Transversity and its many Friends: Experimental Status

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& Josh Rubin, the Animagician!

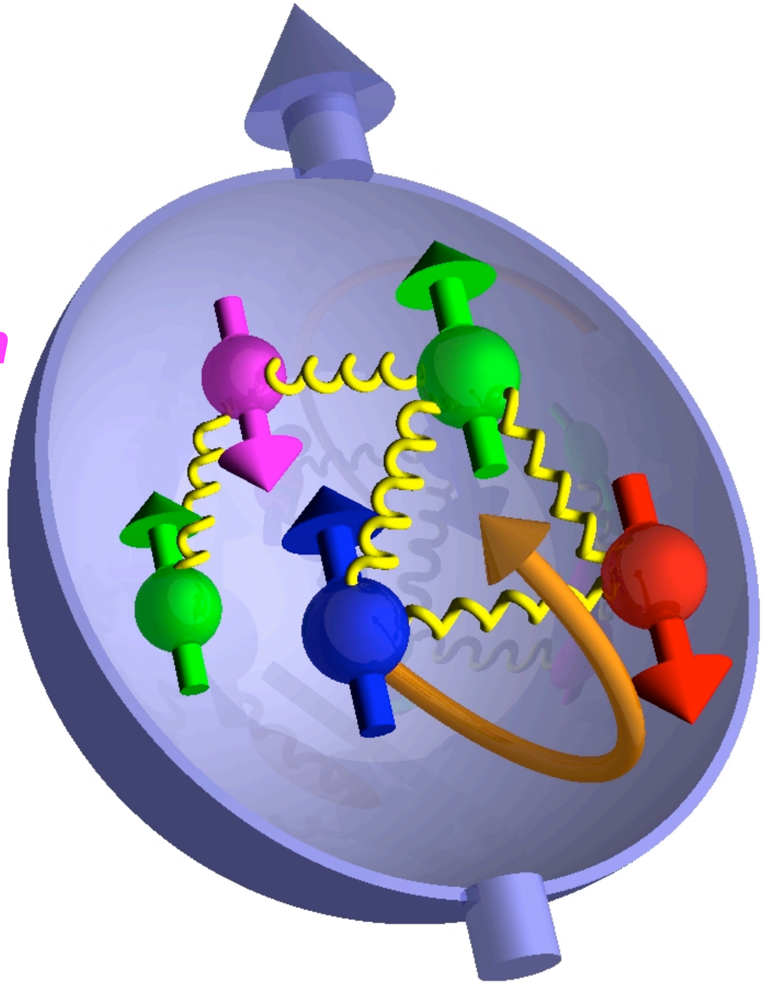
Outline

- The rich world of **proton substructure**
  ... especially when spin is involved ...

- **Single-Spin Asymmetries**:
  What do they tell us about ***orbital motion*** at the subatomic level?

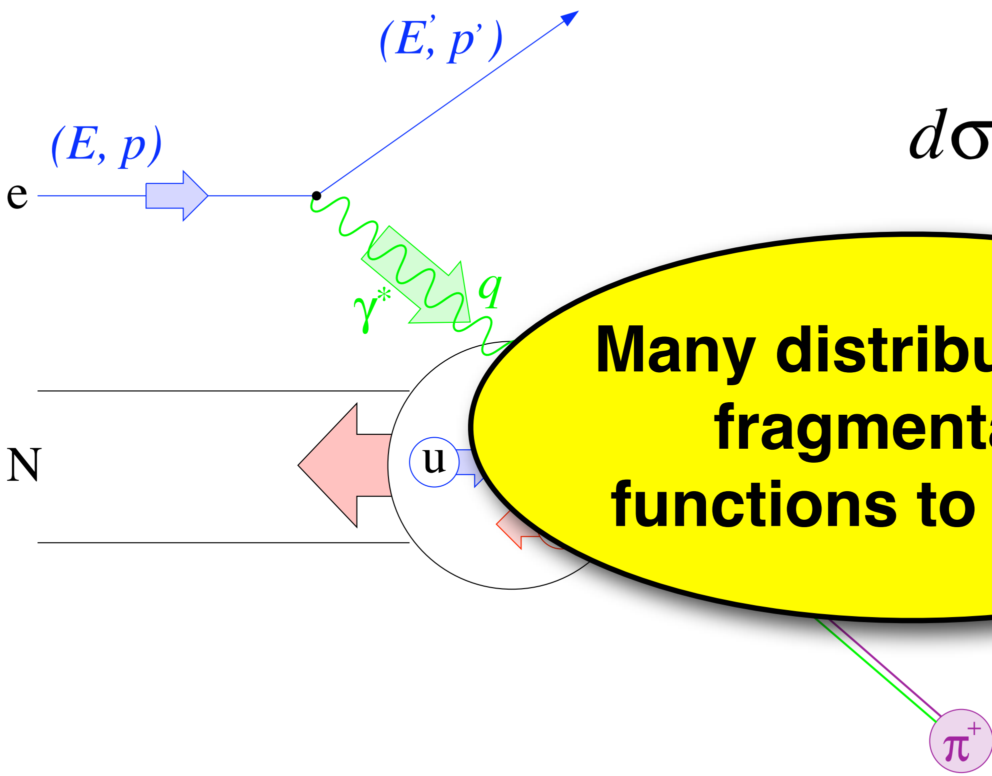
- **Results**: Current & Upcoming

  - The Collins Effect
  - The Sivers Effect
  - The Boer-Mulders, Cahn, and other Effects



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
...on-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 ...

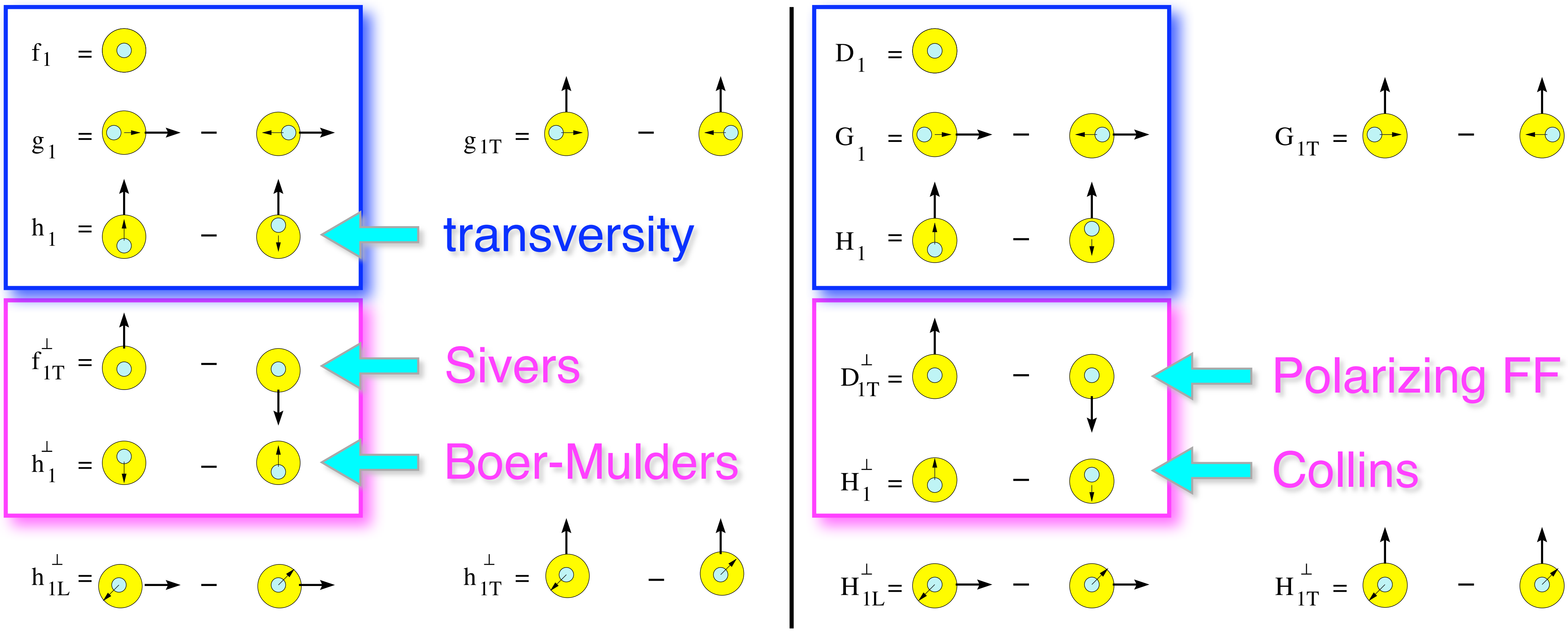
Functions surviving on integration over Transverse Momentum

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



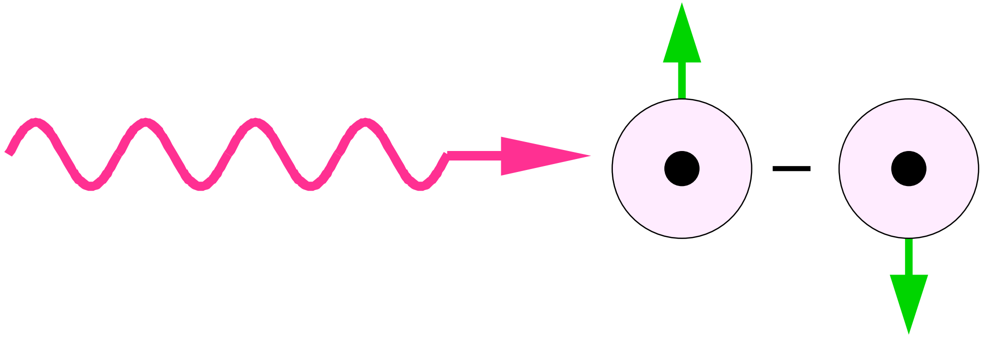
Functions **odd** under **naive time reversal** ⇒ generate **SSA's**

Sensitive to ***spin-orbit*** correlations of quarks and gluons ⇒ ***orbital angular momentum***

Functions surviving on integration over Transverse Momentum

The **others** are sensitive to ***intrinsic k_T*** in the nucleon & in the fragmentation process

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



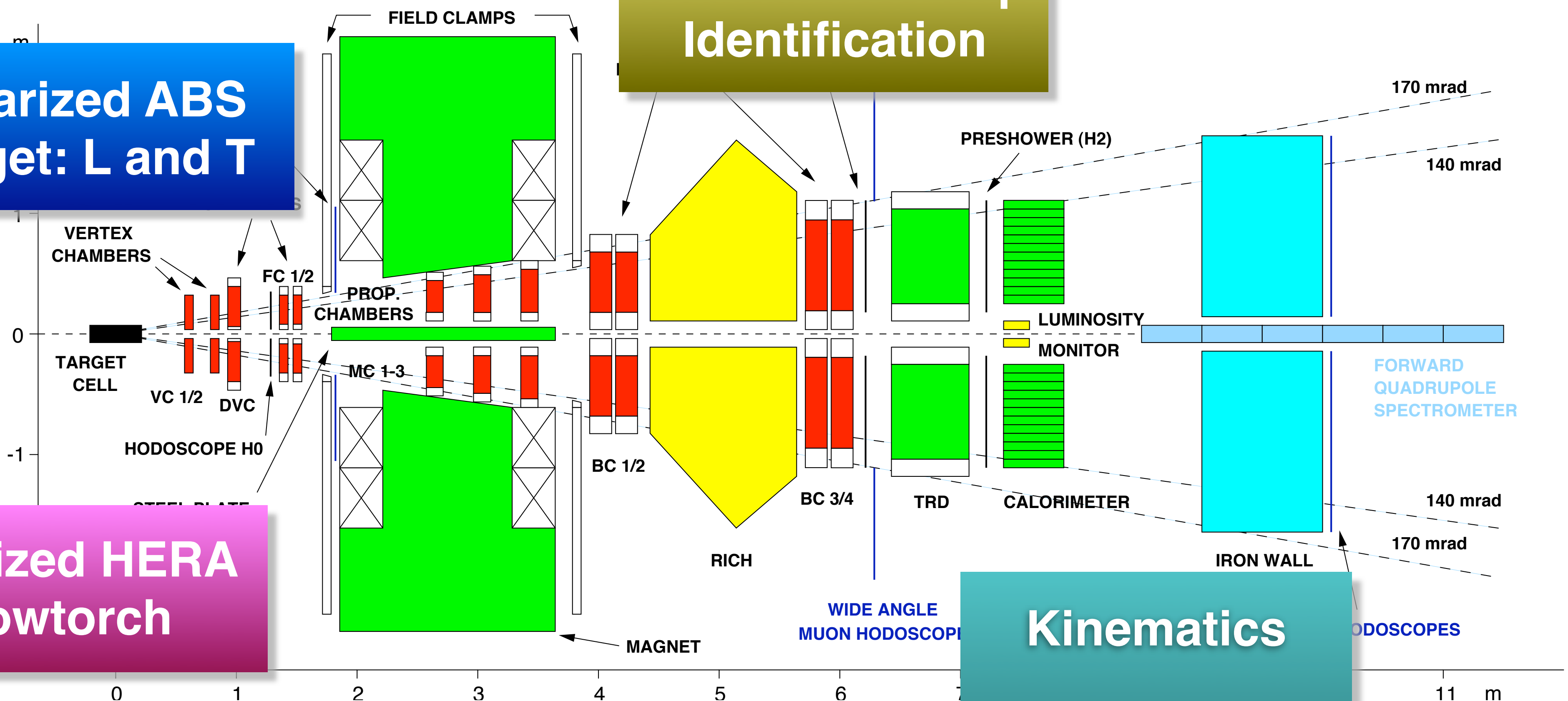
Functions **odd** under **naive time reversal** ⇒ generate **SSA's**

Sensitive to ***spin-orbit*** correlations of quarks and gluons ⇒ ***orbital angular momentum***

Hamburg, Germany

The HERMES Experiment at HERA

Key Features



RICH for π / K / p Identification

Polarized ABS Target: L and T

Polarized HERA Blowtorch

Open Geometry Spectrometer

Kinematics

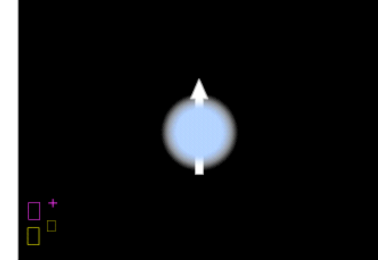
$Q^2 > 1$ GeV^2

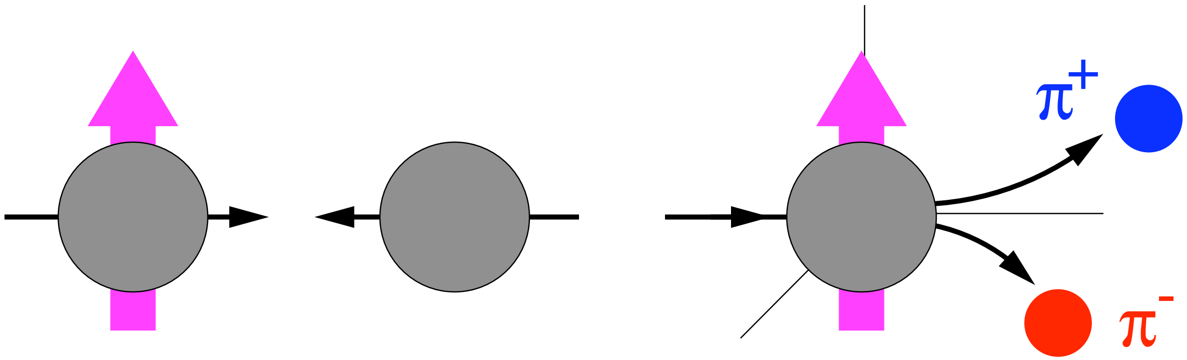
$W^2 > 10$ GeV^2

$0.02 < x < 0.6$

Single-Spin Asymmetries

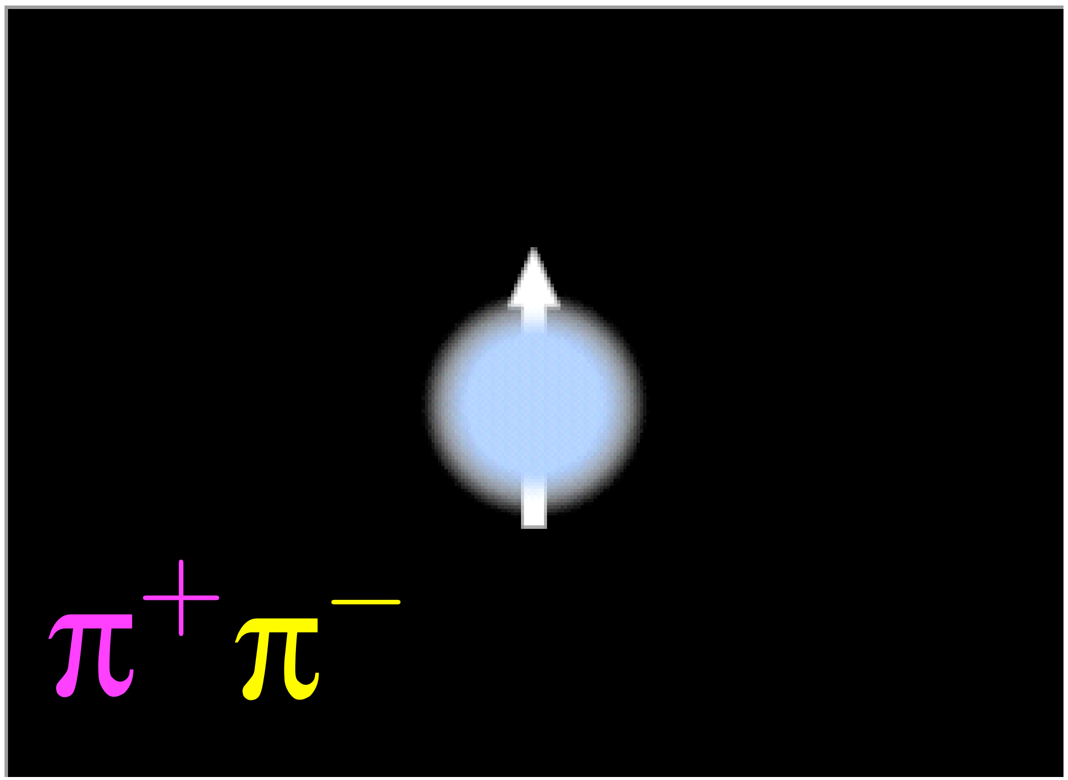
Fermilab E704: SSA's in $p^{\uparrow}p \rightarrow \pi X$ at 200 GeV





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 !

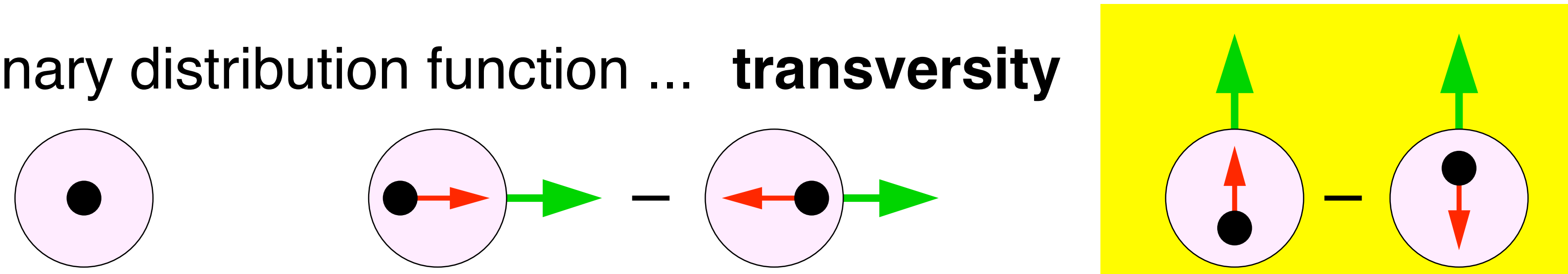
- Opposite sign for $\pi^{+} = u\bar{d}$ than for $\pi^{-} = d\bar{u}$
- Effect larger for forward production
- Observable: $\vec{S}_{\text{beam}} \cdot (\vec{p}_{\text{beam}} \times \vec{p}_{\pi})$
  odd under naive Time-Reversal

∴ can't be due to hard subprocess ...

⇒ ***spin-orbit correlation*** *in* ***distribution*** *and/or* ***fragmentation func***

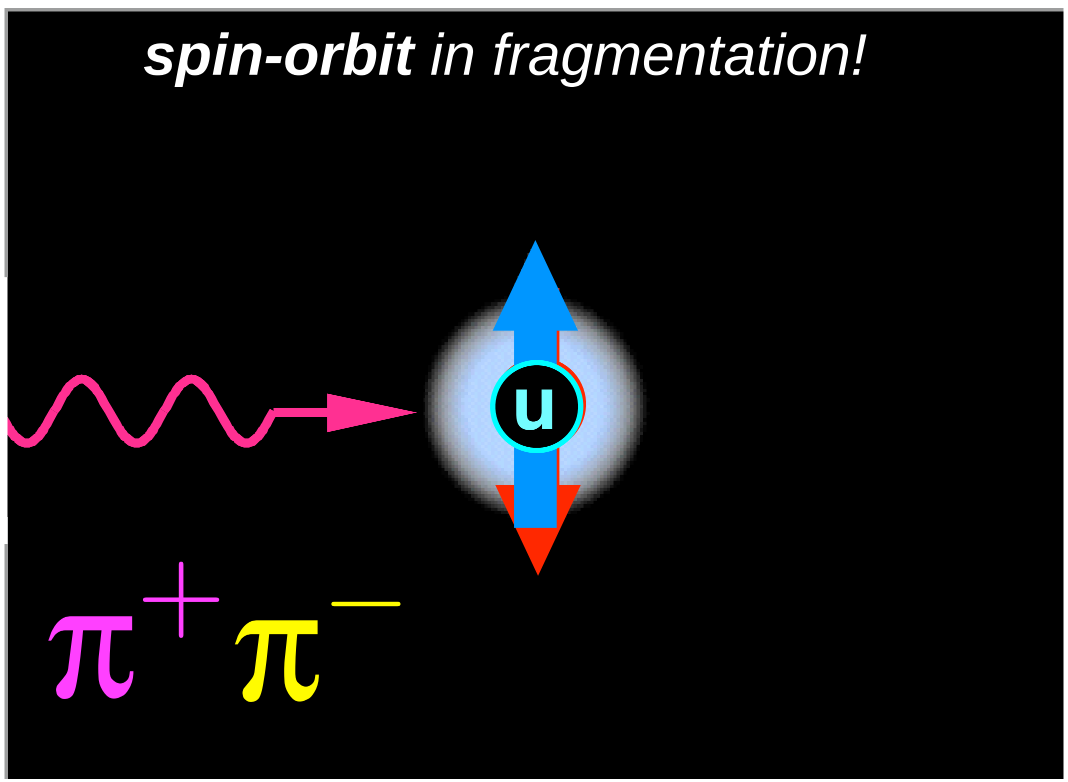
E704 Possible Mechanism #1: The “Collins Effect”

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

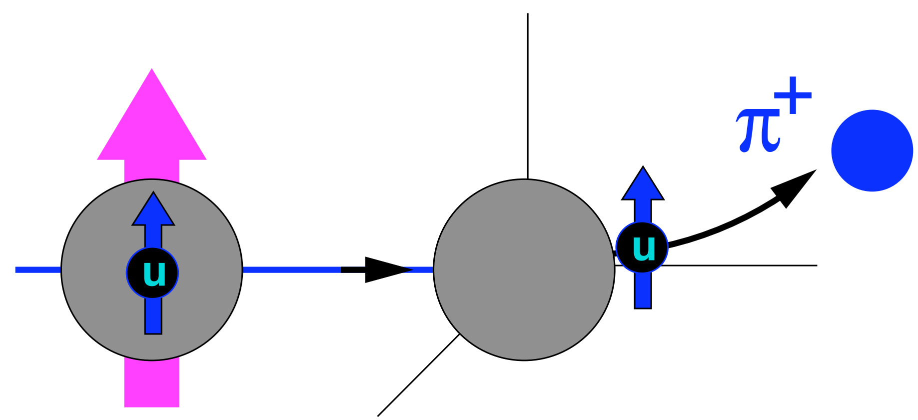


$q(x)$ $\Delta q(x)$ $h_1(x)$

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



E704 effect:



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

E704 Possible Mechanism #2: The “Sivers Effect”

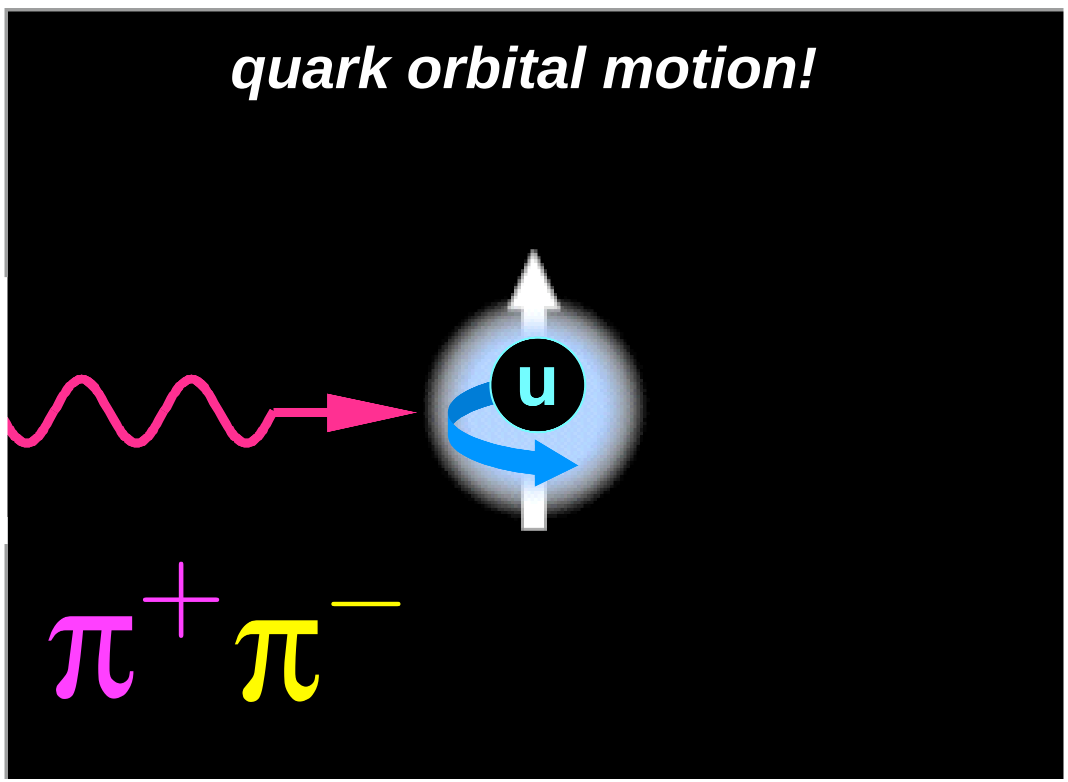
Need the ordinary fragmentation function $D_1(z)$

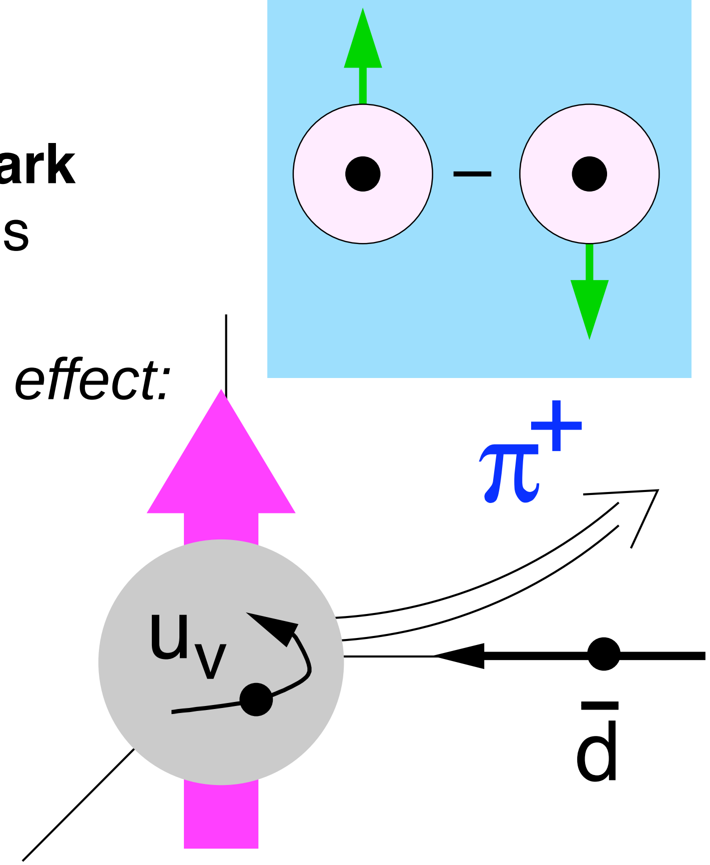
... with a new, **T-odd “Sivers” distribution function**

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

Phenomenological model of **Meng & Chou**:

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

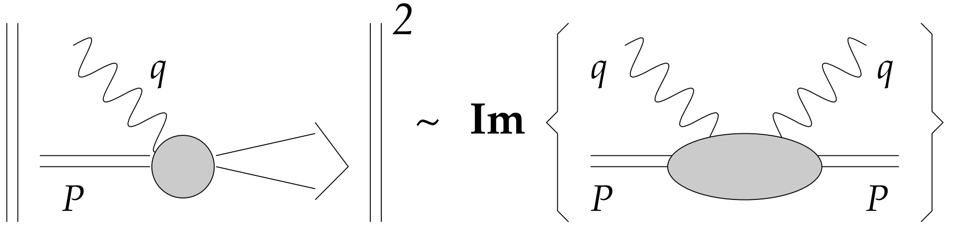




$f_{1T}^{\perp}(x, k_T) \otimes D_1(z)$

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?



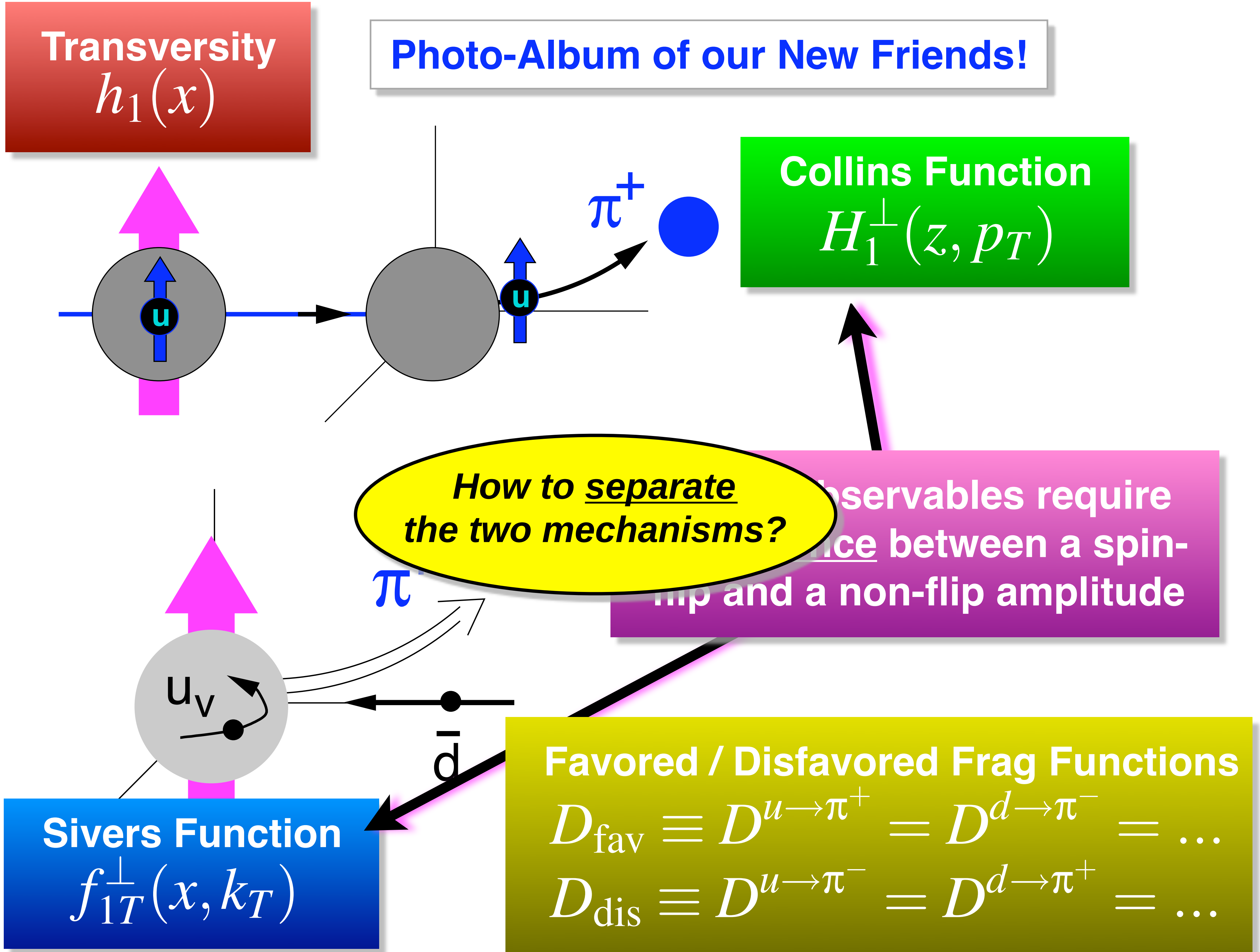
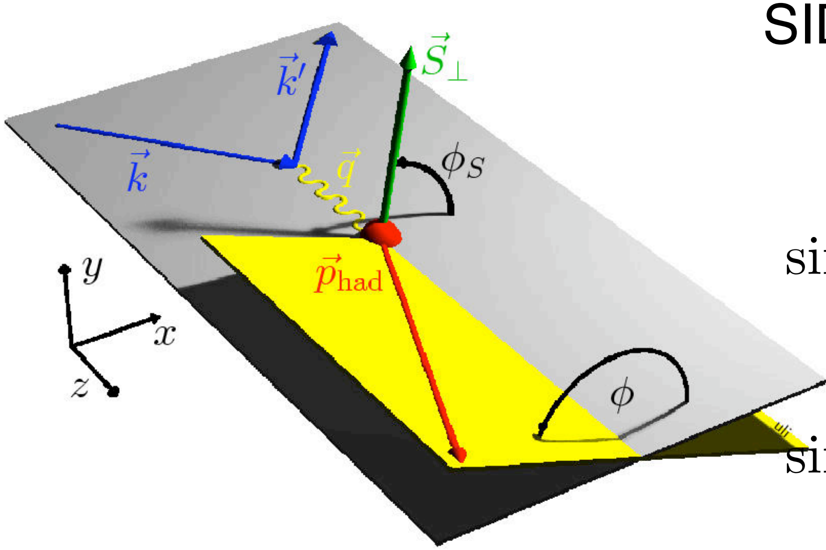


Photo-Album of our New Friends!
Transversity
$h_1(x)$
u
u
π^+
Collins Function
$H_1^\perp(z, p_T)$
How to separate the two mechanisms?
bservables require
nce between a spin-
lip and a non-flip amplitude
π
u_v
$\bar{d}$
Sivers Function
$f_{1T}^\perp(x, k_T)$
Favored / Disfavored Frag Functions
$D_{\text{fav}} \equiv D^{u\to\pi^+} = D^{d\to\pi^-} = \ldots$
$D_{\text{dis}} \equiv D^{u\to\pi^-} = D^{d\to\pi^+} = \ldots$

Separating the Mechanisms: Experimental Observables

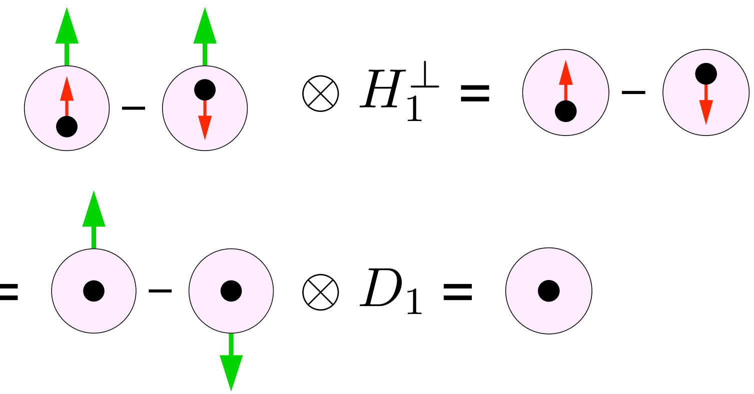
Lepto-production: SIDIS with Transverse Target



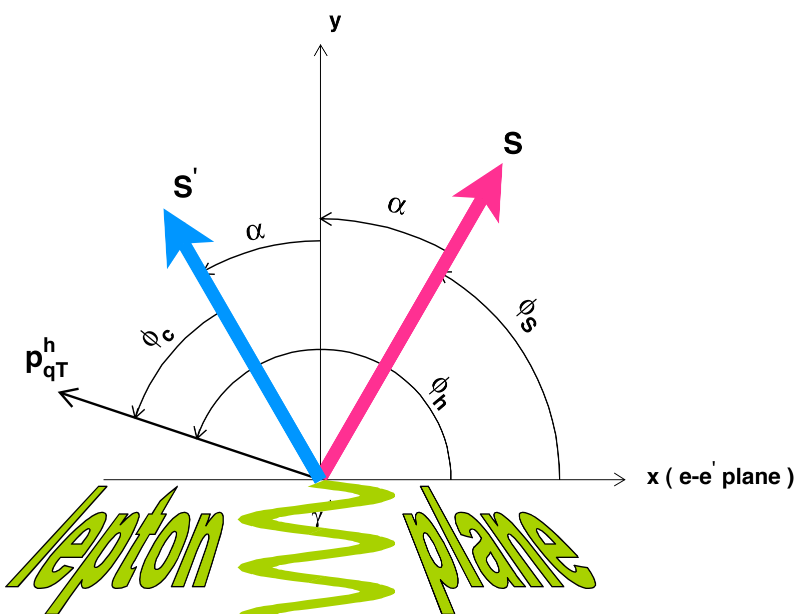
SIDIS xsec with *transverse target* polarization has ***two*** similar terms:

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

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



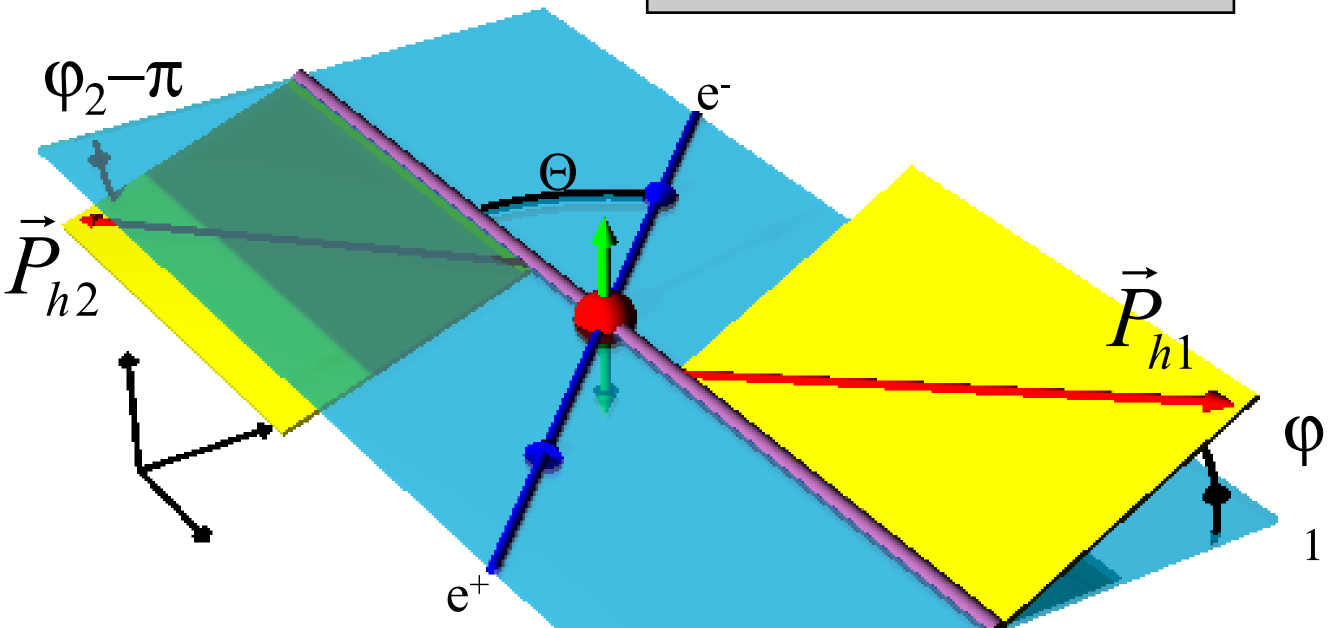
seperate Sivers and Collins mechanisms

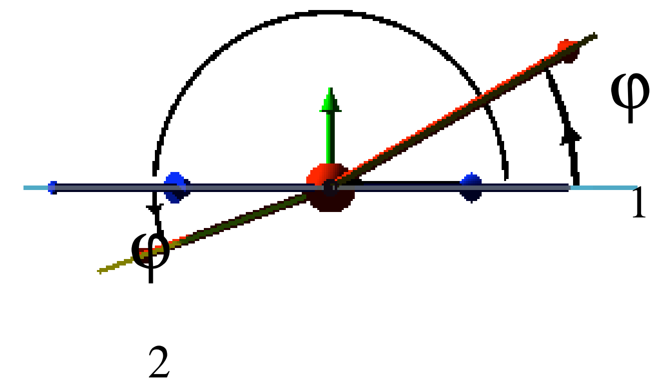


- $(\phi_h^l - \phi_S^l)$ = angle of hadron relative to **initial** quark spin
- $(\phi_h^l + \phi_S^l) = \pi + (\phi_h^l - \phi_S^{l'})$ = hadron relative to **final** quark spin

Collins fragmentation: Angles and Cross section $\cos(\phi_1+\phi_2)$ method

e$^+$e$^-$ CMS frame:





2-hadron inclusive transverse momentum dependent cross section:

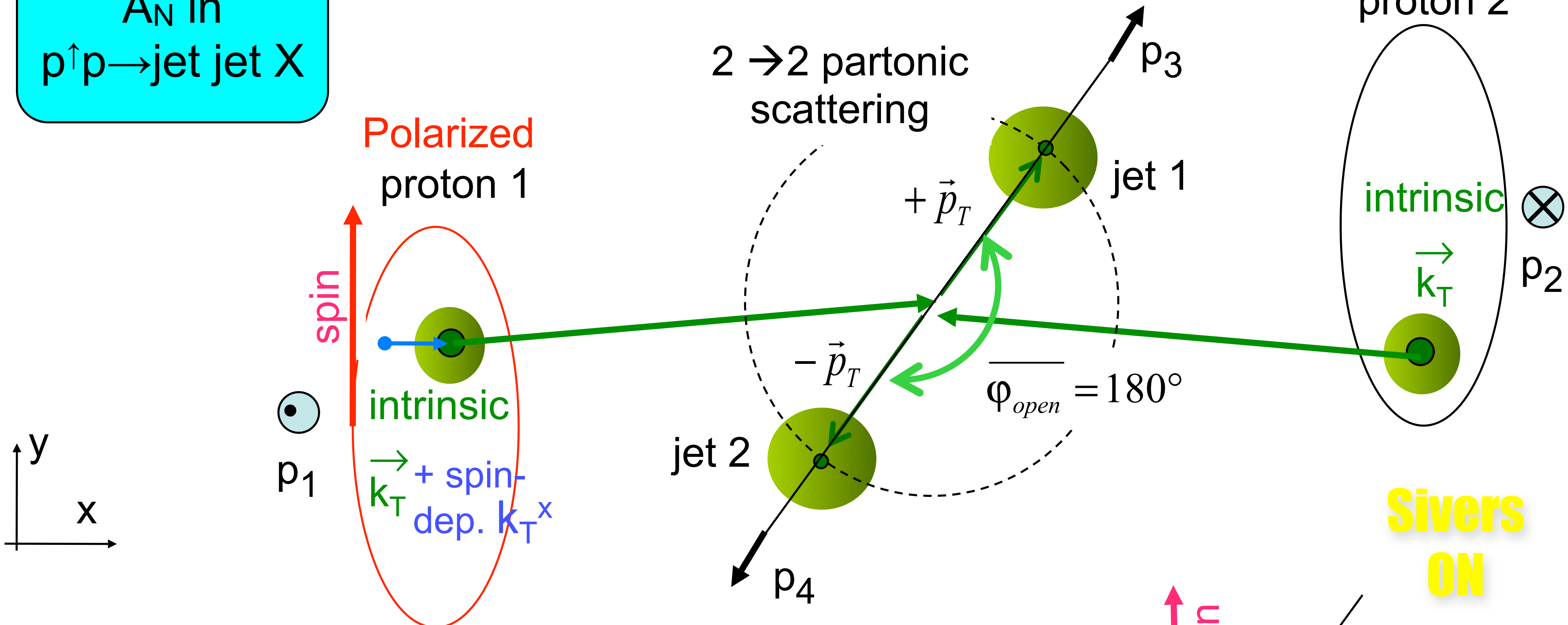
$$\frac{d\sigma\left(e^+e^- \to h_1 h_2 X\right)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\cos\left(\varphi_1+\varphi_2\right) H_1^{\perp[1]}(z_1)\overline{H}_1^{\perp[1]}(z_2)$$

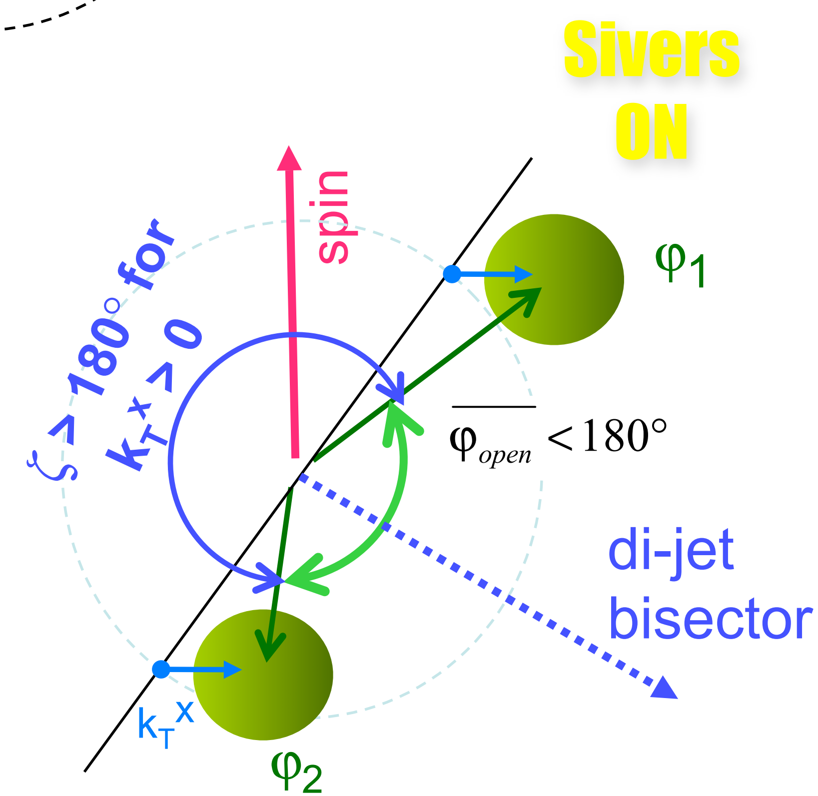
$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4}\sin^2\Theta$$

Net anti-alignment of transverse quark spins

Sivers Mechanism of SSA

A_N in $p^{\uparrow}p \rightarrow$ jet jet X



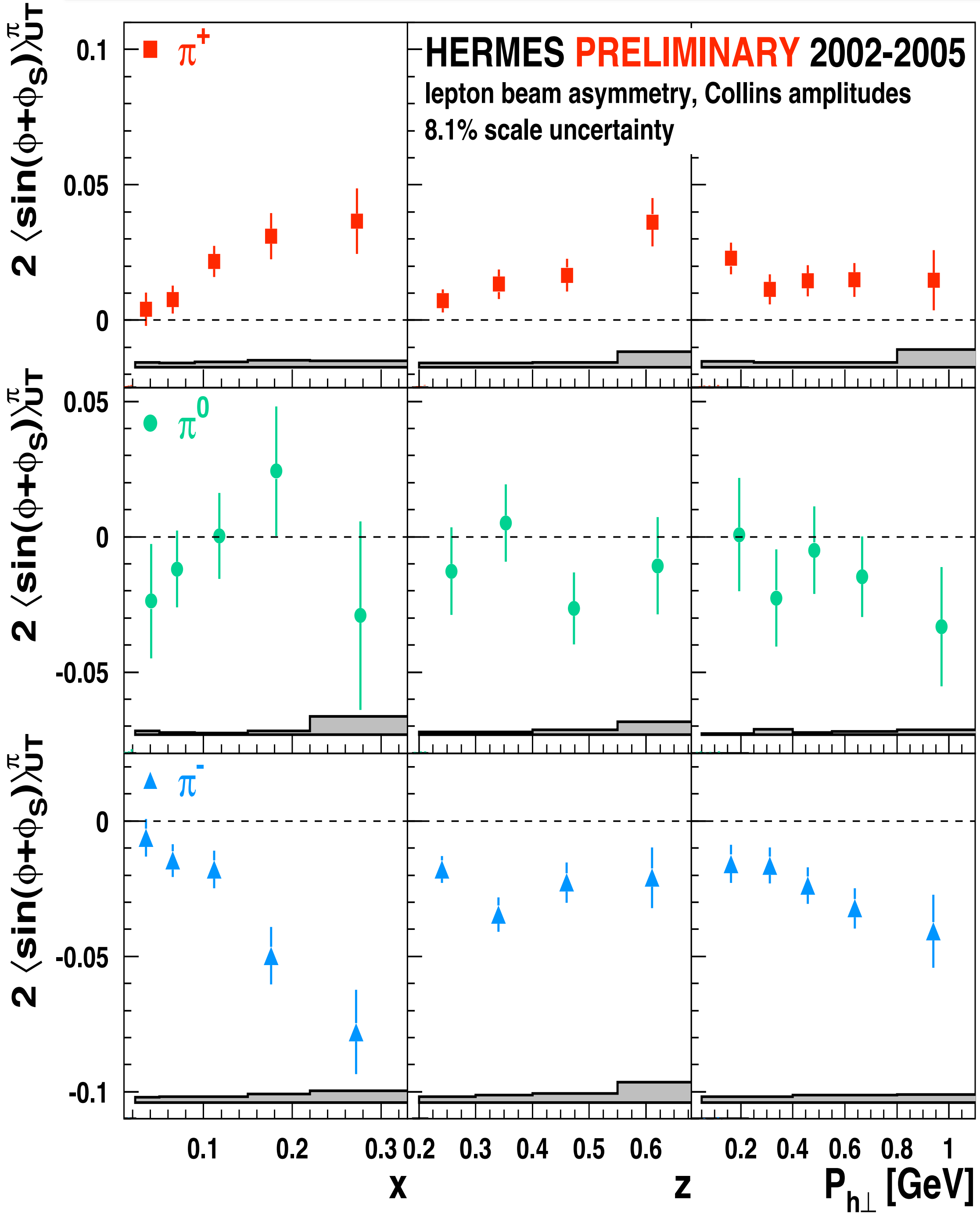


Spin dependent k_T^X offset

- deflects both jets in the same direction
- reduces average di-jet opening angle
- **can be measured** from **correlation** between **di-jet bisector vs. spin direction**
- from accumulated **ζ-spectra (spin)**

Collins Effect Results :
SIDIS and e^+e^- Annihilation

Collins Moments for π⁺ π⁻ π⁰ from Transverse H↑ Data



It exists!

- First evidence for **non-zero Collins function** ...
  and **transversity**!

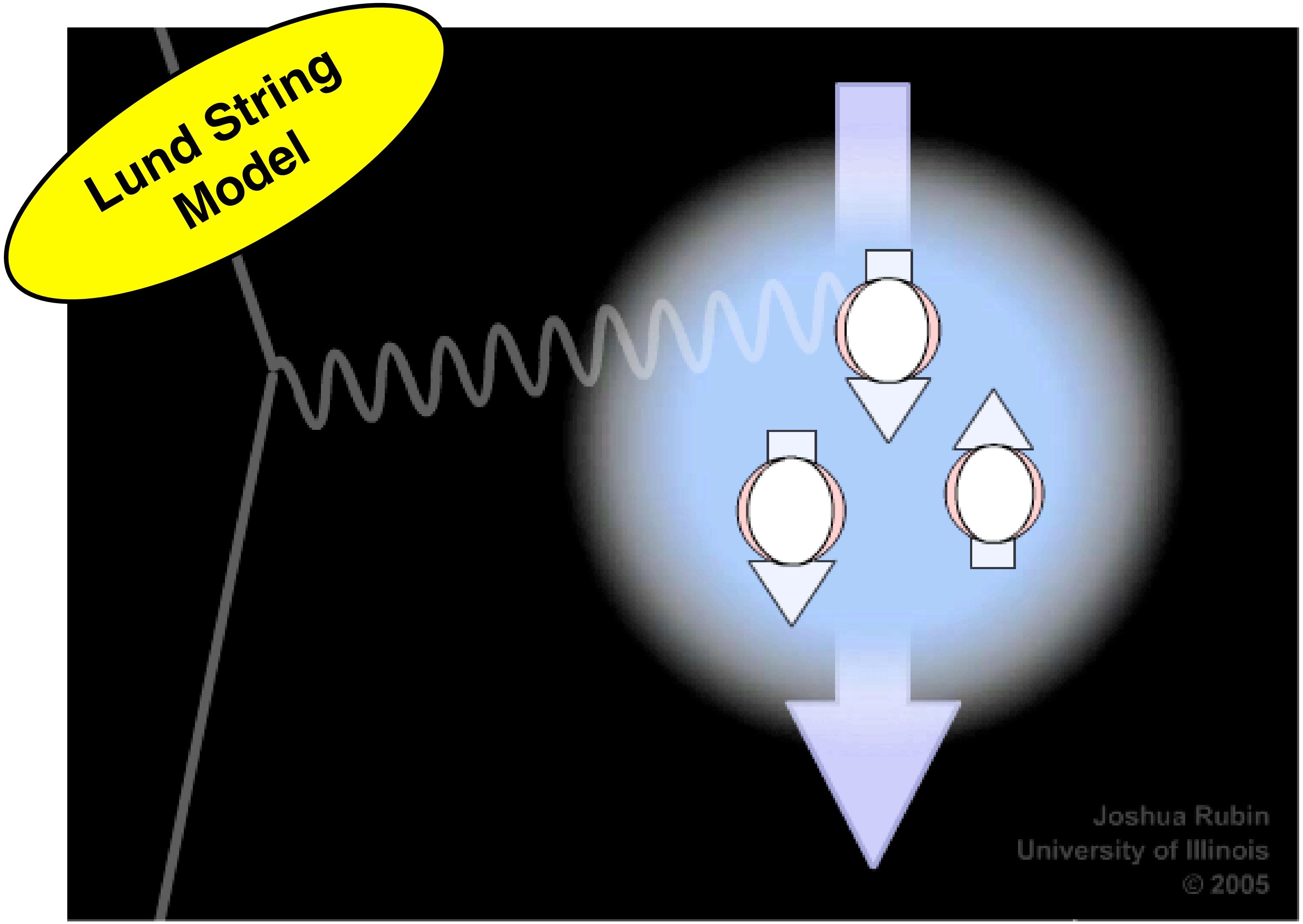
- Positive for **π⁺**...
  Negative and *larger* for **π⁻**...
  π⁰ consistent with isospin-sym

Systematic error bands include acceptance and smearing effects, and contributions from unpolarized <cos(2ϕ)> and <cos(ϕ)> moments

Understanding the Collins Effect

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

Is the Artru mechanism responsible?

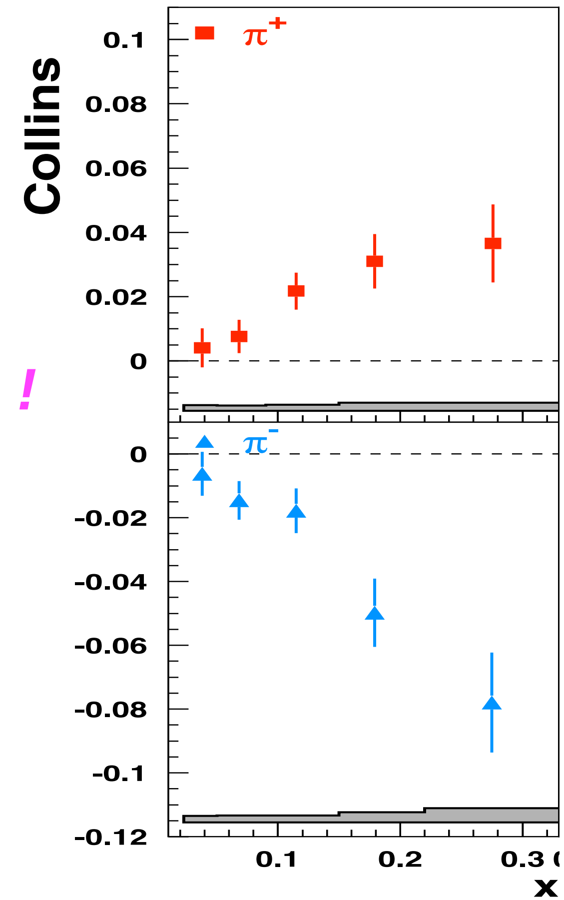


Why are the Collins π⁻ asymmetries so large?

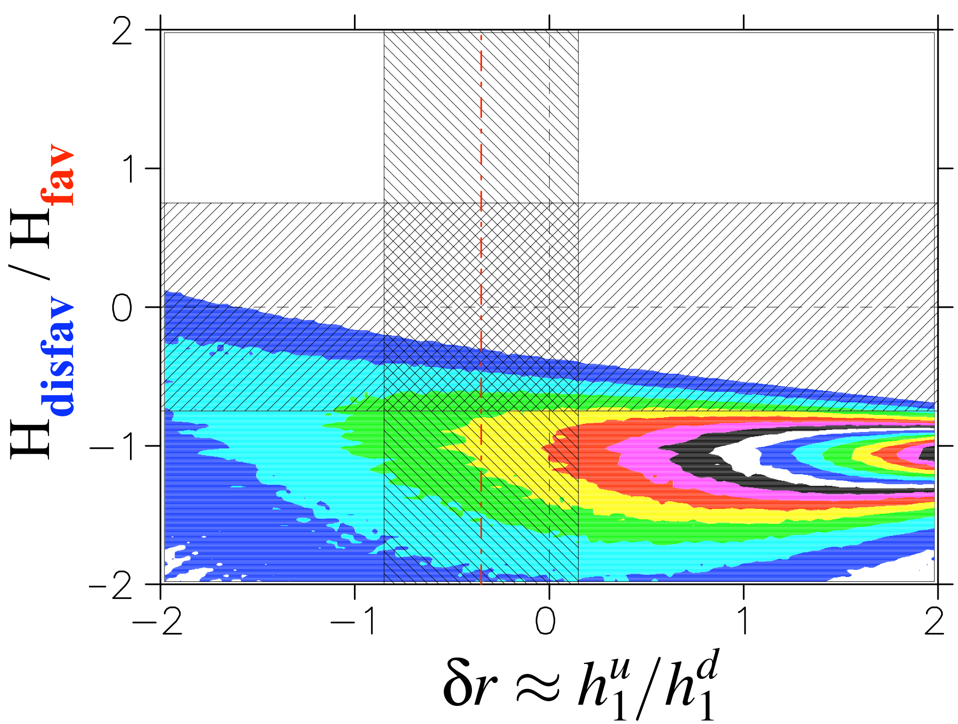
DIS on proton target always dominated by *u-quark scattering*

$A_{\mathrm{Col}}^{\pi^+} \sim h_1^u \, H_{1,\mathbf{favored}}^{\perp}$ ... expected: **positive**

$A_{\mathrm{Col}}^{\pi^-} \sim h_1^u \, H_{1,\mathbf{disfavored}}^{\perp}$ ... expected: **~ zero**



Data indicate *disfavored* Collins FF is *large & negative !*



Map out solution space ...
find $H_{\mathrm{disfav}} \approx -H_{\mathrm{fav}}$

N.C.R. Makins, CLAS12 RICH Workshop, Jan 28-29, 2008

Collins Global Fit: HERMES & BELLE

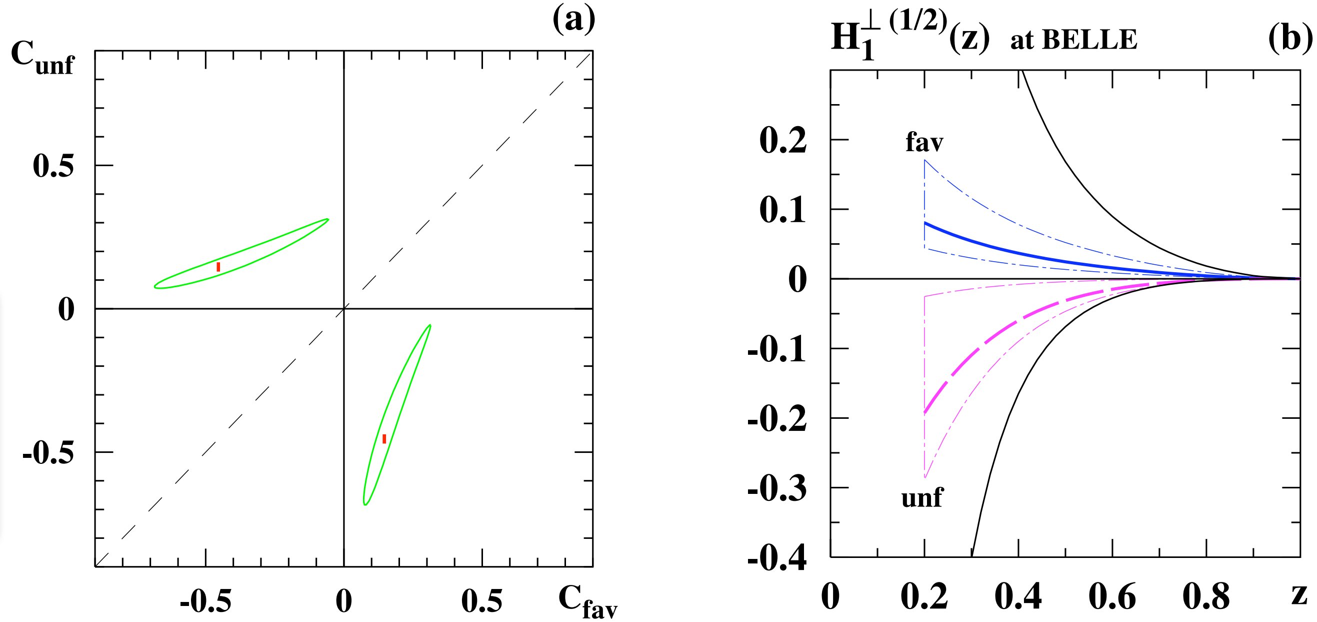
Efremov, Goeke, Schweitzer, hep-ph/0603054

Fit **BELLE** *z*-dependent results to

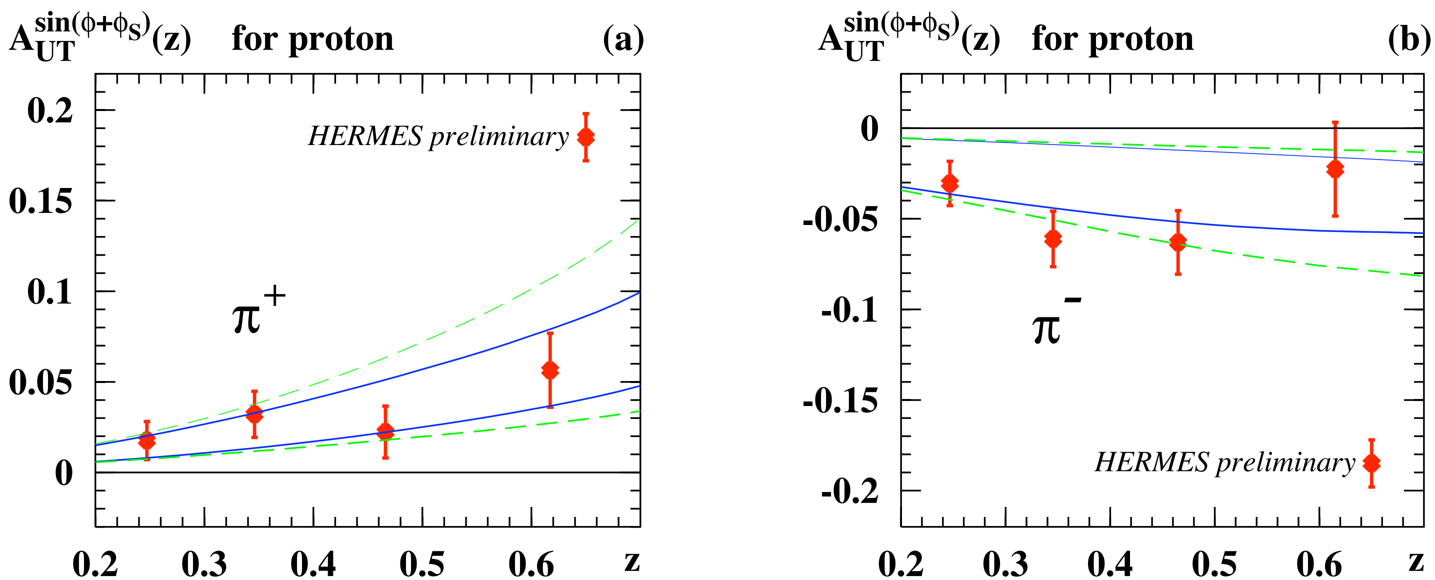
$$H_1^{\perp(1/2)a}(z) = C_a\, z\, D_1^a(z)$$

C_{fav} = 0.15, C_{unf} = –0.45

and so $H_1^{fav} \approx -H_1^{unf}$



Resulting Collins FF also fits **HERMES** & **COMPASS** data well



… with $h_1(x)$ from XQSM

Collins Global Fit: HERMES & BELLE

Fit **BELLE** *z*-de[p…]
results t[o…]

$$H_1^{\perp(1/2)a}(z) = C_a \ldots$$

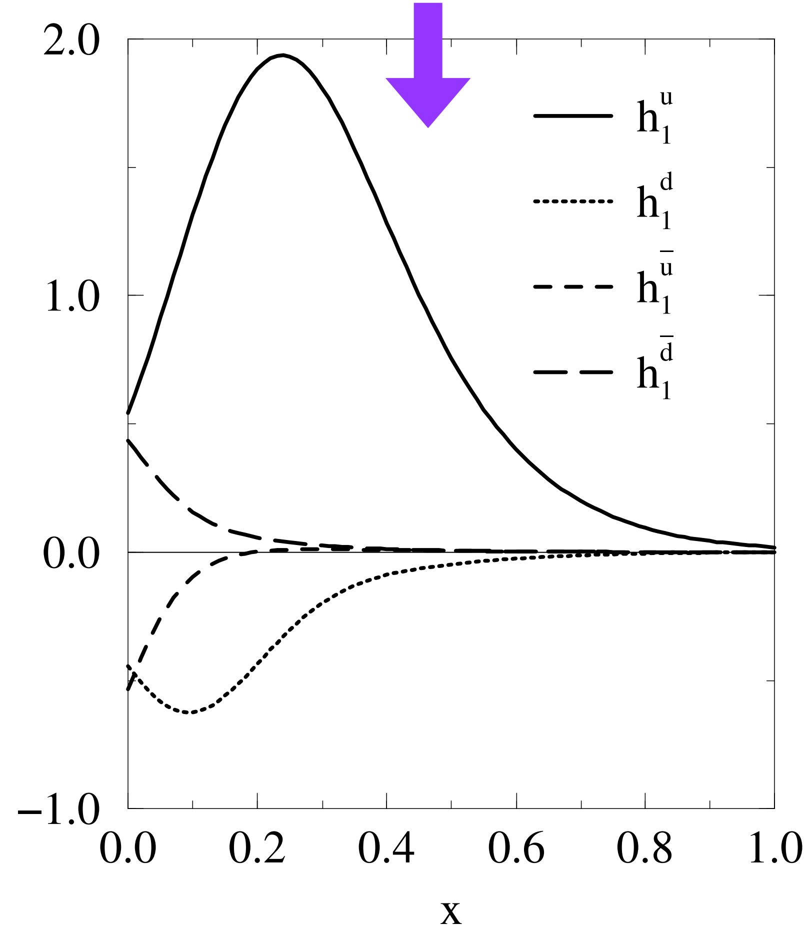
C_{fav} = 0.15, C_{unf} …

and so $H_1^{fav} \approx$ …

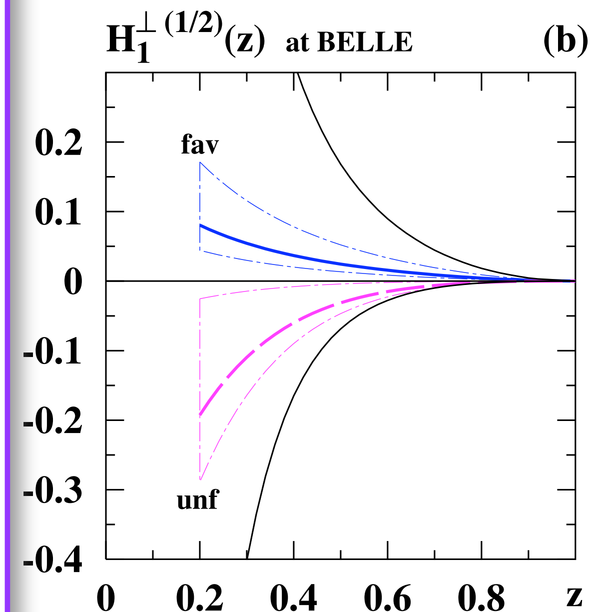
Resulting
Collins FF
also fits
HERMES &
COMPASS
data well

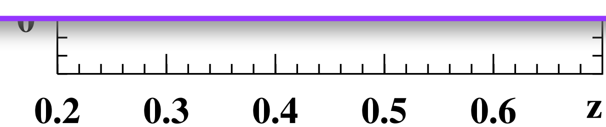
… with $h_1(x)$ from XQSM

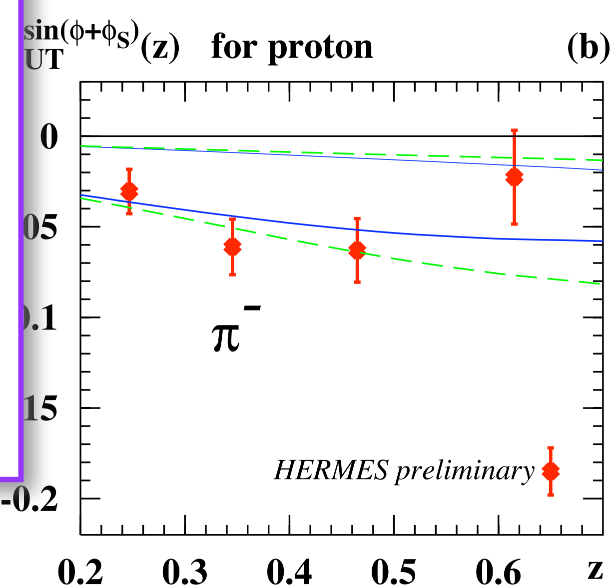
$h_1(x)$ from XQSM = Chiral-Quark Soliton Model:



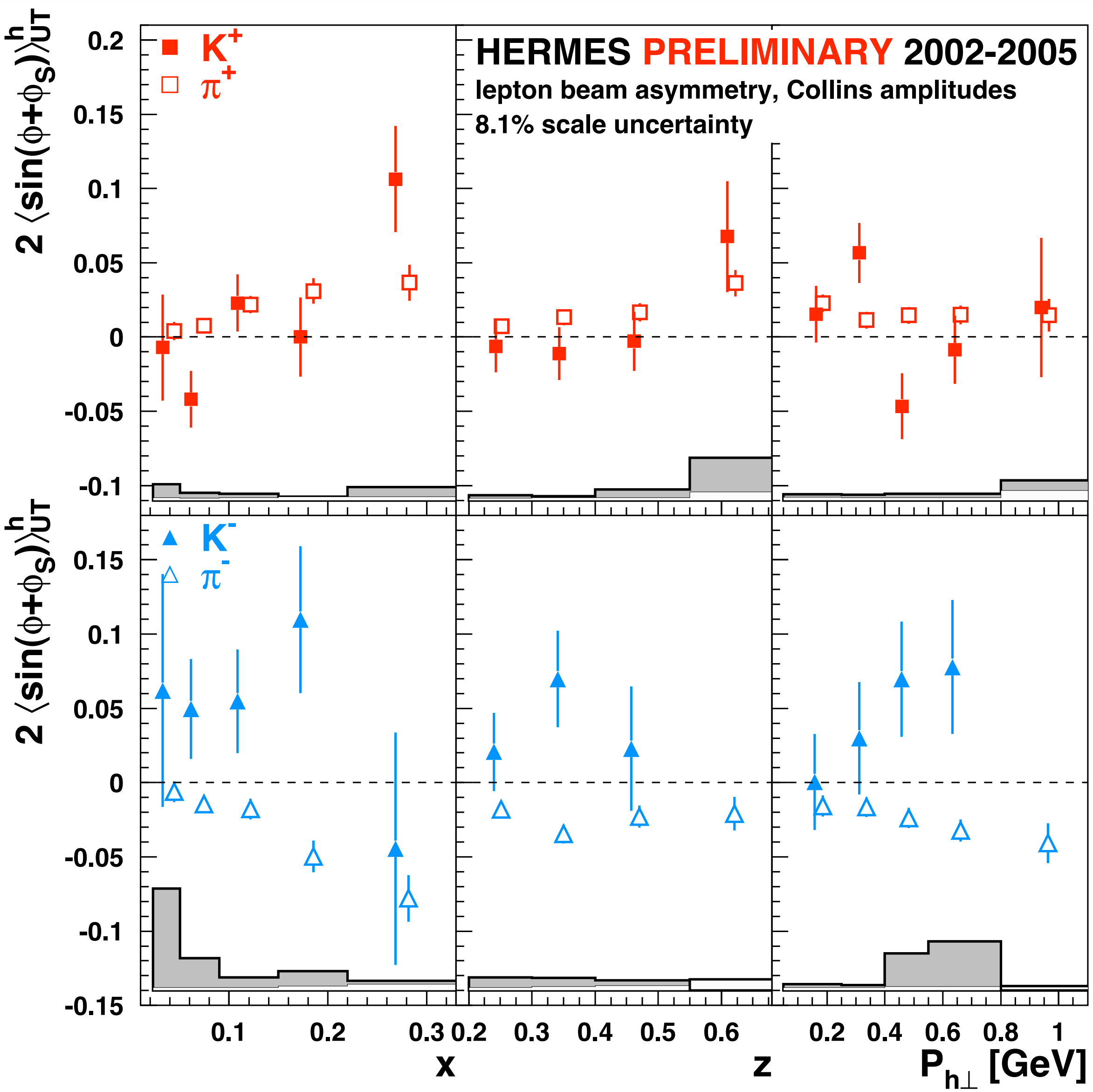
…e, Schweitzer, hep-ph/0603054







Collins moments for Kaons from Transverse H↑ Data

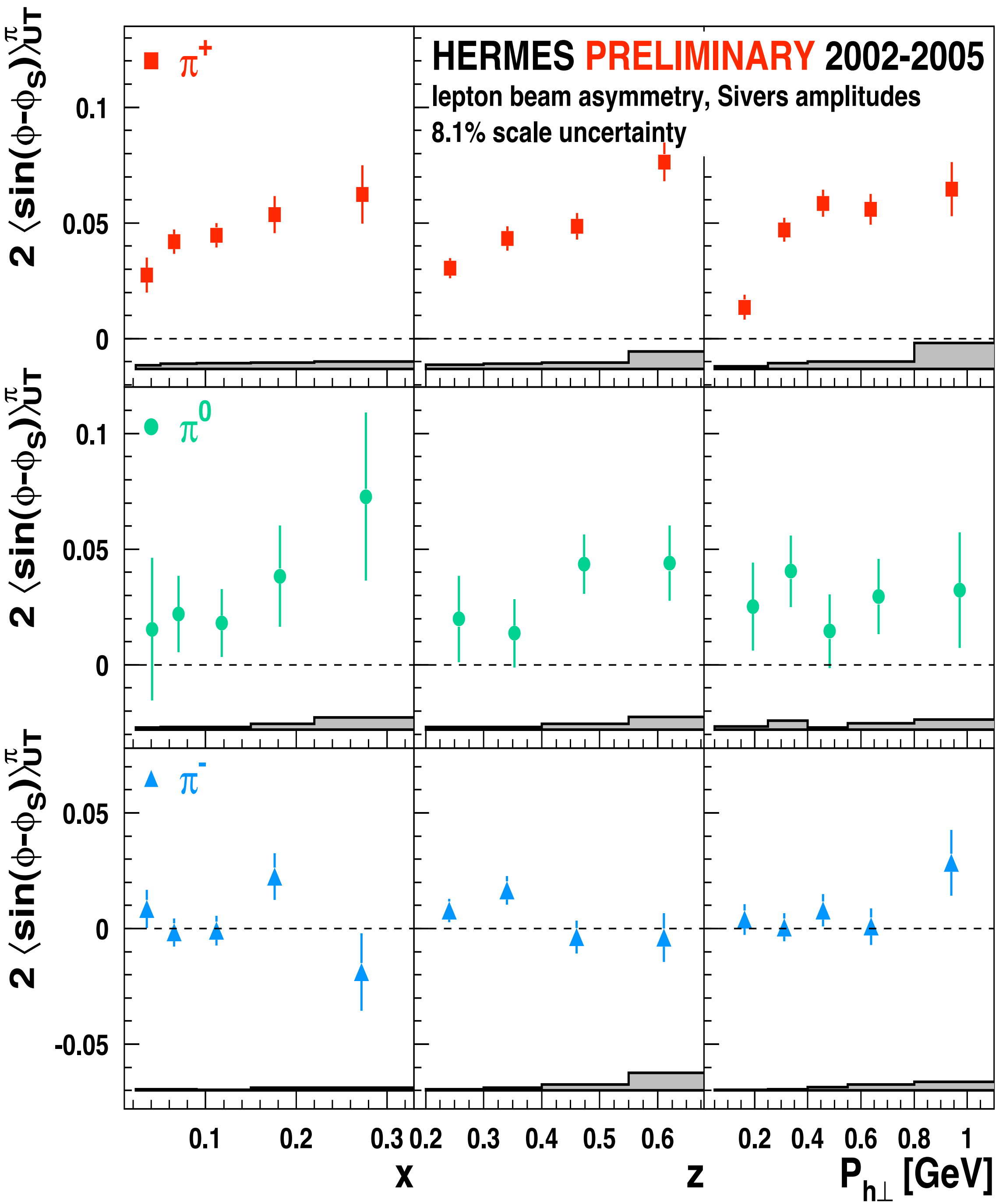


\+ K^+ consistent with π^+, as expected from ***u-quark dominance***

− $K^- = s\bar{u}$ = ***all sea*** ... data suggests ***opposite sign*** to $\pi^- = d\bar{u}$ ...

Sivers Effect Results:
SIDIS and dijet production

Sivers Moments for π^+ π^- π^0 from Transverse $H^{\uparrow}$ Data



It exists too!

- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for π^+...
  Consistent with zero for π^-...
  π^0 consistent with isospin-sym

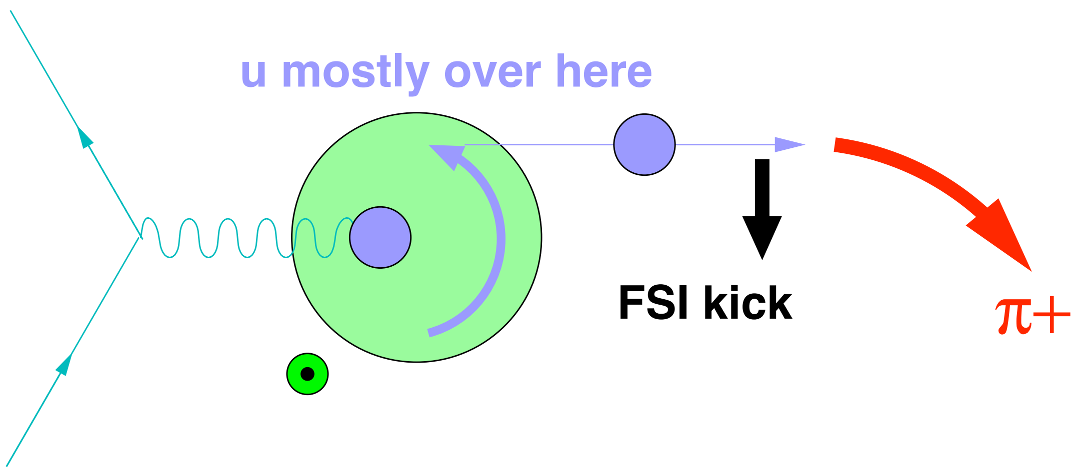
Systematic error bands include acceptance and smearing effects, and contributions from unpolarized $\langle\cos(2\phi)\rangle$ and $\langle\cos(\phi)\rangle$ moments

Phenomenology: Sivers Mechanism

Many models predict $L_u > 0$ ...

M. Burkardt: Chromodynamic lensing

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



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

(and opposite for π^-)

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

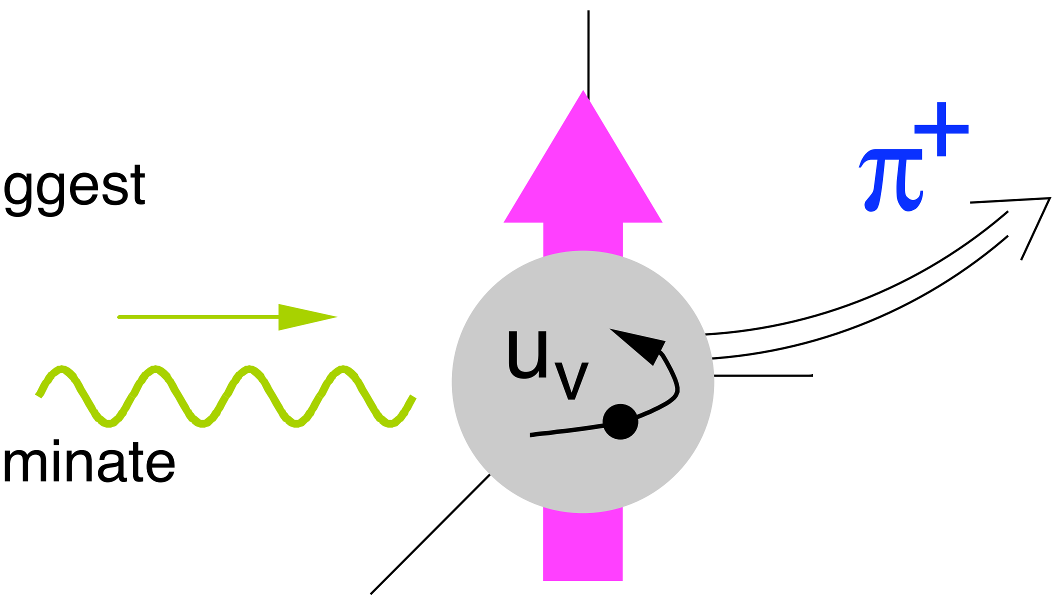
Model agrees!

D. Sivers: Jet Shadowing

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

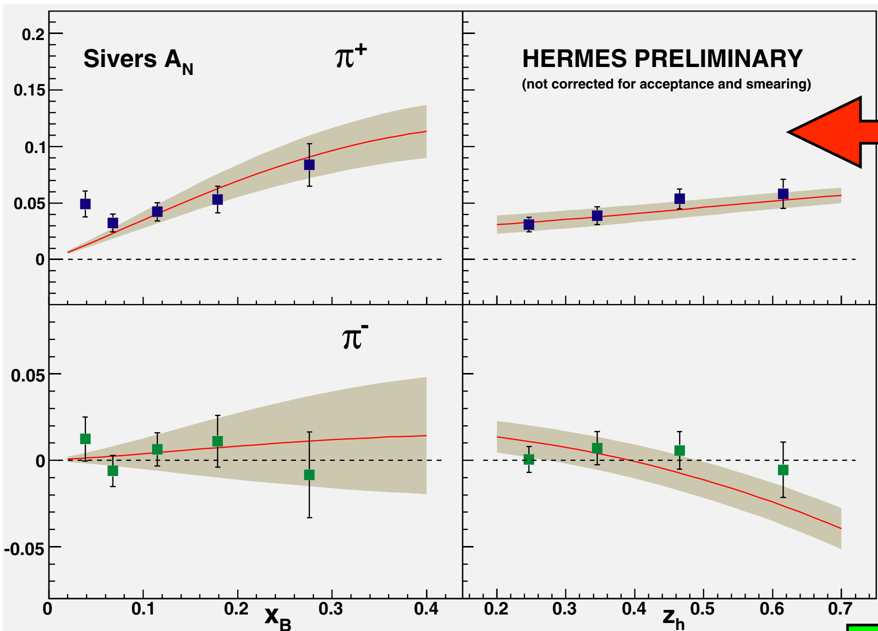
➡ quarks from "far" surface should dominate

Opposite sign to data ...



Sivers Global Fit: HERMES & COMPASS

Vogelsang & Yuan, PRD 72 (2005) 054028



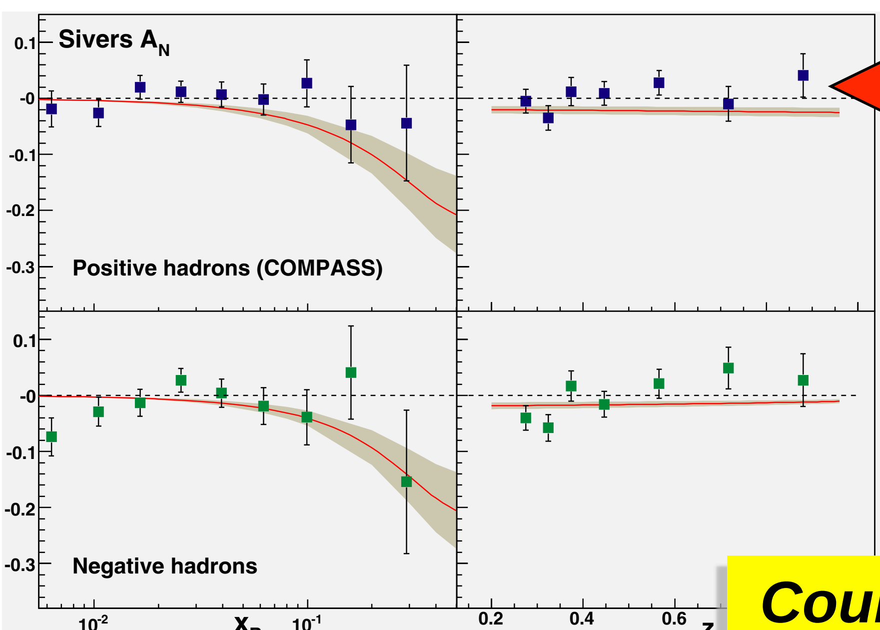
For convenience: $q_T(x) \equiv f_{1T}^{\perp,q}(x)$

Fit HERMES A_{UT} to Sivers func^n of form:

$$\frac{u_T^{(1/2)}(x)}{u(x)} = S_u\, x(1-x), \quad \frac{d_T^{(1/2)}(x)}{u(x)} = S_d\, x(1-x)$$

- assume **no antiquark** Sivers func: $\bar{q}_T(x) = 0$
- unpol PDFs = GRV-LO, unpol FFs = Kretzer

$$S_u = -0.81 \pm 0.07, \quad S_d = 1.86 \pm 0.28$$



Fits COMPASS deuterium data well

But a surprise! $|S_d| \gg |S_u|$!

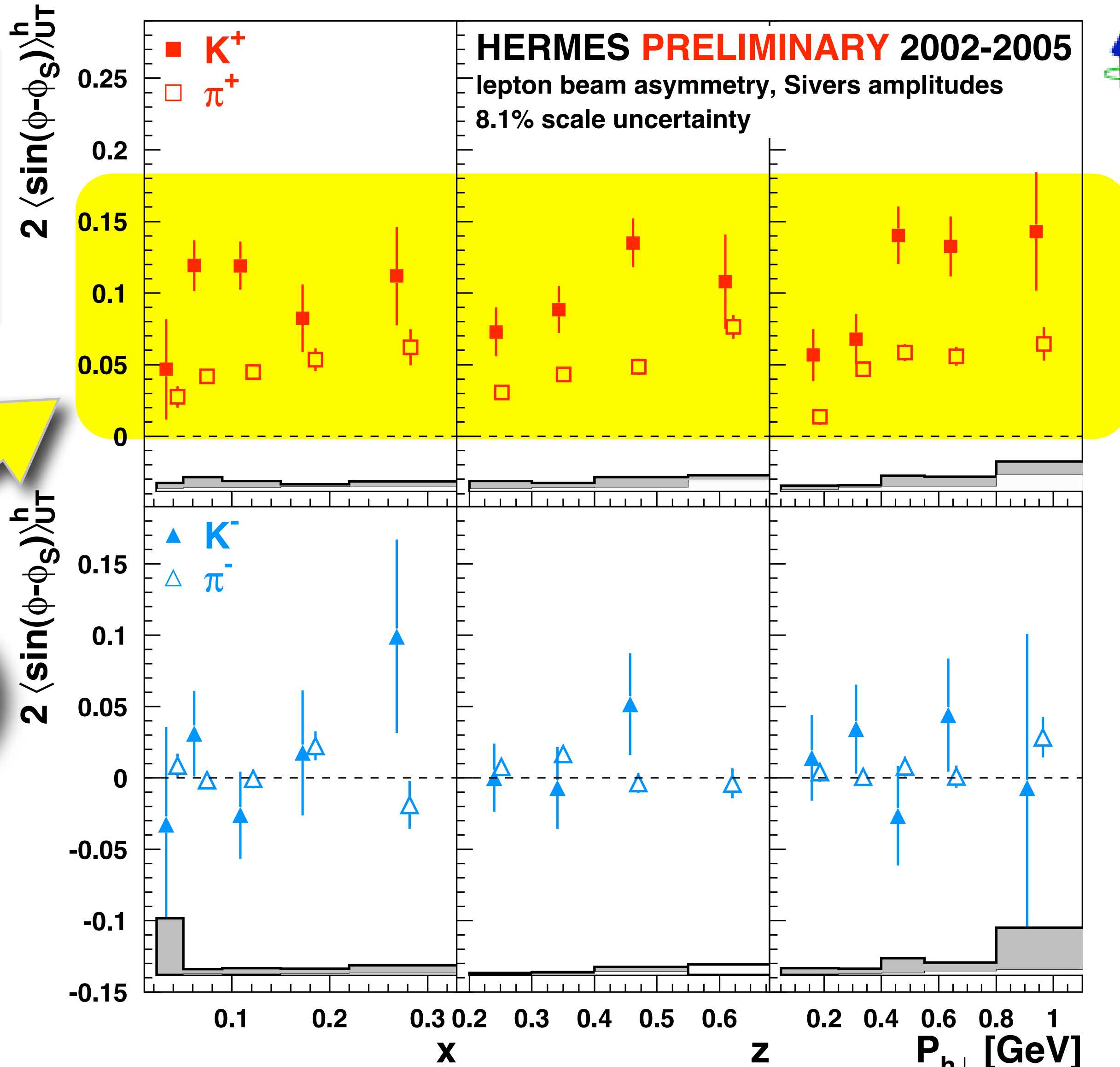
e.g., large-N_C expectation: $u_T(x) \approx -d_T(x)$

Hmm ... S_u *actually* reflects $u_T + \bar{d}_T/4$

... S_d *actually* reflects $d_T + 4\bar{u}_T$

Could Sivers (and L) be large for antiquarks?

Sivers moments for Kaons from full 2002–05 data



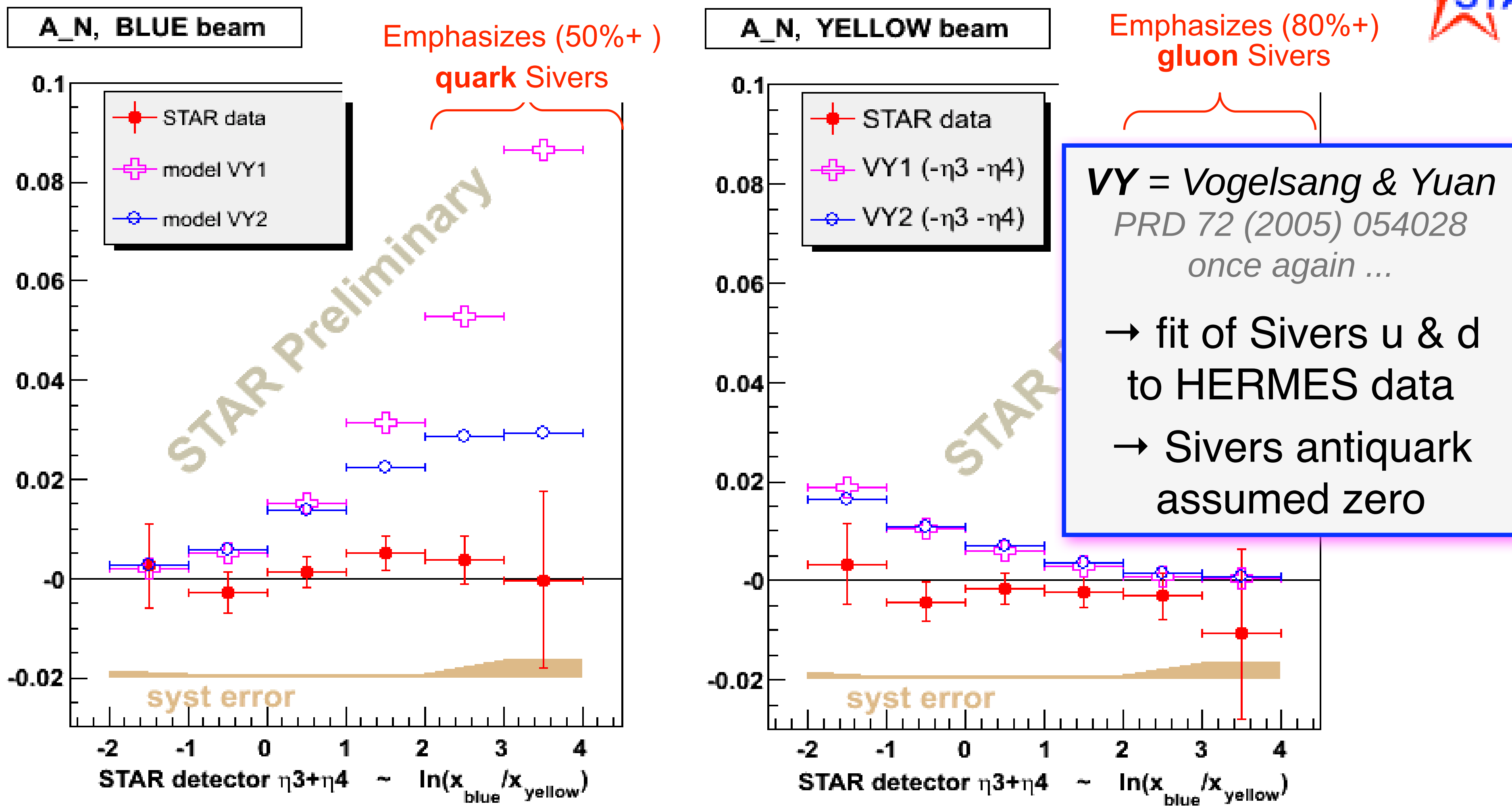
Sivers K^+ much larger than for π^+ !

– Effect about **equal** for $K^- = s\bar{u}$ and $\pi^- = d\bar{u}$ → note: same antiquark ...

+ Effect *seems **larger*** for $K^+ = u\bar{s}$ than $\pi^+ = u\bar{d}$ at $x \approx 0.1$ ... !

→ significant ***antiquark*** Sivers functions? and strongly flavor-dependent?

Measured Sivers A_N for Di-jets vs. Theory



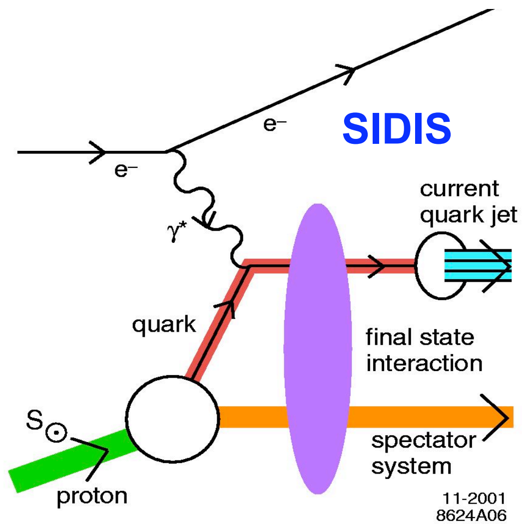
- Model w/o hadronization, integrated over STAR η, $5<p_T<10$ GeV/c, includes only quark Sivers -- predicts $A_N \sim A_N^{HERMES}$ where q Sivers dominates
- Sign of predictions reversed to adhere to Madison A_N sign convention

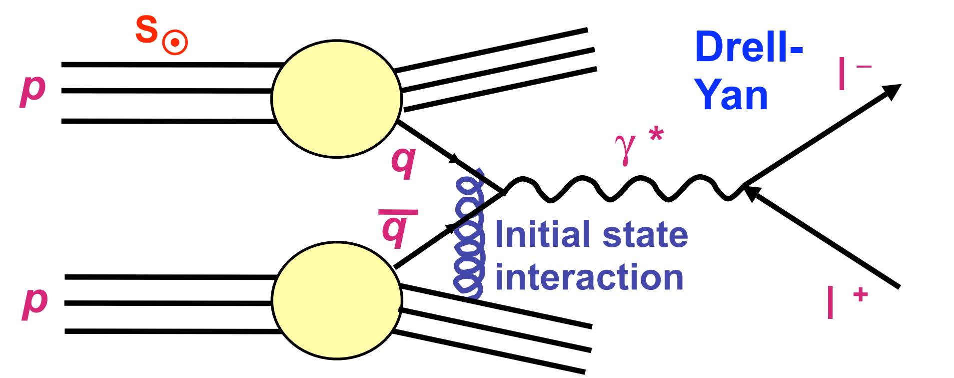
STAR measured A_N all consistent with zero ⇒ both quark and gluon Sivers effects much smaller in $\vec{p}p$ → di-jets than in HERMES SIDIS !!

Theory - exp't discrepancy raises questions!

Are observed di-jet Sivers SSA much smaller than predictions because:

- ***ISI & FSI both important in $\vec{p}p \to$ jets and tend to cancel?***





ISI for Drell-Yan vs. FSI for SIDIS ⇒ opposite sign predicted for Sivers SSA

- ***Need $\bar{q}$ Sivers or different q Sivers x, k_T - shapes in HERMES fits?***

- ***If ISI / FSI cancel at mid-rapidity, does their balance change at high η to yield sizable Sivers contribution to observed $\vec{p}p \to \pi^0 X$ SSA?***

Parameterization of the Sivers distribution function

Update of Phys. Rev. D71 (2005) 074006
→ *in progress ...*

$$h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M}\,e^{-k_\perp^2/M^2}$$

- add HERMES K± and COMPASS data to fit
- use new Sassot FF's

$$\Delta^N f_{q/p^\uparrow}(x,k_\perp) = 2\,\mathcal{N}_q(x)\;h(k_\perp)\;f_{q/p}(x,k_\perp)$$

$$\mathcal{N}_q(x) = N_q\,x^{a_q}\,(1-x)^{b_q}\,\frac{(a_q+b_q)^{(a_q+b_q)}}{a_q^{a_q}\,b_q^{b_q}}$$

with $-1 \le N_q \le 1$

$$f_{q/p}(x,k_\perp) = f_{q/p}(x)\,\frac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle}$$

$|\mathcal{N}_q(x)|$ and $|h(k_\perp)|$ are smaller than 1 for any x and for any

Positivity Bound

$$\frac{|\Delta^N f_{q/p^\uparrow}(x,k_\perp)|}{2\,f_{q/p}(x,k_\perp)} \le 1$$

automatically satisfied

A smattering of upcoming
SSA results

hermes

"The Magnificent 8" PDFs

main** SSA-SIDIS analyses still **in progress

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	$\cos(\phi_h^l - \phi_S^l)$	$\otimes g_{1T} =$	$\otimes D_1 =$

❶ cos(Φ),(2Φ)

5D-unfolding
of unpol xsec

❷ p_T-weighted moments

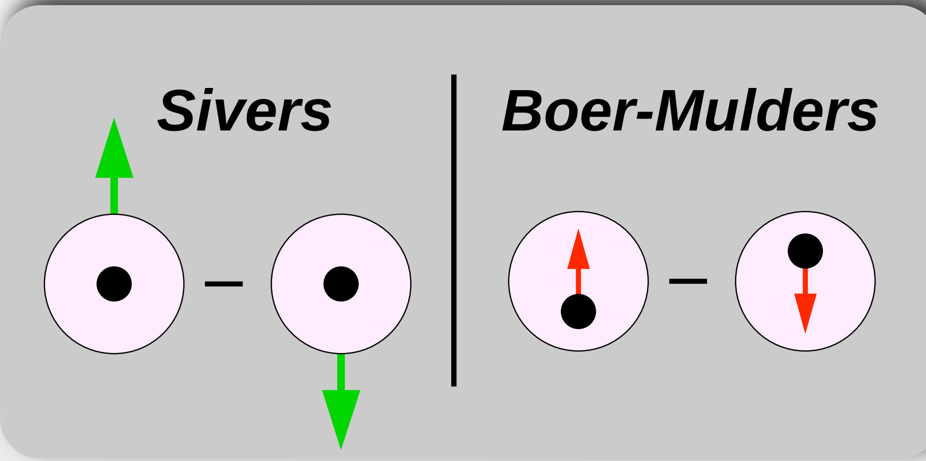
acceptance effects
& assoc syst uncert

❸ A_{LT} moments

just a matter of ***time*** & ***people*** ☺

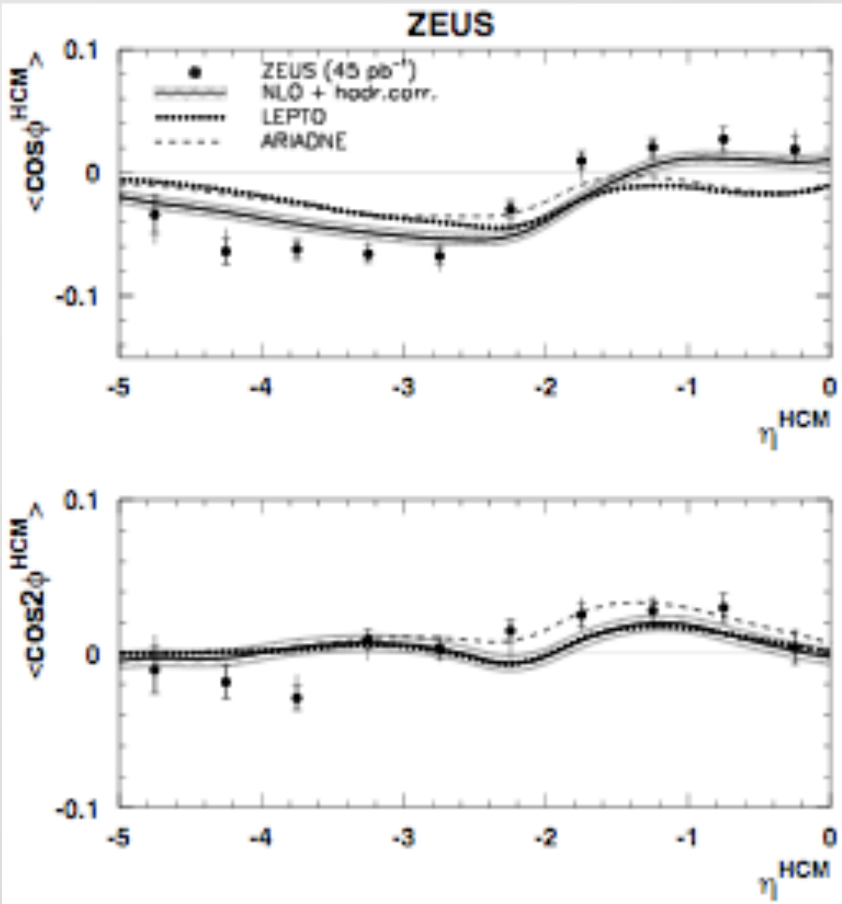
Existing Measurements

Boer-Mulders DF $h_1^\perp$
T-odd partner of Sivers



cos(2ϕ)

- EMC ($h^\pm$ on H; 27K SIDIS)
- Zeus ($h^\pm$ on H)
- HERMES (π^+, π^-, K^+, K^-, p^+, p^- on H and D; ~5M SIDIS of each)



cos(ϕ)

- E665 ($h^\pm$ on H)
- EMC ($h^\pm$ on H)
- Zeus ($h^\pm$ on H)
- HERMES (π^+, π^-, K^+, K^-, p^+, p^- on H and D; ~5M SIDIS of each)

Cahn effect
excellent probe of quark $\langle k_T \rangle$

Conclusions

- **Collins** effect isolated
  - **disfavored** Collins fragmentation function of **opposite sign** and similar magnitude to **favored** function
  - **sign** of effect supports **$^3P_0$ picture** of color string breaking
  - result **confirmed** by new data from **BELLE**, + successful global analyses including **COMPASS** data
  - **XQSM** estimate of **transversity** fits SIDIS data quite well
- **Sivers** effect is ***non-zero*** in DIS
  - successful global analysis of **HERMES** (H) & **COMPASS** (D)
  - ... and suggests large **antiquark** contributions to **orbital *L***
  - HERMES data on **Kaon produc^n** seem to support this ...

Main Conclusion → ***CLAS12 needs Kaon ID***