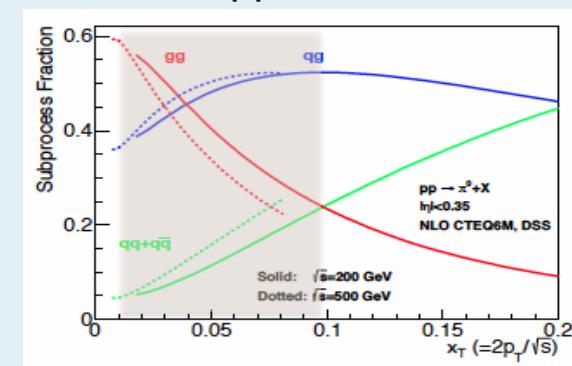
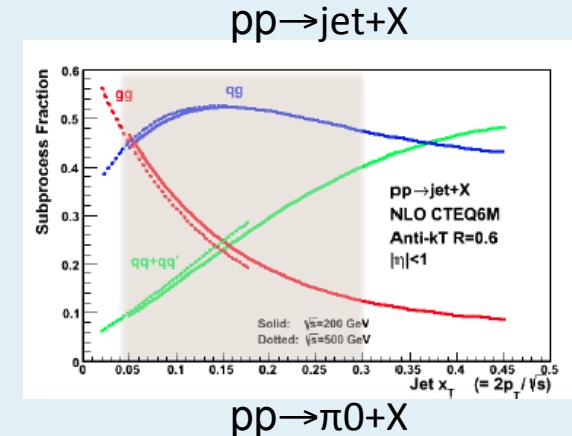
$$\Delta g/g^{\text{LO}} = 0.113 \pm 0.038(\text{stat}) \pm 0.035(\text{syst})$$

Hint on positive ΔG at $x \sim 0.1$

pp: ΔG

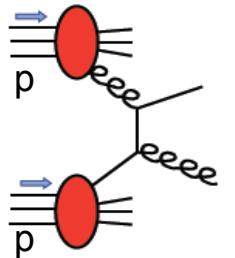


$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{\sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \rightarrow fX} \cdot \hat{a}_{LL}^{f_a f_b \rightarrow fX} \otimes D_f^h}{\sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \rightarrow fX} \otimes D_f^h}$$

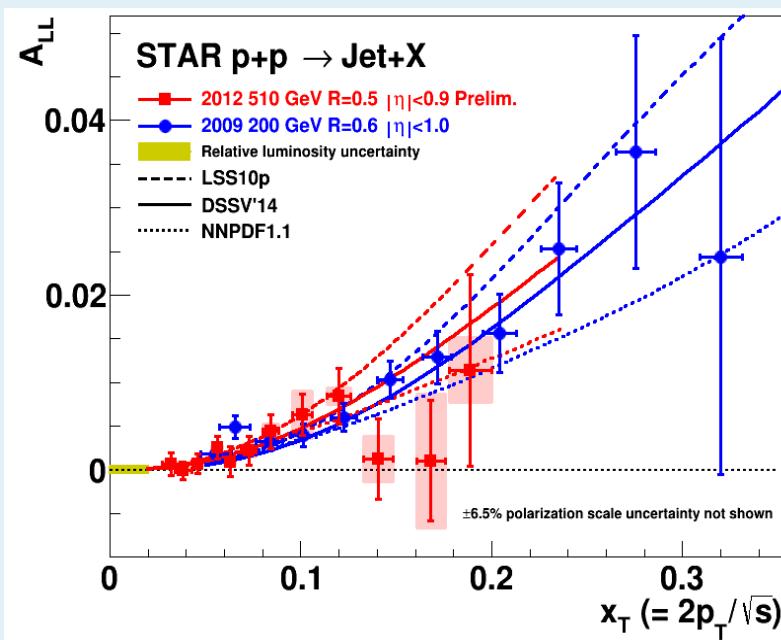


Double longitudinal spin asymmetry A_{LL} is sensitive to ΔG

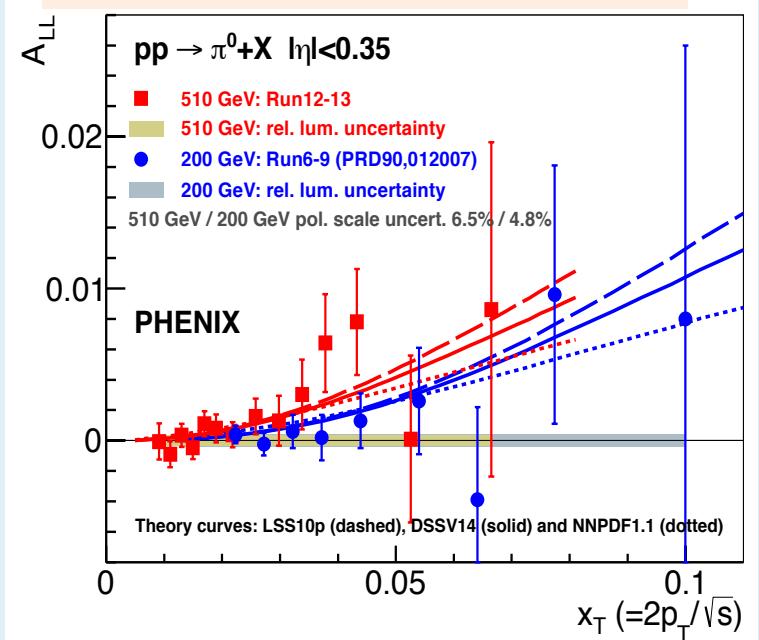
pp: ΔG



STAR: PRL 115, 092002 (2015)



PHENIX: PRD 90, 012007 (2014)
PRD 93, 011501 (2016)

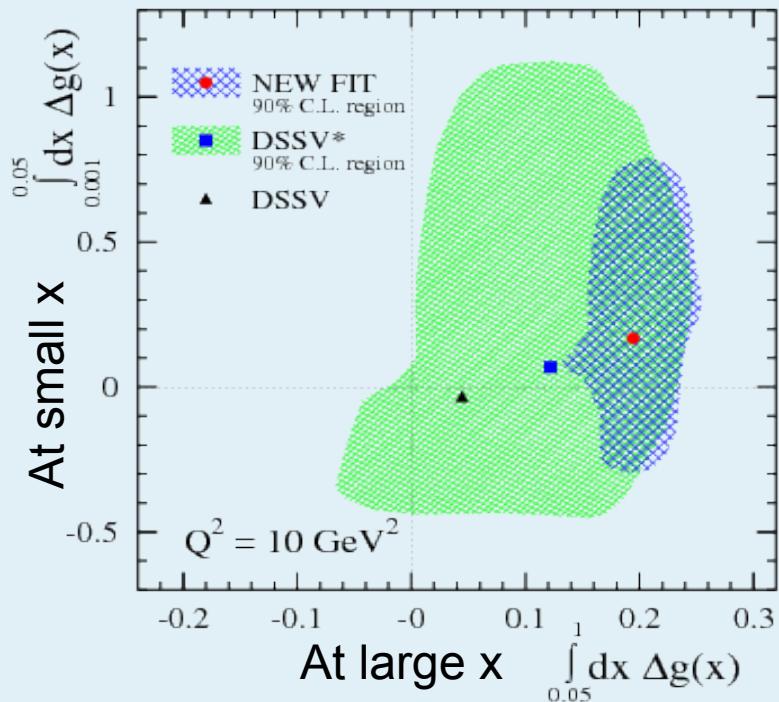


Observation of non-zero A_{LL}
associated with non-zero ΔG !

ΔG : global QCD fit

DSSV:

D. de Florian
R. Sassot
M. Stratmann
W. Vogelsang



DSSV: Phys Rev Lett, 101, 072001 (2008)
Data from up to 2006

New DSSV: Phys Rev Lett, 113, 012001 (2014)
Data from up to 2009 ($\sqrt{s}=500$ GeV not included)

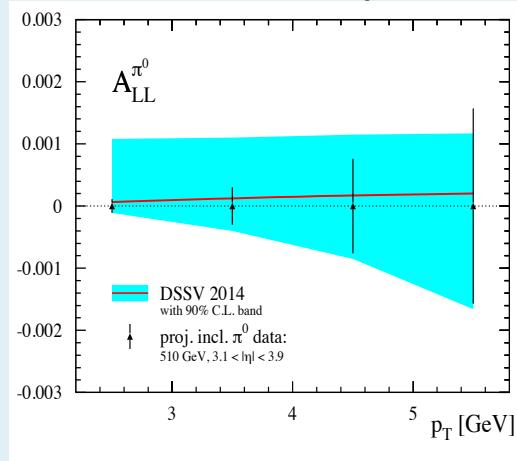
$$\int_{0.05}^1 dx \Delta g(x) = 0.2^{+0.06}_{-0.07} \quad 90\% CL$$

Significant non-zero $\Delta g(x)$ in the kin. region probed by RHIC
Similar result from another global fit NNPDF
Still huge uncertainty in unmeasured region ($x < 0.05$)
=> Measurements at higher \sqrt{s} and forward rapidity

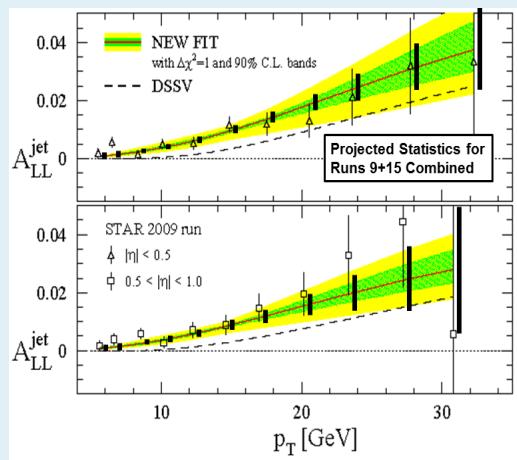
pp: ΔG , Near Term Projections

From already available data from 2011-15

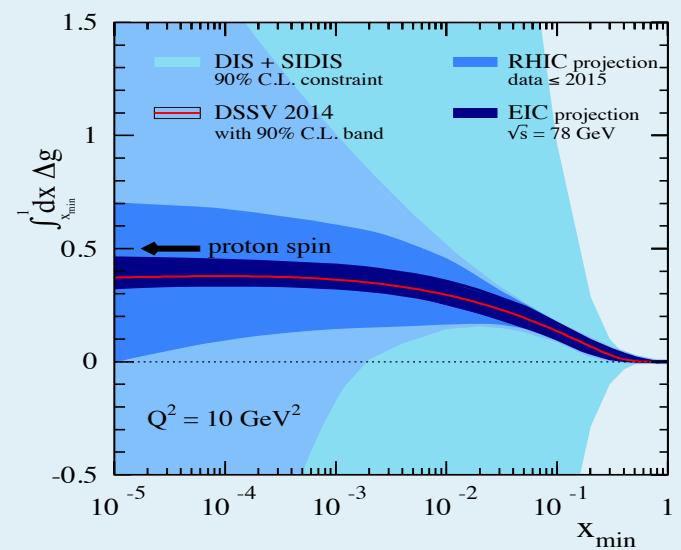
π^0 : $3.1 < |\eta| < 3.9$



Jets: $|\eta| < 1$



Aschenauer, Stratmann,Sassot: 1509.06489



Other channels also being measured
(but with weaker stat. power)

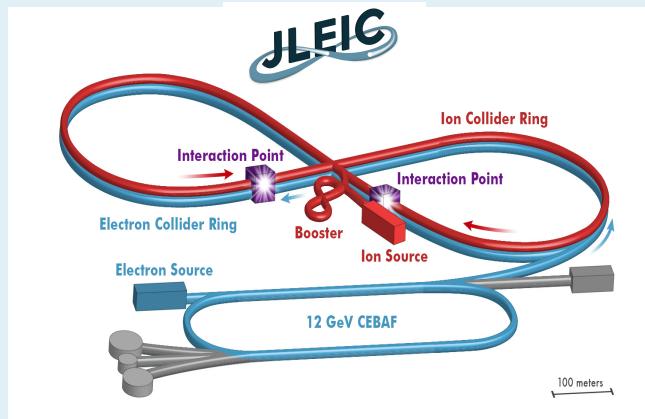
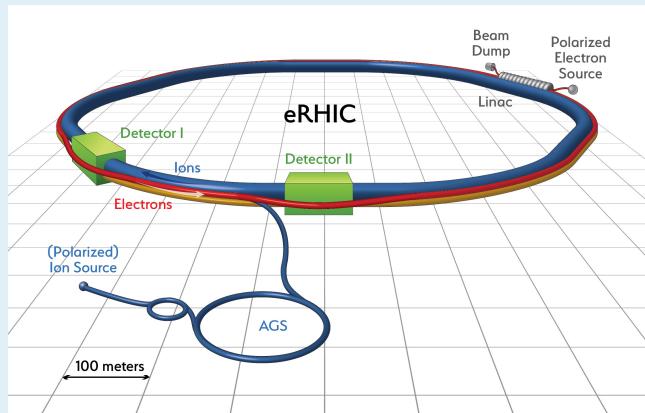
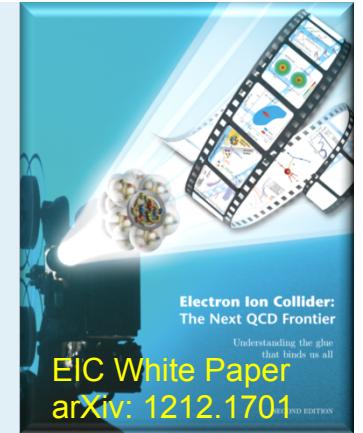
$\gamma, \eta, \pi^\pm, h^\pm$, heavy flavor through e and μ , jet-jet, h-h

Great improvement expected
... Still not enough precision for ΔG full integral

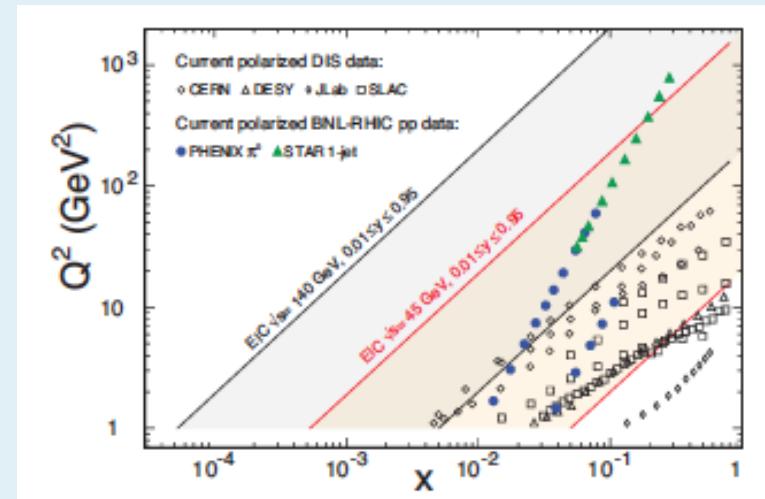
Electron-Ion Collider

2015 NSAC Long Range Plan:

We recommend a high-energy, high-luminosity polarized **Electron Ion Collider as the highest priority for new facility construction** following the completion of FRIB

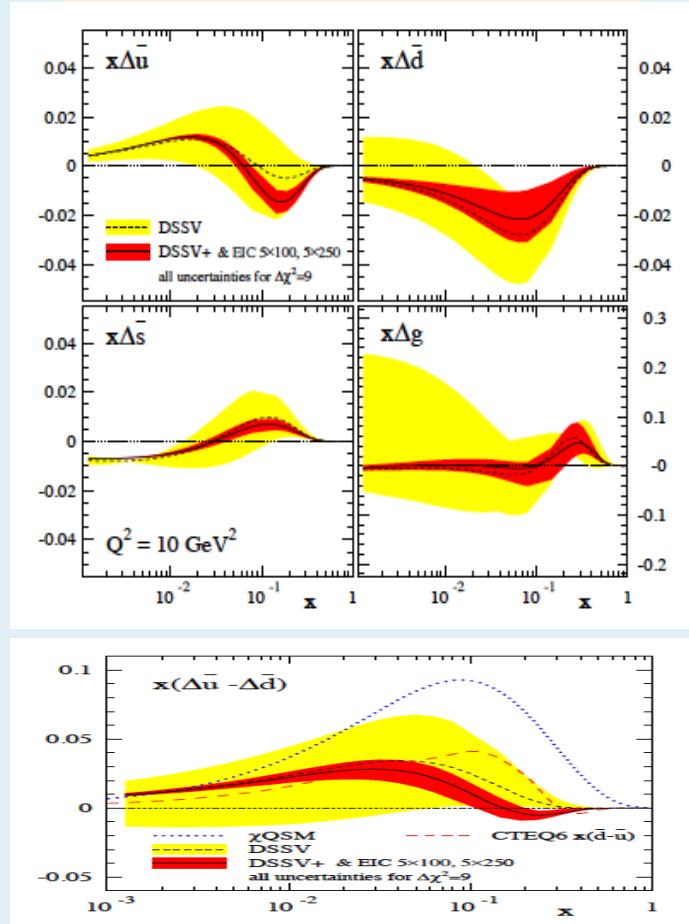


- Both e and p ($d/{}^3He$) polarized
- Luminosity $L_{ep} \sim 10^{33-34} \text{ cm}^{-2} \text{ sec}^{-1}$
 $\times 100-1000$ as HERA
- $\sqrt{s}=20-140 \text{ GeV}$
- Also eA



EIC: Helicity PDF

Aschenauer, Stratmann, Sassot,
PRD 86 (2012), 054029



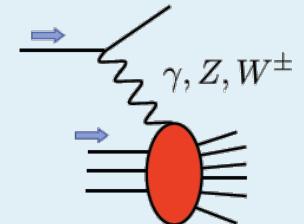
- $\Delta g(x)$ from scaling violation
- $\Delta\bar{u}, \Delta\bar{d}, \Delta s$ from SIDIS
- Flavor separation at high Q^2 via CC DIS:

$$g_1^{W^+} = \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{c} + \Delta s$$

$$g_1^{W^-} = \Delta u + \Delta d + \Delta c + \Delta \bar{s}$$

$$g_5^{W^+} = \Delta\bar{u} - \Delta\bar{d} + \Delta\bar{c} - \Delta s$$

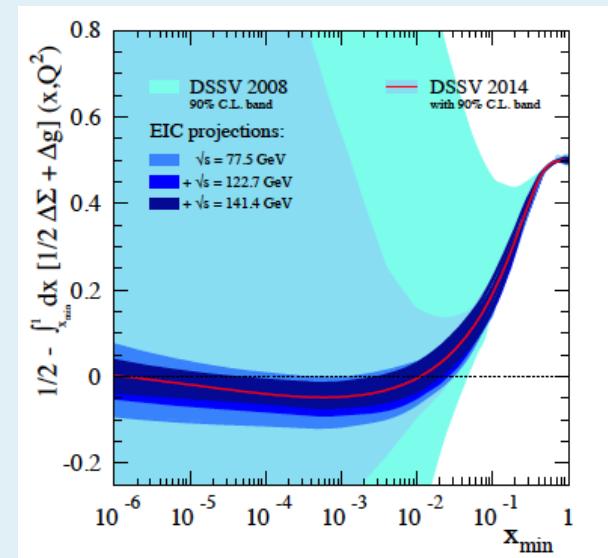
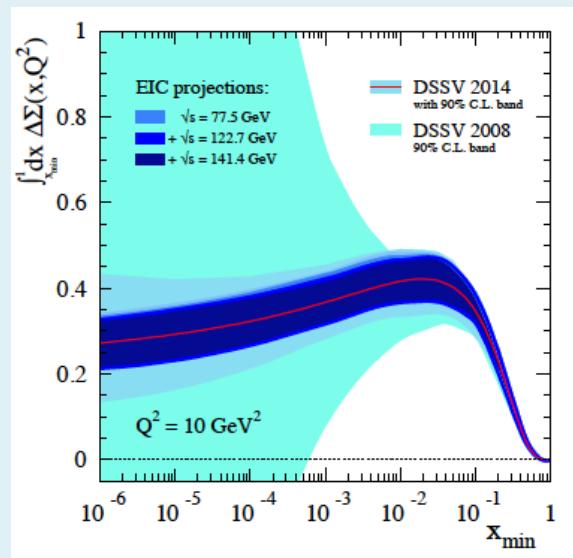
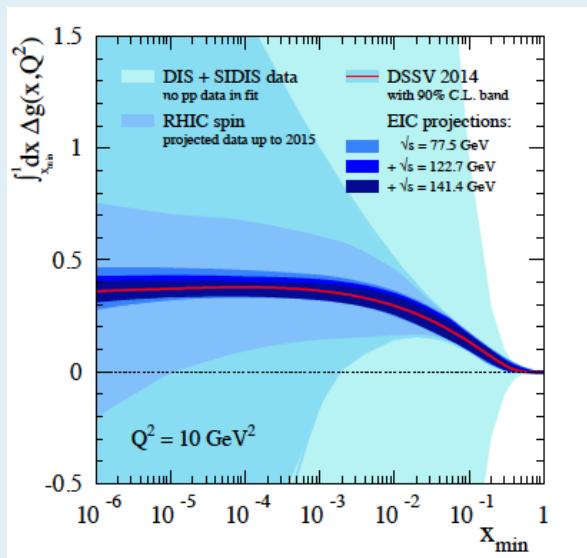
$$g_5^{W^-} = -\Delta u + \Delta\bar{d} - \Delta c + \Delta\bar{s}$$



EIC: Proton Spin

$$\frac{1}{2} = \frac{1}{2} \sum_q [\Delta q + \Delta \bar{q}] + \Delta g + L$$

Aschenauer, Stratmann,Sassot
arXiv: 1509.06489



$\frac{1}{2}$ - Gluon - Quarks =

Orbital angular momentum

Also GPD for independent OAM extraction

Spin puzzle will be solved

Global NLO fits

Compilation by M.Stratmann (2015 Jlab Users Meeting)

overview of recent helicity PDF fits @ NLO

latest paper				uncertainties	features & focus
NNPDF 1406.5539 Ball, Forte, Guffanti, Nocera, Rodolfi, Rojo	✓	✗	✓ jets W's	100 MC replicas stat. approach	pp data w/ reweighing method
DSSV 0904.3821 1404.4293 de Florian, Sassot, MS, Vogelsang	✓	✓	✓ jets pions	Lagrange mult. (Hessian)	pp data fitted fast Mellin method
JAM 1403.3355 Jimenez-Delgado, Accardi, Avakian, Melnitchouk, Sato, ...	✓	✗	✗	Hessian	large x / JLab region pp soon
LSS 1010.0574 Leader, Sidorov, Stamenov	✓	✓	✗	Hessian	higher twist, Δs
BBS 1502.02517 1408.7057 Bourrely, Buccella, Soffer	✓	✗	✗	Hessian	statistical approach unpol/pol simult. fit
BB 1010.3113 Blumlein, Bottcher	✓	✗	✗	Hessian	α_s , higher twist
⋮	⋮	⋮	⋮	⋮	⋮
GRSV 9508347 0011215 Gluck, Reya, MS, Vogelsang	✓	✗	✗	1 st NLO analysis 1995	

Moving towards NNLO

Higher Twist

Including more probes

Summary

Good progress !

More precise data => More advanced QCD analysis => Better PDF accuracy

Proton Spin contributors:

Quarks: ~30%; Gluon: ~40% (in the limited x range)

=> more data coming

Hint on asymmetry in pol. sea

=> more data coming

Strange quark role still contradictory

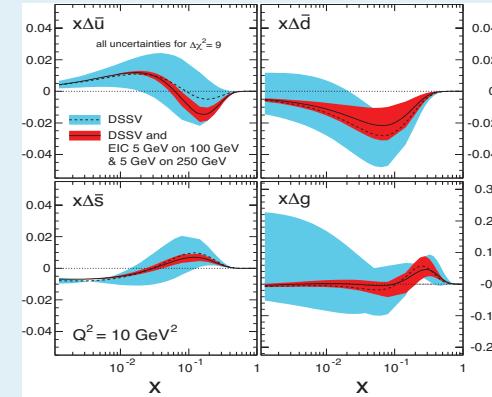
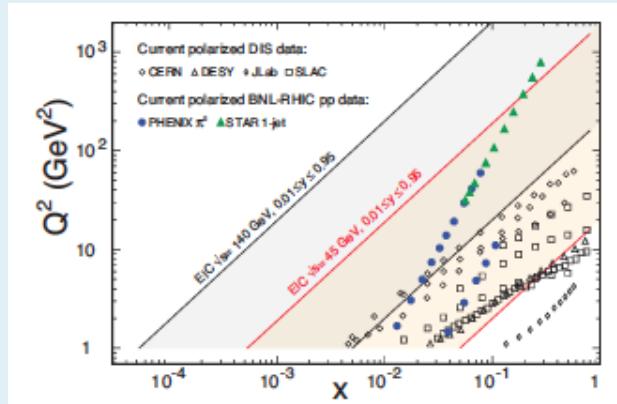
=> more data coming

New data to come from COMPASS, JLab, RHIC

Plans for polarized beams & targets discussed at FermiLab (US), J-PARC (Japan), NICA (Russia), U-70 (Russia)

Low x measurements are crucial => EIC

EIC – the only option to resolve the proton spin issue(s)



Backup

High Energy Spin Experiments

Aidala, Bass, Hasch, Mallot, Rev. Mod. Phys. 85 (2013), 655

TABLE I. High-energy spin experiments: the kinematic ranges in x and Q^2 correspond to the average kinematic values of the highest statistics measurement of each experiment, which is typically the inclusive spin asymmetry; x denotes Bjorken x unless specified.

Experiment	Year	Beam	Target	Energy (GeV)	Q^2 (GeV 2)	x
Completed experiments						
SLAC: E80, E130	1976–1983	e^-	H-butanol	$\lesssim 23$	1–10	0.1–0.6
SLAC: E142/3	1992–1993	e^-	NH_3 , ND_3	$\lesssim 30$	1–10	0.03–0.8
SLAC: E154/5	1995–1999	e^-	NH_3 , 6LiD , 3He	$\lesssim 50$	1–35	0.01–0.8
CERN: EMC	1985	μ^+	NH_3	100, 190	1–30	0.01–0.5
CERN: SMC	1992–1996	μ^+	H/D-butanol, NH_3	100, 190	1–60	0.004–0.5
FNAL: E581/E704	1988–1997	p	p	200	~ 1	$0.1 < x_F < 0.8$
Analyzing and/or running						
DESY: HERMES	1995–2007	e^+, e^-	H, D, 3He	~ 30	1–15	0.02–0.7
CERN: COMPASS	2002–2012	μ^+	NH_3 , 6LiD	160, 200	1–70	0.003–0.6
JLab6: Hall A	1999–2012	e^-	3He	$\lesssim 6$	1–2.5	0.1–0.6
JLab6: Hall B	1999–2012	e^-	NH_3 , ND_3	$\lesssim 6$	1 – 5	0.05–0.6
RHIC: BRAHMS	2002–2006	p	p (beam)	$2 \times (31–100)$	$\sim 1–6$	$-0.6 < x_F < 0.6$
RHIC: PHENIX, STAR	2002+	p	p (beam)	$2 \times (31–250)$	$\sim 1–400$	$\sim 0.02–0.4$
Approved future experiments (in preparation)						
CERN: COMPASS-II	2014+	μ^+, μ^-	Unpolarized H ₂	160	$\sim 1–15$	$\sim 0.005–0.2$
		π^-	NH_3	190		$-0.2 < x_F < 0.8$
JLab12: Halls A/B/C	2014+	e^-	HD, NH_3 , ND_3 , 3He	$\lesssim 12$	$\sim 1–10$	$\sim 0.05–0.8$

Exp. Technique

$$A = \frac{\sigma_{S1} - \sigma_{S2}}{\sigma_{S1} + \sigma_{S2}} \Rightarrow \frac{1}{P_B P_T f} \cdot \frac{N_{S1} - N_{S2}}{N_{S1} + N_{S2}}$$

$$\delta_A \sim \frac{1}{P_B P_T f} \cdot \frac{1}{\sqrt{N}}$$

Measure asymmetry between different spin configurations (with precision to 10^{-3} - 10^{-4})
 ⇒ High Beam polarization P_B
 ⇒ High Target polarization P_T , small or no dilution ($f=1$)
 ⇒ High luminosity (N)
 ⇒ Small syst. uncert. (⇒ frequent polarization flip)

Fixed target Experiments

SLAC:

e^- beam $P_B = 0.80 - 0.85$

Solid target $P_B = 0.80 - 0.85$ ($f=0.1 - 0.5$)

HERMES:

Gas target $P_T = 0.85 - 0.88$ ($f=1$), spin flip every $\sim 1\text{ms}$

EMC, SMC:

μ polarized beam from π weak decay, $P_B \sim 0.80$

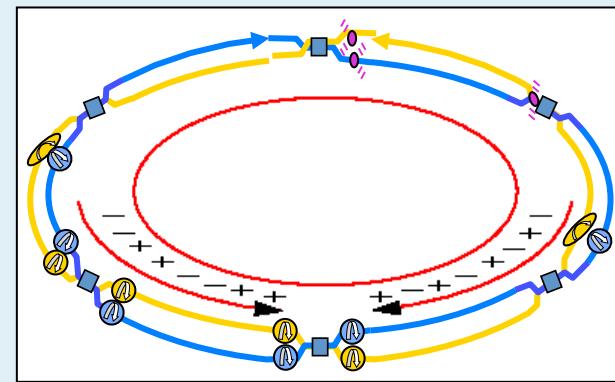
COMPASS:

2-3 cell target with opposite polarizations

JLab:

High intensity polarized e beam, spin flip every 30ms

Collider (RHIC)



- ✓ Bunch spin configuration alternates every 106 ns, $P_B \sim 0.6$
- ✓ Data for all bunch spin configurations are collected at the same time
- ⇒ Possibility for false asymmetries is greatly reduced

Bjorken and Ellis-Jaffe Sum Rules

$$\begin{aligned}\Gamma_1^p &= \frac{1}{2} \left(\frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \right) \\ &= \frac{1}{12} (\Delta u - \Delta d) + \frac{1}{36} (\Delta u + \Delta d - 2\Delta s) + \frac{1}{9} (\Delta u + \Delta d + \Delta s).\end{aligned}$$

$$\Gamma_1^{p(n)} = \pm \frac{1}{12} a_3 + \frac{1}{36} a_8 + \frac{1}{9} a_0$$

Axial charges:

$$a_3 = \Delta u - \Delta d$$

-Isovctor

$$A_{5\mu}^j = \bar{\Psi} \gamma_\mu \gamma_5 \frac{\lambda_j}{2} \Psi$$

$$a_8 = \Delta u + \Delta d - 2\Delta s$$

-Octet

$$2 \langle P, S | A_{5\mu}^3 | P, S \rangle = a_3 S_\mu$$

$$a_0 = \Delta u + \Delta d + \Delta s$$

-Singlet

$$\begin{aligned}2\sqrt{3} \langle P, S | A_{5\mu}^3 | P, S \rangle &= a_8 S_\mu \\ \langle P, S | A_{5\mu}^0 | P, S \rangle &= a_0 S_\mu\end{aligned}$$

Isospin invarince: $a_3 = F+D = g_A/g_V = 1.270 \pm 0.002$, from neutron β decay

SU(3)_f symmetry: $a_8 = 3F-D = 0.585 \pm 0.025$, from hyperon β decays

F, D are symmetric and antisymmetric couplings obtained from hyperon decays

Ellis-Jaffe: $\Delta s=0$ ($\Rightarrow a_0=a_8$)

Bjorken:

$$\Gamma_1^{p(n)} = \frac{1}{12} \left\{ \left(\pm (a_3 + \frac{1}{3} a_8) \right) E_{NS}(Q^2) + \frac{4}{3} a_0 E_S(Q^2) \right\}$$

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} a_3 E_{NS} \equiv \frac{1}{6} \left| \frac{g_A}{g_V} \right| E_{NS}$$

$$E_{NS}(Q^2) = 1 - \frac{\alpha_s}{\pi} - (3.5833) \left(\frac{\alpha_s}{\pi} \right)^2 - (20.2153) \left(\frac{\alpha_s}{\pi} \right)^3 - (130) \left(\frac{\alpha_s}{\pi} \right)^4 \dots$$

$$E_S(Q^2) = 1 - \frac{\alpha_s}{\pi} - (1.0959) \left(\frac{\alpha_s}{\pi} \right)^2 - (6) \left(\frac{\alpha_s}{\pi} \right)^3 \dots,$$

DIS kinematics

Helicity PDF: first moments

DIS: COMPASS, arXiv:1503.08935

First moment	Value range at $Q^2 = 3 \text{ (GeV}/c)^2$
$\Delta\Sigma$	[0.26 , 0.36]
$\Delta u + \Delta \bar{u}$	[0.82 , 0.85]
$\Delta d + \Delta \bar{d}$	[-0.45 , -0.42]
$\Delta s + \Delta \bar{s}$	[-0.11 , -0.08]

SIDIS: COMPASS, PLB693,227 (2010)

Table 4

First moments of the quark helicity distributions at $Q_0^2 = 3 \text{ (GeV}/c)^2$ truncated to the range of the measurements and derived with the DSS fragmentation functions. The first error is statistical, the second one systematic. The values of the sea quark distributions for $x \gtrsim 0.3$ are assumed to be zero.

x range	$0.004 < x < 0.3$	$0.004 < x < 0.7$
Δu	$0.47 \pm 0.02 \pm 0.03$	$0.69 \pm 0.02 \pm 0.03$
Δd	$-0.27 \pm 0.03 \pm 0.02$	$-0.33 \pm 0.04 \pm 0.03$
$\Delta \bar{u}$	$0.02 \pm 0.02 \pm 0.01$	-
$\Delta \bar{d}$	$-0.05 \pm 0.03 \pm 0.02$	-
$\Delta s(\Delta \bar{s})$	$-0.01 \pm 0.01 \pm 0.01$	-
Δu_v	$0.46 \pm 0.03 \pm 0.03$	$0.67 \pm 0.03 \pm 0.03$
Δd_v	$-0.23 \pm 0.05 \pm 0.02$	$-0.28 \pm 0.06 \pm 0.03$
$\Delta \bar{u} - \Delta \bar{d}$	$0.06 \pm 0.04 \pm 0.02$	-
$\Delta \bar{u} + \Delta \bar{d}$	$-0.03 \pm 0.03 \pm 0.01$	-
$\Delta \Sigma$	$0.15 \pm 0.02 \pm 0.02$	$0.31 \pm 0.03 \pm 0.03$

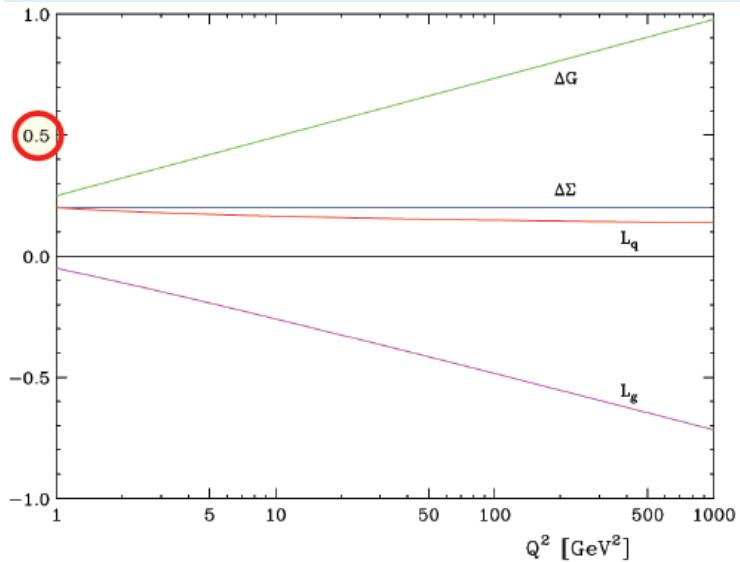
Global: DSSV, PRL 101, 072001 (2008)

TABLE II. First moments $\Delta f_j^{1,[x_{\min} \rightarrow 1]}$ at $Q^2 = 10 \text{ GeV}^2$.

	$x_{\min} = 0$ best fit	$x_{\min} = 0.001$ $\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta \bar{u}$	0.813	$0.793^{+0.011}_{-0.012}$	$0.793^{+0.028}_{-0.034}$
$\Delta d + \Delta \bar{d}$	-0.458	$-0.416^{+0.011}_{-0.009}$	$-0.416^{+0.035}_{-0.025}$
$\Delta \bar{u}$	0.036	$0.028^{+0.021}_{-0.020}$	$0.028^{+0.059}_{-0.059}$
$\Delta \bar{d}$	-0.115	$-0.089^{+0.029}_{-0.029}$	$-0.089^{+0.090}_{-0.080}$
$\Delta \bar{s}$	-0.057	$-0.006^{+0.010}_{-0.012}$	$-0.006^{+0.028}_{-0.031}$
Δg	-0.084	$0.013^{+0.106}_{-0.120}$	$0.013^{+0.702}_{-0.314}$
$\Delta \Sigma$	0.242	$0.366^{+0.015}_{-0.018}$	$0.366^{+0.042}_{-0.062}$

Before RHIC Run9 data for ΔG
No W data yet

Q² dependence



ΔG is dynamic value – Q^2 dependent

ΔG can be large at large Q^2 (and can be $>>1/2$) no matter how small it is at some low Q^2

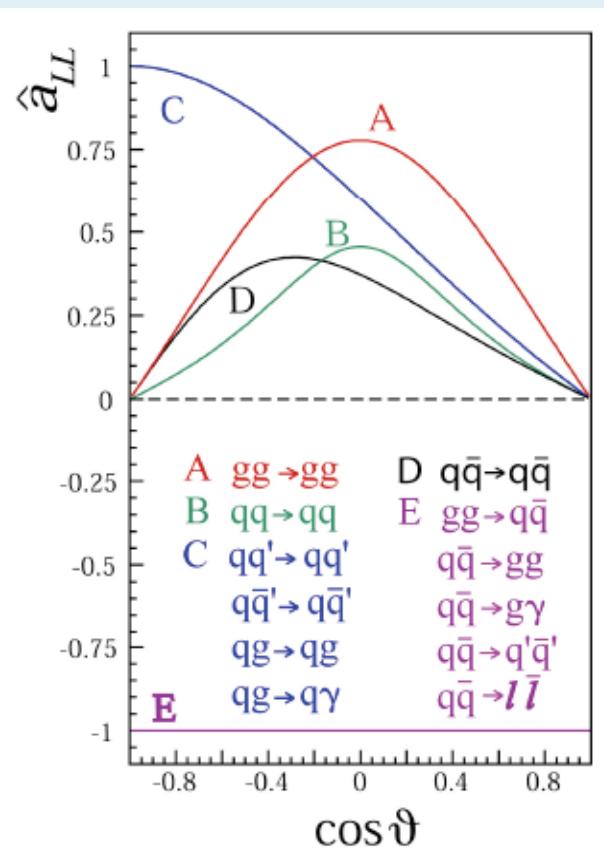
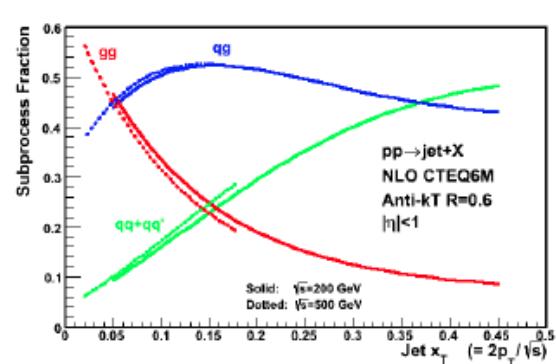
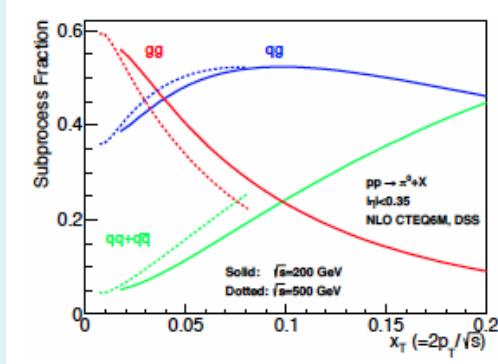
Large ΔG at large Q^2 is compensated by L_g

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

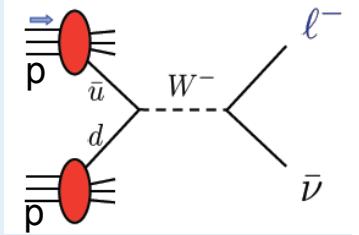
At large Q^2 :

$$\frac{1}{2} \Delta \Sigma + L_q = \frac{1}{2} \frac{3n_f}{3n_f + 16} = 0.18$$

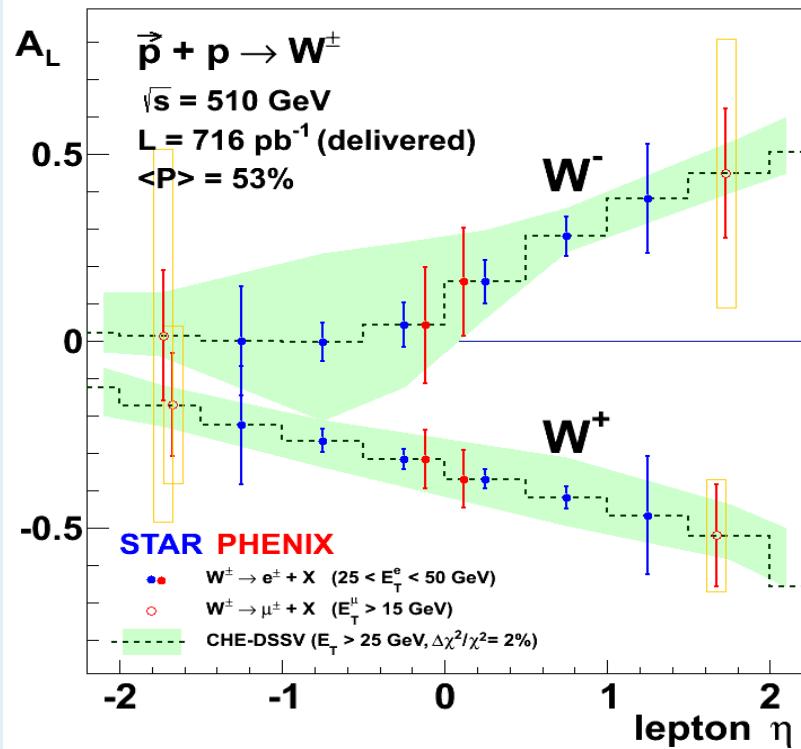
$$\Delta g + L_g = \frac{1}{2} \frac{16}{3n_f + 16} = 0.32$$



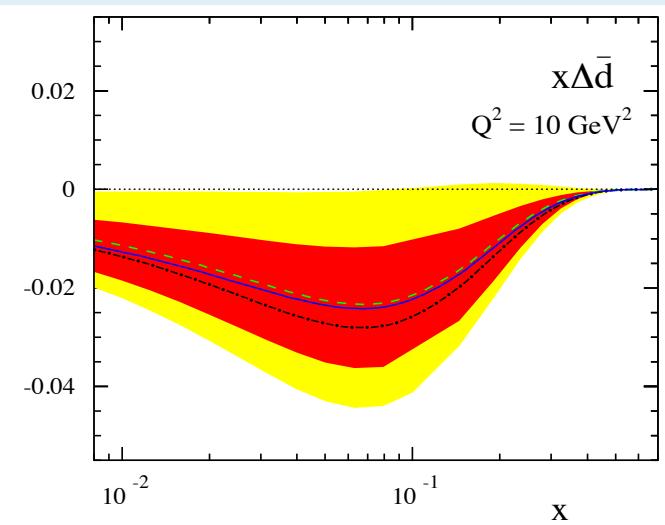
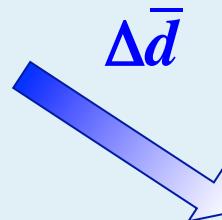
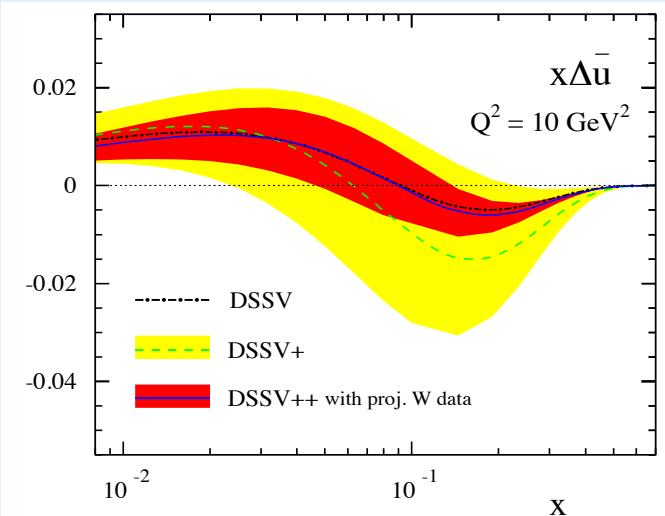
$p\bar{p} \rightarrow W^\pm \rightarrow l^\pm$



Projection



$\Delta \bar{u}$

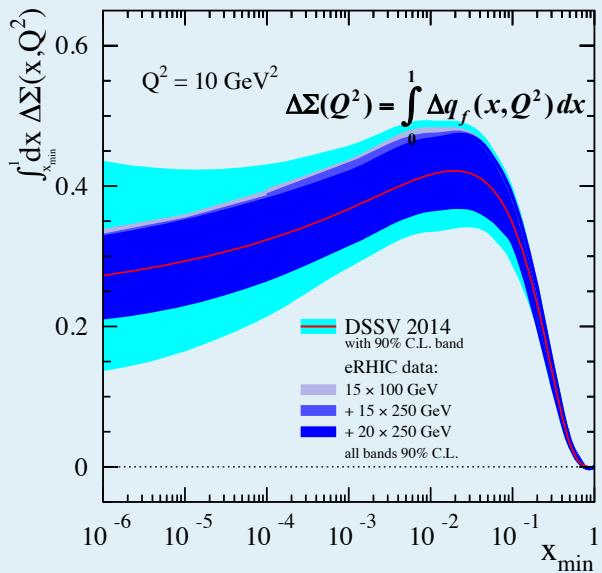


RHIC W-data will give a significant constraint on anti-quark polarization in the proton

$\Delta\Sigma$: The status

DSSV:

D. de Florian
R. Sassot
M. Stratmann
W. Vogelsang



Drop in the integral due to shape of polarized sea quark PDF

Important to measure flavor separated sea quark PDF

- ✓ To understand dynamics of the quark-antiquark fluctuations
- ✓ Unpolarized sea is not symmetric: $\bar{u} \neq \bar{d}$
 \Rightarrow what about polarized sea?

$$\int_{0.001}^1 dx \Delta\Sigma \sim 0.366 \pm^{0.042}_{0.062} @ 10 \text{ GeV}^2$$

↙

$$\int_{10^{-6}}^{10^{-2}} dx \Delta\Sigma \sim 0.242 @ 10 \text{ GeV}^2$$

