Lepton-Nucleon Spin Physics

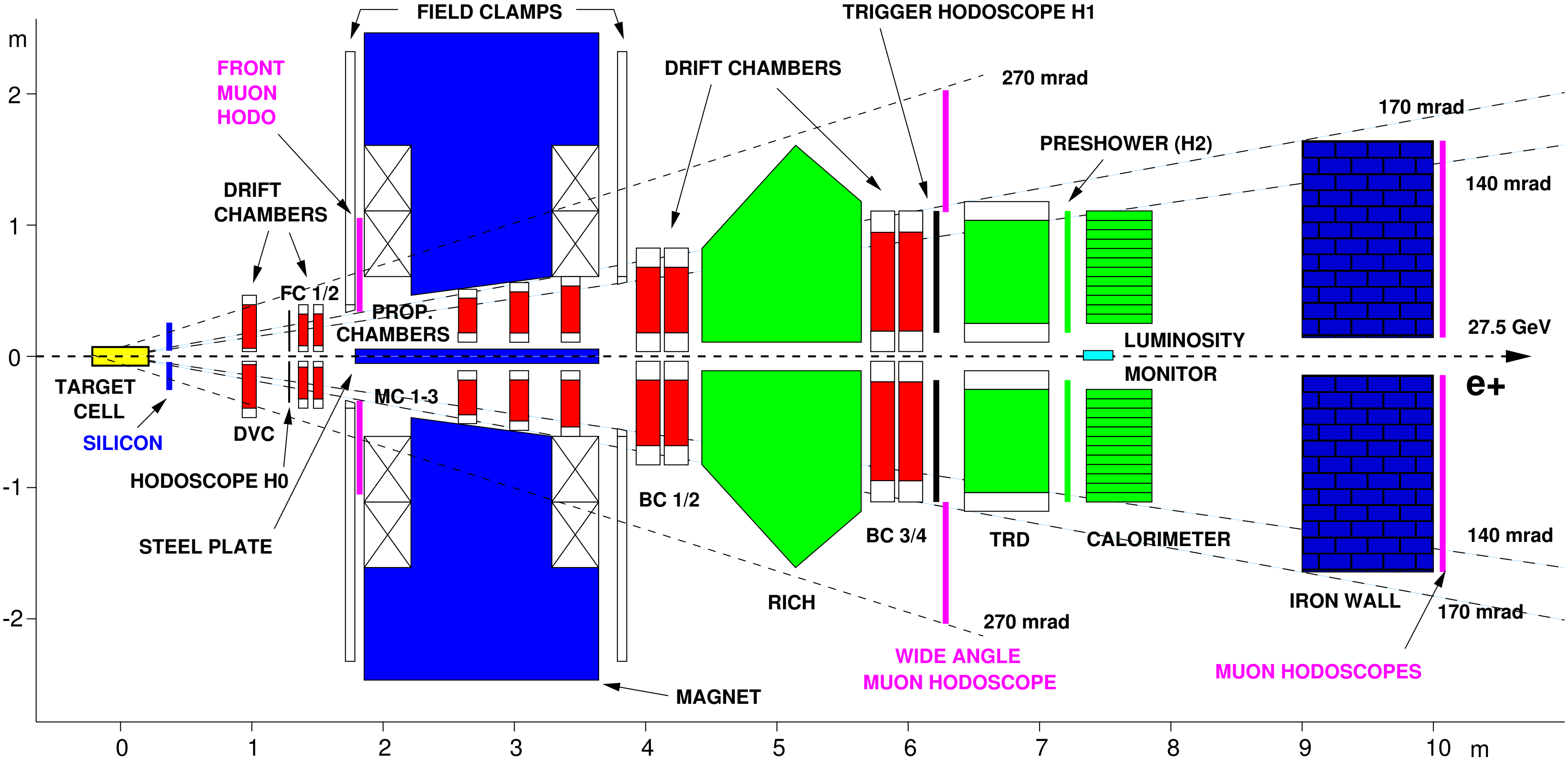
- Traditionally: Lepton-nucleon spin physics
  - Helicity distribution $g_1(x)$
  - Helicity sum rule $\Delta\Sigma$
  - g_2, ...
- New(er) topics
  - Transversity distribution
  - Collins, Sivers, ... effects
  - Higher twist contributions
  - Fragmentation in semi-inclusive DIS

Lepton-Nucleon Spin Physics

- HERMES @ DESY
- COMPASS @ CERN
- Hall A @ JLAB
- CLAS (Hall B) @ JLAB

Lepton-Nucleon Spin Physics

- HERMES @ DESY



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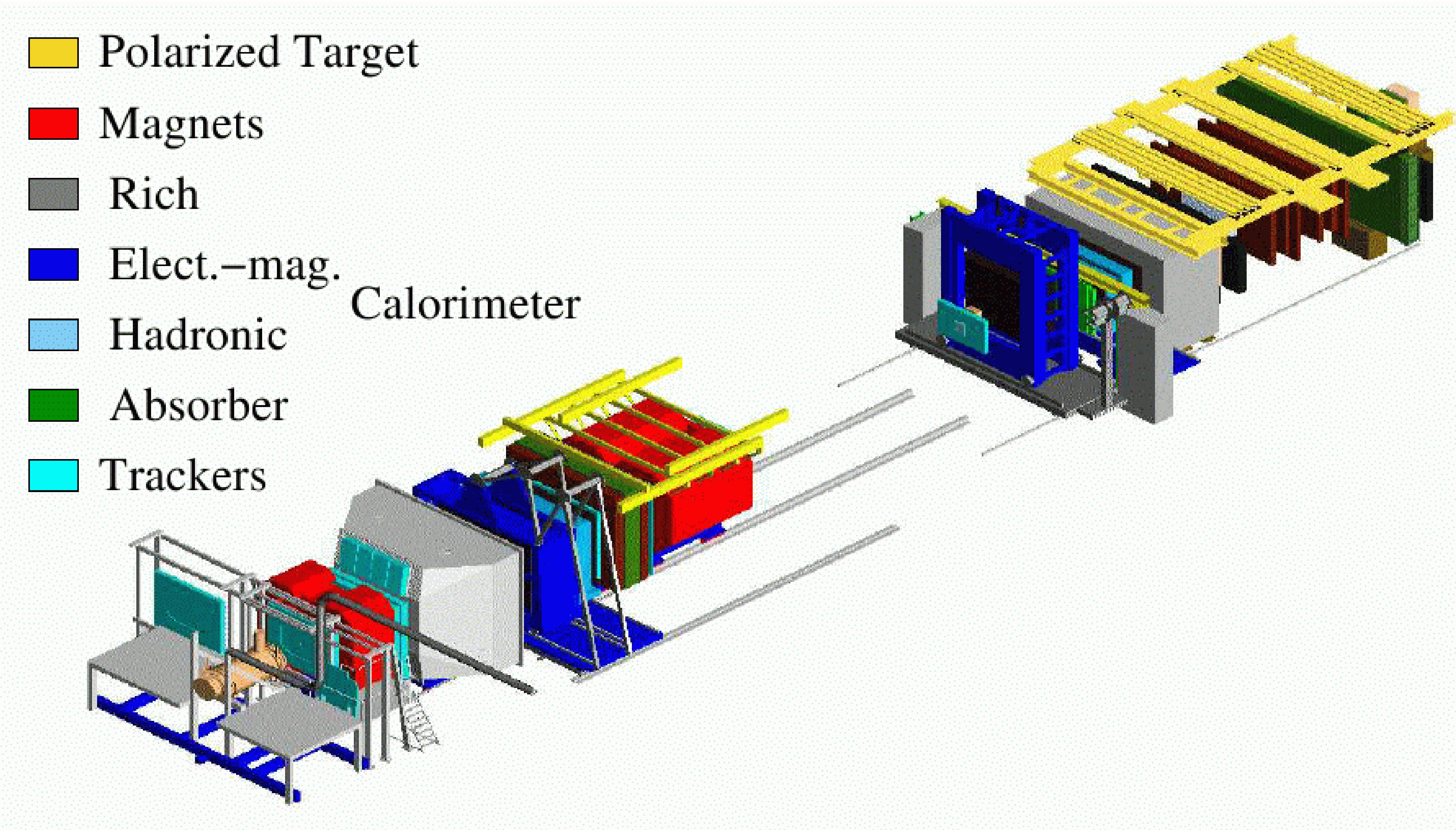

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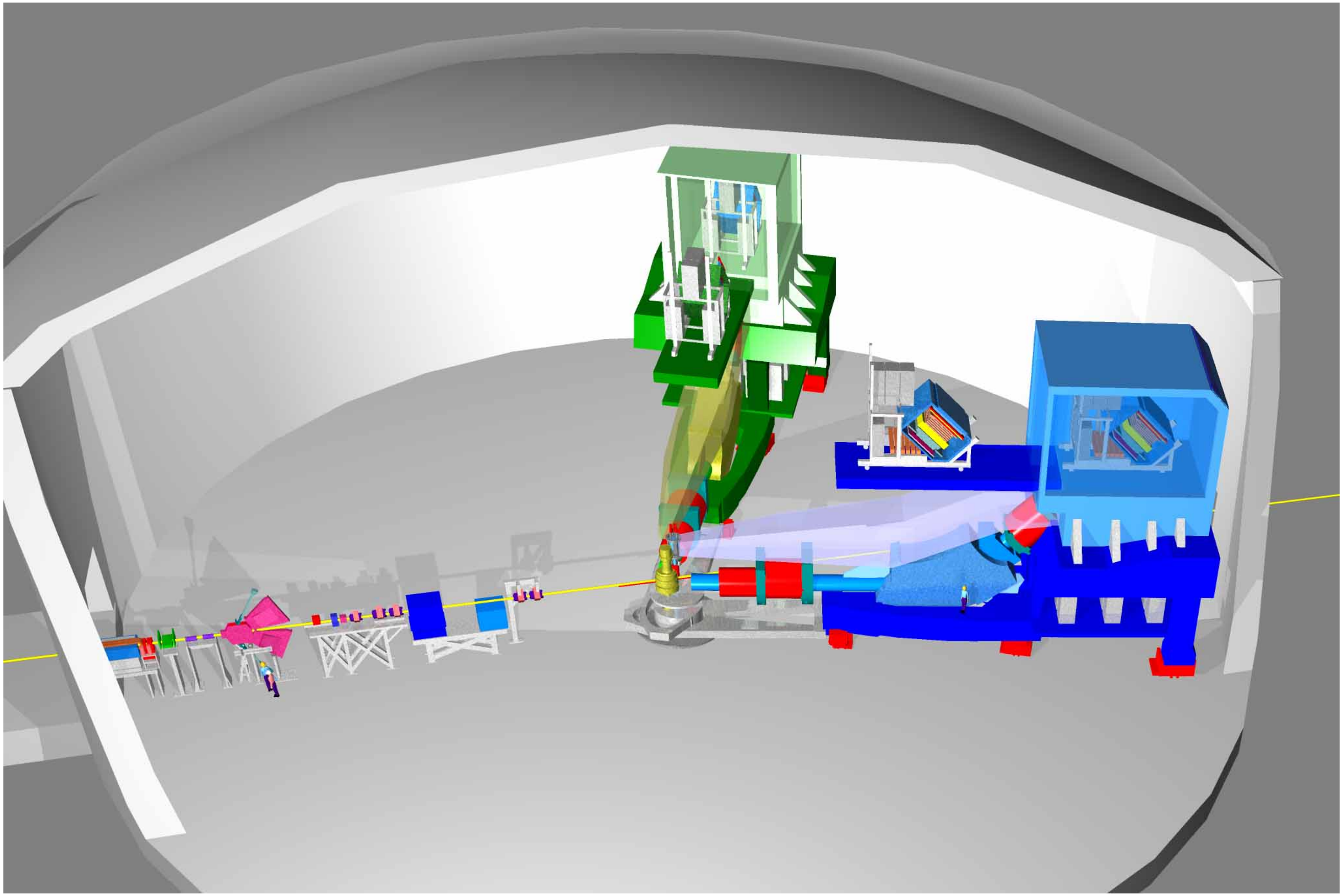

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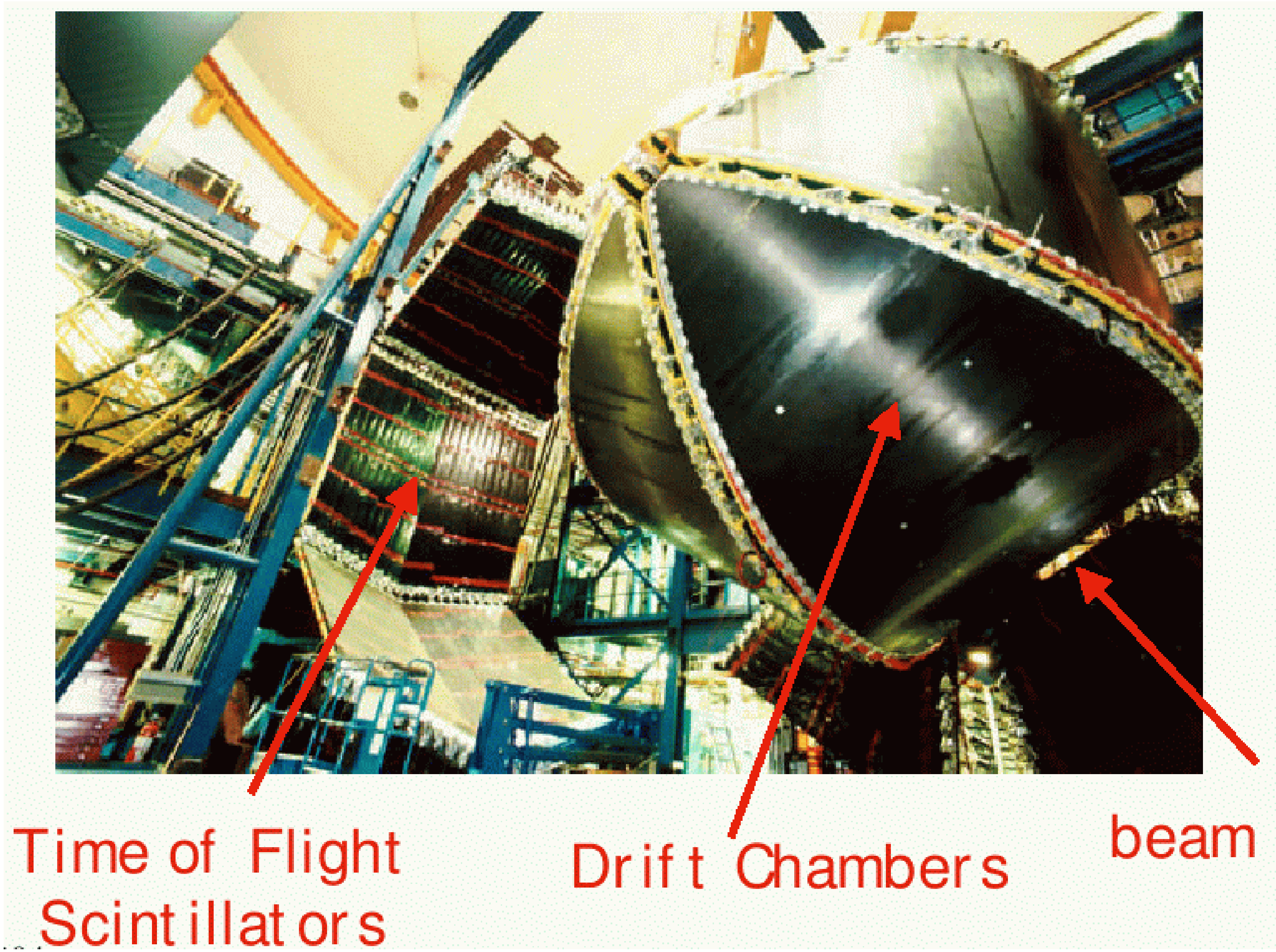

Lepton-Nucleon Spin Physics

exp	E_b (GeV)	x	Q^2 (GeV^2)	P_b
HERMES	27.6 $e^{\pm}$	0.02-0.6	1 - 15	$\pm$0.55
COMPASS	160 μ	0.003 - 0.6	1 - 100	-0.76
JLAB	<6 e^{-}	0.1 - 0.7	1 - 4.5	$\pm$0.7

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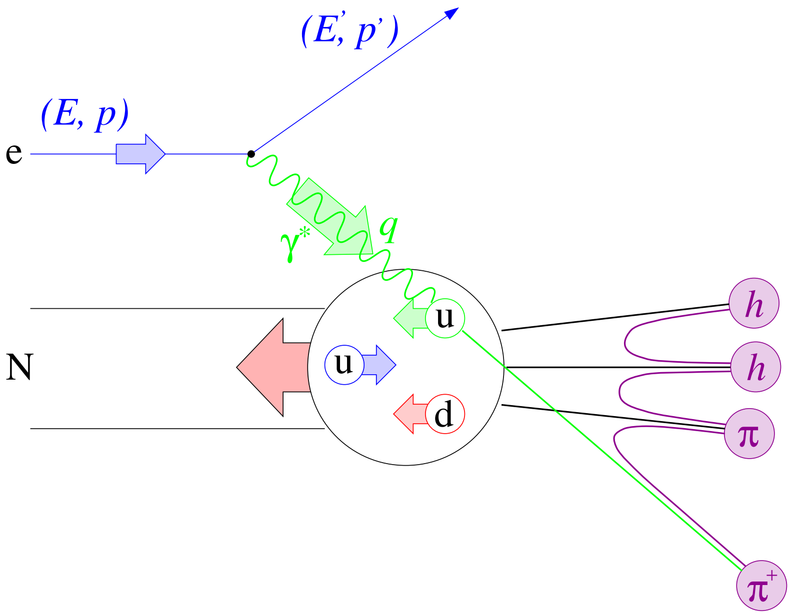
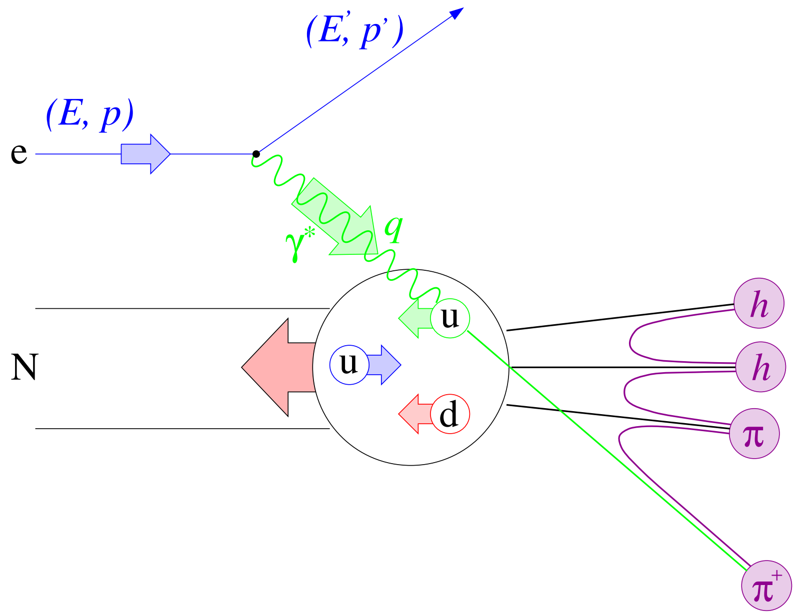
exp	P_t	target	$\mathcal{L}$ (cm^{-2}s^{-1})
HERMES	0.85	$\vec{\mathrm{H}}, \vec{\mathrm{D}}$	10^{31}
COMPASS	0.50	$\vec{\mathrm{Li}}\vec{\mathrm{D}}$	$5 \cdot 10^{32}$
Hall A	0.35	$^3\vec{\mathrm{He}}$	10^{36}
CLAS	0.8 (0.3)	NH_3 (ND_3)	10^{34}

Helicity distributions



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

Helicity distributions



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

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$$+ i\epsilon^{\mu\nu\lambda\sigma} \frac{q_\lambda}{\nu} \left(S_\sigma g_1(x,Q^2) + \frac{1}{\nu}(p\cdot q S_\sigma - S\cdot q p_\sigma) g_2(x,Q^2)\right)$$

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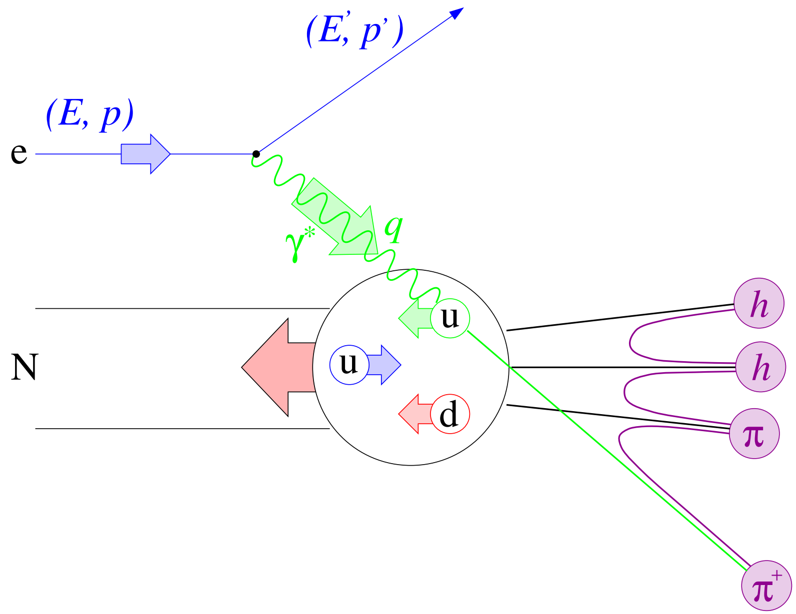

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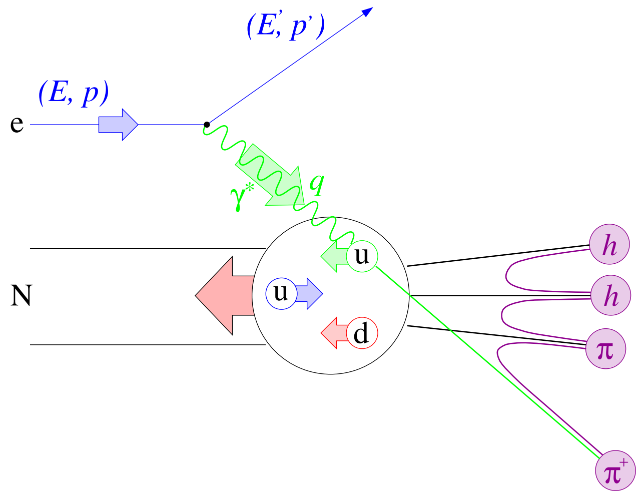
- g_1, g_2: polarized structure functions
  $\Rightarrow$ spin structure from quark spin

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 [q^+(x) - q^-(x)] = \frac{1}{2}\sum_q e_q^2 \Delta q(x)$$

Helicity distributions



Measure: $A_{\parallel} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}}$

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

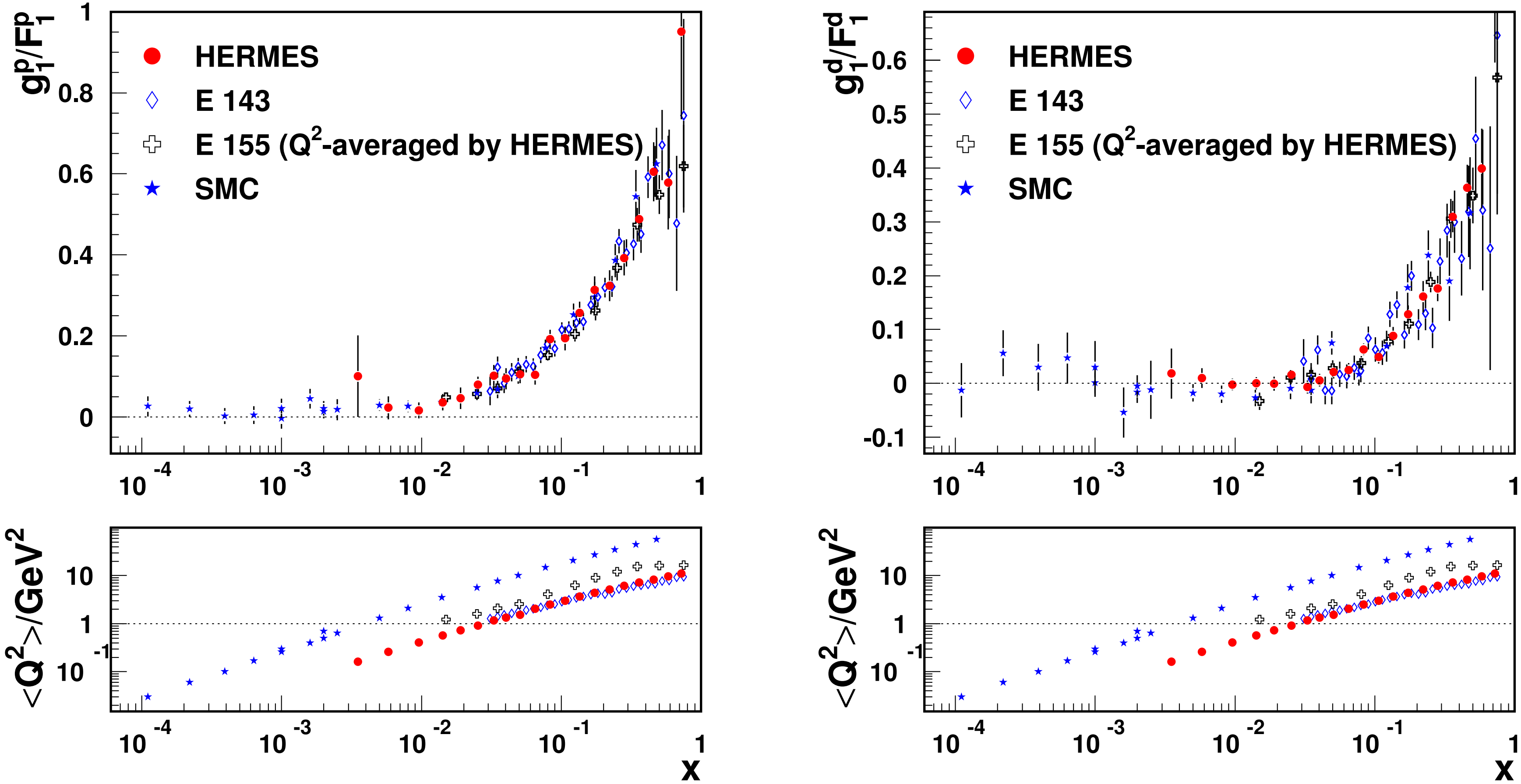
$$A_{\parallel} = D.(A_1 + \eta A_2)$$

$$D = \frac{y(2-y)}{y^2 + 2(1-y)(1+R)}$$

$$R = \frac{\sigma_L}{\sigma_T}$$

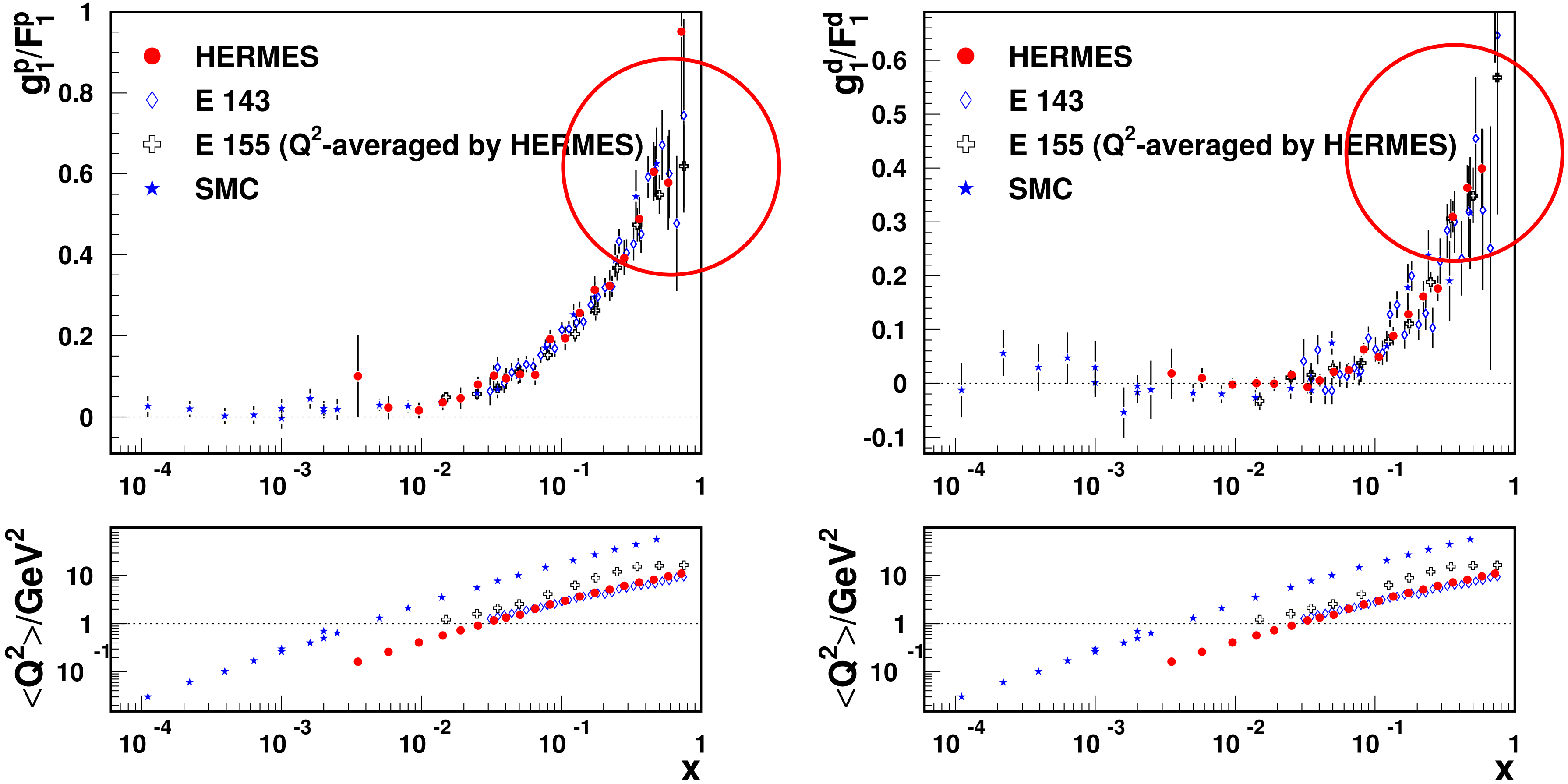
$$\frac{g_1}{F_1} = \frac{1}{1+\gamma^2}\left(\frac{A_{\parallel}}{D} - (\eta - \gamma)A_2\right)$$

Helicity distribution



→ talk by D.Reggiani

Helicity distribution



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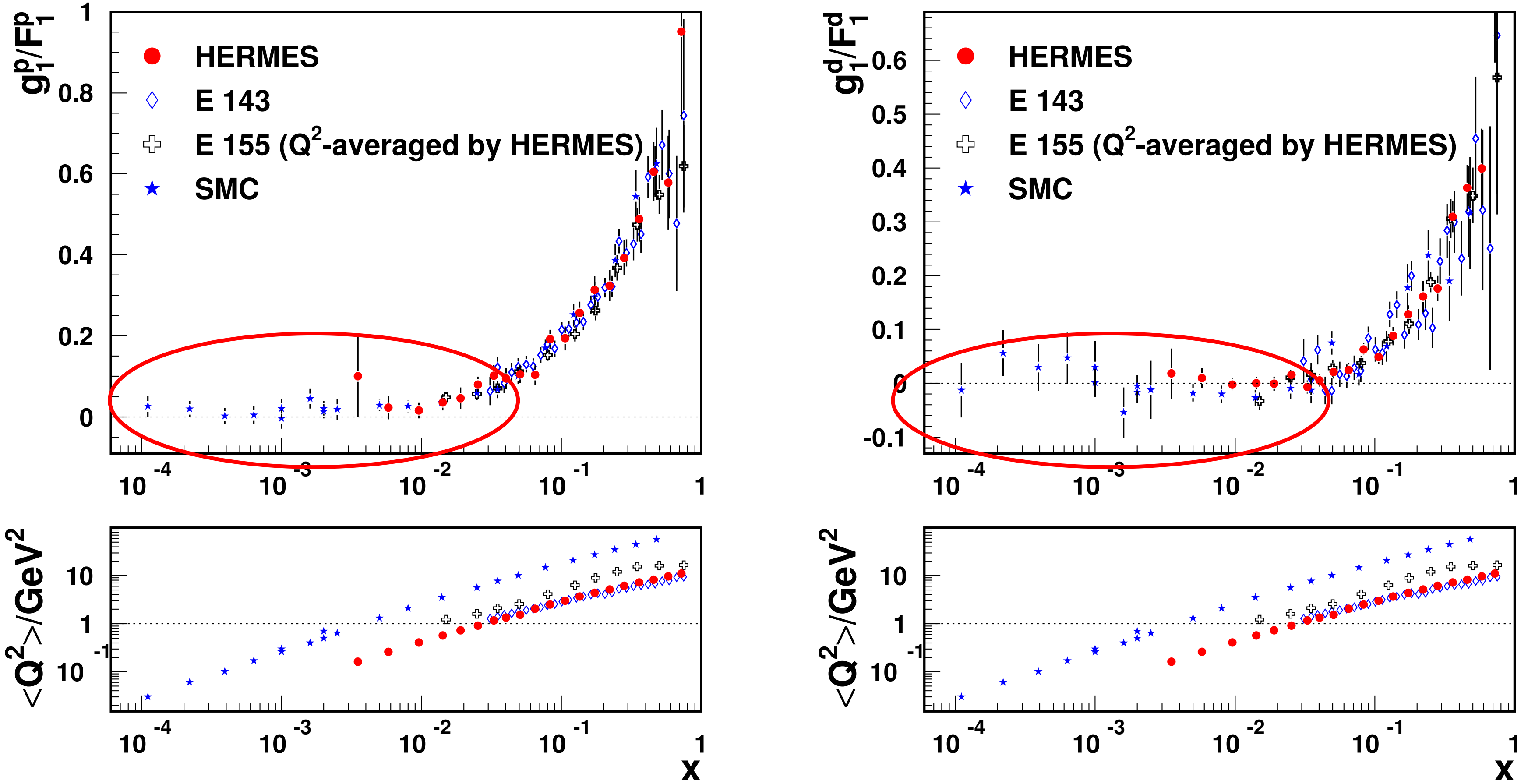
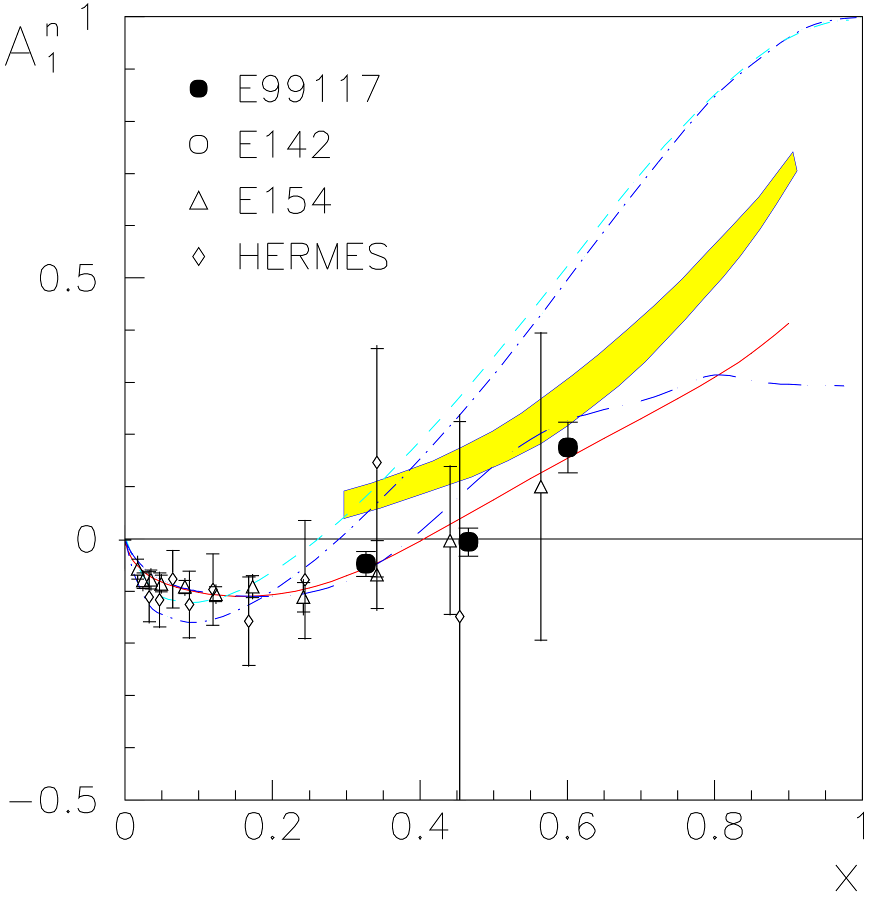


A_1 @ high x



Hall A @ JLAB

PRL 92, 012004 (2004)

PRC 70, 065207 (2004)

→ talk by J-P. Chen

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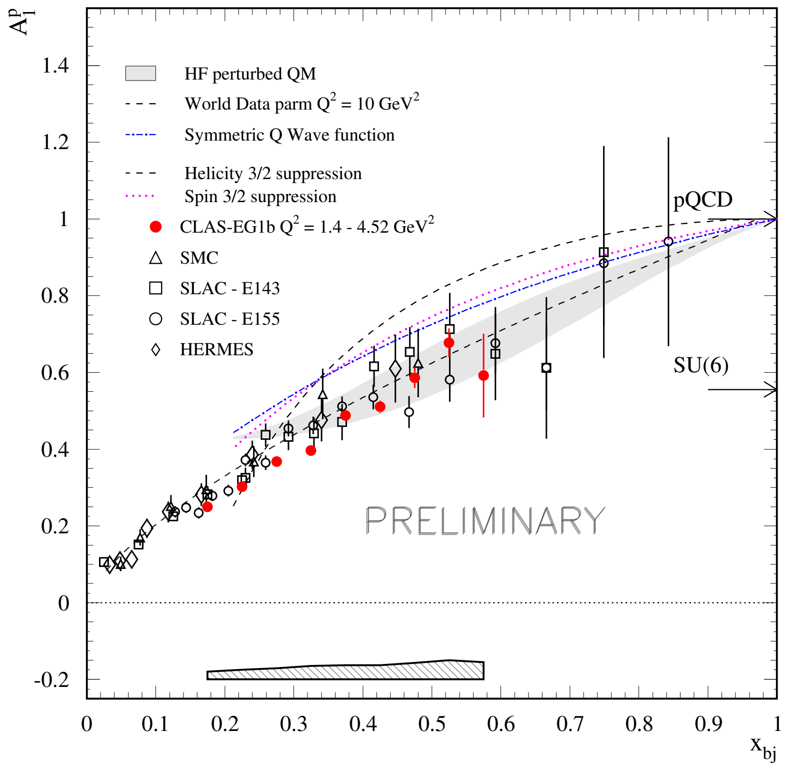
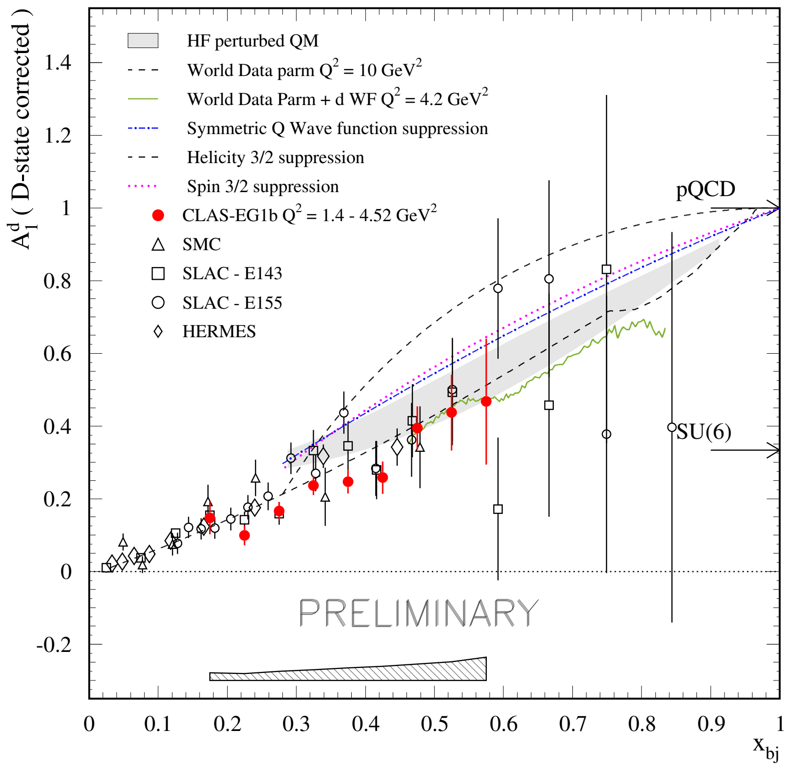
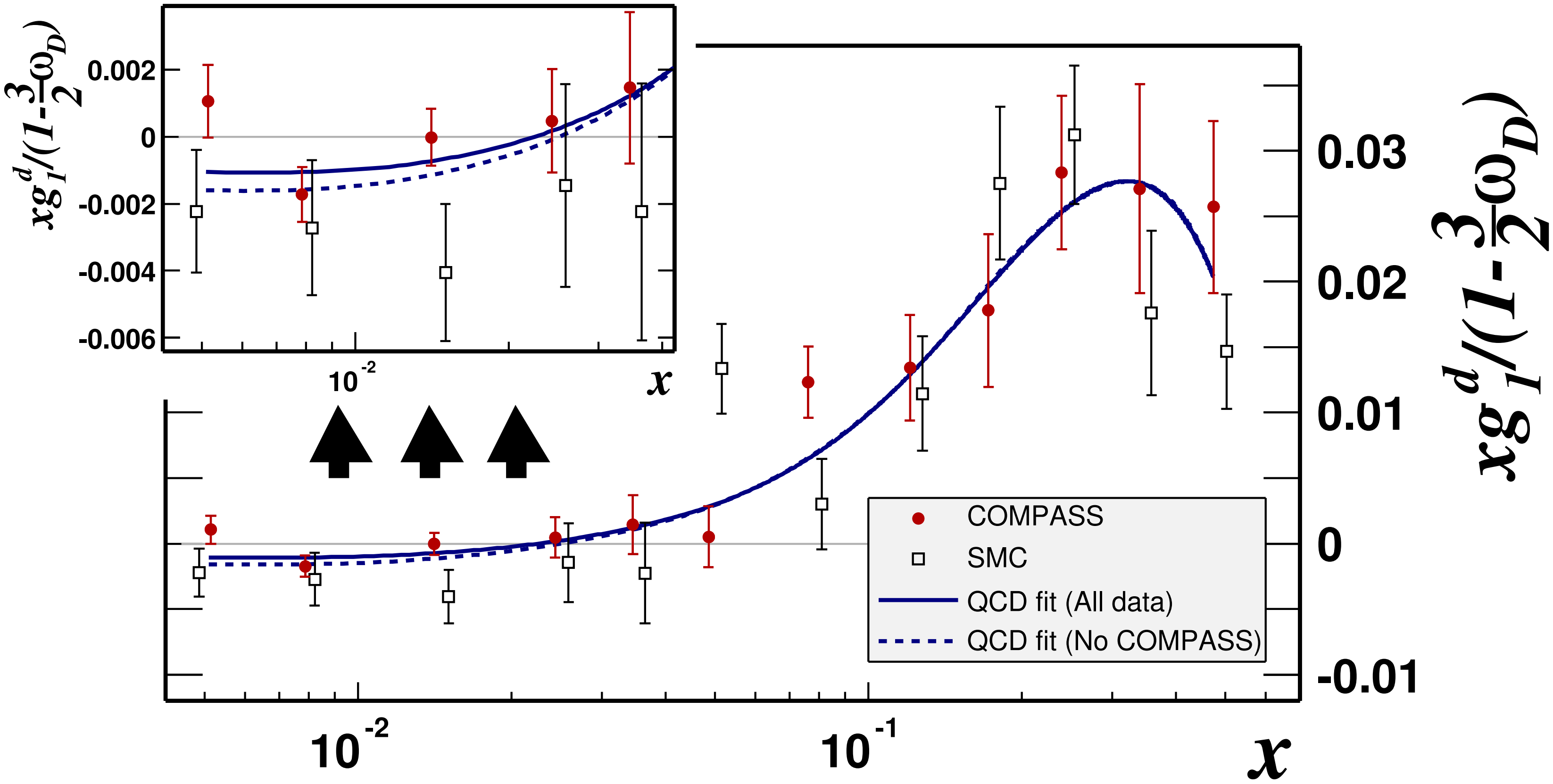




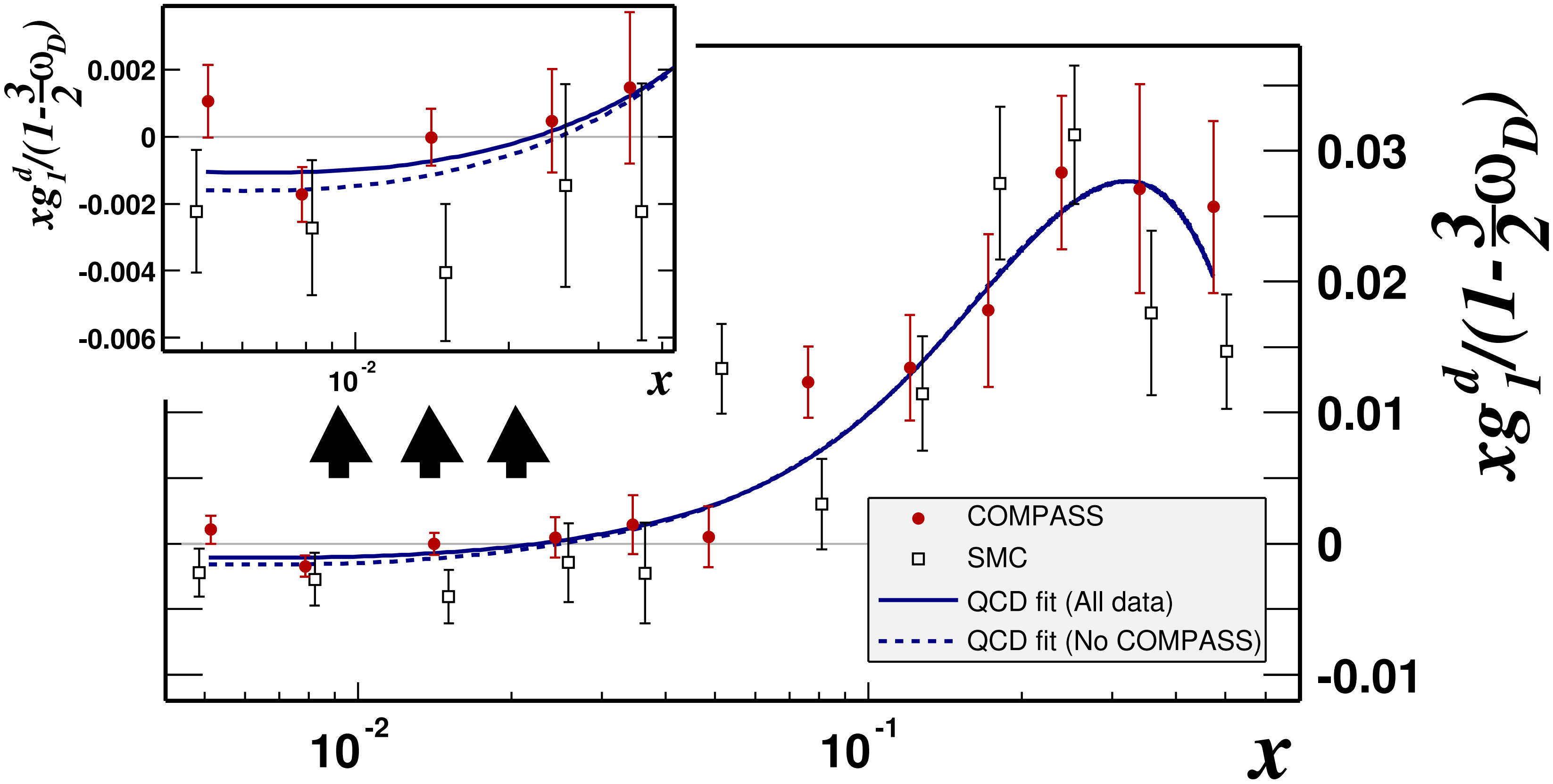
CLAS @ JLAB

g_1 @ low x



→ talk by J.Hannappel

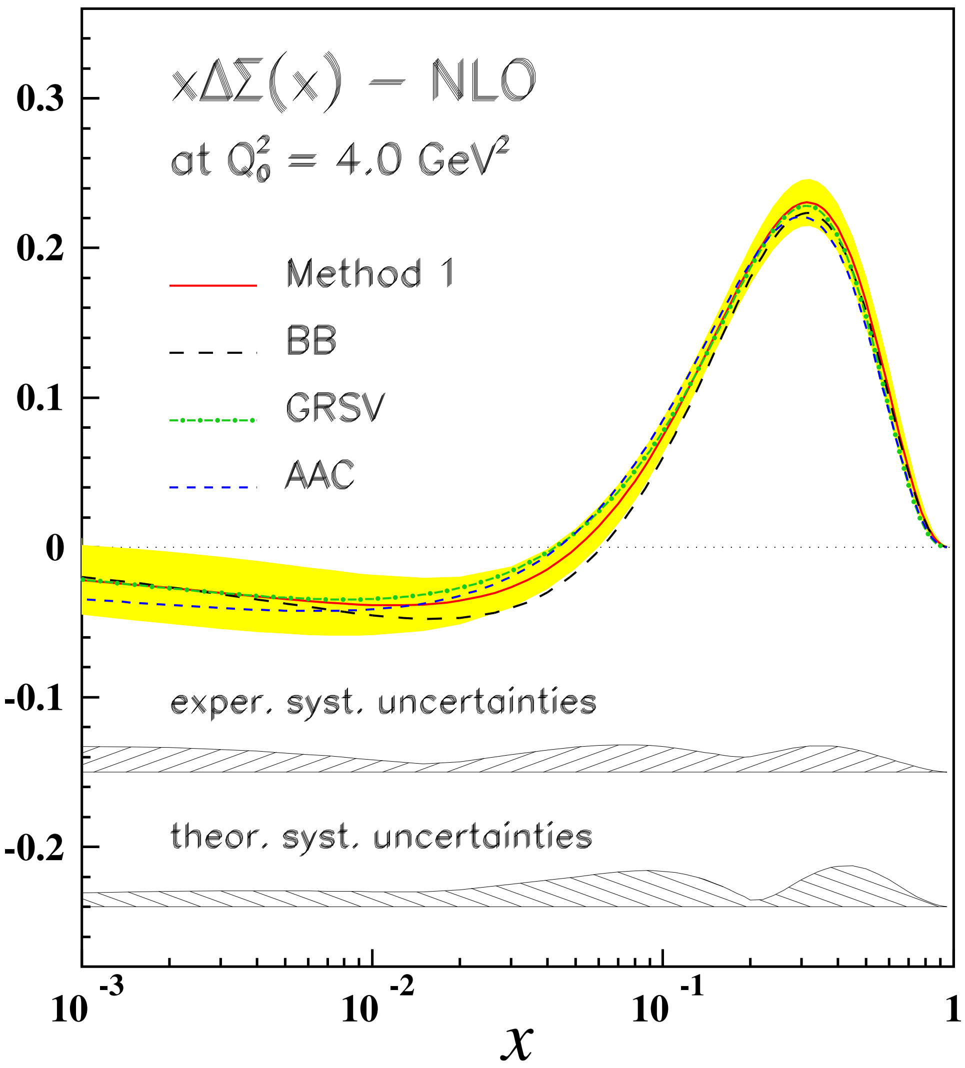
g_1 @ low x



Important for low-x extrapolation $\Rightarrow \Delta\Sigma$

$$\Delta\Sigma(Q^2 = 4) = 0.202^{+0.042}_{-0.077} \rightarrow 0.237^{+0.024}_{-0.029}$$

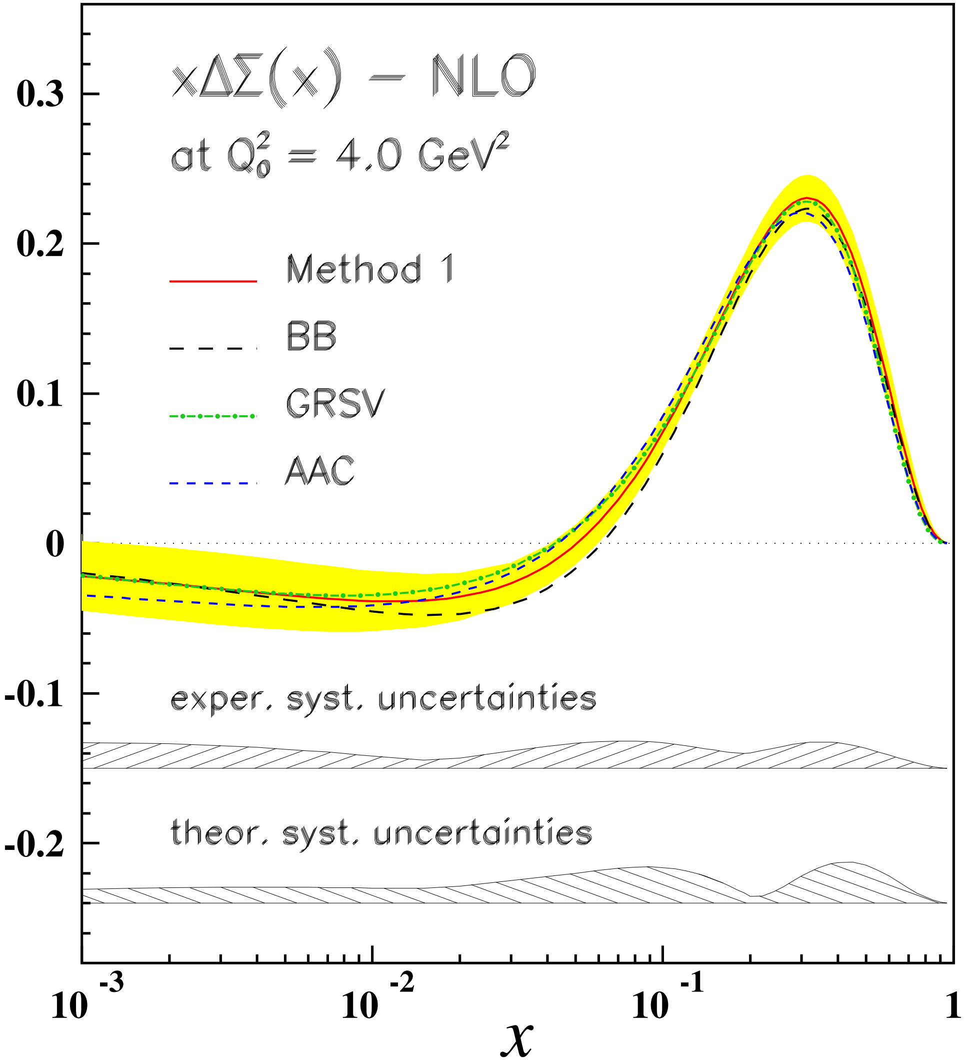
NLO - QCD fit



Blümlein & Böttcher

HERMES preliminary

NLO - QCD fit

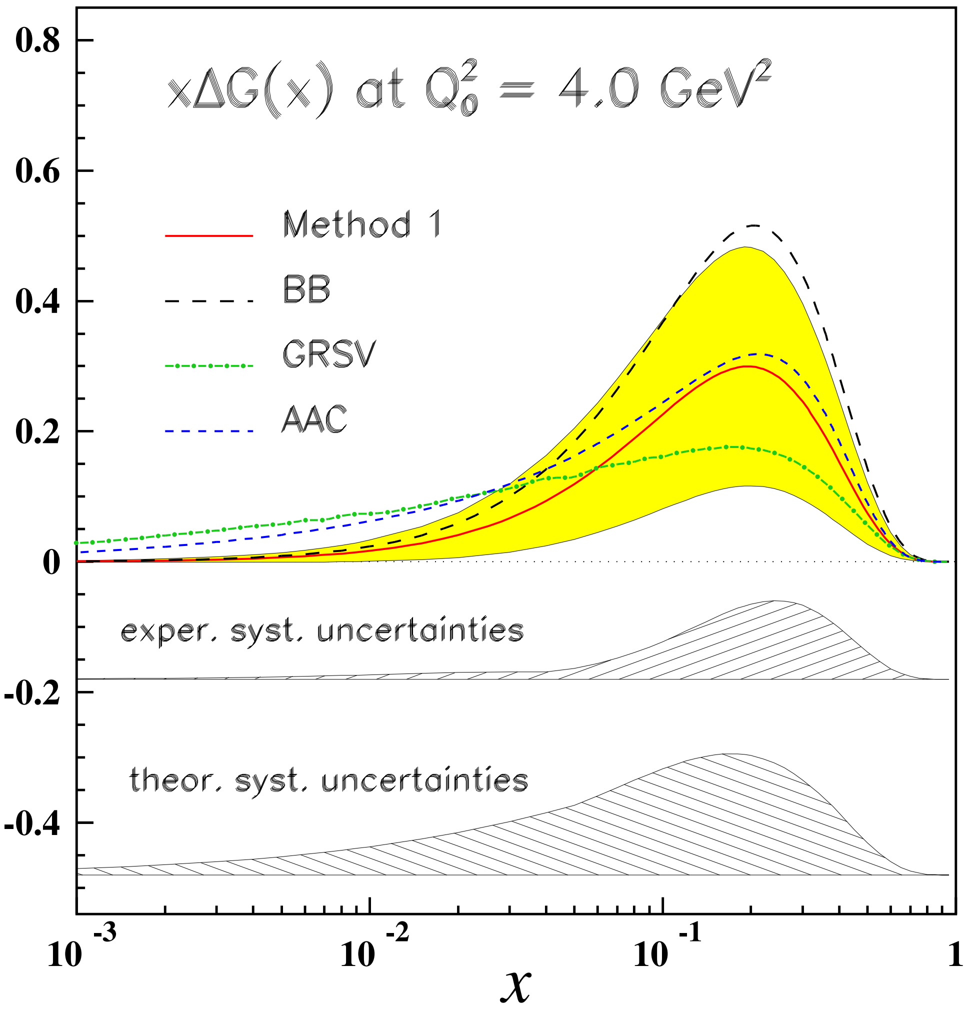


Blümlein & Böttcher

HERMES preliminary

- Well established in valence region
- Extrapolation to $x \to 0$ problematic
- $\Delta\Sigma = 0.14 \cdots 0.20$

NLO - QCD fit



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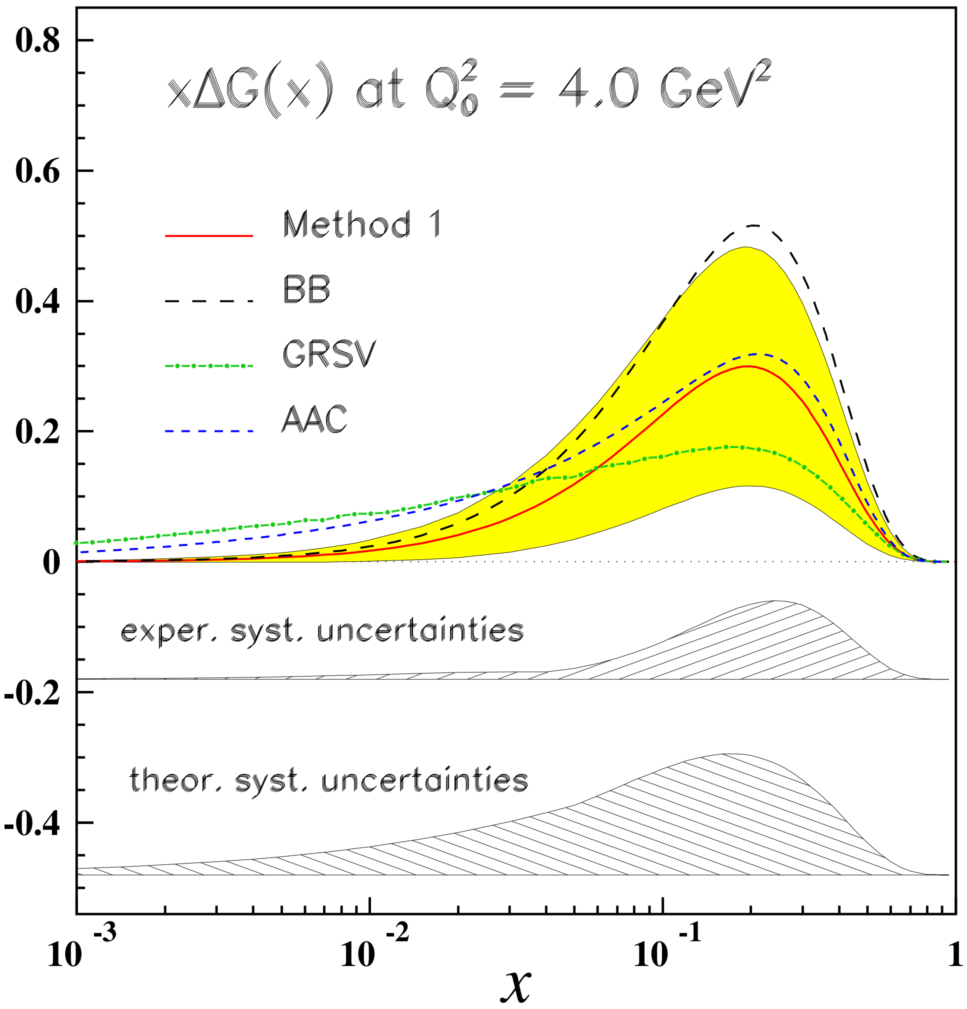

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HERMES preliminary

- Large uncertainties
- $\Delta G = 0.68 \cdots 1.26$

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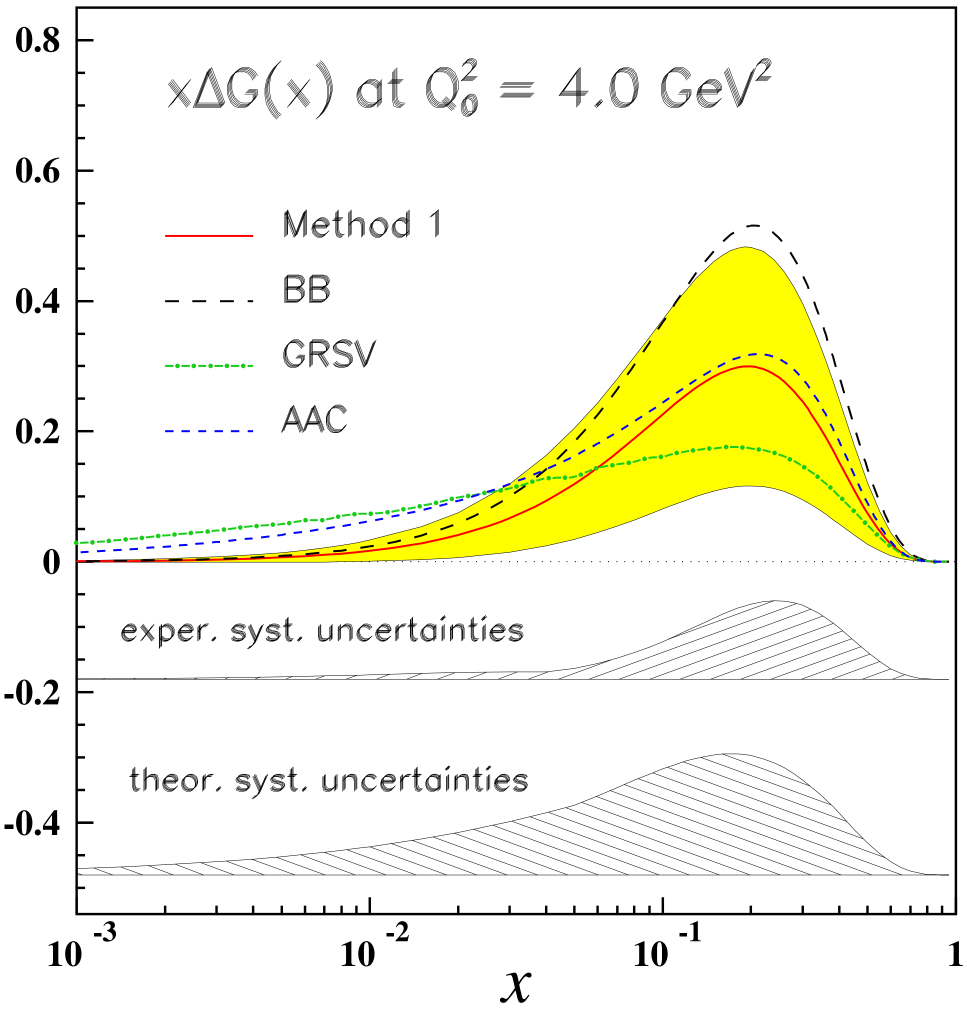

Blümlein & Böttcher

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Need direct method

Photon-gluon fusion

Use fluctuation of g into $q\bar{q}$ to interact with γ^*

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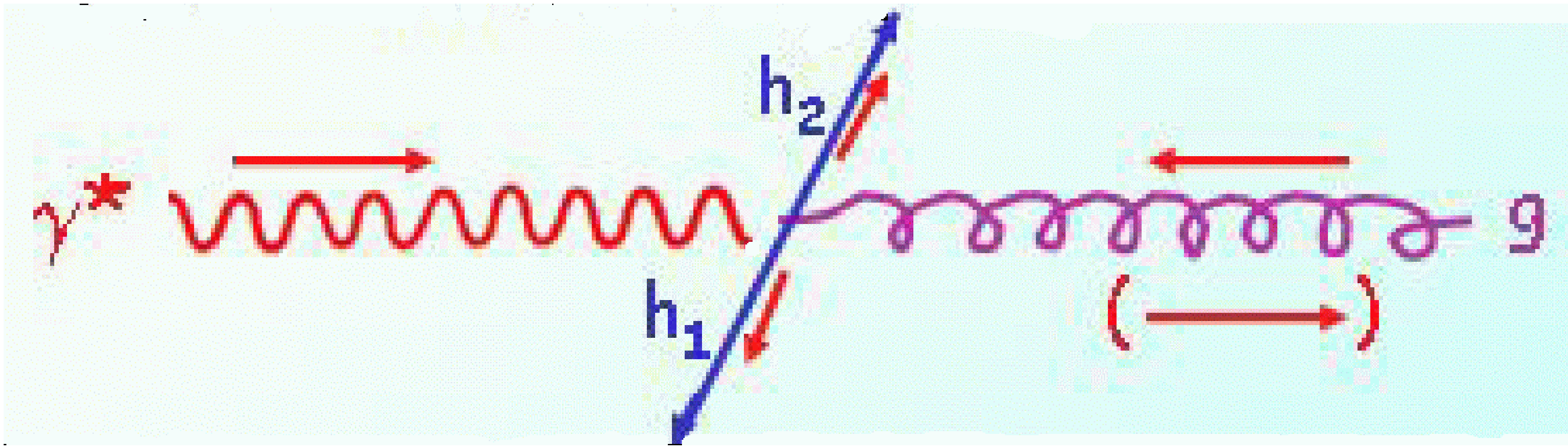
Tag through:

- production of high-p_T hadrons
- (open-)charm production



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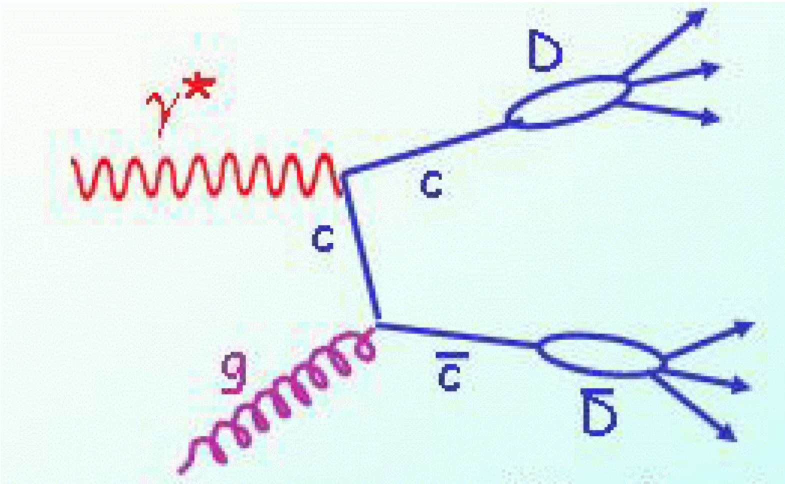
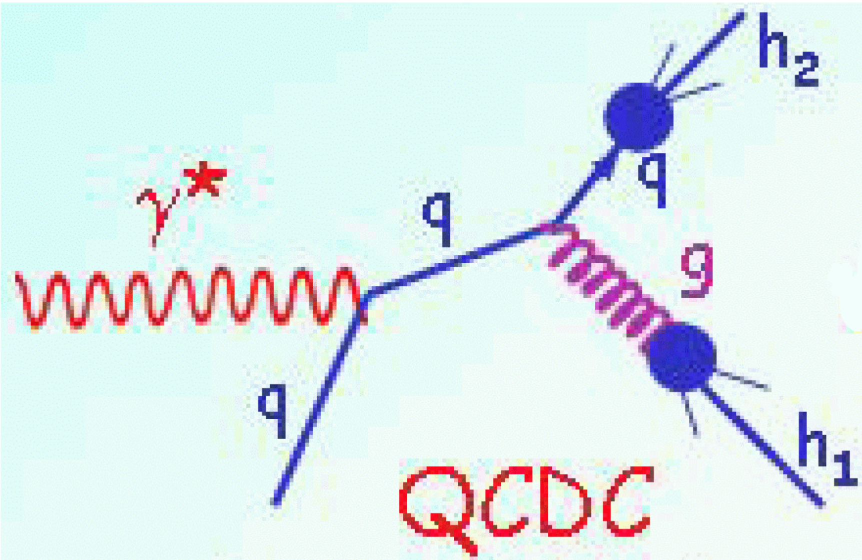
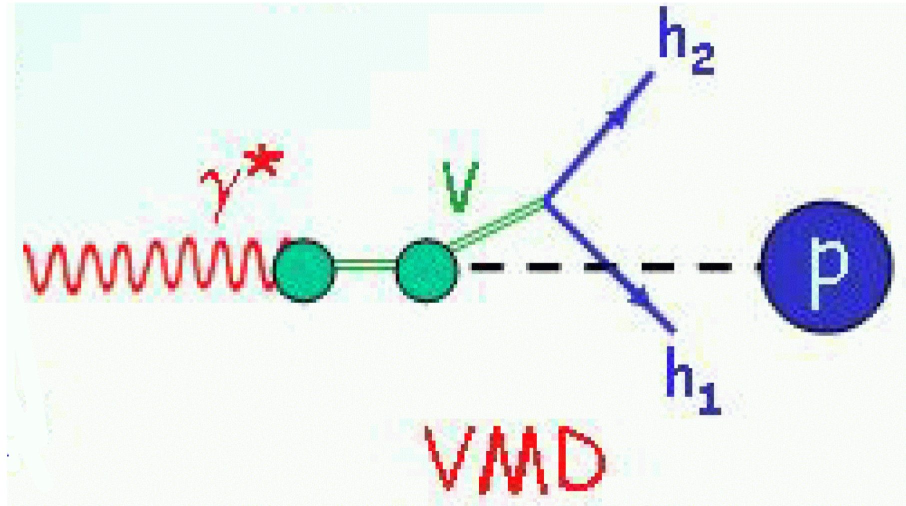


High-p_T pairs

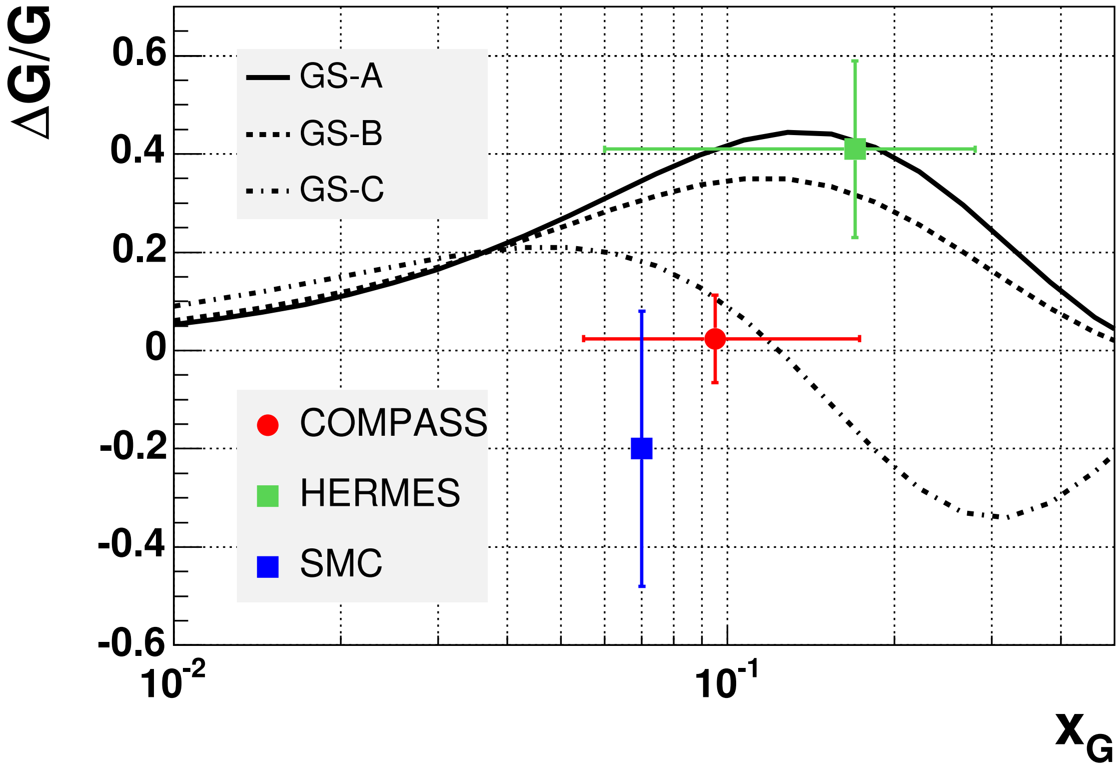
Competing mechanisms generate background





- Relative contributions
- from model (HERMES)
- Individual asymmetries
- small (COMPASS)

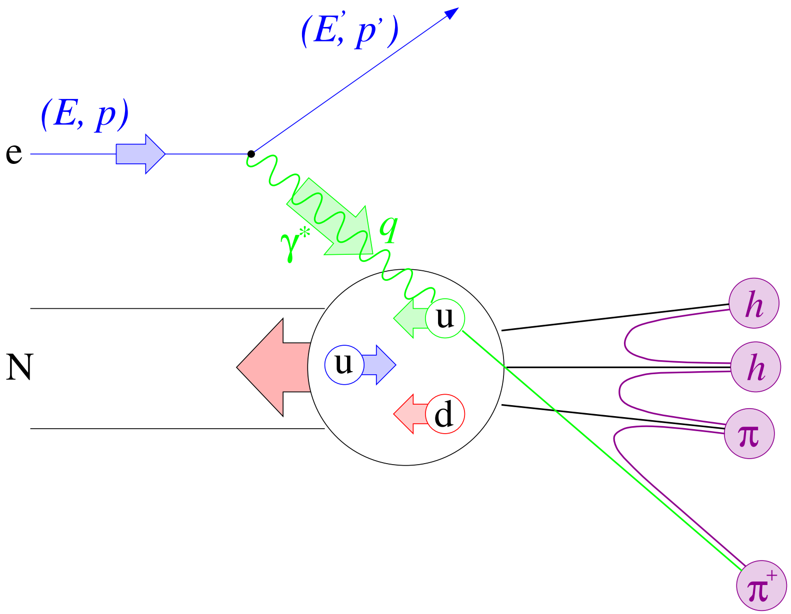
Gluon polarization



- Large ΔG less likely: $\Delta G \approx 0.5$
- 2004 data of COMPASS still to come

$\rightarrow$ talk by C.Bernet

g_2 structure function



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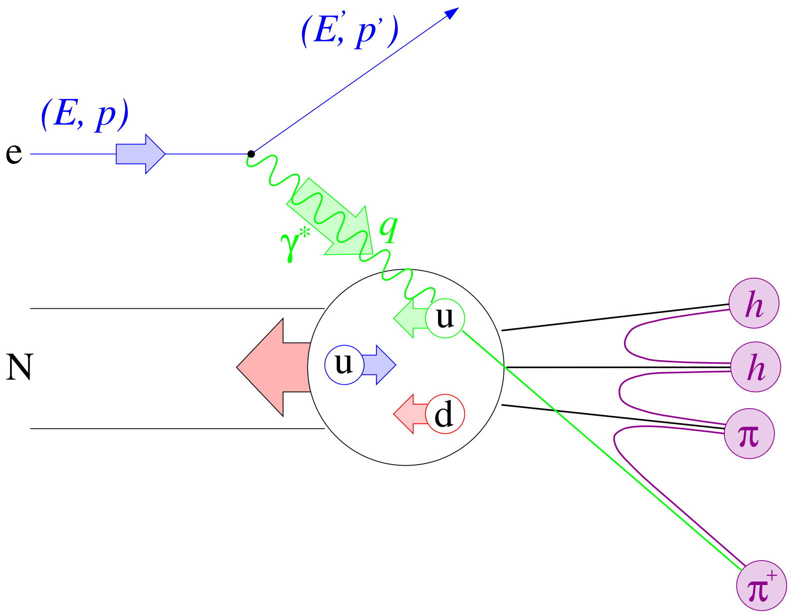

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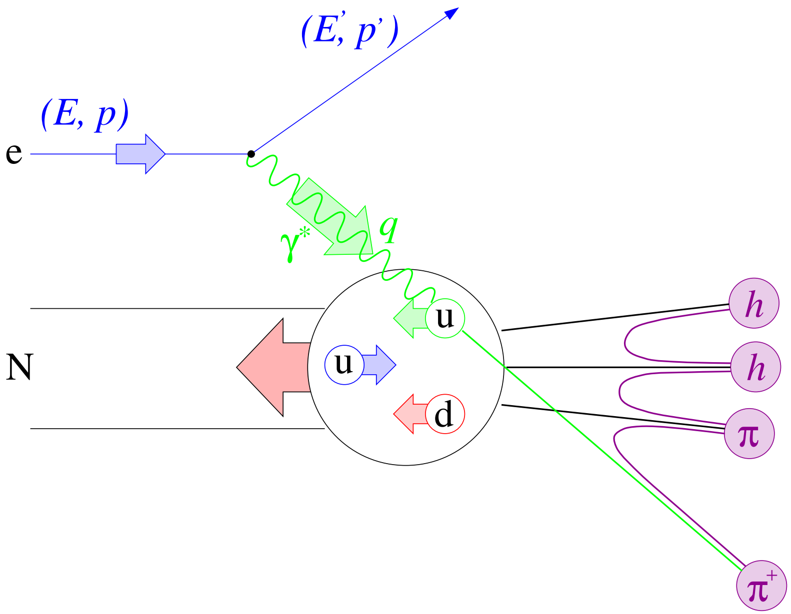

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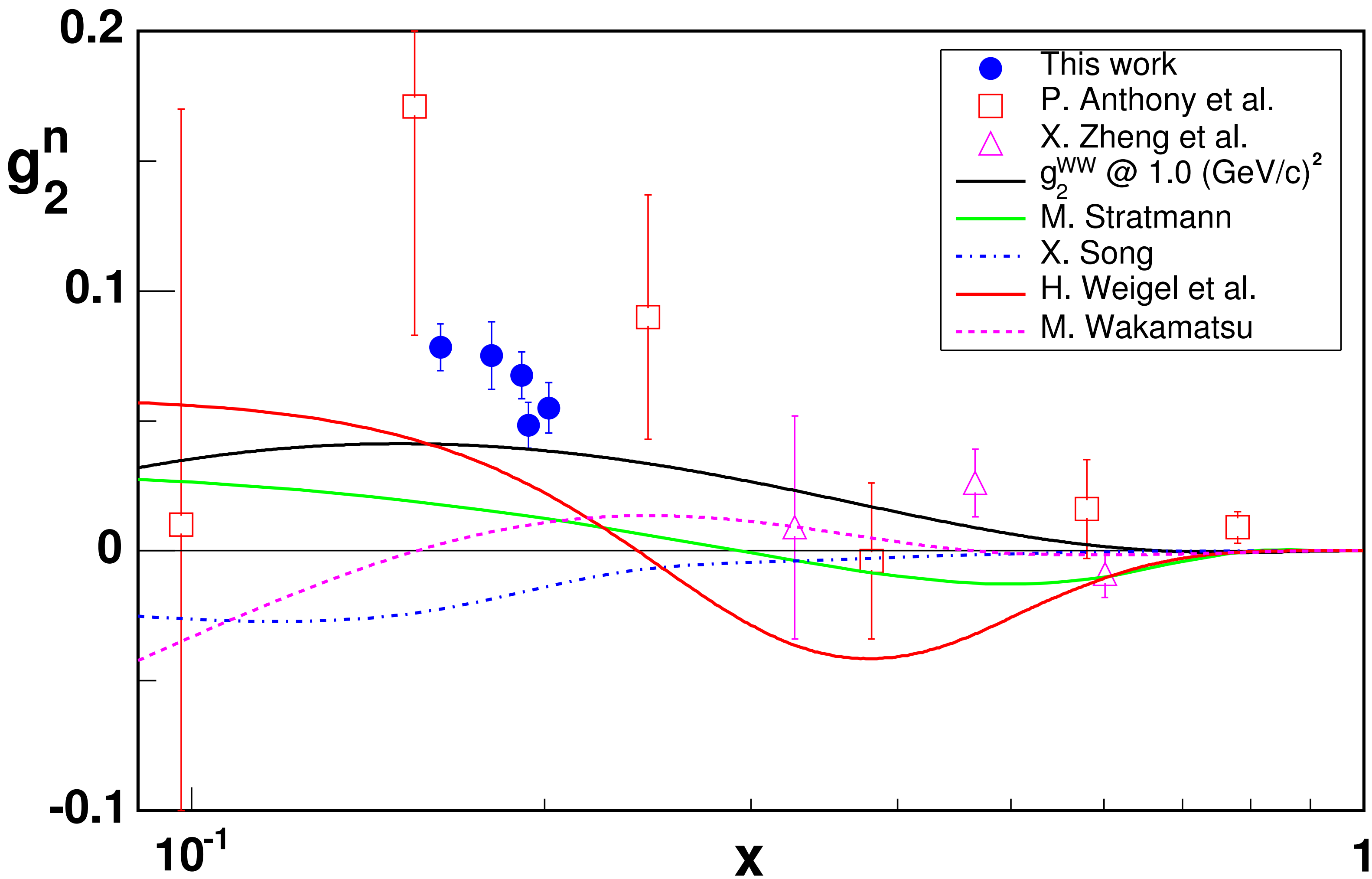
- $g_2(x) = -g_1(x) + \int_x^1 g_1(x')dx'/x' + \tilde{g}_2(x) = g_2^{WW}(x) + \tilde{g}_2(x)$
- $\tilde{g}_2(x)$: twist-3 operator

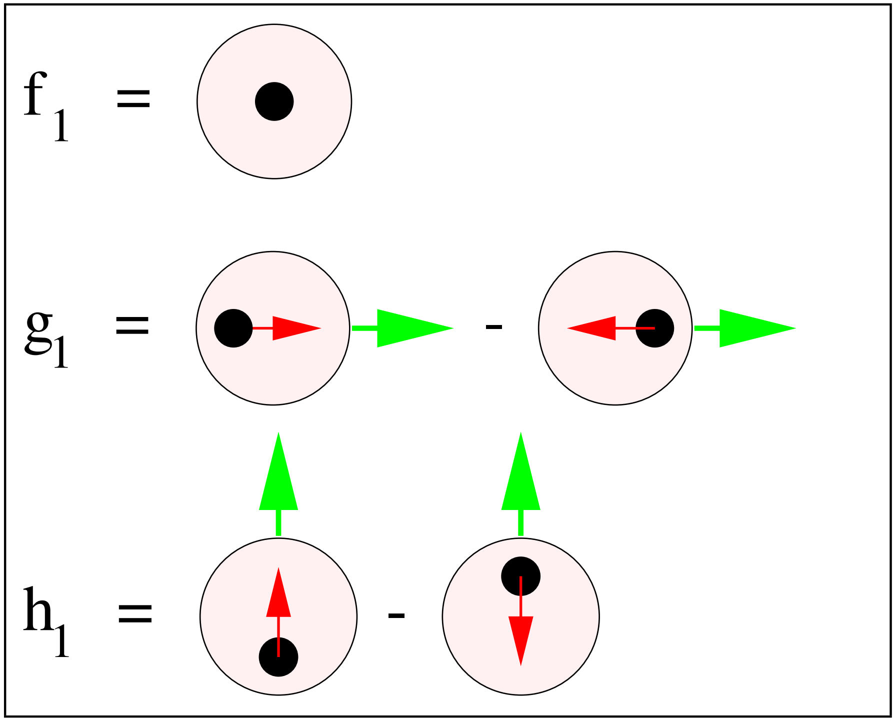
g_2 structure function



→ talks by J-P.Chen, T.Signal

Transversity $h_1(x)$

Complete description of nucleon in leading order QCD:
3 Distribution Functions



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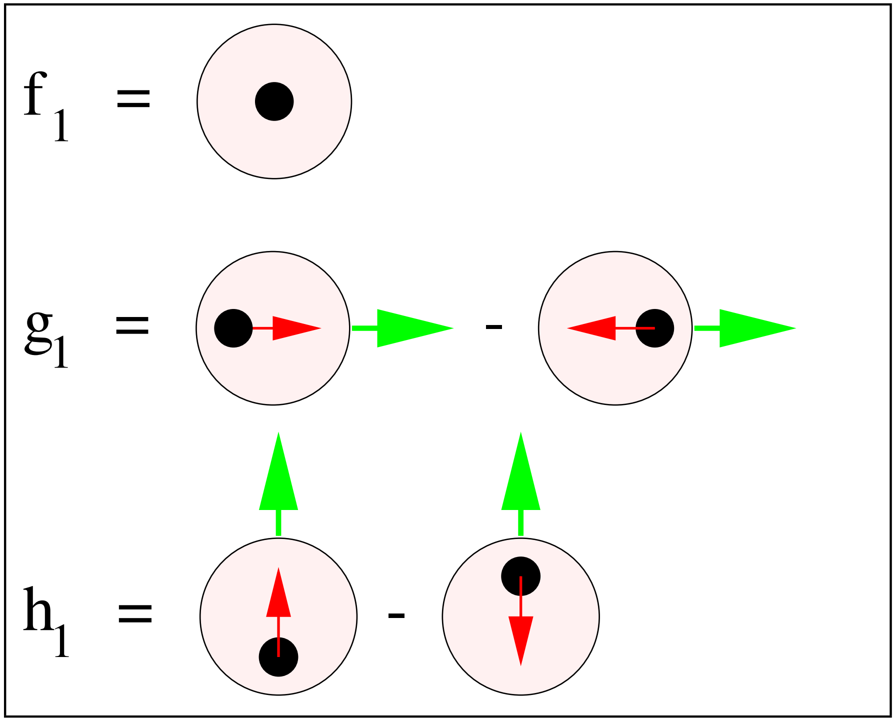

$\sim \tilde{\psi}\gamma^{\mu}\psi$

$\sim \tilde{\psi}\gamma^{\mu}\gamma_5\psi$

$\sim \tilde{\psi}\sigma^{\mu\nu}\gamma_5\psi$

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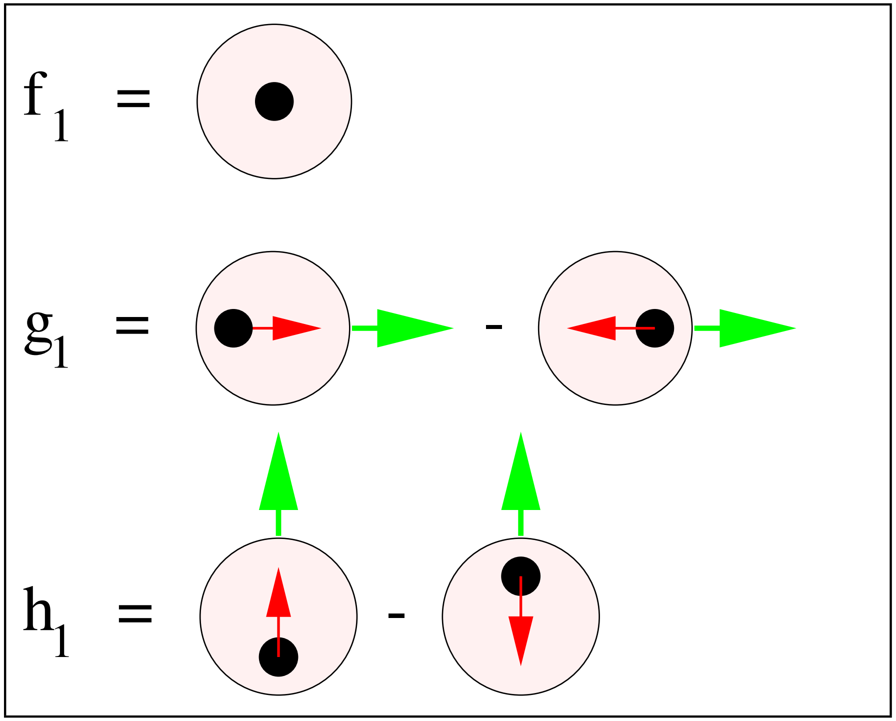

$\sim \tilde{\psi}\gamma^{\mu}\psi$ Quark density

$\sim \tilde{\psi}\gamma^{\mu}\gamma_5\psi$ Helicity

$\sim \tilde{\psi}\sigma^{\mu\nu}\gamma_5\psi$ Transversity

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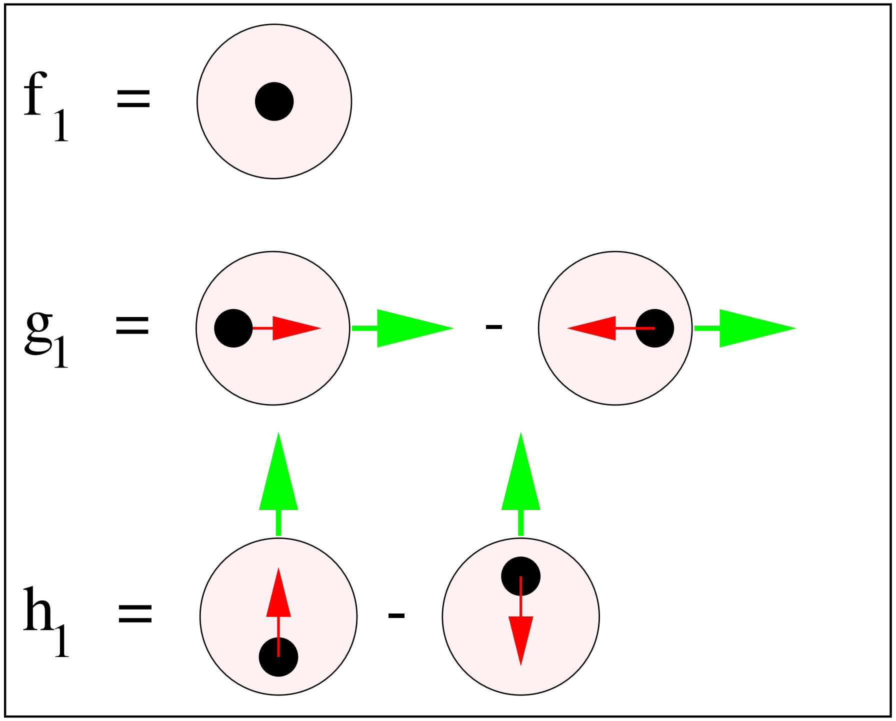

$\sim \tilde{\psi}\gamma^{\mu}\psi$ Vector charge

$\sim \tilde{\psi}\gamma^{\mu}\gamma_5\psi$ Axial charge

$\sim \tilde{\psi}\sigma^{\mu\nu}\gamma_5\psi$ Tensor charge

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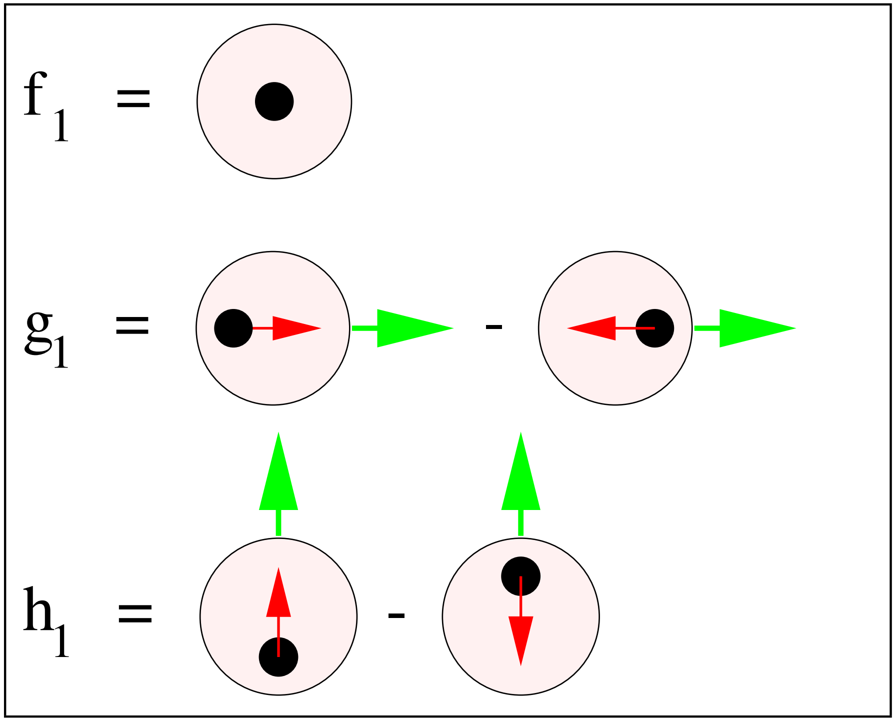

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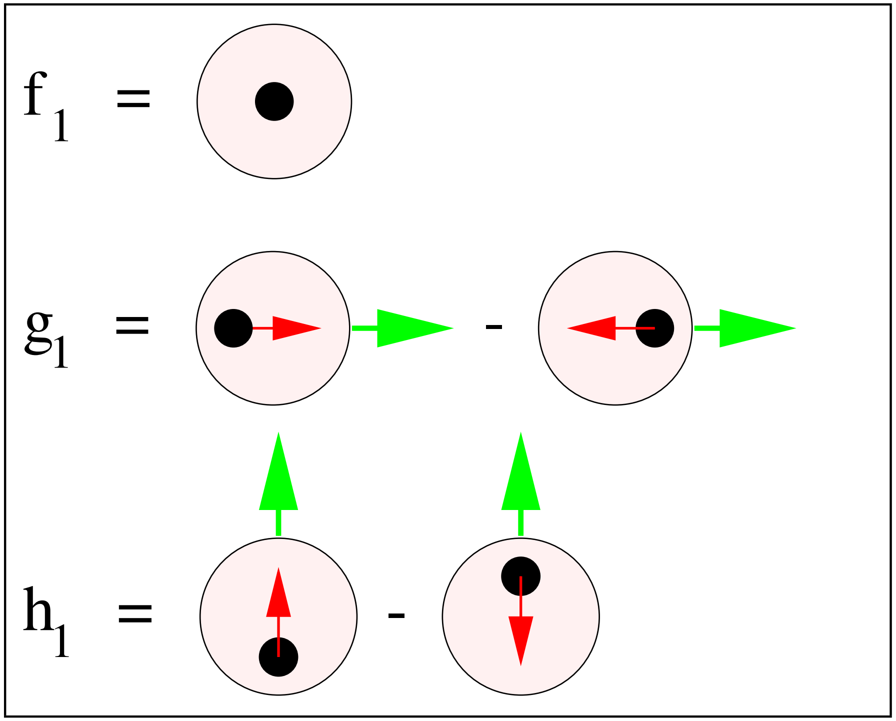

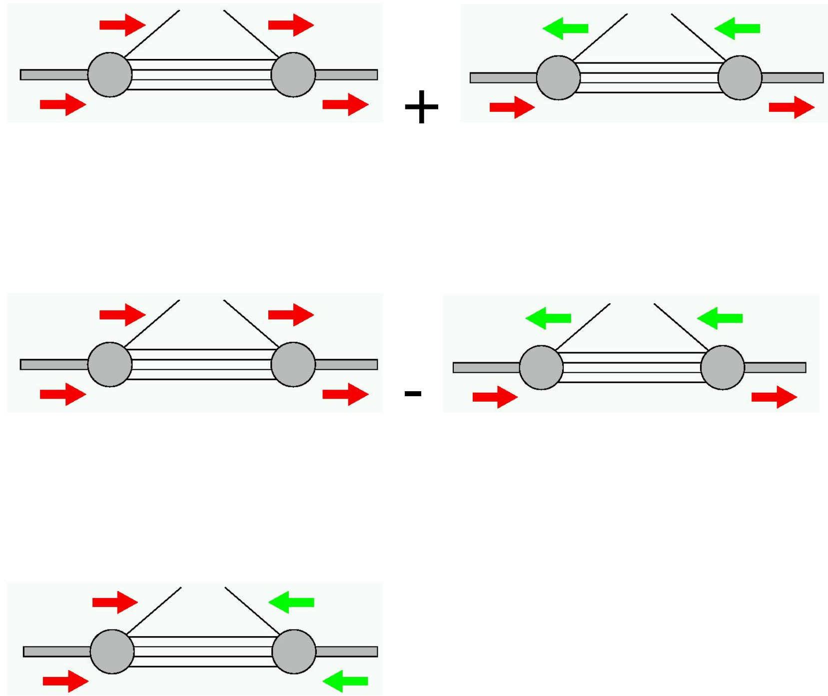

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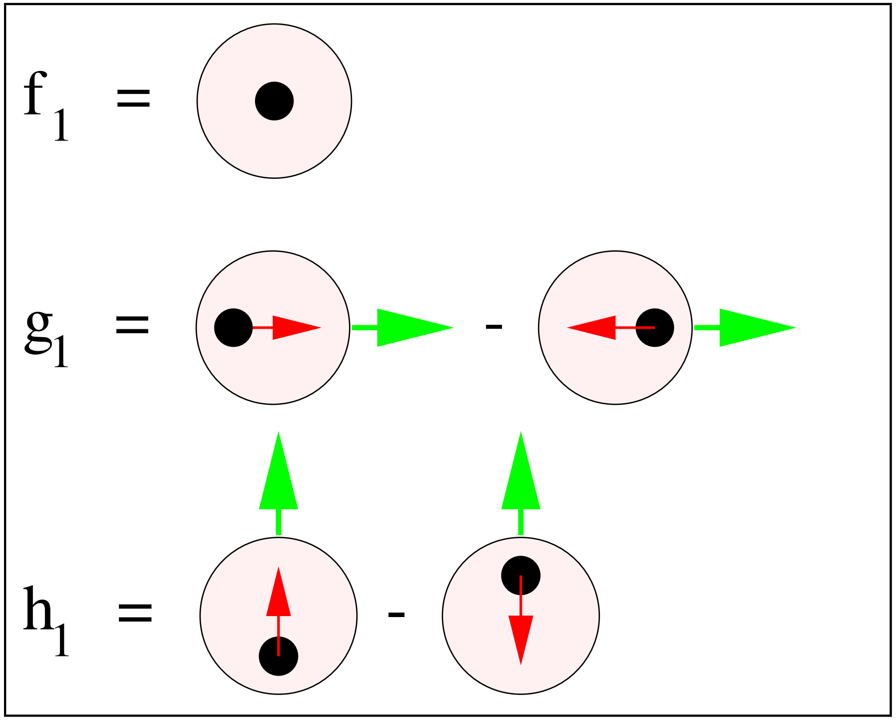

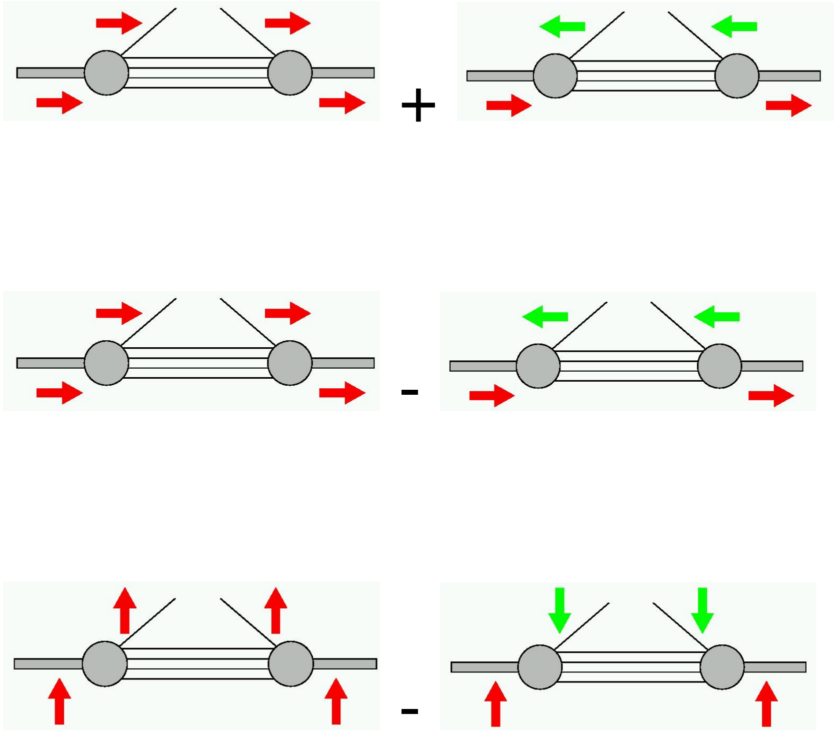

Transversity $h_1(x)$

- For relativistic quarks: $h_1^q(x) \neq g_1^q(x)$

Transversity $h_1(x)$

- For relativistic quarks: $\delta q(x) \neq \Delta q(x)$

Transversity $h_1(x)$

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Transversity $h_1(x)$

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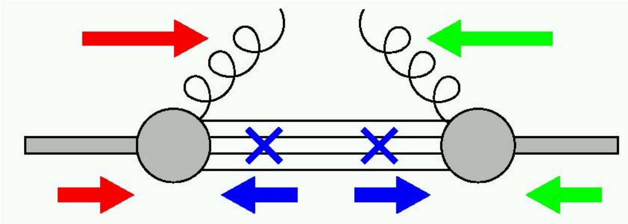
- Decouples from gluons: 

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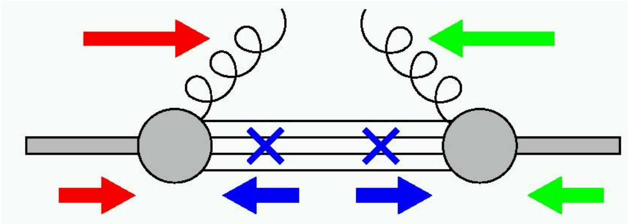
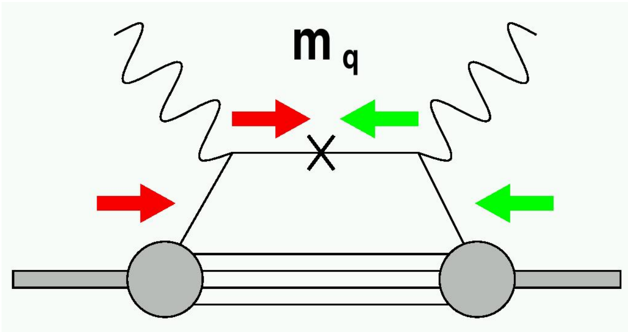


- Inaccessible in inclusive DIS



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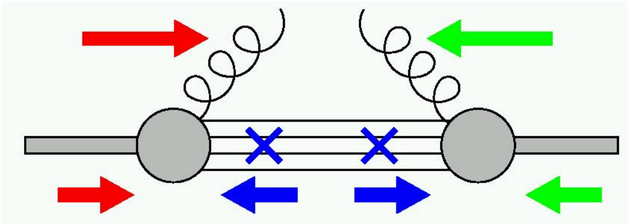
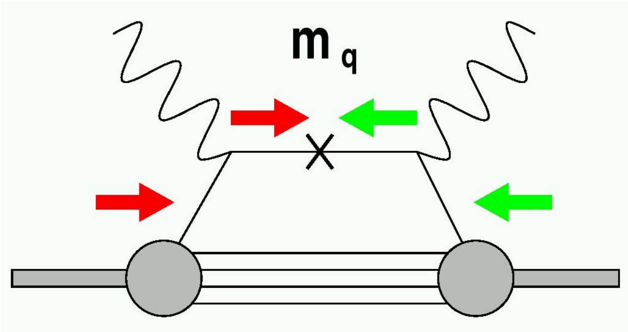
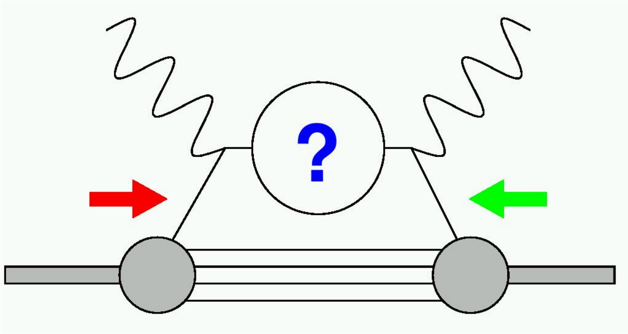
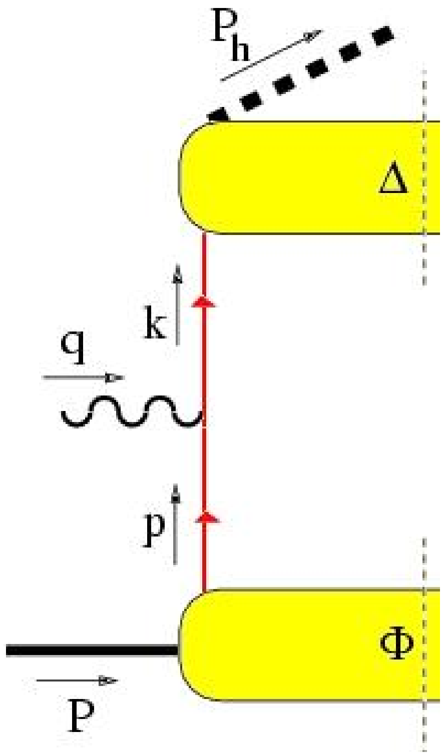
- Decouples from gluons: 
- Inaccessible in inclusive DIS 

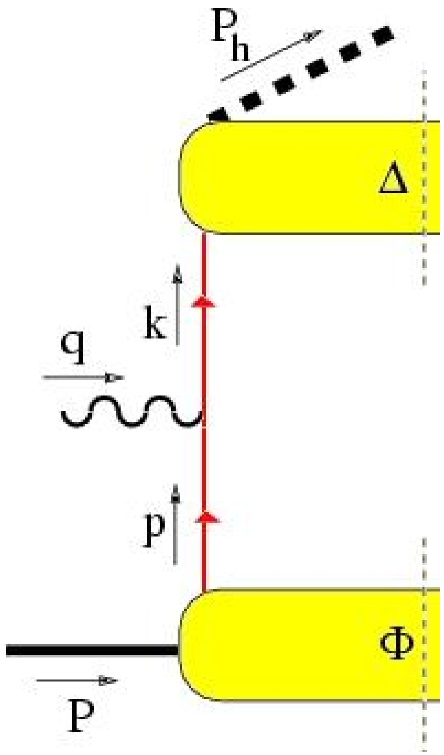
- Need e.g. fragmentation function 

Semi-inclusive DIS



$$\sigma^{ep\to ehX} = \sum_q f^{p\to q} \otimes \sigma^{eq\to eq} \otimes D^{q\to h}$$

Semi-inclusive DIS



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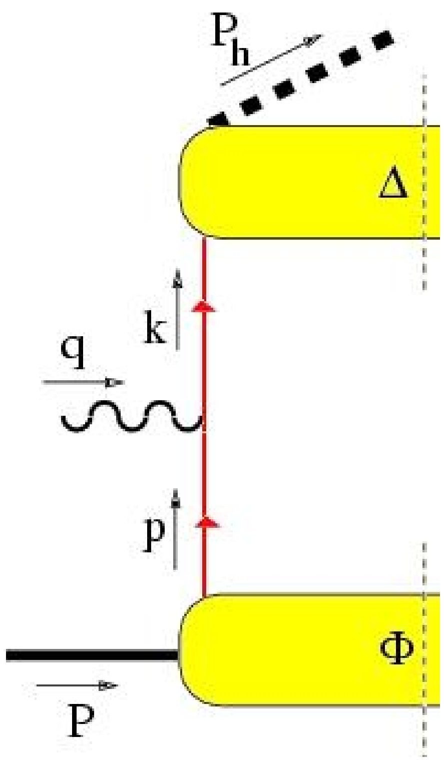
Longitudinally polarized: $g_1(x)$ $D_1(z)$

Semi-inclusive DIS



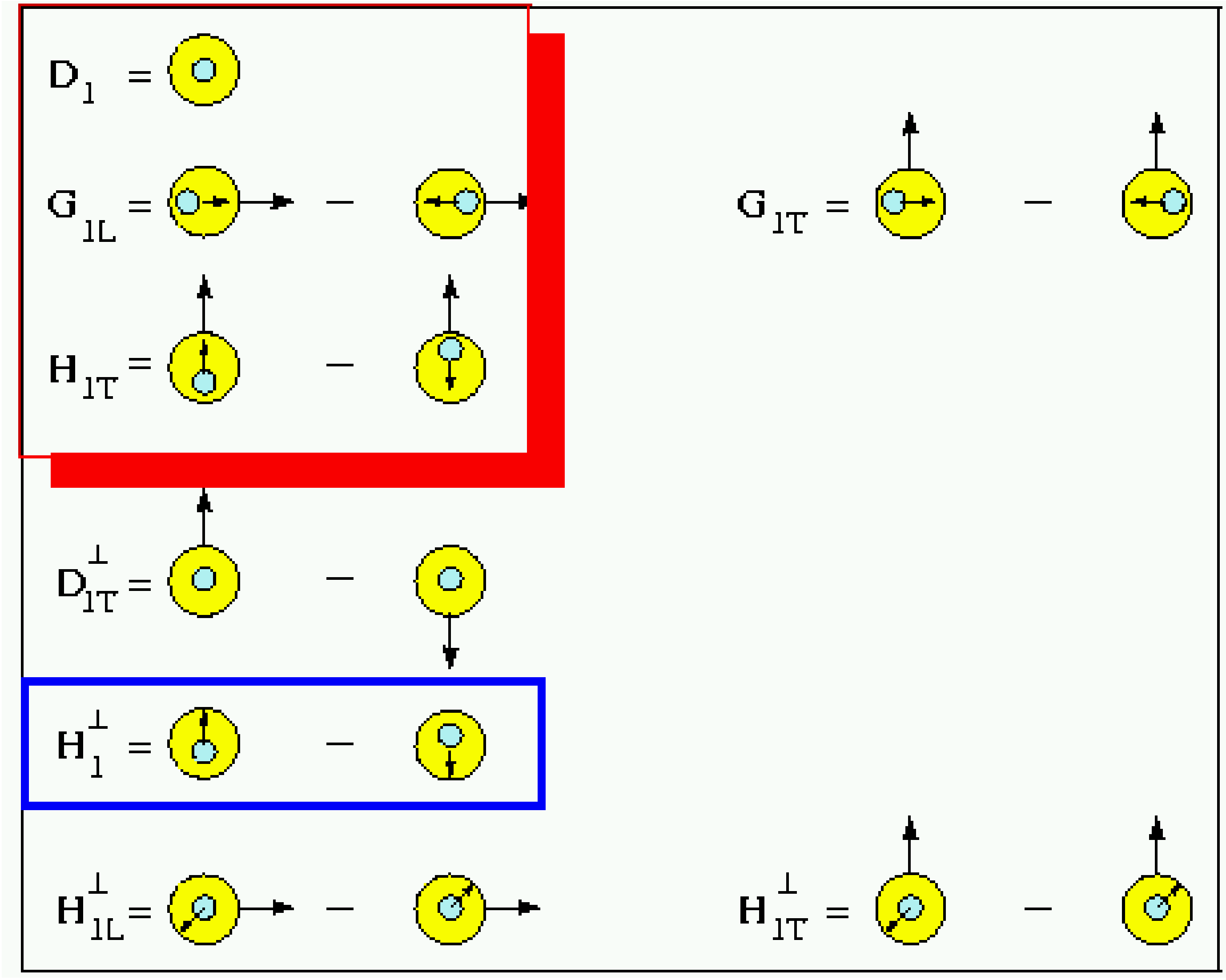
$$\sigma^{ep\to ehX} = \sum_q f^{p\to q} \otimes \sigma^{eq\to eq} \otimes D^{q\to h}$$

Longitudinally polarized: $g_1(x)$ $D_1(z)$

Transversely polarized: $h_1(x)$ $H_1^{\perp}(z)$

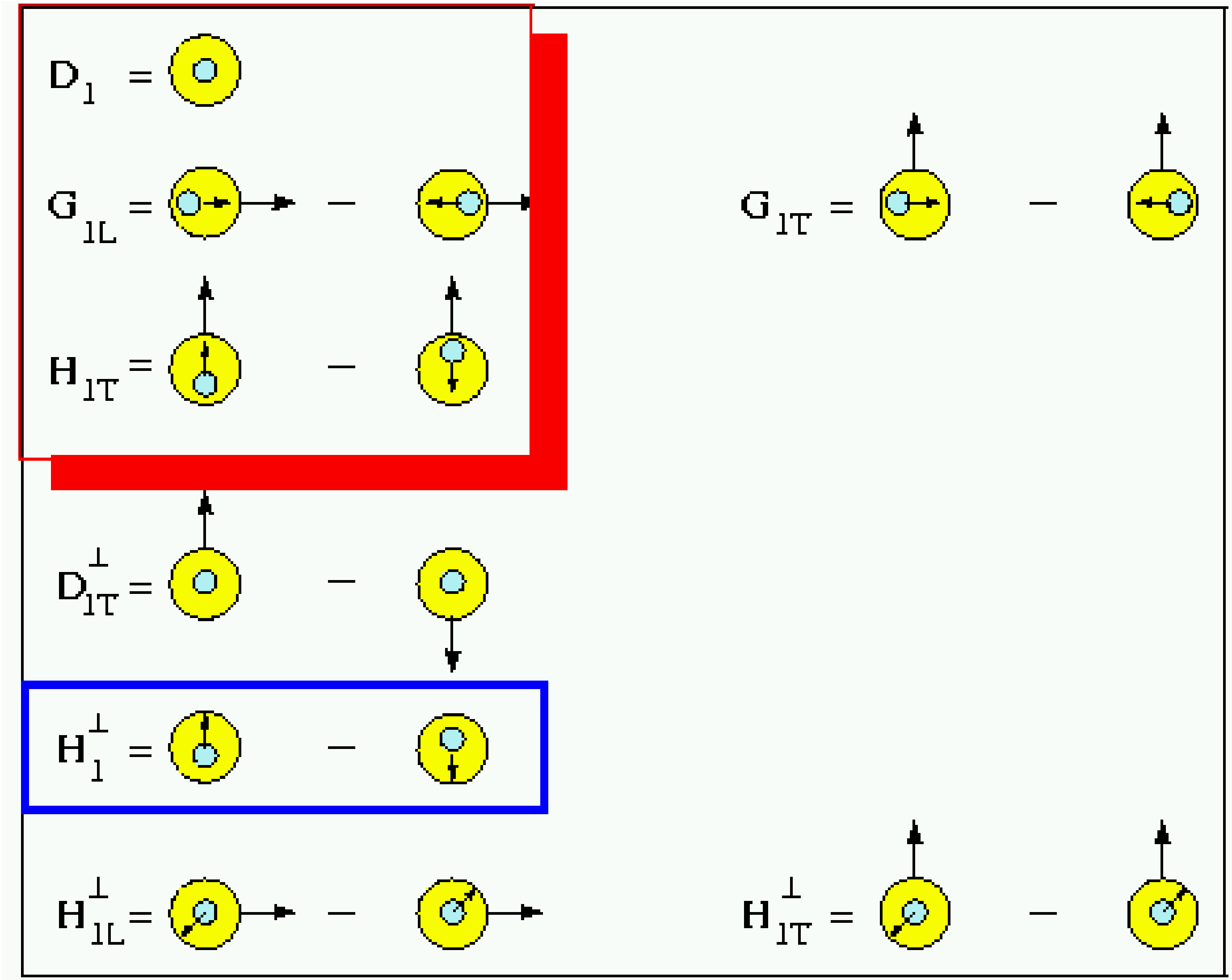
Both chiral odd

Quark *Fragmentation* functions



Quark *Fragmentation* functions

Functions surviving integration over intrinsic transv. momentum



Quark *Fragmentation* functions

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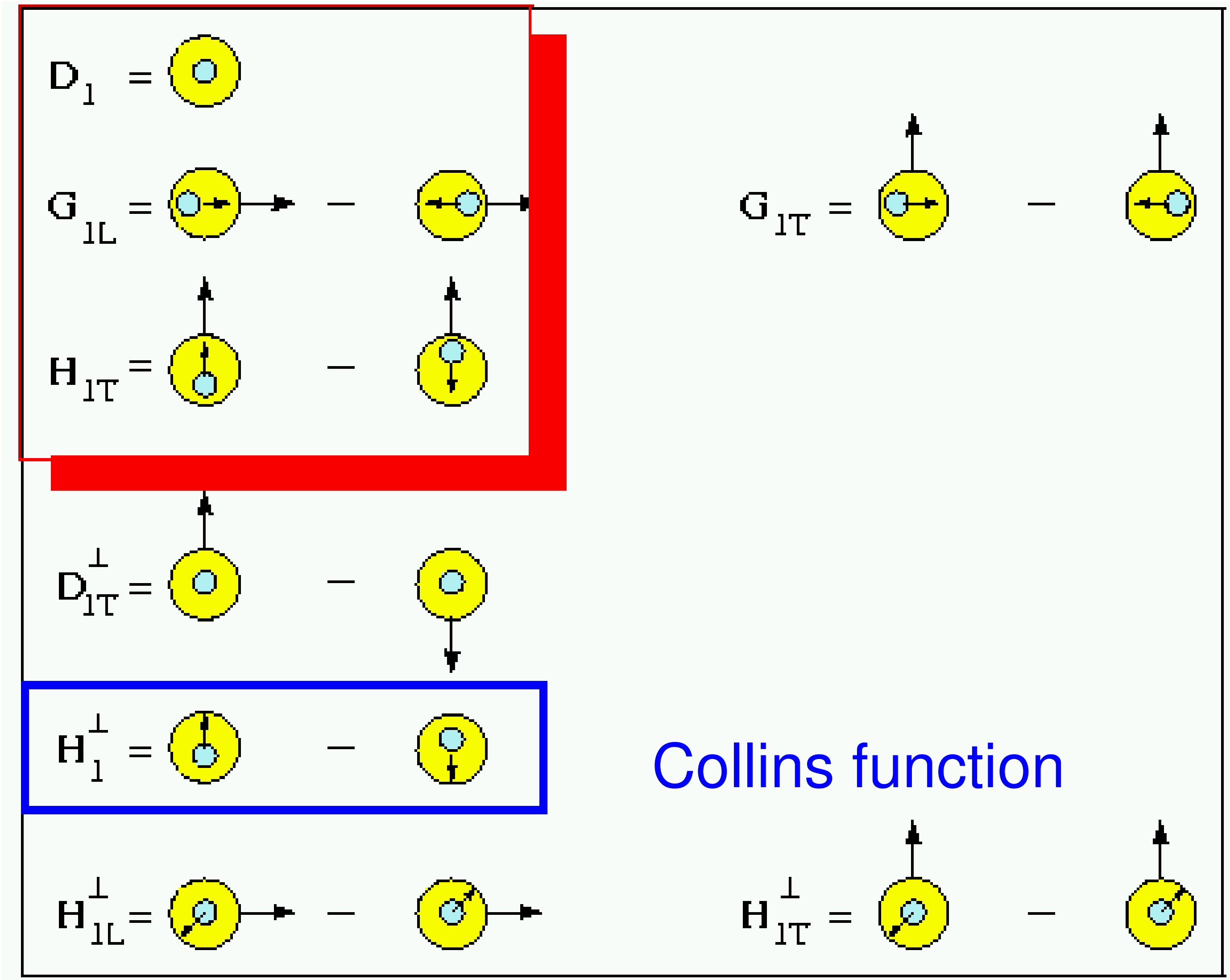
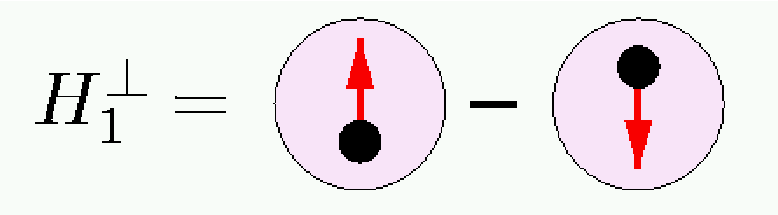


Collins effect

- Chiral odd fragmentation function
- 

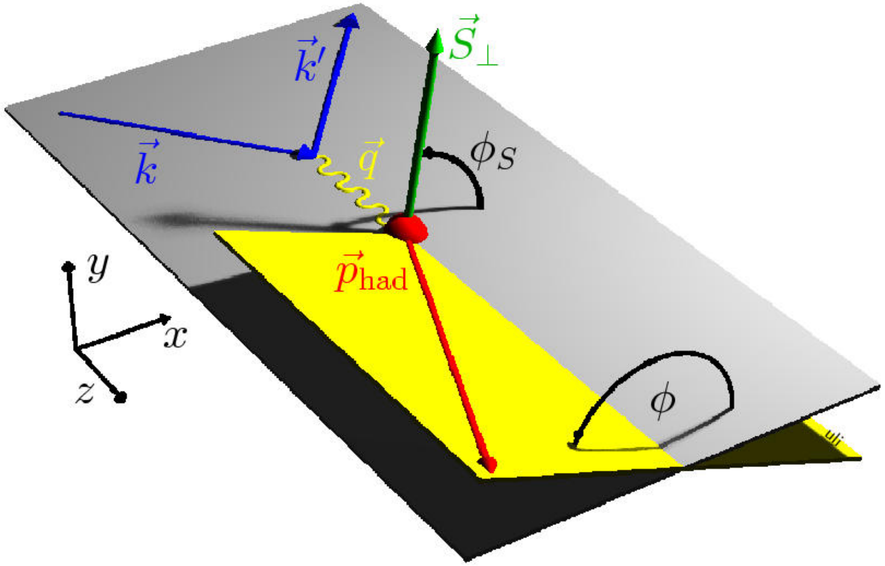
- Transverse spin of quark $\rightarrow$ transverse motion of hadron
- Some estimates from LEP:

$$\left| \frac{< H_1^\perp >}{< D_1 >} \right| = 6.3\%, 12.5\%, \approx 4\%, ...???$$

- Can be negative!
  Correlation between direction of outgoing hadron and transverse spin of quark
- Manifests itself in Single-Spin Azimuthal asymmetry

Single Spin Asymmetries

$$e + p \rightarrow e' + \pi + X$$



Azimuthal distribution of π's:

$$A(\Phi) = \frac{N^+(\Phi) - N^-(\Phi)}{N^+(\Phi) + N^-(\Phi)}$$

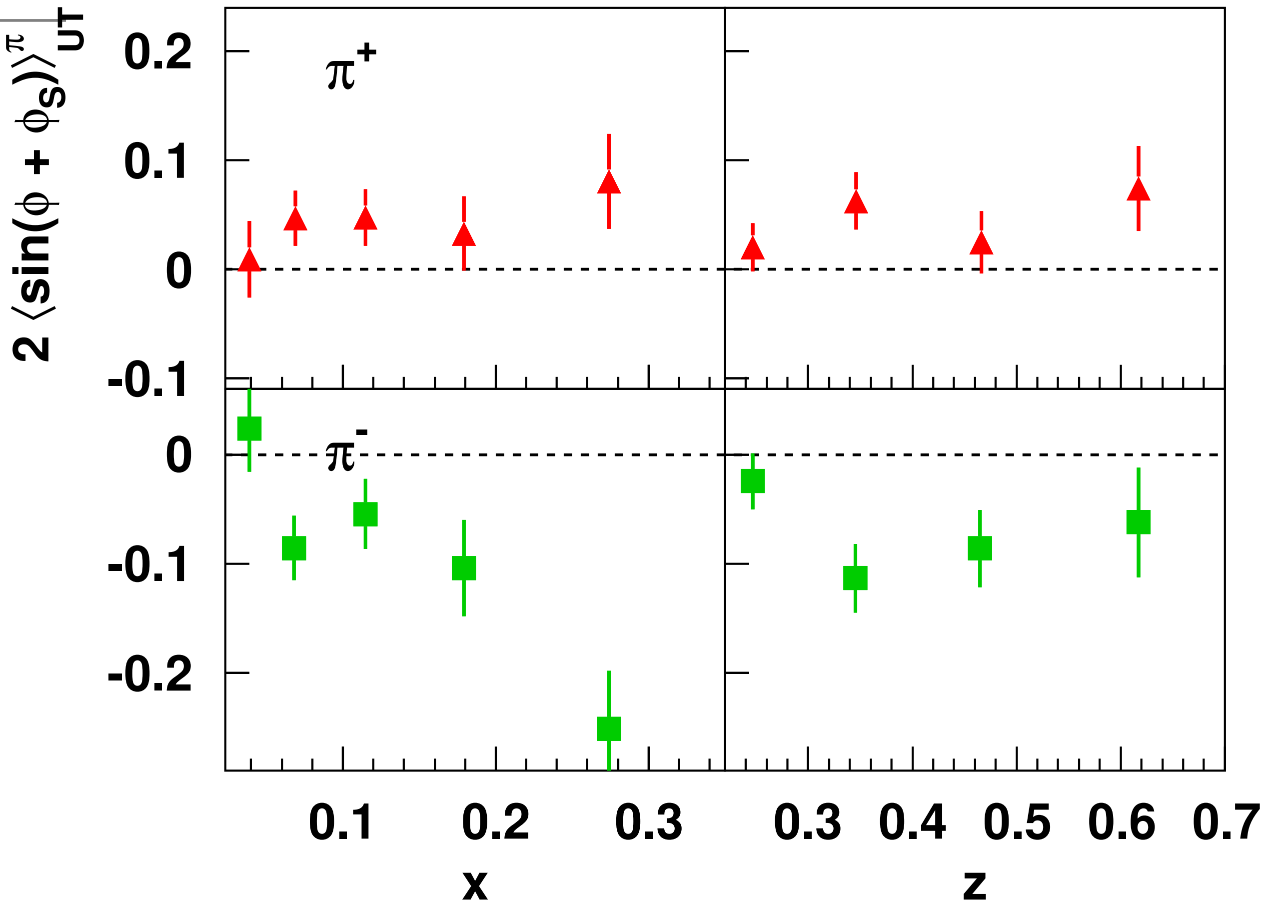
Transversely polarized target:

$$A_{UT}^{\sin\Phi} \propto \frac{\sum_q e_q^2 h_1^q(x) H_1^{\perp,q}(z)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)}$$

$\Phi = \phi + \phi_S$ Collins angle

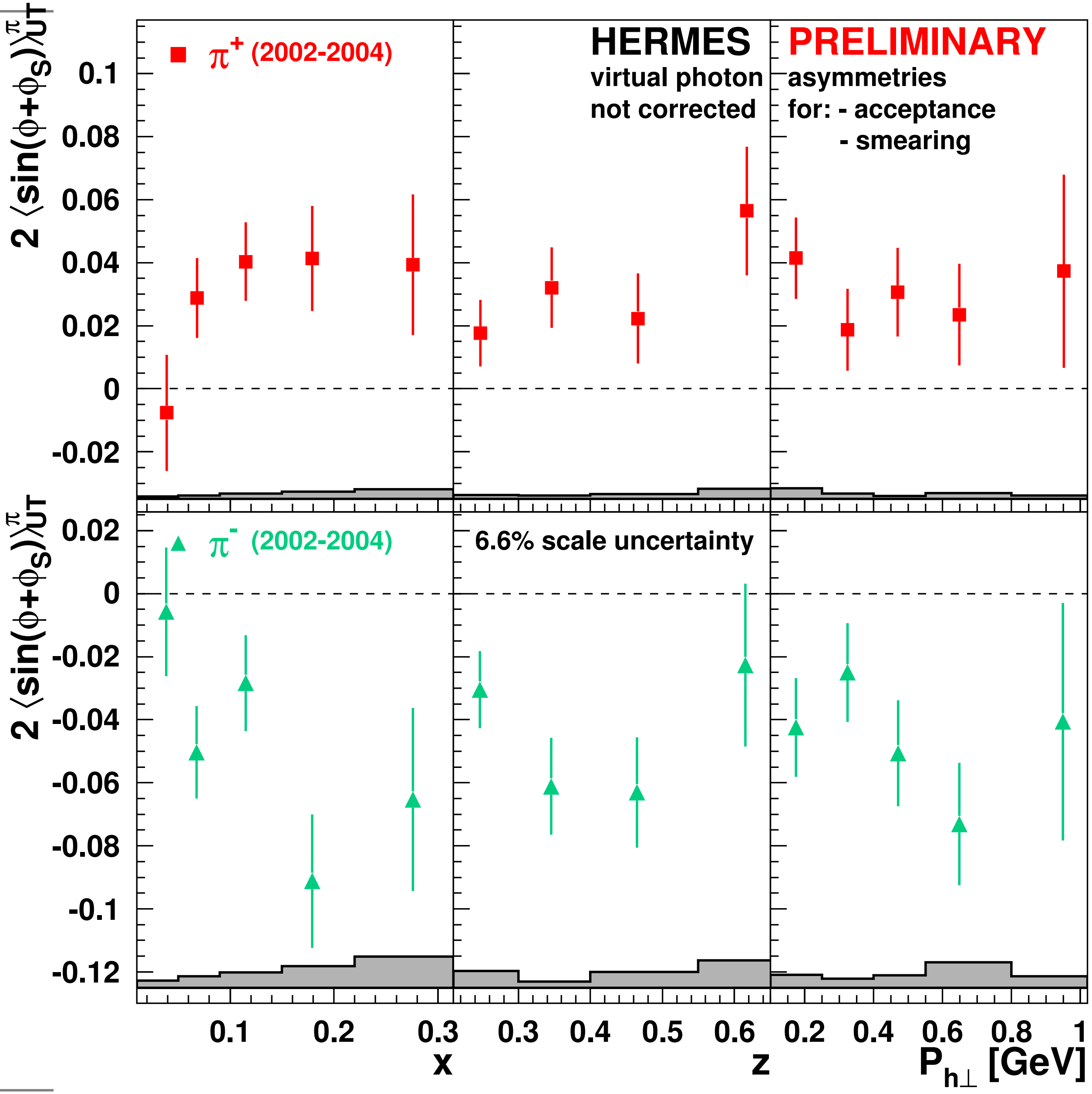
Different definitions!

Collins asymmetry



- $A^{\pi^+}_{UT} > 0$
- $A^{\pi^-}_{UT} < 0$
- $|A^{\pi^-}_{UT}| \gtrapprox |A^{\pi^+}_{UT}|$

Collins asymmetry



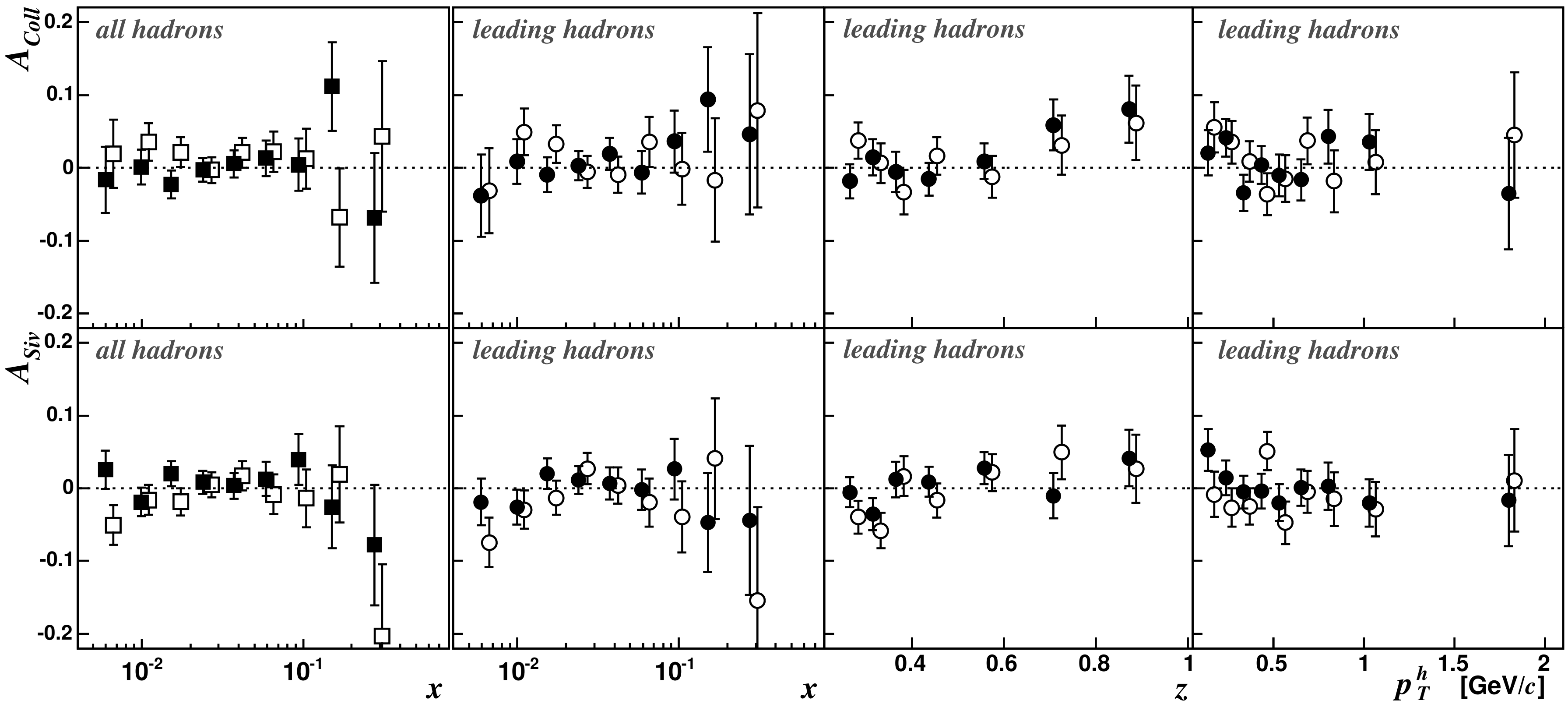
HERMES 02-04 data

→ talk by M.Diefenthaler

- $A^{\pi^+}_{UT} > 0$
- $A^{\pi^-}_{UT} < 0$
- $|A^{\pi^-}_{UT}| \gtrapprox |A^{\pi^+}_{UT}|$

Collins asymmetry

COMPASS, hep-ex/0503002



- COMPASS 02 data
- Deuterium target
- Consistent with 0

→ talk by P.Pagano

Collins asymmetry

- proton: $|A_{UT}^{\pi^-}| \gtrapprox |A_{UT}^{\pi^+}|$
- deuteron: $A_{UT}^{\pi^-} \approx A_{UT}^{\pi^+} \approx 0$

Collins asymmetry

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$\Rightarrow$

- cancellation between p and n asymmetries
- non-trivial behaviour of Collins FF
- ...

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$\Rightarrow$

- cancellation between p and n asymmetries
- non-trivial behaviour of Collins FF
- ...

$\Rightarrow$ need independent access to h_1
e.g. two-hadron production through "interference FF"

$\rightarrow$ talks by P.Van der Nat, R.Joosten

Collins asymmetry

- proton: $|A_{UT}^{\pi^-}| \gtrapprox |A_{UT}^{\pi^+}|$
- deuteron: $A_{UT}^{\pi^-} \approx A_{UT}^{\pi^+} \approx 0$

$\Rightarrow$

- cancellation between p and n asymmetries
- non-trivial behaviour of Collins FF
- ...

$\Rightarrow$ need independent access to $H_1^\perp$
e.g. from high-statistics e^+e^- BELLE data

$\rightarrow$ talk by R.Seidl

Sivers effect

$A_{UT}^{\sin\Phi} \propto \sum_q e_q^2 f_{1}^{\perp,q}(x) D_1(z)$

Sivers effect

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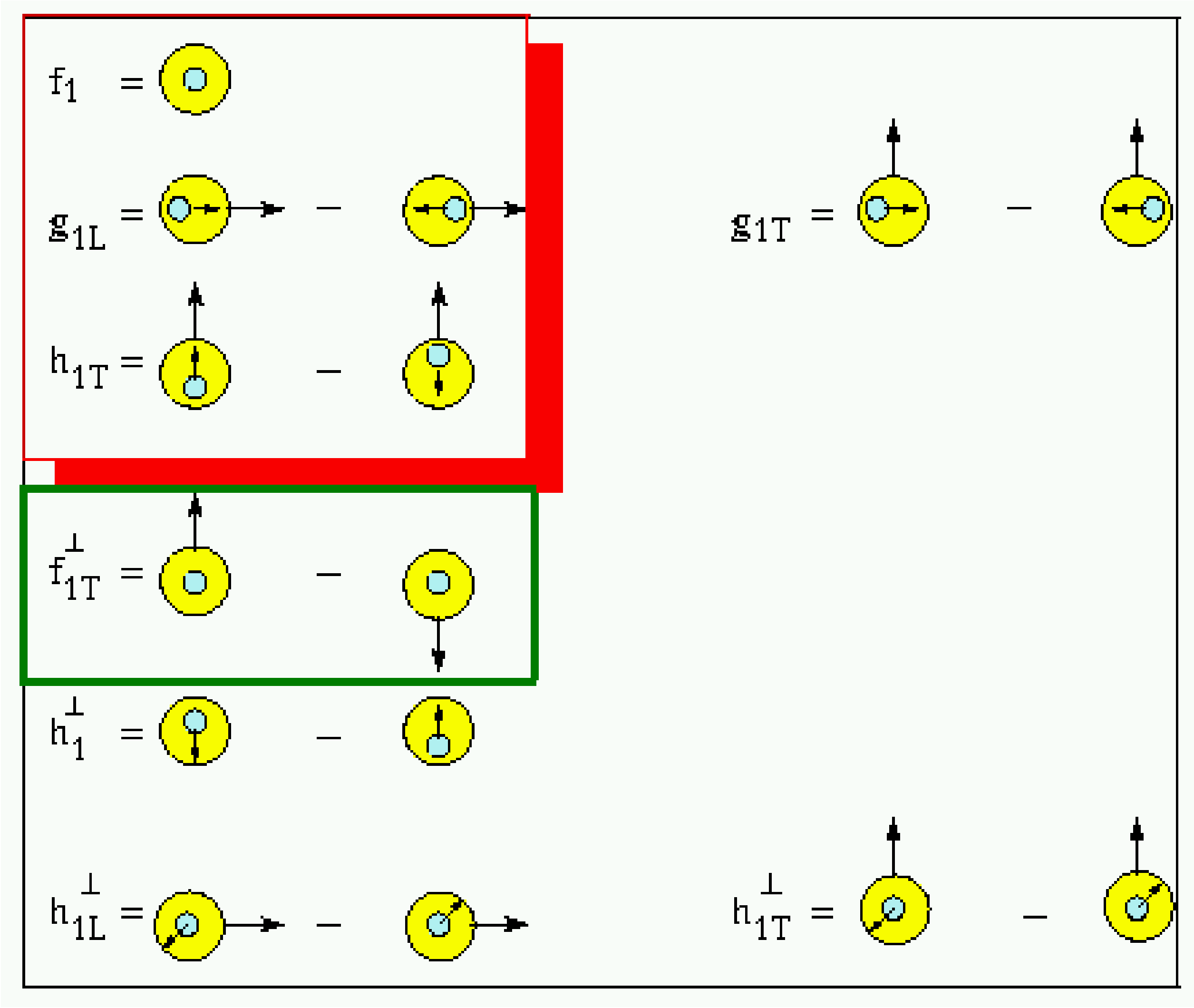

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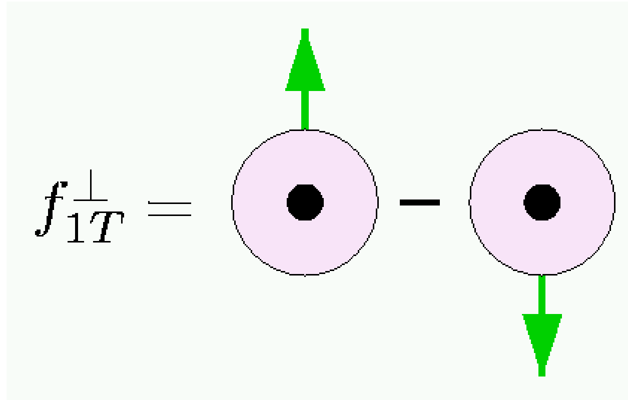


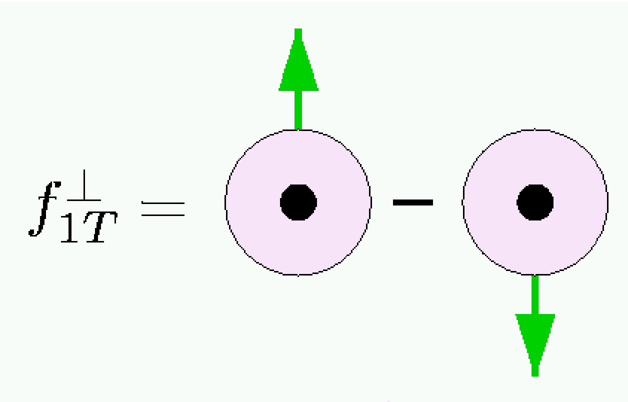
Chiral odd distribution function?

Several recent ideas:

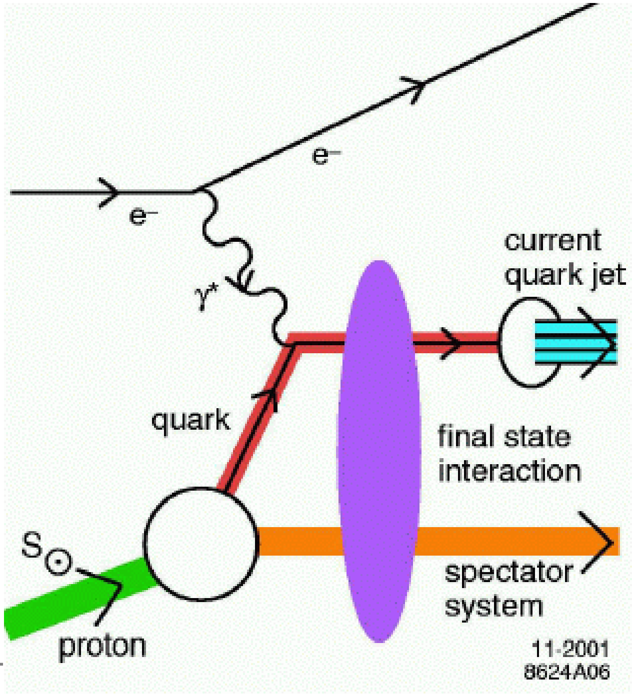
Sivers effect

$$A_{UT}^{\sin\Phi} \propto \sum_q e_q^2 f_1^{\perp,q}(x) D_1(z)$$

Chiral odd distribution function?



Several recent ideas: Brodsky, Hwang, Schmidt

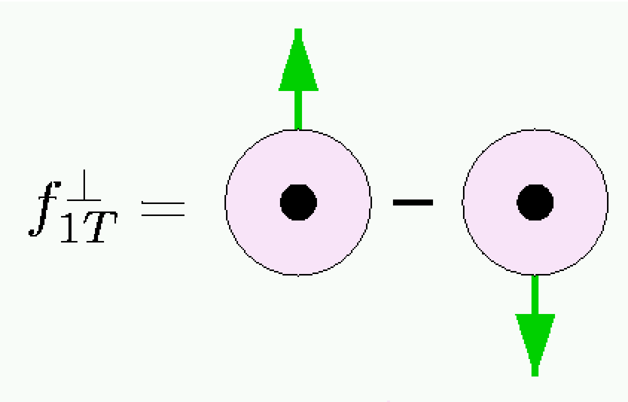


- Quark rescattering
- Generates SSA
- Requires L_z of quarks

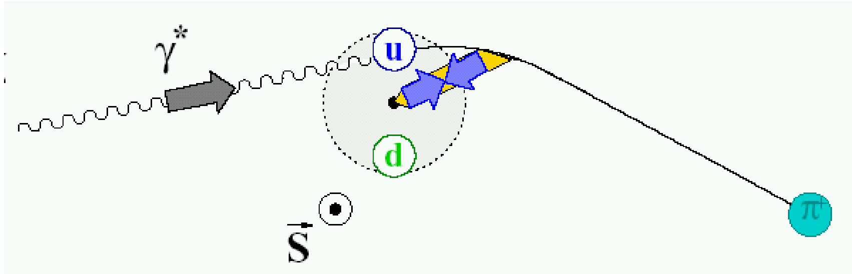
Sivers effect

$A_{UT}^{\sin\Phi} \propto \sum_q e_q^2 f_1^{\perp,q}(x) D_1(z)$

Chiral odd distribution function?



Several recent ideas: Burkardt



- Spatial distortion of q-distribution
- Attractive QCD-potential
- Generates SSA
- Implies L_z of quarks

Collins vs Sivers effect

- Appear at leading twist
- Depend on different azimuthal angles:
  - Collins: correlation spin struck quark and momentum hadron
  - Sivers: correlation spin nucleon and transverse momentum quark

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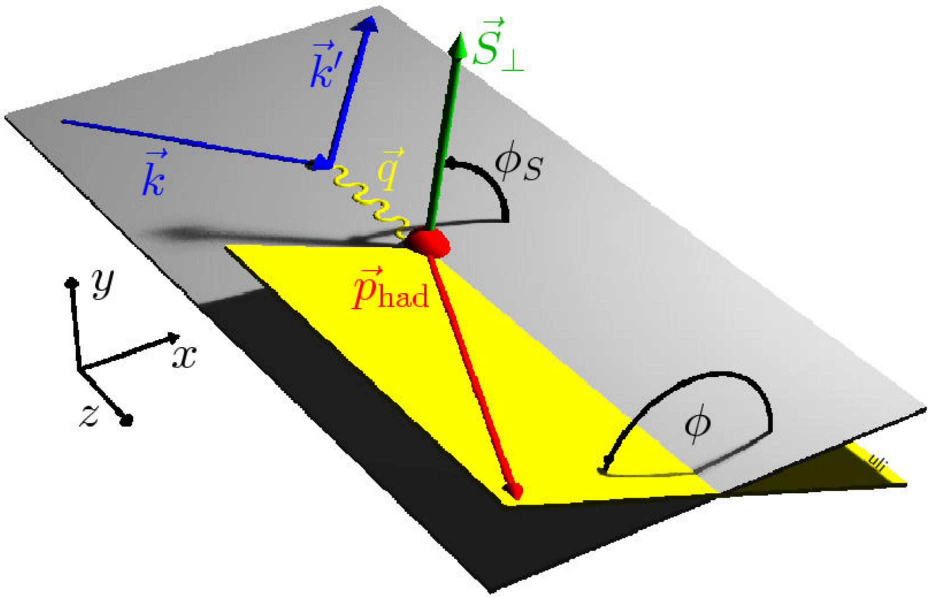
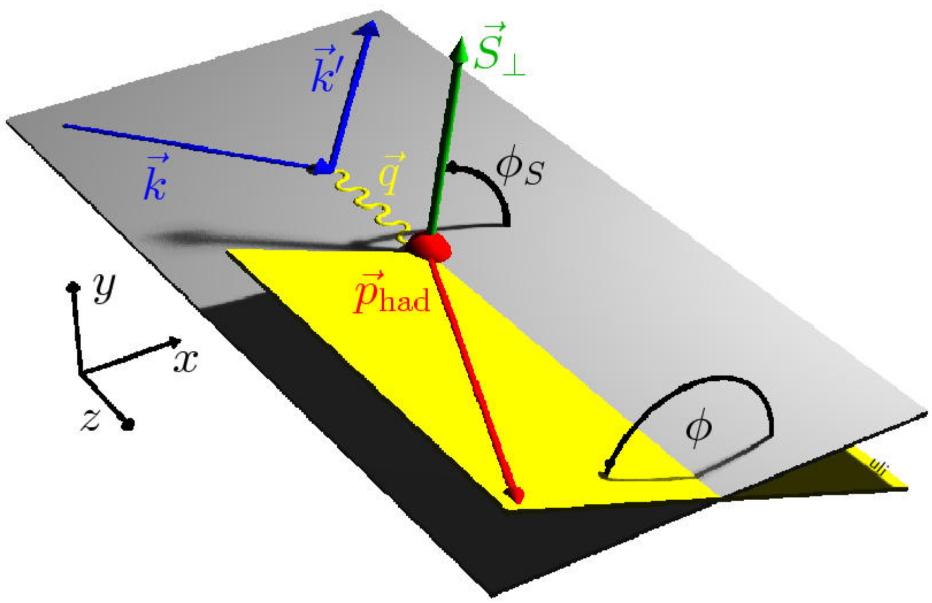


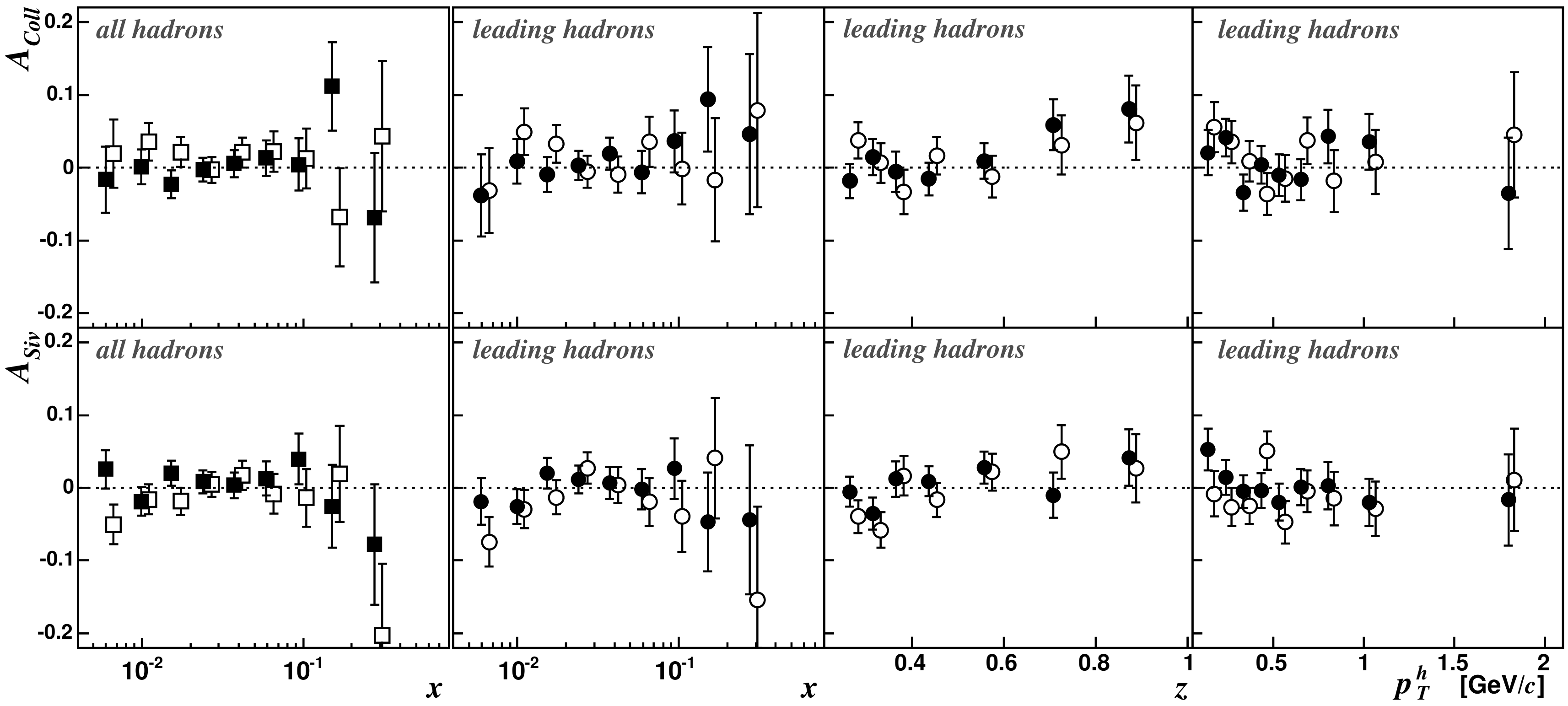
Collins vs Sivers effect

- Appear at leading twist
- Depend on different azimuthal angles:
  - Collins: correlation spin struck quark and momentum hadron $\Rightarrow \phi_C = \phi + \phi_S$
  - Sivers: correlation spin nucleon and transverse momentum quark $\Rightarrow \phi_S = \phi - \phi_S$



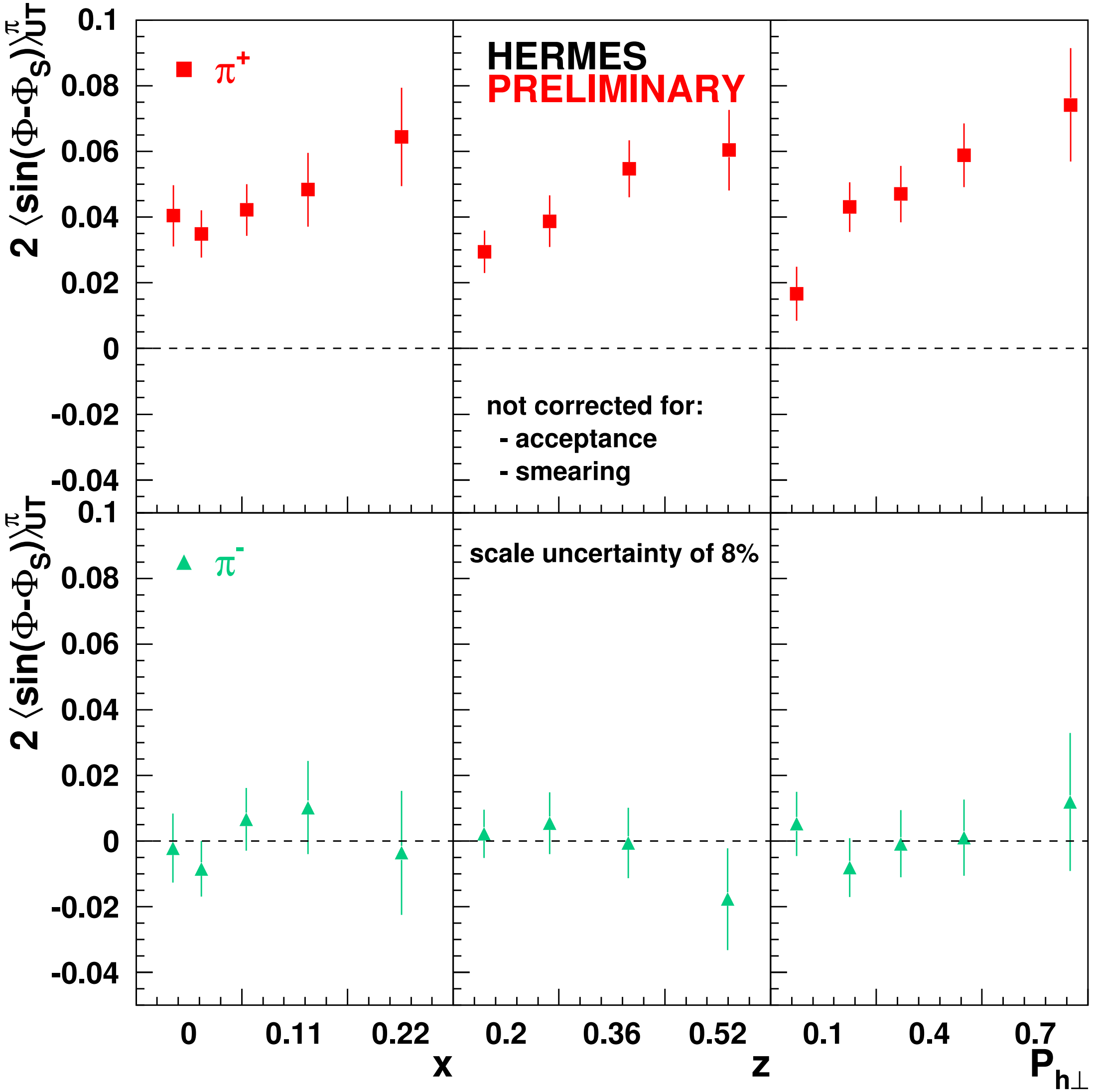
Sivers asymmetries

New COMPASS results on D -target:



Sivers asymmetries

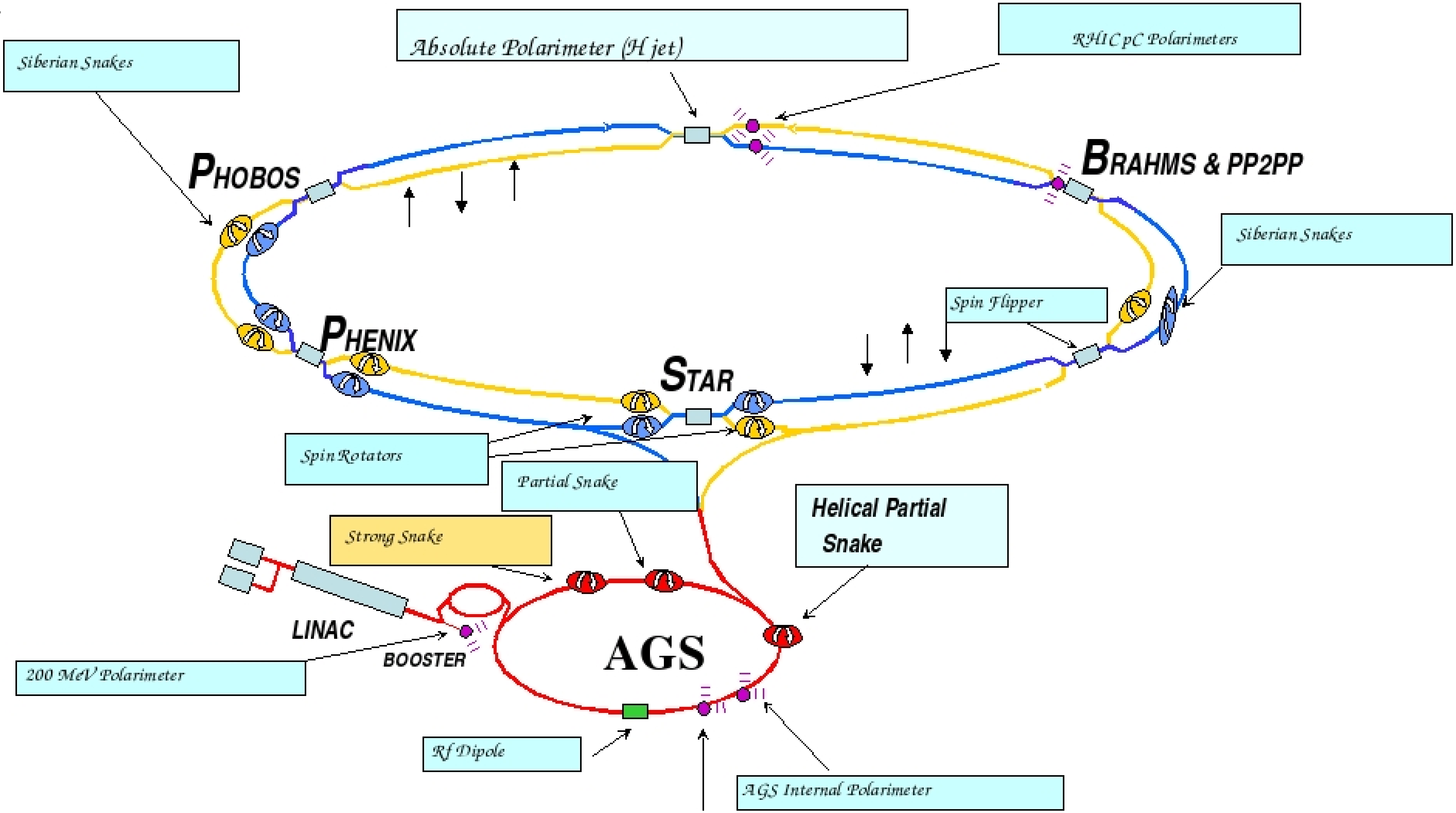
New HERMES results on H -target:



Sivers asymmetries

- Good statistics data available
- Orbital angular momentum $L_z \neq 0$
- Flavour separation possible
- Has importance beyond lepton-nucleon scattering
  pp-scattering

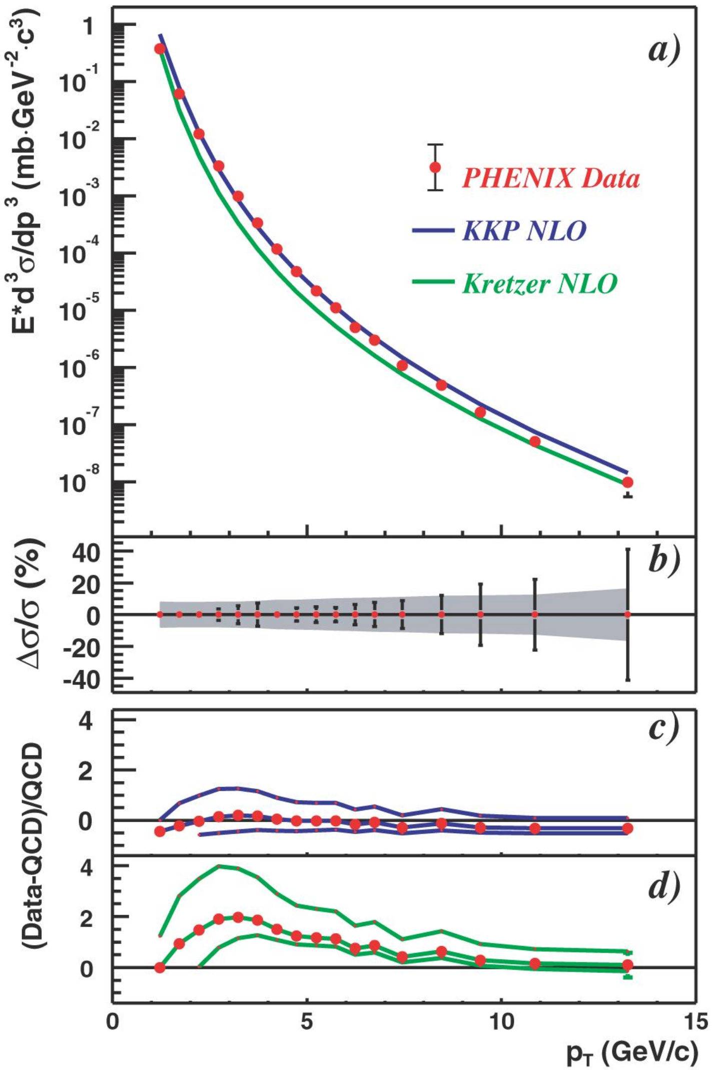
RHIC - spin



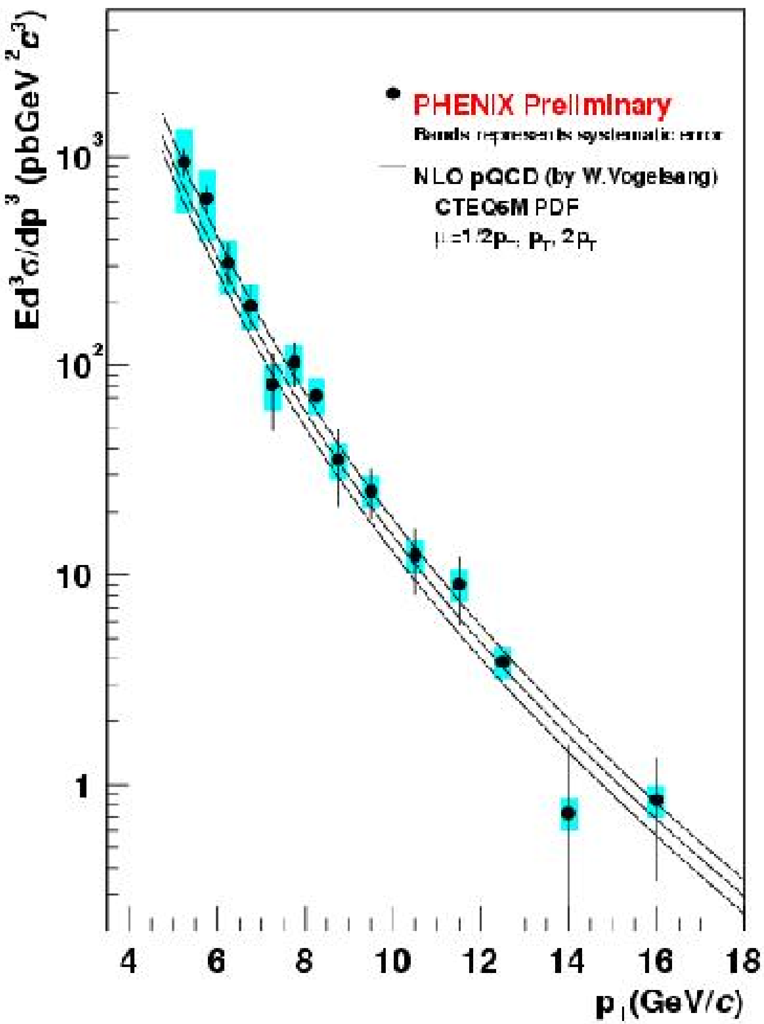
$\mathcal{L}_{\text{peak}} = 1 \cdot 10^{31} \text{cm}^{-2}\text{s}^{-1}$ $P_b \sim 45\%$

RHIC: pQCD

π^0 $|\eta| < 0.35$



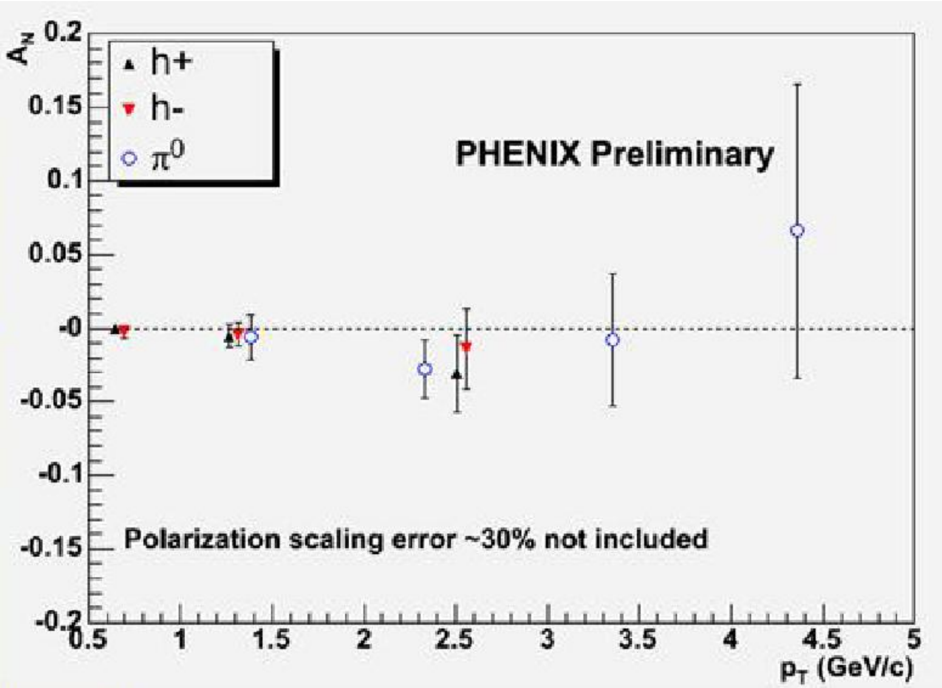
Direct photon $|\eta| < 0.35$

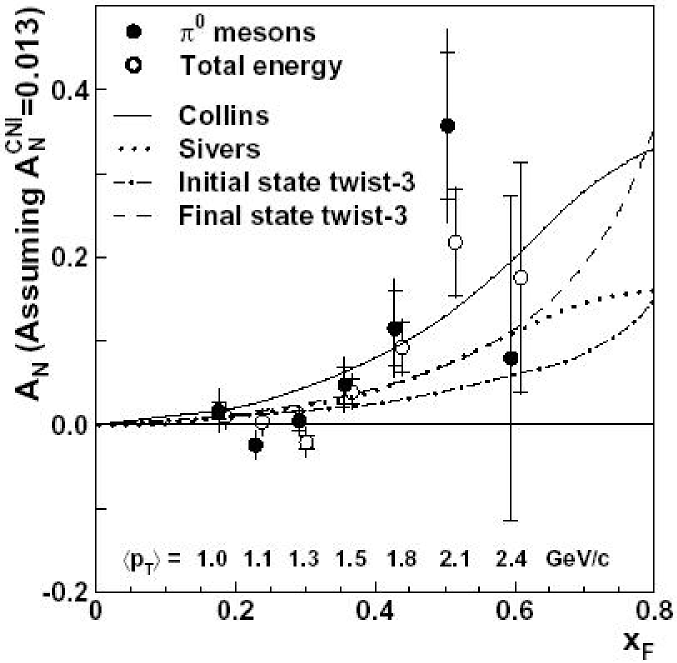


NLO pQCD agrees well with data

RHIC: single spin asymmetries

PHENIX $|\eta| < 0.35$ STAR $3.4 < \eta < 4.0$



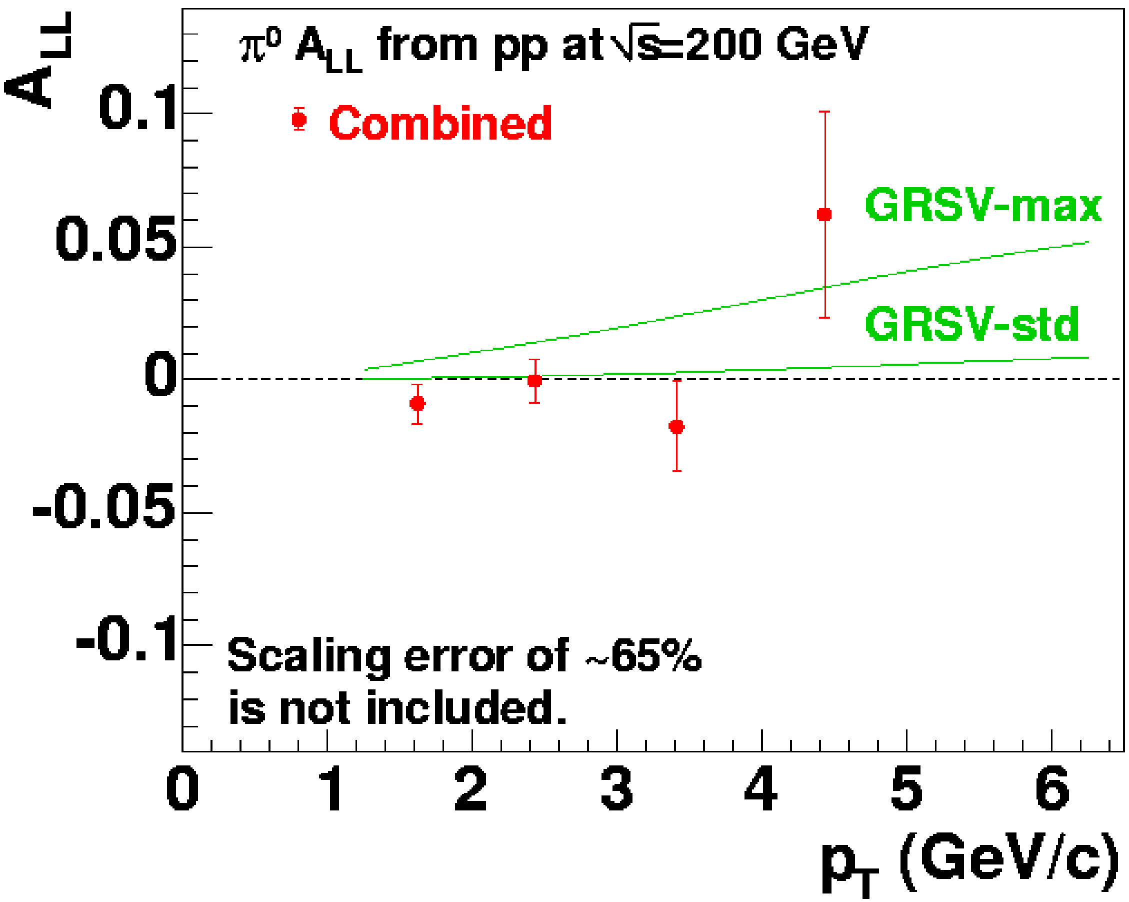


Run 02 data ($P_b \sim 0.15$)
Experiments ready for high-statistics runs

→ talks by S.Heppelmann, M.Chiu, F.Videbaek

RHIC: double spin asymmetries

Polarized $\vec{p}\vec{p}$ scattering also offers access to ΔG



→ talks by A.Desphande, R.Cadman

Higher twist effects

- g_2 measurements
- HERMES longitudinal SSA
  contain Collins, Sivers and Twist-3 part
  $\rightarrow$ talk by M.Diefenthaler
- Beam-spin SSA
  depend on Twist-3 DF $\otimes$ Collins FF
  $\rightarrow$ talk by H.Avakian

Summary

- Very active field, also theory
- “Old” topics: much improved accuracy
- “New” topics, new facilities

Looking forward to lively discussions in Working Group