The Spin Structure of the Nucleon

E.C. Aschenauer

DESY-ZEUTHEN

on behalf of the hermes Collaboration

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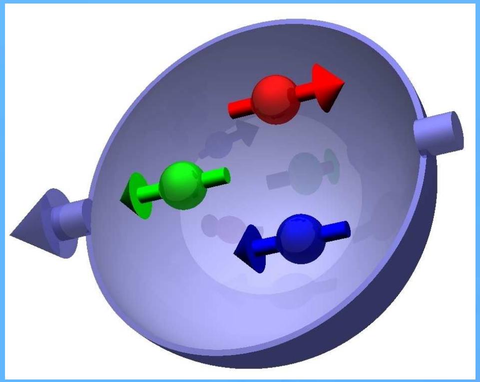

Naive Parton Model:

$$\Delta u_v + \Delta d_v = 1$$

$$\Longrightarrow \Delta u_v = \frac{4}{3}, \Delta d_v = \frac{-1}{3}$$

BUT

1988 EMC measured:

$\Delta\Sigma$ **= 0.123 $\pm$ 0.013 $\pm$ 0.019**

$\Longrightarrow$ **Spin Puzzle**

$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v)$$

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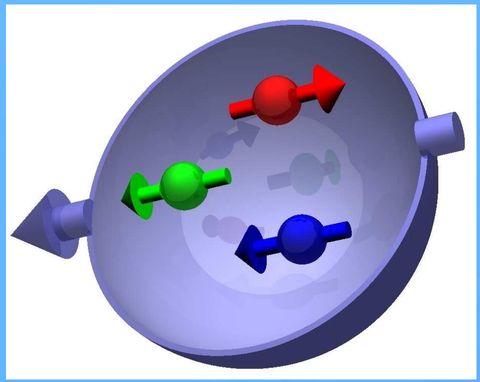

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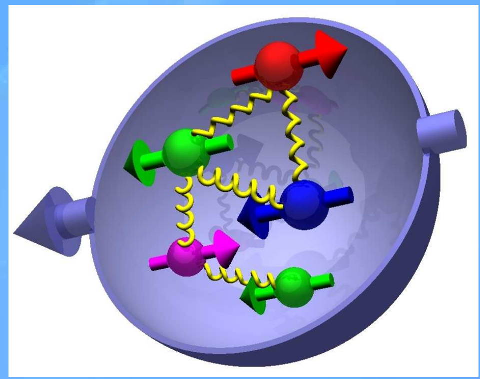

from unpolarized data:

Gluons are important !

$\Longrightarrow$ **sea quarks Δq_s**

$\Longrightarrow$ ΔG

$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v + \underbrace{\Delta q_s}_{\Delta u_s, \Delta d_s, \Delta \bar{u}, \Delta \bar{d}, \Delta s, \Delta \bar{s}}) + \Delta G$$

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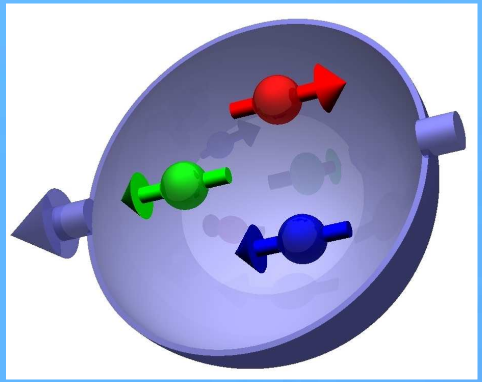

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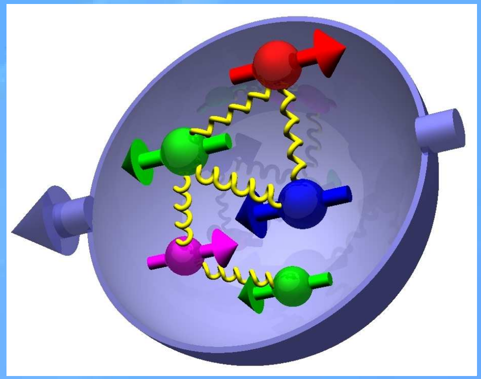

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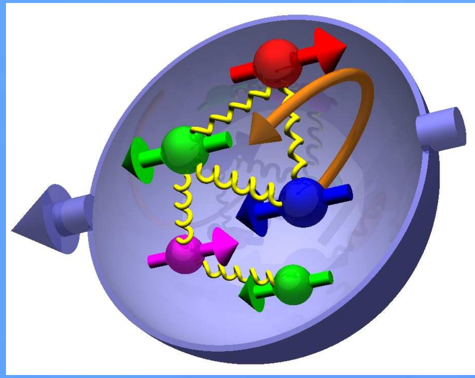


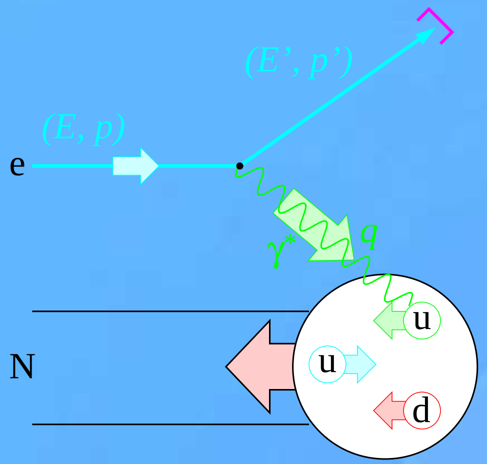
Full description of J$_q$ & J$_g$

needs

orbital angular momentum

$$\frac{1}{2} = \frac{1}{2}\underbrace{(\Delta u_v + \Delta d_v + \Delta q_s)}_{\mathbf{\Delta\Sigma}} + \mathbf{L_q} + (\mathbf{\Delta G} + \mathbf{L_g})$$

Inclusive Scattering:

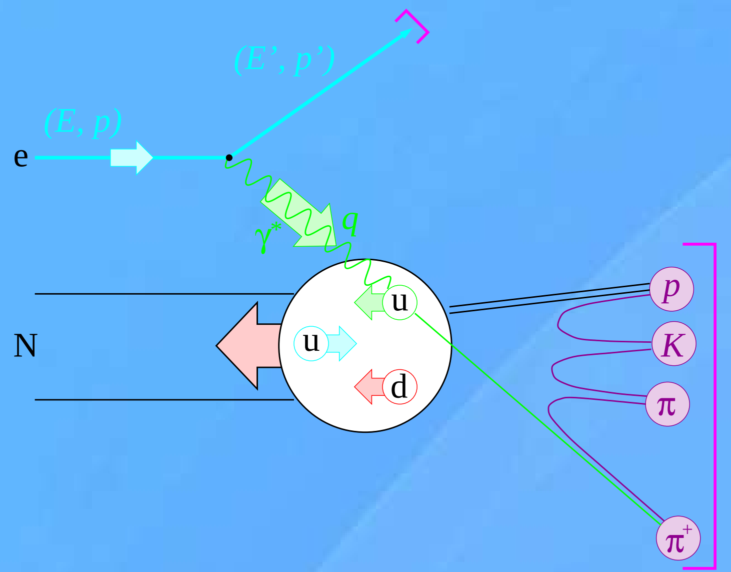


detect scattered lepton

$$\mathbf{Q^2} \stackrel{lab}{=} \mathbf{4EE'}\sin^{\mathbf{2}}\left(\frac{\theta}{\mathbf{2}}\right)$$

$$\mathbf{x} \stackrel{lab}{=} \frac{\mathbf{Q^2}}{\mathbf{2M}\nu} \qquad \mathbf{y} \stackrel{lab}{=} \frac{\nu}{\mathbf{E}} = \frac{\mathbf{p}\cdot\mathbf{q}}{\mathbf{p}\cdot\mathbf{k}}$$

Semi-Inclusive Scattering:



detect scattered lepton and produced hadrons

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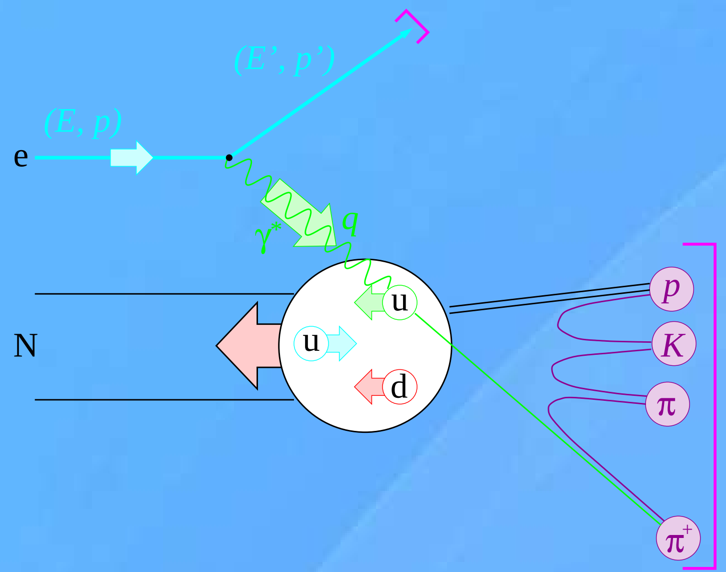
$$\mathbf{z} \overset{lab}{=} \frac{\mathbf{E_h}}{\nu}$$

Deep Inelastic Scattering

Semi-Inclusive Scattering:



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$$\mathbf{z} \stackrel{lab}{=} \frac{\mathbf{E_h}}{\nu}$$

Cross Section: $\frac{d^2\sigma}{d\Omega dE^2} = \frac{\alpha^2 E'}{Q^2 E} L_{\mu\nu} W^{\mu\nu}$

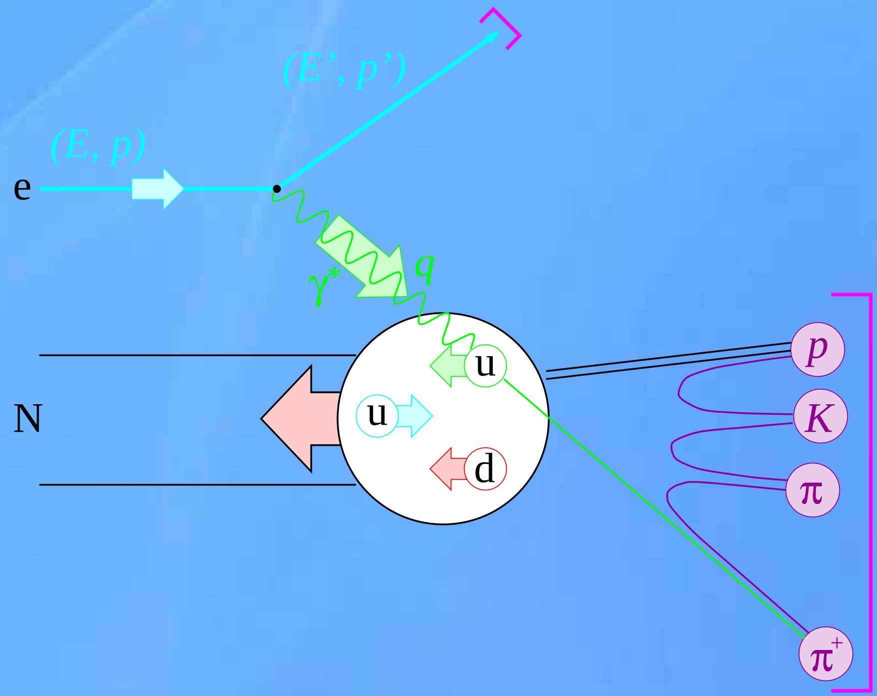
$L_{\mu\nu}$**: purely electromagnetic** $\Longrightarrow$ **calculable**

$W^{\mu\nu} \sim F_1(x, Q^2)$ **+** $F_2(x, Q^2)$ **+** $g_1(x, Q^2) + g_2(x, Q^2)$

(for spin 1) $-b1(x, Q^2) + \frac{1}{6}b2(x, Q^2) + \frac{1}{2}b3(x, Q^2) + \frac{1}{2}b4(x, Q^2)$

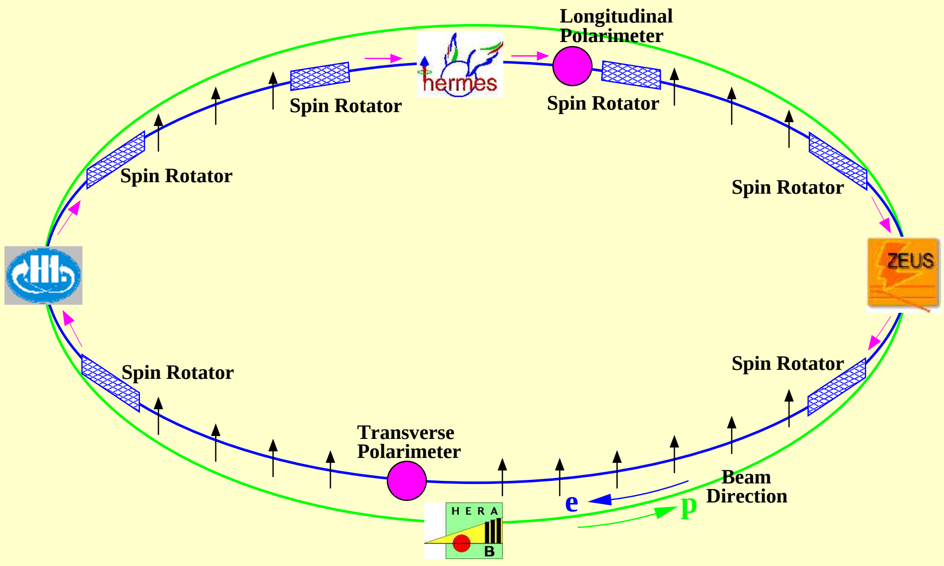
F_1,F_2 **/** g_1,g_2 $\Longrightarrow$ **Unpolarized / Polarized Structure Functions**

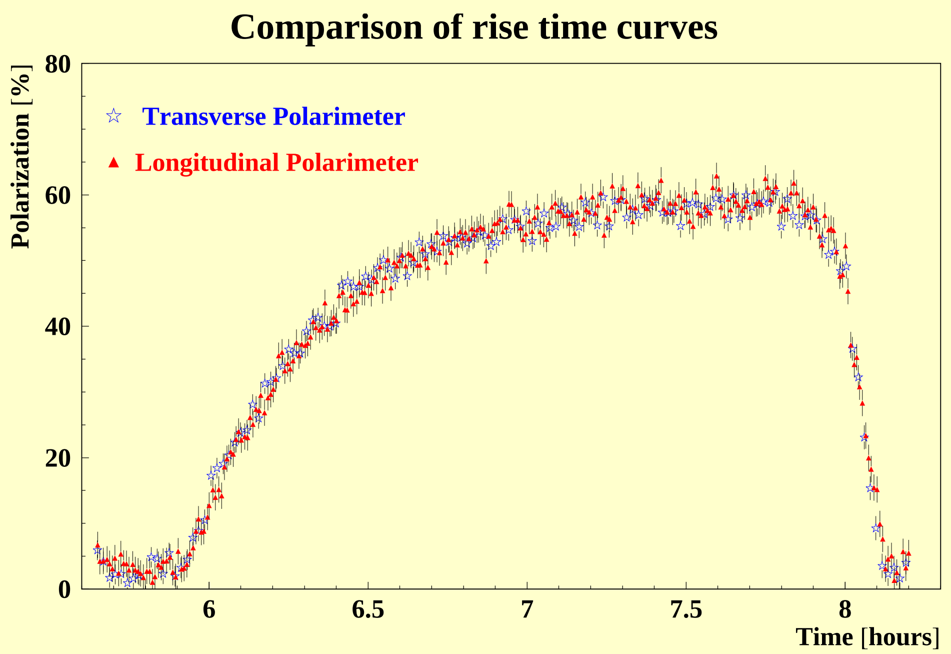
Experimental Prerequisites



Experimental Prerequisites

HERA long. pol. positron beam 27.5 GeV





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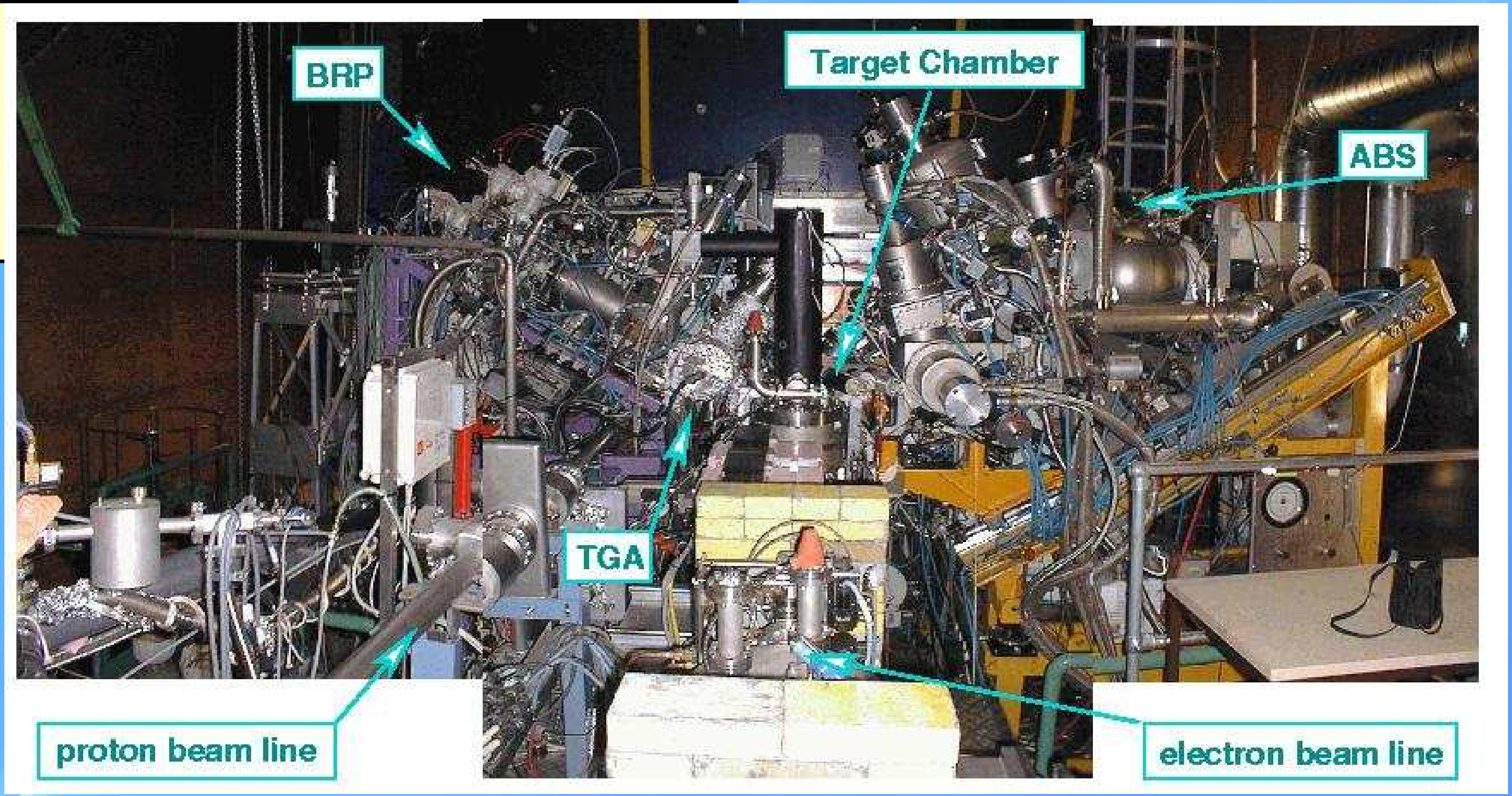

HERMES polarized gas target: $\overrightarrow{\mathrm{H}e}$, $\overrightarrow{\mathrm{D}}$, $\overrightarrow{\mathrm{H}}$, **H**$^{\uparrow}$

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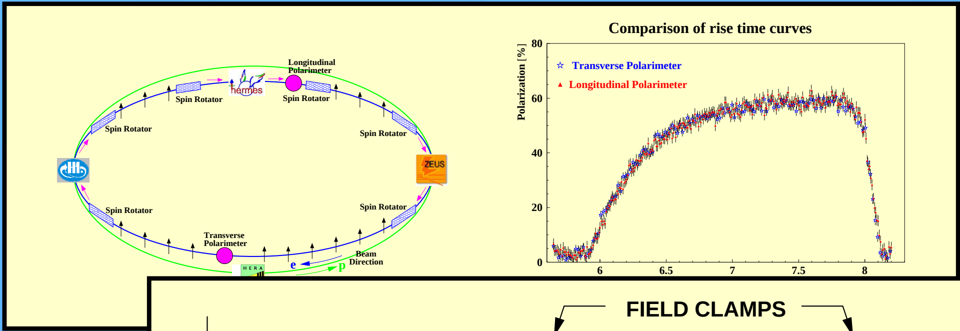
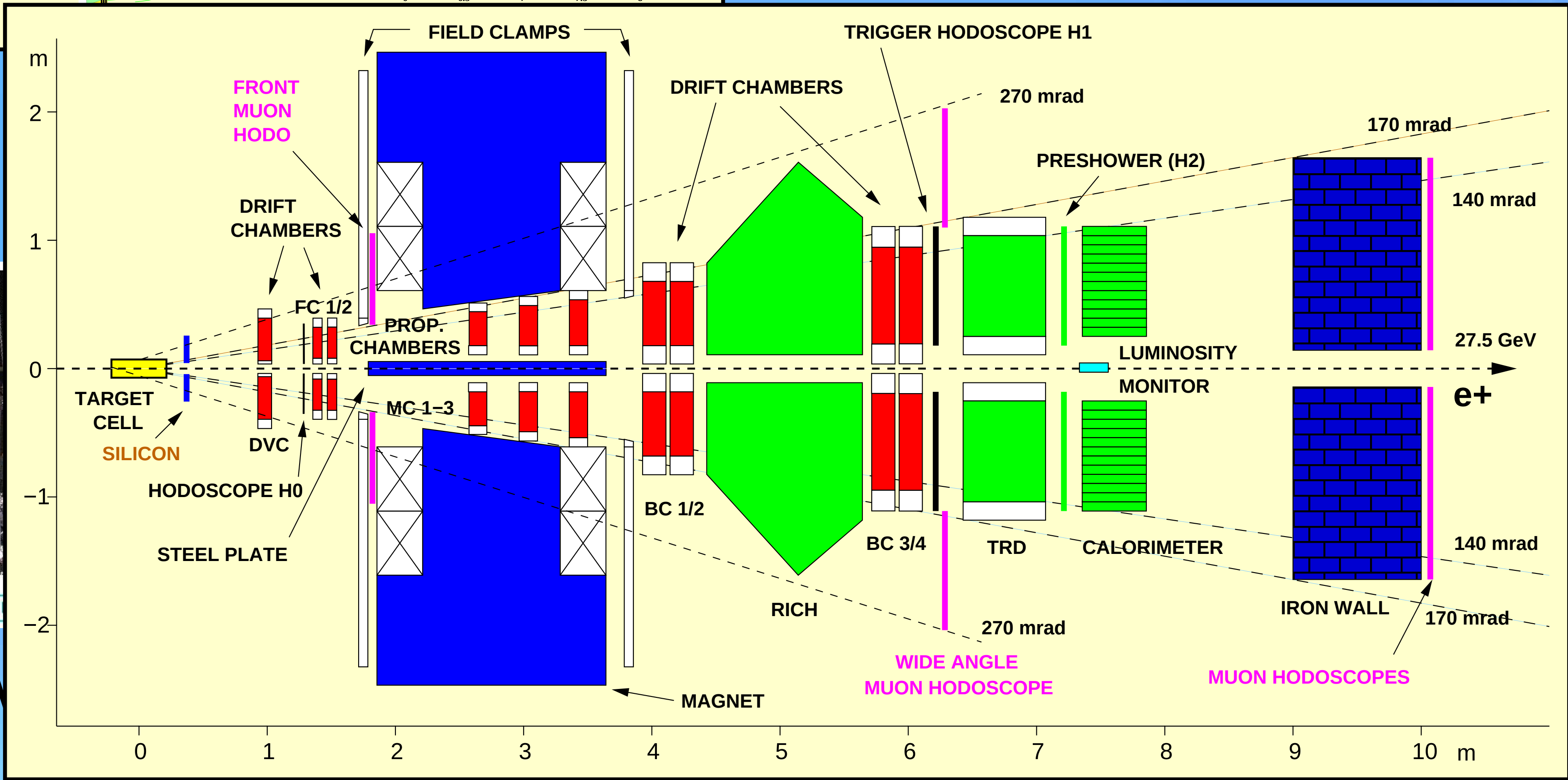


HERMES spectrometer



HERM

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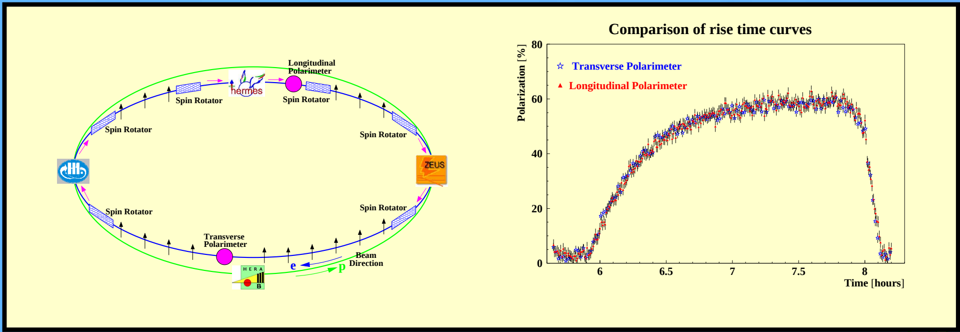

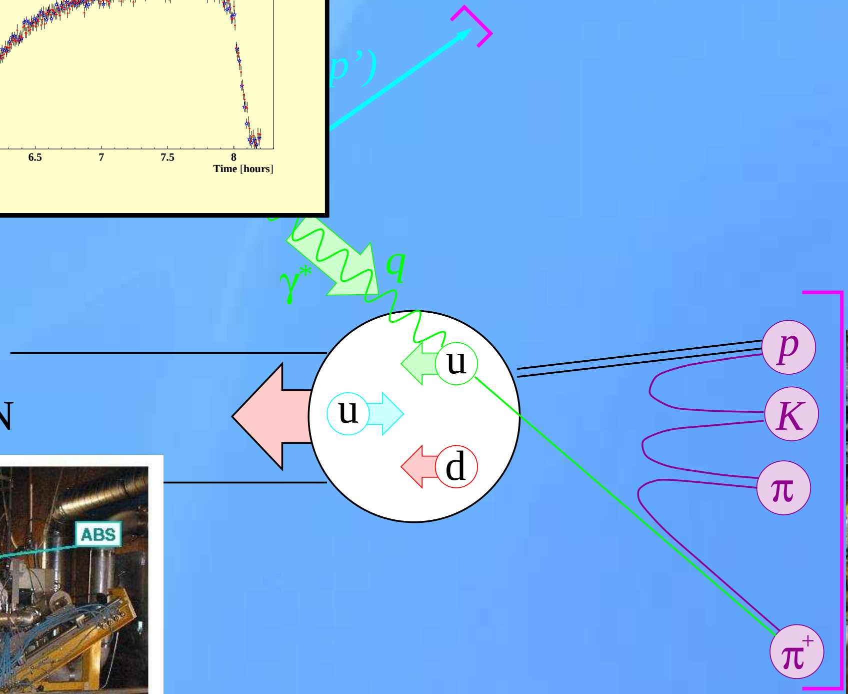

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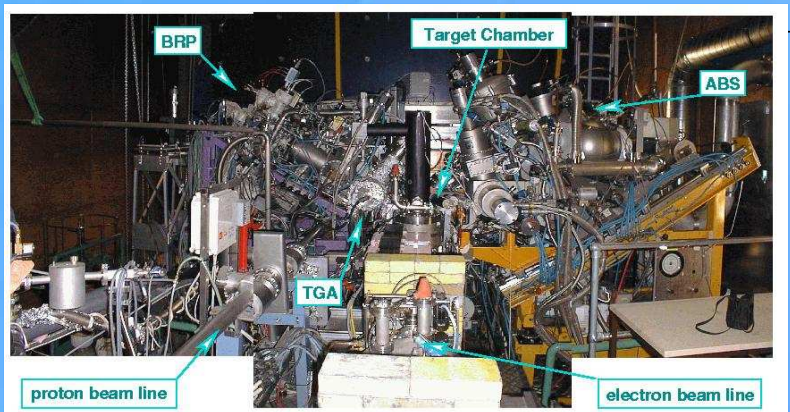

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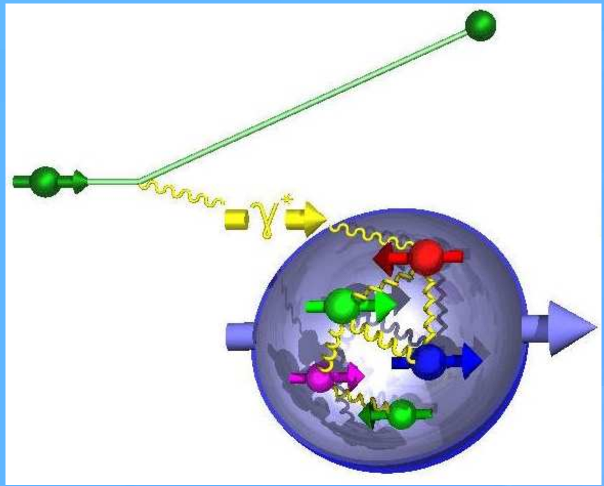
Virtual Photon Asymmetry



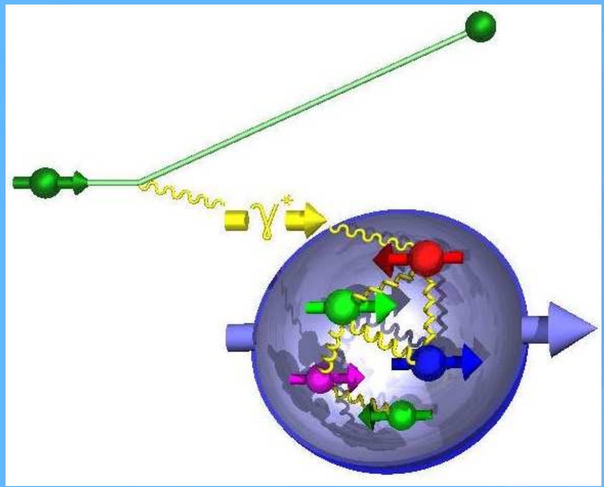
$\sigma_{3/2} \sim \mathbf{q}^{-}(\mathbf{x})$

$\vec{S}_\gamma$ + $\vec{S}_N$ = 3/2

$\vec{S}_N$ = $-\vec{S}_q$

- **Virtual photon γ^* can only couple to quarks of opposite helicity**

Virtual Photon Asymmetry



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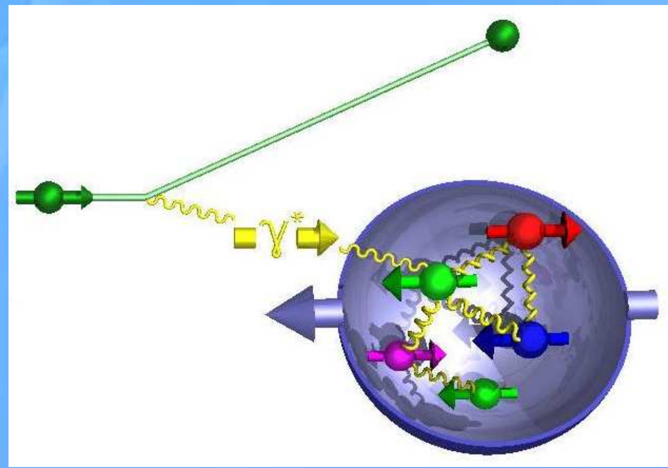


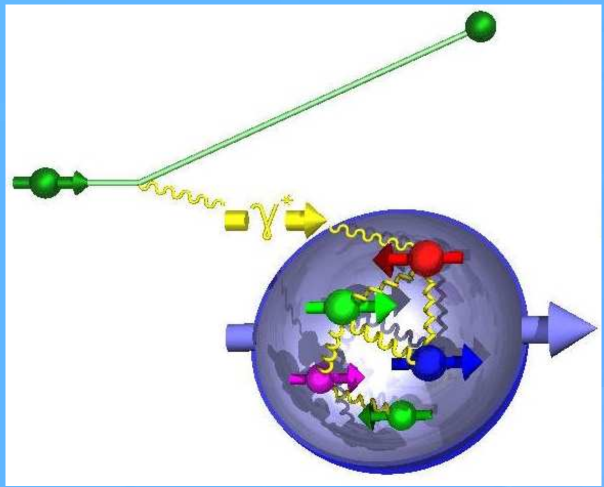
$\sigma_{1/2} \sim \mathbf{q}^{+}(\mathbf{x})$

$\vec{S_\gamma}$ + $\vec{S_N}$ = 1/2

$\vec{S_N}$ = $\vec{S_q}$

- **Virtual photon γ^* can only couple to quarks of opposite helicity**
- **Select $\mathbf{q}^{+}(\mathbf{x})$ or $\mathbf{q}^{-}(\mathbf{x})$ by changing the orientation of target nucleon spin or helicity of incident lepton beam**

Virtual Photon Asymmetry



$\sigma_{3/2} \sim \mathbf{q^-(x)}$

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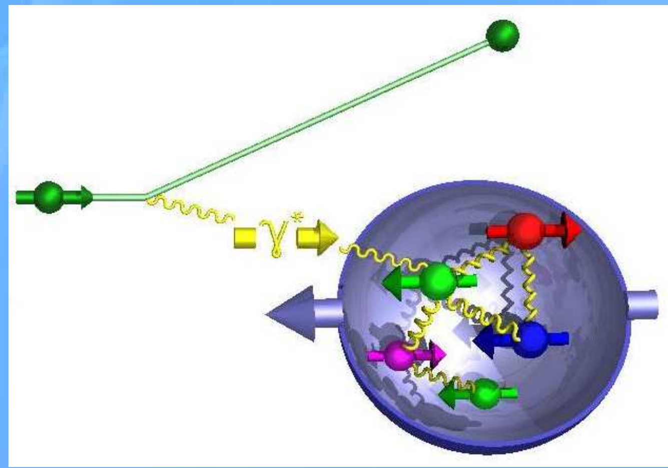

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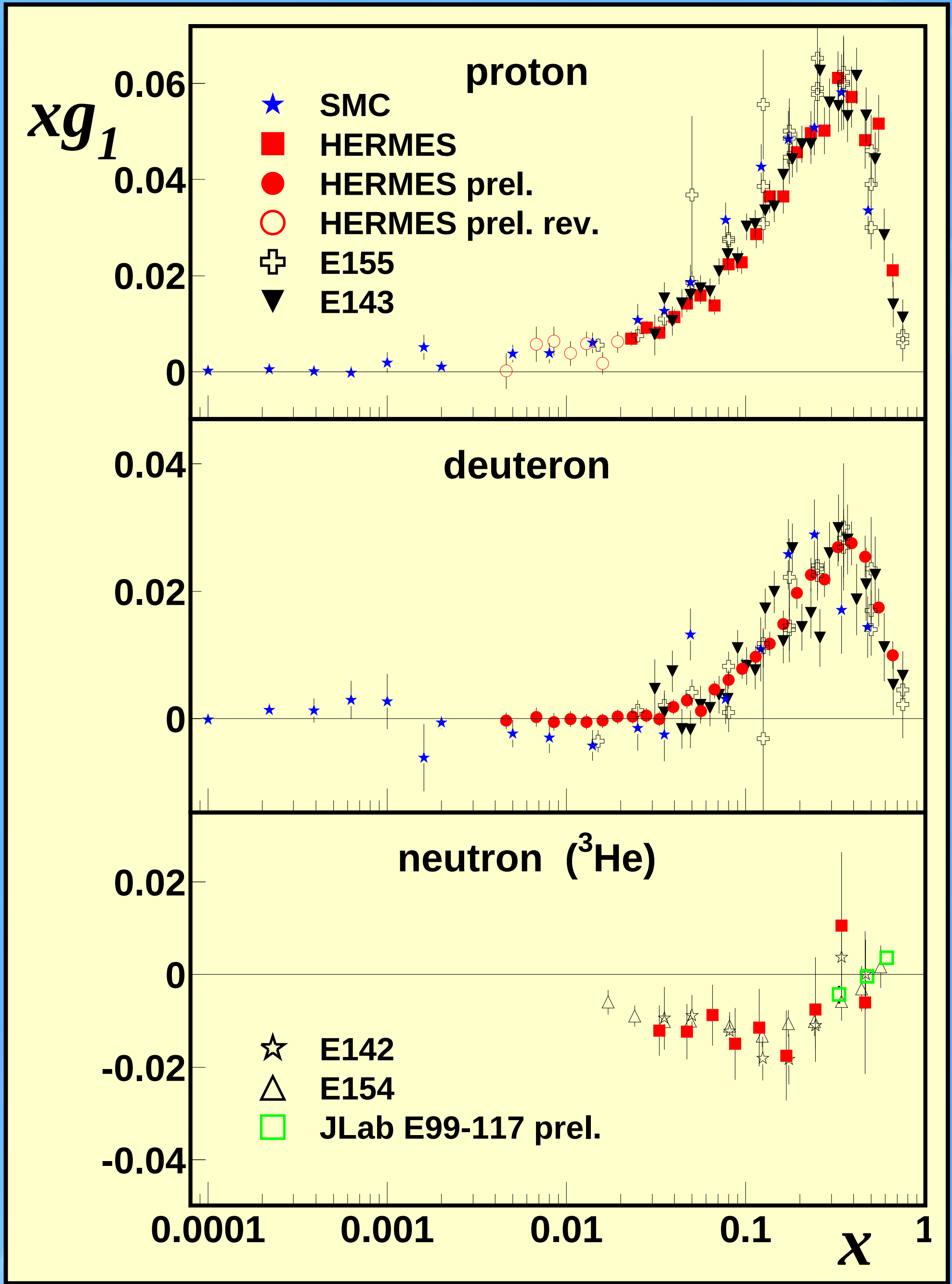
- **Virtual photon γ^* can only couple to quarks of opposite helicity**
- **Select $\mathbf{q^+(x)}$ or $\mathbf{q^-(x)}$ by changing the orientation of target nucleon spin or helicity of incident lepton beam**
- **Different targets $\Longrightarrow$ sensitivity to different quark flavors**

Quark Helicity Distributions:

$$\boxed{\Delta q_f(x) := q_f^+(x) - q_f^-(x)} \quad (f : u, d, s, \overline{u}, \overline{d}, \overline{s})$$



Data given at measured $< Q^2 >$: 0.02 - 58 GeV^2

World data on $g_1(x, Q^2)$

Virtual Photon Asymmetries:

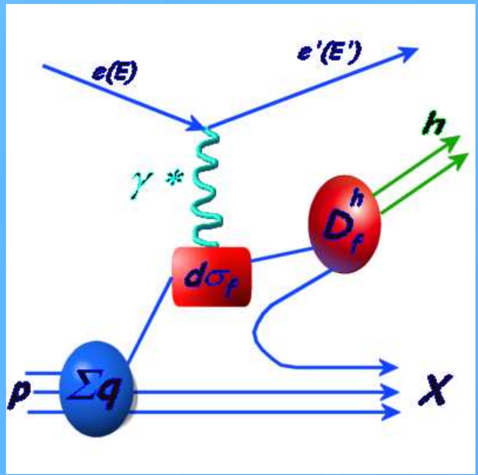
$$A_1 = \frac{\sigma_{\frac{1}{2}} - \sigma_{\frac{3}{2}}}{\sigma_{\frac{1}{2}} + \sigma_{\frac{3}{2}}} \sim \frac{g_1}{F_1}$$

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 (q_i^+(x) + q_i^-(x))$$
$$= \frac{1}{2}\sum_i e^2 q_i(x)$$

2xF$_1$: momentum distribution

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 (q_i^+(x) - q_i^-(x))$$
$$= \frac{1}{2}\sum_i e^2 \Delta q_i(x)$$

g$_1$: spin distribution of quarks



Semi-inclusive DIS

Correlation between detected hadron and struck $\mathbf{q_f}$

$\Longrightarrow$ **'Flavor - Separation'**

Inclusive DIS: $\Delta\Sigma \sim \sum_i e^2(\Delta q_i(x) + \Delta\bar{q}_i(x))$

Semi-inclusive DIS: Δu, $\Delta\bar{u}$, Δd, $\Delta\bar{d}$, Δs, $\Delta\bar{s}$

In LO-QCD:

$$\mathbf{A_1^h(x,Q^2)} = \frac{\sigma^{\mathbf{h}}_{\mathbf{1/2}} - \sigma^{\mathbf{h}}_{\mathbf{3/2}}}{\sigma^{\mathbf{h}}_{\mathbf{1/2}} + \sigma^{\mathbf{h}}_{\mathbf{3/2}}} \sim \frac{\sum_{\mathbf{f}} \mathbf{e_f^2}\,\boldsymbol{\Delta}\mathbf{q_f(x,Q^2)} \int \mathbf{dzD_f^h(z,Q^2)}}{\sum_{\mathbf{f}} \mathbf{e_f^2 q_f(x,Q^2)} \int \mathbf{dzD_f^h(z,Q^2)}}$$

$$\sim \sum_{\mathbf{q}} \underbrace{\frac{e_q^2 q(x) \int dz D_q^h(z)}{\sum_{q'} e_{q'}^2 q'(x) \int dz D_{q'}^h(z)}}_{P_q^h(x,z)} \frac{\boldsymbol{\Delta}\mathbf{q(x)}}{\mathbf{q(x)}}$$

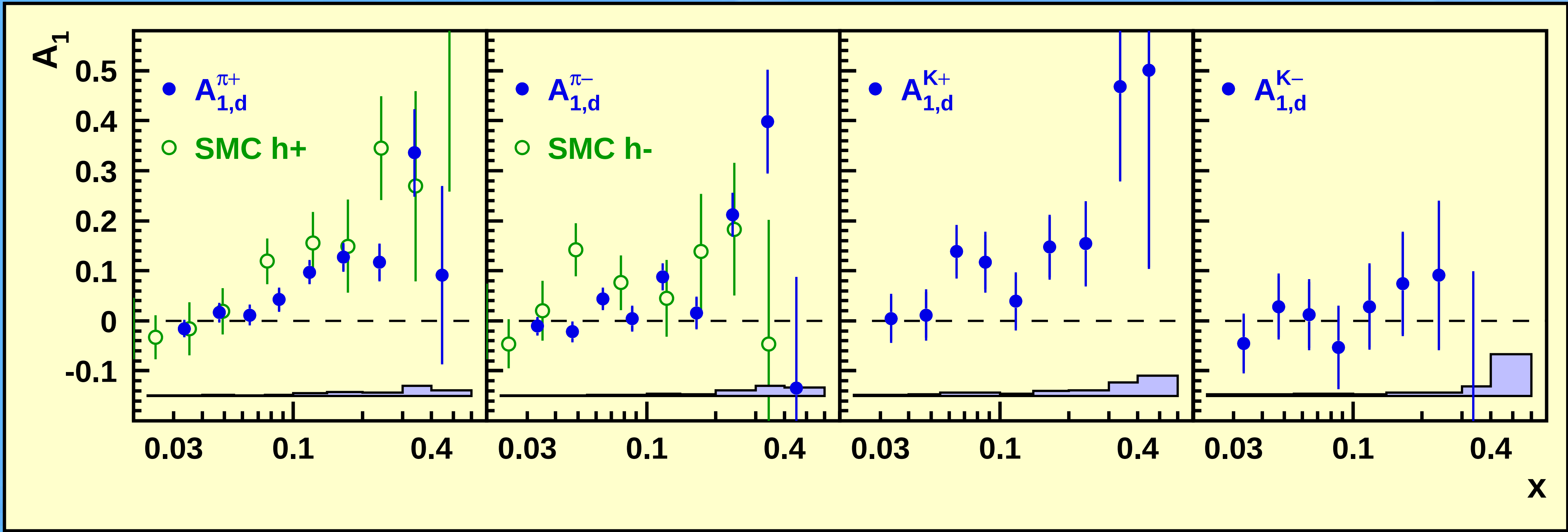
- **Solve linear system for $\vec{Q}$ with**

$$\tilde{\mathbf{A}} = (\mathbf{A_{1,p}(x)}, \mathbf{A_{1,d}(x)}, \mathbf{A_{1,p}^{\pi^\pm}(x)}, \mathbf{A_{1,d}^{\pi^\pm}(x)}, \mathbf{A_{1,d}^{K^\pm}(x)})$$

$$\tilde{\mathbf{Q}} = \left(\frac{\boldsymbol{\Delta}\mathbf{u}}{\mathbf{u}}, \frac{\boldsymbol{\Delta}\mathbf{d}}{\mathbf{d}}, \frac{\boldsymbol{\Delta}\bar{\mathbf{u}}}{\bar{\mathbf{u}}}, \frac{\boldsymbol{\Delta}\bar{\mathbf{d}}}{\bar{\mathbf{d}}}, \frac{\boldsymbol{\Delta}\mathbf{s} + \boldsymbol{\Delta}\bar{\mathbf{s}}}{\mathbf{s} + \bar{\mathbf{s}}}\right)$$

$$\vec{\mathcal{A}} = \mathcal{P}\vec{\mathcal{Q}}$$

Hadron Asymmetries on the Deuteron



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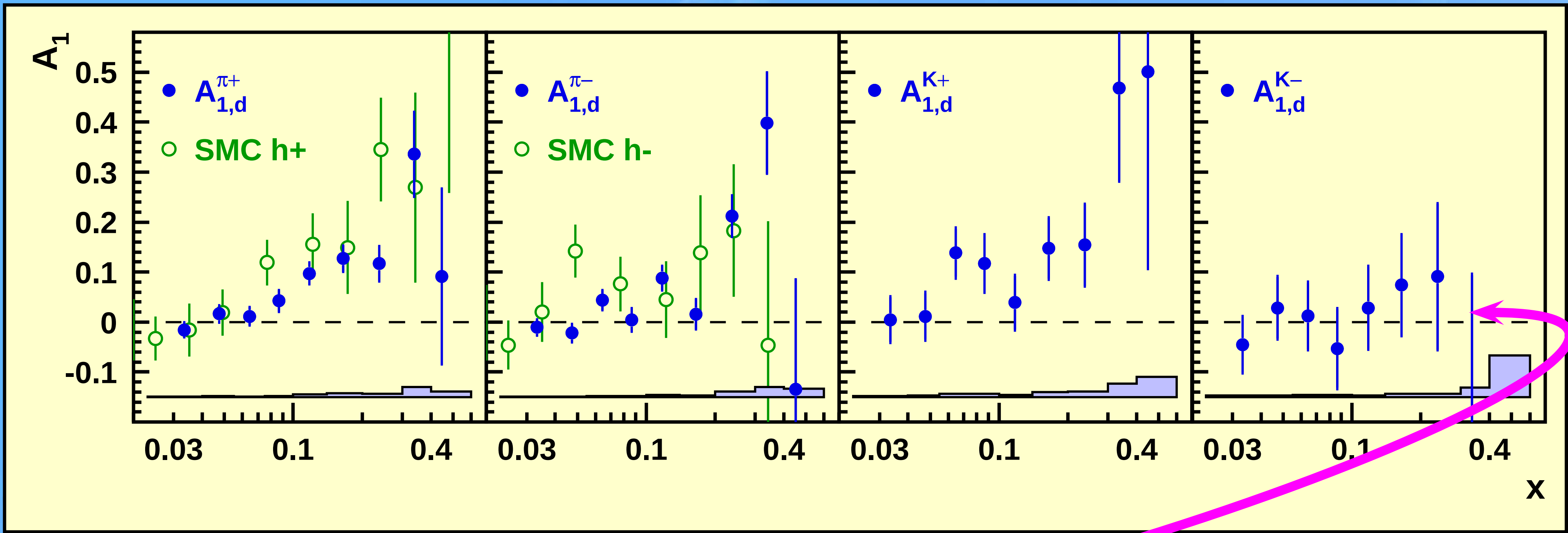
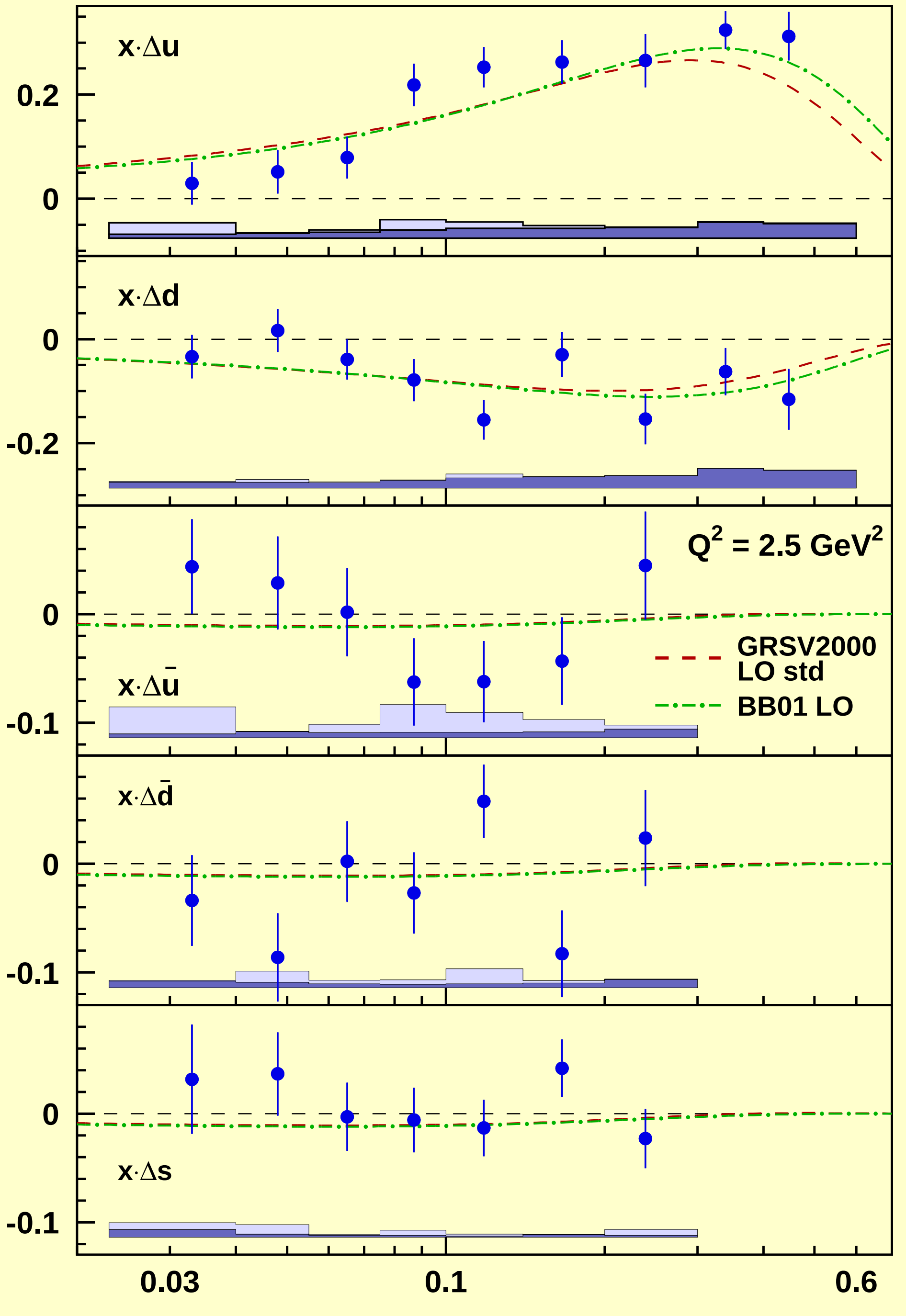
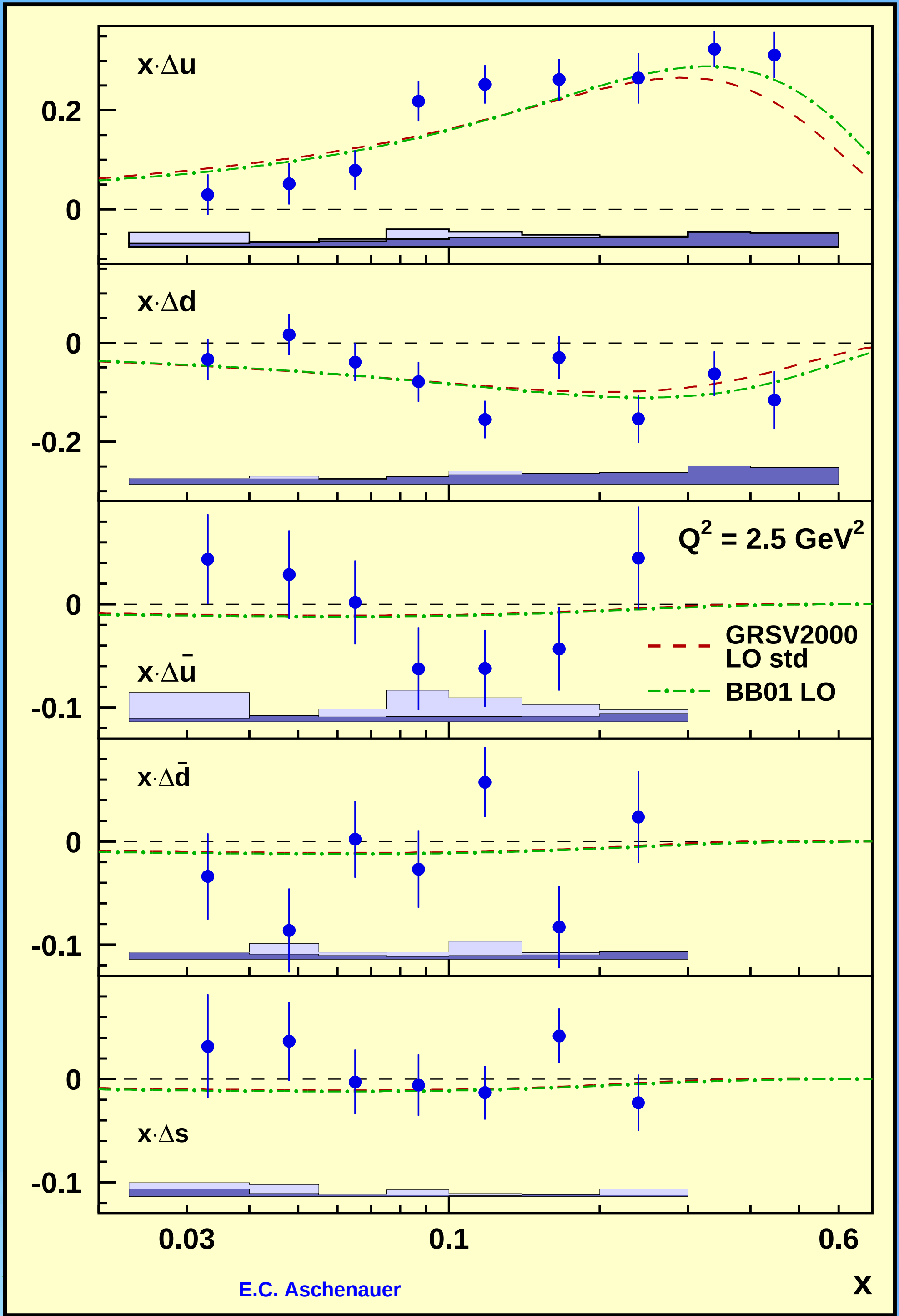


- $A_1^{K^-}(x) \approx 0$ **!!** $\Longrightarrow K^- = (\bar{u}s)$ **is an all–sea object**

Polarized Quark Densities

$$\Delta q_f(x) := q_f^+(x) - q_f^-(x)$$

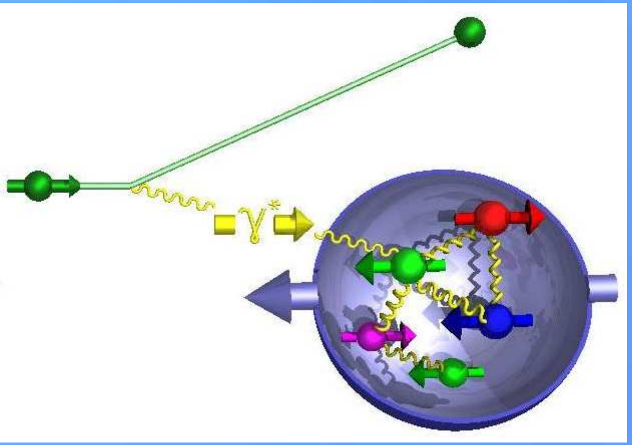




Polarized Quark Densities

$$\mathbf{\Delta q_f(x) := q_f^+(x) - q_f^-(x)}$$

- $\mathbf{\Delta u(x) > 0}$
  $\Longrightarrow$ **polarized parallel to the proton**



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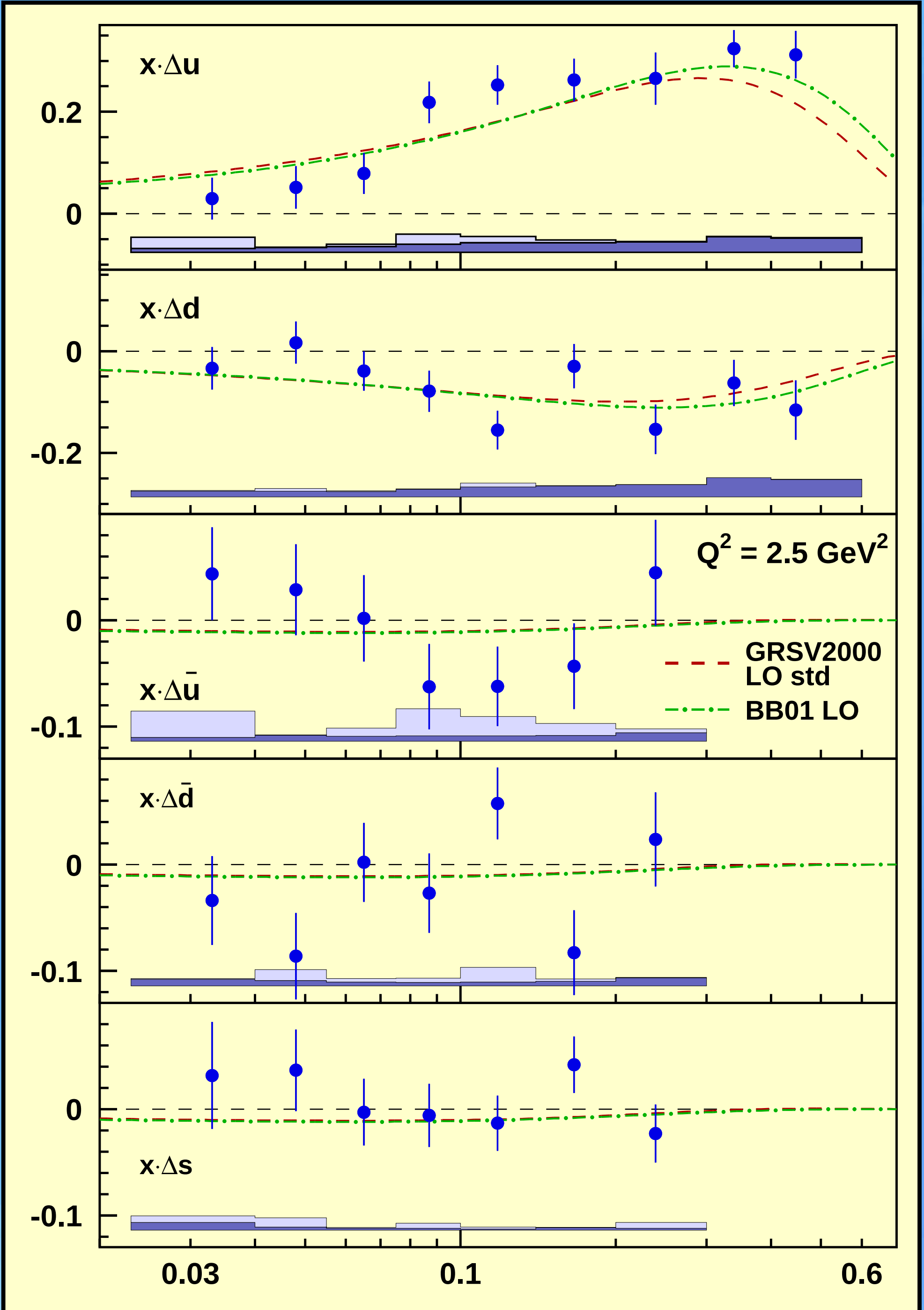

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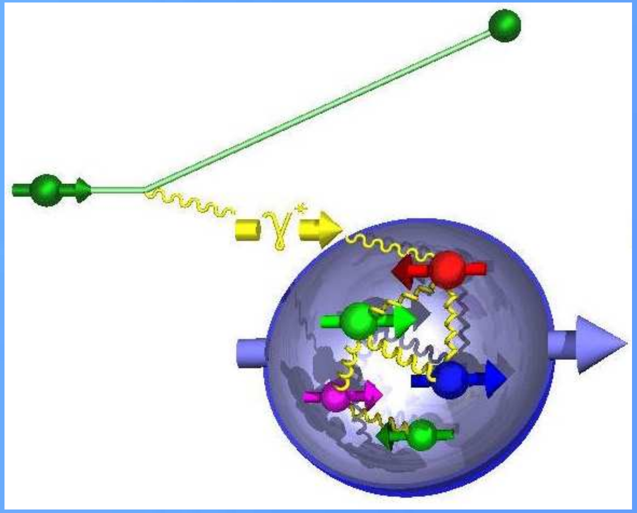

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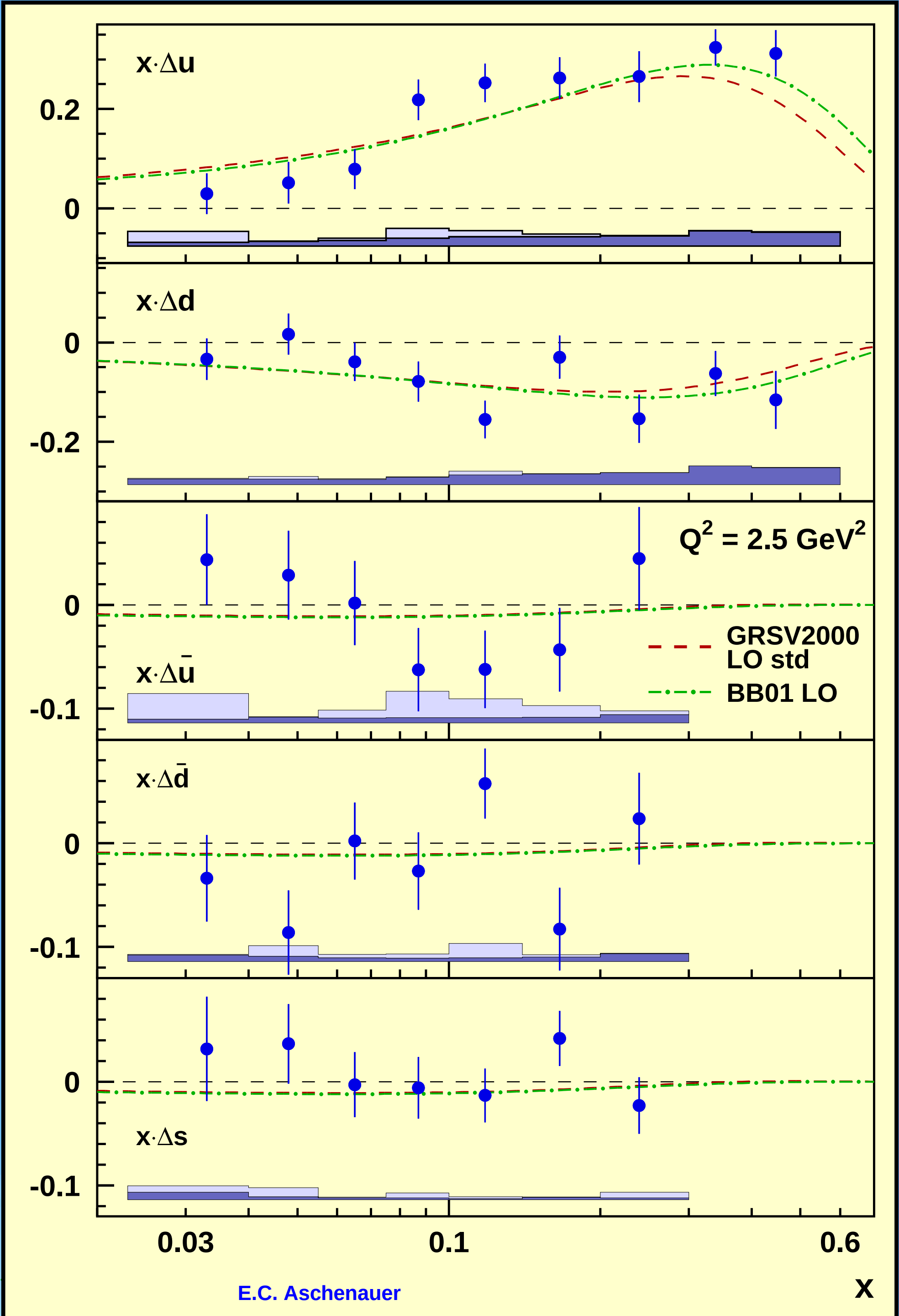

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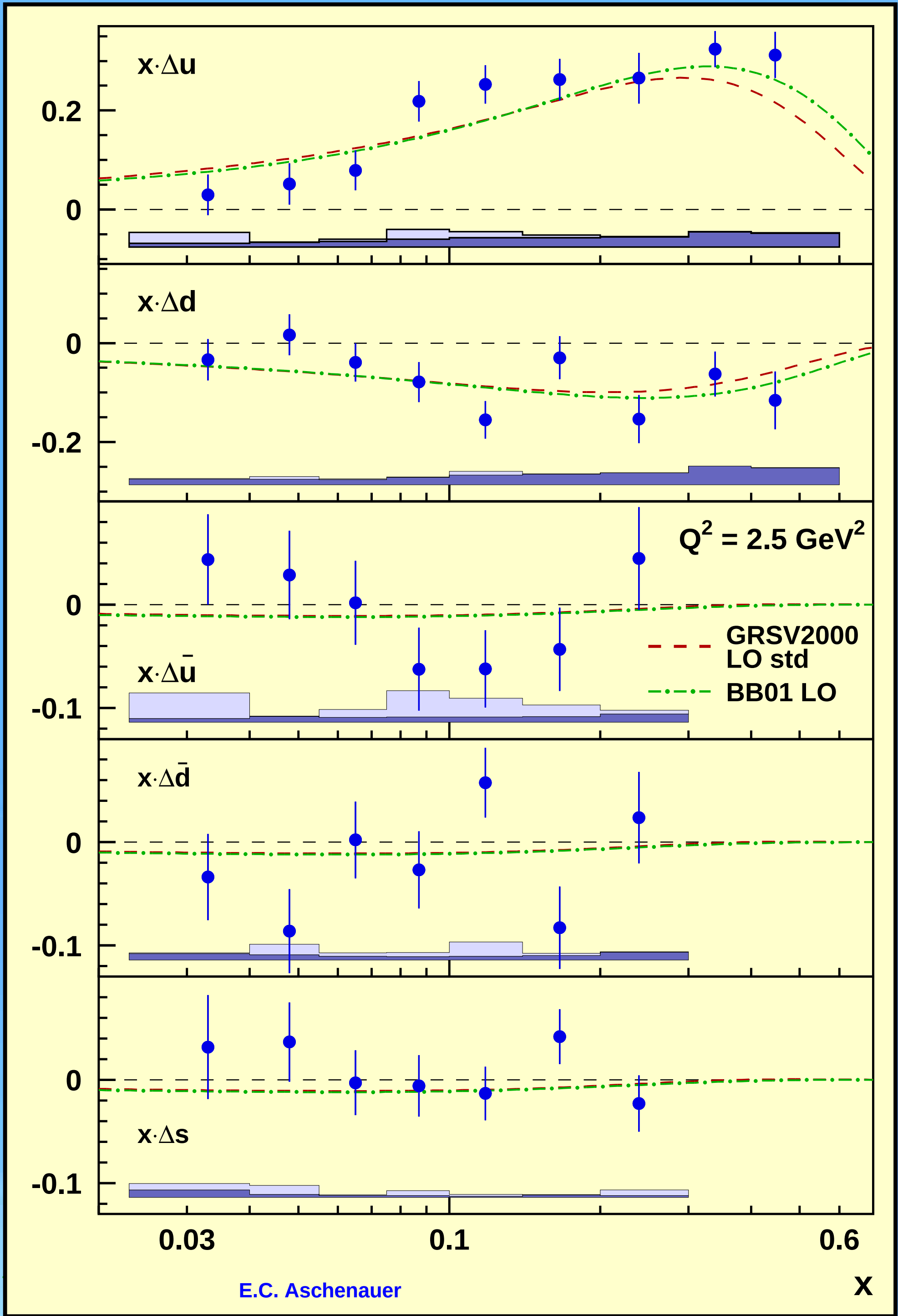
- $\mathbf{\Delta u(x)}$ **and** $\mathbf{\Delta d(x)}$
  good agreement with NLO-QCD fit

Polarized Quark Densities



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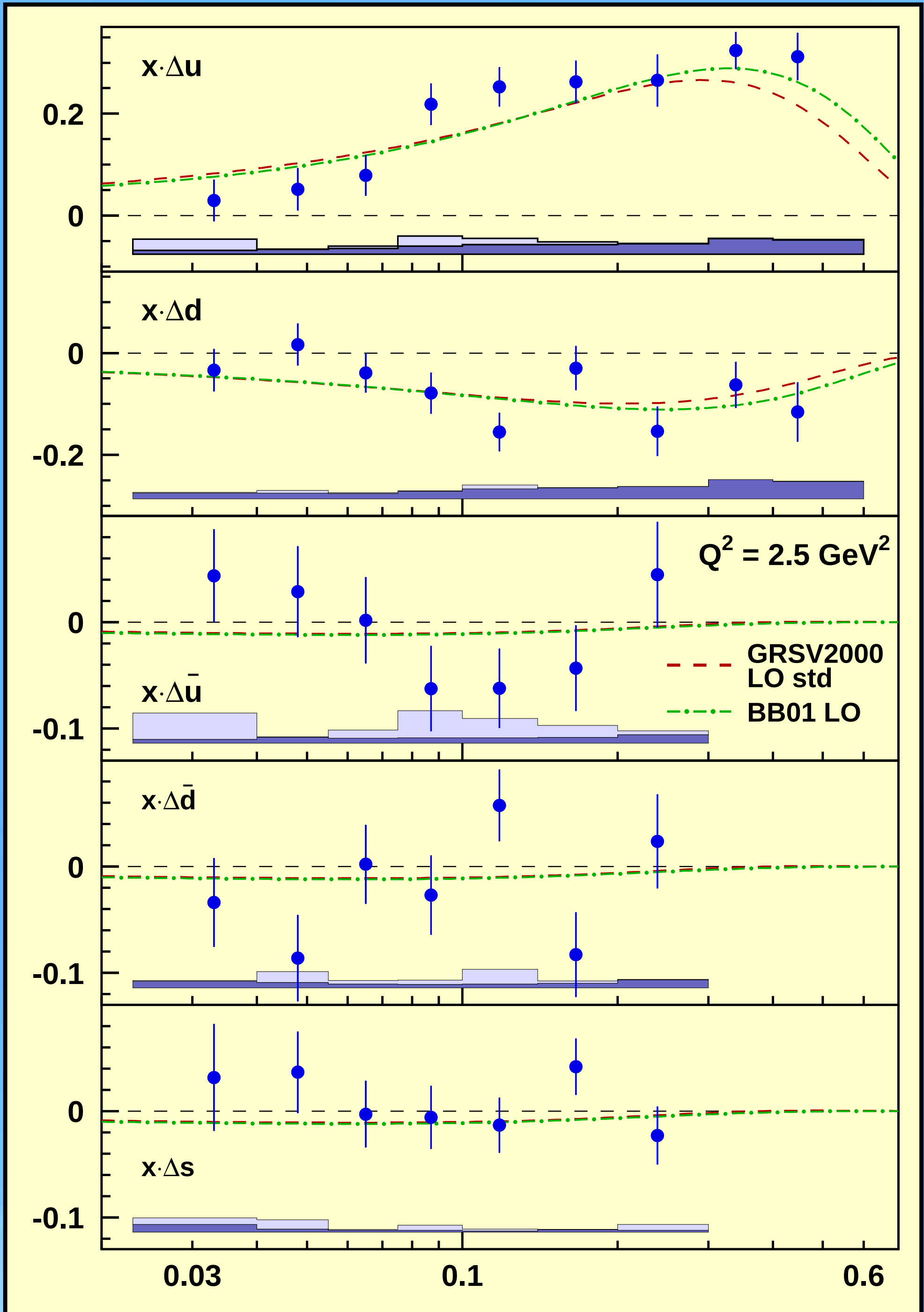
- $\mathbf{\Delta \bar{u}(x), \Delta \bar{d}(x)} \sim 0$



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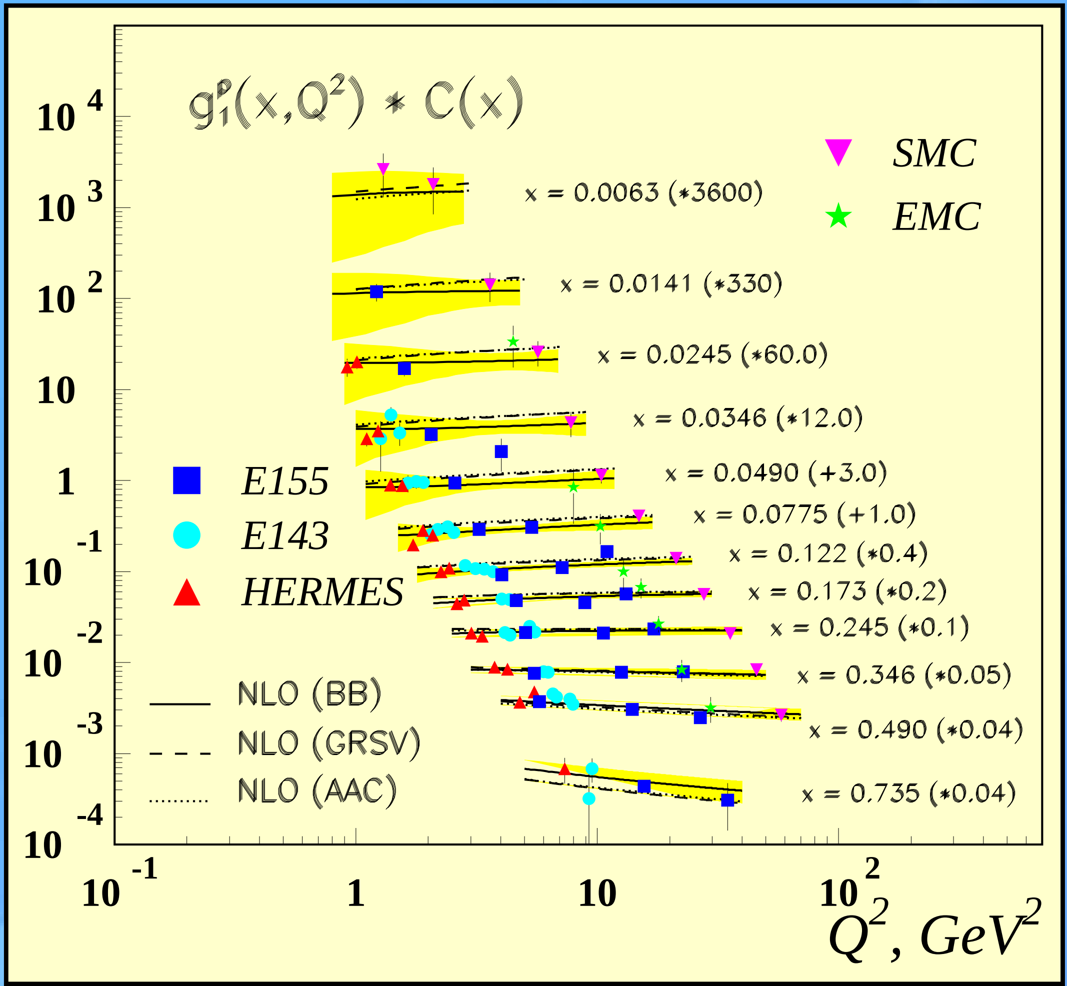
- $\mathbf{\Delta u(x)}$ **and** $\mathbf{\Delta d(x)}$
  good agreement with NLO-QCD fit
- $\mathbf{\Delta \bar{u}(x), \Delta \bar{d}(x)} \sim 0$
- **No indication for** $\mathbf{\Delta s(x)} < 0$

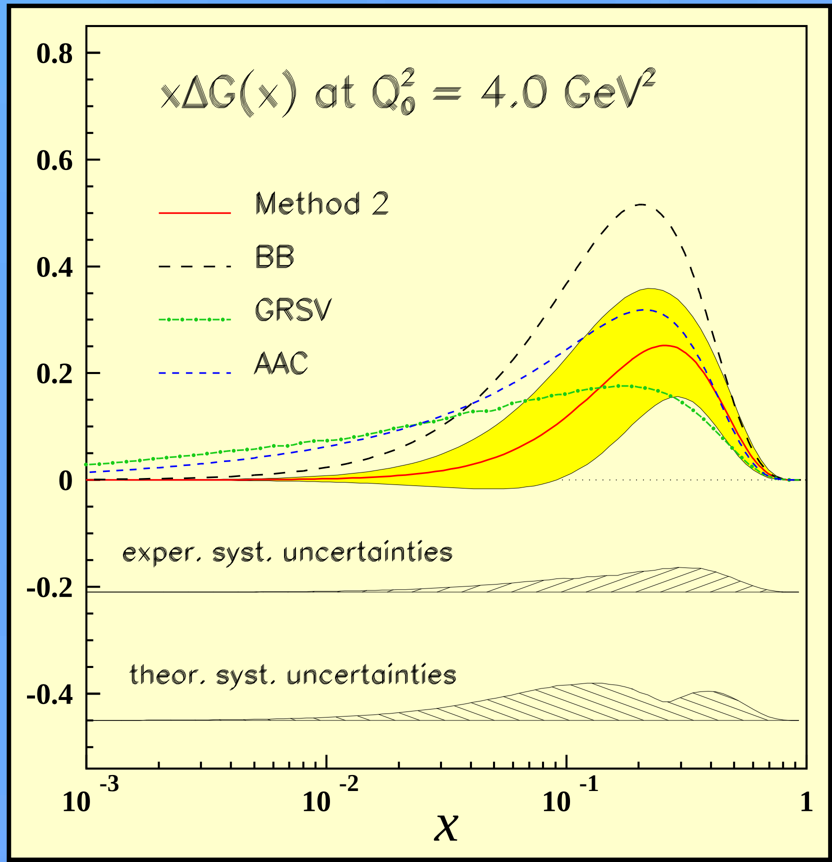
- **"Indirect" from scaling violation**

How to measure ΔG

- **"Indirect" from scaling violation**
  Polarized case:

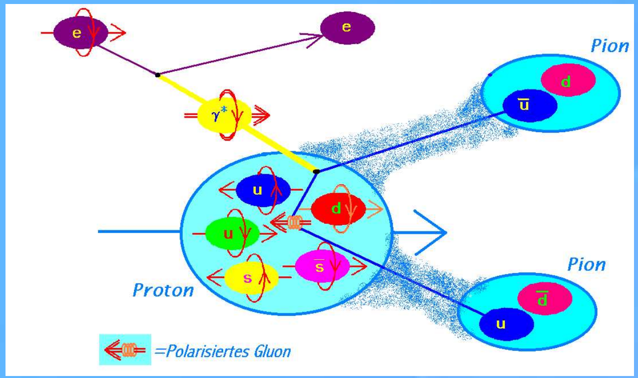


- **fixed target experiments**
  $\Longrightarrow$ **small $Q^2 - x_{bj}$ lever arm**
- **determines only sign of $\Delta G(x)$**



Direct Measurements of ΔG

Isolate the photon-gluon fusion process



pairs of high-P_T hadrons

$$\mathbf{p_T(h_1^{\pm}, h_2^{\mp}) > 1GeV}$$

$$\mathbf{A_{||}} = \frac{\mathbf{N^{\overrightarrow{\Leftarrow}}_{h_1^{\pm} h_2^{\mp}} - N^{\overrightarrow{\Rightarrow}}_{h_1^{\pm} h_2^{\mp}}}}{\mathbf{N^{\overrightarrow{\Leftarrow}}_{h_1^{\pm} h_2^{\mp}} + N^{\overrightarrow{\Rightarrow}}_{h_1^{\pm} h_2^{\mp}}}}$$

$$\mathbf{A^{\gamma^* p \rightarrow h_1^{\pm} + h_2^{\mp}} \sim -\Delta G / G}$$

additionally:
use identified hadrons

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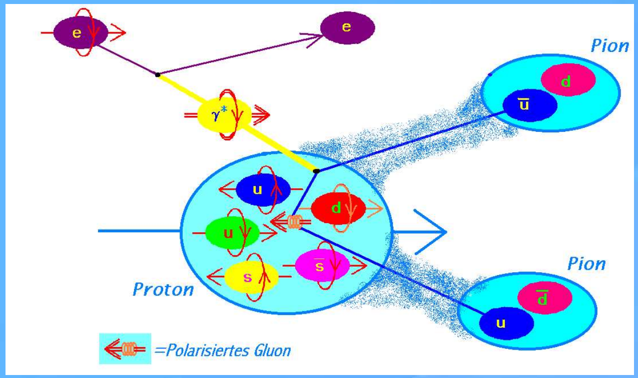
Isolate the photon-gluon fusion process



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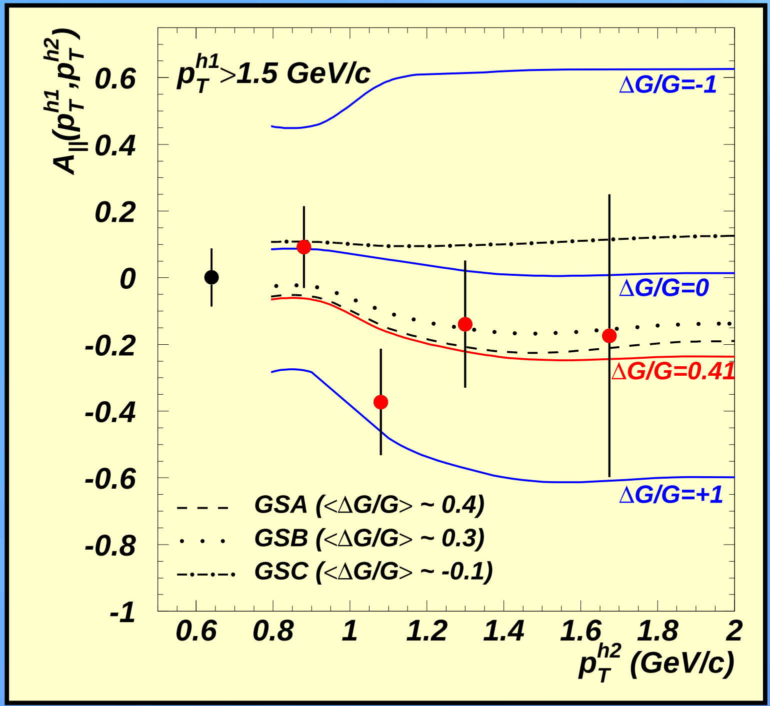
additionally:
use identified hadrons



within LO pQCD and PYTHIA5 MC model

$$\mathbf{\Delta G/G = 0.41 \pm 0.18\,(stat.) \pm 0.03\,(exp.syst.)}$$

at $\langle \mathbf{x_G} \rangle = \mathbf{0.17}\text{and}\langle \mathbf{\hat{p}_T^2} \rangle = \mathbf{2.1GeV^2}$

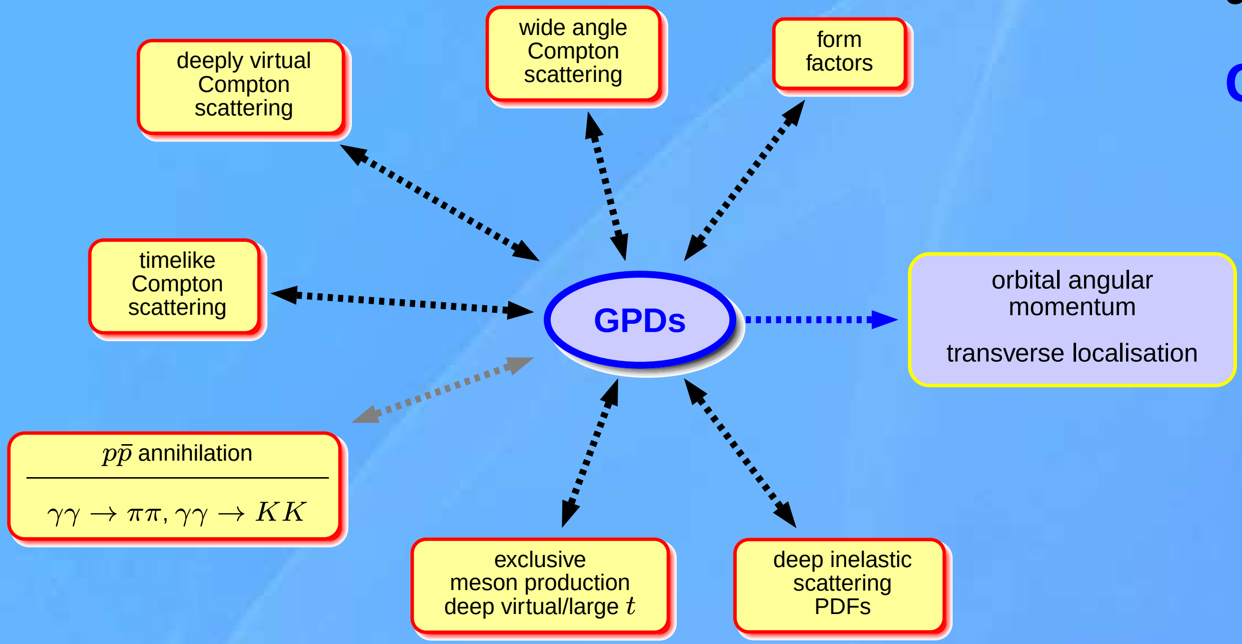
Extraction strongly Model dependent
New extraction of $\Delta G/G$ using polarized Deuterium data

The Hunt for $\mathrm{L_q}$

Study of hard exclusive processes leads to a new class of PDFs

Generalised Parton Distributions

$H^q, E^q, \tilde{H}^q, \tilde{E}^q$



$\Rightarrow$ **possible access to orbital angular momentum**

$$J_q = \frac{1}{2}\left(\int_{-1}^{1} x \mathrm{d}x (H^q + E^q)\right)_{t\to 0}$$
$$J_q = \frac{1}{2}\Delta\Sigma + L_q$$

exclusive: all products of a reaction are detected

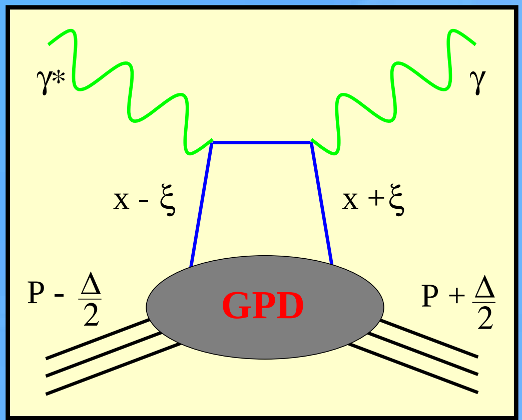
$\Longrightarrow$ **missing energy ($\Delta\mathrm{E}$) and missing Mass ($\mathrm{M_x}$) = 0**

GPDs Introduction

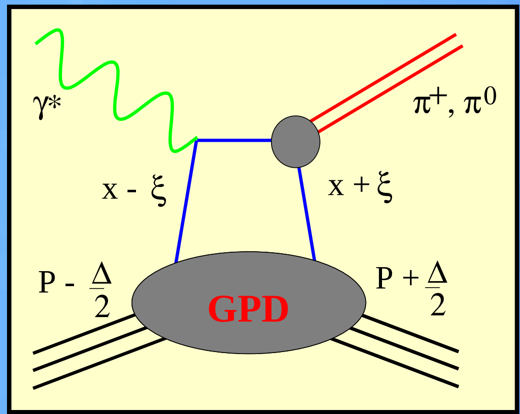
What does GPDs characterize?

unpolarized	polarized	
$H^q(x,\xi,t)$	$\tilde{H}^q(x,\xi,t)$	**conserve nucleon helicity**
		$H^q(x,0,0) = q$ **,** $\tilde{H}^q(x,0,0) = \Delta q$
$E^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$	**flip nucleon helicity**
		not accessible in DIS

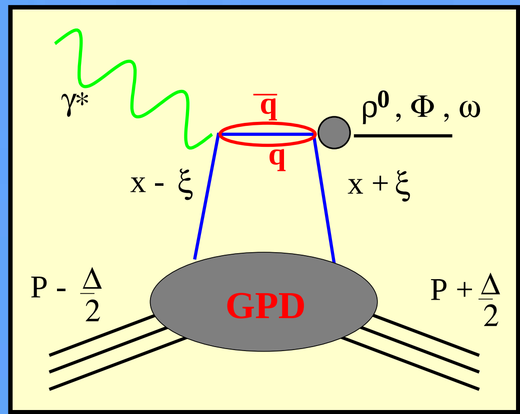
quantum numbers of final state $\Rightarrow$ select different GPDs



DVCS:
$H^q, E^q, \tilde{H}^q, \tilde{E}^q$



pseudo-scalar mesons
$\tilde{H}^q, \tilde{E}^q$



vector mesons
H^q, E^q

x, t, ξ **defined on the light cone**

x: **longitudinal momentum fraction**

t: **momentum transfer** ($t = \Delta^2$)

ξ: **exchanged longitudinal momentum fraction** ($\xi = \frac{x_{Bj}/2}{1-x_{Bj}/2}$)

DVCS azimuthal asymmetries

$$d\sigma \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + (\mathcal{T}^*_{BH}\mathcal{T}_{DVCS} + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH})$$

isolate BH-DVCS interference term $\Longrightarrow$ non-zero azimuthal asymmetries

- **imaginary part $\propto$ beam helicity asymmetry:**

$$d\sigma_{\overleftarrow{e^+}} - d\sigma_{\overrightarrow{e^+}} \propto \mathrm{Im}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS})$$
$$\propto \sin\phi \Longrightarrow H^u(x,\xi,t)$$

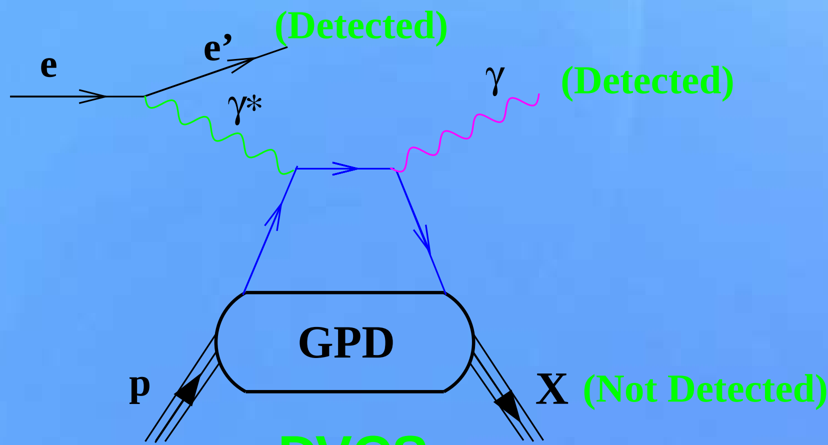
$\Rightarrow$ asymmetry measured by HERMES and JLAB

- **real part $\propto$ beam charge asymmetry:**

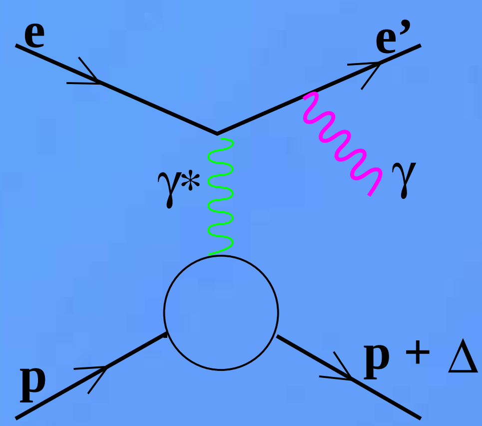
$$d\sigma_{e^+} - d\sigma_{e^-} \propto \mathrm{Re}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS})$$
$$\propto \cos\phi \Longrightarrow H^u(x,\xi,t)$$

$\Rightarrow$ asymmetry measured by HERMES

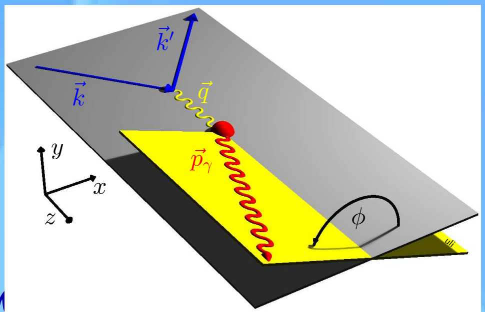
- **no polarized target needed**



DVCS



Bethe-Heitler

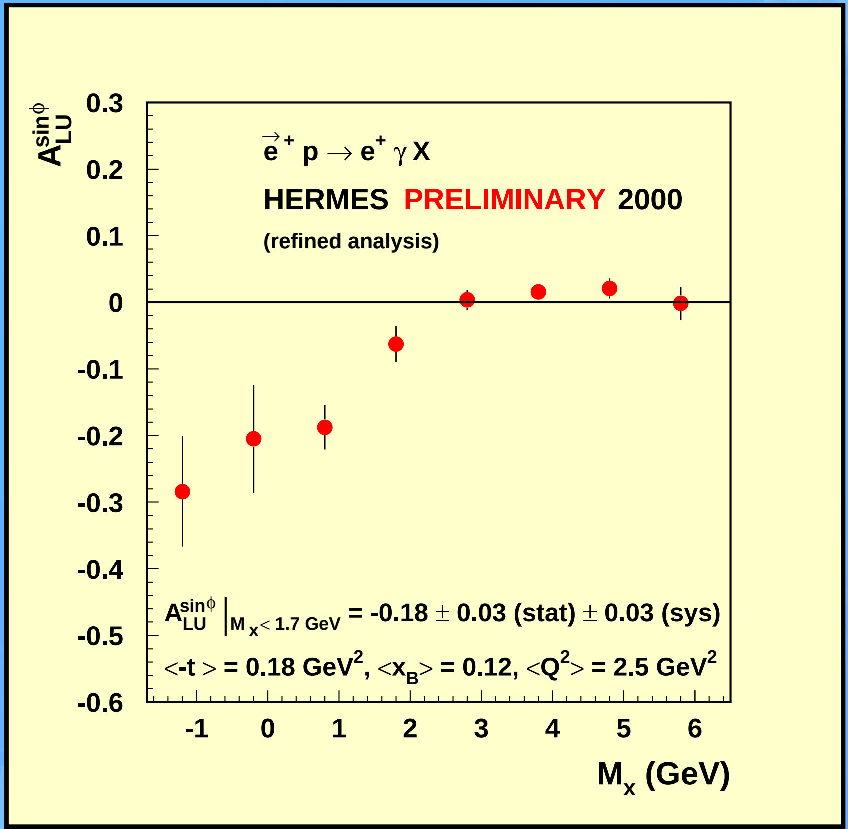


ϕ: azimuthal angle between lepton scattering plane and the $\gamma^*\gamma$ - plane

DVCS BSA and BCA

$$\mathbf{d}\sigma_{\overleftarrow{\mathbf{e}^+}} - \mathbf{d}\sigma_{\overrightarrow{\mathbf{e}^+}}$$

sensitive to $\mathrm{Im}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS})$

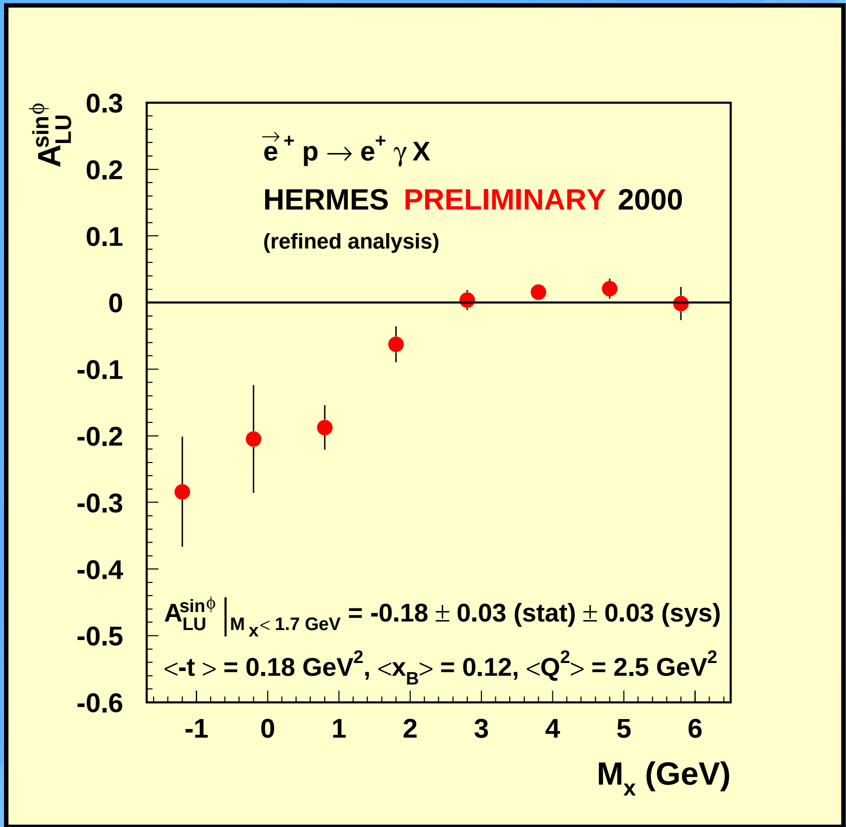


measures GPD $(\mathrm{x}, \xi, \mathrm{t})$ **at** $\mathrm{x} = \xi$

DVCS BSA and BCA

$$d\sigma_{\overleftarrow{e^+}} - d\sigma_{\overrightarrow{e^+}}$$

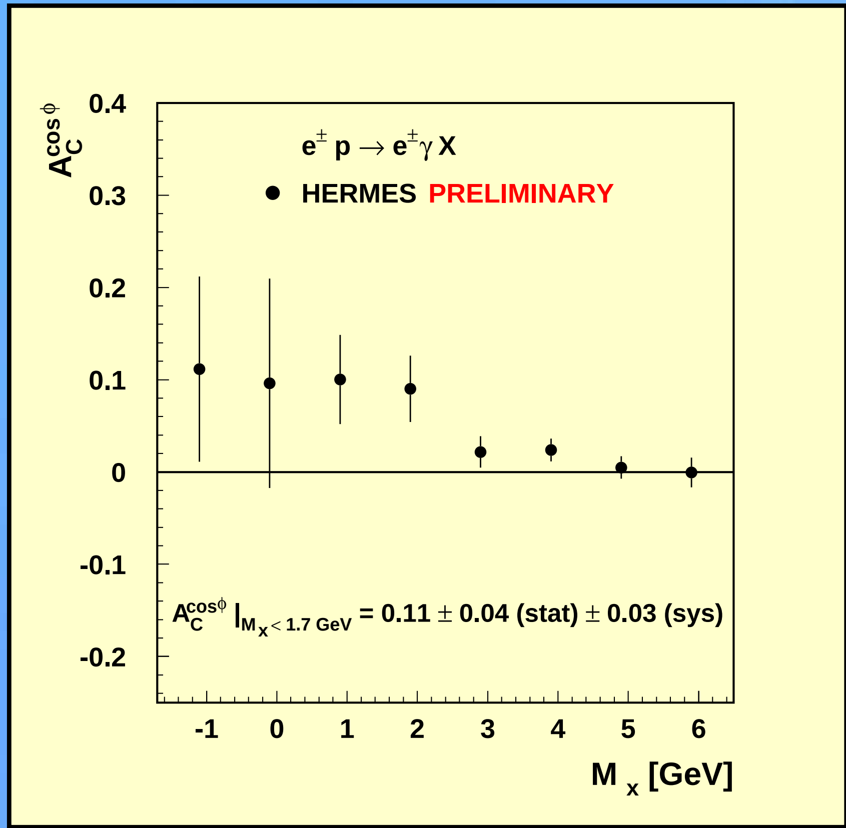
sensitive to $\mathrm{Im}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS})$



measures GPD (x, ξ, t) **at** $x = \xi$

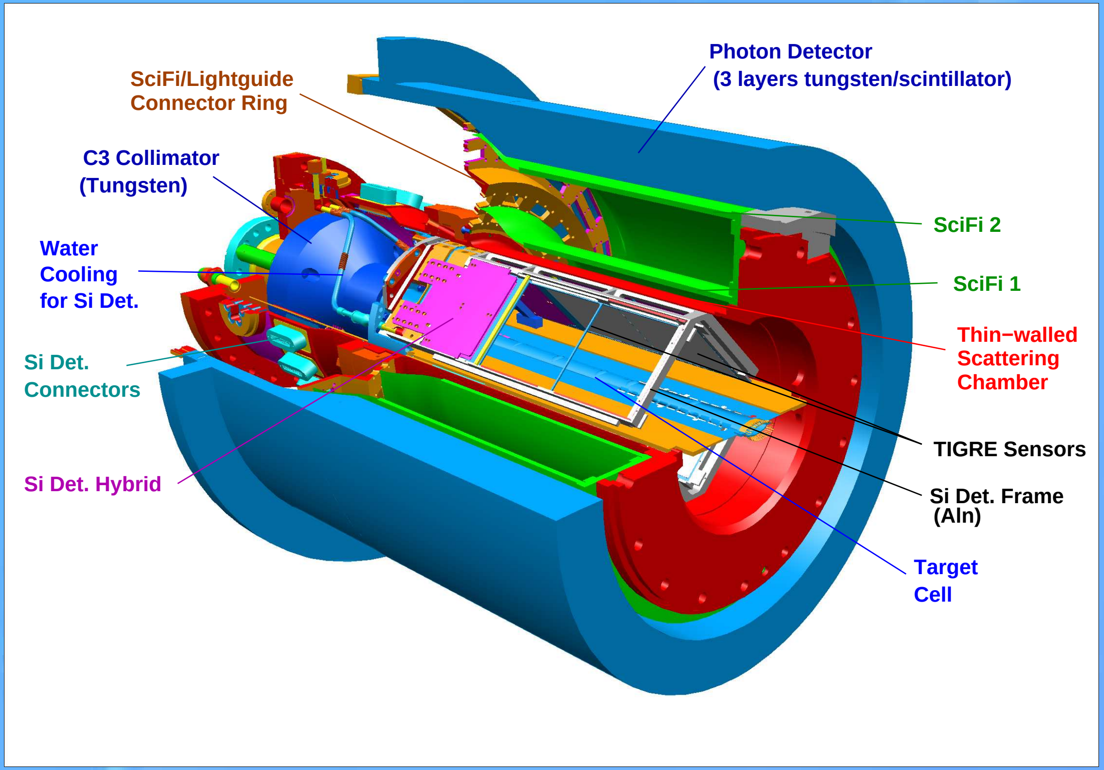
$$d\sigma_{e^+} - d\sigma_{e^-}$$

sensitive to $\mathrm{Re}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS})$



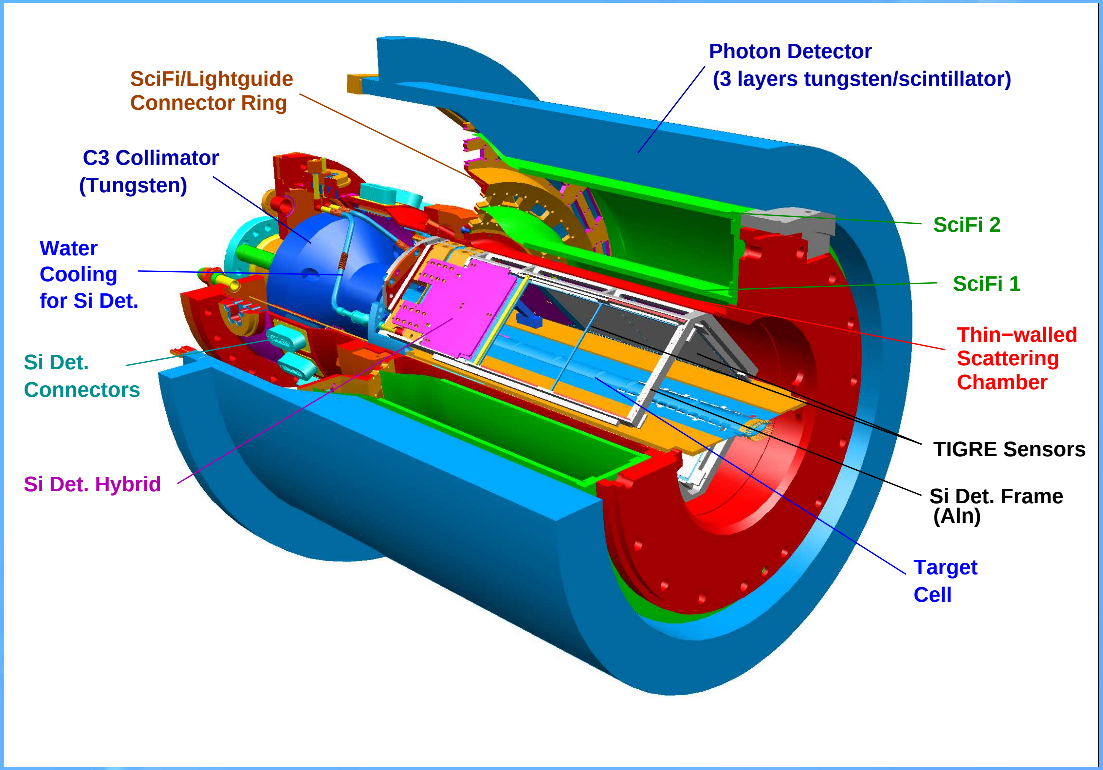
Access to $q\bar{q}$ **content of mesonic correlations in nucleon**

The HERMES Recoil Detector



build by DESY, Erlangen, Ferrara, Frascati, Gent, Giessen Glasgow

The HERMES Recoil Detector



build by DESY, Erlangen, Ferrara, Frascati, Gent, Giessen Glasgow

- **detection of the recoiling proton**
  $\Rightarrow$ p: 135 - 1200 MeV /c
  $\Rightarrow$ 76 % ϕ acceptance
  $\Rightarrow$ π/p-PID via dE/dx
- **Background Suppression**
  $\Rightarrow$ improved exclusivity
  $\Rightarrow$ suppress Δ contribution
- **improve t-resolution by factor 10**
  $\Rightarrow$ study kinematical dependences
- **data taking through last 2 years of HERA**

Deep Inelastic Scattering Cross Section

Cross Section: $\frac{d^2\sigma}{d\Omega dE^2} = \frac{\alpha^2 E'}{Q^2 E} \underbrace{L_{\mu\nu}(k,q,s)}_{\text{leptonic}} \underbrace{W^{\mu\nu}(P,q,S)}_{\text{hadronic}}$

$L_{\mu\nu}$: **purely electromagnetic** $\Longrightarrow$ **calculable in QED**

$W^{\mu\nu}$ **=** $-g^{\mu\nu} F_1\left(x,Q^2\right) + \frac{p^\mu p^\nu}{\nu} F_2\left(x,Q^2\right)$

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

(for spin 1) **+ quadrupole terms** (b_1, b_2, b_3, b_4)

No Information on

relativistic effects, intrinsic k_T, masses and correlations of quarks

DIS and SIDIS Cross Section

$$\mathbf{d}\sigma = \mathbf{d}\sigma_{\mathbf{UU}} + \mathbf{cos2}\phi\mathbf{d}\sigma_{\mathbf{UU}} + \frac{\mathbf{1}}{\mathbf{Q}}\cos\phi\mathbf{d}\sigma_{\mathbf{UU}} + \lambda\frac{\mathbf{1}}{\mathbf{Q}}\sin\phi\mathbf{d}\sigma_{\mathbf{LU}}$$

$$+\mathbf{S_L}[\sin\mathbf{2}\phi\mathbf{d}\sigma_{\mathbf{UL}} + \frac{\mathbf{1}}{\mathbf{Q}}\sin\phi\mathbf{d}\sigma_{\mathbf{UL}}] + \lambda\mathbf{S_L}[\sigma_{\mathbf{LL}} + \frac{\mathbf{1}}{\mathbf{Q}}\cos\phi\mathbf{d}\sigma_{\mathbf{LL}}] +$$

$$\mathbf{S_T}[\sin(\phi+\phi_{\mathbf{S}})\mathbf{d}\sigma_{\mathbf{UT}} + \sin(\phi-\phi_{\mathbf{S}})\mathbf{d}\sigma_{\mathbf{UT}} + \sin(\mathbf{3}\phi-\phi_{\mathbf{S}})\sigma_{\mathbf{UT}} + \frac{\mathbf{1}}{\mathbf{Q}}\sin(\mathbf{2}\phi-\phi_{\mathbf{S}})\mathbf{d}\sigma_{\mathbf{UT}}]$$

$$+\lambda\mathbf{S_T}[\cos(\phi-\phi_{\mathbf{S}})\mathbf{d}\sigma_{\mathbf{LT}} + \frac{\mathbf{1}}{\mathbf{Q}}\cos(\mathbf{2}\phi-\phi_{\mathbf{S}})\mathbf{d}\sigma_{\mathbf{LT}}] + ...$$

$\Longrightarrow$ **non zero Single Spin Azimuthal Asymmetries**

$\sigma_{\mathbf{LT}}$

↙ ↘

Beam Target polarization

Mulders and Tangermann (NP B 461 (1996) 197)

DIS and SIDIS Cross Section

$$\mathbf{d}\sigma = \mathbf{d}\sigma_{\mathbf{UU}} + \cos 2\phi\, \mathbf{d}\sigma_{\mathbf{UU}} + \frac{\mathbf{1}}{\mathbf{Q}} \cos\phi\, \mathbf{d}\sigma_{\mathbf{UU}} + \lambda \frac{\mathbf{1}}{\mathbf{Q}} \sin\phi\, \mathbf{d}\sigma_{\mathbf{LU}}$$

$$+\mathbf{S_L}[\sin 2\phi\, \mathbf{d}\sigma_{\mathbf{UL}} + \frac{\mathbf{1}}{\mathbf{Q}} \sin\phi\, \mathbf{d}\sigma_{\mathbf{UL}}] + \lambda \mathbf{S_L}[\sigma_{\mathbf{LL}} + \frac{\mathbf{1}}{\mathbf{Q}} \cos\phi\, \mathbf{d}\sigma_{\mathbf{LL}}] +$$

$$\mathbf{S_T}[\sin(\phi+\phi_{\mathbf{S}})\mathbf{d}\sigma_{\mathbf{UT}} + \sin(\phi-\phi_{\mathbf{S}})\mathbf{d}\sigma_{\mathbf{UT}} + \sin(\mathbf{3}\phi-\phi_{\mathbf{S}})\sigma_{\mathbf{UT}} + \frac{\mathbf{1}}{\mathbf{Q}} \sin(\mathbf{2}\phi-\phi_{\mathbf{S}})\mathbf{d}\sigma_{\mathbf{UT}}]$$

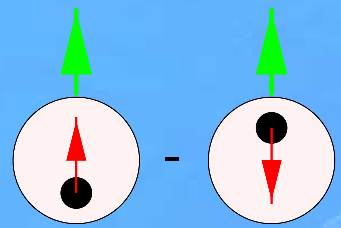
$$+\lambda \mathbf{S_T}[\cos(\phi-\phi_{\mathbf{S}})\mathbf{d}\sigma_{\mathbf{LT}} + \frac{\mathbf{1}}{\mathbf{Q}} \cos(\mathbf{2}\phi-\phi_{\mathbf{S}})\mathbf{d}\sigma_{\mathbf{LT}}] + \ldots.$$

$\mathbf{f_1}$ $\mathbf{g_1}$ $\mathbf{h_1}$ $\mathbf{f_{1T}^{\perp}}$

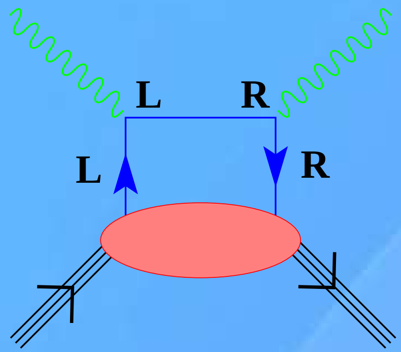
$\Longrightarrow$ **3 leading twist DFs survive k_t integration**

Peculiarities of Transversity & Sivers

TRANSVERSITY

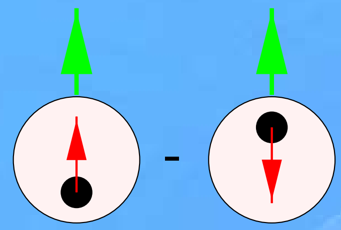
$h_1^q =$ 

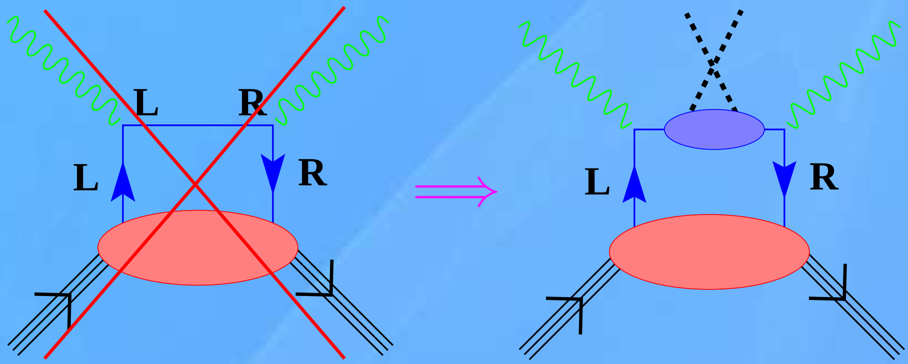
Single helicity flip ⇒ Chiral odd



Peculiarities of Transversity & Sivers

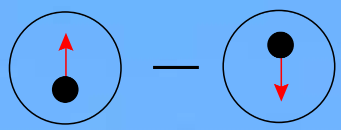
TRANSVERSITY

h_1^q =




$\Longrightarrow$ **double helicity flip** $\Longrightarrow$ **SIDIS**

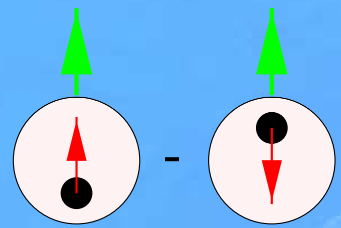
$\Longrightarrow$ **chiral-odd Collins FF** $H_1^\perp$

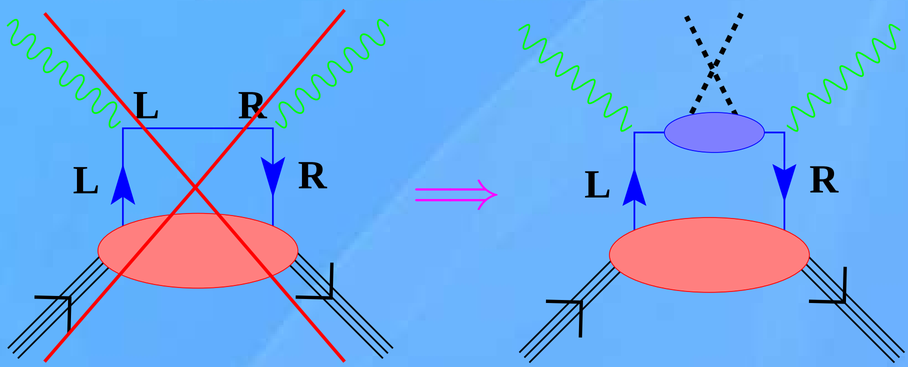
$H_1^\perp$ =


Peculiarities of Transversity & Sivers

TRANSVERSITY

h_1^q =

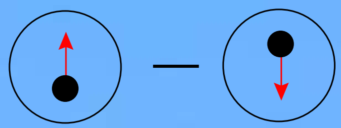




⟹ **double helicity flip** ⟹ **SIDIS**

⟹ **chiral-odd Collins FF** $H_1^\perp$

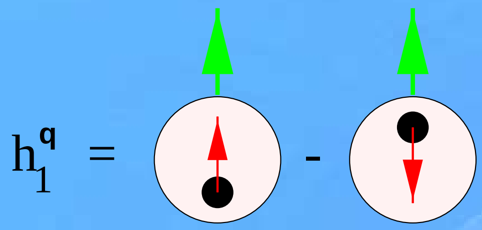
$\mathbf{H_1^\perp}$ =



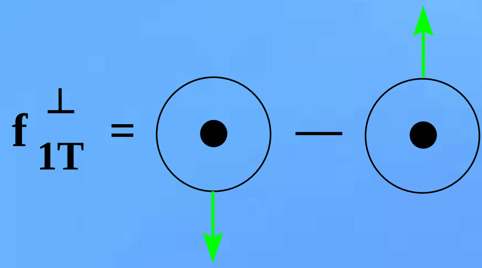
- $\delta\mathbf{q}$ **probes relativistic nature of quarks**
- $\delta\mathbf{q}$ **=** $\delta\mathbf{q} - \delta\bar{\mathbf{q}}$
  high sensitivity to valence quarks

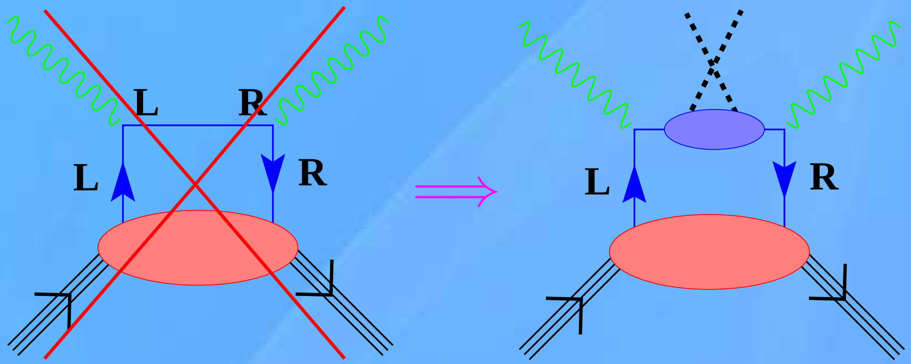
Peculiarities of Transversity & Sivers

TRANSVERSITY



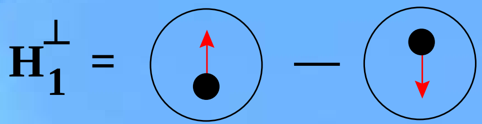
SIVERS FUNCTION





$\Longrightarrow$ **double helicity flip** $\Longrightarrow$ **SIDIS**

$\Longrightarrow$ **chiral-odd Collins FF** $H_1^\perp$



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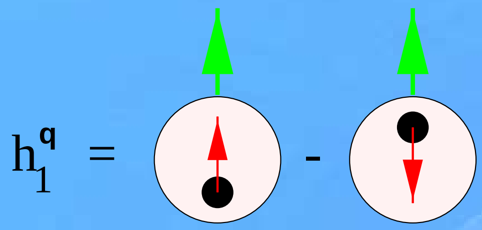
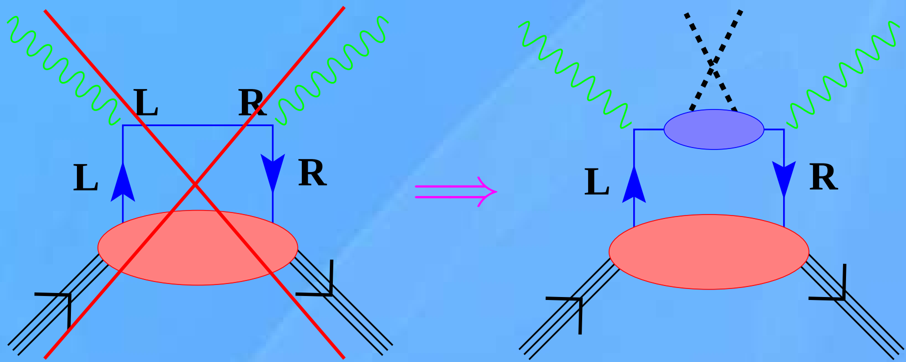
Peculiarities of Transversity & Sivers

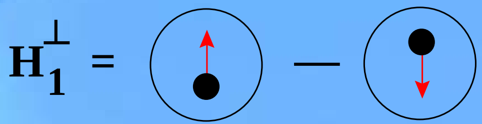
TRANSVERSITY





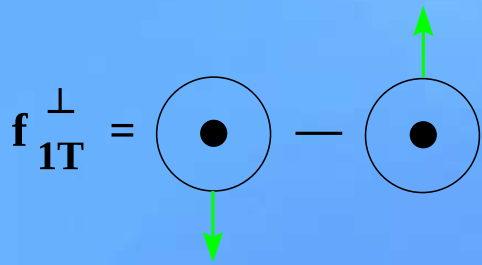
$\Longrightarrow$ double helicity flip $\Longrightarrow$ SIDIS

$\Longrightarrow$ chiral-odd Collins FF $H_1^\perp$



- δq probes relativistic nature of quarks
- δq = $\delta q - \delta \bar{q}$
  high sensitivity to valence quarks

SIVERS FUNCTION



- Chiral-even distribution function
- naive T-odd distribution function
- $f_{1T}^\perp \neq 0$
  indicates non-vanishing orbital angular momentum of quarks $L_q \neq 0$
- Violates naive universality of PDFs
  $\Longrightarrow$ Different sign of $f_{1T}^\perp$ in DY and DIS

How can one measure Transversity / Sivers

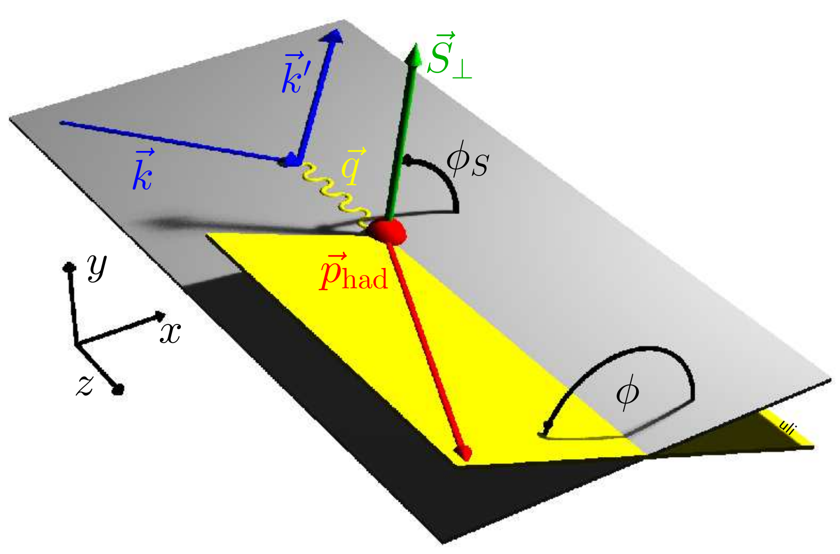
Single spin azimuthal asymmetries with a transverse polarized target

$$ep^{\uparrow} \longrightarrow e'\pi X$$

$$\sigma^{ep\to e\pi X} = \sum_q f^{N\to q} \otimes \sigma^{eq\to eq} \otimes D^{q\to\pi}$$

Distribution-function ($f^{N\to q}$)

Fragmentat.-function ($D^{q\to\pi}$)



$$A^h_{UT}(\phi,\phi_s) = \frac{1}{|S_T|}\frac{N^{\uparrow}_h(\phi,\phi_s) - N^{\downarrow}_h(\phi,\phi_s)}{N^{\uparrow}_h(\phi,\phi_s) + N^{\downarrow}_h(\phi,\phi_s)}$$

$$= A^{Collins}_{UT}\sin(\phi+\phi_s) + A^{Sivers}_{UT}\sin(\phi-\phi_s)$$

$$A^{Collins}_{UT} \propto \frac{\sum_q e_q^2\, \delta q(x)\, H_1^{\perp,q}(z)}{\sum_q e_q^2\, q(x)\, D_1^q(z)}$$

$$A^{Sivers}_{UT} \propto \frac{\sum_q e_q^2\, f_{1T}^q\, D_1^q(z)}{\sum_q e_q^2\, q(x)\, D_1^q(z)}$$

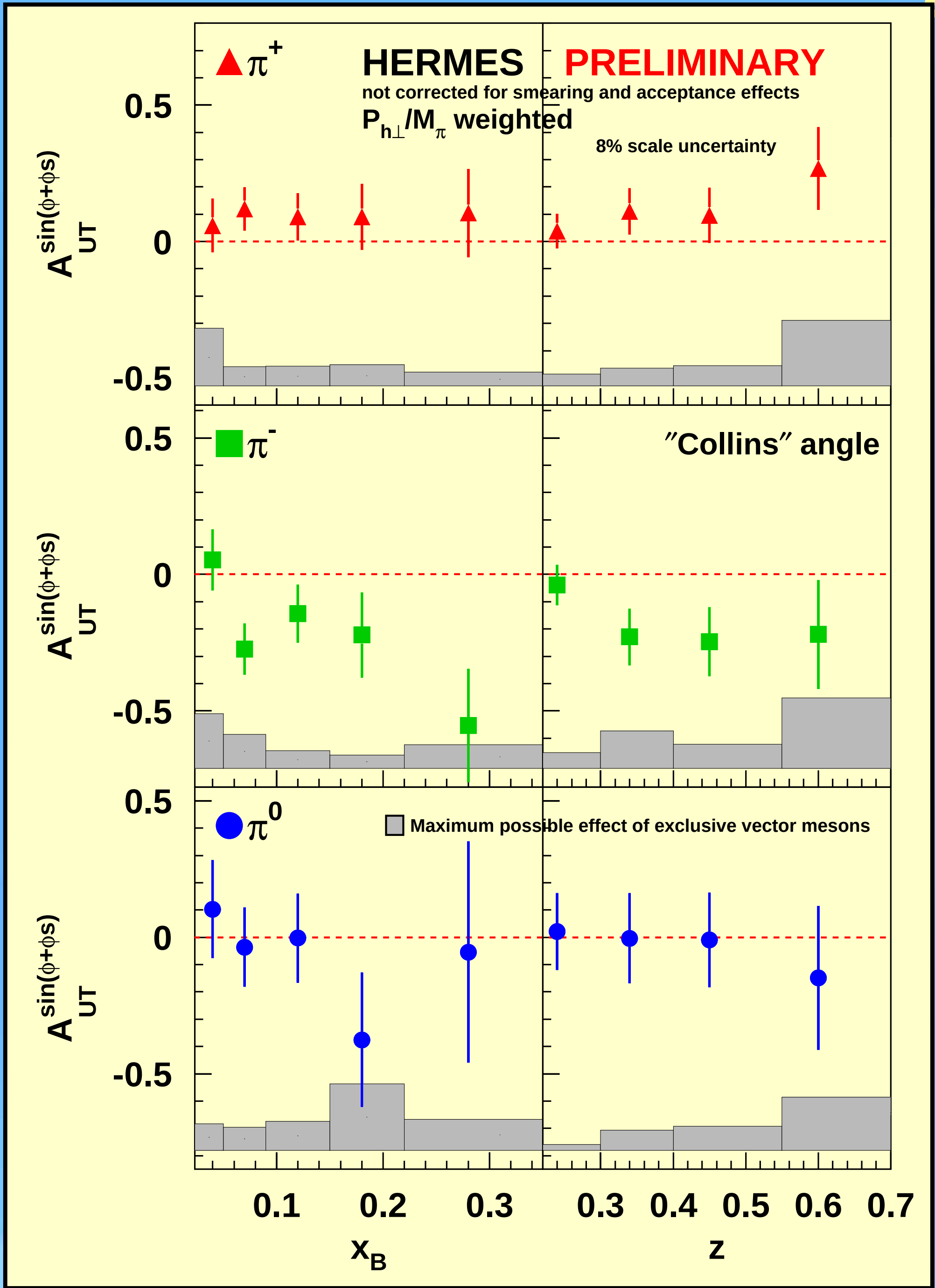
Collins–Angle: $\Phi = \phi + \phi_s$

Angle of hadron relative to final quark spin

Sivers–Angle: $\Phi = \phi - \phi_s$

Angle of hadron relative to initial target spin

First glimpse of Transversity!



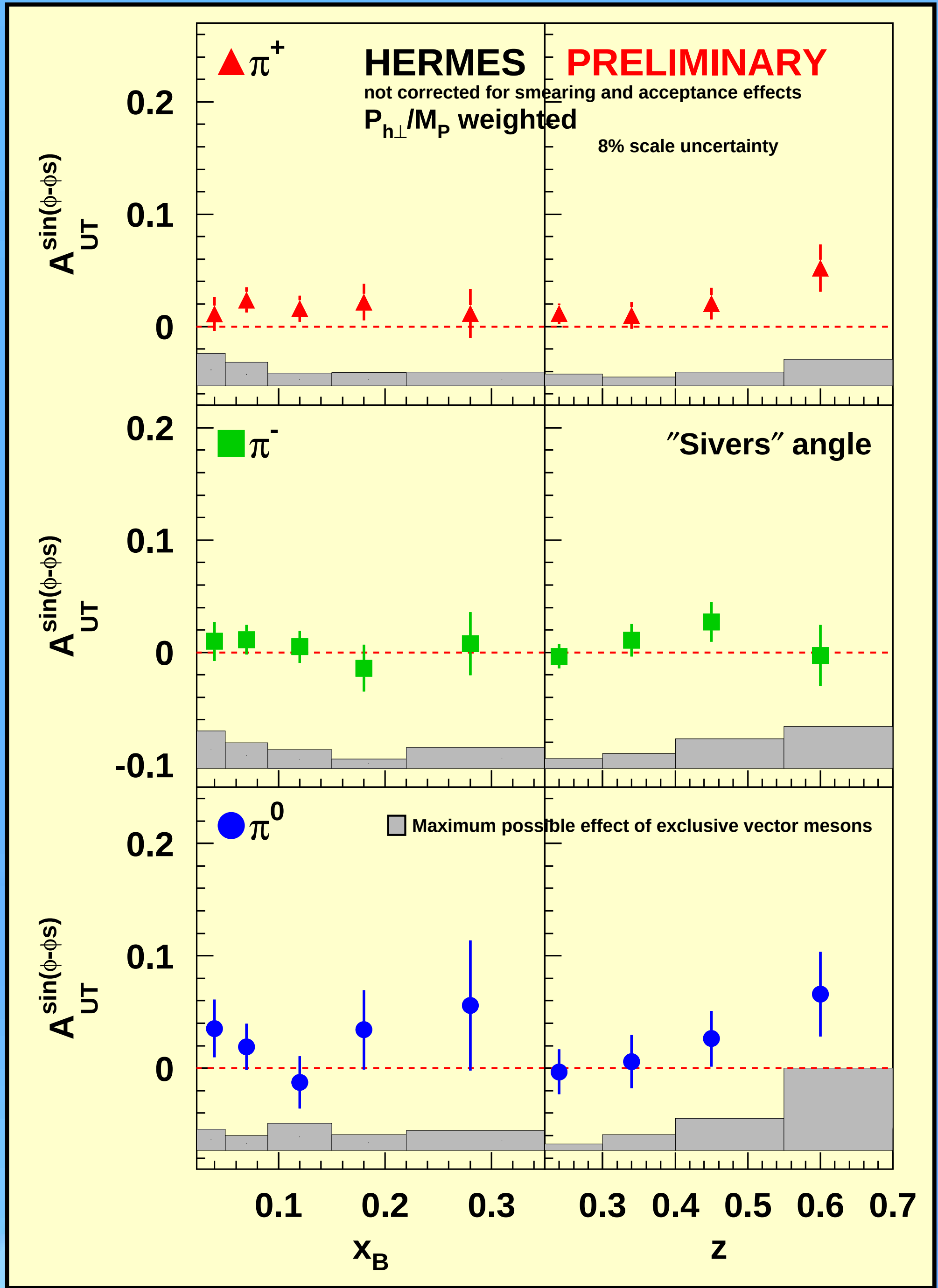
$$A_{UT}^{Collins} \propto \frac{\sum_q e_q^2\, \delta q(x)\, H_1^{\perp,q}(z)}{\sum_q e_q^2\, q(x)\, D_1^q(z)}$$

- $\pi^+ : A_{UT}^{\sin\Phi} > 0 \Longrightarrow \frac{\delta u}{u} > 0$
- $\pi^- : A_{UT}^{\sin\Phi} < 0 \Longrightarrow$ **very surprising**

BUT

- **only 1/7 of finally needed statistics to disentangle Collins-FF effects from quark polarizations**

First glimpse of Sivers!



$$A_{UT}^{Sivers} \propto \frac{\sum_q e_q^2 f_{1T}^q D_1^q(z)}{\sum_q e_q^2 q(x) D_1^q(z)}$$

- **First measurement of naive T-odd DF in DIS**
- $\pi^+ : A_{UT}^{\sin\Phi} > 0 \Longrightarrow L_u > 0?$

BUT

only 1/7 of finally needed statistics

- **to perform purity-analysis a la Δq**
- **more theoretical input needed to clarify interpretation**
- **Wait for RHIC DY data to check sign?**

Summary

- **HERMES first experiment trying to disentangle all components to the spin of the nucleon**

$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v + \Delta q_s) + L_q + (\Delta G + L_g)$$

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- **Inclusive and Semi-Inclusive**
  - $g_1(x)$ **high precision data on proton, deuteron and neutron**
  - **first time complete flavor separated quark spin distribution functions**

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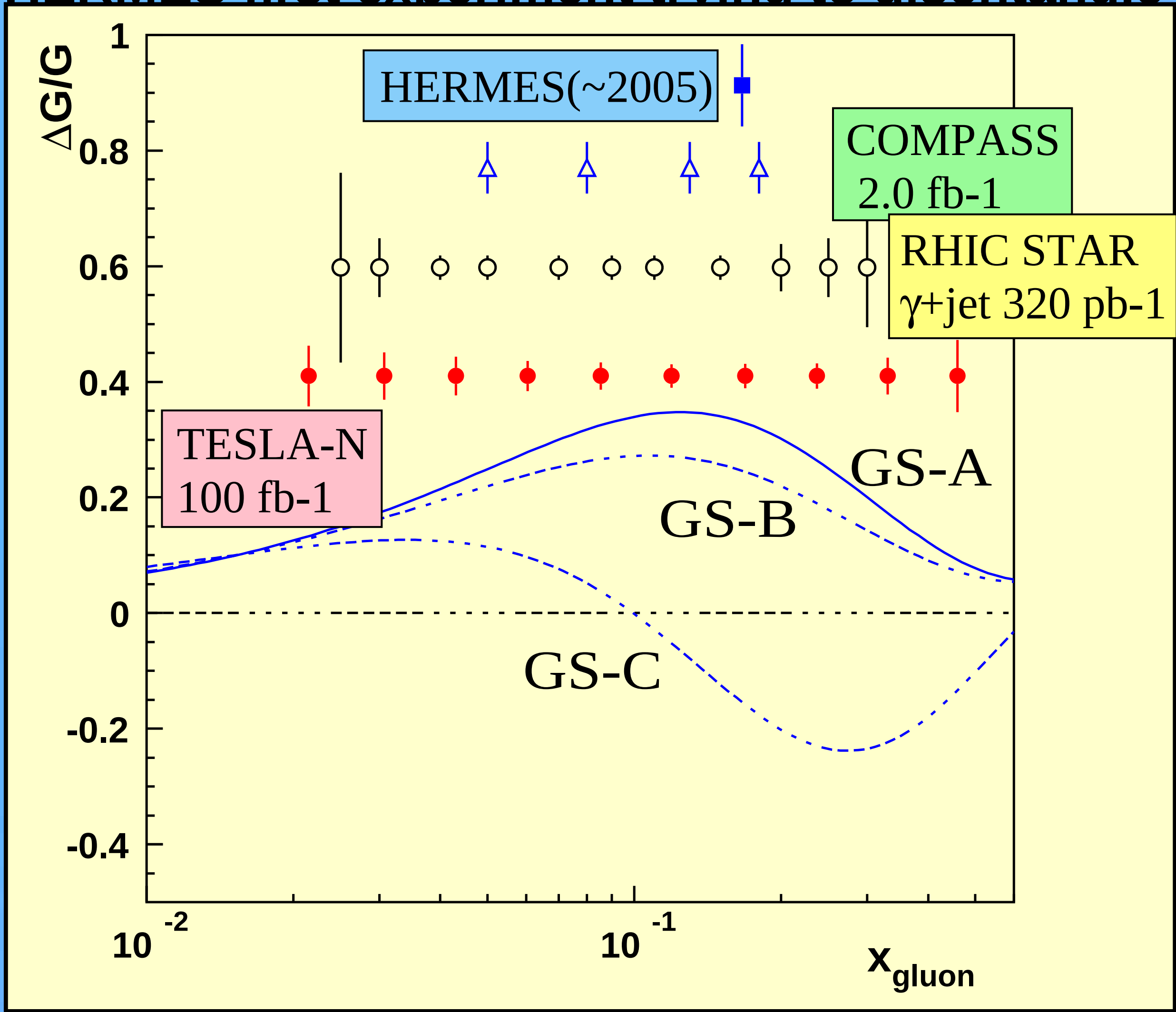
- $\Delta G(x)/G(x)$
  - first indication of sign from
    $\Longrightarrow$ scaling violation of $g_1(x)$ & isolating PGF (pairs of high p_T hadrons)
  - $\Delta G(x)/G(x)$ needs results from RHIC and COMPASS

Summary

- HERMES first experiment trying to disentangle all



$\Delta G + L_g)$

on and neutron

pin distribution functions

F (pairs of high p_T hadrons)

COMPASS

Summary

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  - $\Delta G(x)/G(x)$ **needs results from RHIC and COMPASS**
- **Orbital Angular Momentum** L_q
  - **GPDs: new avenue to study the structure of the nucleon**
  - **exclusive reactions with different final states are experimentally establishe**
  - **need Recoil Detector to ensure exclusivity and improve t-resolution**

Summary

- HERMES first experiment trying to disentangle all components to the spin of the nucleon

$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v + \Delta q_s) + L_q + (\Delta G + L_g)$$

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  - first time complete flavor separated quark spin distribution functions
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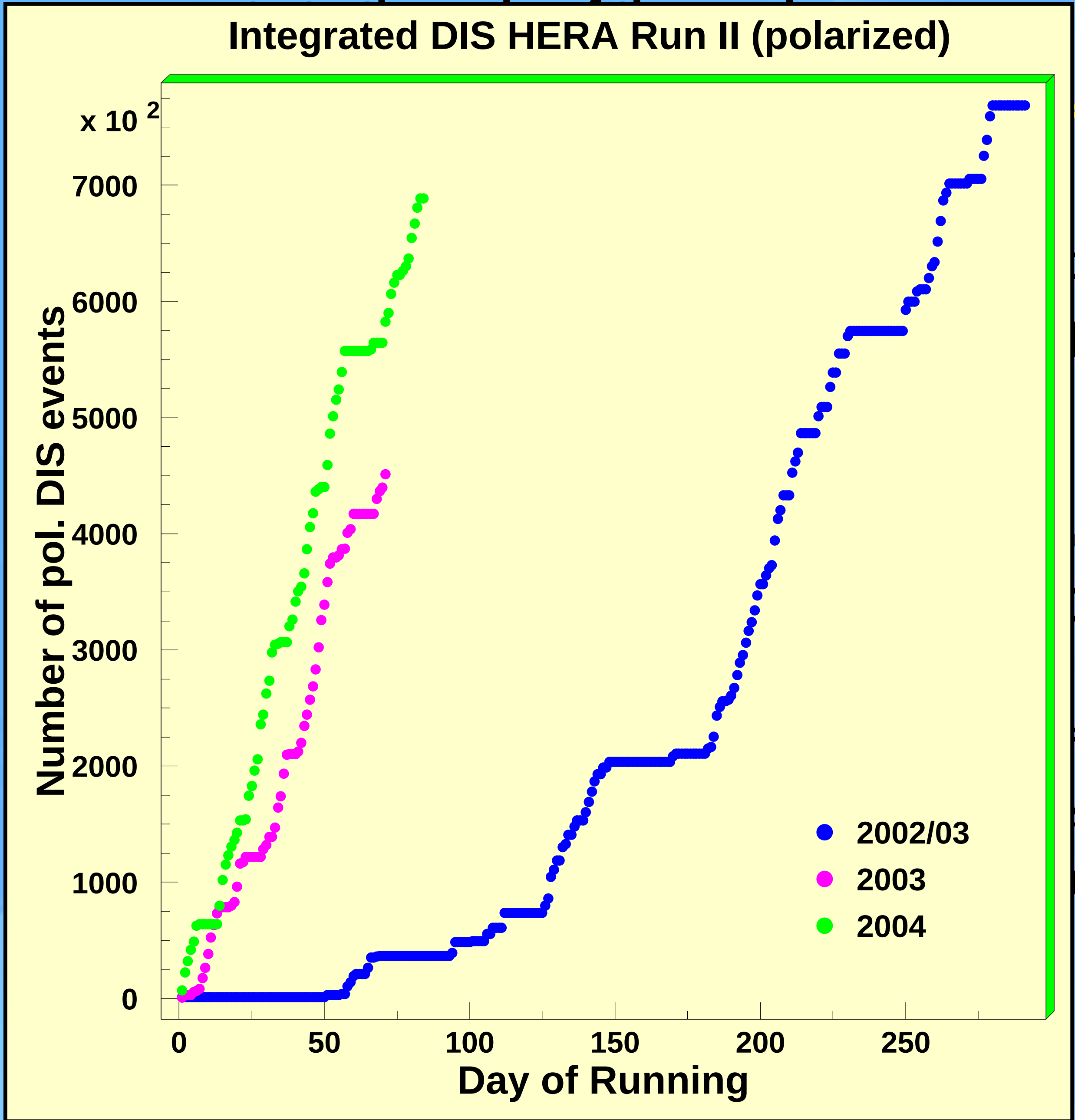
  - GPDs: new avenue to study the structure of the nucleon
  - exclusive reactions with different final states are experimentally established
  - need Recoil Detector to ensure exclusivity and improve t-resolution
- The transverse spin structure of the nucleon
  - first observation of non-zero Sivers effect
  - sizeable Collins asymmetries measured for $\pi^{0,\pm}$;

Summary

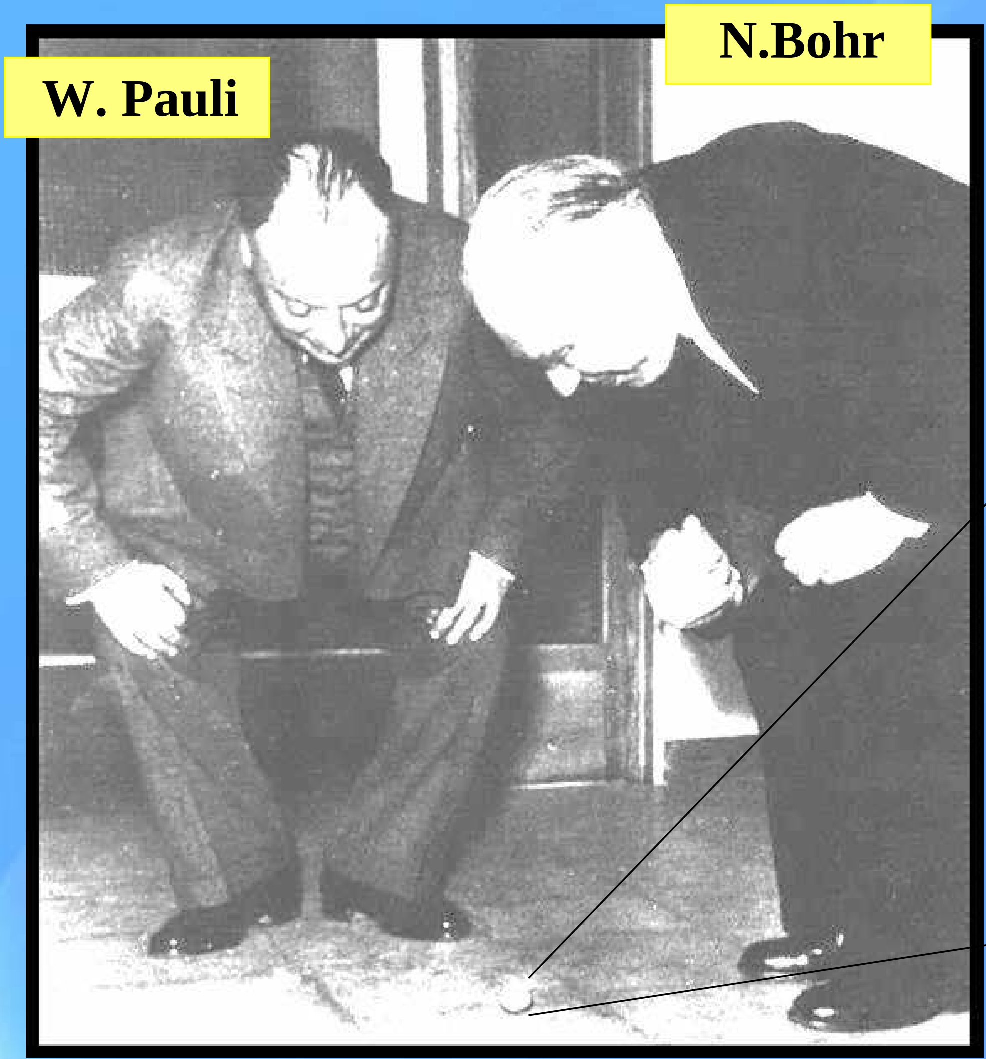
- HERMES first experiment trying to disentangle all

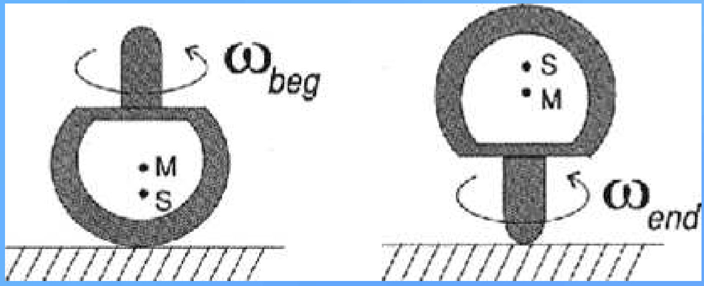


$\Delta G + L_g)$

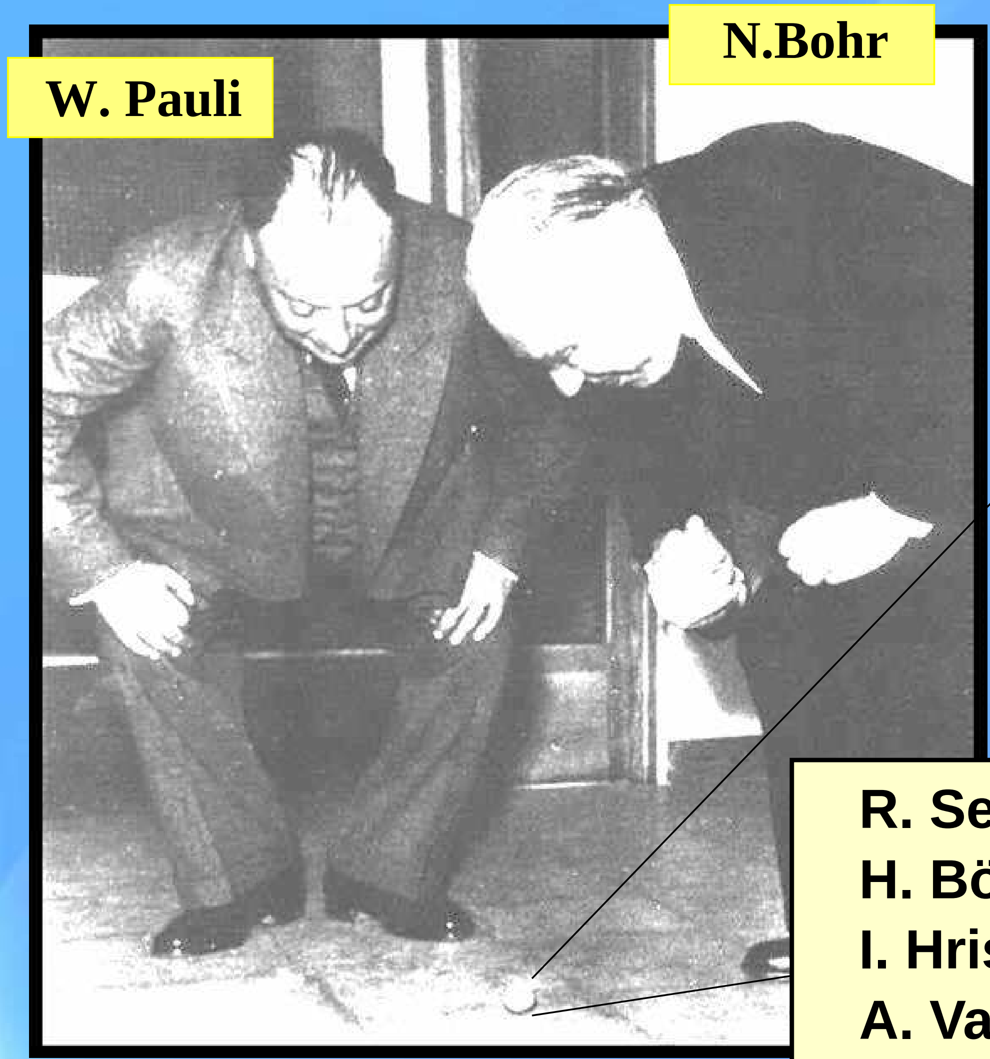
- on and neutron
- pin distribution functions
- F (pairs of high p_T hadrons)
- COMPASS
- f the nucleon
- s are experimentally established
- and improve t-resolution
- $\pi^{0,\pm}$;
- Data taking continues

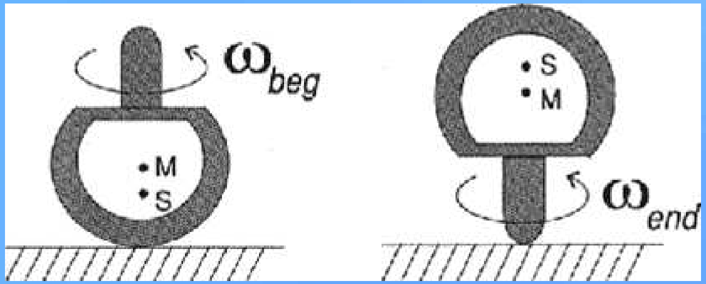
Fascinated by Spin ?





Fascinated by Spin ?





R. Seidl Mo. 17.30 T107.7
H. Böttcher Mo 17.45 T107.8
I. Hristova Tu. 17.45 T301.8
A. Vandenbroucke We. 14:00 T401.1
Z. Ye We. 14:00 T401.5
W.D. Nowak We. 18.30 T506.10