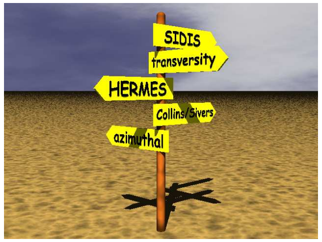
Transverse Spin Structure of the Proton Studied in Semi–inclusive DIS

Ulrike Elschenbroich

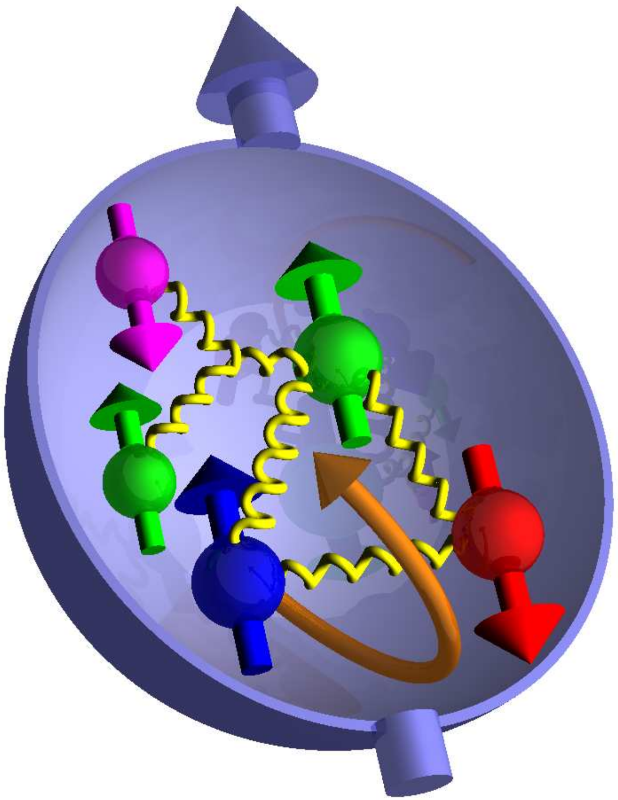
Outline

- The Inner Structure of the Nucleon
- The HERMES Experiment
- Azimuthal Asymmetry Moments
- Interpretation of the Asymmetry Moments
- Conclusions



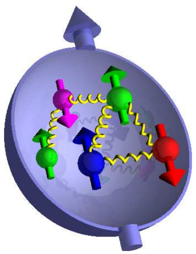
Spin of the Nucleon

Where does the spin of the nucleon come from?

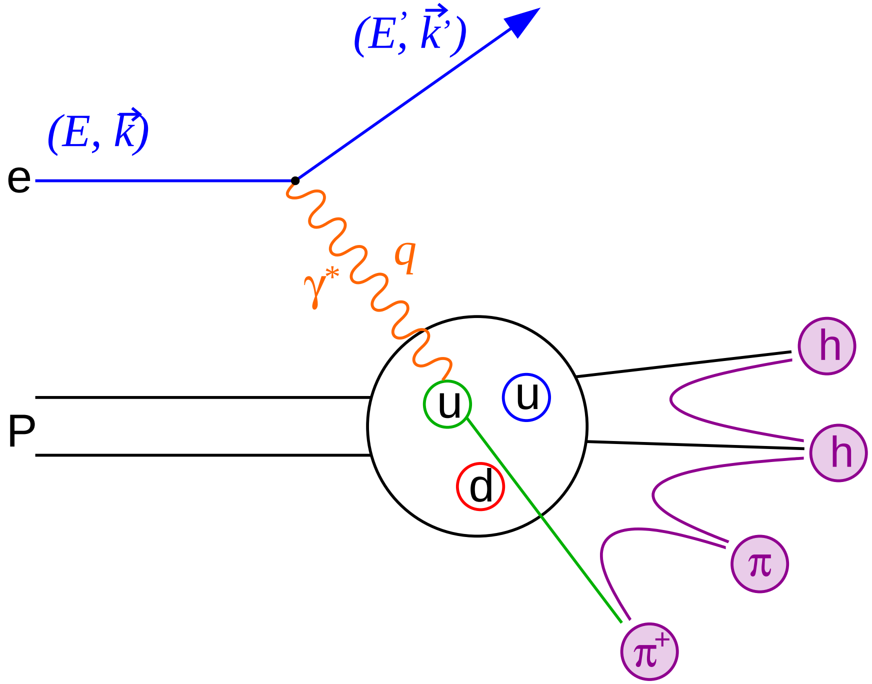


Contributions from:

- spin of the valence quarks
- spin of the sea quarks
- spin of the gluons
- orbital angular momentum of quarks
- orbital angular momentum of gluons



Semi–inclusive Deep–inelastic Scattering



$$Q^2 = -q^2 = -(k - k')^2$$

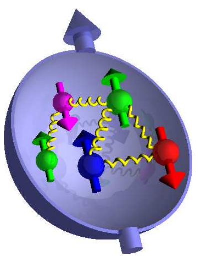
$$\nu \stackrel{\text{lab}}{=} E - E'$$

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

$$z \stackrel{\text{lab}}{=} \frac{E_{\text{had}}}{\nu}$$

Cross section contains Distribution Functions and Fragmentation Functions:

$$\sigma^{ep\rightarrow eh} \sim \sum_q \mathrm{DF}^{p\rightarrow q} \otimes \sigma^{eq\rightarrow eq} \otimes \mathrm{FF}^{q\rightarrow h}$$



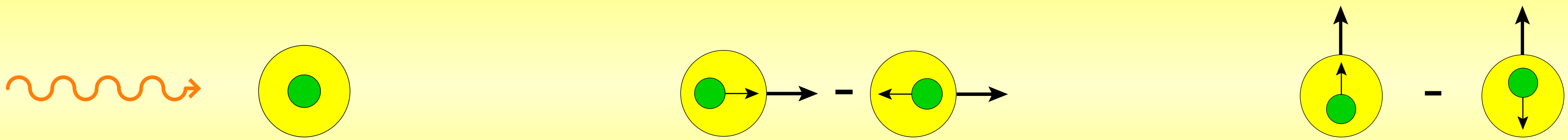
DF: distribution of quarks in the nucleon

FF: evolution of (struck) quark into hadronic final state

Distribution Functions

3 DFs survive the integration over transverse quark momenta

unpolarised DF	Helicity	Transversity

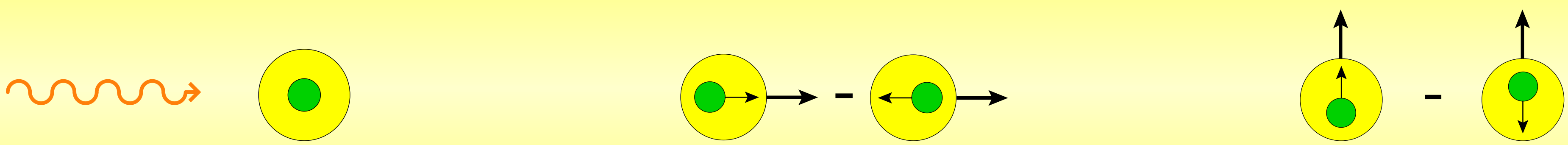


$q(x, Q^2)$	$\Delta q(x, Q^2)$	$\delta q(x, Q^2)$
well known	known	unknown
	HERMES 1996-2000	HERMES 2002-2005

Distribution Functions

3 DFs survive the integration over transverse quark momenta

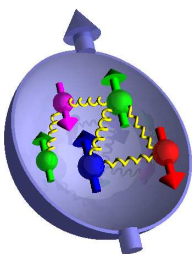
unpolarised DF | **Helicity** | **Transversity**



$q(x,Q^2)$ | $\Delta q(x,Q^2)$ | $\delta q(x,Q^2)$

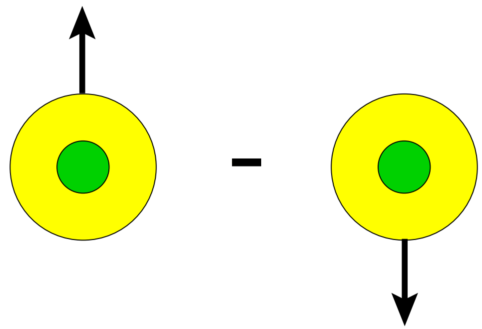
Transversity δq is chiral–odd function, i.e., involves helicity flip

➜ access in combination with other chiral–odd object

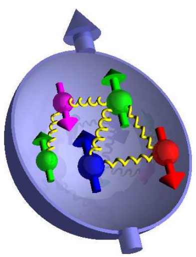


➜ **chiral–odd Collins FF** $H_1^{\perp q\rightarrow h}(z)$

Sivers Function $f_{1T}^{\perp}$



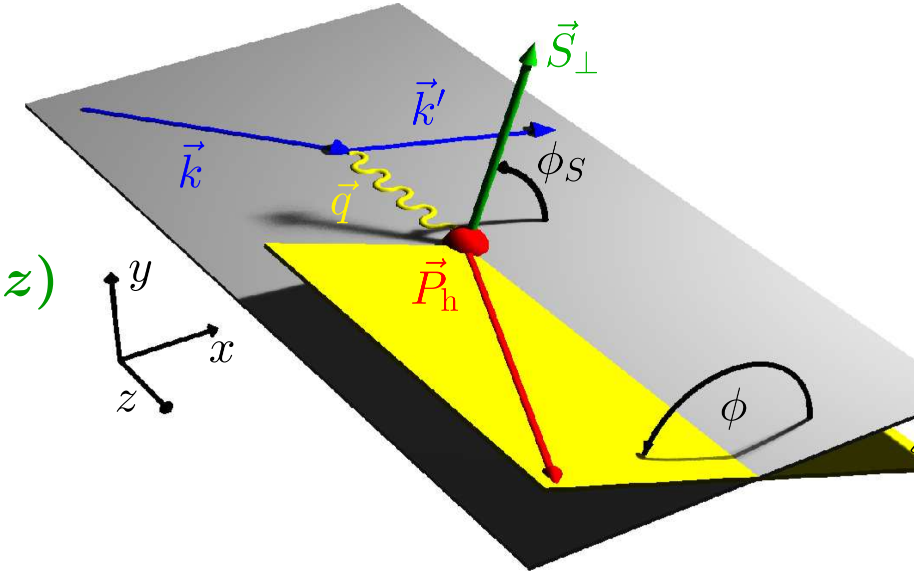
- describes correlation between intrinsic transverse quark momentum $\vec{p}_T$ and transverse nucleon spin
- naïve T–odd function: allowed due to final state interactions (FSI): quark rescattering via a soft gluon
- non–zero Sivers function requires non–vanishing orbital angular momentum in the nucleon
- direct functional relation between Sivers function and orbital angular momentum for individual quark flavours so far only in models

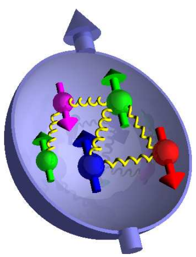


Cross Sections

unpolarised cross section:

$$\frac{d^6\sigma}{dx\ dz\ dy\ d\phi_S\ d^2P_{h\perp}} \sim \cdots \sum_q e_q^2\ \boldsymbol{q(x)} \cdot \boldsymbol{D_1^q(z)}$$





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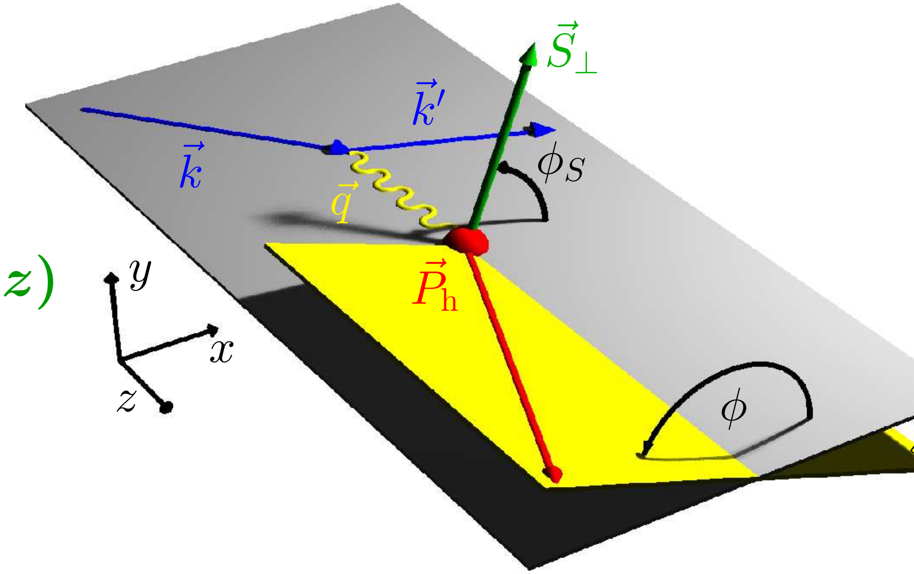


unpolarised cross section:

$$\frac{\mathrm{d}^6\sigma}{\mathrm{d}x\ \mathrm{d}z\ \mathrm{d}y\ \mathrm{d}\phi_S\ \mathrm{d}^2 P_{h\perp}} \sim \cdots \sum_q e_q^2\ \boldsymbol{q(x)} \cdot \boldsymbol{D_1^q(z)}$$

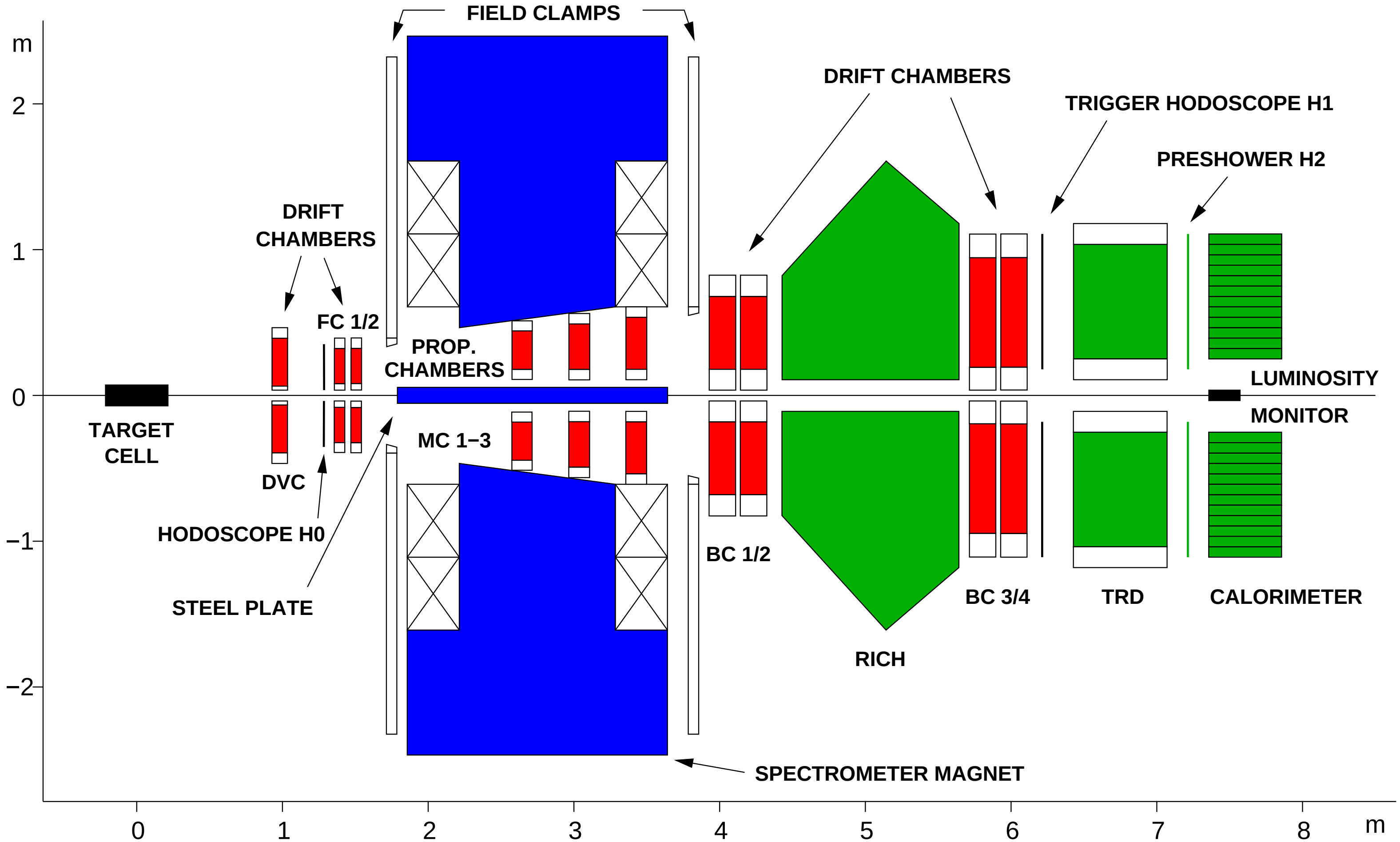
cross section for transversely polarised target:

$$\frac{\mathrm{d}^6\sigma^{\Uparrow} - \mathrm{d}^6\sigma^{\Downarrow}}{\mathrm{d}x\ \mathrm{d}z\ \mathrm{d}y\ \mathrm{d}\phi_S\ \mathrm{d}^2 P_{h\perp}} \sim \ \ldots\ \sin(\phi + \phi_S) \sum_q e_q^2\ \boldsymbol{\delta q(x, \vec{p}_T^{\,2})} \cdot \boldsymbol{H_1^{\perp(1/2)q}(z, \vec{k}_T^{\,2})}$$

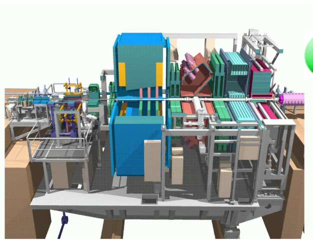
$$+ \ \ldots\ \sin(\phi - \phi_S) \sum_q e_q^2\ \boldsymbol{f_{1T}^{\perp(1/2)q}(x, \vec{p}_T^{\,2})} \cdot \boldsymbol{D_1^q(z, \vec{k}_T^{\,2})}$$

$$+ \ \ldots$$

The HERMES Spectrometer



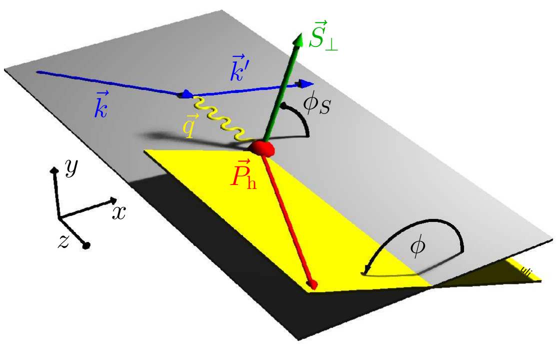
- tracking detectors: momentum resolution $< 2.6\,\%$
- particle identification: positron/electron identification $> 98\,\%$
  RICH detector allows discrimination between charged π, K, p



zimuthal symmetries

Measurement of cross section asymmetries depending on the azimuthal angles ϕ and ϕ_S:

$$A(\phi, \phi_S) \;=\; \frac{1}{S_\perp} \frac{N^\uparrow(\phi, \phi_S) - N^\downarrow(\phi, \phi_S)}{N^\uparrow(\phi, \phi_S) + N^\downarrow(\phi, \phi_S)}$$



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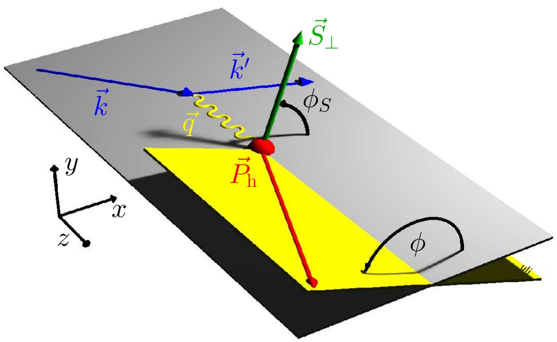
$$
\begin{aligned}
A(\phi,\phi_S) &= \frac{1}{S_\perp}\frac{N^\uparrow(\phi,\phi_S)-N^\downarrow(\phi,\phi_S)}{N^\uparrow(\phi,\phi_S)+N^\downarrow(\phi,\phi_S)} \\
&\sim \ldots \ \sin(\phi+\phi_S)\frac{\sum_q e_q^2\ \boldsymbol{\delta q(x,\vec{p}_T^{\,2})}\cdot \boldsymbol{H_1^{\perp(1/2)q}(z,\vec{k}_T^{\,2})}}{\sum_q e_q^2\ \boldsymbol{q(x)}\cdot\boldsymbol{D_1^q(z)}} \\
&+ \ \ldots \ \sin(\phi-\phi_S)\frac{\sum_q e_q^2\ \boldsymbol{f_{1T}^{\perp(1/2)q}(x,\vec{p}_T^{\,2})}\cdot \boldsymbol{D_1^q(z,\vec{k}_T^{\,2})}}{\sum_q e_q^2\ \boldsymbol{q(x)}\cdot\boldsymbol{D_1^q(z)}} \\
&+ \ \ldots
\end{aligned}
$$



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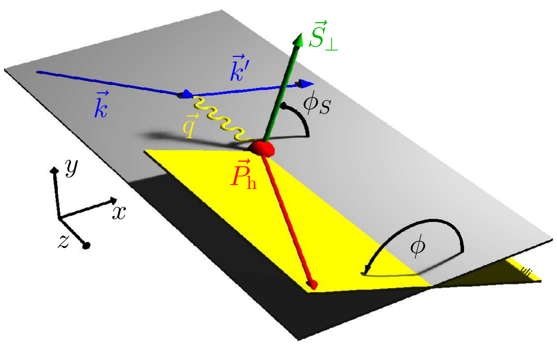
$$\sim \ldots \sin(\phi+\phi_S)\frac{\sum_q e_q^2\ \delta q(x,\vec{p}_T^{\,2})\cdot H_1^{\perp(1/2)q}(z,\vec{k}_T^{\,2})}{\sum_q e_q^2\ q(x)\cdot D_1^q(z)}$$

$$+ \ \ldots \sin(\phi-\phi_S)\frac{\sum_q e_q^2\ f_{1T}^{\perp(1/2)q}(x,\vec{p}_T^{\,2})\cdot D_1^q(z,\vec{k}_T^{\,2})}{\sum_q e_q^2\ q(x)\cdot D_1^q(z)}$$

$$+ \ \ldots$$

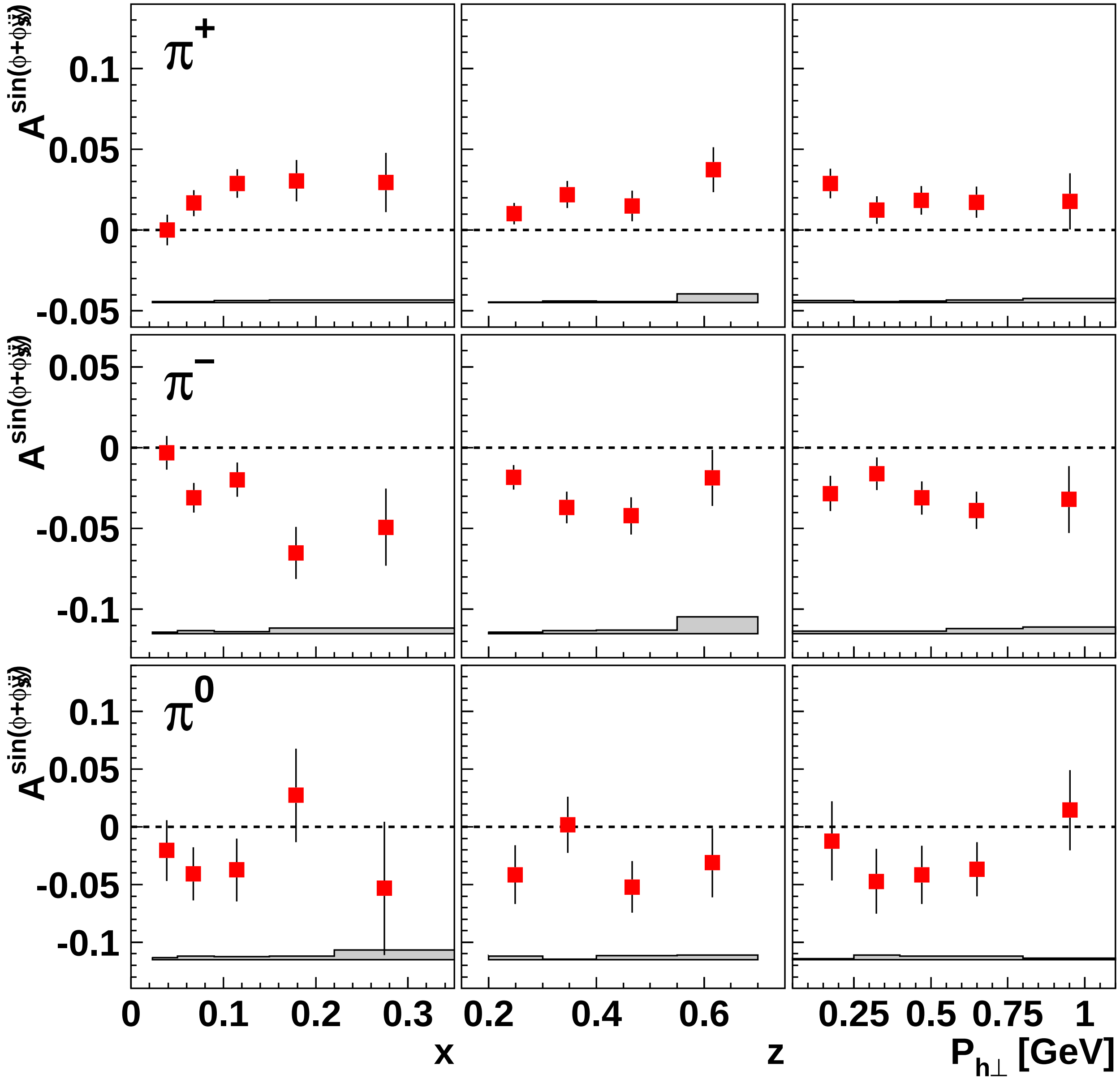
extract asymmetry amplitudes $A^{\sin(\phi+\phi_S)}$ and $A^{\sin(\phi-\phi_S)}$ by two–dimensional fit

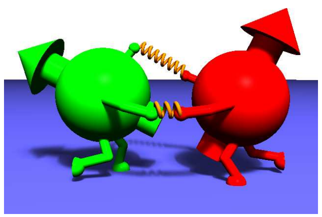


Pion Collins mplitudes

$$A^{\sin(\phi+\phi_S)} \sim \delta q \cdot H_1^{\perp(1/2)}$$

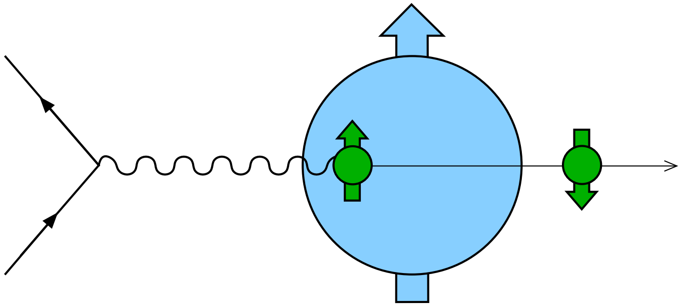
- analysed data set: 2002 – 2004
- positive π^+ amplitude
- negative π^- and π^0 amplitudes
- overall scale uncertainty 6.6 %

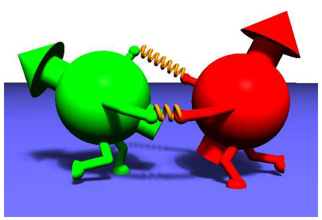




rtru Model

- polarisation component in lepton scattering plane reversed by photoabsorption:





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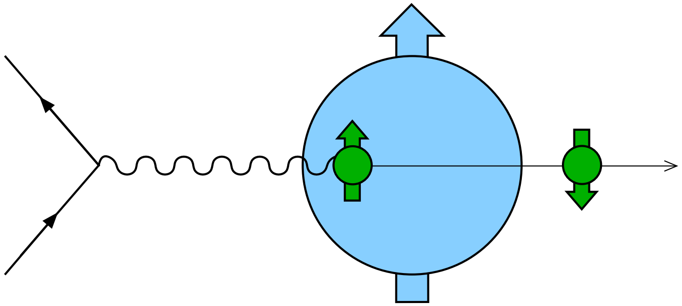
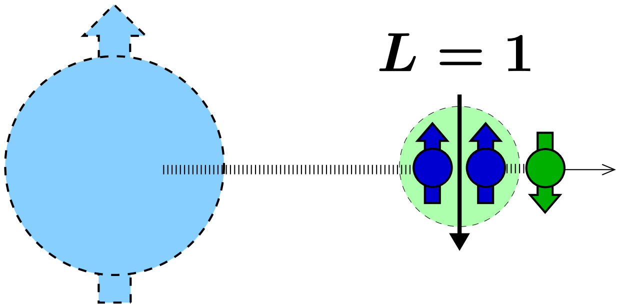
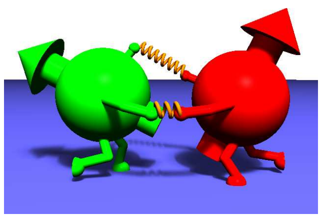


- string break, quark–antiquark pair with vacuum quantum numbers:





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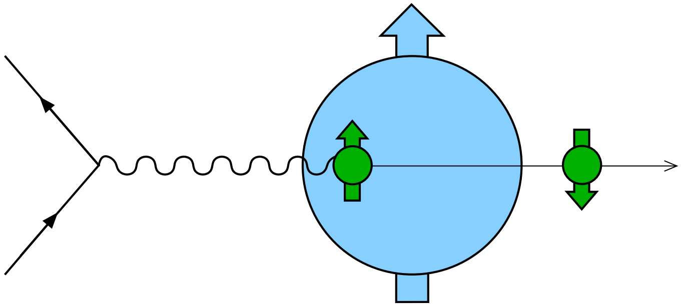

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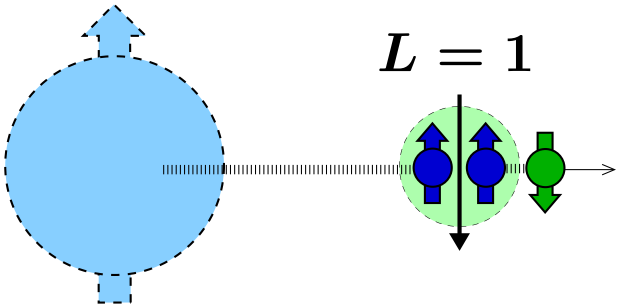
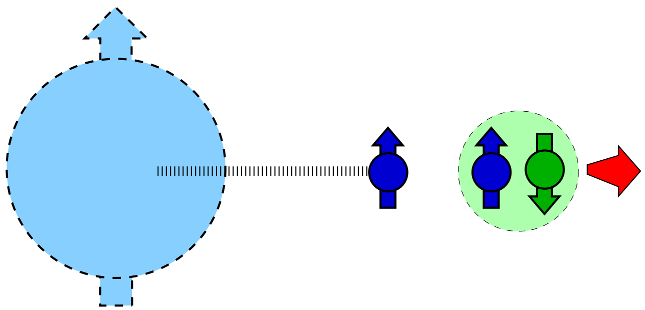
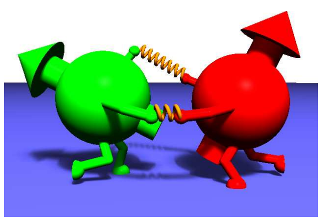


- orbital angular momentum creates transverse momentum:





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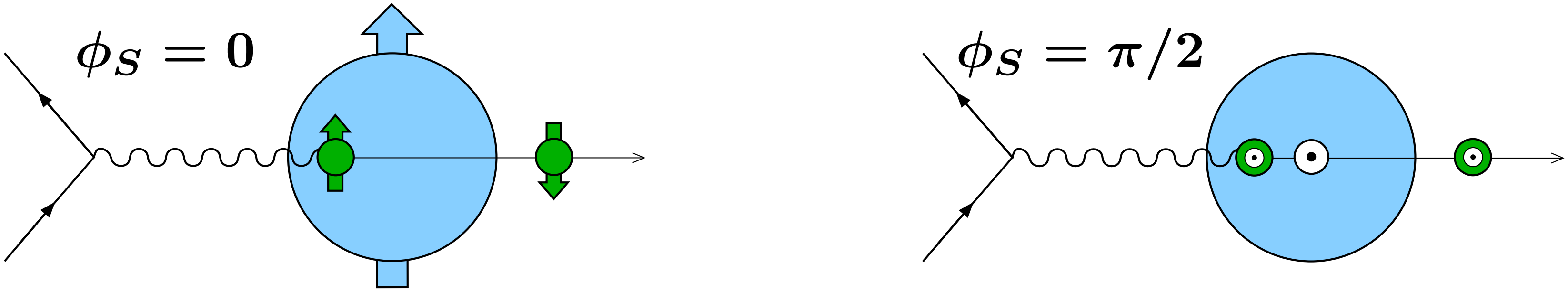

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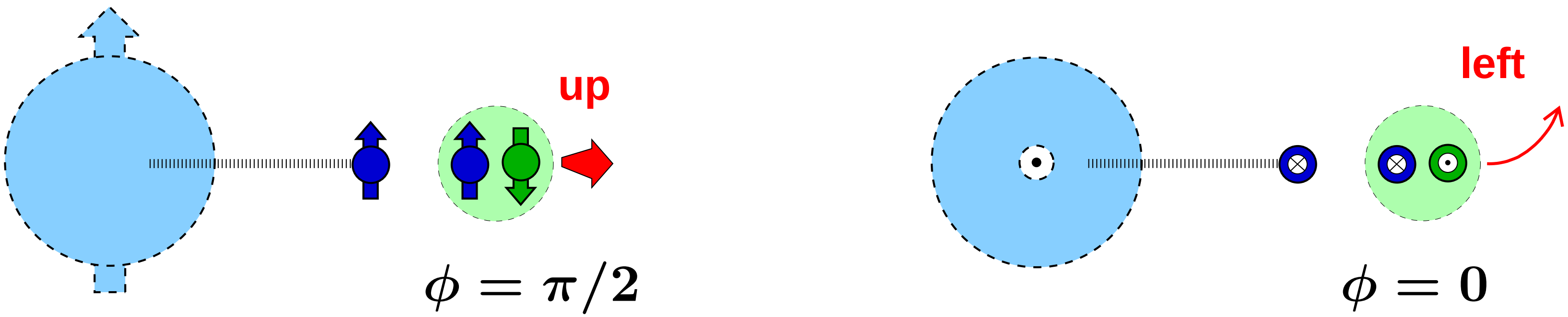
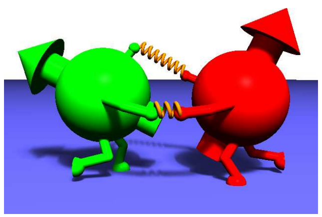




rtru Model

$$\delta q > 0 \rightarrow \sin(\phi + \phi_S) = \sin \pi/2 > 0$$

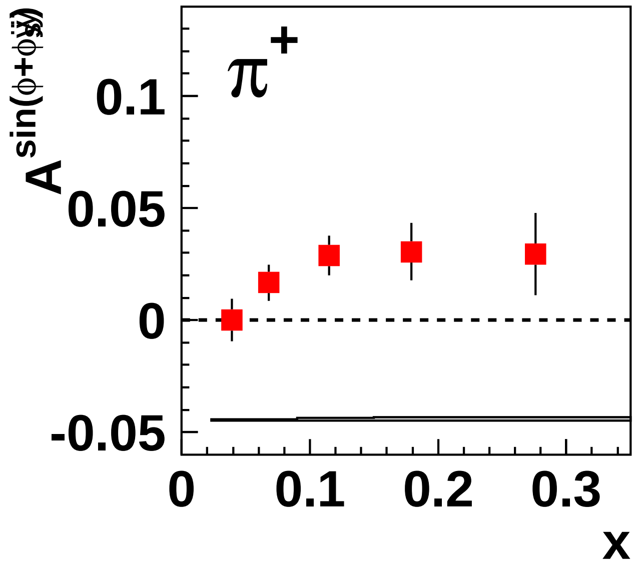
- positive transversity ➜ Artru model predicts positive Collins amplitude

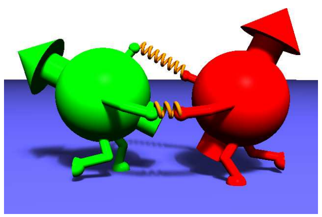
- π^+ production dominated by u quarks

  ➜ positive π^+ Collins amplitude means

  $$\delta u > 0$$

  as predicted by all models for transversity

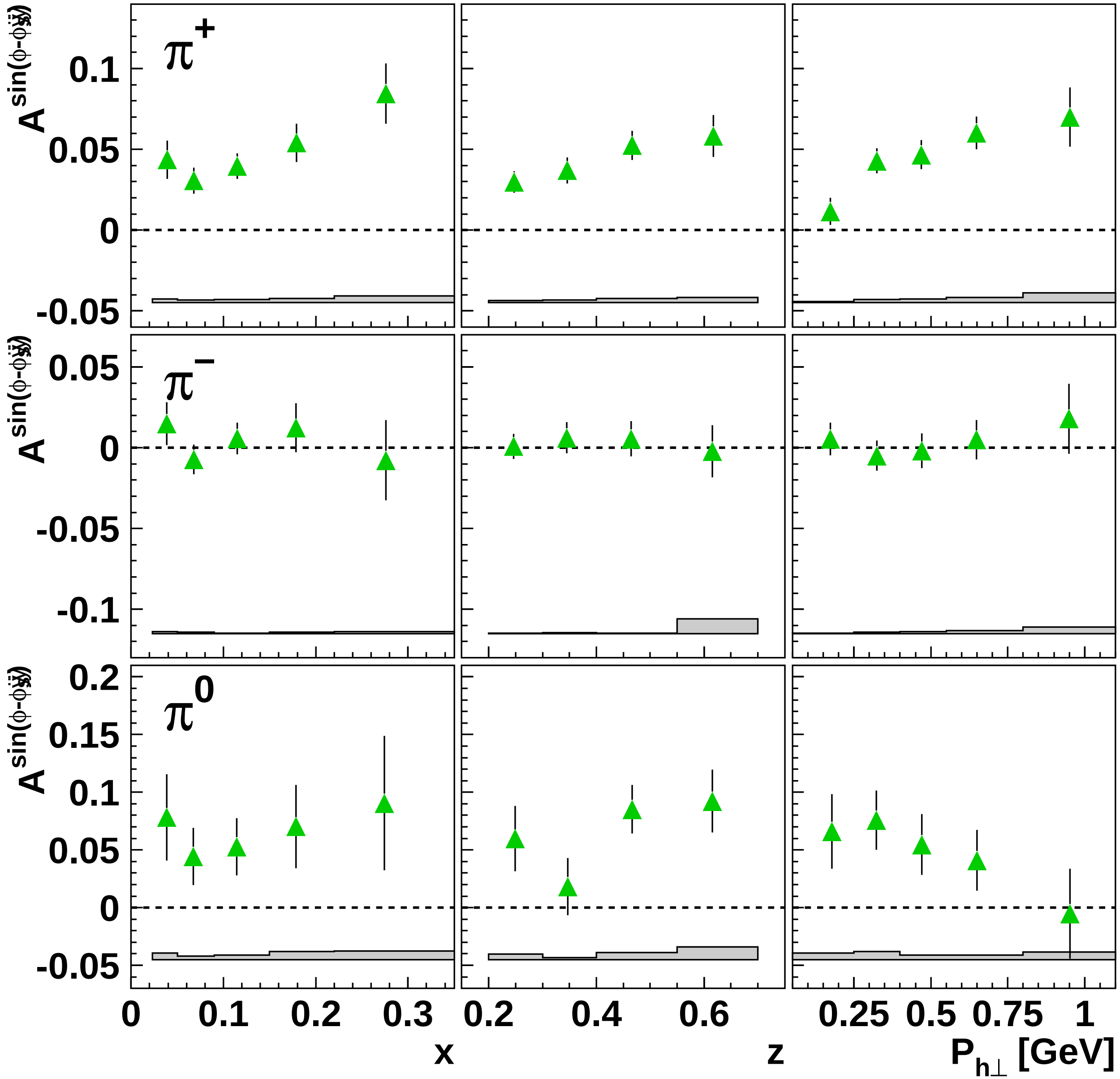


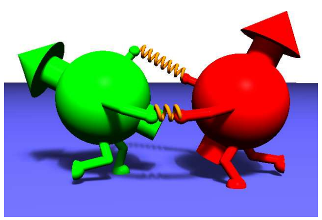


Pion Sivers mplitudes

$$A^{\sin(\phi-\phi_S)} \sim f_{1T}^{\perp(1/2)} \cdot D_1$$

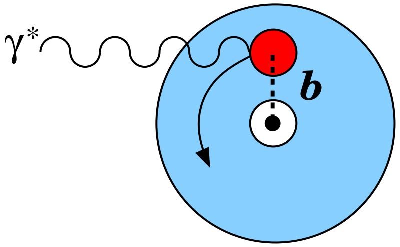
- analysed data set: 2002 – 2004
- positive $\pi^{+/0}$ amplitudes
- π^- amplitude consistent with zero
- overall scale uncertainty 6.6 %

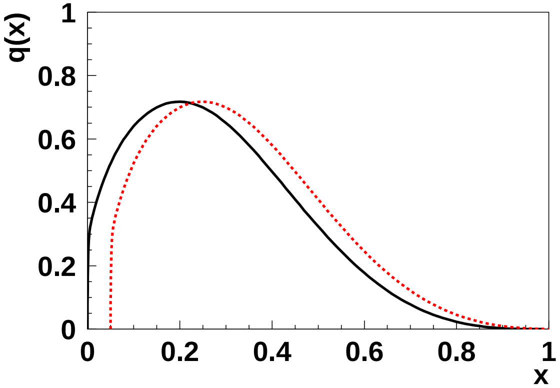




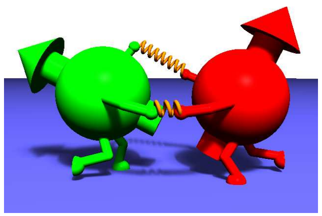
Burkardt Model

- quarks with orbital angular momentum:
  observed quark momentum x_{obs} depends on impact parameter $\boldsymbol{b}$





$\boldsymbol{b > 0 : x_{\text{obs}} > x}$



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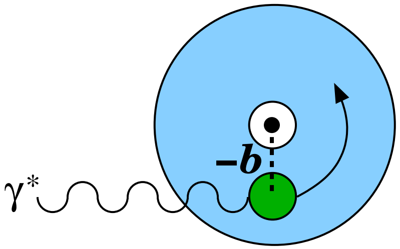
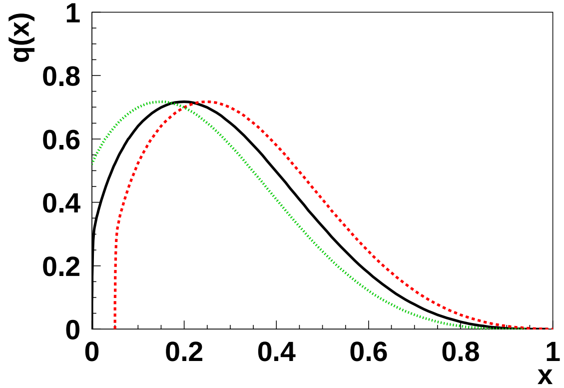
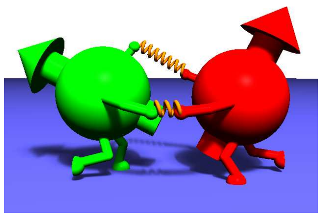




$b > 0 : x_{\text{obs}} > x$

$b < 0 : x_{\text{obs}} < x$



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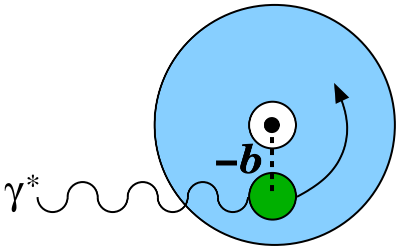
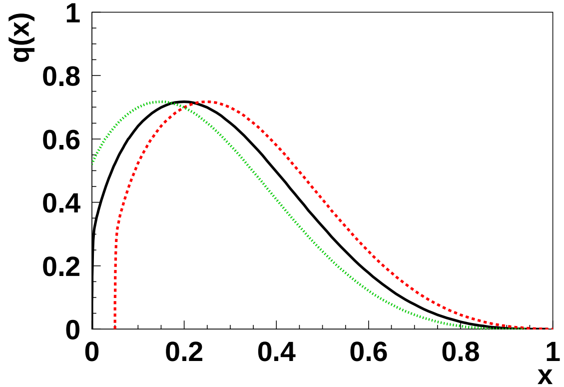


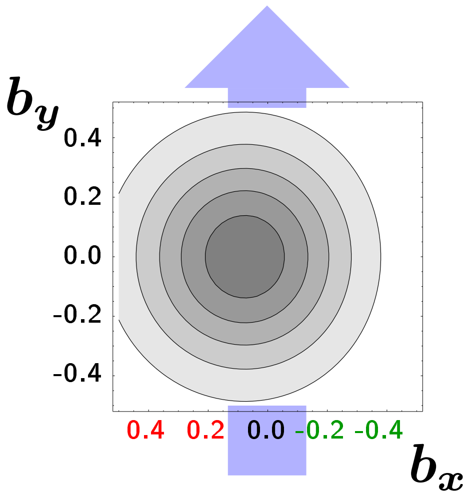


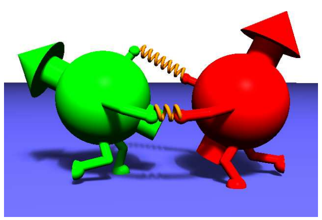
$b > 0 : x_{\text{obs}} > x$

$b < 0 : x_{\text{obs}} < x$

- quark distribution distorted perpendicular to nucleon spin

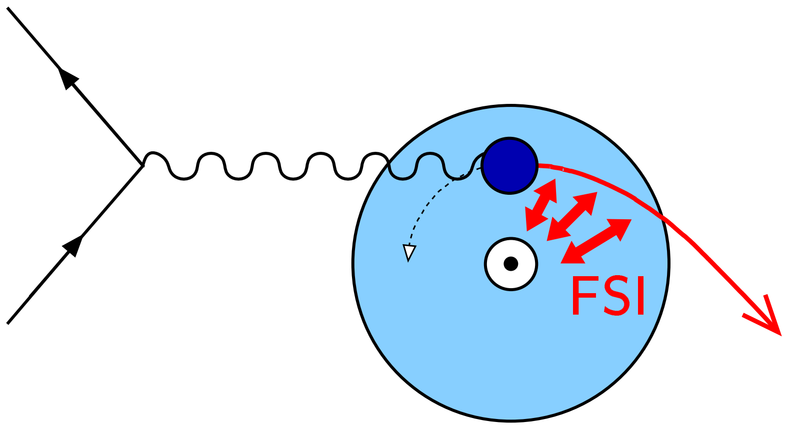
$x = 0.3$:

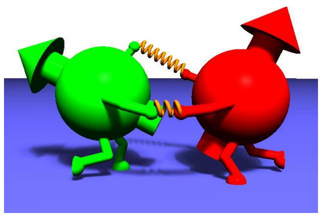




Burkardt Model

- attractive FSI deflects quark towards centre of momentum
  ➜ left–right distribution asymmetry is converted into left–right momentum asymmetry





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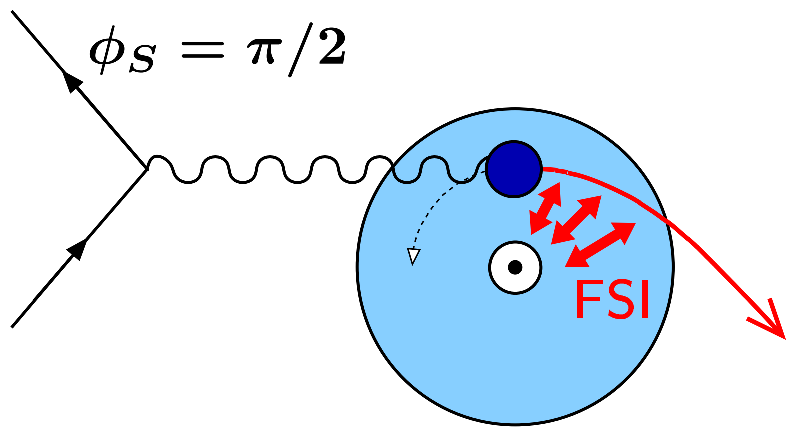
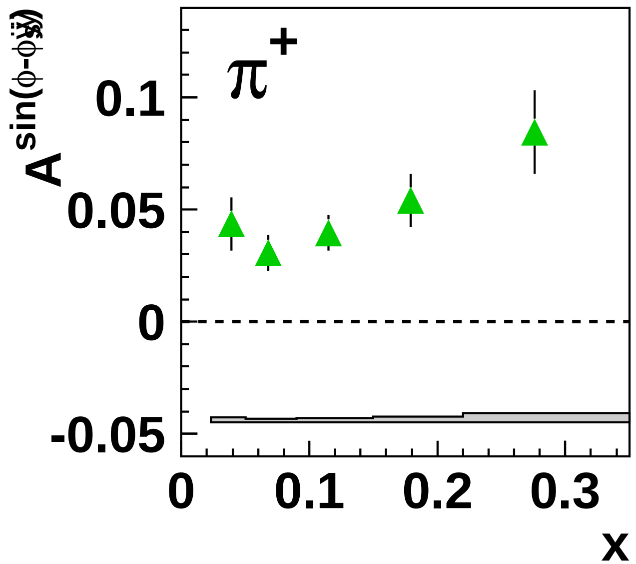
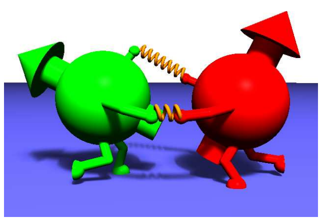


- positive orbital angular momentum
  ➜ $\sin(\phi - \phi_S) > 0$ ➜ positive Sivers amplitude



semi–classical picture yields $L_z^u > 0$



Conclusions

- First measurement of Collins and Sivers amplitudes for charged and neutral pions in semi–inclusive DIS.
- positive Collins amplitudes for positive pions, negative Collins amplitudes for negative pions.
- Artru model yields positive u quark transversity.
- Positive Sivers amplitudes for positive and neutral pions is the first signal of a non–zero naïve T–odd DF.
- Burkardt model yields positive orbital angular momentum for u quarks.


THANK YOU