Physics Program at the ENC

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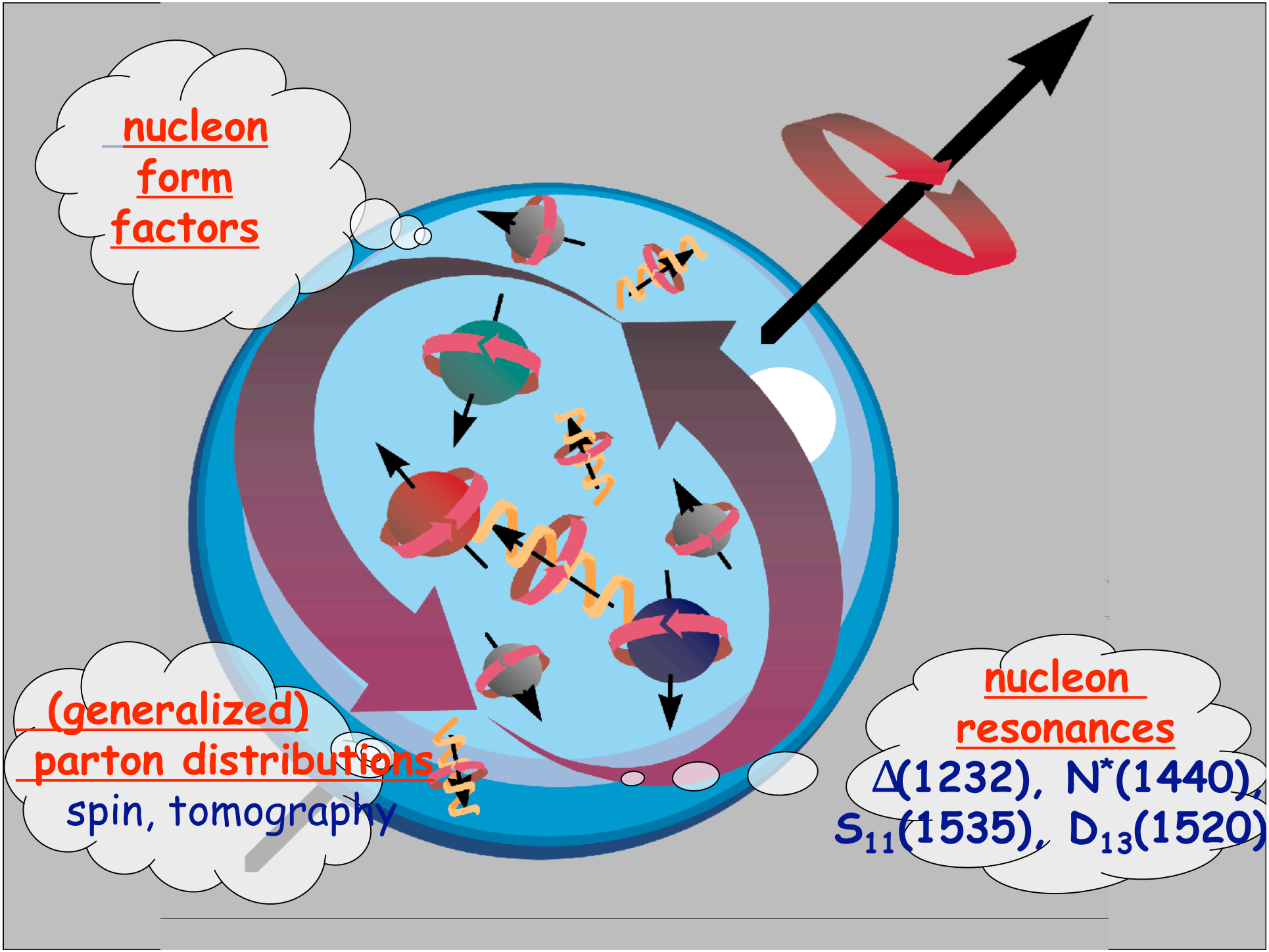
Johannes Gutenberg Universität, Mainz

Common ENC/EIC Workshop at GSI

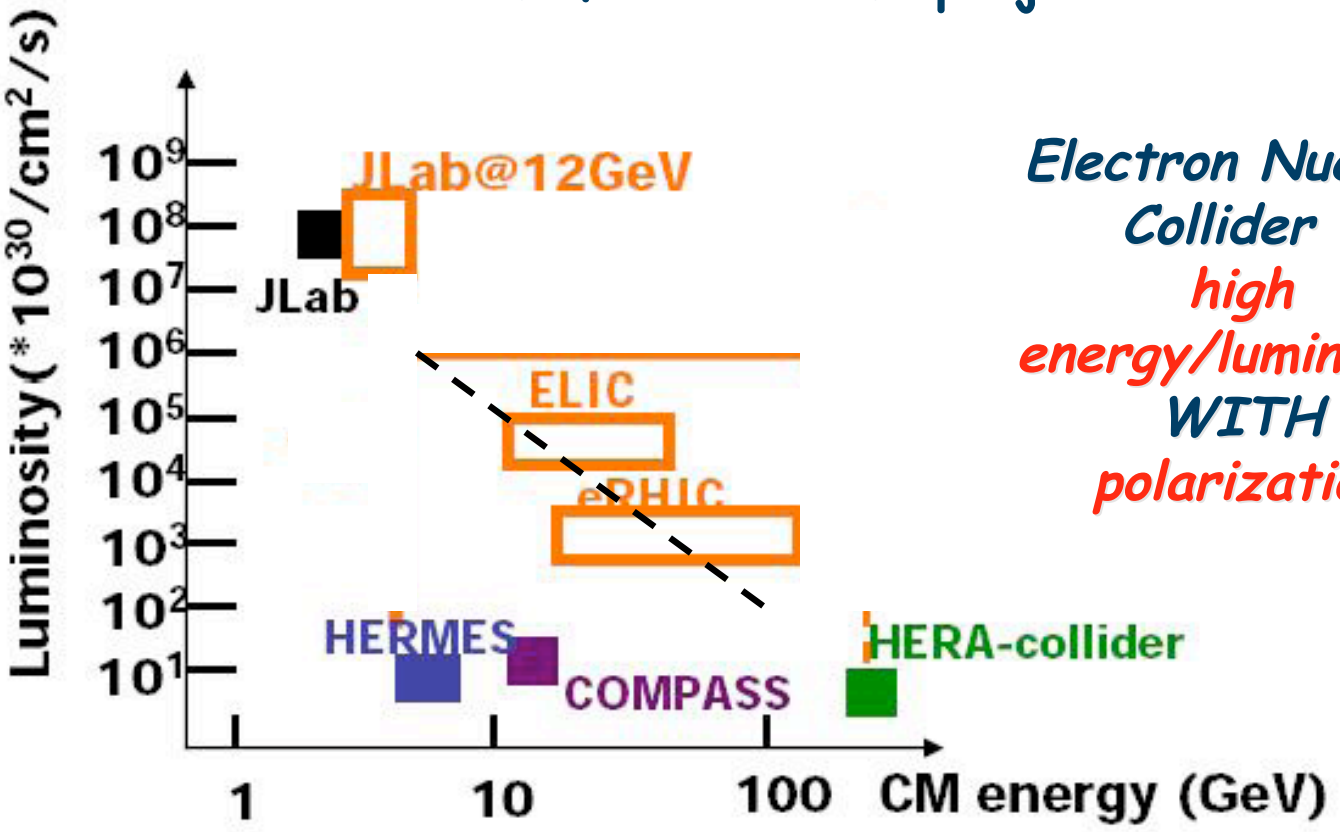
Darmstadt, May 28-30, 2009


nucleon
form
factors
(generalized)
parton distributions
spin, tomography
nucleon
resonances
Δ(1232), N*(1440),
S11(1535), D13(1520)

Energy / Luminosity landscape

Hadron structure investigations with electromagnetic probes :

Present facilities and projects



Electron Nucleon Collider : high energy/luminosity WITH polarization

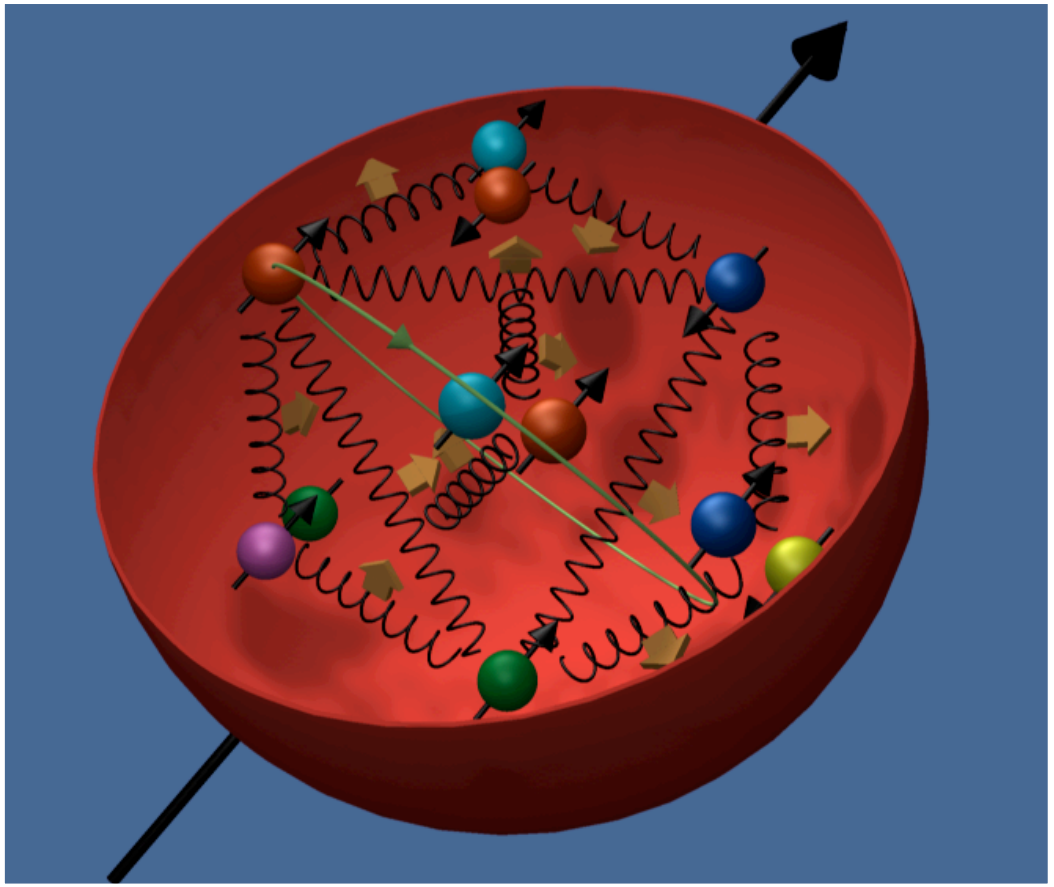
Understanding QCD origin of the nucleon spin

Quark spins Gluon spins

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

Orbital angular momenta

$\Delta\Sigma \neq 1$



EMC : (1988)

$\Delta\Sigma = 0{,}12 \pm 0{,}09 \pm 0{,}14$

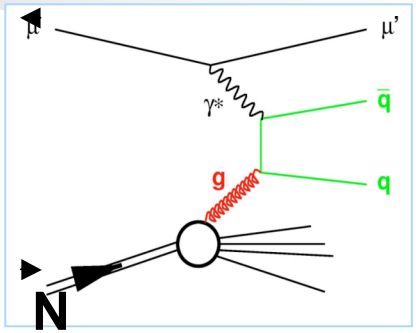
HERMES (2007) : $\Delta\Sigma = 0{,}330 \pm 0{,}025 \pm 0{,}011 \pm 0{,}028$

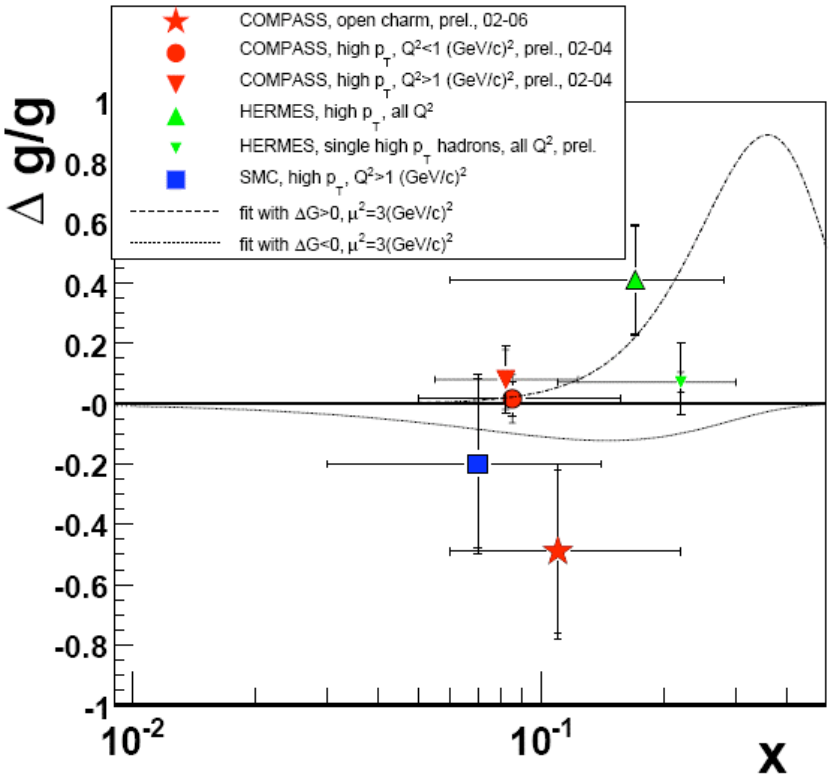
courtesy : K. Rith

COMPASS (2007) : $\Delta\Sigma = 0{,}33 \pm 0{,}03 \pm 0{,}05$

Gluon helicity contribution

Photon-gluon fusion

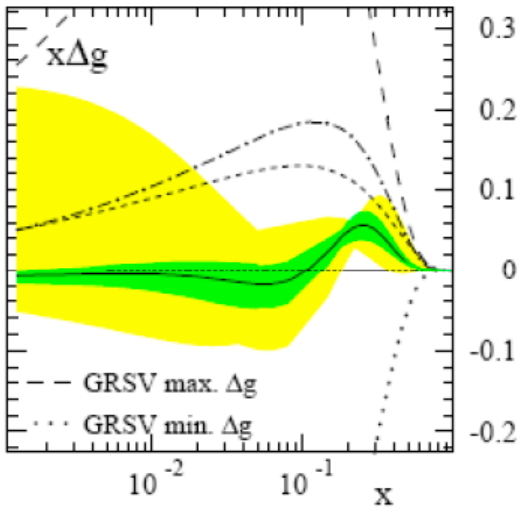




Hadrons with high p_T

Charm production

NLO analysis of helicity parton densities — De Florian et al. (2008)

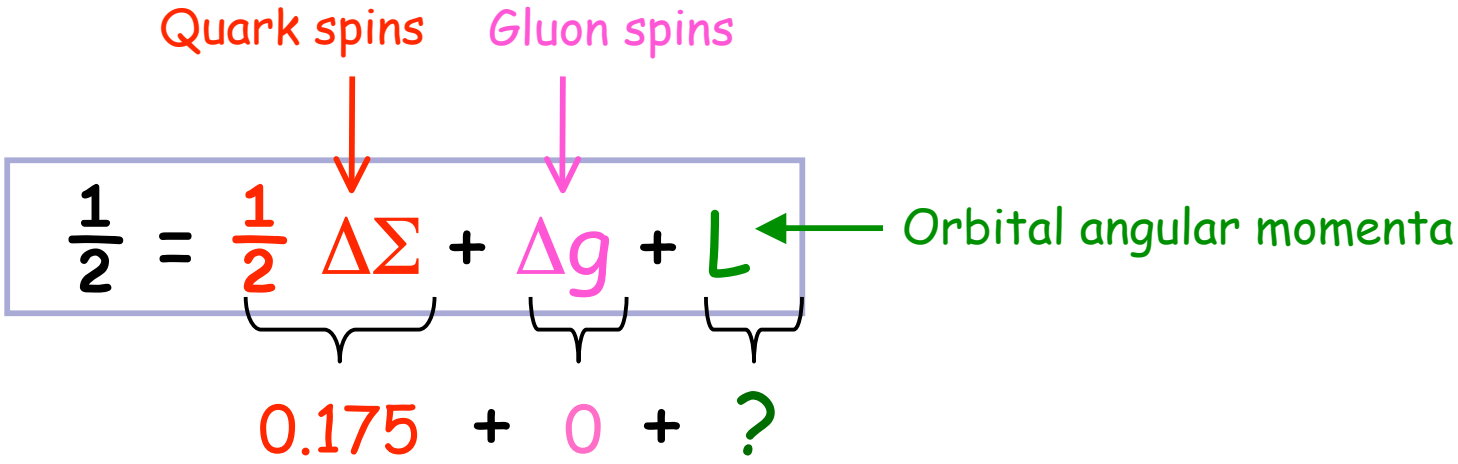


± 1σ

$\Delta g = -0.1 \pm 0.1$

Gluon helicity contribution is small

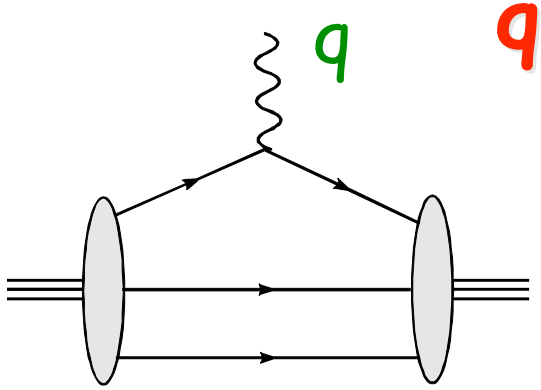
What have we learned from polarized DIS so far ?

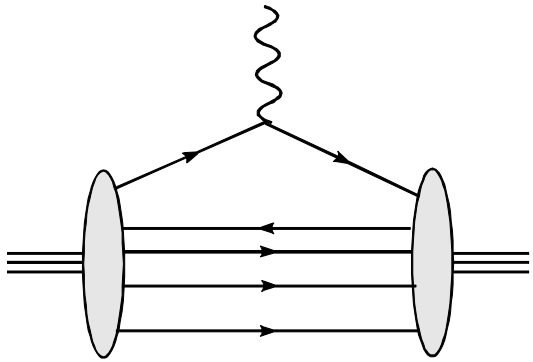


Origin of nucleon spin still unclear:

- where do the remaining ~65% come from ?
- how accurate do we know Δg ?
- what is the contribution of orbital angular momenta L ?

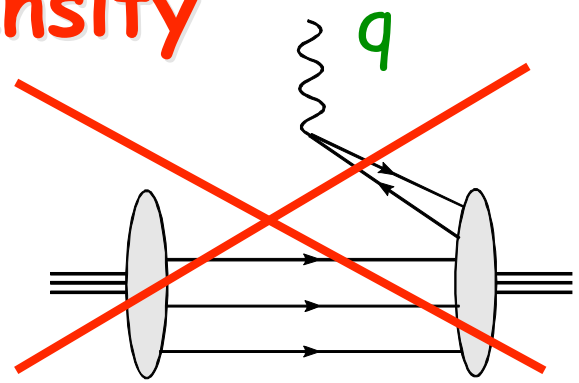
interpretation of Form Factor as quark density





overlap of wave function Fock components with same number of quarks

interpretation as probability/charge density



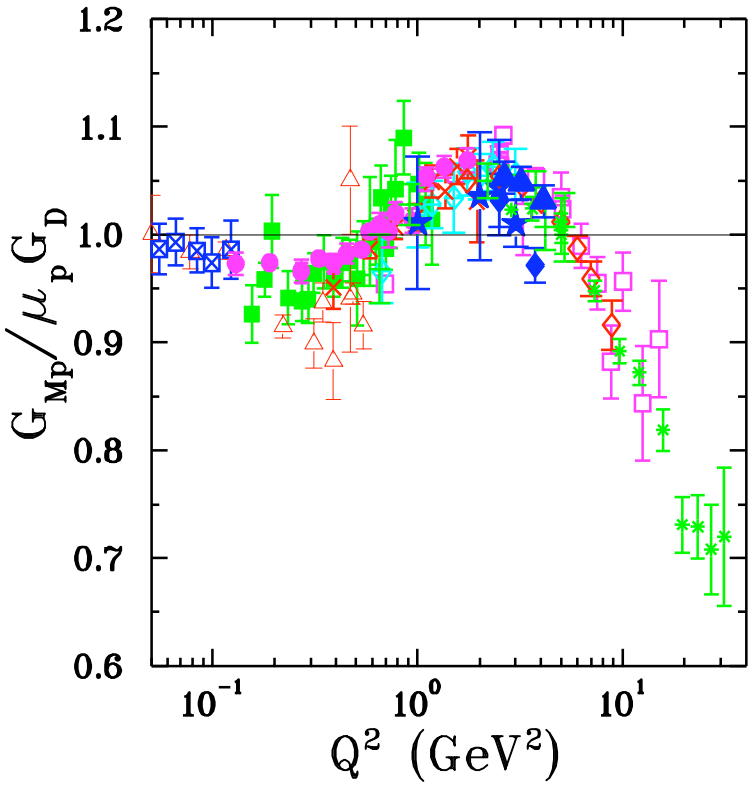
overlap of wave function Fock components with different number of constituents

NO probability/charge density interpretation

absent in a LIGHT-FRONT frame !

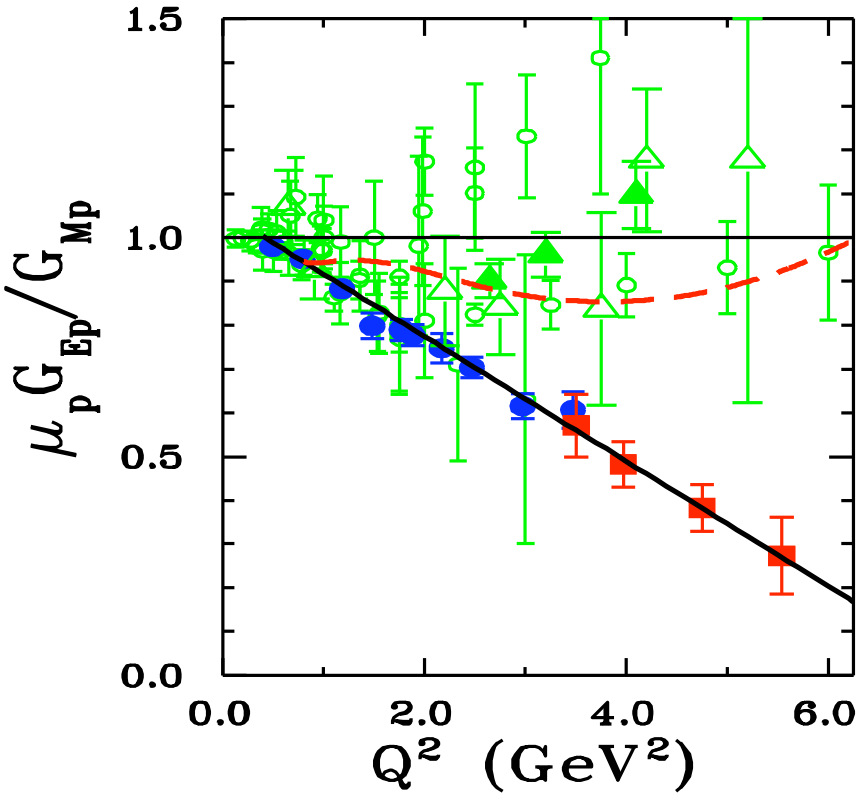
$$q^+ = q^0 + q^3 = 0$$

proton e.m. form factor : status



△ Han63 ◆ Bar73
■ Jan66 ⊠ Bor75
□ Cow68 ✳ Sil93
◆ Lit70 ◇ And94
● Pri71 ★ Wal94
× Ber71 + Chr04
☆ Han73 ▲ Qat05

new MAMI/A1 data up to $Q^2 \approx 0.7$ GeV^2



green : Rosenbluth data (SLAC, JLab)

● Pun05 ■ Gay02 } JLab/HallA recoil pol. data

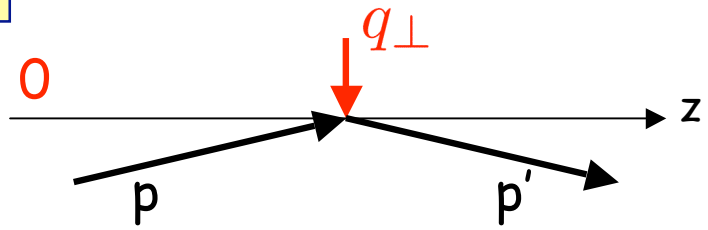
new JLab/HallC recoil pol. exp. (spring 2008) : extension up to $Q^2 \approx 8.5$ GeV^2

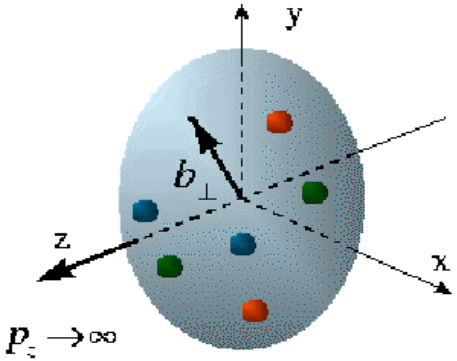
quark transverse charge densities in nucleon (I)

light-front

$q^+ = q^0 + q^3 = 0$

$Q^2 \equiv \vec{q}_\perp^{\,2}$

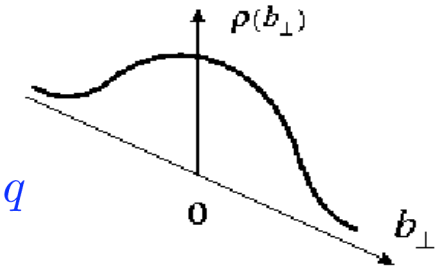




photon only couples to forward moving quarks

quark charge density operator

$$J^+ \equiv J^0 + J^3 = \bar{q}\gamma^+ q = 2\, q_+^\dagger\, q_+, \quad \text{with} \quad q_+ \equiv \frac{1}{4}\gamma^-\gamma^+\, q$$



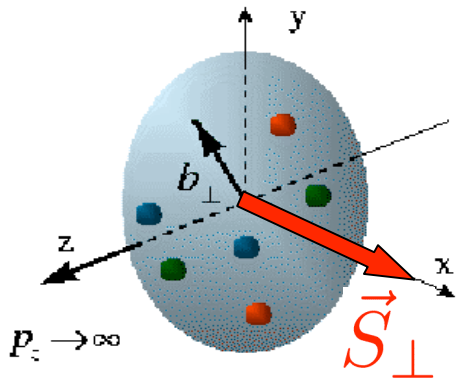
★ longitudinally polarized nucleon

$$\rho_0^N(\vec{b}) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2}\, e^{-i\,\vec{q}_\perp\cdot\vec{b}}\, \frac{1}{2P^+}\, \langle P^+, \frac{\vec{q}_\perp}{2}, \lambda \,|\, J^+(0) \,|\, P^+, -\frac{\vec{q}_\perp}{2}, \lambda\rangle$$

$$= \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(b\,Q) F_1(Q^2)$$

Miller (2007)

quark transverse charge densities in nucleon (II)

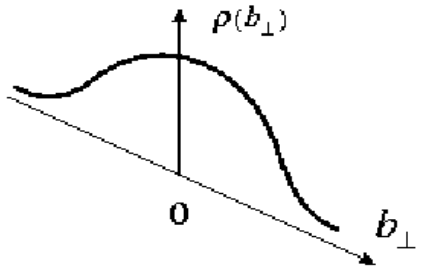


★ transversely polarized nucleon

transverse spin $\vec{S}_\perp = \cos\phi_S\,\hat{e}_x + \sin\phi_S\,\hat{e}_y$

e.g. along x-axis : $\phi_S = 0$

$\vec{b} = b\,(\cos\phi_b\,\hat{e}_x + \sin\phi_b\,\hat{e}_y)$



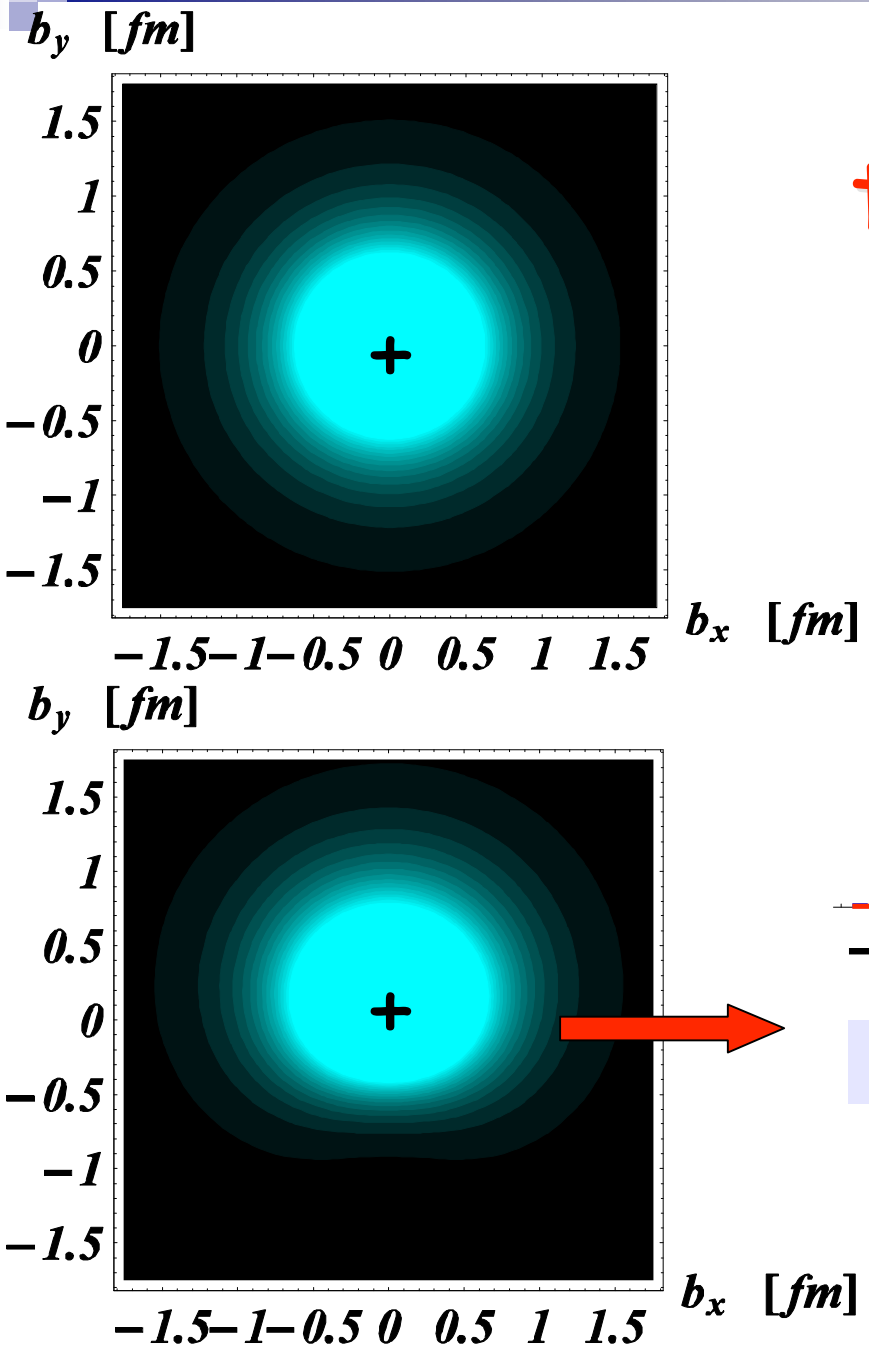
$$\rho_T^N(\vec{b}) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2}\, e^{-i\,\vec{q}_\perp\cdot\vec{b}}\, \frac{1}{2P^+}\, \langle P^+, \frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2}\,|\,J^+(0)\,|\,P^+, -\frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2}\rangle$$

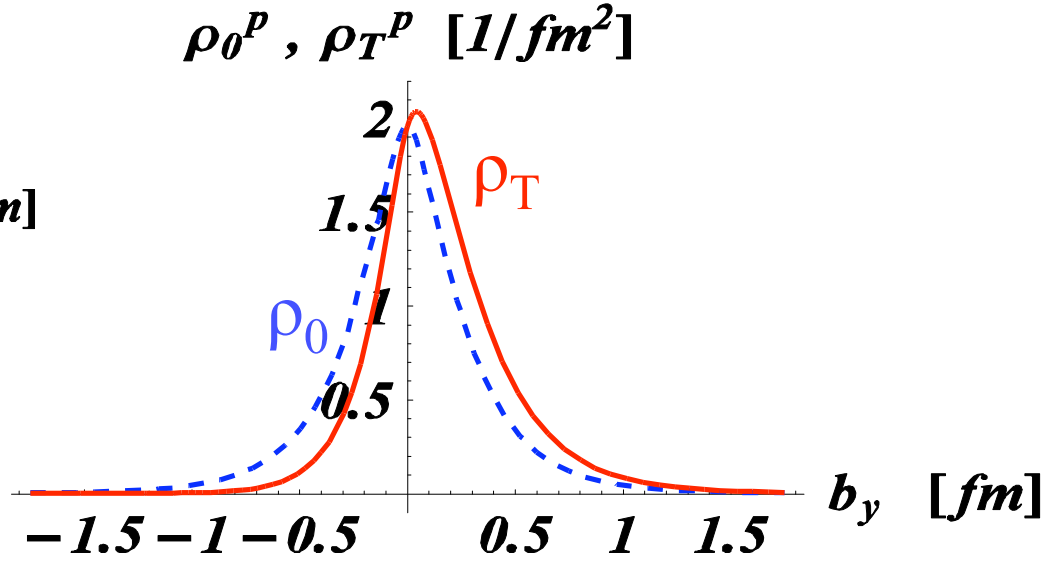
$$= \rho_0^N(b) + \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi}\, \frac{Q^2}{2M_N}\, J_1(b\,Q) F_2(Q^2)$$

dipole field pattern

Carlson, Vdh (2007)

empirical quark transverse densities in proton





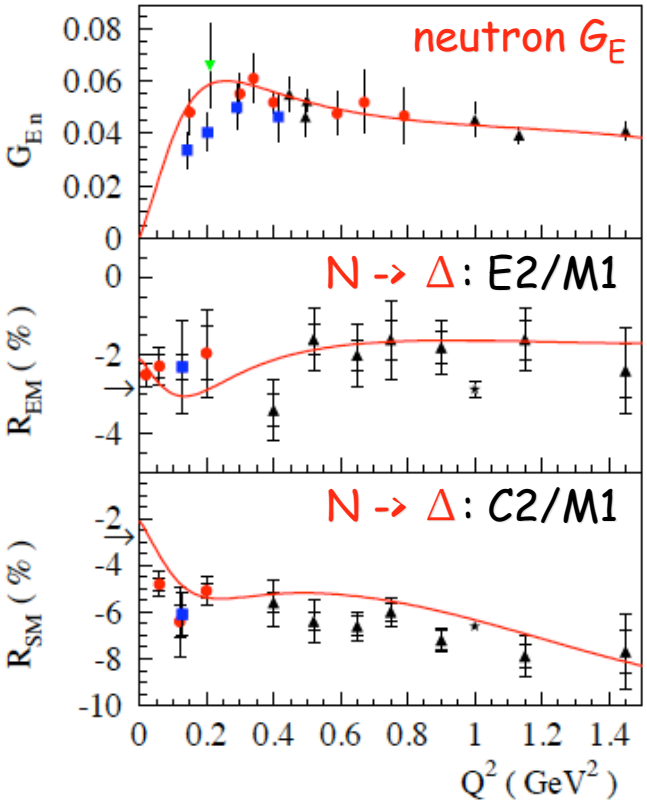
induced EDM : $d_y = F_{2p}(0) \cdot e / (2 M_N)$

data : Arrington, Melnitchouk, Tjon (2007)

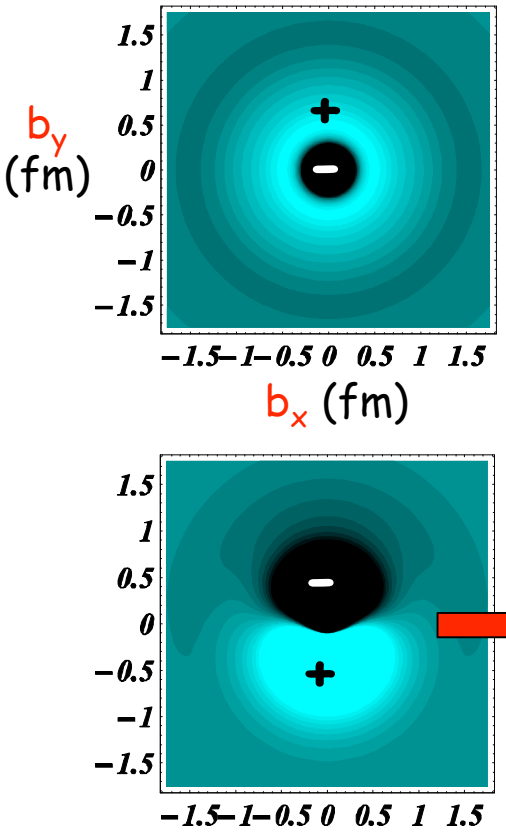
densities : Miller (2007); Carlson, Vdh (2007)

Form Factors : transverse quark charge densities

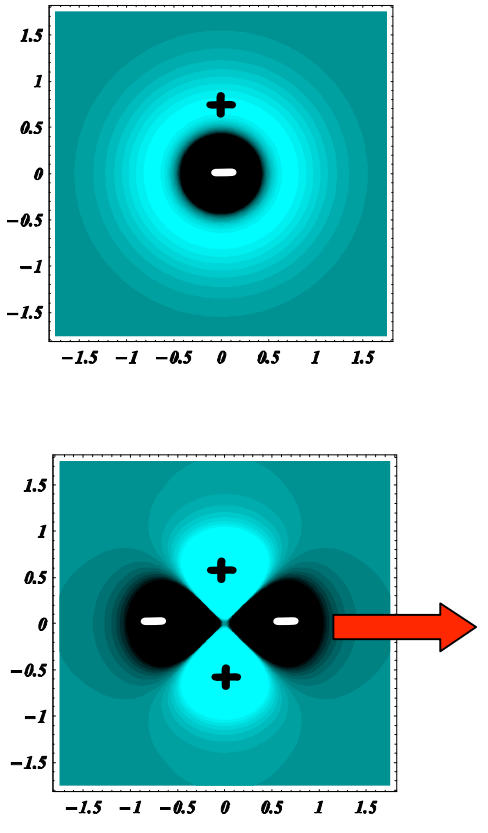
data : MAMI, NIKHEF, MIT-Bates, JLab



n



p -> $\Delta^+(1232)$



Miller (2007), Carlson, Vdh (2007)

quadrupole pattern

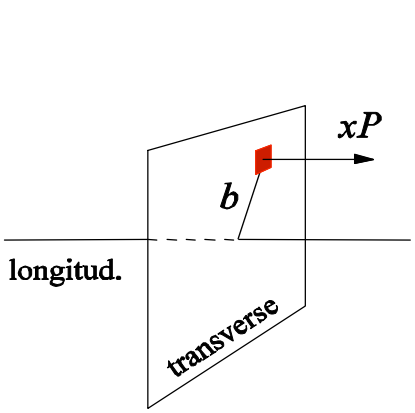
Generalized Parton Distributions (GPDs) : 3D picture of nucleon

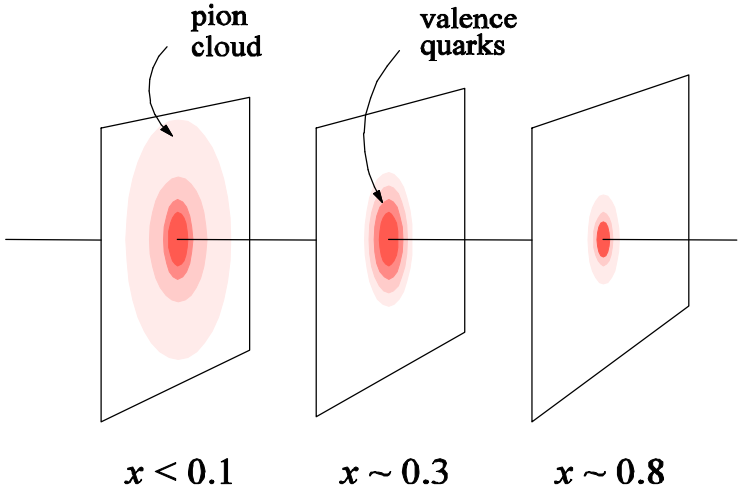
DIS
longitudinal
quark distribution
in momentum space

Unifying concept

Elastic Scattering
transverse quark
distribution in
coordinate space

fully-correlated
quark distributions in **both**
coordinate and momentum space

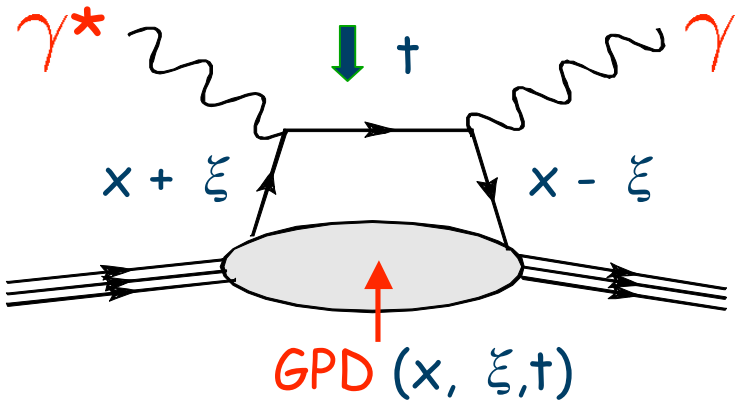




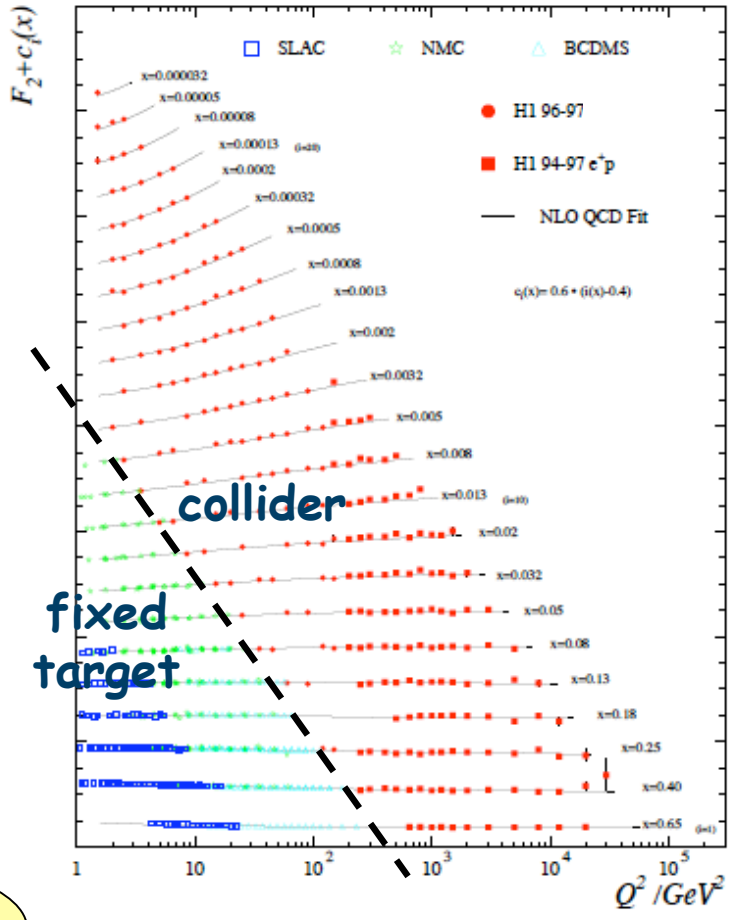
Burkardt (2000, 2003),
Belitsky, Ji, Yuan (2004)

QCD factorization : tool to access GPDs

$Q^2 >> 1\ GeV^2$



world data on proton F_2



➡ at large Q^2 : **QCD factorization theorem** :

hard exclusive process described by GPDs
model independent !

Müller et al. (1994),
Ji (1995), Radyushkin (1995),
Collins, Frankfurt, Strikman (1996)

➡ **KEY** Q^2 leverage required to test

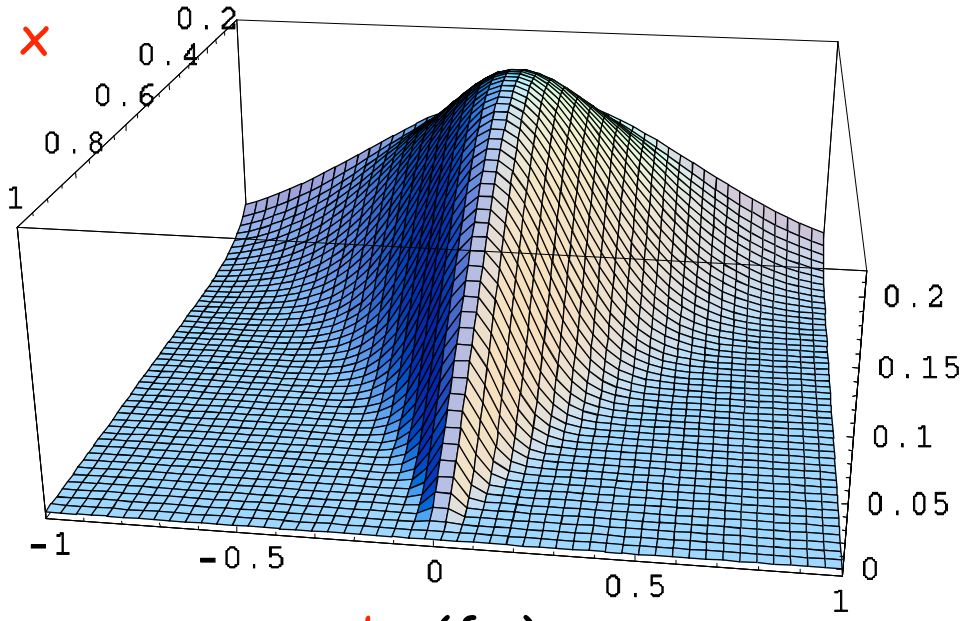
QCD scaling ➡ **e N collider**

GPDs : transverse image of nucleon

GPDs : quark distributions w.r.t. longitudinal momentum x and transverse position $b_\perp$

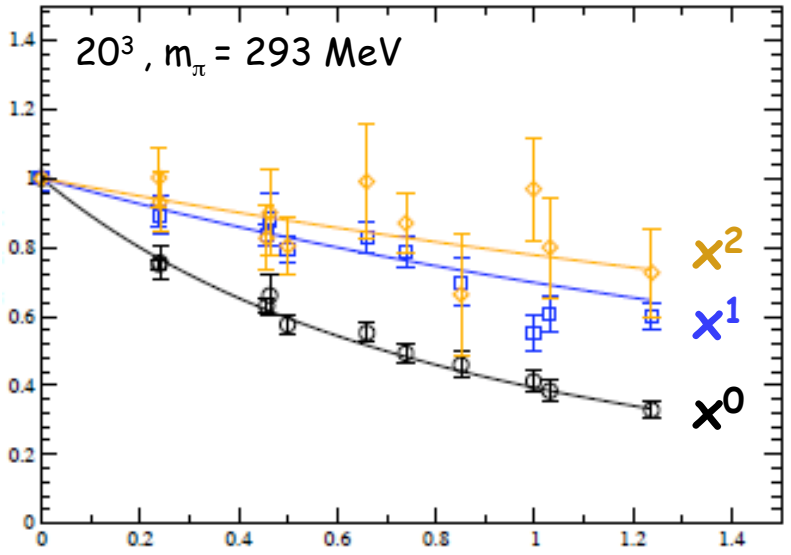
lattice QCD : moments of GPDs

$H^u(x, b_\perp)$



$b_\perp$ (fm)

x^n moment of H^{u-d}



Fourier transform

-t (GeV^2)

LHPC Coll.

Guidal, Polyakov, Radyushkin, Vdh (2005),

Diehl, Feldmann, Jakob, Kroll (2005)

GPDs : total angular momentum sum rule

➡ total angular momentum $J^q = \frac{1}{2}\Delta q + L^q$ ← quark **orbital** angular momentum

X. Ji (1997)

$$2\,J^q = M_2^q + \int_{-1}^{1} dx\, x\, E^q(x,0,0)$$

with known $M_2^q = \int_0^1 dx\, x\, [q(x) + \bar{q}(x)]$

➡ parametrizations for GPD E^q : Goeke, Polyakov, Vdh (2001)

PROTON	M_2^q	$2\,J^q$ GPD model	$2\,J^q$ Lattice (**QCDSF**)
u	0.37	0.58	0.66 ± 0.04
d	0.20	-0.06	-0.04 ± 0.04
s	0.04	0.04	
u + d + s	**0.61**	**0.56**	**0.62 ± 0.08**

lattice : full QCD,

no disconnected diagrams so far

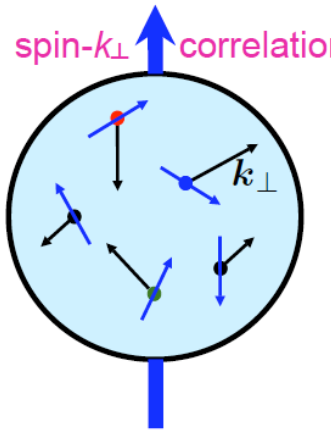
Transverse Momentum Dependent Parton distributions

Quark distribution functions

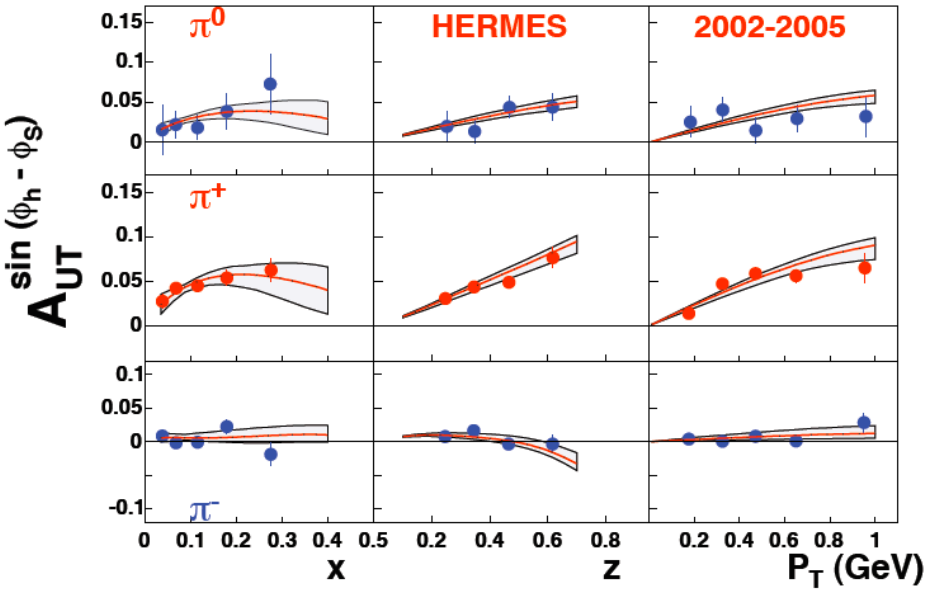
nucleon	quark: U	quark: L	quark: T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Sivers DF

spin-$k_\perp$ correlations



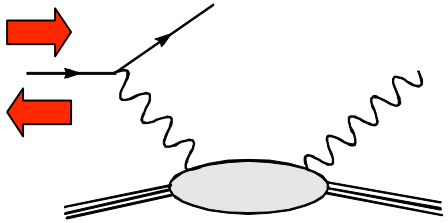
➡ accessible in **semi-inclusive DIS**



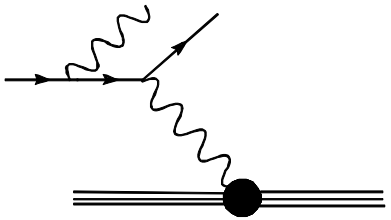
theory curves : Anselmino et al.(2009)

DVCS : beam spin asymmetry

A_{LU} =
(BH) * Im(DVCS)
* sin Φ

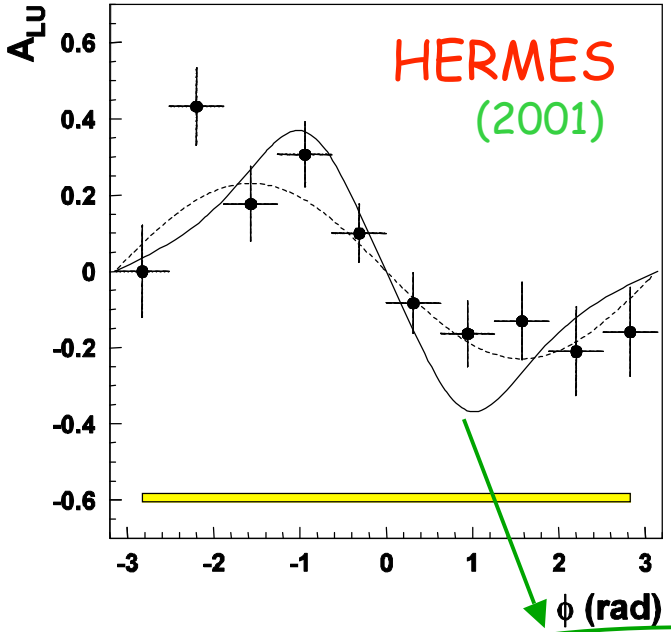


DVCS

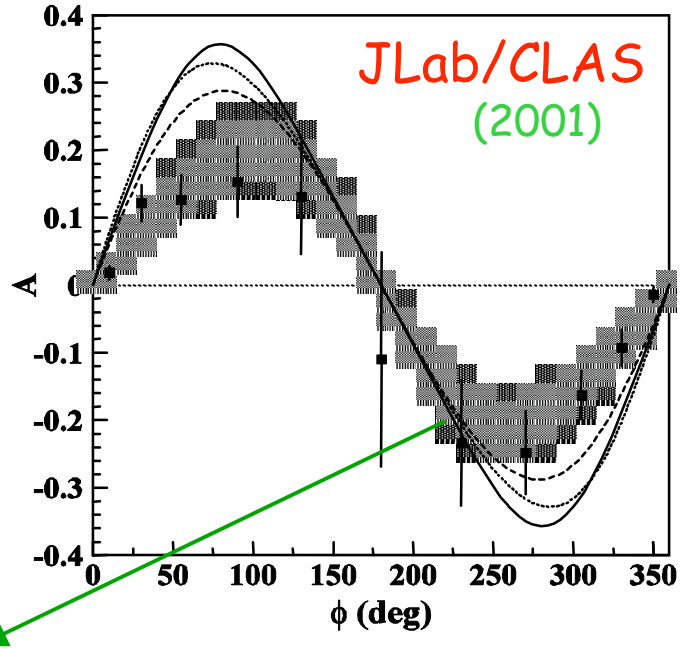


Bethe-Heitler

Q^2 = 2.6 GeV^2 , x_B = 0.11, -t = 0.27 GeV^2



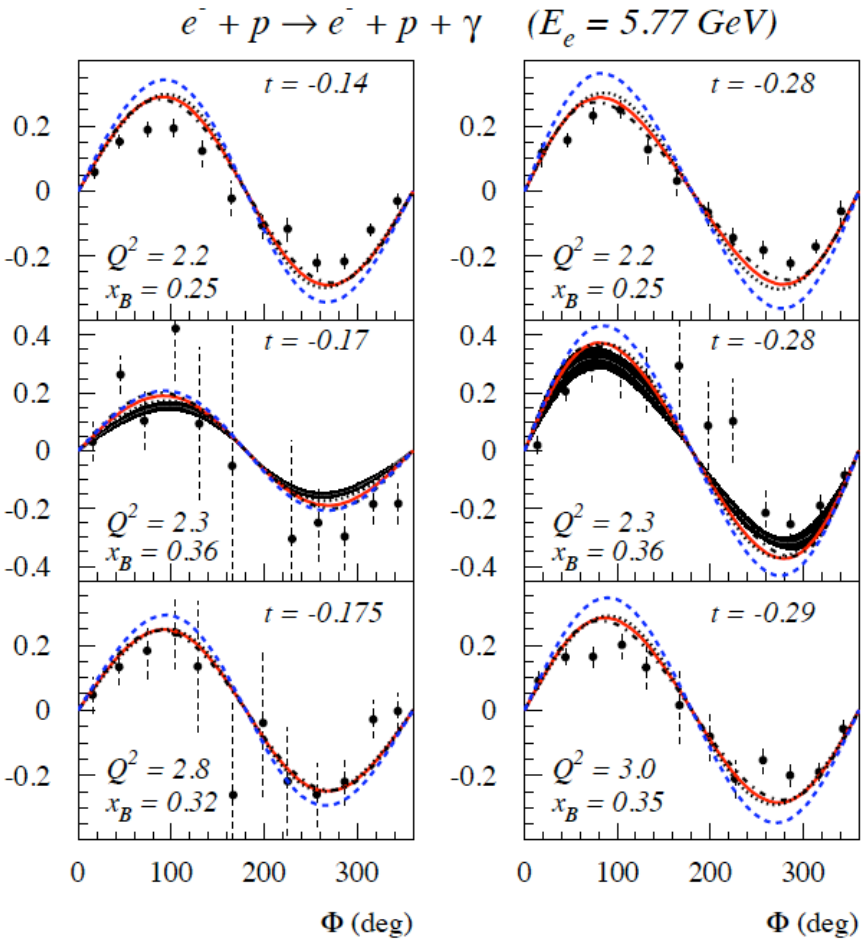
Q^2 = 1 – 1.5 GeV^2 , x_B = 0.15 – 0.25,
-t = 0.1 - 0.25 GeV^2



twist-2 + twist-3 : Kivel, Polyakov, Vdh (2000)

DVCS : beam spin asymmetry (contd.)

data : JLab/CLAS



Harmonic analysis : ~ **sin (Φ)**

amplitude gives **GPD** for one value of its arguments

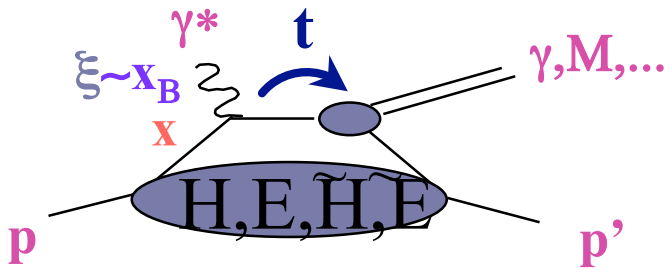
GPD ($x_B/2$, $x_B/2$, t)

Range in Q^2 of existing data very limited

curves : dual GPD model

Moiseeva, Semenov, Polyakov, Vdh (2008)

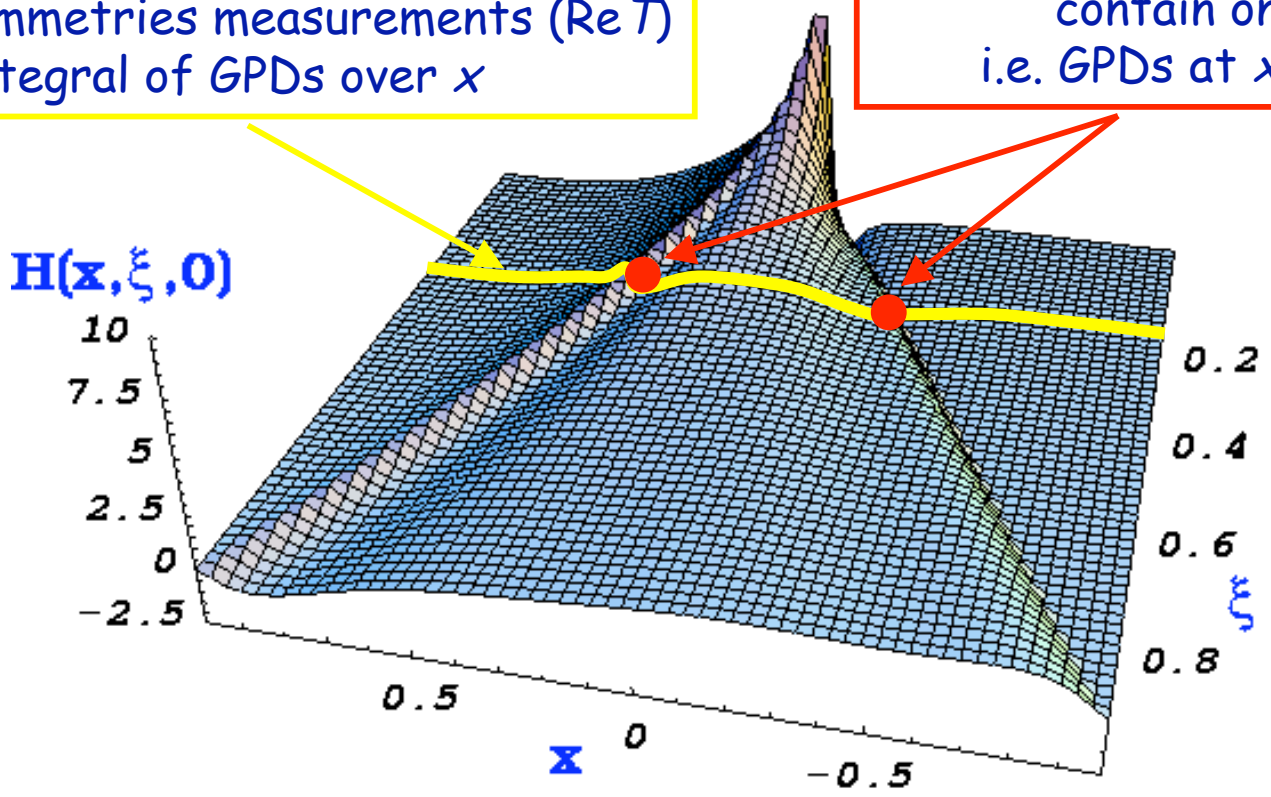
link GPDs and observables



$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$

Cross sections and
charge asymmetries measurements (Re T)
Integral of GPDs over x

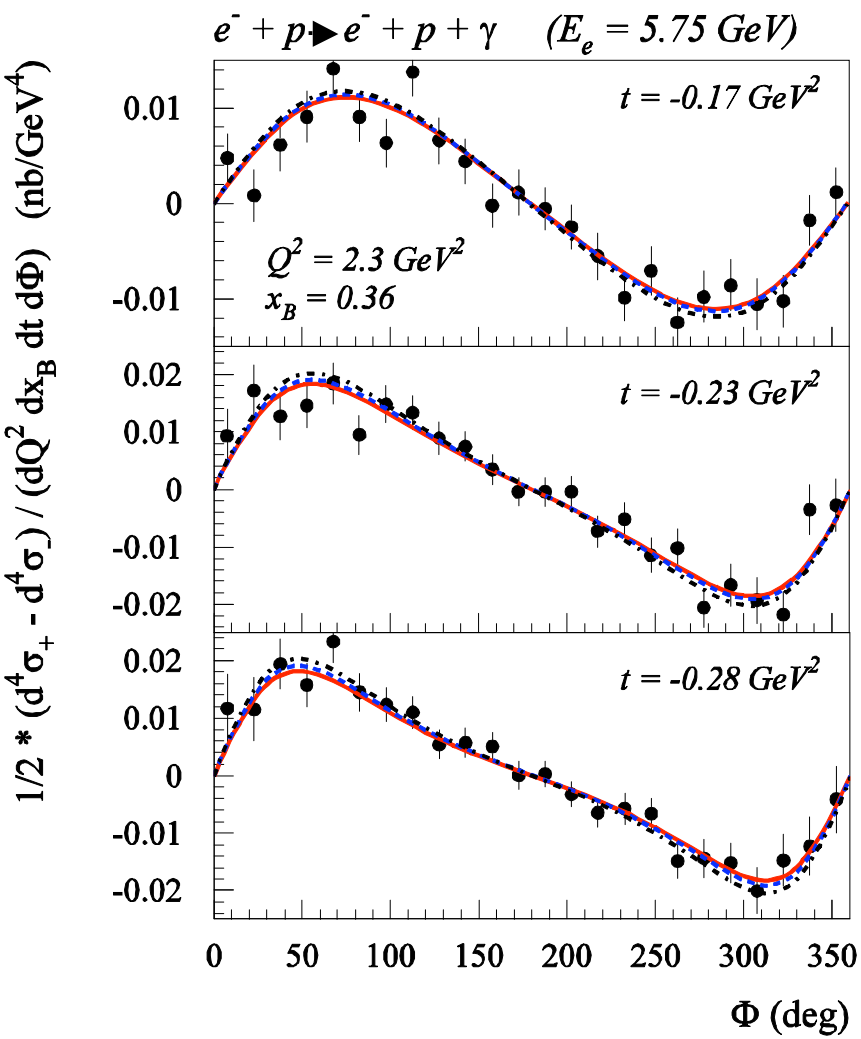
Beam or target spin asymmetries
contain only Im T,
i.e. GPDs at $x = \xi$ and $-\xi$



DVCS : cross sections

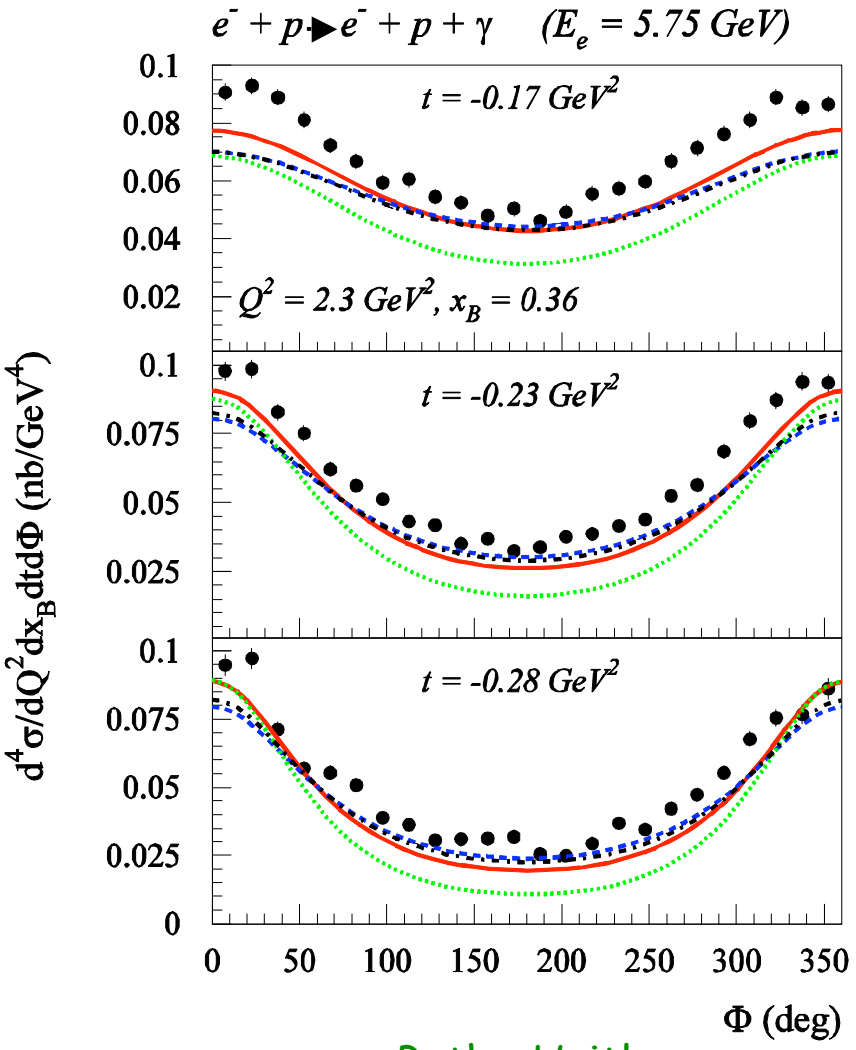
data : JLab/Hall A

polarized



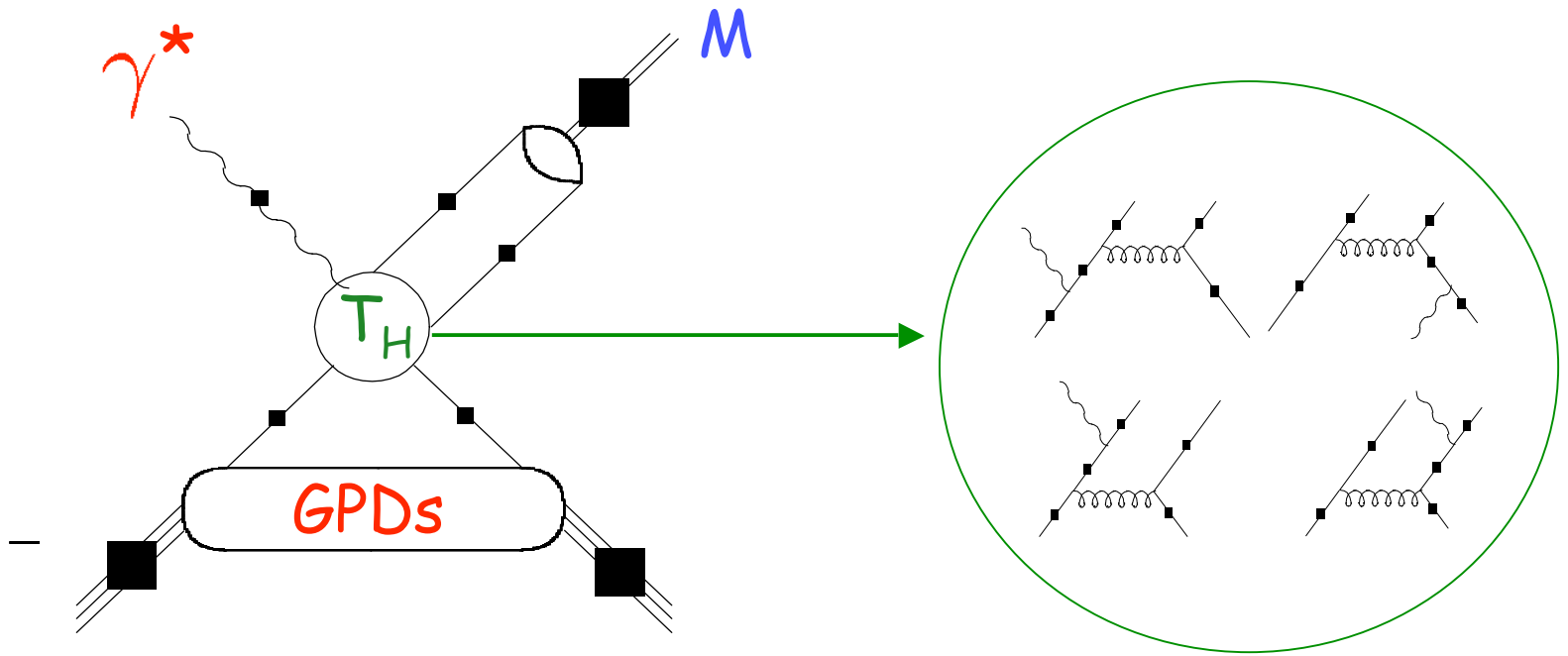
Moiseeva, Semenov, Polyakov, Vdh (2008)

unpolarized



Bethe-Heitler

Hard electroproduction of mesons ($\rho^{0,\pm}$, ω , ϕ, π, ...)



Factorization theorem shown for longitudinal photon

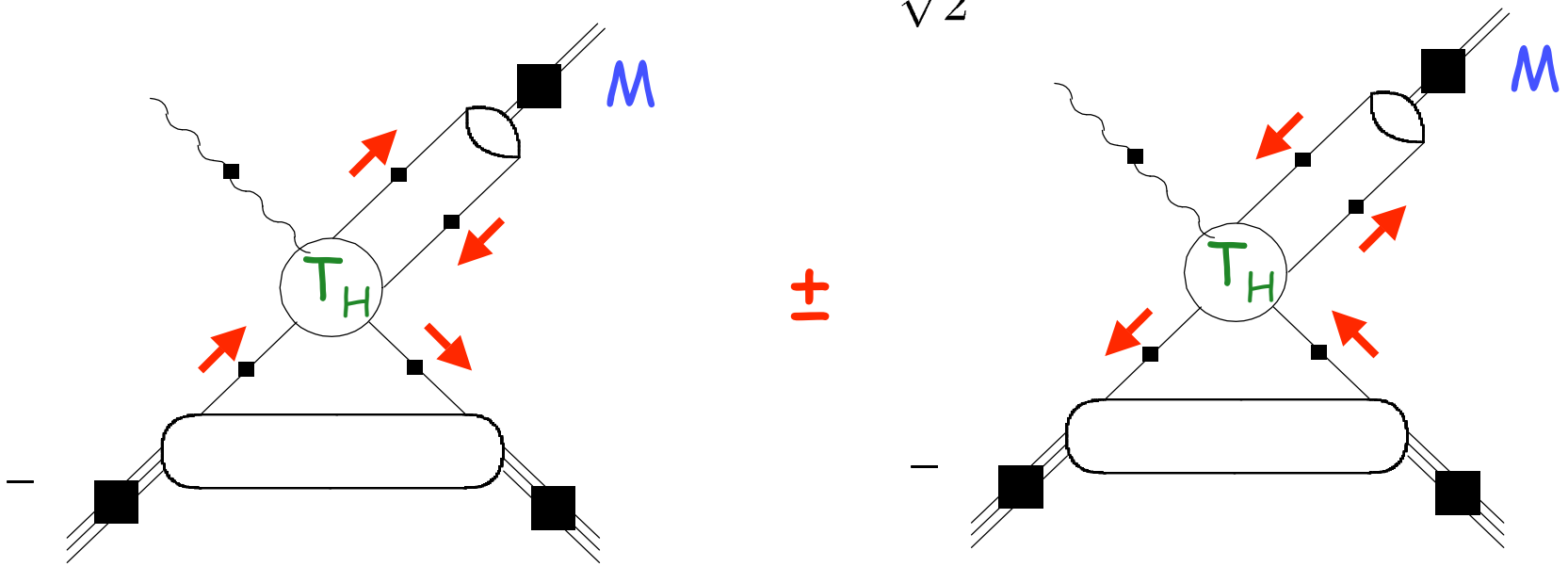
hard scattering amplitude

Collins, Frankfurt, Strikman (1997)

Meson acts as helicity filter

longitudinally pol. Vector meson $|\rho_L\rangle = \frac{1}{\sqrt{2}}|\uparrow\downarrow + \downarrow\uparrow\rangle$

PseudoScalar meson $|\pi\rangle = \frac{1}{\sqrt{2}}|\uparrow\downarrow - \downarrow\uparrow\rangle$



➡ Vector meson : accesses unpolarized GPDs H and E

➡ PseudoScalar meson : accesses polarized GPDs $\tilde{H}$ and $\tilde{E}$

DVCS simulations for PANDA@ENC

$e^- p \rightarrow e^- p \gamma$: acceptance (3 GeV e^- on 15 GeV p)

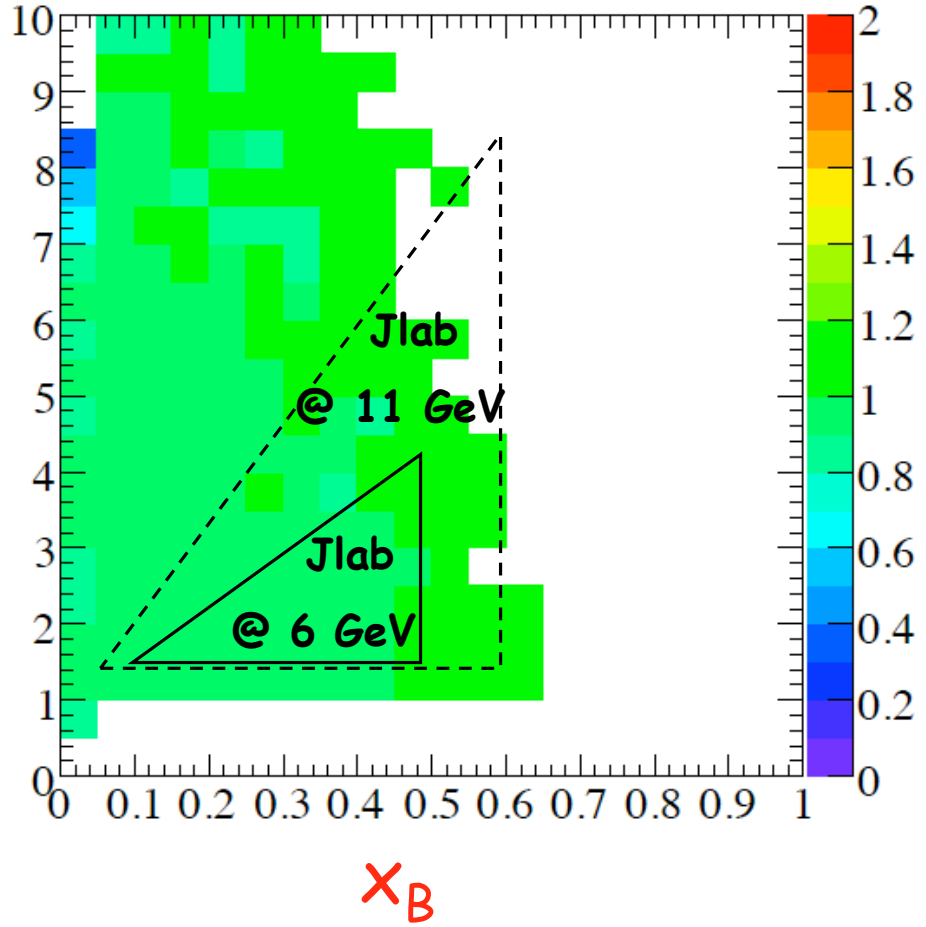
Probability of **exclusive** reconstruction of all 3 particles in final state

using **PANDA** detector (e.g. PANDA @ ENC)

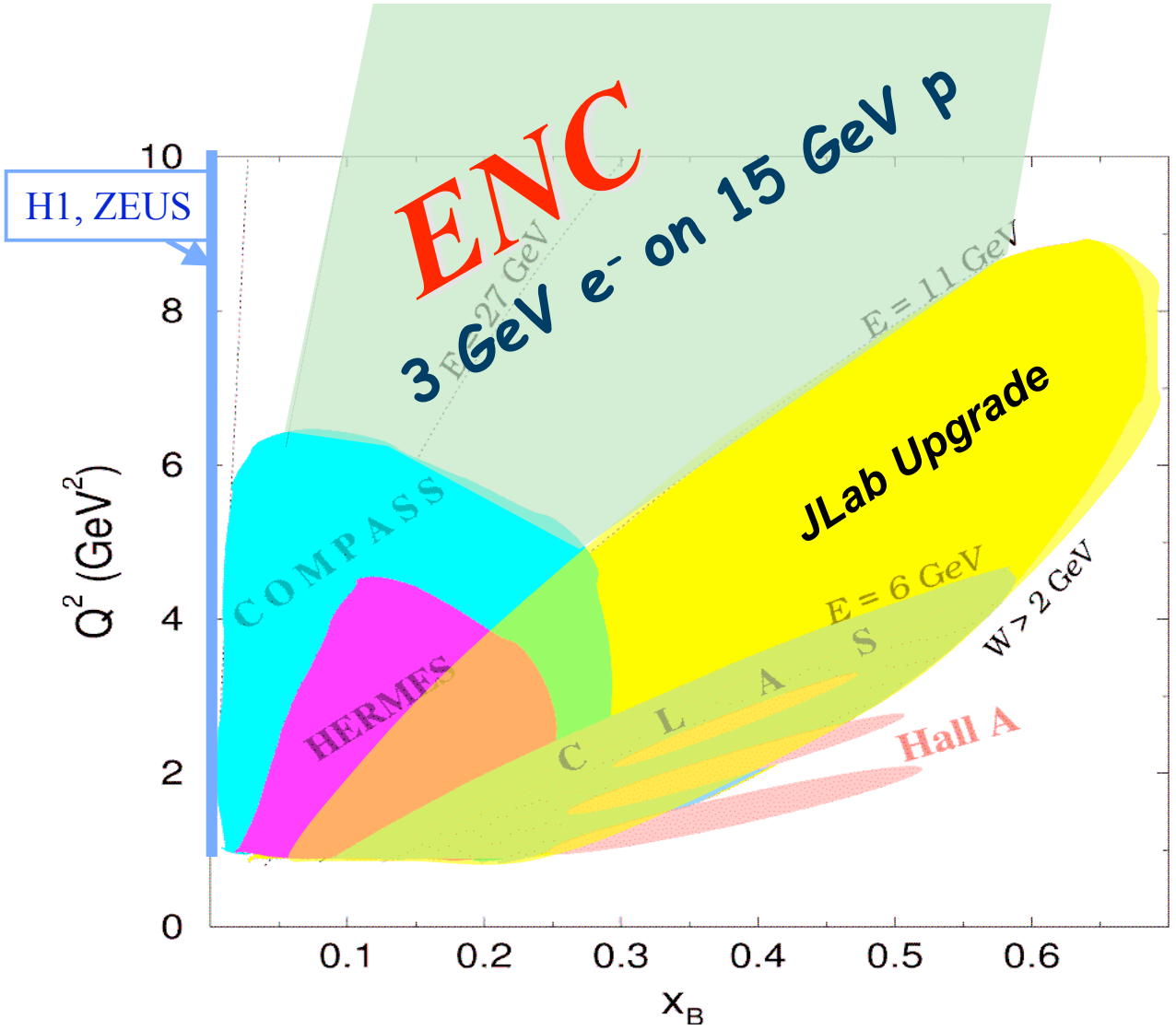
DVCS generator

first simulation studies

see talks : Gradl, Kang

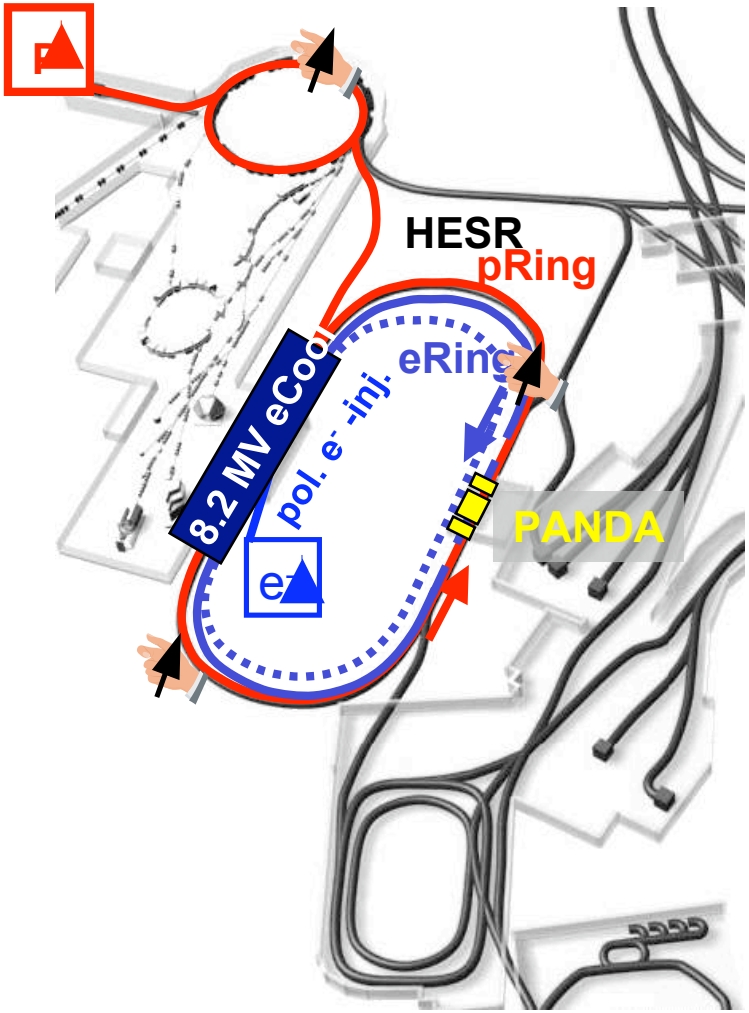


ENC : The Energy / Luminosity Frontier

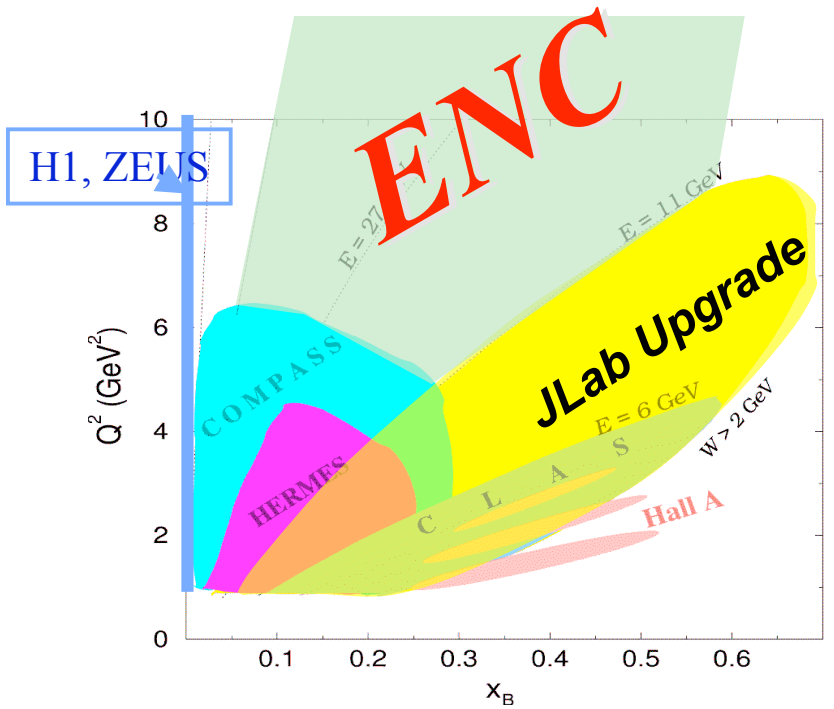


high energy
and
high luminosity
required
+
polarization

ENC @ FAIR



see next talk



L > 4·10³² /cm²s

s^1/2 > 10 GeV (3.3 GeV e⁻ ↔ 15 GeV p)

polarised e⁻ (80%)

↔

polarised p / d (80%)

(transversal + longitudinal)