Results on the spin structure of the nucleon from HERMES

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Unibertsitatea

hermes

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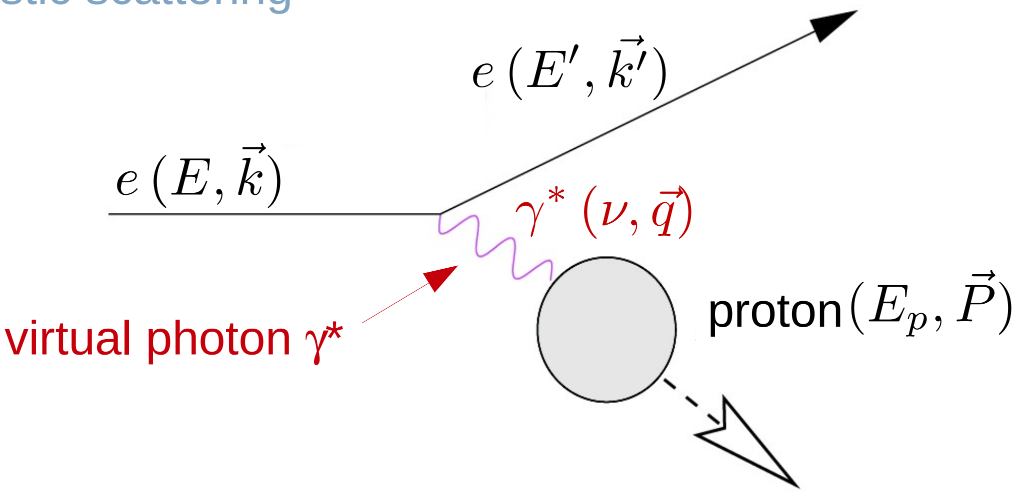
Quark-gluon Structure of the Nucleon
November 8, 2012 – Tokyo Institute of Techonology

Outline

- studying the proton: deep-inelastic scattering
- structure functions and parton model
- HERMES experiment
- quark-helicity distribution from deep-inelastic scattering
- semi-inclusive deep-inelastic scattering
  - quark-helicity, gluon helicity distribution and transversity
  - transverse-momentum distribution functions:
    Sivers and Boer-Mulders
- orbital angular momentum: GPDs and DVCS

Studying the proton

elastic scattering



Studying the proton

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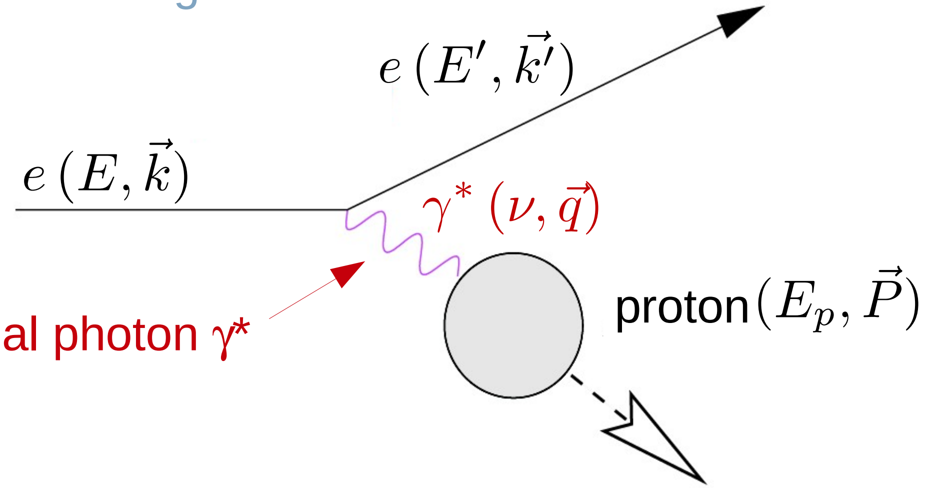
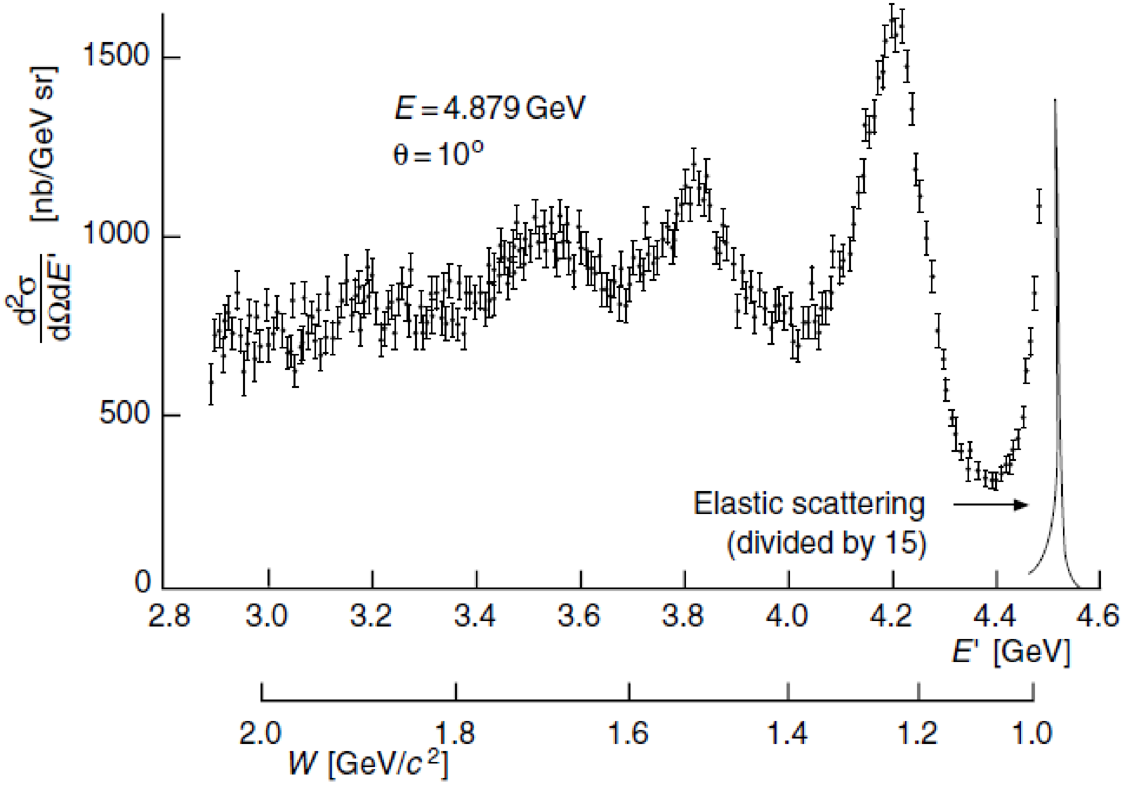


virtual photon γ*



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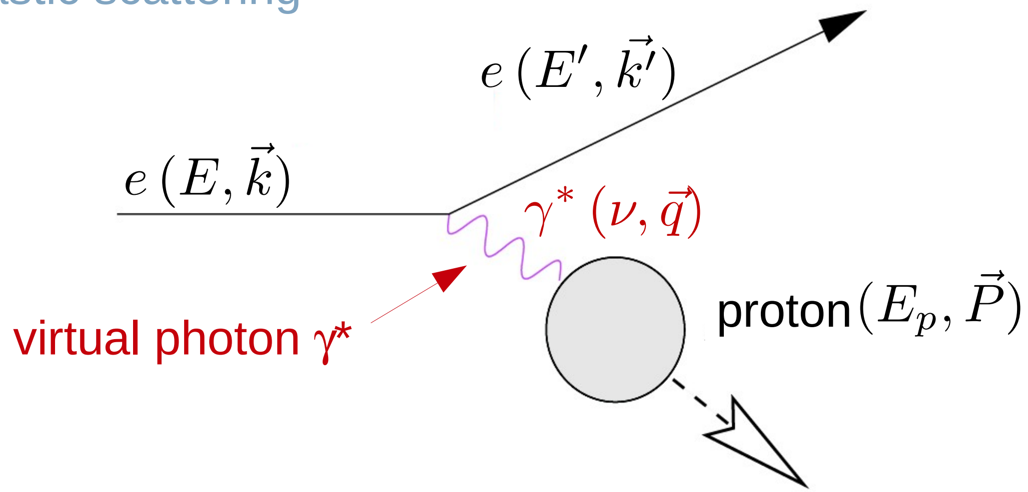

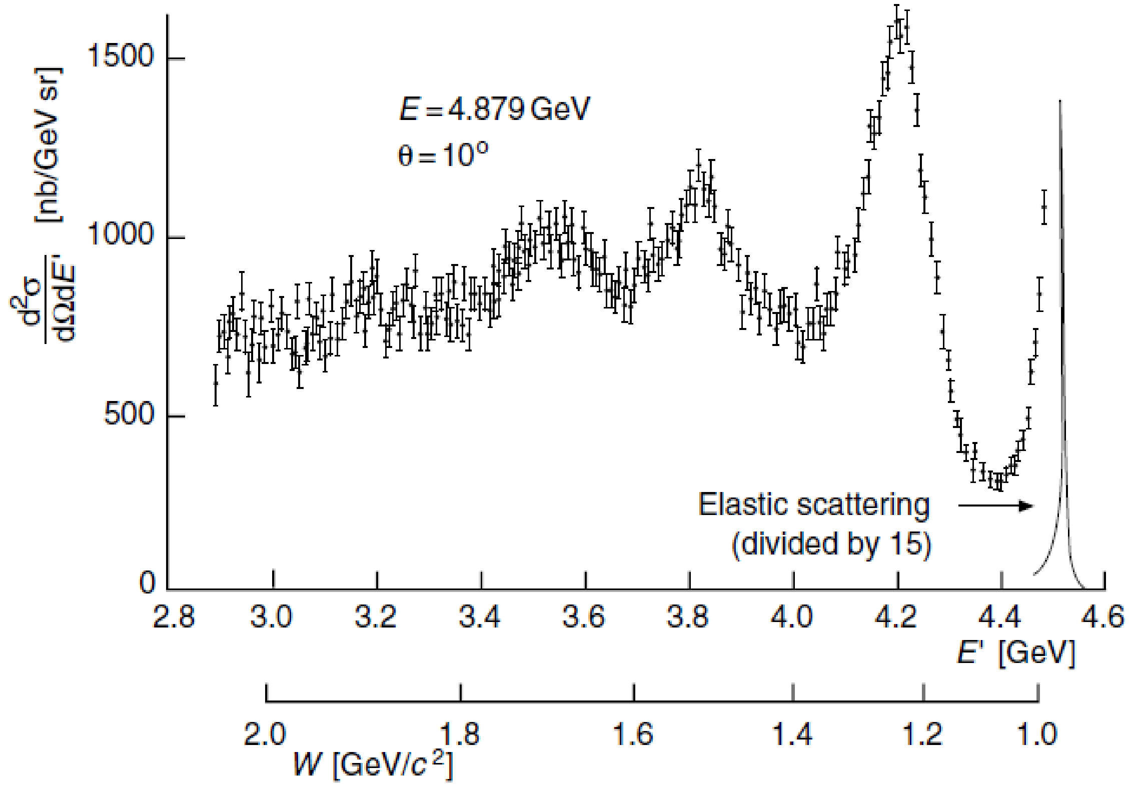

invariant mass W

$$W^2 \equiv (P+q)^2$$
$$= M^2 + 2Pq + q^2$$

Studying the proton

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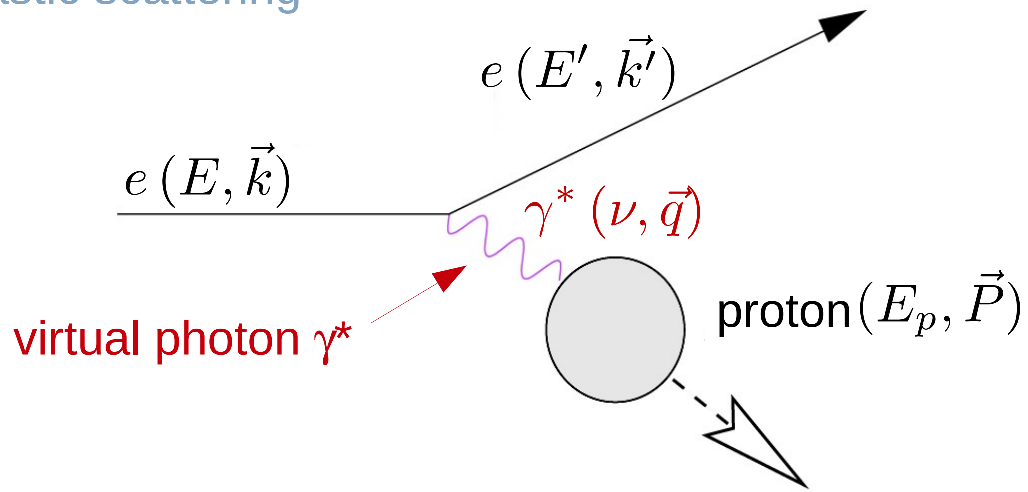

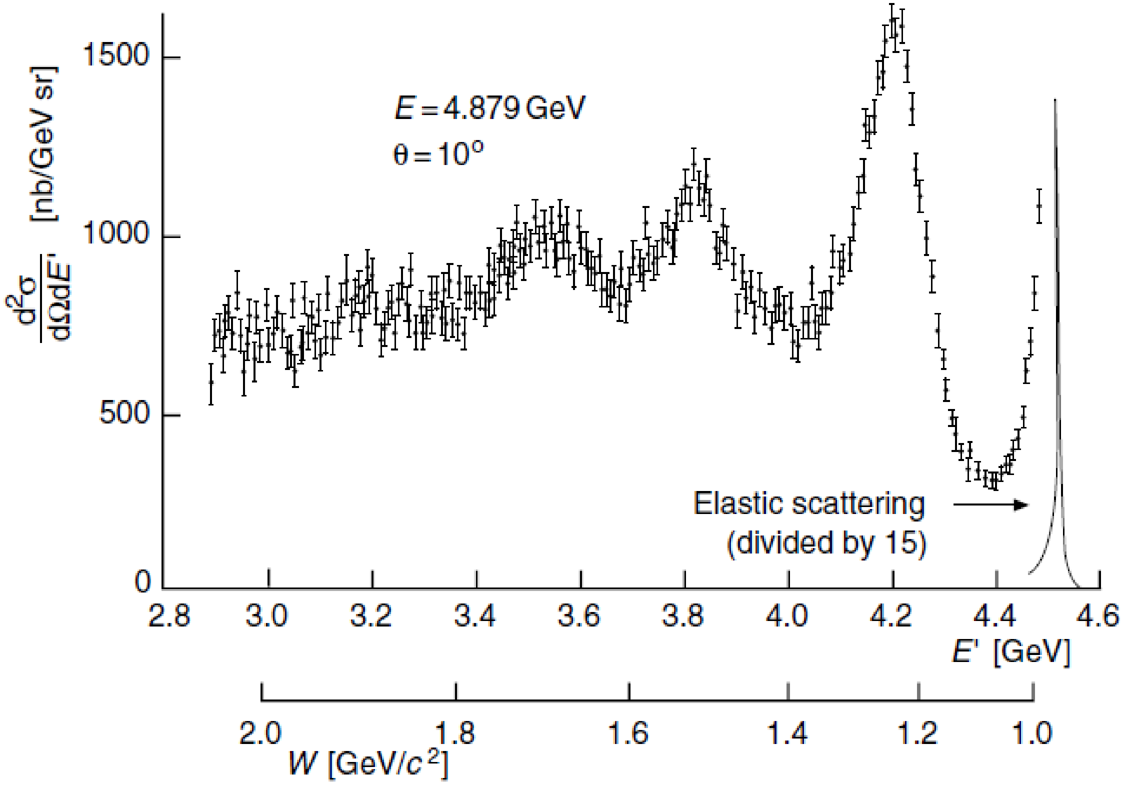

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Studying the proton

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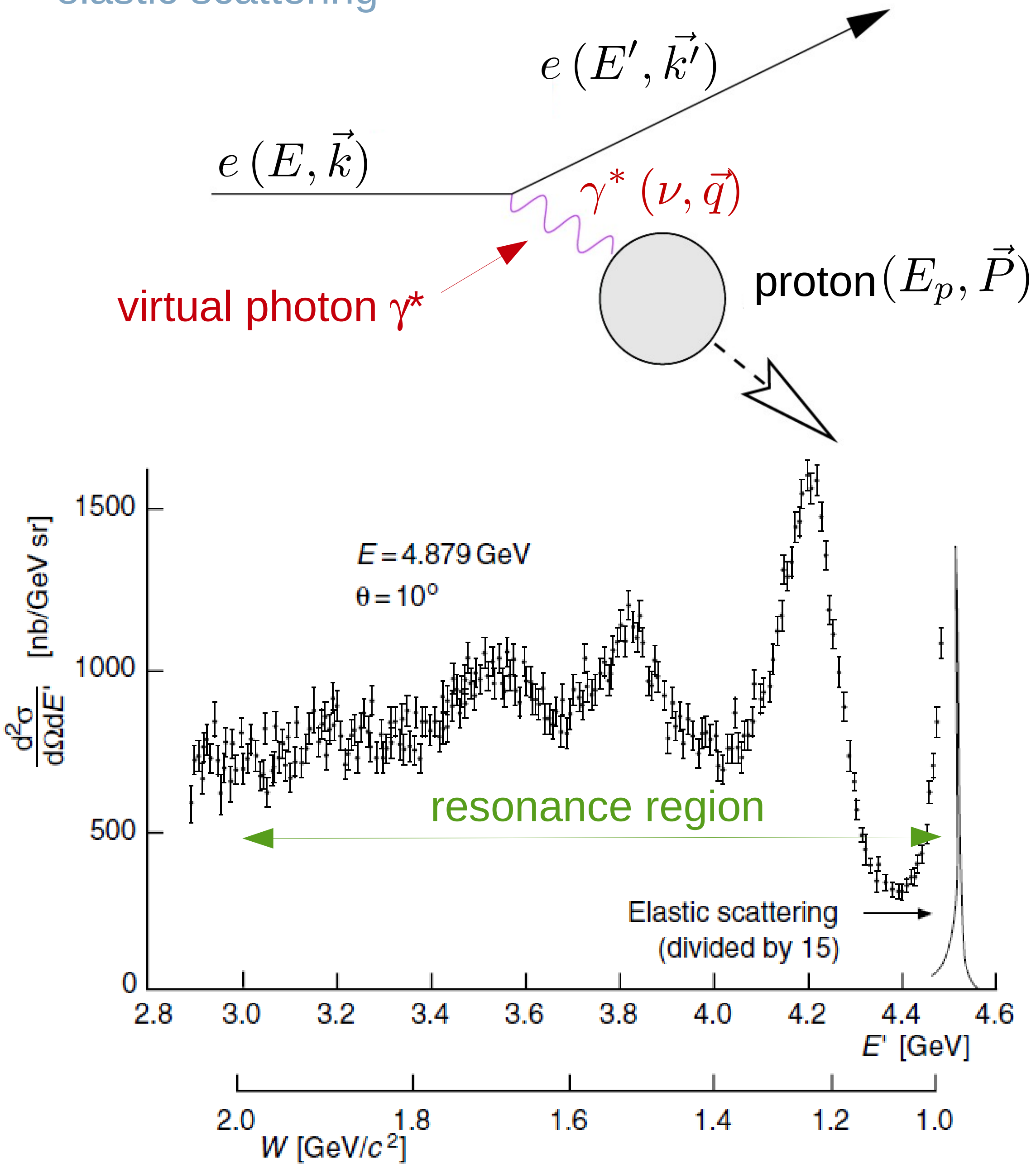

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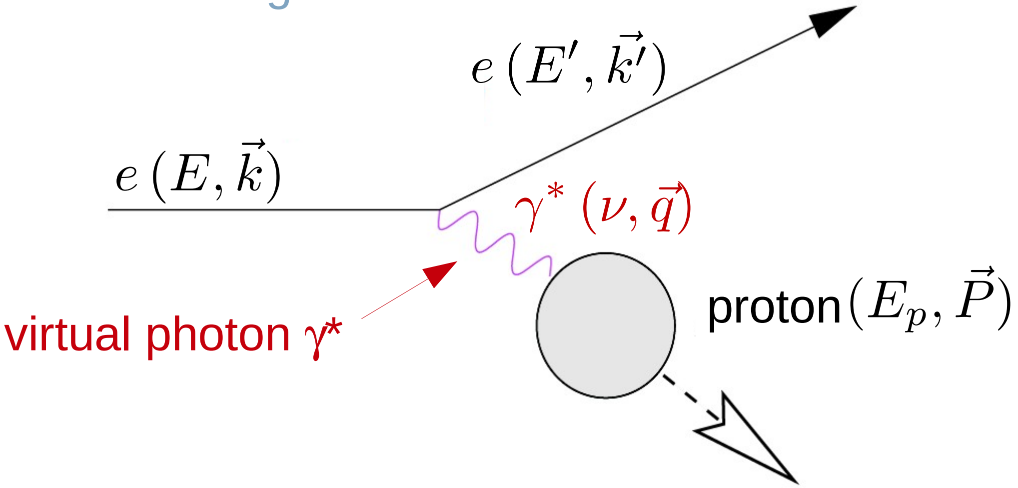
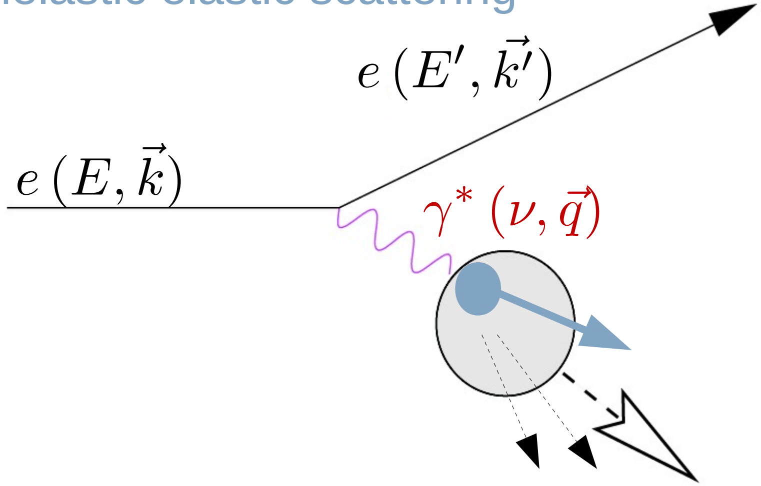
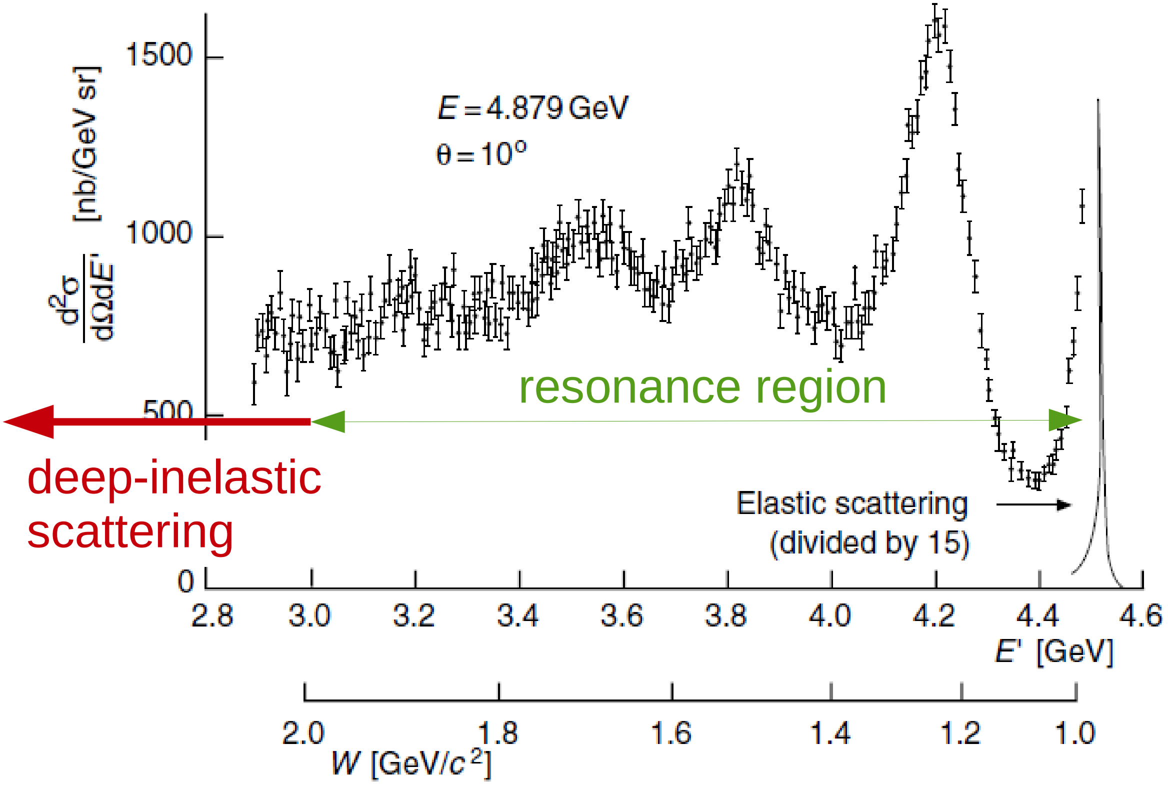
Studying the proton

elastic scattering



deep-inelastic elastic scattering





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Studying the proton

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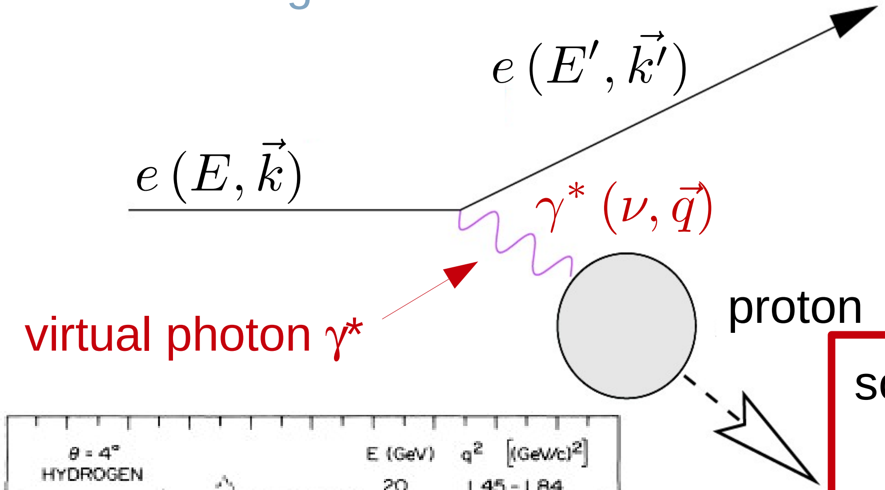


$e\,(E,\vec{k})$

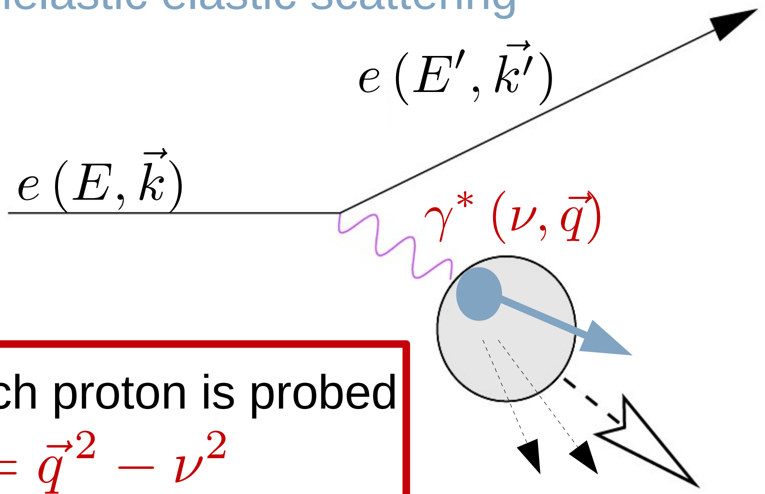
$e\,(E',\vec{k'})$

$\gamma^*\,(\nu,\vec{q})$

virtual photon γ^*

proton

deep-inelastic elastic scattering



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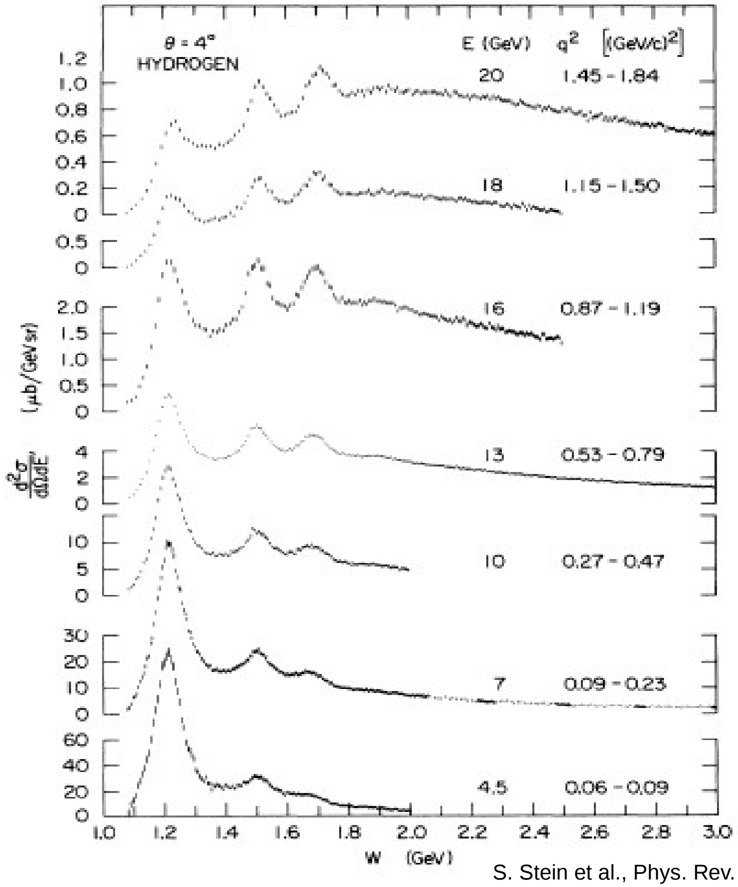
scale at which proton is probed

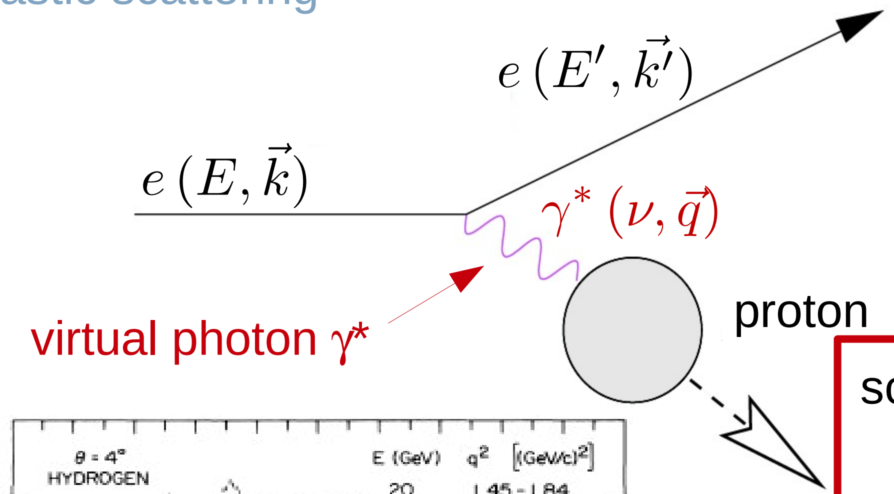
$$Q^2 = \vec{q}^{\,2} - \nu^2$$



S. Stein et al., Phys. Rev. D **12** (1975) 1884

Studying the proton

elastic scattering



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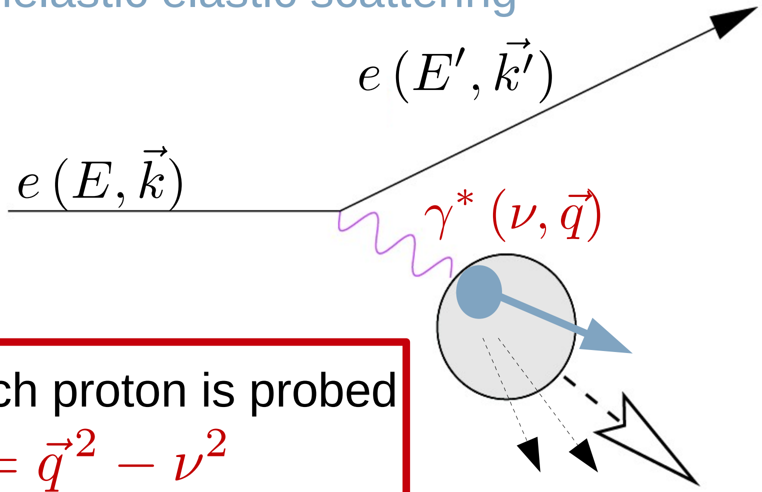

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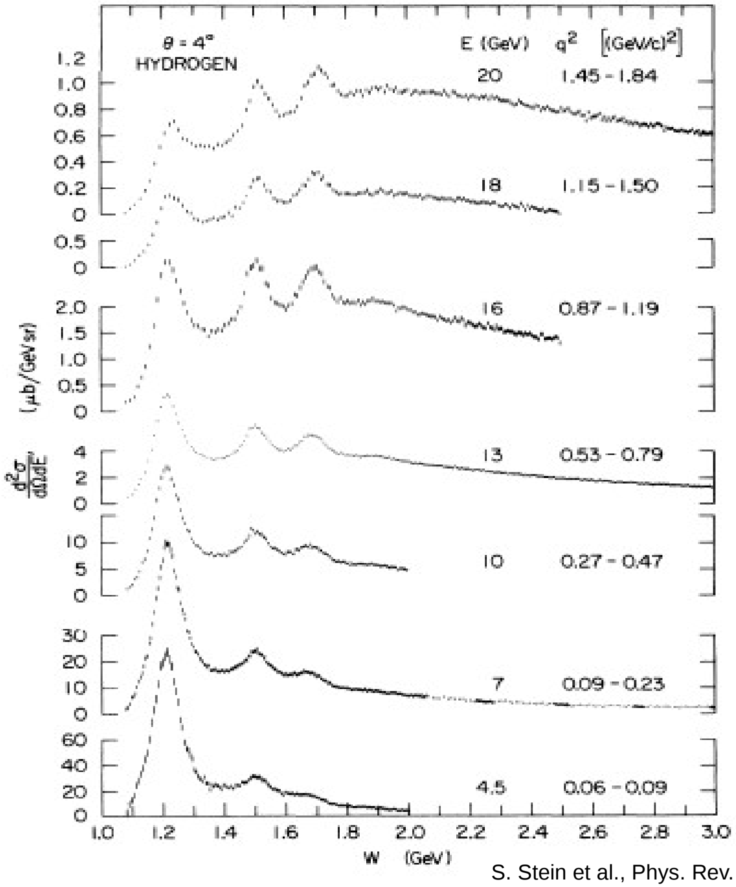

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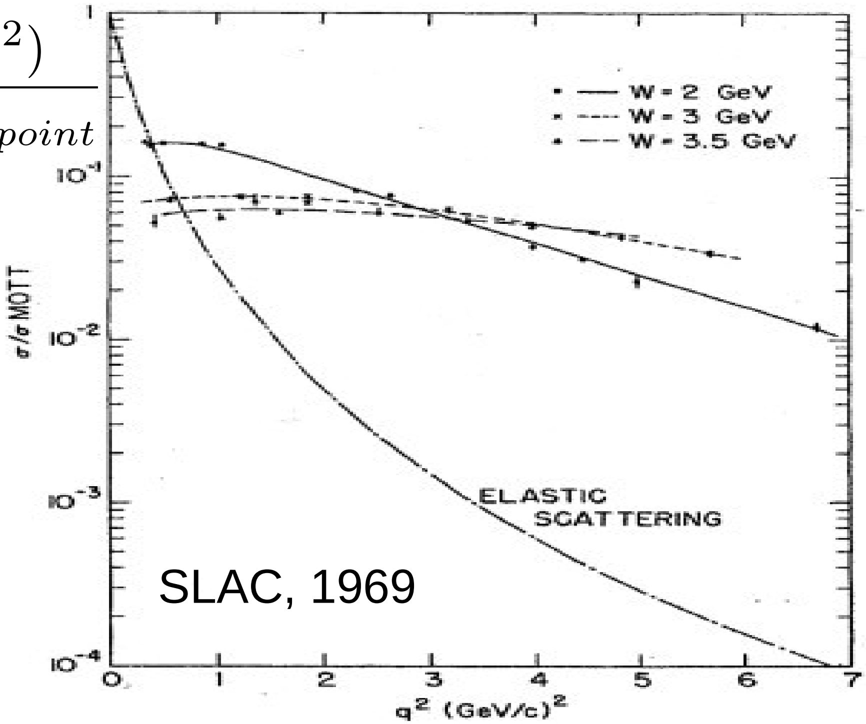
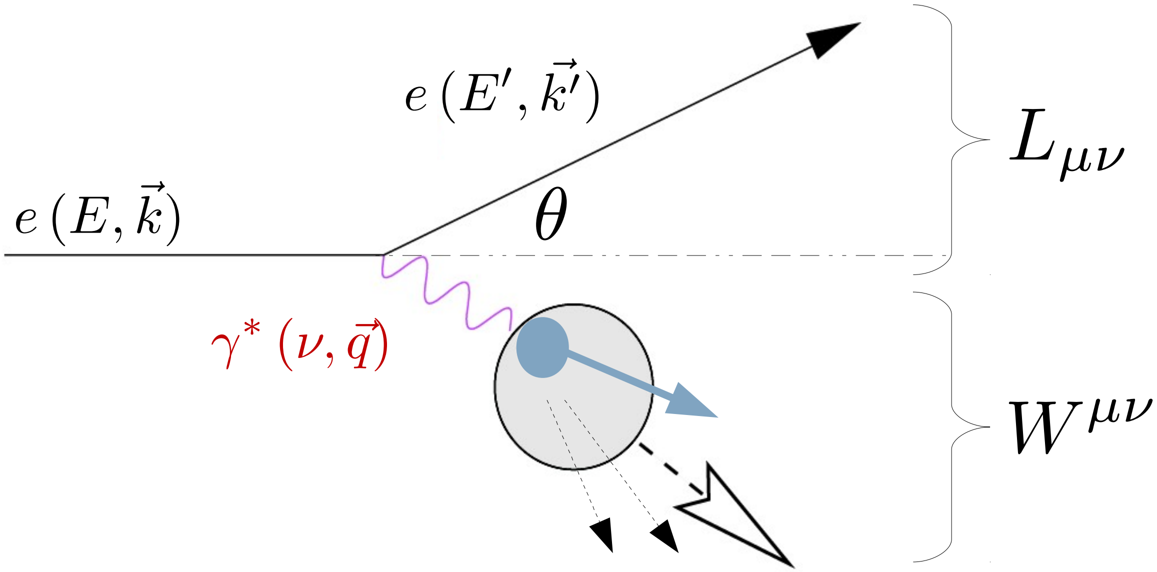
$$\frac{\sigma(Q^2)}{\sigma(Q^2)_{point}}$$



SLAC, 1969

Deep-inelastic scattering cross section

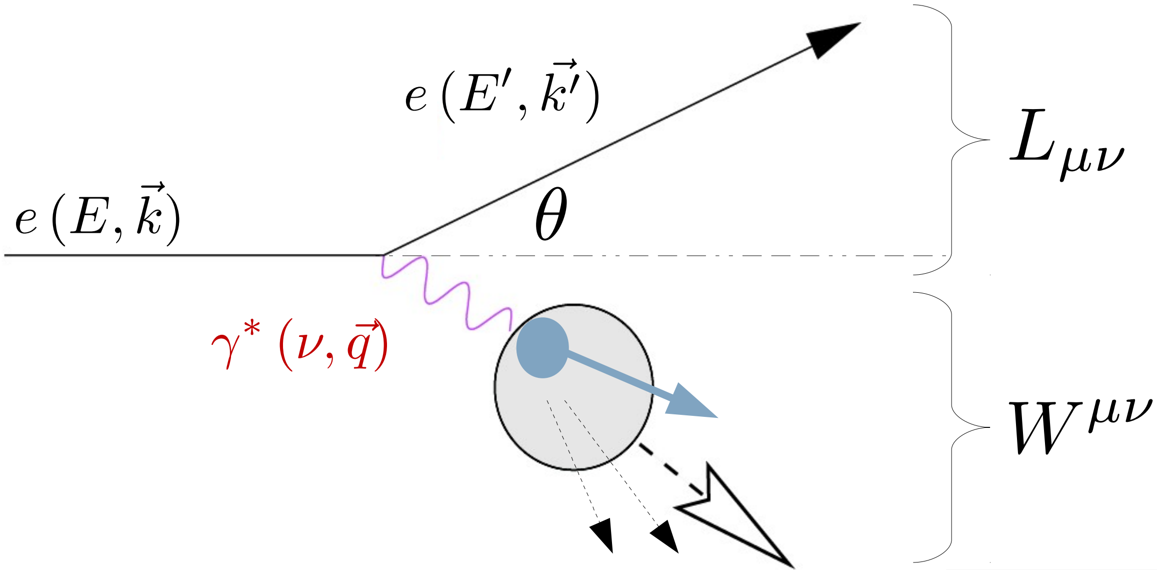


$$\frac{d^2\sigma}{dx_B dQ^2} \propto L_{\mu\nu} W^{\mu\nu}$$

$$Q^2 \equiv -q^2 \overset{lab}{=} 4EE' \sin^2(\frac{\theta}{2})$$

$$x_B \equiv \frac{Q^2}{2Pq} = \frac{1}{1 + \frac{W^2 - M^2}{Q^2}}$$

Deep-inelastic scattering cross section



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inelastic scattering : $W > M \rightarrow 0 < x_B < 1$

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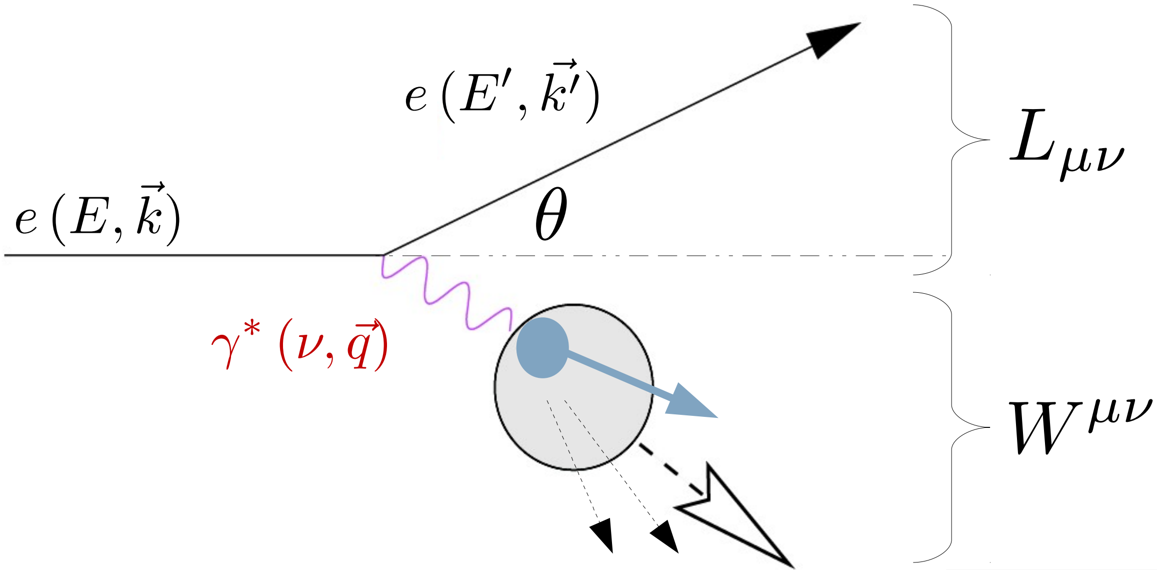

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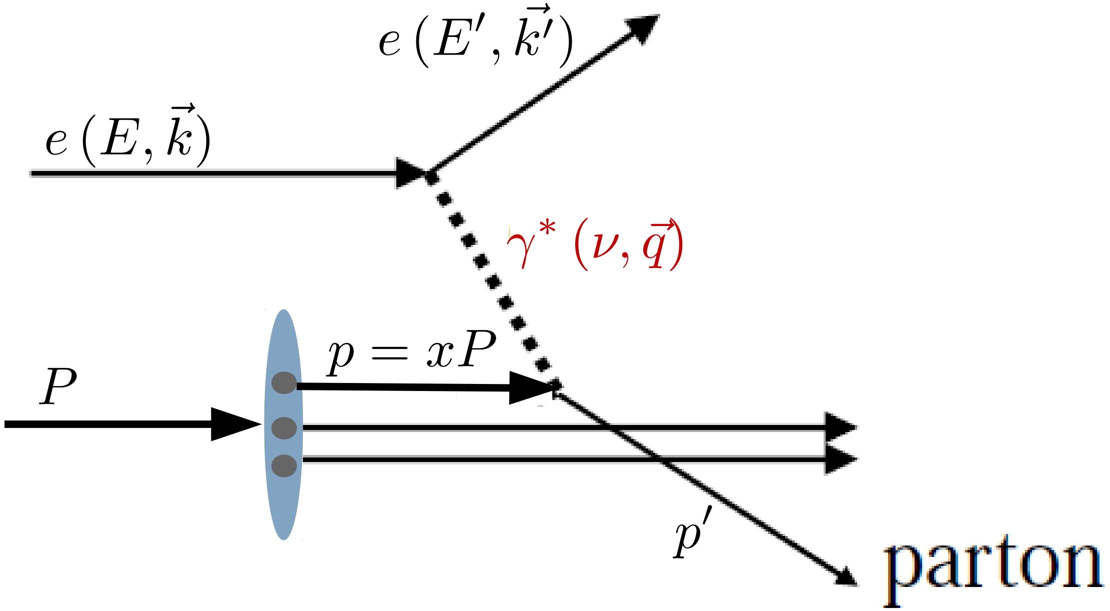
$L_{\mu\nu}$: calculable in QED

$$W_{\mu\nu} = \left(-g_{\mu\nu} - \frac{q_\mu q_\nu}{Q^2}\right) F_1 + \left(P_\mu + \frac{Pq}{Q^2}q_\mu\right)\left(P_\nu + \frac{Pq}{Q^2}q_\nu\right)\frac{F_2}{Pq}$$
$$+ i\epsilon_{\mu\nu\alpha\beta}q^\alpha \frac{M}{Pq}\left[S^\beta g1 + \left(S^\beta - \frac{Sq}{Pq}P^\beta\right) g_2\right]$$

unpolarized structure functions F_1 and F_2

polarized structure functions g_1 and g_2 only contribute if both target and beam polarized

The parton model



<u>proton in infinite-momentum frame</u>
neglect masses and
transverse momenta of quarks

$$
\begin{aligned}
p &= xP \\
p'^2 &= (p+q)^2 \\
&= p^2 + 2pq - Q^2 \\
0 &= 0 + 2xPq - Q^2
\end{aligned}
$$

$$\Downarrow$$

$$x = \frac{Q^2}{2Pq} = x_B$$

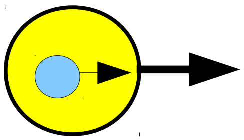
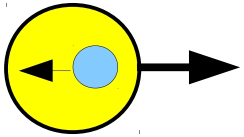
The parton model

proton spin
(anti-)quark spin

$$F_1(x) = \frac{1}{2}\sum_q e_q^2 q(x) = \frac{1}{2}\sum_q e_q^2 \left(\overset{\Rightarrow}{\vec{q}}(x) + \overset{\Rightarrow}{\overset{\leftarrow}{q}}(x) \right)$$

$$F_2(x) = 2xF_1$$

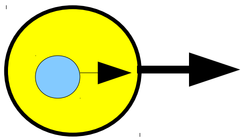
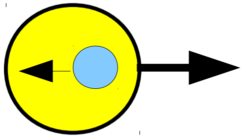
spin-independent parton distribution function (PDF)

$q(x) =$  $+$ 

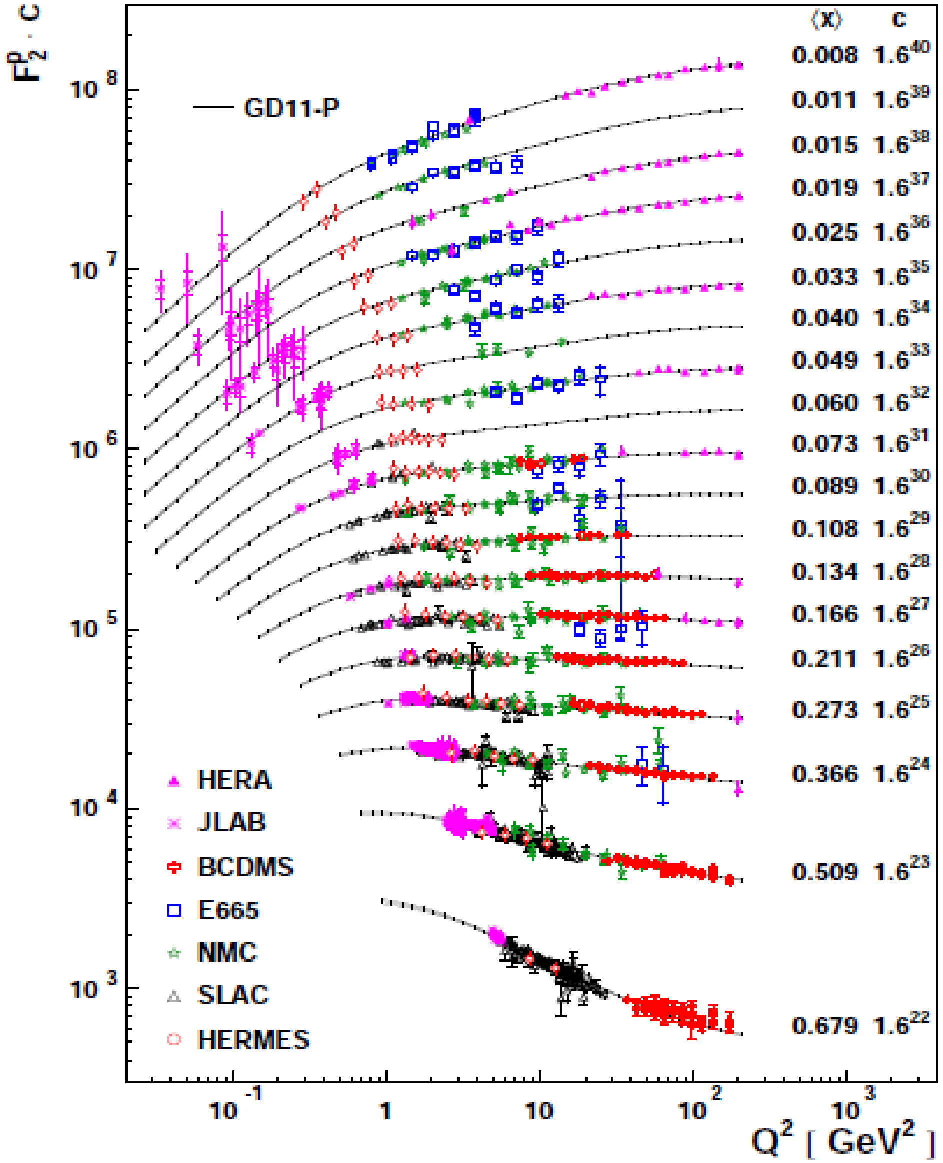
$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \Delta q(x) = \frac{1}{2}\sum_q e_q^2 \left(\overset{\Rightarrow}{\vec{q}}(x) - \overset{\Rightarrow}{\overset{\leftarrow}{q}}(x) \right)$$

$$g_2(x) = 0$$

helicity parton distribution function (PDF)

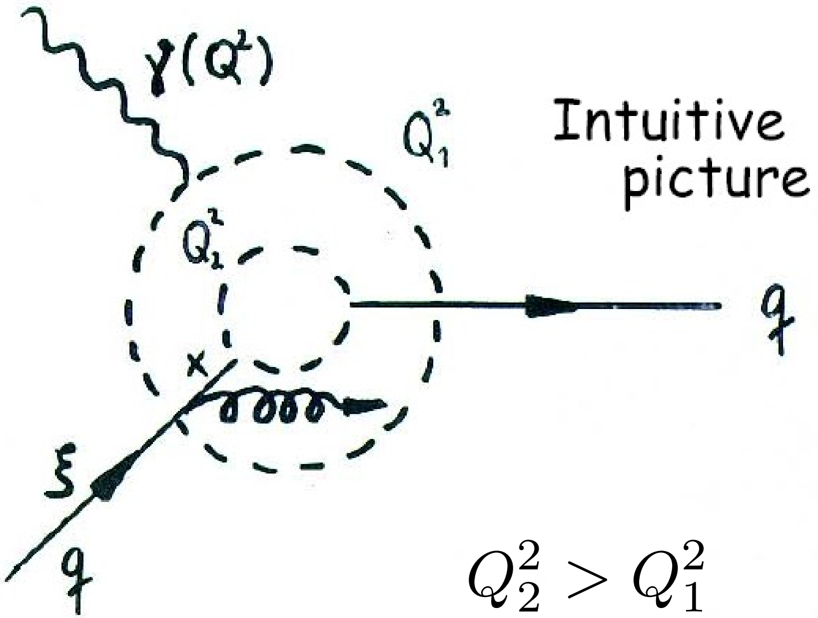
$\Delta q(x) =$  $-$ 

Spin-independent structure functions



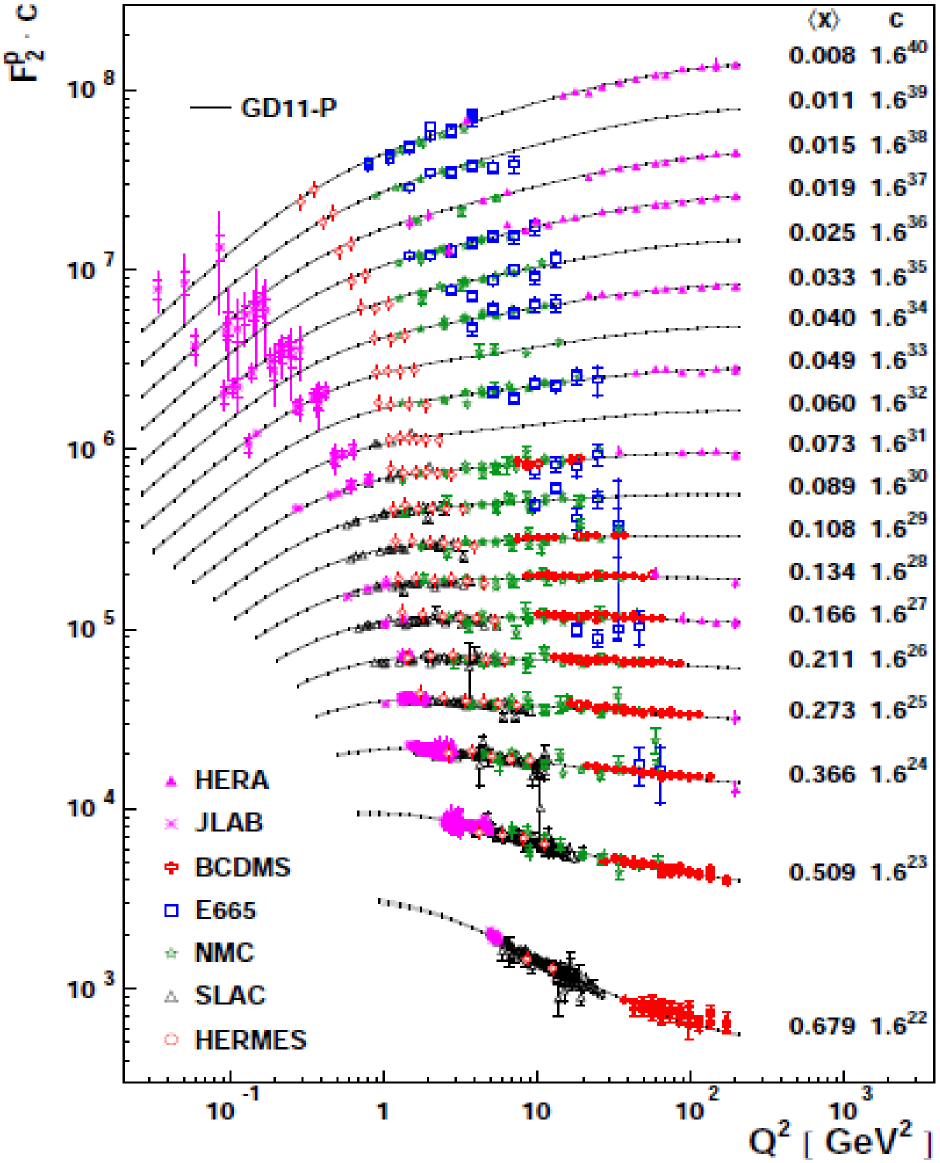
scaling violation:

structure functions and PDFs depend on x_B and Q^2



$$Q_2^2 > Q_1^2$$

Spin-independent structure functions



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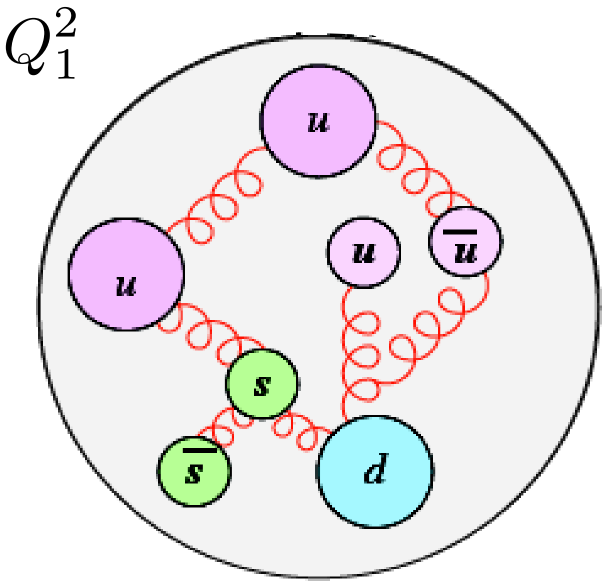

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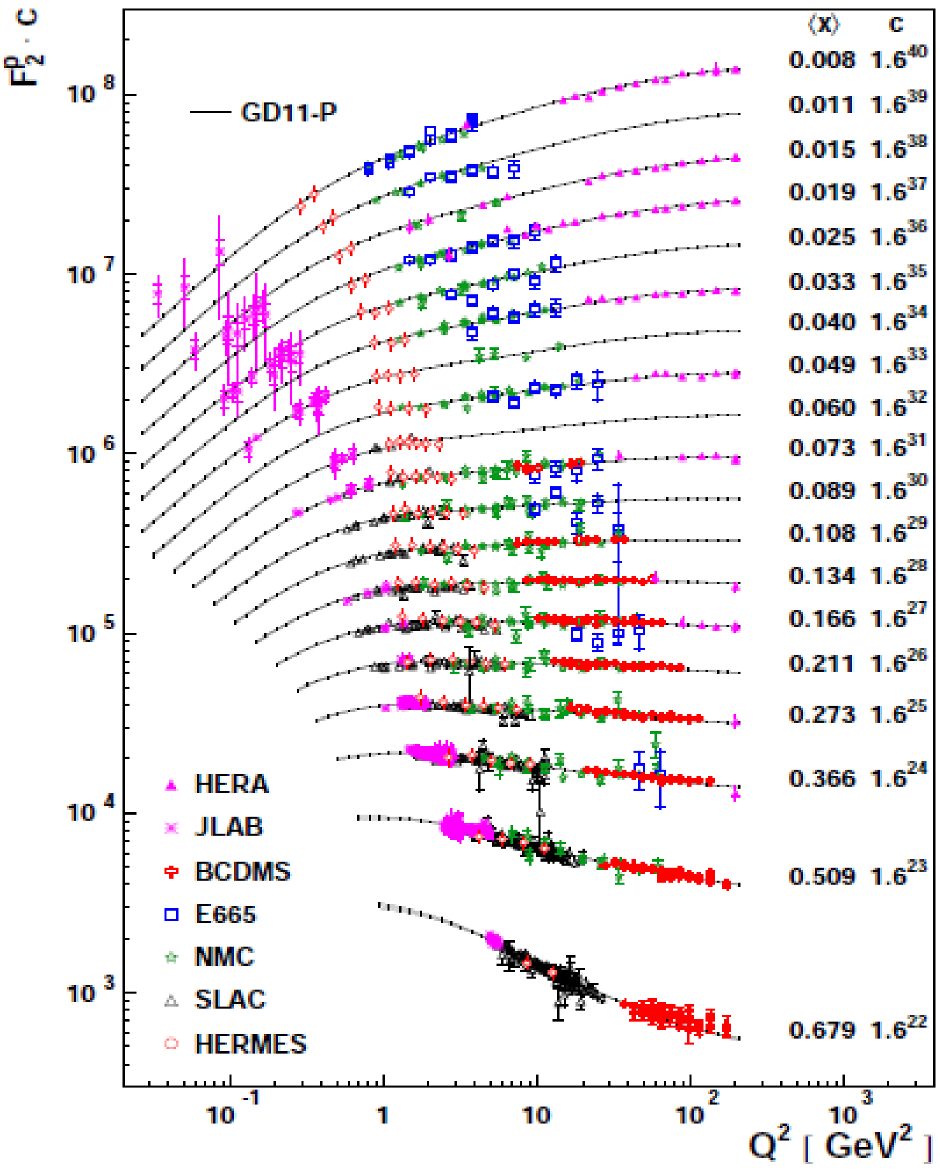

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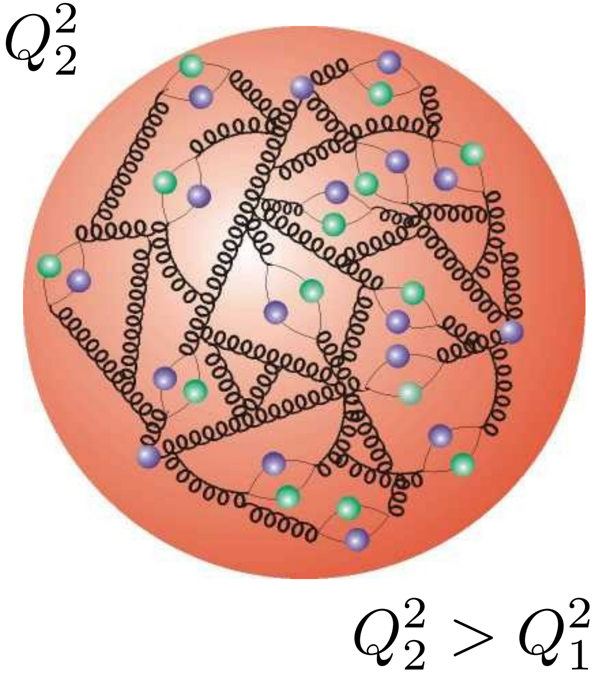

Helicity-dependent structure functions

measurement of

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \Delta q(x) = \frac{1}{2}\sum_q e_q^2 \left(\overset{\Rightarrow}{\vec{q}}(x) - \overset{\Rightarrow}{\overset{\leftarrow}{q}}(x) \right)$$

$$\Downarrow$$

$$\Delta\Sigma = \int_0^1 dx_B\, \Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta\bar{u}(x) + \Delta\bar{d}(x) + \Delta\bar{s}(x)$$

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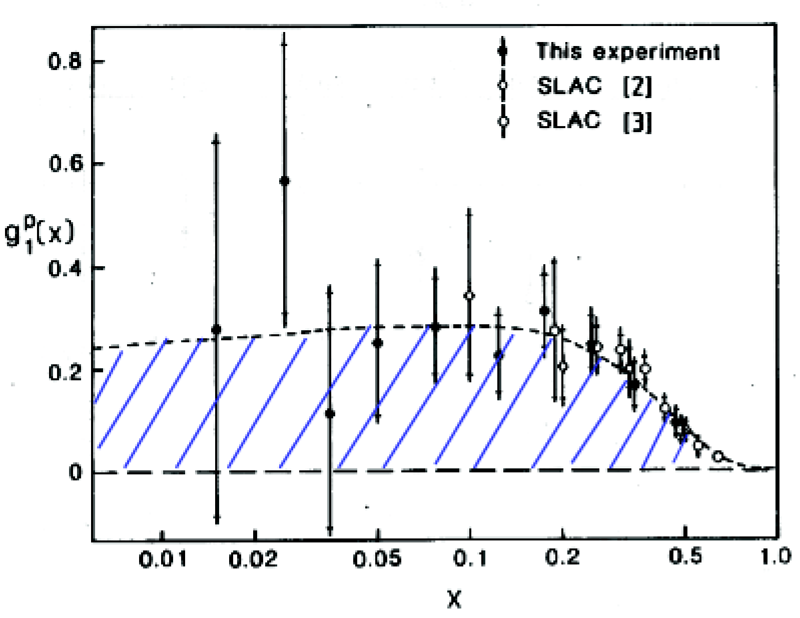
first measurement: EMC, 1988



$$\Delta\Sigma = 0.14 \pm 0.09 \pm 0.21$$

J. Ashman et al., Phys. Lett. B **206** (1988) 364; Nucl. Phys. B **328** (1989) 1

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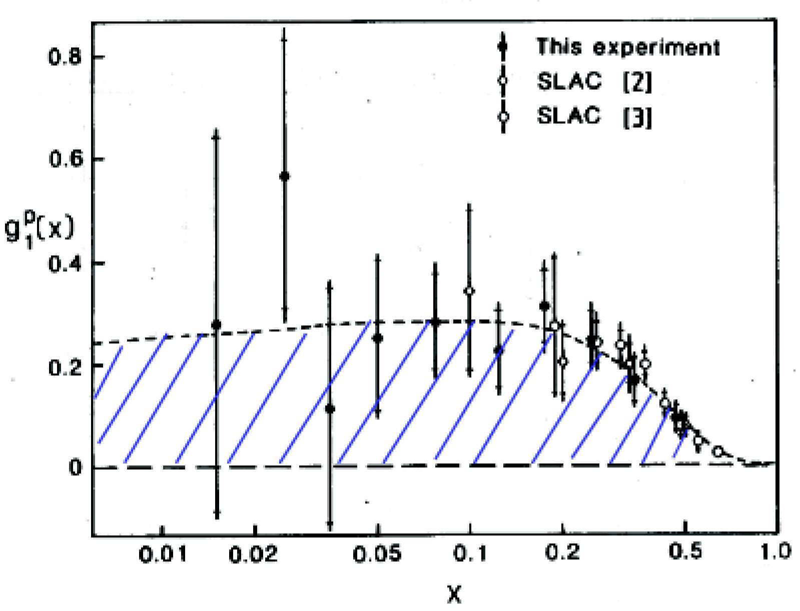

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Spin Puzzle

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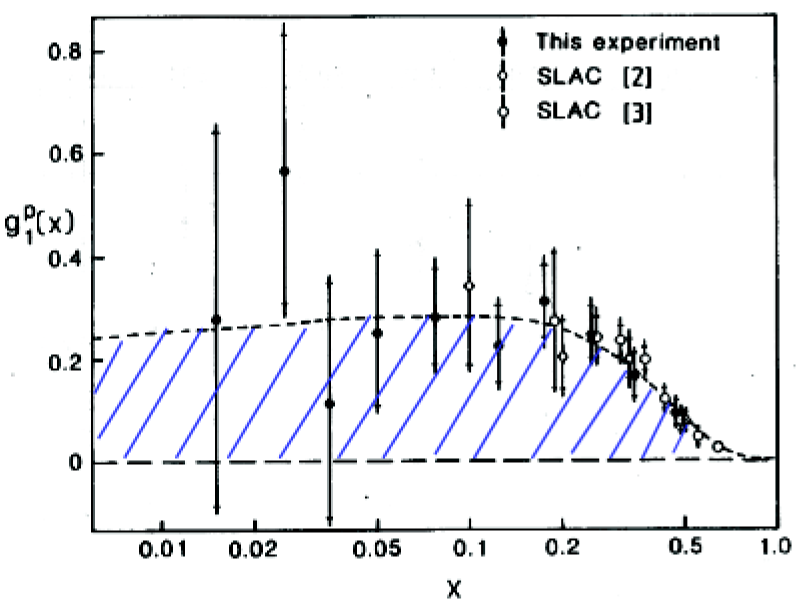

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Spin Puzzle

Spin Crisis!

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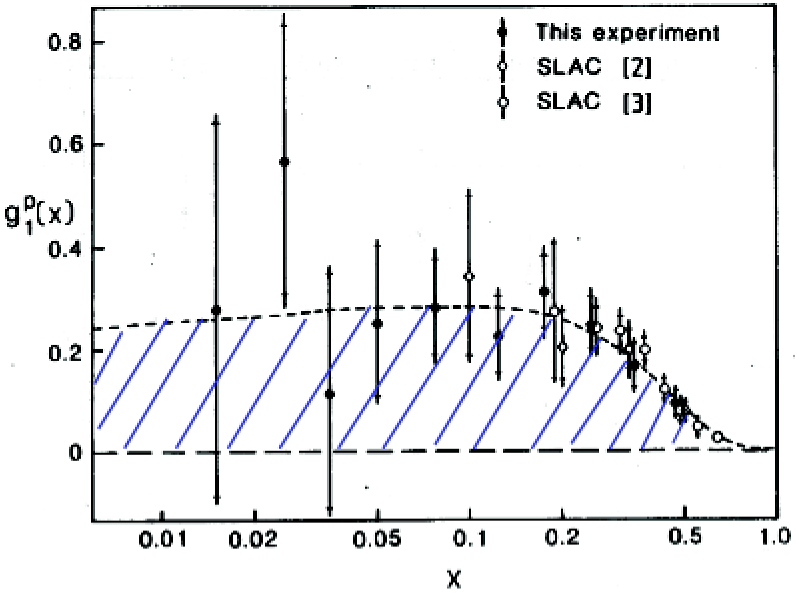

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Spin Puzzle

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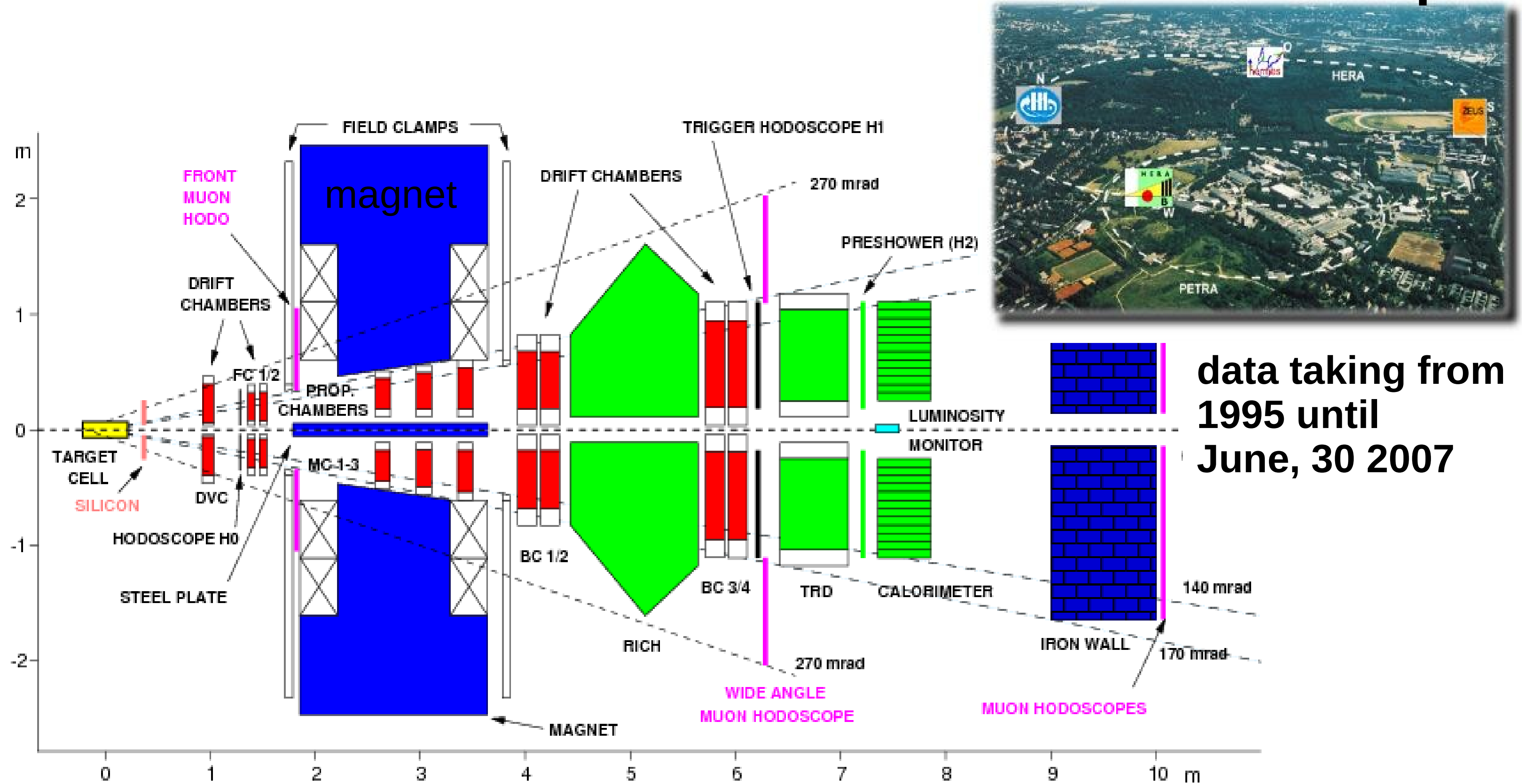
HERMES: HERA MEasurement of Spin



data taking from 1995 until June, 30 2007

Beam	Gaseous internal target
longitudinally pol.	transversely pol. H (~75%)
e^+ & e^-	unpol. H,D,He,Ne,Kr,Xe
E= 27.6 GeV	longitudinally pol. H,D,He (~85%)

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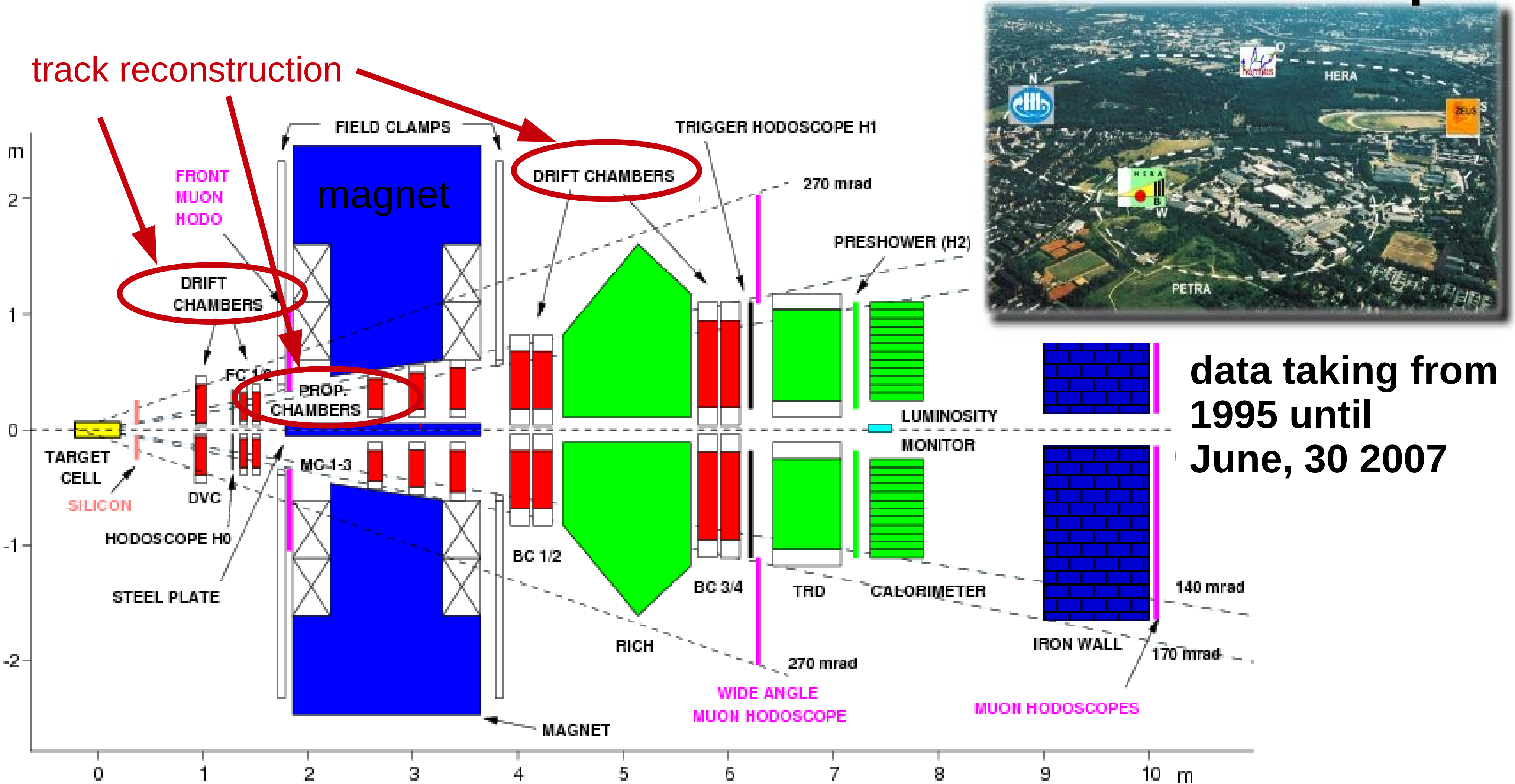
track reconstruction



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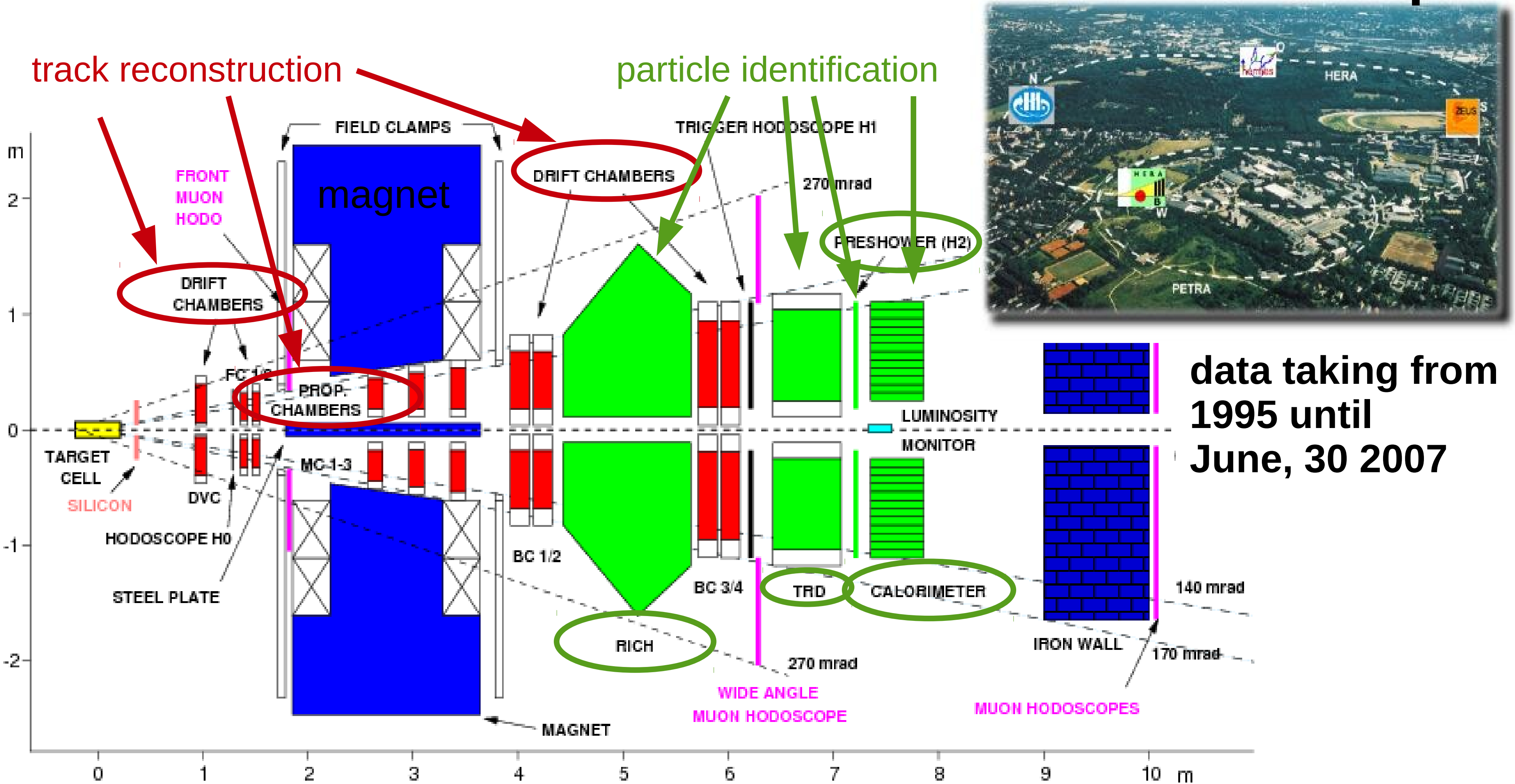

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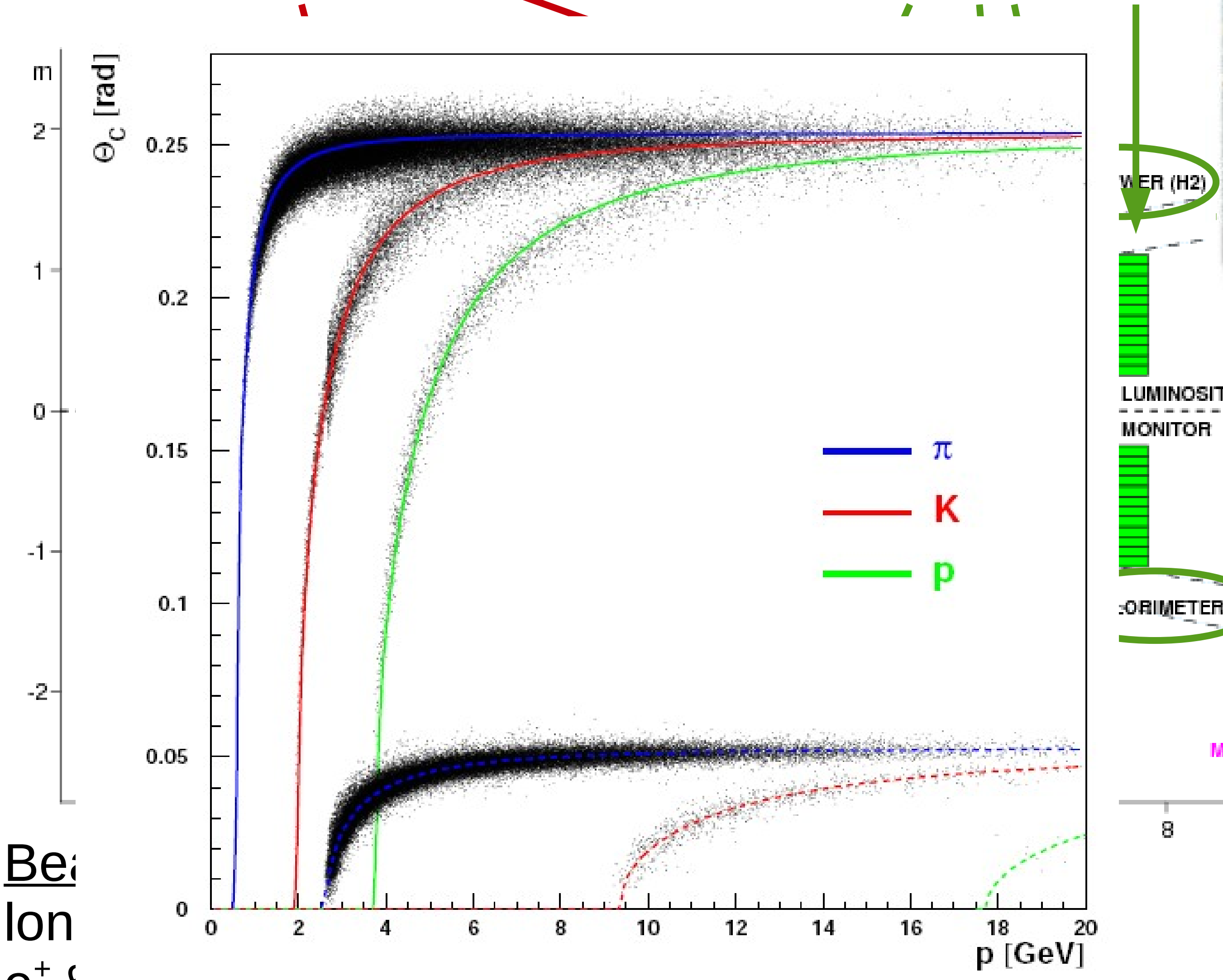
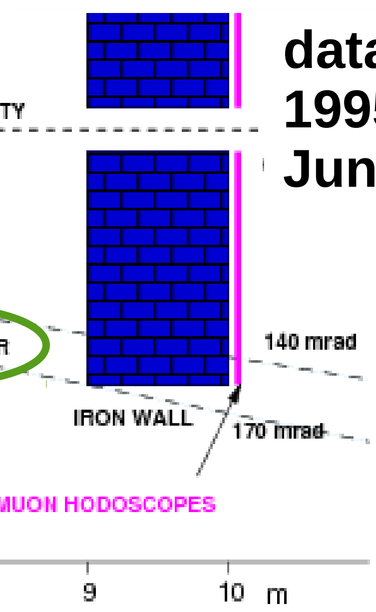
- **lepton-hadron PID: high efficiency (>98%) & low contamination (<1%)**
- **hadron PID: RICH 2-15 GeV**

HERMES: HERA MEasurement of Spin

track reconstruction

particle identification





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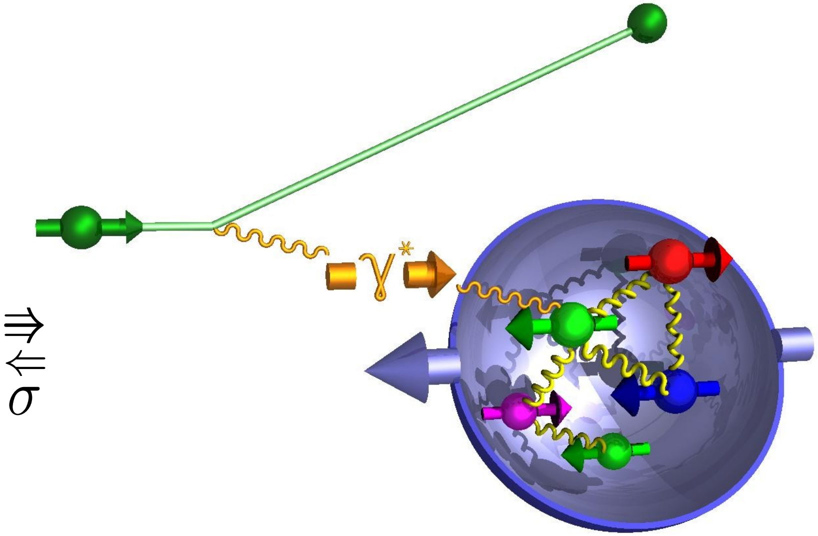
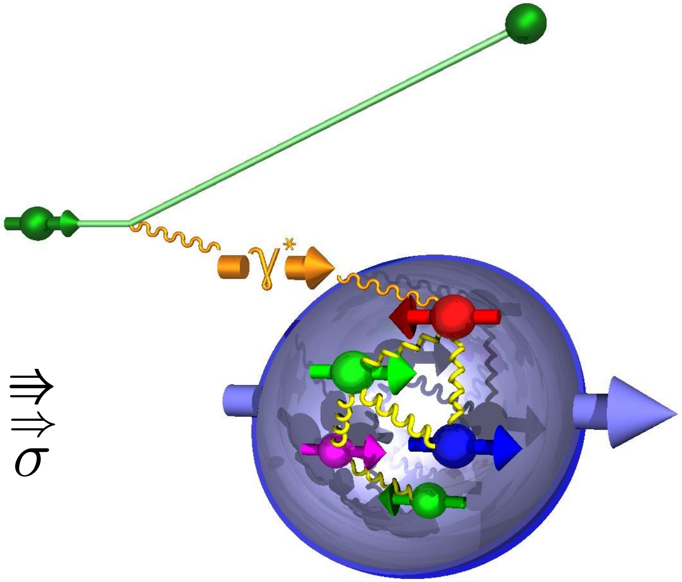
Accessing g_1 at HERMES



$\overset{\overset{\Rrightarrow}{\Leftarrow}}{\sigma}$



$\overset{\overset{\Rrightarrow}{\Rightarrow}}{\sigma}$

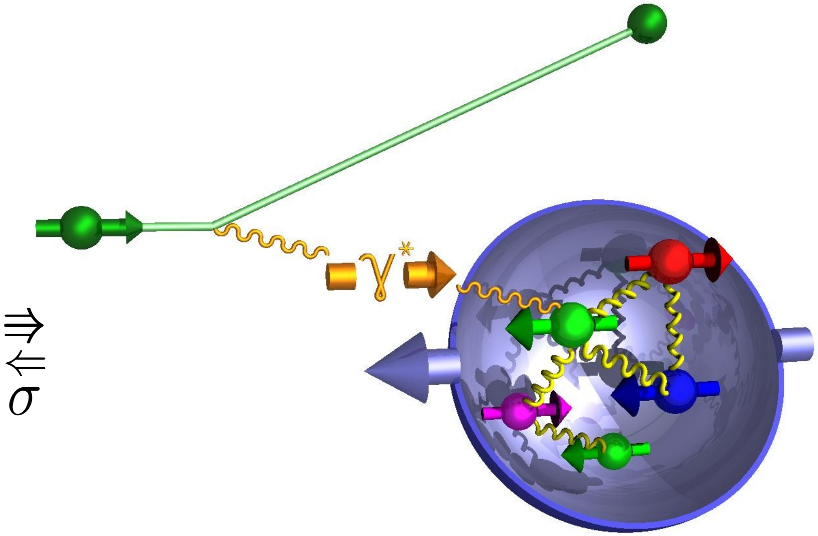
$$A_1 \simeq \frac{\overset{\overset{\Rrightarrow}{\Leftarrow}}{\sigma} - \overset{\overset{\Rrightarrow}{\Rightarrow}}{\sigma}}{\overset{\overset{\Rrightarrow}{\Leftarrow}}{\sigma} + \overset{\overset{\Rrightarrow}{\Leftarrow}}{\sigma}}$$

photon spin
proton spin

$$\simeq \frac{\sum_q e_q^2 \Delta q(x_B, Q^2)}{\sum_q e_q^2 q(x_B, Q^2)}$$

$$\simeq \frac{g_1(x_B, Q^2)}{F_1(x_B, Q^2)}$$

g_1 from HERMES



$\overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}}$

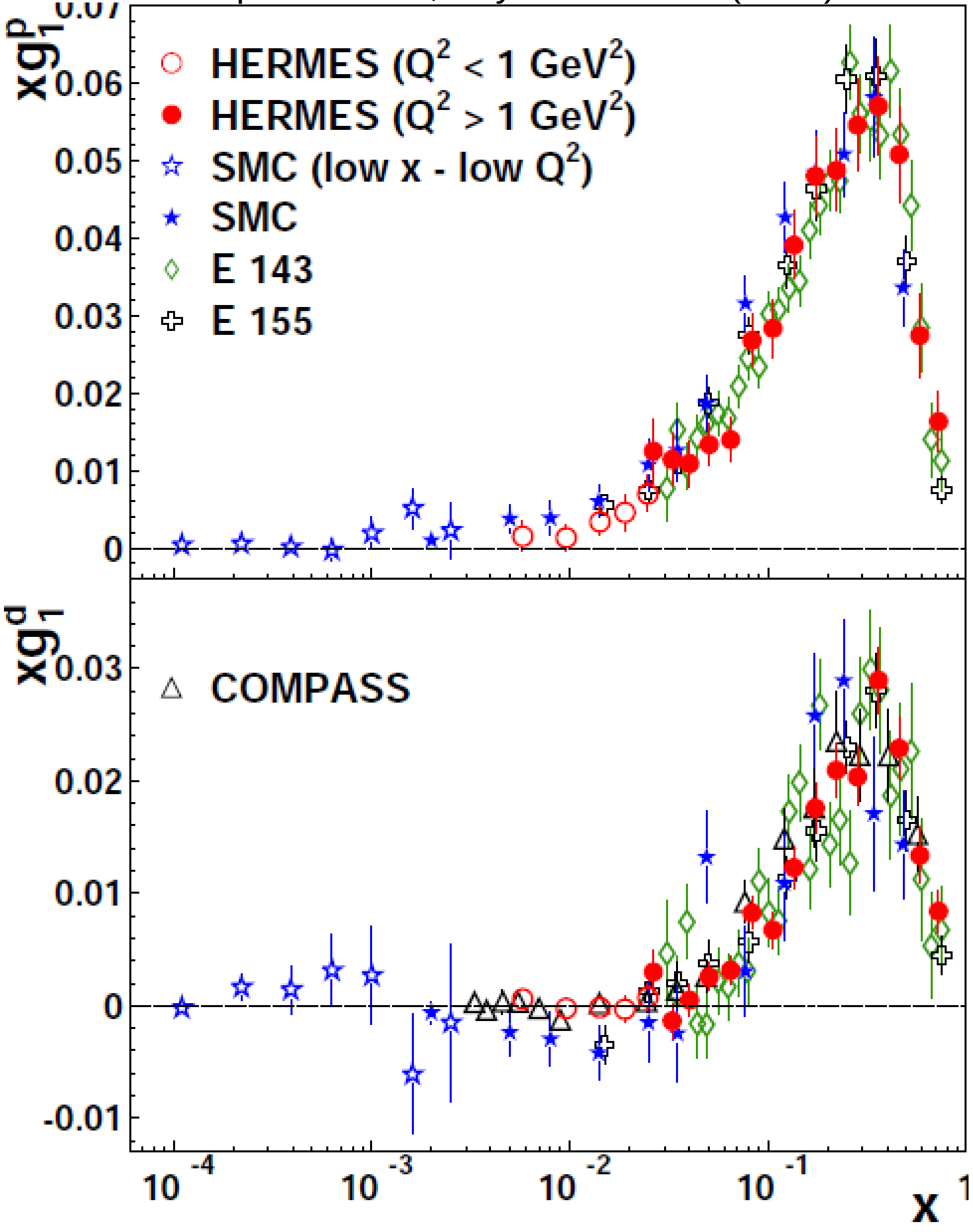
$$A_1 \simeq \frac{\overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}} - \overset{\Rrightarrow}{\overset{\Rightarrow}{\sigma}}}{\overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}} + \overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}}}$$

photon spin
proton spin

$$\simeq \frac{\sum_q e_q^2 \Delta q(x_B, Q^2)}{\sum_q e_q^2 q(x_B, Q^2)}$$

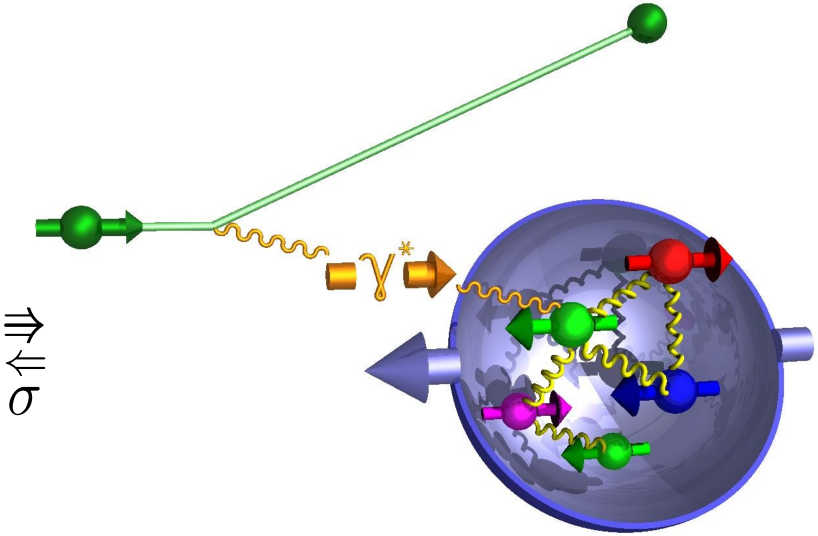
$$\simeq \frac{g_1(x_B, Q^2)}{F_1(x_B, Q^2)}$$

A. Airapetian et al., Phys. Rev. D **75** (2007) 012007

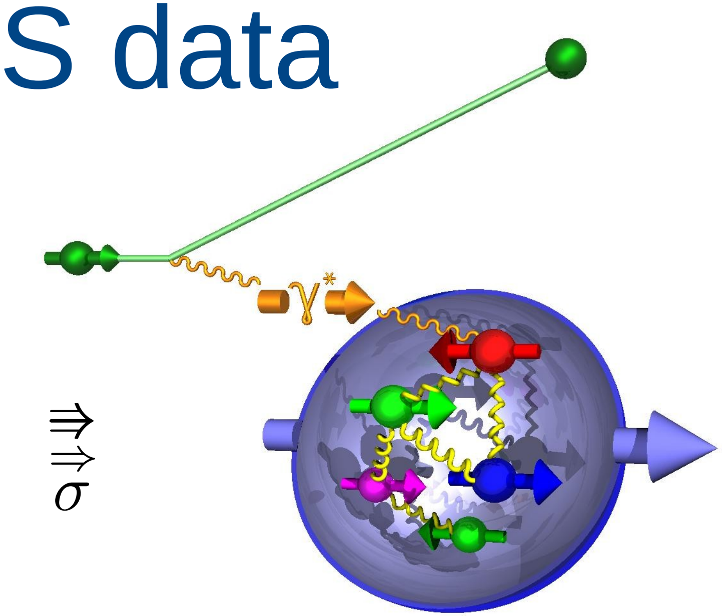


Quark spin contribution from HERMES data

$\overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}}$



$\overset{\Rrightarrow}{\overset{\Rightarrow}{\sigma}}$



photon spin
proton spin

$$A_1 \simeq \frac{\overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}} - \overset{\Rrightarrow}{\overset{\Rightarrow}{\sigma}}}{\overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}} + \overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}}}$$

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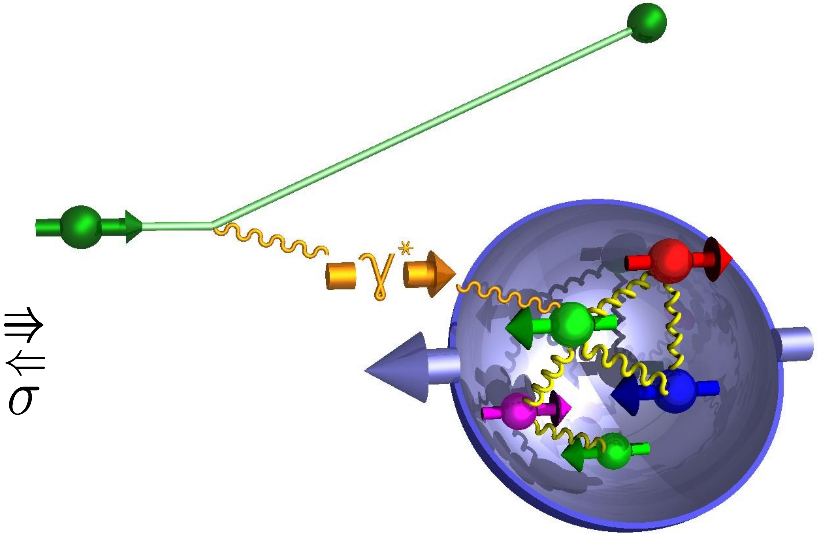
$$\simeq \frac{g_1(x_B, Q^2)}{F_1(x_B, Q^2)}$$

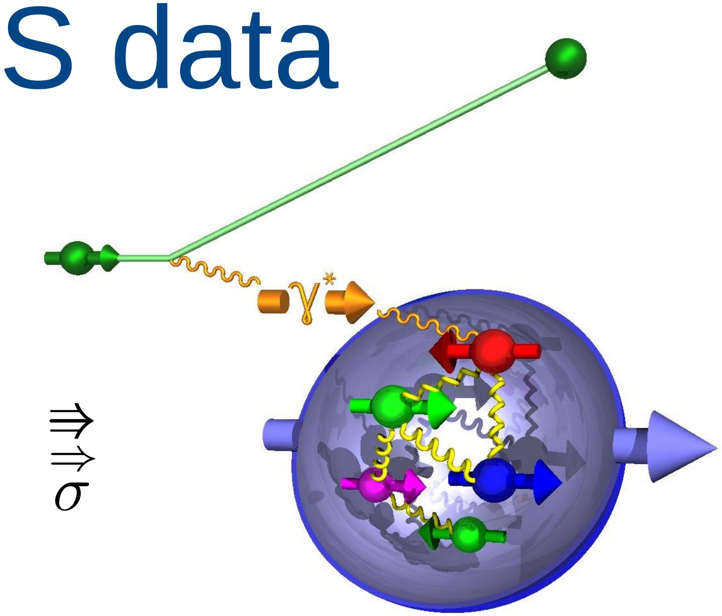
$$\Delta\Sigma = 0.330 \pm \underset{\text{(exp.)}}{0.025} \pm \underset{\text{(theor.)}}{0.011} \pm \underset{\text{(evol.)}}{0.028}$$

Quark spin contribution from HERMES data

$\overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}}$



$\overset{\Rrightarrow}{\overset{\Rightarrow}{\sigma}}$



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→ photon spin
→ proton spin

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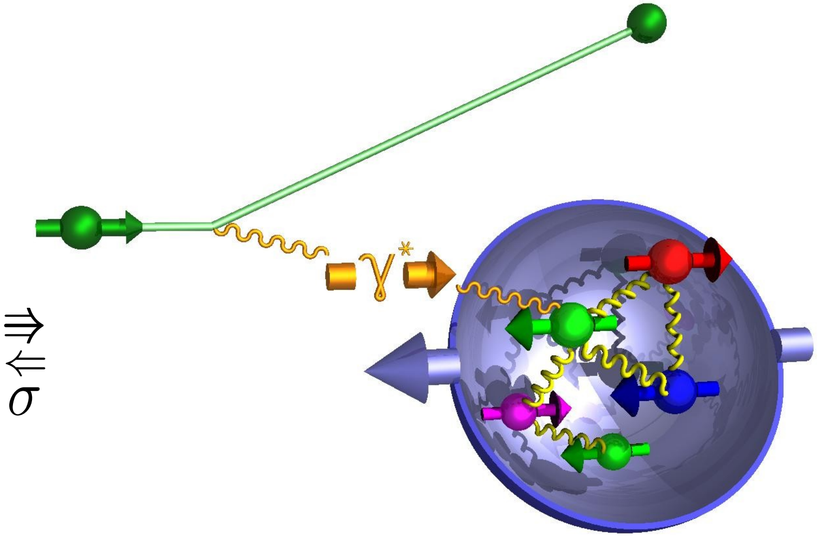
⇒ $\Delta\Sigma = 0.330 \pm \underset{\text{(exp.)}}{0.025} \pm \underset{\text{(theor.)}}{0.011} \pm \underset{\text{(evol.)}}{0.028}$

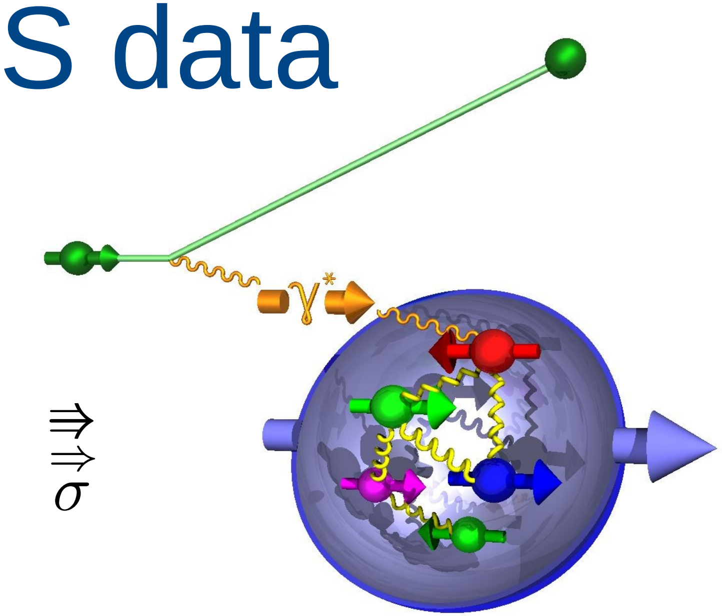
Spin Puzzle

Where is the other 70%?

Quark spin contribution from HERMES data



$\overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}}$



$\overset{\Rrightarrow}{\overset{\Rightarrow}{\sigma}}$

photon spin

proton spin

$$A_1 \simeq \frac{\overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}} - \overset{\Rrightarrow}{\overset{\Rightarrow}{\sigma}}}{\overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}} + \overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}}}$$

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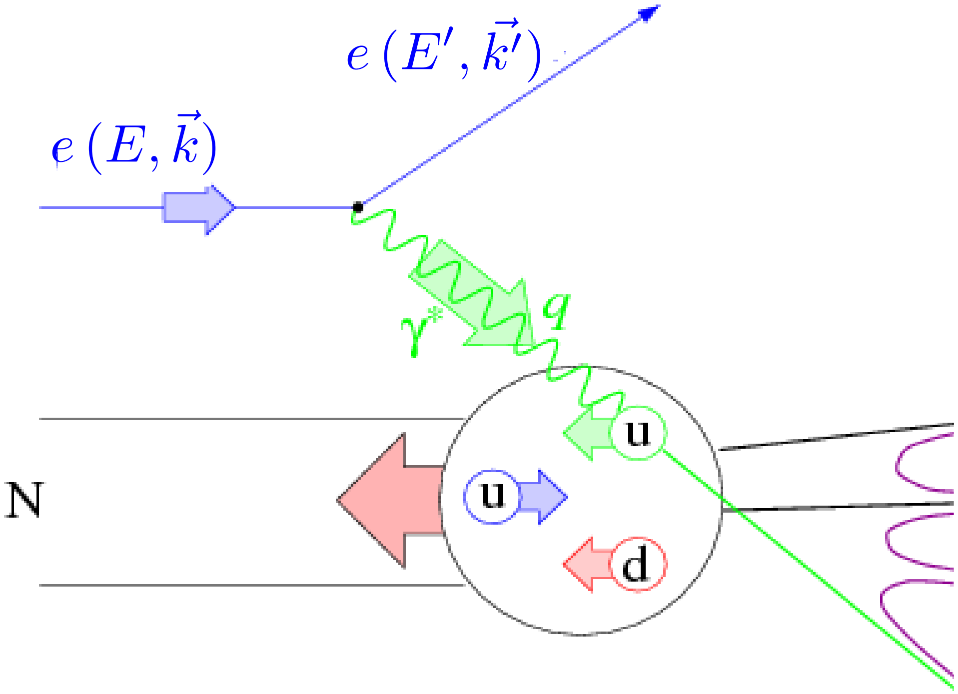
Spin Puzzle

gluon spin?
orbital angular momentum?

Tagging the quark flavor

inclusive deep-inelastic scattering



$$Q^2 \equiv -q^2$$

$$\nu \equiv \frac{Pq}{M} \overset{lab}{=} E - E'$$

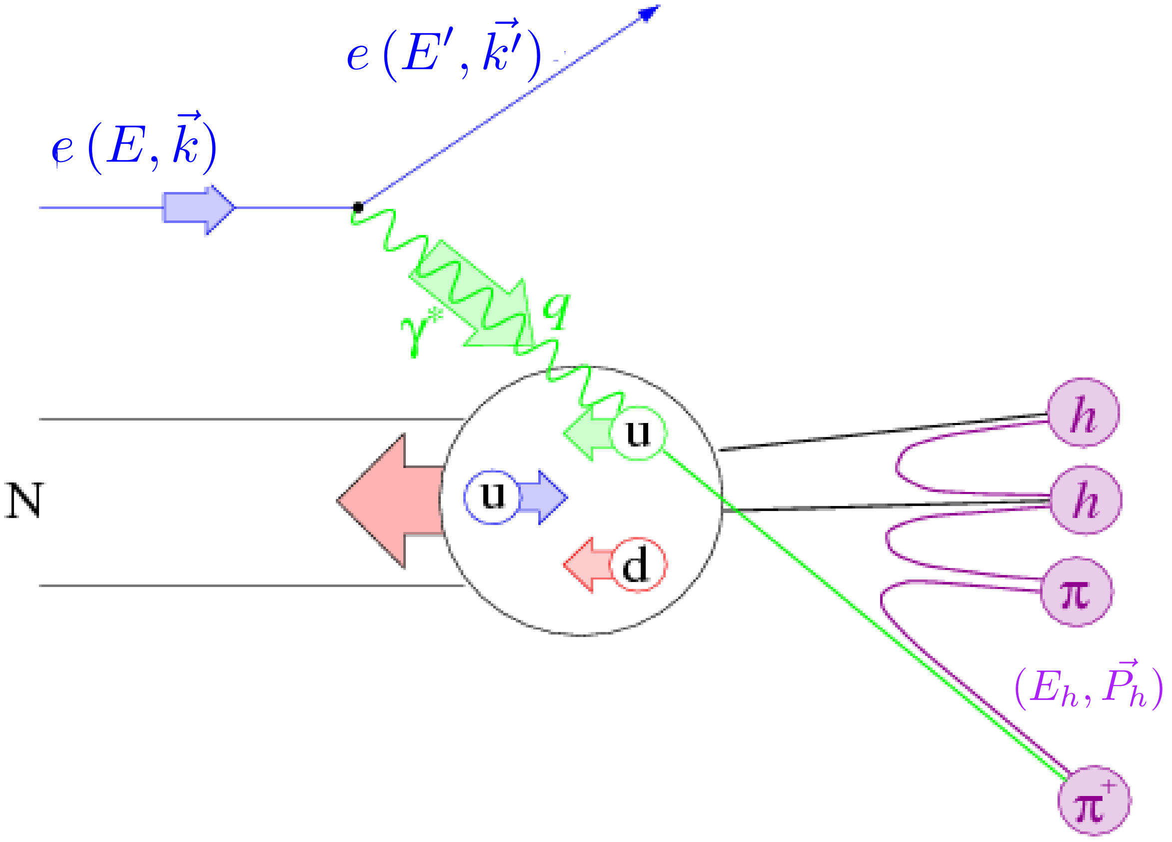
$$y \equiv \frac{Pq}{Pk} \overset{lab}{=} \frac{\nu}{E}$$

$$W^2 \equiv M^2 + 2M\nu - Q^2$$

$$x_B \equiv \frac{Q^2}{2Pq}$$

Tagging the quark flavor

semi-inclusive deep-inelastic scattering



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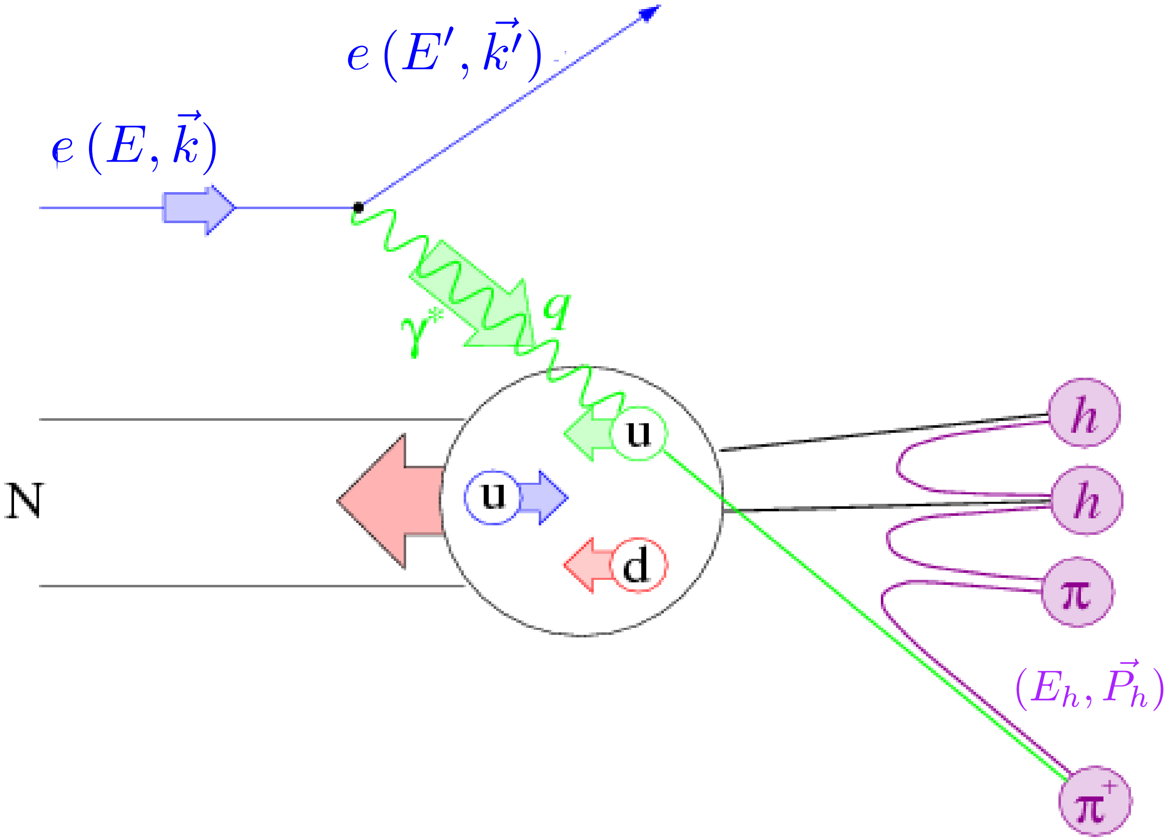
$$x_B \equiv \frac{Q^2}{2Pq}$$

$$z \equiv \frac{PP_h}{Pq} \overset{lab}{=} \frac{E_h}{\nu}$$

$$P_{h\perp} = \frac{|\vec{q} \times \vec{P}_h|}{|\vec{q}|}$$

Tagging the quark flavor

semi-inclusive deep-inelastic scattering



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$$P_{h\perp} = \frac{|\vec{q} \times \vec{P}_h|}{|\vec{q}|}$$

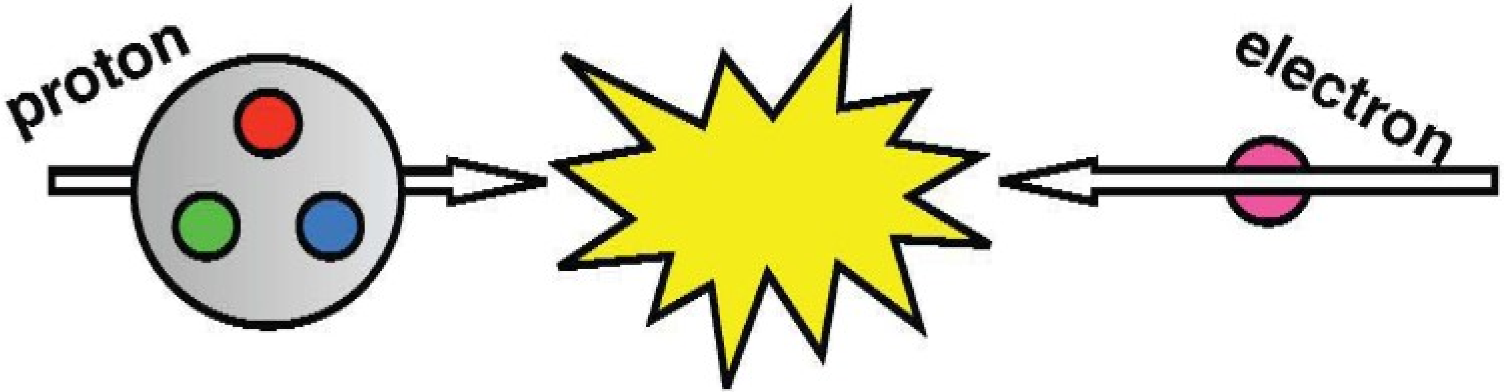
$$\sigma^{ep\to eh} = \sum_q DF^{p\to q}(x_B, p_T^2, Q^2) \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}(z, k_T^2, Q^2)$$

distribution function (DF):
distribution of quarks in nucleon
p_T : transverse momentum of struck quark

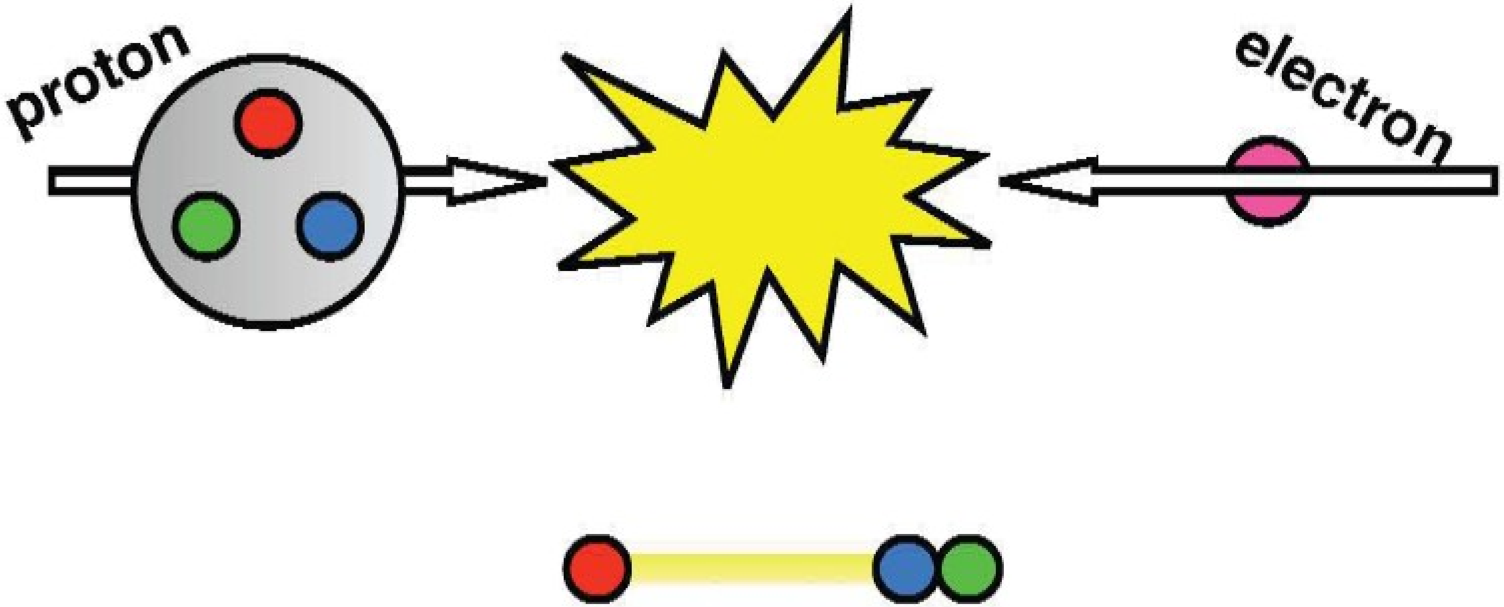
fragmentation function (FF): fragmentation of struck quark into final-state hadron
k_T : transverse momentum of fragmenting quark

Fragmentation

Fragmentation



Fragmentation



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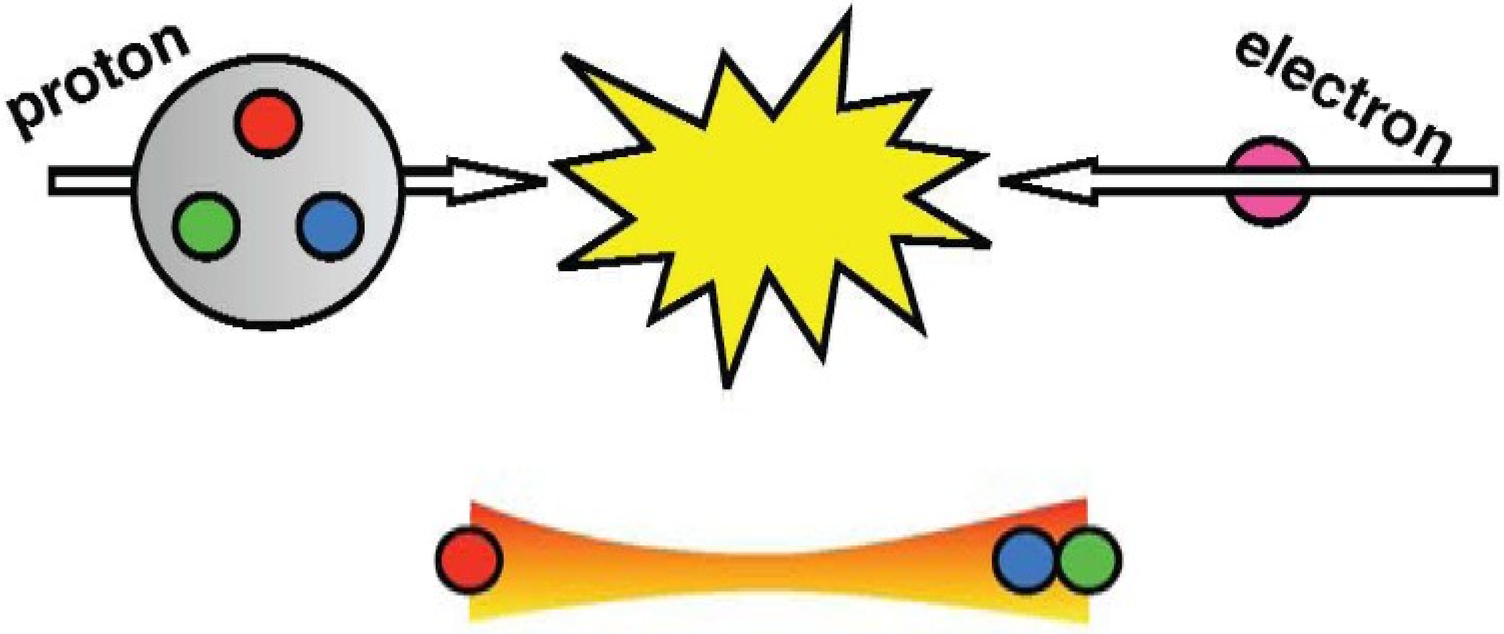
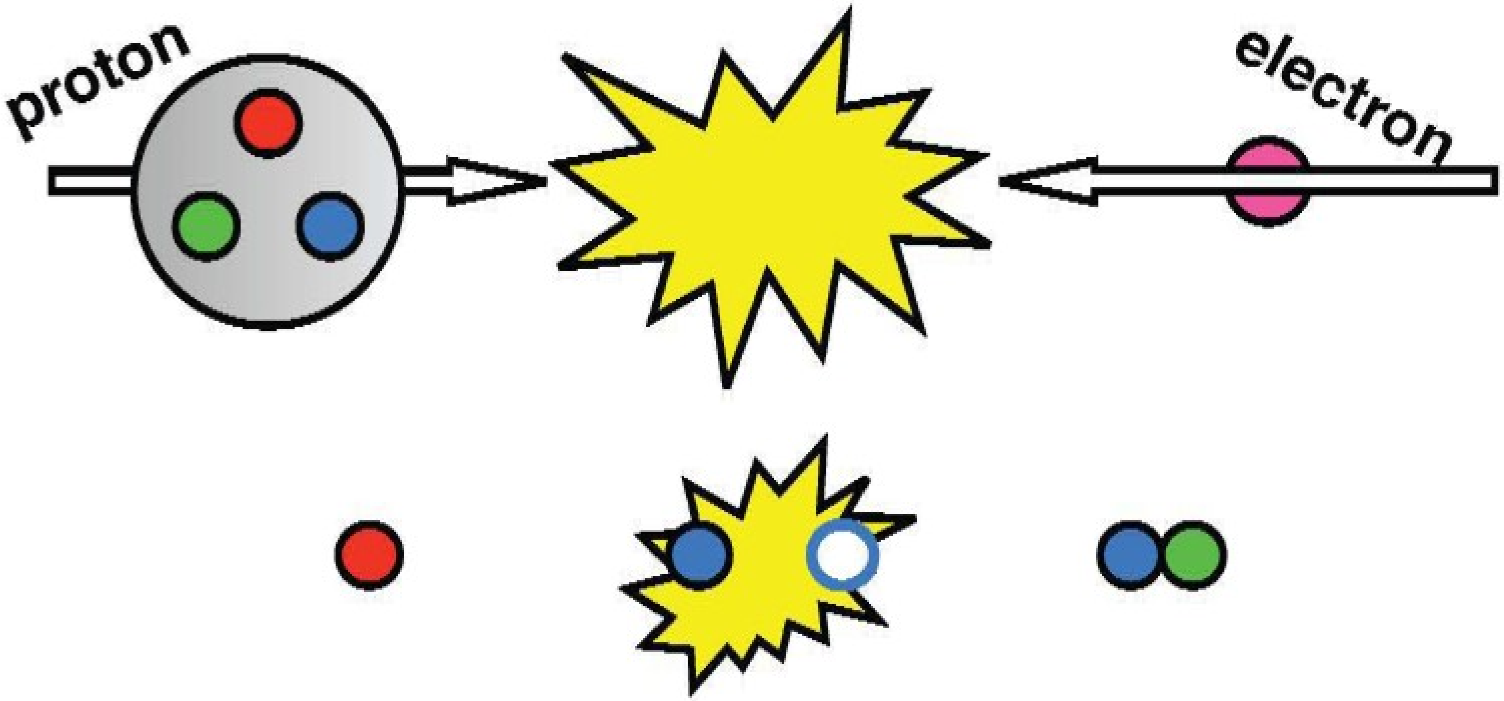
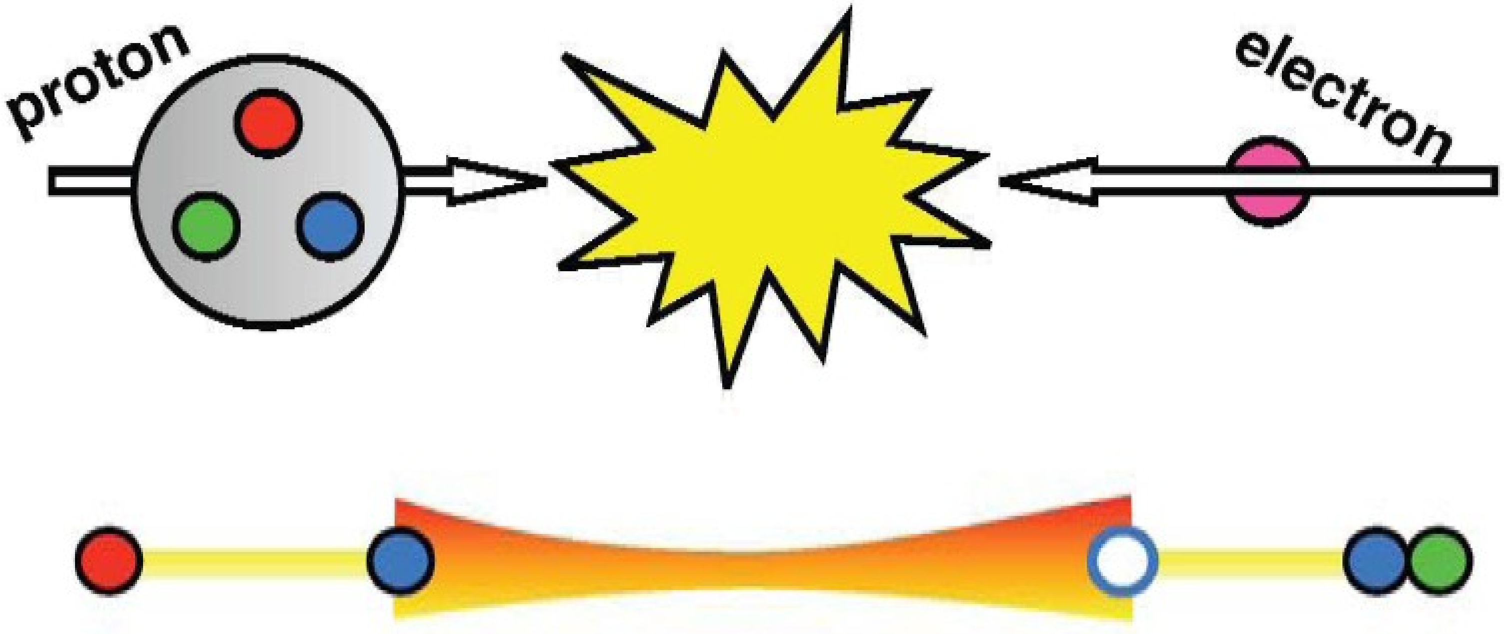


Fragmentation



Fragmentation



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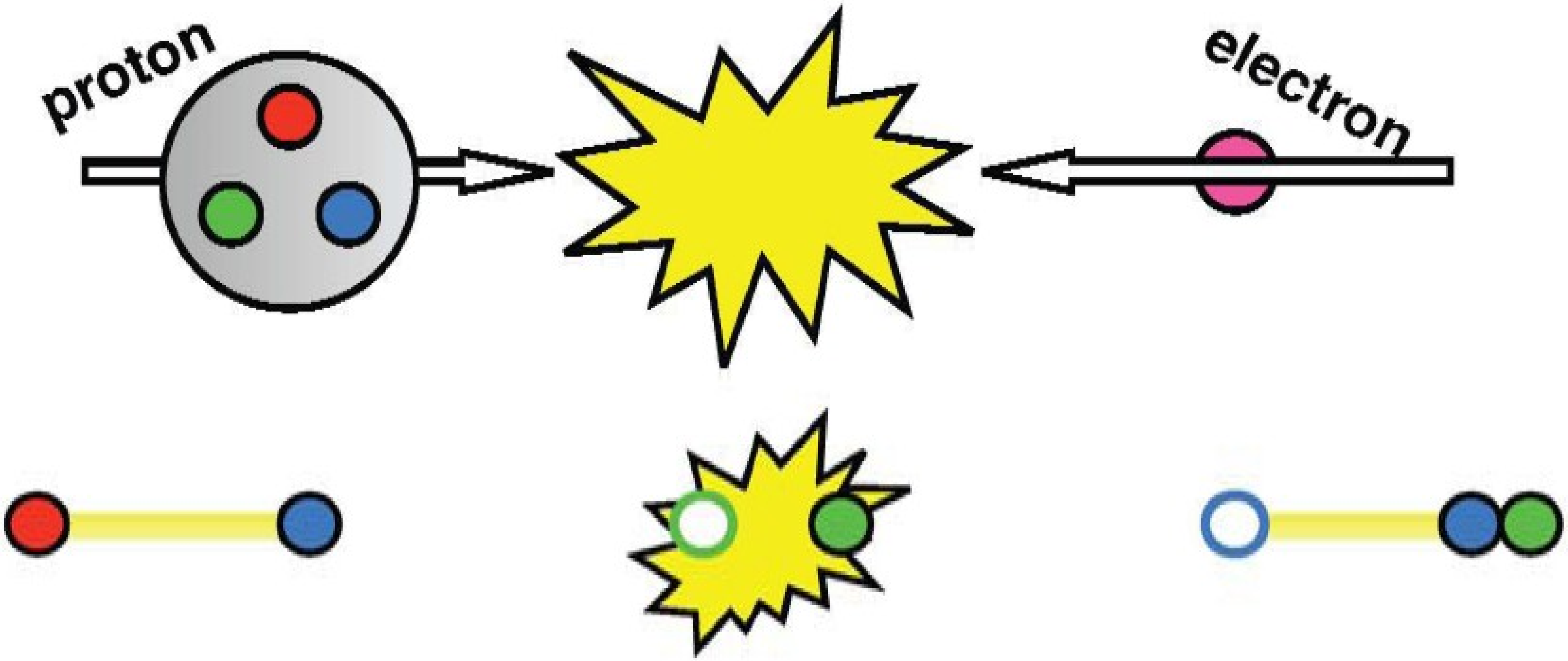
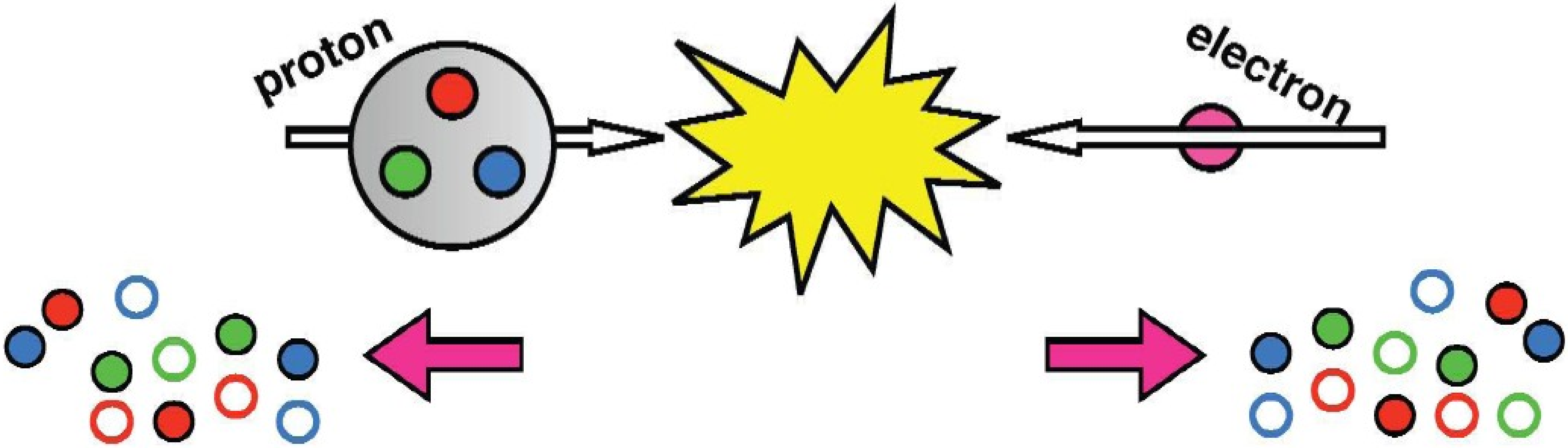


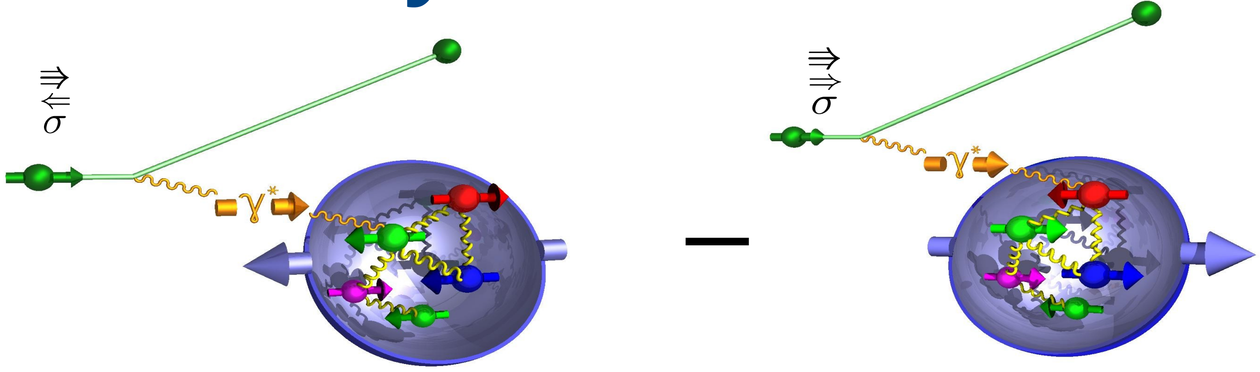
Fragmentation



Quark helicity distribution

$$A_1^h \simeq \frac{\overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}} - \overset{\Rrightarrow}{\overset{\Rightarrow}{\sigma}}}{\overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}} + \overset{\Rrightarrow}{\overset{\Leftarrow}{\sigma}}}$$

$$\propto \sum_q e_q^2 \, \Delta q(x_B, Q^2) \, D_q^h(z, Q^2)$$



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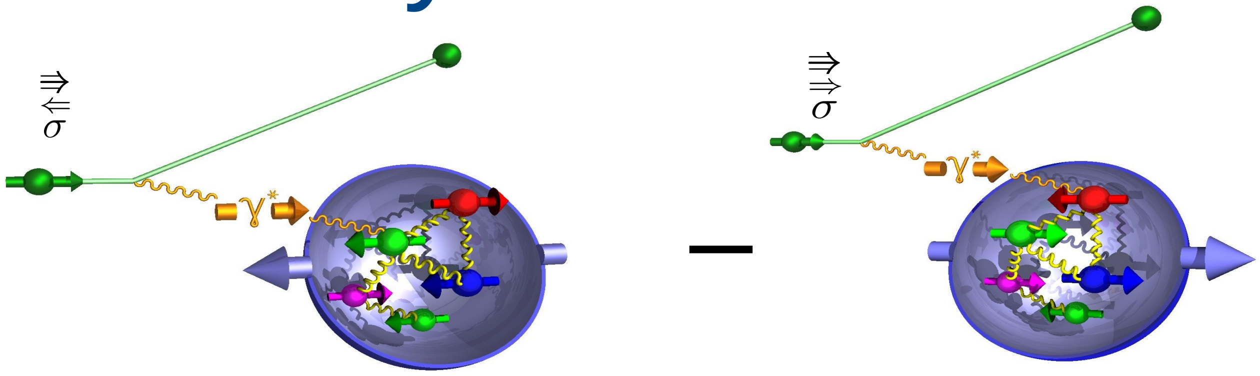
proportional to square
of quark electric charge



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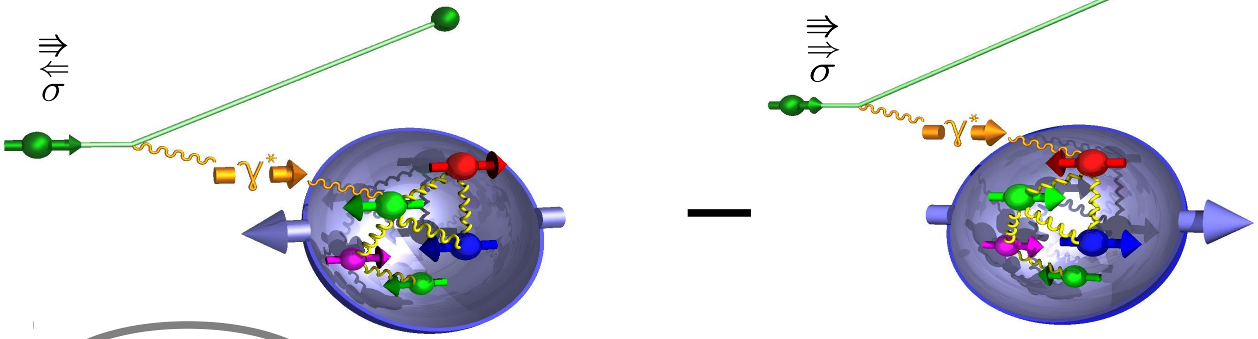

proportional to square
of quark electric charge

favored fragmentation

$u \rightarrow \pi^+ = |u\bar{d}>$

$d \rightarrow \pi^- = |\bar{u}d>$

unfavored fragmentation

$d \rightarrow \pi^+ = |u\bar{d}>$

$u \rightarrow \pi^- = |\bar{u}d>$

Quark helicity distribution

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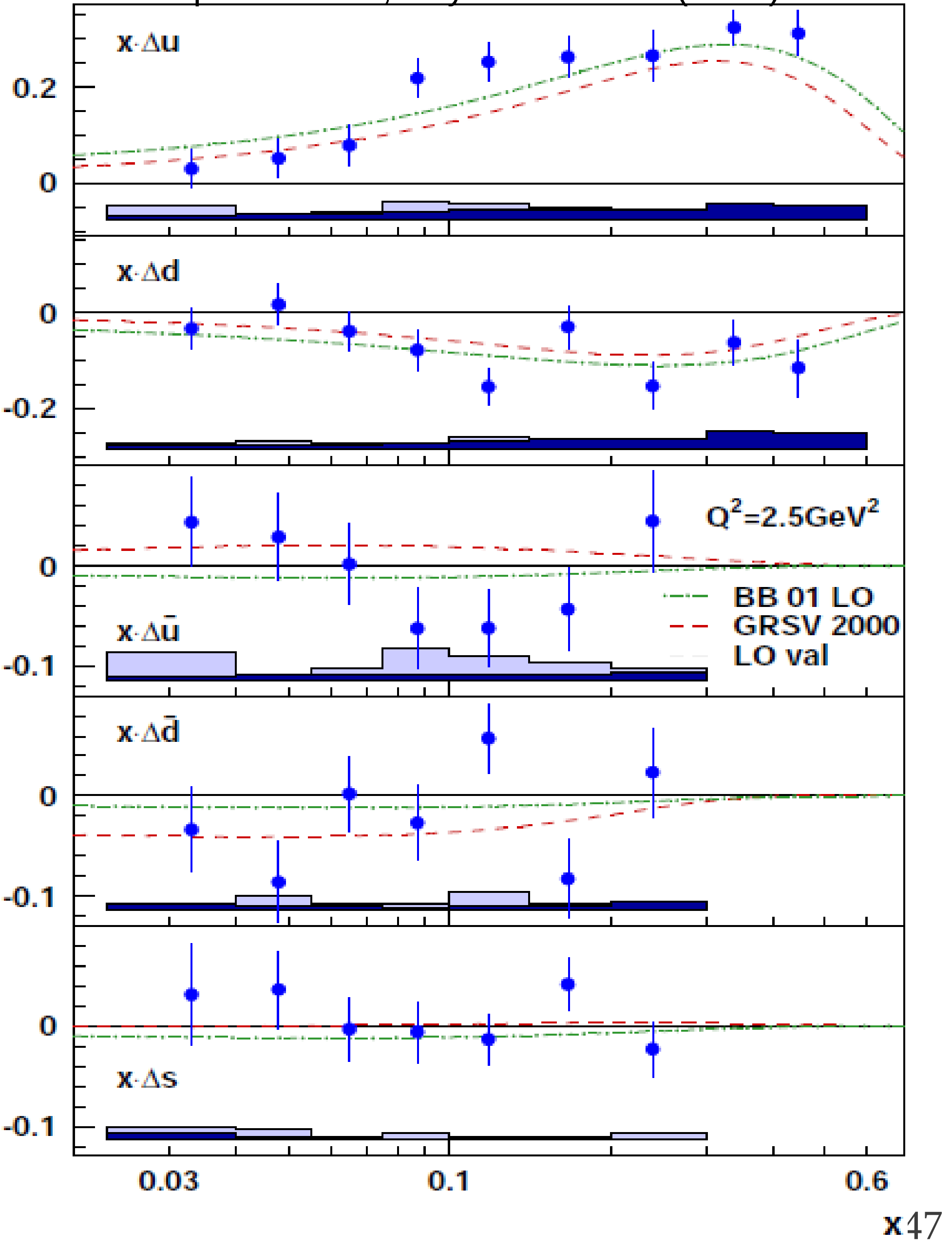
A. Airapetian et al., Phys. Rev. Lett. **92** (2004) 012005
A. Airapetian et al., Phys. Rev. D **71** (2005) 012003

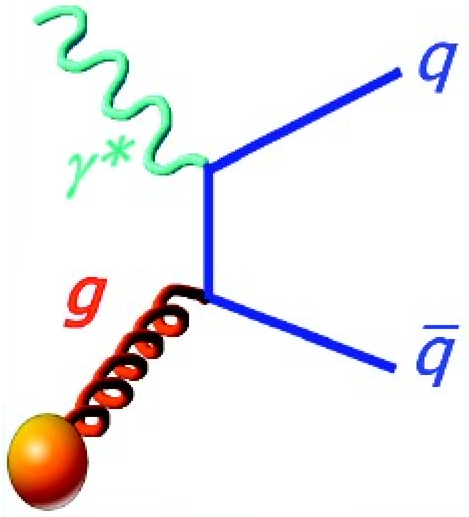


Gluon helicity distribution

$$A_1^h \simeq \frac{\overset{\overset{\Rrightarrow}{\Leftarrow}}{\sigma} - \overset{\overset{\Rrightarrow}{\Rrightarrow}}{\sigma}}{\overset{\overset{\Rrightarrow}{\Leftarrow}}{\sigma} + \overset{\overset{\Rrightarrow}{\Leftarrow}}{\sigma}}$$

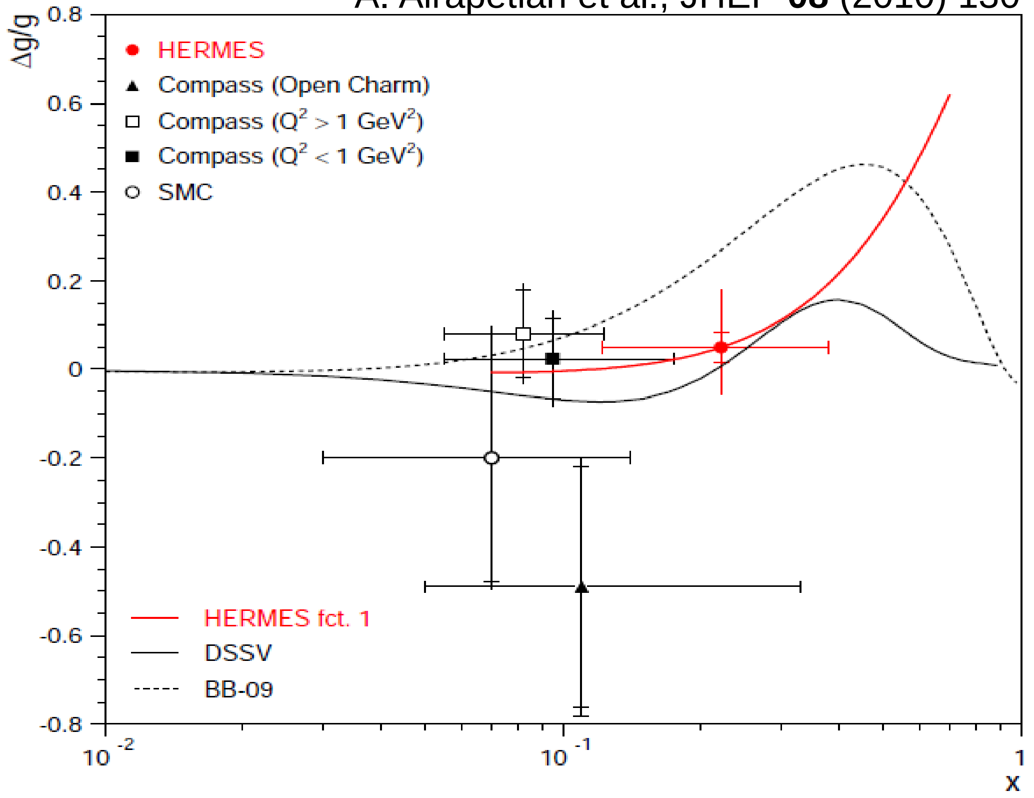
$$\propto \frac{\Delta g(x_B, Q^2)}{g(x_B, Q^2)}$$

select high-$\mathrm{P}_{h\perp}$ hadrons



photon-gluon fusion

A. Airapetian et al., JHEP **08** (2010) 130



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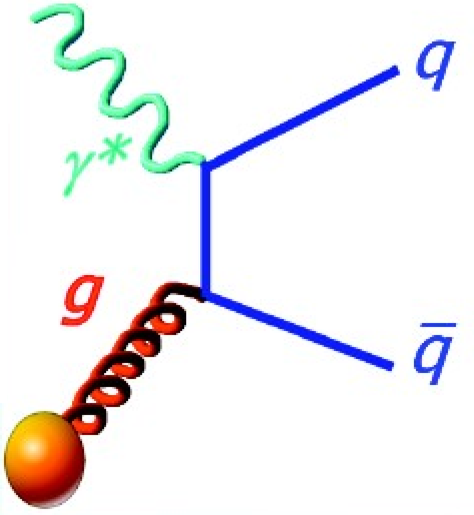

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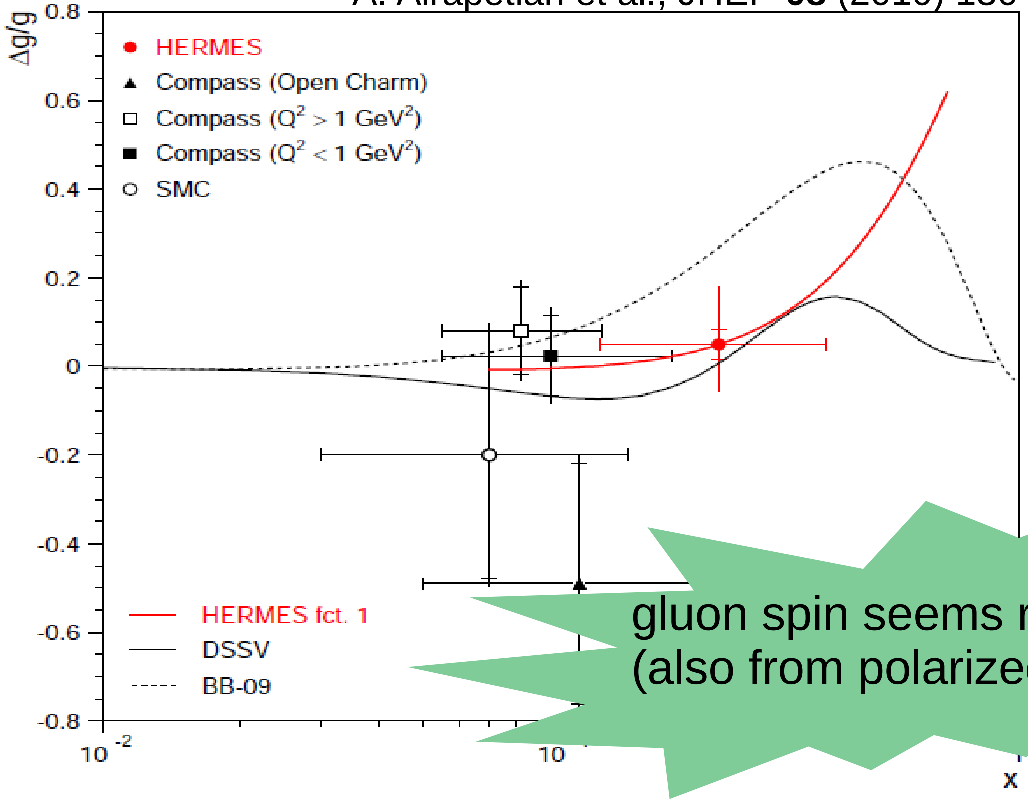
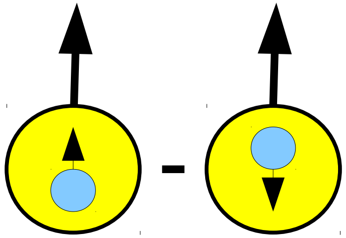


gluon spin seems rather small
(also from polarized pp data)

Transversity

$h_{1T}^{q}(x, p_T^2) =$



Transversity

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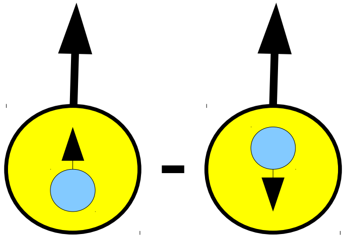
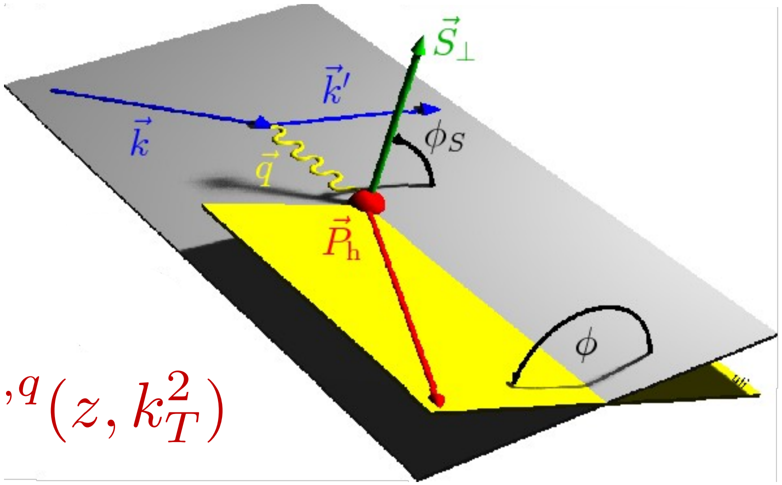


access through single-spin asymmetry on transversely polarized target

$$A_{UT} = \frac{1}{\langle|S_T|\rangle}\frac{N^\uparrow(\phi,\phi_S)-N^\downarrow(\phi,\phi_S)}{N^\uparrow(\phi,\phi_S)+N^\downarrow(\phi,\phi_S)}$$

$$\sim \sin(\phi+\phi_S)\sum_q e_q^2 \frac{\vec{k}_T.\hat{P}_{h\perp}}{M_h} h_{1T}^q(x,p_T^2)\otimes H_1^{\perp,q}(z,k_T^2)$$

chiral-odd chiral-odd

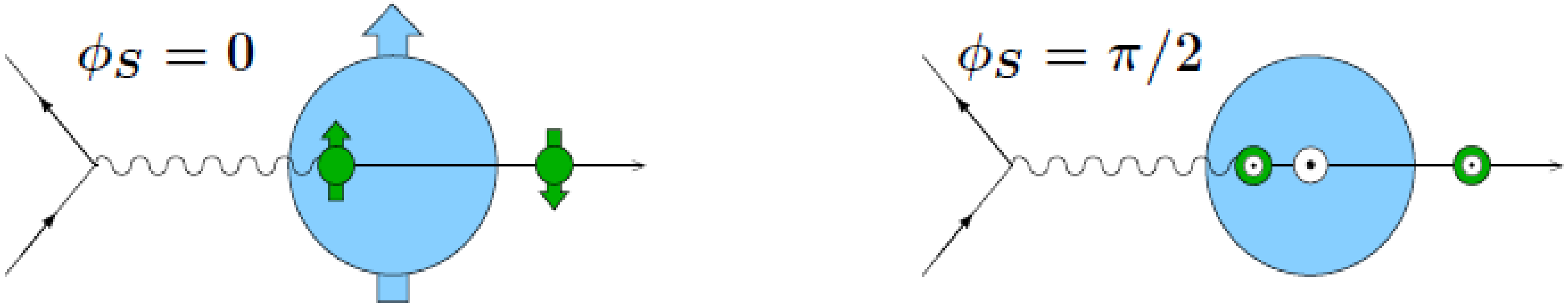


$H_1^{\perp,q}(z,k_T^2)$: **Collins fragmentation function**

fragmentation of a tranversely polarized quark into an unpolarized hadron

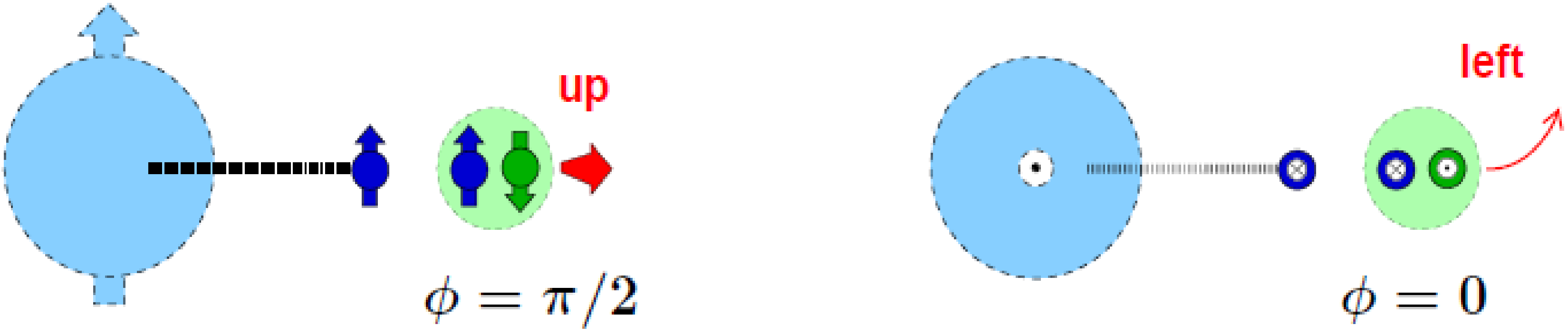
Collins fragmentation functions
Artru model

polarisation component in lepton scattering plane reversed by photoabsorption:



string break, quark-antiquark pair with vacuum numbers:

orbital angular momentum creates transverse momentum:

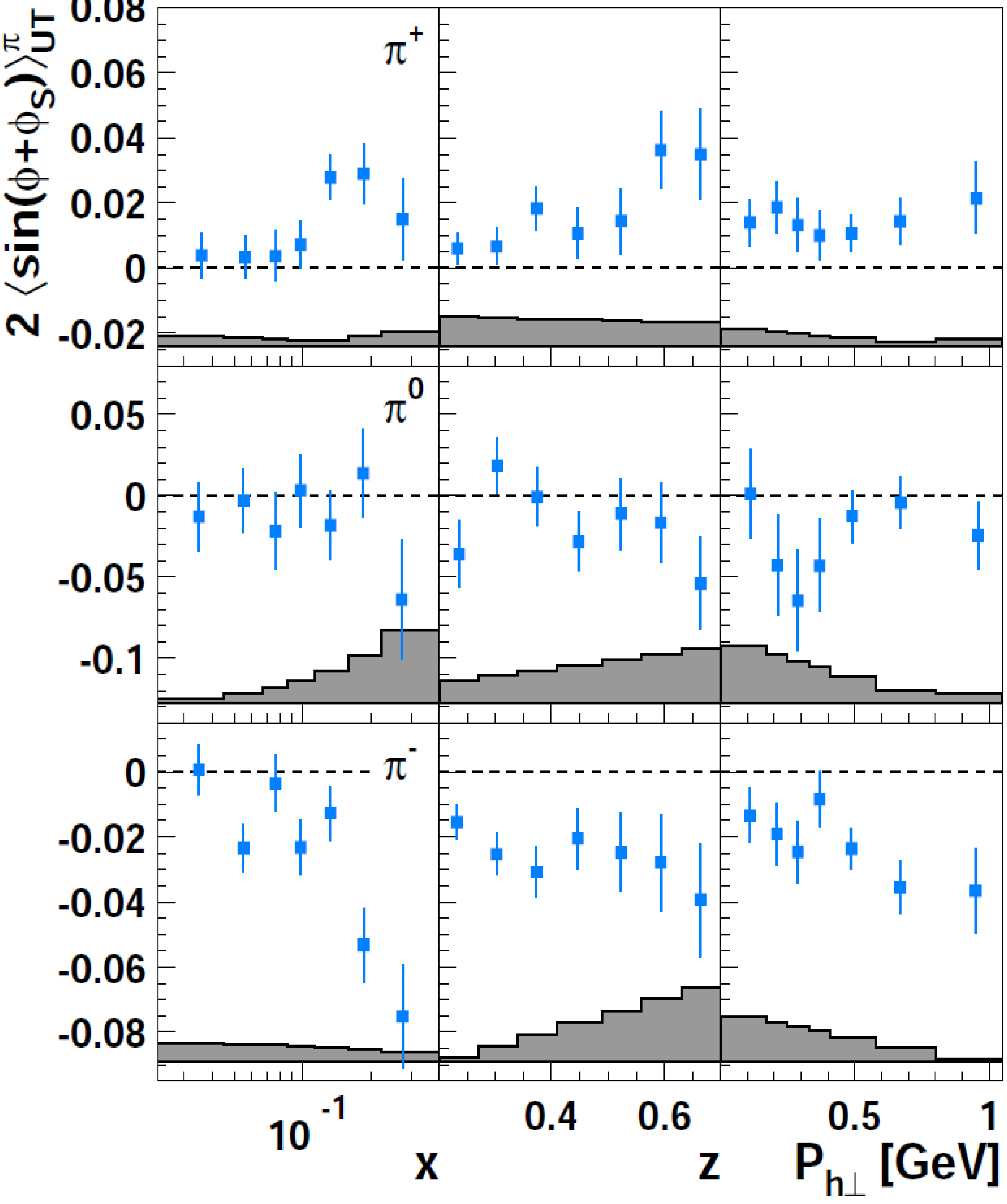


X. Artru et al. , Z. Phys. C**73** (1997) 527

courtesy from U. Elschenbroich

Collins amplitudes for pions

A. Airapetian et al., Phys. Lett. B**693** (2010) 11-16



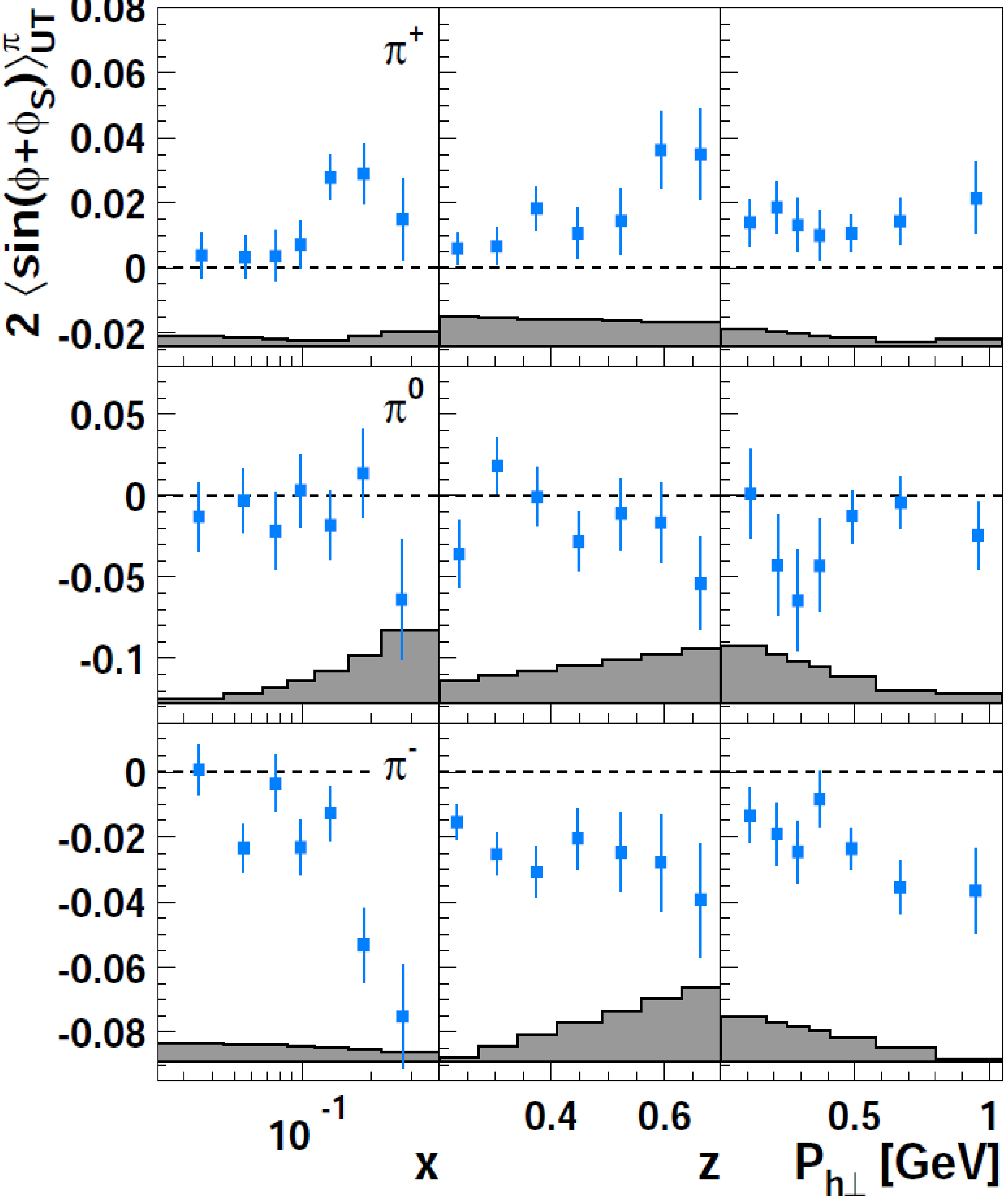
- $\pi^{\pm}$ increasing with z
- positive for π^+
- large & negative for π^-

$$H_1^{\perp,fav} \approx -H_1^{\perp,unfav}$$

- isospin symmetry fulfilled

Collins amplitudes for pions

A. Airapetian et al., Phys. Lett. B**693** (2010) 11-16

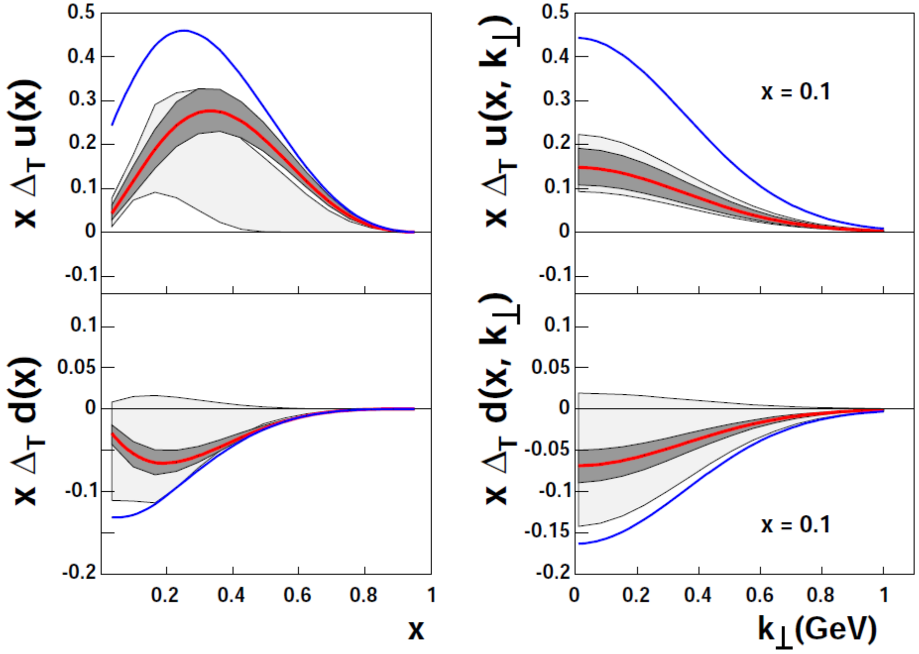


- $\pi^\pm$ increasing with z
- positive for π^+
- large & negative for π^-

$$H_1^{\perp,fav} \approx -H_1^{\perp,unfav}$$

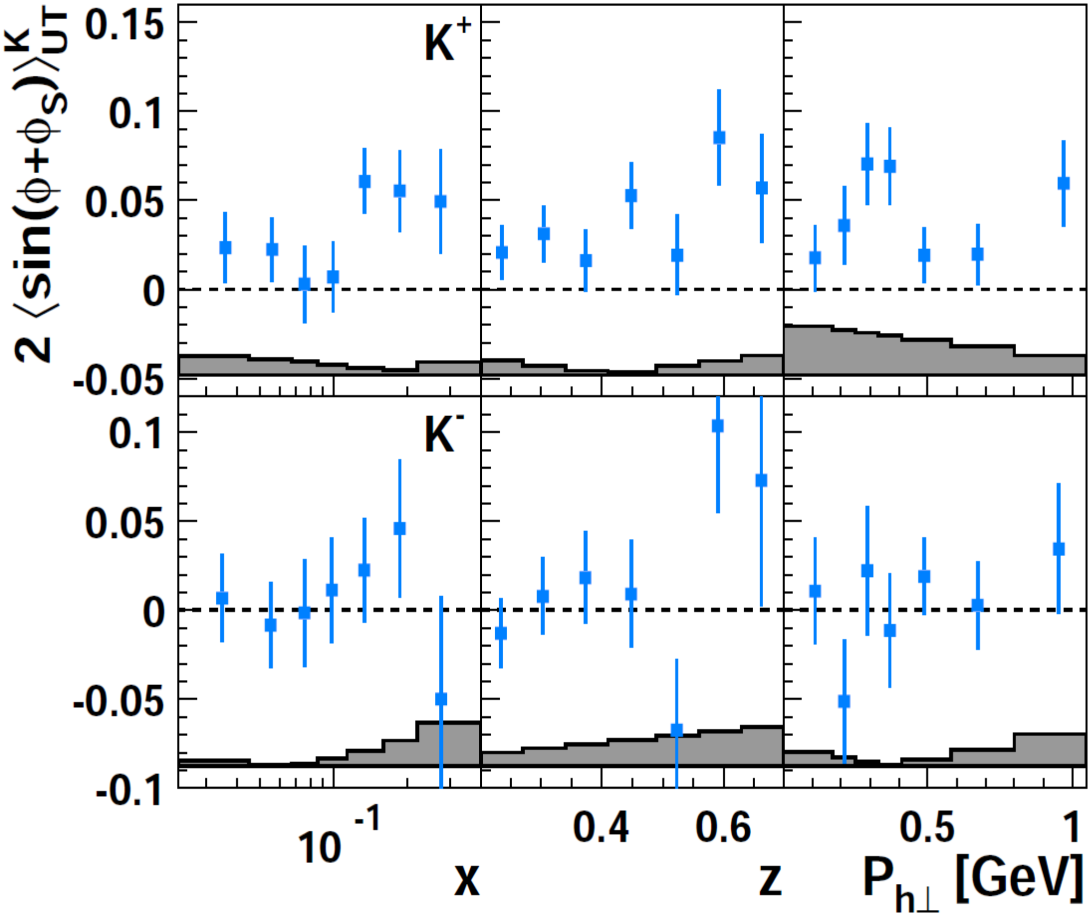
- isospin symmetry fulfilled
- data from BELLE, COMPASS & HERMES → extraction of h_{1T}

Anselmino et al., arXiv: 0807.0173



Collins amplitudes for kaons

A. Airapetian et al., Phys. Lett. B**693** (2010) 11-16



- K^+: increasing with z
- positive for K^+ & larger than for π^+
  - role of s-quark
  - u-dominance $\xrightarrow{?}$

$$H_1^{\perp,u\to K^+} > H_1^{\perp,u\to\pi^+}$$

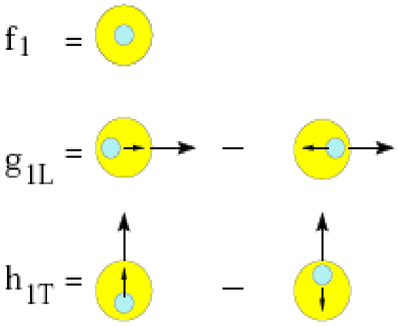
- $K^- \approx 0$, $\neq$ from π^-

  K^- is pure sea object:
- sea-quark transversity expected to be small

Transverse-momentum-dependent distributions

<u>Distribution functions</u>

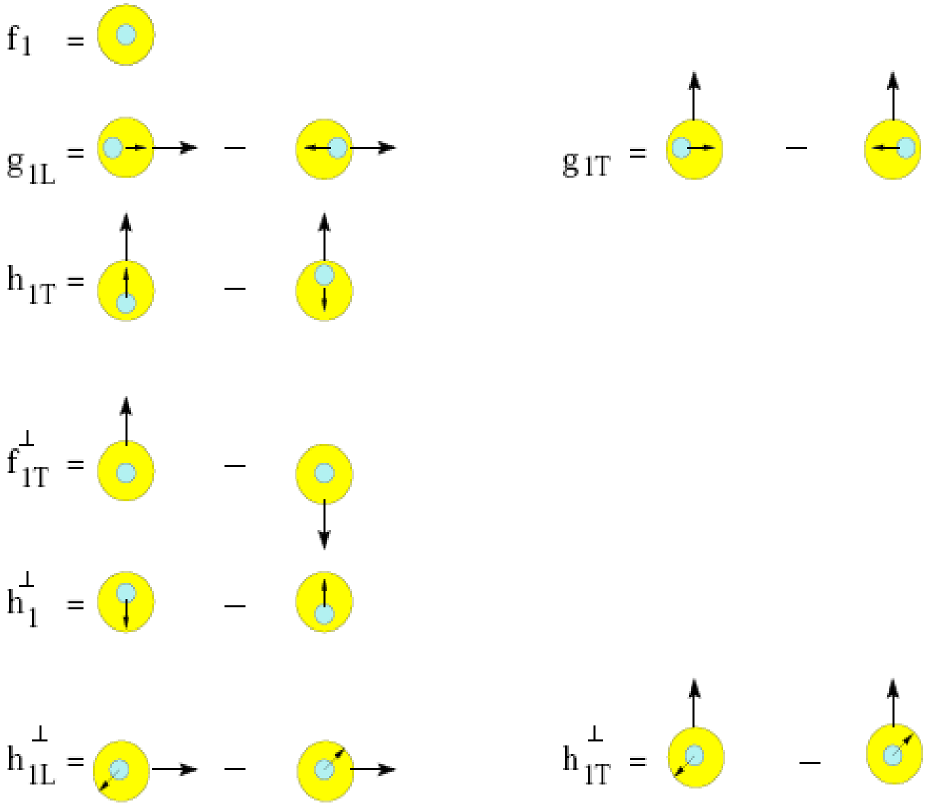
leading twist



Transverse-momentum-dependent distributions

Distribution functions

leading twist



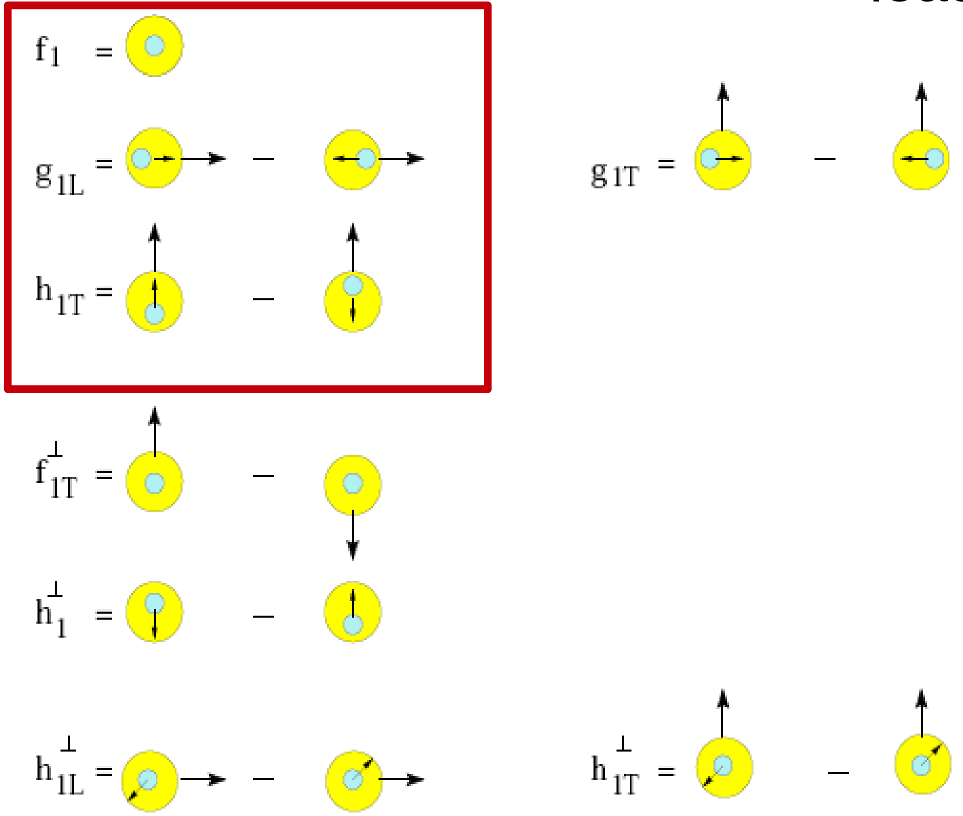
the eight leading-twist transverse-momenum-dependent parton distribution functions describing the DIS cross section for hadron production

.

Transverse-momentum-dependent distributions

Distribution functions

leading twist



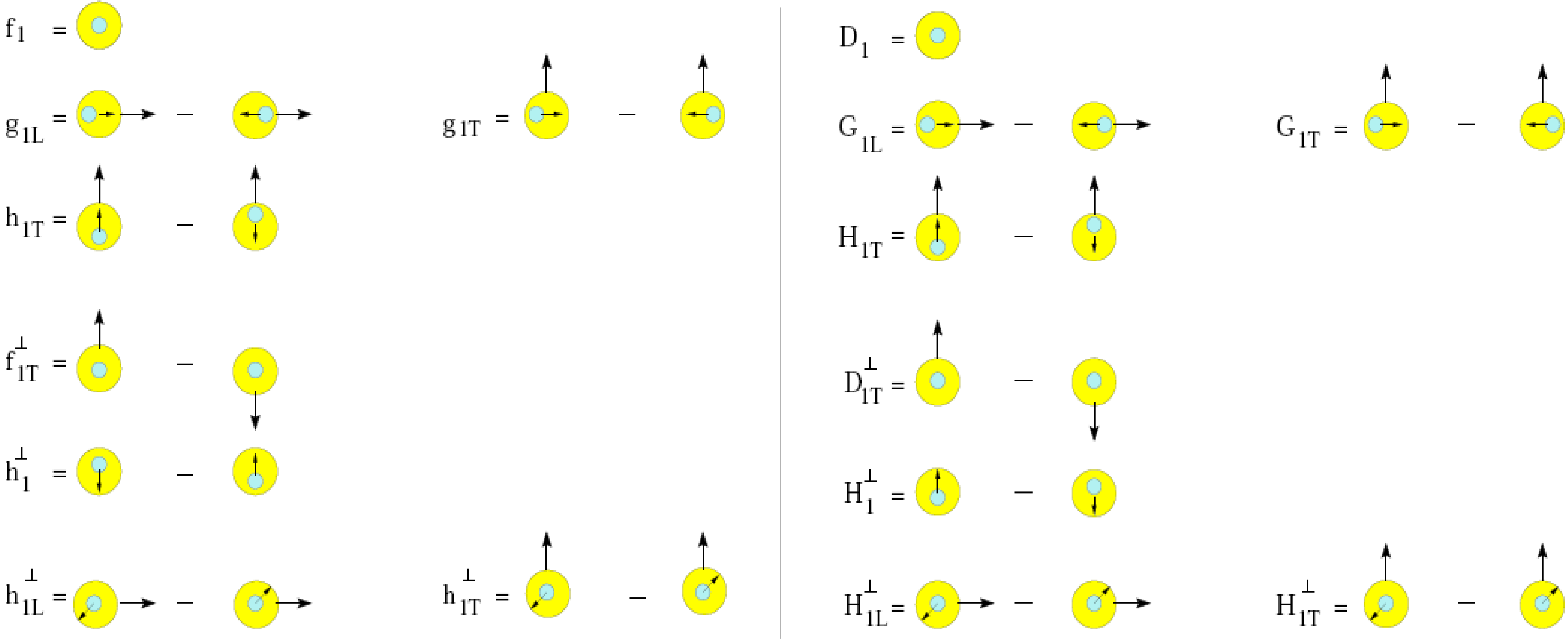
only distribution functions that survive integration over transverse momentum

Transverse-momentum-dependent distributions

Distribution functions

leading twist

Fragmentation functions

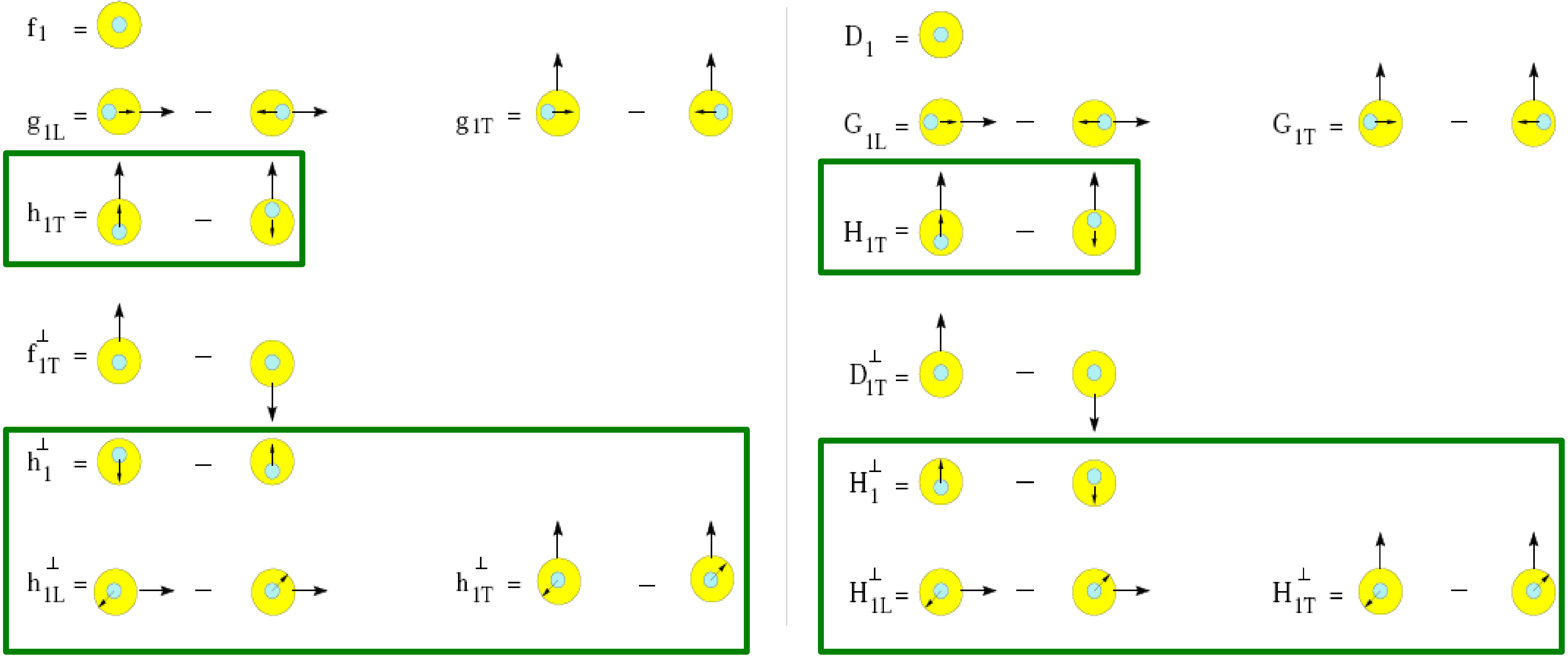


Transverse-momentum-dependent distributions

Distribution functions

leading twist

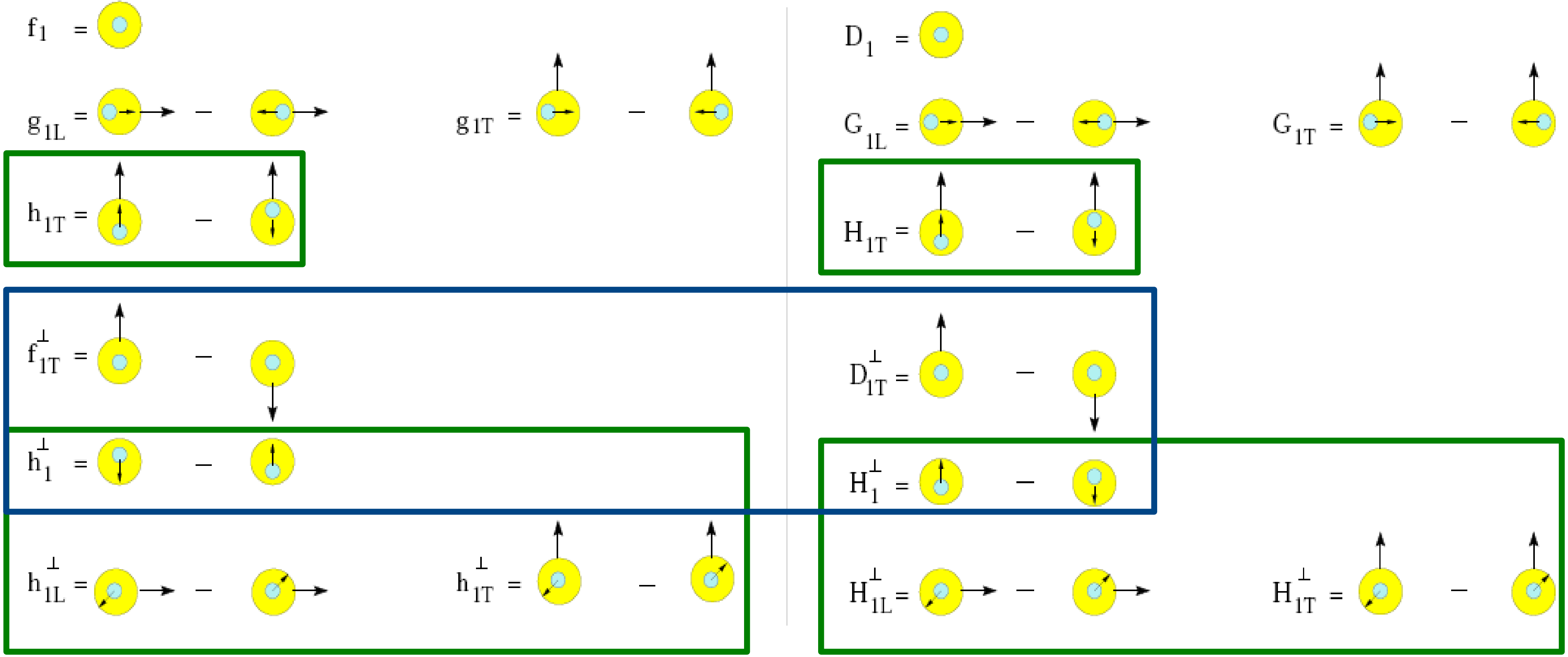
Fragmentation functions



chiral odd: involve helicity flip of quark → appear in pairs in cross section

Transverse-momentum-dependent distributions

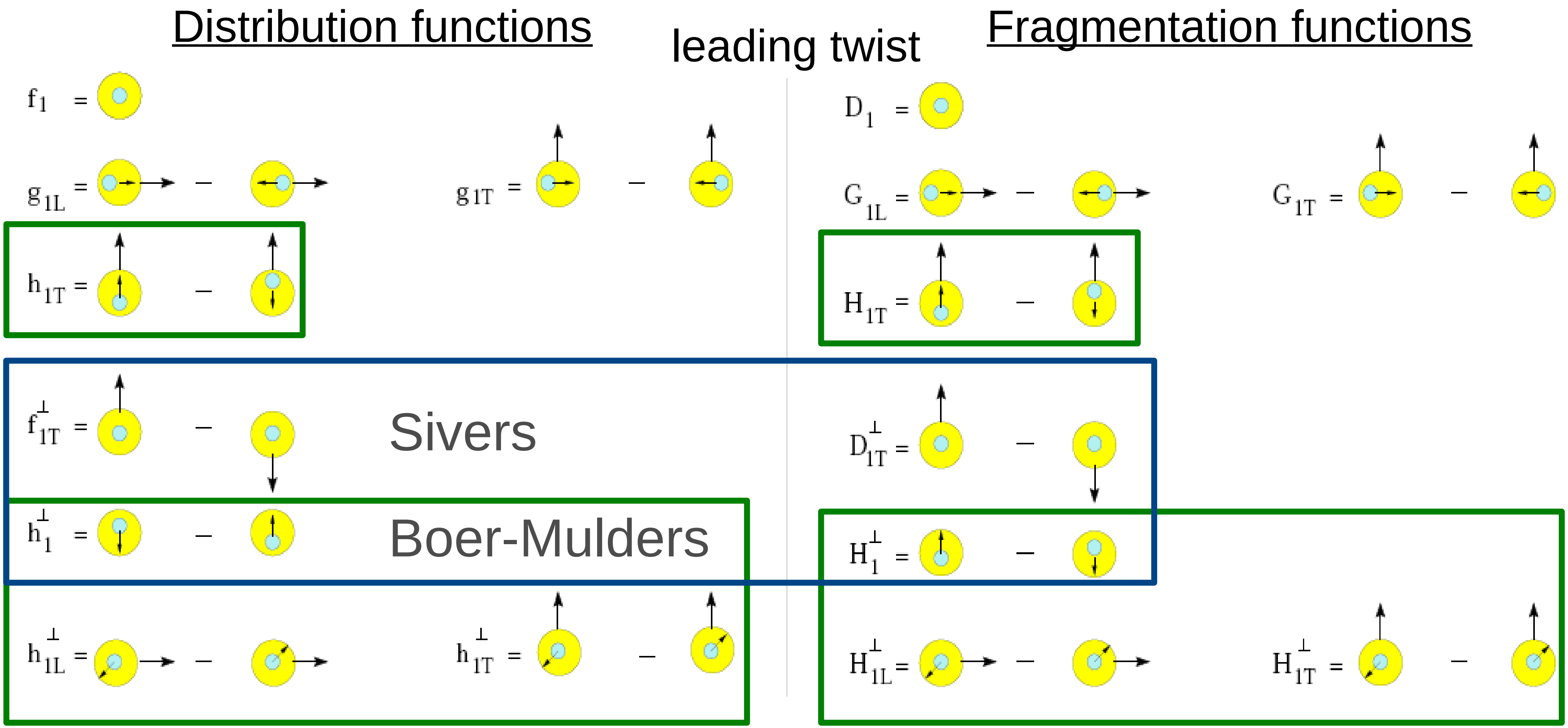
Distribution functions leading twist Fragmentation functions



chiral odd: involve helicity flip of quark → appear in pairs in cross section

T-odd: appear in pairs in spin-independent x-section & double-spin asymmetries
single in single-spin asymmetries

Transverse-momentum-dependent distributions



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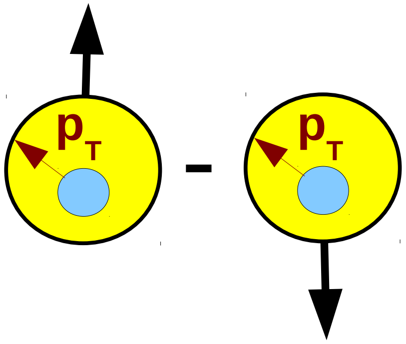
Sivers distribution function

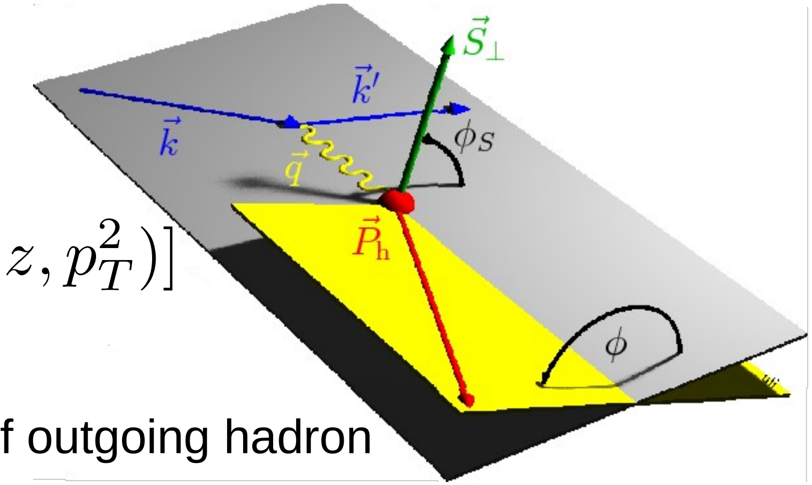
$f_{1T}^{\perp}{}^{q}(x, p_T^2) =$



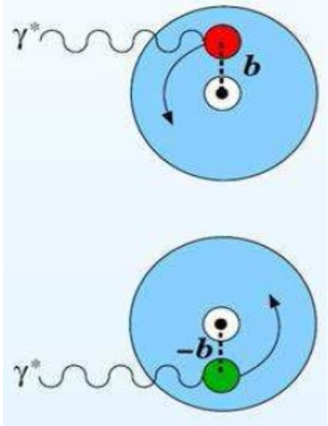
access through single-spin asymmetry on transversely polarized target

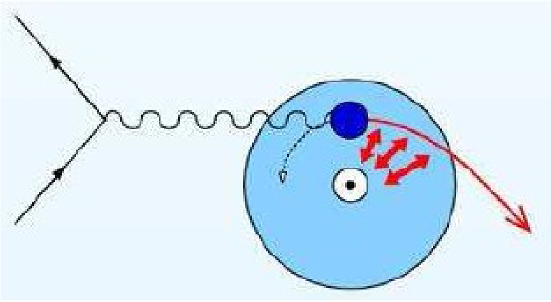
$$A_{UT} = \frac{1}{\langle|S_T|\rangle} \frac{N^{\uparrow}(\phi,\phi_S) - N^{\downarrow}(\phi,\phi_S)}{N^{\uparrow}(\phi,\phi_S) + N^{\downarrow}(\phi,\phi_S)}$$

$$\sim \sin(\phi - \phi_S) \sum_q e_q \mathcal{I}[\frac{\vec{k}_T.\hat{P}_{h\perp}}{M_h} f_{1T}^{\perp,q}(x, k_T^2) D_1^q(z, p_T^2)]$$



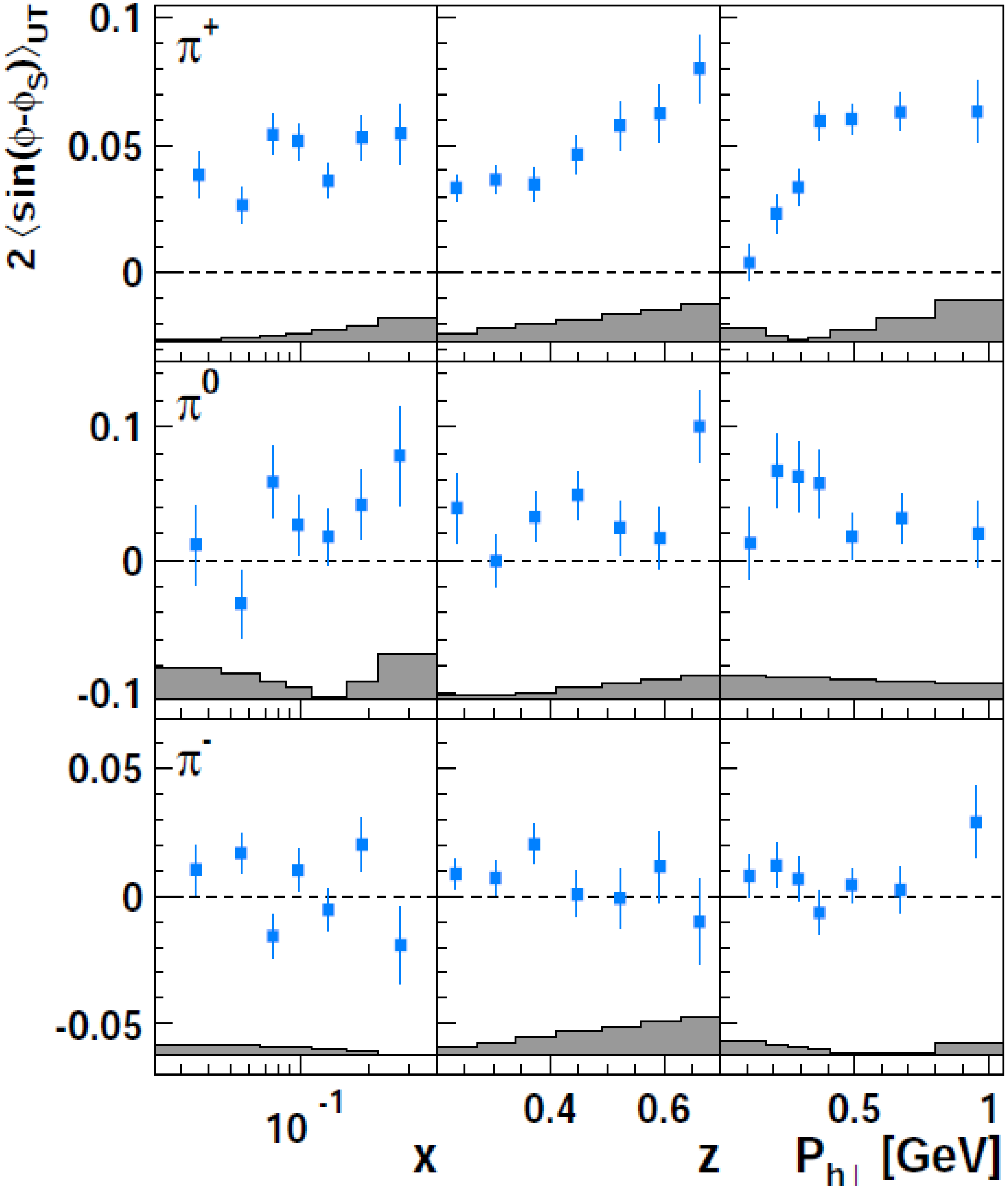
- requires non-zero quark orbital angular momentum
- FSI → left-right (azimuthal) asymmetry in direction of outgoing hadron





Sivers amplitude for pions

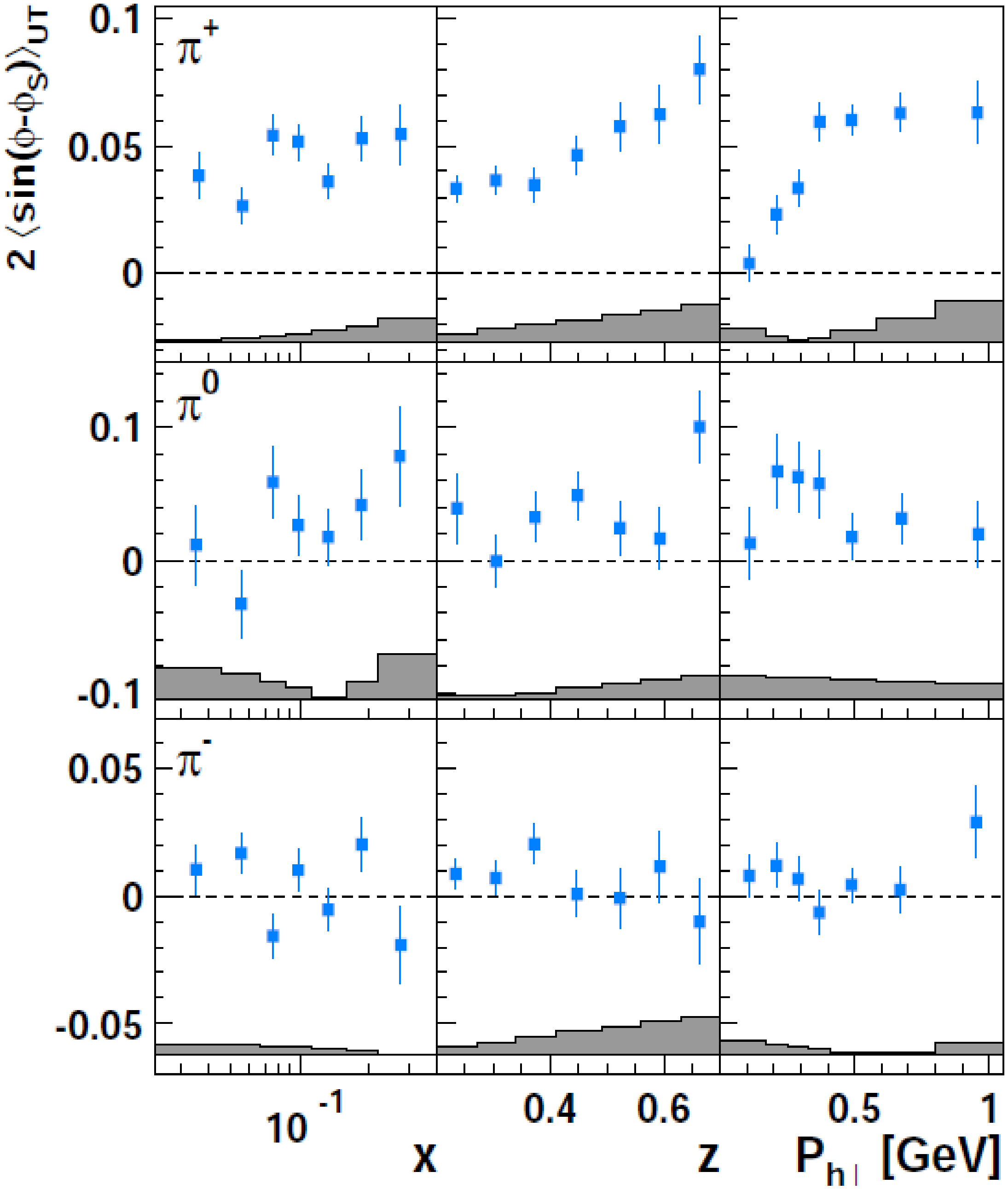
A. Airapetian et al., Phys. Rev. Lett. **103** (2009) 152002



- π^+
  - significantly positive

non-zero orbital angular momentum!

Sivers amplitude for pions



A. Airapetian et al., Phys. Rev. Lett. **103** (2009) 152002

- π^+
  - significantly positive
  - clear rise with z
  - rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
  - amplitude dominated by u-quark scattering:

non-zero orbital angular momentum!

$$\approx -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

→ $f_{1T}^{\perp,u}(x,p_T^2) < 0$

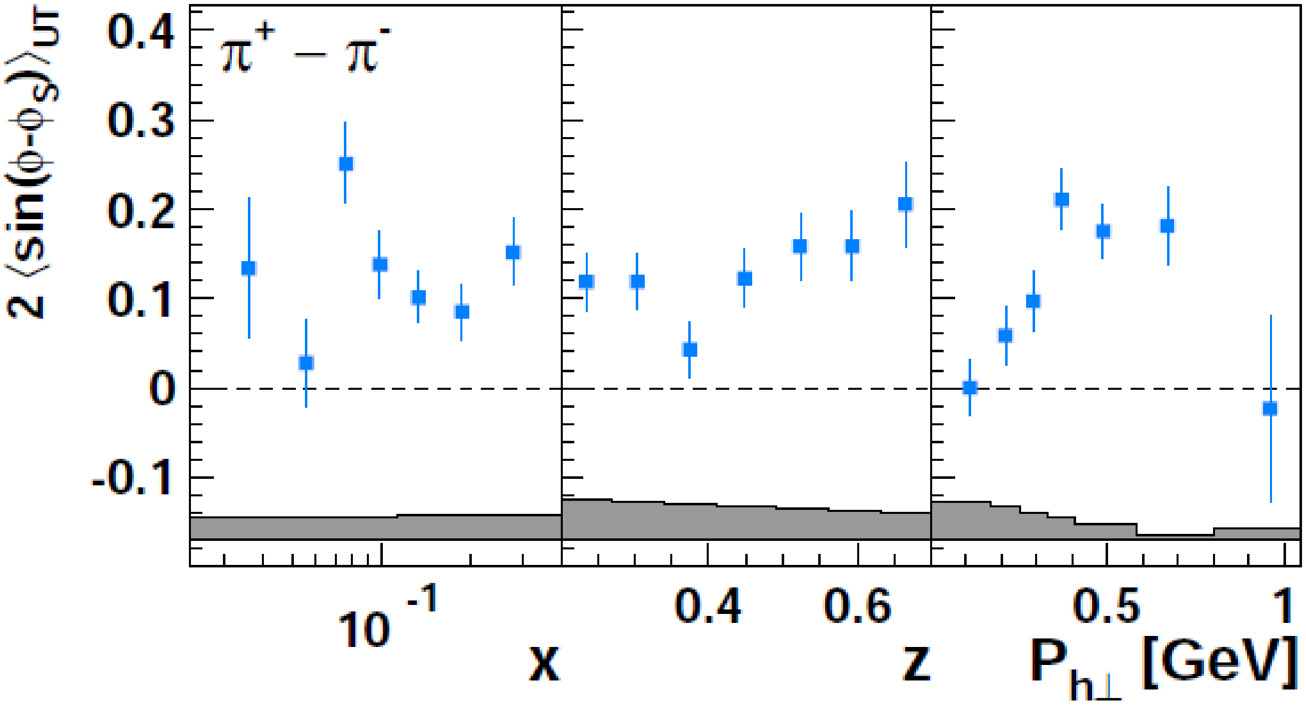
- π^-
  - consistent with zero
  - u- and d- quark cancellation
  - $f_{1T}^{\perp,d}(x,p_T^2) > 0$
- π^0
  - slightly positive
  - isospin symmetry fulfilled

Sivers distribution for valence quarks

$$A_{UT}^{\pi^+-\pi^-} = \frac{1}{\langle|S_T|\rangle} \frac{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) - (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) + (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}$$

→ suppressed exclusive VM (ρ^0) contribution

$$\longrightarrow \quad \langle\sin(\phi - \phi_S)\rangle_{UT}^{\pi^+-\pi^-} \approx -\frac{4f_{1T}^{\perp,u_v} - f_{1T}^{\perp,d_v}}{4f_1^{u_v} - f_1^{d_v}}$$


A. Airapetian et al., Phys. Rev. Lett. **103** (2009) 152002

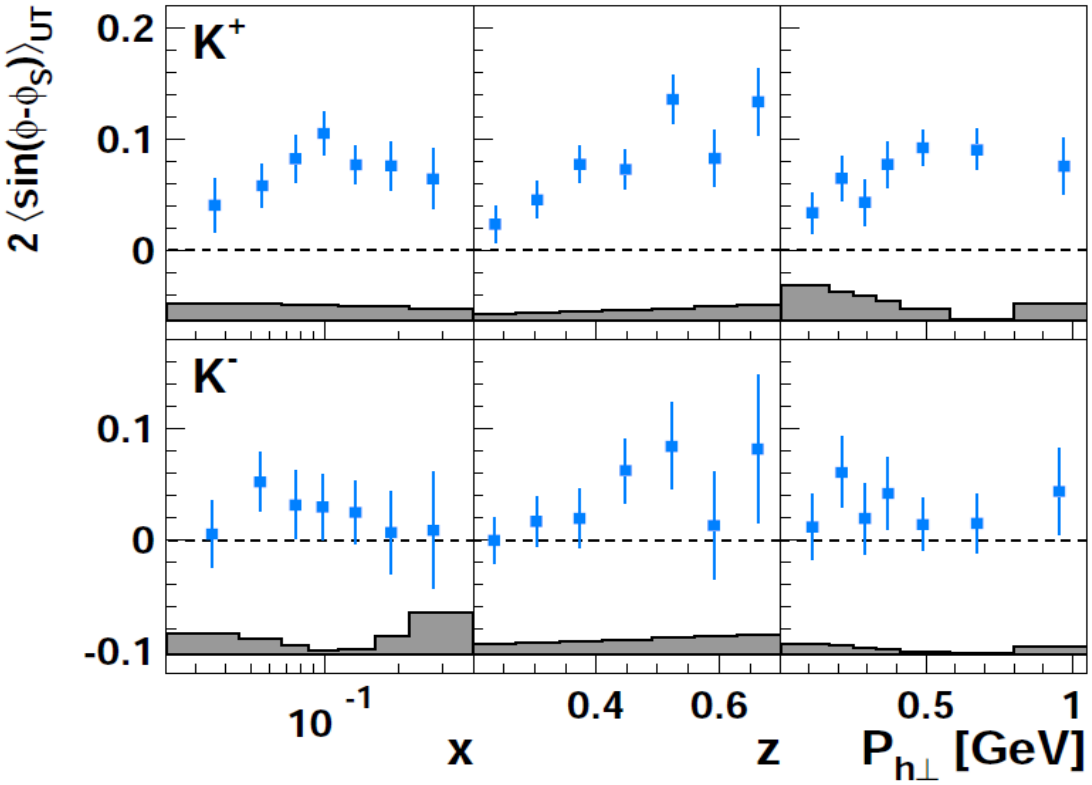
- Sivers distribution for d-valence >> u-valence

  or

- Sivers distribution for u-valence is large & <0 (more likely)

Sivers amplitude for kaons

A. Airapetian et al., Phys. Rev. Lett. **103** (2009) 152002



- K^+
  - significantly positive
  - clear rise with z
  - rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
  - larger than π^+

non-trivial role of sea quarks?

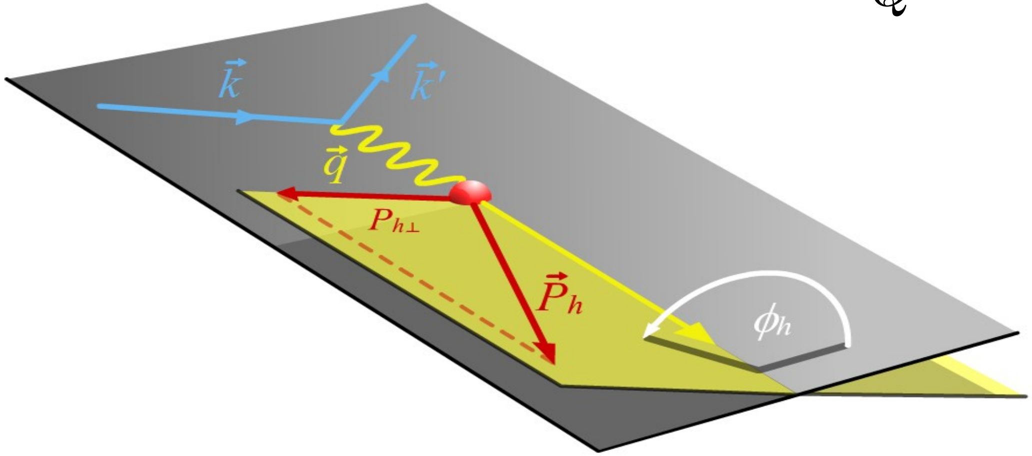
- K^-
  - slightly positive

Spin-independent semi-inclusive non-collinear DIS cross section

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi_h} = \frac{\alpha^2}{xyQ^2}(1+\frac{\gamma^2}{2x})\{A(y)F_{UU,T} + B(y)F_{UU,L}$$

$$+C(y)\cos\phi_h F_{UU}^{\cos\phi_h} + B(y)\cos 2\phi_h F_{UU}^{\cos 2\phi_h}\}$$

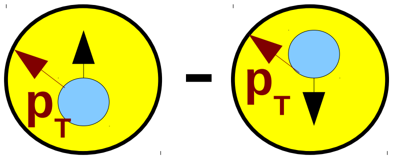
$$\gamma = \frac{2Mx}{Q},\ \ F = F(x, Q, z, \vec{P_{h\perp}})$$



Spin-independent semi-inclusive non-collinear DIS cross section

leading twist

$$F_{UU}^{\cos 2\phi_h} = \mathcal{I}[-\frac{2(\hat{P}_{h\perp}.\vec{p}_T)(\hat{P}_{h\perp}.\vec{k}_T) - \vec{p}_T.\vec{k}_T}{M_h M} h_1^\perp H_1^\perp]$$



Boer-Mulders DF

- chiral odd
- naïve-T-odd

↔

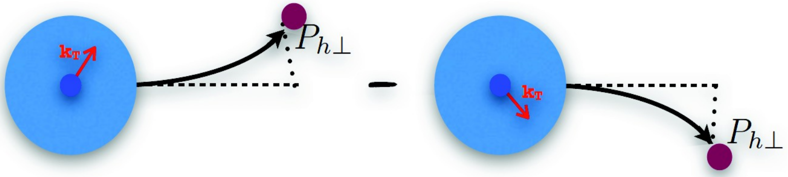
Collins FF

- chiral odd
- naïve-T-odd

sub-leading twist

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{I}[-\frac{\hat{P}_{h\perp}.\vec{p}_T}{M} f_1 D_1 - \frac{\hat{P}_{h\perp}.\vec{k}_T}{M_h}\frac{p_T^2}{M^2} h_1^\perp H_1^\perp + \ldots]$$

Cahn effect

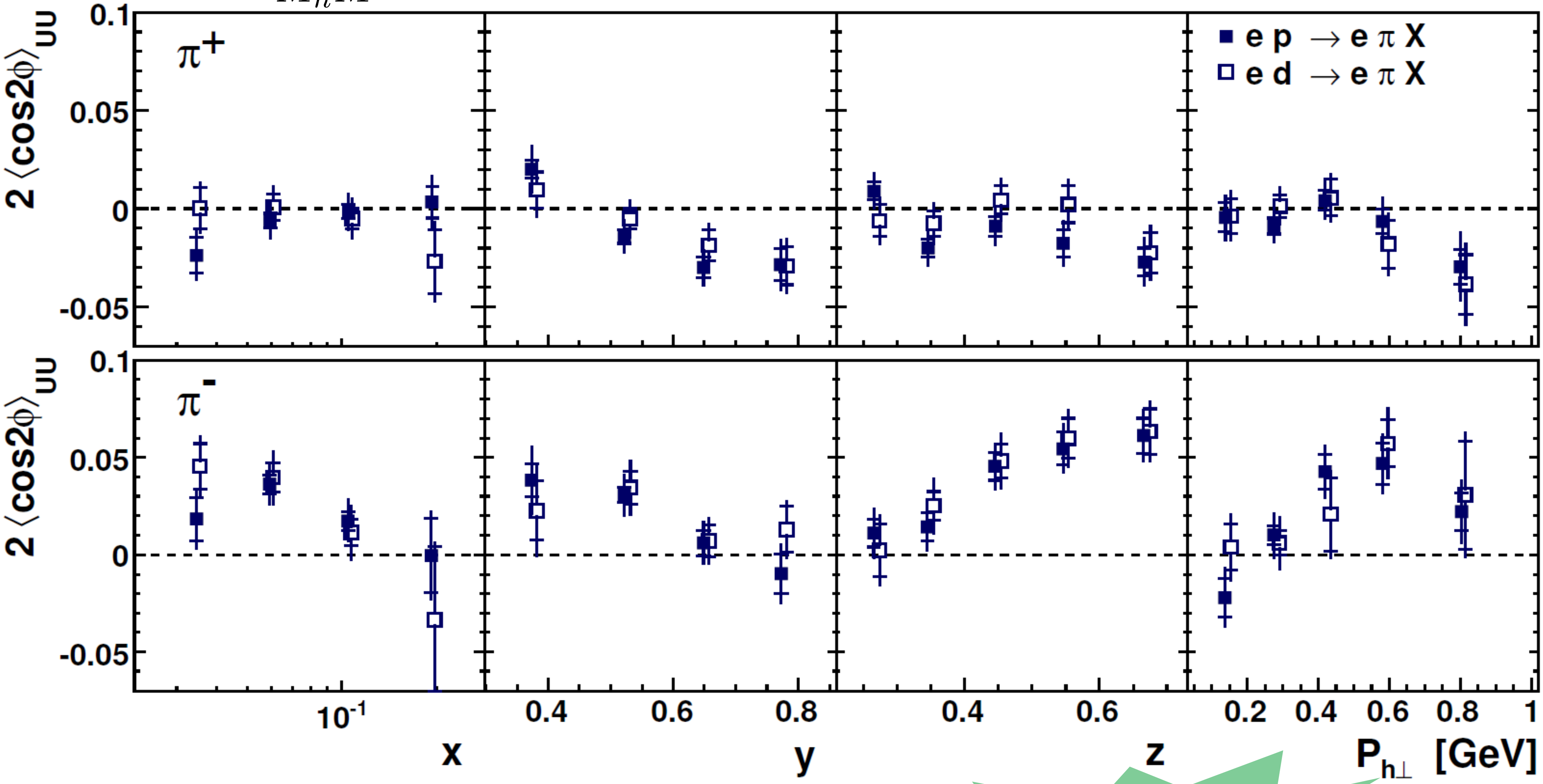


quark-gluon-quark correlations

Results for <cos 2ϕ_h>: pions

$$\mathcal{I}[-\frac{2(\hat{P}_{h\perp}.\vec{p}_T)(\hat{P}_{h\perp}.\vec{k}_T)-\vec{p}_T.\vec{k}_T}{M_h M}h_1^\perp H_1^\perp]$$

A. Airapetian et al., arXiv:1204.4161



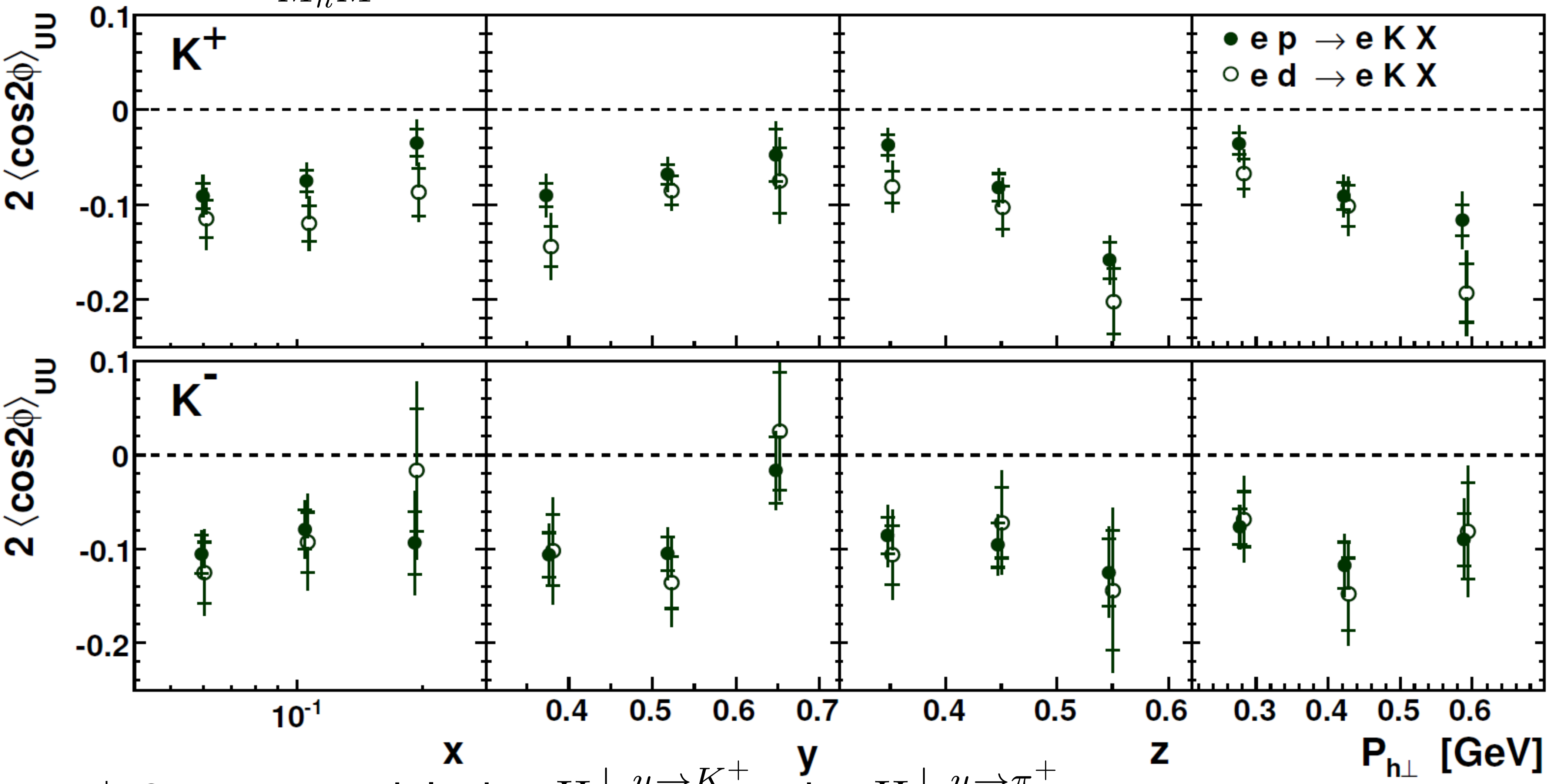
- H-D comparison: $h_1^{\perp,u} \approx h_1^{\perp,d}$
- π⁻ > 0 ⟷ π⁺⩽ 0: $H_1^{\perp,fav} \approx -H_1^{\perp,unfav}$

non-zero orbital angular momentum!

Results for <cos 2ϕ_h>: kaons

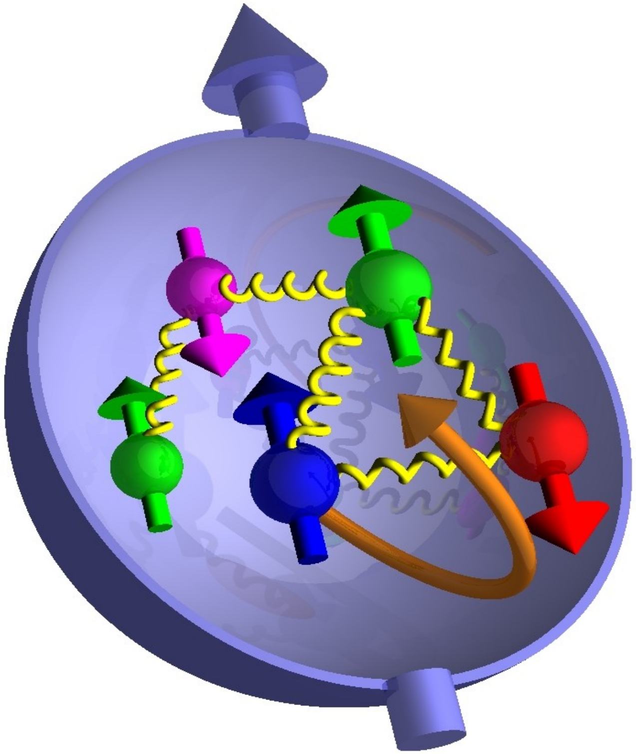
$$\mathcal{I}[-\frac{2(\hat{P}_{h\perp}.\vec{p}_T)(\hat{P}_{h\perp}.\vec{k}_T)-\vec{p}_T.\vec{k}_T}{M_h M}h_1^\perp H_1^\perp]$$

A. Airapetian et al., arXiv:1204.4161



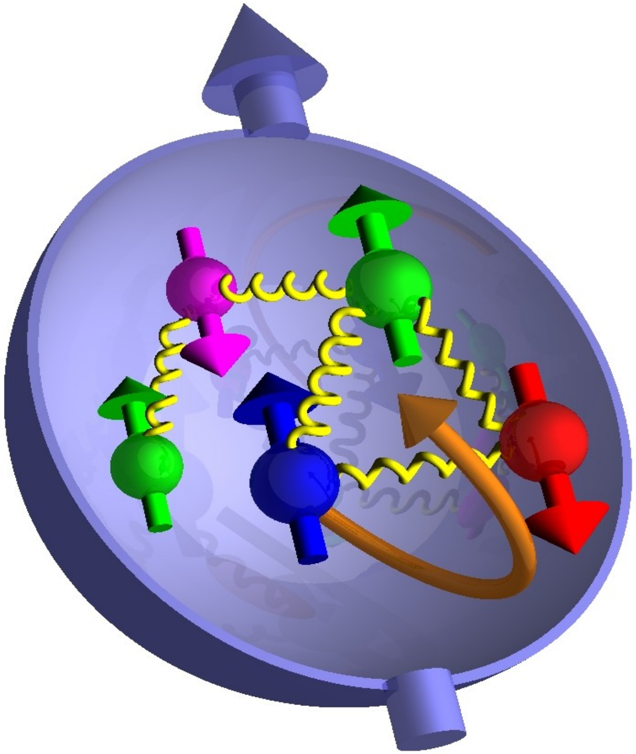
- K$^+$<0: - Artru model: sign $\mathrm{H}_1^{\perp,u\to K^+}$ = sign $\mathrm{H}_1^{\perp,u\to\pi^+}$
- K$^-$≃ K$^+$: - u-dominance $\xrightarrow{?}$ $\mathrm{H}_1^{\perp,u\to K^+} \approx H_1^{\perp,u\to K^-}$
  - role of sea-quarks

Spin budget of proton



$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L^Q}_{J^Q} + J^g$$

Spin budget of proton



$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L^Q}_{J^Q} + J^g$$

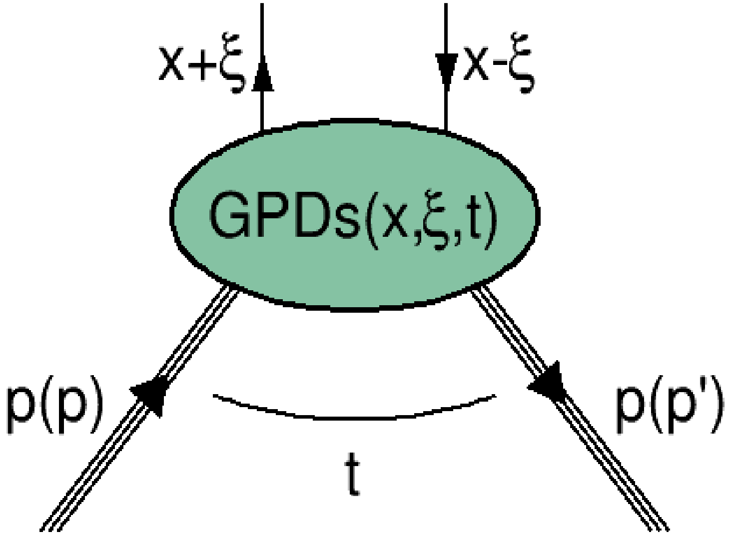
GPDs

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

X. Ji, Phys. Rev. Lett. **78** (1997) 610

$$\boxed{L^Q = \sum_q L^q = \sum_q (J^q - \Delta q)}$$

Generalized Parton Distributions (GPDs)



- x=average longitudinal momentum fraction
- 2ξ=average longitudinal momentum transfer
- t= squared momentum transfer to nucleon

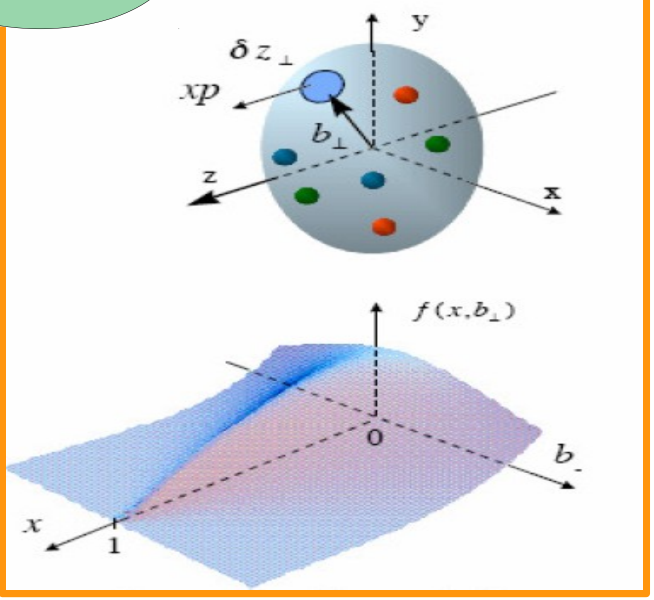
Four quark helicity-conserving GPDs at twist-2

$\mathrm{H}^q(x,\xi,t)$	$E^q(x,\xi,t)$	spin independent
$\widetilde{H}^q(x,\xi,t)$	$\widetilde{E}^q(x,\xi,t)$	spin dependent
proton helicity non-flip	proton helicity flip	

Generalized Parton Distributions (GPDs)

$H, \tilde{H}$

unpolarized nucleon



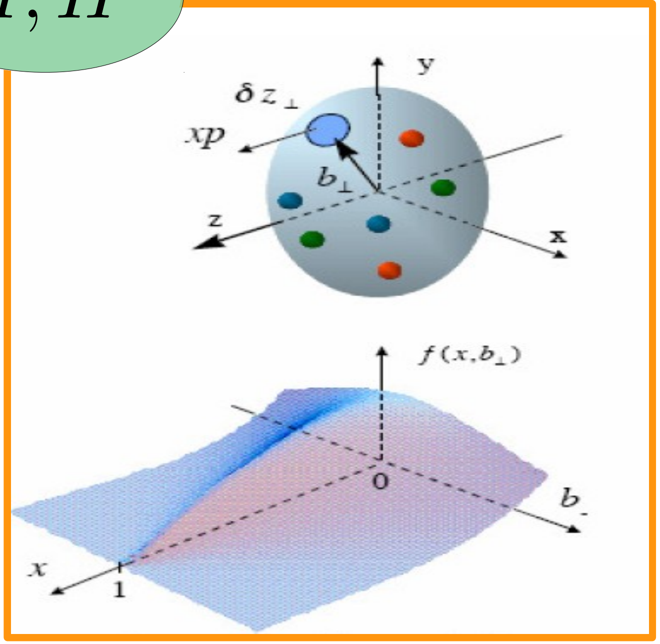
helicity-(in)dependent probability distribution of quarks as a function of their longitudinal fractional momentum and transverse position

M. Burkardt, Phys. Rev. D **62** (2000) 071503

Generalized Parton Distributions (GPDs)

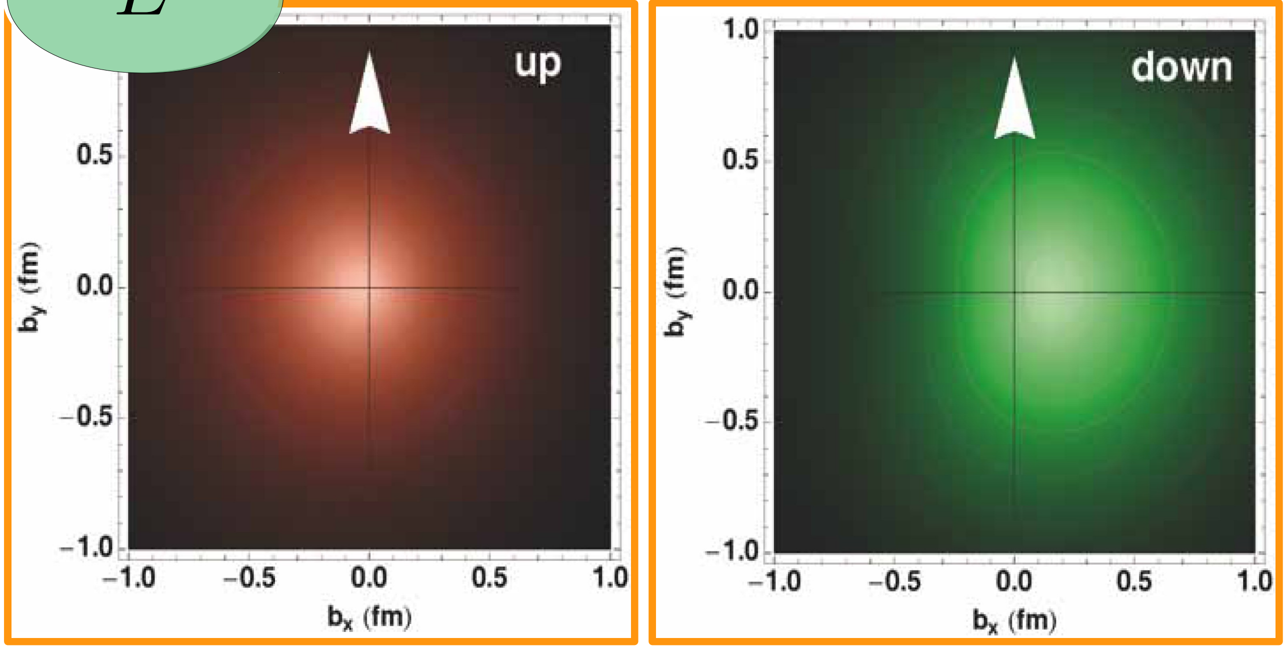
$H, \tilde{H}$

unpolarized nucleon



E

transversely polarized nucleon



pictures taken from A. Bacchetta and M. Contalbrigo, Il Nuovo Saggiatore **28** (2012) 1-2

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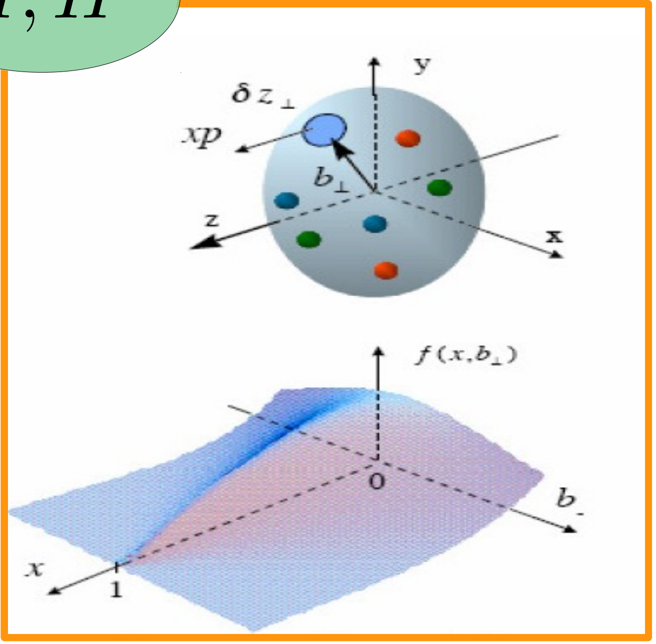
M. Burkardt, Phys. Rev. D **62** (2000) 071503

distortion of quark probability distribution compared to unpolarized nucleon

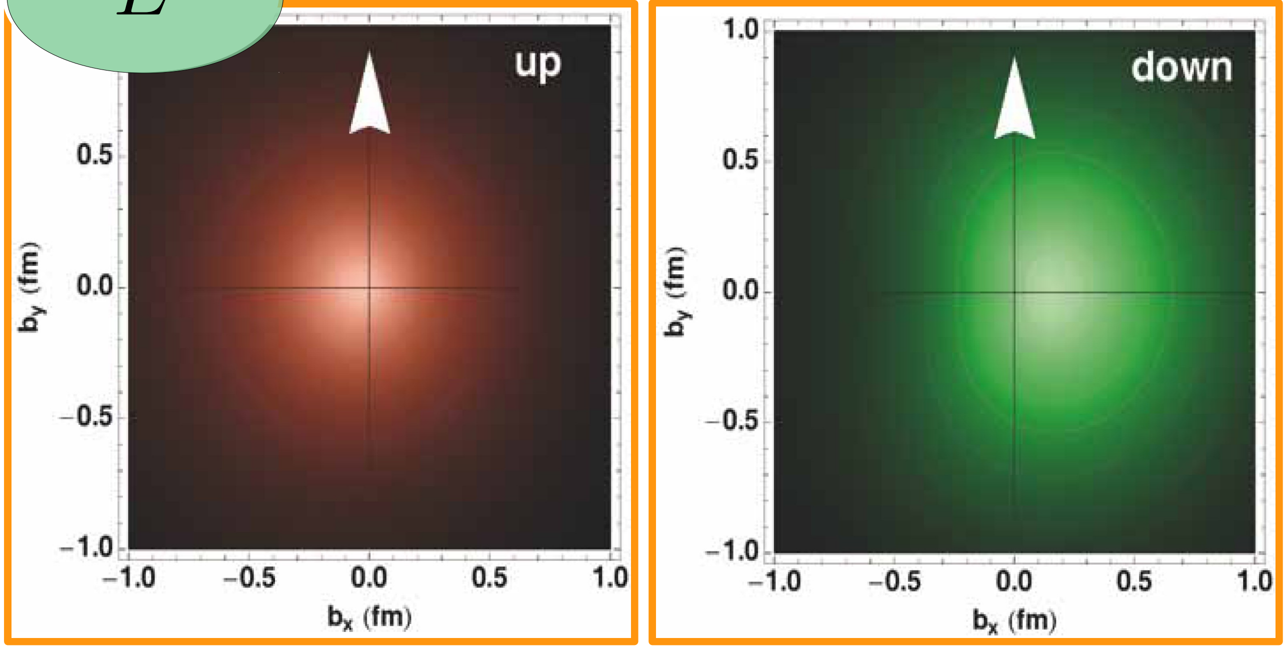
M. Burkardt, Phys. Rev. D **66** (2002) 114005

Generalized Parton Distributions (GPDs)

$H, \tilde{H}$ unpolarized nucleon



E transversely polarized nucleon



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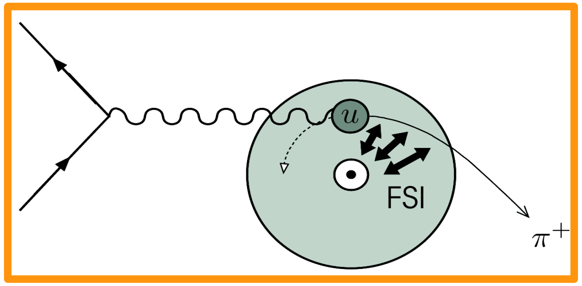
M. Burkardt, Phys. Rev. D **62** (2000) 071503

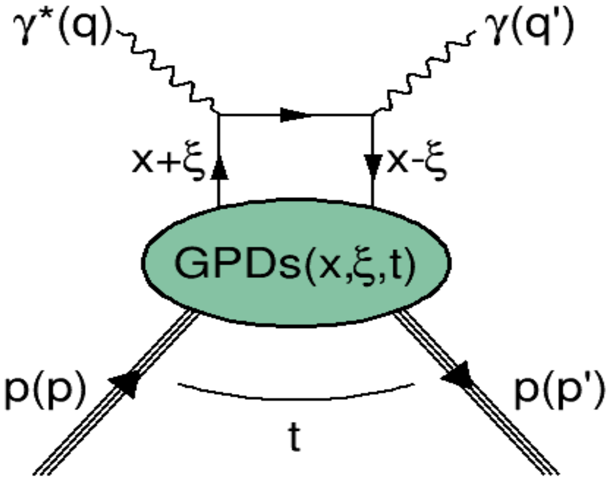
distortion of quark probability distribution compared to unpolarized nucleon

M. Burkardt, Phys. Rev. D **66** (2002) 114005

qualitative link to Sivers distribution



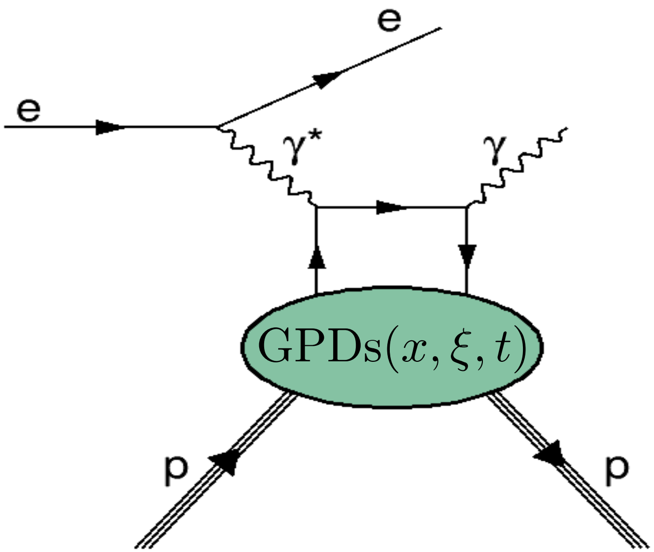
Deeply virtual Compton scattering



$$\xi \approx \frac{x_B}{2 - x_B}$$

Exclusive lepto-production of real photons

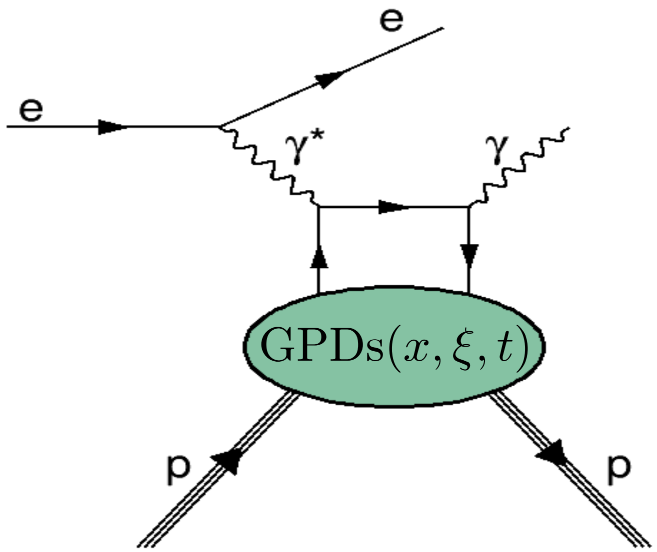
exclusive deep-inelastic scattering



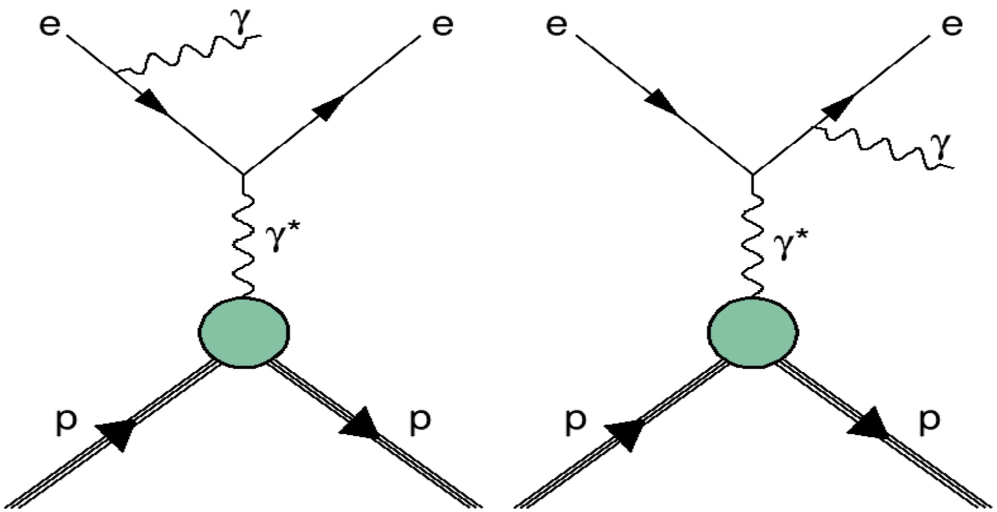
DVCS

Exclusive lepto-production of real photons

exclusive deep-inelastic scattering



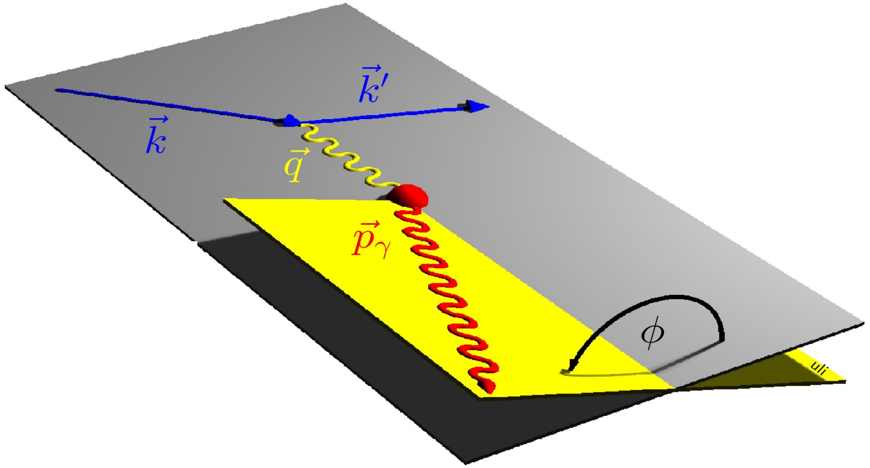
DVCS



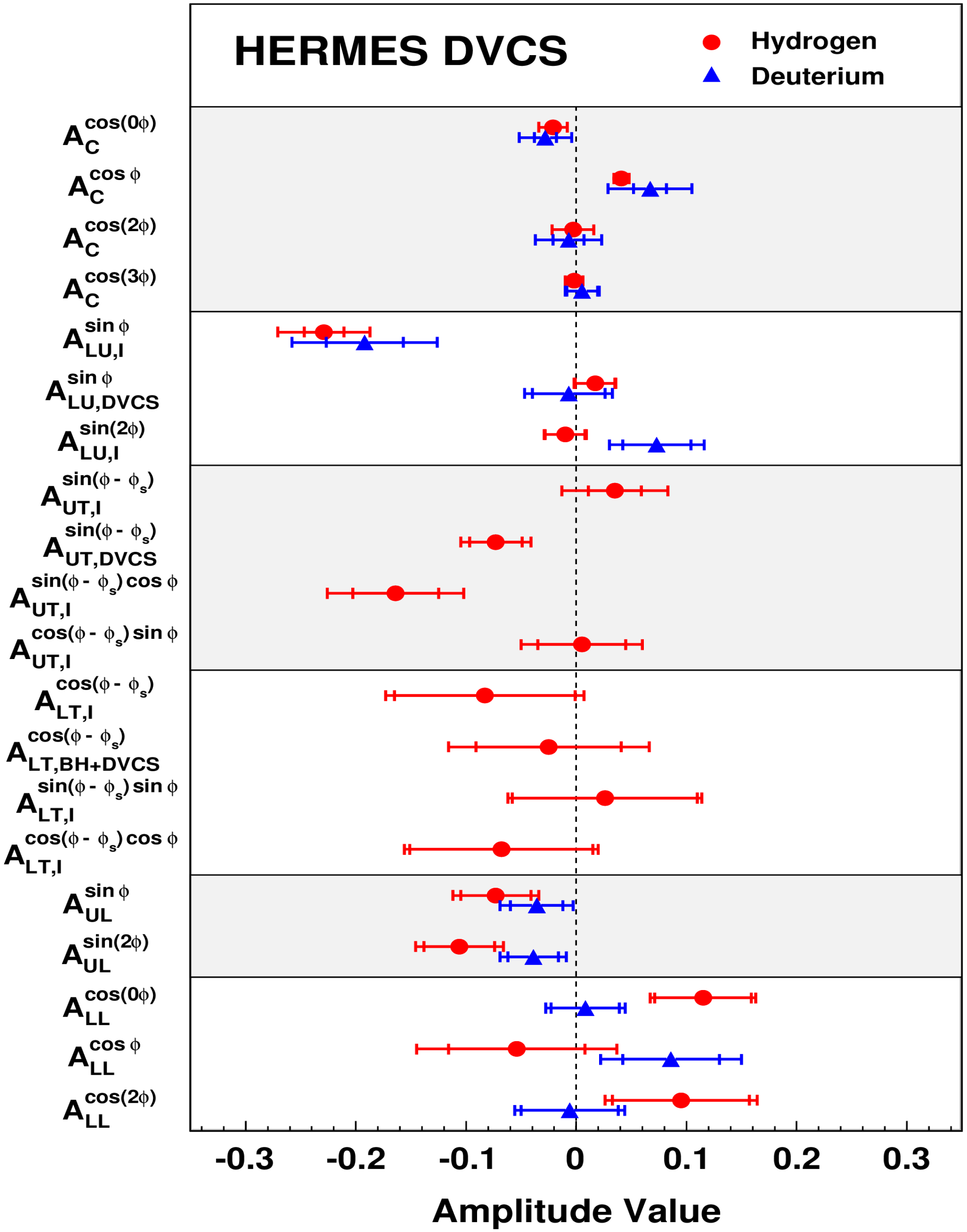
Bethe-Heitler

$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{BH}\,\tau^*_{DVCS} + \tau_{DVCS}\,\tau^*_{BH}$$

- $|\tau_{BH}|$: calculable (form factors)
- $|\tau_{BH}| \gg |\tau_{DVCS}|$ at HERMES
- interference term:
  through azimuthal asymmetries



DVCS at HERMES



beam-charge asymmetry
JHEP **07** (2012) 32
Nucl. Phys. B 829 (2010) 1

beam-helicity asymmetry
JEHP **07** (2012) 32
Nucl. Phys. B 829 (2010) 1

GPD H

transverse target-spin asymmetry
JHEP **06** (2008) 066

double spin (LT) asymmetry
Phys. Lett. B **704** (2011) 15

GPD E

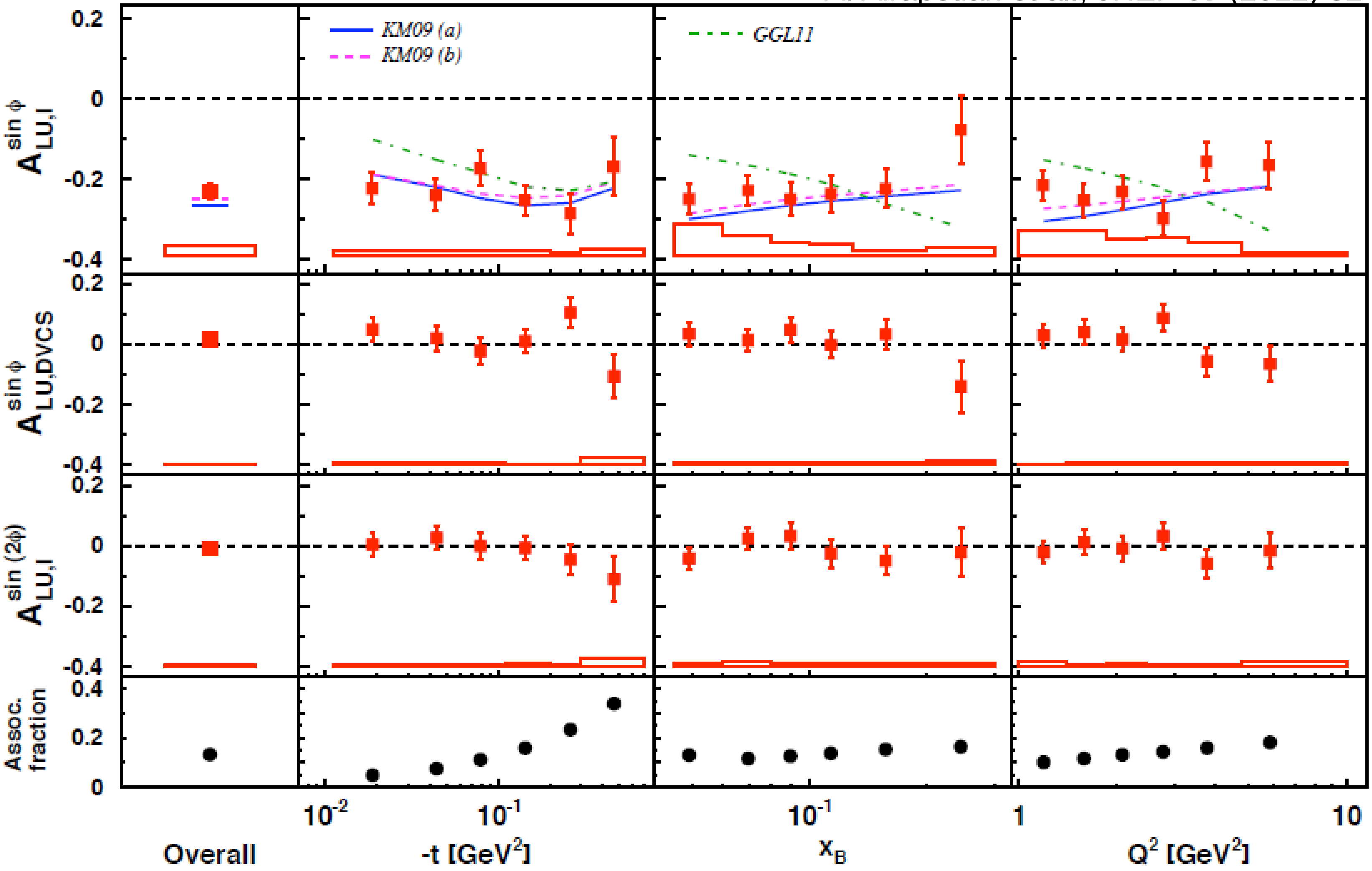
longitudinal target-spin asymmetry
JHEP **06** (2010) 019
Nucl. Phys. B 842 (2011) 265

double spin (LL) asymmetry
JHEP **06** (2010) 019
Nucl. Phys. B 842 (2011) 265

GPD $\tilde{H}$

Charged-separated beam-helicity asymmetry

A. Airapetian et al., JHEP **07** (2012) 32

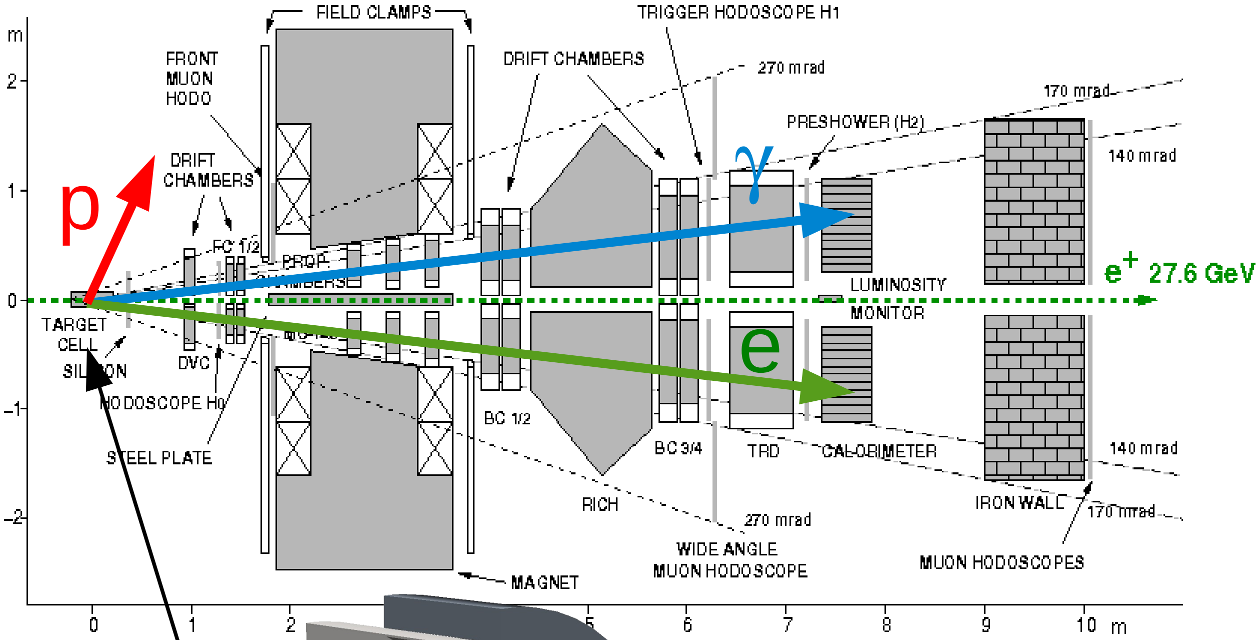


KM09: Nucl. Phys. B **841** (2010) 1:
fit to HERMES, ZEUS, H1 data
Fit to HERMES, ZEUS, H1, Jefferson Lab data

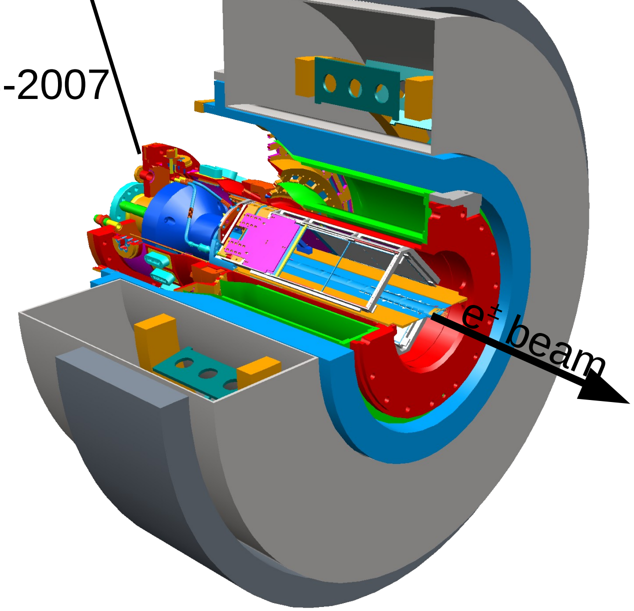
GGL11:Phys. Rev. D **84** (2011) 034007

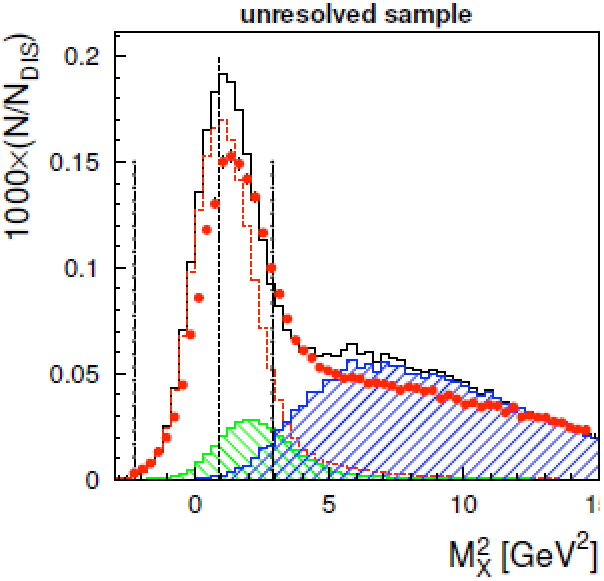
- data collected from 1996-2007 (74% of data from 2006-2007)
- additional 3.2% scale uncertainty from beam polarization

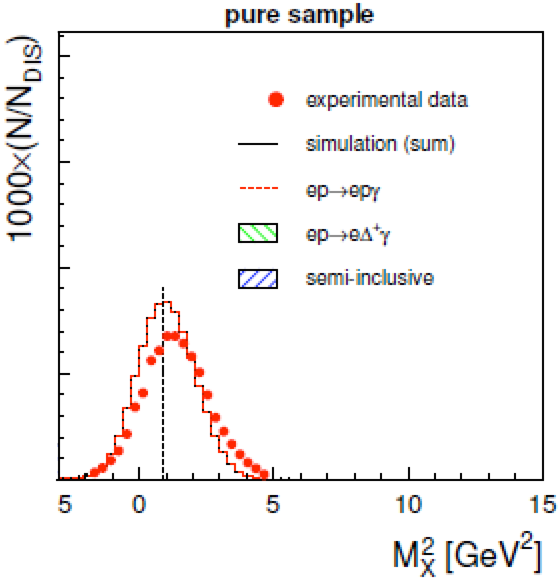
DVCS event selection

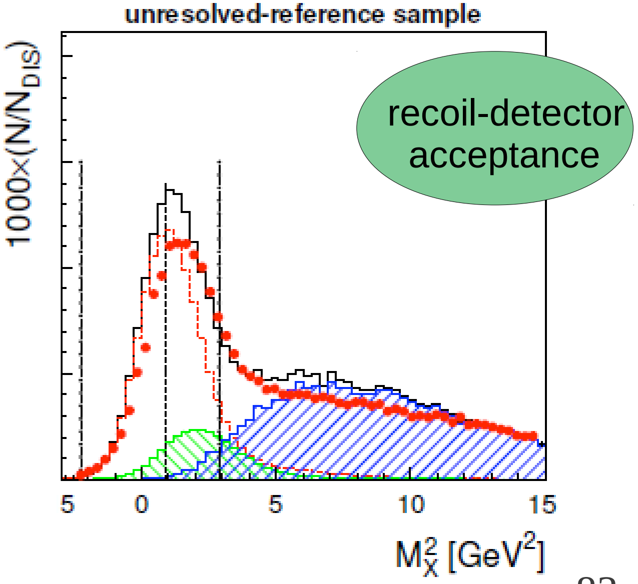


2006-2007





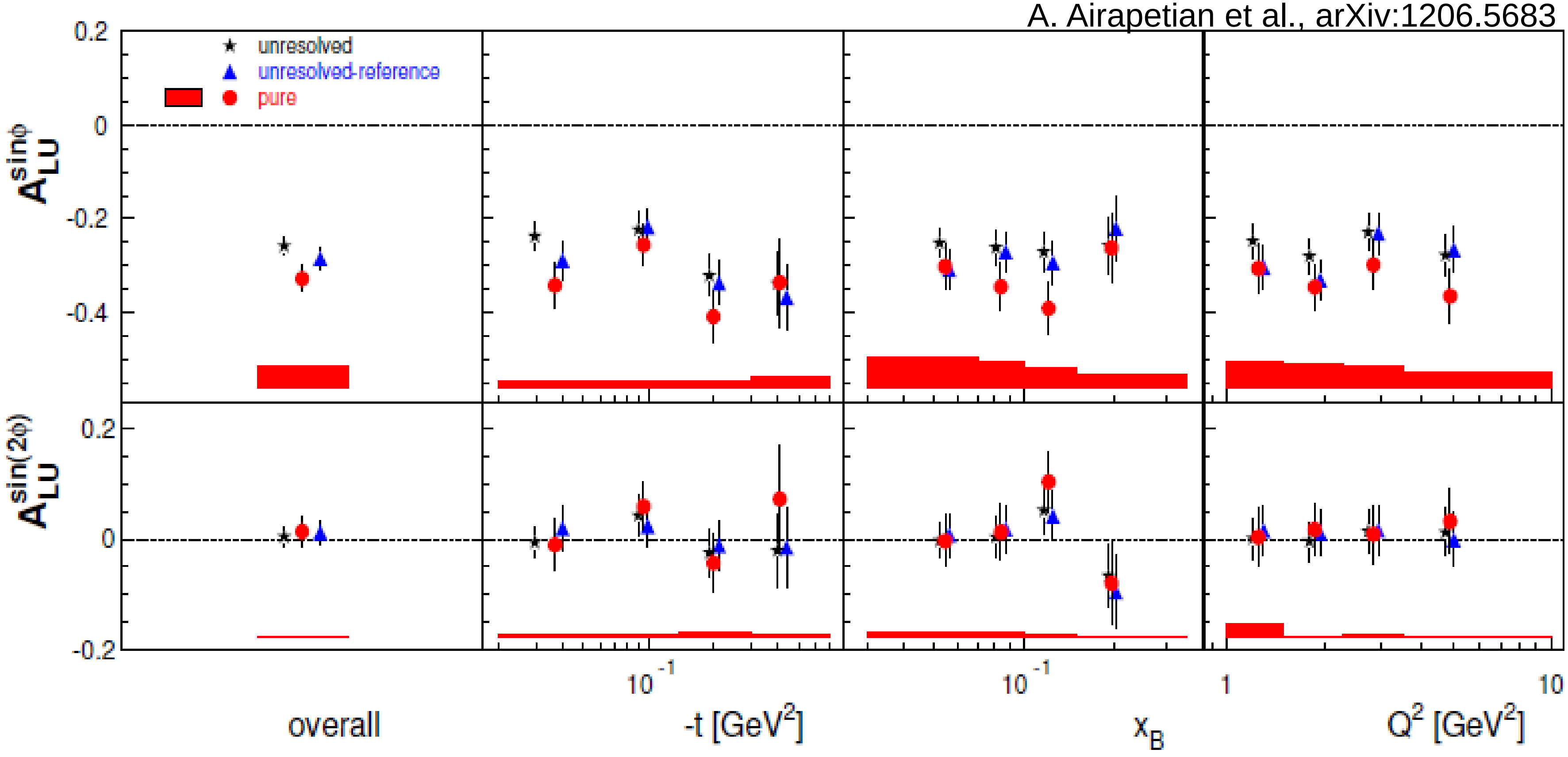




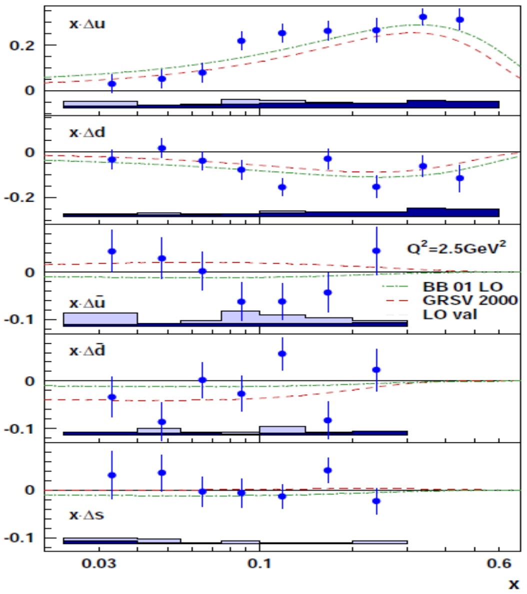
recoil-detector acceptance

Beam-helicity asymmetry

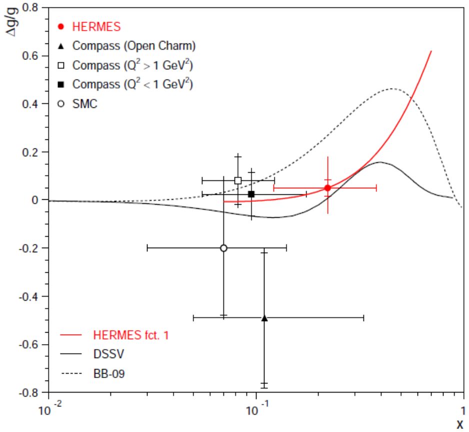
A. Airapetian et al., arXiv:1206.5683



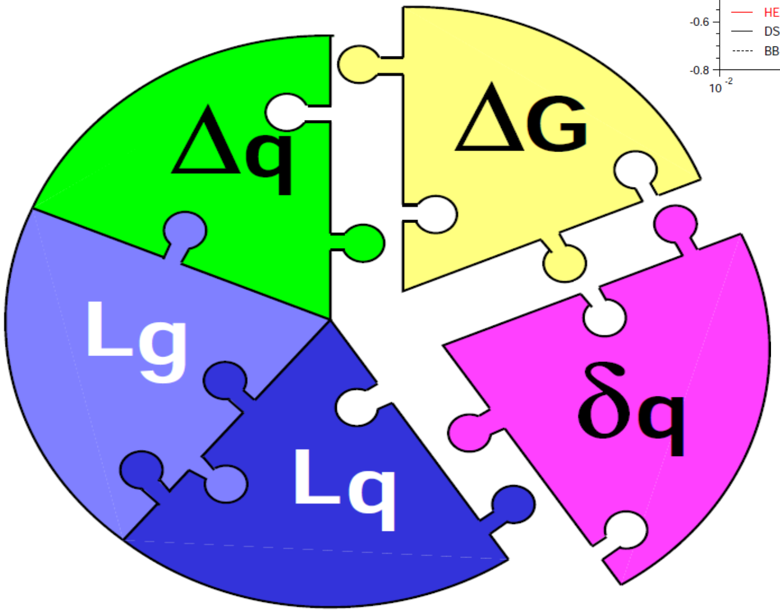
- additional 1.96 % scale uncertainty from beam polarization



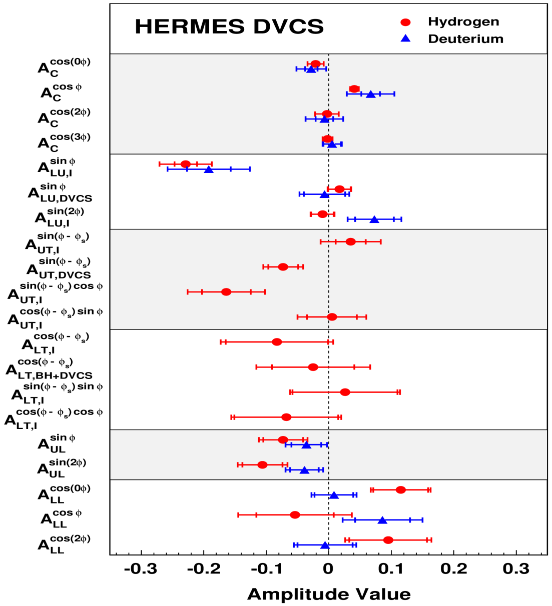
$x \cdot \Delta u$
0.2
0
$x \cdot \Delta d$
0
-0.2
Q^2=2.5GeV^2
0
-0.1
$x \cdot \Delta \bar{u}$
BB 01 LO
GRSV 2000
LO val
$x \cdot \Delta \bar{d}$
0
-0.1
$x \cdot \Delta s$
0
-0.1
0.03
0.1
0.6
x



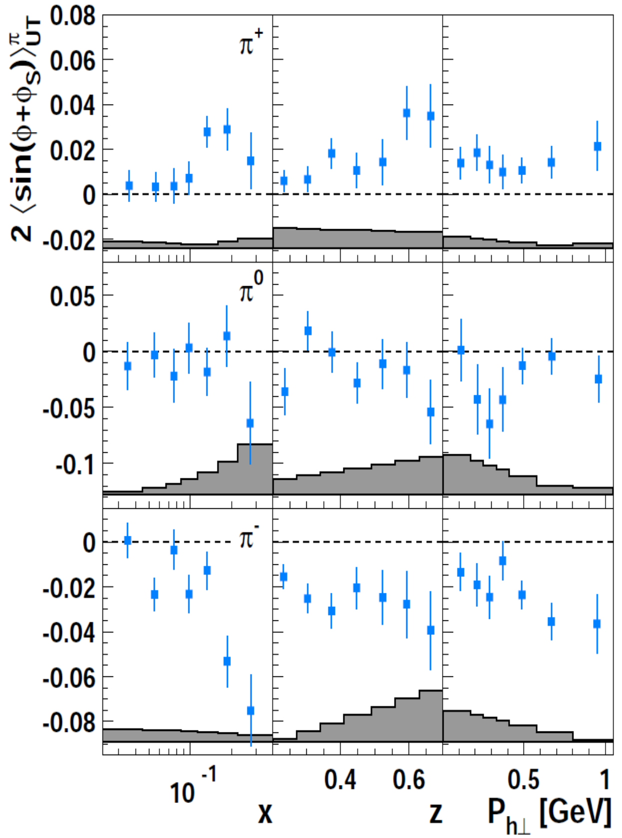
$\Delta g/g$
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
HERMES
Compass (Open Charm)
Compass ($Q^2 > 1$ GeV^2)
Compass ($Q^2 < 1$ GeV^2)
SMC
HERMES fct. 1
DSSV
BB-09
10^{-2}
10^{-1}
1
x



Δq
ΔG
Lg
Lq
δq



HERMES DVCS
Hydrogen
Deuterium
$A_C^{\cos(0\phi)}$
$A_C^{\cos\phi}$
$A_C^{\cos(2\phi)}$
$A_C^{\cos(3\phi)}$
$A_{LU,I}^{\sin\phi}$
$A_{LU,DVCS}^{\sin\phi}$
$A_{LU,I}^{\sin(2\phi)}$
$A_{UT,I}^{\sin(\phi-\phi_s)}$
$A_{UT,DVCS}^{\sin(\phi-\phi_s)}$
$A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi}$
$A_{UT,I}^{\cos(\phi-\phi_s)\sin\phi}$
$A_{LT,I}^{\cos(\phi-\phi_s)}$
$A_{LT,BH+DVCS}^{\cos(\phi-\phi_s)}$
$A_{LT,I}^{\sin(\phi-\phi_s)\sin\phi}$
$A_{LT,I}^{\cos(\phi-\phi_s)\cos\phi}$
$A_{UL}^{\sin\phi}$
$A_{UL}^{\sin(2\phi)}$
$A_{LL}^{\cos(0\phi)}$
$A_{LL}^{\cos\phi}$
$A_{LL}^{\cos(2\phi)}$
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
Amplitude Value



$2\langle\sin(\phi+\phi_S)\rangle_{UT}^{\pi}$
0.08
0.06
0.04
0.02
0
-0.02
π^+
0.05
0
-0.05
-0.1
π^0
0
-0.02
-0.04
-0.06
-0.08
π^-
10^{-1}
x
0.4
0.6
z
0.5
1
$P_{h\perp}$ [GeV]

Thank you for your attention!

Back up

Extraction of the cosine moments

$$\langle \cos(n\phi_h) \rangle \overset{th.}{=} \frac{\int d\phi_h \cos(n\phi_h) \sigma_{UU}(\omega, \phi_h)}{\int d\phi_h \sigma_{UU}(\omega, \phi_h)}$$

$$\omega = (x, y, z, P_{h\perp}^2)$$

$$\Big\updownarrow$$

$$\langle \cos(n\phi_h) \rangle \overset{exp.}{=} \frac{\int d\phi_h \cos(n\phi_h) \epsilon_{acc}(\omega, \phi_h) \epsilon_{rad}(\omega, \phi_h) \sigma_{UU}(\omega, \phi_h)}{\int d\phi_h \epsilon_{acc}(\omega, \phi_h) \epsilon_{rad}(\omega, \phi_h) \sigma_{UU}(\omega, \phi_h)}$$

extraction is challenging!

azimuthal modulations also possible due to

- detector geometrical acceptance
- higher-order QED effects

Extraction of the cosine moments

$$\langle\cos(n\phi_h)\rangle \overset{th.}{=} \frac{\int d\phi_h \cos(n\phi_h)\sigma_{UU}(\omega,\phi_h)}{\int d\phi_h \sigma_{UU}(\omega,\phi_h)}$$

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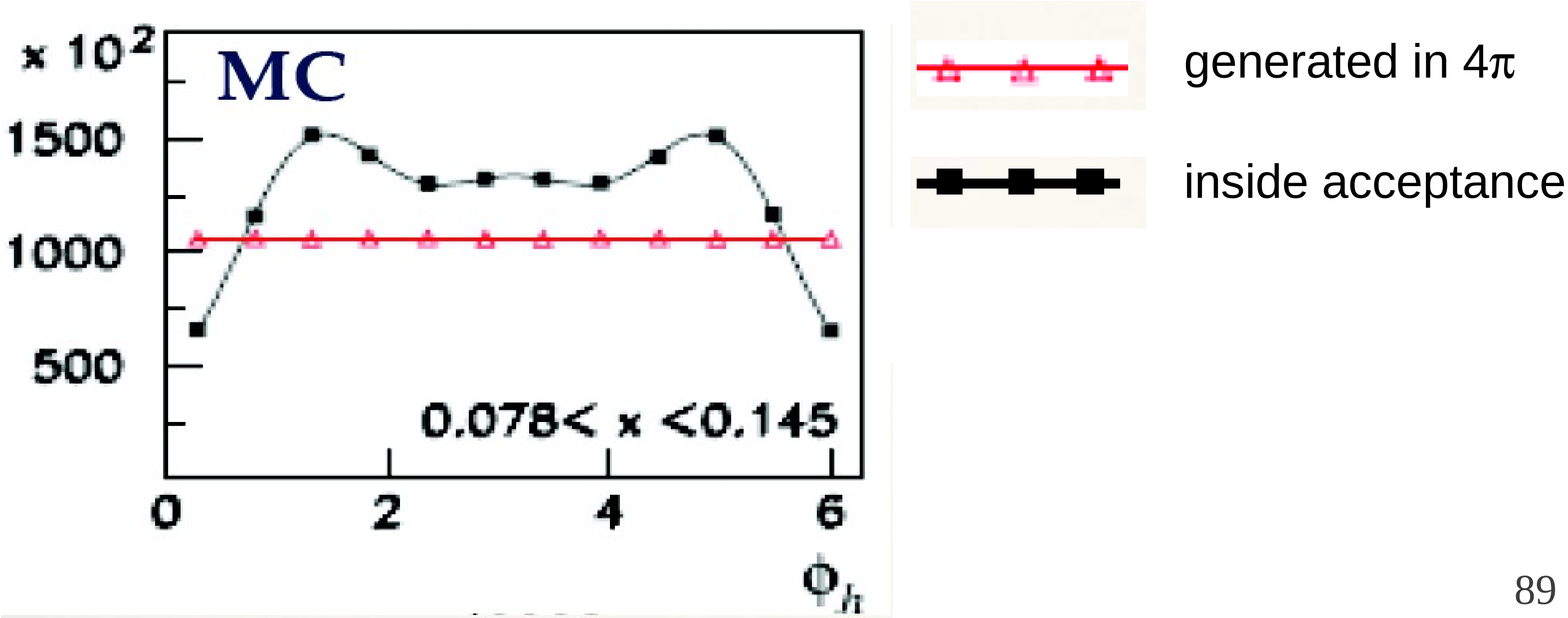

Extraction of the cosine moments

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$$\updownarrow$$

$$\langle\cos(n\phi_h)\rangle \overset{exp.}{=} \frac{\int d\phi_h \cos(n\phi_h)\epsilon_{acc}(\omega,\phi_h)\epsilon_{rad}(\omega,\phi_h)\sigma_{UU}(\omega,\phi_h)}{\int d\phi_h \epsilon_{acc}(\omega,\phi_h)\epsilon_{rad}(\omega,\phi_h)\sigma_{UU}(\omega,\phi_h)}$$

extraction is challenging!

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fully differential analysis needed

unfolding procedure with 400 x 12 bins

BINNING 400 kinematic bins x 12 ϕ-bins							
Variable	Bin limits						#
x	0.023	0.042	0.078	0.145	0.27	1	5
y	0.3	0.45	0.6	0.7	0.85		4
z	0.2	0.3	0.45	0.6	0.75	1	5
P_{hT}	0.05	0.2	0.35	0.5	0.75		4

Extraction of the cosine moments

$$\langle\cos(n\phi_h)\rangle \overset{th.}{=} \frac{\int d\phi_h \cos(n\phi_h)\sigma_{UU}(\omega,\phi_h)}{\int d\phi_h \sigma_{UU}(\omega,\phi_h)}$$

$$\omega = (x, y, z, P_{h\perp}^2)$$

$$\updownarrow$$

$$\langle\cos(n\phi_h)\rangle \overset{exp.}{=} \frac{\int d\phi_h \cos(n\phi_h)\epsilon_{acc}(\omega,\phi_h)\epsilon_{rad}(\omega,\phi_h)\sigma_{UU}(\omega,\phi_h)}{\int d\phi_h \epsilon_{acc}(\omega,\phi_h)\epsilon_{rad}(\omega,\phi_h)\sigma_{UU}(\omega,\phi_h)}$$

extraction is challenging!

azimuthal modulations also possible due to

- detector geometrical acceptance
- higher-order QED effects

$$\Downarrow$$

fully differential analysis needed

unfolding procedure with 400 x 12 bins

$$\Downarrow$$ unfolding

$$\langle\cos(n\phi_h)\rangle\Big|_{\text{bin i}} \approx \frac{\int d\phi_h \cos(n\phi_h)\sigma_{UU}(\omega,\phi_h)}{\int d\phi_h \sigma_{UU}(\omega,\phi_h)}\Bigg|_{\text{bin i}}$$

BINNING 400 kinematic bins x 12 ϕ-bins							
Variable	Bin limits						#
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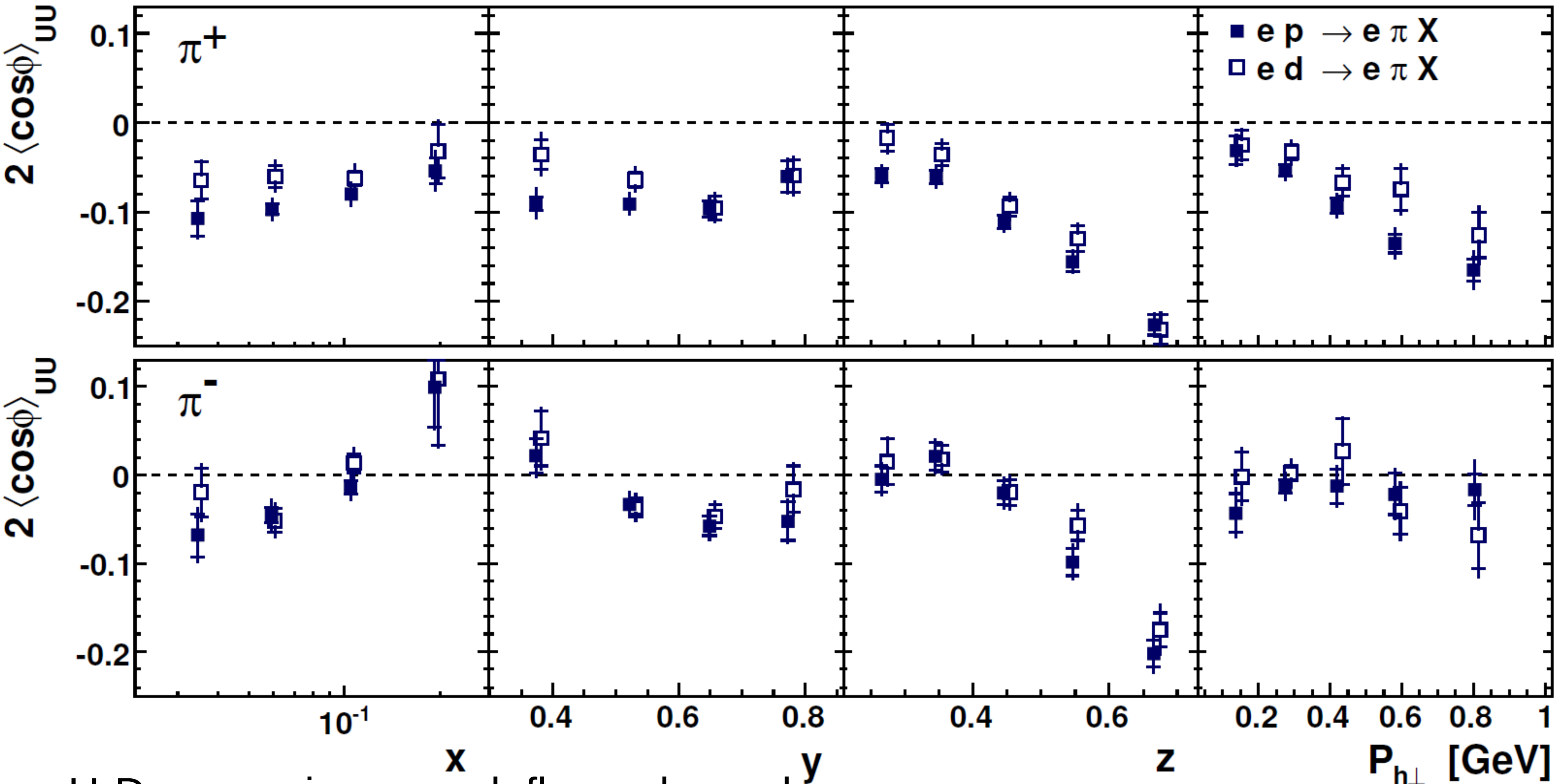
Results for <cos ϕ_h>: pions

$$\mathcal{I}[-\frac{\hat{P}_{h\perp}.\vec{p}_T}{M} f_1 D_1 - \frac{\hat{P}_{h\perp}.\vec{k}_T}{M_h}\frac{p_T^2}{M^2} h_1^\perp H_1^\perp + ...]$$

A. Airapetian et al., arXiv:1204.4161

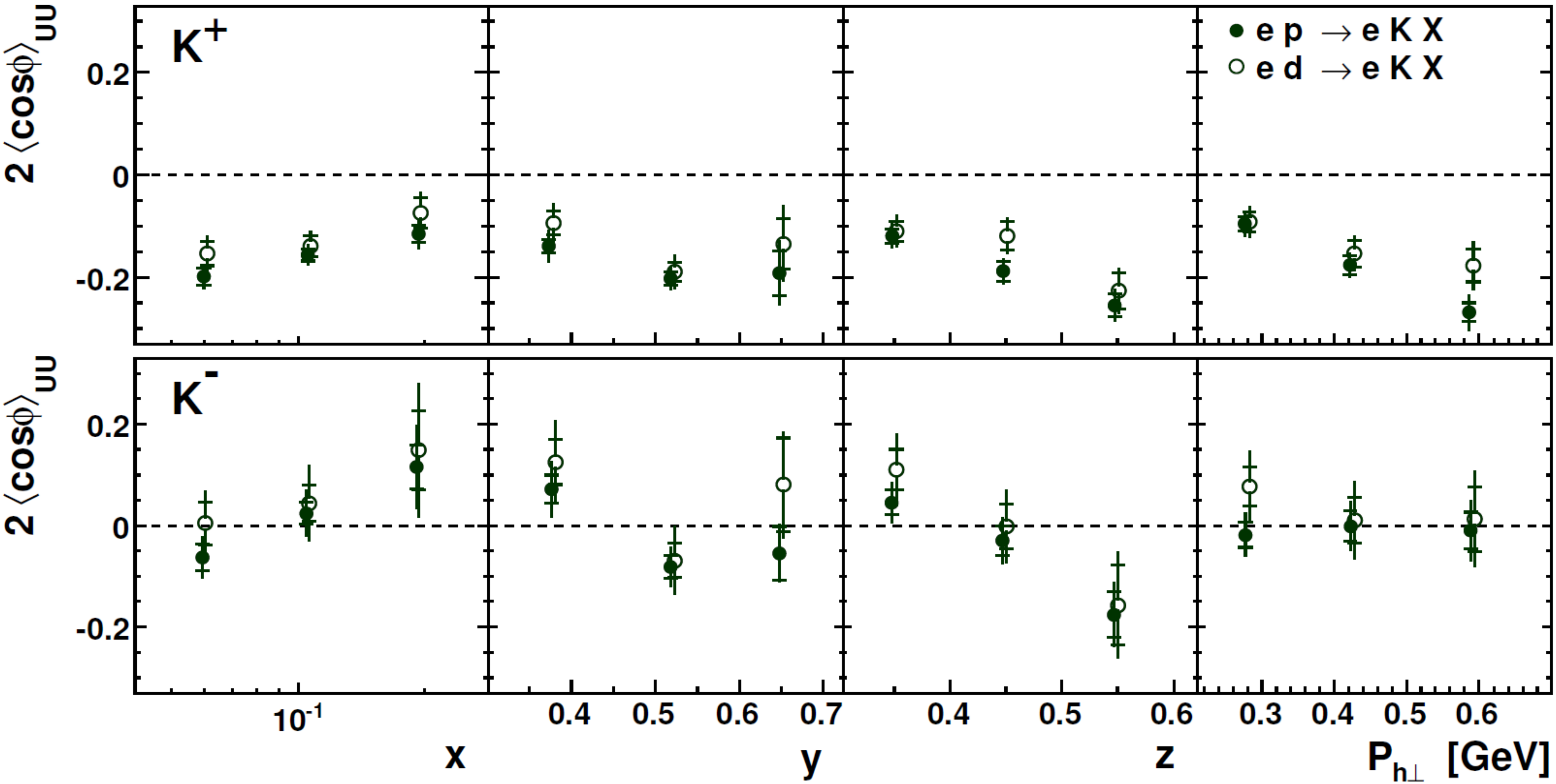


- H-D comparison: weak flavor dependence
- magnitude increases with z
- π^+: magnitude increases with $P_{h\perp}$

Results for <cos ϕ_h>: kaons

$$\mathcal{I}[-\frac{\hat{P}_{h\perp}.\vec{p}_T}{M} f_1 D_1 - \frac{\hat{P}_{h\perp}.\vec{k}_T}{M_h} \frac{p_T^2}{M^2} h_1^\perp H_1^\perp + ...]$$

A. Airapetian et al., arXiv:1204.4161



- $K^+<0$, larger in magnitude than π^+
- $K^- \simeq 0$