Nucleon Longitudinal Spin Structure
Experimental overview

Fabienne KUNNE
CEA /IRFU Saclay, France

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

Measurements at RHIC, COMPASS, HERMES, JLab

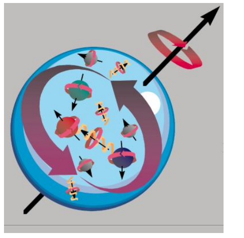
irfu
cea
saclay

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

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

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

Today, 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 $L_{u,d}$

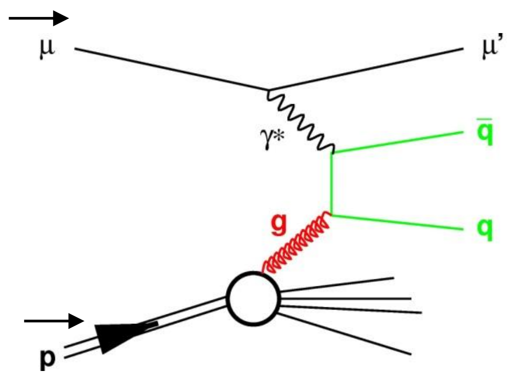
Large experimental effort on ΔG measurement

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

Three ways to study gluon contribution ΔG

1. $\overrightarrow{\text{Lepton}}$ $\overrightarrow{\text{Nucleon}}$

Photon Gluon Fusion



ΔG/G(x)

SMC, HERMES, COMPASS

2. $\overrightarrow{\text{Proton}}$ $\overrightarrow{\text{Proton}}$ collisions

Gluon-Quark + Gluon-Gluon +…

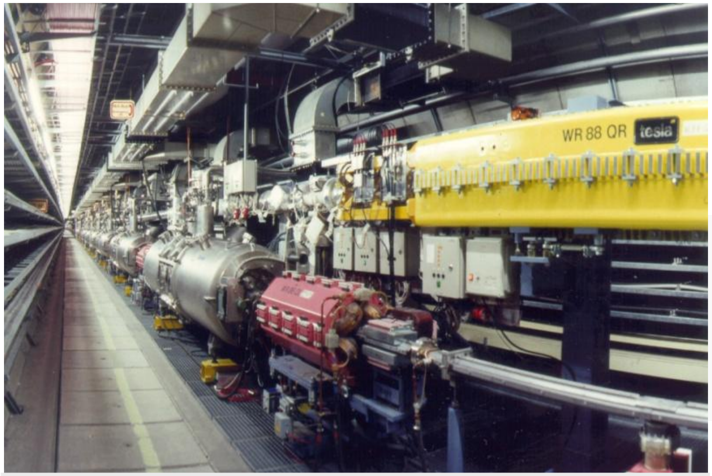
$$\frac{\Delta G}{G} \times \frac{\Delta q}{q} + \frac{\Delta G}{G} \times \frac{\Delta G}{G} + \ldots$$

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

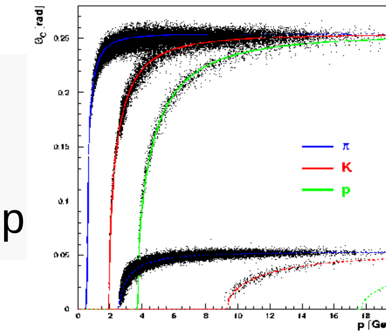
longitudinally polarized ~ 54%

1995 to 2007

Spectrometer :

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

Excellent separation of π, K, p

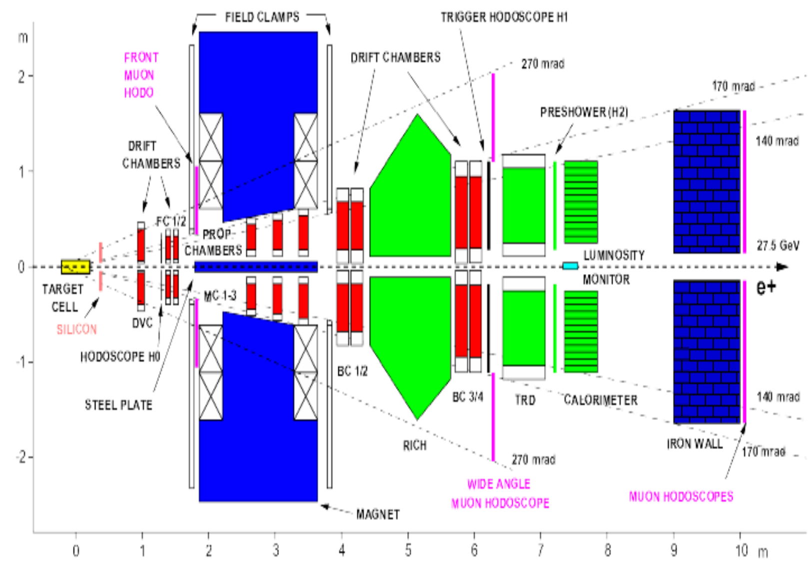


Gaseous internal target

Longit. Polar. 85% H, D, He

Transv. Polar H

Unpol H, D, Ne, Kr



COMPASS at CERN

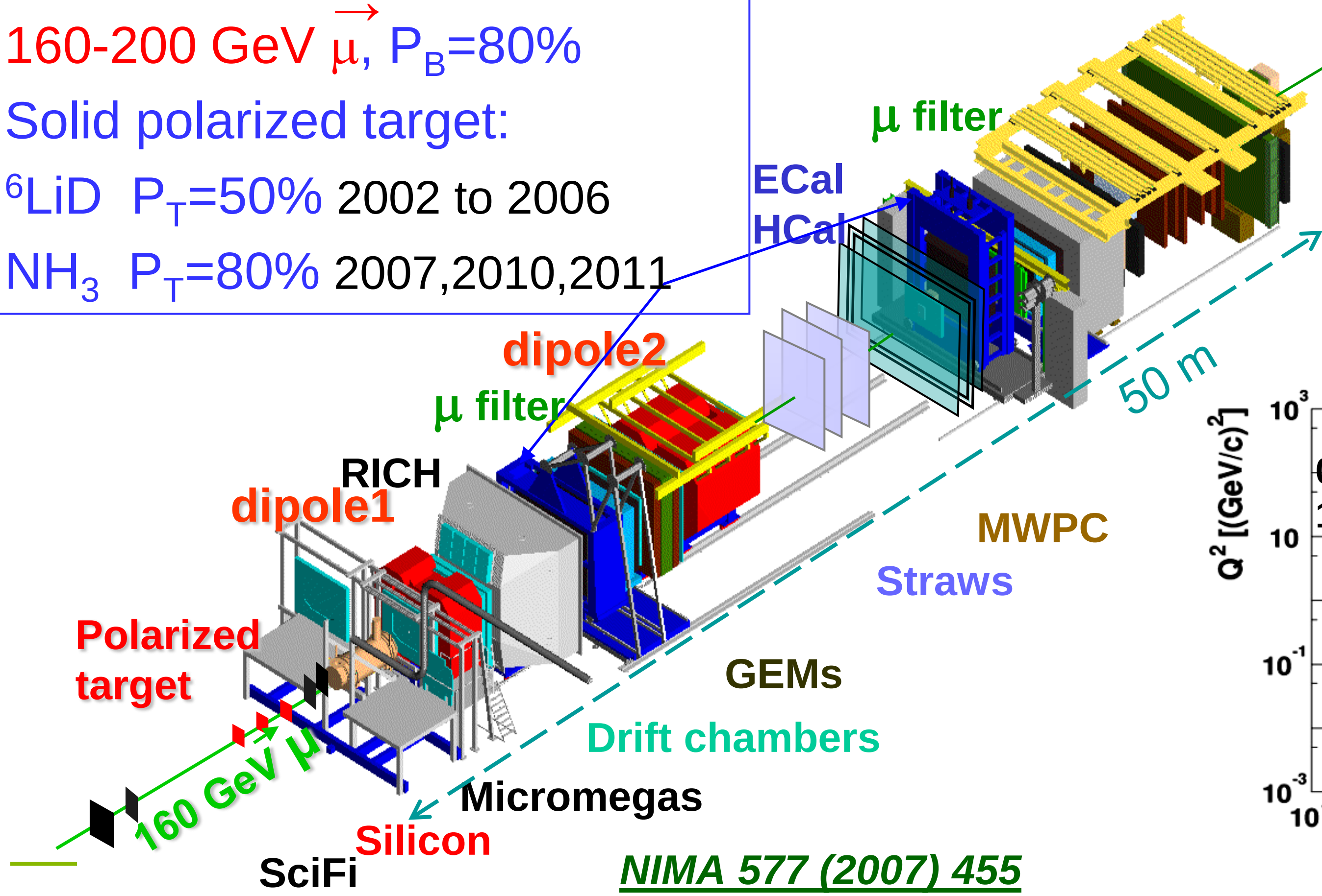
Fixed target
Secondary beams from SPS

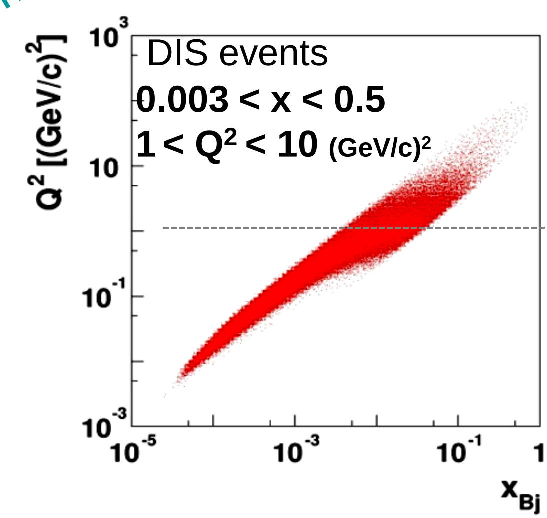
Nucleon spin structure

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



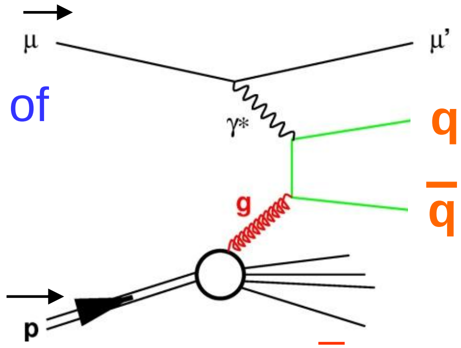


NIMA 577 (2007) 455

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



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

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

Fraction of process — Analyzing power

Two signatures for PGF:

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

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 $q\,\bar{q} \to h\,h$

High statistics

pQCD scale Q^2 or Σp_T^2

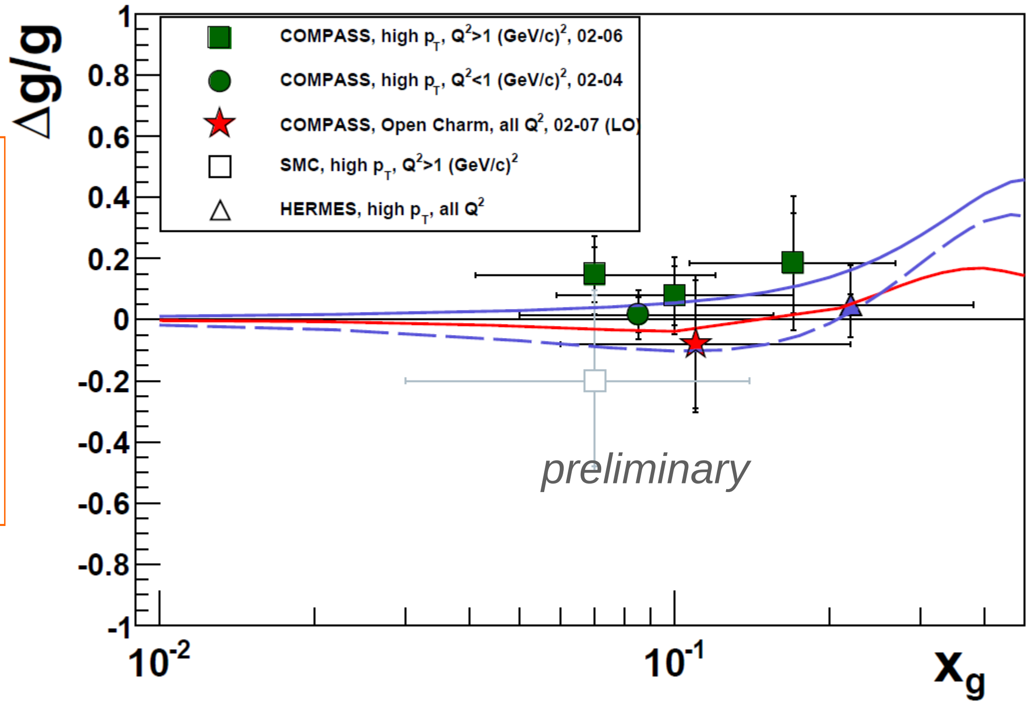
Physical background, better described for high Q^2

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



LSS10, ΔG~ + 0.32
LSS10, ΔG~ - 0.33
at Q^2= 4
DSSV, ΔG= 0.02
at Q^2=3

- **All measurements compatible with 0**
- **Constraint on <ΔG> for 0.05 < x < 0.3**
- **Results disfavour value of the integral larger than… ~ ± 0.3, i.e. ± 60% of the ½ nucleon spin**

Note that these data are NOT included in global fits

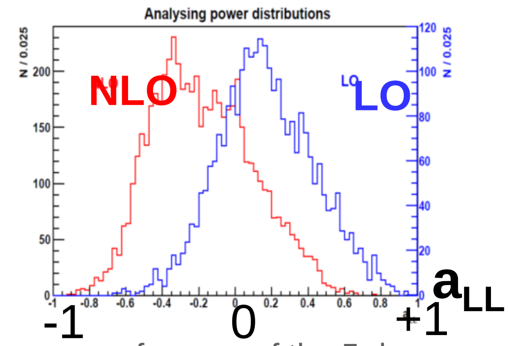
COMPASS charm: from LO to NLO

$$A_{\gamma N} = \frac{a_{LL}^{PGF}(NLO)}{D}\frac{\Delta G}{G} + \frac{a_{LL}^{q}(NLO)}{D} A_1$$

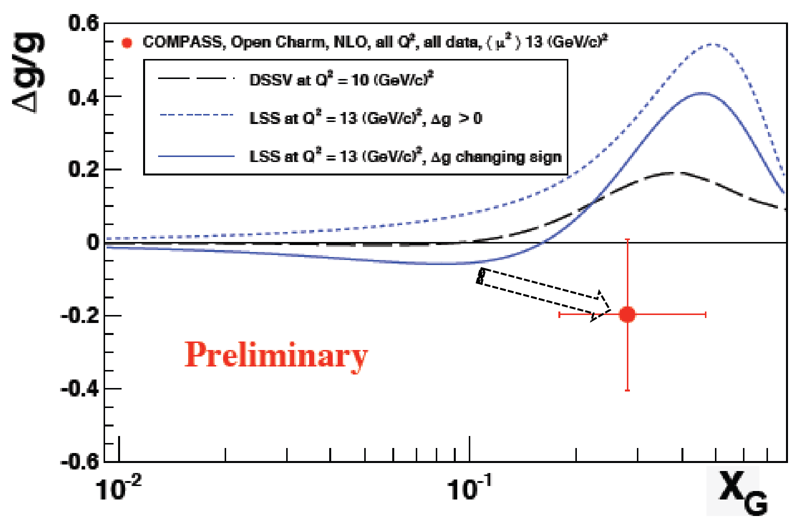
Analysing power **a_{LL}** calculated at NLO

Distribution shifted.

Induces a change in <Δ G>, but also in the relative weight of events, hence a change in <x>



a_{LL} for one of the 5 decay channels used for charm



New: K.Kurek, DIS 2011

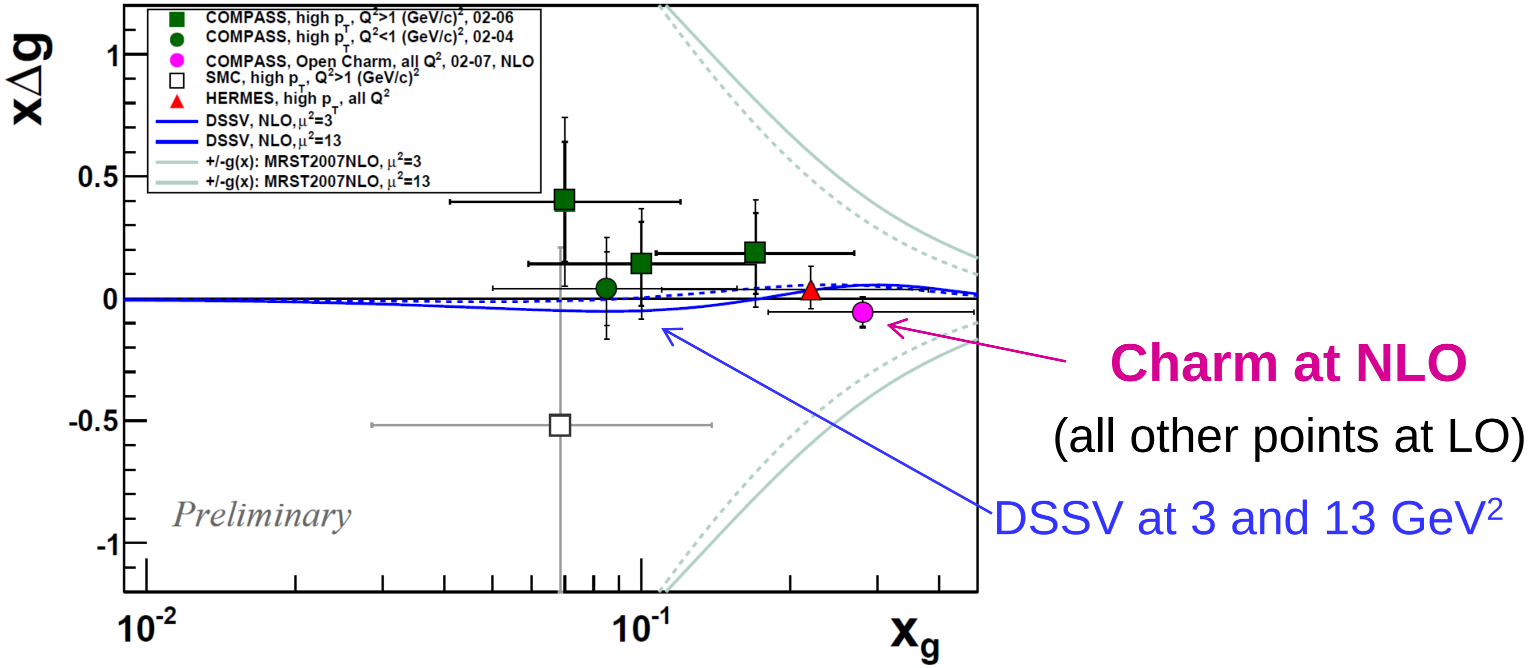
Theoretical uncertainty under study

ΔG_NLO= -0.20 ± 0.21± 0.08(syst) at <x>=0.28

Value still compatible with zero, <x> range higher

i r f u
cea
saclay

COMPASS charm: from LO to NLO

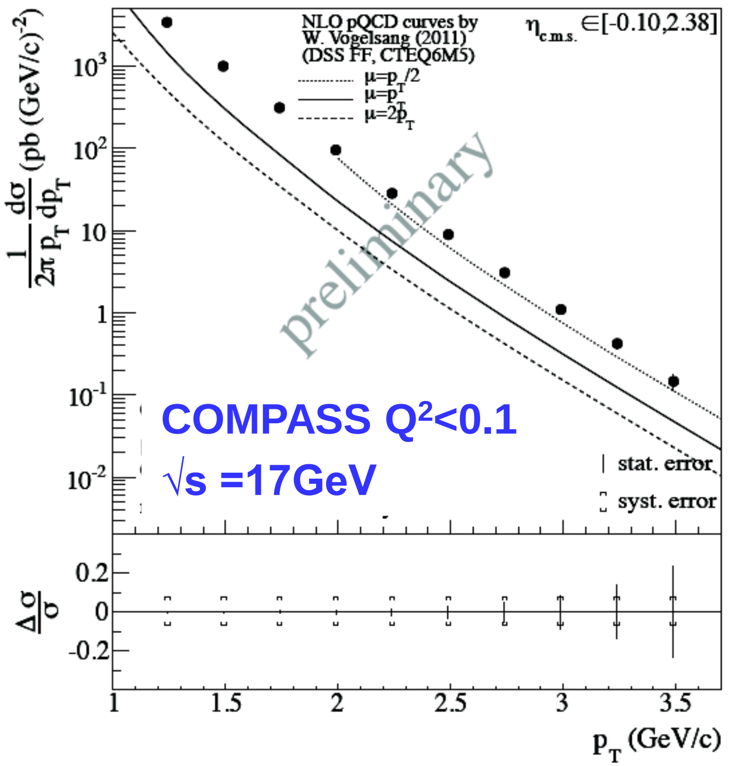


- First extraction of **ΔG at NLO**
- **Constrains ΔG at larger x**
- **Charm result can be included in global NLO fits:** model independent asymmetries $A_{LL}(p_T, E_D)$ available

COMPASS high p_T hadron : Cross section

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

Quasi real photo production of hadron



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

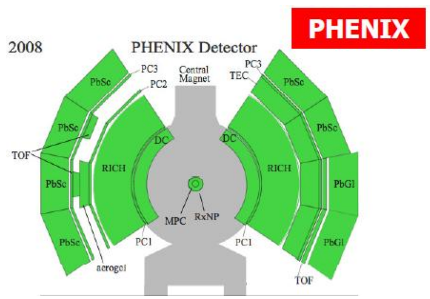
Data agree with NLO pQCD over 5 orders of magnitude
(within theory uncertainty)

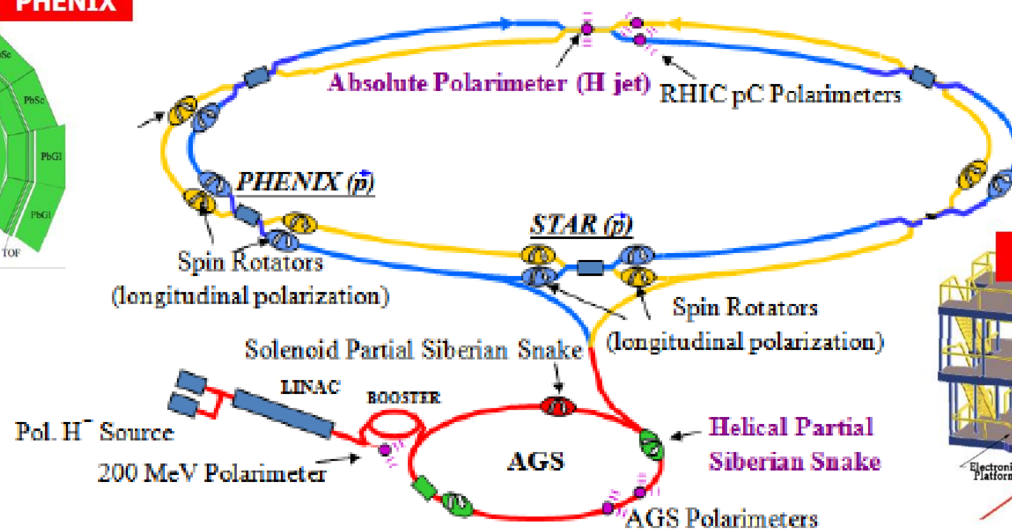
Settles the theory framework for ΔG high p_T

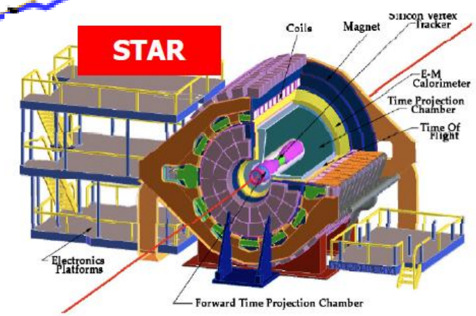
Next step: produce spin asymmetries $A_{LL}(p_T)$ for same events

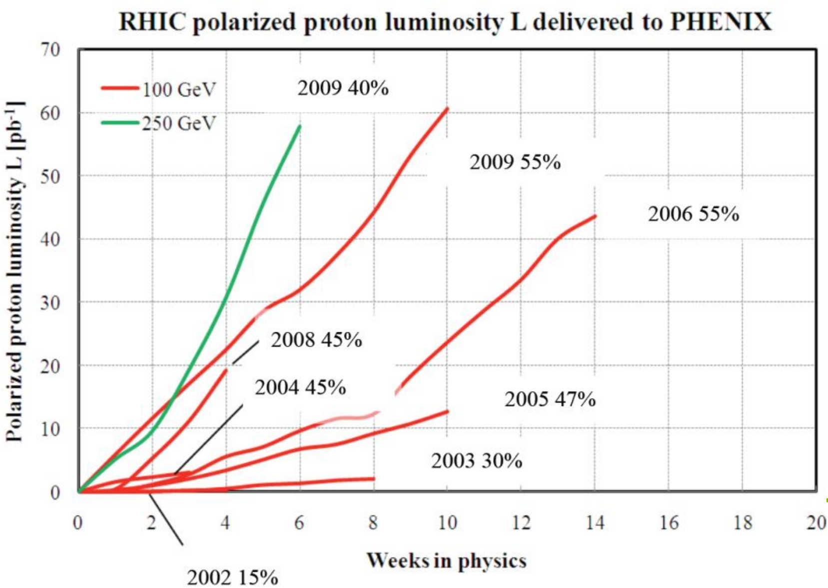
2. $\vec{p}\,\vec{p}$ collisions at RHIC

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





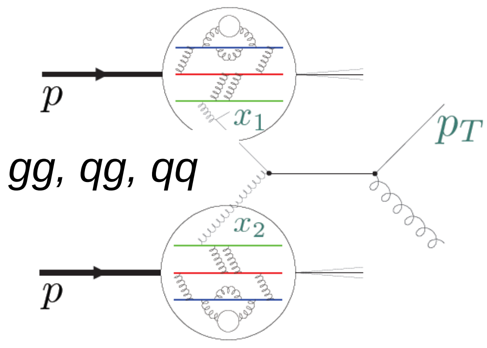




- Longitudinal spin asymmetries <ΔG>, <Δq>
- Transverse spin

- luminosity almost doubled each year
- run 9 : first time at 500 GeV

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



Di-Jet production

More abundant channels

$p\,p \rightarrow \pi^0\,X$ **PHENIX**

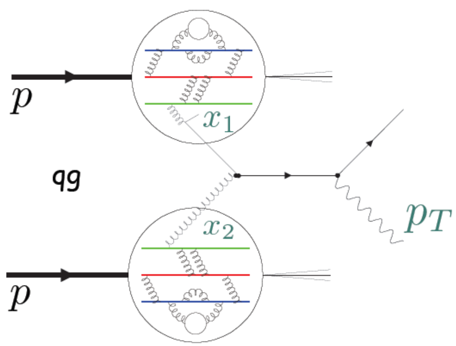
$p\,p \rightarrow$ jet X **STAR**

3 processes contribute

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

Other channels

$p\,p \rightarrow$ jet jet proj. STAR 500 GeV, low x



Photon-Jet production

$p\,p \rightarrow \gamma$ jet

1 process → cleaner $\Delta G(x_1)\,.\Delta q(x_2)$

Full kinematics reconstructed

Low statistics

$p\,p \rightarrow \gamma\ X$

…

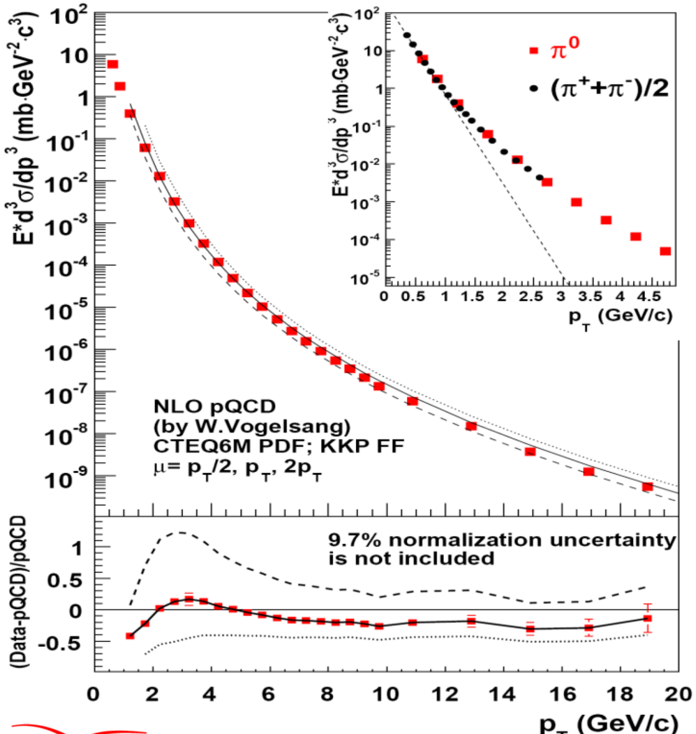
Other channels: $\pi+$, $\pi-$, η, …

High potential for ΔG from various channels, various kinematics

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

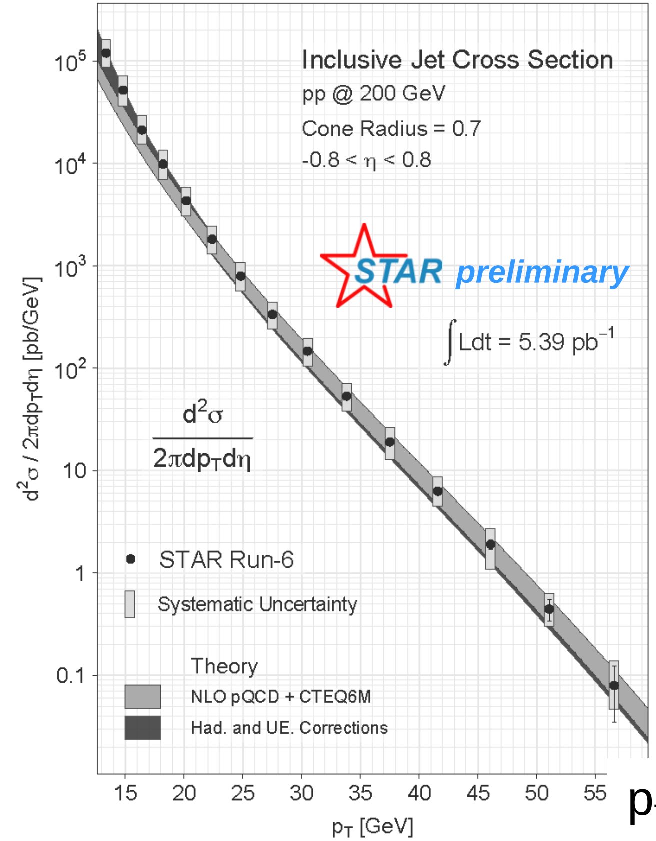
Two examples

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



PHENIX PRD76(2007) 051106

Inclusive jets at STAR



p_T [GeV/c]

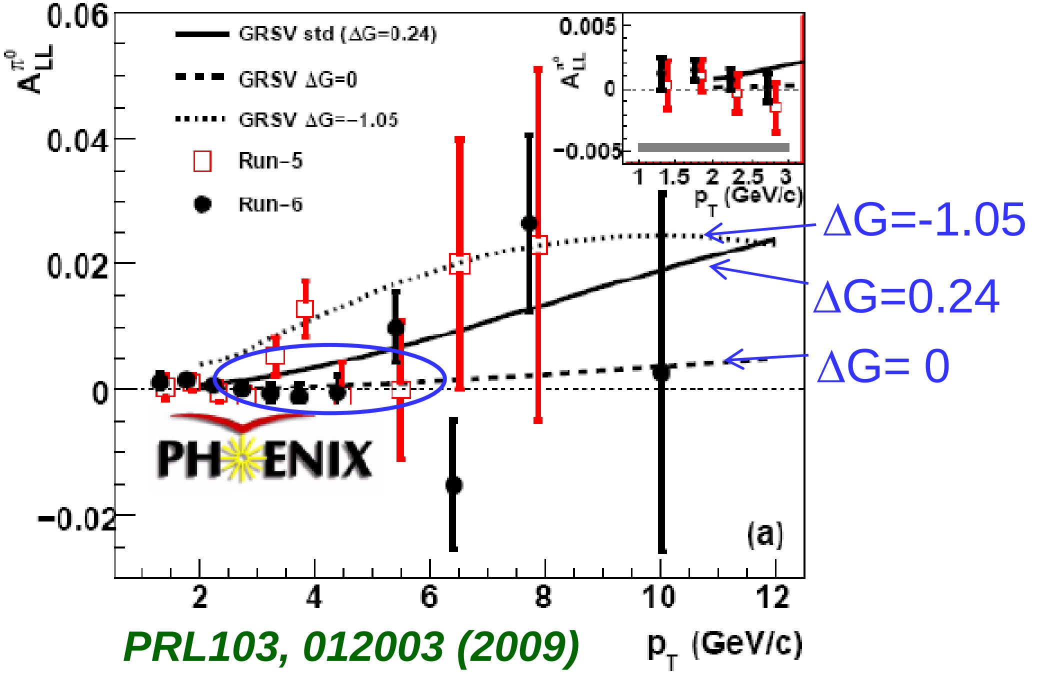
pQCD + Hadronization+ Underlying Event corrections (significant at low jet p_T)

- 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: π^0 production at PHENIX

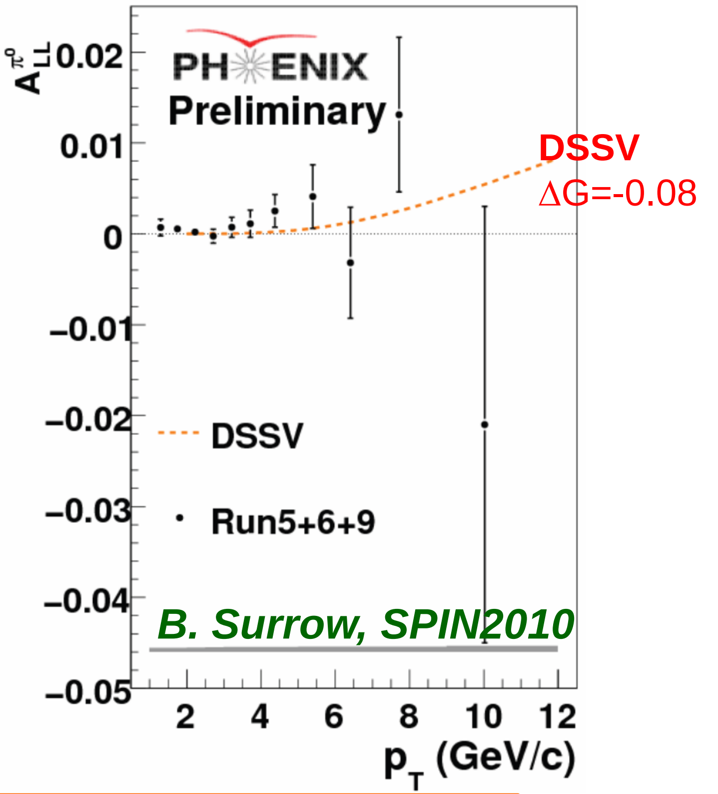
$\vec{p}\,\vec{p} \rightarrow \pi^0 X$ Measure double spin asymmetry A_{LL} (p_T)
Compare data to global fits with various $\Delta G(x)$ parameterizations

200 GeV. **Run 6** compared to **GRSV fits**



PRL103, 012003 (2009)

Run 5+6+9 compared to **DSSV fit**



B. Surrow, SPIN2010

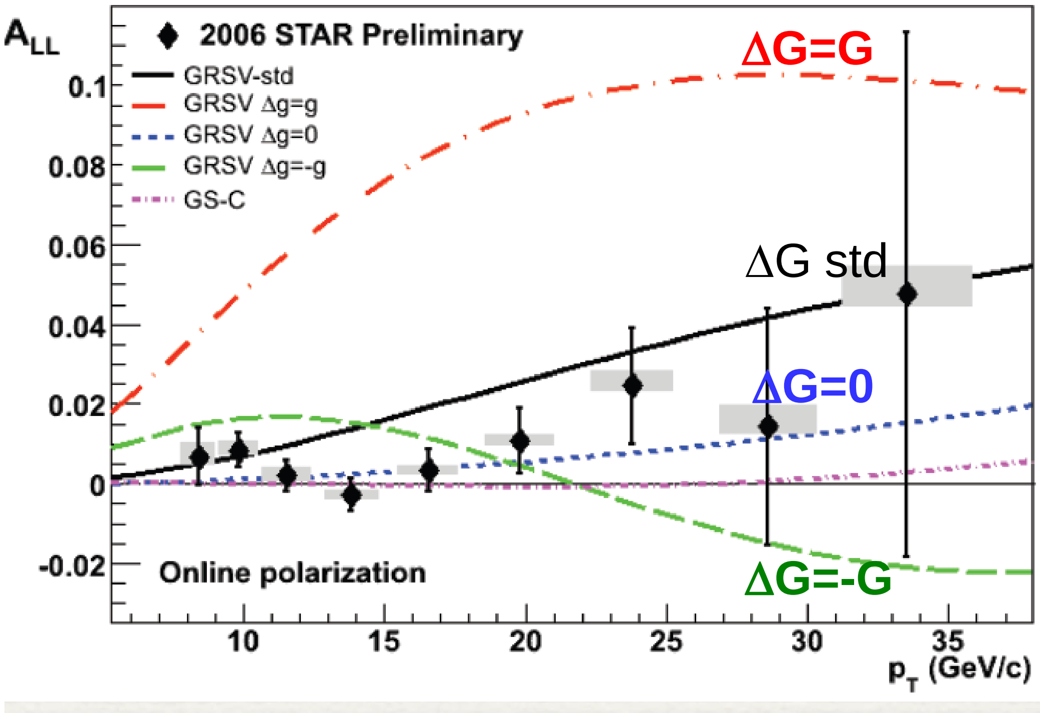
- **Data favor fits with ΔG close to 0**
- **Strong constraint on $<\Delta G>$ in x range probed $0.05<x<0.3$**

irfu
cea
saclay

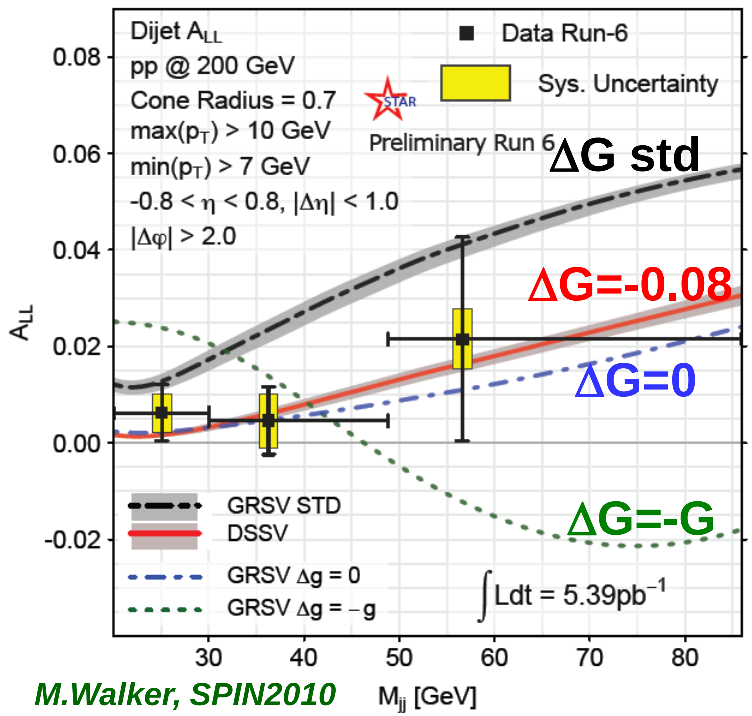
$\vec{p}\vec{p}$ collisions at RHIC: inclusive jet & dijet at STAR

200 GeV, $\vec{p}\,\vec{p} \rightarrow$ jet +X

Double spin asymmetry A_{LL} (p_T)



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



M.Walker, SPIN2010

Both channels, Inclusive jet and dijet, provide strong constraint on ΔG in measured range, favoring parameterizations with ΔG close to 0

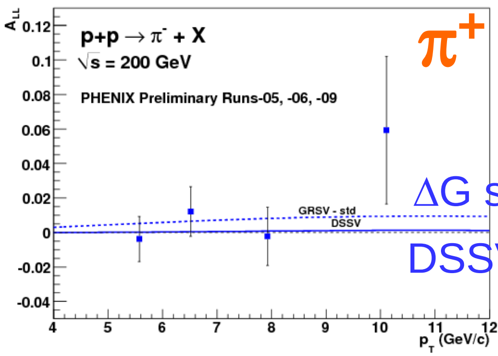
$\vec{p}\vec{p}$ collisions at RHIC: other channels

charged pions: different FF for favored or unfavored

different *qg* contributions for $\pi^{0,+,-}$ → access **sign of ΔG**

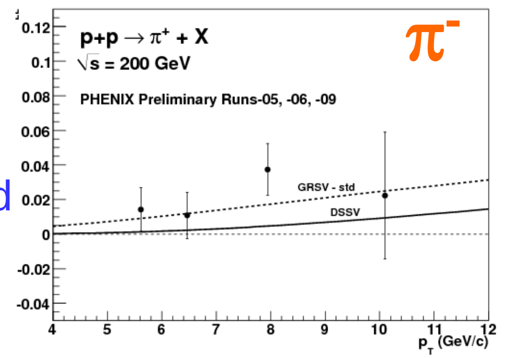
$$A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-} \Rightarrow \Delta G > 0$$

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



ΔG std

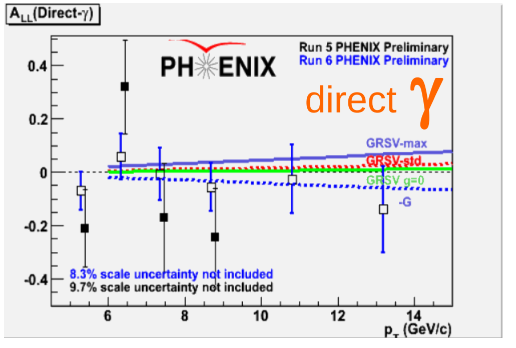
DSSV



direct γ

clean channel

qg dominates

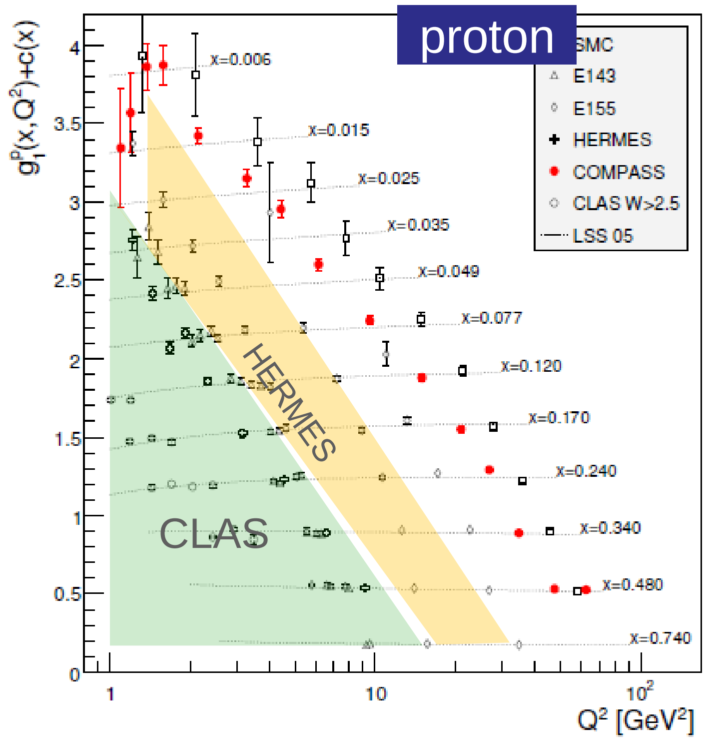


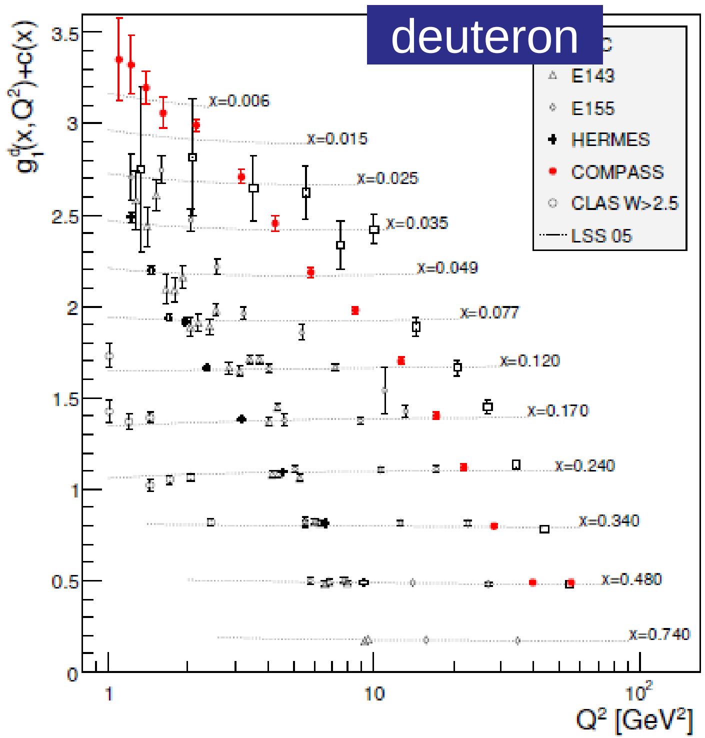
Promising channels when more statistics available

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
Use also constraint from pp data (DSSV)

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

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

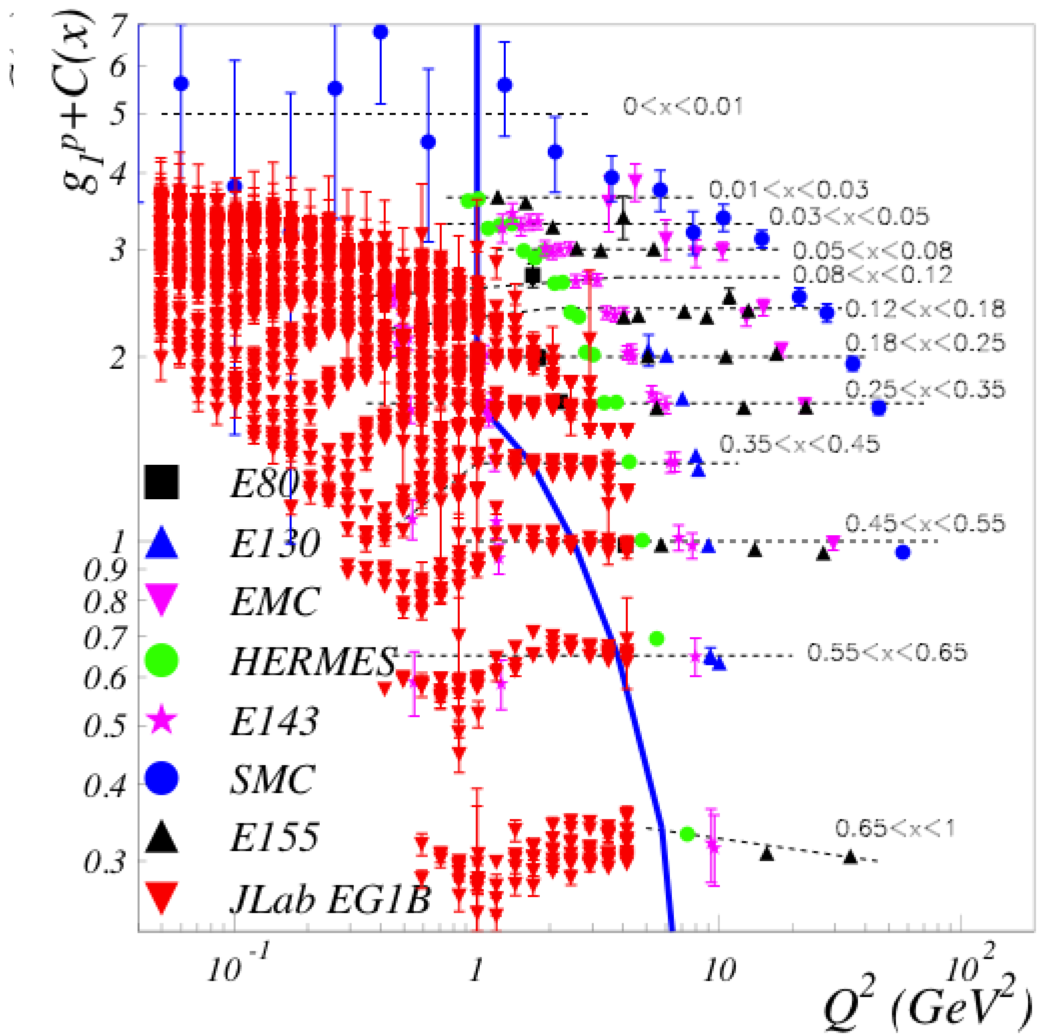
From Yelena Prok's talk at DIS'11:

World data on the proton before JLab (without COMPASS)

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

W > 2; Q^2 > 1

Data included in LSS fit



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

LSS '10

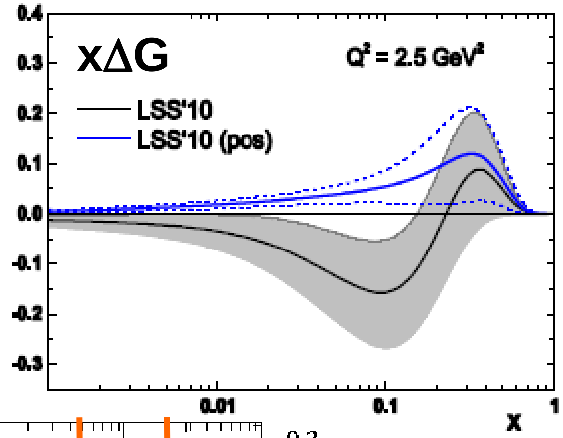
Only DIS & SIDIS data

Leader, Sidorov, Stamenov,

ΔG= 0.25± 0.19

ΔG= -0.40± 0.43

at Q^2=2.5GeV/c^2



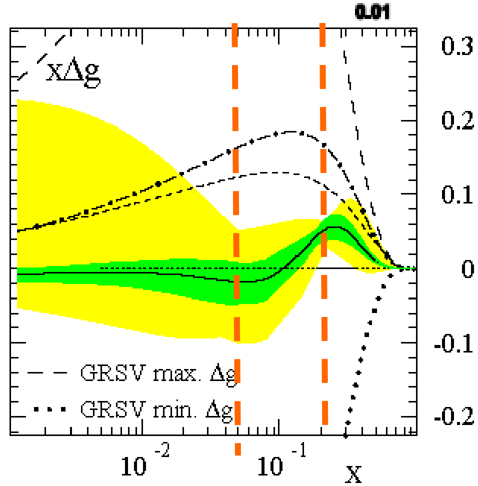
DSSV

DIS, SIDIS & pp

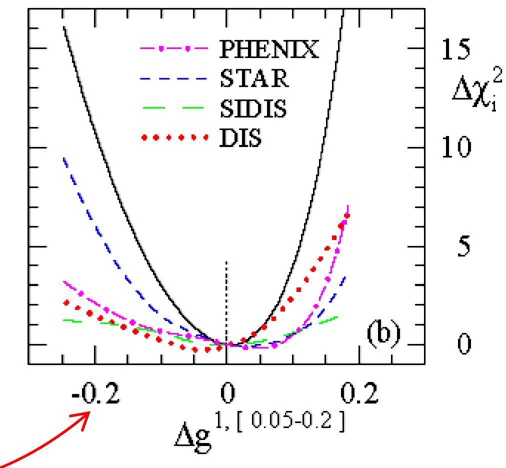
De Florian, Sassot, Stratmann, Vogelsang PRL101 (2008)072001

ΔG= -0.08 ± ?

at Q^2= 10 GeV/c^2



~0 in measured range (node)



- **Data favor fits with ΔG close to 0, excluding ΔG std**
- **Strong constraint on <ΔG> in x range probed 0.05 < x < 0.3**
- **No constraint outside**

irfu cea saclay

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

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

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

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

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

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

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

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

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

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:

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

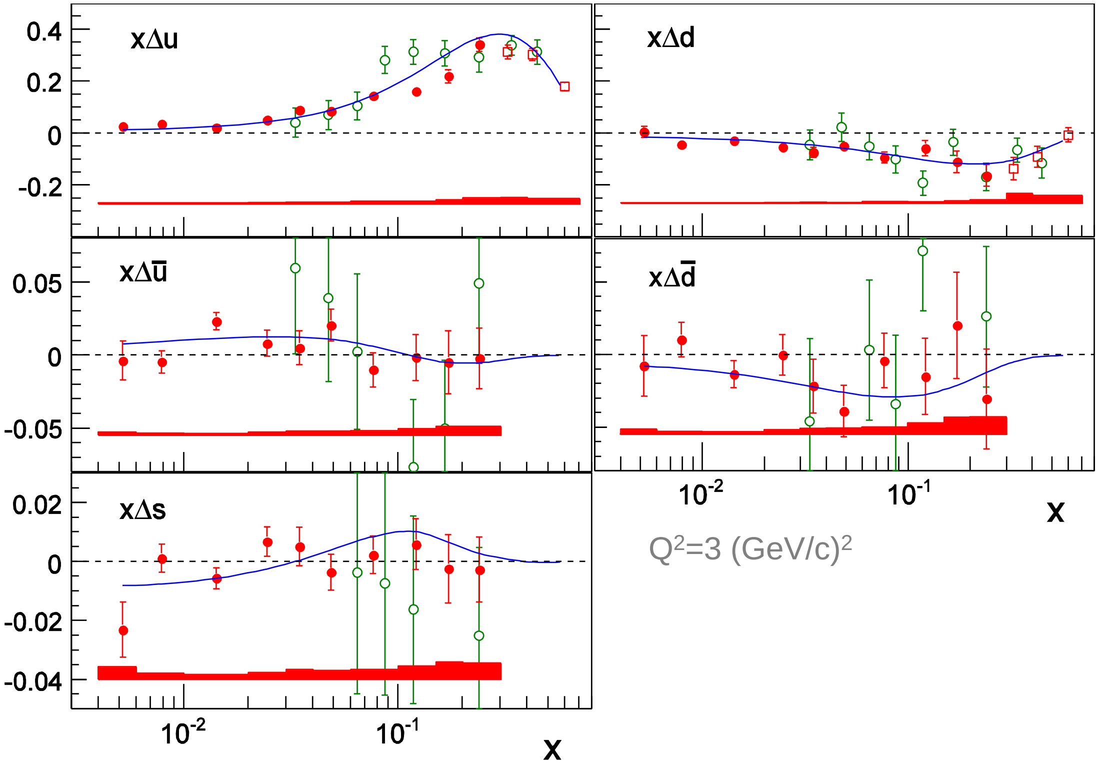
Measuring the first moments provides a test of the Bjorken sum rule,

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

PDG value:
1.268 ±0.003

i r f u
cea
saclay

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

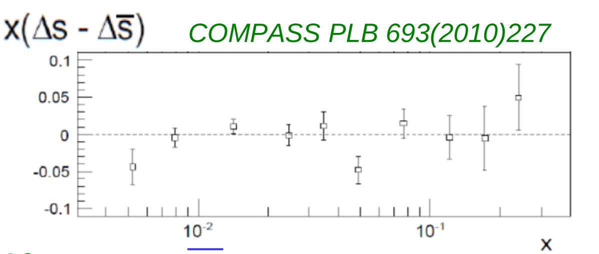
PLB693(2010)227, using DSS FF

o HERMES

PRD71(2005)012003

__ DSSV

COMPASS PLB 693(2010)227



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

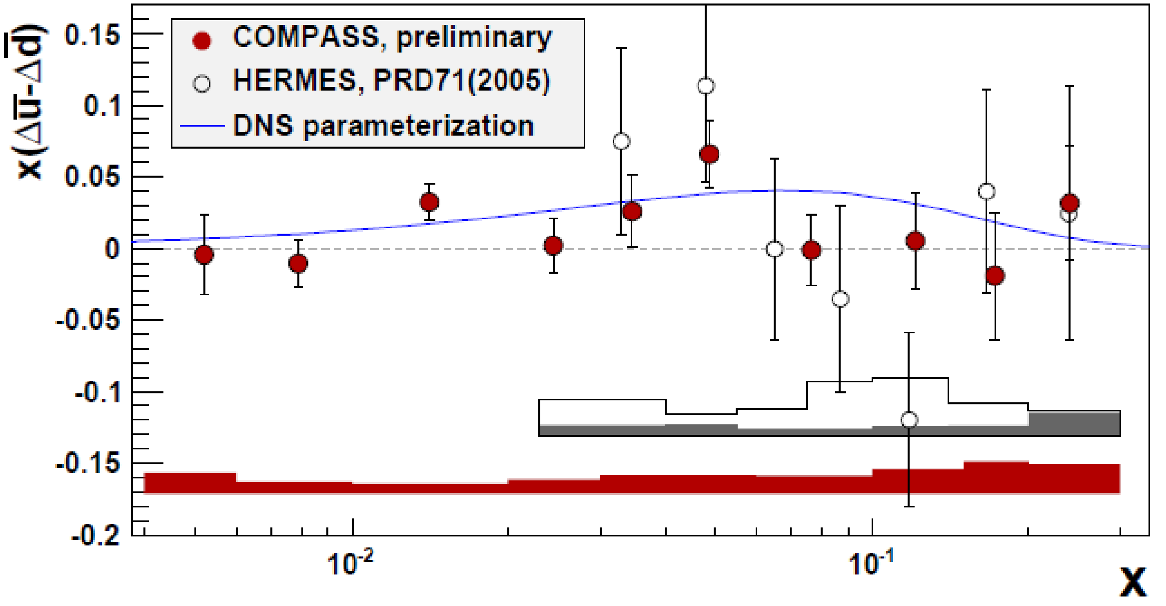
HERMES $\Delta s+\overline{\Delta s}$=0.037 ± 0.019 (stat) ± 0.027 (syst), *PLB666(2008)466*

COMPASS Δs = - 0.01 ± 0.01 (stat) ± 0.01 (syst), 0.003<x<0.3

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

Light sea quark polarized distributions

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



• COMPASS
o HERMES

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

Slightly positive, compatible with zero.

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

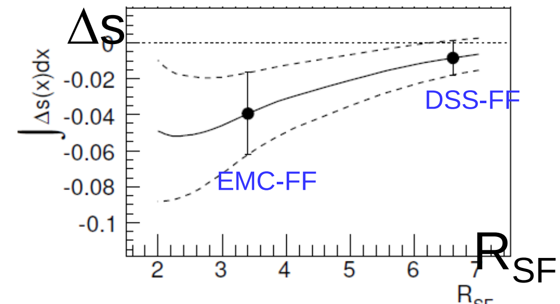
Δs puzzle

- 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)

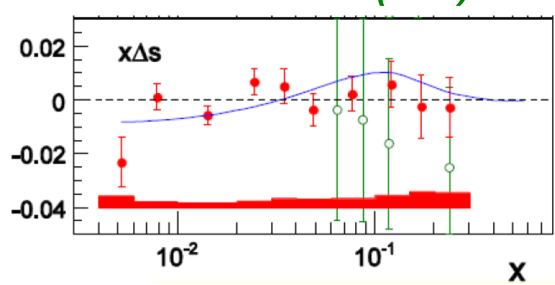
  → $\int \Delta s + \Delta\bar{s} = -0.08 \pm 0.01 \pm 0.02$

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

  → $\Delta s(x) \approx 0$



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

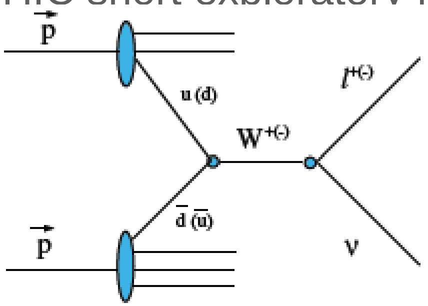
COMPASS run 2011 at 200 GeV

Certainly a physics case for EIC

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

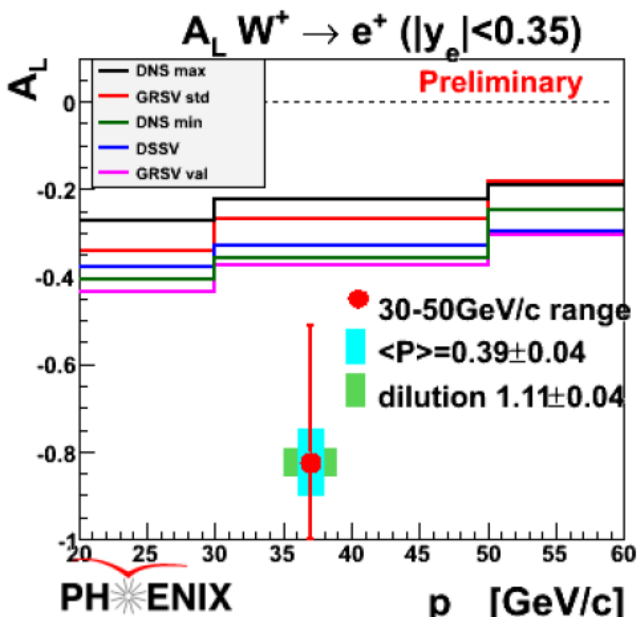
RHIC short exploratory run :first collisions at 500 GeV

Parity violating, single spin asymmetry
No fragmentation function uncertainty



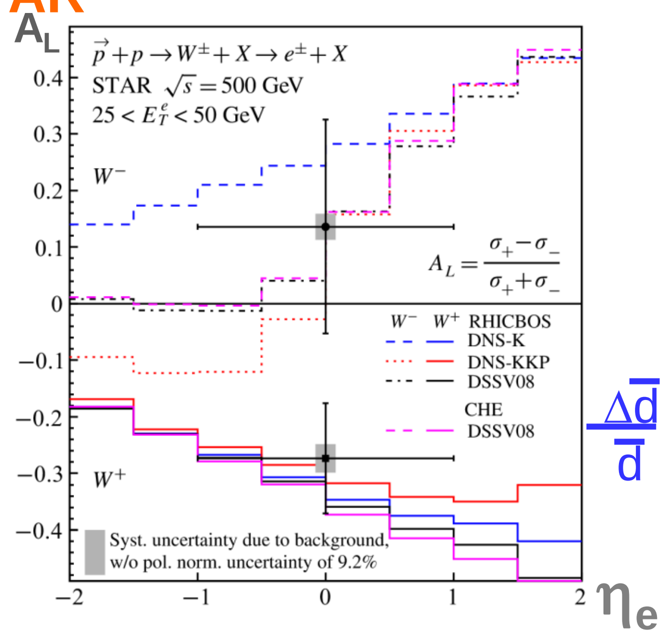
$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu$$
$$\bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}$$

PHENIX



J. Haggerty ICHEP2010

STAR

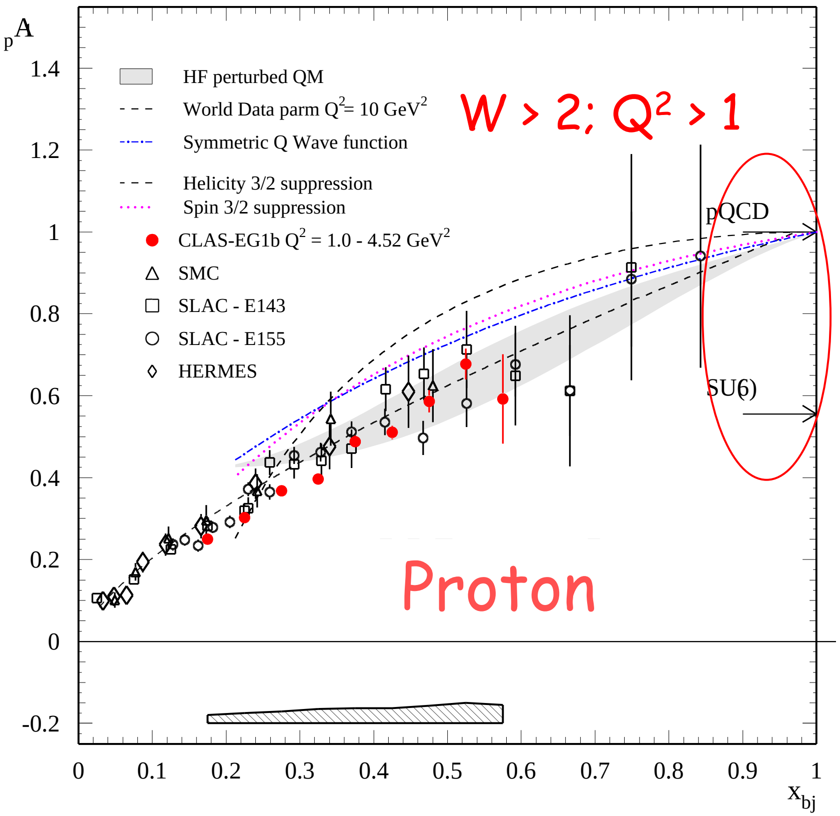


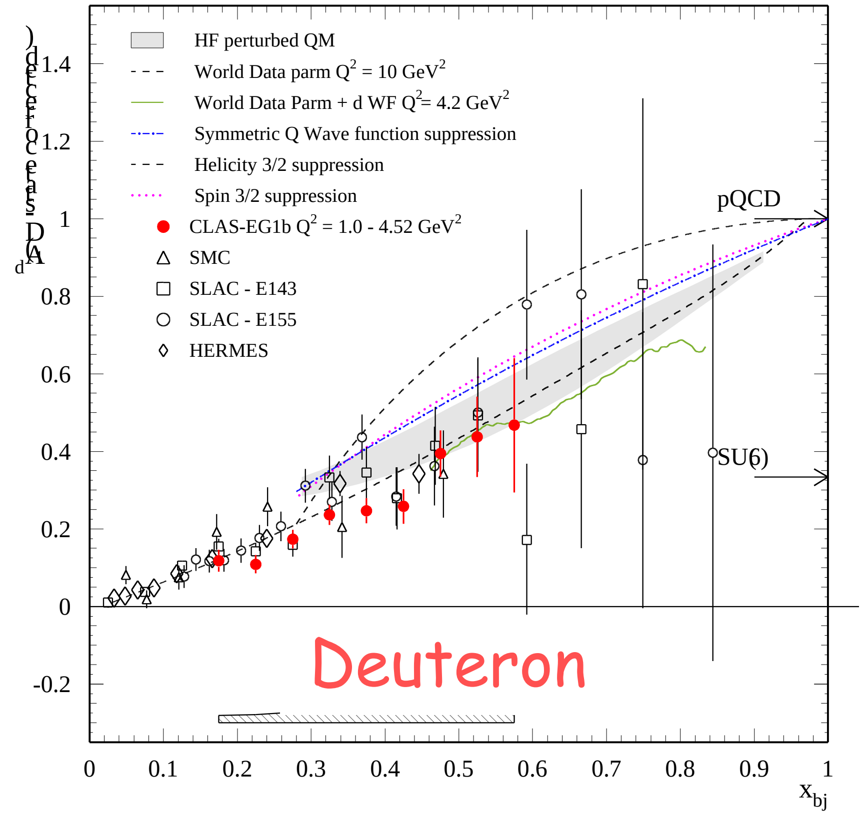
$$\frac{\Delta\bar{d}}{\bar{d}} - \frac{\Delta u}{u}$$

Phys.Rev.Lett. 106 (2011) 062002

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

Jlab – CLAS A_1^p A_1^d

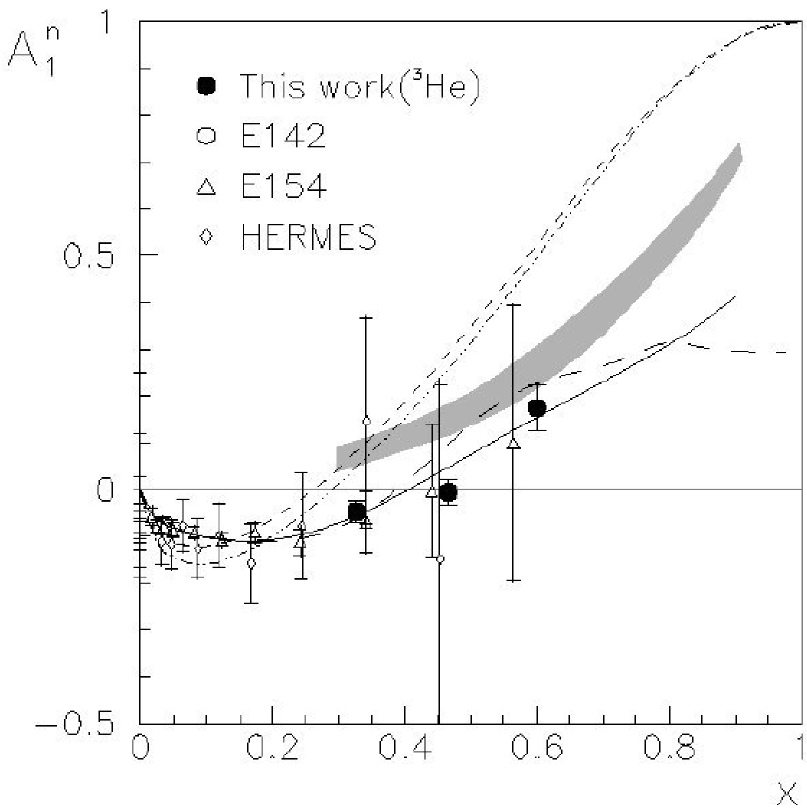




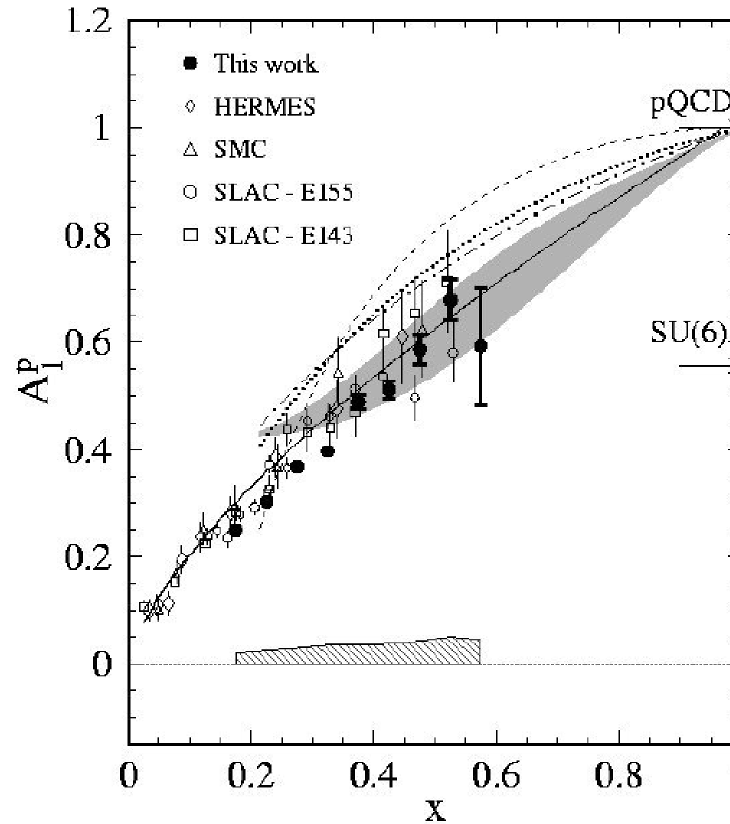
Jlab – A_1^n A_1^p high x

$W > 2; Q^2 > 1$

Neutron



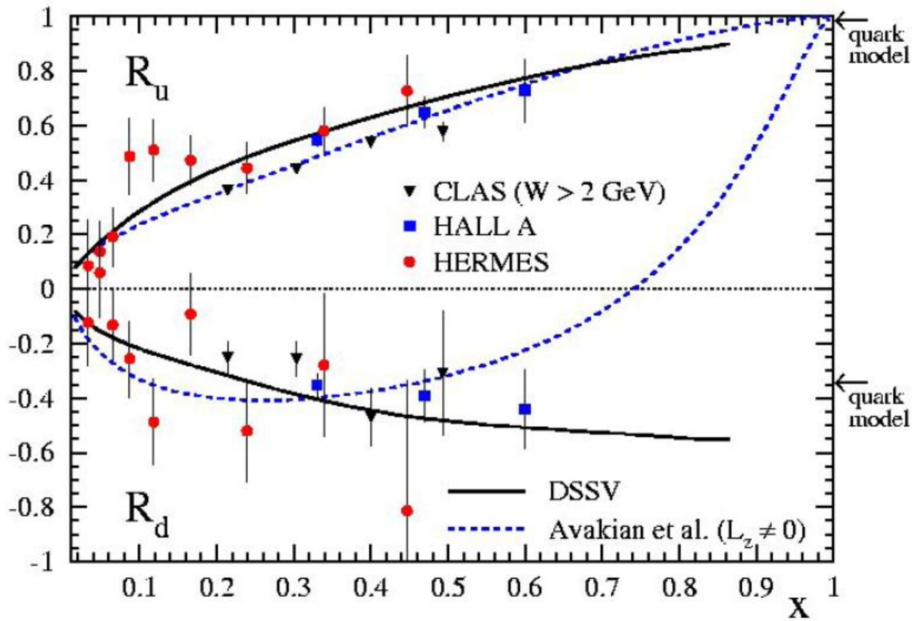
Proton



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

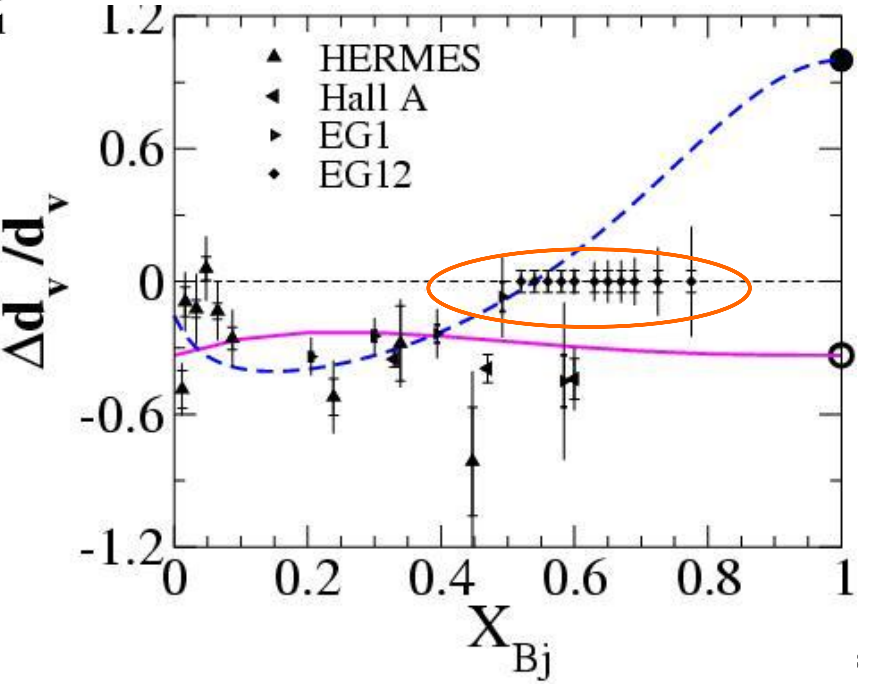
A_1^n at $x \to 1$, SU(6) symmetry breaking?

Quark helicities , valence region



CLASS EG1b PLB 641(2006)11

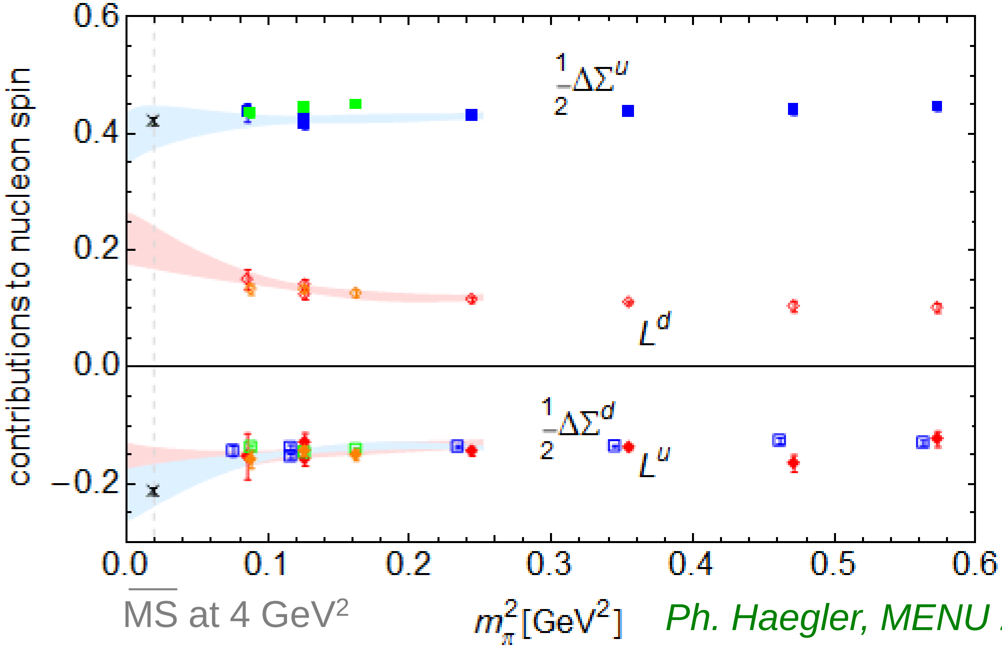
$$R_u = \frac{\Delta u + \Delta \bar{u}}{u + \bar{u}}$$



Jlab

existing and future data

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. Strong constraint on fits from RHIC.

Only $0.05 < x < 0.3$ probed: cannot exclude yet a substantial contribution

Quark contribution to nucleon spin

Extraction for all flavours from SIDIS

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

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

Spares

Consequence for nucleon spin

$\Delta G = \int \Delta g(x)dx$ not large, both from measurements (essentially PGF + RHIC) and g_1 QCD fit: $|\Delta G|<0.35$

$$\Delta\Sigma = a_0 + \underbrace{(3\alpha_s/2\pi)\,\Delta G}$$

within $\pm$ 0.06 for ΔG within $\pm$ 0.35 at $Q^2=3$

$\rightarrow \Delta\Sigma \sim 0.30$ small ($\neq$ predictions)
in good agreement with Lattice

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L$$

possible scenarios:

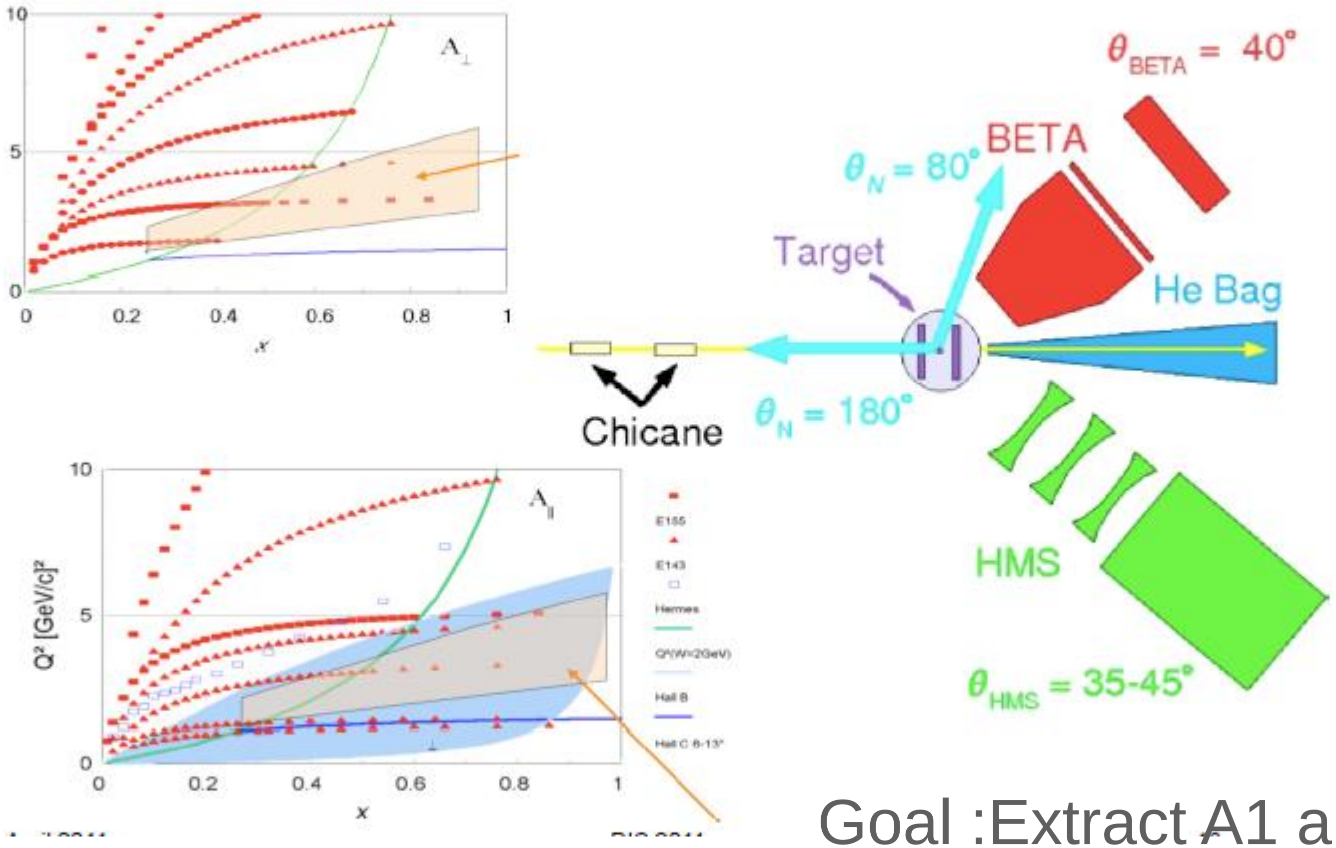
$\tfrac{1}{2}0.3 + 0.35 + 0.0$

$\tfrac{1}{2}0.3 + 0.0 + 0.35$

$\tfrac{1}{2}0.3 - 0.35 + 0.7$

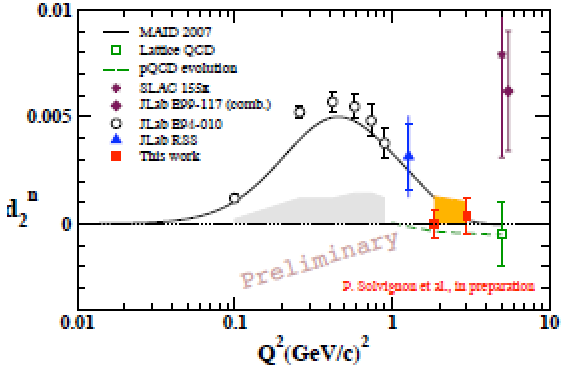
Jlab - SANE A_1 and A_2

★WG6PSH1: Hovhannes Baghdasaryan *Preliminary proton spin asymmetry results from SANE*



Goal :Extract A1 and A2 in model independent way

Jlab- Hall A g_2^n



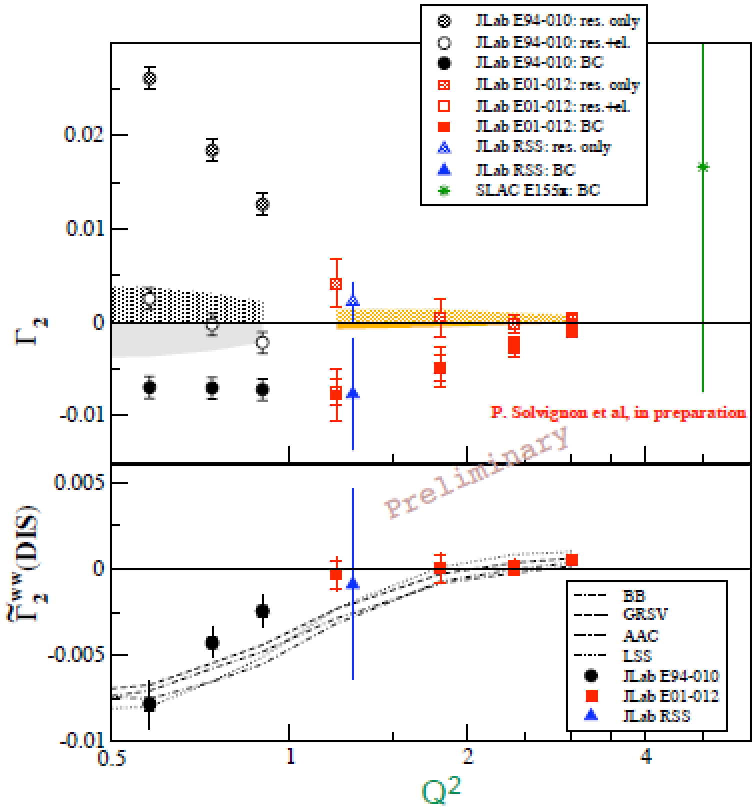
- higher twist coefficient

$$d_2(Q^2) = \int_0^1 dx\, x^2 [2g_1(x,Q^2) + 3g_2(x,Q^2)]$$

- Burkhardt-Cottingham Sum Rule

$$\int_0^1 g_2(x,Q^2)dx = 0$$

- Γ_2^{WW} is sum of g_2^{WW} for W>2 GeV



Jlab-CLAS: A1=g1/F1

eg1-dvcs

★WG6PST3: Sucheta Jawalkar *Spin azimuthal asymmetries on longitudinally polarized proton*

$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

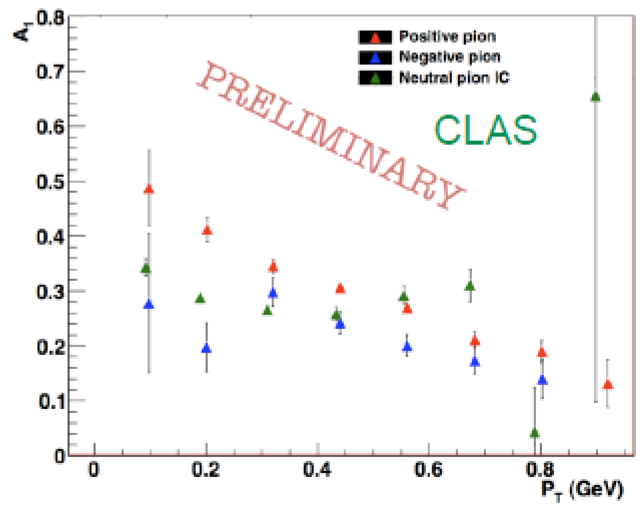
$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

$$D_1^q(z,p_T) = D_1(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_T^2}{\mu_D^2}\right),$$

$$\frac{g_1}{F_1} \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)} e^{-z^2 P_T^2 \frac{(\mu_0^2-\mu_2^2)}{(\mu_D^2+z^2\mu_0^2)(\mu_D^2+z^2\mu_2^2)}}$$

- eg1-dvcs data (25%) of total
- P_T dependence → $\mu_0 \neq \mu_2$
- For π^+, π^- and π^0

CLAS



g1/ F1 sensitive to $\mu_0^2 - \mu_2^2$ → k_T dependence

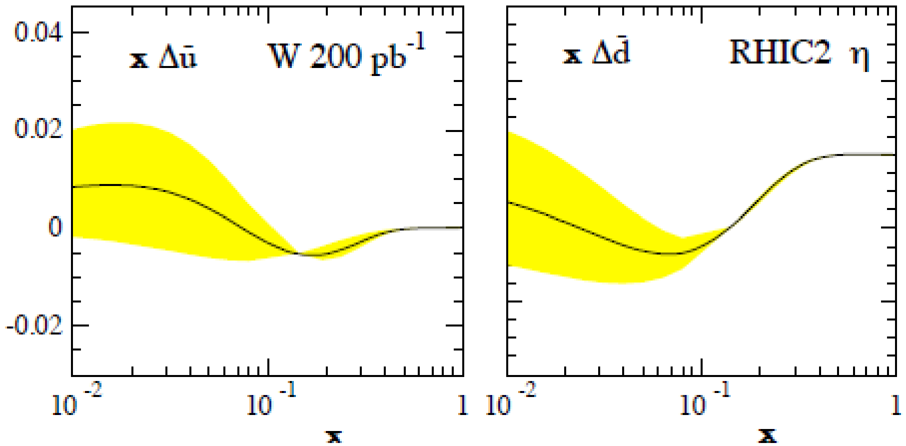
Spin at RHIC-II 2011 to 2015

Accelerator & detector configuration

- **RHIC reaches max performance:**
  - **Polar.**=0.5 (2011) → 0.65 (2014)
  - L_{max}=1 x $10^{31}cm^{-2}s^{-1}$ (2011)→ 3 x $10^{31}cm^{-2}s^{-1}$
- **Upgrades of STAR & PHENIX complete for 2012 run**
- **New Drell-Yan experiment for transverse spin AnDY**

Major Physics goals (related to longitudinal spin)

- **Anti-quark helicity distributions in polarized W-production**



Courtesy M.Grosse-Perdekamp

- ***ΔG(x)* and low *x* with A_{LL} from di-jets and di-hadrons**
- **Sivers asymmetries in Drell-Yan (sign!) and jet production (large x)**
- **Collins asymmetries in di-hadron FF and hadrons in jets (large x)**

Future of COMPASS 2011-2016

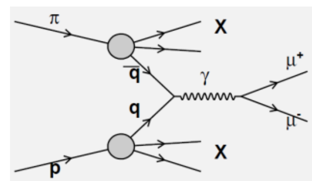
2010 Transverse spin run : *Collins, Sivers, TMDs*
2011 Longitudinal spin run at 200 GeV : *g_1, Δq at lower x, ΔG…*
2012 hadron run: *Primakoff* **+ short muon run** *GPD preparation*

2014 and beyond, COMPASS-II :

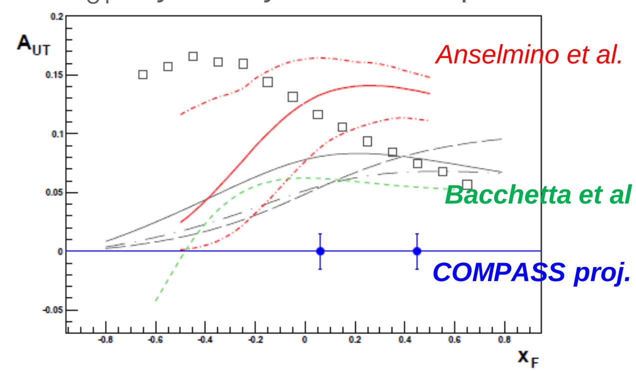
see talk of B, Badelek

- **Polarized Drell-Yan $\pi p^{\uparrow} \rightarrow \mu^+\mu^- X$**

transversely polarised proton target
TMDs, Sivers & Boer-Mulders
Test of factorization approach:
comparison SIDIS/ Drell-Yan

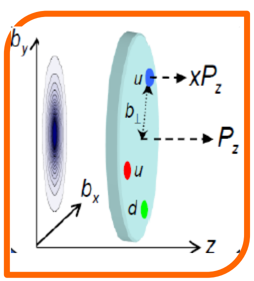


Ex: A_{UT} asymmetry in Drell-Yan process

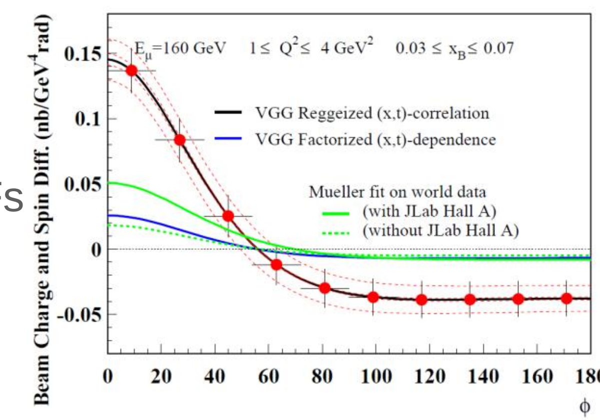


- **GPD** (Generalized Parton Distributions) $\mu p \rightarrow \mu p \gamma$

by exclusive reactions DVCS, DVMP



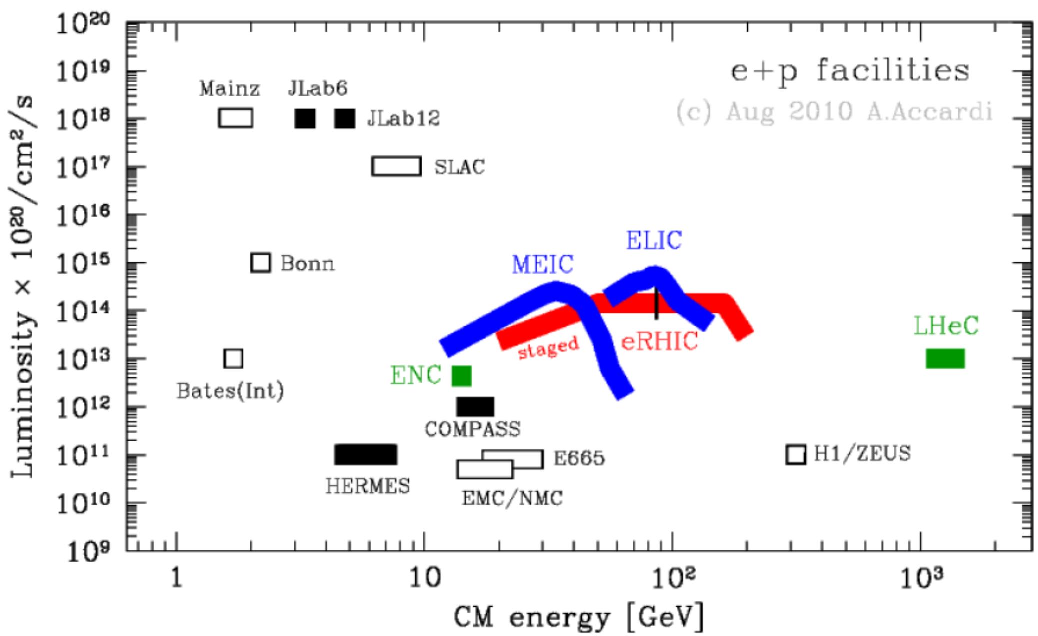
•Unified descrition of form factors & PDFs
•Transverse imaging 2+1 dim.

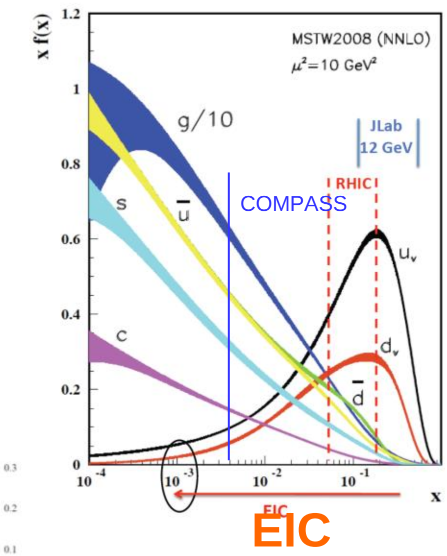


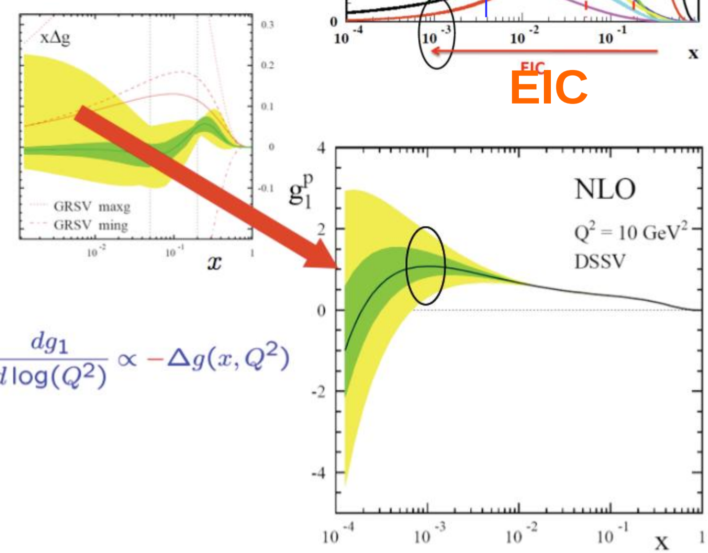
Future polarized ep collider

- **Goal: access lower x in (polarized) DIS and with higher luminosity**
- **Wide physics program:**

Polarized **sea q** and **g**, Hard exclusive reactions, TMDs, gluon saturation…







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

EIC / ENC projects in US and Europe