Nucleon spin and parton distribution functions

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Hadron 2011, Munich

Motivation

Motivation I:

Where does the Nucleon Spin come from?

$$\frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_G$$

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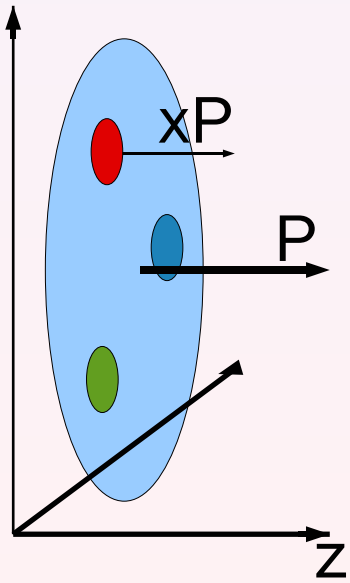

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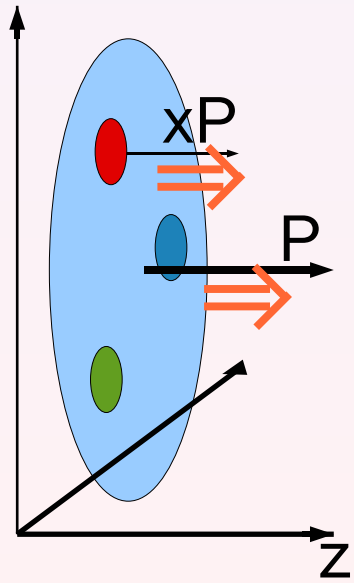

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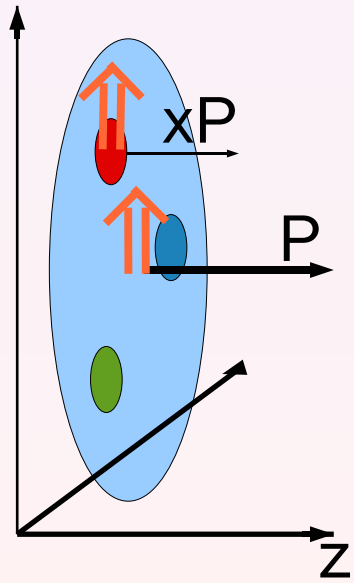

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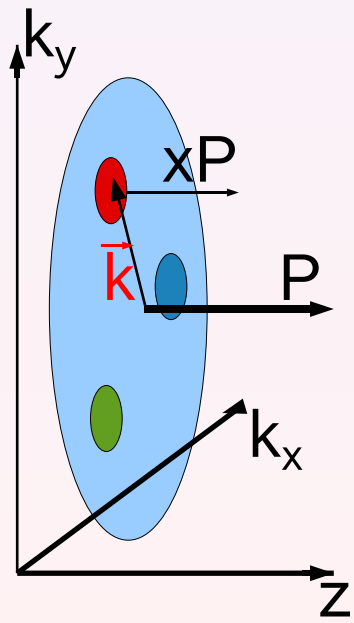

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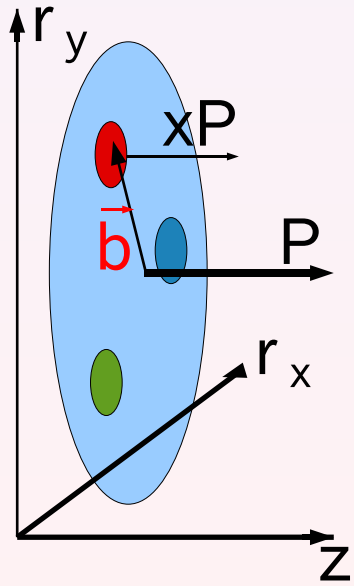

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$$\Delta\Sigma = \int_0^1 \Delta u(x) + \Delta\bar{u}(x) + \Delta d(x) + \Delta\bar{d}(x) + \Delta s(x) + \Delta\bar{s}(x)\mathrm{d}x$$

$$\Delta G = \int_0^1 \Delta g(x)\mathrm{d}x$$

L_q related to TMDs

$\Delta\Sigma + L_q$ related to GPDs

Outline

- Motivation
- Helicity distribution of quarks and gluons
  mainly results from deep inelastic scattering
  (polarized $pp \Rightarrow$ E. Aschenauer)
- Transversity distributions & Transverse Momentum Dependent (TMD) distributions
  mainly asymmetries
  (extraction of TMDs $\Rightarrow$ M. Anselmino)
- Future measurements

Helicity Distributions

What do we know?

- helicity contribution of quarks to nucleon spin: $\Delta\Sigma \approx 30\%$
  But how do contributions of different flavors
  $\Delta q(\mathbf{x}), q = u, d, s, \bar{u}, \bar{d}, \bar{s}$ look like?
- gluon helicity distribution $\Delta G = \int_0^1 \Delta g(x)\mathrm{d}x$ small?
  But how small? How does $\Delta g(\mathbf{x})$ look like?

Helicity distributions

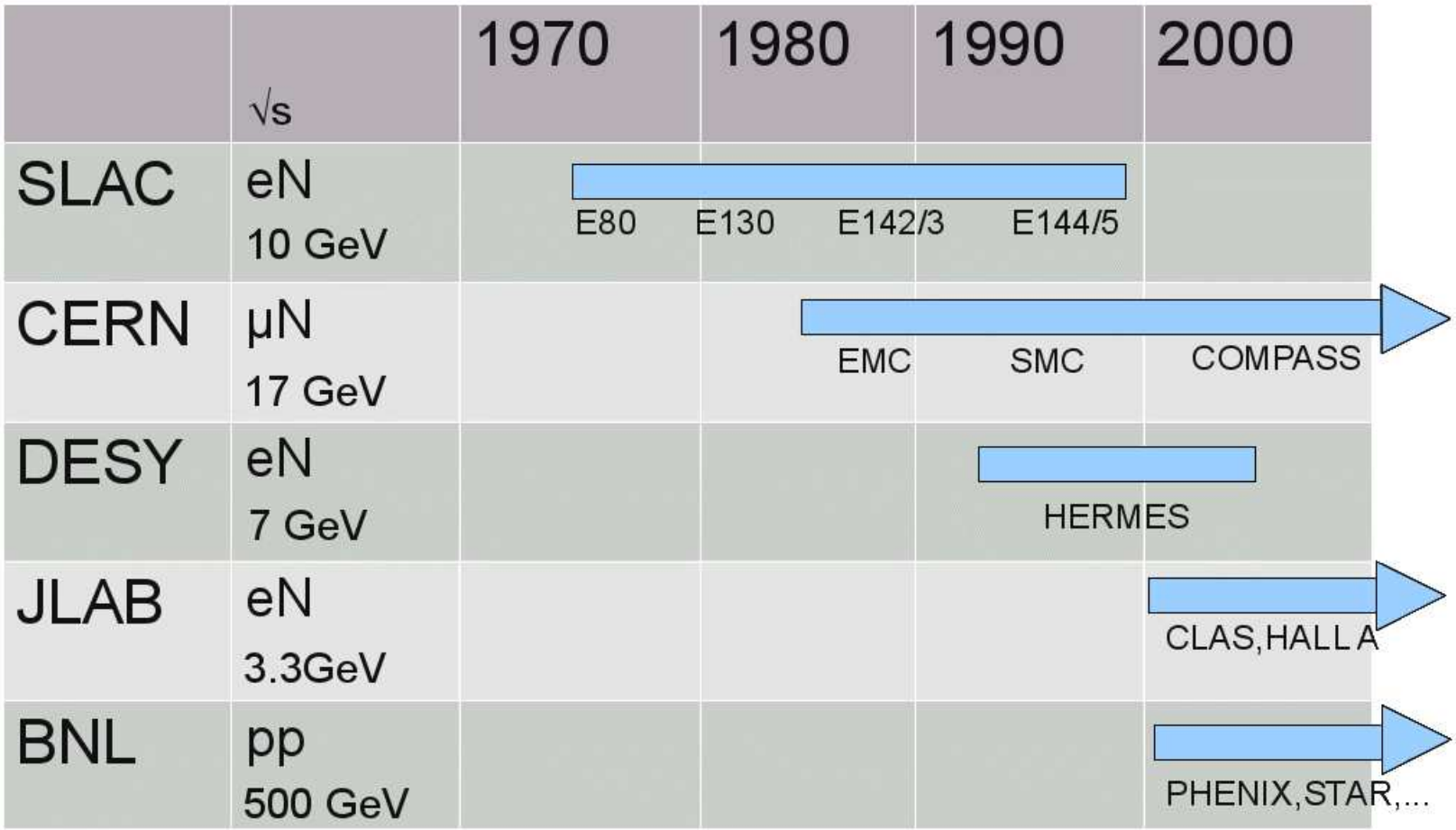
How can they by measured?

> Find a process where one probes interaction with quark/gluon of a given polarization with respect to the parent nucleon.

Can be done in two ways, using

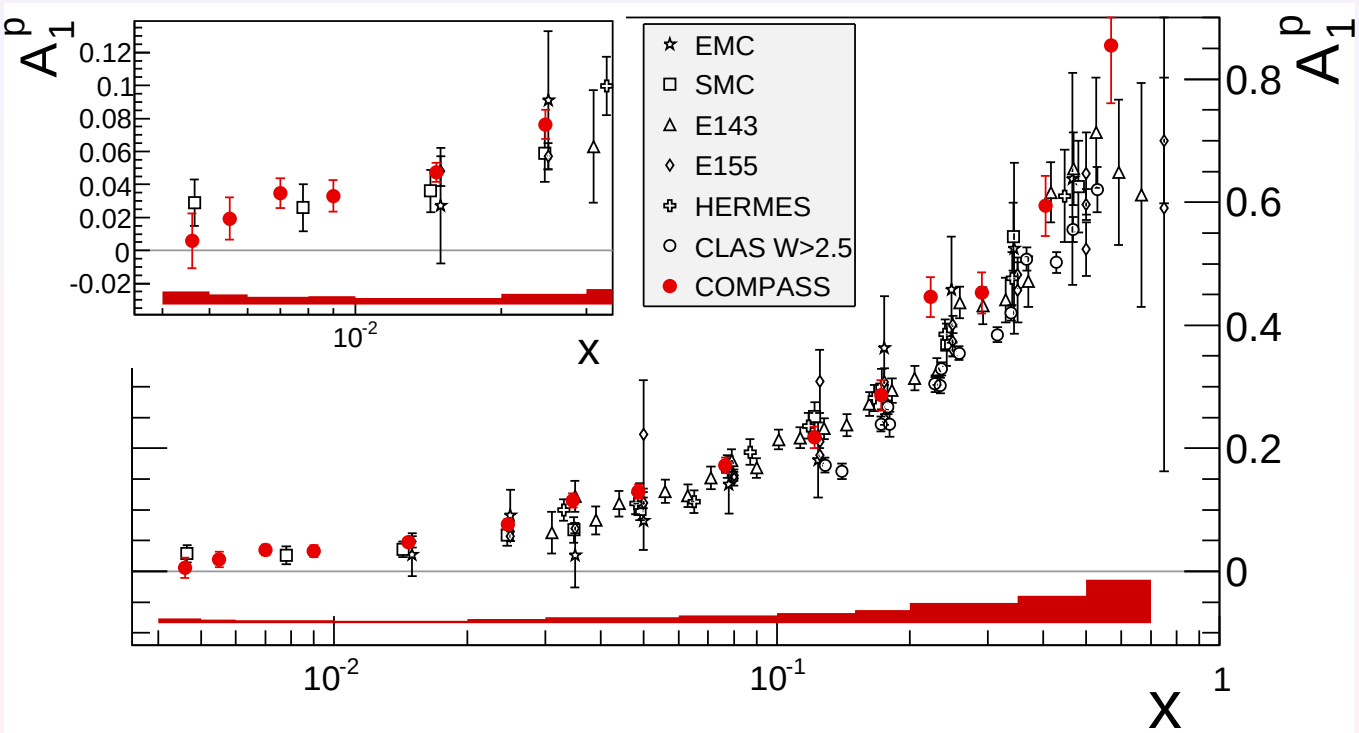
1. double polarization
   in Deep Inelastic Scattering: $\vec{\ell} + \vec{N} \to \ell' + \text{hadrons} + X$
   Proton-Proton Scattering: $\vec{p} + \vec{p} \to \text{Jet}/\gamma/\text{hadrons} + X$
2. single polarization & weak interaction:
   $\vec{p} + p \to W^{\pm} \to e^{\pm} + \nu$

Experiments



Proton Asymmetry

$$\vec{\ell}(k) + \vec{N}(p) \to \ell'(k') + X(P_X)$$



$Q^2 = -(k - k)^2$

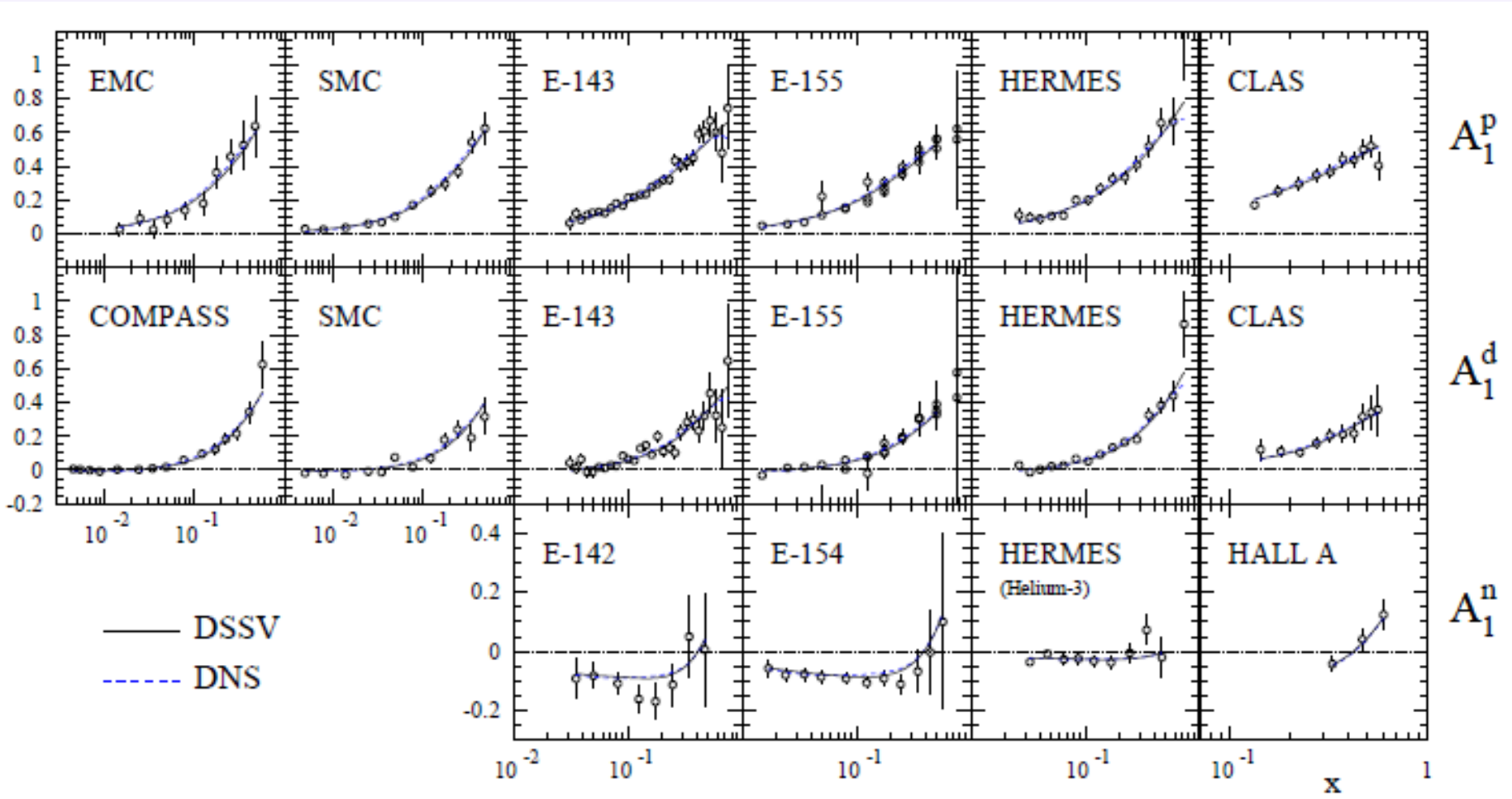
$Q^2 > 1$ GeV^2

$x = \frac{Q^2}{2p\cdot(k-k')}$

good agreement, although different Q^2 at same x

$$\frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} \propto A_1^p = \frac{g_1^p}{F_1^p} = \frac{4(\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s})}{4(u+\bar{u}) + (d+\bar{d}) + (s+\bar{s})}$$

Stamp Collection: inclusive asymmetries



Result on first moments $\Delta q = \int_0^1 \Delta q(x) \mathrm{d}x$

using inclusive & semi-inclusive asymmetries, $\vec{p}\vec{p}$, neutron & hyperon decay:

		global analysis[1)]	
$\Delta\Sigma$	$=$	0.25 ± 0.05	
$\Delta u + \Delta\bar{u}$	$=$	0.81 ± 0.03	
$\Delta d + \Delta\bar{d}$	$=$	-0.46 ± 0.03	
$\Delta s + \Delta\bar{s}$	$=$	-0.11 ± 0.06	

at $Q^2 = 10\mathrm{GeV}^2$

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up to now only information on first moments of $\Delta q + \Delta\bar{q}$, because $e_q^2 = e_{\bar{q}}^2$

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Helicity distributions

How to separate contributions from $\Delta q(x)$ and $\Delta\bar{q}(x)$?

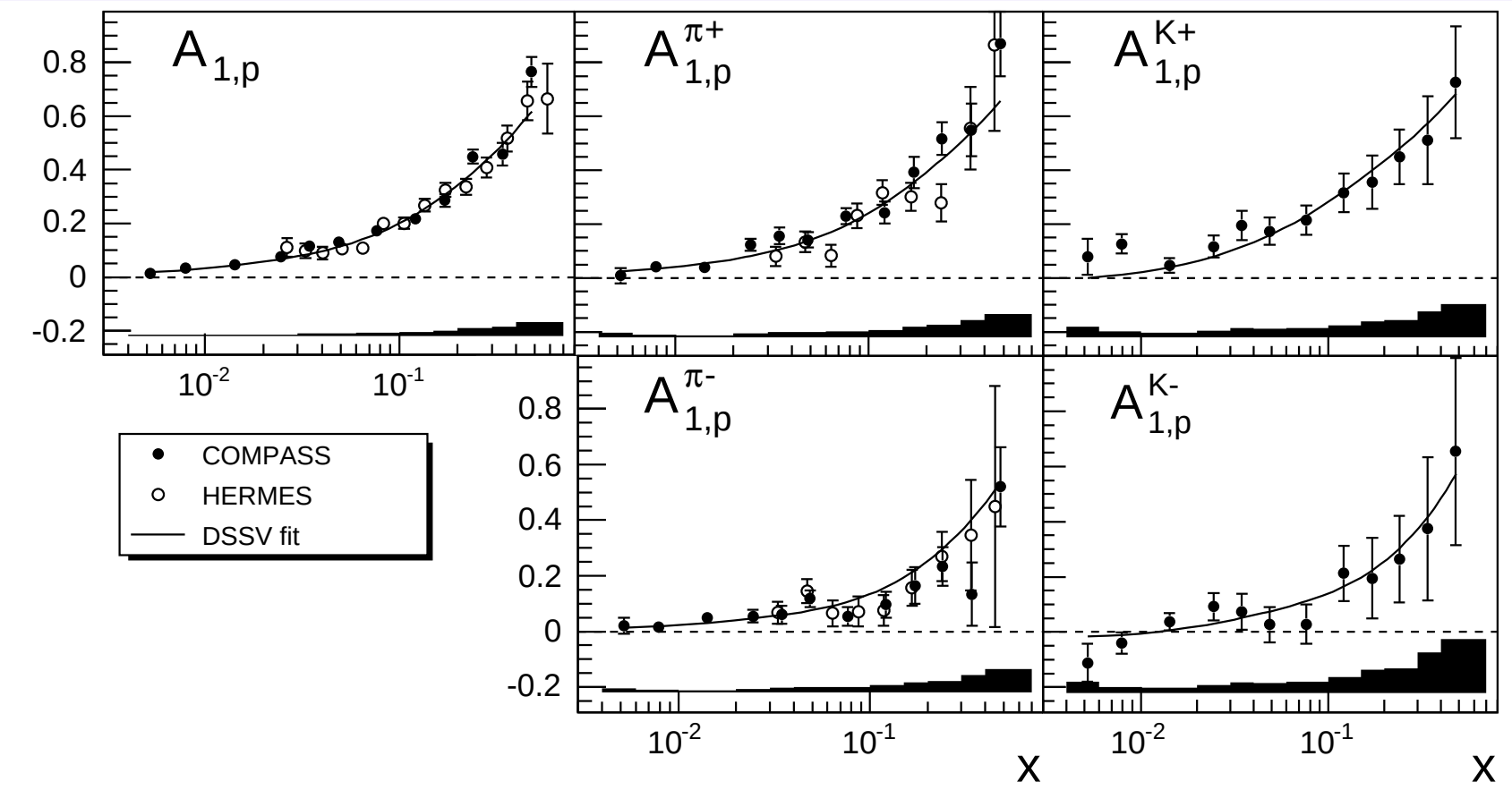
Principle:
Measure double spin asymmetries of various hadronic final states h in $\vec{\ell} + \vec{N} \to \ell' + X + \textit{hadrons}$

$$\frac{N_h^{\uparrow\downarrow} - N_h^{\uparrow\uparrow}}{N_h^{\uparrow\downarrow} + N_h^{\uparrow\uparrow}} \propto A^h = \frac{\sum_q e_q^2 \left(\Delta q(x) D_q^h(z) + \Delta\bar{q}(x) D_{\bar{q}}^h(z)\right)}{\sum_q e_q^2 \left(q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z)\right)}$$

- D_q^h: fragmentation function
- $D_q^h(z)\mathrm{d}z$ = number of hadrons of type h produces from a quark q with energy fraction in $[z, z + \mathrm{d}z]$
- $D_u^{\pi^+} > D_{\bar{u}}^{\pi^+}$
- Kaon asymmetries are for example are sensitive to Δs

(→ N. Makke, Tue 16.50)

Semi-Inclusive Asymmetries



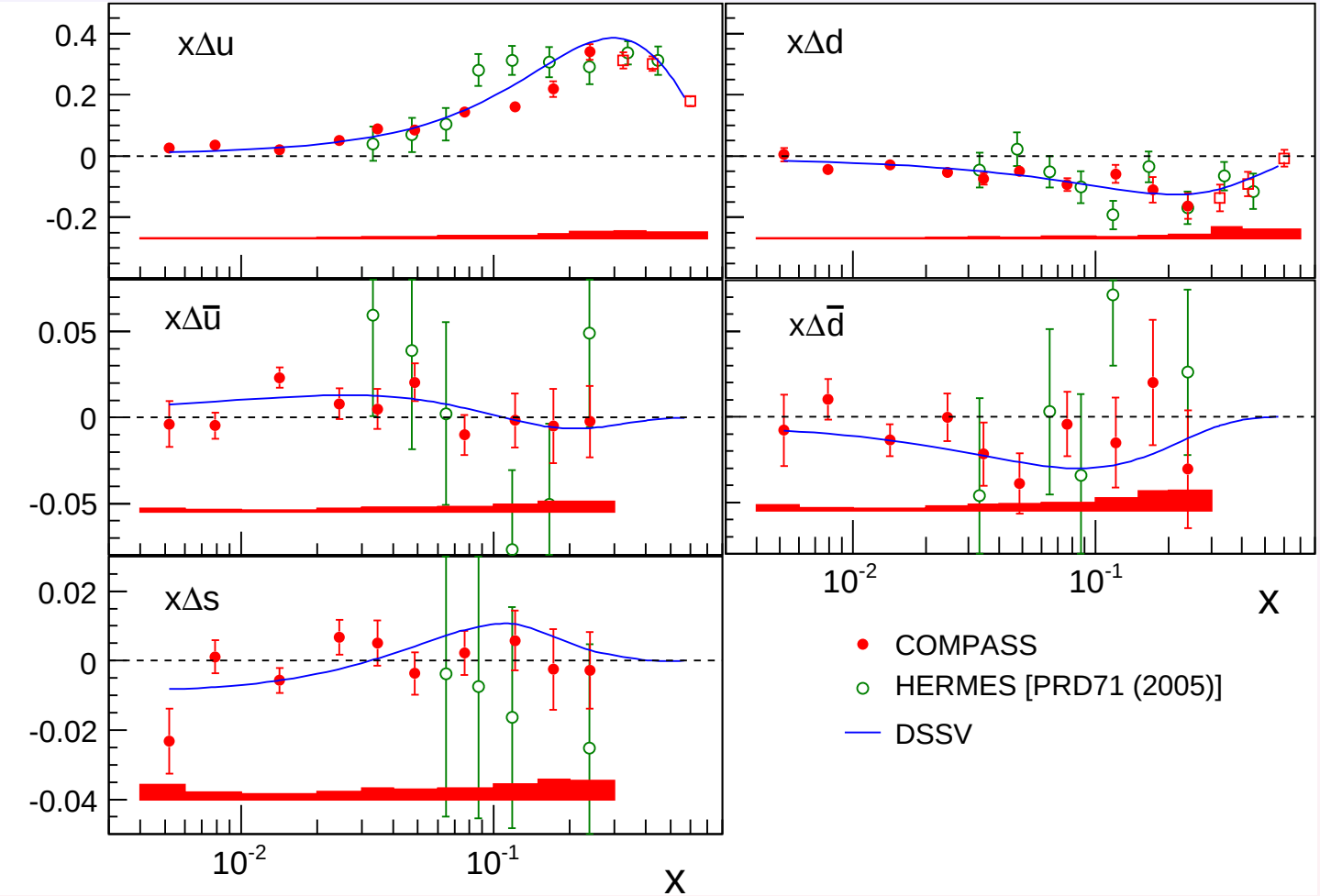
Asymmetries $\rightarrow \Delta q$ in LO QCD

Solve:

$$\vec{A} = B\Delta\vec{q}$$

- $\vec{A} = (A_{1,p}, A_{1,p}^{\pi^+}, A_{1,p}^{K^+}, \ldots, A_{1,d}, \ldots, A_{1,d}^{K^-})$
- $\Delta\vec{q} = (\Delta u, \Delta d, \Delta s, \Delta\bar{u}, \Delta\bar{d}, \Delta\bar{s})$
- $B(q, \int D_q^h \mathrm{d}z)$

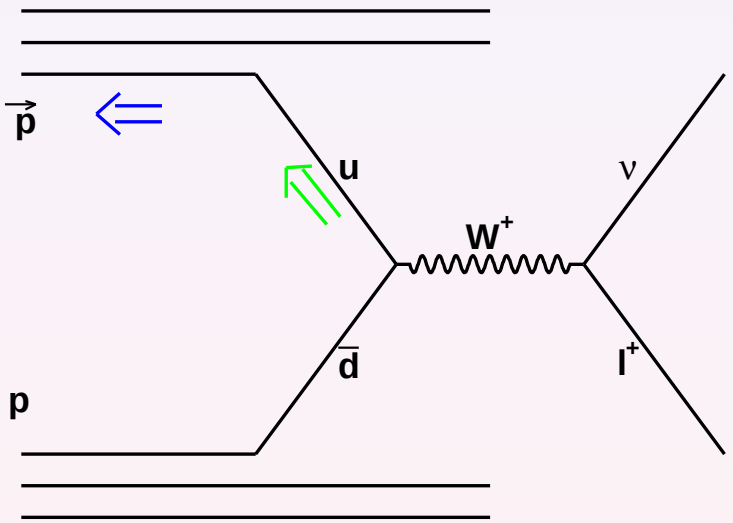
$\Delta u(x), \Delta d(x), \Delta s(x), \Delta \bar{u}(x), \Delta \bar{d}(x), \Delta \bar{s}(x)$



assuming $\Delta s = \Delta \bar{s}$

Helicity distributions from $\vec{p}p$ at RHIC

- Instead of measuring double spin asymmetries, one can measure single spin asymmetries and use weak interaction
- Done at RHIC ($\vec{p} + p \to W^{\pm} \to e^{\pm} + \nu$ at $\sqrt{s} = 500$ GeV)

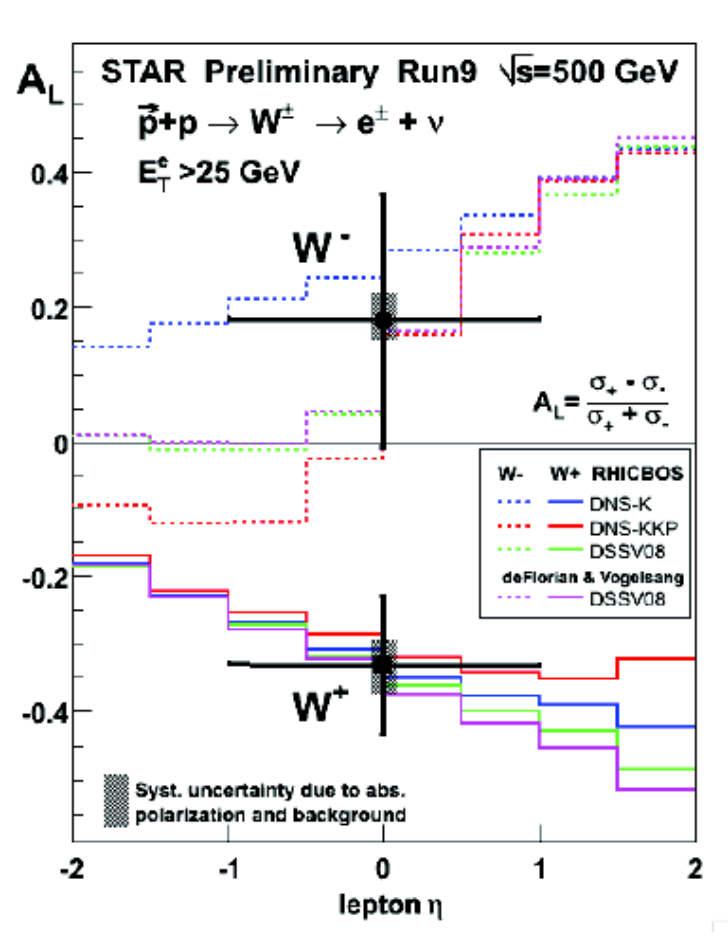


$$A_L^{W^+} = \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$
$$A_L^{W^-} = (u \leftrightarrow d)$$

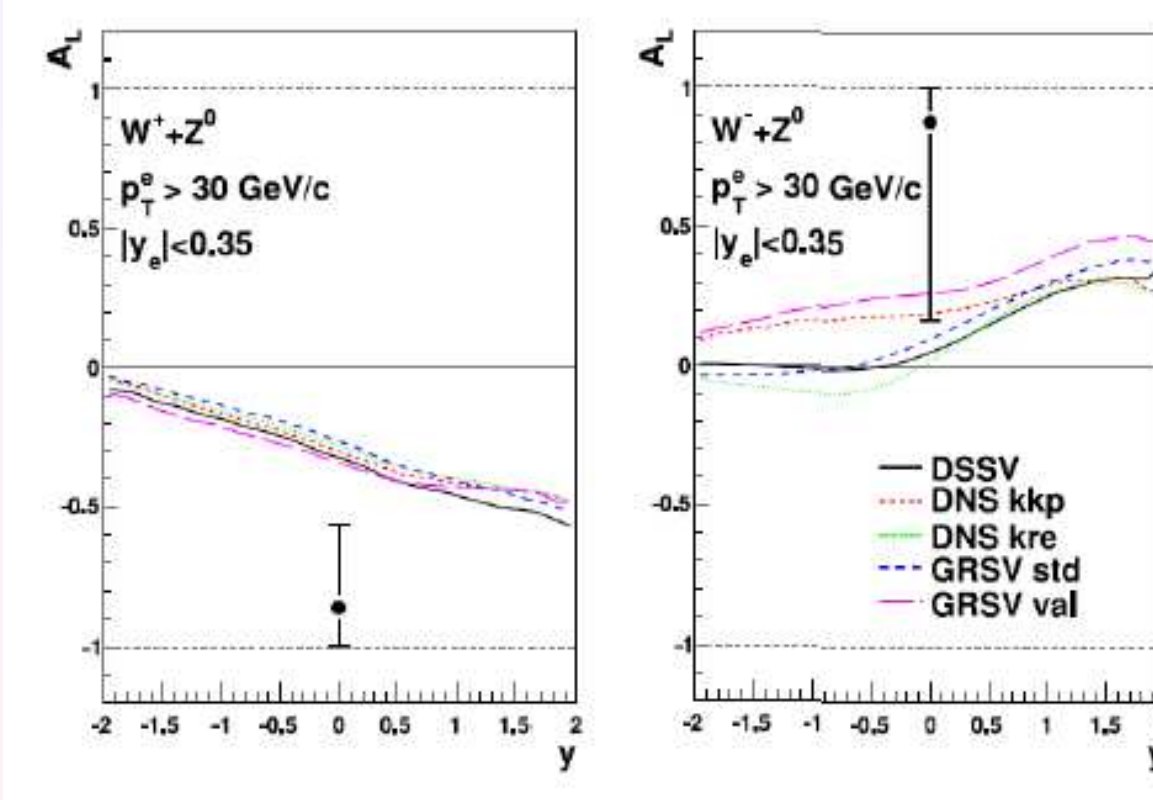
no fragmentation func.!

Results

STAR



PHENIX



Gluon Helicity

How to measure ΔG?

Deep Inelastic scattering	
$\vec{\ell}\vec{N} \to \ell' +$ high p_T hadrons $+ X$	$A \propto \Delta q \& \Delta g$ contribution of Δg enhanced due to selection of high p_T
$\vec{\ell}\vec{N} \to \ell' +$ charmed meson $+ X$	$A \propto \Delta g$ clean tag of glue
Polarized pp scattering	
$\vec{p}\vec{p} \Rightarrow$ hadrons $+ X$ $\vec{p}\vec{p} \to$ jet $+ X$ $\vec{p}\vec{p} \to$ jet $+$ jet $+ X$ $\vec{p}\vec{p} \to \gamma +$ jet $+ X$ $\vec{p}\vec{p} \to \gamma + X$	$A \propto \Delta q \Delta q \& \Delta q \Delta g \& \Delta g \Delta g$ reconstruction of momentum fraction $A \propto \Delta q \Delta g$
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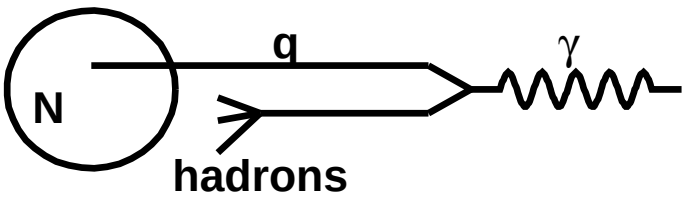
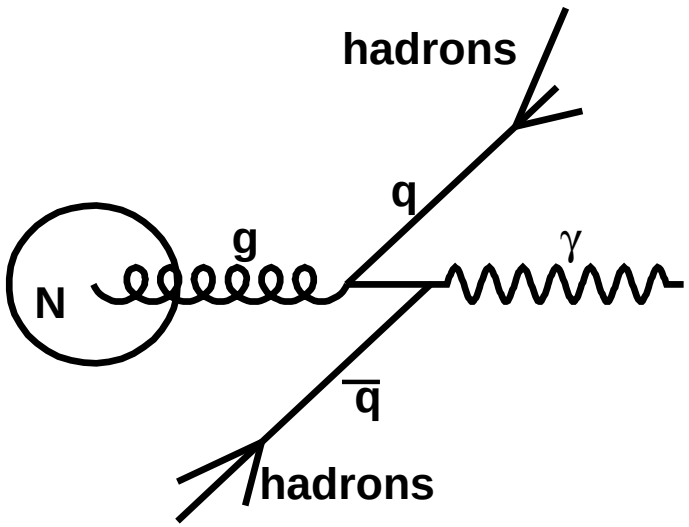


Leading order



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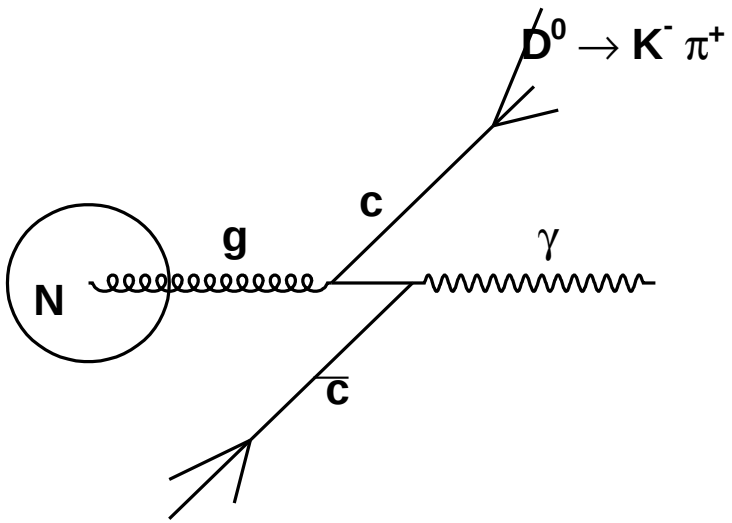
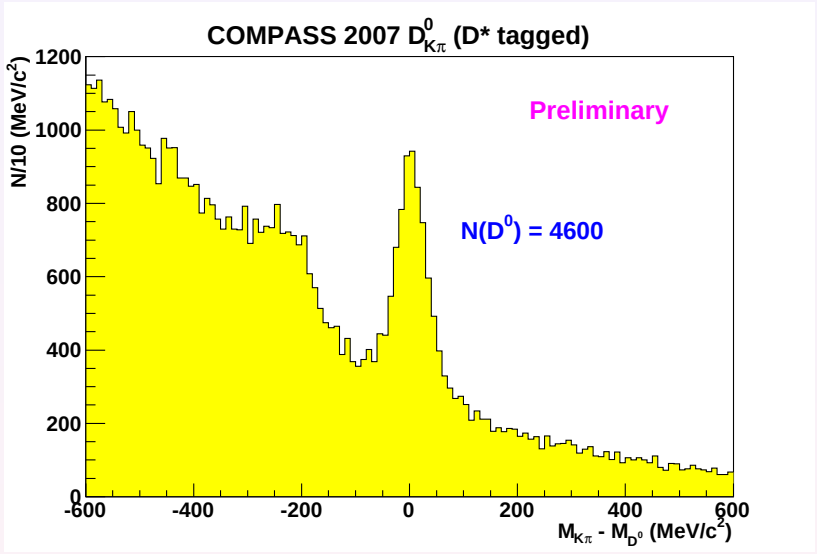


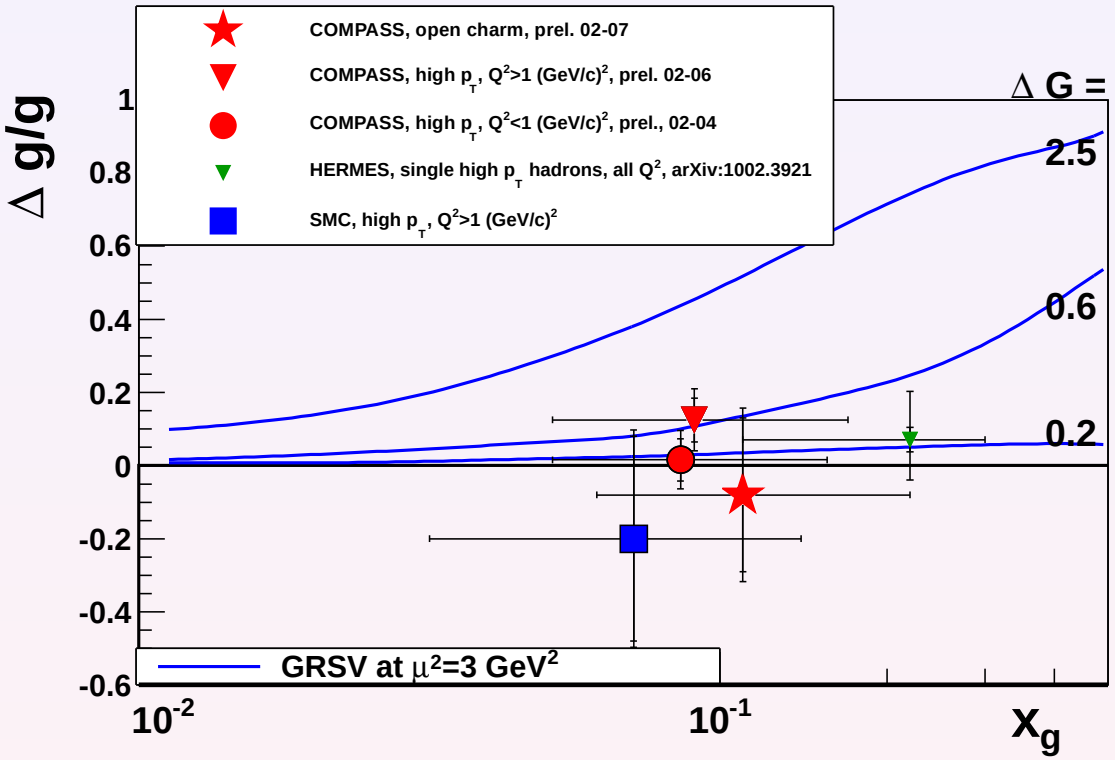
photon gluon fusion

$$D^{*+} \rightarrow D^0 \pi^+_{soft} \rightarrow K^- \pi^+ \pi^+_{soft}$$



$$\frac{N^{\uparrow\downarrow}_{D^0} - N^{\uparrow\uparrow}_{D^0}}{N^{\uparrow\downarrow}_{D^0} + N^{\uparrow\uparrow}_{D^0}} \propto \frac{\Delta g}{g}$$

Results on ΔG from DIS (high p_T and open charm)



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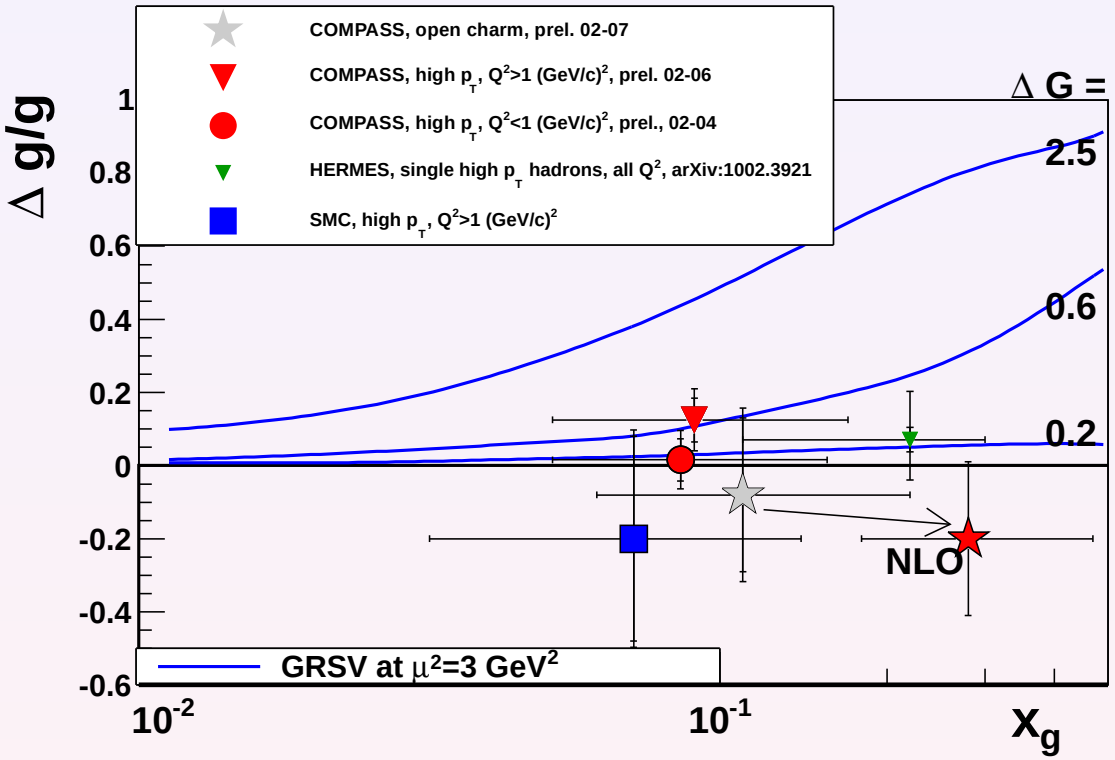

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- Result of open charm NLO analysis

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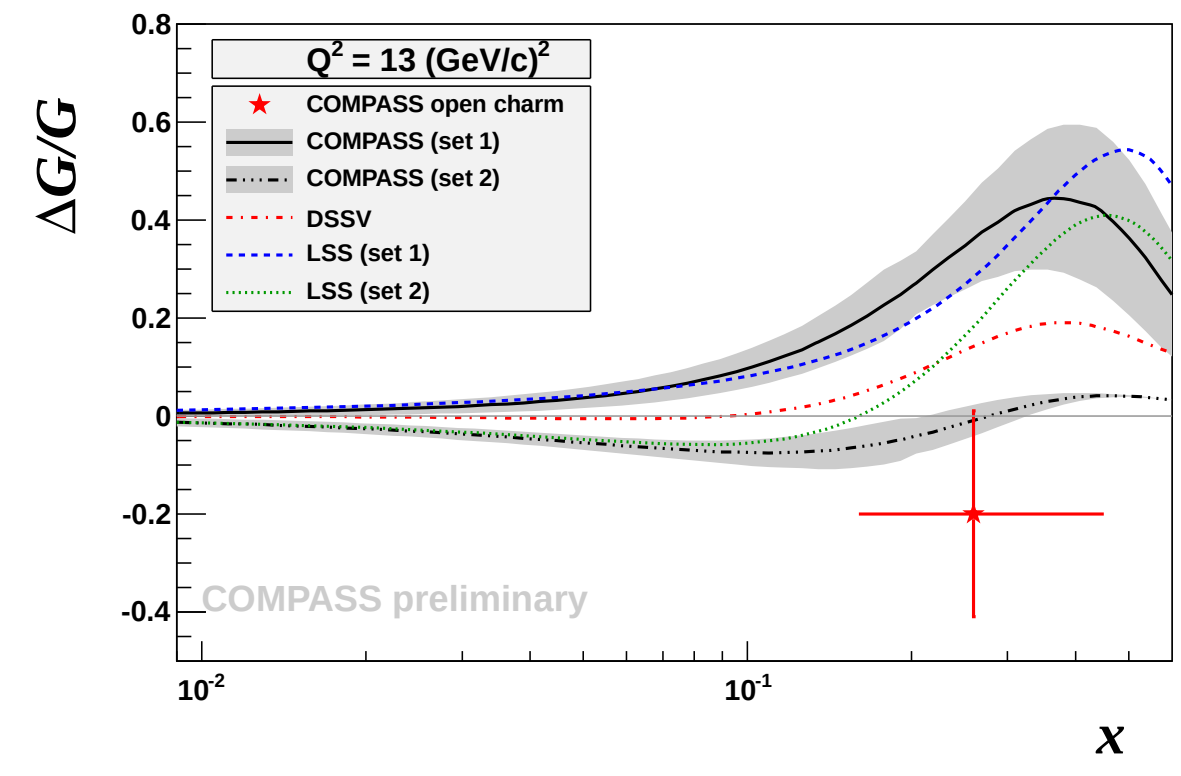

- Compared with NLO 'global' analyses
  - COMPASS: inclusive asymmetries & open charm
  - LSS: E. Leader, A. V. Sidorov and D. B. Stamenov, arXiv:1012.5033 [hep-ph], inclusice & semi-inclusive asymmetries
  - DSSV: inclusice, semi-inclusive asymmetries & pp data

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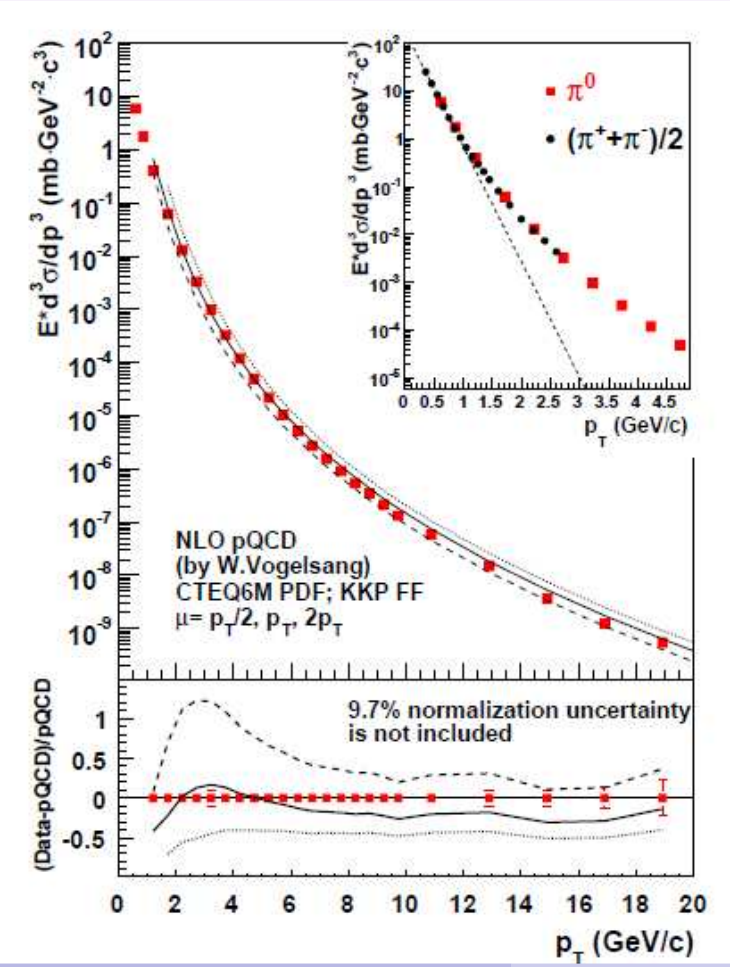
Results from RHIC

Two examples from RHIC

PHENIX: π^0 production cross section



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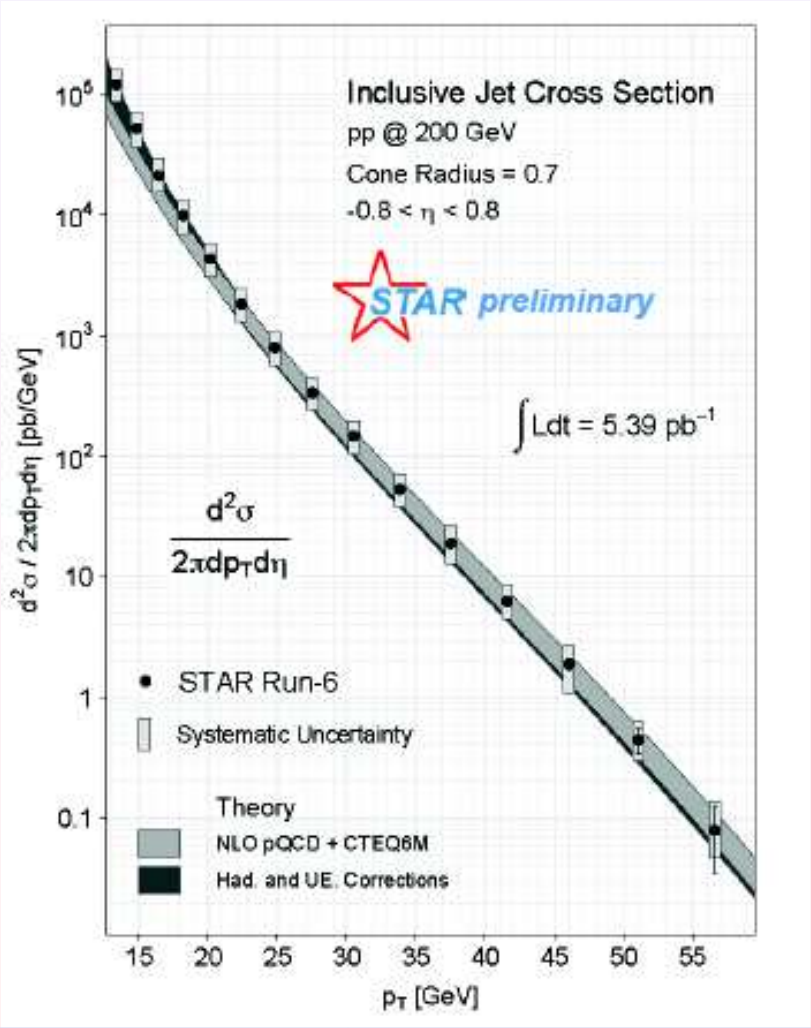

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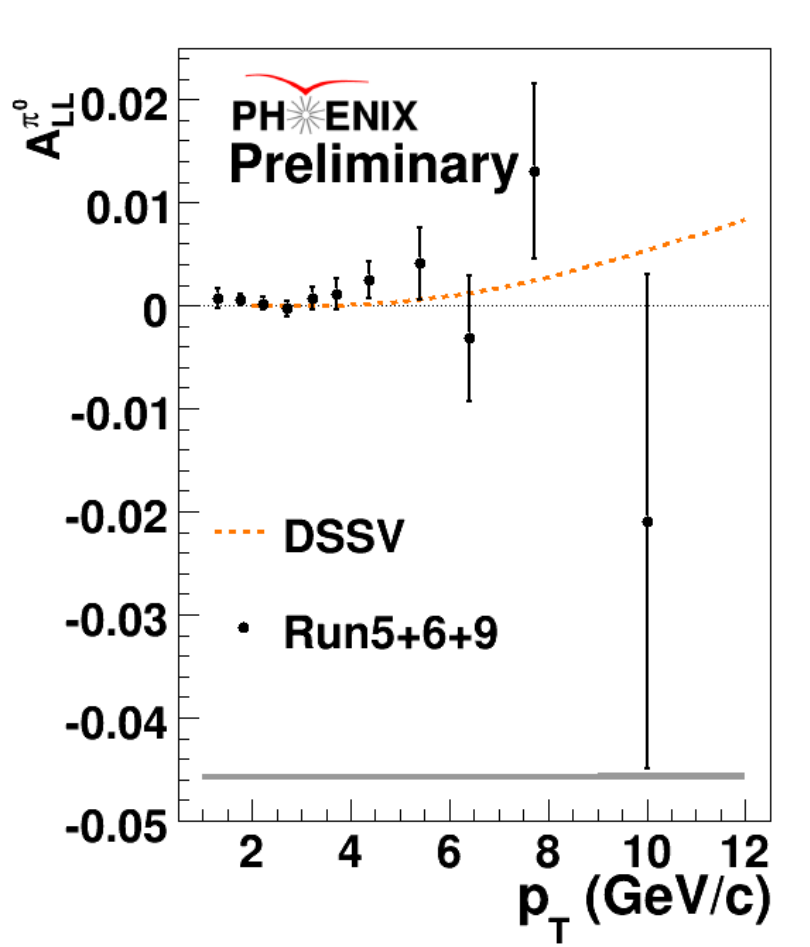

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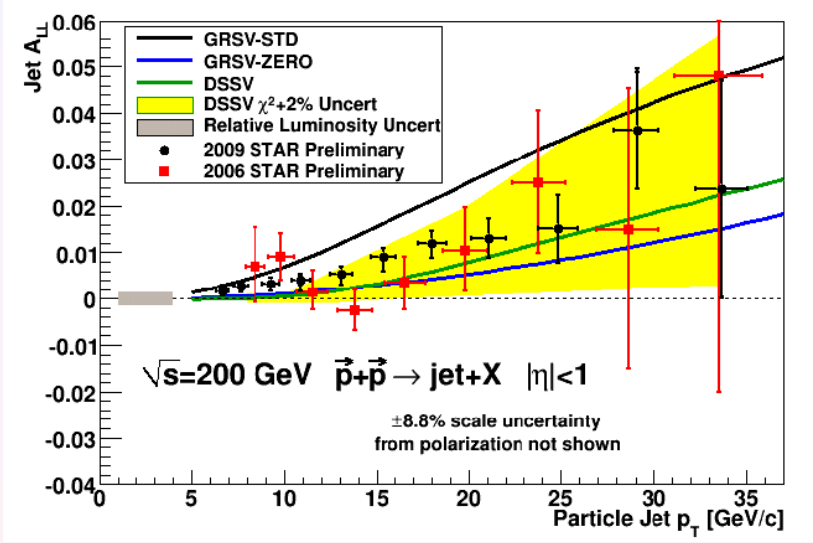

(more polarized pp $\Rightarrow$ E. Aschenauer)

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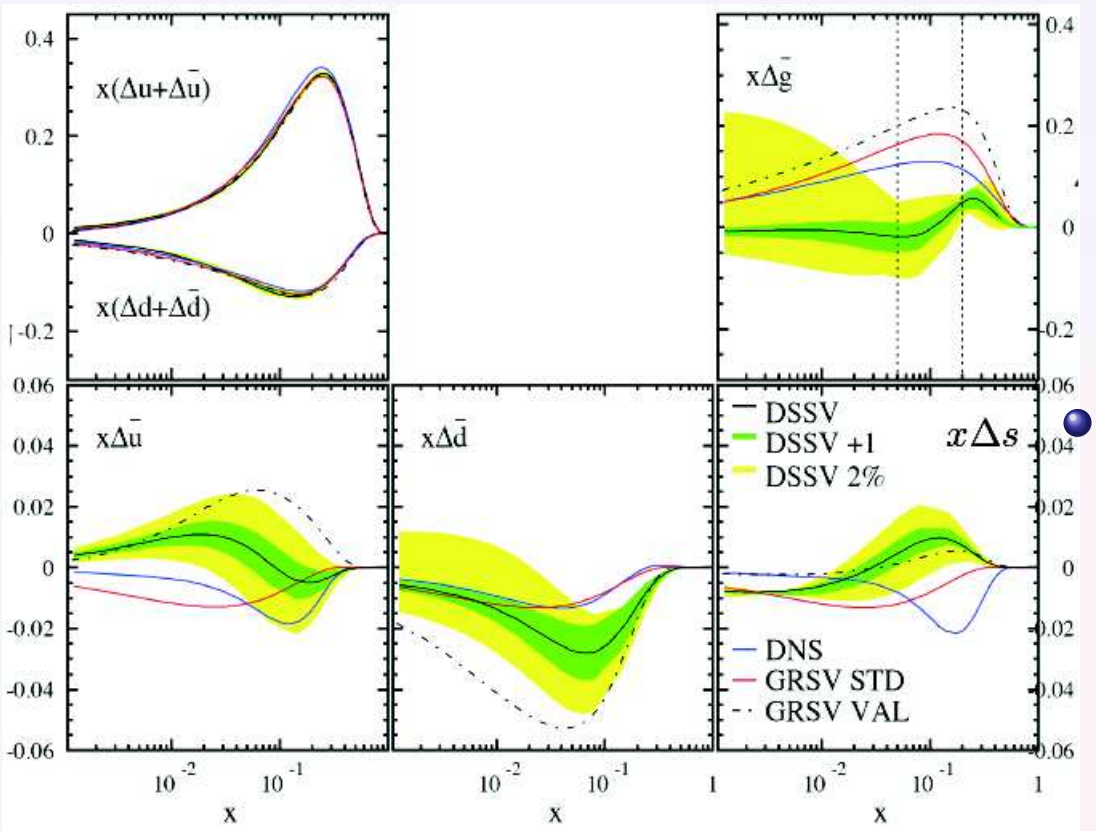
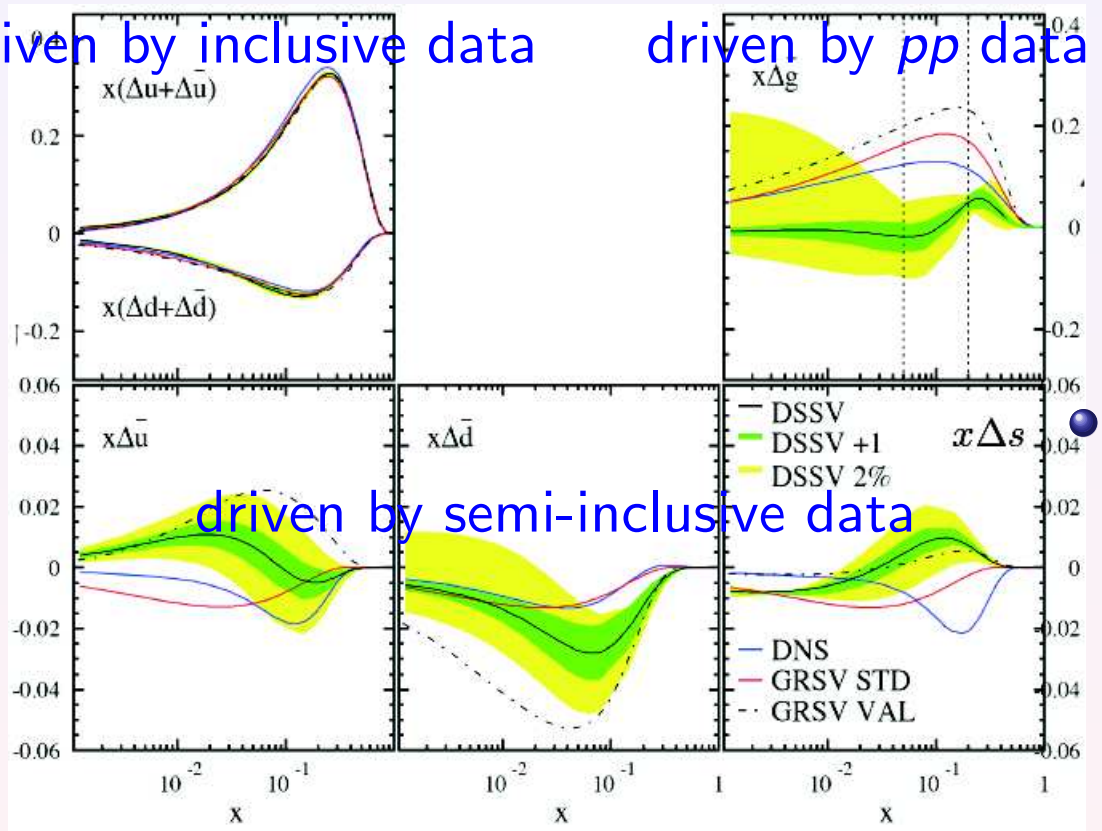
Results from global fit on all helicity pfds



- about 500 data points fitted, inclusive & semi-inclusive asymmetries, RHIC *pp* data
- analysis does not (yet) include direct measurements from DIS, because NLO calculation are not available, (except for open charm)

M. Stratmann, DIS 2011
D. de Florian, R. Sassot, M. Stratmann and W. Vogelsang, Phys. Rev. D **80** (2009) 034030, [arXiv:0904.3821 [hep-ph]]

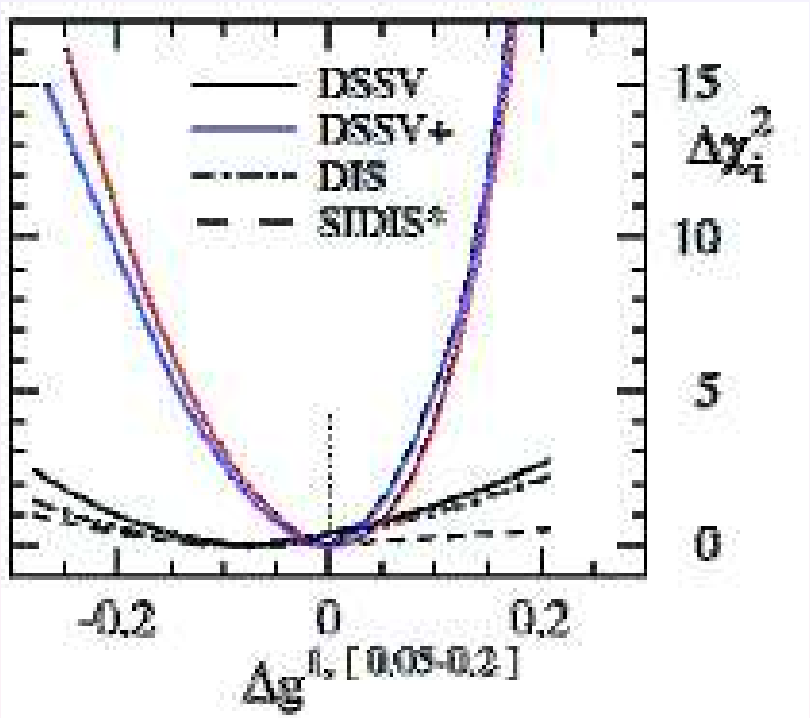
Results from global fit on all helicity pfds



- about 500 data points fitted, inclusive & semi-inclusive asymmetries, RHIC *pp* data
- analysis does not (yet) include direct measurements from DIS, because NLO calculation are not available, (except for open charm)

M. Stratmann, DIS 2011
D. de Florian, R. Sassot, M. Stratmann and W. Vogelsang, Phys. Rev. D **80** (2009) 034030, [arXiv:0904.3821 [hep-ph]]

Error on Δg



'truncated' first moments:

$$\int_{0.05}^{0.2} \Delta g(x)\mathrm{d}x = 0.005^{+0.129}_{-0.164}$$

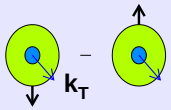
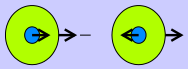
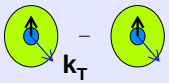
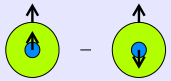
$$\int_{0.001}^{1} \Delta g(x)\mathrm{d}x = 0.013^{+0.702}_{-0.314}$$

Summary Helicity distributions

- $\Delta G = \int_0^1 \Delta g(x) \mathrm{d}x \approx 0 \pm \frac{1}{2}$
  certainly small compared to large values $\Delta G \approx 2 - 3$
  proposed to explain $\Delta\Sigma \approx 25\%$,
  not small compared to the total spin of the proton of $\frac{1}{2}$!
- x-dependence of $\Delta g(x)$ not very well determined
- only limited x-range ($0.05 < x < 0.3$) is covered
- $\Delta\Sigma = 0.25 \pm 0.05$
- Δu and Δd rather well known
- open questions: $\Delta\bar{u} = \Delta\bar{d}$, $\Delta s = \Delta\bar{s}$?

Transverse Momentum Dependent Distributions

Transverse Momentum Dependent Distributions

quark \ nucleon	unpol.	long.	trans.
unpol.	$f_1(q)$  unpolarized		$f_{1T}^{\perp}(\Delta_0^T q)$  Sivers
long.		$g_1(\Delta q, \Delta g)$  helicity	g_{1T}
trans.	$h_1^{\perp}$  Boer-Mulders	h_{1L}	$h_1(\Delta_T q), h_{1T}^{\perp}$  transversity

- 8 distributions at leading twist,
- many more at higher leading twist,

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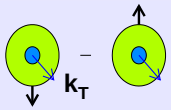
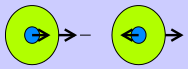
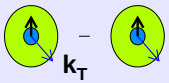
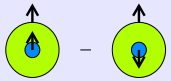
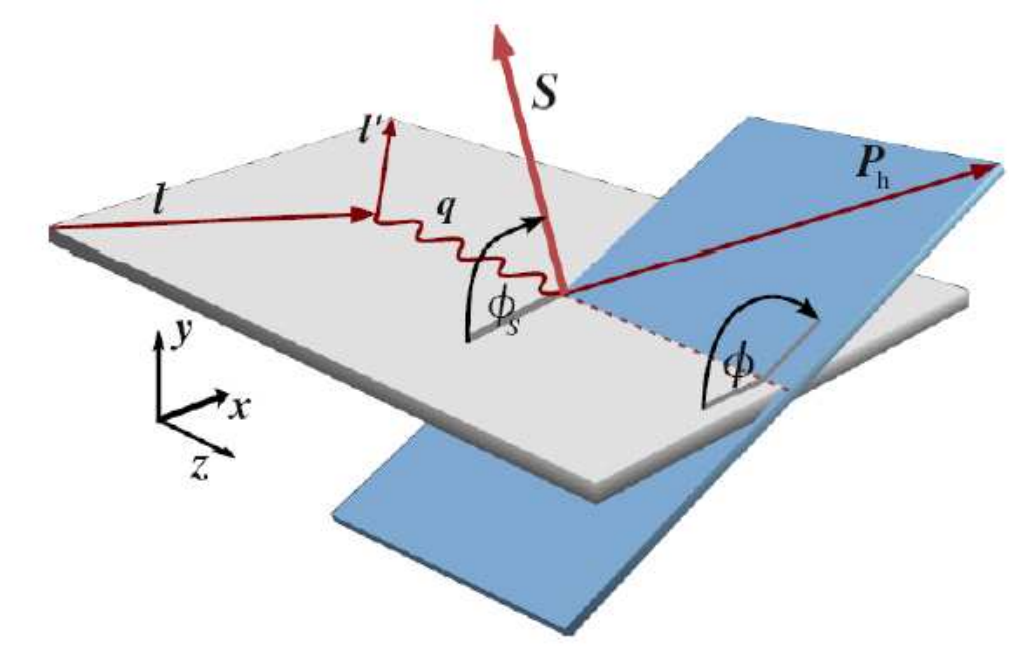
unpol.	$f_1(q)$  unpolarized		$f_{1T}^{\perp}(\Delta_0^T q)$  Sivers
long.		$g_1(\Delta q, \Delta g)$  helicity	g_{1T}
trans.	$h_1^{\perp}$  Boer-Mulders	h_{1L}	$h_1(\Delta_T q), h_{1T}^{\perp}$  transversity

- 8 distributions at leading twist,
- many more at higher leading twist,
- Concentrate on the two most prominent ones: Transversity (Collins) & Sivers

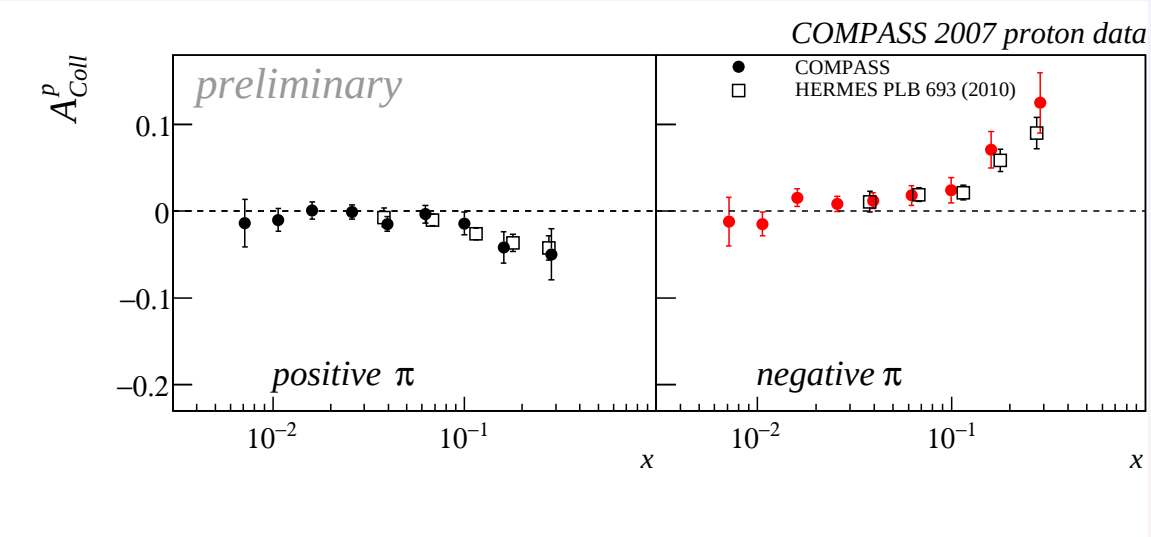
Collins & Sivers asymmetries in semi-incl. DIS



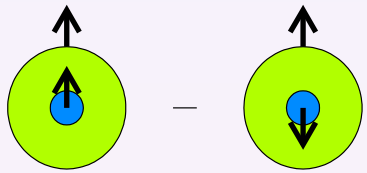
$$N \propto 1 + A_{\text{Coll}} \sin(\Phi_h - \Phi_S - \pi) + A_{\text{Siv.}} \sin(\Phi_h + \Phi_S) + \ldots$$

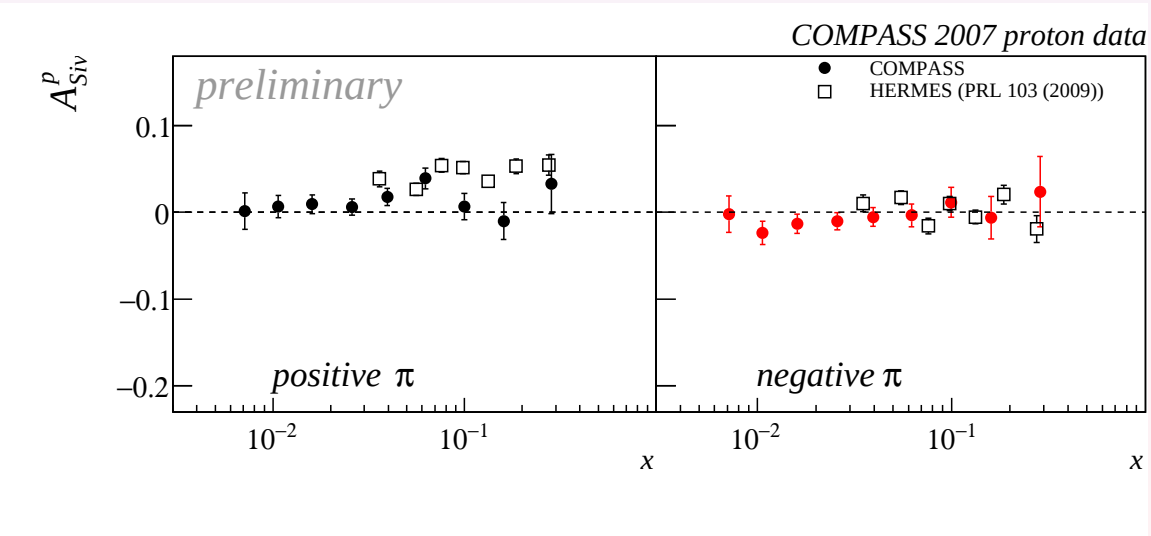
$$A_{\text{Coll.}} = \frac{\sum e_q^2 \Delta_T q \Delta_T^0 D_q^h}{\sum e_q^2 q \Delta_T^0 D_q^h}, \qquad A_{\text{Siv.}} = \frac{\sum e_q^2 \Delta_0^T q D_q^h}{\sum e_q^2 \Delta_T^0 D_q^h}$$

Collins & Sivers asymmetries in semi-incl. DIS

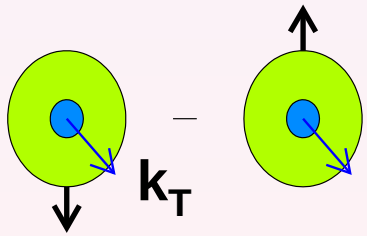


Transversity



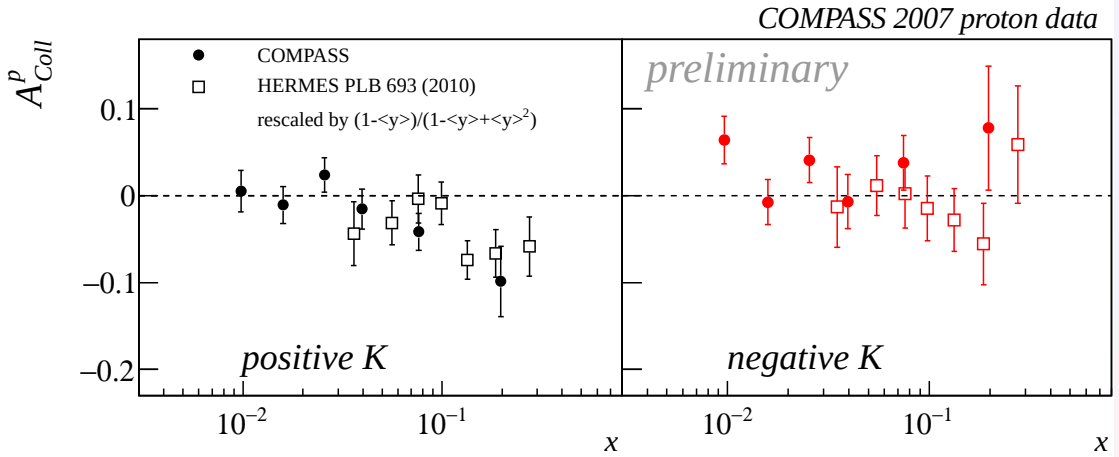


Sivers

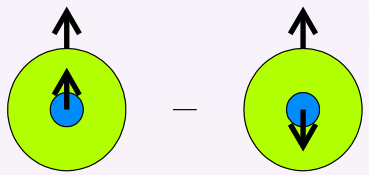


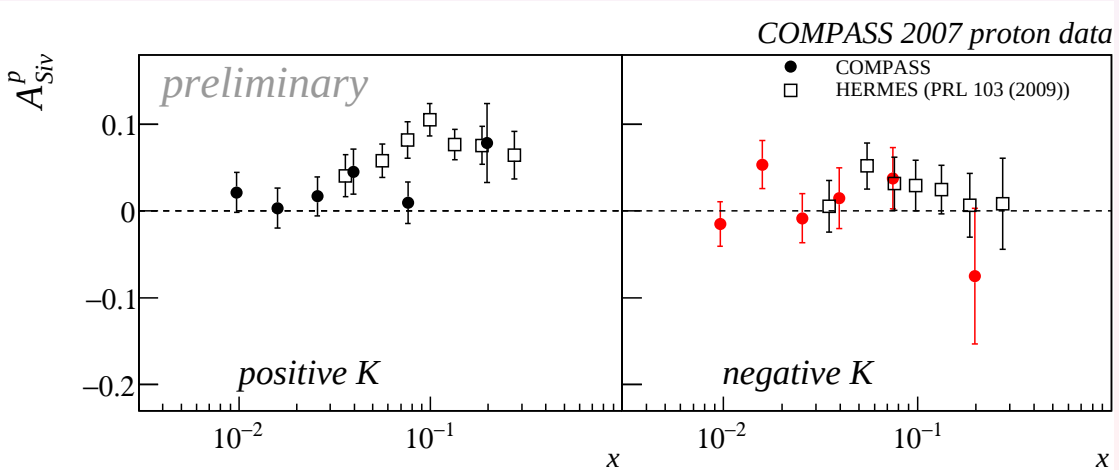
Collins & Sivers asymmetries in semi-incl. DIS

for kaons

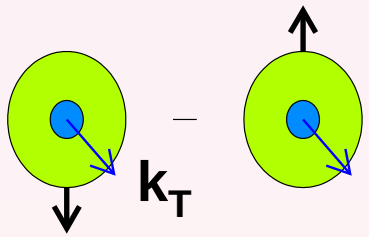


Transversity



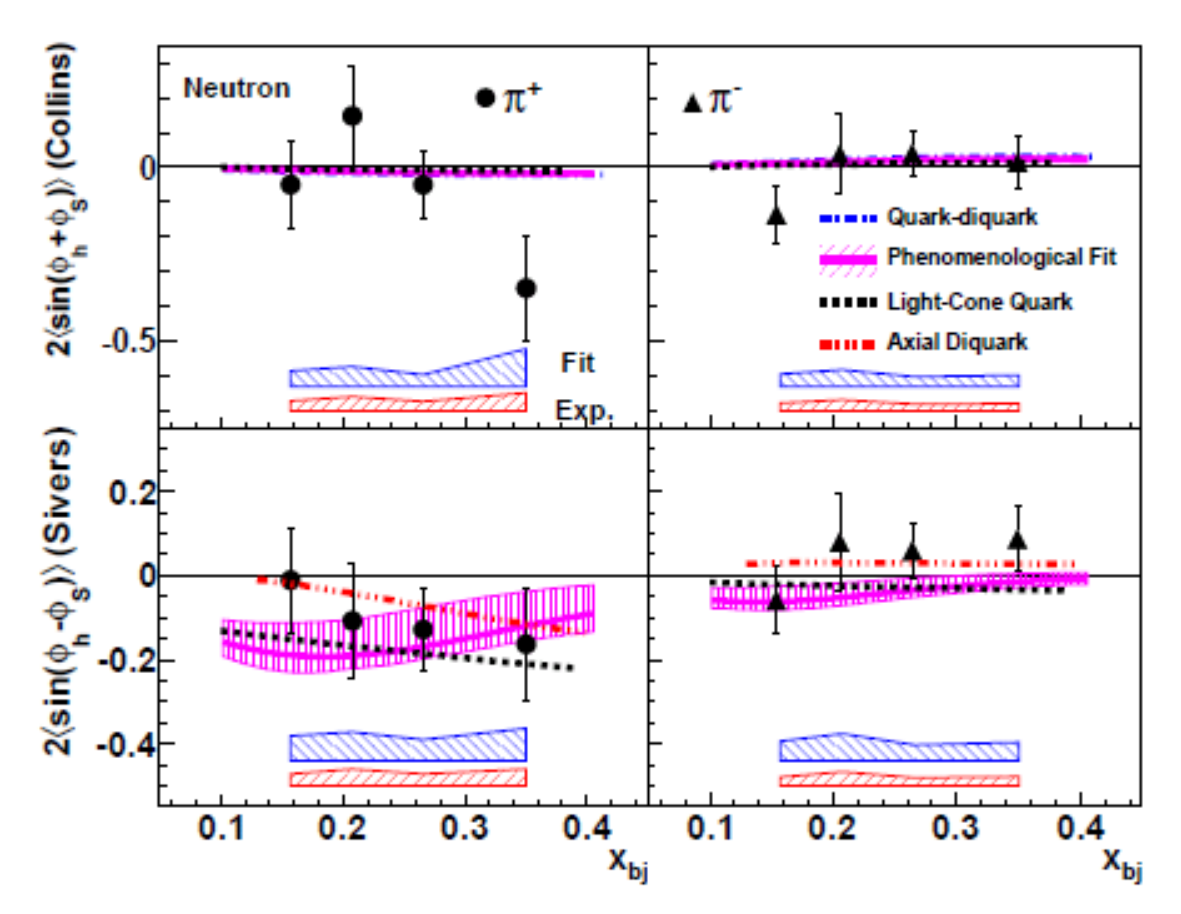


Sivers



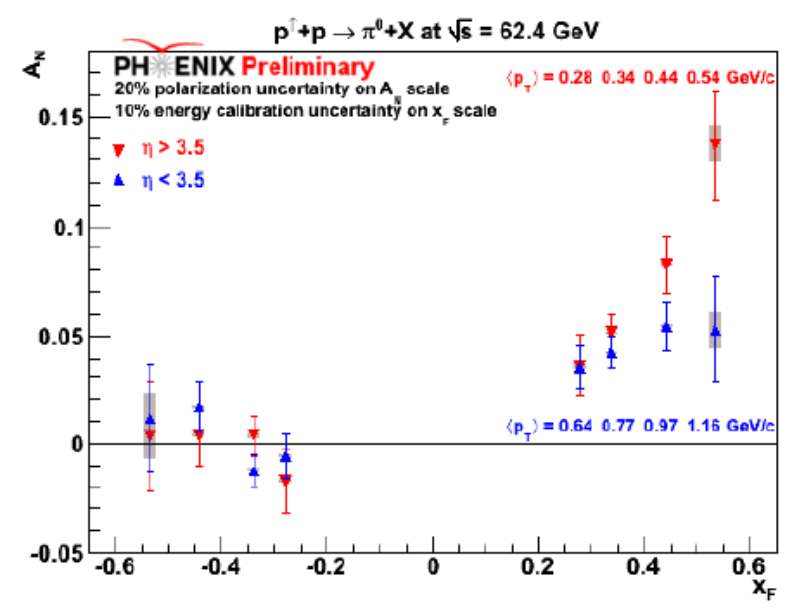
Collins & Sivers asymmetries from JLab Hall A

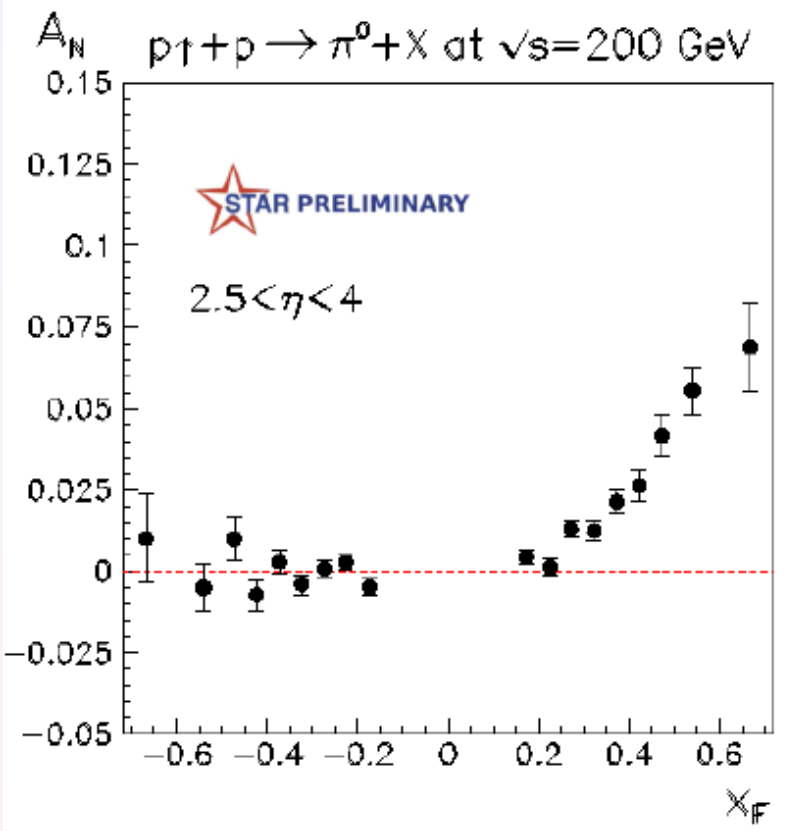
neutron Collins and Sivers moments obtained from ^{3}He target



1106.0363v1 [nucl-ex]

A_N from $p\uparrow p \to \pi^0 + X$





$$A_N \propto \underbrace{\Delta_T q \Delta_T^0 D_q^h}_{\textit{Collins}} + \underbrace{\Delta_0^T q D_q^h}_{\textit{Sivers}} + \ldots$$

Summary Transversity & Sivers

- Measured asymmetries on different targets for different hadrons in the final state allow for a global analysis to extract various pdfs
- Wait for next presentation by M. Anselmino

Future Experiments

Future programs

- Continuation of measurements
  COMPASS, RHIC, JLab
- polarized Drell-Yan process give access to TMDs
  (particular interesting Sivers function:
  $f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS)$)
  COMPASS, RHIC, FAIR, J-PARC, NICA
- Deep Virtual Compton Scattering to measure correlated space-momentum distributions in the nucleon, i.e. Generalized Parton Distributions (GPDs)
  COMPASS, JLab
- Polarized electron nucleon collider

talks related to these subjects:
($\rightarrow$ E.-M. Kabuß, Tue. 16.30, H. Moutarde, Tue. 15.30, B. Musch, Tue. 14.30)

Future polarized Electron Nucleon Collider

Experiment	JLab (12 GeV)	HERMES	ENC @FAIR/GSI	COMPASS	EIC @BNL/JLab
s/GeV^2	23	50	180	300	10000
$x_{bj,min} = \frac{1}{ys}$ for $y = 0.9$ and $Q^2 > 1\text{GeV}^2$	$5 \cdot 10^{-2}$	$2 \cdot 10^{-2}$	$6 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	10^{-4}
$\mathcal{L}/(1/\text{cm}^2/\text{s})$	$\approx 10^{38}$	$\approx 10^{32}$	$\approx 10^{32-33}$	$\approx 10^{32}$	$\approx 10^{33-34}$
$(P_T P_B f)^2$	0.026	0.16	0.41	0.026	0.24

Talk on EIC → J. Lee, Thu. 14.55

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- Huge gain in effective luminosity $(P_T P_B f)^2 \mathcal{L}$ for polarization measurements,
- plus gain due to better reconstruction of hadronic final state compared to fixed (solid state) target experiments
  $\rightarrow$ better reconstruction of gluon momentum fraction x
  $\rightarrow$ measurement of $\Delta g(\mathbf{x})$

Talk on EIC $\rightarrow$ J. Lee, Thu. 14.55

Summary & Outlook

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- New results on helicity distributions Δq, Δg, transversity and TMDs

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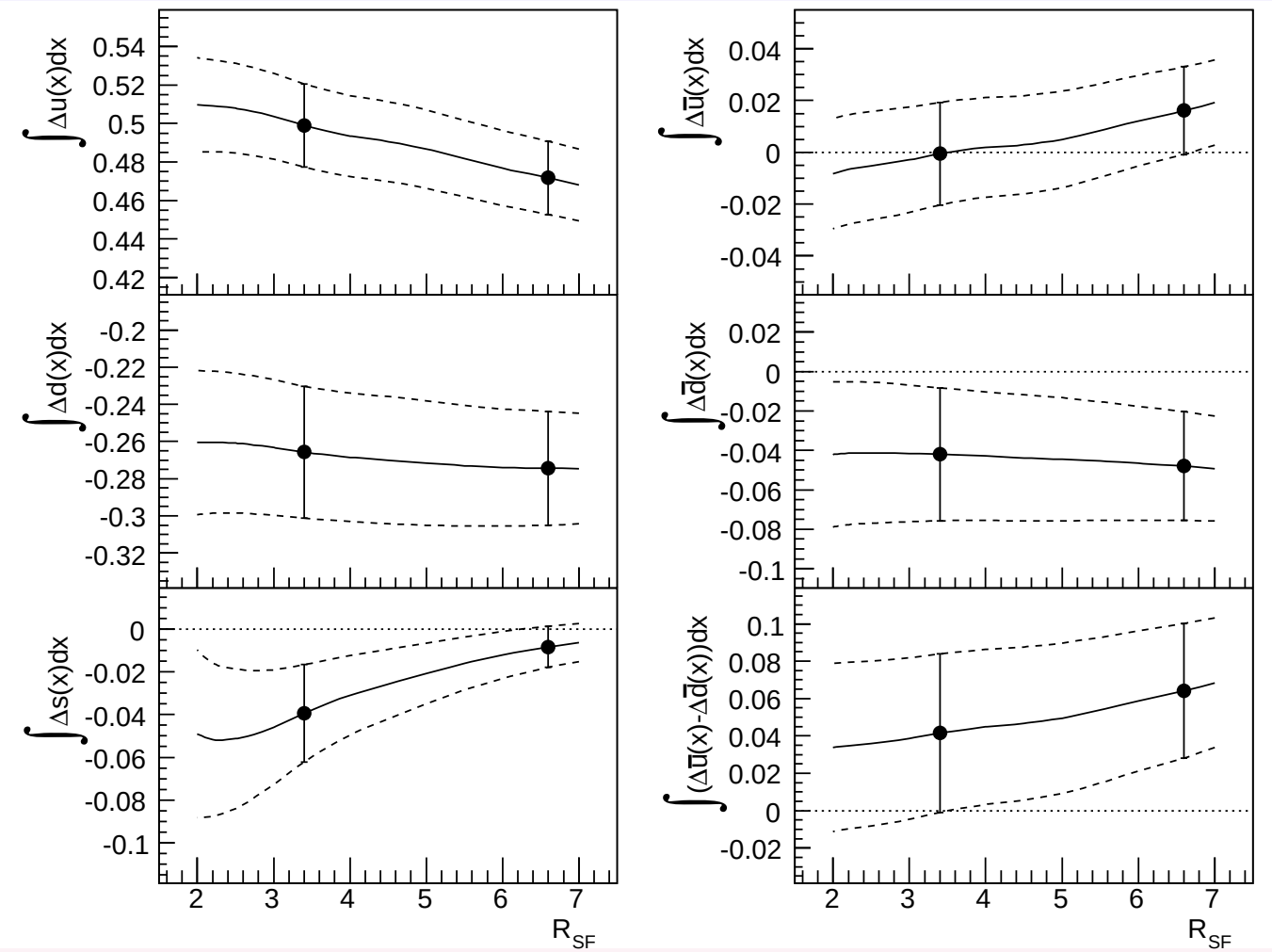
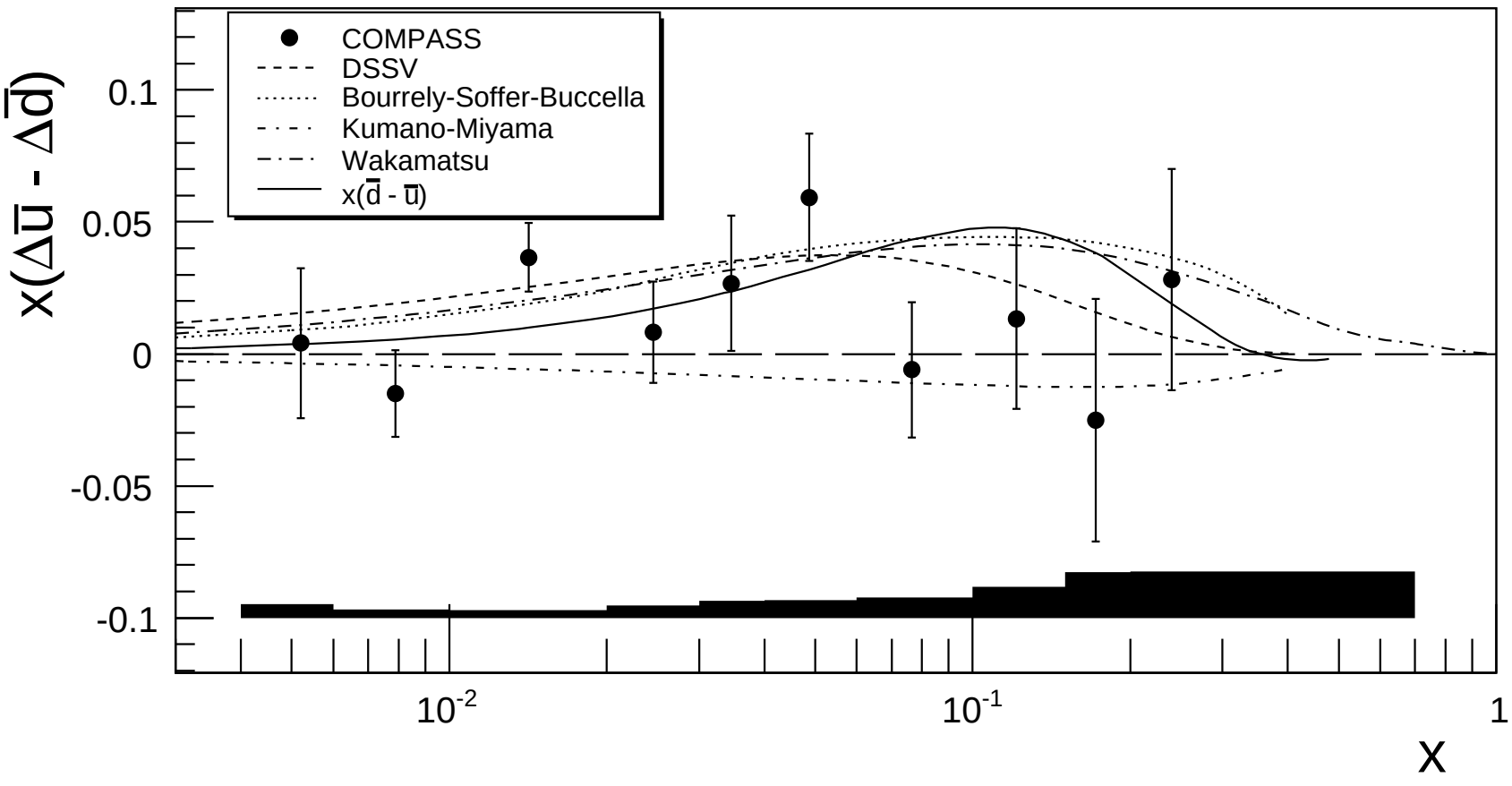
- An **polarized electron nucleon collider** would offer high potential for polarization measurements

Spare



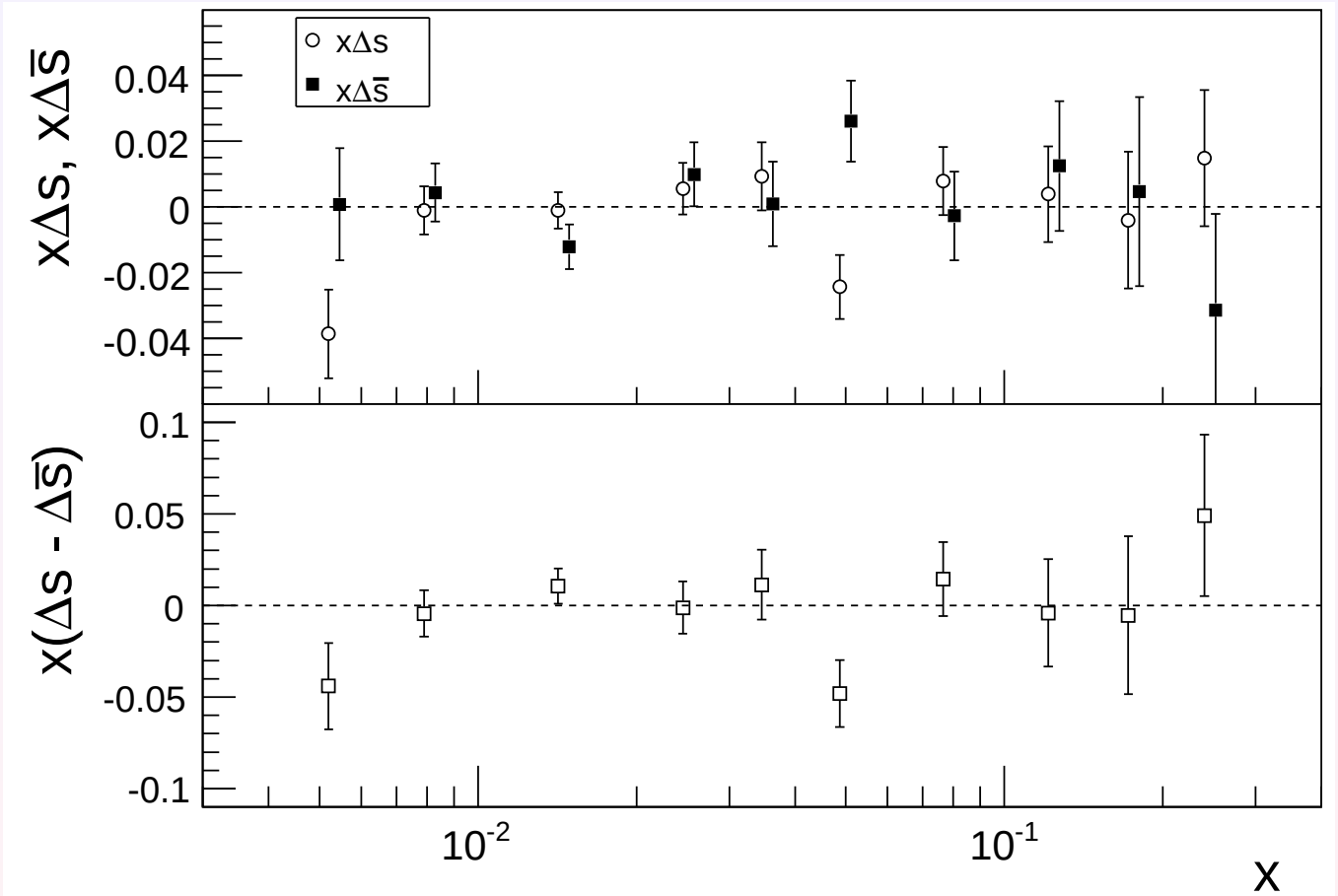
$$R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)\mathrm{dz}}{\int D_{u}^{K^+}(z)\mathrm{dz}}$$

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

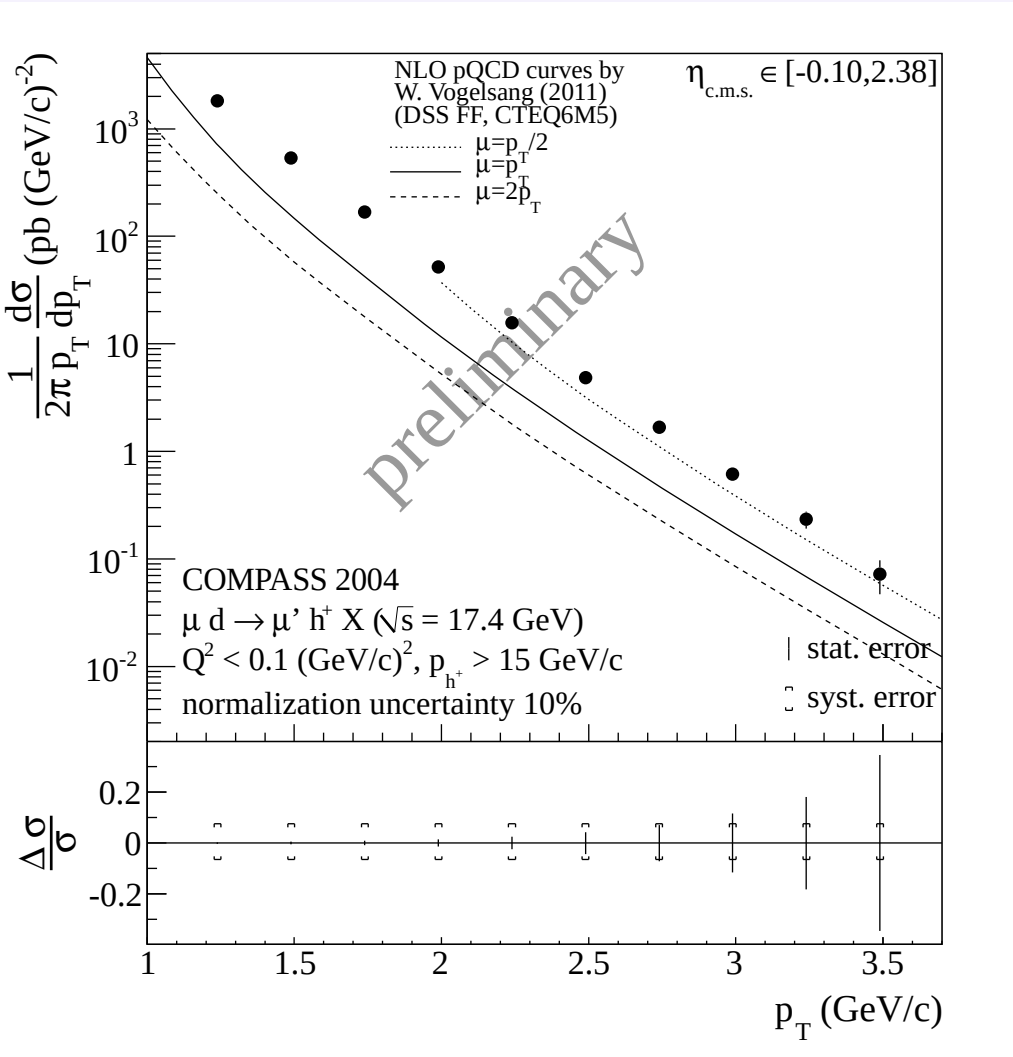


$$\int_{0.004}^{0.3} \Delta\bar{u}(x) - \Delta\bar{d}(x)\mathrm{d}x = 0.06 \pm 0.04 \pm 0.02$$

$\Delta s(x)$ and $\Delta\bar{s}(x)$ from COMPASS Data



Cross Section vs. p_T



Unpolarized PDFs