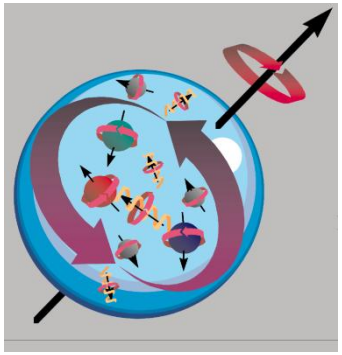
Nucleon spin structure
Experimental overview

Fabienne KUNNE
CEA /IRFU Saclay, France

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



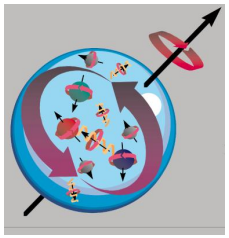
Disclaimer: more than 50 talks directly related to spin in parallel session. Not all cited here.

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

Parton spin parallel or anti parallel to nucleon spin

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

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

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

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

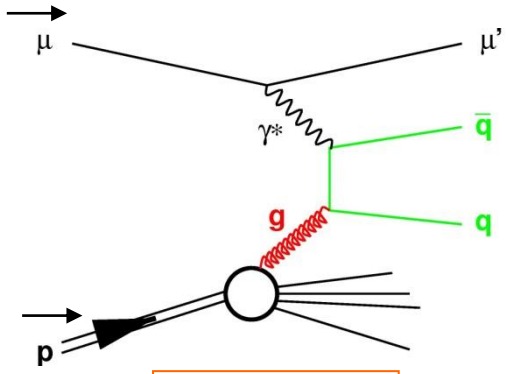
Large experimental effort on ΔG measurement

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

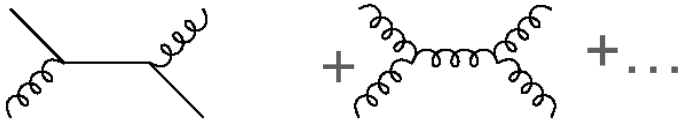


ΔG/G(x)

SMC, HERMES, COMPASS

2. Proton Proton collisions

Gluon-Quark + Gluon-Gluon +…



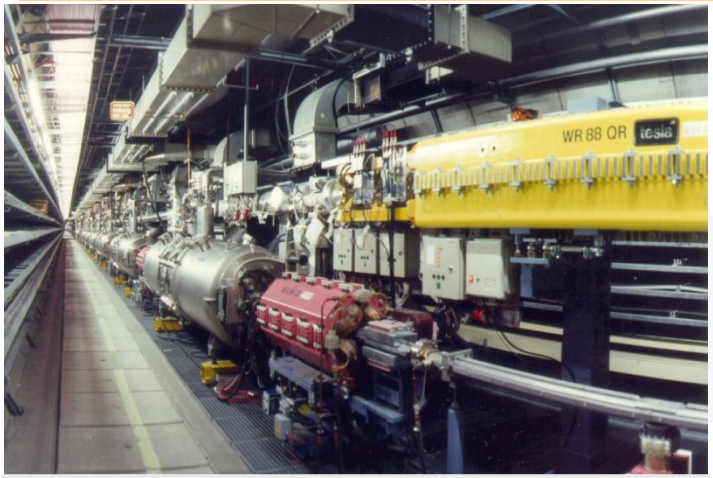
$$\frac{\Delta G}{G}\times\frac{\Delta q}{q} \qquad + \frac{\Delta G}{G}\times\frac{\Delta G}{G} + \ldots$$

A_{LL} (p_T)

RHIC : PHENIX & STAR

3. QCD 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

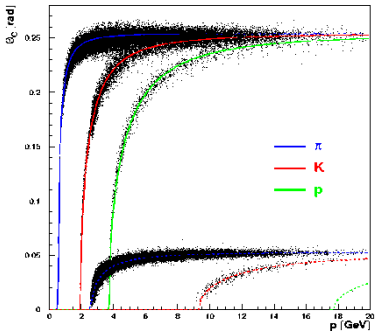


1995 to 2007

Spectrometer :

Δp/p~2%, ΔΘ<1 mrad

Excellent separation of π, K, p



HERA e^+ & e^- 27 GeV

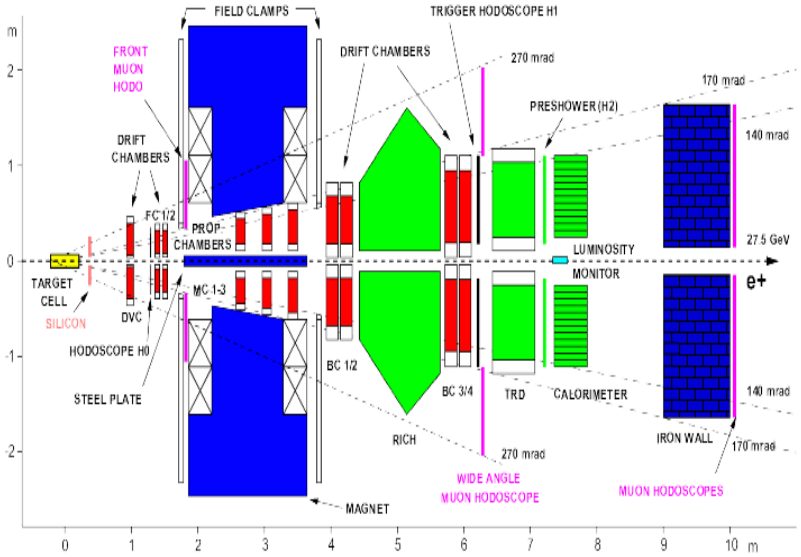
longitudinally polarized ~ 54%

Gaseous internal target

Longit. Polar. 85% H, D, He

Transv. Polar H

Unpol H, D, Ne, Kr



COMPASS at CERN

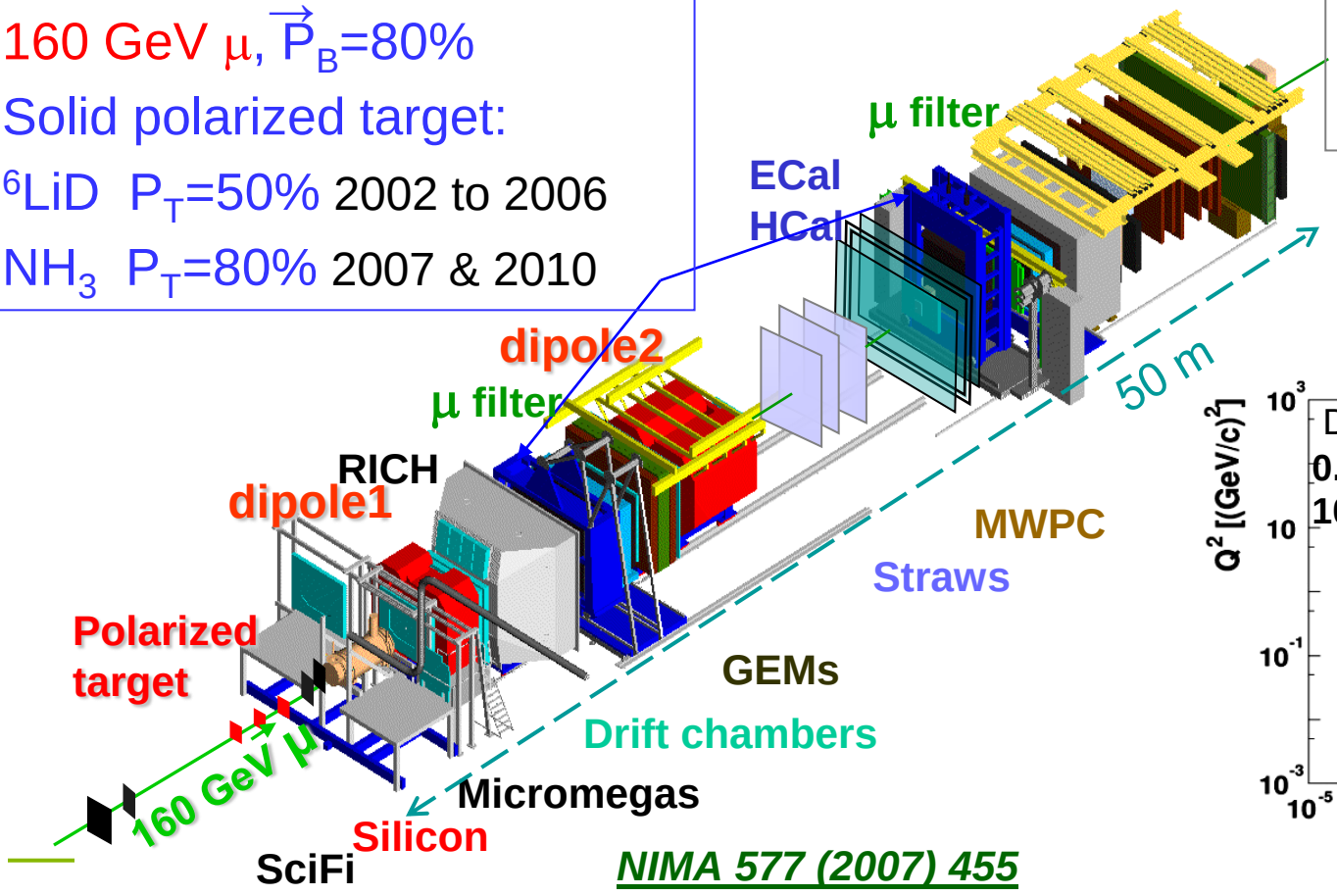
Fixed target
Secondary beams from SPS

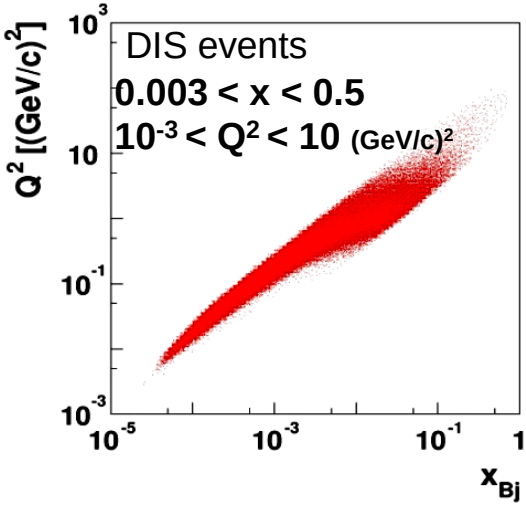
Nucleon spin structure

Polarized muon beam:
160 GeV μ, $\vec{P}_B$=80%
Solid polarized target:
^{6}LiD P_T=50% 2002 to 2006
NH_3 P_T=80% 2007 & 2010

Meson spectroscopy

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





NIMA 577 (2007) 455

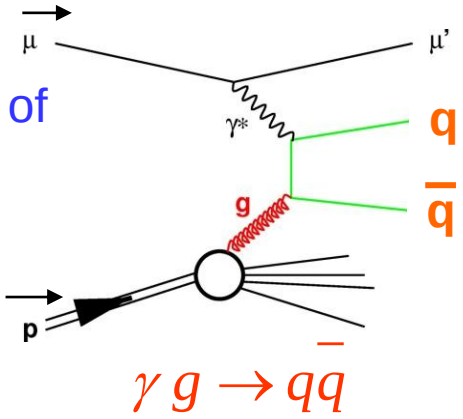
1. ΔG/G from *lepton* $\vec{N}$ scattering

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

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

Combinatorial background & limited statistics

→ Difficult experiment

COMPASS 160 GeV 1 result

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

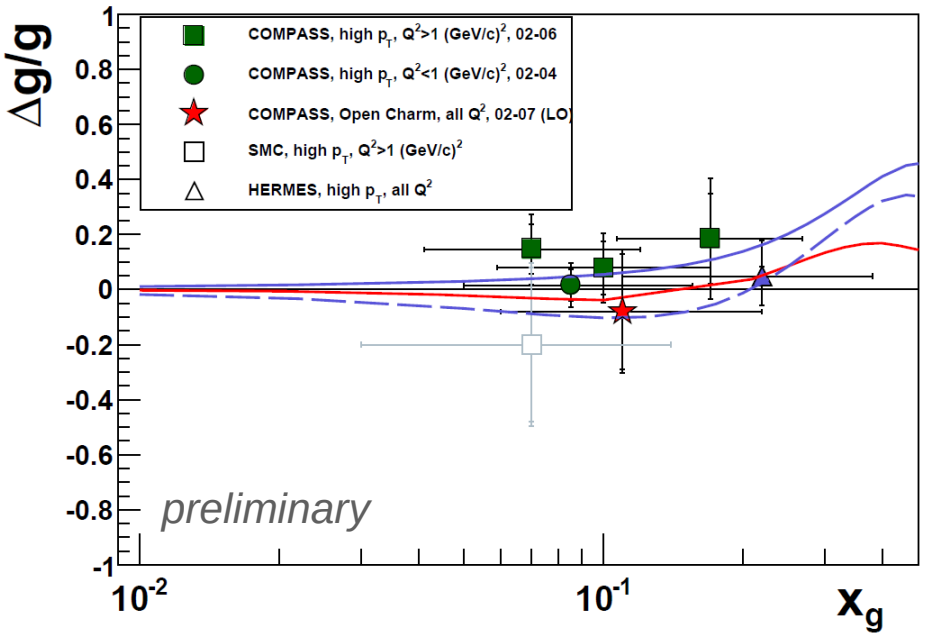
High statistics

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



LSS10
Q^2=3
DSSV

see talks of C.Marchand and K.Kurek

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

Open charm: Q^2= 13

LSS10, ΔG~ + 0.32 at Q^2= 4
LSS10, ΔG~ - 0.33 (node)
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, although the measured spin asymmetries, model independent, are available for some channels

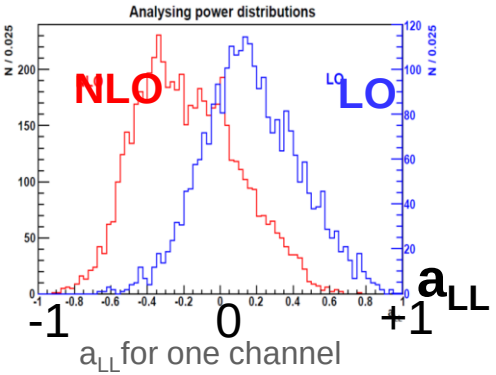
COMPASS charm: from LO to NLO

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

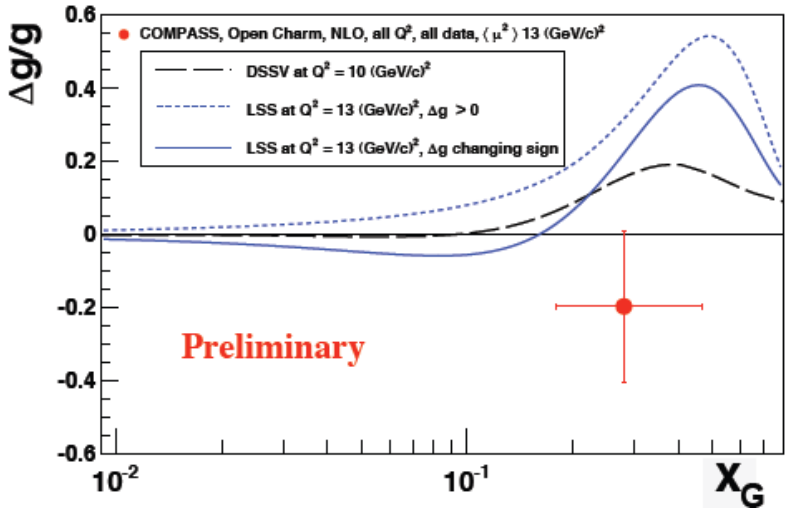
Analysing power a_{LL} calculated at NLO (AROMA)

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 channel



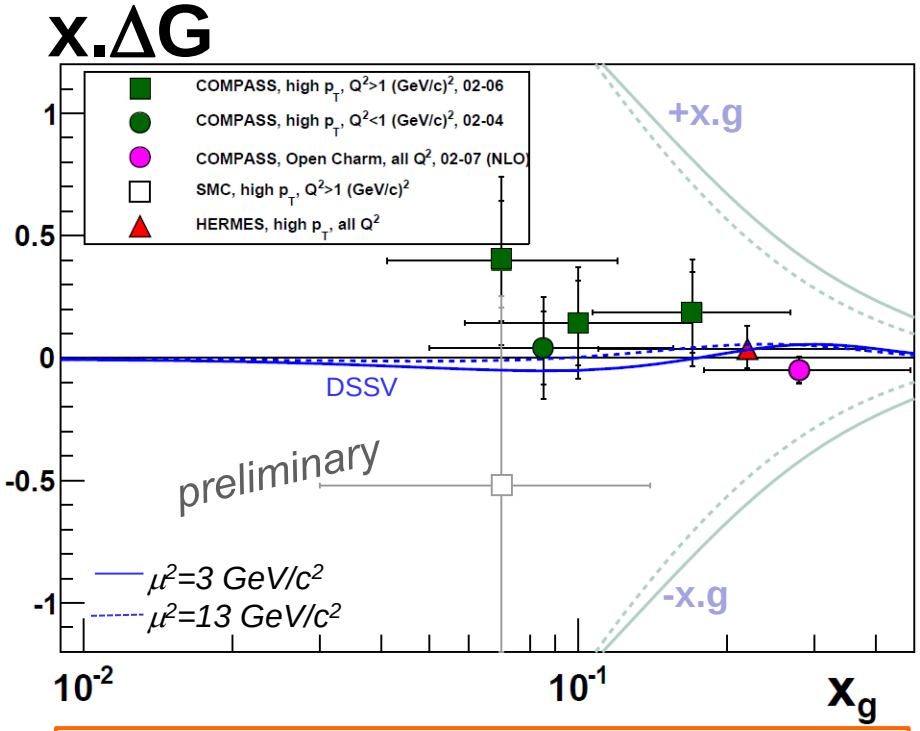
see talk of K.Kurek

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

Theoretical uncertainty under study

Value still compatible with zero, <x> range higher

COMPASS charm: from LO to NLO



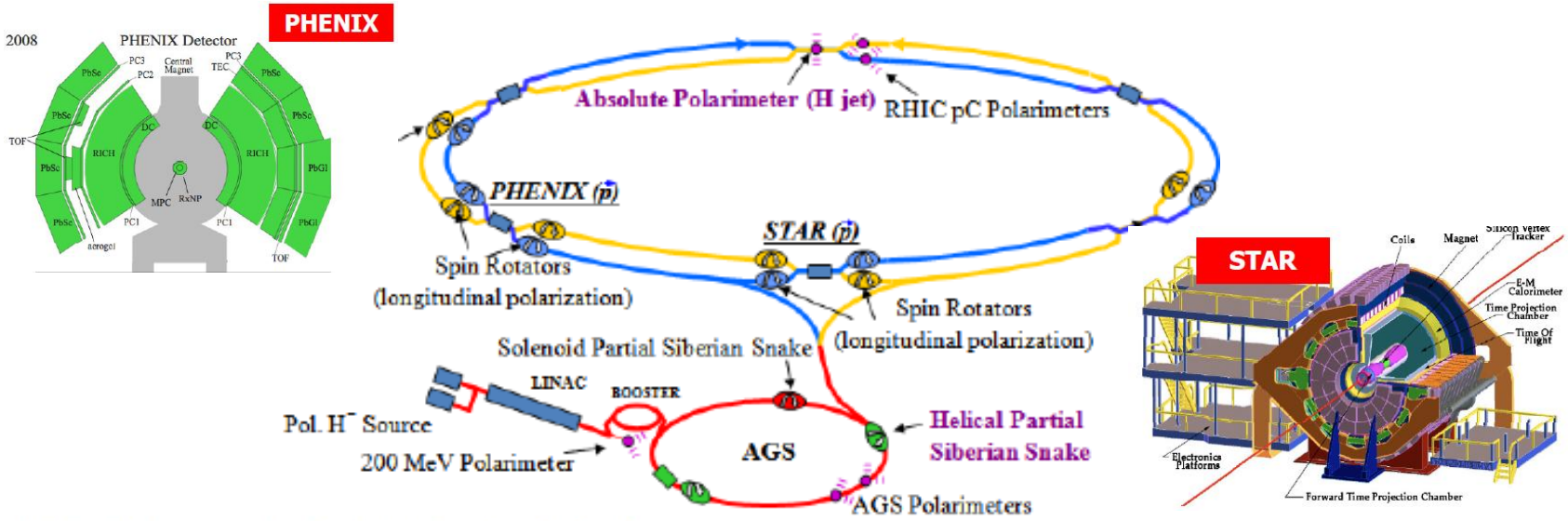
Charm at NLO, all other points at LO

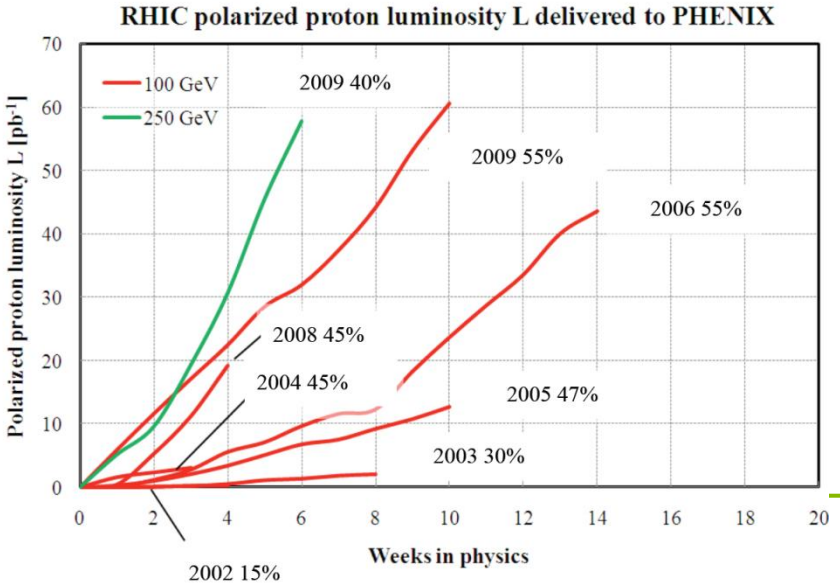
- First extraction of **ΔG at NLO**
- Constrains ΔG at larger x
- **Data to be included in global NLO fits:**

model independent asymmetries $A_{LL}(p_T, E_D)$ available

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

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

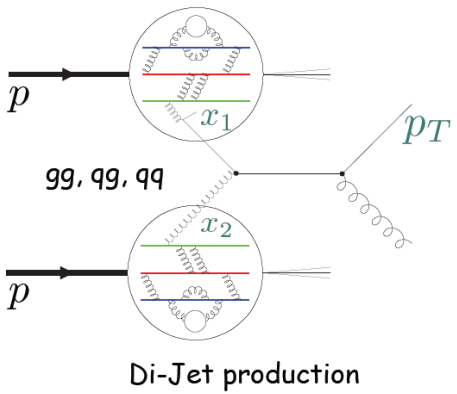




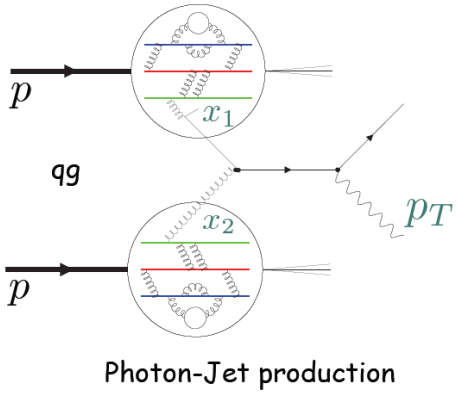
- Longitudinal spin asymmetries <ΔG>, <Δq>
- Transverse spin

- 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



Photon-Jet production

see talks of A.Datta, M.Walker, P.Djawotho

More abundant channels

p p → π^0 X **PHENIX**

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

p p → γ jet

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

Full kinematics reconstructed

Low statistics

p p → γ X

…

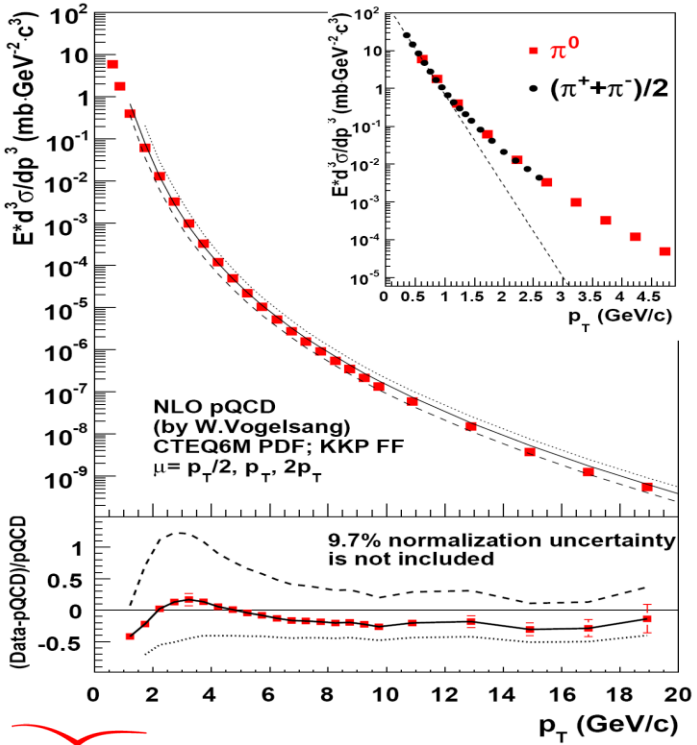
Other channels: $\pi+$, $\pi-$, η, …

High potential for ΔG from various channels, various kinematics

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

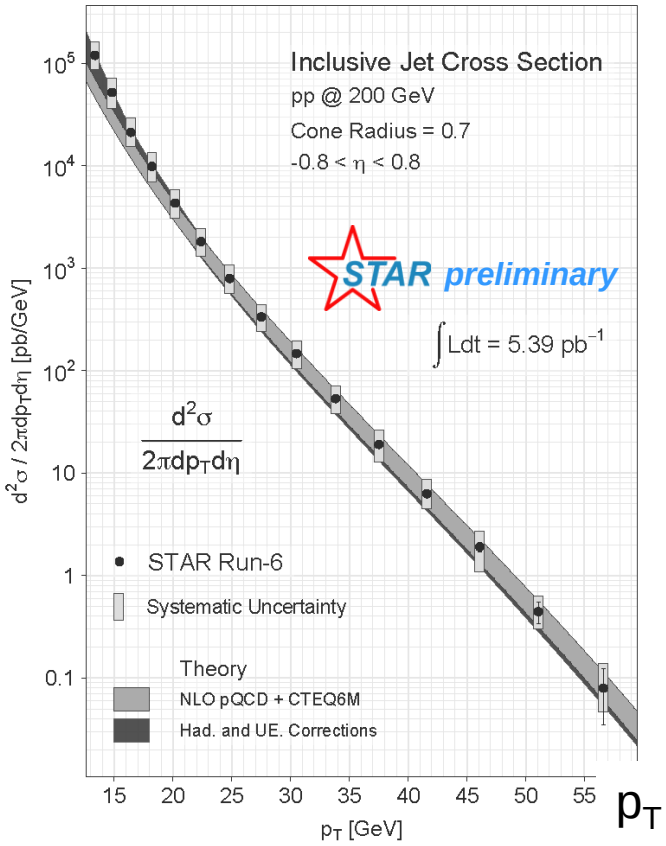
Two examples

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



PHENIX PRD76(2007) 051106

Inclusive jets at STAR



p_T [GeV/c]

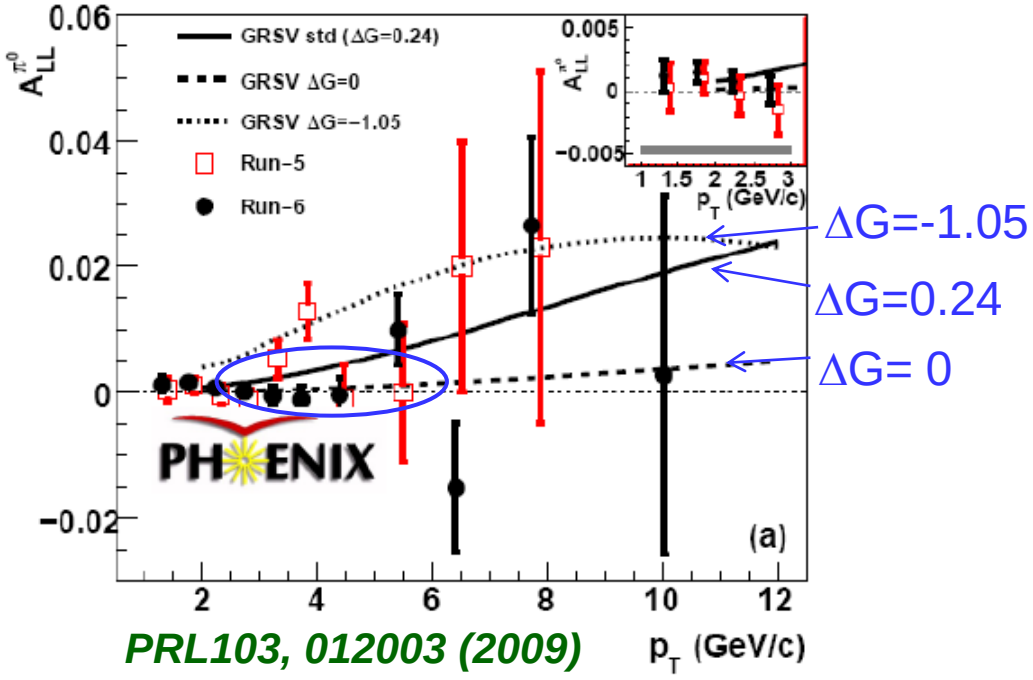
pQCD + Hadronization+ Underlying Event corrections (significant at low jet p_T)

- **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

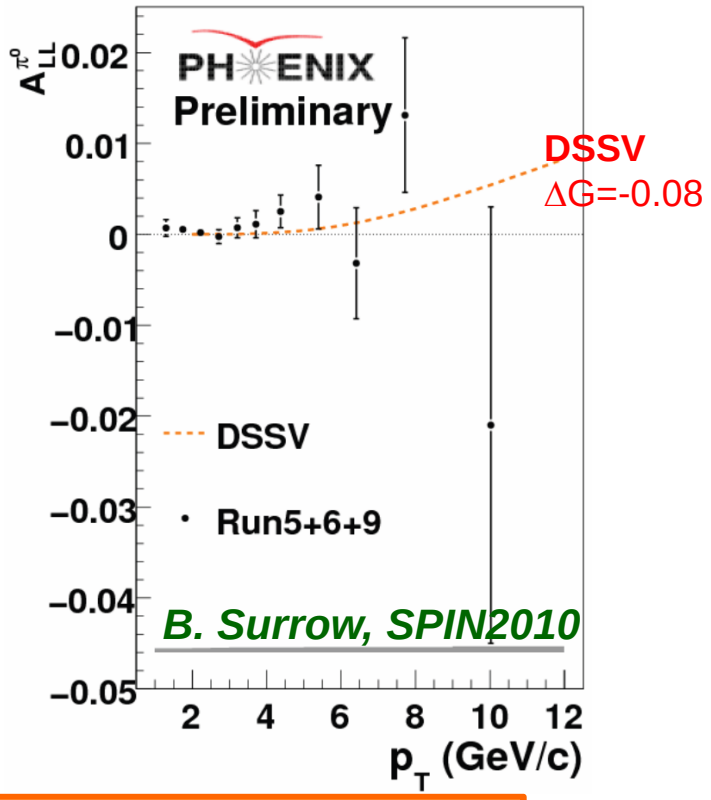
200 GeV. **Run 6** compared to **GRSV fits**



ΔG=-1.05
ΔG=0.24
ΔG= 0

PRL103, 012003 (2009)

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

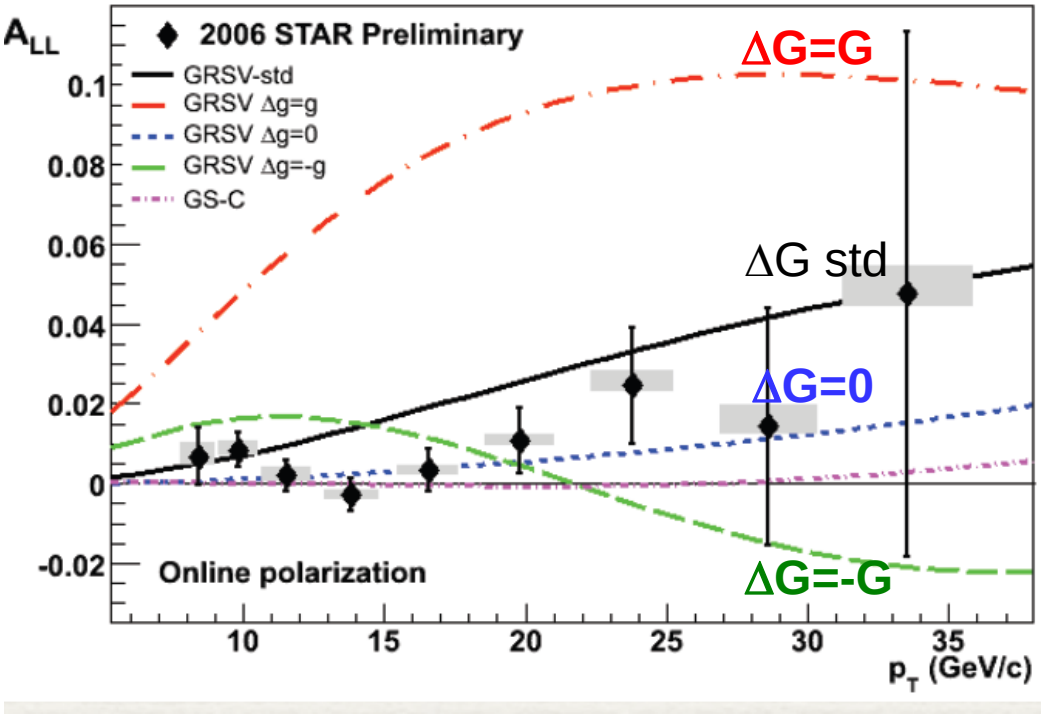


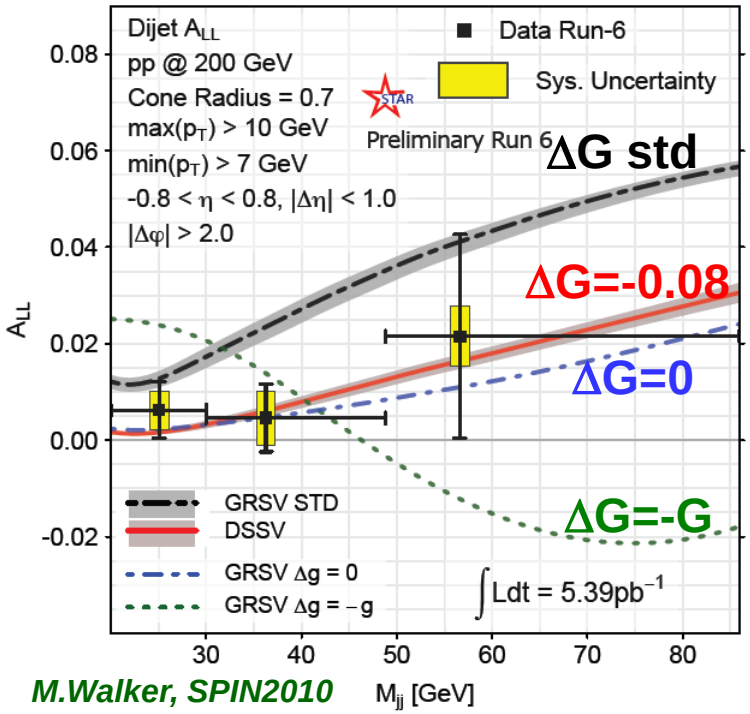
- **Data favor fits with ΔG close to 0**
- **Strong constraint on <ΔG> in x range probed 0.05<x<0.3**

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

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

Double spin asymmetry A_{LL} (p_T)





M.Walker, SPIN2010

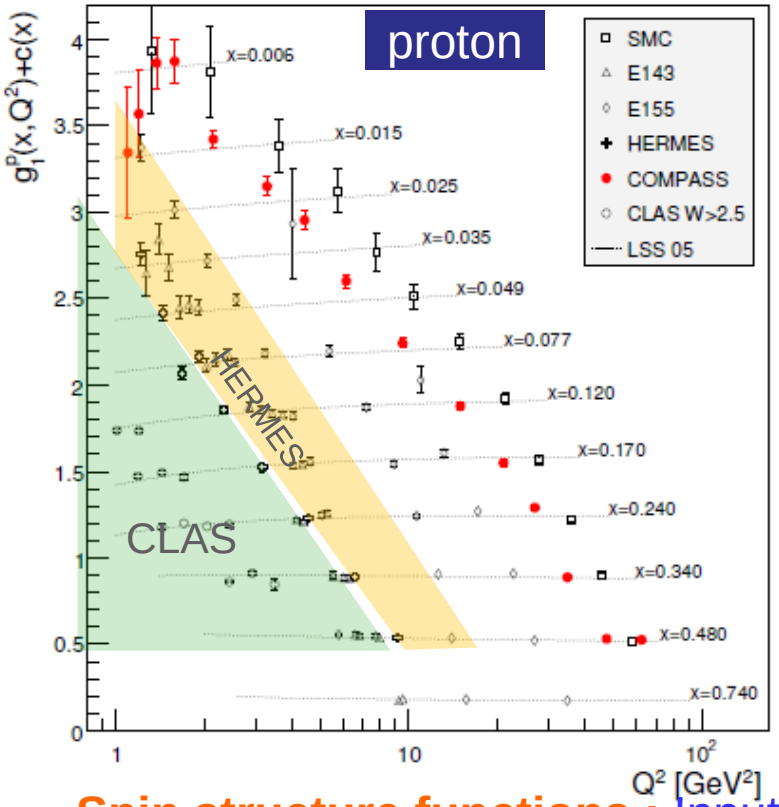
Both channels, Inclusive jet and dijet, provide strong constraint on ΔG in measured range, favoring parameterizations with ΔG close to 0

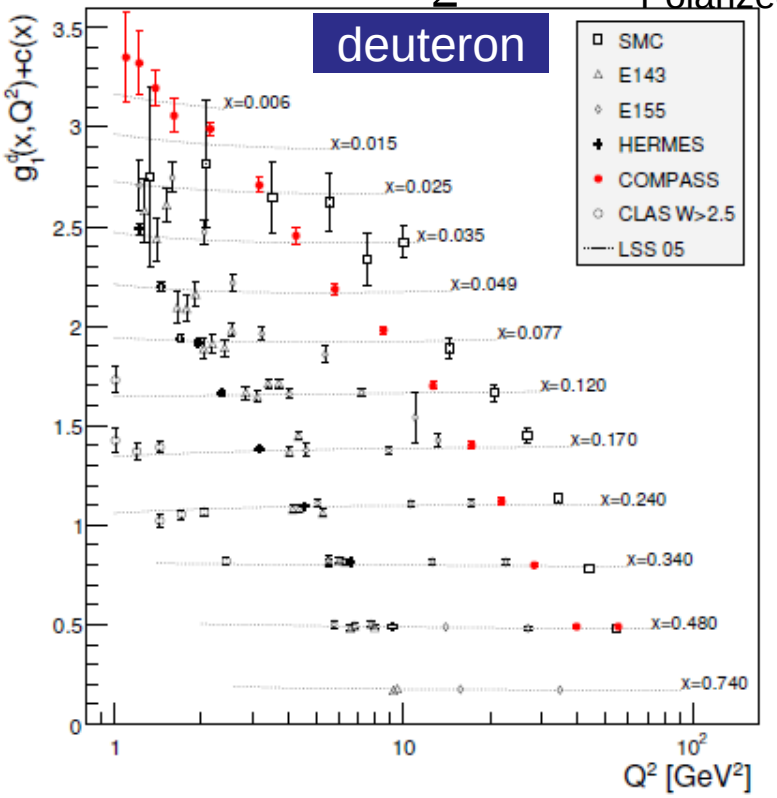
3. ΔG from global fits

Polarized DIS, spin structure function g_1

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

Polarized PDFs





Spin structure functions : Input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta G(x)$ using evolution equations.

However x and Q^2 coverage not yet sufficient

Use constraint from pp data (DSSV)

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

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

LSS '10

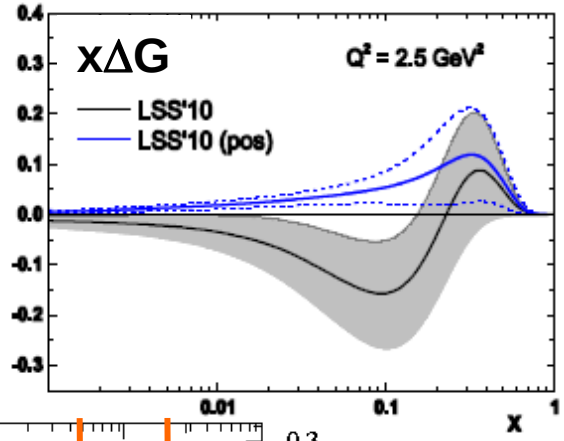
Only DIS & SIDIS data

Leader, Sidorov, Stamenov,

$\Delta G = 0.25 \pm 0.19$

$\Delta G = -0.40 \pm 0.43$

at $Q^2 = 2.5\ GeV/c^2$



DSSV

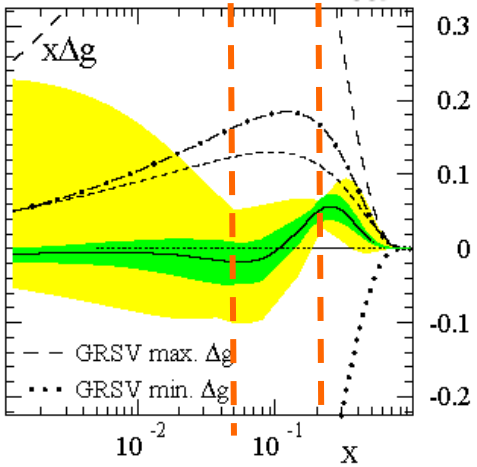
DIS, SIDIS & $\vec{p}$ $\vec{p}$

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

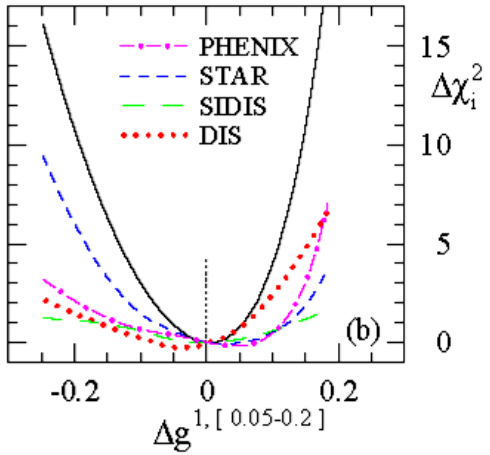
$\Delta G = -0.08 \pm ?$

at $Q^2 = 10\ GeV/c^2$

see talks of S. Taneja & M.Stratmann

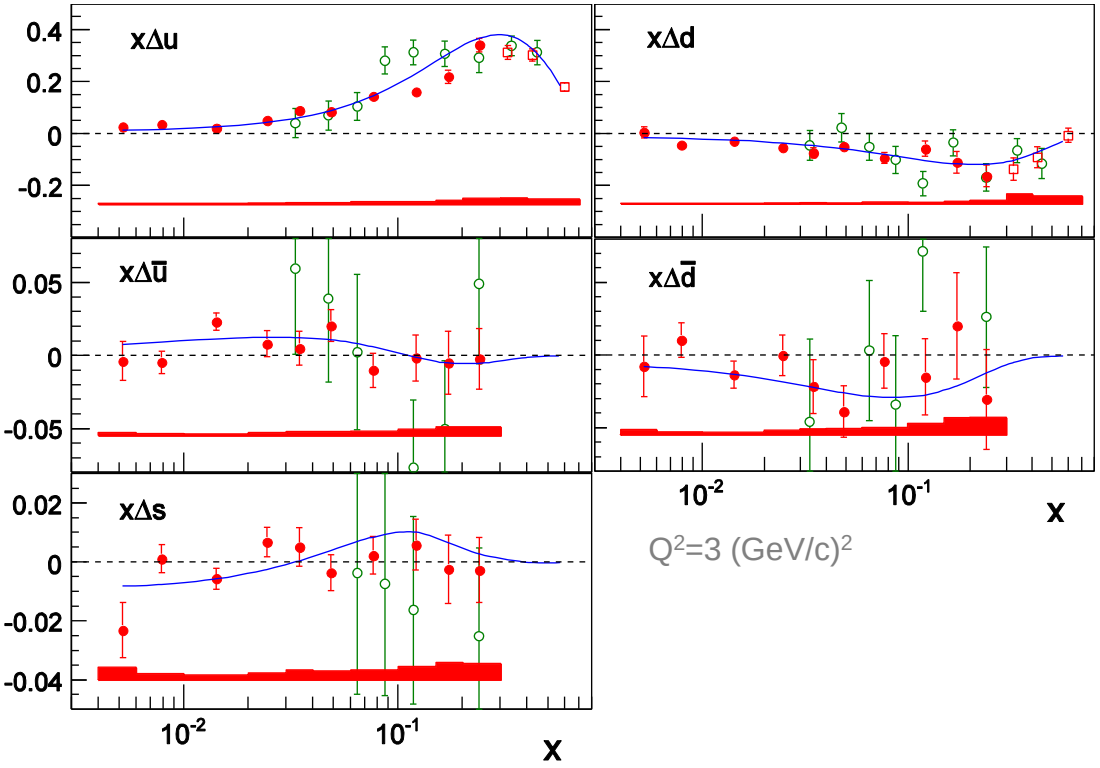


~0 in measured range (node)



- **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**

Quark helicities from Semi-Inclusive DIS



Q^2=3 (GeV/c)^2

Extraction at LO

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

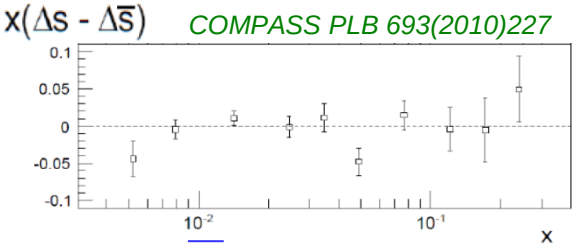
- COMPASS

PLB693(2010)227, using DSS FF

o HERMES

PRD71(2005)012003

__ DSSV



Δs – Δs̄ 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

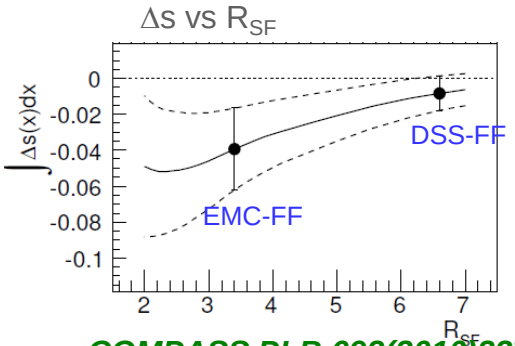
- **Full flavour separation → x~0.004**
- **Sea quark distributions ~ zero**
- **Good agreement with global fits**

Δs puzzle

• The integral of Δs can be extracted from the integral of g_1 using two other inputs (n decay, hyperon decay, SU(3))

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

• It can also be computed from Δs(x) measured from SIDIS data: kaon spin asymmetries, assuming FF known → **Δs(x)≈ 0**



COMPASS PLB 693(2010)227

Several possible explanations to the discrepancy :

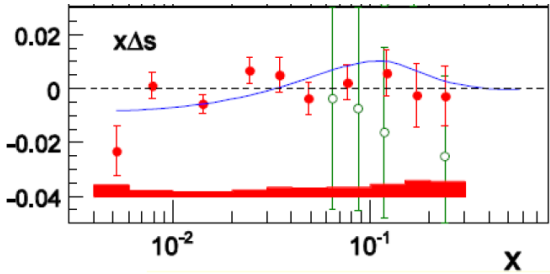
• Uncertainty on quark fragmentation functions (s→ K)
- would need value twice bigger than DSS

See also LSS arXiv1103.5979 & talk of D.Stamenov

• 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 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

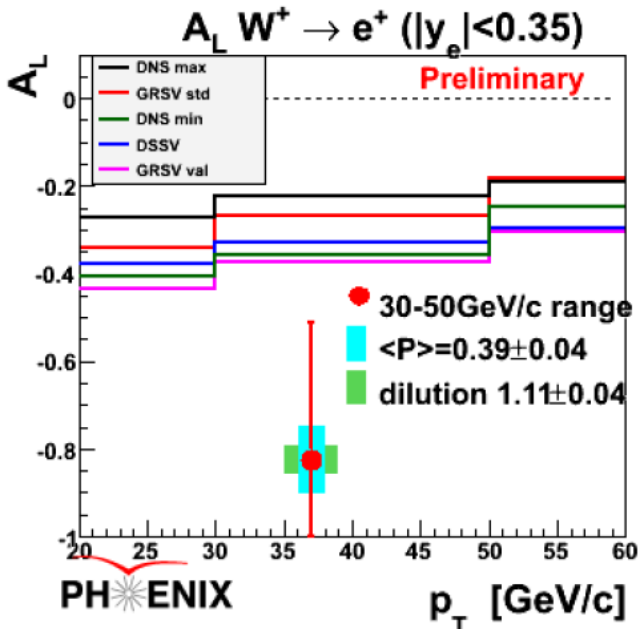
$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu$$
$$\bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}$$

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

Parity violating, single spin asymmetry
No fragmentation function uncertainty

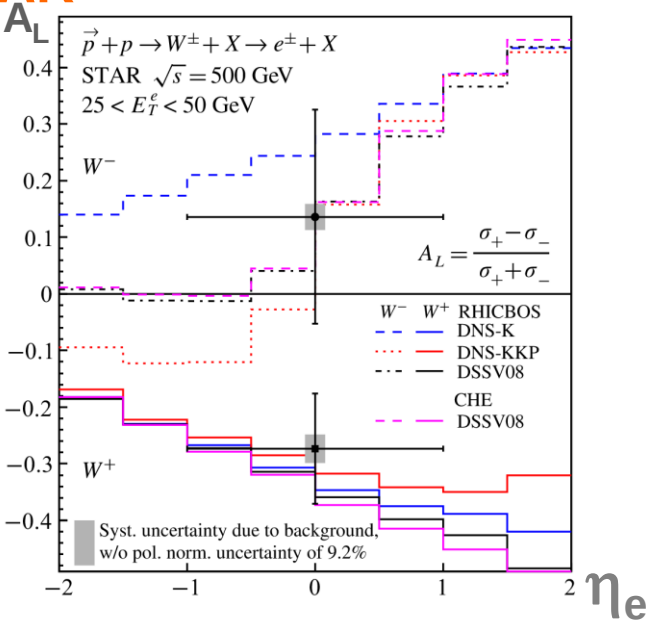
see talks of R.Towel & J.Seele

PHENIX



J. Haggerty ICHEP2010

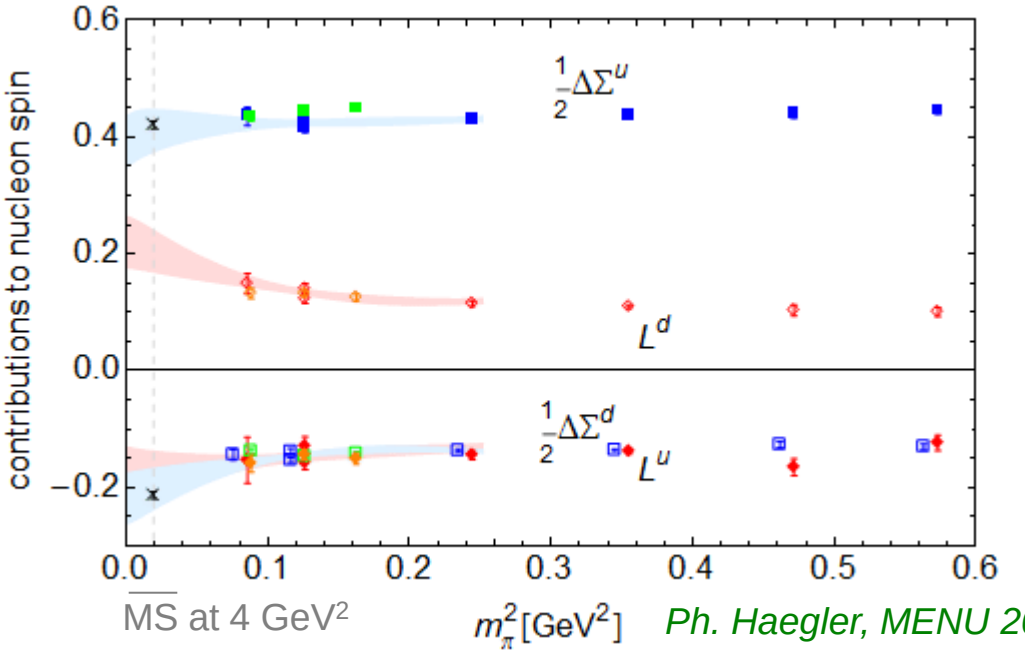
STAR



Phys.Rev.Lett. 106 (2011) 062002

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

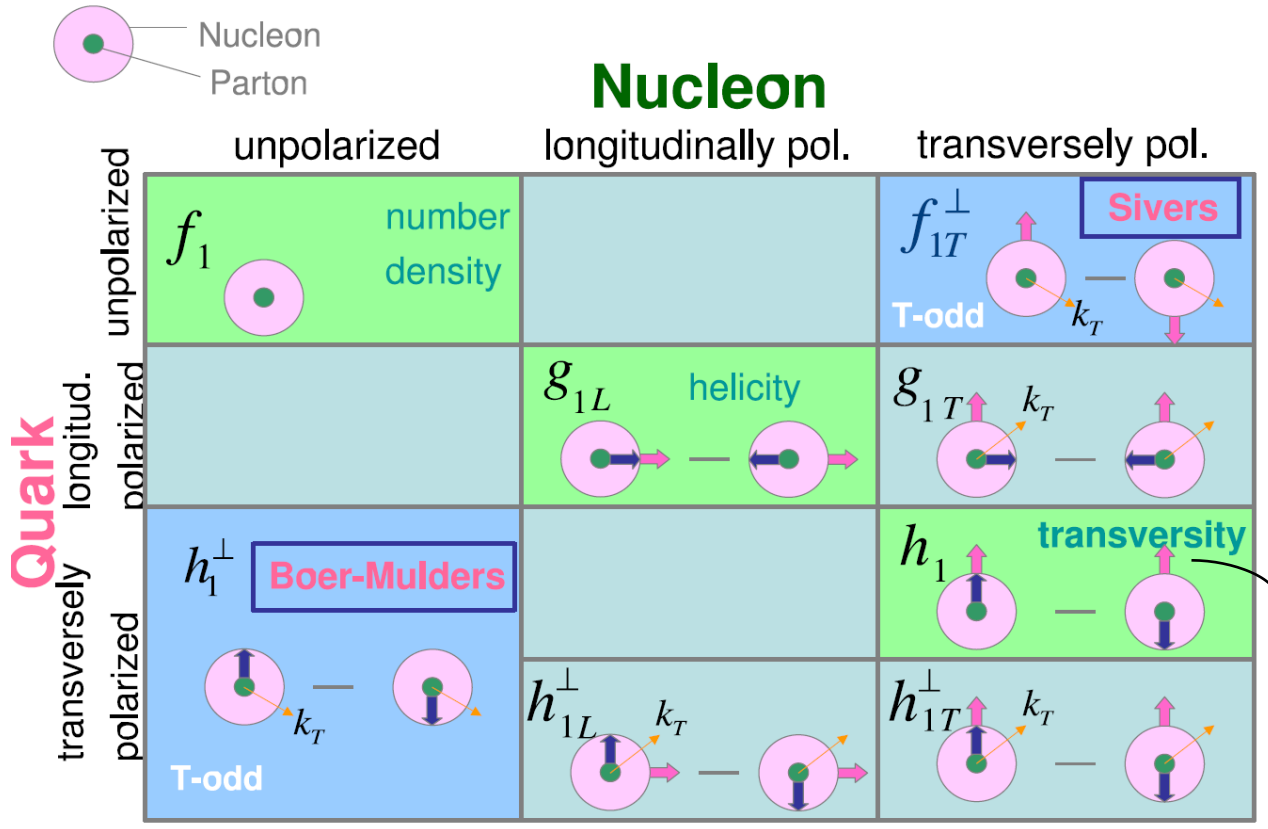
Lattice : quark spin and angular momentum



Ph. Haegler, MENU 2010

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

Nucleon Structure Functions



Off diagonal: Transverse Momentum (k_T) Dependent

- **TMDs express correlations between spin, momentum,…**
- **Experimentally: azimuthal modulations of outgoing hadron in SIDIS cross section *lp → lp h***

Collins and Sivers asymmetries in 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.

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

Collins fragmentation function, depends on spin

Sivers

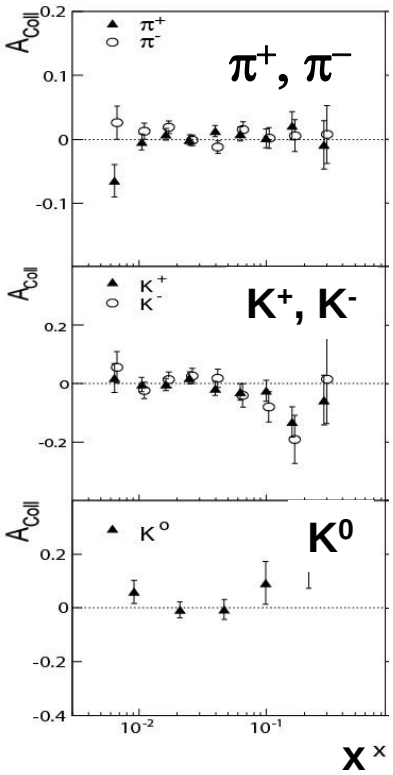
Usual quark fragmentation function

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

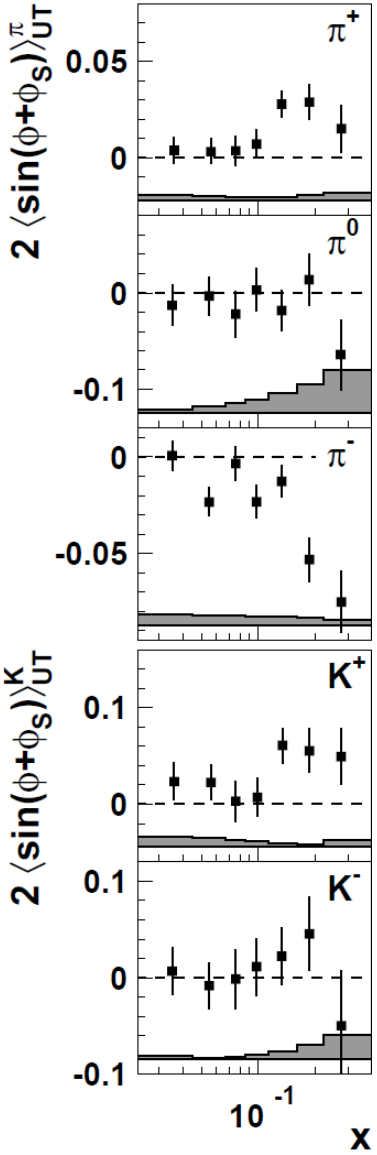
note: $\Delta_T q$ also measured using
- ''Two hadron'' fragmentation function
- lambda Transverse. Polarization

Transversity : Collins Asymmetry $l\,p^{\uparrow} \rightarrow l\,p\,h^{+/-}$

deuteron
COMPASS



Compatible with zero:
→ $\Delta_t u$ & $\Delta_T d$ opposite



proton
HERMES

- Large signals in valence region for π^{+-} & K^{+-}
→ both transverse quark distribution $\Delta_T q(x)$ and Collins FF non zero

- Opposite for + and – hadrons:
→opposite u and d CollinsFF

- larger for K+ than for π+
→role of sea quarks

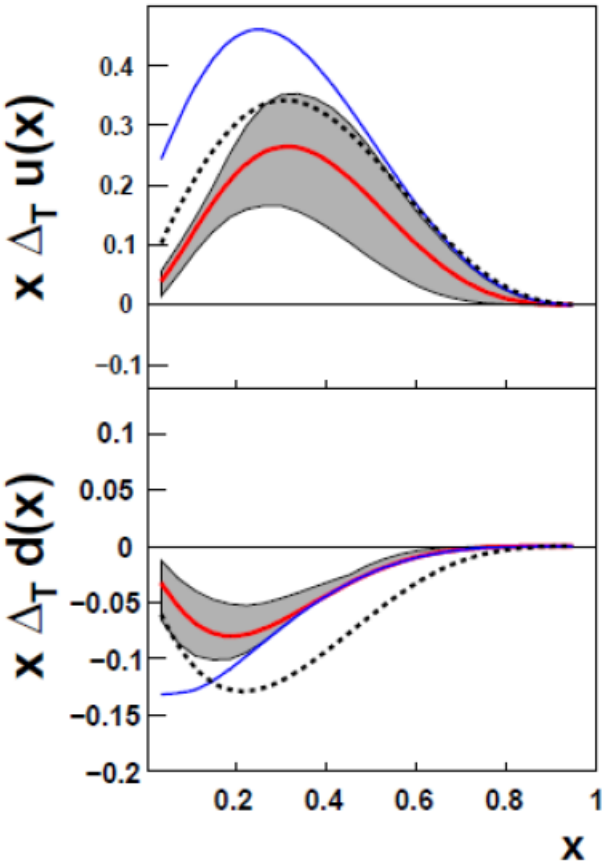
- Excellent agreement between HERMES p and COMPASS p data (not shown here)

irfu
cea
saclay

Transversity – Collins Asymmetry

Several combined analyses of

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



Cloet, Bentz and Thomas PLB659 (08)
Bacchetta, Conti, Radici, PRD(09)
Anselmino et al 2009.

- **$\Delta_T u > 0$ and $\Delta_T d < 0$**

u quark transversity along nucleon spin

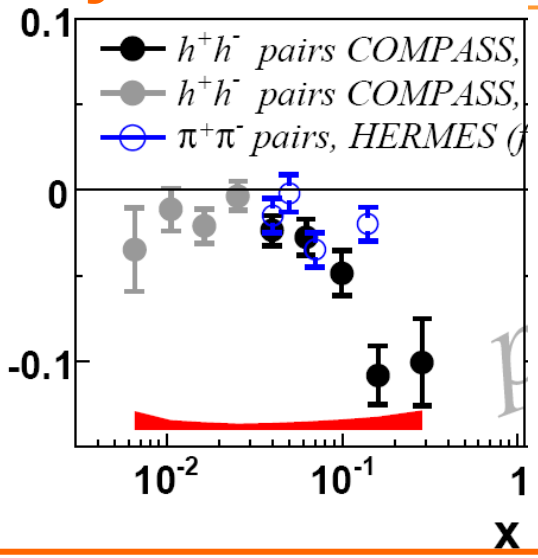
- Do not saturate Soffer bound
- Smaller than helicity

Also predictions for sea quarks

Ex: M. Anselmino et al. arXiv:0812.4366

Transversity via "two hadrons"

SIDIS A_{RS}^{p}



as an alternative for $\Delta_T u$ and $\Delta_T d$.

HERMES

COMPASS

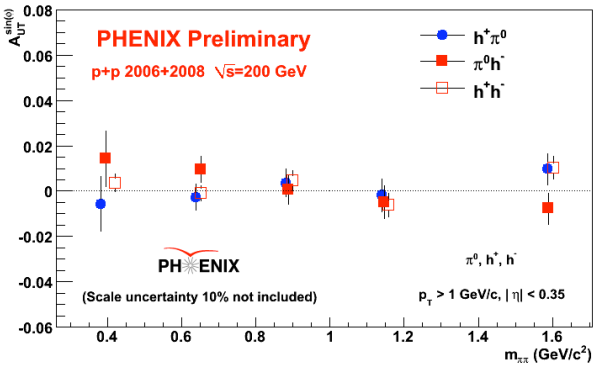
- **Confirms signal at large x.** Larger than Collins asymmetry
- COMPASS signal larger than HERMES'one

  Different phase space, but difficult to describe both simultaneously

A.Bacchetta et al., Mah et al.

see talk of A.Courtoy

Similar approach in pp



A_{UT} constistent with zero.

but different kinematics:

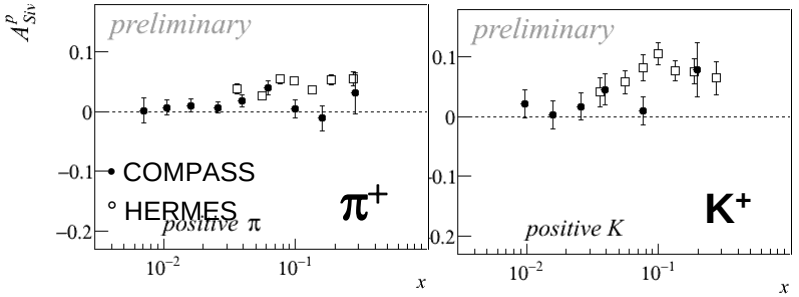
dominated by gluons

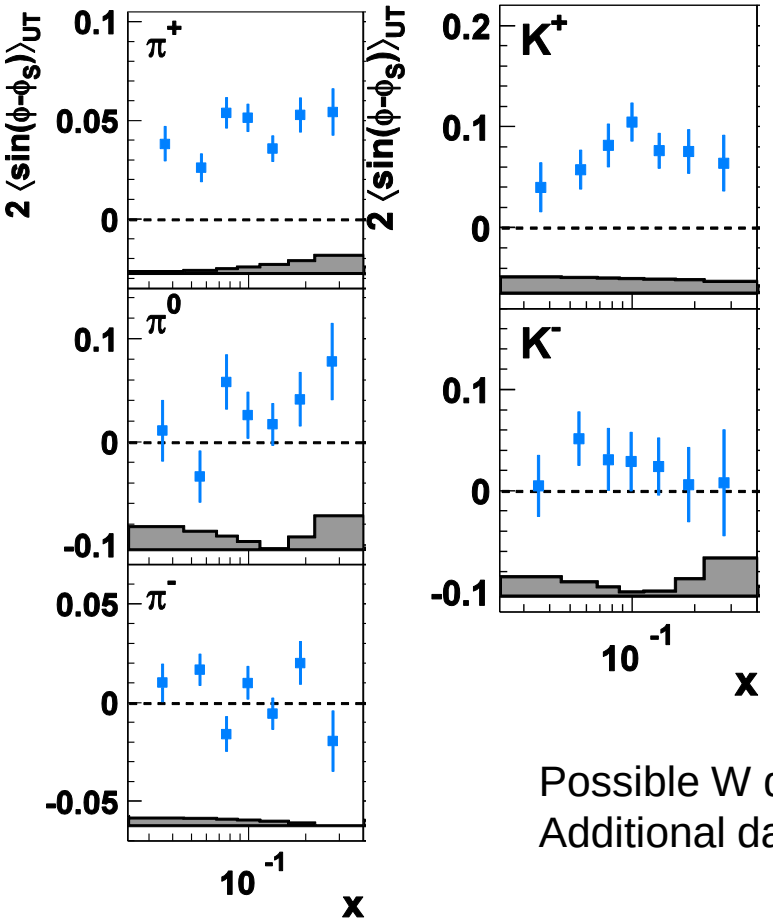
Sivers asymmetry - $l\,p^{\uparrow} \rightarrow l\,p\,h^{+/-}$

Correlation between nucleon spin & **quark transverse momentum k_T**

- **deuteron :** shown to be zero by COMPASS
- **proton:** Signal in π^+, K^+ **HERMES**

COMPASS & HERMES





PRL103 (2009) 152002

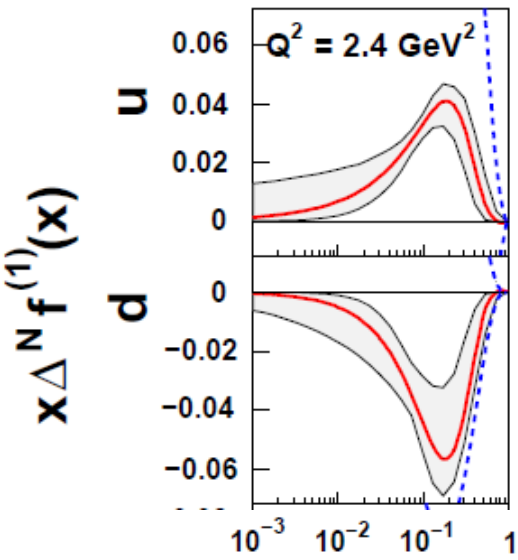
- Clear Signal in HERMES π^+ and K^+
- Smaller signal in COMPASS.

Possible W dependence
Additional data will come from COMPASS 2010 run

Sivers function

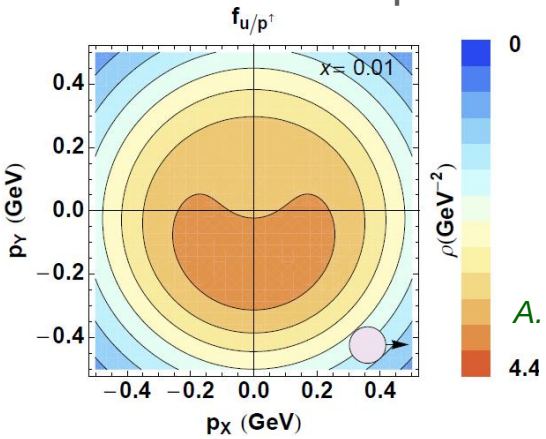
Extraction of Sivers function
(from HERMES **p** and COMPASS **d)**

see talk of S.Melis



M.Anselmino et al., arXiv:0812.4366

Nucleon Transverse spin and quark k_T



A. Bacchetta

→ Tomographie in momentum space

- **Much progress in data on Sivers from polarized SIDIS**
  u and d quark Sivers function opposite
- **Still more statistics needed to separate all variables: x, z, p_T**

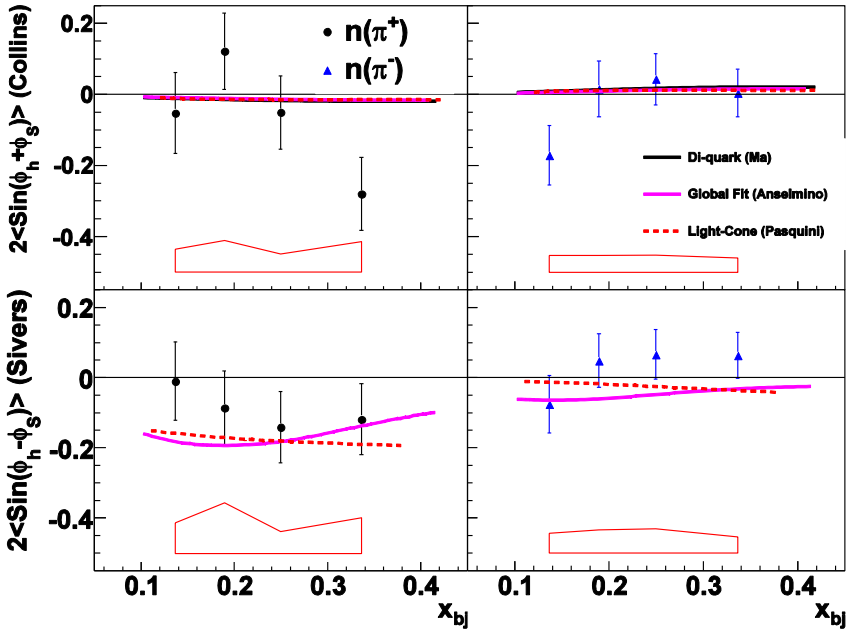
Other processes:
- Single transverse spin pp asymmetries (RHIC, following E704),
- Future polarized Drell-Yan, where Sivers effect is expected, but with opposite sign.

Collins and Sivers Asymmetry – neutron

Preliminary results from Jlab on neutron (He^3 target)

Collins

Sivers



Diquark Model (Ma)
Global Fit (Anselmino)
Light cone (Pasquini)

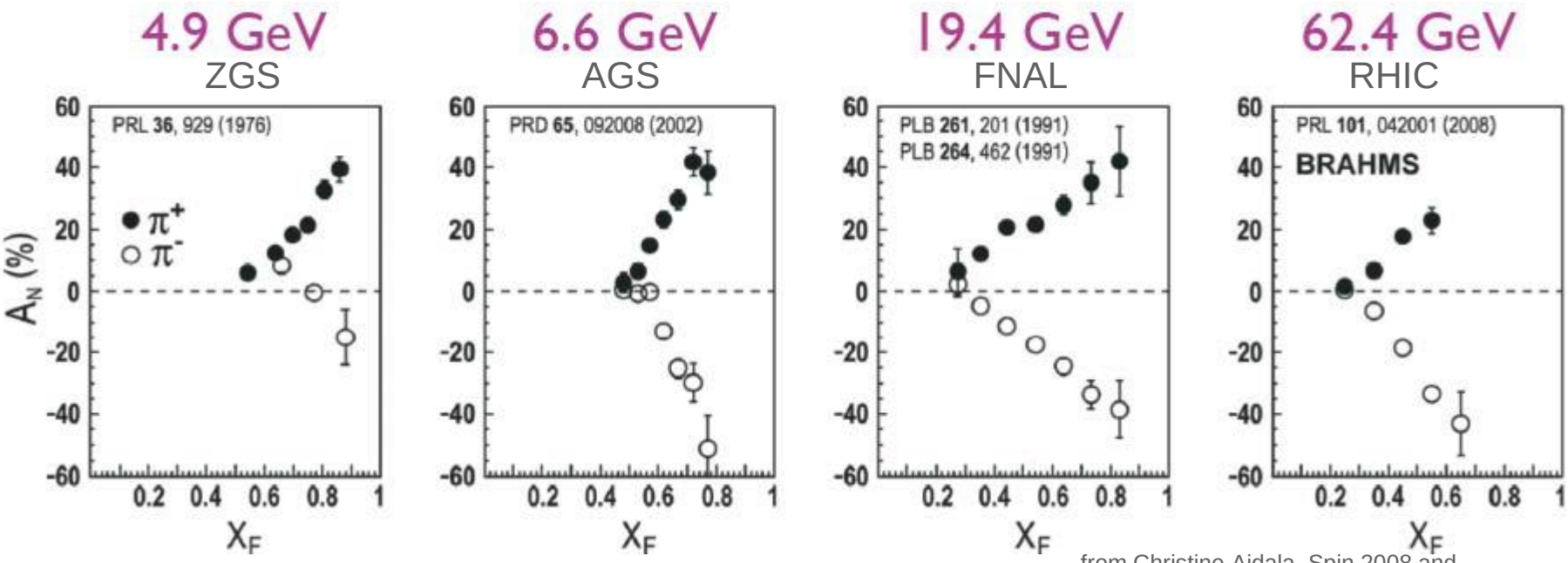
Systematics under study

Z.Meziani, IWHSS'11 Paris 2011

Sivers Asymmetry smaller than expected,
Follow trend of Anselmino et al.
Lead to smaller d - Sivers function.

Single transverse spin asymmetries

$p p^{\uparrow} \rightarrow \pi^{+/-/o} + X$ predicted to vanish at high energy



from Christine Aidala, Spin 2008 and Don Crabb & Alan Krisch in then Spin 2008 Summary, CERN Courier, 6-2009

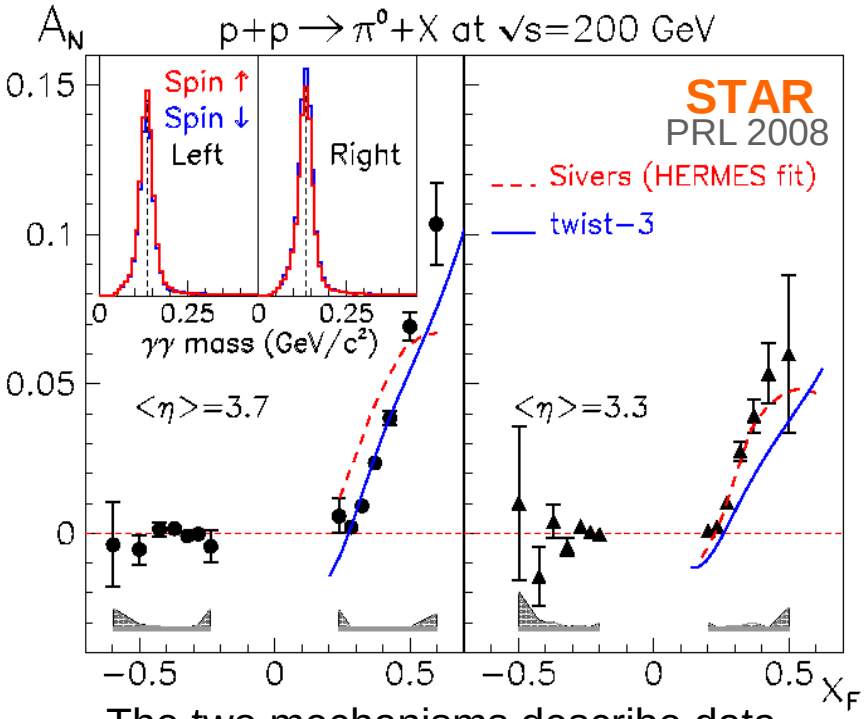
Large transverse single spin asymmetries, persisting at high energy

Single spin asymmetries

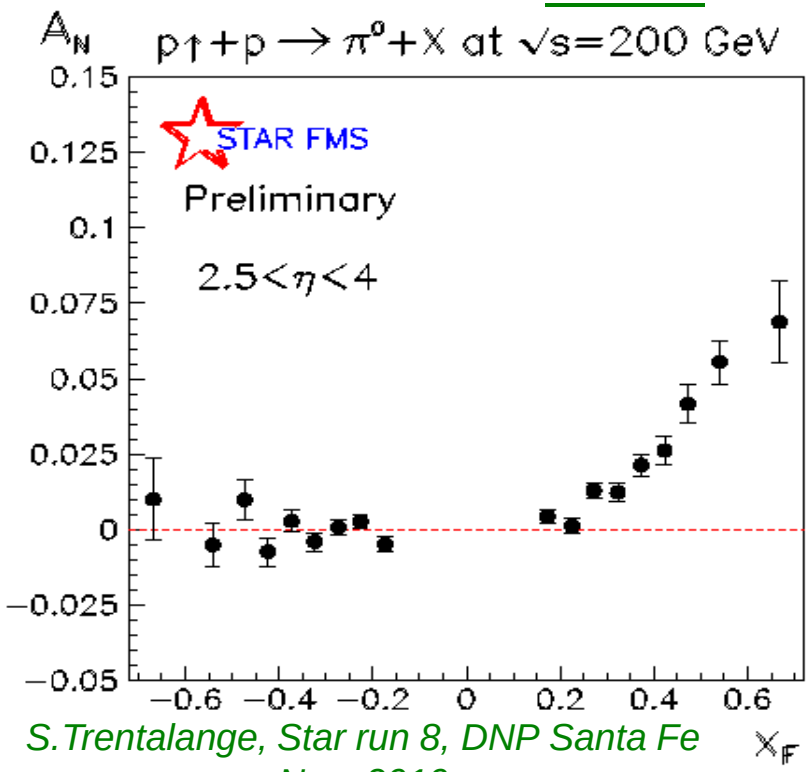
$pp\uparrow \rightarrow \pi^{+/-/o} + X$

Extensive measurements at BRAHMS + PHENIX & STAR

see talk of F.Wei & R.Fersch



The two mechanisms describe data



S.Trentalange, Star run 8, DNP Santa Fe Nov 2010

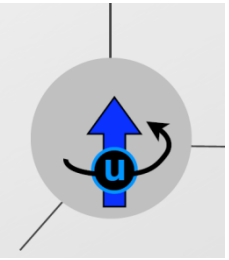
- **Confirms large pion asymmetries at higher energy**
- **Investigating mechanism: Collins, Sivers, twist-3**
- **Will extend measurements to higher mesons, xF, p_T**

Other Transverse Momentum Dependent DFs

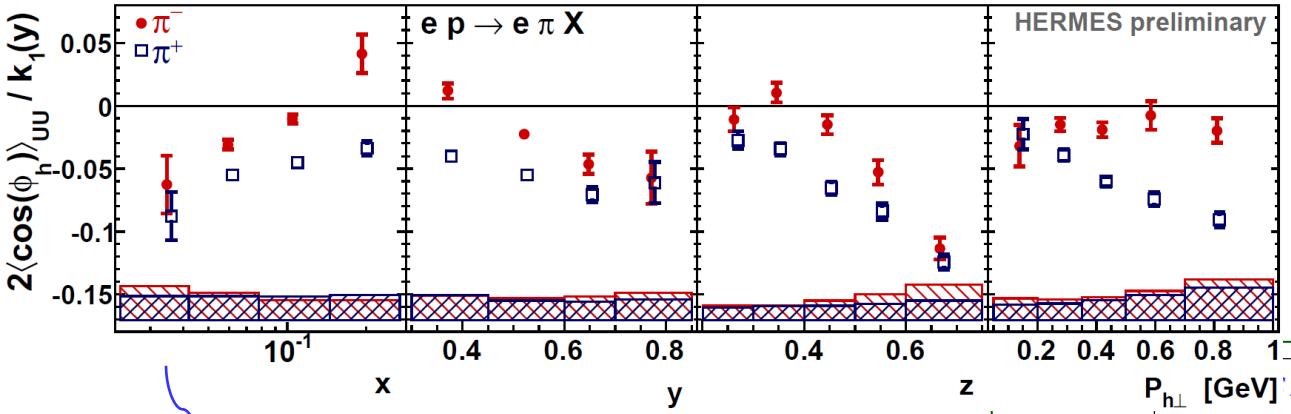
k_T effects → modulations in (unpolarized) SIDIS cross-section.

Ex., spin orbit effect **Boer-Mulders DF**

correlation between quark transverse motion and transverse spin



HERMES, cos ϕ

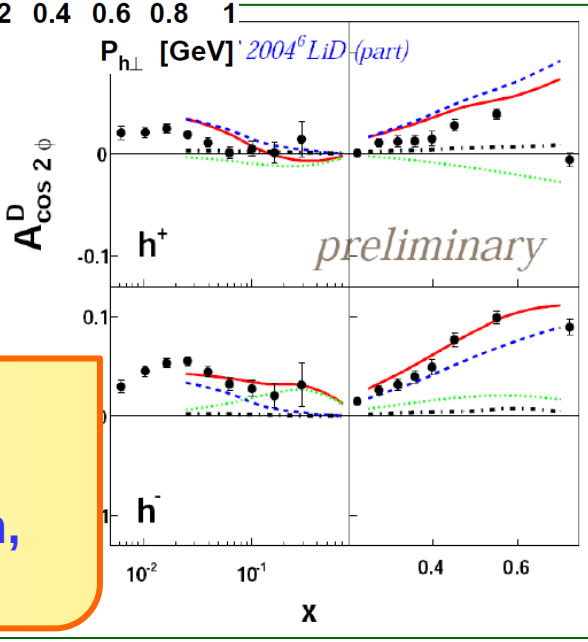


Depends on π charge, not expected for Cahn:

- Boer-Mulders term important?
- k_T effect flavour dependent?

see talks of C.Schill, L.Pappalardo,

COMPASS, cos 2ϕ



Cahn

Total

pQCD

Boer-Mulders

- **Major progress in TMD measurement**
- **Powerful tool to understand correlations**
- **Lattice: Strong correlations between spin, position and momentum also observed**

V.Barone,A.Prokudin, B.Q.Ma, arXiv:0804.3024

Spin at RHIC-II 2011 to 2015

Accelerator & detector configuration

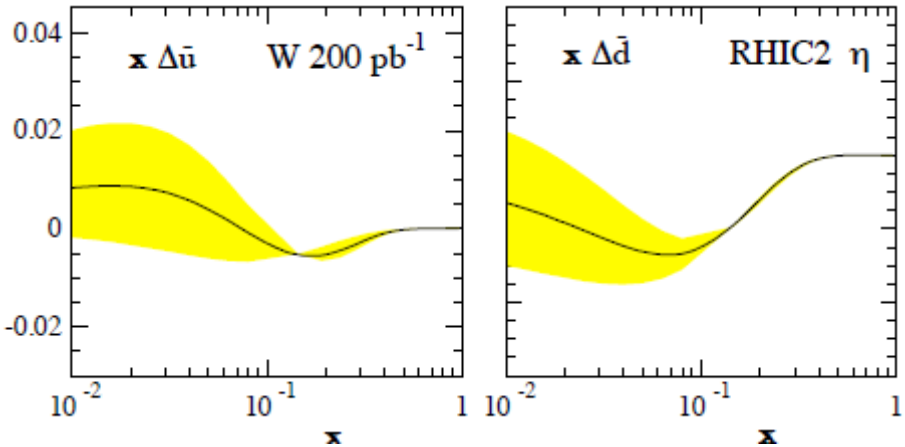
Polar.=0.5 (2011) → 0.65 (2014)
L_{max}=1 x $10^{31}cm^{-2}s^{-1}$ (2011)→ 3 x $10^{31}cm^{-2}s^{-1}$

- **RHIC reaches max performance:**
- **Upgrades of STAR & PHENIX complete for 2012 run**
- **New Drell-Yan experiment for transverse spin AnDY**

see talks of E. O'Brien & J.Dunlop

Major Physics goals

- **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)**

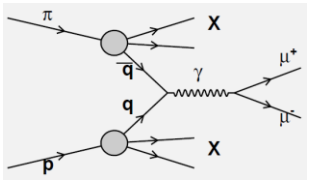
Future of COMPASS 2011-2016

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*

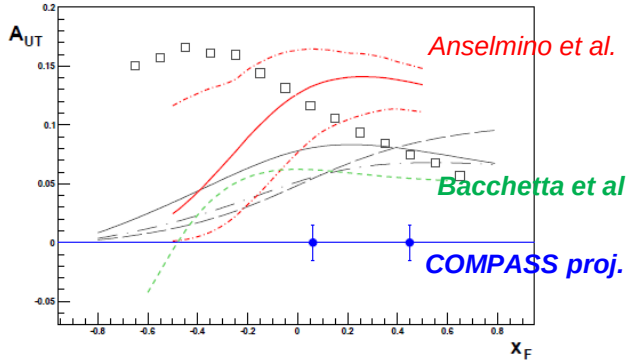
2014 and beyond, COMPASS-II :

- **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

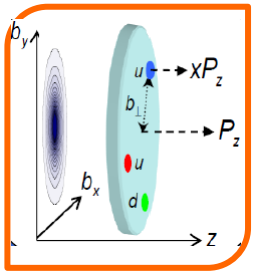


Ex: A_{UT} asymmetry in Drell-Yan process

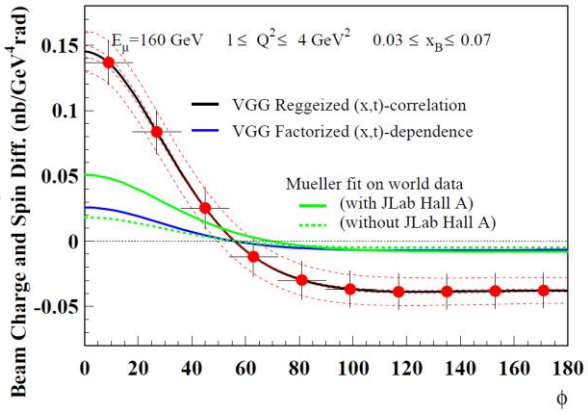


- **GPD** (Generalized Parton Distributions) $\mu p \rightarrow \mu p \gamma$

by exclusive reactions DVCS, DVMP



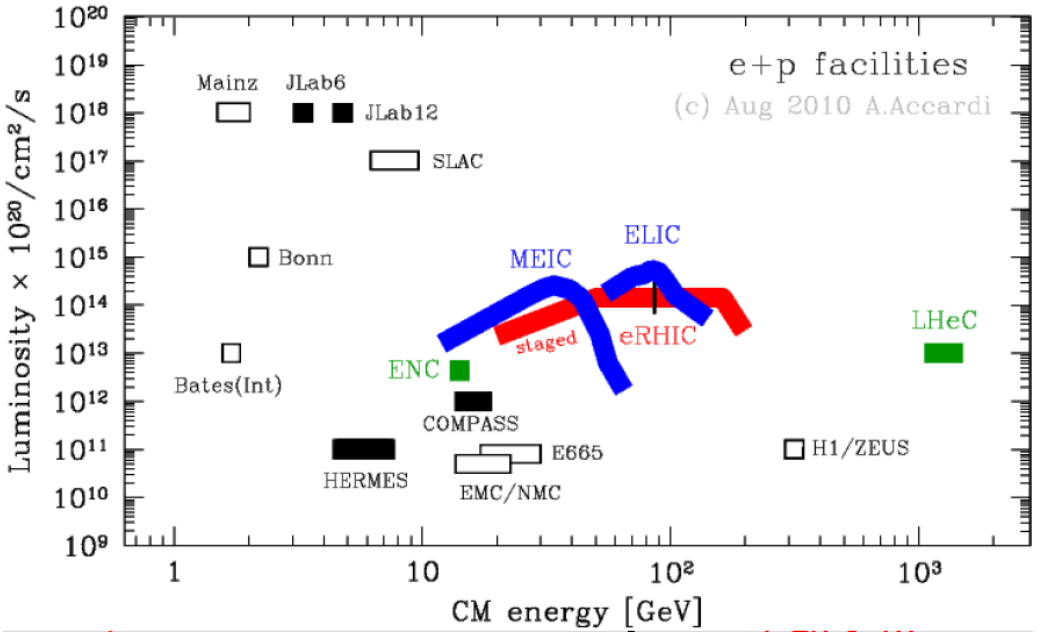
- Unified descrition of form factors & PDFs
- Transverse imaging 2+1 dim.

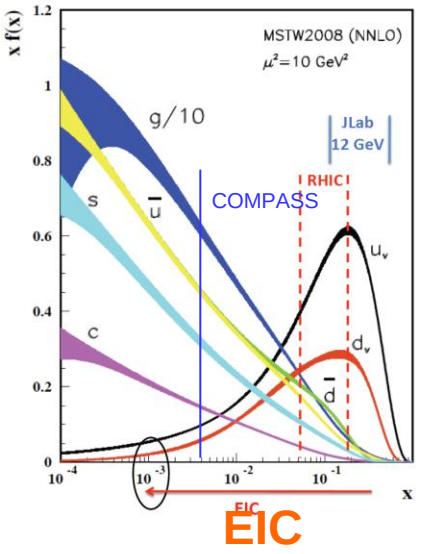


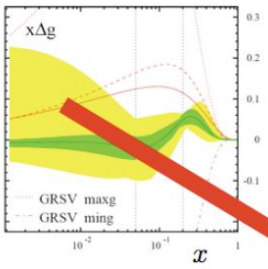
see talk of C.Quintans

Future polarized ep collider

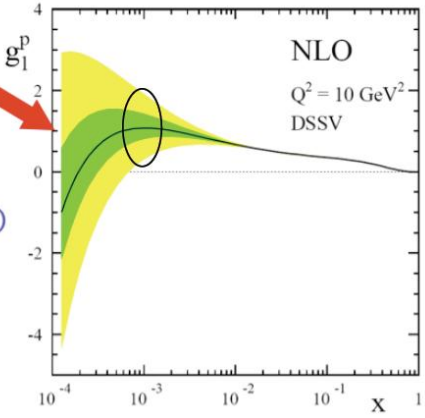
- **Goal: access lower x in (polarized) DIS and with higher luminosity**
- **Wide physics program:**
  Polarized **sea q** and **g**, Hard exclusive reactions, TMDs, gluon saturation…







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



EIC / ENC projects in US and Europe

see talk of A.Deshpande

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 SISIS
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

Transversity and TMDs

A large set of data → $\Delta_T u > 0$ and $\Delta_T d < 0$
Sivers u and d opposite
Statistics needed to disentangle all variables

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