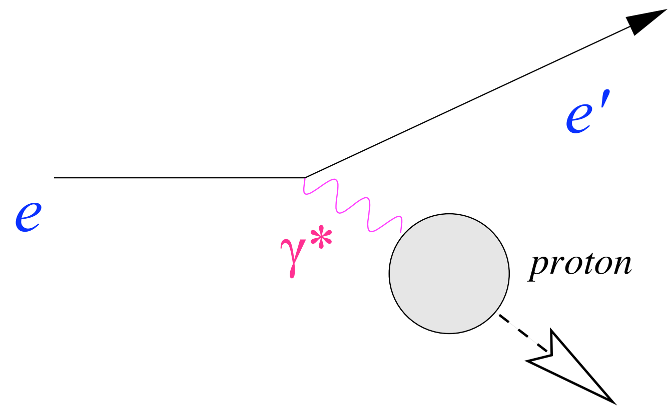
Deep-inelastic scattering

The virtual photon and Q^2



In relativistic quantum mechanics = **quantum field theory**, scattering due to a force between particles (e.g. E&M) is treated as if a **virtual particle** were **exchanged** between beam and target

force	carrier
E & M	photon γ
strong	gluon g
weak	W, Z

The **virtual photon** γ^* is just a combination of E and B fields ... "**virtual**" → *short-lived*

Kinematic variables of electron scattering

electron beam e $\quad k = [E, \vec{k}] = [E, 0, 0, k]$

scattered electron e' $\quad k = [E', \vec{k}']$

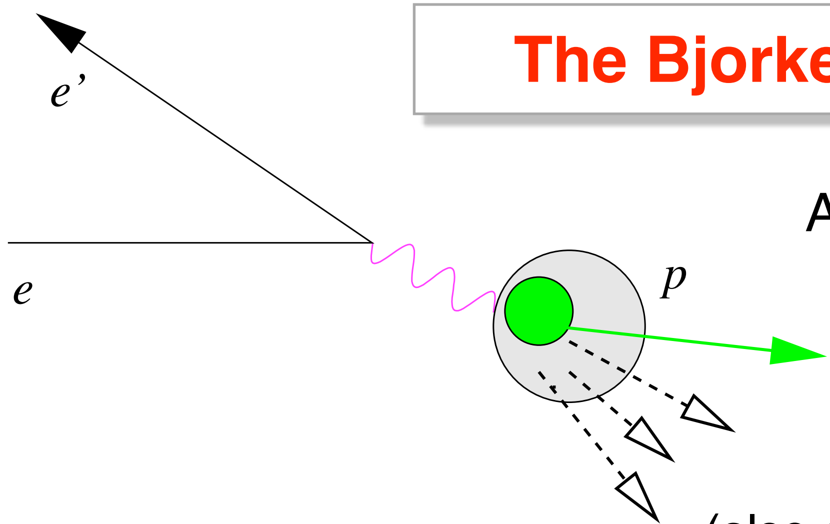
virtual photon γ^* $\quad q = [\nu, \vec{q}] = [E - E', \vec{k} - \vec{k}']$

$$m_e^2 = k \cdot k = k' \cdot k'$$

$$Q^2 \equiv -q \cdot q = |\vec{q}|^2 - \nu^2 > 0!$$

→ *Virtual photon has **imaginary mass**, unlike a real photon!*

The Bjorken scaling variable x



At fixed beam energy, electron scattering xsecs depend on **two variables**: Q^2 and ν of the γ^*

... or E' and θ of the scattered beam:

$$Q^2 = 4EE'\sin^2(\theta/2)$$
$$\nu = E - E'$$

(also define $y \equiv \nu/E$ = fractional energy of γ^*, range 0 → 1)

At high enough Q^2 and W^2 we scatter not from the whole proton, but from a collection of **pointlike, nearly-massless quarks**

Elastic electron-quark scattering:

$$k + p_q = k' + p'_q \quad \rightarrow \quad p'_q = q + p_q$$

$$(p'_q)^2 = m_q^2 = (q+p_q)^2 = q^2 + p_q^2 + 2q\cdot p_q \quad \rightarrow \quad 2q\cdot p_q = -q^2 = Q^2$$

Suppose the **struck quark** carries a **fraction x** of the target **proton's 4-momentum** P

$$p_q = xP$$

$\rightarrow \; p_q = xP \; = [xM_p, 0]$ in lab frame

$\rightarrow Q^2 = 2q\cdot p_q = 2\nu \, xM_N$

$$x = \frac{Q^2}{2M_p\nu}$$

We measure this for every event!

Deep-inelastic scattering

$p_q = xP$

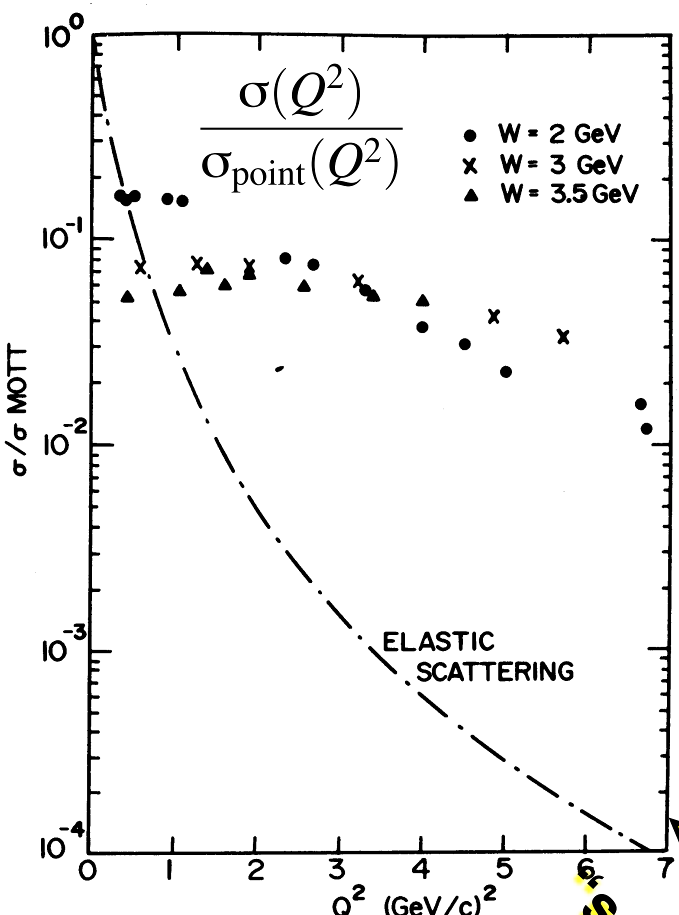
$$x = \frac{Q^2}{2M_p \nu}$$

When we are scattering from individual pointlike quarks within the target, we are in the regime of **deep-inelastic scattering**

$$\frac{d\sigma}{dx\,dQ^2} = \left(\frac{d\sigma}{dx\,dQ^2}\right)_{\mathrm{point(eq\to eq)}} \cdot \sum_{q=u,d,s,\bar{u},\bar{d},\bar{s}} e_q^2\, q(x,Q^2)$$

The interesting, **proton substructure** part of the xsec is described by **parton distribution functions** $q(x)$

$$q(x,Q^2)$$



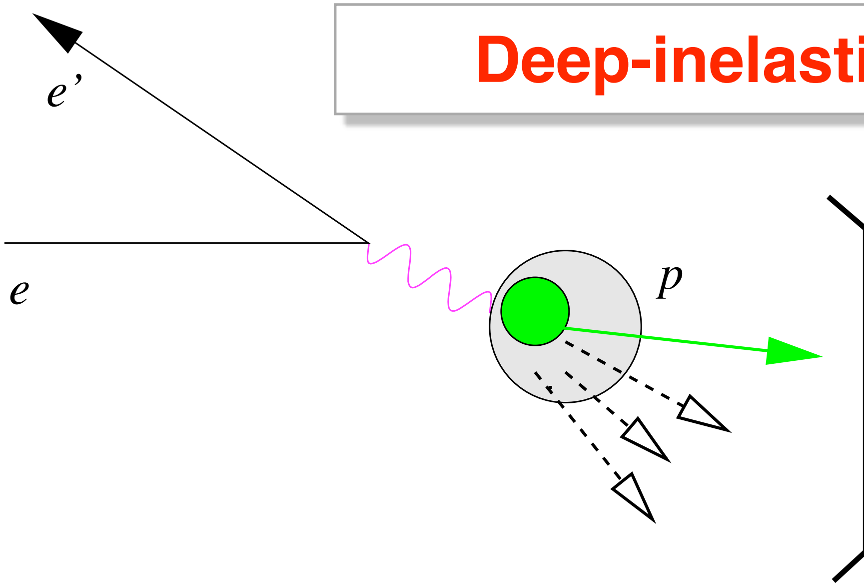
"scaling"

- PDFs describe **number density** of quarks at different momentum-fractions ***x***
- one PDF per **quark flavour**

$$\{q(x)\} = u(x), d(x), s(x), \bar{u}(x), \bar{d}(x), \bar{s}(x)$$

- PDFs depend only very-weakly on Q^2

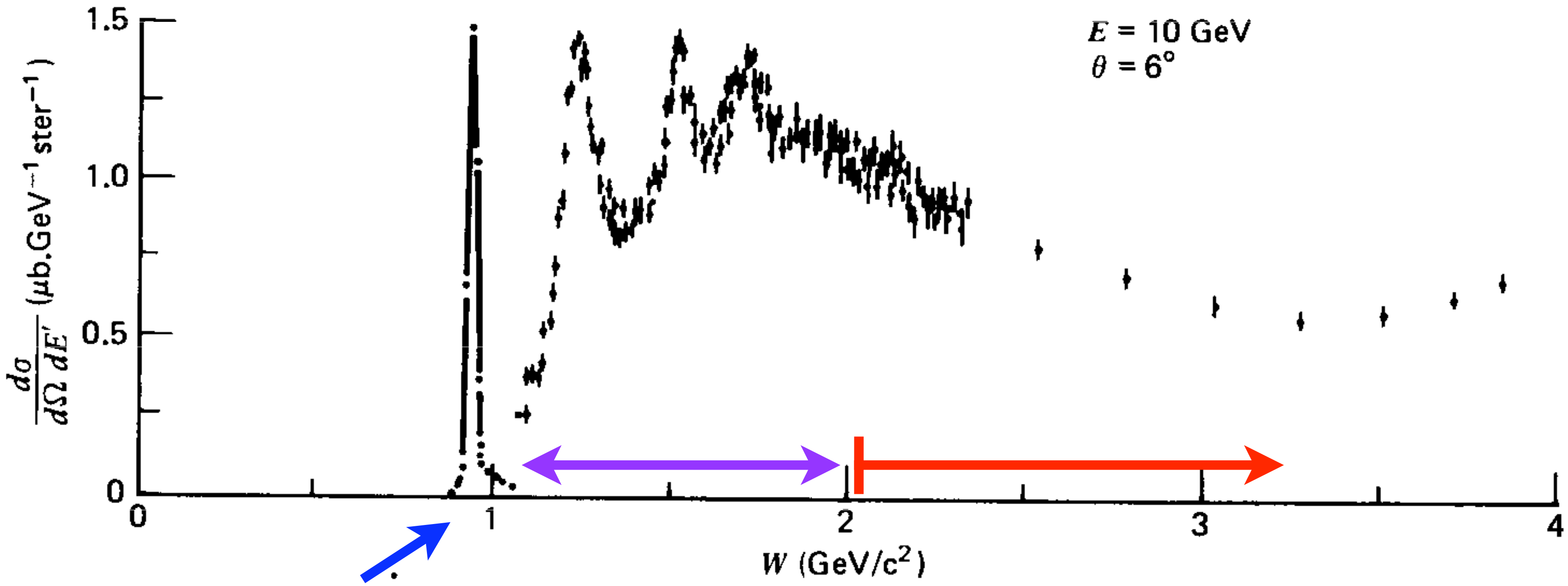
Deep-inelastic scattering and W²



hadronic final state: total **invariant-mass** W

In DIS, the proton **breaks up** into many hadrons ("fragmentation")

$$W^2 = (q+P)^2 = (\nu+M_p)^2 - |q|^2$$
$$= M_p^2 - Q^2 + 2\, M_p\, \nu$$



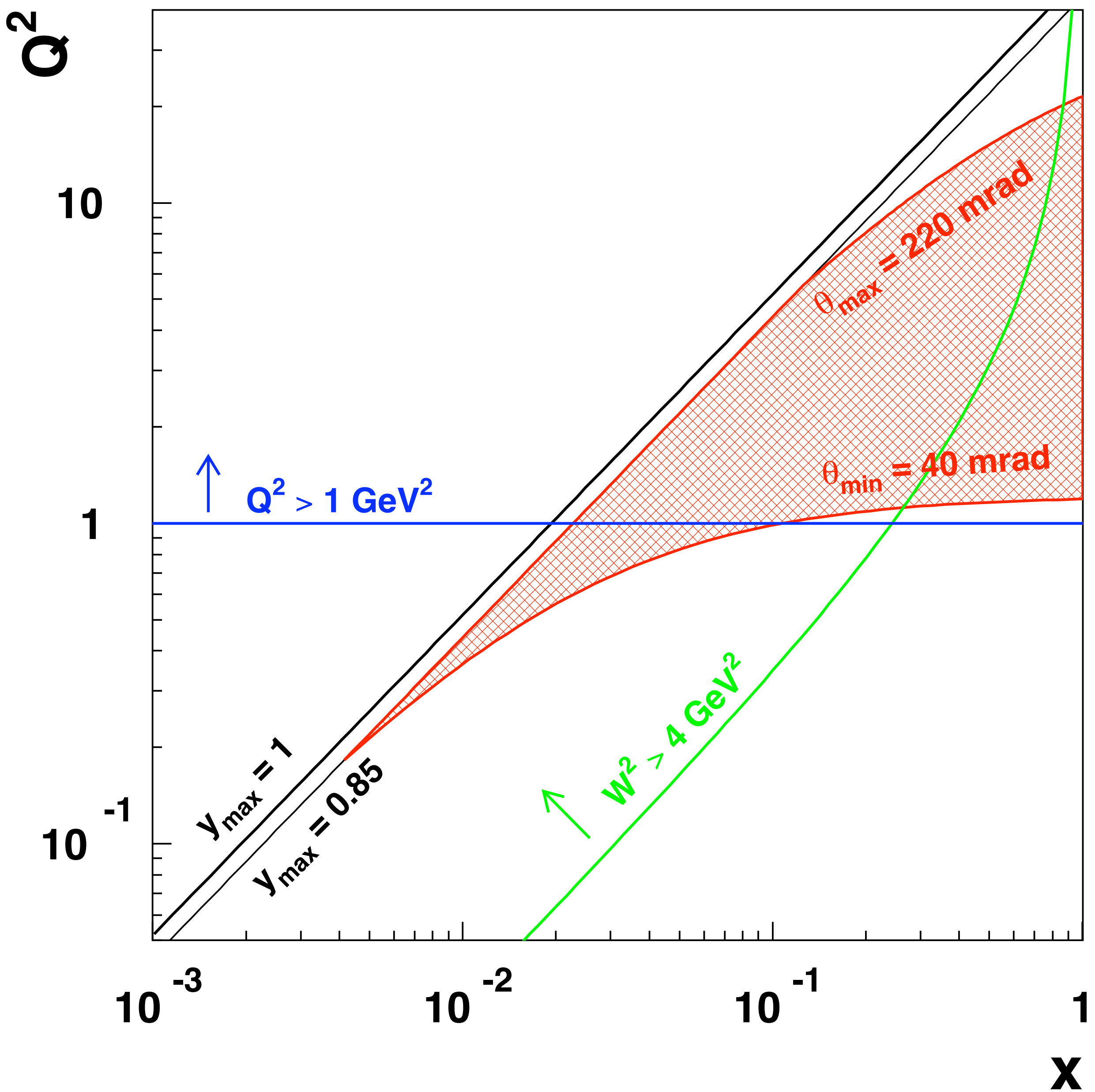
elastic scattering
ep → ep

resonance region
ep → eΔ, eN*, ...

DIS regime: W > 2 GeV
ep → e(X = many hadrons)

HERMES kinematics

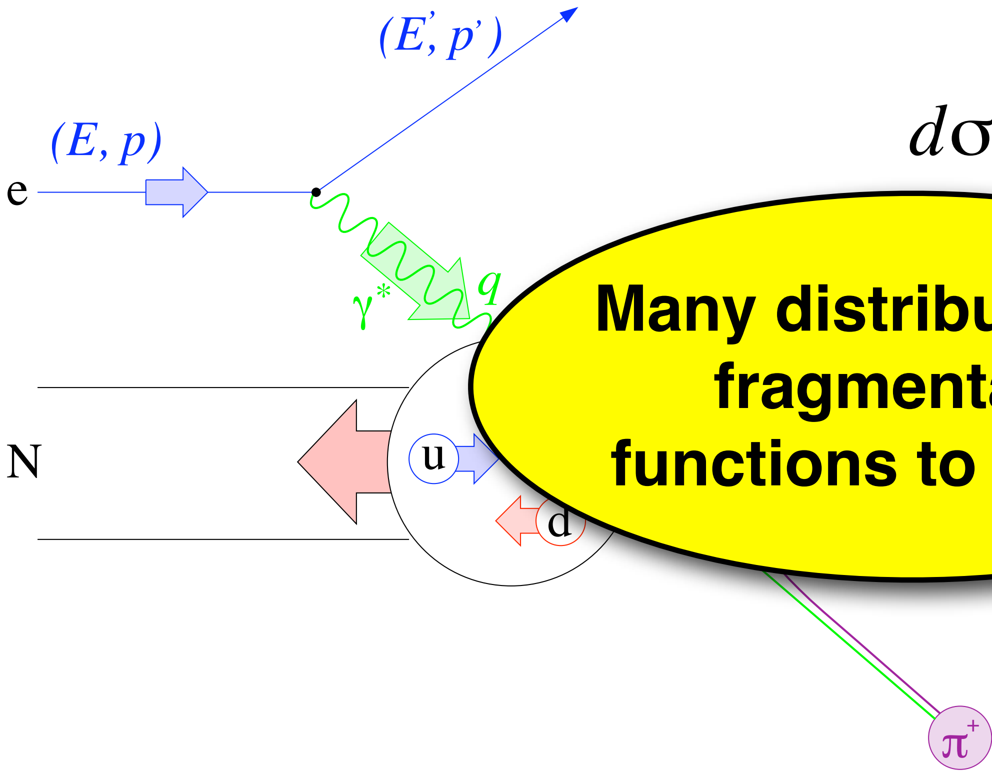
Beam energy 27.6 GeV



N.C.R. Makins, NNPSS11

Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

*In SIDIS, a **hadron h** is detected in **coincidence** with the scattered lepton:*



Factorization of the cross-section:

$$d\sigma^h \sim \sum_q e_q^2 \, q(x) \cdot \hat{\sigma} \cdot D^{q\rightarrow h}(z)$$

Many distribution and fragmentation functions to explore!

perturbative part

-section for elementary
hoton-quark ***subprocess***

Large energies ➡ asymptotic freedom
➡ can calculate!

The Distribution Function

momentum ***distribution of quarks q***
within their proton bound state

➡ **lattice QCD** progressing steadily

The Fragmentation Function

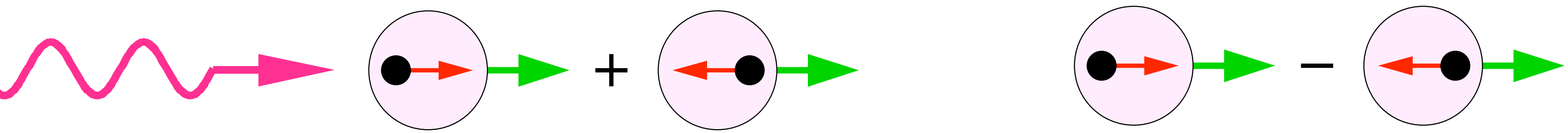
momentum ***distribution of hadrons h***
formed from quark *q*

➡ not even lattice can help ...

The Proton Spin Puzzle:
Quark and Gluon Polarization

The Pieces of the Spin Puzzle

$$q(x) = \overrightarrow{q}(x) + \overleftarrow{q}(x) \qquad \Delta q(x) = \overrightarrow{q}(x) - \overleftarrow{q}(x)$$



only three possibilities

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

❶ Quark polarization

$$\Delta\Sigma \equiv \int dx\, (\Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta\bar{u}(x) + \Delta\bar{d}(x) + \Delta\bar{s}(x)) \approx 25\% \text{ only}$$

❷ Gluon polarization

$$\Delta G \equiv \int dx\, \Delta g(x) \quad \text{small…?}$$

❸ Orbital angular momentum

$$L_z \equiv L_q + L_g$$

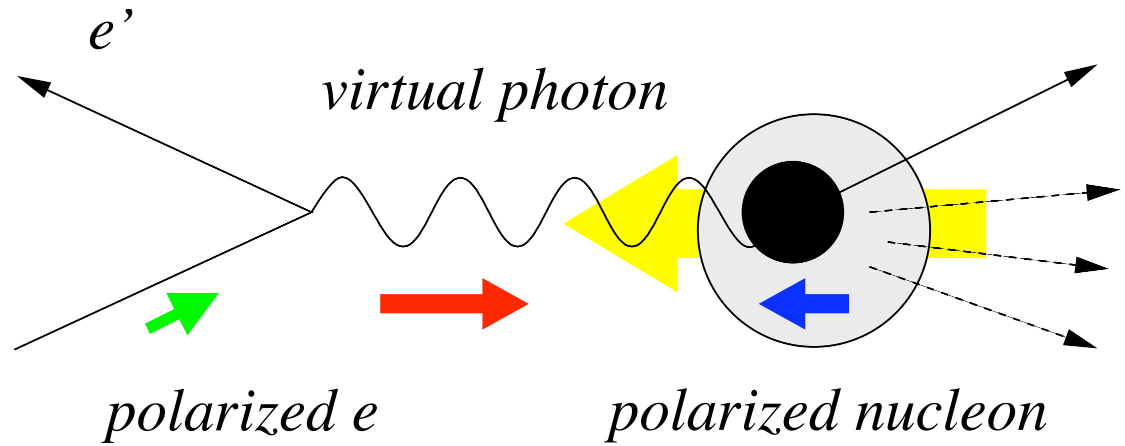
State of the art: DSSV global fit to Δq and ΔG

full next-to-leading order QCD

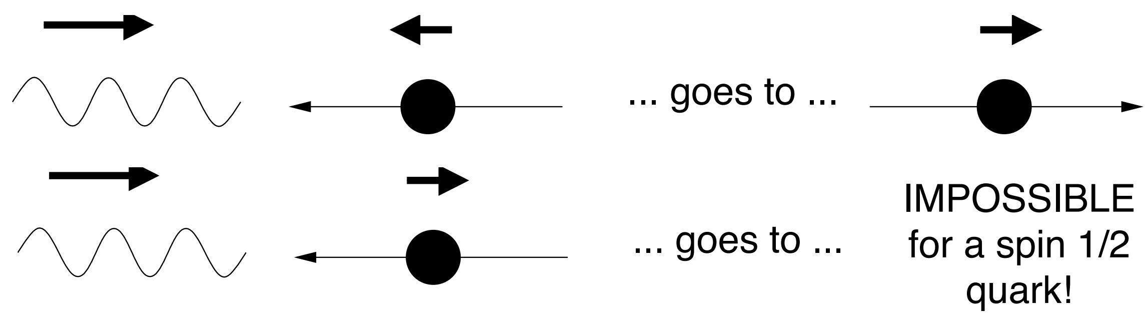
DeFlorian, Sassot, Stratmann, Vogelsang, PRL 101 (2008) and PRD 80 (2009)

World Data: polarized **eN** and **pp** scattering

Spin-Dependent Deep Inelastic Scattering (DIS)



The polarized photon selects certain quark polarizations :



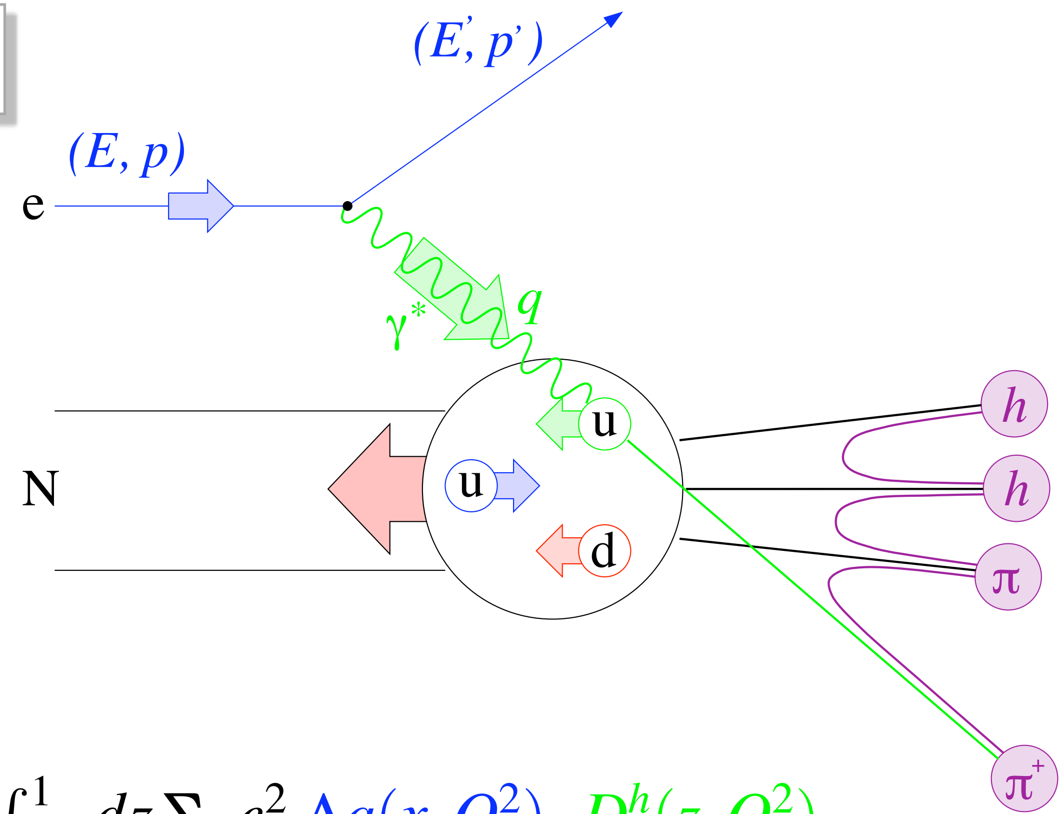
Double spin asymmetries are measured :

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \simeq \frac{g_1}{F_1} = \frac{\sum_q e_q^2 \, \Delta q(x, Q^2)}{\sum_q e_q^2 \, q(x, Q^2)}$$

The story so far ... from inclusive measurements of $g_1(x,Q^2)$

- $\Delta\Sigma$ is around 20-30 %
- some indication that Δs may be negative ... (-10% ??)
- some indication that ΔG may be positive ... ?

Semi-Inclusive DIS (SIDIS)



In SIDIS, a ***hadron*** ***h*** *is detected* ***in coincidence*** *with the scattered lepton*

Flavor Tagging in LO QCD:

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

$D_q^h(z,Q^2)$ **: Fragmentation function**

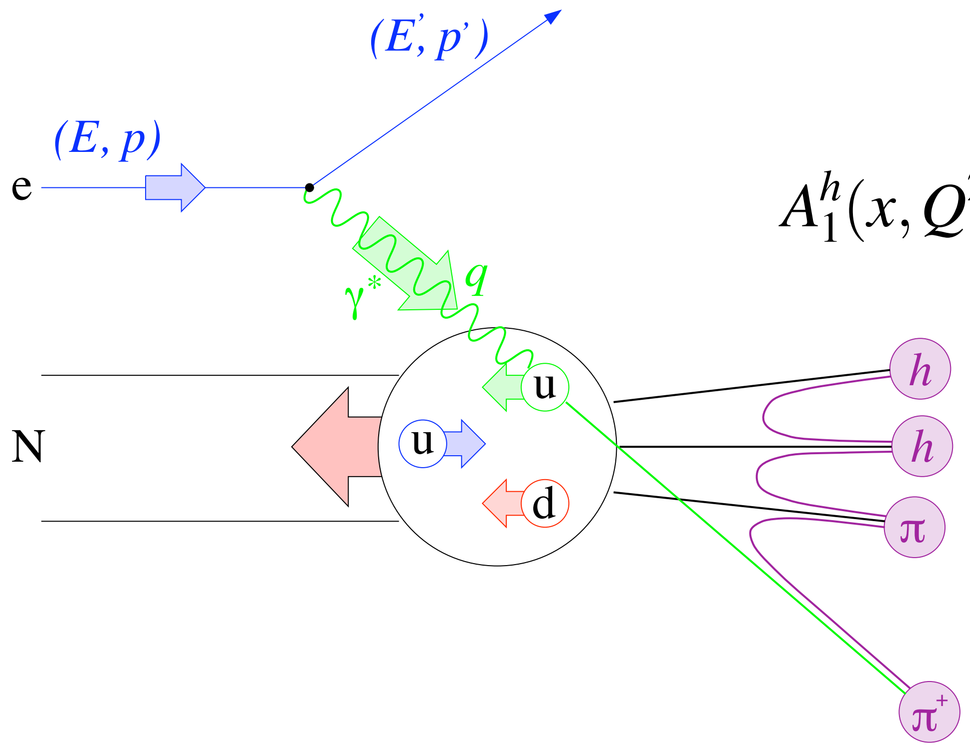
Measures probability for struck quark q to produce a hadron h with

Energy fraction

$$z \equiv \frac{E_h}{\nu}$$

Quark Polarization from Semi-Inclusive DIS (SIDIS)

In SIDIS, a hadron h is detected in coincidence with the scattered lepton:



Flavor Tagging

Flavor content of observed hadron h is related to flavor of **struck quark *q*** via the **fragmentation functions *D***

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

Rewriting ...

$$A_1^h(x,z) = \sum_q P_q^h(x,z)\frac{\Delta q(x)}{q(x)}$$

Purity matrix** P_q^h **= probability that hadron h came from struck quark q

Purities are *spin-independent* ... compute using Monte Carlo

What results might we expect?

Constituent Quarks

Spin from the SU(6) Proton Wave Function

The 3 quarks are **identical fermions** ⇒ ψ **antisymmetric** under exchange

$$\psi = \psi(\text{color}) * \psi(\text{space}) * \psi(\text{spin}) * \psi(\text{flavor})$$

❶ **Color**: All hadrons are color singlets = **antisymmetric**

$$\psi(\text{color}) = 1/\sqrt{6}\,(RGB - RBG + BRG - BGR + GBR - GRB)$$

❷ **Space**: proton has $l = l' = 0 \rightarrow \psi(\text{space})$ = **symmetric**

❸ **Spin**: $2 \otimes 2 \otimes 2 = (\,3_S \oplus 1_A\,) \otimes 2 = 4_S \oplus 2_{MS} \oplus 2_{MA}$

- 4_S symmetric states have spin 3/2, e.g. $\left|\frac{3}{2},+\frac{3}{2}\right\rangle = \uparrow\uparrow\uparrow$
- 2_{MS} and 2_{MA} have spin 1/2 and **mixed symmetry**:
  S or A under exchange of *first 2* quarks only, e.g.

$$\left|\frac{1}{2},+\frac{1}{2}\right\rangle_{MS} = (\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow - 2\uparrow\uparrow\downarrow)/\sqrt{6} \qquad \left|\frac{1}{2},+\frac{1}{2}\right\rangle_{MA} = (\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)/\sqrt{2}$$

❹ **Flavor**: symmetry groups SU(2)-spin and SU(3)-color are exact ...

- strong force is ***flavor blind***
- constituent q masses ***similar***: $m_u, m_d \approx$ 350 MeV, $m_s \approx$ 500 MeV

➡ SU(3)-flavor is ***approximate*** for u, d, s

SU(3)-flavor gives $3 \otimes 3 \otimes 3 = 10_S \oplus 8_{MS} \oplus 8_{MA} \oplus 1_A$

➤ **Proton**: $\psi(s{=}1/2)$ from spin $2_{MS}, 2_{MA}$ $\otimes$ $\psi(uud)$ from flavor $8_{MS}, 8_{MA}$

$$|p^{\uparrow}\rangle = (u^{\uparrow}u^{\downarrow}d^{\uparrow} + u^{\downarrow}u^{\uparrow}d^{\uparrow} - 2u^{\uparrow}u^{\uparrow}d^{\downarrow} + \text{2 permutations})/\sqrt{18}$$

➤ Count the number of quarks with spin up and spin down:

➤ Quark contributions to proton spin are:

$\Delta u = N(u^{\uparrow}) - N(u^{\downarrow}) = +\frac{4}{3}$ $\Delta d = N(d^{\uparrow}) - N(d^{\downarrow}) = -\frac{1}{3}$

$\Rightarrow \Delta\Sigma = \Delta u + \Delta d + \Delta s = 1$ ***All spin present & accounted for!***

Proton Spin Structure: the Sea

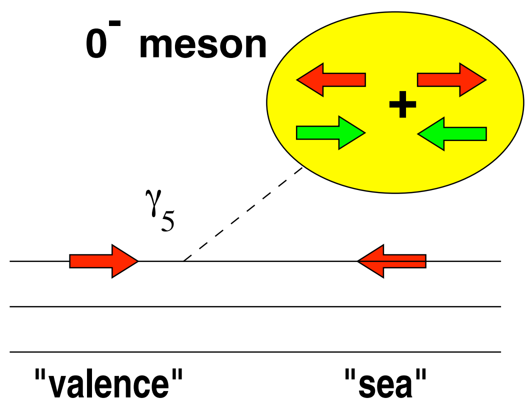
Constituent Quark Model

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

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

Meson Cloud Models

Li, Cheng, hep-ph/9709293



➡ $\Delta q_{\text{valence}} > 0$

➡ $\Delta q_{\text{sea}} < 0$

➡ $\Delta \bar{q} = 0$

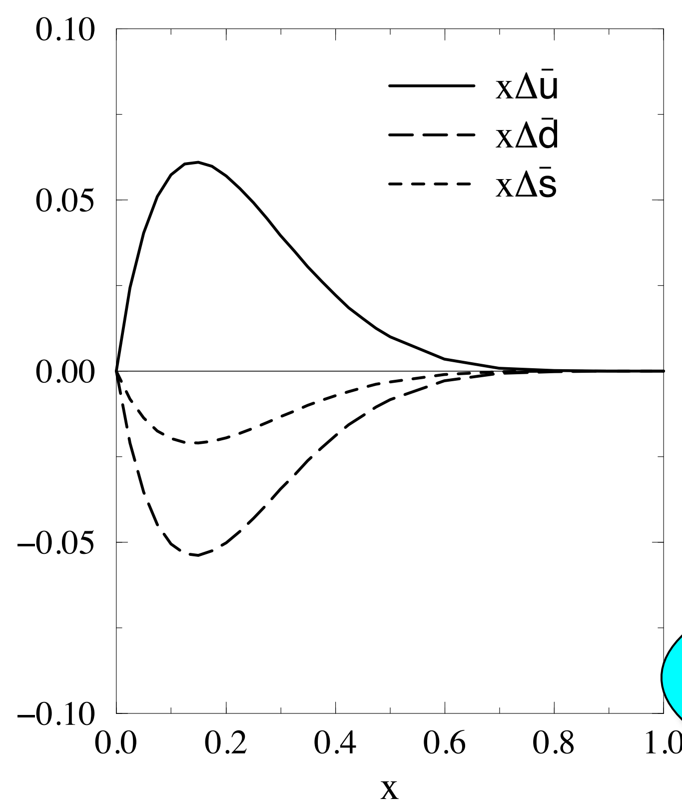
"Higher-order" cloud of vector mesons can generate a small polarization.

Chiral-Quark Soliton Model

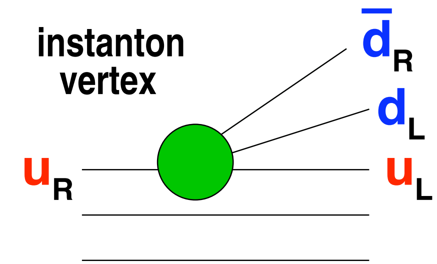
Goeke et al, hep-ph/0003324

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

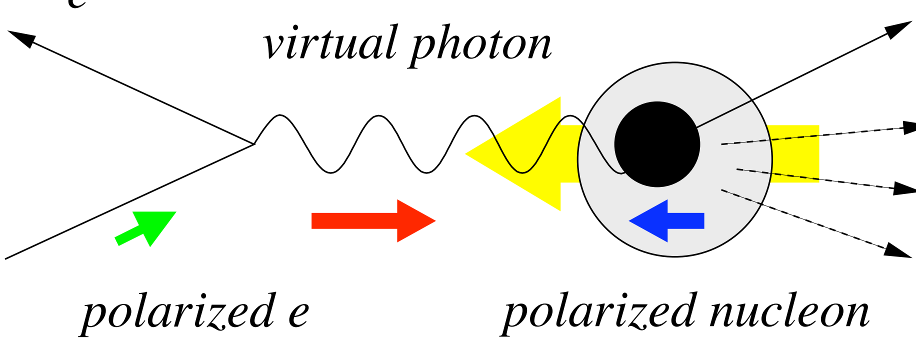
No gluons in these models

What results do we get?

A Wealth of Spin Data

Polarized Deep-Inelastic Scattering

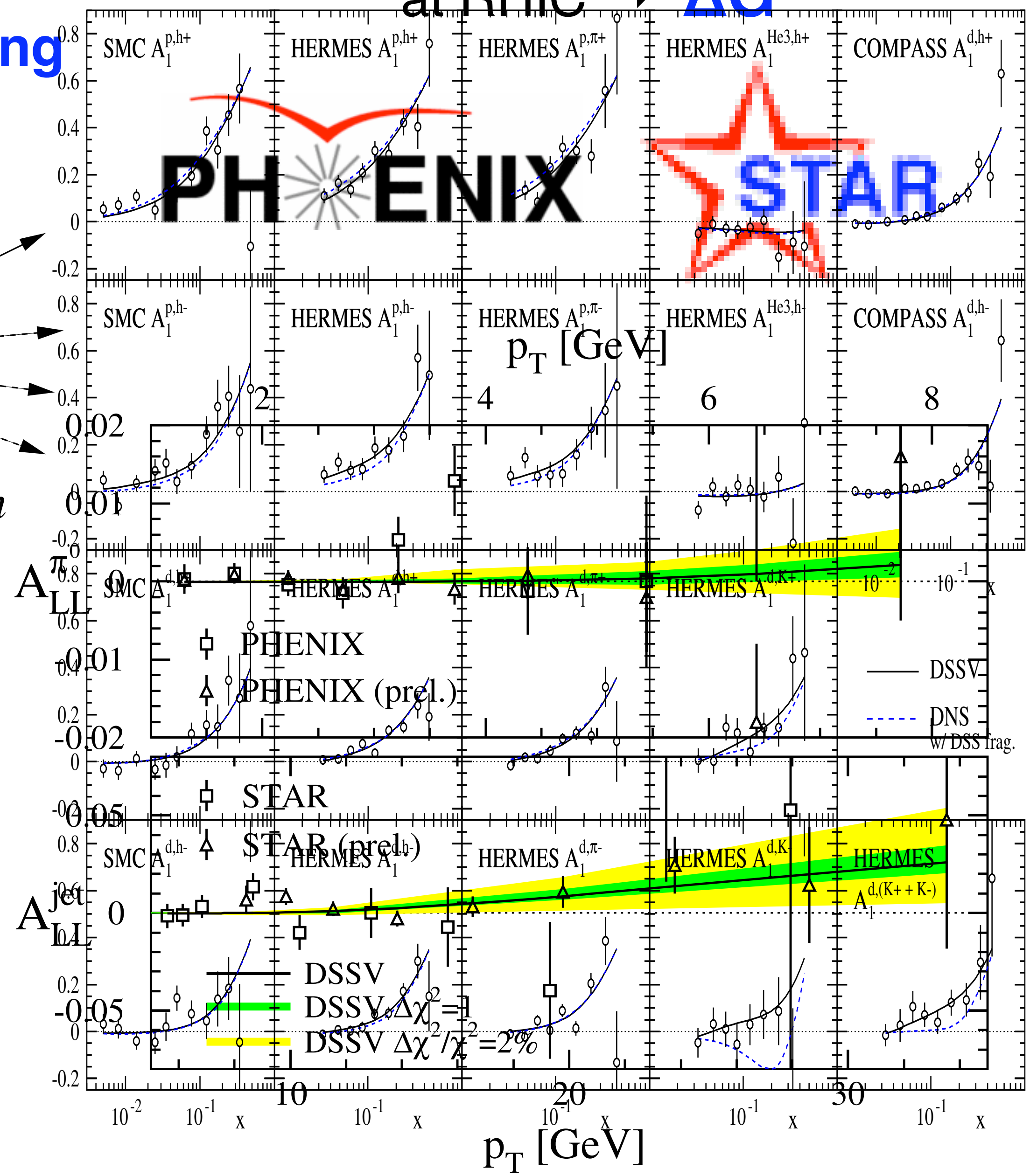
electron / muon beams → Δq



a sample ...

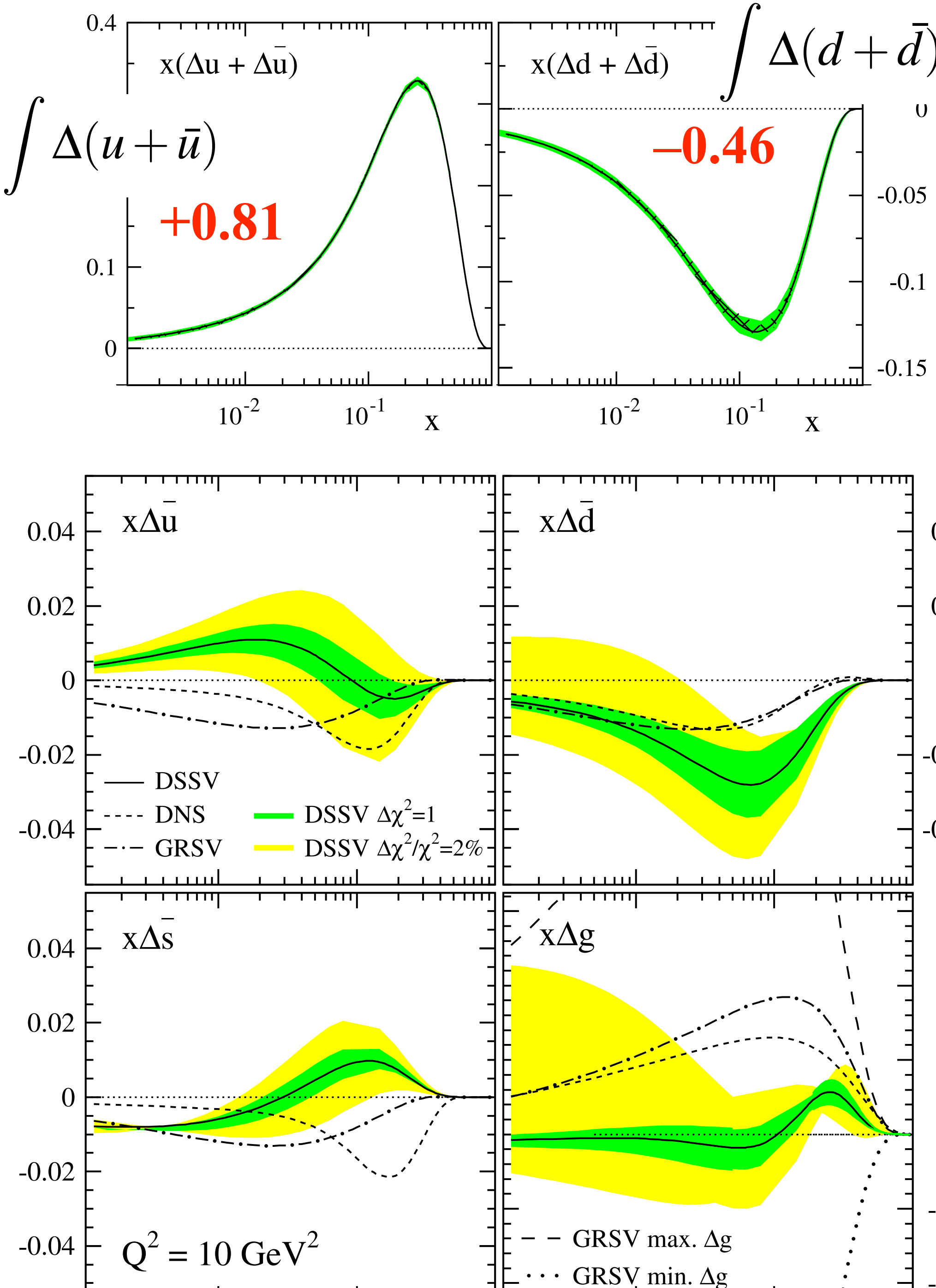
Polarized p-p Scattering

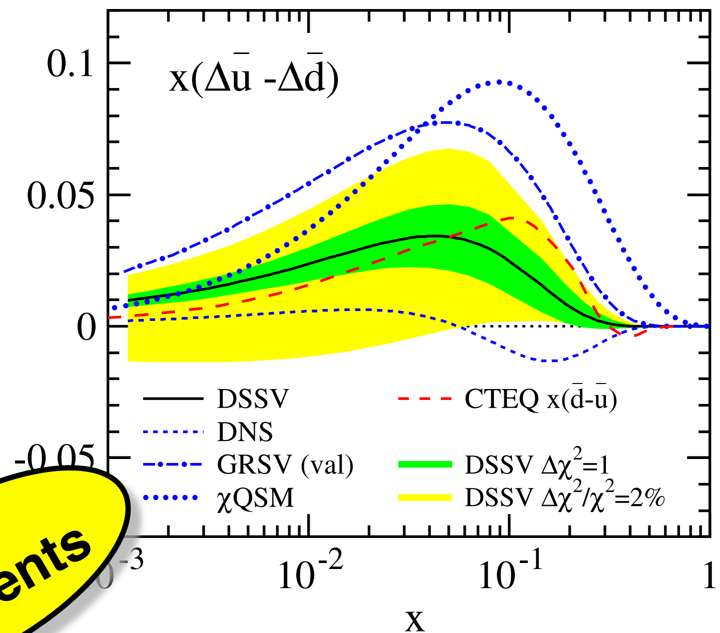
at RHIC → ΔG



DSSV NLO global fit: Δq & Δg

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





1st moments

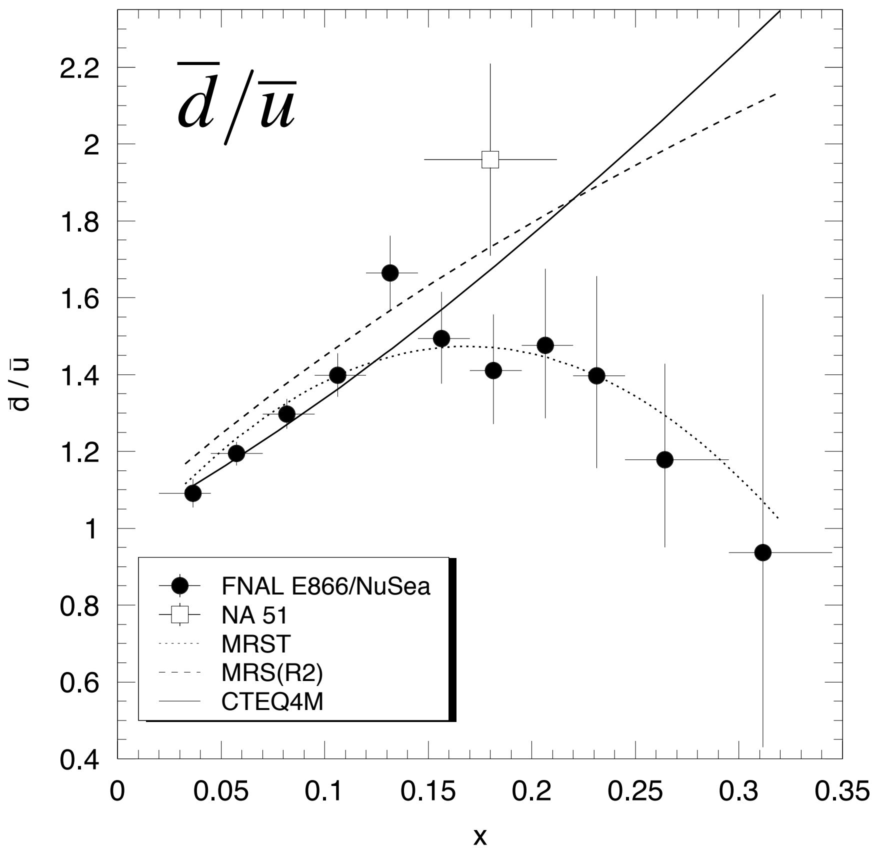
	meas: x > .001	extrap: all x	error
ΔΣ	0.37	0.24	+0.04 –0.06
$\Delta\bar{u}$	0.03	0.04	±0.06
$\Delta\bar{d}$	–0.09	–0.12	±0.09
Δs	–0.01	–0.06	±0.03
ΔG	0.01	–0.08	+0.7 –0.3

gluons & sea: spin-polarizations

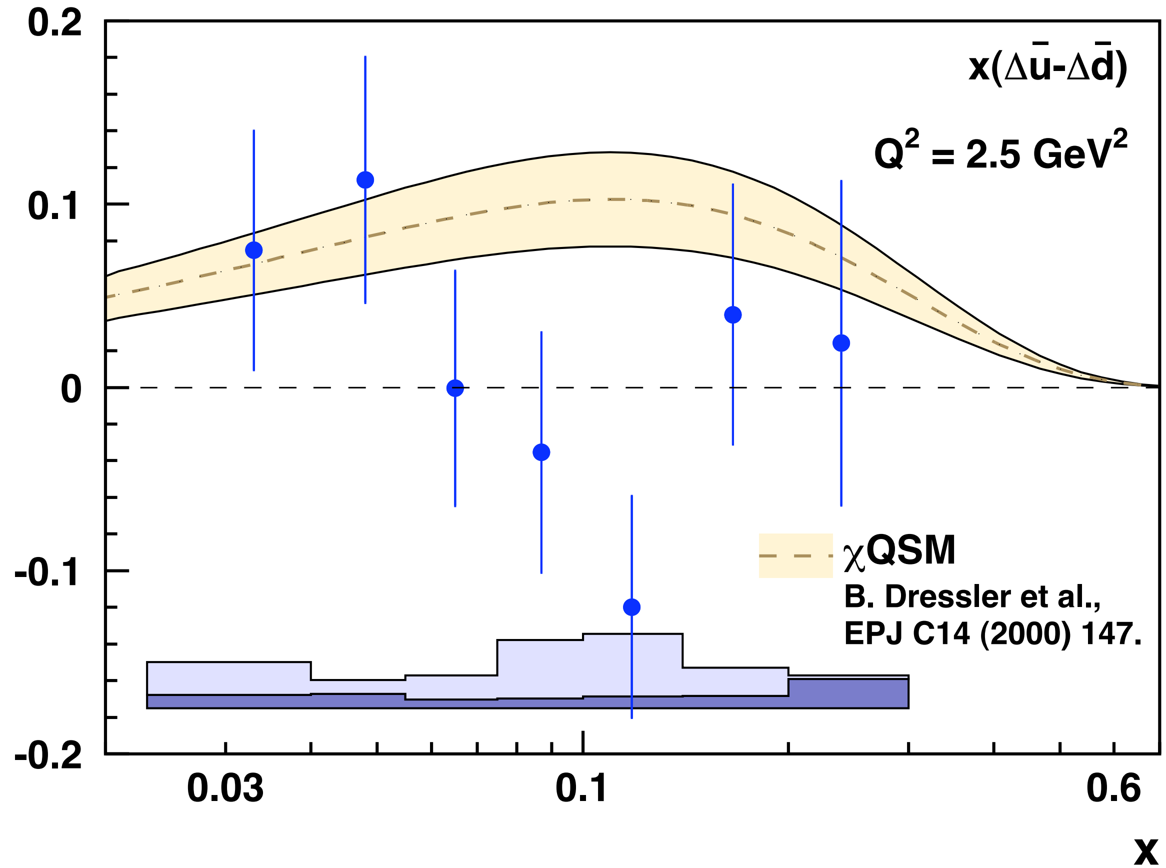
*all negative-ish **zeros***

Isospin Symmetry of the Light Sea

Unpolarized PDF's for $\bar{u}$ and $\bar{d}$:
strong isospin-symmetry breaking



Polarized PDF's for $\bar{u}$ and $\bar{d}$ ...

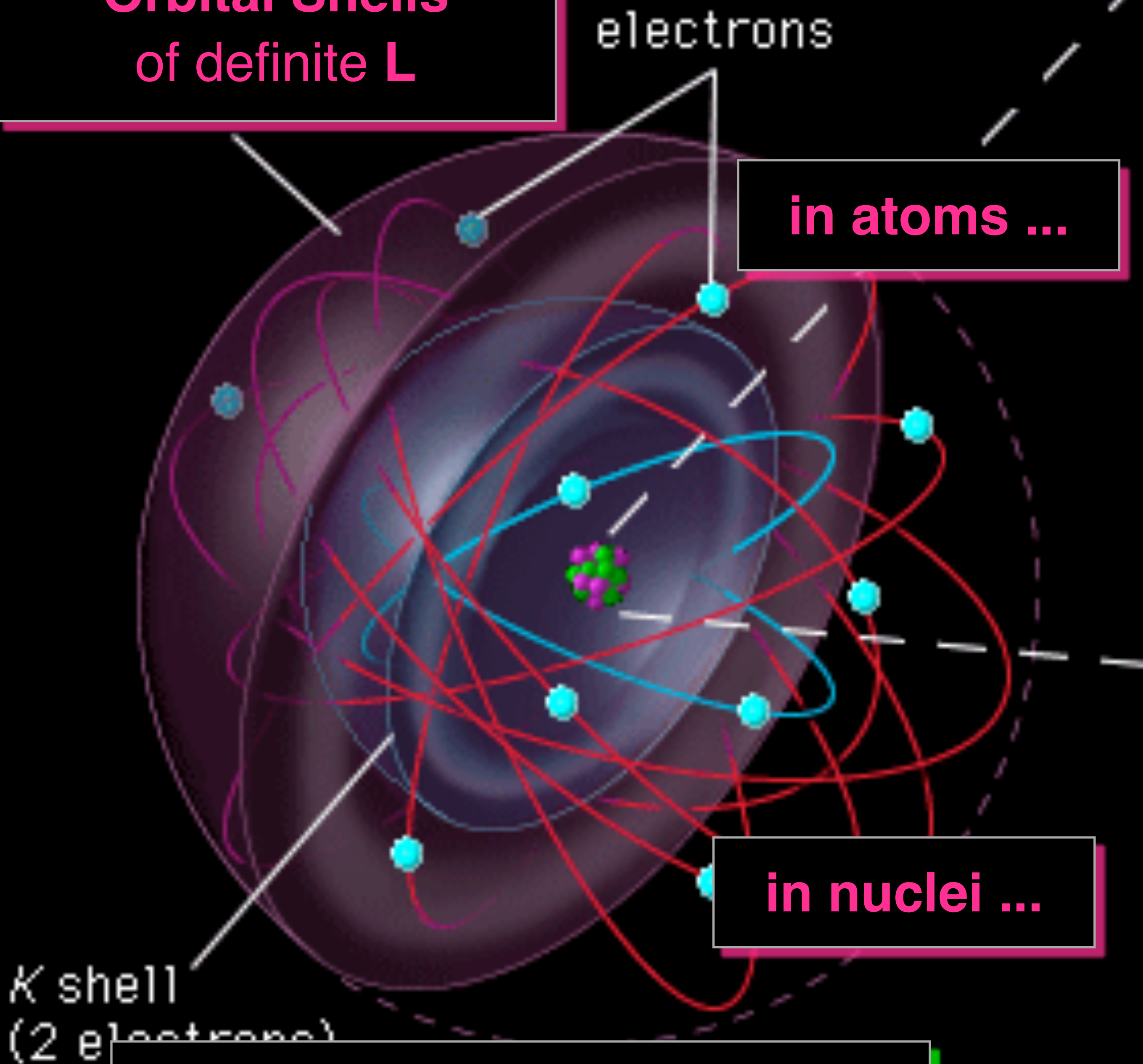


- ***No*** isospin-asymmetry observed in the light sea polarization

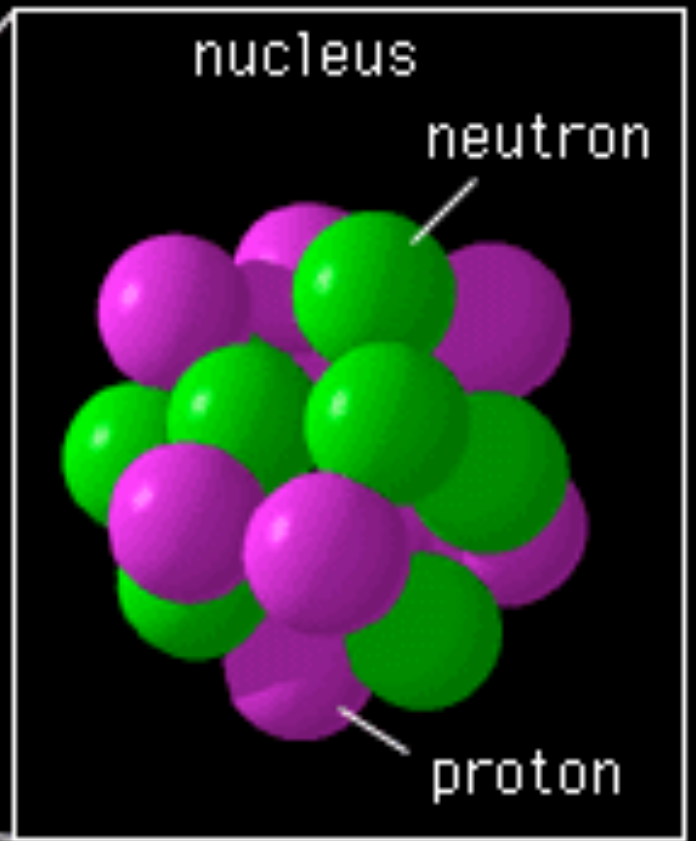
➡ ***results favor meson cloud picture, not chiral-quark soliton model***

So what's left?

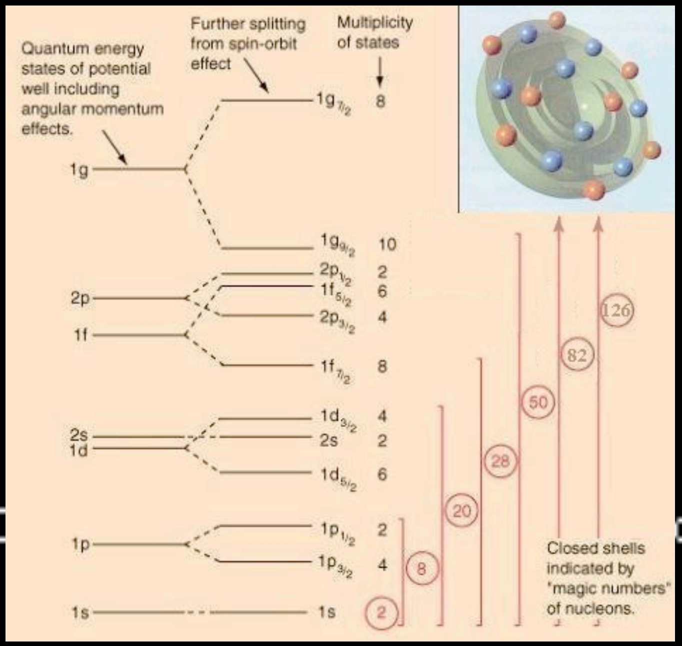
Orbital Shells
of definite **L**



in atoms ...



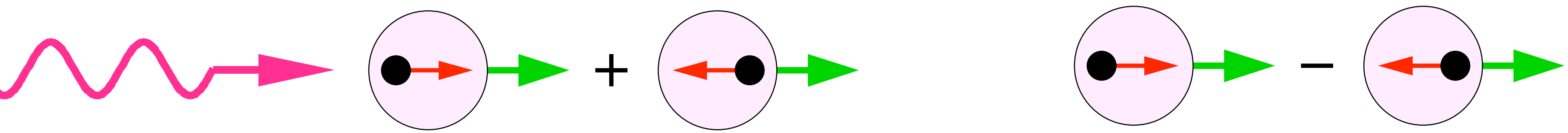
in nuclei ...



... and within the proton? ...

The Pieces of the Spin Puzzle

$q(x) = \overrightarrow{q}(x) + \overleftarrow{q}(x)$ $\Delta q(x) = \overrightarrow{q}(x) - \overleftarrow{q}(x)$



only three possibilities

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

❶ Quark polarization

$\Delta\Sigma \equiv \int dx\, (\Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta\bar{u}(x) + \Delta\bar{d}(x) + \Delta\bar{s}(x)) \approx$ 30% only

❷ Gluon polarization

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

❸ Orbital angular momentum

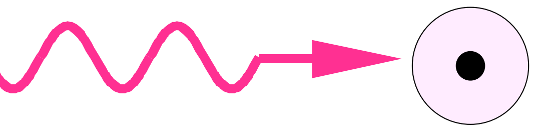
$L_z \equiv L_q + L_g$ **?**

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

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

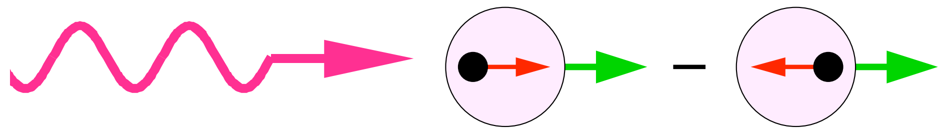
N.C.R. Makins, NNPSS 2011

Unpolarized PDF

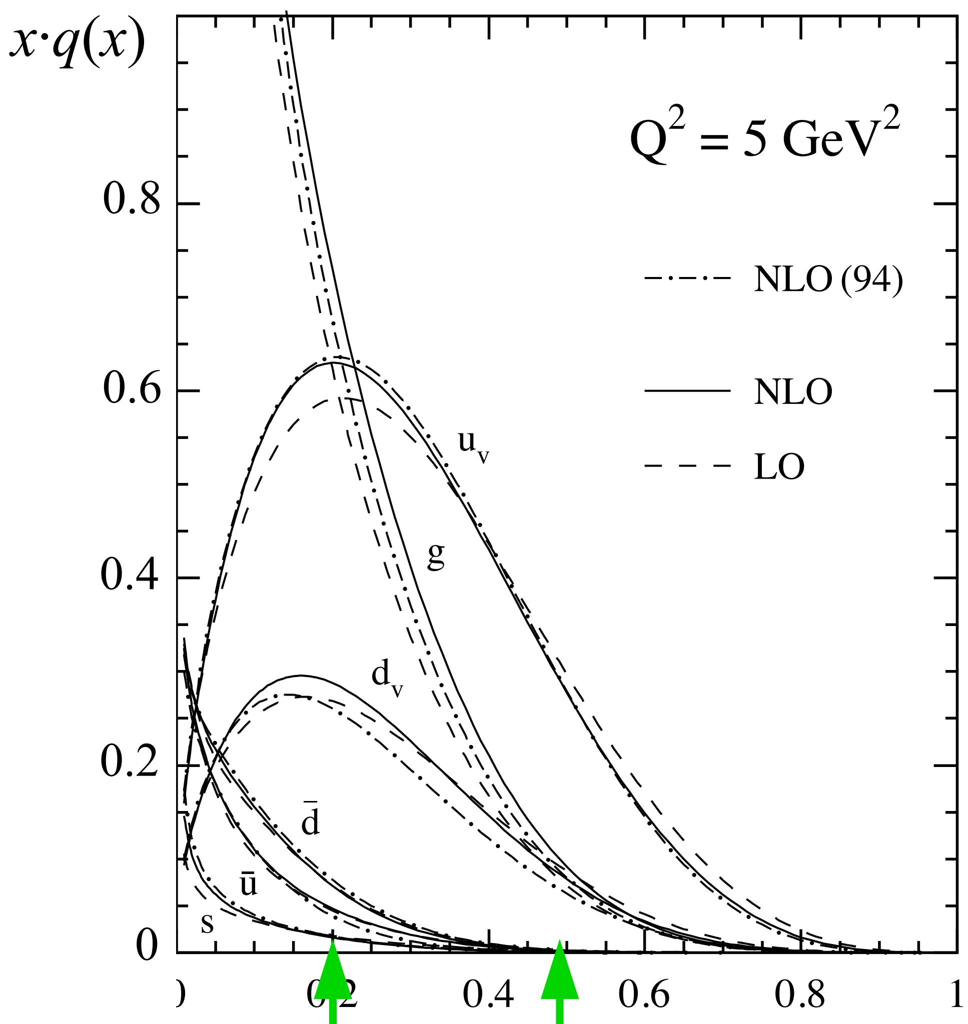


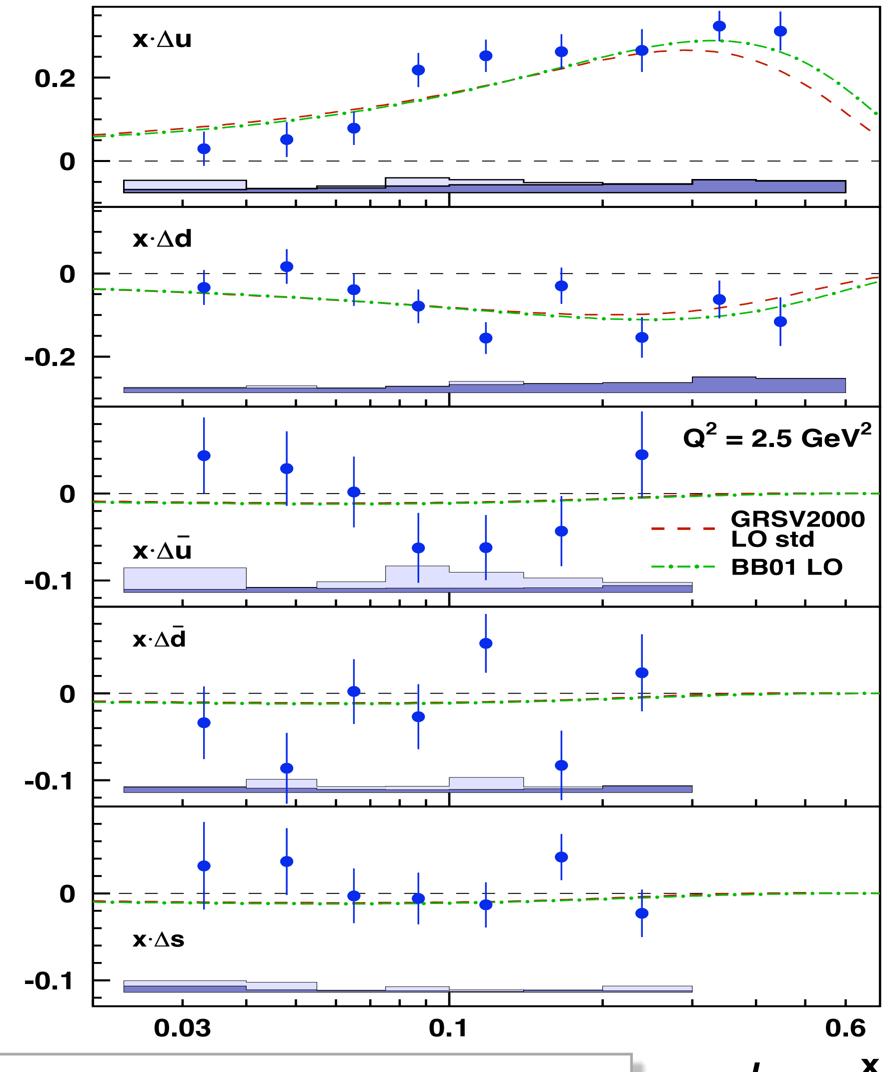
$= q(x)$

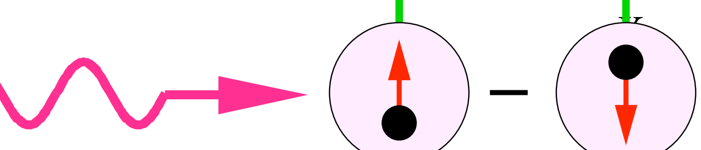
Polarized PDF



$= \Delta q(x)$







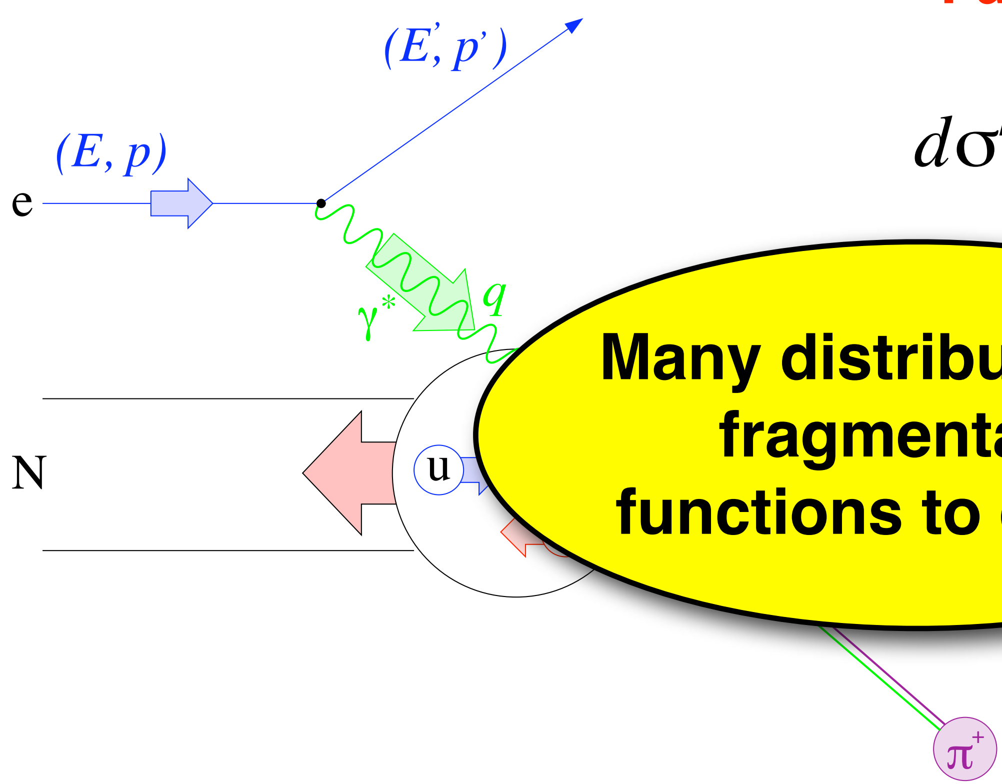
$= \delta q(x)$

PDF #3 “Transversity”

under study .....

Strategy: Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

*In SIDIS, a **hadron h** is detected in **coincidence** with the scattered lepton:*



Factorization of the cross-section:

$$d\sigma^h \sim \sum_q e_q^2 \, q(x) \cdot \hat{\sigma} \cdot D^{q\rightarrow h}(z)$$

Many distribution and fragmentation functions to explore!

e perturbative part

section for elementary
ton-quark ***subprocess***

Large energies ➡ asymptotic freedom
➡ can calculate!

The Distribution Function

momentum ***distribution of quarks q***
within their proton bound state

➡ **lattice QCD** progressing steadily

The Fragmentation Function

momentum ***distribution of hadrons h***
formed from quark *q*

➡ not even lattice can help ...

N.C.R. Makins, NNPSS 2011

PDFs and the Optical Theorem

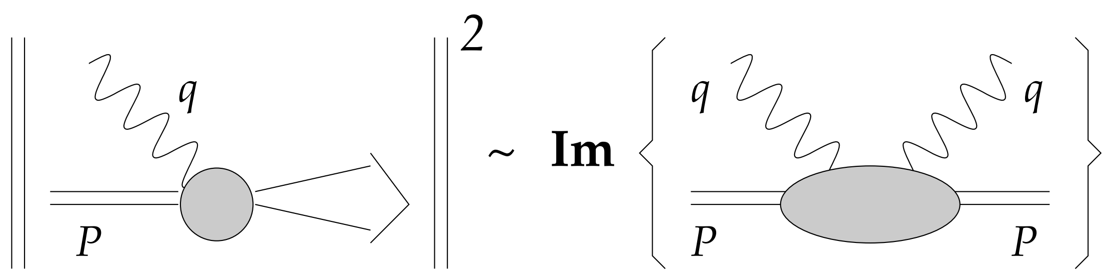
Proton Matrix Elements

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

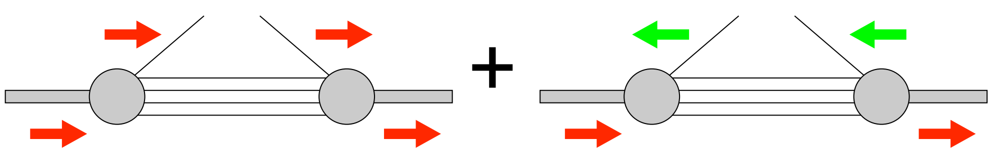
the Optical Theorem



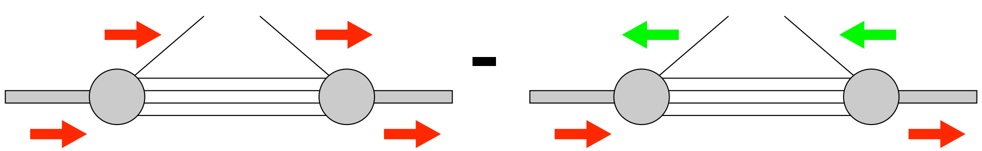
Forward Scattering Amplitudes

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

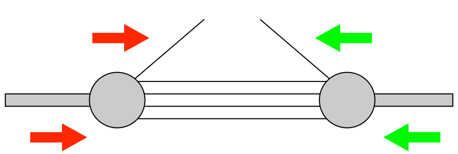
$q(x) \sim$



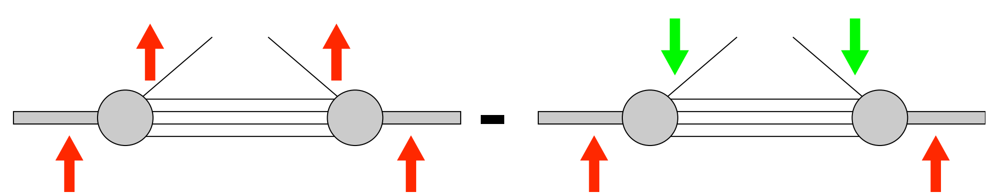
$\Delta q(x) \sim$



$\delta q(x) \sim$

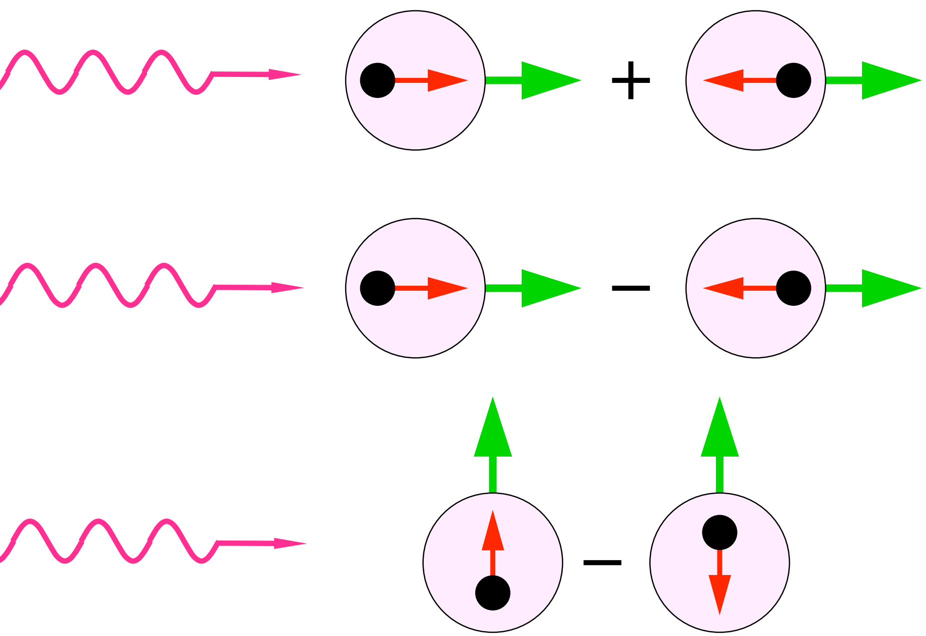


... or in transverse basis ...



3 Classes of Parton Distribution Functions

❶ Traditional PDFs



$$f_{1,q}(x) = \overrightarrow{q}(x) + \overleftarrow{q}(x)$$

$$g_{1,q}(x) = \overrightarrow{q}(x) - \overleftarrow{q}(x)$$

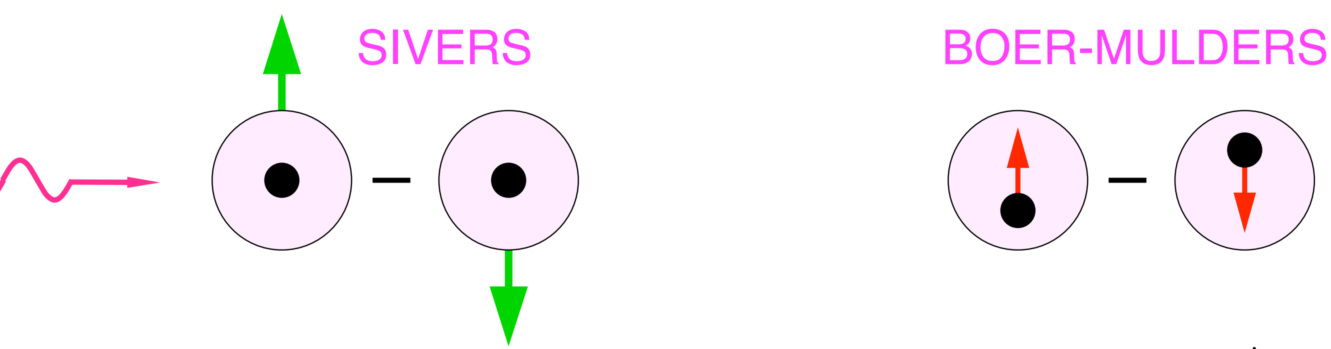
$$h_{1,q}(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$$

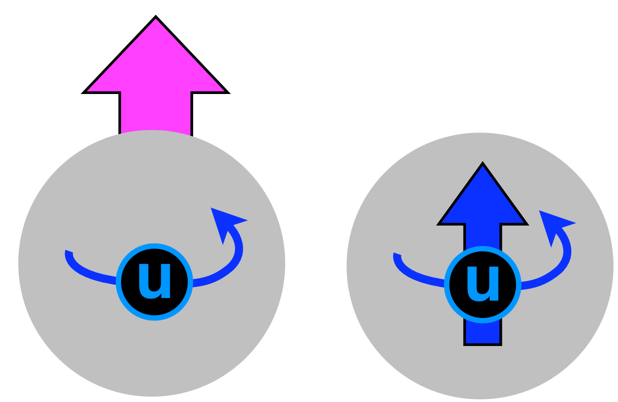
TRANSVERSITY

❷ **TMDs**: Transverse Momentum Dependent PDFs

SIVERS

BOER-MULDERS





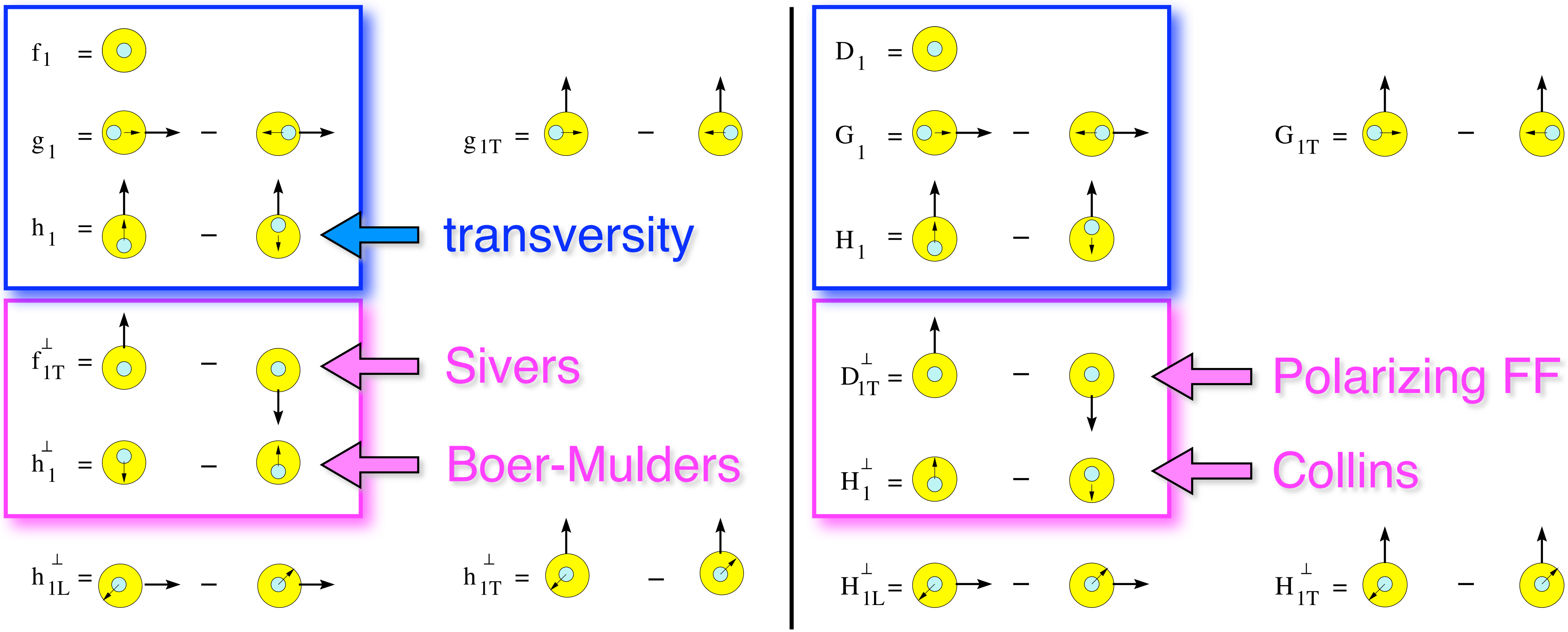
$$f_{1T,q}^{\perp}(x,k_T) \sim \vec{L}_q \cdot \vec{S}_p \qquad h_{1,q}^{\perp}(x,k_T) \sim \vec{L}_q \cdot \vec{S}_q$$

Functions surviving on integration over Transverse Momentum

The others are sensitive to ***intrinsic*** $\boldsymbol{k_T}$ in the nucleon & in the fragmentation process

Mulders & Tangerman, NPB 461 (1996) 197

Distribution Functions | Fragmentation Functions



One ***T-odd function*** required to produce ***single-spin asymmetries*** in SIDIS

Measuring: Azimuthal Asymmetries

SIDIS, at leading twist

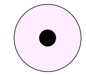
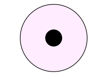
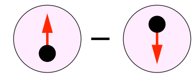
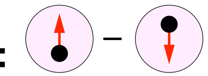
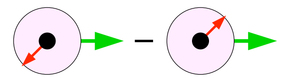
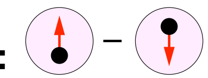
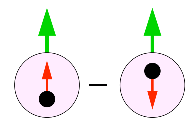
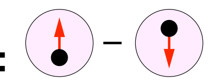
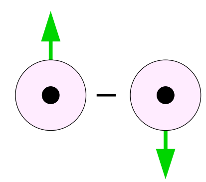
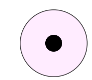
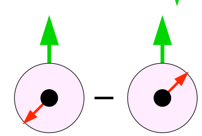
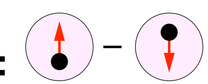
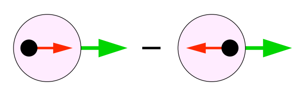
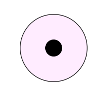
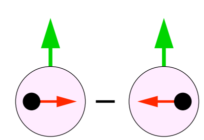
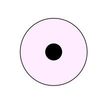
beam polⁿ / target polⁿ			
UU	1	$\otimes\, f_1 =$ 	$\otimes\, D_1 =$ 
	$\cos(2\phi_h^l)$	$\otimes\, h_1^\perp =$ 	$\otimes\, H_1^\perp =$ 
UL	$\sin(2\phi_h^l)$	$\otimes\, h_{1L}^\perp =$ 	$\otimes\, H_1^\perp =$ 
UT	$\sin(\phi_h^l + \phi_S^l)$	$\otimes\, h_1 =$ 	$\otimes\, H_1^\perp =$ 
	$\sin(\phi_h^l - \phi_S^l)$	$\otimes\, f_{1T}^\perp =$ 	$\otimes\, D_1 =$ 
	$\sin(3\phi_h^l - \phi_S^l)$	$\otimes\, h_{1T}^\perp =$ 	$\otimes\, H_1^\perp =$ 
LL	1	$\otimes\, g_1 =$ 	$\otimes\, D_1 =$ 
LT	$\cos(\phi_h^l - \phi_S^l)$	$\otimes\, g_{1T} =$ 	$\otimes\, D_1 =$ 

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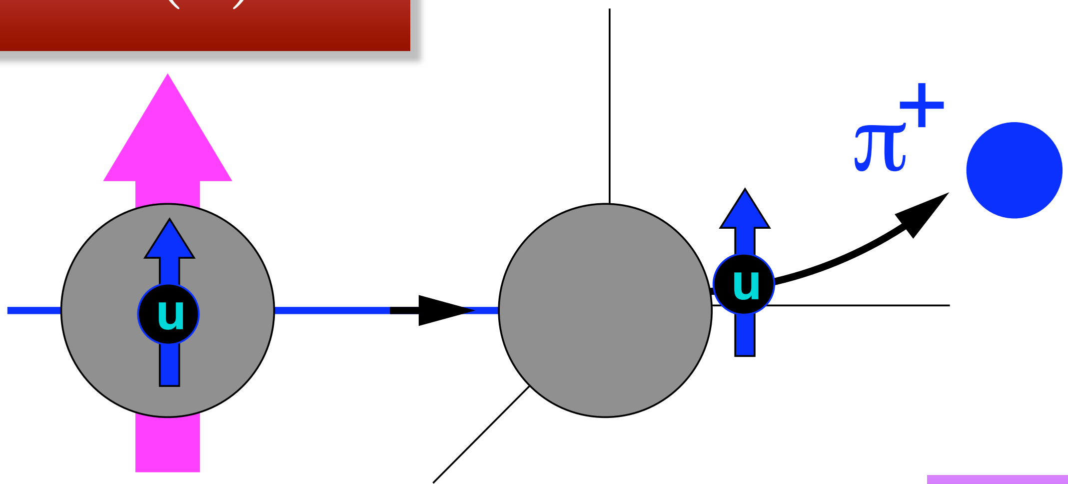
Photo-Album of our New Friends!

Transversity

$h_1(x)$

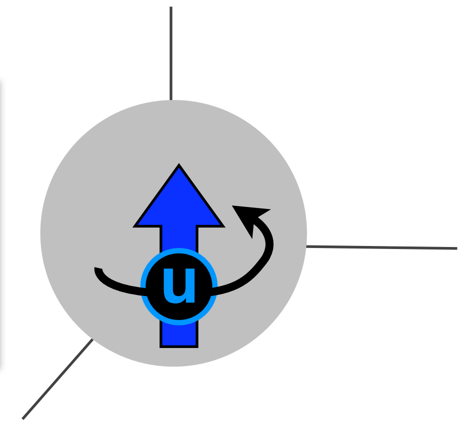


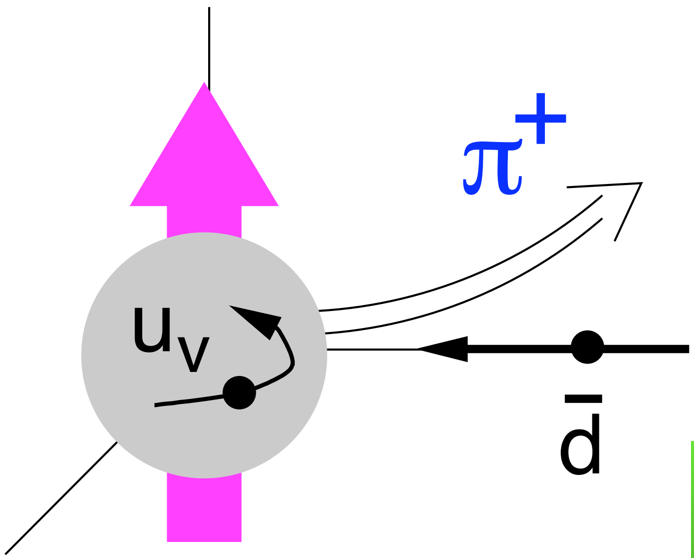
Collins

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

Boer-Mulders

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





Sivers

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

Favored / Disfavored Frag Functions

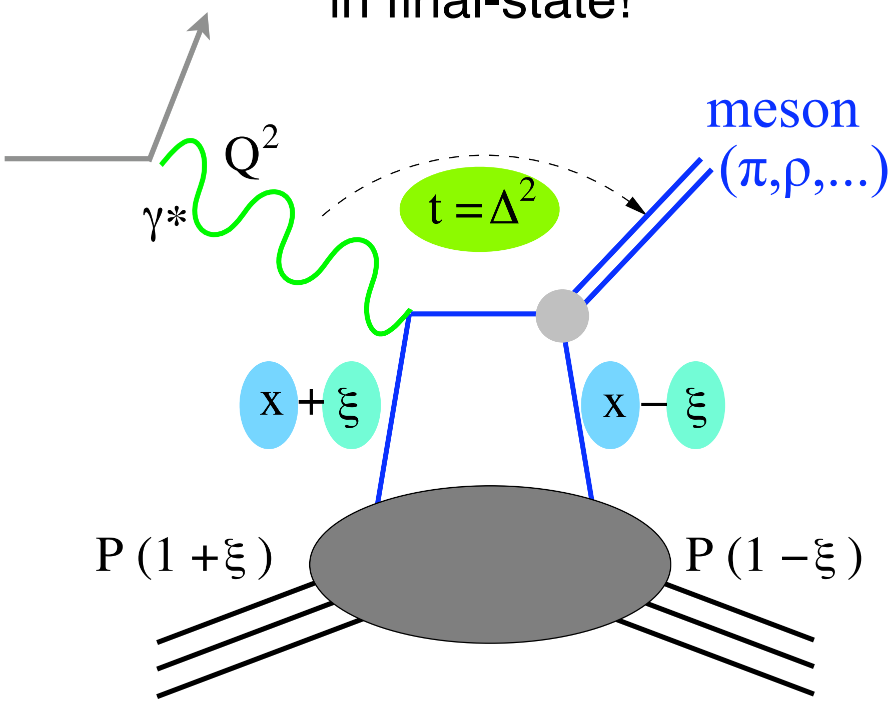
$$D_{\rm fav} \equiv D^{u\to\pi^+} = D^{d\to\pi^-} = \ldots$$

$$D_{\rm dis} \equiv D^{u\to\pi^-} = D^{d\to\pi^+} = \ldots$$

❸ Generalized Parton Distributions

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

Scattering at high Q^2 and W^2
... but ***create only one particle***
in final-state!



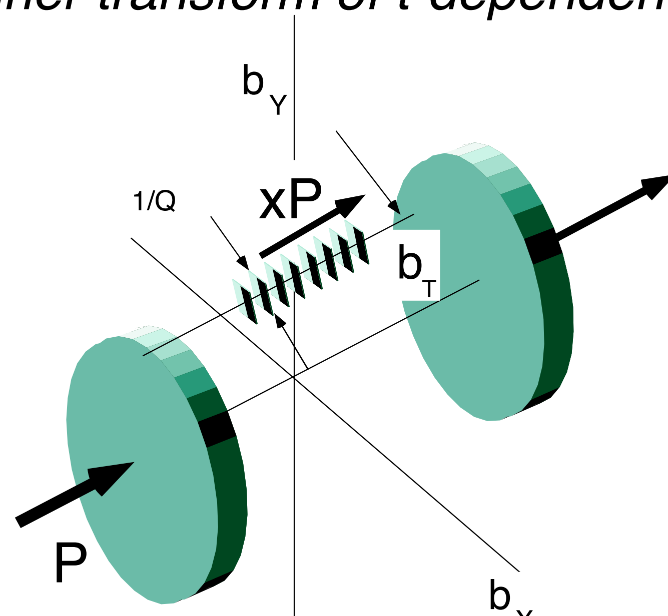
- x: average quark momentum frac^n
- ξ: "skewing parameter" = $x_1 - x_2$
- t: 4-momentum transfer^2 to target

Four new distributions = "GPDs"

helicity conserving $\rightarrow$ $H(x,\xi,t), E(x,\xi,t)$
helicity flip $\rightarrow$ $\tilde{H}(x,\xi,t), \tilde{E}(x,\xi,t)$

"Femto-photography" of the proton

Fourier transform of t-dependence ...



➡ ***spatial distribution*** of partons !

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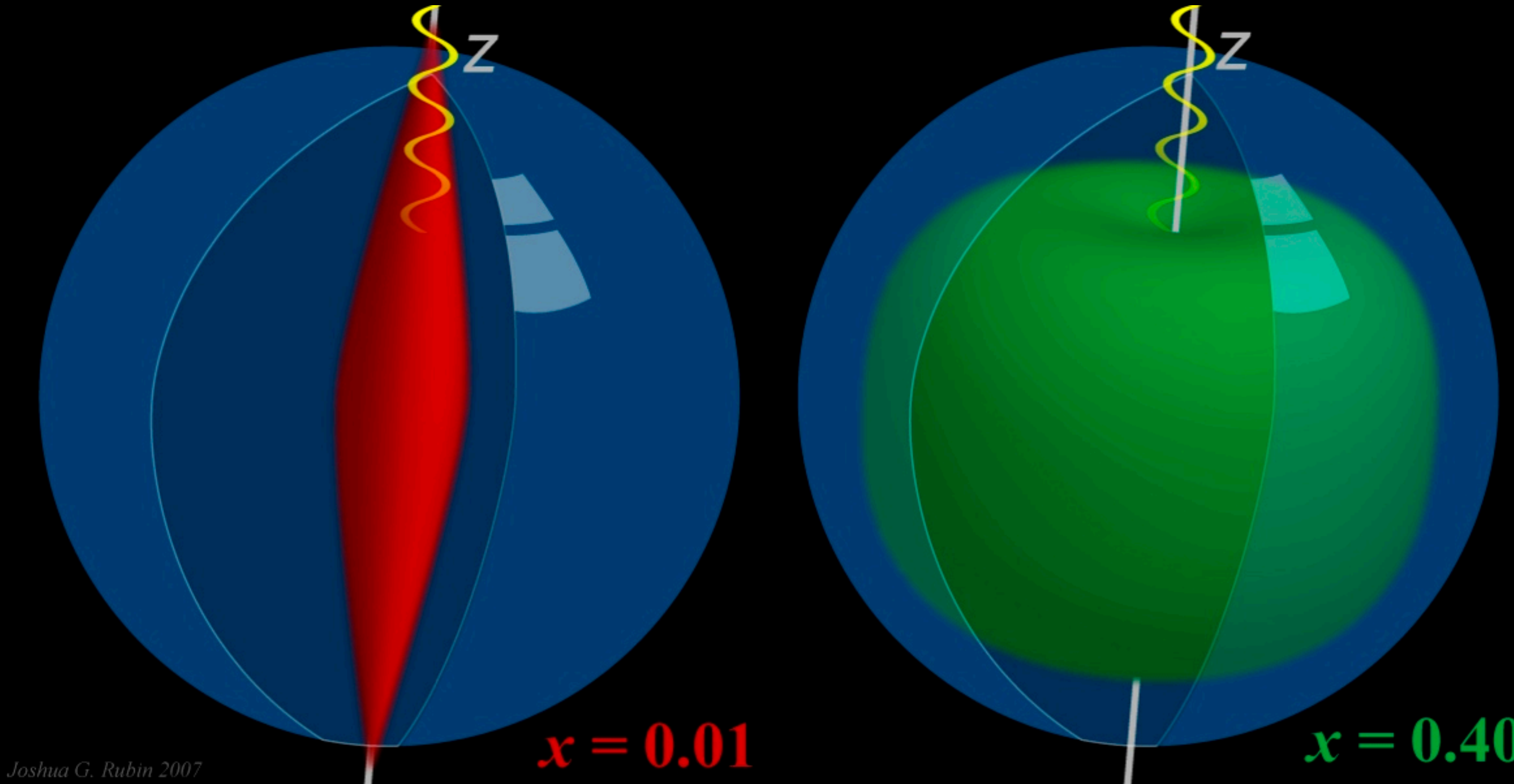

z
z
Joshua G. Rubin 2007
x = 0.01
x = 0.40

- **DIS structure func's**: forward limit ($\xi = 0$, $t = 0$)

$$q(x) = H^q(x, \xi = 0, t = 0)$$
$$\Delta q(x) = \tilde{H}^q(x, \xi = 0, t = 0)$$

Connection to many observables

- **Elastic form factors**: first moments in *x*

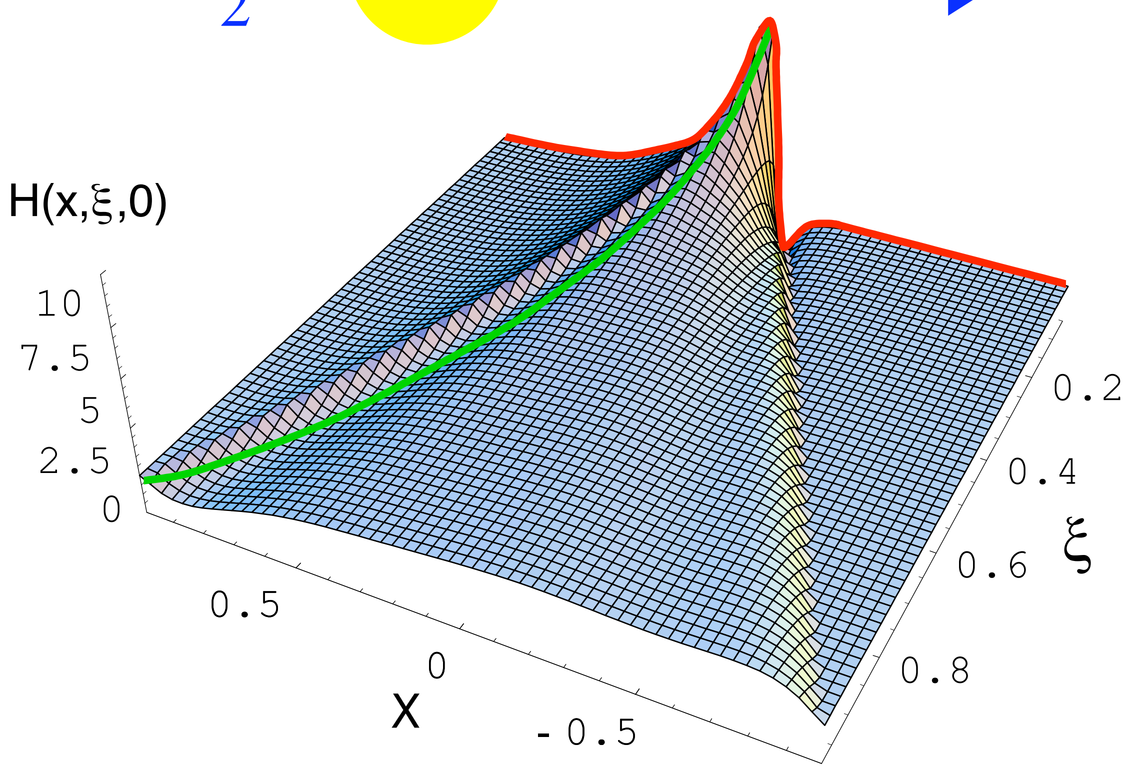
$$F_1^q(t) = \int_{-1}^{1} dx\, H^q(x, \xi, t) \qquad F_2^q(t) = \int_{-1}^{1} dx\, E^q(x, \xi, t)$$

- **Ji sum rule**:

$$J^q = \frac{1}{2}\int_{-1}^{1} x\, dx \left[H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)\right]$$

$$J^q = \frac{1}{2}\Delta\Sigma + L^q$$

→ ***model-independent access to L !***



Note connection of *H*, *E* to Dirac, Pauli form factors ... and their connection to nucleon *magnetic moment:*

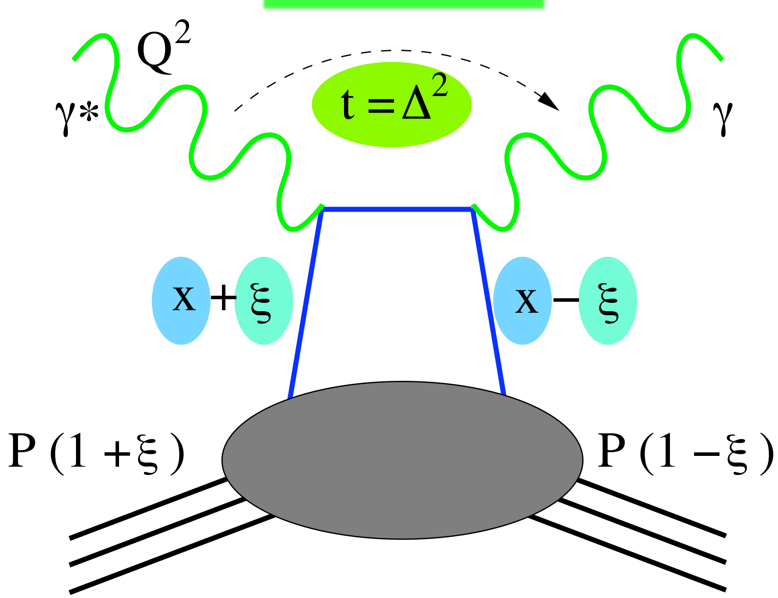
$$F_1^N(0) + F_2^N(0) = \mu_N$$

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"

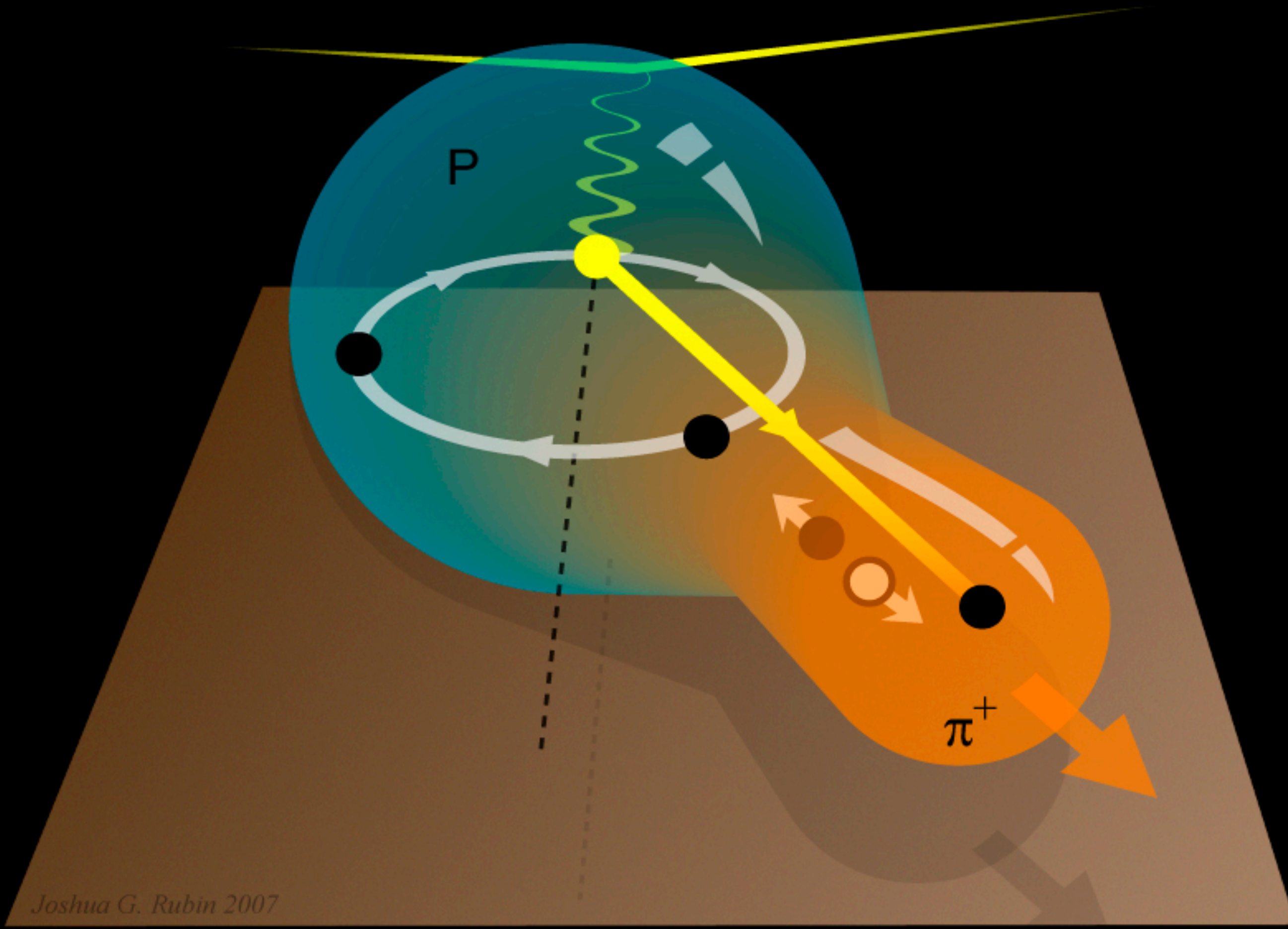
q helicity sum $\longrightarrow$ $H_T(x,\xi,t), E_T(x,\xi,t)$

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

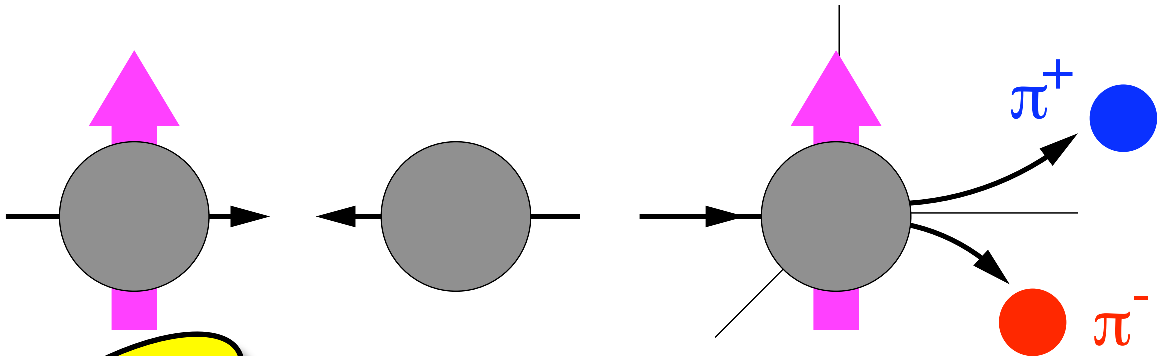
Generalized **T**ransversity **D**istrib's are

- **chiral odd**
- also called "tensor GPDs" because of presence of $\sigma^{\mu\nu}$ in their definition

In Search of L:
Transverse Single-Spin Asymmetries



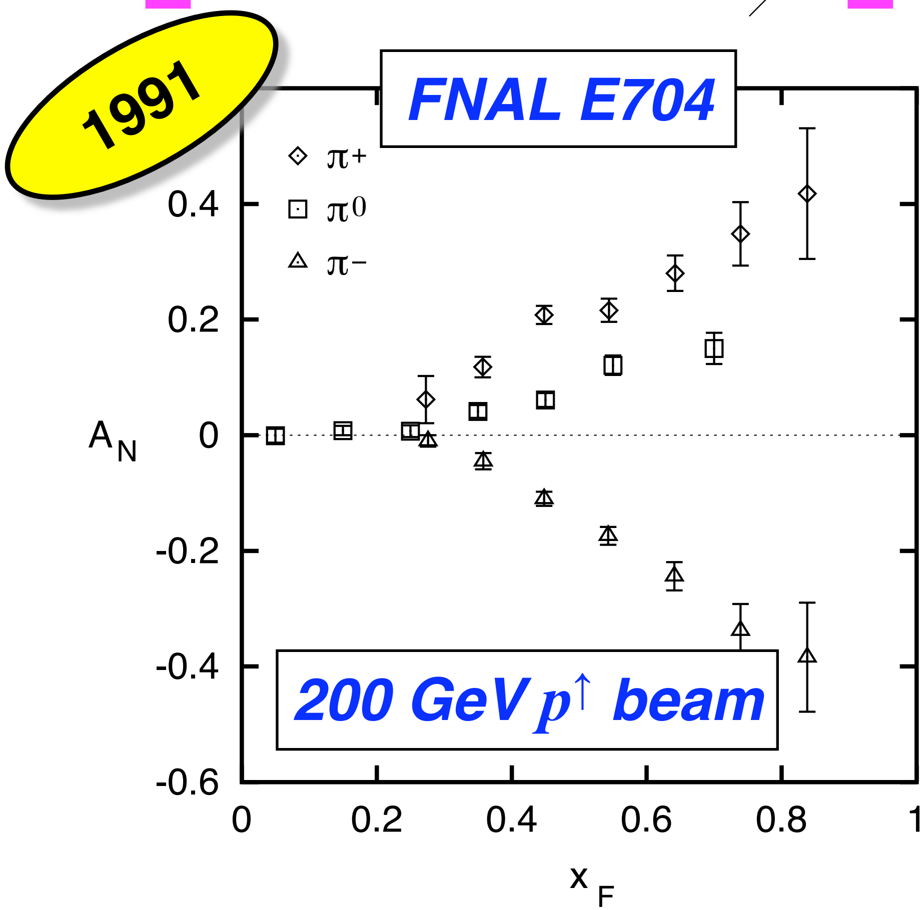
Single-spin asymmetries in $p^{\uparrow}p \rightarrow \pi X$

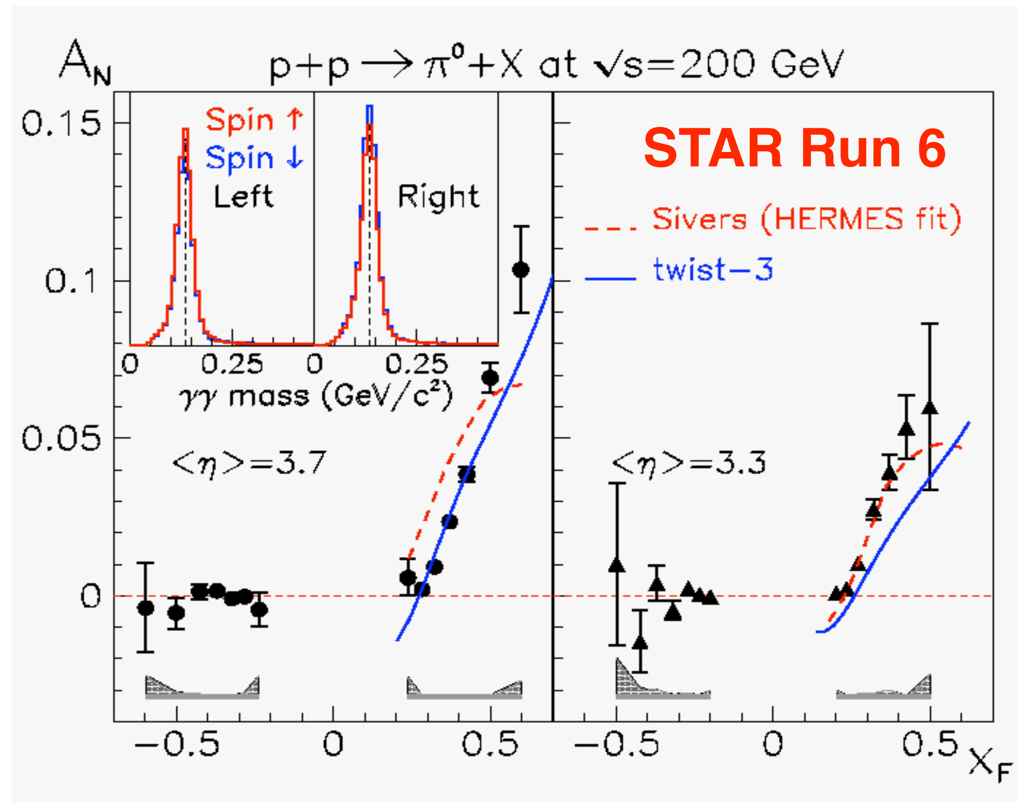


Analyzing Power

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

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

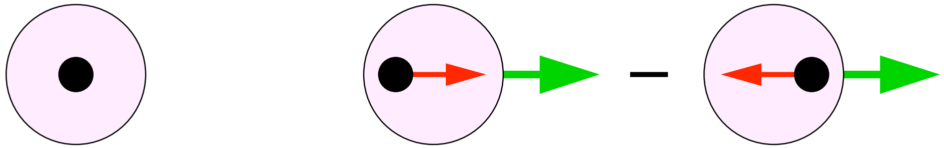




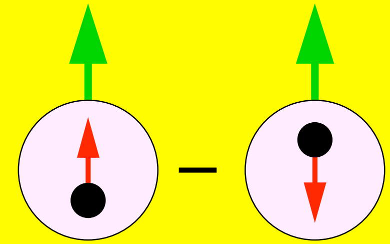
Observable $\vec{S}_{\text{beam}} \cdot (\vec{p}_{\text{beam}} \times \vec{p}_{\pi})$ ***odd*** *under naive* ***Time-Reversal***

E704 Mechanism #1: The “Collins Effect”

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

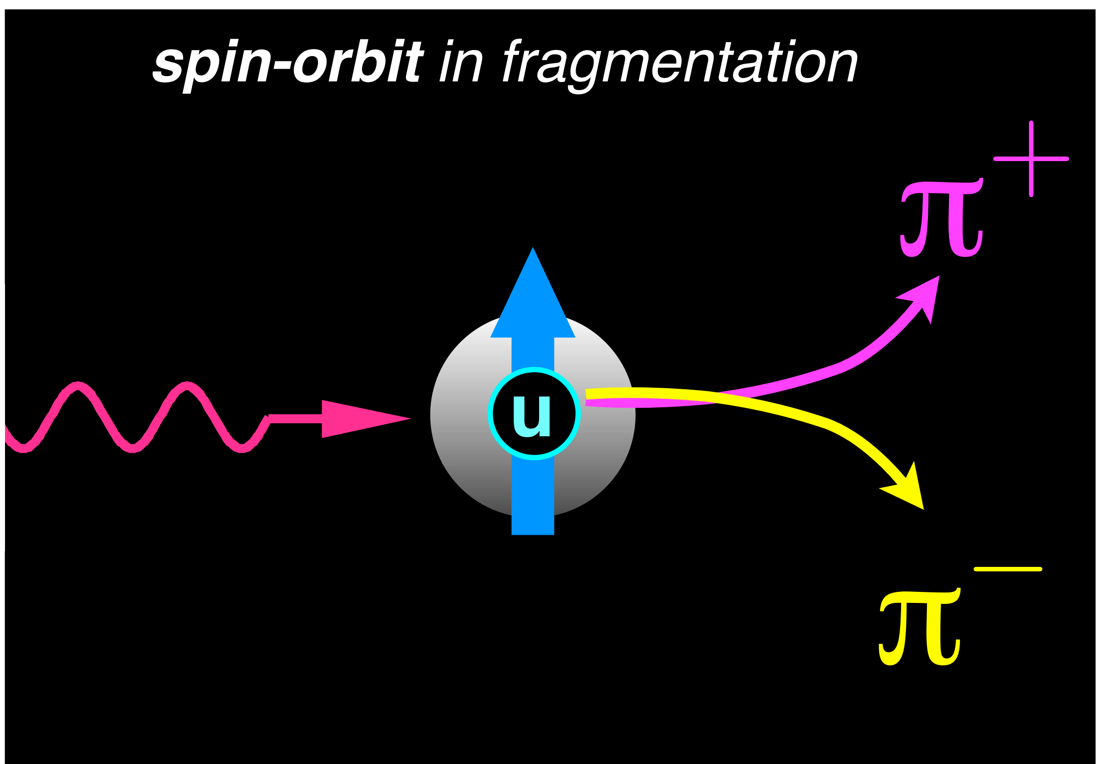


$q(x)$ $\qquad$ $\Delta q(x)$

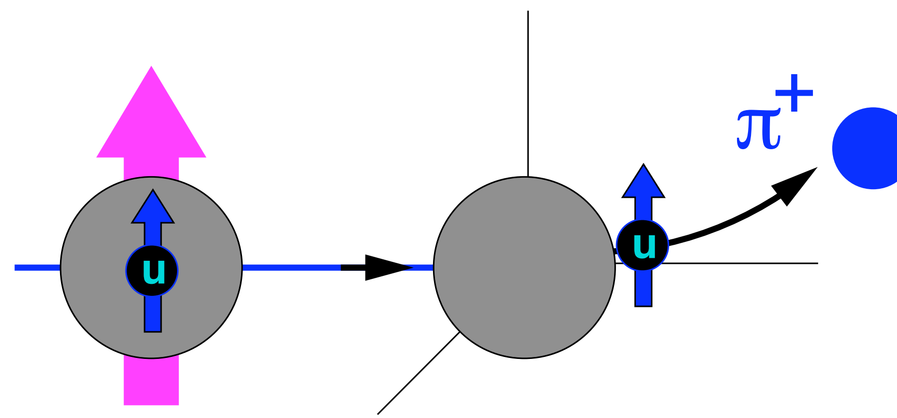


$h_1(x)$

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



E704 effect:



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

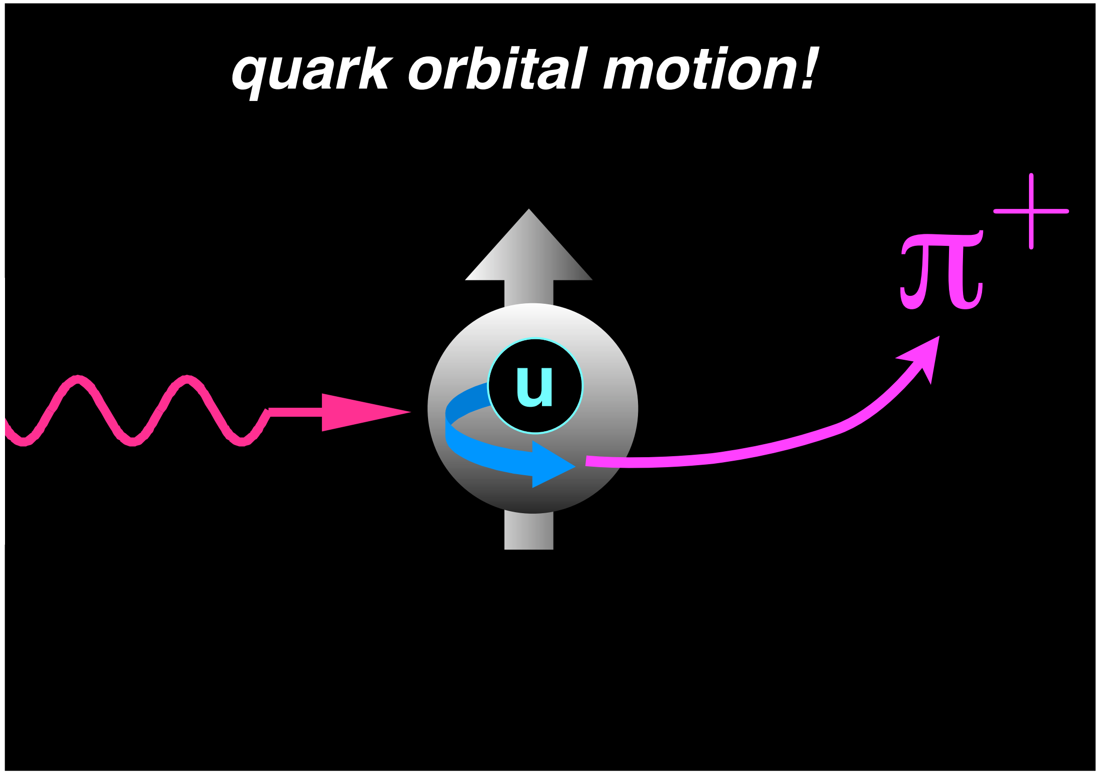
E704 Mechanism #2: The "Sivers Effect"

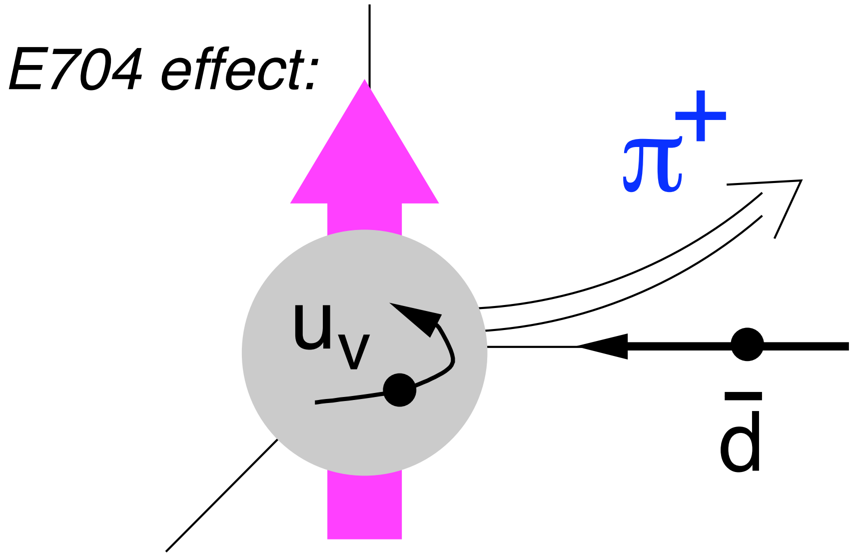
Need the ordinary fragmentation function $D_1(z)$

... 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





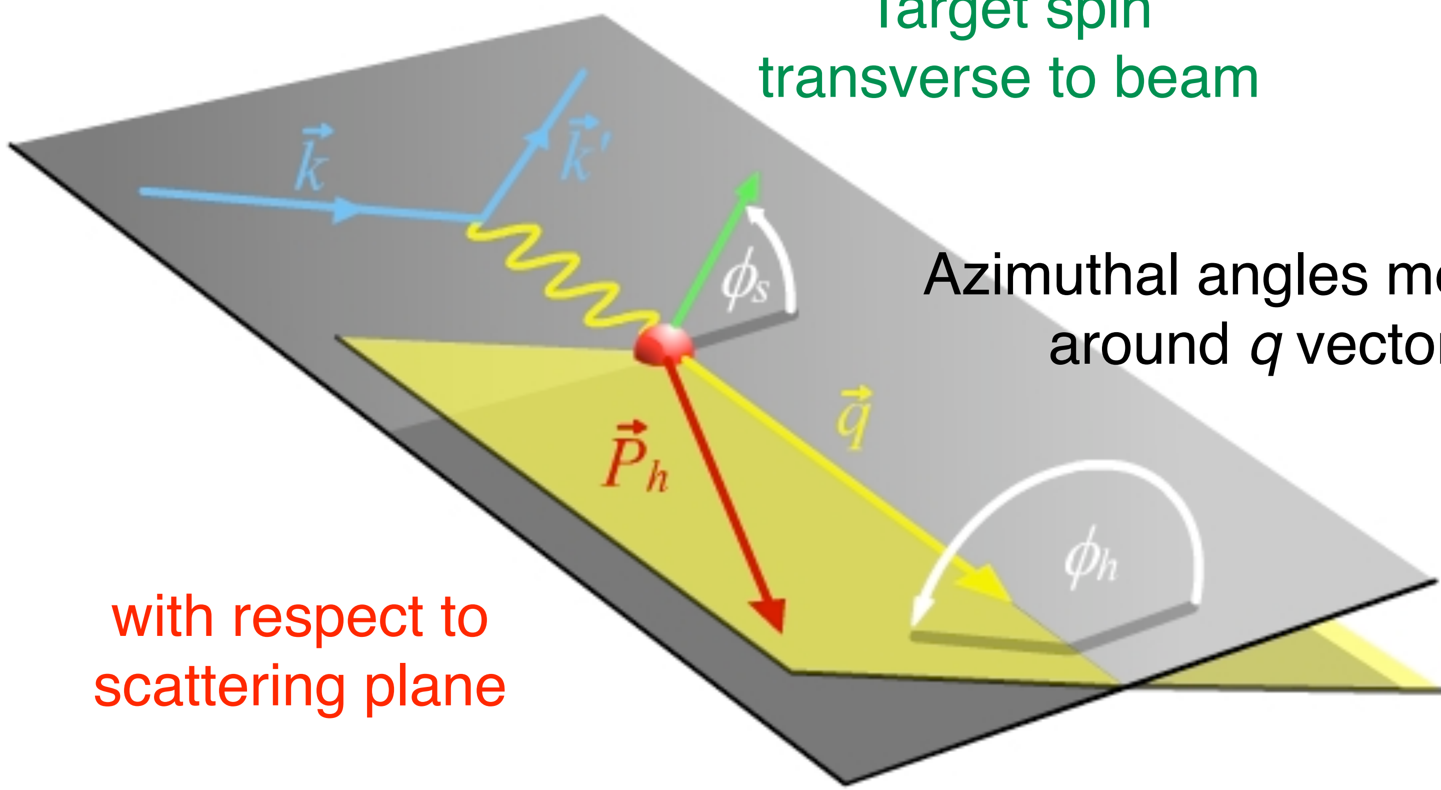
$$f_{1T}^{\perp}(x, k_T) \otimes D_1(z)$$

Electro-Production of Hadrons with Tranvserse Target

Measure dependence of hadron production on
two azimuthal angles

Electron beam defines
scattering plane

Target spin
transverse to beam

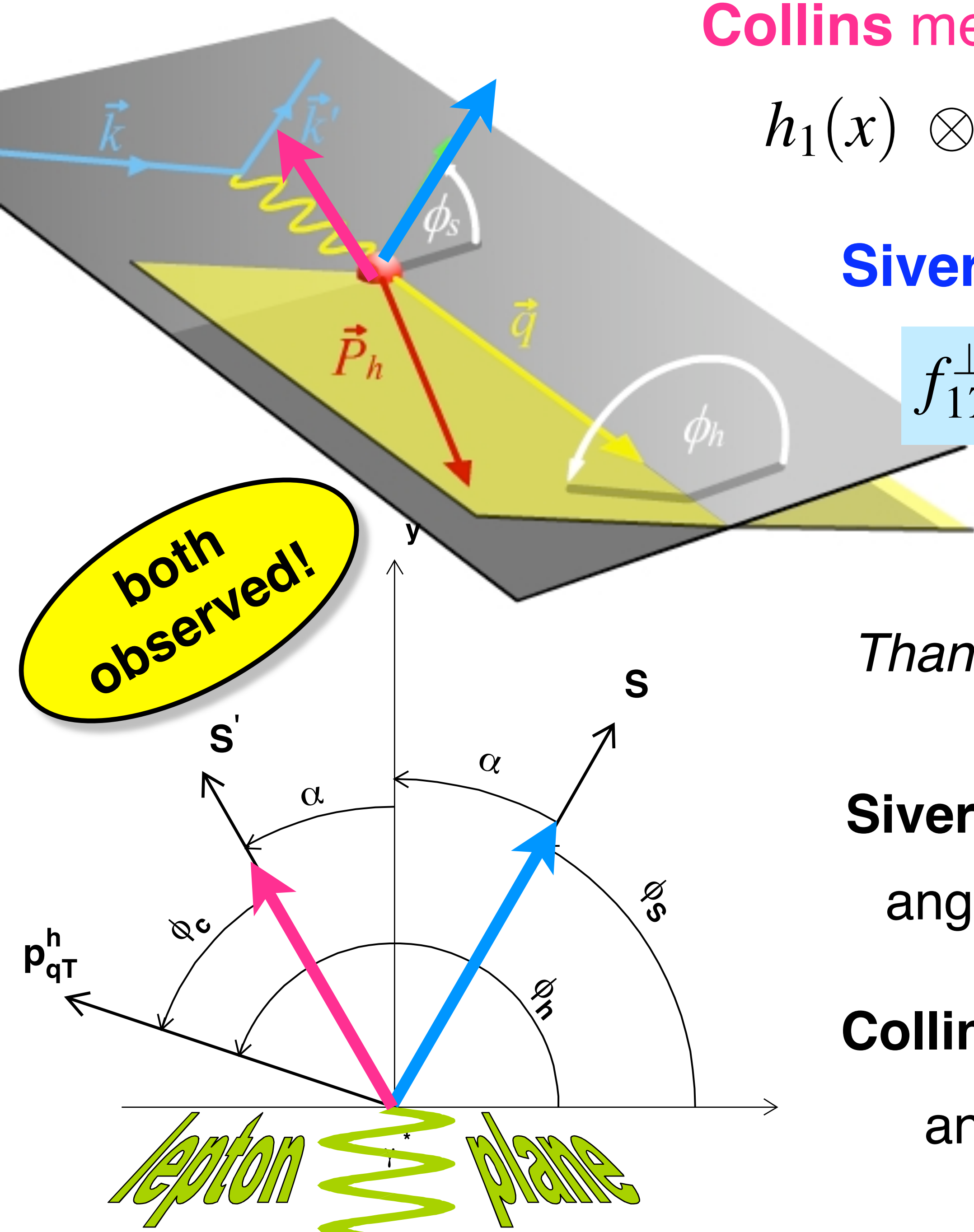


Azimuthal angles measured
around *q* vector ...

with respect to
scattering plane

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

Separating Collins and Sivers



Collins mechanism

$$h_1(x) \otimes H_1^{\perp}(z, p_T) \Rightarrow \sin(\phi_h + \phi_S)$$

Sivers mechanism

$$f_{1T}^{\perp}(x, k_T) \otimes D(z) \Rightarrow \sin(\phi_h - \phi_S)$$

Separate mechanisms!

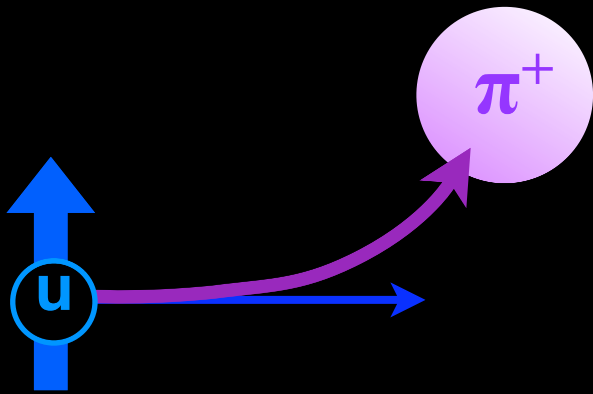
Thanks to <u>linear polarization</u> of photon ...

Sivers: $(\phi_h - \phi_S)$

angle of pion relative to **initial** quark spin

Collins: $(\phi_h + \phi_S) = \pi + (\phi_h - \phi_S)$

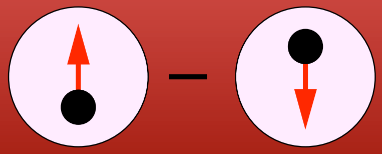
angle of pion relative to **final** quark spin



L_q in fragmentation

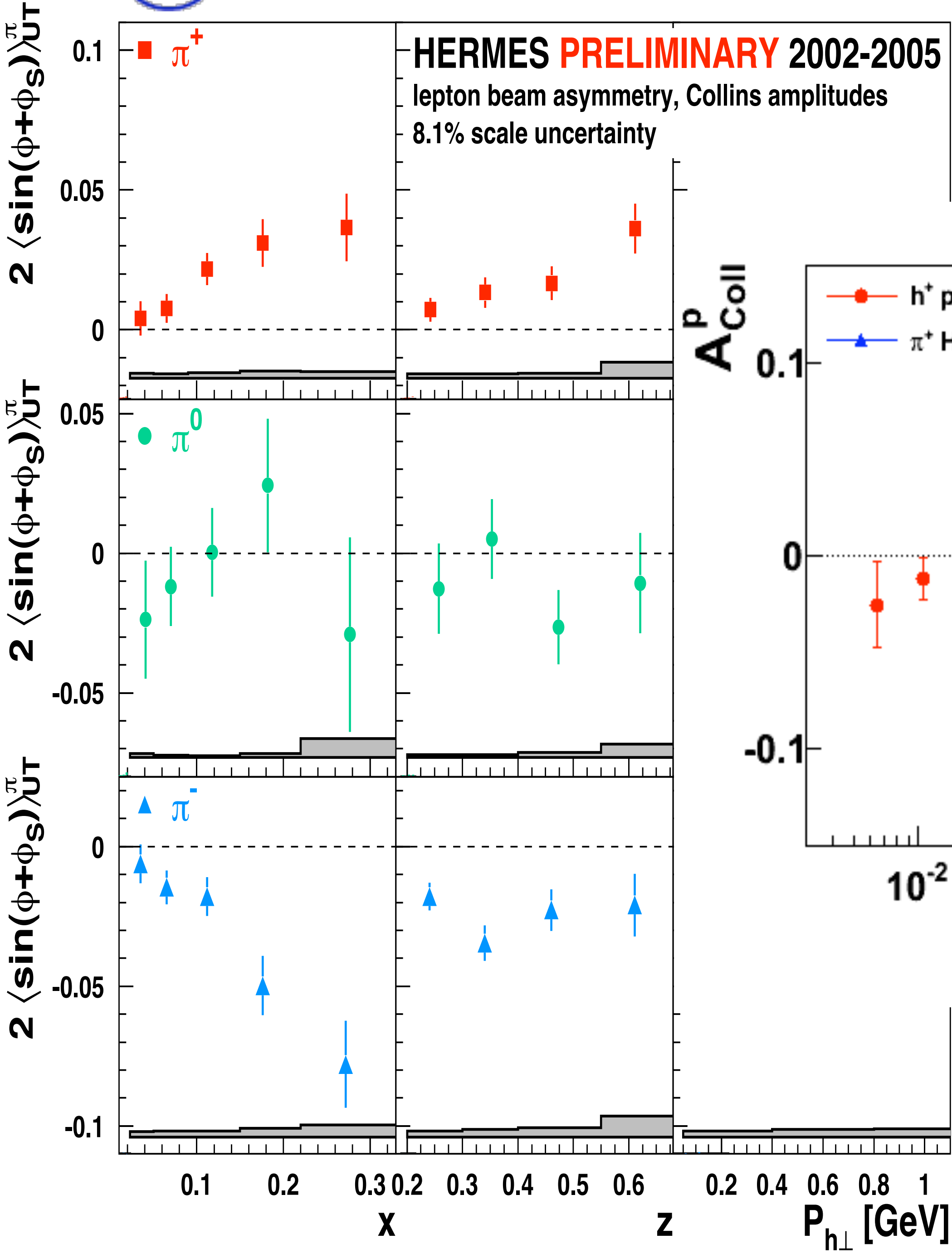
The Collins Fragmentation Function

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

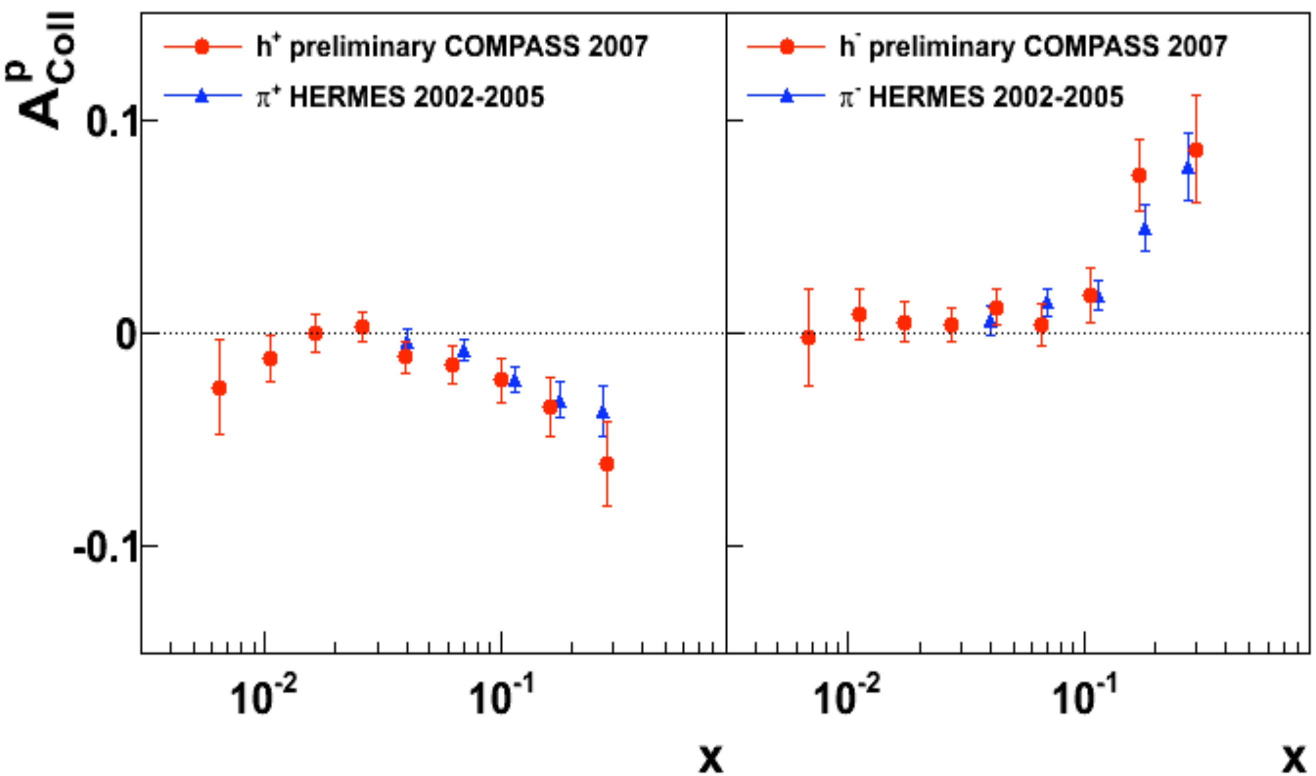


Collins Moments for π from $H^{\uparrow}$

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



Magnificent agreement at very different scales!



Final papers submitted:

COMPASS arXiv:1005.5609

HERMES arXiv:1006.4221

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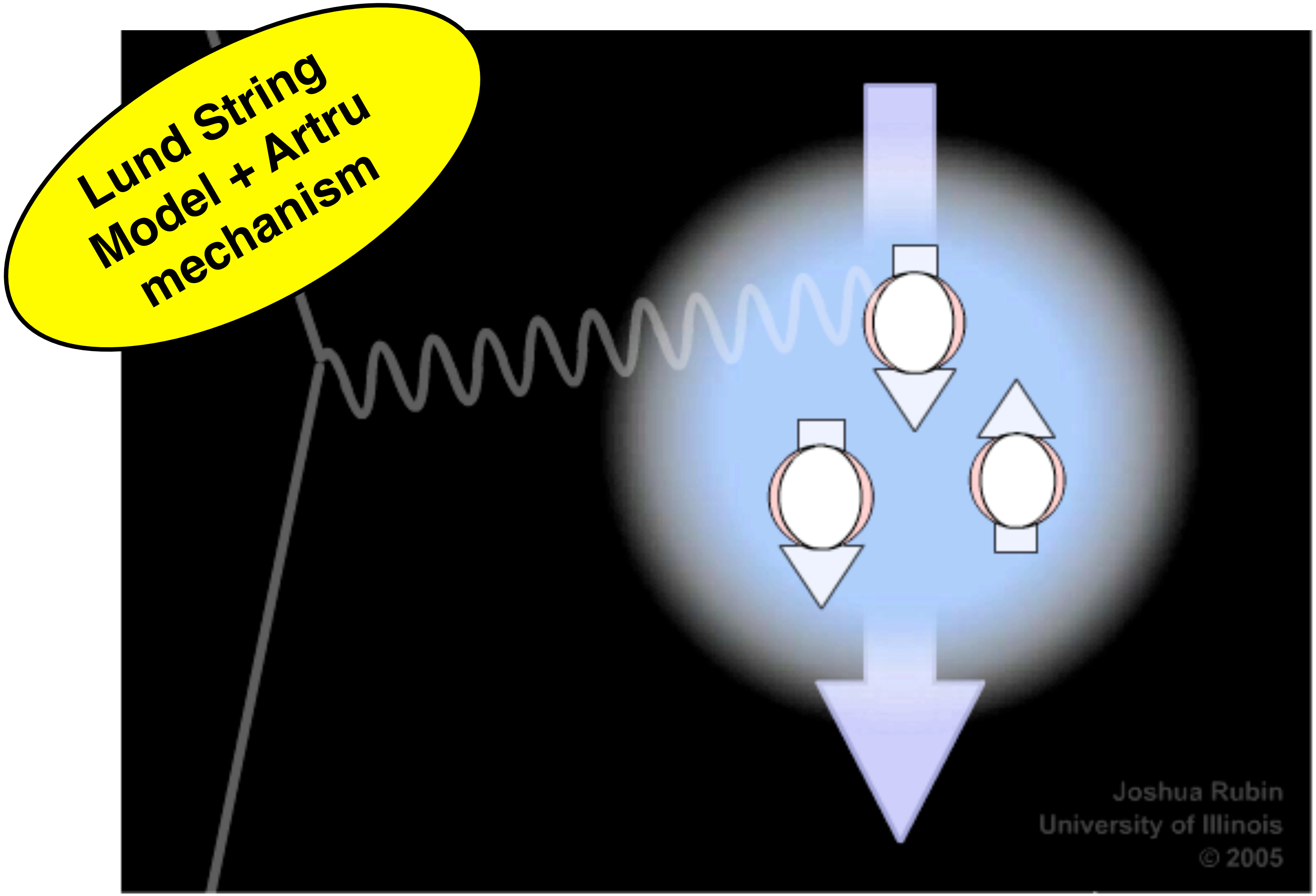
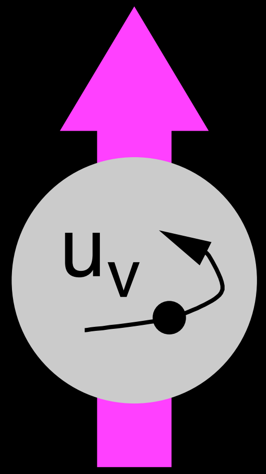
Understanding the Collins Effect

The Collins fragmentation function exists

➡ **spin-orbit correlations in pion formation**

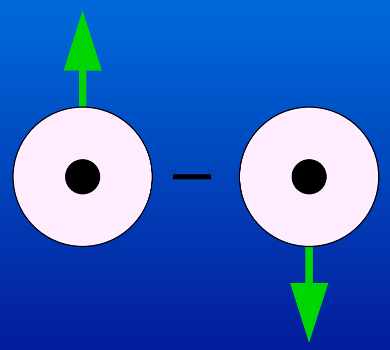




L_q within the proton

The Sivers Function

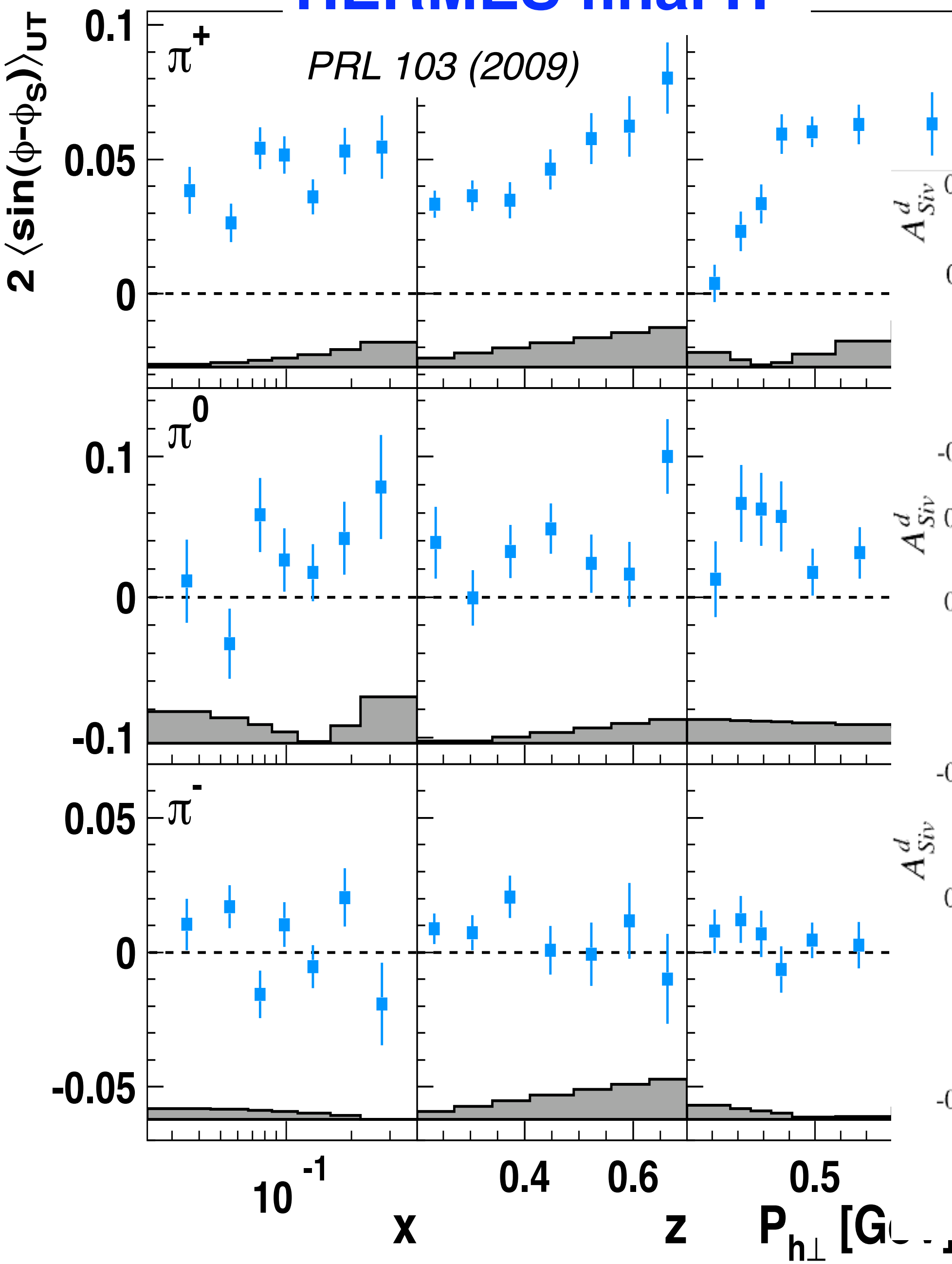
$$f_{1T}^{\perp}(x, k_T)$$



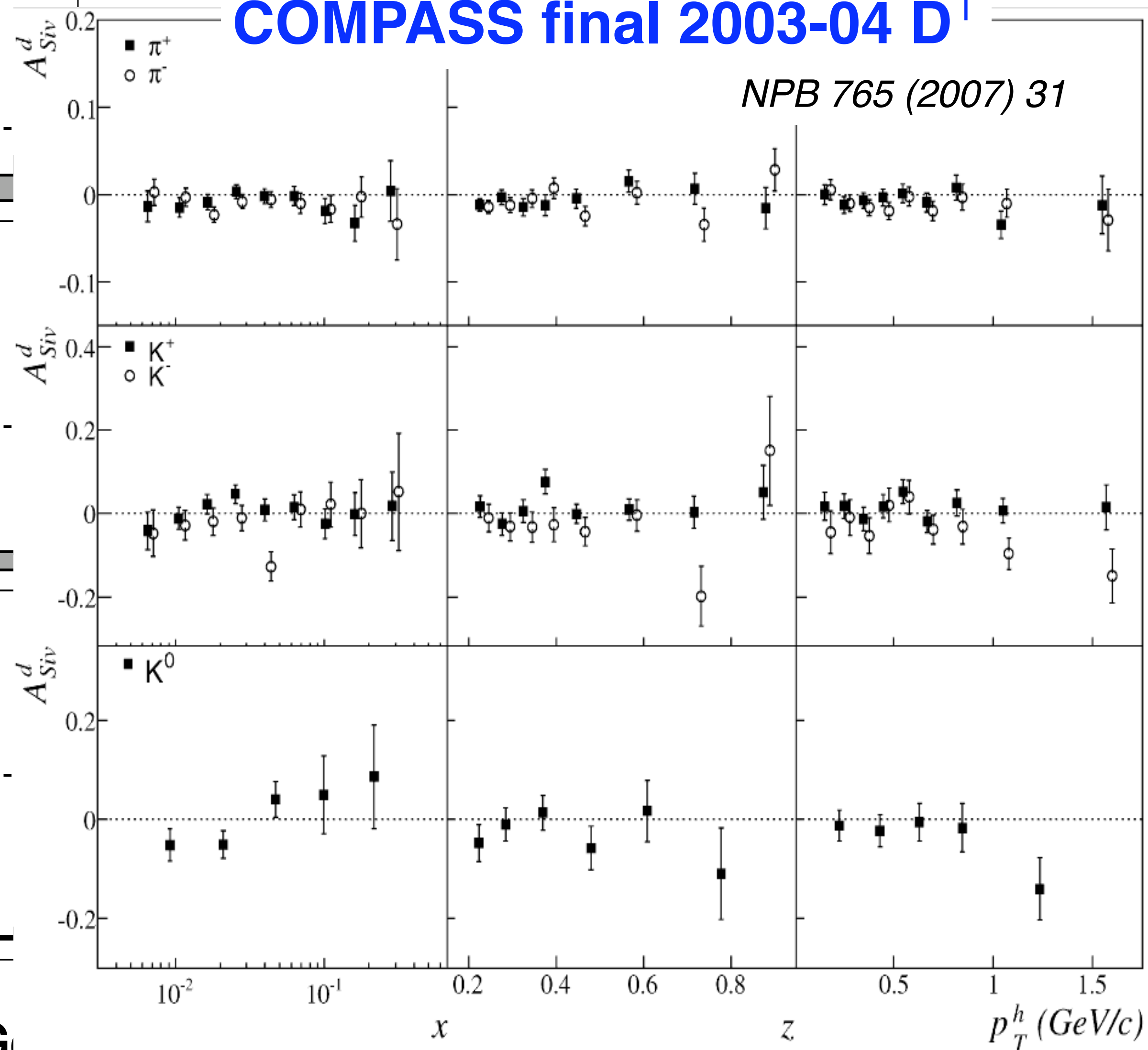
Sivers Moments for π and K from H$^{\uparrow}$ & D$^{\uparrow}$

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

HERMES final H$^{\uparrow}$



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



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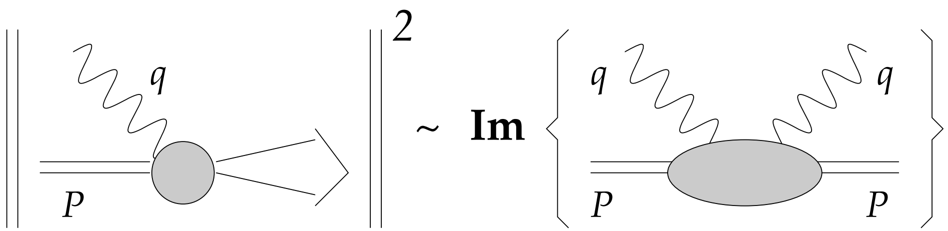
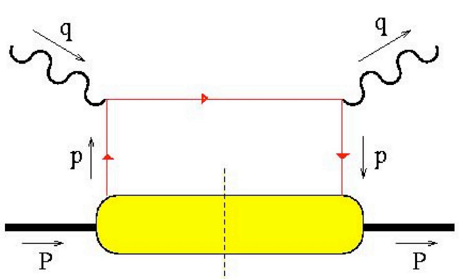
Jargon Alert

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

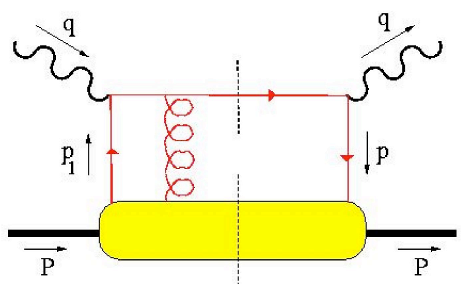
A T-odd function like $f_{1T}^{\perp}$ ***must*** arise from ***interference*** ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?



Brodsky, Hwang, & Schmidt 2002



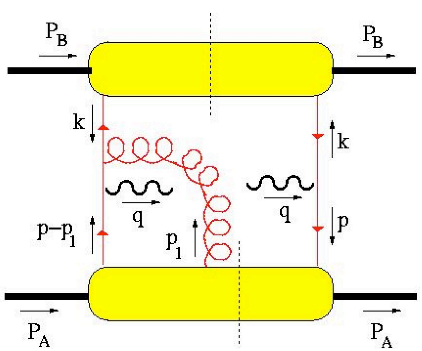
can interfere with



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

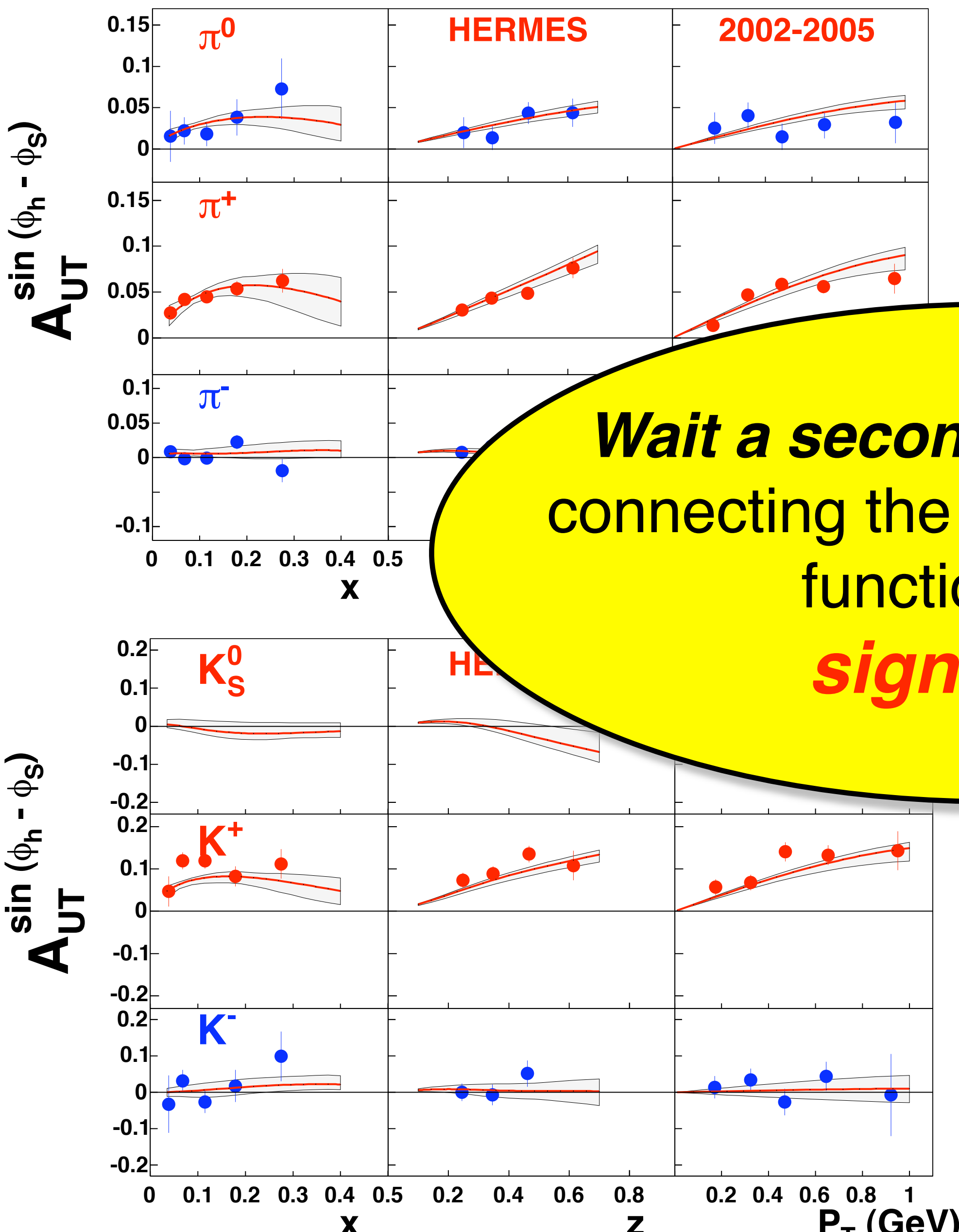
It looks like higher-twist ... but no , these are soft gluons = "gauge links" required for color gauge invariance

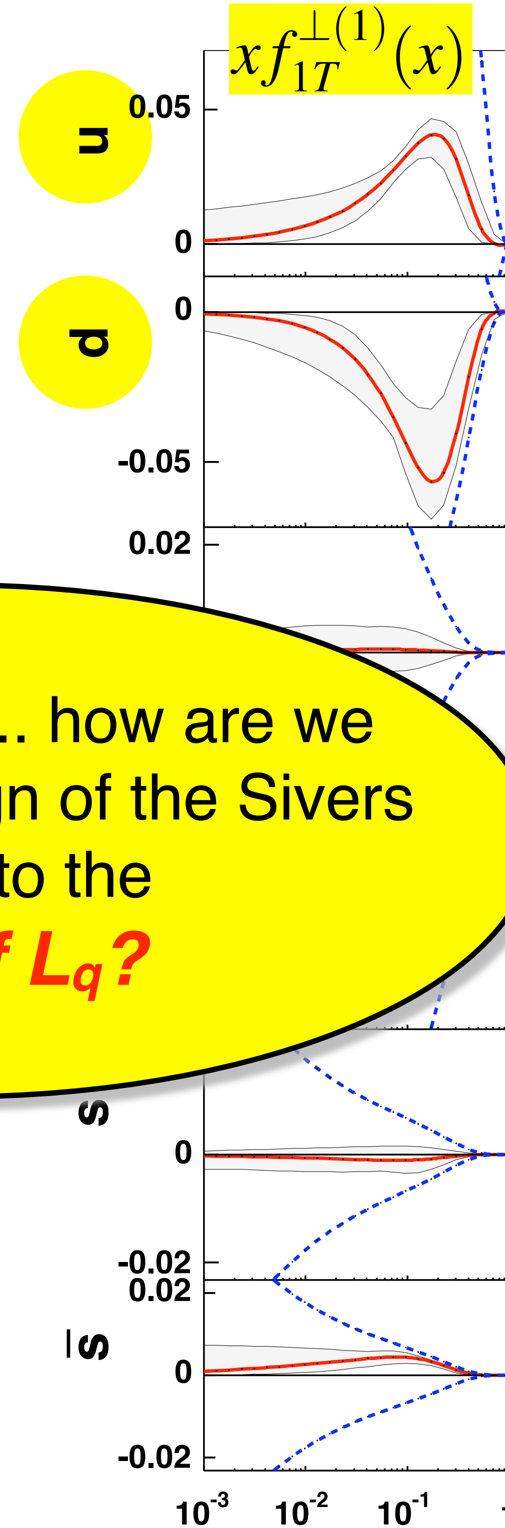
Such soft-gluon reinteractions with the soft wavefunction are ***final (or initial) state interactions*** ... and may be ***process dependent*** ! ➡ new ***universality issues***



e.g. Drell-Yan

Global Fit to Sivers Asymmetries

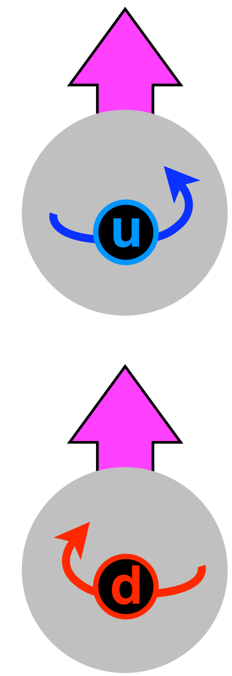




Wait a second ... how are we connecting the sign of the Sivers function to the ***sign of L_q?***

E. Boglione, Transversity2008

Anselmino et al, arXiv:0805.2677



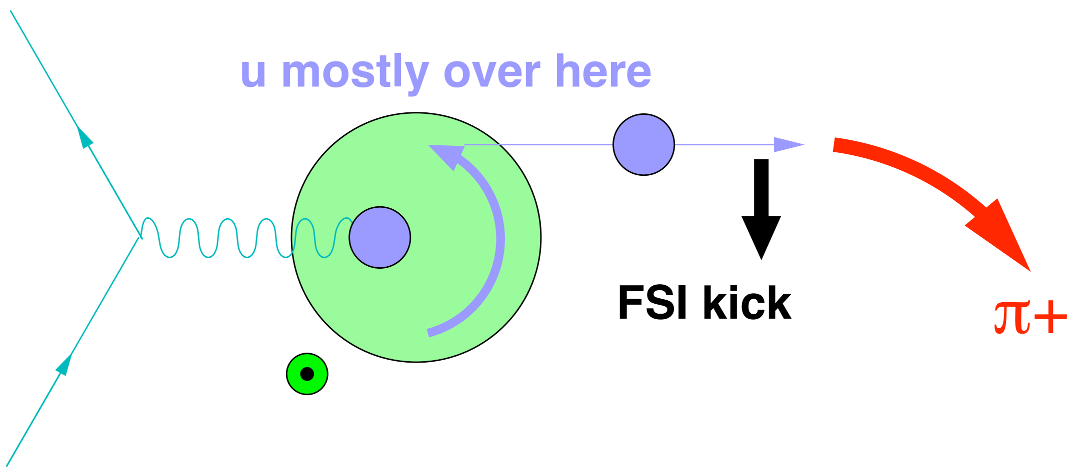
antiquark orbital L ≠ 0 favoured!

Phenomenology: Sivers Mechanism

Nearly all 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

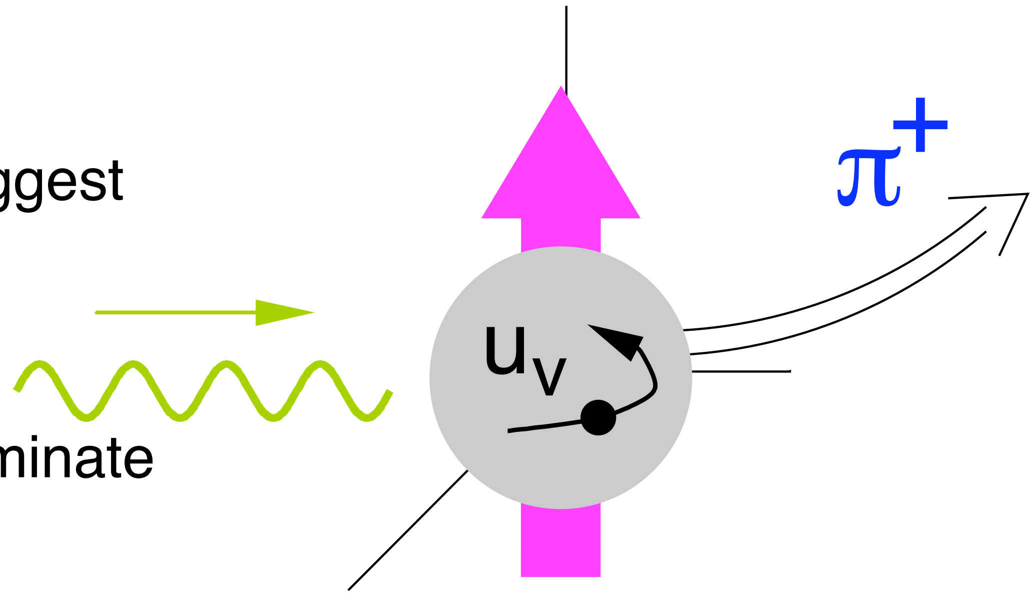
Model agrees!

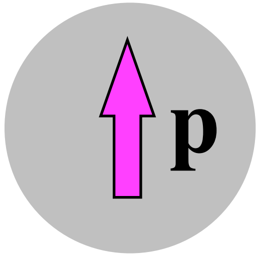
D. Sivers: Jet Shadowing

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

➡ quarks from "far" surface should dominate

Opposite sign to data ...





Meson Cloud on the back of an Envelope

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

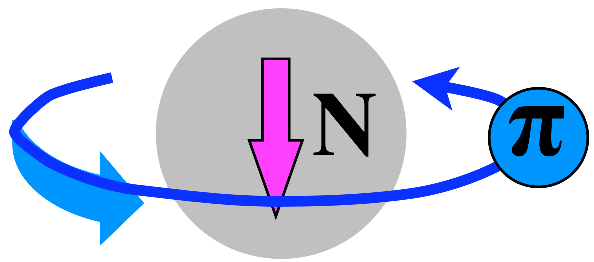
Pions have $J^P = 0^-$ = **negative parity** ...
→ ***need <u>L = 1</u>*** to get ***and an <u>orbiting</u> <u>sea</u>!***

$N\pi$ cloud:

u

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

$\otimes$



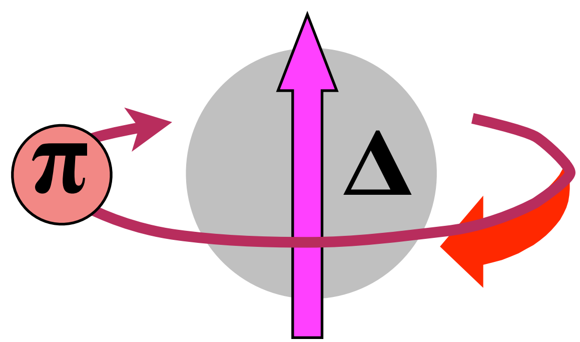
2/3 $L_z = +1$
1/3 $L_z = 0$

$\Delta\pi$ cloud:

d

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

$\otimes$



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

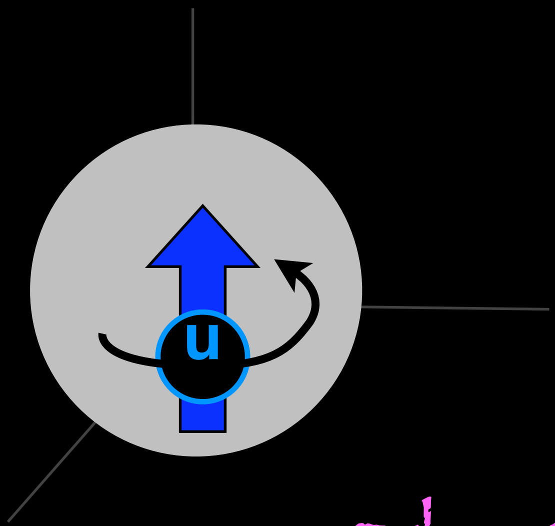
Dominant source of:

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

⇒

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

N.C.R. Makins, NNPSS 2011

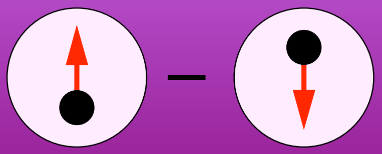


L_q within the proton

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

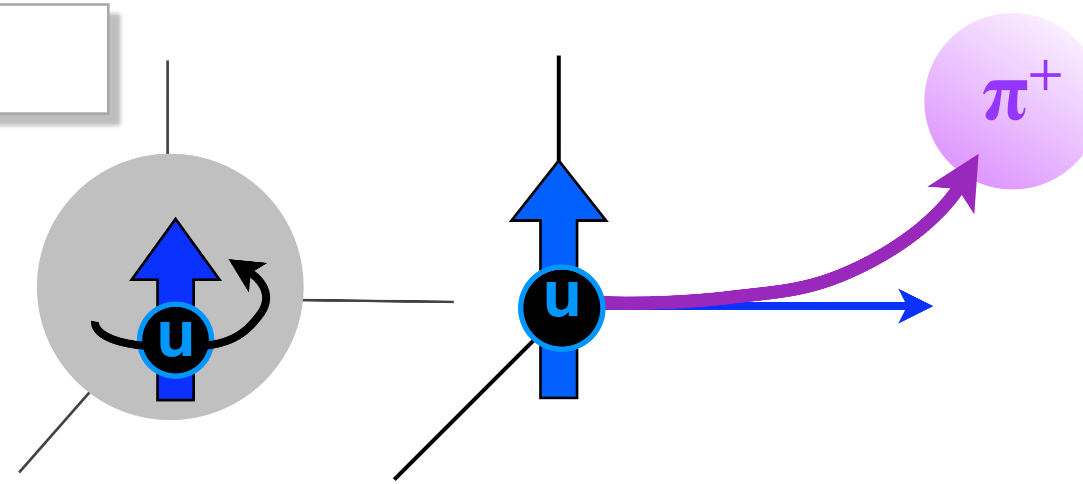
The Boer-Mulders function

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



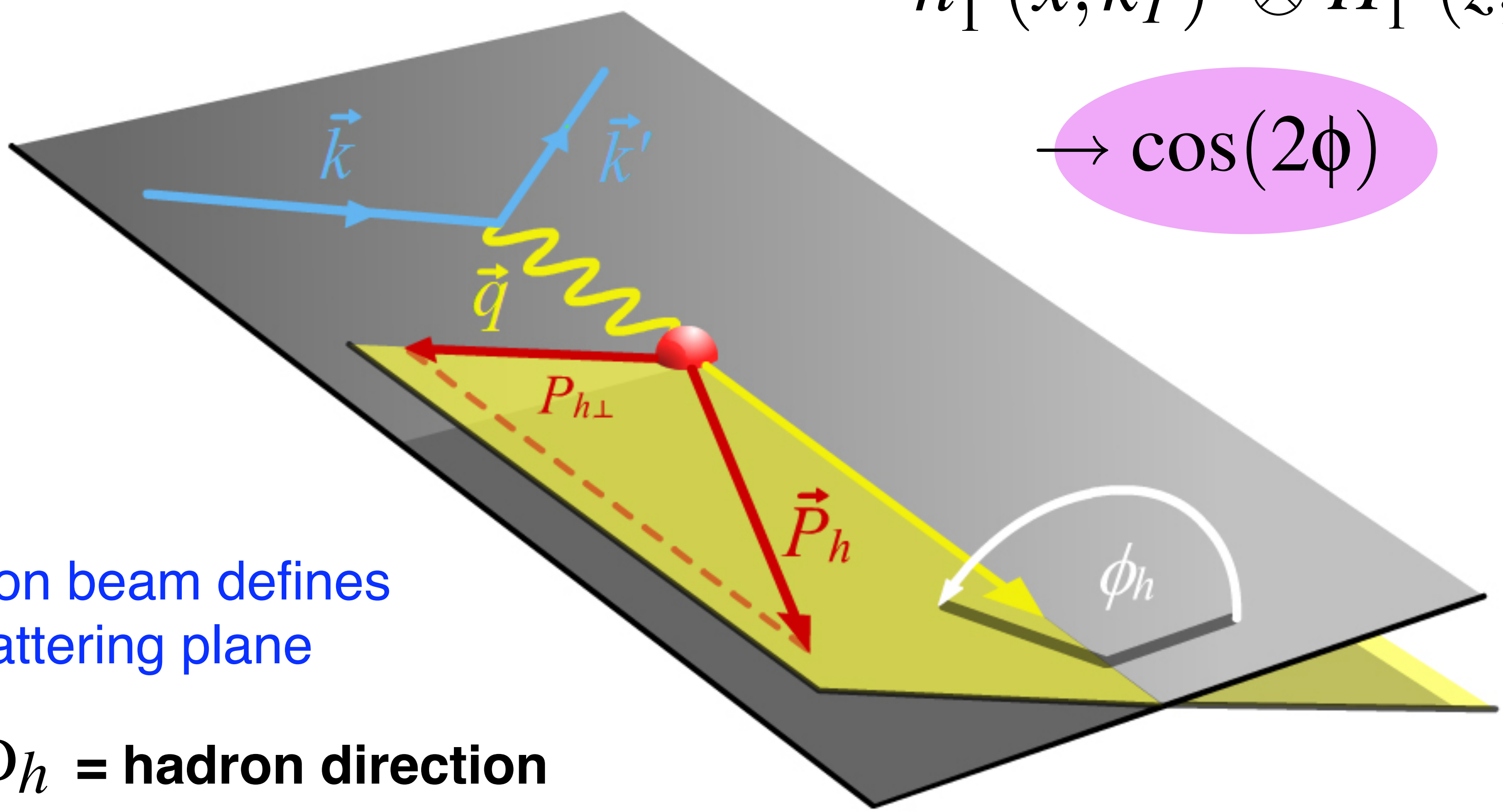
The Boer-Mulders function

produces an azimuthal modulation with **unpolarized** beam and target



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

$$\rightarrow \cos(2\phi)$$

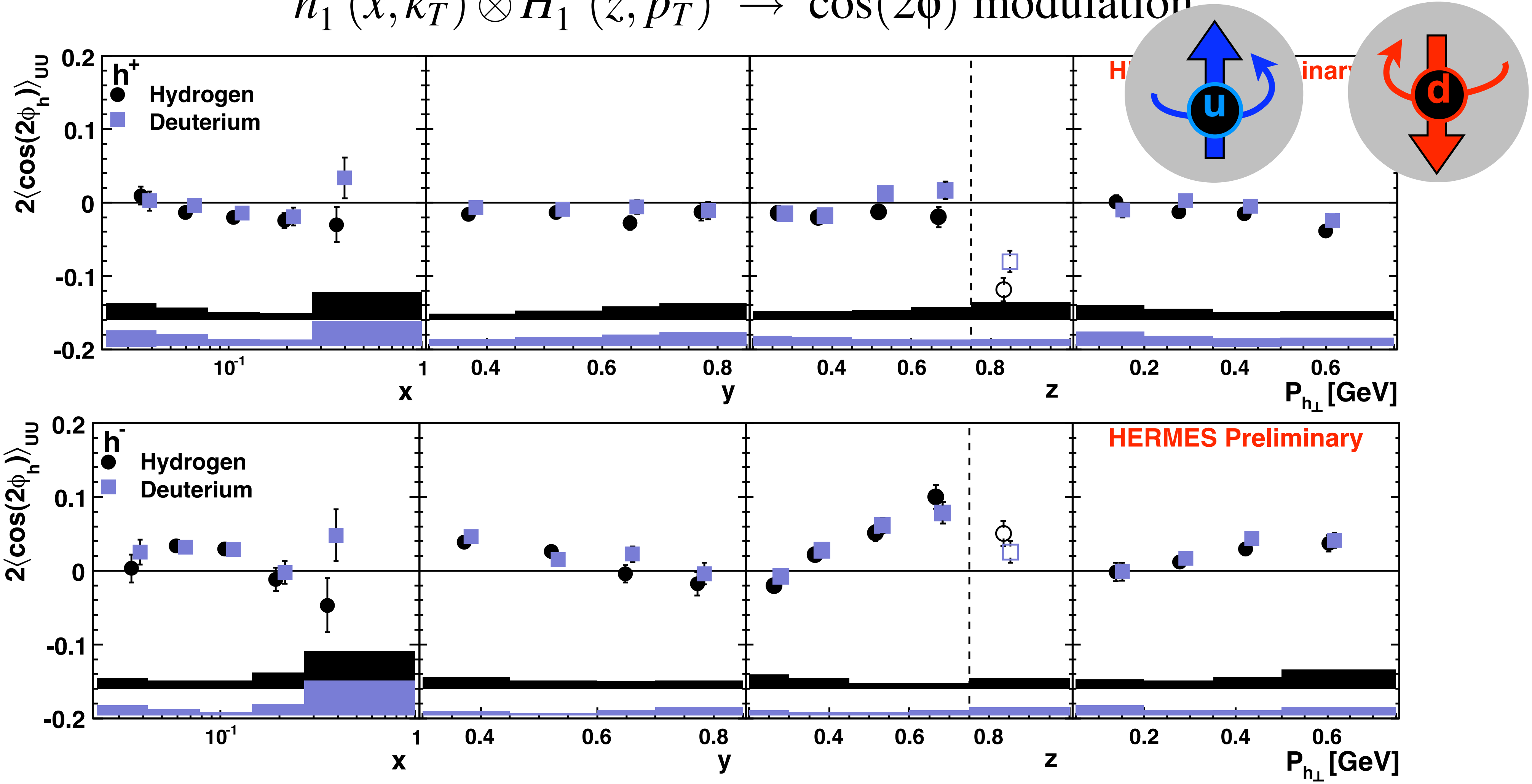


Electron beam defines scattering plane

ϕ_h = **hadron direction**

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 **up** and **down** quarks (both negative, similar magnitudes)*

$\langle\cos(2\phi_h)\rangle$: Model 3

One illustration of H ≈ D impact

Zhang et al.

B. Zhang et al., Phys.Rev.D78:034035,2008

Boer-Mulders extracted from unpolarized p+D Drell-Yan data

$$h_1^{\perp,q}(x,\mathbf{k}_T^2) = h_1^{\perp,q}(x)\frac{\exp(-\mathbf{k}_T^2/p_{bm}^2)}{\pi p_{bm}^2},$$

$$\begin{aligned}
h_1^{\perp,u}(x) &= \omega H_u\, x^c\,(1-x)\, f_1^u(x),\\
h_1^{\perp,d}(x) &= \omega H_d\, x^c\,(1-x)\, f_1^d(x),\\
h_1^{\perp,\bar{u}}(x) &= \frac{1}{\omega} H_{\bar{u}}\, x^c\,(1-x)\, f_1^{\bar{u}}(x),\\
h_1^{\perp,\bar{d}}(x) &= \frac{1}{\omega} H_{\bar{d}}\, x^c\,(1-x)\, f_1^{\bar{d}}(x),
\end{aligned}$$

	Set I	Set II
H_u	3.99	4.44
H_d	3.83	-2.97
$H_{\bar{u}}$	0.91	4.68
$H_{\bar{d}}$	-0.96	4.98
p_{bm}^2	0.161	0.165
c	0.45	0.82
$\chi^2/d.o.f.$	0.79	0.79

Set II:

Boer-Mulders extracted assuming $h_1^{\perp,u}$ and $h_1^{\perp,d}$ of **opposite signs**

-> results in **large** $h_1^{\perp}$ for antiquarks

Collins parameterization to SIDIS and e+e- from M. Anselmino et al., Phys. Rev. D 75, 054032 (2007).

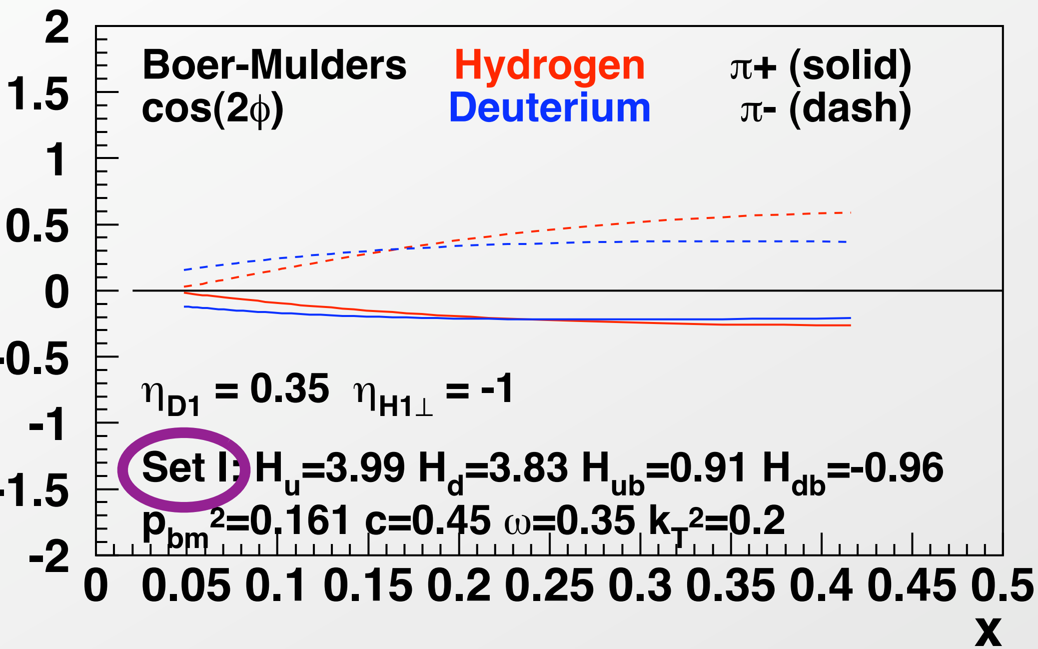
f_1 MRST2001 LO

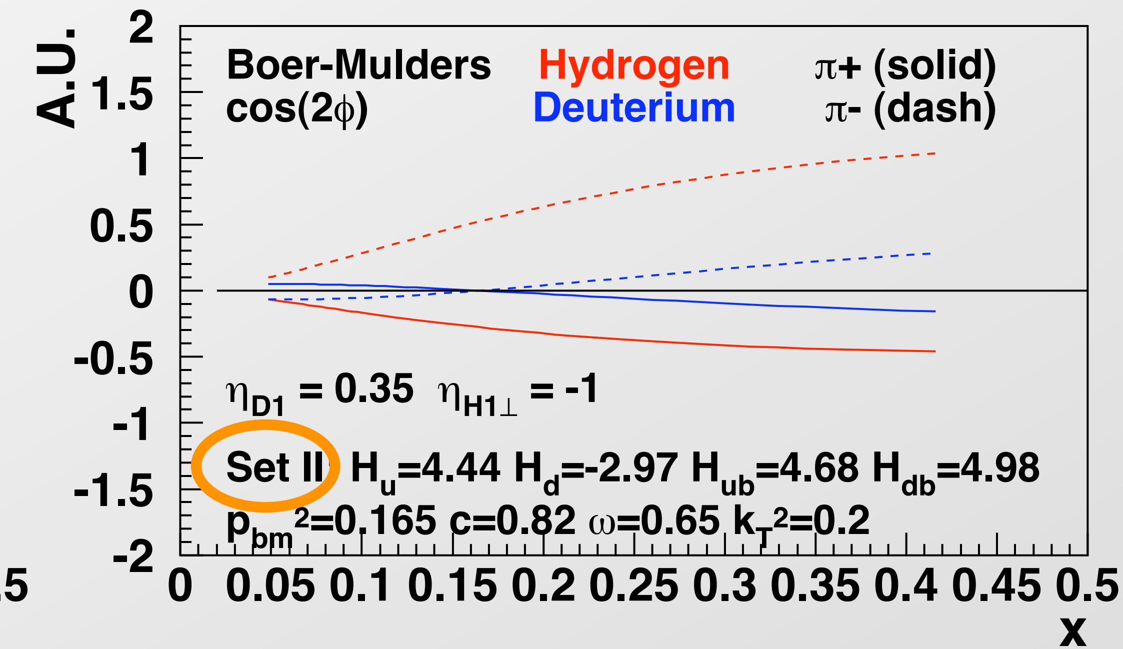
D_1 Kretzer

<cos(2ϕh)>: Hydrogen vs Deuterium

in the (roughly implemented) Zhang model

So given that we are doing something reasonable for H, let's calculate D...

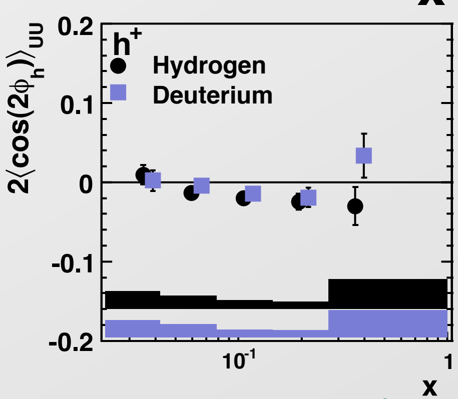


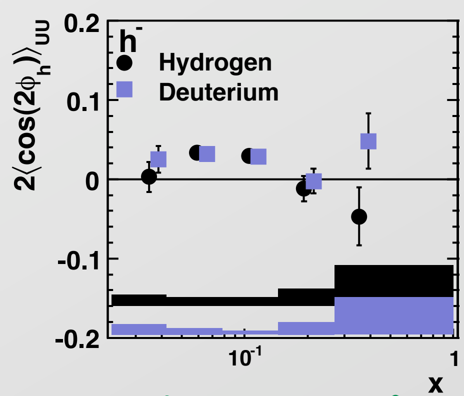


Set 1

Like the data

H~D





Set 2

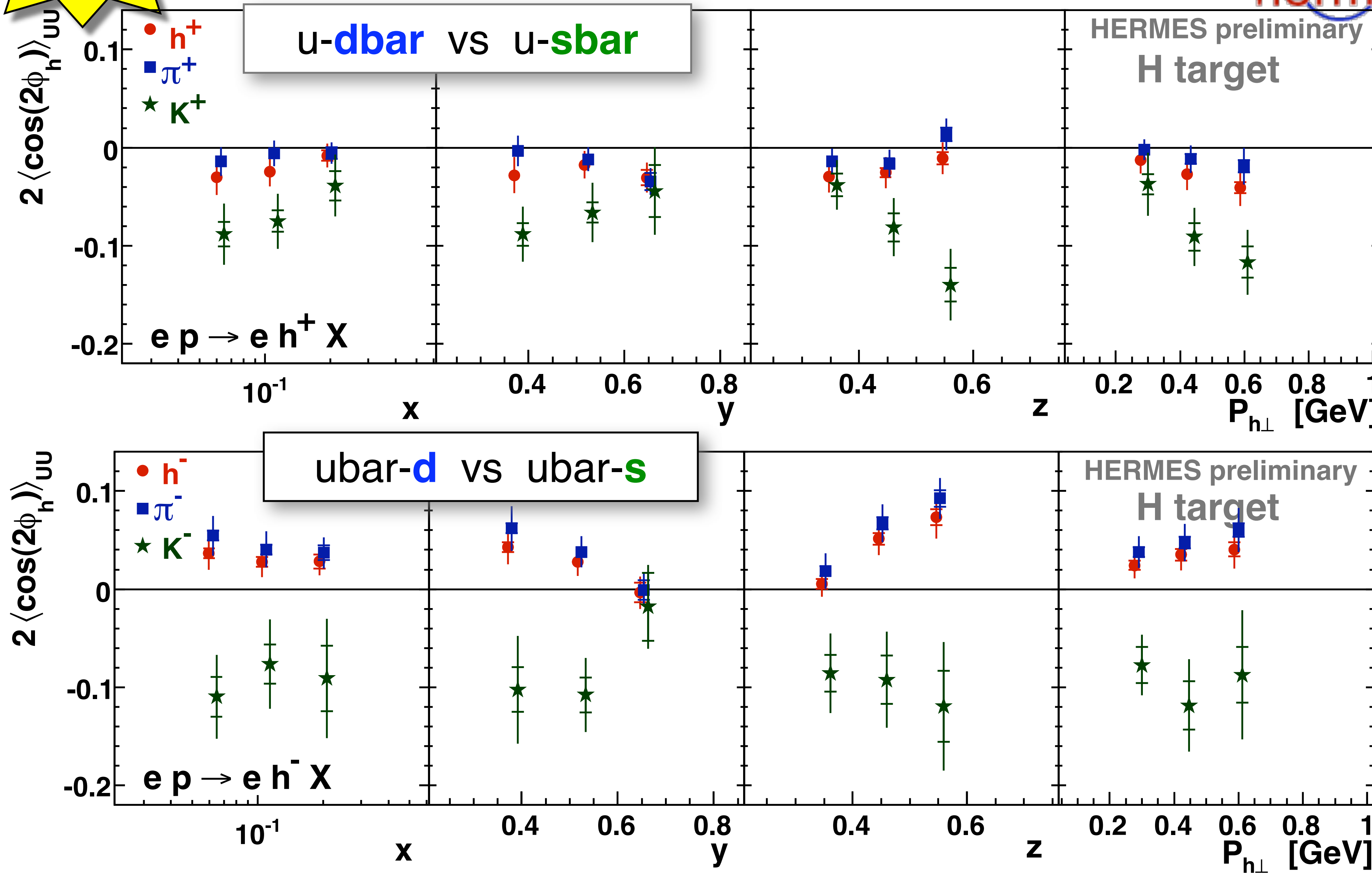
Not like the data

H~large D~0

We MUST use H AND D data to determine the u/d sign!!!

... and then there were Kaons: $\langle\cos(2\Phi)\rangle_{UU}$

NEW



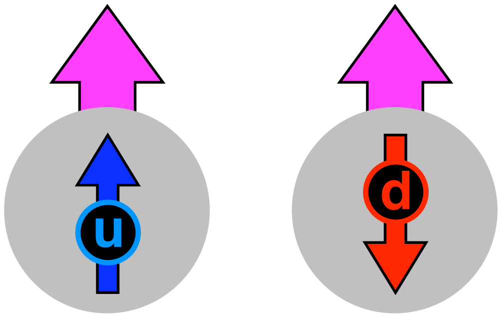
<u>dramatic</u> effects for Kaons, with strange quarks! → L in the <u>sea</u>?

A Coherent Picture Yet?

A Coherent Picture?

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

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

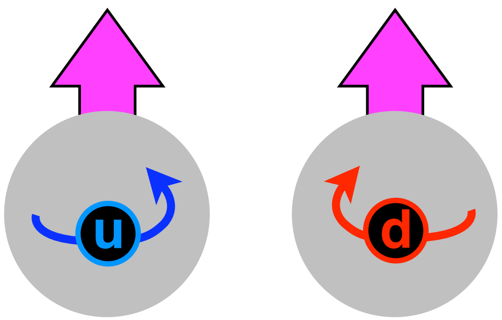


- **Sivers**: $f_{1T^\perp,u} < 0 \quad f_{1T^\perp,d} > 0$

  → relat^n to **anomalous magnetic moment***

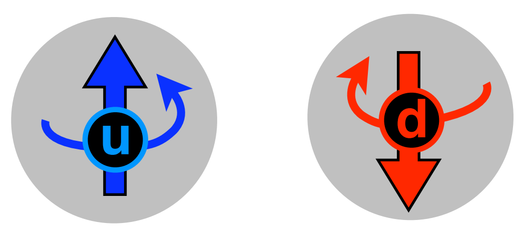
  $f_{1T^\perp,q} \sim \kappa_q$ where $\kappa_u \approx +1.67 \quad \kappa_d \approx -2.03$

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

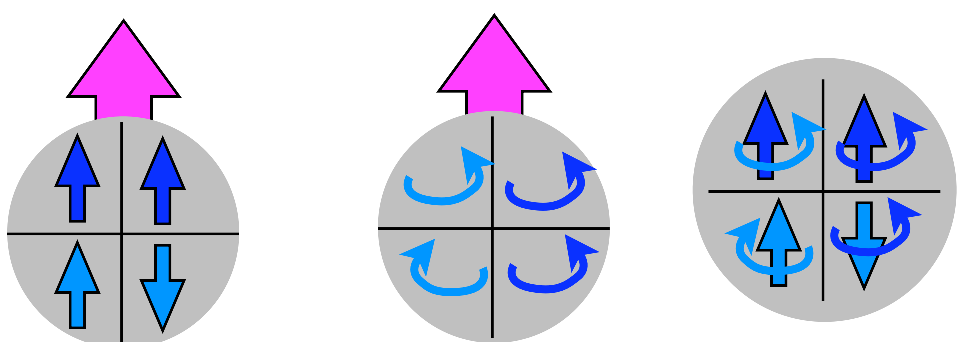


- **Boer-Mulders:** follows that $h_1{}^\perp{}_{,u}$ and $h_1{}^\perp{}_{,d} < 0$?

  → QCD analogue of Sokolov-Ternov effect?



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;*

- **DIS structure func's**:
  forward limit ($\xi = 0$, $t = 0$)

$$q(x) = H^q(x, \xi = 0, t = 0)$$

$$\Delta q(x) = \tilde{H}^q(x, \xi = 0, t = 0)$$

$$h_{1,q}(x) = H_T^q(x, \xi = 0, t = 0)$$

Connection to many observables

- **Elastic form factors**:
  first moments in *x*

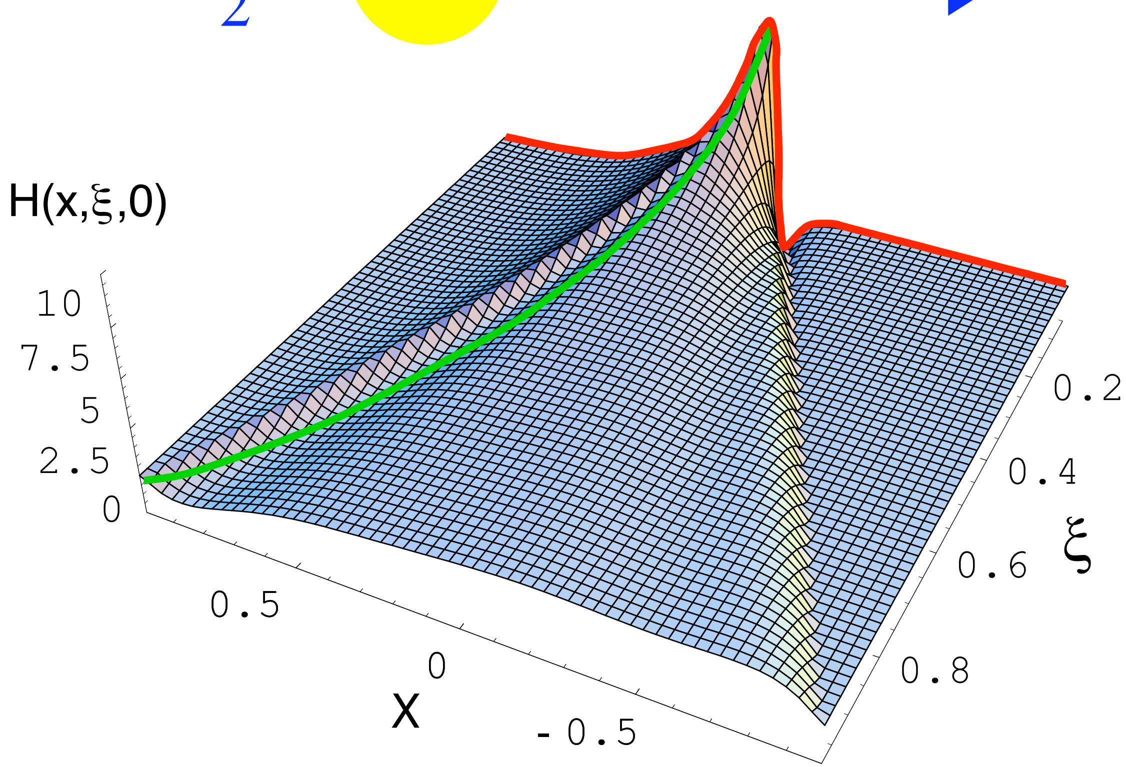
$$F_1^q(t) = \int_{-1}^{1} dx\, H^q(x, \xi, t) \qquad F_2^q(t) = \int_{-1}^{1} dx\, E^q(x, \xi, t)$$

- **Ji sum rule**:

$$J^q = \frac{1}{2}\int_{-1}^{1} x\, dx\, [H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)]$$

$$J^q = \frac{1}{2}\Delta\Sigma + L^q$$

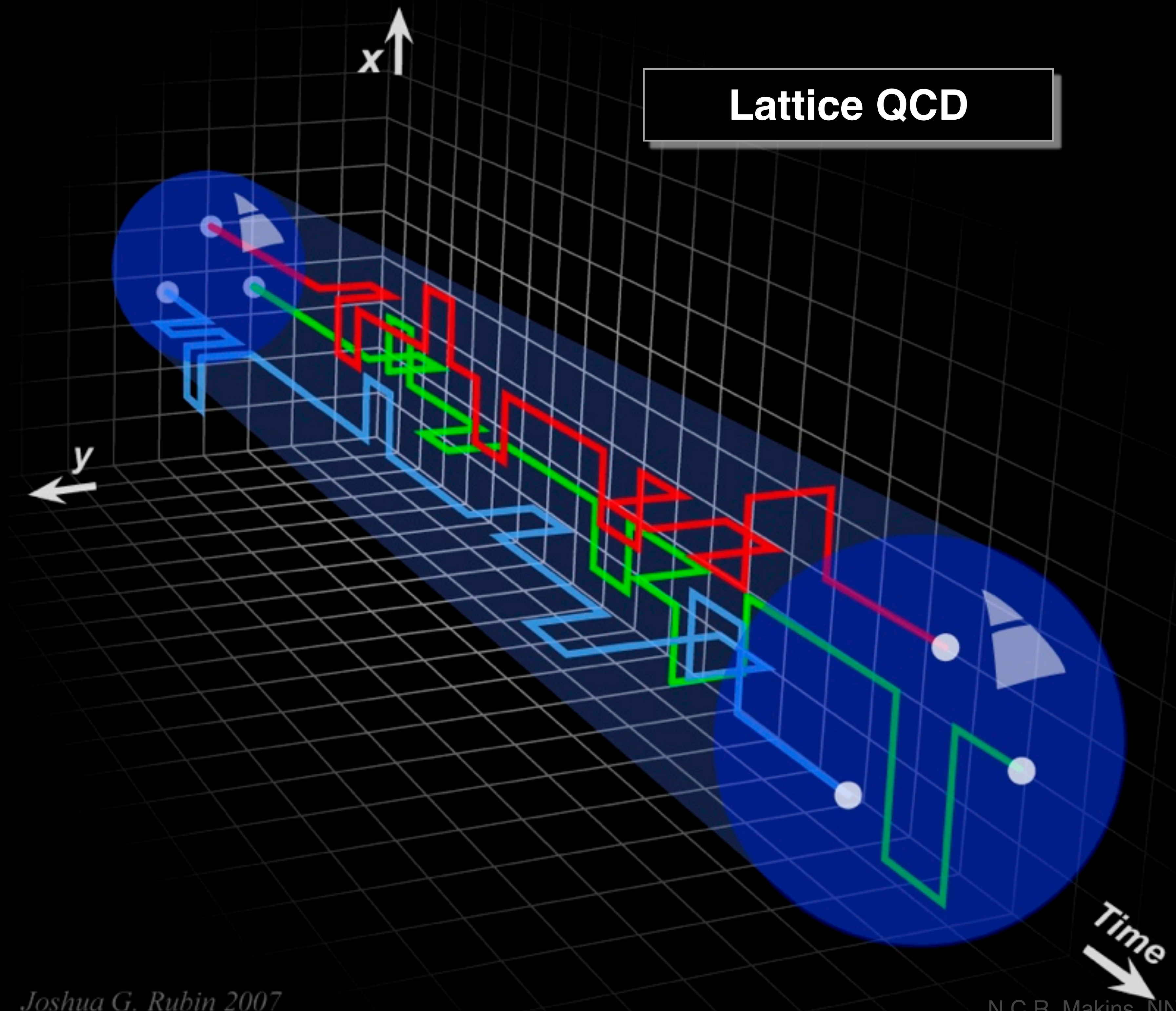
→ ***model-independent** access to **L***



Note connection of H, E to Dirac, Pauli form factors ... and their connection to nucleon *magnetic moment*:

$$F_1^N(0) + F_2^N(0) = \mu_N$$

Lattice QCD

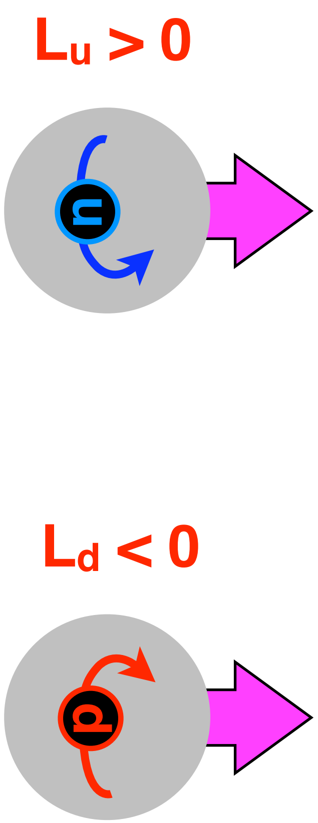


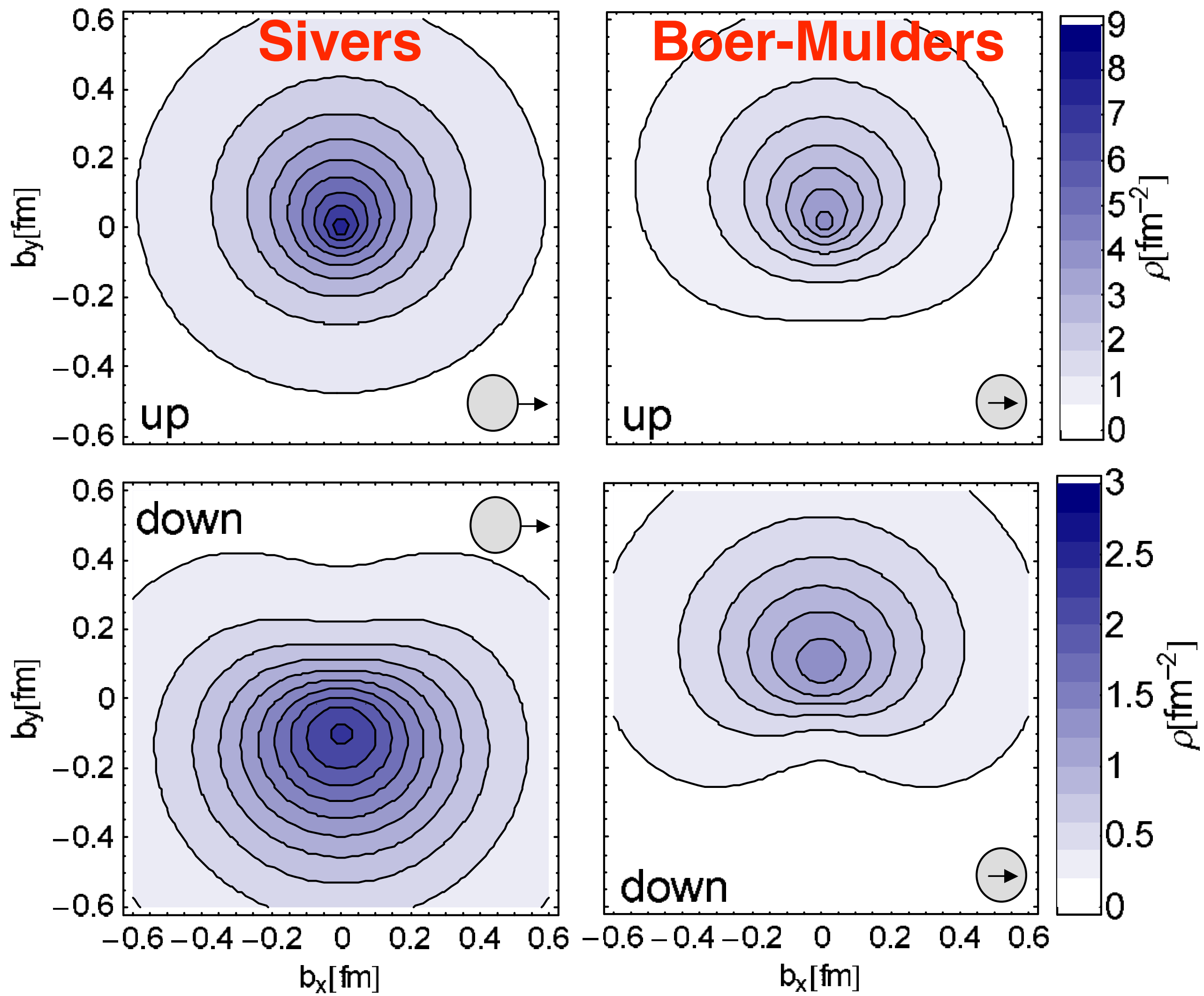
Transverse spin on the lattice

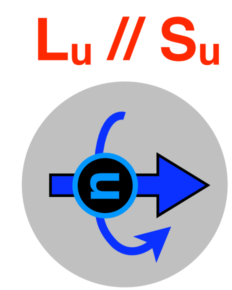
Hagler et al, PRL98 (2007)

Compute ***quark densities*** *in* ***impact-parameter space*** *via GPD formalism*

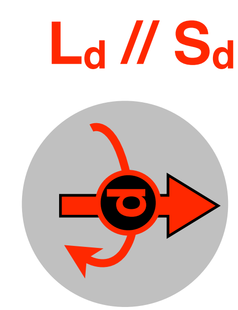
nucleon coming out of page ... observe spin-dependent **shifts** in quark densities:







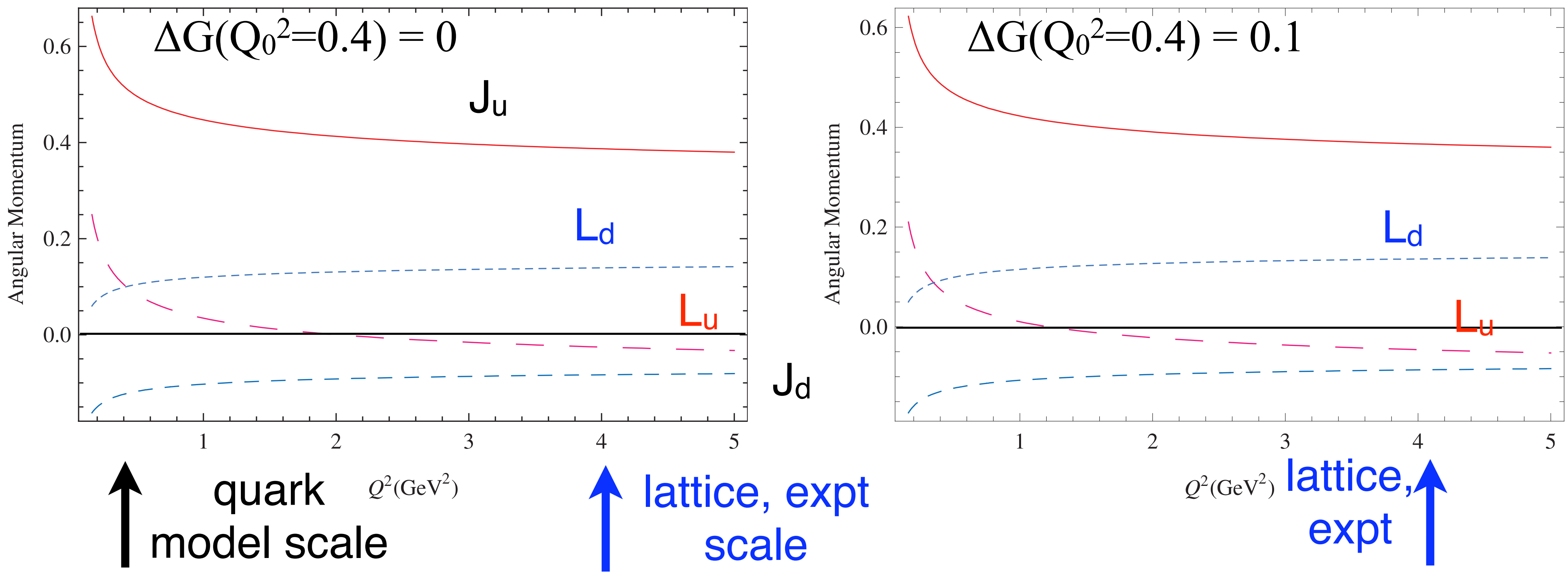
Expected picture *from* ***quark models + lensing***



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

Thomas, PRL101 (2008)

→ no disconnected graphs, evolution applied via Ji, Hoodbhoy



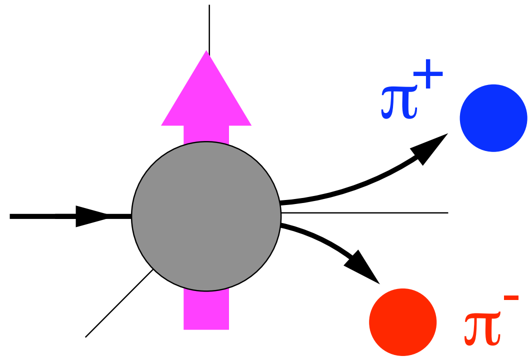
→ ***lattice shows $L_u < 0$ and $L_d > 0$ in longitudinal case at expt'al scales!***

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

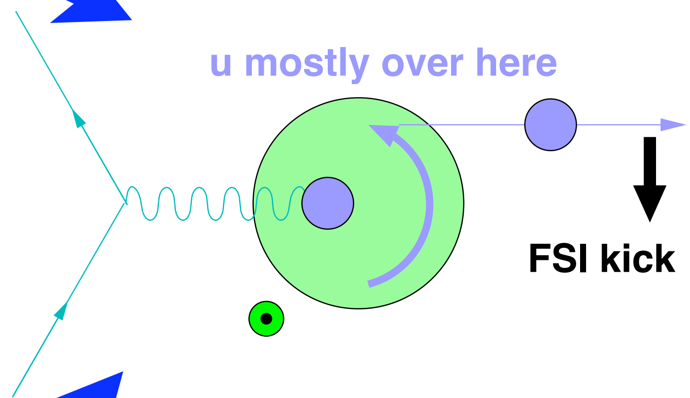
Are <u>disconnected graphs</u> – sea quarks – the reason for apparent L_u & L_d sign change from longitudinal to transverse ?

The L Scorecard

Data Transverse:
Sivers moments



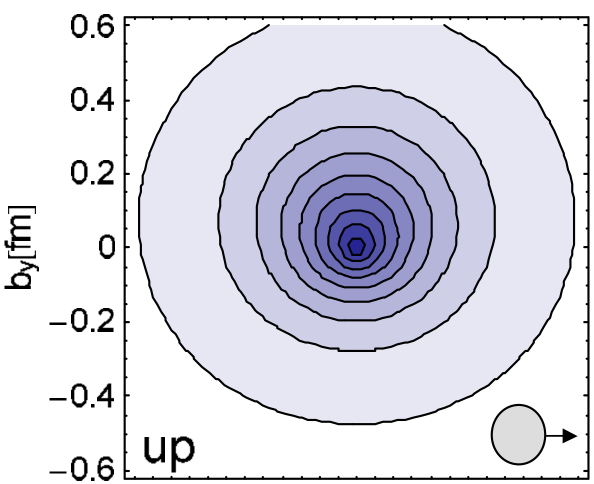
Chromodynamic Lensing



∴ **$L_u > 0$**
Transverse
at high Q^2

? ?

Lattice Transverse:
q density shifts



Lattice Longitudinal:
$L_u < 0$ at high Q^2

Quark models:
$L_u > 0$ at low Q^2

Lattice

Ji, PRL 78 (1997) 610

Ji L

What's going on?

- The quark **density shift is E**
- **E is <u>not</u> L:** $J^q = \frac{1}{2}\Delta\Sigma + L^q = \frac{1}{2}\int_{-1}^{1} x\,dx\,[H^q(x,\xi,t) + E^q(x,\xi,t)]_{t=0}$

PDF momentum sum $\int x\,q(x)\,dx$ ***not Δq!***

Burkardt, Brodsky proofs

- **E <u>is</u>** the anomalous magnetic moment **κ / Pauli F_2**
  (∵ GPD basics)
- **F_2** (Brodsky) and **κ** (Burkardt) **<u>require L ≠ 0</u>** (∵ N spin flip amplitudes)

Contradiction?

Jaffe L

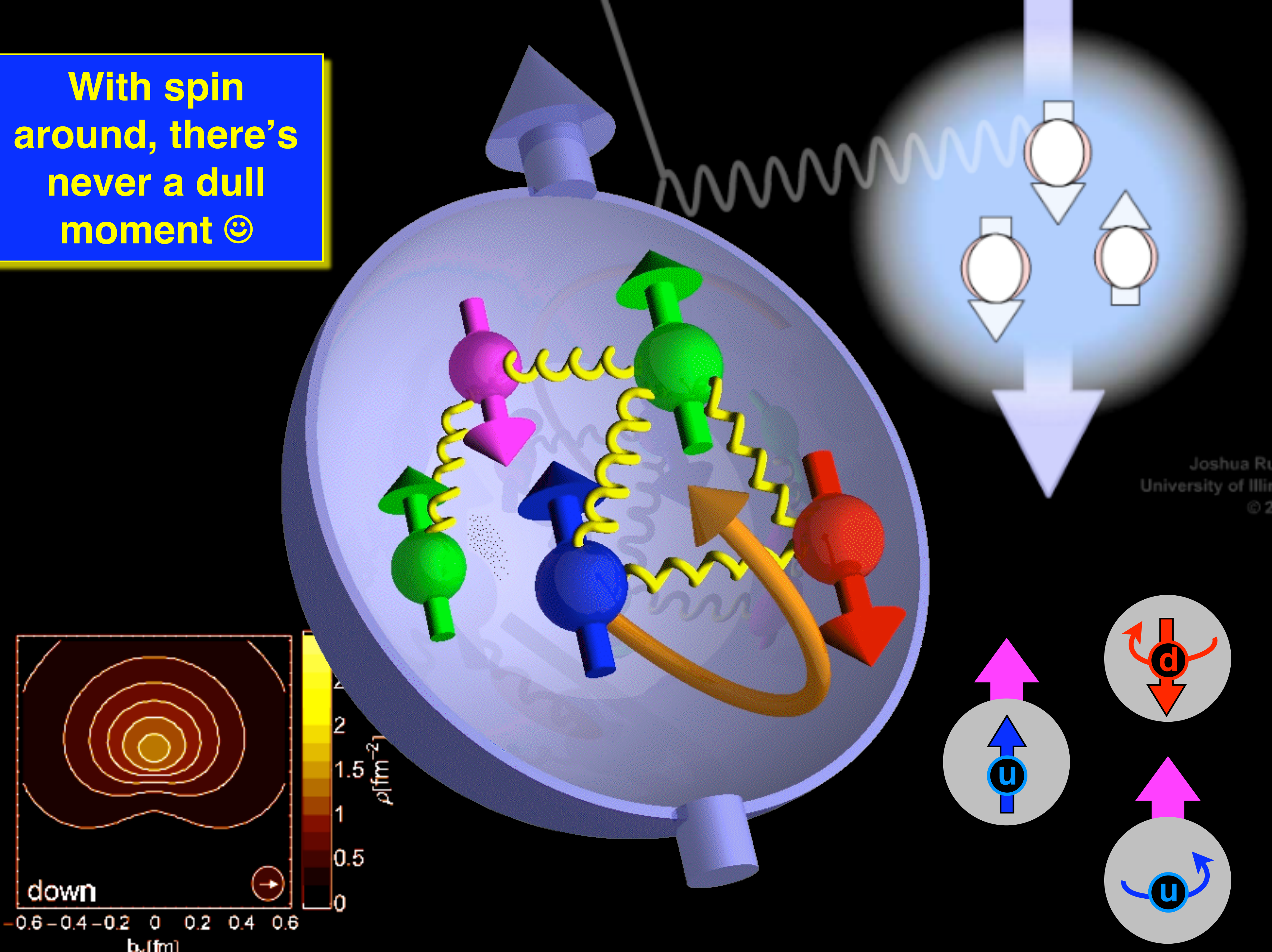
"L" not yet uniquely defined

Bashinsky, Jaffe, NPB 536 (1998) 303

➡ ***Which "L"** conrols **chromodynamic lensing?** Maybe neither*

➡ *Are **longitudinal** and **transverse L_q** the **same?** Maybe not*

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



DIS and Quark Parton Model

- Cross Section – Nucleon structure functions F_1 and F_2:

$$\frac{d\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4\left(\frac{\theta}{2}\right)} \left[\frac{F_2(\nu, Q^2)}{\nu} \cos^2\left(\frac{\theta}{2}\right) + \frac{2F_1(\nu, Q^2)}{M} \sin^2\left(\frac{\theta}{2}\right) \right]$$

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_2 M}{F_1 \nu}\left(1 + \frac{\nu^2}{Q^2}\right) - 1$$

$$\nu = E - E'$$

$$Q^2 = 4EE' \sin^2(\theta/2)$$

- Quark-Parton Model (QPM) interpretation in terms of quark probability distributions $q_i(x)$ (large Q^2 and ν):

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x) \qquad F_2(x) = x\sum_i e_i^2 q_i(x)$$

- Bjorken x: fraction of nucleon momentum carried by struck quark:

$$x = Q^2 / 2M\nu$$

F_2^n / F_2^p in Quark Parton Model

- Assume isospin symmetry:

$$u^p(x) \equiv d^n(x) \equiv u(x) \qquad \bar{u}^p(x) \equiv \bar{d}^n(x) \equiv \bar{u}(x)$$

$$d^p(x) \equiv u^n(x) \equiv d(x) \qquad \bar{d}^p(x) \equiv \bar{u}^n(x) \equiv \bar{d}(x)$$

$$s^p(x) \equiv s^n(x) \equiv s(x) \qquad \bar{s}^p(x) \equiv \bar{s}^n(x) \equiv \bar{s}(x)$$

- Proton and neutron structure functions:

$$F_2^p = x\left[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s})\right]$$

$$F_2^n = x\left[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}) + \frac{1}{9}(s+\bar{s})\right]$$

high x limit:

$$\frac{F_2^n}{F_2^p} \rightarrow \frac{1+4d/u}{4+d/u}$$

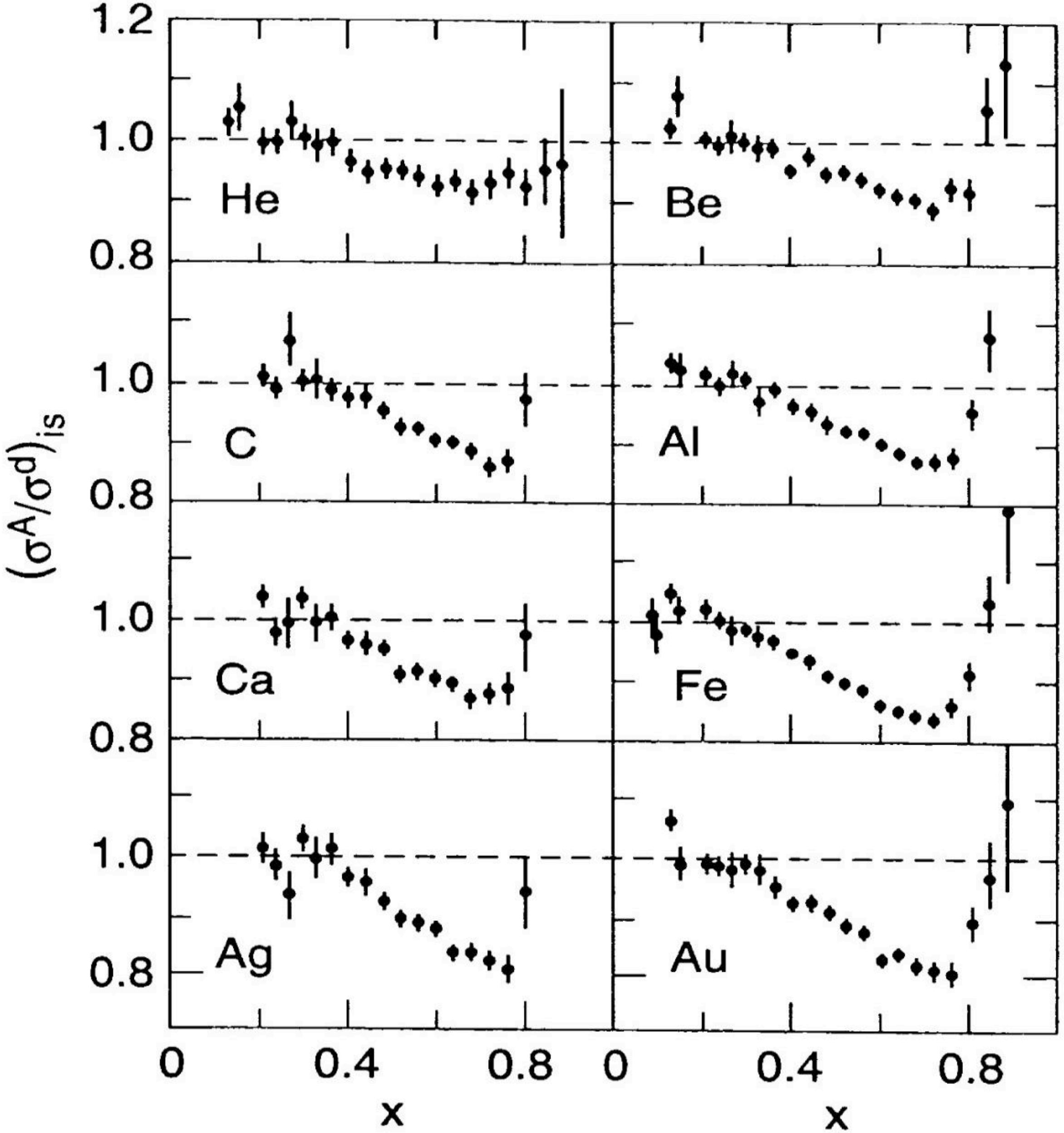
- Nachtmann inequality: $1/4 \leq F_2^n / F_2^p \leq 4$

F_2^n/F_2^n, d/u Ratios and A_1 Limits for $x \rightarrow 1$

	F_2^n/F_2^p	d/u	A_1^n	A_1^p
SU(6)	2/3	1/2	0	5/9
Diquark Model/Feynman	1/4	0	1	1
Quark Model/Isgur	1/4	0	1	1
Perturbative QCD	3/7	1/5	1	1
QCD Counting Rules	3/7	1/5	1	1

A_1: Asymmetry measured with polarized electrons and nucleons. Equal in QPM to probability that the quark spins are aligned with the nucleon spin. Extensive experimental programs at CERN, SLAC, DESY and JLab.

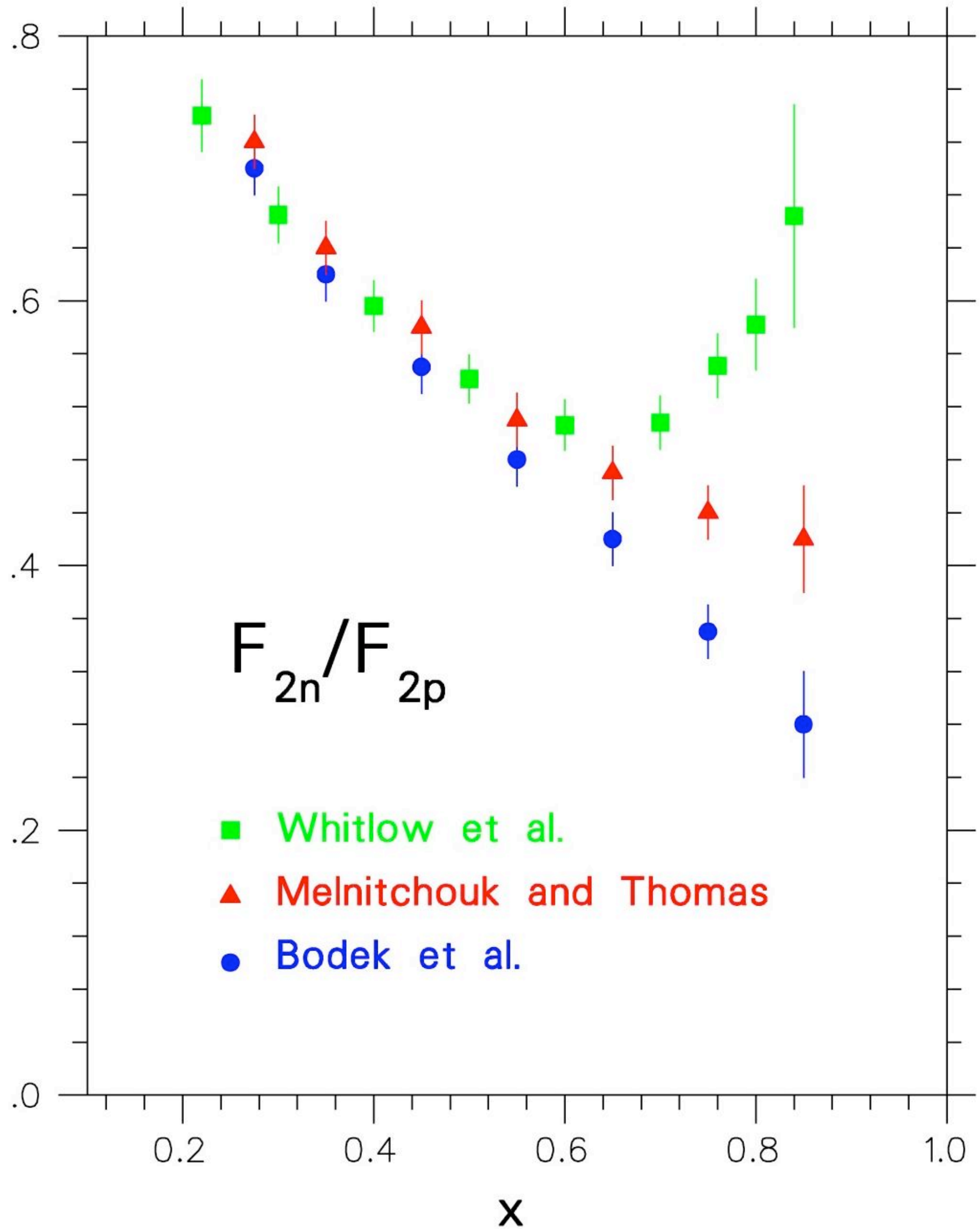
Extensive recent review on the valence/high-x structure of the nucleon: R. J. Holt and C. D. Roberts, Rev. Mod. Phys. 82, 2991 (2010).



A Dependence
EMC Effect

SLAC E139, 1984
J. Gomez et al.

Nucleon momentum probability distributions in nuclei different than those in deuterium. Effect increases with mass number *A*.

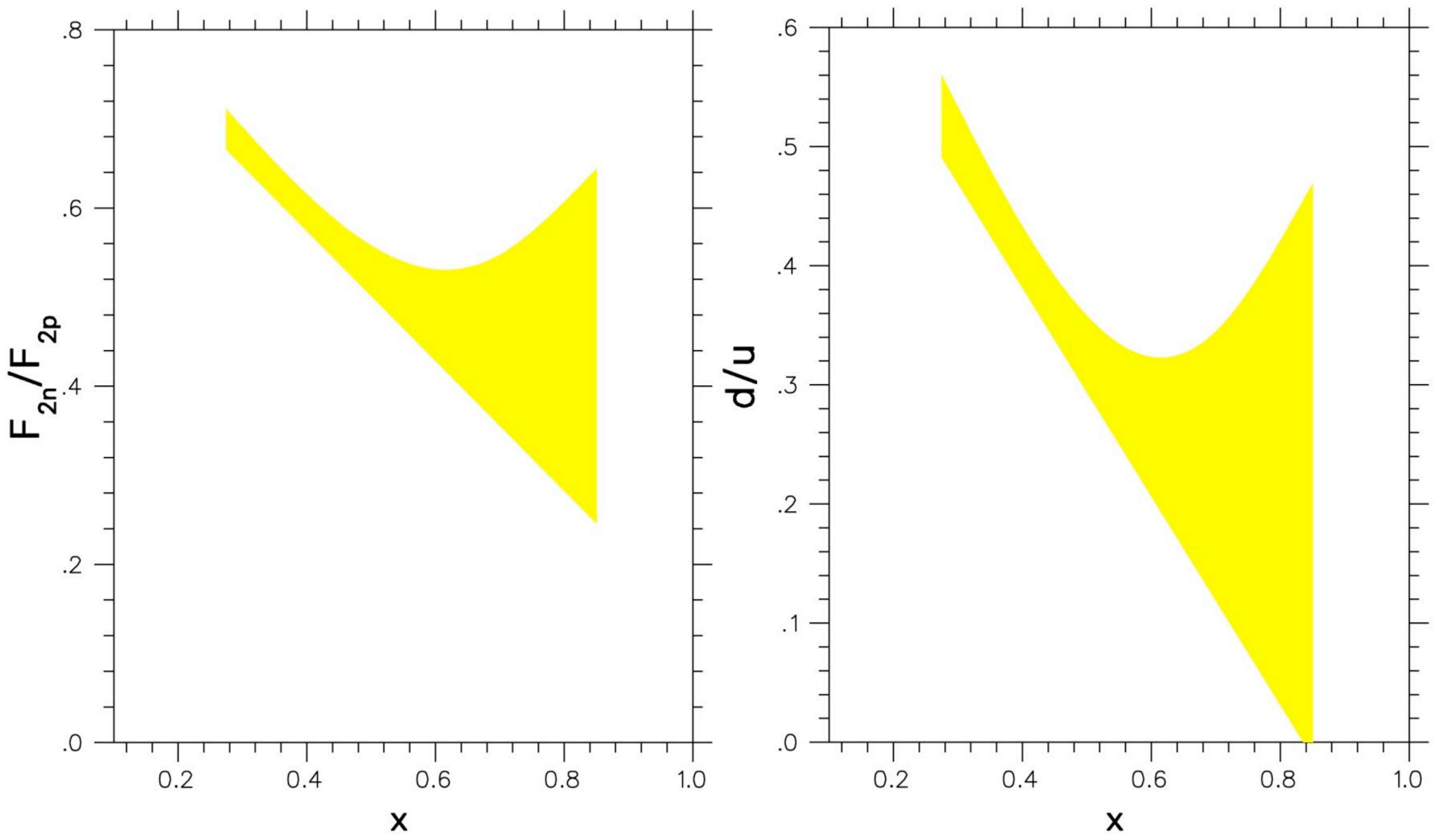


SLAC DIS Data

Whitlow: Density Model

M&T: Convolution Model

Bodek: Fermi-Smearing
Paris N-N potential



The three analysis methods indicate tremendous uncertainties in high-*x* behavior of F_2^n/F_2^p and *d/u* ratios … *d/u* essentially unknown at large *x*!

Nucleon F_2 Ratio Extraction from ^{3}He/^{3}H

- Form the "SuperRatio" of EMC ratios for A=3 mirror nuclei:

$$R(^3He) = \frac{F_2^{^3He}}{2F_2^p + F_2^n} \qquad R(^3H) = \frac{F_2^{^3H}}{F_2^p + 2F_2^n} \qquad R^* = \frac{R(^3He)}{R(^3H)}$$

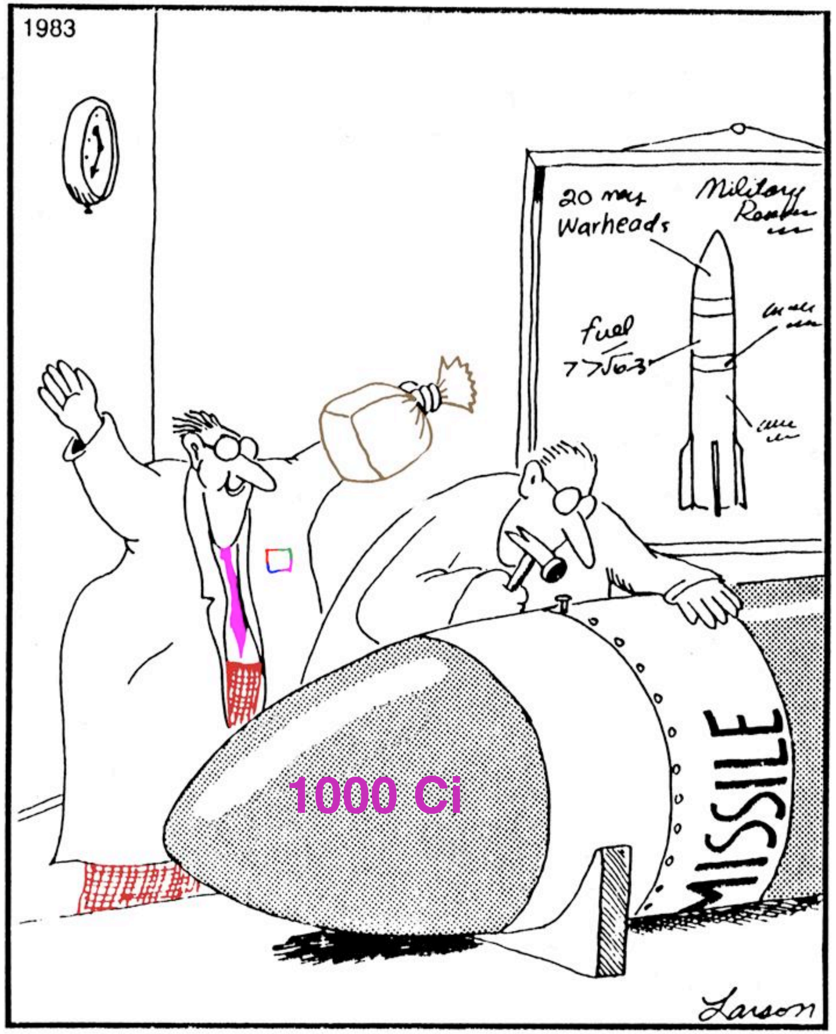
- If $R=\sigma_L/\sigma_T$ is the same for ^{3}He and ^{3}H, measured DIS cross section ratio must be equal to the structure function ratio as calculated from above equations:

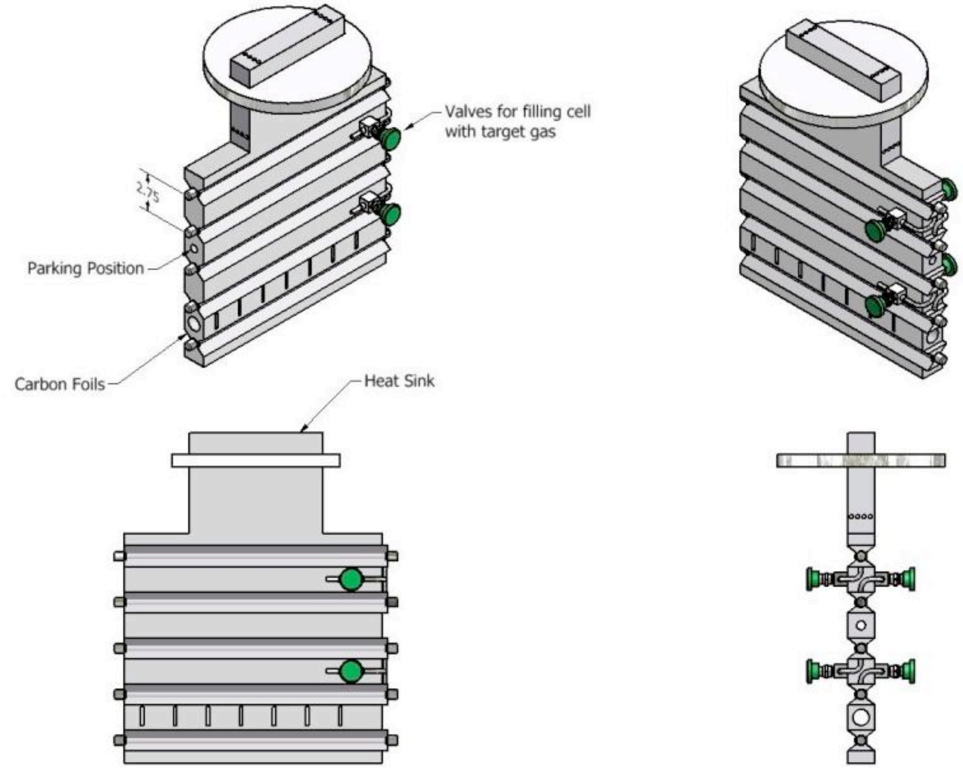
$$\frac{\sigma^{^3He}}{\sigma^{^3H}} = \frac{F_2^{^3He}}{F_2^{^3H}} = R^* \frac{2F_2^p + F_2^n}{F_2^p + 2F_2^n}$$

- Solve for the nucleon F_2 ratio and calculate R^* (expected to be very close to unity) using a theory model:

$$\frac{F_2^n}{F_2^p} = \frac{2R^* - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - R^*}$$

Tritium Target at JLab





Tritium Target Task Force

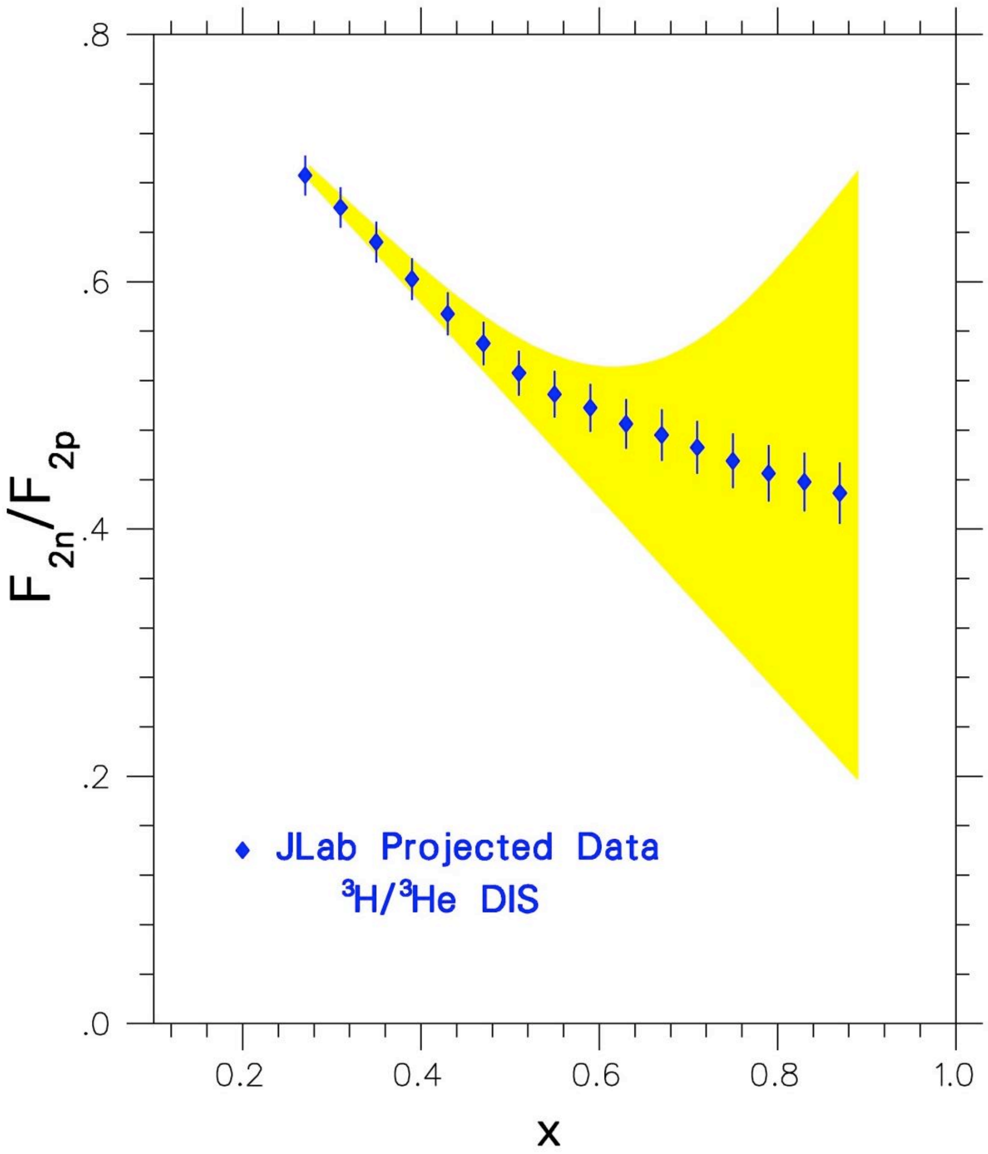
E. J. Beise (U. of Maryland)
B. Brajuskovic (Argonne)
R. J. Holt (Argonne)
W. Korsch (U. of Kentucky)
A. T. Katramatou (Kent State U.)
D. Meekins (JLab)
T. O'Connor (Argonne)
G. G. Petratos (Kent State U.)
R. Ransome (Rutgers U.)
P. Solvignon (JLab)
B. Wojtsekhowski (JLab)

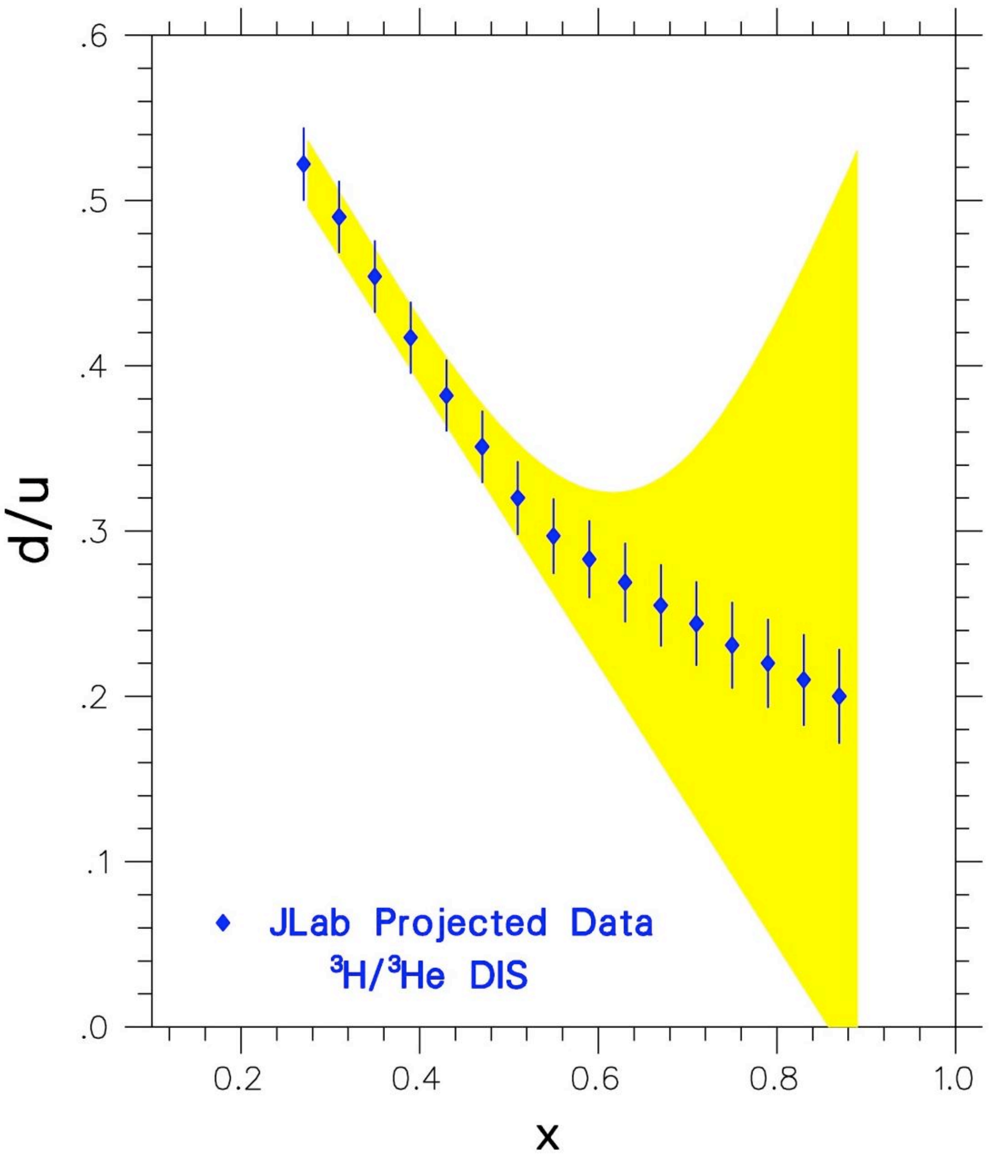
JLab Review: June 3, 2010:

"No direct show stopper"

Details: *Conceptual Design of a ^{3}H Gas Target for JLab*, Tritium Target Task Force, Roy J. Holt *et al.*, May 2010.

Possible Jlab - Hall A Data for F_2^n/F_2^p and d/u Ratios





Constituent Quarks

Spin from the SU(6) Proton Wave Function

The 3 quarks are **identical fermions** ⇒ ψ **antisymmetric** under exchange

$$\psi = \psi(\text{color}) * \psi(\text{space}) * \psi(\text{spin}) * \psi(\text{flavor})$$

❶ **Color**: All hadrons are color singlets = **antisymmetric**

$$\psi(\text{color}) = 1/\sqrt{6}\,(RGB - RBG + BRG - BGR + GBR - GRB)$$

❷ **Space**: proton has $l = l' = 0 \rightarrow \psi(\text{space})$ = **symmetric**

❸ **Spin**: $2 \otimes 2 \otimes 2 = (\,3_S \oplus 1_A\,) \otimes 2 = 4_S \oplus 2_{MS} \oplus 2_{MA}$

- 4_S symmetric states have spin 3/2, e.g. $\left|\frac{3}{2},+\frac{3}{2}\right\rangle \uparrow$
- 2_{MS} and 2_{MA} have spin 1/2 and **mixed symmetry**: S or A under exchange of *first 2* quarks only, e.g.

$$\left|\frac{1}{2},+\frac{1}{2}\right\rangle_{MS} = (\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow - 2\uparrow\uparrow\downarrow)/\sqrt{6} \qquad \left|\frac{1}{2},+\frac{1}{2}\right\rangle_{MA} = (\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)/\sqrt{2}$$

❹ Flavor: symmetry groups SU(2)-spin and SU(3)-color are exact ...

- strong force is ***flavor blind***
- constituent q masses ***similar***: $m_u, m_d \approx$ 350 MeV, $m_s \approx$ 500 MeV

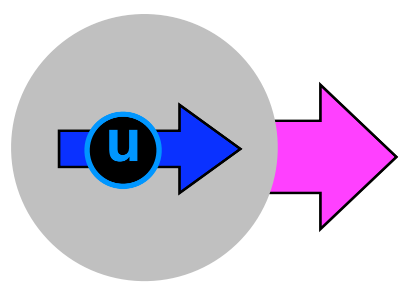
➡ SU(3)-flavor is ***approximate*** for u, d, s

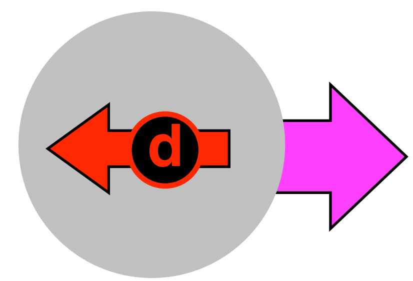
SU(3)-flavor gives $3 \otimes 3 \otimes 3 = 10_S \oplus 8_{MS} \oplus 8_{MA} \oplus 1_A$

➤ **Proton**: $\psi(s=1/2)$ from spin $2_{MS}, 2_{MA}$ $\otimes$ $\psi(uud)$ from flavor $8_{MS}, 8_{MA}$

$$|p^\uparrow\rangle = (u^\uparrow u^\downarrow d^\uparrow + u^\downarrow u^\uparrow d^\uparrow - 2u^\uparrow u^\uparrow d^\downarrow + \text{ 2 permutations})/\sqrt{18}$$

➤ Count the number of quarks with spin up and spin down:





➤ Quark contributions to proton spin are:

$$\Delta u = N(u^\uparrow) - N(u^\downarrow) = +\frac{4}{3}$$

$$\frac{10\uparrow}{6} - \frac{2\downarrow}{6}$$

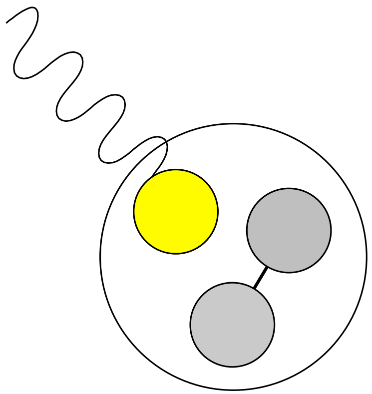
$$\Delta d = N(d^\uparrow) - N(d^\downarrow) = -\frac{1}{3}$$

$$\frac{2\uparrow}{6} - \frac{4\downarrow}{6}$$

$\Rightarrow \Delta\Sigma = \Delta u + \Delta d + \Delta s = 1$ ***All spin present & accounted for!***

easy to see: ν *of struck quark* → *energy of* Λ

① Quark-Diquark Model



spectator diquark D in scalar or vector state

$$\psi_D(x,k_\perp) \sim \exp -[\frac{1}{8\beta_D^2}(\frac{m_q^2+k_\perp^2}{x}+\frac{m_D^2+k_\perp^2}{1-x})]$$

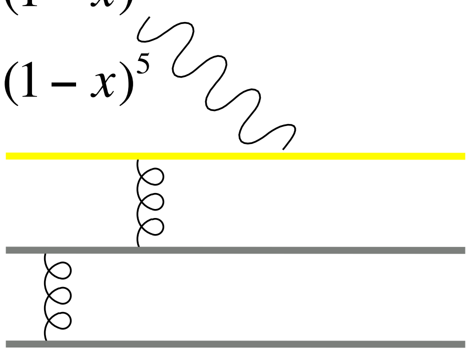
... as $x \to 1$, VECTOR diq config$^{\underline{n}}$ suppressed

→
$$\frac{d}{u} \to 0 \qquad \frac{F_2^n}{F_2^p} \to \frac{1}{4}$$
$$\frac{\Delta u}{u} \to 1 \qquad \frac{\Delta d}{d} \to -\frac{1}{3}$$

② pQCD Model

$q^{\uparrow}(x) \sim (1-x)^3$

$q^{\downarrow}(x) \sim (1-x)^5$



$x \to 1$ wavefn obtained from "normal" wavefn by exchange of large invariant mass gluons from spectator q's ... propagators $\sim \frac{1}{p^2}$ small
$\to$ small couplings, perturbative methods possible

→
$$\frac{d}{u} \to \frac{1}{5} \text{ thus } \frac{F_2^n}{F_2^p} \to \frac{3}{7}, \ \frac{\Delta q}{q} \to 1 \text{ for } u \text{ and } d$$

For Λ: Both models predict $\frac{\Delta q^\Lambda}{q^\Lambda} \to 1$ for all flavours!

Me**A**surement of the F_2^n/F_2^p, d/u **RA**tios and A=3 EMC Effect in Deep Inelastic Electron Scattering Off the **T**ritium and **H**elium Mirr**O**r **N**uclei.

Jefferson Lab PAC37 Proposal, December 2010

The JLab **MARATHON** Collaboration

J. Arrington, D. F. Geesaman, K. Hafidi, R. J. Holt, D. Potterveld, P. Reimer, J. Rubin, J. Singh, X. Zhan
Argonne National Laboratory, Argonne, Illinois, USA

K. A. Aniol, D. J. Margaziotis, M. B. Epstein
California State University, Los Angeles, California, USA

G. Fanourakis
Demokritos National Center for Scientific Research, Athens, Greece

J. Annand, D. Ireland, R. Kaiser, G. Rosner
University of Glasgow, Scotland, UK

E. Cisbani, F. Cussano, S. Frullani, F. Garibaldi, M. Iodice, L. Lagamba, R. De Leo, E. Pace, G. Salmè, G. M. Urciuoli
Istituto Nazionale di Fisica Nucleare, Rome and Bari, Italy

J.-P. Chen, E. Chudakov, J. Gomez, J.-O. Hansen, D. W. Higinbotham, C. W. de Jager, J. LeRose, D. Meekins, W. Melnitchouk, R. Michaels, S. K. Nanda, B. Sawatsky, P. Solvignon, A. Saha, B. Wojtsekhowski
Jefferson Lab, Newport News, Virginia, USA

B. D. Anderson, A. T. Katramatou, D. M. Manley, S. Margetis, G. G. Petratos, W.-M. Zhang
Kent State University, Kent, Ohio, USA

W. Korsch
University of Kentucky, Lexington, Kentucky, USA

X. Jiang, A. Puckett
Los Alamos National Laboratory, Los Alamos, New Mexico, USA

E. Beise
University of Maryland, College Park, Maryland, USA

J. R. Calarco, K. Slifer
University of New Hampshire, Durham, New Hampshire, USA

C. Ciofi degli Atti, S. Scopetta
University of Perugia, Perugia, Italy

R. Gilman, R. D. Ransome
Rutgers, The State University of New Jersey, New Brunswick, New Jersey, USA

M. N. Olson
St. Norbert College, De Pere, Wisconsin, USA

N. Sparveris
Temple University, Philadelphia, Pennsylvania, USA

D. Day, S. Liuti, O. Rondon
University of Virginia, Charlottesville, Virginia, USA

Spokesperson: G. G. Petratos (gpetrato@kent.edu)
Co-spokespersons: J. Gomez, R. J. Holt and R. D. Ransome

PAC30: Physics goals of experiment: "Highlights of 12 GeV Program"

Conditional approval based on on "review of safety aspects of ^3H target"

PAC36: Physics again very highly rated. Conditional approval based on detailed SBS detector design

^3H target conditional approval removed

MARATHON & BONUS

Possible Jlab - Hall A Data for F_2^n/F_2^p and *d/u* Ratios