New Results on Nucleon Spin Structure

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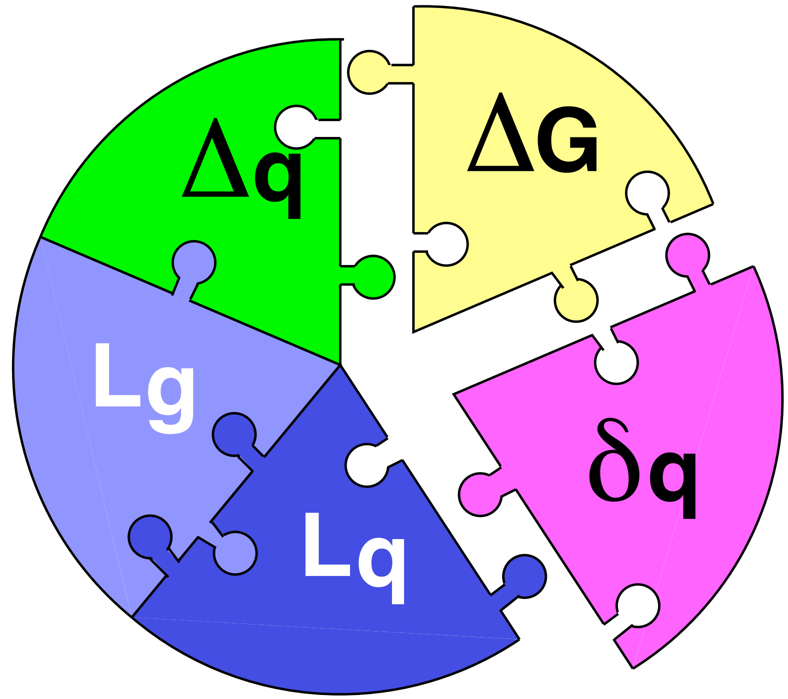


Outline

- Some phenomenlogical models
- Quark polarization: status
- Gluon polarization: new results
- Transversity & Friends: new structures to explore
- New transverse-spin data

New results from several experiments!

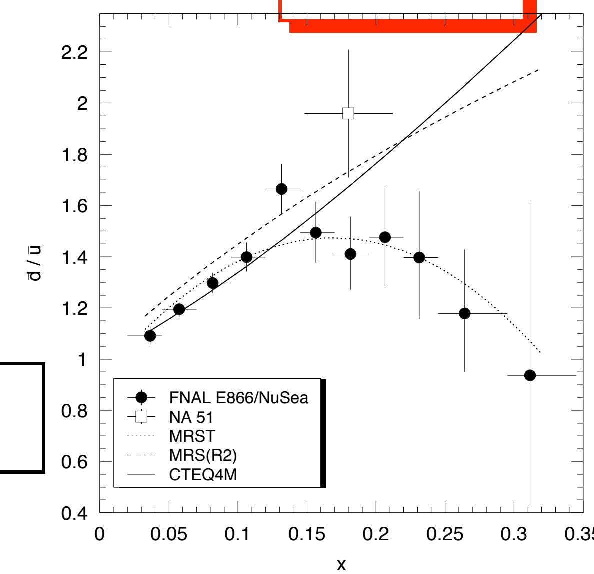
- This talk: HERMES, SMC, STAR, PHENIX
- COMPASS ➡ talk by F. Bradamante
- JLAB ➡ talk by Z.-E. Mezziani

Flavor Structure of the Proton

- **Constituent Quark Model**
  Pure valence description: proton = $2u + d$

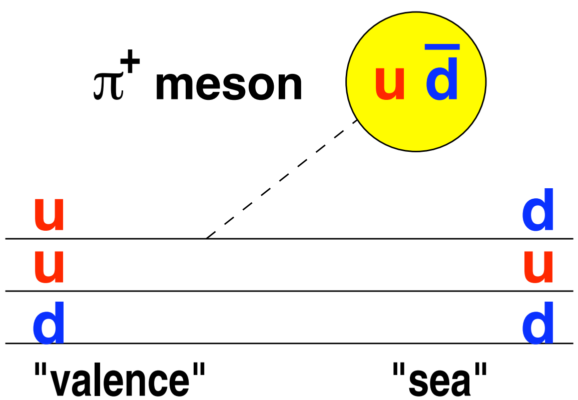
- **Perturbative Sea** Sea quark pairs from $g \longrightarrow q\bar{q}$ should be flavor symmetric: $\bar{u} = \bar{d}$

E866: $\bar{d}/\bar{u} > 1$



Non-perturbative models : alternate deg's of freedom

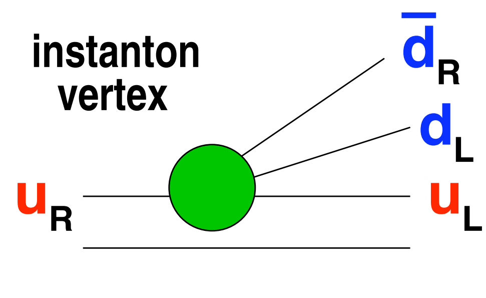
Meson Cloud Models



Quark sea from cloud of 0^- mesons: $\bar{d} > \bar{u}$

Chiral-Quark Soliton Model

- quark degrees of freedom in a pion mean-field
- nucleon = chiral soliton
- one parameter: dynamically-generated quark mass
- expand in $1/N_c$



'tHooft instanton vertex $\sim \bar{u}_R u_L \bar{d}_R d_L$

$\Rightarrow \bar{d} > \bar{u}$

Spin Structure of the Proton

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

Parton Distribution Functions

unpolarized: $q(x) = q^{\uparrow}(x) + q^{\downarrow}(x)$

polarized: $\Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$

- **Constituent Quark Model**

$\Delta u = +\frac{4}{3},\ \Delta d = -\frac{1}{3} \rightarrow$ $\Delta\Sigma = 1$

- **Relativistic Quark Model**

relativistic *current quarks* with light masses, orbital angular momentum is important

$\Delta\Sigma \simeq 0.60 - 0.75$ $\quad L_q = \frac{1}{2}(1 - \Delta\Sigma)$

Neutron/Hyperon β-decay Constants

give 2 conserved moments:

$$a_3 = \Delta u - \Delta d = 1.267$$
$$a_8 = \Delta u + \Delta d - 2\Delta s = 0.585$$

- **Neglecting sea quarks** entirely,

$$\Delta\Sigma = \Delta u + \Delta d = a_8 = 0.59$$

Now add sea: $\Delta u \rightarrow \ \Delta u_v + \Delta u_s + \Delta\overline{u}$

...

- **Assuming SU(3)-symmetric sea** ,

$$\Delta u_s = \Delta\overline{u} = \Delta d_s = \Delta\overline{d} = \Delta s = \Delta\overline{s},$$

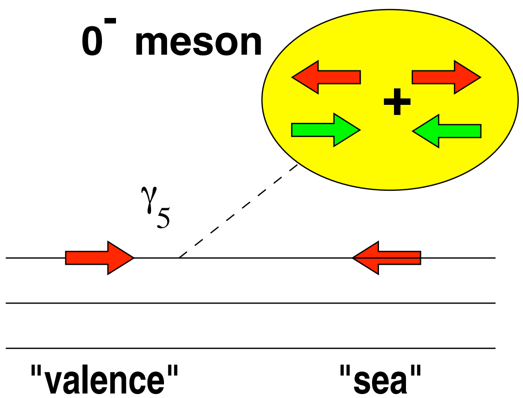
$$\Delta u_v = (a_8 + a_3)/2 = +0.93$$
$$\Delta d_v = (a_8 - a_3)/2 = -0.34$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = a_8 + 6\,\Delta\overline{q} = ?$$

Anti-quark Spin in the Proton

Meson Cloud Models

Li, Cheng, hep-ph/9709293



$\Rightarrow \Delta q_{valence} > 0$

$\Rightarrow$ $\Delta q_{sea} < 0$,

but ...

$\Rightarrow$ $\Delta \overline{q} = 0$

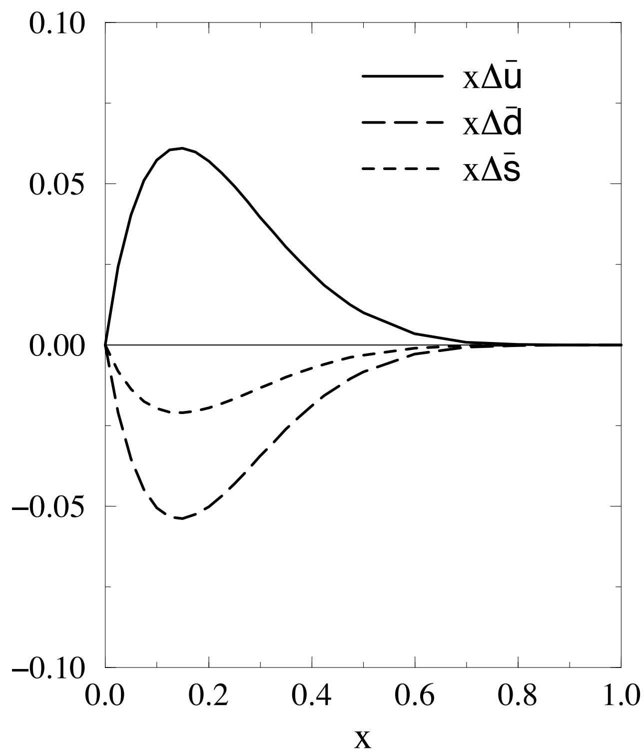
"Higher-order" cloud of vector mesons can generate a small $\Delta \overline{q}$ polarization.

Chiral-Quark Soliton Model

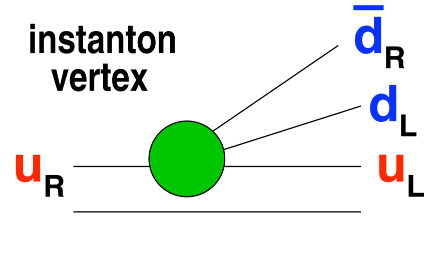
Goeke et al, hep-ph/0003324

Light anti-quarks polarized:

$$\Delta \overline{u} \simeq -\Delta \overline{d} > 0$$

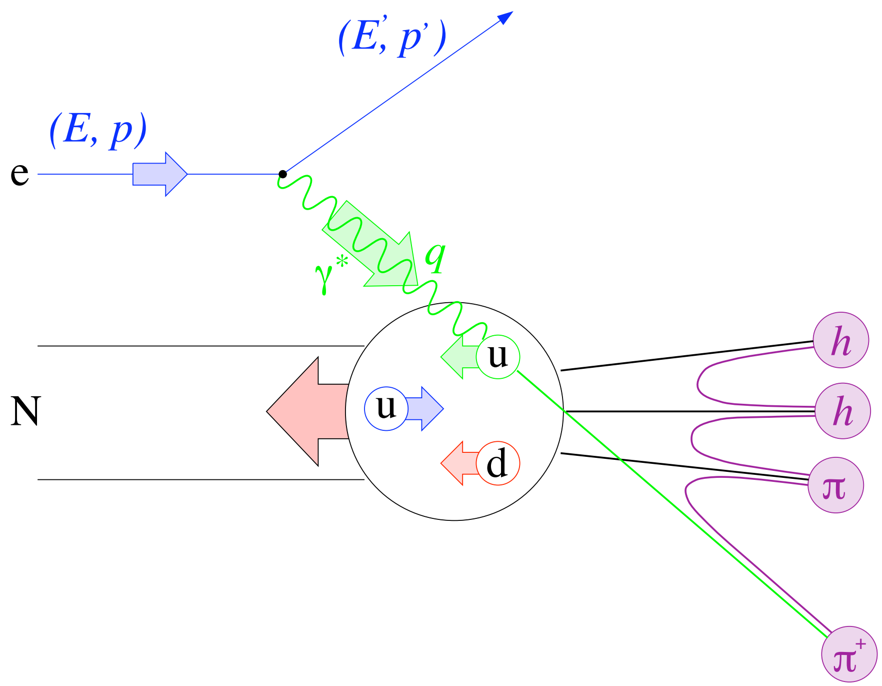


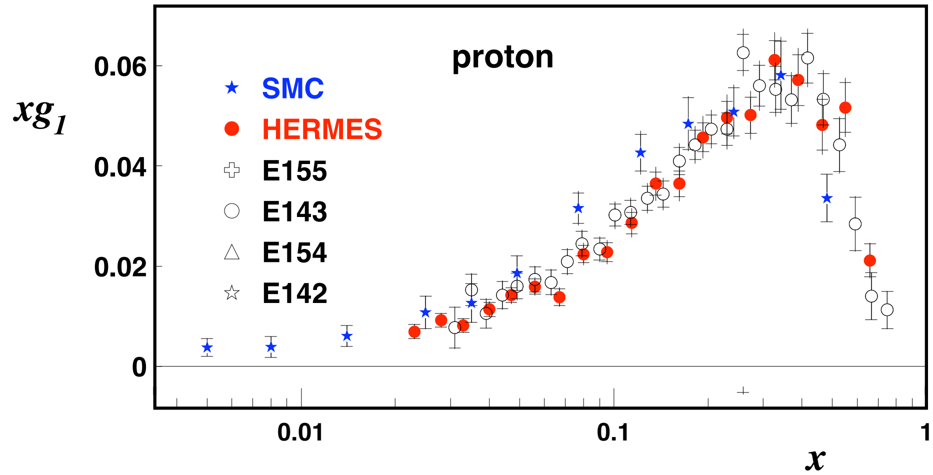
Instanton Mechanism



'tHooft instanton vertex $\sim \overline{u}_R u_L \overline{d}_R d_L$ transfers helicity from valence u quarks to $d\overline{d}$ pairs

Polarized Deep-Inelastic Scattering





Measure g_1 **structure function**

$$g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \, \Delta q(x, Q^2)$$

via inclusive double-spin asymmetries

$$A_1 = \frac{\sigma_{J=1/2} - \sigma_{J=3/2}}{\sigma_{J=1/2} + \sigma_{J=3/2}} = \frac{g_1}{F_1}$$

First moment: (E155, Q^2 = 5 GeV^2)

$$\Gamma_1^p = \int g_1^p \, dx = 0.118 \pm 0.008$$

Assuming **flavour-symmetric sea** ,

$$\Gamma_1^p = \frac{1}{6}\left[\frac{a_3}{2} + \frac{5\,a_8}{6} + 4\,\Delta\bar{q}\right]$$

$\Delta\bar{q} \simeq -0.10$ $\Rightarrow$ $\Delta\Sigma \simeq 0!$

i.e., the "Spin Crisis" ... but we can do a lot better than this analysis ... !

NLO pQCD Fits to World Data on g_1^p, g_1^n, g_1^d

$$g_1^{p(n)}(x,Q^2) = \frac{1}{9}\left(C_{NS}\otimes\left[\pm\frac{3}{4}\Delta q_3 + \frac{1}{4}\Delta q_8\right] + C_S\otimes\Delta\Sigma + 2N_f C_g\otimes\Delta G\right)$$

Ingredients:

- Parametrization at some scale μ_0, e.g.

$$\Delta q(x,\mu_0^2) = N\,x^\alpha(1-x)^\beta q(x,\mu_0^2)$$

- Moments from β-decay:

$$a_3 = 1.267 = \Delta U + \Delta D$$
$$a_8 = 0.585 = \Delta U + \Delta D - 2\Delta S$$

where $Q \equiv q + \overline{q}$

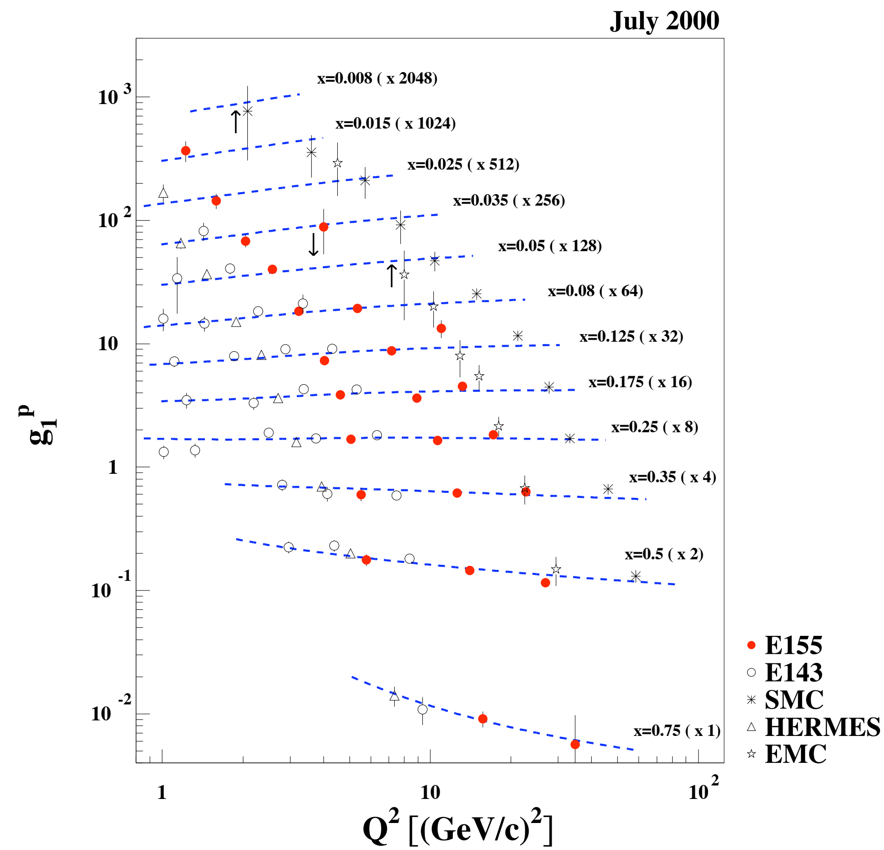
- Sea-flavour assumption:

(a) $\Delta u_s = \Delta\overline{u} = \Delta d_s = \Delta\overline{d} = \ldots$

(GRSV-standard, AAC, BB, HERMES)

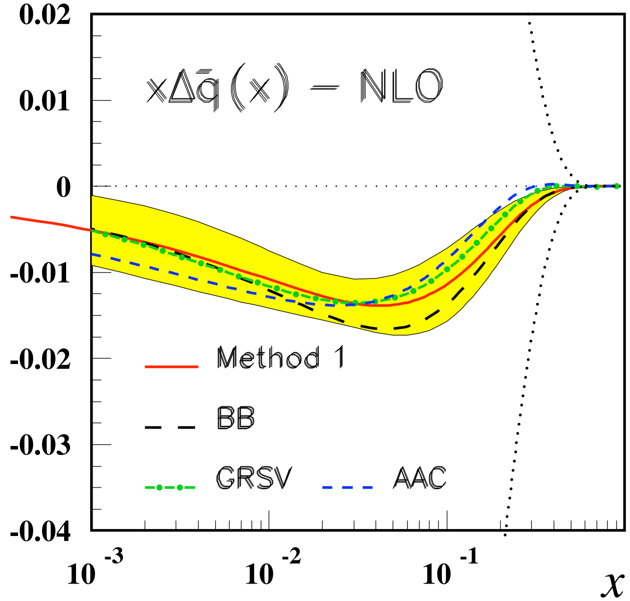
(b) $\Delta\overline{d}/\Delta\overline{u} = \Delta u/\Delta d$

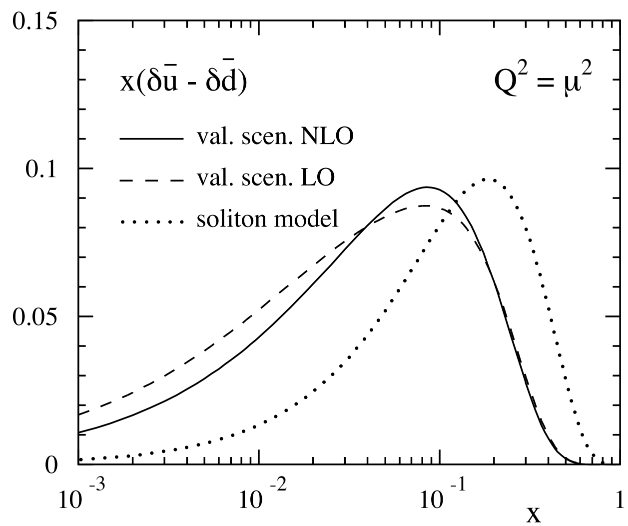
$\Delta s = \Delta\overline{s} = 0$ (GRSV-valence)



- Factorization scheme (usu. $\overline{\mathrm{MS}}$)
- Optional: higher-twist terms $\sim 1/Q$

NLO pQCD Fits to g_1: Quark-Polarization Results





First moments at Q^2 = 4.0 GeV^2:

SU(3)-symmetric sea assumption:

(all: $\Delta u_v = 0.93 \pm 0.07$, $\Delta d_v = -0.34 \pm 0.12$)

	$\Delta\bar{q}$	$\Delta\Sigma$
GRSV 2000 std	-0.064	0.197
BB 2002	-0.072 ± 0.015	0.153 ± 0.093
AAC 2003	-0.062 ± 0.023	0.213 ± 0.138
HERMES prelim	-0.064 ± 0.021	0.201 ± 0.119

GRSV "valence" scenario:

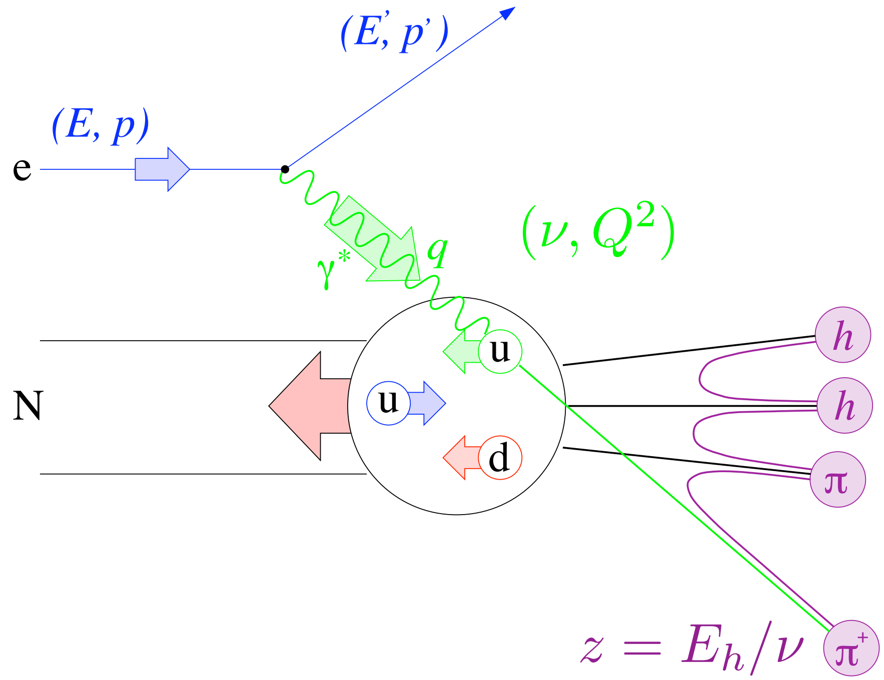
	$\Delta\bar{u}$	$\Delta\bar{d}$	$\Delta\Sigma$
GRSV 2000 valence	0.085	-0.235	0.273

χ^2/dof cannot distinguish between SU(3)-symmetric sea (GRSV-"standard") and fully flavour-broken "valence" scenario

Quark Polarization from Semi-Inclusive DIS

In ***semi-inclusive DIS*** a hadron h is detected in coincidence with the scattered lepton ...

➡ *Goal:* ***flavor separation*** *of quark and antiquark helicity distributions*



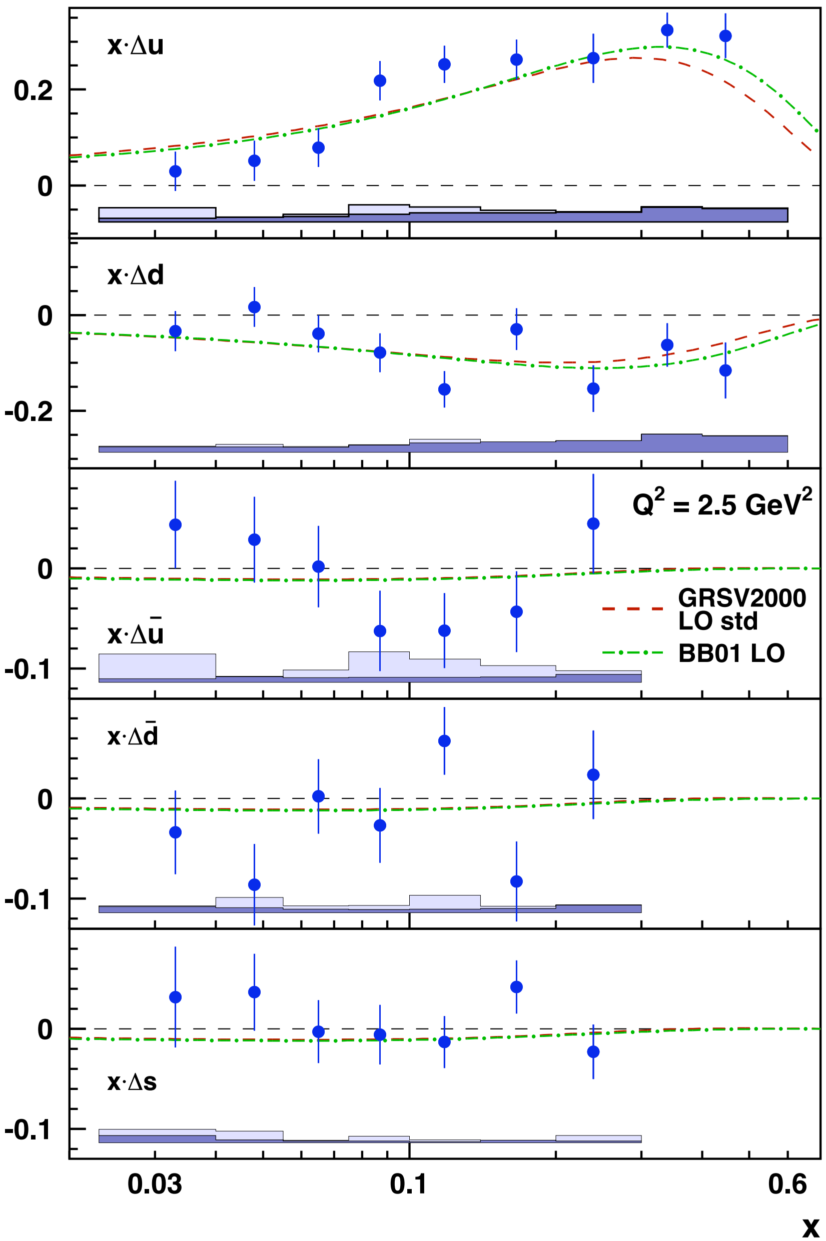
Technique: Flavor Tagging

The flavor content of final state hadrons is related to the flavor of the struck quark via the **fragmentation functions** $D_q^h(z, Q^2)$. In LO QCD:

$$A_1^h(x, Q^2) = \frac{\int_{z_{\rm min}}^1 dz \sum_q e_q^2 \, \Delta q(x, Q^2) \cdot D_q^h(z, Q^2)}{\int_{z_{\rm min}}^1 dz \sum_q e_q^2 \, q(x, Q^2) \cdot D_q^h(z, Q^2)} = \sum_q P_q^h(x, z) \frac{\Delta q(x)}{q(x)}$$

Purity matrix P_q^h ***is spin-independent & may be computed by Monte Carlo***

Final HERMES Δq Measurement from SIDIS



- input: $A_{1,p}$, $A_{1,p}^{\pi^\pm}$, $A_{1,d}$, $A_{1,d}^{\pi^\pm}$, $A_{1,d}^{K^\pm}$
- Assumption: $\Delta\bar{s} = 0 \pm 1/\sqrt{3}$

First 5-flavor fit to $\Delta q(x)$

- **No significant $\bar{q}$ polarization seen**

... but ...

- Results **perfectly consistent** with **inclusive** fits $\Rightarrow$ χ^2/dof = 0.6 – 1.6 vs BB (SU3-sym) ***and*** GRSV-valence ☹
- In **measured range** (x = .023 – .6),

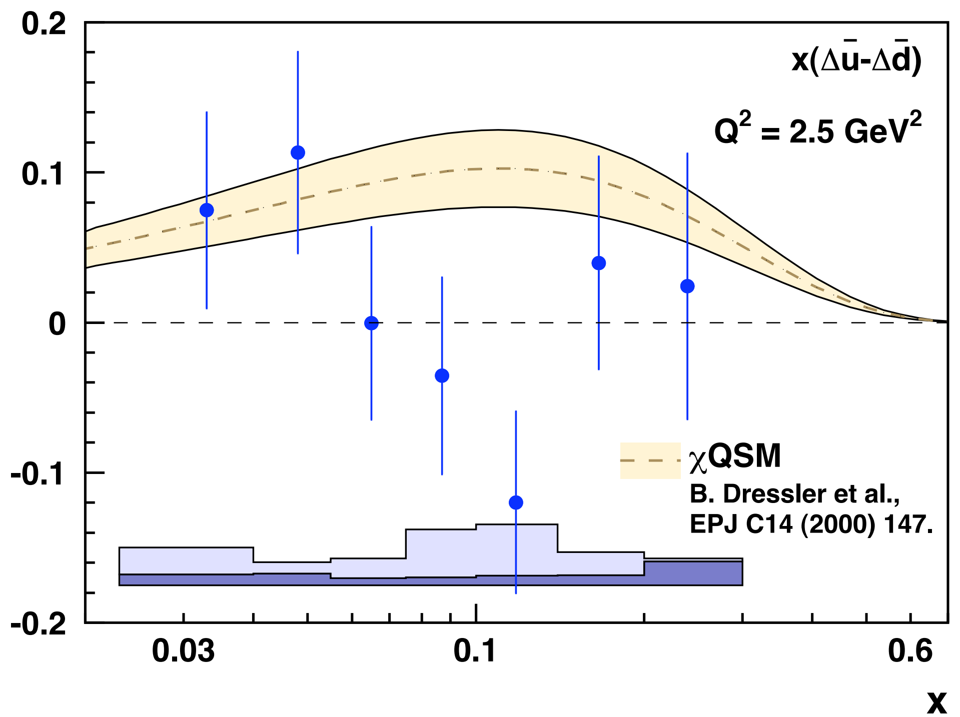
$$\int \Delta\bar{u} = -0.002 \pm 0.043$$

$$\int \Delta\bar{d} = -0.054 \pm 0.035$$

$$\int \Delta s = +0.028 \pm 0.034$$

Flavor-Asymmetry of Sea & Future Data on $\Delta q(x)$

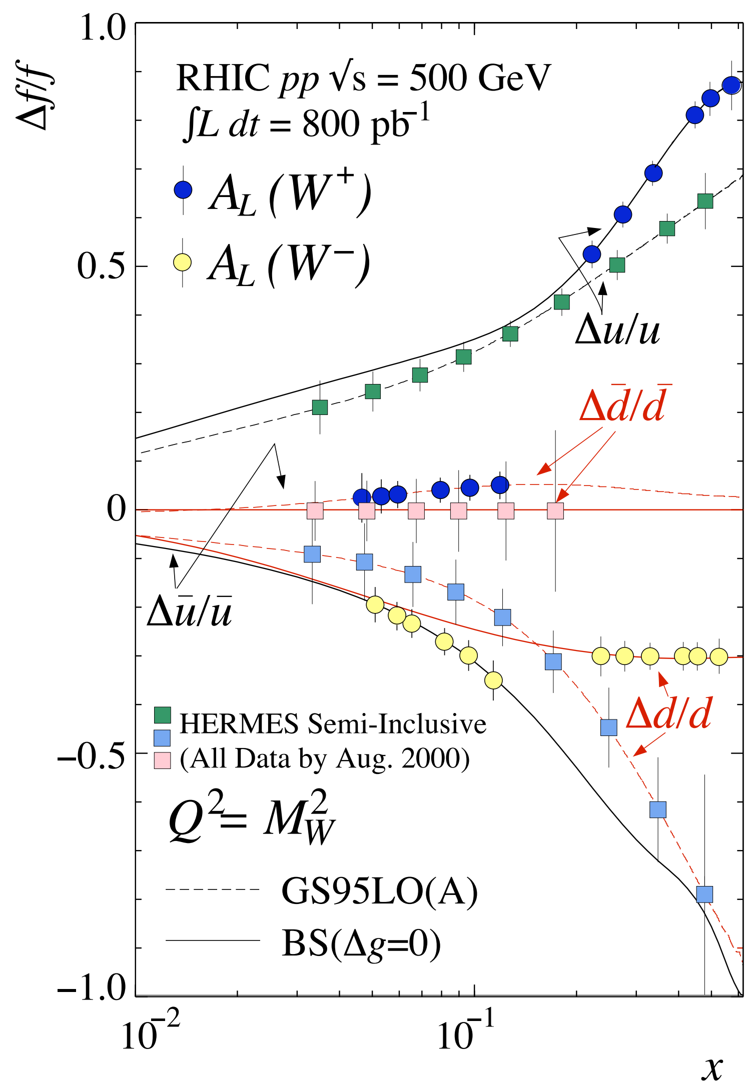
Comparison with Chiral-Quark Soliton Model calculation "not great" ...



Lack of flavor-asym $\Delta\overline{u} \neq \Delta\overline{d}$ more reminiscent of ***meson-cloud picture*** ...

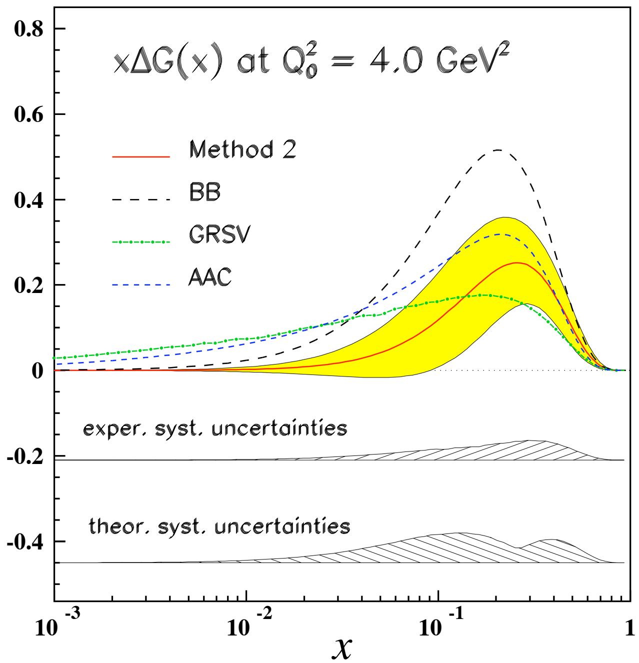
More SIDIS data coming from COMPASS!

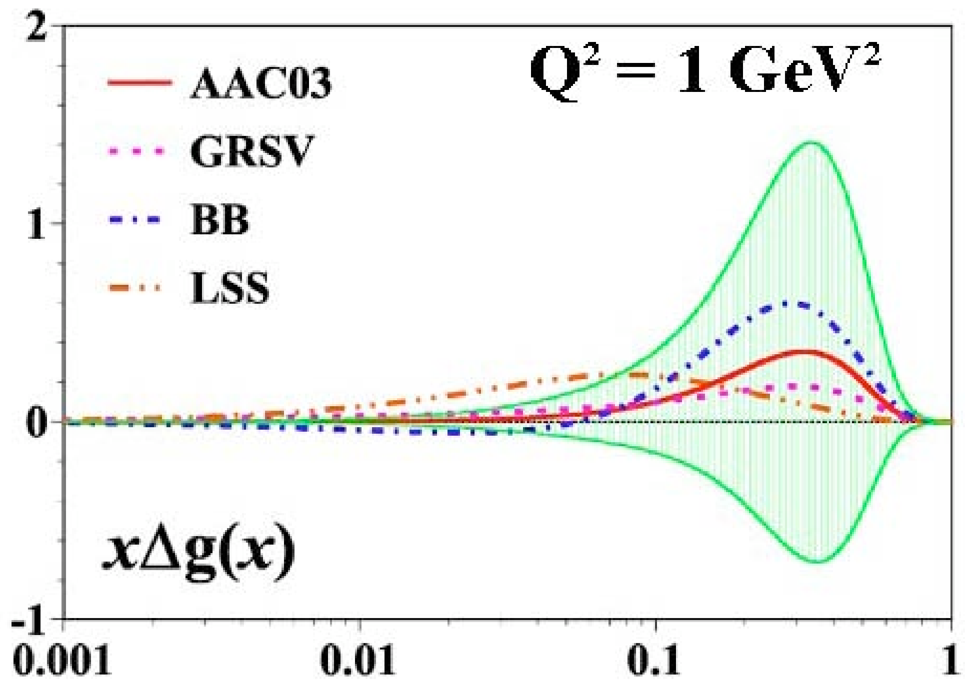
New channel coming from RHIC $\Rightarrow W$-production!



Gluon Polarization from NLO Fits to $g_1(x, Q^2)$

$$g_1^{p(n)}(x,Q^2) = \frac{1}{9}\left(C_{NS}\otimes\left[\pm\frac{3}{4}\Delta q_3 + \frac{1}{4}\Delta q_8\right] + C_S\otimes\Delta\Sigma + 2N_f C_g\otimes\Delta G\right)$$



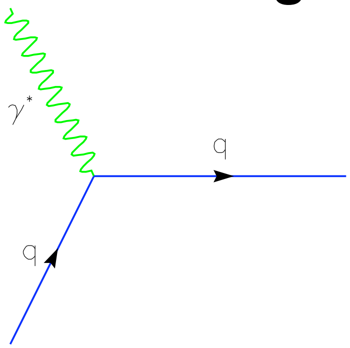


	Q^2 (GeV)^2	ΔG
AAC 2003	1	0.499 ± 1.266
HERMES fit #1	2.5	0.616 ± 0.601
HERMES fit #2	2.5	0.357 ± 0.253
BB 2002 ISET = 3	4	1.026 ± 0.549
BB 2002 ISET = 4	4	0.931 ± 0.669

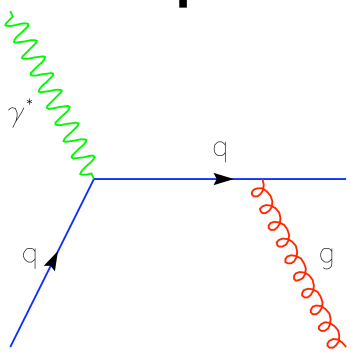
some indication of positive ΔG ... ?

Gluon Polarization from SIDIS

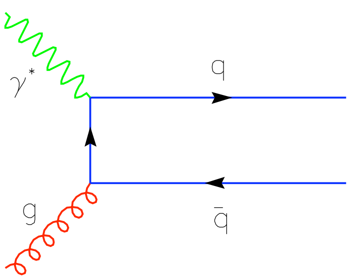
LO: single-q scattering



NLO: QCD-Compton



NLO: PGF



Find SIDIS channel that enhances Photon-Gluon Fusion process

① **Charm production** ➡ COMPASS talk (F. Bradamante)!

② **High-pT hadron-pair production**

- HERMES 1997: $Q^2 \approx 0$, $\sum p_T > 2.5$ GeV

  $\Delta G/G = +0.41 \pm 0.18 \pm 0.03$ at $\langle x_G \rangle = 0.17$

- **new** SMC analysis #1: $Q^2 > 1$, $\sum p_T^2 > 2.5$ GeV^2

  $\Delta G/G = -0.07 \pm 0.40 \pm 0.12$ at $\langle x_G \rangle = 0.09$

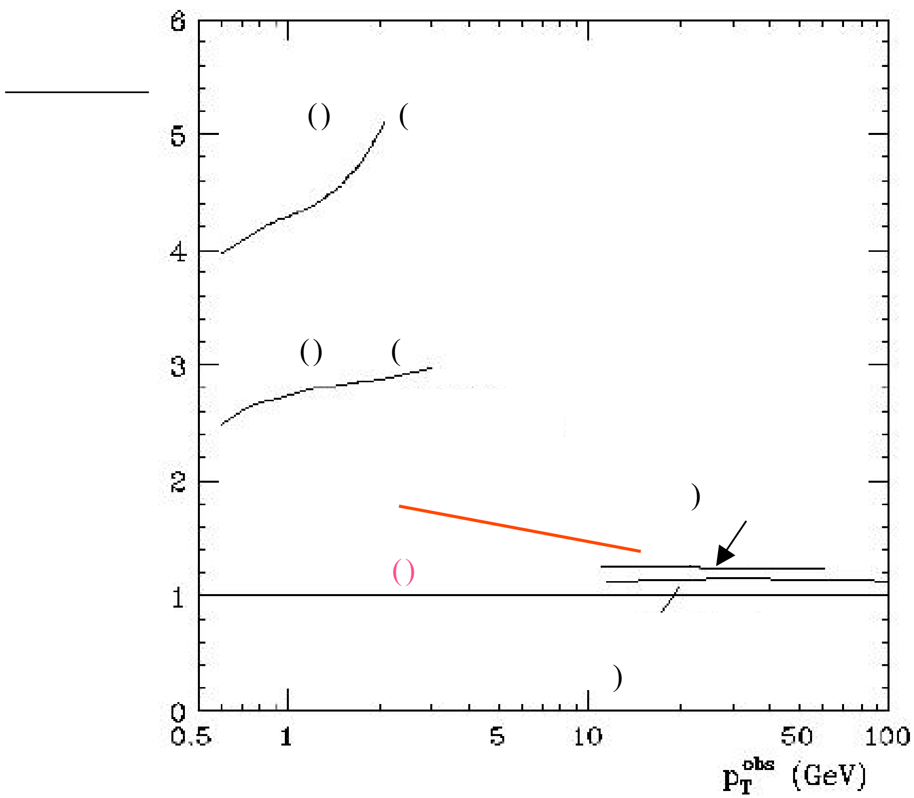
- **new** SMC analysis #2: $Q^2 > 1$, neural-net cuts

  $\Delta G/G = -0.20 \pm 0.28 \pm 0.10$ at $\langle x_G \rangle = 0.07$

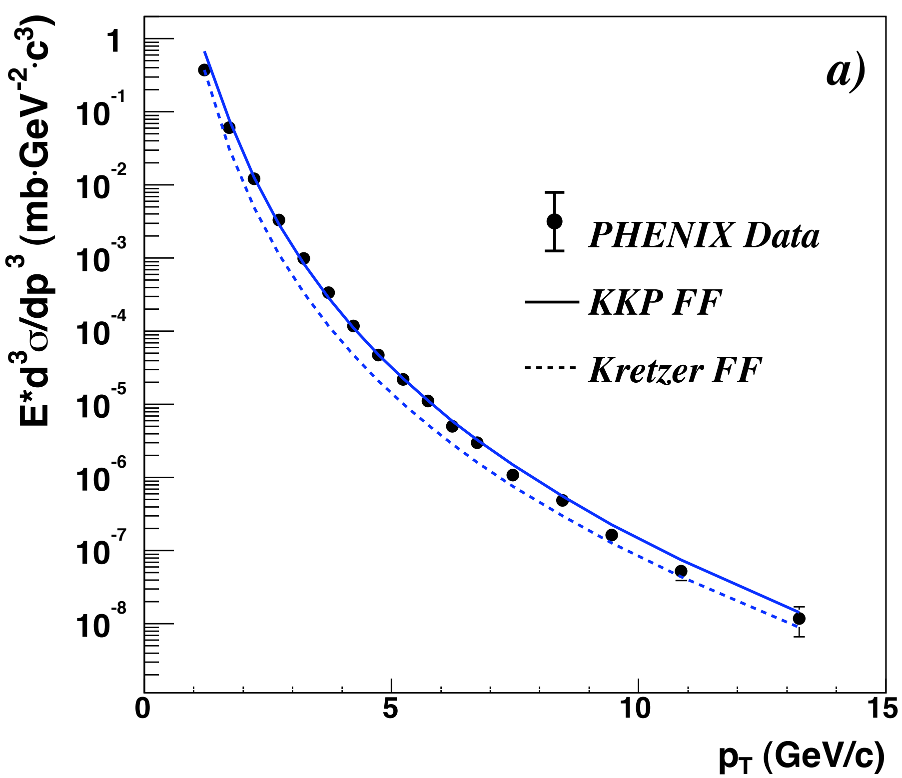
Gluon Polarization at RHIC

Channels: ① Direct-photon ② Heavy-quark production ③ Jet / hadron production

Uncomfortable scale-dependence of hadron-pair xsec at HERMES and COMPASS kinematics ...

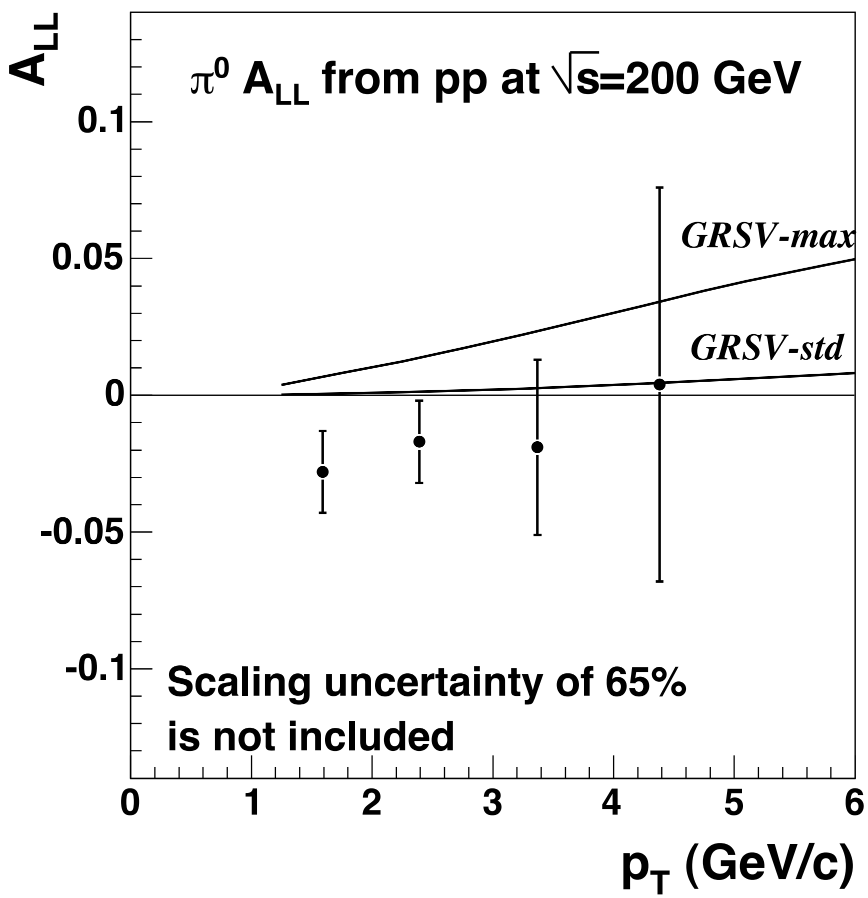


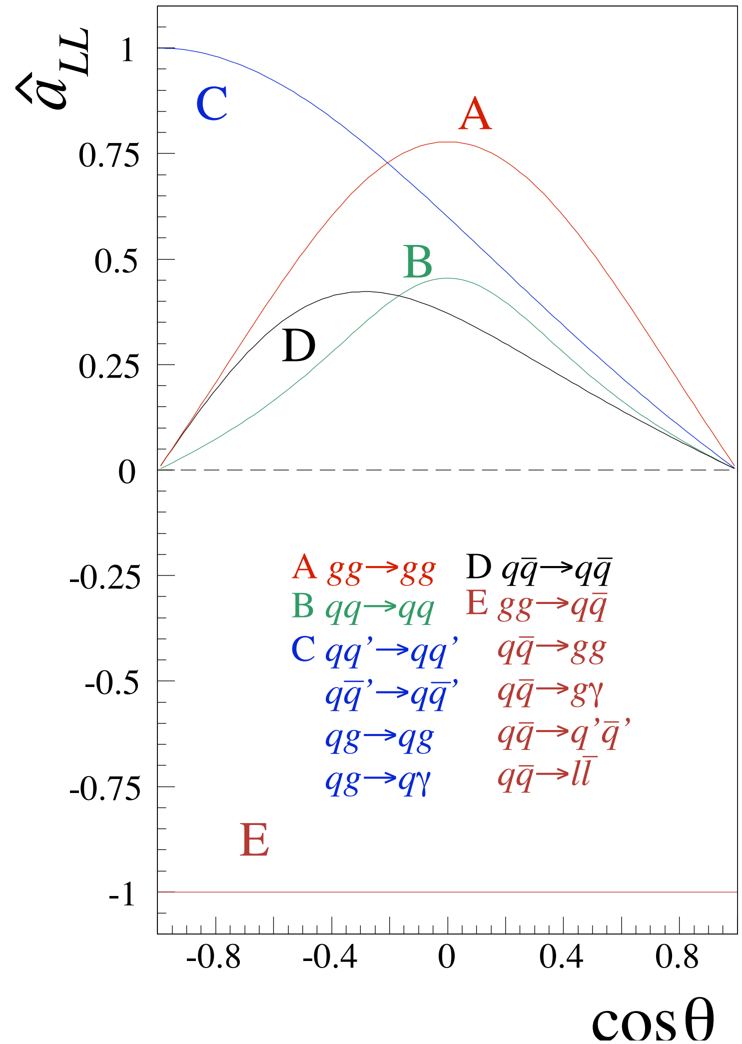
Happier situation at RHIC: much less scale-dependence ... π^0 xsec well explained by NLO-pQCD:



New Results from PHENIX! $A_{LL}^{\pi^0}$ at mid-rapidity

Asymmetry favours negative value ...

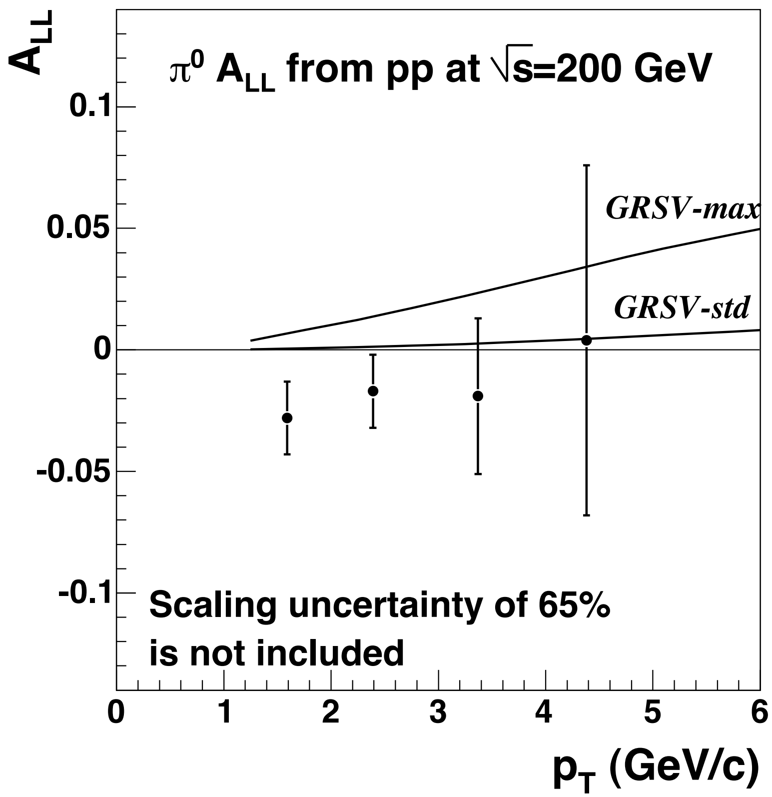




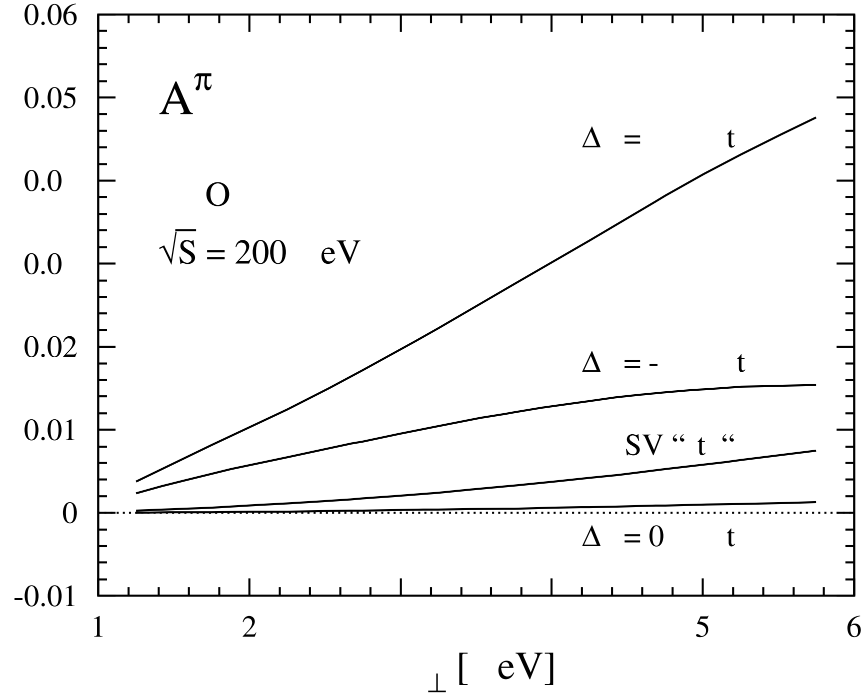
Jäger, Stratmann, Kretzer, Vogelsang, PRL 92 (2004) 121803

Many subprocesses ... but ***only*** $gg \to q\bar{q}$ *has*
negative *subprocess asymmetry* $\hat{a}_{LL} < 0$ *...*

Interpretation of PHENIX $A_{LL}^{\pi^0}$

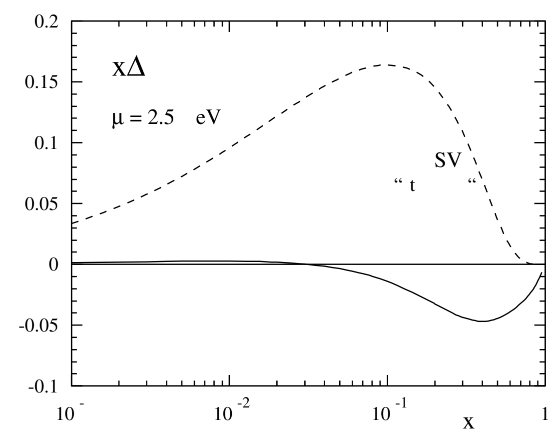


... even $\Delta g = 0$ or $\Delta g = -g$ produces *positive* asymmetry



Jäger, Stratmann, Kretzer, Vogelsang, PRL 92 (2004) 121803

*Finding: pQCD at **leading power in $p_\perp$ ⇒ lower bound** $A_{LL}^{\pi} \geq \mathcal{O}(-10^{-3})$ for $p_\perp \simeq$ 1 – 4 GeV.*



Answers await more statistics → higher p_T coverage

New Spin-Structure Function: Transversity $\delta q(x)$

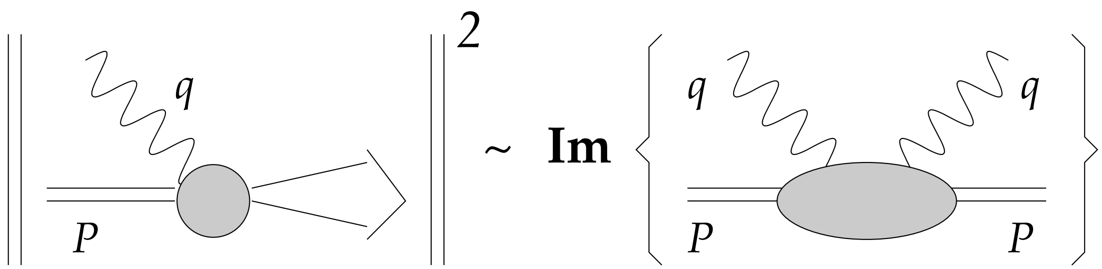
Proton Matrix Elements

vector charge $\langle PS|\overline{\psi}\gamma^{\mu}\psi|PS\rangle = \int_0^1 dx\; q(x) - \overline{q}(x) \longrightarrow$ # valence quarks

axial charge $\langle PS|\overline{\psi}\gamma^{\mu}\gamma_5\psi|PS\rangle = \int_0^1 dx\; \Delta q(x) + \Delta\overline{q}(x) \longrightarrow$ net quark spin

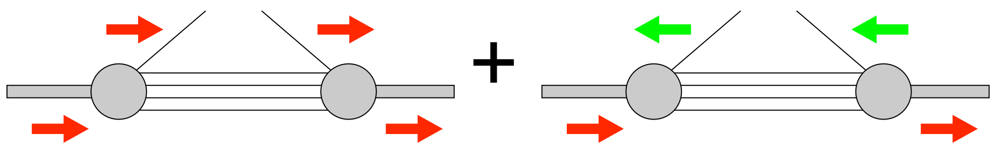
tensor charge $\langle PS|\overline{\psi}\sigma^{\mu\nu}\gamma_5\psi|PS\rangle = \int_0^1 dx\; \delta q(x) - \delta\overline{q}(x) \longrightarrow$???

Forward Helicity Amplitudes

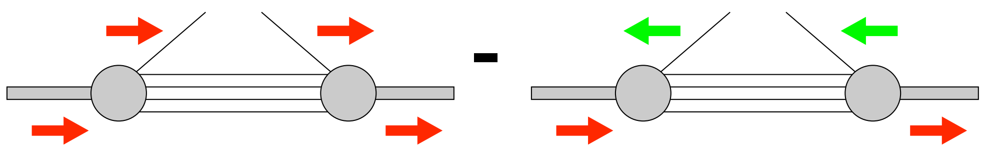


(optical theorem applied to DIS)

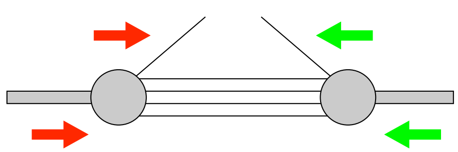
$q(x) \sim$



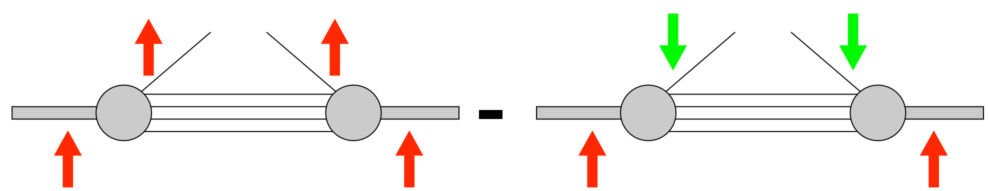
$\Delta q(x) \sim$



$\delta q(x) \sim$



... but in transverse basis ...

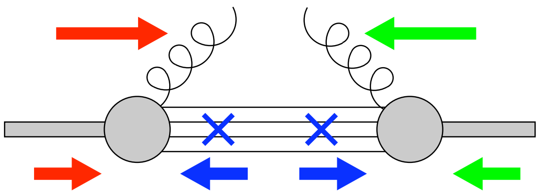


Properties of Transversity

- **In Non-Relativistic Case,** boosts and rotations commute: $\delta q(x) = \Delta q(x)$

  ... but bound quarks are highly ***relativistic*** in nature

- **No Gluons**



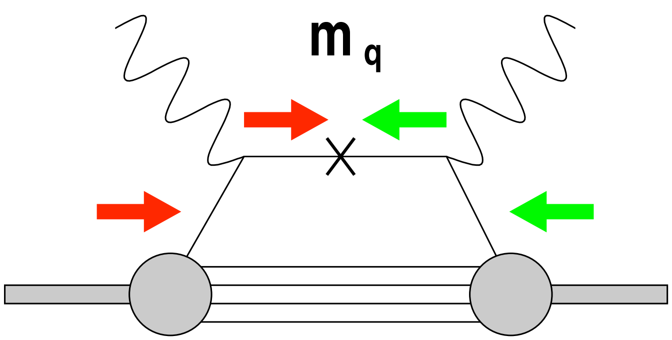
Angular momentum conservation: $\Lambda - \lambda = \Lambda' - \lambda'$

$\Rightarrow$ transversity has ***no gluon*** component

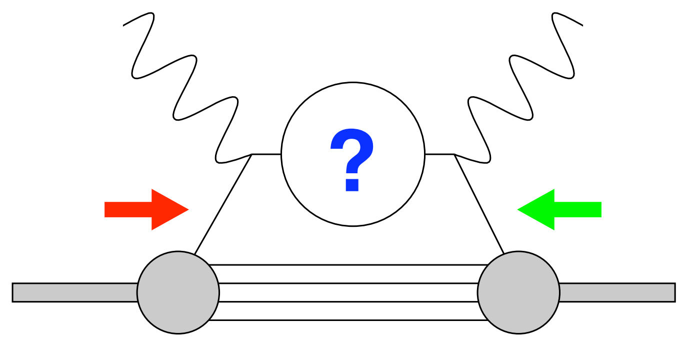
$\Rightarrow$ different Q^2 ***evolution*** than $\Delta q(x)$

- **Chiral Odd**

Helicity flip amplitudes occur only at $\mathcal{O}(m_q/Q)$ in inclusive DIS ...

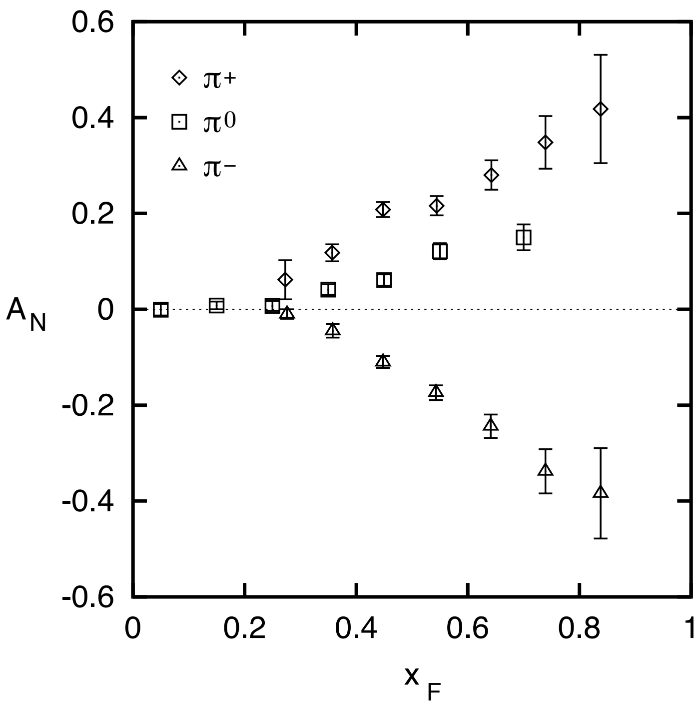


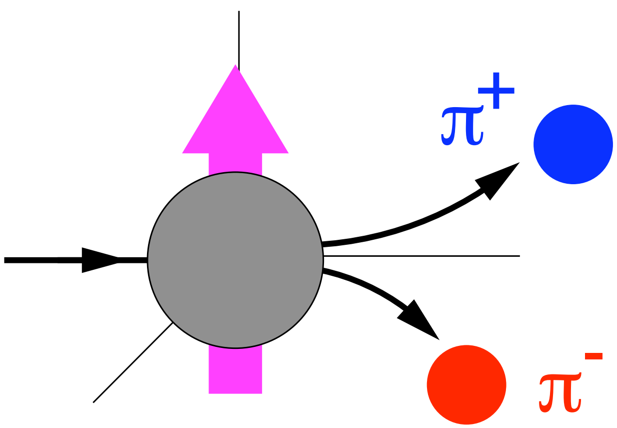
but they are observable in e.g. **semi-inclusive** reactions



Single-Spin Asymmetries at Hard Scales

E704: $p^{\uparrow}p \to \pi X$





T-odd observables

SSA observables $\sim \vec{\mathbf{J}} \cdot (\vec{\mathbf{p_1}} \times \vec{\mathbf{p_2}})$
$\Rightarrow$ ***odd*** under naive ***time-reversal***

Since QCD amplitudes are T-even, must arise from **interference** between **spin-flip** and non-flip amplitudes with **different phases**

Suppressed in pQCD hard-scattering

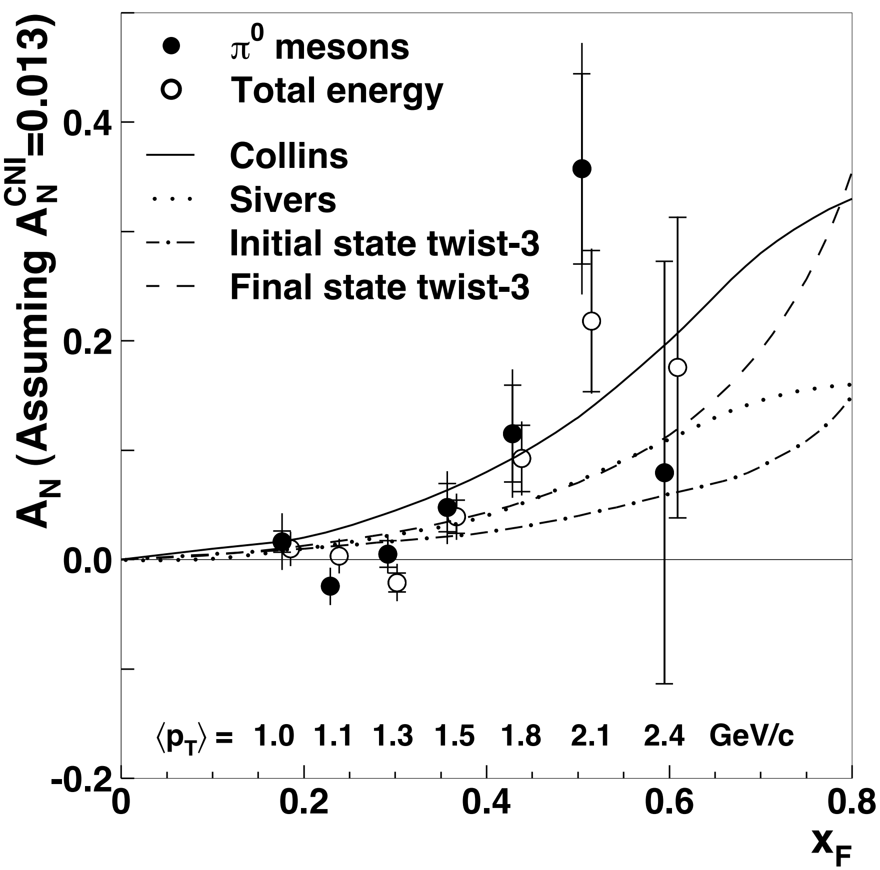
- q helicity flip suppressed by $m_q/\sqrt{s}$
- need α_s-suppressed loop-diagram to generate necessary phase

At hard (enough) scales, SSA's must arise from soft physics: T-odd distribution / fragmentation functions

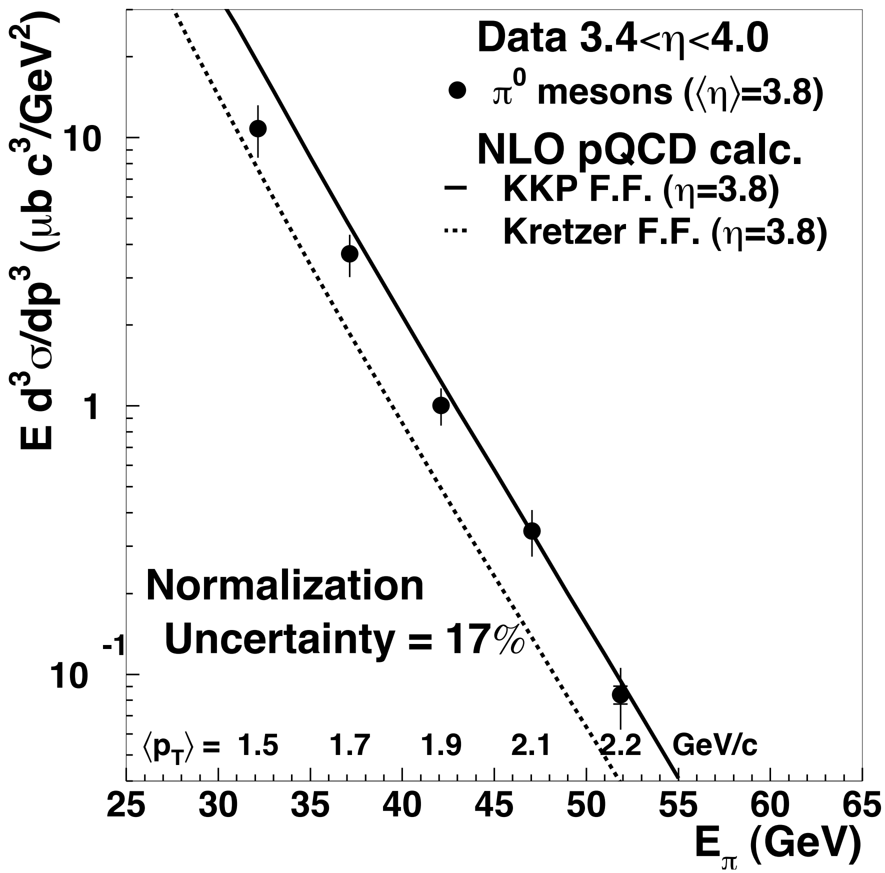
Results from STAR: $A_N^{\pi^0}$ at forward rapidity

Was E704 at a hard-enough scale for reliable pQCD analysis?
well RHIC certainly is!

Clear evidence of analyzing power



Xsec well-described by pQCD

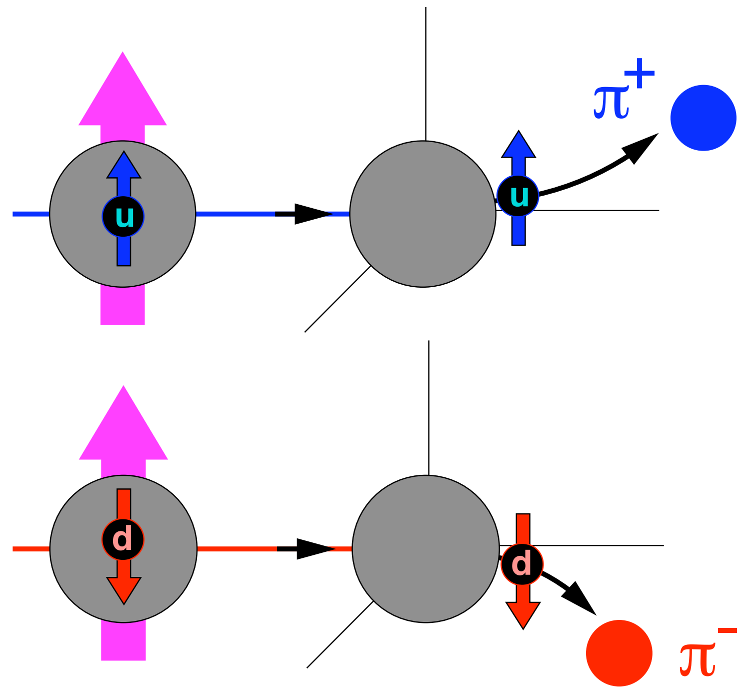


Asymmetry shows similar **rise with x_F** as observed at E704

Possible Mechanism #1: The "Collins Effect"

$H_1^\perp(z, k_T)$ **T-odd fragmentation func**

- intrinsically k_T-dependent
- chiral-odd, like transversity

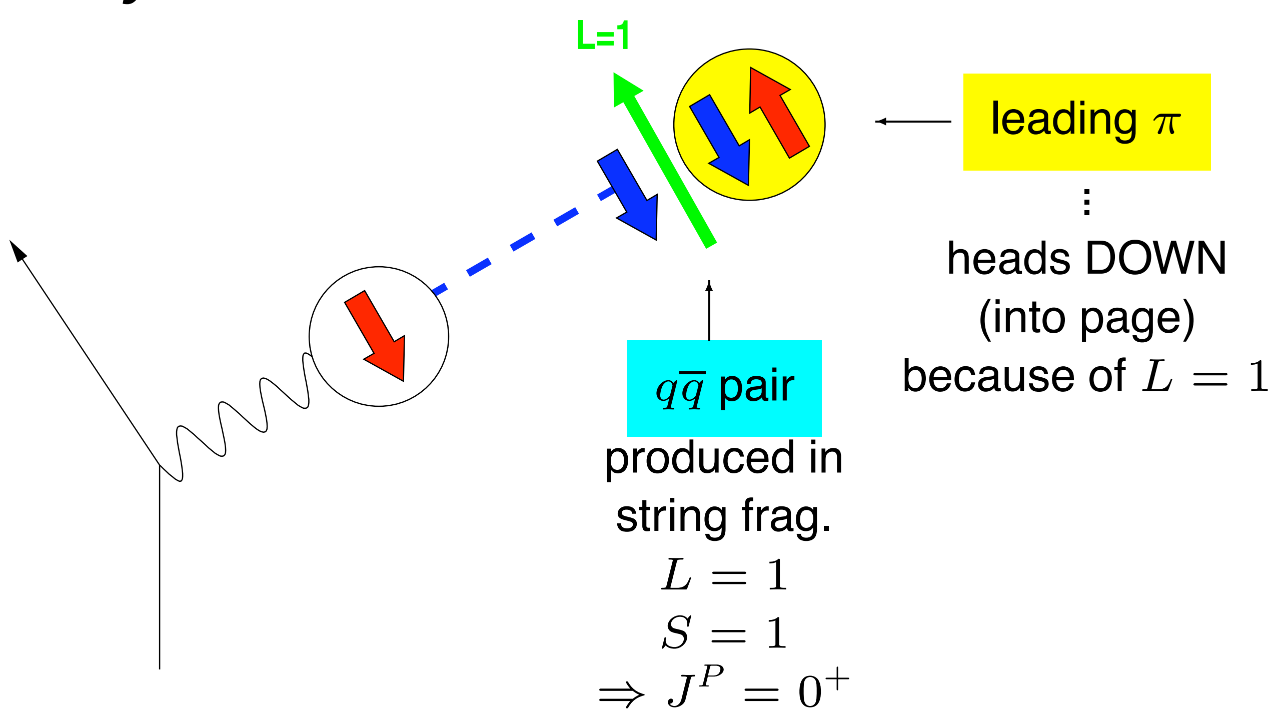


➡ **Collins Effect** $A_N \sim h_1(x)\, H_1^\perp(z)$

access to transversity!

Artru model

based on Lund-string fragmentation picture



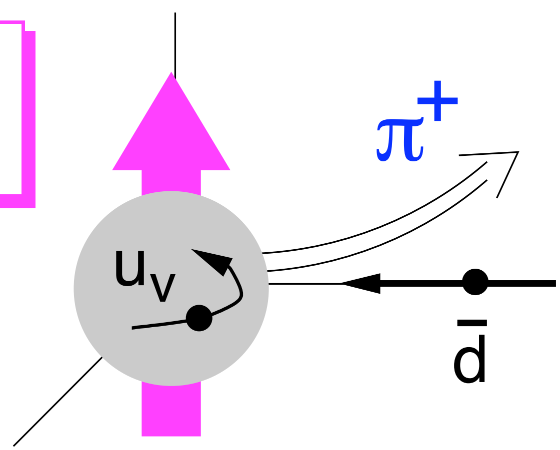
Possible Mechanism #2: The "Sivers Effect"

$f_{1T}^{\perp}(x, k_T)$ **Sivers distribution func**

New type of DF: T-odd, and depends **intrinsically** on **quark transverse-momentum** $\Rightarrow$ on quark ***orbital motion***

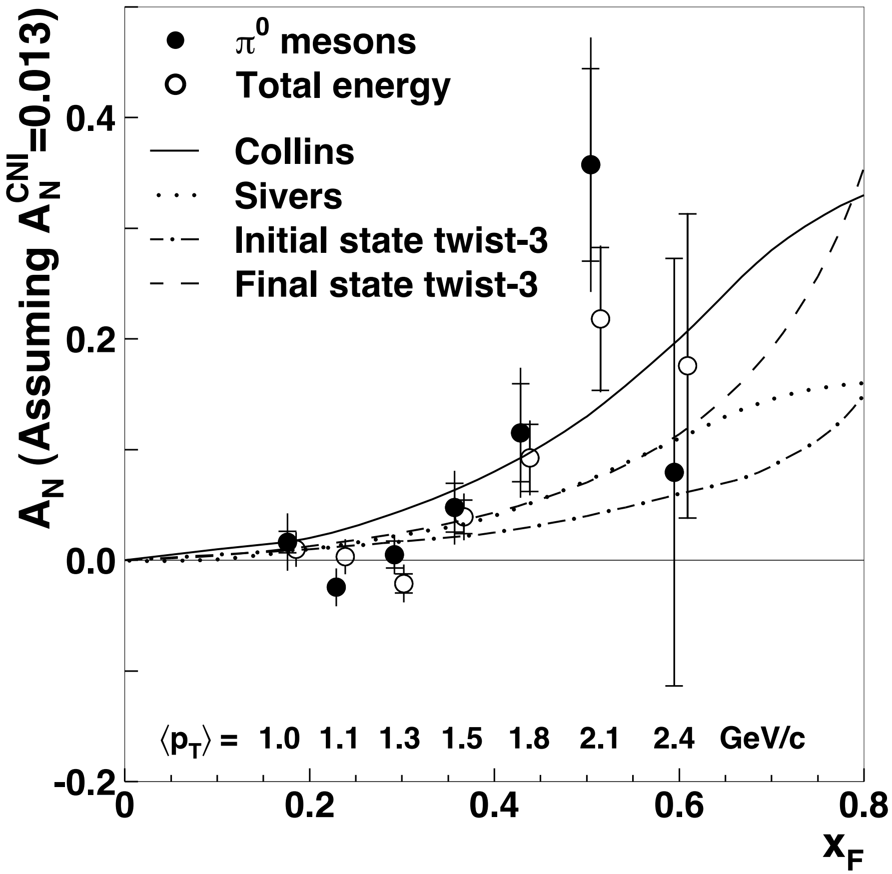
➡ **Sivers Effect** $A_N \sim f_{1T}^{\perp}(x)\, D_1(z)$

Model of Meng, Chou, Yang



Forward π^+ produced from orbiting u_v quark by recombination at ***front surface*** of beam

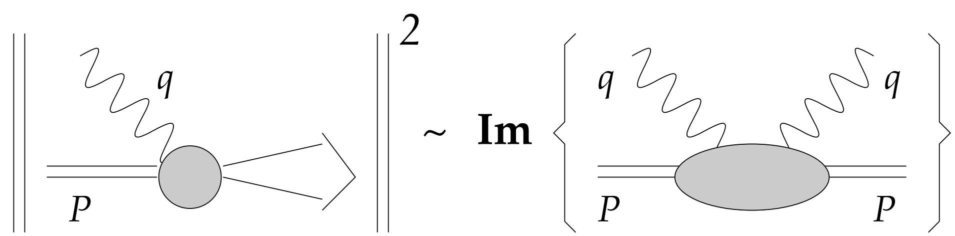
How to Separate?



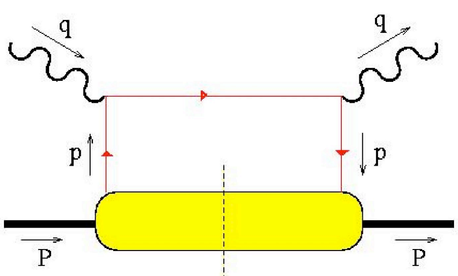
Until 2002, it was believed that the **Sivers** effect could **not exist** in **DIS** $\rightarrow$ requires T-odd **interference effect** in **initial state** ...

The Leading-Twist Sivers Function: Can it Exist in DIS?

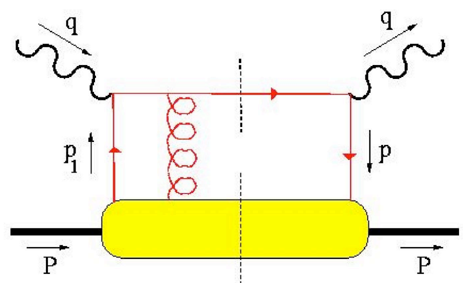
A T-odd function like $f_{1T}^{\perp}$ ***must*** arise from ***interference*** ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?



Brodsky, Hwang, & Schmidt 2002



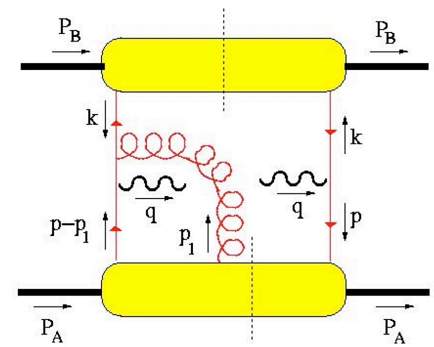
can interfere with



and produce a T-odd effect! (also need $L_z \neq 0$)

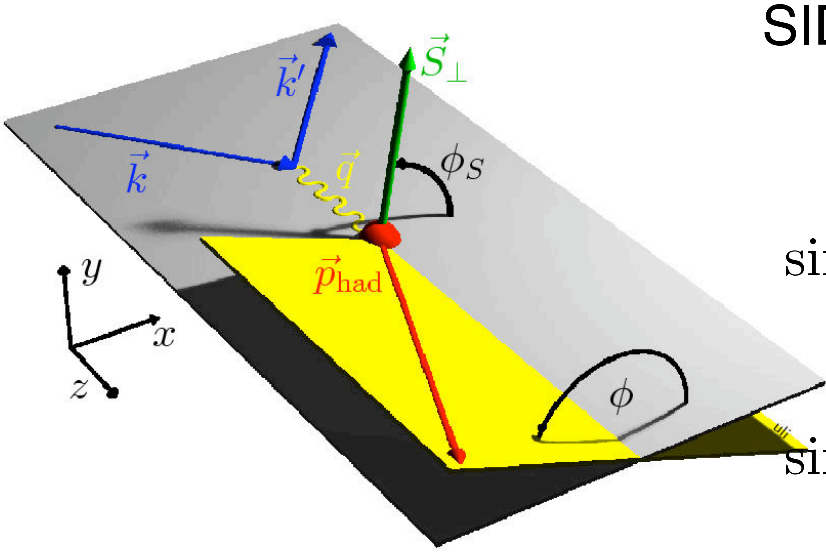
It looks like higher-twist ... but no, these are soft gluons = "gauge links" required for color gauge invariance

Such soft-gluon reinteractions with the soft wavefunction are ***final (or initial) state interactions*** ... and may be ***process dependent*** ! ➡ new ***universality issues***

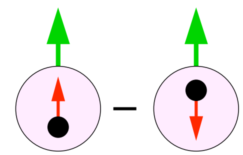
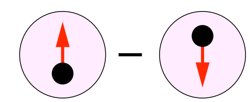


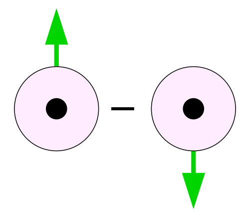
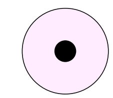
e.g. Drell-Yan

T-odd Distribution vs Fragmentation Function

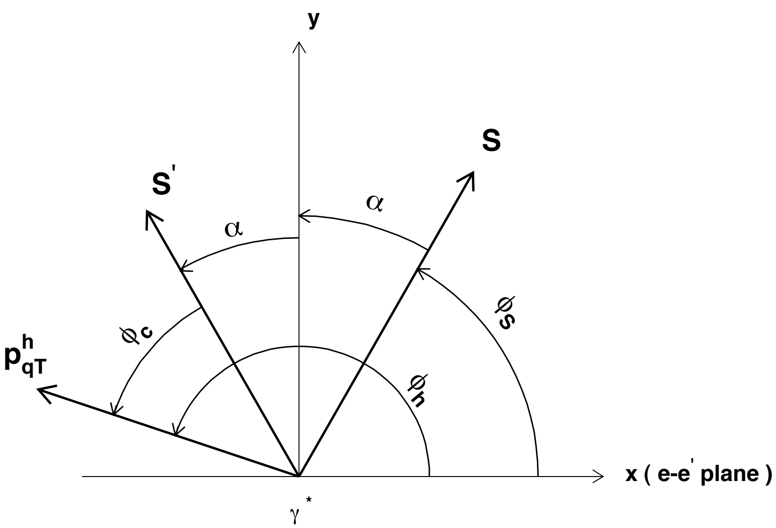


SIDIS xsec with ***transverse target*** polarization has ***two*** similar terms:

$\sin(\phi_h^l + \phi_S^l) \Rightarrow h_1$ =  $\otimes H_1^\perp$ = 

$\sin(\phi_h^l - \phi_S^l) \Rightarrow f_{1T}^\perp$ =  $\otimes D_1$ = 

seperate Sivers and Collins mechanisms

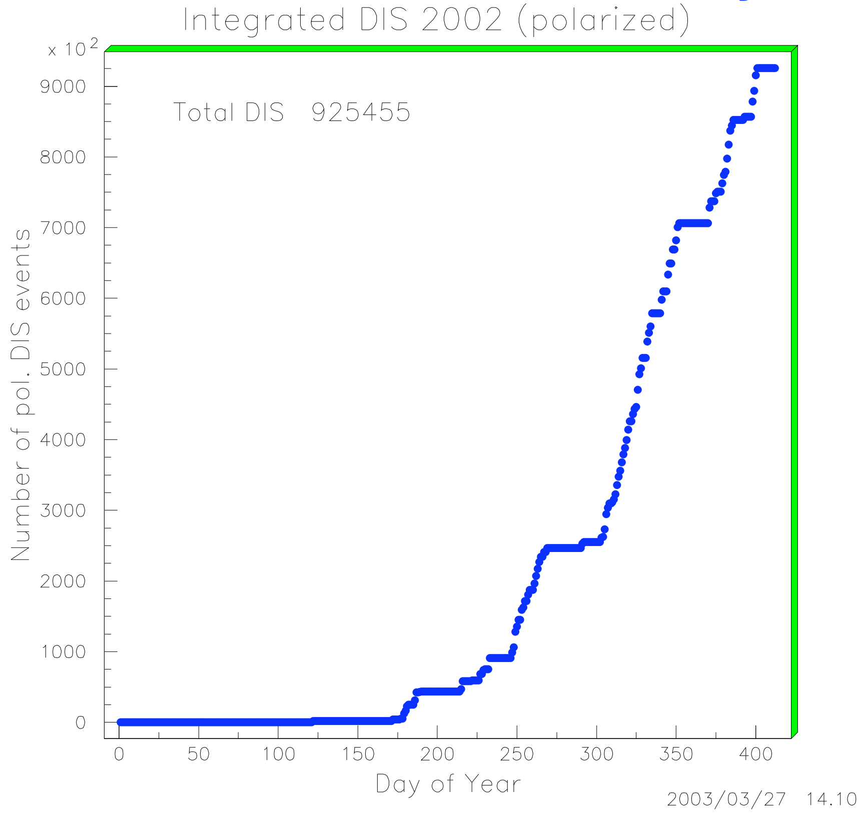


- $(\phi_h^l - \phi_S^l)$ = angle of hadron relative to **initial** quark spin
- $(\phi_h^l + \phi_S^l) = \pi + (\phi_h^l - \phi_S^{l'})$ = hadron relative to **final** quark spin

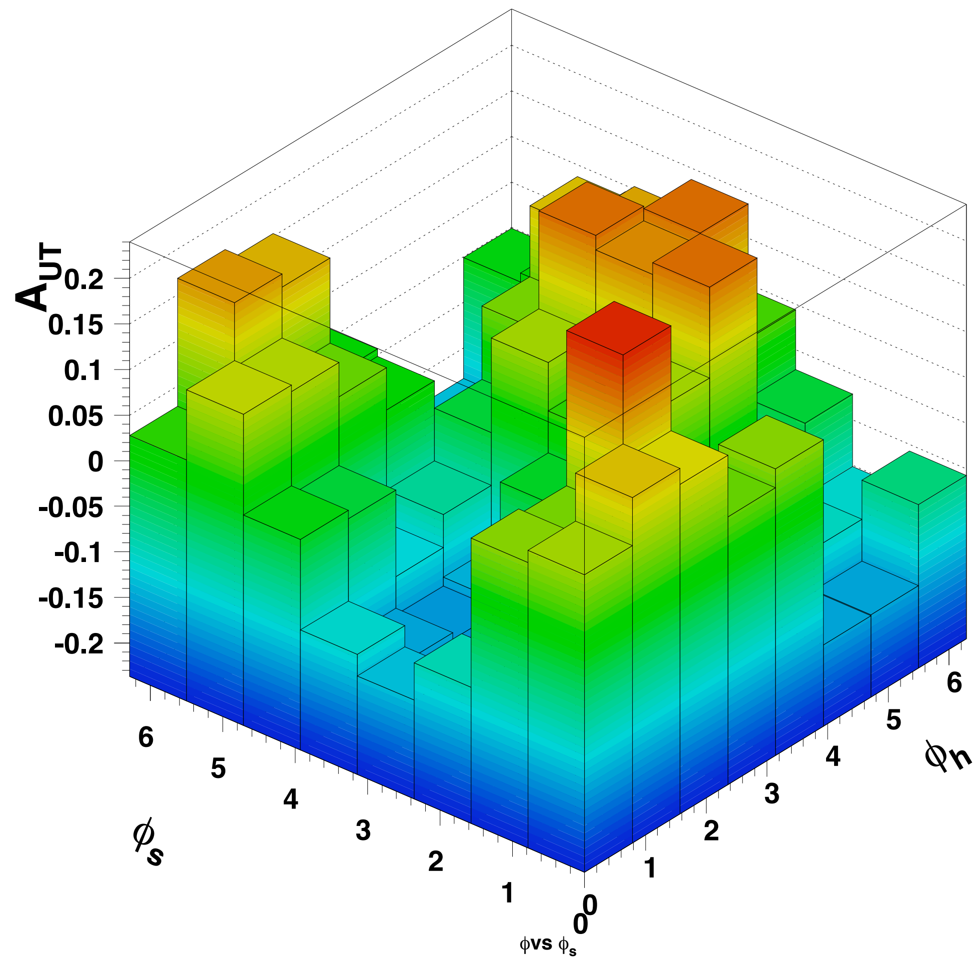
First Data from HERMES Run 2

Transverse Hydrogen target installed in 2001

not so much lumi collected yet ...



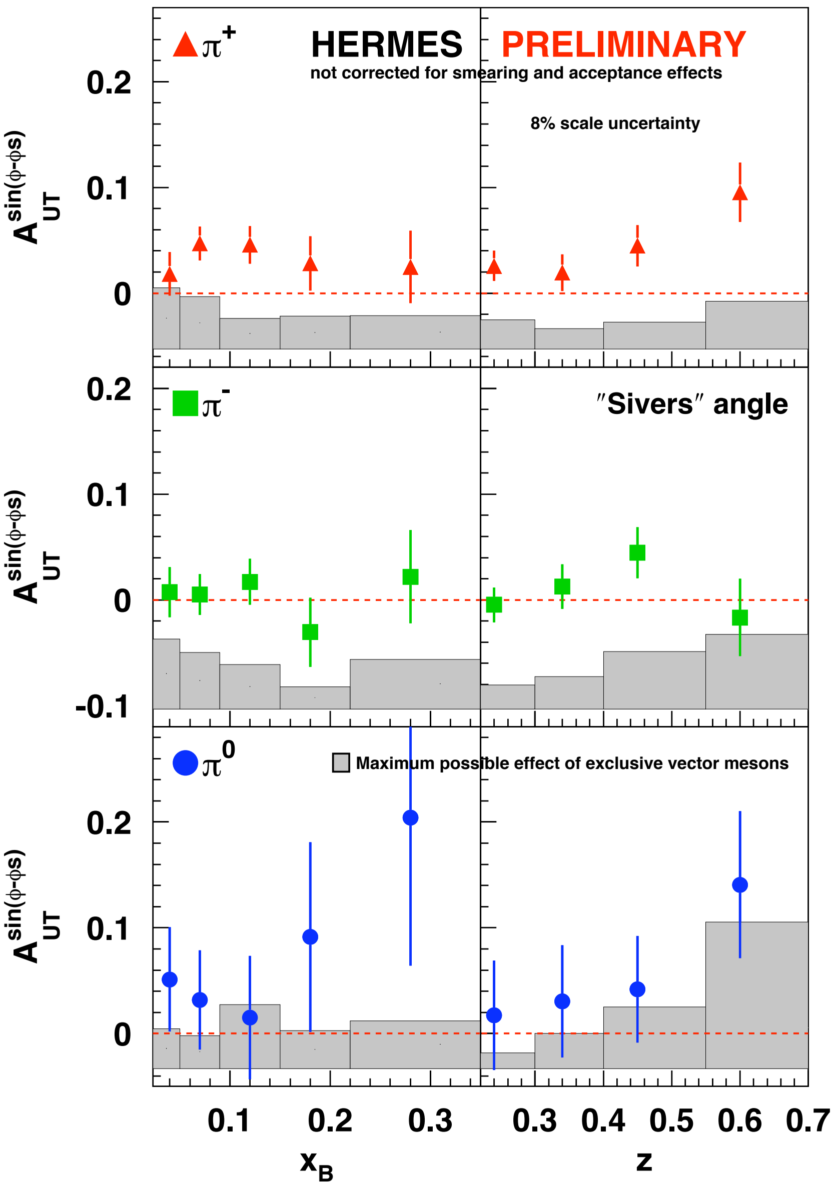
year	target gas	spin	# pol. DIS
96-97	hydrogen	L	2.4 M
98-00	deuterium	L	9.1 M ☺
02-03	hydrogen	T	0.7 M ☹



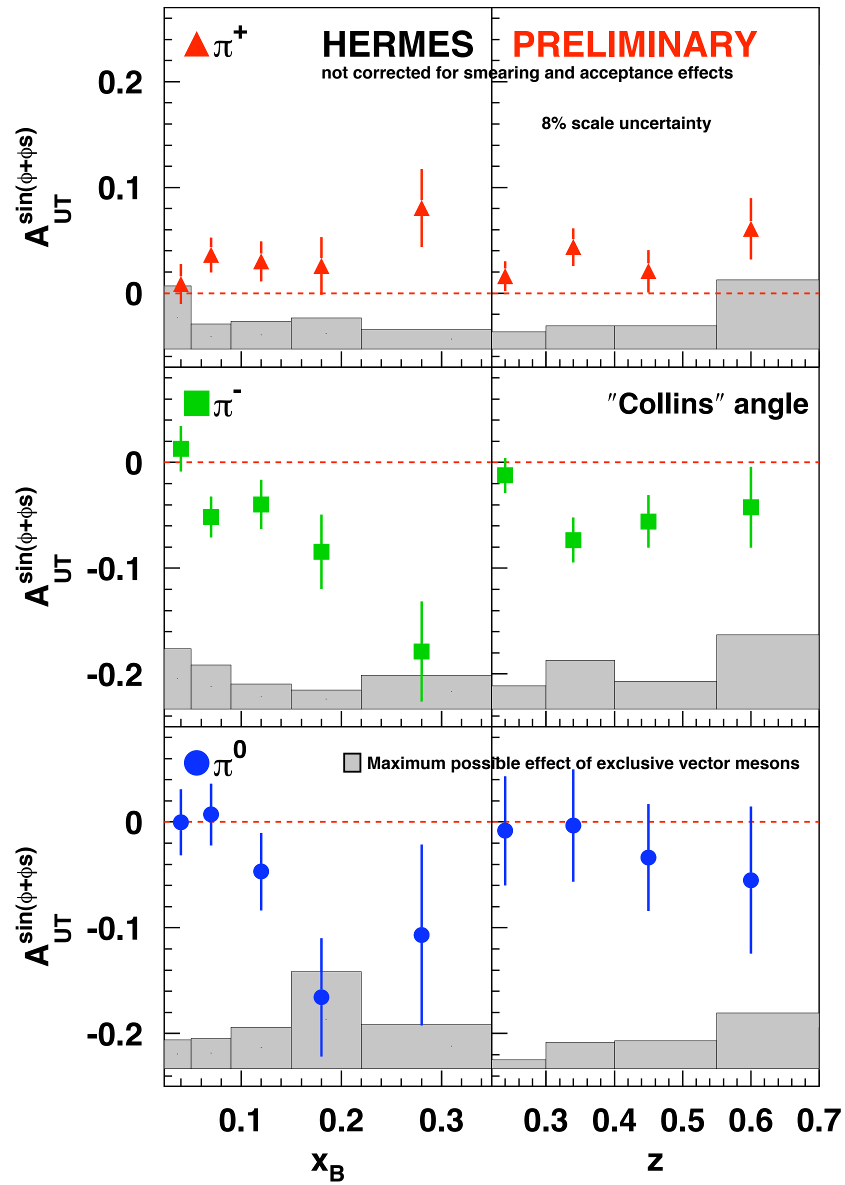
Fit $\sin(\phi_h - \phi_S)$ ***and*** $\sin(\phi_h + \phi_S)$ ***moments simultaneously***

Results I: Unweighted Moments

“Sivers” Moments



“Collins” Moments



Sivers $\langle A^{\pi^+}\rangle$ ***3σ away from zero*** **...** **Collins asym** ***large for π^0 and π^-***

Interpretation of Collins Results

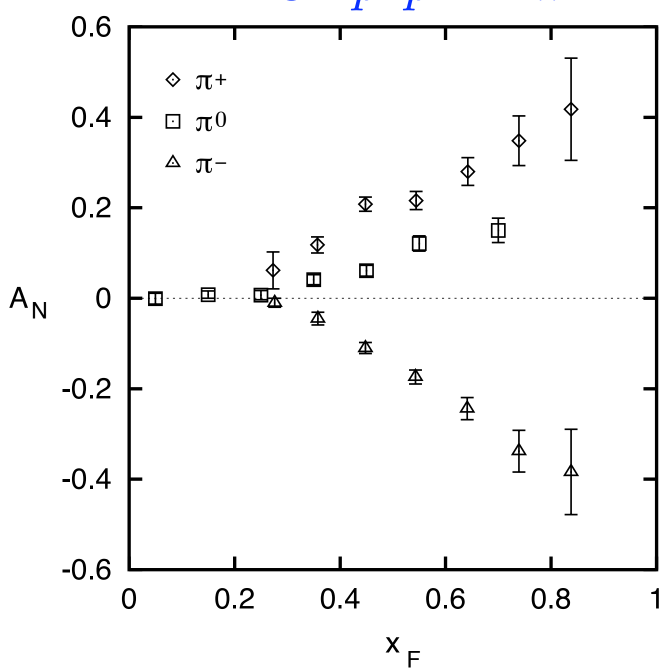
The Collins results for π^+, π^-, π^0 show an unexpected pattern ...

Expect$^{\underline{\text{n}}}$: ***u-quark dominance*** (esp. in DIS)

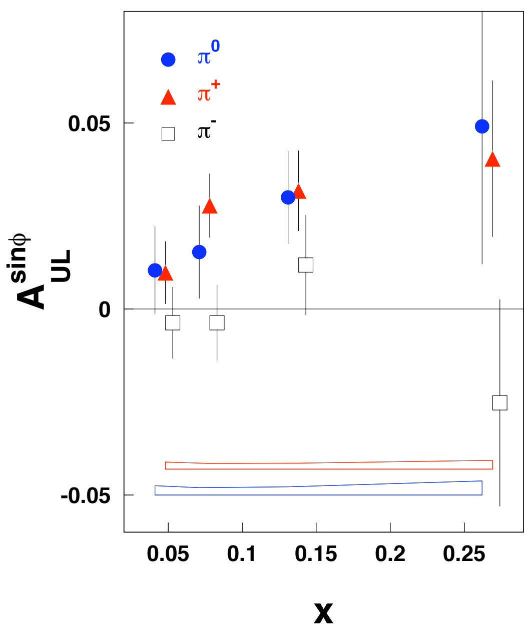
and ***quark polarization*** $\Delta u > 0$, $\Delta d < 0$

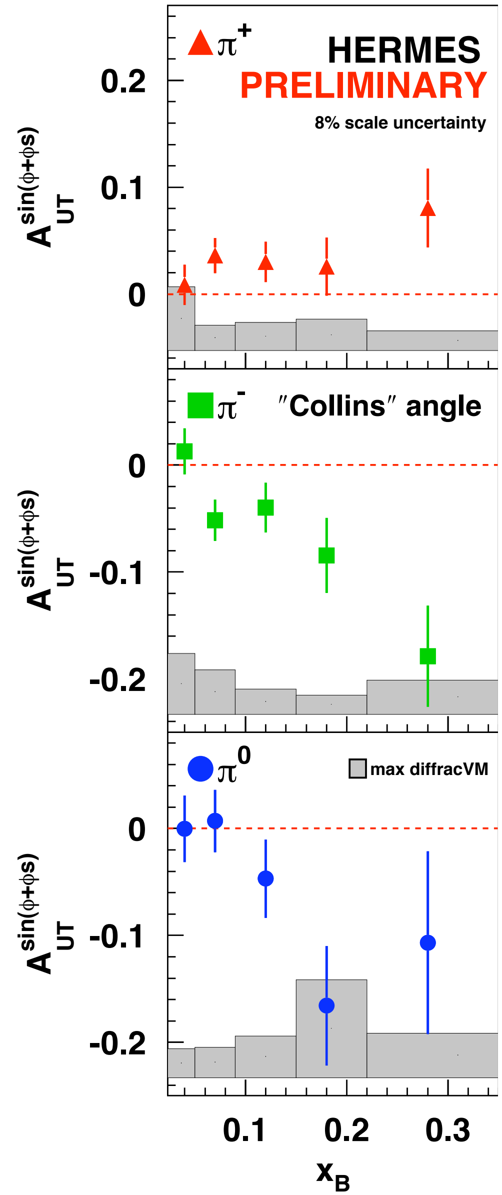
$\Rightarrow A^{\pi^+} \approx A^{\pi^0} > 0$ and $A^{\pi^-} \leq 0$ & smaller

E704 $p^{\uparrow}p \rightarrow \pi X$



A_{UL} **on proton**





New Data for $A_{\mathrm{UT}}^{\mathrm{Collins}}$ show

$A^{\pi^+} > 0$, but $A^{\pi^0} \approx A^{\pi^-} < 0$ and <u>larger</u> ...

Interpretation: Minimal Assumptions

- A_{UT}^{Collins} is ***leading twist***
- Collins FF obeys ***favored / disfav*** symmetry:

$$H_{\text{fav}} \equiv H_{1\perp}^{u\to\,\pi^+} = H_{1\perp}^{d\to\,\pi^-} = H_{1\perp}^{\overline{u}\to\,\pi^-} = H_{1\perp}^{\overline{d}\to\,\pi^+}$$
$$H_{\text{dis}} \equiv H_{1\perp}^{u\to\,\pi^-} = H_{1\perp}^{d\to\,\pi^+} = H_{1\perp}^{\overline{u}\to\,\pi^+} = H_{1\perp}^{\overline{d}\to\,\pi^-}$$

$$\Rightarrow\quad A^{\pi^+} = k\frac{(4\delta u + \delta\overline{d})H_{\text{fav}} + (\delta d + 4\delta\overline{u})H_{\text{dis}}}{(4u + \overline{d})D_{\text{fav}} + (d + 4\overline{u})D_{\text{dis}}}$$

Some definitions

$$r \equiv \frac{d + 4\overline{u}}{u + \overline{d}/4} \qquad \eta \equiv \frac{D_{\text{dis}}}{D_{\text{fav}}}$$

$$\delta r \equiv \frac{\delta d + 4\delta\overline{u}}{\delta u + \delta\overline{d}/4} \qquad \eta_H \equiv \frac{H_{\text{dis}}}{H_{\text{fav}}}$$

Consider Asymmetry Ratios

$$\alpha^- \equiv \frac{A^{\pi^-}}{A^{\pi^+}} = \left(\frac{4\eta_H + \delta r}{4\eta + r}\right)\left(\frac{4 + r\eta}{4 + \delta r\eta_H}\right), \qquad \alpha^0 \equiv \frac{A^{\pi 0}}{A^{\pi^+}} = \frac{(4 + \delta r)(1 + \eta_H)}{(4 + r)(1 + \eta)}\left(\frac{4 + r\eta}{4 + \delta r\eta_H}\right)$$

⇒ Leads to Constraint Equ$^{\underline{n}}$ involving ***only unpolarized*** quantities

$$\alpha^- C = \alpha^0(1 + C) - 1 \qquad \text{where} \qquad C \equiv \frac{4\eta + r}{4 + \eta r}$$

⇒ Solution Space in η_H vs δr can be determined:

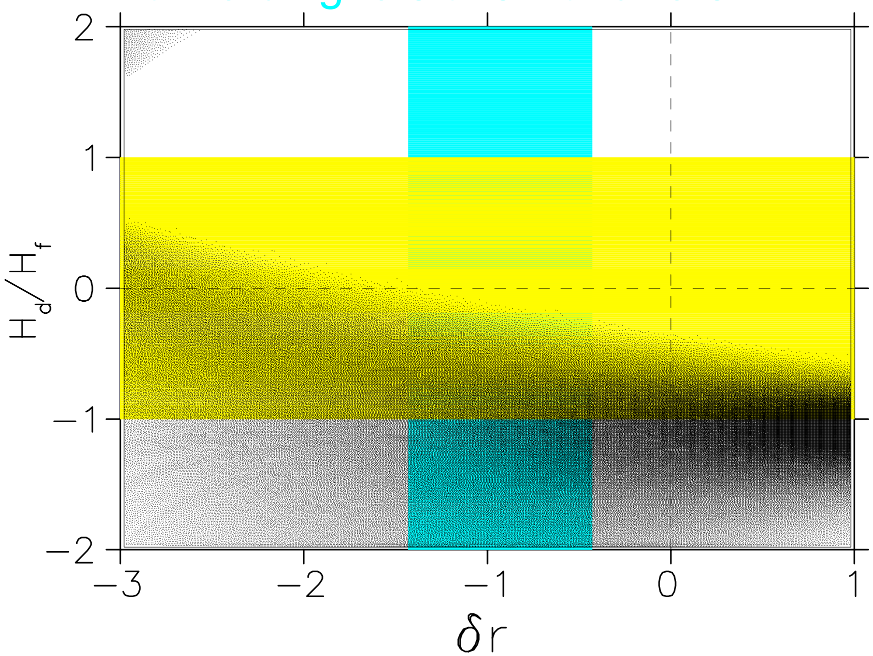
$$\eta_H = \frac{\delta r - 4(\alpha^- C)}{(\alpha^- C)\delta r - 4} \qquad \text{and} \qquad \eta_H = \frac{\delta r - 4(\alpha^0(1 + C) - 1)}{(\alpha^0(1 + C) - 1)\delta r - 4}$$

Interpretation of Collins Results

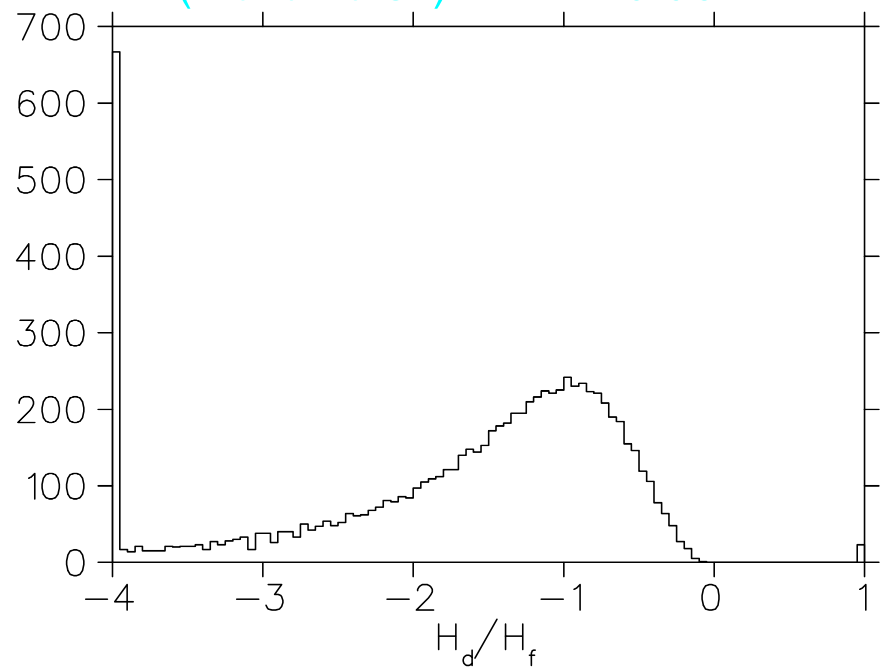
① **Constraint equation:** well satisified by both weighted and unweighted asymmetries (within 1σ statistical) ➡ no problem with internal consistency

② **Solution space** for $\delta r \approx \delta d / \delta u$ vs $\eta_H = H_{\rm dis}/H_{\rm fav}$

solution space populated according to statistical errors



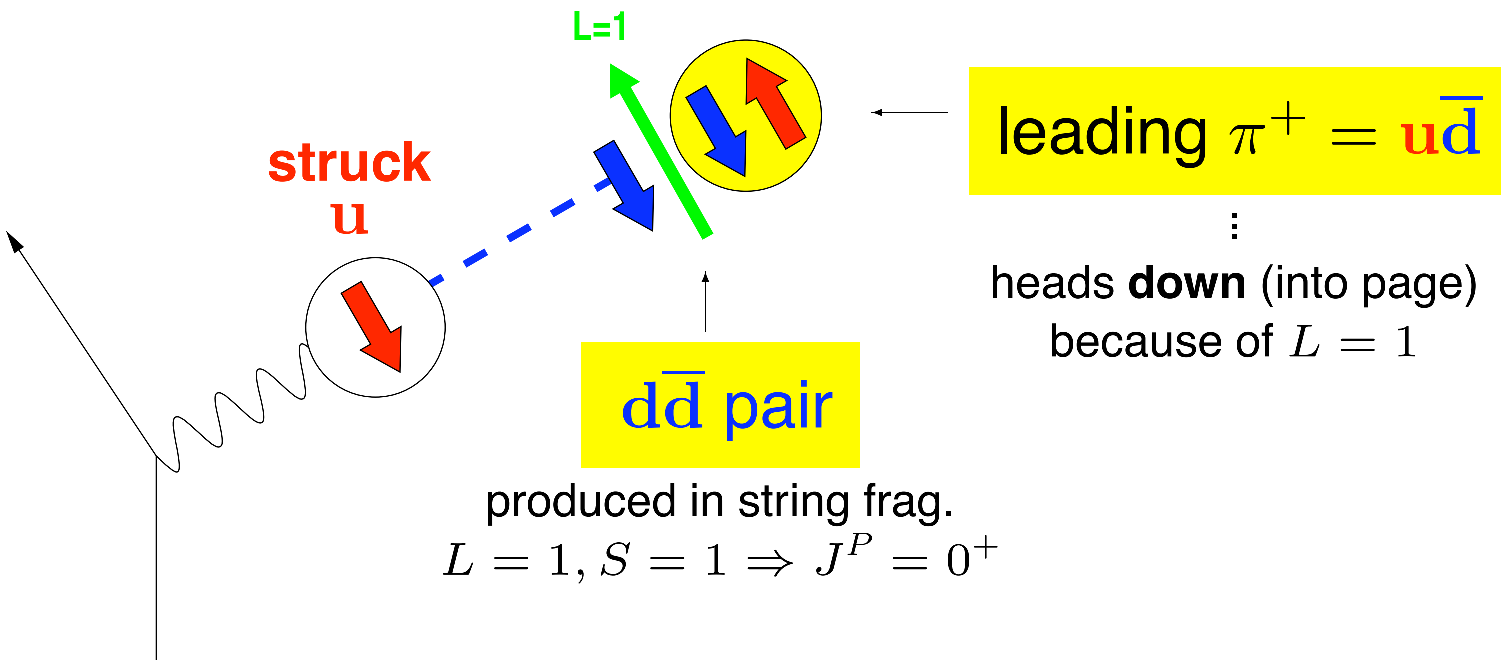
η_H solutions at χQSM value (Wakamatsu) $\delta r = -0.93$



Neglecting possible diffractive contamination , there seems to be a pronounced indication that $H_{\rm fav} \approx -H_{\rm dis}$

Interpretation of Collins Results

Artru model, based on phenomenological ***Lund string-fragmentation model*** and ***$^3P_0$ hypothesis*** for $q\bar{q}$-pair formation



- leading π^+= ***favored*** transition, heads ***into page***
- subleading pcle (prob π^-) = ***disfavored*** transition, heads ***out of page***

Perhaps $H_{\rm dis} \approx -H_{\rm fav}$ is not only reasonable, but likely ?

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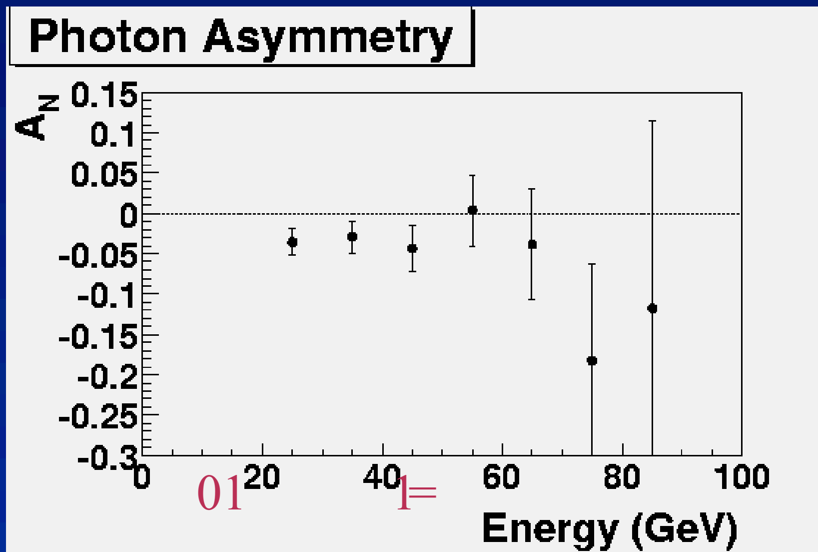
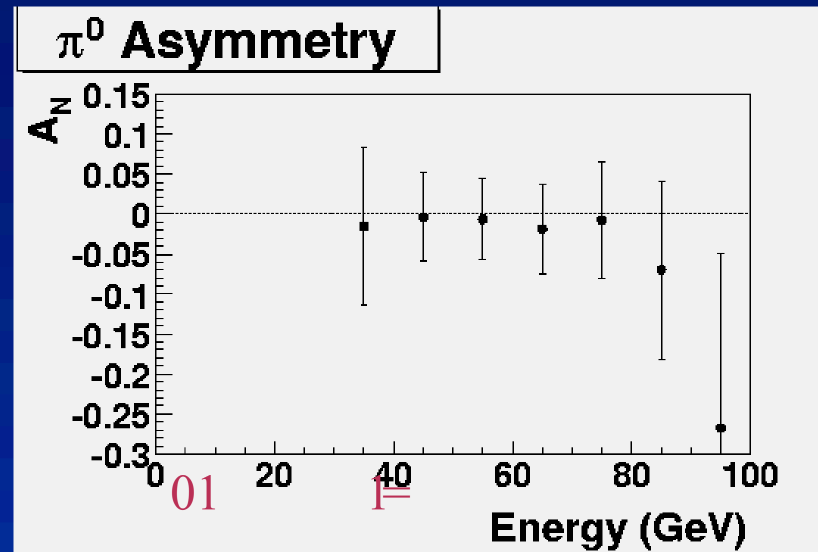
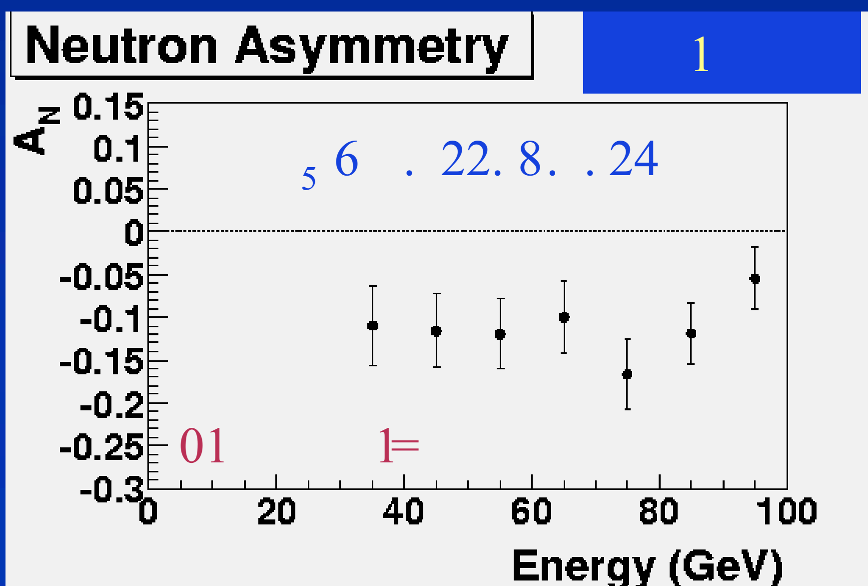


Photon Asymmetry
A_N
Energy (GeV)
01
1=

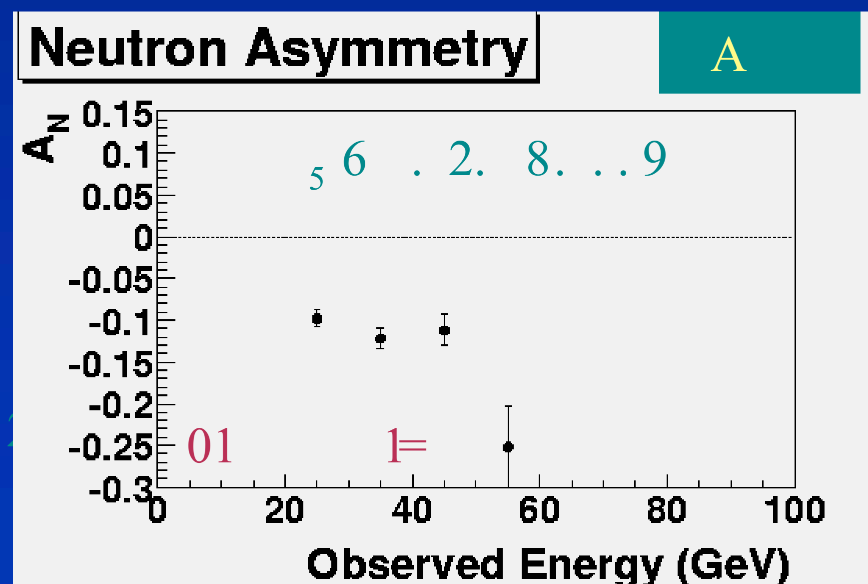


π^0 Asymmetry
A_N
Energy (GeV)
01
1=



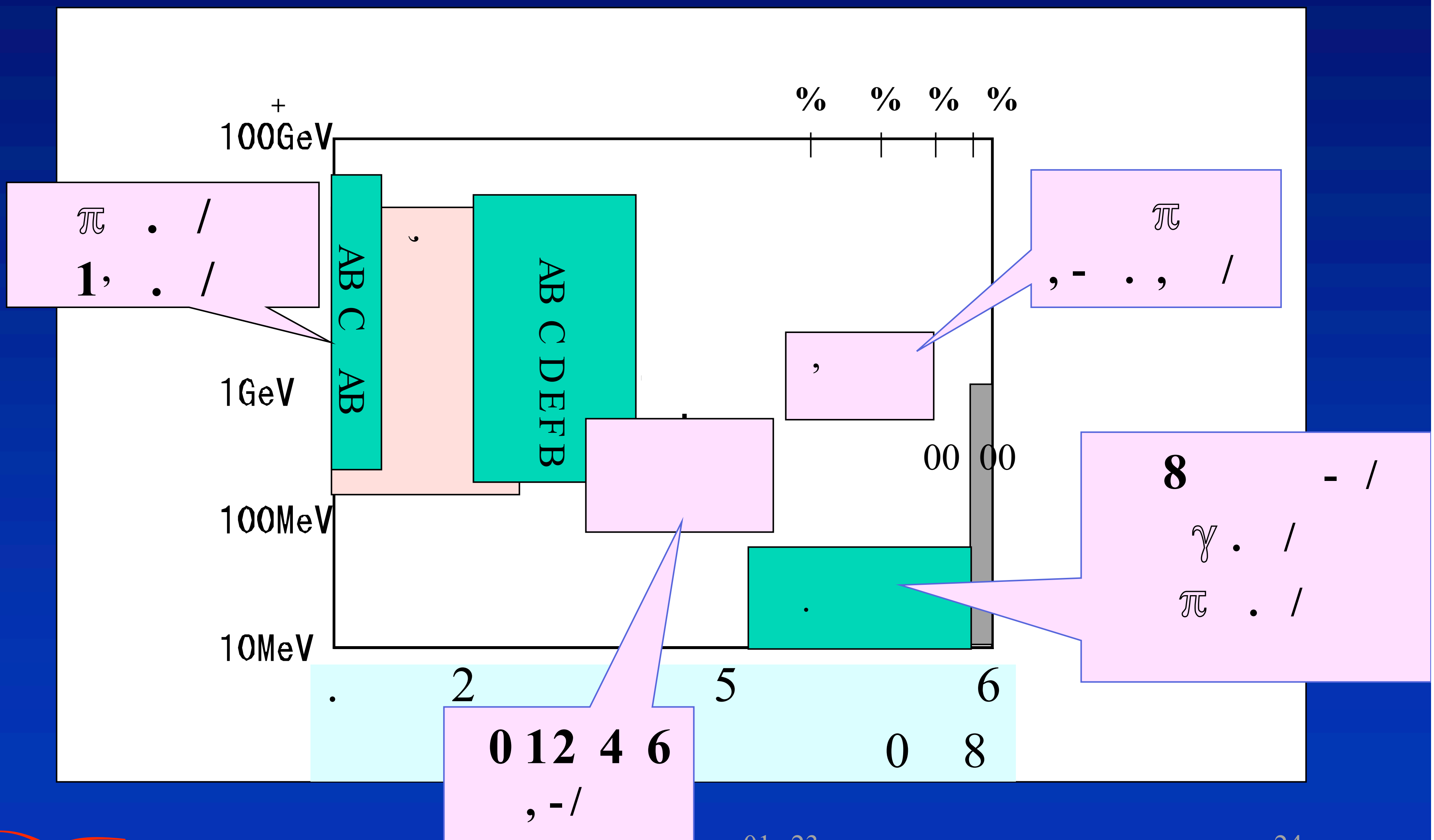
Neutron Asymmetry
1
5 6 . 22. 8. . 24
A_N
Energy (GeV)
01
1=

1=



Neutron Asymmetry
A
5 6 . 2. 8. . . 9
A_N
Observed Energy (GeV)
01
1=

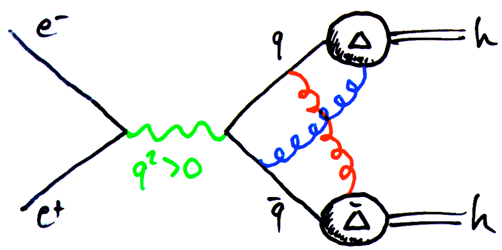
PHENIX


100GeV
1GeV
100MeV
10MeV
AB C AB
AB C DEFB
π
γ
00 00

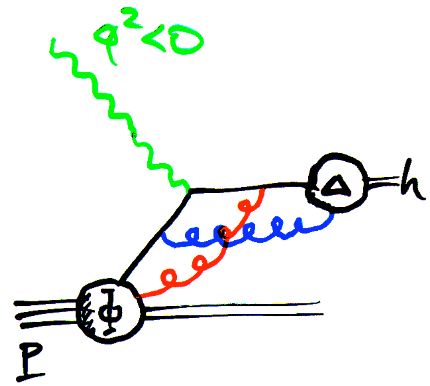
Universality of k_T-dependent Functions

These proceses have similar gauge-link topology:

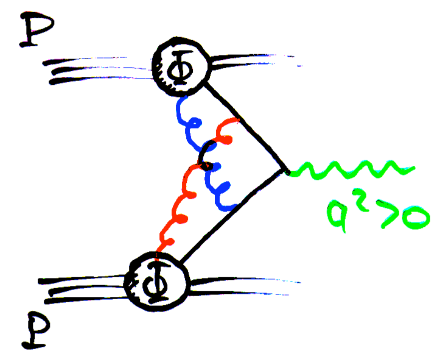
e^+e^- **Annihilation**



SIDIS



Drell-Yan

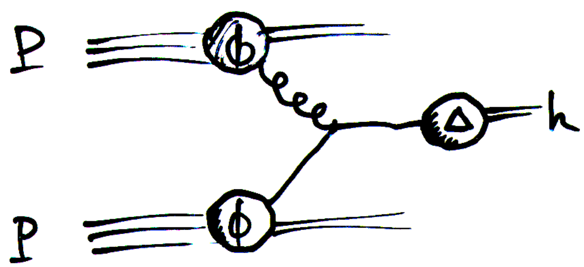


Expectation: T-odd functions will ***change sign*** ***between spacelike*** ***(SIDIS) and*** ***time-like*** ***(e^+e^- and DY) processes***

BELLE e^+e^- Experiment

- Analysis of ***Collins function*** from high-statistics BELLE data in progress!
- Critical for providing ***normalization point*** for SIDIS and pp data $\sim h_1 \, H_1^\perp$

Universality of E704 / RHIC
$p^\uparrow p \rightarrow \pi X$ not yet clear ...



3 "soft blobs" ...
gauge-link topology
more complex

Conclusions: A lot has happened in the past year!

Sea-Quark Polarization

- **Inclusive DIS data** favour Δq_s of about **-6% per flavor**
  ... but can't separate by flavor
- Final HERMES **SIDIS data** place **new constraints** on $\Delta\overline{u}$, $\Delta\overline{d}$, Δs

Gluon Polarization

- First A_{LL} data from **PHENIX**: Unexpectedly, asymmetry favors **negative sign**, origin not yet understood

Surprise!

Transverse Effects & Single-Spin Asymmetries

- First A_{UT} data from **HERMES**: **Sivers** effect **non-zero**
  ... but **Collins** function shows **unexpected behavior**

Surprise!

- **STAR** $A_N^{\pi^0}$ confirms "E704 effect" at forward rapidity
- Mid-rapidity A_N^h at **PHENIX** is zero, not surpising, ...
  but **unexpected** $A_N^n \approx -10\%$ seen at 0°

Surprise!

And this is only the beginning ! ☺