3rd lecture :

Deeply virtual Compton scattering & generalized parton distributions

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(NON-FORWARD) DEEPLY VIRTUAL COMPTON SCATTERING (DVCS)

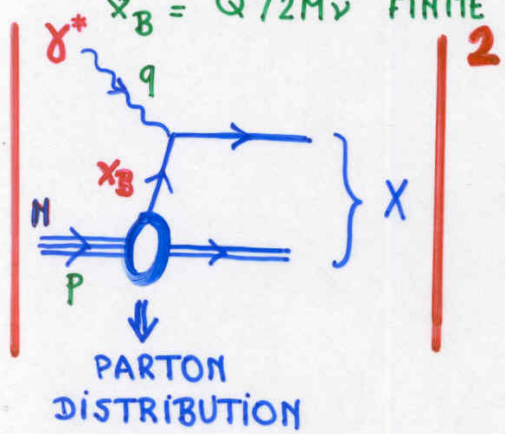
• INCLUSIVE DIS ⟷ FORWARD DVCS

BJORKEN LIMIT

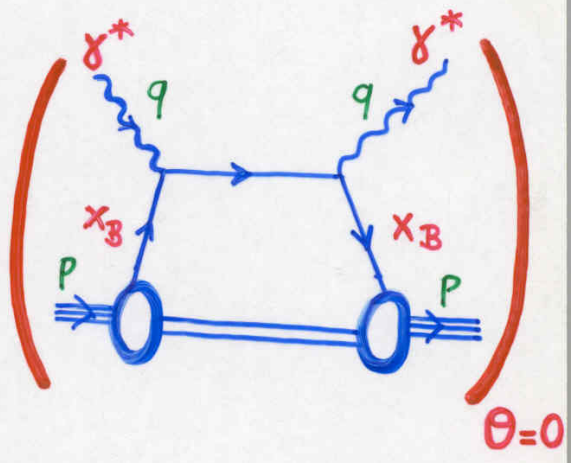
$Q^2 \gg$ HARD SCALE $\Rightarrow$ PQCD

$\nu \gg$

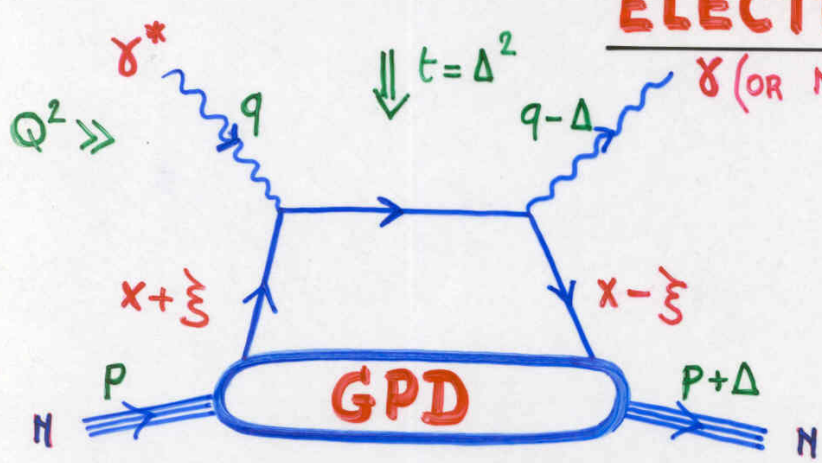
$x_B = Q^2/2M\nu$ FINITE



^{2} $\sim \mathrm{Im}$



• HARD EXCLUSIVE, NON-FORWARD ELECTROPRODUCTION



Δ NON-ZERO BUT SMALL

$t \equiv \Delta^2 \quad (-t \lesssim 1\ \mathrm{GeV}^2)$

$\mathrm{GPD}(x, \xi, t) \xrightarrow{Q^2 \gg}$ 4 LORENTZ STRUCTURES $\begin{cases} H & (V) \\ E & (T) \\ \tilde{H} & (A) \\ \tilde{E} & (PS) \end{cases}$

GENERALIZED PARTON DISTRIBUTION

GENERALIZED PARTON DISTRIBUTION

DEEPLY VIRTUAL COMPTON SCATTERING

IN BJORKEN LIMIT $\left(Q^2 \gg ,\ \nu_L \gg ,\ x_B = \frac{Q^2}{2M\nu_L} \text{ FINITE} \right)$

$\Downarrow$

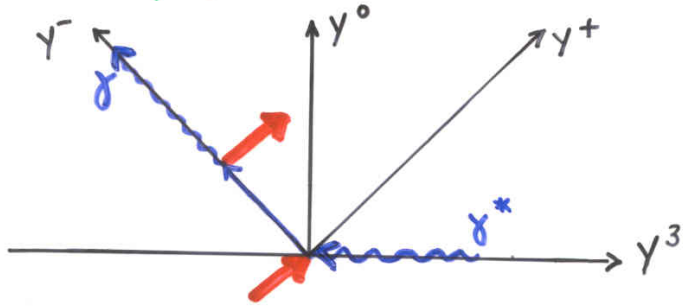
HANDBAG DIAGRAMS (VALENCE REGION)

+ CROSSED DIAGRAM

$P \to$ LARGE P^+

$q \to$ LARGE q^-, q^+

$k^+ = x P^+$	$\Delta^+ = -2\xi P^+$	$\Delta^2 = t$



$$\xi = \frac{x_B/2}{1 - x_B/2}$$

$$P^\mu = P^+(1,0,0,1)$$

$$n^\mu = \frac{1}{2P^+}(1,0,0,-1)$$

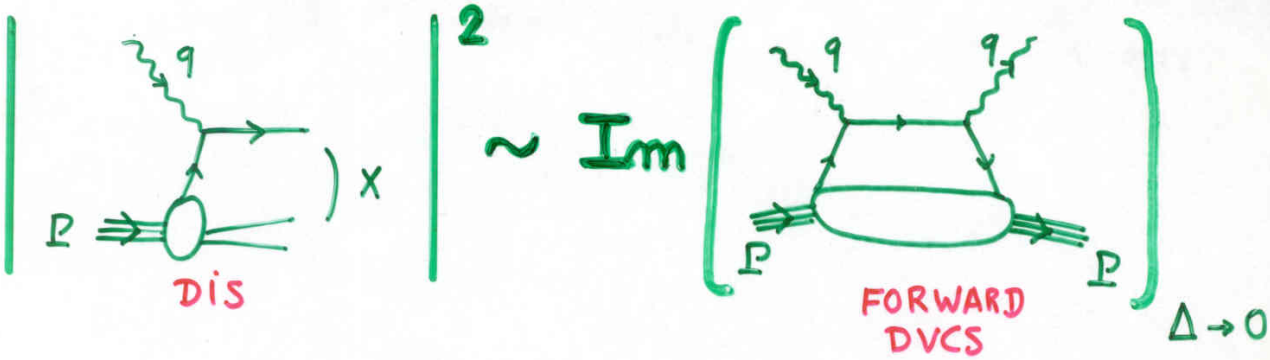
$$\frac{P^+}{2\pi} \int dy^- \, e^{ixP^+y^-} \langle P' | \bar{q}\left(-\frac{y}{2}\right) \not{n} \, q\left(\frac{y}{2}\right) | P \rangle_{\substack{y^+=0 \\ \bar{y}_\perp = 0}}$$

$$= \bar{N}(P') \left\{ H(x,\xi,t) \not{n} + E(x,\xi,t) \, i\sigma^{\nu\alpha} \frac{\Delta_\alpha}{2M} n_\nu \right\} N(P)$$

$$\frac{P^+}{2\pi} \int dy^- \, e^{ixP^+y^-} \langle P' | \bar{q}\left(-\frac{y}{2}\right) \not{n} \gamma_5 \, q\left(\frac{y}{2}\right) | P \rangle_{y^+=0, \bar{y}_\perp = 0}$$

$$= \bar{N}(P') \left\{ \tilde{H}(x,\xi,t) \not{n} \gamma_5 + \tilde{E}(x,\xi,t) \gamma_5 \frac{\Delta^\nu}{2M} n_\nu \right\} N(P)$$

- LINK BETWEEN GPD & 'ORDINARY' PARTON DISTRIBUTIONS

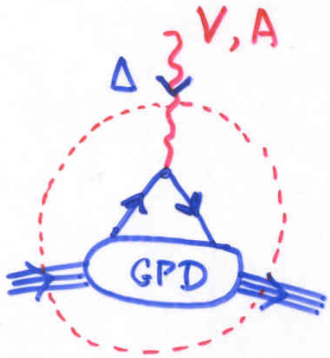


$H(x, \xi=0, \Delta^2=0) = q(x)$ ← QUARK DISTRIBUTION

$\tilde{H}(x, \xi=0, \Delta^2=0) = \Delta q(x)$ ← QUARK HELICITY DISTR.

! $E, \tilde{E}$ DO <u>NOT</u> APPEAR IN DIS ⇒ NEW INFO !

- ELECTROWEAK FORM FACTOR SUM RULES



$$\int_{-1}^{1} dx\, H(x, \xi, \Delta^2) = F_1(\Delta^2)$$

$$\int_{-1}^{1} dx\, E(x, \xi, \Delta^2) = F_2(\Delta^2)$$

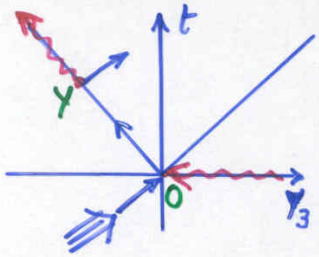
$$\int_{-1}^{1} dx\, \tilde{H}(x, \xi, \Delta^2) = G_A(\Delta^2)$$

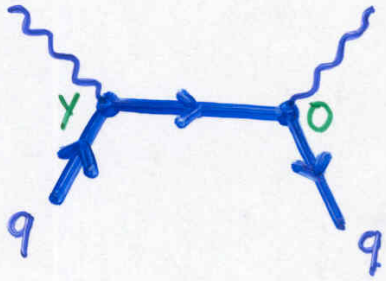
$$\int_{-1}^{1} dx\, \tilde{E}(x, \xi, \Delta^2) = G_P(\Delta^2)$$

← π - POLE

ξ INDEPENDENCE (LORENTZ INV.)

HANDBAG (BILOCAL) OPERATOR
PROVIDES **NEW** WAYS TO PROBE THE NUCLEON





"GENERALIZED" PROBE

$$\bar{q}(0)\begin{Bmatrix}\gamma^\mu \\ \gamma^\mu\gamma_5\end{Bmatrix} q(y)$$

$$\underset{y^-\simeq 0}{=} \bar{q}(0)\begin{Bmatrix}\gamma^\mu \\ \gamma^\mu\gamma_5\end{Bmatrix} q(0) + y^- \bar{q}(0)\begin{Bmatrix}\gamma^\mu \\ \gamma^\mu\gamma_5\end{Bmatrix} \partial^+ q(0) + \cdots$$

$(y^+=0, \bar{y}_\perp=0)$

$\Downarrow$ cfr $\gamma, W^\pm, Z$ PROBE

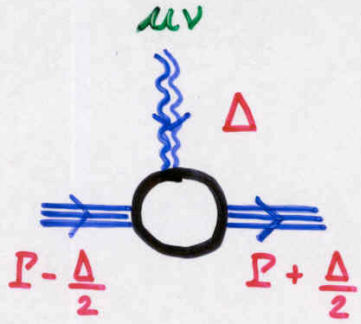
$\Downarrow$ cfr. GRAVITON, PSEUDO-GRAVITON PROBE

$\langle N| \ldots |N\rangle$ $\Downarrow$ ELECTROWEAK FORM FACTORS

$\langle N| \ldots |N\rangle$ $\Downarrow$ ENERGY-MOMENTUM TENSOR FORM FACTORS

$\therefore$ HANDBAG OPERATOR MEASURES GENERALIZED FORM FACTORS

FORM FACTORS OF ENERGY-MOMENTUM TENSOR



$\Delta^2 = t$

$$\Rightarrow \boxed{\begin{aligned} &\langle P + \tfrac{\Delta}{2} | T^{\mu\nu}(0) | P - \tfrac{\Delta}{2} \rangle \\ &= \bar{N}(P + \tfrac{\Delta}{2}) \Big\{ \underset{\text{"DIRAC"}}{A(t)} \; \gamma^{(\mu} P^{\nu)} \\ &\qquad + \underset{\text{"PAULI"}}{B(t)} \; P^{(\mu} i \sigma^{\nu)\alpha} \frac{\Delta_\alpha}{2M} \\ &\qquad + C(t) \frac{1}{M} \left(\Delta^\mu \Delta^\nu - \Delta^2 g^{\mu\nu} \right) \Big\} N(P - \tfrac{\Delta}{2}) \end{aligned}}$$

$a^{(\mu} b^{\nu)} \equiv \frac{1}{2}(a^\mu b^\nu + a^\nu b^\mu)$

$\Downarrow$ GORDON IDENTITY

$$\begin{aligned} = \bar{N}(P + \tfrac{\Delta}{2}) \Big\{ & A(t) \; P^\mu P^\nu / M \\ & + \big(A(t) + B(t) \big) \; P^{(\mu} i \sigma^{\nu)\alpha} \Delta_\alpha / 2M \\ & + C(t) \left(\Delta^\mu \Delta^\nu - \Delta^2 g^{\mu\nu} \right) / M \Big\} N(P - \tfrac{\Delta}{2}) \end{aligned}$$

⇒ MOMENTUM

$$\langle P | \hat{P}^\nu | P \rangle = \langle P | \int d^3\bar{x} \; T^{0\nu}(x) | P \rangle$$

$$= \lim_{\Delta \to 0} \langle P + \tfrac{\Delta}{2} | \int d^3\bar{x} \; T^{0\nu}(x) | P - \tfrac{\Delta}{2} \rangle$$

$$= \lim_{\Delta \to 0} \underbrace{\int d^3\bar{x} \; e^{-i\bar{x}.\bar{\Delta}}}_{(2\pi)^3 \delta^3(\bar{\Delta})} \langle P + \tfrac{\Delta}{2} | T^{0\nu}(0) | P - \tfrac{\Delta}{2} \rangle$$

$$= A(0) \, P^\nu \underbrace{(2P^0)(2\pi)^3 \delta^3(0)}_{\langle P | P \rangle}$$

$$\Downarrow$$

$$\boxed{\langle P | \hat{P}^\nu | P \rangle = A(0) \, P^\nu \langle P | P \rangle}$$

* TOTAL SYSTEM : ENERGY- MOMENTUM CONSERVATION

$$\Downarrow$$

$$A(0) = 1$$

* PHYSICAL INTERPRETATION IN TERMS OF

QUARKS $\rightarrow$ $A_q(0)$

& GLUONS $\rightarrow$ $A_g(0)$

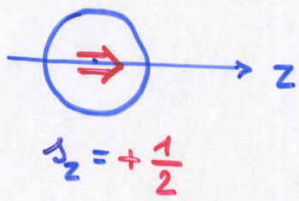
WITH $A_q(0) + A_g(0) = 1.$ (MOMENTUM SUM RULE)

⇒ ANGULAR MOMENTUM

CONSIDER N IN REST FRAME $P^\mu(M,0,0,0)$

$S^\mu(0,0,0,1)$

$(S^2=-1,\ S.P=0)$



$$\langle P,+\tfrac{1}{2}|\,\hat{J}^{12}\,|P,+\tfrac{1}{2}\rangle = \underset{\text{TOTAL SPIN}}{J}\ \langle P,+\tfrac{1}{2}|P,+\tfrac{1}{2}\rangle$$

$$= \langle P,+\tfrac{1}{2}|\int d^3\bar{x}\left\{x^1\,T^{02}(x) - x^2\,T^{01}(x)\right\}|P,+\tfrac{1}{2}\rangle$$

OF FORM $(\bar{x}\times\hat{\bar{P}})^z$

$$= \varepsilon_{ij3}\lim_{\Delta\to 0}\langle P+\tfrac{\Delta}{2},+\tfrac{1}{2}|\int d^3\bar{x}\ x^i\,T^{0j}(x)\,|P-\tfrac{\Delta}{2},+\tfrac{1}{2}\rangle$$

$$= \varepsilon_{ij3}\lim_{\Delta\to 0}\underbrace{\int d^3\bar{x}\ x^i\,e^{-i\bar{x}.\bar{\Delta}}}_{\left[i\frac{\partial}{\partial\Delta^i}(2\pi)^3\delta^3(\bar{\Delta})\right]}\langle P+\tfrac{\Delta}{2},+\tfrac{1}{2}|\,T^{0j}(0)\,|P-\tfrac{\Delta}{2},+\tfrac{1}{2}\rangle$$

$$= \varepsilon_{ij3}\lim_{\Delta\to 0}(2\pi)^3\delta^3(\bar{\Delta})\left(-i\frac{\partial}{\partial\Delta^i}\right)\Big\{\left[A(t)+B(t)\right]\bar{N}\,P^{(0}\,i\sigma^{j)\alpha}\frac{\Delta_\alpha}{2M}N$$

$+$ TERMS INDEPENDENT OF Δ

$+$ TERMS QUADRATIC IN $\Delta\Big\}$

$$= \varepsilon_{ij3}\,(2\pi)^3\,\delta^3(0)\,\left[A(0)+B(0)\right]\cdot\frac{1}{2M}$$

$$\cdot\ \bar{N}(\underline{P},+\tfrac{1}{2})\,(-\tfrac{1}{2})\left\{\underset{\underset{M}{\parallel}}{P^0}\,\sigma^{ji}+\underset{\underset{0}{\parallel}}{P^j}\,\sigma^{0i}\right\}N(\underline{P},+\tfrac{1}{2})$$

IN N REST FRAME

$$= (2\pi)^3\,\delta^3(0)\,\left[A(0)+B(0)\right]\cdot\frac{1}{2M}\cdot M\ \underbrace{\bar{N}(\underline{P},+\tfrac{1}{2})\,\underset{\underset{\Sigma^3}{\parallel}}{\sigma^{12}}\,N(\underline{P},+\tfrac{1}{2})}_{2M}$$

$$\therefore\ \langle \underline{P},+\tfrac{1}{2}\,|\,\hat{J}^{12}\,|\,\underline{P},+\tfrac{1}{2}\rangle = J\,\langle \underline{P}\,|\,\underline{P}\rangle$$

$$= \frac{1}{2}\left[A(0)+B(0)\right]$$

$$\boxed{J = \frac{1}{2}\left[A(0)+B(0)\right]}$$

* TOTAL SYSTEM : ANGULAR MOMENTUM CONSERVATION

$J=\frac{1}{2}$

$$A(0)+B(0)=1$$

$$B(0)=0$$

NO ANOMALOUS GRAVITO-MAGNETIC MOMENT !

* PHYSICAL INTERPRETATION IN QUARK & GLUON SPIN CONTRIBUTIONS (X. Ji)

$$\boxed{J_{q,g} = \frac{1}{2}\left[A_{q,g}(0)+B_{q,g}(0)\right]}\qquad J_q+J_g=\frac{1}{2}$$

$\Rightarrow$ FORM FACTORS OF $T_q^{\mu\nu}$ IN TERMS OF GPDs

- $$\langle P+\tfrac{\Delta}{2} | T_q^{\mu\nu}(0) | P-\tfrac{\Delta}{2} \rangle n_\mu n_\nu$$

$$= \langle P+\tfrac{\Delta}{2} | \bar{q}\, i\gamma^{(\mu} \overleftrightarrow{D}^{\nu)} q(0) | P-\tfrac{\Delta}{2} \rangle n_\mu n_\nu$$

$$= \bar{N}(P+\tfrac{\Delta}{2}) \Big\{ \frac{1}{M} \Big[A(t) + 4\xi^2 C(t) \Big] + \Big[A(t) + B(t) \Big] i\sigma^{\nu\alpha} \frac{\Delta_\alpha}{2M} n_\nu \Big\} N(P-\tfrac{\Delta}{2})$$

- $$\frac{P^+}{2\pi} \int dy^- \, e^{ixP^+y^-} \langle P+\tfrac{\Delta}{2} | \bar{q}(-\tfrac{y}{2})\, i\not{n}\, n.\overleftrightarrow{D}\, q(\tfrac{y}{2}) | P-\tfrac{\Delta}{2} \rangle \quad \begin{matrix} y^+=0 \\ \bar{y}_\perp = 0 \end{matrix}$$

$$-i\overleftrightarrow{D}.n = x\, P.n = x$$

$$= x \frac{P^+}{2\pi} \int dy^- \, e^{ixP^+y^-} \langle P+\tfrac{\Delta}{2} | \bar{q}(-\tfrac{y}{2})\, \not{n}\, q(\tfrac{y}{2}) | P-\tfrac{\Delta}{2} \rangle \quad \begin{matrix} y^+=0 \\ \bar{y}_\perp = 0 \end{matrix}$$

$$= \bar{N}(P+\tfrac{\Delta}{2}) \Big\{ \frac{1}{M} x\, H(x,\xi,t) + x \Big[H(x,\xi,t) + E(x,\xi,t) \Big] i\sigma^{\nu\alpha} \frac{\Delta_\alpha}{2M} n_\nu \Big\} N(P-\tfrac{\Delta}{2})$$

- $$\int_{-1}^{1} dx \, \frac{P^+}{2\pi} \int dy^- \, e^{ixP^+y^-} \ldots$$

$$= \int dy^- \, \delta(y^-) \ldots$$

$$\int_{-1}^{1} dx \; x \; H(x,\xi,t) = A(t) + 4\xi^2 C(t)$$

$$\int_{-1}^{1} dx \; x \; E(x,\xi,t) = B(t) - 4\xi^2 C(t)$$

$$\int_{-1}^{1} dx \; x \left[H(x,\xi,t) + E(x,\xi,t) \right] = A(t) + B(t)$$

$\Uparrow$ 'MEASURABLE' IN HARD EXCLUSIVE PROCESSES

$\Uparrow$ FORM FACTORS OF ENERGY-MOMENTUM TENSOR

$(X.J_i)$

$$\boxed{J_q = \frac{1}{2}\left[A_q(0) + B_q(0)\right] = \frac{1}{2}\int_{-1}^{1} dx \; x \left[H_q(x,\xi,0) + E_q(x,\xi,0)\right]}$$

ANALOGOUS FOR GLUONS

- INTERPRETATION $(X.J_i)$

$$\boxed{\frac{1}{2} = J_q + J_g = \frac{1}{2}\Delta\Sigma + L_q + J_g}$$

$$\rightarrow \vec{J}_q = \int d^3\bar{x} \left[\psi^+ \underbrace{\frac{\Sigma}{2}}_{\Delta\Sigma/2} \psi + \underbrace{\psi^+ \bar{x} \times (-i\vec{D})\psi}_{L_q} \right]$$

GAUGE INV.

$$\rightarrow \vec{J}_g = \int d^3\bar{x} \; \bar{x} \times (\vec{E} \times \vec{B})$$

Where does main part of nucleon spin come from ?

QUARK GLUON

$$\frac{1}{2} = J_q + J_g$$

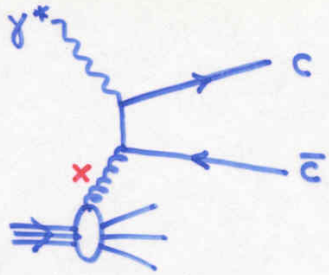
$$= \Delta\Sigma + L_q + \Delta G + L_g$$

QUARK SPIN — GLUON SPIN

QUARK ORBITAL — GLUON

$\Longrightarrow$ GLUON contribution

ΔG

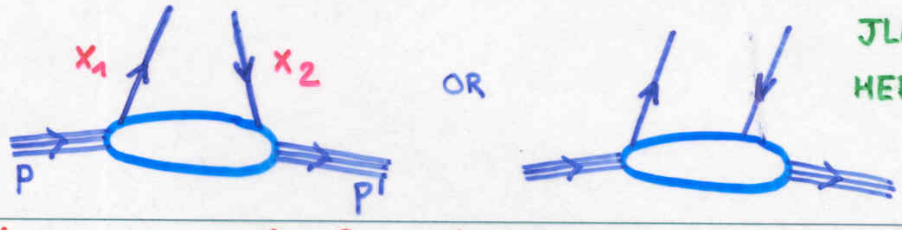


HERMES
COMPASS
SLAC
RHIC SPIN

$\Longrightarrow$ ORBITAL contribution

accessible through Generalized Parton Distributions (GPD)

L_q



JLAB
HERMES

GPDs : 'microsurgery' of nucleon at quark level

SEPARATED QUARK SPIN DISTRIBUTIONS

- **SEMI-INCLUSIVE DIS** (SMC, HERMES)

HERMES RESULTS AT $Q^2 = 2.5\ GeV^2$

$$\Delta u_v = 0.57 \pm 0.05 \pm 0.08$$

$$\Delta d_v = -0.22 \pm 0.11 \pm 0.13$$

$$\Delta \bar{u} = -0.01 \pm 0.02 \pm 0.03$$

$$\Downarrow$$

$$\Delta \Sigma \simeq 0.3$$

GPD E^q & QUARK SPIN CONTRIBUTION

- GENERAL $\quad E^q(x, \xi=0, t=0) \equiv e^q(x)$

→ NORMALIZATION

$$\int_{-1}^{1} dx \; e^q(x) = K^q \quad \begin{cases} K^u = 2K^p + K^n = 1.673 \\ K^d = K^p + 2K^n = -2.033 \end{cases}$$

→ TOTAL SPIN OF NUCLEON CARRIED BY QUARKS

$$J^q = \frac{1}{2} \int_{-1}^{1} dx \; x \left\{ H^q(x,0,0) + E^q(x,0,0) \right\}$$

$$\Big\downarrow \quad \Big\| \; M_2^q \equiv \int_0^1 dx \; x \left[q(x) + \bar{q}(x) \right]$$

$$\boxed{J^q = \frac{1}{2} M_2^q + \frac{1}{2} \int_{-1}^{1} dx \; x \; e^q(x)}$$

- VALENCE MODEL

$e^u(x) = \frac{1}{2} u_v(x) \, K^u$	$e^d(x) = d_v(x) \, K^d$	$e^s(x) = 0$

$\Downarrow$

$$\Big\| \quad J^u = \frac{1}{2}\left(M_2^u + \frac{1}{2} K^u M_2^{u_v} \right) \qquad \Big\| \; M_2^{q_v} \equiv \int_0^1 dx \; x \; q_v(x)$$

$$J^d = \frac{1}{2}\left(M_2^d + K^d M_2^{d_v} \right)$$

$$J^s = \frac{1}{2} M_2^s$$

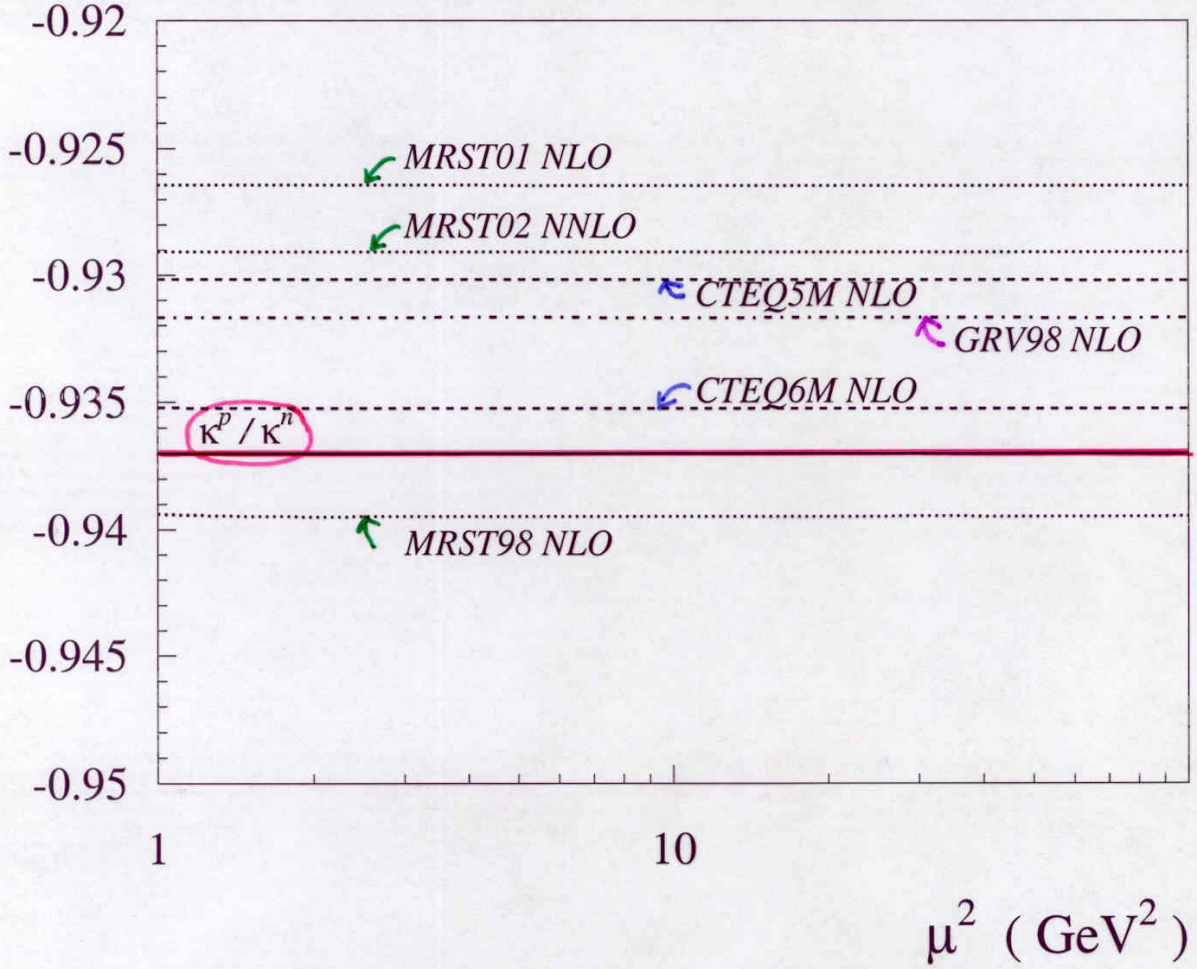
OBSERVATION : $\frac{1}{2} K^u M_2^{u_v} \approx - K^d M_2^{d_v}$

$$K^u \int_0^1 dx\, x\, u_{val}(x) \approx -2\, K^d \int_0^1 dx\, x\, d_{val}(x)$$

$$\Downarrow$$

$$\boxed{\frac{K^p}{K^n} \approx -\frac{1}{2}\, \frac{4 M_2^{d_{val}} + M_2^{u_{val}}}{M_2^{d_{val}} + M_2^{u_{val}}}}$$

GOEKE, POLYAKOV, VDH (2001)



! VERIFIED TO 1% LEVEL !

SPIN OF NUCLEON

VALENCE MODEL FOR $e^q(x)$

- J^q @ $\mu^2 = 1\ \mathrm{GeV}^2$ (MRST 98 FORWARD QUARK DISTR)

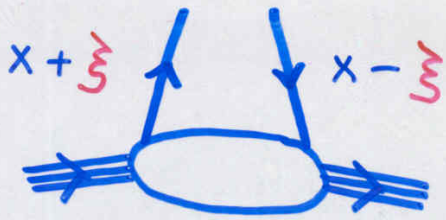
	$M_2^{q\,val}$	M_2^q	$2J^q$	LATTICE QCDSF 2003
u	0.34	0.40	0.69	0.74 ± 0.12
d	0.14	0.22	−0.07	−0.08 ± 0.08
s	0	0.03	0.03	
u + d + s	0.49	0.65	0.65	0.66 ± 0.14

$$\therefore \sum_q 2J^q \approx \sum_q M_2^q$$

- $\boxed{J^q = \frac{1}{2}\Delta q + L^q}$ @ $\mu^2 = 2.5\ \mathrm{GeV}^2$

	$2J^q$	Δq (HERMES)	$2L^q$
u	0.61	0.57 ± 0.04	0.04 ∓ 0.04
d	−0.05	−0.25 ± 0.08	0.20 ∓ 0.08
s	0.04	−0.01 ± 0.05	0.05 ∓ 0.05
u + d + s	0.60	0.30 ± 0.10	0.30 ∓ 0.10
		EXP.	VALENCE MODEL

PHYSICS CONTAINED IN ξ - DEPENDENCE



- POLYNOMIAL CONDITION (X. Ji)

↳ CONSEQUENCE OF LORENTZ INVARIANCE

x^N MOMENT OF GPD

e.g. $N = 1$

$$\int_{-1}^{1} dx \; x \; H^q(x, \xi, t) = A(t) + (2\xi)^2 \, C(t)$$

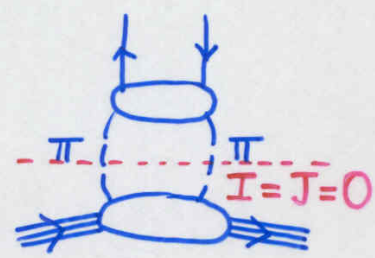
$$\int_{-1}^{1} dx \; x \; E^q(x, \xi, t) = B(t) - (2\xi)^2 \, C(t)$$

DOUBLE DISTRIBUTION

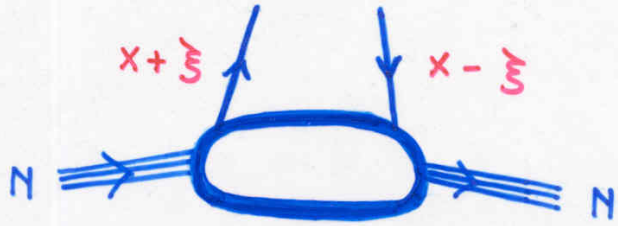
'D - TERM' (POLYAKOV, WEISS)

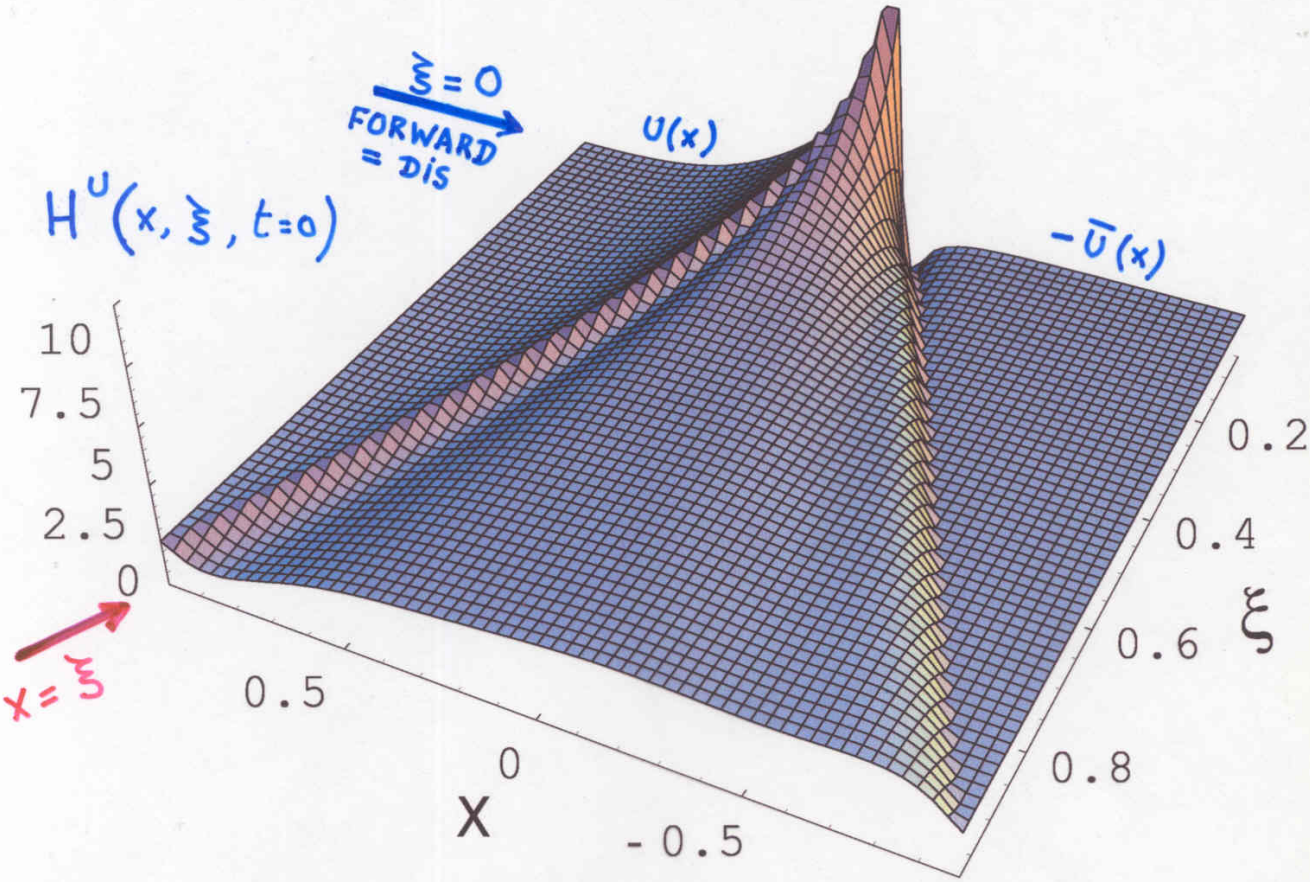
TOTAL ANGULAR MOMENTUM

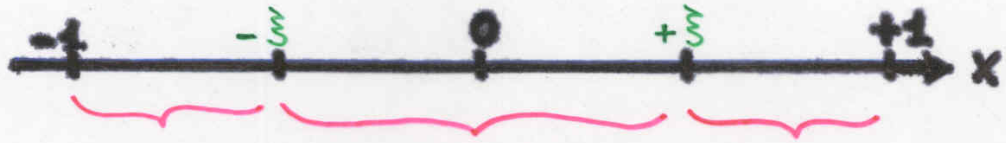
$$J_q = \frac{1}{2} \left\{ A(0) + B(0) \right\}$$



GENERALIZED PARTON DISTRIBUTION



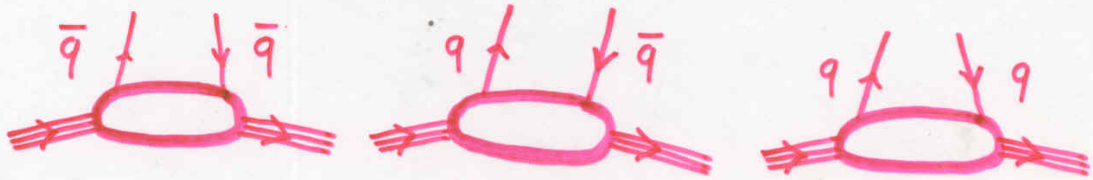




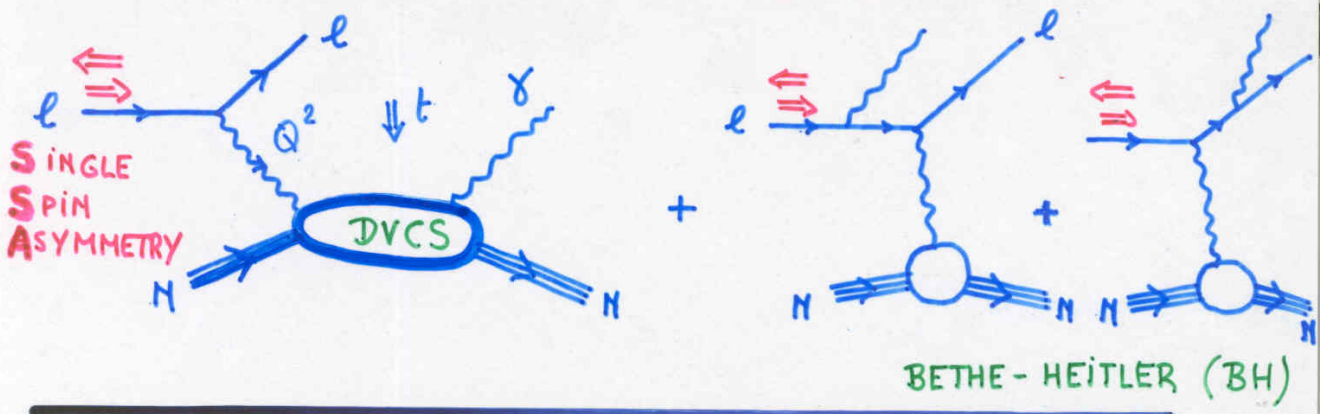
$\bar{q}$ DISTRIBUTION FUNCTION

$q\bar{q}$ DISTRIBUTION AMPLITUDE

q DISTRIBUTION FUNCTION



DVCS SSA @ HERMES and CLAS

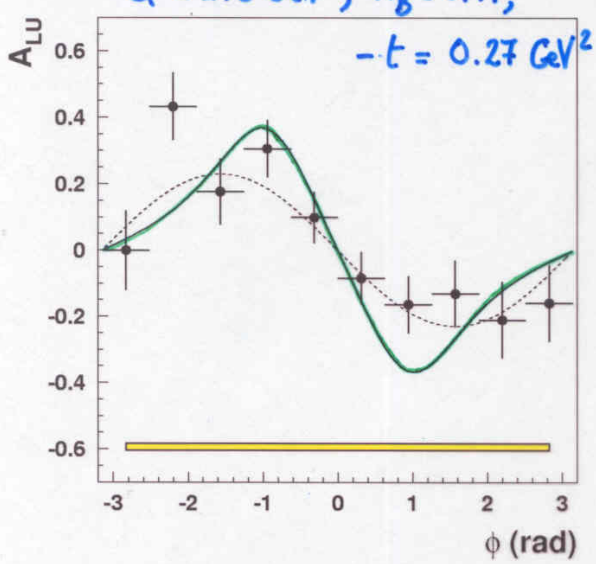


$$\sigma_{\Rightarrow} - \sigma_{\Leftarrow} \sim (\mathrm{BH}) \cdot \mathrm{Im}(\mathrm{DVCS}) \cdot \sin\phi$$

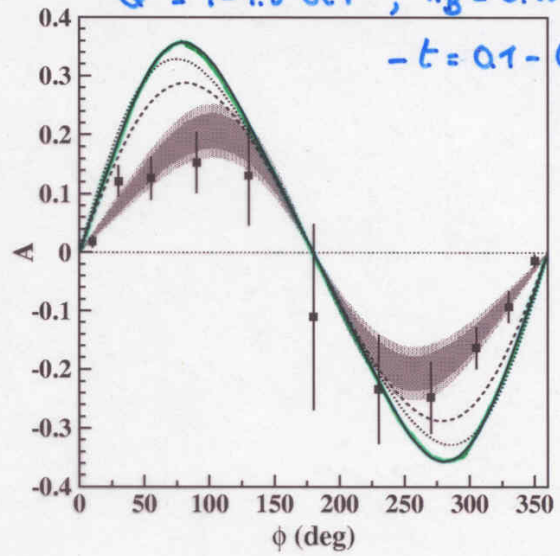
↳ ANGLE BETWEEN 2 PLANES

HERMES (2001) **JLAB/CLAS**

$Q^2 = 2.6\ \mathrm{GeV}^2$, $x_B = 0.11$, $-t = 0.27\ \mathrm{GeV}^2$



$Q^2 = 1 - 1.5\ \mathrm{GeV}^2$, $x_B = 0.15 - 0.25$, $-t = 0.1 - 0.25\ \mathrm{GeV}^2$



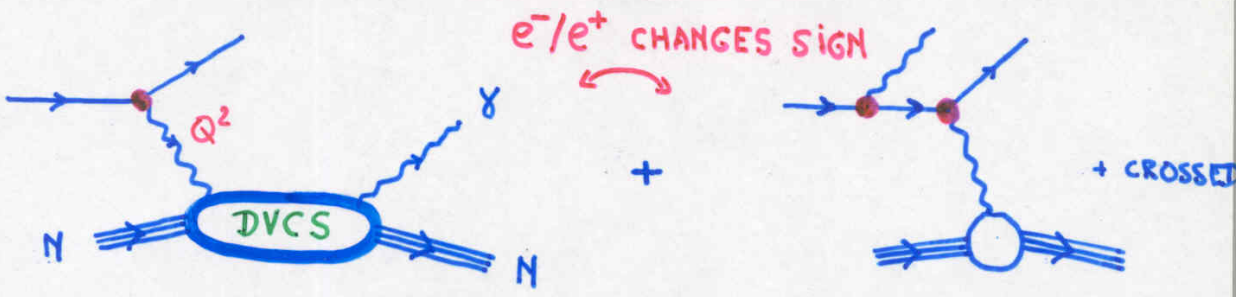
—— DVCS TWIST-2 + TWIST-3 CALCULATION

KIVEL, POLYAKOV, VDH (2000)

DVCS SSA : measures GPD(x, ξ, t) at $x = \xi$

$$\xi = \frac{x_B/2}{1 - x_B/2}$$

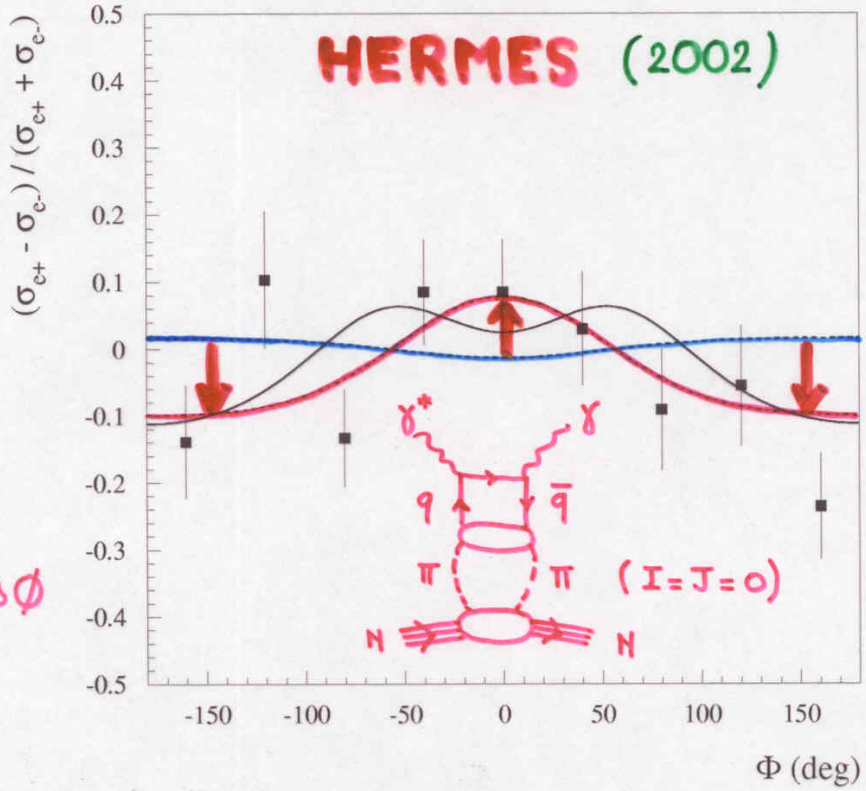
Signature of $q\bar{q}$ correlations in DVCS beam-charge asymmetry



$\Longrightarrow$ Accesses REAL PART of DVCS amplitude

$$e^-/e^+ + p \rightarrow e^-/e^+ + p + \gamma$$

$E_e = 27\ GeV,\ Q^2 = 2.5\ GeV^2,\ x_B = 0.11,\ t = -0.25\ GeV^2$



TWIST-2

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

$\sim P_1 + P_2 \cos\phi$

NO $q\bar{q}$ CORREL.

+ $q\bar{q}$ CORREL.

+ TWIST 3

CALCULATIONS

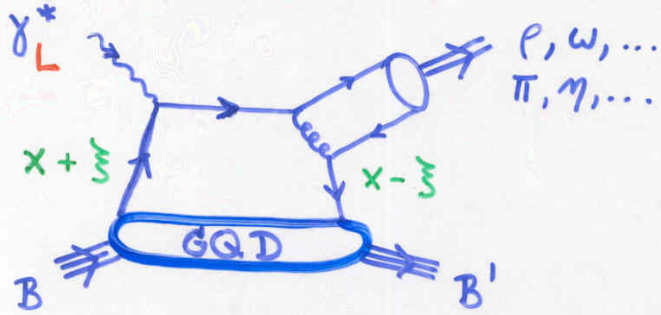
KIVEL, POLYAKOV, VDH (2000)

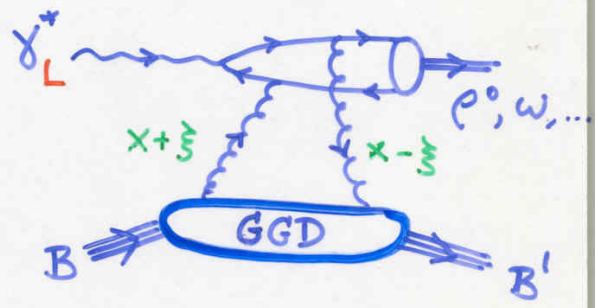
Accesses $q\bar{q}$ content of mesonic correlations in nucleon

HARD ELECTROPRODUCTION OF MESONS ($\pi, \rho, \omega, \ldots$)

- **QCD FACTORIZATION PROOF**

COLLINS, FRANKFURT, STRIKMAN (1997); RADYUSHKIN (1997)

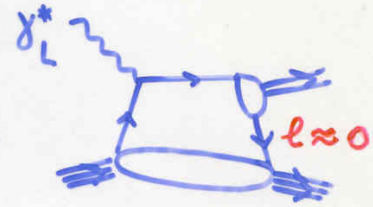




$$\Rightarrow \mathcal{M}_{\gamma_L^* B \to M B'} \sim \frac{1}{Q} \quad \Rightarrow \quad \frac{d\sigma}{dt} \sim \frac{1}{Q^6}$$

$\Rightarrow$ FOR γ_L^* : LEADING ORDER

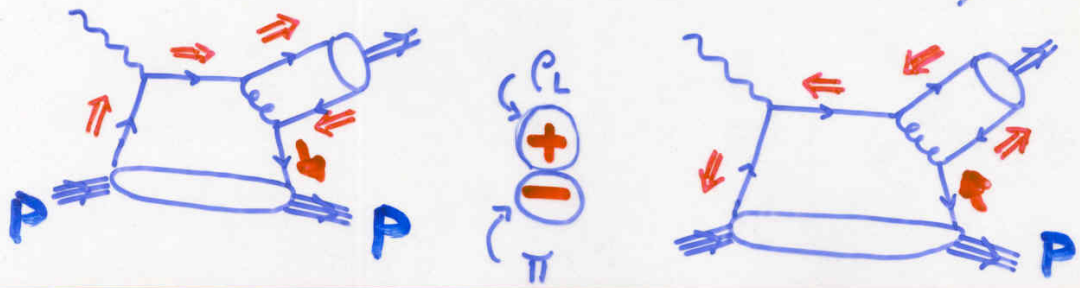
e.g. SOFT OVERLAP SUPPRESSED



- **MESON : HELICITY FILTER**

$$|\rho_L\rangle = \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle \right)$$

$$|\pi\rangle = \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$



V : $\rho, \omega, \ldots$	$\Rightarrow$ 'UNPOLARIZED' GPDs	H, E
PS : $\pi, \eta, \ldots$	$\Rightarrow$ 'POLARIZED' GPDs	$\tilde{H}, \tilde{E}$

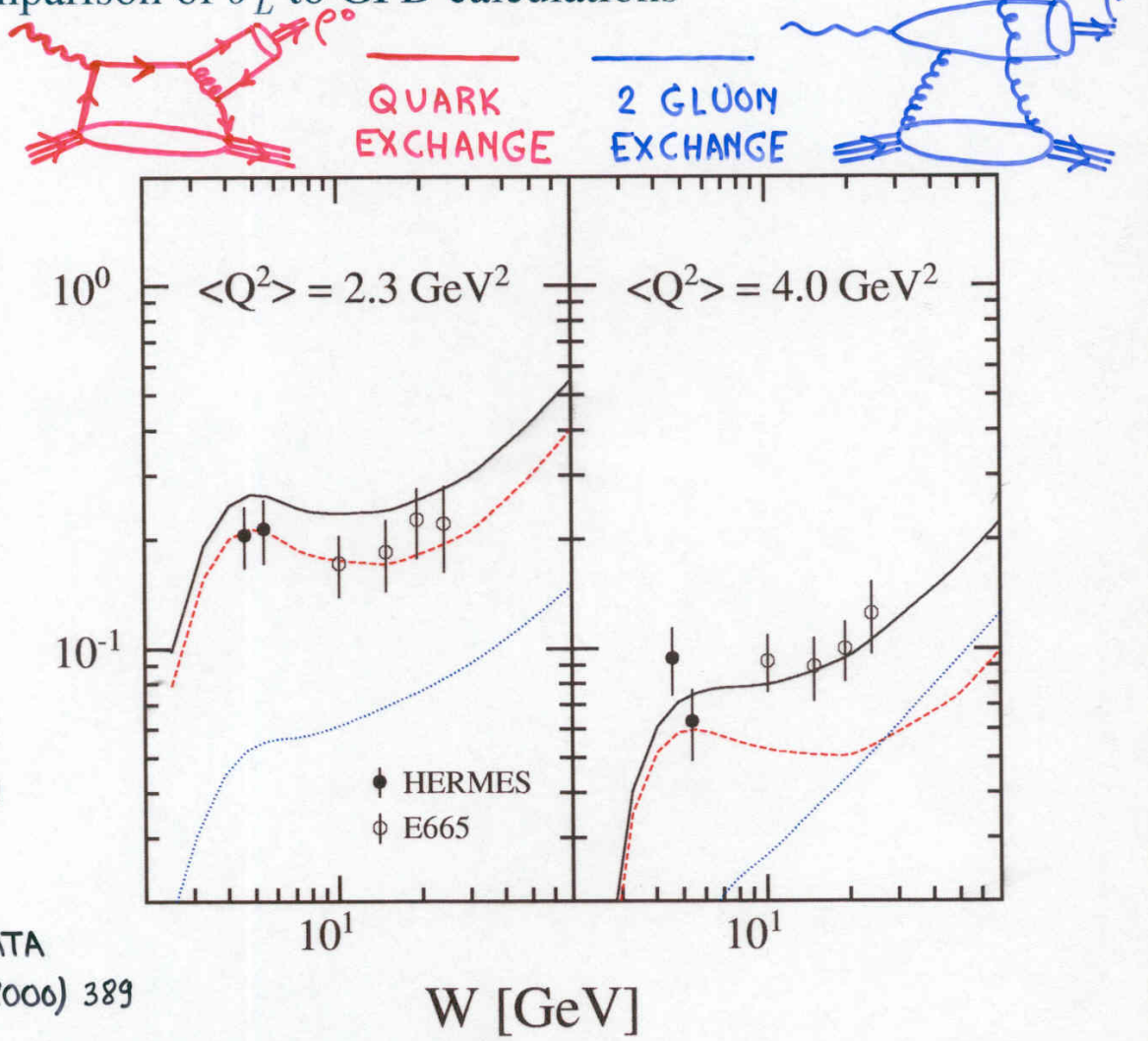
Quark exchange in ρ^0_L electroproduction

- Evaluate longitudinal cross section

$$\sigma_L = \frac{R}{1 + \varepsilon R} \sigma_{tot}$$

Take $R = \sigma_L / \sigma_T$ from ρ^0 decay angular distribution

- Comparison of σ_L to GPD calculations



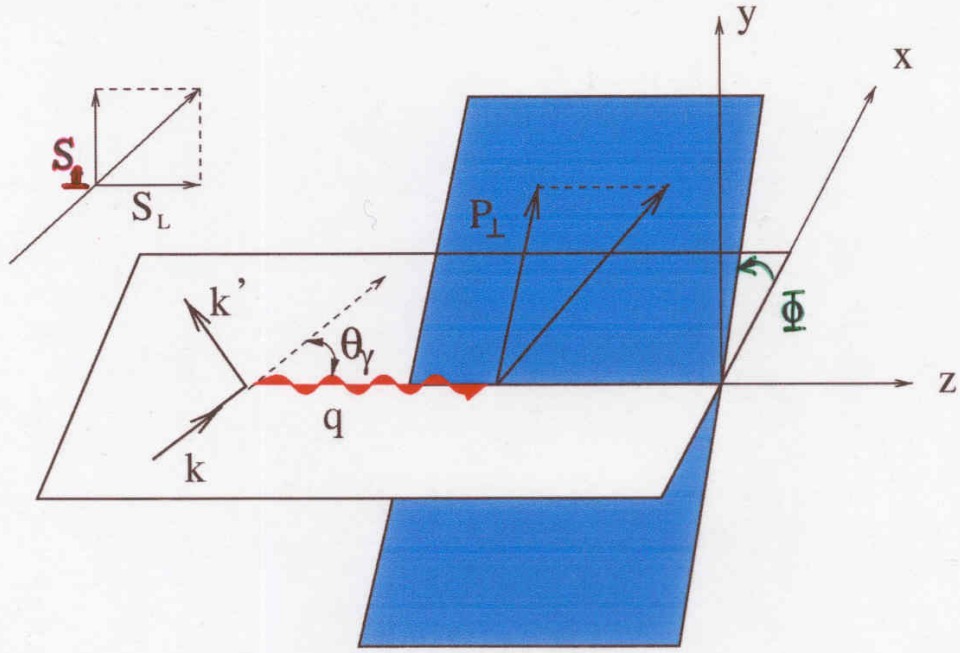
HERMES DATA
EPJC 17 (2000) 389

- Quark exchange dominates in the region W ≈ 4 - 10 GeV (valence region)

(CALCULATIONS => M. VDH, P. GUICHON, M. GUIDAL
PRD 60 (1999) 094017)

Transverse spin asymmetry in hard meson electroproduction

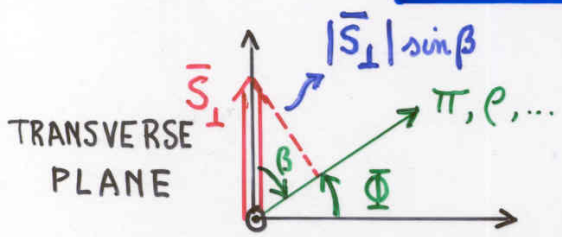
ASYMMETRY for a TRANSVERSELY polarized target



in LEADING ORDER (in Q) $\Rightarrow$ 2 OBSERVABLES

$$\sigma = \sigma_L + P_n \, \sigma_L^n$$

$$P_n = |\vec{S}_\perp| \sin\beta$$



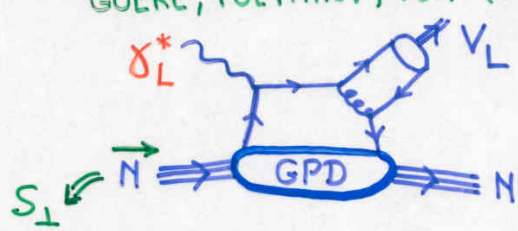
$(\beta = 90 - \Phi)$

$$\mathcal{A} = \frac{1}{|S_\perp|} \frac{\int_0^\pi d\beta\, \sigma(\beta) - \int_\pi^{2\pi} d\beta\, \sigma(\beta)}{\int_0^{2\pi} d\beta\, \sigma(\beta)} = \frac{2\,\sigma_L^n}{\pi\,\sigma_L}$$

Transverse spin asymmetry in longitudinal vector meson electroproduction

$$\mathcal{A}_{V_L N} = -\frac{2|\Delta_\perp|}{\pi} \times \frac{\mathrm{Im}(AB^*)\,/\,m_N}{|A|^2(1-\xi^2) - |B|^2\,(\xi^2 + t/(4m_N^2)) - \mathrm{Re}(AB^*)\,2\,\xi^2}$$

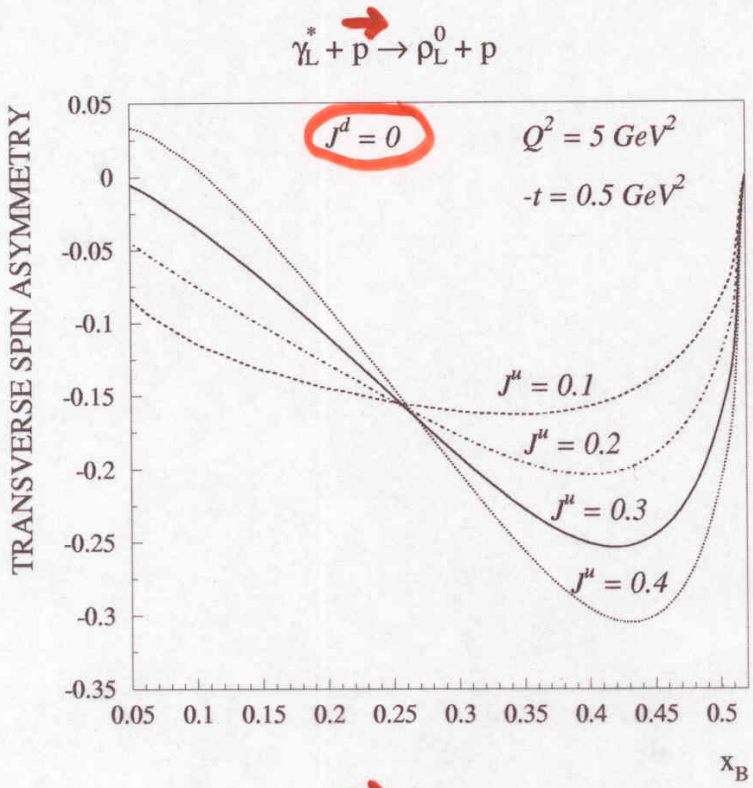
GOEKE, POLYAKOV, VDH (2001)



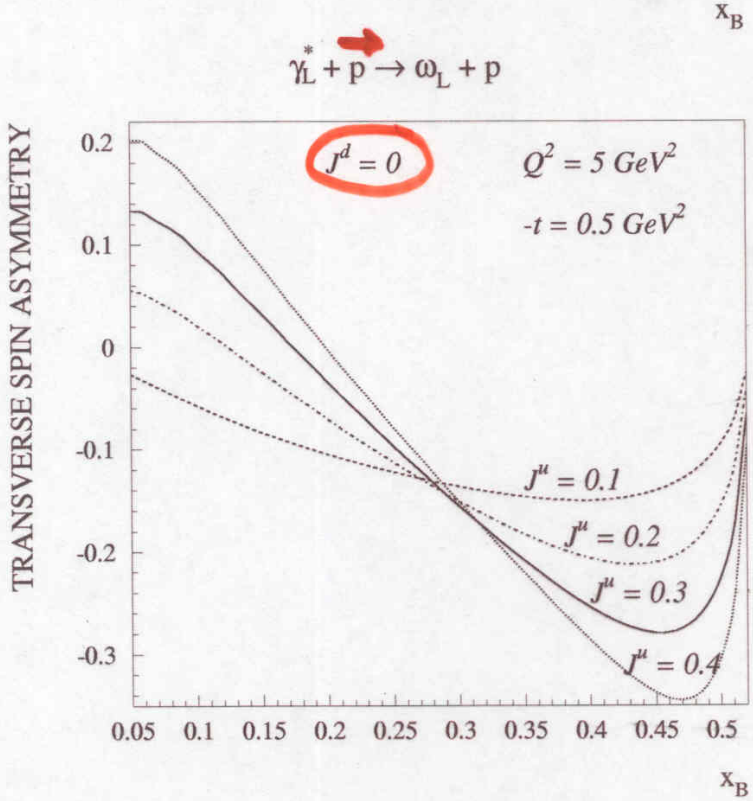
- $A \Rightarrow$ GPD H
- $B \Rightarrow$ GPD E
- LINEAR dependence on the GPD E
  $\leftrightarrow$ unpolarized cross sections
- Ratio $\Rightarrow$ LESS sensitive to NLO and higher twist effects
- sensitivity to J^u, J^d

$\mathcal{A}_{V_L N} \Rightarrow$ "measure" of the TOTAL quark angular momentum contributions to the proton spin !

Transverse spin asymmetry in ρ_L^0 and ω_L production



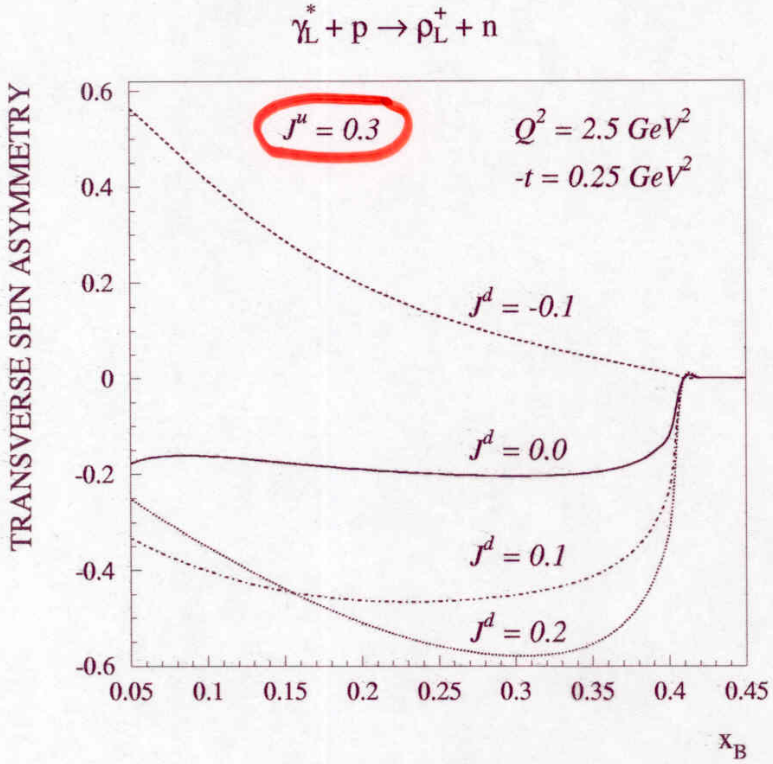
ρ_L SENSITIVE TO $(2J^u + J^d)$



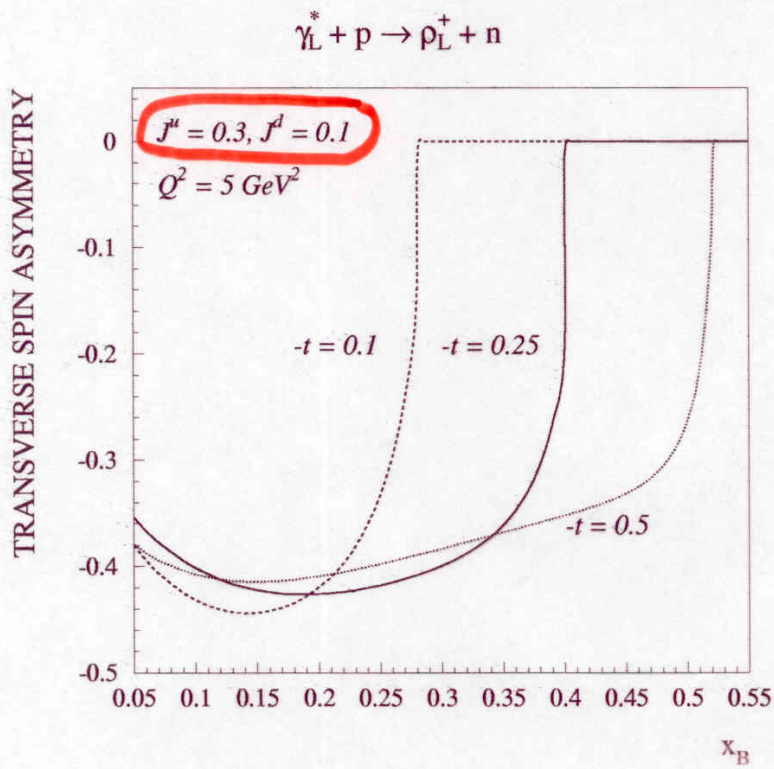
ω_L SENSITIVE TO $(2J^u - J^d)$

(GOEKE, POLYAKOV, VDH (2001))

Transverse spin asymmetry in ρ_L^+ production



ρ_L^+ SENSITIVE TO $(J^u - J^d)$!



⇐ t - DEPENDENCE OF ASYMMETRY

GOEKE, POLYAKOV, VDH (2001)