Experimental probes
(mostly e & μ)

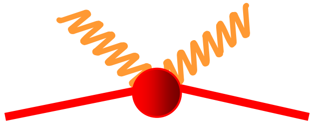
of hadron structure
(mostly nucleon)

Michel Garçon – SPhN/Saclay

EINN05 Conference (Milos, September 2005)

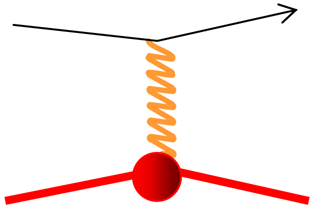
Nucleon structure: means of investigation

Compton scattering
$(\gamma^{(*)}N \rightarrow \gamma N)$



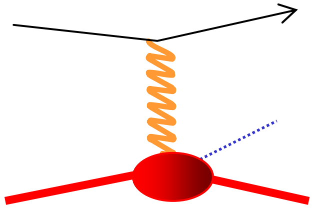
Polarisabilities

Lepton elastic scattering



Form factors

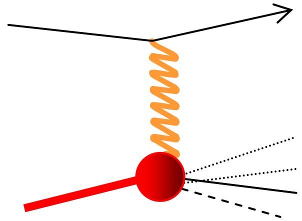
Inelastic scattering
$(\gamma N,\ eN,\ \pi N\ldots)$



Excited states (résonances)

.....

Deeply inelastic scattering



Structure functions
(→ parton distributions)
+
Transverse Momentum Distr.
+
Generalized Parton Distr.

+ **Crossed channels** $e^+e^- \leftrightarrow p\bar{p}$

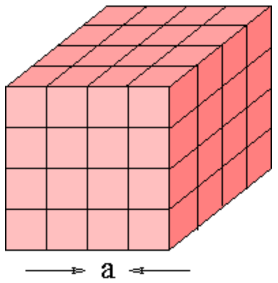
+ **High energy** pp **and** $p\bar{p}$ **interactions**

+ **Neutrinos**

One word on theoretical tools

QCD

Lattice calculations



⚠

- Continuum limit a → 0,
- Thermodynamical limit V → ∞,
- “Quenched” approximation
- Extrapolation m_π → 140 MeV

Effective theory
(chiral perturbation)

Models

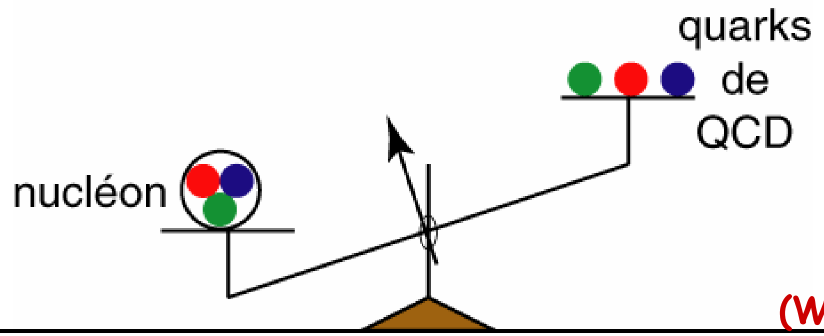
Quarks from QCD
(m ~ 0)

$|p\rangle = |uud\rangle + |uudq\bar{q}\rangle + |uudg\rangle + \ldots$

Constituent quarks
(m ~ M/3)

$|p\rangle = |u_c u_c d_c\rangle$

Nucleon structure : we are studying
- *not only* the most fundamental building brick of the (visible) universe,
- *but also* the theory of strong interactions, QCD.



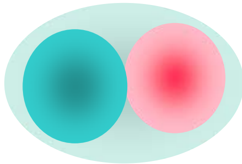
(W. Weise's intro + C. Michael's talk + contributions)

Santorini 2003 – G. van der Steenhoven :

Hadron spectroscopy

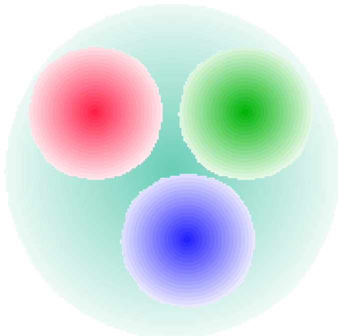
Harvest 2002 – 2003:

- $q\bar{q}$ states $\rightarrow$ mesons



Discovery $D_{sJ}^{*+}(2317)$

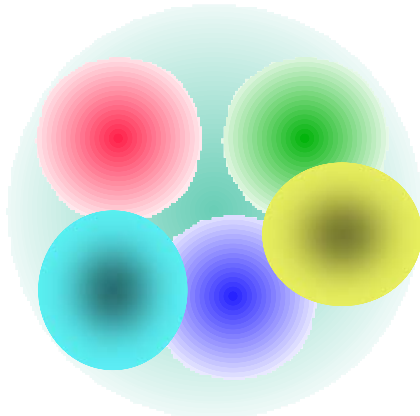
- qqq states $\rightarrow$ baryons



Discovery $\Xi_{cc}^{+}(3520)$

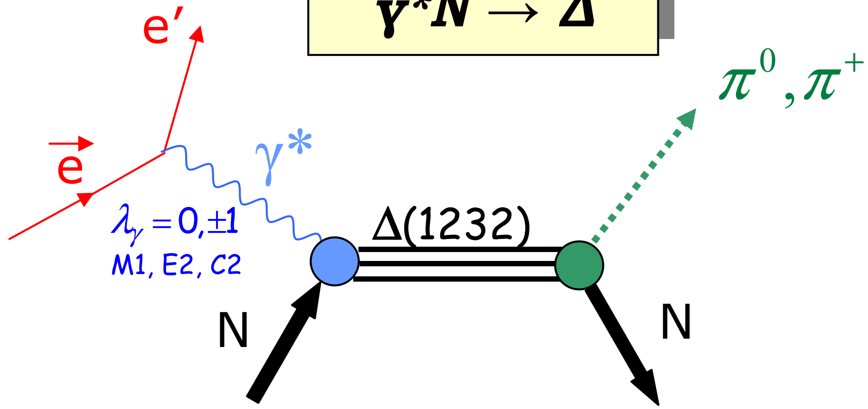
- $qqqq\bar{q}$ states $\rightarrow$ *pentaquarks?*

Discovery $\theta^{+}(1540)$

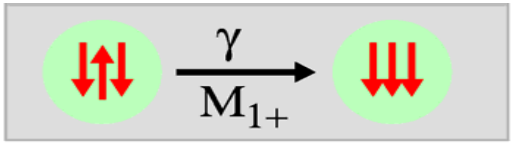


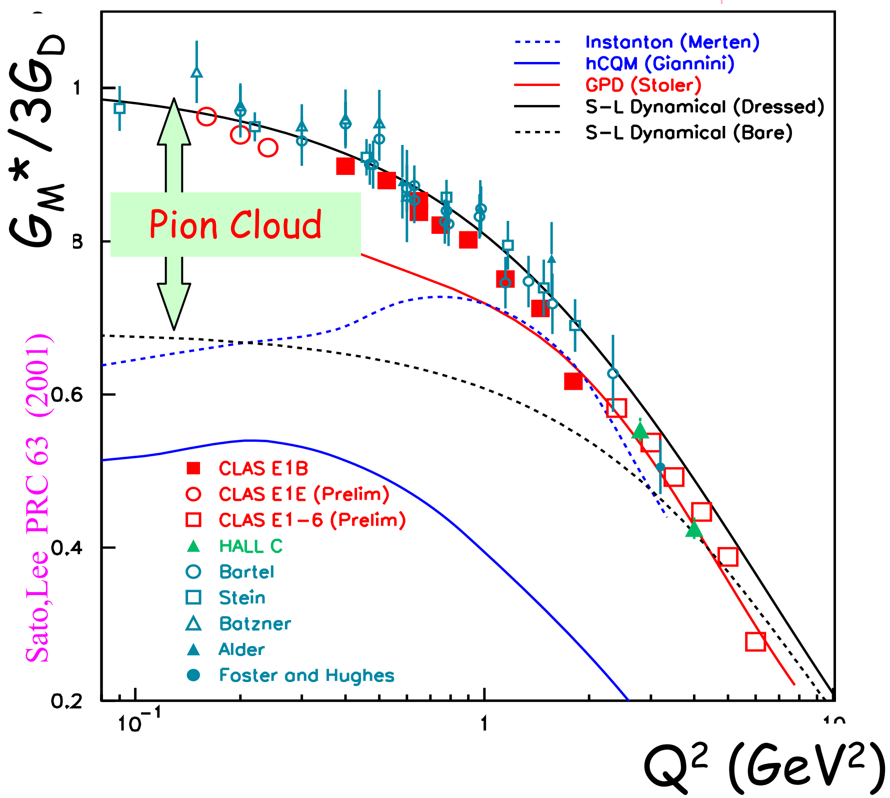
Milos 2005: turn to V. Burkert/F. Close's talk to clarify "facts and fancy"

$\gamma^* N \rightarrow \Delta$



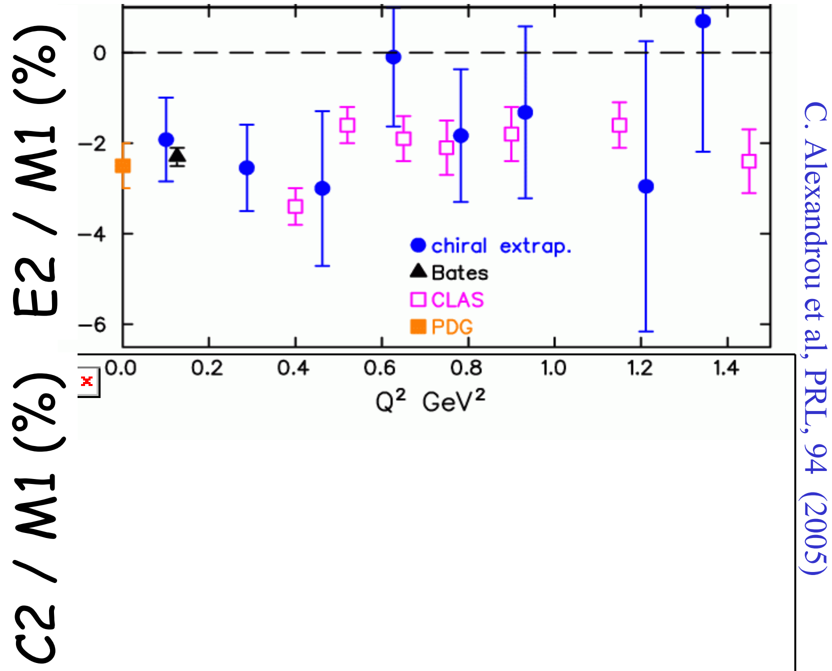
Dominant magnetic dipole transition and the pion cloud





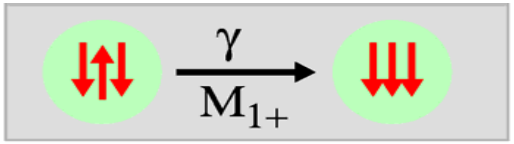
Fits of dynamical pion models to π photoproduction data suggest 30-50% of M1 photocoupling strength near $Q^2=0$ due to meson rescattering at EM vertex.

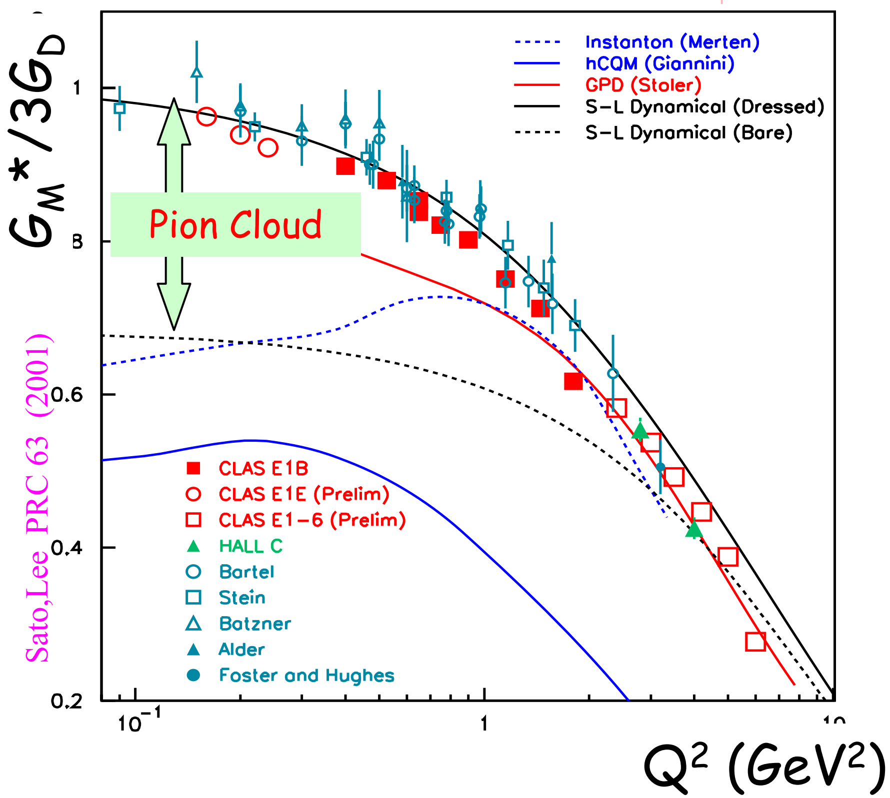
Small quadrupole transitions and lattice QCD



(D. Drechsel's talk + contributions)

Dominant magnetic dipole transition and the pion cloud





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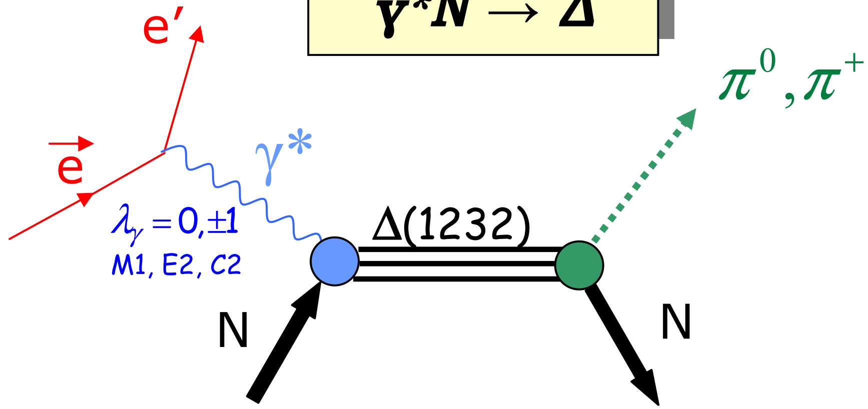
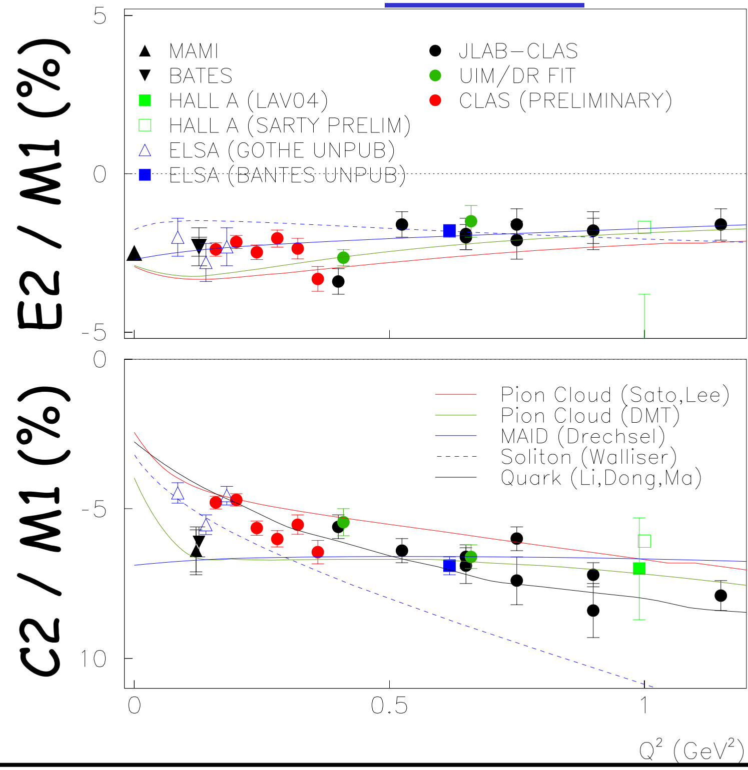


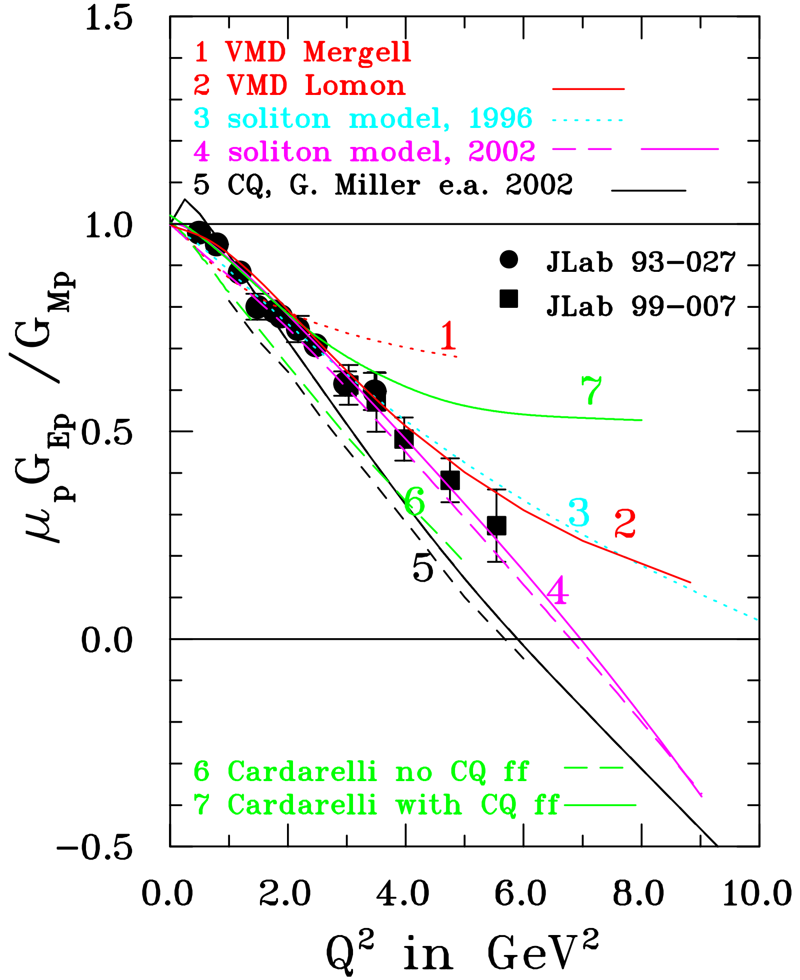
Small quadrupole transitions and new data



Electromagnetic form factors

Observables of elastic scattering *eN*:

- cross sections $\rightarrow \alpha G_E^2 + \beta G_M^2$ (+ 2γ)
- polarization $\rightarrow G_E / G_M$

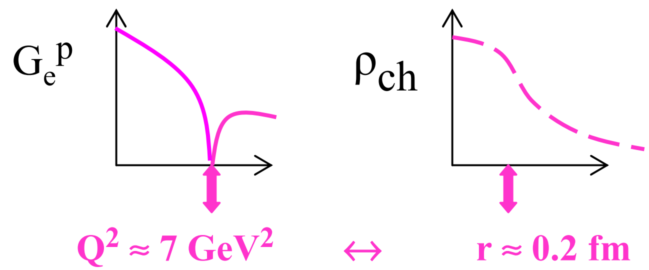


(W. Brooks' and M. Vanderhaeghen's talks)

1) $G_E^p < 0$? (not forbidden / could have been expected)

Distributions of charge and magnetization in the proton are not proportional.

Non-relativistically, as in a nucleus, the **node** of the form factors gives the spatial extension of the nucleon core:



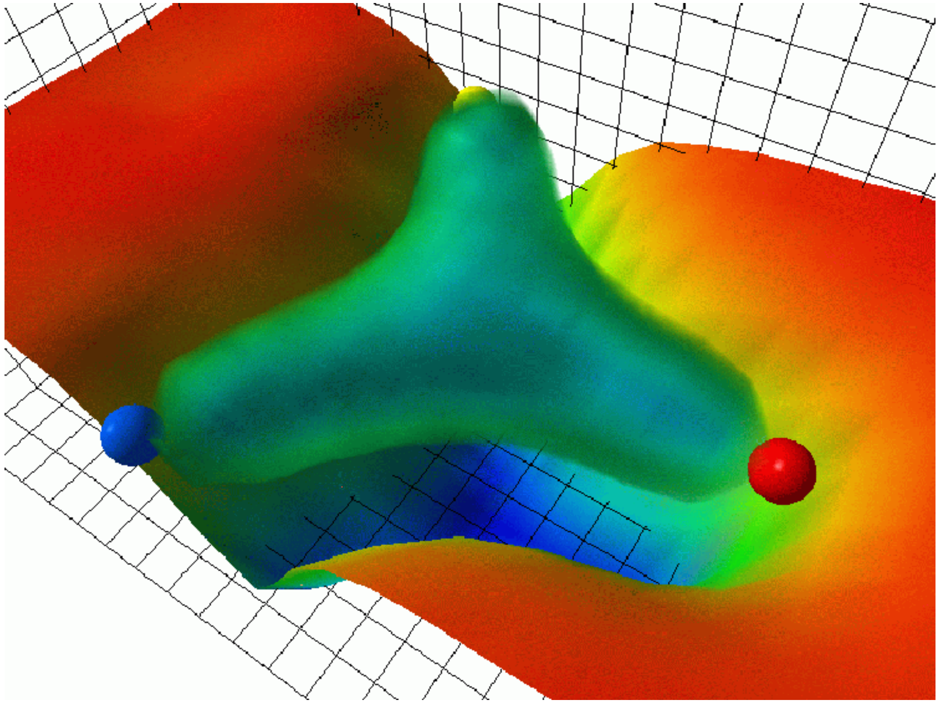
This interpretation is *wrong* ($Q^2 > M^2$), but it could indicate qualitatively the existence of a small **core** at the center of the nucleon.

2) Asymptotic behaviour:

F(Δh=1)/F(Δh=0) ~ 1/Q

instead of $1/Q^2$ (pQCD).

One *interpretation* links this observation to orbital angular momentum of the quarks within the nucleon (see GPD).



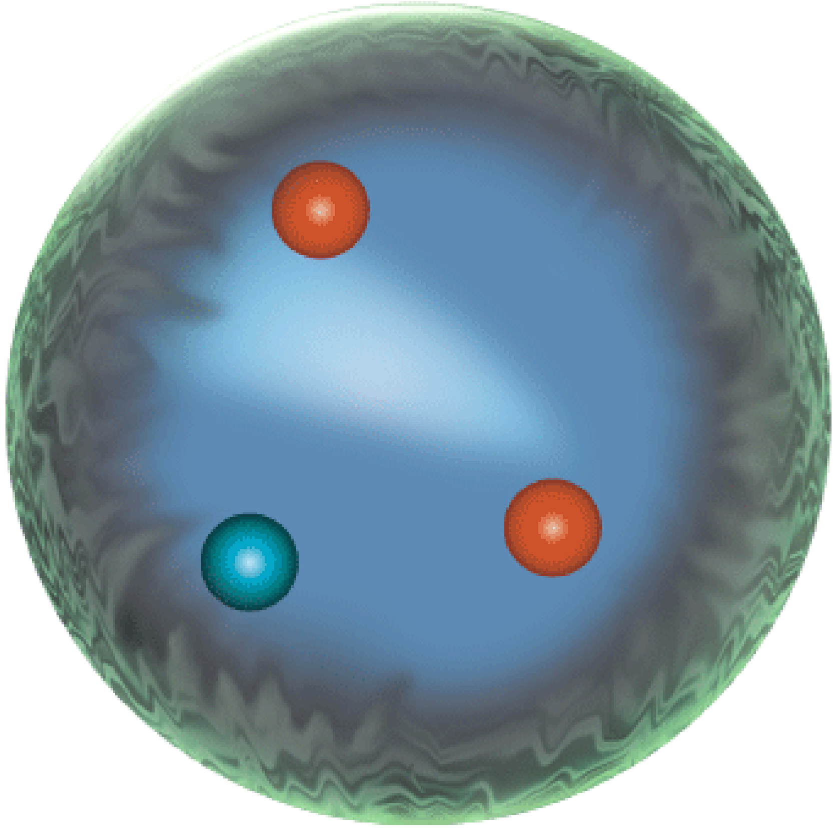
Experiment is now sensitive to

sea-quark contributions to form factors :

Density (G_E^s)

Magnetic properties (G_M^s)

of strange quark-antiquark pairs



Weak form factors - Strangeness

Strange quark s : the lightest of the sea-only quarks
$\rightarrow$ good candidate to study $q\bar{q}$ sea in the nucleon.

Mass: $\pi N \rightarrow \langle N | \bar{s}s | N \rangle$

Spin: $\Delta\Sigma \rightarrow \langle N | \bar{s}\gamma_5\gamma_\mu s | N \rangle$

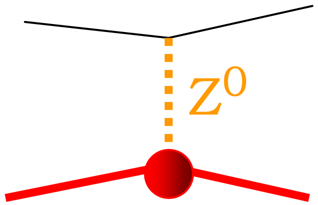
Hints of a "non-zero strangeness" in the nucleon.

Decomposition of electromagnetic form factors on an SU(3) basis:

$$G_{E,M} = \sum_{q=u,d,s} e^{\gamma}_{q} G^{q}_{E,M}$$

$(p,n) \times (E,M) \Rightarrow$ 4 equations for 6 contributions $G^{q}_{E,M}$

$\Rightarrow$ Use a probe which "sees" a different charge:



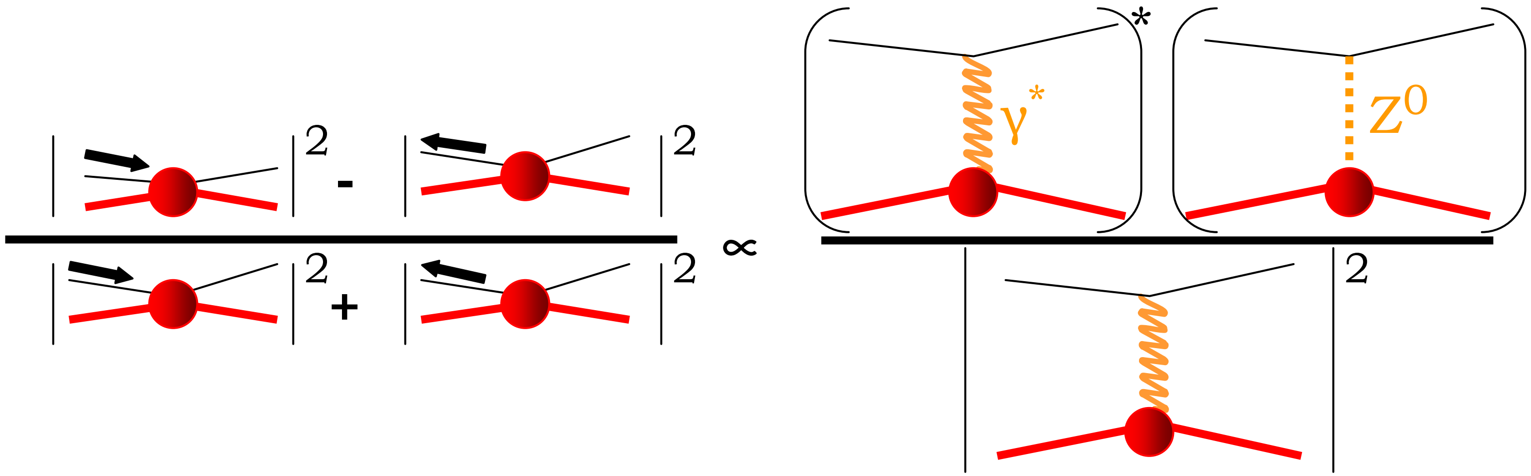
$$GZ_{E,M} = \sum_{q=u,d,s} e^{Z}_{q} G^{q}_{E,M}$$

Two proton <u>weak form factors</u>,
and equivalently two <u>strange form factors</u>,
may be extracted from these new measurements.

$$G^{s}_{E,M} \leftrightarrow \langle N | \bar{s}\gamma_\mu s | N \rangle$$

Weak form factors - Experiments

Observable = parity violation asymmetry



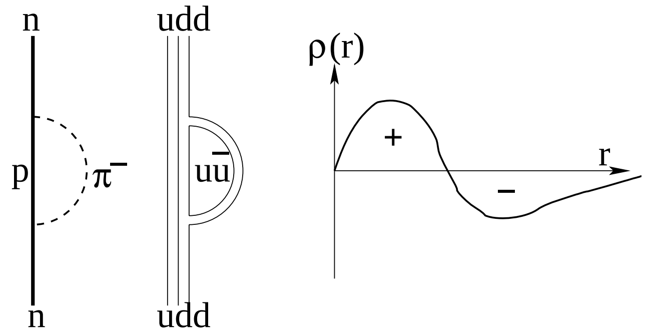
$$\sim A_0 + \lambda \mathbf{G_E^s} + \mu \mathbf{G_M^s} + \nu G_A^{(p+n)} \sim 10^{-6}$$

	SAMPLE (MIT-Bates) *1998-2002*	HAPPEX (JLab) *1998*	PVA4 (MAMI) *2002-04*	HAPPEX2 $+^4$He (JLab) *2003-2004*	G0 (JLab) *2003-2005*
Q^2 $(GeV)^2$	0.04 et 0.1	0.47	0.11, 0.23	0.1	0.12 - 1
Sensitivity	$\mathbf{G_M^s}$, $G_A^{(p+n)}$	$\mathbf{G_E^s} + 0.4\mathbf{G_M^s}$	$\mathbf{G_E^s} + 0.1/0.2\mathbf{G_M^s}$	$\mathbf{G_E^s}$, $\mathbf{G_M^s}$	$\mathbf{G_e^s} + 0.1/0.9\mathbf{G_M^s}$

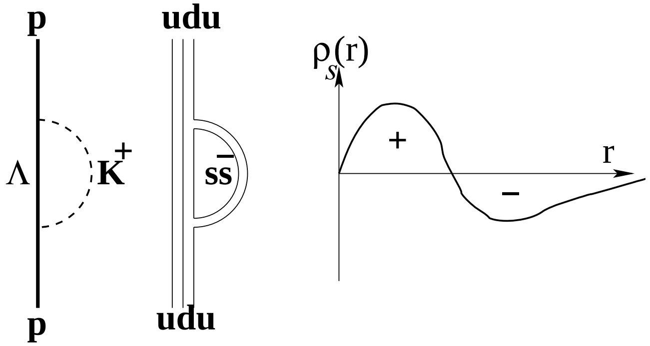
Strange form factors

INTUITION

In analogy with
electric charge distribution in the neutron :

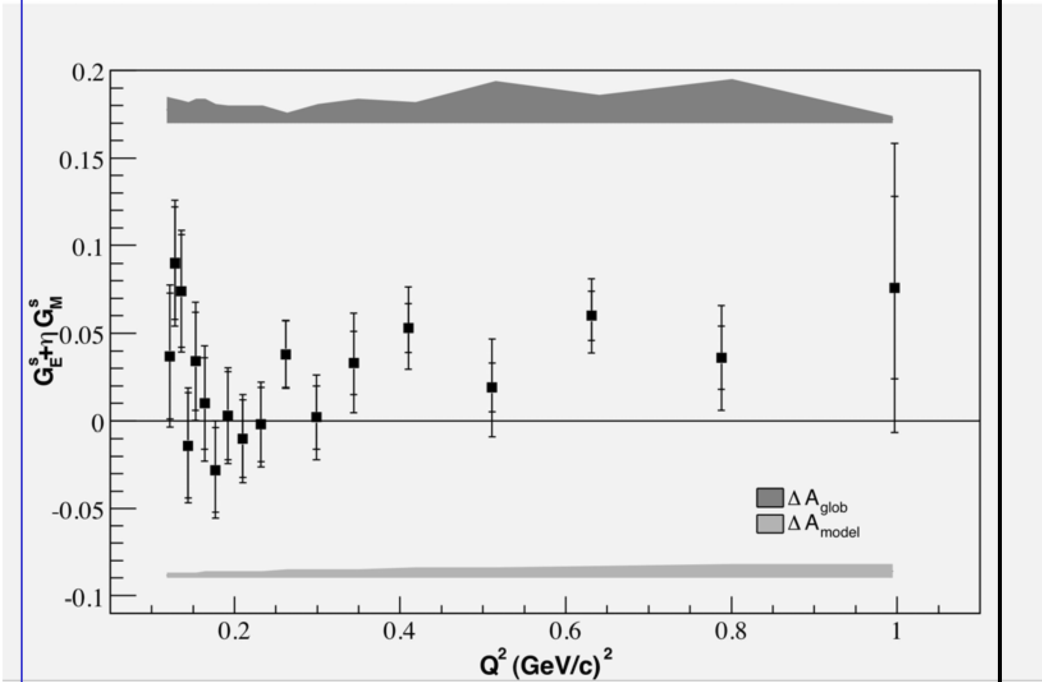


Strangeness distribution in the proton :



→ $G_E^s > 0$

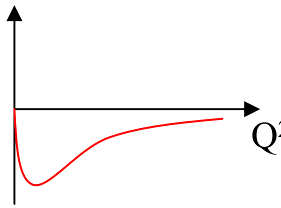
RESULTS

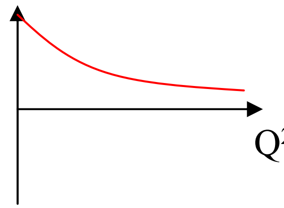


G0, PRL 95 (2005)

Tentatively interpreted,
together with other PV experiments as:

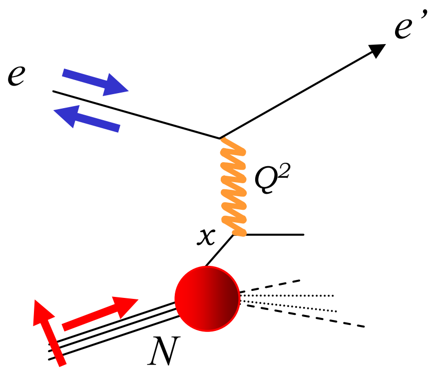
$G_E^s < 0$ and $G_M^s > 0$ (1.5 σ ??)





(K. Paschke's talk, B. Guillon's contr.)

Quark helicity distributions Δq



Using
longitudinally polarized electron beam
onto
longitudinally (//) or transversely (⊥) polarized target,
measure asymmetries with respect to the beam helicity
for inclusive scattering $eN \rightarrow e'X$

Asymmetries with respect to beam direction		*Asymmetries with respect to virtual photon direction*		*Polarized structure functions*
$A_{//}$, $A_{\perp}$	⟷	A_1, A_2	⟷	$g_1(x,Q^2)$, $g_2(x,Q^2)$

In the quark parton model $$g_1(x) = \frac{1}{2}\sum_{q,\bar{q}} e_q^2 \left[q^{\uparrow}(x) - q^{\downarrow}(x)\right] = \frac{1}{2}\sum_{q,\bar{q}} e_q^2 \Delta q(x)$$

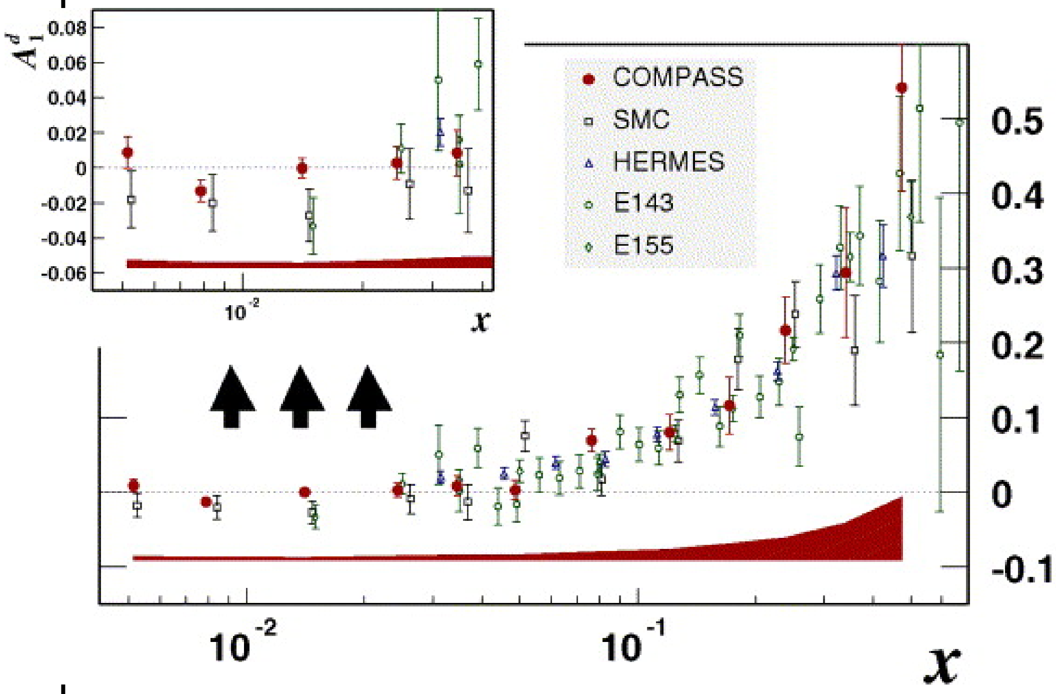
→ how does the quark spin contribute to the nucleon spin ?

g_2 represents interactions beyond the quark parton model

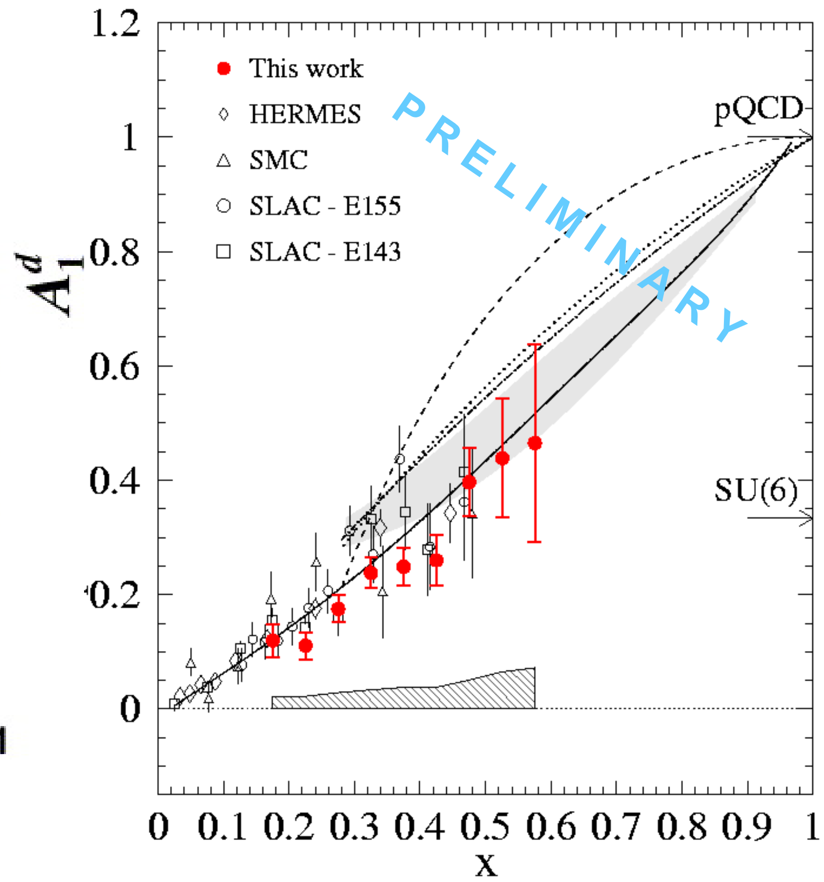
→ a tool to study higher twist effects, sensitive to quark-gluon correlations.

(R. De Vita's talk)

New results for A_1^d at low and high x



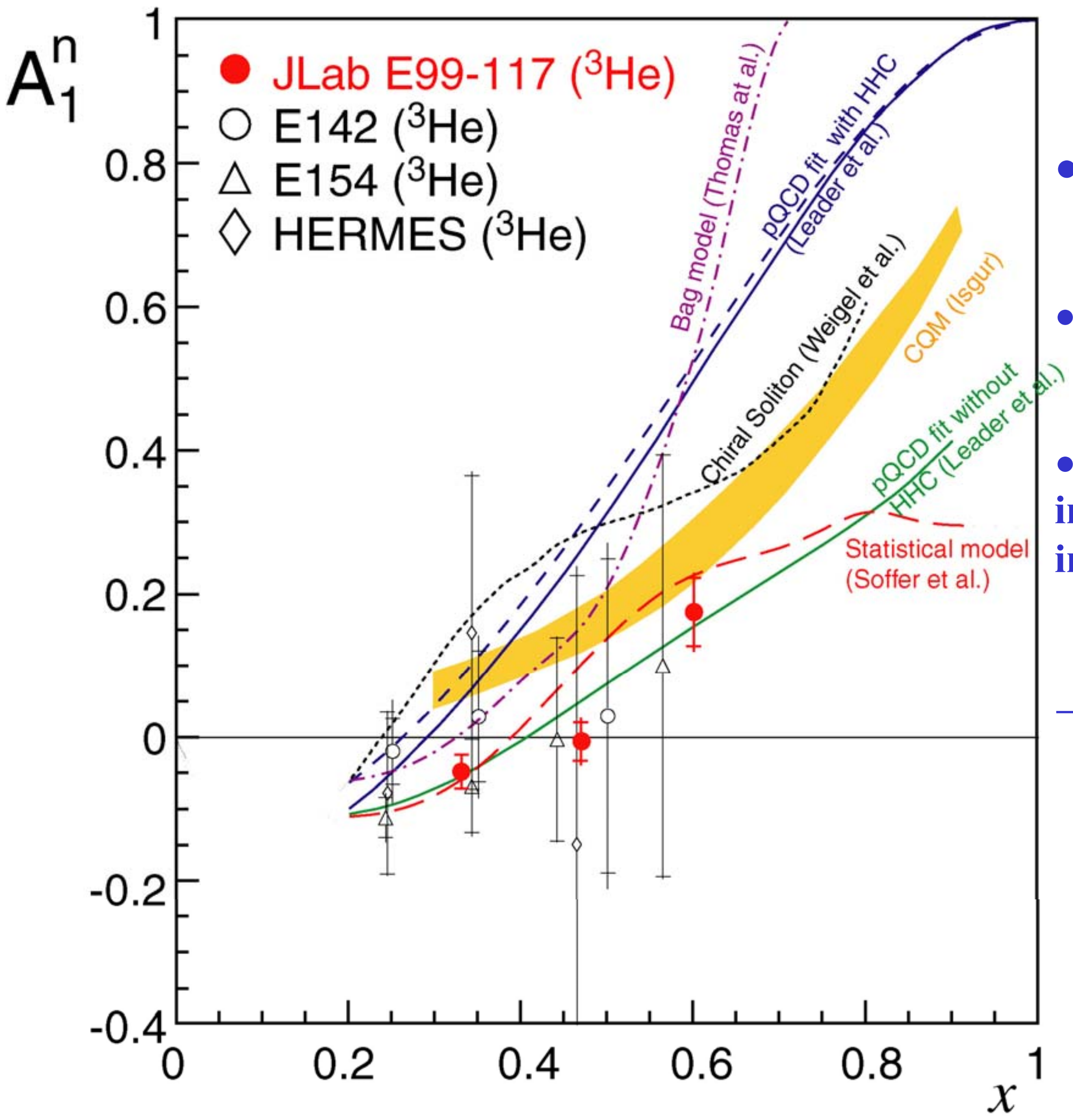
COMPASS, PLB 612 (2005)



CLAS, to be published

→ increased precision on fraction of nucleon spin carried by quark spin:
ΔΣ within 10% uncertainty

Results for n (Hall A/He3)

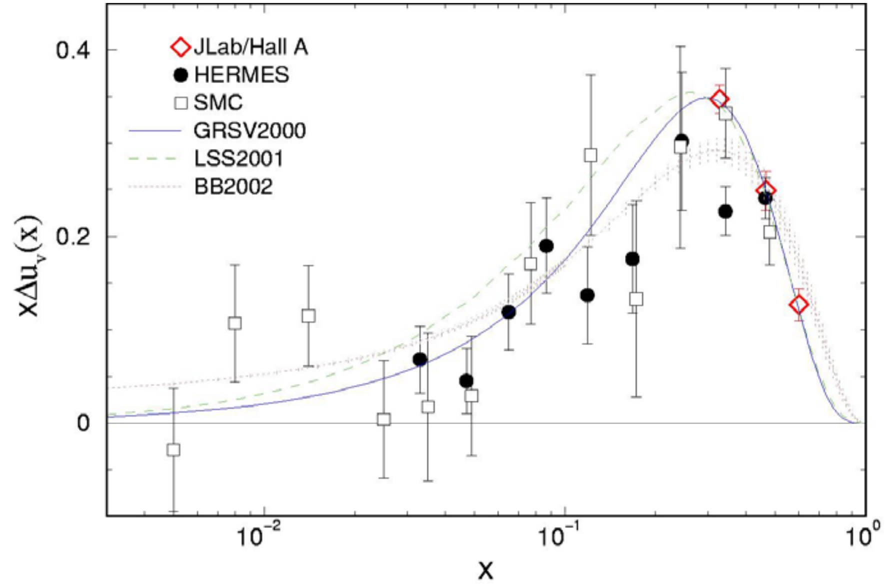


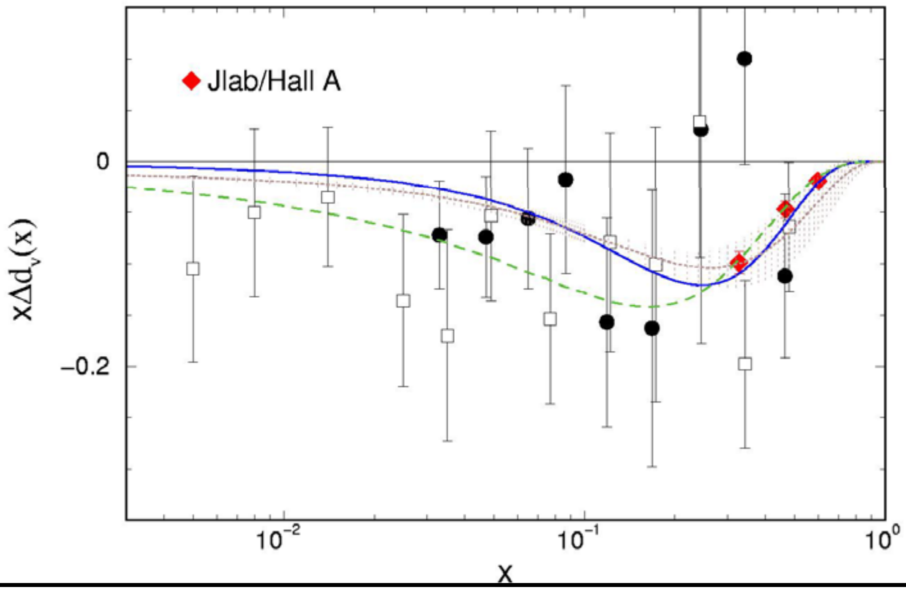
- **First clear signature of $A_1^n > 0$**
- **PQCD-based HHC may be ruled out**
- **(Rel.) constituent quark model introduces SU(6)-breaking hyperfine interaction**

→ ***quark orbital angular momentum***

X. Zheng et al., PRC70 (2004)

Flavour decomposition from p/n (2)





Since the difference

$$\frac{\Delta q + \Delta \bar{q}}{q + \bar{q}} - \frac{\Delta q_v}{q_v}$$

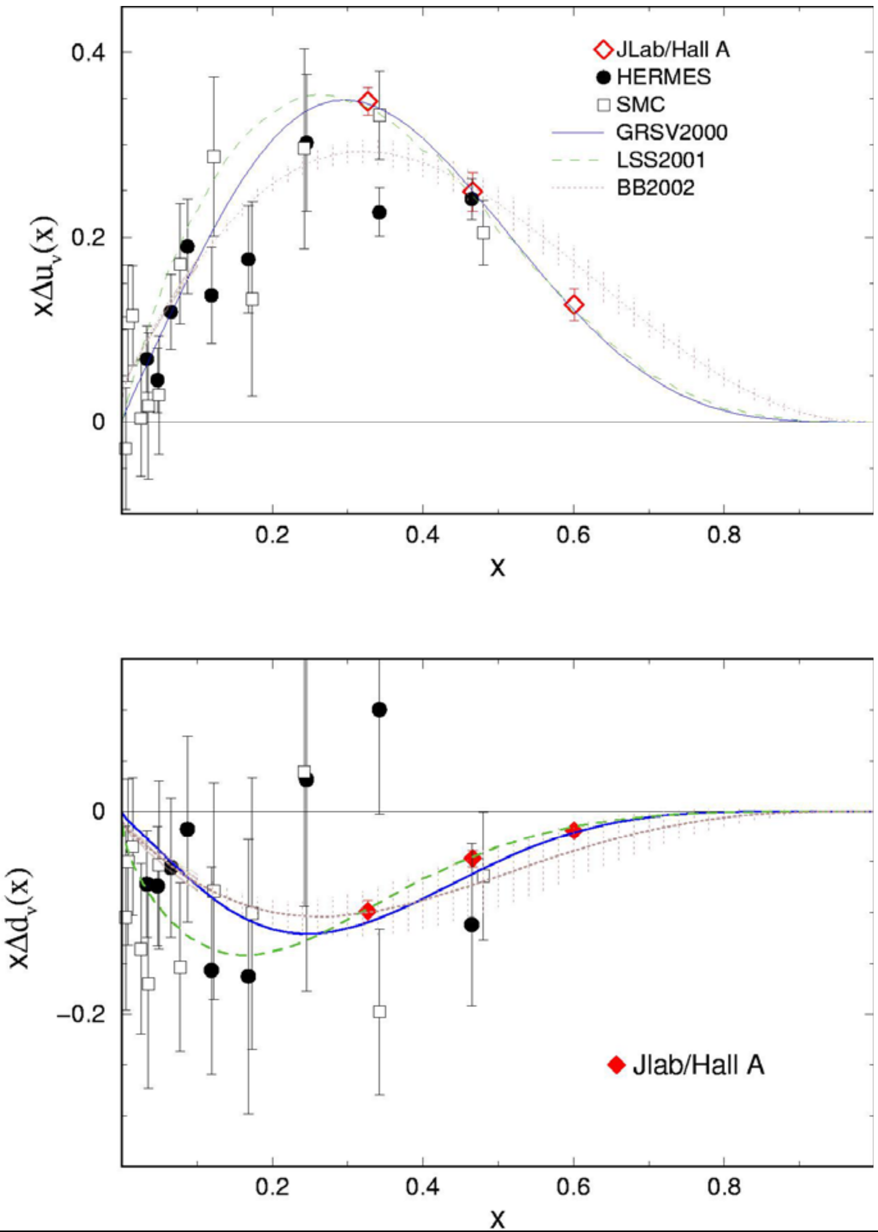
is smaller than experimental uncertainties,

extract

<u>polarized valence quark distributions</u>

(figure adapted from
Review of Particle Properties, PLB 592.)

Flavour decomposition from p/n (3)



<u>Polarized valence quark distributions</u>

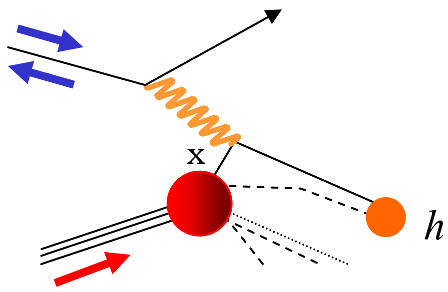
(linear *x*-scale)

using the results of X. Zheng et al.

More from CLAS

to come soon

SIDIS Spin Asymmetries



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

Detect the hadron from the current fragmentation and measure the **double spin asymmetry** $A_{//}^{h}$ in the semi-inclusive process eN → e *h* X

Assuming leading order (naïve) *x-z* factorization, get for each species *h:*

$$A_{1N}^{h}(x,Q^2,z) \equiv \frac{\Delta\sigma^h(x,Q^2,z)}{\sigma^h(x,Q^2,z)} = \frac{\sum_q e_q^2\,\Delta q(x,Q^2)\cdot D_q^h(z,Q^2)}{\sum_q e_q^2\,q(x,Q^2)\cdot D_q^h(z,Q^2)}$$

Measure **double-spin asymmetries**

Semi-inclusive: $h = \pi^+, \pi^-, K^+, K^-$

Inclusive A_1

for both proton and deuteron

and extract

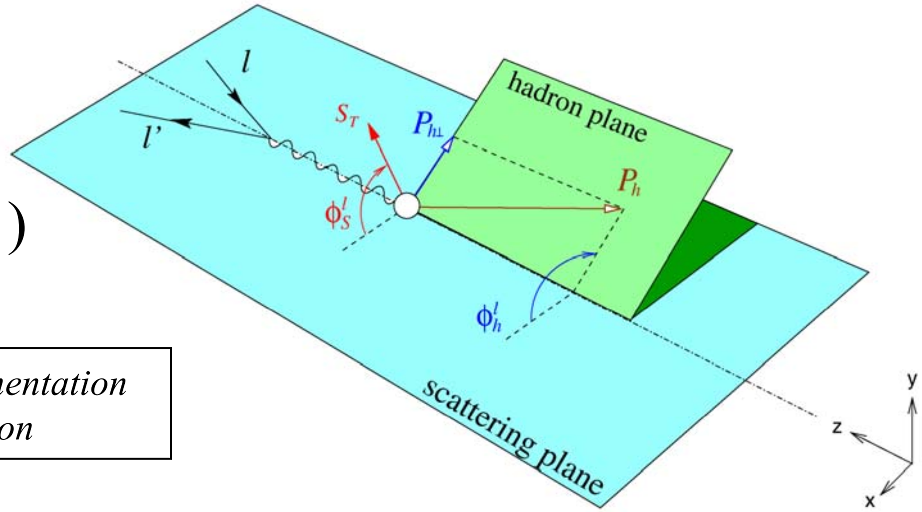
5 polarized quark distribution functions

$$\Delta u > 0,\ \ \Delta d < 0,$$
$$\Delta\bar{u},\ \Delta\bar{d},\ \Delta s \text{ compatible with } 0$$

SMC PLB 420 (1998), **HERMES** PRD 71 (2005) + **JLab** exp.[t] in preparation

Transversity

In semi-inclusive d.i.s., at leading order, one can define 8 response functions (see Mulders).
With a transversely polarized target (S_T), 2 of the 3 contributions should be measurable:



$$\sin(\phi_h^l - \phi_S^l) \times \sum_{q,\bar{q}} e_q^2 \, f_{1T}^{\perp(1)q}(x) \cdot D_1^q(z, P_{h\perp}^2)$$

Asymmetric distribution of $k_\perp$ in a polarized nucleon

Usual fragmentation function

$$\sin(\phi_h^l + \phi_S^l) \times \sum_{q,\bar{q}} e_q^2 \, h_1^q(x) \cdot H_1^{\perp q}(z, P_{h\perp}^2)$$

*"**Transversity**" distribution: quark transverse polarization in a transversely polarized nucleon*

Fragmentation function which describes the correlation of $P_{h\perp}$ with the quark transverse polarization (Collins function)

Transversity (2)

After $q(x)$ and $\Delta q(x)$,

$\boldsymbol{h_1}$ (or $\boldsymbol{\delta q(x)}$ or $\boldsymbol{\Delta_\perp q(x)}$)

is the third $k_\perp$-independent twist-2 quark distribution function

It measures the probability of having quarks with momentum fraction x

and

with transverse polarization in the same direction as the transversely polarized target.

Some characteristics :

$h_1(x) = \Delta q(x)$ for non relativistic quarks

$h_1(x)$ does not mix with gluon distributions in its evolution

$h_1(x)$ suppressed at low x with respect to Δq

Its first moment yields the tensor charge δq calculable in lattice QCD

Transversity (3)

Key experimental issue:

Transverse nucleon polarization

Induces transverse quark polarization → *Collins*

Affects quark transverse momentum distribution → *Sivers*

Both effects visible in transverse momentum distribution of hadron from fragmentation ($e\vec{N} \to e' h X$)

Single Spin Asymmetry **measurements** using transversely polarized
p (**HERMES** PRL 94) ,
d (**COMPASS** PRL 94)
^{3}He (**JLab E03-004** in preparation) .

In the future (**FAIR/PAX & ASSIA**)
double-polarized Drell-Yan production in $\vec{p}\vec{\bar{p}}$ collisions will give direct access to h_1^2 .

(G. Schnell's and Milner/Rathmann's talks)

Single spin asymmetries in SIDIS

- **Rich phenomenology associated with various SSA**

  (HERMES/CLAS A_{UL}/A_{LU} measurements in ep → eπX,
  but also pp → πX)

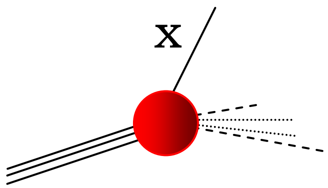
- **SSA linked to transverse momentum distributions (TMD) of partons in the nucleon**

- **SSA ↔ orbital angular momentum**

  ↔ GPD E, Pauli form factor F_2

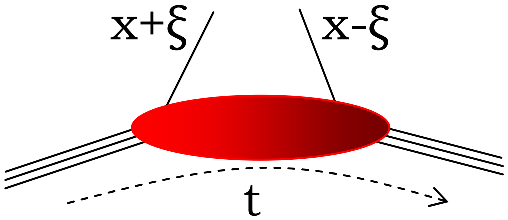
(M. Anselmino' talk)

Generalized Parton Distributions



Probability $|\psi(x)|^2$ that a quark carries a fraction x of the proton momentum

→ "Ordinary" distributions of partons **q(x), Δq(x)** measured in inclusive reactions (D.I.S.)



Coherence $\psi^*(x+\xi)\bullet\psi(x-\xi)$, or interference,

between states of different longitudinal momenta,

+ t-dependence related to transverse distributions

→ **Generalized parton distributions (GPD)**

$H, \tilde{H}, E, \tilde{E}\ (x,\xi,t)$

measured in exclusive reactions (D.E.S.)

Generalized Parton Distributions

Very schematically, for 3q configurations represented by a wave function $\psi(x_1,\vec{k}_1,x_2,\vec{k}_2,x_3,\vec{k}_3)$

Ordinary parton distributions integrate over "spectator" quarks and over all transverse momenta:

$$q(x) \sim \int \left|\psi(x,\vec{k}_1,x_2,\vec{k}_2,x_3,\vec{k}_3)\right|^2 [dX]$$

while GPD's contain correlations

- between states of different longitudinal momenta

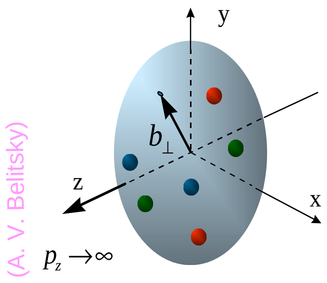
- between longitudinal momentum and transverse position :

$$H(x,\xi,t) \sim \int \psi^*(x-\xi,\vec{k}_1+\vec{\Delta}_\perp,\ldots)\cdot\psi(x+\xi,\vec{k}_1,\ldots)[dX]$$

$$[dX] = \delta(x+x_2+x_3-1)\delta^{(2)}(\vec{k}_1+\vec{k}_2+\vec{k}_3)dx_2dx_3d\vec{k}_1d\vec{k}_2d\vec{k}_3$$

x and t dependence of GPDs: a femto-photography of the nucleon

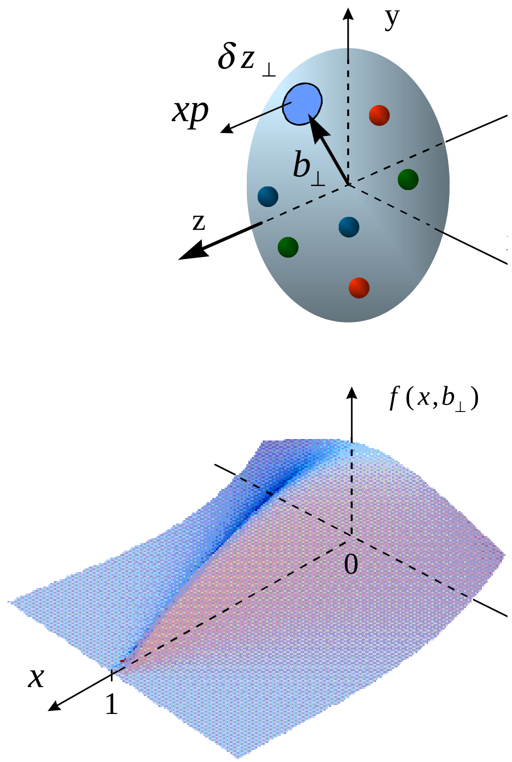
ℱ {Form factor F(t)}



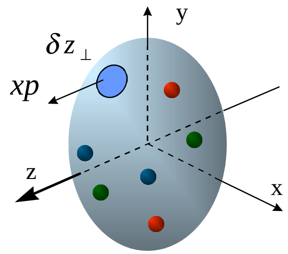
"Actually ***all*** the electromagnetic structure of the proton is, in principle, described by the behavior of these quantities (*the FF*) as a function of *q*."

Hofstadter, 1961

ℱ {GPD (x,0,t)}



Quark distribution q(x)



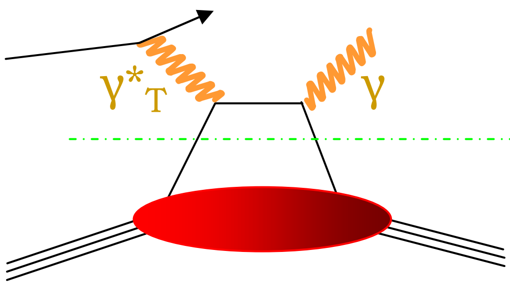
"This expression [..] summarizes ***all*** the information about the structure of the target-particles (nucleon) obtainable by scattering unpolarized electrons from an unpolarized target."

Kendall, 1990

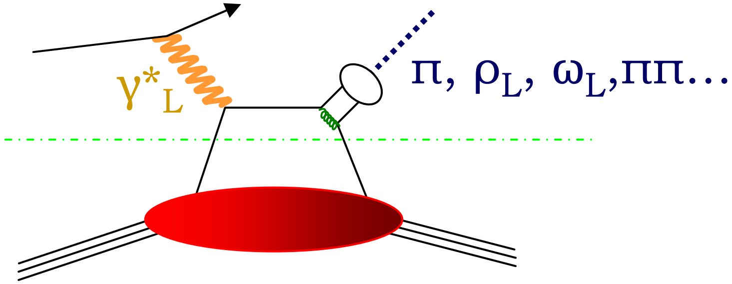
GPDs, while connecting the form factors and parton distributions,
contain much more (but still ***not all***) information about the e-m. structure of the nucleon.

They also have a direct link with orbital angular momentum

Deeply virtual exclusive reactions (DES)



Factorization theorems



DVCS
(Virtual Compton)

- Leading order/twist accessible at moderate Q^2,
- Interference with Bethe-Heitler process,
- Different observables have different sensitivity to the four GPDs,

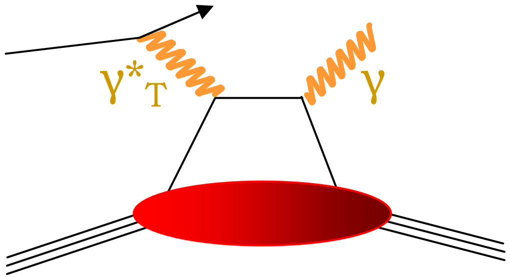
(C. Muñoz Camacho's talk and M. Mazouz' contr.)

DVMP
(Meson production)

- Handbag diagram dominance expected to be reached at higher Q^2,
- Allows a separation (H,E) ↔ ($\tilde{H}$,$\tilde{E}$) and according to quark flavors,
- Necessary to extract longitudinal contribution to observables (σ_L, …).

(C. Hadjidakis' talk)

Deeply virtual exclusive reactions (DES)



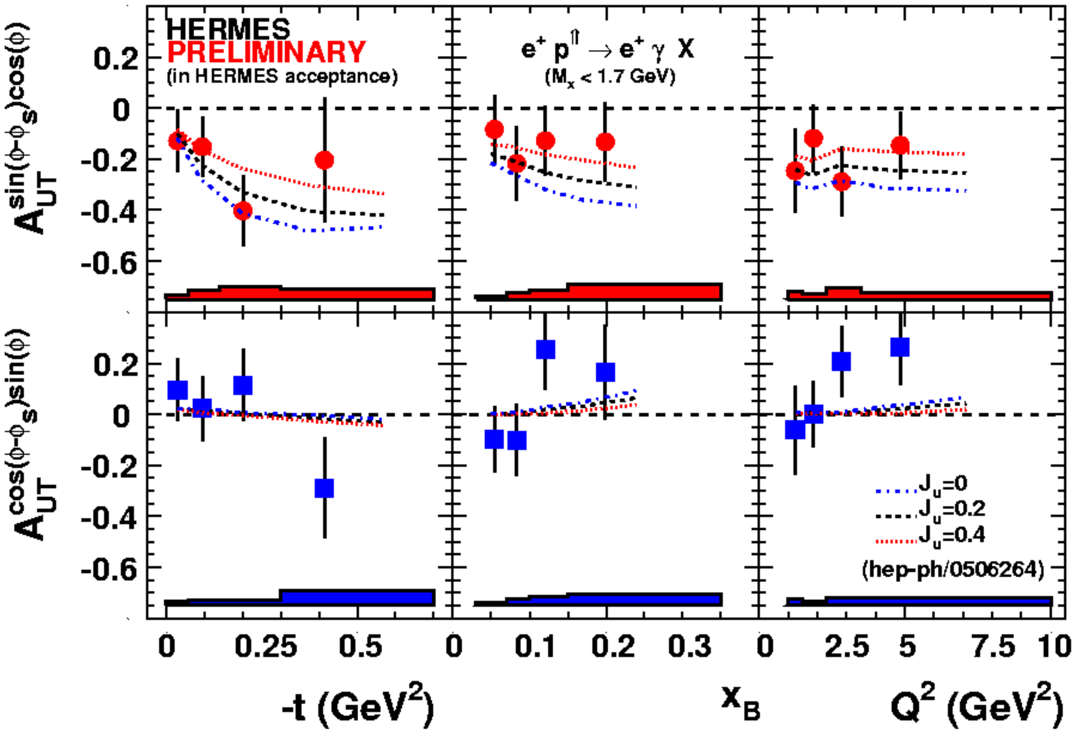
DVCS
(Virtual Compton)

- Leading order/twist accessible at moderate Q^2,

- Interference with Bethe-Heitler process,

- Different observables have different sensitivity to the four GPDs,

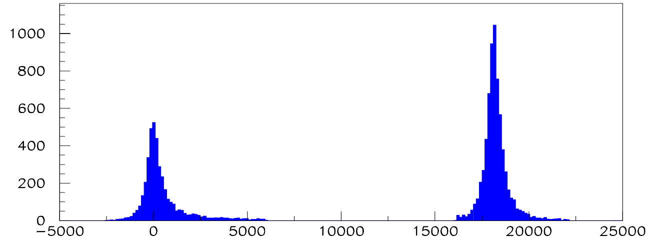
e.g. recent results on transverse target spin asymmetry (A_{UT})



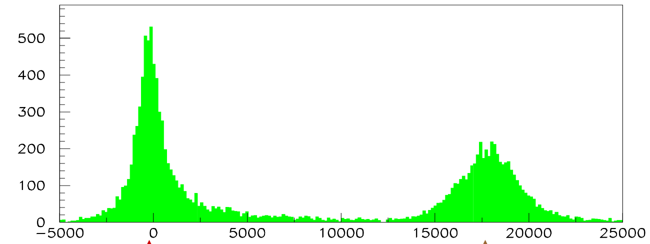
(C. Muñoz Camacho's talk and M. Mazouz' contr.)

D.E.S.: an experimental challenge

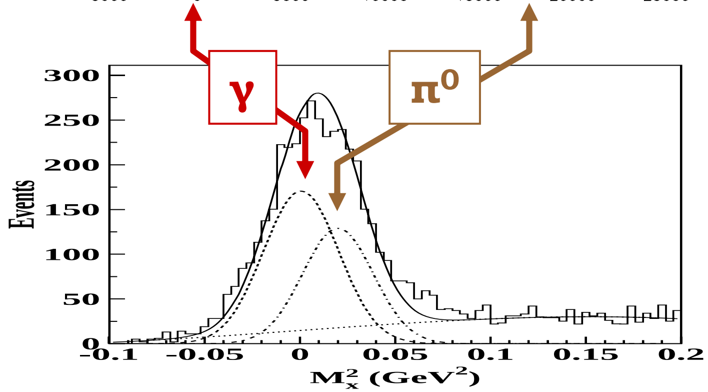
Missing mass M_X^2



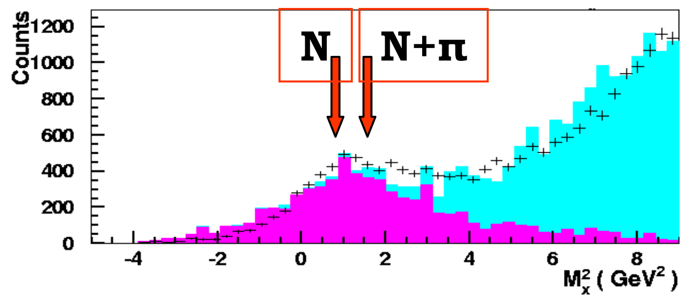
ep → epX
MAMI 850 MeV



ep → epX
Hall A
4 GeV



ep → epX
CLAS
4.2 GeV



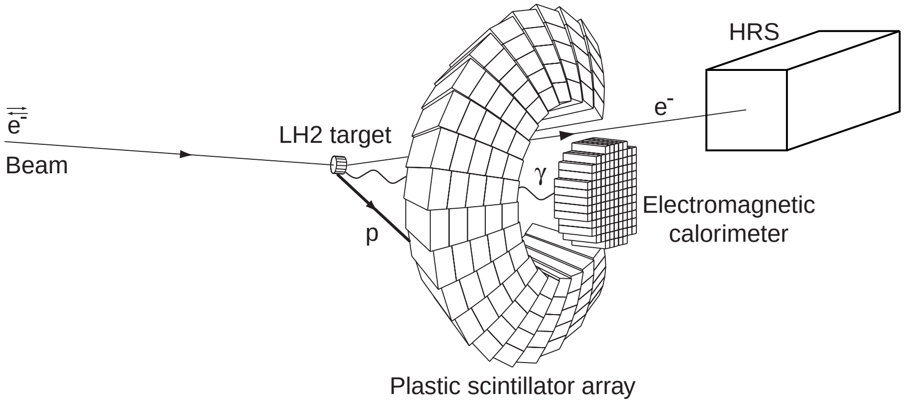
ep → eγX
HERMES
28 GeV

→ Require :

Exclusivity
→ resolution
→ redundant constraints
High Q^2
→ luminosity × acceptance

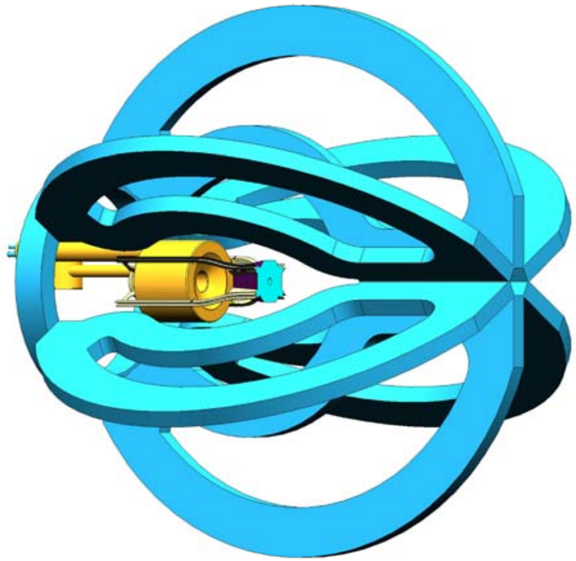
JLab dedicated DVCS experiments in 2004 - 2005

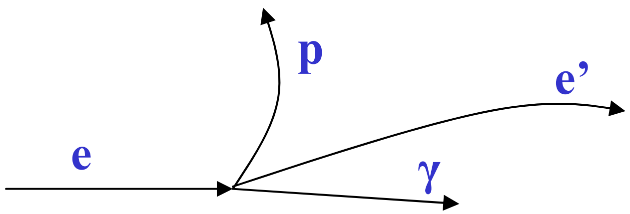
JLab/Hall A



JLab/CLAS

Calorimetrer and supraconducting magnet within CLAS torus





<u>Dedicated, high statistics, DVCS experiments</u>

→ Virtual Compton scattering at the quark level

→ If scaling laws are observed (up to $Q^2 \sim 5$ GeV^2),
or deviations thereof understood,
first significant measurement of GPDs.

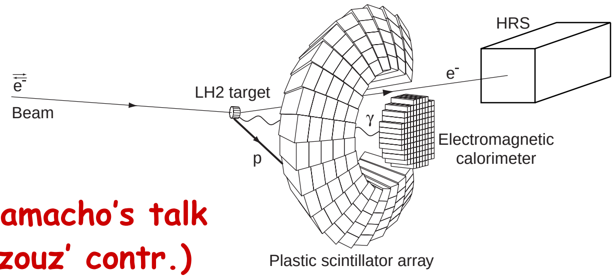
→ Large kinematical coverage in x_B and t
leads to 3D-picture of the nucleon

D.E.S.: an experimental challenge

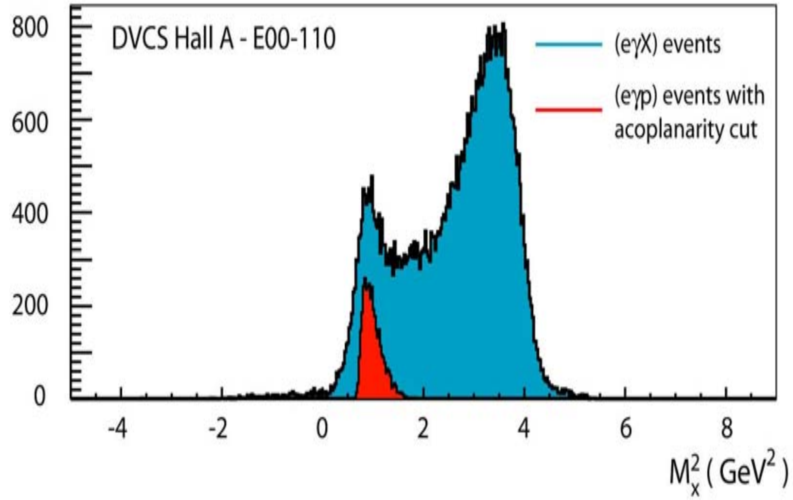
Exclusivity
- → resolution
- → redundant constraints

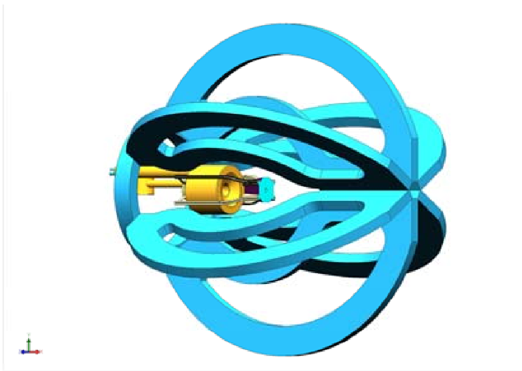
High Q^2
- → luminosity × acceptance

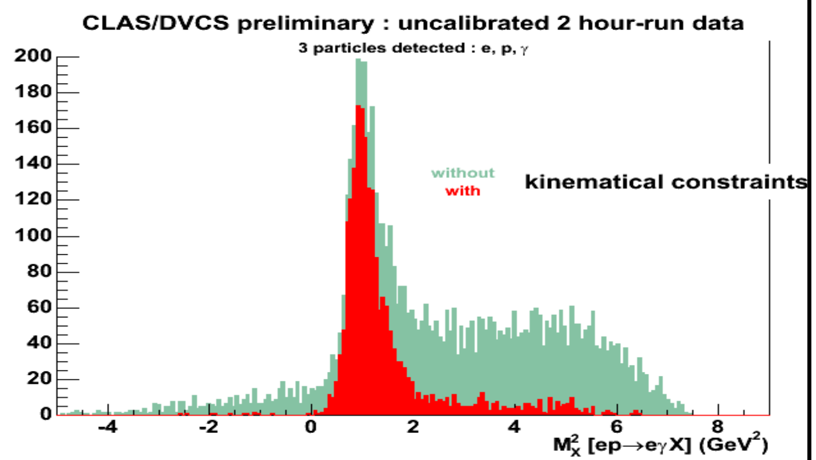
ep → epγ
Hall A & CLAS
5.75 GeV



(C. Muñoz Camacho's talk and M. Mazouz' contr.)



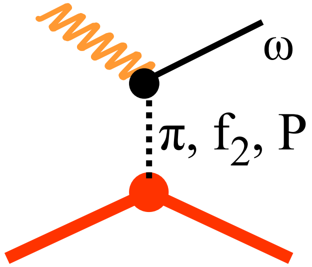




Deeply virtual meson production

Meson and Pomeron (or two-gluon) exchange …

(Photoproduction)

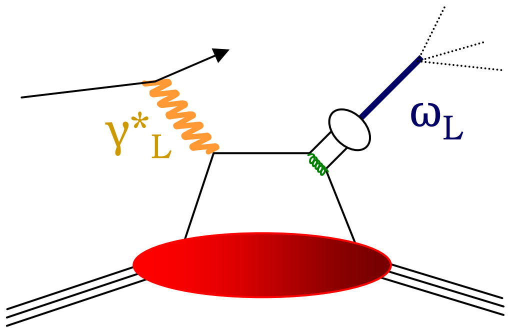


ρ^0	(σ), f_2, P
ω	π, f_2, P
Φ	P

… or scattering at the quark level ?

Flavor sensitivity of DVMP on the proton:

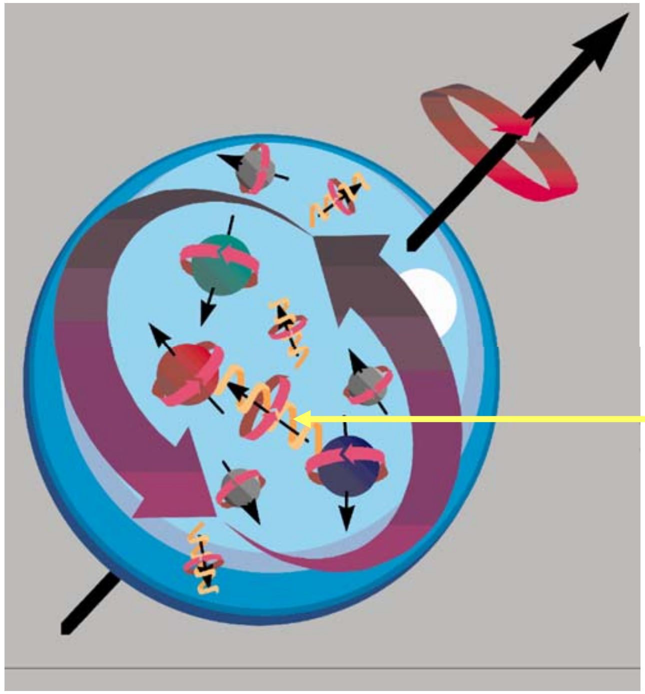
ρ^0	2u+d, 9g/4
ω	2u-d, 3g/4
Φ	s, g
ρ^+	u-d



$$\frac{d\sigma_L}{dt} \propto \frac{1}{Q^4}\left[\frac{\alpha_S}{Q}\sum\iint\frac{\psi_M(z)}{z}\frac{1}{x\pm\xi\mp i\varepsilon}(aH+bE)(x,\xi,t)\,dx\,dz\right]^2 \propto \frac{f(\xi,t)}{Q^6}$$

(C. Hadjidakis' talk)

Nucleon Spin : the role of glue



$$\frac{1}{2} = \left(\frac{1}{2}\Delta\Sigma + L_q\right) + \left(\Delta G + L_g\right)$$

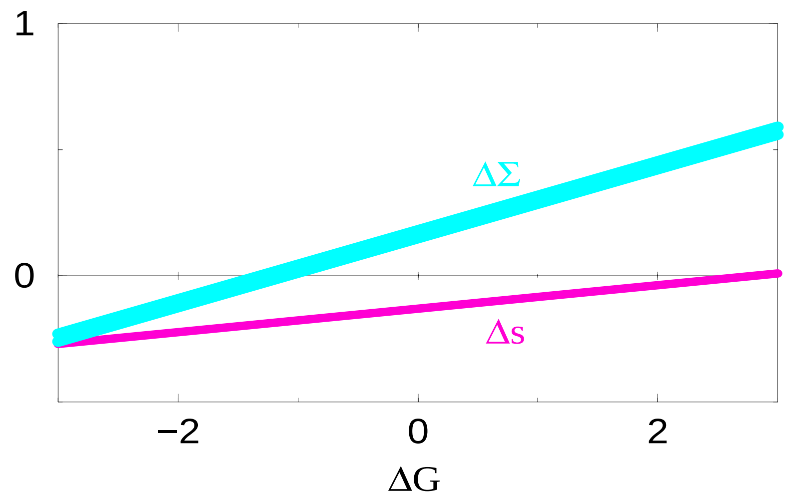
Already measured: $\Delta\Sigma + O(\alpha_s)\Delta G$

$\rightarrow$ **Spin crisis**

Is the contribution of quark intrinsic spin only about 20% ?

role of strange quarks ?

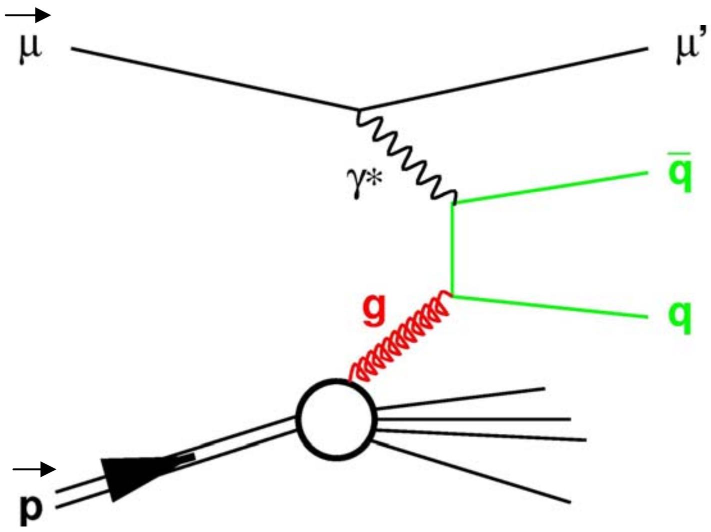
role of gluons ? ΔG ~1 ??



(For a precision: δ(ΔG/G) ~ 0.11)

ΔG/G measurements

Photon gluon fusion (HERMES/COMPASS) $\gamma g \to q\bar{q}$



high p_T hadron pair $q\,\bar{q}$ $\to h^+h^-$

scale : Q^2 or p_T^2

large statistics

but… physical background

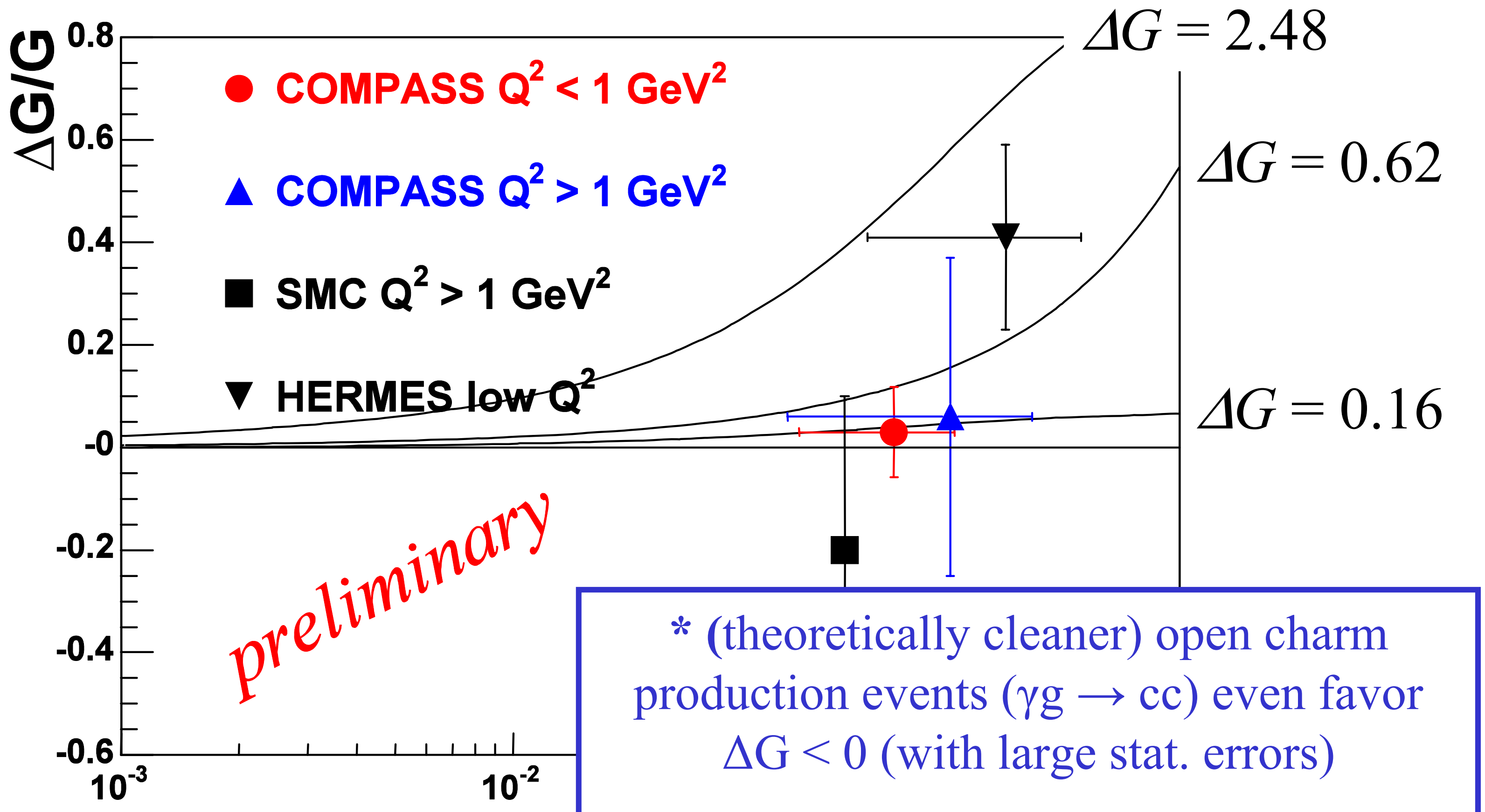
Pion inclusive production (from FNAL E704 to RHIC) $\vec{p}\vec{p} \to \pi^0 X$

PHENIX, PRL 93 (2004)

Gets contributions from *gg→gg, gq→gq, qq→qq:*

$$A_{LL} \propto a\left(\frac{\Delta G}{G}\right)^2 + b\left(\frac{\Delta G}{G}\right) + c$$

ΔG/G measurements



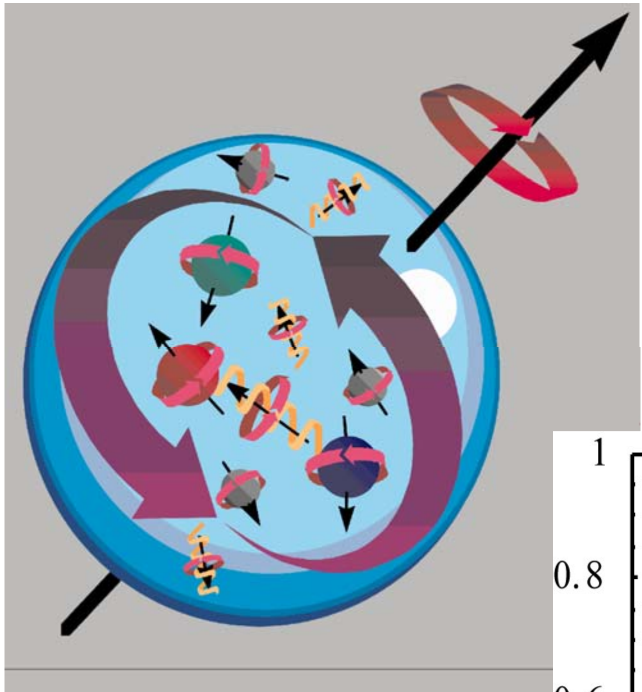
* (theoretically cleaner) open charm production events ($\gamma g \rightarrow cc$) even favor $\Delta G < 0$ (with large stat. errors)

* RHIC A_{LL} favors a small ΔG

IF *ΔG also* is small, where is the spin ?

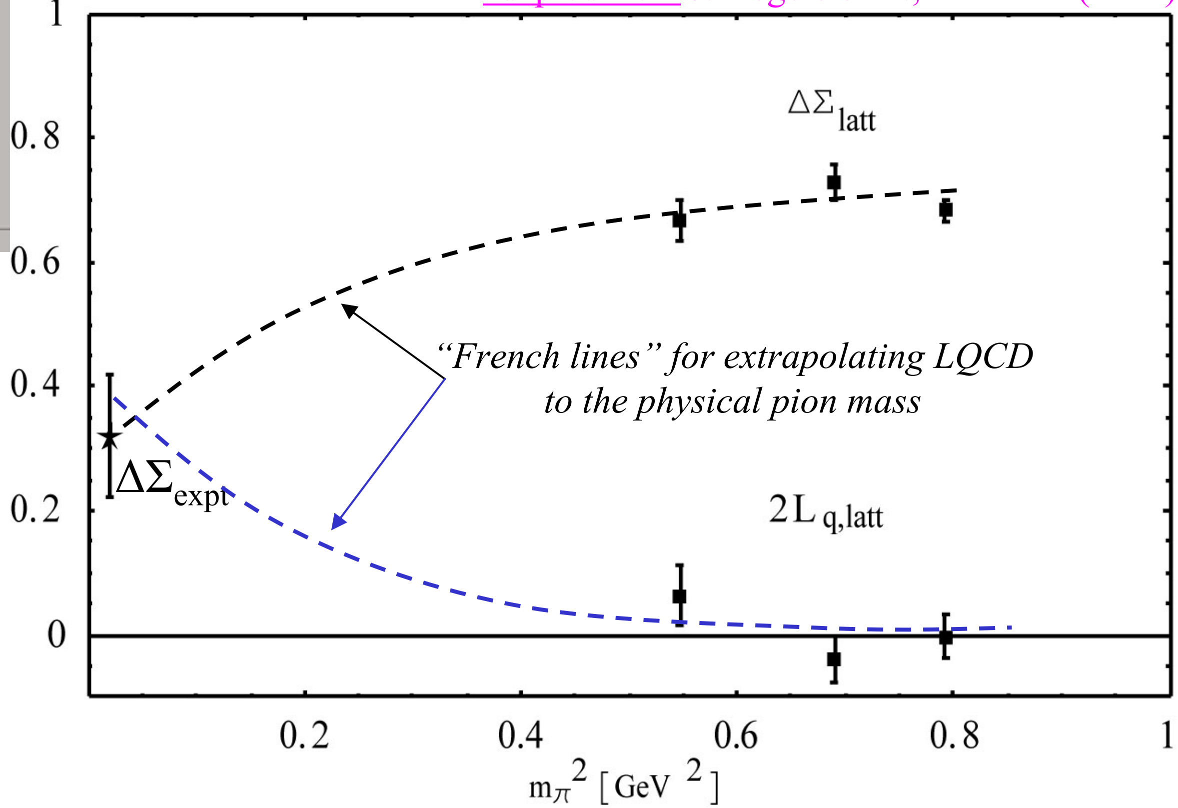
(F. Tessarotto's talk)

Where is the nucleon spin ?



$$\frac{1}{2} = \left(\frac{1}{2}\Delta\Sigma + L_q\right) + \left(\Delta G + L_g\right)$$

adapted from J. Negele et al., NPB 128 (2004)



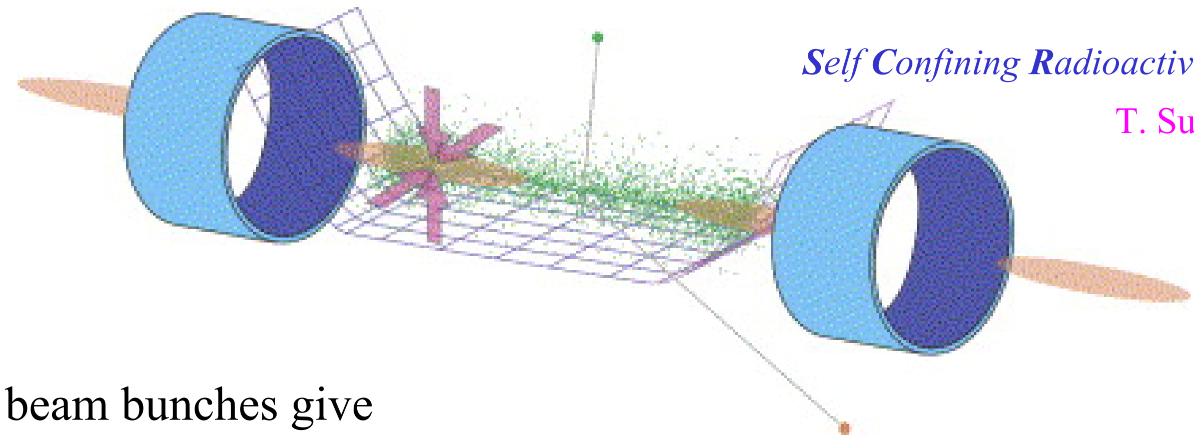
A tentative (and unproven) scenario - at low Q^2 scale :

(see e.g. chiral soliton model Wakamatsu, hep-ph/0506089)

A technical note : e-RI scattering

Electron – Radioactive Isotopes collider still far away (GSI): need L ~ 10^{28} $cm^{-2}s^{-1}$

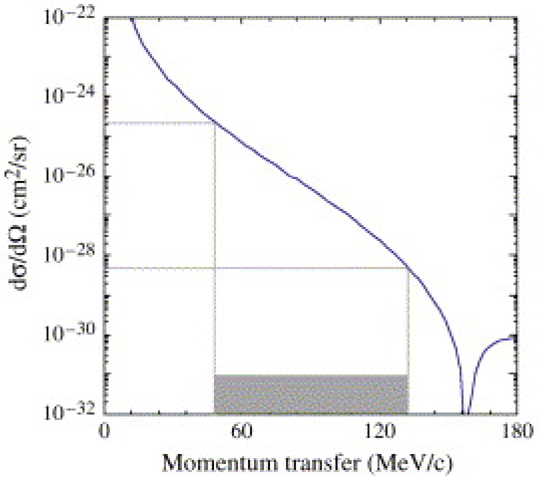
Another method (SCRIT) is being developed at RIKEN:

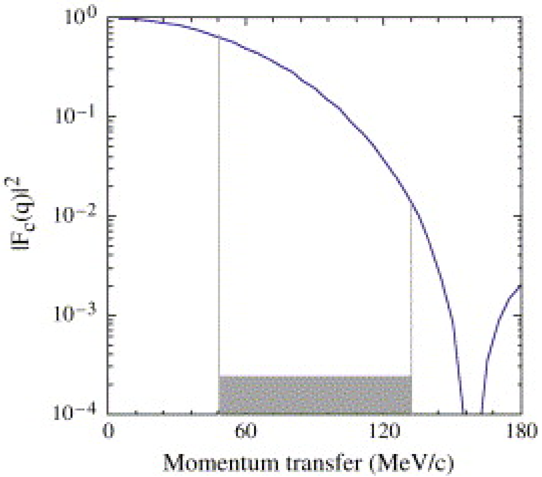


***S**elf **C**onfining **R**adioactive **I**sotope **T**arget*

T. Suda, PPNP 55 (2005)

- electron beam bunches give focusing kick to ions (ion trapping)
- electrodes in the storage ring generate a localized trapped target
- goal: 10^{25} $cm^{-2}s^{-1}$ with stable Cs → 1 Hz





Conclusions and outlook

Nucleon structure:

Precise and exciting new data coming now and in the near future:

Form factors, (polarized) parton distributions, GPD, ΔG,…..

Many topics not (or hardly) addressed in this talk

Hadronic probes

Meson/Baryon spectroscopy

Few-nucleon systems

Hadrons in nuclear matter

Connection with AA collisions: a new state of hadronic matter

Experimental outlook:

New facilities ! **(L. Cardman, H. Shimizu & G. Rosner talks)**