Lepton Beam

Spin Physics at Existing Facilities

^

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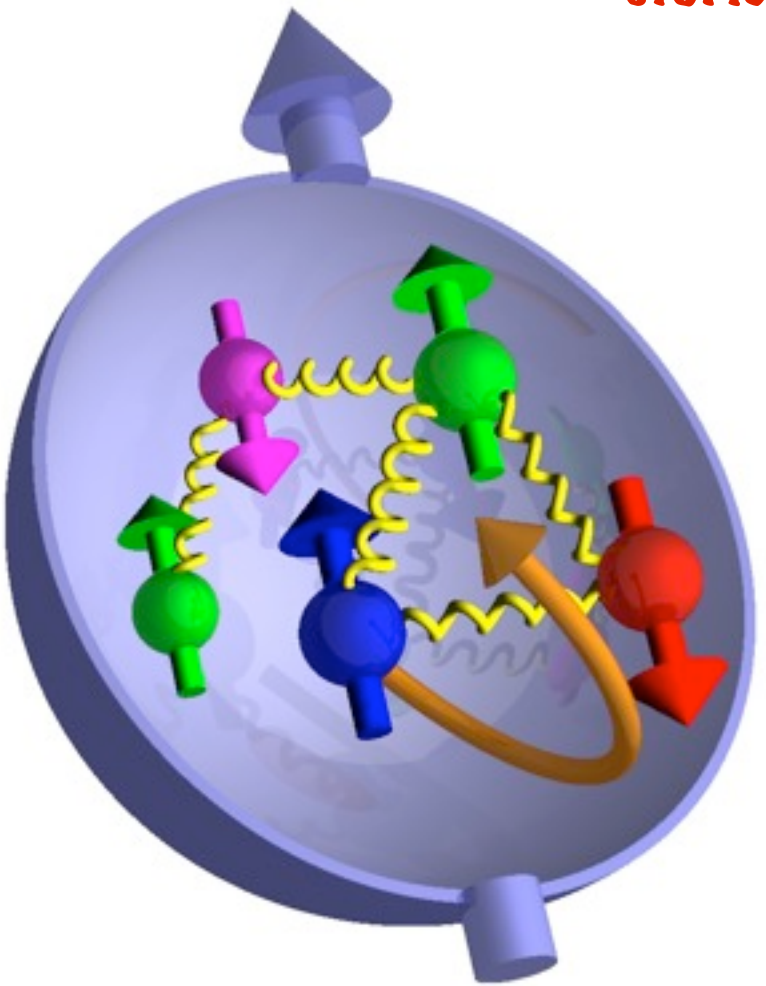
see other talks for proton-beam stories!

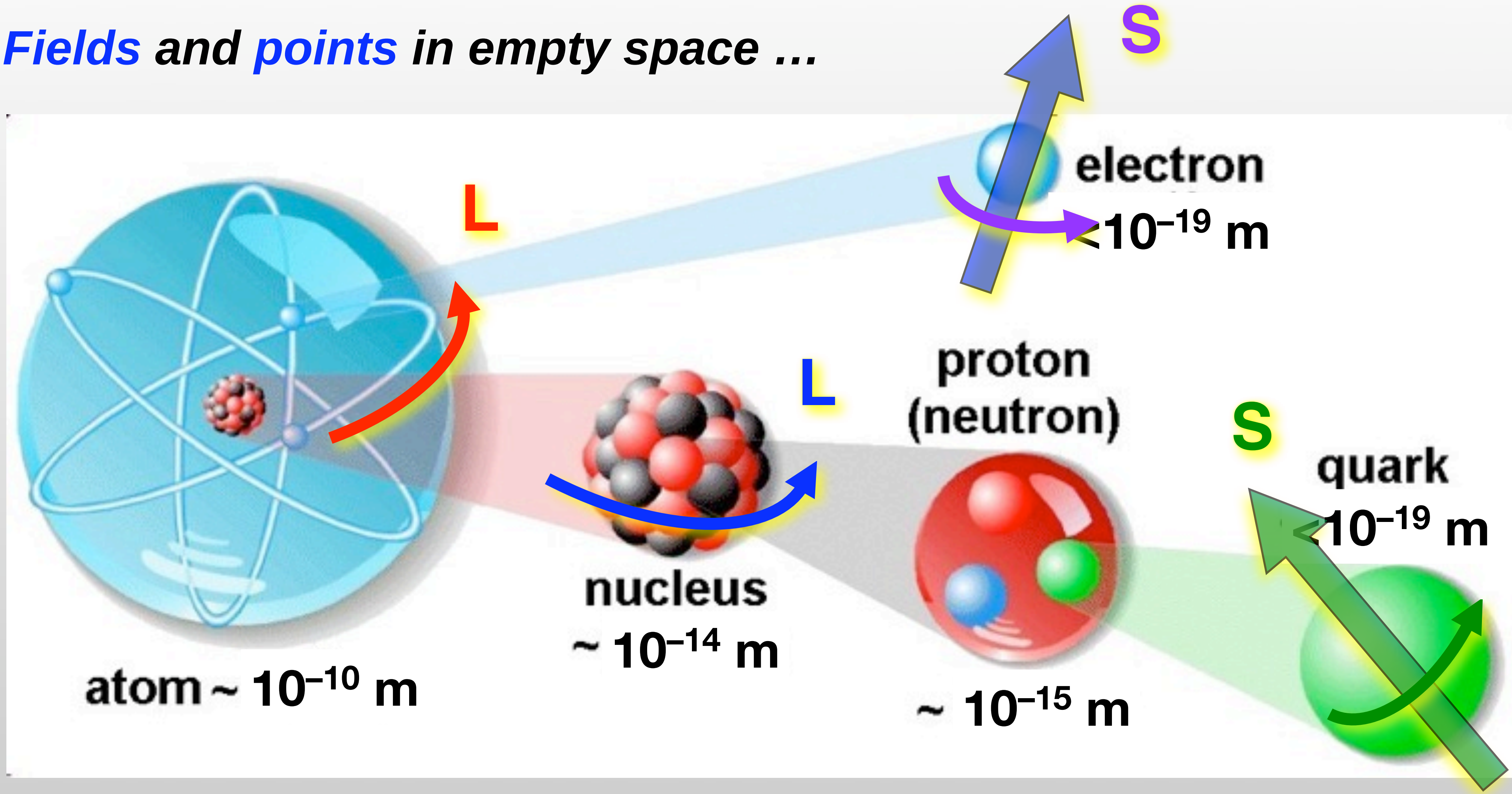
Outline

- **Spin at the Heart of Matter**: the restless world within the atom
- **Single-spin asymmetries**: a key to the spin kingdom
- **Inside the proton**: quark spin & orbital motion
- **A coherent picture**: Are we there yet?



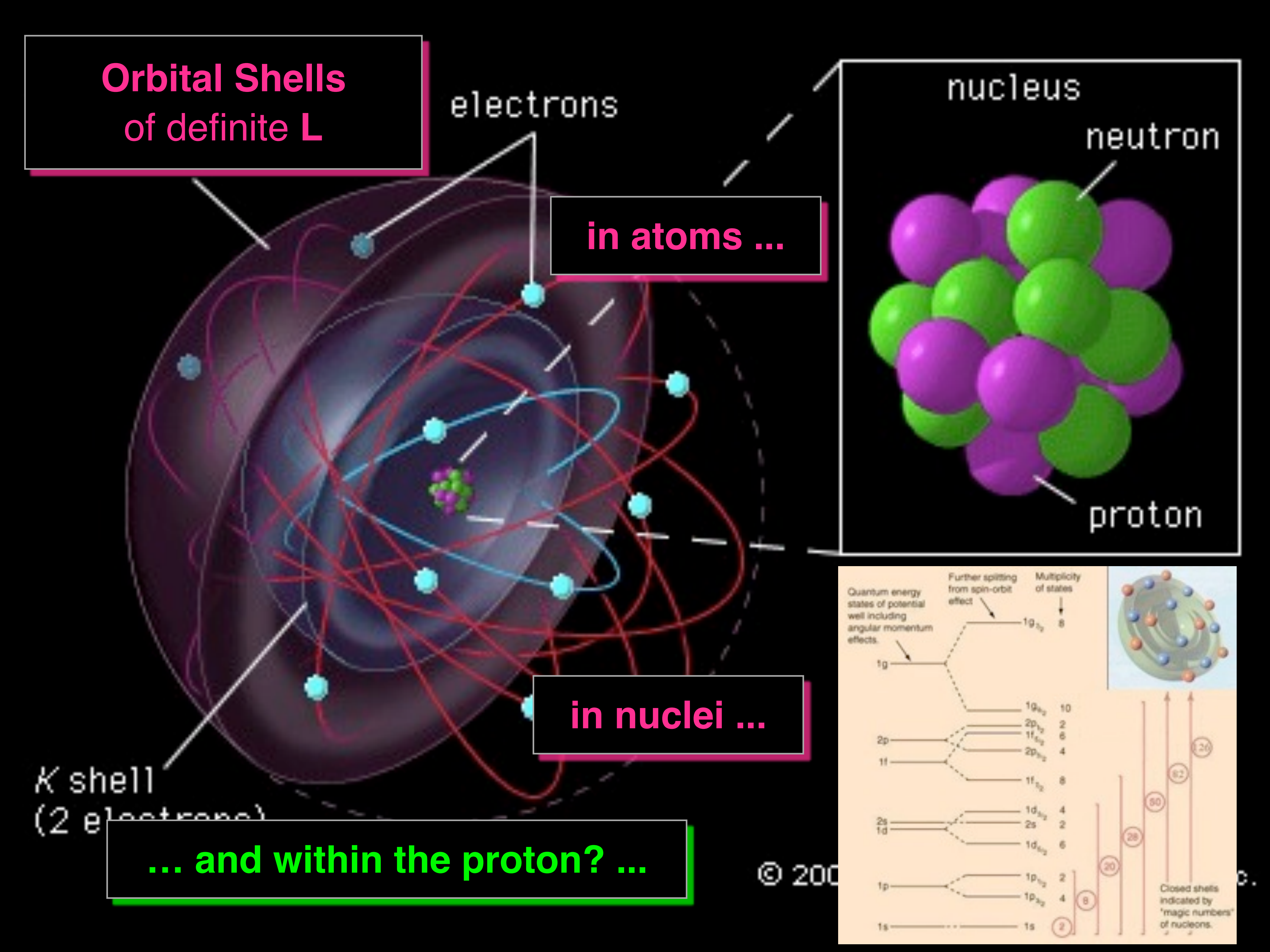
The Strange Nature of Matter

***Fields** and **points** in empty space …*



… and at every level, there is motion:

pointlike particles, forever spinning and orbiting ...

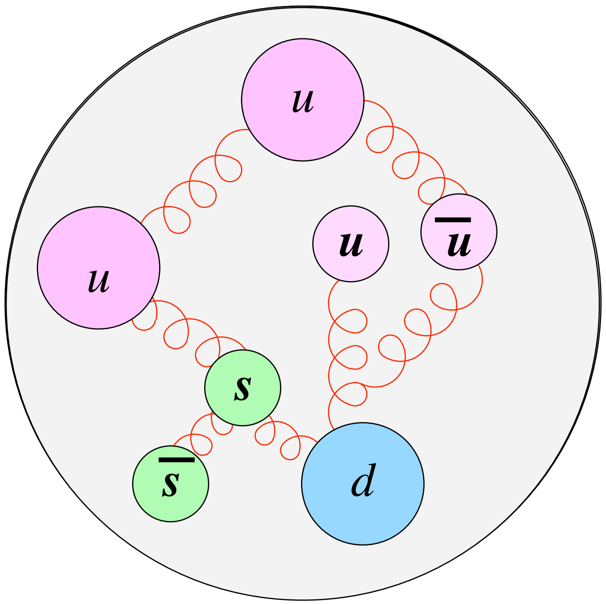


Orbital Shells
of definite L
electrons
in atoms ...
nucleus
neutron
proton
in nuclei ...
K shell
... and within the proton? ...
Quantum energy states of potential well including angular momentum effects.
Further splitting from spin-orbit effect
Multiplicity of states
1g
2p
1f
2s
1d
1p
1s
$1g_{7/2}$ 8
$1g_{9/2}$ 10
$2p_{1/2}$ 2
$1f_{5/2}$ 6
$2p_{3/2}$ 4
$1f_{7/2}$ 8
$1d_{3/2}$ 4
2s 2
$1d_{5/2}$ 6
$1p_{1/2}$ 2
$1p_{3/2}$ 4
1s
2
8
20
28
50
82
126
Closed shells indicated by 'magic numbers' of nucleons.

Parton Distribution Functions

Look ***inside*** the proton with high energy beams ...

⇒ a rich substructure is revealed!



sea quarks : virtual quark-antiquark pairs that fluctuate in and out of the vacuum

gluons : the color fields of the strong force

x fraction of proton momentum carried by struck quark

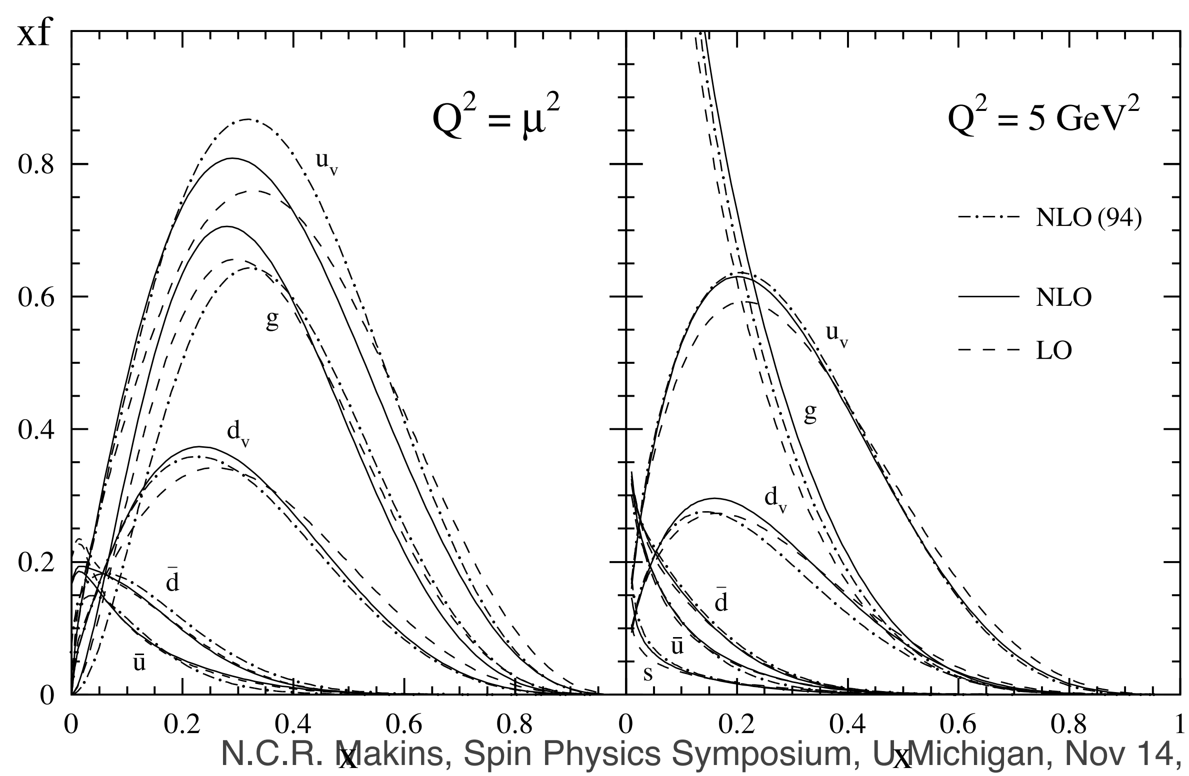
$q(x)$ parton distribution func^n

(number density for quark flavor q)

3 **constituent quarks** of mass ≈ 350 MeV

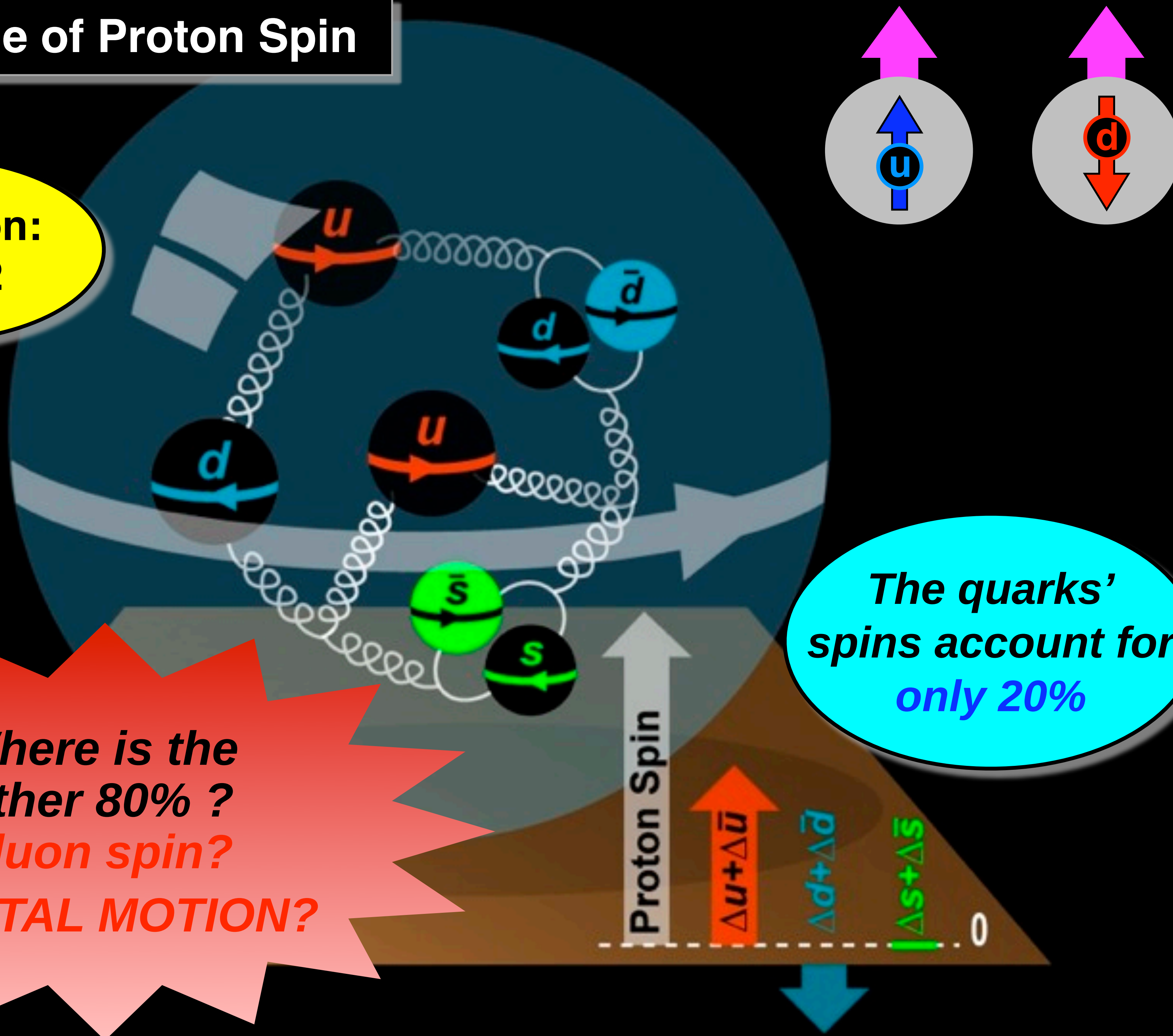
⬇

many **bare quarks** of tiny mass ≈ 5 MeV, and **gluons** account for > 40% of the momentum, ***~all of the mass ...***



The Puzzle of Proton Spin

The proton: spin 1/2

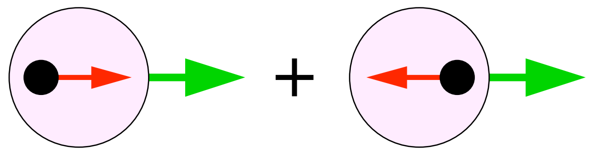


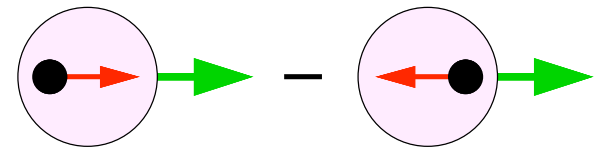
The quarks' spins account for only 20%

Where is the other 80% ?
gluon spin?
ORBITAL MOTION?

Whence comes the proton spin?

$$q(x) = q^{\uparrow}(x) + q^{\downarrow}(x) \qquad \Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$$





only three possibilities →

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

❶ Quark polarization

$$\Delta\Sigma \equiv \int dx\,(\Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta\bar{u}(x) + \Delta\bar{d}(x) + \Delta\bar{s}(x)) \approx 20\%\text{ only}$$

❷ Gluon polarization

$$\Delta G \equiv \int dx\,\Delta g(x) \quad ?$$

❸ Orbital angular momentum

$$L_z \equiv L_q + L_g \quad ?$$

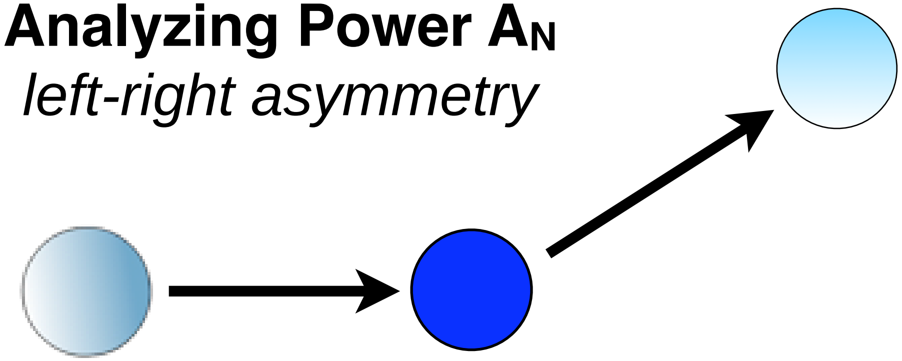
In friendly, **non-relativistic** bound states like atoms & nuclei (& constituent quark model), particles are in ***eigenstates of L → shells***

Not so for bound, ***relativistic Dirac particles*** ...
Noble "l" is ***not a good quantum number***

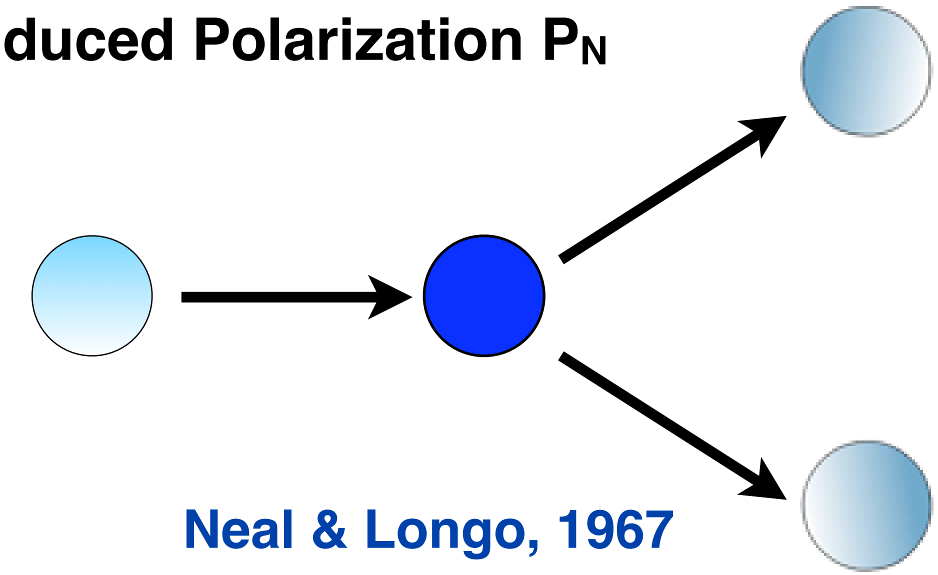
Single-Spin Asymmetries

Single-Spin Asymmetries in Elastic pp Scattering

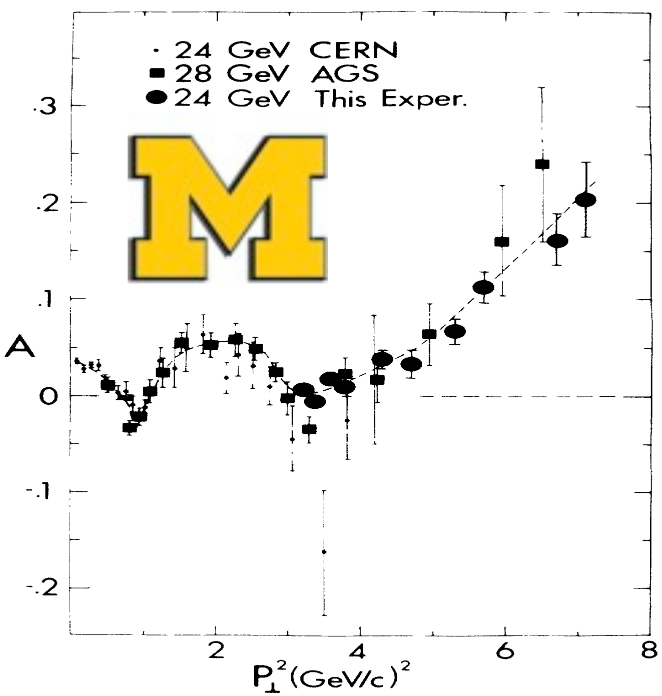
Analyzing Power A_N
left-right asymmetry



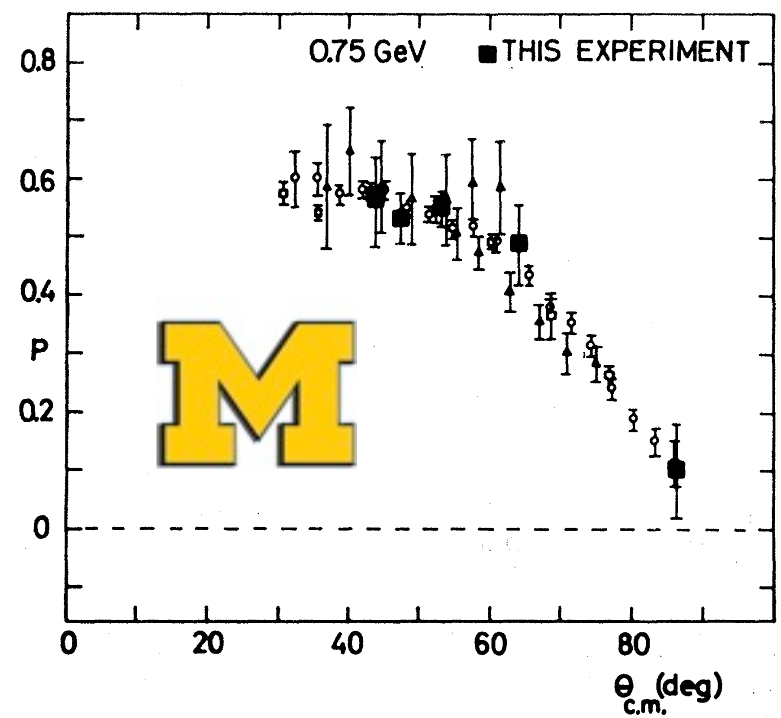
Induced Polarization P_N



Crab, Krisch et al, 1990



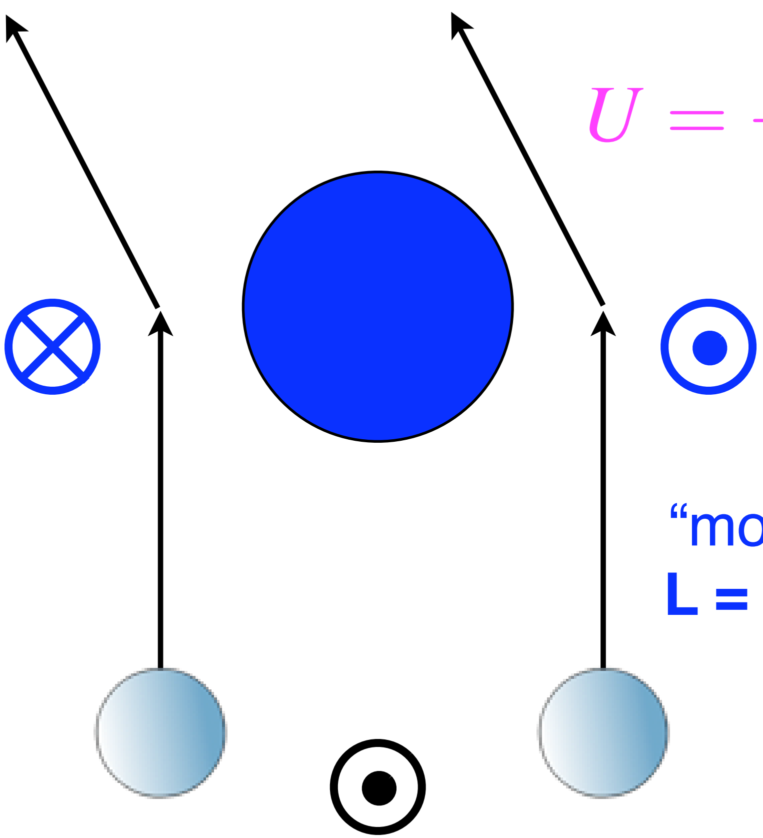
Neal & Longo, 1967



The Spin-Orbit Interaction

particles on **left / right** sides
head for **stronger / weaker** *B*

$$U = -\vec{\mu}\cdot\vec{B}$$



B Field of
"moving" target //
L = r x p of beam
particles

Spin S // Magnetic Moment
of beam polarized

Let *V*(*r*) = target's potential field,
in target rest frame.

Lorentz boost to beam frame:

$$\vec{B}' = -\gamma\frac{\vec{v}}{c^2}\times\vec{E} = \frac{\vec{p}}{mc^2}\times\frac{\vec{r}}{r}\frac{dV}{dr}$$

Using $\vec{r}\times\vec{p} = \vec{l}\hbar$ and

$$U = -\vec{\mu}\cdot\vec{B}' \sim -\vec{s}\cdot\vec{B}'$$

➡ **spin-orbit interaction**

$$U_{s-o} = \frac{\text{const}}{r}\,\frac{dV}{dr}\;\vec{s}\cdot\vec{l}$$

Note: The **origin** of the underlying
potential *V*(*r*) doesn't matter

➡ the result follows from **relativity**

Spin-Orbit Interaction for the short-range Nuclear Force

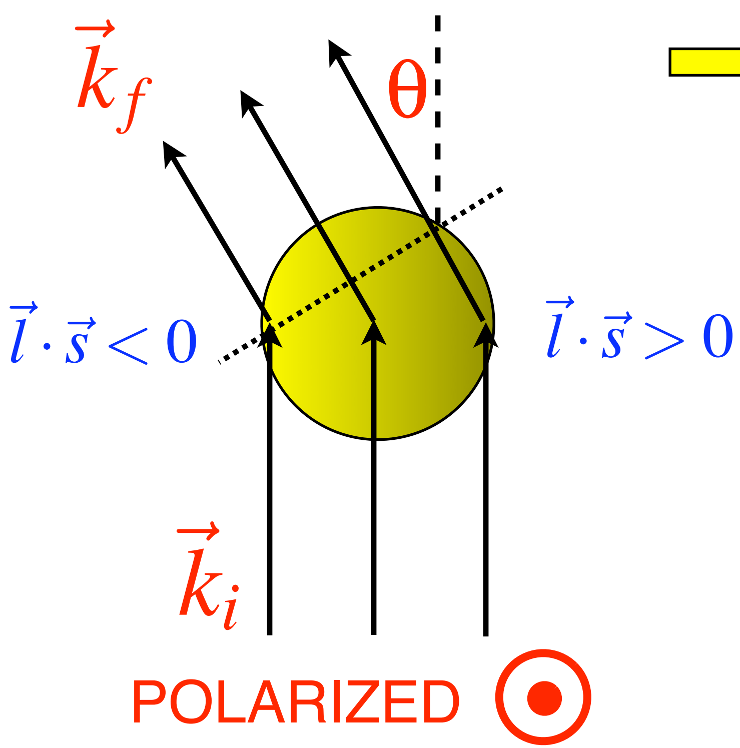
With ρ(r) = target density,

$$U_{s-o} \sim \frac{dV}{dr}\,\vec{s}\cdot\vec{l} \sim \frac{d\rho}{dr}\,\vec{s}\cdot\vec{l}$$

nuclear spin-orbit interaction active at **target surfaces**

SSA: A_N in $p^{\uparrow}p \to pp$

→ sin(θ) term in xsec



$$\psi_{scat} \sim (U_1 + iU_2)e^{ikr} - U_{s-o}e^{ik(r-R\theta)} + U_{s-o}e^{ik(r+R\theta)}$$

$$= (U_1 + iU_2 + 2iU_{s-o}\sin k\theta R)e^{ikr}$$

$$\Rightarrow \frac{d\sigma}{d\Omega} \sim |\psi_{scat}|^2 \sim U_1^2 + U_2^2 + 4U_{s-o}^2\sin^2 k\theta R$$

$$+4U_2 U_{s-o}\sin k\theta R$$

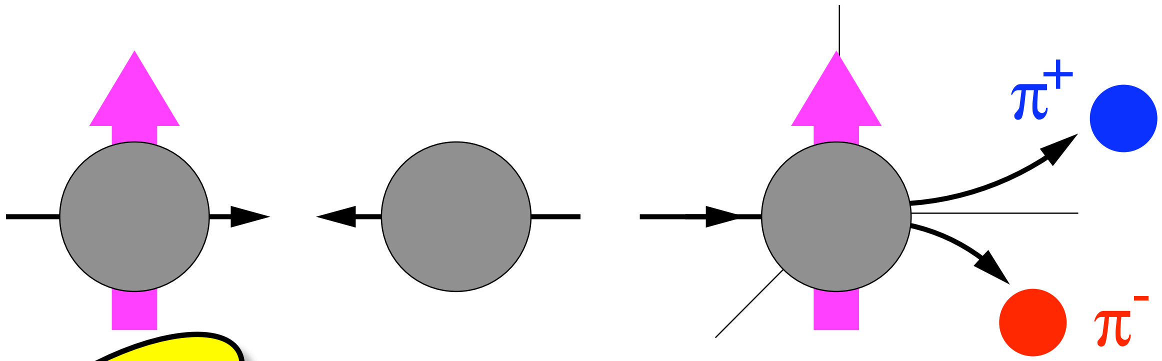
- **Interference**, between an imaginary, spin-independent term U_2 in volume potential and a spin-dependent spin-orbit term U_{s-o}
- **Surfaces** where target density has a gradient → target with structure

Krisch, Crabb, Lin, Raymond, Roser, Wong, et UMich-al, PRL 65 (1990) 3241

While many theoretical models have been suggested to explain the large spin effects found in strong interactions, models based on perturbative QCD imply that the analyzing power should be zero at high energy and large $P_\perp^2$.

Our new high-precision data make it difficult to assume that this disagreement between theory and experiment will disappear because the nonzero A_N is a statistical fluctuation. Perhaps one should now try to gain some new theoretical understanding of strong interactions that is consistent with this and other large and unexpected spin effects.

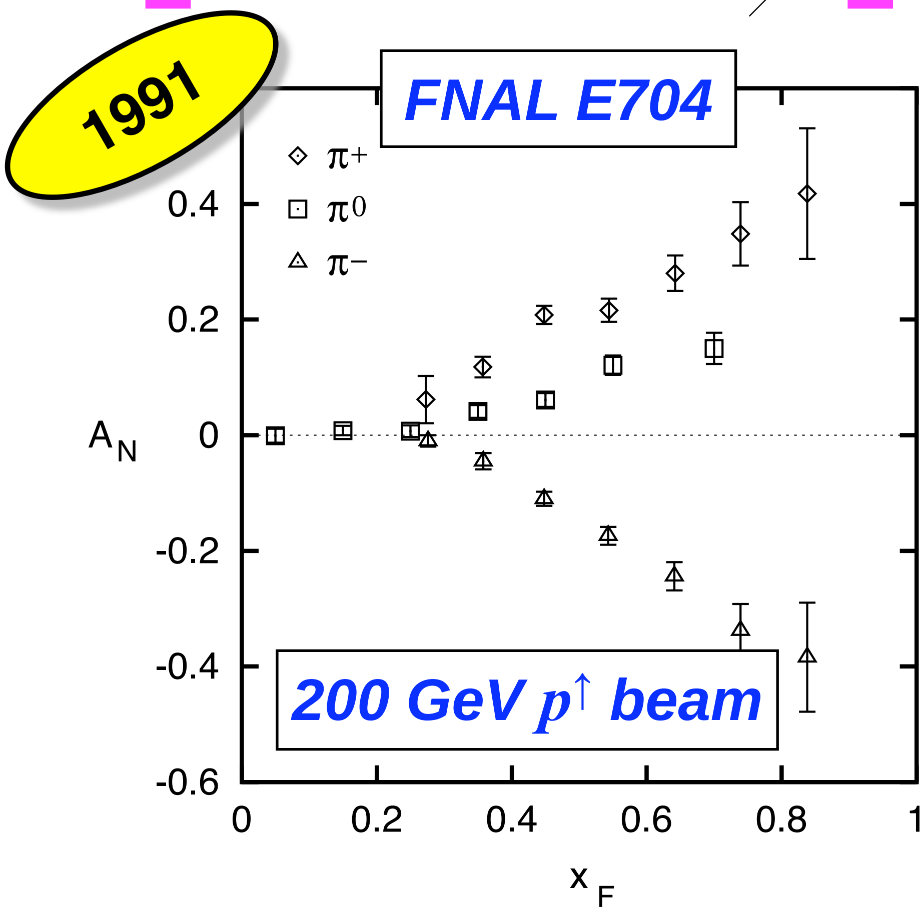
Single-spin asymmetries in $p^{\uparrow}p \rightarrow \pi X$

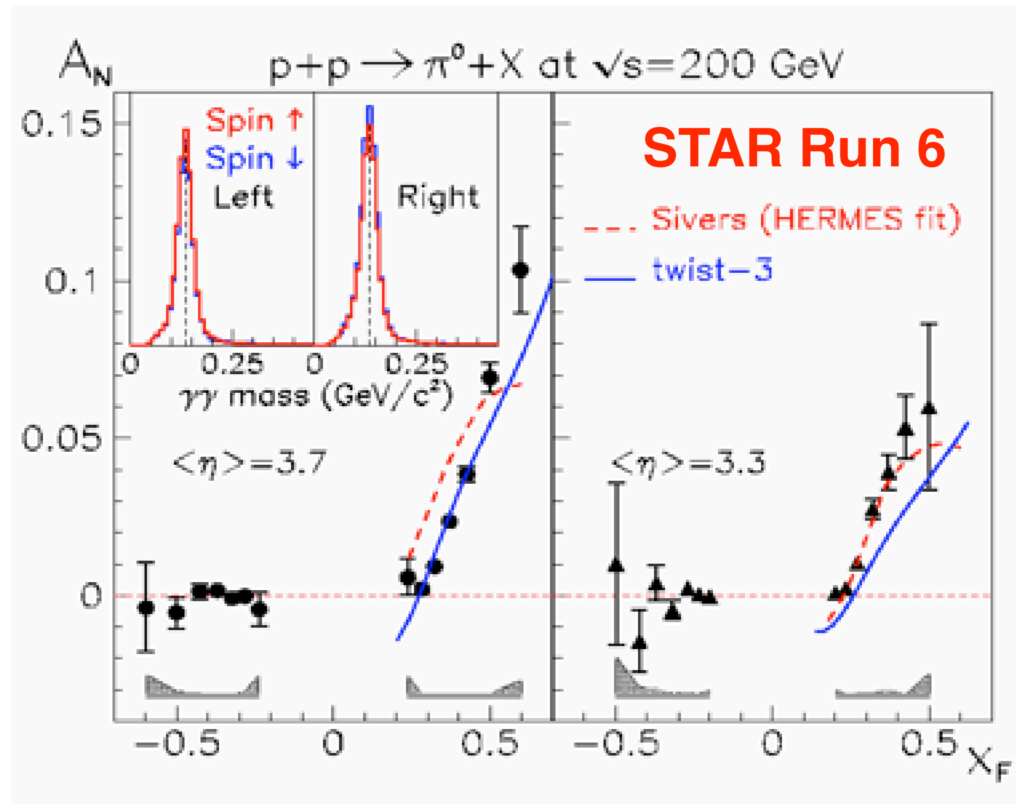


Analyzing Power

$$A_N = \frac{1}{P_{\text{beam}}} \frac{N^{\pi}_{\text{left}} - N^{\pi}_{\text{right}}}{N^{\pi}_{\text{left}} + N^{\pi}_{\text{right}}}$$

Huge ***single-spin asymmetry***
for ***forward meson production***

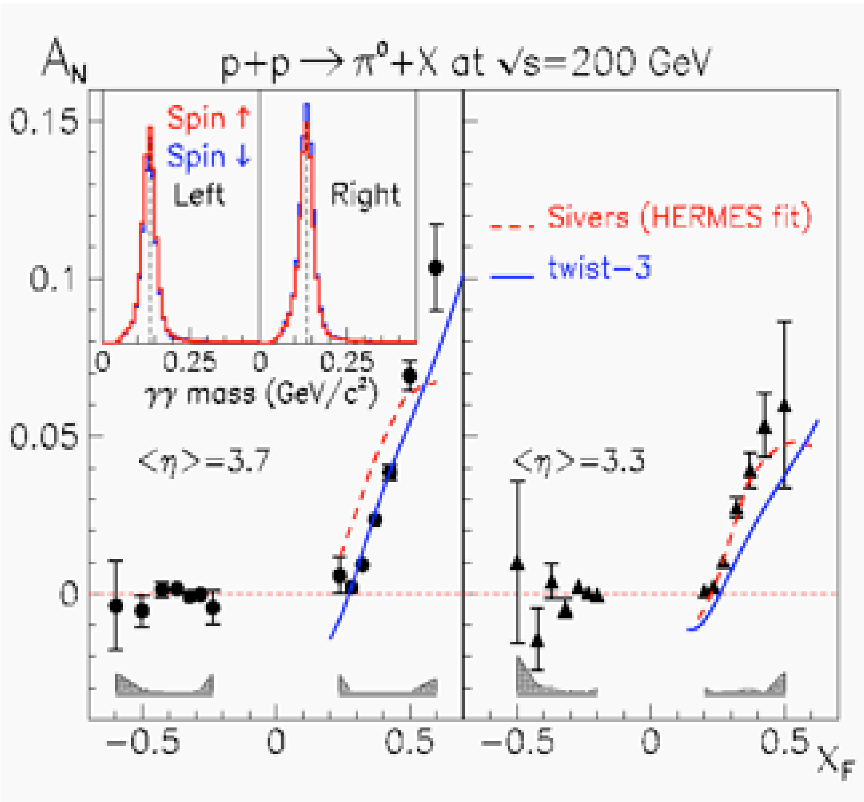




Observable $\vec{S}_{\text{beam}} \cdot (\vec{p}_{\text{beam}} \times \vec{p}_{\pi})$ ***odd*** *under naive* ***Time-Reversal***

SSA's at high-energies

STAR Run 6



T-odd observables

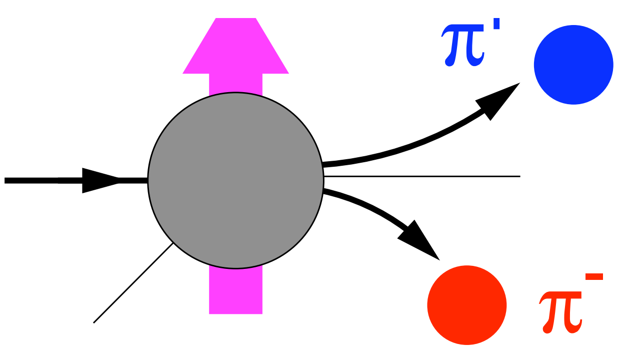
SSA observables $\sim \vec{\mathbf{J}} \cdot (\vec{\mathbf{p_1}} \times \vec{\mathbf{p_2}})$

$\Rightarrow$ ***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**

an't come from perturbative subprocess xsec:

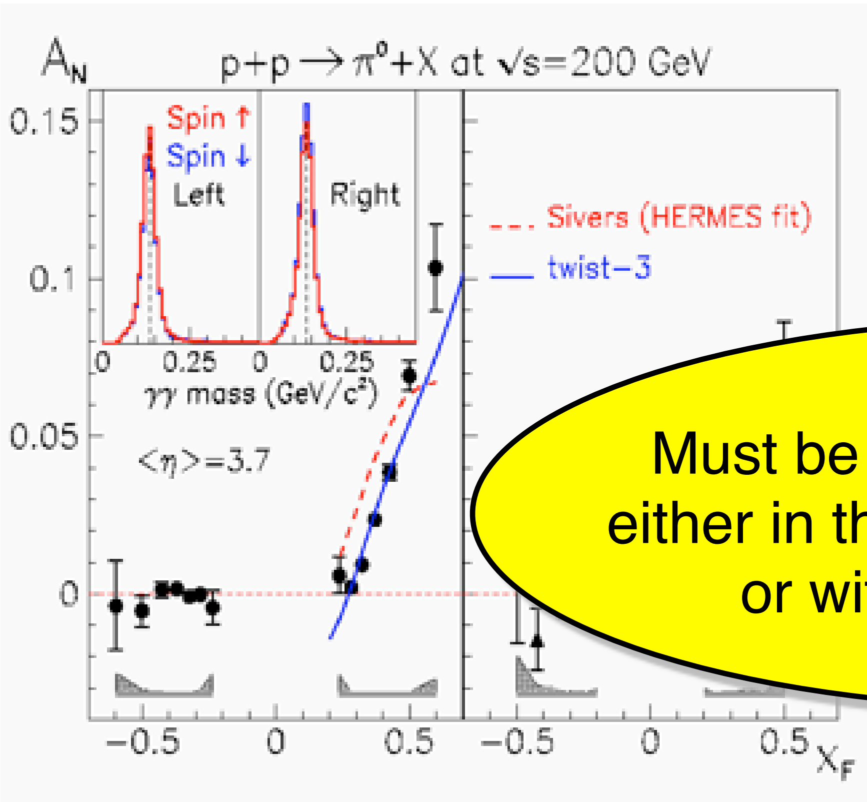
- q helicity flip suppressed by $m_q/\sqrt{s}$
- need α_s-suppressed loop-diagram to generate necessary phase



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

SSA's at high-energies

STAR Run 6



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***

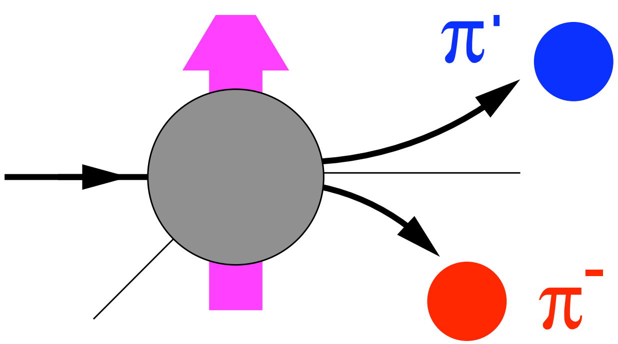
Since QCD amplitudes are T-even, must arise **from interference** between **spin-flip** and ... **different phases**

...**ubprocess xsec:**

...ed by $m_q/\sqrt{s}$

- need α_s-suppressed loop-diagram to generate necessary phase

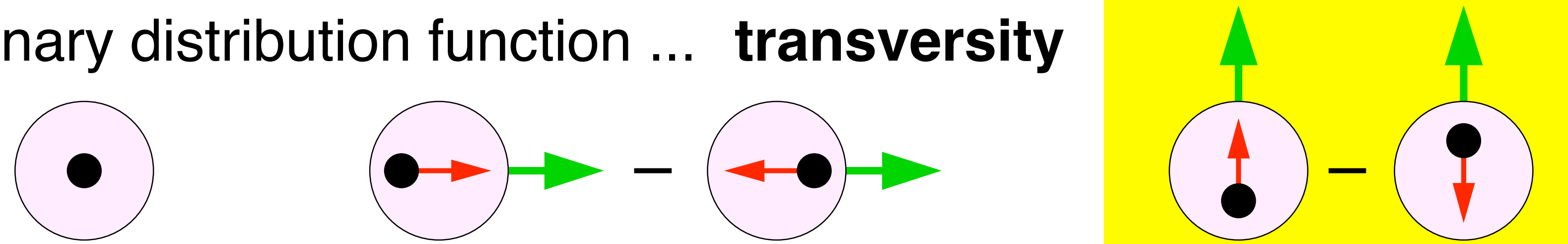
Must be a **spin-orbit structure** either in the fragmentation process or within the proton itself



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

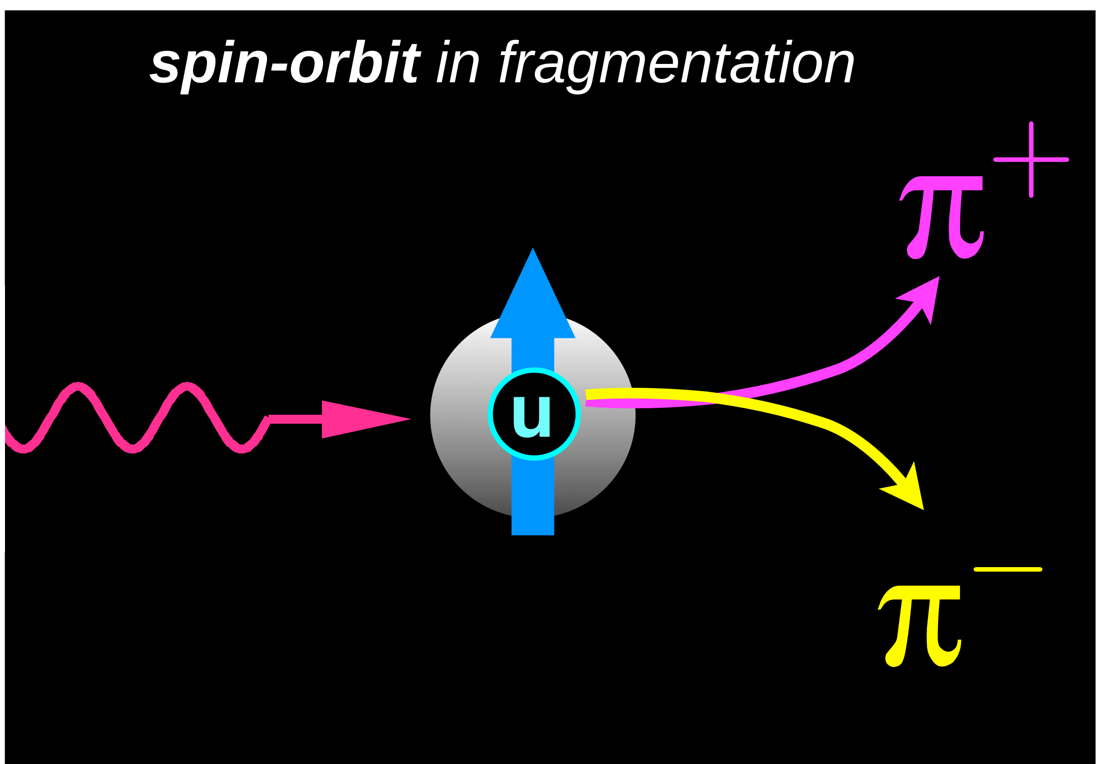
E704 Mechanism #1: The "Collins Effect"

Need an ordinary distribution function ... **transversity**

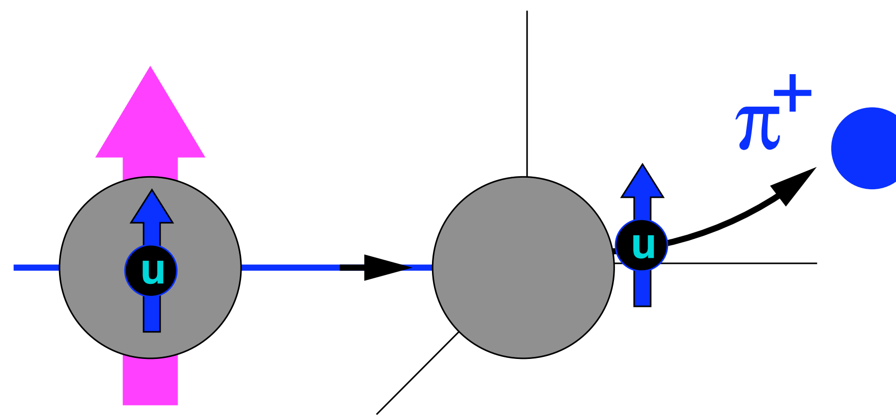


$q(x)$ $\Delta q(x)$ $h_1(x)$

... with a new, **T-odd "Collins" fragmentation function** $H_1^{\perp}(z, p_T)$



E704 effect:



$$h_1(x) \otimes H_1^{\perp}(z, p_T)$$

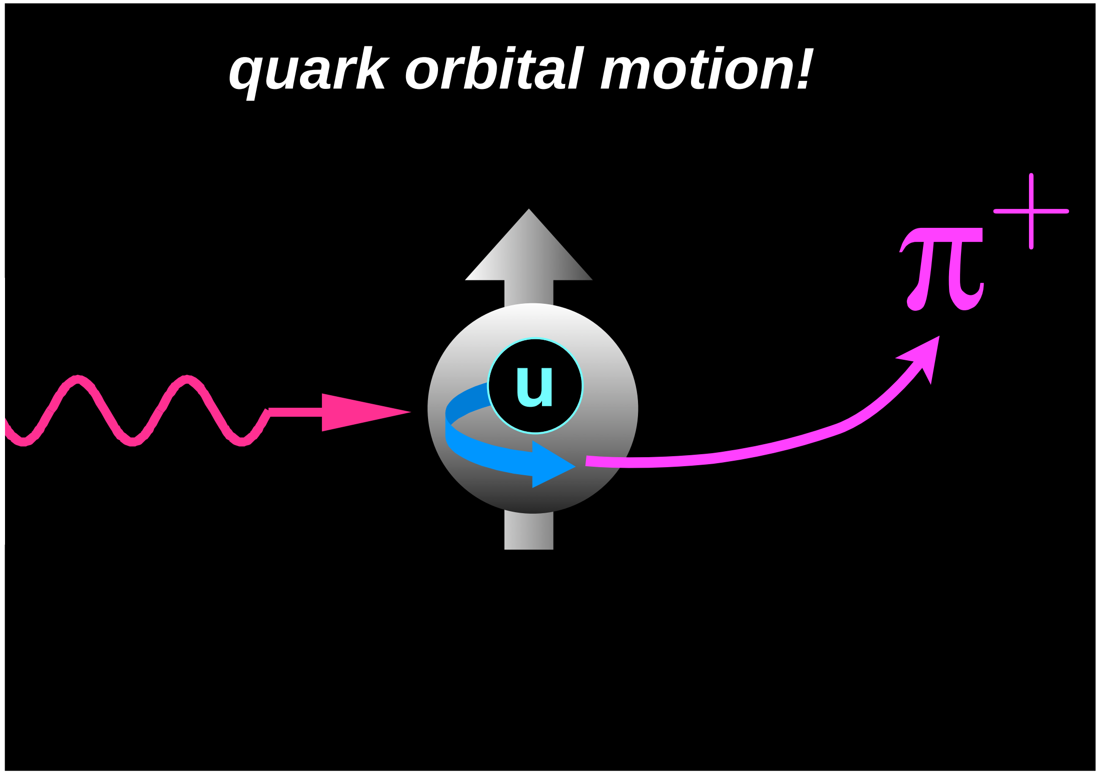
E704 Mechanism #2: The "Sivers Effect"

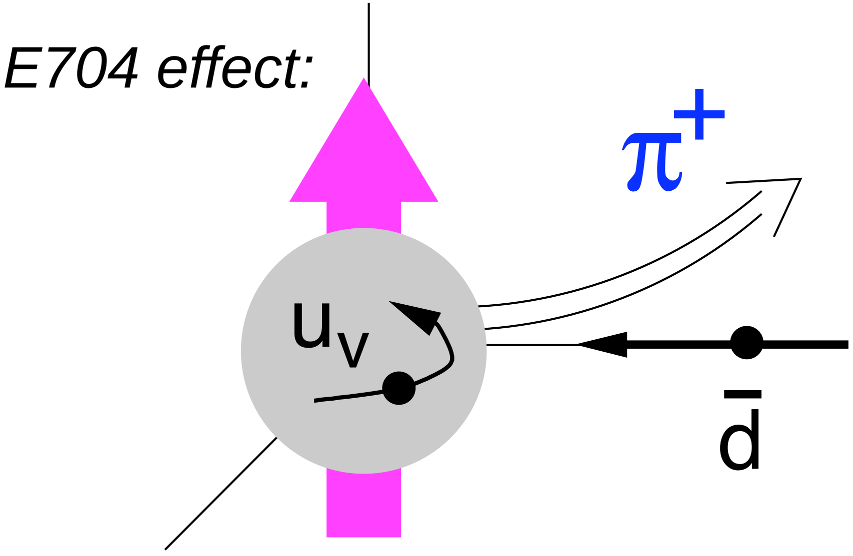
Need the ordinary fragmentation function $D_1(z)$

... with a new, **T-odd "Sivers" distribution function** $f_{1T}^{\perp}(x, k_T)$

Phenomenological model of **Meng, Boros, Liang**:

Forward π+ produced from **orbiting valence-u quark** by recombination at *front surface* of beam protons





$$f_{1T}^{\perp}(x, k_T) \otimes D_1(z)$$

Electro-Production of Hadrons with Tranvserse Targets

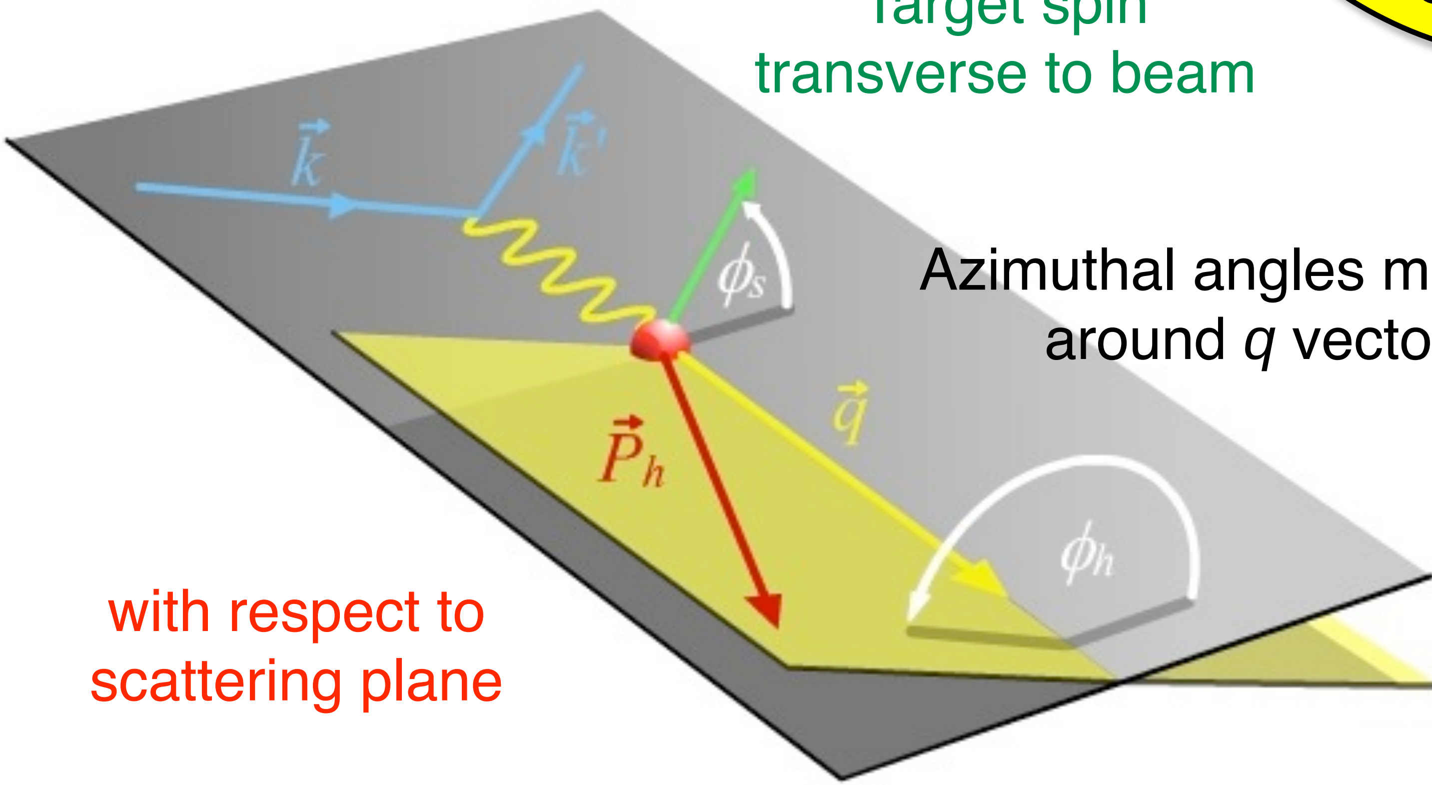
Measure dependence of hadron production on **two azimuthal angles**

lepton beams!

Electron beam defines scattering plane

Target spin transverse to beam

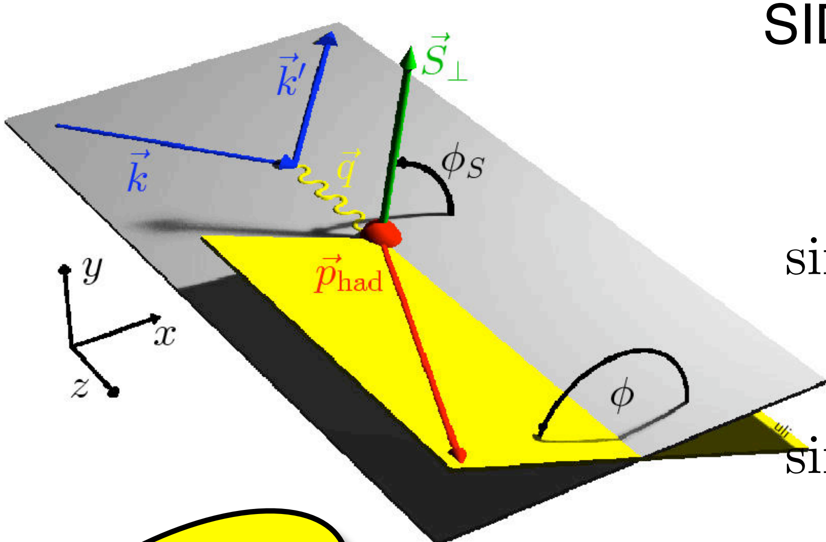
Azimuthal angles measured around *q* vector ...



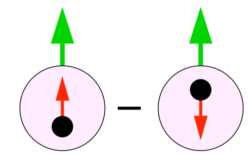
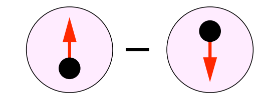
with respect to scattering plane

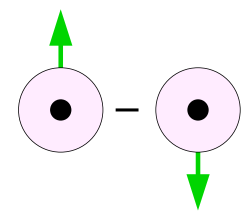
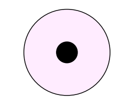
ϕ_S **= target spin orientation** ϕ_h **= hadron direction**

Electroproduction of Pions with Transverse Target



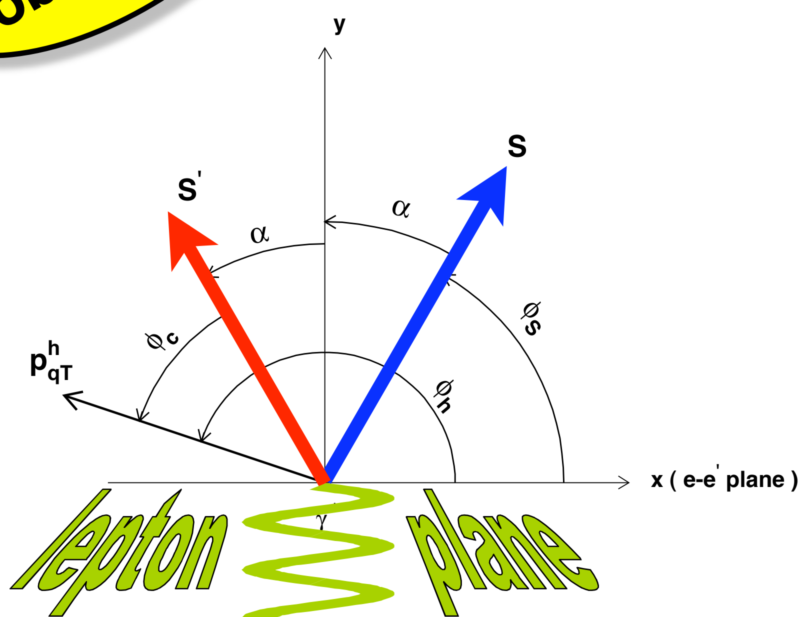
SIDIS xsec with ***transverse target*** polarization has ***two*** similar terms:

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

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

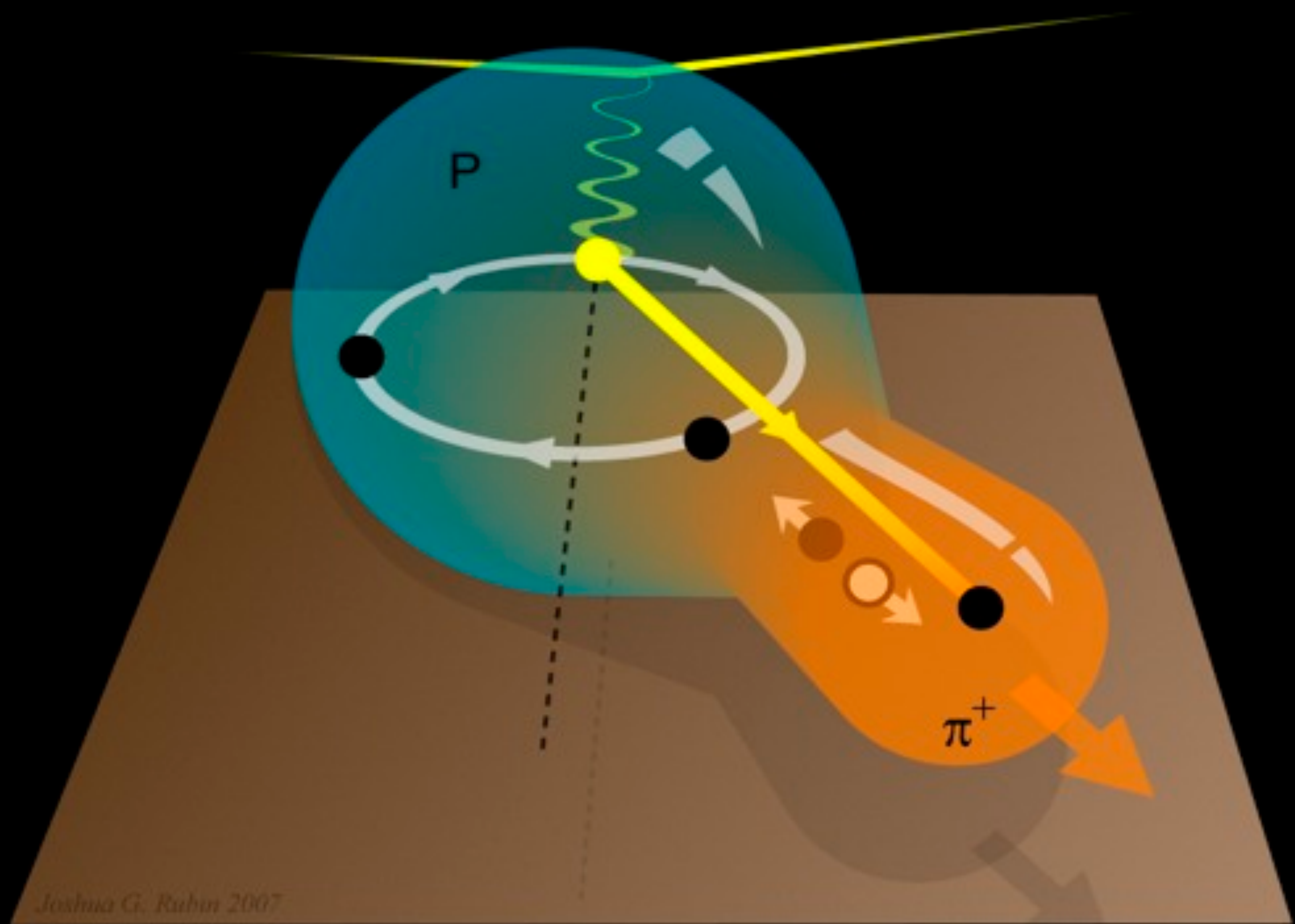
both observed!

separate 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

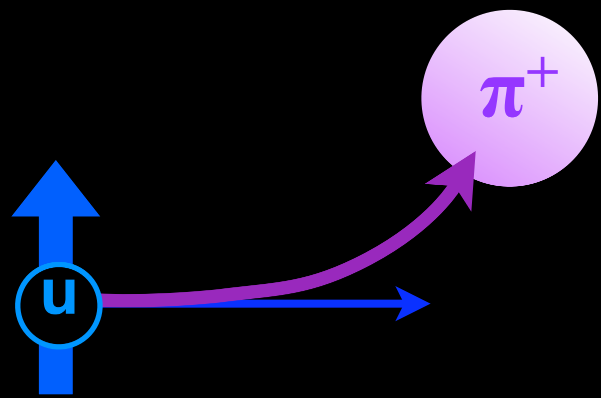
Results from lepton beams: Collins, Sivers, and friends



hermes

COMPASS

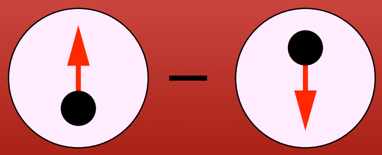
BELLE



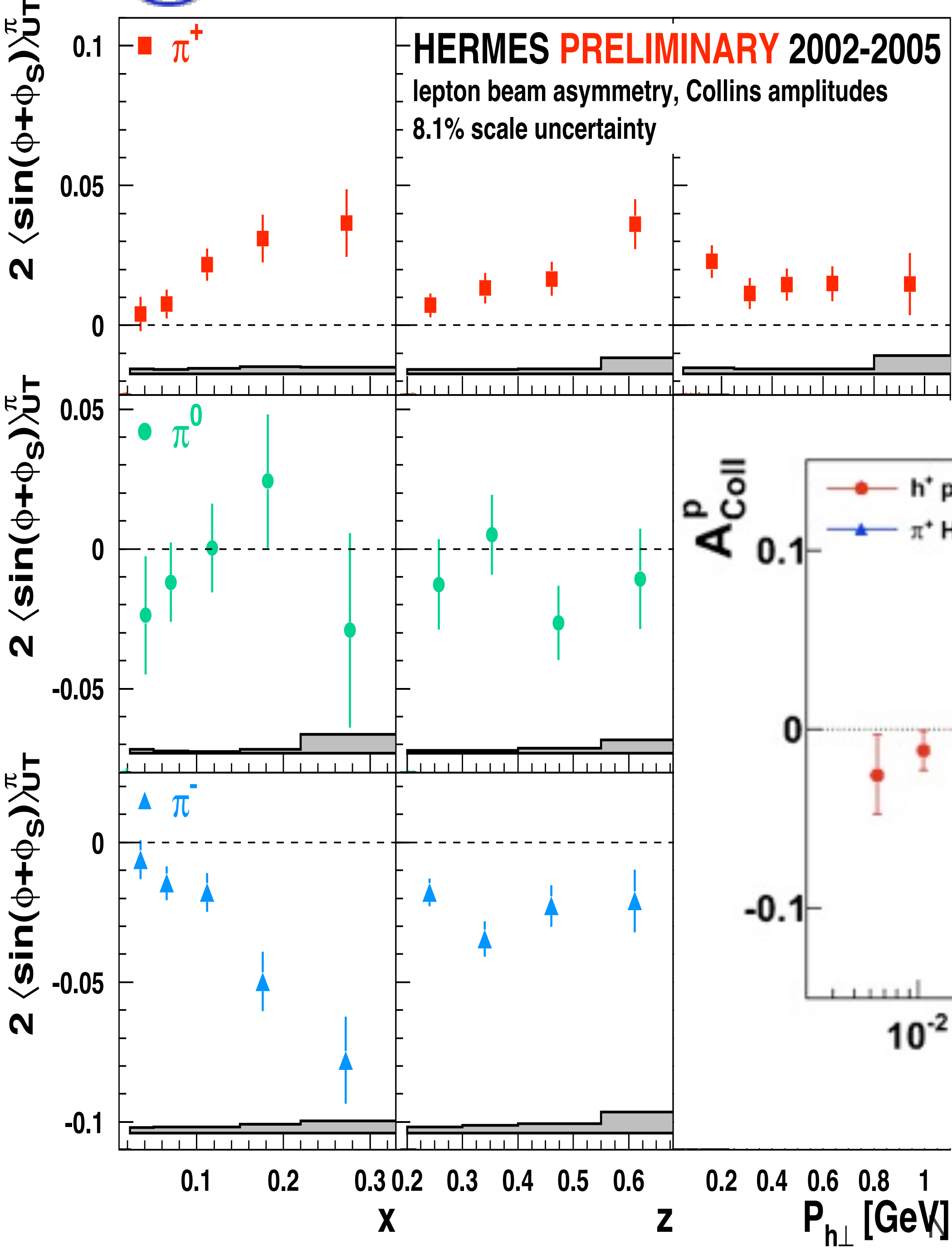
S·L in fragmentation

The Collins Fragmentation Function

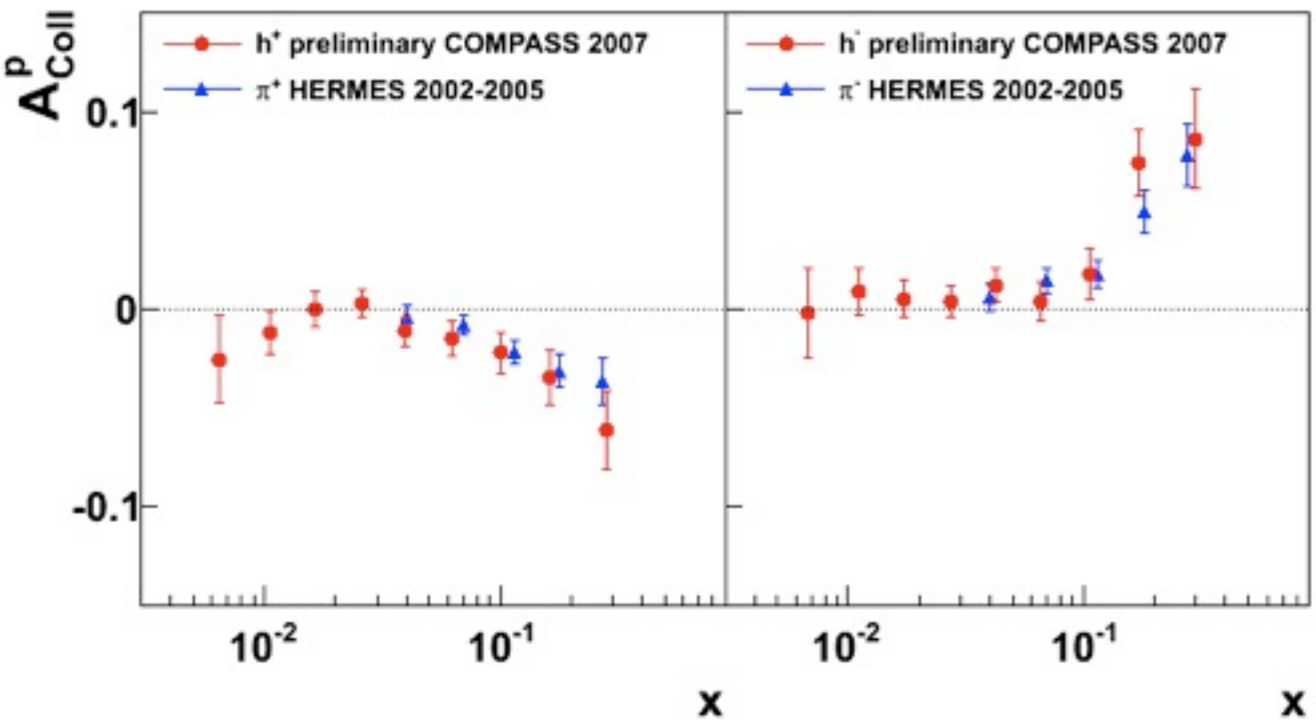
$$H_1^{\perp}(z, p_T)$$



Collins Moments for pions from H$^{\uparrow}$



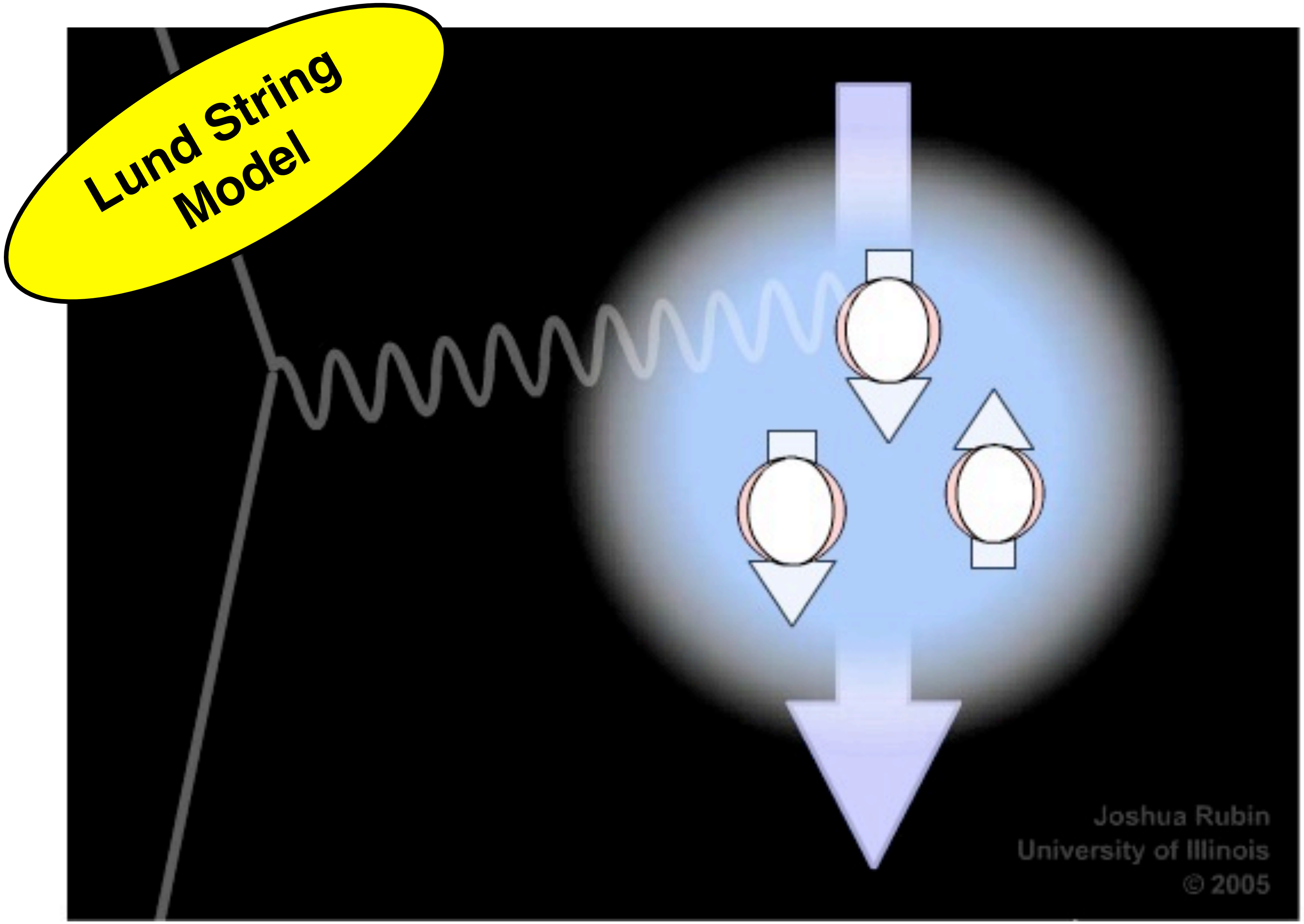
Magnificent agreement at very different scales!

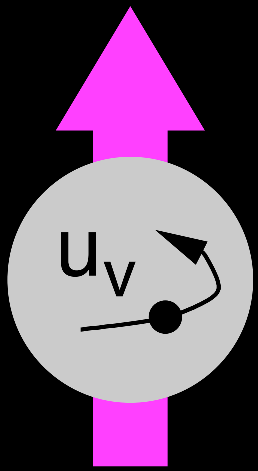


Understanding the Collins Effect

The Collins function exists! ➡ **spin-orbit correlations in π formation**

*Is the **Artru mechanism** responsible?*

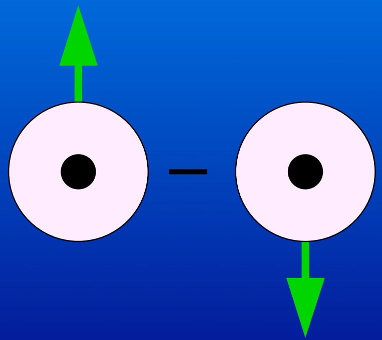




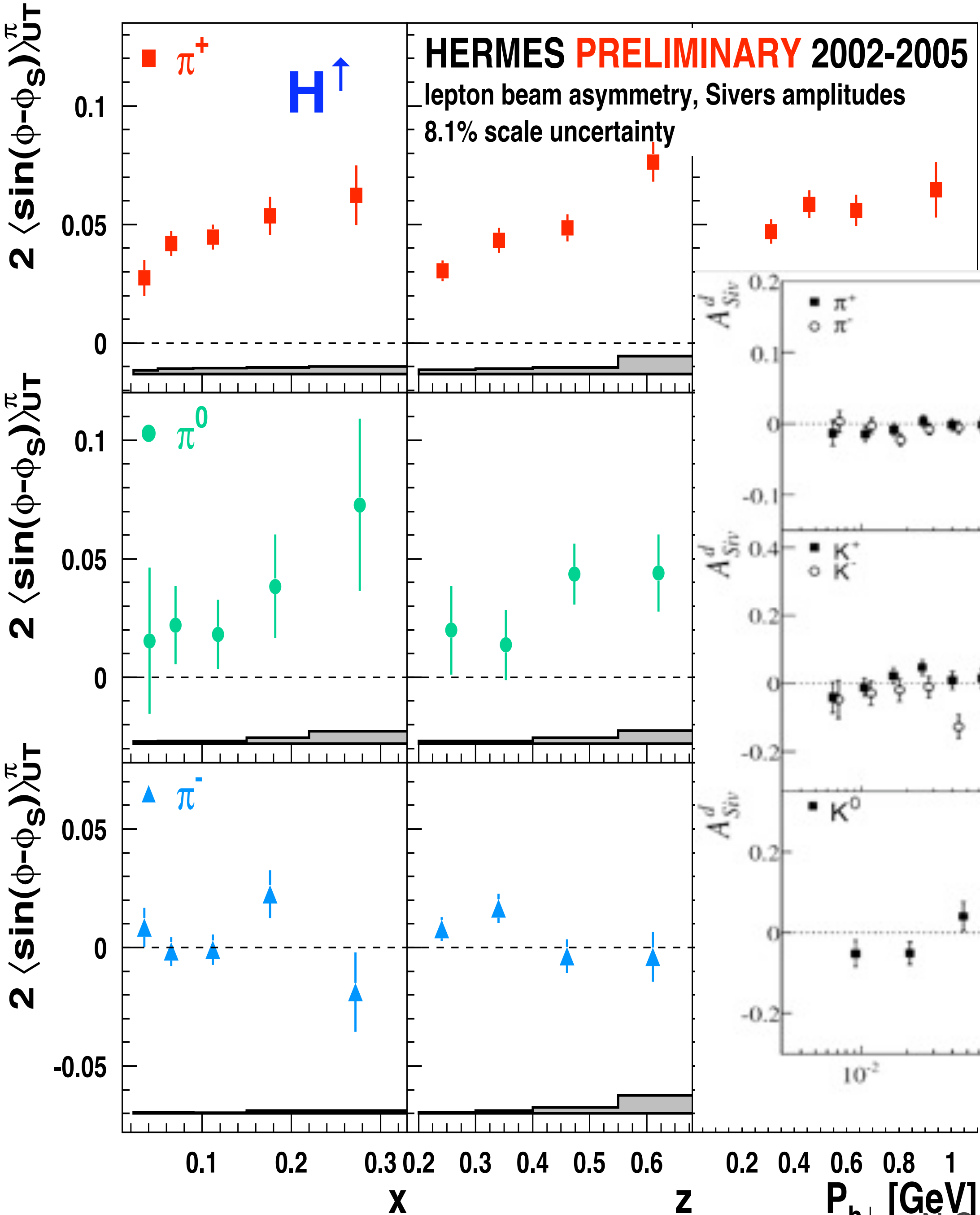
L_q within the proton

The Sivers Function

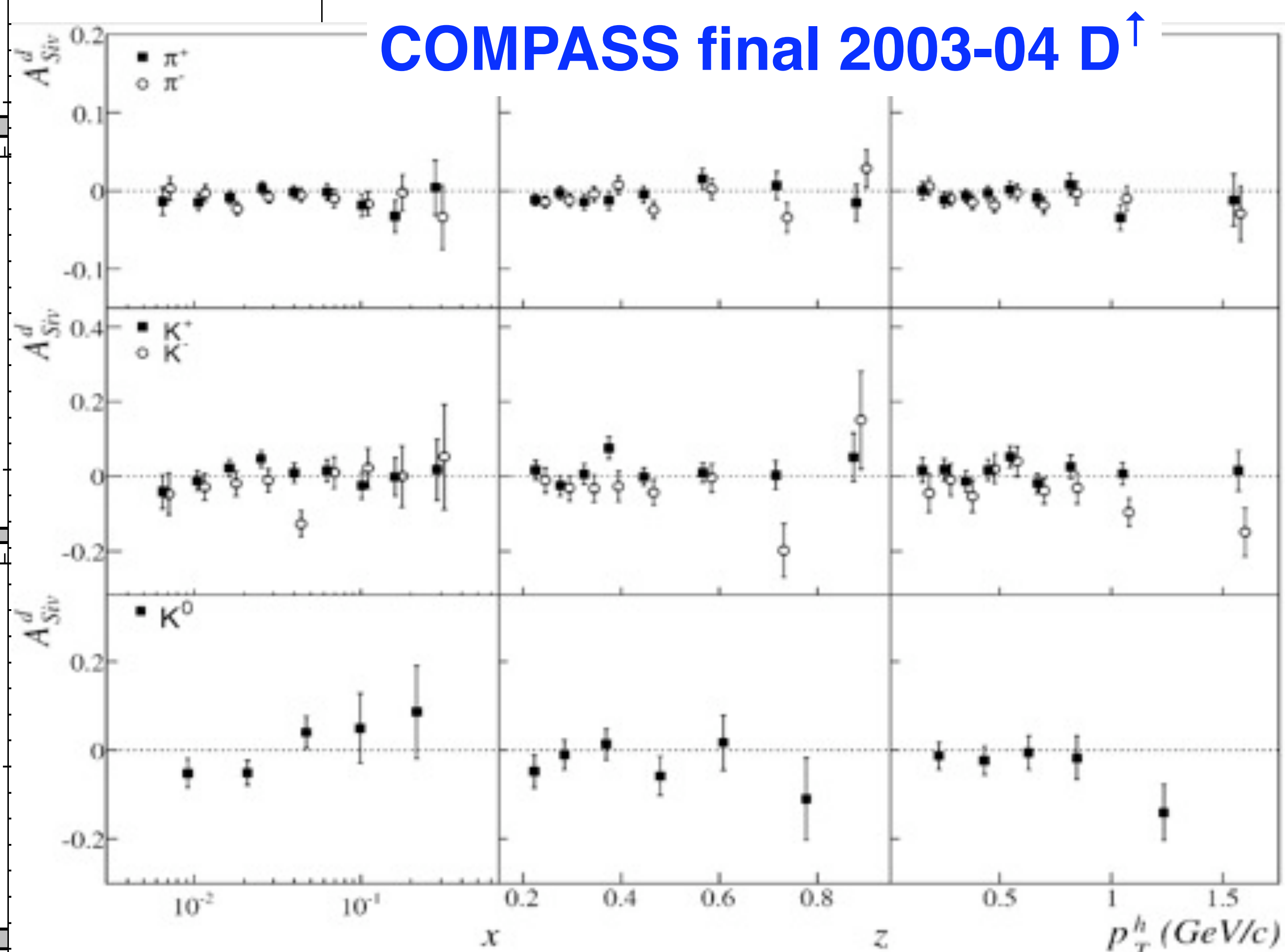
$$f_{1T}^{\perp}(x, k_T)$$



Sivers Moments for pions from H↑ Data



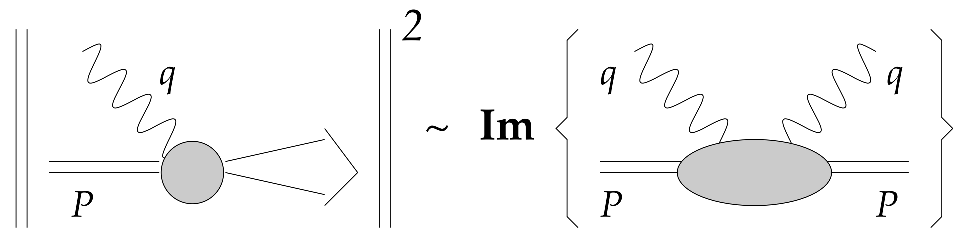
*brief **sample** of current results*



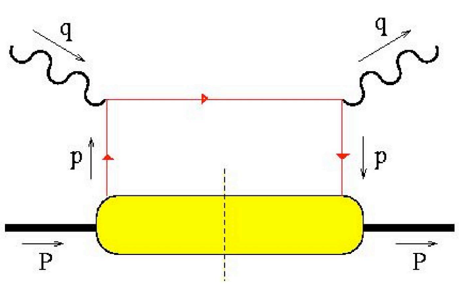
N.C.R. Makins, Spin Physics Symposium, U Michigan, Nov 14, 2009

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

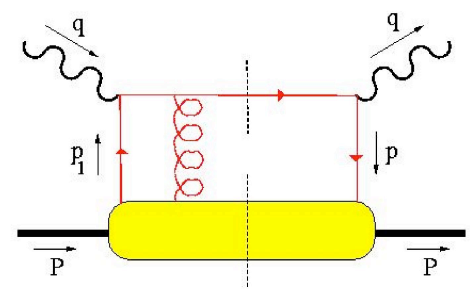
A T-odd function like $f_{1T}^{\perp}$ ***must*** arise from ***interference*** ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?



Brodsky, Hwang, & Schmidt 2002



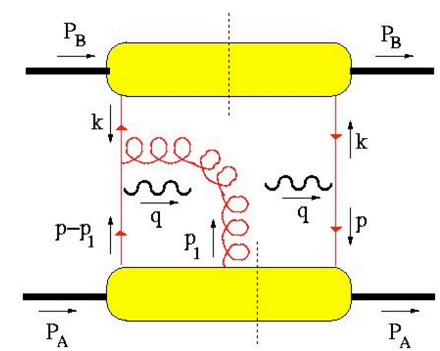
can interfere with



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

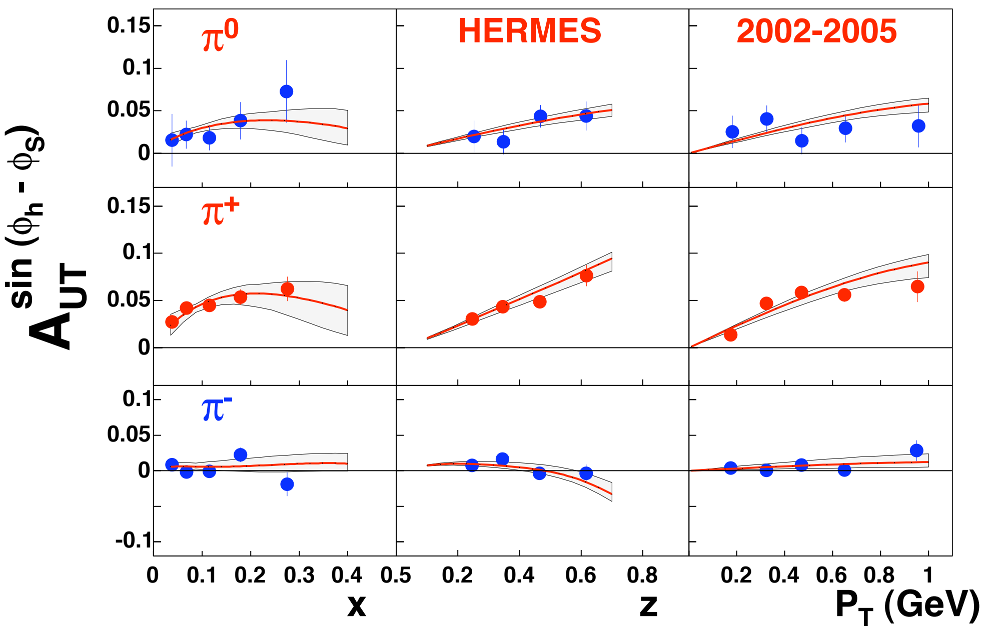
It looks like higher-twist ... but no, these are soft gluons = "gauge links" required for color gauge invariance

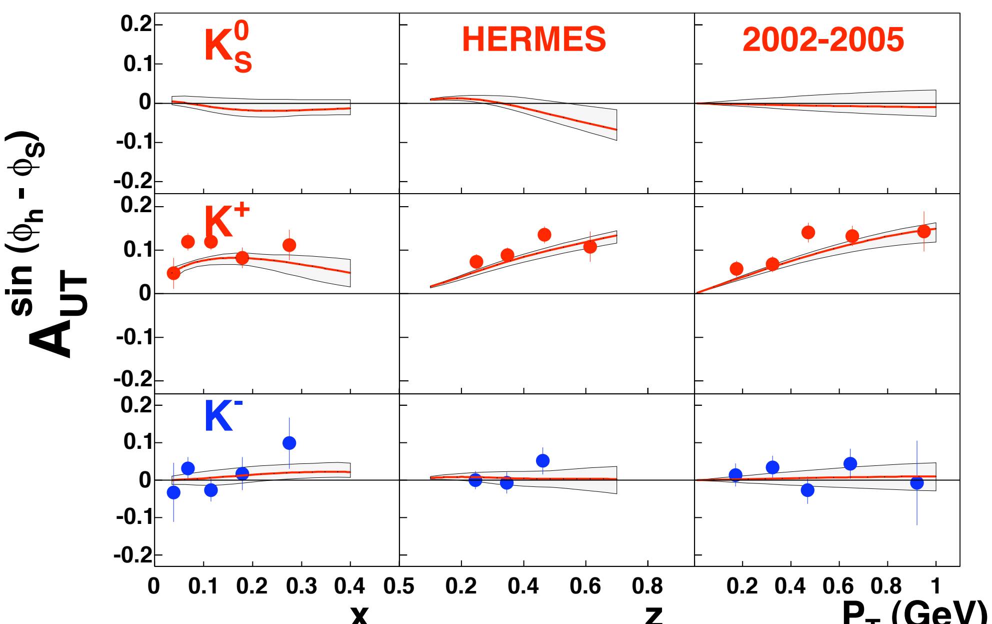
Such soft-gluon reinteractions with the soft wavefunction are ***final (or initial) state interactions*** ... and may be ***process dependent*** **!** ⇒ new ***universality issues***

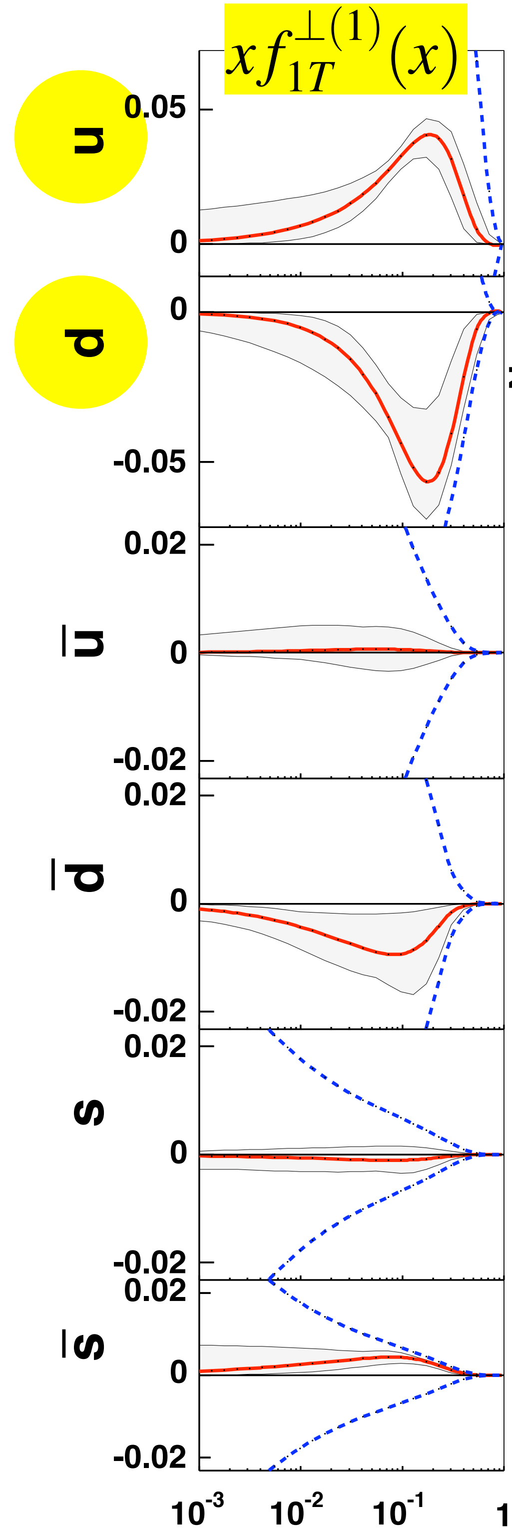


e.g. Drell-Yan

Global Fit to Sivers Asymmetries

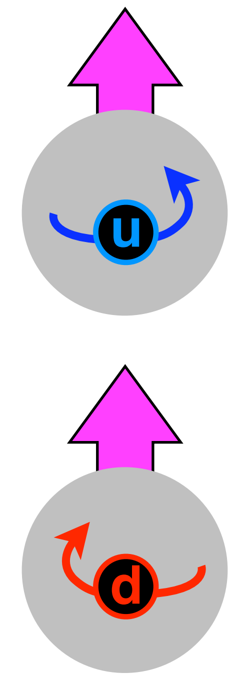






E. Boglione, Transversity2008

Anselmino et al, arXiv:0805.2677



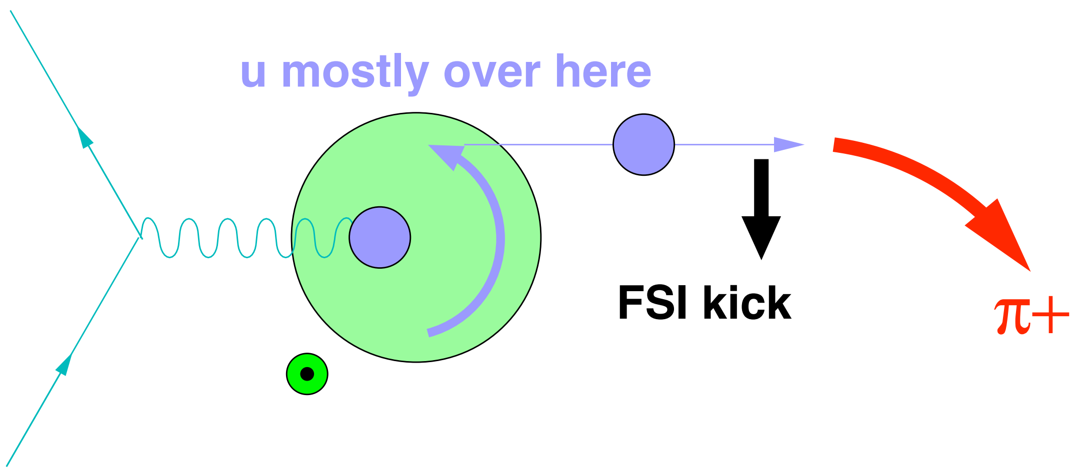
antiquark orbital L ≠ 0 favoured!

Phenomenology: Sivers Mechanism

Many models predict $L_u > 0$ ...

M. Burkardt: Chromodynamic lensing

Electromagnetic coupling $\sim (J_0 + J_3)$ ***stronger for oncoming quarks***



We observe $\langle \sin(\phi_h^l - \phi_S^l) \rangle_{UT}^{\pi^+} > 0$

(and opposite for π^-)

$\therefore$ for $\phi_S^l = 0,\ \phi_h^l = \pi/2$ preferred

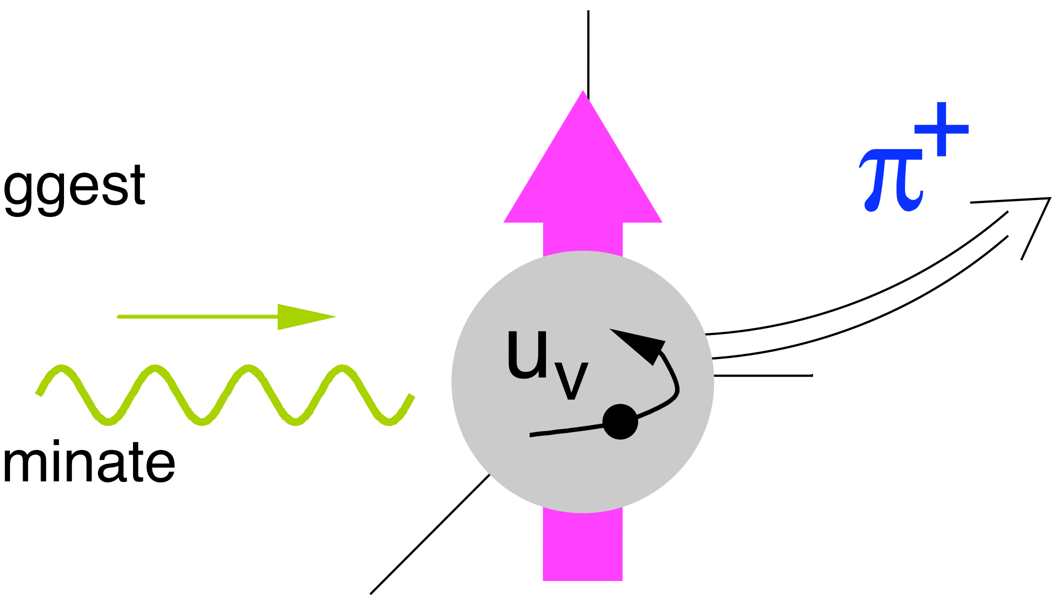
Model agrees!

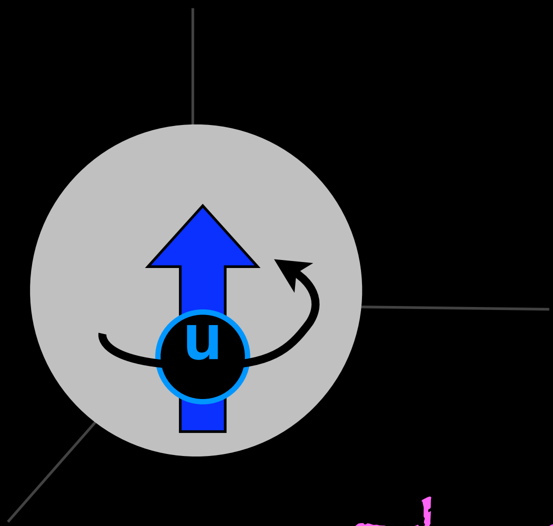
Jet Shadowing

Parton energy loss considerations suggest ***quenching of jets*** from ***"near" surface of target***

➡ quarks from "far" surface should dominate

Opposite sign to data ...



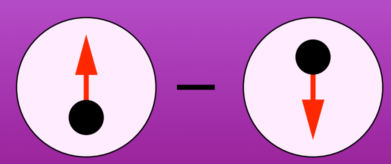


L_q within the proton

... now correlated with the quark's **own** spin ...

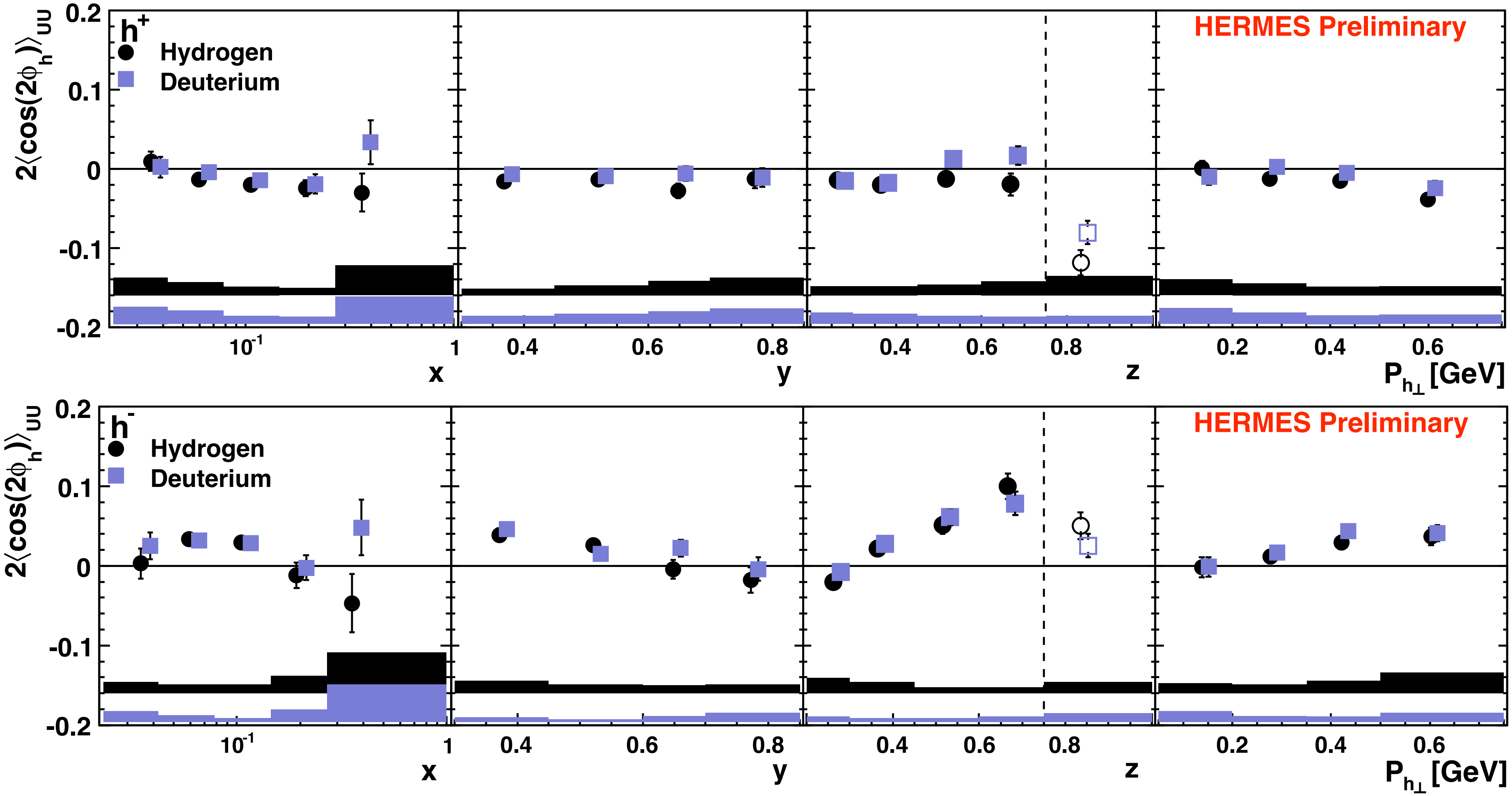
The Boer-Mulders function

$$h_1^{\perp}(x, k_T)$$



First charge-separated data on <cos(2Φ)>UU

$$h_1^\perp(x,k_T) \otimes H_1^\perp(z,p_T) \;\rightarrow\; \cos(2\phi)\text{ modulation}$$



***deuterium ≈ hydrogen** values → indicate **Boer-Mulders** functions of **same sign** for **u and d** quarks (both negative & similar magnitudes)*

A Coherent Picture?

- **Transversity**: $h_{1,u} > 0 \quad h_{1,d} < 0$

  $\rightarrow$ same as $g_{1,u}$ and $g_{1,d}$ in NR limit

- **Sivers**: $f_{1T}^{\perp}{}_{,u} < 0 \quad f_{1T}^{\perp}{}_{,d} > 0$

  $\rightarrow$ relat[n] to **anomalous magnetic moment***

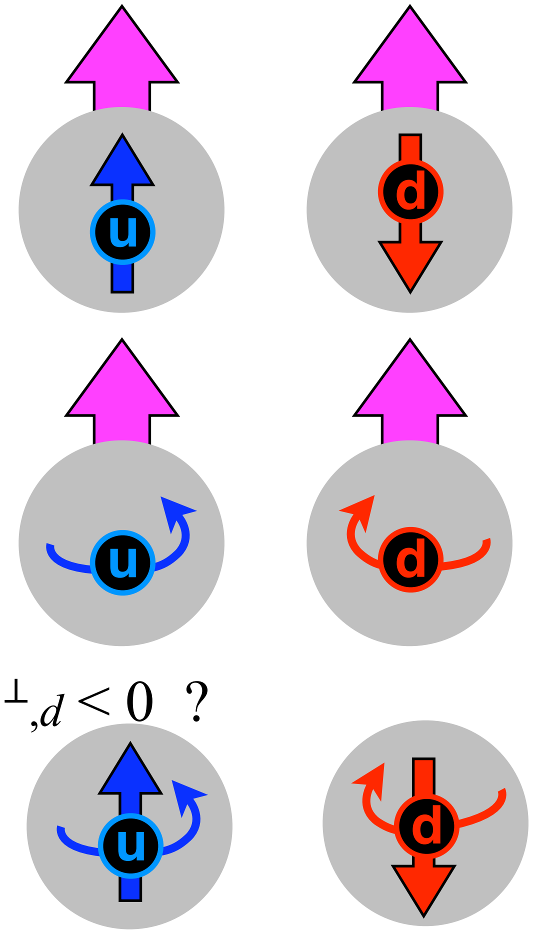
  $\boldsymbol{f_{1T}^{\perp}{}_{,q} \sim \kappa_q}$ where $\kappa_u \approx +1.67 \quad \kappa_d \approx -2.03$

  values achieve $\kappa^{p,n} = \Sigma_q \, e_q \, \kappa_q$ with u,d only

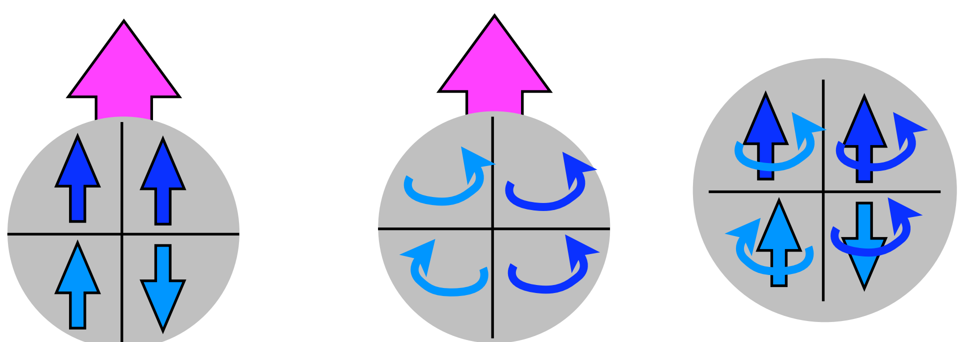
- **Boer-Mulders:** should follow that $h_1^{\perp}{}_{,u}$ and $h_1^{\perp}{}_{,d} < 0$?

  $\rightarrow$ relat[n] to **tensor magnetic moment***

  $\rightarrow$ possible analogue to Sokolov-Ternov?



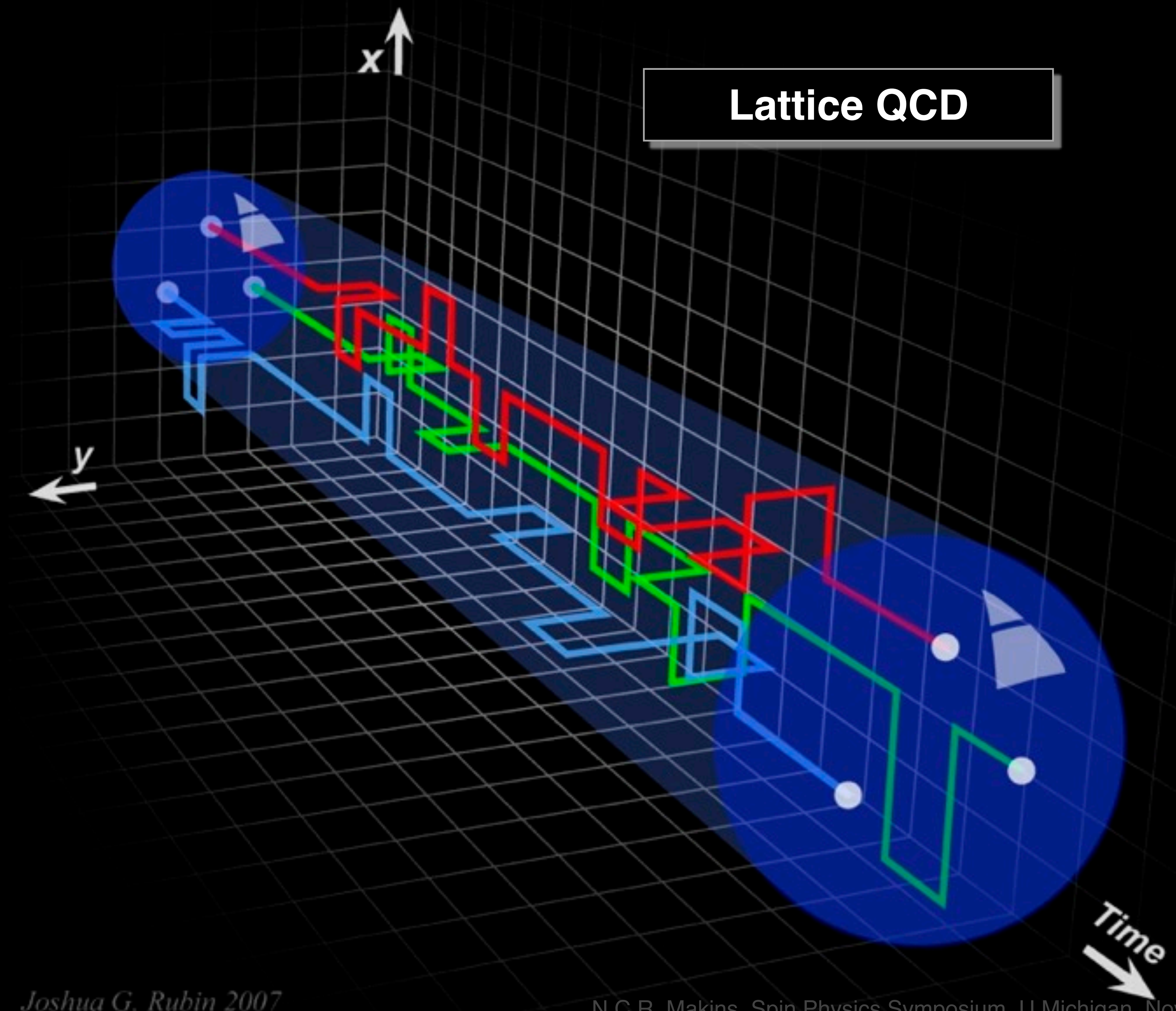
***but** these*
TMDs are all
independent



$\langle \vec{s}_u \cdot \vec{S}_p \rangle = +0.5 \quad \langle \vec{l}_u \cdot \vec{S}_p \rangle = +0.5 \quad \langle \vec{s}_u \cdot \vec{l}_u \rangle = 0$

** Burkardt PRD72 (2005) 094020;*
Barone et al PRD78 (1008) 045022;

Lattice QCD



Transverse spin on the lattice

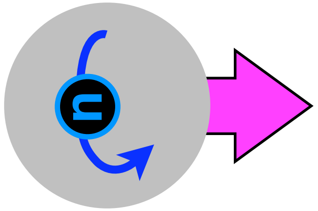
Hagler et al, PRL98 (2007)

Compute quark densities in impact-parameter space via GPD formalism

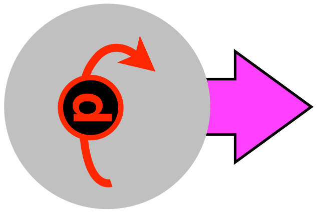
nucleon coming out of page ...

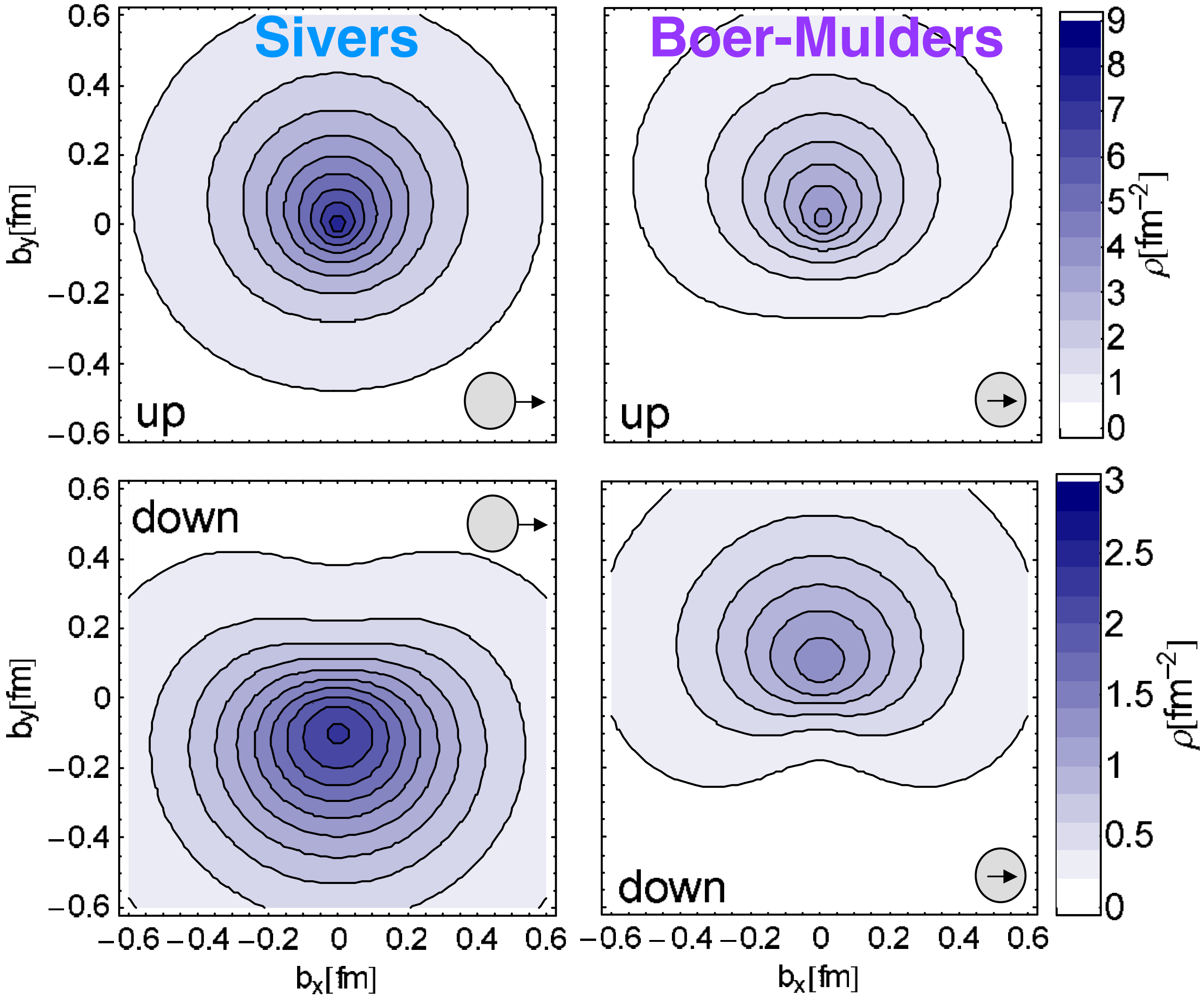
spatial shifts → infer L_q direction via chromodynamic lensing

$L_u > 0$

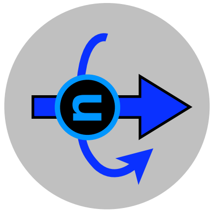


$L_d < 0$



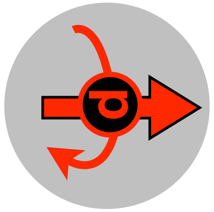


$L_u // S_u$



Expected picture from relativistic quark models

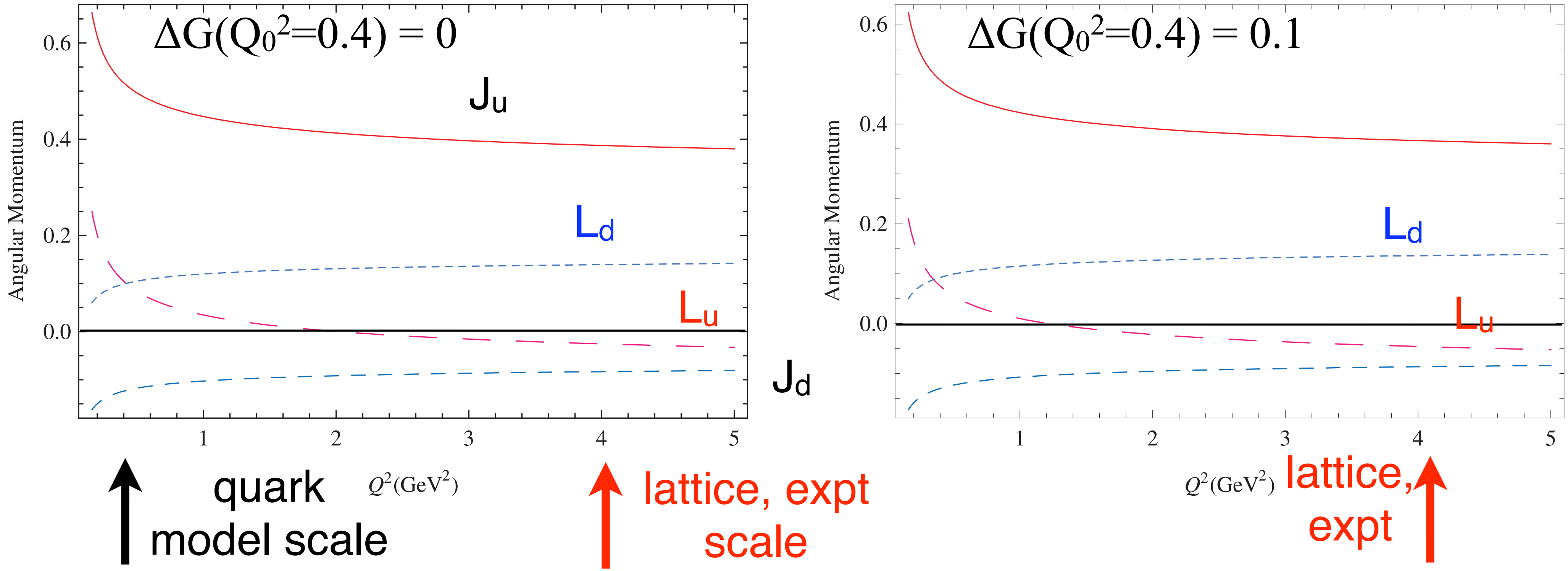
$L_d // S_d$



... and longitudinal spin on the lattice ...

Thomas, PRL101 (2008)

→ no disconnected graphs, evolution applied via Ji, Hoodbhoy



→ ***lattice shows $L_u < 0$ and $L_d > 0$ in longitudinal case at expt'al scales!***

Evolution might explain disagreement with quark models,
*but not with lattice calculations of **transverse** spin.*

Are <u>disconnected graphs</u> – sea quarks – the reason for apparent L_u & L_d sign change from longitudinal to transverse ?

With spin around, there's never a dull moment ☺

Congratulations, Prof. Krisch, and Thank You!

the Spin Kids