The Nucleon Structure

Bogdan Wojtsekhowski, Hall A

- Nucleon Constituents
- Electromagnetic Form Factors
- Neutron GEN experiment
- Flavor Form Factors
- IMF densities
- Large Q^2 program

Experimental study of structure

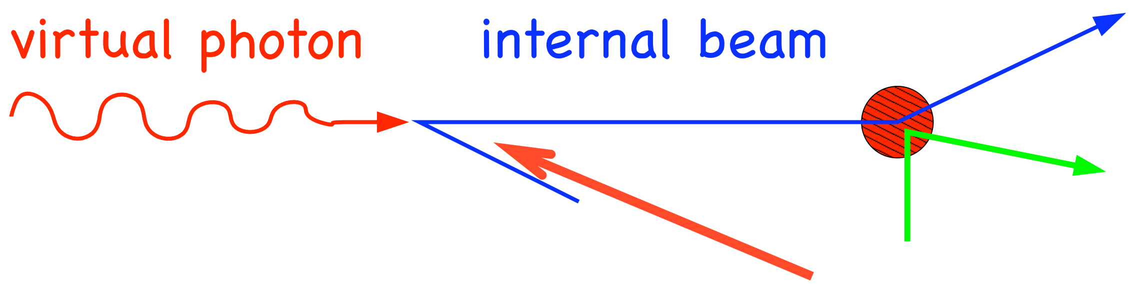
The beam and the target are required for study

e.g. an electron beam and atomic electrons

How one can study the quark-quark "potential" ?

Create "an internal beam" inside the nucleon

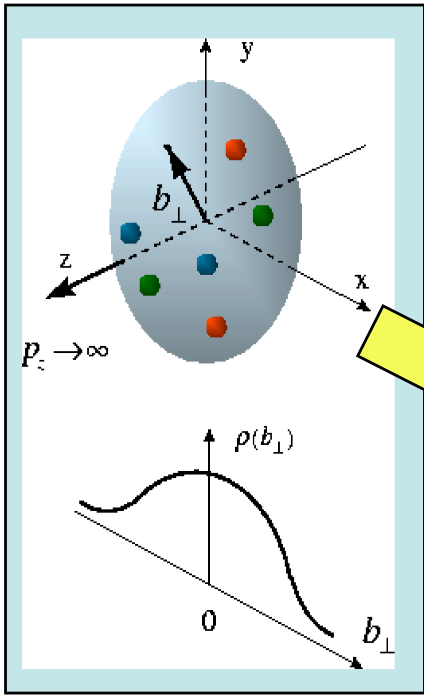
Virtual photon absorption used to accelerate quark

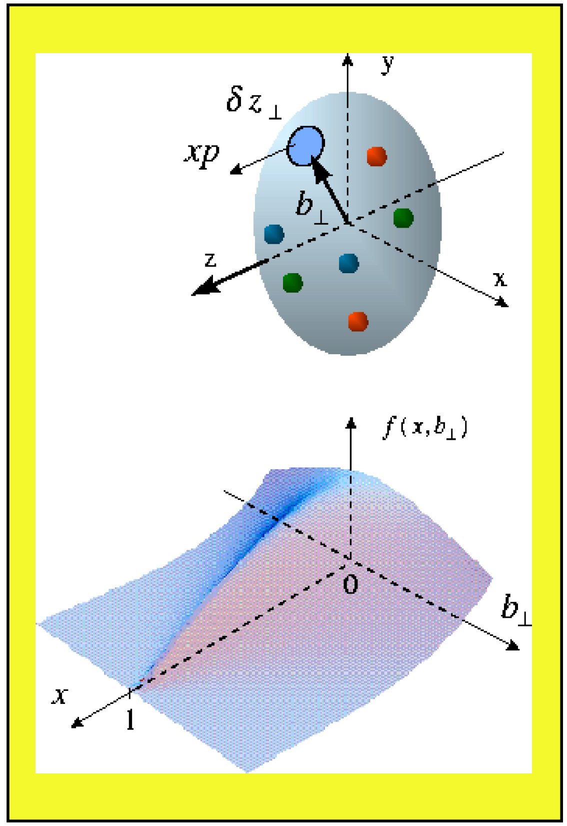


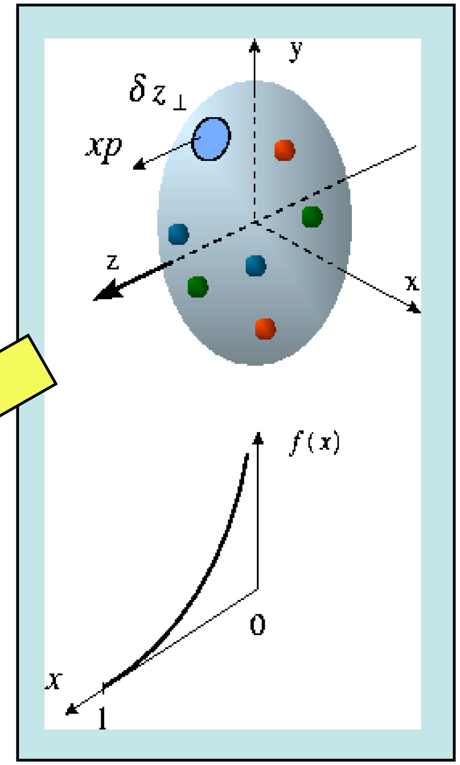
Very productive investigations are DIS, FFs, DVCS, ...

At large Q^2 FF is a measure of q-q correlations at short distances

3-d picture of the nucleon in IMF







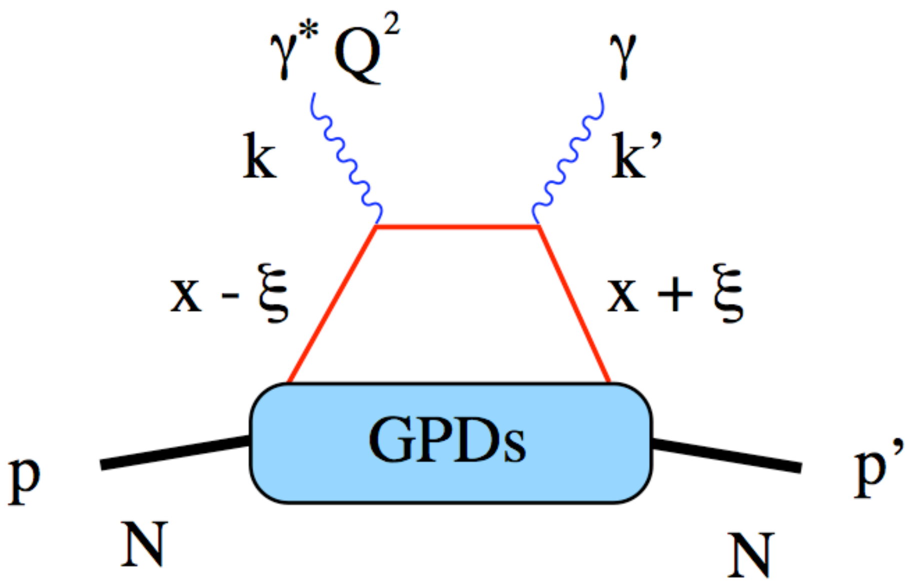
Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

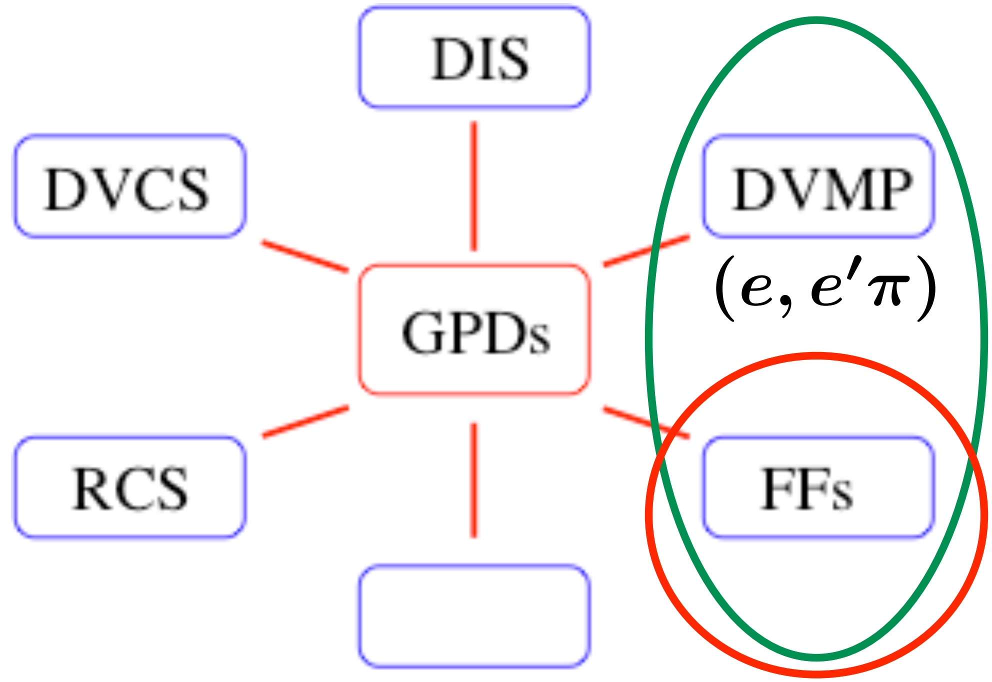
Structure functions, quark longitudinal momentum & helicity distributions

GPDs of the nucleon

Ji, Muller, Radyushkin (1994-1997)



where $\xi = (p_q^+ - p_q'^+)/(p_q^+ + p_q'^+)$



Quark dynamics of the nucleon are encoded in GPDs functions
$H(x, \xi, t)$, $\tilde{H}(x, \xi, t)$ hadron helicity-conserving ;
$E(x, \xi, t)$, and $\tilde{E}(x, \xi, t)$ helicity-flipping distributions.

GPDs information

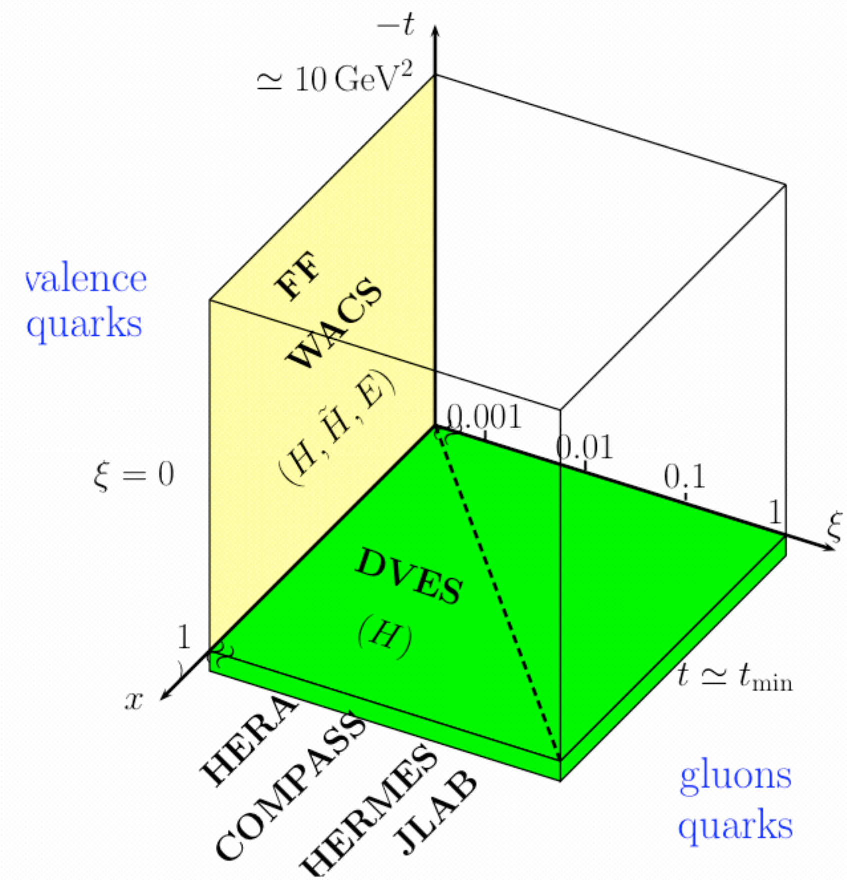
Reduction formulas at $\boldsymbol{\xi = t = 0}$
for DIS and $\boldsymbol{\xi = 0}$ for FFs

$$\boldsymbol{H^q(x, \xi = 0, t = 0) \;=\; q(x)}$$

$$\boldsymbol{\tilde{H}^q(x, \xi = 0, t = 0) \;=\; \Delta q(x)}$$

$$\boldsymbol{\int_{-1}^{+1} dx\, H^q(x, 0, Q^2) \;=\; F_1^q(Q^2)}$$

$$\boldsymbol{\int_{-1}^{+1} dx\, E^q(x, 0, Q^2) \;=\; F_2^q(Q^2)}$$



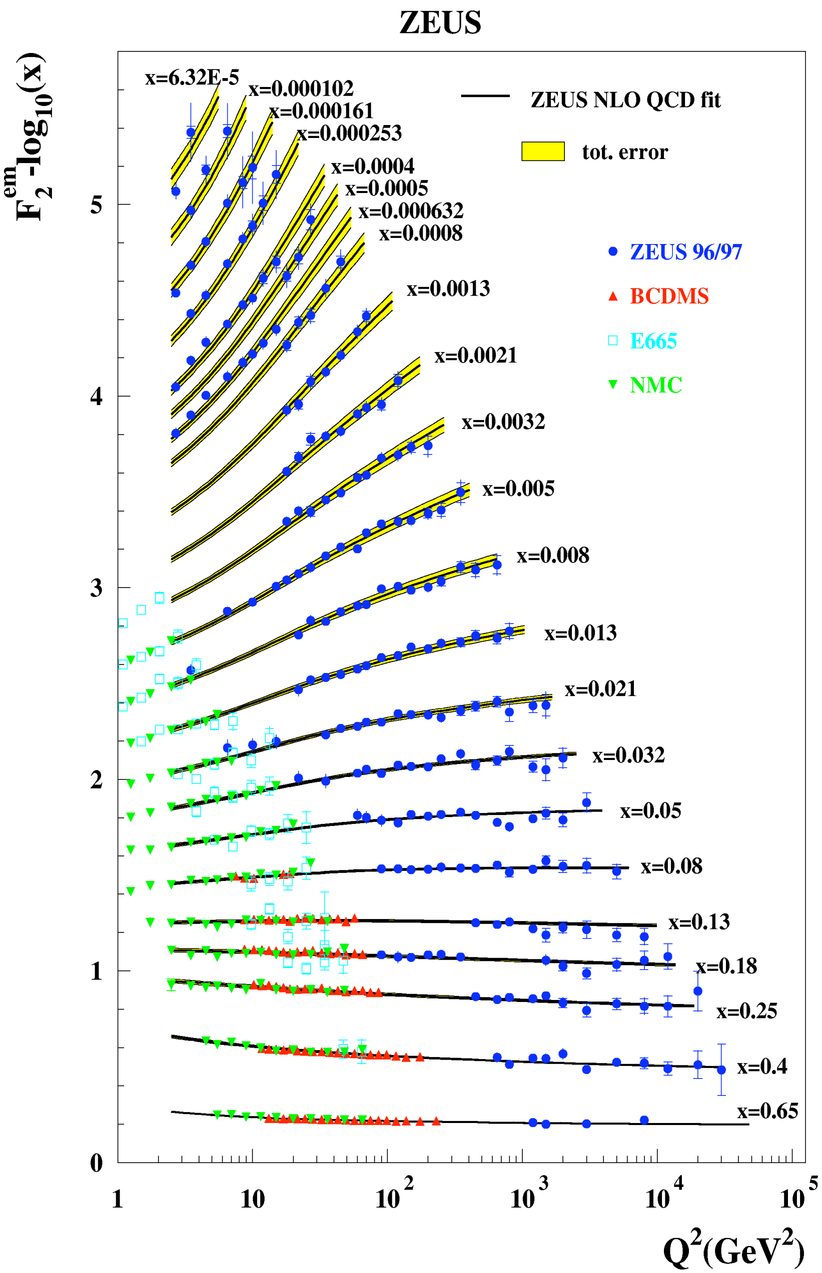
Ji's sum rule for quark orbital momentum

$$\boldsymbol{\langle L^q_v \rangle = \frac{1}{2} \int_0^1 dx [x E^q_v(x, \xi = 0, t = 0) + x q_v(x) - \Delta q_v(x)]}$$

DVCS will access low $\boldsymbol{t}$, large $\boldsymbol{Q^2}$ kinematics

FFs presently are the main source for $\boldsymbol{E^q_v}$

Unpolarized and Polarized Structure functions



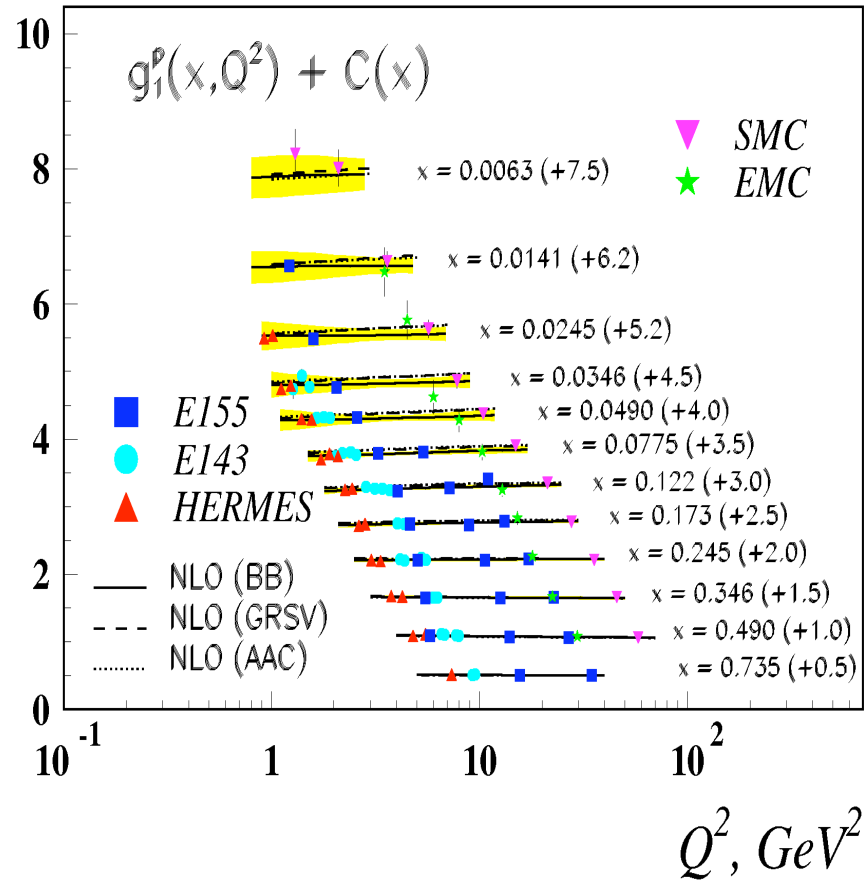
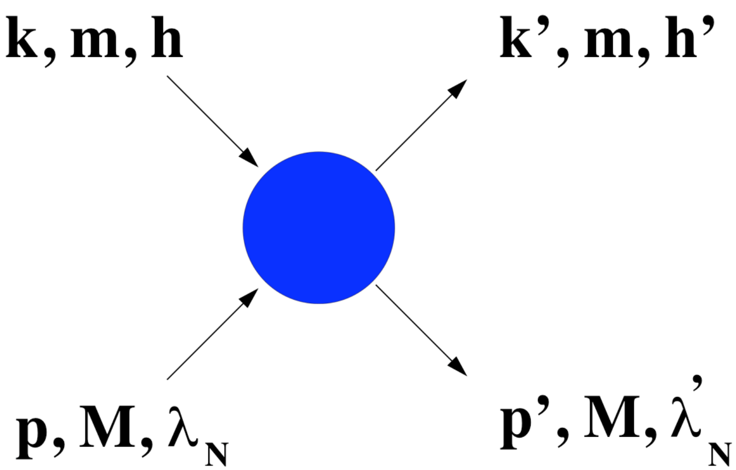


Figure 7: The polarized structure function g_1^p as function of Q^2 in intervals of x. The error bars shown are the statistical and systematic uncertainties added in quadrature. The data are well described by our QCD NLO curves (solid lines), ISET=3, and its fully correlated 1σ error bands calculated by Gaussian error propagation (shaded area). The values of $C(x)$ are given in parentheses. Also shown are the QCD NLO curves obtained by AAC (dashed lines) [15] and GRSV (dashed–dotted lines) [16] for comparison.

Now the focus is Form Factors

Lepton-Nucleon scattering



$$l(k,h) + N(p,\lambda_N) \to l(k',h') + N(p'\lambda'_N)$$

h, h', λ_N, and λ'_N are helicities

$$P = \frac{p+p'}{2},\ K = \frac{k+k'}{2},\ q = k - k' = p' - p$$

$$s = (p+k)^2,\ t = q^2 = -Q^2,\ u = (p-k')^2$$

$$T^{h',h}_{\lambda'_N,\lambda_N} \equiv \langle k', h'; p', \lambda'_N \,|\, T \,|k, h; p, \lambda_N\rangle$$

Total 16 amplitudes.
Parity invariance $\to$ number of independent helicity amplitudes from 16 to 8.
Time reversal invariance $\to$ to 6.
When neglect the lepton mass $\to$ to 3.

Three complex amplitudes

$$T^{+,+}_{+,+}\ ;\quad T^{+,+}_{-,-}\ ;\quad T^{+,+}_{-,+} = T^{+,+}_{+,-}$$
which are functions of $(s-u)$ and t.

Dirac, Pauli and Sachs Form Factors

Hadron current, one-photon approximation, α_{em} = 1/137, Rosenbluth,1950

$$\mathcal{J}^{\mu}_{hadron} = ie\bar{N}(p_f)\left[\gamma^{\nu} F_1(Q^2) + \frac{i\sigma^{\mu\nu} q_{\nu}}{2M} F_2(Q^2)\right] N(p_i)$$

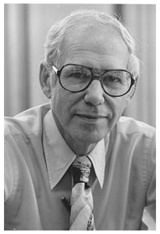
Cross section and asymmetry for electron-nucleon scattering

$$d\sigma = d\sigma_{NS}\,\underline{\{\varepsilon(G_E)^2 + \tau(G_M)^2\}} \cdot [1 + h_e A(G_E, G_M)]$$

$$A = A_{\perp} + A_{\parallel} = \frac{a\cdot G_E G_M \sin\theta^{\star} \cos\phi^{\star}}{G_E^2 + c\cdot G_M^2} + \frac{b\cdot G_M^2 \cos\theta^{\star}}{G_E^2 + c\cdot G_M^2}$$

Sachs, 1962

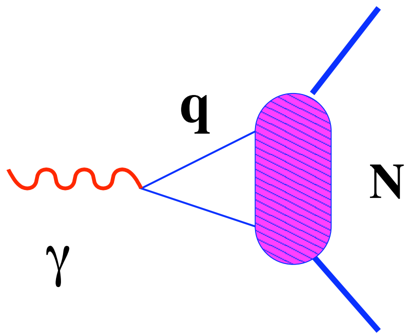
Does a nucleon have a core ?



$$G_E = F_1(Q^2) - \frac{Q^2}{4M^2} F_2(Q^2) \qquad G_M = F_1(Q^2) + F_2(Q^2)$$

$$J_{fi} = 2E \cdot F(-\vec{q}^{\,2}), \quad \vec{J} = 0 \qquad \rho(r) = \frac{1}{(2\pi)^3} \int F(-\vec{q}^{\,2}) e^{i\vec{q}\vec{r}} d^3\vec{q}$$

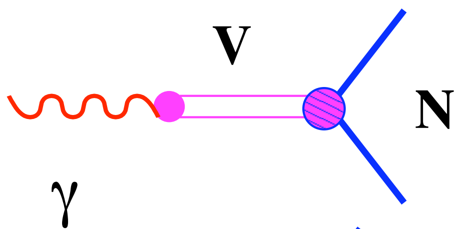
The mechanism of electron-nucleon scattering



Generalized Parton Distributions

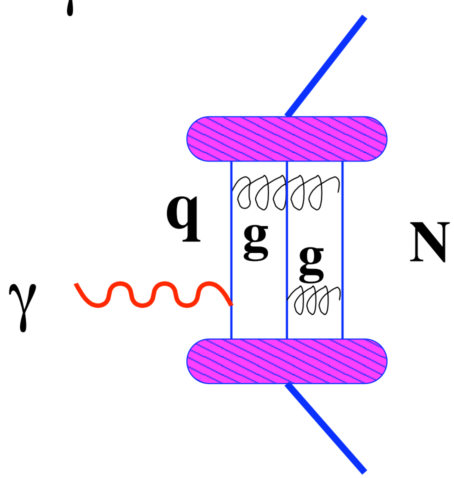
$$F_1(Q^2) = \sum_q \int H_q(x, Q^2)dx$$

$$F_2(Q^2) = \sum_q \int E_q(x, Q^2)dx$$



Vector Meson Dominance

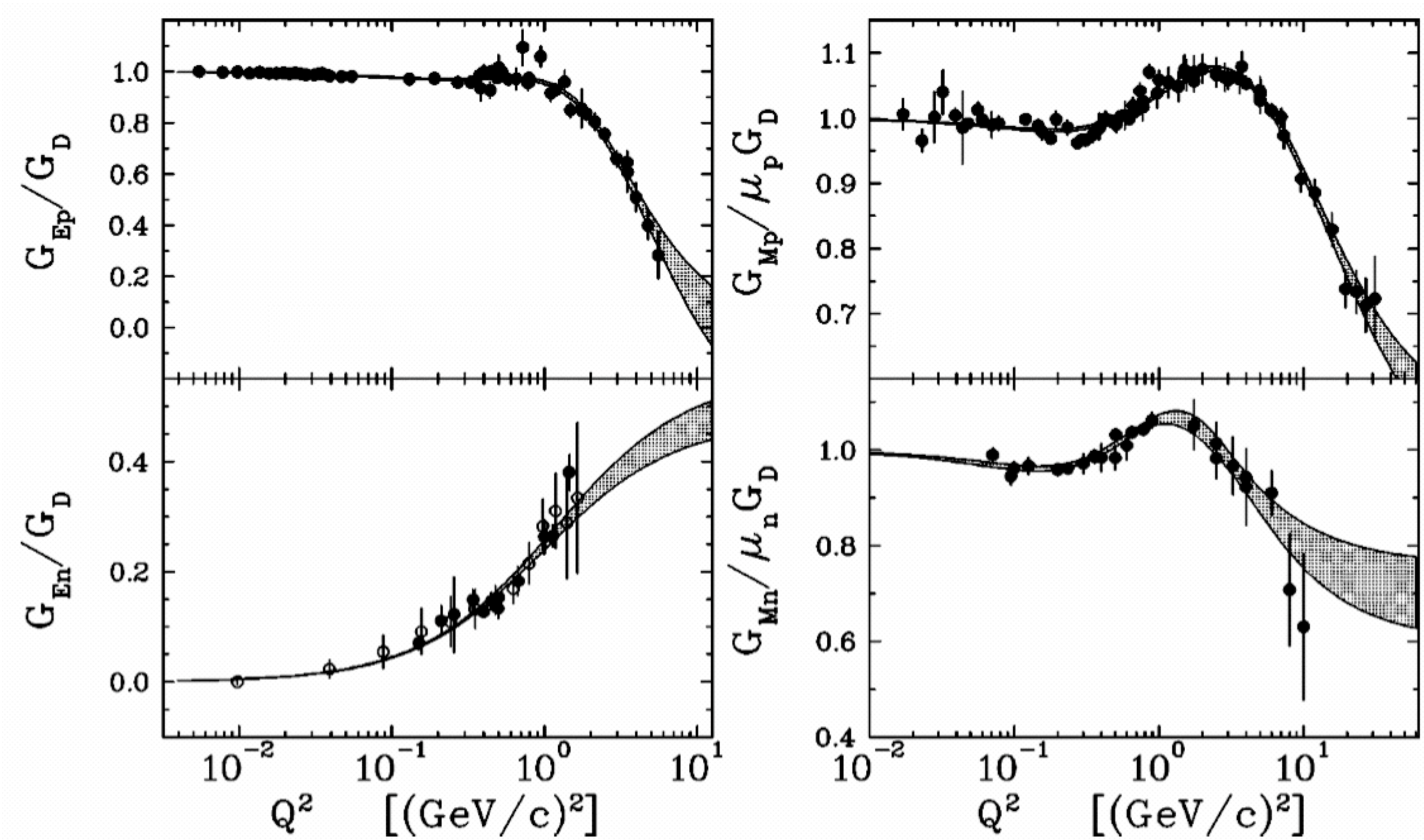
$$V = \rho,\ \rho',\ \omega \ldots$$



Two-gluon exchange (with OAM)

$$F_2/F_1 \propto \frac{1}{Q^2} ln^2(Q^2/\Lambda^2)$$

Kelly's Parameterization

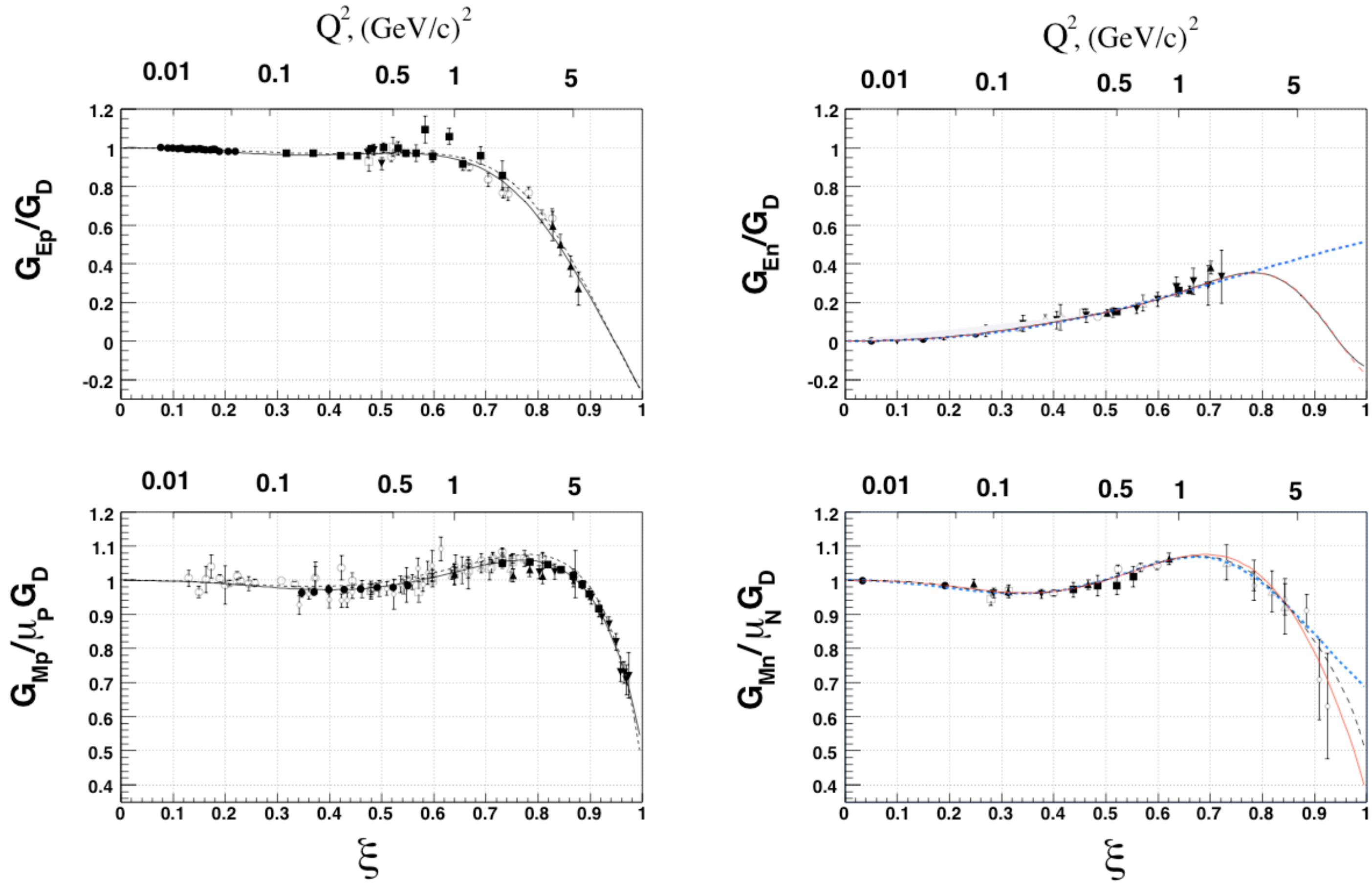


J. Kelly, PRC 70, 068202 (2004)

$$G\left(Q^2\right) = \sum_{k=0}^{n=1} a_k \tau^k / (1 + \sum_{k=1}^{n+2=3} b_k \tau^k)$$

scaling constraint: $Q \to \infty$, $G \sim Q^{-4}$

Duality constrained parameterization



Bodek, Avvakumov, Bradford, Budd arXiv:hep-ex 0708.1946

ξ is Nachtman scaling variable

Two constraints QCD motivated

Kelly's

(d/u) = 0, 0.2

$$\xi^{p,n} = 2/(1+\sqrt{1+\tau^{-1}_{p,n}})$$

constrains: at $\xi \to 1$

$$G_{BABB} = A(\xi) \times G_{Kelly}(Q^2)$$

1) $\dfrac{G^2_{Mn}}{G^2_{Mp}} = \dfrac{1+4(d/u)}{4+(d/u)}$ 2) $\dfrac{G^2_{En}}{G^2_{Mn}} = \dfrac{G^2_{Ep}}{G^2_{Mp}}$

Now the focus is GEn

Why we study the neutron Charge Form Factor?

- Test of the QCD motivated FF models is a powerful approach to the understanding of confinement
- Charge density is a fundamental property of the neutron
- Flavor separated FFs are a productive test of lattice QCD
- Unique constraint on the model of GPDs E_u and E_d
- Dirac/Pauli density for up and down quarks and its connection to the Siver's effect
- Applications e.g. for the neutrino-nuclei cross section

Concept of High Q^2 G_E^n experiment

- **Optimization** of the large-acceptance high-luminosity G_E^n experiment:
  - a polarized ^{3}He target (re-use E94-010 target)
  - a dipole magnet for electron arm (re-use BigBite from NIKHEF)
  - a matching neutron detector (re-use UVa and CMU bars)
  - a trigger with a calorimeter (re-use E99-114 electronics)

- **A key idea:** focus on higher Q^2
  at 2-3 GeV^2 there is G_E^p/G_M^p effect, 3q-state dominance at high Q^2
  also $Q^2 > 2$ GeV^2 Glauber method becomes sufficiently accurate

- **Target Figure-of-Merit:** $J_{beam}^{max} \, t_{target} \, P_{target}^2$

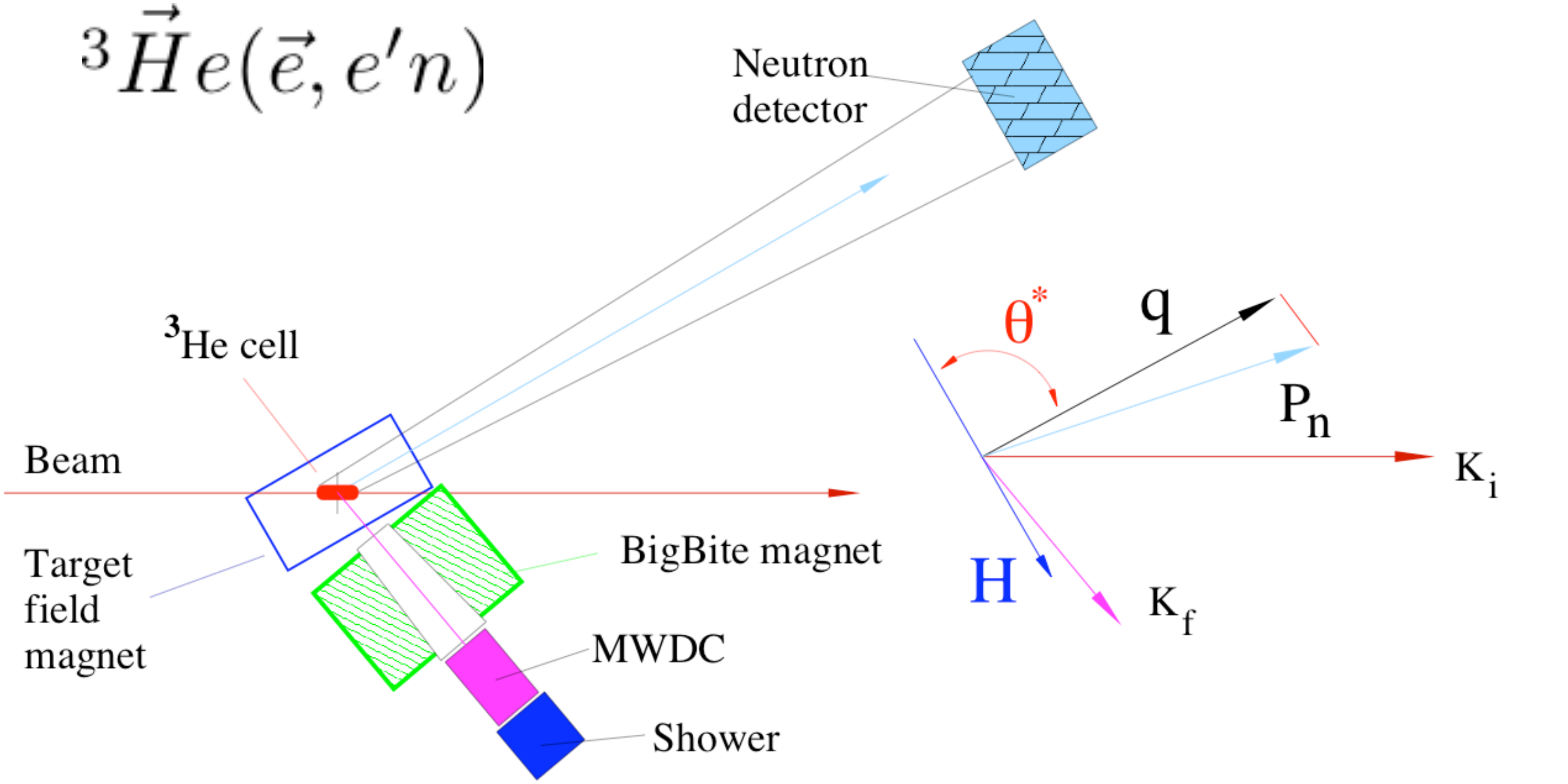
  Electron-polarized neutron luminosity and high polarization of ^{3}He target make the measurement about 10 times more effective than with ND_3 polarized target.

- **Productivity of experiment** – target FoM in combination with a large acceptance electron spectrometer: the total enhancement is more than 100, which is a key to reaching Q^2=3.5 GeV^2

Conceptual setup of E02-013

$$A_{phys} = A_\perp + A_\parallel = \frac{a \cdot G_E G_M \sin\theta^\star \cos\phi^\star}{G_E^2 + c \cdot G_M^2} + \frac{b \cdot G_M^2 \cos\theta^\star}{G_E^2 + c \cdot G_M^2}$$

$$^3\vec{He}(\vec{e}, e'n)$$



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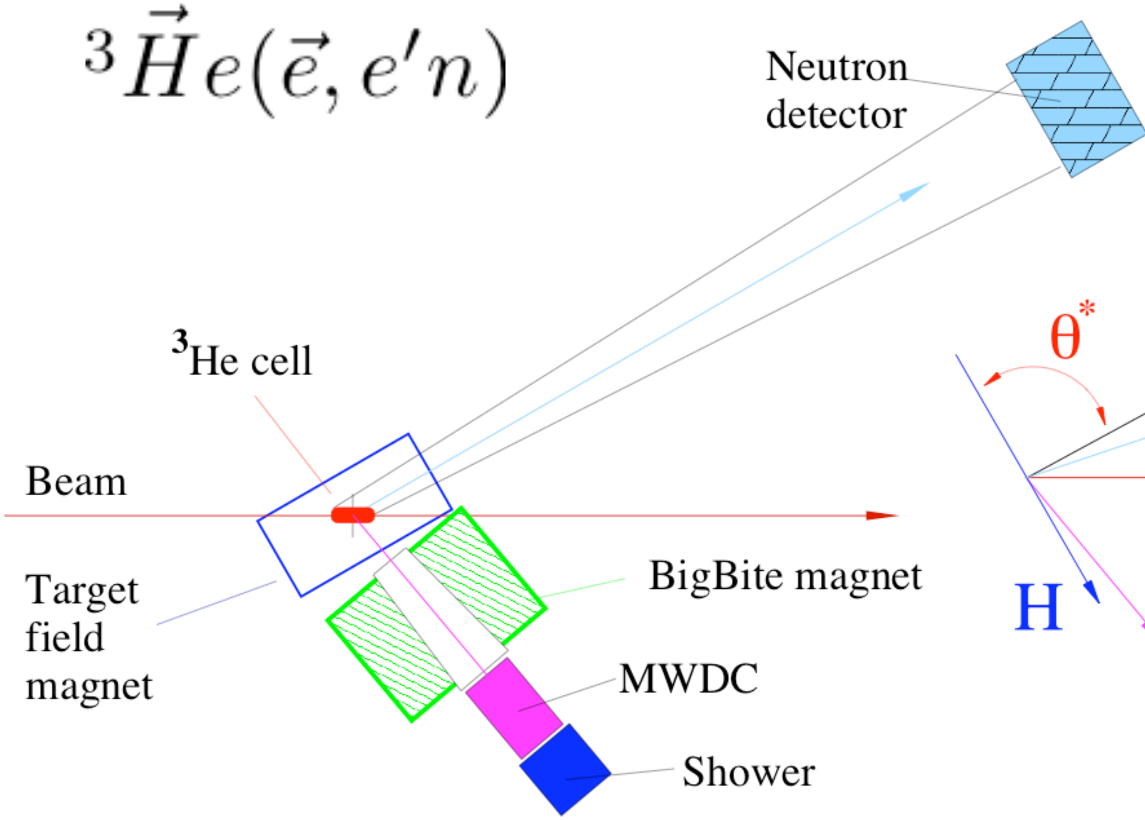
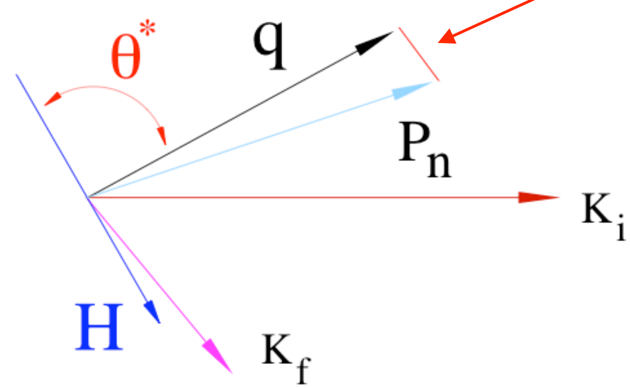
$$^3\vec{H}e(\vec{e}, e'n)$$

$\theta^* \sim 90°$

$A_{phys} \propto G_E^n$

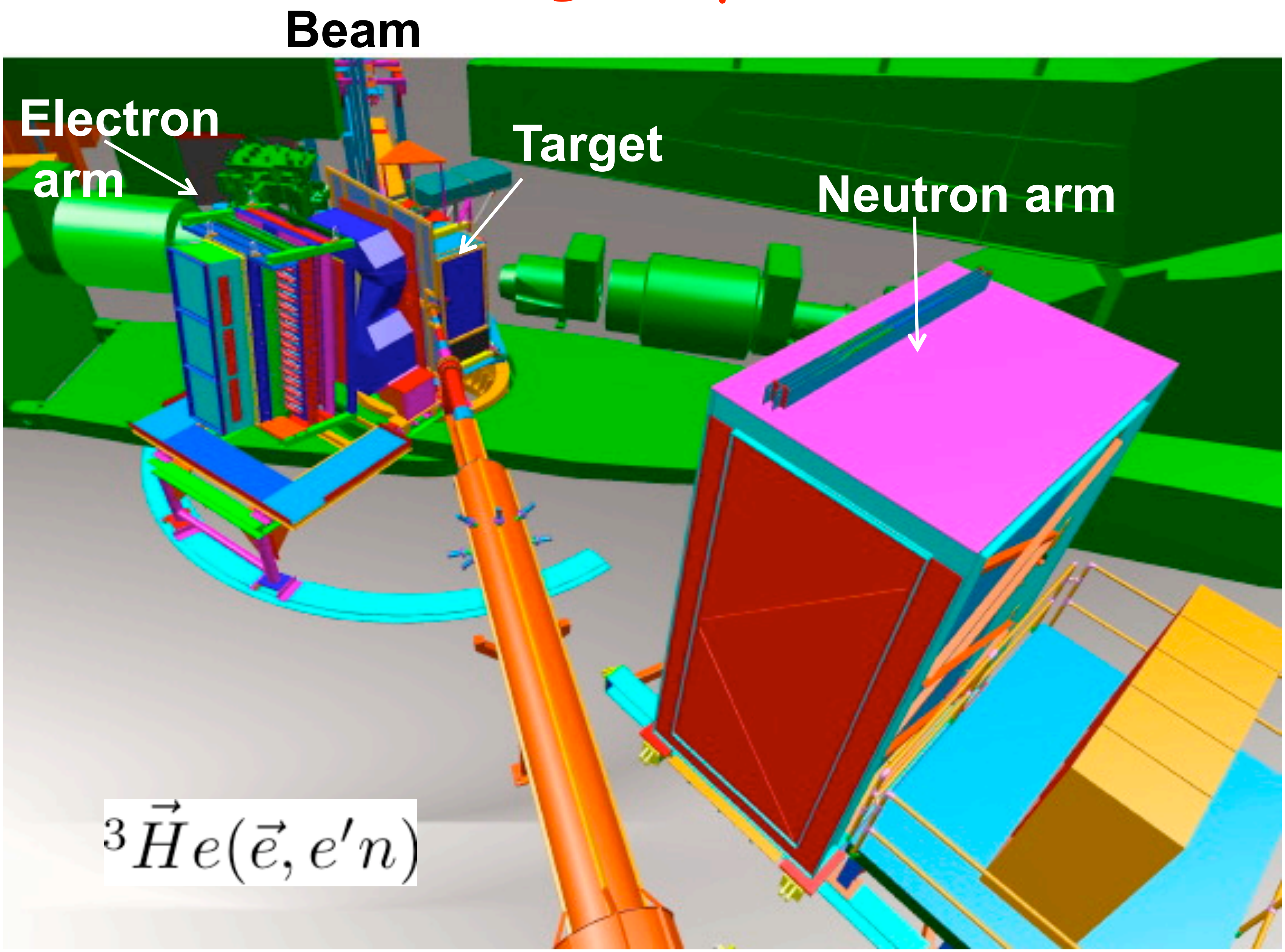
$p_{\perp} = |(\vec{p}_n - \vec{q}) \perp \vec{q}|$





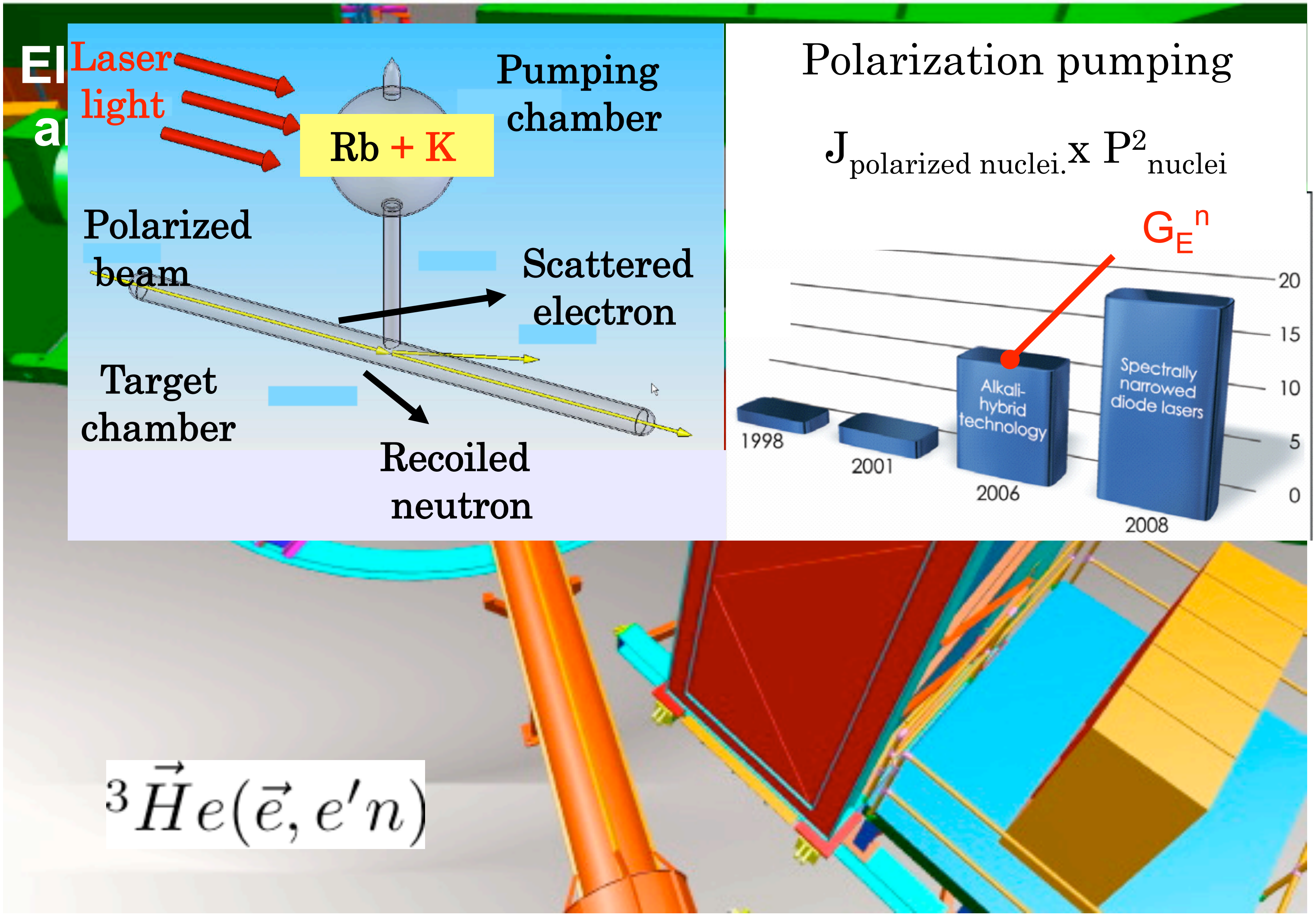
Selection of Quasi-Elastic
by cut $P_{\perp} < 150$ MeV

Hall A G_E^n experiment



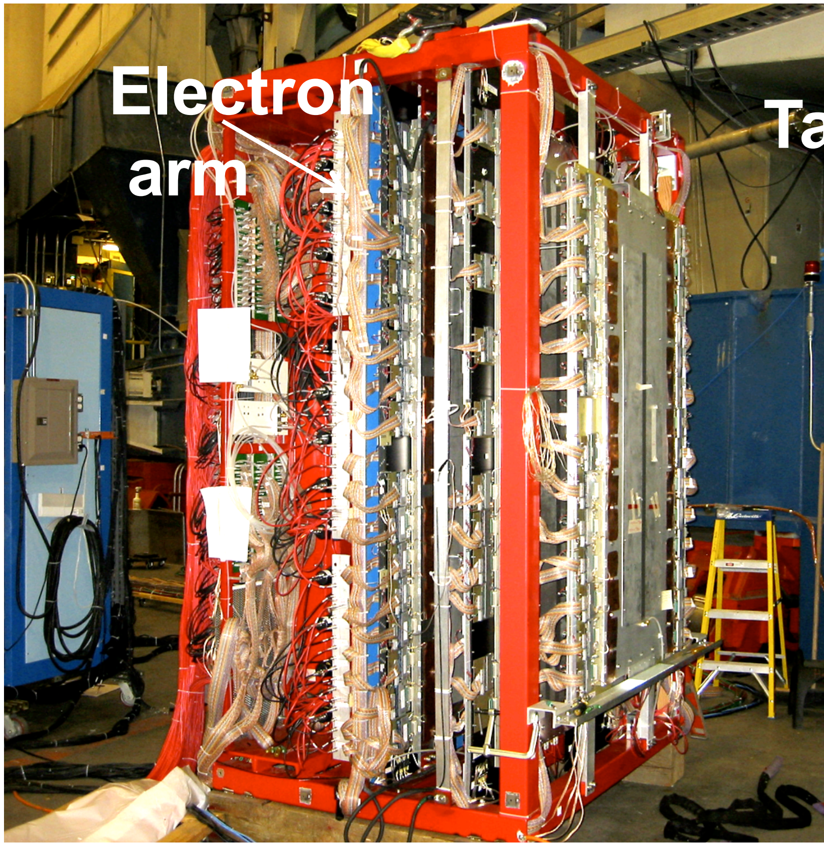
Hall A G_E^n experiment

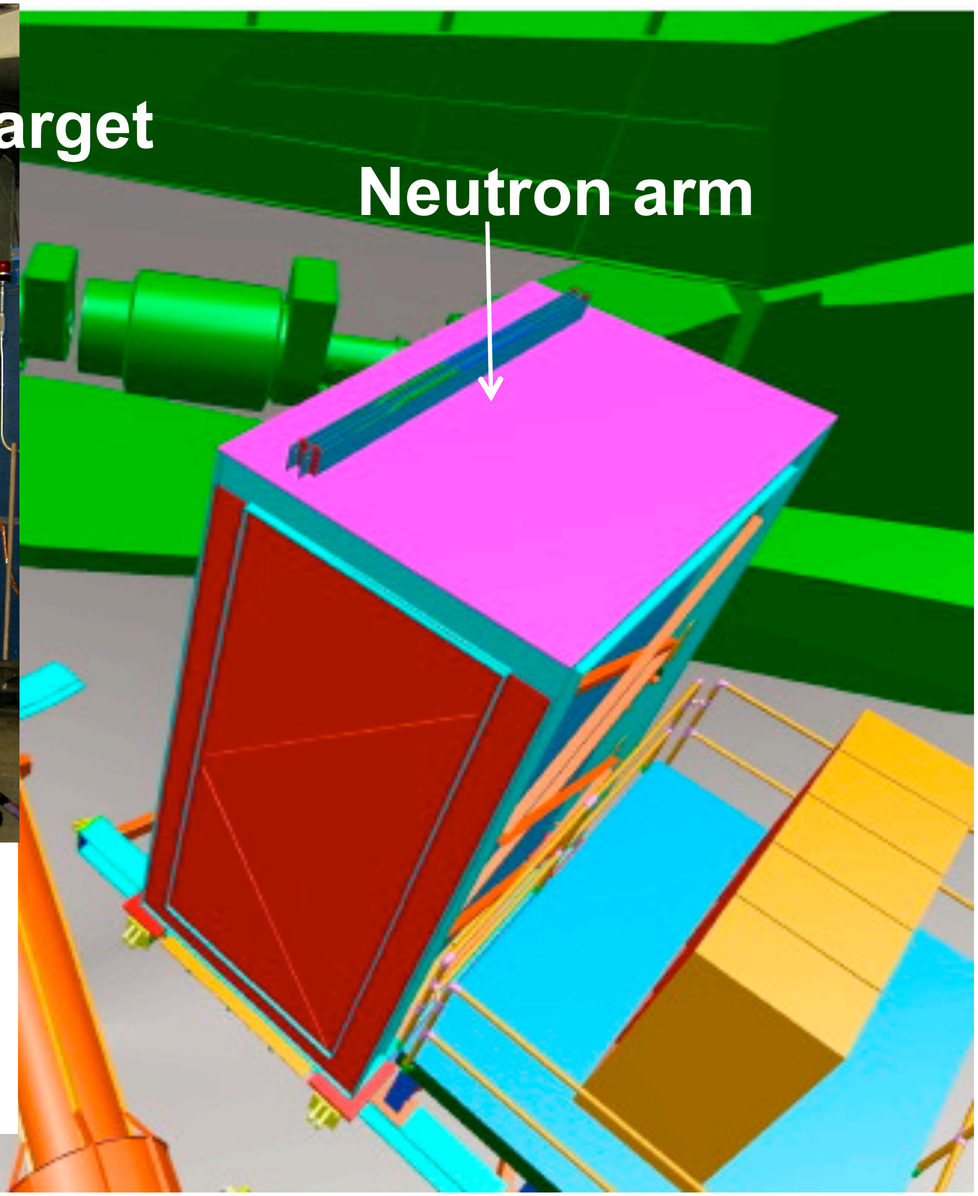
Beam



$^3\vec{H}e(\vec{e},e'n)$

Hall A G_E^n experiment

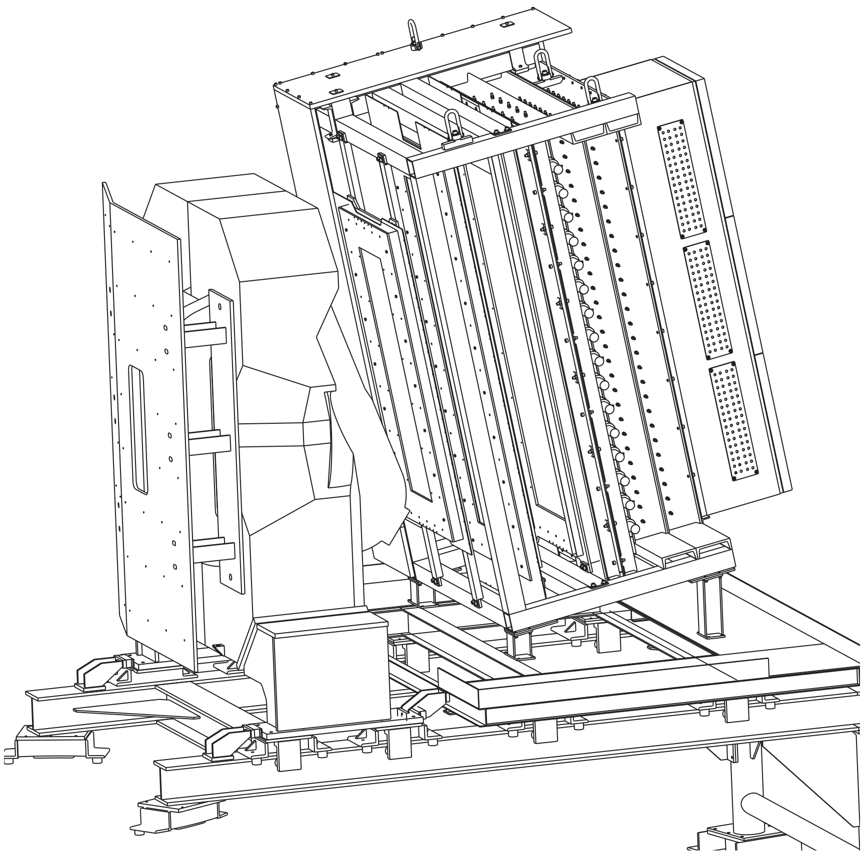


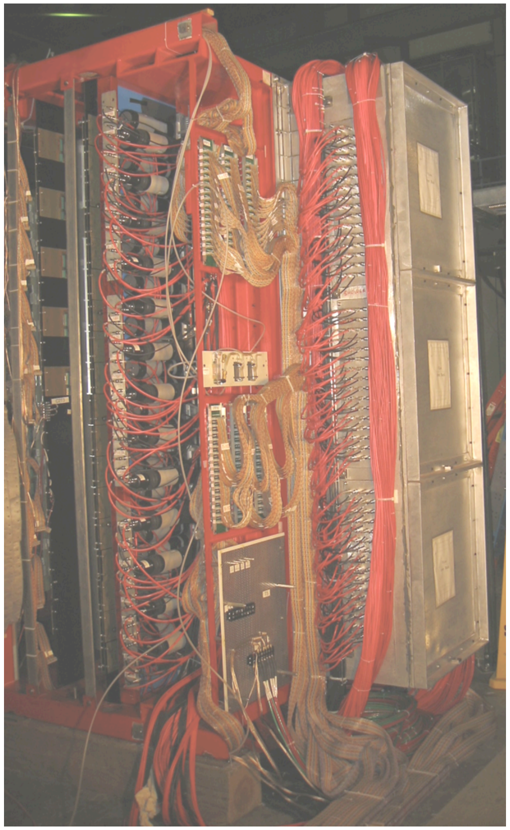


- Solid angle of 76 msr
  (12 times higher than HRS)
- 40 cm long target
- Momentum resolution of 1%

Electron Spectrometer

Optimization of acceptance: for $\Delta Q^2/Q^2 \sim 0.1$ with max Ω leads to a large aspect ratio, limited by $\cos(\phi^*)$ for asymmetry. BigBite was designed at NIKHEF for aspect ratio $\Delta\theta/\Delta\phi = 1/5$! Spectrometer has solid angle (for 40 cm long target) 76 msr.

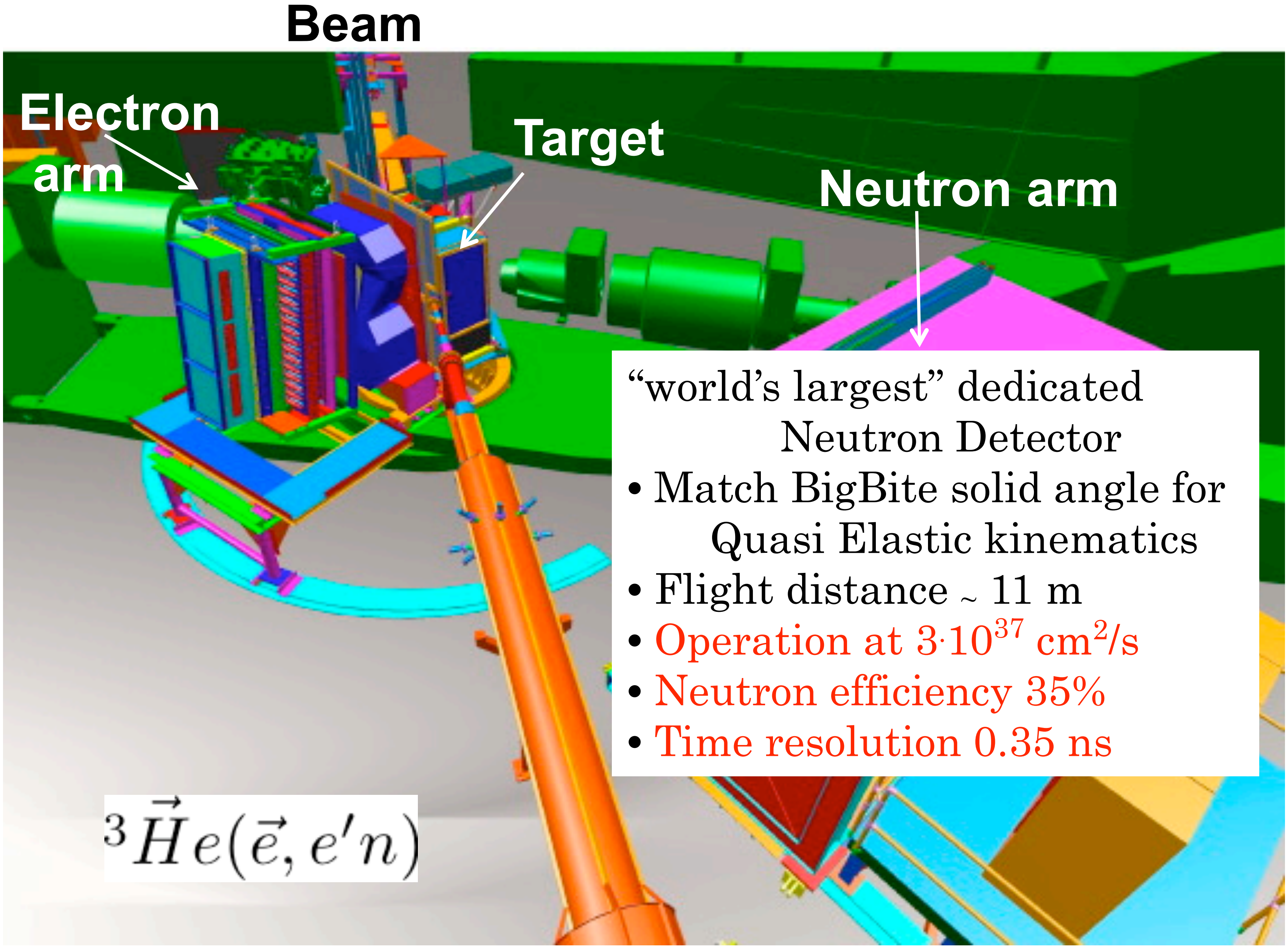




Detector:

15 planes of MWDCs (X,U,V)
Two-layer lead-glass calorimeter
Segmented Scint. Plane

Hall A G_E^n experiment



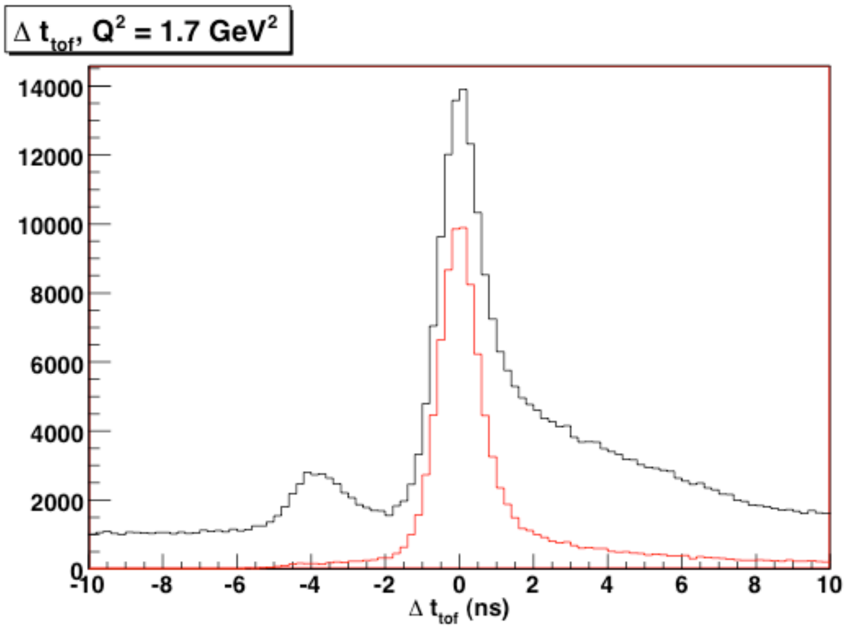
Considerations/Optimization

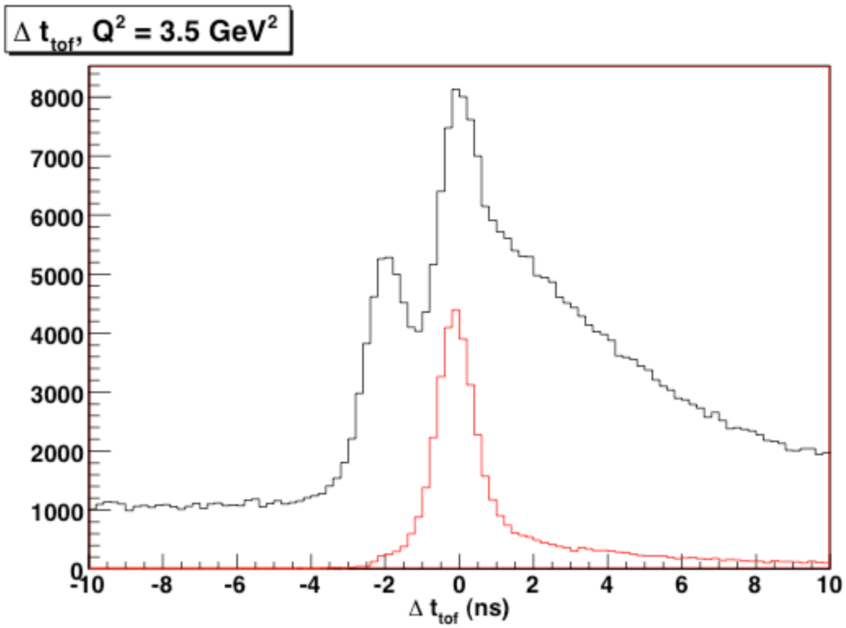
$$^3\vec{H}e(\vec{e},e'n)$$

- Range of the momentum transfer should be < 10%
  => angular acceptance < 10^{o}
- Asymmetry vs. polarization direction, q-vector, and the e,e' plane
  => azimuth coverage < 60^{o}
- Electron arm resolution requirement => 1%
- Neutron arm rate limitations => luminosity
- MWDC rate limitations => luminosity
- Trigger and DAQ capabilities => calorimeter
- Field gradient at the target < 1 mT/cm => "sheet-metal" dipole

Configuration of E02-13 is close to **ideal**
for a Form Factor experiment

Data analysis: step 1 – Time-of-Flight



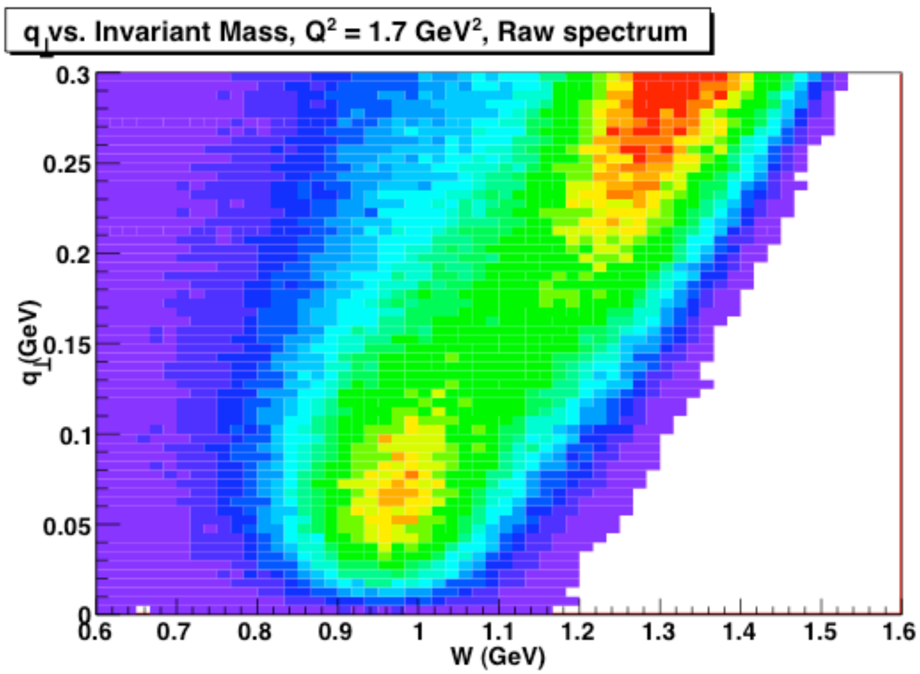


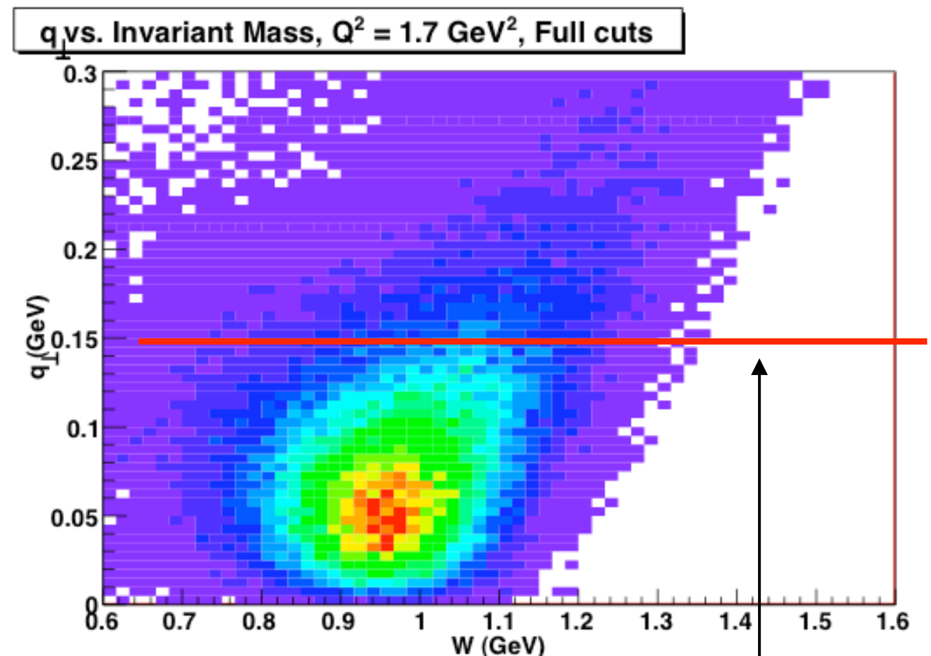
Raw events (BLACK lines) have significant accidental level and large tail for slower protons

RED lines present events after cut on e'-n angular correlation: accidentals and tails almost gone

Analysis: step 2 - $q_\perp$ vs W; 1.7 GeV^2

perpendicular "q" = q x sin(θ_{qh}); $W^2 = M^2 + 2M(E-E') - Q^2$

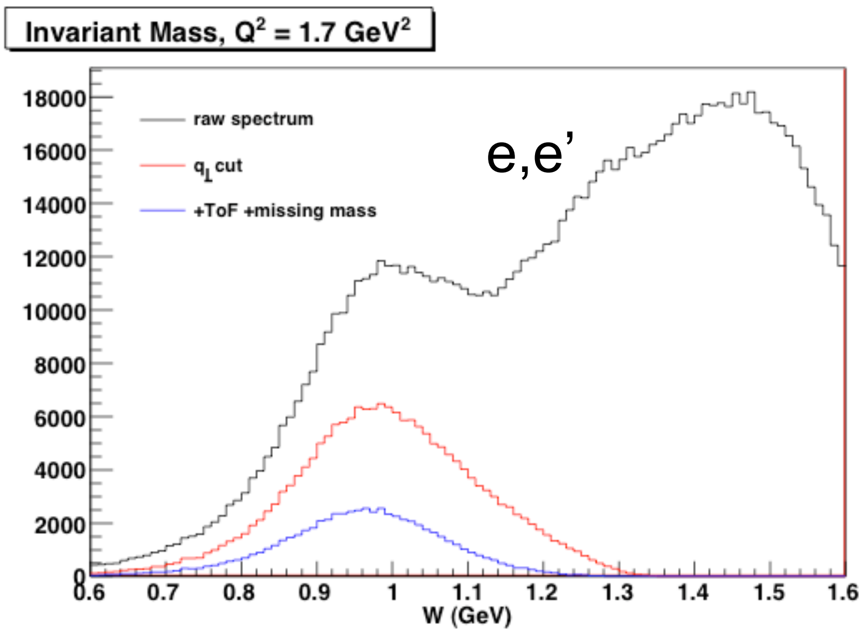


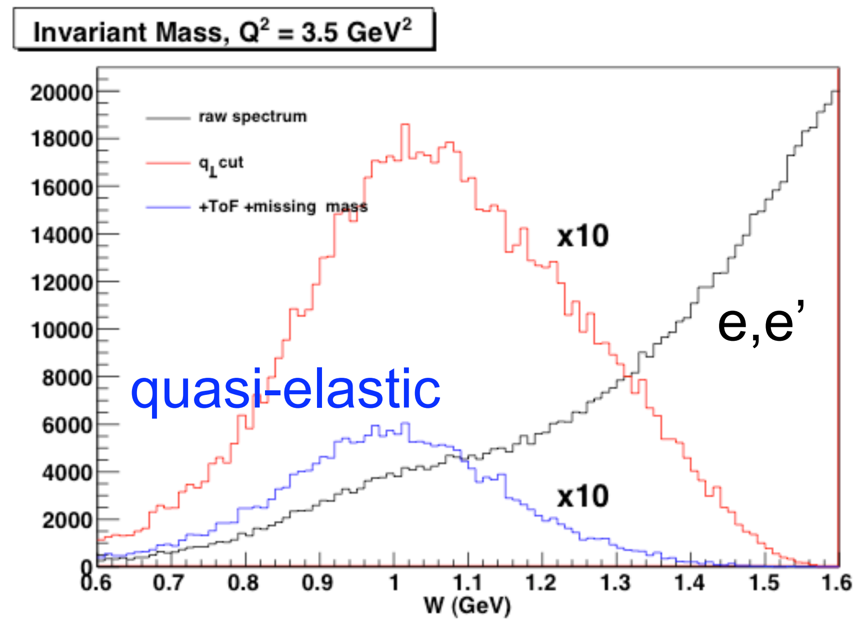


Quasi elastic events dominates after Full Cuts applied

max value of used perp. q

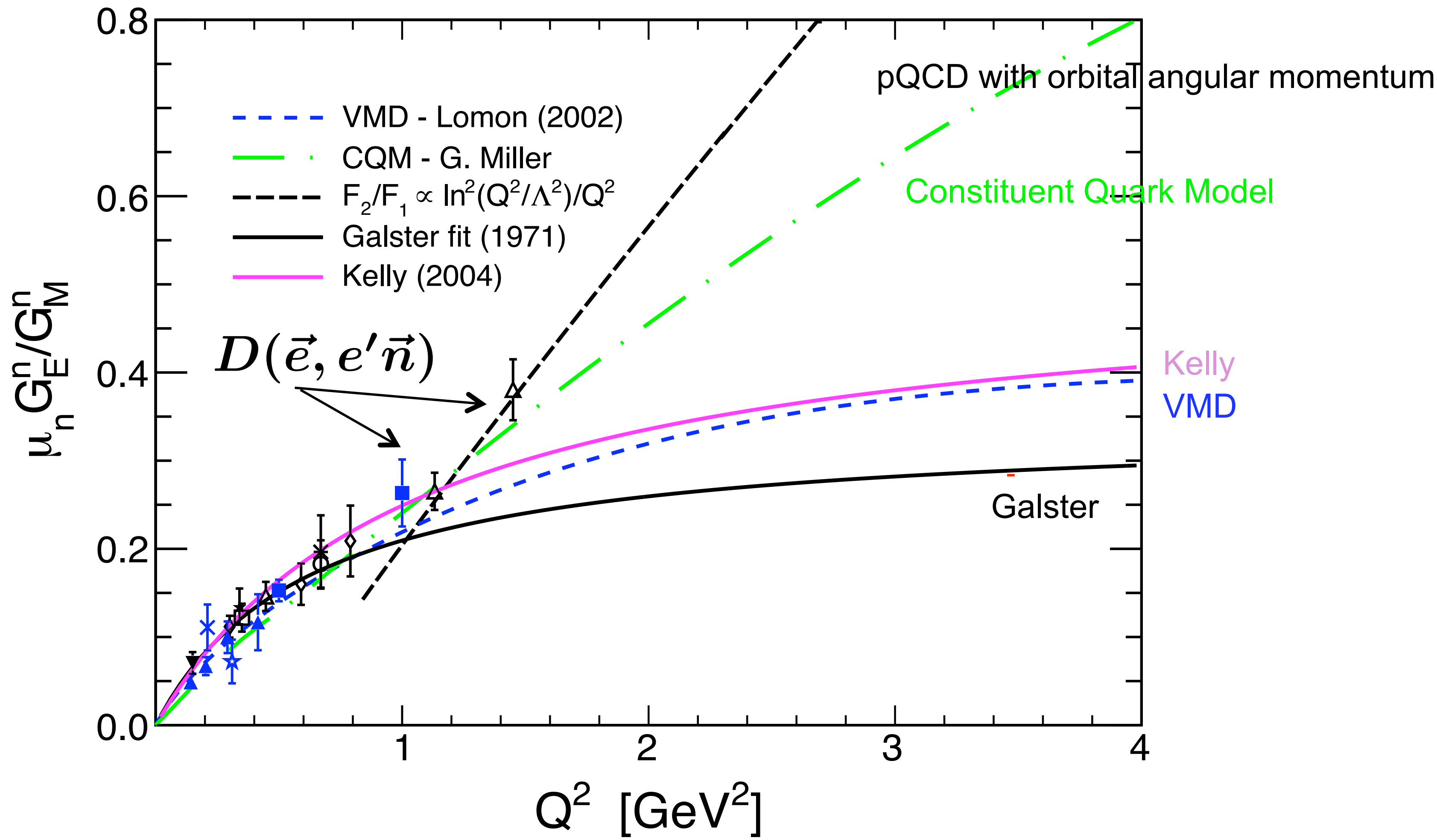
Analysis: step 3 - W distribution





for 3.5 GeV^2 the quasi-elastic signal is very small in e,e' spectrum. However, after angular correlation cut applied the peak is just as supposed to be for quasi-elastic process

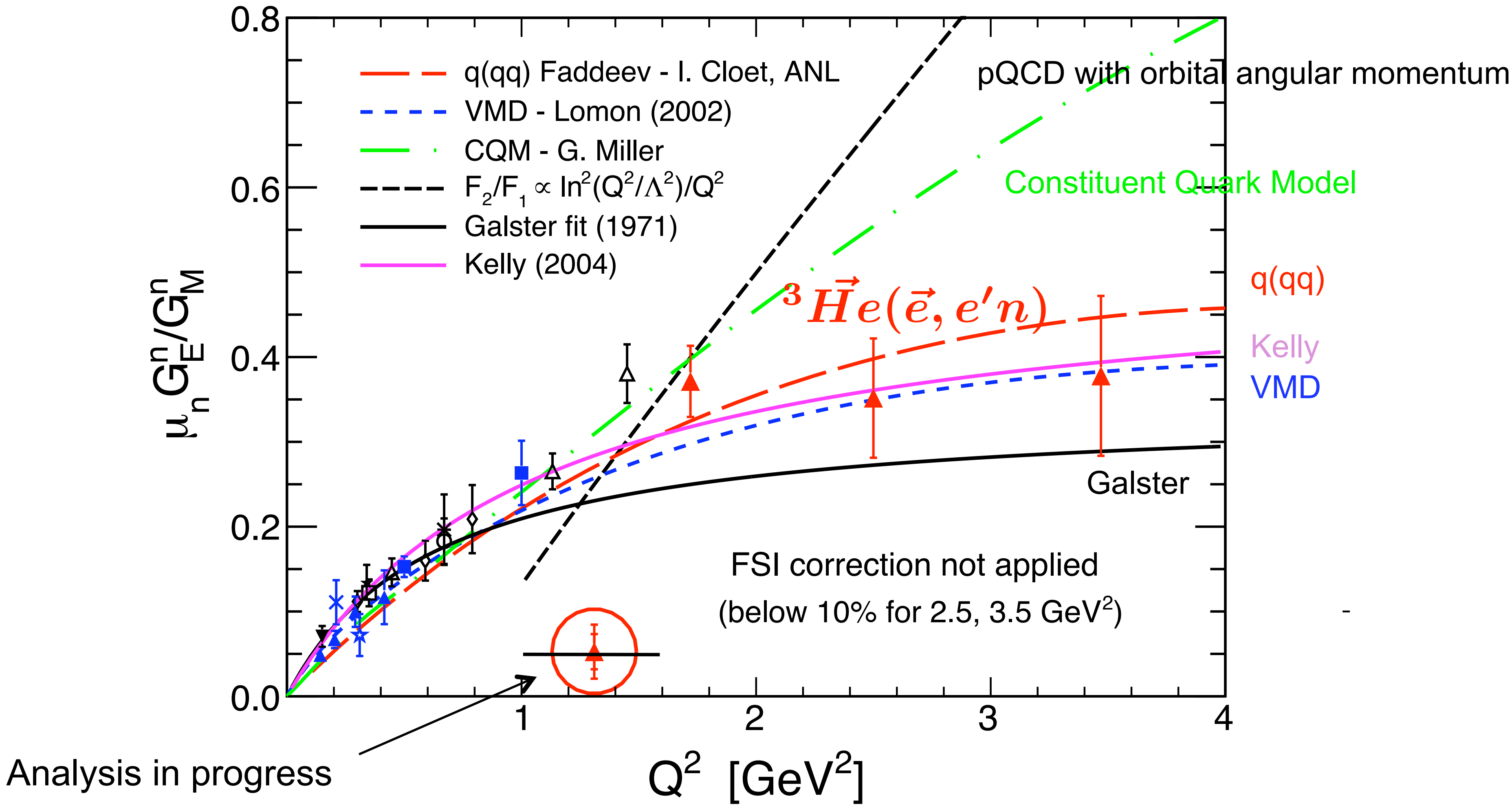
G_E^n before our experiment



The pQCD log-scaling provided a good fit to the G_E^p/G_M^p data.

- Is pQCD log-scaling good fit for the G_E^n/G_M^n from 1.5 GeV^2?
- How large Q^2 will be a limit for Constituent Quark Model?

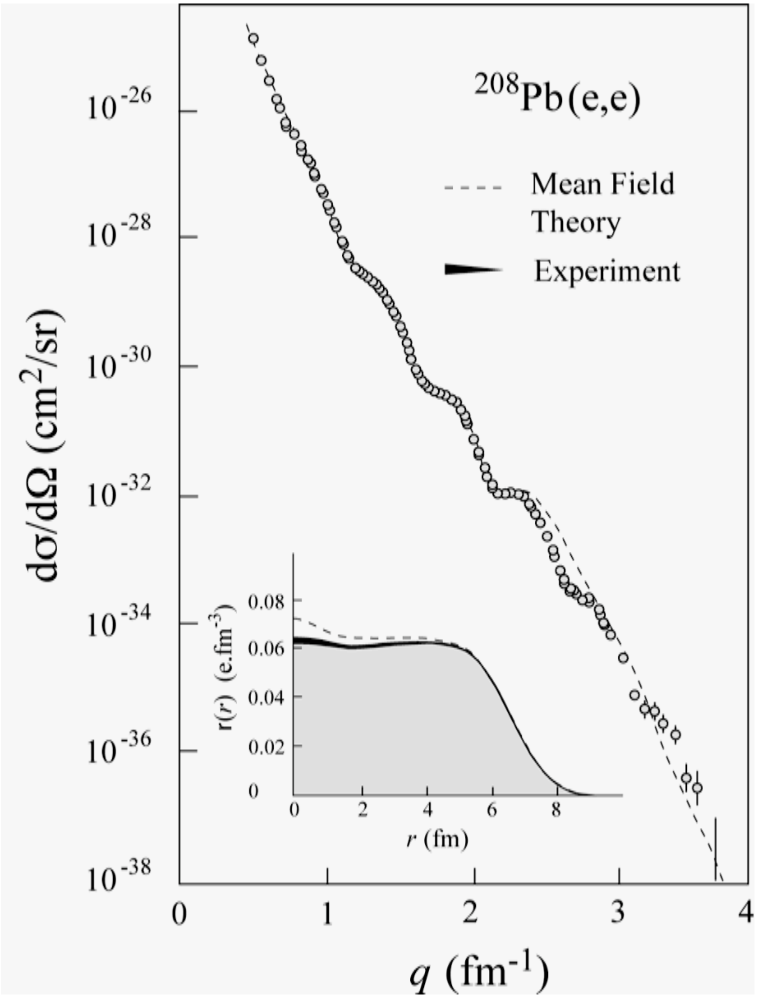
The semi-final results E02-013



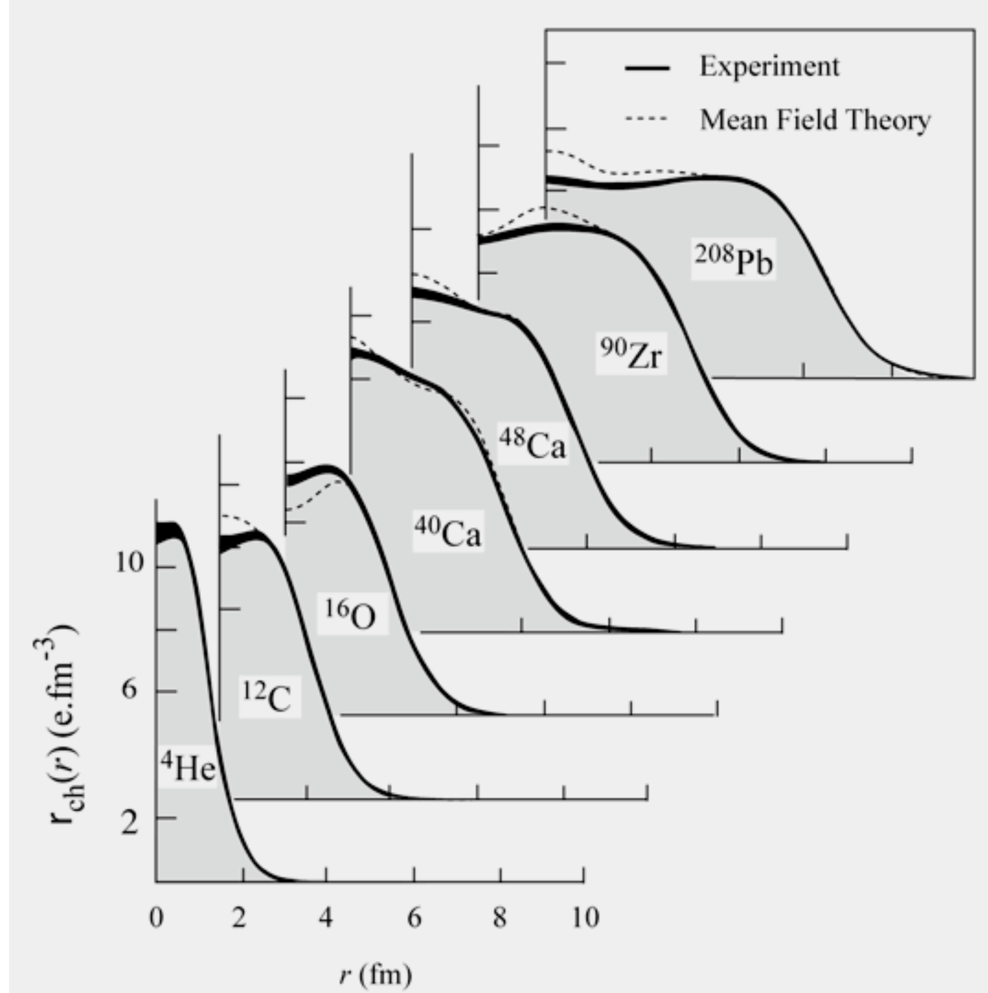
- The pQCD log-scaling should wait much larger Q^2
- Constituent Quark Model doesn't work above 2 GeV^2
- The q(qq), ANL model is only one in agreement with the data

Now return to structure

(e,e') ⇒ Nuclear Charge Distributions



From Stanford to Saclay and Nikhef



Model-independent analysis -> accurate nuclear charge distributions

Study of nucleon structure requires IMF GPDs in the impact parameter representation

$$F_1(t) = \sum_q e_q \int dx H_q(x,t)$$

Muller, Ji, Radyushkin

$$q(x,\mathrm{b}) = \int \frac{d^2q}{(2\pi)^2} e^{i\,\mathrm{q}\cdot\mathrm{b}} H_q(x, t=-\mathrm{q}^2)$$

M.Burkardt

$$\rho(b) \equiv \sum_q e_q \int dx\, q(x,\mathrm{b}) = \int d^2q F_1(\mathrm{q}^2) e^{i\,\mathrm{q}\cdot\mathrm{b}}$$

P.Kroll: u/d segregation

$$\rho(b) = \int_0^\infty \frac{Q\cdot dQ}{2\pi} J_0(Qb) \frac{G_E(Q^2)+\tau G_M(Q^2)}{1+\tau}$$

G.Miller

center of momentum $R_\perp = \sum_i x_i \cdot r_{\perp,i}$

b is defined relative to $R_\perp$

Transverse center of the quarks longitudinal momentum fractions

QCD: Dirac and Pauli densities

impact parameter b
is defined relatively to the transverse center of the quarks longitudinal momentum fractions

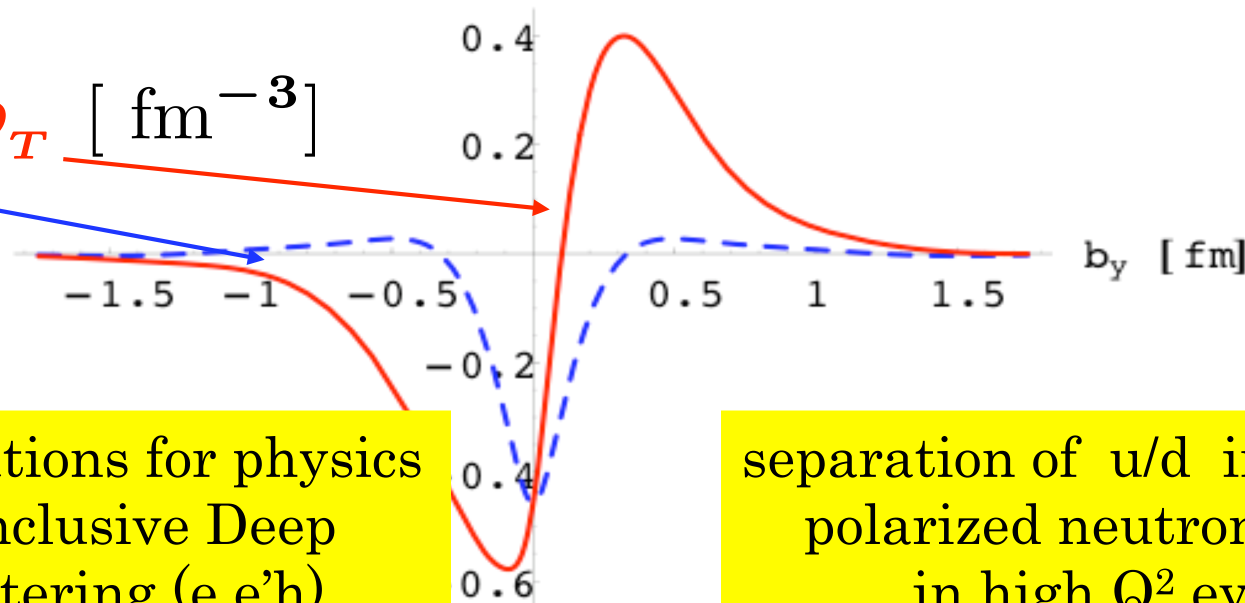
$$R = \sum x_i r_i$$

$$\rho_{Dirac}(b) = \int_0^\infty \frac{QdQ}{2\pi} J_o(bQ) F_1(Q^2)$$

$$\rho_{Pauli}(b) = \int_0^\infty \frac{Q^2 dQ}{4\pi\, M} J_1(bQ) F_2(Q^2)$$

$$\rho_T(\vec{b}) = \rho_{Dirac} - \sin(\phi_b - \phi_S)\rho_{Pauli}$$

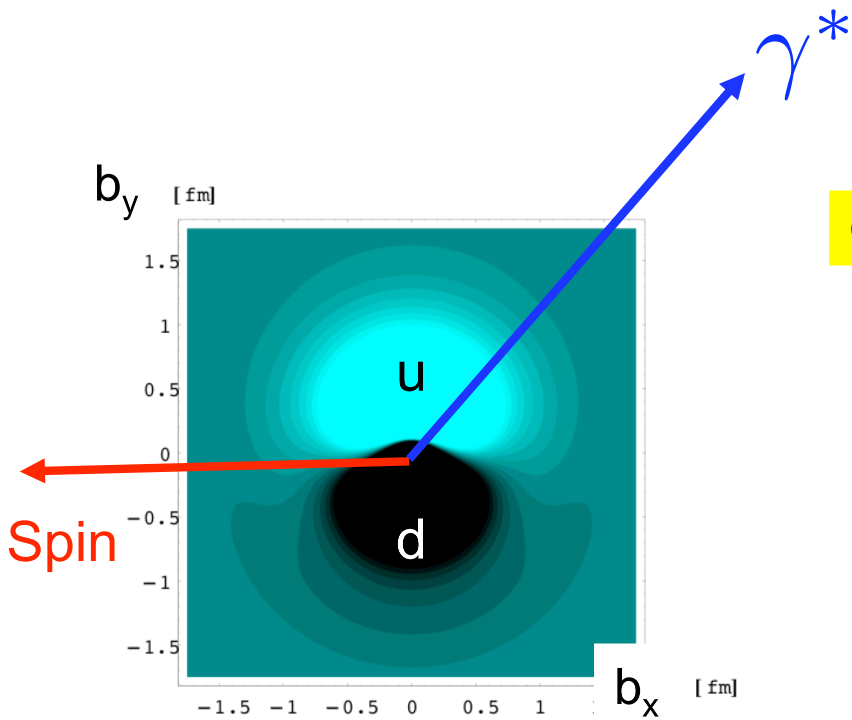
ρ_{Dirac}, ρ_T [fm^{-3}]



direct implications for physics of the Semi Inclusive Deep Inelastic Scattering (e,e'h)

separation of u/d in transversely polarized neutron (along X) in high Q^2 events

Polarized neutron



Carlson&Vanderhaeghen

SIDIS should have many effects due to this u/d separation

Rotation of u/d quarks in neutron

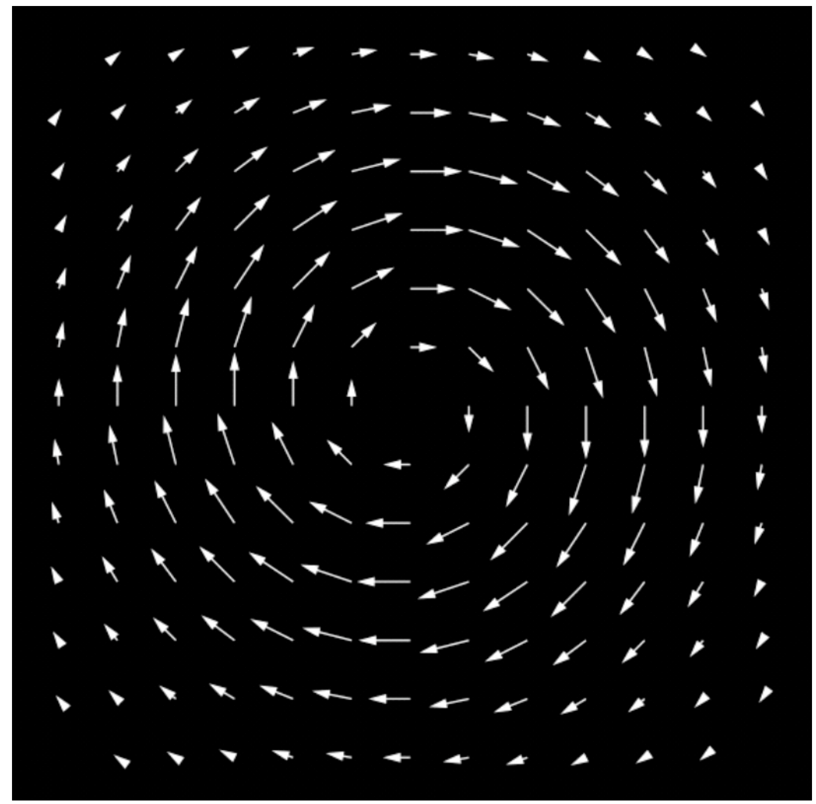
Let see how quark rotation leads to u/d separation:

M.Burkardt (2003)

amplitude is small

virtual photon quark

amplitude is large

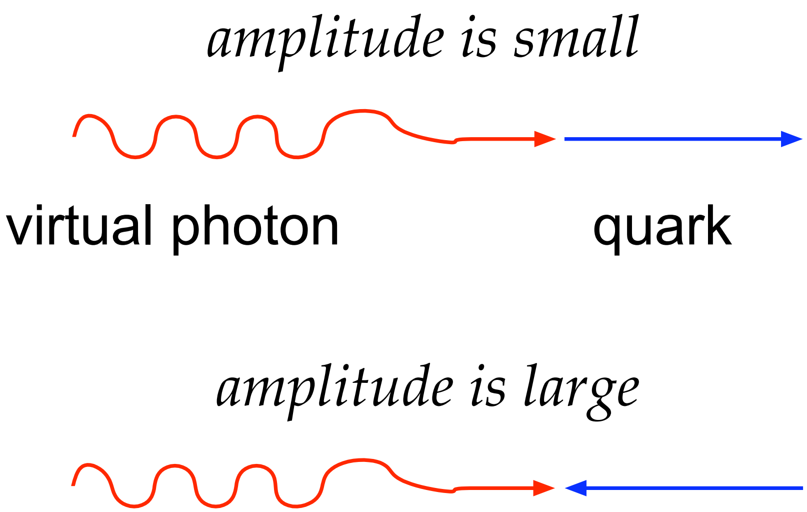


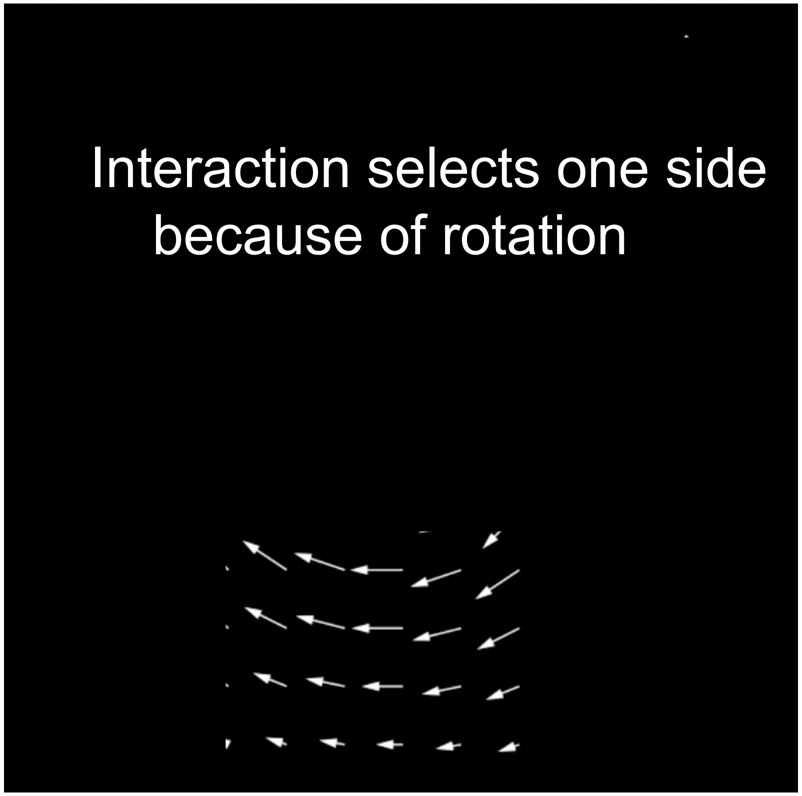
motion inside nucleon

Rotation of u/d quarks in neutron

Let see how quark rotation leads to u/d separation:

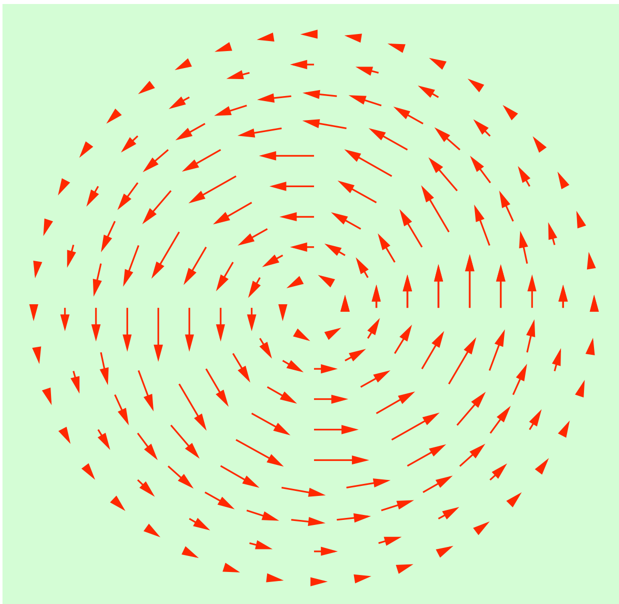
M.Burkardt (2003)



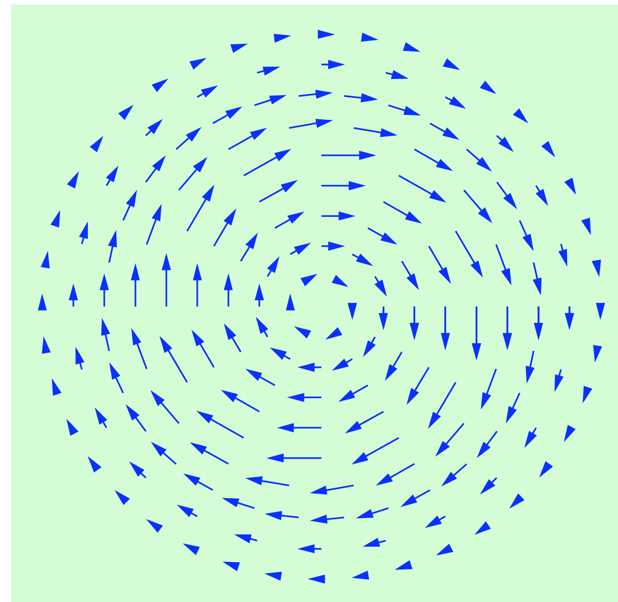


Rotation of u/d quarks in neutron

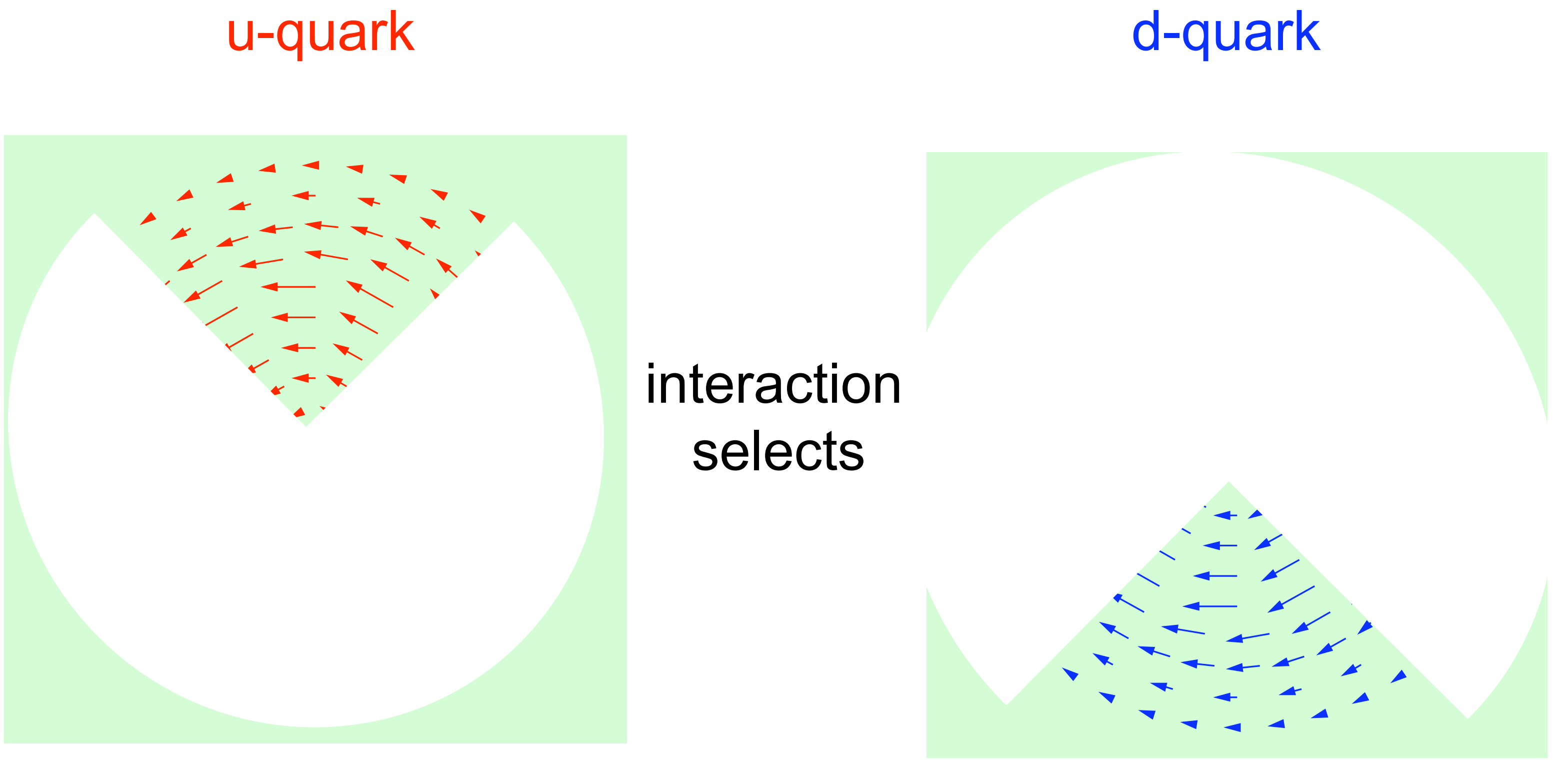
u-quark



d-quark



Rotation of u/d quarks in neutron



The u/d separation, observed in Form Factor data, is possibly a result of

the collective rotation of the u-quark and the d-quark,
which is going in opposite directions

Flavor view with EMFFs

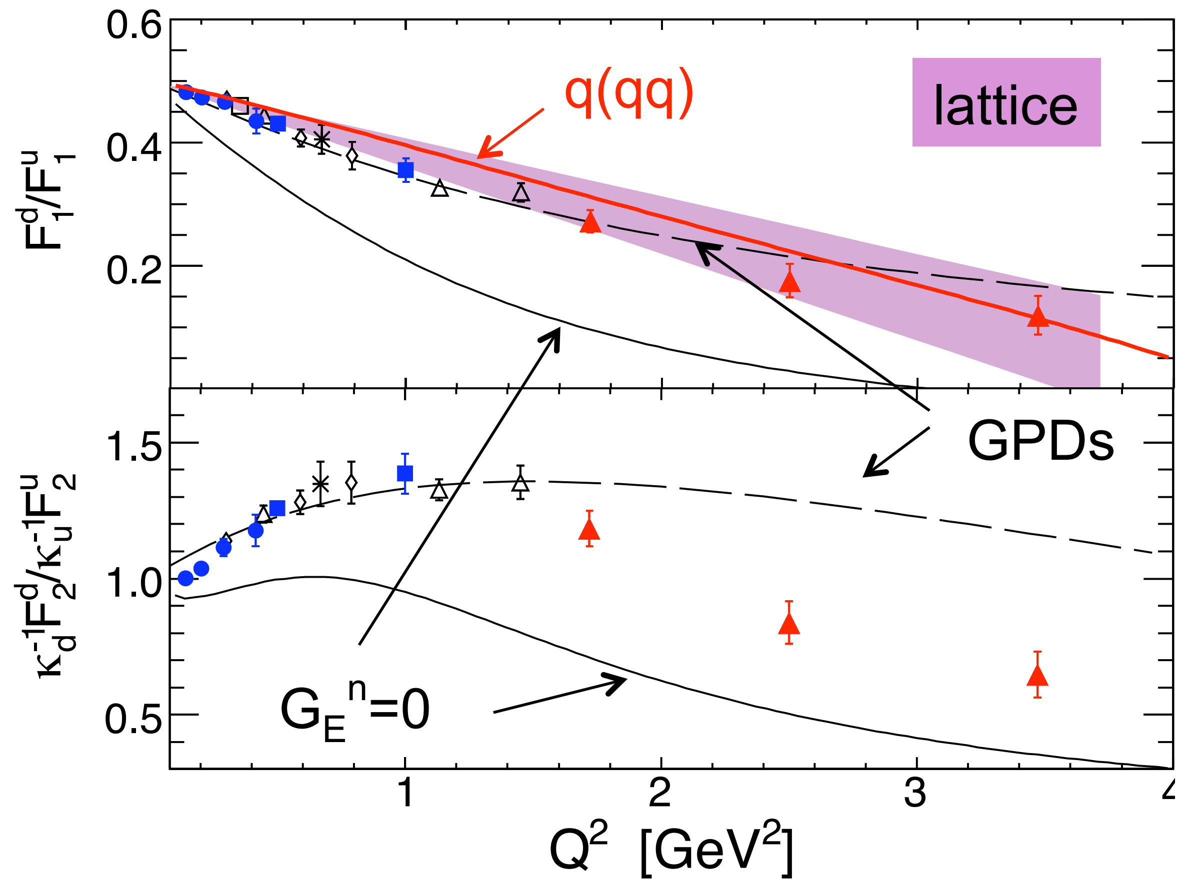
$F_1^d{}_{(2)}/F_1^u{}_{(2)}$ with proton and neutron FFs

$$F_1 = \frac{G_E + \tau G_M}{1+\tau}$$

$$F_2 = -\frac{G_E - G_M}{1+\tau}$$

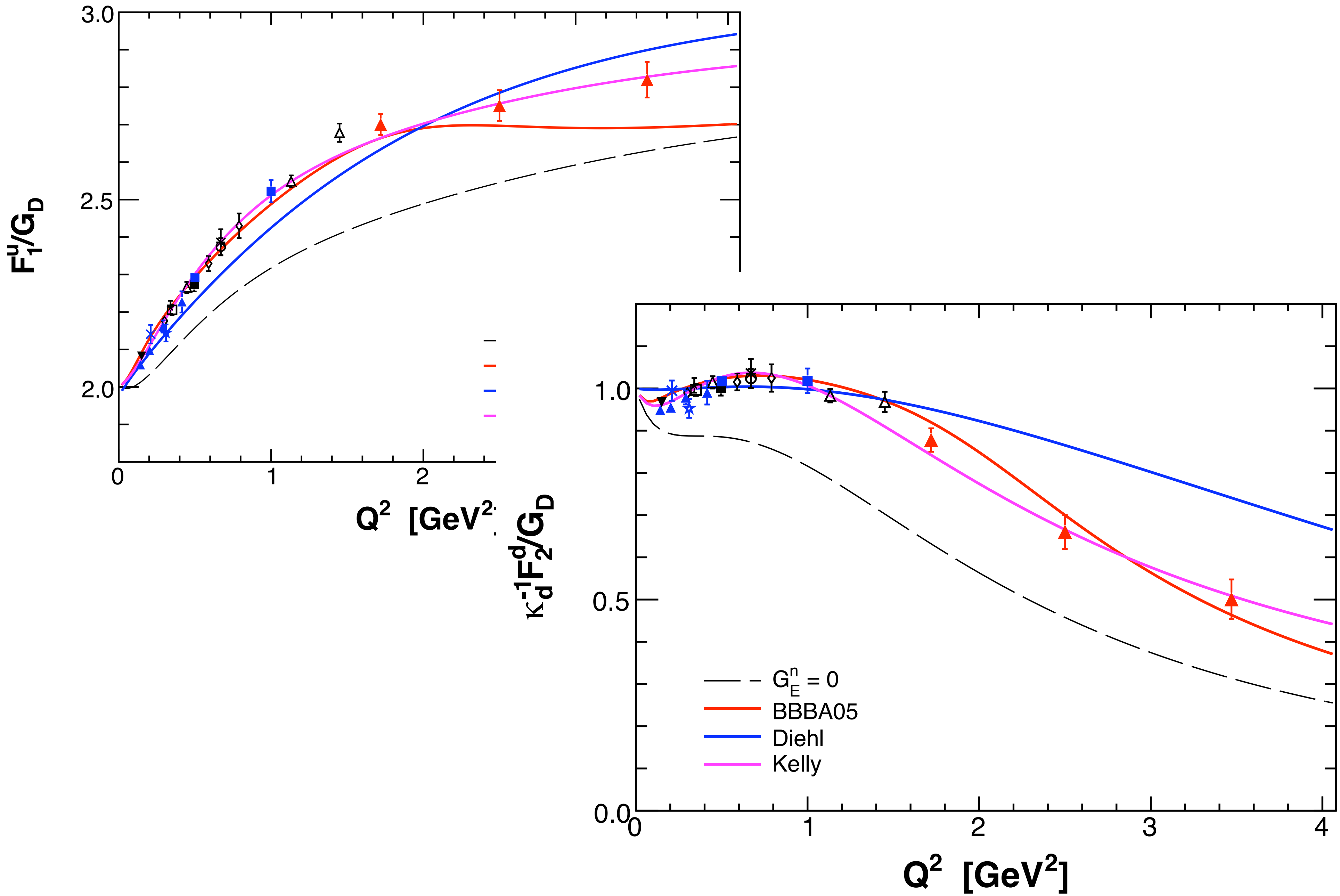
$$F_1^u = 2\,F_{1p} + F_{1n}$$

$$F_1^d = 2\,F_{1n} + F_{1p}$$



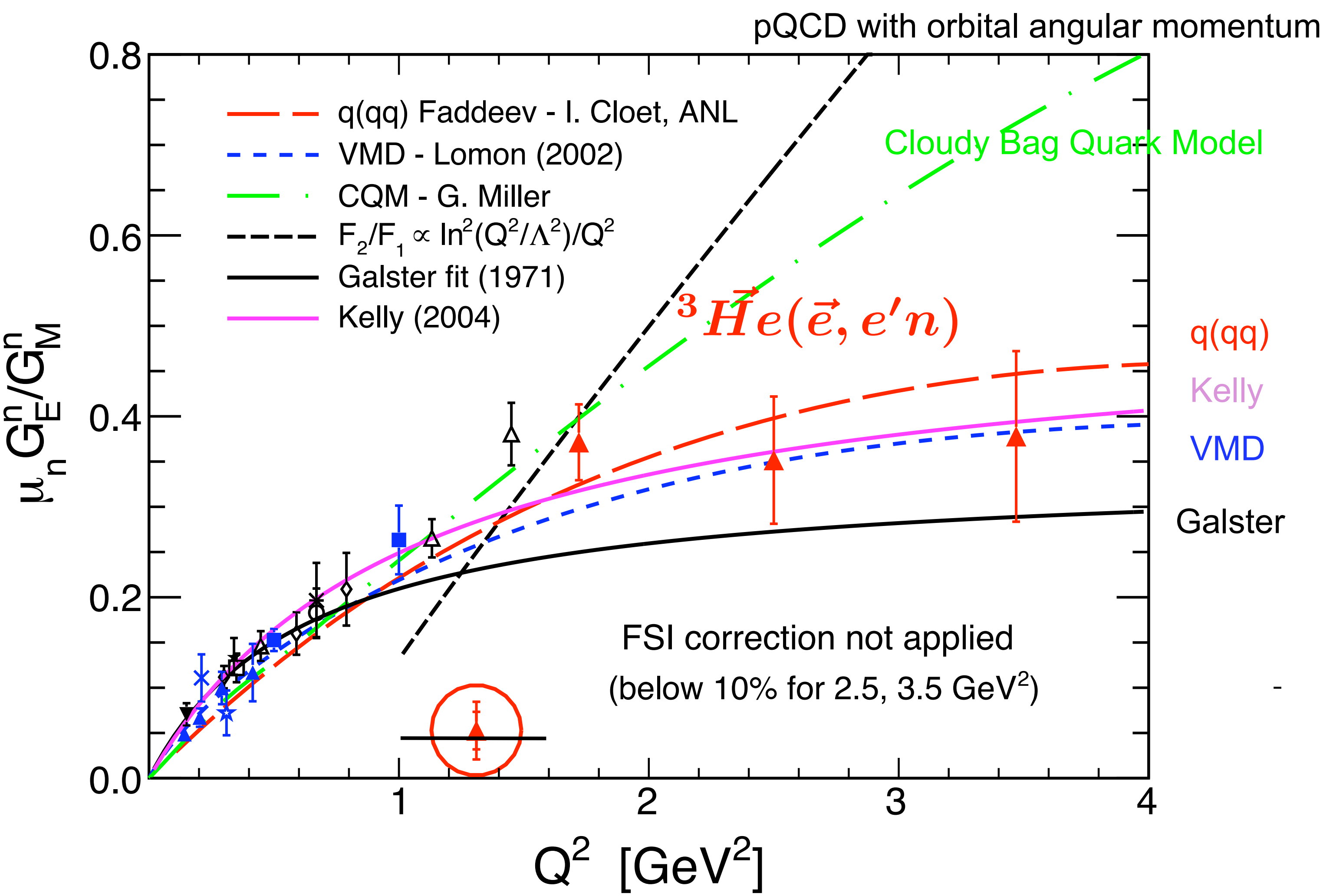
Lattice calculation => very good agreement with the trend, need accuracy
q(qq) ANL => good, possibly a signature of dominant degrees of freedom
Our data will require a new fit of E_d and E_u GPDs

$F_1^d{}_{(2)}$, $F_1^u{}_{(2)}$ with proton and neutron FFs



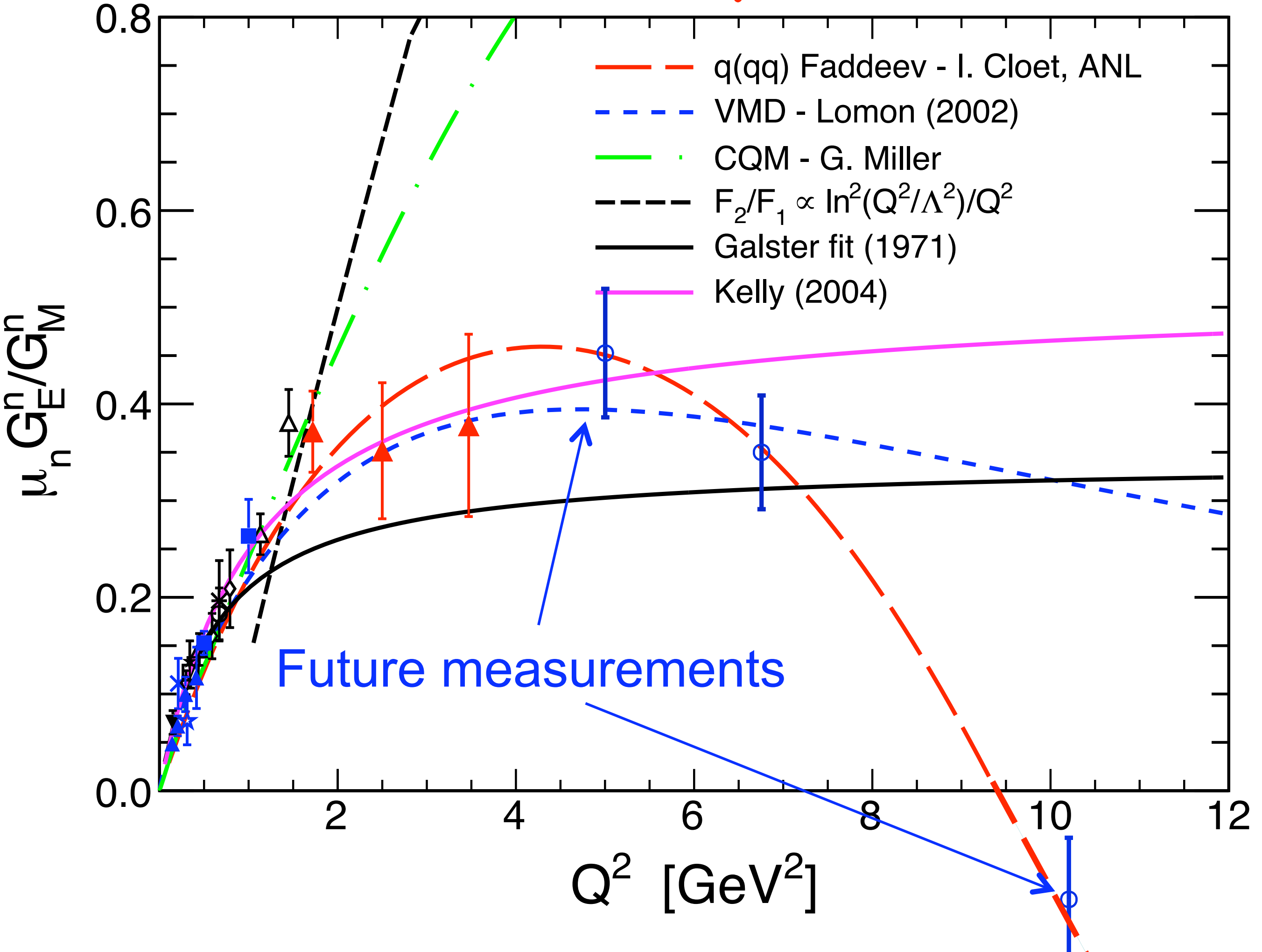
Why need higher Q^2?

The semi-final results E02-013



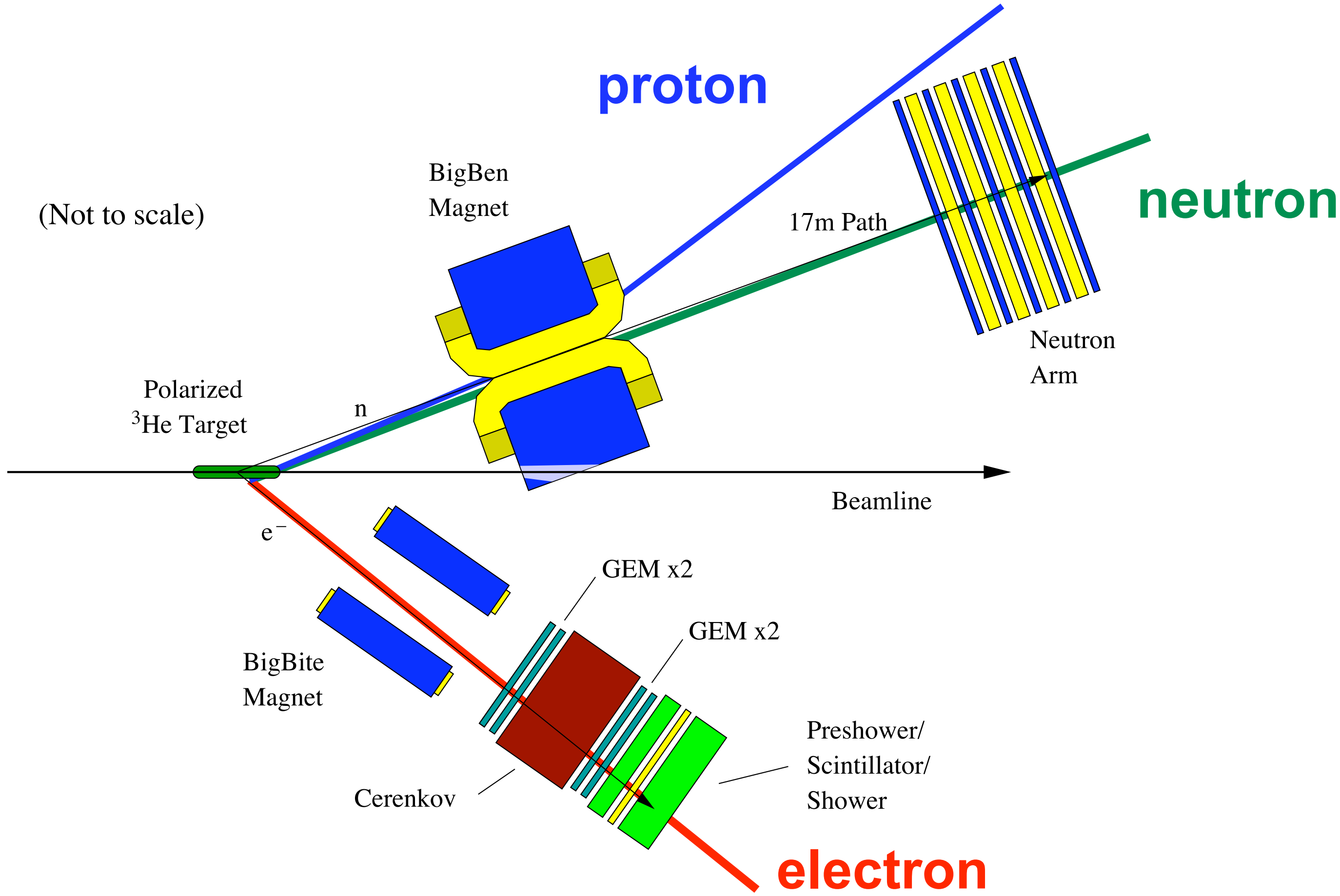
What is happening at higher Q^2?

E09-016: G_E^n up to 10 GeV^2



Additional advance in polarized target and the Super BigBite components (the magnet and a high-resolution high-rate capability GEM tracker) are required to extend experiment to 10 GeV^2.

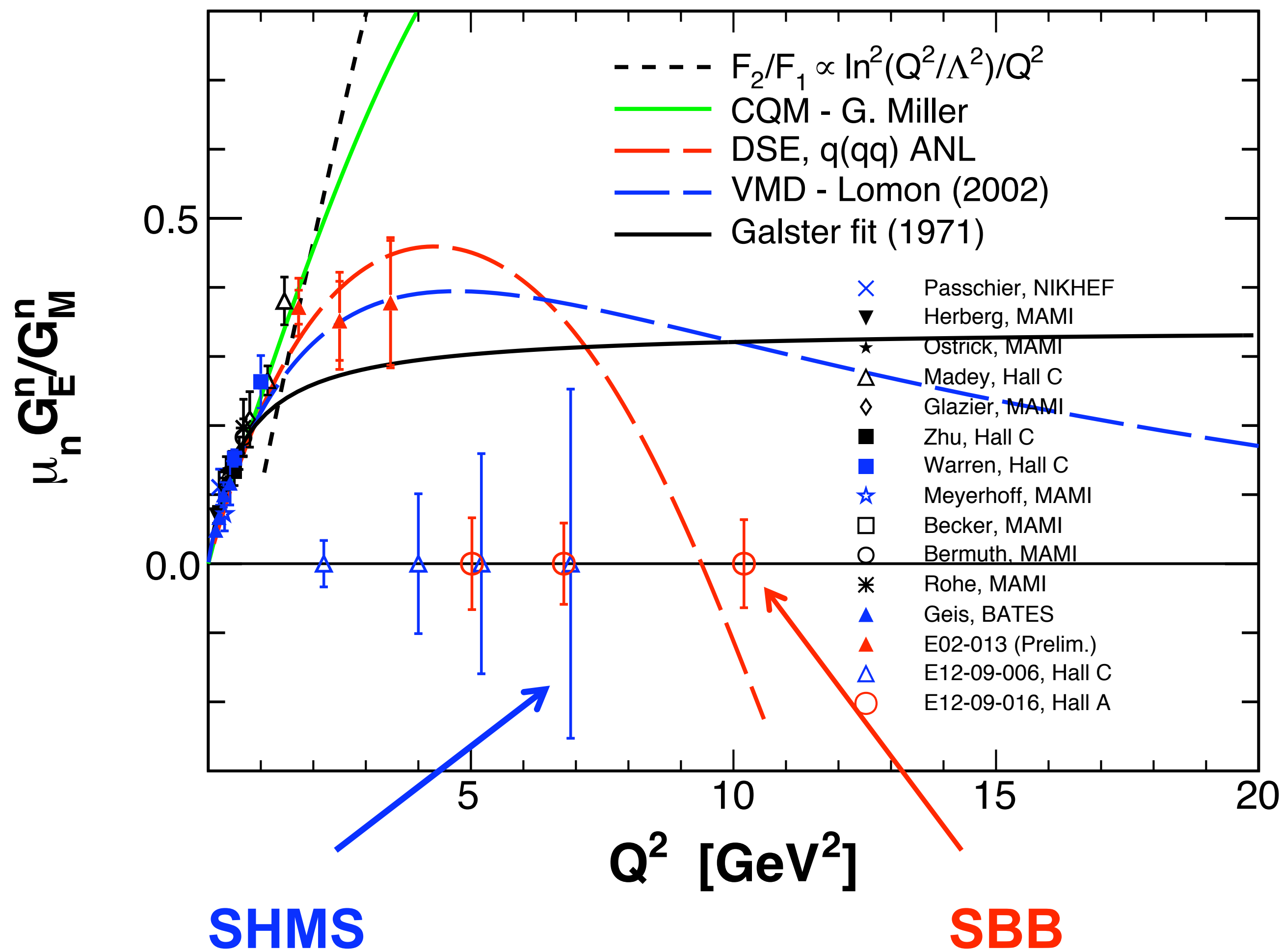
GEn/GMn at 10 GeV^2



Beam energy of 8.8 GeV, 60 μA. Target: He-3, polarization 60%, 36 days

G_E^n at 10 GeV^2 with uncertainty of 20% * $G_{Galster}$ (or 0.07 G_{Dipole}).

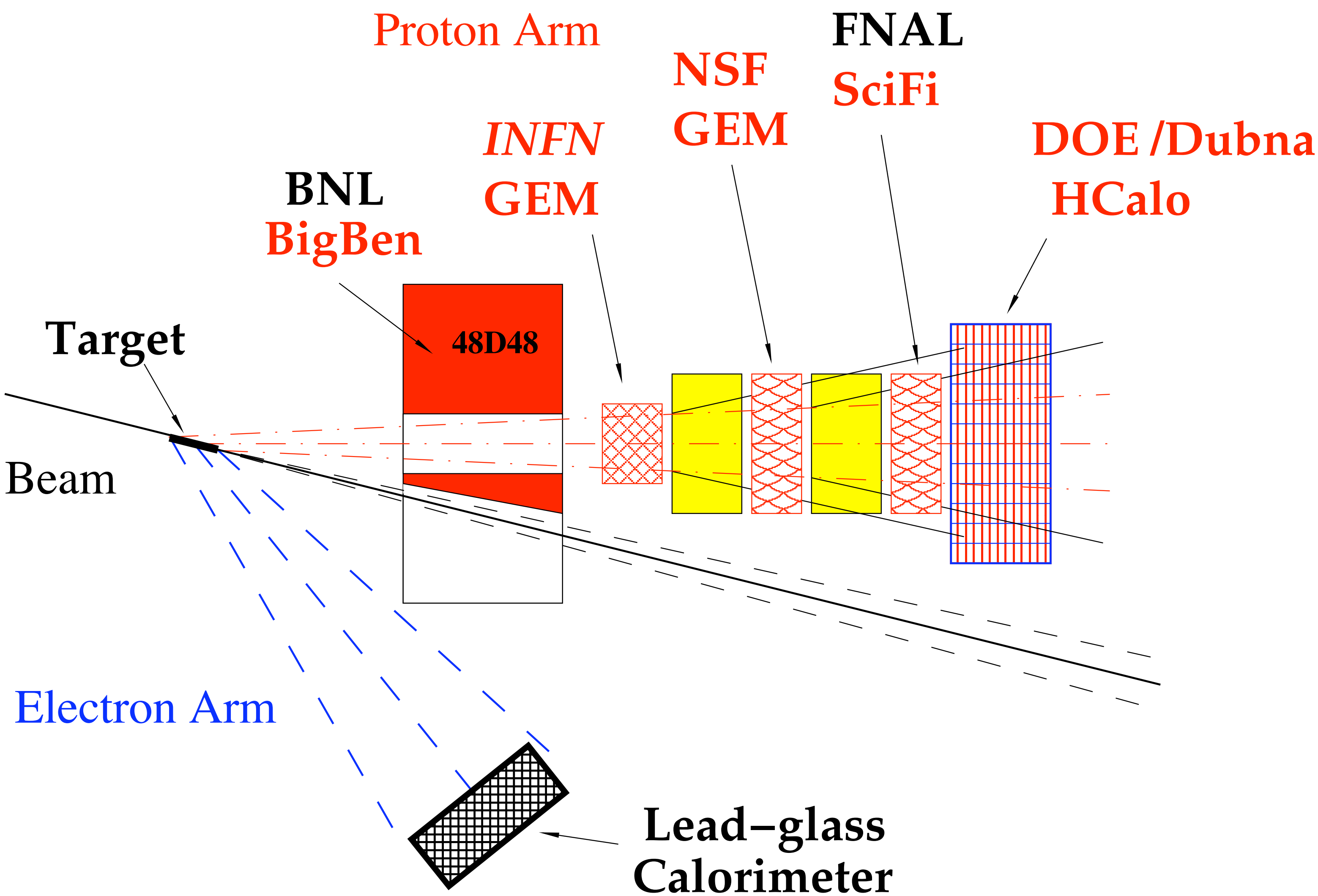
12 GeV approved GEn experiments



Super BigBite apparatus

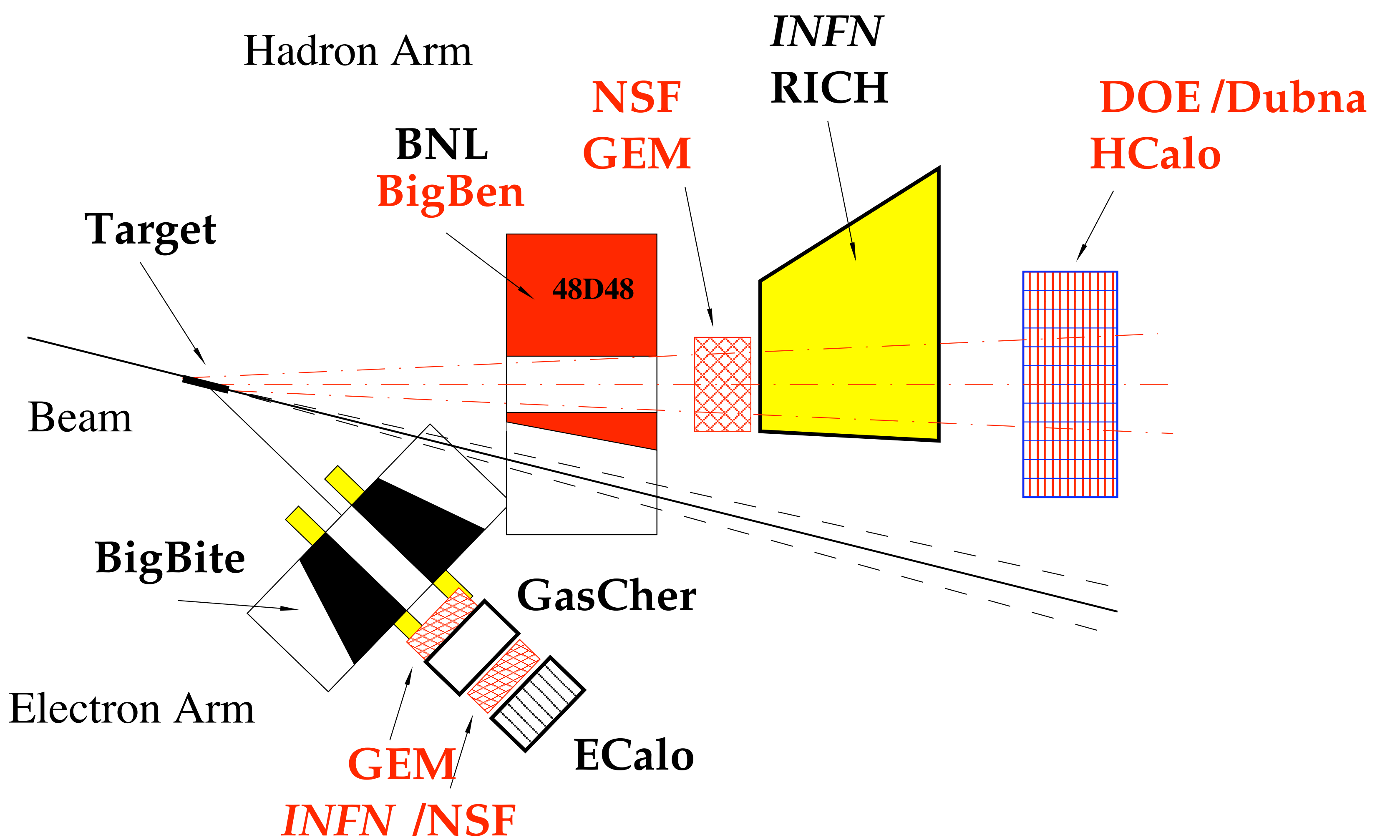
Proton G_E^p/G_M^p with SBS

Proton form factors ratio, E12–07–109



Neutron Transversity with SBS

Neutron Transversity, E–09–018



Single settings of SBS will provide full coverage for all $P_{\perp} <$ 1/6 of $P_{||}$

SBS physics program

- **GEP** : reach unique high 15 $(GeV/c)^2$ - productivity !
- GMN: reach absolute max 18 $(GeV/c)^2$
- GEN: reach fantastic value 10 $(GeV/c)^2$
- SSA in nSIDIS: 30,000 gain vs HERMES

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- **A1n**/d2n – productivity gain ~ 20-30 compare with SHMS
- F_{π} – new approach with a polarimeter for the forward going neutron will allow to perform L/T separation without Rosenbluth
- $H(e,e'\phi)p$ – access to gluon at JLab

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- A1p/d2p – as for A1n has a very large gain of productivity
- D(e,e'd) – elastic A, event rate gain ~ 50 at 6 $(GeV/c)^2$
- $T/^3He(e,e')$ – u/d at high-x
- SRC: e'(HRS) + p(SBS) + N(BB)
- PVDIS – gain 10-15 compare with two HRSs
- A(e,e'p), $A(e,e'\pi^{+/-})$ - each item is a big program