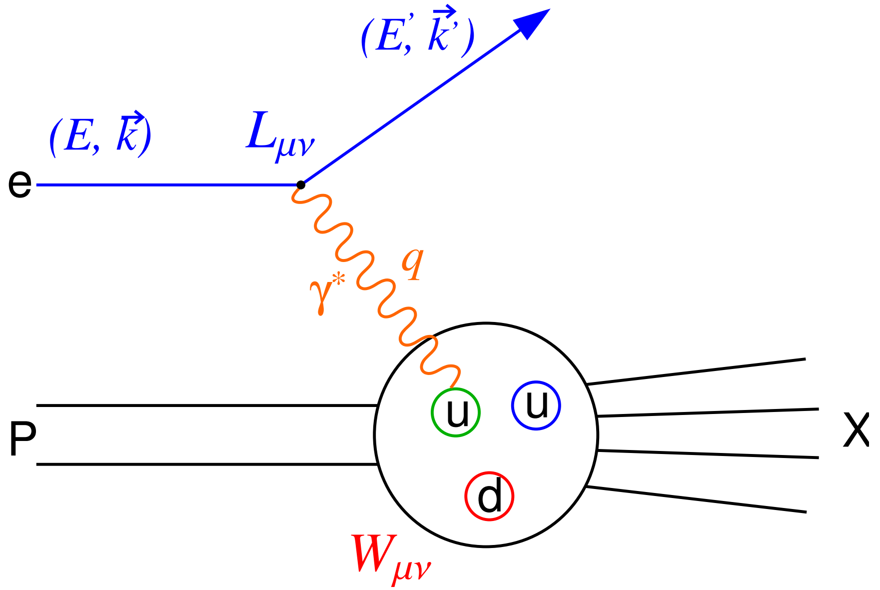
Measurement of the Sivers Effect at Hermes

- Deep-Inelastic Scattering and the Sivers Function
- The HERMES Experiment
- Data and Monte Carlo Results of the Sivers Amplitude

Ulrike Elschenbroich
Universiteit Gent, België

Seminar in Regensburg
July 19, 2005

Deep-Inelastic Scattering



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

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

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

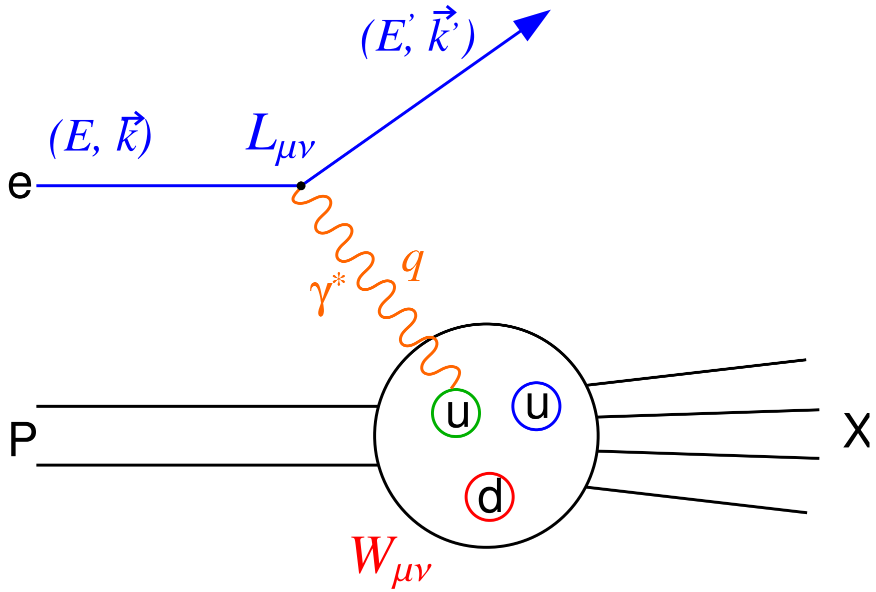
$$y = \frac{\nu}{E}$$

cross section: $$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{MQ^4}\frac{E'}{E} L_{\mu\nu} W^{\mu\nu}$$

$L_{\mu\nu}$ leptonic tensor: purely electromagnetic ➜ calculable in QED

$W_{\mu\nu}$ hadronic tensor: parametrisations necessary

Deep-Inelastic Scattering



quark-parton model

$$Q^2 > M^2 \approx 1 \text{ GeV}^2$$

→ incoherent lepton scattering off a quark inside the nucleon

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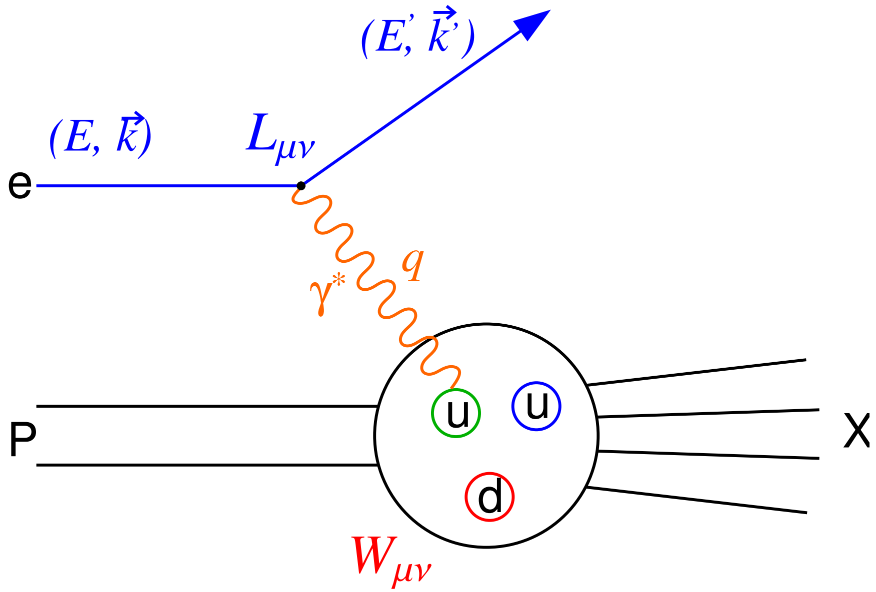

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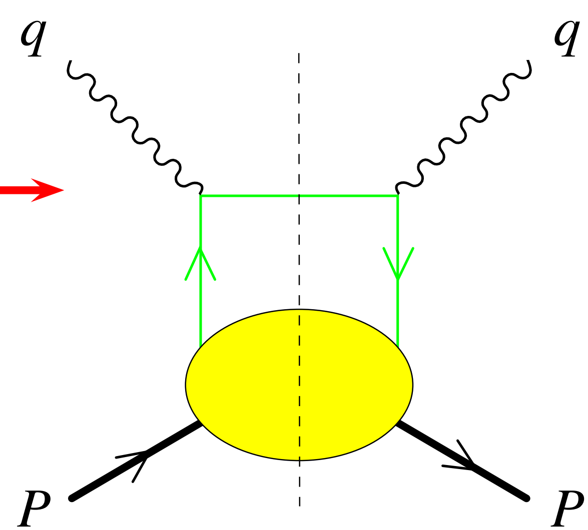

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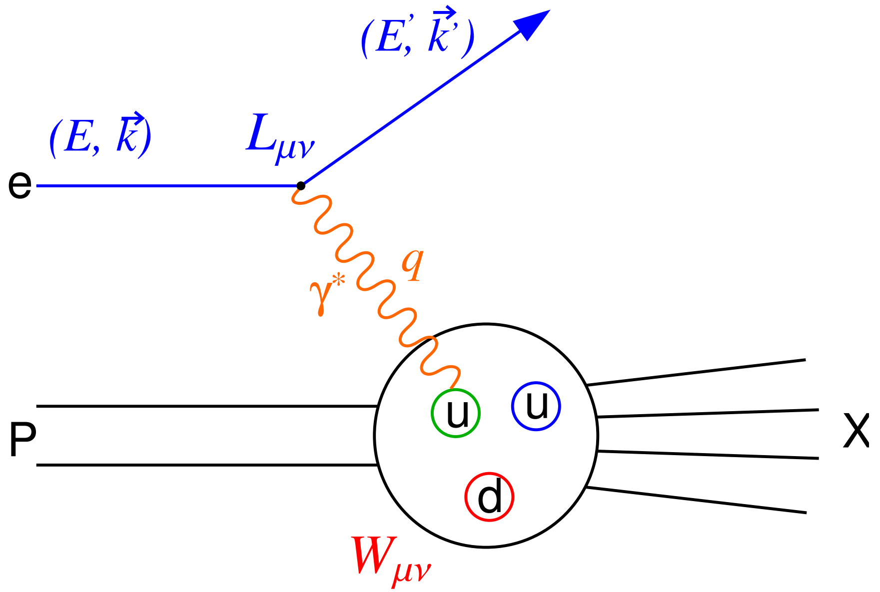

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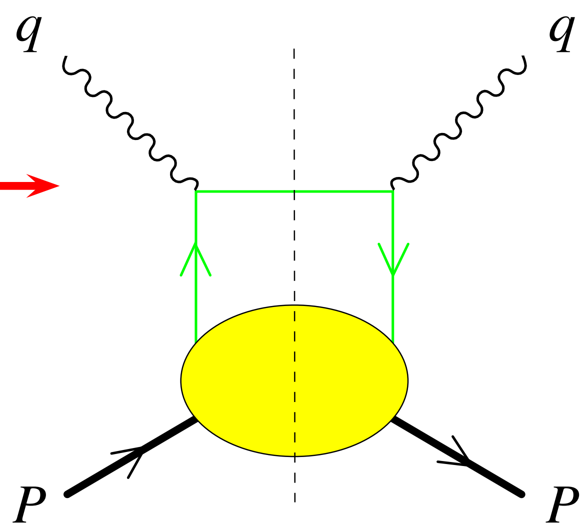
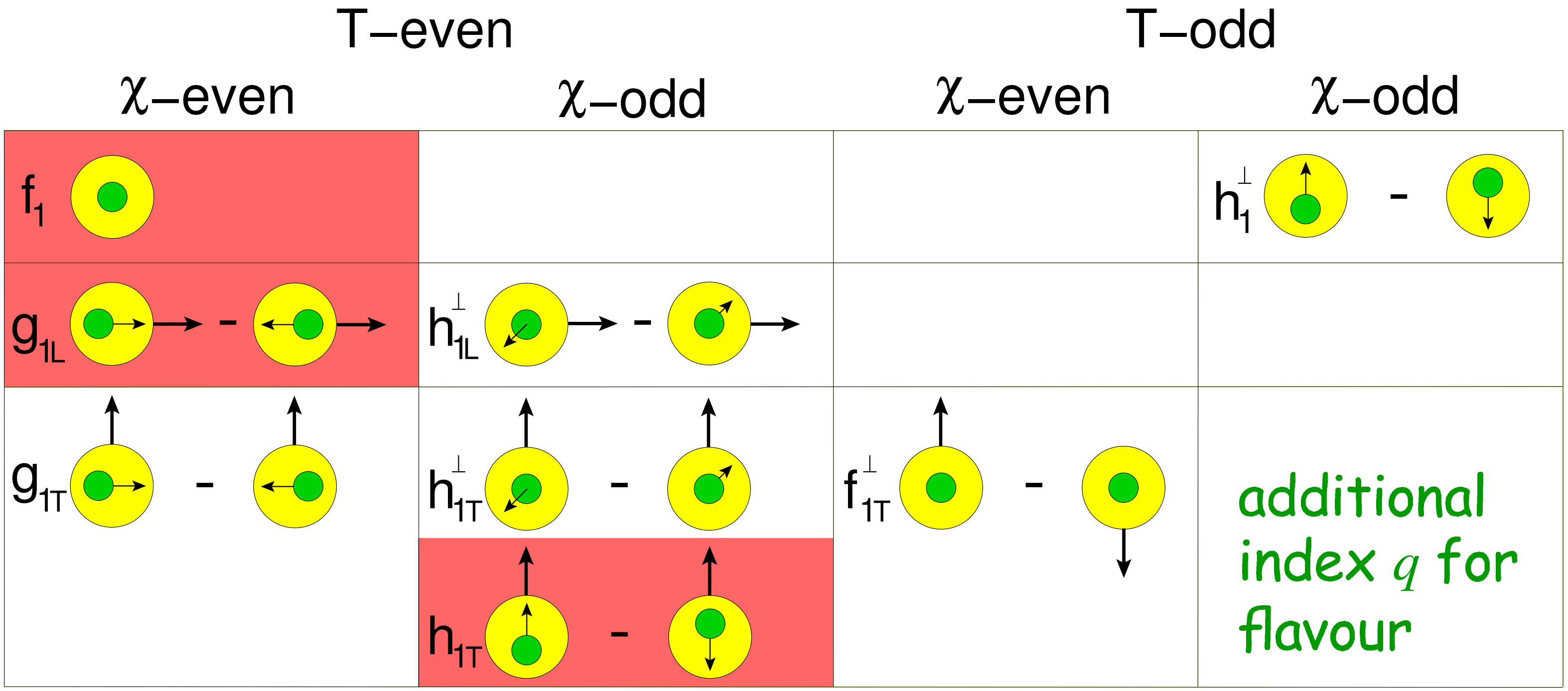


$$\sigma^{ep} \sim \sum_q \mathbf{PDF}^q \otimes \sigma^{eq}$$

Parton Distribution Function

Leading Twist Distribution Functions



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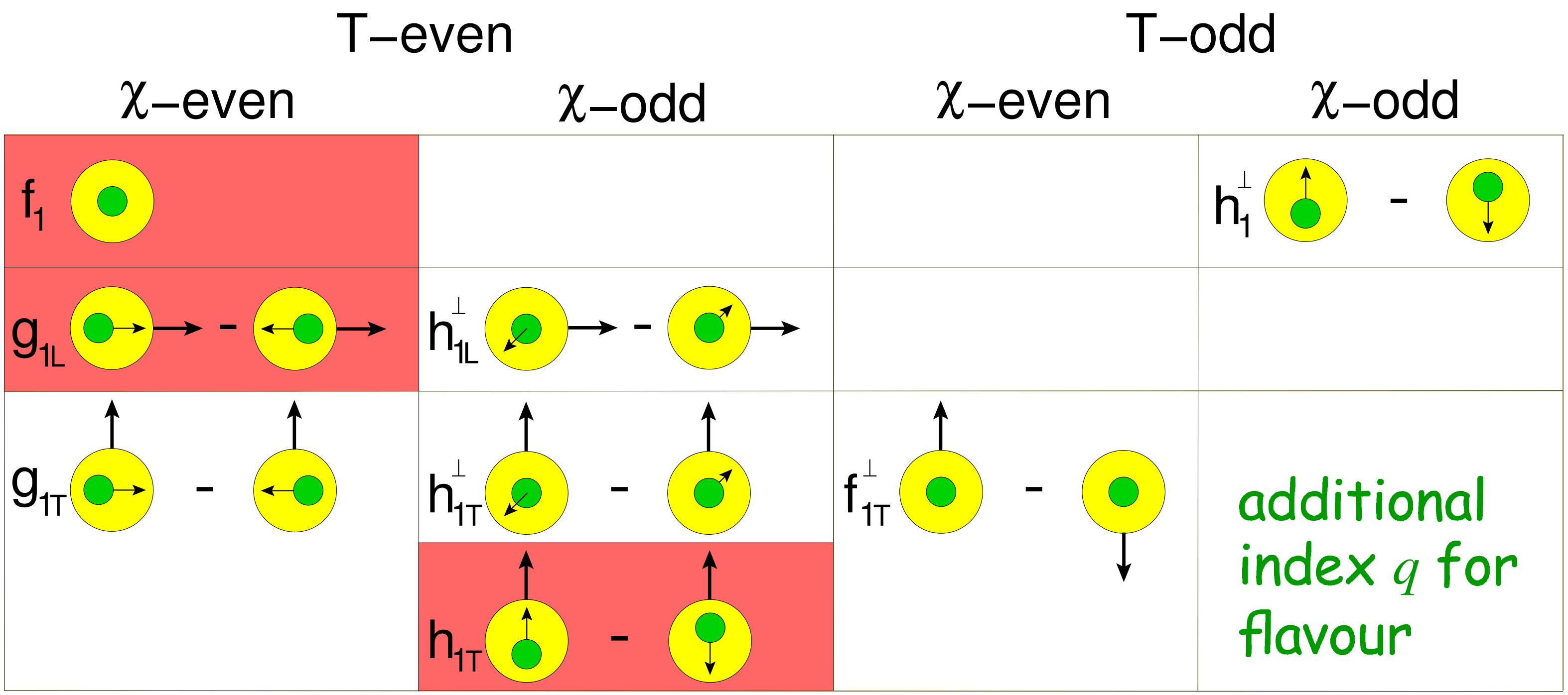

all PDFs depend on x and initial quark transverse momentum $\vec{p}_T$

3 PDFs survive integration over $\vec{p}_T$:

1 unpolarised DF $f_1^q(x, \vec{p}_T^2) \rightarrow q(x)$ or $f_1^q(x)$

2 helicity DF $g_{1L}^q(x, \vec{p}_T^2) \rightarrow \Delta q(x)$ or $g_1^q(x)$

3 transversity DF $h_{1T}^q(x, \vec{p}_T^2) + \frac{\vec{p}_T^2}{2M} h_{1T}^{\perp q}(x, \vec{p}_T^2) \rightarrow \delta q(x)$ or $h_1^q(x)$

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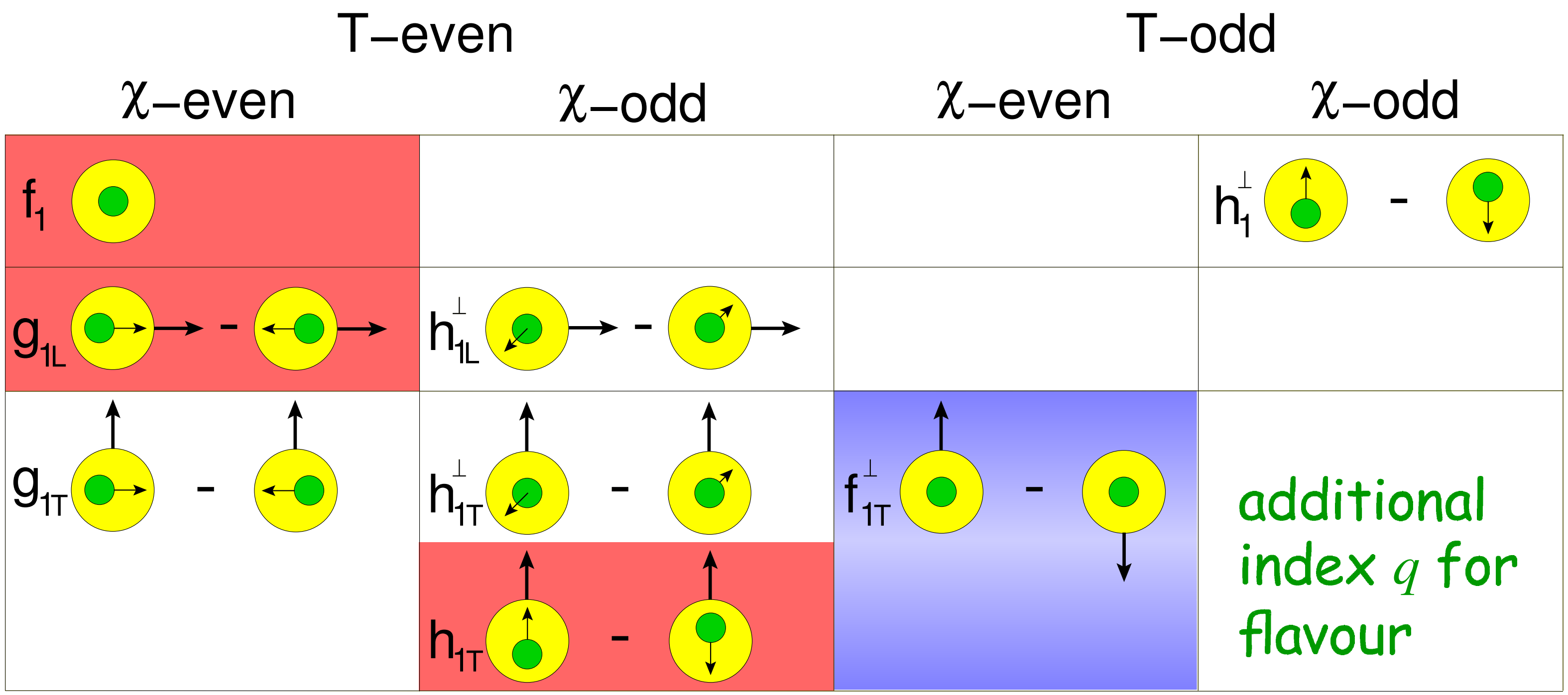

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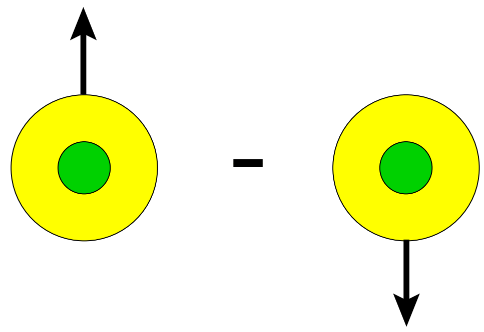
Sivers Function $f_{1T}^{\perp}$

- describes correlation between intrinsic transverse quark momentum $\vec{p}_T$ and transverse nucleon spin



- chiral-even function
- T-odd ➜ forbids its existence?

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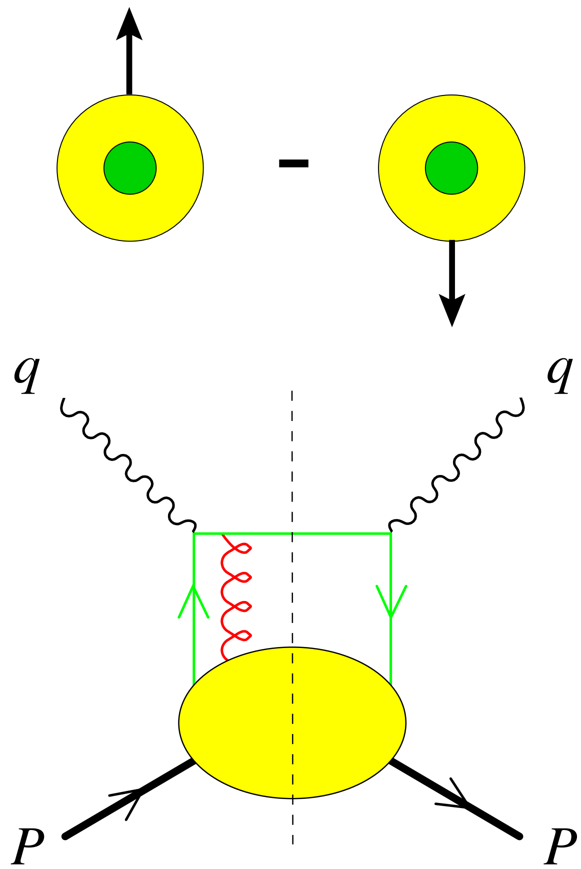


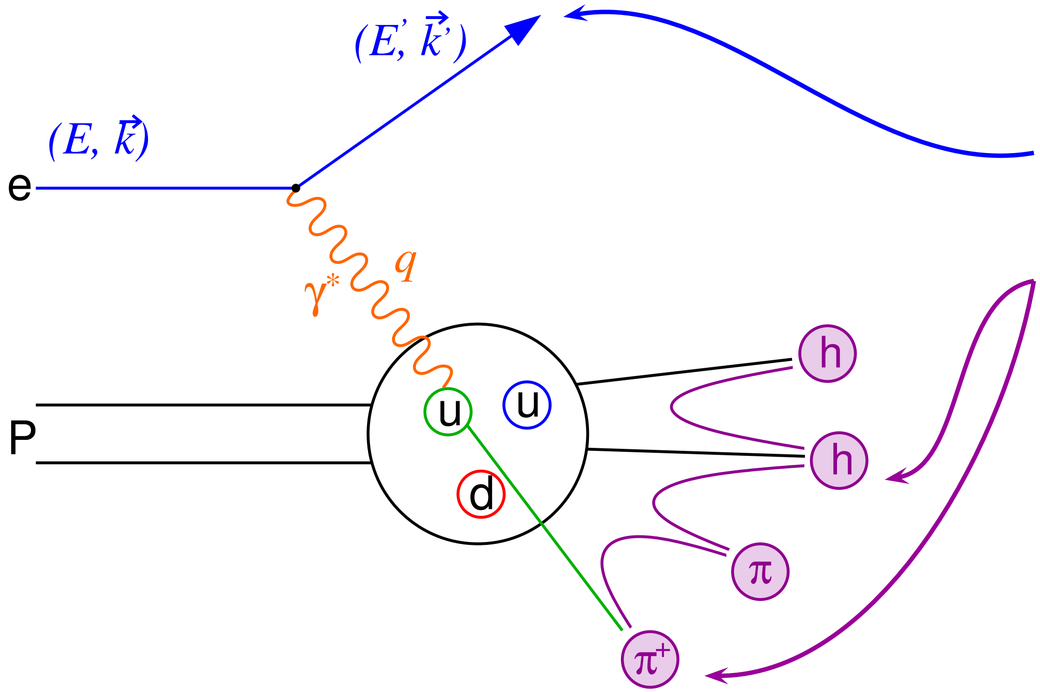
- chiral-even function

- T-odd functions allowed due to
  final state interactions (FSI):
  quark rescattering via a soft gluon

  time-reversal invariance condition change
  ➜ naïve T-odd

- non-zero Sivers function requires non-vanishing quark orbital angular momentum (contributing to nucleon spin)

Semi-inclusive DIS



inclusive: lepton detection

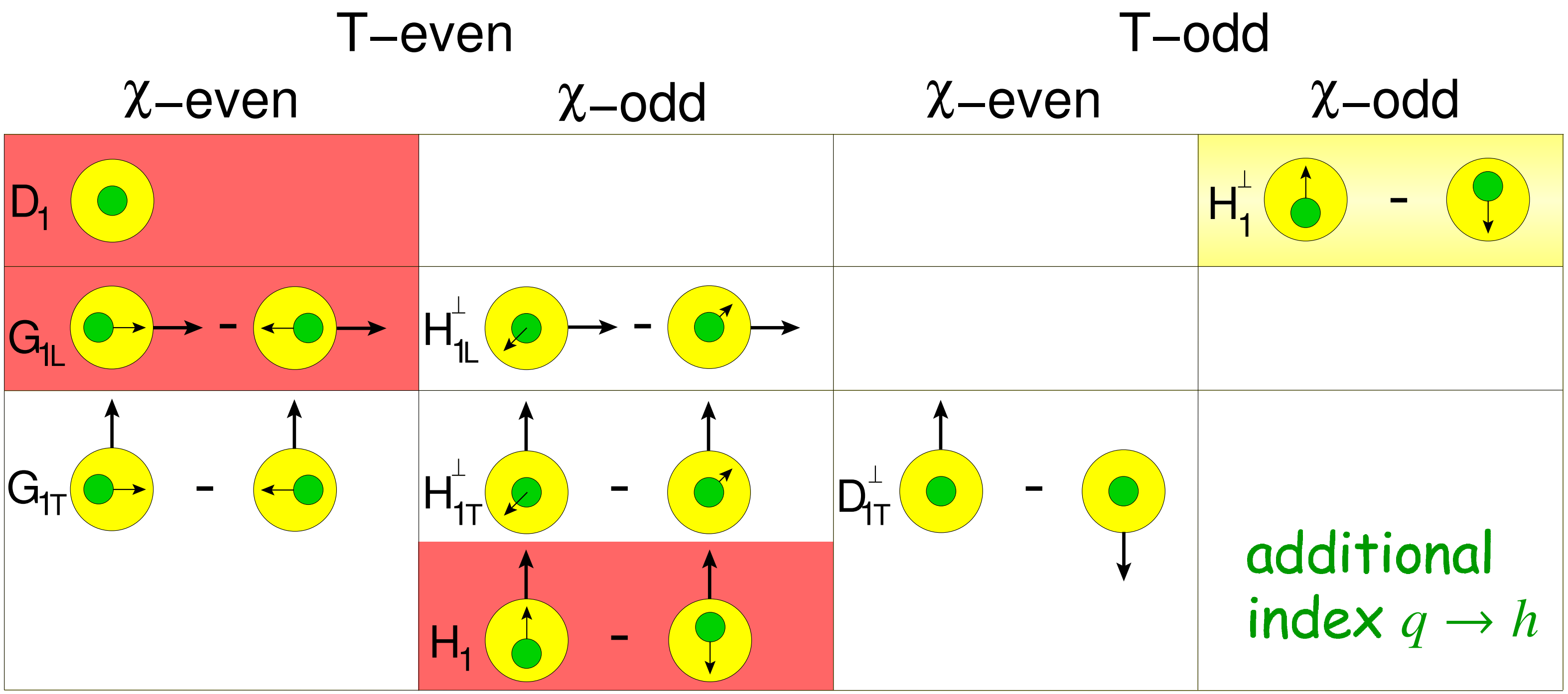
semi-inclusive: in addition detection of produced hadrons

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

evaluation of the cross section in $\mathcal{O}(1/Q)$ contains quark distribution and fragmentation functions

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

Fragmentation Functions



all FF depend on z and final quark transverse momentum $\vec{k}_T$

without measurement of polarisation of produced hadrons:

- unpolarised fragmentation function $D_1(z)$
- Collins fragmentation function $H_1^\perp(z, \vec{k}_T^2)$

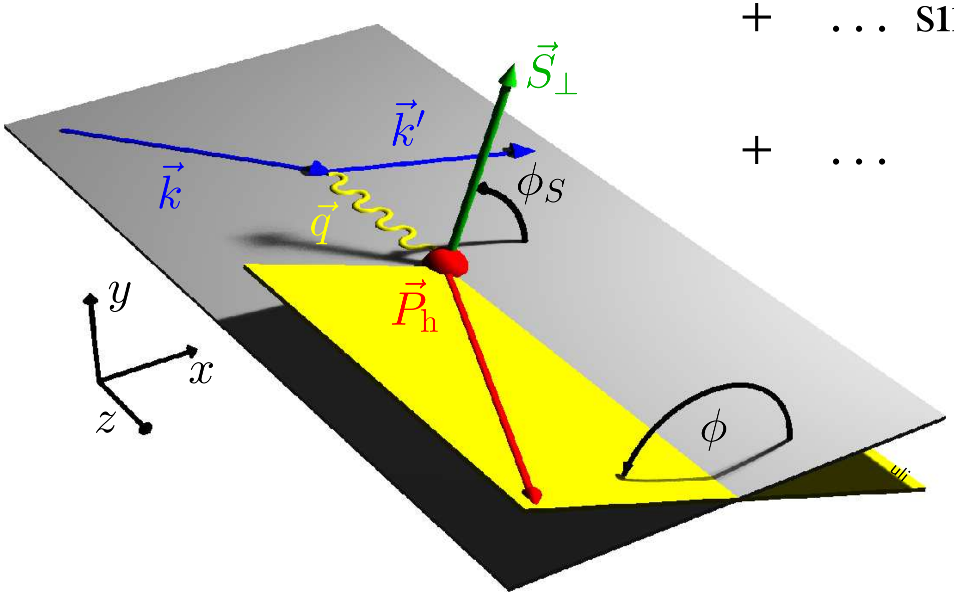
SIDIS Cross Sections

unpolarised cross section:

$$\frac{\mathrm{d}^6\sigma}{\mathrm{d}x\;\mathrm{d}z\;\mathrm{d}y\;\mathrm{d}\phi_S\;\;\mathrm{d}^2P_{h\perp}} \sim \cdots \sum_q e_q^2\; f_1^q(x) \cdot D_1^q(z)$$

cross section for transverse polarised target:

$$\begin{aligned}\frac{\mathrm{d}^6\sigma^{\Uparrow} - \mathrm{d}^6\sigma^{\Downarrow}}{\mathrm{d}x\;\mathrm{d}z\;\mathrm{d}y\;\mathrm{d}\phi_S\;\;\mathrm{d}^2P_{h\perp}} &\sim \;\; \ldots\; \sin(\phi-\phi_S)\sum_q e_q^2\; \mathcal{I}\left[\ldots f_{1T}^{\perp q}(x,\vec{p}_T^{\,2})\cdot D_1^q(z,\vec{k}_T^{\,2})\right] \\ &+ \;\; \ldots\; \sin(\phi+\phi_S)\sum_q e_q^2\; \mathcal{I}\left[\ldots h_1^q(x,\vec{p}_T^{\,2})\cdot H_1^{\perp q}(z,\vec{k}_T^{\,2})\right] \\ &+ \;\; \ldots\end{aligned}$$



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$$+ \ldots \sin(\phi+\phi_S)\sum_q e_q^2\;\mathcal{I}\left[\ldots h_1^q(x,\vec{p}_T^{\,2})\cdot H_1^{\perp q}(z,\vec{k}_T^2)\right]$$

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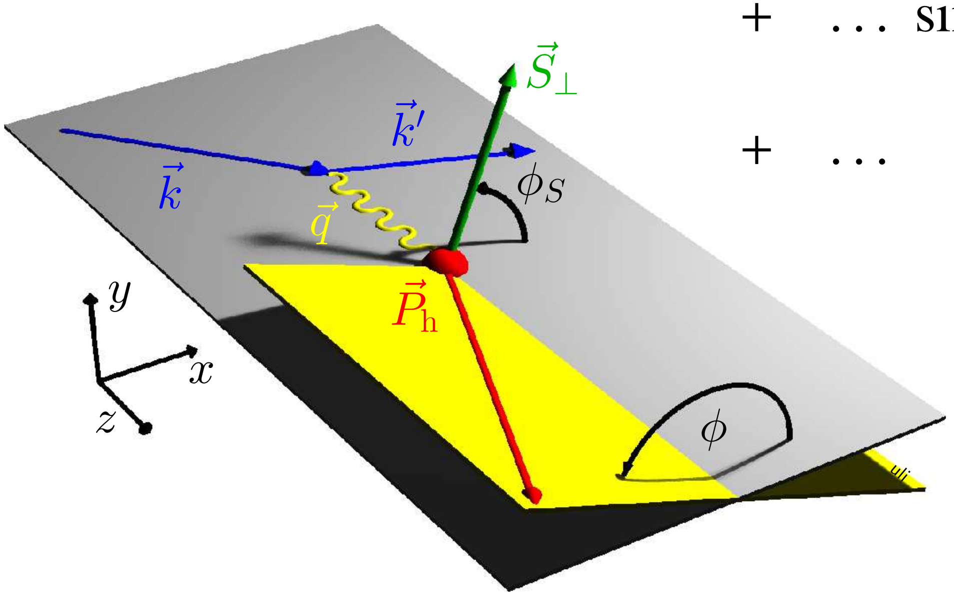
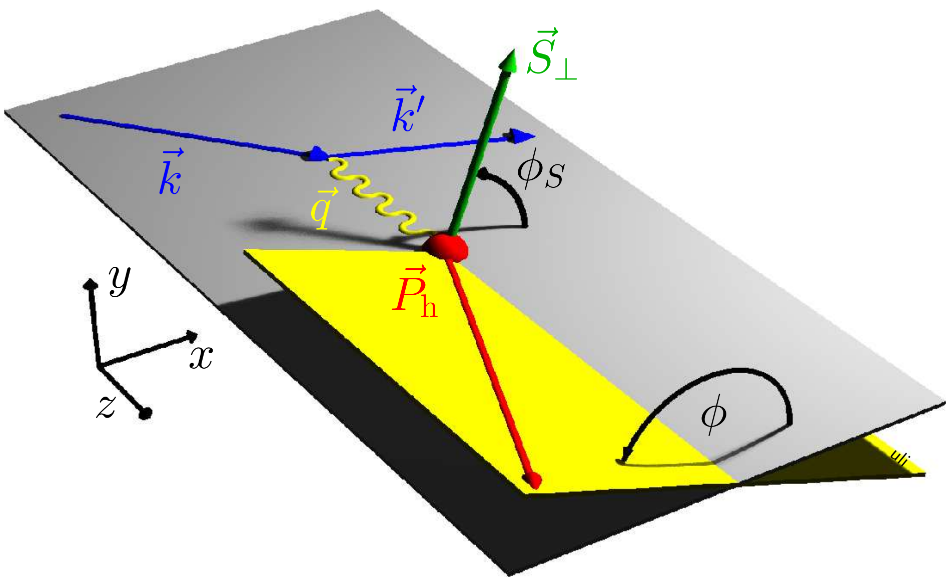


$\mathcal{I}\,[\ldots]$: convolution integral over quark transverse momenta $\vec{p}_T$ and $\vec{k}_T$

Sivers Effect

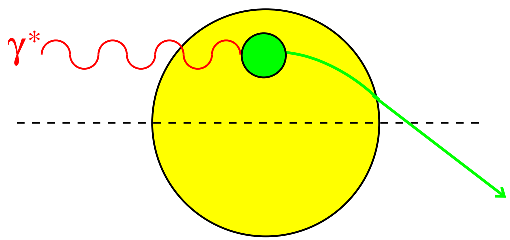
- $\phi - \phi_S$: angle between production plane and transverse spin component
- $\sin(\phi - \phi_S)$: left-right asymmetry in number of produced hadrons
- existence of $f_{1T}^{\perp}$ proposed by Sivers in 1990 to explain single-spin asymmetries observed in proton-proton scattering



Sivers Effect

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

lensing effect



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- impact parameter formalism [M. Burkardt, hep-ph/0309269]
  - orbital angular momentum of quarks
    ➜ virtual photon sees different x for different b

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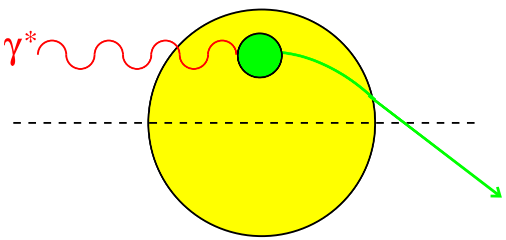

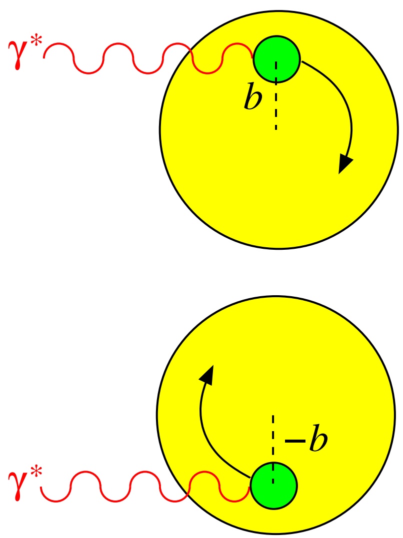

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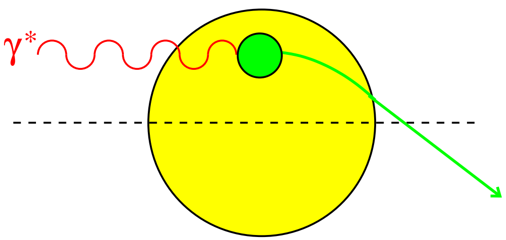
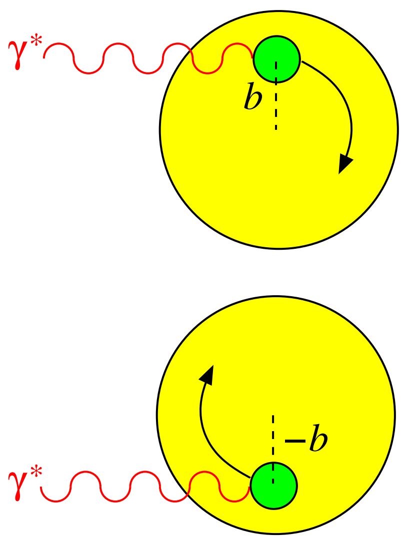
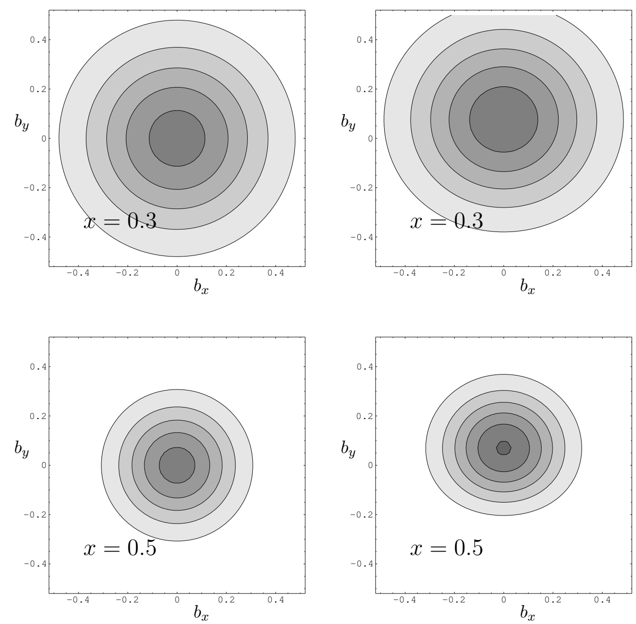
  - orbital angular momentum of quarks
    ➜ virtual photon sees different x for different b
  - quark distributions depend on impact parameter b

lensing effect

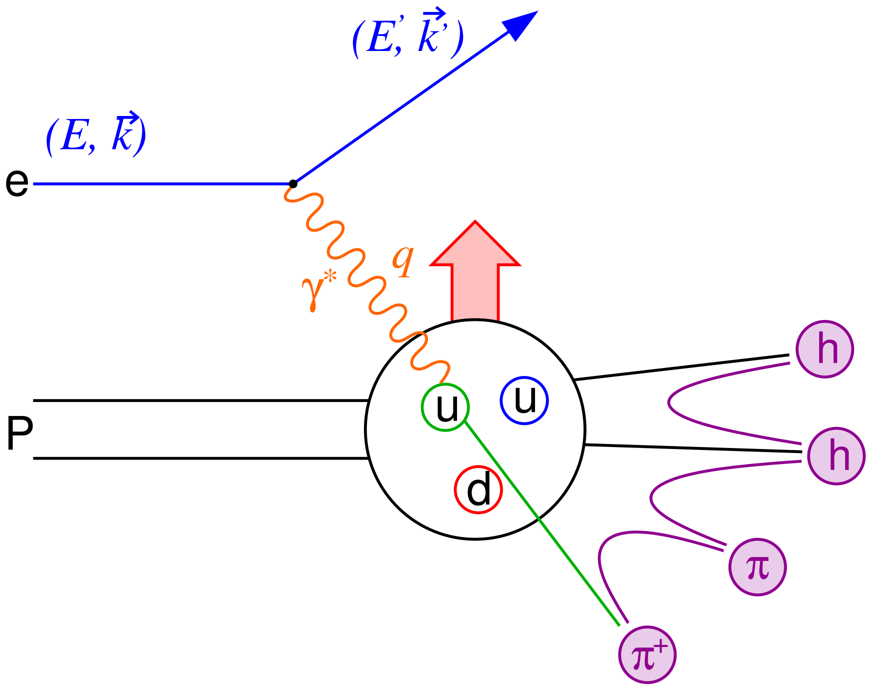




$u(x, b)$



The HERMES Experiment at HERA



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HERA positron beam 27.5 GeV

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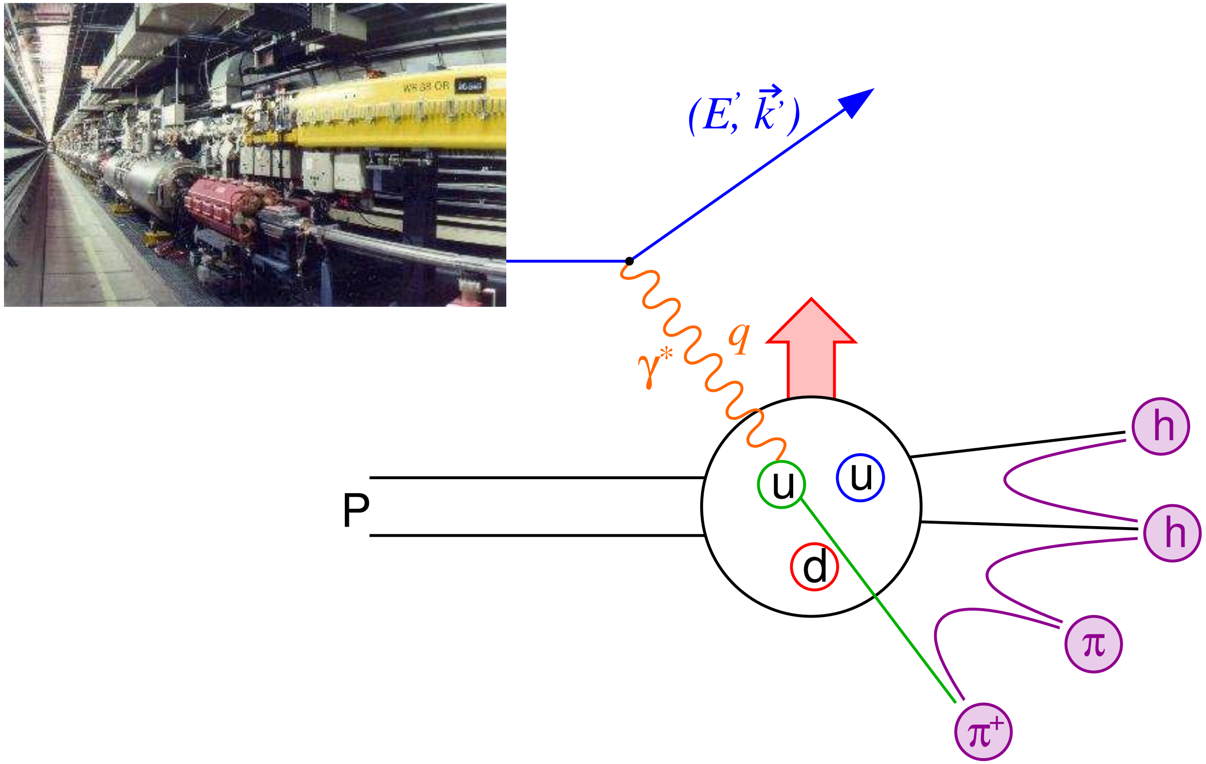

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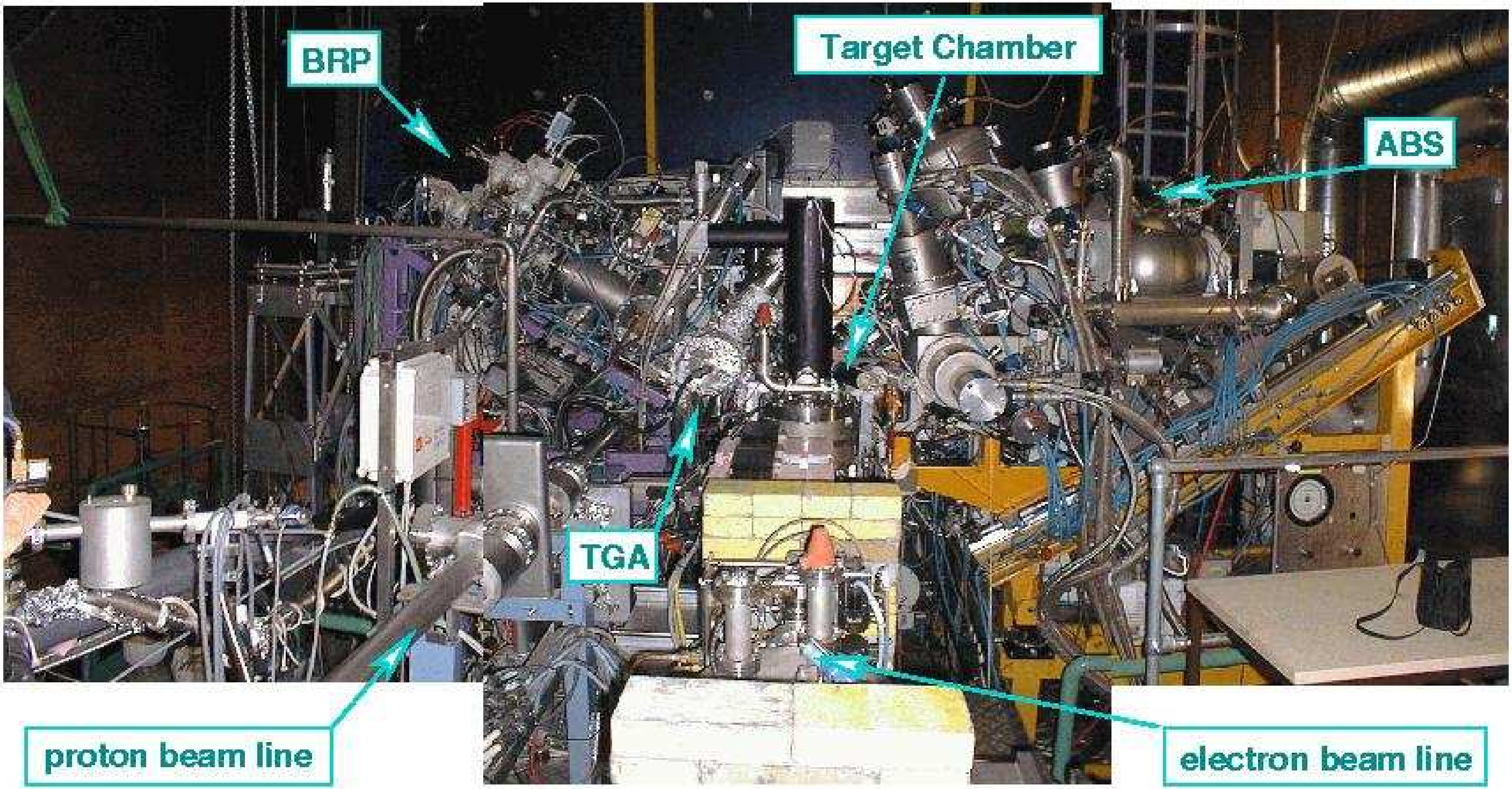

transversely polarised atomic Hydrogen $\langle P \rangle \approx 80$ %

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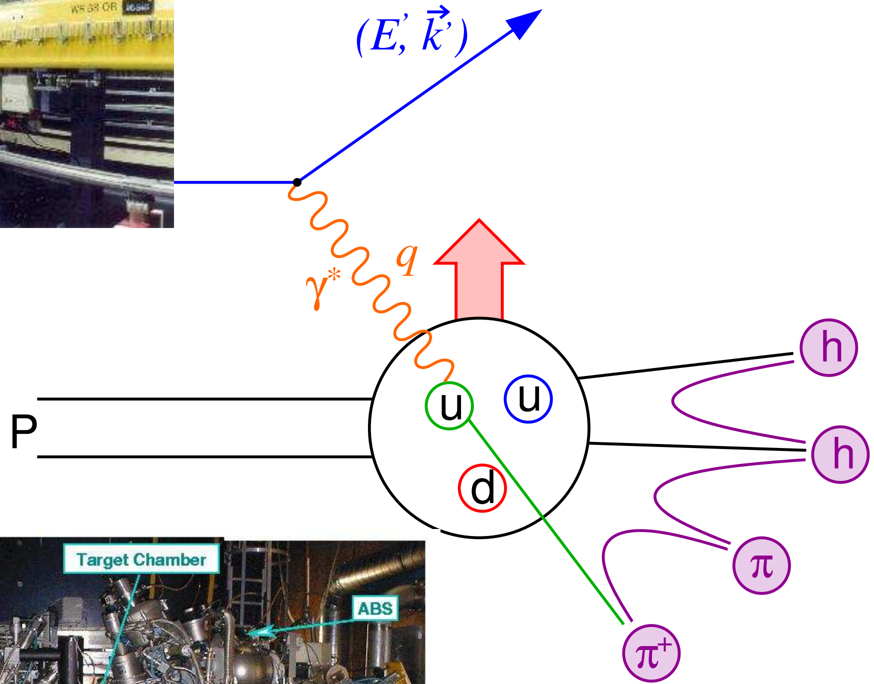

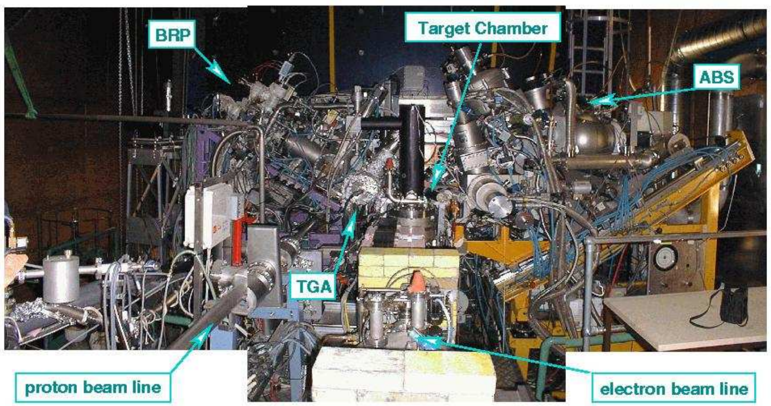

since 2002

transversely polarised atomic Hydrogen $\langle P \rangle \approx 80\ \%$

The HERMES Experiment at HERA

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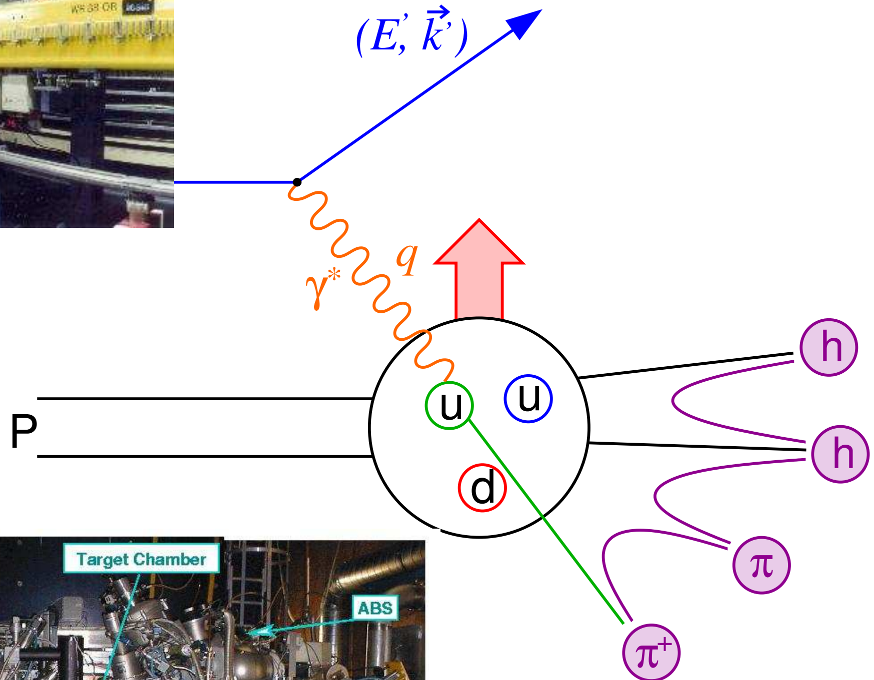
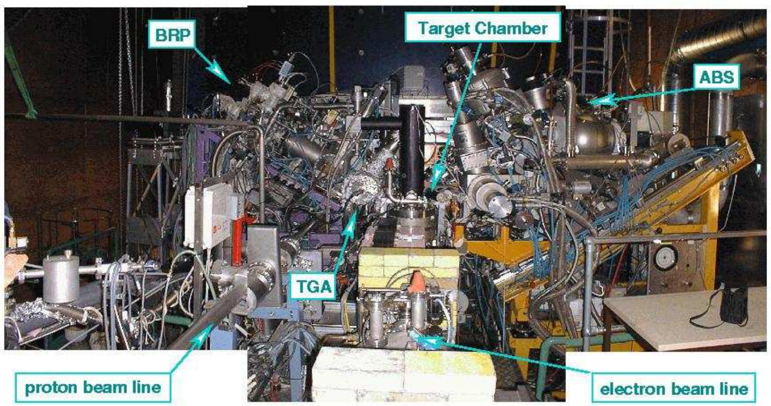
HERA positron beam 27.5 GeV

HERMES spectrometer





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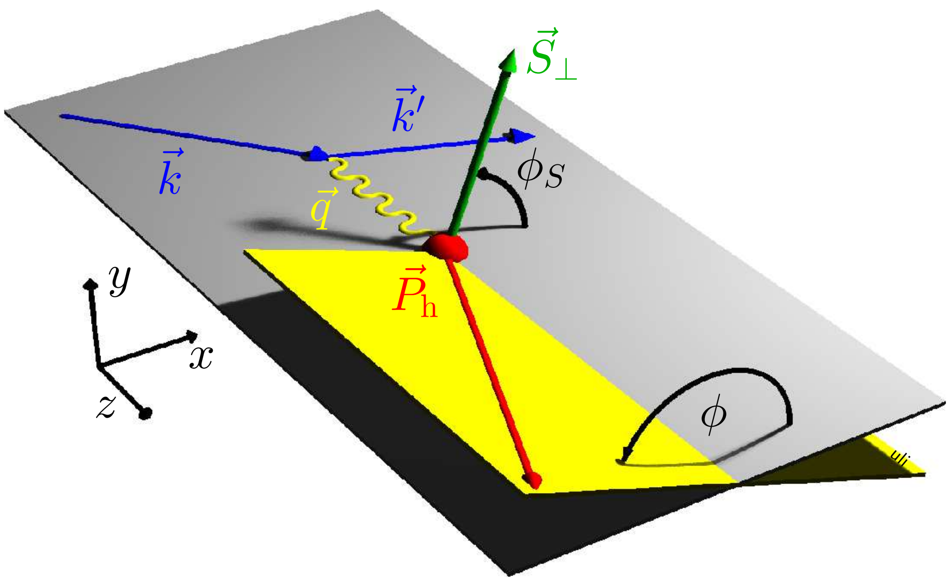
Azimuthal Asymmetries

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

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



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$$\sim \ldots \sin(\phi-\phi_S)\frac{\sum_q e_q^2\, \mathcal{I}\left[\ldots f_{1T}^{\perp q}(x,\vec{p}_T^{\,2})\cdot D_1^q(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\, f_1^q(x)\cdot D_1^q(z)}$$

$$+ \ldots \sin(\phi+\phi_S)\frac{\sum_q e_q^2\, \mathcal{I}\left[\ldots h_1^q(x,\vec{p}_T^{\,2})\cdot H_1^{\perp q}(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\, f_1^q(x)\cdot D_1^q(z)}$$

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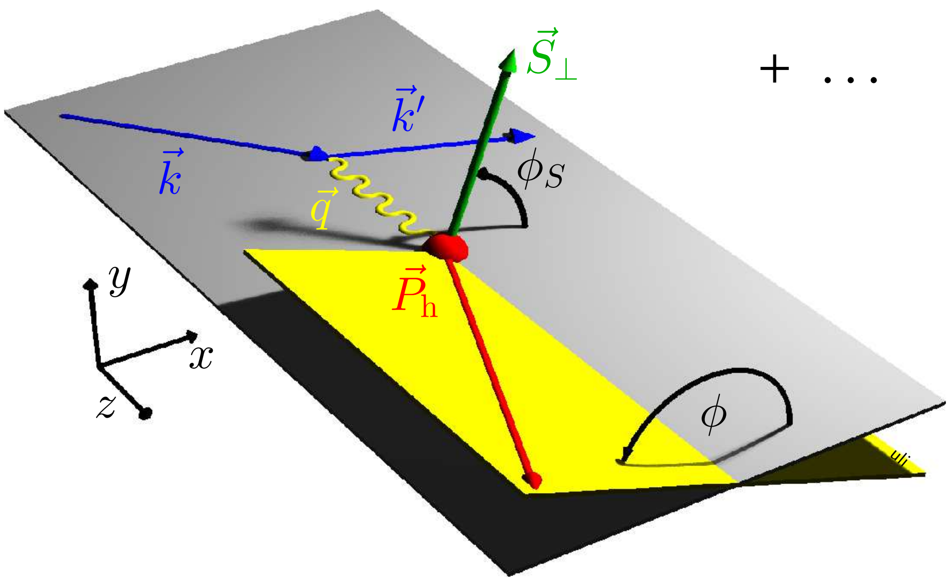

How to Disentangle . . .

. . . distribution and fragmentation functions?

Assume a Gaussian distribution for $\vec{p}_T$ and $\vec{k}_T$ dependence:

$$A_{\mathrm{UT}}(\phi, \phi_S) \sim \ldots \sin(\phi - \phi_S) \sum_q e_q^2 \cdot f_{1T}^{\perp(1/2)\,q}(x) \cdot D_1^q(z)$$
$$+ \ldots \sin(\phi + \phi_S) \sum_q e_q^2 \cdot h_1^q(x) \cdot H_1^{\perp(1/2)\,q}(z)$$

(1/2): $\vec{p}_T^{\,2}, \vec{k}_T^{\,2}$ moment of
distribution / fragmentation function

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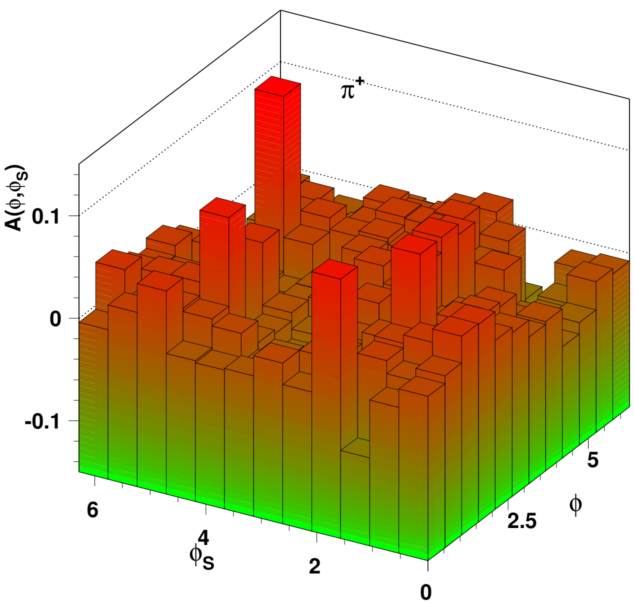
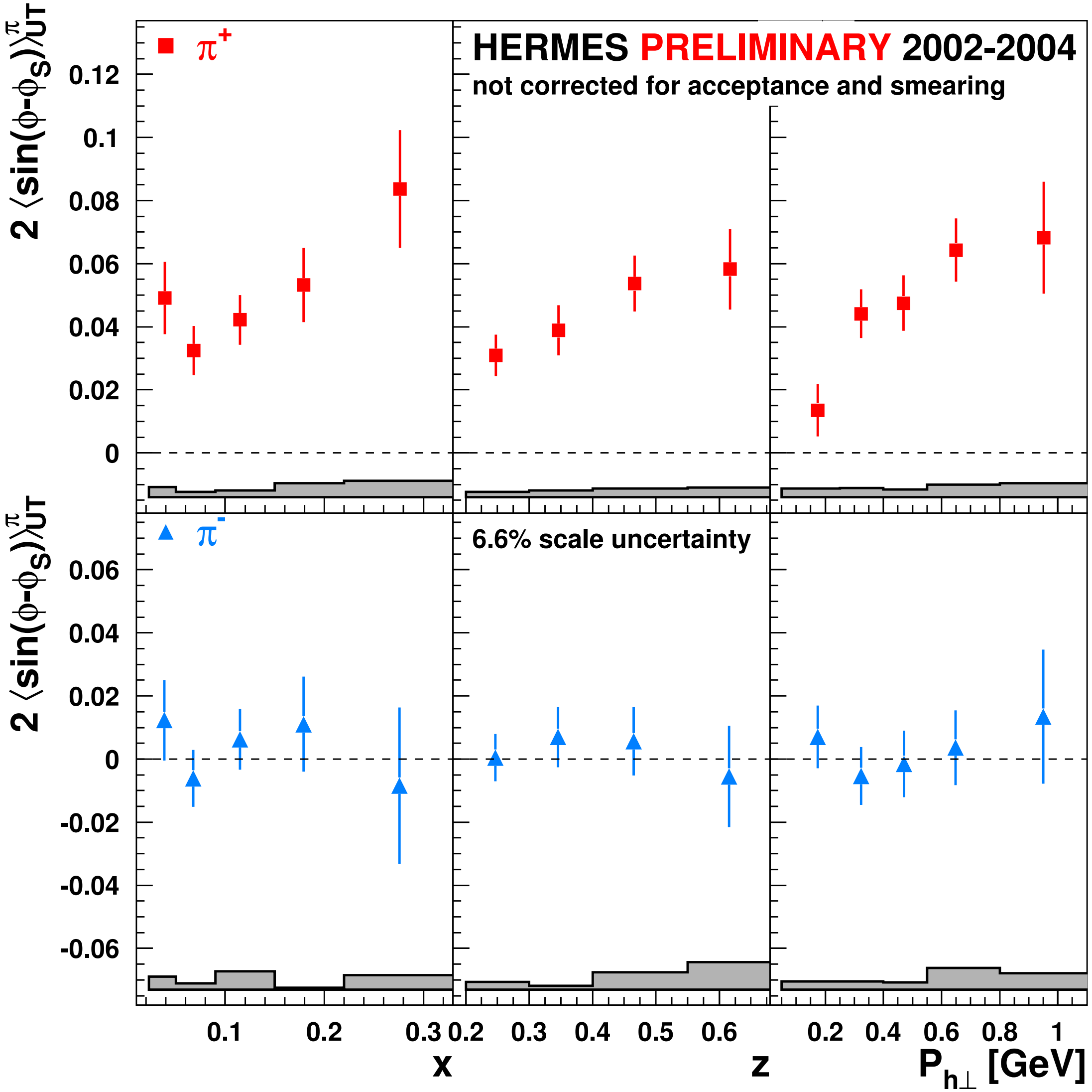


asymmetry amplitudes $A_{\rm UT}^{\sin(\phi-\phi_S)}$ and $A_{\rm UT}^{\sin(\phi+\phi_S)}$

bin $A_{\rm UT}(\phi,\phi_S)$ in 12×12 bins,
perform two dimensional fit

Results for the Sivers Amplitudes



- significantly positive for π^+
- → first hint of naïve T-odd DF from DIS

- π^- asymmetry consistent with zero

Monte Carlo Generator . . .

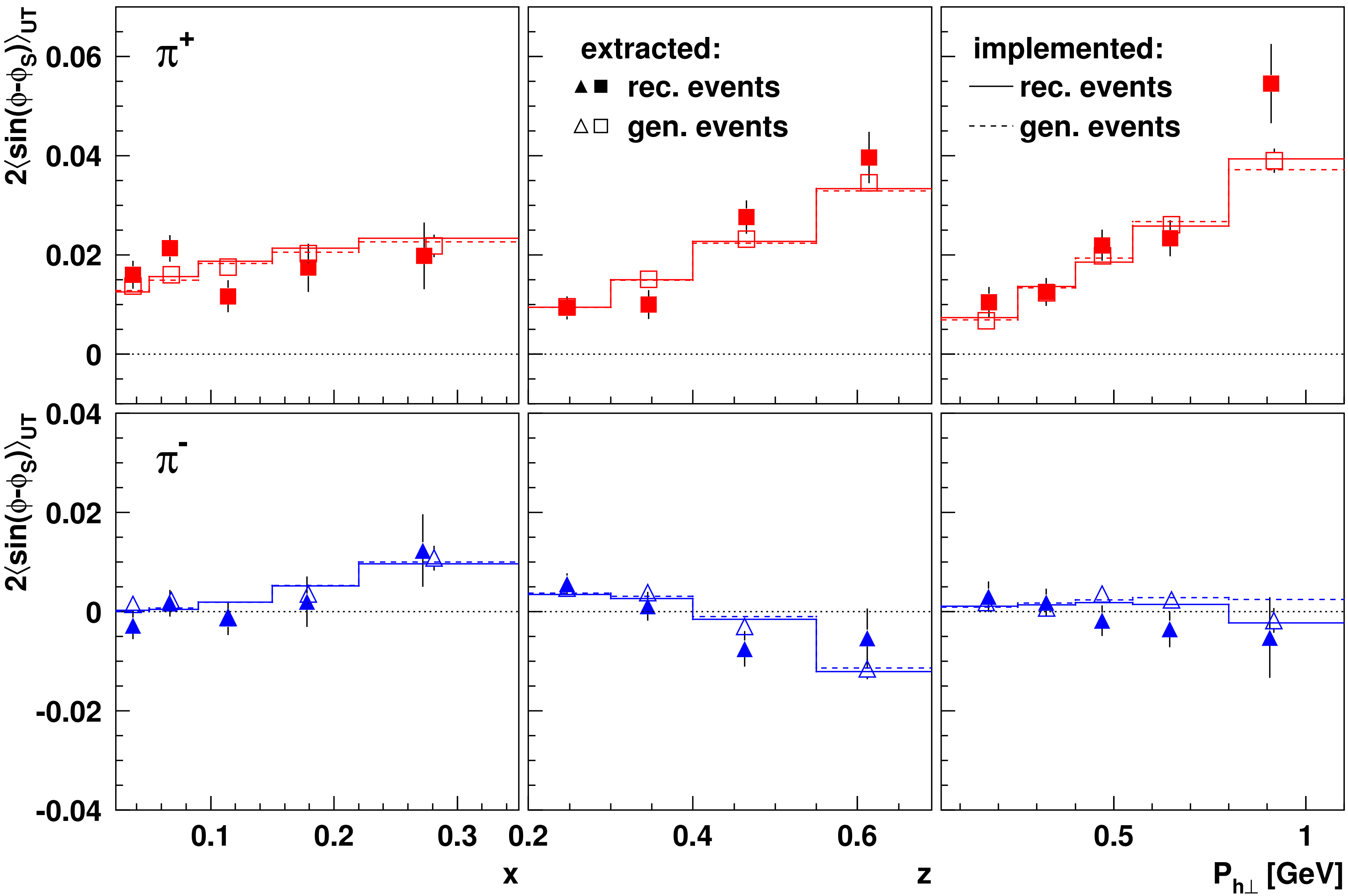
. . . for Transverse Asymmetries

- use Gaussian distributions for transverse momenta
- generate events according to polarised cross section
- ansatz for Sivers function used: $f_{1T}^{\perp q} \sim f_1^q$

➜ Sivers amplitude analytically calculable for kinematics of each event

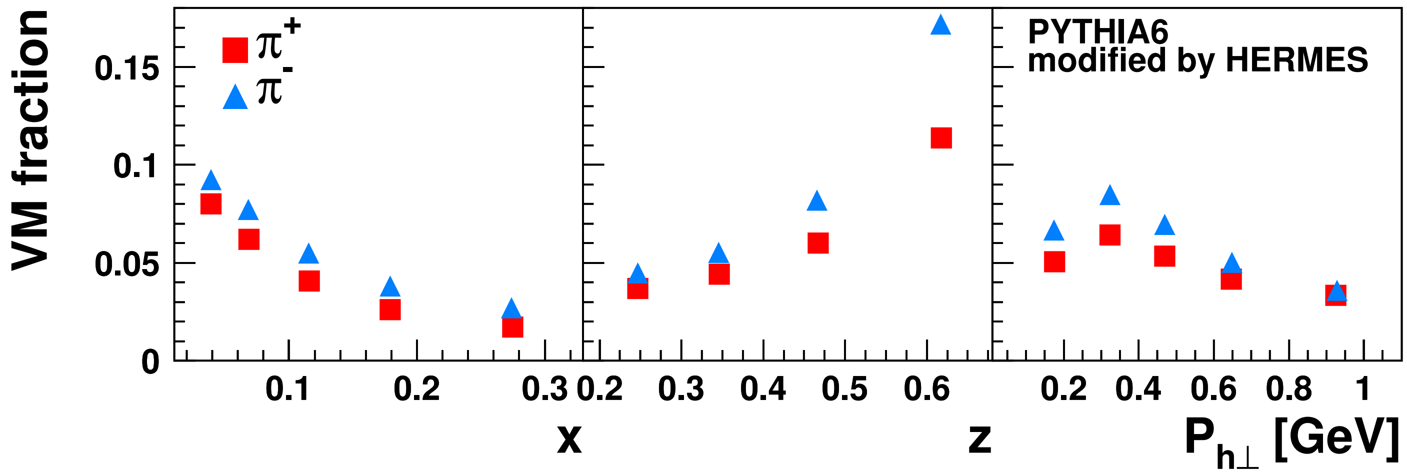
implemented amplitudes can be compared to extracted amplitudes

Monte Carlo Results



Vector Meson Contribution

Contribution to pion sample exist from
exclusively produced vector mesons (mainly ρ^0).



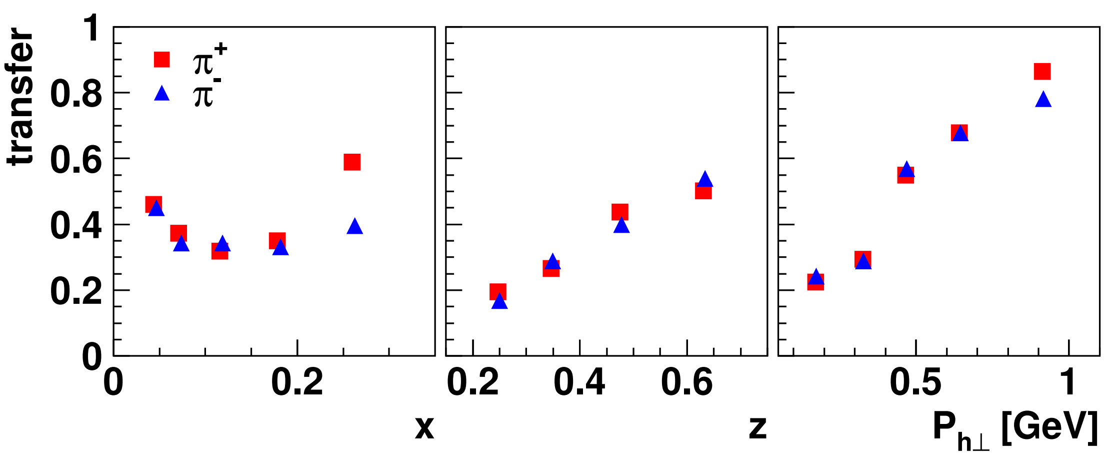
- Has contribution to be treated as background?
  - not present in string fragmentation models
  - contributing diagrams in Feynman-diagram based models
    What happens if contribution of one type of diagrams dominates?

Vector Meson Contribution

Two sources for Sivers amplitude in decay pion sample:

1 transferred amplitude from vector meson:

$$A_{\mathrm{VM}\to\pi} = T \cdot A_{\mathrm{VM}}$$



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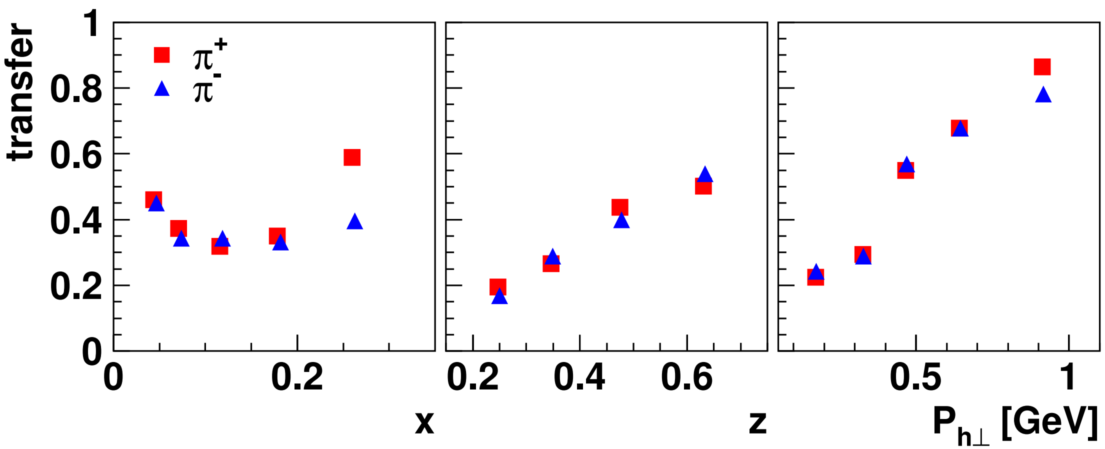

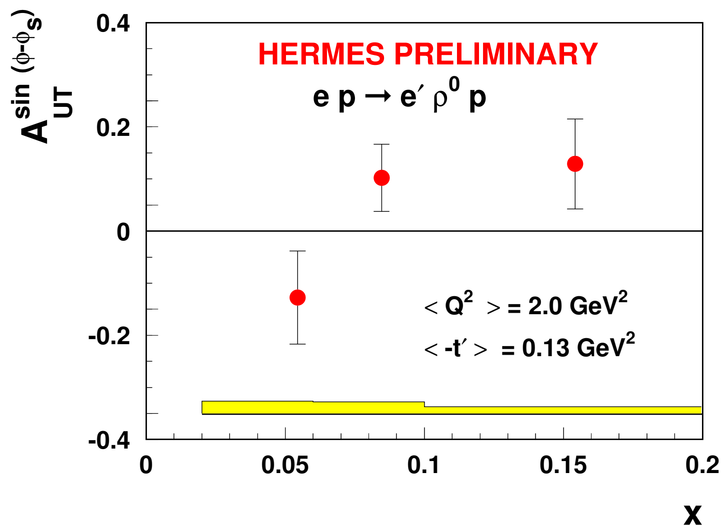

transfer coefficents can be determined with PYTHIA6

first measurement of $A_{UT}^{\sin(\phi-\phi_S)}$ for exclusive ρ^0!

Vector Meson Contribution

- vector meson fraction determined with PYTHIA6 below 10 % in almost all bins
- transfer coefficients $T \sim 0.2 - 0.8$
- exclusive asymmetry amplitude in the order of 10 %

➜ maximum distribution: $10\ \% \cdot 10\ \% \cdot 0.8 \approx 0.008$
cannot cause amplitude of ~ 0.05!

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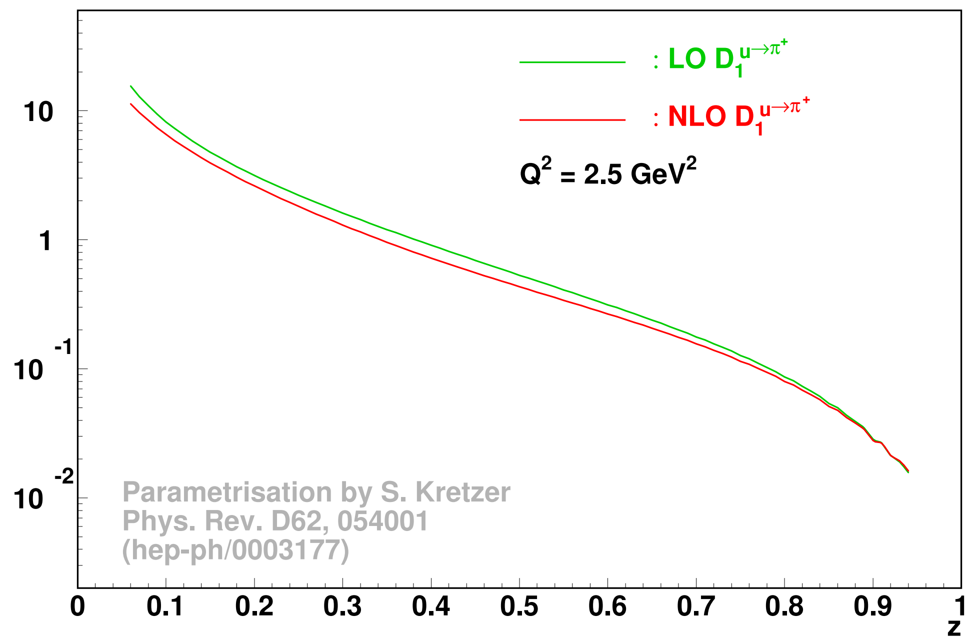
2 amplitude acquired in decay process

- no information from experiments available
- only one theoretical publication from 1974 on the market

Extraction of the Sivers Functions

$$\sum_q f_{1T}^{\perp(1/2)q}(x) \cdot D_1^q(z)$$

- measure $A_{\mathrm{UT}}^{\sin(\phi-\phi_S)}$ in many (x,z) bins ➜ large statistics necessary
- information about unpolarised fragmentation function: $D_1^{q\to h}(z)$ for some hadrons h sufficiently known

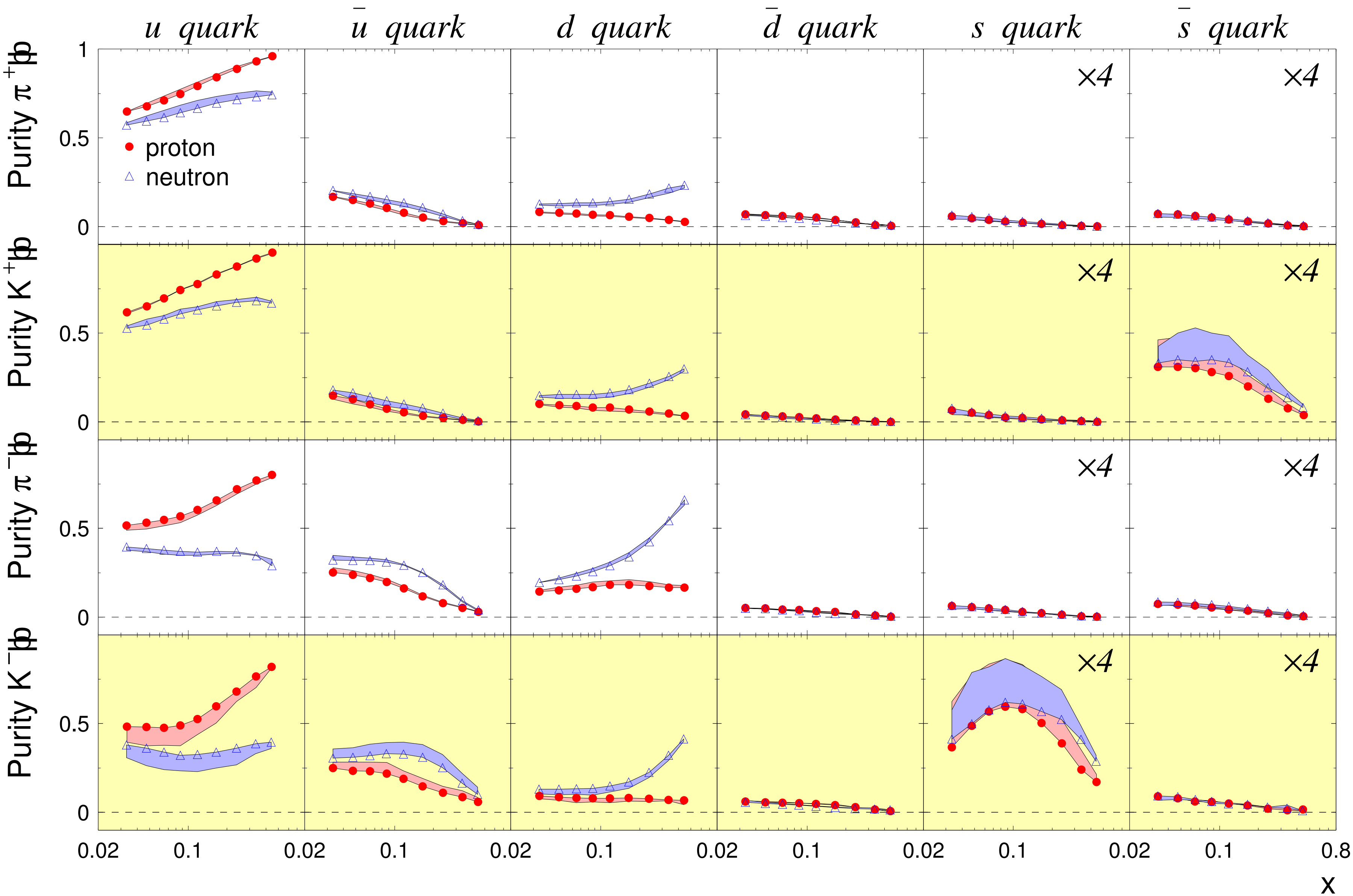


Purity Formalism

$$A_{UT}^{\sin(\phi-\phi_S)} \sim \frac{\sum_q f_{1T}^{\perp(1/2)q}(x) \cdot D_1^q(z)}{\sum_q f_1^q(x) \cdot D_1^q(z)} = \sum_q \underbrace{\frac{f_1^q(x) \cdot D_1^q(z)}{\sum_{q'} f_1^{q'}(x) \cdot D_1^{q'}(z)}}_{\mathcal{P}_q^h(x,z)} \cdot \frac{f_{1T}^{\perp(1/2)q}(x)}{f_1^q(x)}$$

- purity $\mathcal{P}_q^h(x,z)$ is unpolarised object
- can be determined from high precision results of a large number of unpolarised DIS experiments
- formalism already used for extraction of helicity DF
  ➜ experience exists in Hermes collaboration

Purity Formalism



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➜ Sivers function extraction possible
test of universality violation:
final state interactions cause opposite sign in Drell-Yan

Summary and Outlook

- The Sivers function can be accessed in SIDIS combined with the unpolarised fragmentation function.
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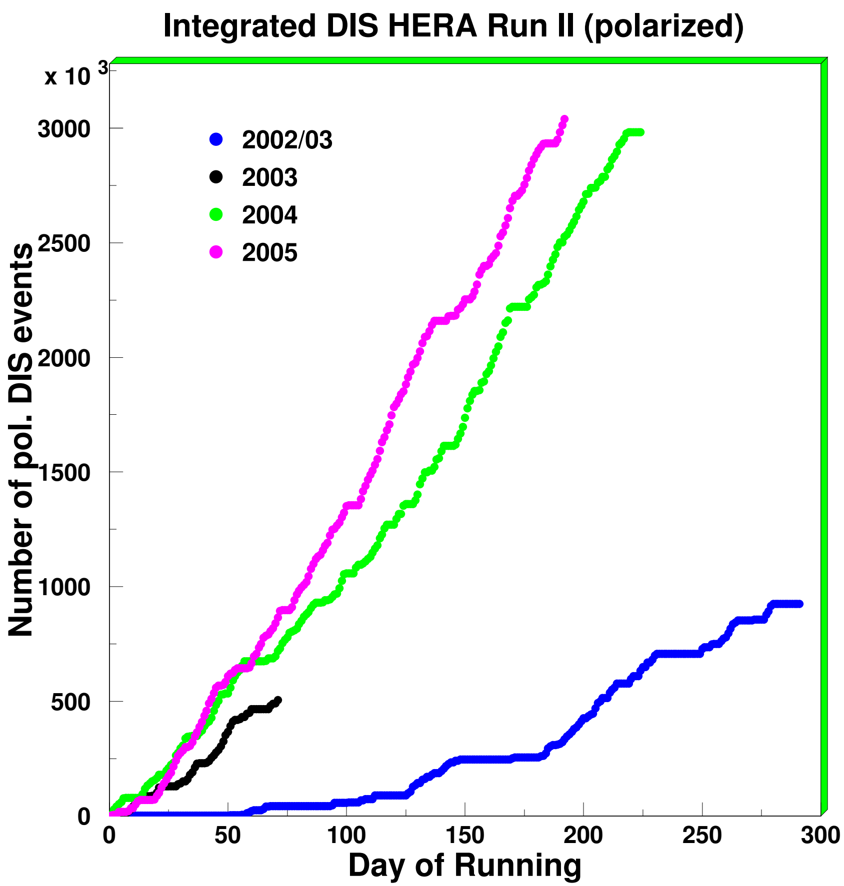

- Steep rise of number of DIS events in 2005, HERMES continues data taking till November.
- Ongoing work on extraction of Sivers function.
- Better statistics for measurement of ρ^0 amplitudes.