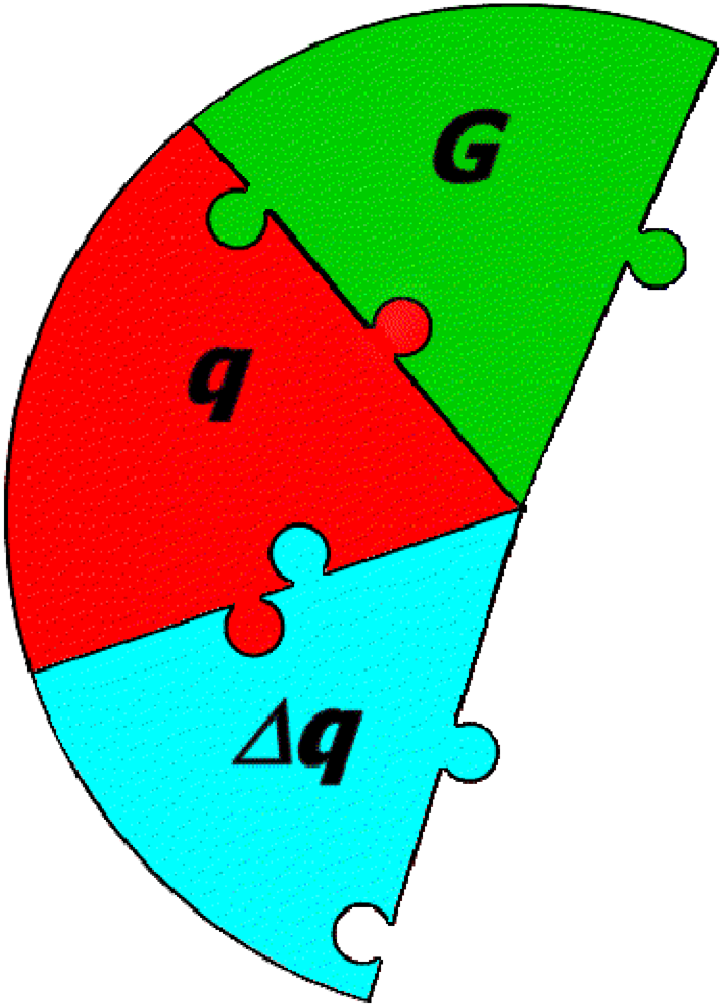
Summary of Spin Physics @ DIS 2005

Pasquale Di Nezza

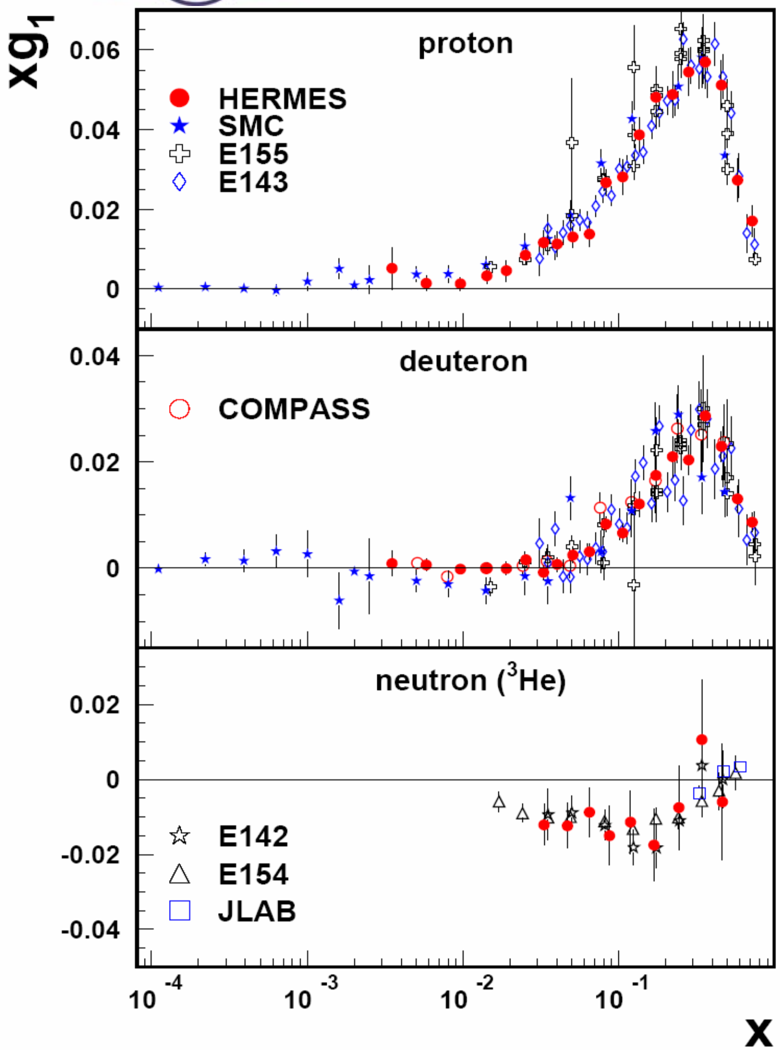
INFN Frascati

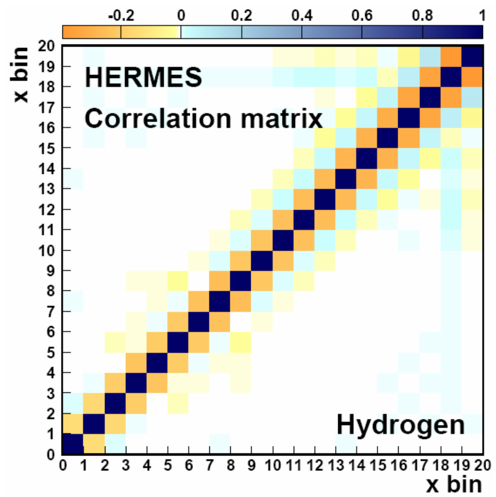
DESY, Hamburg 10/05/05

(Spin)-Structure of the Nucleon



Polarized Structure Functions: g_1





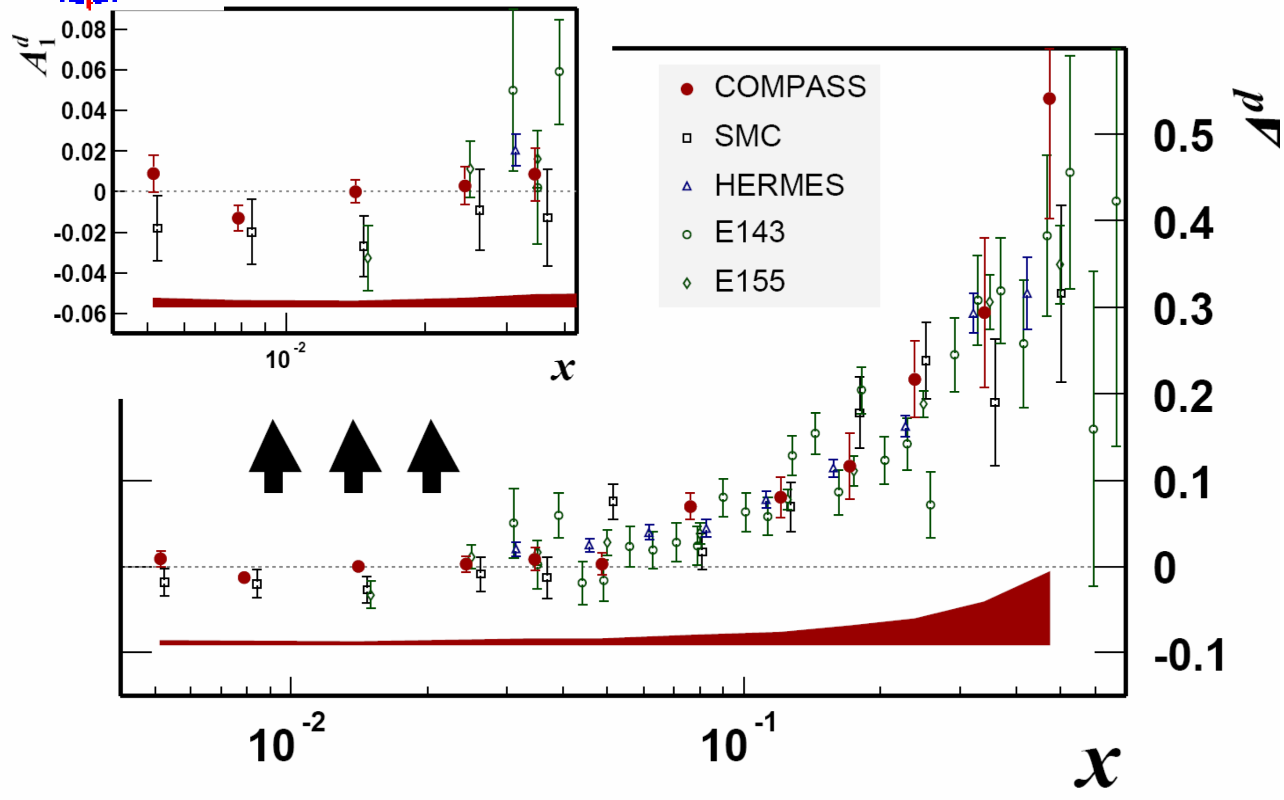
New treatment of smearing. Correlation matrix:

- removes systematical correlations
- introduces statistical correlations

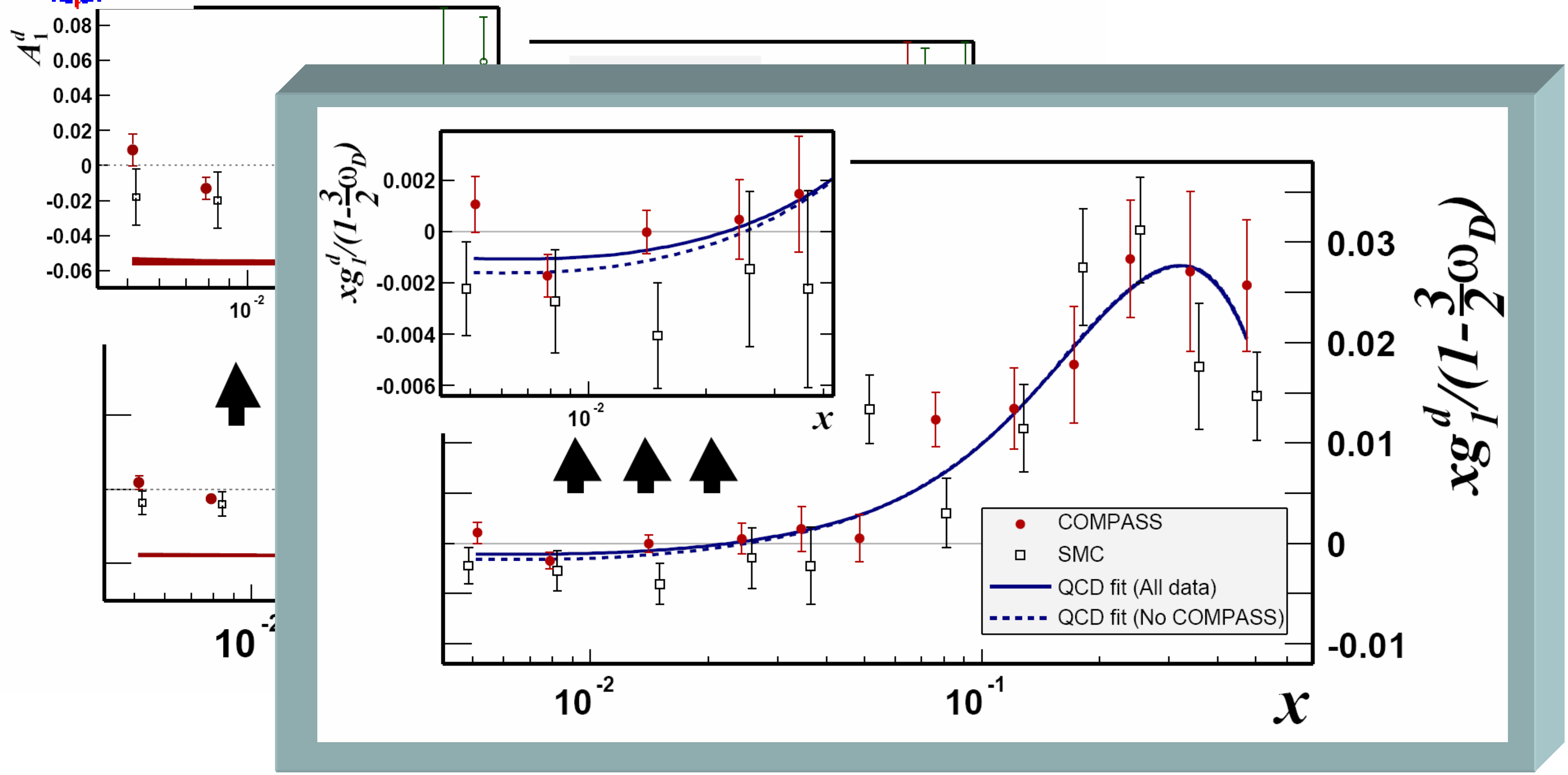
First Moments Calculation

Exp.	$Q^2(GeV^2)$	x range	Target	Moment	HERMES Moment
SMC	5	0.03-0.7	p	0.128 ± 0.006	**0.1141 ± 0.0026**
E143	5	0.03-0.8	p	0.117 ± 0.003	**0.1174 ± 0.0027**
SMC	5	0.03-0.7	d	0.043 ± 0.007	**0.0416 ± 0.0013**
E143	5	0.03-0.8	d	0.043 ± 0.003	**0.0433 ± 0.0013**

Polarized Structure Functions: g_1



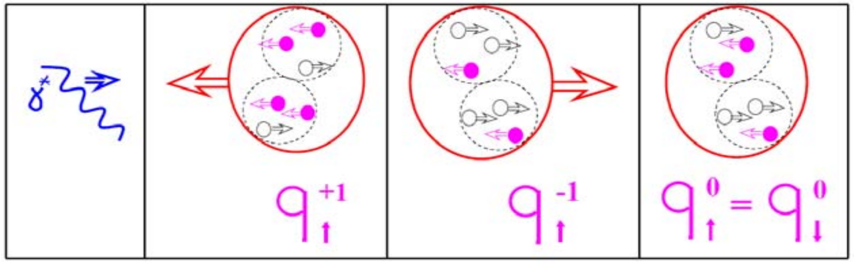
Polarized Structure Functions: g_1

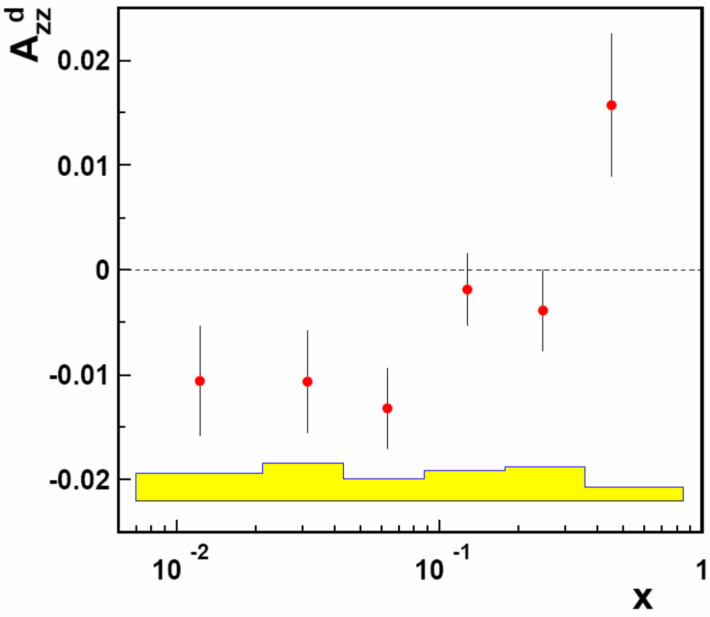


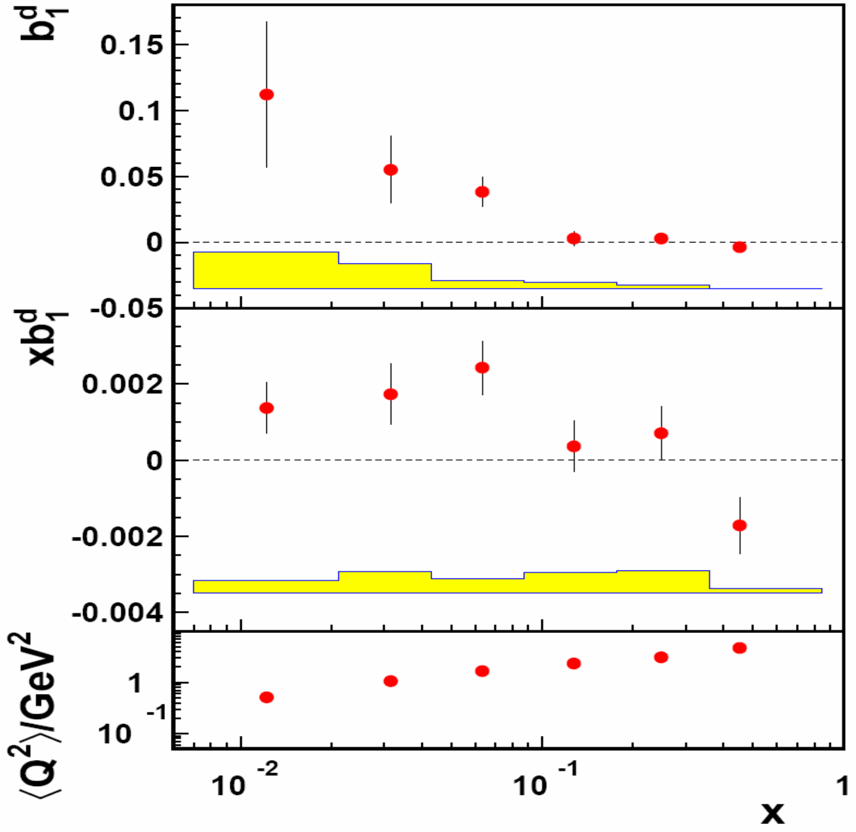
Extended x-range with higher accuracy.

COMPASS systematically > SMC at low-x.

Tensor Structure Function b_1^d





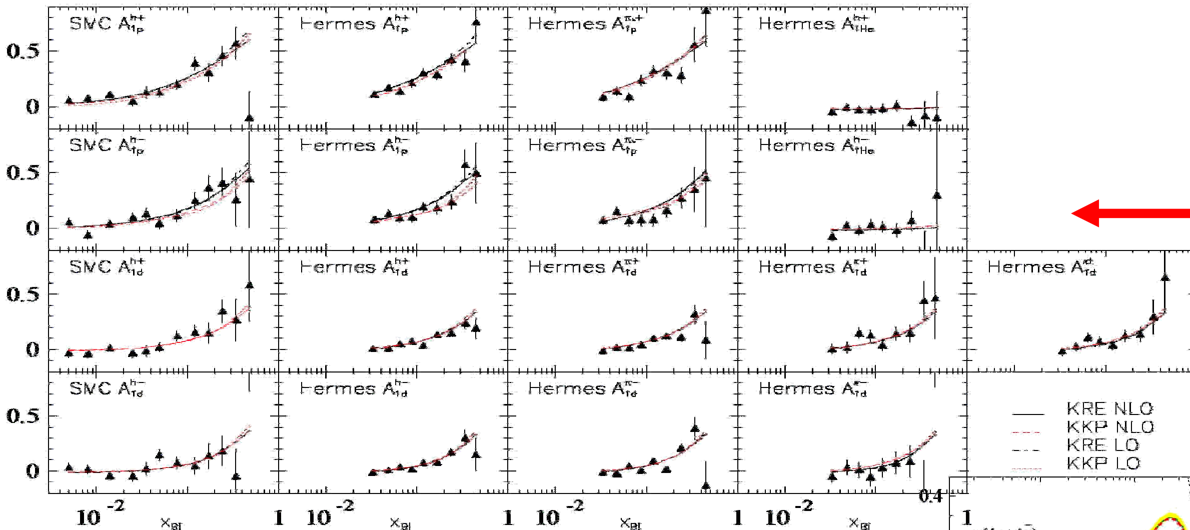


First measurement of b_1^d: different from 0 at small x

$A_{zz} \sim \mathcal{O}(1\%) \rightarrow$ small impact on g_1

(Semi)-Inclusive (Th.)

Sassot



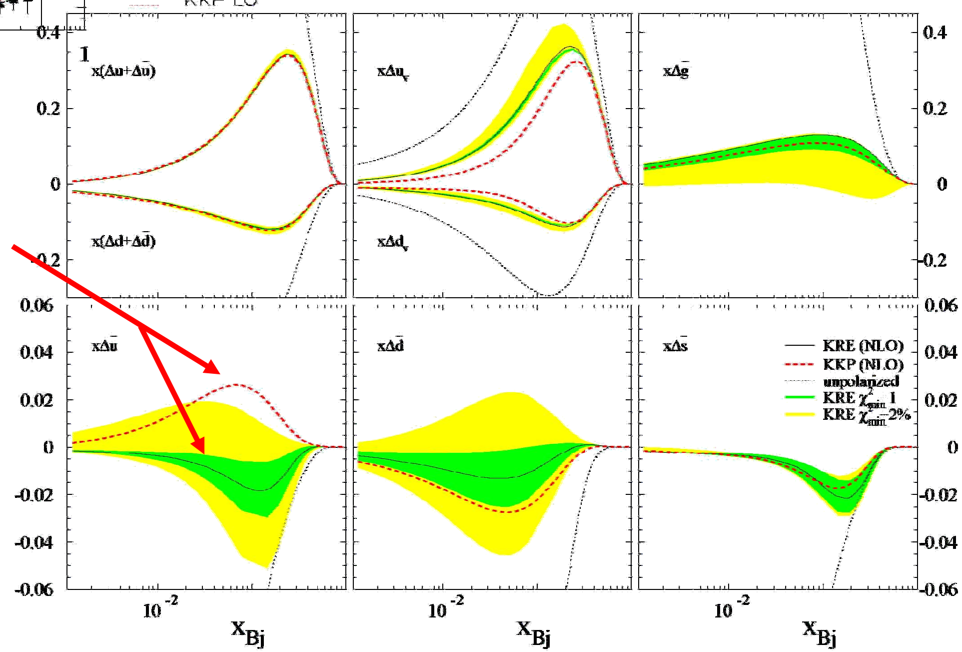
DIS&SIDIS data nicely described

sea depends on choice of FFs

(dashed vs. solid lines)

best fit favors SU(3) sea

(solid lines)



Inclusive (Th.)

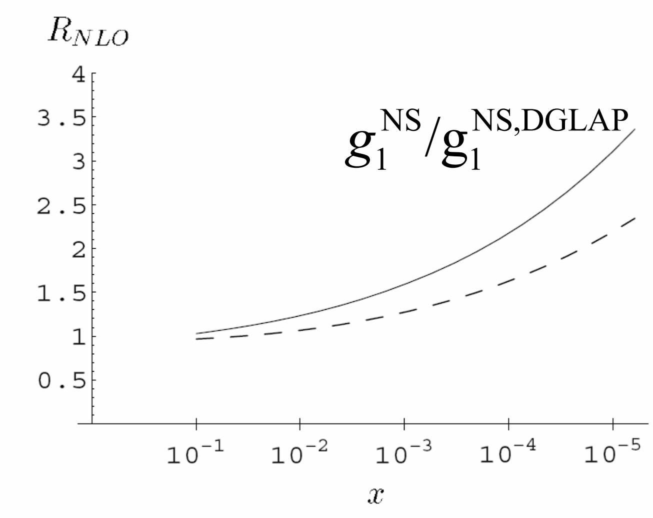
- theoretical issues – small x: Ermolaev hep-ph/0503019

small x behavior of g1 should be more than just DGLAP

DGLAP: $g_1 \approx \exp(\sqrt{C \ln(1/x) \ln\ln Q^2})$

resum (IREE) $[\alpha_s \ln^2(1/x)]^k$

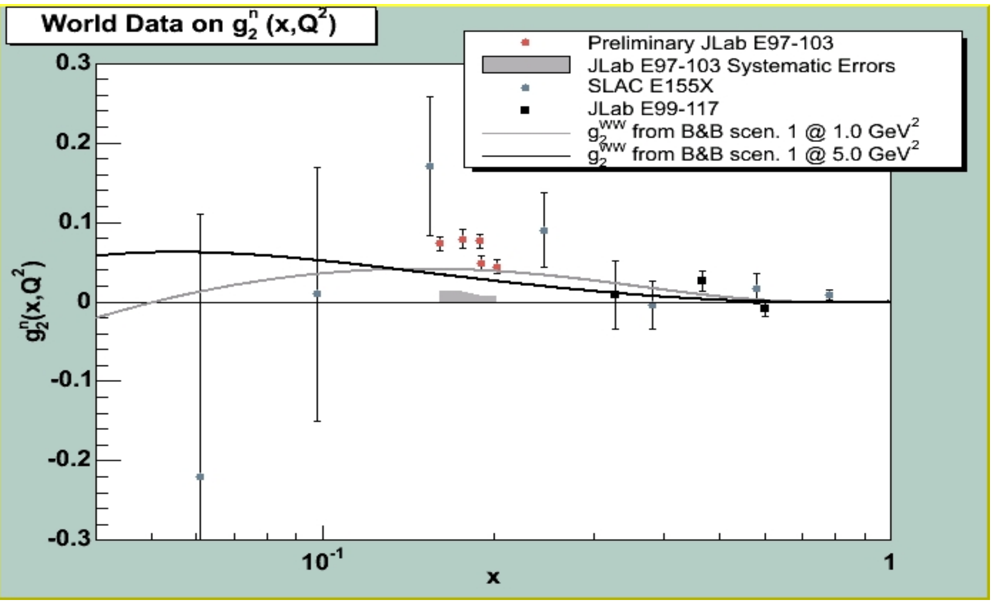
DLA → $g_1 \approx (1/x)^{\Delta}$ $\Delta_{NS} \approx 0.43,\ \Delta_S \approx 0.86$

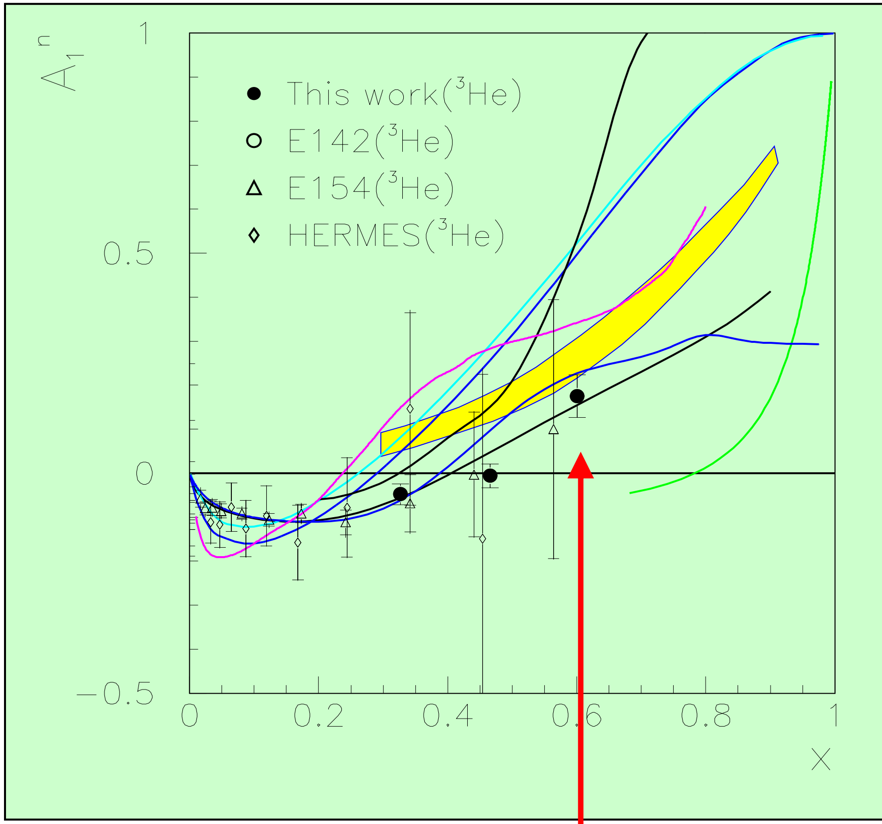


to describe entire x-range:
merge small-x resummation w/ DGLAP

small x behavior can be scrutinized at a future pol. ep-collider like eRHIC

Spin Structure at high x





Precision measurements at high x for:

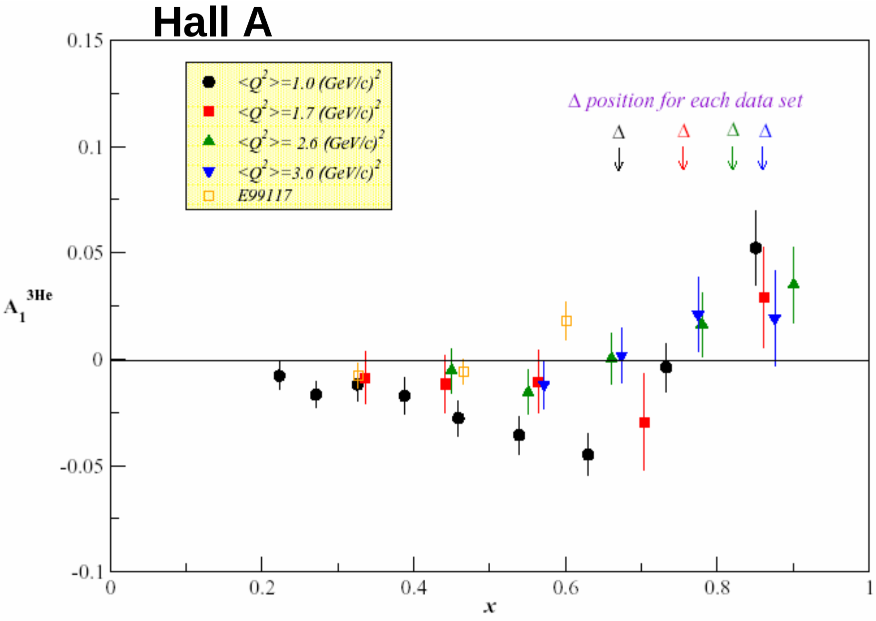
A_1^n, $\Delta u/u$, $\Delta d/d$, A_2^n, g_1^n, g_2^n, A_1^p, A_1^d, g_2^n, …

> 0

Sometimes statistical errors improved of 1 order of magnitude

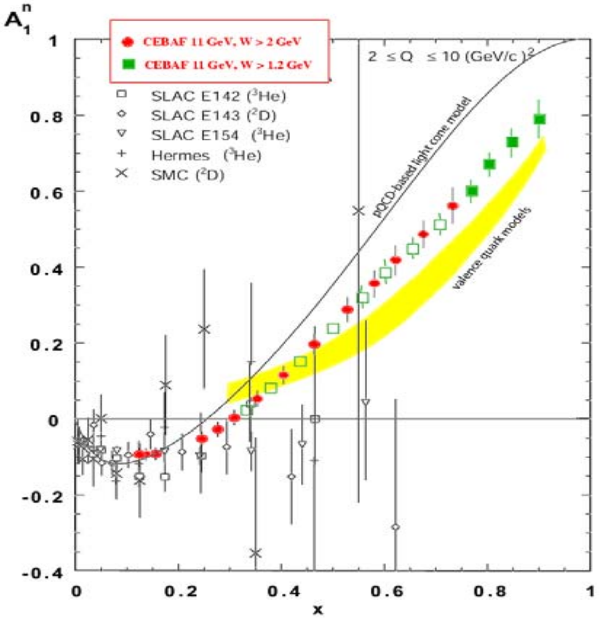
Duality in Spin Structure

- Precision data for $1<Q^2<4$ GeV^2
- Direct extraction of g1 and g2 (and A1/A2)
- Test of spin-flavor dependence of duality



Data have same behavior up to x~0.55

Duality starts for Q^2~2 GeV^2



(Semi)-Inclusive (Th.)

- calc. from 1st principles or models: Schierholz, Signal
  lattice / meson cloud

lattice simulations based on OPE → provide moments

$$a_n^q(\mu) = \int_0^1 dx\, x^n \Delta q(x,\mu^2) \quad = \Delta^n q \qquad a_0^q = \Delta q, \qquad \boxed{g_A = \Delta u - \Delta d}$$

$$2\int_0^1 dx\, x^n g_1(x,Q^2) = e_{1,n}(Q^2/\mu^2, g(\mu^2))\, a_n(\mu)$$

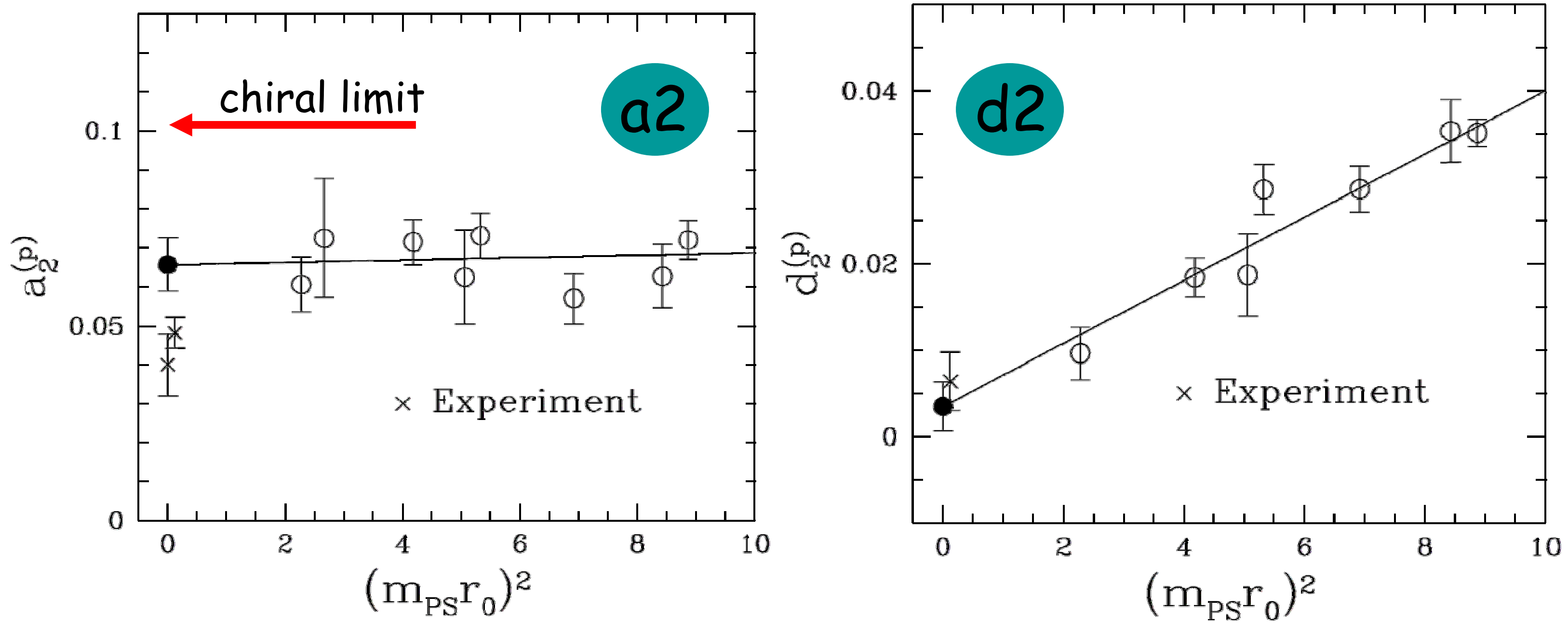
$$2\int_0^1 dx\, x^n g_2(x,Q^2) = \frac{n}{n+1}\left[e_{2,n}(Q^2/\mu^2, g(\mu^2))\, d_n(\mu) - e_{1,n}(Q^2/\mu^2, g(\mu^2))\, a_n(\mu)\right]$$

twist-3
parton-parton correlation

(Semi)-Inclusive (Th.)

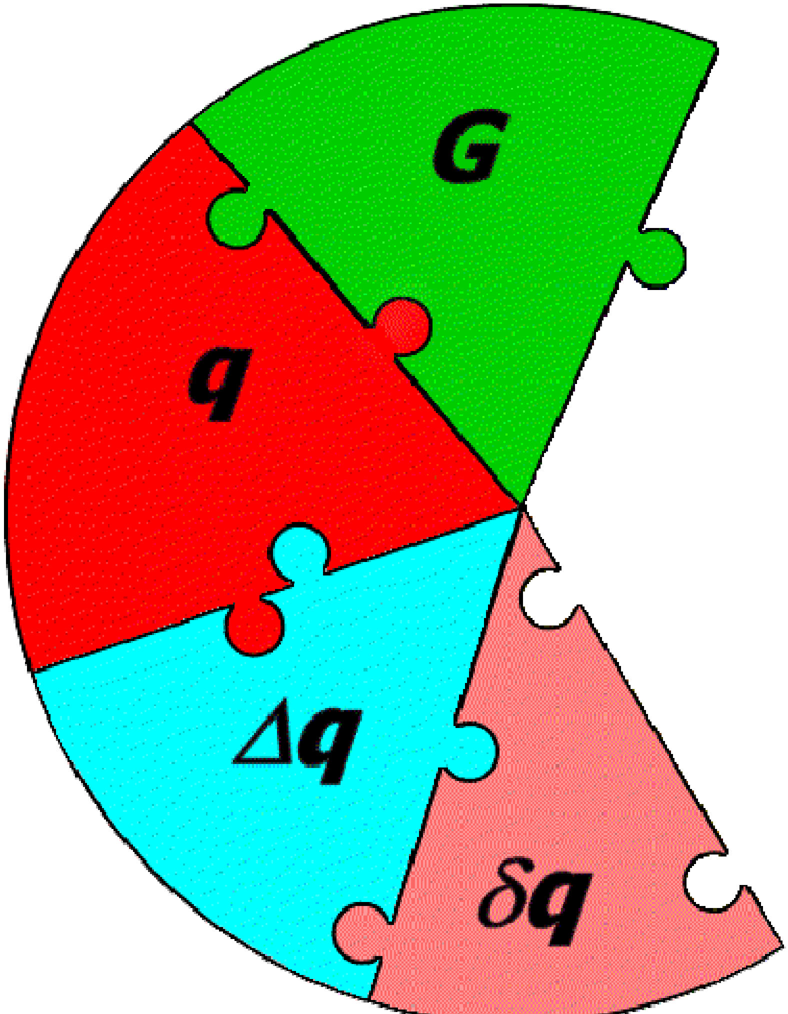
Schierholz

e.g., 2nd moment (dyn. Wilson fermions, 2 flavors)



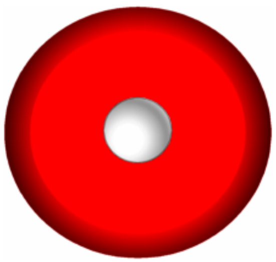
suggests that twist-3 might be small

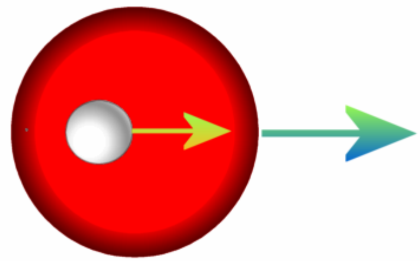
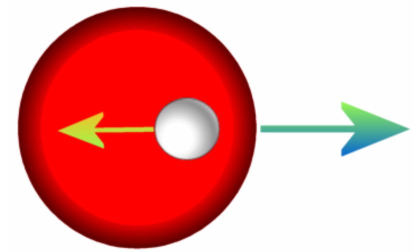
(Spin)-Structure of the Nucleon



Operator decomposition of the Correlation Function at Tw-2

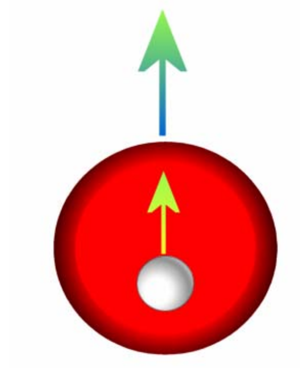
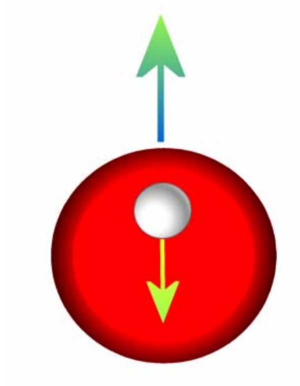
$$\Phi^{Tw\,2}_{Corr}(x) = \frac{1}{2}\{f_1(x) + S_L g_1(x)\gamma_5 + h_1(x)\gamma_5 \gamma S_T\}\gamma^-$$

$f_1 =$ 

$g_{1L} =$  $-$ 

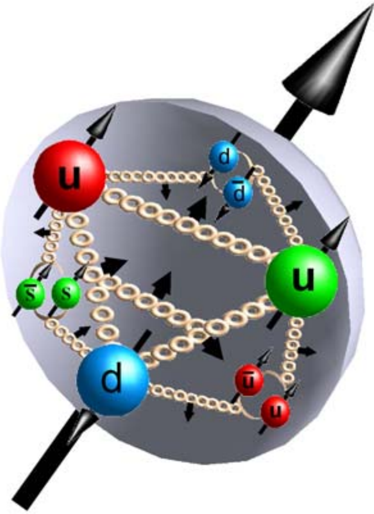
Operator decomposition of the Correlation Function at Tw-2

$$\Phi^{Tw\,2}_{Corr}(x) = \frac{1}{2}\left\{ f_1(x) + S_L g_1(x)\gamma_5 + h_1(x)\gamma_5\gamma S_T \right\}\gamma^-$$

$h_1 =$  $-$ 

… *transversity*, last unknown twist-2 density

DIS + SIDIS cross section



$$d\sigma = d\sigma_{UU} + \cos 2\phi\, d\sigma_{UU} + \frac{1}{Q}\cos\phi\, d\sigma_{UU} + \lambda \frac{1}{Q}\sin\phi\, d\sigma_{LU}$$

$$+ S_L\left[\sin 2\phi\, d\sigma_{UL} + \frac{1}{Q}\sin\phi\, d\sigma_{UL}\right] + \lambda S_L\left[d\sigma_{LL} + \frac{1}{Q}\cos\phi\, d\sigma_{LL}\right]$$

$$+ S_T\left[\underbrace{\sin(\phi+\phi_S)\, d\sigma_{UT}} + \underbrace{\sin(\phi-\phi_S)\, d\sigma_{UT}} + \sin(3\phi-\phi_S)\, d\sigma_{UT} + \frac{1}{Q}\sin(2\phi-\phi_S)\, d\sigma_{UT}\right]$$

$h_1 \otimes H_1^{\perp}$ $\ldots s(\phi - \phi_S \ldots$ $f_{1T}^{\perp} \otimes D_1$ $\ldots (2\phi - \phi_S)\, d\sigma_{LT} + \sin(3\phi - \phi_S)\, d\sigma_{LT}\Big] + \ldots\ldots$

(Collins) (Sivers)

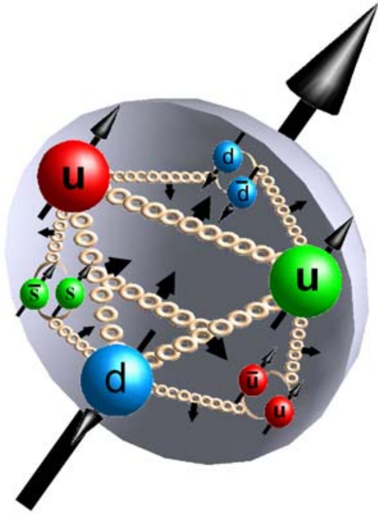
Chiral-odd Distribution Function

Relativistic nature of quark.
In absence of relativistic effects $h_1(x)=g_1(x)$

Q^2 -evolution. Unlike for $g_1^p(x)$,
the gluon doesn't mix with quark in $h_1^p(x)$

High sensitivity to the valence quark polarization
q and $\bar{q}$ have opposite sign.

Tensor charge: first moment of h_1.
Calculable by lattice QCD.



$\ldots \sin\phi\, d\sigma_{LU}$

$\ldots_{L} + \frac{1}{Q}\cos\phi\, d\sigma_{LL} \Big]$

$+ S_T \Big[\underbrace{\sin(\phi+\phi_S)\, d\sigma_{UT}}_{} + \underbrace{\sin(\phi-\phi_S)\, d\sigma_{UT}}_{} + \sin \ldots$

$h_1 \otimes H_1^{\perp}$

(Collins)

$f_{1T}^{\perp} \otimes D_1$

(Sivers)

$\ldots s(\phi - \phi_S \ldots$

Peculiarity of $f_{1t}^{\perp}$

- Chiral-even naïve T-odd DF
- Related to parton orbital momentum
- Violates naïve universality of PDF

- Different sign of $f_{1t}^{\perp}$ in DY

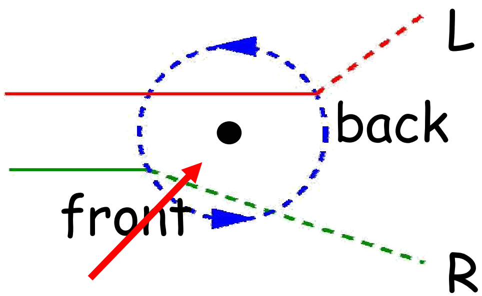
Transversity

Sivers

- remarks on T-oddness, SSA, factorization:

• T-oddness must not be confused
with true time reversal invariance
better call it "artificial/naive" time reversal
(all SSA are odd under parity x naive time reversal)

• simple model:
scattering off a rotating object



initial/final-state int. essential for SSA

• simple model to understand SSA (breakdown of orbital symmetry)
• possible way to understand factorization for SSA

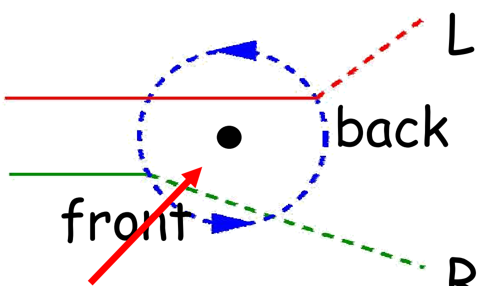
Transversity

Sivers

- remarks on T-oddness, SSA, factorization:

- T-oddness must not be
  with true time reversa
  better call it "artificial
  (all SSA are odd under

- simple model:
  scattering off a r



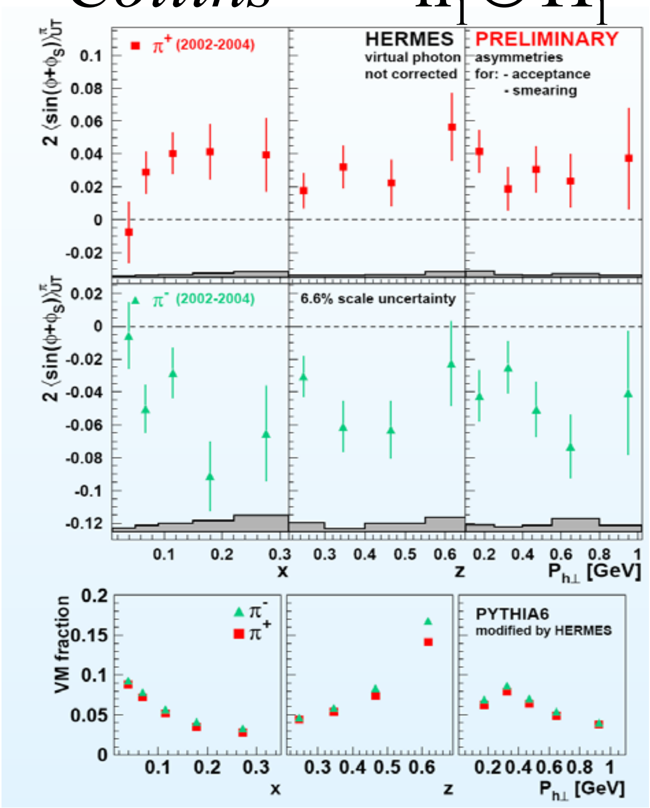
initial/final-state int. essential for S

- simple model to underst
- possible way to understand factorization for SSA

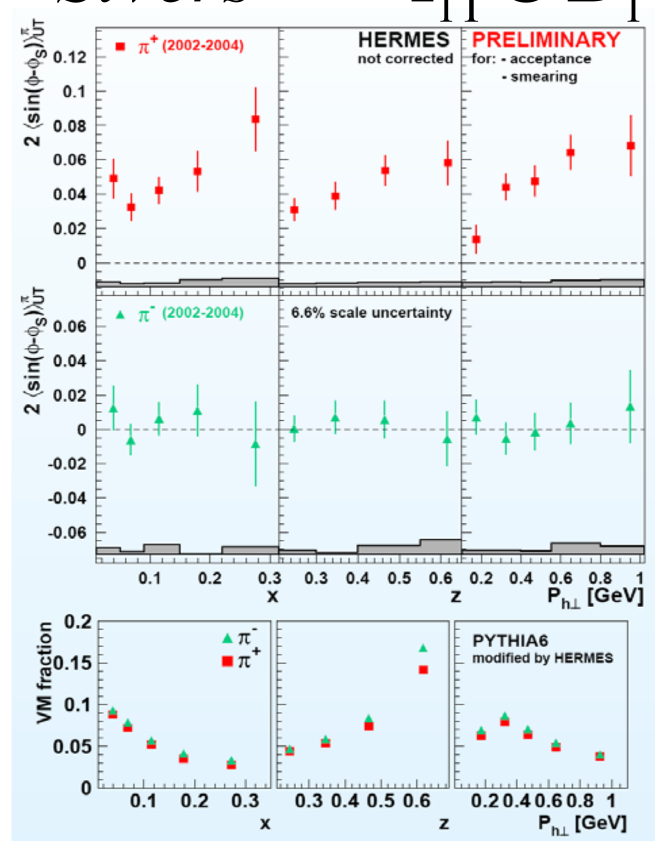
On line experiment by a theoretician...

Transversity

Collins $h_1 \otimes H_1^{\perp}$



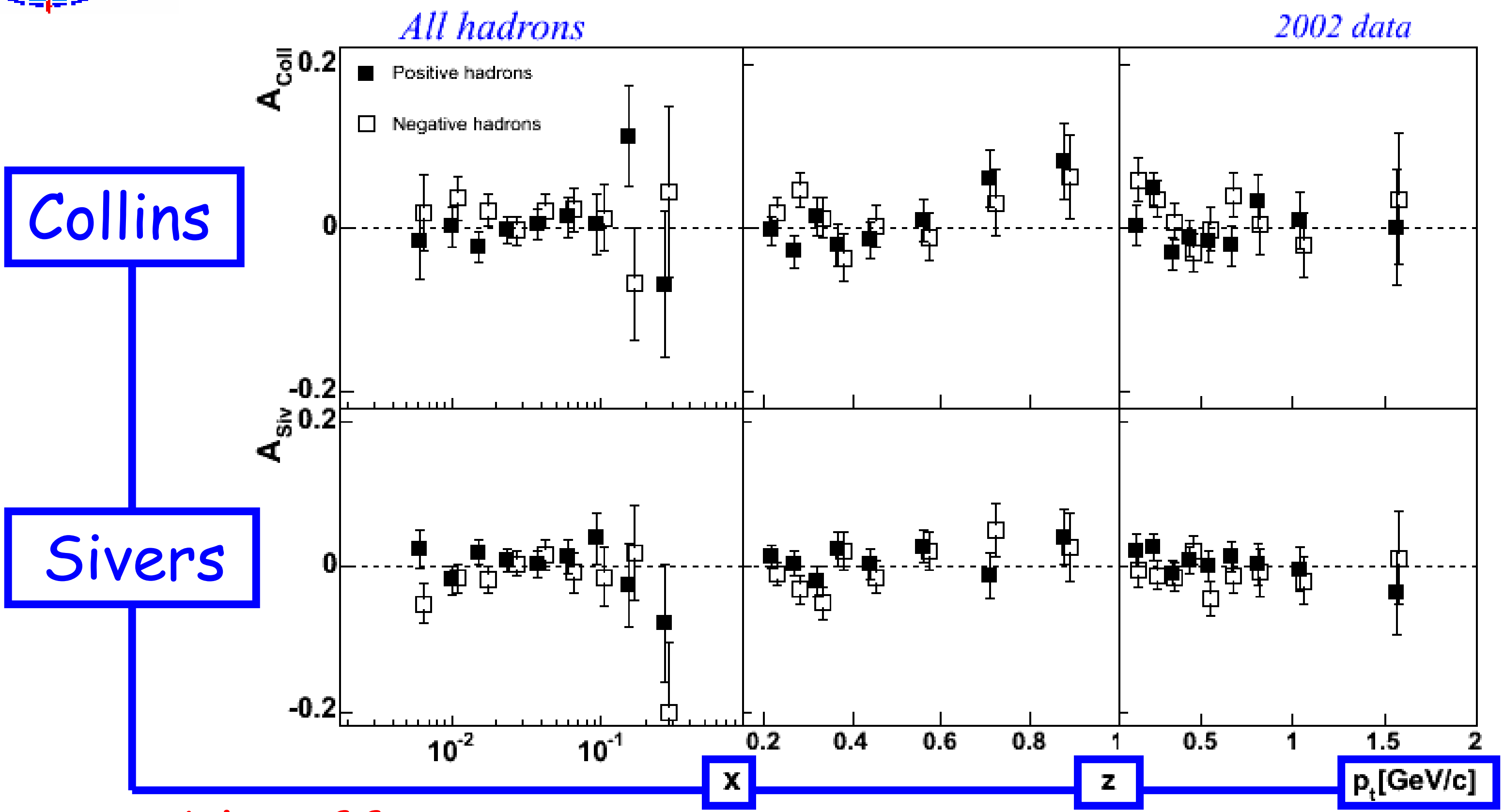
Sivers $f_{1T}^{\perp} \otimes D_1$



Statistical sample (not final) largely improved. Clear evidence for both Collins and Sivers asymmetry

→ Non vanish L_q

Transversity



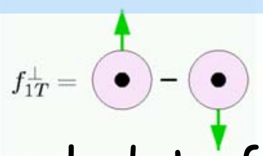
No sizeable effect.

Possible cancellations in isoscalar target (^{6}LiD)

⟹ Expected 3*statistic, 2006 runs on p target (NH_3)

Transversity (Th.)

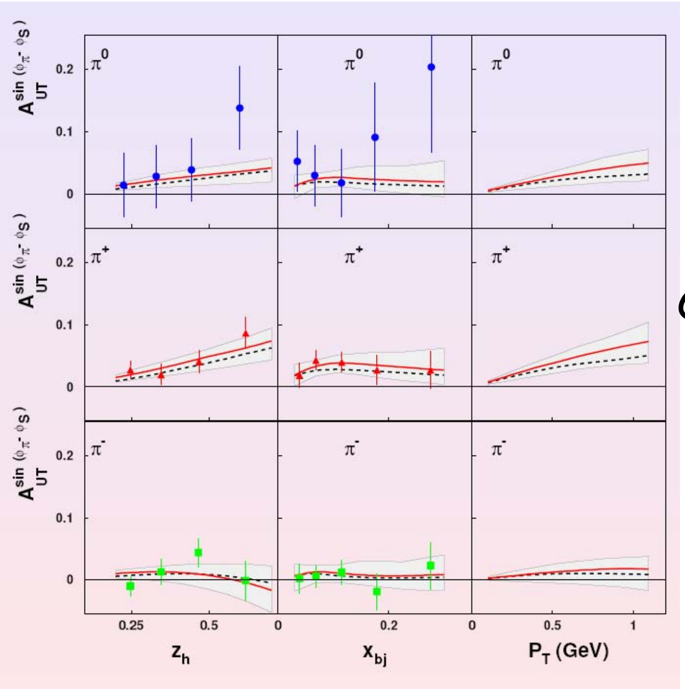
- extraction of "Sivers function":



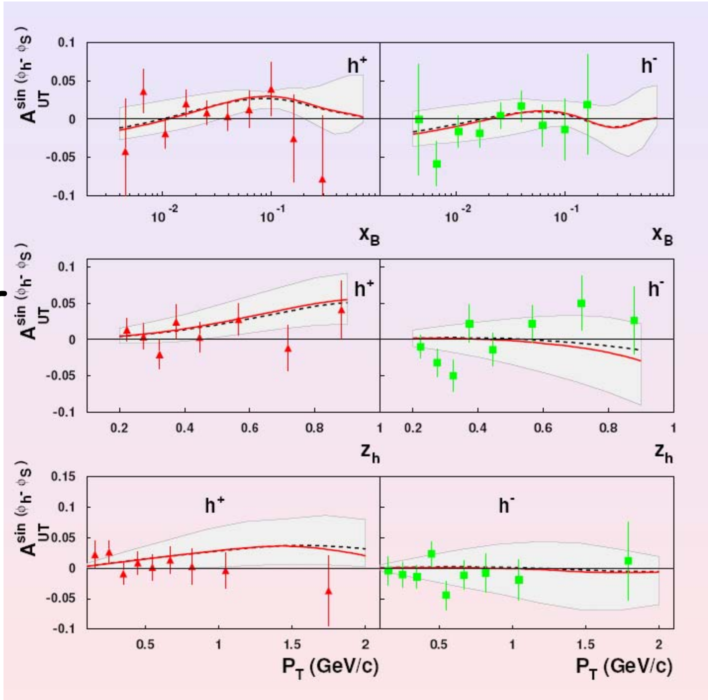
Prokudin
hep-ph/0501196

strategy: (1) fix intr. trans. mom. from unpol. data first
(2) estimate Sivers fct. from HERMES data
(3) check COMPASS data

HERMES



consistent



COMPASS

Transversity

In transverse polarised target

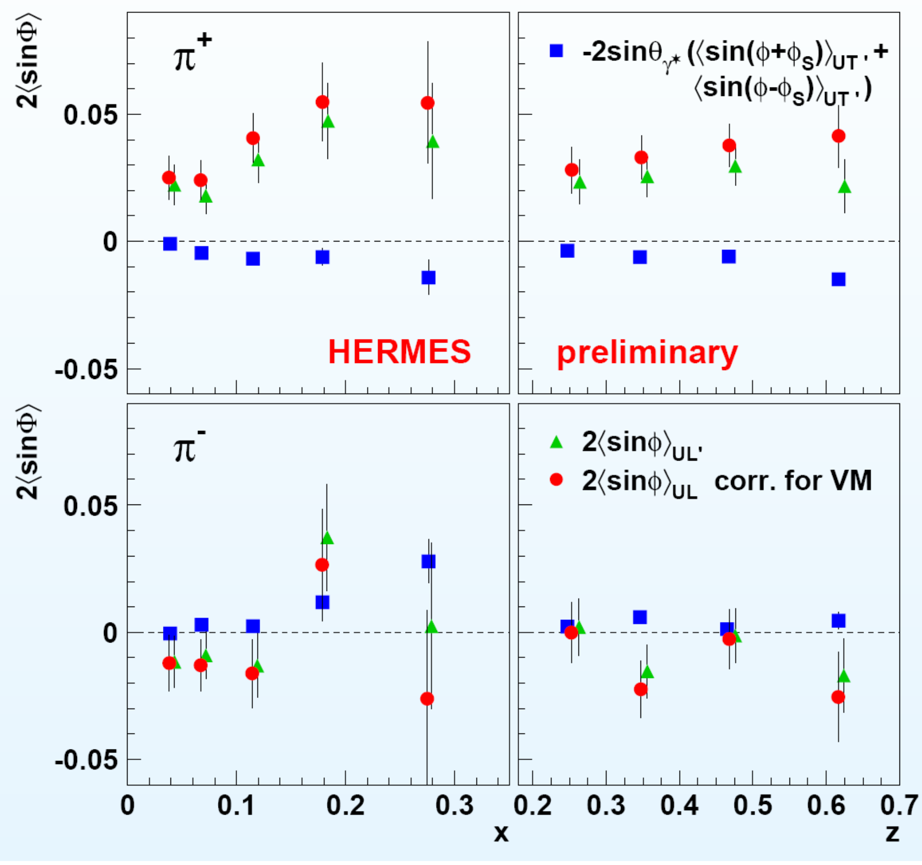
• Theory: polarization w.r.t. γ^*

• Exp: polarization w.r.t. lepton beam

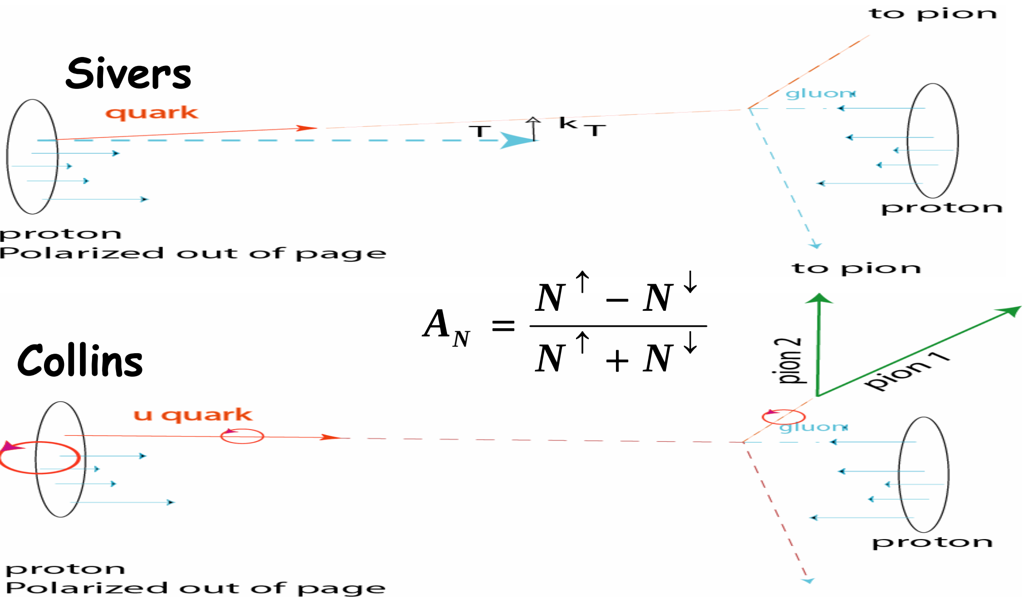
Conversion with subleading-twist term:

$$A^{\sin(\Phi\pm\Phi_S)}_{UT,q} \approx A^{\sin(\Phi\pm\Phi_S)}_{UT,l} - \frac{1}{2}\sin\theta_{\gamma^*} A^{\sin\Phi}_{UL,l}$$

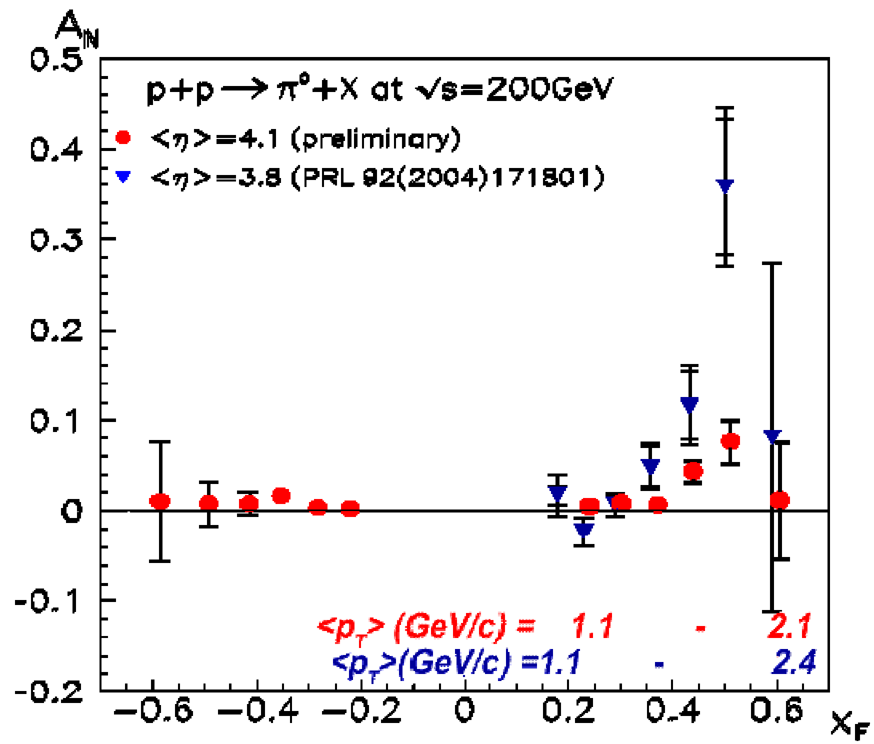
- $A^{\sin\Phi}_{UL,q}$ is about $2-5\%$ for π^+
- and approximately zero for π^-
- Systematic uncertainty is less than 0.003.
- Maximum difference $|A_{UT,q} - A_{UT,l}| < 0.004$



Transversity

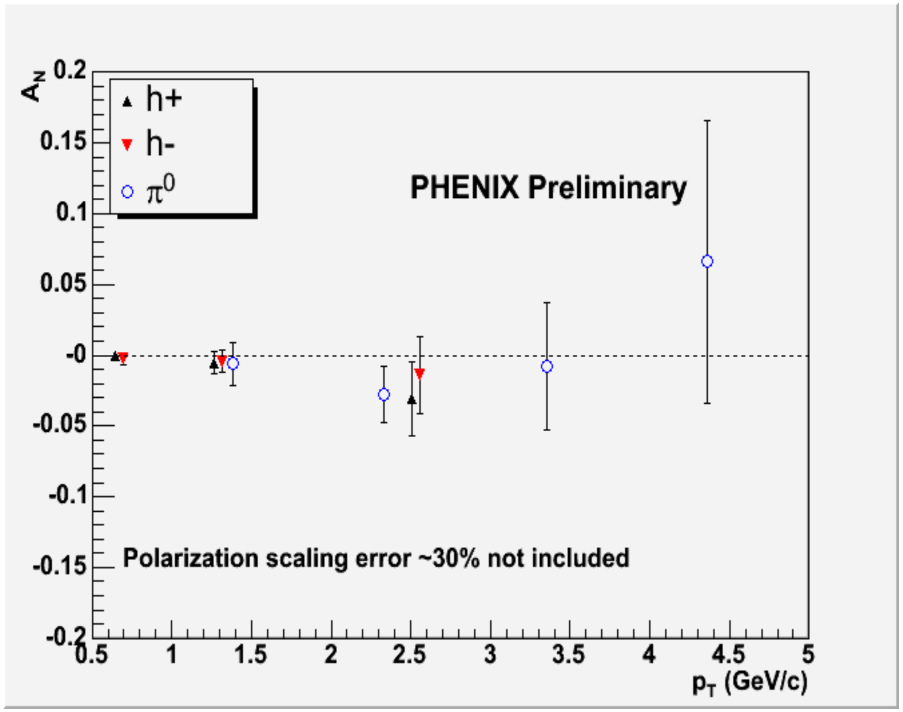


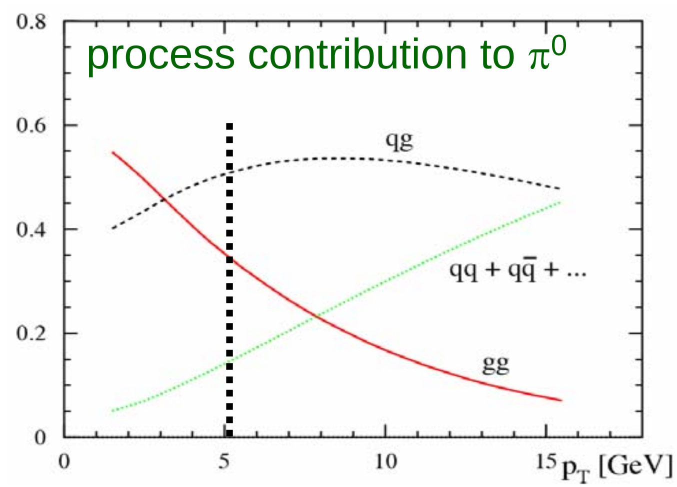
$$A_N = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$



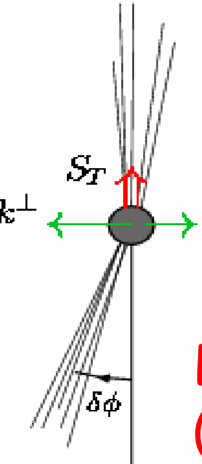
- Large spin effects for forward π^0 similar to that seen at FNAL.
- No significant asymmetry observed at backward angles.
- A new Forward Calorimeter (proposal) could resolve origin of A_N and characterization of nuclear shadowing at small x.
  - Initial state (Sivers)
  - Final State (Collins).

Transversity





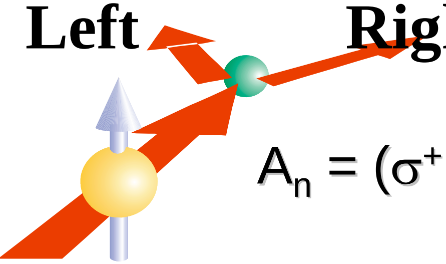
Possibility to map out pT↔ x ↔ g/q dependence



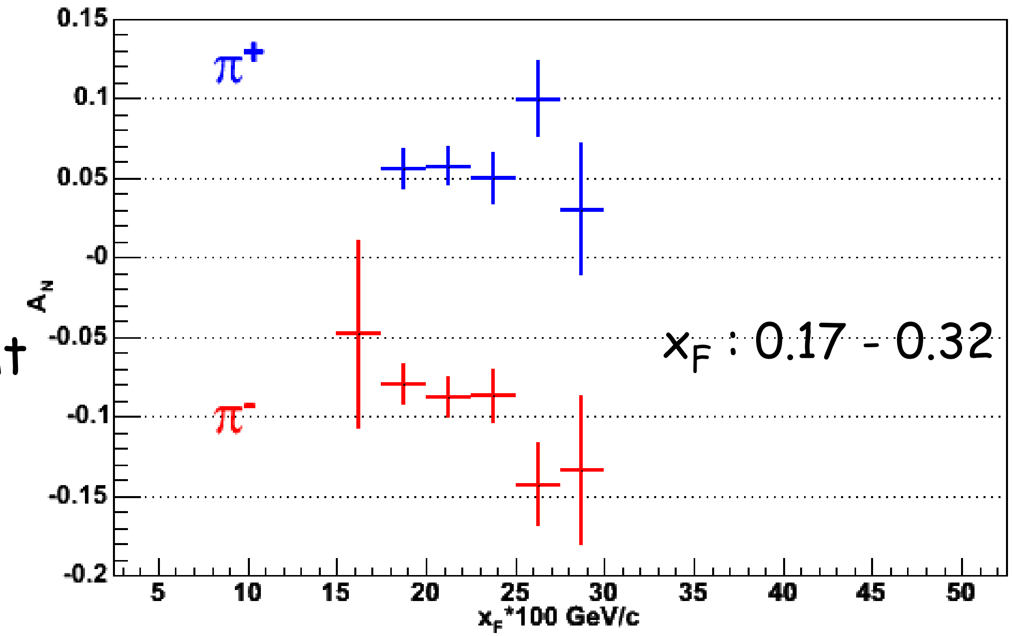
A_N for both charged hadrons and neutral pions consistent with zero at midrapidity.
(Data taken 0.15 pb^{-1} and 15 % beam polarization)
Few weeks ago: ~50% beam polarization!

Back to back di-hadron correlations identifies Sivers effects (deconvolute specific effects in A_N) … soon accuracy of 1%

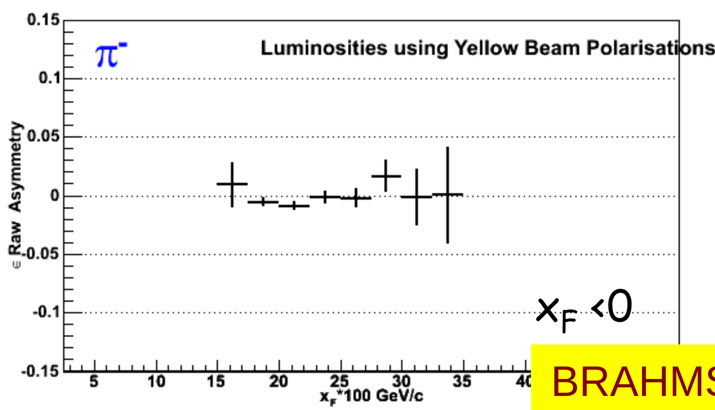
Transversity

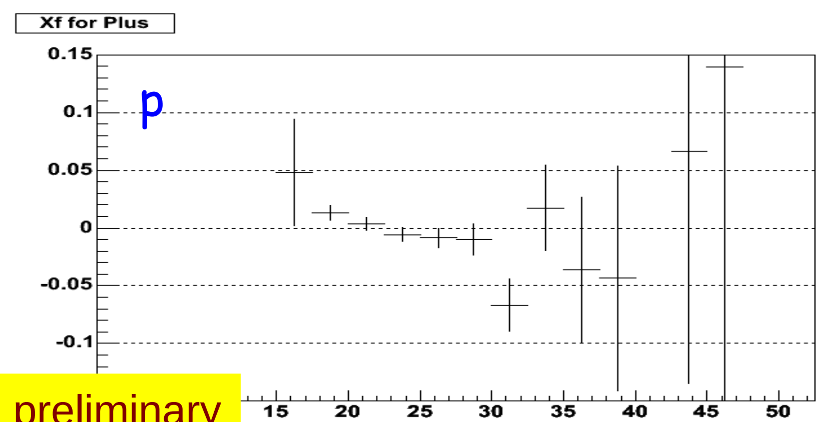


$A_n = (\sigma^+ - \sigma^-) / (\sigma^+ + \sigma^-)$



- π^- < 0 at ~ 3 sigma, π^+ >0 at ~1.5 sigma level. Sign consistent with lower energy results.
- A_n at negative x_F for π^+ and π^- are consistent with 0 (as also found by STAR for π^0)
- The protons are found to have A_N ~0





BRAHMS preliminary

Transversity & Friends

2π fragmentation xsection(UT):

$$
\begin{aligned}
d^9\sigma_{OT} = \sum_a \frac{\alpha^2 e_a^2}{2\pi Q^2 y} |\vec{S}_T|\, A(y) \Bigg\{ & \frac{|\vec{R}_T|}{M_h} \sin(\phi_R - \phi_S)\, \mathcal{I}\left[\frac{\vec{p}_T \cdot \vec{k}_T}{2MM_h} g_{1T}\, G_1^{\perp}\right] \\
& - \frac{|\vec{R}_T|}{M_h} \cos(\phi_R - \phi_S)\, \mathcal{I}\left[\frac{(\vec{p}_T \cdot \hat{P}_{h\perp})(\hat{P}_{h\perp} \wedge \vec{k}_T) - (\vec{k}_T \cdot \hat{P}_{h\perp})(\hat{P}_{h\perp} \wedge \vec{p}_T)}{2MM_h} g_{1T}\, G_1^{\perp}\right] \\
& - \frac{|\vec{R}_T|}{M_h} \sin(2\phi_h - \phi_R - \phi_S)\, \mathcal{I}\left[\frac{2(\vec{p}_T \cdot \hat{P}_{h\perp})(\vec{k}_T \cdot \hat{P}_{h\perp}) - \vec{p}_T \cdot \vec{k}_T}{2MM_h} g_{1T}\, G_1^{\perp}\right] \\
& - \frac{|\vec{R}_T|}{M_h} \cos(2\phi_h - \phi_R - \phi_S)\, \mathcal{I}\left[\frac{(\vec{p}_T \cdot \hat{P}_{h\perp})(\hat{P}_{h\perp} \wedge \vec{k}_T) + (\vec{k}_T \cdot \hat{P}_{h\perp})(\hat{P}_{h\perp} \wedge \vec{p}_T)}{2MM_h} g_{1T}\, G_1^{\perp}\right] \\
& + \sin(\phi_h - \phi_S)\, \mathcal{I}\left[\frac{\vec{p}_T \cdot \hat{P}_{h\perp}}{M} f_{1T}^{\perp}\, D_1\right] + \cos(\phi_h - \phi_S)\, \mathcal{I}\left[\frac{\hat{P}_{h\perp} \wedge \vec{p}_T}{M} f_{1T}^{\perp}\, D_1\right]\Bigg]\Bigg\} \\
+ \sum_a \frac{\alpha^2 e_a^2}{2\pi Q^2 y} |\vec{S}_T|\, B(y) \Bigg\{ & \sin(\phi_h + \phi_S)\, \mathcal{I}\left[\frac{\vec{k}_T \cdot \hat{P}_{h\perp}}{M_h} h_1\, H_1^{\perp}\right] \\
& + \cos(\phi_h + \phi_S)\, \mathcal{I}\left[\frac{\hat{P}_{h\perp} \wedge \vec{k}_T}{M_h} h_1\, H_1^{\perp}\right] + \boxed{\frac{|\vec{R}_T|}{M_h} \sin(\phi_R + \phi_S)\, \mathcal{I}\left[h_1\, \bar{H}_1^{\lhd}\right]} + \sin(3\phi_h - \phi_S) \\
& \times \mathcal{I}\left[\frac{4(\vec{p}_T \cdot \hat{P}_{h\perp})^2(\vec{k}_T \cdot \hat{P}_{h\perp}) - 2(\vec{p}_T \cdot \hat{P}_{h\perp})(\vec{p}_T \cdot \vec{k}_T) - \vec{p}_T^{\,2}(\vec{k}_T \cdot \hat{P}_{h\perp})}{2M^2 M_h} h_{1T}^{\perp}\, H_1^{\perp}\right] \\
& + \cos(3\phi_h - \phi_S)\, \mathcal{I}\Bigg[\Bigg(\frac{2(\vec{p}_T \cdot \hat{P}_{h\perp})^2(\hat{P}_{h\perp} \wedge \vec{k}_T) + 2(\vec{k}_T \cdot \hat{P}_{h\perp})(\vec{p}_T \cdot \hat{P}_{h\perp})(\hat{P}_{h\perp} \wedge \vec{p}_T)}{2M^2 M_h} \\
& - \frac{\vec{p}_T^{\,2}(\hat{P}_{h\perp} \wedge \vec{k}_T)}{2M^2 M_h}\Bigg) h_{1T}^{\perp}\, H_1^{\perp}\Bigg] + \frac{|\vec{R}_T|}{M_h} \sin(2\phi_h + \phi_R - \phi_S)\, \mathcal{I}\left[\frac{2(\vec{p}_T \cdot \hat{P}_{h\perp})^2 - \vec{p}_T^{\,2}}{2M^2} h_{1T}^{\perp}\, \bar{H}_1^{\lhd}\right] \\
& + \frac{|\vec{R}_T|}{M_h} \cos(2\phi_h + \phi_R - \phi_S)\, \mathcal{I}\left[\frac{(\vec{p}_T \cdot \hat{P}_{h\perp})(\hat{P}_{h\perp} \wedge \vec{p}_T)}{2M^2} h_{1T}^{\perp}\, \bar{H}_1^{\lhd}\right]\Bigg]\Bigg\}
\end{aligned}
$$

After integration over $P_{h\perp}$

$$\sigma_{UT} \propto \sum_q e_q^2 \sin(\phi_{R\perp} + \phi_S) h_1 H_1^{\lhd}$$

Advantages:

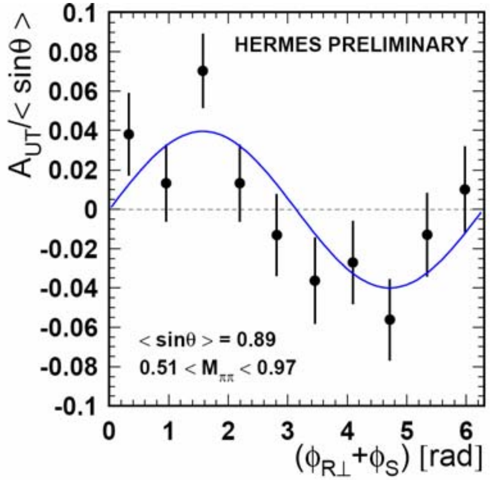
- cross section asymmetry directly proportional to $h_1 H_1^{\lhd}$ (No weighting needed)
- No Collins/Sivers ‘entanglement’
- Completely independent from 1π analysis

Disadvantages:

- less statistics
- $H_1^{\lhd}$ unknown (but can be measured at Belle & Babar)

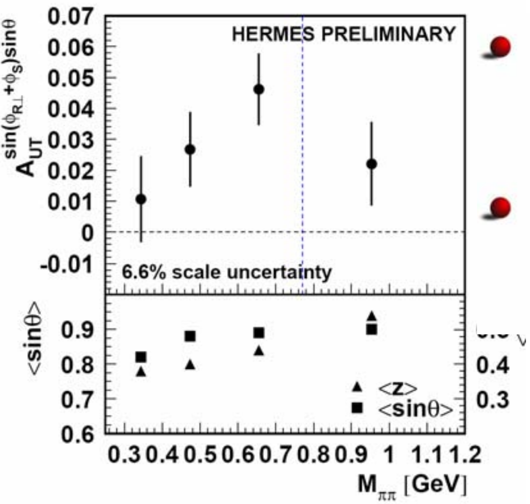
Transversity & Friends

p target



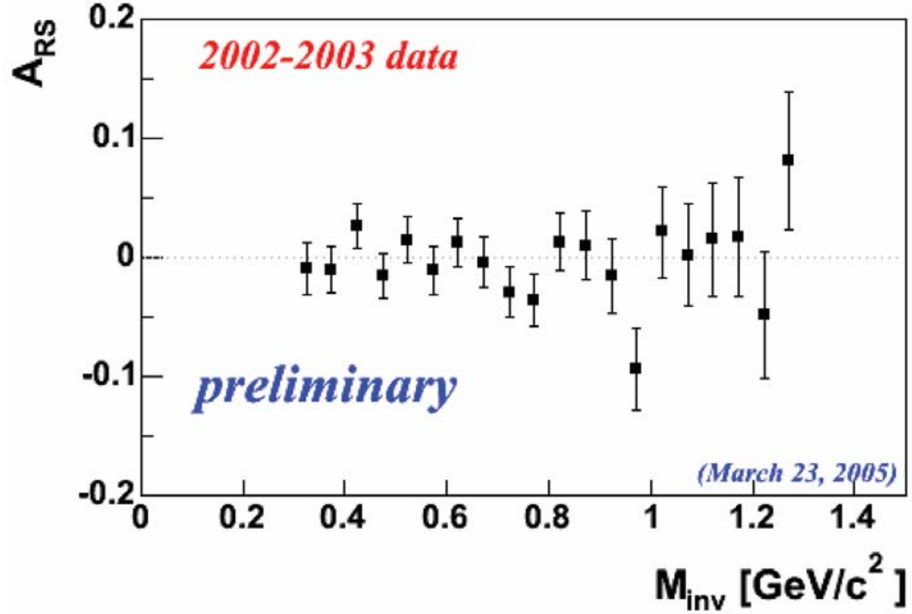
significant $\sin(\phi_{R\perp}+\phi_S)$ behavior!

$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta} = 0.040 \pm 0.009 \text{ (stat)} \pm 0.003 \text{ (syst)}$$



- positive asymmetry moment for all invariant mass bins
- result rules out predicted sign change at the ρ^0 mass (Jaffe et al.)

D target

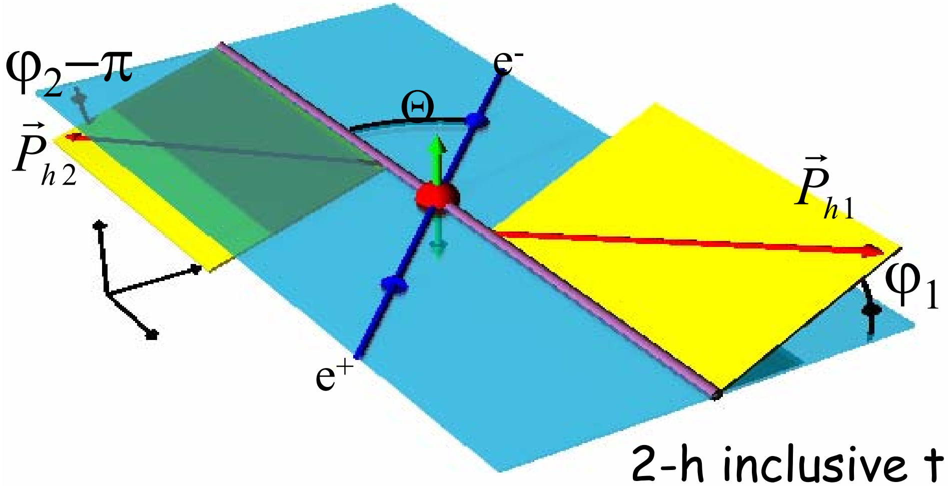


Asymmetry vs M_{inv}, x, z consistent with 0 or small.

More results expected with:
- Improved statistic
- RICH information
- Runs using p-target (NH_3)

Transversity & Friends

All the previous Spin dependent Fragmentation function analyses yields information on the Collins and the Interference Fragmentation function !
→Always 2 unknown functions involved which cannot be measured independently



In e+e- only the Collins FF appears!

2-h inclusive transverse momentum dependent Xsection:

$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\cos(\varphi_1 + \varphi_2) H_1^{\perp[1]}(z_1)\overline{H}_1^{\perp[1]}(z_2)$$

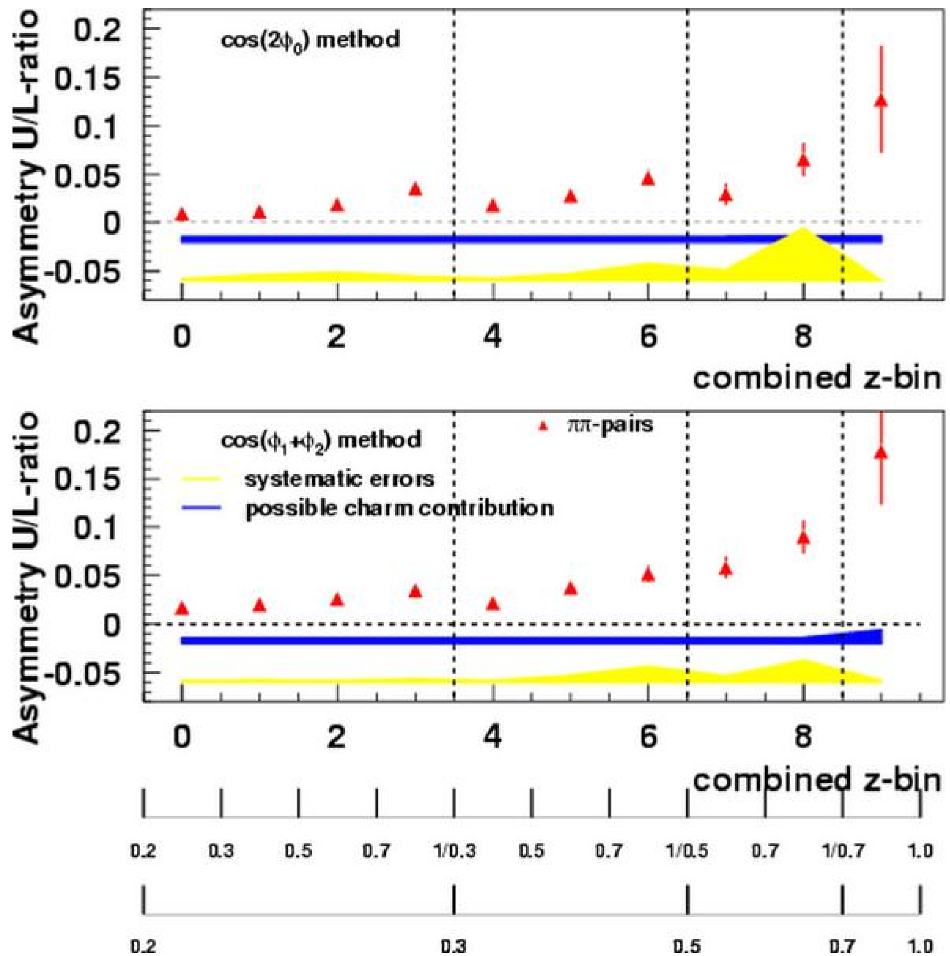
$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4}\sin^2\Theta$$

Transversity & Friends

Milestone!

The *double ratio method* shows:

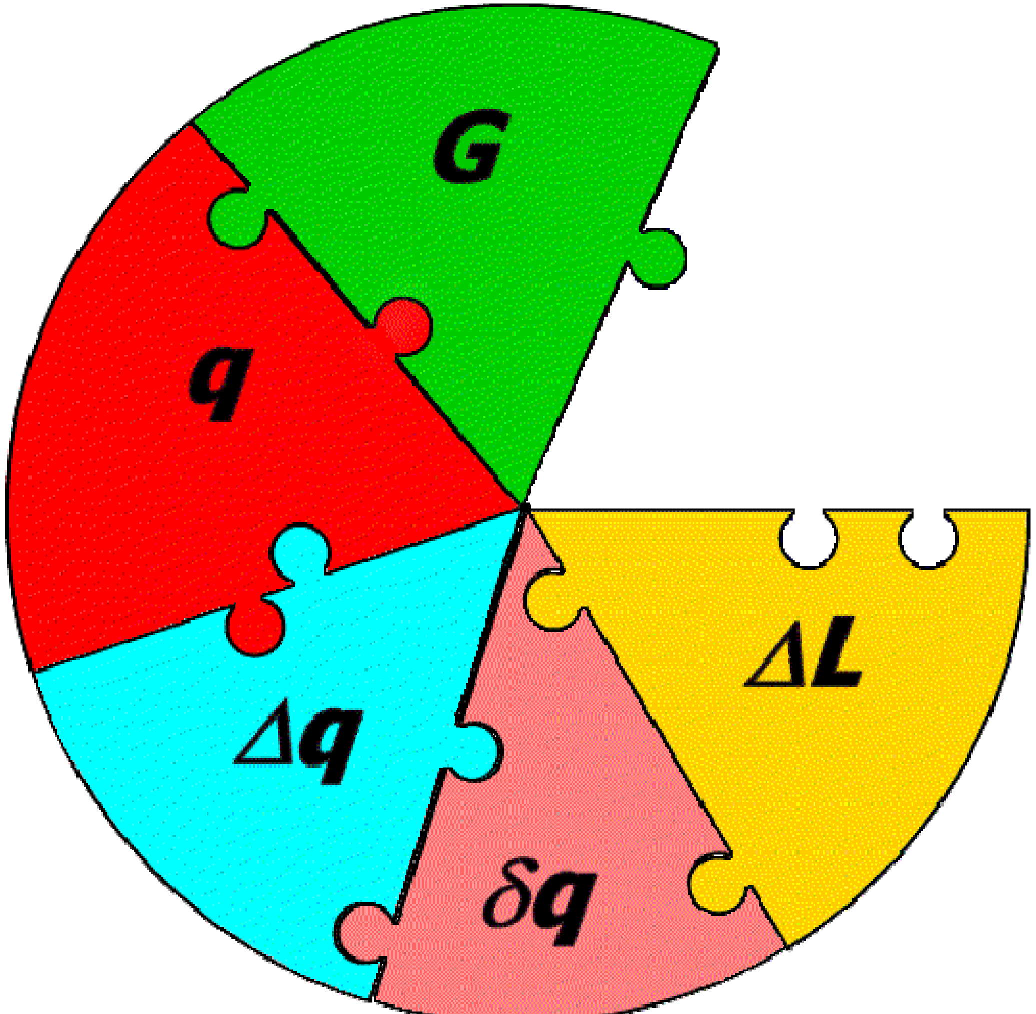
- Significant non-zero asymmetries
- Rising behaviour vs. z
- First direct measurement of the Collins function



Only first steps, however:

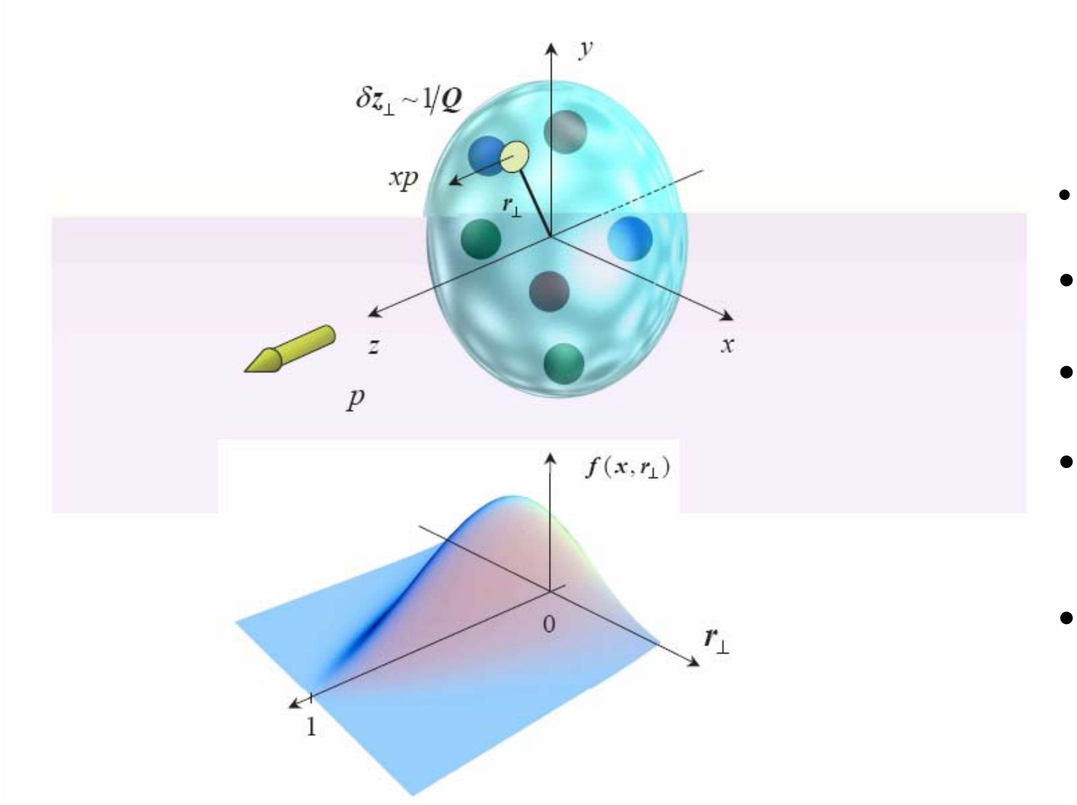
Naïve LO analysis shows significant Collins effect

(Spin)-Structure of the Nucleon



GPDs and Exclusive Processes

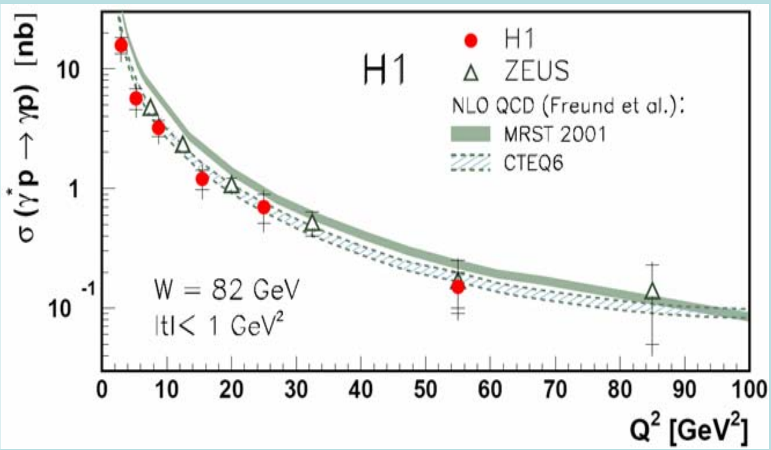
- GPDs are powerful objects :



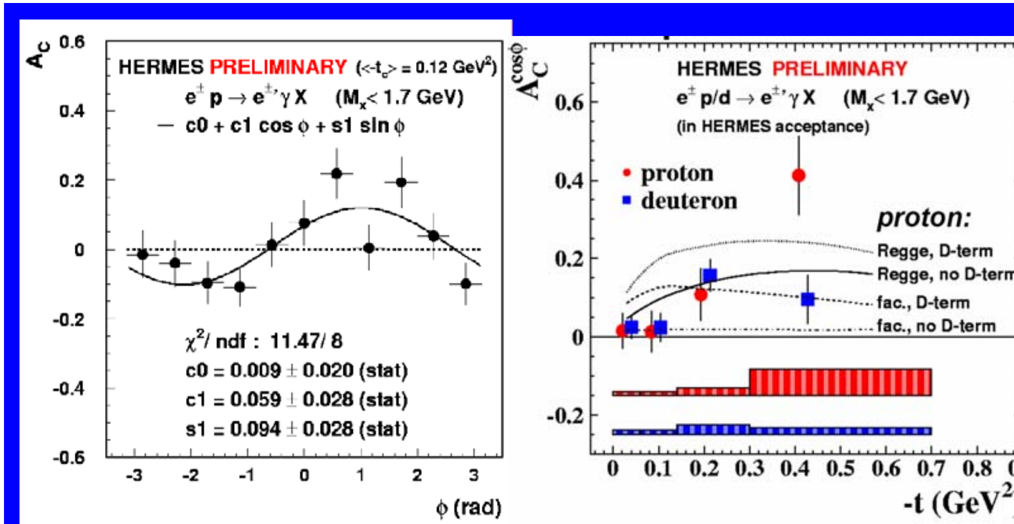
- 3D structure of hadrons
- contain form factors
- contain structure fcts.
- angular momentum contribution to spin sum
- ....

GPDs and Exclusive Processes

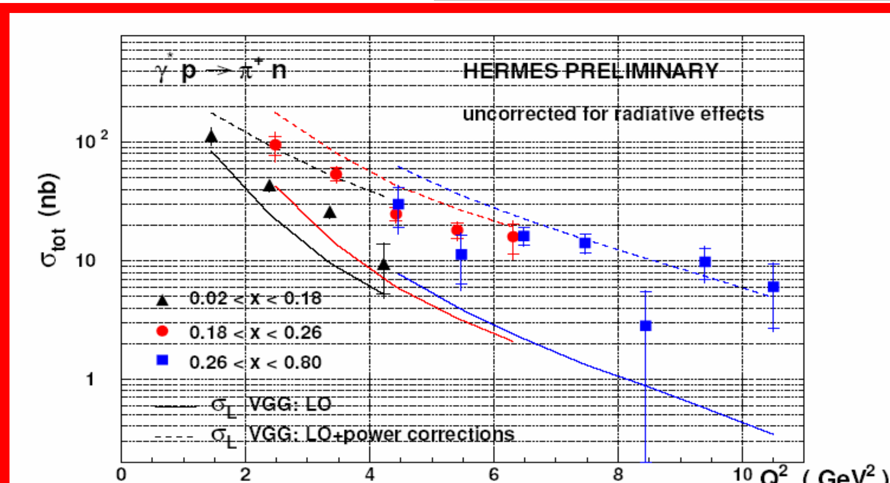
Joint Working Groups: Spin Physics + Diffraction & VM



Xsection for DVCS vs Q^2,W,t



Extraction for Beam Charge Asymmetry



Xsection for exclusive π^+

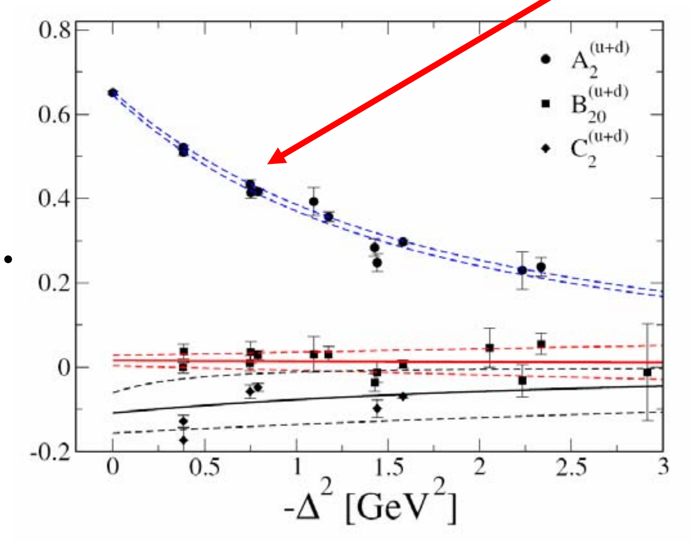
GPDs and Exclusive Processes (Th.)

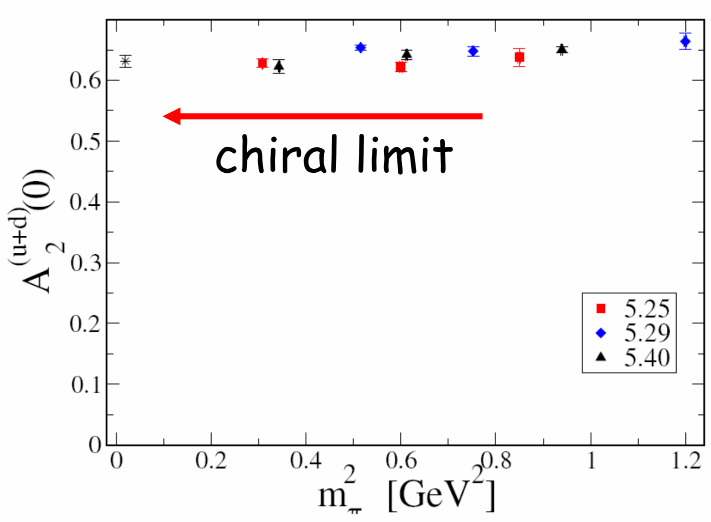
Schierholz
hep-ph/0501029

- recent lattice results:

$$\langle p_1, s|\, \mathcal{O}^q_{\{\mu_1\cdots\mu_n\}}\, |p_2, s\rangle = \bar{u}(p_1, s)\left[A^q_n(\Delta^2)\gamma_{\{\mu_1} + \frac{i\Delta^\alpha}{2m_N} B^q_n(\Delta^2)\sigma_{\alpha\{\mu_1}\right]\bar{p}_{\mu_2}\cdots\bar{p}_{\mu_n\}}\, u(p_2, s) + \cdots$$

e.g.





angular momentum:

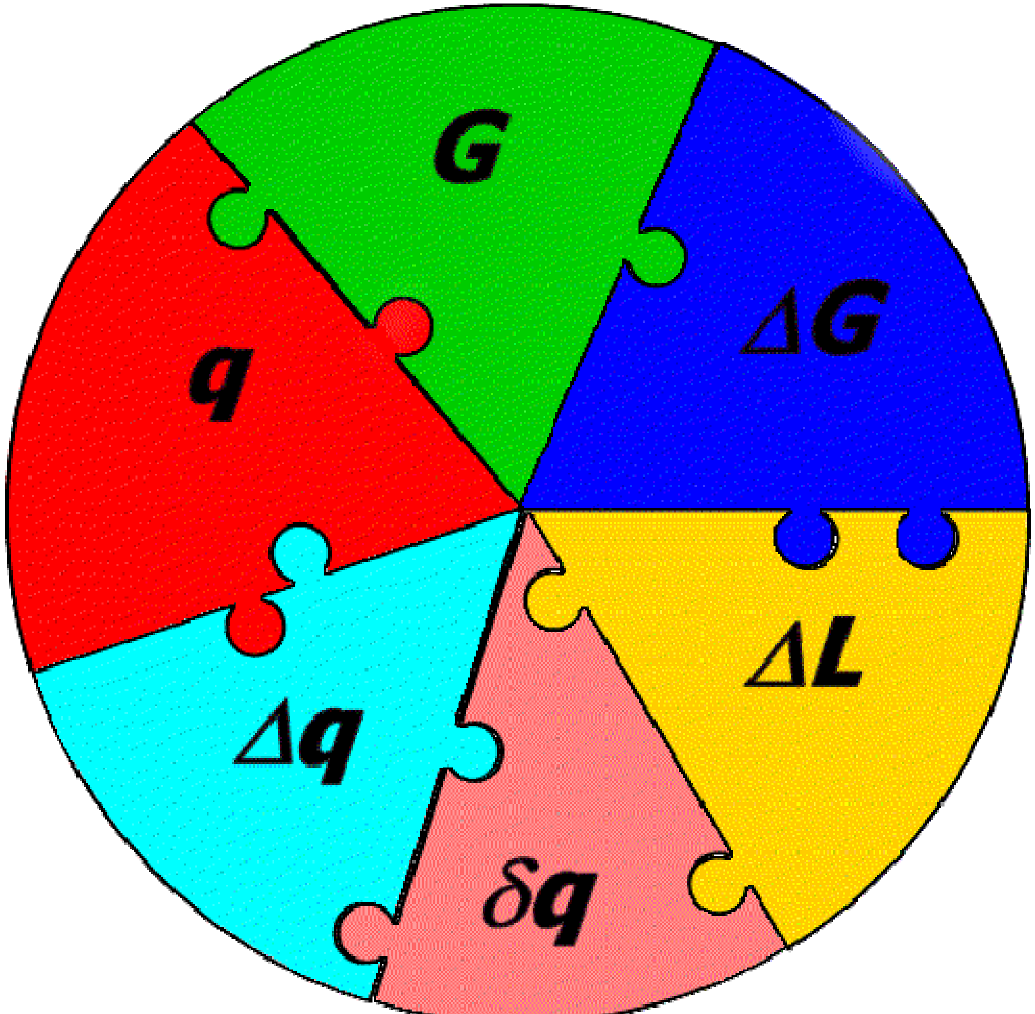
$$A^q_2(0) + B^q_2(0) = J^q$$

$$L^{u+d} = 0.03(7)$$

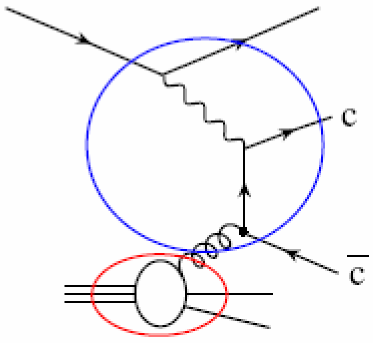
$$L^{u-d} = -0.45(6)$$

strong cancellations

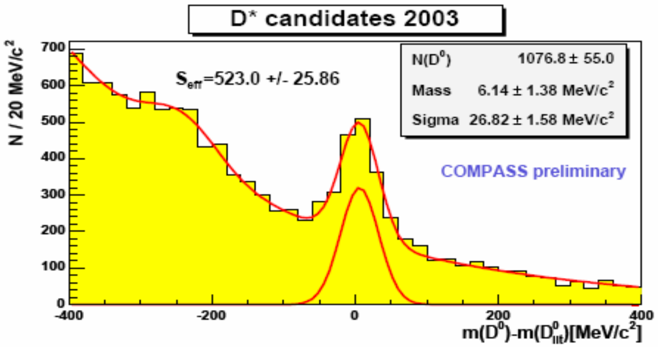
(Spin)-Structure of the Nucleon



Gluon Polarization



Direct measurement of ΔG/G via open charm production has still too few events.



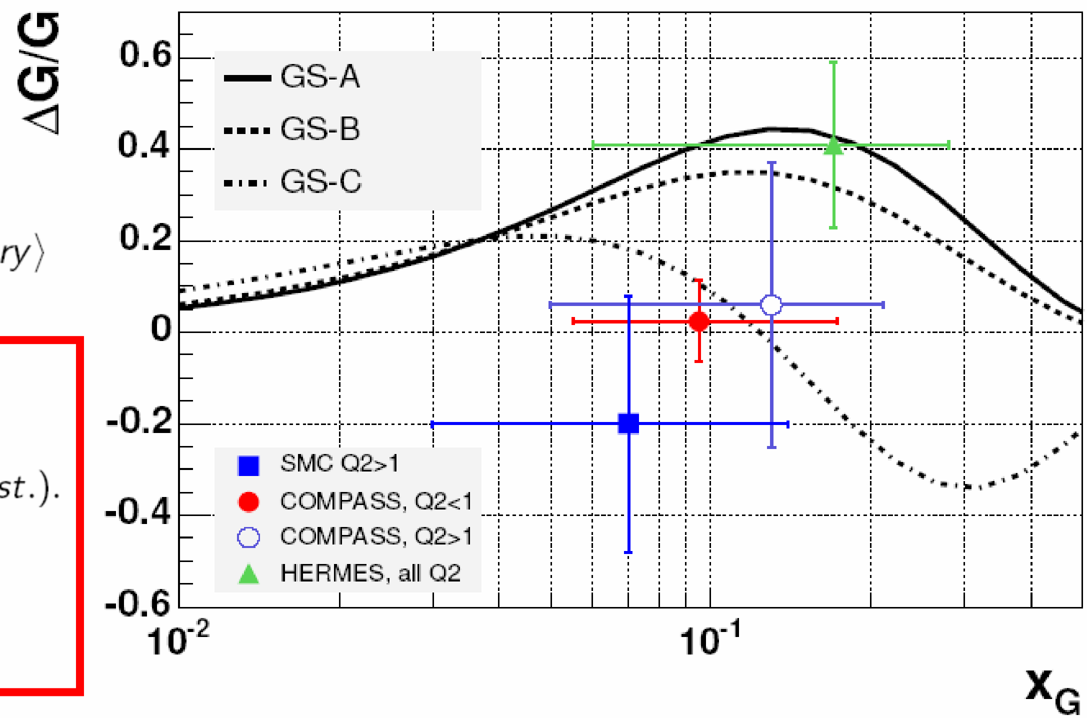
Measurement of ΔG/G via high Pt hadrons more powerful but model dependent

$$A_{||} = R_{pgf} \langle \hat{a}_{pgf} \rangle \frac{\Delta G}{G} + \langle background\ asymmetry \rangle$$

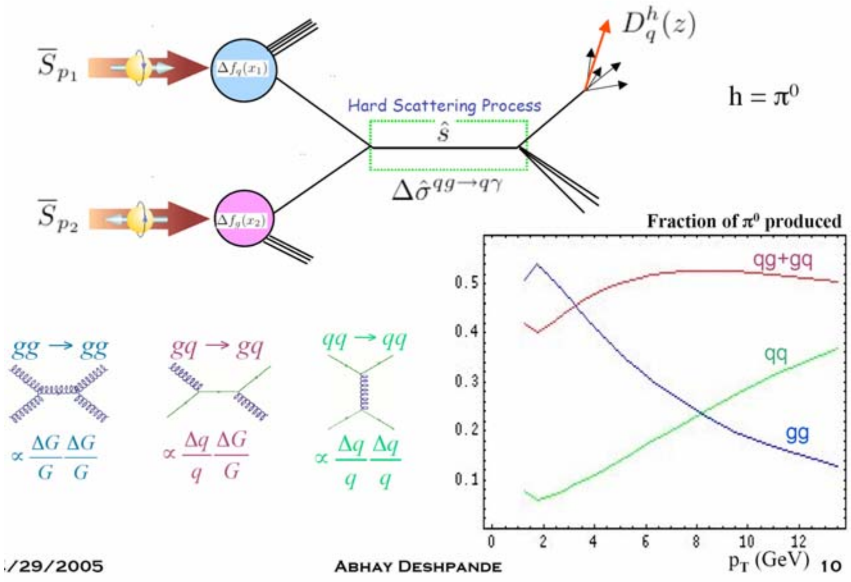
2002+2003 data, $Q^2 < 1$ GeV^2

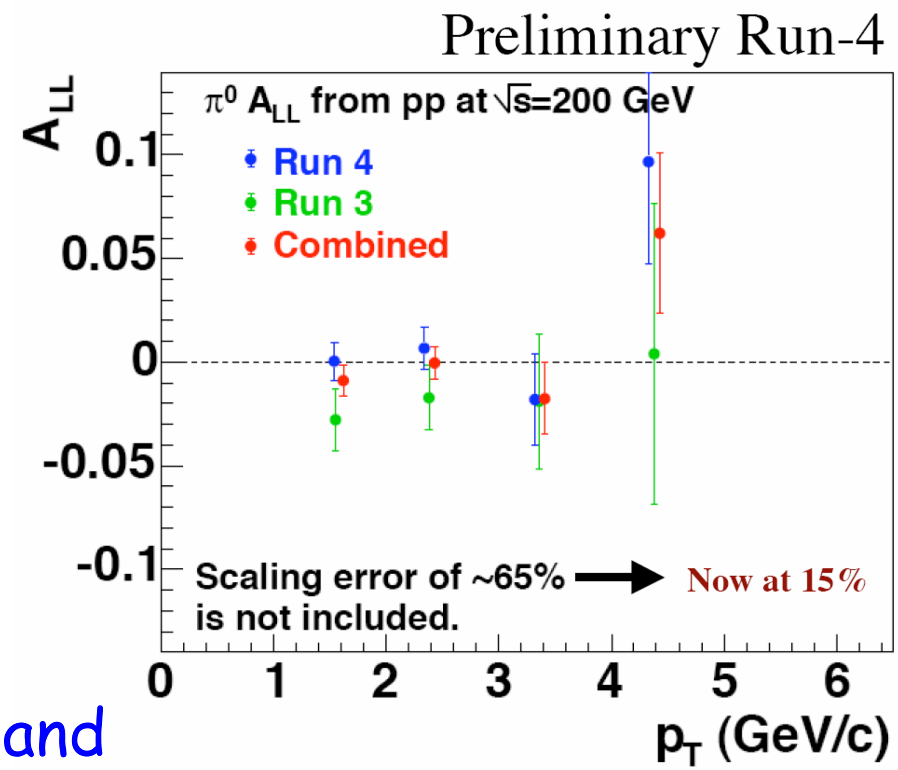
$$\frac{\Delta G}{G} = 0.024 \pm 0.089(stat.) \pm 0.057(syst.).$$

- either ΔG is small,
- either $\Delta G/G$ has to cross 0 around $x_G = 0.1$.



Gluon Polarization

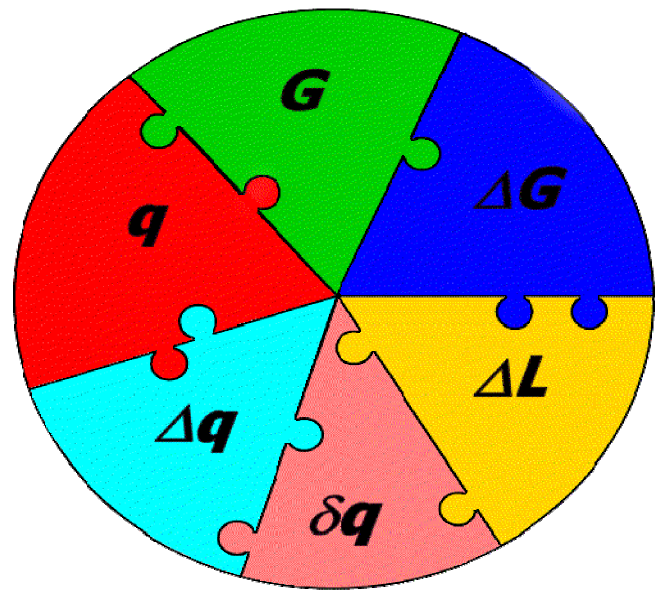




- Uncertainty still large $\left(P^2\sqrt{L}\right)$.
- Dramatic improvement by lumi and beam polarization (~70%)

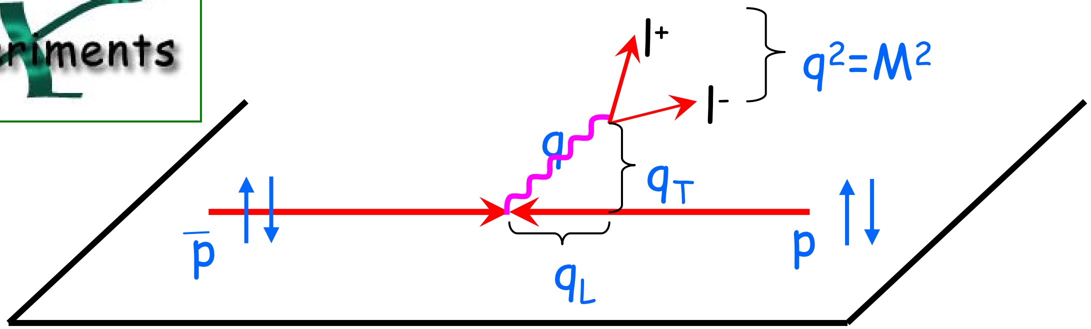
New silicon VTX will increase the x range coverage for ΔG

The nucleon puzzle is going FAR to be completed ...

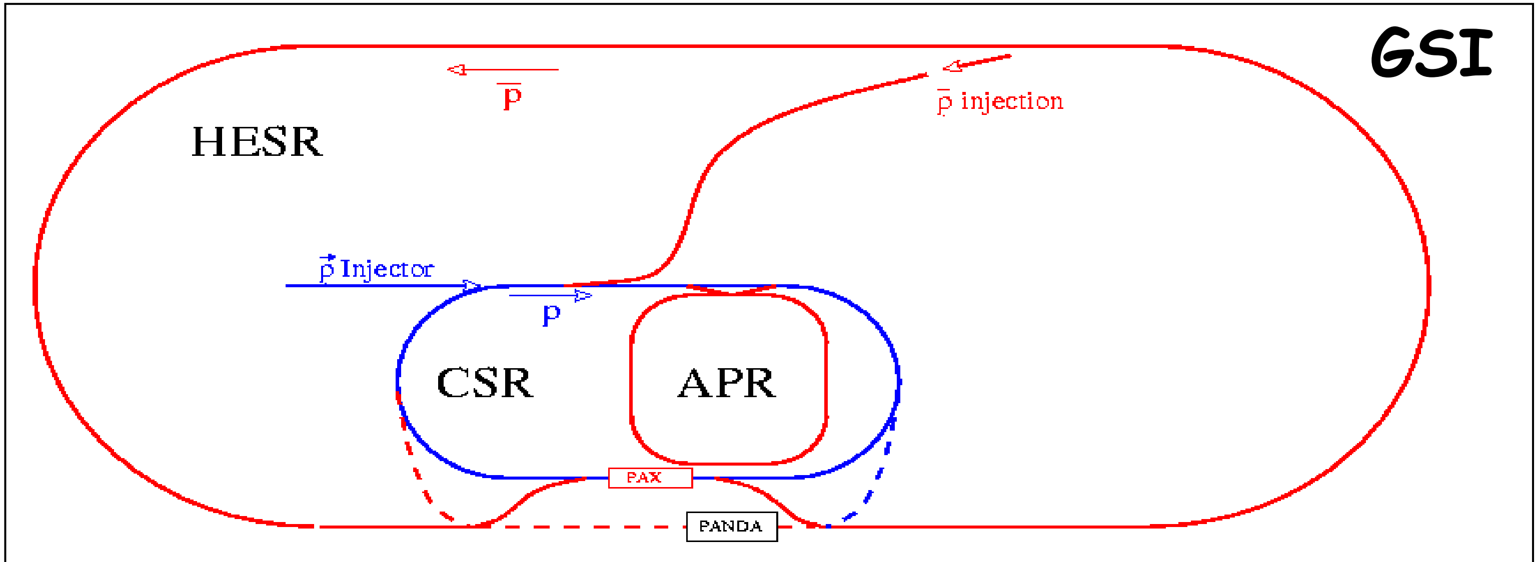


Future: Transversity in DY

Polarized Antiproton EXperiments

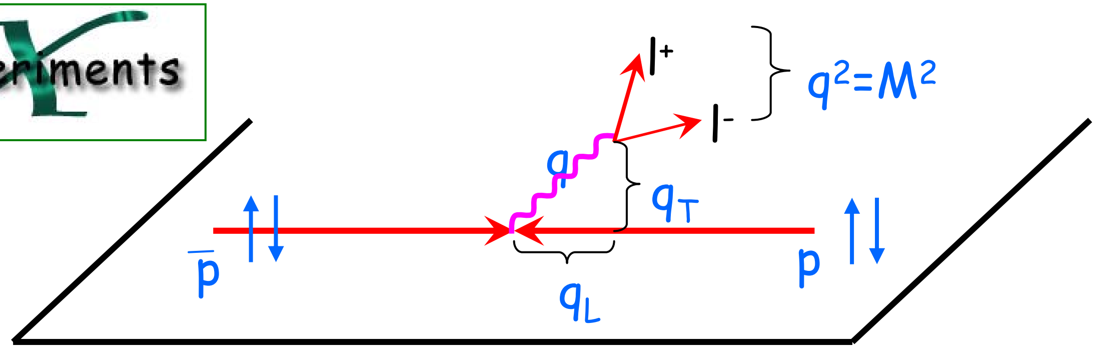


$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2) h_1^{\bar{q}}(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2) \bar{q}(x_2, M^2)}$$

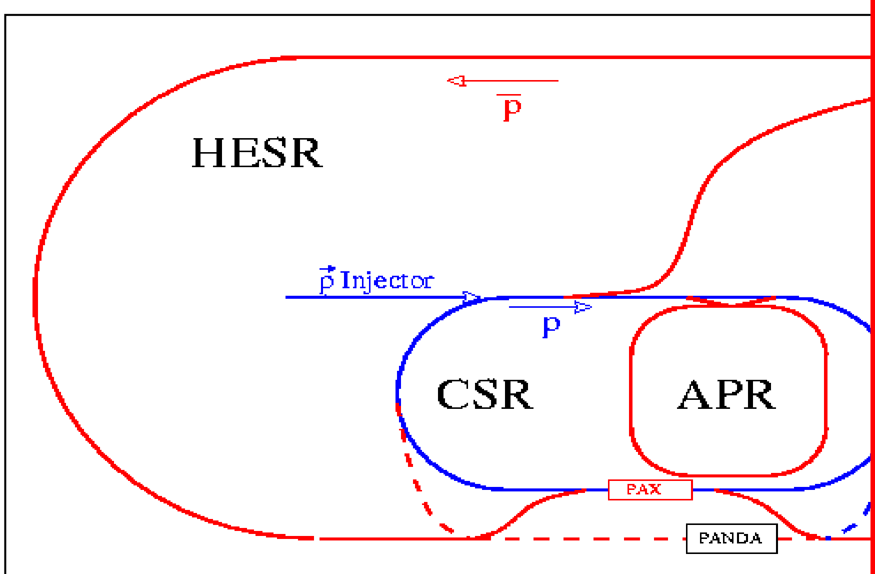


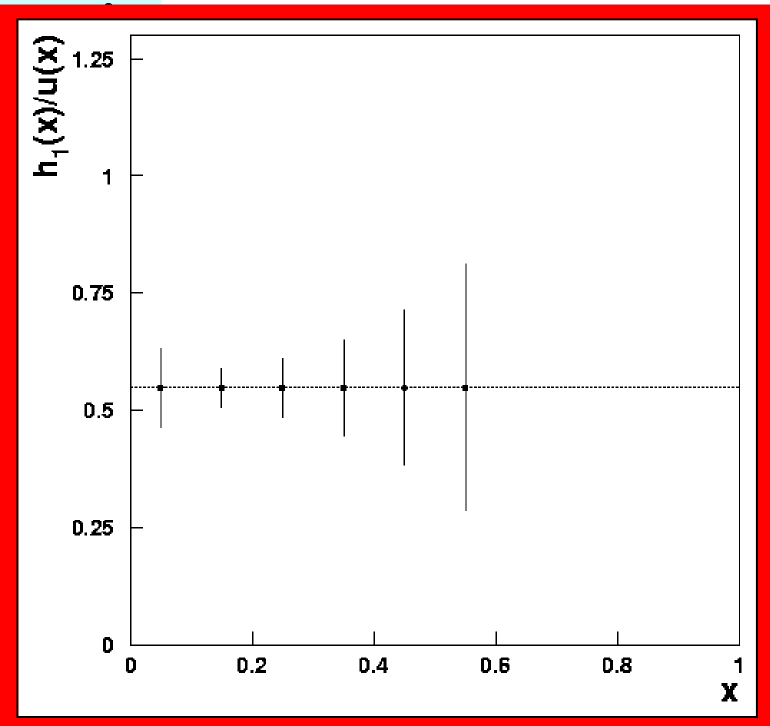
Future: Transversity in DY

Polarized Antiproton EXperiments



$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2) h_1^{\bar{q}}(x \ldots}{\sum_q e_q^2 q(x_1, M^2) \bar{q}(x_2 \ldots}$$

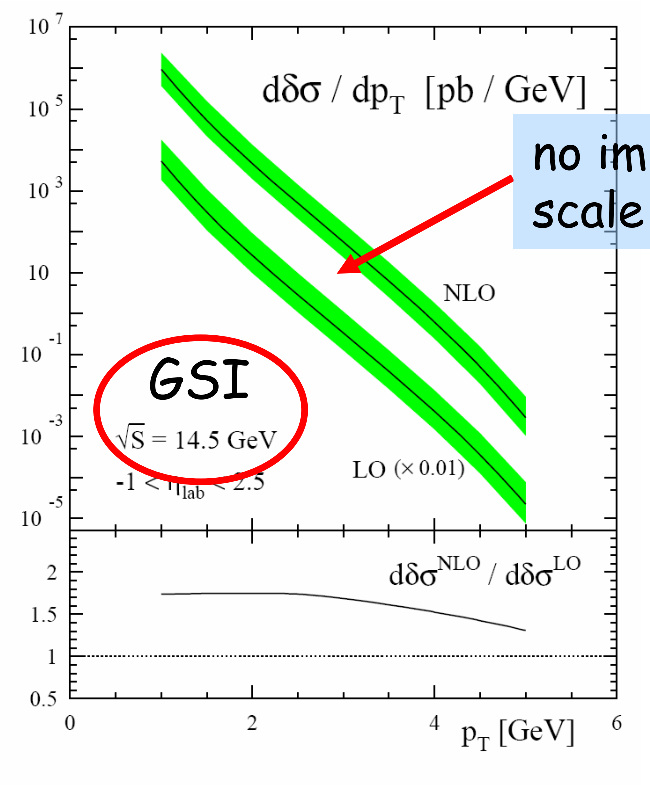




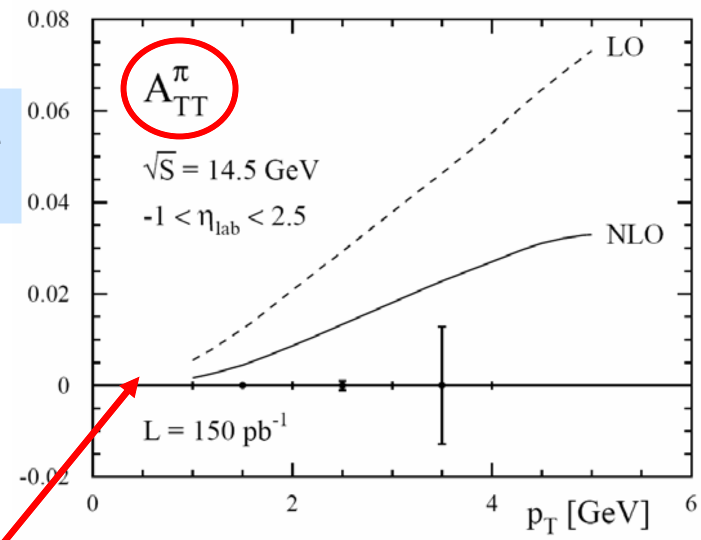
1 yr of data taking

SSA & transversity (Th.)

- new NLO results: single-incl. hadrons:



no improvement in scale dependence



interesting tool to learn about transversity
no other unknown (TMD) fcts. involved here!

<u>at RHIC energies</u>: much improved scale dep. but small asymmetries

Spin physics is a very active field

Many experimental results and theories

High precision measurements (other just around the corner)

New dedicated experiments and detectors

Stimulating discussion … including homework

INFN Frascati Pasquale Di Nezza