The Questions of Hadronic Physics

L: parton OAM

- … **quantitatively** describe the **non-perturbative** …blems of hadron substructure and hadron formation?
  → experiment vs <u>lattice QCD</u>

- Can we achieve an **intuitive understanding** of hadron structure and formation? What are the best **degrees of freedom** with which to think about the strong force in confined systems?
  → experiment vs <u>phenomenology</u> / <u>effective theories</u>

- Are the **theoretical tools** we use to describe our data accurate and well-understood, for both familiar and novel distribution and fragmentation functions?
  → experiment vs <u>pQCD</u>, <u>factorization</u>, & <u>evolution</u>

- How does the **nuclear environment** affect the partonic structure of the nucleon?
  → experiment vs <u>medium-effect models</u>

L + Relativity ≈ Weirdness

Dirac free plane-wave particle with spin $S_z = +1$

Boosting a Dirac Spinor

How is L_z affected by boosts?

at rest $\vec{p} = 0$

$$\psi = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} e^{-imt}$$

BOOST

in **–x direc^n** with

$$\beta = p'/E' = \tanh\phi$$

$$\hat{B}(\hat{x},\phi) = e^{\frac{\phi}{2}\vec{\alpha}\cdot\hat{x}} = \cosh\frac{\phi}{2}\,\mathbf{1} + \sinh\frac{\phi}{2}\,\boldsymbol{\alpha}_x$$

$\vec{p}\,' = p'\,\hat{x}$

$$\psi' = N \begin{pmatrix} 1 \\ 0 \\ 0 \\ \dfrac{p'}{E'+m} \end{pmatrix} e^{i(p'x'-E't')}$$

What's its spin?

$$\frac{\psi^\dagger \vec{\Sigma}\, \psi}{\psi^\dagger \psi} = \hat{z}$$

$$\vec{\Sigma} = \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & \vec{\sigma} \end{pmatrix}$$

$$\vec{\sigma} = \begin{pmatrix} \hat{z} & \hat{x} - i\hat{y} \\ \hat{x} + i\hat{y} & -\hat{z} \end{pmatrix}$$

$$\frac{\psi'^\dagger \vec{\Sigma}\, \psi'}{\psi'^\dagger \psi'} = \hat{z}\left[1 - \left(\frac{p'}{E'+m}\right)^2\right]$$

$$\approx \hat{z}\,\frac{1}{\gamma^2} \quad \text{for } \gamma \gg 1$$

Why there are no transversely polarized electron machines!

Spin, L, and the free Dirac Hamiltonian

$$\mathbf{H} = \boldsymbol{\alpha}\cdot\vec{p} + \boldsymbol{\beta} m = \begin{pmatrix} m\mathbf{1} & -i\vec{\boldsymbol{\sigma}}\cdot\vec{\nabla} \\ -i\vec{\boldsymbol{\sigma}}\cdot\vec{\nabla} & m\mathbf{1} \end{pmatrix}$$

$$\vec{\mathbf{L}}(\vec{x}) = \mathbf{1}\ \vec{x}\times\vec{p} = -\mathbf{1}\ i\,\vec{x}\times\vec{\nabla}$$

➡ **L** position-dependent, doesn't commute w ∂_i in **H**

$$[\ \mathbf{H}, \vec{\mathbf{L}}(x_i)\ ] = -\vec{\boldsymbol{\alpha}}\times\vec{\nabla}$$

L NOT CONSERVED

no shells!

$$\vec{\boldsymbol{\Sigma}} = \begin{pmatrix} \vec{\boldsymbol{\sigma}} & 0 \\ 0 & \vec{\boldsymbol{\sigma}} \end{pmatrix}$$

➡ Pauli matrices in **Σ** and **H** don't commute

$$[\ \mathbf{H}, \vec{\boldsymbol{\Sigma}}\ ] = 2\vec{\boldsymbol{\alpha}}\times\vec{\nabla}$$

$$[\ \boldsymbol{\sigma}_i, \boldsymbol{\sigma}_j\ ] = 2i\,\varepsilon_{ijk}\,\boldsymbol{\sigma}_k$$

SPIN NOT CONSERVED

intuition?

➡ $$\left[\ \mathbf{H}, \vec{\mathbf{L}} + \tfrac{1}{2}\vec{\boldsymbol{\Sigma}}\ \right] = \left[\ \mathbf{H}, \vec{\mathbf{J}}\ \right] = 0$$

J CONSERVED

Liang, Meng, ZPA 344 (1992)

Dirac particle in a central potential

We denote the solution of the above-mentioned equation by the Dirac four-spinor ψ and/or its upper- and lower-component, the corresponding two-spinors φ and χ. The stationary states are characterized by the following set of quantum numbers ε, j, m and P which are respectively the eigenvalues of the operators $\hat{H}$ (the Hamiltonian), $\hat{\mathbf{j}}^2$, $\hat{j}_z$ (total angular momentum and its z-component) and $\hat{P}$ (the parity). Since every eigenstate of the valence quark characterized by ε, j, m and P corresponds to two different orbital angular momenta l and $l'=l\pm 1$, (see Appendix A), it is clear that *orbital motion is involved in every stationary state*. This is true *also when the valence quark is in its ground state* ($\psi_{\varepsilon jmP}$ where $\varepsilon=\varepsilon_0$, $j=1/2$, $m=\pm 1/2$, $P=+$[2]). This state can be expressed as follows:

$$\psi_{\varepsilon 0 1/2\ m+}(r,\theta,\phi)=\begin{pmatrix} f_0(r)\,\Omega_0^{1/2\ m}(\theta,\phi) \\ g_1(r)\,\Omega_1^{1/2\ m}(\theta,\phi)\end{pmatrix}. \tag{2.1}$$

The angular part of the two-spinors can be written in terms of spherical functions $Y_{ll_z}(\theta,\phi)$ and (non-relativistic) spin-eigenfunctions which are nothing else but the Pauli-spinors $\xi(\pm 1/2)$:

$$\Omega_0^{1/2\ m}(\theta,\phi)=Y_{00}(\theta,\phi)\,\xi(m),$$

The spherical solutions of a Dirac particle in a central potential are discussed in some of the text books (see, for example, Landau, L.D., Lifshitz, E.M.: Course of theoretical physics. Vol. 4: Relativistic quantum theory. New York: Pergamon 1971). The notations and conventions we use here are slightly different. In order to avoid possible misunderstanding, we list the general form of some of the key formulae in the following:

In terms of spherical variables, a state with given ε, j, m and P can be written as:

$$\psi_{\varepsilon jmP}(r,\theta,\phi)=\begin{pmatrix} f_{\varepsilon l}(r)\,\Omega_l^{jm}(\theta,\phi) \\ (-1)^{(l-l'+1)/2}g_{\varepsilon l'}(r)\,\Omega_{l'}^{jm}(\theta,\phi)\end{pmatrix}. \tag{A1}$$

Here $l=j\pm 1/2$, $l'=2j-l$ and $P=(-1)^l$; Ω_l^{jm} and $\Omega_{l'}^{jm}$ are two-spinors which, for the possible values of l, are given by:

$$\Omega_{l=j-1/2}^{jm}(\theta,\phi)=\sqrt{\frac{j+m}{2j}}\,Y_{l\,l_z=m-1/2}(\theta,\phi)\,\xi(1/2)+\sqrt{\frac{j-m}{2j}}\,Y_{l\,l_z=m+1/2}(\theta,\phi)\,\xi(-1/2), \tag{A2}$$

$$\Omega_{l=j+1/2}^{jm}(\theta,\phi)=-\sqrt{\frac{j-m+1}{2j+2}}\,Y_{l\,l_z=m-1/2}(\theta,\phi)\,\xi(1/2)+\sqrt{\frac{j+m+1}{2j+2}}\,Y_{l\,l_z=m+1/2}(\theta,\phi)\,\xi(-1/2). \tag{A3}$$

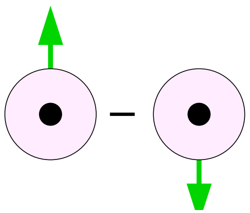
Here, $\xi(\pm 1/2)$ stand for the eigenfunctions for the spin-operator $\hat{\sigma}_z$ with eigenvalues ± 1, and $Y_{ll_z}(\theta,\phi)$ for the spherical harmonics which form a standard basis for the orbital angular momentum operators $(\hat{\mathbf{l}}^2, \hat{l}_z)$. The function $f_{\varepsilon l}(r)$ and $g_{\varepsilon l'}(r)$ are solutions of the coupled differential equations:

The Wacky World of Hyperon Polarization

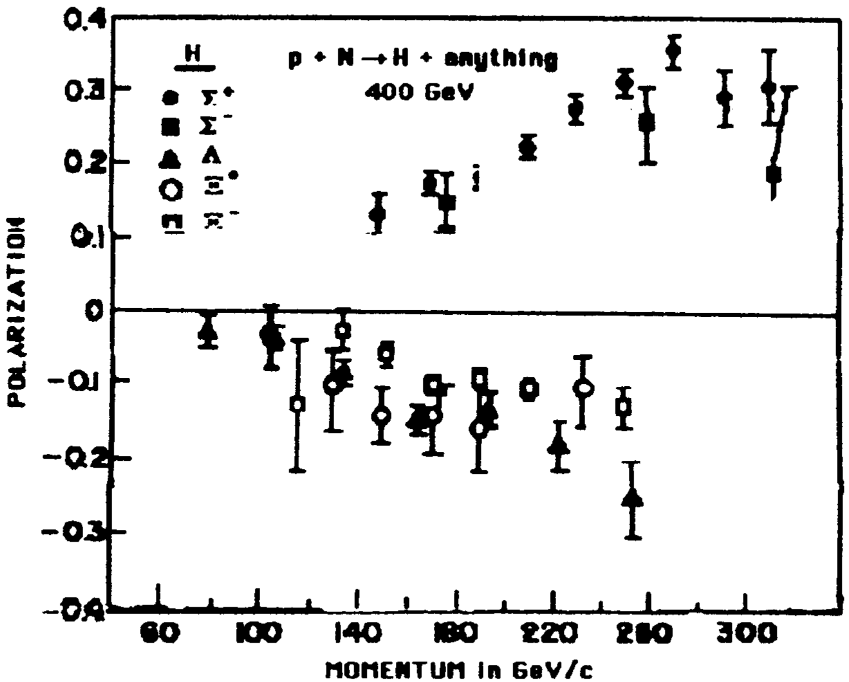
Unpolarized beams on unpolarized targets produce hyperons which are strongly polarized!

... direction is $\boxed{\hat{n} = \mathbf{p}_{\rm beam} \times \mathbf{p}_Y}$

$$d\sigma_{UUT} \sim \sin(\phi_h^l - \phi_{S_h}^l) \cdot f_1(x)\, D_{1T}^{\perp(1)}(z) =$$



$pN \to Y^{\uparrow} X$ data



Hyperon spin structure in CQM:

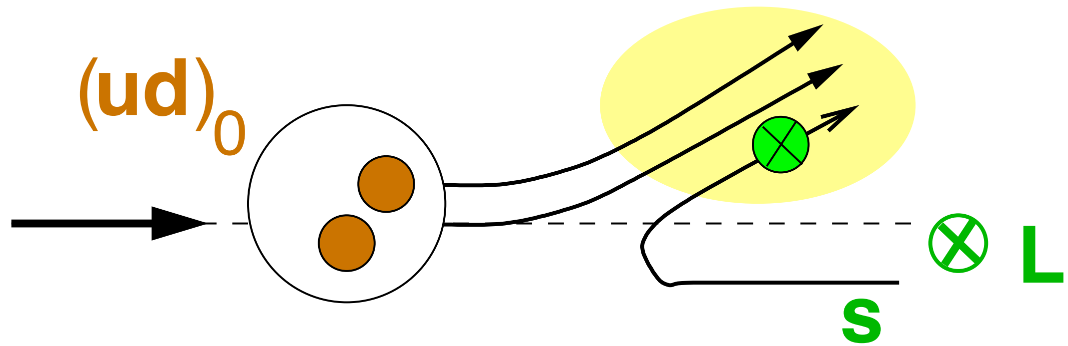
p	$\Delta u = +4/3,\ \Delta d = -1/3,$	$\Delta s = 0$
Λ	$\Delta s = +1,$	$\Delta u = \Delta d = 0$
$\Sigma^{\pm}$	$\Delta s = -1/3,$	$\Delta u, d = +4/3$
$\Xi^{\pm}$	$\Delta s = +4/3,$	$\Delta u, d = -1/3$

$\Rightarrow$ ***sign of polarization is opposite to*** Δs ***...***

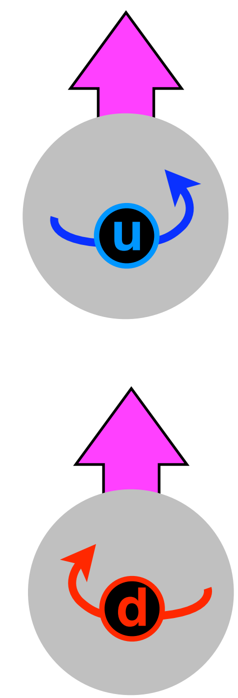
Thomas Precession & the DGM Model

Thomas precession: relativistic effect due [boost, rotation] ≠ 0 ...
→ ***'spin-orbit'*** *pseudo-force* that ***aligns L*** and ***S*** of ***accelerating particle***

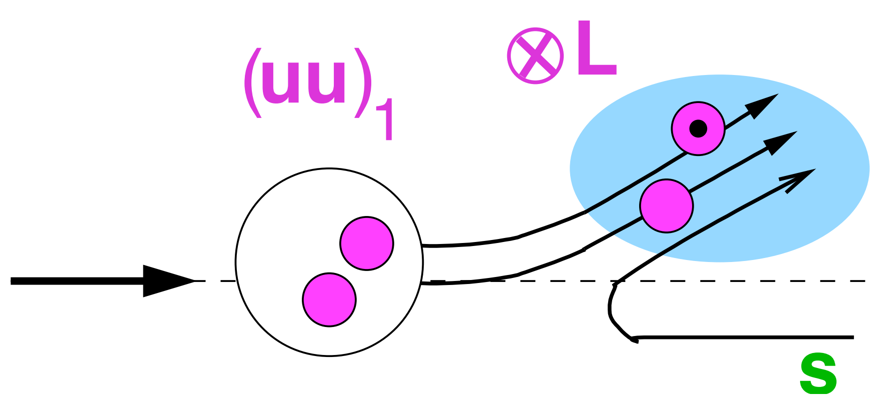
Λ: $\Delta s = +1$ — P_Λ from accelerated sea s quark



relevant?



Σ^+: $\Delta u = +4/3$ — P_Σ from accelerated valence $(uu)_1$ diquark



DGM model did pretty well

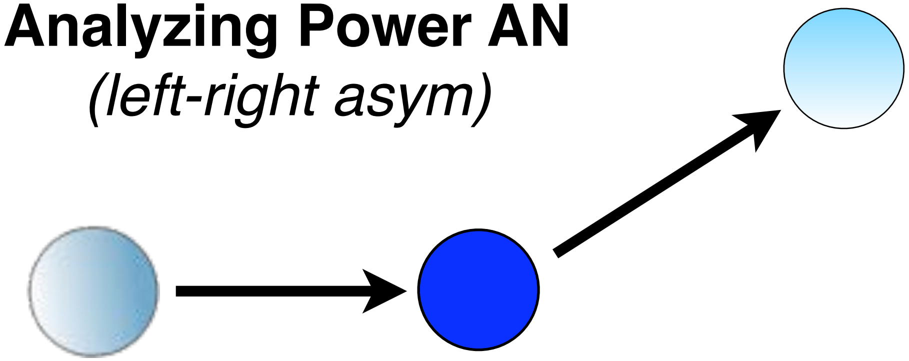
Non-Relativistic SSA's:
Any lessons?

SSA's in Low-energy Elastic pp Scattering

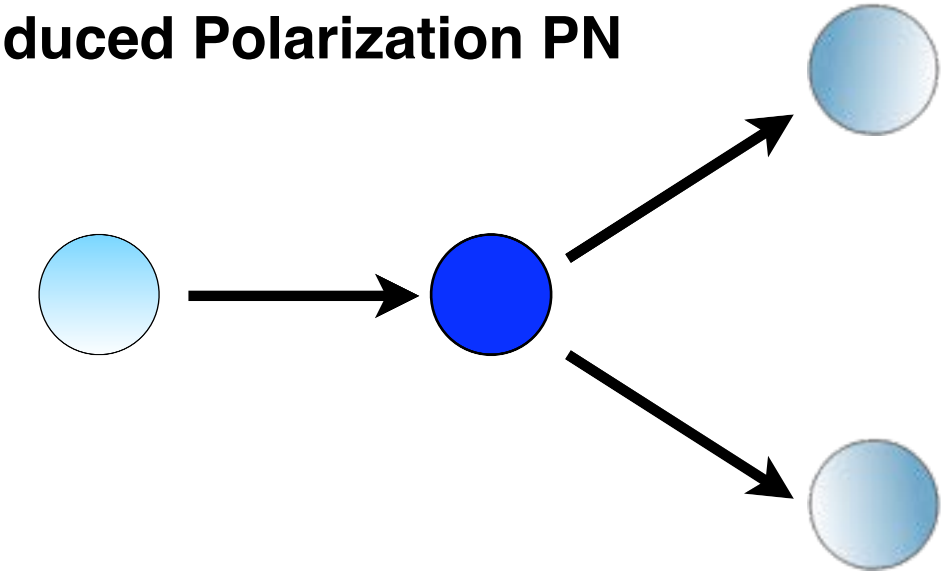
Well-known effects!

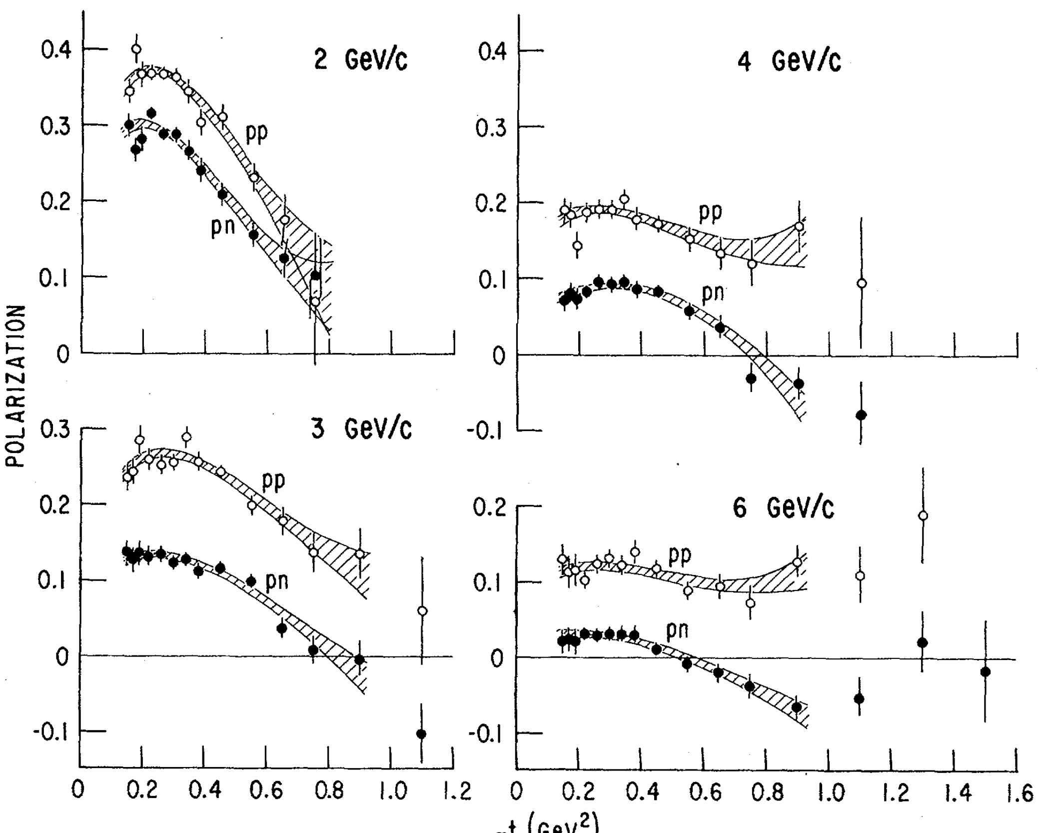
Analyzing Power AN

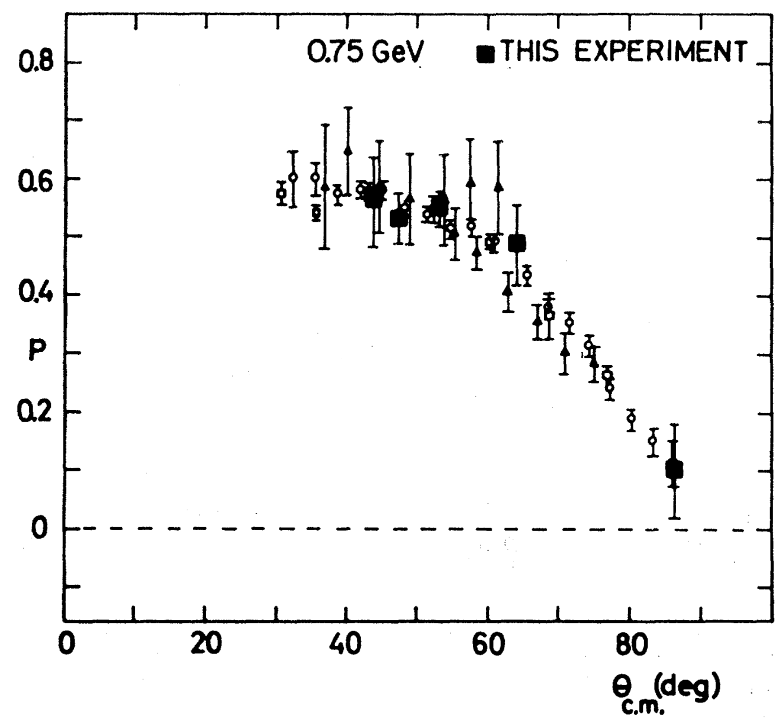
(left-right asym)



Induced Polarization PN



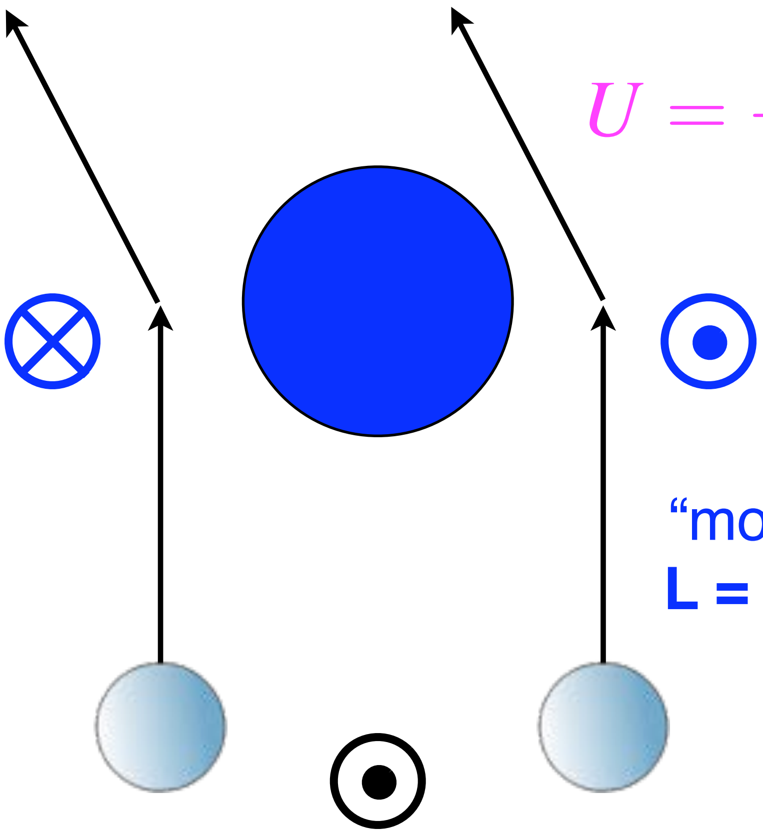




The Spin-Orbit Interaction in Good-Old E&M

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**

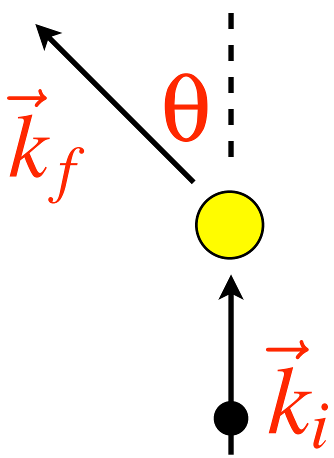
Spin-Orbit Interaction: Nuclear Force

The **strong interaction** between nucleons is **short-range** ...
can approximate as a **contact interaction** (unlike E&M!)

With ρ(r) = target density,

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

nuclear s-o interaction
active at **target surfaces**



Let's calculate! Non-relativistic scattering:

$$\psi = e^{ikz} + f(\theta)\,\frac{e^{ikr}}{r}$$

INCOMING PLANE WAVE   OUTGOING SPHERICAL WAVE

Cross-section:

$$\frac{d\sigma}{d\theta} = |f(\theta)|^2$$

Short-range Born approximation:

$$f(\theta) = -\frac{\mu}{2\pi\hbar^2}\int e^{i(\vec{k}_i-\vec{k}_f)\cdot\vec{r}'}\,V(r')\,d^3r'$$

Angular pattern of scatt amplitude
➡ **Fourier transform** of target *V*

Spin-Orbit Interaction: Nuclear Force

*Now for a **polarized proton** beam!*

.....

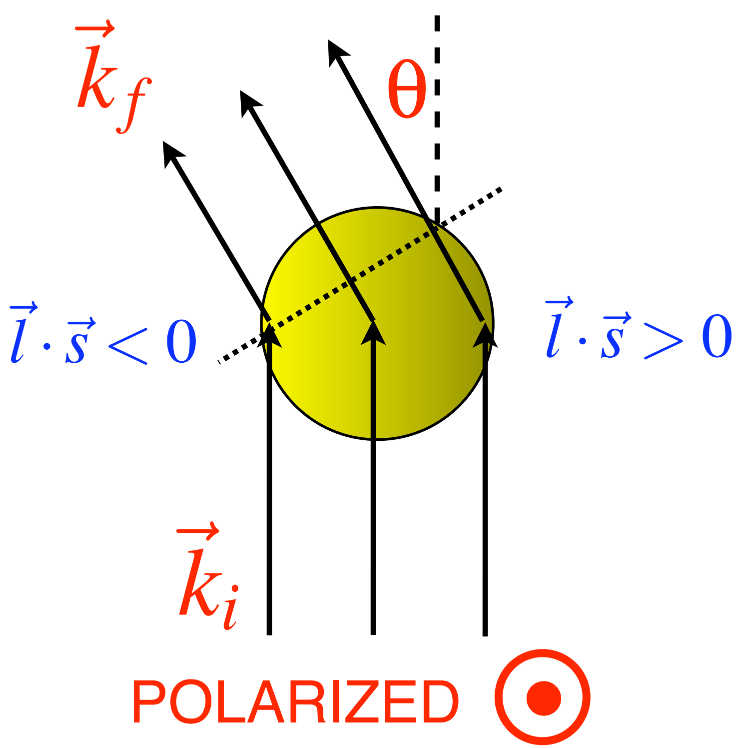
Analyzing power
→ sin(θ) term in xsec

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

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

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

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

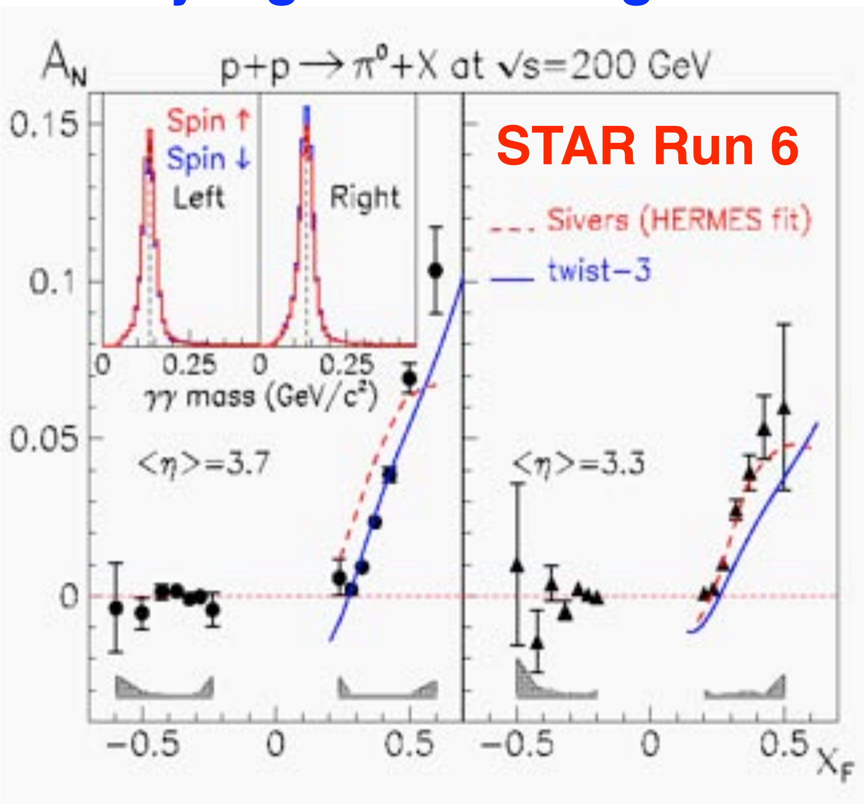


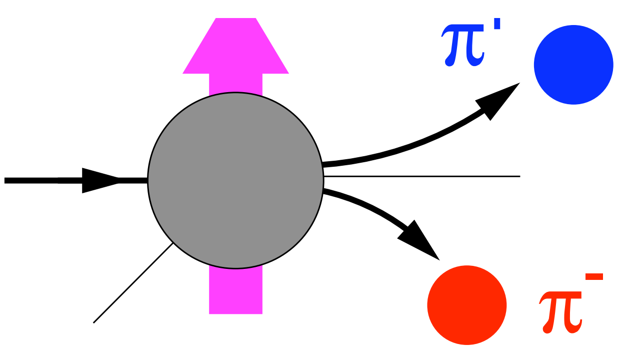
Single-spin asym in $p^{\uparrow}p \rightarrow pp$ involves:

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

SSA's at high-energies

Large SSAs persist at very high RHIC energies





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***

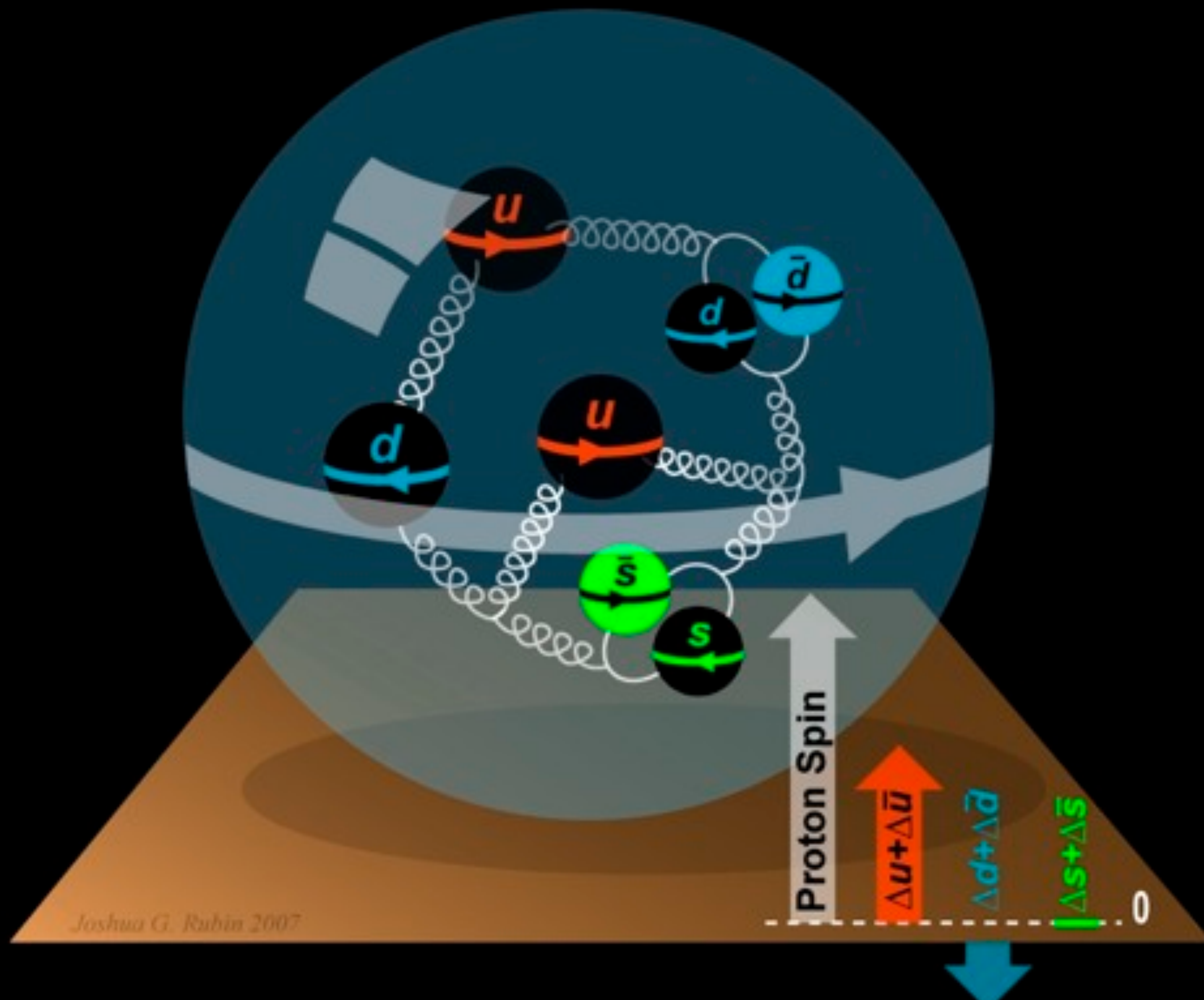
Since QCD amplitudes are T-even, must arise from **interference** between **spin-flip** and non-flip amplitudes with **different phases**

Can't come from perturbative subprocess:

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

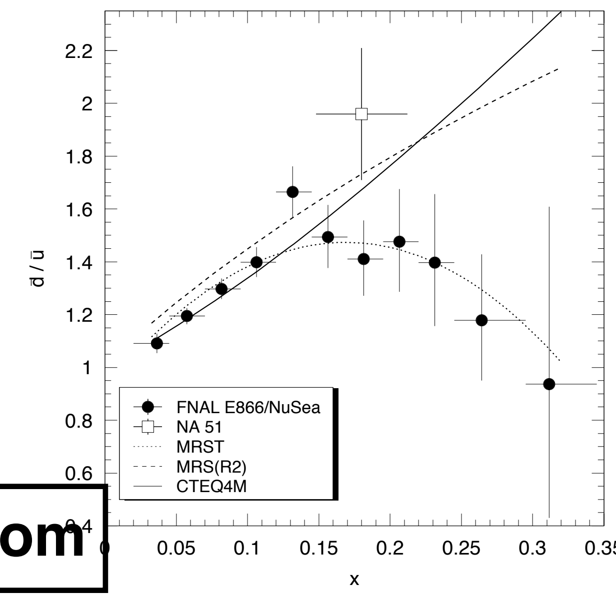
At hard (enough) scales, SSA's must arise from soft physics: T-odd distribution / fragmentation functions

Models: seeking an intuitive picture



Flavor Structure of the Proton

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



Constituent Quark Model

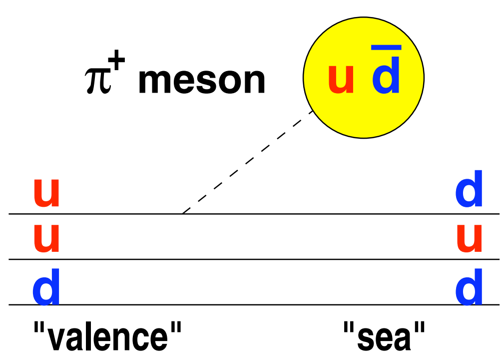
Pure valence description: proton = $2u + d$

Perturbative Sea

Sea quark pairs from $g \rightarrow q\overline{q}$ should be flavor symmetric: $\overline{u} = \overline{d}$

Non-perturbative models: alternate **deg's of freedom**

Meson Cloud Models

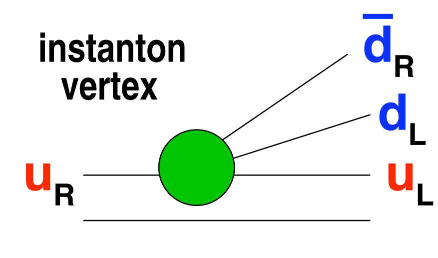


Quark sea from cloud of 0^- mesons: $\overline{d} > \overline{u}$

Chiral-Quark Soliton Model

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

$\overline{d} > \overline{u}$



'tHooft instanton vertex

$$\sim \overline{u}_R u_L \overline{d}_R d_L$$

Spin of the Sea Quarks

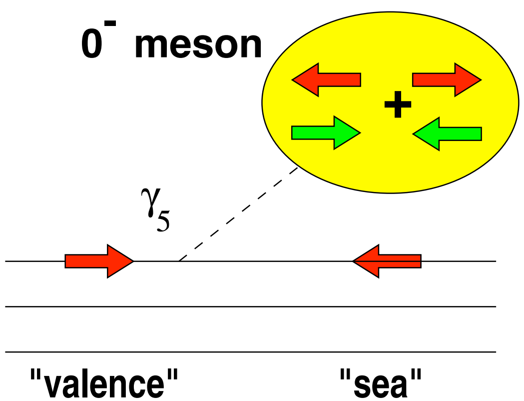
Constituent Quark Model

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

$$\Delta q \equiv N^{\uparrow} - N^{\downarrow}$$

Meson Cloud Models

Li, Cheng, hep-ph/9709293



→ $\Delta q_{\text{valence}} > 0$

→ $\Delta q_{\text{sea}} < 0$

→ $\Delta\bar{q} = 0$

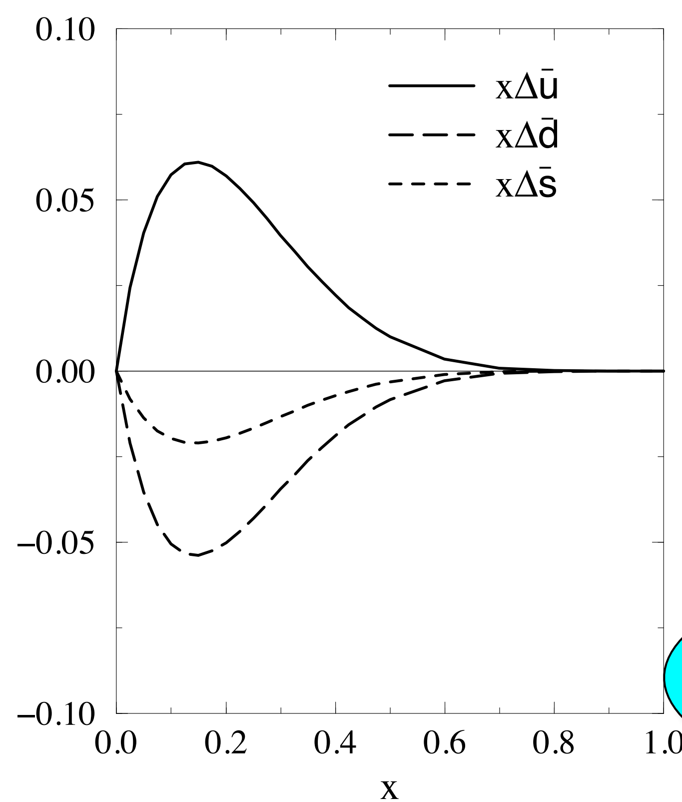
"Higher-order" cloud of vector mesons can generate a small polarization.

Chiral-Quark Soliton Model

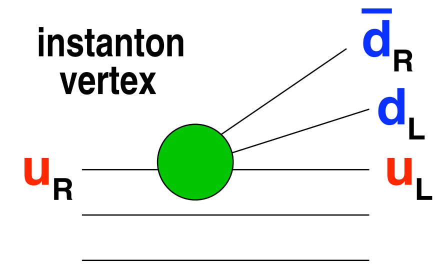
Goeke et al, hep-ph/0003324

Light sea quarks polarized:

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



Instanton Mechanism

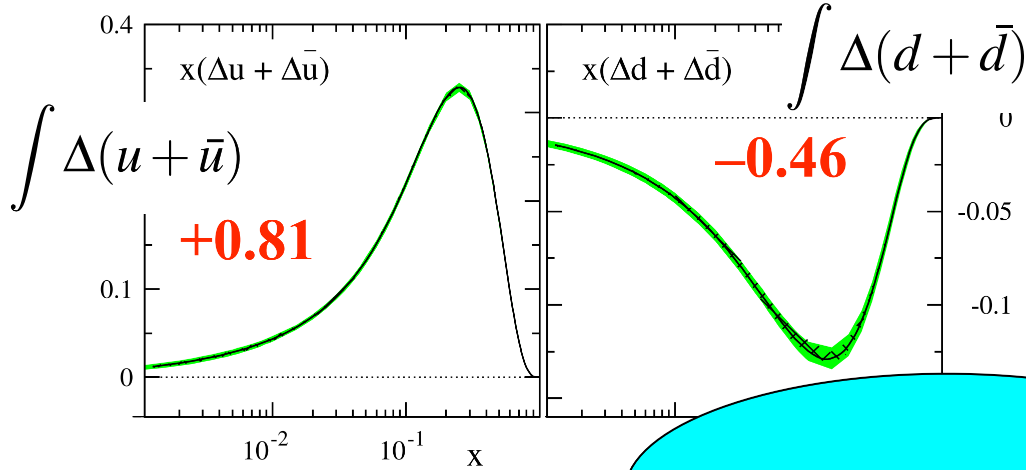


'tHooft instanton vertex $\sim \bar{u}_R u_L \bar{d}_R d_L$ transfers helicity from valence u quarks to $d\bar{d}$ pairs

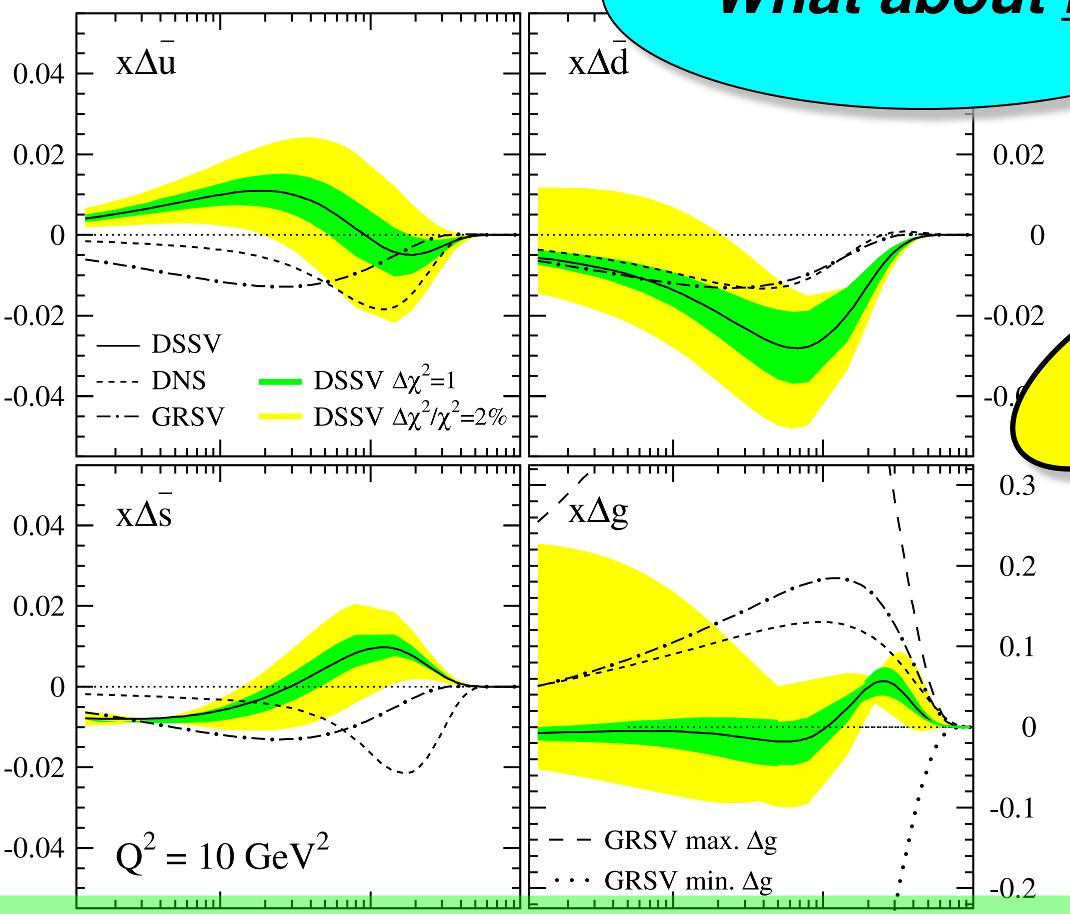
What about <u>gluon</u> spin?

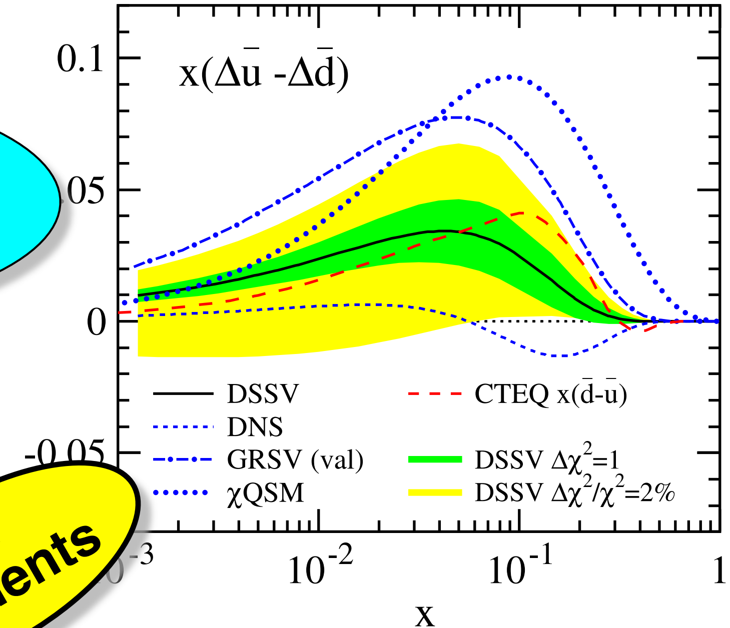
DSSV NLO global fit: Δq & Δg

DeFlorian, Sassot, Stratmann, Vogelsang,
PRL 101 (2008) 071001, PRD 80 (2009) 034030



What about L?





1st moments

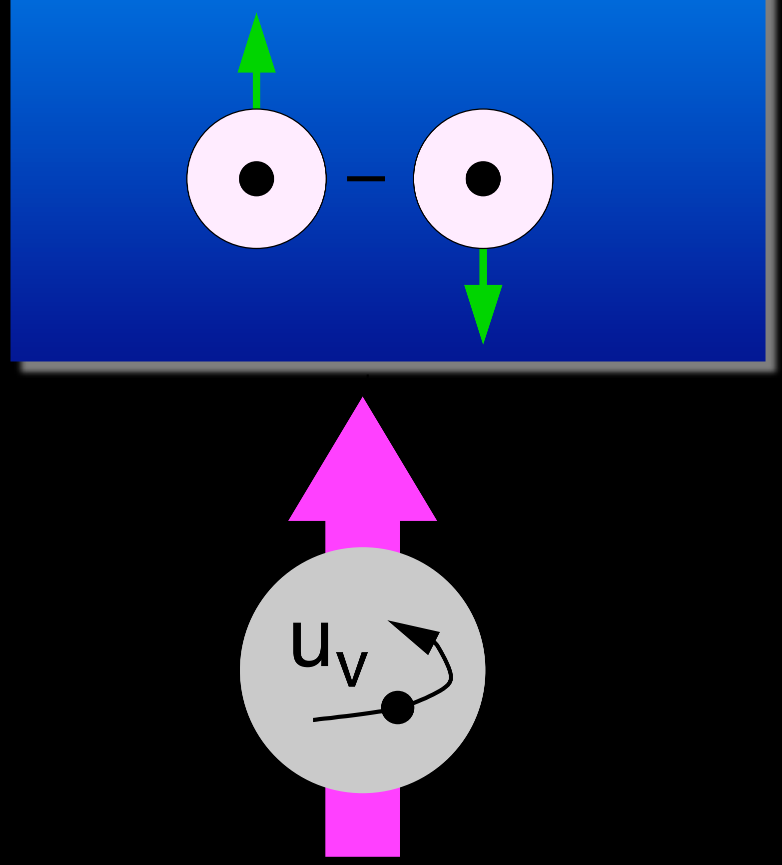
	meas: x > .001	extrap: all x	error
ΔΣ	0.37	0.24	+0.04 –0.06
Δū	0.03	**0.04**	±0.06
Δd̄	–0.09	**–0.12**	±0.09
Δs	–0.01	**–0.06**	±0.03
ΔG	0.01	**–0.08**	+0.7 –0.3

gluons & sea: spin-polarizations
*all negative-ish **zeros***

Models: a tantalizing strawman for L

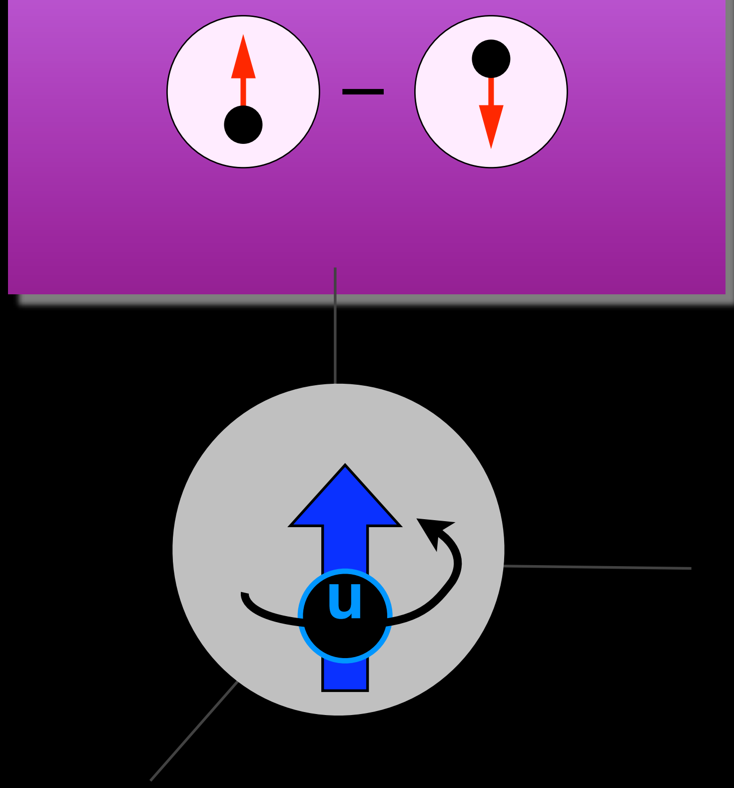
Sivers

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



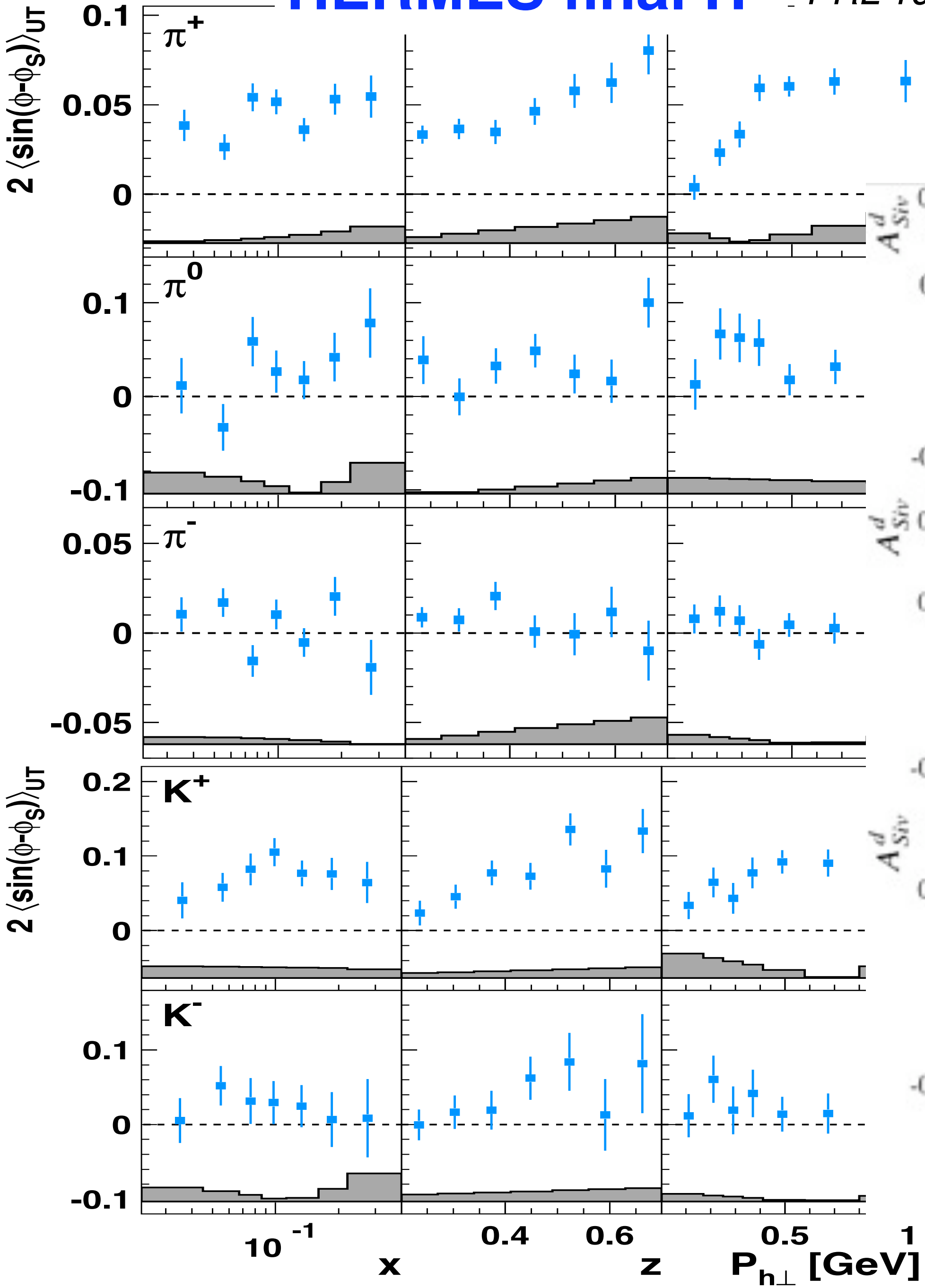
Boer-Mulders

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



Sivers Moments for π and K from H$^{\uparrow}$ & D$^{\uparrow}$

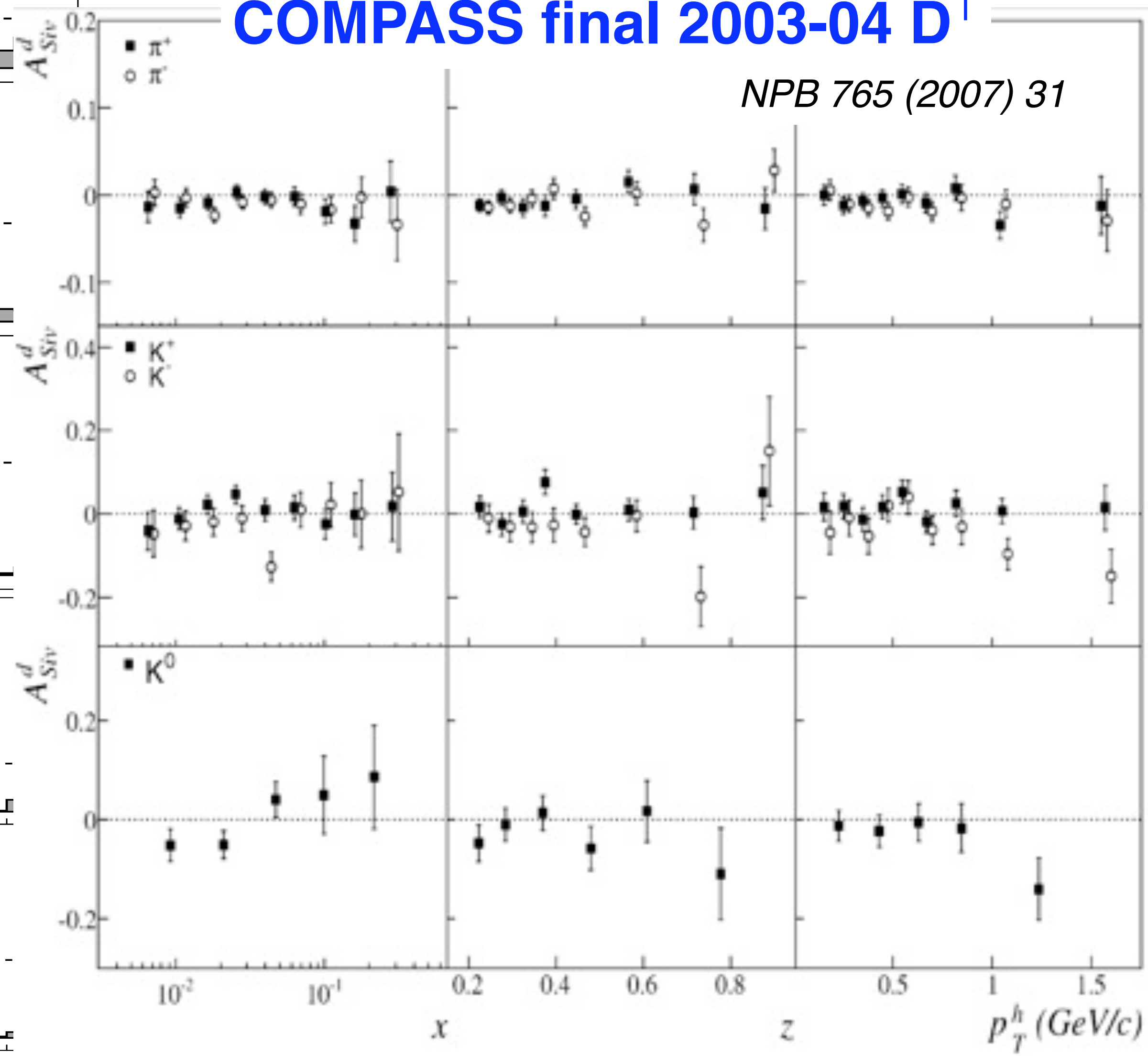
HERMES final H$^{\uparrow}$ *PRL 103 (2009)*



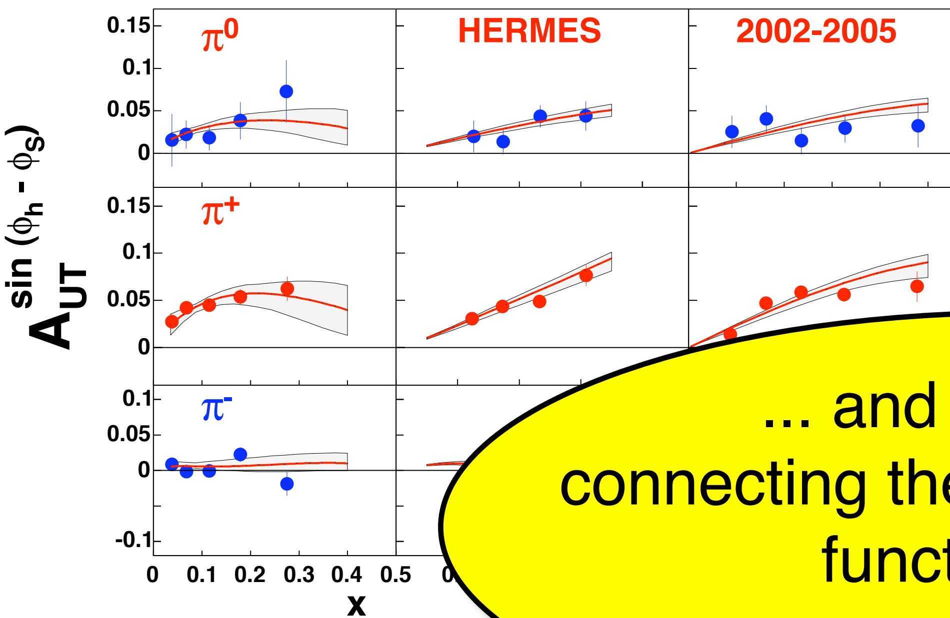
$$f_{1T}^{\perp}(x,k_T)\otimes D_1^{\perp}(z)$$

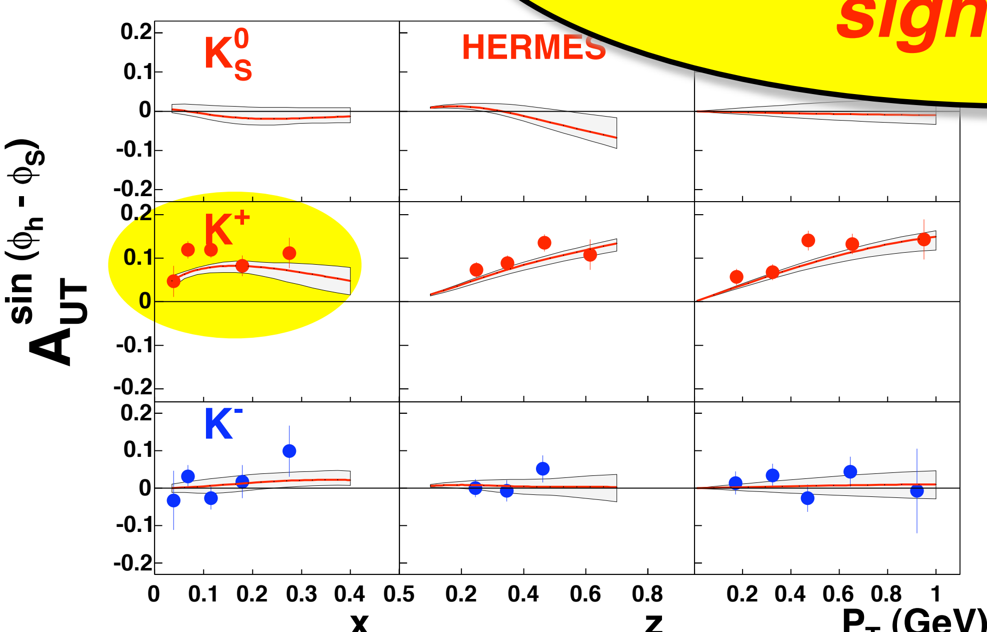
COMPASS final 2003-04 D$^{\uparrow}$

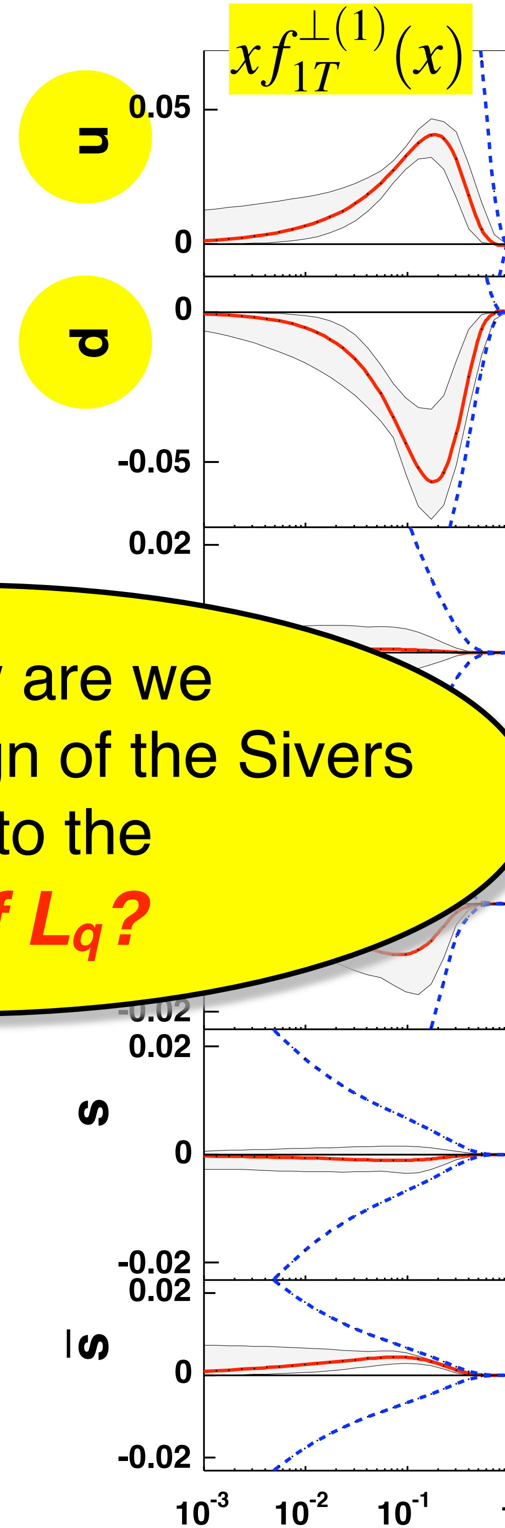
NPB 765 (2007) 31



Global Fit to Sivers Asymmetries

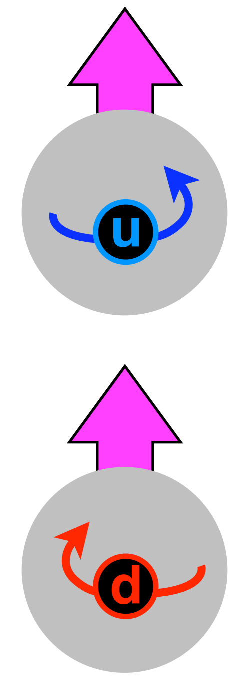






E. Boglione, Transversity2008

Anselmino et al, arXiv:0805.2677



... and how are we connecting the sign of the Sivers function to the ***sign of L_q?***

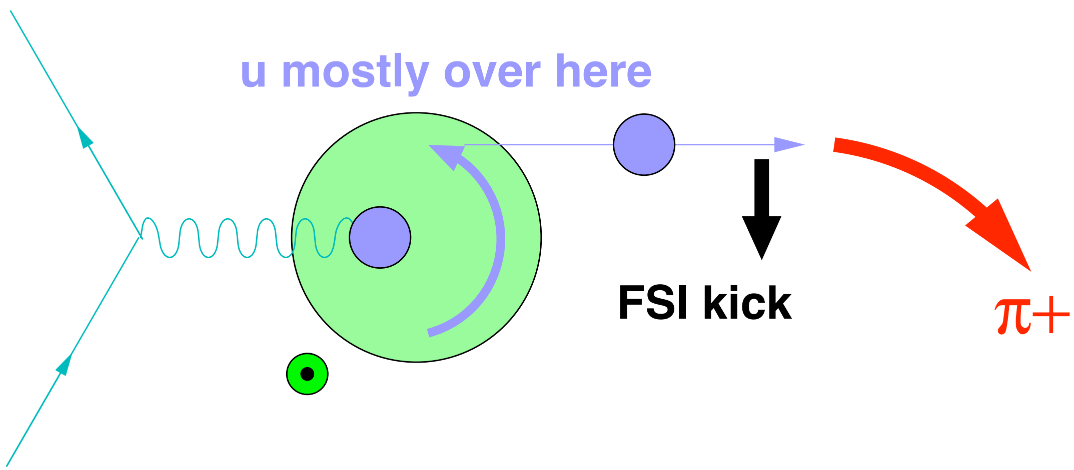
antiquark orbital $L \neq 0$ favoured

Phenomenology: Sivers Mechanism

Assuming $L_u > 0$ *Why?*

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

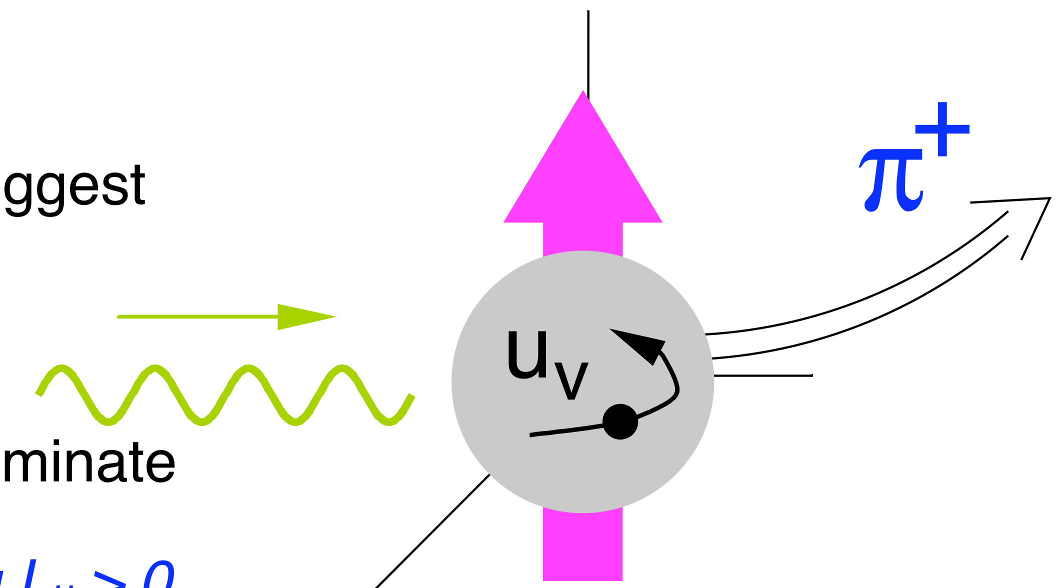
Model agrees!

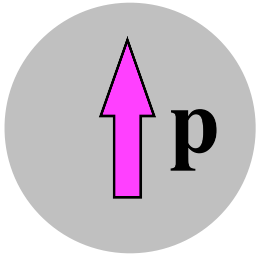
D. Sivers: Jet Shadowing

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

➡ quarks from "far" surface should dominate

Opposite sign to data … *assuming $L_u > 0$* ...





Meson Cloud on an Envelope

$|p\rangle = p + N\pi$
$+ \Delta\pi + \ldots$

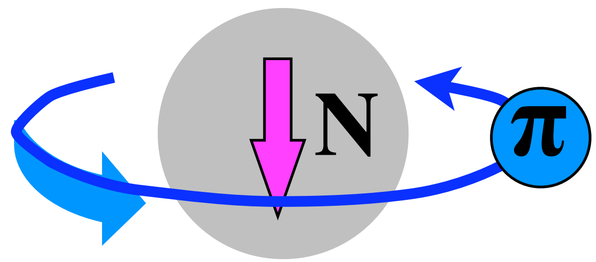
Pions have $J^P = 0^-$ = **negative parity** ...
→ ***need <u>L = 1</u>*** to get proton's $J^P = ½^+$

Nπ cloud:

u

2/3 $n\,\pi^+$
1/3 $p\,\pi^0$

⊗



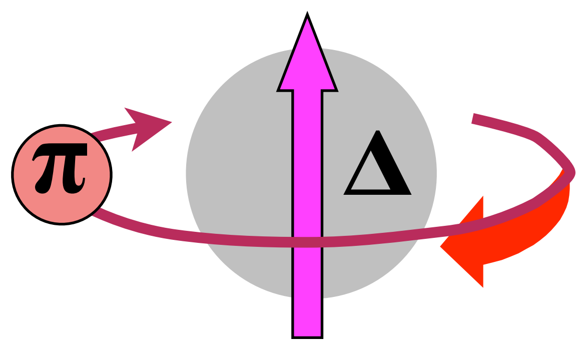
2/3 $L_z = +1$
1/3 $L_z = 0$

Δπ cloud:

d

1/2 $\Delta^{++}\,\pi^-$
1/3 $\Delta^+\ \pi^0$
1/6 $\Delta^0\ \pi^+$

⊗



1/2 $L_z = -1$
1/3 $L_z = 0$
1/6 $L_z = +1$

Dominant source of:

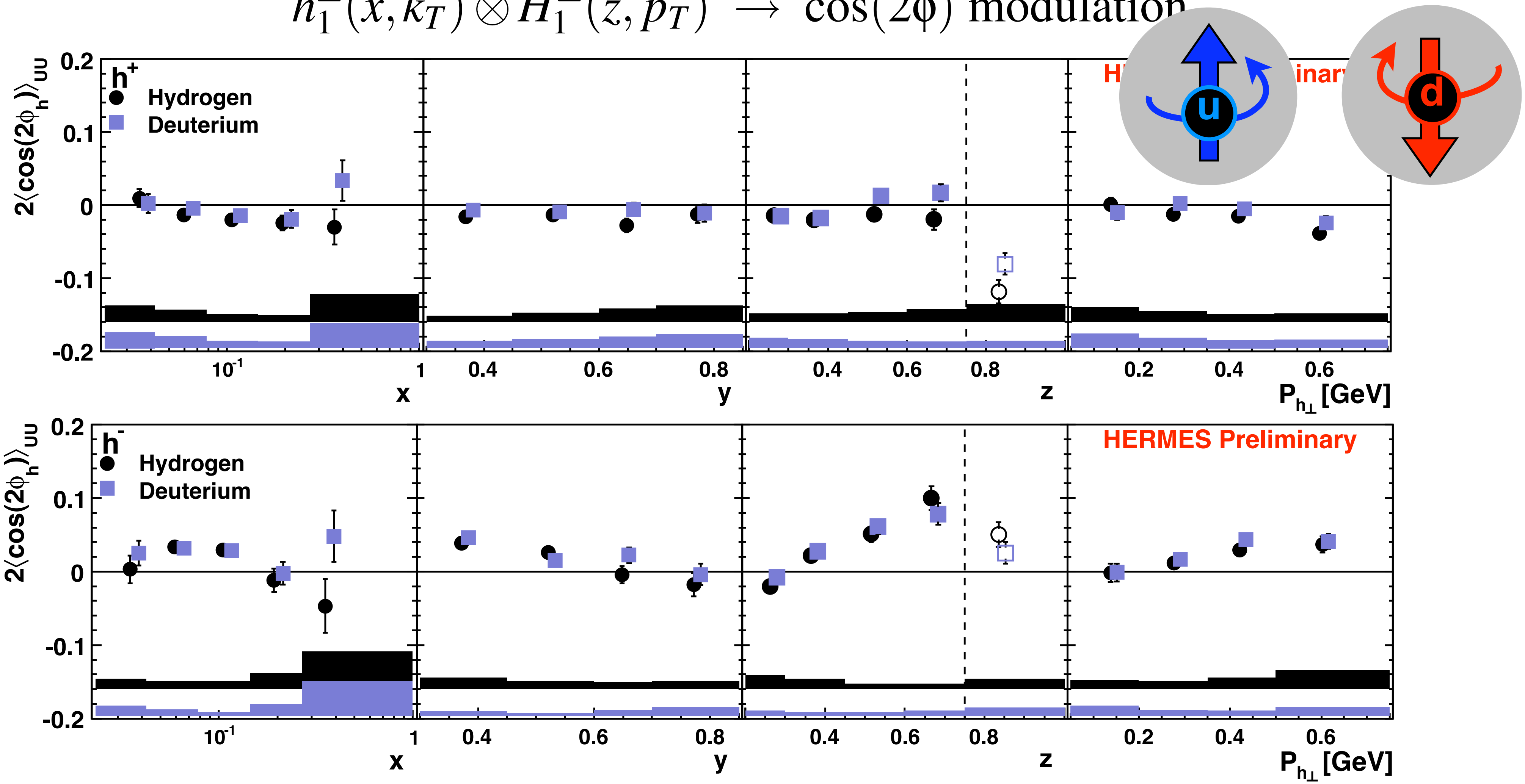
orbiting u: **$n\,\pi^+$** with **$L_z(\pi) > 0$**
orbiting d: **$\Delta^{++}\,\pi^-$** with **$L_z(\pi) < 0$**

⇒

$L_u > 0$
$L_d < 0$
$L_{qbar} \neq 0$

Boer-Mulders: $\langle\cos(2\Phi)\rangle_{UU}$ from HERMES

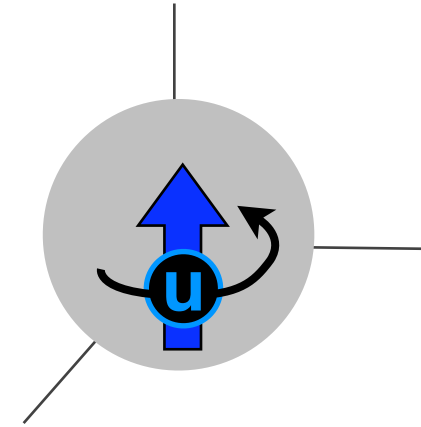
$$h_1^\perp(x,k_T) \otimes H_1^\perp(z,p_T) \;\rightarrow\; \cos(2\phi) \text{ modulation}$$



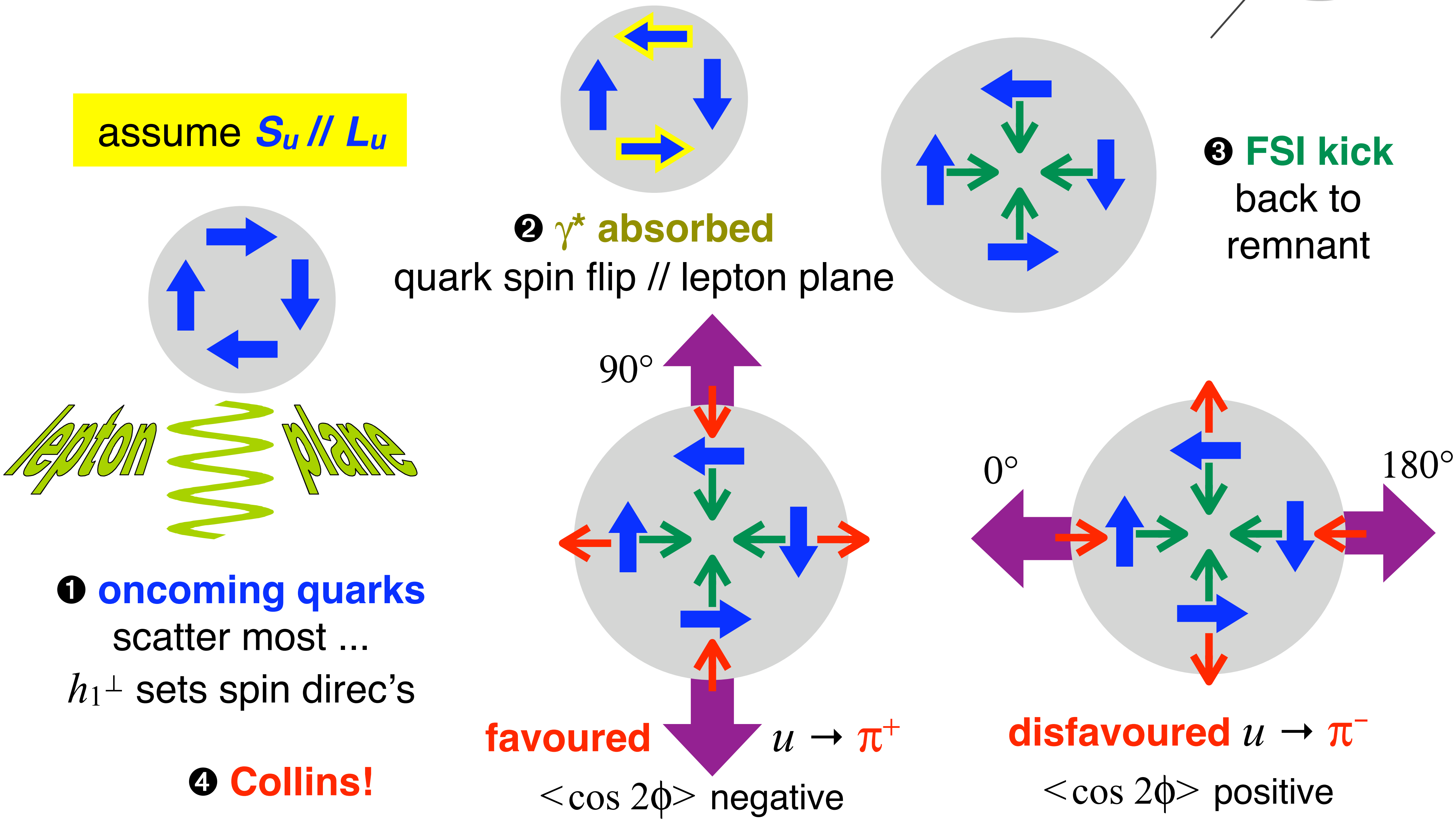
***deuterium ≈ hydrogen** values → indicate **Boer-Mulders** functions of*
***SAME SIGN** for **up** and **down** quarks (both negative, similar magnitudes)*

cos(2ϕ)

Boer-Mulders: *correlation between* $\boldsymbol{S_q}$ *and* $\boldsymbol{L_q}$



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



The Tantalizing Strawman

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

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

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

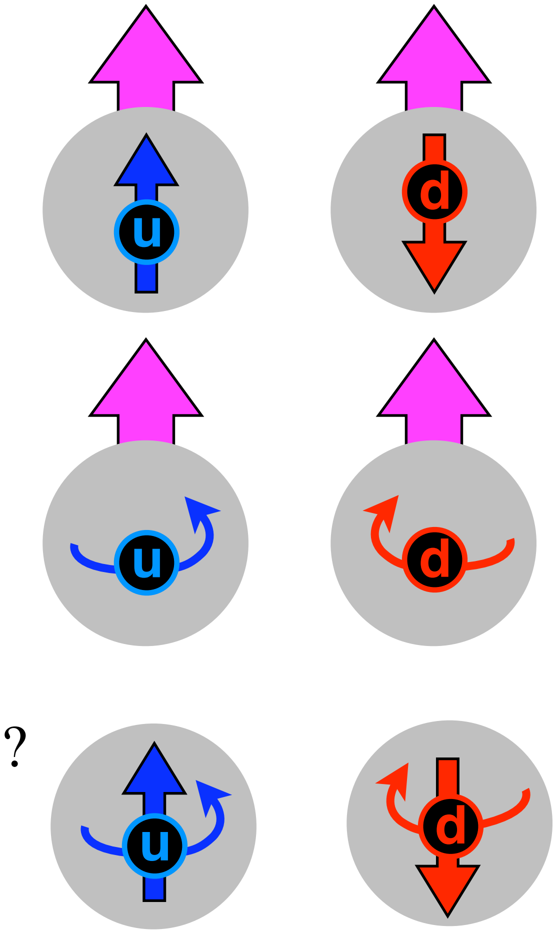
  $\rightarrow$ relat^{n} to **anomalous magnetic moment***

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

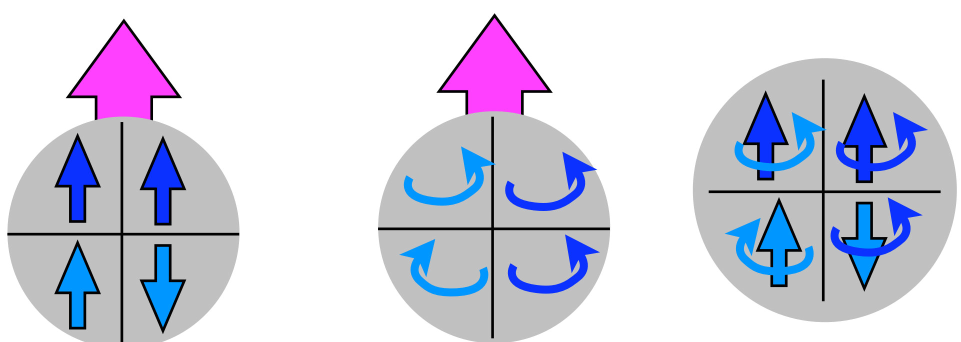
  values achieve $\kappa^{p,n} = \Sigma_q\, e_q\, \kappa_q$ with u,d only

- **Boer-Mulders:** follows that $h_{1^{\perp},u}$ and $h_{1^{\perp},d} < 0$?

  $\rightarrow$ **results** on **<cos(2Φ)>$_{UU}$** suggest yes:



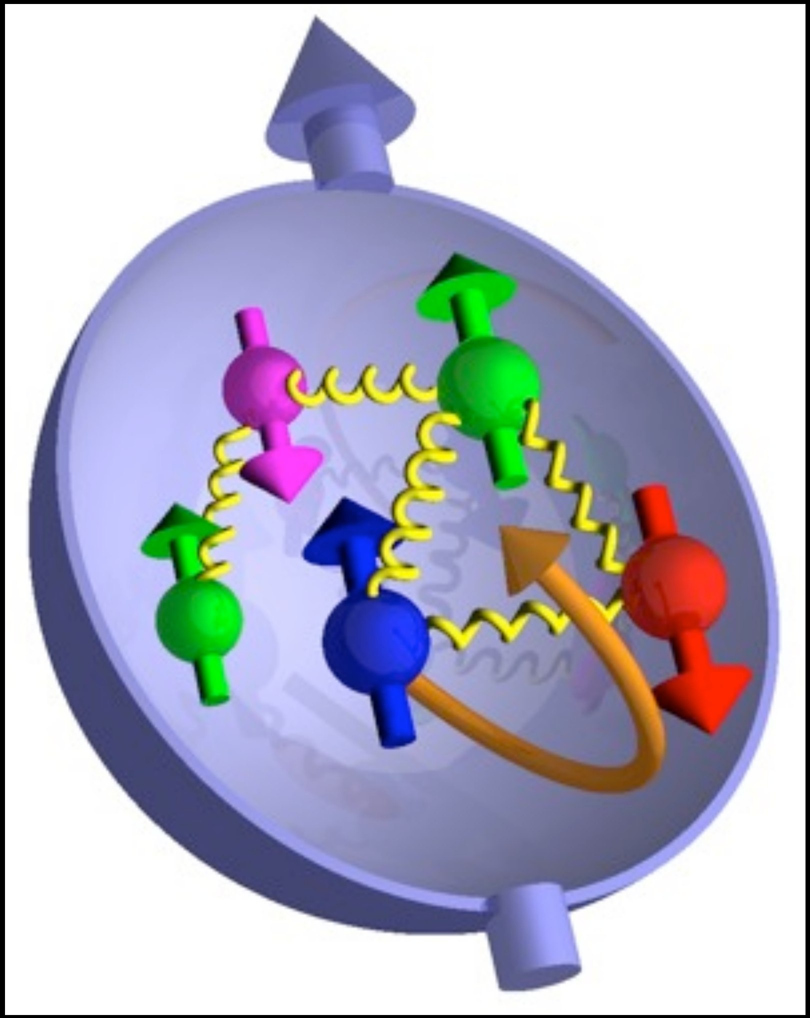
but** these TMDs are all **independent



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

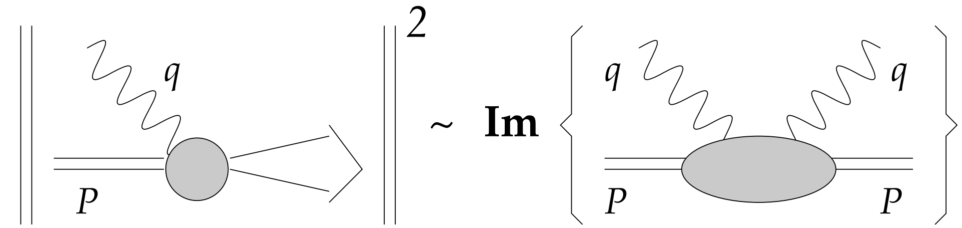
** Burkardt PRD72 (2005) 094020; Barone et al PRD78 (1008) 045022;*

Models: can we calculate Sivers & Boer-Mulders reliably from a model wavefunc^{n} + gauge links?

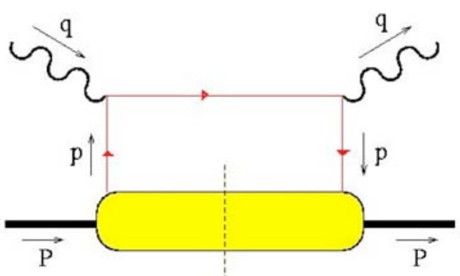


The Leading-Twist Sivers Function: Can it Exist in DIS?

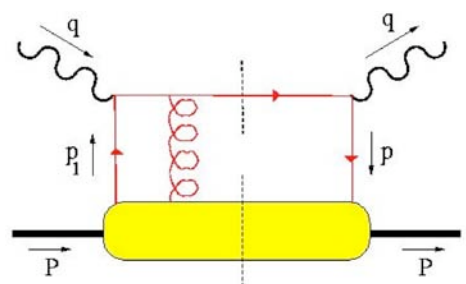
A T-odd function like $f_{1T}^{\perp}$ ***<u>must</u>*** arise from ***<u>interference</u>*** ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?



Brodsky, Hwang, & Schmidt 2002



can interfere with

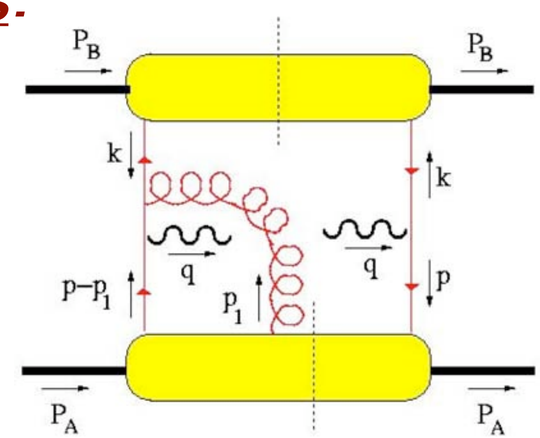


and produce a T-odd effect! (also need $L_z \neq 0$)

It looks like higher-twist ... but no, these are <u>soft gluons</u>: "gauge links" required for color gauge invariance

Such soft-gluon reinteractions with the soft wavefunction are ***final / initial state interactions*** ... and ***<u>process-dependent</u>*** ...

e.g. ***Drell-Yan***: → Sivers effect should have **<u>opposite sign</u>** cf. SIDIS



Modelling the T-odd dist and frag functio

Ancient slide from 2004

__Many__ groups now calculating these functions via the Brodsky-Hwang-Schmidt gauge-link

T-Odd Distribution Functions

- ***Yuan***: MIT bag model + 1-gluon exchange

$$f_{1T}^{\perp(1)u} = -0.01 \quad f_{1T}^{\perp(1)d} = +0.003$$

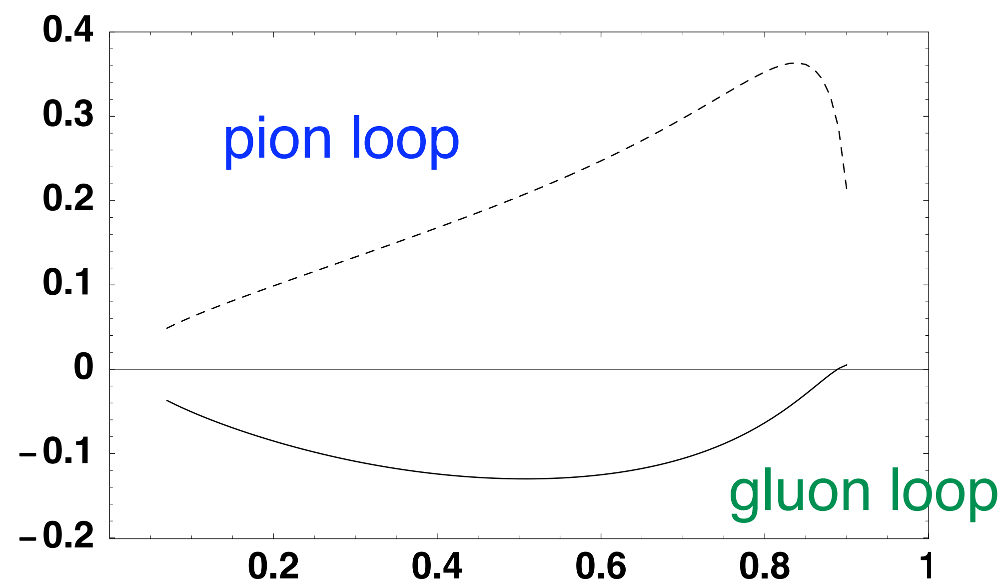
- ***Bacchetta***: quark-diquark spectator model + 1-gluon exchange

$$f_{1T}^{\perp(1)u} = +0.037 \quad f_{1T}^{\perp(1)d} = -0.011$$

T-Odd Fragmentation Functions

e.g. ***Metz et al***: Collins FF via 1-gluon and 1-pion exchange in Georgi-Manohar model

$$H_1^{\perp(1/2)}(z)/D_1(z)$$

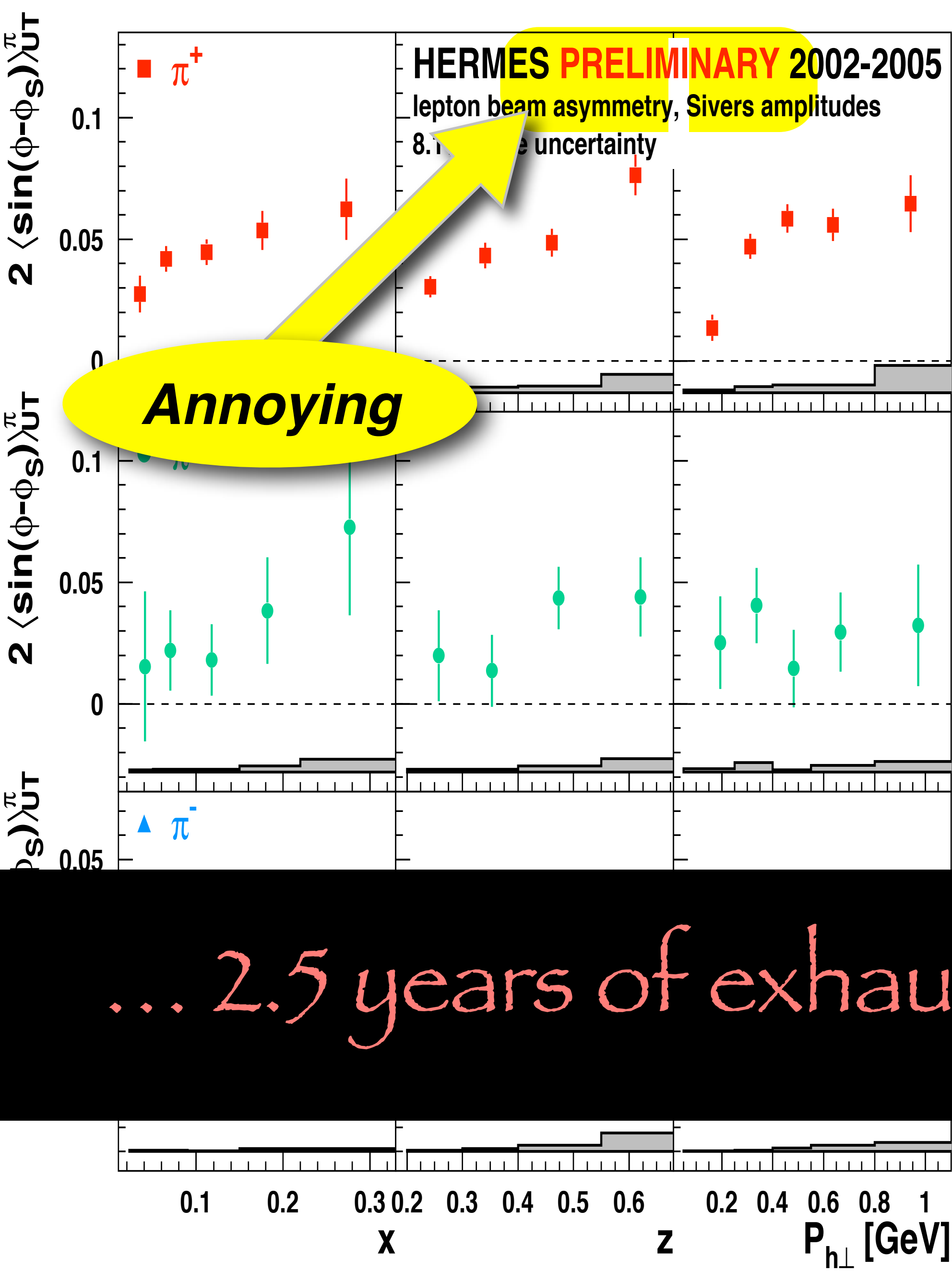


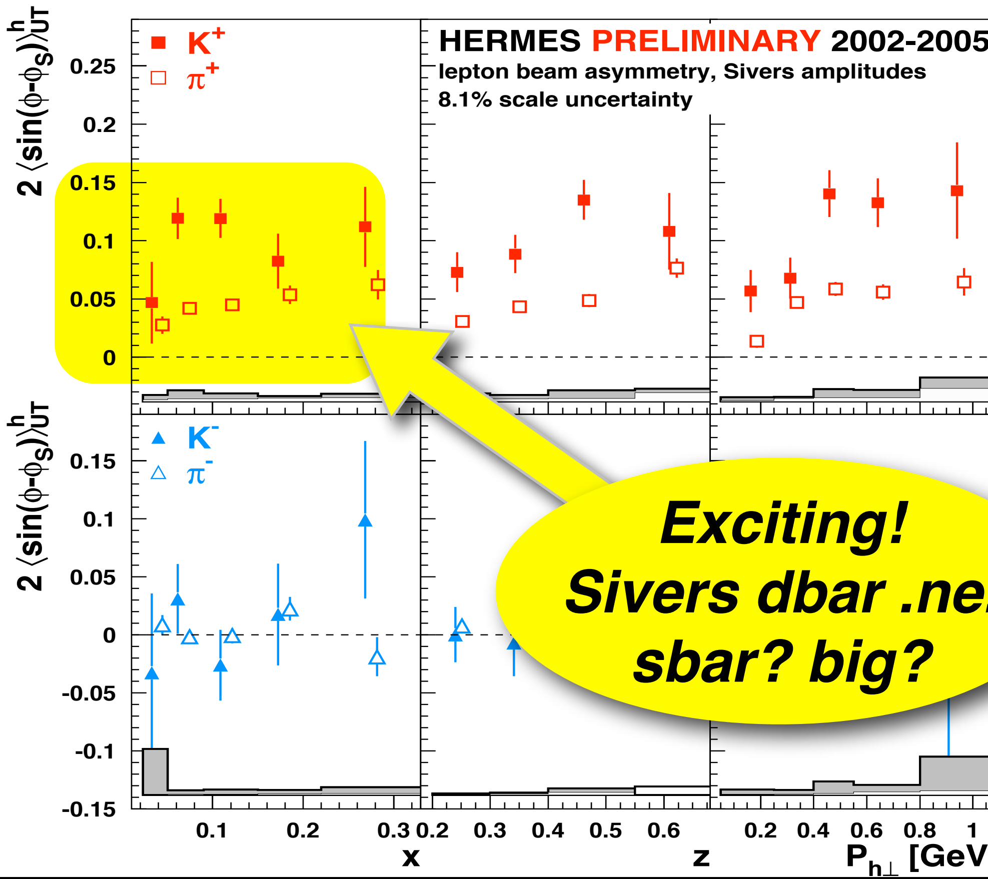
How good an approximation is __one-anything__ exchange?

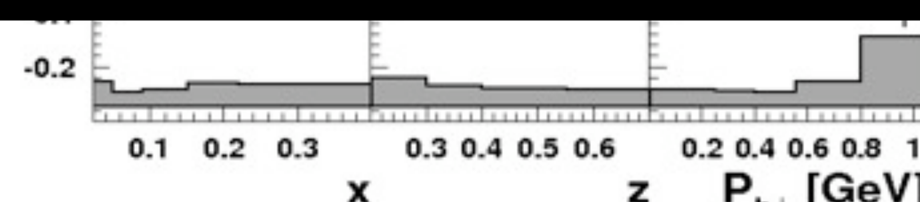
"Experimental" Issues

- The Kaon Collection
- Scale-dependence:
  Evolution & Higher Twist
- The Missing Spin Programme

Sivers Moments for π, K from H↑ Data

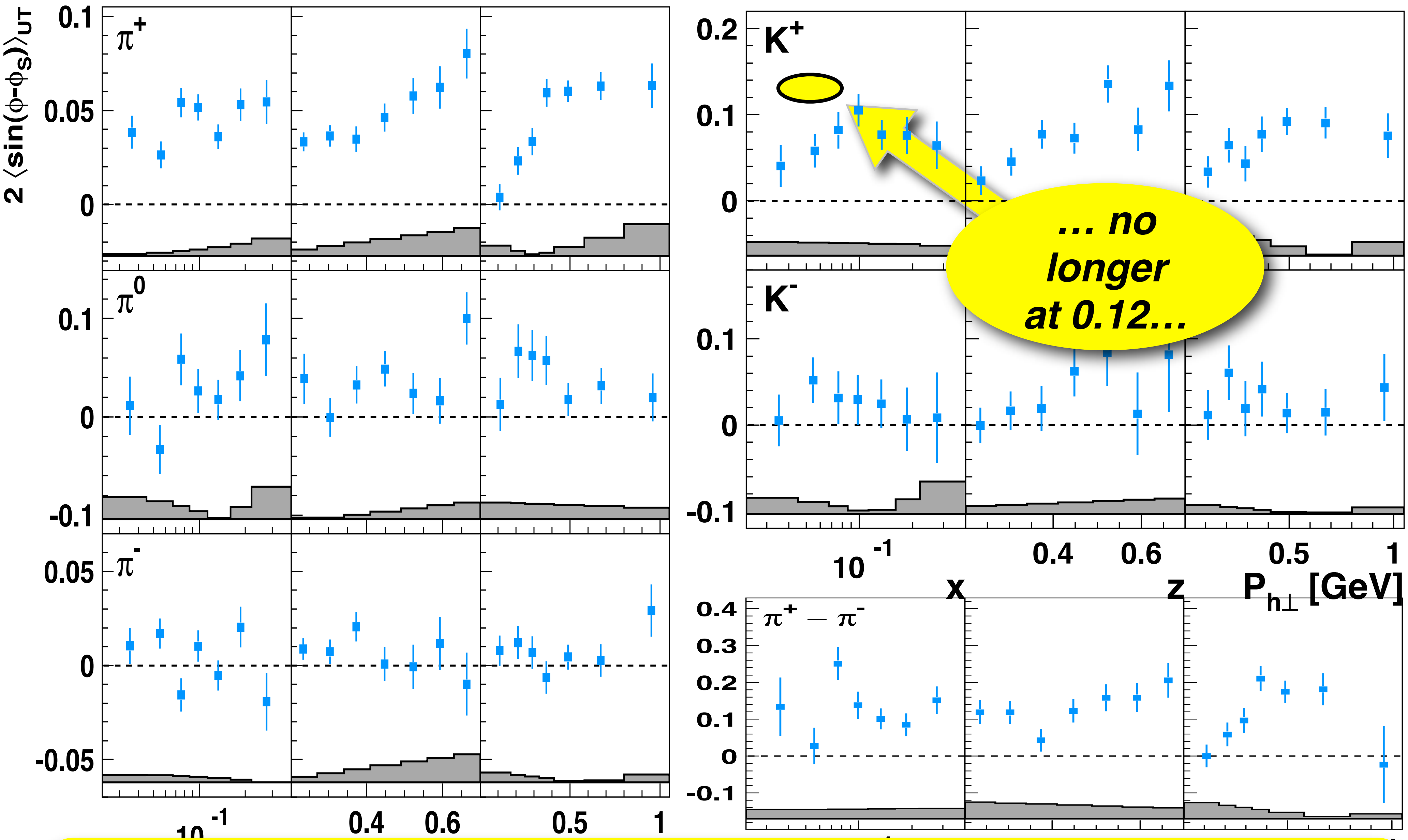






… 2.5 years of exhausting analysis later ….

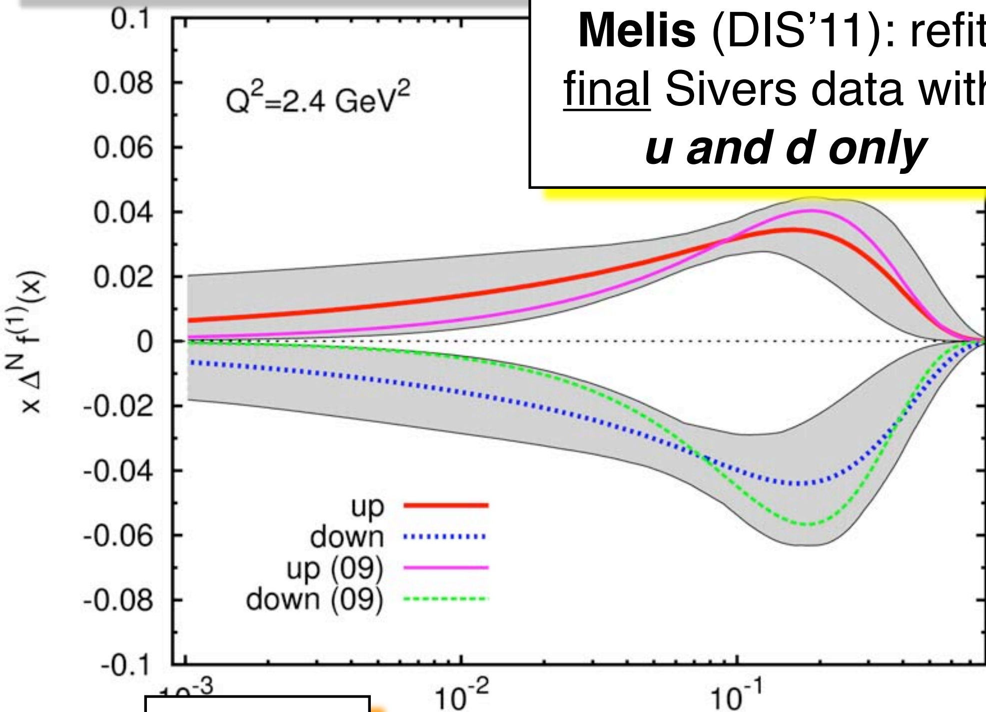
Published Sivers Moments from $H^{\uparrow}$: PRL 103 (2009)



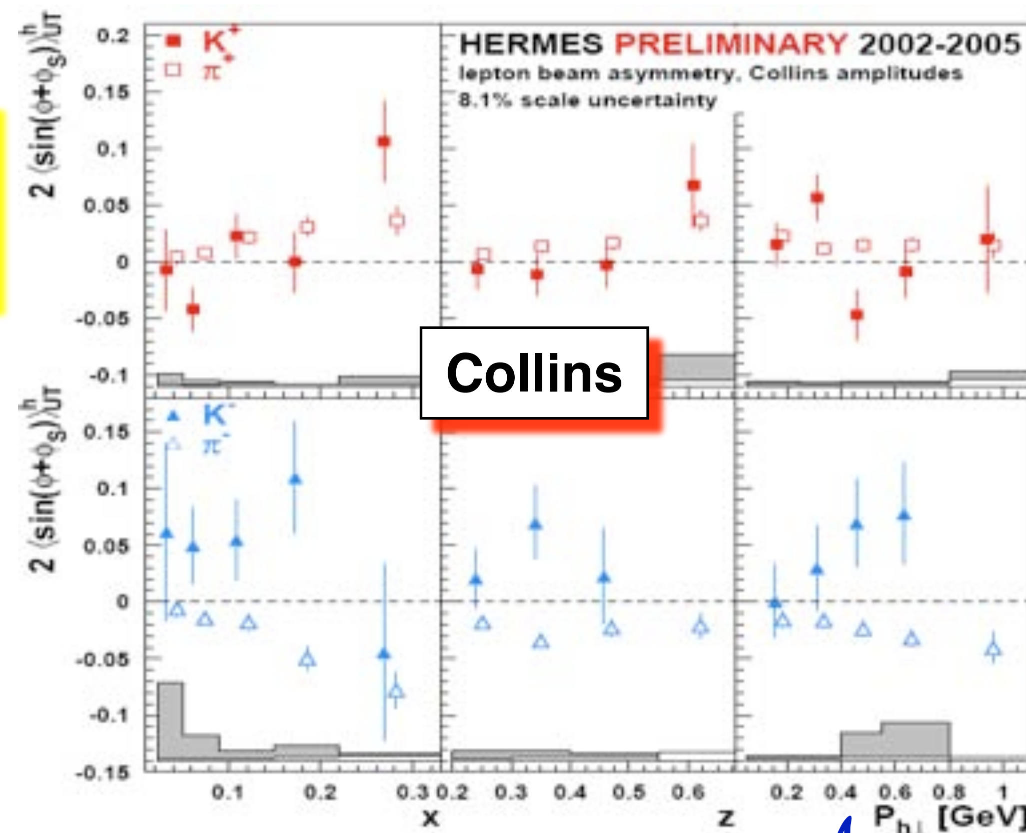
Finer binning, better systematics evalution, … message unchanged

The Kaon Collection

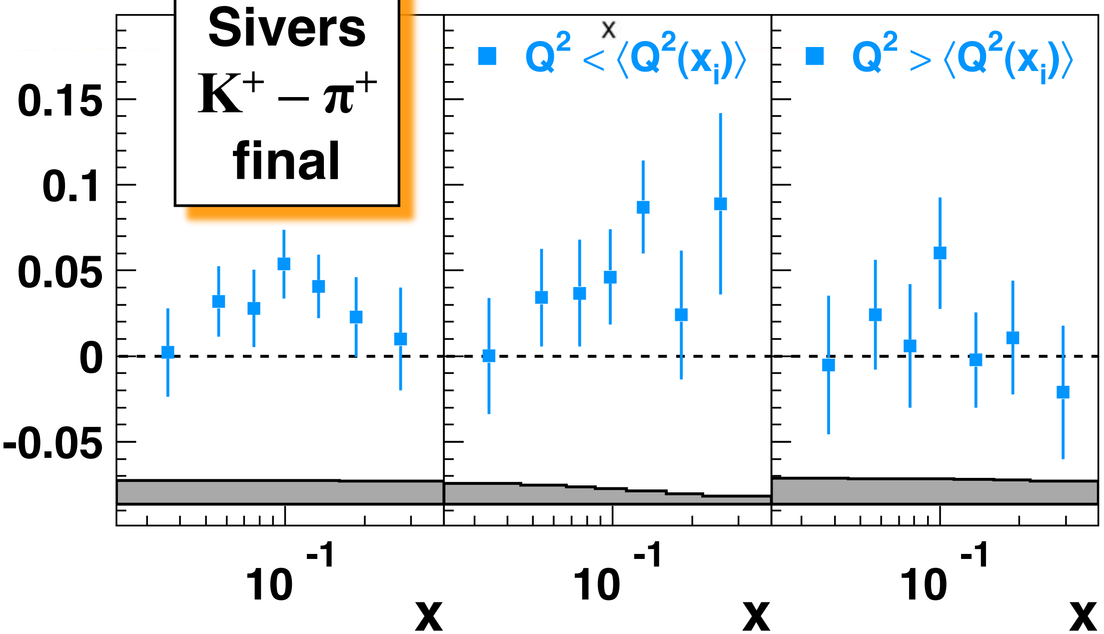
Melis (DIS'11): refit <u>final</u> Sivers data with ***u and d only***



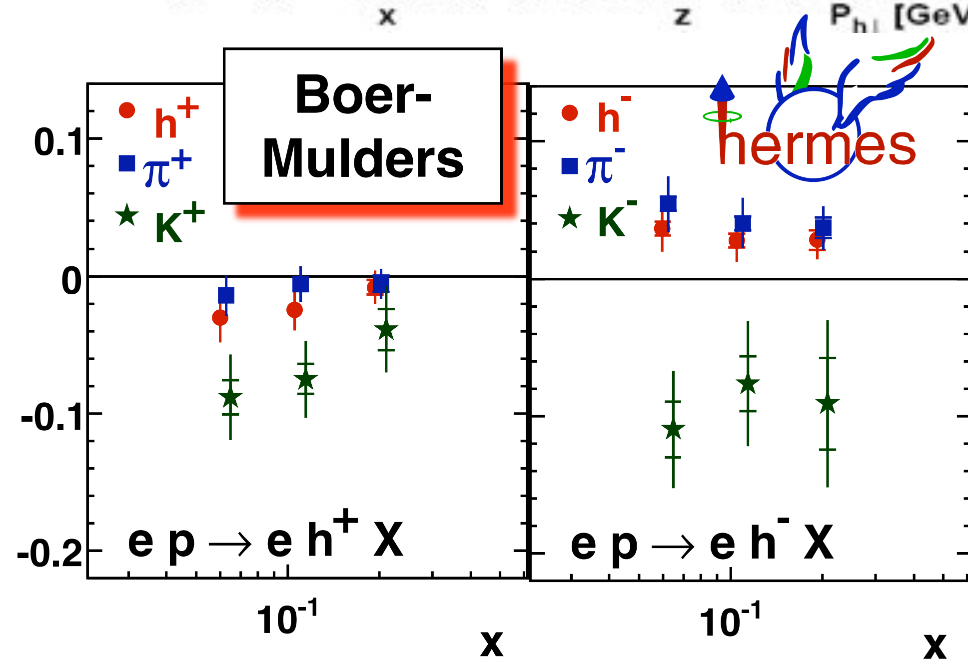
Collins



Sivers
$K^+ - \pi^+$
final



Boer-Mulders



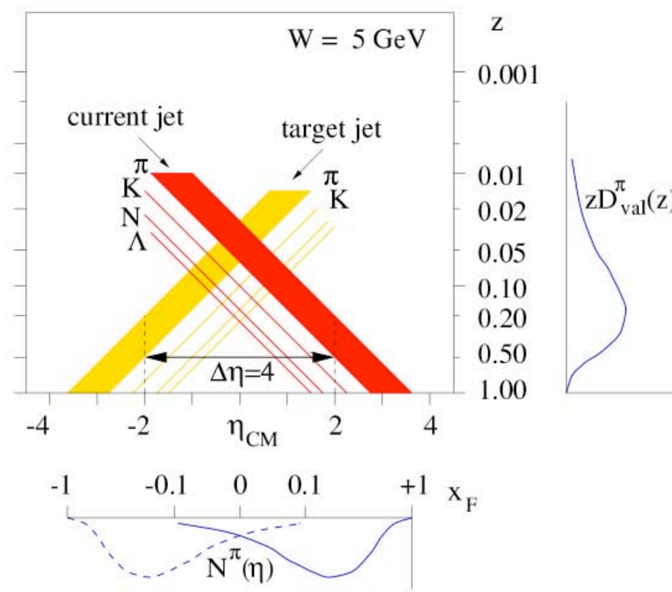
... and BRAHMS SSA's for kaons, never explained ...

SIDIS Multiplicities → Understanding Fragmentation

- How well do the **favored / disfavored** symmetries & **x-z factoriz^{n}** hold?
  ... assumed in ≈ all FF global fits & PDF extractions
  ... not exact at HERMES energies, acc to Lund MC

$$D_{\rm fav} \equiv D_u^{\pi^+} = D_d^{\pi^-} = \ldots$$

$$D_{\rm disfav} \equiv D_u^{\pi^-} = D_d^{\pi^+} = \ldots$$



- Are there **any** such FF symmetries for ***Kaons***?

- Does **intrinsic quark <k$_T$>** vary with ***x***?
  ... with ***flavor*** ? (holy grail!)

- Can the **Lund model** describe fragmentation at different **energies** / different **processes** (SIDIS vs e+e–) ***without retuning*** ?

hermes

$d\sigma(x,z,p_T)$
$d\sigma(Q^2,z,p_T)$

paper permanently in progress

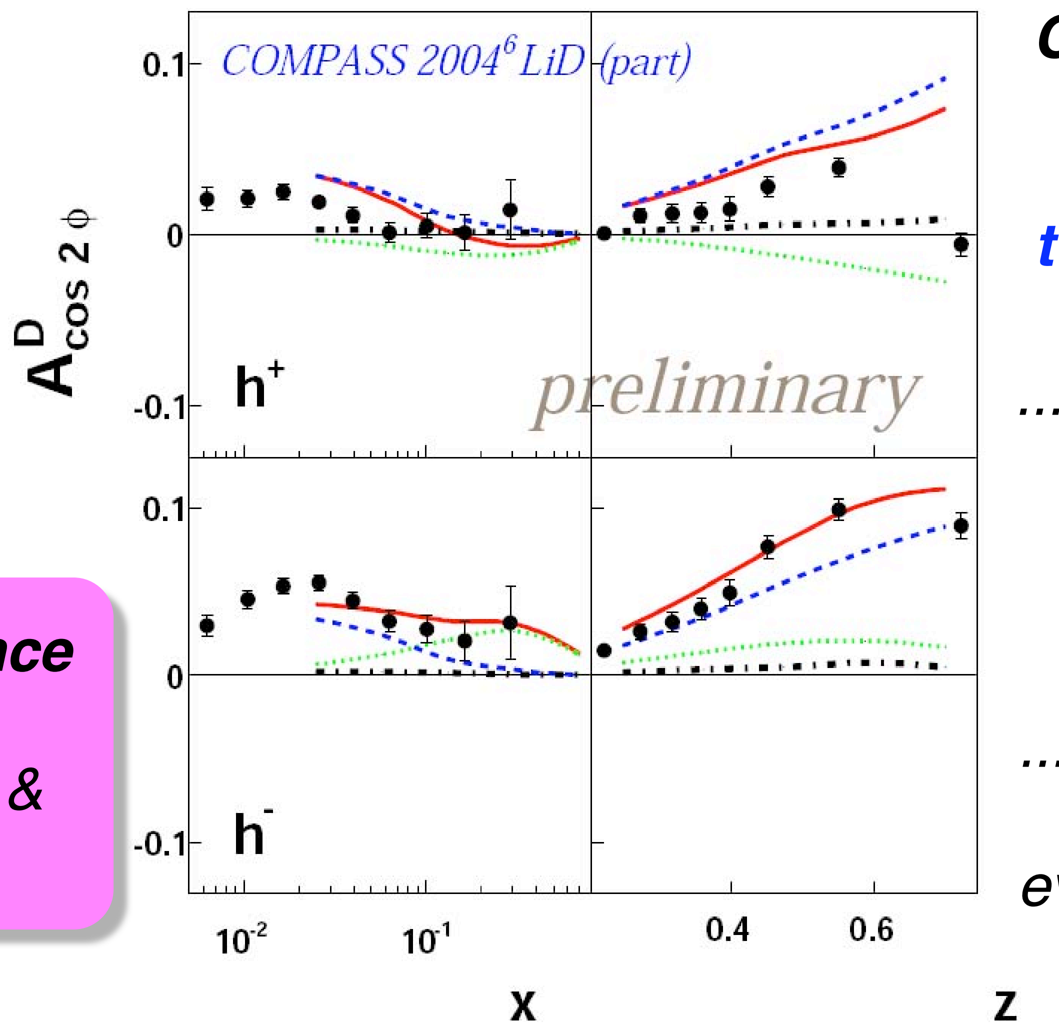
for $\pi^{\pm}$, π^0,$K^{\pm}$, p, pbar

compare

COMPASS-II $\mu^{\pm}$p
- pure LH2 target
- higher energy
- RICH upgrade
- full 4D binning

Boer-Mulders #2: $\langle\cos(2\Phi)\rangle_{UU}$ from COMPASS

different picture @ higher Q2



total	Boer Mulders
Cahn	pQCD

errors shown are statistical only

COMPASS cos(2Φ) *well explained by dominant* ***twist-4 Cahn effect***

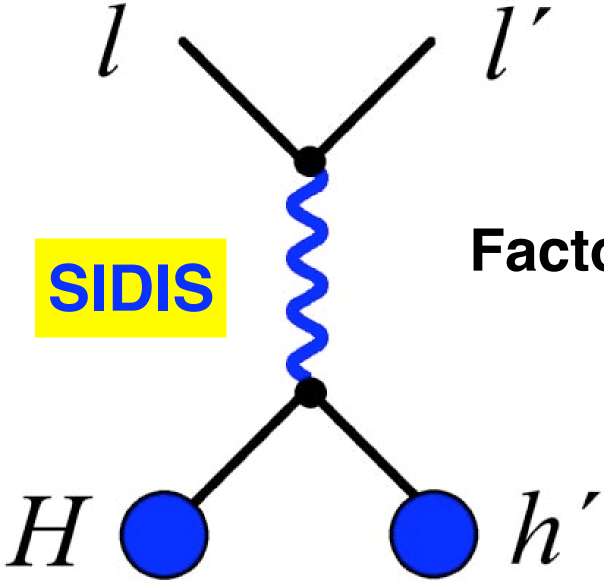
... but Cahn contrib^n seems small in ***HERMES*** *data, at lower Q^2*

... Can ***BELLE*** *data on Collins FF be evolved to all SIDIS scales?*

Scale-dependence *challenges:* ***TMD evolution*** *&* ***higher twist***

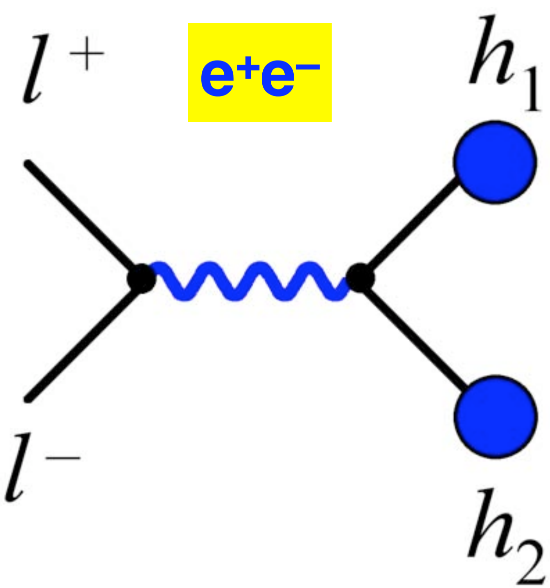
V.Barone, A.Prokudin, B.Q.Ma
arXiv:0804.3024 [hep-ph]

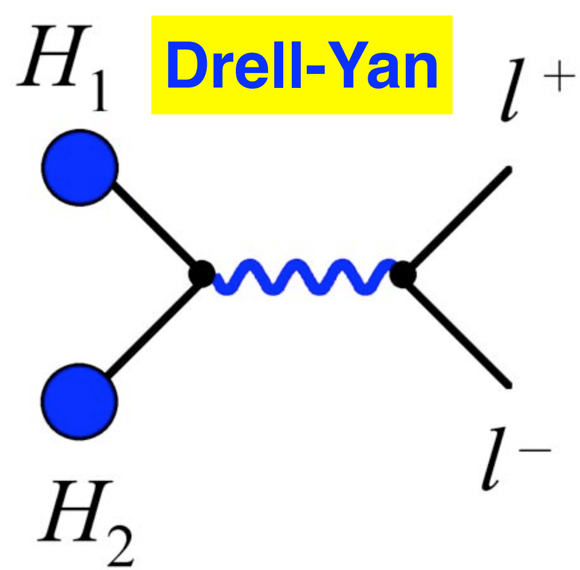
Leptons: clean, surgical tools



Factorization: $d\sigma \sim \sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H})}(x) \; \mathbf{D}_{\mathbf{q}}^{\mathbf{h}'}(z)$

- *Disentangle* ***distribution*** *(f) and* ***fragmentation*** *(D) functions → measure* ***all process***
- *Disentangle* ***quark flavours*** *q → measure as many* ***hadron species*** *H,h as possible*

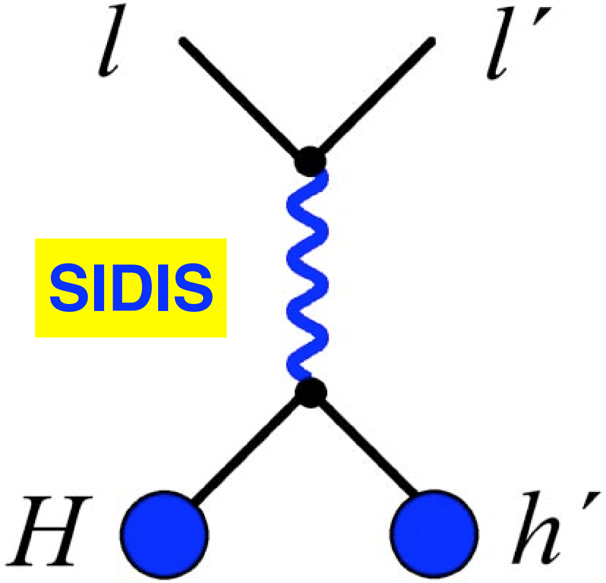




$$\sum_q e_q^2 \; \mathbf{D}_{\mathbf{q}}^{\mathbf{h}_1}(z_1) \; \mathbf{D}_{\bar{\mathbf{q}}}^{\mathbf{h}_2}(z_2)$$

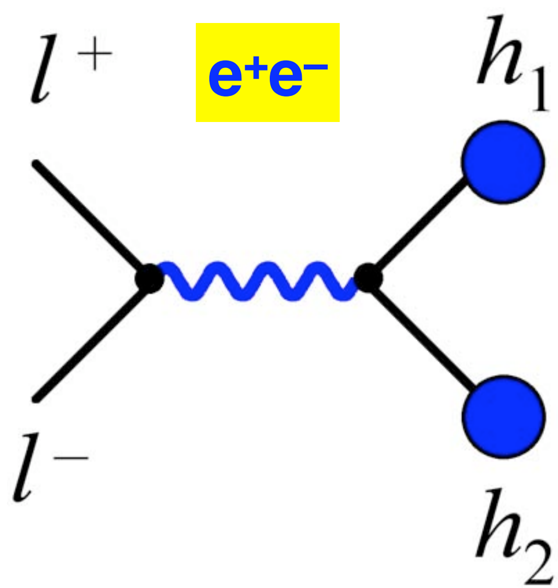
$$\sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H}_1)}(x_1) \; \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H}_2)}(x_2)$$

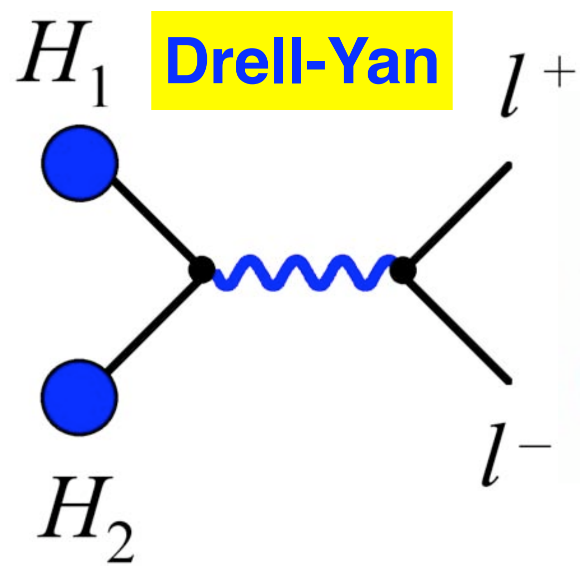
Leptons: clean, surgical tools



$$\sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H})}(x) \; \mathbf{D}_{\mathbf{q}}^{\mathbf{h}'}(z)$$

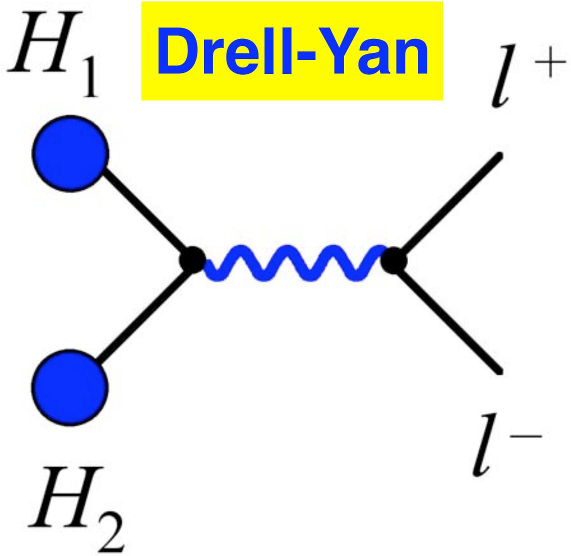
Spin Programs





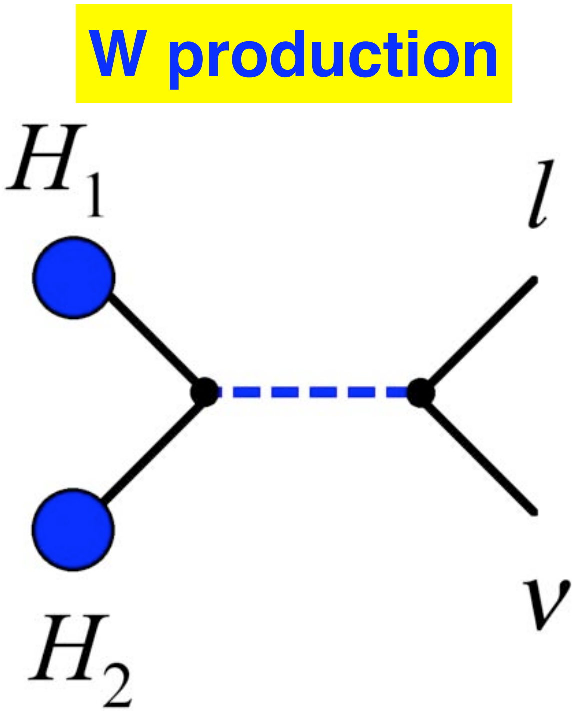
$$\sum_q e_q^2 \; \mathbf{D}_{\mathbf{q}}^{\mathbf{h_1}}(z_1) \; \mathbf{D}_{\bar{\mathbf{q}}}^{\mathbf{h_2}}(z_2)$$

$$\sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H_1})}(x_1) \; \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H_2})}(x_2)$$



The Missing Spin Program: Drell-Yan

$$\sum_q e_q^2 \, \mathbf{f}_{\mathbf{q}}^{(\mathbf{H_1})}(x_1) \, \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H_2})}(x_2)$$



- Clean access to **sea quarks**
  e.g. $\Delta\bar{u}(x), \Delta\bar{d}(x)$ at RHIC
- Crucial test of **TMD formalism**
  → sign change of T-odd functions
- A **complete** spin program requires multiple hadron species
  → **nucleon & meson beams**

Theory Issues

- The TMD-GPD Connection

  … or lack thereof

- The Transverse Spin Sum Rule

  … elusive unicorn

- The Definition of L

PDFs and the Optical Theorem

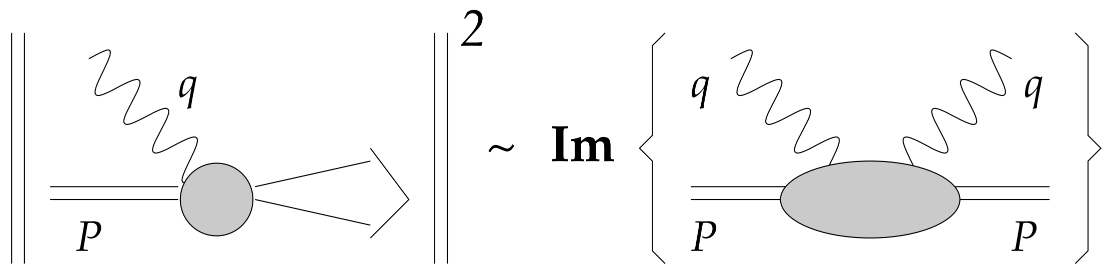
Proton Matrix Elements

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

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

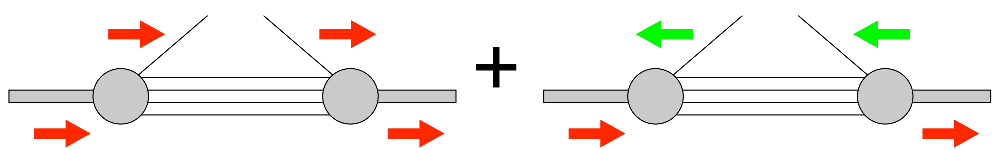
tensor charge $\langle PS|\overline{\psi}\sigma^{\mu\nu}\gamma_5\psi|PS\rangle = \int_0^1 dx\; \delta q(x) - \delta\overline{q}(x)$ $\rightarrow$???

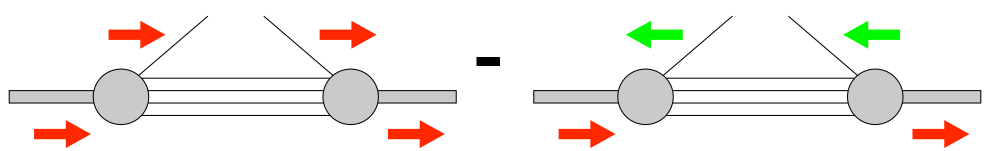
the Optical Theorem

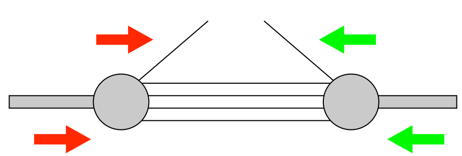


Forward Scattering Amplitudes

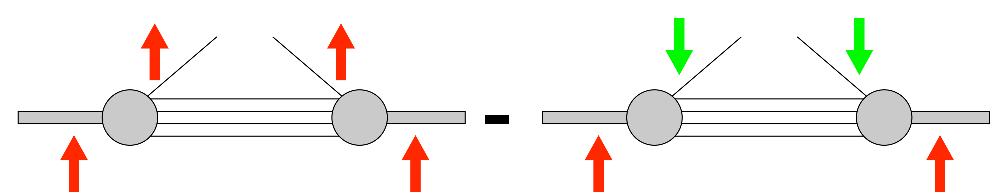
the **DIS xsec** ... can be calculated from ...

$q(x) \sim$ 

$\Delta q(x) \sim$ 

$\delta q(x) \sim$ 

... or in transverse basis ...



Danger !
"Pauli-Lubanski" ...
h_1 is ***not*** $< \Sigma\perp >$

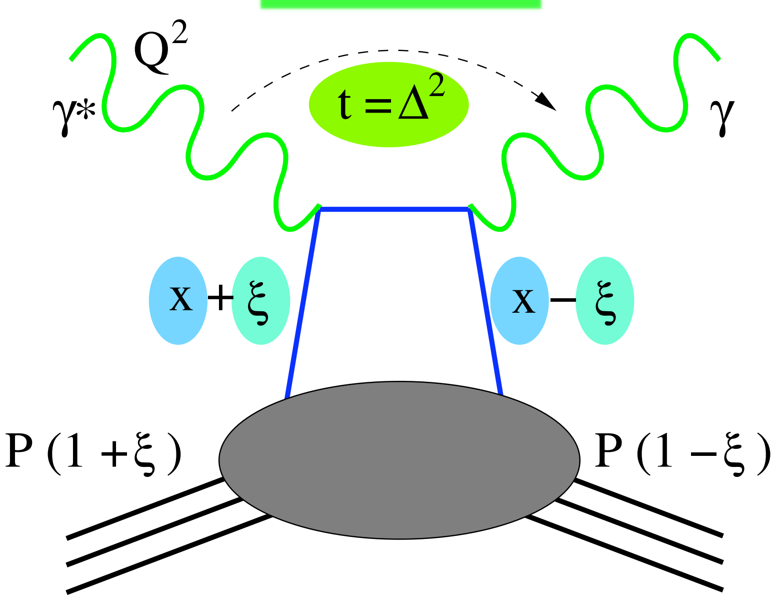
TRANSVERSITY

Generalized Parton Distributions

Analysis of ***hard exclusive processes*** leads to a new class of parton distributions

Cleanest example: Deeply Virtual Compton scattering

DVCS



- x: average quark momentum frac[n]
- ξ: "skewing parameter" = $x_1 - x_2$
- t: 4-momentum transfer[2]

Four new distributions = "GPDs"

q helicity sum $\longrightarrow$ $H(x,\xi,t), E(x,\xi,t)$

q helicity difference $\longrightarrow$ $\tilde{H}(x,\xi,t), \tilde{E}(x,\xi,t)$

- involve quark helicity-conserving amplit's

Four with q helicity flip = "GTDs"

q helicity sum $\longrightarrow$ $H_T(x,\xi,t), E_T(x,\xi,t)$

q helicity difference $\longrightarrow$ $\tilde{H}_T(x,\xi,t), \tilde{E}_T(x,\xi,t)$

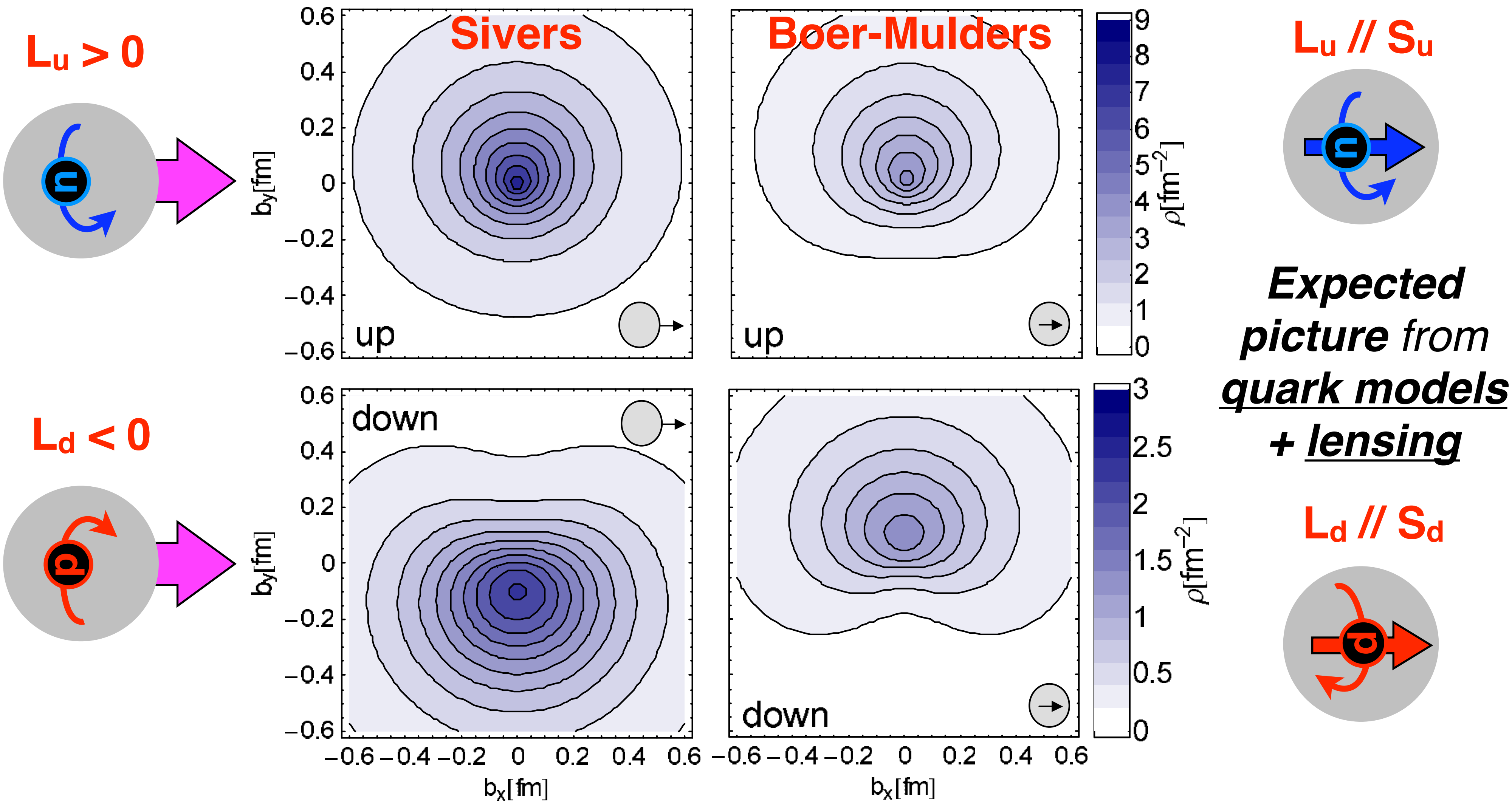
Generalized **T**ransversity Distrib's are
- chiral odd
- also called "tensor GPDs" because of presence of $\sigma^{\mu\nu}$ in their definition

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 ... observe spin-dependent **shifts** in quark densities:



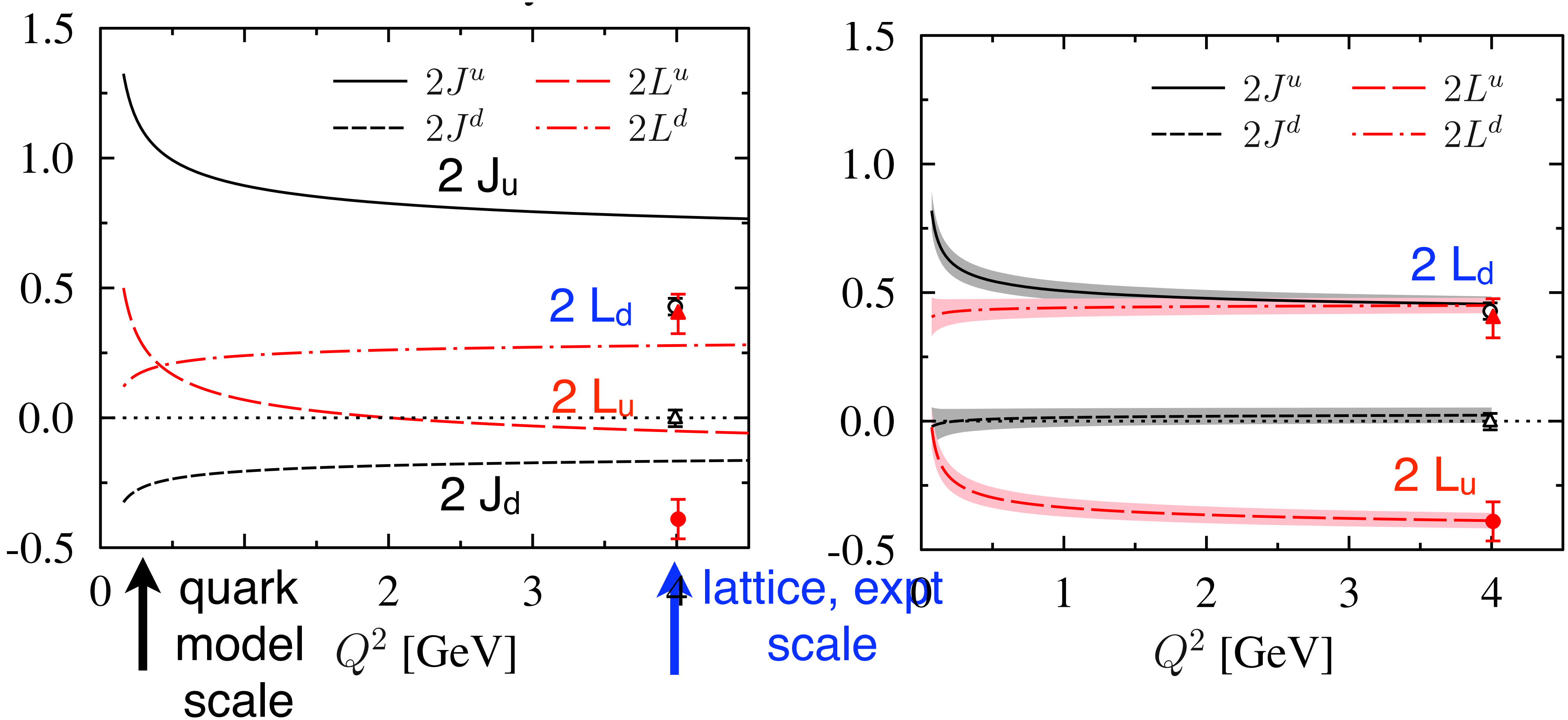
Expected picture** from **<u>quark models</u> + <u>lensing</u>

Thomas, PRL101 (2008)

... and Longitudinal spin on the lattice ...

Wakamatsu, EPJA44 (2010)

Thomas: **cloudy bag model** evolved up to Q^2 of expt / lattice



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

Evolution might explain disagreement with quark models ...

or not. *Wakamatsu evolves down → insensitive to uncertain scale of quark models*

The Mysterious E

- **Density shifts** seen on lattice due to GPD $\mathbf{E_q}(x,\xi,t)$

- **E requires L**

  Brodksy, Drell (1980) ; Burkardt, Schnell, PRD 74 (2006)

  - ∫ **E** dx = Pauli $\mathbf{F_2}$ $\rightarrow_{(t=0)}$ anomalous magnetic moment **κ** ∵ GPD basics
  - both $\mathbf{F_2}$ and **κ** **require L ≠ 0** ∵ N spin-flip amplitudes

Jaffe L?

- **E is not L**

Ji Sum Rule

$$2\,J_q = \int x\, H_q|_{t=0}\, dx + \int x\, E_q|_{t=0}\, dx$$

momentum fraction $\int x\, q(x)\, dx \leftarrow \langle \mathbf{x} \rangle_\mathbf{q} + \mathbf{E_q^{(2)}} \rightarrow$ **"anomalous gravito-magnetic moment"**

Spin Sum Rule

$$2\,J_q = \Delta q + 2\,L_q$$

$$\therefore 2L_q = \left[\langle x\rangle_q + E_q^{(2)}\right]_{=J_q} - \Delta q$$

Ji L

"L" not uniquely defined

Contradiction?

Ji, PRL 78 (1997)

Proton Spin Decompositions

Jaffe & Bashinsky, NPB 536 (1998)

$$J^{\text{Ji}} = \underbrace{\frac{i}{2}q^\dagger(\vec{r}\times\vec{D})^z q}_{L_q} + \underbrace{\frac{1}{2}q^\dagger\sigma^z q}_{\Delta q} + \underbrace{2\,\mathrm{Tr}\,E^j(\vec{r}\times\vec{D})^z A^j}_{L_g} + \underbrace{\mathrm{Tr}(\vec{E}\times\vec{A})^z}_{\Delta g}$$

$$J^{\text{Jaffe}} = \frac{1}{2}q_+^\dagger(\vec{r}\times i\vec{\nabla})^z q_+ + \frac{1}{2}q_+^\dagger\gamma_5 q_+ + 2\,\mathrm{Tr}\,F^{+j}(\vec{r}\times i\vec{\nabla})^z A^j + \varepsilon^{+-ij}\mathrm{Tr}F^{+i}\vec{A}^j$$

Ji: ❸ gauge invariant $\Delta q, L_q, J_g$

- ✘ **access Δg**: no GI sep^n of Δg, L_g
- ✔ **measure L_q** (expt & lattice): yes → via GPDs & DVCS
- ✘ **interpret L_q**: covariant derivative $D^\mu = \partial^\mu + ig^\mu$ ← **gluon interac's**

Jaffe: ❹ gauge invar $\Delta q, L_q, \Delta g, L_g$

- ✔ **access Δg**: this is what's being measured at RHIC, COMPASS
- ✔ **interpret L_q**: $\vec{r}\times\vec{p}$ → field-free OAM ... in ∞ momentum frame
- ✘ **measure L_q** (expt & lattice): involves **non-local** operators except in **lightcone gauge** $A^+=0$

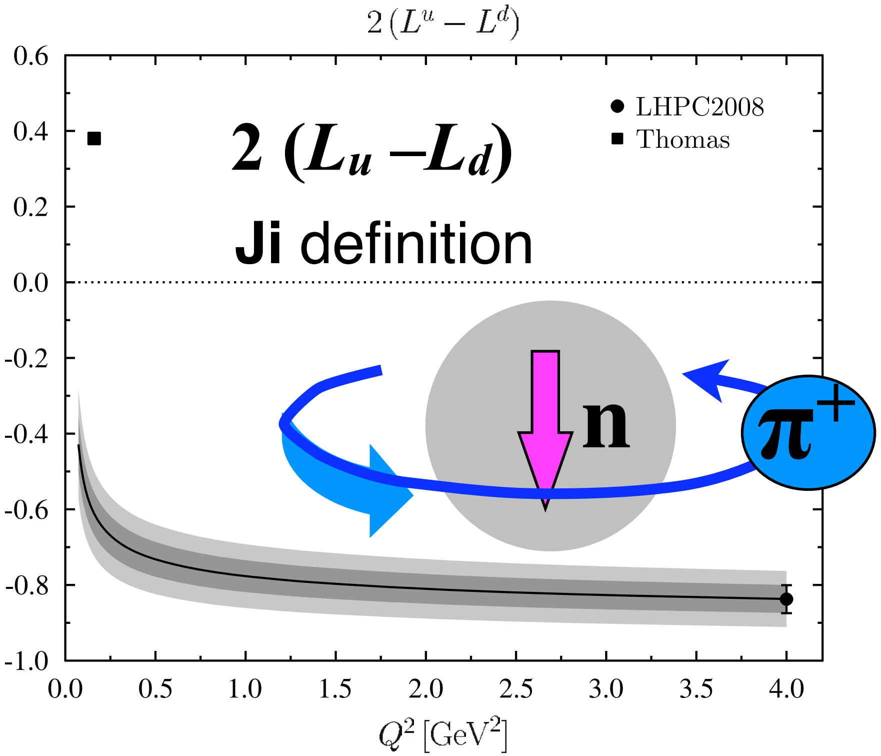
New Ideas

Ongoing work of **Chen** et al *PRL 100 (2008), 103 (2009)*
& **Wakamatsu** *PRD 81 (2010), 83 (2011)*

Insights from the χQSM

Wakamatsu, EPJA 44 (2010)

Theory: Ji's L_{u-d} is rock-solid & **negative**



$$2\,L_q^{\mathrm{Ji}} = \underbrace{\left[\langle x\rangle_q + E_q^{(2)}\right]}_{=J_q} - \Delta q$$

- $<x>_{u-d}$: well known
- $\Delta u - \Delta d = g_A$: well known
- $E^{(2)}{}_{u-d}$: **<u>all</u> lattice** calculat^{n}s **<u>and</u> XQSM** agree

Compare Jaffe & Ji
calculate explicitly in χQSM;
at quark-model scale:

	L_{u-d} Jaffe	L_{u-d} Ji
Valence	+0.147	–0.142
Sea	–0.265	–0.188
Total	–0.115	–0.330

Negative model value dominated by sea quark L !

Need <u>direct measurement</u> of Sivers for <u>sea quarks</u>:

spin-dependent Drell-Yan with *p* or π^+ beam


Hmmm
down
-0.6 -0.4 -0.2 0 0.2 0.4 0.6
b_x [fm]
0.5
0
d
u
u