Spin Structure of the Nucleon: Theory

Werner Vogelsang

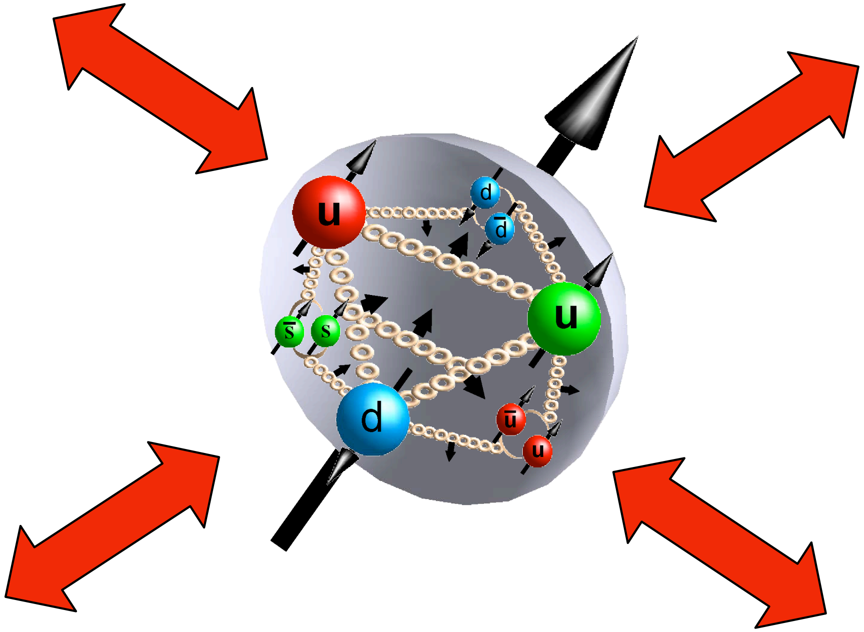
BNL Nuclear Theory

EIC workshop, LBL, 12/13/2008

Exploring the nucleon: a fundamental quest

Know what we
are made of !

Test our ability
to *use* QCD:
Asymptotic Freedom
Factorization



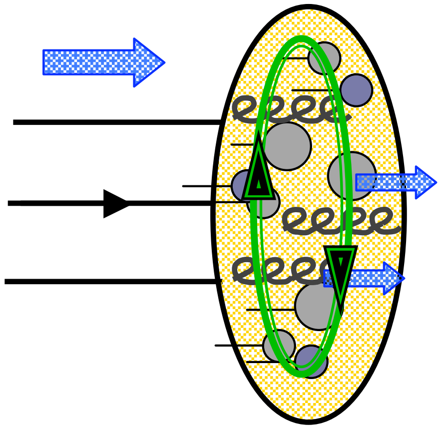
Explore and
Understand QCD:
Confinement
Lattice
Models

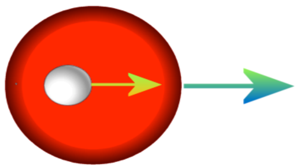
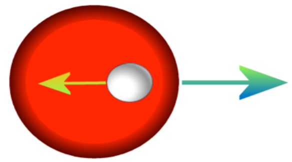
Nucleon as tool for
discovery:
RHIC Heavy Ions,
LHC, …

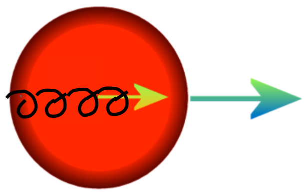
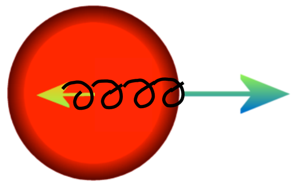
Outline:

- Nucleon helicity structure
- Transverse-spin phenomena in QCD
- Conclusions

Nucleon helicity structure

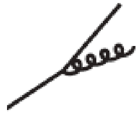


$\Delta q(x) =$  $-$ 

$\Delta g(x) =$  $-$ 

$$\Delta\, q(x) \;=\; \frac{1}{4\pi}\int dy^-\, \mathrm{e}^{-iy^- xP^+}\,\langle\, P, S\,|\,\bar{\psi}_q(0, y^-, \mathbf{0}_\perp)\;\gamma^+\gamma_5\,\psi_q(0)\,|\,P, S\,\rangle$$

- **DGLAP evolution:**

$$\mu^2 \frac{\mathrm{d}}{\mathrm{d}\mu^2} \begin{pmatrix} \Delta q(x,\mu^2) \\ \Delta g(x,\mu^2) \end{pmatrix} = \int_x^1 \frac{dz}{z} \begin{pmatrix} \Delta\mathcal{P}_{qq} & \Delta\mathcal{P}_{qg} \\ \Delta\mathcal{P}_{gq} & \Delta\mathcal{P}_{gg} \end{pmatrix} \begin{pmatrix} \Delta q \\ \Delta g \end{pmatrix} \left(\frac{x}{z},\mu^2\right)$$

$$\Delta\mathcal{P}_{ij}(z,\alpha_s) = \underbrace{\frac{\alpha_s}{2\pi}\Delta P_{ij}^{(0)}(z)}_{\text{“LO”}} + \underbrace{\left(\frac{\alpha_s}{2\pi}\right)^2 \Delta P_{ij}^{(1)}(z)}_{\text{“NLO”}} + \ldots$$

(Ahmed,Ross; Altarelli,Parisi; Mertig,van Neerven; WV)

- NNLO: Moch, Rogal, Vermaseren, Vogt

- *give q and g spin contributions to proton spin:*

Jaffe, Manohar; Ji, Hoodbhoy;
Jaffe, Bashinsky; Brodsky; Chen et al.

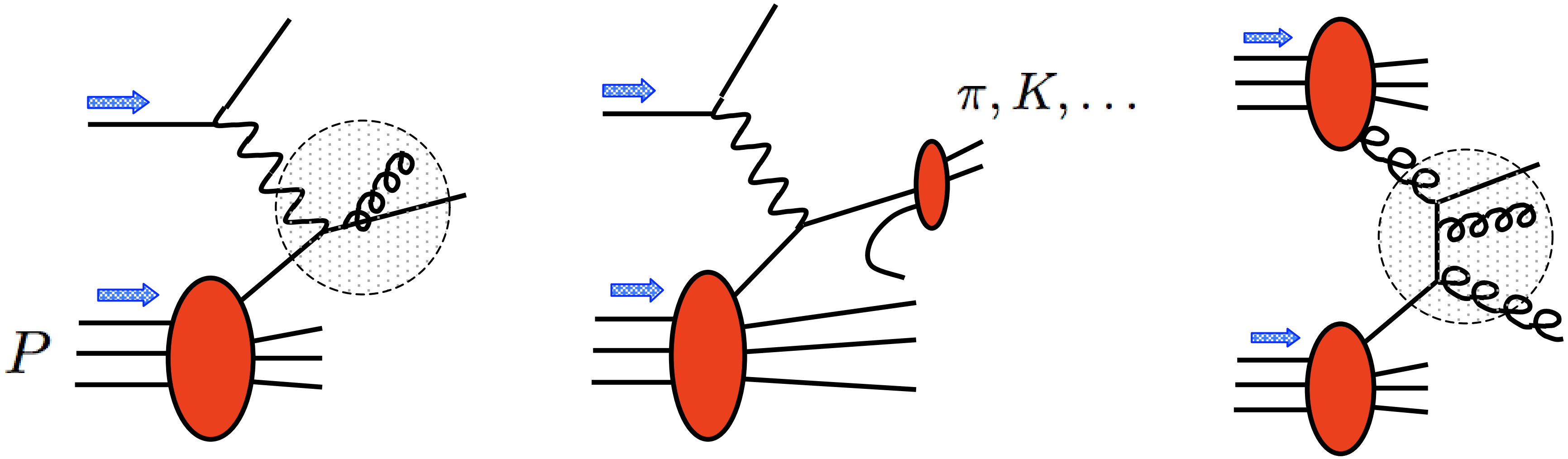
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

$$\Delta\Sigma = \int_0^1 dx \left[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right](x)$$

$$\Delta G = \int_0^1 dx\, \Delta g(x)$$

- *accessible in high energy polarized scattering at large momentum transfer*

The probes of nucleon helicity structure :



DIS SIDIS pp (RHIC)

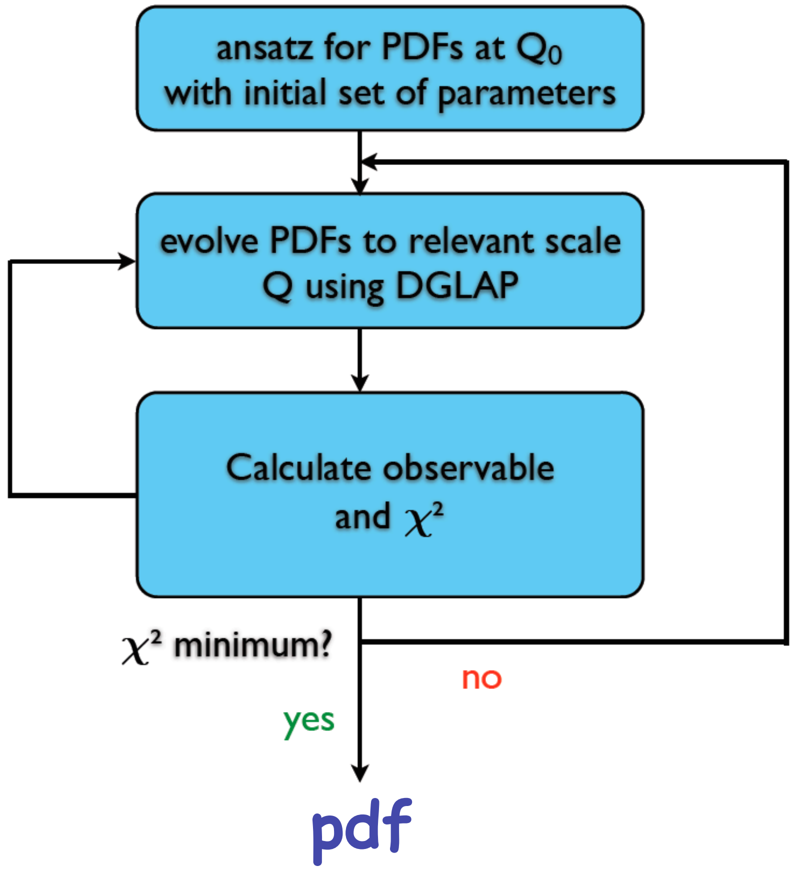
DIS $$\Delta\sigma = \sum_{f=q,\bar{q},g} \int dx\, \Delta f(x, Q^2)\, \Delta\hat{\sigma}^f(xP, \alpha_s(Q^2)) + \text{P.C.}$$

pp $$\Delta\sigma = \sum_{a,b=q,\bar{q},g} \int dx_a\, \Delta f_a(x_a, p_\perp^2) \int dx_b\, \Delta f_b(x_b, p_\perp^2) \Delta\hat{\sigma}^{ab}(x_a P, x_b P', \alpha_s(p_\perp^2)) + \text{P.C.}$$

$$\Delta\hat{\sigma} = \Delta\hat{\sigma}_{\text{LO}} + \alpha_s \Delta\hat{\sigma}_{\text{NLO}} + \ldots$$

Long history of NLO QCD analyses of helicity parton distributions in DIS:

GRSV	Glück, Reya, Stratmann, WV
ABFR	Altarelli, Ball, Forte, Ridolfi/SMC
GS	Gehrmann, Stirling
BB	Blümlein, Böttcher/HERMES
BBS	Bourrely, Buccella, Soffer
LSS	Leader, Sidorov, Stamenov
AAC	Hirai, Kumano, Saito
DNS	de Florian,Navarro,Sassot
...	



New: "Global analysis" of all DIS, SIDIS, RHIC data sets

DSSV de Florian, Sassot, Stratmann, WV (PRL 101, 2008)

(→ tool for EIC studies)

There is some additional information:

$$\Delta\Sigma_q \equiv \int_0^1 dx\ (\Delta q + \Delta\bar{q})\,(x)\ \propto\ \langle\, P, s\,|\,\bar{\psi}_q\,\gamma^\mu\gamma_5\,\psi_q\,|\,P, s\,\rangle$$

axial charges

use SU(3) to obtain non-singlet combinations from baryon decays:

Bjorken; Karliner, Lipkin; Ratcliffe;...

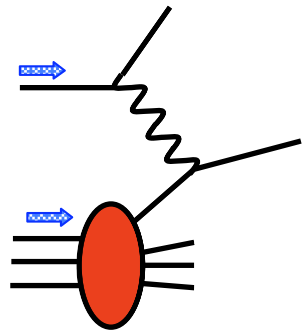
$$\Delta\Sigma_u - \Delta\Sigma_d = g_A = 1.257 \pm \ldots$$

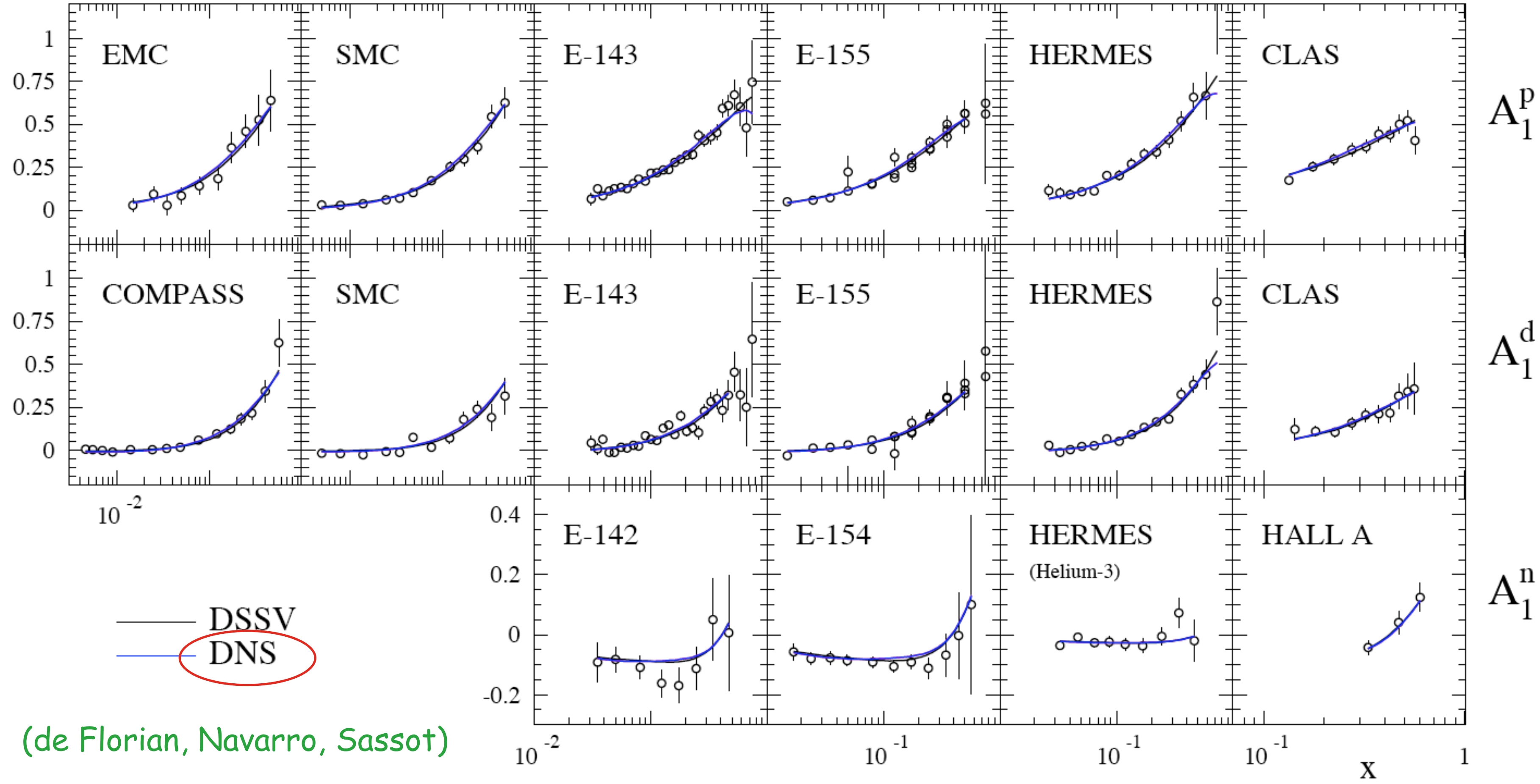
$$\Delta\Sigma_u + \Delta\Sigma_d - 2\Delta\Sigma_s = 3F - D = 0.58 \pm 0.03$$

$$\longrightarrow\ \Delta\Sigma = \Delta\Sigma_u + \Delta\Sigma_d + \Delta\Sigma_s = 3F - D + 3\Delta\Sigma_s$$

- sizable negative strange contribution ?

Spin asymmetries in inclusive DIS:



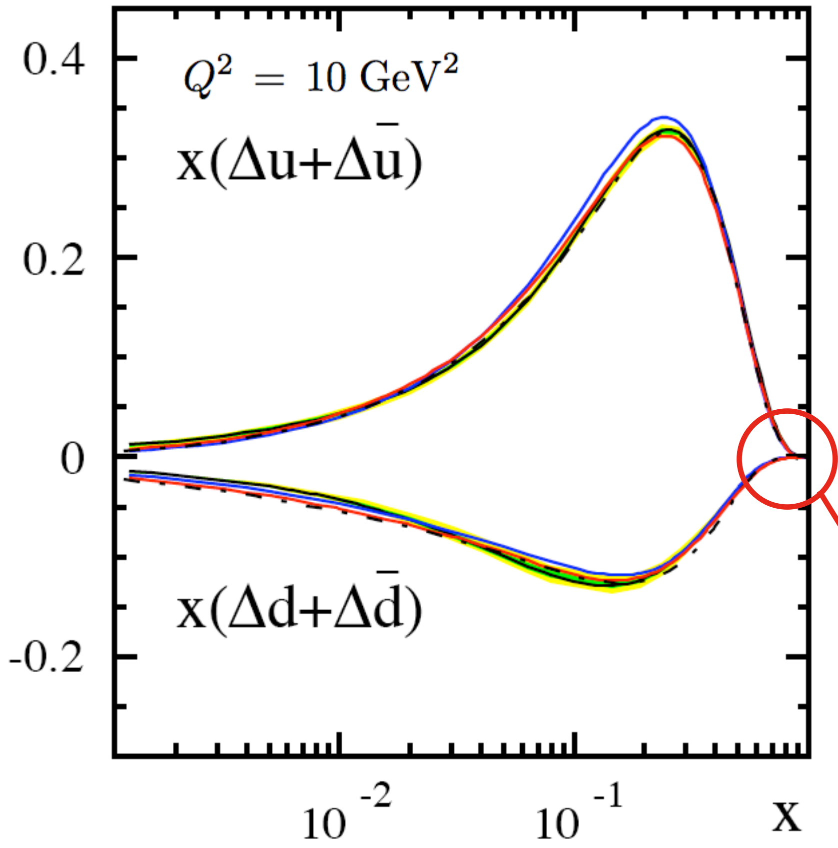


(de Florian, Navarro, Sassot)

(likewise for semi-inclusive DIS)

What's the emerging picture ?

- best determined: $\Delta u + \Delta\bar{u}$, $\Delta d + \Delta\bar{d}$



Comparison with:

DNS de Florian,Navarro,Sassot

GRSV Glück, Reya, Stratmann, WV

Similar results:

Leader, Stamenov, Sidorov

Blümlein, Böttcher; & HERMES

Hirai, Kumano, Saito (AAC)

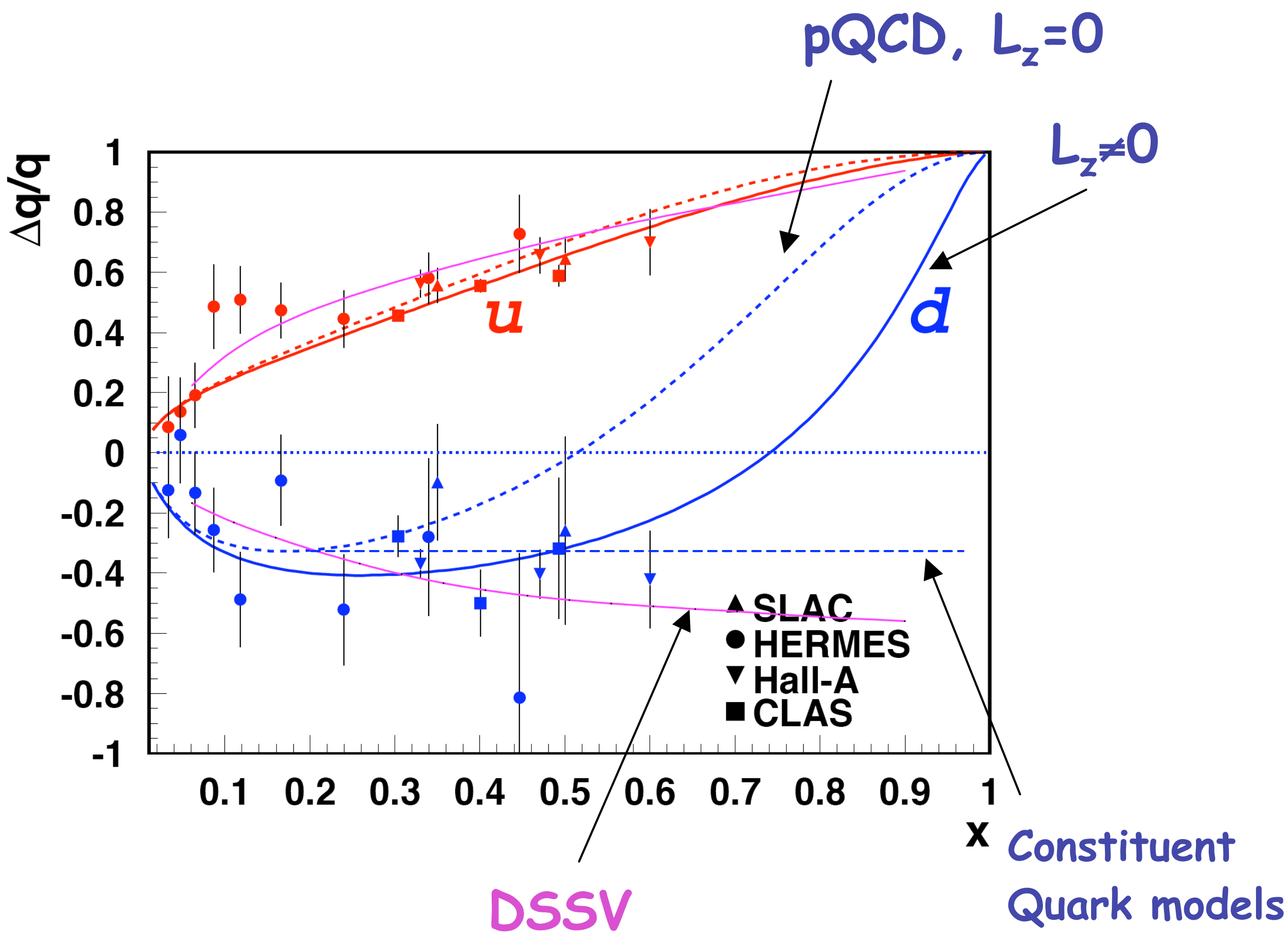
COMPASS

$\Delta u/u \to 1$

$\Delta d/d < 0$

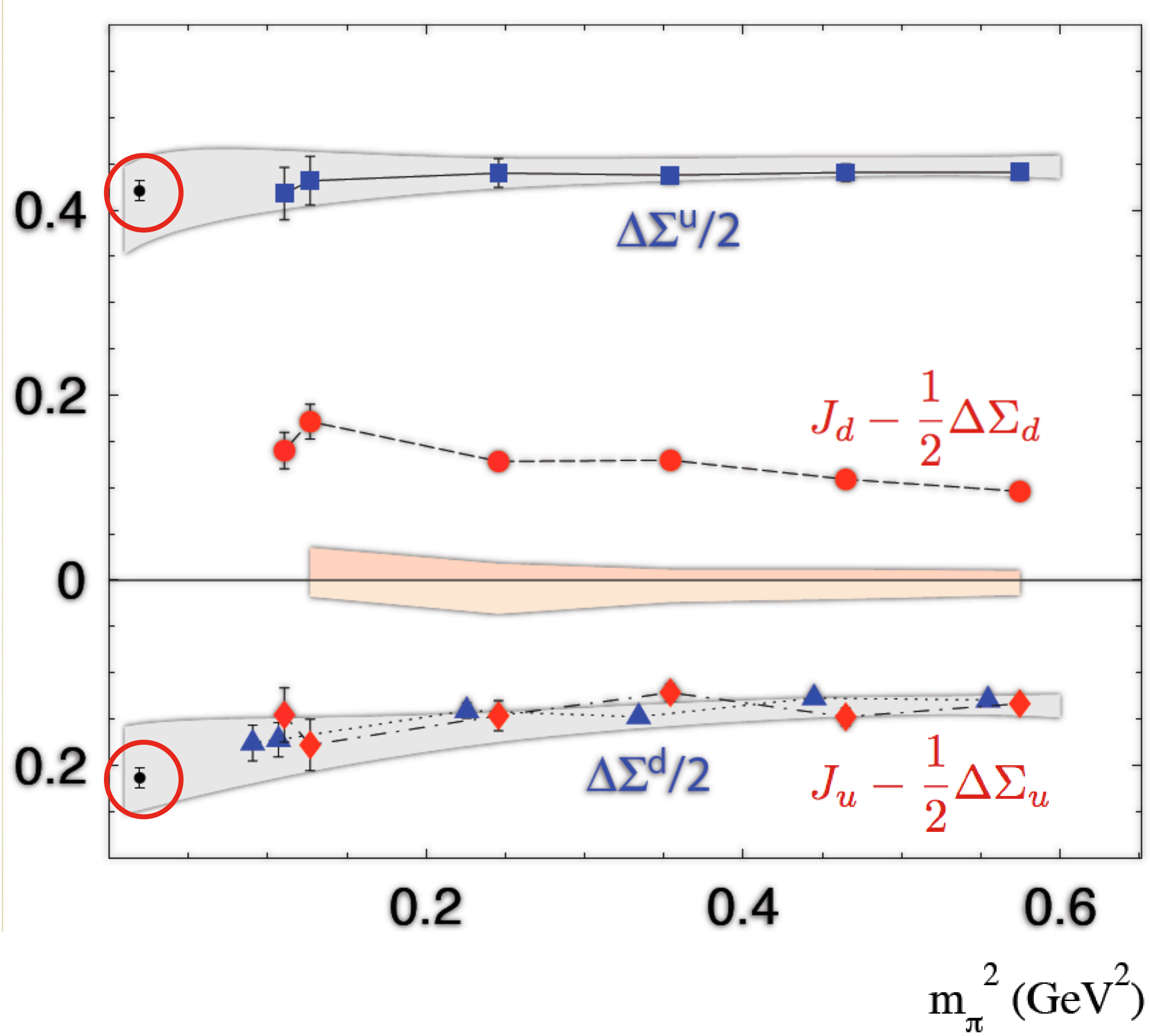
Avakian, Brodsky, Deur, Yuan

- large-x region :



- on the lattice :

LHPC Collab., P. Hägler et al.



disconnected diagrams not yet included

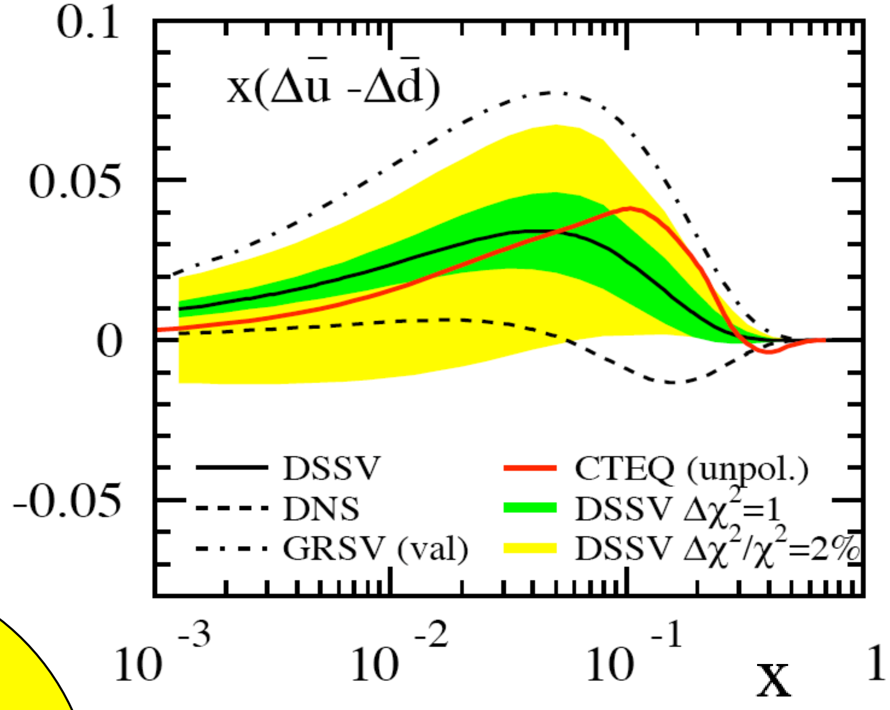
- gives confidence in small-x extrapolations

• light flavor sea :

Driven by SIDIS. (Reliable ?)

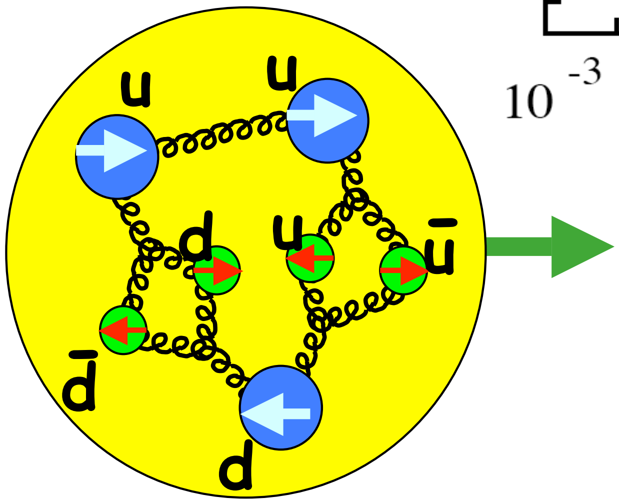
$$\Delta\bar{u} > 0$$

$$\Delta\bar{d} < 0$$



• qualitatively:

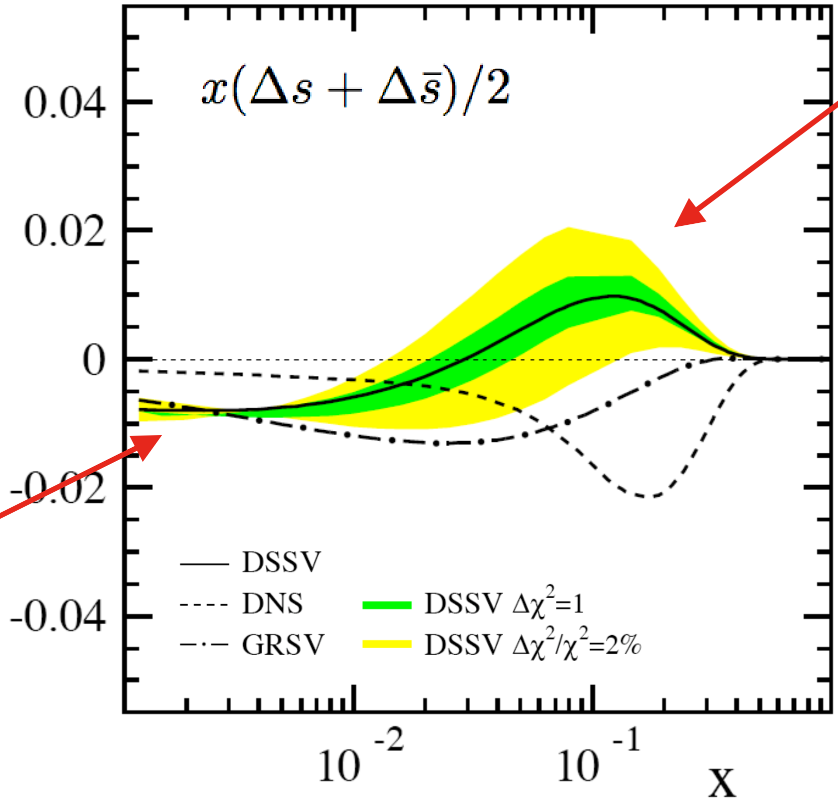
Glück,Reya;…



• large-N_c, chiral quark models, meson cloud

Thomas,Signal,Cao; Holtmann,Speth,Fässler; Diakonov,Polyakov,Weiss; Schäfer,Fries; Kumano; Wakamatsu; Bourrely, Soffer …

- strangeness :



driven by SIDIS (kaons … fragm. fcts.?)

driven by SU(3) (3F-D)

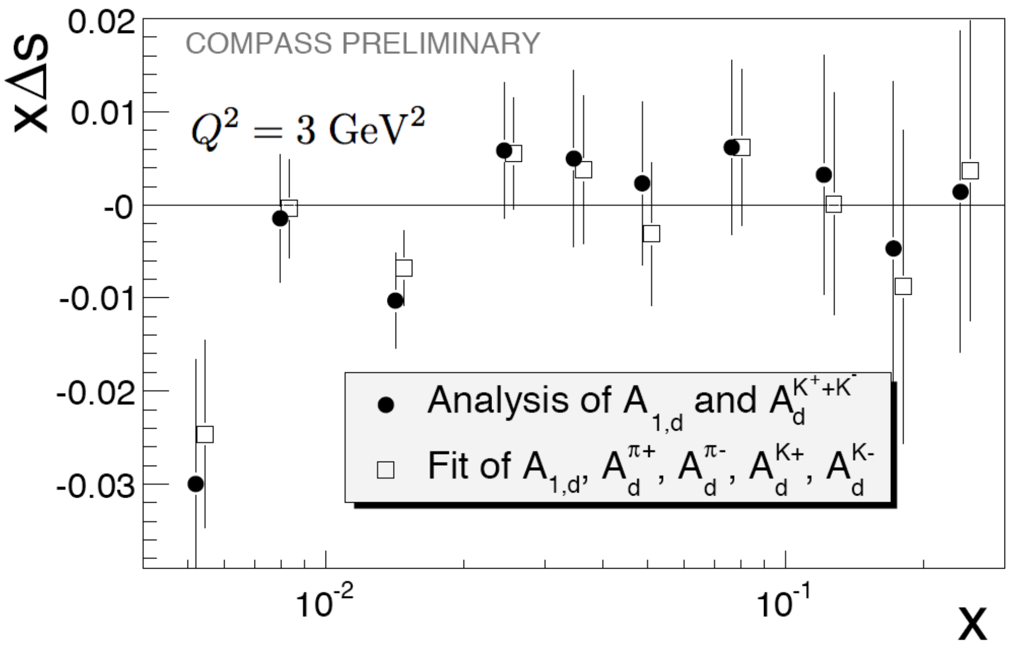
$$\int_{0.001}^{1} dx\, \Delta s(x) \;=\; -0.006 \pm 0.01 \qquad (\Delta\chi^2 = 1)$$

$$\int_{0}^{1} dx\, \Delta s(x) \;=\; -0.057 \pm ?$$

using F,D and SU(3)

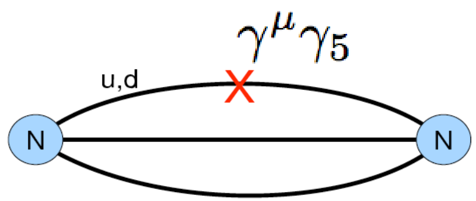
- very recently:

  COMPASS

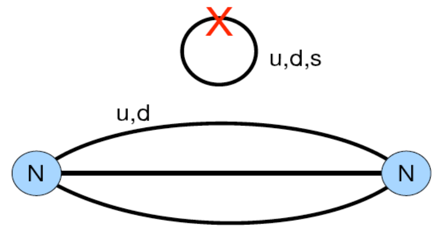


- lattice :

connected



disconnected

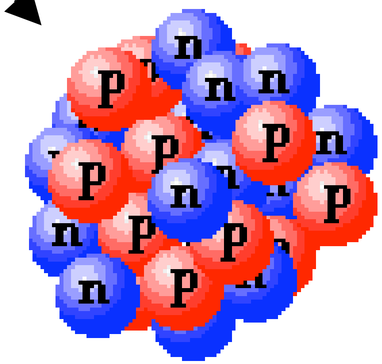


$$\frac{1}{2}\int dx\,[\Delta s + \Delta\bar{s}] \;=\; \begin{cases} -0.0061(21) & \text{Babich et al.} \\ -0.01\,\ldots\,0.01\ (95\%\mathrm{CL}) & \text{Bali et al.} \end{cases}$$

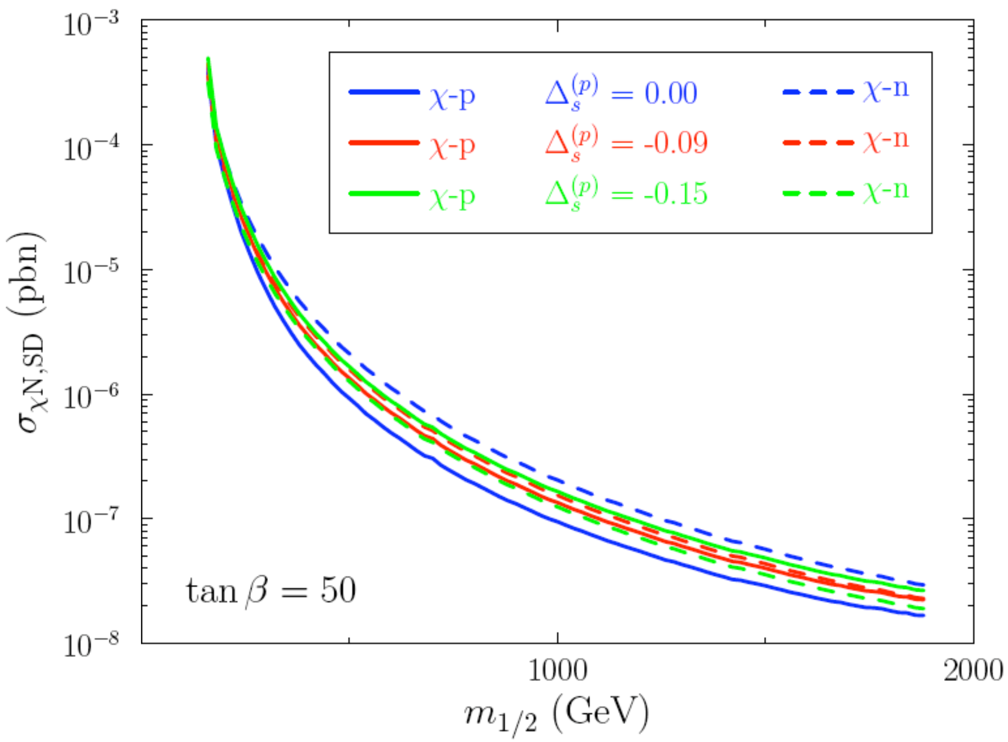
- perhaps : $\Delta s \approx -\Delta\bar{s}$?

- this is interesting not "just" for nucleon structure enthusiasts:

neutralino χ



$$\mathcal{L} = \alpha_i\,(\bar{\chi}\,\chi)\,(\bar{q}_i\,q_i) + \beta_i\,(\bar{\chi}\,\gamma^{\mu}\gamma^{5}\,\chi)\,(\bar{q}_i\,\gamma_{\mu}\gamma^{5}\,q_i)$$



gives spin-dep. cross sec.

Ellis, Olive, Savage

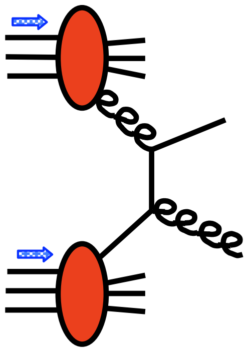
- total quark and anti-quark spin contribution :

$$\int_{0.001}^{1} dx \Delta\Sigma = 0.366 \pm 0.016 \qquad (\Delta\chi^2 = 1)$$

$$\int_{0}^{1} dx \Delta\Sigma = 0.242 \pm ?$$

- in any case, $\Delta\Sigma \ll 1$

- polarized glue ?

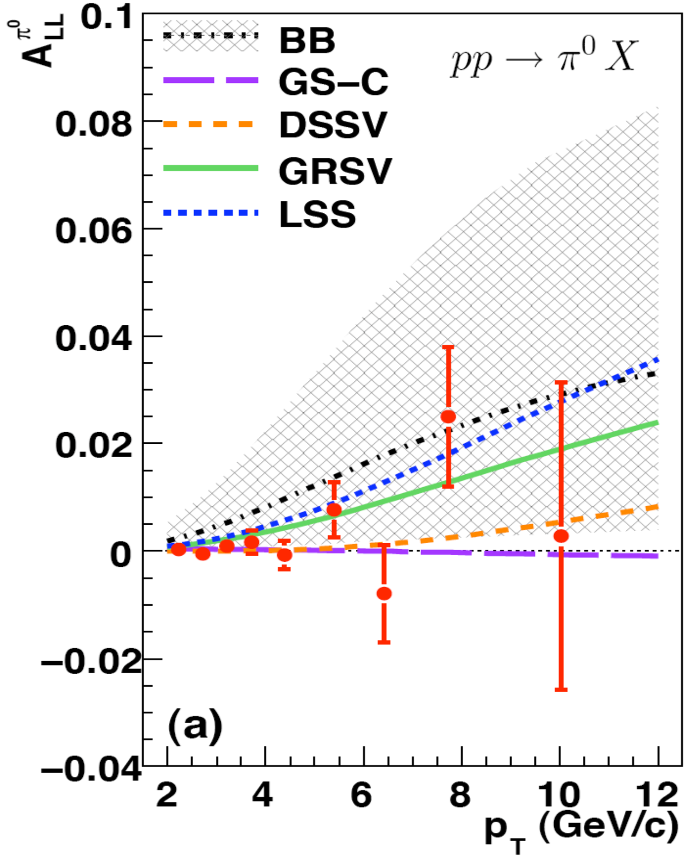


$$\Delta G \approx 1.8$$

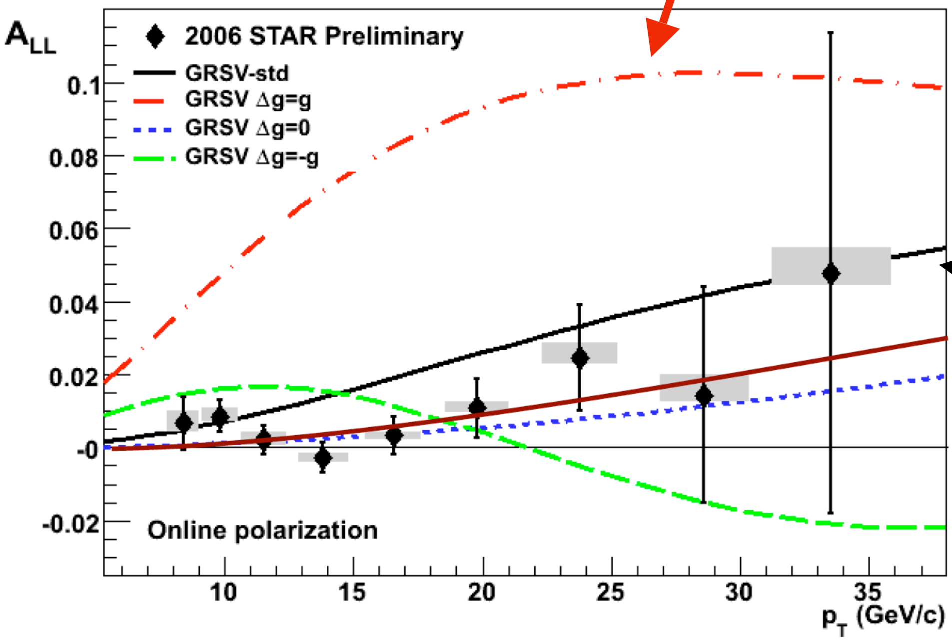
"axial anomaly" Altarelli et al.

$$\Delta\Sigma \;\rightarrow\; \Delta\Sigma - n_f \frac{\alpha_s(Q^2)}{2\pi}\Delta G(Q^2)$$

PHENIX



$pp \rightarrow \text{jet}\, X$

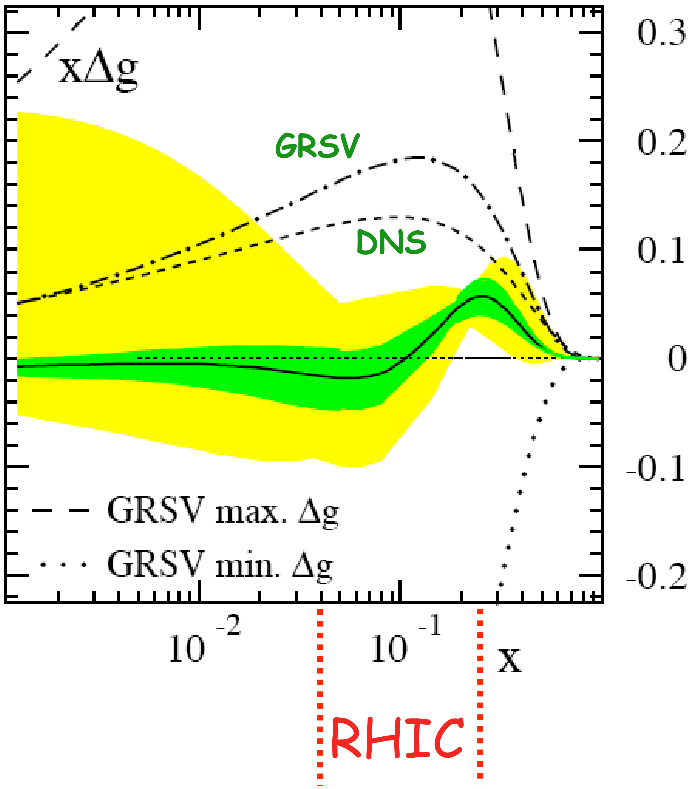


$$\Delta G \approx 0.4 \quad (Q^2 = 1\,\mathrm{GeV}^2)$$

DSSV

$$\Delta G = 0$$

STAR

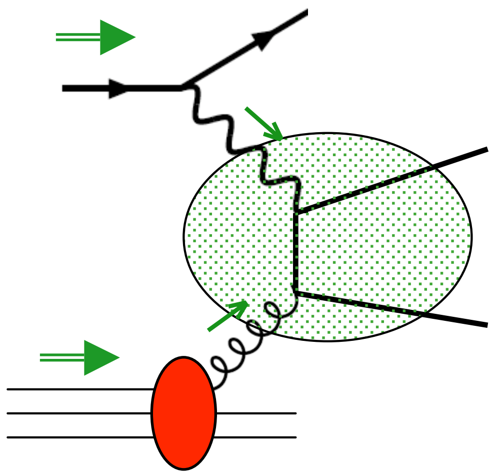


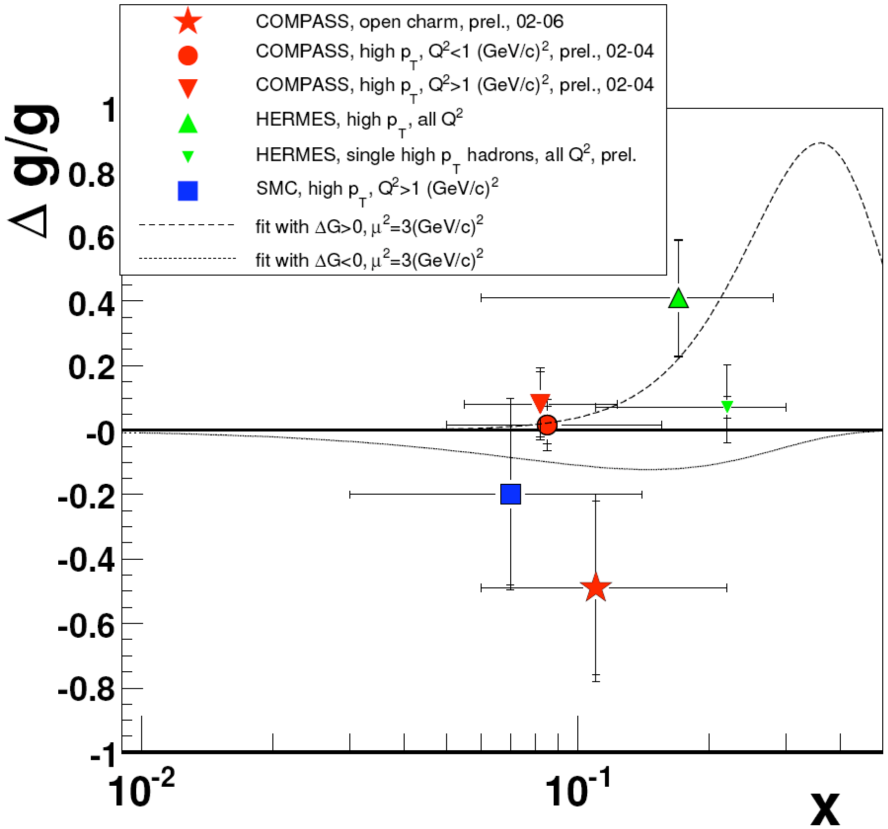
$$\int_{0.05}^{0.2} dx\, \Delta g = 0.006 \pm 0.06 \qquad (\Delta\chi^2 = 1)$$

$$\int_{0}^{1} dx\, \Delta g = -0.084 \pm ?$$

- there could still be significant contribution to proton spin
- gluons paired to spin-0 ?   Kharzeev, Levin, Tuchin

HERMES, COMPASS:





(not yet included in DSSV)

Future avenues: some examples

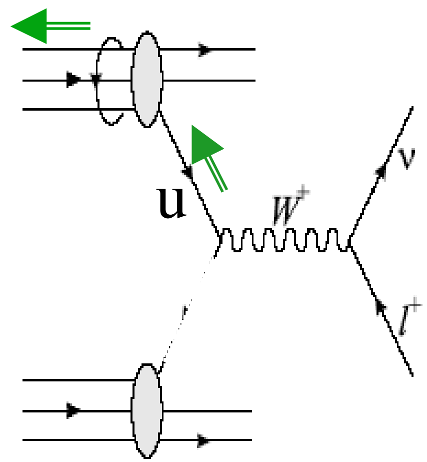
Quark/anti-quark polarizations:

- extensive studies at Jlab-12: (semi-)inclusive, large-x
- W program at RHIC:

Parity violation: can have

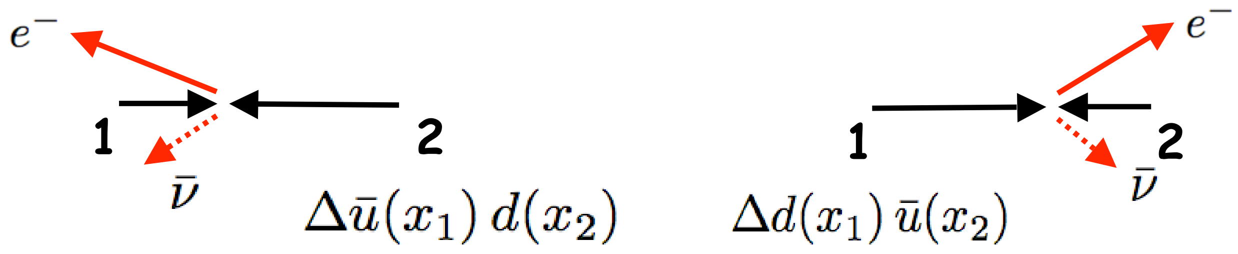
$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \neq 0$$

unpol.

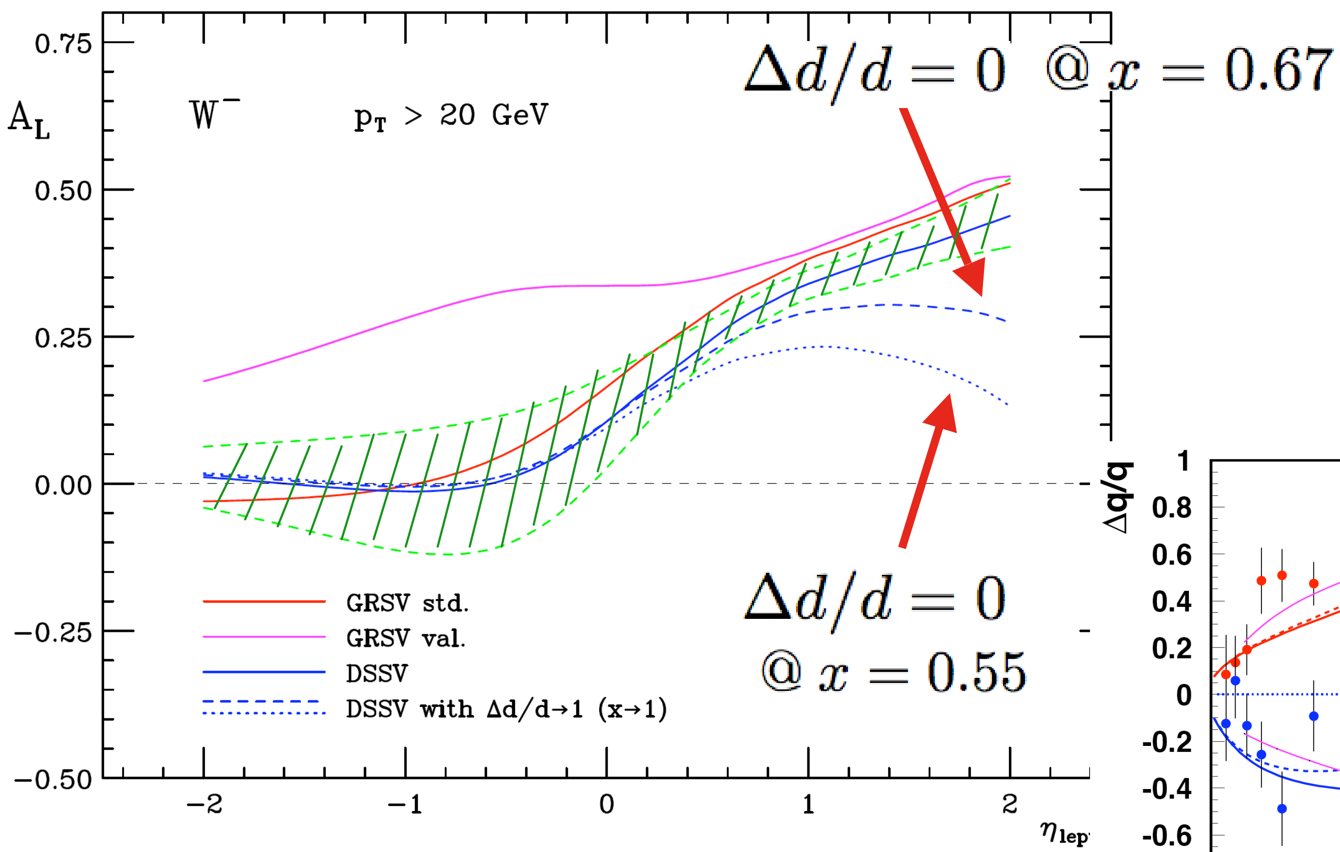


- EIC: (SI)DIS at higher Q^2, Parity-violating str. fcts.

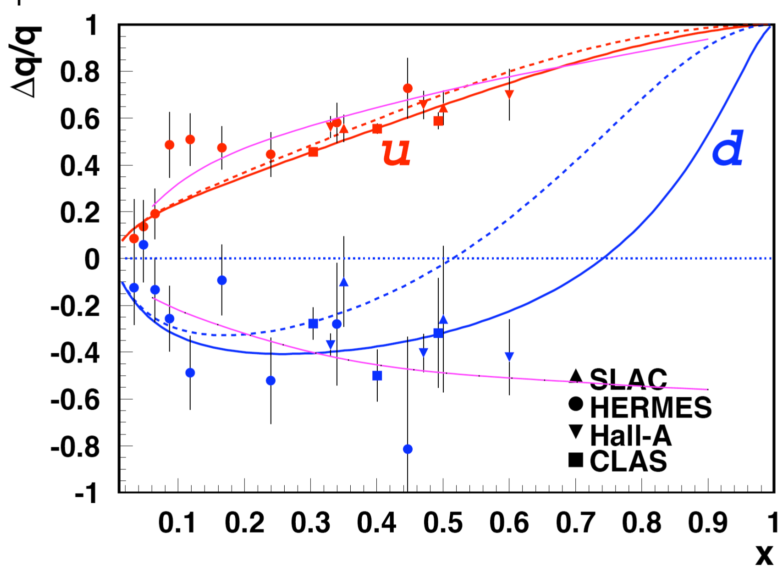
Generally: smaller x and/or higher Q^2



e^-
1
2
$\bar{\nu}$
$\Delta\bar{u}(x_1)\,d(x_2)$
e^-
1
2
$\bar{\nu}$
$\Delta d(x_1)\,\bar{u}(x_2)$

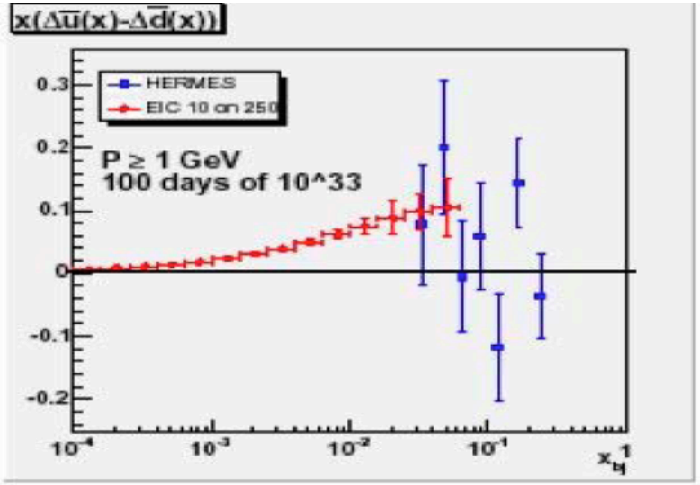


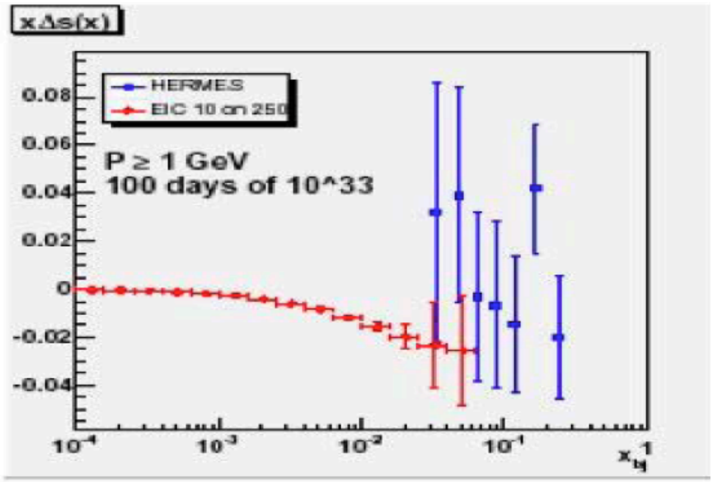
A_L
W^-
$p_T > 20$ GeV
$\Delta d/d = 0$ @ $x = 0.67$
$\Delta d/d = 0$
@ $x = 0.55$
GRSV std.
GRSV val.
DSSV
DSSV with Δd/d→1 (x→1)
η_{lep}



Δq/q
u
d
SLAC
HERMES
Hall-A
CLAS
x

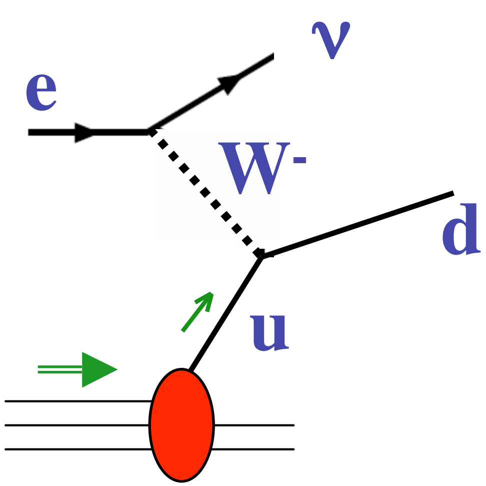
EIC:

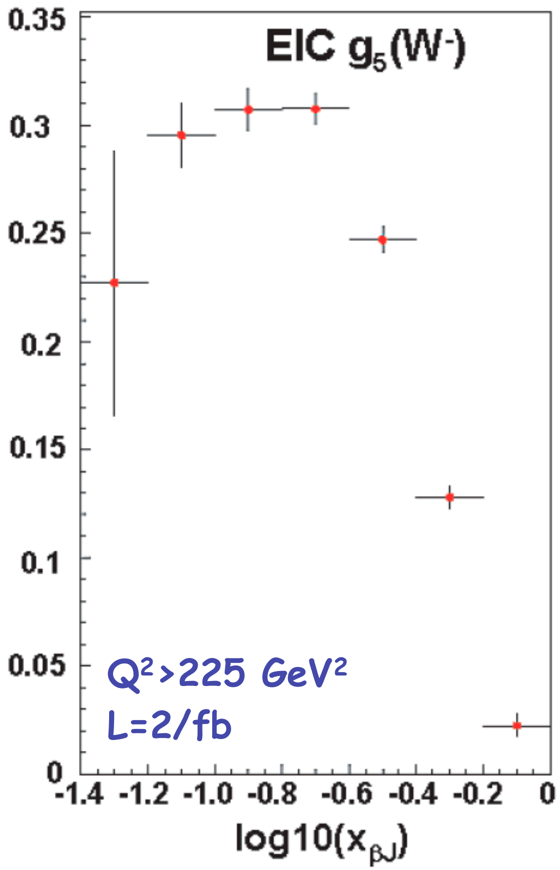




J. Seele

- also:



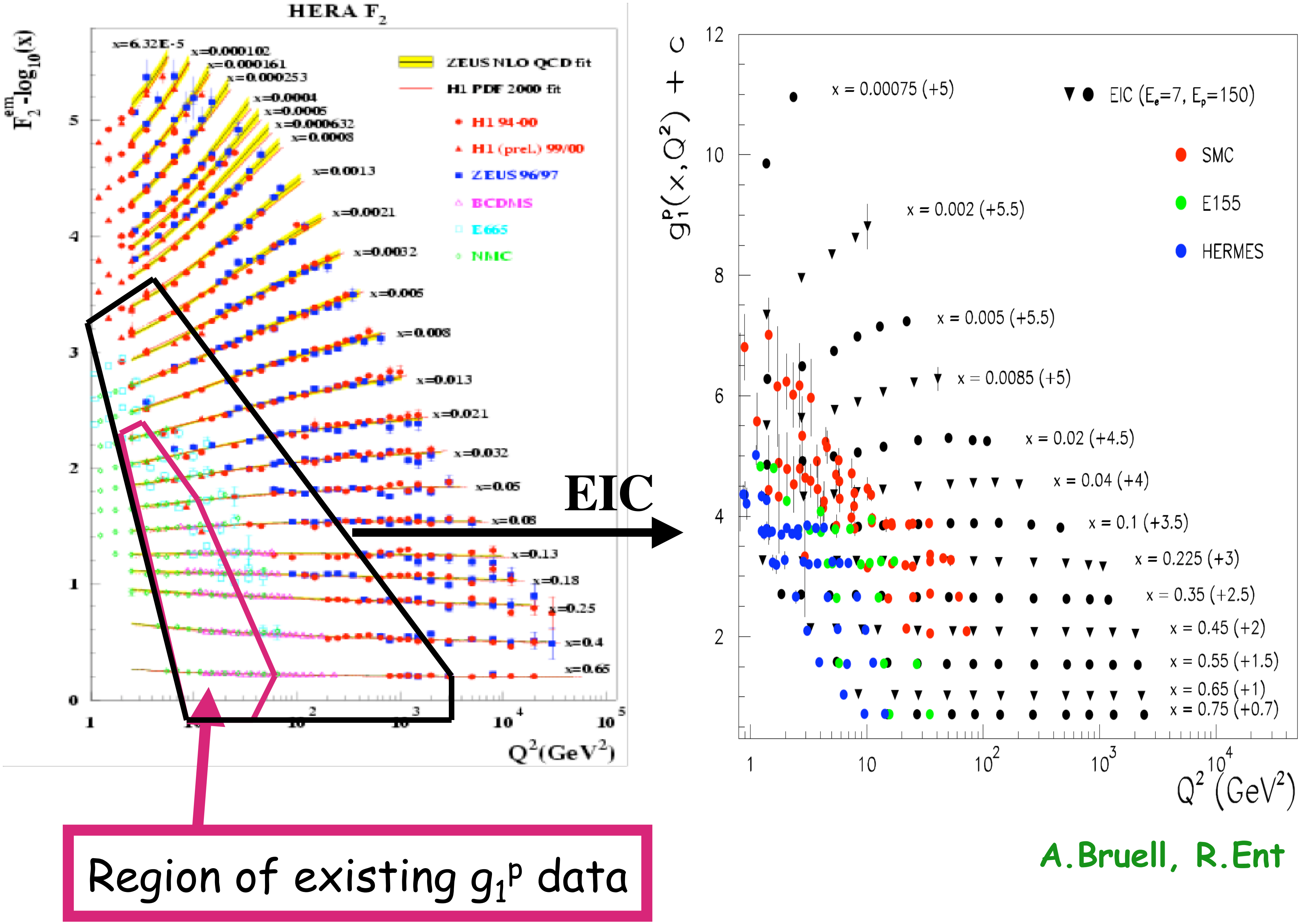


$$g_5 \propto \Delta u - \Delta\bar{d} - \Delta\bar{s}$$

Gluon polarization

RHIC:

- improve statistics for presently accessible x range
- detailed scans of $\Delta g(x)$
- extend to lower x by studies of 2-particle correlations, and by 500-GeV running



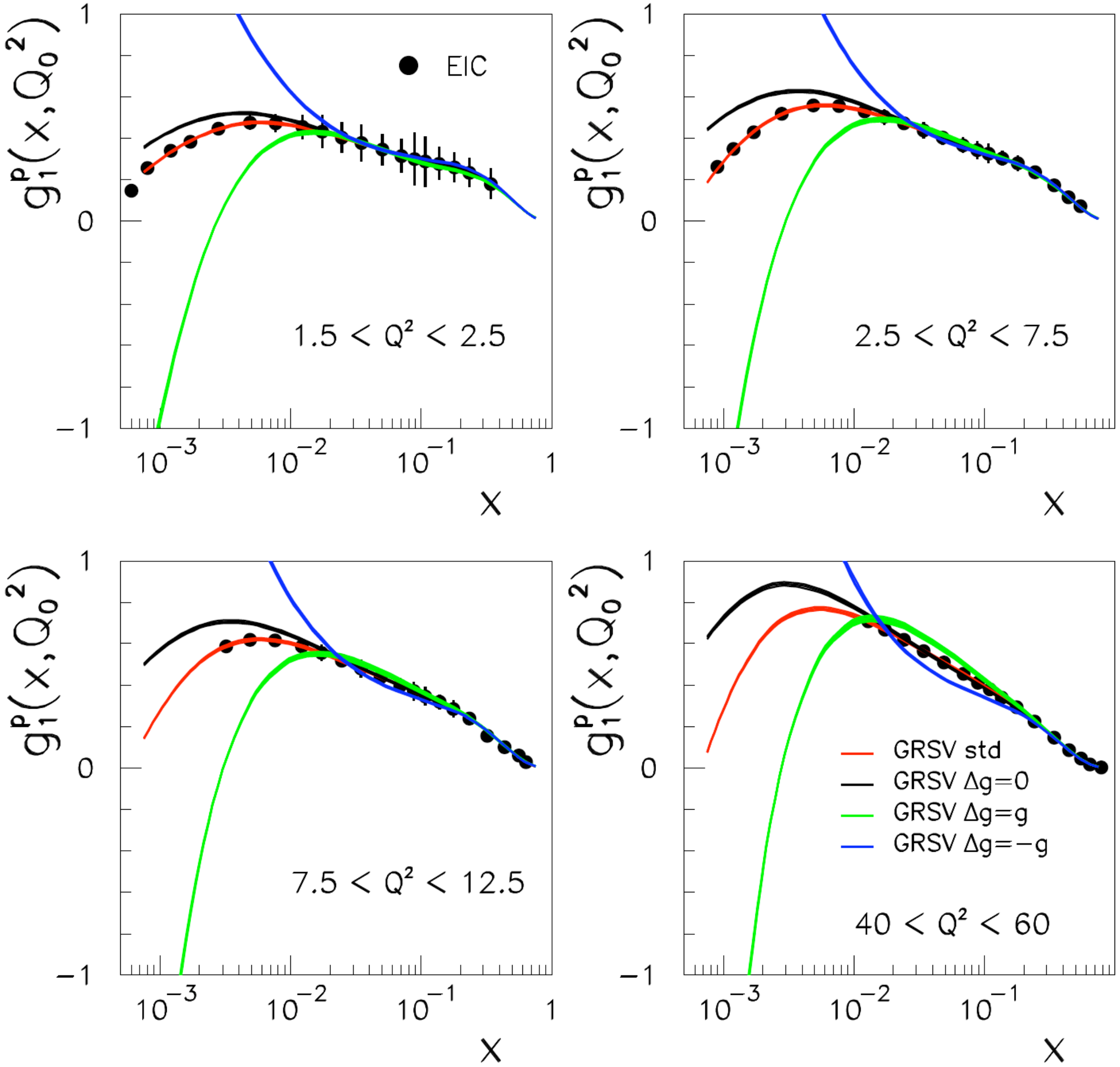
A.Bruell, R.Ent

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

at small x

$\sim$ 4 on 250 ...

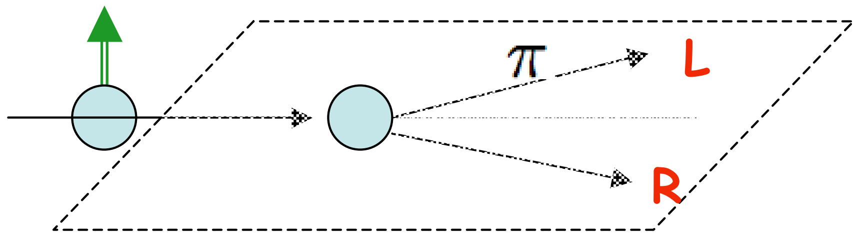
E_e=7, E_p=150 at L=10^{33}



A. Bruell, R. Ent

Transverse-spin phenomena

$$p^{\uparrow}p \;\rightarrow\; \pi X$$



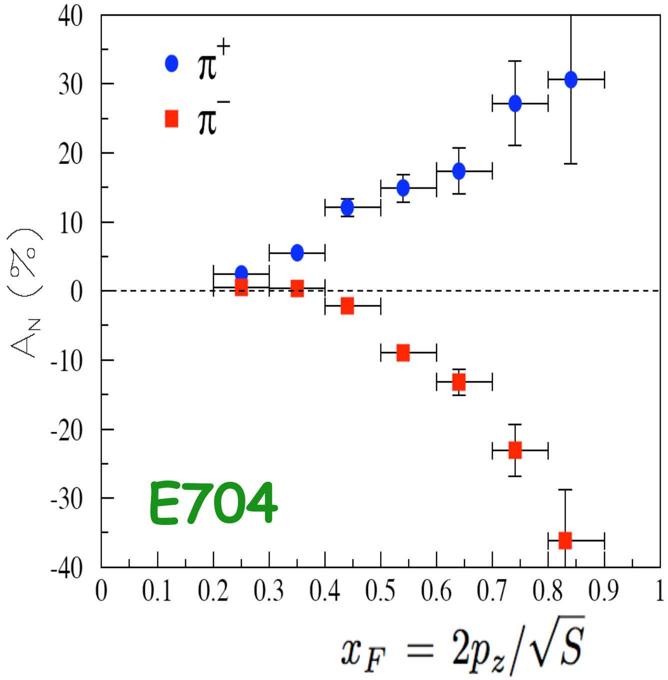
$$A_N \;=\; \frac{L-R}{L+R}$$

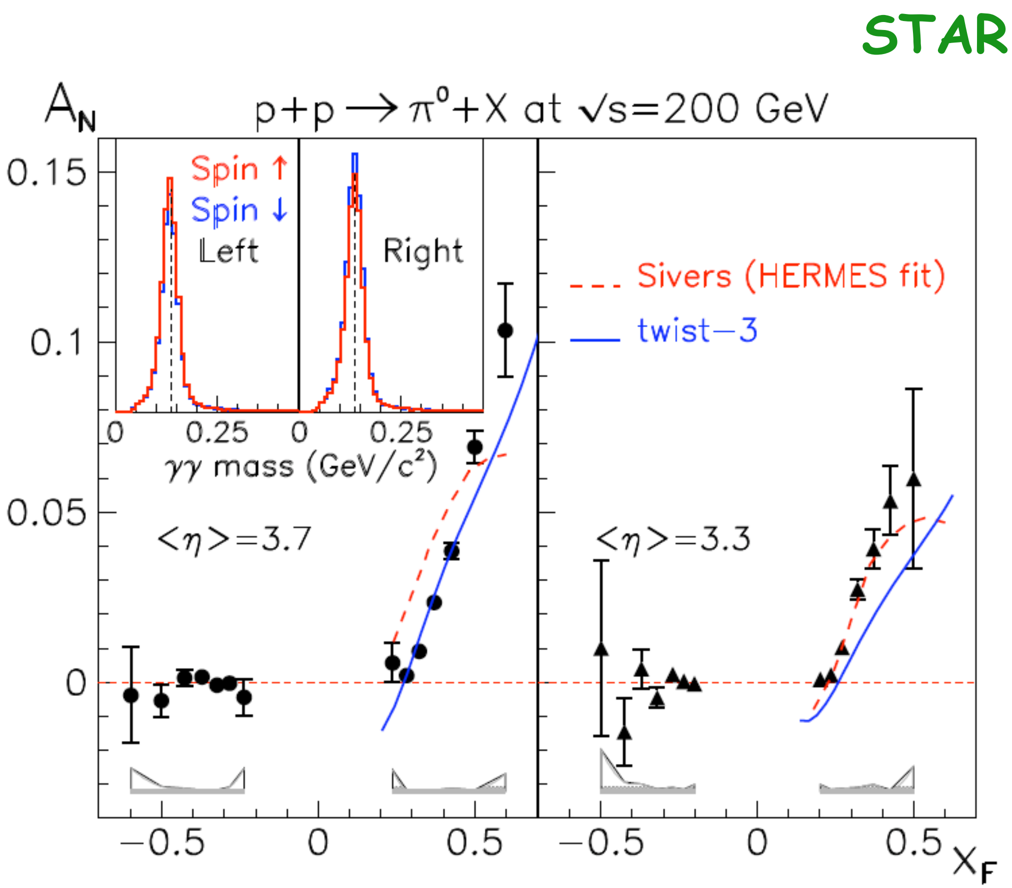
$$A_N \;\sim\; \mathcal{I}m(\,M_+\,M_-^*\,)$$

$$\vec{S}_\perp \cdot \left(\vec{P} \times \vec{p}_\perp^{\,\pi}\right)$$

- two requirements:

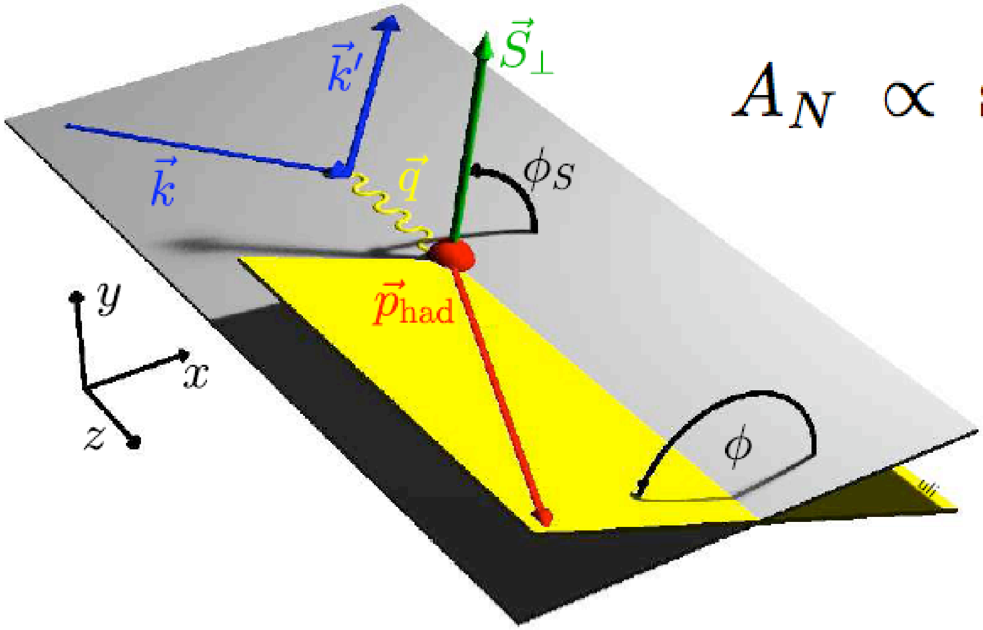
  nucleon helicity flip and phase



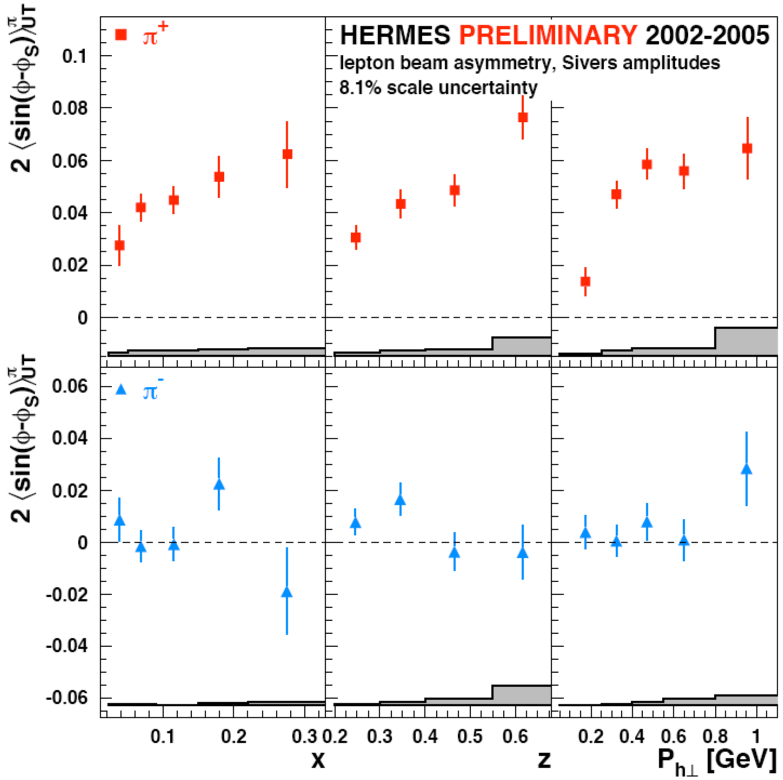


Also: BRAHMS, PHENIX

$\mathbf{e\,p^{\uparrow} \rightarrow e\,\pi\,X}$

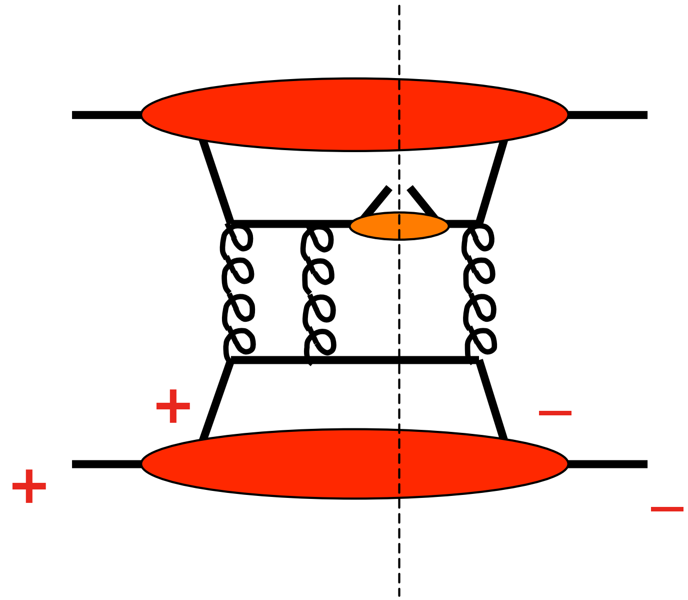


$$A_N \propto \sin(\phi + \phi_S)\ ,\ \sin(\phi - \phi_S)$$



SMC, HERMES,
COMPASS, CLAS

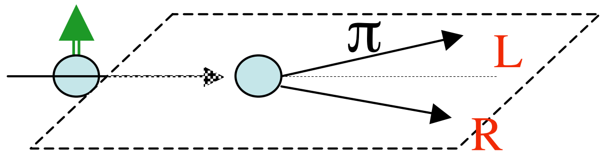
- simple parton model:



A_N expected as $\frac{m_q}{p_\perp}\alpha_s \ll 1$

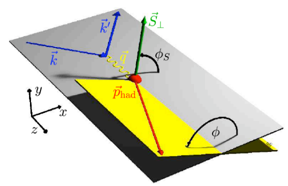
Kane, Pumplin, Repko '78

- *SSA for single-inclusive process* (pp → πX)
  - ∗ a single large scale (p_T)
  - ∗ power-suppressed $1/p_T$ ("twist-3")
  - ∗ collinear factorization

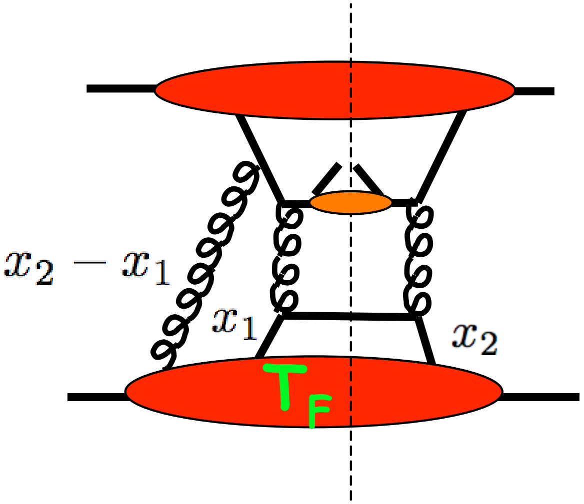


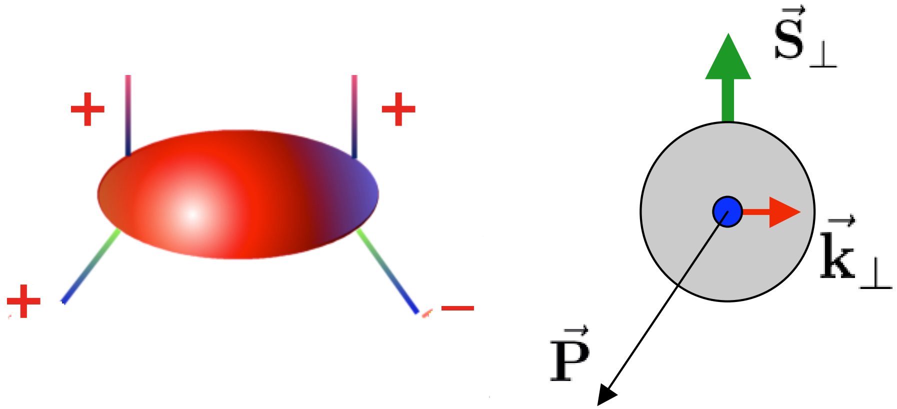
Efremov, Teryaev; Qiu, Sterman

- SSA with two scales: $Q \gg q_T \sim \Lambda_{QCD}$ (SIDIS A_N)
  - ∗ not suppressed as $1/Q$
  - ∗ Transverse-momentum dependent (TMD) factorization (Sivers, Collins fcts. & other)



Brodsky, Hwang, Schmidt; Collins; Belitsky, Ji, Yuan; Ji, Ma, Yuan; Boer, Mulders, Pijlman





"Quark-gluon correlation":

$$T_F(x_1, x_2) \sim \mathrm{FT}_{x_1,x_2}\Big(\langle P, S_\perp | \bar{\psi}\,\gamma^+ F_\sigma{}^+ \psi | P, S_\perp\rangle\Big)$$

- **hel. ok because of qgq**
- **phase in hard scattering**

Efremov, Teryaev; Qiu, Sterman; Koike et al.; Kouvaris, Qiu, WV, Yuan; Yuan, Zhou; Kang, Qiu; …

"TMD":

$$f_{1T}^{\perp}(x, k_\perp) \sim \mathrm{FT}_{x,k_\perp}\Big(\langle P, S_\perp | \bar{\psi}\,\gamma^+ \mathcal{U}\,\psi | P, S_\perp\rangle\Big)$$

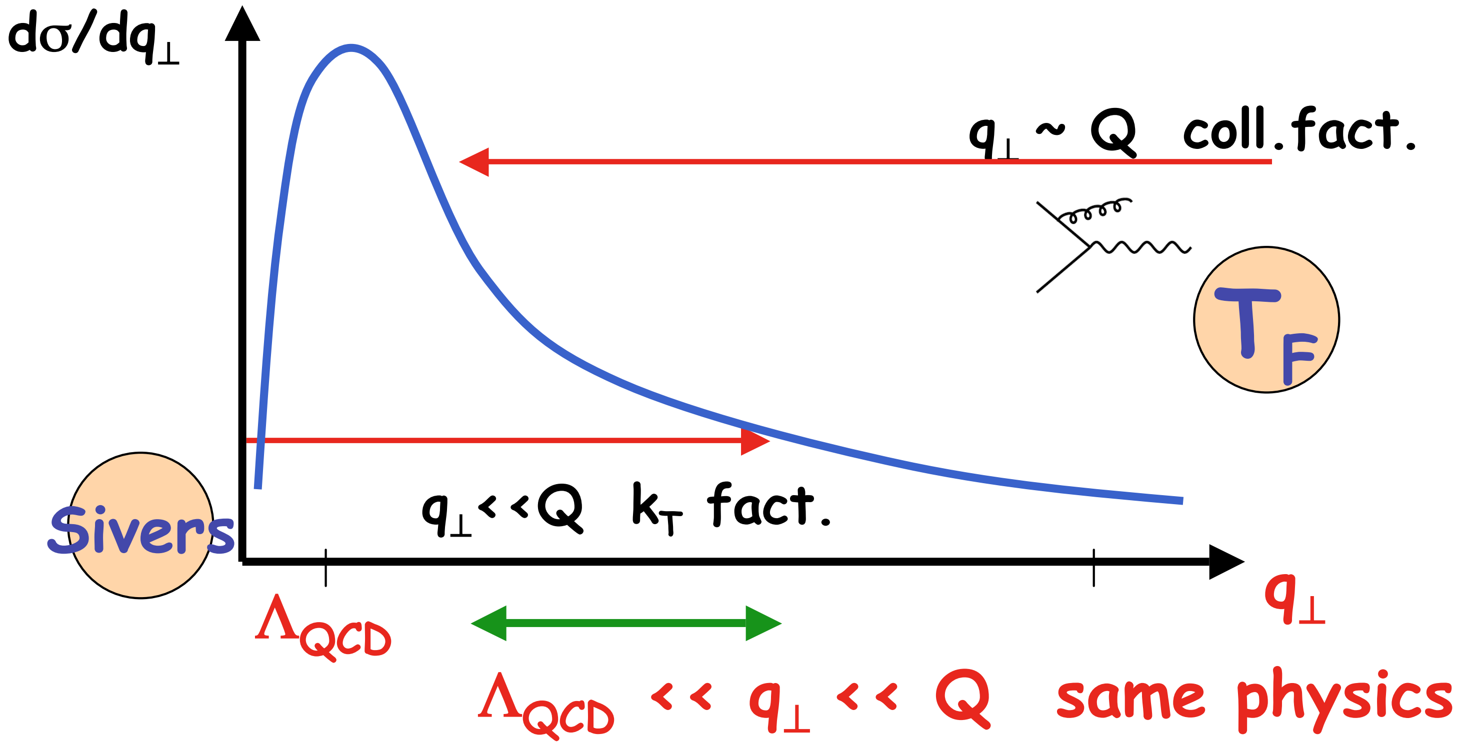
$$\mathcal{U} = \mathcal{P}\exp\left(-ig\int_0^z d\xi^\mu\, A_\mu(\xi)\right)$$

- **phase from gauge link**
- **hel. flip because of OAM**

Sivers; Brodsky, Hwang, Schmidt; Collins; Belitsky, Ji, Yuan; Bomhof; Mulders, Pijlman; Burkardt, Schnell

Mechanisms are closely related:

- Boer, Mulders, Pijlman $$T_F(x,x) \sim \int d^2k_\perp \, k_\perp^2 \, f_{1T}^\perp(x,k_\perp)$$
- Ji, Qiu, WV, Yuan; Koike, WV, Yuan; Bacchetta, Boer, Diehl, Mulders



- testable QCD predictions for $q_\perp$ dependence

A lot of recent progress

Twist-3 nucleon matrix elements:

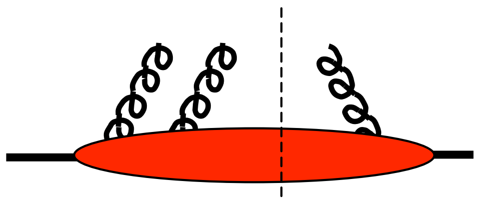
- Q^2 evolution

Kang, Qiu
Zhou, Yuan, Liang

- NLO correction to SSA in Drell-Yan

WV, Yuan

- studies of three-gluon correlations



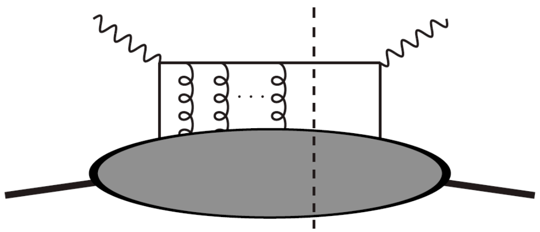
Yuan, Zhou
Kang, Qiu
Kang, Qiu, WV, Yuan

Sivers function:

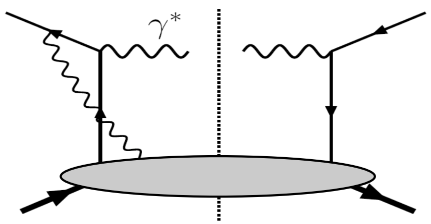
- gauge link has profound implications:

Brodsky, Hwang, Schmidt; Collins; Belitsky, Ji, Yuan; Boer, Mulders, Pijlman

$$f_{\rm DY}^{\rm Sivers}(x,k_\perp) = - f_{\rm DIS}^{\rm Sivers}(x,k_\perp)$$



DIS

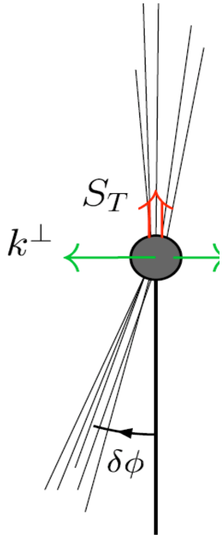


DY

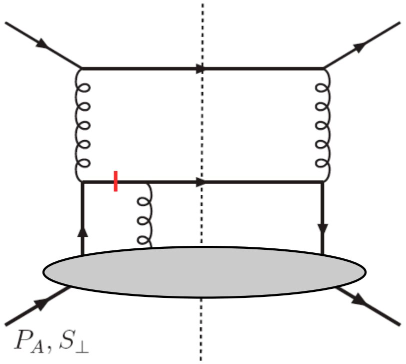
tests many of our concepts for the description of hard hadronic processes

- extension to general QCD hard scattering:

Bomhof, Pijlman, Mulders
Boer, Bacchetta
Qiu, Yuan, WV
Collins, Qiu

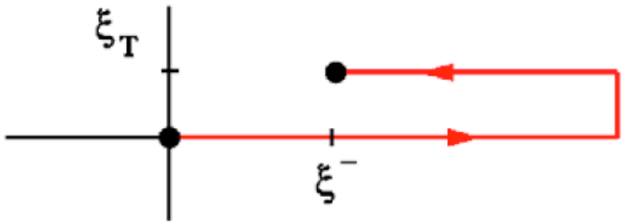


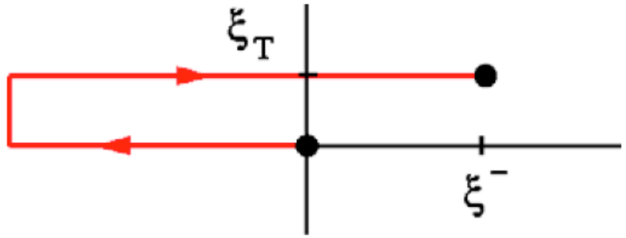
qq'→qq'



+ ...

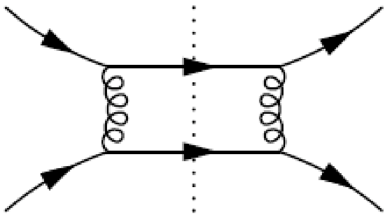
$$f_q(x,k_\perp) \sim \int dz^- d^2 \mathrm{z}_\perp\, \mathrm{e}^{iz^- xP^+ + i\mathrm{z}_\perp\cdot \mathrm{k}_\perp}\, \langle P, s_\perp \,|\, \bar\psi_q(0)\gamma^+ \;\; \mathcal{U} \;\; \psi_q(z^-,\mathrm{z}_\perp)\,|\, P, s_\perp\rangle$$



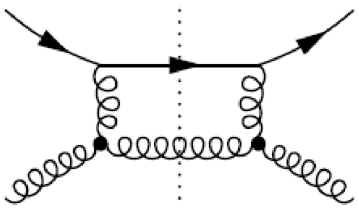


DIS $\langle\, \overline{\psi}(0)\,\mathcal{U}^{[+]}\,\psi(\xi)\,\rangle$

DY $\langle\, \overline{\psi}(0)\,\mathcal{U}^{[-]}\,\psi(\xi)\,\rangle$



$$\langle\, \overline{\psi}(0) \left\{ \frac{N_c^2+1}{N_c^2-1}\, \frac{\mathrm{Tr}\left[\mathcal{U}^{[\square]}\right]}{N_c} \mathcal{U}^{[+]} - \frac{2}{N_c^2-1}\, \mathcal{U}^{[\square]}\mathcal{U}^{[+]} \right\} \psi(\xi)\,\rangle$$



$$\langle\, \overline{\psi}(0) \left\{ \frac{1}{2}\, \frac{N_c^2}{N_c^2-1}\, \frac{\mathrm{Tr}\left[\mathcal{U}^{[\square]}\right]}{N_c}\, \frac{\mathrm{Tr}\left[\mathcal{U}^{[\square]\dagger}\right]}{N_c} \mathcal{U}^{[+]} + \right.$$

$$\left. + \frac{1}{2}\, \frac{N_c^2}{N_c^2-1}\, \frac{\mathrm{Tr}\left[\mathcal{U}^{[\square]}\right]}{N_c} \mathcal{U}^{[-]} - \frac{1}{N_c^2-1}\, \mathcal{U}^{[+]} \right\} \psi(\xi)\,\rangle$$

Non-universality ! Bomhof, Mulders, Pijlman; Collins, Qiu; Yuan, WV

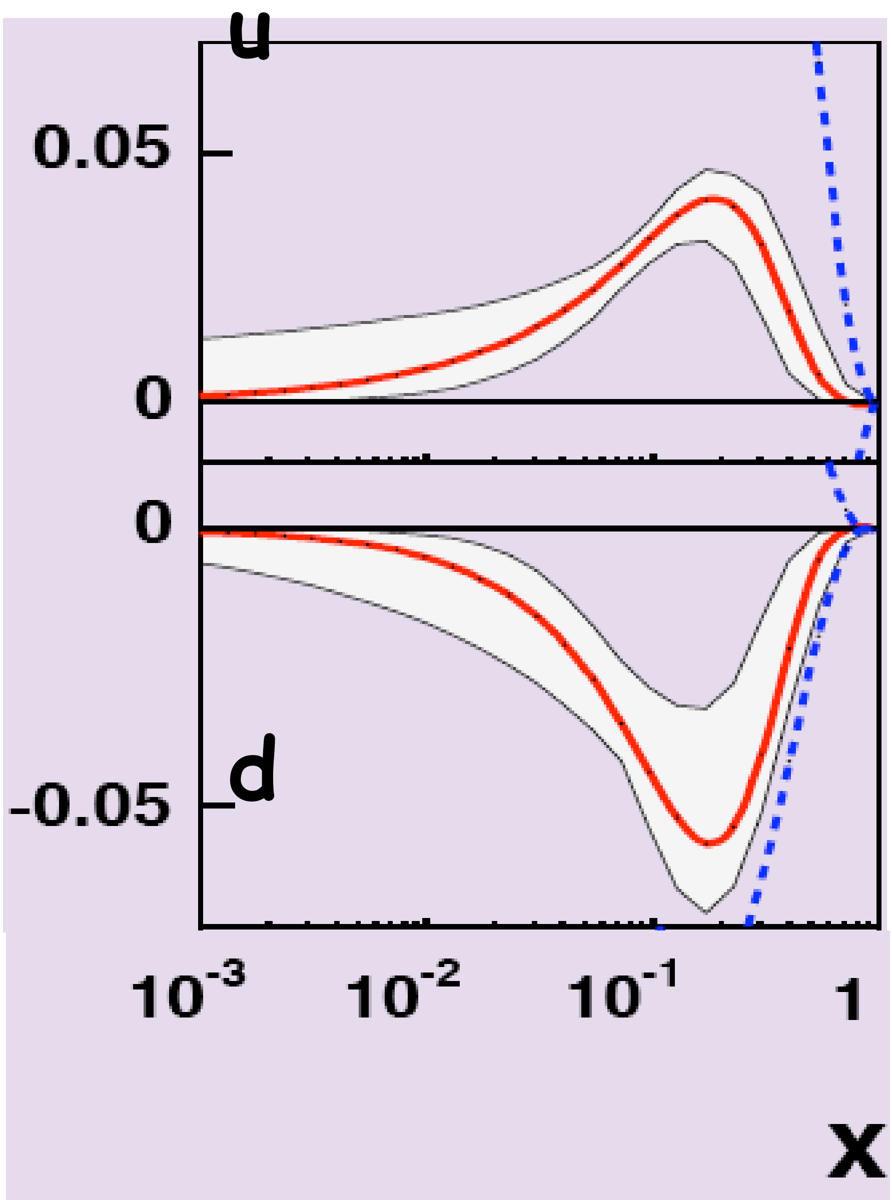
- ramifications also for spin-averaged case

- phenomenology of Sivers functions:

$$\int d^2k_\perp \, \frac{k_\perp}{4m_p} \, f_q^{\mathrm{Sivers}}(x, k_\perp)$$

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Türk

(Goeke et al.; Yuan, WV)



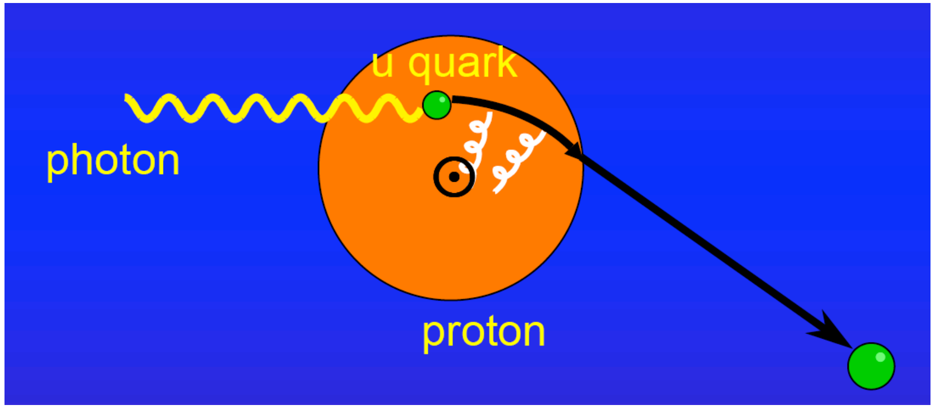
- connection to GPDs / spatial distributions (within models)

Burkardt; Diehl, Hägler; Brodsky, Gardner; Meißner, Metz, Goeke

$$\int d^2\mathbf{k}_\perp k_\perp (\mathbf{k}_\perp \times \mathbf{s}_\perp)\, f^{\text{Sivers}}(x,k_\perp) \sim \int d^2\mathbf{b}_\perp\, \mathcal{I}(b_\perp)\,(\mathbf{b}_\perp \times \mathbf{s}_\perp)\,\frac{\partial}{\partial b_\perp^2}\mathcal{E}(x,b_\perp^2)$$

"Lensing function"

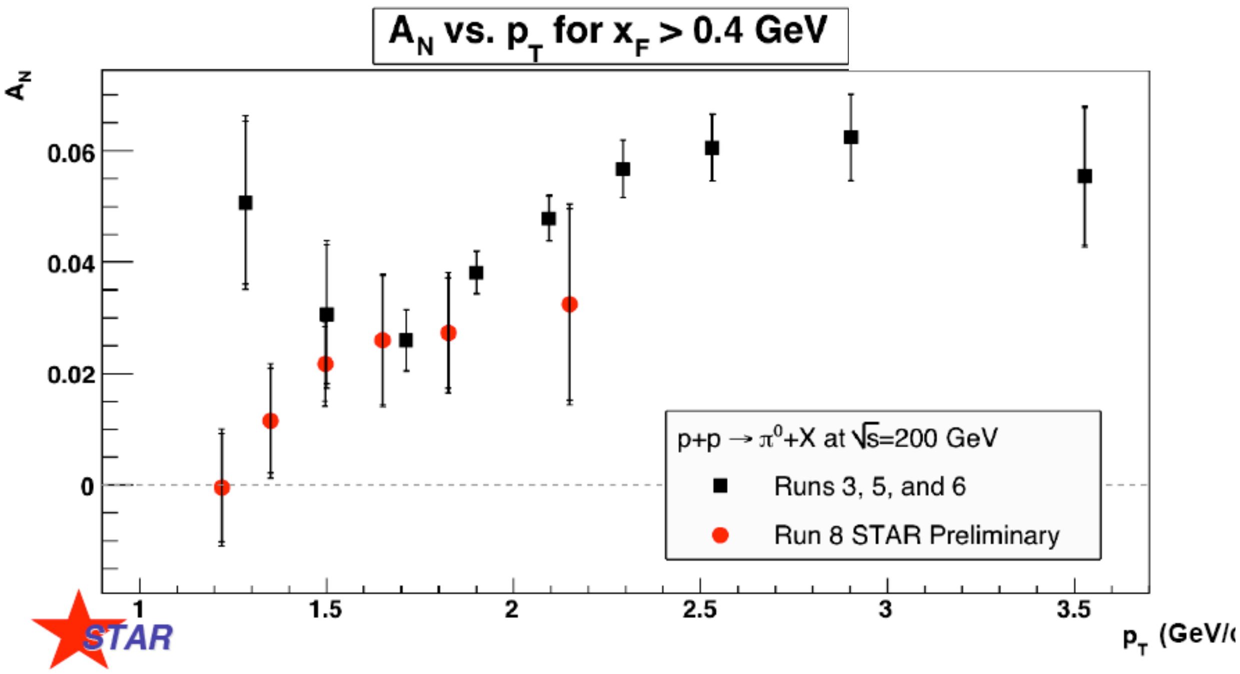
- Suggests: spatial deformation as origin of asym.



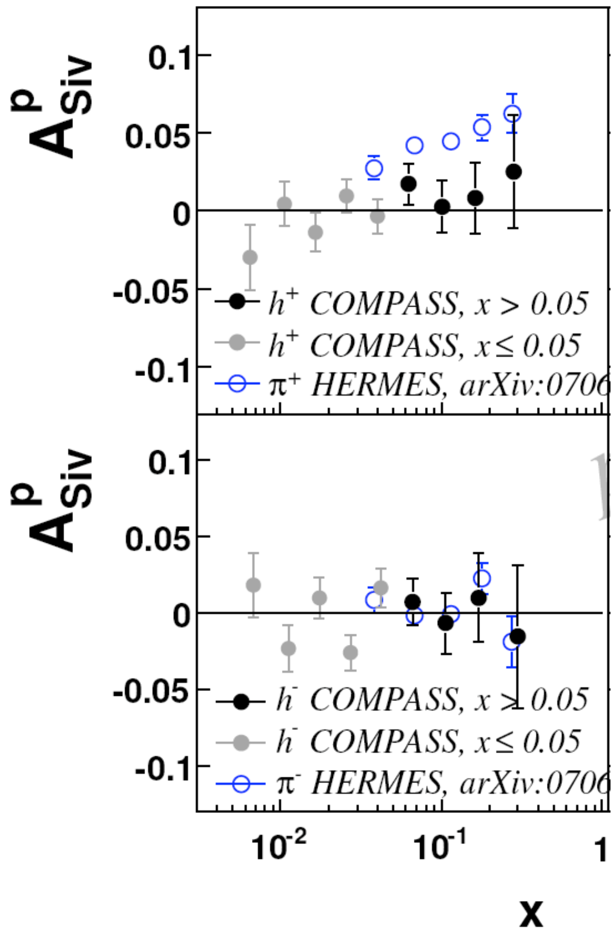
Burkardt;
Diehl, Hägler

- expected signs of $f_{u,d}^{\text{Sivers}}$ consistent with phenomenology

- New data provide new puzzles:

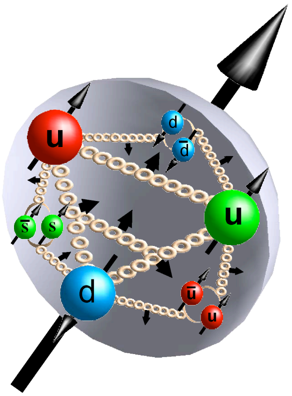


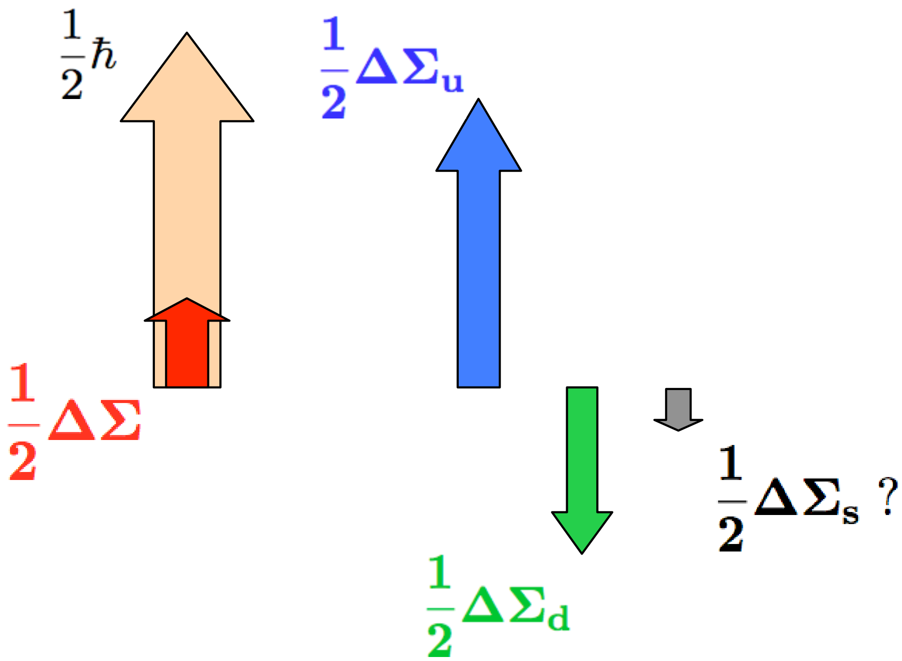
STAR



COMPASS

Conclusions:





- RHIC & HERMES,COMPASS closing in on Δg :
  small in accessible x-region. Small overall ?
- flavor asymmetry $\Delta\bar{u} - \Delta\bar{d} > 0$? Strangeness puzzle?
- new insights into QCD from single-spin asymmetries
- even after RHIC, Jlab-12 many of the current questions will not have been answered *definitively*