Nucleon Spin Structure
Experimental overview

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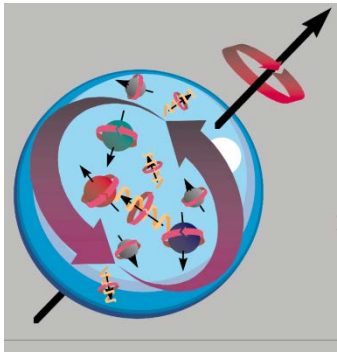

- **Longitudinal spin : Gluon and quark helicities**
- **Transverse spin**
- **Outlook**

Measurements at RHIC, COMPASS, HERMES, JLab

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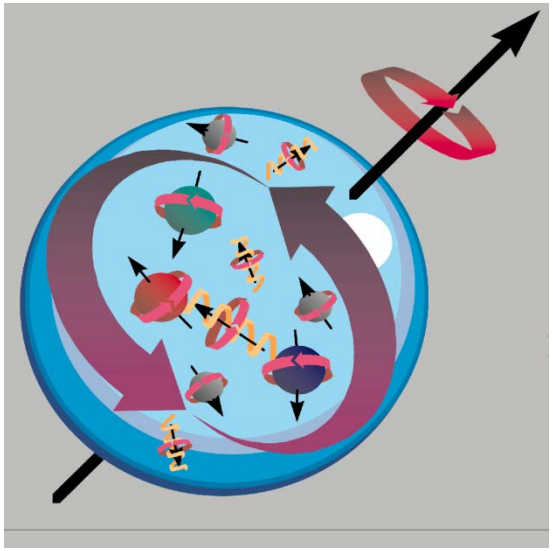
Nucleon spin structure

- Nucleon Almost all visible matter
- Spin Fundamental quantum number
  Pauli principle
  Important for symmetry tests: parity /time reversal



Nucleon contains
quarks, anti quarks, gluons

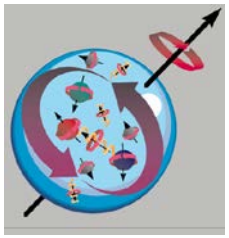
How is spin distributed in the nucleon?

Nucleon spin

How is the nucleon spin distributed among its constituents?

Nucleon Spin $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$

quark gluon orbital momentum



$\Delta\Sigma$: sum over u, d, s, $\bar{u}$, $\bar{d}$, $\bar{s}$

can take any value: superposition of several states

$\Delta q = \overrightarrow{q} - \overleftarrow{q}$

Parton spin parallel or anti parallel to nucleon spin

Past:

Theory: QPM estimations, with relativistic effects $\Delta\Sigma \sim 0.6$

Experiment: "Spin crisis" in 1988, when EMC measured $a_0 = \Delta\Sigma = 0.12 \pm 0.17$ ($\overline{\text{MS}}$ scheme)

Today:

Precise world data on polarized DIS $g_1 + SU_f(3)$ $a_0 = \Delta\Sigma \sim 0.3$

First results from Lattice QCD on $\Delta\Sigma_{u,d}$ and $L_{u,d}$

Large experimental effort on ΔG measurement

also because $a_0 = \Delta\Sigma - n_f\,(\alpha_s/2\pi)\,\Delta G$ (AB scheme)

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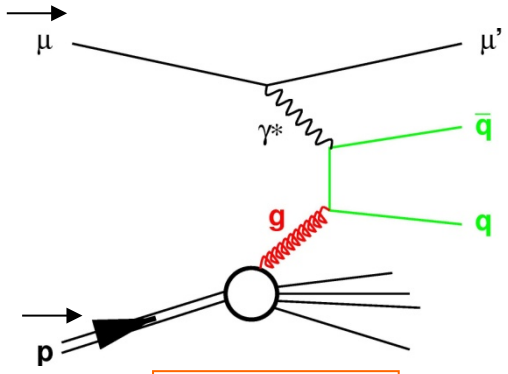
Three ways to study gluon contribution ΔG

1. Lepton Nucleon

Photon Gluon Fusion

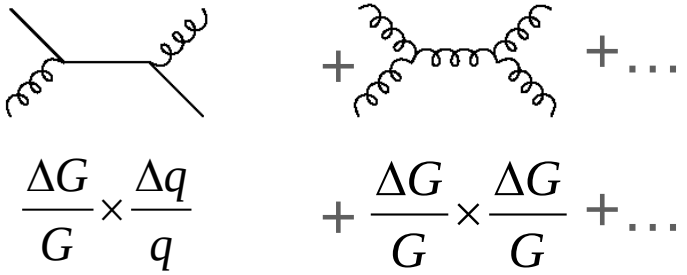


ΔG/G(x)

SMC, HERMES, COMPASS

2. Proton Proton collisions

Gluon-Quark + Gluon-Gluon +…

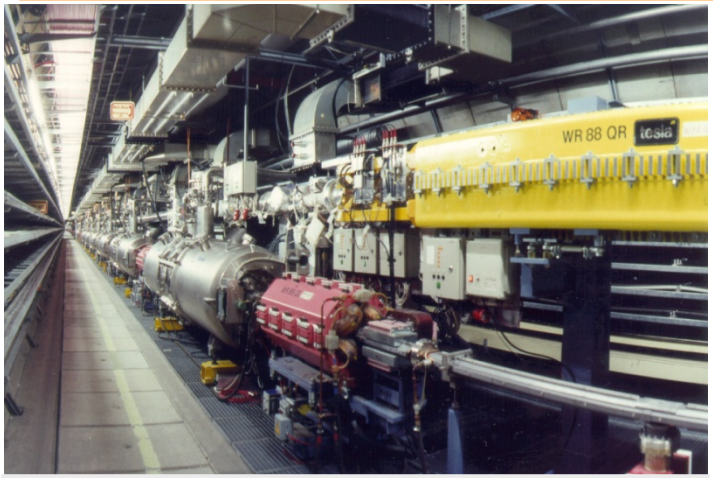


A_{LL} (p_T)

RHIC : PHENIX & STAR

3. QCD Q^2 evolution of spin structure function $g_1(x,Q^2)$:
Indirect determination assuming a functional form ΔG(x).
Global fits include polarized DIS, SIDIS and pp data

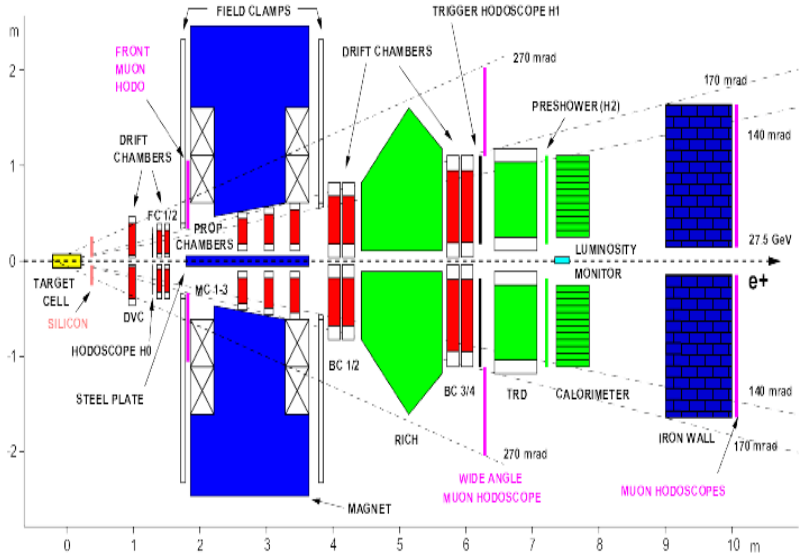
HERMES at DESY



HERA e^+ & e^- 27 GeV

longitudinally polarized ~ 54%

1995 to 2007



Gaseous polarized target

Longit. Polar. 85% **H, D**, He

Transv. Polar H

Unpol H, D, Ne, Kr

COMPASS at CERN

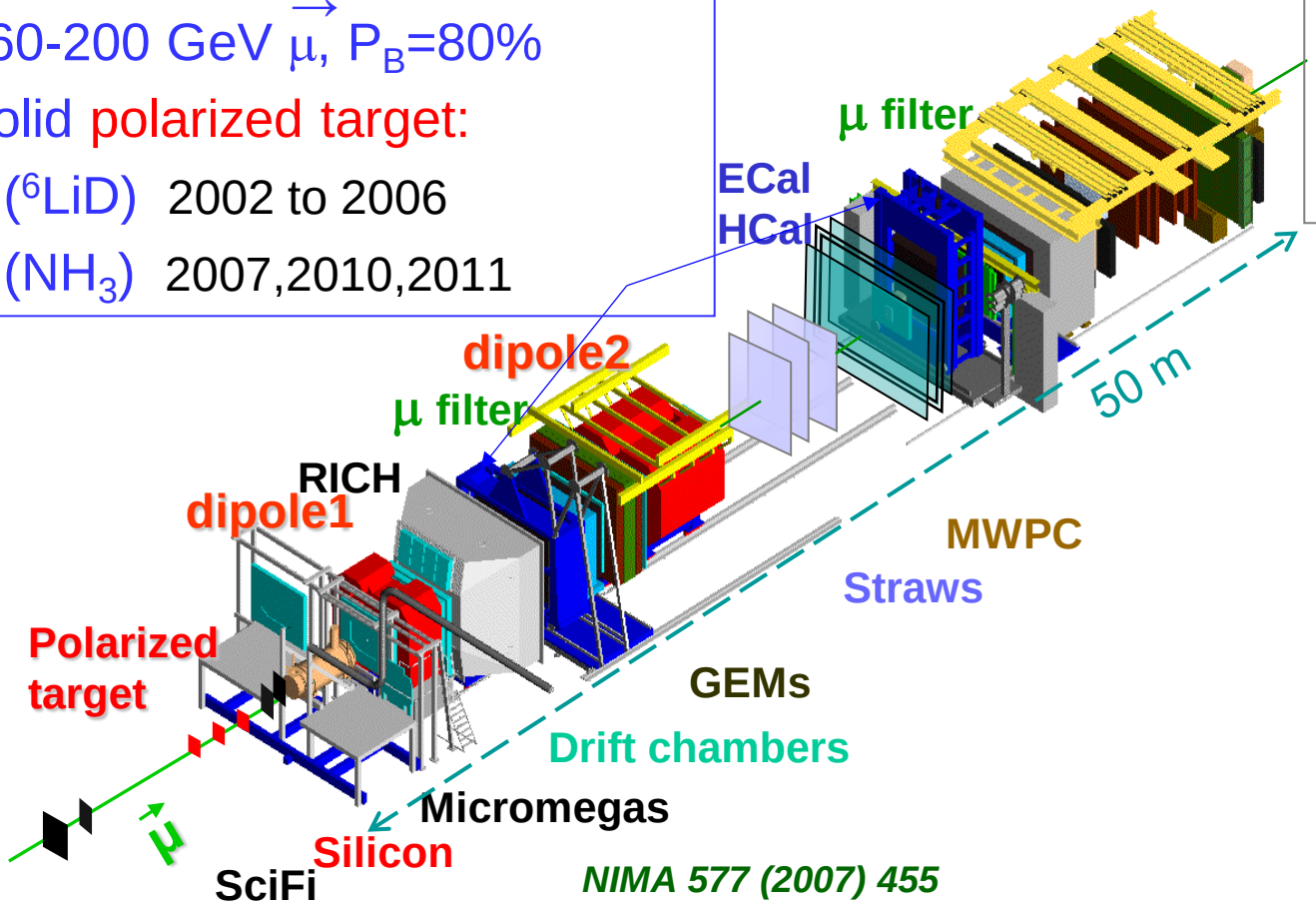
Fixed target
Secondary beams from SPS

Nucleon spin structure

Polarized muon beam:
160-200 GeV $\vec{\mu}$, P_B=80%
Solid polarized target:
d (^{6}LiD) 2002 to 2006
p (NH_3) 2007,2010,2011

Meson spectroscopy

Hadron beam :
190 GeV π / p
LH_2 2008-2009-2012



NIMA 577 (2007) 455

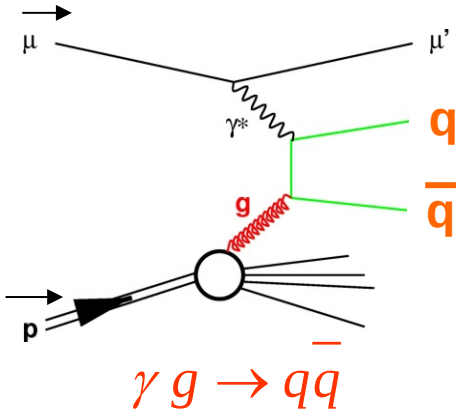
1. ΔG/G from *lepton* $\vec{N}$ scattering

Photon Gluon Fusion (PGF) process

Asymmetry of cross sections for longitudinal polarizations of beam and target, parallel and antiparallel

$$A_{LL} = R_{PGF} \langle a_{LL} \rangle \langle \Delta G/G \rangle + A_{background}$$

Fraction of process — Analyzing power



$\gamma\, g \rightarrow q\bar{q}$

Two signatures for PGF:

1/ q=c open charm $c \rightarrow D^0 \rightarrow K\,\pi$

Clean signature of PGF

Limited statistics & large combinatorial background

COMPASS :1 point

2/ q= u,d,s high p_T hadron pair $q\,\bar{q} \rightarrow h\,h$

High statistics

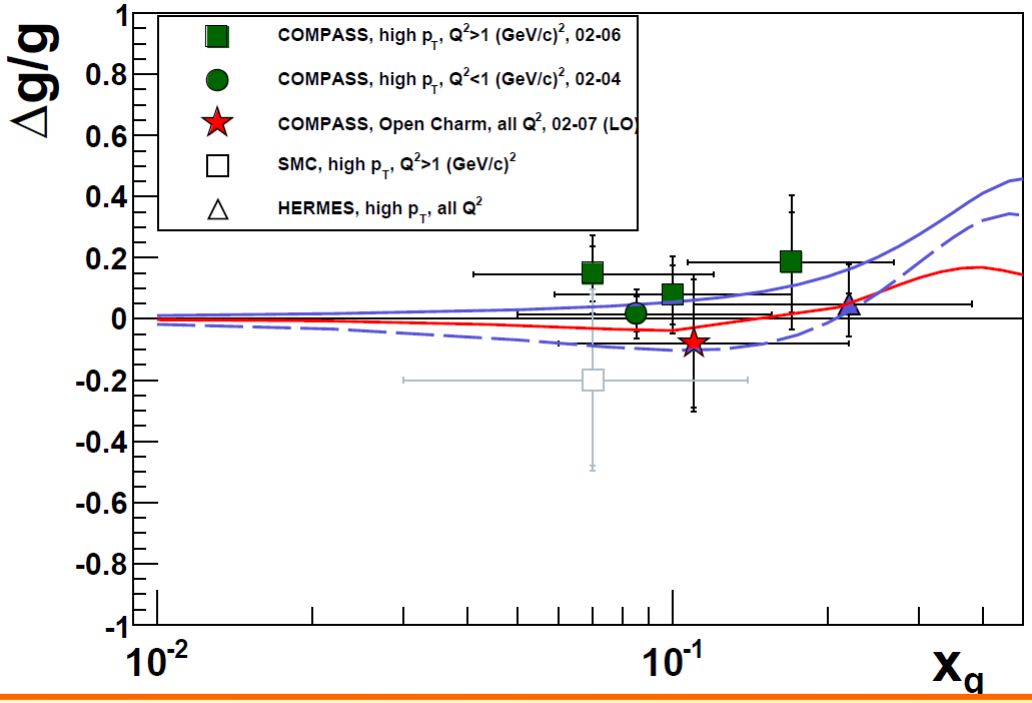
Physical background

COMPASS : 4 points + HERMES &SMC

Δ G/G at LO : SMC, HERMES and COMPASS

High p_T hadrons:
Q^2~ 3
with model for physical background

Open charm:
Q^2= 13



LSS10, ΔG~ + 0.32

LSS10, ΔG~ - 0.33
at Q^2= 4

DSSV, ΔG= 0.02
at Q^2=3

- **All direct measurements compatible with 0**
- **ΔG measured for 0.05 < x < 0.3**
- **Results disfavour value of the integral > ~ ± 0.3**
  i.e. ± 60% of the ½ nucleon spin
- **Contribution to <ΔG> outside measured x range not excluded**

Note that these data are NOT included in global fits of DSSV and LSS

De Florian, Sassot, Stratmann, Vogelsang ***Leader, Sidorov, Stamenov***

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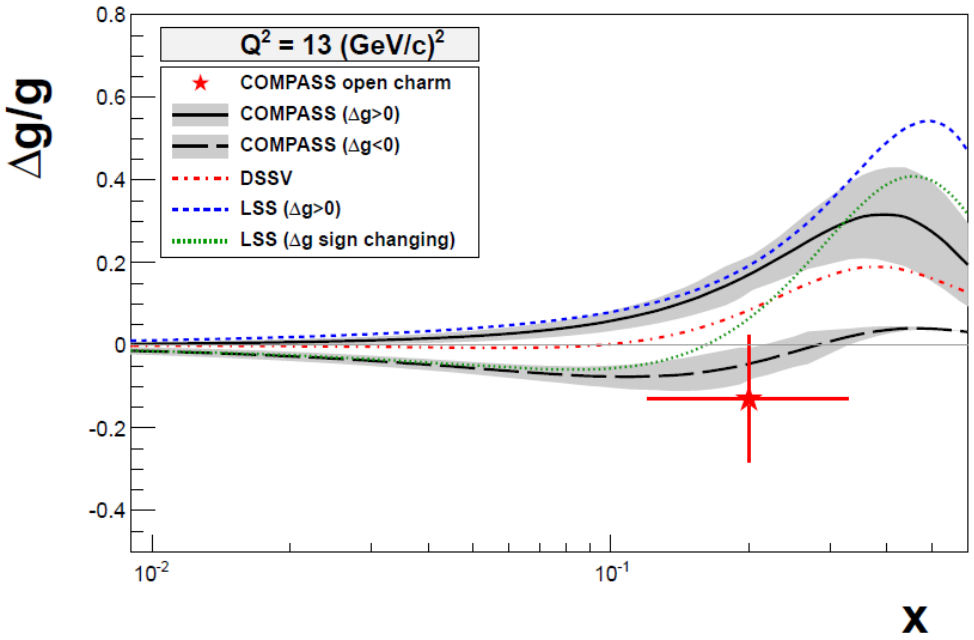
Δ G/G at NLO : charm channel

The only channel for which the analyzing power a_{LL} is calculated at NLO.

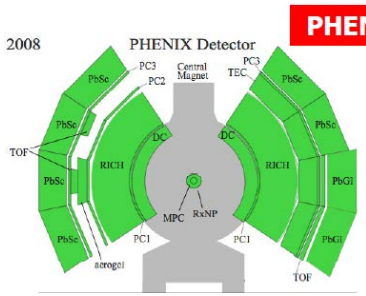
a_{LL} distribution shifted in x → Induces a change in **<ΔG>,** but also in the relative weight of events, hence a change in **<x>**

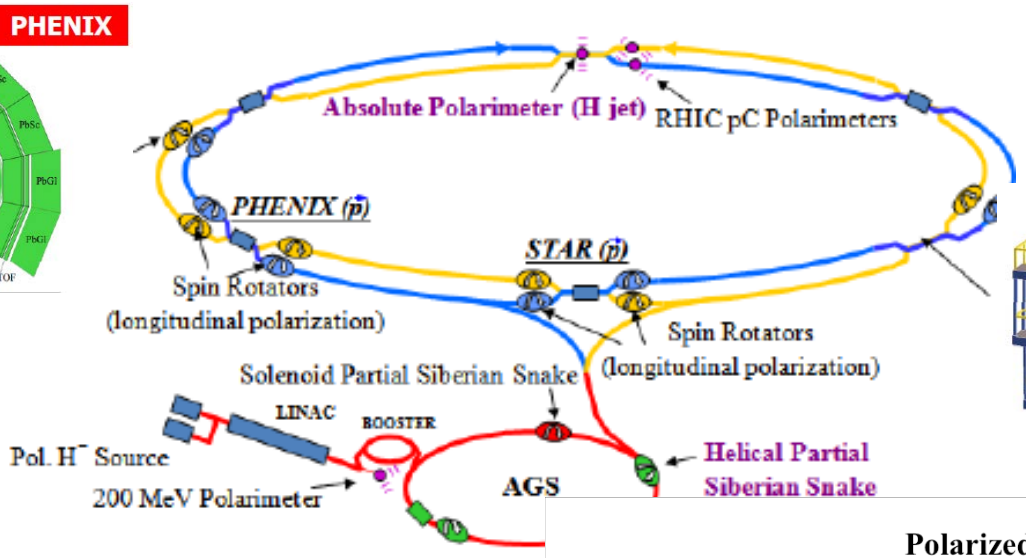


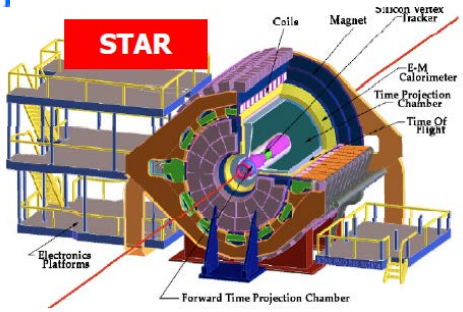
COMPASS PRD87(2013)052018

Value of ΔG still compatible with zero; higher <x > measured

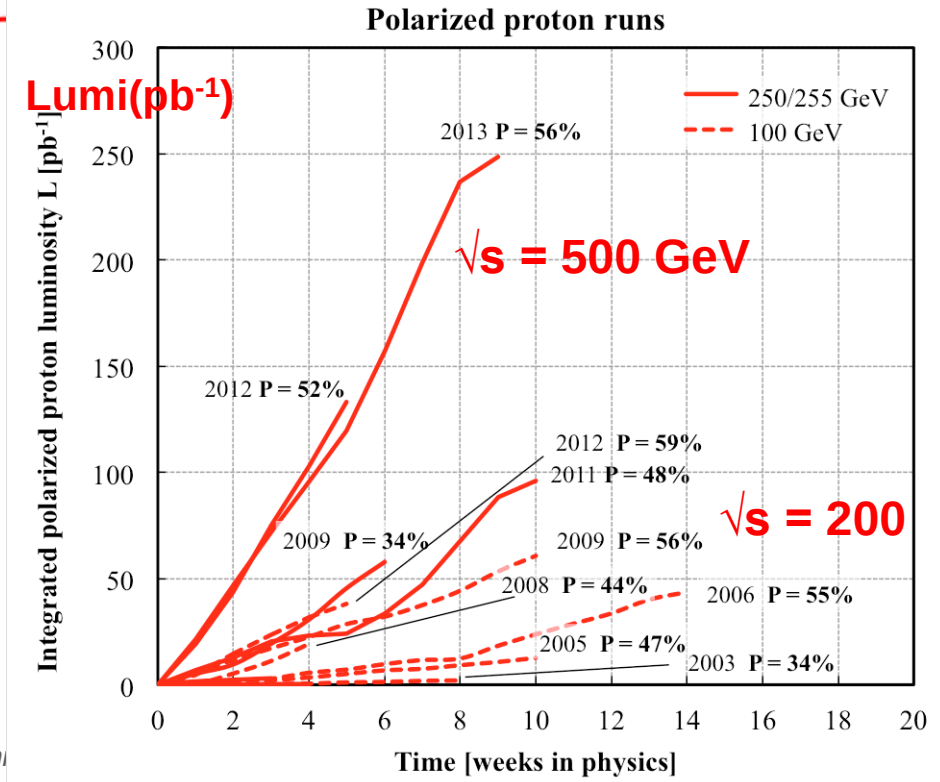
2. $\vec{p}\,\vec{p}$ collisions at RHIC







- **Longitudinal spin**
  - hadron production for **<ΔG>**
  - W production for **<Δq>**
- **Transverse spin**



2. $\vec{p}\,\vec{p}$ collisions at RHIC, channels for ΔG

- More abundant channels

p p → π^0 X **PHENIX**

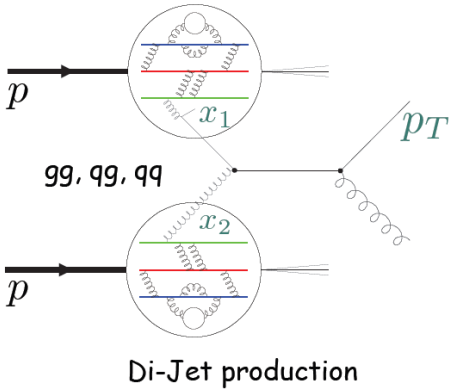
p p → **jet** X **STAR**

3 processes contribute *gg, qg, qq*

$\Delta G(x_1) . \Delta G(x_2)$

$\Delta G(x_1) . \Delta q(x_2)$

$\Delta q(x_1) . \Delta q(x_2)$



Di-Jet production

- Other channels

p p → jet jet 500 GeV, low x

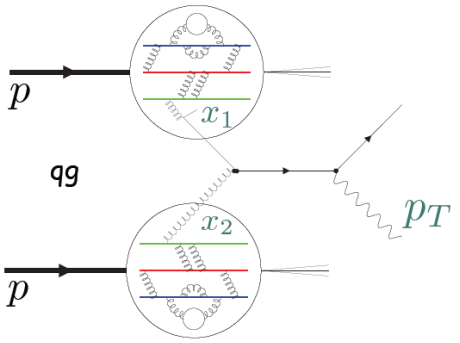
p p → γ jet

1 single process *qg* → cleaner

Full kinematics reconstructed

Low statistics

$\Delta G(x_1) . \Delta q(x_2)$



Photon-Jet production

p p → γ X

- Other channels: $\pi+$, $\pi-$, η, …

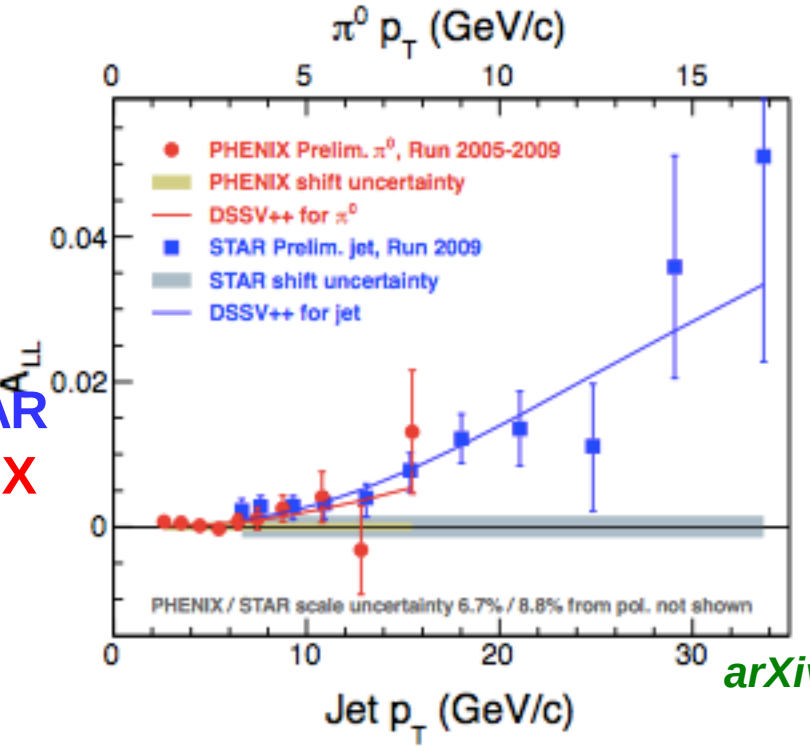
High potential for ΔG from various channels, various kinematics

$\vec{p}\vec{p}$ collisions at RHIC: jet at STAR, π^0 at PHENIX

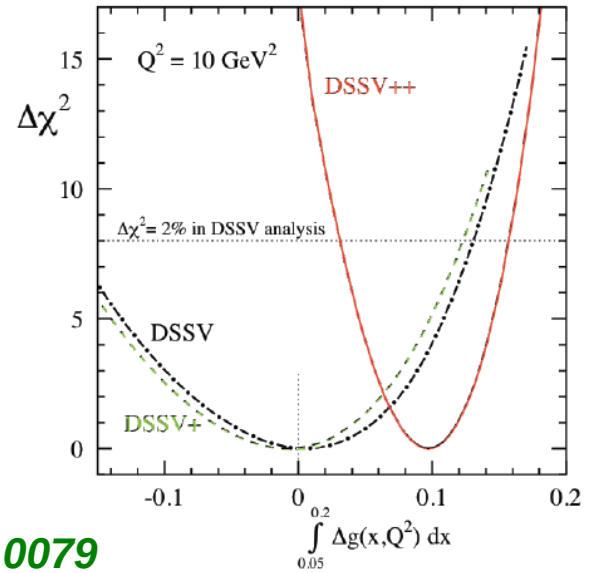
$\vec{p}\,\vec{p}$ → **jet/ π^0** +X

Measure double spin asymmetry A_{LL} (p_T)
Compare data to global fits with a given $\Delta G(x)$ parameterization

Jet at STAR
π^0 at PHENIX



High stat. run 9
→ New fit DSSV++



arXiv:1304.0079

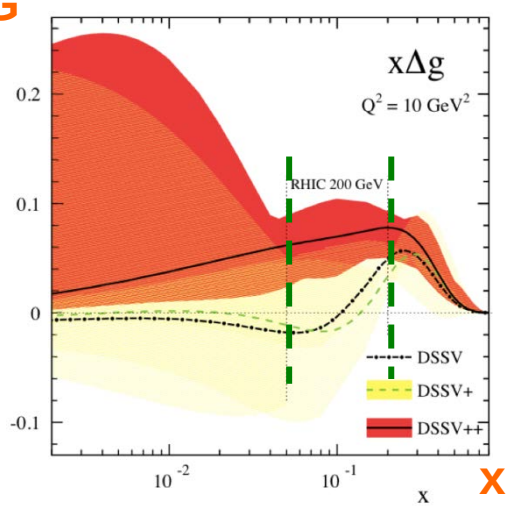
Strong constraint on ΔG in measured range giving ΔG positive ~ 0.1 for 0.05<x<0.2

ΔG – Low x contribution?

Shape of ΔG distribution unknown.

Very large error band at low x, which might bring ΔG to big value.

xΔG



DVSV++ & arXiv:1304.0079

Lower x?

RHIC 2012+2013 500 GeV: inclusive jet, dijets,

& expect to double 200 GeV statistics in 2015 run

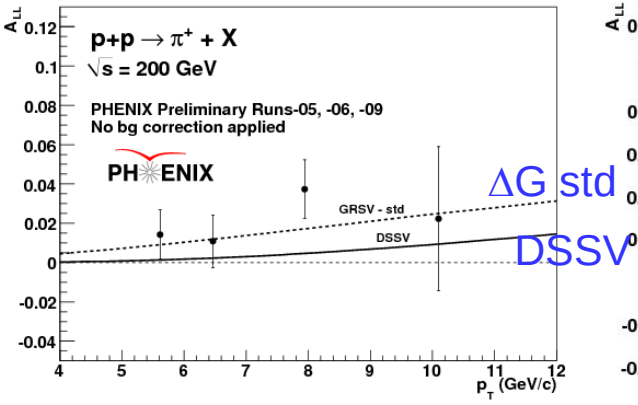
But **expect very small A_{LL} since** $\propto \frac{\Delta G}{G}$

$\vec{p}\vec{p}$ collisions at RHIC: other channels

charged pions: different FF for favored or unfavored
different *qg* contributions for $\pi^{0,+,-}$ → access **sign of ΔG**

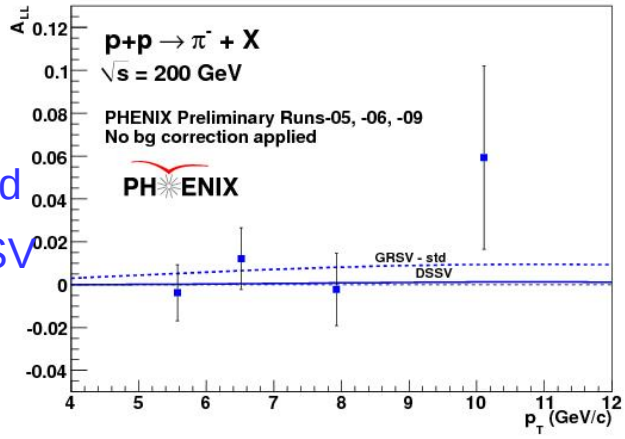
$$A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-} \Rightarrow \Delta G > 0$$
$$A_{LL}^{\pi^+} < A_{LL}^{\pi^0} < A_{LL}^{\pi^-} \Rightarrow \Delta G < 0$$

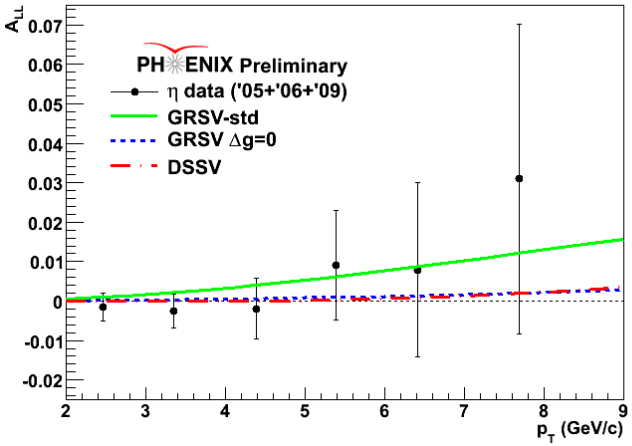
π^+ π^- η



ΔG std

DSSV





Sensitive to s fragmentation

Promising channels when more statistics available

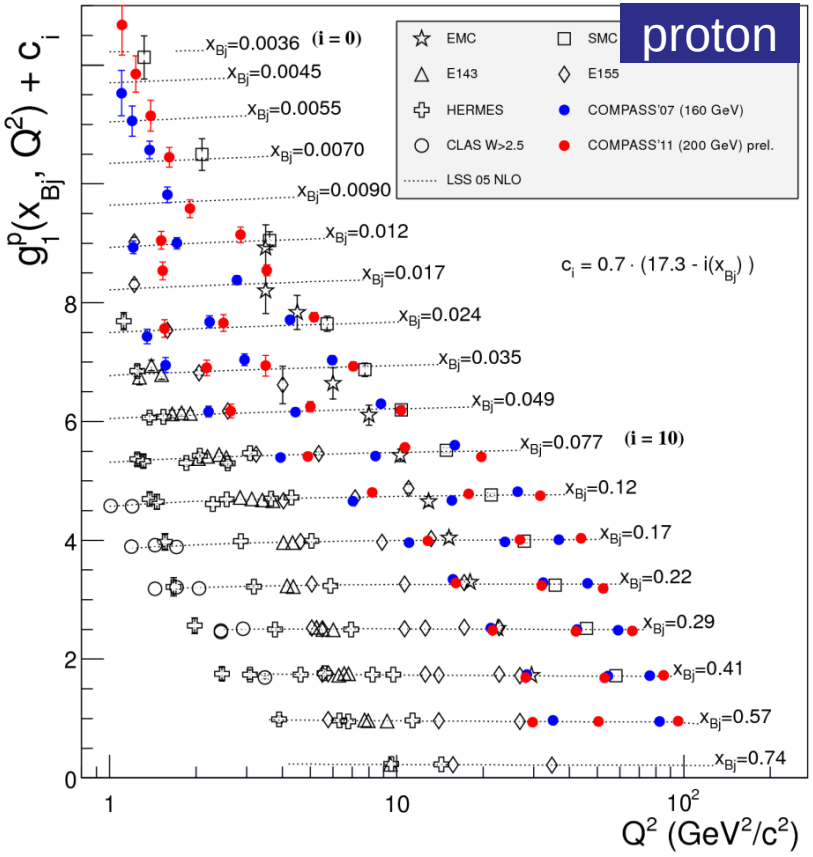
3. ΔG from Q^2 evolution of g_1. Global QCD fits

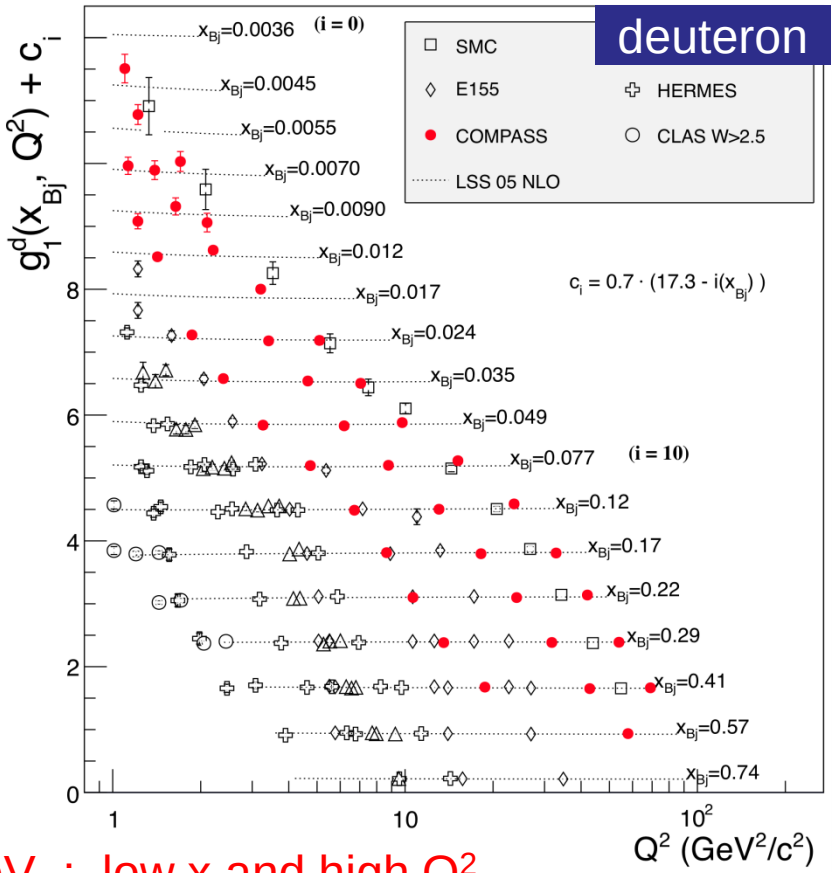
Pol. deep Inelastic Scattering
➔ spin structure functions g_1

$$\frac{d\,g_1}{d\,Log(Q^2)} \propto -\Delta g(x,Q^2)$$

$$A_1^{DIS} \propto g_1(x) \propto \frac{1}{2}\Sigma e_q^2\left(\Delta q(x) + \Delta\bar{q}(x)\right)$$

→ g_1 as input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta G(x)$



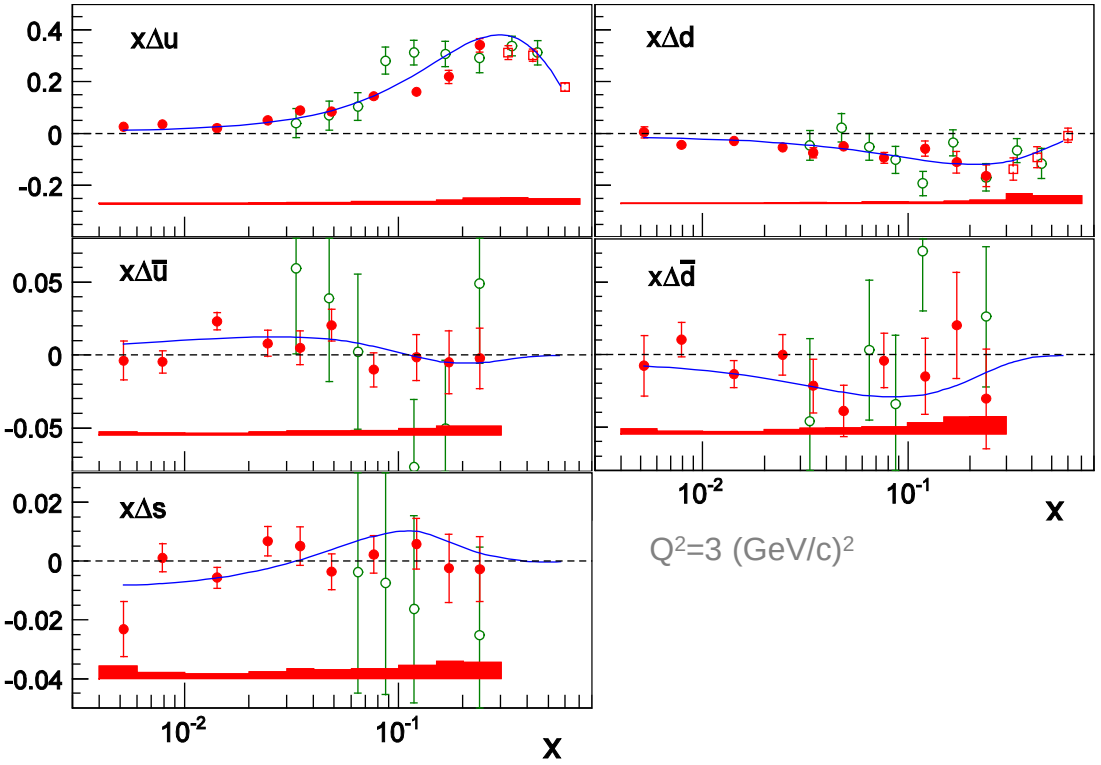


New data from COMPASS 200 GeV : low x and high Q^2
However x and Q^2 coverage not yet sufficient for precise ΔG
Use also constraint from pp data (DSSV)

Quark helicities from semi-inclusive DIS

$l^{\rightarrow} p^{\rightarrow} \rightarrow l\, h^{+/-}\, \mathrm{x}$

Hadron tags quark flavor
(quark fragmentation functions)



- **COMPASS**
  PLB693(2010)227, using DSS FF
- **HERMES**
  PRD71(2005)012003
- DSSV

- **Full flavour separation → x~0.004**
- **Sea quark distributions ~ zero**
- **Good agreement with global fits**

Strange quark polarization – Δs puzzle

• **DIS data**: **Integral of Δs** is extracted from the integral of g_1 using two other inputs (n and hyperon decay) & SU(3)

→ $\int \Delta s + \Delta\bar{s} = -0.08 \pm 0.01 \pm 0.02$

• **SIDIS data**: **Δs(x)** measured from **kaon** spin asymmetries, using quark fragmentation functions, in particular Ds^K, (s quark fragmentation into K)

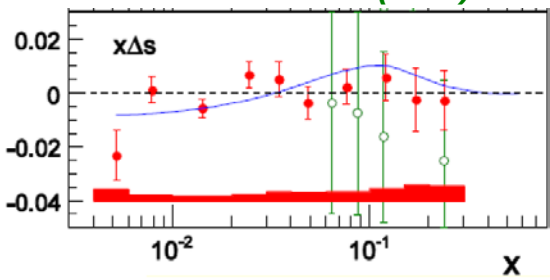
→ **Δs(x)≈ 0**

Several possible explanations to the discrepancy :

- Uncertainty on Ds^K
- Global fits (DSSV, LSS) suggest negative Δs at low x reconciles the two approaches
- Assume SU(3) violation a_8 from 0.58 to 0.42

→ Δs=-0.02 ***Bass &Thomas, PLB 684(2010)216***

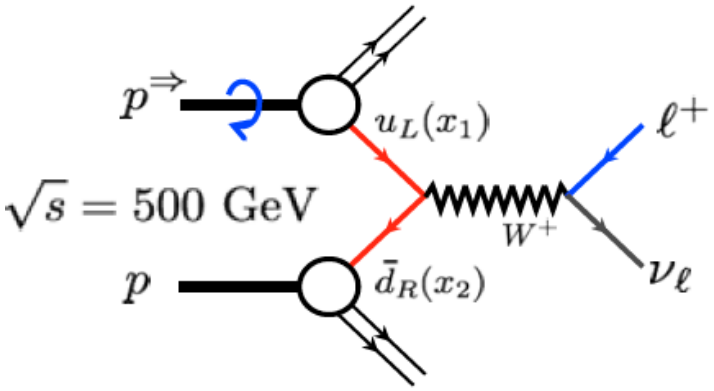
COMPASS PLB 693(2010)227



Recent data on quark fragmentation functions **HERMES/COMPASS**

Recent data on Δs at low x **COMPASS 200 GeV**

Quark helicities from W production in $\vec{p}\vec{p}$

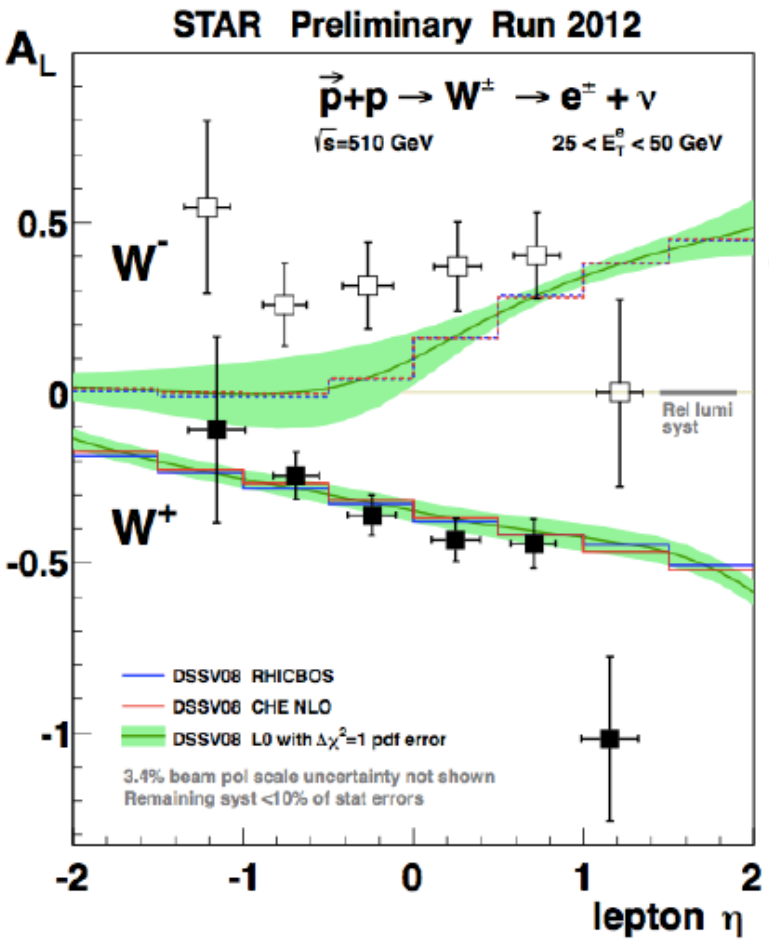


Single spin asymmetry measured at STAR and PHENIX
Parity violating
No quark fragmentation function needed
High energy scale

$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu \quad \rightarrow \Delta\bar{d}$$

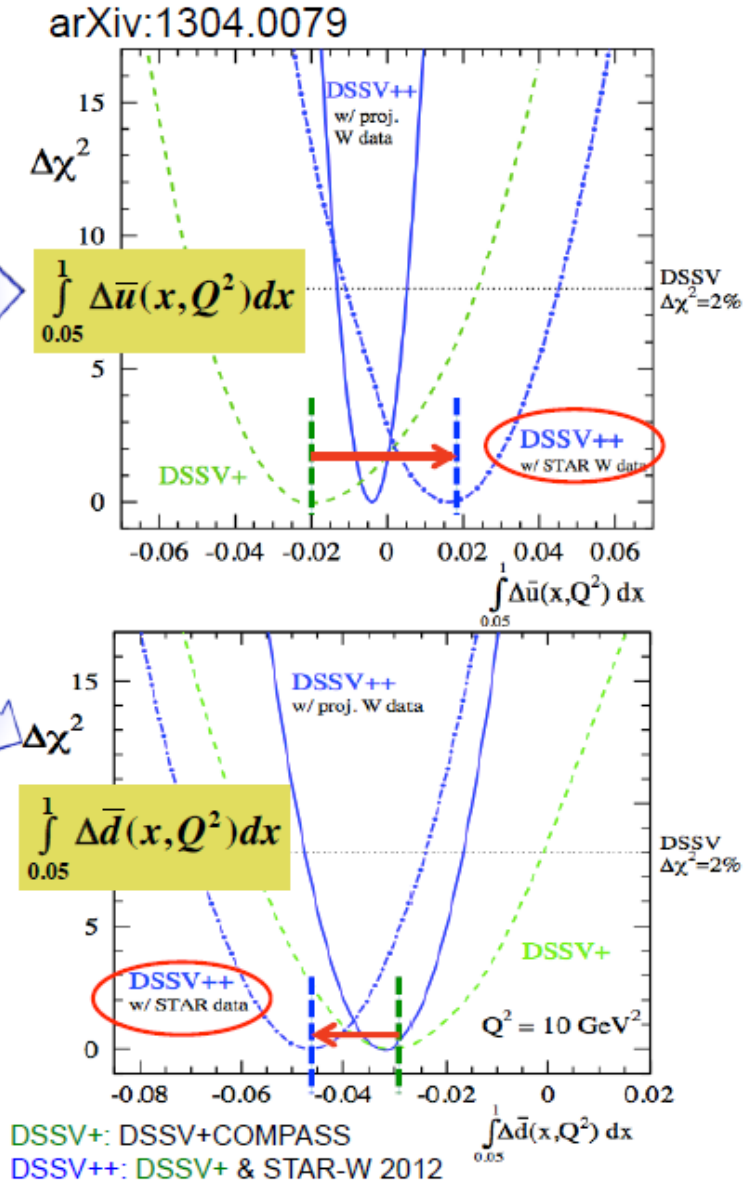
$$\bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu} \quad \rightarrow \Delta\bar{u}$$

W results from STAR and global analysis



$\Delta\bar{u}$

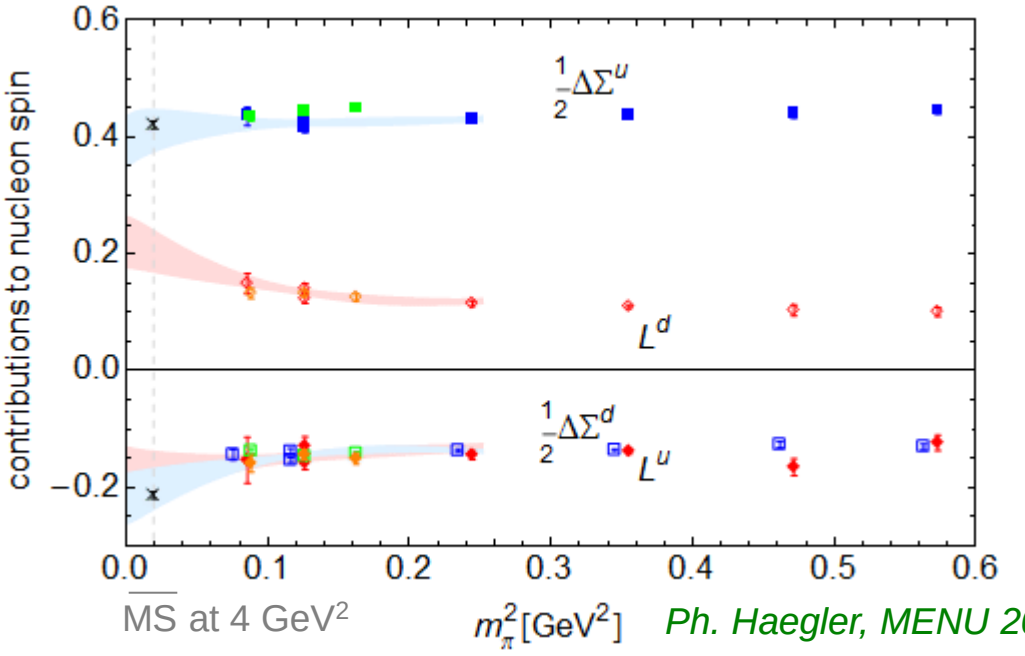
$\Delta\bar{d}$



STAR 2012 W results provide significant constraints on $\Delta\bar{u}, \Delta\bar{d}$.

from Qinghua Xu, DSPIN-2013

Lattice : quark spin and angular momentum

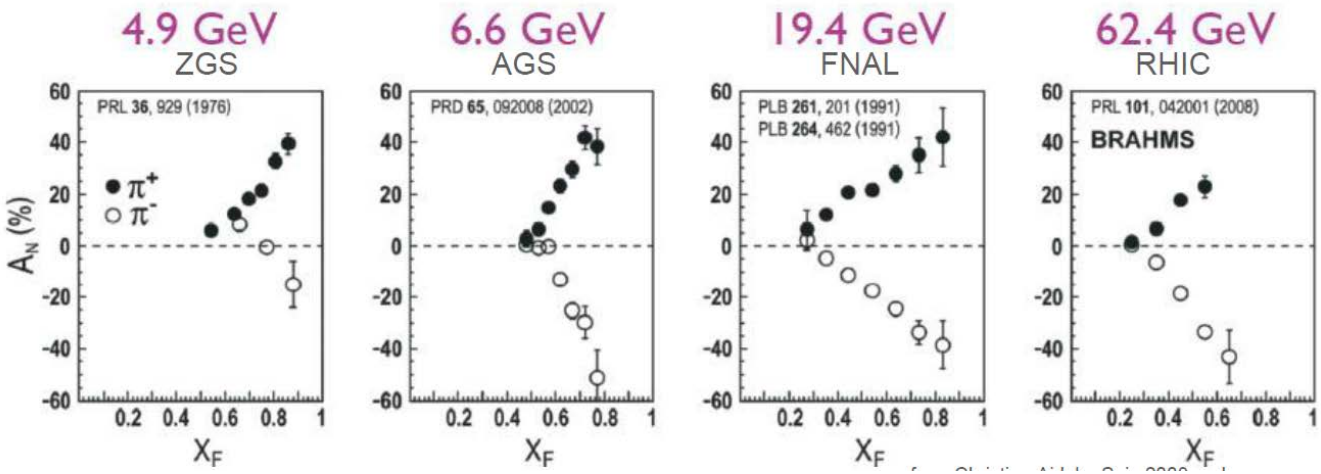


Ph. Haegler, MENU 2010

- **Impressive results from lattice QCD**
- **Agreement with measurements for quark spin**
- **Predictions for angular momentum**

Transverse spin

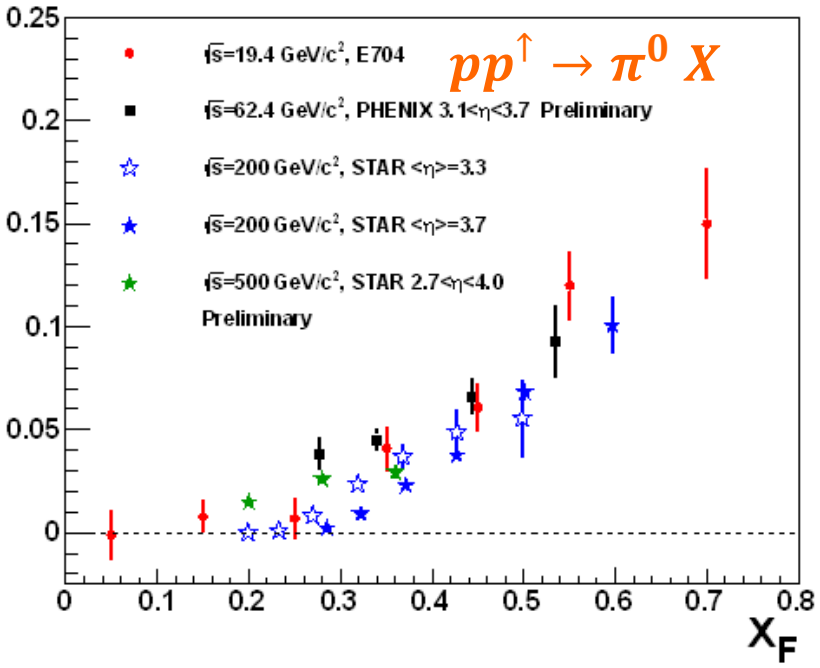
Where it all started from... (1978) $pp^{\uparrow} \rightarrow \pi X$ $\frac{\sigma\uparrow-\sigma\downarrow}{\sigma\uparrow+\sigma\downarrow}$ large p_T



Unexpected large single spin asymmetry $A_N^{\pi^0}$

Attributed to correlations between nucleon spin, orbital angular momentum, transverse momentum k_T of partons…

E704… and latest RHIC results from PHENIX and STAR on π^0 , following BRAMS and others.



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Transversity

Three distribution functions are necessary to describe the structure of the nucleon at LO in the collinear case:

- **q(x) :** number density or **unpolarised distribution**
- $\Delta q(x) = q^{\rightrightarrows} - q^{\leftrightarrows}$: longitudinal polarization or **helicity distribution**
- $\Delta_T q(x) = q^{\uparrow\uparrow} - q^{\downarrow\uparrow}$: transverse polarization or **transversity distribution**

All 3 of equal importance

Further distributions exist, Transverse Momentum Dependent (**TMD**) , revealing correlations between **nucleon spin, quark spin** and **quark transverse momentum k_T.**

All measured simultaneously in SIDIS.

Among them, the **Sivers** function.

Transversity- Collins and Sivers asymmetries

- Access via **SIDIS**, transversely polarized target $l\ p^{\uparrow} \rightarrow l\ p\ h^{+/-}$

- Measure simultaneously several azimuthal asymmetries, out of which :

  Collins: Outgoing hadron direction & quark transverse spin

  Sivers: Nucleon spin & quark transverse momentum k_T

at LO:

Collins

q transverse spin distr.

$$A_{Coll} = \frac{\sum_q e_q^2 \Delta_T q \otimes \Delta_T \circ D_q^h}{\sum_q e_q^2 \cdot q \otimes D_q^h}$$

Collins fragmentation function, depends on spin

Sivers

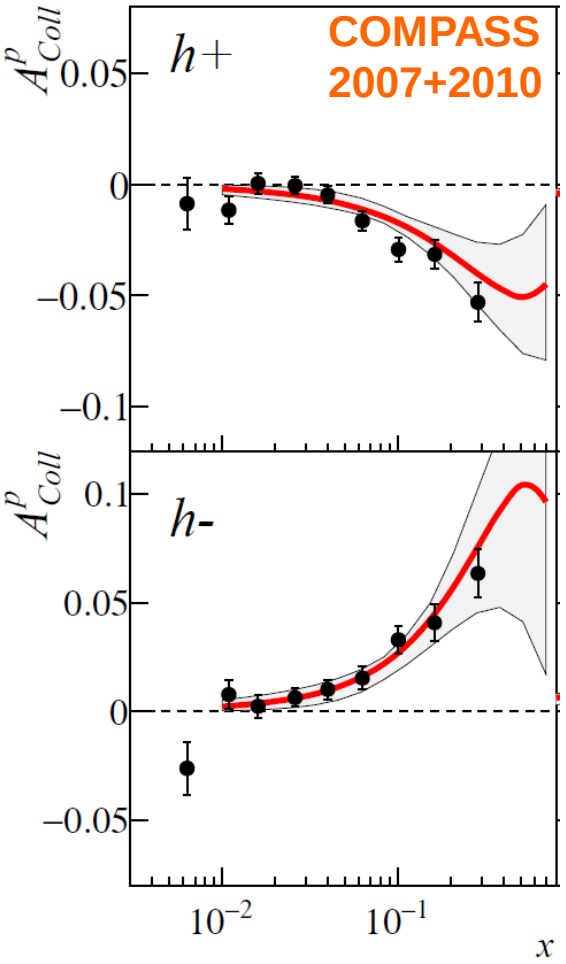
Usual quark fragmentation function

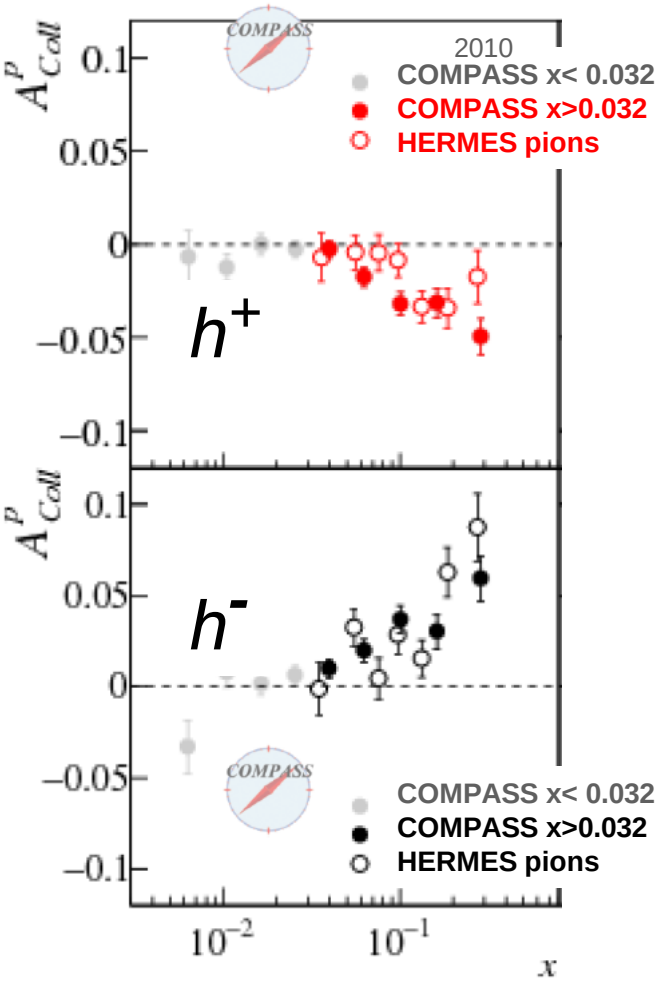
$$A_{Siv} = \frac{\sum_q e_q^2 \cdot f_{1Tq}^{\perp} \otimes D_q^h}{\sum_q e_q^2 \cdot q \otimes D_q^h}$$

note: $\Delta_T q$ also measured in SIDIS using
- ''Two hadron'' fragmentation function
- lambda Transverse Polarization

Also accessed in pp

Collins asymmetry- latest results on proton





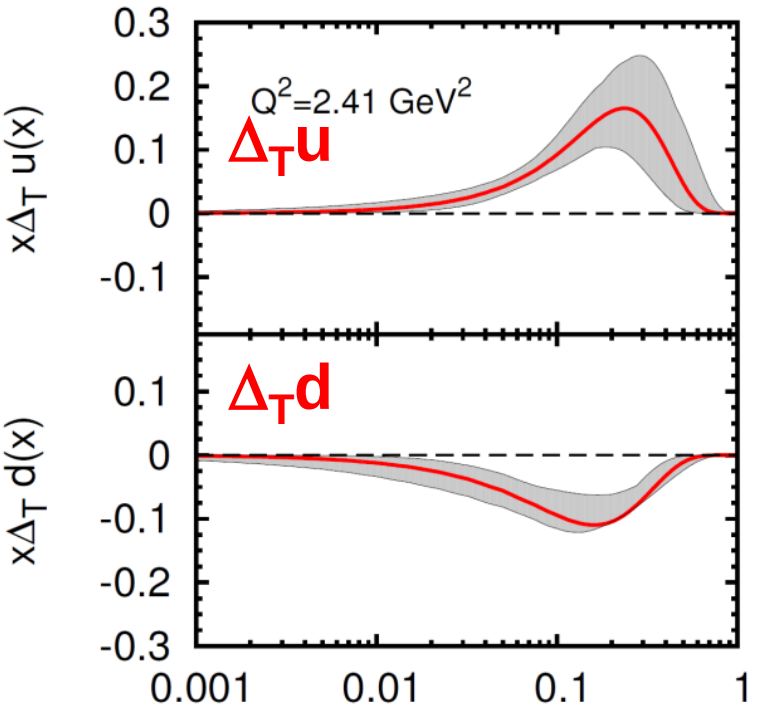
- **Large signal with proton target.** (Is zero with deuteron target)
- **Same signal strength seen by HERMES and COMPASS, although different Q^2 , by factor of ~4. (New)**

Transversity – from Collins Asymmetry

Several combined analyses of polarized SIDIS data

HERMES-proton, COMPASS–p and deuteron, and **BELLE fragm.fct.** data

Flavor separation



M. Anselmino et al., PRD87 (2013) 094019

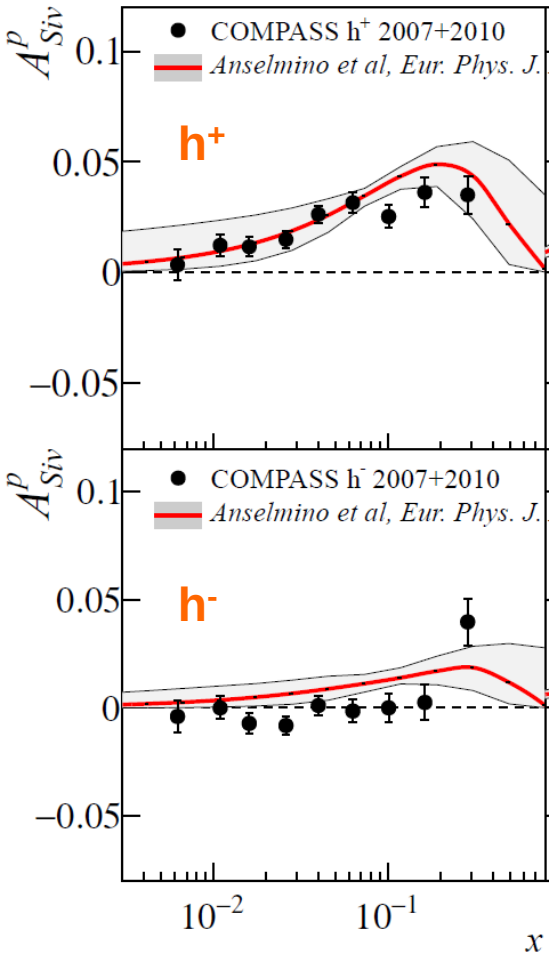
- Cloet, Bentz and Thomas PLB659 (08)
- Bacchetta, Conti, Radici, PRD(09)
- Anselmino et al.
- ...

- **$\Delta_T u > 0$ and $\Delta_T d < 0$**
- Do not saturate Soffer bound
- Smaller than helicity

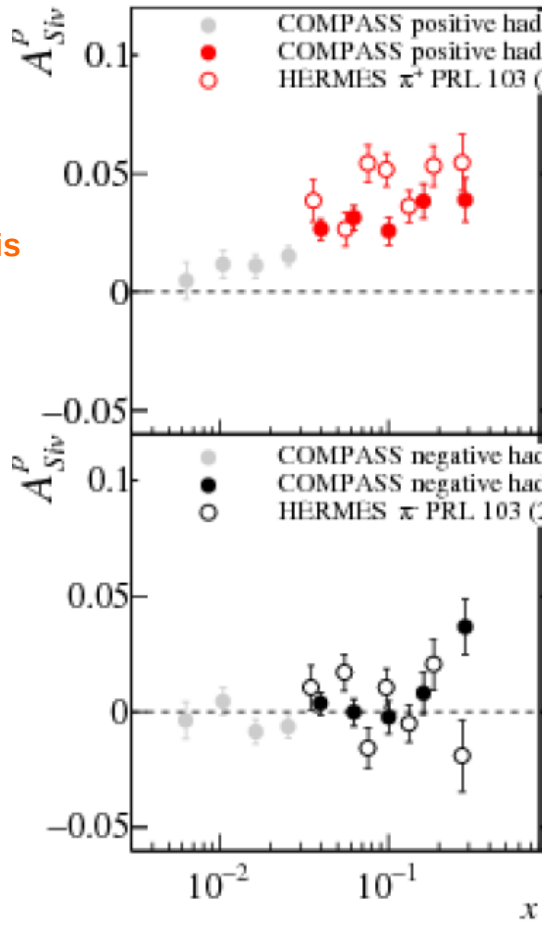
- Also extractions for sea quarks
- More data large/small x, with p, d, n targets needed to map z,Q^2, p_T dependence

Sivers asymmetry- latest result on proton

Correlation between Nucleon spin & quark transverse momentum k_T



COMPASS With Anselmino et al. global analysis



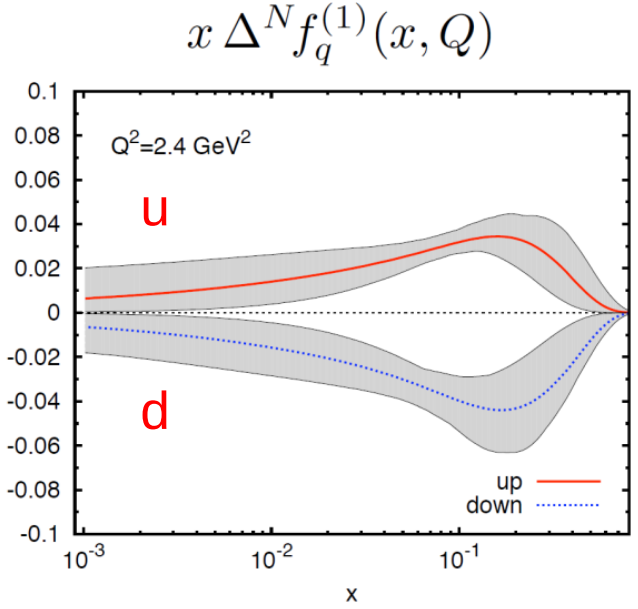
HERMES vs COMPASS limited range X>0.032

Large signal with proton target and h+
Was measured to be zero on deuteron
Smaller strength at larger Q^2 (COMPASS).

Sivers function – extraction

using HERMES p
and COMPASS p, d.

→ u and d quark Sivers function opposite



M.Anselmino et al.,QNP2012

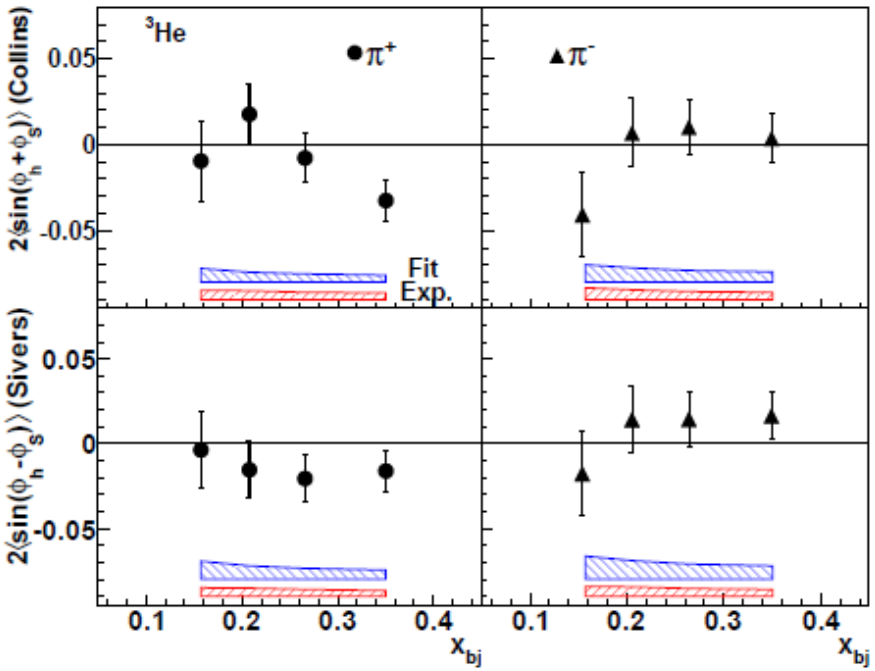
- **Much progress on Sivers (and all TMDs) from polarized SIDIS data**
- **Still more statistics needed to separate all variables: x, z, p_T,Q^2**
- **Future:**

Polarized Drell-Yan (COMPASS), where Sivers effect is expected, but with opposite sign → test of factorization approach

Collins and Sivers asym. on neutron - JLab

Jlab Hall A, E06-010

$$^3\mathrm{He}^{\uparrow}(e,e'h),\ h=\pi^+,\pi^-$$



X. Qian at al., PRL 107:072003(2011)

^{3}He Collins SSA small, non-zero at highest x for π^+

^{3}He Sivers SSA: negative for π^+,

Conclusions

Gluon contribution to nucleon spin

Direct measurements point to zero or small contribution. Strong constraint on fits from RHIC. Only $0.05 < x < 0.2$ probed. Need lower x data.

Quark contribution to nucleon spin

Extraction for all flavours from SIDIS, down to x ~ 0.004.

$\Delta\bar{u}$ and $\Delta\bar{d}$ also from W production

Towards agreement with Lattice QCD calculation for $\Delta\Sigma$

$\Delta s(x) \sim 0$ from SIDIS in measured region, and $\int \Delta s < 0$ from DIS:

more data and strange quark fragmentation functions expected soon.

Transversity and TMDs

Precise results on Collins and Sivers

Much progress on all azimuthal asymmetries for TMDs (not shown)

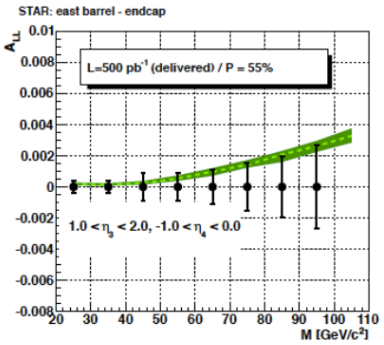
Exciting future programs in preparation at RHIC, COMPASS-II & Jlab-12GeV

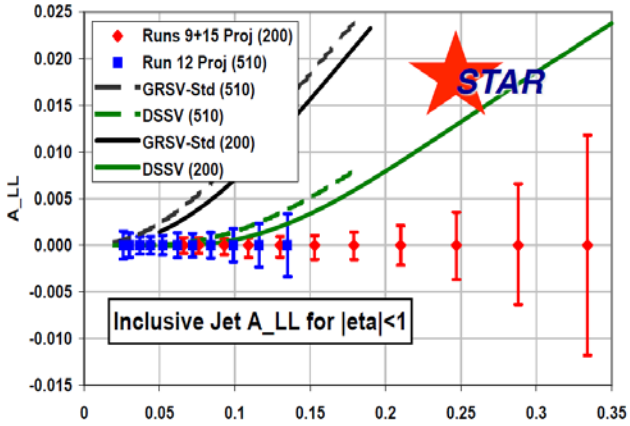
A glance at future prospects

RHIC projections for 2012+2013 data (and more expected in 2015):

Spin asymmetries A_{LL} for ΔG ;

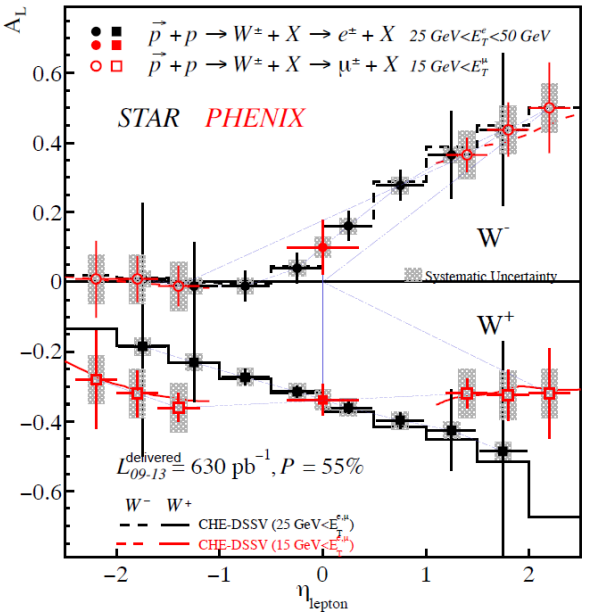
p+p→ jet+jet+X at 500 GeV





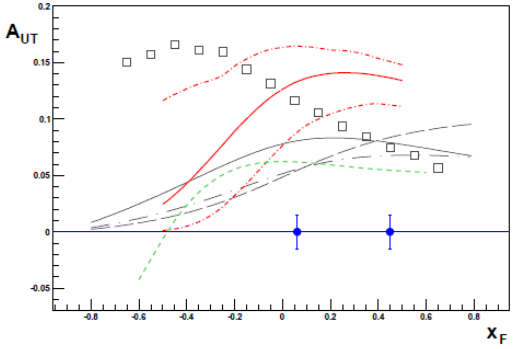
W for $\Delta\bar{u}$ and $\Delta\bar{d}$

arXiv:1304.0079
(pseudo-data randomized around DSSV)



COMPASS 2015 Polarized Drell-Yan

$\pi p^{\uparrow} \rightarrow \mu^{+}\mu^{-}X$ test sign change of Sivers



COMPASS 2016-2017:

- DVCS
- Polarized SIDIS (TMDs)

+ JLab12 polarized SIDIS, and later EIC…

spares

Quark spin contribution $\Delta\Sigma$ from QCD fits

COMPASS $\Delta\Sigma$ **=0.30** ± 0.01 (stat) ± 0.02 (evol)

fit to $g_1^{p,n,d}$ world data, $\overline{\text{MS}}$ scheme, Q^2=3 $(\text{GeV/c})^2$ *PLB 647 (2007) 8*

$\Delta s + \Delta\bar{s}$ =-0.08 ± 0.01 (stat) ± 0.02 (evol) COMPASS data only

HERMES $\Delta\Sigma$ **=0.33** ± 0.011 (stat) ± 0.025 (theo) ± 0.028 (evol)

HERMES g_1^d data, $\overline{\text{MS}}$ scheme, Q^2=5 $(\text{GeV/c})^2$, neglecting x < 0.02contrib., *PRD75 (2007)012007*

$\Delta s + \Delta\bar{s}$ =-0.085 ± 0.013 (th) ± 0.008 (exp) ± 0.009(evol)

DSSV $\Delta\Sigma$ **=0.24** Q^2=10 $(\text{GeV/c})^2$ *arXiv:0804.0422*

LSS '10

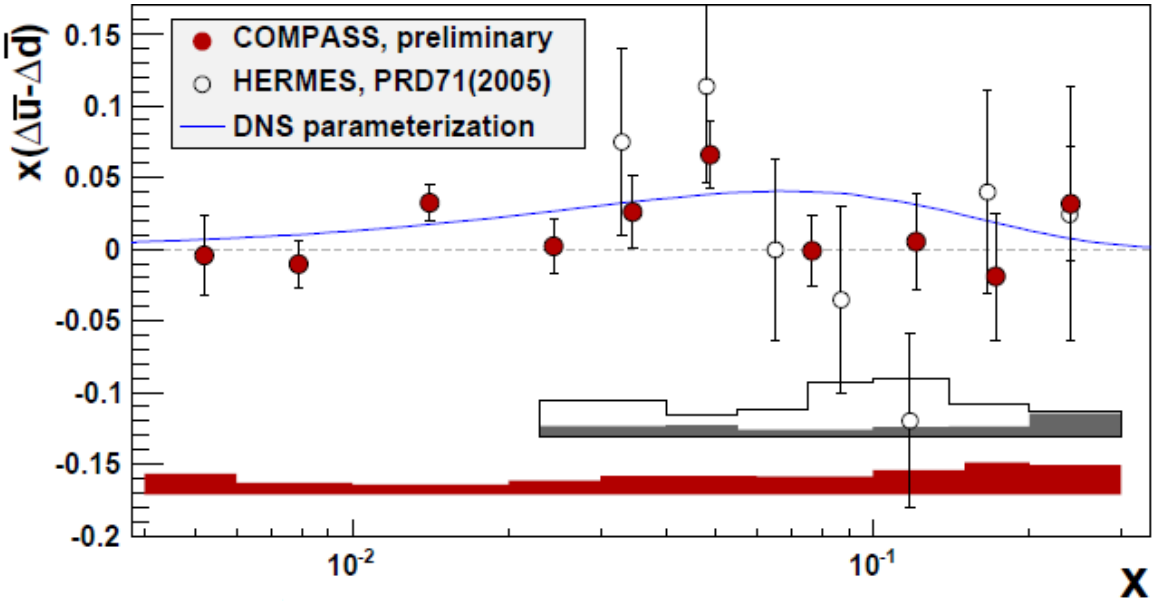
$\Delta\Sigma$ **=0.25** ± 0.04 ΔG with node Q^2=10 $(\text{GeV/c})^2$,

$\Delta\Sigma$ **=0.21** ± 0.03 ΔG >0

Light sea quark polarized distributions

From polarized SIDIS measurements

$x(\Delta\bar{u}-\Delta\bar{d})$



• **COMPASS**
o HERMES

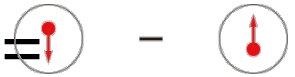
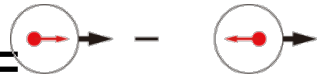
$$\int_{0.004}^{0.3}(\Delta\bar{u}-\Delta\bar{d})dx = 0.052 \pm 0.035(\text{stat.}) \pm 0.013(\text{syst.})$$

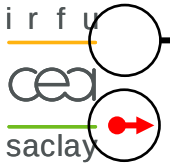
Slightly positive, compatible with zero.

Recall value for unpolarized case: $\int(\bar{d}-\bar{u})dx = 0.118 \pm 0.012$

More results to come from RHIC

TMD PDFs

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	f_1 = 		$h_1^\perp$ =  Boer-Mulders
L		g_1 =  Helicity	$h_{1L}^\perp$ =  Worm Gear
T	$f_{1T}^\perp$ =  Sivers	g_{1T} =  Worm Gear	h_1 =  Transversity $h_{1T}^\perp$ =  Pretzelosity



Nucleon Spin

Quark Spin

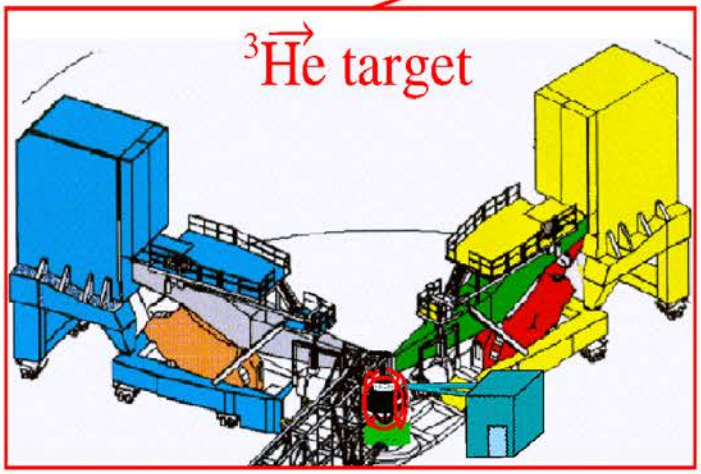
Jlab experimental halls

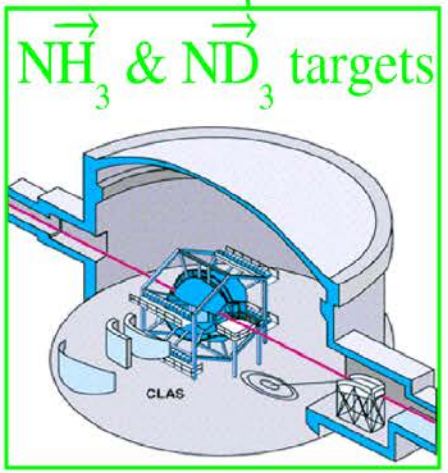
6 GeV **polarized**

CW electron beam

Pol=85%, 200μA

Will be upgraded to 12 GeV by ~2014





HallA: two HRS'

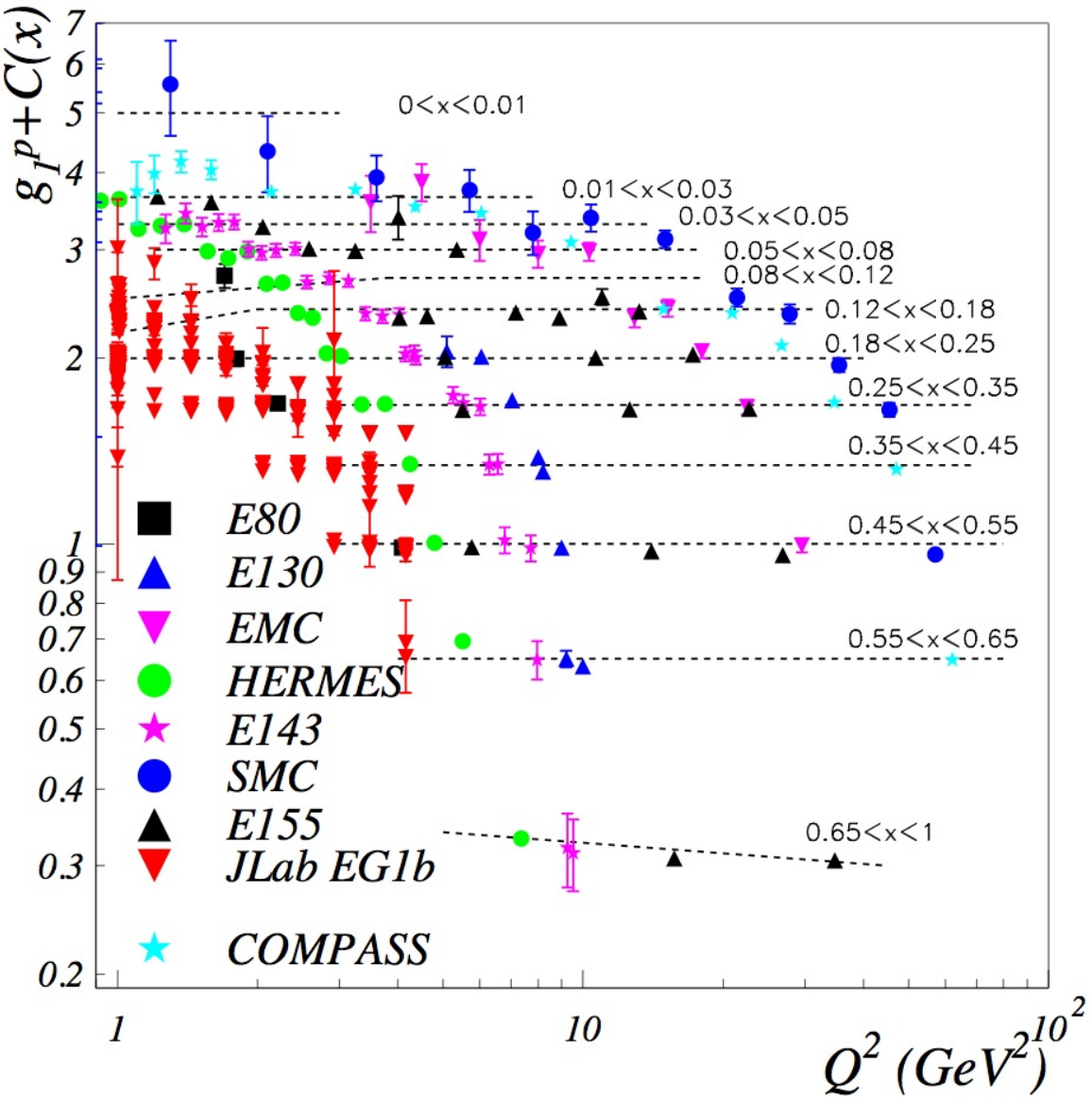
Hall B:CLAS

Hall C: HMS+SOS

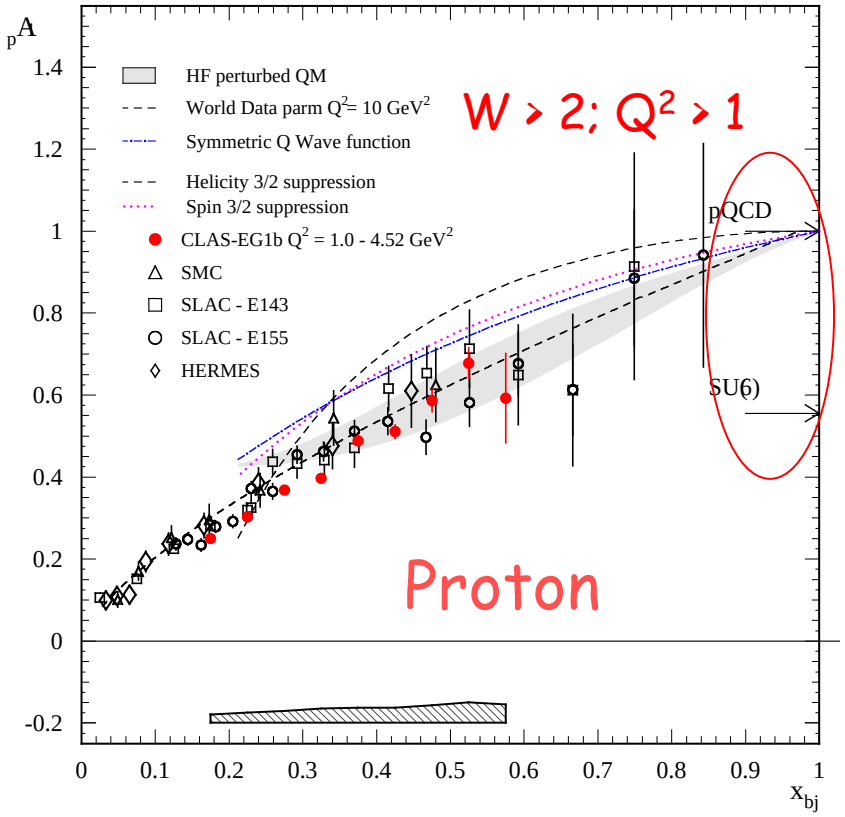
Jlab CLAS- $g_1(x,Q2)$ for the proton

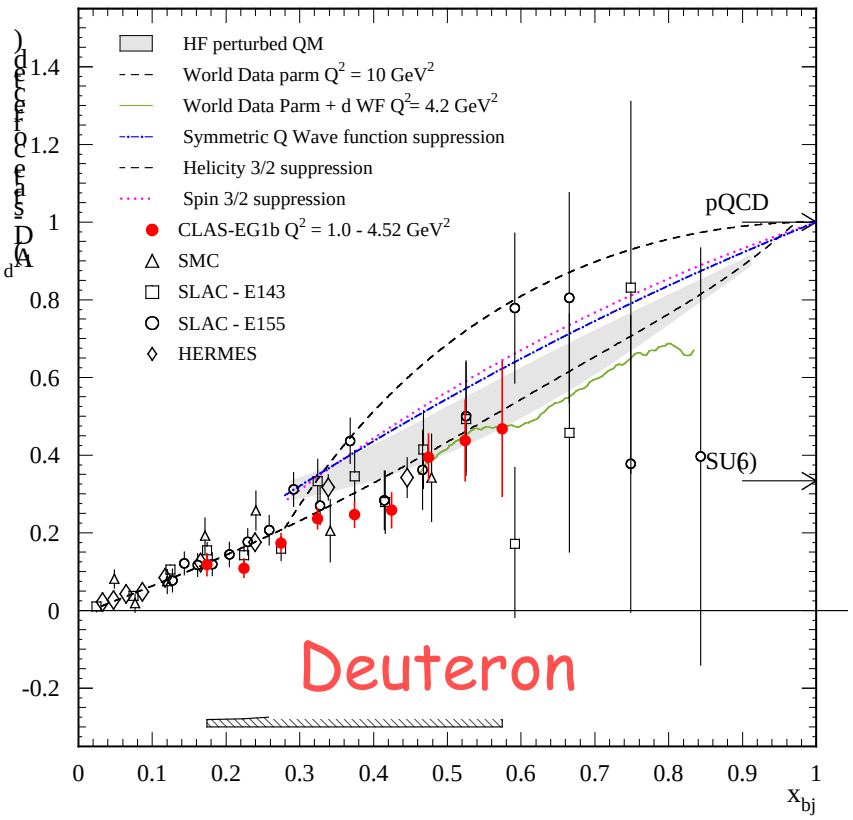
Jlab/ CLAS - EG1
5.7 GeV e-
Polarized NH_3
(and ND_3) targets

Data included
in LSS fit



Jlab – CLAS A_1^p A_1^d

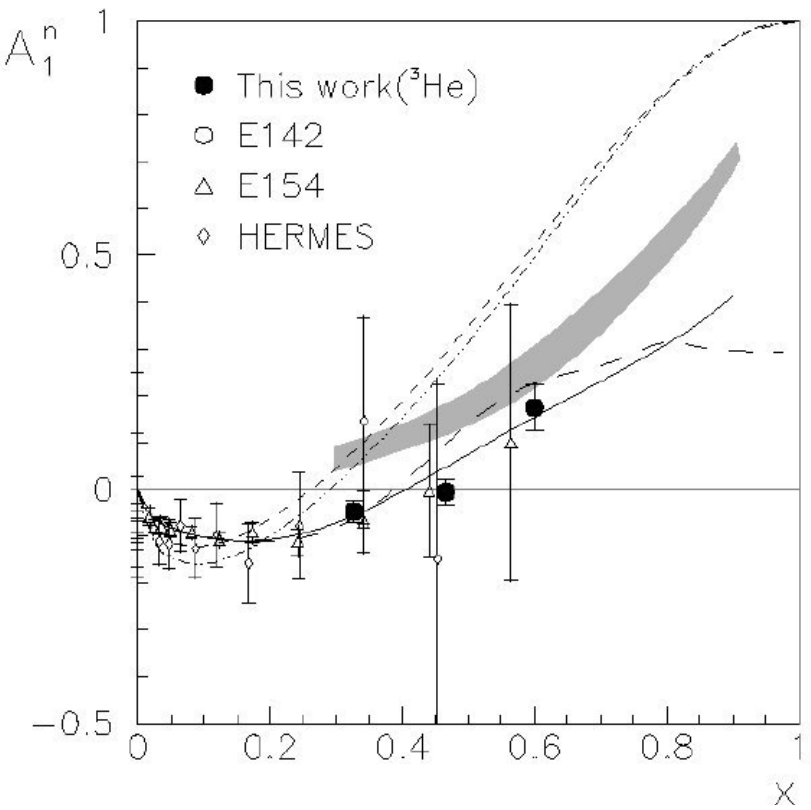




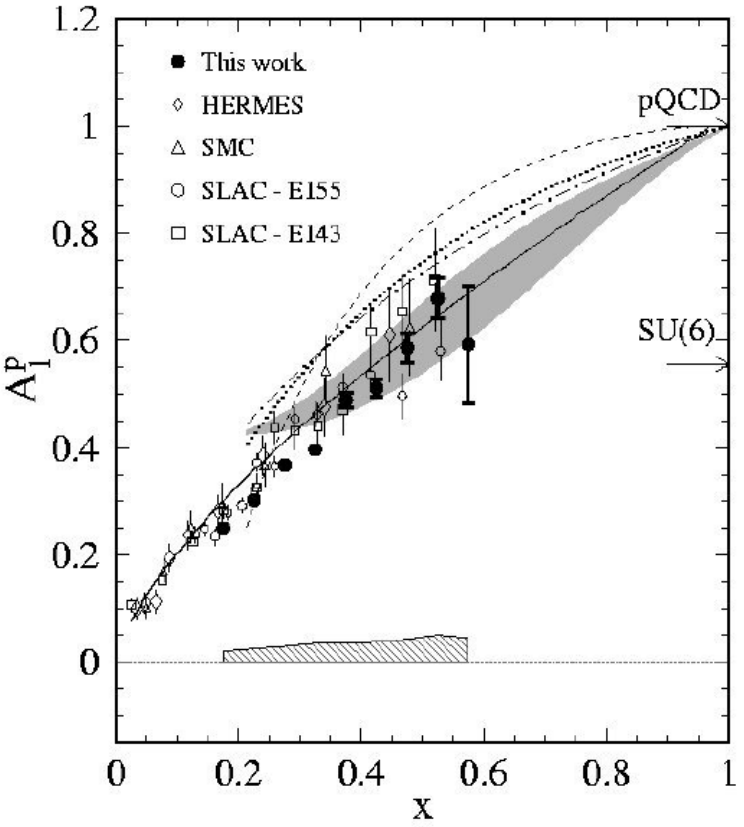
Jlab – A_1^n A_1^p

$W > 2$; $Q^2 > 1$

Neutron



Proton



JLAB, Hall A, PRL 92 (2004) 012004 and JLAB CLAS, PL B 641 (2006)

A_1^n at $x \rightarrow 1$, SU(6) symmetry breaking?

Polarized Quark Distributions- Valence sector

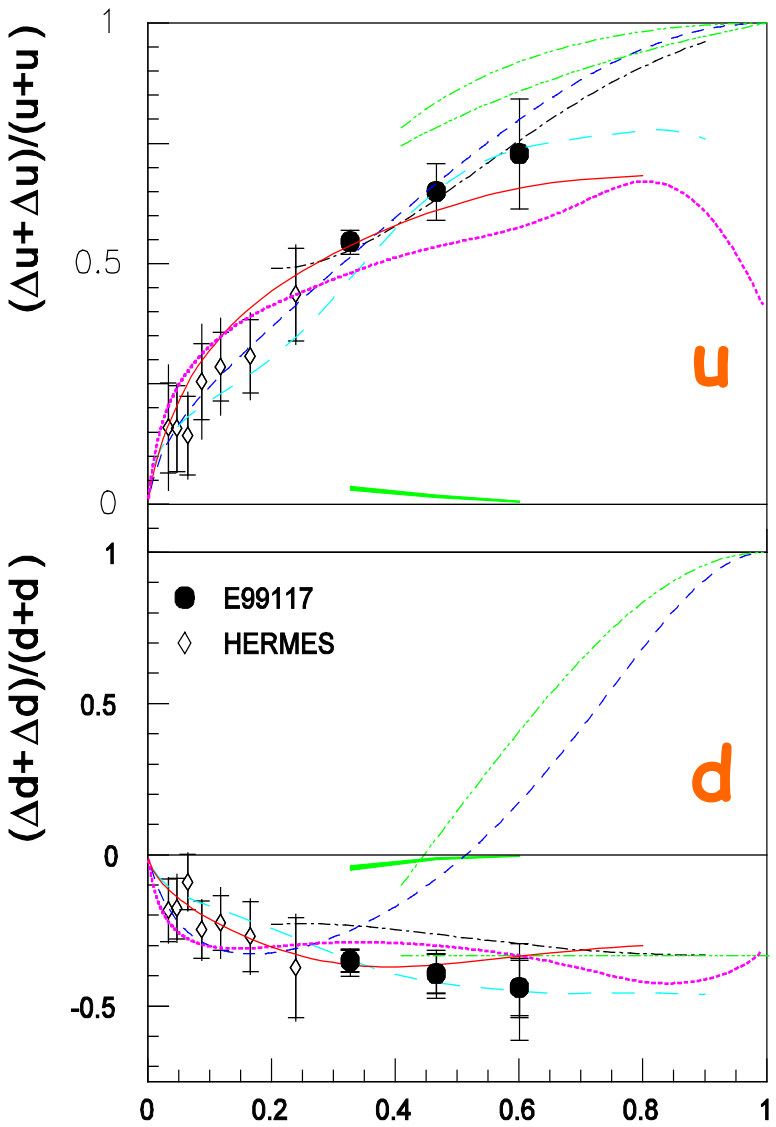
From A_1^n and A_1^p results

u quark spin as expected

d quark spin stays negative

- Disagree with pQCD model calculations assuming HHC (hadron helicity conservation)
- Quark orbital angular momentum

Consistent with valence quark models and pQCD PDF fits without HHC constraint



Chen, Seattle OAM Workshop, Feb2011