Proton longitudinal spin structure- RHIC and COMPASS results

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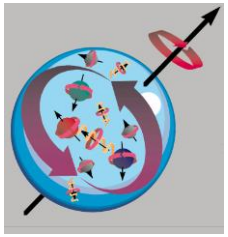
- **Gluon helicity**
  - **PHENIX & STAR: pp→ jets, pp→ π^0**
  - **COMPASS g_1 QCD fit + ΔG direct measurements**
- **Quark helicity**
- **Others**
  - **Bjorken sum rule**
  - **Quark Fragmentation Functions**

Nucleon spin

How is the nucleon spin distributed among its constituents?

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

quark gluon orbital momentum



$\Delta\Sigma$: sum over u, d, s, $\bar{u}$, $\bar{d}$, $\bar{s}$
can take any value: superposition of several states

$\Delta q = \overrightarrow{q} - \overleftarrow{q}$
Parton spin parallel or anti parallel to nucleon spin

Past:

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

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

Today:

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

Confirmed by first results from Lattice QCD on $\Delta\Sigma_{u,d}$. (Results exist also on $L_{u,d}$)

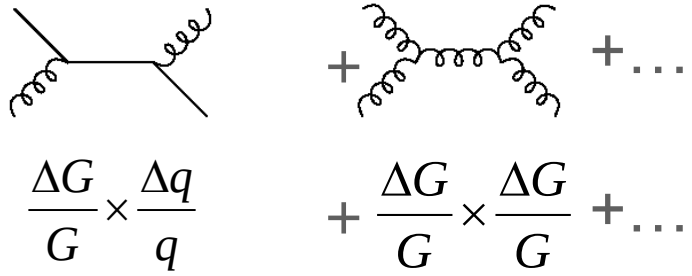
Large experimental effort on ΔG measurement

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

Three ways to study gluon spin contribution ΔG

1. $\vec{p}$ $\vec{p}$ collisions

Gluon-Quark + Gluon-Gluon +…

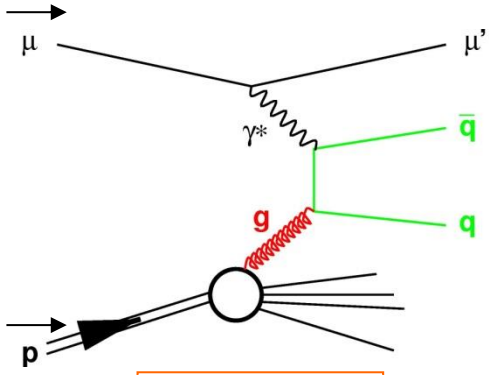


A_{LL} (p_T)

RHIC : PHENIX & STAR

2. $\vec{l}$ $\vec{N}$ Lepton Nucleon

Photon Gluon Fusion



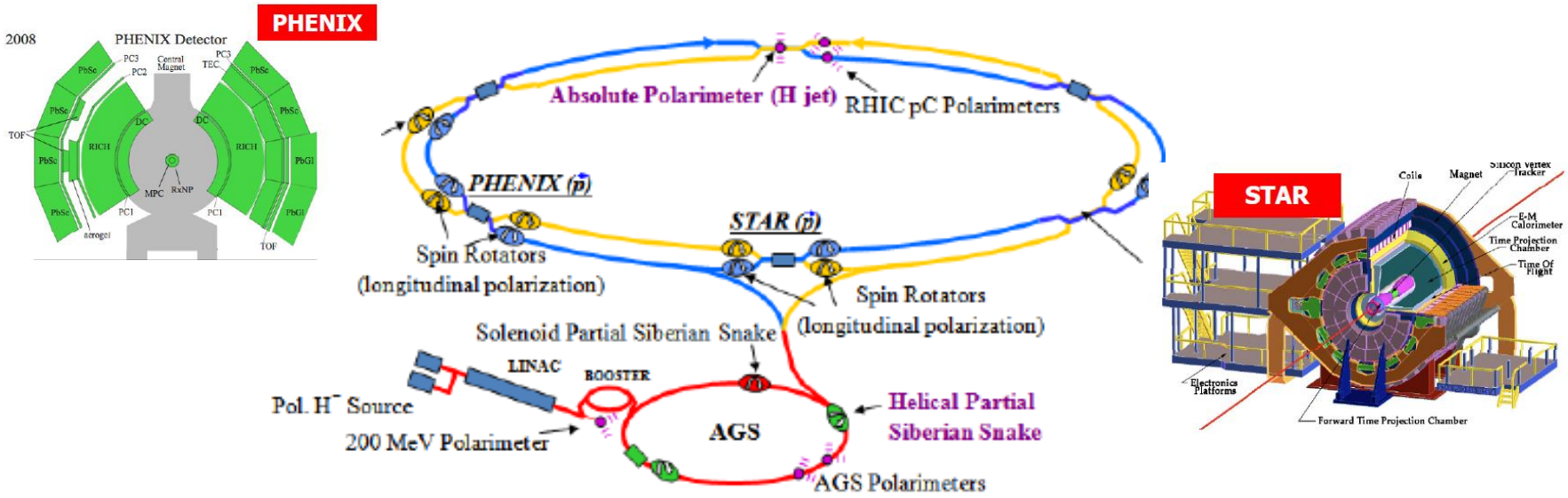
ΔG/G(x)

CERN: COMPASS

3. QCD Q^2 evolution of spin structure function $g_1(x,Q^2)$:

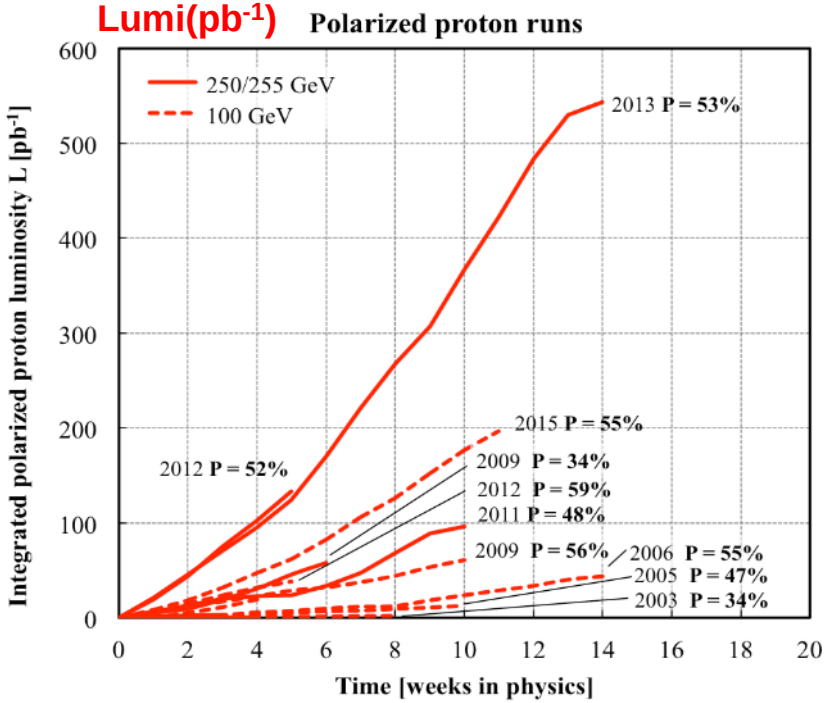
Indirect determination assuming a functional form ΔG(x).
Global fits include polarized DIS, SIDIS and pp data

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



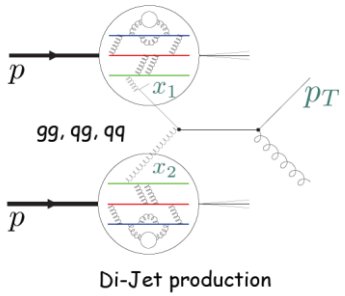
Longitudinal spin

- hadron production for $\langle \Delta G \rangle$
- W production for $\langle \Delta q \rangle$



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

Various channels



3 processes contribute *gg, qg, qq*

$$\begin{bmatrix} \Delta G\,(x_1)\,.\Delta G\,(x_2) \\ \Delta G\,(x_1)\,.\Delta q\,(x_2) \\ \Delta q\,(x_1)\,.\Delta q\,(x_2) \end{bmatrix}$$

More abundant channels

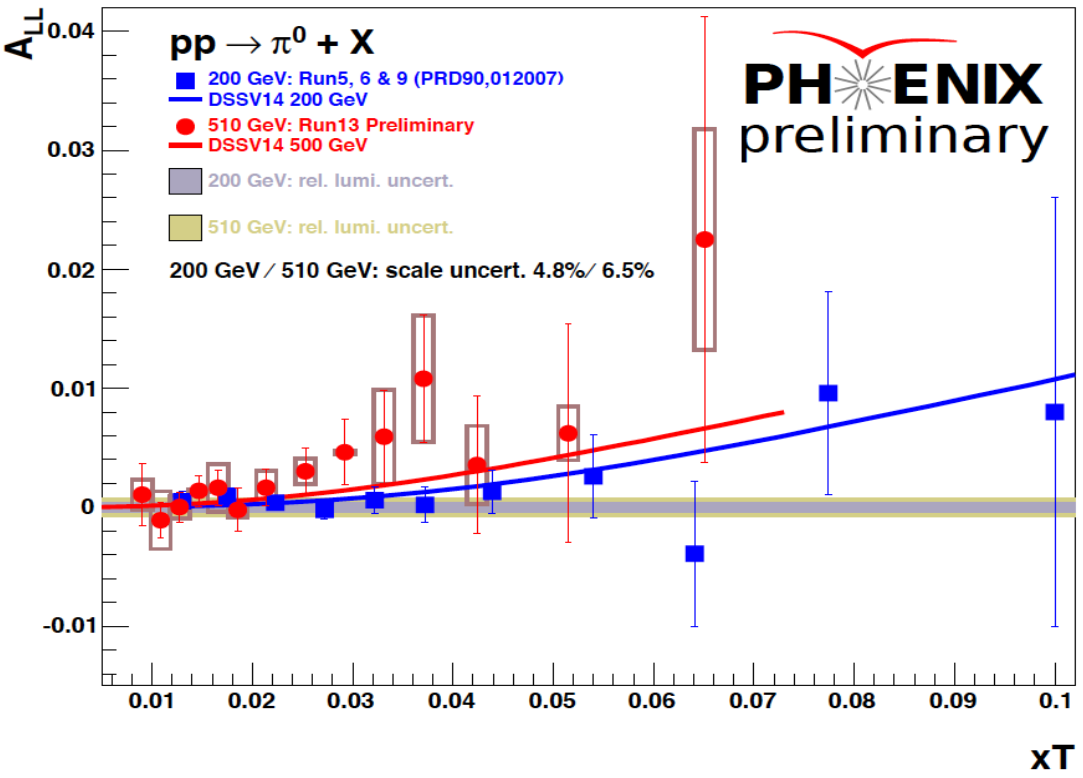
p p → π^0 X **PHENIX**

p p → **jet** X **STAR**

RHIC- PHENIX ΔG from π^0 production

$\vec{p}\,\vec{p} \rightarrow \pi^0 + X$ Measure double spin asymmetry A_{LL} (p_T)
Compare data to global fits with a given ΔG(x) parameterization

earlier data 200 GeV & **prelim. 2013 data $\sqrt{s} = 510$ GeV**



curves: **DSSV14**, which includes 2009 data

Significant non-zero A_{LL} (ΔG) observed
x range extended to x~0.01

arXiv: 1501.01220

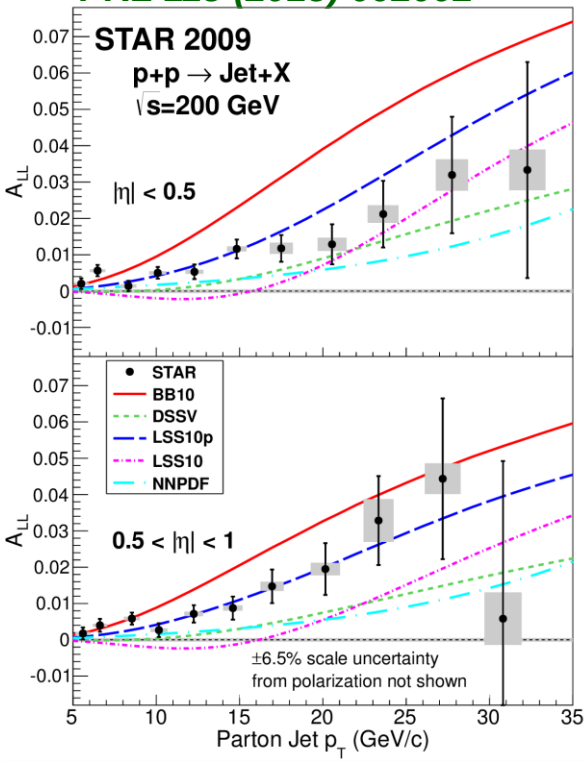
RHIC- STAR ΔG from jet production

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

2009 data at $\sqrt{s} = 200$ GeV

- A_{LL}>0 for large p_T, indicate ΔG>0
- agree with LSS10p (ΔG>0)

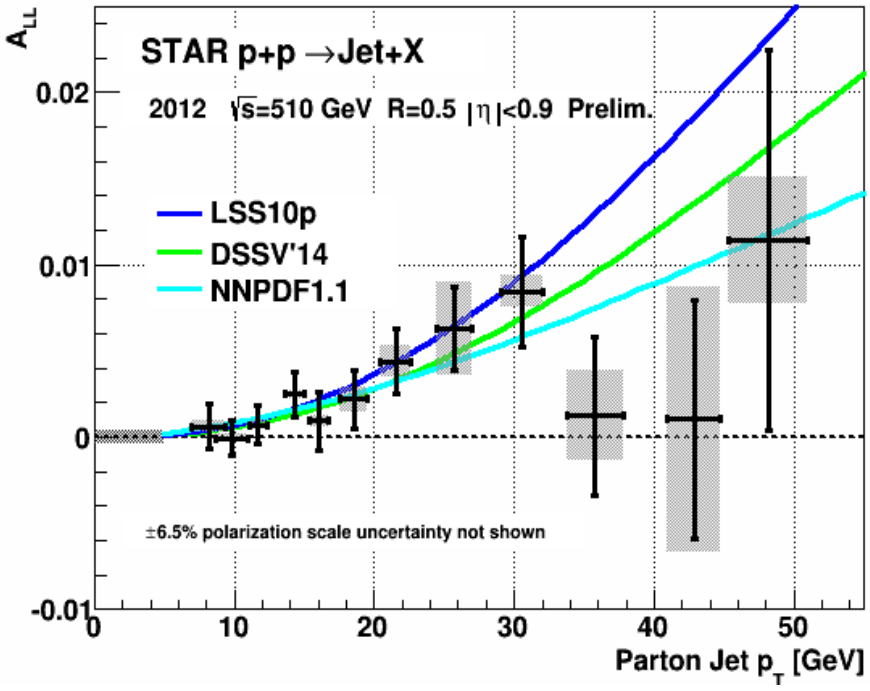
PRL 115 (2015) 092002



Prelim. 2012 data, $\sqrt{s} = 510$ GeV

- agree with 2009 data
- LSS10p and **DSSV14** which includes 2009 data

arXiv: 1501.01220

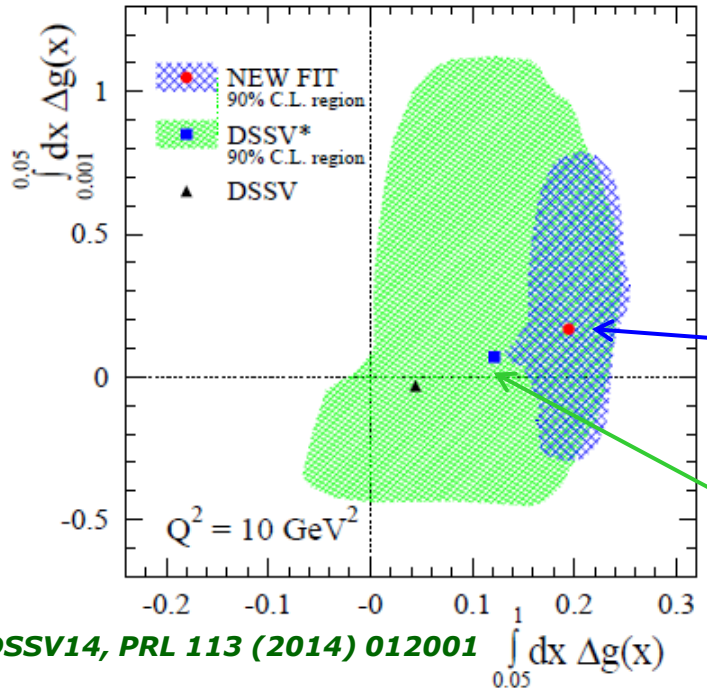


Large impact of RHIC data on ΔG from QCD fits

Significantly positive ΔG in measured range: $\int_{0.05}^{1} \Delta g(x)\mathrm{d}x \simeq 0.20$

Low-x vs high-x contributions to ΔG:

low x part
0.001<x<0.05



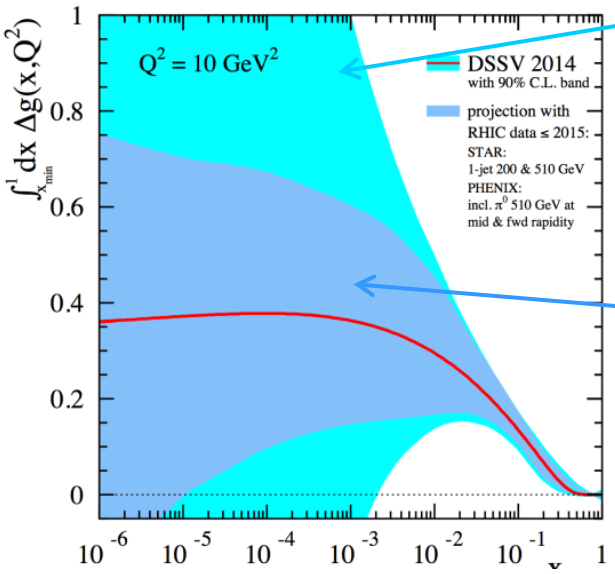
DSSV14 with 2009 data

without

DSSV14, PRL 113 (2014) 012001

ΔG trunc. high x part
0.05<x<1

Running ΔG from x_{min} to 1



DSSV14

Proj. with data→2015

arXiv 1501.01220

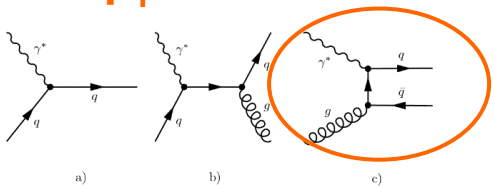
x_{min}

Need data at small *x*

2.a ΔG/G from hadron prod. in DIS ($Q^2>1(GeV/c)^2$)

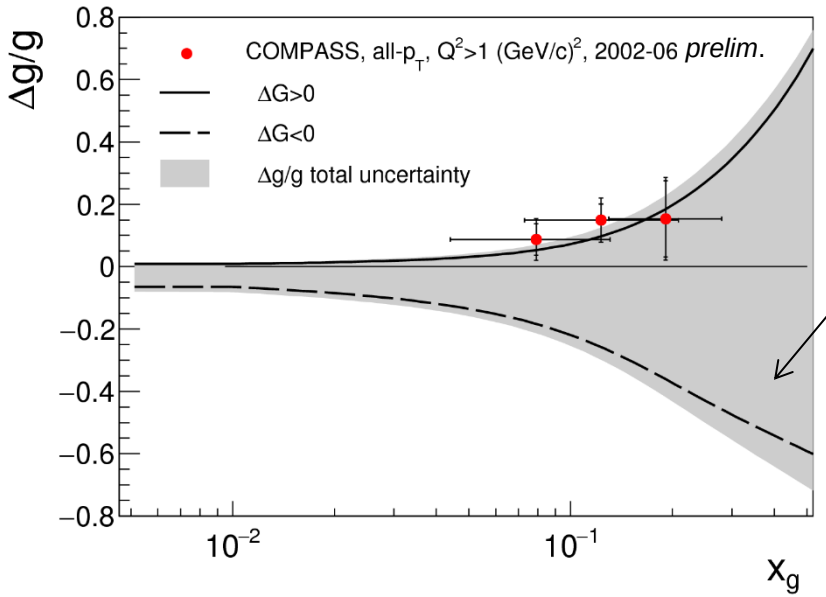
New COMPASS result 'all-p_T' - PGF

$\vec{\mu}\,\vec{p} \rightarrow h + h + X$



Photon Gluon Fusion

$Q^2>1(GeV/c)^2$
3 x-bins



2 solutions from COMPASS NLO QCD fit of g_1 world data (presented later)

$\Delta g/g$ *(x=0.1)* = 0.11 ± 0.04 ± 0.04

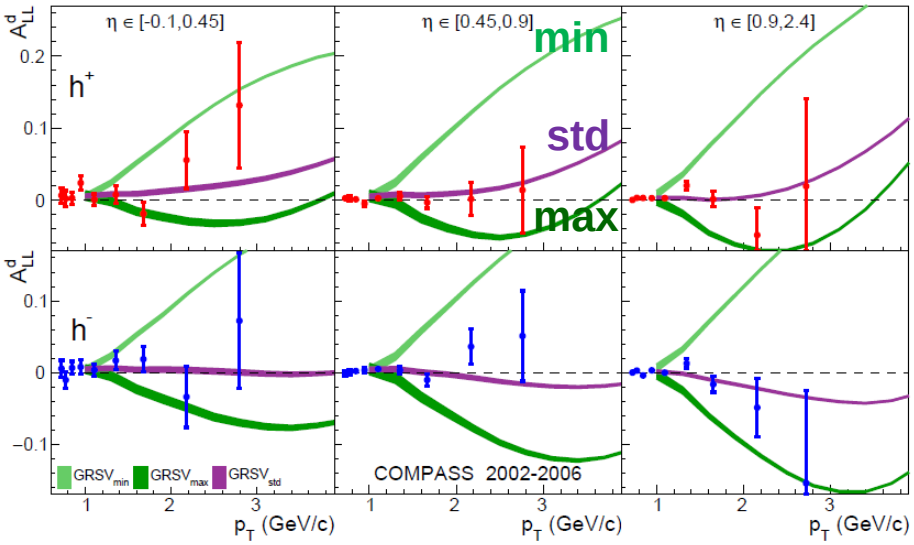
- **COMPASS DIS data indicate ΔG >0 at x ~0.1**
- **caveat: extraction at LO only**

2.b COMPASS ΔG from A_{LL} (pT) low Q^2 data

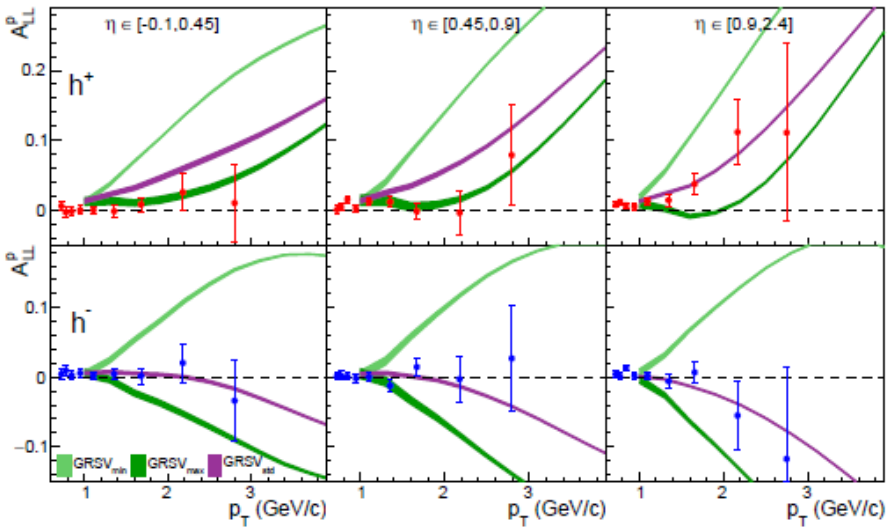
$\vec{\mu}\ \vec{\vec{p}} \rightarrow h + X$ **New COMPASS result, $Q^2 < 0.1(GeV/c)^2$**

- quasi-real photoproduction of single hadrons, ($A_{LL}(p_T)$ '*à la RHIC*')
- calculation based on W.Vogelsang et al. (data-theory agreement for unpolarised case)

deuteron



proton

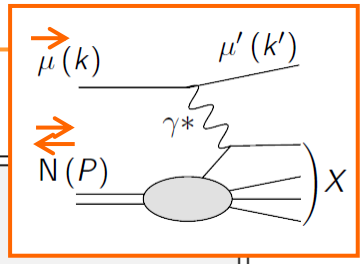


arXiv:1509.03526
to be published in PLB

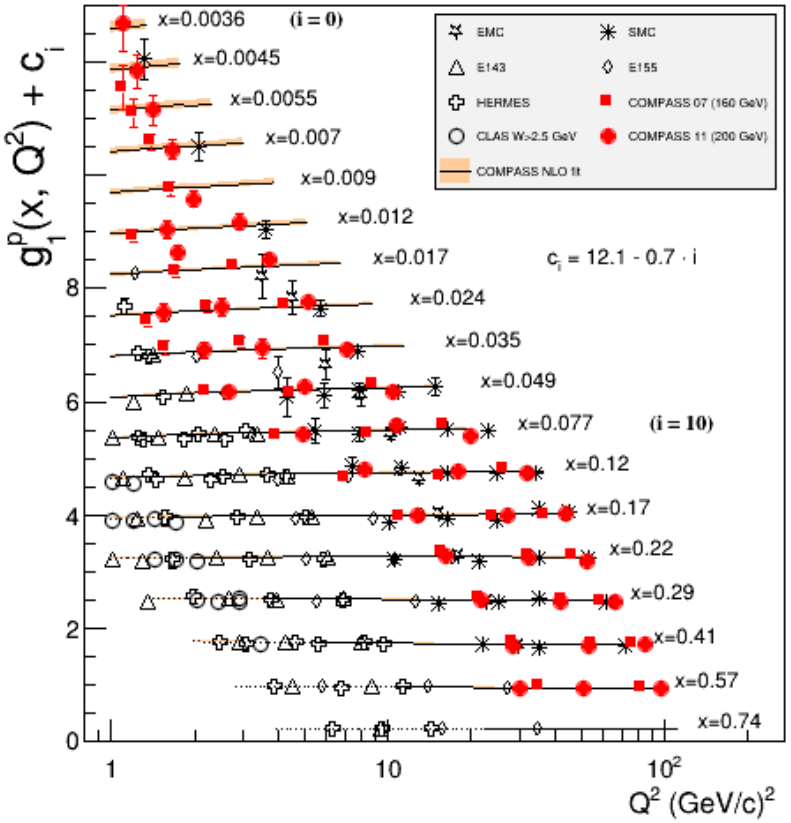
- **COMPASS low Q^2 A_{LL} data prefer also ΔG>0**
- **Caveat: NNL resummation missing for polar.case and large dependence on fragmentation functions**

3. QCD fits- World data on g_1^p and g_1^d

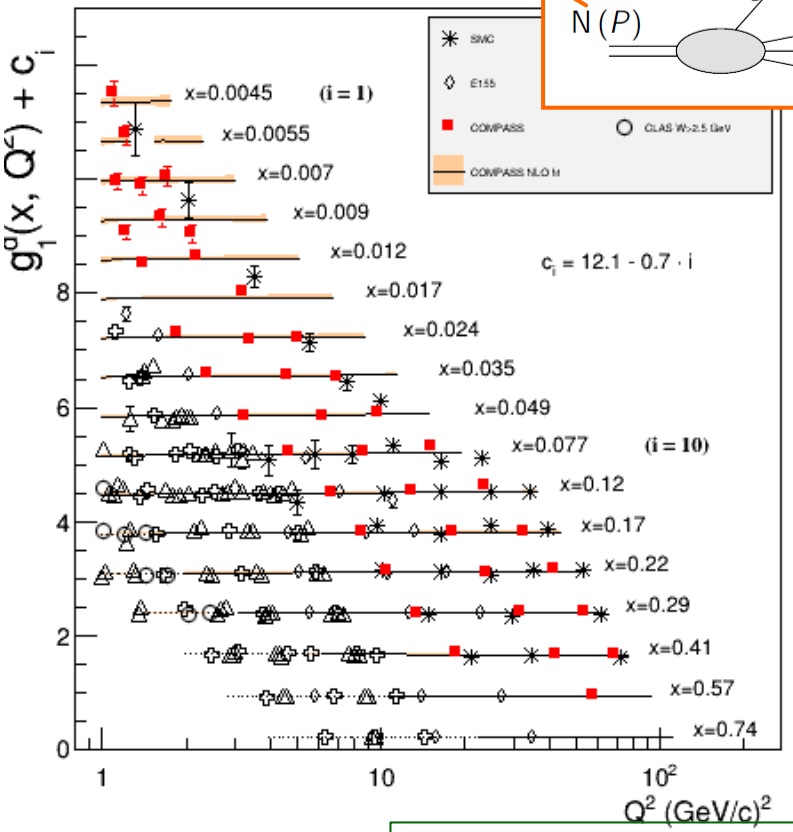
DIS



proton



deuteron



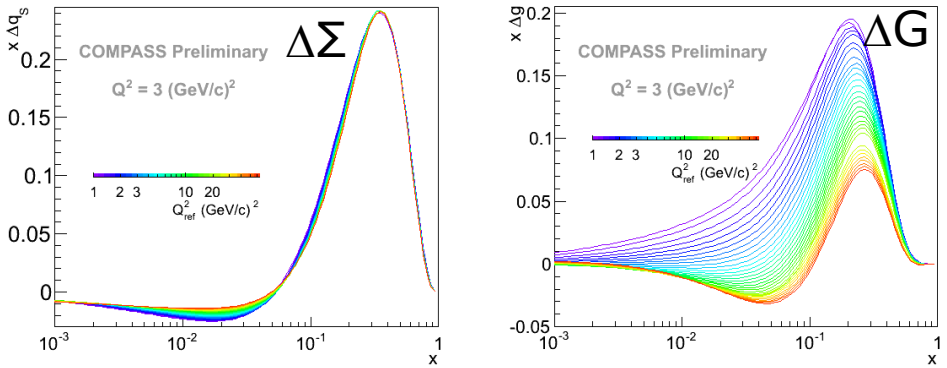
hep-ex/1503.08935
to be published in PLB

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

COMPASS NLO QCD fit to world DIS data

- Need wide coverage in x and Q^2
- Need to assume the functional form of the polarized PDFs $\Delta\Sigma$, ΔG and Δq^{NS}, at a starting Q^2_{ref} $\Delta q_{Si}(x|Q_0^2) = \eta_s x^{\alpha_s}(1-x)^{\beta_s}(1+\gamma_s x)/N_s$
- Fit to g_1 data, using DGLAP for Q^2 evolution → Obtain parametrisations.
- Explore various functional forms of polarized PDF, and wide range for Q^2_{ref}

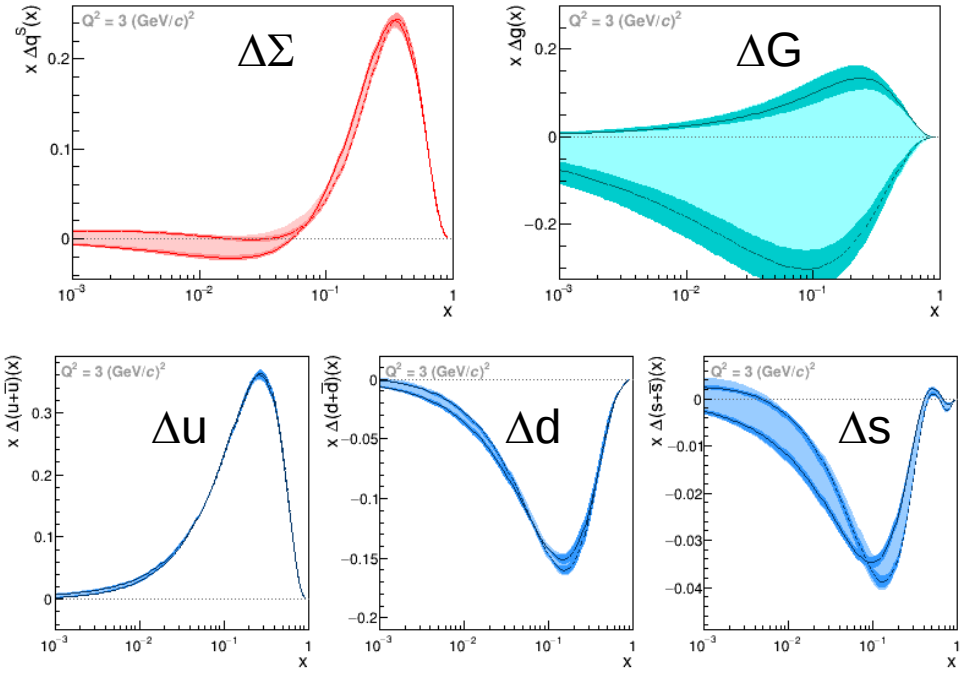
  Example Q^2_{ref} varied between 1 and 60 (GeV/c)²:



All give similar good $\chi 2$. Does not affect much $\Delta\Sigma$, does change ΔG (~ equivalent to changing the functional form).

COMPASS NLO pQCD fit of g_1 world data

→ 2 classes of solutions, ΔG>0 and ΔG<0



using different functional shapes and Q^2_{ref}

$$0.82 \leq \Delta U \leq 0.85$$
$$-0.45 \leq \Delta D \leq -0.42$$
$$-0.11 \leq \Delta S \leq -0.08$$

hep-ex/1503.08935
to be published in PLB

- Quark spin contribution : $0.26 < \Delta\Sigma < 0.36$ at Q^2=3 (GeV/c)^2

Largest uncertainty comes from the bad knowledge of functional forms.

Result in fair agreement with other global fits

- Gluon spin contribution: ΔG not well constrained, even the sign, using DIS only
  Solution with ΔG>0 agrees with result from DSSV++ using RHIC pp data

Results for Bjorken sum rule from g_1 COMPASS data

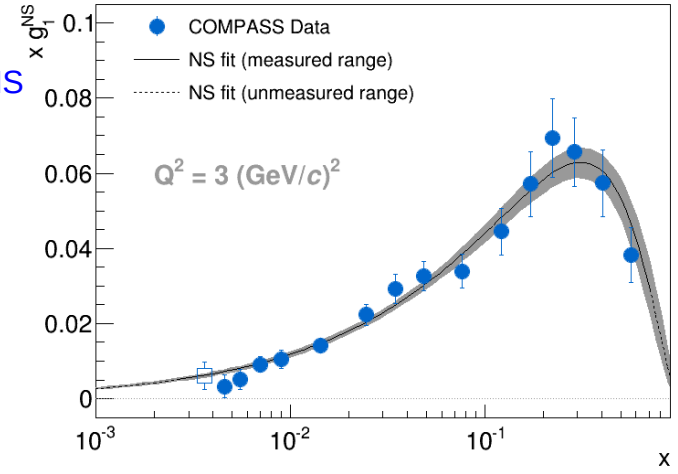
Fundamental QCD sum rule, which relates proton and neutron spin structure functions g_1. $\int_0^1 \left(g_1^p(x,Q^2) - g_1^n(x,Q^2)\right) dx = \frac{1}{6} \mid \frac{g_A}{g_V} \mid C_1^{NS}(Q^2)$

Using COMPASS data alone:

- Non-singlet fit: independent from ΔG
- Reduce systematics

94% of the sum is from the measured range

xg_1^{NS}



x

COMPASS $(g_A/g_V)_{NLO} = 1.22 \pm 0.05 \pm 0.10$

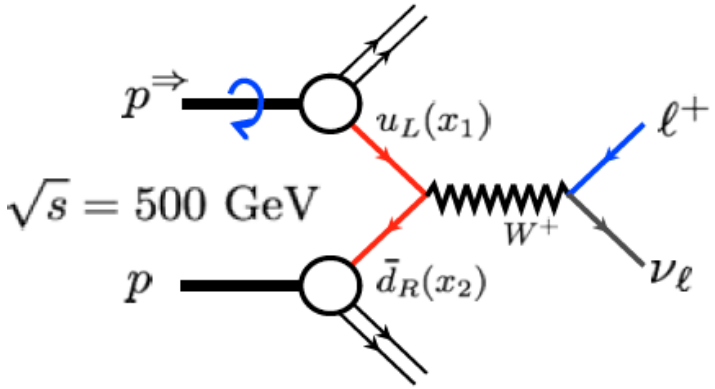
neutron β decay $|g_A/g_V| = 1.269 \pm 0.002$

→ **Bjorken sum rule verified to 8%**

Better statistics and extended systematics studies compared to past

Note that experimental value increases from 1.22 to 1.25 when C_1^{NS} at NNLO

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

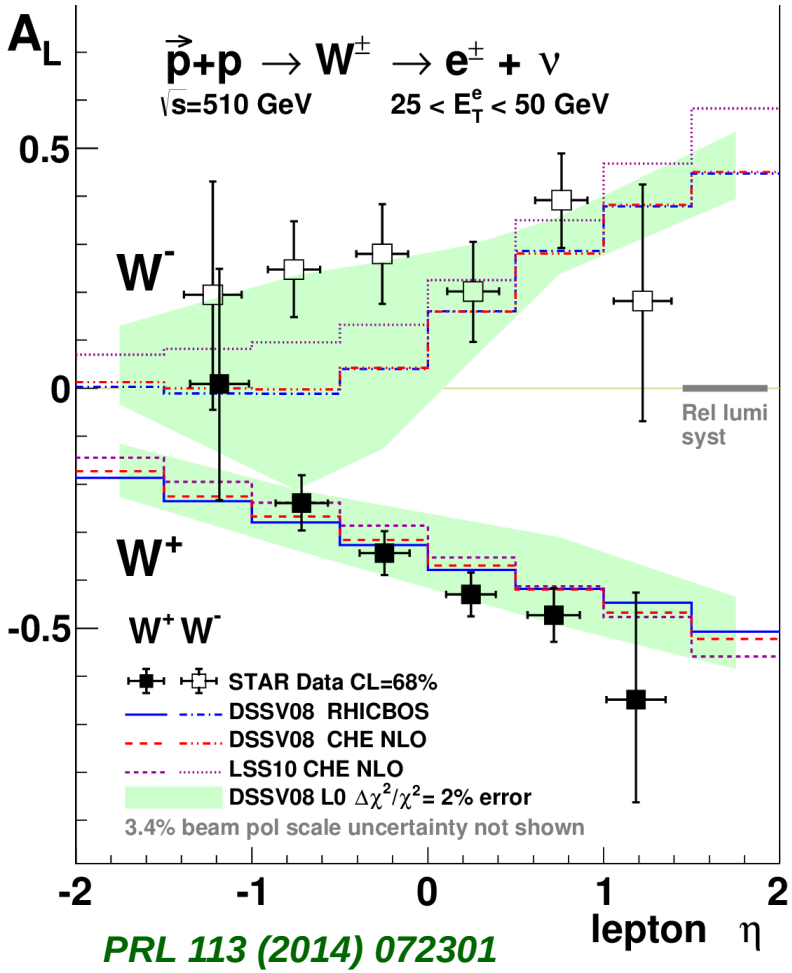


$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu \quad \rightarrow \quad \Delta\bar{d}$$

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

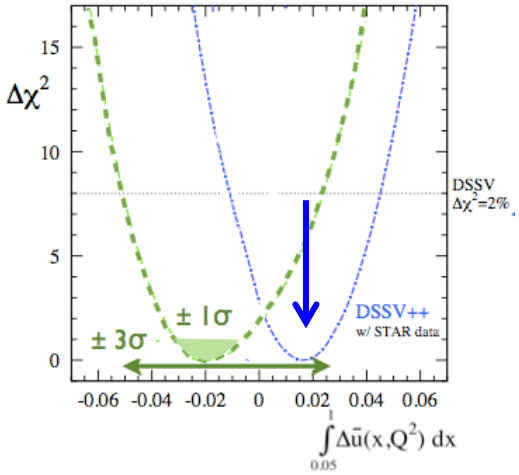
- Single spin asymmetry - STAR and PHENIX
- Parity violating
- No quark fragmentation function needed
- High energy scale

W results from STAR and global analysis



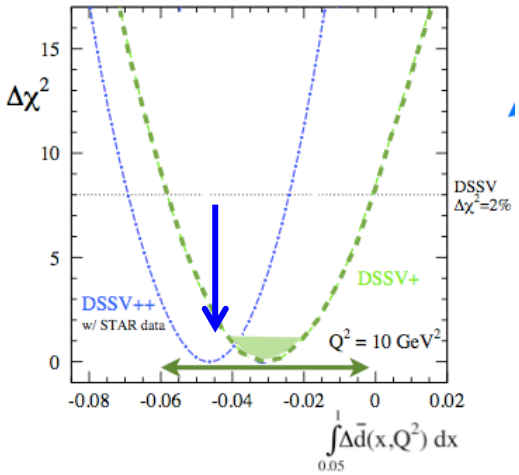
PRL 113 (2014) 072301

→ $\Delta\bar{u}$



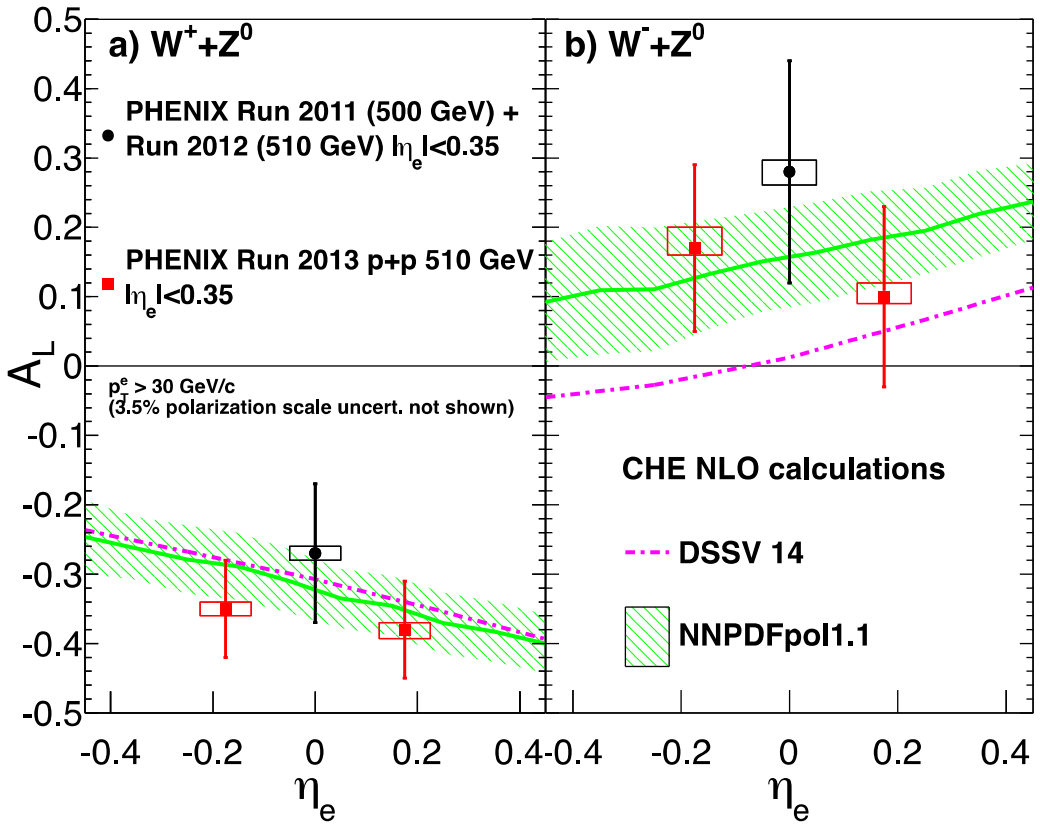
DSSV++, incl.STAR data

→ $\Delta\bar{d}$



- run 11+12, $|\eta_e| < 1.2$
- 0.05 < x < 0.2

PHENIX W^{+-} production

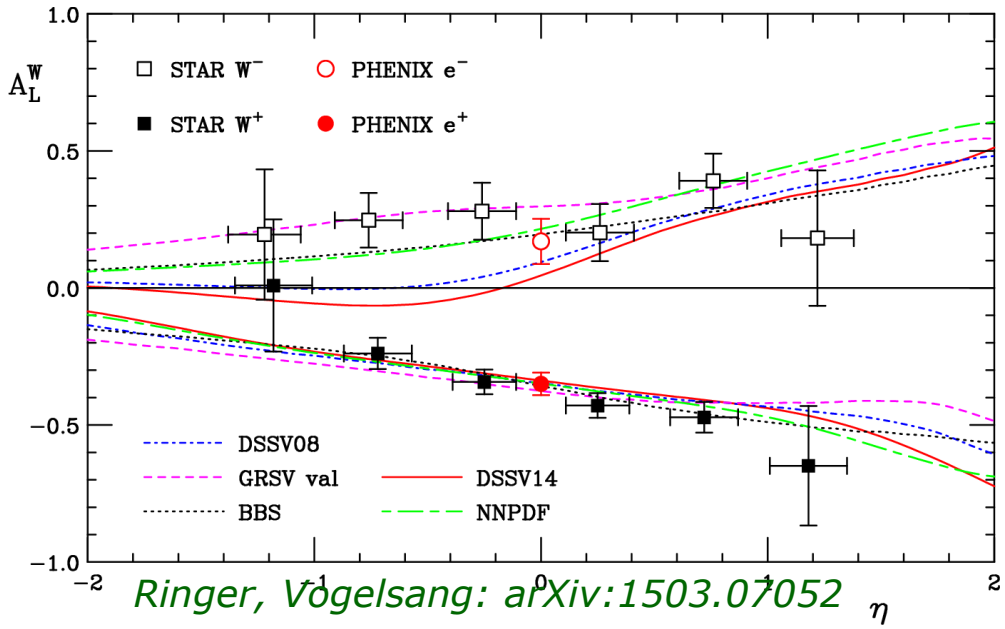


Run 12+13, $|\eta| < 0.35$ *arXiv:1504.07451*

Also larger A_L for W^-
wrt to DSSV14

recent NNPDF1.1
includes RHIC W data

W+- prod. from STAR and PHENIX and QCD fits



Ringer, Vogelsang: arXiv:1503.07052

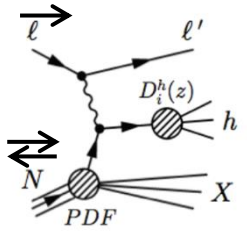
- -NNPDF1.1
— DSSV14

- - GRSV

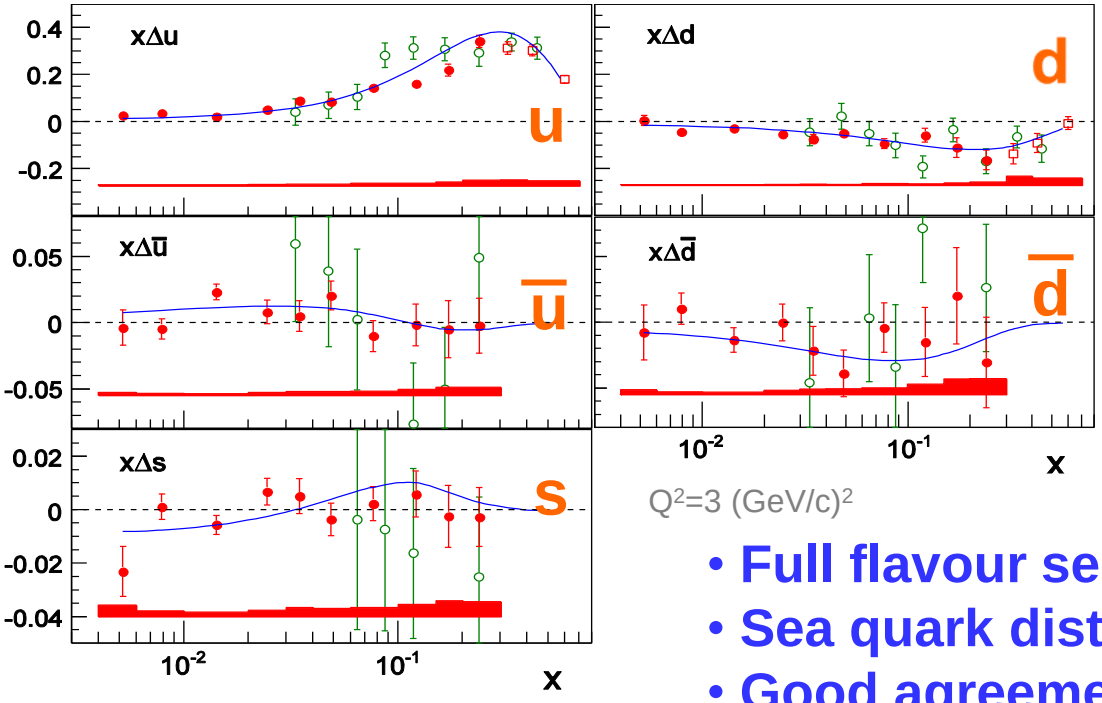
Quark helicities from semi-inclusive DIS

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

Hadron tags quark flavor
(quark fragmentation functions)



Leading order extraction of quark helicities from spin asymmetries:



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

- **COMPASS**

PLB693(2010)227, using DSS quark FFs

o **HERMES**

PRD71(2005)012003

__ DSSV at NLO

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

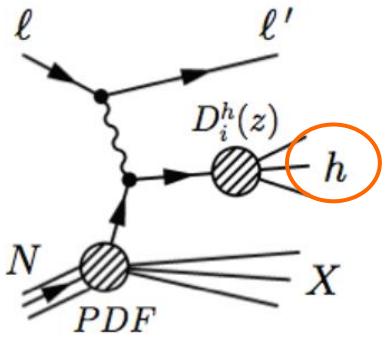
- What about **Δs**? for which the integral is found negative from inclusive data (with SU3)?
- Here from SIDIS data, x> ~ 0.005, Δs compatible with zero. Lower x?
- NB: The extraction assumes quark Fragmentation Functions known (DSS here)

Quark Fragmentation Functions (FF)

FFs : - Non perturbative object; needed to describe various reactions

- Strange quark FF= **largest uncertainty in Δs extraction** from polarized SIDIS. Data exist from e^+e^- and pp reactions, but unsufficient and at too high Q^2

→ Measure π, K, p multiplicities in **SIDIS** $\mu^+ d \rightarrow \mu^+ h^\pm X$



$z = E_h/(E_\mu - E_\mu')$

PDFs FFs

$$\frac{dM^h(x,Q^2,z)}{dz} \underset{\text{at LO}}{=} \frac{\sum_q e_q^2 f_q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 f_q(x,Q^2)}$$

PDFs depend on *x*, while FFs depend on *z*

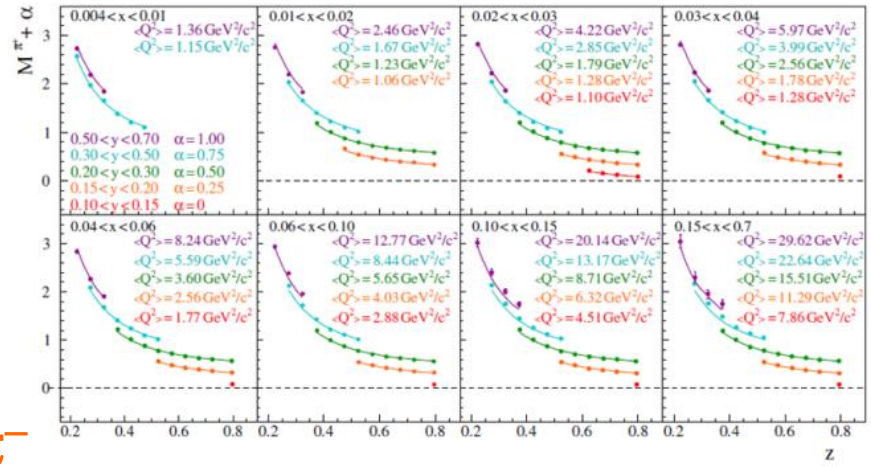
Data obtained in a fine binning in x, z, Q^2

→ **Constitute an input to global NLO QCD analyses to extract quark FFs**

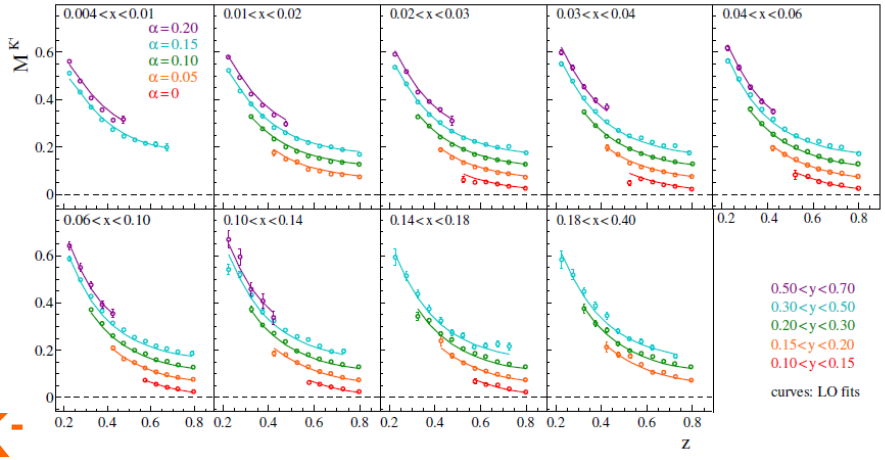
COMPASS π and K multiplicities vs z in (x,y) bins

preliminary

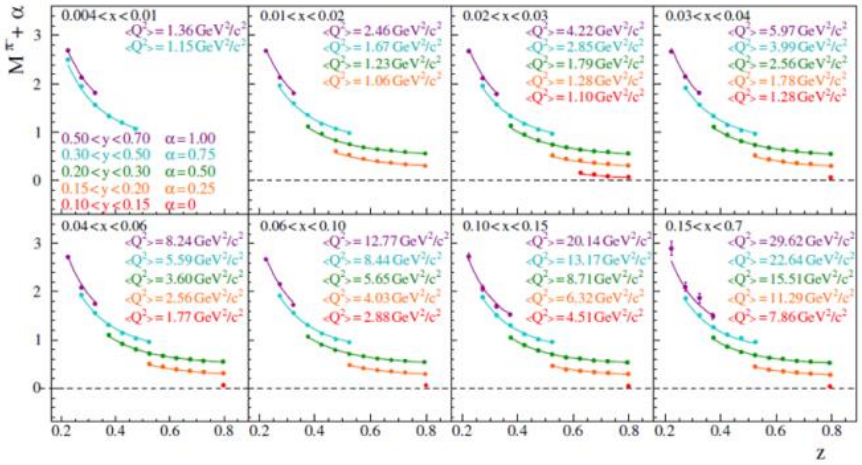
π^+



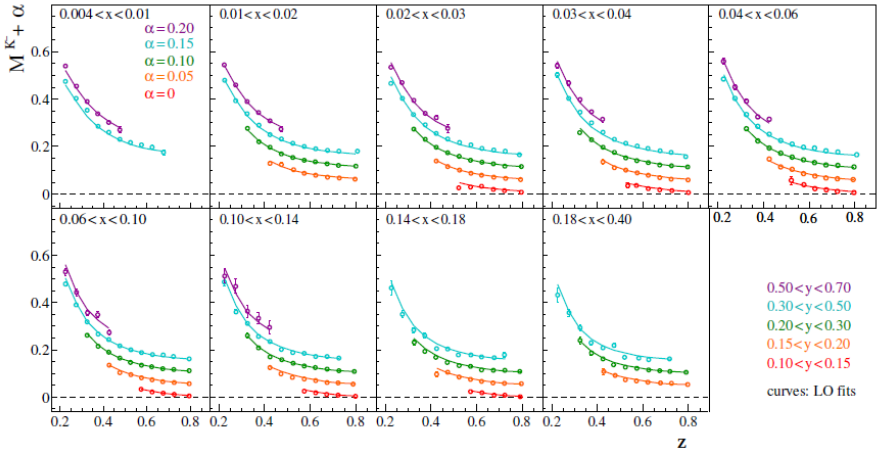
K^+



π^-



K^-



- ~400 data points for π and 400 for K
- Strong z dependance
- $M\pi^+ \sim M\pi^-$ and $MK^+ > MK^-$

Extraction of quark FFs from COMPASS LO fits

- Assume isospin and charge symmetry:

Pions : 2 independent FFs

$$D_{\text{fav}}^{\pi} = D_u^{\pi^+} = D_{\bar{d}}^{\pi^+} = D_{\bar{d}}^{\pi^-} = D_{\bar{u}}^{\pi^-}$$

$$D_{\text{unf}}^{\pi} = D_{\bar{d}}^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_{\bar{u}}^{\pi^-} = D_{\bar{d}}^{\pi^-}$$

Assume also $D_s^{\pi^+} = D_s^{\pi^-} = D_{unf}^{\pi^+}$

Kaons : 3 independent FFs

D_{fav}^{K}

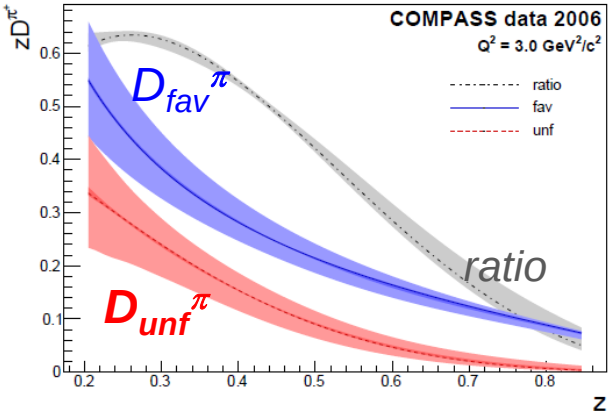
D_{unf}^{K}

D_{str}^{K}

- Choose functional forms for FFs (z); Chose PDF set ; use DGLAP for Q^2 evolution
- Fit π^+ and π^- multiplicity data and extract the independent FFs
- Idem for Kaons

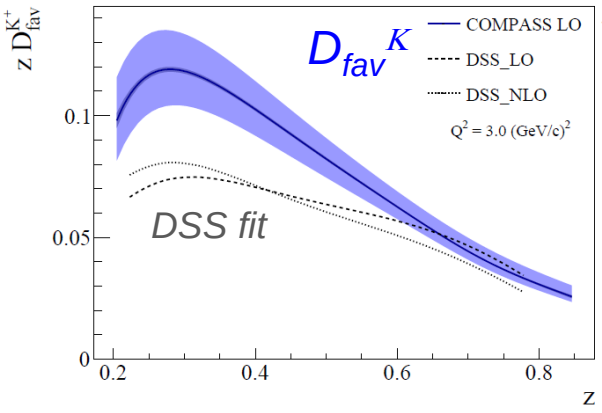
Quark FFs from COMPASS LO fits

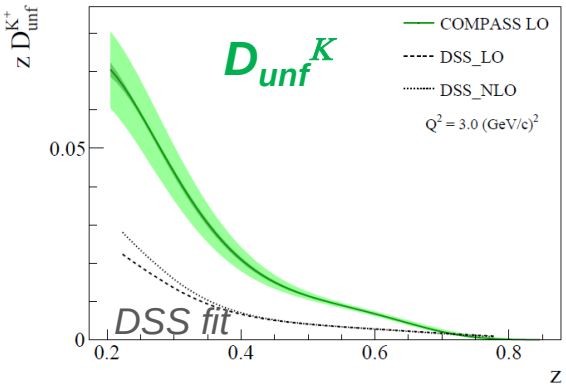
Pions



- As expected, $D_{fav} > D_{unf}$.
- COMPASS results ~agree with DSS and LSS NLO fits (not shown here)

Kaons





- $D_{fav} > D_{unf}$.
- D_{fav} and D_{unf} **larger than DSS and LSS NLO fits** (which do not include these kaon data)
- D_{str}^{K} **unstable** (not shown; depends on choice of functional form)

Sum of *z* integrated multiplicities $\pi^+ + \pi^-$ & $K^+ + K^-$

For isoscalar target, simple dependence on FFs:

$$M^{\pi^+ + \pi^-} = (1 - \cancel{2S/(5Q+2S)})\, D_{fav} + D_{unf}$$

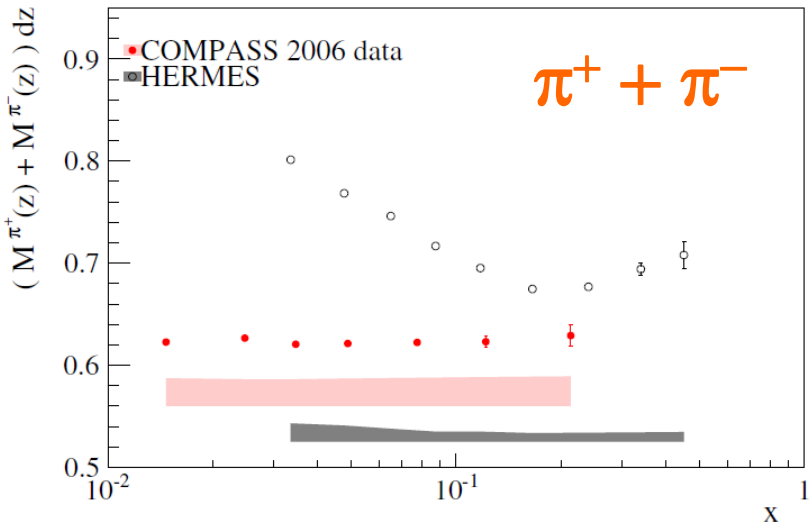
$$5M^{K^+ + K^-} = D_Q^K + S/Q\ D_S^K$$

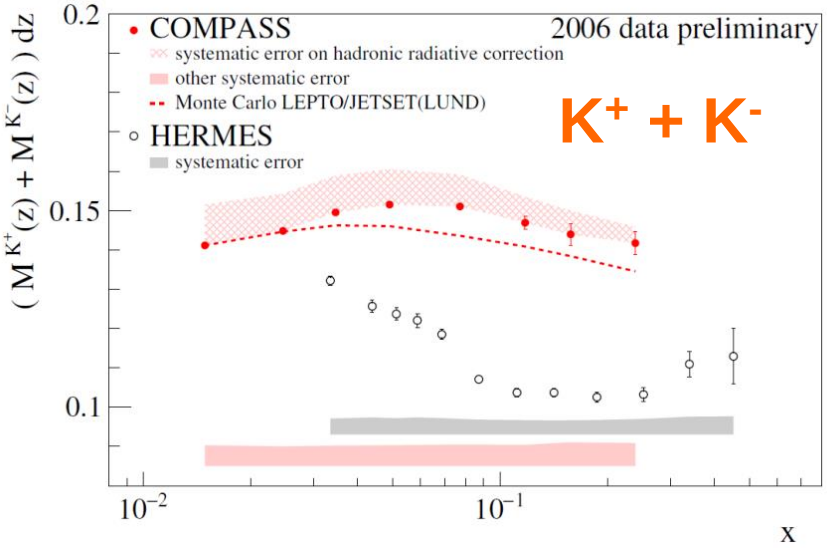
high x data *low x data*

where:

$$\begin{cases} Q = u + \bar{u} + d + \bar{d}, \\ S = s + \bar{s} \\ D_Q^K = 4D_{fav}^K + 6D_{unf}^K \end{cases}$$

~ no *x* dependence expected





COMPASS pion data:

- **significantly below HERMES**
- **no x dependence**

  (as in EMC h, but not shown here)

COMPASS kaon data:

- **significantly above HERMES one**
- **agree with MC simulation (LUND)**
- **Indicate smaller D_S^K, and larger D_Q^K**

Summary

- **ΔG: High impact data from RHIC**
  STAR: pp→ jets and PHENIX pp→ π^0 :
  → $\int_{0.05}^{1} \Delta g(x)\mathrm{d}x \simeq 0.20$ (undetermined at low x).

  COMPASS data at low Q^2 and at high Q^2 also favor ΔG>0.

- **COMPASS NLO QCD fit of g_1 world data:**
  $0.26 < \Delta\Sigma < 0.36$ Uncertainty dominated by initial functional forms
  ΔG : Not constrained enough by DIS data alone

- **Bjorken sum rule from COMPASS p and d data:** Verified to 8%

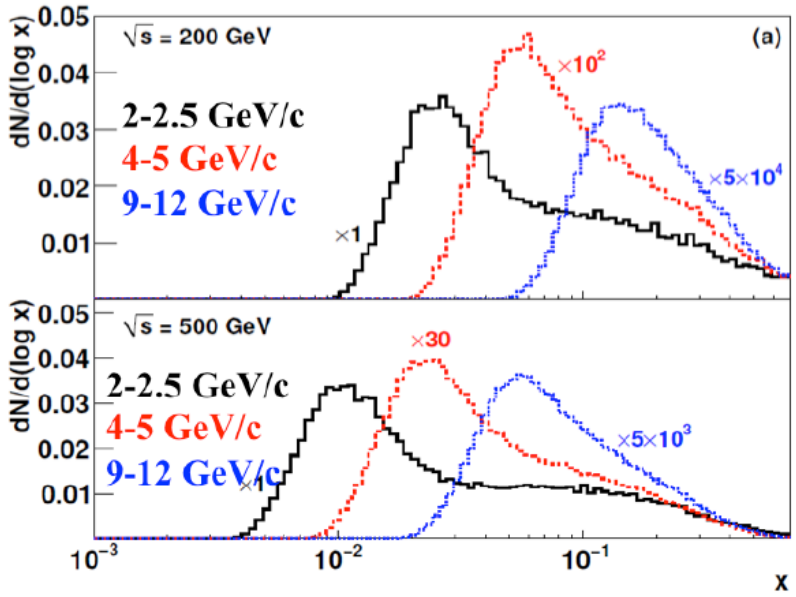
- **RHIC data on W production: constrain $\Delta\bar{u}$ and $\Delta\bar{d}$;** & more to come

- **Quark Fragmentation Functions from LO fit of multiplicities for h^+,h-, π^+, π^-, K^+,K^-** Large discrepancies between COMPASS and HERMES data in the sum of integrated multiplicities. Hint for smaller D_{str}^{K} from COMPASS?

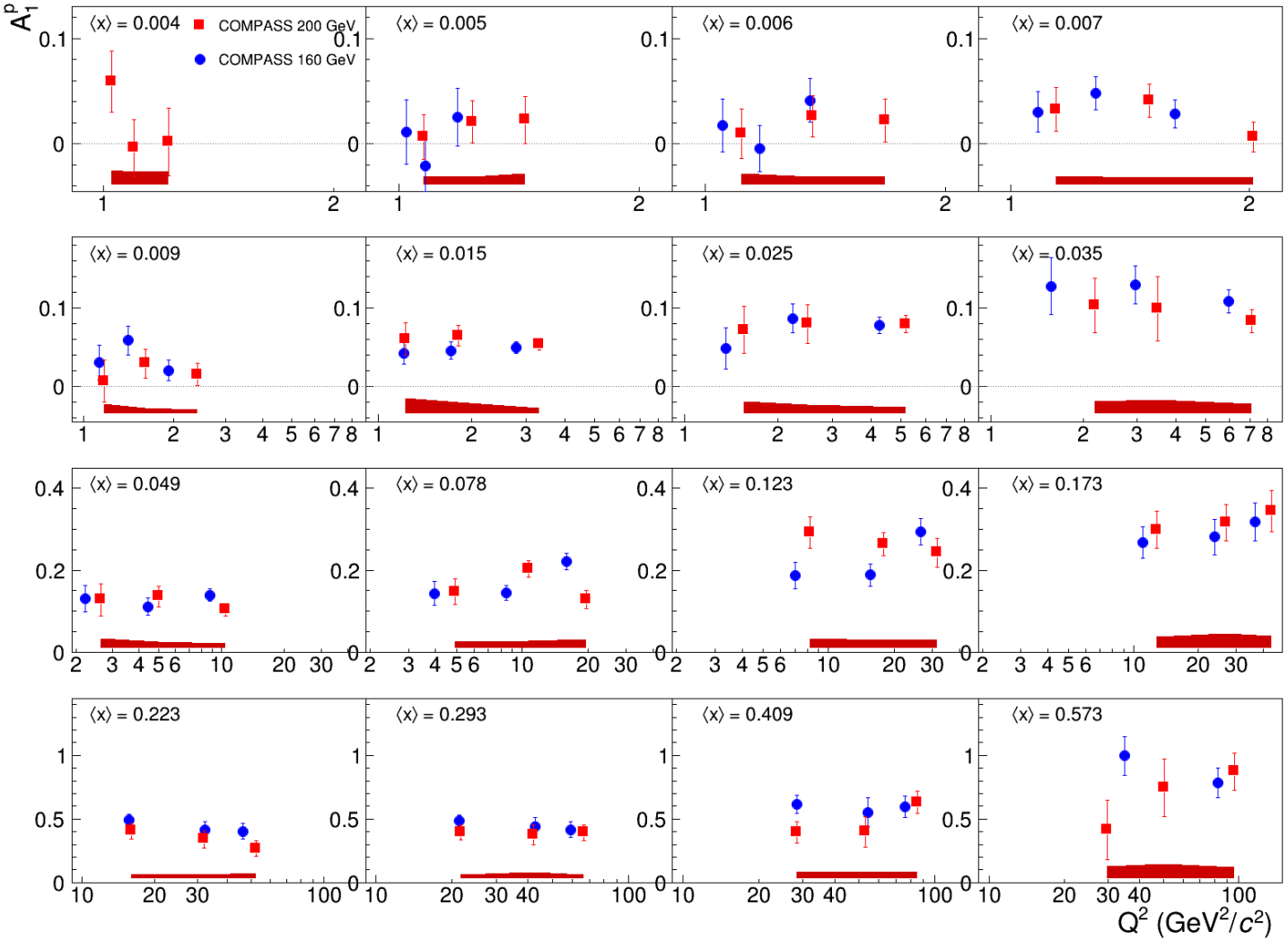
Backup

RHIC

Probed x_g, for various p_T of π^0



A_1^p (Q^2) at various <x>



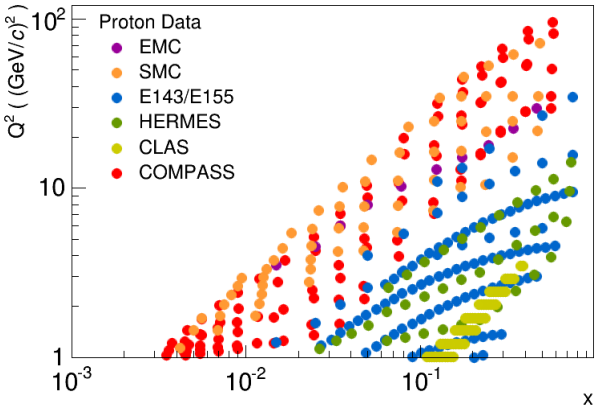
160 and 200 GeV data: no Q^2 dependence observed

hep-ex/1503.08935
to be published in PLB

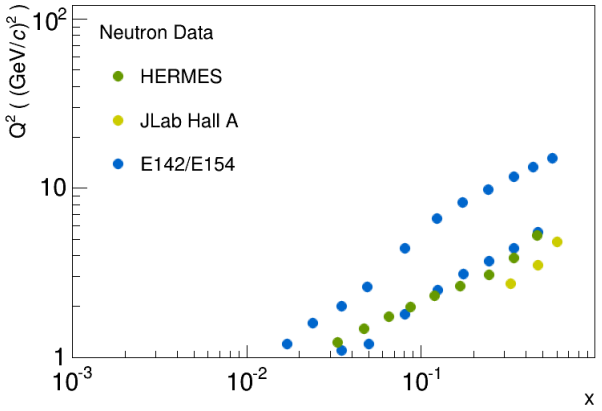
Fit to proton, neutron and deuteron world data

x-Q^2 coverage of world data

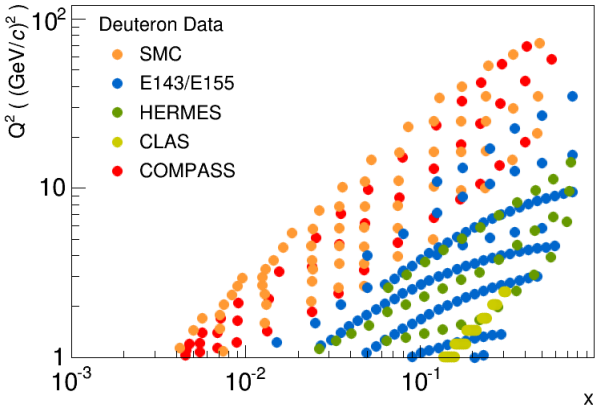
proton



neutron



deuteron



NLO fit:

- Assume functional forms for $\Delta\Sigma$, ΔG and Δq^{NS} at a reference $Q_0^2 = 1(GeV/c)^2$

  e.g.: $\Delta q_{Si}(x|Q_0^2) = \eta_s x^{\alpha_s}(1-x)^{\beta_s}(1+\gamma_s x)/N_s$

- Assume SU_3
- Use DGLAP equations
- Fit world data

  495 points with W>10 GeV

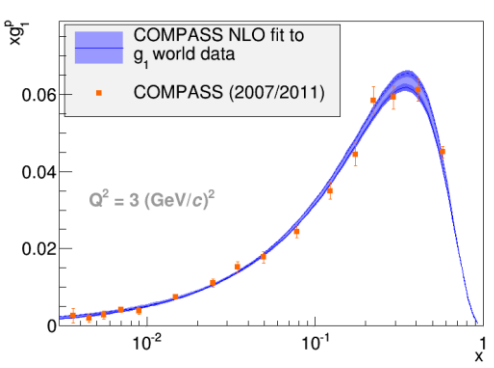
  138 are from COMPASS, 11 free parameters.

g_1^p and g_1^d

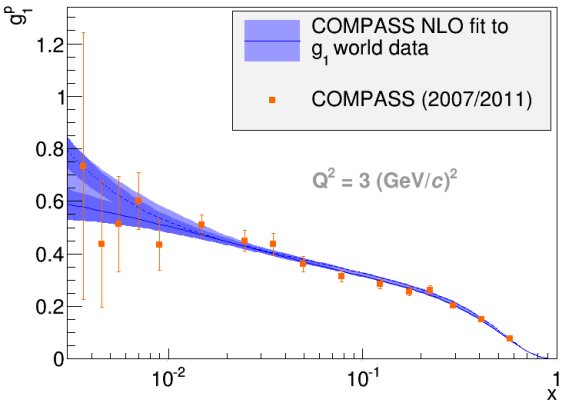
COMPASS data and NLO QCD fit to world data

- - - $\Delta G < 0$ solution
____ $\Delta G > 0$ solution

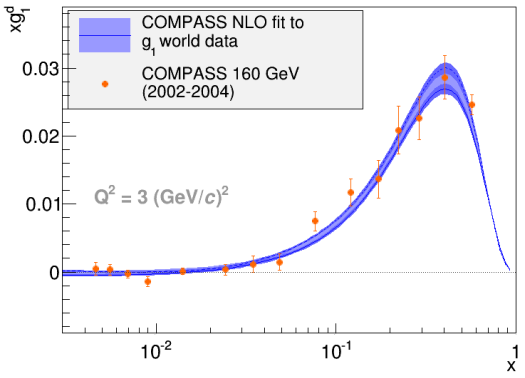
xg_1^p



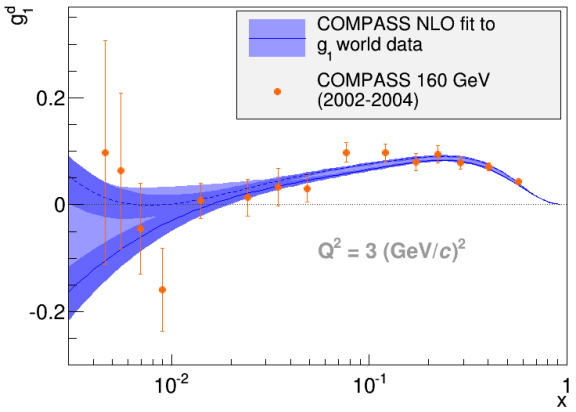
g_1^p



xg_1^d



g_1^d

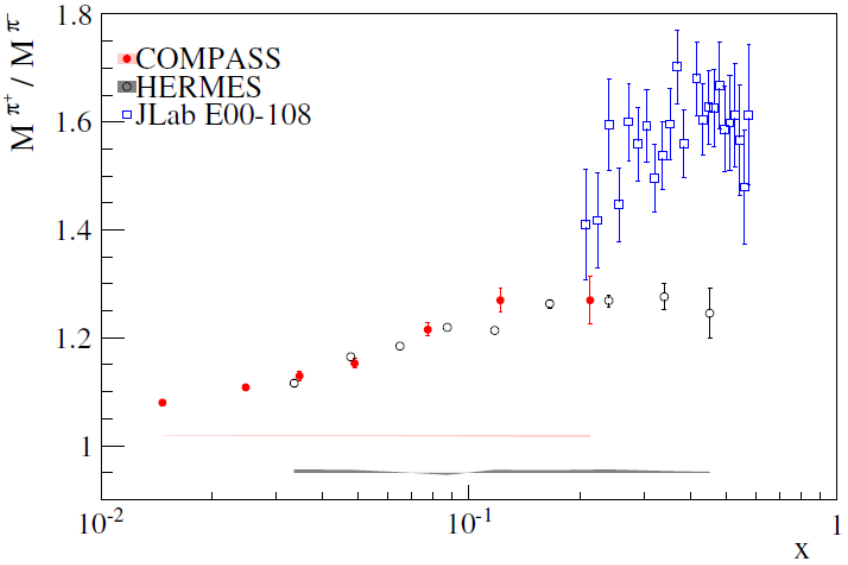


- **g_1^p positive at low x**
- **Lower x data needed for sensitivity to ΔG**

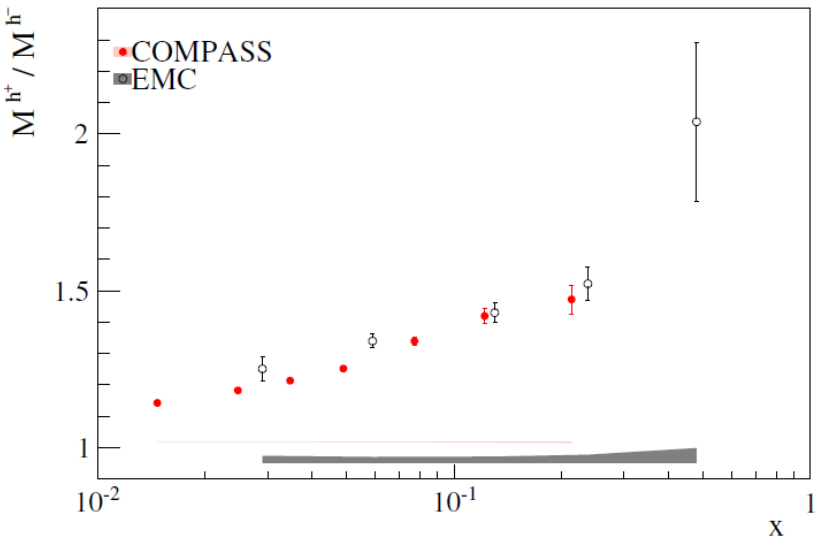
Ratio of z integrated multiplicities π^+ / π^-

Interesting because many systematic errors cancel in the ratio

π^+ / π^-



h^+ / h^-



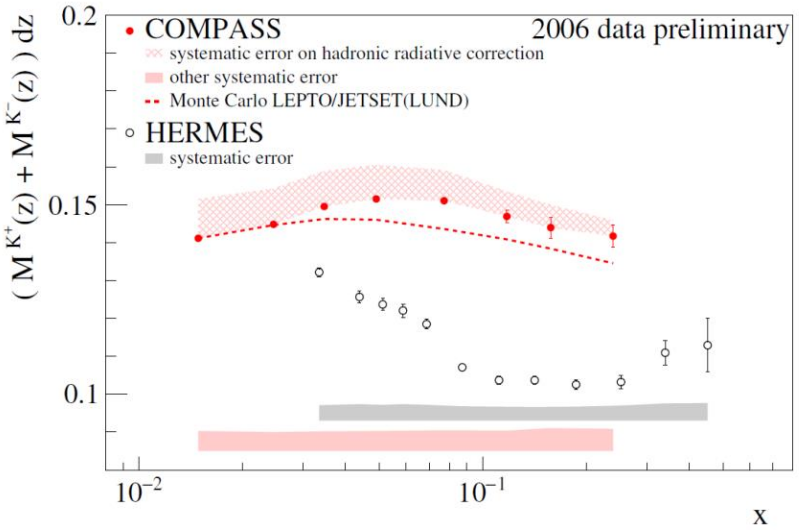
Pions:

- Good agreement COMPASS-HERMES.
- Jlab data higher, but at lower W

Hadrons:

Good agreement COMPASS - EMC.

Sum of *z* integrated multiplicities $K^+ + K^-$



$$5M^{K^+ + K^-} = D_Q^K + S/Q\ D_S^K$$

high x *low x data*

where: $\begin{cases} D_Q^K = 4D_{fav}^K + 6D_{unf}^K \\ Q = u + \bar{u} + d + \bar{d} \\ S = s + \bar{s} \end{cases}$

- **COMPASS data significantly above HERMES one**
- **agree rather well with MC simulation LEPTO+JETSET (LUND)**

Hints on kaon fragmentation functions:

$\int D_Q^K$

from these data at high x: **0.70**
from DSS analysis: **0.43**

***D_Q^K* COMPASS result >> DSS** one, as seen in LO fit where D_{fav} and D_{unfav} both larger for COMPASS than DSS

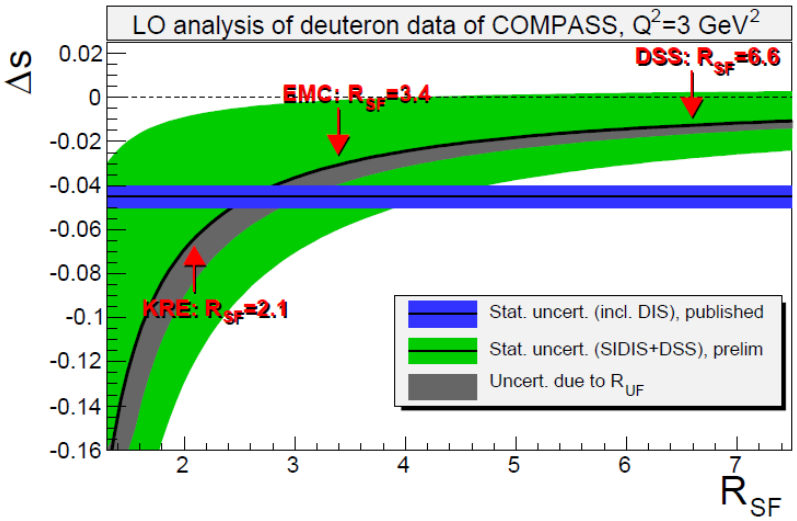
$S/Q \int D_S^K$

Low x data, agree well with MC/Lund
Suggest much lower *D_{str}* than DSS

Quark Fragmentation Functions (FF)

- Non perturbative objects
- Process independent
- Needed to access strange quark polarization Δs from polarized SIDIS.

strange quark FF = largest uncertainty in this extraction



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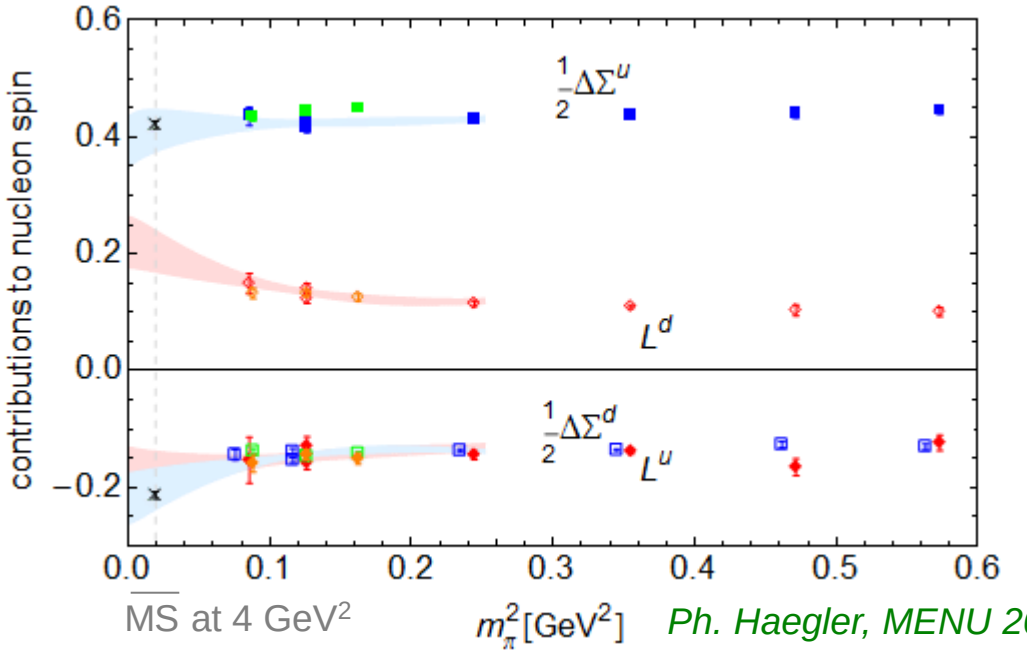
Lattice : quark spin and angular momentum



Ph. Haegler, MENU 2010

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