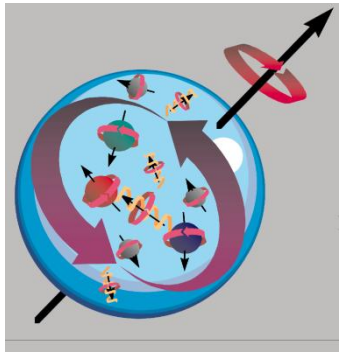
Nucleon spin structure
Experimental overview

Fabienne KUNNE
CEA /IRFU Saclay, France

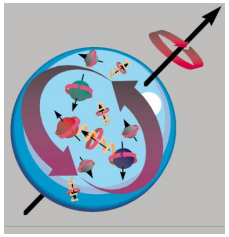
- **Gluon and quark helicities**
- **Transverse spin**
- **Outlook**



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, $\bar{u}$, $\bar{d}$, $\bar{s}$ $\Delta q = \overrightarrow{q} - \overleftarrow{q}$ 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 $a_0 = \Delta\Sigma = 0.12 \pm 0.17$

$\overline{\text{MS}}$ 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 $L_{u,d}$

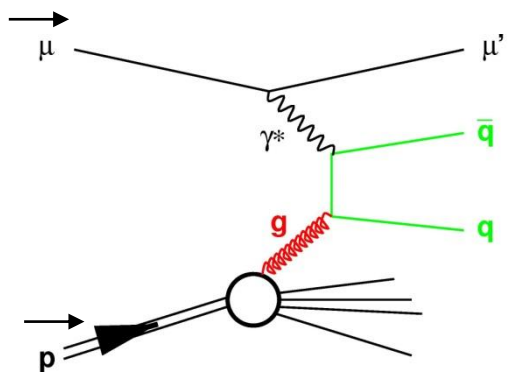
Large experimental effort on ΔG measurement

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

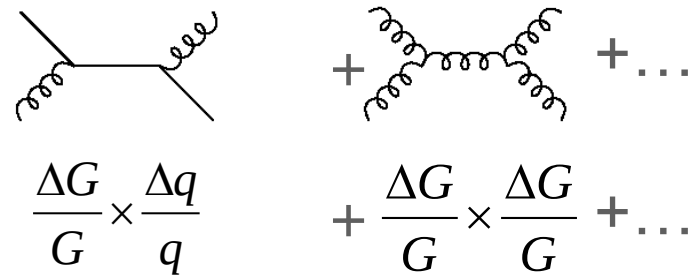


ΔG/G(x)

SMC, HERMES, COMPASS

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

Gluon-Quark + Gluon-Gluon +…

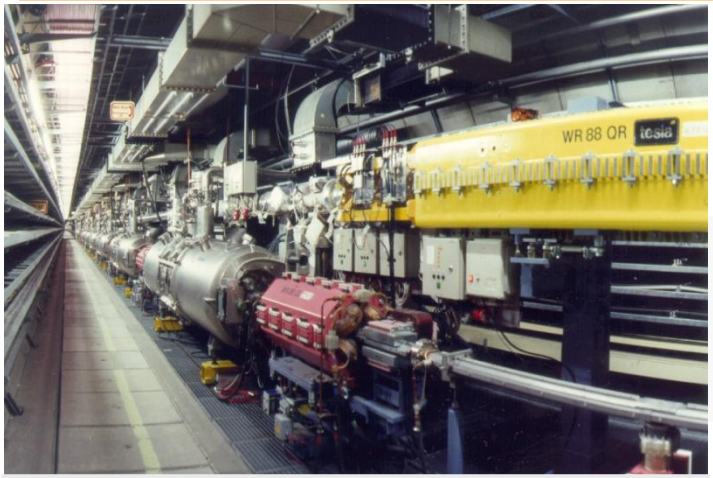


A_{LL} (p_T)

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



HERA e^+ & e^- 27 GeV

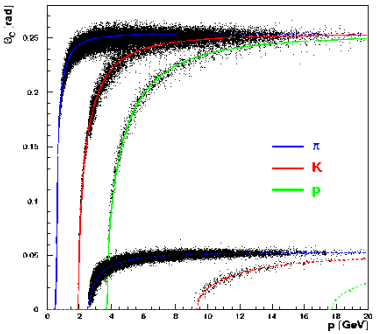
longitudinally polarized ~ 54%

1995 to 2007

Spectrometer :

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

Excellent separation of π, K, p

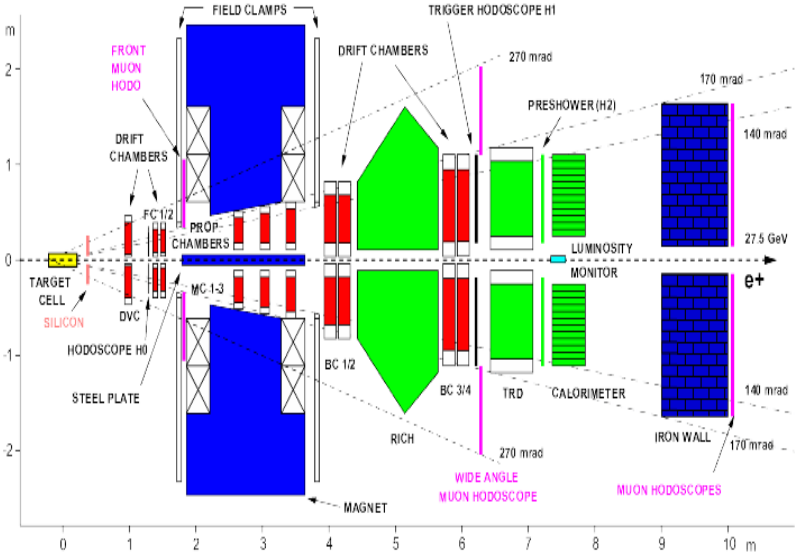


Gaseous internal target

Longit. Polar. 85% H, D, He

Transv. Polar H

Unpol H, D, Ne, Kr



COMPASS at CERN

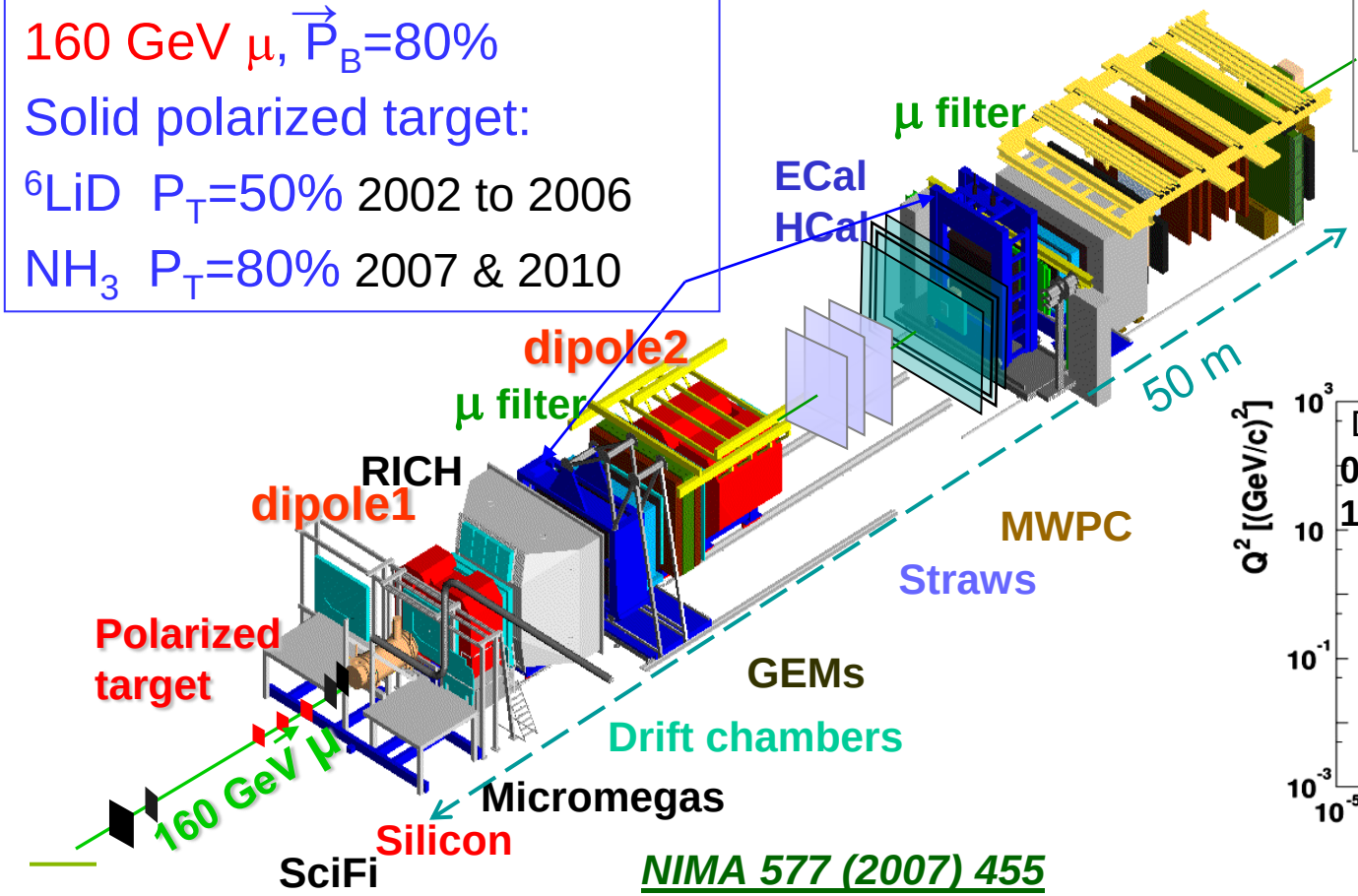
Fixed target
Secondary beams from SPS

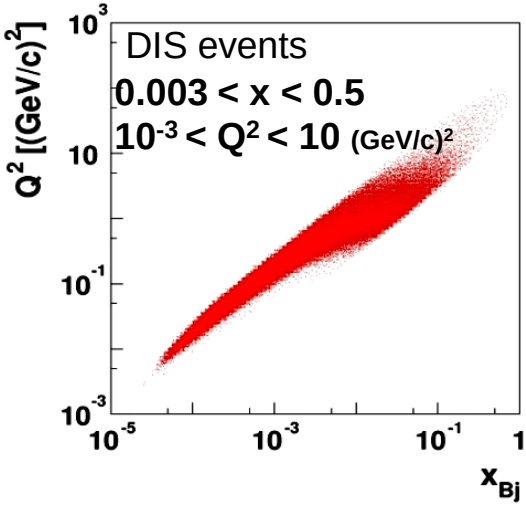
Nucleon spin structure

Polarized muon beam:
160 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

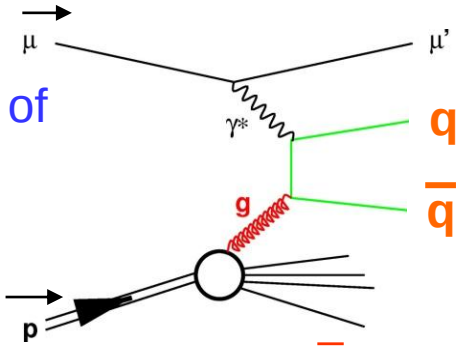
1. ΔG/G from *lepton* $\vec{N}$ scattering

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

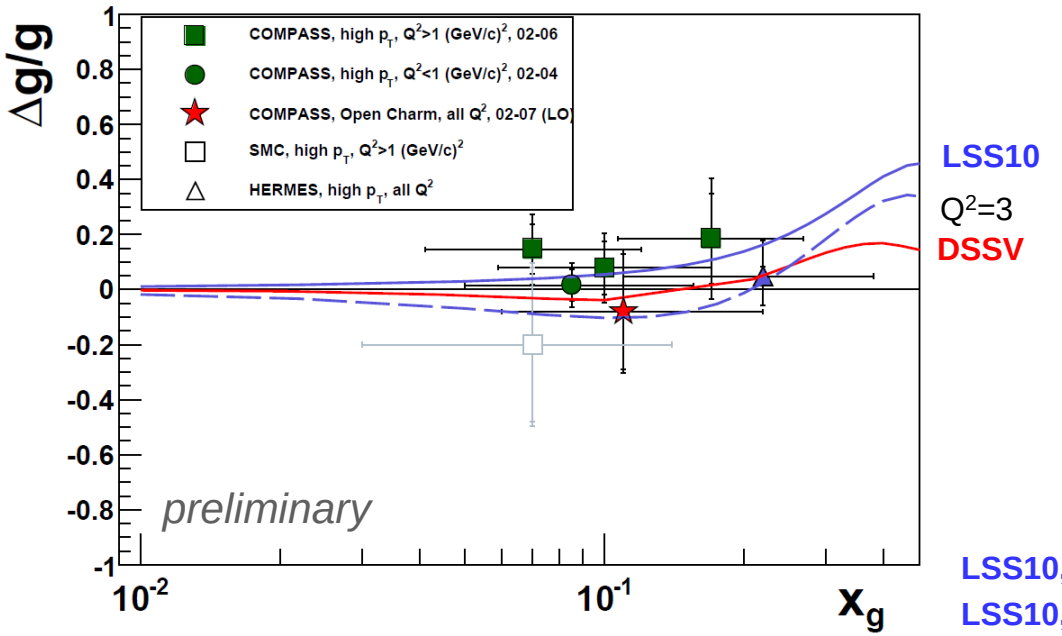
High statistics

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



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

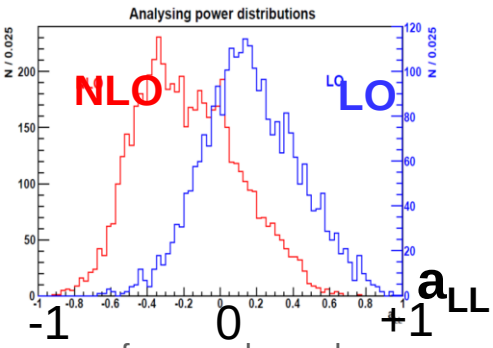
COMPASS charm: from LO to NLO

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

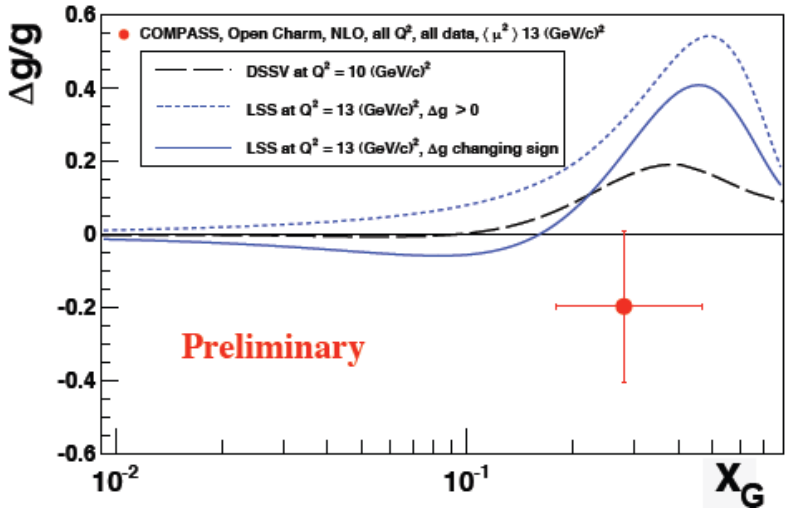
Analysing power a_{LL} calculated at NLO (AROMA)

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



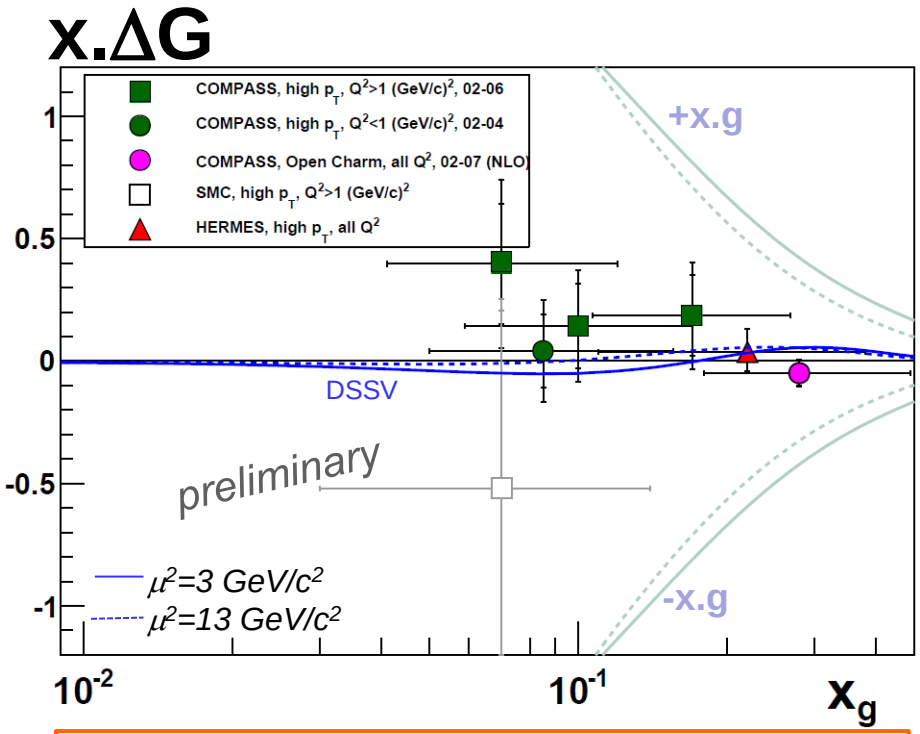
see talk of K.Kurek

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

COMPASS charm: from LO to NLO



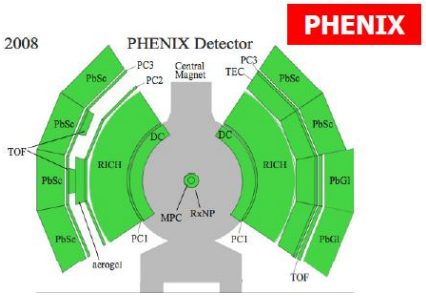
Charm at NLO, all other points at LO

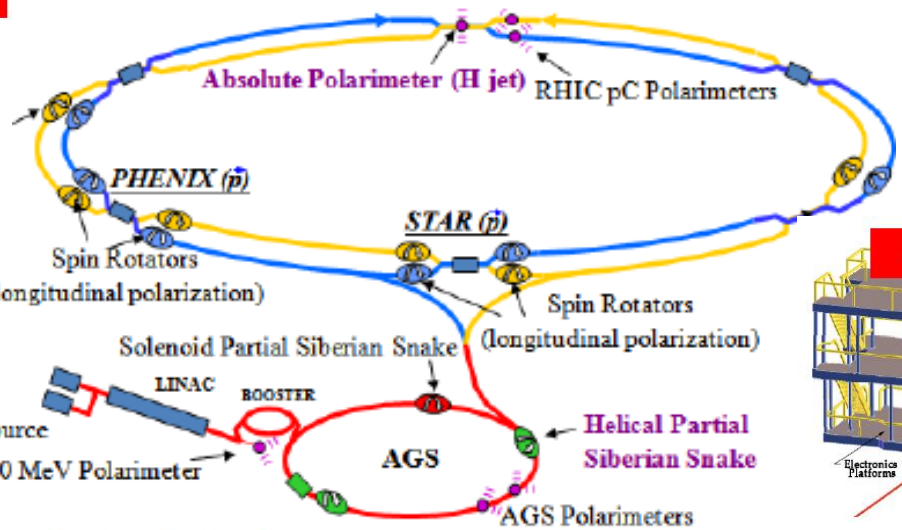
- First extraction of **ΔG at NLO**
- Constrains ΔG at larger x
- **Data to be included in global NLO fits:**

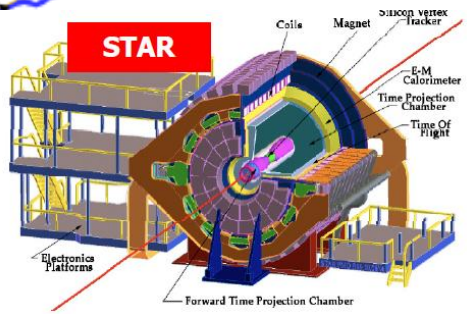
model independent asymmetries $A_{LL}(p_T, E_D)$ available

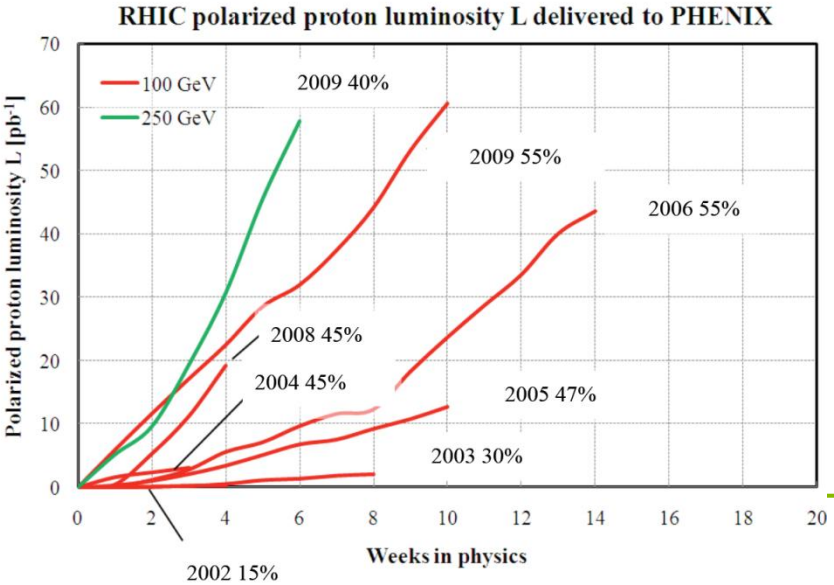
2. $\vec{p}\,\vec{p}$ collisions at RHIC

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







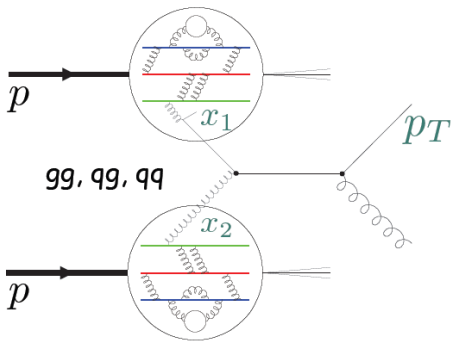


- Longitudinal spin asymmetries <ΔG>, <Δq>
- Transverse spin

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

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

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



Di-Jet production

More abundant channels

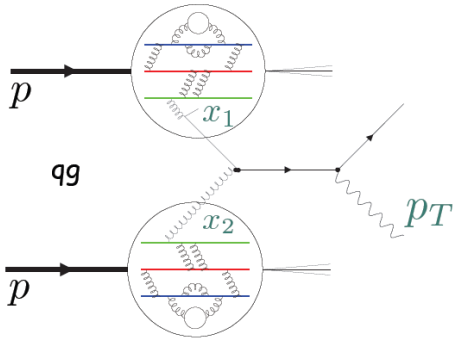
p p → π^0 X **PHENIX**

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



Photon-Jet production

p p → γ jet

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

Full kinematics reconstructed

Low statistics

p p → γ X

…

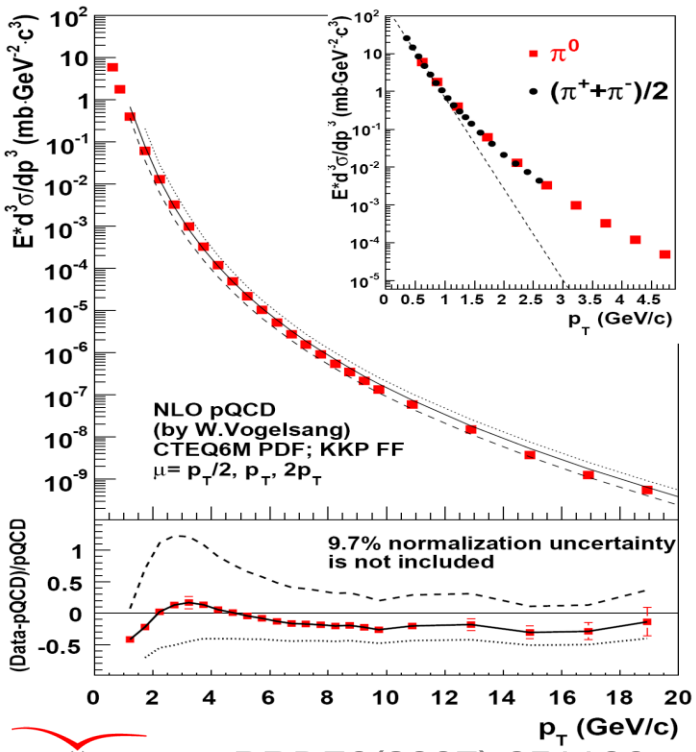
Other channels: $\pi+$, $\pi-$, η, …

High potential for ΔG from various channels, various kinematics

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

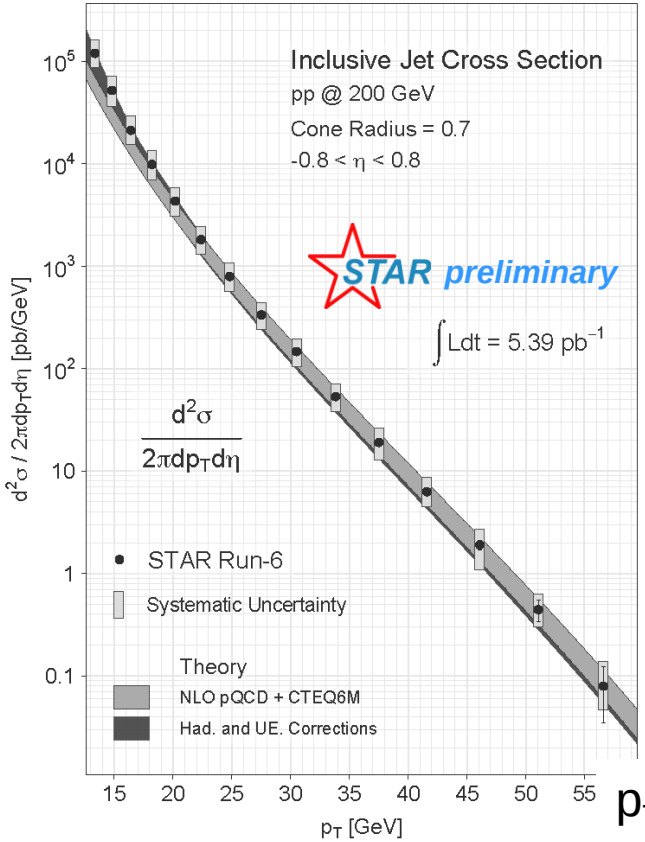
Two examples

$pp \rightarrow \pi^0 X$ 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)

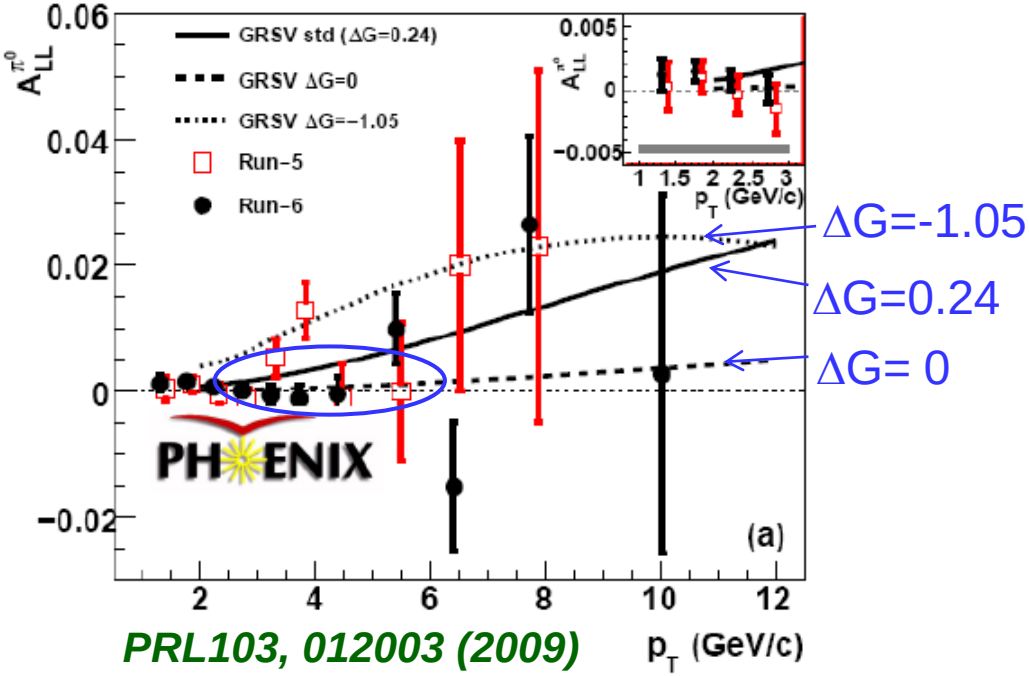
- **Good agreement between data and pQCD calculations**
- **Exist also for other channels: π^+, π^-, dijet, direct γ, γ +jet, η, etc.**
- **Establishes validity of pQCD frame→ validates method for ΔG extraction**

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

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

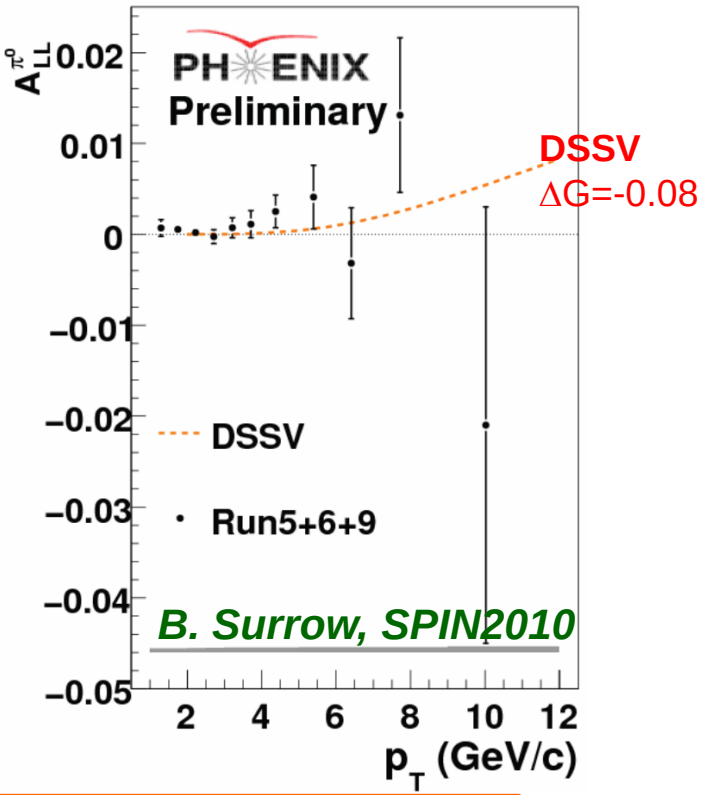
Measure double spin asymmetry $A_{LL}(p_T)$
Compare data to global fits with various $\Delta G(x)$ parameterizations

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



PRL103, 012003 (2009)

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



B. Surrow, SPIN2010

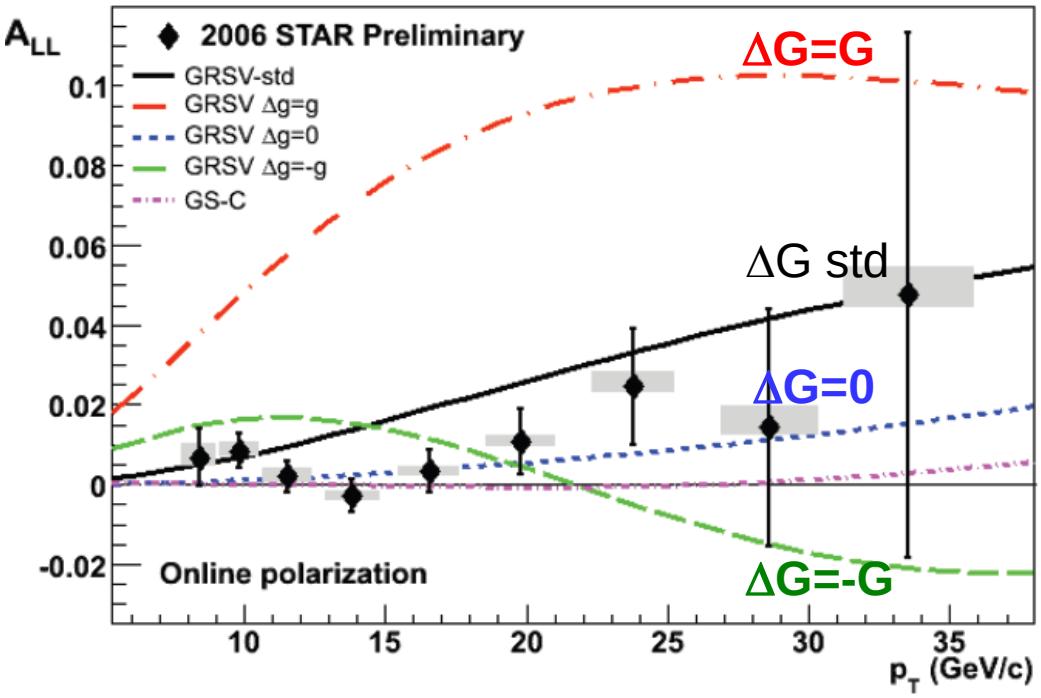
- **Data favor fits with ΔG close to 0**
- **Strong constraint on $\langle\Delta G\rangle$ in x range probed $0.05<x<0.3$**

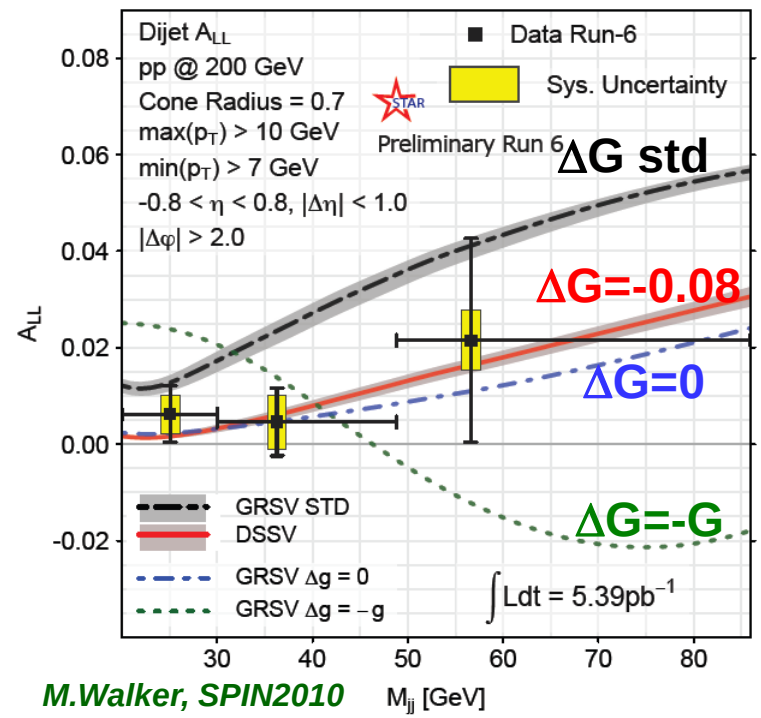
$\vec{p}\vec{p}$ collisions at RHIC: inclusive jet & dijet at STAR

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

Double spin asymmetry A_{LL} (p_T)

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





M.Walker, SPIN2010

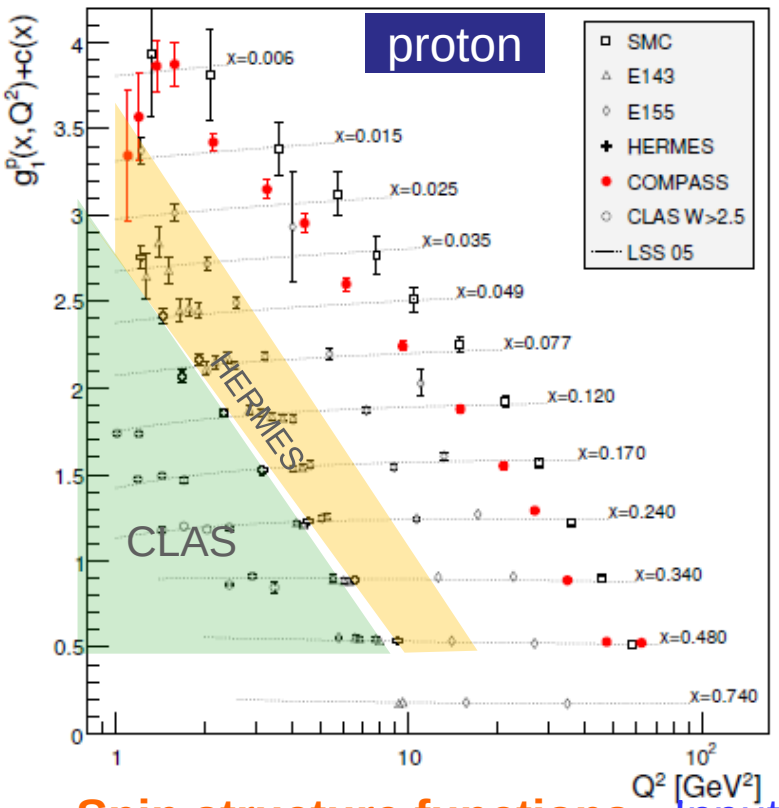
Both channels, Inclusive jet and dijet, provide strong constraint on ΔG in measured range, favoring parameterizations with ΔG close to 0

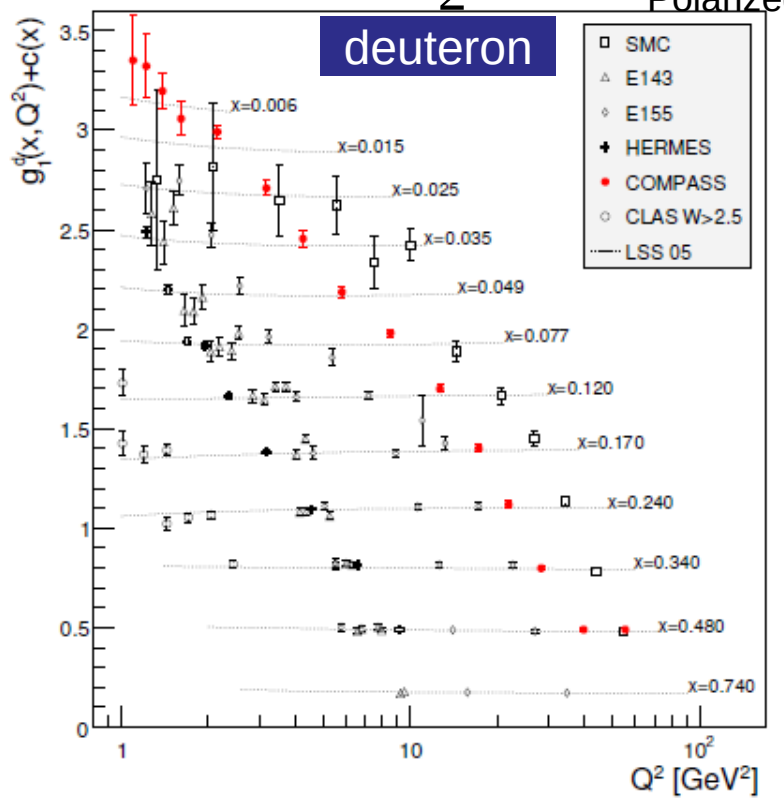
3. ΔG from global fits

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

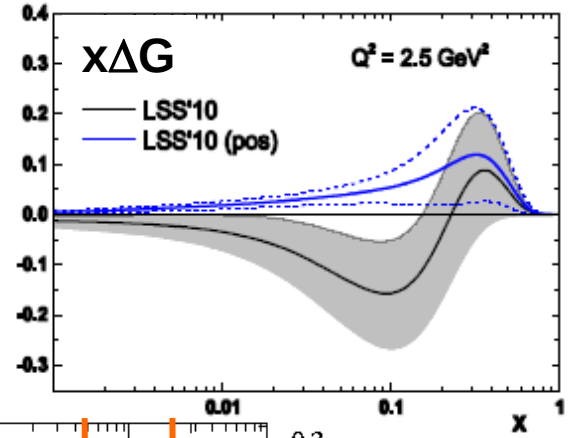
Only DIS & SIDIS data

Leader, Sidorov, Stamenov,

ΔG= 0.25± 0.19

ΔG= -0.40± 0.43

at Q^2=2.5GeV/c^2



DSSV

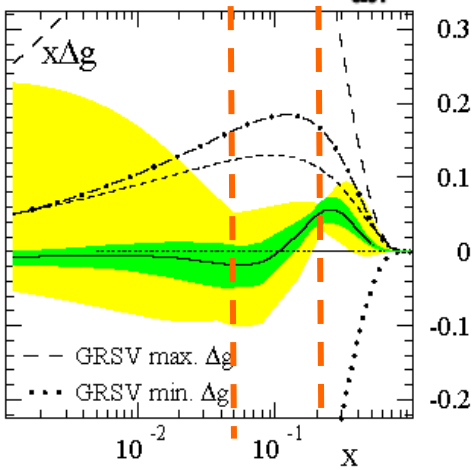
DIS, SIDIS & $\vec{p}$ p →

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

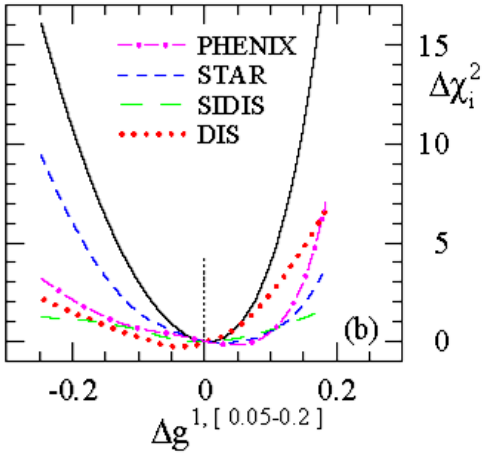
ΔG= -0.08 ± ?

at Q^2= 10 GeV/c^2

see talks of S. Taneja & M.Stratmann

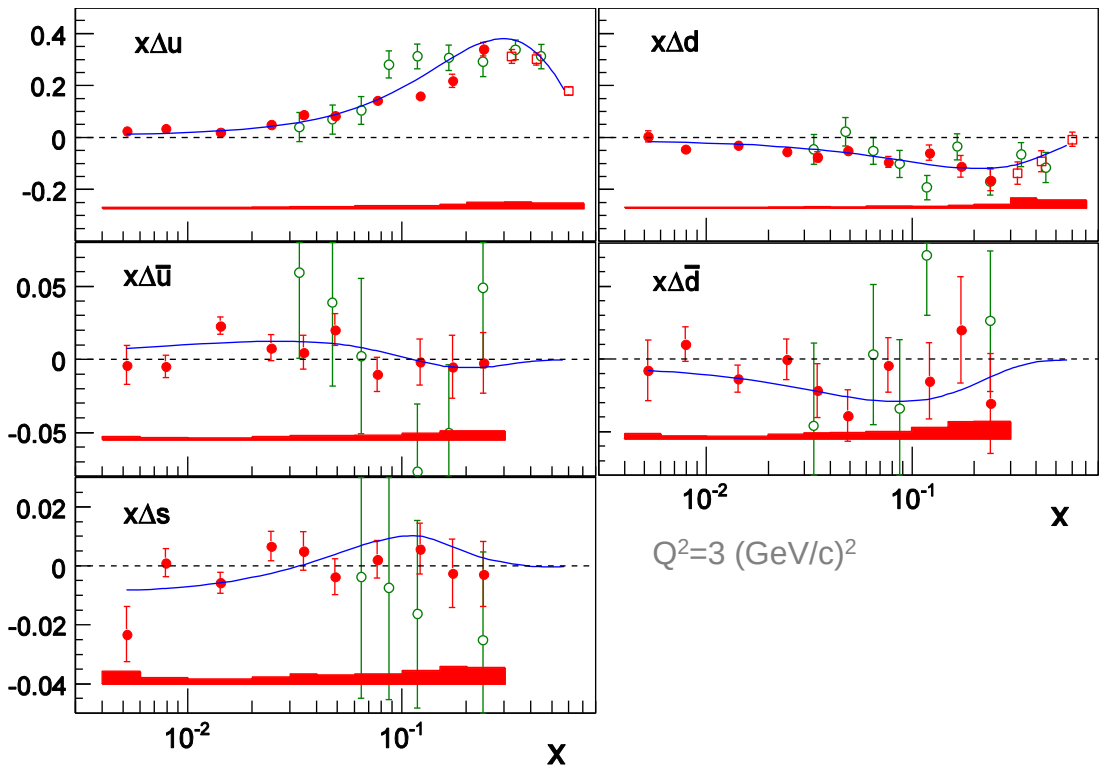


~0 in measured range (node)



- **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

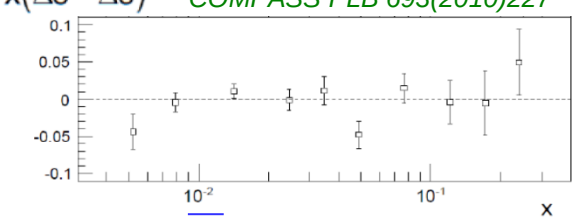
PLB693(2010)227, using DSS FF

o HERMES

PRD71(2005)012003

— DSSV

$x(\Delta s - \Delta\bar{s})$ *COMPASS PLB 693(2010)227*



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

HERMES $\Delta s+\Delta\bar{s}$=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

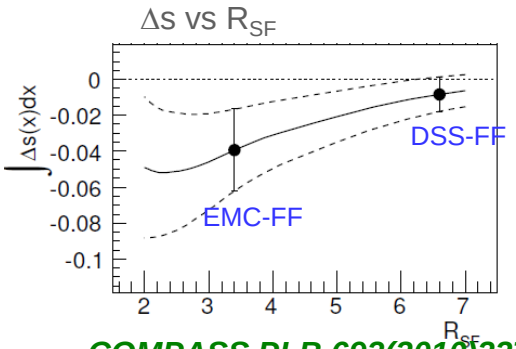
- **Full flavour separation → x~0.004**
- **Sea quark distributions ~ zero**
- **Good agreement with global fits**

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**



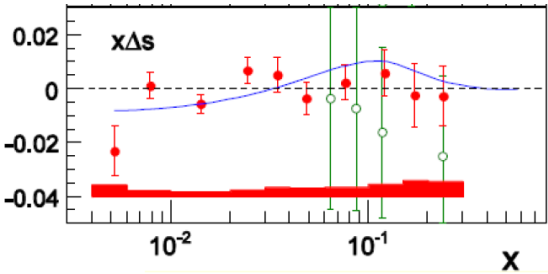
COMPASS PLB 693(2010)227

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

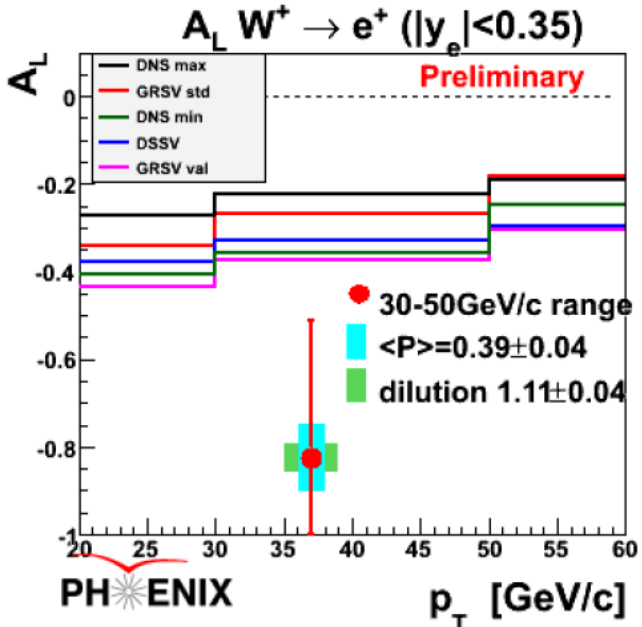
$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu$$
$$\bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}$$

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

Parity violating, single spin asymmetry
No fragmentation function uncertainty

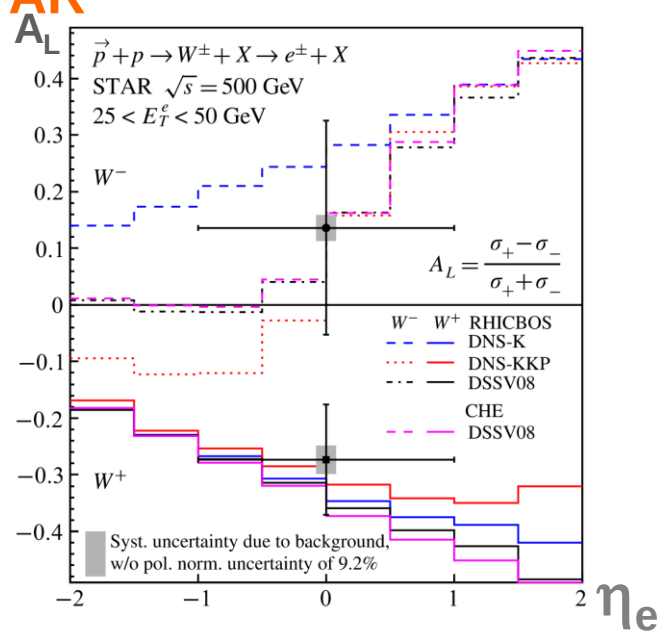
see talks of R.Towel & J.Seele

PHENIX



J. Haggerty ICHEP2010

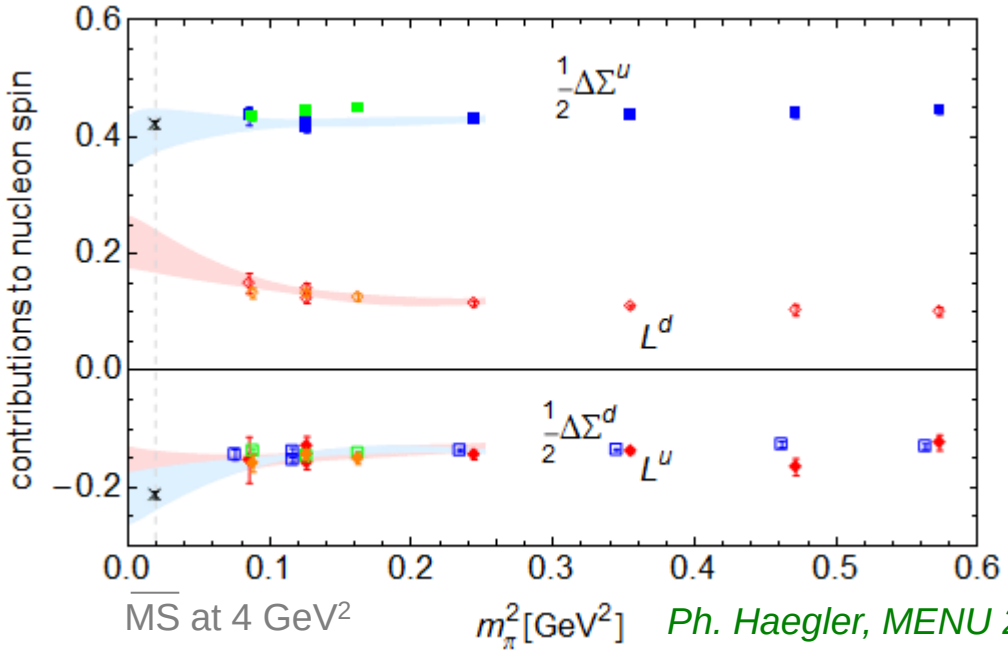
STAR



Phys.Rev.Lett. 106 (2011) 062002

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

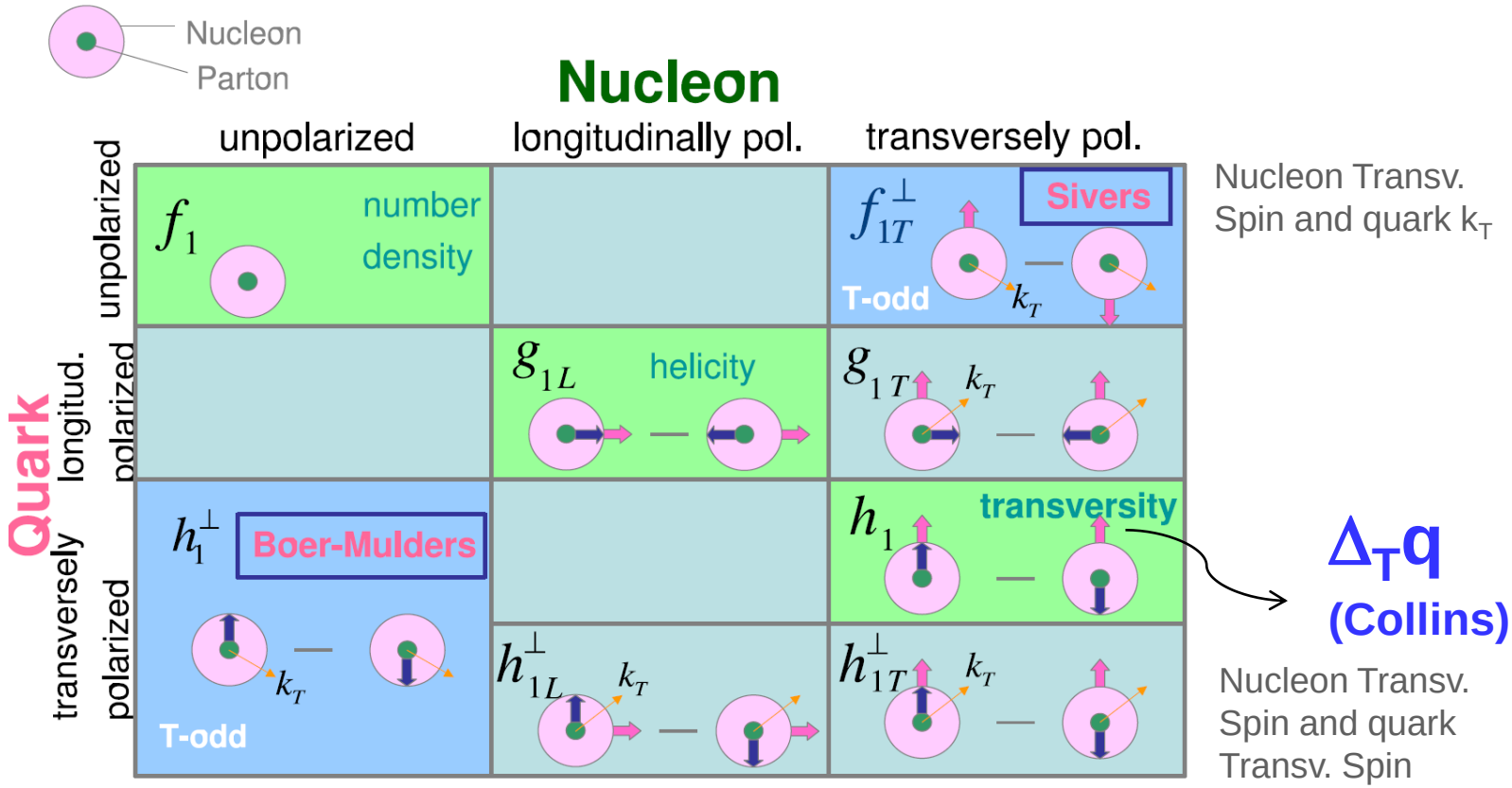
Lattice : quark spin and angular momentum



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

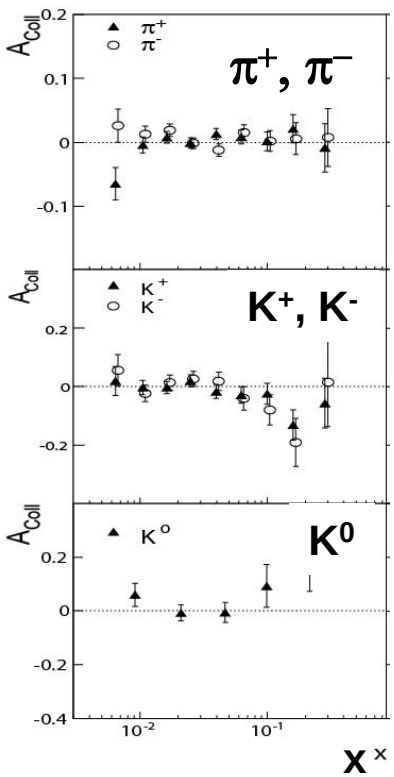
Usual quark fragmentation function

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

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

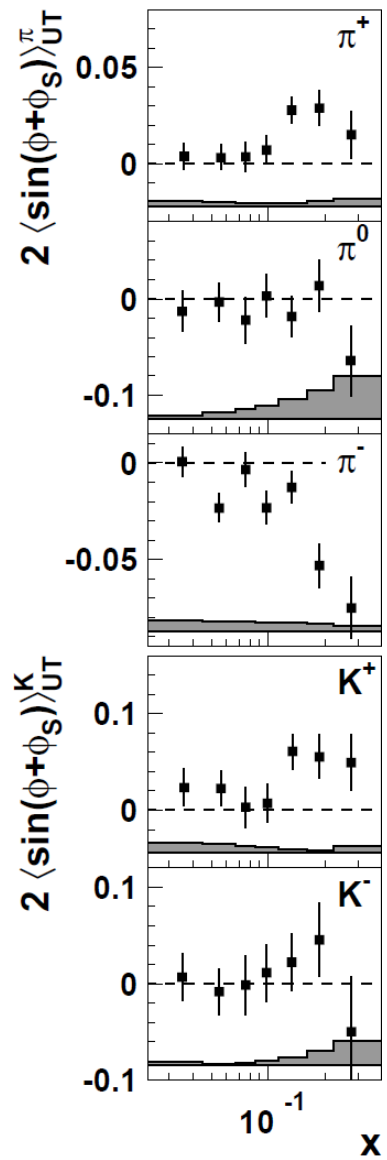
Transversity : Collins Asymmetry $l\,p^{\uparrow} \rightarrow l\,p\,h^{+/-}$

deuteron
COMPASS



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

proton
HERMES

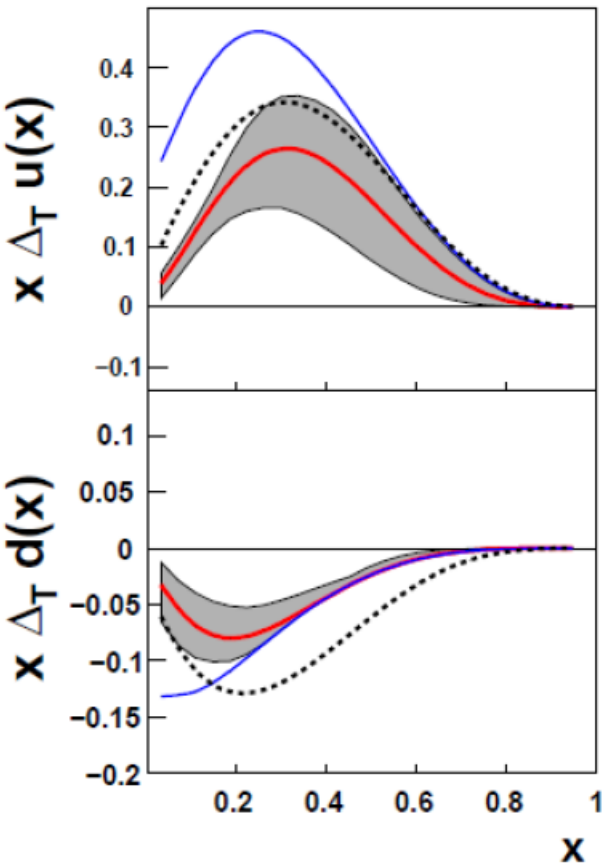


- Large signals in valence region for π^{+-} & K^{+-}
  → both transverse quark distribution $\Delta_T q(x)$ and Collins FF non zero
- Opposite for + and – hadrons:
  →opposite u and d CollinsFF
- larger for K+ than for π+
  →role of sea quarks
- Excellent agreement between HERMES p and COMPASS p data (not shown here)

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

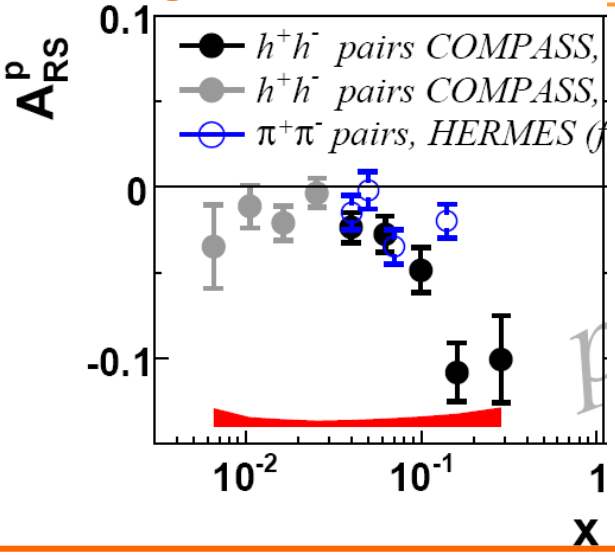
- Do not saturate Soffer bound
- Smaller than helicity

Also predictions for sea quarks

Ex: M. Anselmino et al. arXiv:0812.4366

Transversity via "two hadrons"

SIDIS



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

HERMES

COMPASS

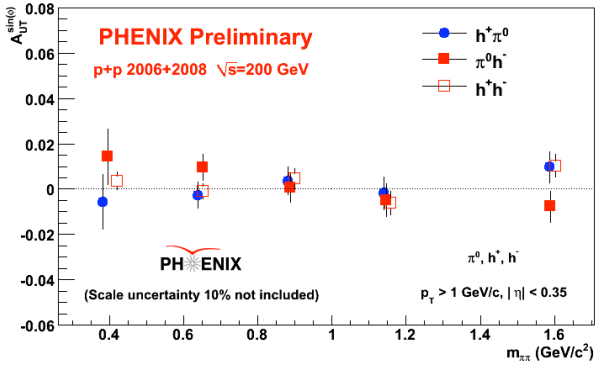
- **Confirms signal at large x.** Larger than Collins asymmetry
- COMPASS signal larger than HERMES'one

  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.

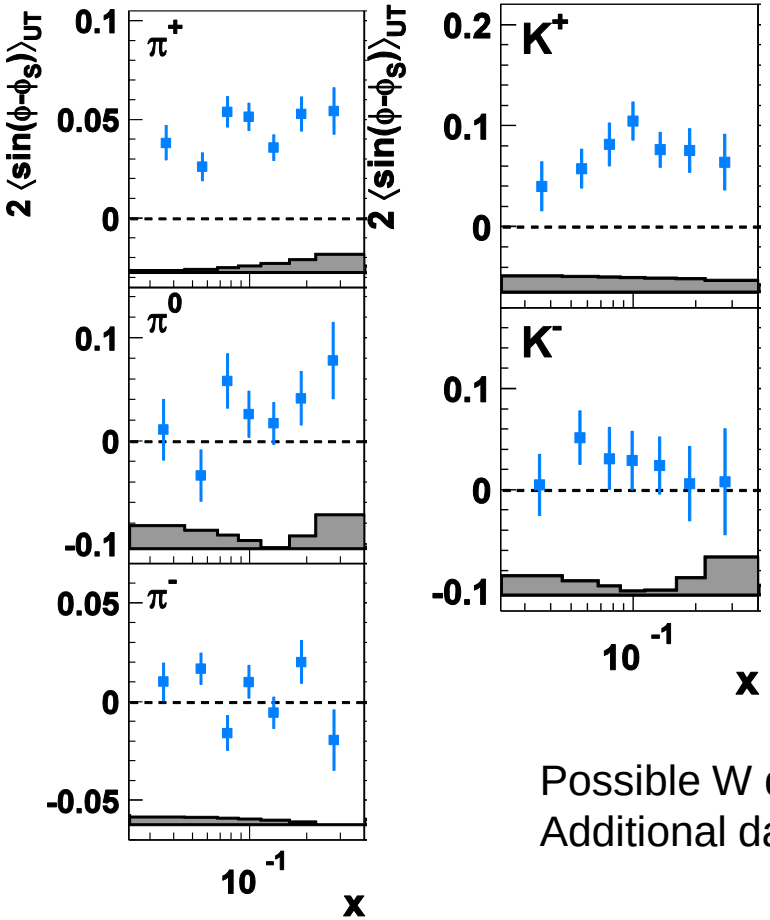
but different kinematics:

dominated by gluons

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

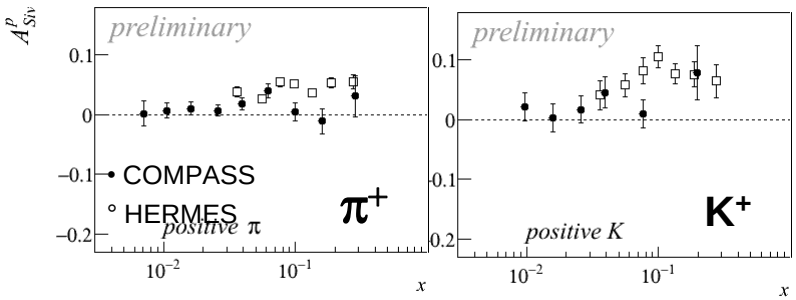
Correlation between nucleon spin & **quark transverse momentum k_T**

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



PRL103 (2009) 152002

COMPASS & HERMES



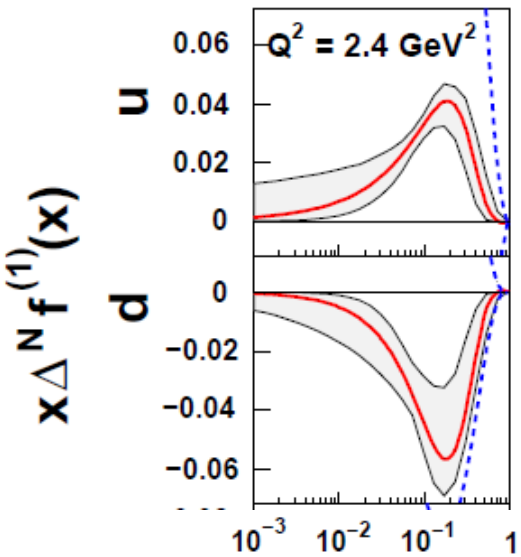
- Clear Signal in HERMES π^+ and K^+
- Smaller signal in COMPASS.

Possible W dependence
Additional data will come from COMPASS 2010 run

Sivers function

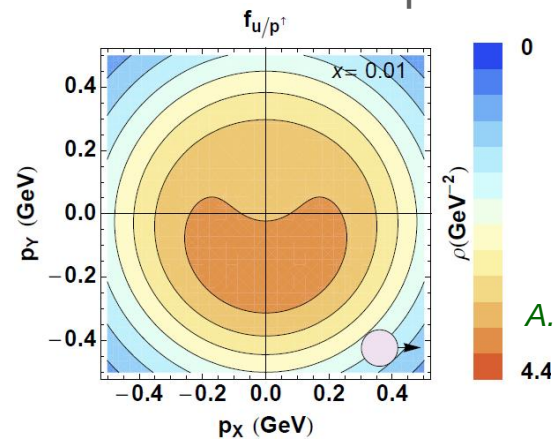
Extraction of Sivers function
(from HERMES **p** and COMPASS **d)**

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**

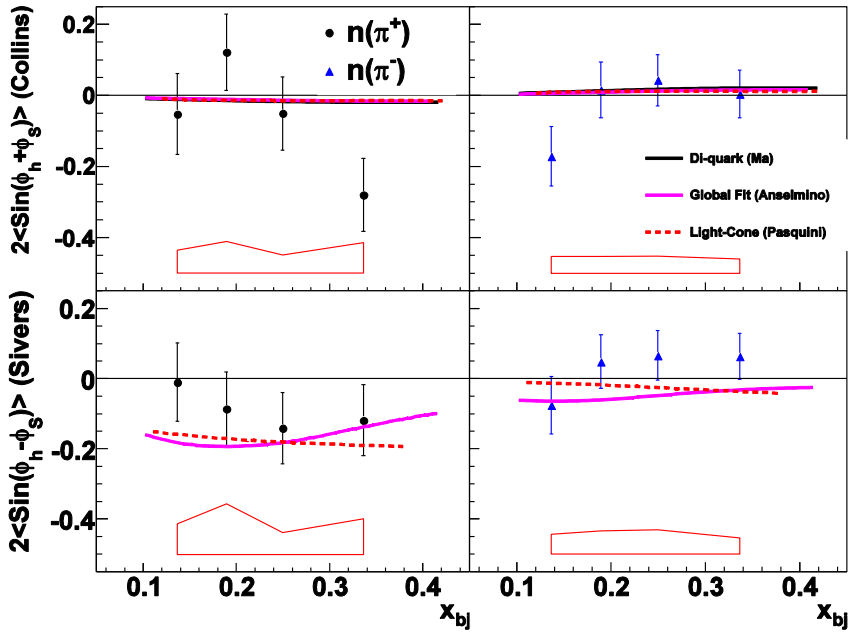
Other processes:
- Single transverse spin pp asymmetries (RHIC, following E704),
- Future polarized Drell-Yan, where Sivers effect is expected, but with opposite sign.

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)

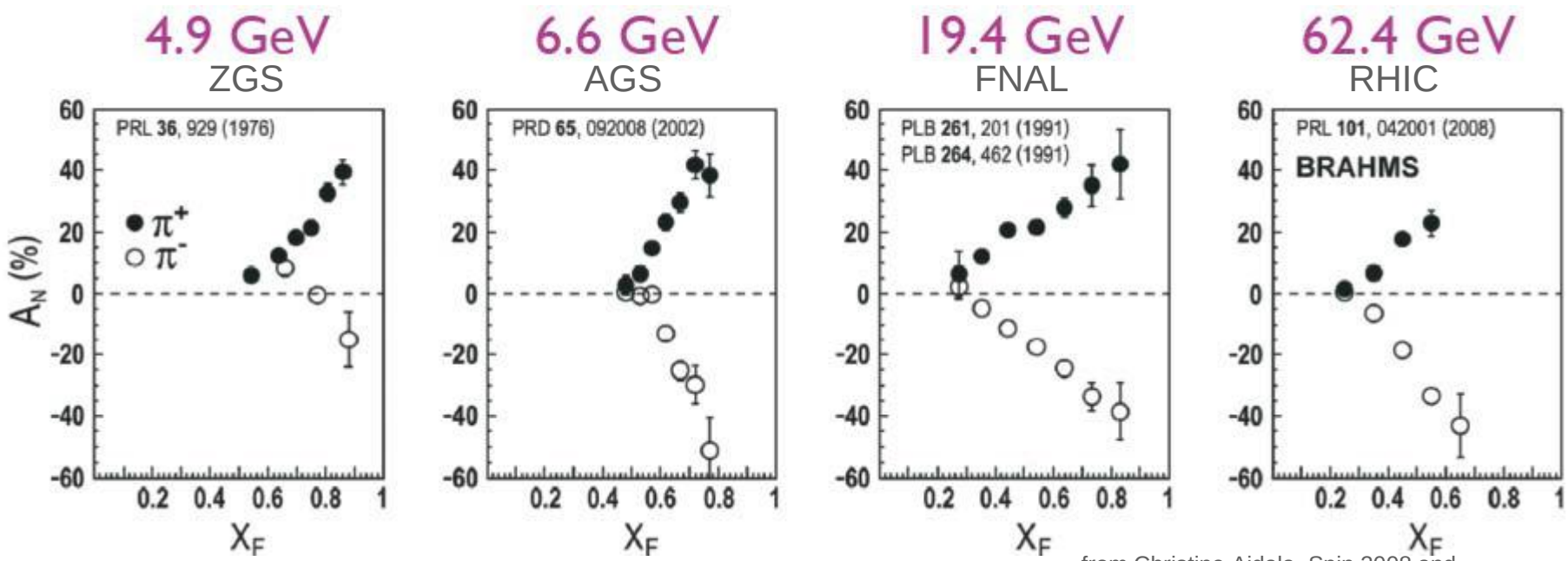
Systematics under study *Z.Meziani, IWHSS'11 Paris 2011*

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

Single transverse spin asymmetries

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

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

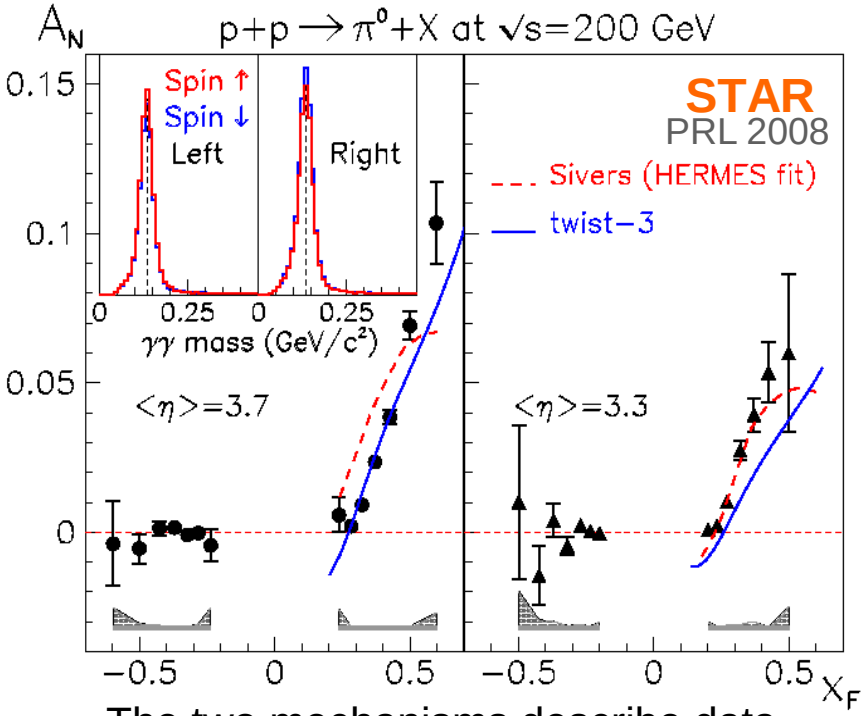
Large transverse single spin asymmetries, persisting at high energy

Single spin asymmetries

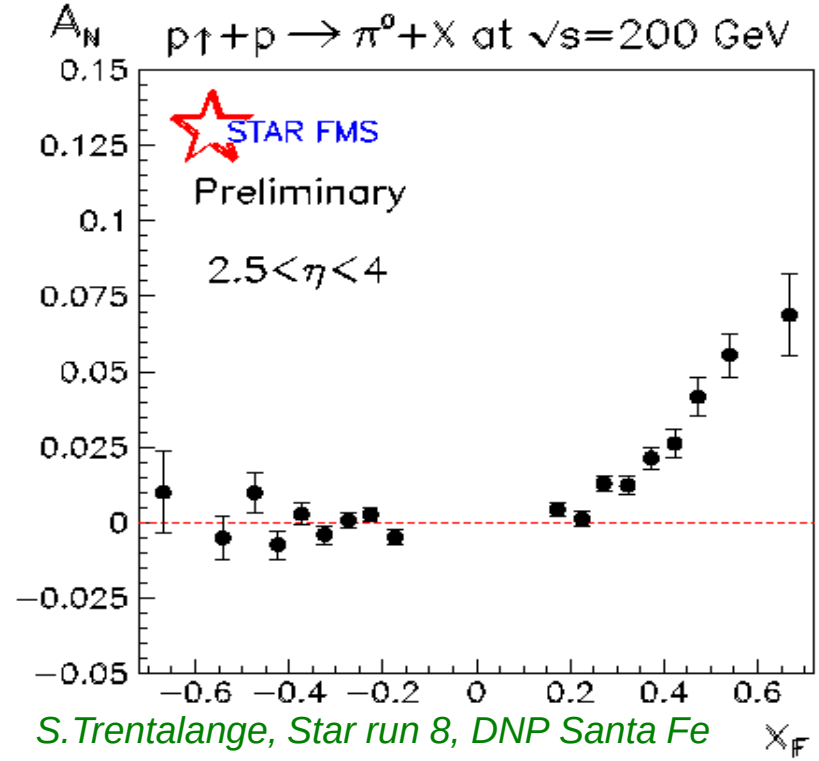
$$pp\uparrow \rightarrow \pi^{+/-/o} + X$$

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

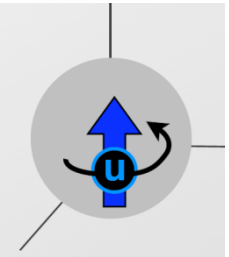
- **Confirms large pion asymmetries at higher energy**
- **Investigating mechanism: Collins, Sivers, twist-3**
- **Will extend measurements to higher mesons, xF, p_T**

Other Transverse Momentum Dependent DFs

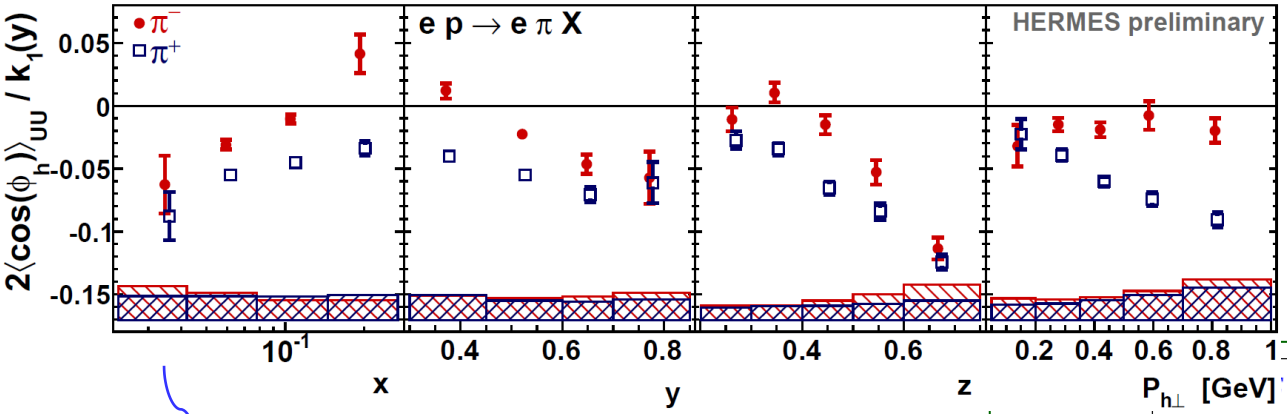
k_T effects → modulations in (unpolarized) SIDIS cross-section.

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

correlation between quark transverse motion and transverse spin

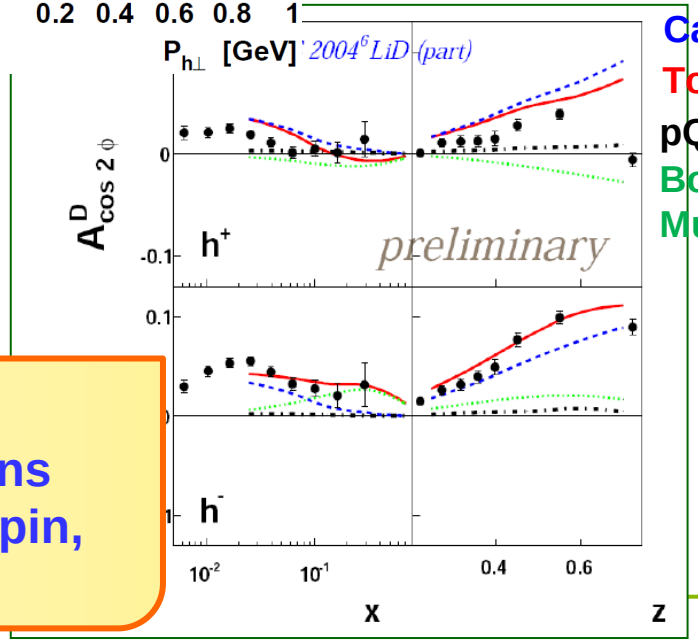


HERMES, cos ϕ



see talks of C.Schill, L.Pappalardo,

COMPASS, cos 2ϕ



Depends on π charge, not expected for Cahn:

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

- **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

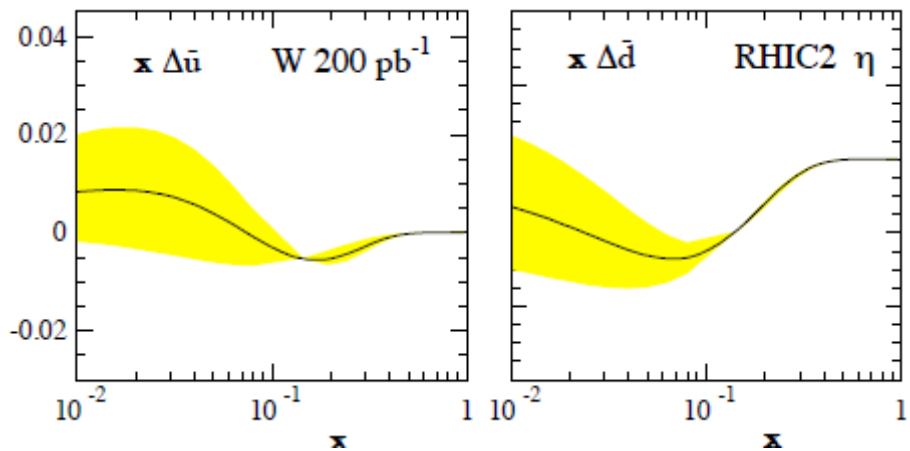
Polar.=0.5 (2011) → 0.65 (2014)
L_{max}=1 x 10^{31}cm^{-2}s^{-1} (2011)→ 3 x 10^{31}cm^{-2}s^{-1}

- **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)**

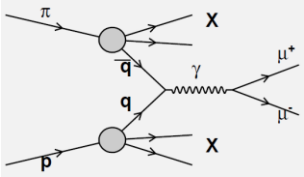
Future of COMPASS 2011-2016

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*

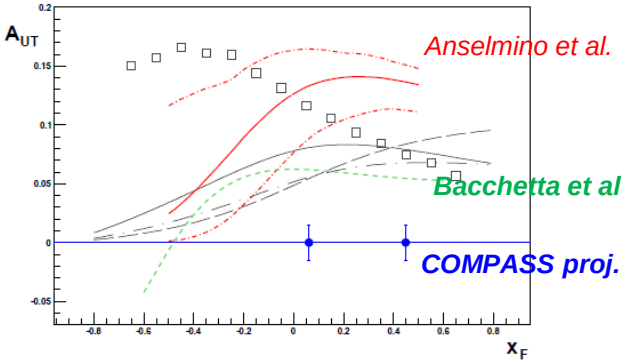
2014 and beyond, COMPASS-II :

- **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

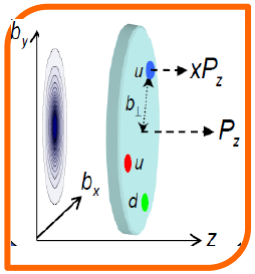


Ex: A_{UT} asymmetry in Drell-Yan process

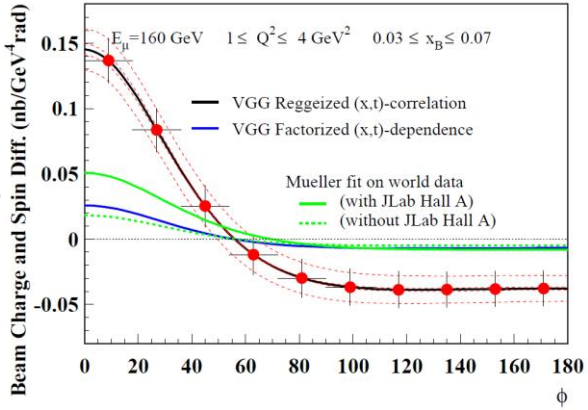


- **GPD** (Generalized Parton Distributions) $\mu p \rightarrow \mu p \gamma$

by exclusive reactions DVCS, DVMP



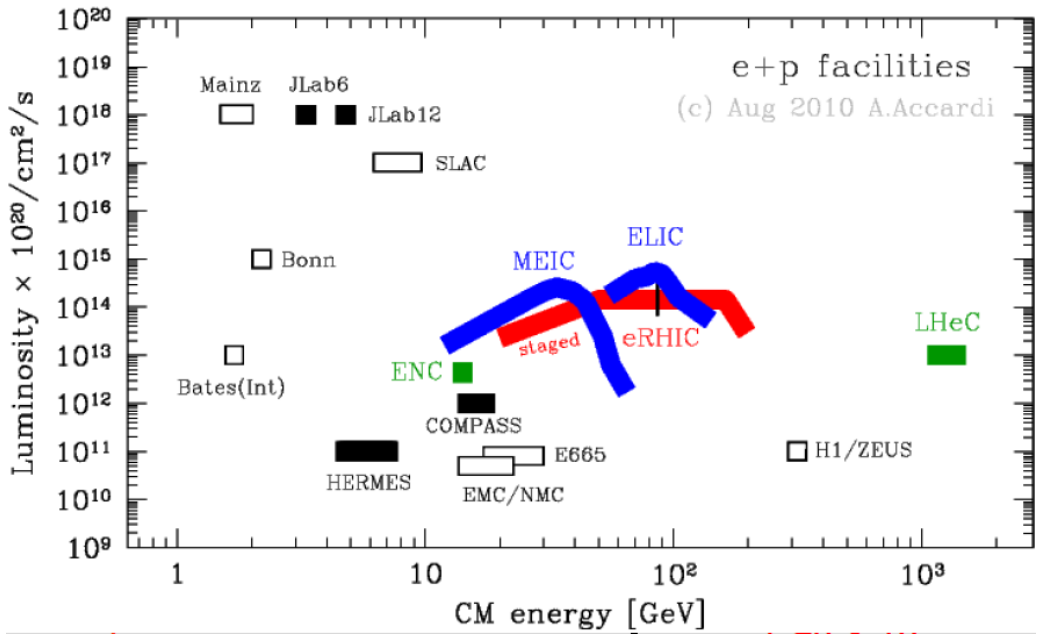
•Unified descrition of form factors & PDFs
•Transverse imaging 2+1 dim.

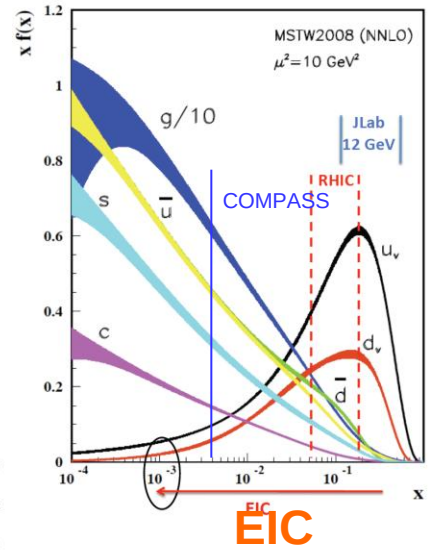


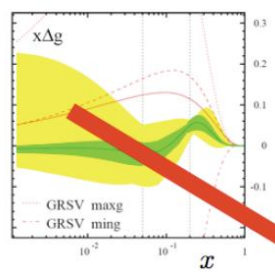
see talk of C.Quintans

Future polarized ep collider

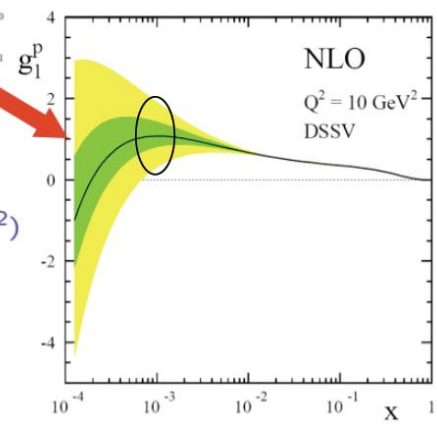
- **Goal: access lower x in (polarized) DIS and with higher luminosity**
- **Wide physics program:**
  Polarized **sea q** and **g**, Hard exclusive reactions, TMDs, gluon saturation…







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



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

Spares

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 < 0.02contrib., *PRD75 (2007)012007*

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

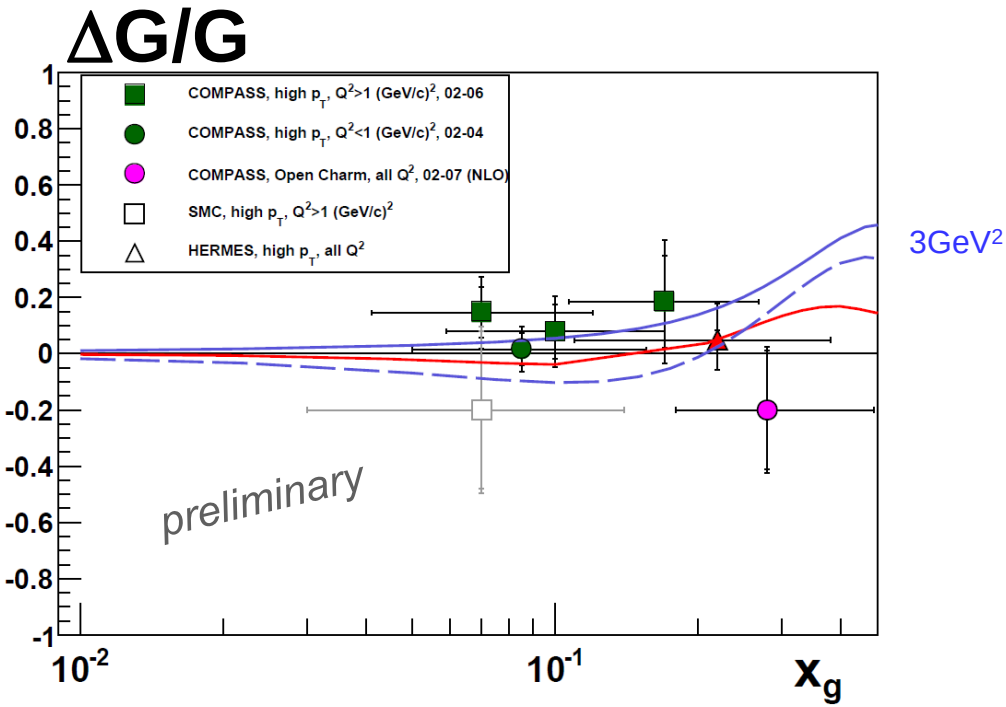
DSSV $\Delta\Sigma = 0.24$ $Q^2=10\ (\text{GeV/c})^2$ *arXiv:0804.0422*

LSS '10

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

$\Delta\Sigma = 0.21 \pm 0.03$ $\Delta G > 0$

NLO extraction of Δ G/G from COMPASS charm



LSS at 4GeV^2, ΔG= 0.32 ΔG=-0.33

DSSV at 3GeV^2 ΔG=0.02

Bjorken sum rule

Non-singlet combination : $g_1^p(x) - g_1^n(x)$

The first moment provides a test of the Bjorken sum rule,
a fundamental result of QCD derived from current algebra

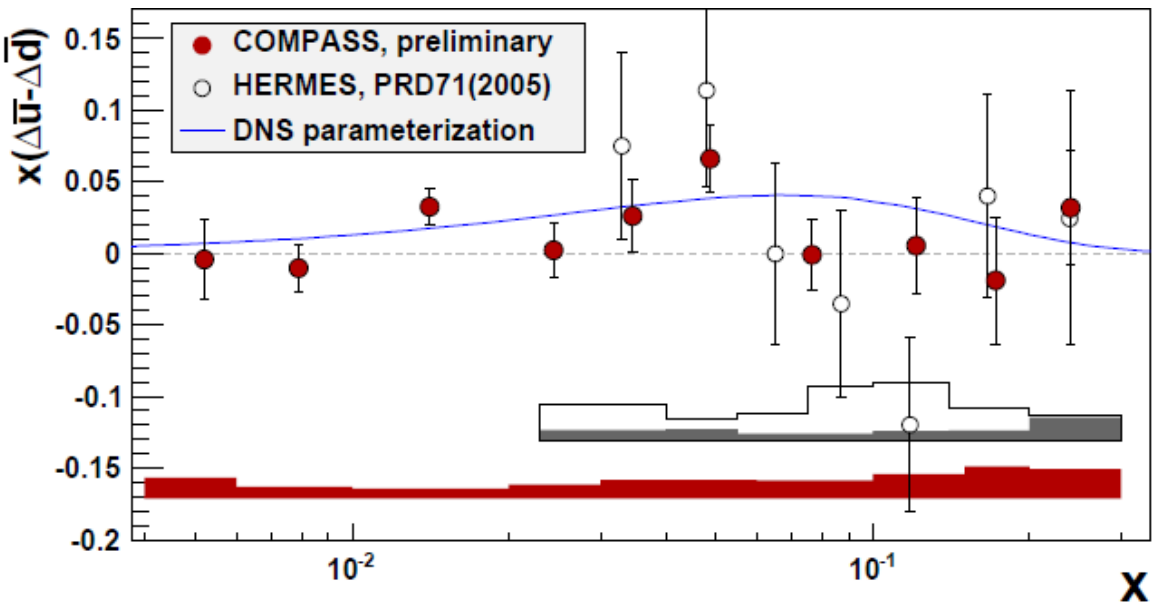
$$\int_0^1 g_1^{NS}(x)dx = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C^{NS}$$

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

PDG value:
1.268 ±0.003

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: $\int (\bar{d} - \bar{u})dx = 0.118 \pm 0.012$

Consequence for nucleon spin

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

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

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

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

possible scenarios:

$$\begin{cases} \tfrac{1}{2}0.3 + 0.35 + 0.0 \\ \tfrac{1}{2}0.3 + 0.0 + 0.35 \\ \tfrac{1}{2}0.3 - 0.35 + 0.7 \end{cases}$$

SIDIS, transverse case

$$\mu\, p^{\uparrow} \rightarrow \mu\, p\, h^{+/-}$$

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{ \ldots$$

$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\varepsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

Sivers

Collins

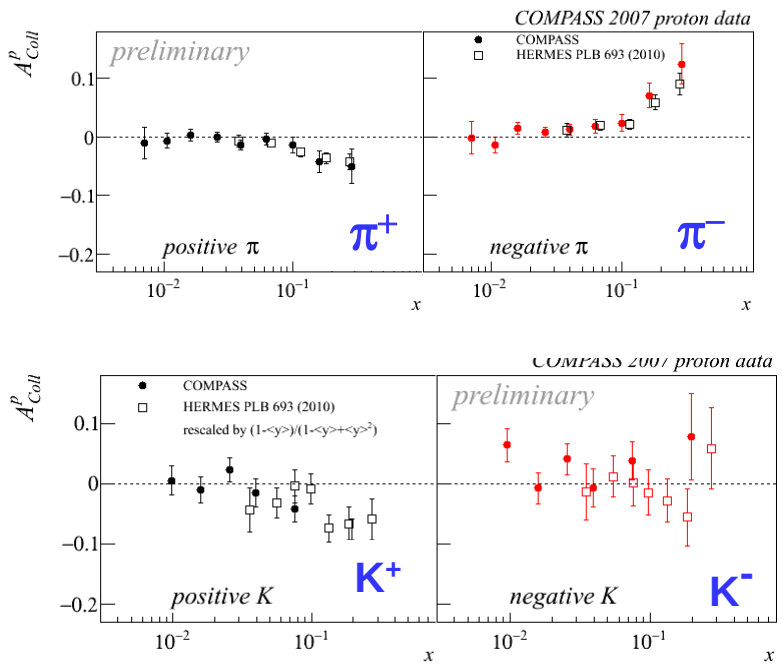
6 other modulations

From A. Bacchetta et al., JHEP 0702:093,2007. e-Print: hep-ph/0611265

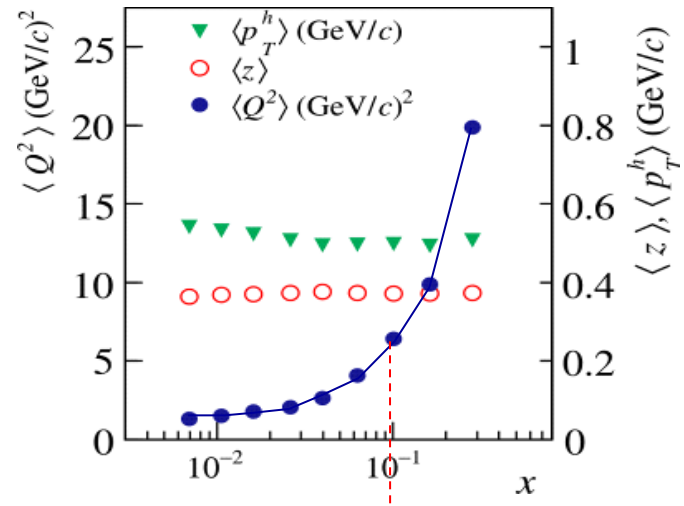
8 azimuthal asymmetries extracted at once

Transversity : Collins Asymmetry

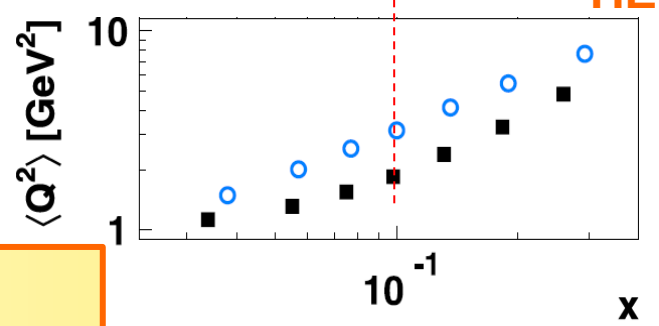
HERMES and COMPASS proton data



COMPASS



HERMES



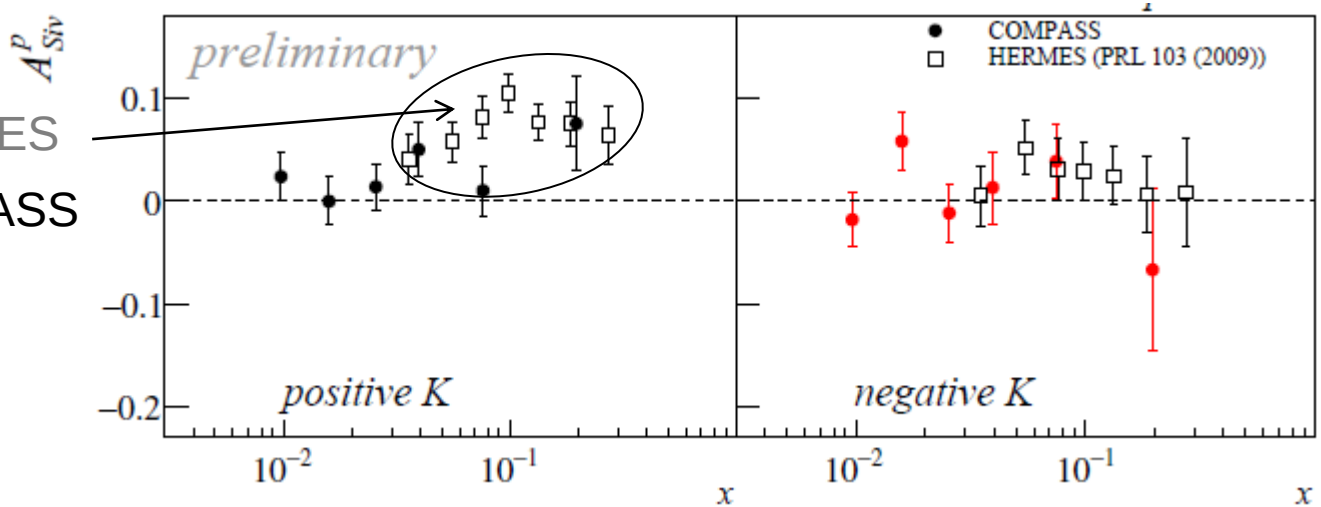
- Weak Q^2 dependence in this energy range.
- Confirms that signal is not higher twist effect

Sivers asymmetry - proton

Signal seen in K+, … but not in K-

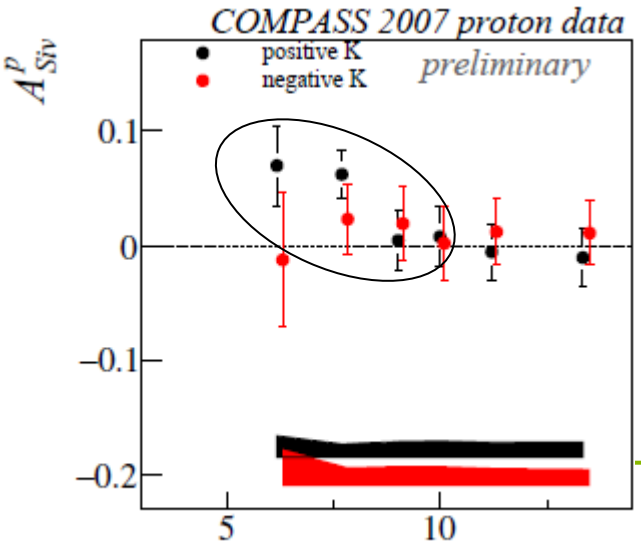
HERMES

COMPASS



Other observation in HERMES and COMPASS: K^+ signal larger than π^+

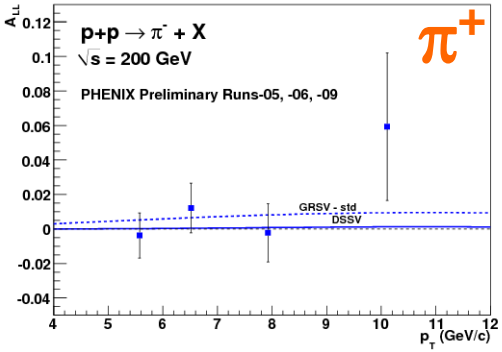
→ Much progress in flavour separation (sea quarks)

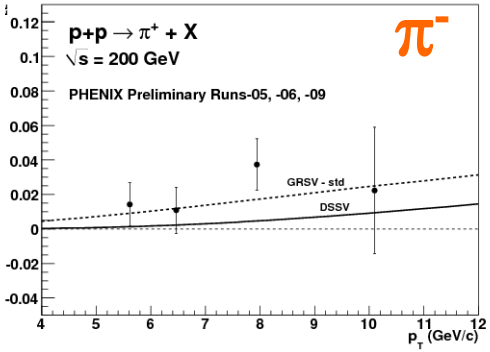


Possible unexpected dependence on W: Higher signal in HERMES (low W) and in low W part of COMPASS data

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

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



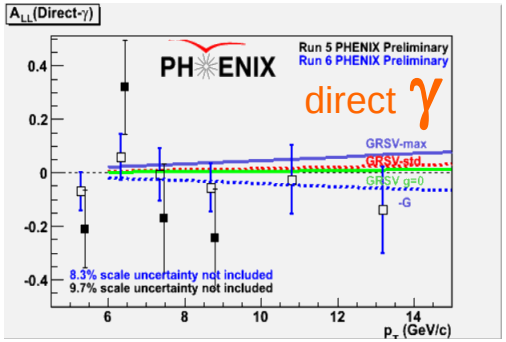


$$A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-} \Rightarrow \Delta G > 0$$

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

direct γ

clean channel
qg dominates



Promising channels when more statistics available