HERMES: HERA MEASUREMENT OF SPIN

The Spin of the Nucleon from HERMES point of view

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- Introduction
- Experimental overview
- HERMES results
  - longitudinal nucleon structure
  - transverse structure of the nucleon
  - GPDs
- Conclusions

Experimental particle physic at DESY - special colloquium for summer students 24 August 2011, DESY

Where does the proton spin come from?

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

Naïve Parton Model

$SU_{spin}(2)$ x $SU_{flavor}(3)$

$$|p\uparrow\rangle = \frac{1}{\sqrt{18}}\left\{2|u\uparrow u\uparrow d\downarrow\rangle - |u\uparrow u\downarrow d\uparrow\rangle - |u\downarrow u\uparrow d\uparrow\rangle + (u \leftrightarrow d)\right\}$$

$$\Delta\Sigma = \Delta u + \Delta d = 1$$

$$\Delta u = \langle p\uparrow|N_{u\uparrow} - N_{u\downarrow}|p\uparrow\rangle = \frac{3}{18}(10-2) = \frac{4}{3}$$

$$\Delta d = \langle p\uparrow|N_{d\uparrow} - N_{d\downarrow}|p\uparrow\rangle = \frac{3}{18}(2-4) = -\frac{1}{3}$$

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$$\Delta\Sigma = \Delta u + \Delta d = 1$$

Measurements:

Neutron decay

$$a_3 = F + D = \Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d} = 1.254 \pm 0.006$$

Hyperon decay

$$a_8 = \frac{1}{\sqrt{3}}(3F - D) = \frac{1}{\sqrt{3}}\left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} - 2(\Delta s + \Delta\bar{s})\right) = 0.397 \pm 0.020$$

Ellis-Jaffe sum rule:

$$\Gamma_p^1 = \frac{1}{12}a_3 + \frac{5}{36}\sqrt{3}a_8 \overset{\Delta s=0}{=} 0.189 \pm 0.005$$

SU(3) flavor symmetry

$\Delta s=0$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta\bar{u} + \Delta\bar{d} + \Delta s + \Delta\bar{s} \approx 0.6$$

quarks carry ~60% of the nucleon spin! BUT!

Where does the proton spin come from?

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

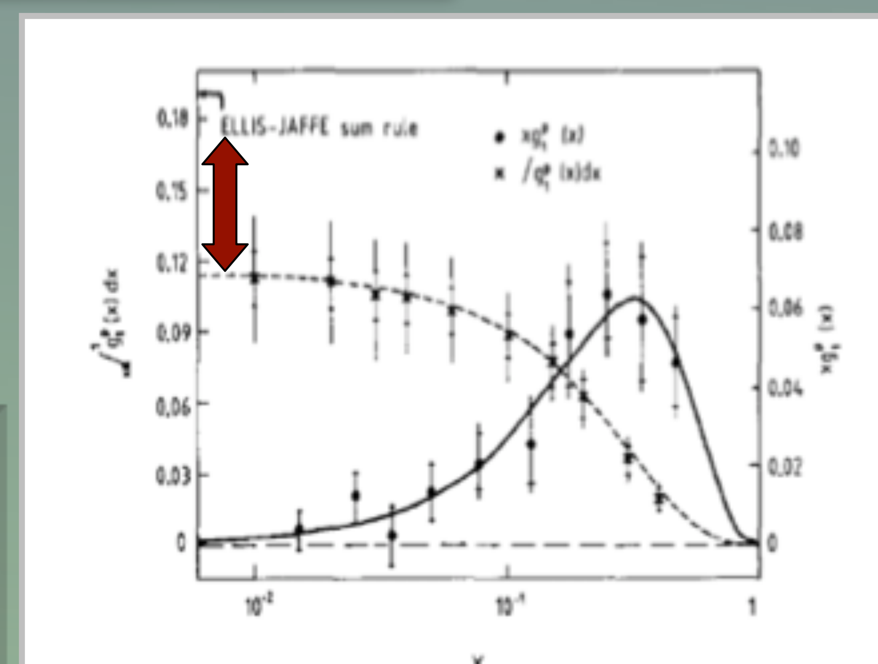
In 1988 EMC measured:

$$\Gamma_1^p = \int_0^1 g_1(x)dx = \frac{1}{2}\left\{\frac{4}{9}(\Delta u + \Delta\bar{u}) + \frac{1}{9}(\Delta d + \Delta\bar{d}) + \frac{1}{9}(\Delta s + \Delta\bar{s})\right\} = 0.114 \pm 0.012$$

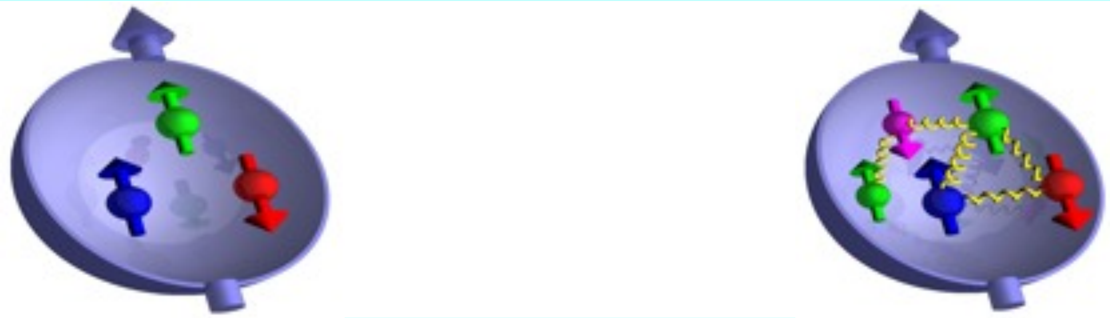
$$\boxed{\Delta\Sigma = 0.12 \pm 0.17}$$

$$\boxed{\Delta s = -0.19 \pm 0.06}$$

SPIN CRISIS!

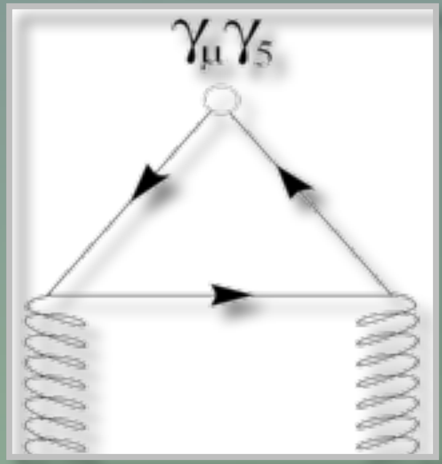


Where does the proton spin come from?



$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G$$

Measurements of F_2 from HERA $\Longrightarrow$ **Gluons are important!**



Axial anomaly contribution:

The contribution of the quark spins $\Delta\Sigma$ is NOT an ***observable***.

The observable is **a_0**, the flavour-singlet axial vector.

$$\boxed{\Delta q + \Delta\bar{q}} \Longrightarrow \boxed{\Delta q + \Delta\bar{q} - \frac{\alpha_s}{2\pi}\Delta G}$$

Where does the proton spin come from?

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g$$

For full description the knowledge of orbital angular momentum is needed

Where does the proton spin come from?

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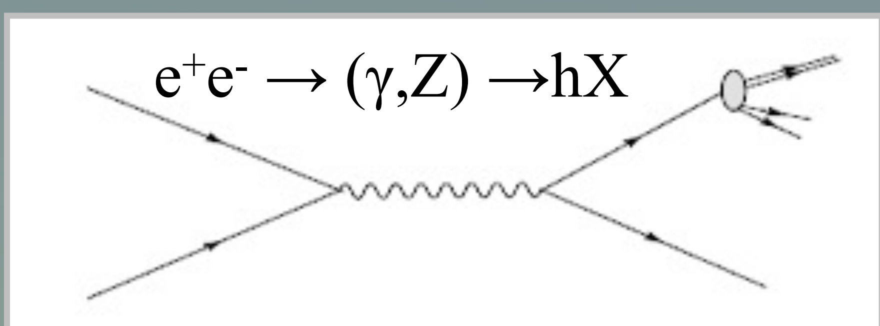
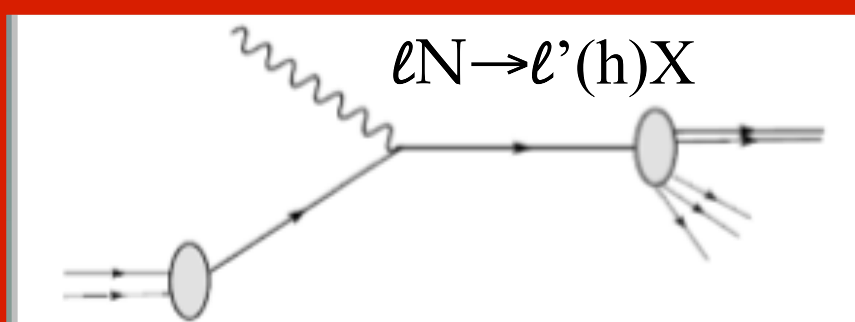
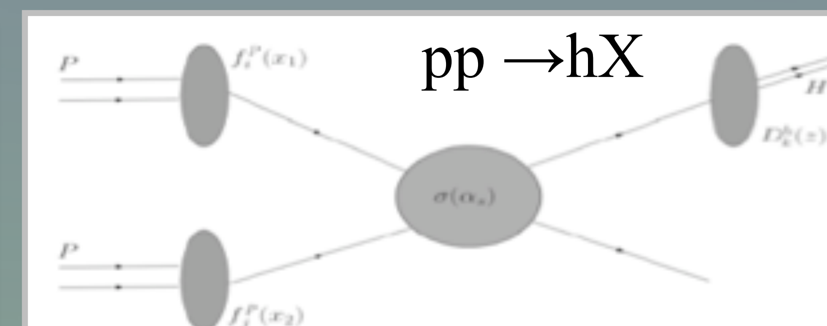


- Clean processes – no proton remnants
- Separation light/heavy flavors
- No flavor/charge separation
- Access to flavor singlet D_Σ
- Not precise at large z
- Three-jet events $q\bar{q}g$
- Gluon FF

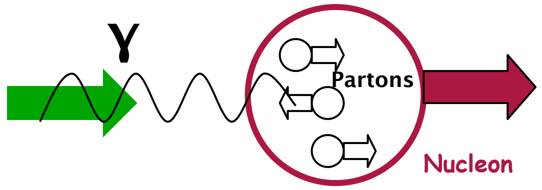


- Flavor/charge separation
- Larger z, smaller Q^2
- Unpolarized PDFs very well
- constrained from DIS
- Gluon in DIS - a small NLO effect (PGF)
- Dependence on PDFs



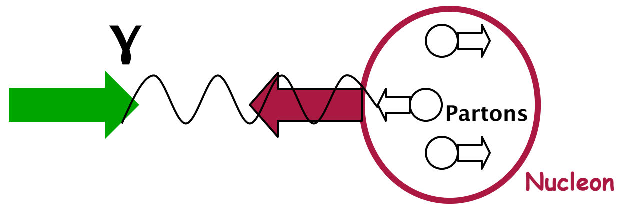
- Very sensitive to D_g
- Large z
- Charge separation
- Several subprocesses
- Different $p_\perp$ scales

Principle of measurements



Selects quarks with spin anti-parallel to the nucleon

$$\sigma_{3/2} \sim q^-(x) \quad S_\gamma + S_N = 3/2$$



$$\sigma_{1/2} \sim q^+(x) \quad S_\gamma + S_N = 1/2$$

Selects quarks with spin parallel to the nucleon

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

Spin Independent Structure Function F_1

$$\sigma_{1/2} + \sigma_{3/2} \propto F_1(x) = \frac{1}{2}\sum_f e^2\left(q^+(x) + q^-(x)\right)$$

Spin Dependent Structure Function g_1

$$\sigma_{1/2} - \sigma_{3/2} \propto g_1(x) = \frac{1}{2}\sum_f e^2\left(\underbrace{q^+(x) - q^-(x)}_{\Delta q}\right)$$

Virtual photon asymmetry:

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \overset{g_2=0}{\approx} \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$

Experimental essentials

asymmetry measurement

- **Longitudinally polarized beam:**

electron, positron

- **Polarized target:**

hydrogen, deuterium, helium3

- **Measurement with high accuracy:**

incoming lepton

energy

direction

scattered lepton

energy

direction

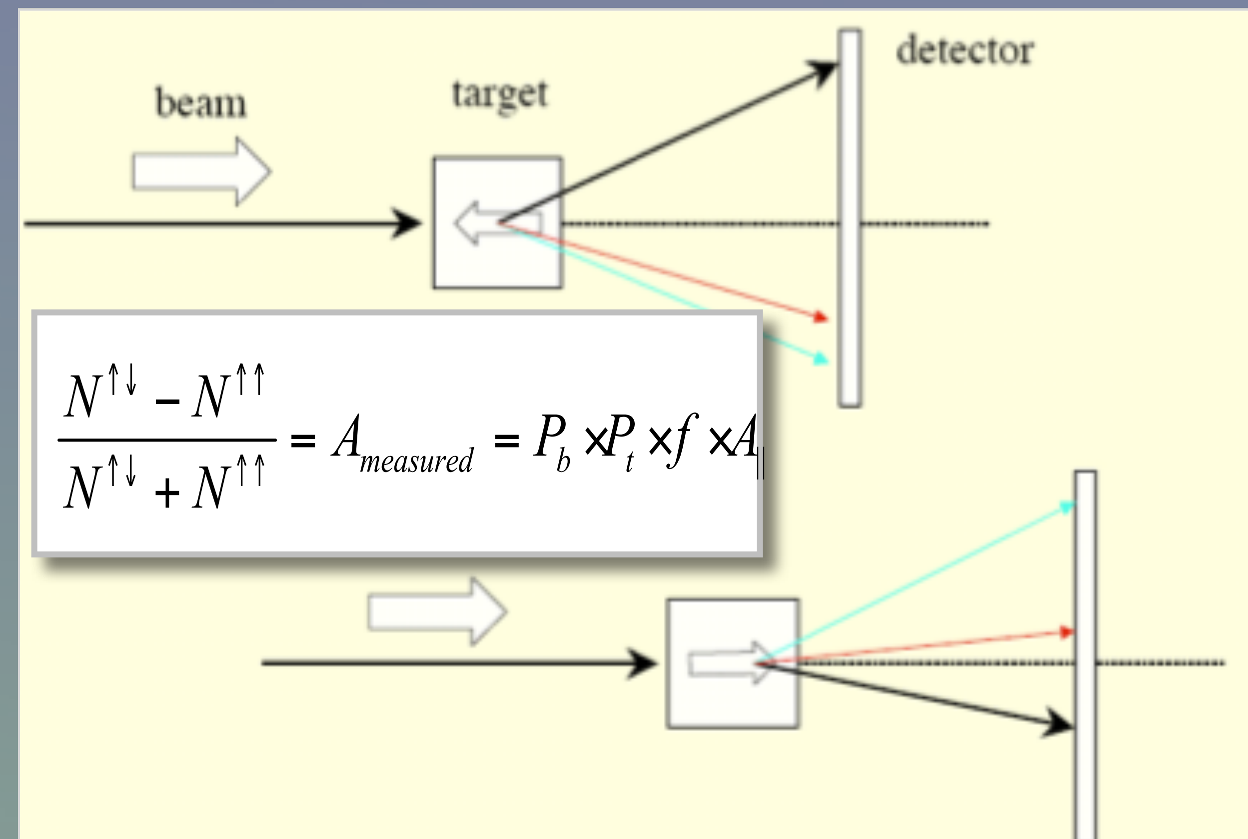
good identification

in semi-inclusive case

good particle identification

- **Control of false asymmetries:**

beam flux, target size, detector size, detector efficiency



$$\frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} = A_{measured} = P_b \times P_t \times f \times A_{\|}$$

N - number of DIS events

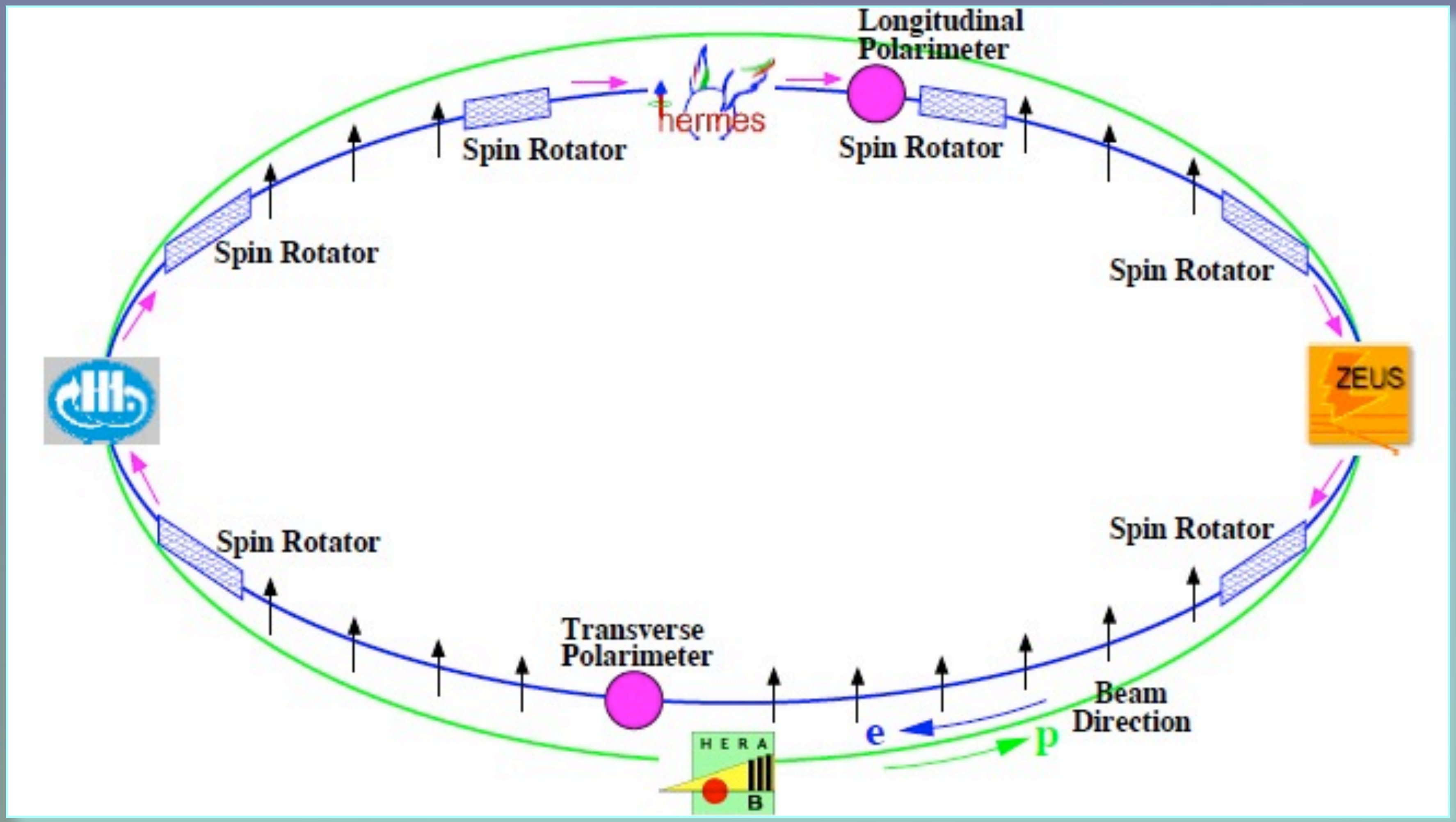
Pb, Pt - beam and target polarizations

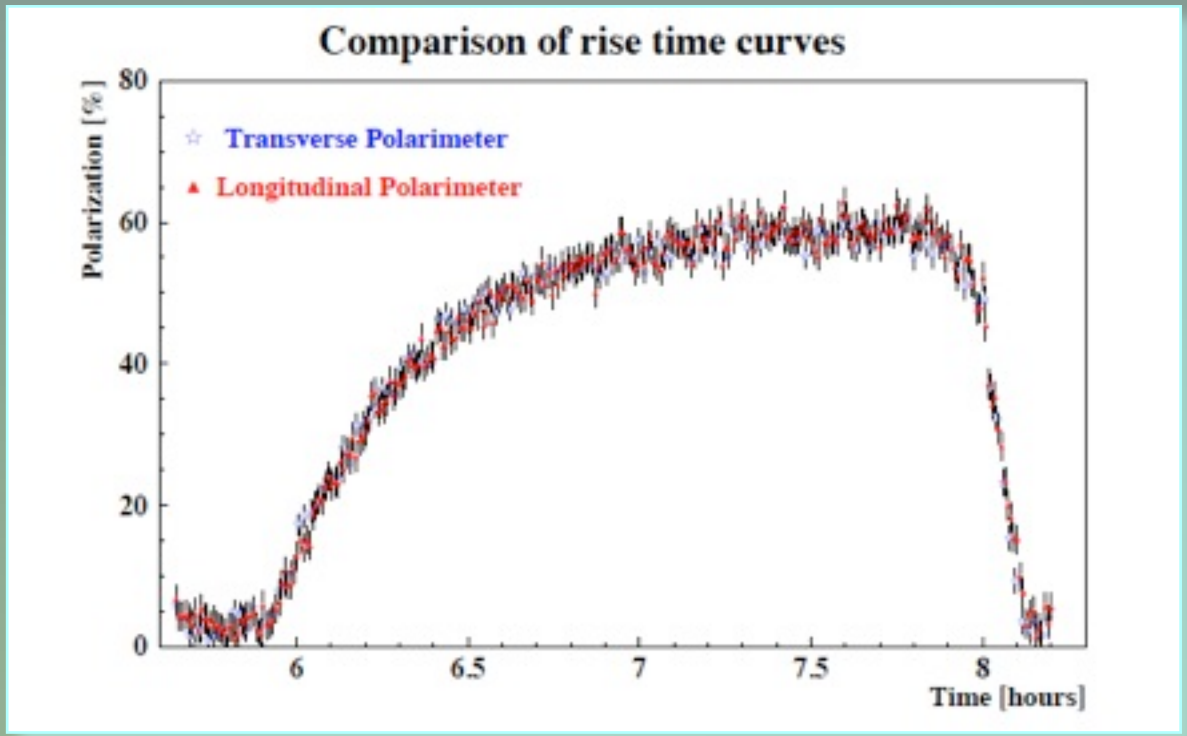
f - target dilution factor=polarizable N/total N

D – depolarization factor (polarization transfer from polarized lepton to photon)

$$A_1 \overset{g_2=0}{\approx} \frac{g_1}{F_1} = \frac{A_{\|}}{D[1+\eta\gamma]}$$

HERMES: longitudinally polarized lepton beam

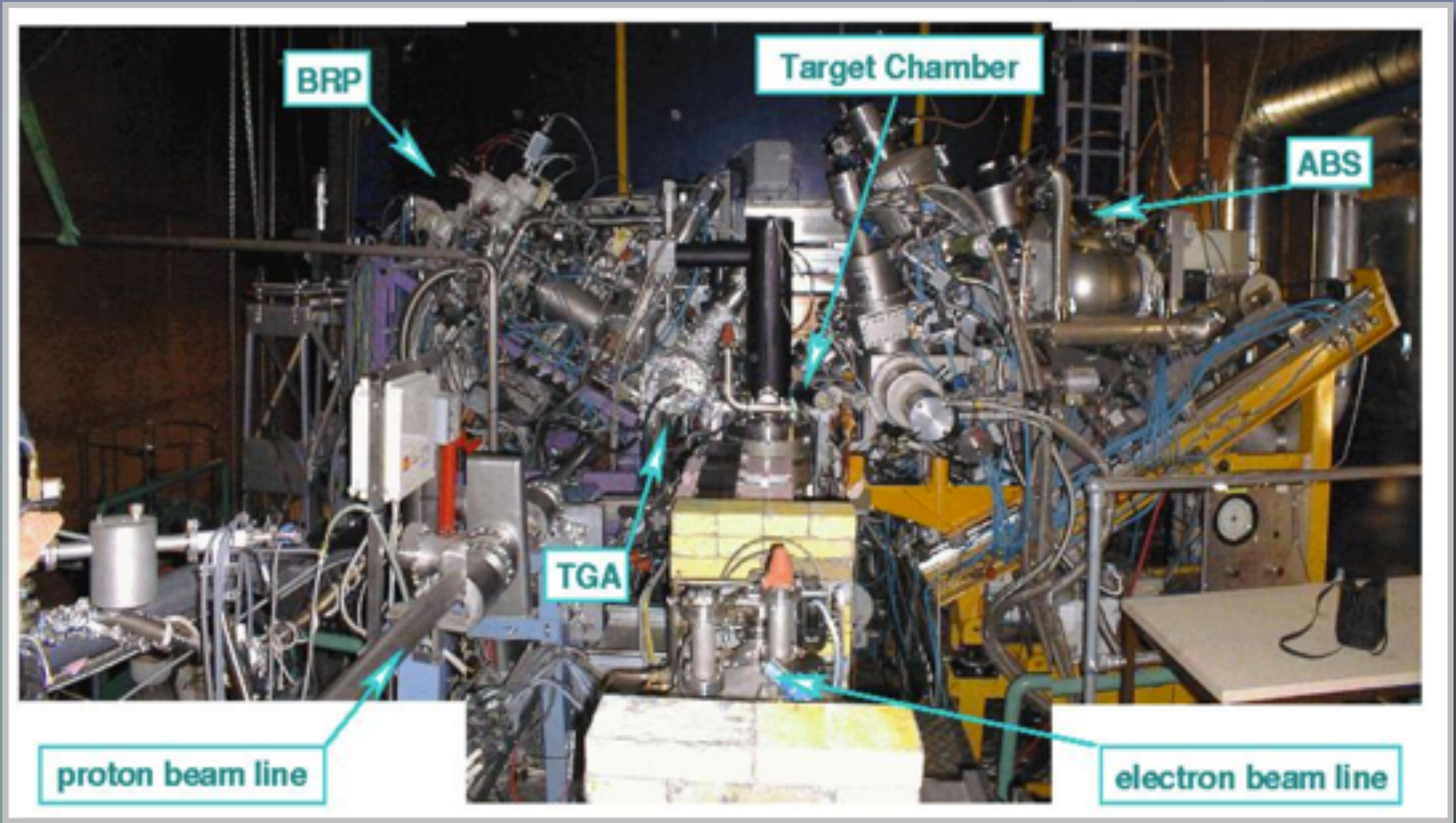




HERA positron beam properties:

- E_e=27.6GeV, I_e<50mA, P_b=0.55
- lifetime=12-14h
- transversely polarized e± in storage ring
- polarization build-up by emission of synchrotron radiation (Sokolov-Ternov effect)
- Spin rotators around HERMES IP

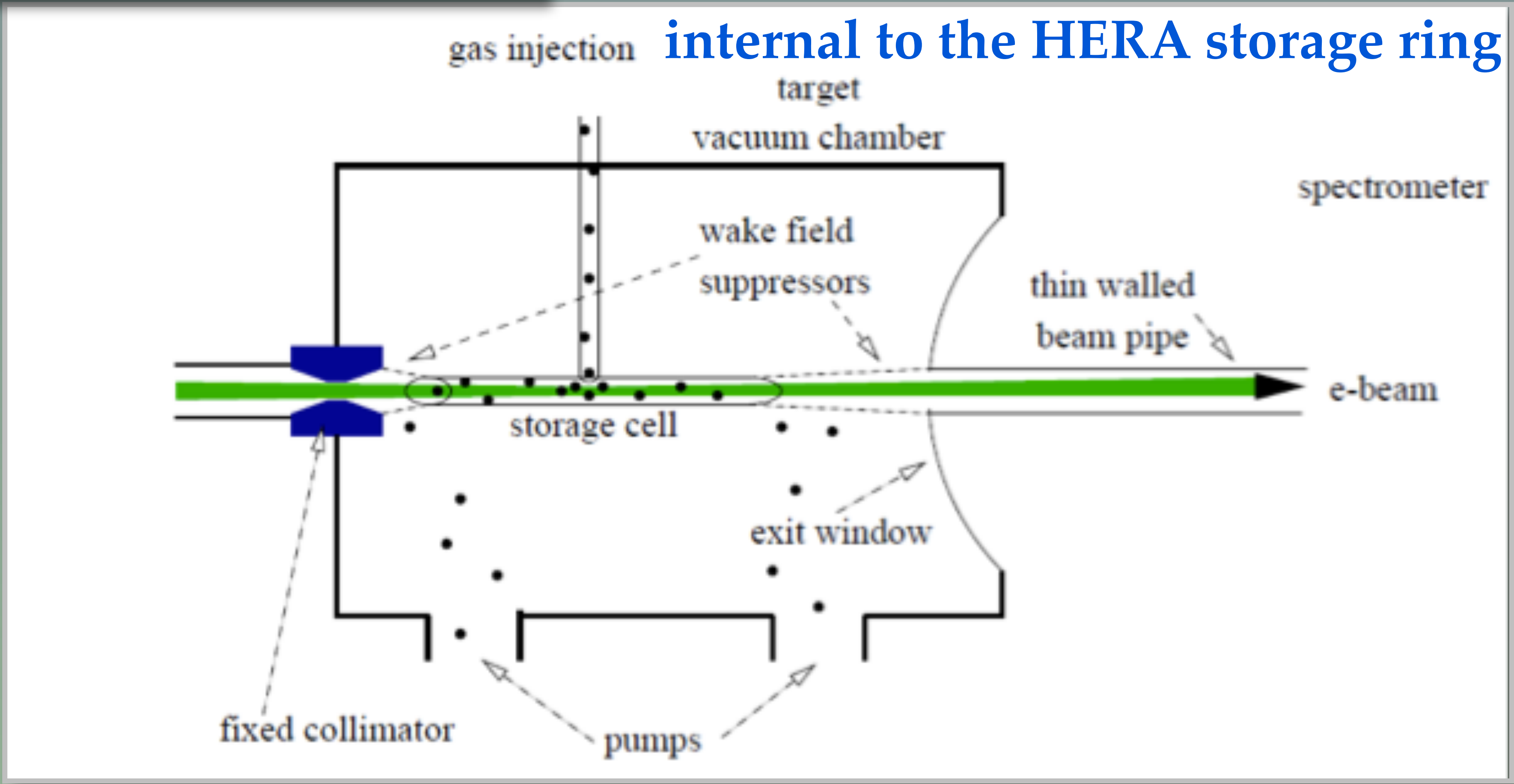
HERMES: gas target



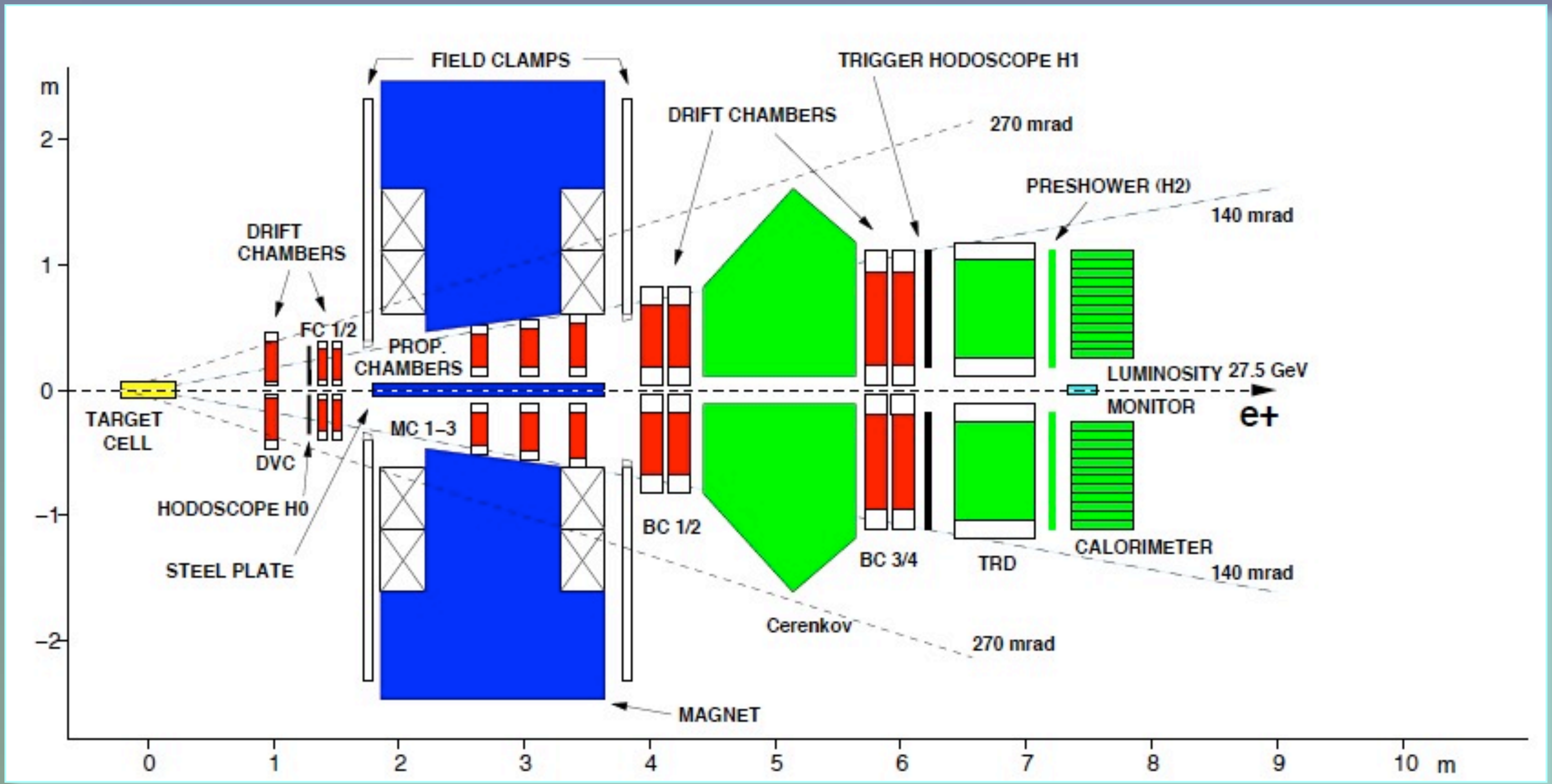
Typical HERMES target properties :

- P_t~0.85; polarized $H^{\uparrow\rightarrow}$, $D^{\rightarrow}$
- dilution factor=1
- Thickness =10^{14}-10^{15} nucl / cm^2
- Temperature=100K

internal to the HERA storage ring



HERMES spectrometer



- **Tracking:** Drift Vertex Chambers, Front Chambers, Magnet Chambers, Back Chambers
- **Particle Identification:**

Čerenkov (RICH) Detector, Transition Radiation Detector, Preshower, Calorimeter
Luminosity Monitor (Bhabha/Møller scattering)

Probing the structure of nucleons

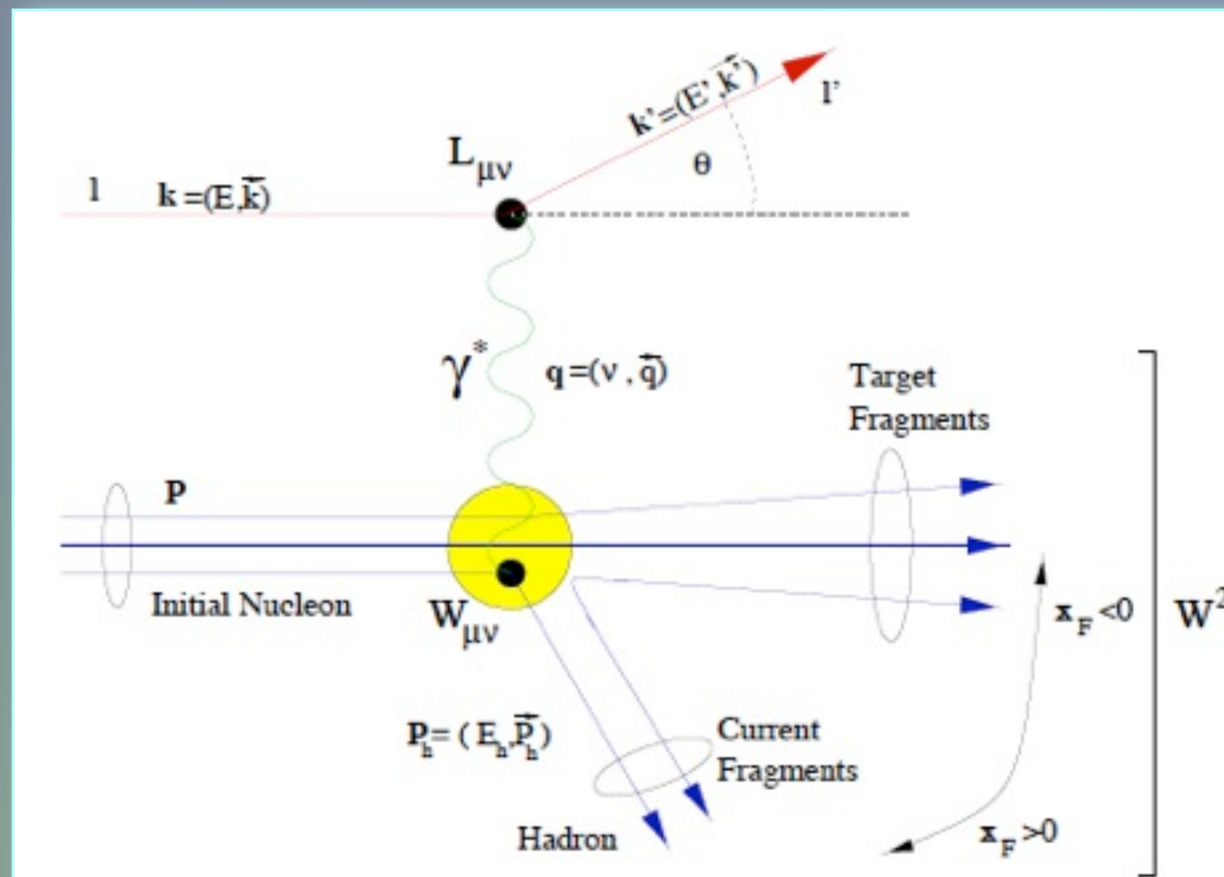
- Deep-inelastic scattering (DIS) plays major role in understanding of nucleon structure
- Lepton-nucleon scattering cleanest way to probe substructure of nucleon
- Exchange of virtual boson, breakup and hadronization in DIS regime

center-of-mass energy (eN)

$$s = (P+k)^2 = M^2 + 2ME$$

invariant mass of hadronic final state

$$W^2 = (P+q)^2 = M^2 + 2M\nu - Q^2$$



For gives s, two kinematic variables completely describe the scattering process in the **inclusive** analysis

photon virtuality

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

or

photon energy (lab)

$$\nu = \frac{P\cdot q}{M} = E - E'$$

Bjørken scaling variable

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

inelasticity

$$y = \frac{P\cdot q}{P\cdot k} = \frac{\nu}{E}$$

Semi-inclusive DIS:

Fraction of the virtual photon energy carried by hadron h

$$z_h = \frac{E_h}{\nu}$$

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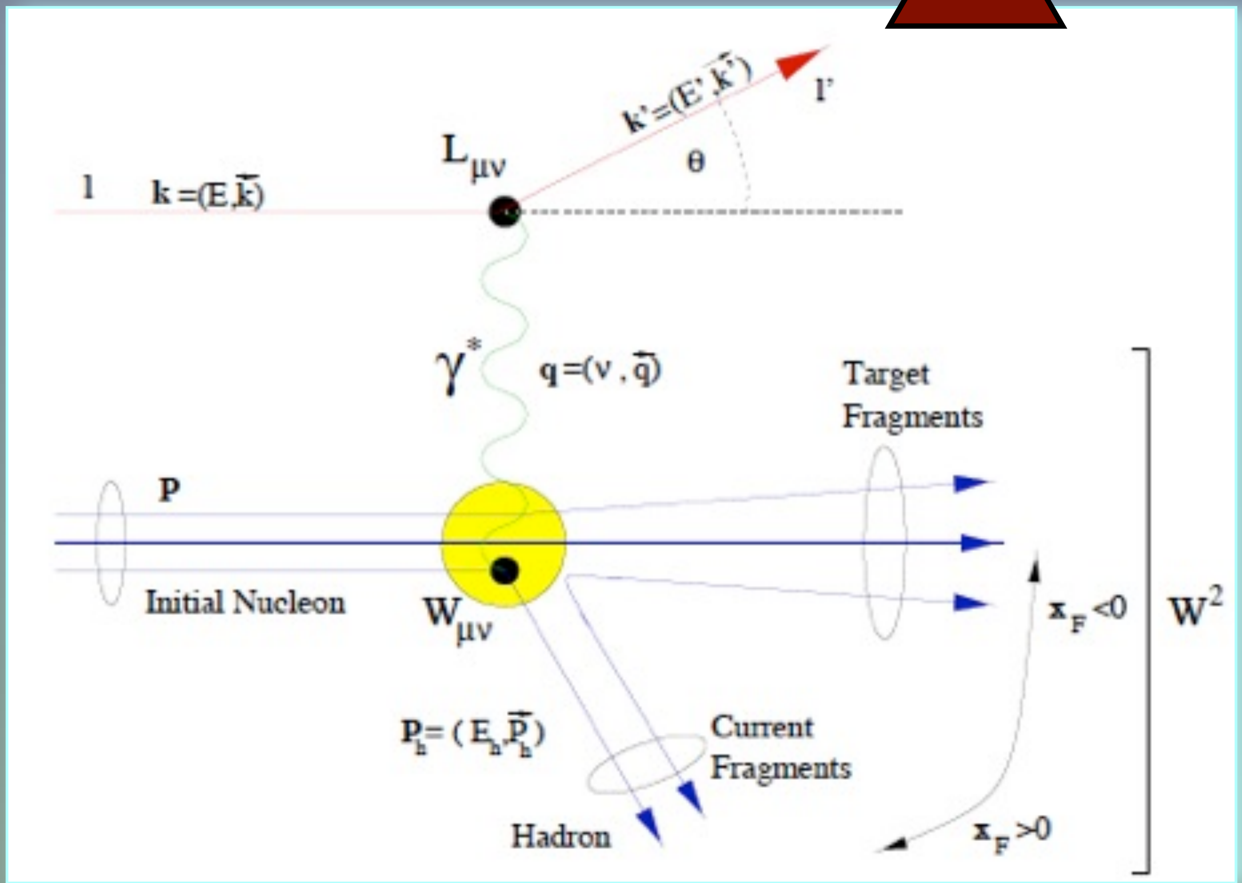

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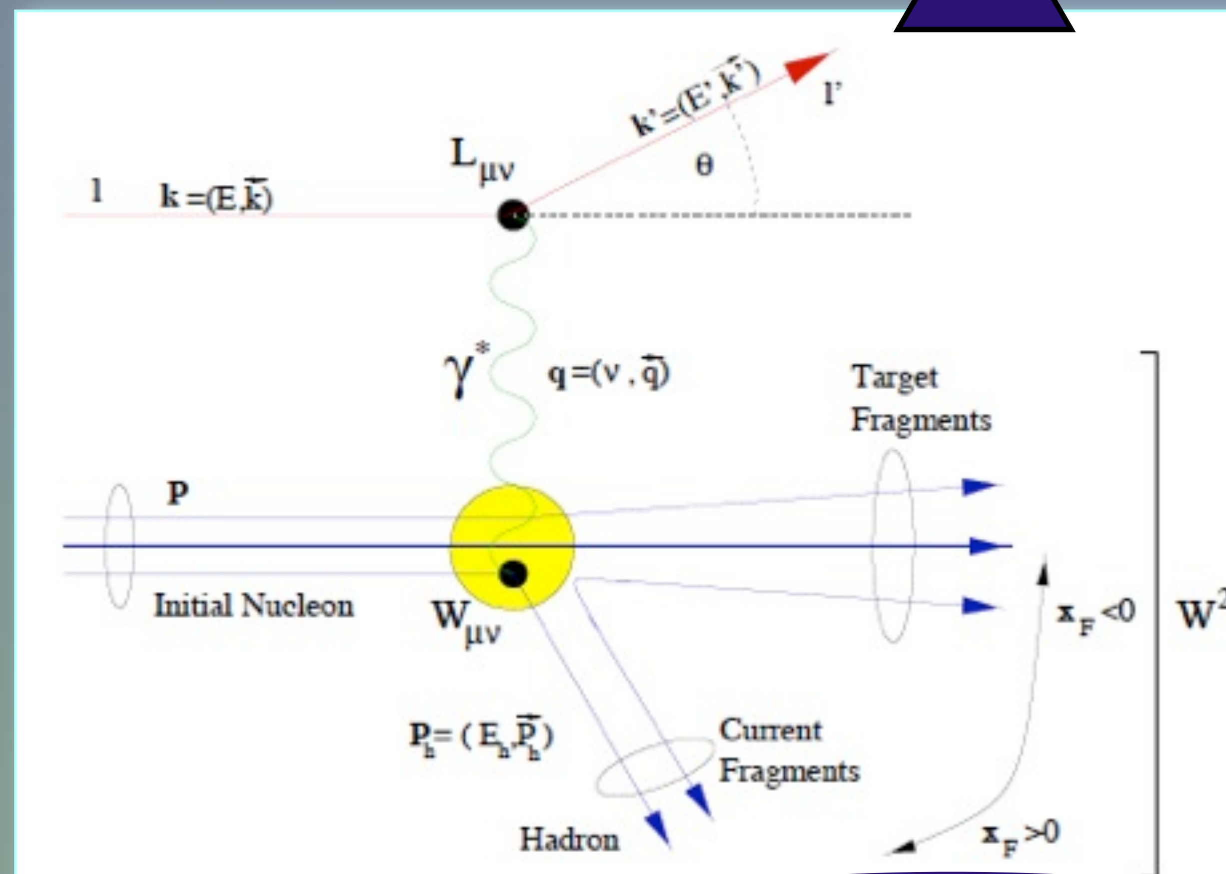

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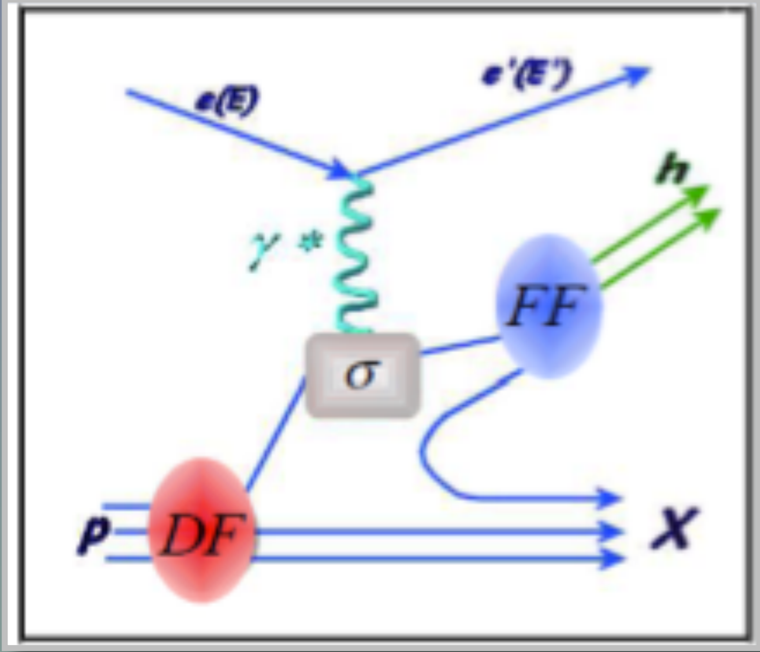
Deep inelastic scattering

cross section

$$\sigma(l + N \to l' + h + X)$$

Factorization:

$$\sigma^{eN\to ehX} = \sum_q DF^{N\to q}(x) \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}(z)$$



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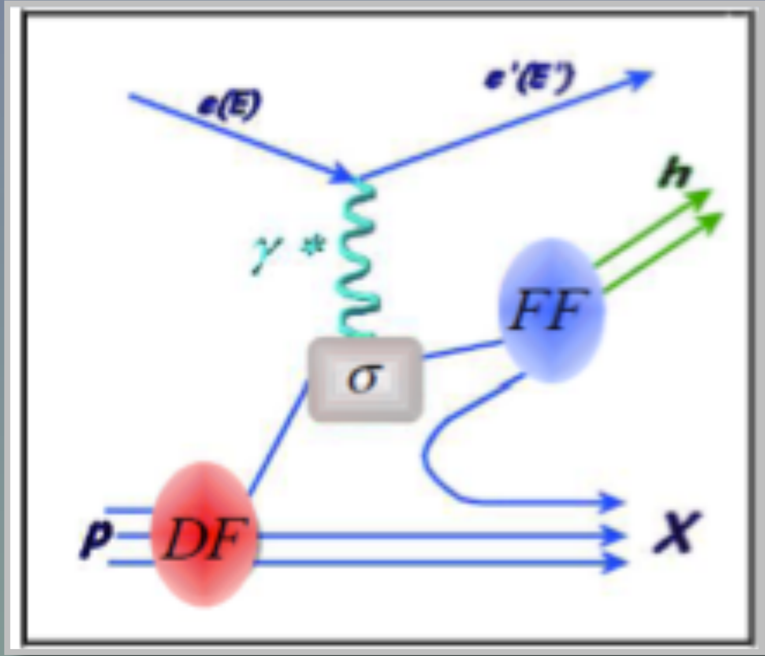

Selection of constituents according to their distribution within the nucleon

Photon hard scattering off the nucleon's constituents

Hadronization of the struck parton into the final hadron

Deep inelastic scattering cross section

$$\sigma(l + N \to l' + h + X)$$

Factorization:

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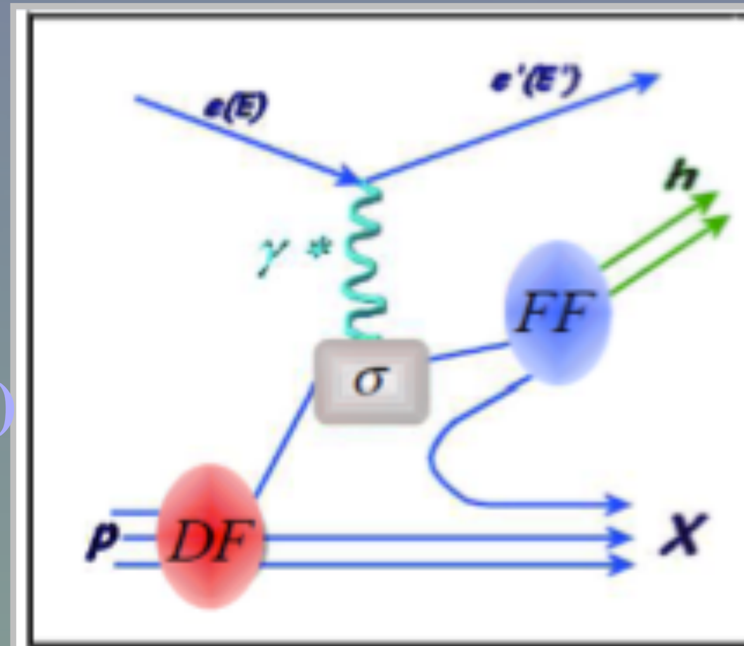
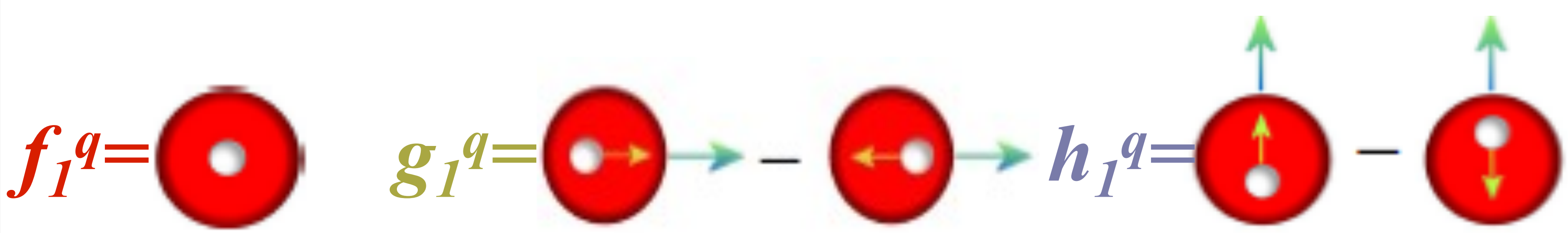


- DF(x,Q^2): Parton Distribution Functions $q(x,Q^2)$, $\Delta q(x,Q^2)$, $\delta q(x,Q^2)$
- σ: the hard-scattering cross section la→l/b (perturbative theory)
- FF(z,Q^2): Fragmentation Functions $D_1(z,Q^2)$, $H_1^{\perp}(z,Q^2)$,…



unpolarized quarks and nucleons

longitudinally polarized quarks and nucleons

transversely polarized quarks and nucleons

$$f_1^q(x) \equiv q(x)$$

$$g_1^q(x) \equiv \Delta q(x)$$

$$h_1^q(x) \equiv \delta q(x)$$

Distribution Functions (DF)			
N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$

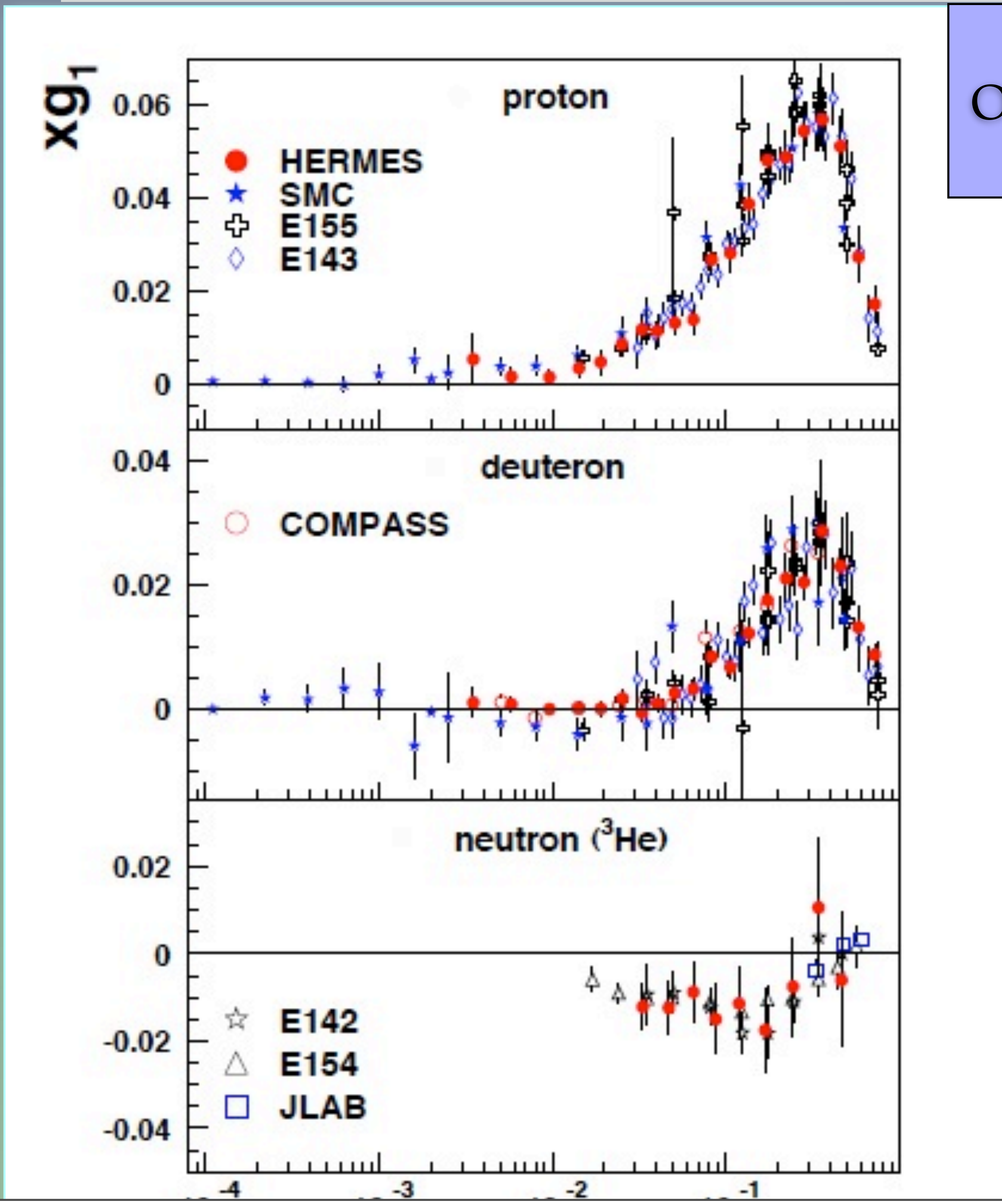
Fragmentation Functions (FF)		
N/q	U	T
U	D_1	$H_1^{\perp}$

Inclusive DIS: polarized structure function g_1

$$g_1(x,Q^2) = \frac{1}{1-\frac{y}{2}-\frac{1}{4}y^2\gamma}\left[\frac{Q^4}{8\pi\alpha^2 y}\frac{\partial^2\sigma_{unpol}}{\partial x\partial Q^2}A_{||}(x,Q^2)+\frac{y}{2}\gamma^2 g_2(x,Q^2)\right]$$

Observable: inclusive double-spin asymmetry

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



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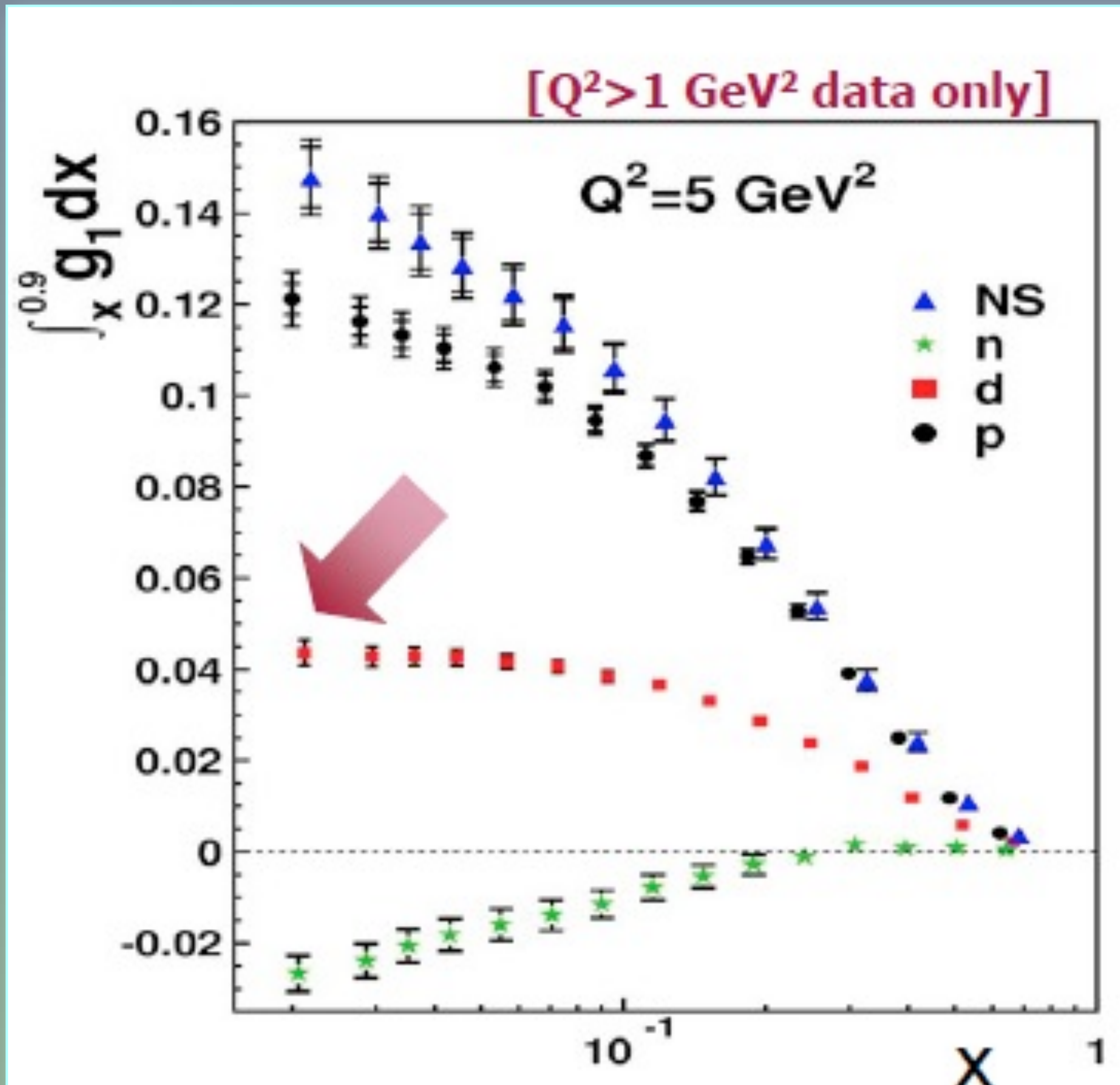
Fragmentation Functions (FF)		
N/q	U	T
U	D_1	$H_1^\perp$

Inclusive DIS: first moment Γ_1 and $\Delta\Sigma$

Use only deuteron data!

Assuming **saturation** of Γ_1^d:

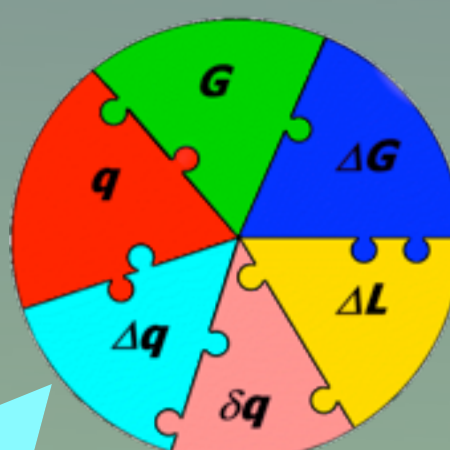
$$\Gamma_1^d = \int dx\, g_1^d(x)$$



from hyperon beta decay

$$a_0 \overset{\bar{M}S}{=} \Delta\Sigma \propto \boxed{\frac{1}{\Delta C_s}}\left[9\Gamma_1^d - \frac{1}{4}\boxed{a_8}\boxed{\Delta C_{NS}}\right]$$

from theory



$$a_0 \overset{\bar{M}S}{=} \Delta\Sigma = 0.330 \pm 0.025(exp) \pm 0.011(theory) \pm 0.028(evol)$$

Semi-inclusive DIS: flavour separation

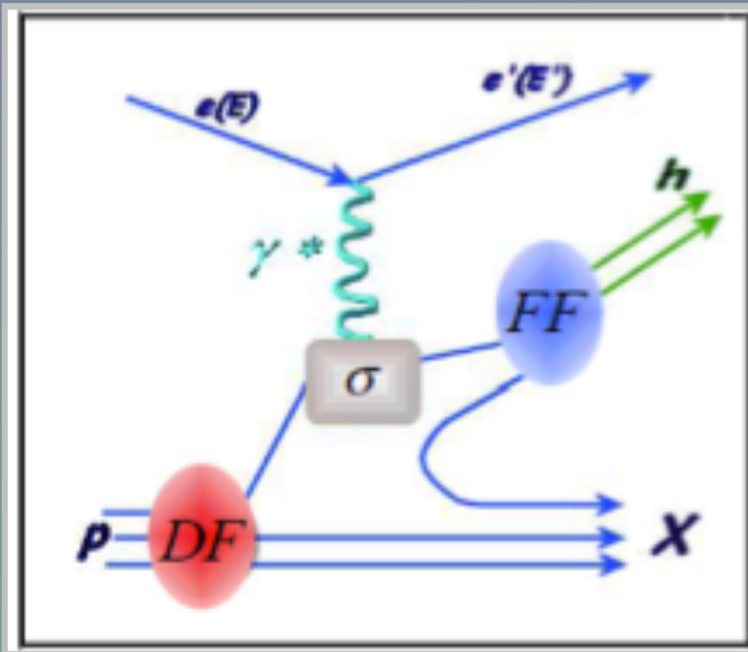
Method (LO):
Use correlation between detected hadron and struck quark → 'Flavor separation'

$$\sigma(l + N \rightarrow l' + h + X)$$

Observable: semi-inclusive double-spin asymmetry

$$A_1^h(x,Q^2) \overset{LO}{\sim} \frac{\sum_q e_q^2 \Delta q(x,Q^2) \int dz D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) \int dz D_q^h(z,Q^2)}$$

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



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T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

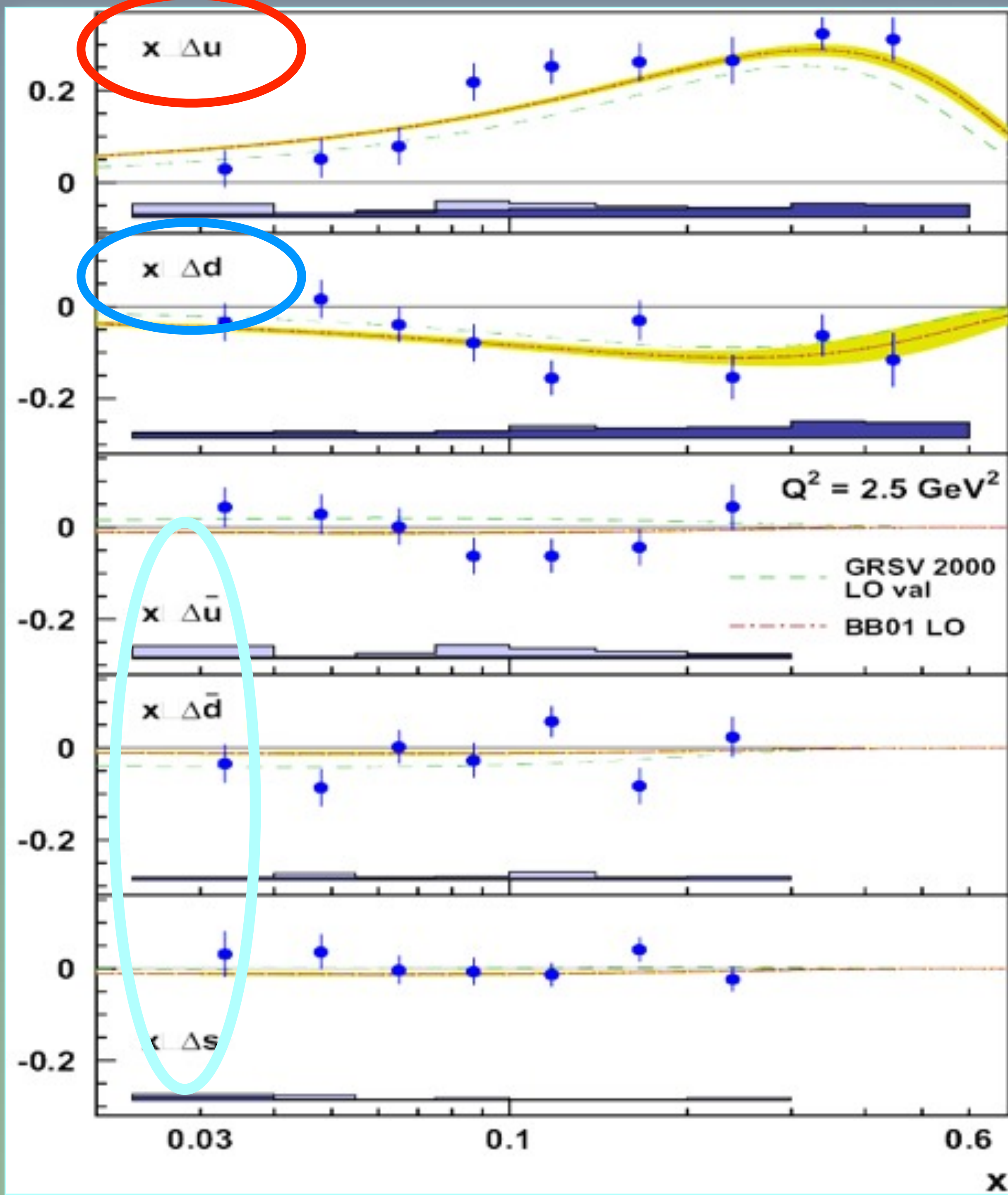
Fragmentation Functions (FF)		
N/q	U	T
U	D_1	$H_1^\perp$

Purity $P_q^h(x,z)$ is conditional probability that hadron of type h in the final state originated from a struck quark of flavour q

Semi-inclusive DIS: flavour separation

$$\left(A_{1p}^{\pi^+}, A_{1p}^{\pi^-}, \ldots A_{1d}^{K^-}\right) \vec{A} = P \cdot \vec{Q} \left(\frac{\Delta u}{u}(x), \frac{\Delta d}{d}(x), .. \frac{\Delta s}{s}(x)\right)$$

SU(3)$_f$ symmetry implicitly assumed

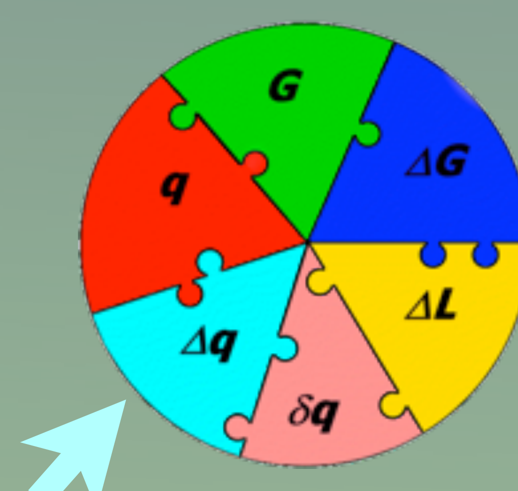


- **u** quark large positive polarization
- **d** quark negative polarization
- **sea** quarks compatible with zero in measured x-range (0.023-0.6):

$$\int \Delta\bar{u} = -0.002 \pm 0.043$$

$$\int \Delta\bar{d} = -0.054 \pm 0.035$$

$$\int \Delta s = +0.028 \pm 0.034$$

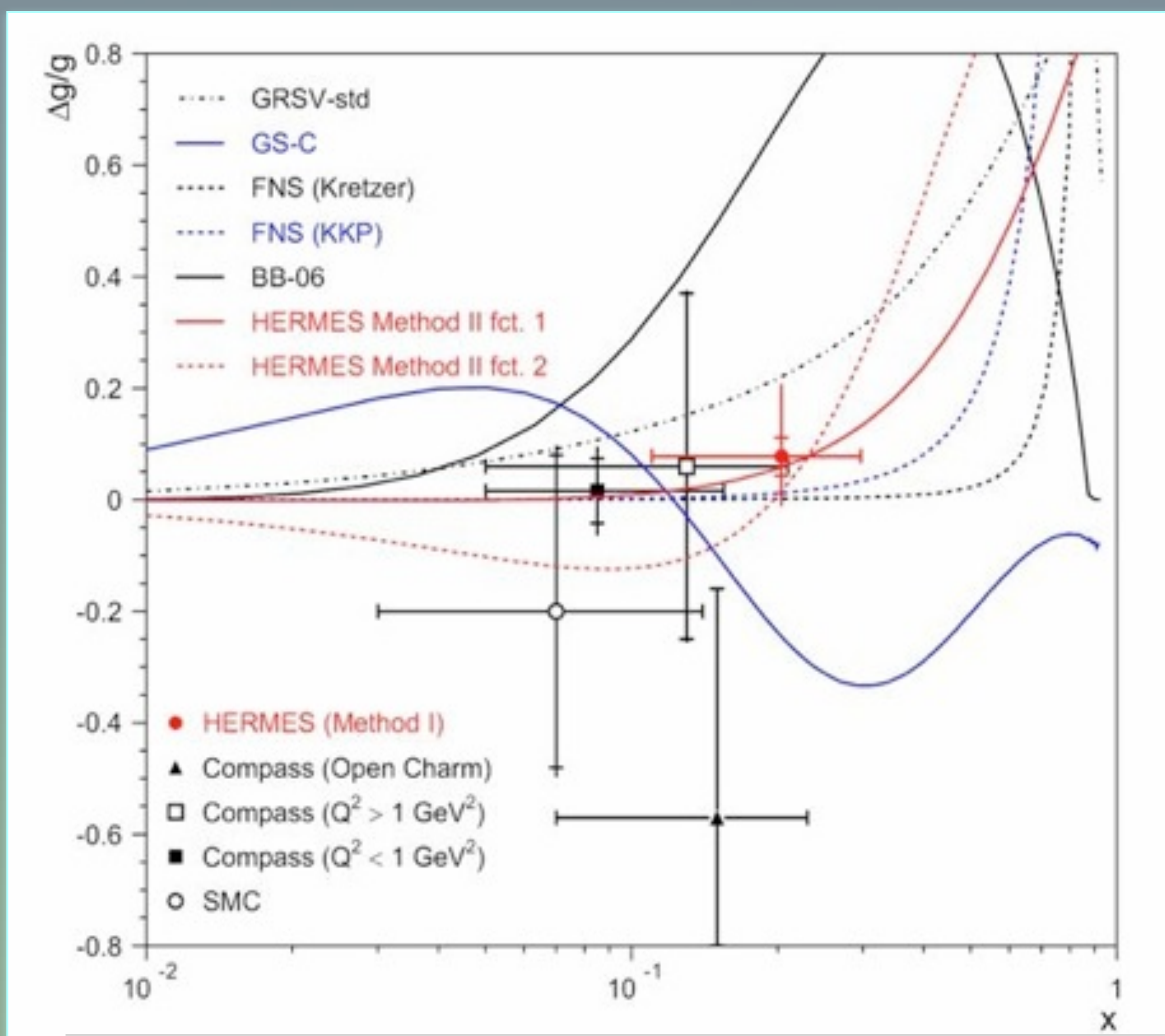


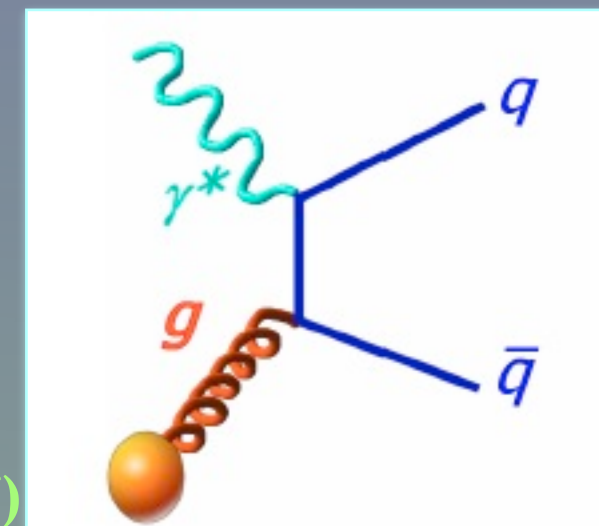
Direct measurement of ΔG

Mechanism: photon-gluon fusion (PGF).
Observable: asymmetry in the hadron production.

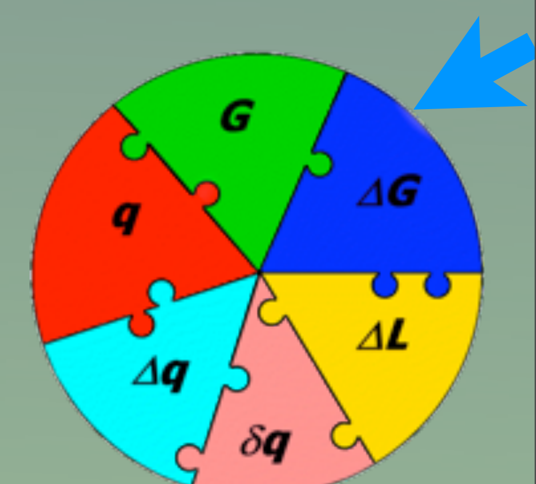
$$\sigma(l + N \rightarrow h + X)$$

- golden channel: charm production
  - ➡ theoretically very clean
  - ➡ experimentally very challenging





- at HERMES ($\sqrt{s}$=7 GeV)
  - hadron production at high P_T
  - ➡ experimentally very clean
  - ➡ highly model dependent due to variety of background processes



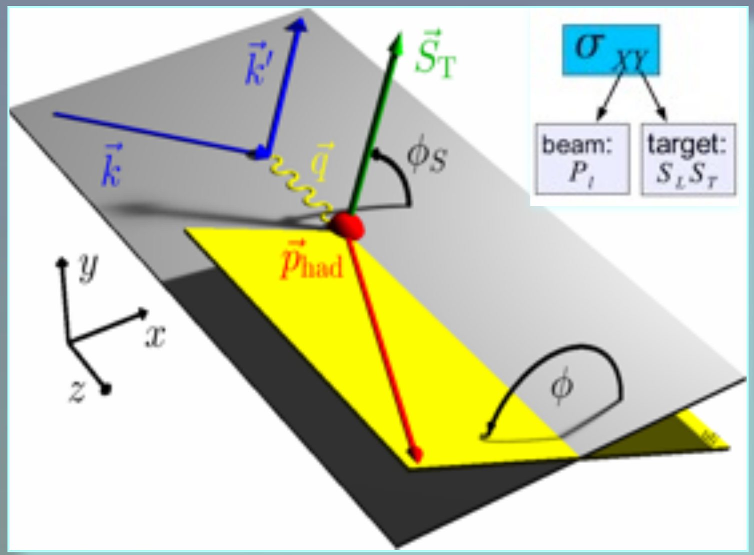
$$\frac{\Delta G}{G} = 0.071 \pm 0.034(stat) \pm 0.010(sys - exp) \; {}^{+0.127}_{-0.105} \; (sys - model)$$

Semi-inclusive DIS: transverse structure

$$\sigma(l + N \to l' + h + X)$$

Transverse-momentum-dependent (TMD) DF

$$\sigma^{eN\to ehX} \propto \sum_q DF^{N\to q}(x, p_T) \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}(z, p_T)$$



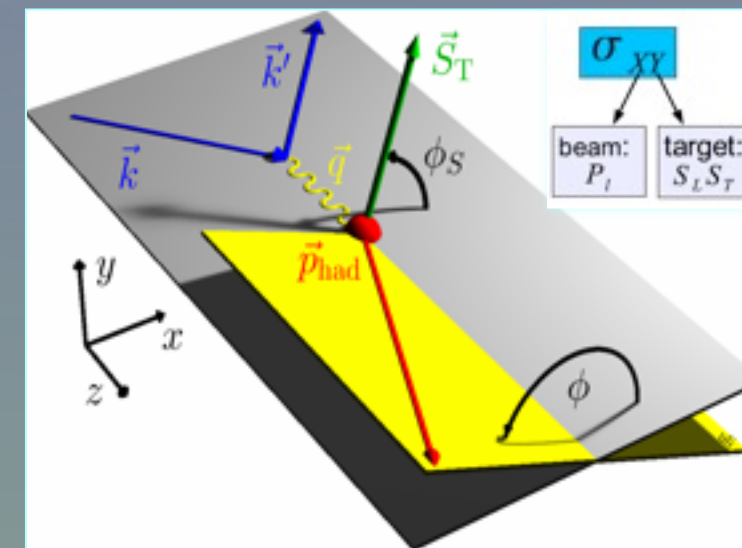
Observable: azimuthal asymmetries in SIDIS.

Semi-inclusive DIS: transverse structure

$$\sigma(l + N \to l' + h + X)$$

Transverse-momentum-dependent (TMD) DF

$$\sigma^{eN\to ehX} \propto \sum_q DF^{N\to q}(x, p_T) \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}(z, p_T)$$



The SIDIS cross section up to twist-3

$$d\sigma = d\sigma^0_{UU} + cos(2\phi)d\sigma^1_{UU} + \frac{1}{Q}cos(\phi)d\sigma^2_{UU} + P_l\frac{1}{Q}sin(\phi)d\sigma^3_{LU}$$
$$+ S_L\left[sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}sin(\phi)d\sigma^5_{UL} + P_L\left(d\sigma^6_{LL} + \frac{1}{Q}sin(\phi)d\sigma^7_{LL}\right)\right]$$
$$+ S_T\Big[sin(\phi-\phi_s)d\sigma^8_{UT} + sin(\phi+\phi_s)d\sigma^9_{UT} + sin(3\phi-\phi_s)d\sigma^{10}_{UT} +$$
$$\frac{1}{Q}sin(2\phi-\phi_s)d\sigma^{11}_{UT} + \frac{1}{Q}sin(\phi_s)d\sigma^{12}_{UT} +$$
$$P_l\left(cos(\phi-\phi_s)d\sigma^1_{LT}3 + \frac{1}{Q}cos(\phi_s)d\sigma^{14}_{LT} + \frac{1}{Q}cos(2\phi-\phi_s)d\sigma^{15}_{LT}\right)\Big]$$

Distribution Functions (DF)

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Fragmentation Functions (FF)

N/q	U	T
U	D_1	$H_1^\perp$

Semi-inclusive DIS: transverse structure

$$\sigma(l + N \to l' + h + X)$$

Transverse-momentum-dependent (TMD) DF

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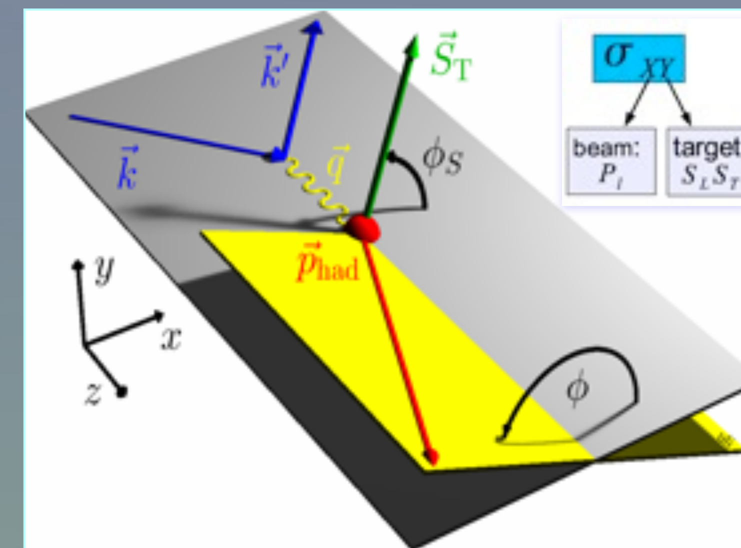

Collins effect

$$\propto \; h_1(x,p_T^2) \otimes H_1^{\perp}(z,k_T^2)$$

correlation between parton transverse polarization in a transversely polarized nucleon and transverse momentum of the produced hadron

$$\ldots(\phi)d\sigma^2_{UU} + P_l \frac{1}{Q} sin(\phi)d\sigma^3_{LU}$$

$$+ S \ldots (d\sigma^6_{LL} + \frac{1}{Q} sin(\phi)d\sigma^7_{LL})\Big]$$

$$+ S_T\Big[sin(\phi-\phi_s)d\sigma^8_{UT} + \boxed{sin(\phi+\phi_s)d\sigma^9_{UT}} + sin(3\phi-\phi_s)d\sigma^{10}_{UT} +$$

$$\frac{1}{Q} sin(2\phi-\phi_s)d\sigma^{11}_{UT} + \frac{1}{Q} sin(\phi_s)d\sigma^{12}_{UT} +$$

$$P_l\left(cos(\phi-\phi_s)d\sigma^1_{LT}3 + \frac{1}{Q} cos(\phi_s)d\sigma^{14}_{LT} + \frac{1}{Q} cos(2\phi-\phi_s)d\sigma^{15}_{LT}\right)\Big]$$

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U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$

Fragmentation Functions (FF)

N/q	U	T
U	D_1	$H_1^{\perp}$

Semi-inclusive DIS   transverse structure

$$\sigma(l + N \to l' + h + X)$$

Transverse-momentum-dependent (TMD) DF

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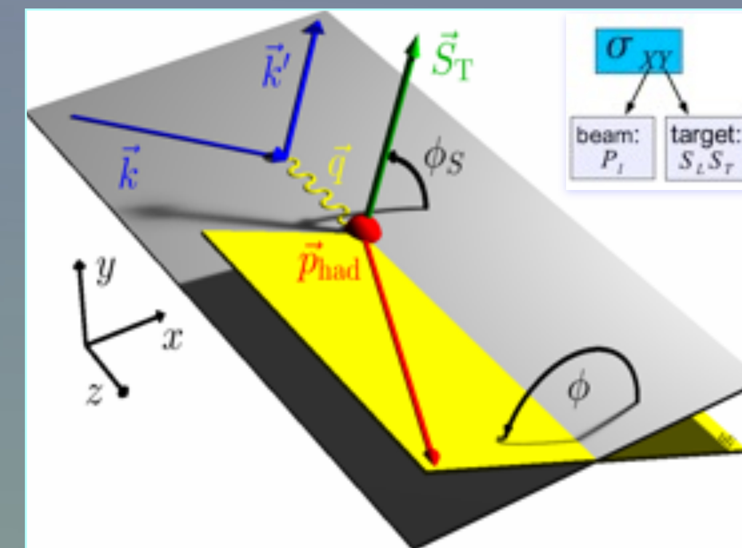

Sivers effect

$$\propto \; f_{1T}^{\perp}(x,p_T^2) \otimes D_1(z,k_T^2)$$

correlation between parton transverse momentum and nucleon transverse polarization

requires orbital angular momentum

$$d\sigma = d\sigma^0_{UU} + cos(2\phi)d\sigma^1_{U} \ldots d\sigma^3_{LU}$$

$$+ S_L\left[sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}sin(\ldots {}^7_{LL})\right]$$

$$+ S_T\left[sin(\phi-\phi_s)d\sigma^8_{UT} + sin(\phi+\phi_s)d\sigma^9_{UT} + sin(3\phi-\phi_s)d\sigma^{10}_{UT} + \right.$$

$$\frac{1}{Q}sin(2\phi-\phi_s)d\sigma^{11}_{UT} + \frac{1}{Q}sin(\phi_s)d\sigma^{12}_{UT} +$$

$$\left. P_l\left(cos(\phi-\phi_s)d\sigma^1_{LT}3 + \frac{1}{Q}cos(\phi_s)d\sigma^{14}_{LT} + \frac{1}{Q}cos(2\phi-\phi_s)d\sigma^{15}_{LT}\right)\right]$$

Distribution Functions (DF)

N/q	U	L	T
U	f_1		$h_1^{\perp}$
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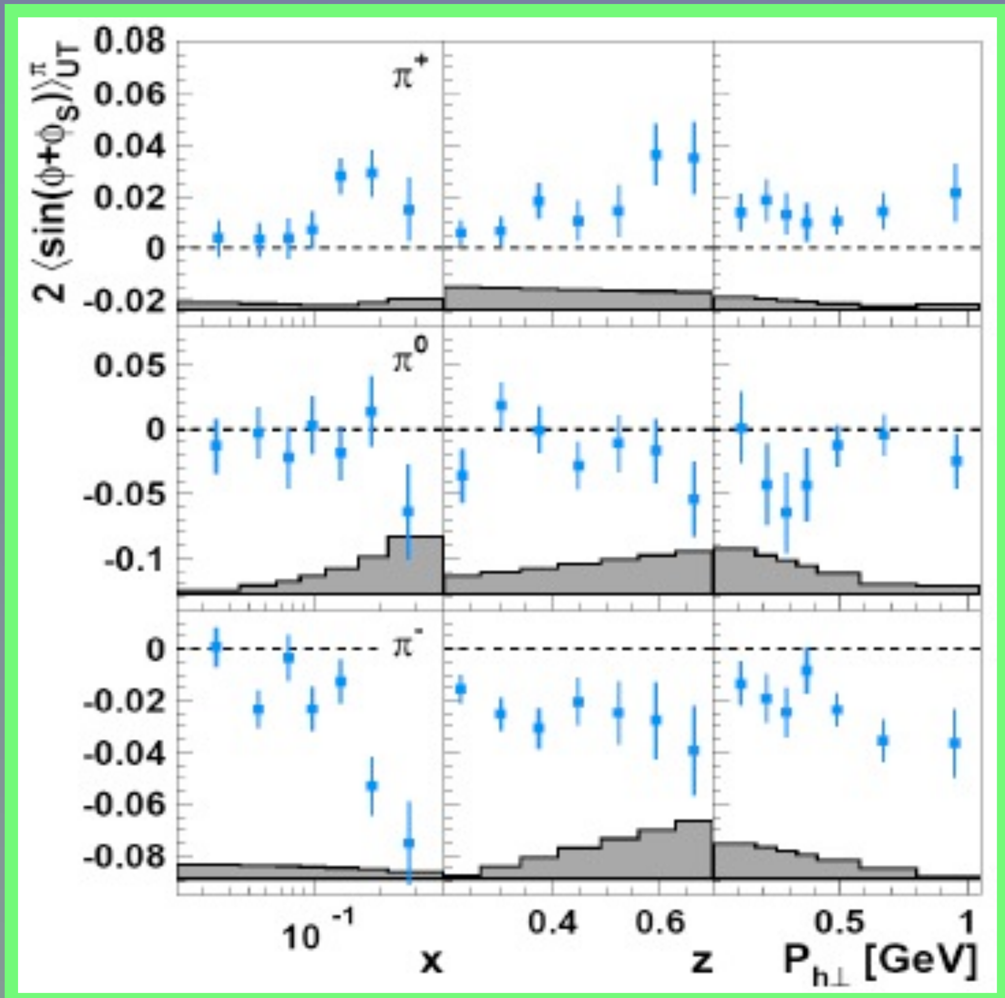
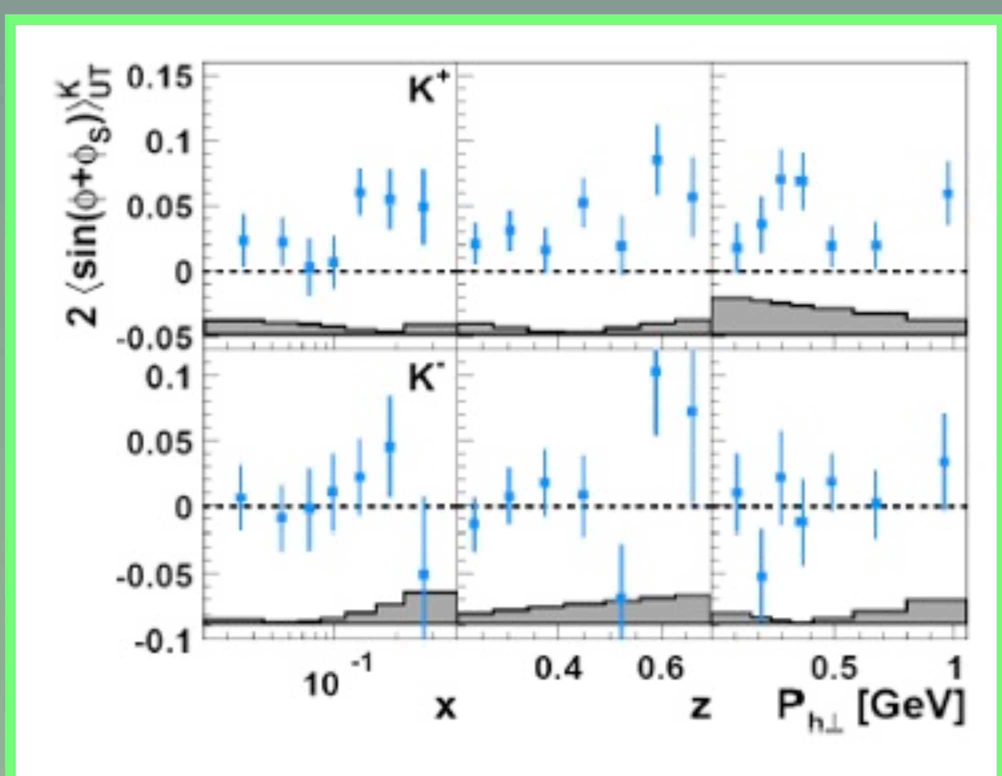
Fragmentation Functions (FF)

N/q	U	T
U	D_1	$H_1^{\perp}$

Semi-inclusive DIS **Collins** moments





$$\sigma(l + N \rightarrow l' + h + X)$$

TMDs can be studied by measuring azimuthal asymmetries in SIDIS

- $\pi^+ > 0$, $\pi^- < 0$
- π^- unexpectedly large!

➡ large *unfavoured* Collins fragmentation function!

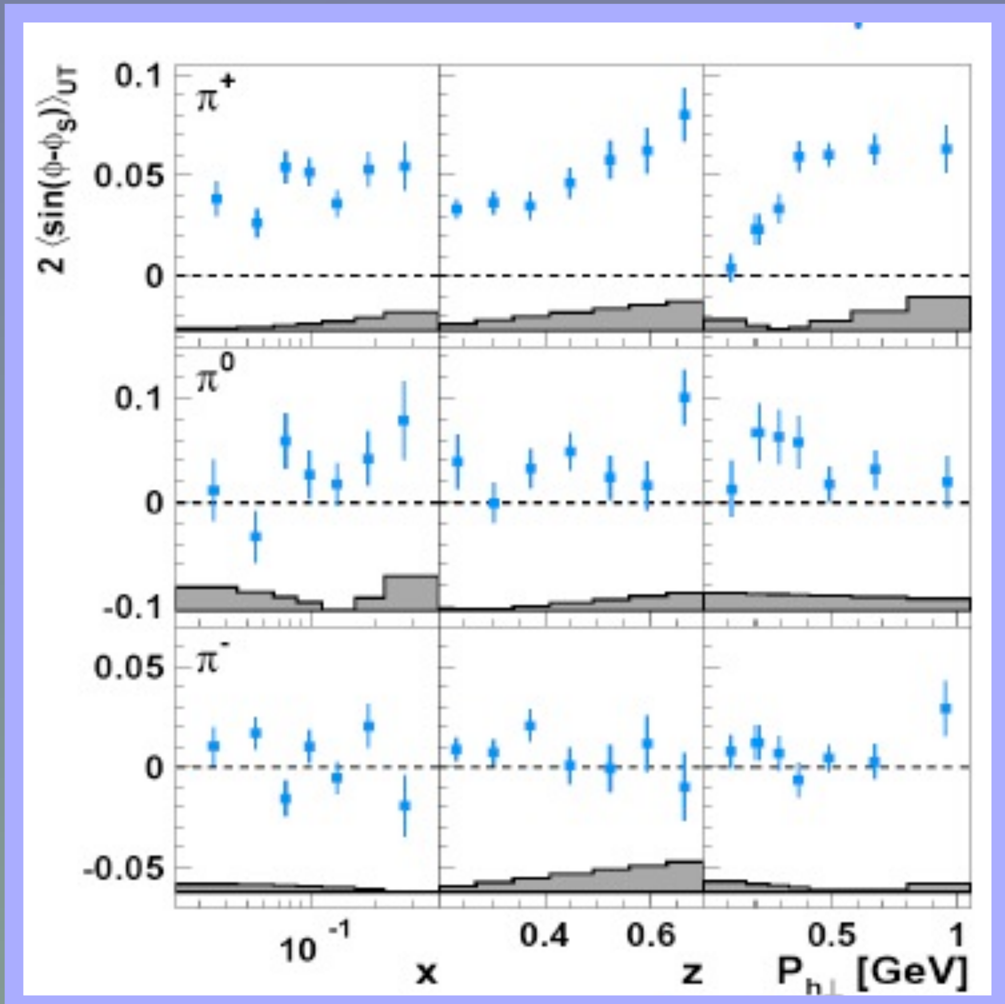
- K^+ consistent with π^+
- K^- (all sea object) opposite sign from π^-

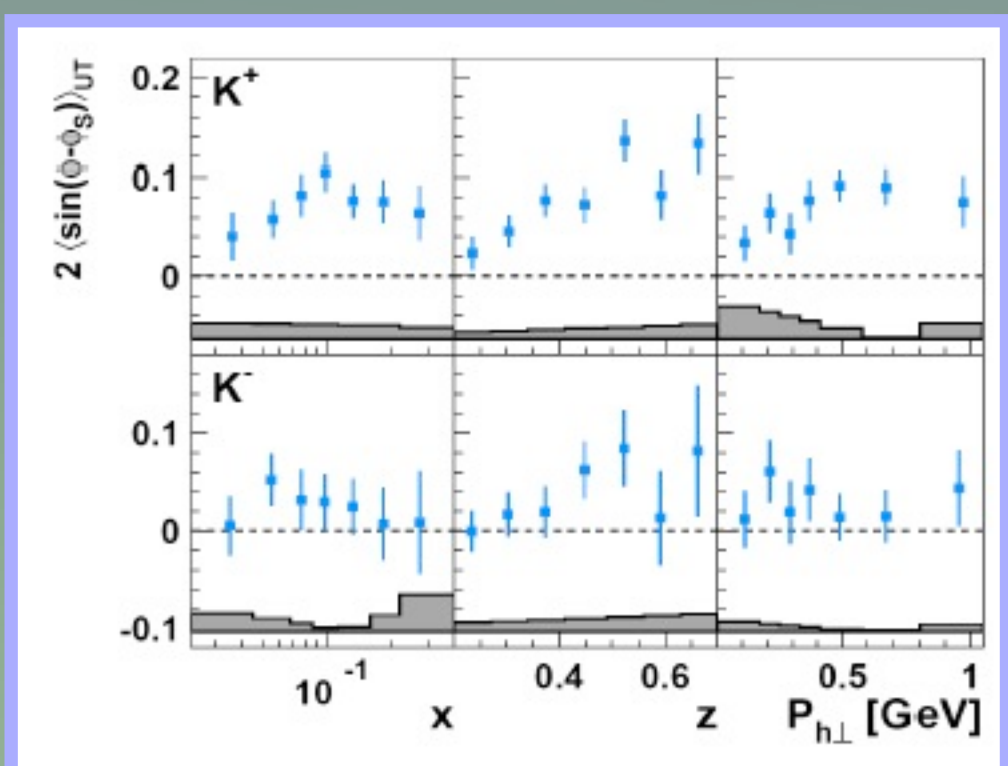
Distribution Functions (DF)			
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Fragmentation Functions (FF)		
N/q	U	T
U	D_1	$H_1^\perp$

Semi-inclusive DIS Sivers moments

$$\sigma(l + N \rightarrow l' + h + X)$$





- significantly positive π^+ moment

➡first evidence of a non zero naïve T-odd DF in DIS

➡requires non-zero orbital angular momentum

- π^- consistent with zero

- K^+ amplitude larger than for π^+ (Sivers for sea quarks)
- K^- consistent with zero

Distribution Functions (DF)

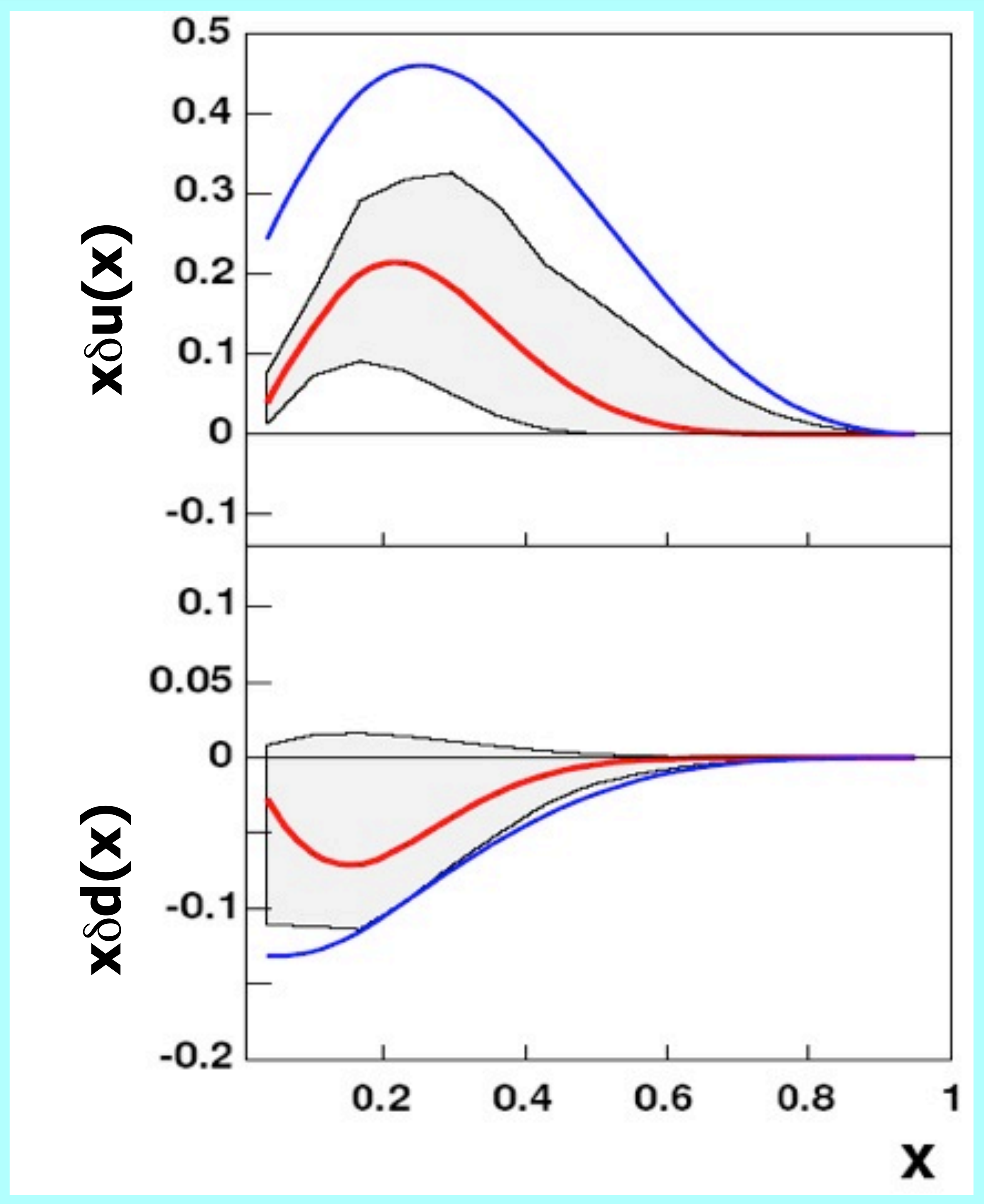
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Fragmentation Functions (FF)

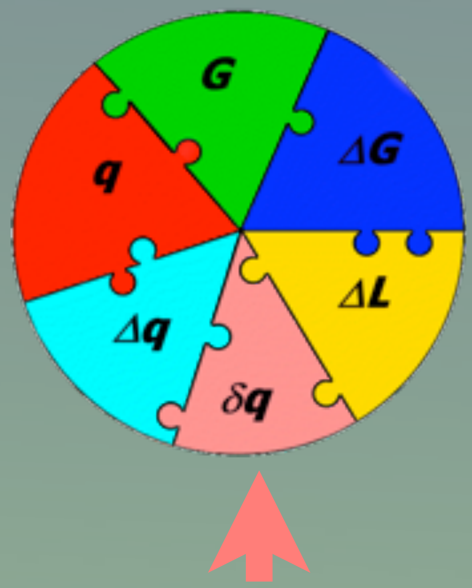
N/q	U	T
U	D_1	$H_1^\perp$

What do we learn from Collins moment?

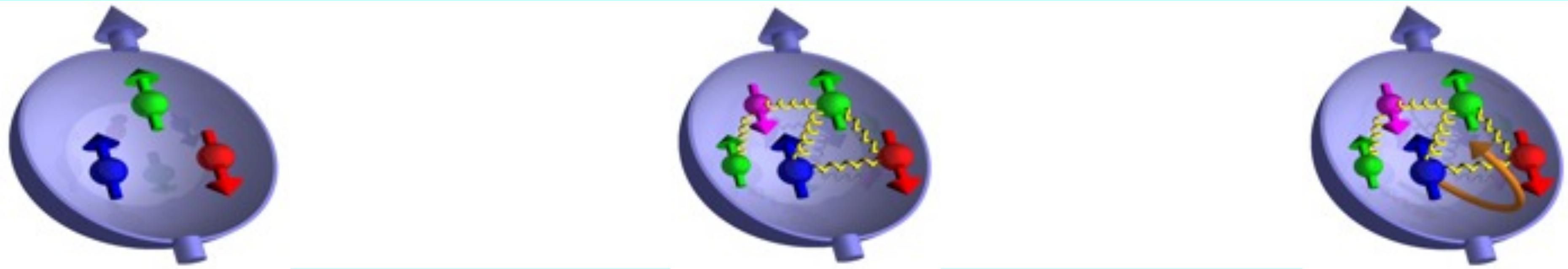
$$\sigma(l + N \rightarrow l' + h + X)$$



First extraction of transversity distribution!!



Where does the proton spin come from?



$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g$$

Where does the proton spin come from?

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g$$

small

poorly known

$\Delta\Sigma \sim 1/3$

Photon-gluon processes in DIS

Where does the proton spin come from?

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g$$

small

unknown

poorly known

$\Delta\Sigma \sim 1/3$

Measurements of scaling violation
Photon-gluon processes in DIS

Ji Sum rule:
GPD: H^q and E^q -
correlation between momentum and the spatial parton distributions

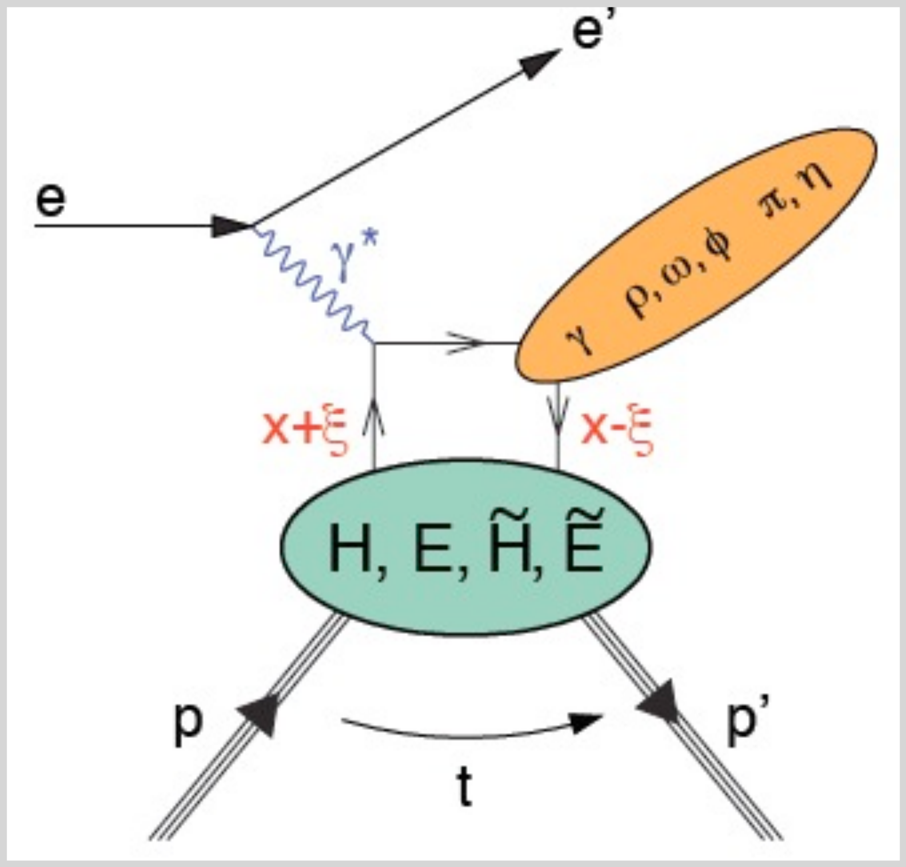
$$J^q = \frac{1}{2}\Delta\Sigma + L_q$$

Ji relation (1997)

$$J_q = \lim_{t \to 0} \int_{-1}^{1} \mathrm{d}x\, x\, (H_q(x,\xi,t) + E_q(x,\xi,t))$$

➜ Moments of certain GPDs relate directly to the total angular momentum of quarks

Probing the orbital angular momentum



Accessing Generalized Parton Distributions (GPDs)

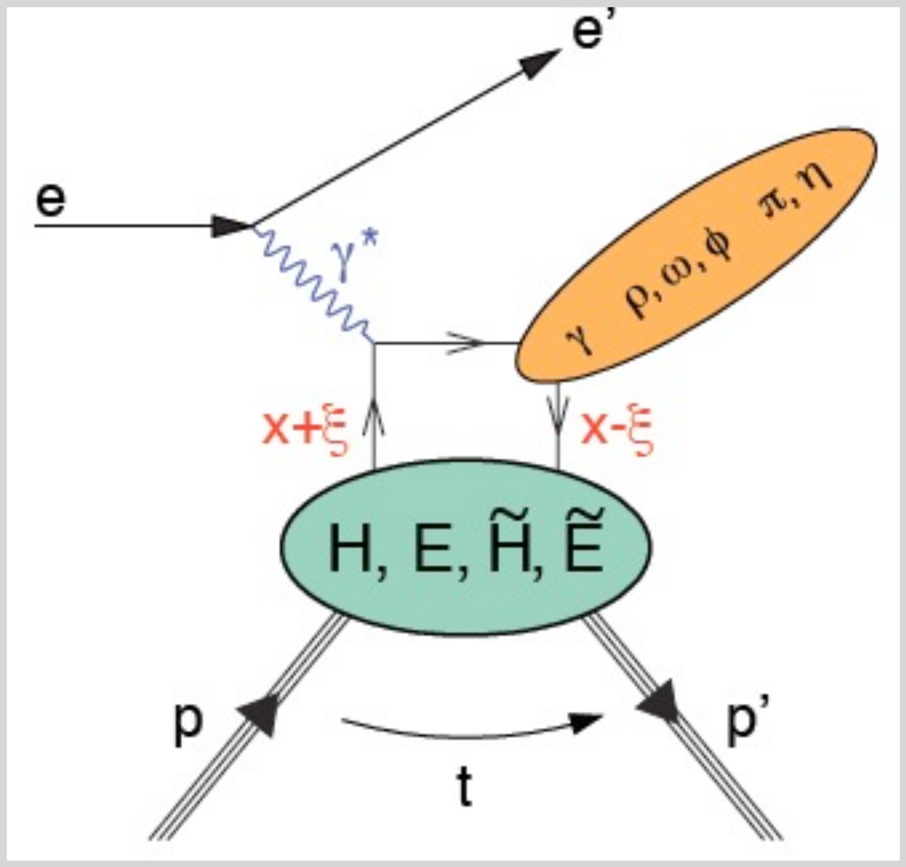
via

Deeply Virtual Compton Scattering (DVCS)

and

exclusive meson production

Probing the orbital angular momentum



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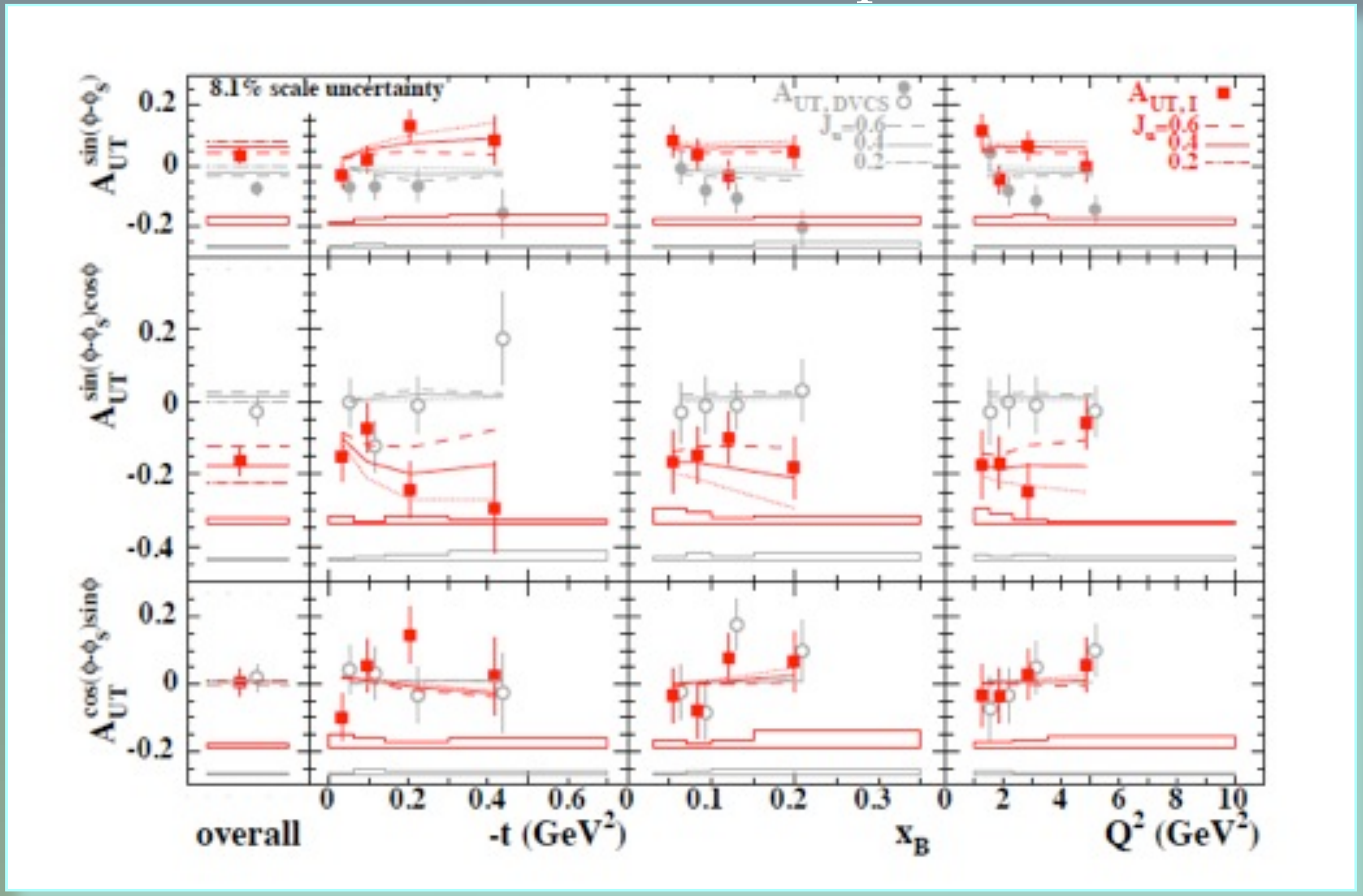
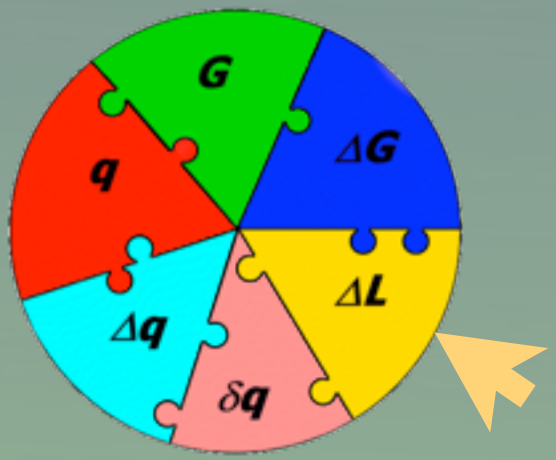




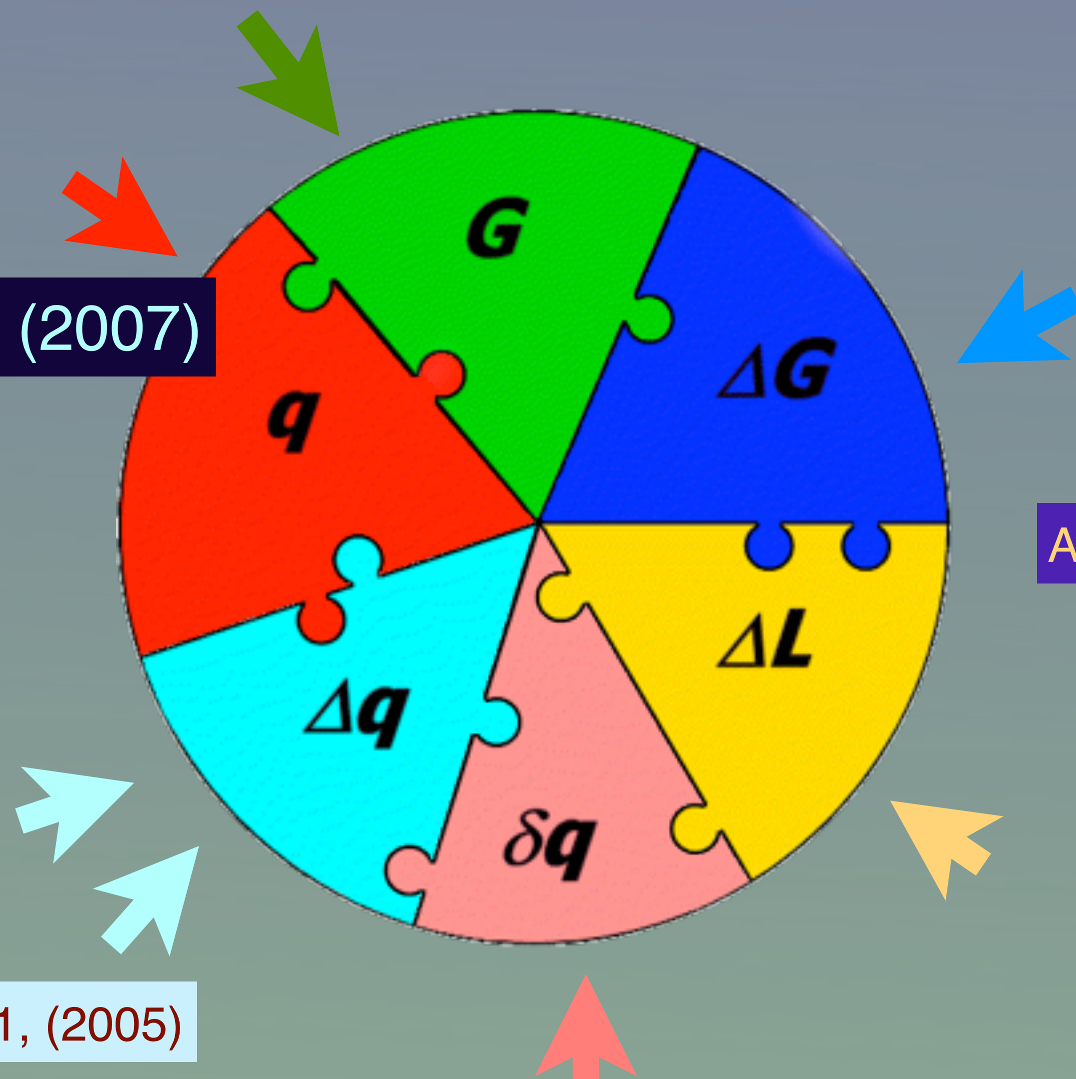
Sensitive to J_q

Where does the proton spin come from?

A. Airapetian et al., JHEP08 (2010) 130

A. Airapetian et al., JHEP05 (2011)126

A. Airapetian et al., PRD 75 (2007)



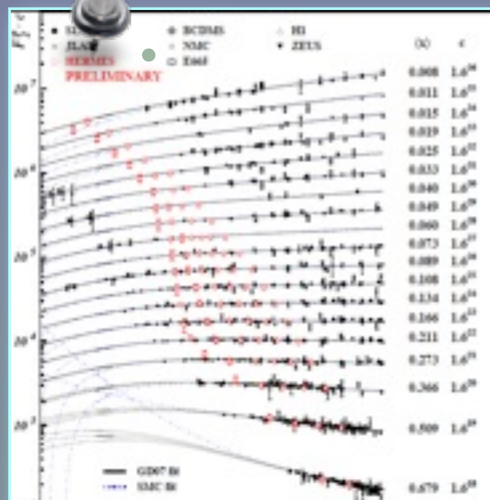
A. Airapetian et al., JHEP 0806:066,2008

A. Airapetian et al., PRD 71, (2005)

A. Airapetian et al., PLB 666, 446 (2008)]

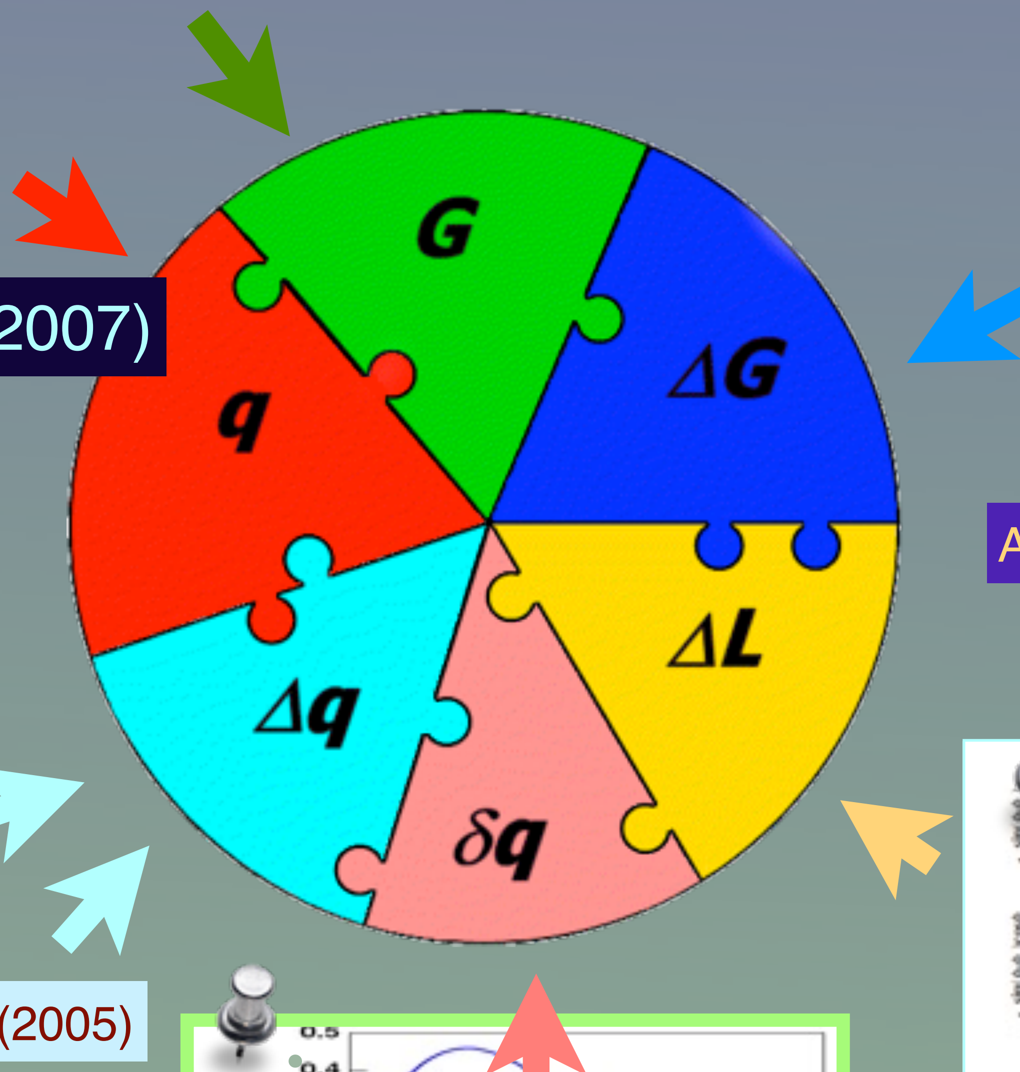
A.Airapetian et al., JHEP06 (2008) 066

Where does the proton spin come from?

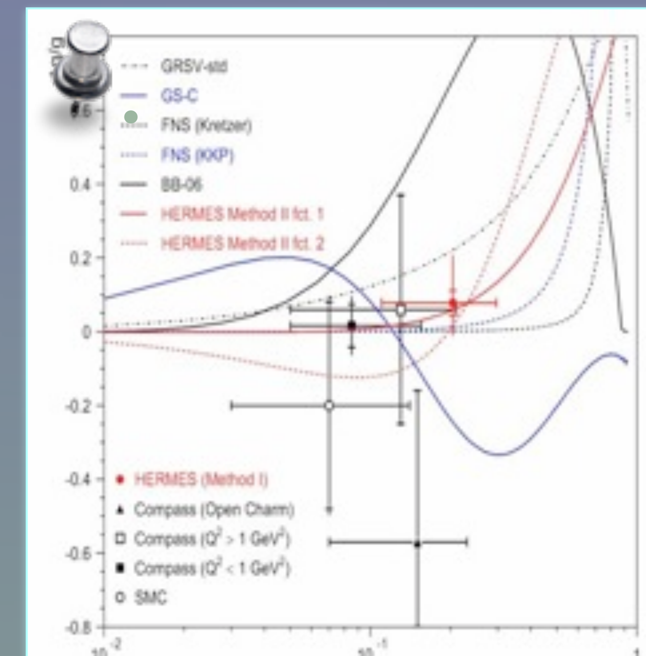


A. Airapetian et al., PRD 75 (2007)

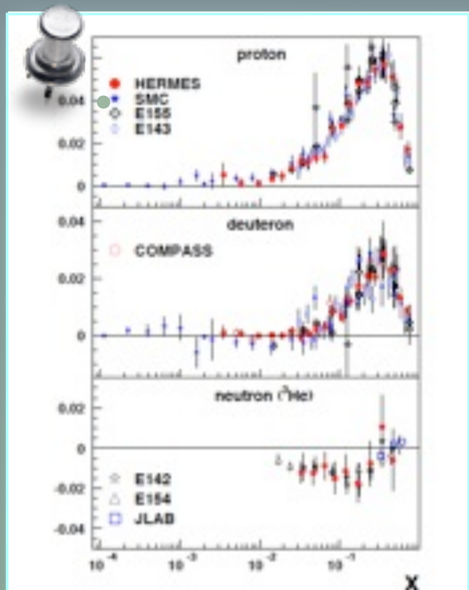
A. Airapetian et al., JHEP05 (2011)126



A. Airapetian et al., JHEP08 (2010) 130



A. Airapetian et al., JHEP 0806:066,2008



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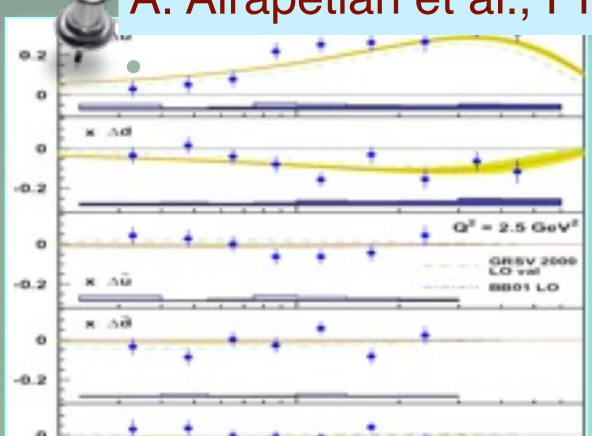
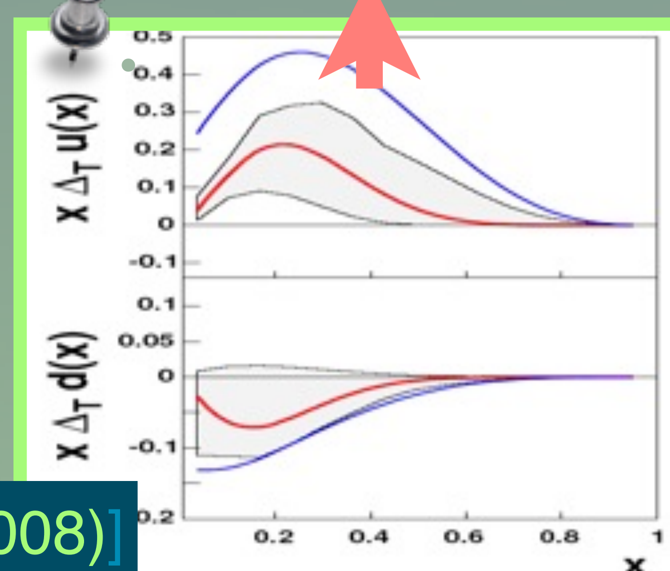
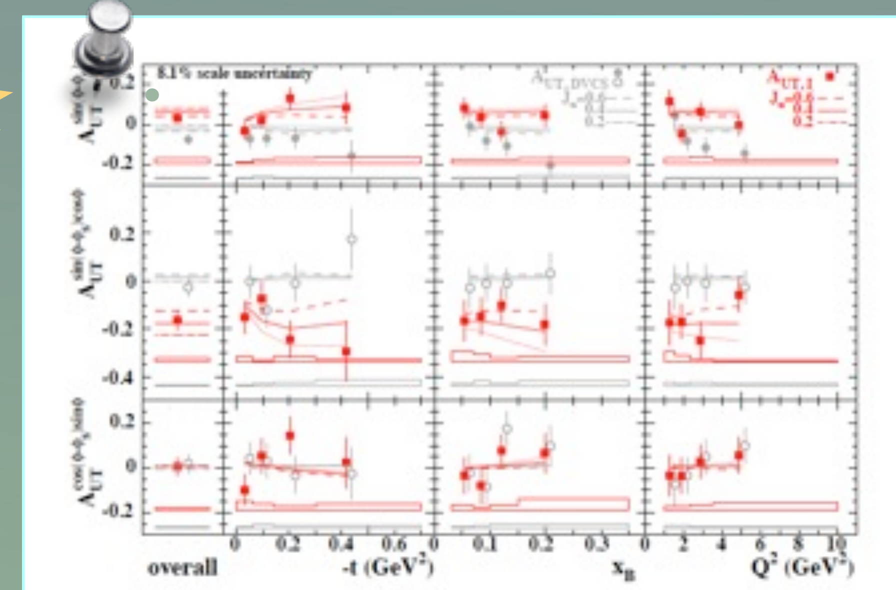


A. Airapetian et al., PLB 666, 446 (2008)





A.Airapetian et al., JHEP06 (2008) 066

Backup slides

Probing the structure of nucleons

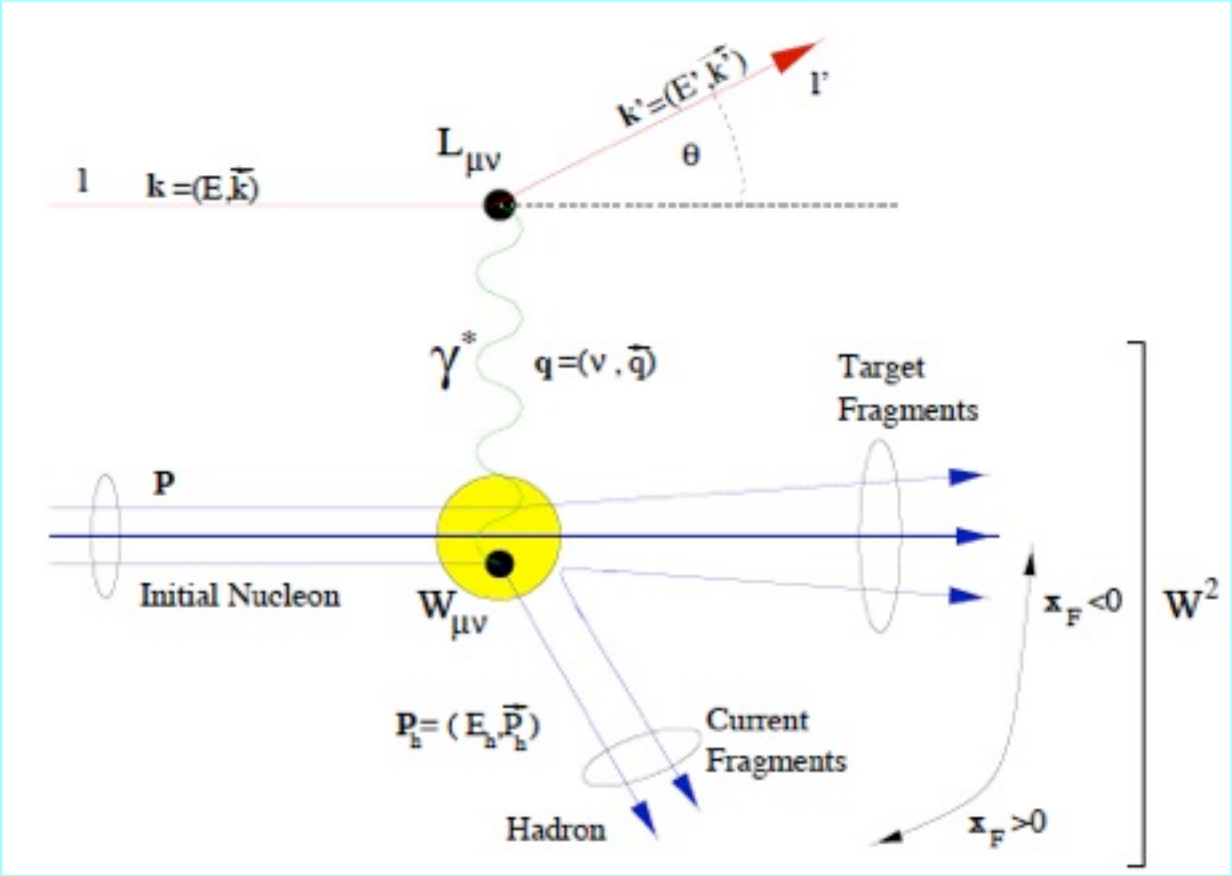
- Deep-inelastic scattering (DIS) plays major role in understanding of nucleon structure
- Lepton-nucleon scattering cleanest way to probe substructure of nucleon
- Exchange of virtual boson, breakup and hadronization in DIS regime

center-of-mass energy (eN)

$$s = (P+k)^2 = M^2 + 2ME$$

invariant mass of hadronic final state

$$W^2 = (P+q)^2 = M^2 + 2M\nu - Q^2$$



For gives s, two kinematic variables completely describe the scattering process in the **inclusive** analysis

photon virtuality

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

Bjørken scaling variable

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

or

photon energy (lab)

$$\nu = \frac{P\cdot q}{M} = E - E^{'}$$

inelasticity

$$y = \frac{P\cdot q}{P\cdot k} = \frac{\nu}{E}$$

Semi-inclusive DIS:

Fraction of the virtual photon energy carried by hadron h

$$z_h = \frac{E_h}{\nu}$$

Deep inelastic scattering cross section

$$\sigma(l + N \to l' + X)$$

Assuming one photon exchange

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

hadronic tensor contains information about hadron structure

leptonic tensor from QED

Deep inelastic scattering — cross section

$$\sigma(l + N \to l' + X)$$

Assuming one photon exchange

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

hadronic tensor contains information about hadron structure

leptonic tensor from QED

unpolarized structure functions
momentum distribution of quarks

$$W^{\mu\nu} = -\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)\boxed{F_1\left(x,Q^2\right)} + \left(P^\mu - \frac{P\cdot q}{q^2}q^\mu\right)\left(P^\nu - \frac{P\cdot q}{q^2}q^\nu\right)\boxed{F_2\left(x,Q^2\right)}$$

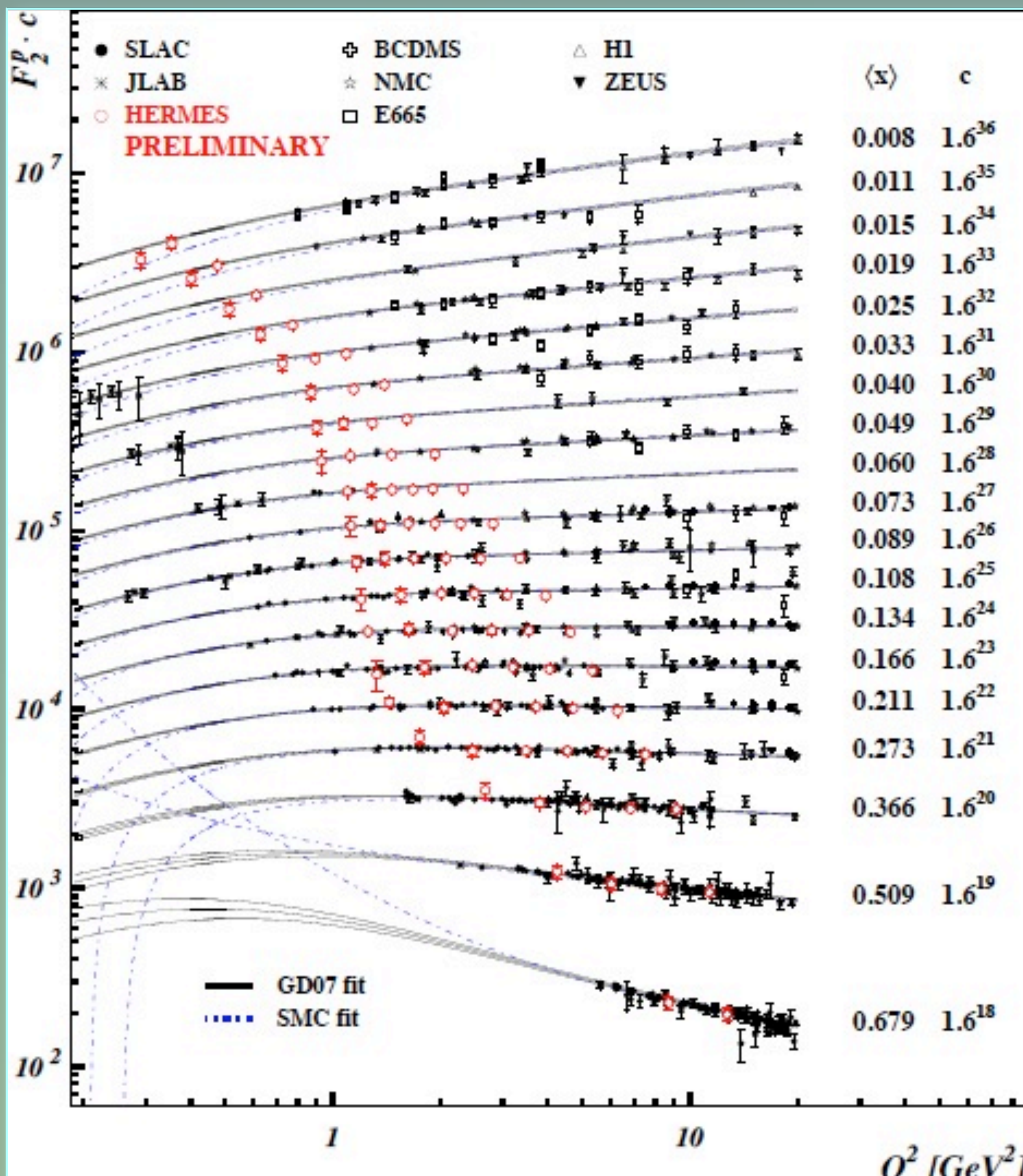
$$+iM\varepsilon^{\mu\nu\rho\sigma}q_\rho\left[\frac{S_\sigma}{P\cdot q}\boxed{g_1\left(x,Q^2\right)} + \frac{S_\sigma(P\cdot q) - P_\sigma(S\cdot q)}{(P\cdot q)^2}\boxed{g_2\left(x,Q^2\right)}\right]$$

polarized structure functions
spin distribution of quarks

Inclusive DIS: unpolarized structure function F_2

measured

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha_{em}^2}{Q^4}\frac{F_2}{x}\times\left[\,1-y-\frac{Q^2}{4E^2}+\frac{y^2+Q^2/E^2}{2(1+R(x,Q^2))}\,\right]$$



in the 1-photon exchange approximation

$$F_1(x) = \frac{1}{2}\sum_q e_q^2 q(x)$$

$$F_2(x) = x\sum_q e_q^2 q(x)$$

Distribution Functions (DF)			
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Fragmentation Functions (FF)		
N/q	U	T
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Inclusive DIS: unpolarized structure function F_2

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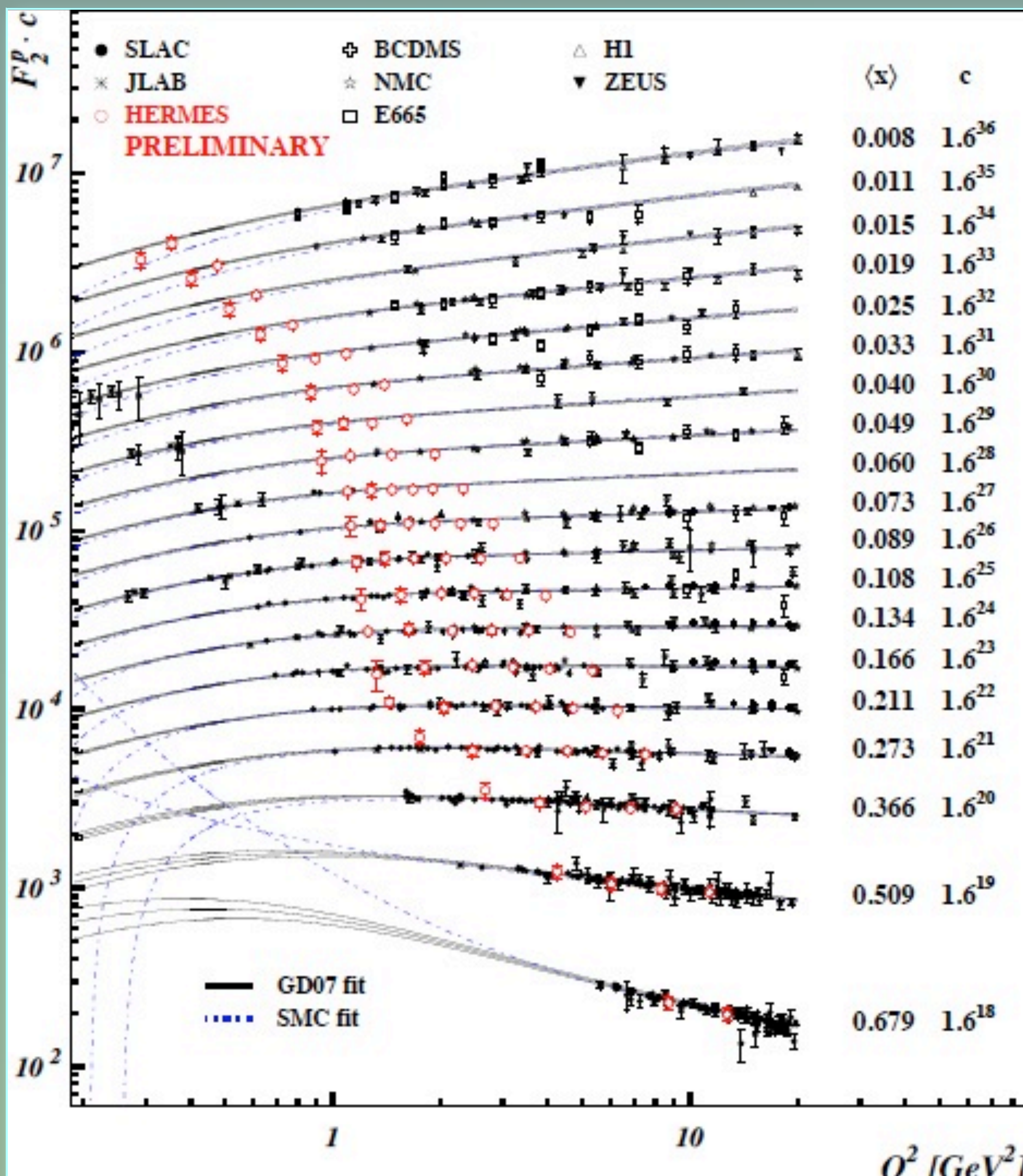

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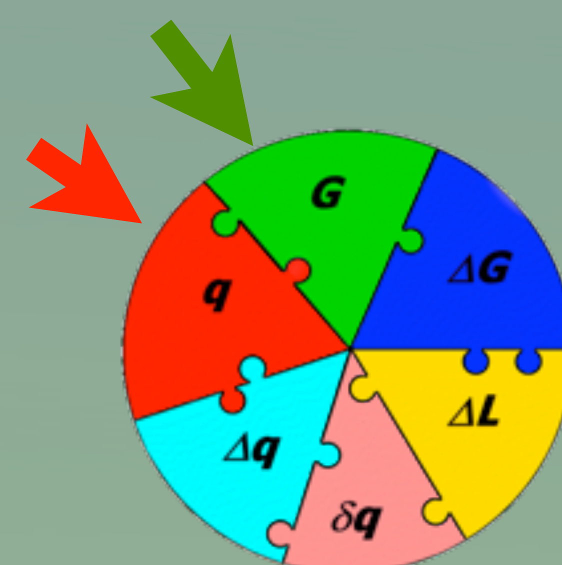


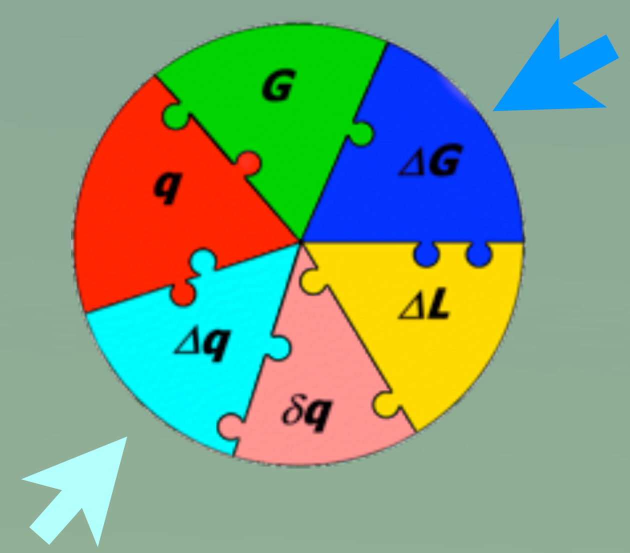
Inclusive DIS: Δq and ΔG

$$g_1^{NLO}(x,Q^2) = g_1^{LO} + \frac{1}{2}e^2\sum_q[\Delta q(x,Q^2)\otimes S_q + \Delta g(x,Q^2)\otimes C_g]$$

$SU(3)_f$ symmetry implicitly assumed

- valence quarks are well determined
$\Delta u_v > 0$ and **$\Delta d_v < 0$**

- **gluons** and **sea** quarks are poorly constraint by data



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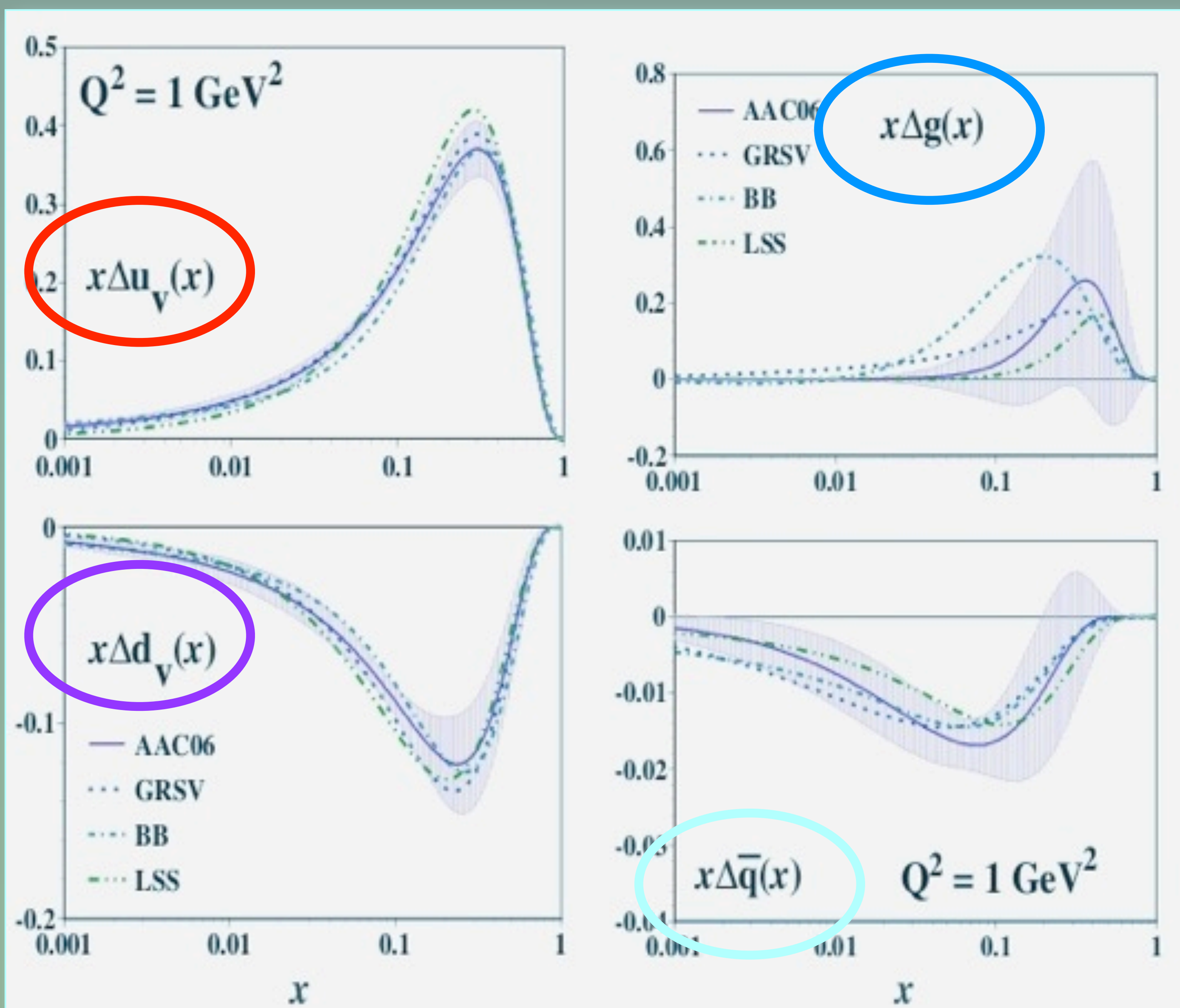

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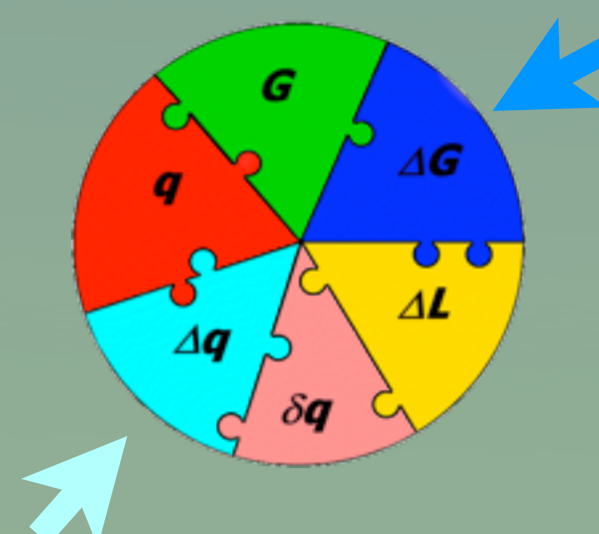
- **gluons** and **sea** quarks are poorly constraint by data

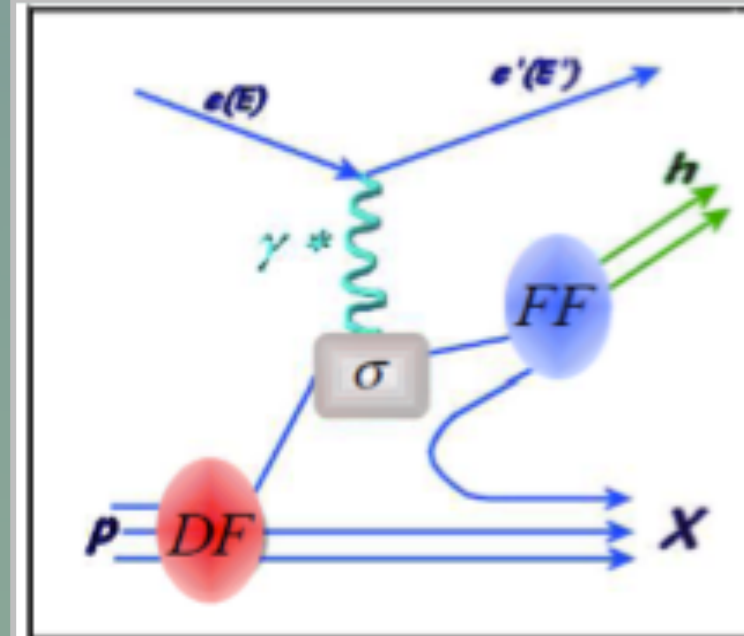


Semi-inclusive DIS: flavour separation

Method (LO):
Use correlation between detected hadron and struck quark → **'Flavor separation'**

$$\sigma(l + N \to l' + h + X)$$

$$\sigma^{eN \to ehX} = \sum_q DF^{N \to q}(x) \otimes \sigma^{eq \to eq} \otimes FF^{q \to h}(z)$$



Probability that struck quark of flavour q fragments into hadron of type h with energy fraction $z=E_h/\nu$

$$A_1^h(x,Q^2) \overset{LO}{\sim} \frac{\sum_q e_q^2 \Delta q(x,Q^2) \int dz D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) \int dz D_q^h(z,Q^2)}$$

$$\sim \sum_q \frac{e_q^2 q(x) \int dz D_q^h(z)}{\sum_{q'} e_{q'}^2 q' \int dz D_{q'}^h(z)} \cdot \frac{\Delta q(x)}{q(x)}$$

Purity $P_q^h(x,z)$ is conditional probability that hadron of type h in the final state originated from a struck quark of flavour q

Distribution Functions (DF)

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Fragmentation Functions (FF)

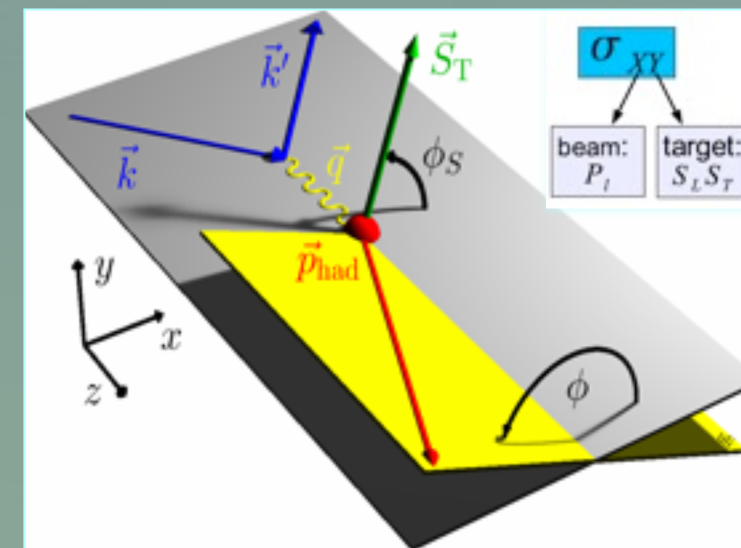
N/q	U	T
U	D_1	$H_1^\perp$

Semi-inclusive DIS: transverse structure

$$\sigma(l + N \rightarrow l' + h + X)$$

Transverse-momentum-dependent (TMD) DF

$$\sigma^{eN\rightarrow ehX} \propto \sum_q DF^{N\rightarrow q}(x, p_T) \otimes \sigma^{eq\rightarrow eq} \otimes FF^{q\rightarrow h}(z, p_T)$$



$$d\sigma = d\sigma^0_{UU} + \boxed{cos(2\phi)d\sigma^1_{UU} + \frac{1}{Q}cos(\phi)d\sigma^2_{UU}} + P_l \frac{1}{Q} sin(\phi) d\sigma^3_{LU}$$

$$+ S_L \left[sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}sin(\phi)d\sigma^5_{UL} + P_L \left(d\sigma^6_{LL} + \frac{1}{Q}sin(\phi)d\sigma^7_{LL}\right)\right]$$

$$+ S_T \Big[sin(\phi - \phi_s)d\sigma^8_{U} \ldots$$

$$\frac{1}{Q} sin(2\phi - \phi_s) \ldots$$

$$P_l \Big(cos(\phi - \phi_s) \ldots \Big) \Big]$$

Boer-Mulders Effect

$$\propto \; h_1^{\perp}(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$$

correlation between parton transverse momentum and parton transverse polarization in an unpolarized nucleon

Distribution Functions (DF)			
N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$

Fragmentation Functions (FF)		
N/q	U	T
U	D_1	$H_1^{\perp}$