Nucleon Longitudinal Spin Structure
Experimental overview

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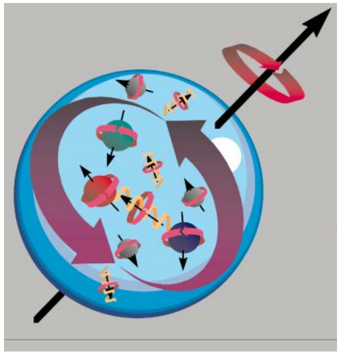
- **Gluon helicity**
- **Quark helicities**
- **Outlook**



Measurements at RHIC, COMPASS, HERMES, JLab

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, $\bar{u}$, $\bar{d}$, $\bar{s}$ $\Delta q = \overrightarrow{q} - \overleftarrow{q}$ 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 $L_{u,d}$

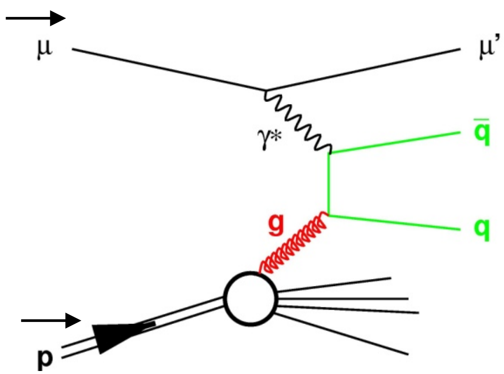
Large experimental effort on ΔG measurement

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

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 +…

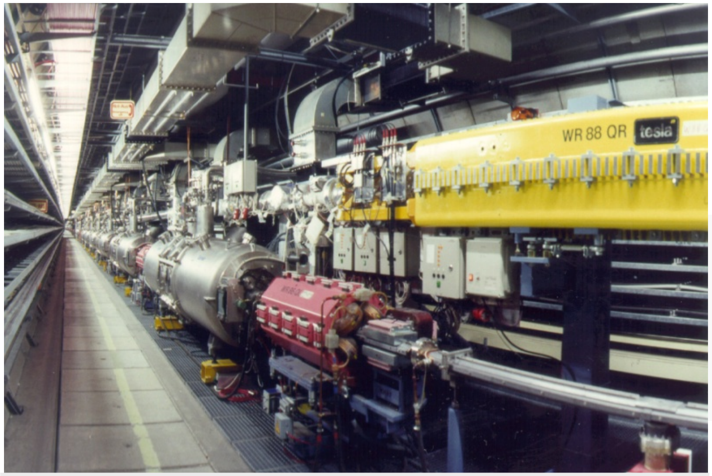
$$\frac{\Delta G}{G}\times\frac{\Delta q}{q} + \frac{\Delta G}{G}\times\frac{\Delta G}{G} + \ldots$$

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

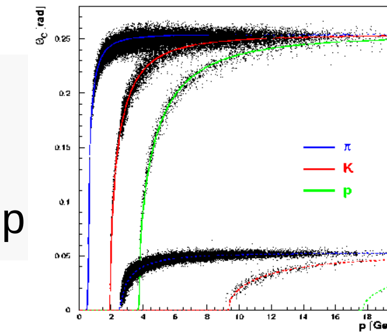
longitudinally polarized ~ 54%

1995 to 2007

Spectrometer :

$\Delta p/p \sim 2\%$, $\Delta\Theta < 1$ mrad

Excellent separation of π, K, p

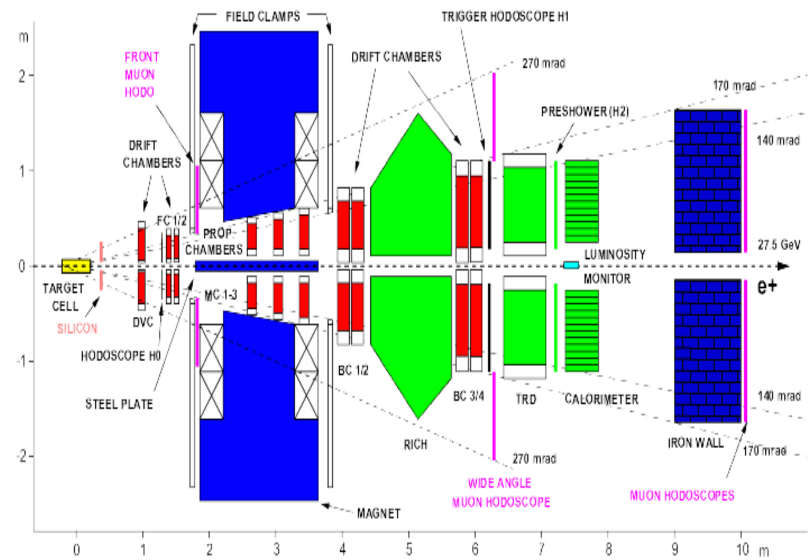


Gaseous internal target

Longit. Polar. 85% H, D, He

Transv. Polar H

Unpol H, D, Ne, Kr



COMPASS at CERN

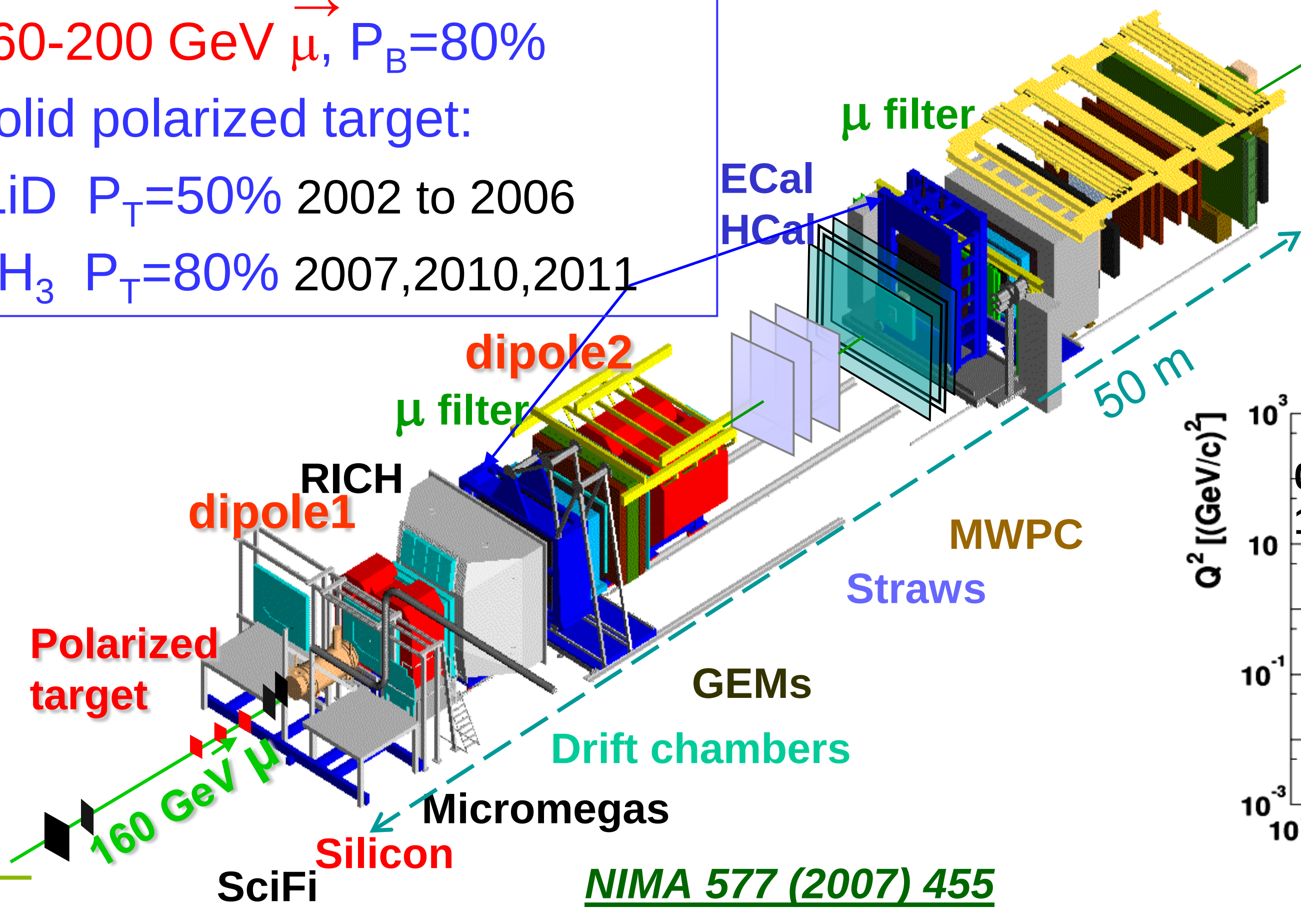
Fixed target
Secondary beams from SPS

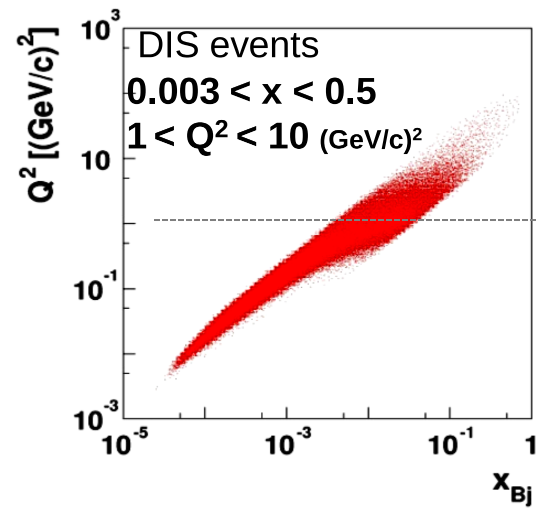
Nucleon spin structure

Polarized muon beam:
160-200 GeV $\vec{\mu}$, P_B=80%
Solid polarized target:
^{6}LiD P_T=50% 2002 to 2006
NH_3 P_T=80% 2007,2010,2011

Meson spectroscopy

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





NIMA 577 (2007) 455

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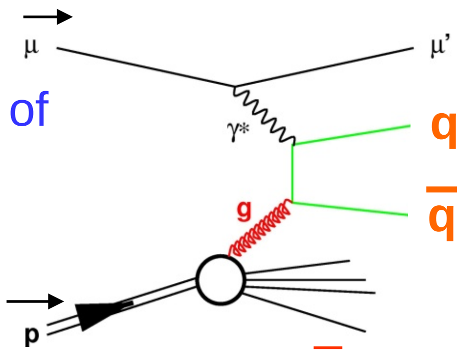
1. ΔG/G from $\overrightarrow{lepton}$ $\overrightarrow{N}$ scattering

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

pQCD scale $\mu^2 = 4\,(m_c^2 + p_T^2)$

Combinatorial background & limited statistics

→ Difficult experiment; 5 decay channels added

COMPASS 160 GeV 1 result

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

High statistics

pQCD scale Q^2 or Σp_T^2

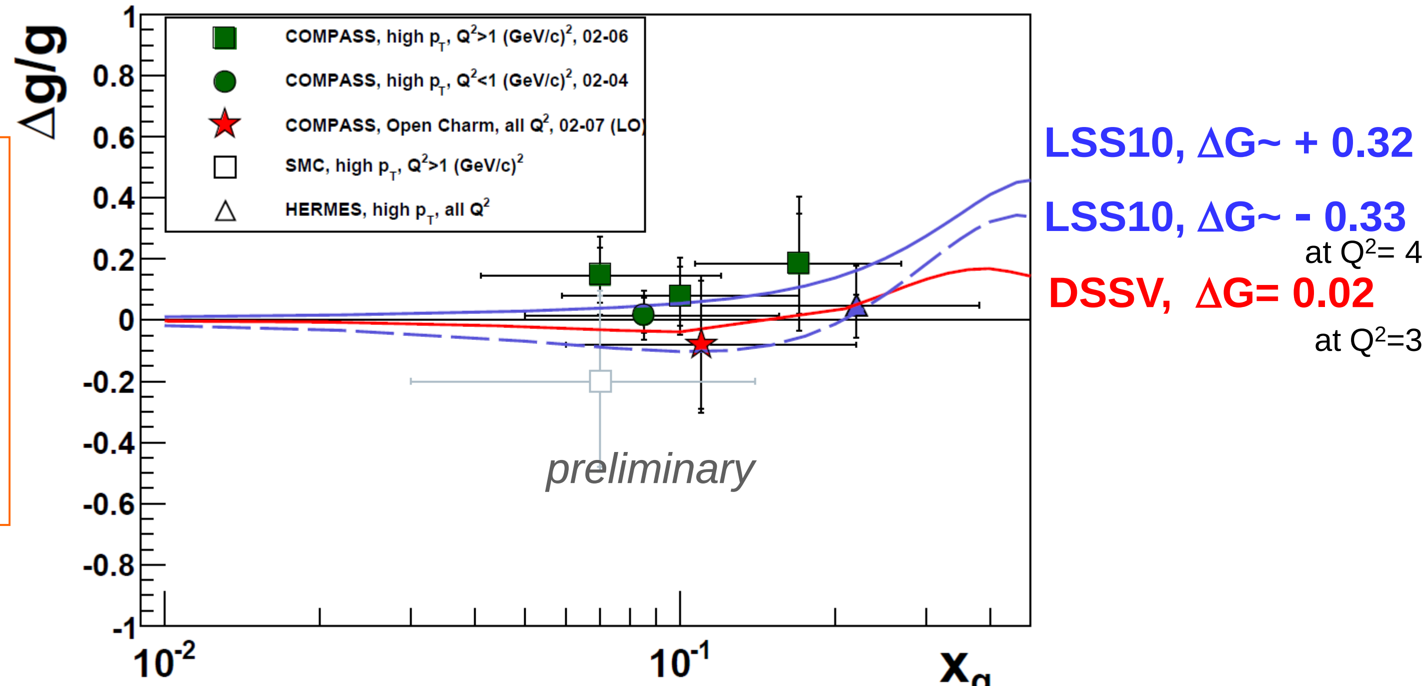
Physical background, better described for high Q^2

HERMES, COMPASS &SMC : 5 points

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



- **All measurements compatible with 0**
- **Constraint on <ΔG> 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**

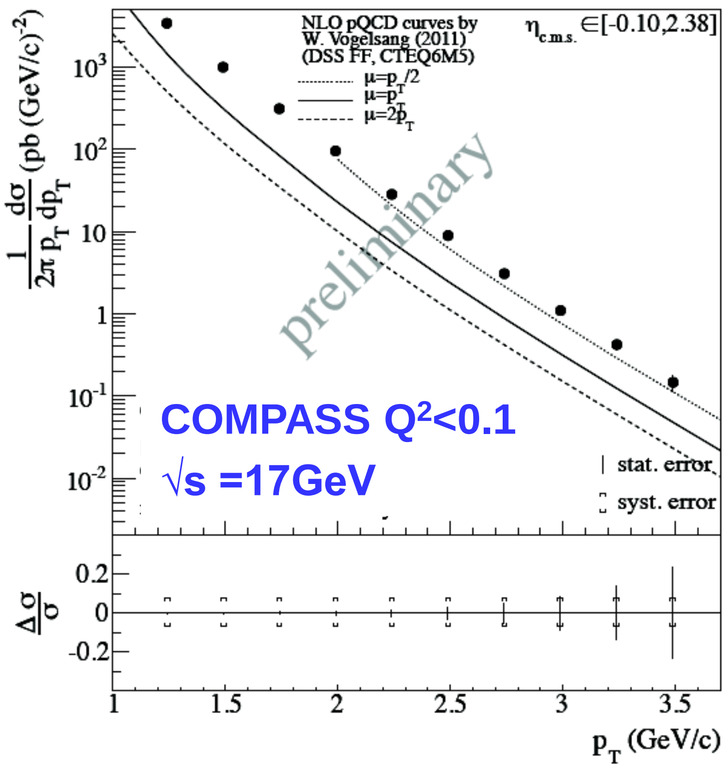
Note that these data are NOT included in global fits

COMPASS high p_T hadron : Cross section

$\mu^+ d \rightarrow \mu^+ h^\pm X$

Quasi real photo production of hadron

Compared to predictions at NLO



Preliminary pQCD calculations by W.Vogelsang, at 3 different scales: $\mu=p_T/2$

$\mu=p_T$

$\mu=2\ p_T$

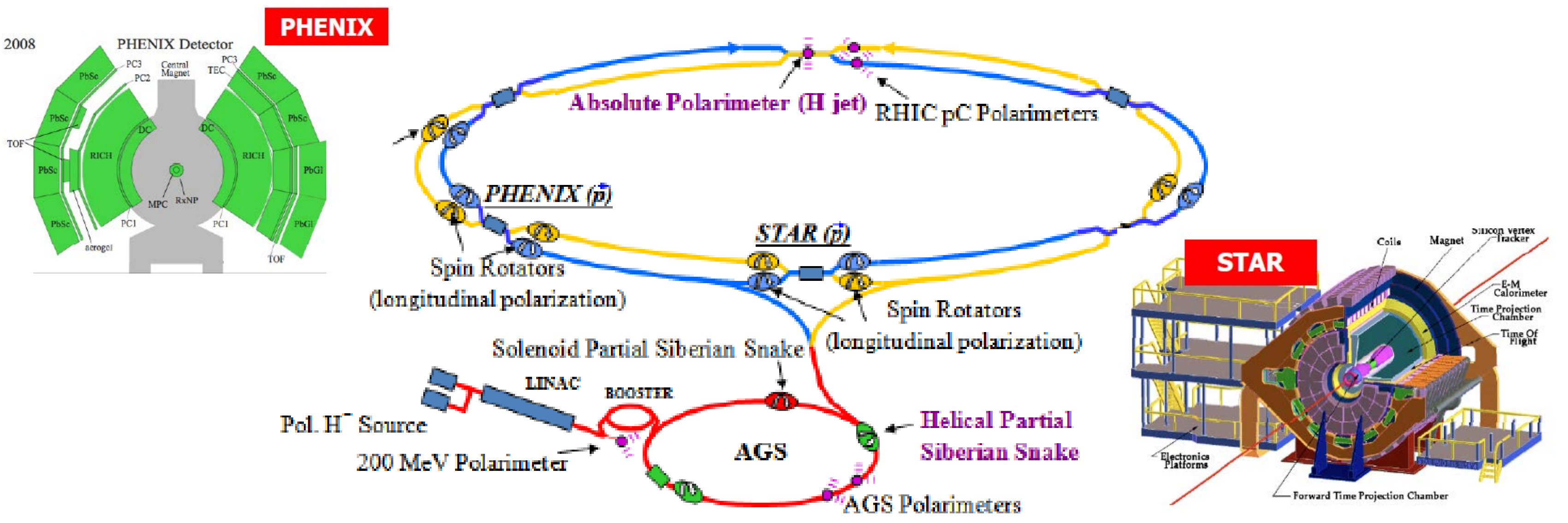
Data agree with NLO pQCD over 5 orders of magnitude
(within theory uncertainty)

Settles the theory framework for ΔG high p_T

Next step: produce spin asymmetries $A_{LL}(p_T)$ for same events

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

$\sqrt{s}$ = 62, 200, 500 GeV



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

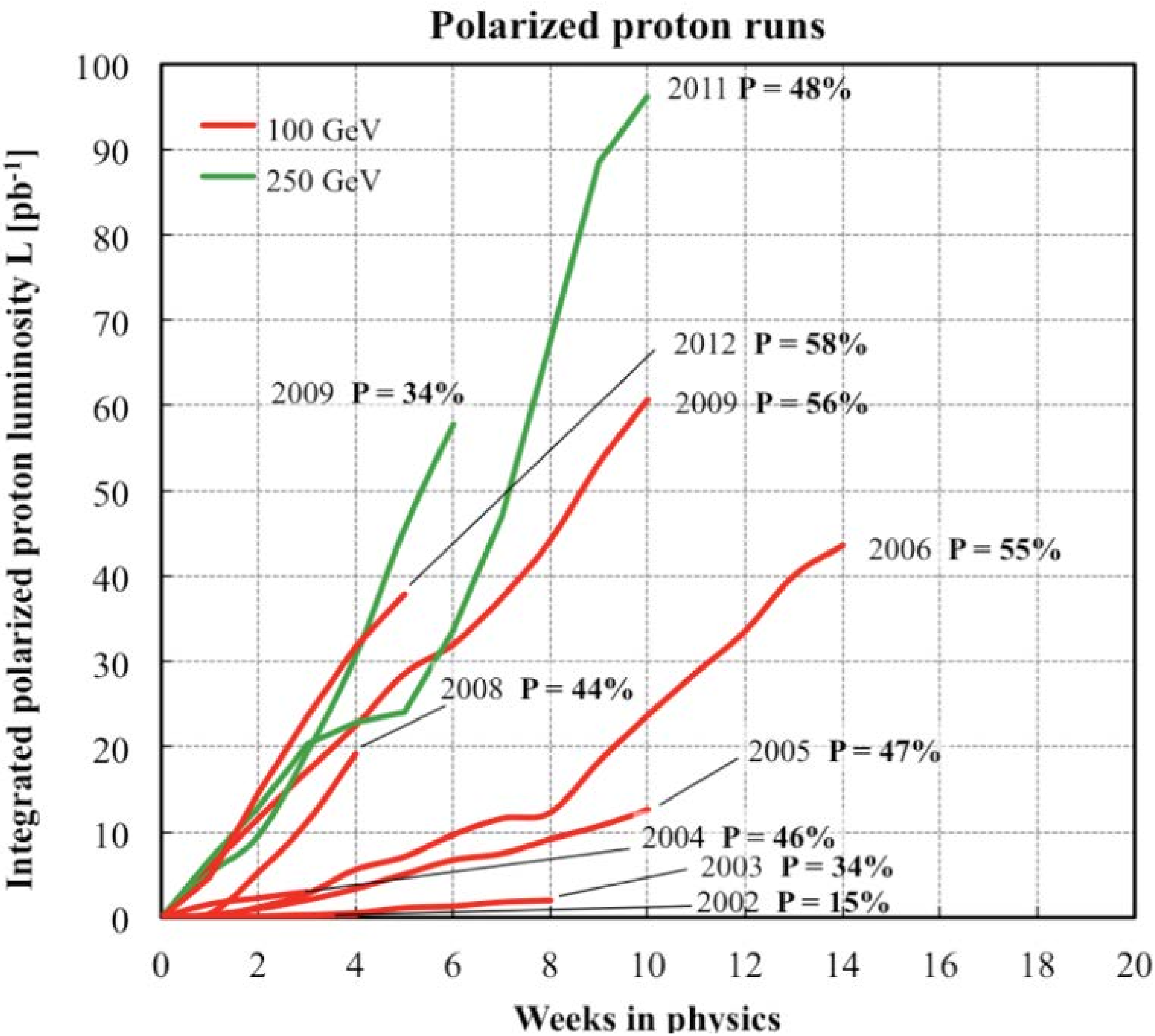
RHIC luminosity increase vs time

- $\sqrt{s}$ =200 GeV

run 5, 6, 9, 12

- $\sqrt{s}$ =500 GeV

run 9, 11



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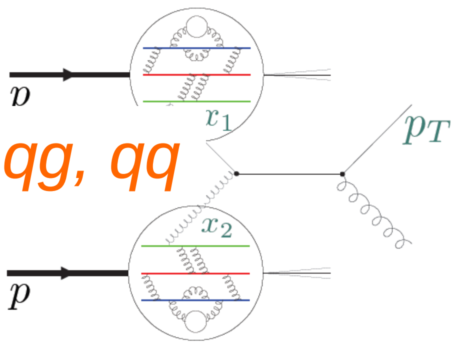
2. $\vec{p}\,\vec{p}$ collisions at RHIC, channels for ΔG

gg, qg, qq



Di-Jet production

- More abundant channels

p p → π^0 X **PHENIX**

p p → **jet** X **STAR**

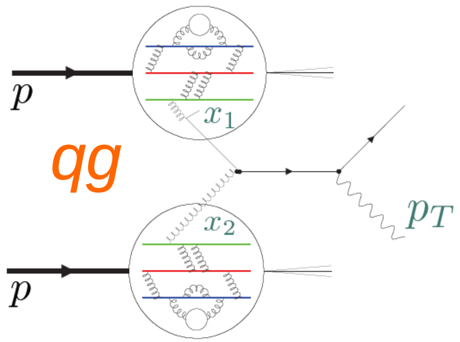
3 processes contribute

ΔG (x_1) .ΔG (x_2)
ΔG (x_1) .Δq (x_2)
Δq (x_1) .Δq (x_2)

- Other channels

p p → jet jet proj. STAR 500 GeV, low x

qg



Photon-Jet production

p p → γ jet

1 process→ cleaner ΔG (x_1) .Δq (x_2)

Full kinematics reconstructed

Low statistics

p p → γ X

…

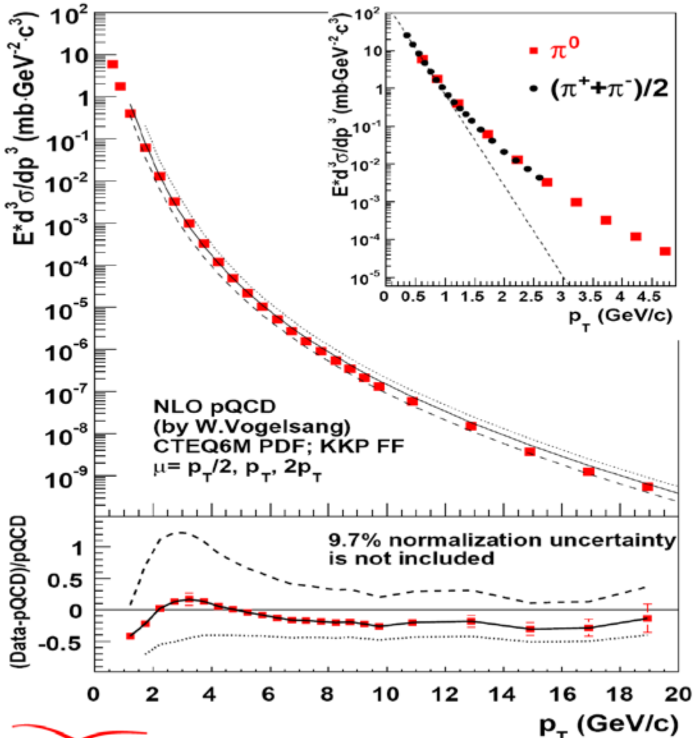
- Other channels: π+, π−, η, …

High potential for ΔG from various channels, various kinematics

$\vec{p}\vec{p}$ collisions at RHIC: cross-sections

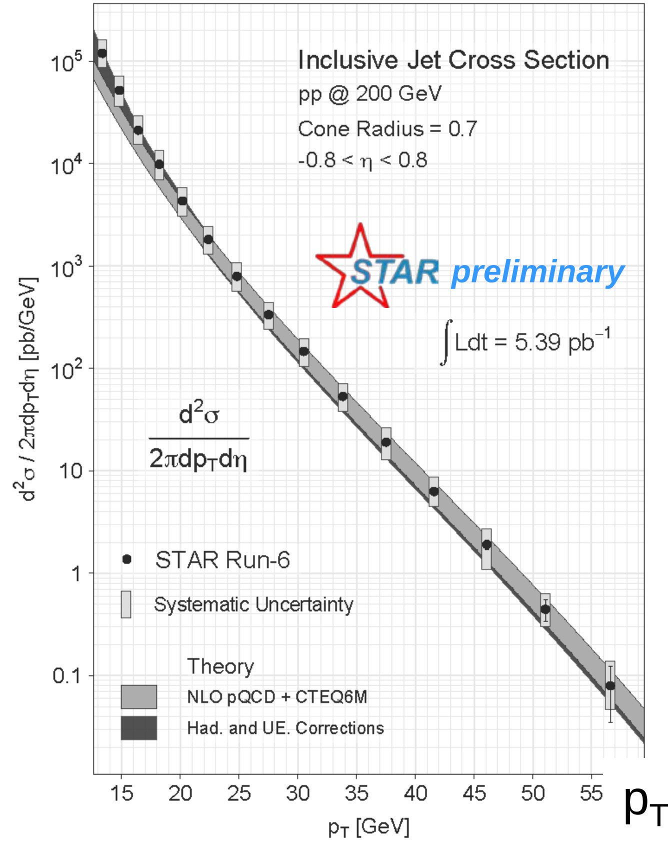
Two examples

$pp \rightarrow \pi^0 X$ at PHENIX



PHENIX PRD76(2007) 051106

Inclusive jets at STAR



pQCD + Hadronization+ Underlying Event corrections (significant at low jet p_T)

- **Good agreement between data and pQCD calculations**
- **Exist also for other channels: π^+, π^-, dijet, direct γ, γ +jet, η, etc.**
- **Establishes validity of pQCD frame→ validates method for ΔG extraction**

$\vec{p}\vec{p}$ collisions at RHIC: inclusive jet at STAR

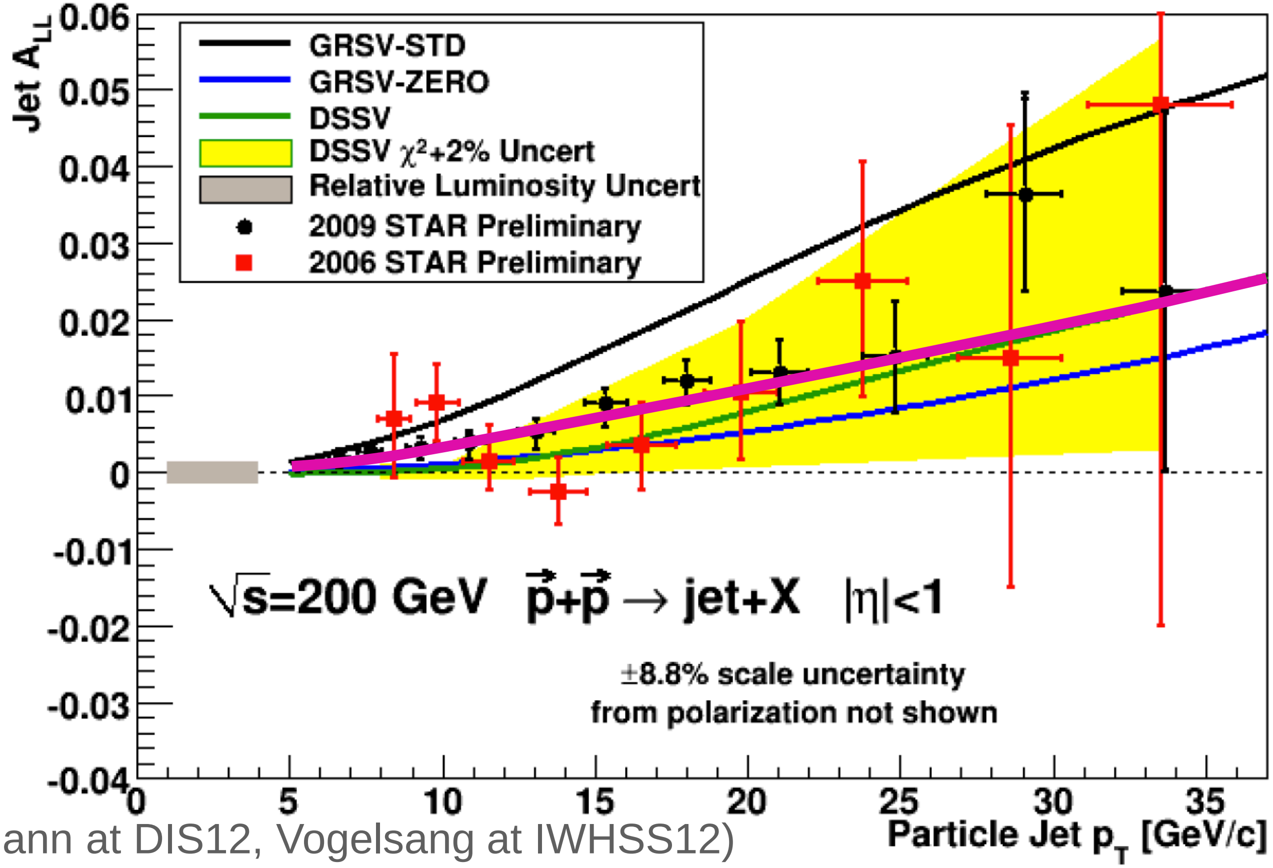
$\vec{p}\,\vec{p} \rightarrow$ **jet** +X

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

High stat. run 9

→ New fit

$$\int_{0.05}^{0.2} dx\, \Delta g \approx 0.1$$



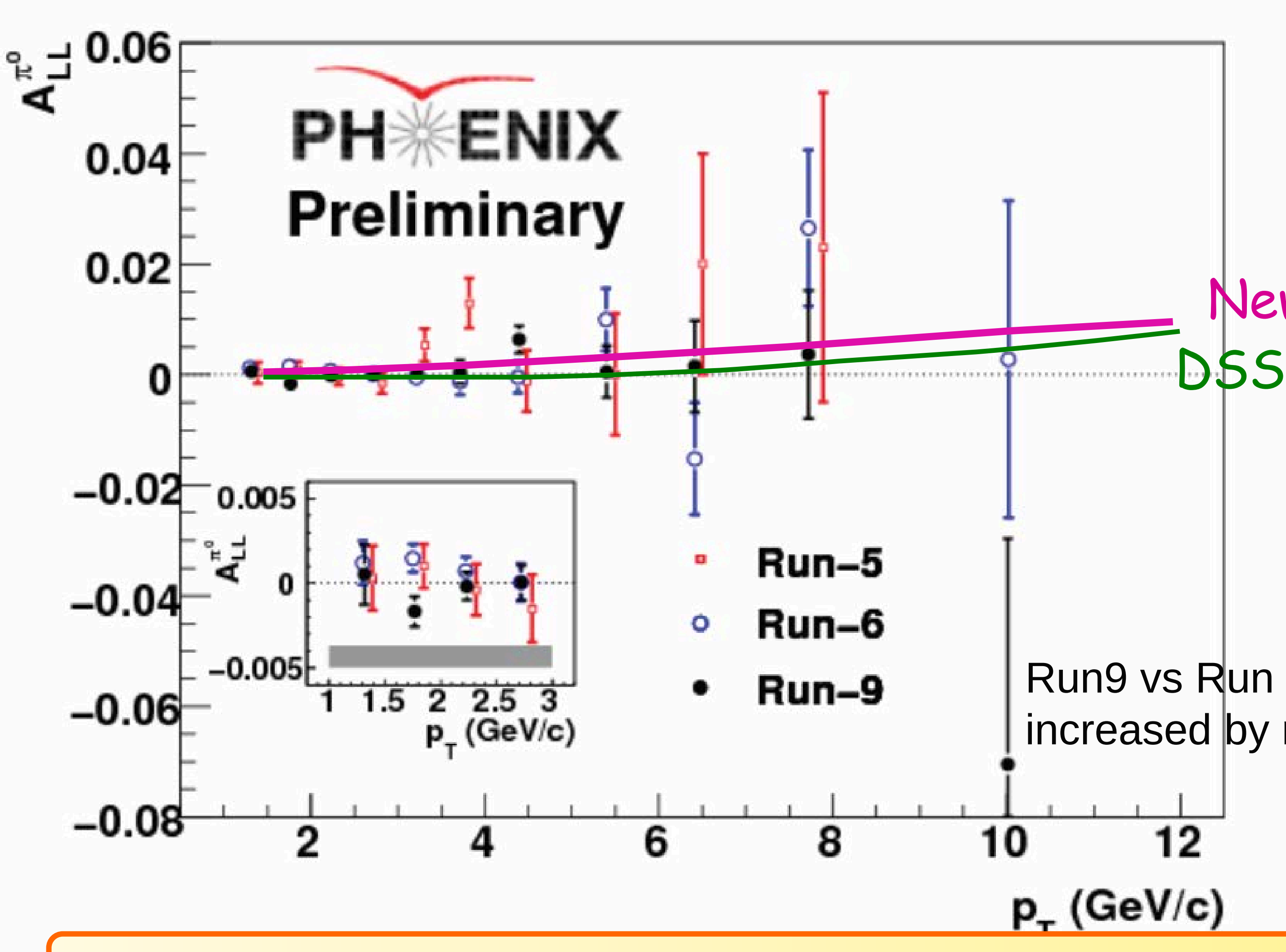
(See: STAR at DIS12,Stratmann at DIS12, Vogelsang at IWHSS12)

Inclusive jet provides strong constraint on ΔG in measured range giving ΔG positive ~ 0.1 for 0.05<x<0.2

$\vec{p}\vec{p}$ collisions at RHIC: π^0 production at PHENIX

$\vec{p}\,\vec{p} \rightarrow \pi^0$ X

Measure double spin asymmetry A_{LL} (p_T)
Compare data to global fits with various ΔG(x) parameterizations

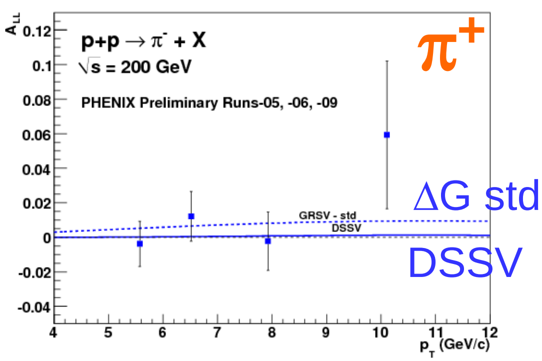


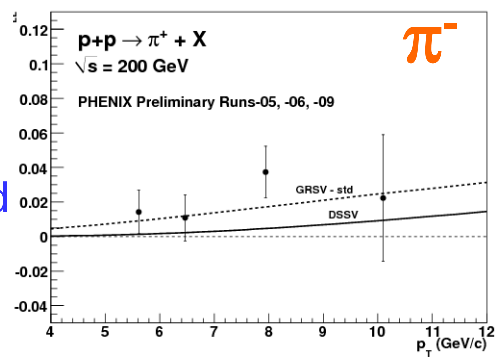
Strong constraint on <ΔG> in x range probed 0.05<x<0.3

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

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

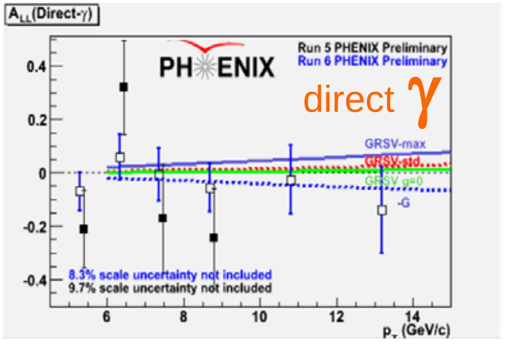
$$A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-} \Rightarrow \Delta G > 0$$
$$A_{LL}^{\pi^+} < A_{LL}^{\pi^0} < A_{LL}^{\pi^-} \Rightarrow \Delta G < 0$$





direct γ

clean channel
qg dominates

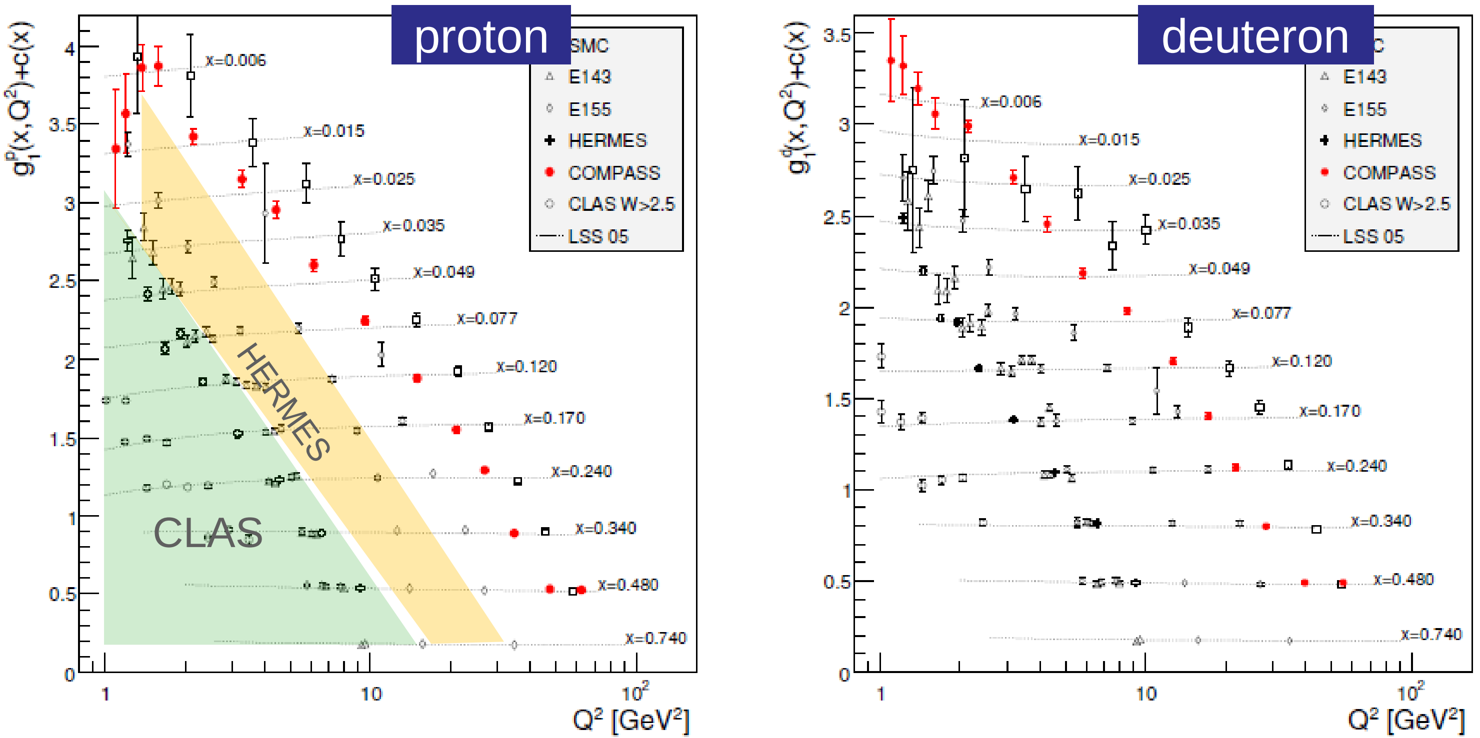


Promising channels when more statistics available

3. ΔG from global fits

Spin structure functions g_1

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



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

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

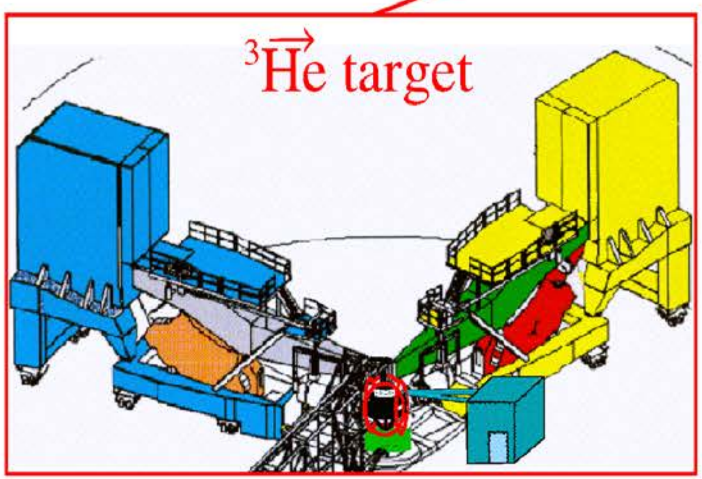
However x and Q^2 coverage not yet sufficient for ΔG
Use also constraint from pp data (DSSV)

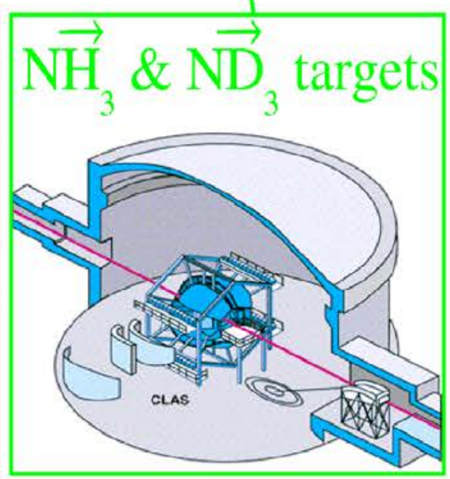
Note: 200 GeV proton data to come from COMPASS 2011 run

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

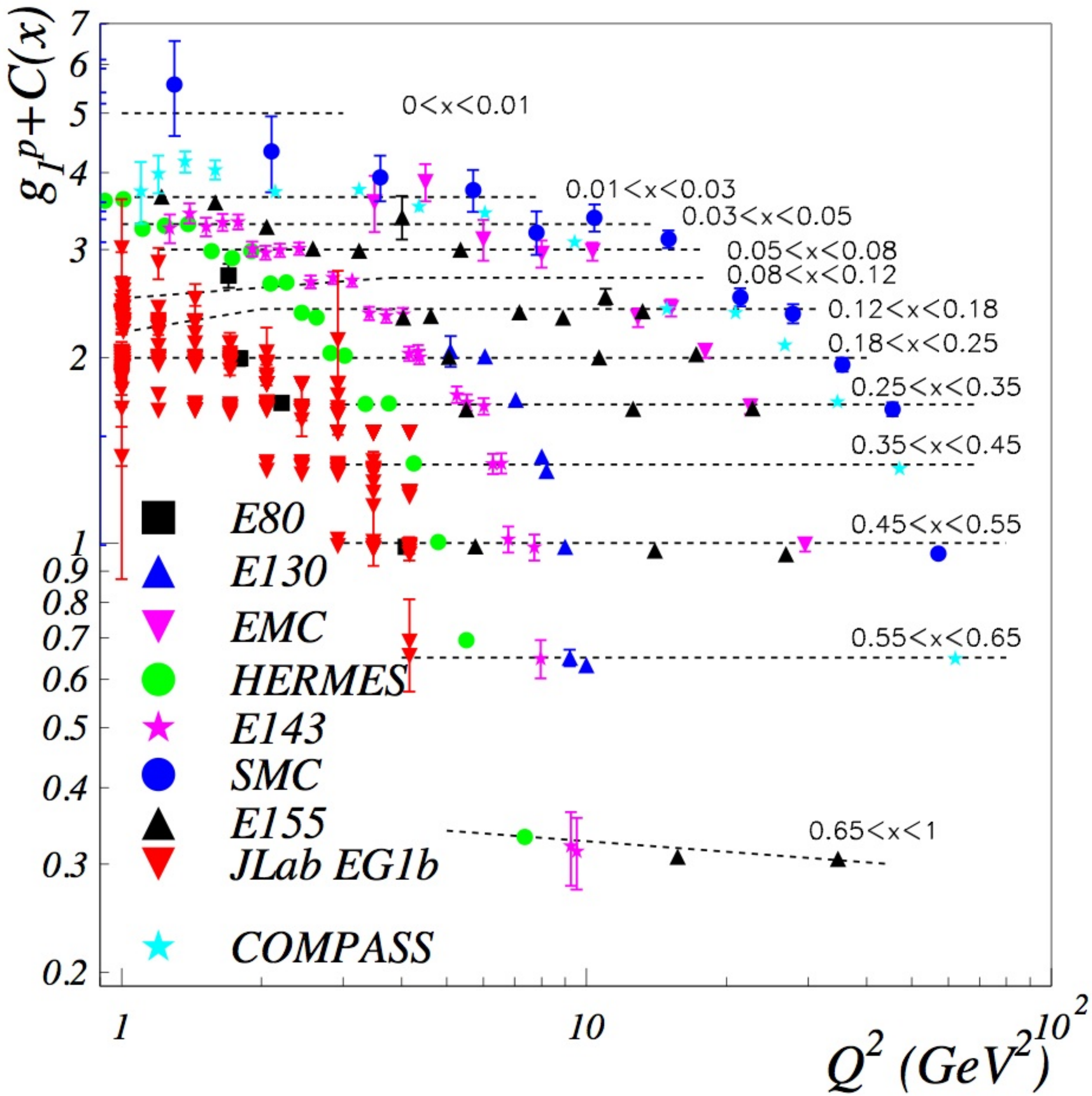
5.7 GeV e-

Polarized NH_3

(and ND_3) targets

Data included

in LSS fit



3. ΔG(x) from global QCD fits of polarized data

LSS '10

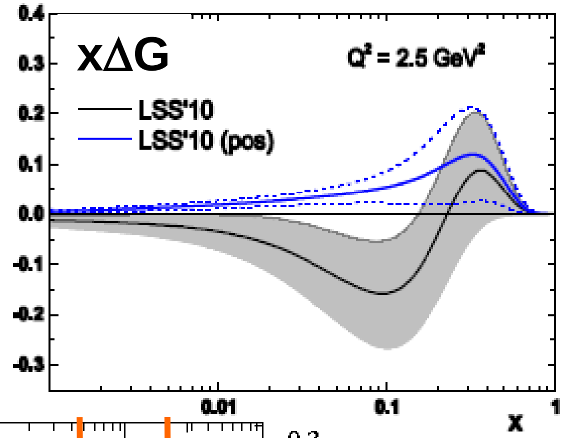
Only DIS & SIDIS data

Leader, Sidorov, Stamenov,

ΔG= 0.25± 0.19

ΔG= -0.40± 0.43

at Q^2=2.5GeV/c^2



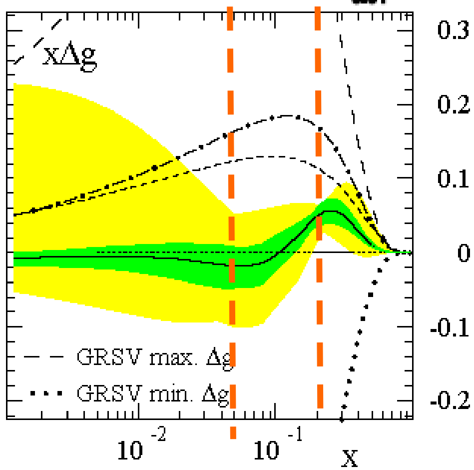
DSSV-2009 (old)

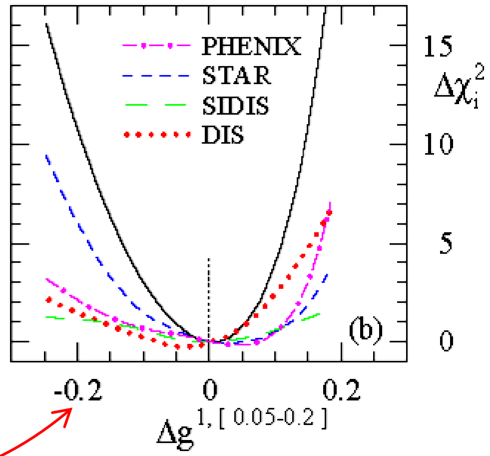
DIS, SIDIS & pp

De Florian, Sassot, Stratmann, Vogelsang PRL101 (2008)072001

ΔG= -0.08 ± ?

at Q^2= 10 GeV/c^2





~0 in measured range (node)

- **Data favored fits with ΔG close to 0, excluding ΔG std (DSSV-2009, LSS10)**
- **Strong constraint on <ΔG> , now > 0 (DSSV+) in x range probed**
- **No constraint outside 0.05 < x < 0.2**

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

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

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

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

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

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

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

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

LSS '10
- $\Delta\Sigma = 0.25 \pm 0.04$ ΔG with node $Q^2=10\ (GeV/c)^2$,
- $\Delta\Sigma = 0.21 \pm 0.03$ $\Delta G > 0$

Bjorken sum rule

A fundamental result of QCD
on the non-singlet combination $g_1^{NS}(x) = g_1^p(x) - g_1^n(x)$
derived from current algebra:

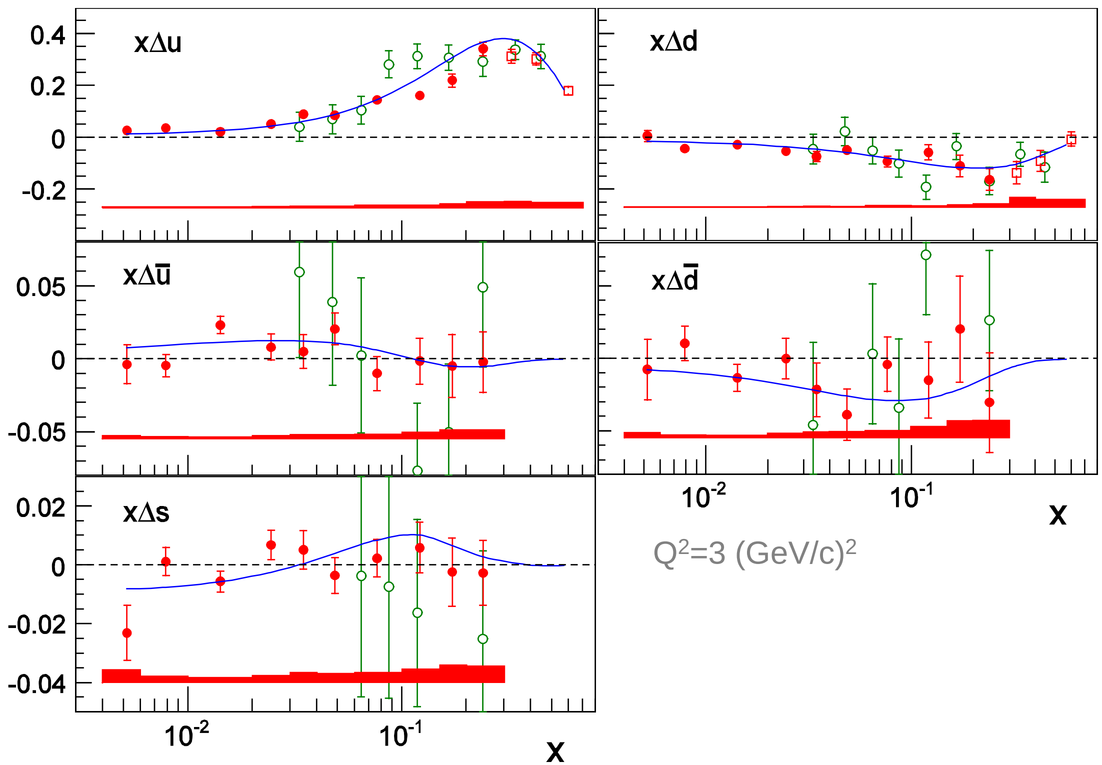
$$\int_0^1 g_1^{NS}(x)dx = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C^{NS}$$

Measuring the first moments provides a test of the Bjorken sum rule,

Fit to COMPASS data: g_A/g_V=
1.28 ±0.07(stat) ± 0.10(syst)

PDG value:
1.268 ±0.003

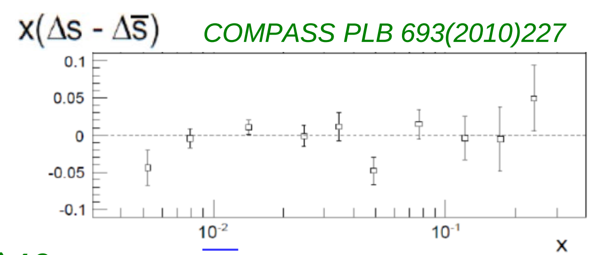
Quark helicities from Semi-Inclusive DIS



Extraction at LO

$$A_1^{h(p/d)}(x) = \frac{\sum_q e_q^2 D_q^h \Delta q(x)}{\sum_q e_q^2 D_q^h q(x)}$$

• COMPASS
PLB693(2010)227, using DSS FF
o HERMES
PRD71(2005)012003
__ DSSV



HERMES $\Delta s + \Delta\bar{s} = 0.037 \pm 0.019$ (stat) ± 0.027 (syst), *PLB666(2008)466*
COMPASS $\Delta s = -0.01 \pm 0.01$ (stat) ± 0.01 (syst), $0.003 < x < 0.3$

$\Delta s - \Delta\bar{s}$ compatible with 0

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

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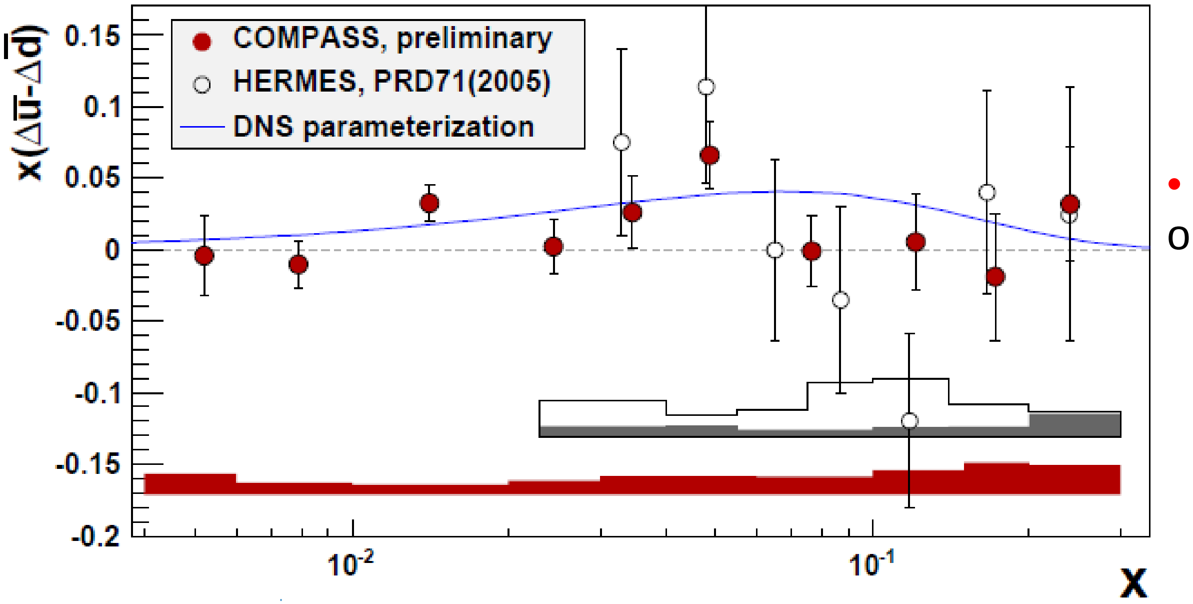
Light sea quark polarized distributions

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



• COMPASS
o HERMES

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

Slightly positive, compatible with zero.

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

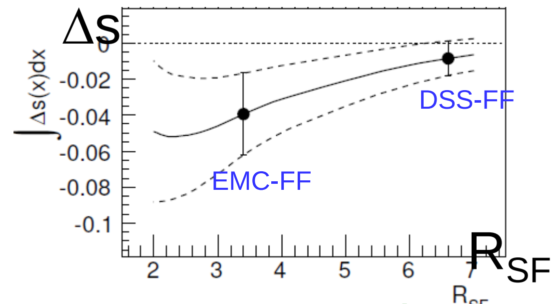
Δs puzzle

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

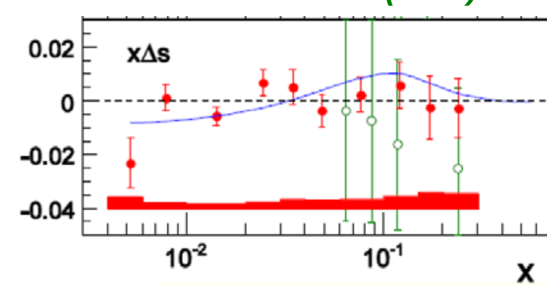
→ $\int \Delta s + \Delta\bar{s}$ = - 0.08 ± 0.01± 0.02

• SIDIS data: the integral of Δs can be computed from Δs(x) measured from kaon spin asymmetries, using quark Fragmentation Functions

→ Δs(x)≈ 0



COMPASS PLB 693(2010)227



Several possible explanations to the discrepancy :

• Uncertainty on quark fragmentation functions (s→ K)
  - would need value twice bigger than DSS

• Global fits (DSSV, LSS) suggest negative Δs at low x
  - reconciles the two approaches

• Assume SU(3) violation a_8 from0.58 to 0.42 → Δs=-0.02
Bass &Thomas, PLB 684(2010)216

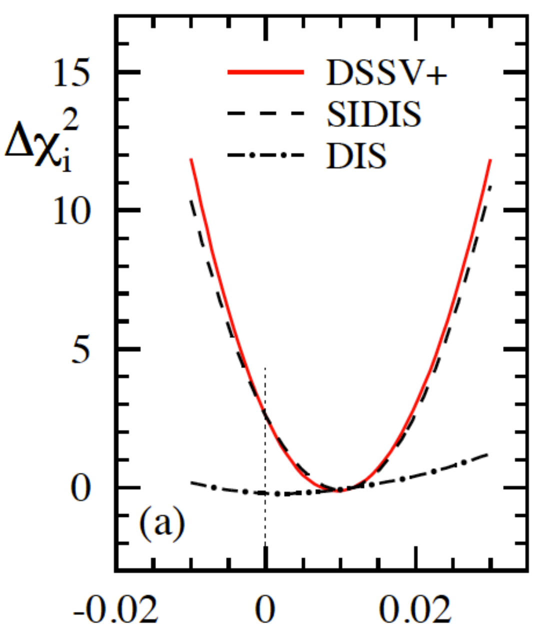
Need more data on quark fragmentation functions

Need more data on Δs at low x

COMPASS run 2011 at 200 GeV

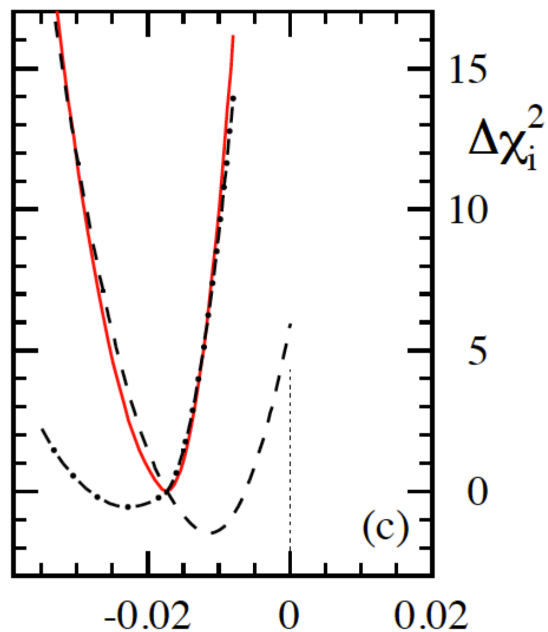
Certainly a physics case for EIC

Δs puzzle cont'd. New fit DSSV+



$$\int_{0.02}^{1} dx\, \Delta s$$

high x



$$\int_{0.001}^{0.02} dx\, \Delta s$$

low x <0

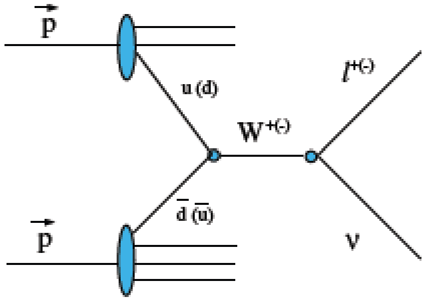
From Stratmann at DIS-2012,
Including COMPASS SIDIS results π, K at low x:

"Tendency toward negative low-x also from SIDIS ?
Heavily relies on Fragmentation Functions '"

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

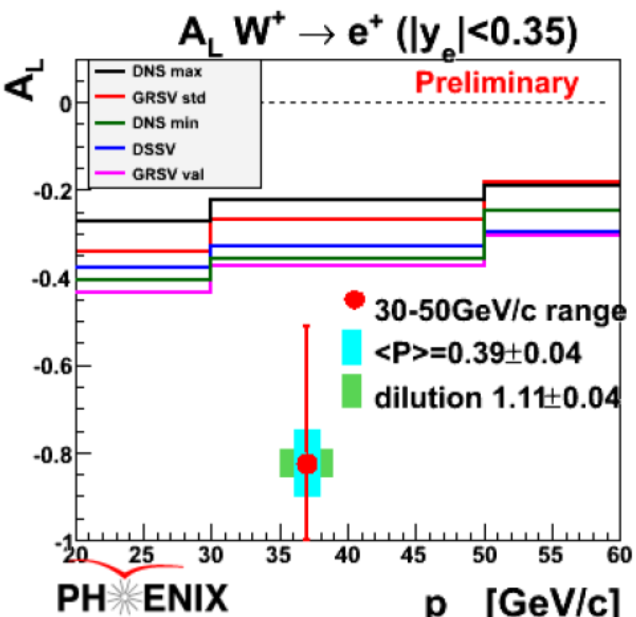
RHIC short exploratory run :first collisions at 500 GeV

Parity violating, single spin asymmetry
No fragmentation function uncertainty



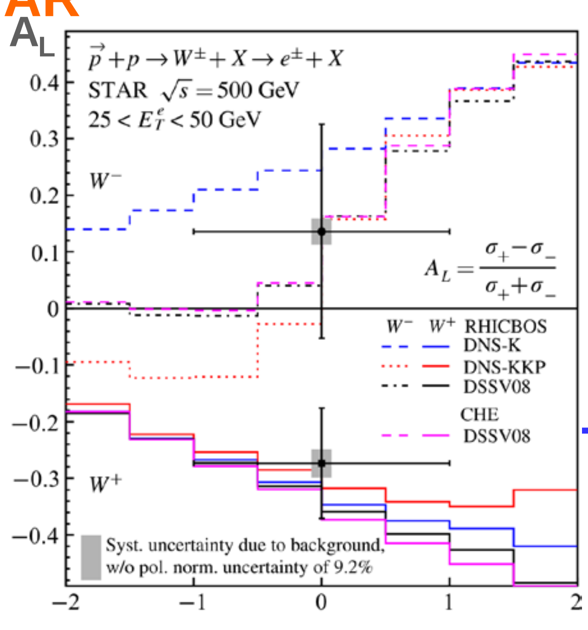
$$u+\bar{d}\rightarrow W^{+}\rightarrow e^{+}+\nu$$
$$\bar{u}+d\rightarrow W^{-}\rightarrow e^{-}+\bar{\nu}$$

PHENIX



J. Haggerty ICHEP2010

STAR

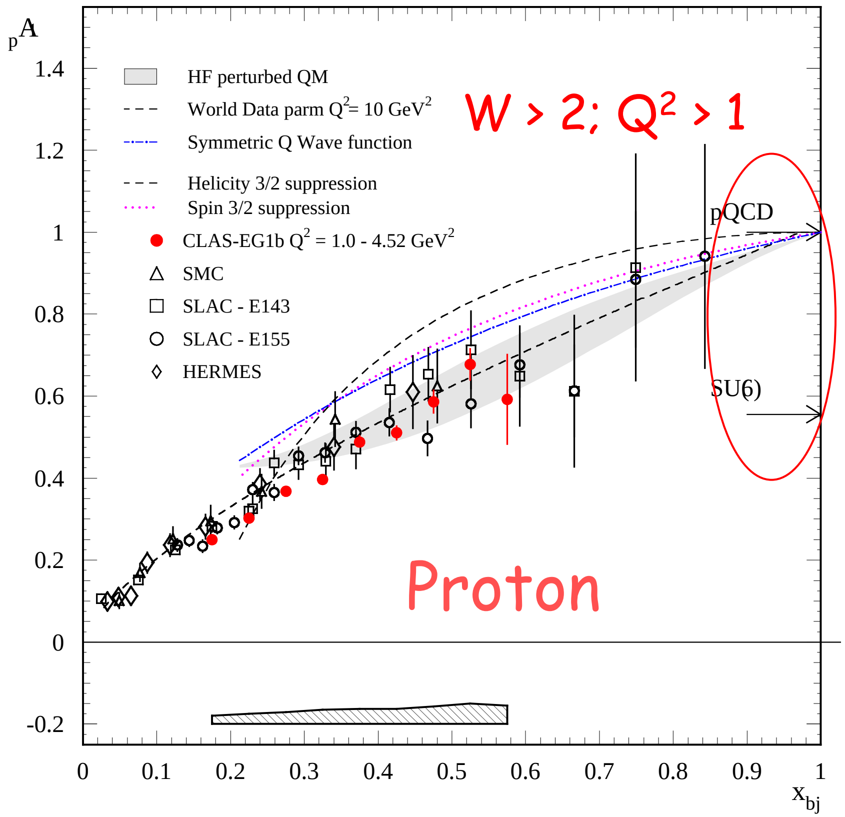


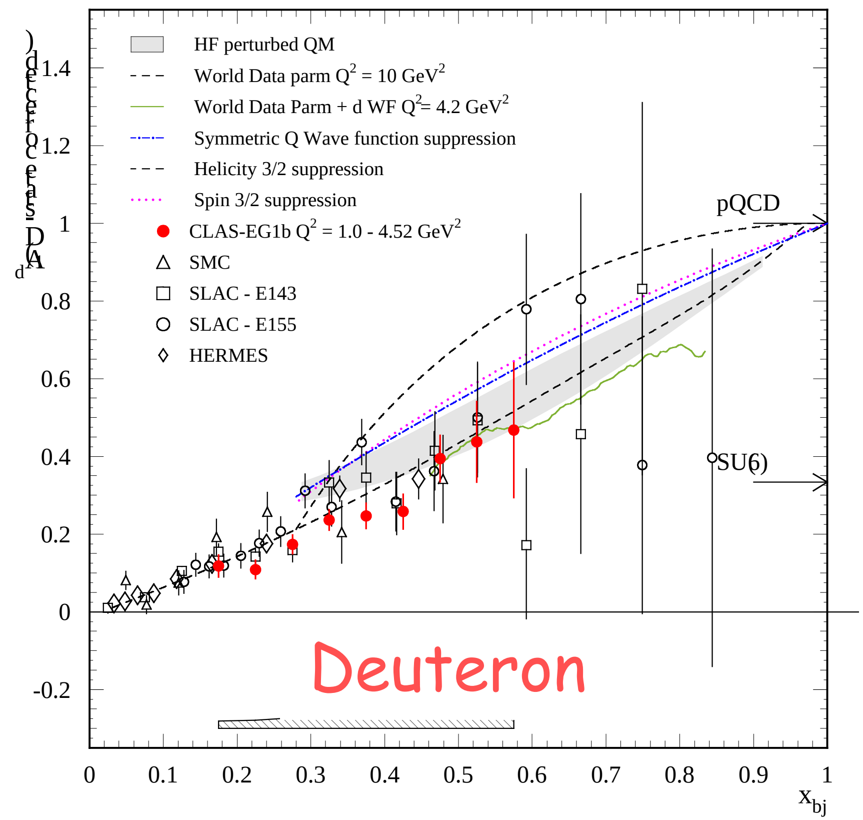
$\frac{\Delta\bar{d}}{\bar{d}} - \frac{\Delta u}{u}$

Phys.Rev.Lett. 106 (2011) 062002

- **Signs as expected from polarized PDFs**
- **Promising channel**

Jlab – CLAS A_1^p A_1^d



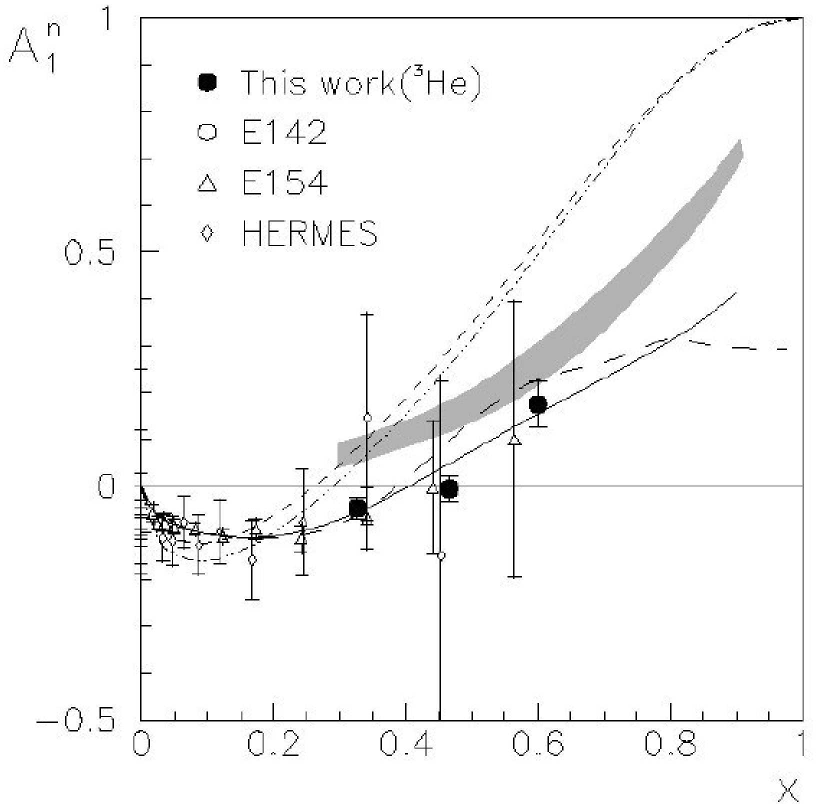


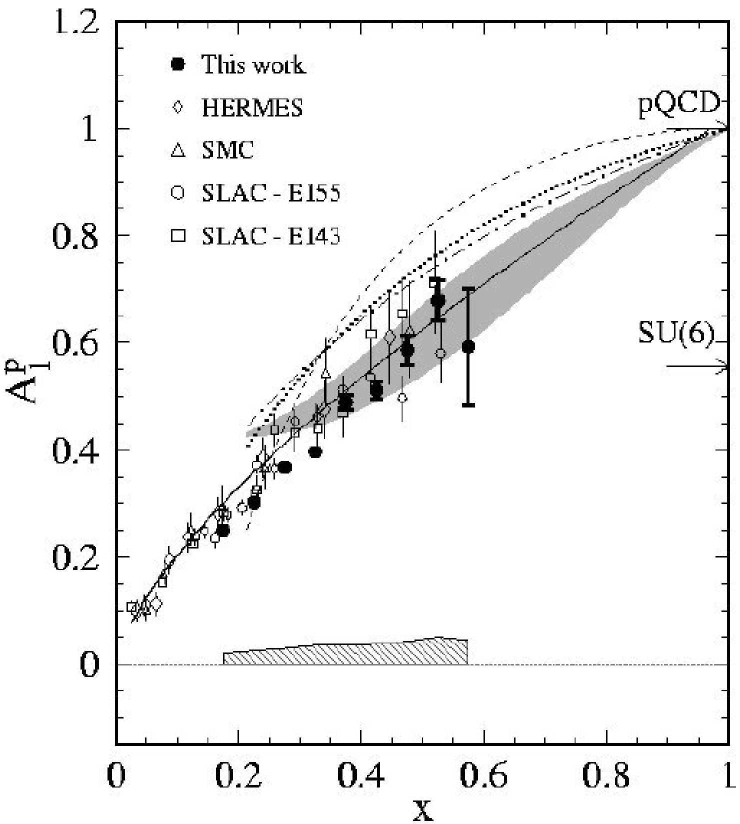
Jlab – A_1^n A_1^p

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?

irfu
cea
saclay

Polarized Quark Distributions- Valence sector

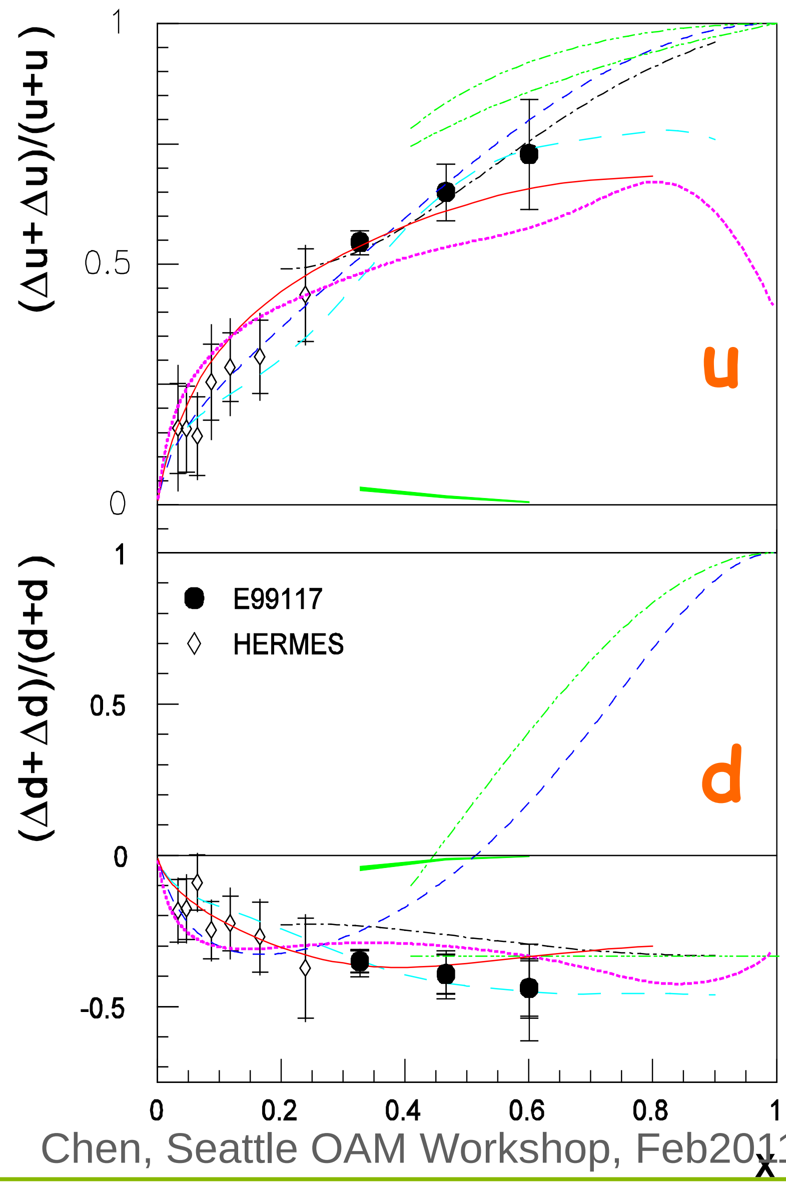
From A_1^n and A_1^p results

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

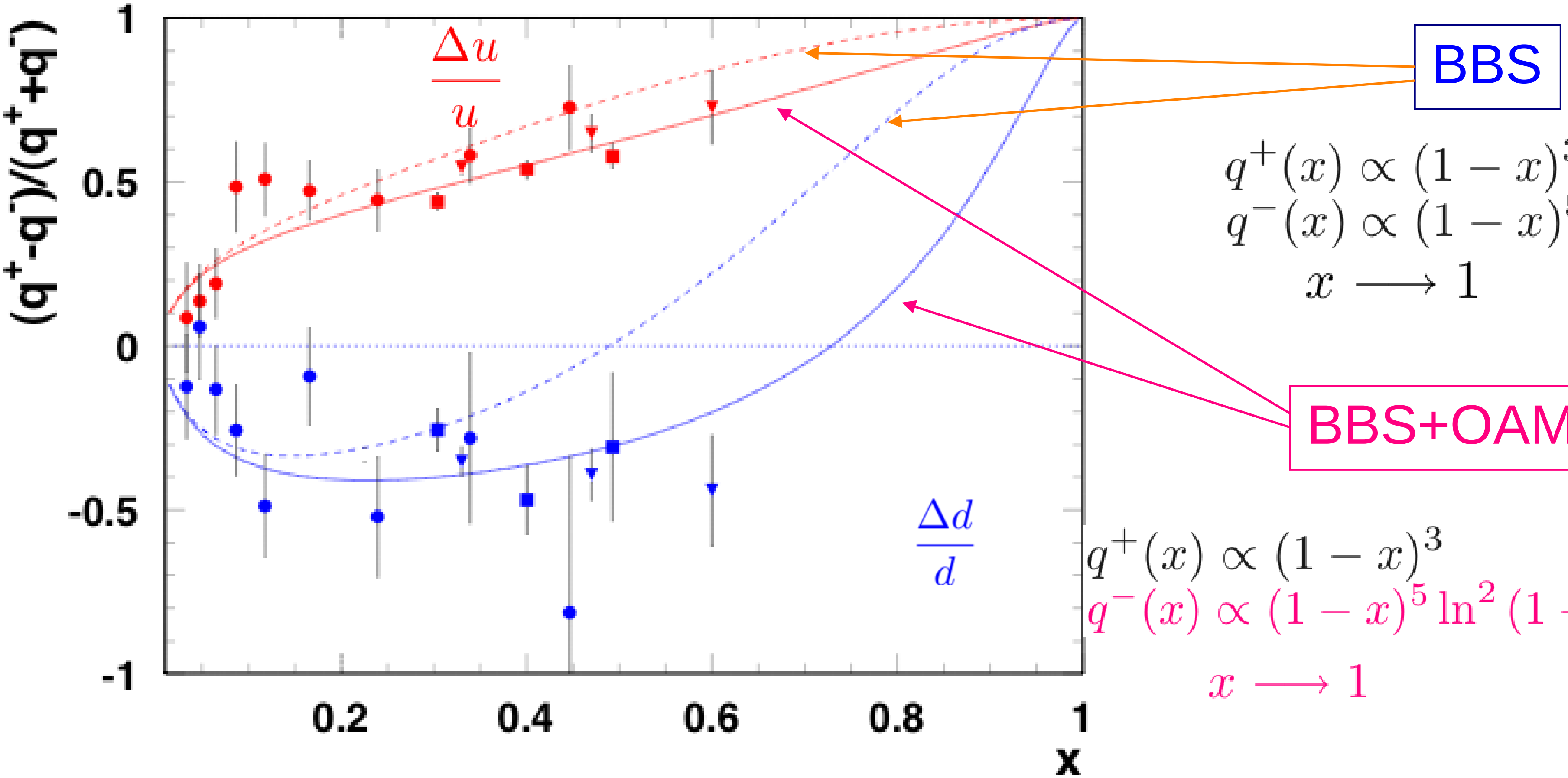


Chen, Seattle OAM Workshop, Feb2011

pQCD with Quark Orbital Angular Momentum

H. Avakian, S. Brodsky, A. Deur, and F. Yuan, PRL 99, 082001 (2007)

Inclusive Hall A and B and Semi-Inclusive Hermes

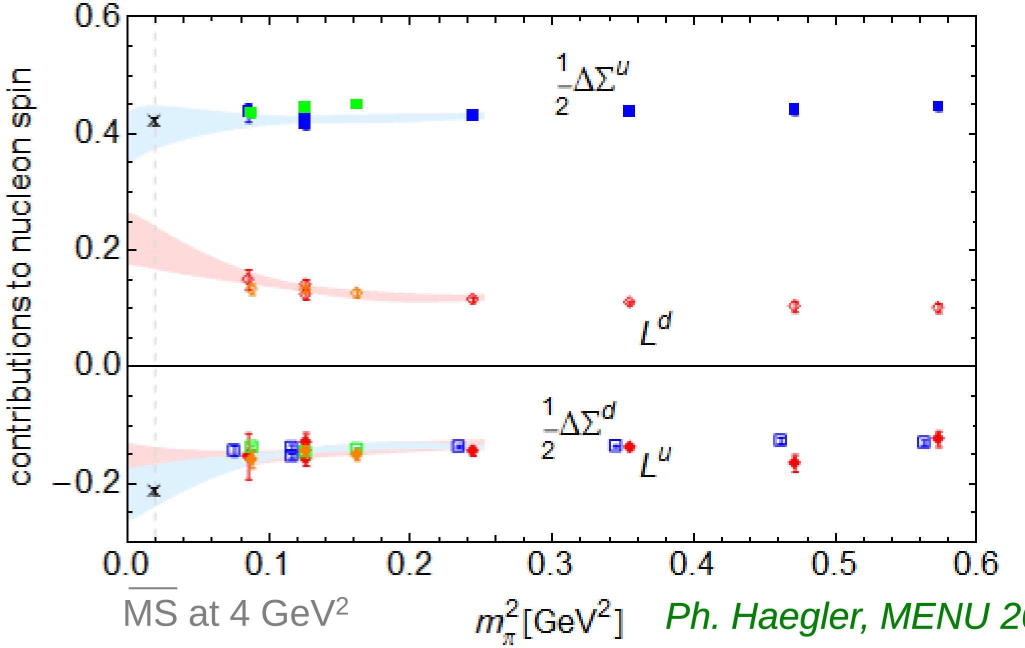


$$q^+(x) \propto (1-x)^3$$
$$q^-(x) \propto (1-x)^5$$
$$x \longrightarrow 1$$

$$q^+(x) \propto (1-x)^3$$
$$q^-(x) \propto (1-x)^5 \ln^2(1-x)$$
$$x \longrightarrow 1$$

Chen, Seattle OAM Workshop, Feb2011

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**

Conclusions

Gluon contribution to nucleon spin

All measurements point to zero or small contribution. Strong constraint on fits from RHIC. Only $0.05< x <0.2$ probed. Need low x measurement.

Quark contribution to nucleon spin

Extraction for all flavours from SIDIS

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:

need more precision and Fragmentation Function knowledge.

Angular momentum

DVCS, DVMP:

data from HERMES & Jlab + projects at Jlab-12GeV & COMPASSII

Good prospects for Lattice QCD

Exciting future programs in preparation at RHIC, COMPASS-II, Jlab-12GeV, and… EIC/ENC