Recent Results on Nucleon Spin Structure

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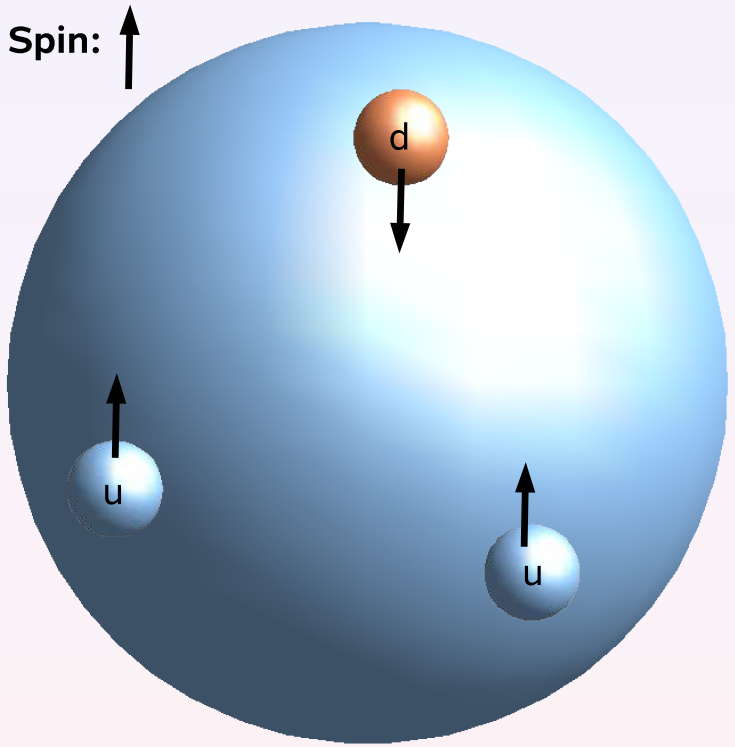
Proton Structure . . .



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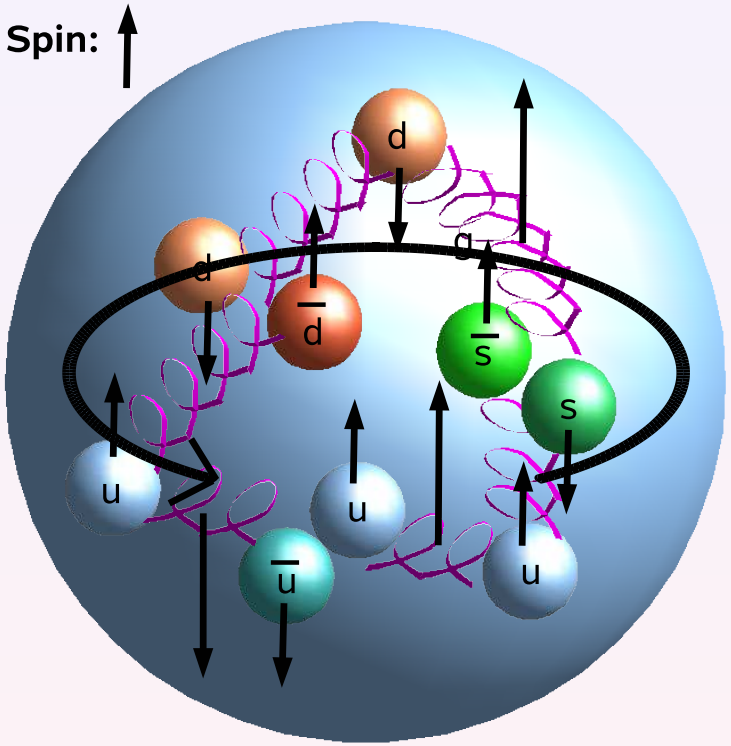

- . . . looks simple in static quark model
- . . . much more complicated in QCD

Outline

- Motivation

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- Helicity Distribution Δq and ΔG

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- Future Projects:
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- Summary & Outlook

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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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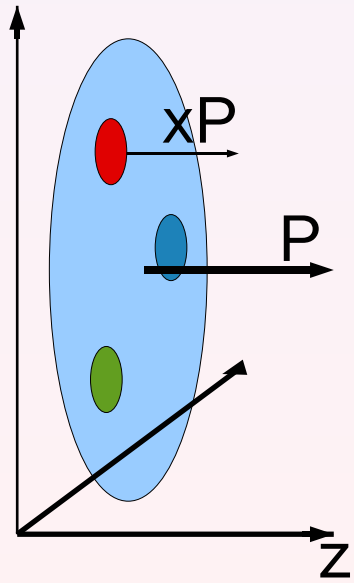

Motivation II:

Parton Distribution Functions:

- unpolarized $q(x)$,$g(x)$

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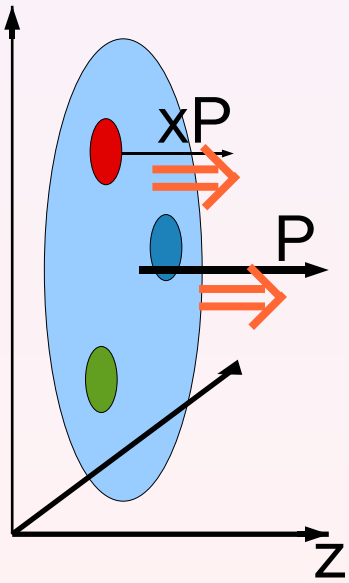

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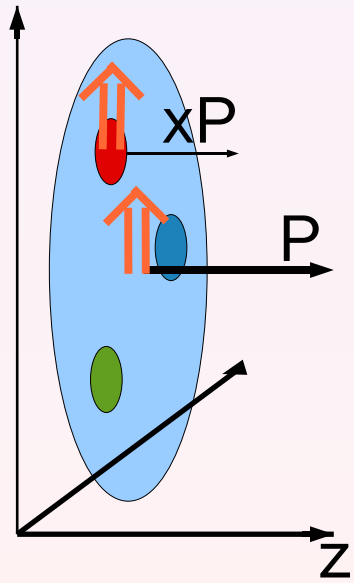

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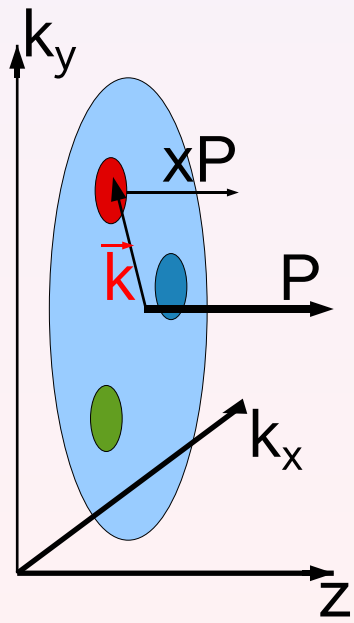

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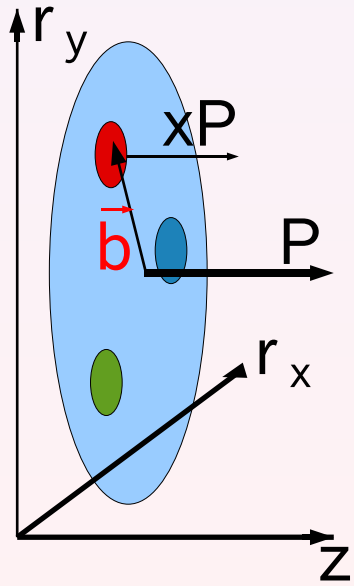

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$$\Delta\Sigma = \int_0^1 \Delta u(x) + \Delta\bar{u}(x) + \Delta d(x) + \Delta\bar{d}(x) + \Delta s(x) + \Delta\bar{s}(x)\mathrm{d}x$$

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

L_q related to TMDs

$\Delta\Sigma + L_q$ related to GPDs

Focus in this talk:

Helicity Distributions of quarks and gluons and quarks: $\Delta q, \Delta g$

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Helicity Distributions of quarks and gluons and quarks: $\Delta q, \Delta g$

Other presentation in the workshop related to the field:

M. Boglione	Transverse Spin Structure of the Nucleon
M. Guidal	Deep Virtual Compton Scattering: from Data to GPDs
W. Vogelsang	QCD Spin Physics
A. Deshpande	Electron Ion Colliders
A. Schäfer	Nucleon Structure from the Lattice

Helicity Distributions

What do we know?

- $\Delta\Sigma \approx 30\%$
  But how do the different $\Delta q(\mathbf{x}), q = u, d, s, \bar{u}, \bar{d}, \bar{s}$ look like?
- $\Delta G = \int_0^1 \Delta g(x)\mathrm{d}x$ small?
  But how small? How does $\Delta g(\mathbf{x})$ look like?

Helicity distributions

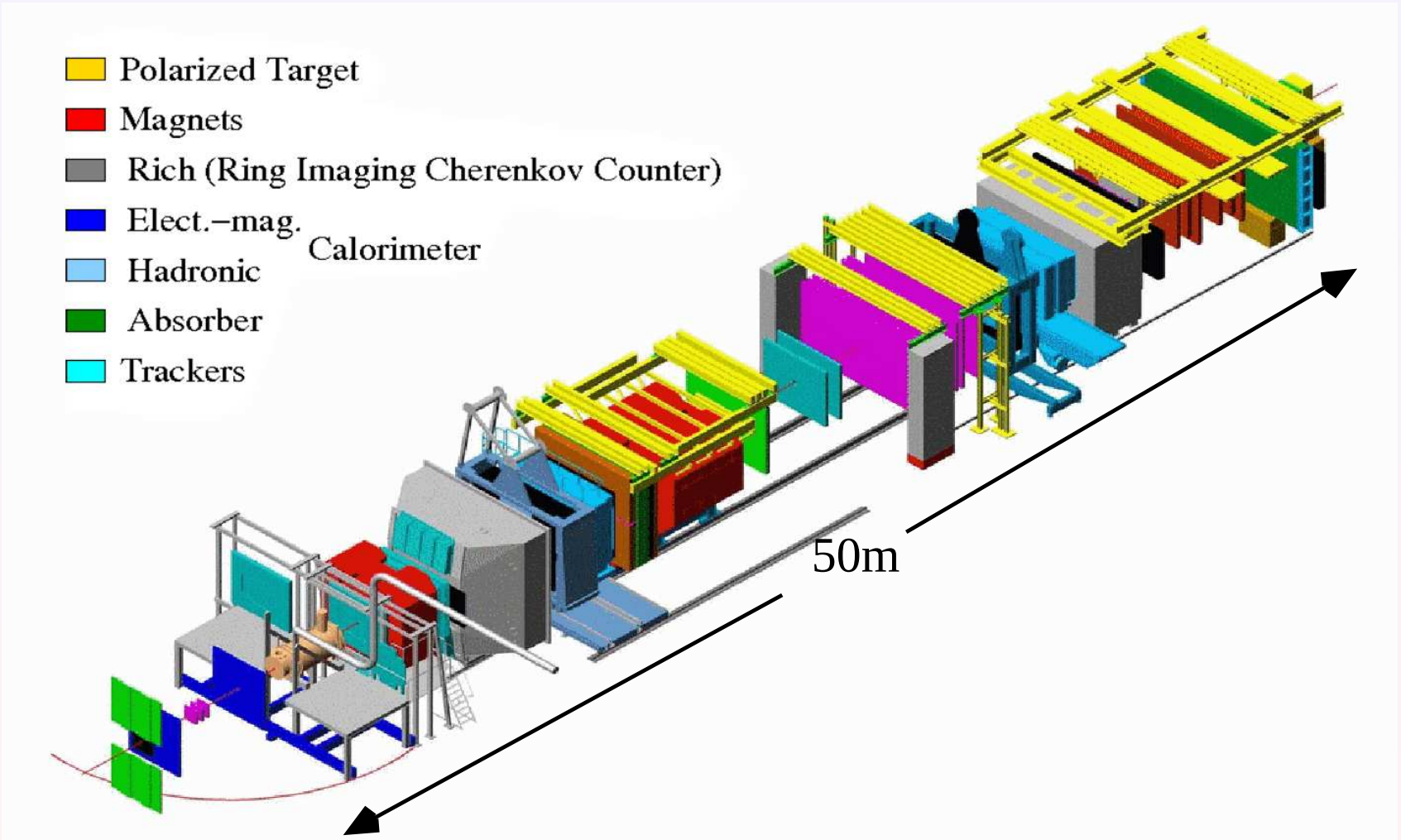
How can they by measured?

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

Can be done in two ways, using

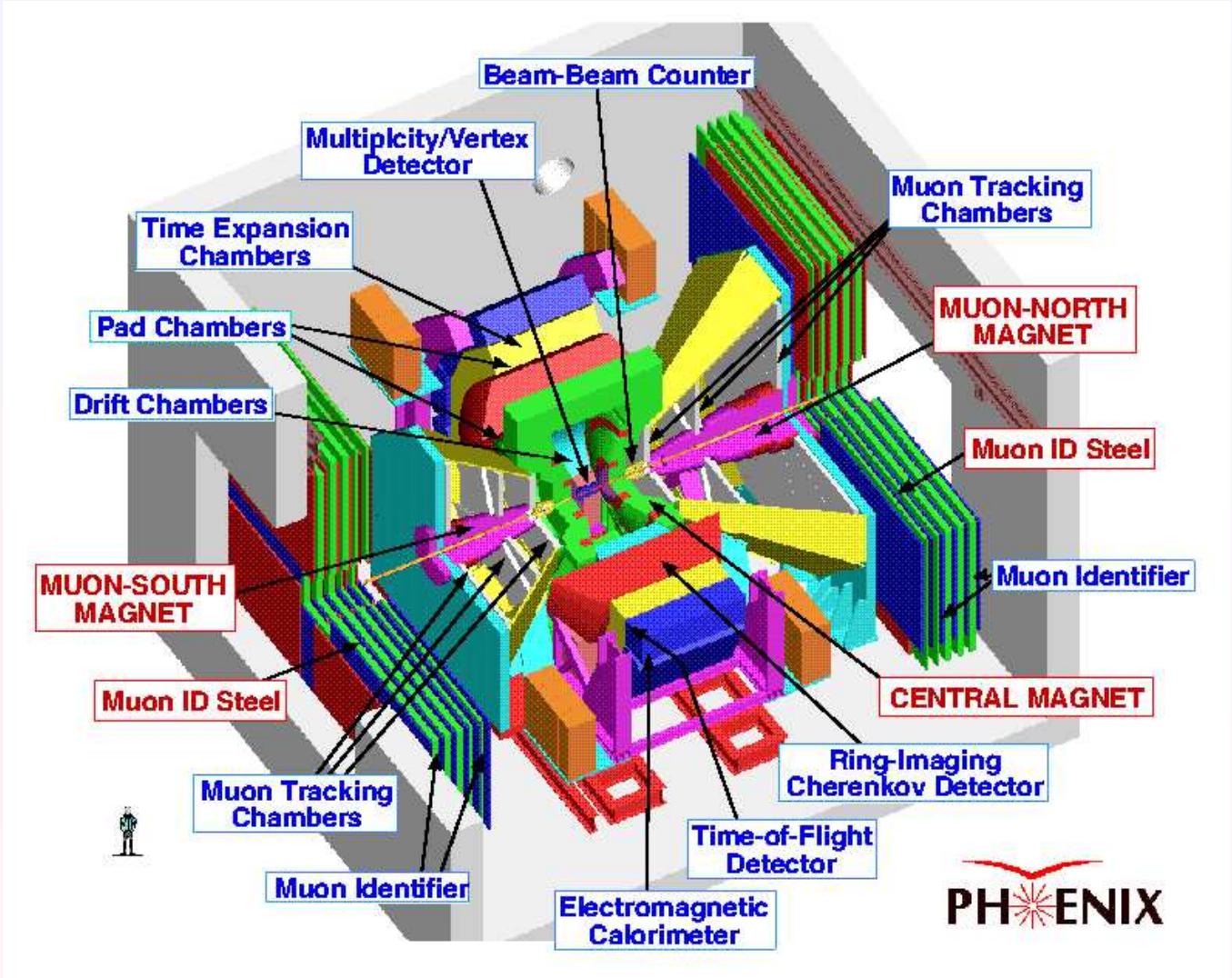
1. double polarisation
   in Deep Inelastic Scattering: $\vec{\ell} + \vec{N} \rightarrow \ell' + \textit{hadrons} + X$
   Proton-Proton Scattering: $\vec{p} + \vec{p} \rightarrow \text{Jet}/\gamma/\text{Hadrons} + X$
2. single polarisation & weak interaction
   $\vec{p} + p \rightarrow W^{\pm} \rightarrow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

COMPASS Experiment at CERN



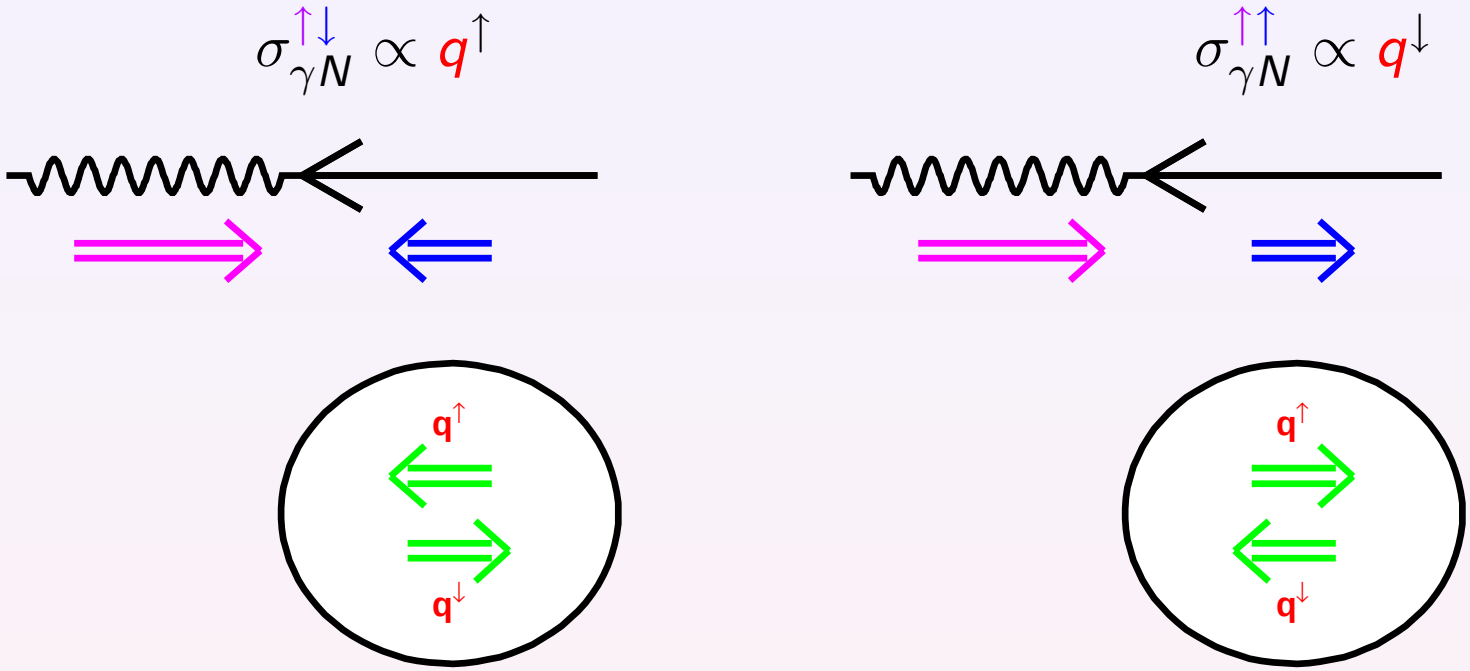
μN scattering at $E_\mu = 160$ GeV ($\sqrt{s} = 18$ GeV)

PHENIX Experiment at BNL



pp collisions at $\sqrt{s} = 200, 500$ GeV

Polarized Inclusive DIS: $\vec{\ell} + \vec{N} \rightarrow \ell' + X$

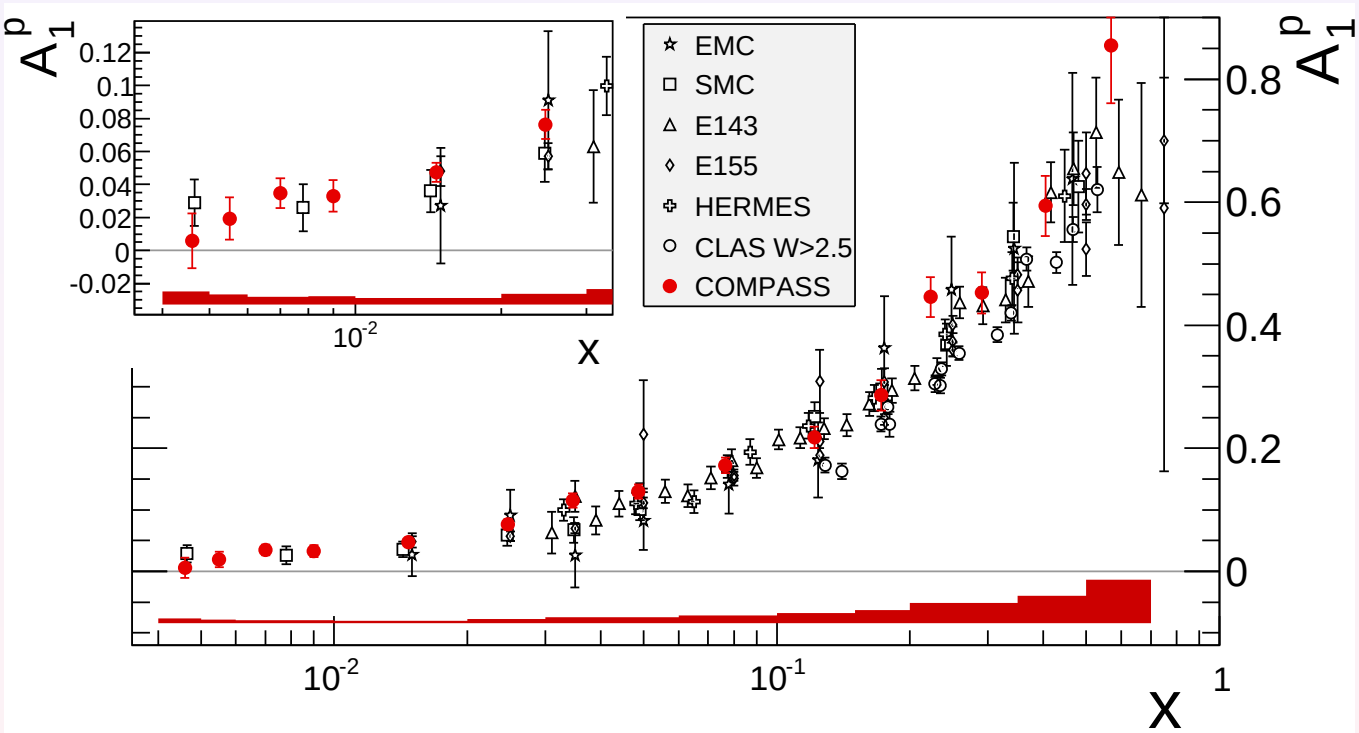


Measure double spin asymmetry:

$$A_1 = \frac{g_1}{F_1} = \frac{\sigma^{\uparrow\downarrow}_{\gamma N} - \sigma^{\uparrow\uparrow}_{\gamma N}}{\sigma^{\uparrow\downarrow}_{\gamma N} + \sigma^{\uparrow\uparrow}_{\gamma N}} = \frac{\Sigma_q e_q^2 (q^{\uparrow} - q^{\downarrow})}{\Sigma_q e_q^2 (q^{\uparrow} + q^{\downarrow})} = \frac{\Sigma_q e_q^2 \Delta q}{\Sigma_q e_q^2 q}$$

Proton Asymmetry

$$\vec{l}(k) + \vec{N}(p) \rightarrow l'(k') + X(P_X)$$



$$Q^2 = -(k - k)^2$$
$$Q^2 > 1 \text{ GeV}^2$$
$$x = \frac{Q^2}{2p\cdot(k-k')}$$

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

Results

using proton, deuteron asymmetries and weak hyperon decay constants F and D:

$$\begin{aligned} \Delta\Sigma &= 0.254 \pm 0.042 \\ \Delta s + \Delta\bar{s} &= -0.110 \pm 0.012 \\ &\text{at } Q^2 = 4 \text{ GeV}^2 \end{aligned}$$

E. Leader, A. V. Sidorov and D. B. Stamenov, arXiv:1010.0574 [hep-ph]

Provides only information about $\Delta q + \Delta\bar{q}$, because $e_q^2 = e_{\bar{q}}^2$

Helicity distributions

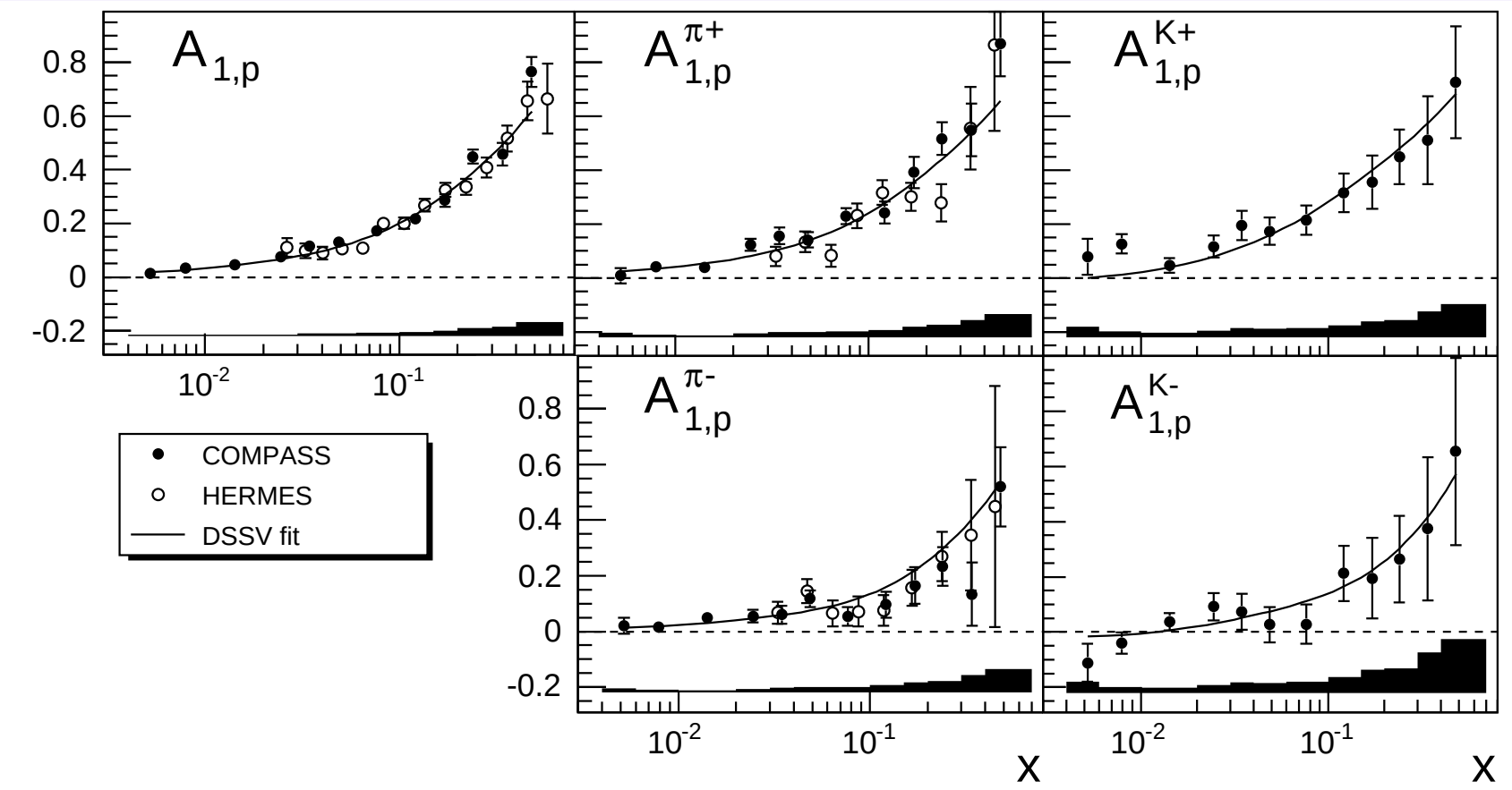
How to measure helicity distributions for different flavors?

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

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

- 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

Semi-Inclusive Aymmetries



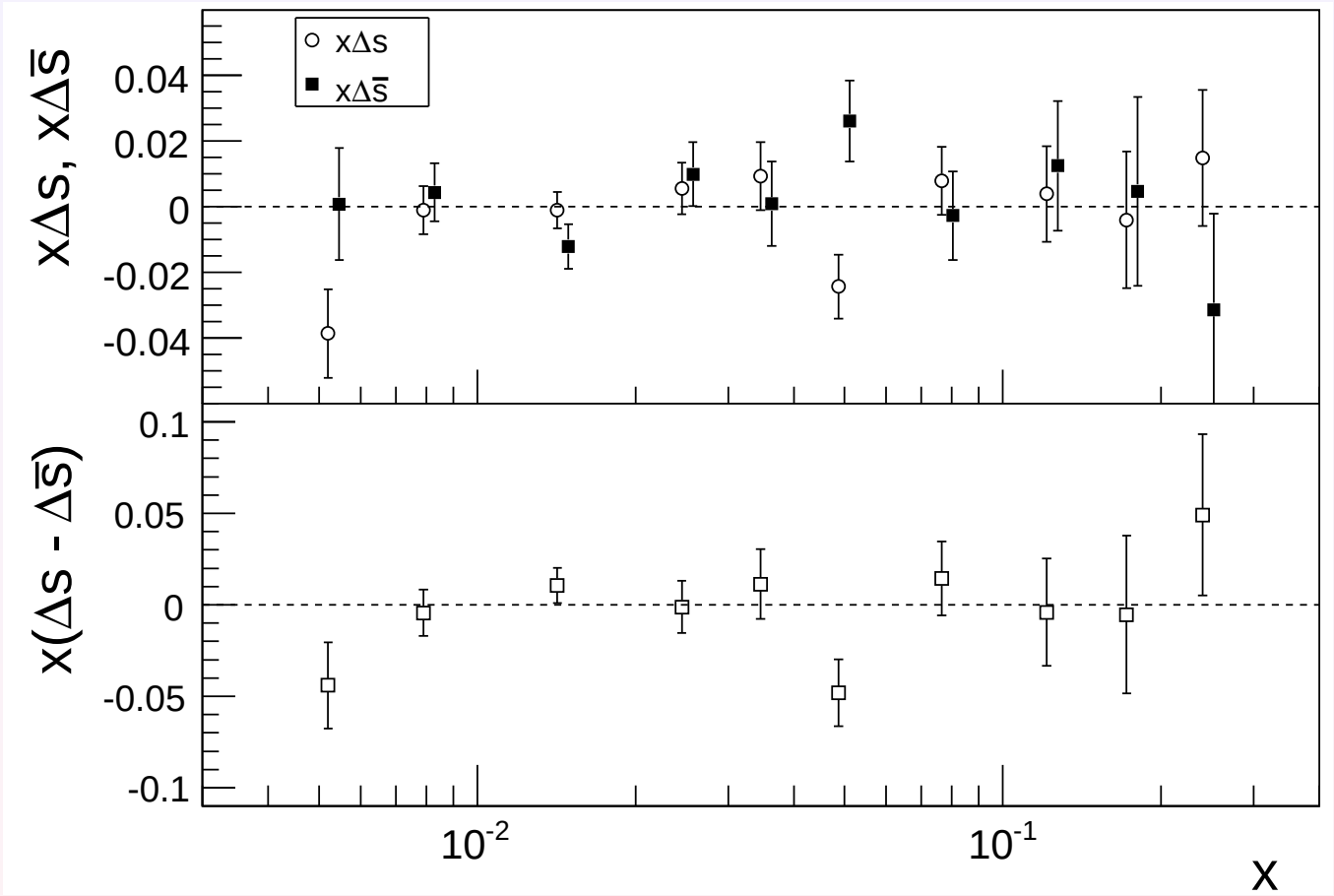
Asymmetries $\longrightarrow \Delta q$

Solve:

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

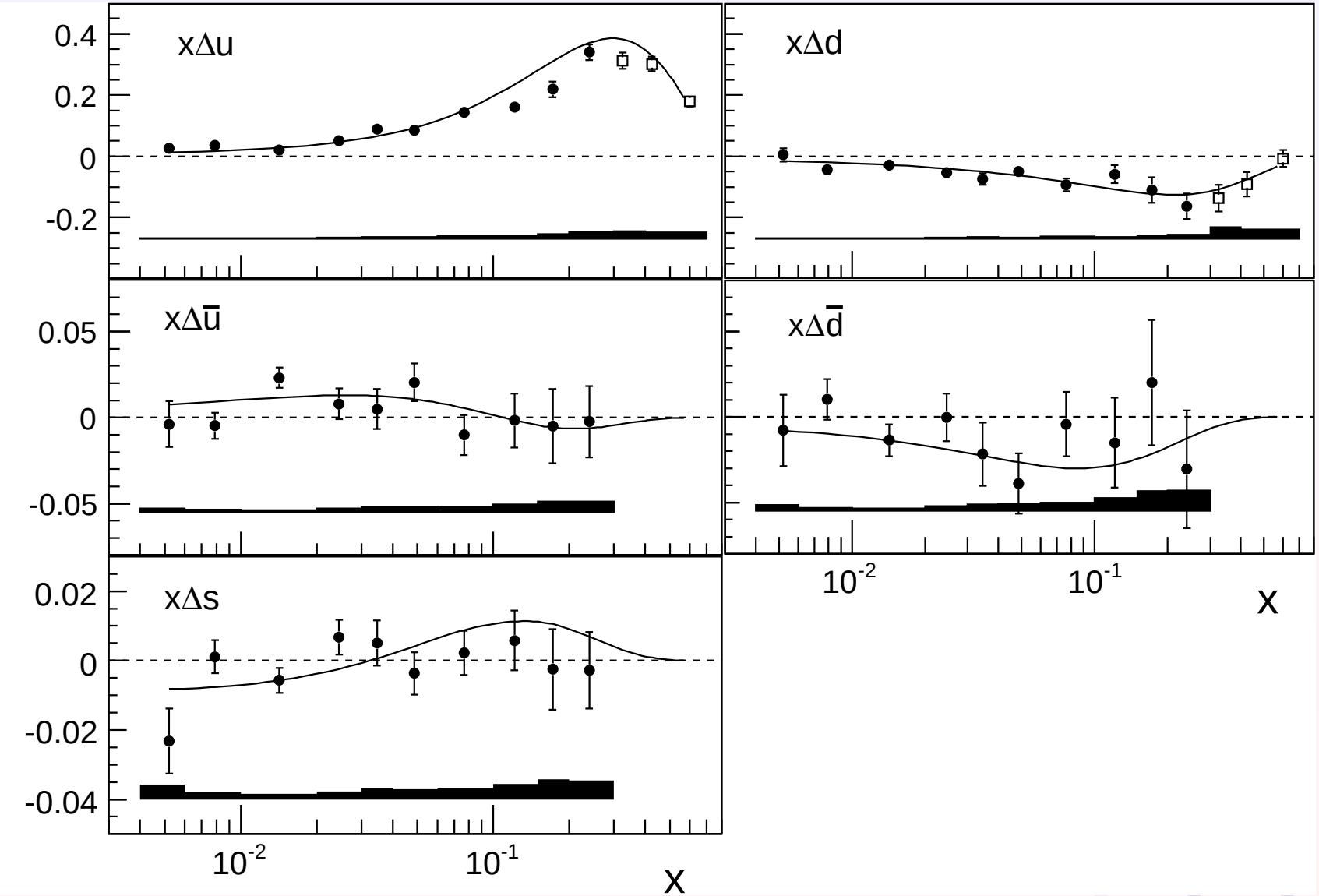
- $\vec{A} = (A_{1,p}, A_{1,p}^{\pi^+}, A_{1,p}^{K^+}, \ldots, A_{1,d}, \ldots, A_{1,p}^{K^-})$
- $\Delta\vec{q} = (\Delta u, \Delta d, \Delta s, \Delta\bar{u}, \Delta\bar{d}, \Delta\bar{s})$
- $B(q, \int D_q^h \mathrm{d}z)$

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

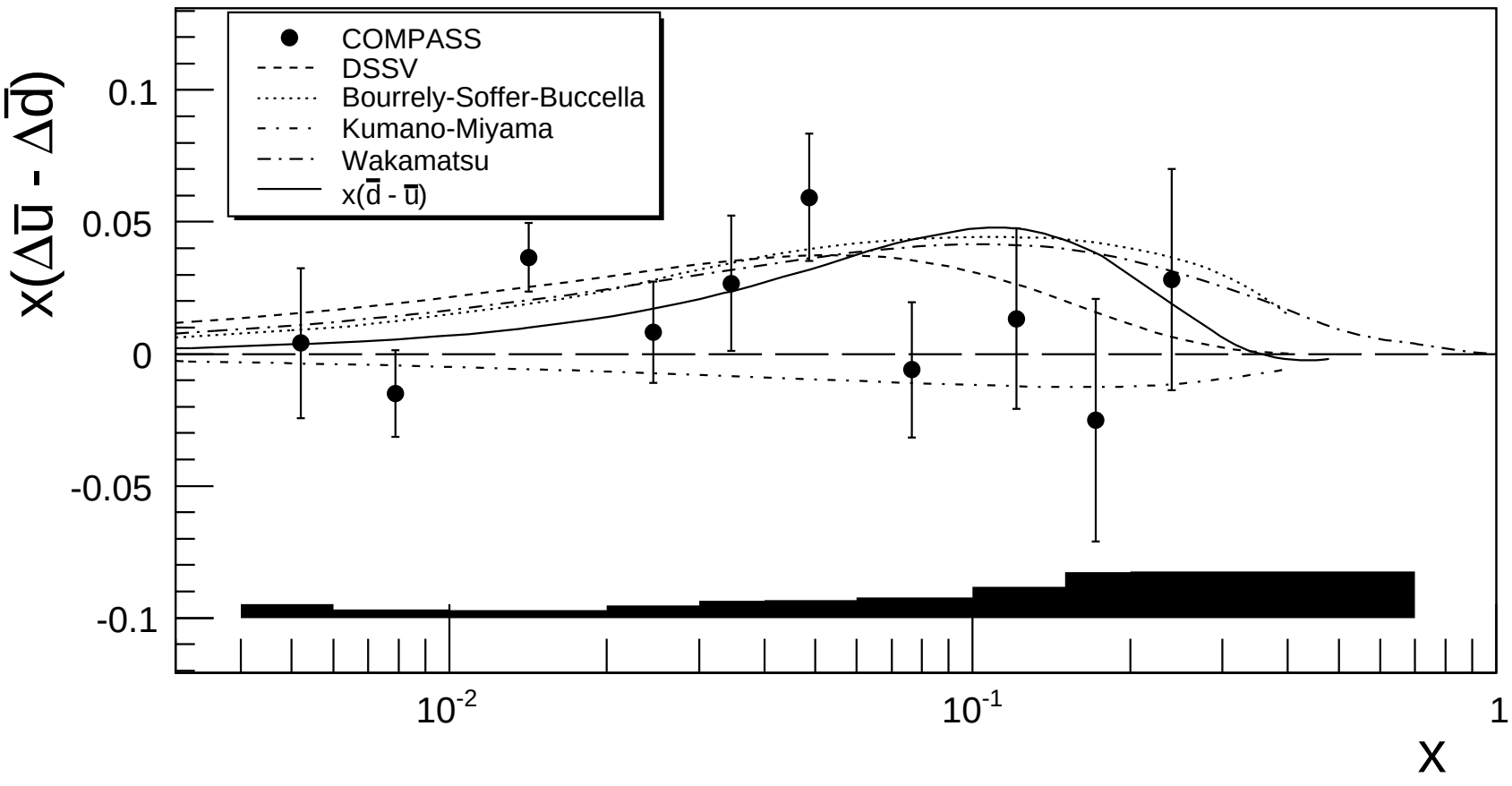


$\Rightarrow$ In the following assume $\Delta s = \Delta\bar{s}$

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



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



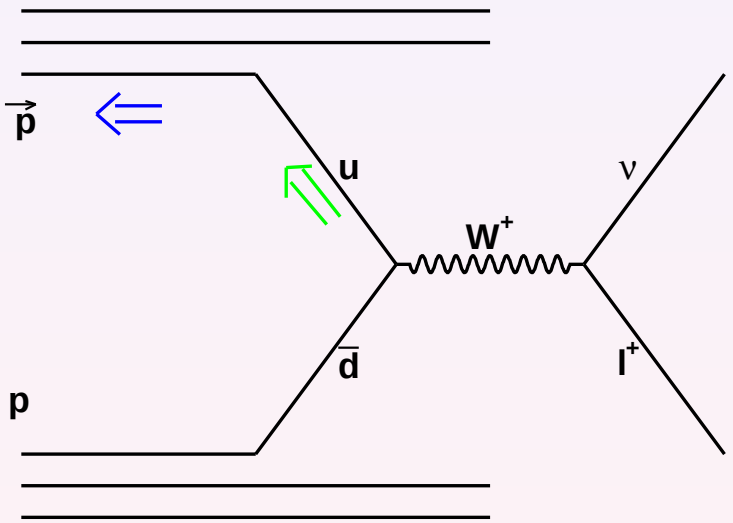
$$\int_{0.004}^{0.3} \Delta\bar{u}(x) - \Delta\bar{d}(x)\mathrm{d}x = 0.06 \pm 0.04 \pm 0.02$$

Summary Δq

- Statistics allowed for the first time to determine all 6 quark flavors from COMPASS data alone
- $\Delta\bar{u} - \Delta\bar{d} > 0$? More data will decide
- $\Delta\Sigma = 0.32 \pm 0.03$ consistent with inclusive result
- No difference found between Δs and $\Delta\bar{s}$
- $\int_{0.004}^{0.3}(\Delta s + \Delta\bar{s})\mathrm{d}x = -0.02 \pm 0.02 \pm 0.02$ in contrast to $\int_{0}^{1}(\Delta s + \Delta\bar{s})\mathrm{d}x = -0.11 \pm 0.01$ from inclusive data & Hyperon decay constants
- Result (mainly Δs) depend on fragmentation functions

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

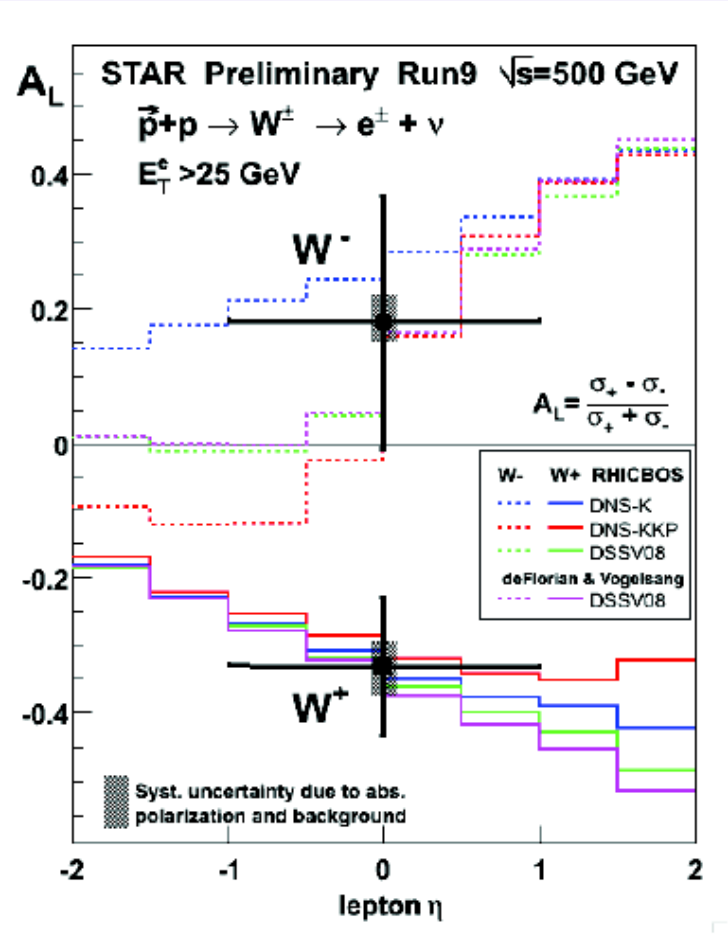
- Instead of measuring double spin asymmetries, one can measure single spin asymmetries and use weak interaction
- Done at RHIC ($\vec{p} + p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$ at $\sqrt{s} = 500$ GeV)



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

Results

STAR



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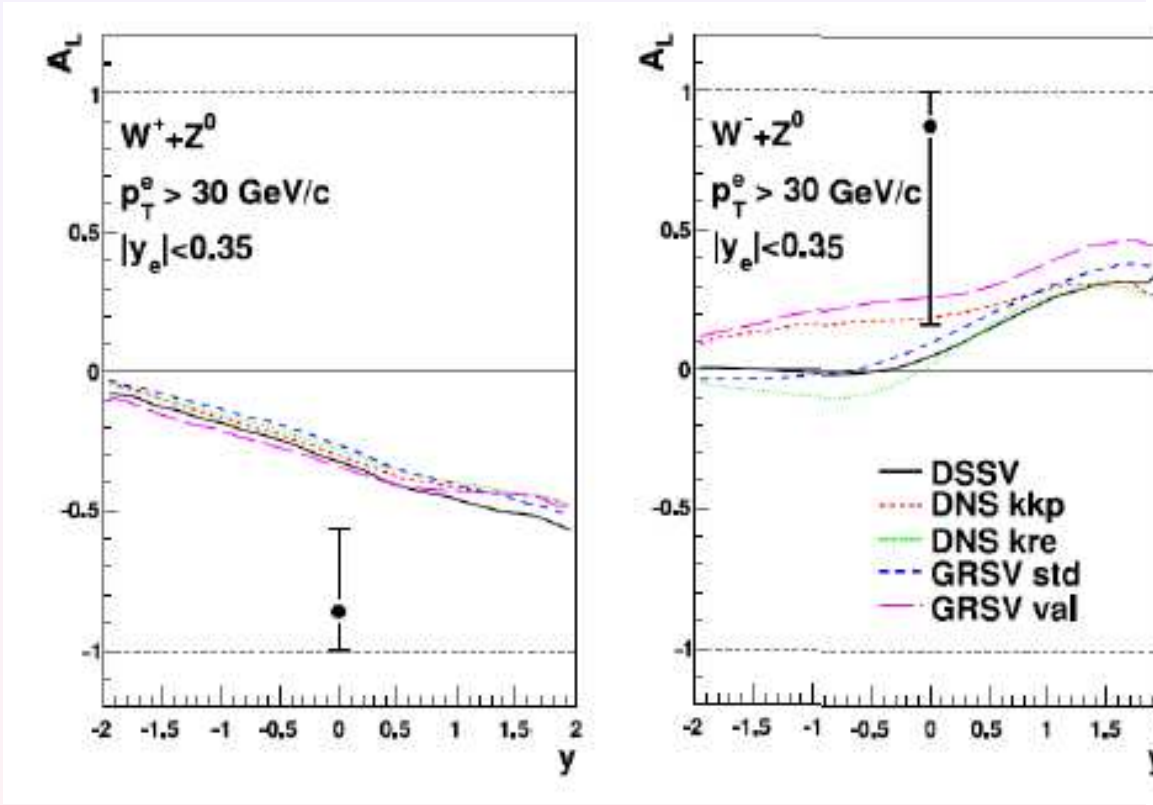
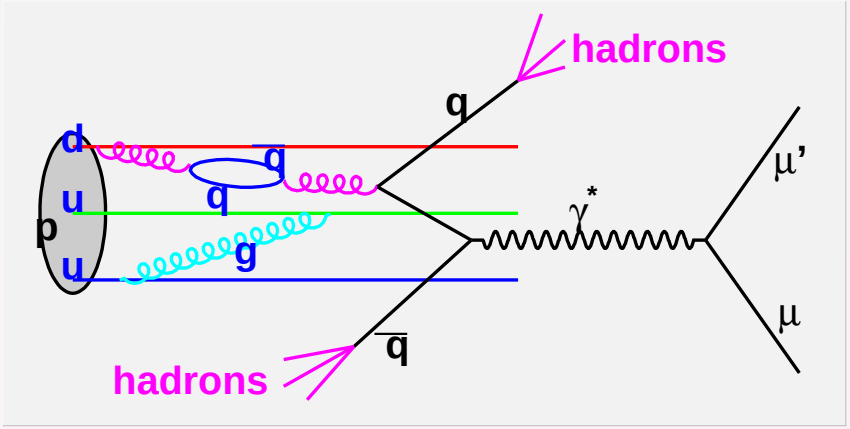


Gluon Helicity

How to measure ΔG?

Use hadronic final state in DIS to tag gluon!

$\vec{\mu} + \vec{N} \rightarrow \mu' + \text{hadrons} + X$



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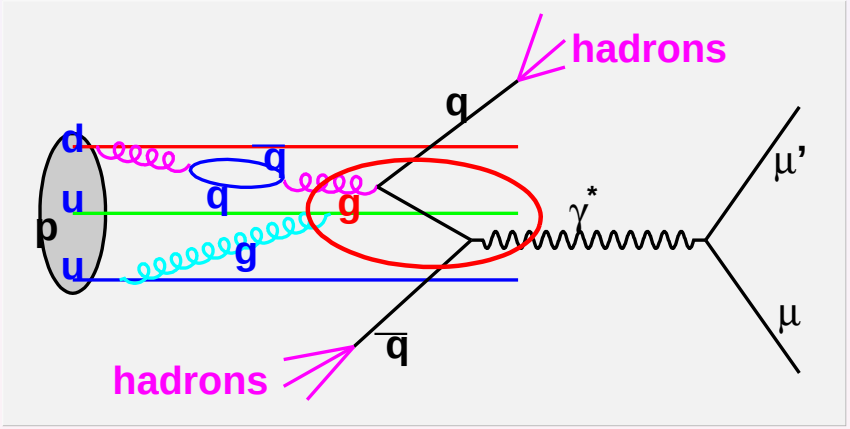
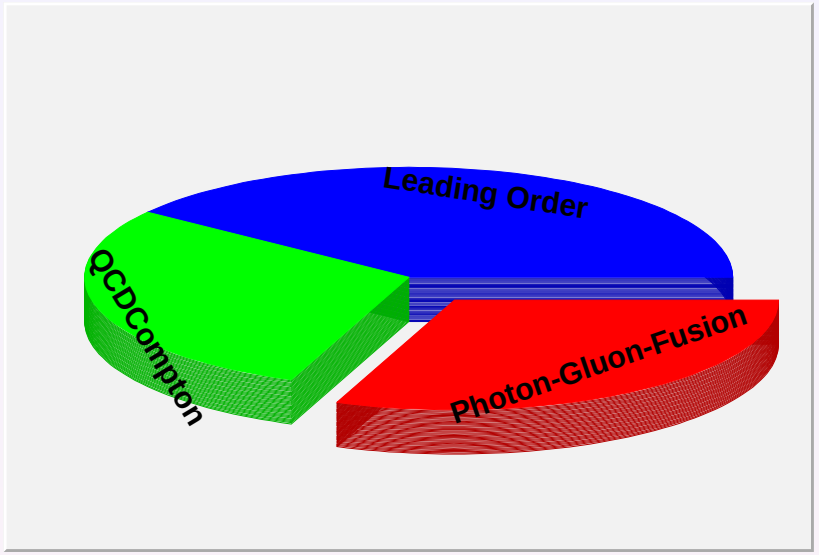


How to tag Photon -Gluon- Fusion sub-process

$\gamma^* g \rightarrow q\bar{q}$?

1. open charm: $\gamma^* g \rightarrow c\bar{c} \rightarrow D^0 + X$
2. high p_T: $\gamma^* g \rightarrow q\bar{q} \rightarrow$ hadrons with large p_T

High p_T

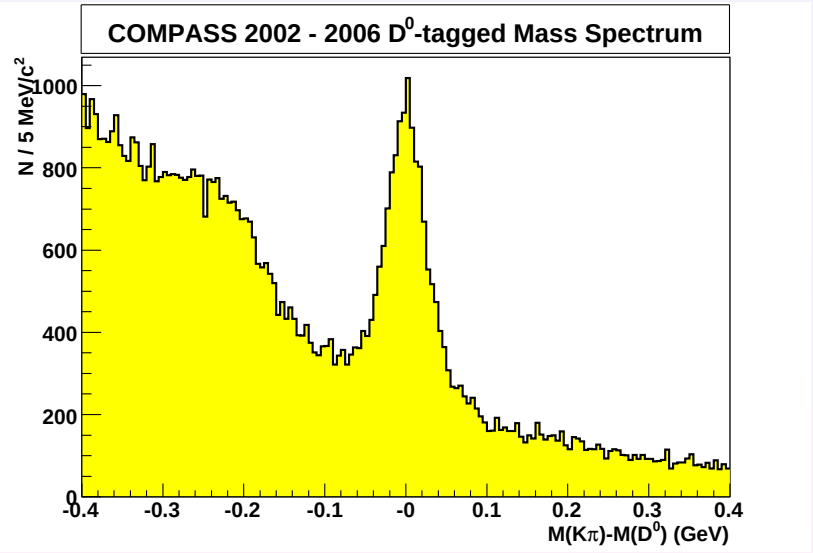


$$R = \frac{\sigma_{PGF}}{\sigma_{PGF}+\sigma_{bgd}} \approx 0.3$$

from LEPTO MC for $Q^2 > 1$ GeV^2
PYTHIA MC for $Q^2 < 1$ GeV^2

Open Charm

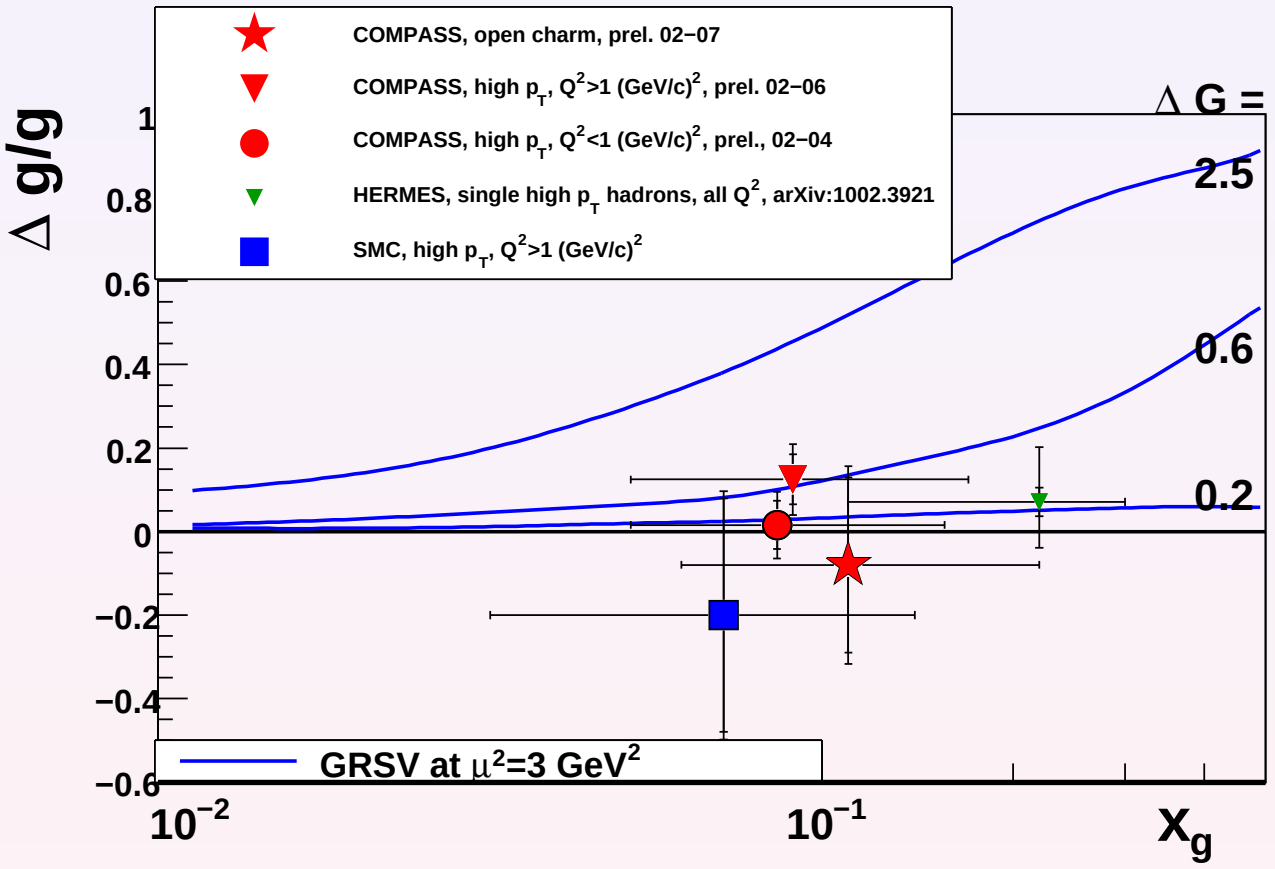
$$D^{*+} \rightarrow D^0\pi^+_{soft} \rightarrow K^-\pi^+\pi^+_{soft}$$



$$R = \frac{\sigma_{PGF}}{\sigma_{PGF}+\sigma_{bgd}} \approx 0.5$$

from data

Results on ΔG from DIS

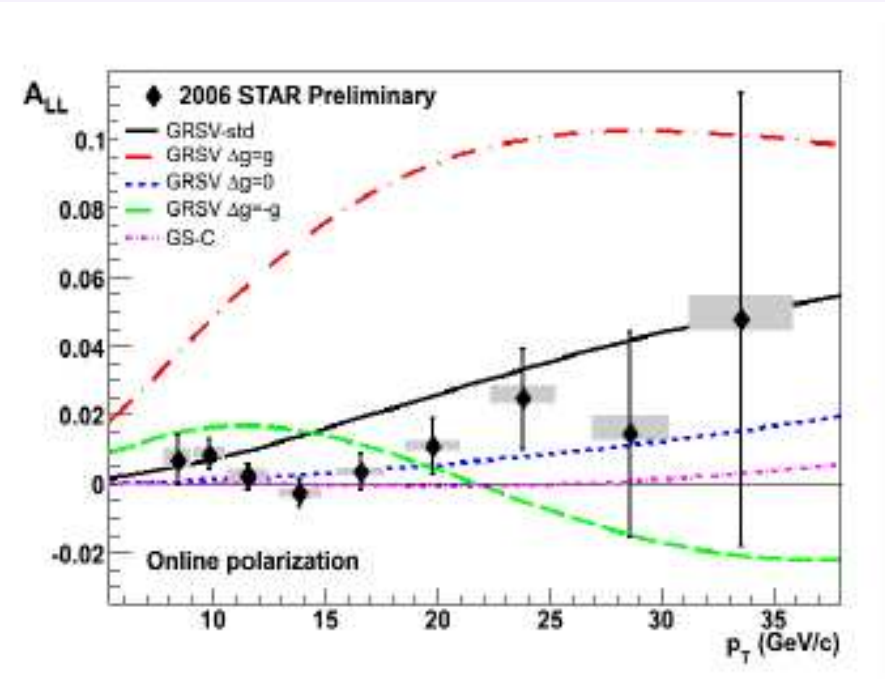


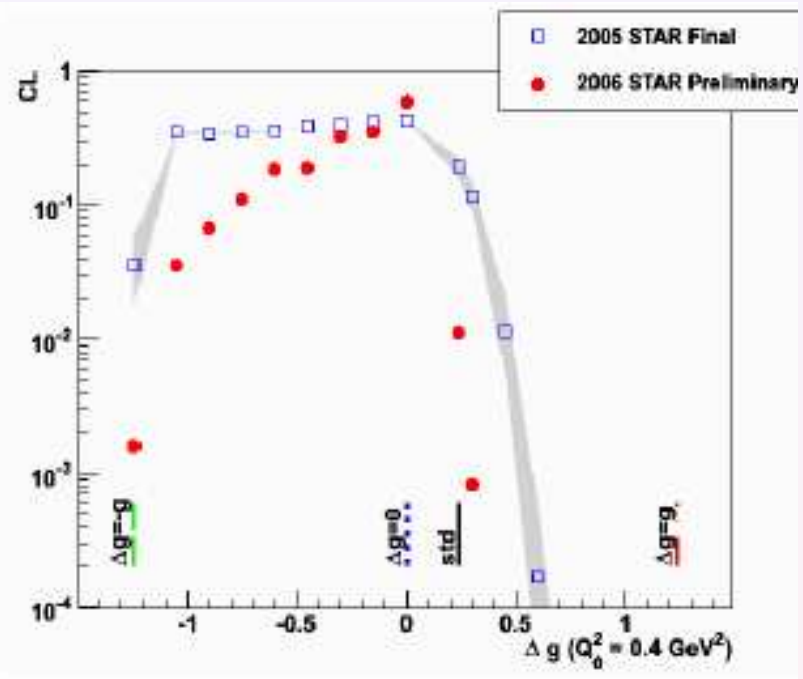
- Data show small values of $\Delta g/g$ at $x_g \approx 0.1$

Results on ΔG from $\vec{p}\vec{p}$

STAR:

$\vec{p} + \vec{p} \rightarrow \text{Jet} + X$





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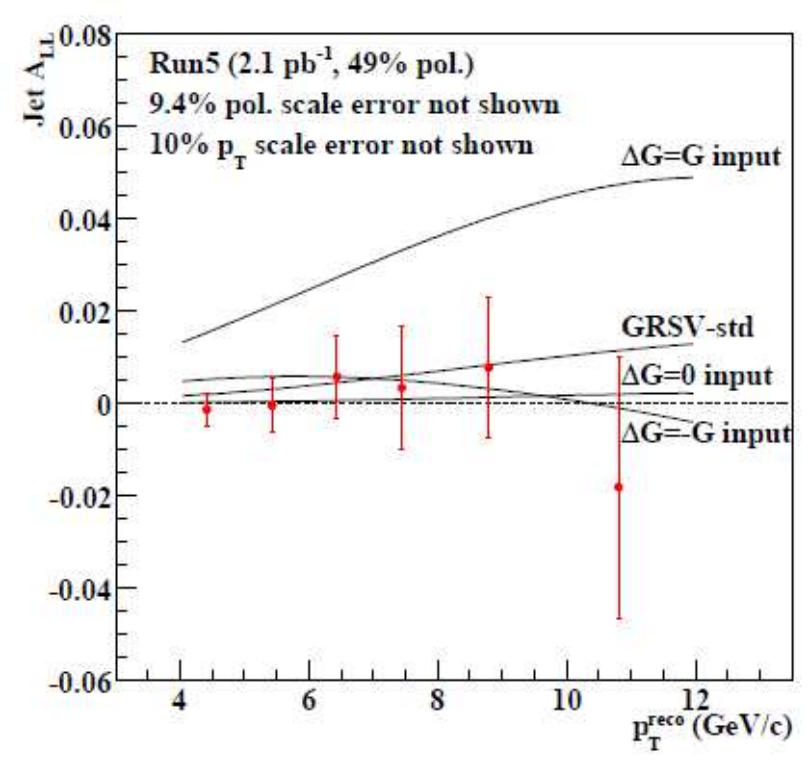

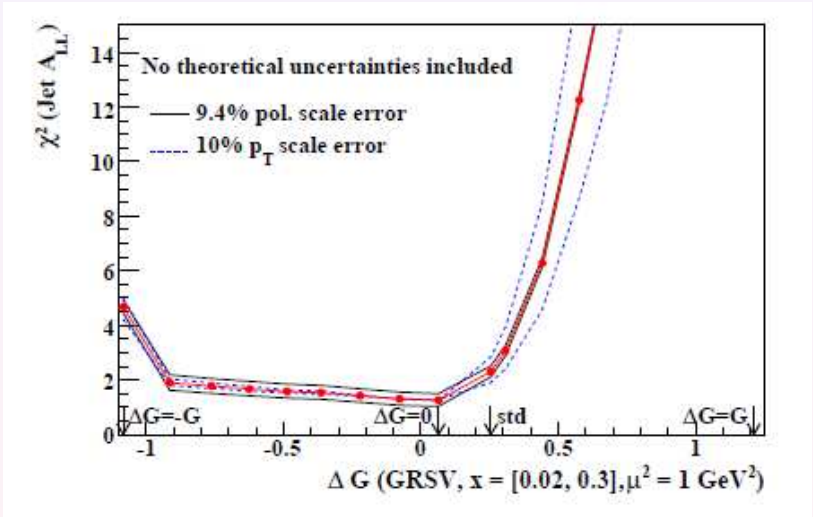

Summary ΔG

- $\Delta G = \int_0^1 \Delta g(x) \mathrm{d}x \approx 0 \pm \frac{1}{2}$
  certainly small compared to large values $\Delta G \approx 2 - 3$
  proposed to explain small of $\Delta\Sigma \approx 30\%$,
  not small compared to the total spin of the proton of $\frac{1}{2}$!
- x-dependence not very well determined
- Note: RHIC results are in NLO QCD, (most) DIS results in LO QCD

Future Projects

The ENC@FAIR project

- add a 3 GeV e^+/e^- accelerator to the already planed 15 GeV HESR (High Energy Storage Ring) for $\bar{p}$, p
- e^- and p polarized ($P \approx 80\%$)
- $\mathcal{L} \approx 10^{32}/\mathrm{cm}^2/\mathrm{s}$
- Use (modified) PANDA detector

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Experiment	JLab(12 GeV)	HERMES	ENC	COMPASS
s/GeV^2	23	50	180	300
$\mathcal{L}/(1/\mathrm{cm}^2/\mathrm{s})$	$\approx 10^{38}$	$\approx 10^{32}$	$\approx 10^{32}$	$\approx 10^{32}$

Luminosity $\longrightarrow$ FOM

More interesting: FOM for polarisation measurements:

$$\text{FOM} = (\text{diluting factors})^2\,\mathcal{L}$$

diluting factors:	beam polarization	P_B
	target polarization	P_T
	target dilution factor	f
	reconstruction efficiency and purity	r

Diluting Factors

	COMPASS	collider
P_T	0.5	0.8
f	0.4	1
P_B	0.8	0.8

COMPASS uses a solid target (^{6}LiD or NH_3)

dilution factor $\approx \frac{\text{nb. of polarisable nucleons}}{\text{nb. of all nucleons}} = \frac{4}{8}$ for ^{6}LiD

Diluting Factors

	diluting factor		ratio
	COMPASS	ENC	
double spin asymmetries $(P_T f P_B)^2$	0.026	0.41	16
reconstruction of hadronic final state			≈ 10
mass resolution	☹	☺	
displaced vertices	☹	☺	
more D^0 deacy ch.	☹	☺	
determination of x_g due to reconstruction of D and $\bar{D}$	☹	☺	

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Huge potential for polarization observables!

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  - $\Delta G \approx 0 \pm \frac{1}{2}$

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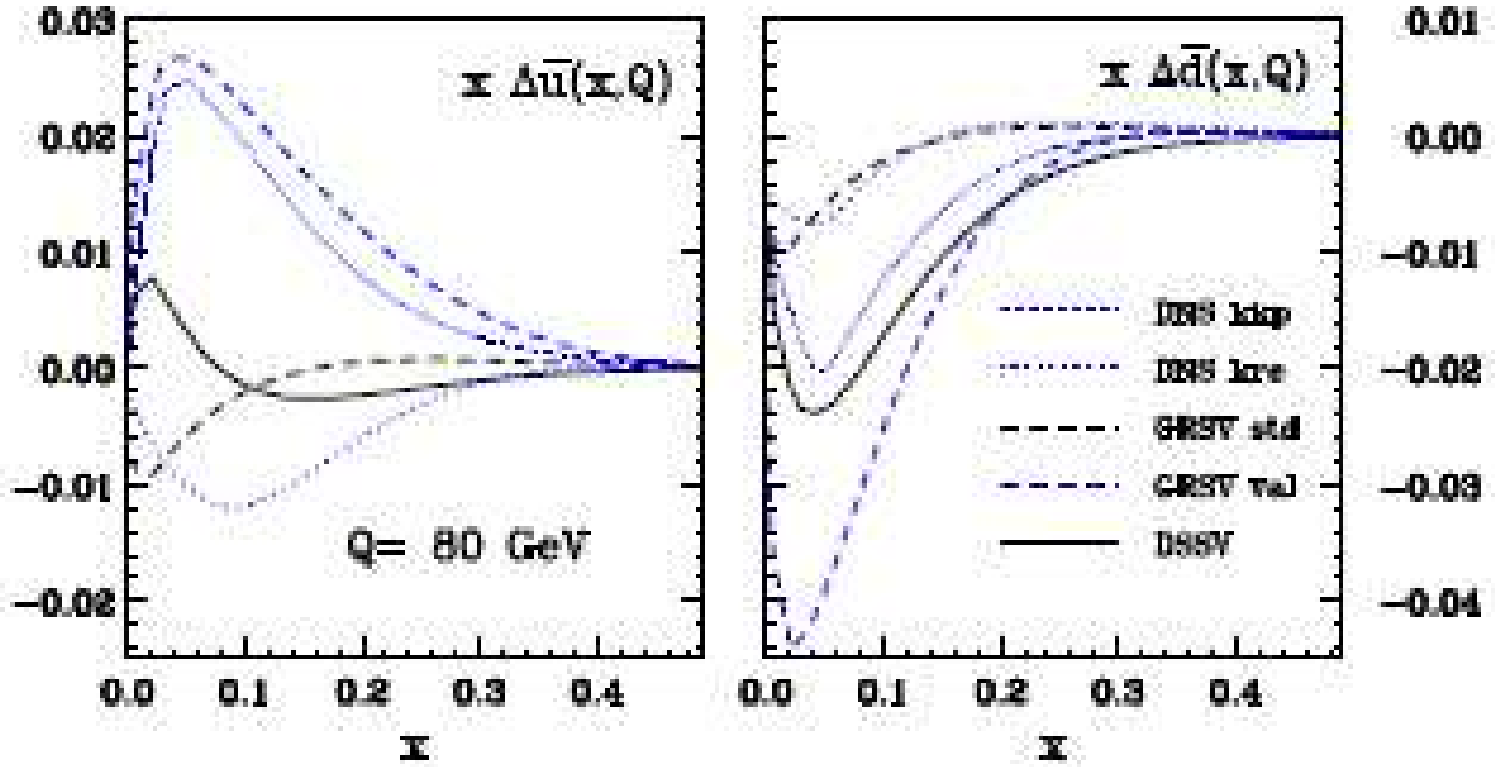
- An **polarized electron nucleon collider** would offer high potential for polarisation measurements

Spare

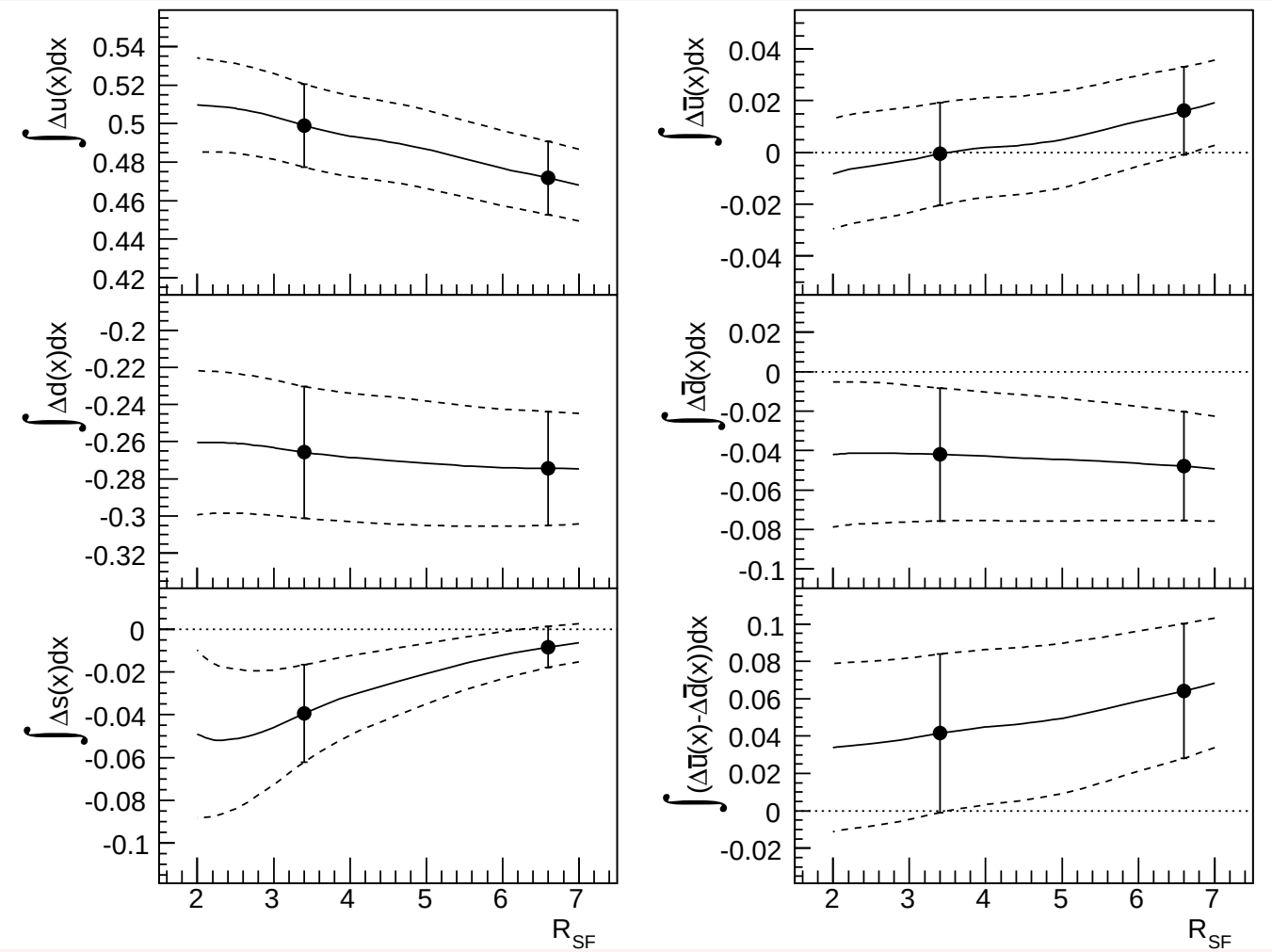
$\Delta\bar{u}$ and $\Delta\bar{d}$

for different curves shown in A_{LL}^{W} plot.



D. de Florian, W. Vogelsang arXiv 1003.4533

Dependence of SIDIS results on FF



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

Unpol. PDFs at $Q^2 = 10$ GeV^2