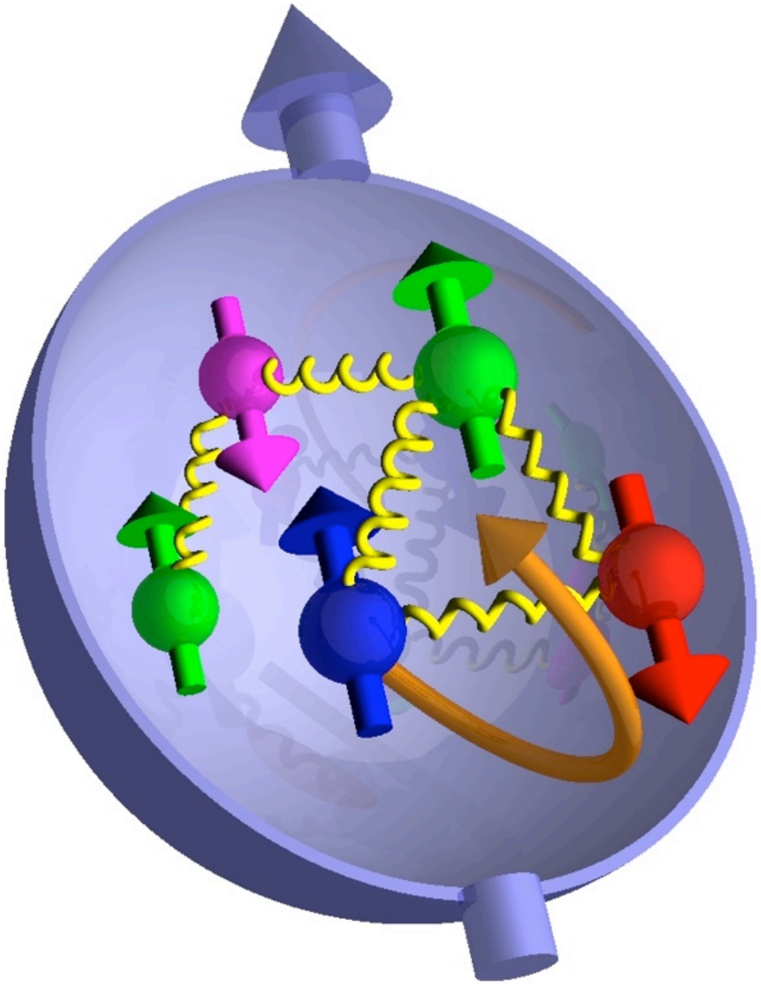
An Experimental(ist's) Overview of TMDs

N.C.R. Makins
University of Illinois at Urbana-Champaign

- **L + QCD = World's Greatest Puzzle!**
  intuition out the window
- **The State of the Data**
  data from COMPASS, HERMES, JLab, and RHIC
- **The State of L**
  parton orbital angular momentum
- **The Missing Spin Programme**
  Drell-Yan + spin



L + Relativity ≈ Weirdness

Boosting a Dirac Spinor

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

at rest $\vec{p} = 0$

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

BOOST
in **–x direc**ⁿ with

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

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

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What's its spin?

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

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

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Boosting a Dirac Spinor

How is L_z affected by boosts?

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

Why there are no transversely polarized electron machines!

Boosting L

$$M^{\mu\nu} = x^\mu p^\nu - x^\nu p^\mu = \begin{pmatrix} 0 & tp_x - xE & tp_y - yE & tp_z - zE \\ \cdot & 0 & L_z & -L_y \\ \cdot & \cdot & 0 & L_x \\ \cdot & \cdot & \cdot & 0 \end{pmatrix}$$

Simple orbit with L_z only: p_z=0, z=0 → L_x=L_y=0 ....
and apply boost β in –x direction

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$$\rightarrow \quad L'_z = \gamma L_z - \gamma\beta p_y (ct) + \gamma\beta y (E/c)$$

$$\approx \gamma\left[L_z - (v_{boost} t)(m\omega R\cos\omega t) + mvR\sin\omega t\right]$$

$$\vec{r}_{CM}(t) \times \vec{p}$$

time-averages to zero

N.C.R. Makins, IWHSS'12, Lisboa, Apr 16-18, 2012

Spin, L, and the free Dirac Hamiltonian

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

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L <u>position-dependent</u>, doesn't commute w ∂_i in **H**

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L **NOT CONSERVED**

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SPIN NOT CONSERVED

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no shells!

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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:

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

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:

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

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:

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

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

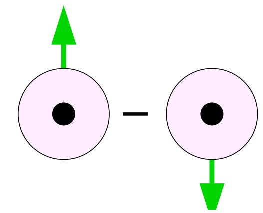
Here, $\xi(\pm 1/2)$ stand for the eigenfunctions for the spin-operator $\hat{\sigma}_z$ with eigenvalues ± 1, and $Y_{ll_z}(\theta,\phi)$ for the spherical harmonics which form a standard basis for the orbital angular momentum operators $(\hat{\mathbf{l}}^2, \hat{l}_z)$. The function $f_{\varepsilon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

The Wacky World of Hyperon Polarization

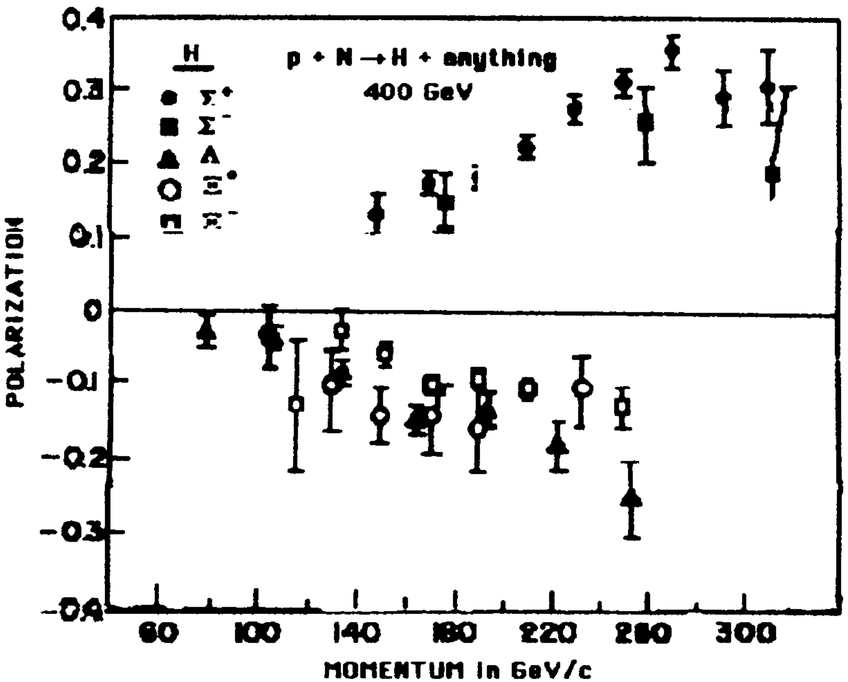
Unpolarized beams on unpolarized targets produce hyperons which are strongly polarized!

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

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



$pN \rightarrow Y^{\uparrow} X$ **data**



Hyperon spin structure in CQM:

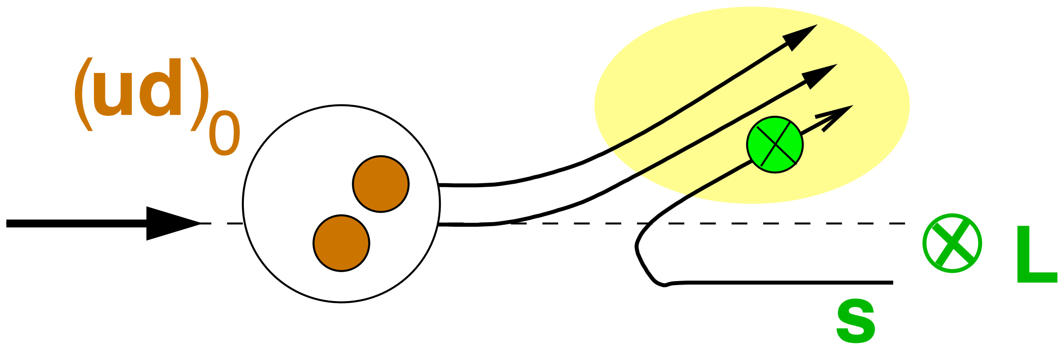
p	$\Delta u = +4/3,\ \Delta d = -1/3,$	$\Delta s = 0$
Λ	$\Delta s = +1,\quad \Delta u = \Delta d = 0$	
$\Sigma^{\pm}$	$\Delta s = -1/3,\ \Delta u, d = +4/3$	
$\Xi^{\pm}$	$\Delta s = +4/3,\ \Delta u, d = -1/3$	

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

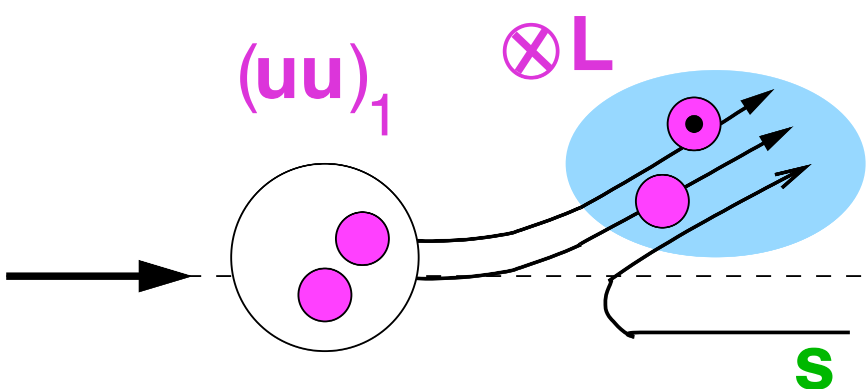
Thomas Precession & the DGM Model

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

<u>Λ: $\Delta s = +1$</u> P_Λ from accelerated sea s quark



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



DGM model did pretty well

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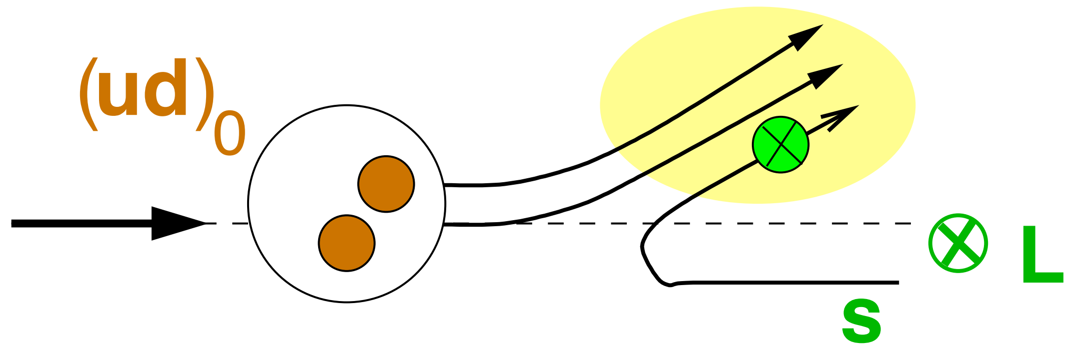

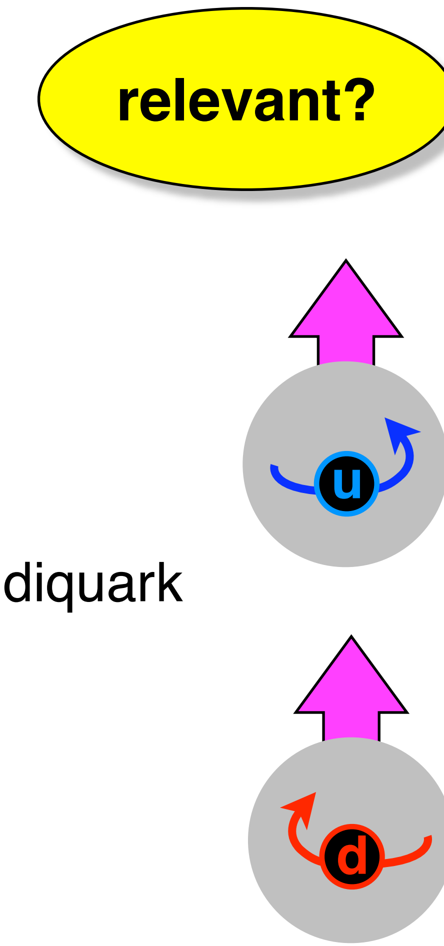

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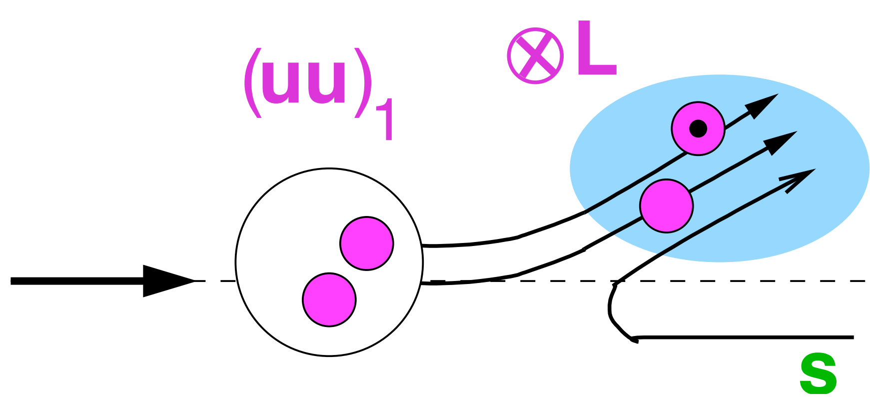

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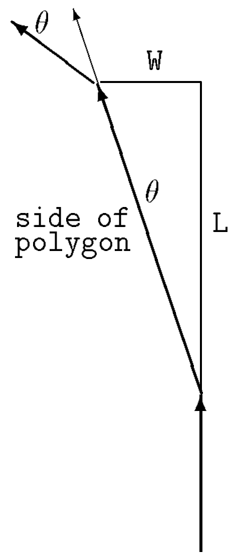
3 A Simple Derivation of the Thomas Precession

G.F. Smoot lecture notes

The follwoing derivation is based upon a suggestion by E.M. Purcell.

Imagine an aricraft flying in a large circular orbit. Approximate the orbit by a polygon of N sides, with N a very large number. As the aircraft traverses each of the N sides, it changes its angle of flight by the angle $\theta = 2\pi/N$ as shown in the figure.



After the aircraft has flown N segments, it is back at its starting point. IN the laboratory frame, the aircraft has rotated through an angle of 2π radians. However in the aircraft's instantaneous rest frame, the triangles shown have a Lorentz-contraction along the direction it is flying but not transversely. Thus at the end of each segment, in the aircraft frame, the aircraft turns by a larger angle than the laboratory $\theta = 2\pi/N$, but by an angle $\theta' = \gamma\theta = W/(L/\gamma) = 2\pi\gamma/N$. After all N segements in the aircraft instanteous rest frame the total angle of rotation is $2\pi\gamma$.

The difference in the reference frame is

$$\Delta\theta = 2\pi(\gamma - 1)$$

Since N has dropped out of the formula for the angle and angle difference, one can let it go to infinity and the motion is circular and the formula is for the rate of precession.

$$\frac{\omega_P}{\omega} = \frac{\Delta\theta/T}{2\pi/T} = \gamma - 1$$

This equation, dispite the simplicity of the derivation, is the exact expression for the Thomas precession . The equation does not include the oscillationg term because the derivation neglected the fact that the front and rear of the inertial bars are not accelerated simultaneously.

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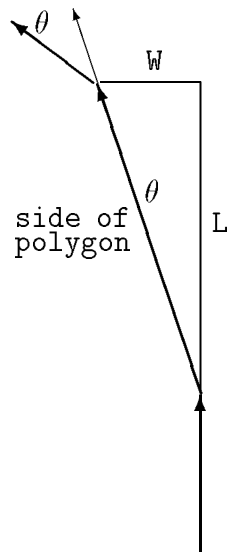

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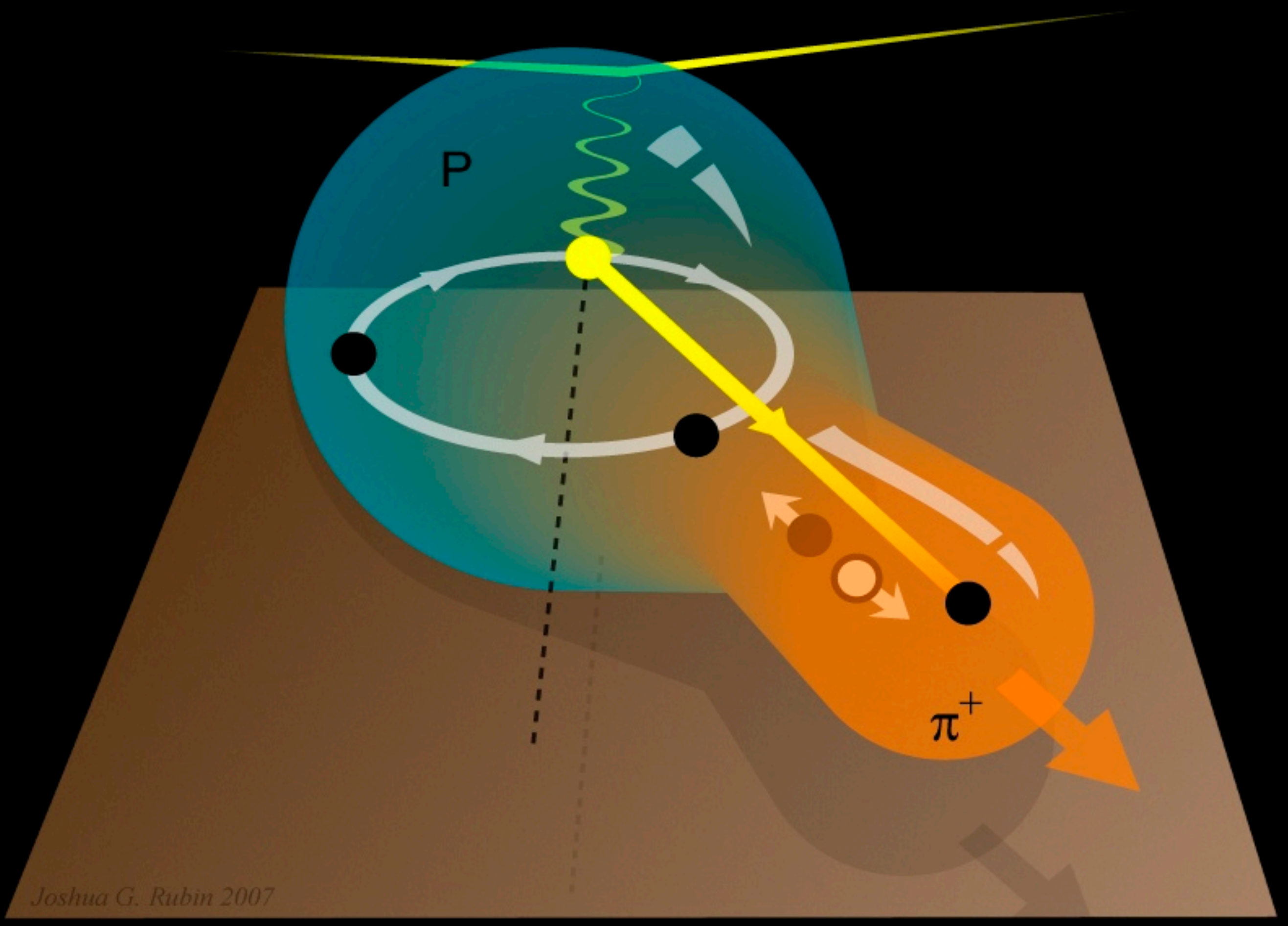
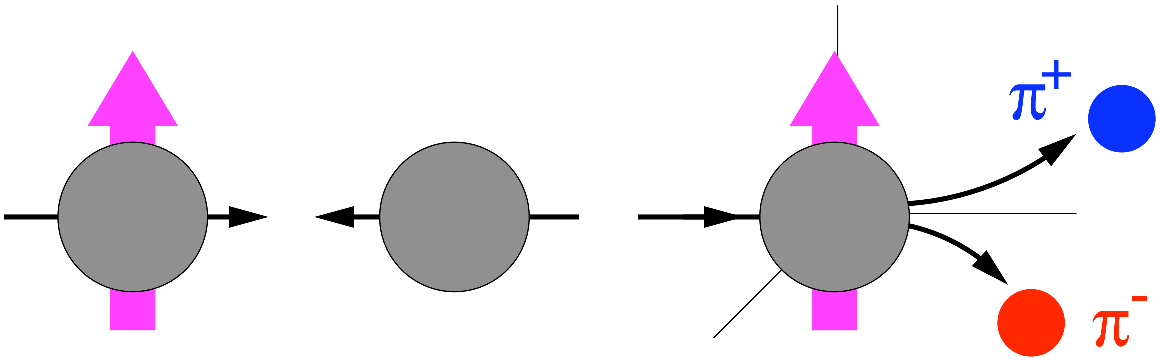
TMDs and Single Spin Asymmetries



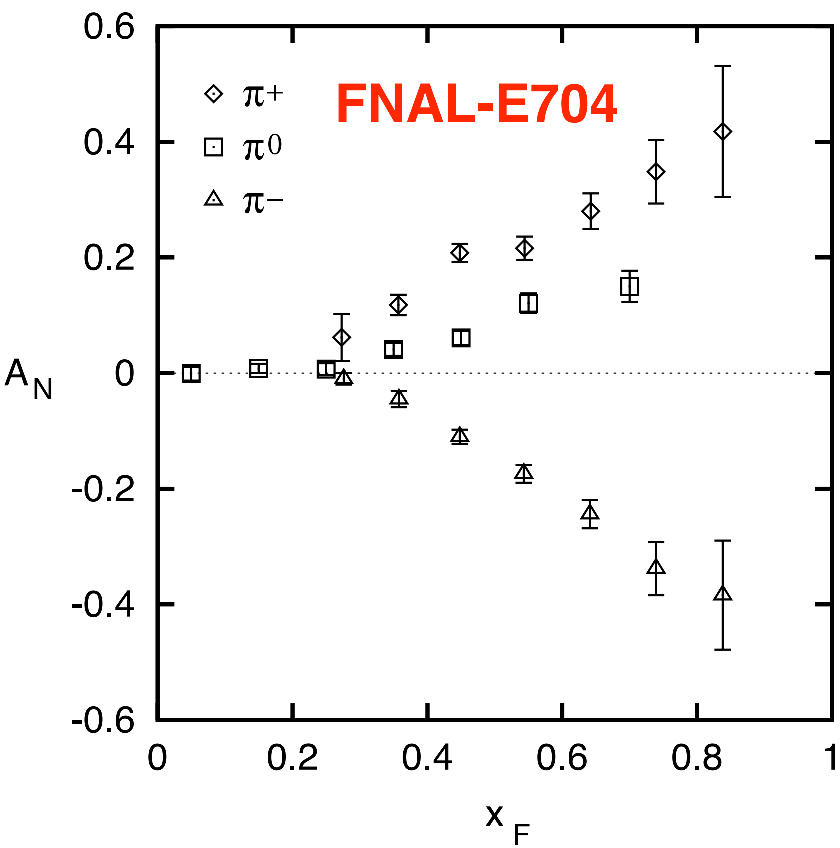
Single-spin asymmetries in $p^{\uparrow}p \rightarrow \pi X$

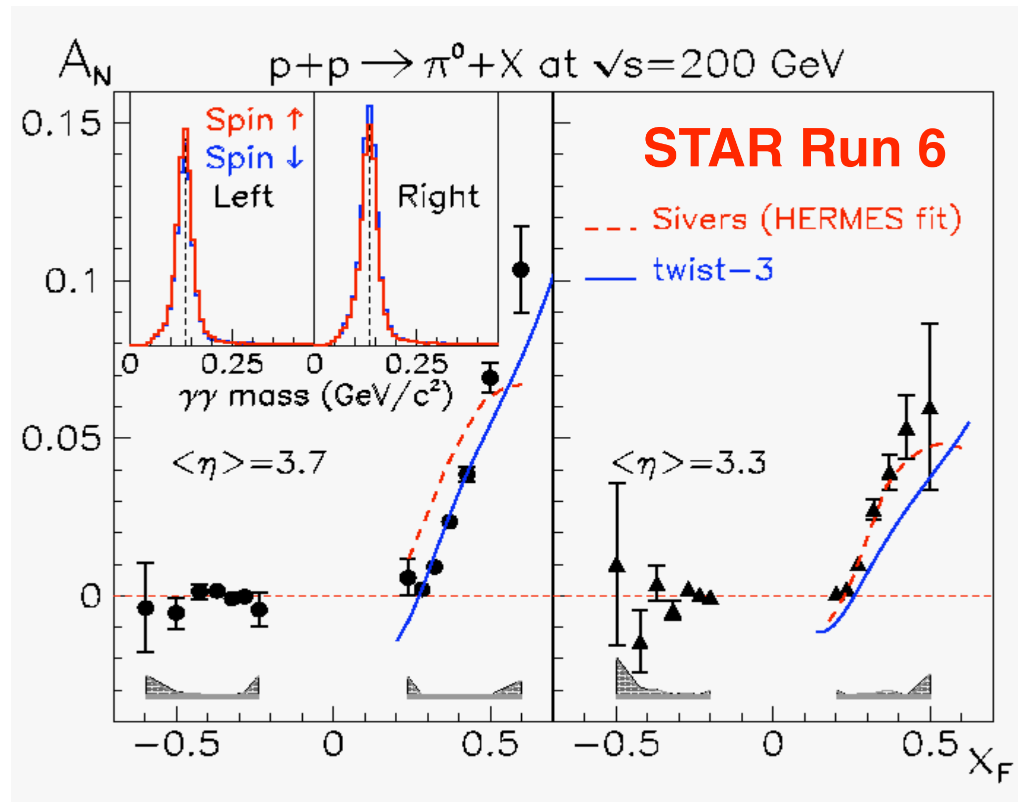


Analyzing Power

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

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***

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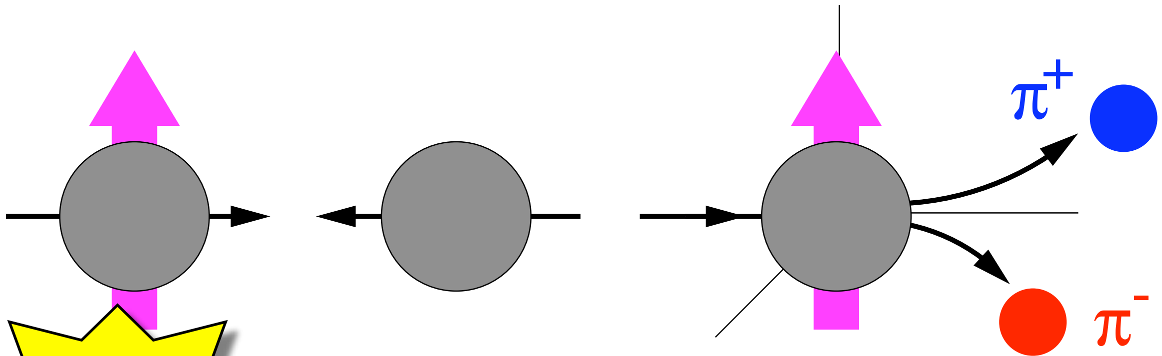

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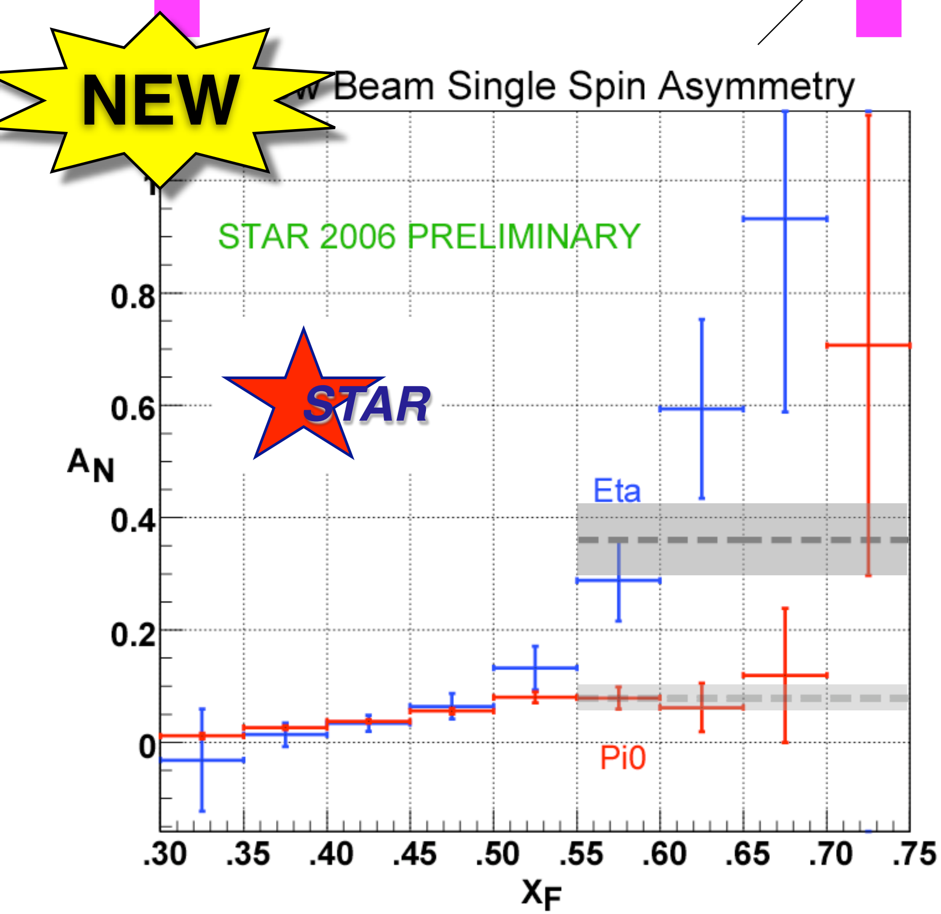

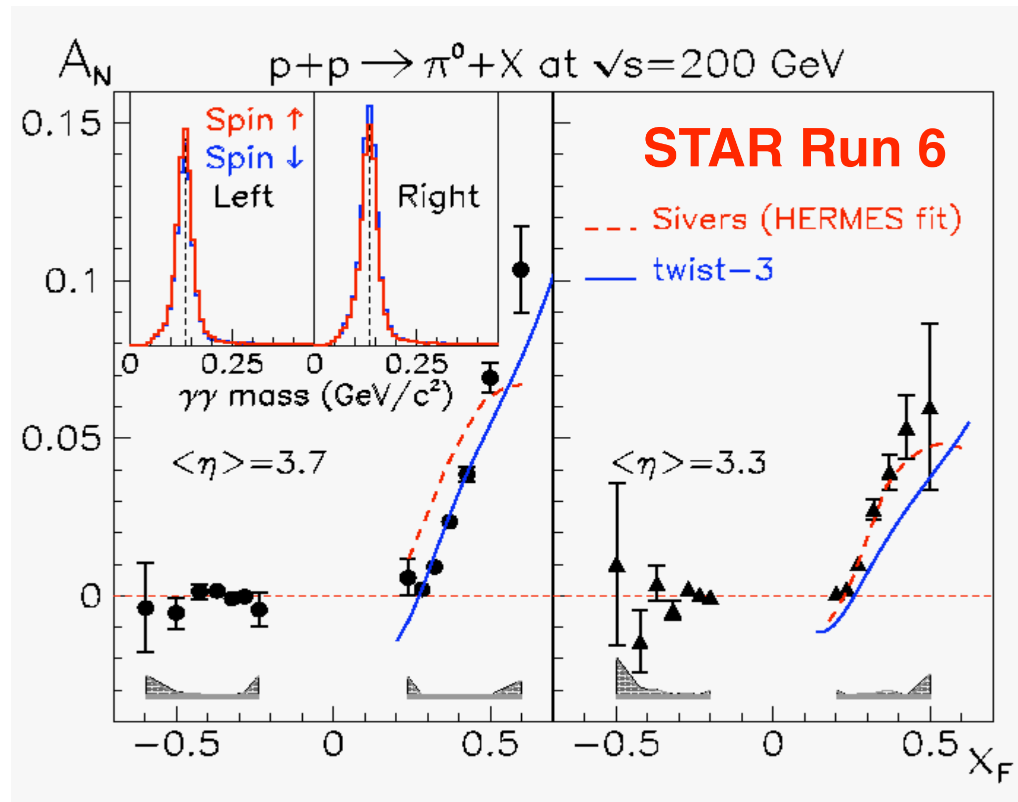

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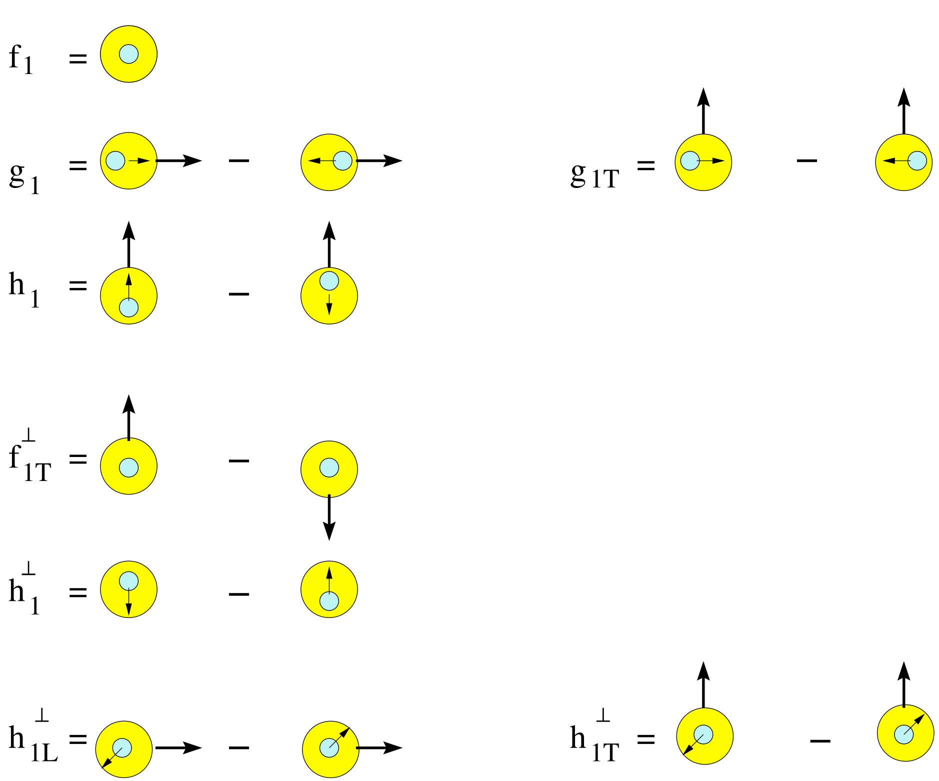
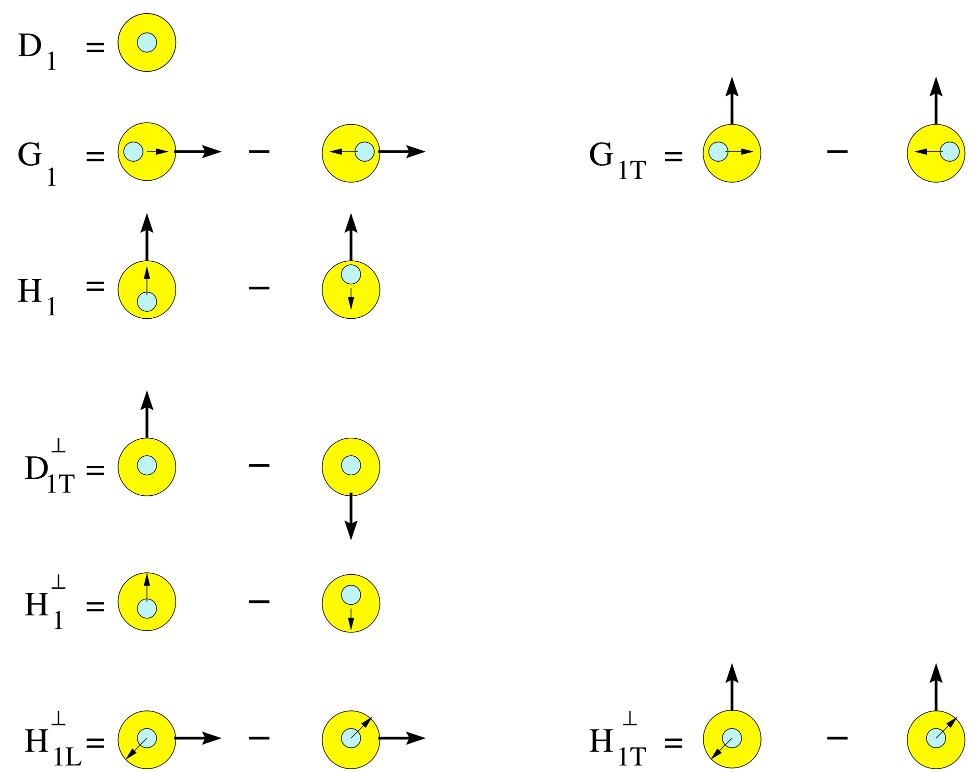
Mulders & Tangerman, NPB 461 (1996) 197

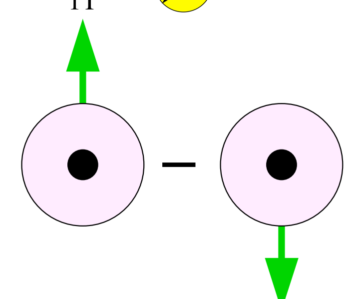
Distribution Functions



Fragmentation Functions



e.g.

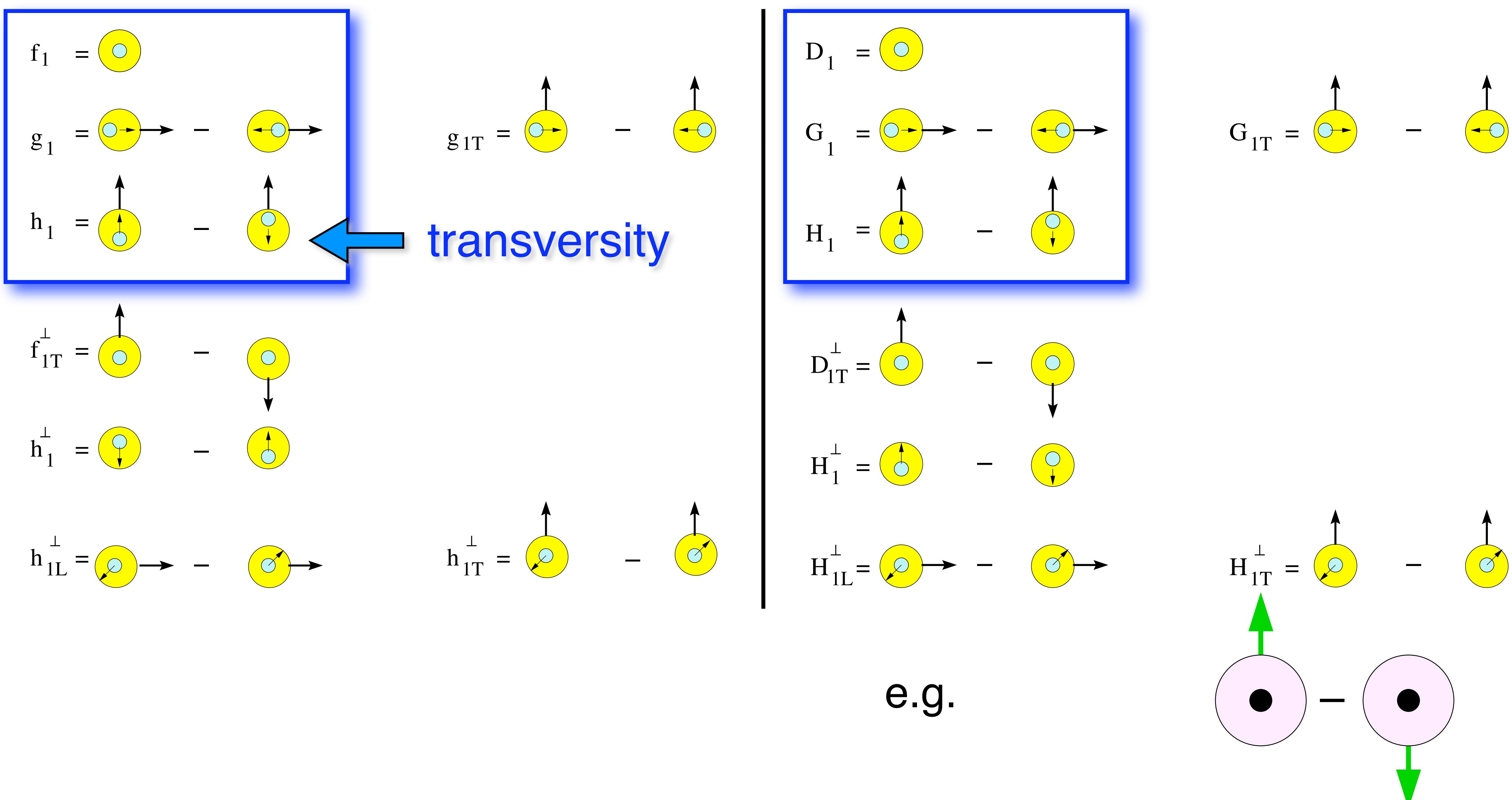


PDFs ***surviving*** on ***integration*** over ***Transverse Momentum***

Mulders & Tangerman, NPB 461 (1996) 197

Distribution Functions

Fragmentation Functions



PDFs ***surviving*** on ***integration*** over ***Transverse Momentum***

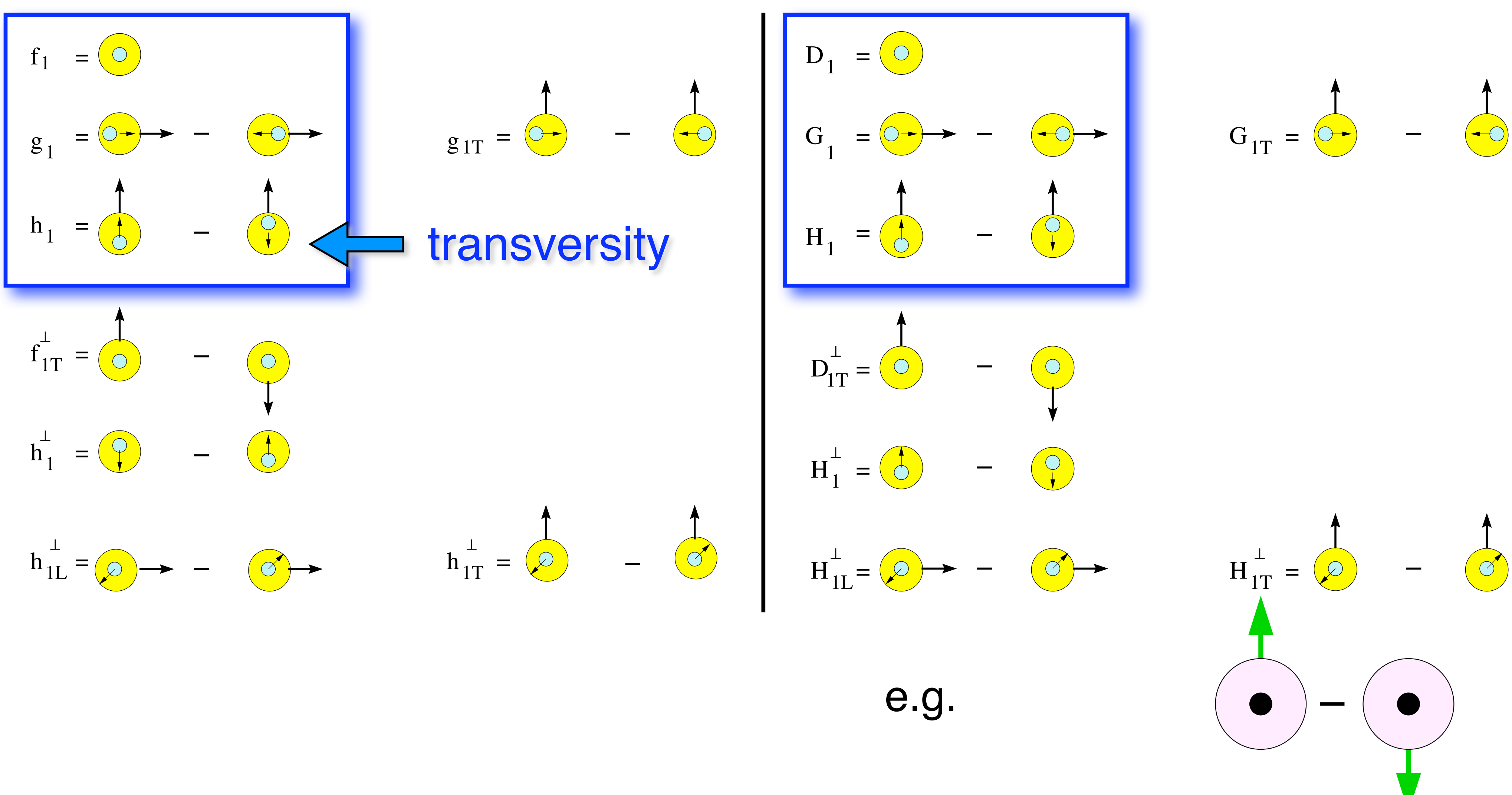
The others are sensitive to ***intrinsic*** $\boldsymbol{k_T}$ in the nucleon & in the fragmentation process

→ ***TMD = transv-momentum dependent*** *func*

Mulders & Tangerman, NPB 461 (1996) 197

Distribution Functions

Fragmentation Functions



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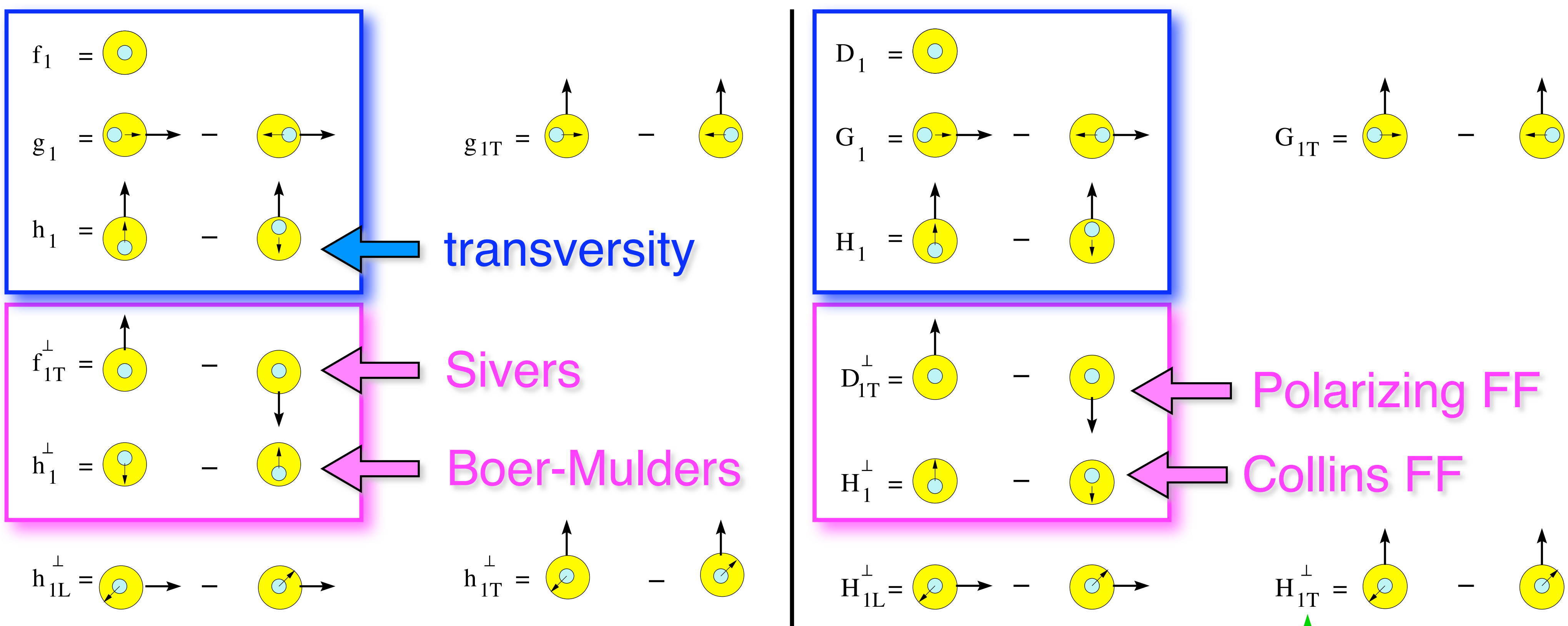
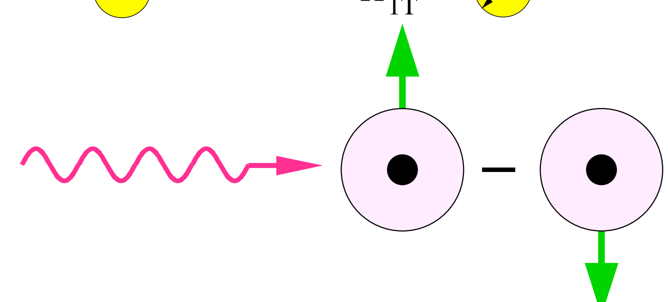
Mulders & Tangerman, NPB 461 (1996) 197

Distribution Functions | Fragmentation Functions



One ***T-odd function*** required to produce ***SSA = single-spin asymmetries*** in hard-scattering → related to parton ***L (OAM)***

e.g.



PDFs ***surviving*** on ***integration*** over ***Transverse Momentum***

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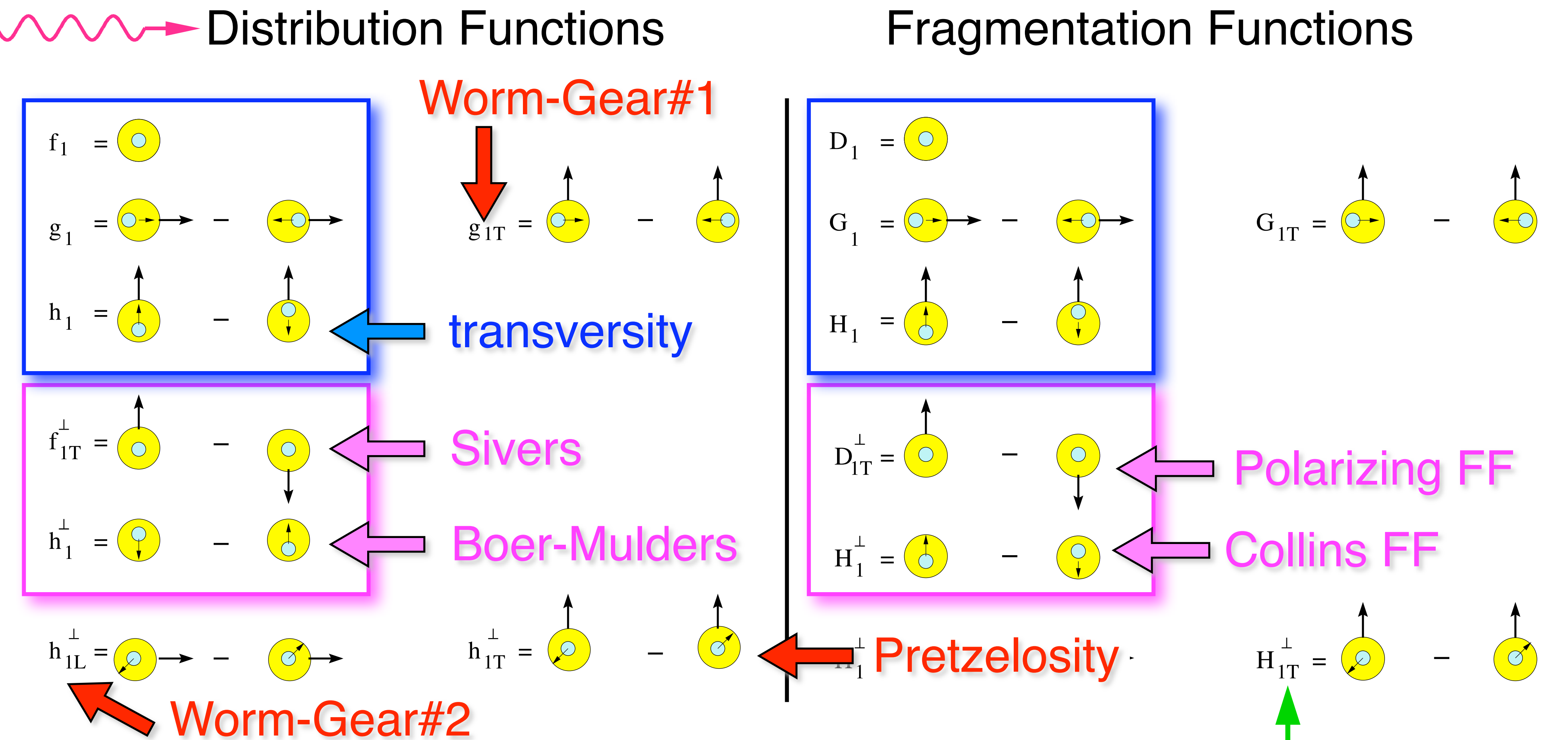
Mulders & Tangerman, NPB 461 (1996) 197



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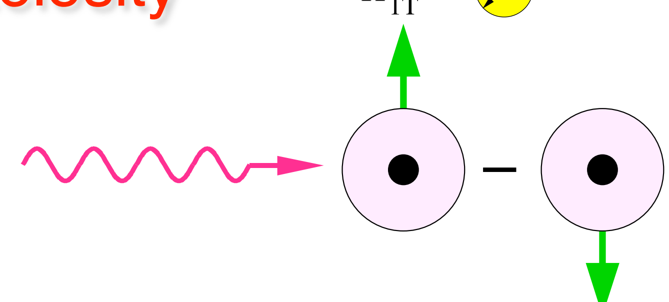
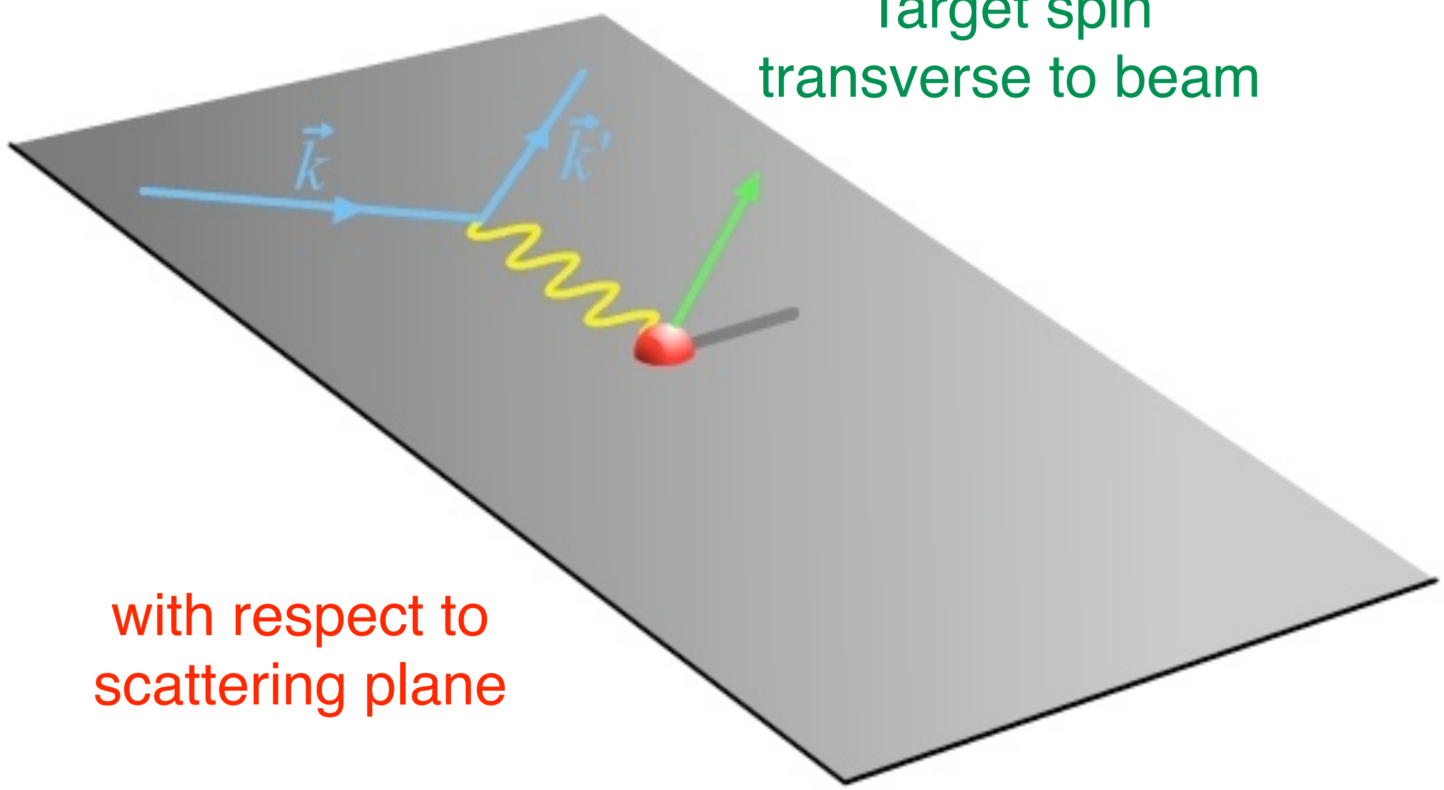


Electro-Production of Hadrons with Tranvserse Target

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

Electron beam defines scattering plane

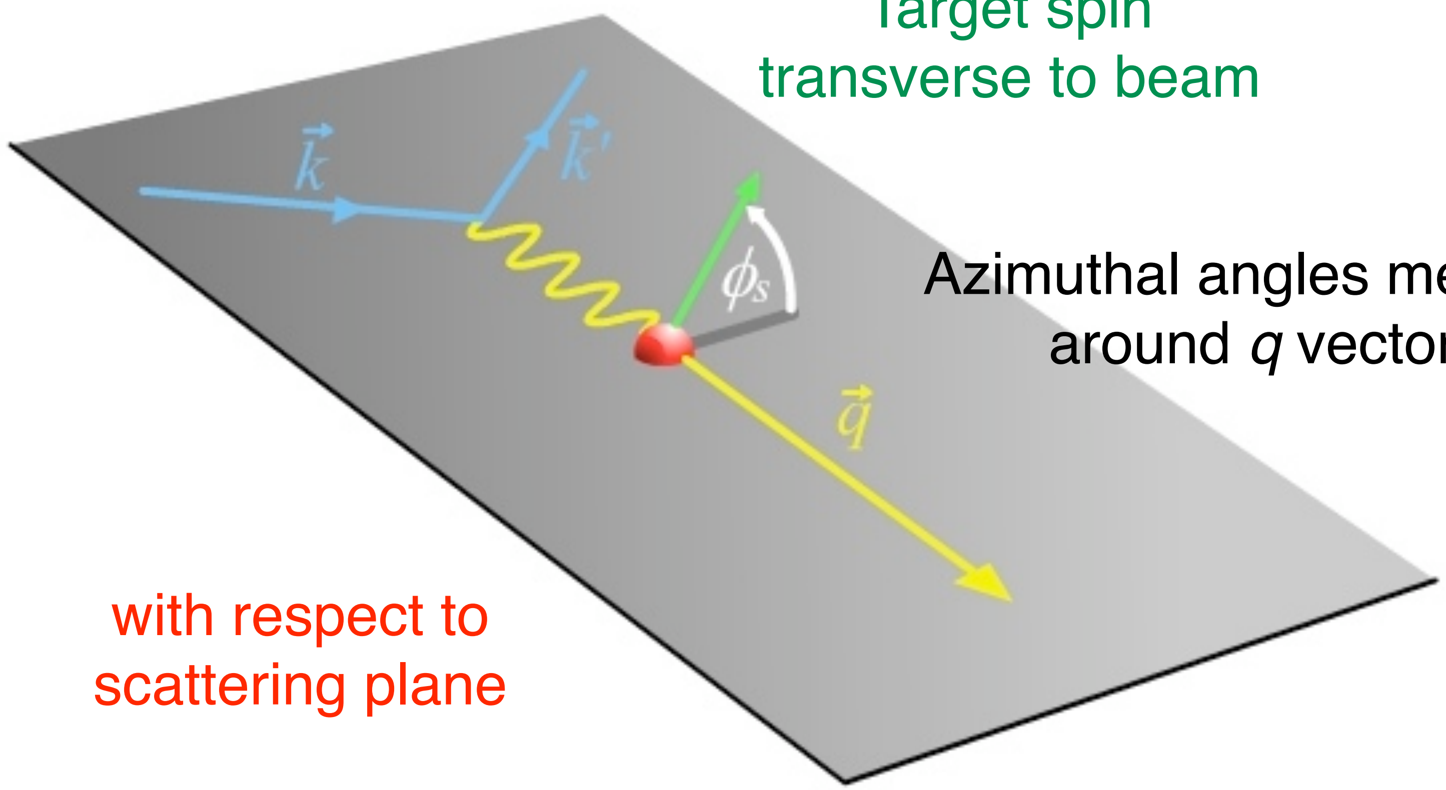
Target spin transverse to beam



with respect to scattering plane

Electro-Production of Hadrons with Tranvserse Target

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



ϕ_S **= target spin orientation**

Electro-Production of Hadrons with Tranvserse Target

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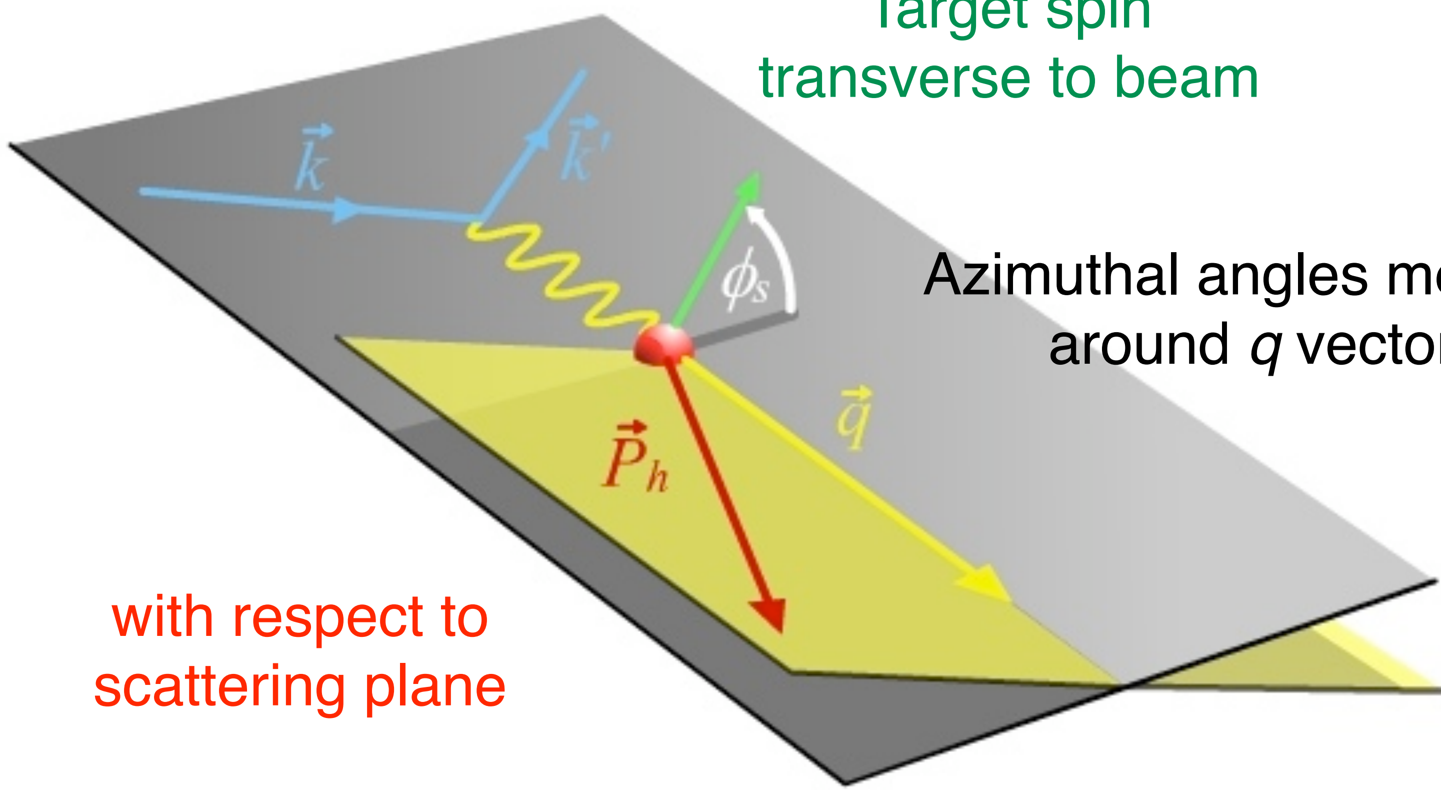


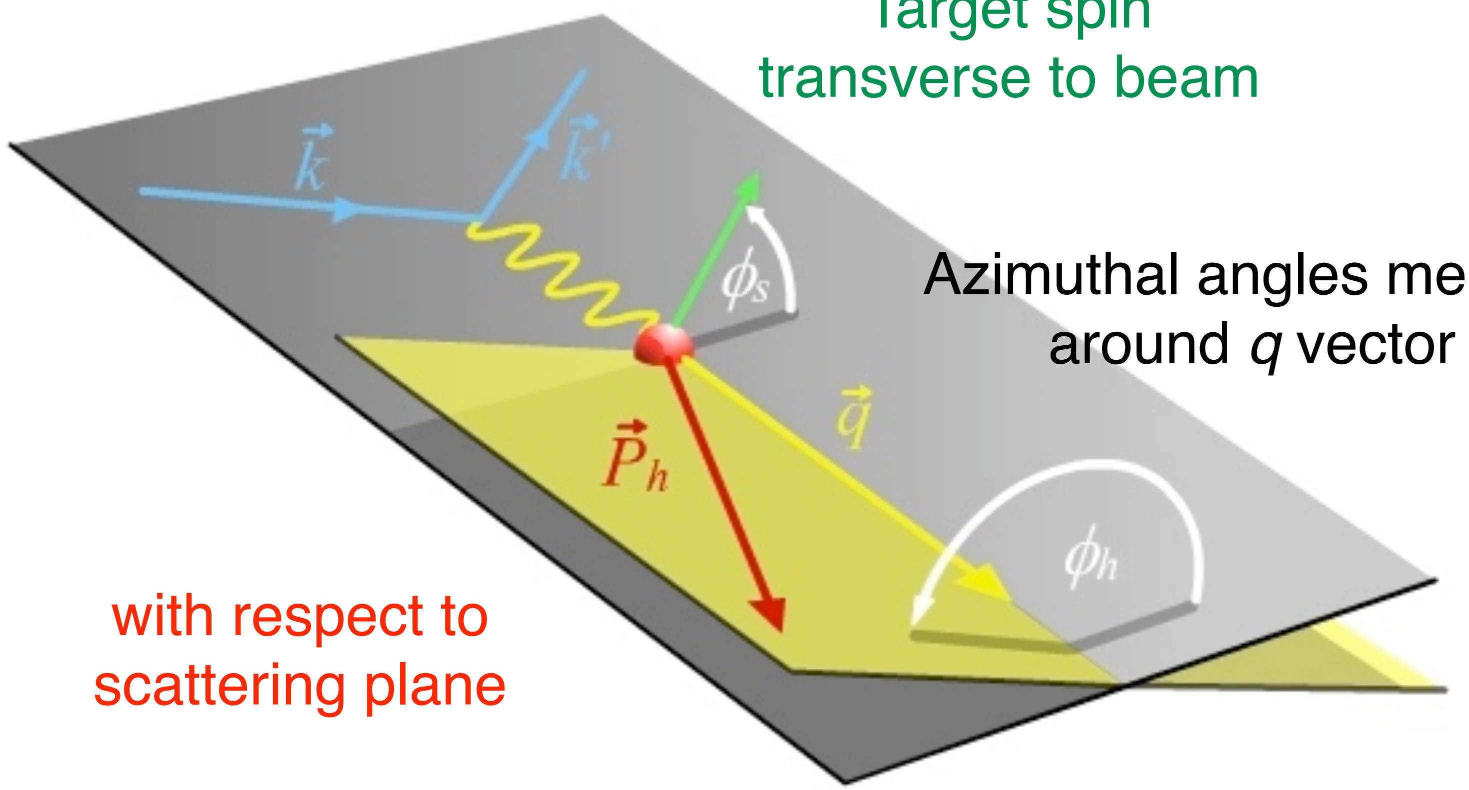
Azimuthal angles measured around *q* vector ...

with respect to scattering plane

ϕ_S **= target spin orientation**

Electro-Production of Hadrons with Tranvserse Target

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



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

Measuring: Azimuthal Asymmetries

beam pol$^{\underline{n}}$ target pol$^{\underline{n}}$

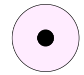
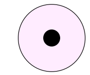
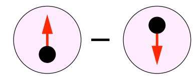
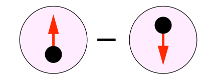
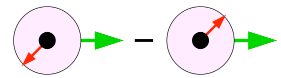
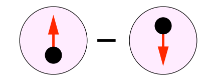
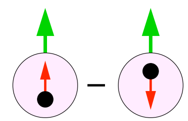
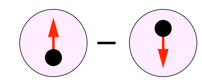
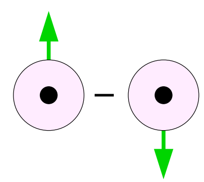
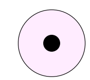
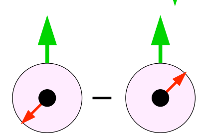
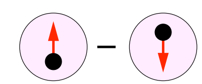
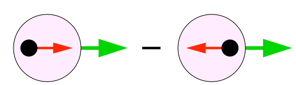
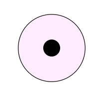
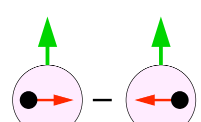
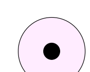
SIDIS, at leading twist

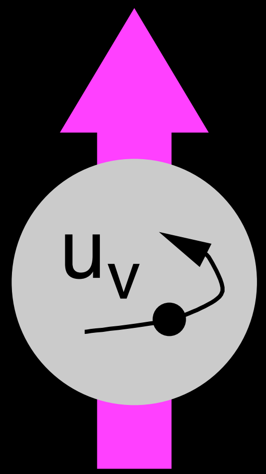
UU	1	$\otimes\, f_1 =$	$\otimes\, D_1 =$
	$\cos(2\phi_h^l)$	$\otimes\, h_1^\perp =$	$\otimes\, H_1^\perp =$
UL	$\sin(2\phi_h^l)$	$\otimes\, h_{1L}^\perp =$	$\otimes\, H_1^\perp =$
UT	$\sin(\phi_h^l + \phi_S^l)$	$\otimes\, h_1 =$	$\otimes\, H_1^\perp =$
	$\sin(\phi_h^l - \phi_S^l)$	$\otimes\, f_{1T}^\perp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

Measuring: Azimuthal Asymmetries

beam pol<u>n</u> **target pol<u>n</u>**

SIDIS, at leading twist

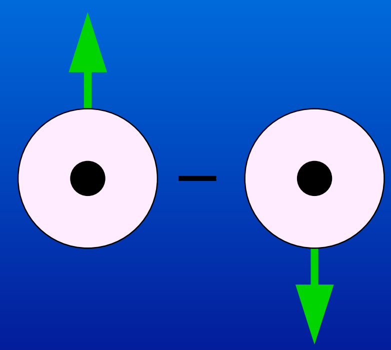
UU	1	$\otimes\, f_1 =$ 	$\otimes\, D_1 =$ 
	$\cos(2\phi_h^l)$	$\otimes\, h_1^\perp =$ 	$\otimes\, H_1^\perp =$ 
UL	$\sin(2\phi_h^l)$	$\otimes\, h_{1L}^\perp =$ 	$\otimes\, H_1^\perp =$ 
UT	$\sin(\phi_h^l + \phi_S^l)$	$\otimes\, h_1 =$ 	$\otimes\, H_1^\perp =$ 
	$\sin(\phi_h^l - \phi_S^l)$	$\otimes\,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



L_q within the proton correlated with the proton's spin

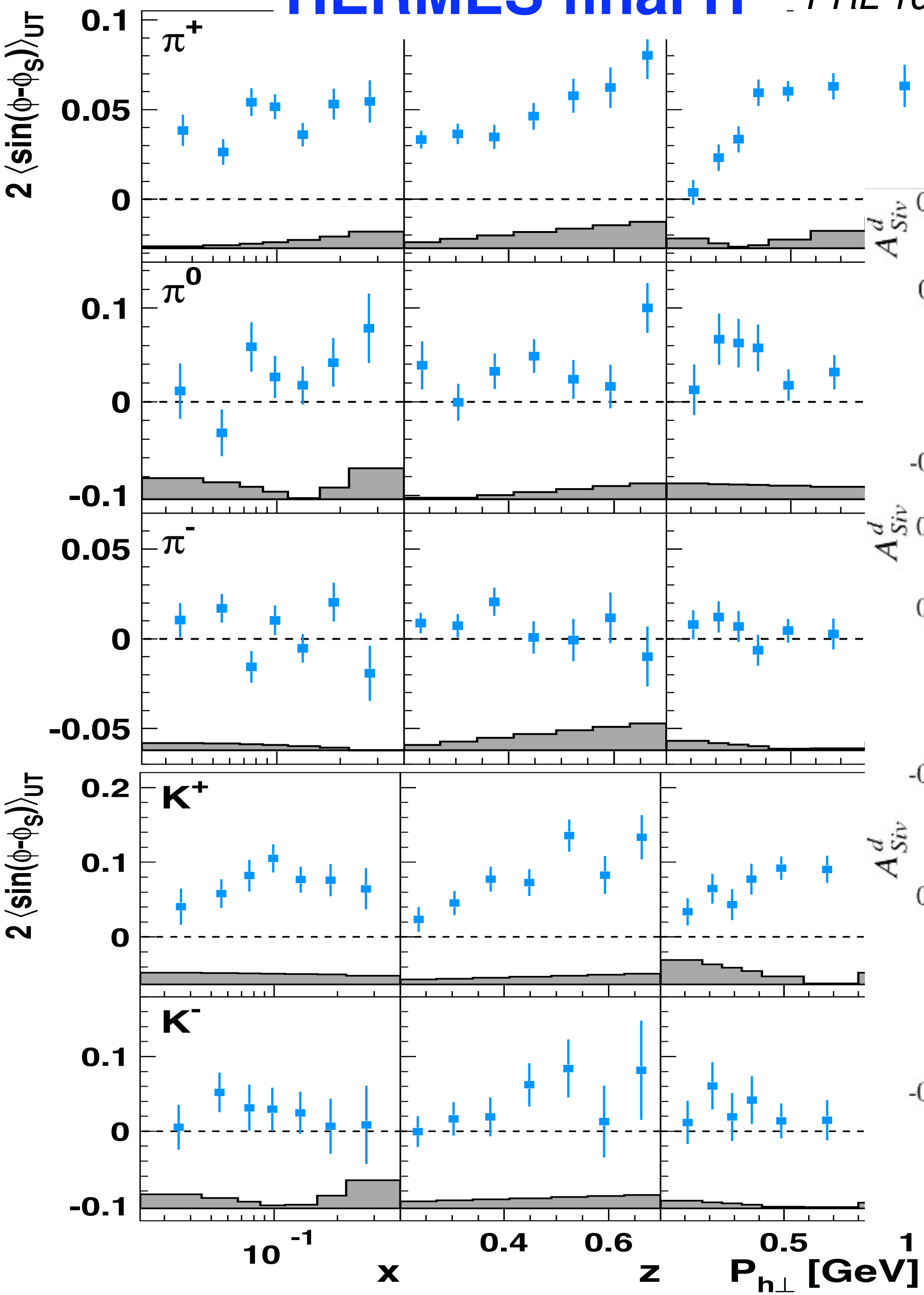
The Sivers Function

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



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

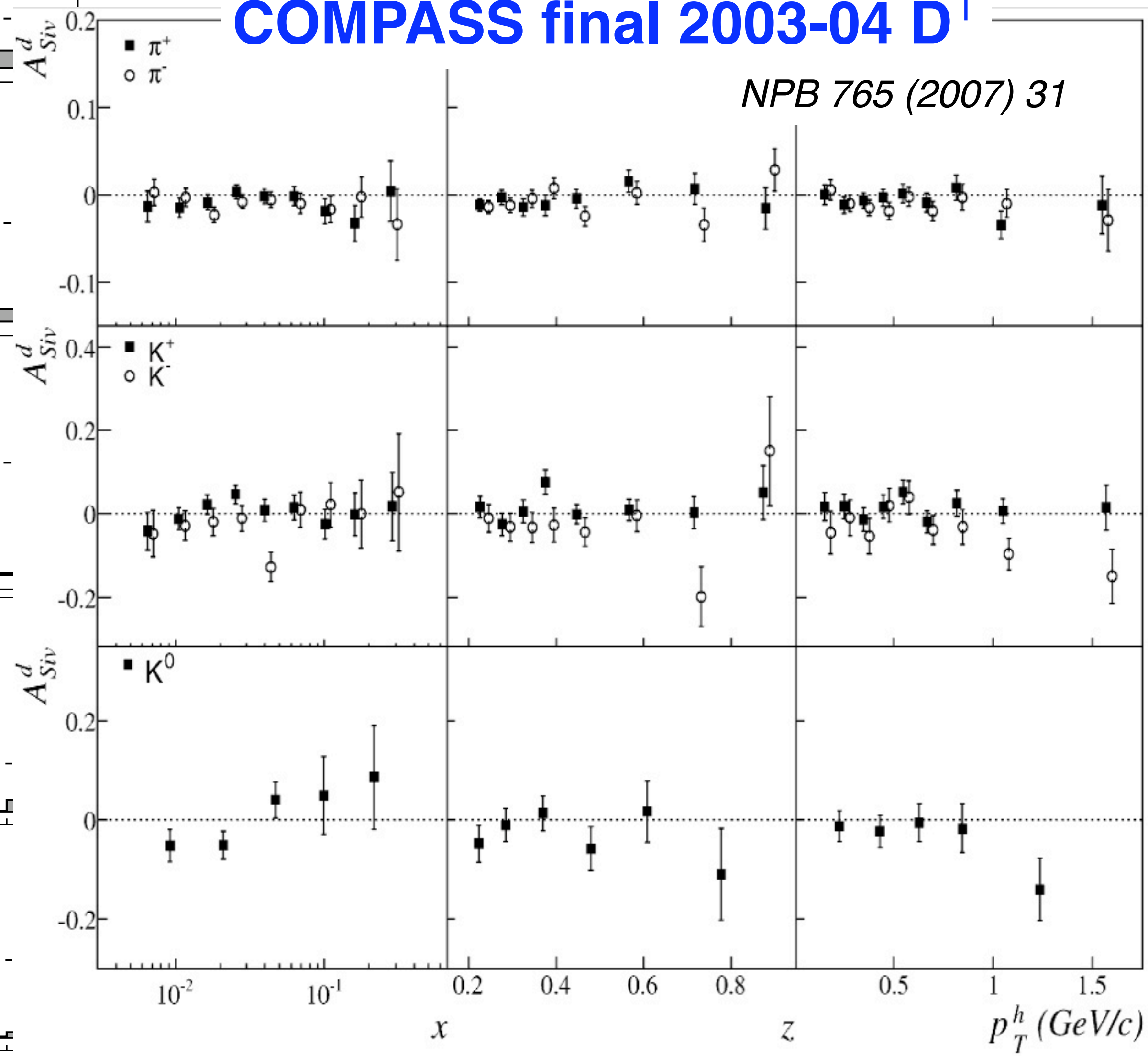
HERMES final H$^{\uparrow}$ *PRL 103 (2009)*



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

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

NPB 765 (2007) 31

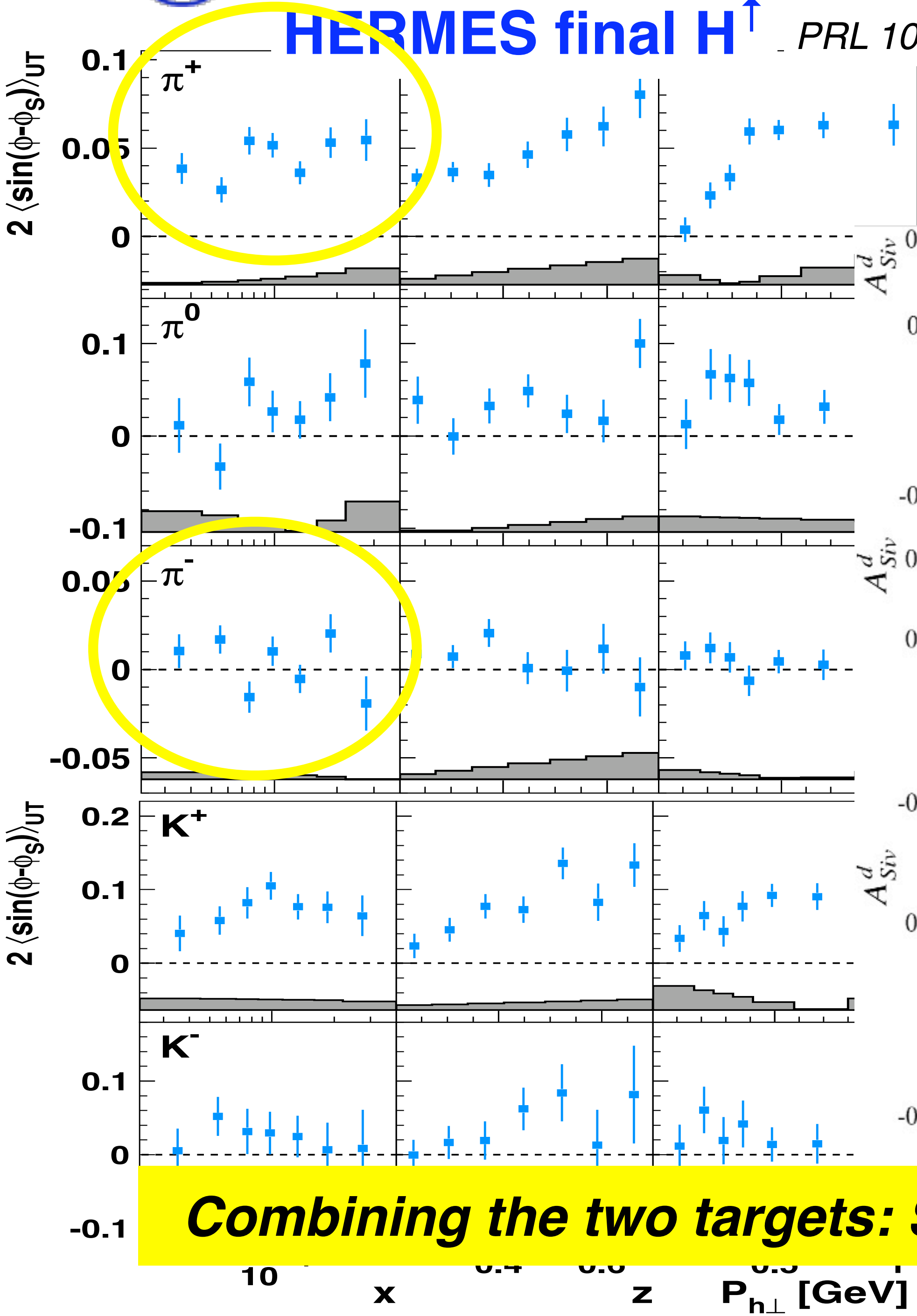


N.C.R. Makins, IWHSS'12, Lisboa, Apr 16-18, 2012

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

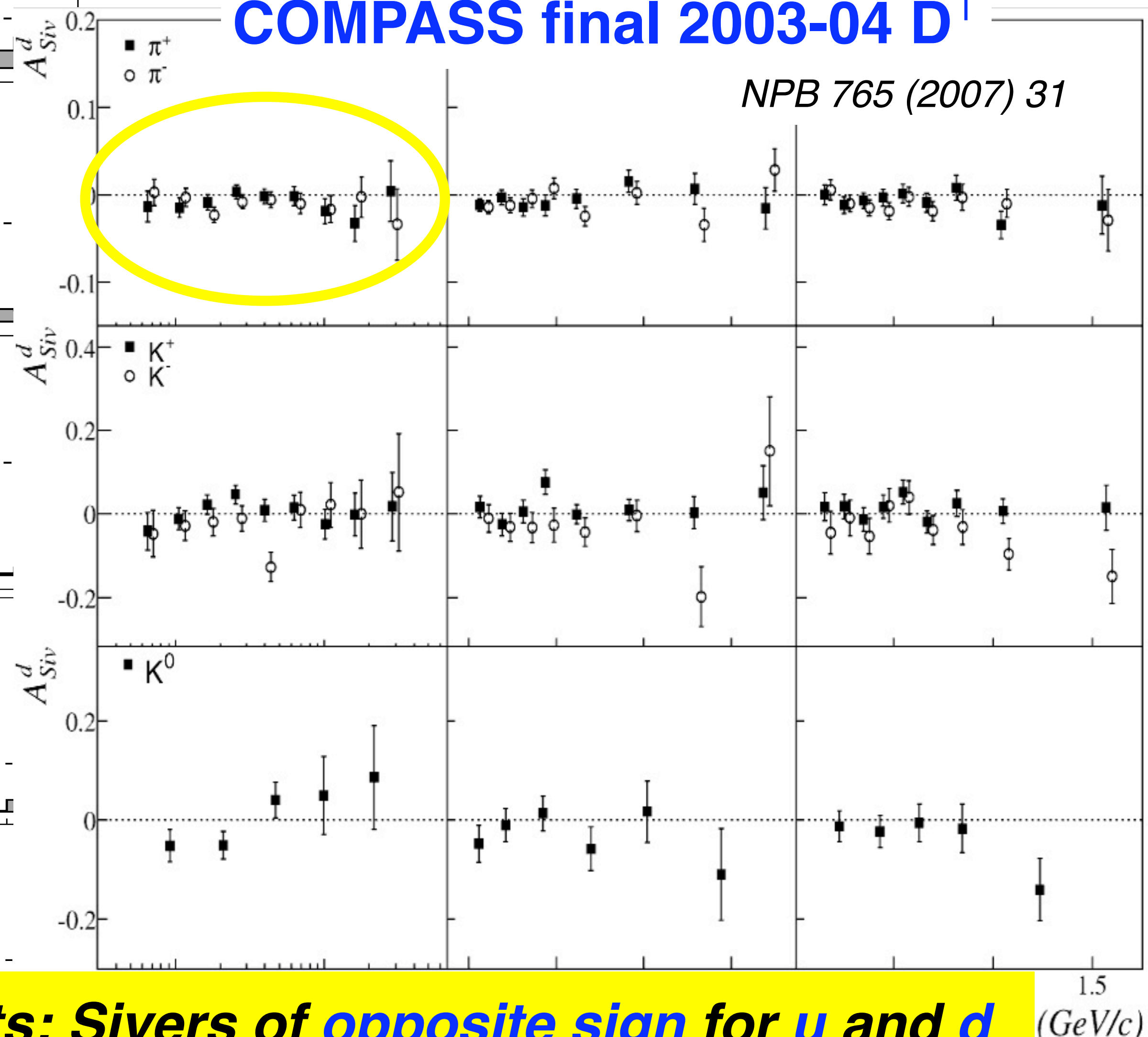
HERMES final $H^{\uparrow}$ *PRL 103 (2009)*

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

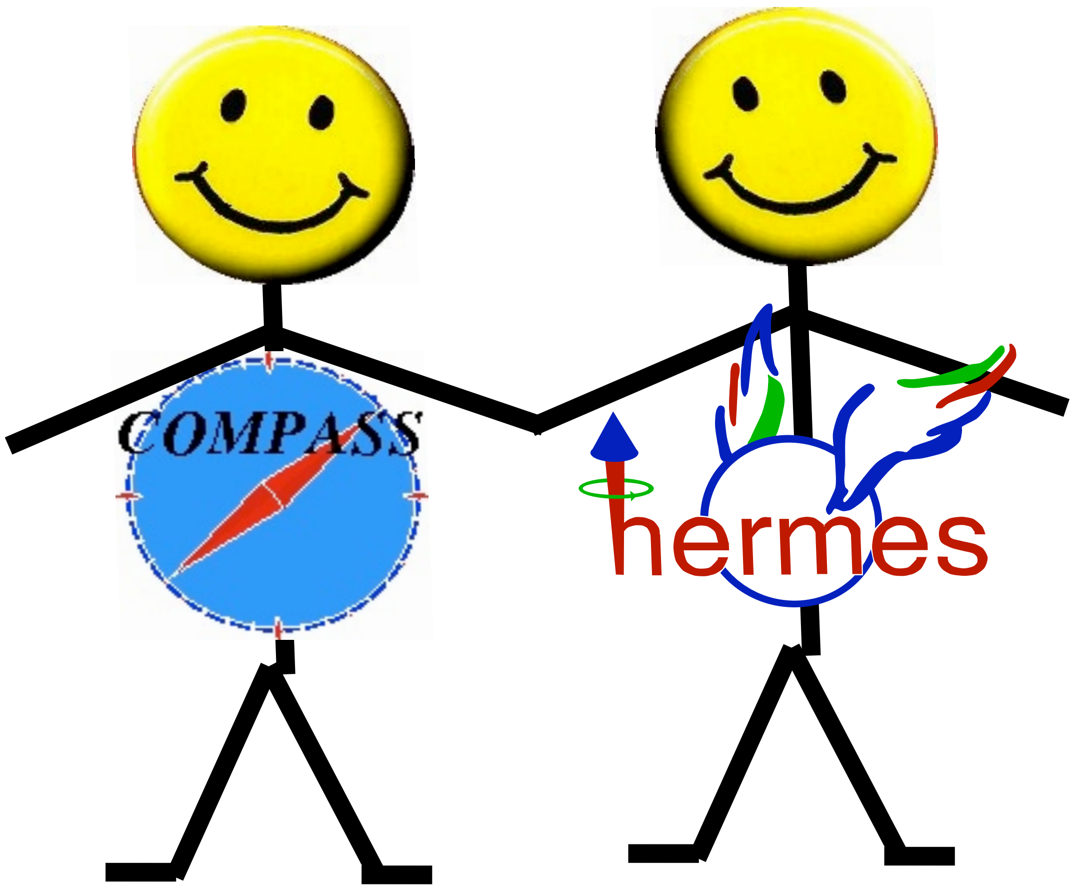


COMPASS final 2003-04 $D^{\uparrow}$

NPB 765 (2007) 31

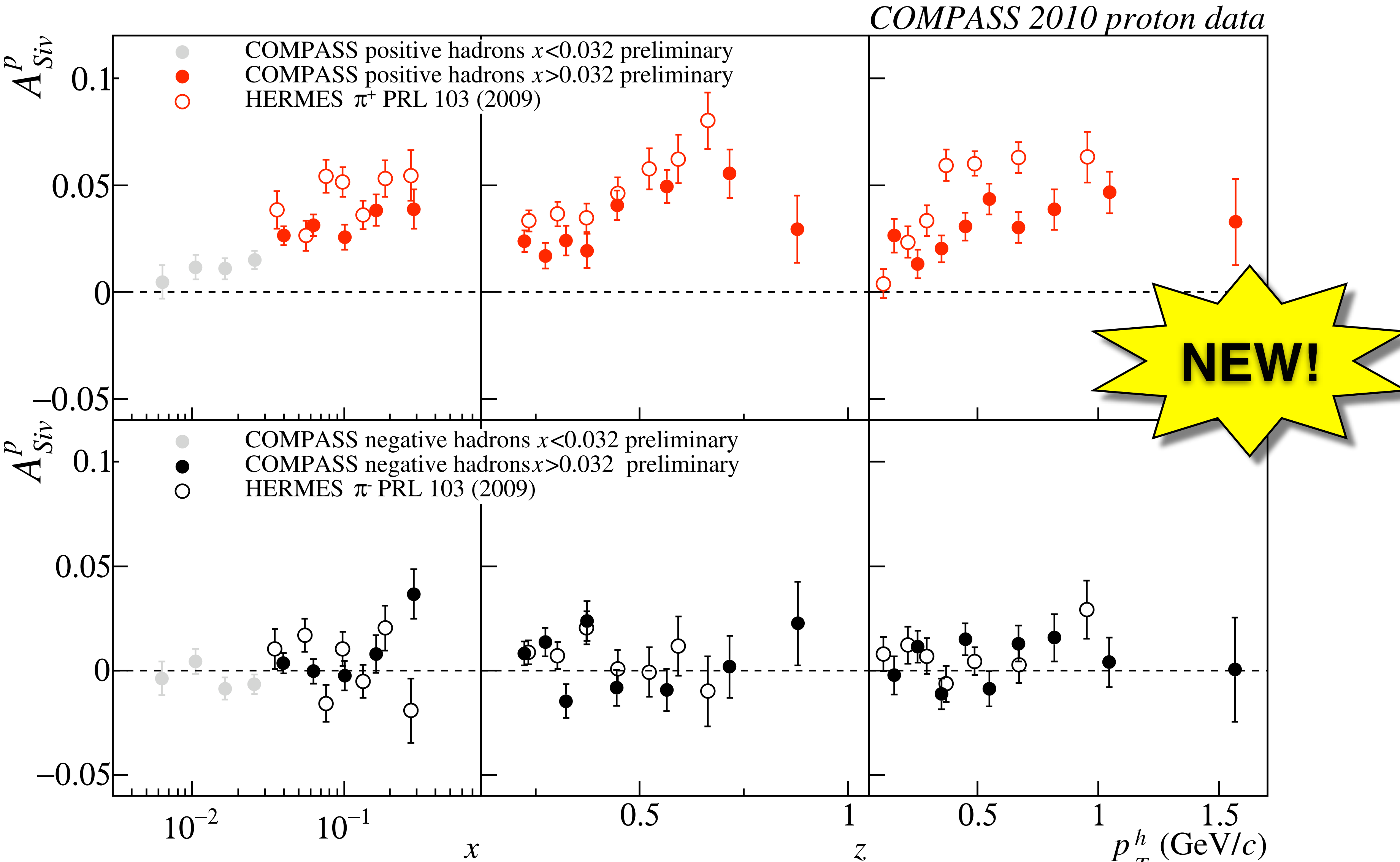


Combining the two targets: Sivers of opposite sign for u and d


COMPASS
hermes

COMPASS proton data: confirmation!

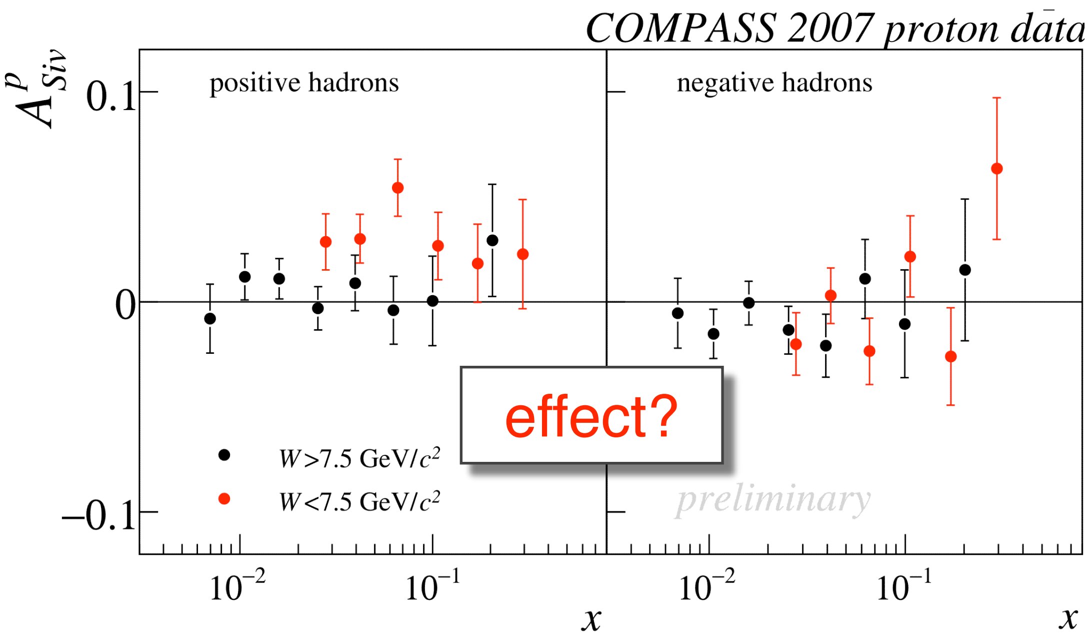
○ HERMES $H^{\uparrow} \rightarrow \pi^{\pm}$ ●● COMPASS 2010 $H^{\uparrow} \rightarrow h^{\pm}$

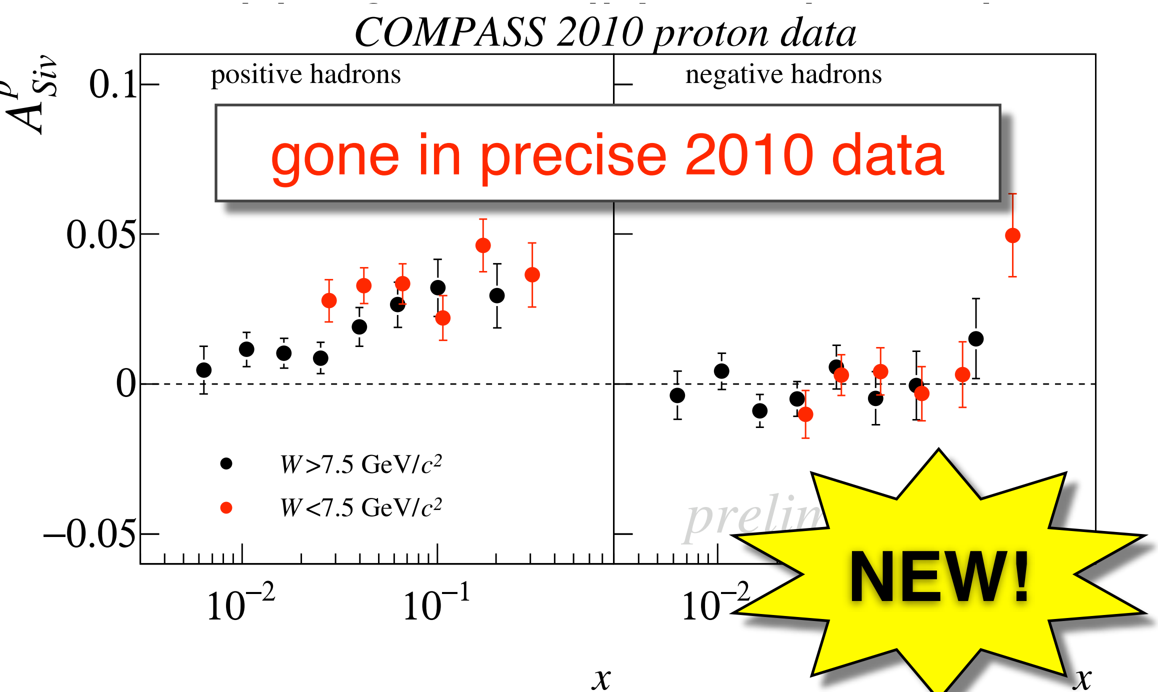


<u>New COMPASS data from H target</u>: high-precision confirmation of non-zero Sivers effect in SIDIS

W-dependence of Sivers

looking for higher twist, factorization breaking





W-dependence of Sivers

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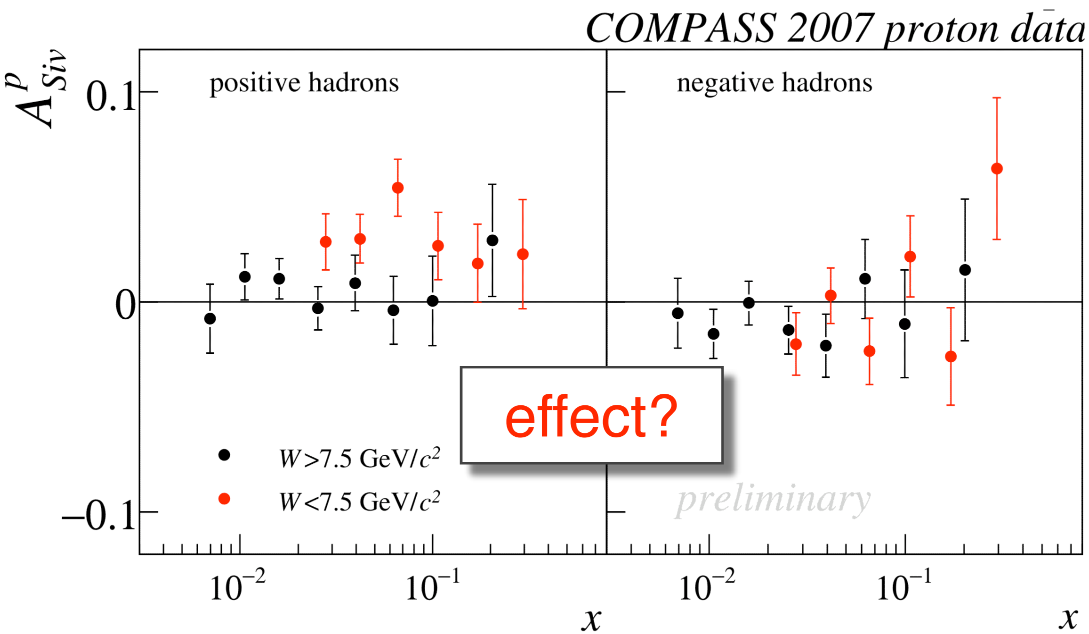
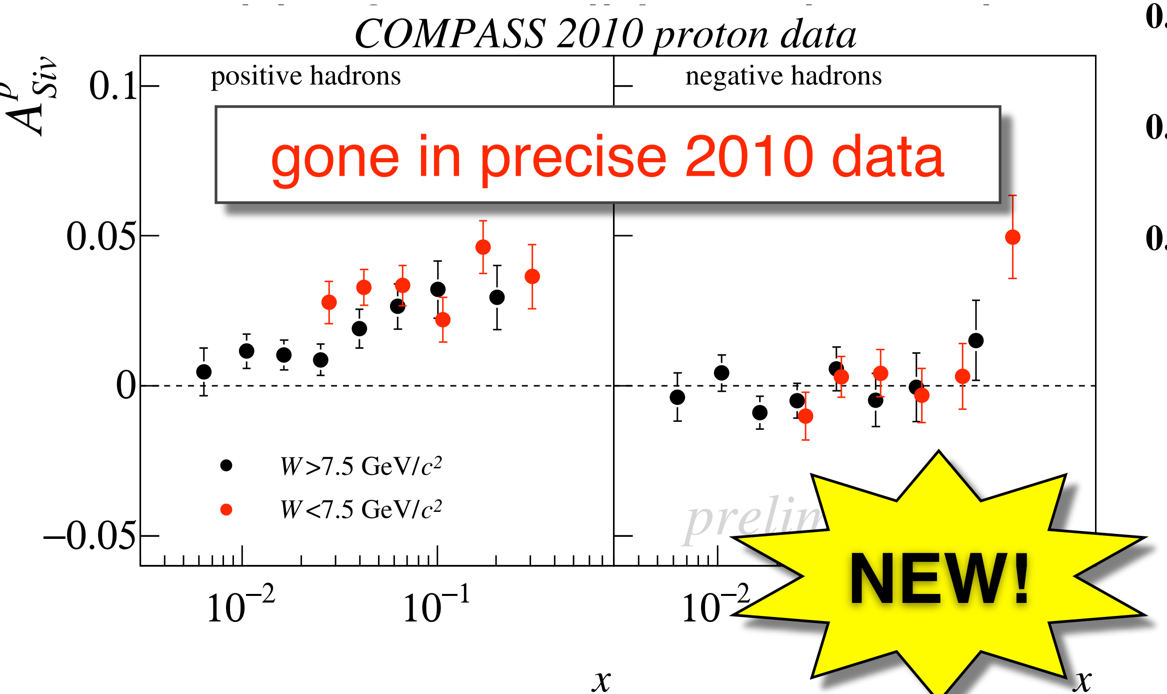
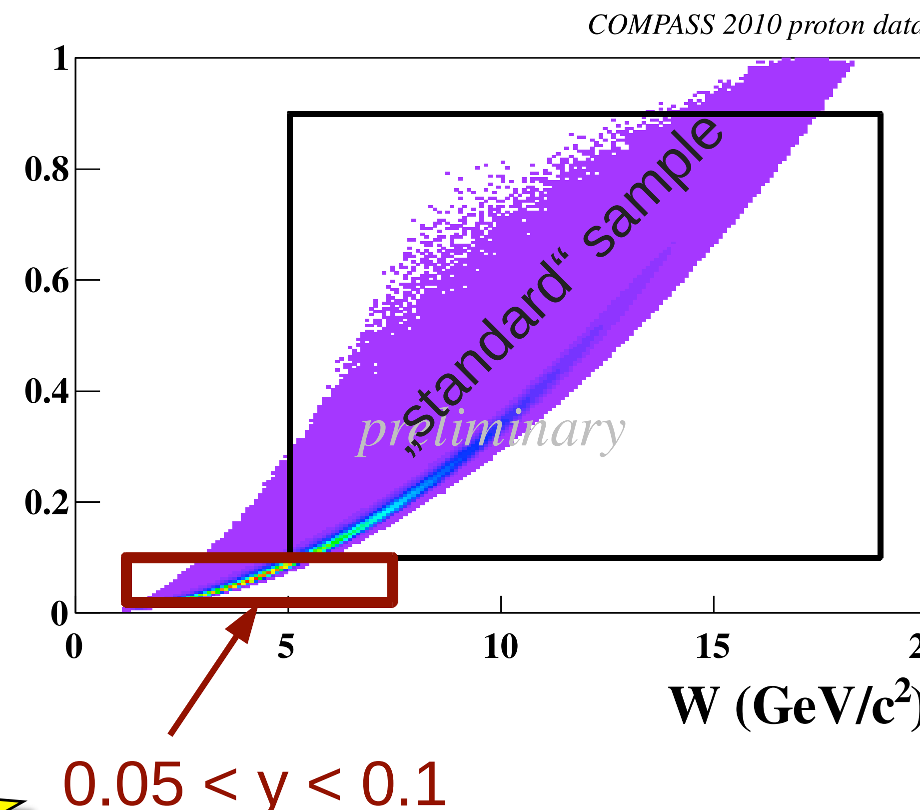




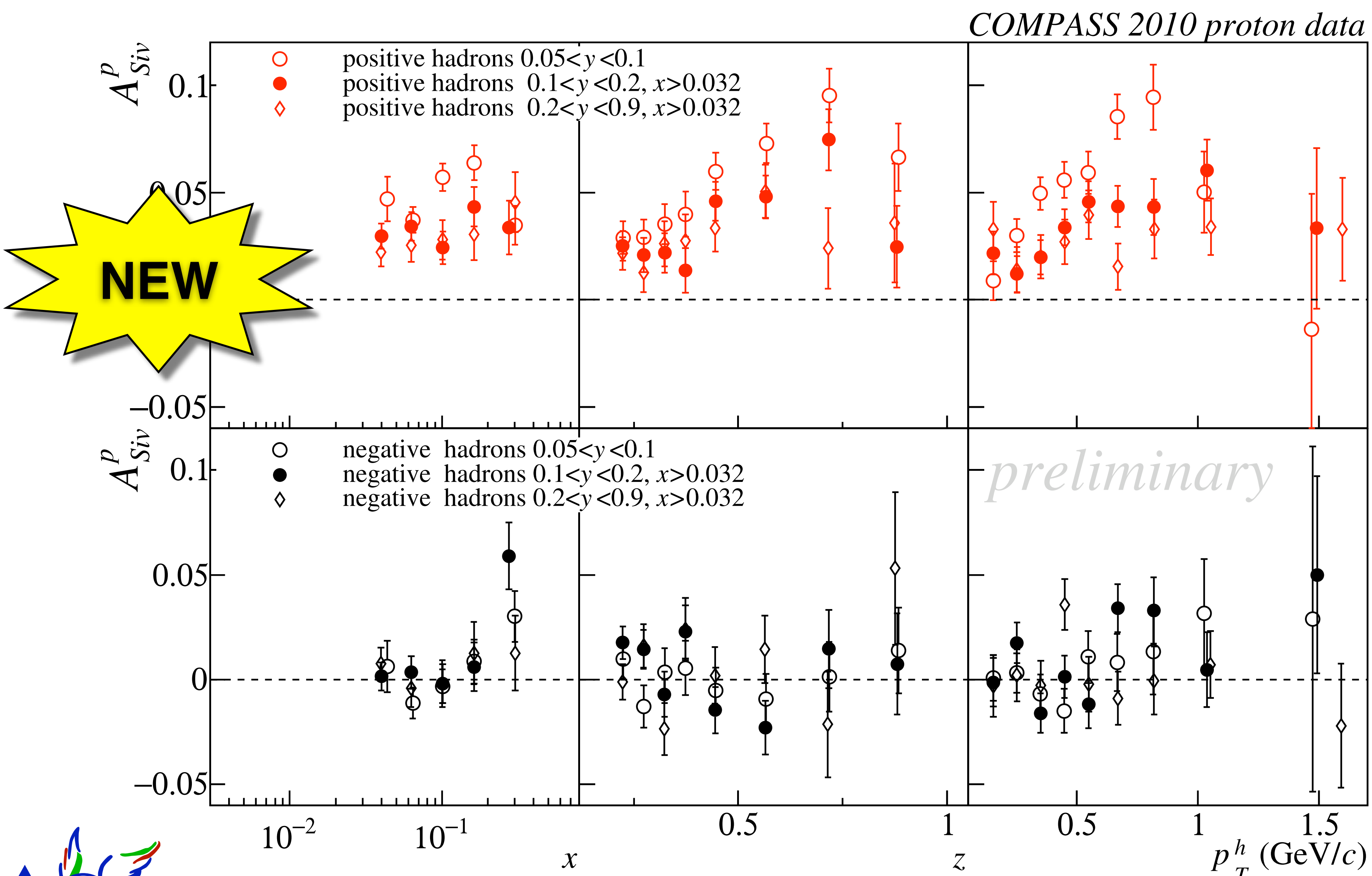
next, push the test to ...

low y: 0.05 < y < 0.1



y-dependence of Sivers

it's baaaack ... ○ at **very low y** (and so **low W < 5 GeV**)

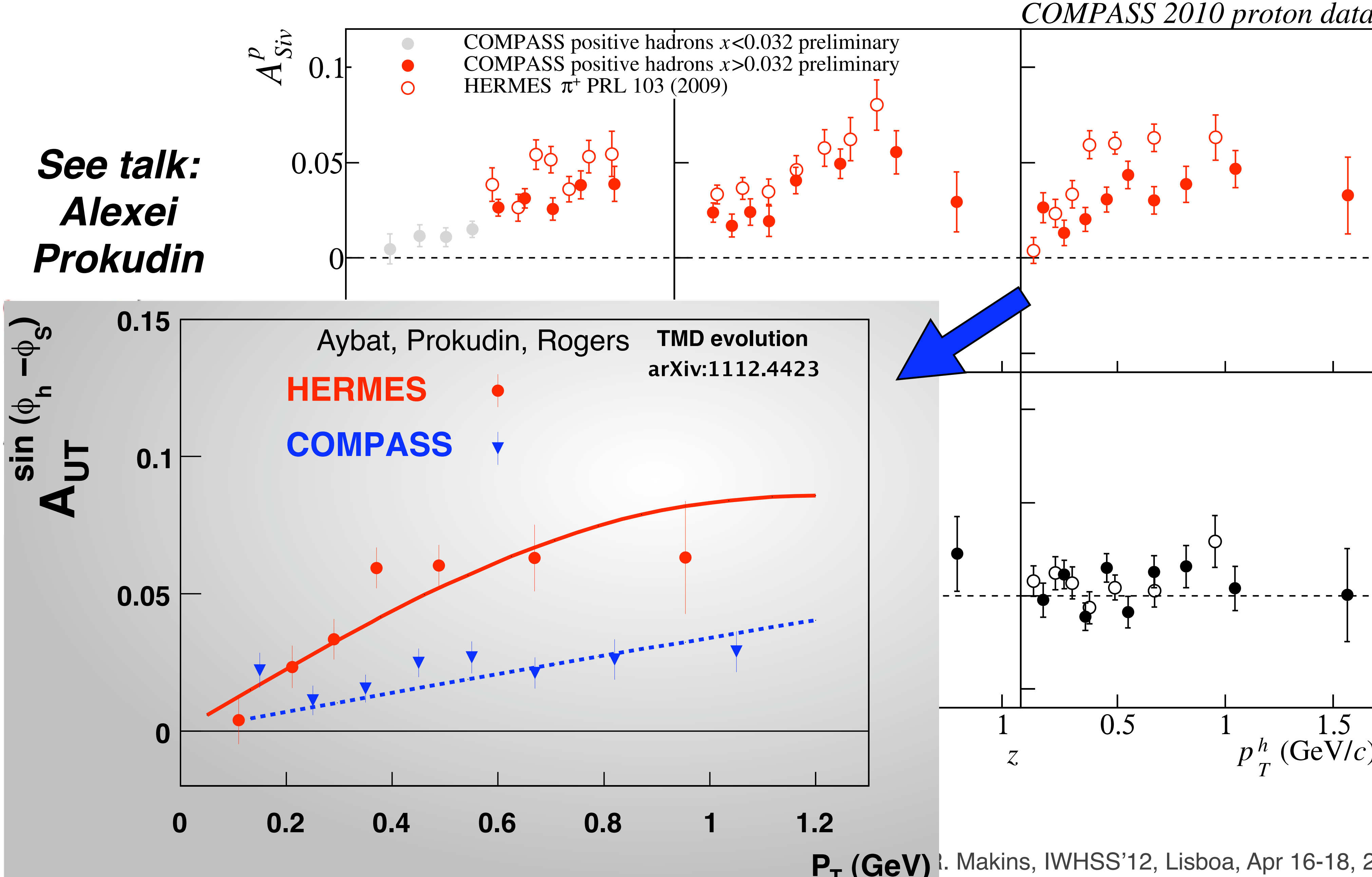


Note: HERMES range is **3.2 < W < 7 GeV**

but TMD Evolution looking good!

○ HERMES $H^{\uparrow} \rightarrow \pi^{\pm}$ ●● COMPASS 2010 $H^{\uparrow} \rightarrow h^{\pm}$

See talk: Alexei Prokudin

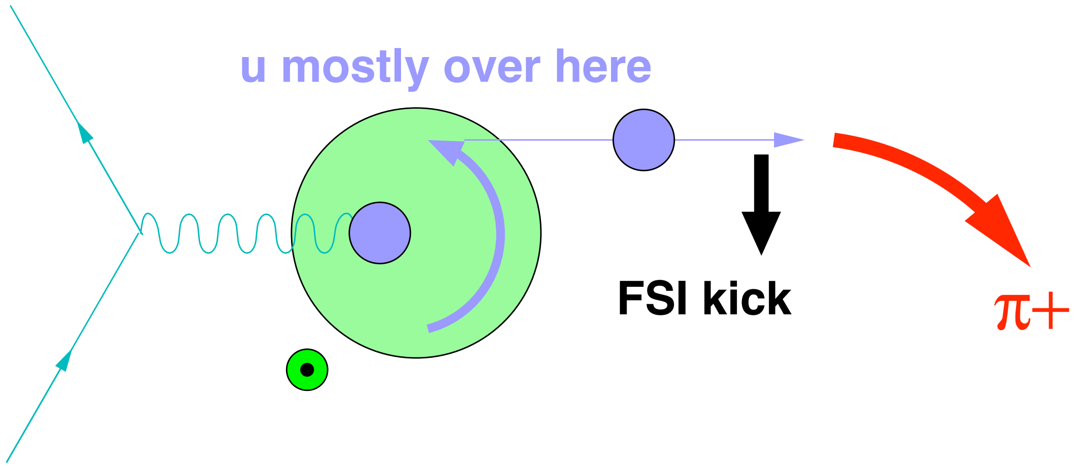


Phenomenology: Sivers Mechanism

Assuming
$L_u > 0$ ...

- **M. Burkardt: Chromodynamic lensing**

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



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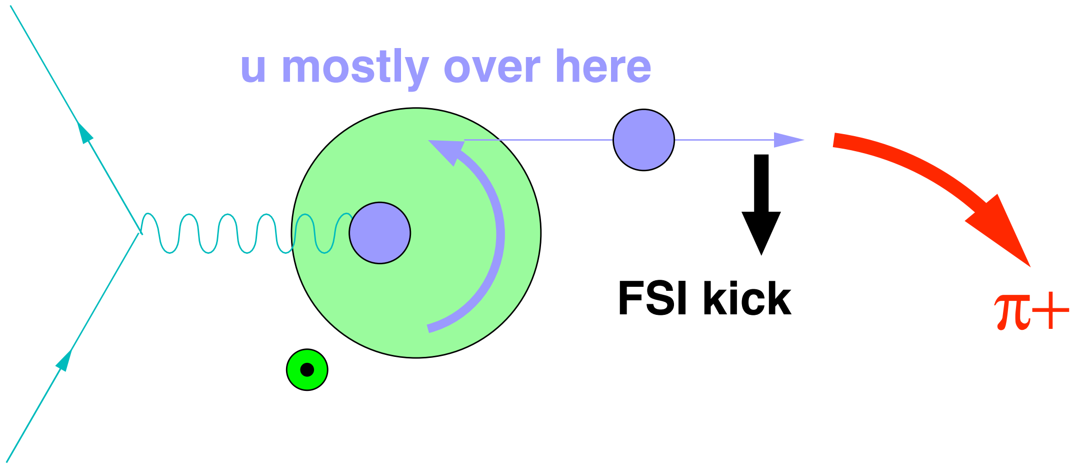

We observe $\langle \sin(\phi_h^l - \phi_S^l) \rangle_{UT}^{\pi^+} > 0$
(and opposite for π^-)
$\therefore$ for $\phi_S^l = 0,\ \phi_h^l = \pi/2$ preferred

Model agrees!

Phenomenology: Sivers Mechanism

Assuming $L_u > 0$ …

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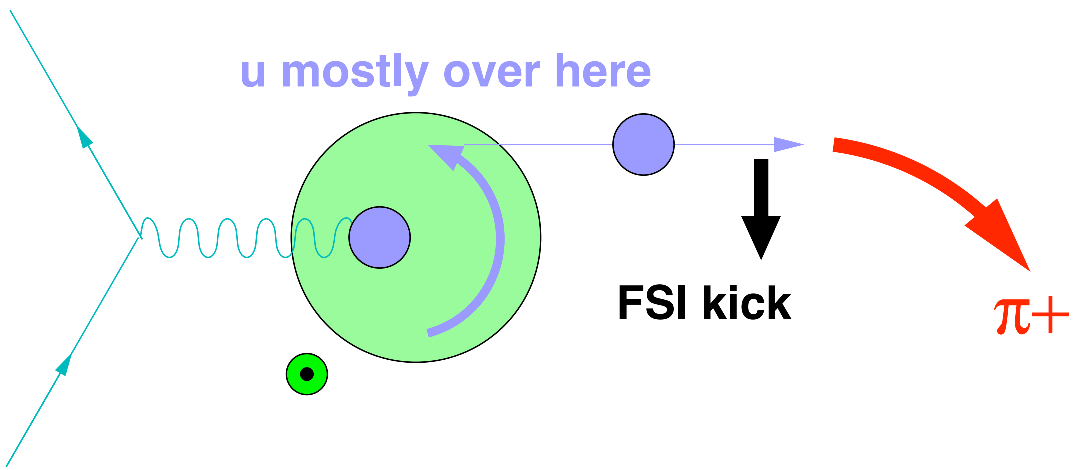

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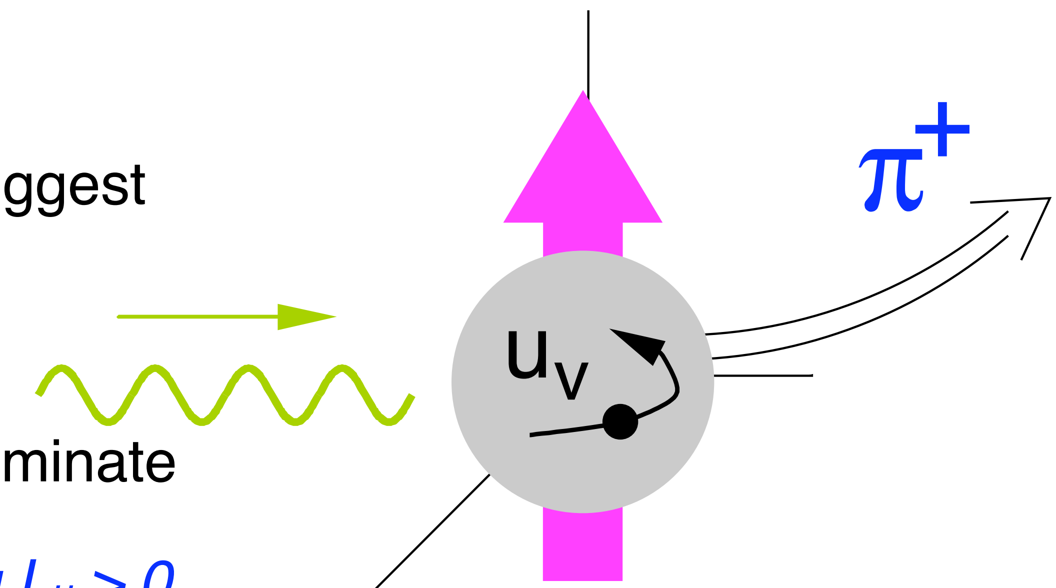
(and opposite for π^-)

$\therefore$ 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 $L_u > 0$ …*

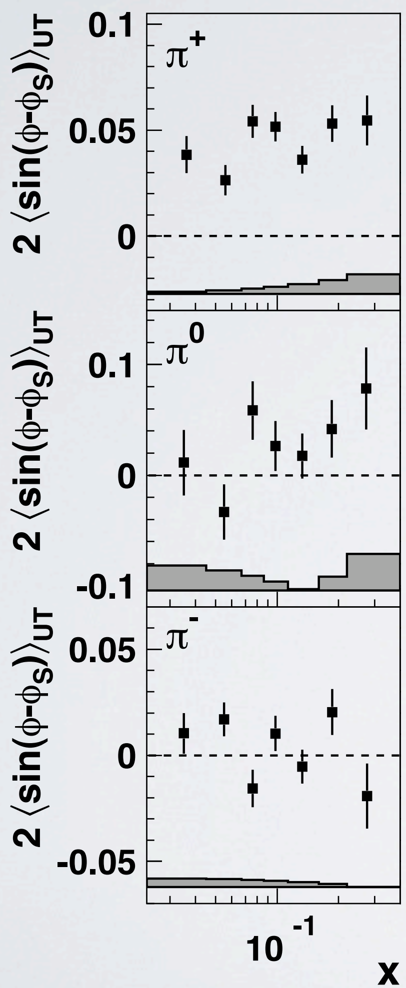
Bacchetta & Radici, PRL 107 (2011)

New Global Fit to Sivers SIDIS Data

Using available data

Sivers → $f_{1T}^{\perp(0)a}$; "lensing funtion" → $L(x)$; GPD E, related to quark OAM (more later) → E^a

$$f_{1T}^{\perp(0)a}(x;Q_L^2) = -L(x)\, E^a(x,0,0;Q_L^2),$$



Use SIDIS Sivers asymmetry data to constrain shape

hermes

COMPASS

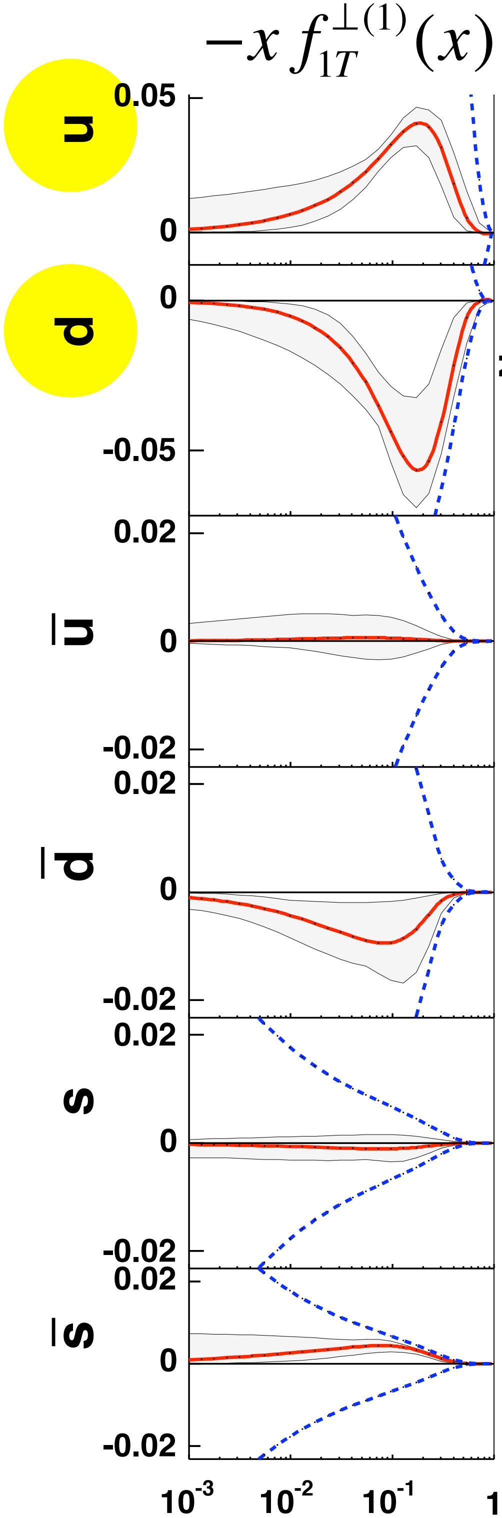
Jefferson Lab

$$\kappa^p = \int_0^1 \frac{dx}{3}\Big[2E^{u_v}(x,0,0) - E^{d_v}(x,0,0) - E^{s_v}(x,0,0)\Big]$$

$$\kappa^n = \int_0^1 \frac{dx}{3}\Big[2E^{d_v}(x,0,0) - E^{u_v}(x,0,0) - E^{s_v}(x,0,0)\Big]$$

Use anomalous magnetic moments to constrain integral

Alessandro Bacchetta, INT Workshop on OAM

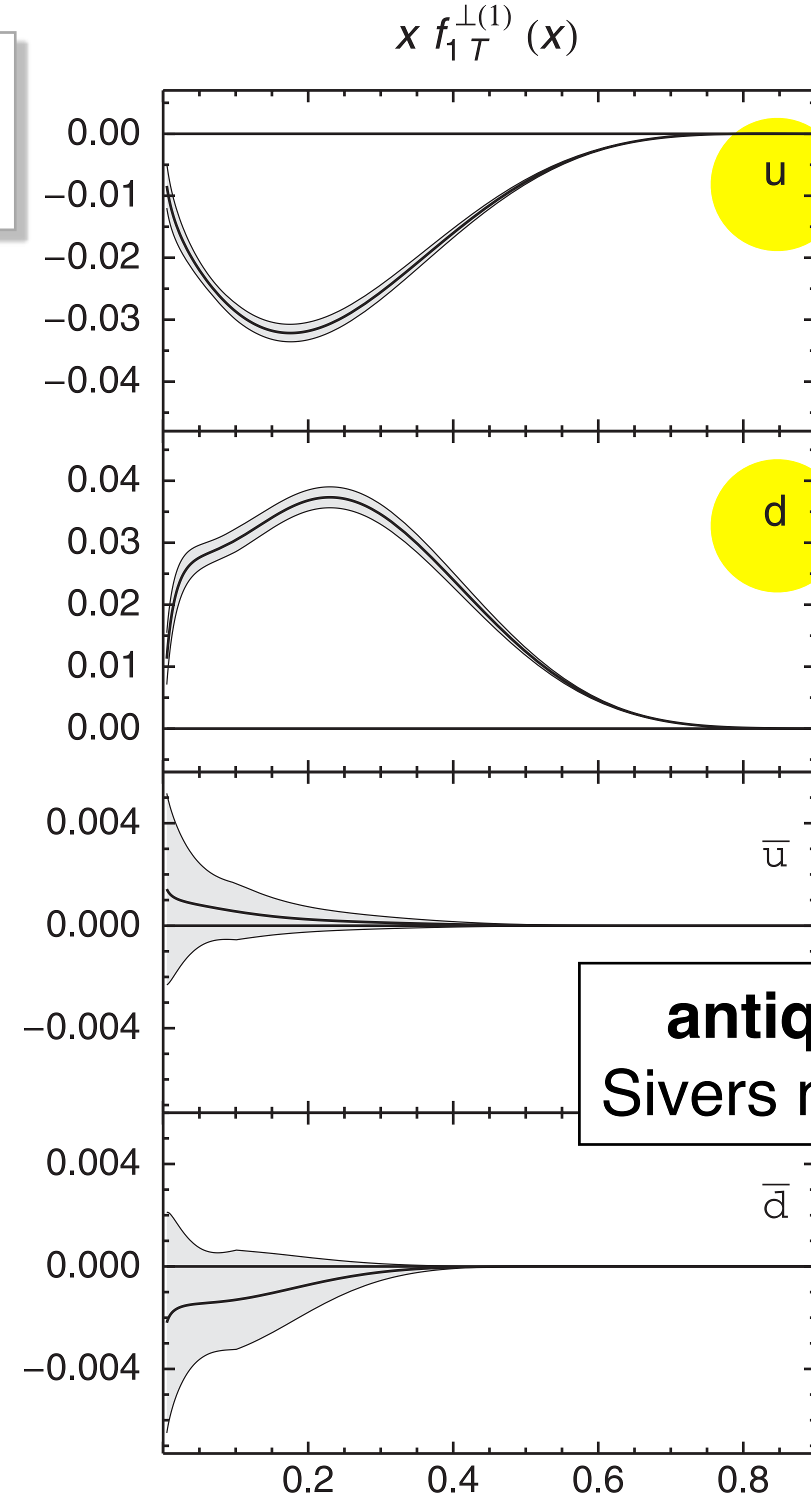


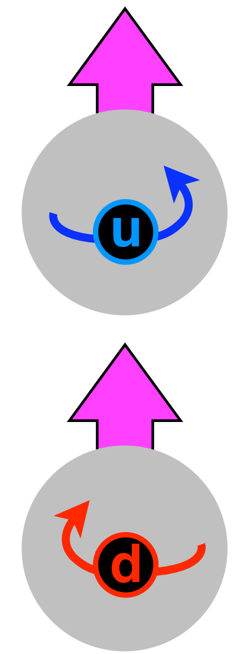
New Global Fit to Sivers

Anselmino et al, arXiv:0805.2677

final data

Bacchetta & Radici, PRL 107 (2011)





antiquark

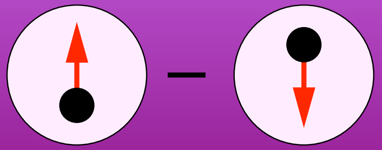
Sivers now ≈ 0

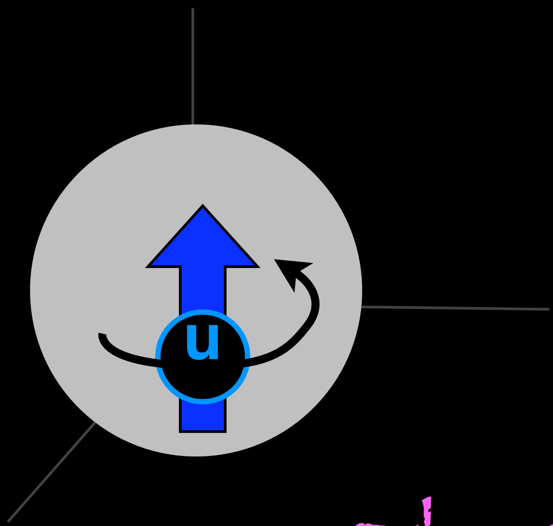
L_q within the proton

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

The Boer-Mulders function

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



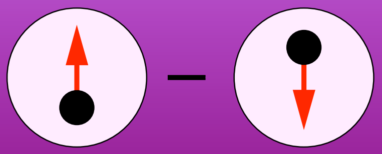


L_q within the proton

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

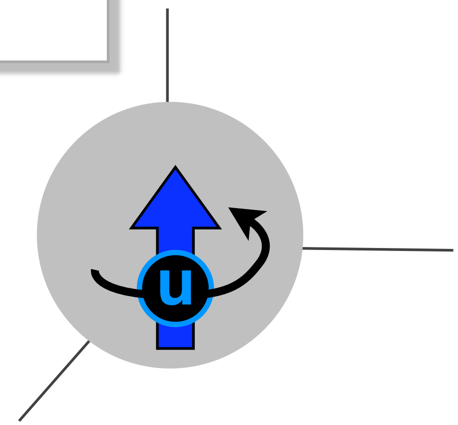
The Boer-Mulders function

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



The Boer-Mulders function

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



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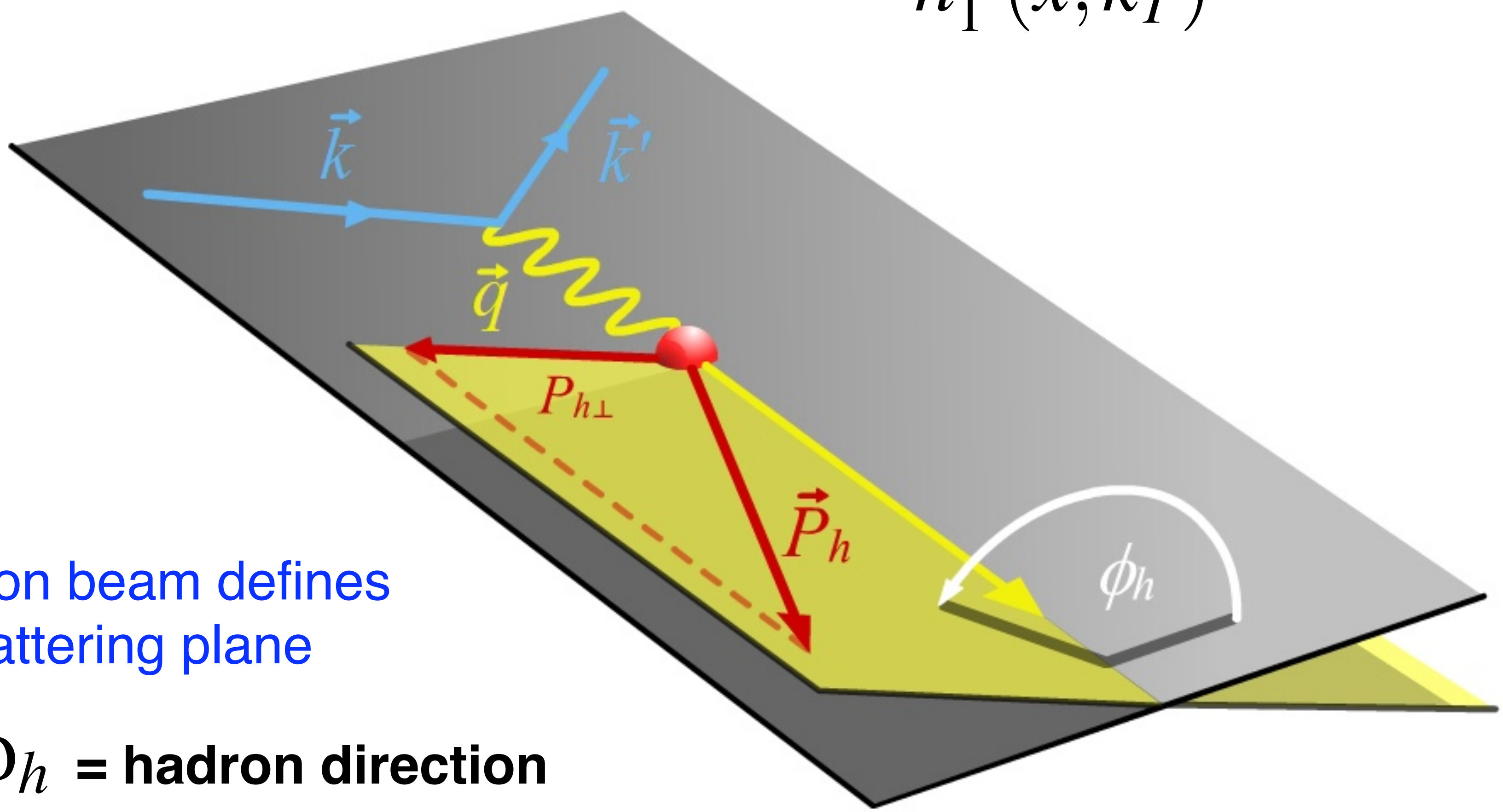

Electron beam defines
scattering plane

ϕ_h **= hadron direction**

The Boer-Mulders function

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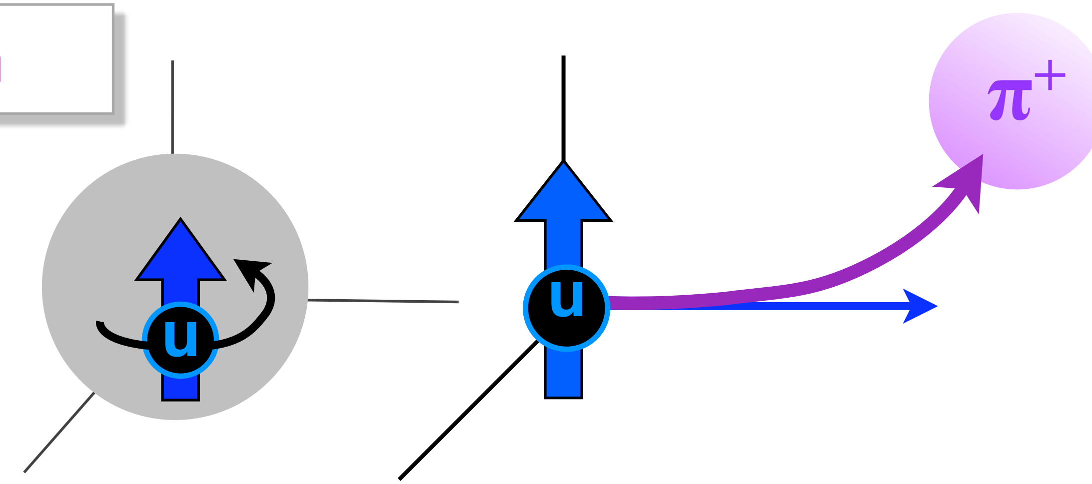
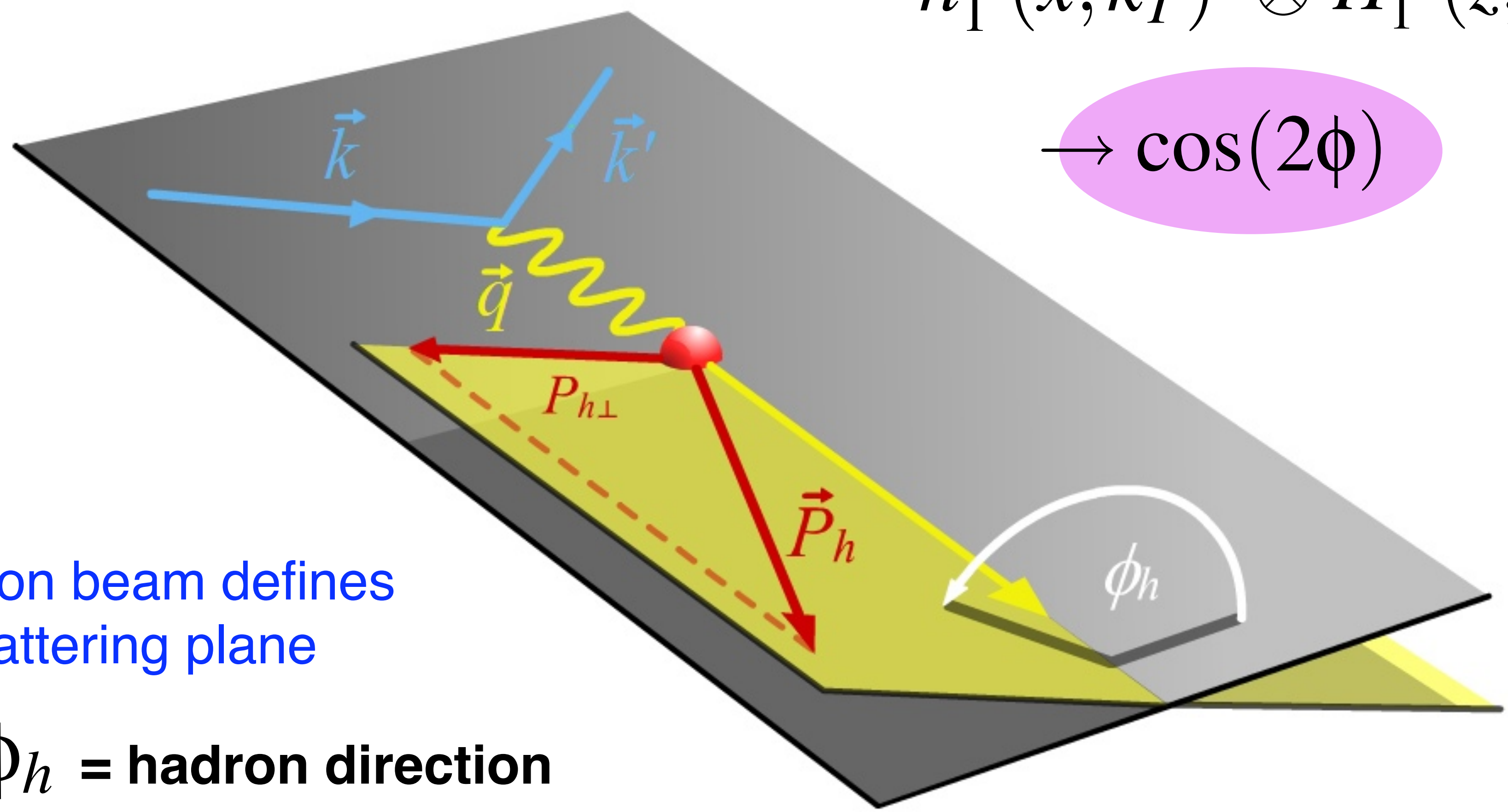


$$h_1^{\perp}(x, k_T) \otimes H_1^{\perp}(z, p_T)$$

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

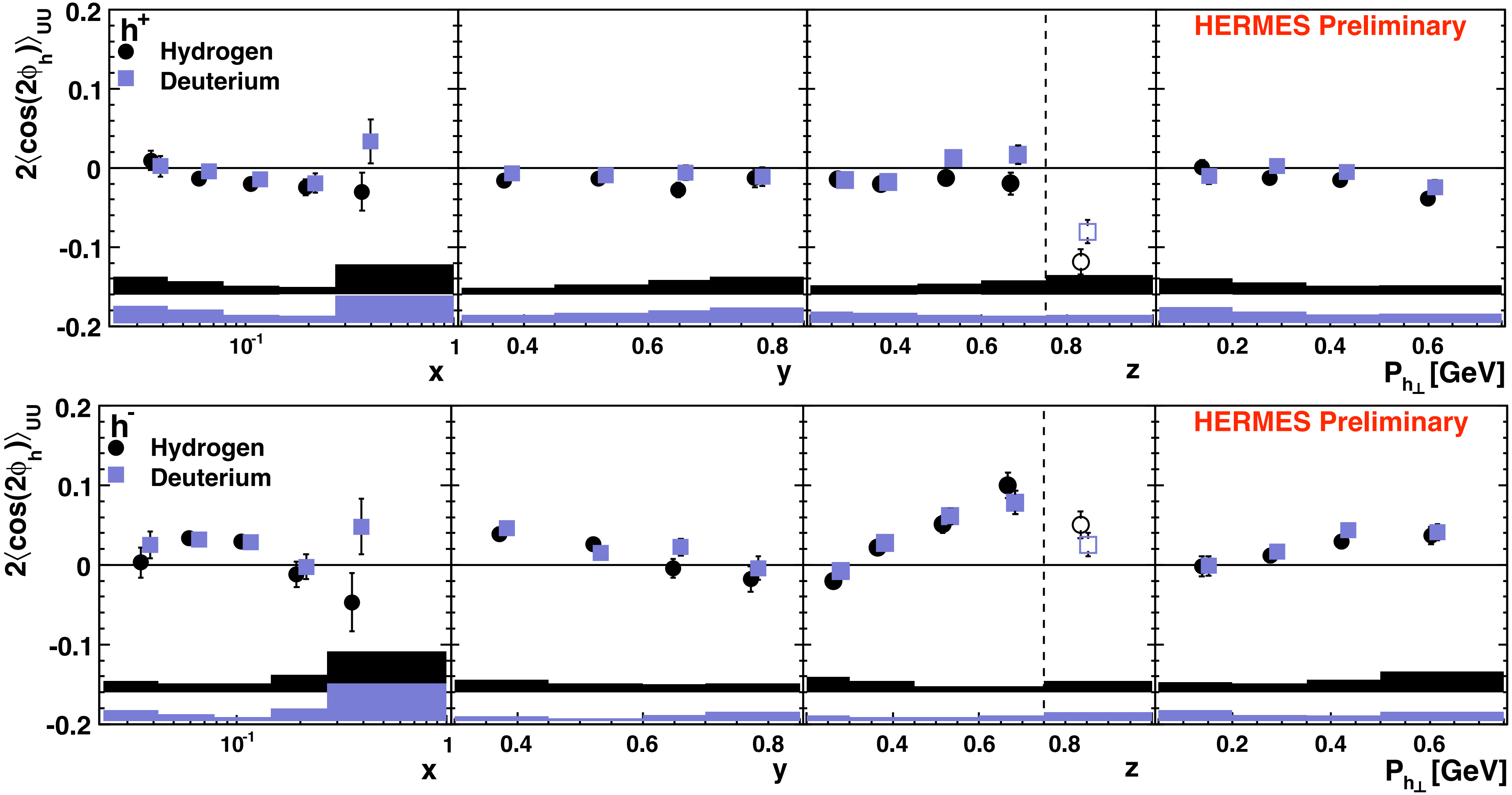


Electron beam defines scattering plane

ϕ_h **= hadron direction**

Boer-Mulders #1: <cos(2Φ)>$_{UU}$ 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)*

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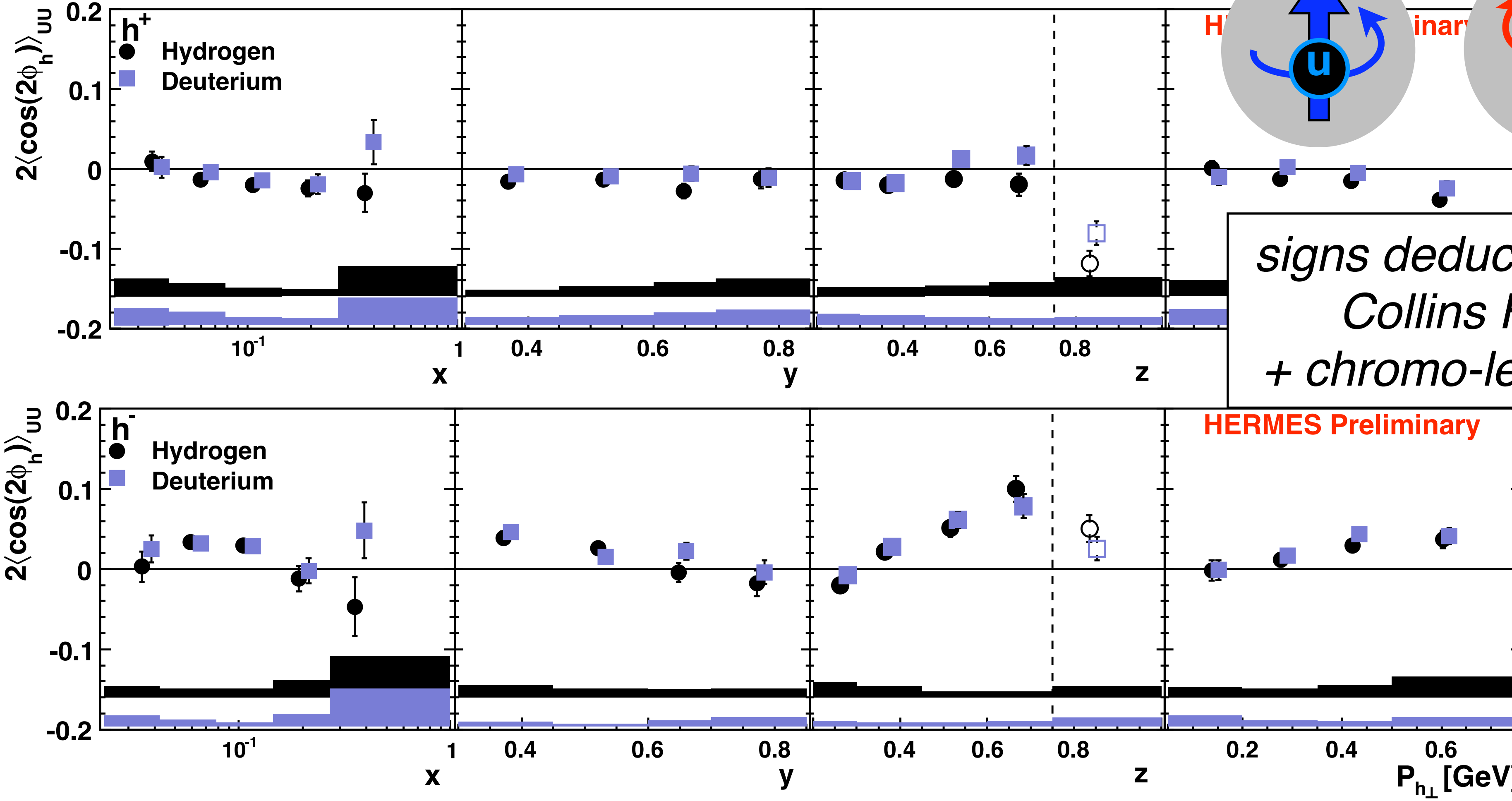
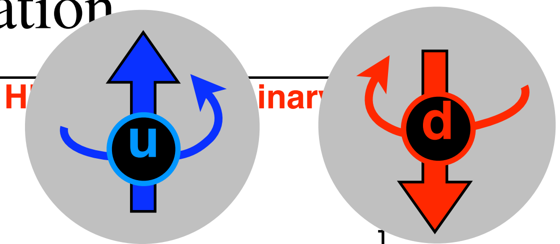




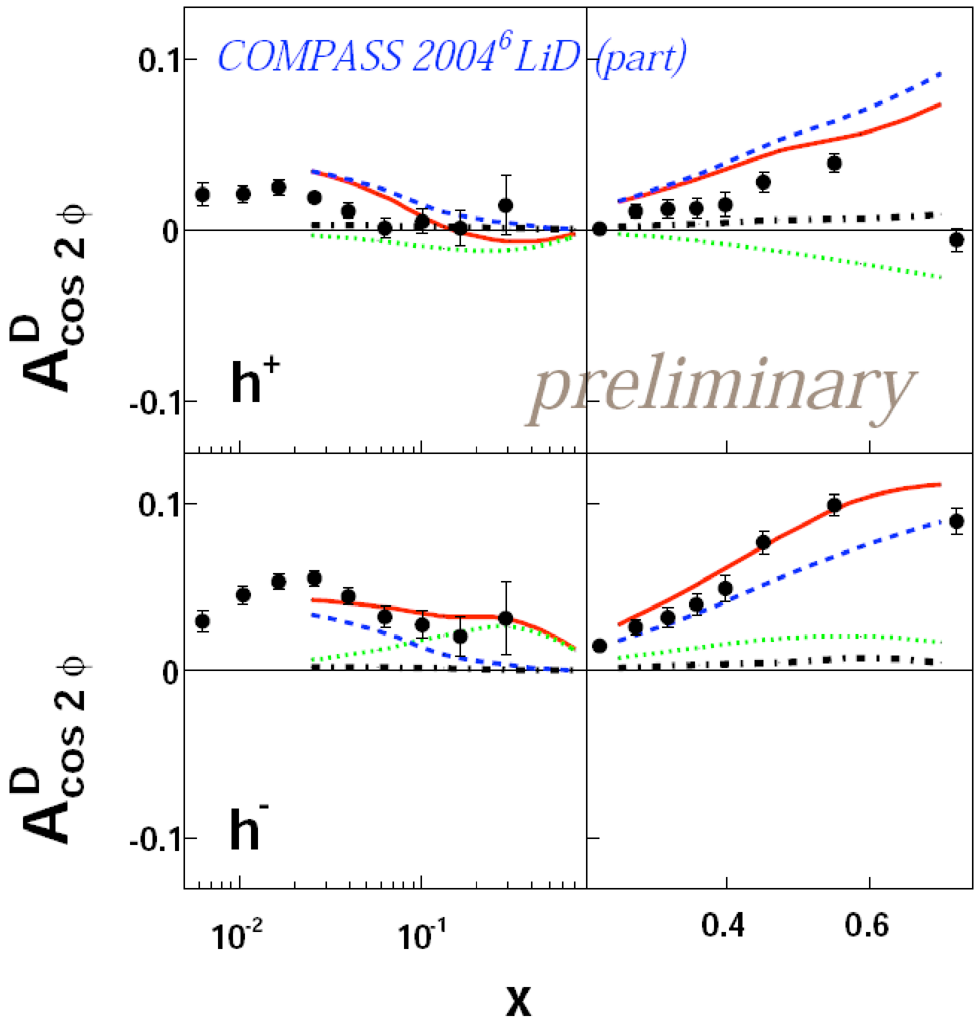
signs deduced via Collins FF + chromo-lensing

***Deuterium ≈ Hydrogen** values → indicate **Boer-Mulders** functions of*

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

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

different picture @ higher Q2



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

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

total — Boer Mulders — Cahn — pQCD

errors shown are statistical only

Wolfgang Käfer, Traversity08 @ Ferrara

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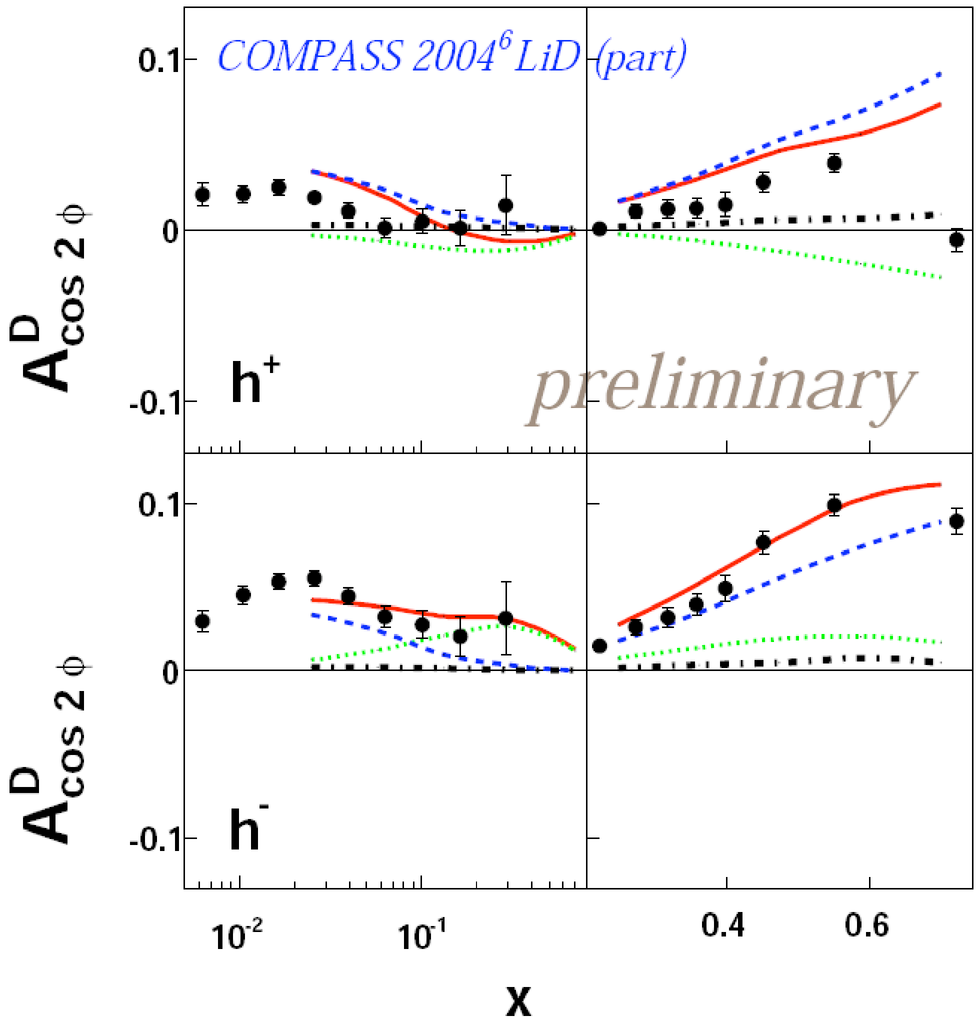

COMPASS cos(2Φ) *well explained by dominant* ***twist-4 Cahn effect***

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

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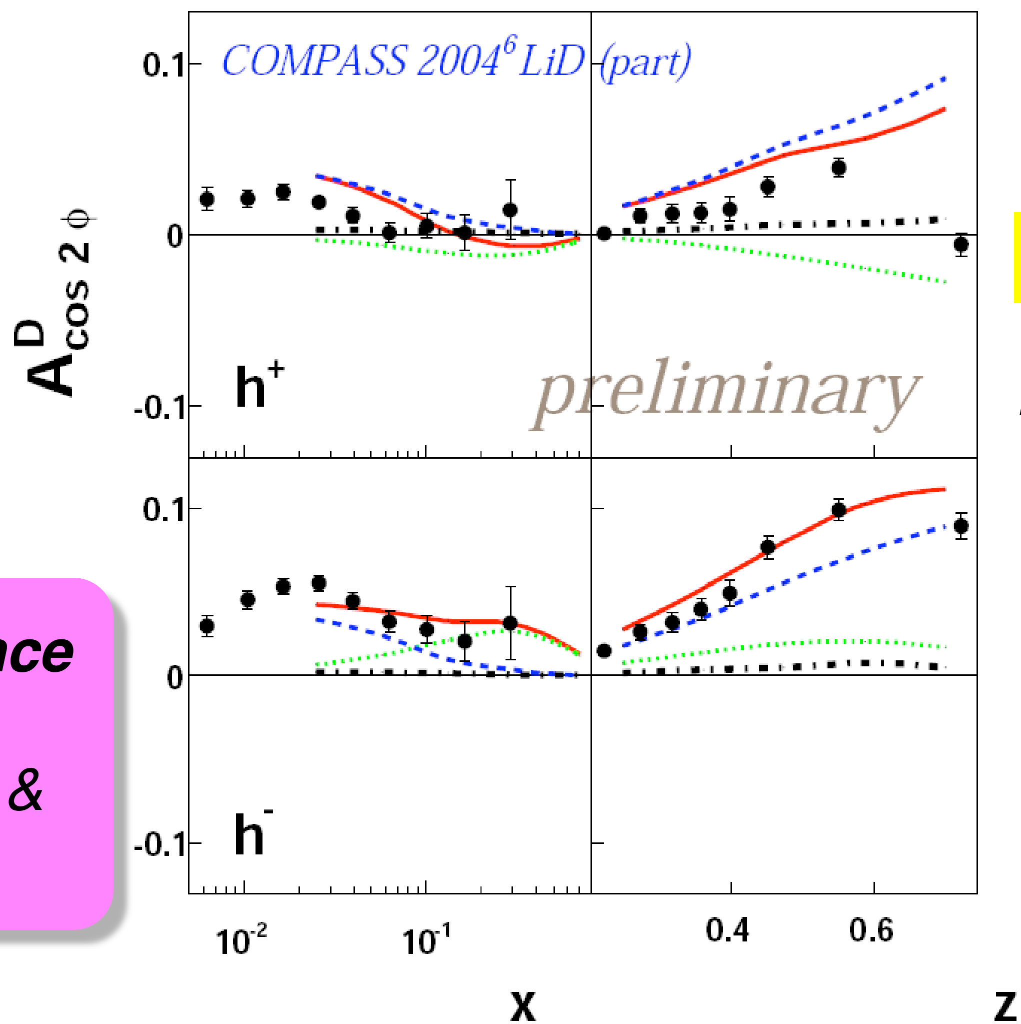

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COMPASS cos(2Φ) *well explained by dominant* ***twist-4 Cahn effect***

... 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***

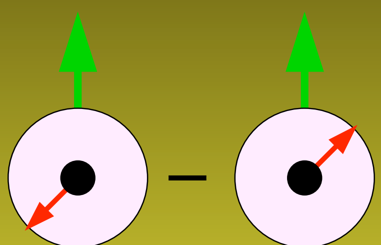
V.Barone, A.Prokudin, B.Q.Ma
arXiv:0804.3024 [hep-ph]

errors shown are statistical only

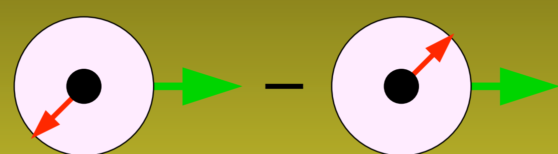
Wolfgang Käfer, Traversity08 @ Ferrara

Pretzelosity & the Worm Gears

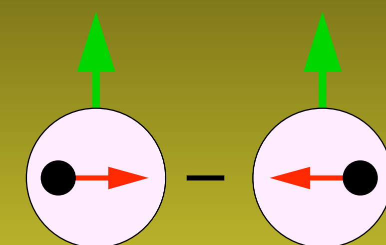
$$h_{1T}^{\perp}(x, k_T)$$



$$h_{1L}^{\perp}(x, k_T)$$



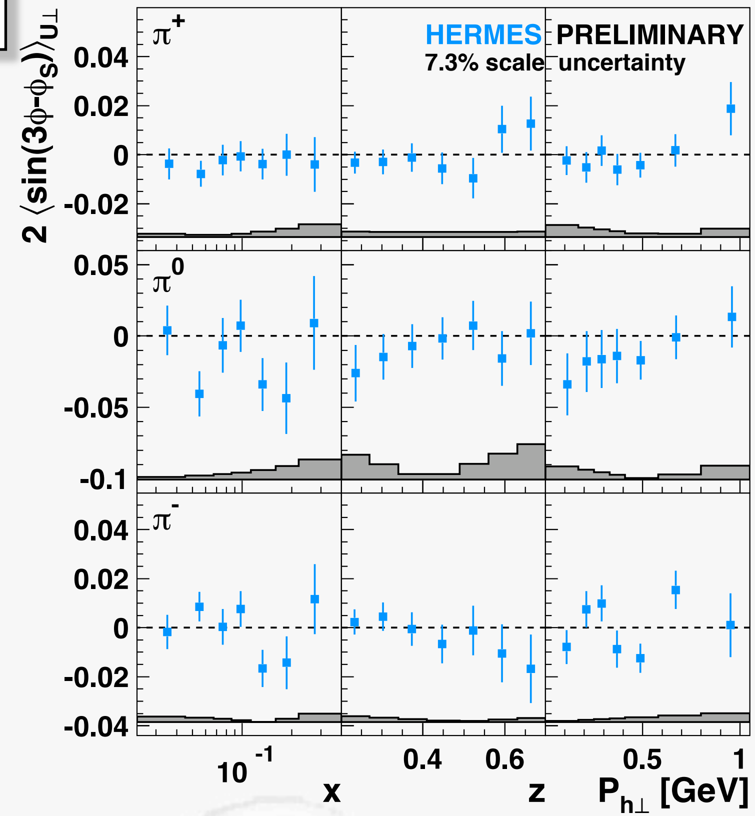
$$g_{1T}(x, k_T)$$



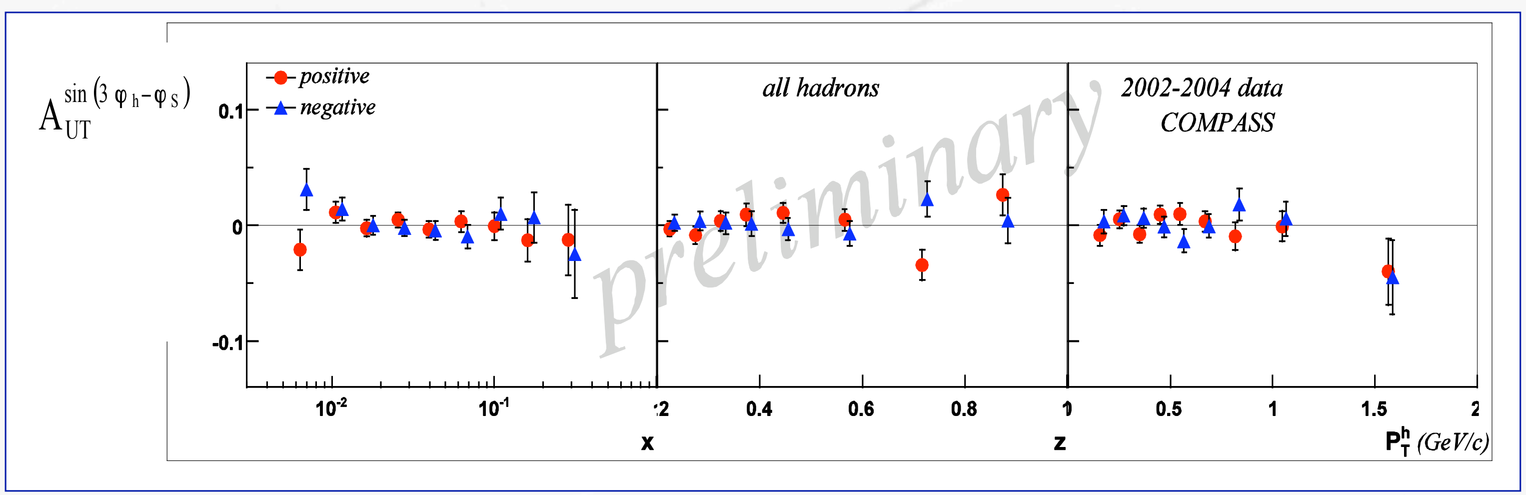
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

In several models, related to $g_1^q - h_1^q$ → relativistic effects

Pretzelosity



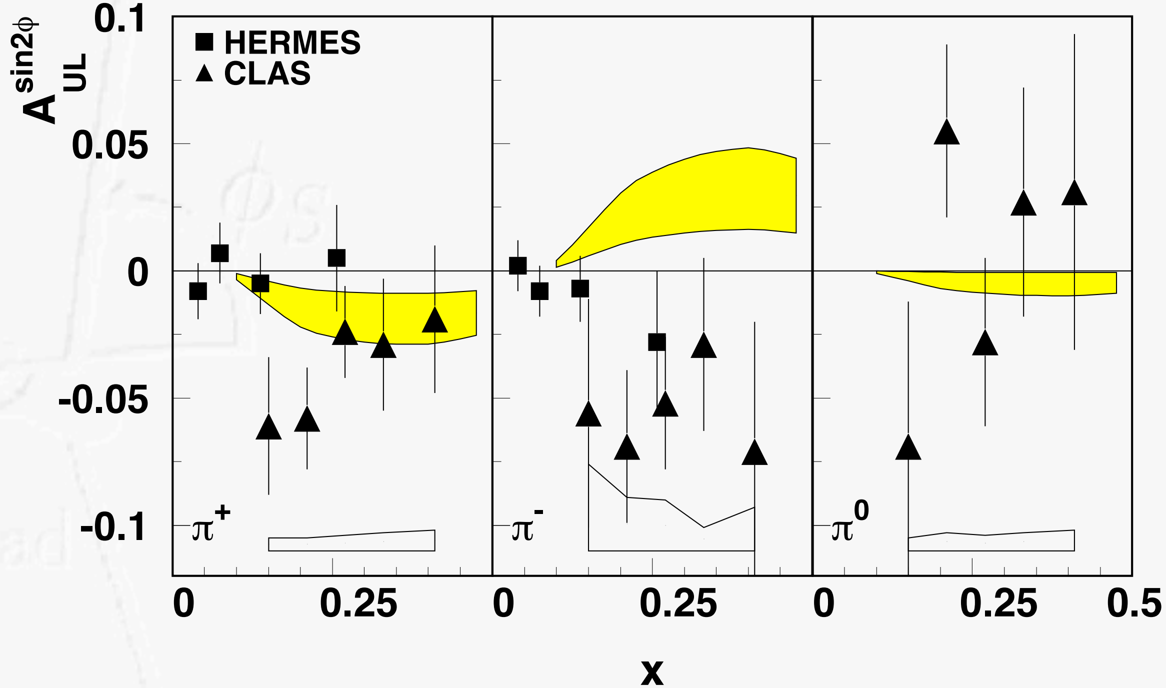
- chiral-odd ➥ needs Collins FF (or similar)
- leads to $\sin(3\phi - \phi_s)$ modulation in A_{UT}
- proton and deuteron data consistent with zero
- cancelations? pretzelosity=zero?
  or just the additional suppression by two powers of $P_{h\perp}$



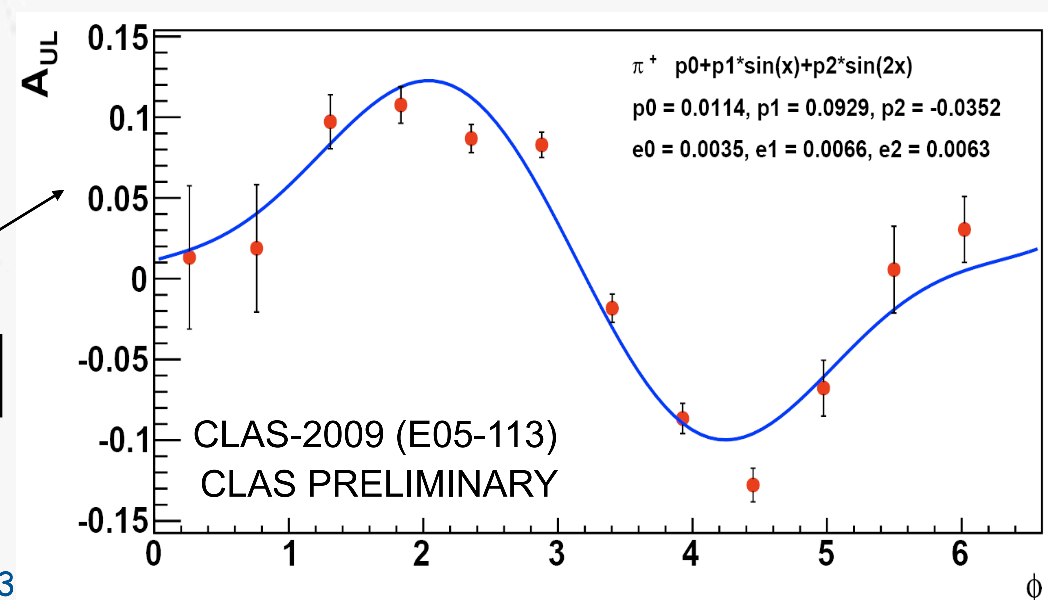
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Worm-Gear I

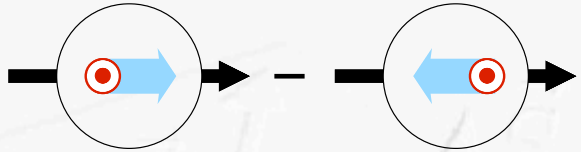
- again chiral-odd
- evidence from CLAS (violating isospin symmetry?)
- consistent with zero at COMPASS and HERMES
- new data from CLAS



~10% of E05-113 data

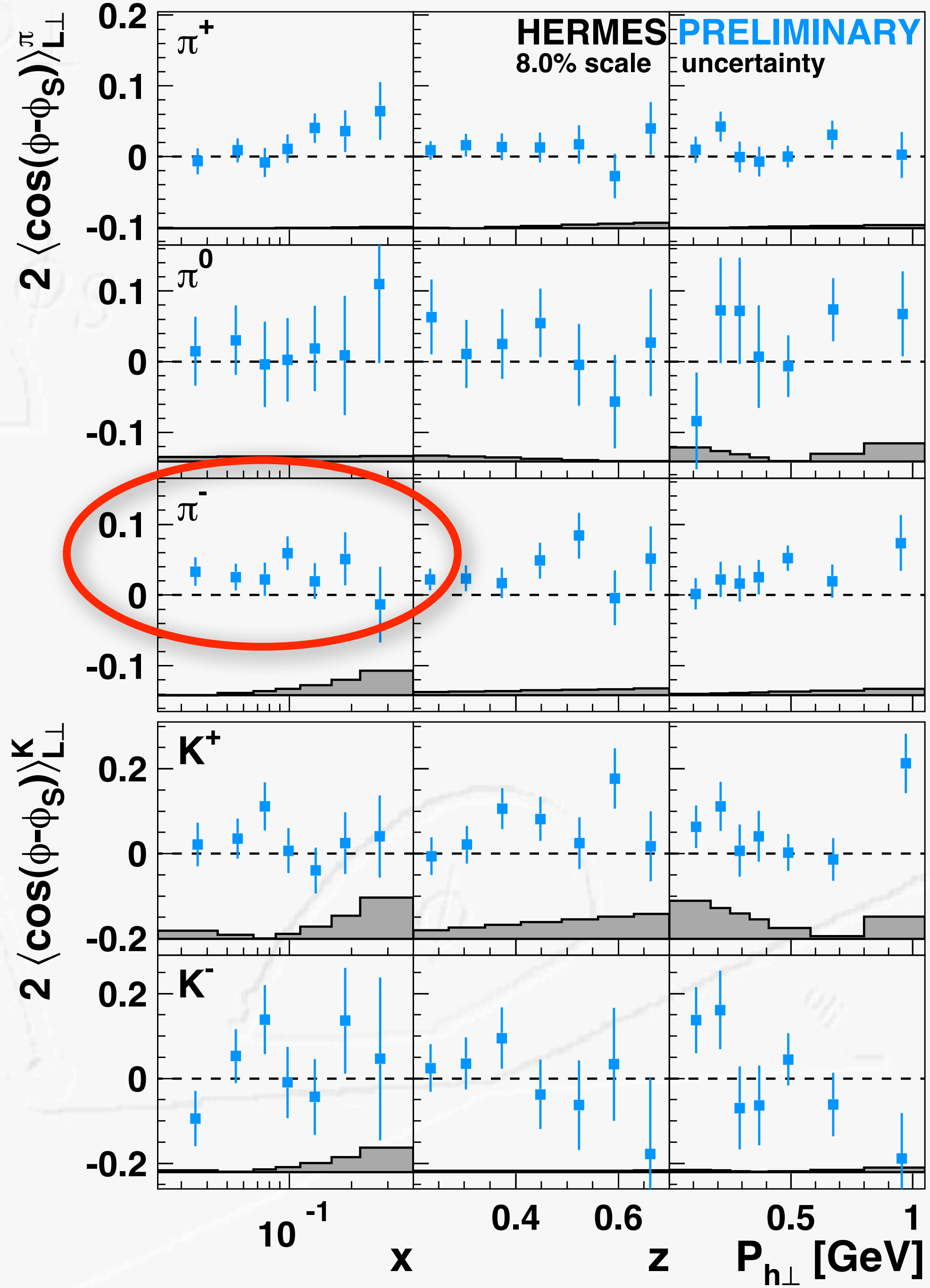


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

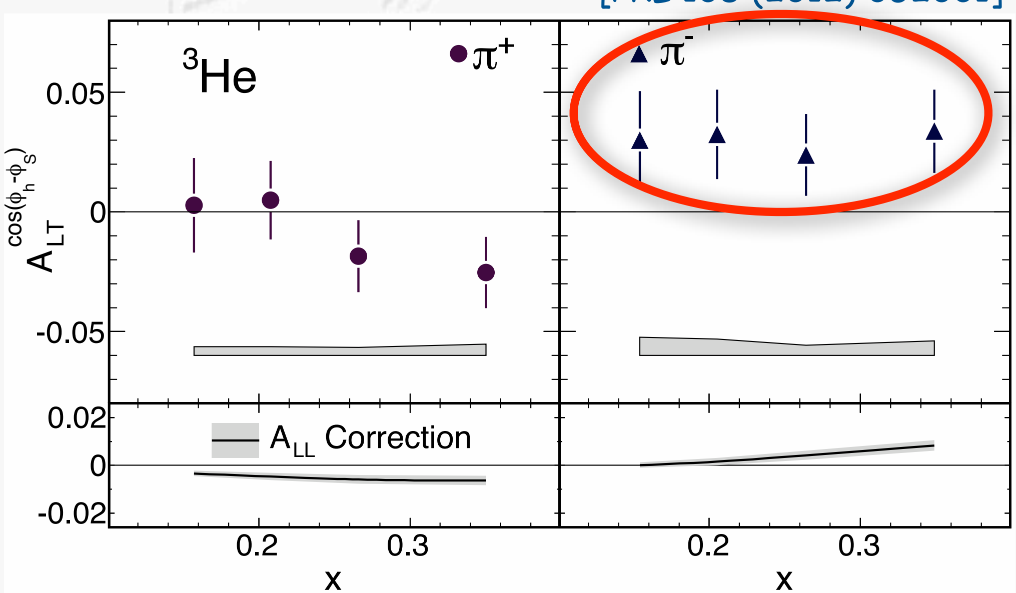


Worm-Gear II

- chiral even
- first direct evidence for worm-gear g_{1T} on
  - ^{3}He target at JLab
  - H target at HERMES



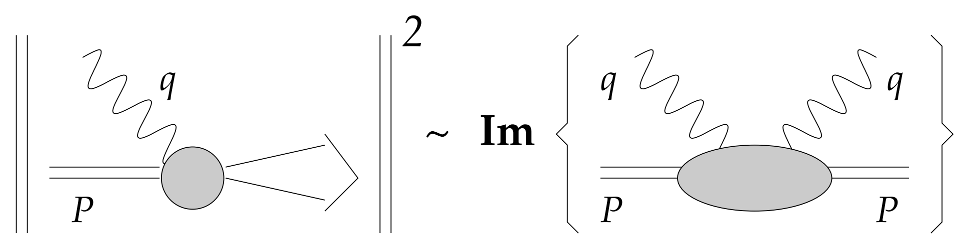
[PRL 108 (2012) 052001]



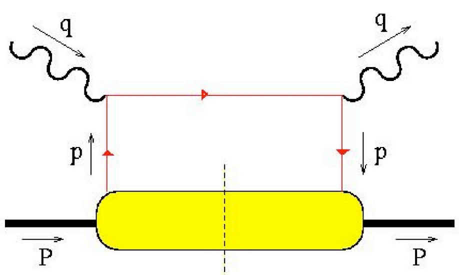
L, Sivers, the Sea, and the Missing Spin Programme

T-odd TMDs → gauge links and L

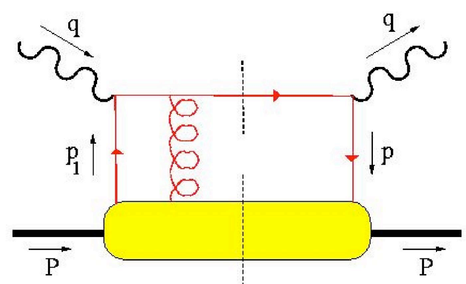
A T-odd function like $f_{1T}^{\perp}$ ***must*** arise from ***interference*** ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?



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

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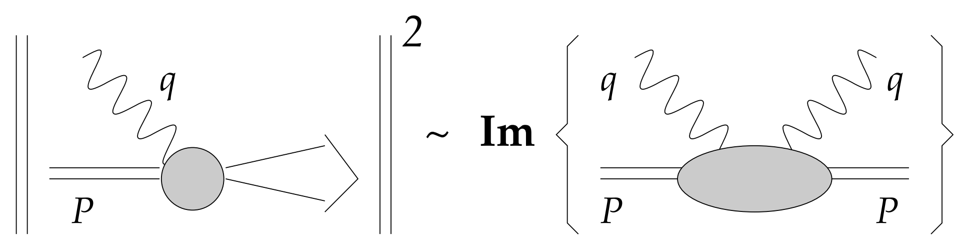

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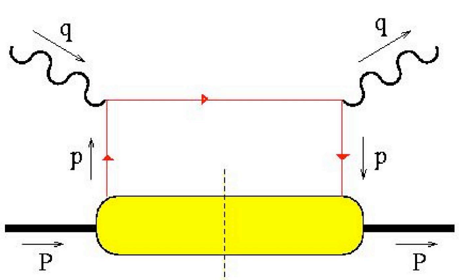

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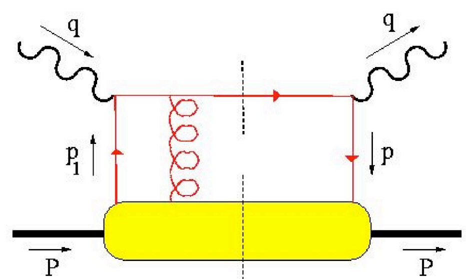

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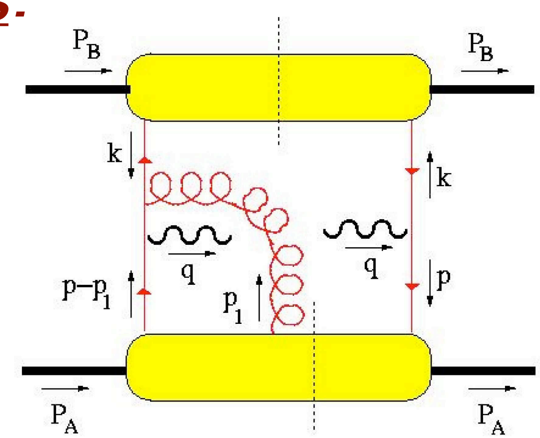
Such soft-gluon reinteractions with the soft wavefunction are ***final / initial state interactions*** ... and ***process-dependent*** ...

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



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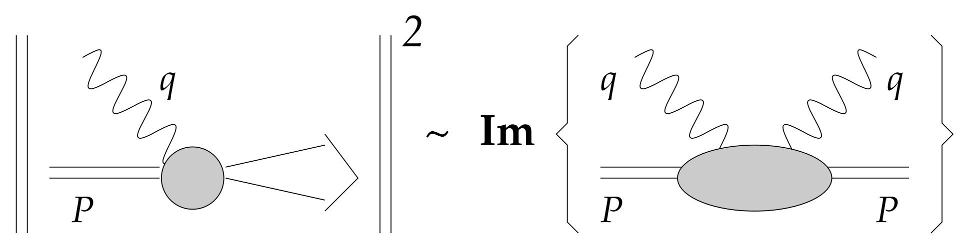

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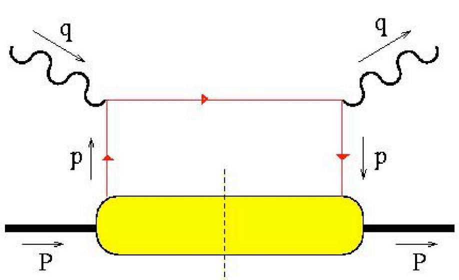

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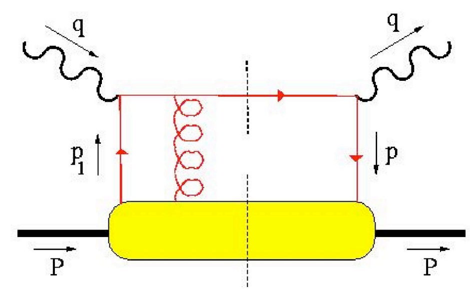

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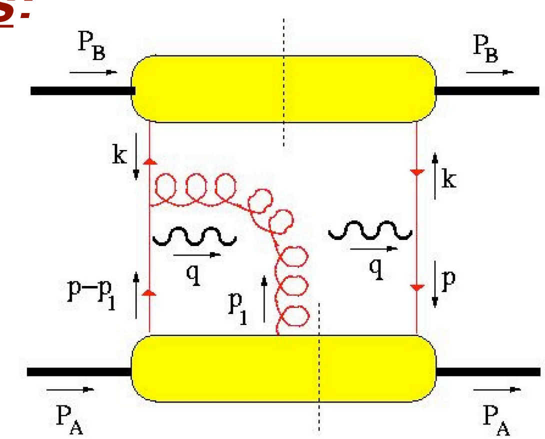
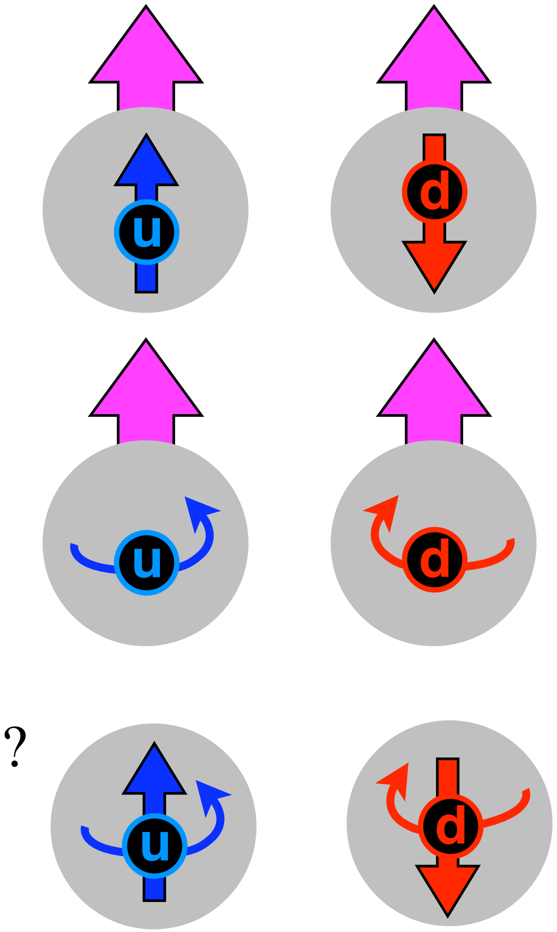


A Tantalizing Picture

- **Transversity**: $h_{1,u} > 0 \quad h_{1,d} < 0$
  $\rightarrow$ same as $g_{1,u}$ and $g_{1,d}$ in NR limit
- **Sivers**: $f_{1T^\perp,u} < 0 \quad f_{1T^\perp,d} > 0$
  $\rightarrow$ relat^n to **anomalous magnetic moment***
  $\boldsymbol{f_{1T^\perp,q} \sim \kappa_q}$ where $\kappa_u \approx +1.67 \quad \kappa_d \approx -2.03$
  values achieve $\kappa^{p,n} = \Sigma_q \, e_q \, \kappa_q$ with u,d only
- **Boer-Mulders:** follows that $h_{1^\perp,u}$ and $h_{1^\perp,d} < 0$?
  $\rightarrow$ **results** on **<cos(2Φ)>$_{UU}$** suggest yes:



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

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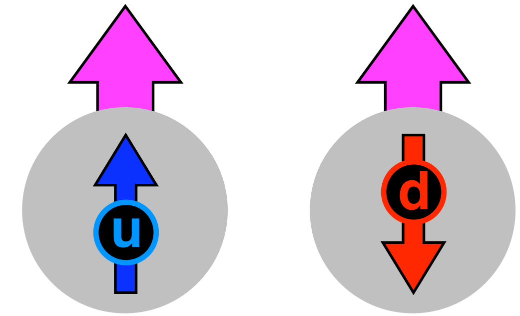

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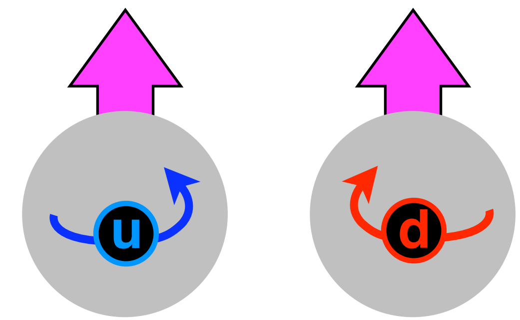

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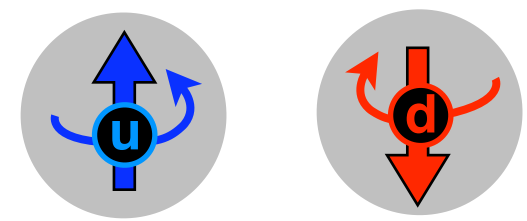
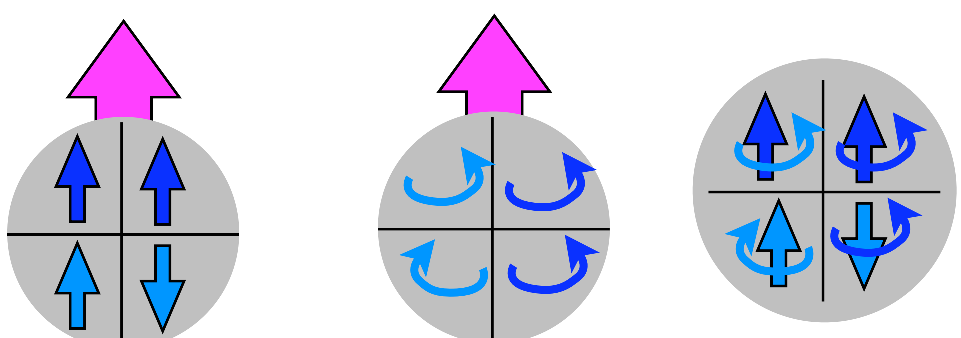


*N.B. these TMDs are all **independent***



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

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

A Tantalizing Picture

is it a HAPPY picture?

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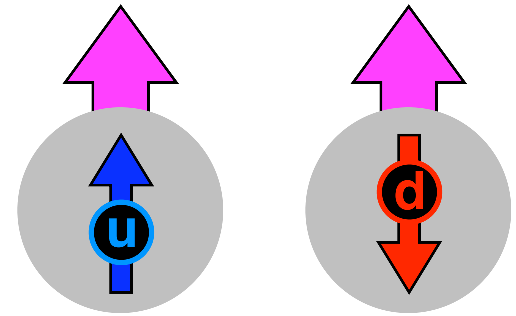

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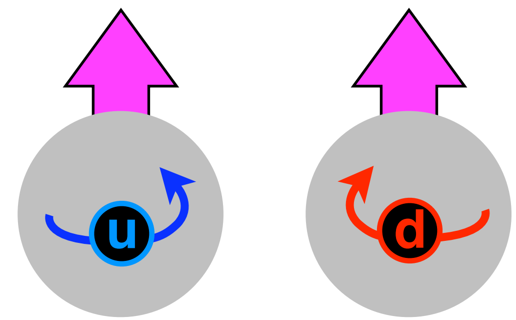

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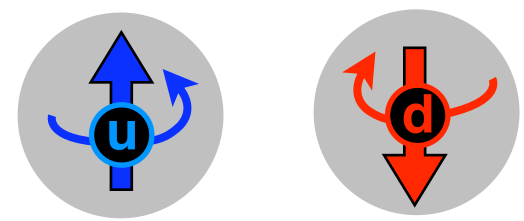

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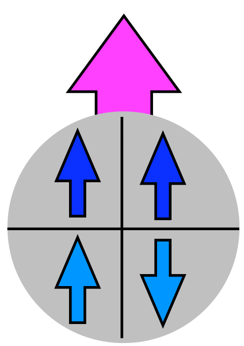
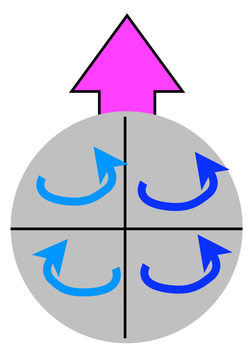
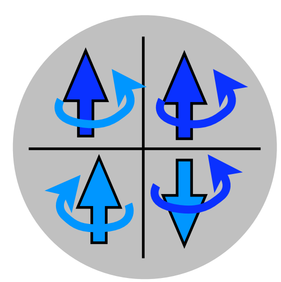


$\langle \vec{s}_u \cdot \vec{S}_p \rangle = +0.5$

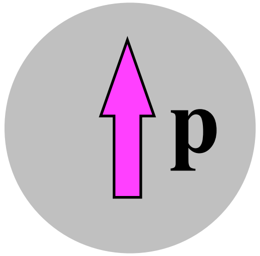


$\langle \vec{l}_u \cdot \vec{S}_p \rangle = +0.5$



$\langle \vec{s}_u \cdot \vec{l}_u \rangle = 0$

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



Meson Cloud on an Envelope → It ORBITS

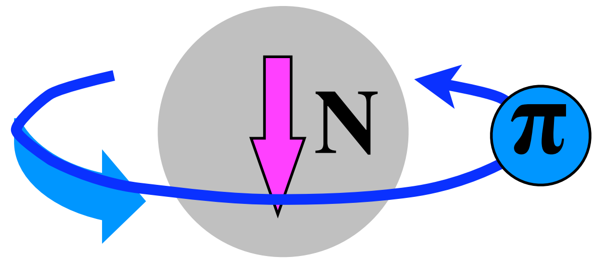
$|p\rangle = p + N\pi$
$+ \Delta\pi + \ldots$

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

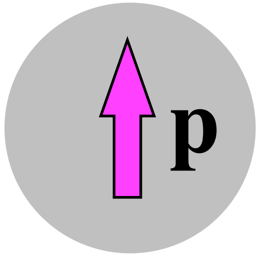
Nπ cloud:

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

$\otimes$



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



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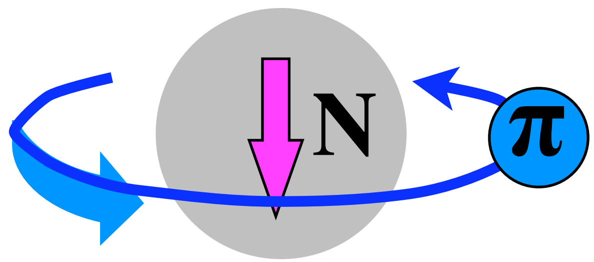
⊗

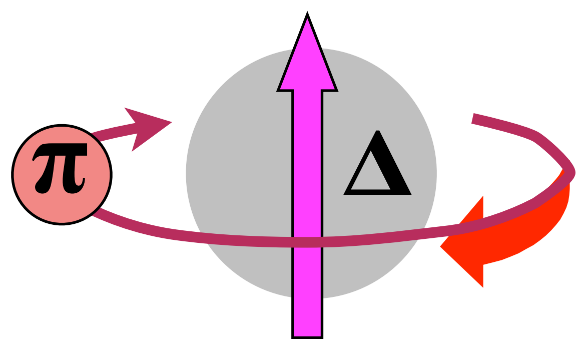


2/3 $L_z = +1$
1/3 $L_z = 0$

Δπ cloud:

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

⊗



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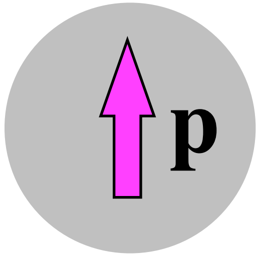


Meson Cloud on an Envelope → It ORBITS

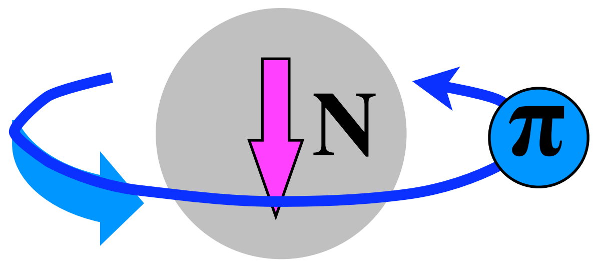
$|p\rangle = p + N\pi + \Delta\pi + \ldots$

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

Nπ cloud:

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

⊗



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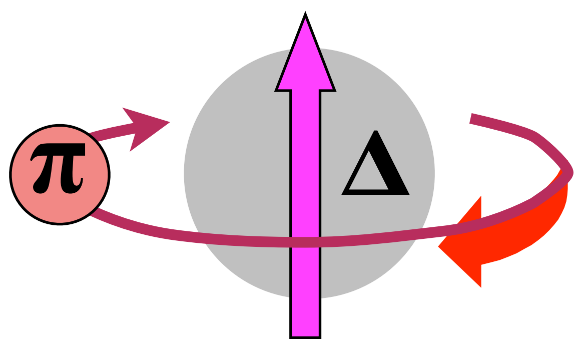

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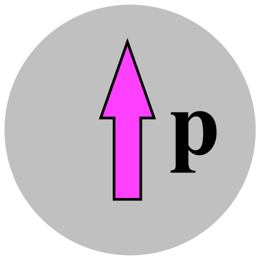

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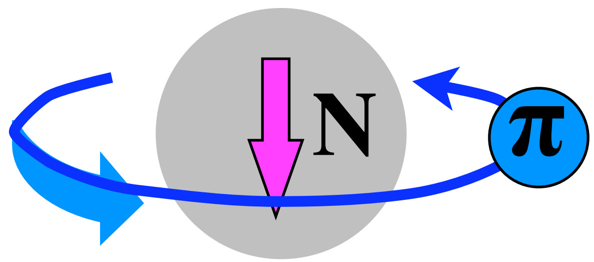

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d

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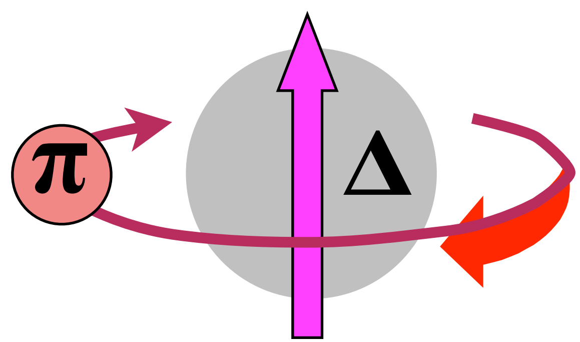
1/6 $\Delta^0\,\pi^+$

⊗



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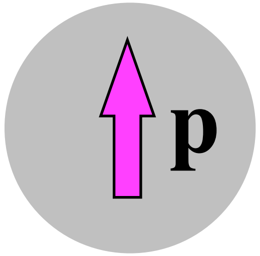

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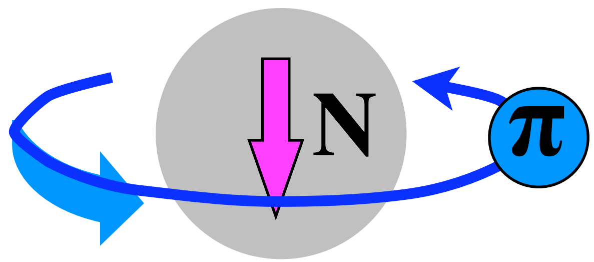

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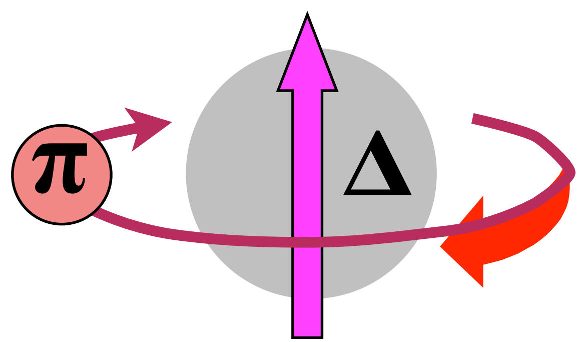

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⇒

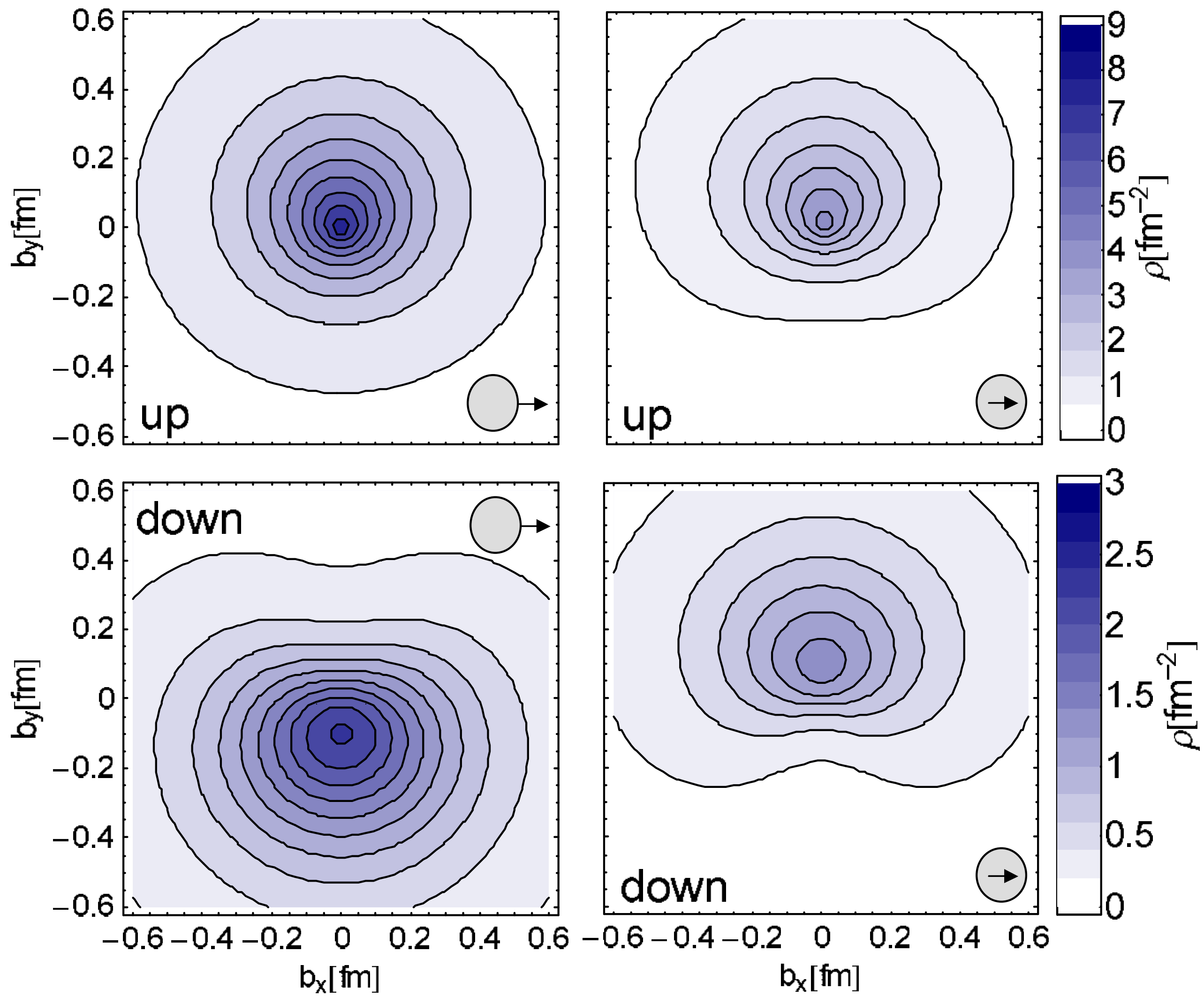
$L_u > 0$
$L_d < 0$
$L_{qbar} \neq 0$

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:*



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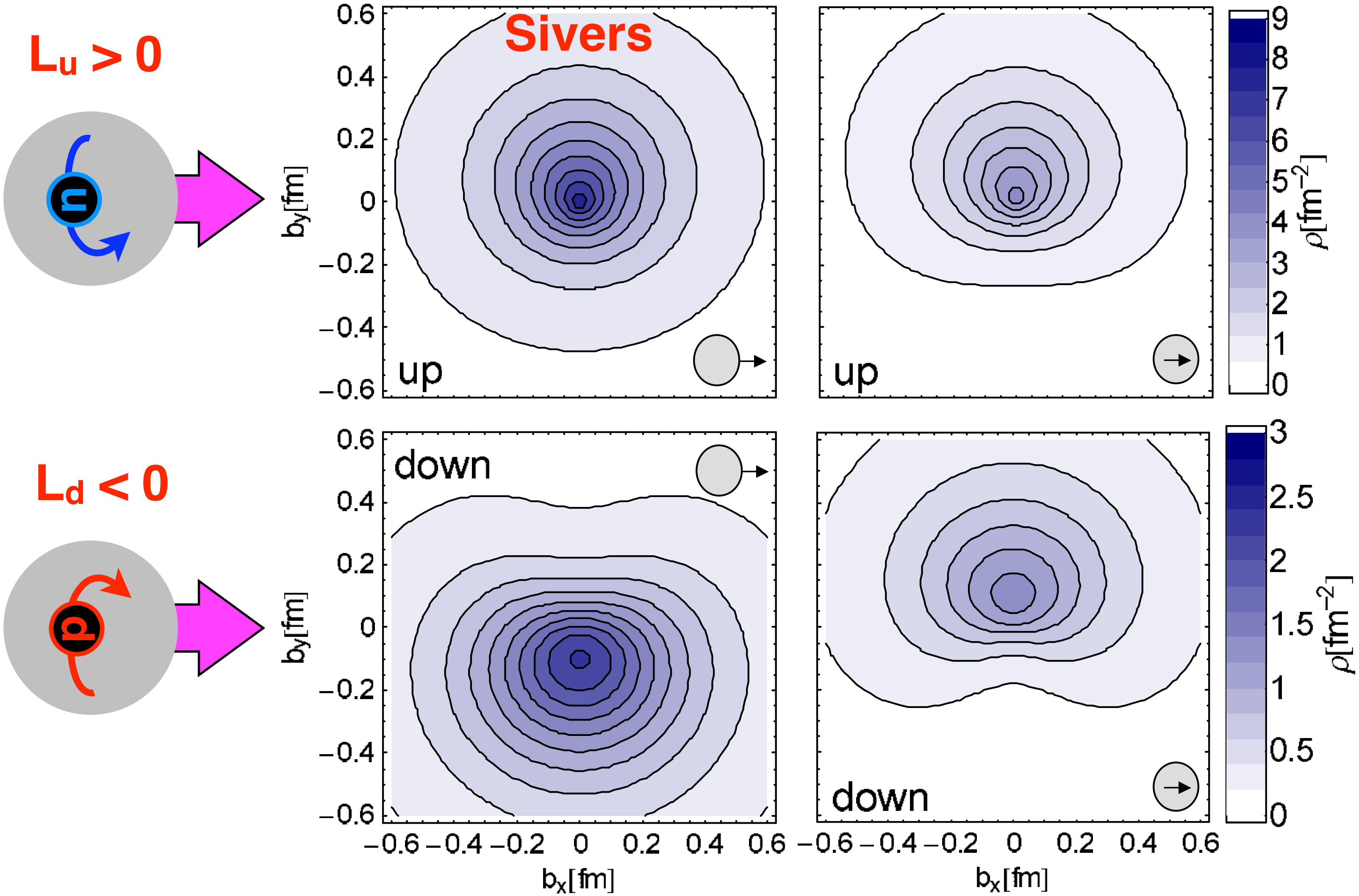

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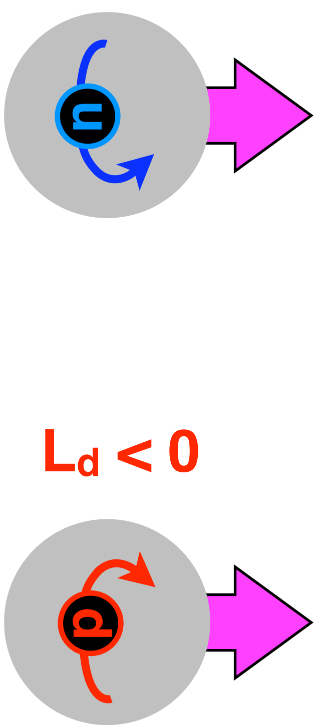
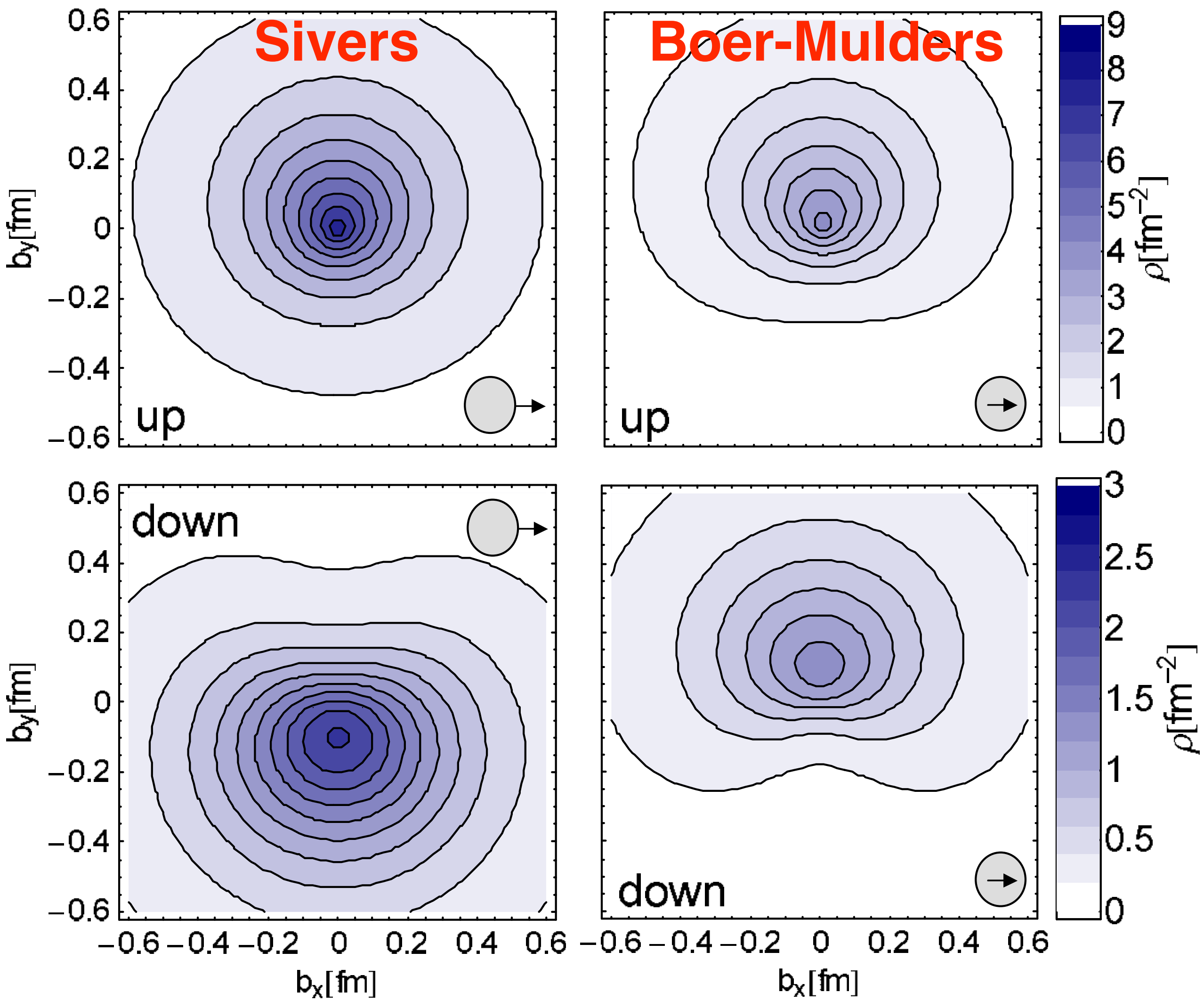
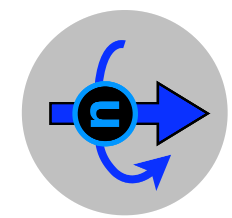


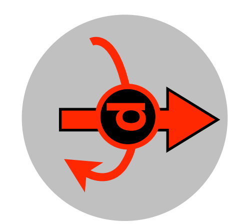


L_u // S_u



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

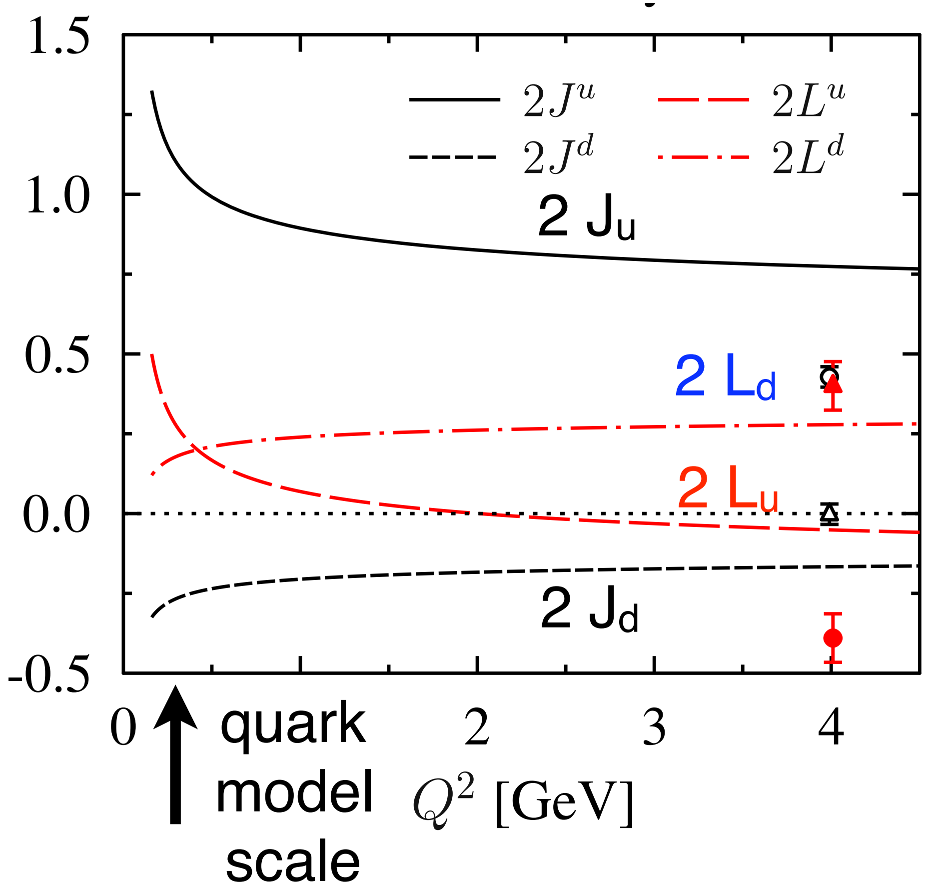
L_d // S_d



Thomas, PRL101 (2008)

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

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



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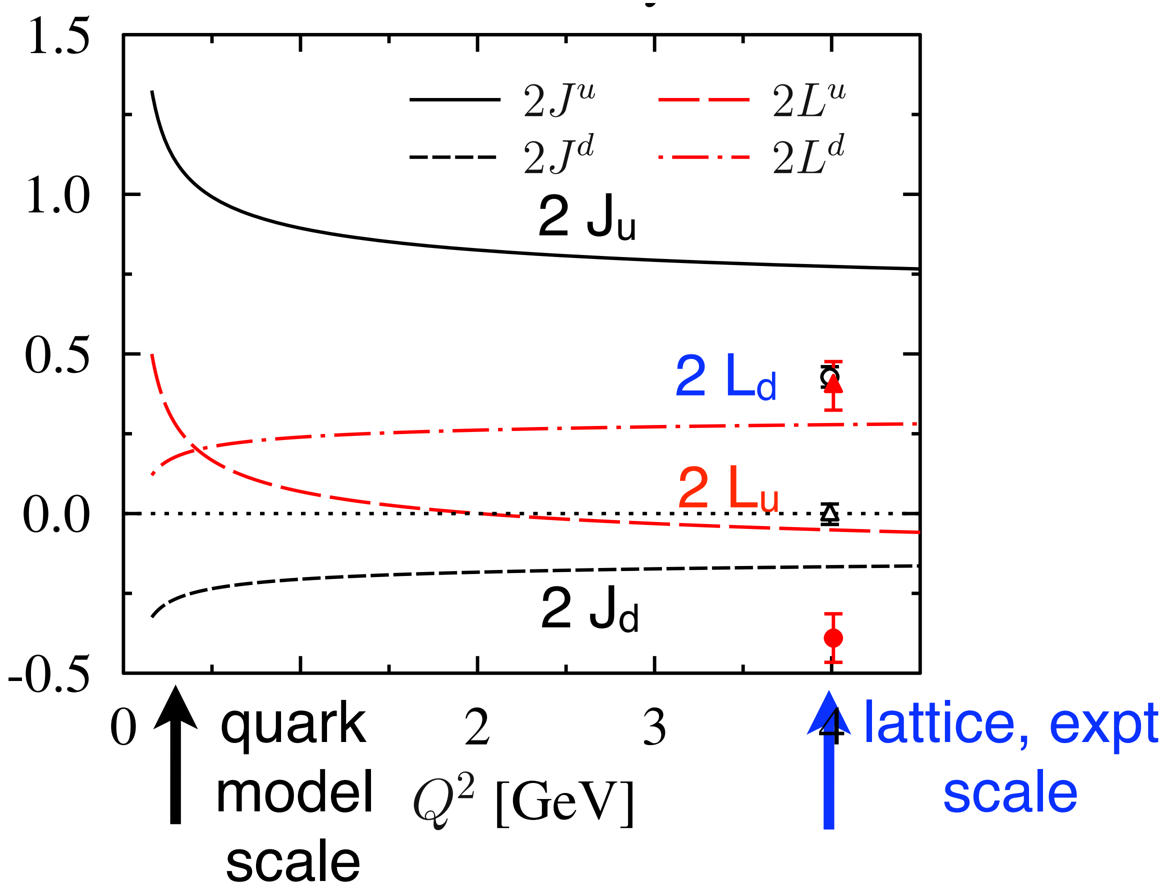

→ ***lattice shows $L_u < 0$ and $L_d > 0$ in longitudinal case at expt'al scales!***

Evolution might explain disagreement with quark models ...

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Wakamatsu, EPJA44 (2010)

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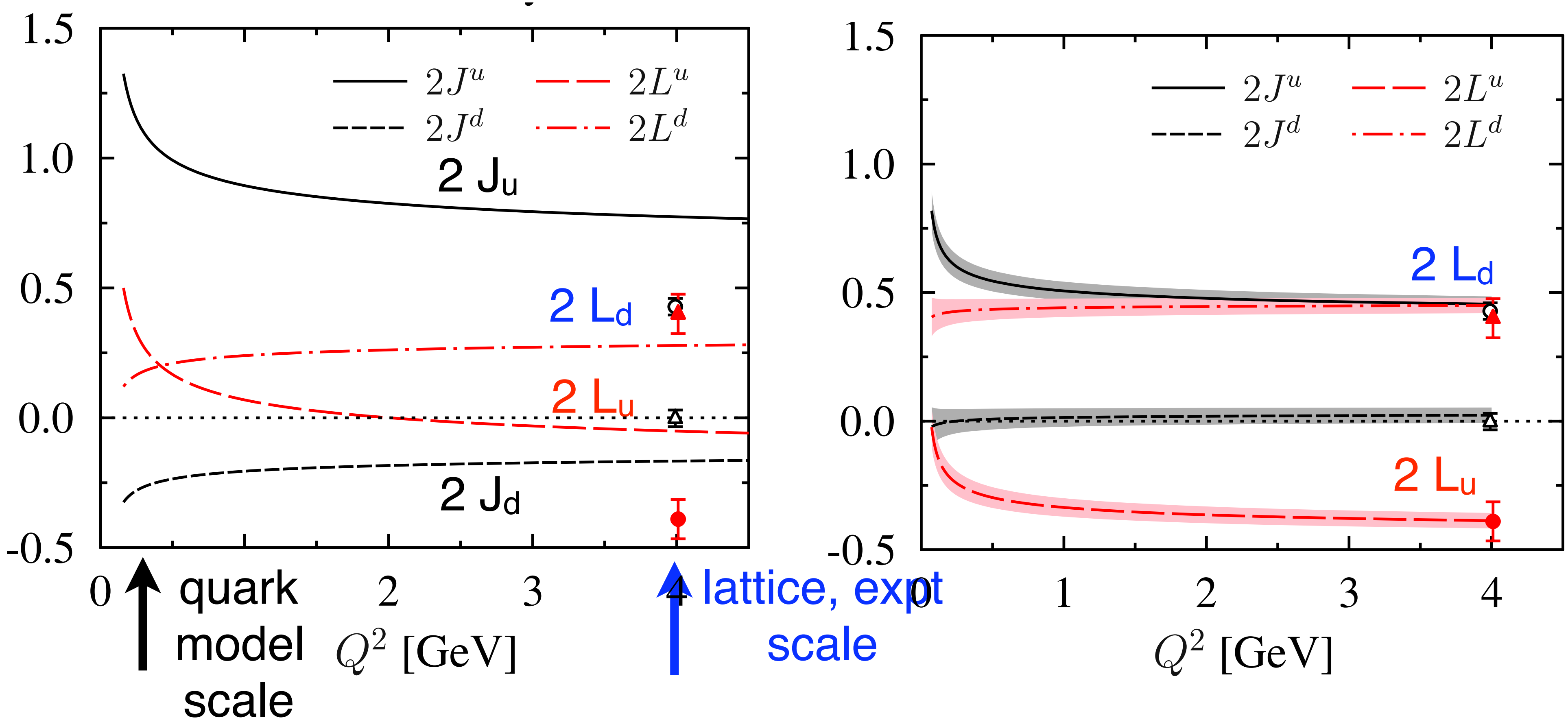

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Evolution might explain disagreement with quark models ...

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

- **Density shifts** + **lensing** function = **Sivers** (model-dependent)

The Mysterious E

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

  - $\int$ **E** dx = Pauli $\mathbf{F_2}$ $\rightarrow_{(t=0)}$ anomalous mag moment **κ** ∵ GPD basics
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$$2\,J_q = \Delta q + 2\,L_q$$

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Contradiction?

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"L" not uniquely defined

Contradiction?

Proton Spin Decompositions

$$J^{\mathbf{Ji}} = \frac{i}{2} q^\dagger (\vec{r} \times \vec{D})^z q + \frac{1}{2} q^\dagger \sigma^z q + 2\,\mathrm{Tr}\, E^j (\vec{r} \times \vec{D})^z A^j + \mathrm{Tr}(\vec{E} \times \vec{A})^z$$

L_q Δq L_g Δg

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

✘ **access** $\boldsymbol{\Delta g}$: no GI sep^n of Δg, L_g

✔ **measure** $\boldsymbol{L_q}$ (expt & lattice):
yes → via GPDs & DVCS

✘ **interpret** $\boldsymbol{L_q}$: covariant derivative
$D^\mu = \partial^\mu + ig^\mu$ ← **gluon interac's**

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Jaffe & Bashinsky, NPB 536 (1998)

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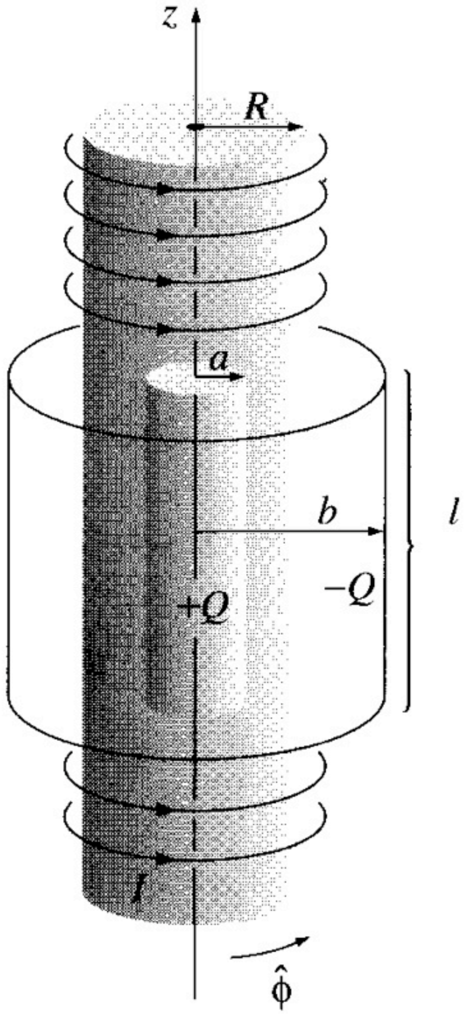
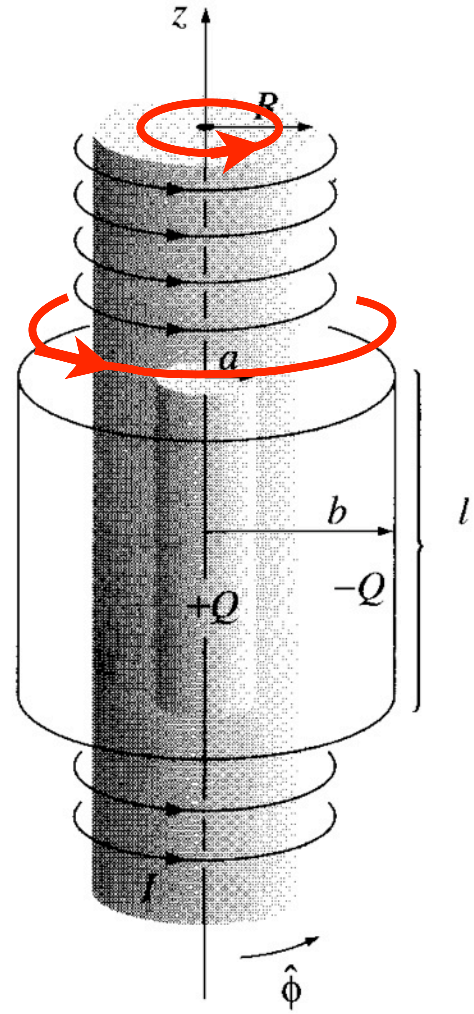
see ongoing work of **Wakamatsu** PRD 81 (2010), 83 (2011)
& **Chen** et al PRL 100 (2008), 103 (2009)

so "dynamical" $p - eA$ is the observable one ...

Solenoid with constant I; charged cylinders stationary



Solenoid I decreases to zero ... dB/dt induces $E \rightarrow$ rotates cylinders



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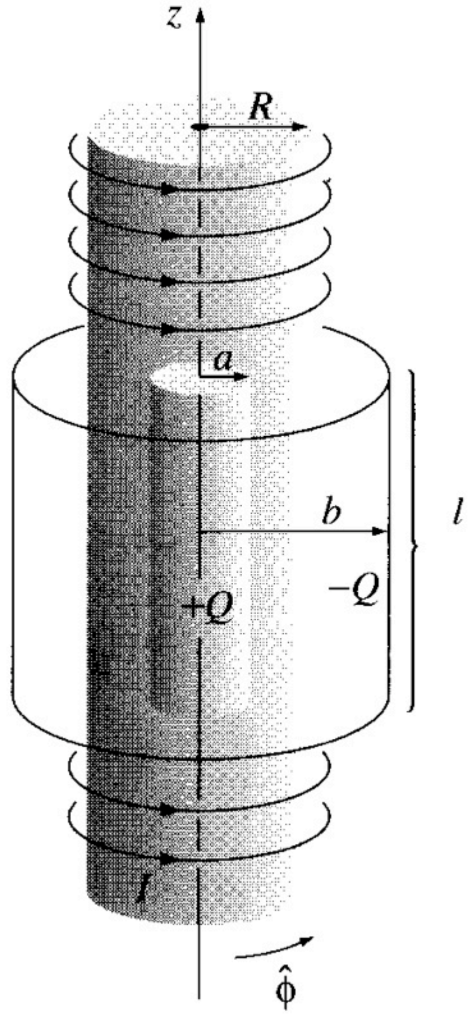

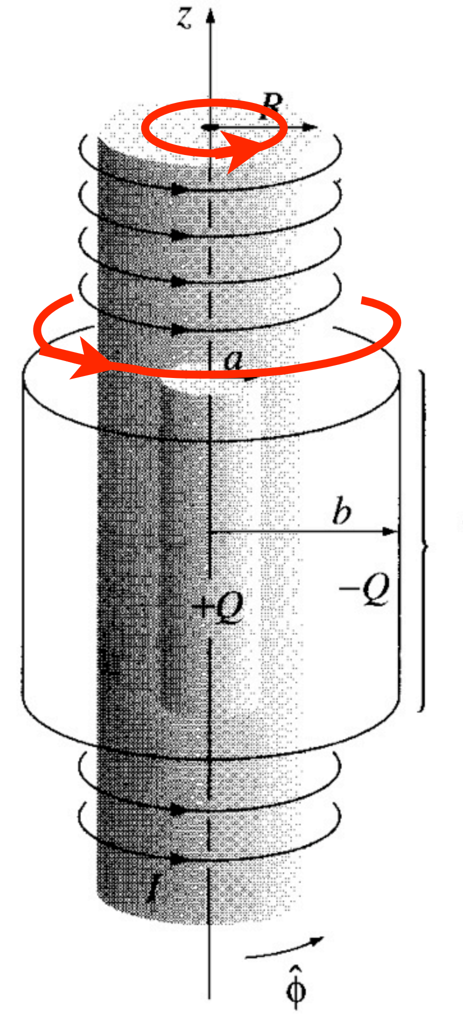

$$\vec{E}_{\text{ind}} = \hat{\phi}\,\frac{\mu_0 n\,|\dot{I}|\,s}{2}$$
for $s < R$

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inner $+Q$ cylinder:

$$\vec{L}_+ = \int a\hat{s} \times Q\,\vec{E}_{\text{ind}}\Big|_{s=a}\,dt$$
$$= \hat{z}\,\frac{\mu_0 n I Q}{2}\,a^2$$

outer $-Q$ cylinder:

$$\vec{L}_- = -\hat{z}\,\frac{\mu_0 n I Q}{2}\,R^2$$

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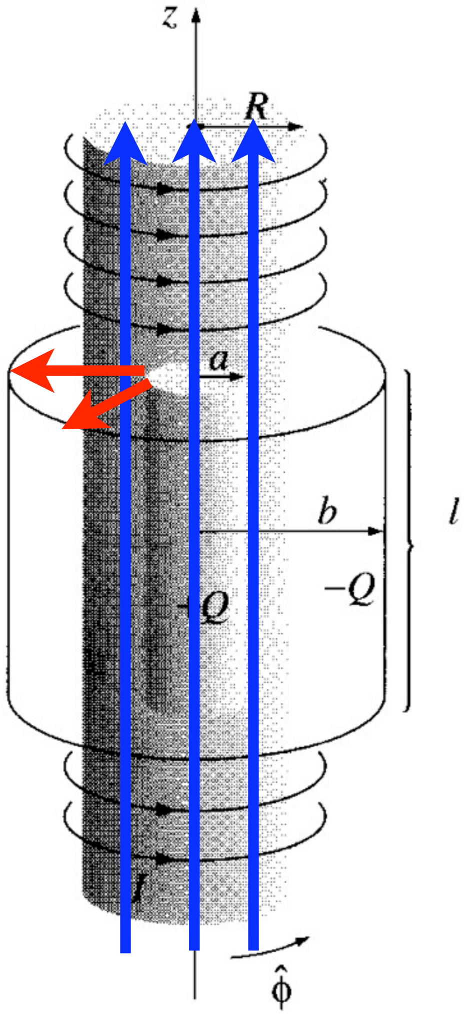
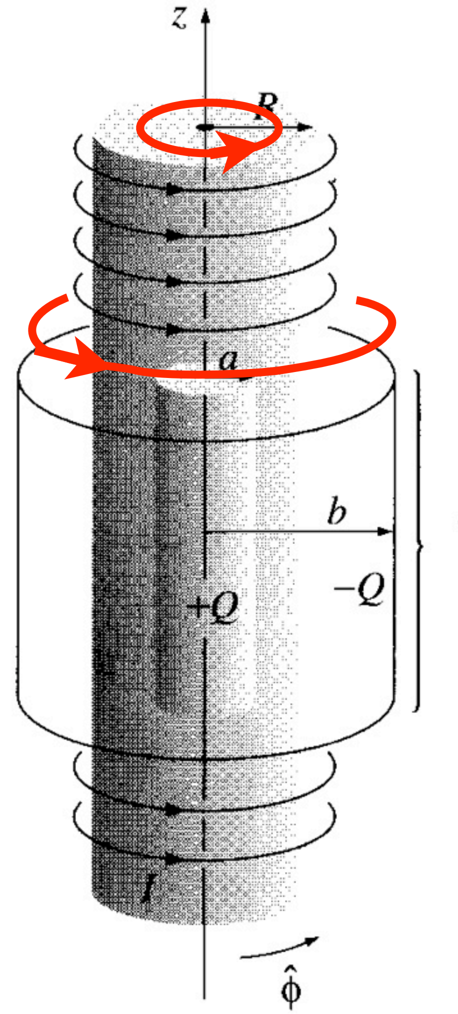
$$\vec{E} = \frac{Q\,\hat{s}}{2\pi\varepsilon_0 l s}$$

for $a < s < b$

$$\vec{B} = \mu_0 n I\,\hat{z}$$

for $s < R$





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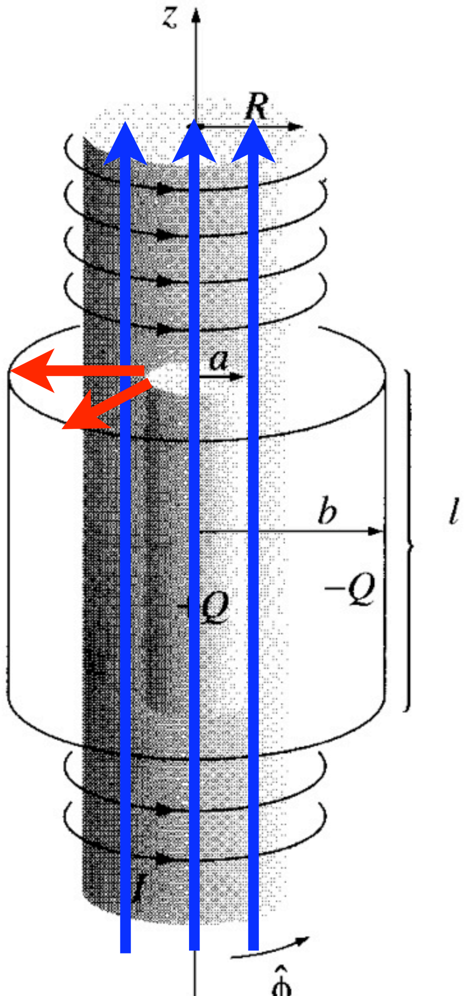

$\vec{E} = \dfrac{Q\,\hat{s}}{2\pi\varepsilon_0 l s}$ for $a < s < b$

$\vec{B} = \mu_0 n I\,\hat{z}$ for $s < R$

$$\therefore \vec{\wp}_{\rm field} = \vec{S}/c^2 = \varepsilon_0 \vec{E}\times\vec{B} = -\hat{\phi}\,\frac{\mu_0 n I Q}{2\pi l s}$$

$$\therefore \vec{\mathbf{L}}_{\rm field} = \int_{s=a}^{s=R} s\hat{s}\times\vec{\wp}_{\rm field}\,dV = -\hat{z}\,\frac{\mu_0 n I Q}{2}(R^2 - a^2)$$

Solenoid I decreases to zero ...
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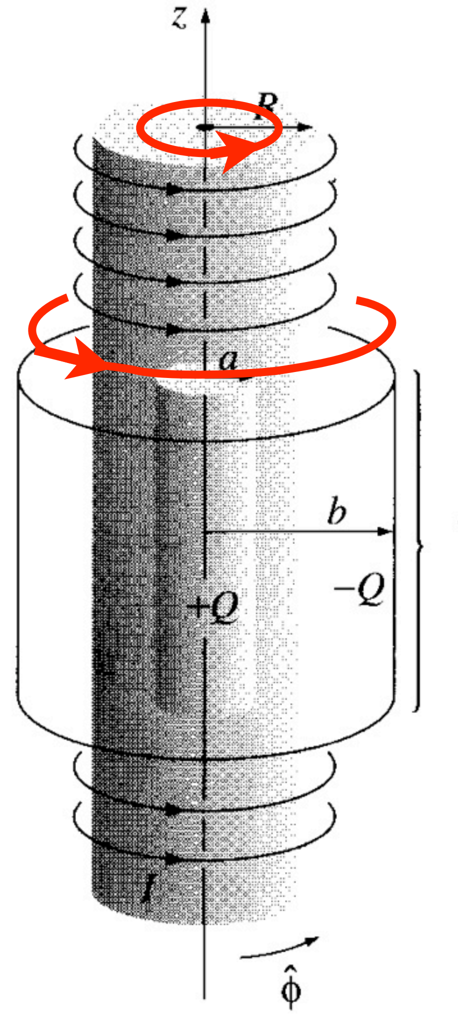

$\vec{E}_{\rm ind} = \hat{\phi}\,\dfrac{\mu_0 n\,|\dot{I}|\,s}{2}$ for $s < R$

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inner $+Q$ cylinder:

$$\vec{L}_+ = \int a\hat{s}\times Q\,\vec{E}_{\rm ind}\Big|_{s=a} dt = \hat{z}\,\frac{\mu_0 n I Q}{2}a^2$$

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so "dynamical" $p - eA$ is the observable one ...

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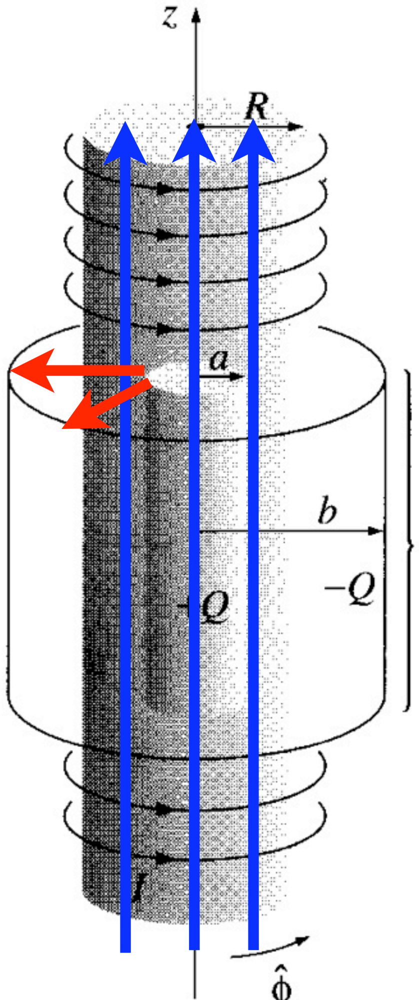

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Both needed to conserve L, but ...

mechanical $\mathbf{L}_{\text{cylinder}}$ = r x p is

- **measurable**
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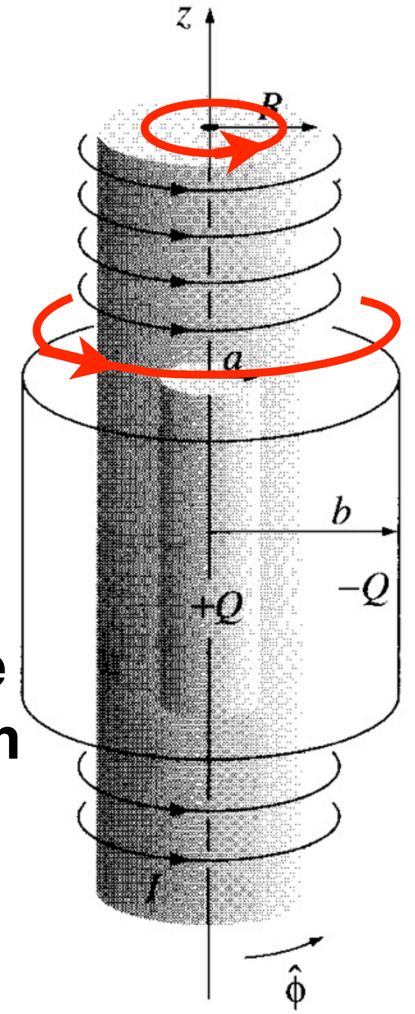

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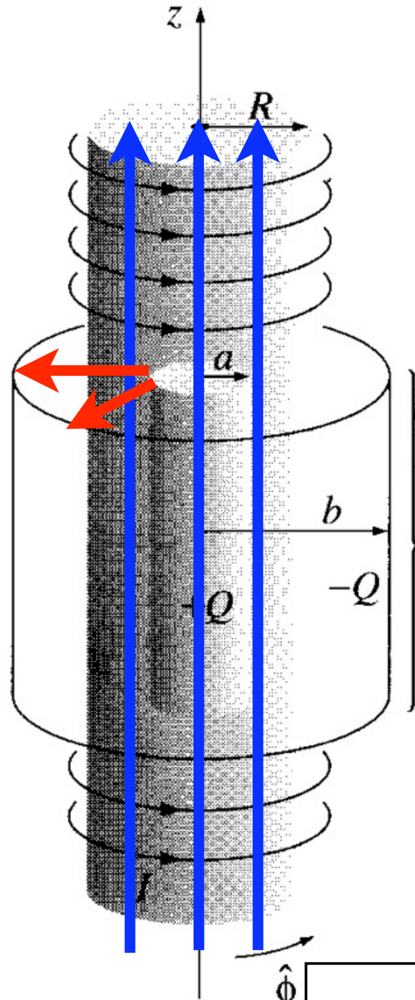

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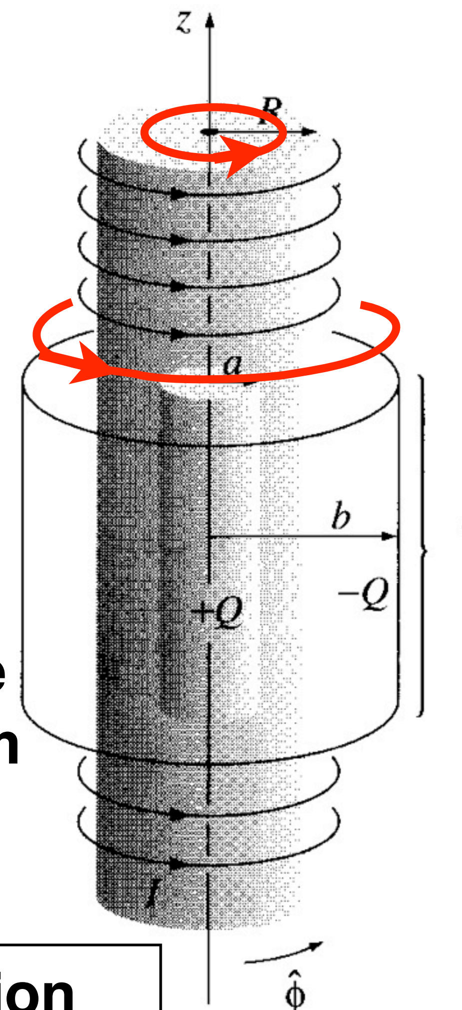
classical intuition doesn't help with the **meaning** of gauge-covariant $iD^\mu = i\partial^\mu - eA^\mu$



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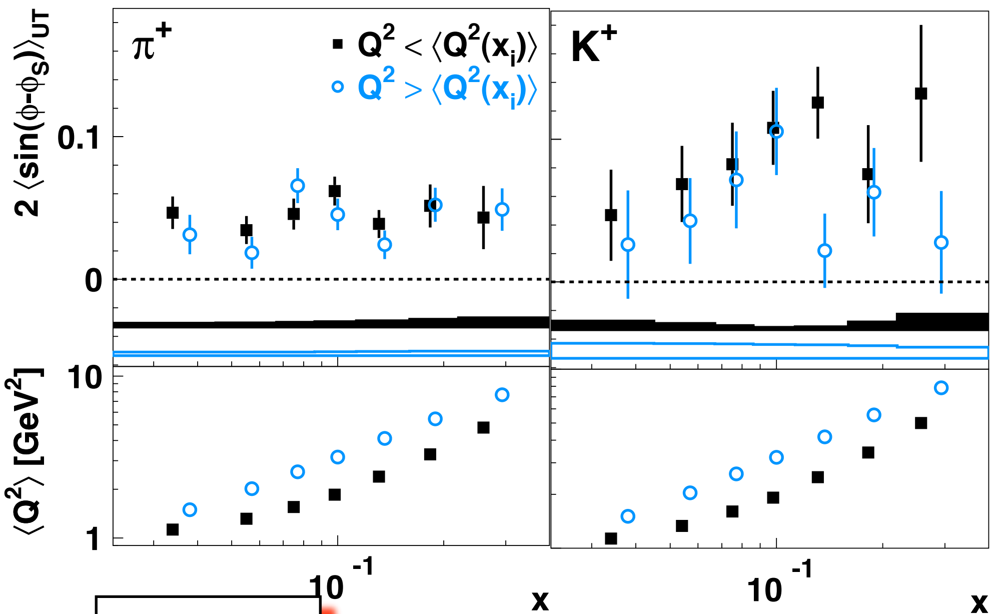
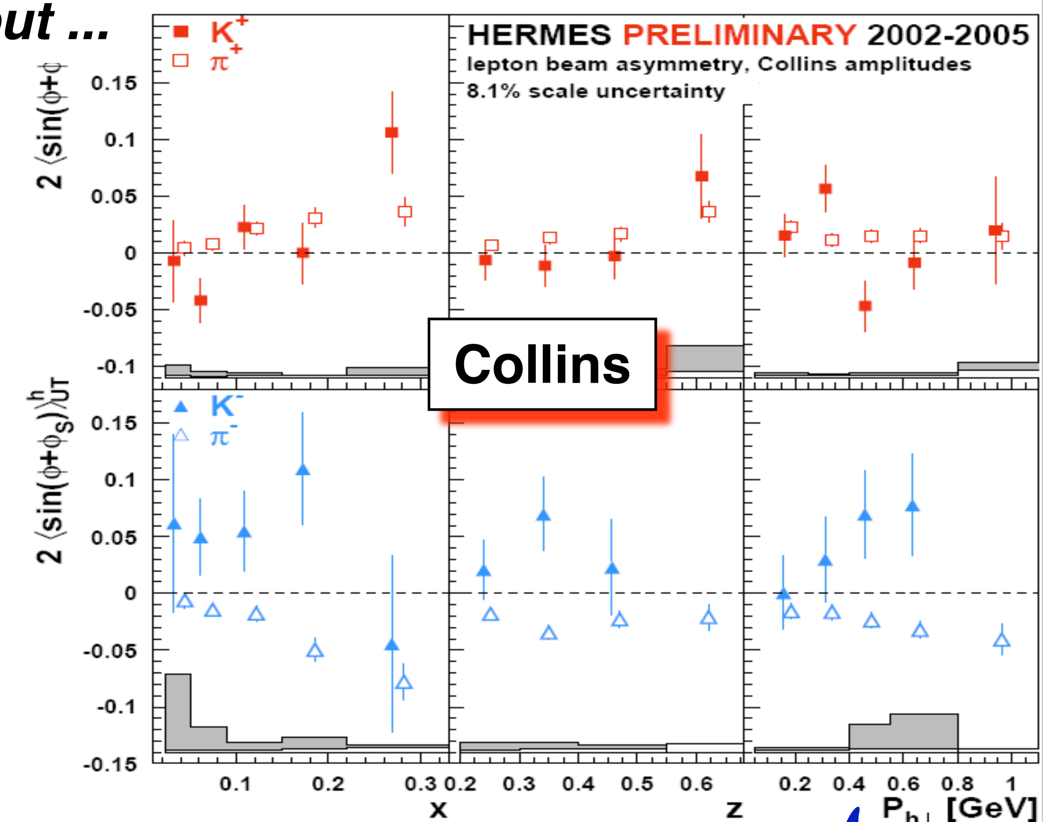
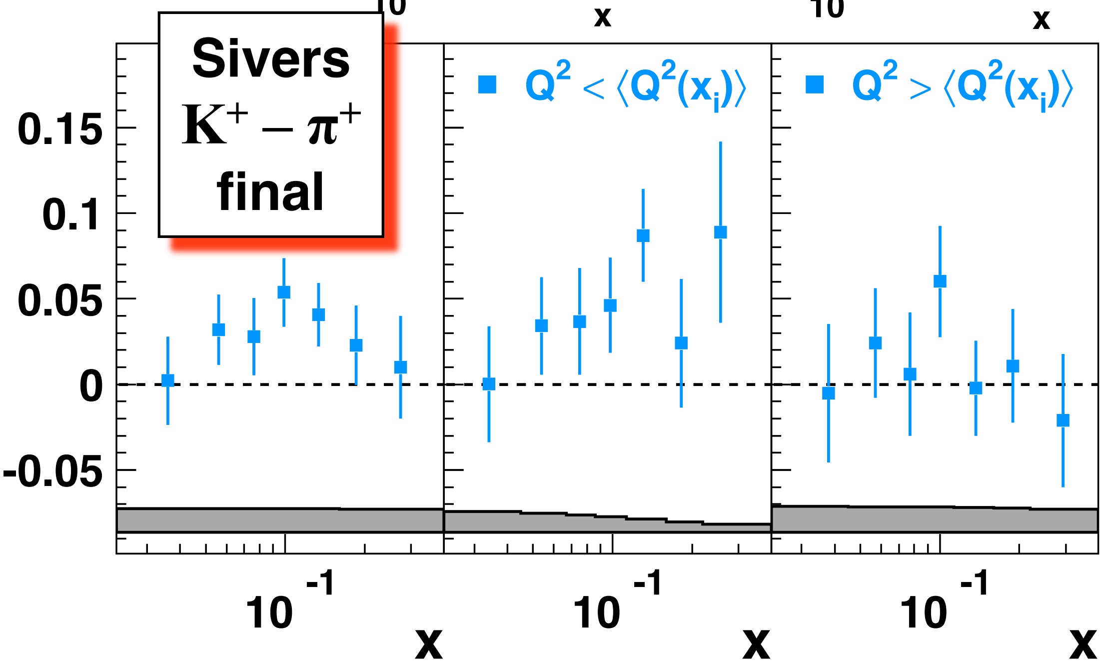
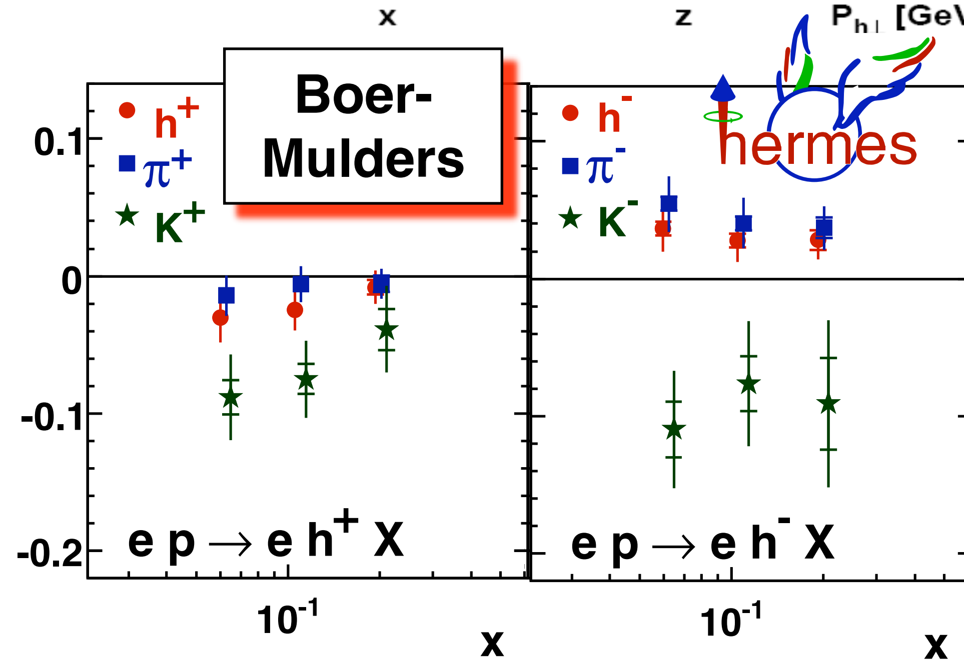
*New **Sivers** fits give ≈0 for antiquarks, but ...*

The Kaon Collection









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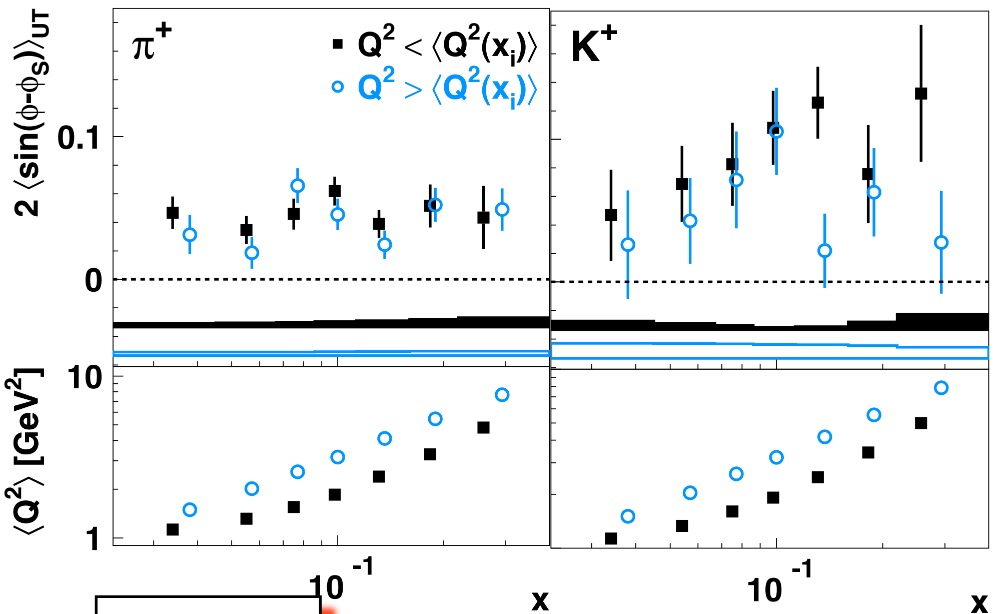

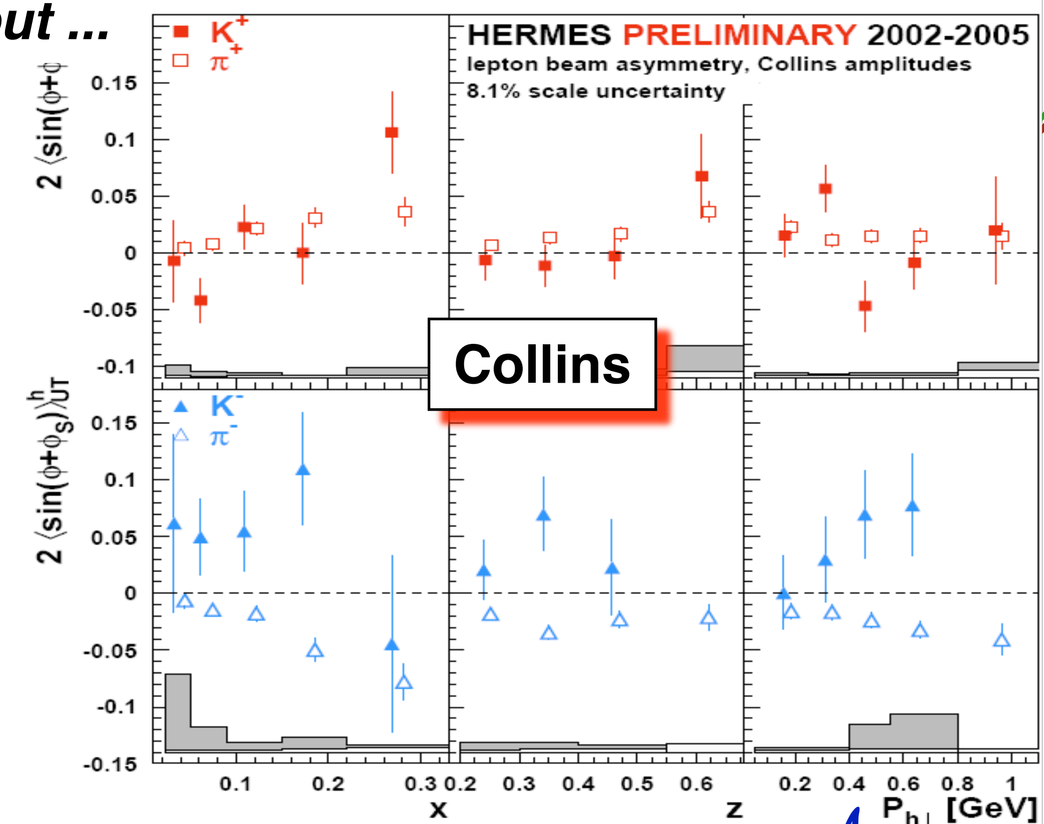

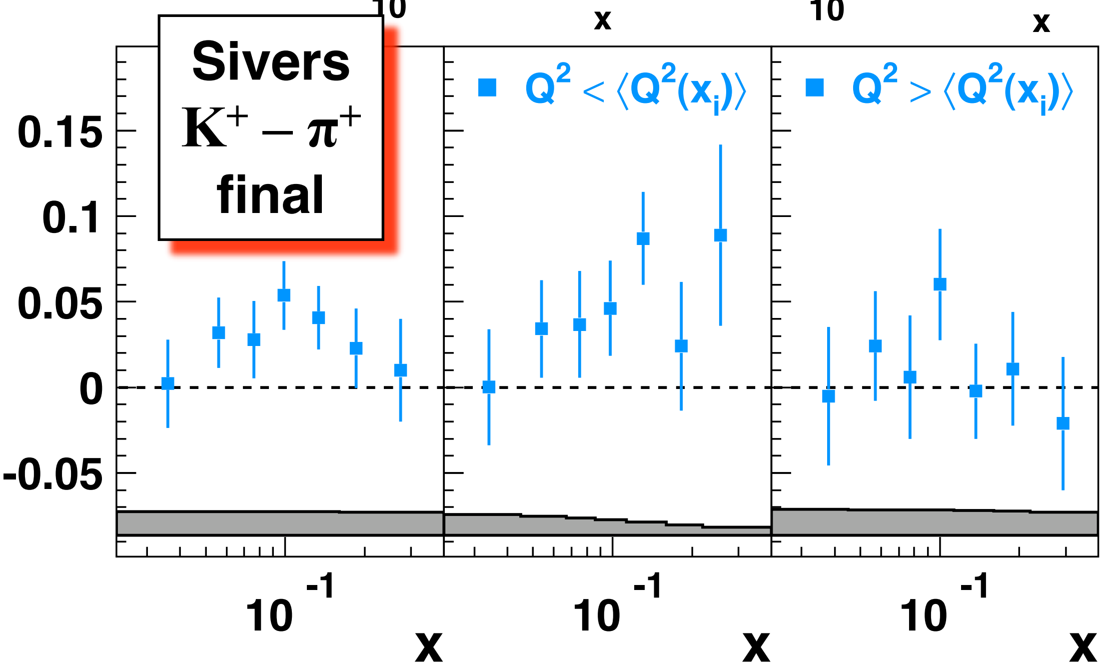

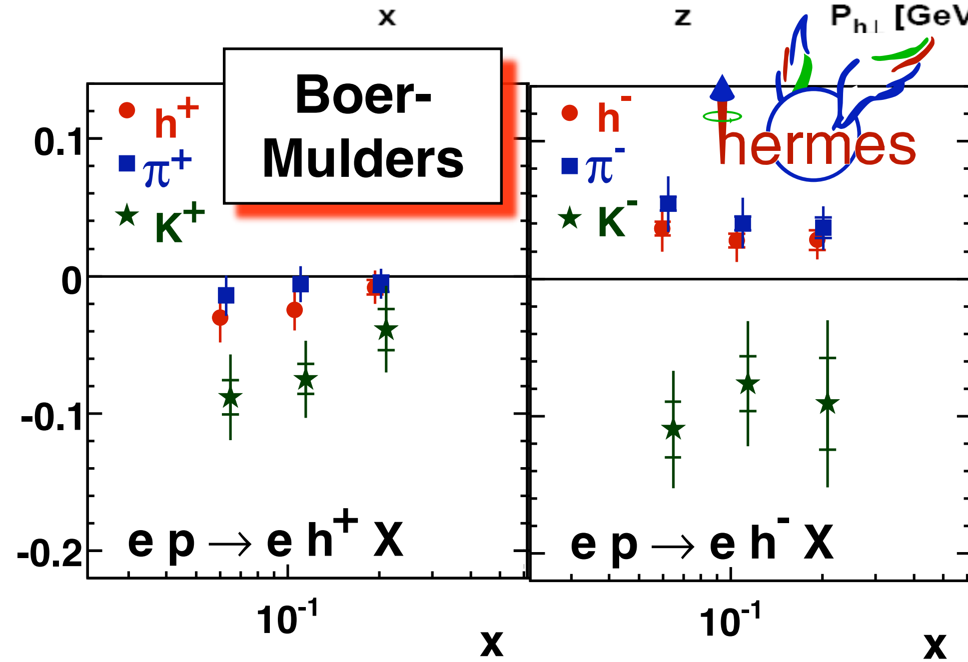

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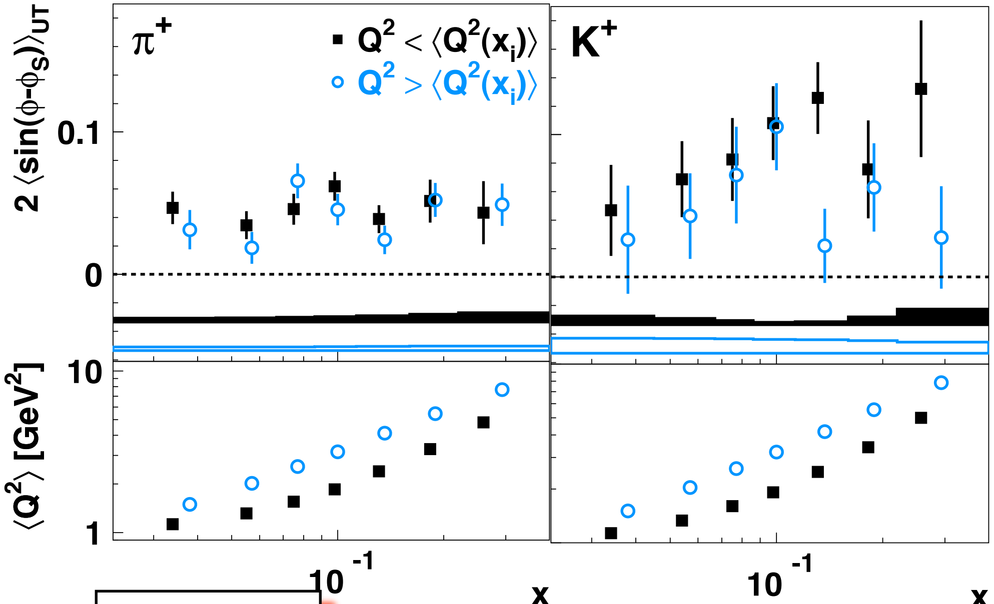
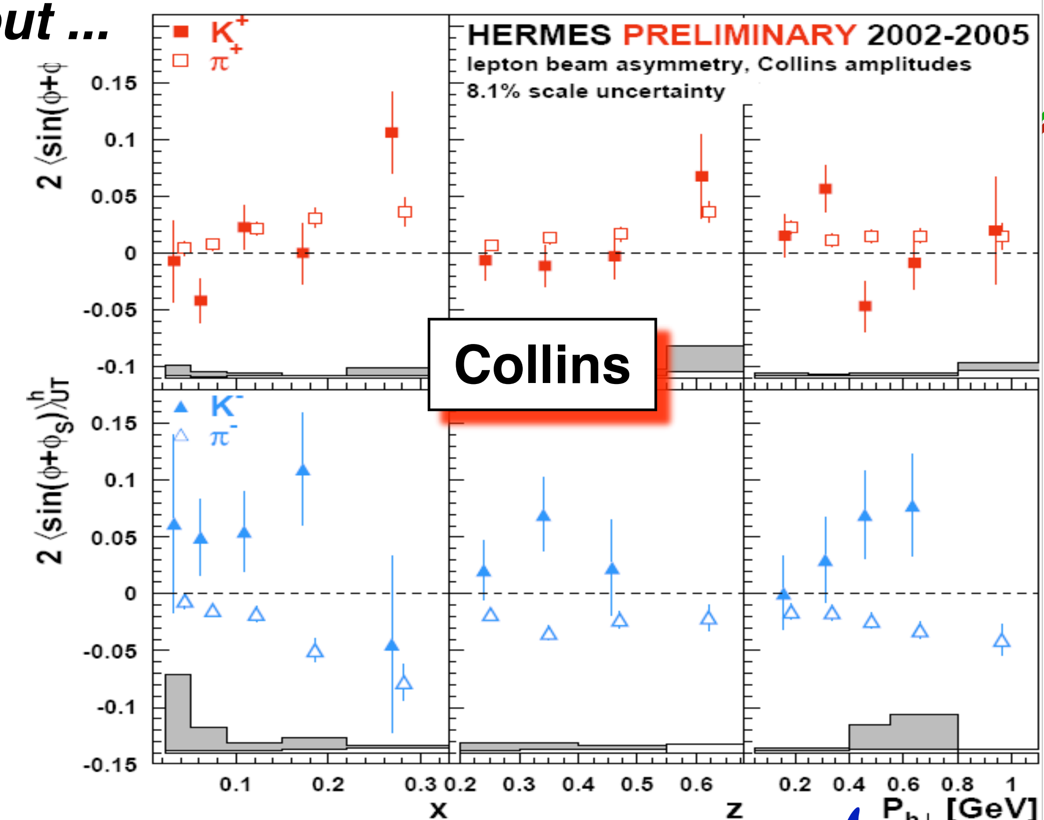
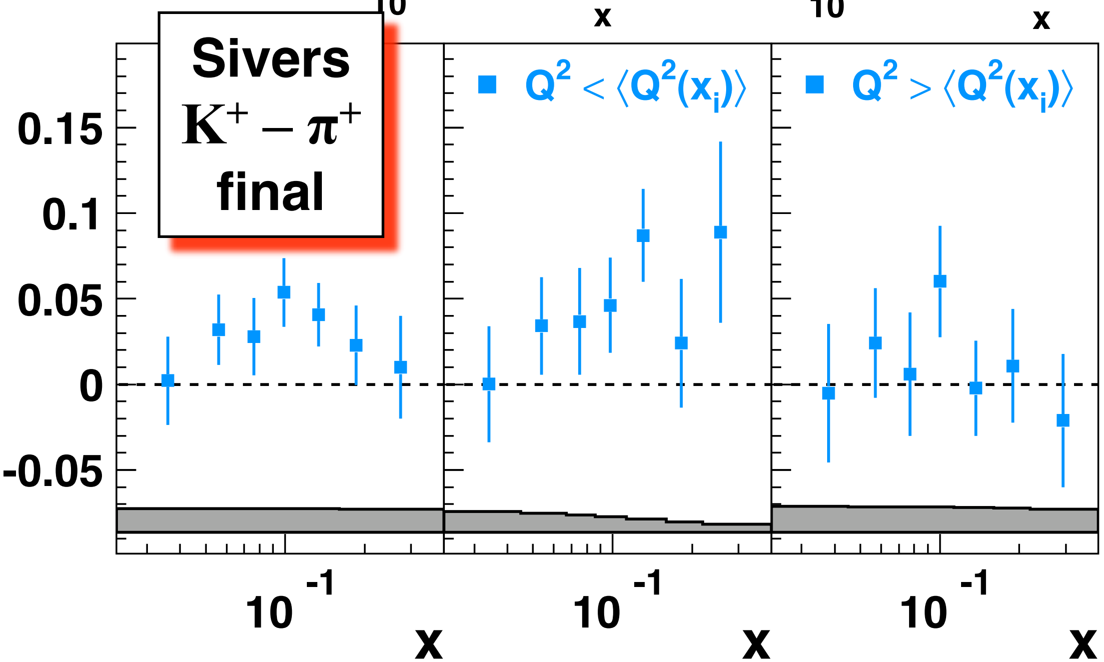
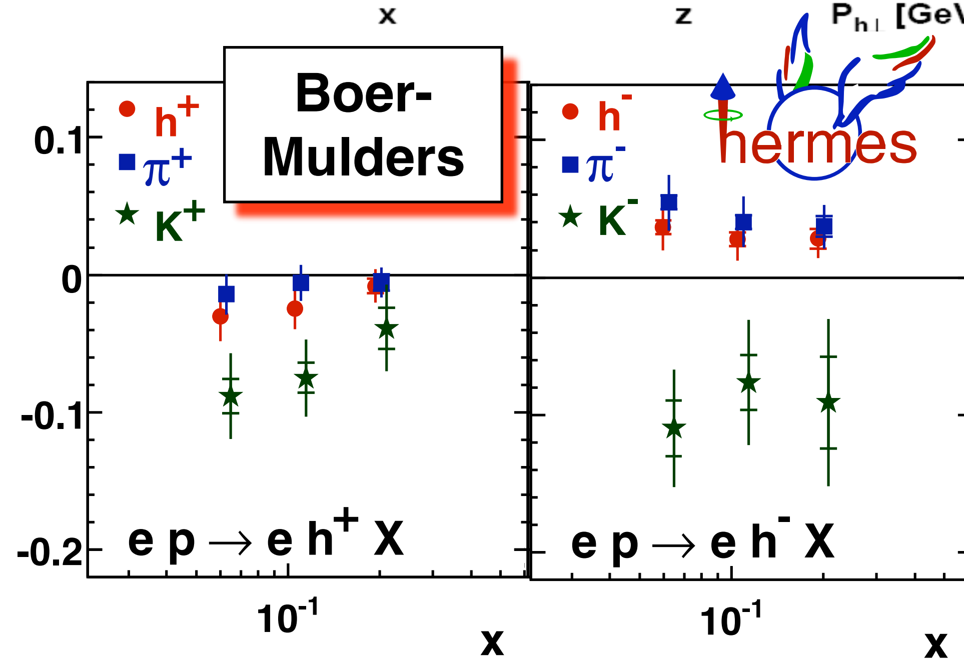






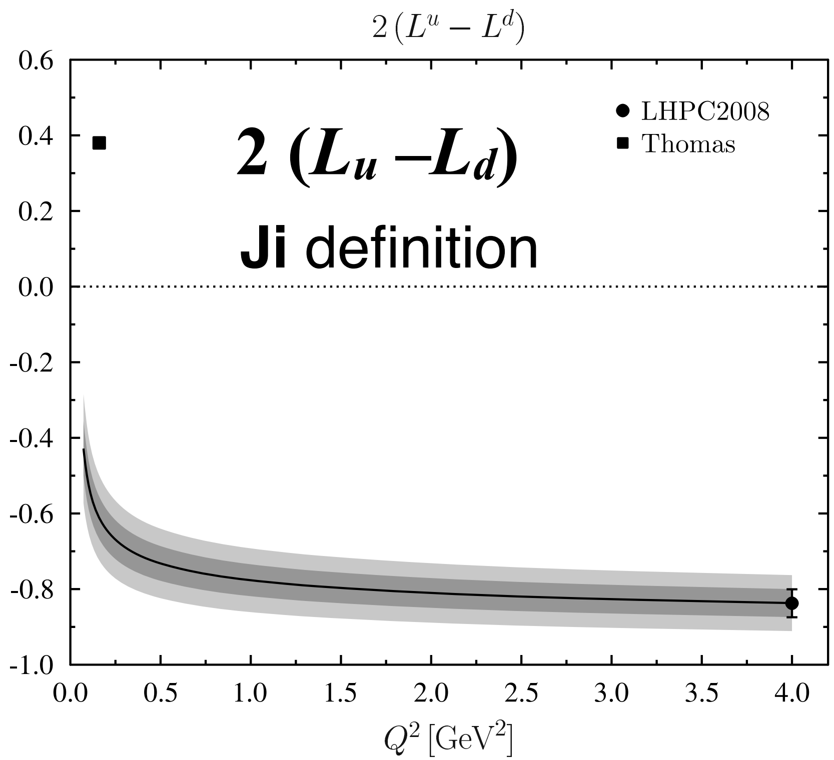


*... and **BRAHMS** SSA's for kaons, never explained ...*

Insights from the χQSM

Wakamatsu, EPJA 44 (2010)

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



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

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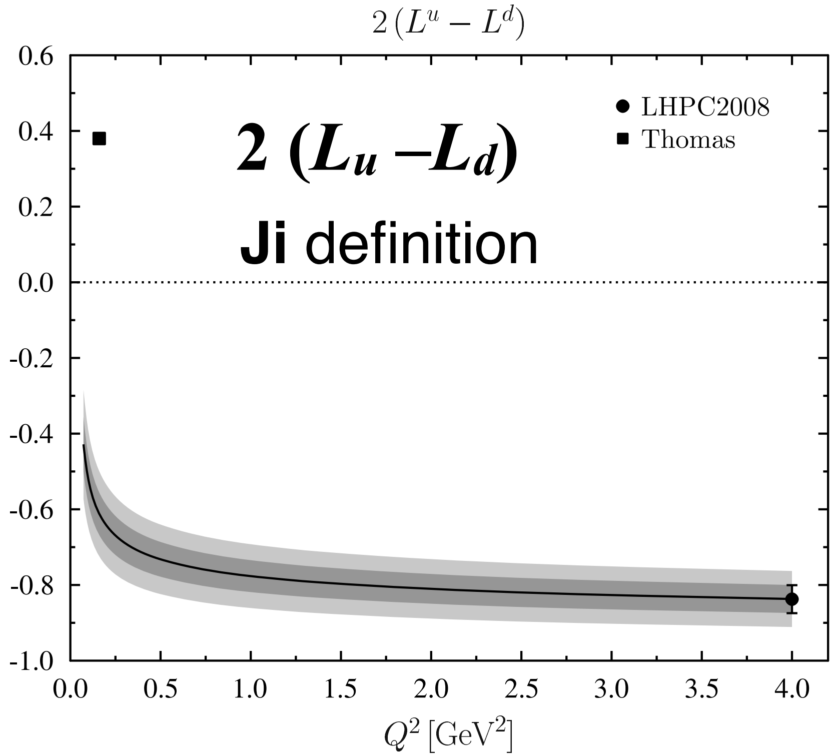

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Compare Jaffe & Ji

calculate explicitly in χQSM; at quark-model scale:

	L_{u-d} Jaffe	L_{u-d} Ji
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Sea	–0.265	–0.188
Total	–0.115	–0.330

Negative model value dominated by sea quark L !

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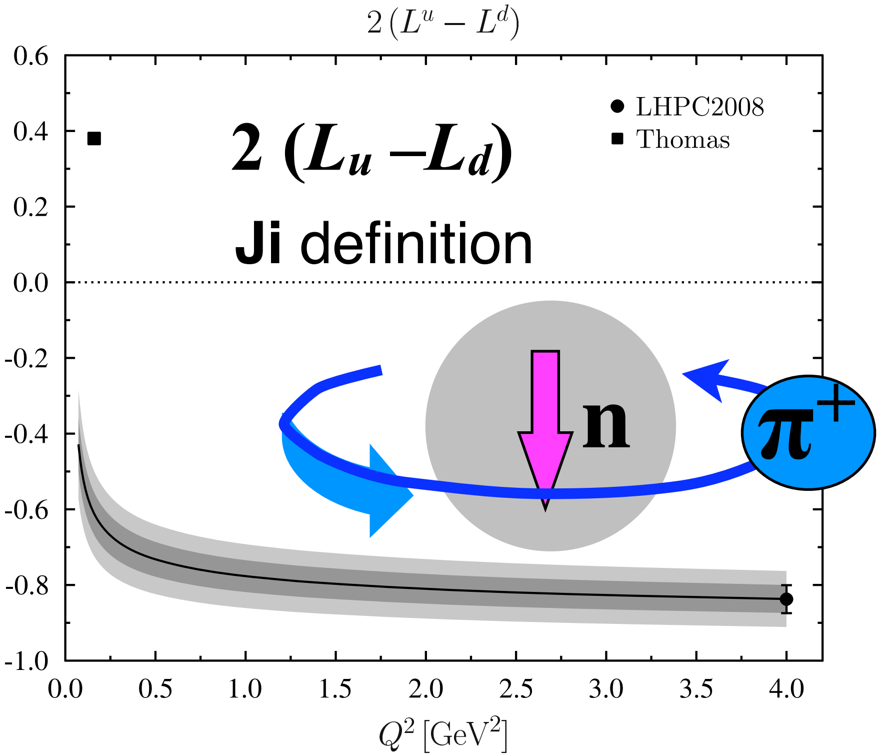

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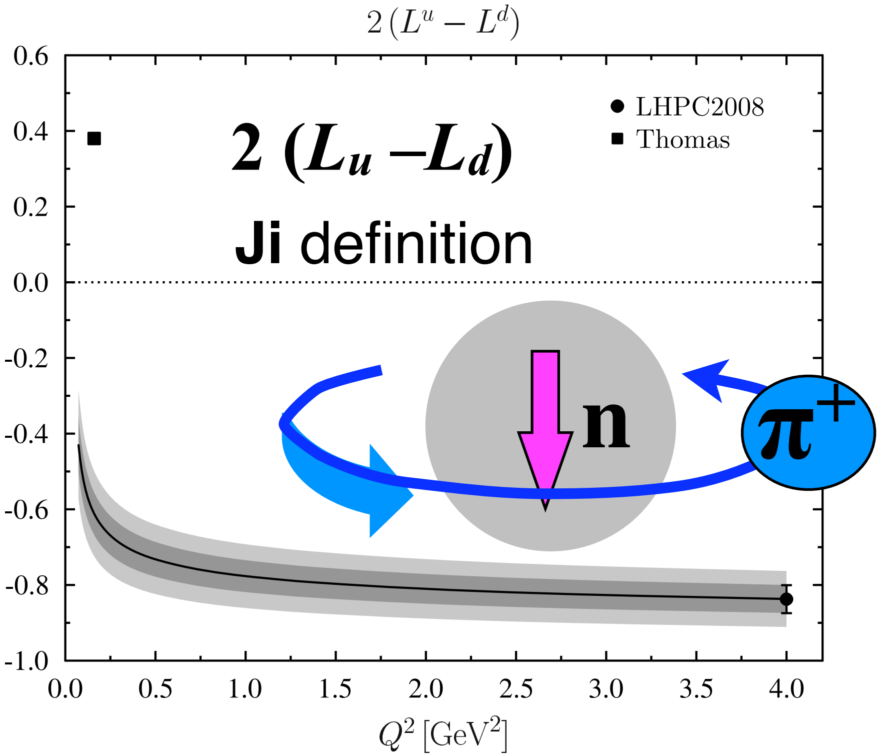

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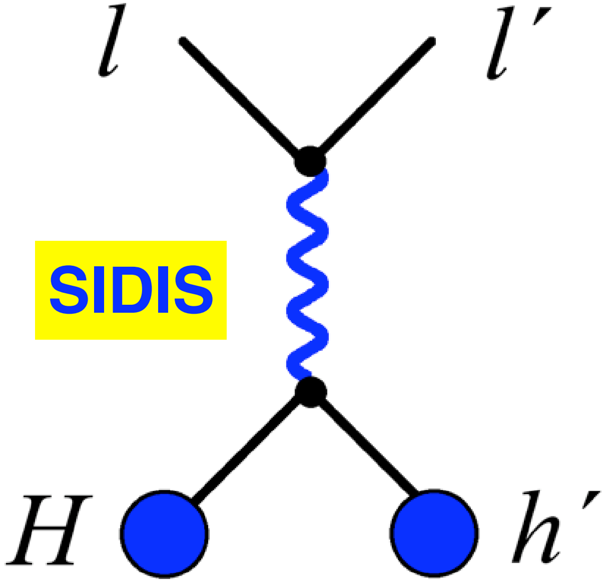
Need direct measurement of Sivers for sea quarks:

Spin-dependent Drell-Yan with p or π^+ beam & pol'd target

Leptons: clean, surgical tools



$$\sum_q e_q^2 \; \mathbf{f_q^{(H)}}(x) \; \mathbf{D_q^{h'}}(z)$$

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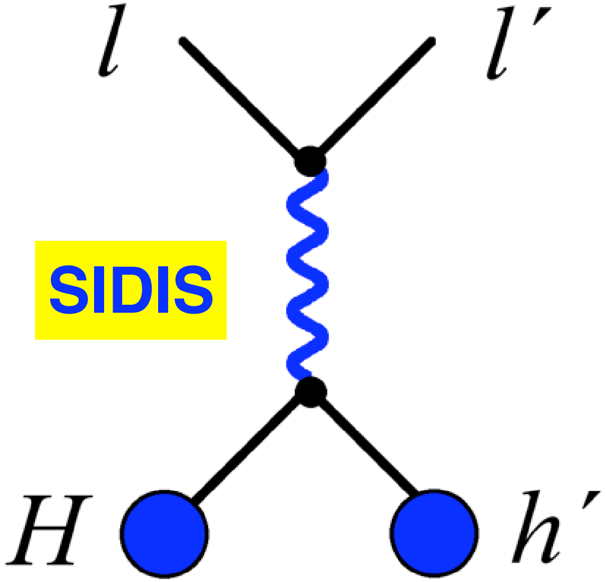

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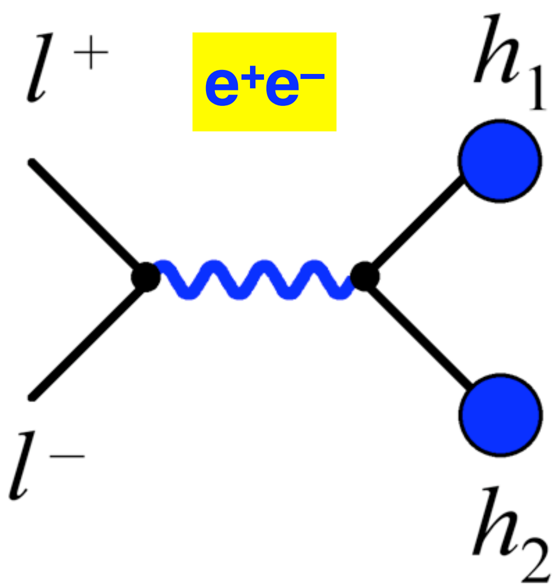

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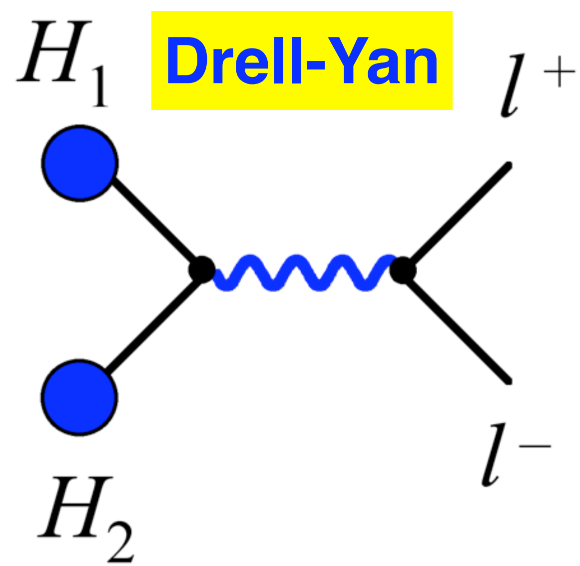

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- *Disentangle* ***distribution*** *(f) and* ***fragmentation*** *(D) functions → measure* ***all process***
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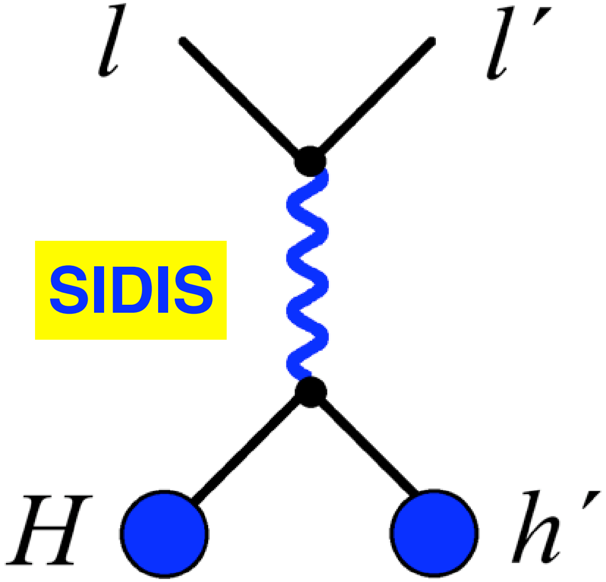

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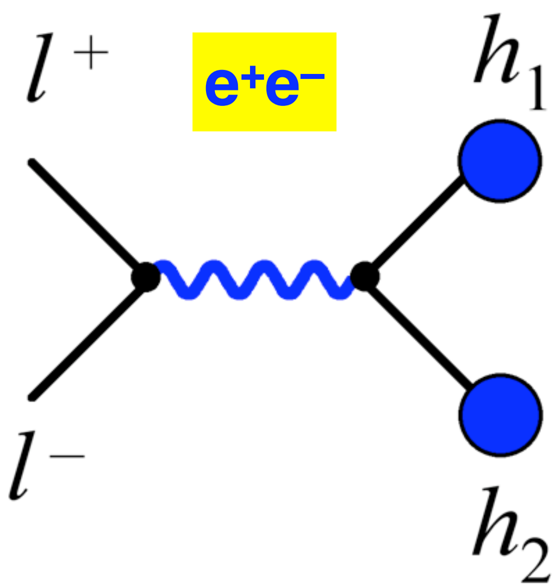

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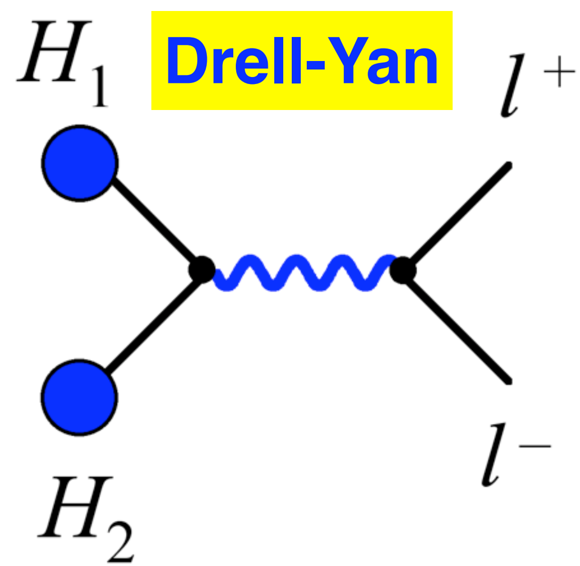

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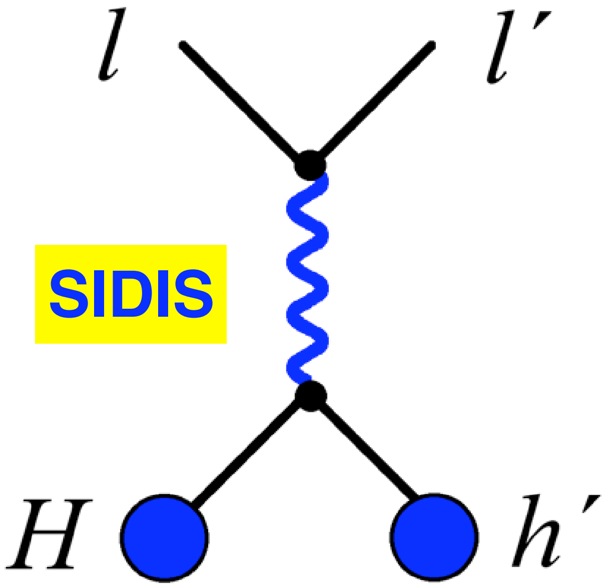

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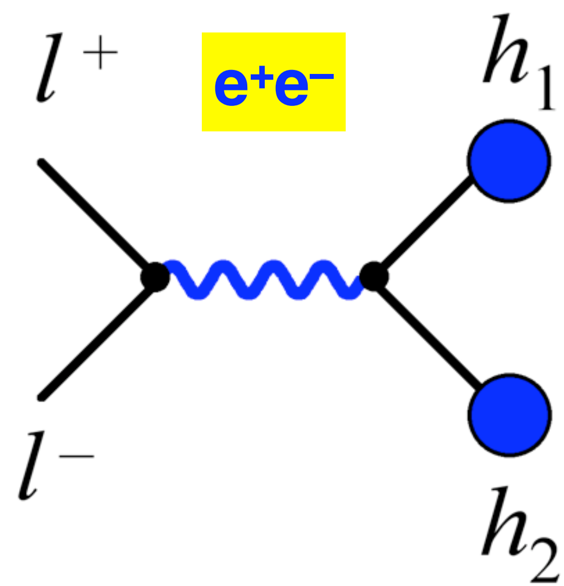
These are the **only** processes where TMD factorization is proven



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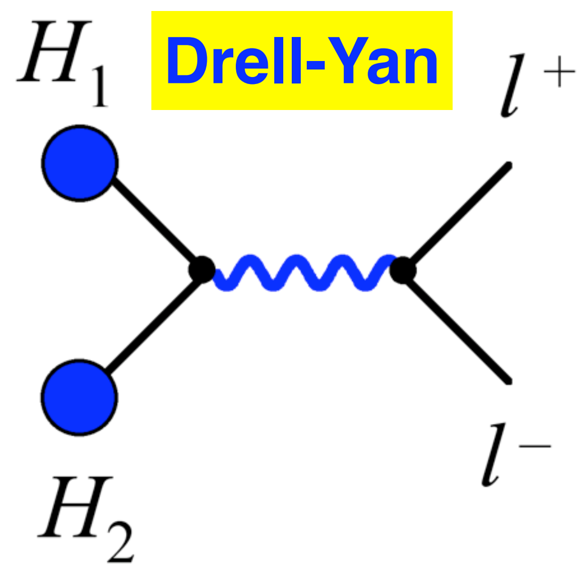

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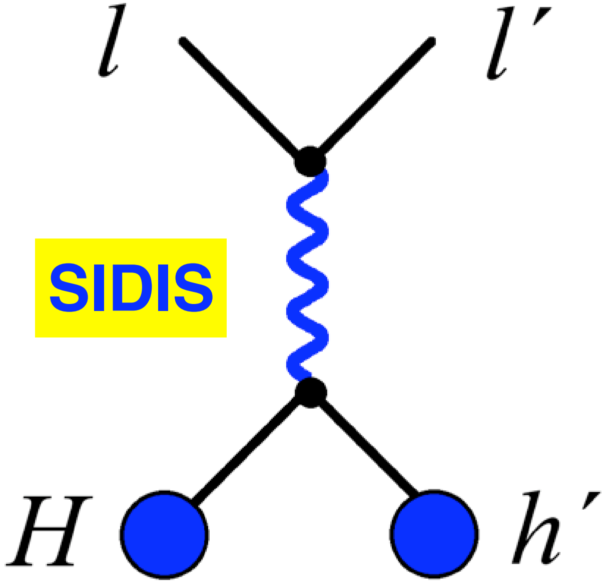

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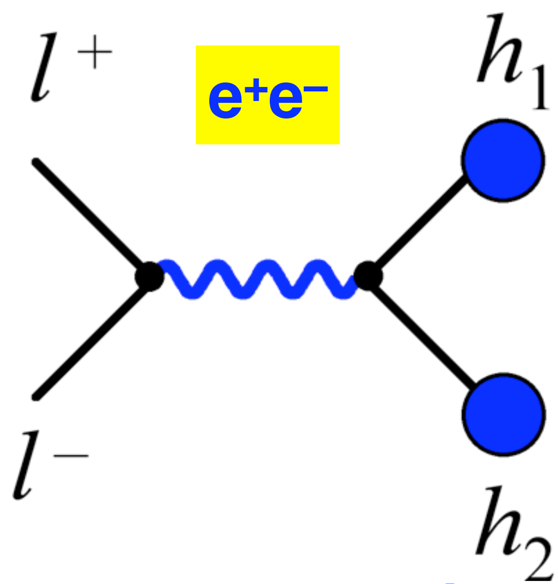

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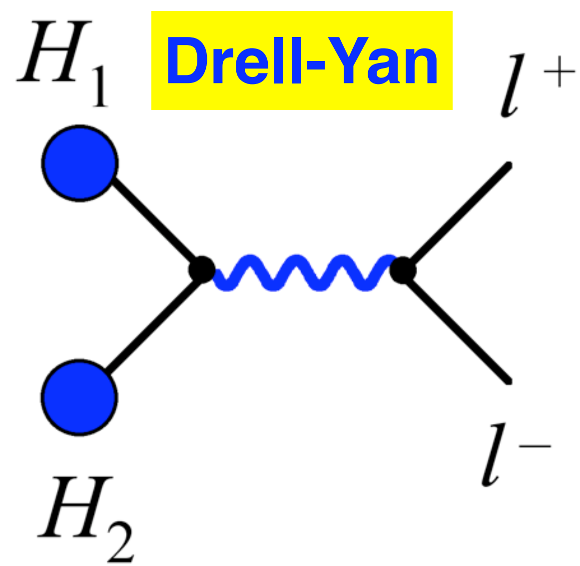

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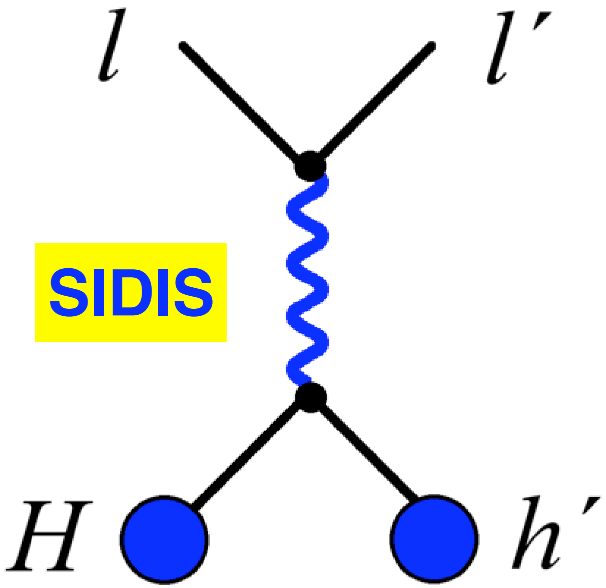
Leptons: clean, surgical tools

Spin Programs



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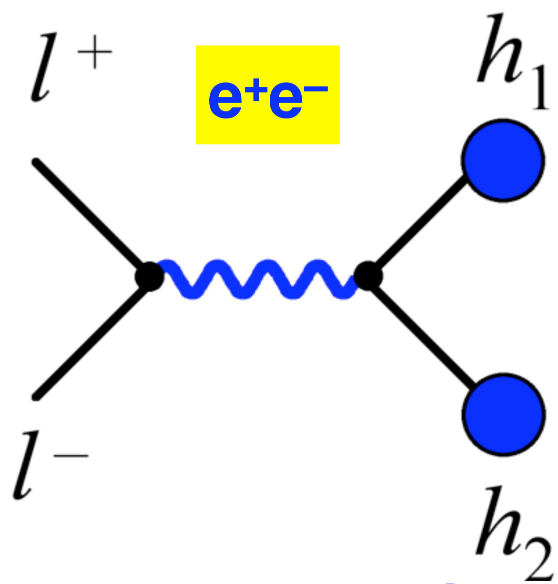

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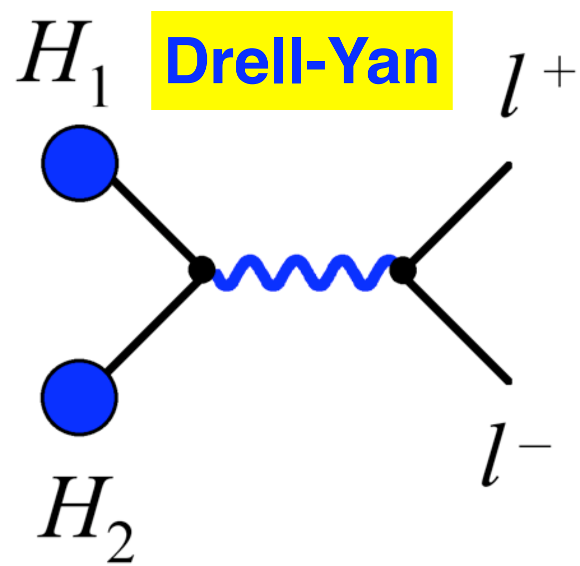

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Leptons: clean, surgical tools

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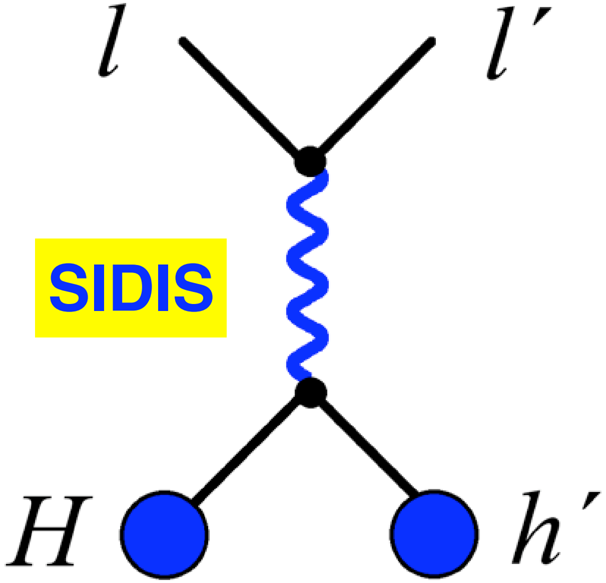

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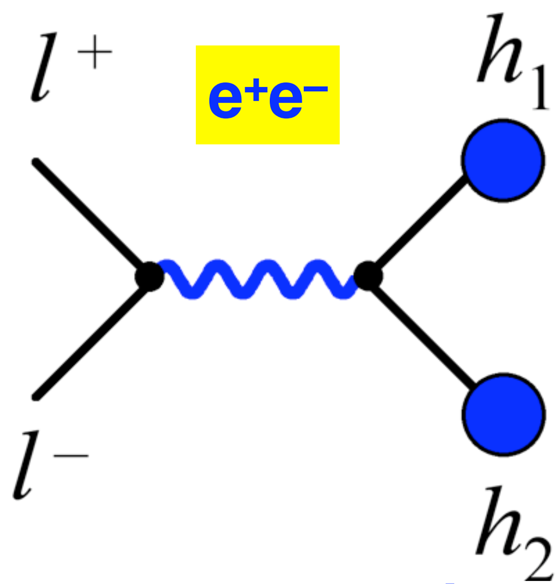

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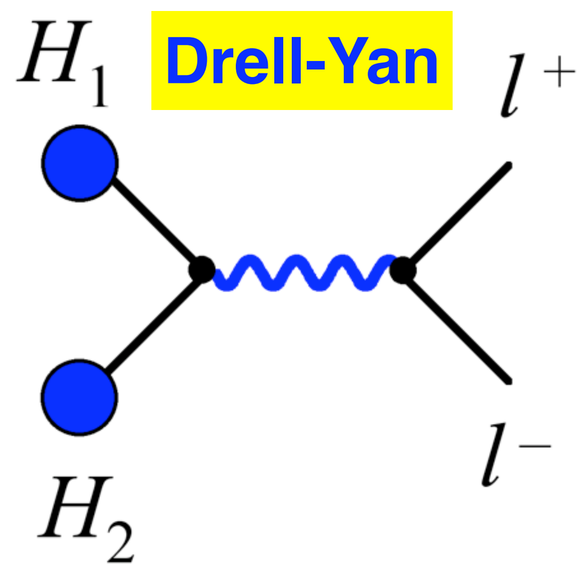

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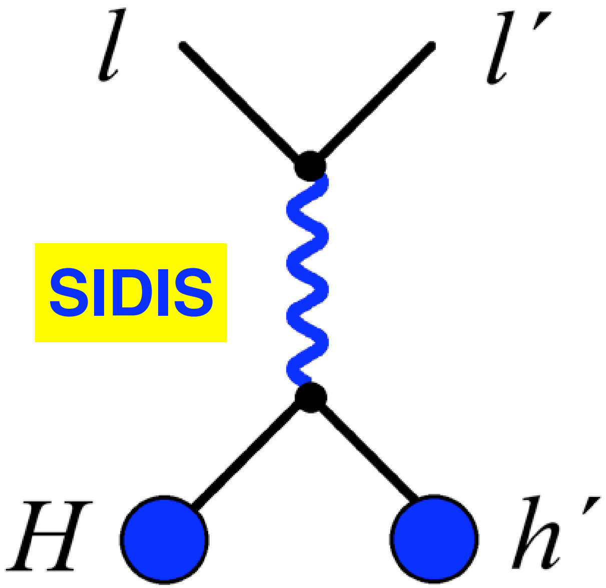
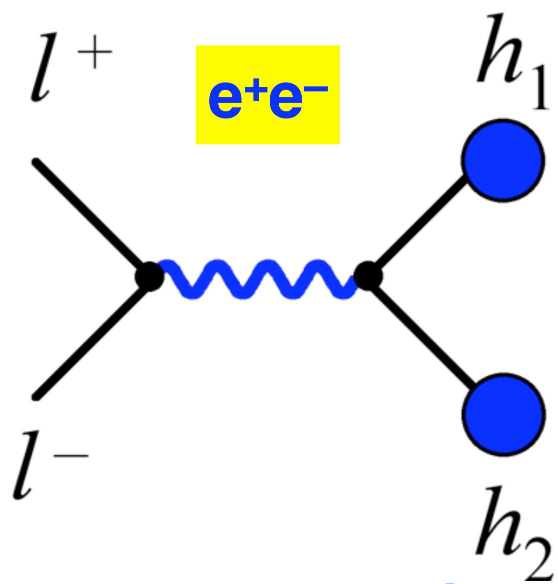
Spin Programs

SIDIS



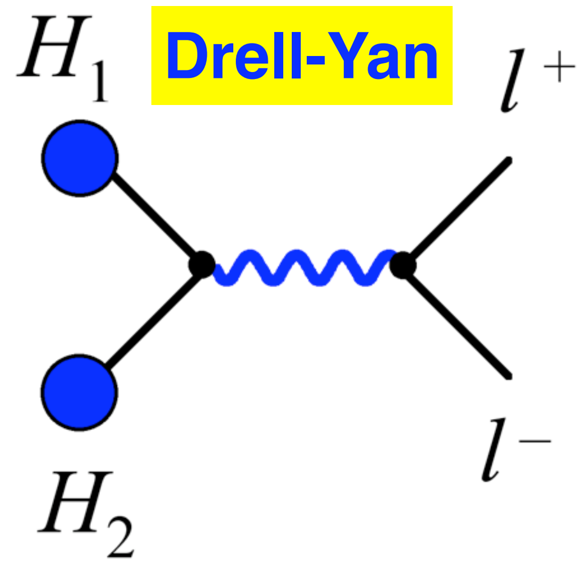
$$\sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H})}(x) \; \mathbf{D}_{\mathbf{q}}^{\mathbf{h}'}(z)$$

e⁺e⁻



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

Drell-Yan



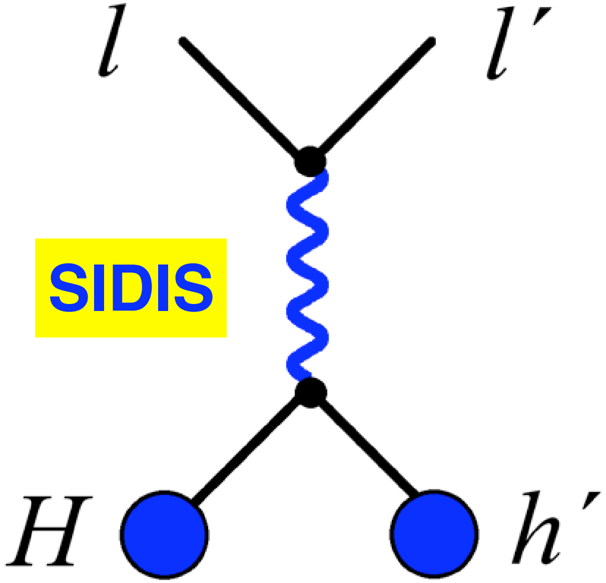
$$\sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H_1})}(x_1) \; \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H_2})}(x_2)$$

Leptons: clean, surgical tools

Spin Programs

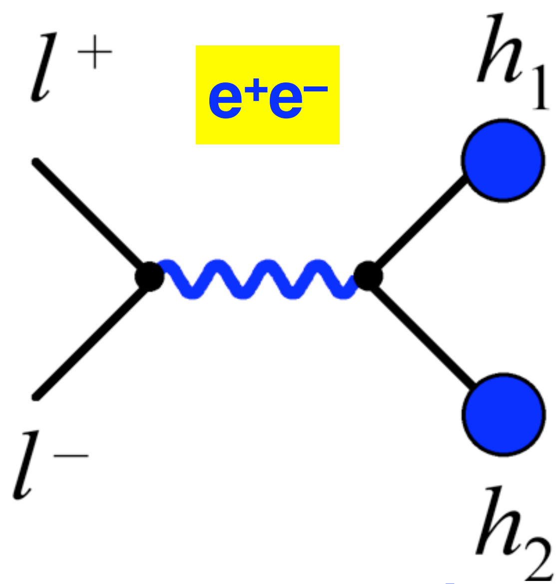
HERMES, COMPASS, Jefferson Lab (Exploring the Nature of Matter), BELLE

SIDIS



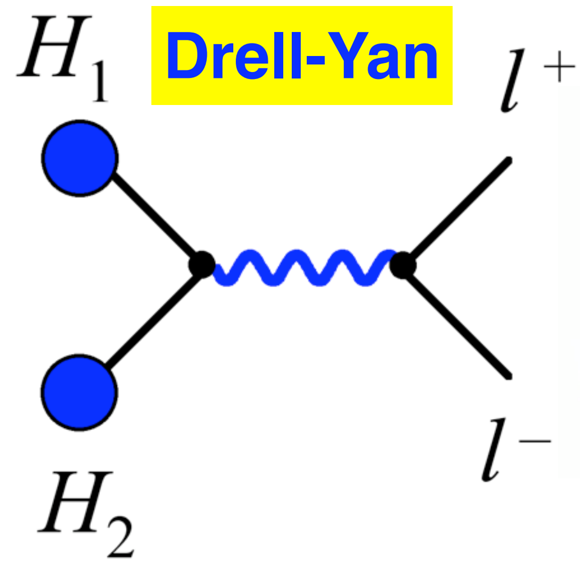
$$\sum_q e_q^2 \; \mathbf{f_q^{(H)}}(x) \; \mathbf{D_q^{h'}}(z)$$

e⁺e⁻



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

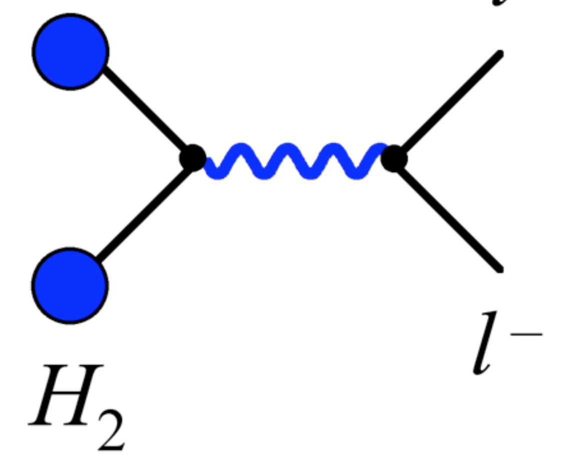
Drell-Yan



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

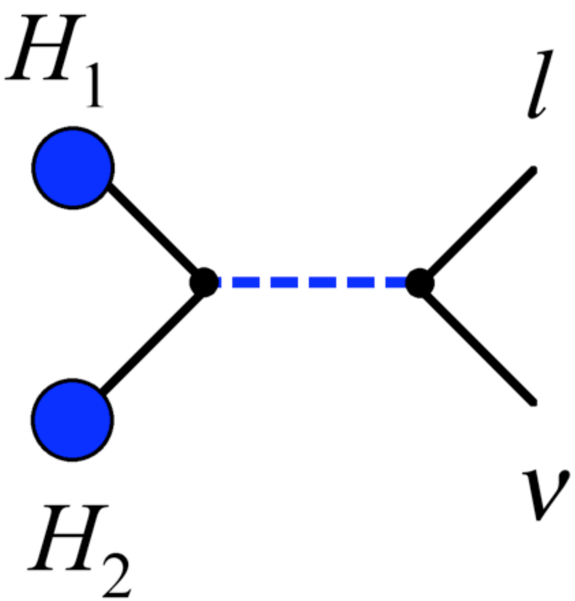
The Missing Spin Program: Drell-Yan

Drell-Yan

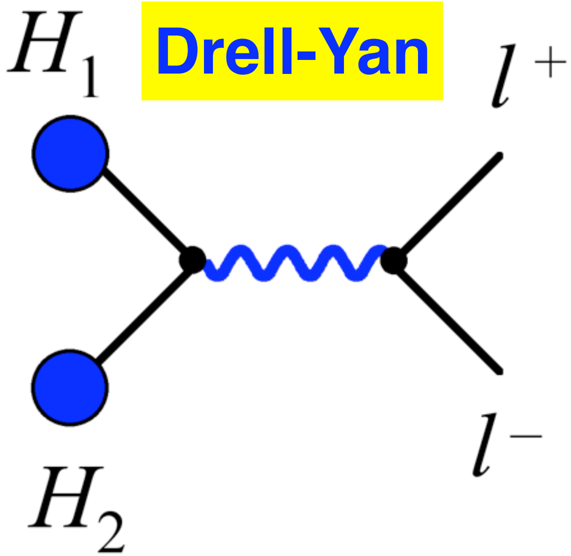


$$\sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H_1})}(x_1) \; \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H_2})}(x_2)$$

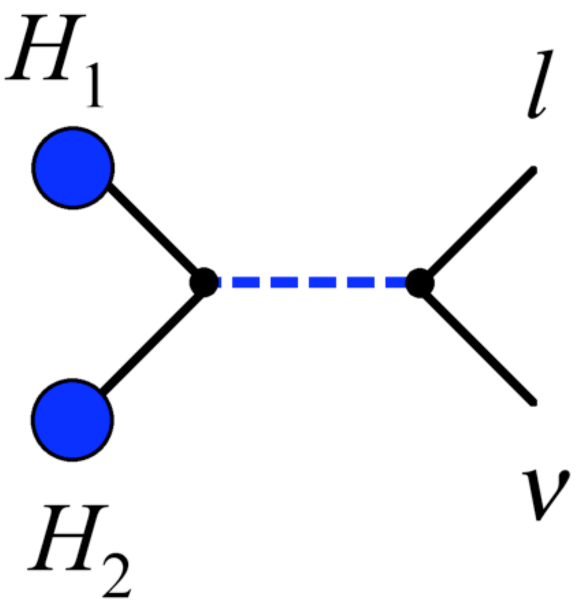
W production



- Clean access to **sea quarks** e.g. $\Delta\bar{u}(x), \Delta\bar{d}(x)$ at RHIC



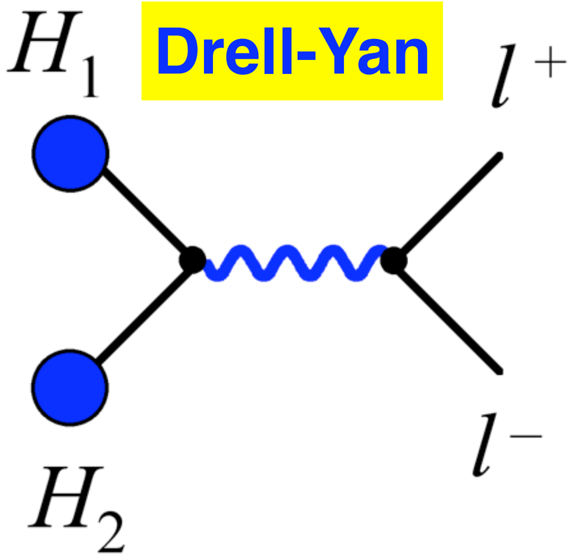
W production



The Missing Spin Program: Drell-Yan

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

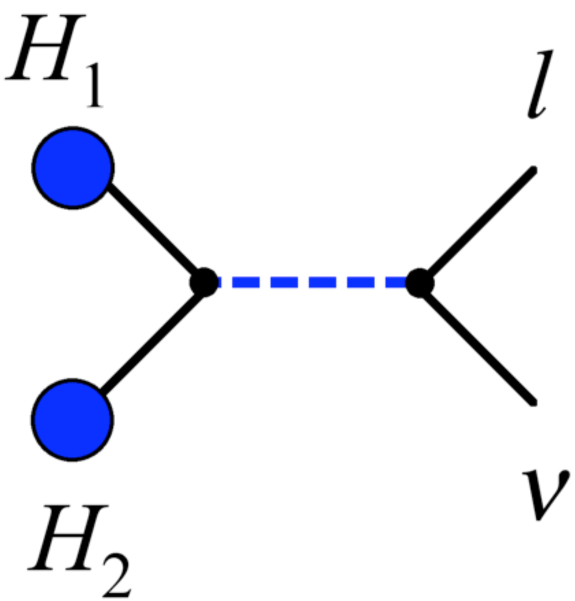
- Clean access to **sea quarks**
  e.g. $\Delta\bar{u}(x), \Delta\bar{d}(x)$ at RHIC
- Crucial test of **TMD formalism**
  → **sign change** of T-odd functions



The Missing Spin Program: Drell-Yan

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

W production

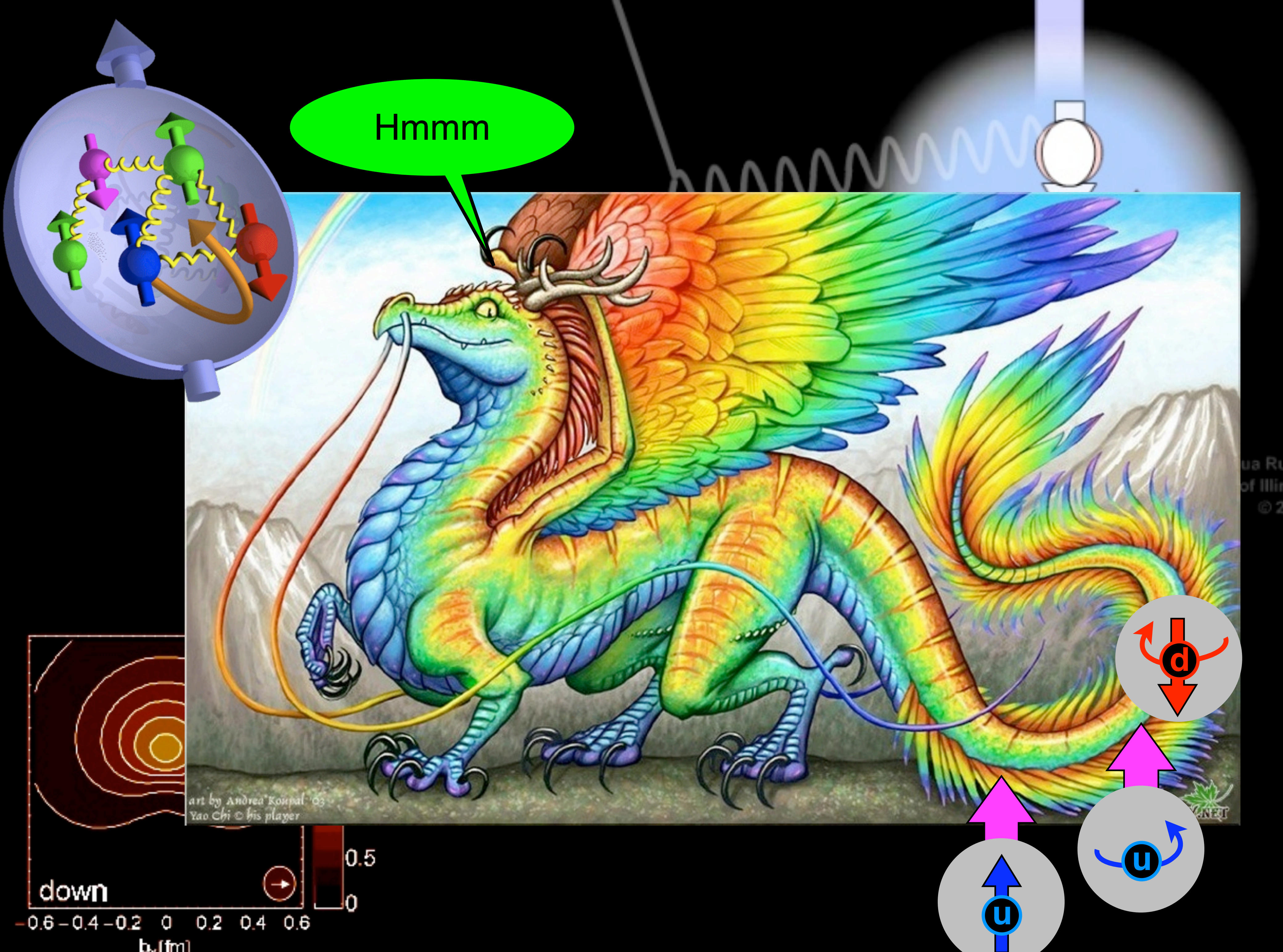


- Clean access to **sea quarks**
  e.g. $\Delta\bar{u}(x), \Delta\bar{d}(x)$ at RHIC

- Crucial test of **TMD formalism**
  → **sign change** of T-odd functions

- A **complete** spin program requires multiple hadron species
  → **nucleon & meson beams**


art by Andrea Koupal '03
Yao Chi © his player
down
-0.6 -0.4 -0.2 0 0.2 0.4 0.6
b_x [fm]
0.5
0
u
d
u


Hmmm
art by Andrea Koupal '03
Yao Chi © his player
down
0.5
0
−0.6 −0.4 −0.2 0 0.2 0.4 0.6
b_x [fm]
d
u
u