Opportunities in nucleon spin physics

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Outline

1. Historical Remarks
2. Polarized gluon distribution Δg
4. Orbital angular momentum & GPDs
5. Transversity
6. Conclusion

Historical remarks

- 17 years ago, a group of experimentalists led by V. Hughes made a remarkable discovery:

A very small fraction of the proton spin is carried by the spin of the quarks!

  - Put the naive but well-accepted and cherished quark model into serious questioning!
  - One of the most cited papers in experimental nuclear & particle physics!
  - Lunched one of the most extensive program in high-energy spin physics!

Historical remarks (cont.)

- An impressive follow-ups
  - SLAC E142,E143,E155,E156
  - SMC
  - HERMES
  - JLAB spin physics program
  - COMPASS
  - RHIC Spin
  - JLAB12 GeV Upgrade

What are we after?

- When the nucleon is polarized, how do quarks and gluons make up and/or respond to this polarization?
  - Where does the spin of the nucleon come from? (spin decomposition)
    - Gluon and quark helicity
    - Orbital angular momentum
  - Interesting polarization-dependent observables
    - Transversity (figure this in a spin sum rule?)
    - G_2 structure function
    - Sivers functions

Is this useful & fundamental?

- Useful
  - QCD accounts for the most of the visible mass in the universe.
  - The proton and neutron structure is crucial for understanding nuclear physics and Higgs production!
- Fundamental
  - QCD is one of the most beautiful but yet unsolved theories ($1M prize from Clay Math Inst. Cambridge,MA)
  - String theorists have spent much of their time studying QCD in the last five years!
    - ADS/CFT correspondence
    - Twistor-string theory & multiple gluon scattering

Spin decomposition

- The spin of the nucleon can be decomposed into contributions from quarks and gluons

$$J = 1/2 = J_q(\mu) + J_g(\mu)$$

- Decomposition of quark contribution

$$J_q = \sum_f [\frac{1}{2}(\Delta q^v{}_f + \Delta q^s{}_f) + L_{qf}]$$

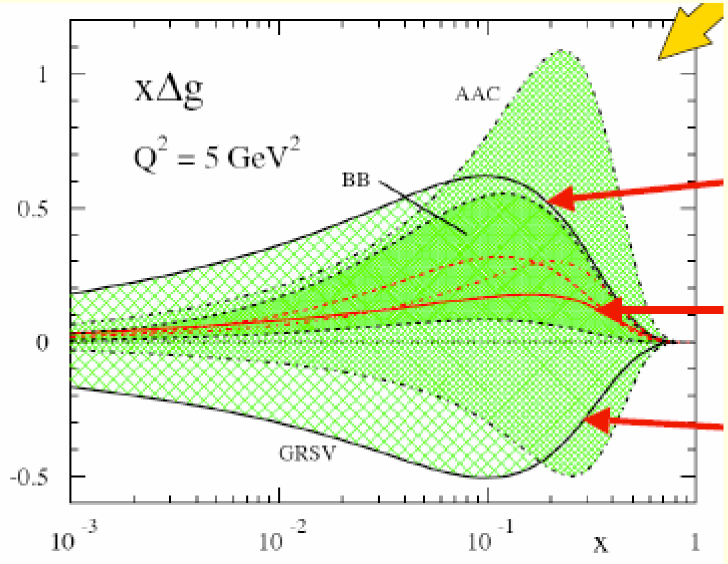
- Decomposition of gluon contribution

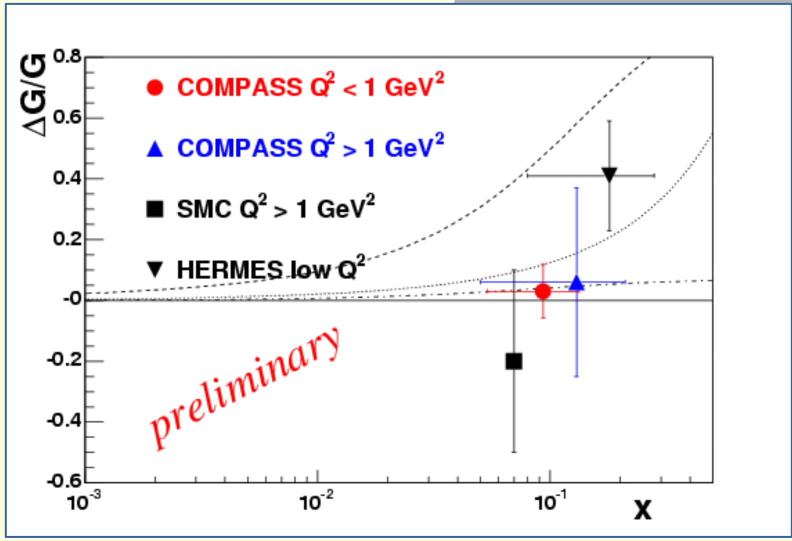
$$J_g = \Delta g + L_g$$

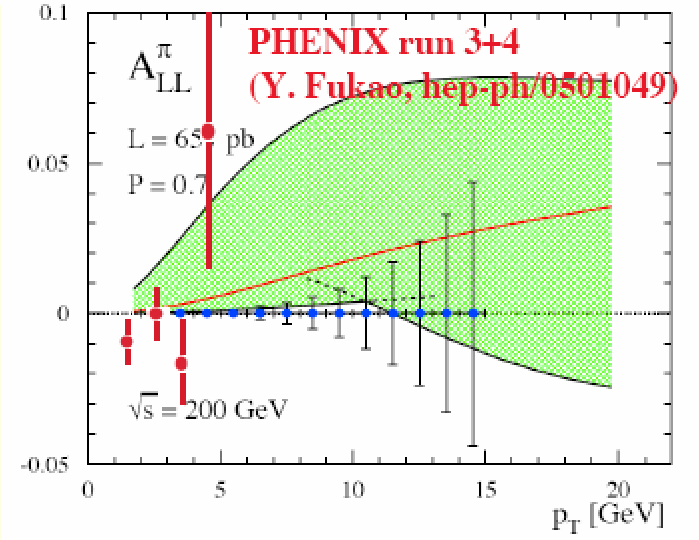
Gluon polarization

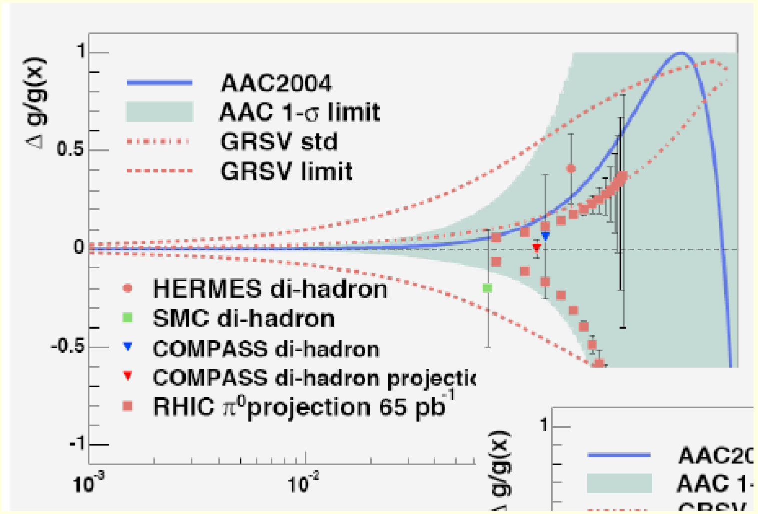
- Thought to large because of the possible role of axial anomaly!
  - 2-4 units of hbar!
- One of the main motivations for COMPASS experiment!
- Surprisingly rapid progress, but the error bars remains large
  - Scale evolution
  - HERMES Collaboration
  - COMPASS
  - RHIC Spin

Experimental progress…



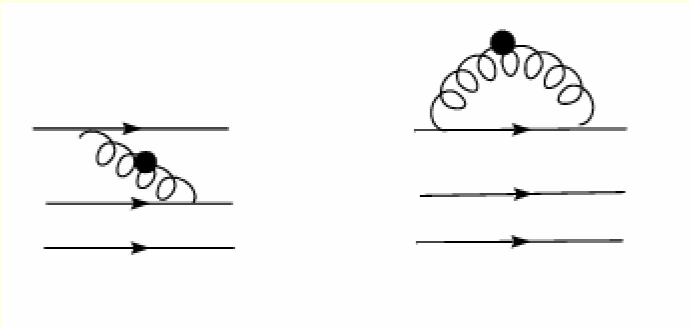






Current theoretical prejudices

- It shall be positive!
  - There was a calculation by Jaffe in 1996 (PRB365), claiming it is negative in NR quark and bag models.
  - However, there are two type of contributions



Barone et al., PRB431,1998

  - Recently it is shown by Ji & Toublan that it is positive-definite in quark models (to be published)

Current theoretical prejudices

- It shall not be as large!
  - The anomaly argument for large Δg is controversial
    - There is also an anomaly contribution to the quark orbital motion.
    - It is un-natural for heavy quarks.
  - Naturalness

$$\Delta\Sigma/2 + \Delta g + L_z = ½$$

if Δg is very large, there must be a large negative L_z to cancel this---(fine tuning) Δg <0.5?

  - Model predictions are around 0.5 hbar.

Additional comments on gluon

- There is no known way to measure L_g
- In principle, one can measure the total gluon contribution through the gluon GPDs.

$$J_g = \frac{1}{2}\int dx x[H_g + E_g]$$

  - Heavy-quark production & two jets
- In practice, it is easier to deduce J_g from the spin decomposition if J_q is known.

$$J_g = 1/2 - J_q$$

Total quark angular momentum & GPDs

- The total angular momentum is related to the GPDs by the following sum rule

$$J_q = \lim_{t\to 0} \frac{1}{2} \int dx x [H_q(x,t,\xi) + E_q(x,t,\xi)]$$

  - Thus, one in principle needs to measure GPDs H and E at a fixed ξ for the full dependence in t and x.
  - GPD E is particularly difficult to measure because it is usually proportional to $t/4M^2$.

Why care about the orbital motion?

- Study of orbital motion of the Mars led to discovery of inverse squared laws: Kepler

  Study of orbital motion of the electron in H led to quantization rules: Bohr
- Quark motion in s-wave was responsible for the proposal of color! (Greenberg)
- In relativistic quark models, the orbital motion is essential, but was never put into a quantitative test!

A Key Observation

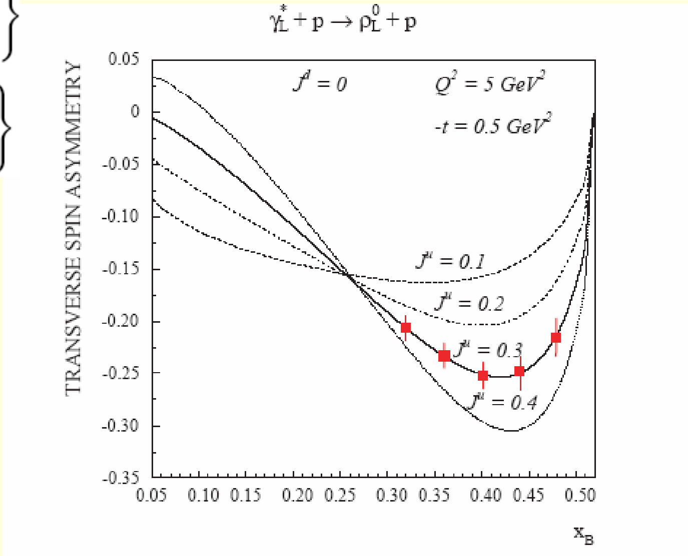
Goeke, Polyakov And Vanderhaghen, Prog. Nucl. Part. Phys. 2001

- The target (transverse) spin asymmetry in vector meson production is sensitive to E.

$$\mathcal{A}_{V_L N} = -\frac{2\,|\Delta_\perp|}{\pi} \frac{\mathrm{Im}(AB^*)/m_N}{|A|^2\,(1-\xi^2) - |B|^2\,(\xi^2 + t/(4m_N^2)) - \mathrm{Re}(AB^*)\,2\,\xi^2}$$

$$A_{\rho_L^0 p} = \int_{-1}^{1} dx\, \frac{1}{\sqrt{2}} \left(e_u\, H^u - e_d\, H^d\right) \left\{ \frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon} \right\}$$

$$B_{\rho_L^0 p} = \int_{-1}^{1} dx\, \frac{1}{\sqrt{2}} \left(e_u\, E^u - e_d\, E^d\right) \left\{ \frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon} \right\}$$



In a GPD model in which angular momentum fraction J_q Is a parameter, the asymmetry can be studied as a function of J_q

Target T-spin asymmetry in DVCS

$\Rightarrow$ **unpolarized beam**

- **transverse target spin asymmetry:**

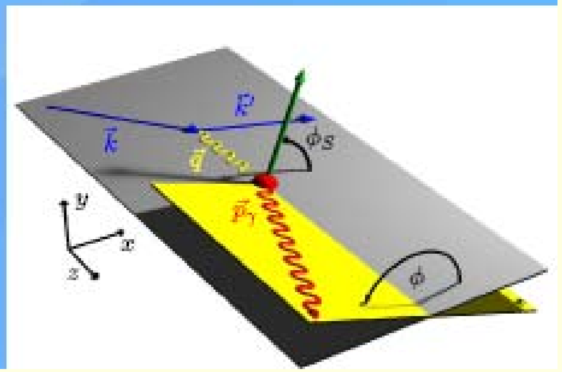
$$d\sigma_{\mathbf{P}\Uparrow} - d\sigma_{\mathbf{P}\Downarrow} \quad \propto \quad \underbrace{\mathrm{Im}(F_2 H_1 - F_1 E_1)}_{\mathbf{A_{UT}^{\sin(\phi-\phi_s)\cos(\phi)}}} \cdot \sin(\phi - \phi_s)\cos(\phi) +$$

$$\underbrace{\mathrm{Im}(F_2 \tilde{H}_1 - F_1 \xi \tilde{E}_1)}_{\mathbf{A_{UT}^{\cos(\phi-\phi_s)\sin(\phi)}}} \cdot \cos(\phi - \phi_s)\sin(\phi)$$

- **2D asymmetry: in ϕ and $(\phi - \phi_s)$**

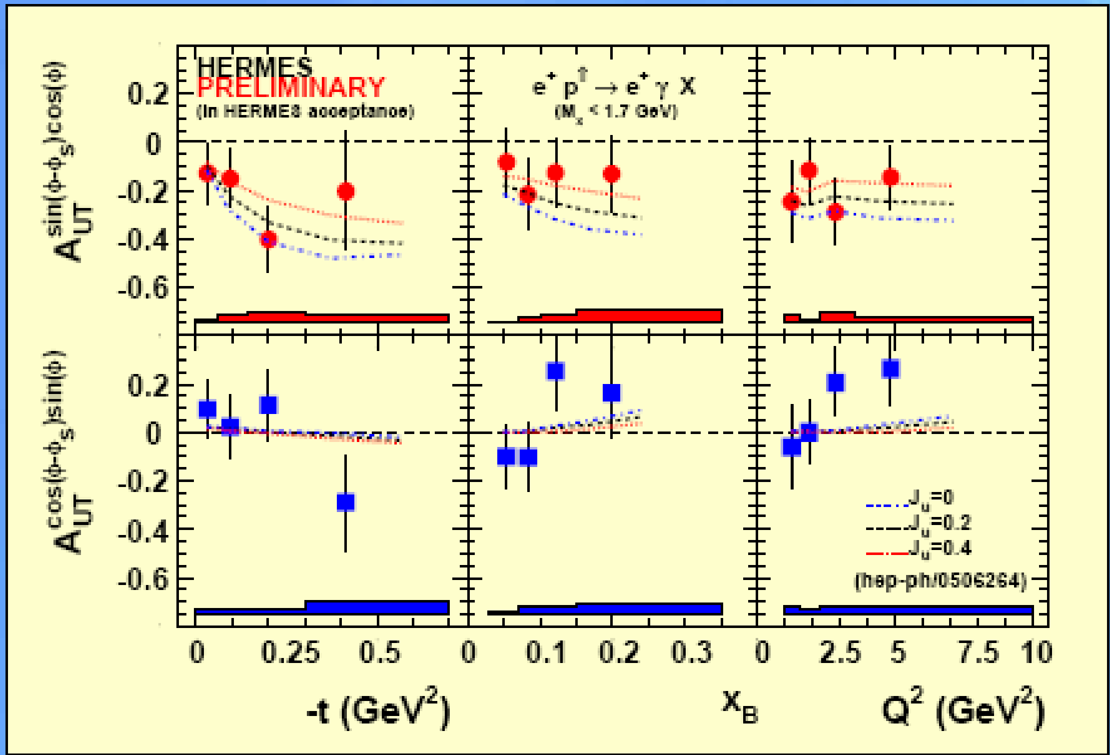
$$\mathrm{A_{UT}}(\phi, \phi_s) = \frac{\mathrm{N}^{\Uparrow}(\phi, \phi - \phi_s) - \mathrm{N}^{\Downarrow}(\phi, \phi - \phi_s)}{\mathrm{N}^{\Uparrow}(\phi, \phi - \phi_s) - \mathrm{N}^{\Downarrow}(\phi, \phi - \phi_s)}$$

- $\mathrm{A_{UT}^{\sin(\phi-\phi_s)\cos(\phi)}}$ **is sensitive 'to parameterizations involving different J_u**



From Aschenauer

First data from HERMES



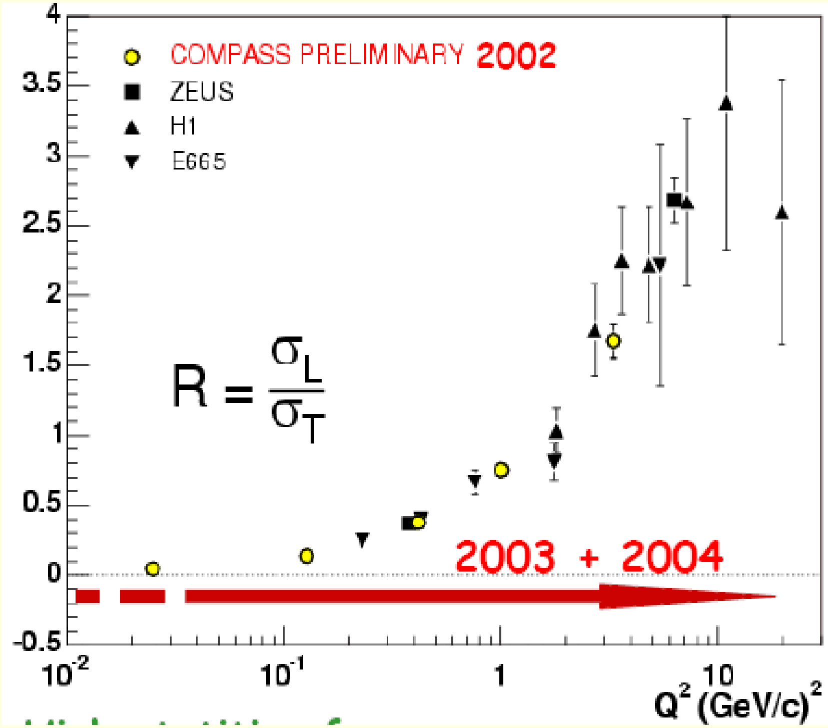
- $A_{UT}^{\sin(\phi-\phi_s)\cos(\phi)} \sim \mathrm{Im}(F_2 H_1 - F_1 E_1)$
- $A_{UT}^{\cos(\phi-\phi_s)\sin(\phi)} \sim \mathrm{Im}(F_2 \tilde{H}_1 - F_1 \xi \tilde{E}_1)$

- $A_{UT}^{\sin(\phi-\phi_s)\cos(\phi)}$ largely independent on all model parameters but J_u
- first model dependent extraction of J_u possible

COMPASS advantage: larger Q^2

- Test the accuracy of the photon production asymmetry at higher Q
- vector-meson production!

• Testing pQCD reaction mechanism $R \sim Q \gg \Lambda_{QCD}$
• For $Q^2 > 2\ GeV^2$, the helicity retantion works quite well !



GPD's independent life: distributions in quantum phase space

- In the past, we only knows how to imagine quarks either in
  - Coordinate space (form factors)
  - Momentum space (parton distributions)
- GPDs provide correlated distributions of quarks and partons in combined coordinate and momentum (phase) space
  - Wigner distribution in Quantum Mechanics (1932)

Wigner distribution

- Define as

$$W(x,p) = \int \psi^*(x-\eta/2)\psi(x+\eta/2)e^{ip\eta}d\eta \ ,$$

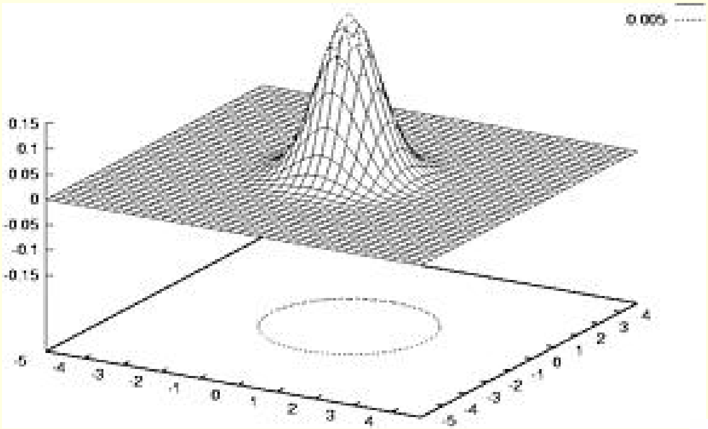
A joint distribution in momentum and coordinate spaces

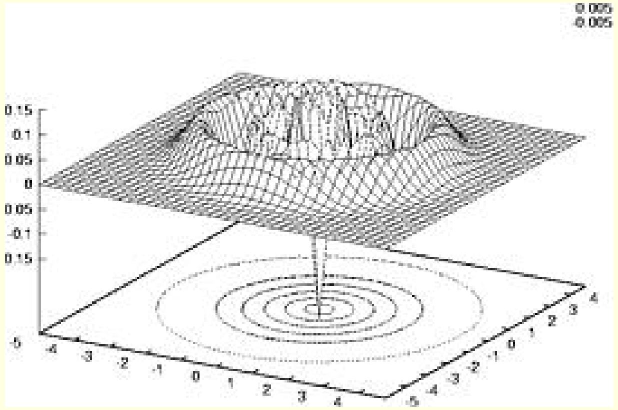
- When integrated over x (p), one gets the momentum (probability) density.
- Not positive definite in general (not strict density), but is in classical limit!
- Any dynamical variable can be calculated as

$$\langle O(x,p)\rangle = \int dxdpO(x,p)W(x,p)$$

Harmonic oscillator & squeezed light

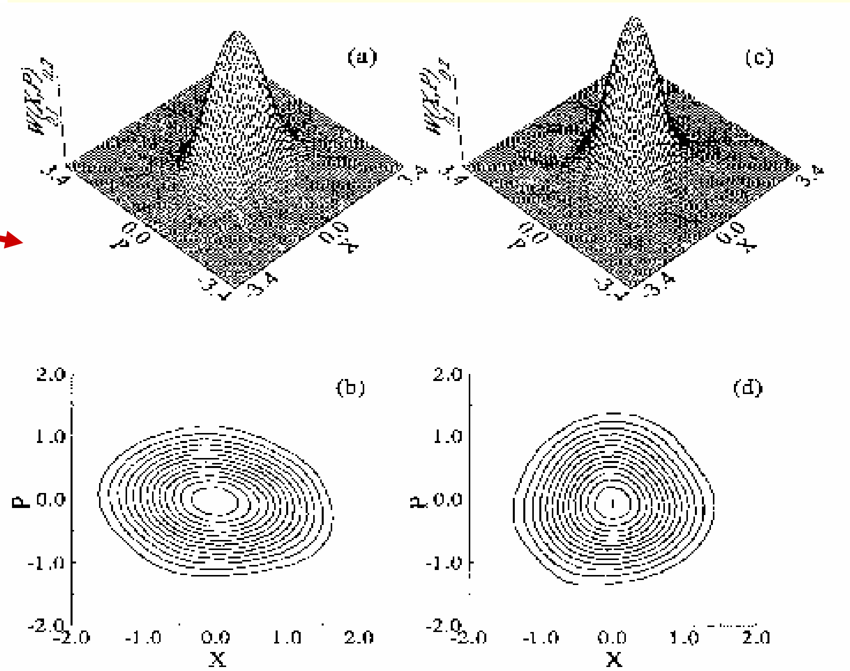
n=0





n=5

Wiger distribution
or squeezed light!



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Measurement of the Wigner Distribution and the Density Matrix of a Light Mode Using Optical Homodyne Tomography: Application to Squeezed States and the Vacuum

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(Received 16 November 1992)

Wigner-type quark distribution

- GPDs depend on x, ξ, and t. ξ and t are conjugate to the 3D coordinate **r**=(z,**b**)

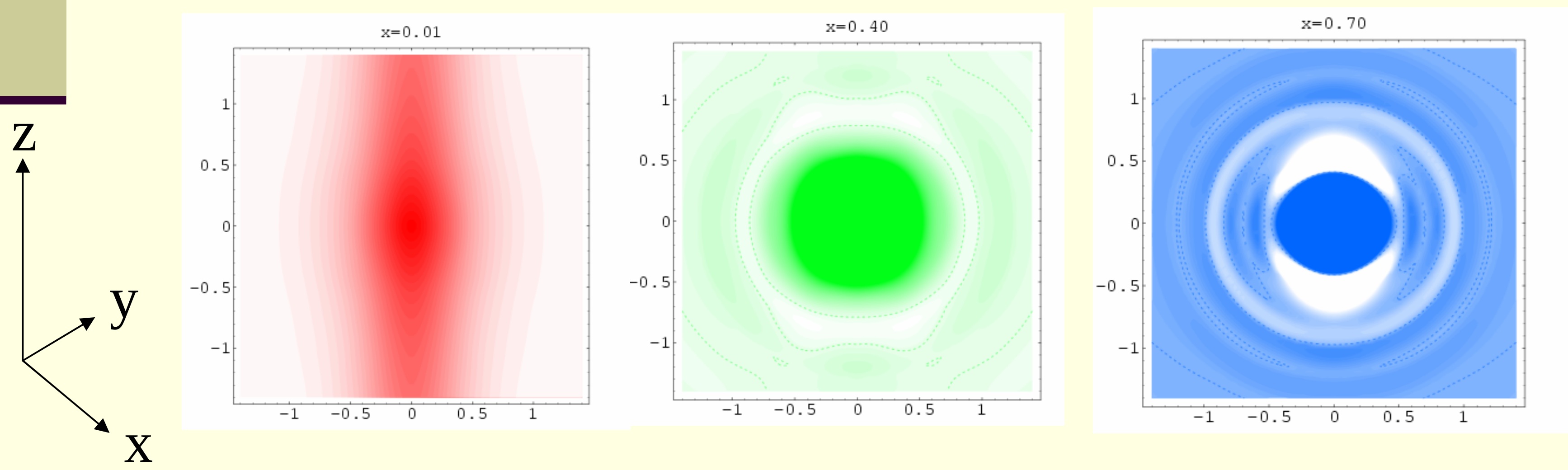
$$f_\Gamma(\vec{r},x) = \frac{1}{2M}\int \frac{d^3\vec{q}}{(2\pi)^3} e^{-i\vec{q}\cdot\vec{r}} F_\Gamma(x,\xi,t) .$$

$$\frac{1}{2M}F_{\gamma^+}(x,\xi,t) = [H(x,\xi,t) - \tau E(x,\xi,t)] + i(\vec{s}\times\vec{q})^z \frac{1}{2M}[H(x,\xi,t)+E(x,\xi,t)] .$$

- f(**r**,x) provides a 3D distribution of quarks with Feynman momentum x.

3D images of quarks at fixed x

- A parametrization which satisfies the following *Boundary Conditions:* (A. Belitsky, X. Ji, and F. Yuan, PRD,2004)
  - Reproduce measured Feynman distributions
  - Reproduce measured form factors
  - Polynomiality condition
  - Positivity



Spin-dependent observables

- There are many observables depending on the spin of the nucleon, but not *directly* related to the angular momentum decomposition.
  - Magnetic moment
  - Transversity distribution and tensor charge
  - g_2-structure function & other higher-twist distributions
  - Sivers functions and other spin and transverse-momentum dependent (TMD) parton distributions.
  - Spin-dependent GPDs

Most interesting ones are related to phenomena of transverse polarization

Arguments for Transversity

- It's one of the three twist-2 distributions.
- It describes the density of transversely polarized quarks in a transversely polarized nucleon.
- It is chirally-odd.
- It is closely related to the axial charge: the quark helicity contribution to nucleon helicity.
- …

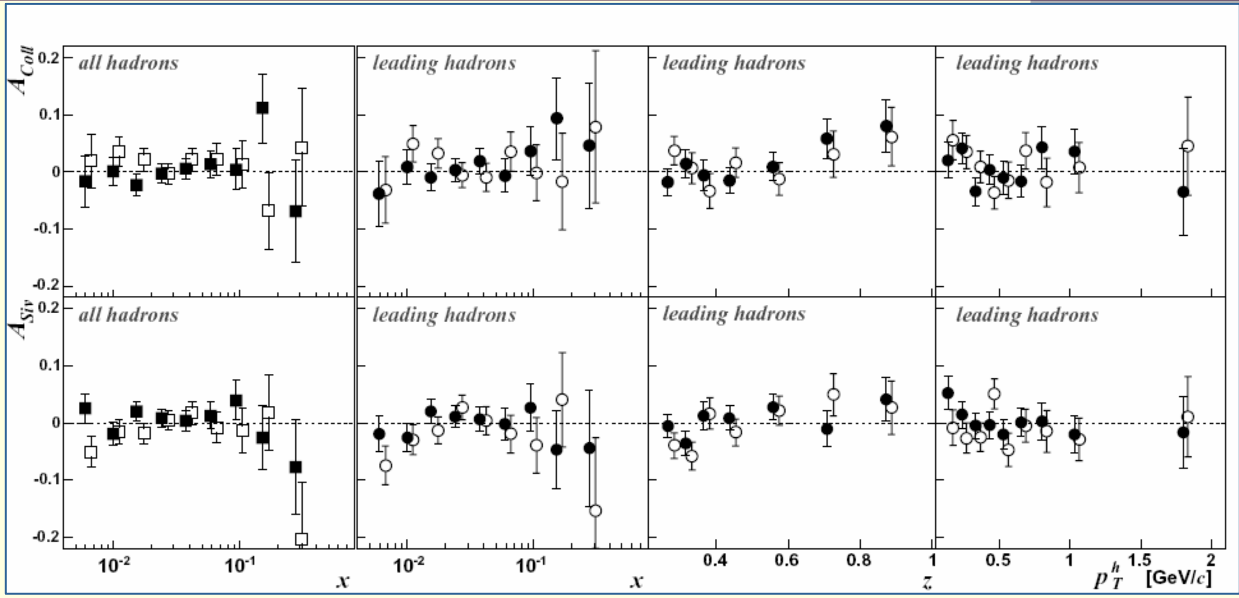
Which is the killer argument?

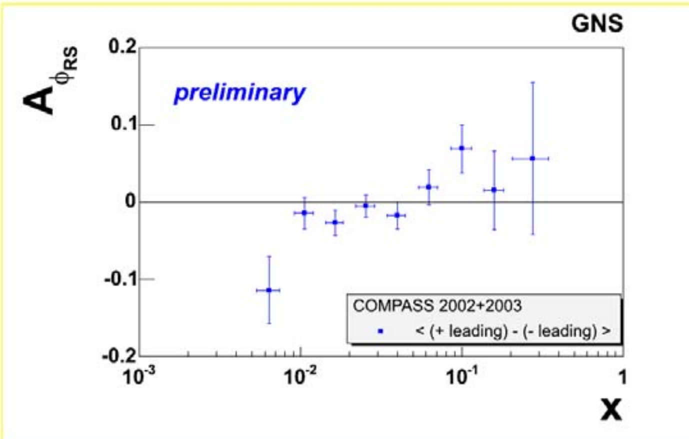
Measurement is hard

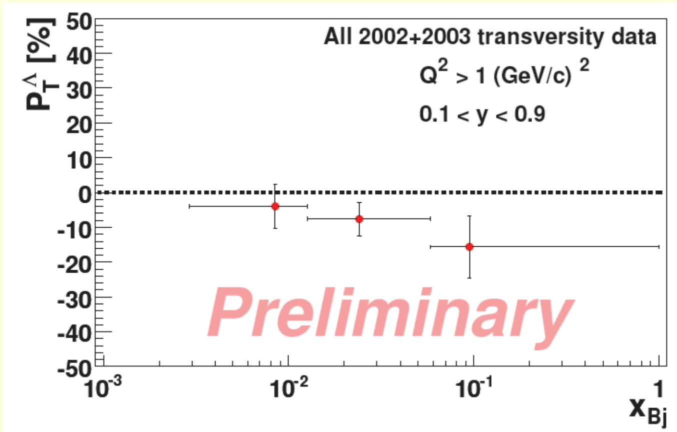
- Many ideas have been proposed
  - In e-p scattering
    - Collins effects, two hadron production
    - Lambda production
    - Twist-3 fragmentation
    - …
  - In pp(p-bar) scattering
    - Drell-Yan
    - …

It will take a lot of more effort to measure the transversity distribution than other twist-2s!

Experimental progress







It is crucial to have higher energy!

- Semi-inclusive process
  - Generally requires higher-Q to see scaling
  - Underlying parton picture: jet fragmentation, but we don't have jets
  - Spin-dependent process generally more delicate
- Questions
  - Can Hermes data be interpreted in parton-physics?
  - How small an error bar can one get?
  - Can we learn something if we don't know the corresponding chiral-odd distribution?
  - Absolute normalization?

Conclusions

- Spin physics since EMC has gone well and strong!
- We may have a rough picture of the gluon polarization quite soon.
- Get the orbital motion of the quarks!
  - Measure GPDs, please!
- Other spin-dependent observables (transversity, sivers function, …,) can potentially teach us a lot about non-perturbative QCD.