Neutron Form Factors

Bogdan Wojtsekhowski, Jefferson Lab

- Neutron structure and EM form factors
- Recent experiment ^{3}He(e,e'n) at Jlab
- Flavor decomposition of nucleon FFs
- The transverse neutron densities
- Future GEN&GMN and GMN/GMP at high Q2

Highlights of the neutron

- Prediction: Rutherford 1920
- Discovery: Chadwick 1932
- Magnetic moment:Esterman&Stern 1934, Alvarez&Bloch 1940
- Determination of spin 1/2: Schwinger 1937
- Direct observation of the structure: Hofstadter 1950th
- SLAC measurement of G^n_M up to 10 GeV^2
- Time like FFs: DM2, FENICE
- Polarizabilities: SAL, Mainz, Lund
- Polarized electron beam era: Sinclair's electron source in 1977
- CEBAF with polarimeter and polarized targets in 1990th
- Unification of DIS/FFs/DVCS in GPDs by Muller, Ji, Radyushkin
- G^n_M/G^p_M precision measurement by Brooks etal in 2001
- Polarized He-3: laser pumping
- G^n_E/G^n_M measurements at NIKHEF, Mainz, JLab, BATES

Electro-Magnetic Form Factors

One-photon approximation, $\alpha_{em} = 1/137$, hadron current

$$\mathcal{J}^{\mu}_{hadronic} = ie\overline{N}(p')\left[\gamma^{\mu}F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M}F_2(Q^2)\right]N(p)$$

At large Q^2 study of G_E require use of polarization observables - FFs at CEBAF

Full expression for M has three complex functions, F_1, F_2, F_3

$$\mathcal{M} = \frac{4\pi\alpha}{Q^2}\bar{u}'\gamma_{\mu}u \cdot \bar{N}'\left(\tilde{F}_1\gamma^{\mu} - \tilde{F}_2[\gamma^{\mu},\gamma^{\nu}]\frac{q_{\nu}}{4M} + \tilde{F}_3K_{\nu}\gamma^{\nu}\frac{P^{\mu}}{M^2}\right)N$$

$$\tilde{G}_{_M} = \tilde{F}_1 + \tilde{F}_2 \qquad \tilde{G}_{_E} = \tilde{F}_1 - \tau\tilde{F}_2$$

$$\tilde{F}_i \text{ are functions of } (s-u) \text{ and } t$$

$$d\sigma = d\sigma_{_{NS}}\left\{\varepsilon\left(\tilde{G}_{_E} + \frac{s-u}{4M^2}\tilde{F}_3\right)^2 + \tau\left(\tilde{G}_{_M} + \varepsilon\frac{s-u}{4M^2}\tilde{F}_3\right)^2\right\}$$

$$\sigma_{_R} = \varepsilon G^2_{_E} + \tau G^2_{_M} +$$

$$+2\tau G_{_M}\mathcal{R}e\left(\delta\tilde{G}_{_M} + \varepsilon\tfrac{s-u}{M^2}\tilde{F}_3\right) + 2\varepsilon G_{_E}\mathcal{R}e\left(\delta\tilde{G}_{_E} + \tfrac{s-u}{M^2}\tilde{F}_3\right)$$

Rosenbluth (1950)

Akhiezer (1958)
Arnold, Carlson
and Gross (1981)

Guichon &
Vanderhaeghen

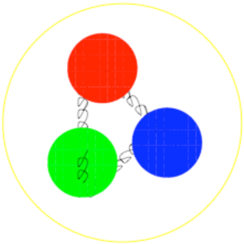
Afanasev et al.
Blunden et al.

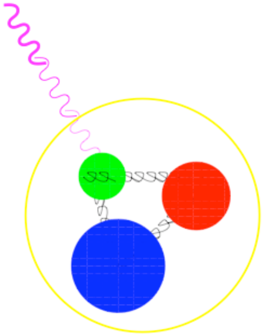
old $G_{E,M}$ are real functions of $t=-Q^2$

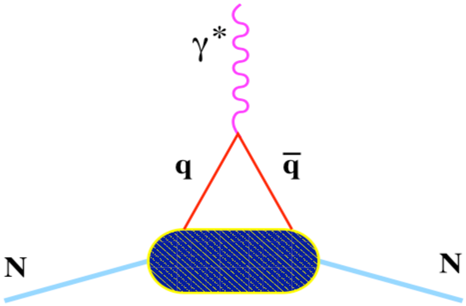
Extra terms contribute less than few % to σ_R

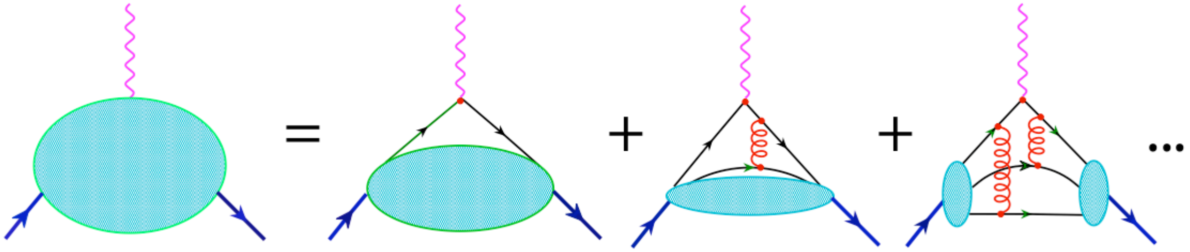
Photon - Neutron Interaction

$Q^2=0$





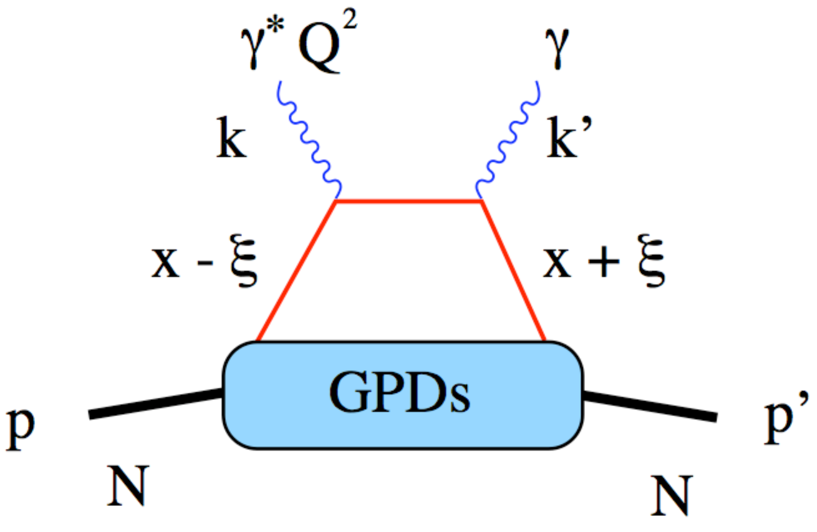


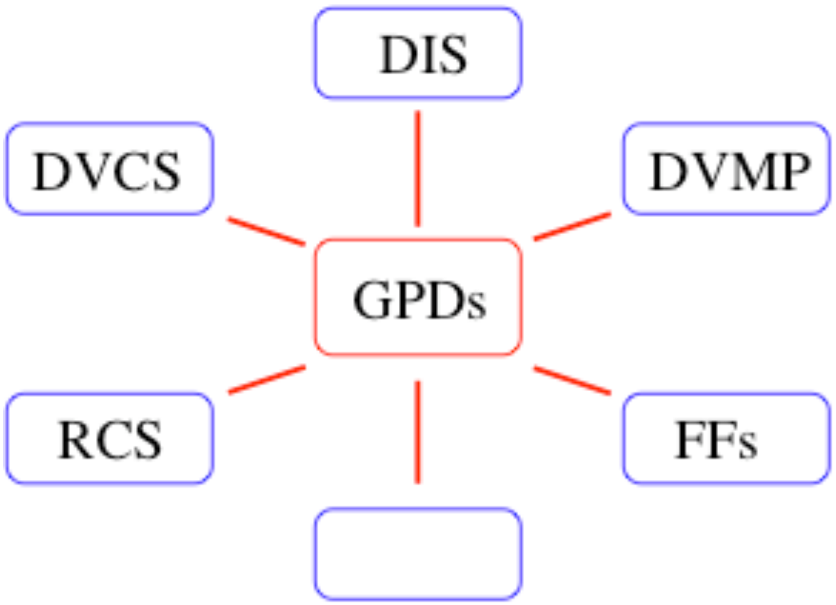


At Q^2 of several GeV^2 massive photon vibrates in q-qbar, which can't propagate far - already inside of the nucleon => still such q-qbar propagates as a VM

GPDs of nucleon

Müller (94), Ji (97), Radyushkin (97)




DIS

DVCS

DVMP

GPDs

RCS

FFs

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

Quark dynamics of nucleon encoded in GPD functions

$H(x,\xi,t)$, $\tilde{H}(x,\xi,t)$ hadron helicity-conserving; vector and axial-vector

$E(x,\xi,t)$, and $\tilde{E}(x,\xi,t)$ helicity-flipping; tensor and pseudo-scalar

GPDs information

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

$$H^q(x, \xi = 0, t = 0) = q(x)$$

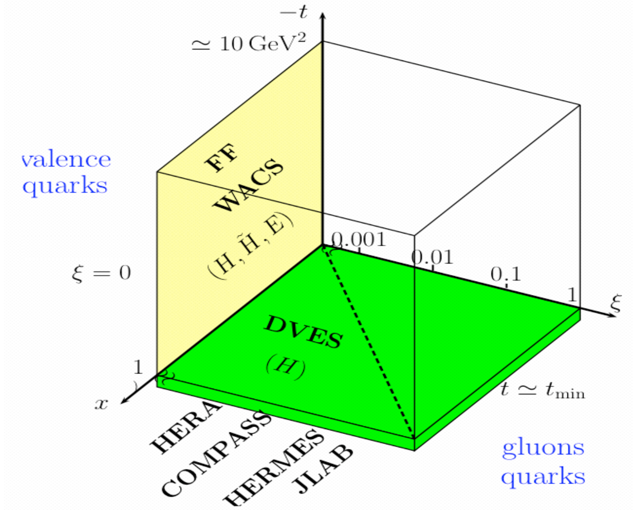
$$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$$

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

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

P.Kroll, Excl.-07

a lot to measure

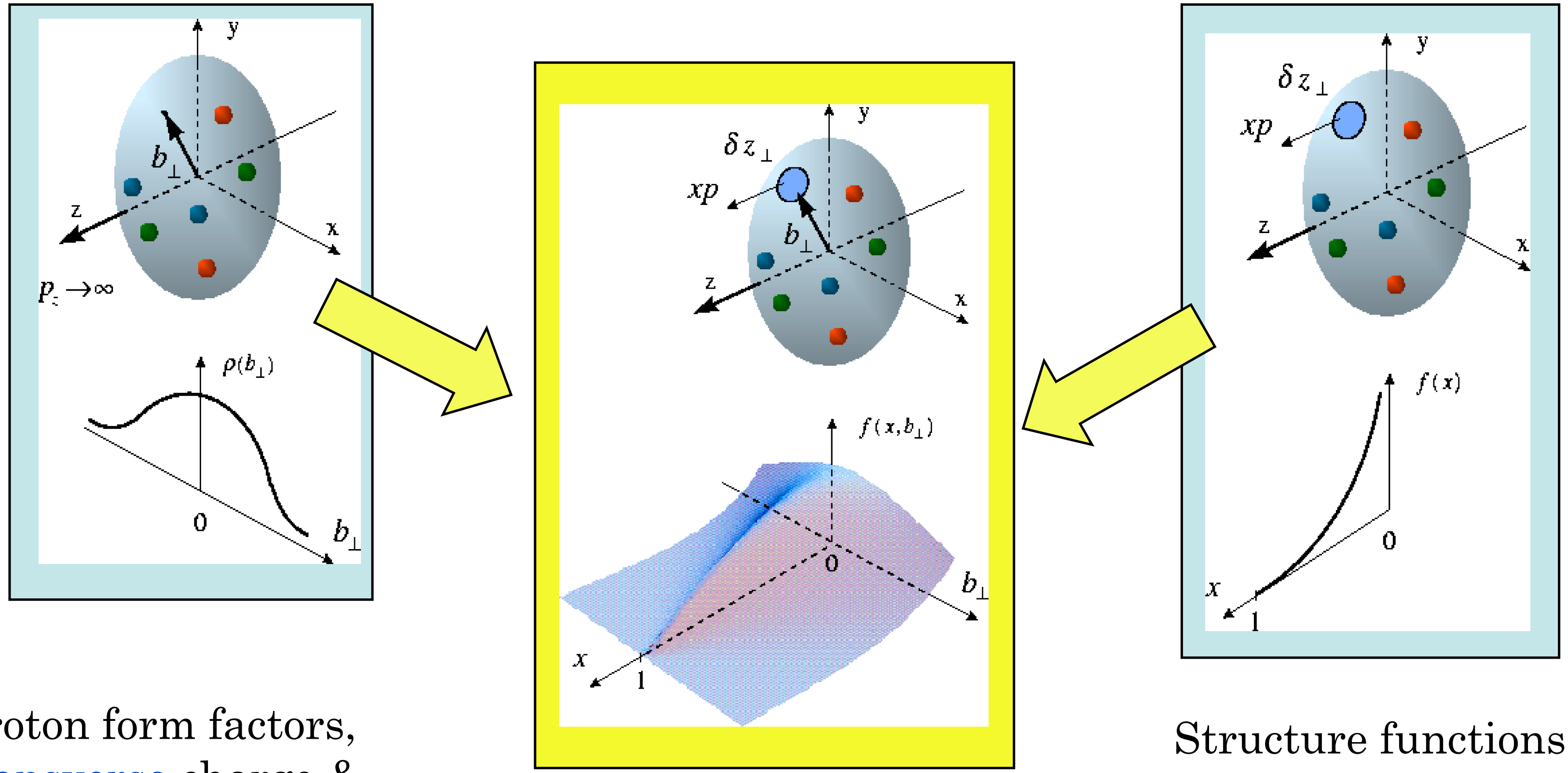


Ji's sum rule for quark orbital momentum

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

DVCS will access low t, large Q^2 kinematics

3-d picture of the nucleon

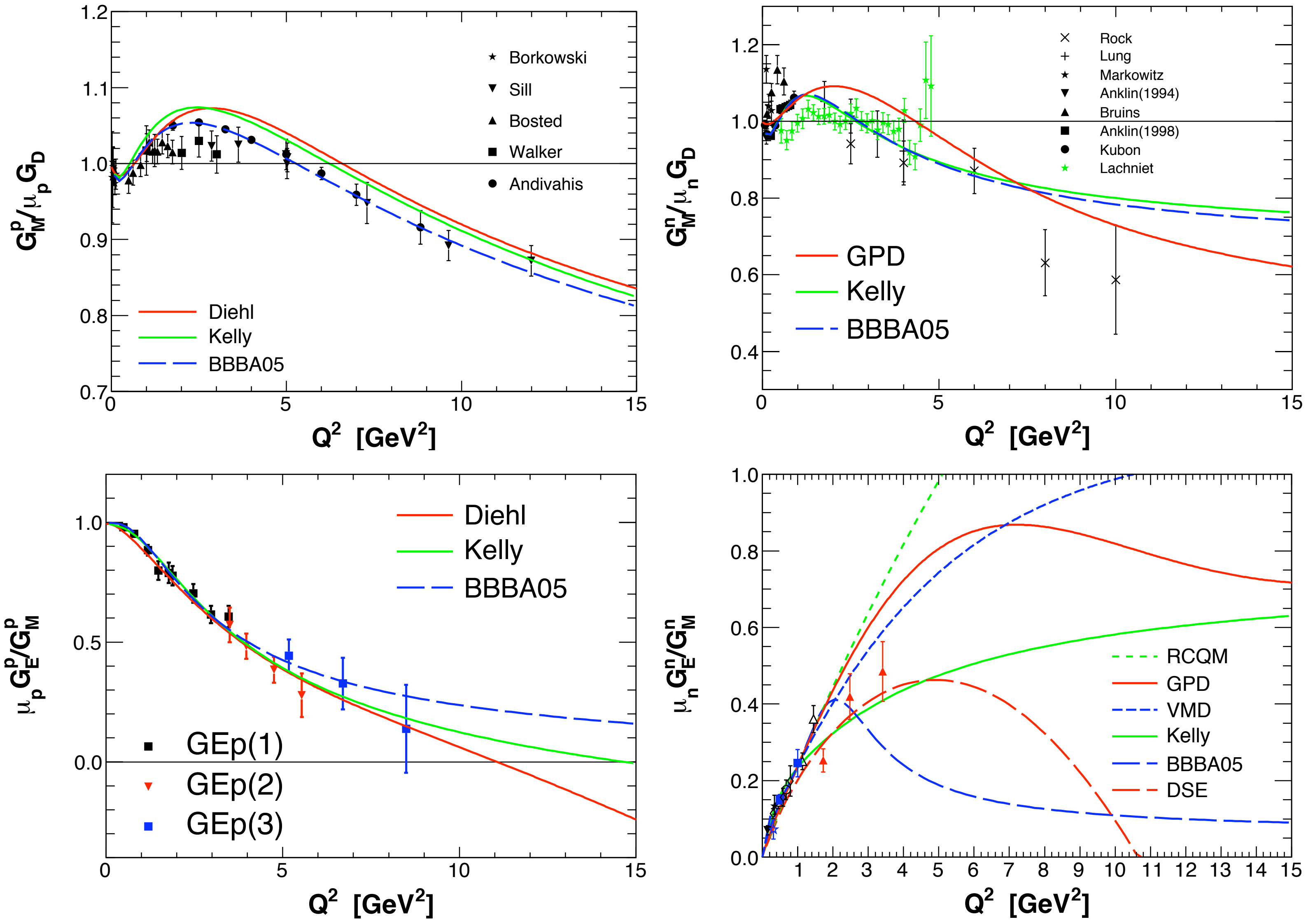


Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Sachs Form Factors of the nucleon



Recent experiment at Jlab

Jlab high Q^2 GEN experiment

✓ Since 1984, when Blankleider&Woloshin suggested $^3\vec{H}e(\vec{e},e'n)$, several experiments of this type have been performed at NIKHEF-K and Mainz (A1, A3) for Q^2 up to 0.7 GeV^2 , a big success in part due to a new accurate 3-body calculation possible at low Q^2 (Glockle et al.)

✓ At Q^2 above 1-2 GeV^2 Glauber method becomes sufficiently accurate (Sarksian)

✓ Electron-polarized neutron luminosity and high polarization of ^{3}He target made measurement about 10 times more effective than with ND_3. In combination with a large acceptance electron spectrometer the total enhancement is more than 100, which allows to reach 3.5 GeV^2

Require super

- Polarized target
- Electron spectrometer
- Neutron detector

Double polarization method

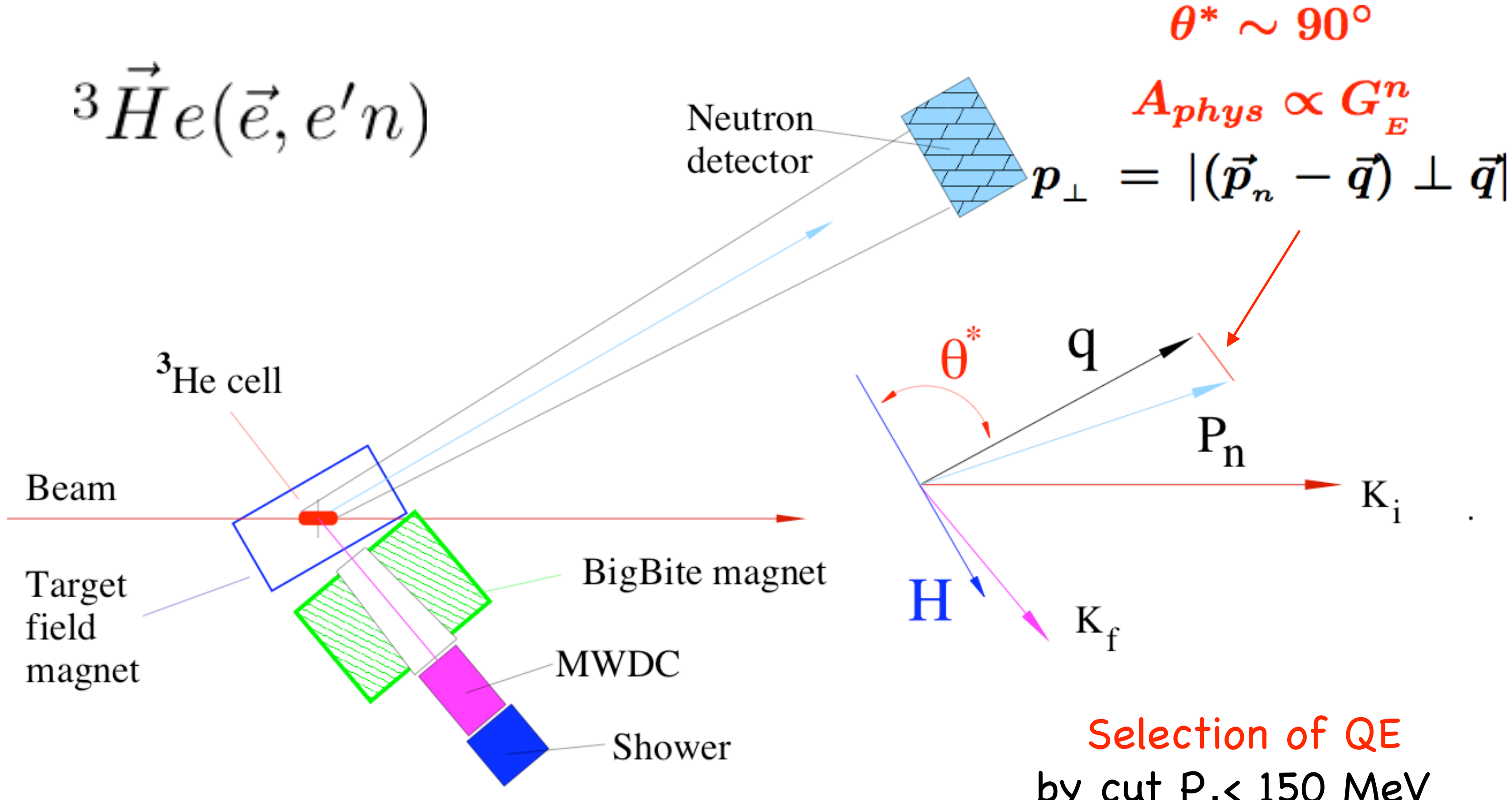
$$A_{phys} = A_{\perp} + A_{\parallel} = \frac{a\cdot G_E G_M \sin\theta^{\star} \cos\phi^{\star}}{G_E^2 + c\cdot G_M^2} + \frac{b\cdot G_M^2 \cos\theta^{\star}}{G_E^2 + c\cdot G_M^2}$$

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

$\theta^{*} \sim 90^{\circ}$

$A_{phys} \propto G_E^n$

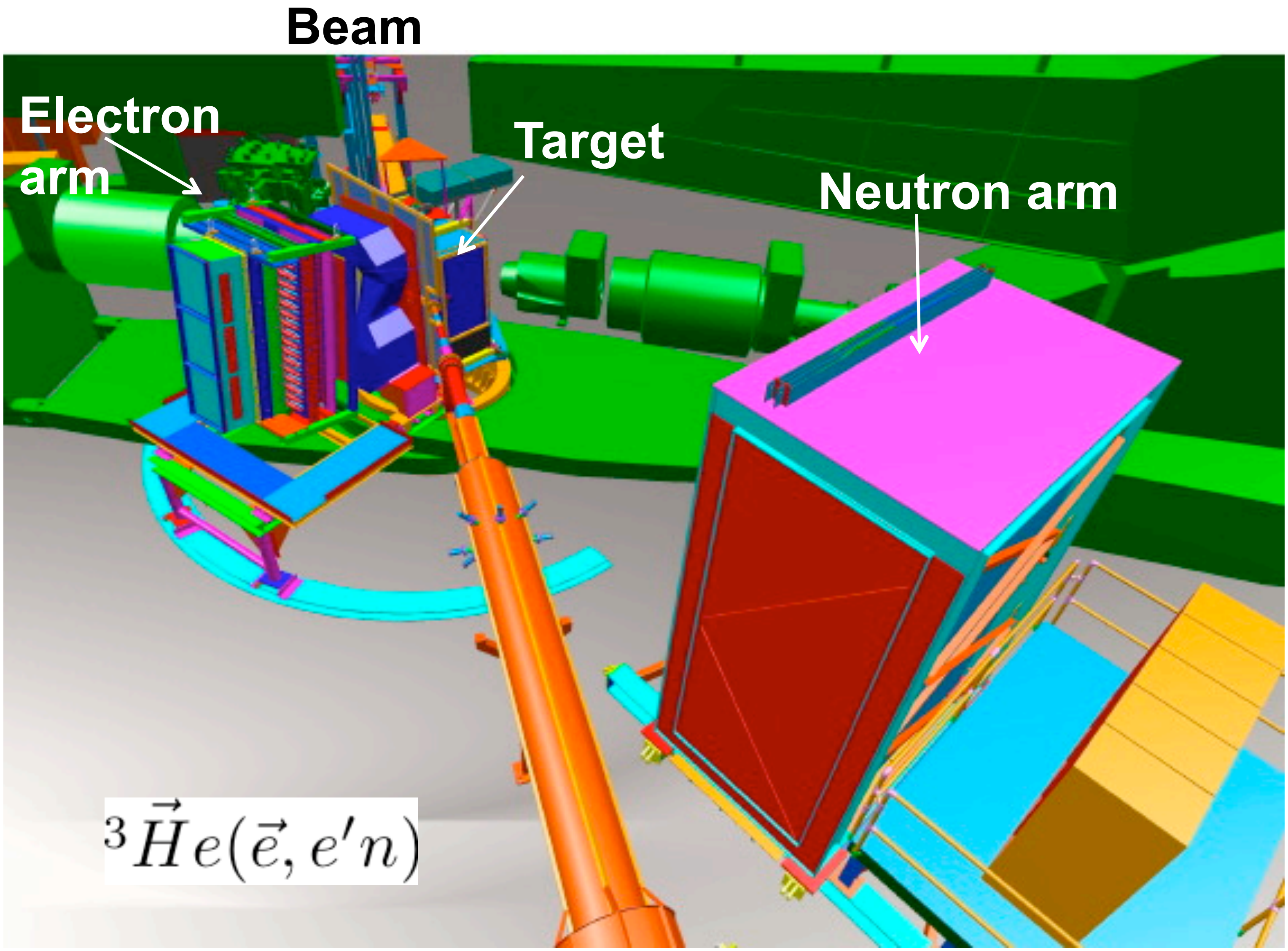
$p_{\perp} = |(\vec{p}_n - \vec{q}) \perp \vec{q}|$



Selection of QE

by cut $P_{\perp} < 150$ MeV

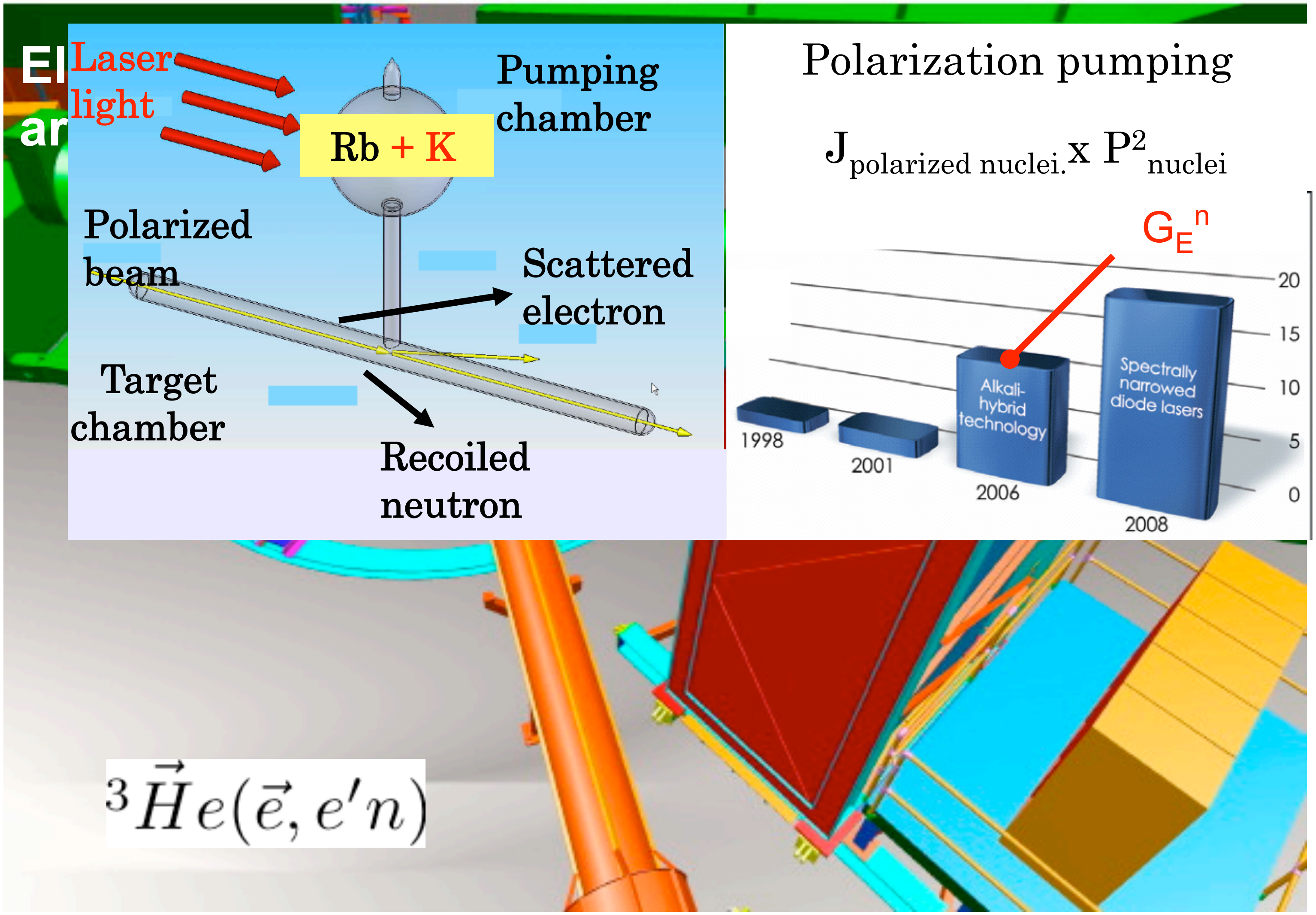
Hall A G_E^n experiment



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

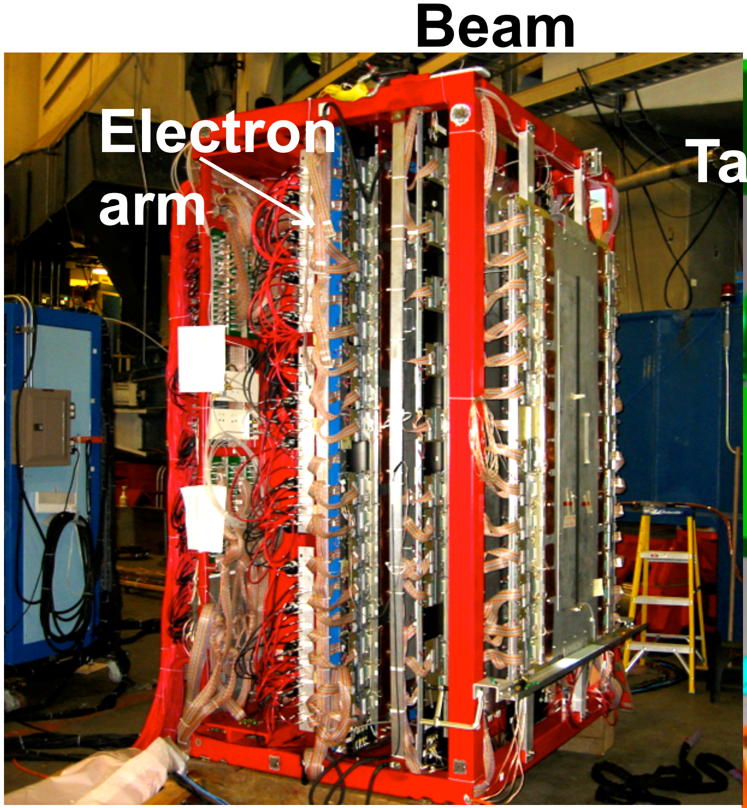
Hall A G_E^n experiment

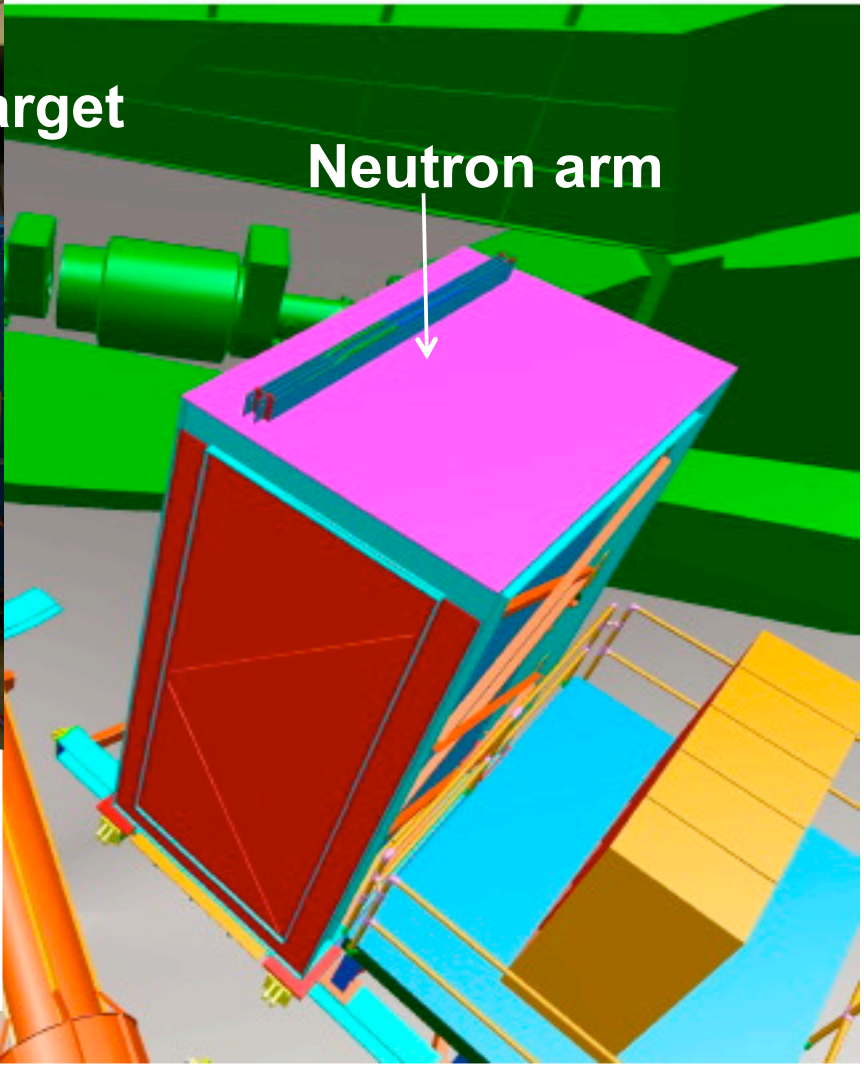
Beam



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

Hall A G_E^n experiment

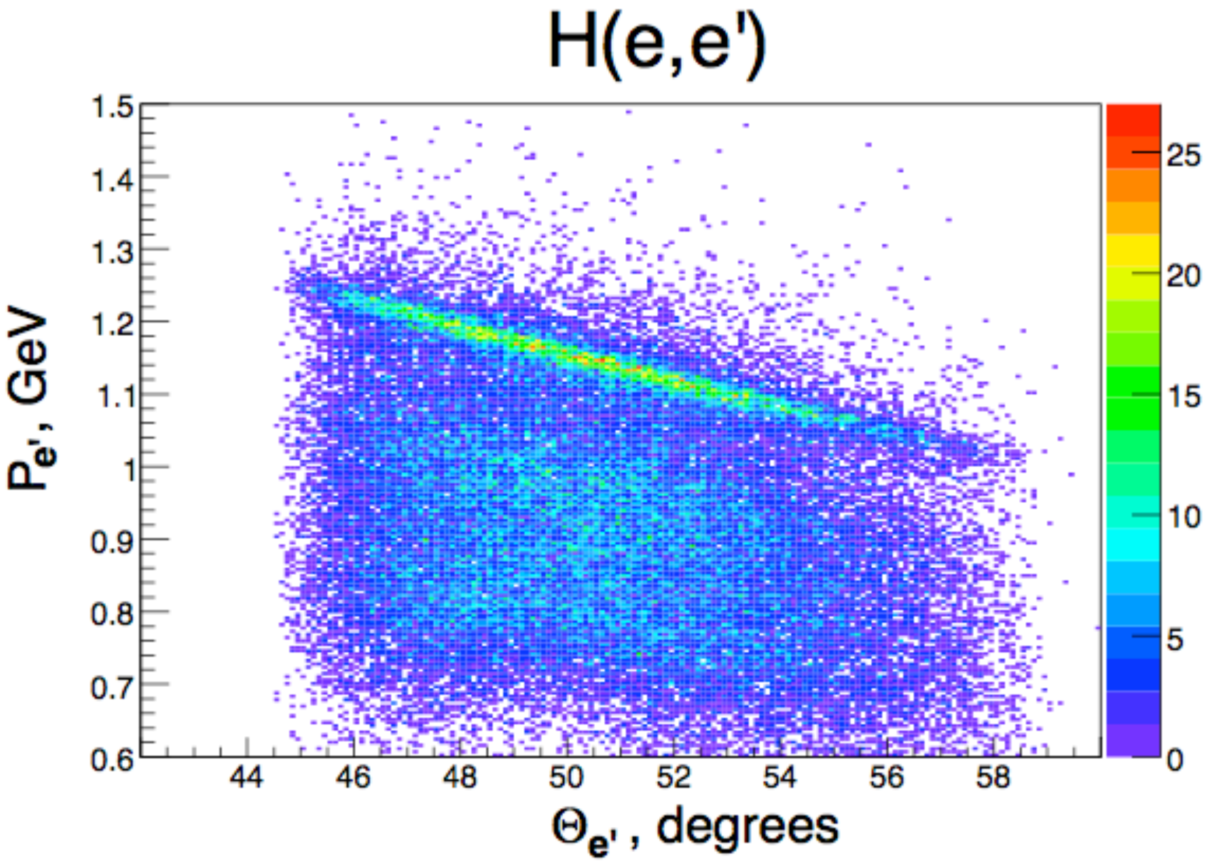




- Solid angle of 76 msr (12 times higher than HRS)
- 40 cm long target
- Momentum resolution of 1%

Electron Spectrometer

Useful $\Delta Q^2/Q^2 \sim 0.1$ with max Ω leads to a large aspect ratio, limited just of 30° for the polar. target. BigBite was designed at NIKHEF for aspect ratio $\Delta\theta/\Delta\phi = 1/5$. Spectrometer has solid angle up to 95 msr.

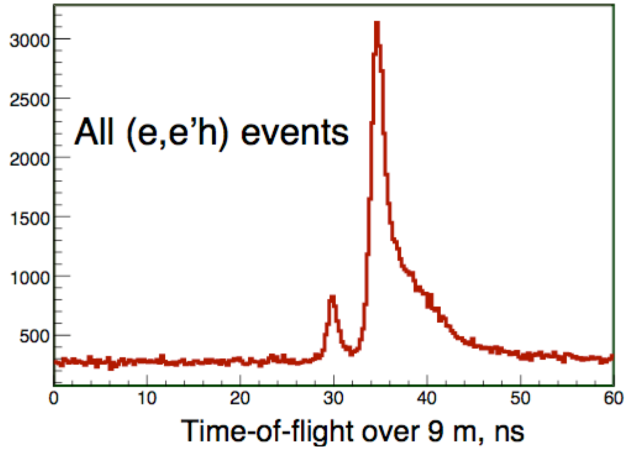


With luminosity of JLab polarized target, 10^{37} cm^{-2}/s, the open geometry - a dipole spectrometer - works well when all MWDCs located behind the magnet.

Neutron Detector

- Match BigBite solid angle
  for QE kinematics
- Flight distance ~ 10 m
- Operation at $3 \cdot 10^{37}$ cm^2/s

- 1.6 x 5 m^2 active area
- 6-7 layers (~ 250 bars)
- 2 veto layers (~ 200)
- 0.38 ns time resolution

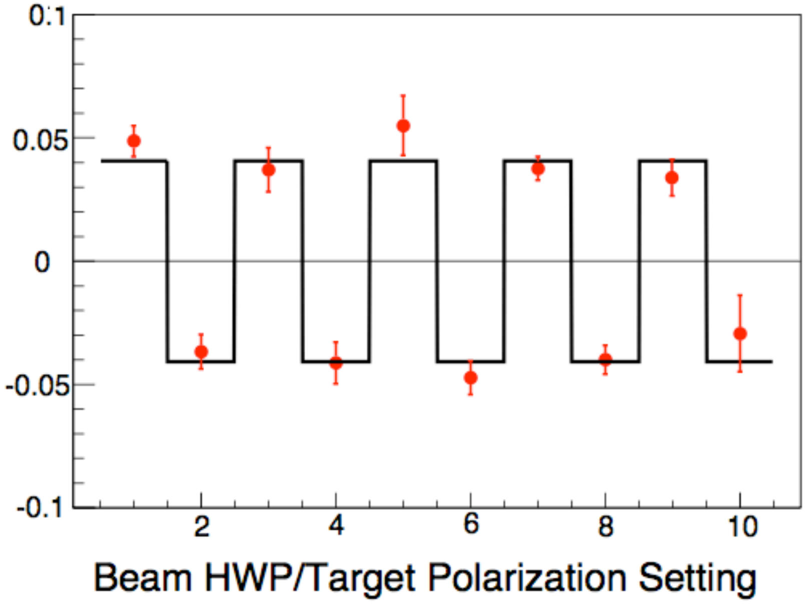


Target monitoring

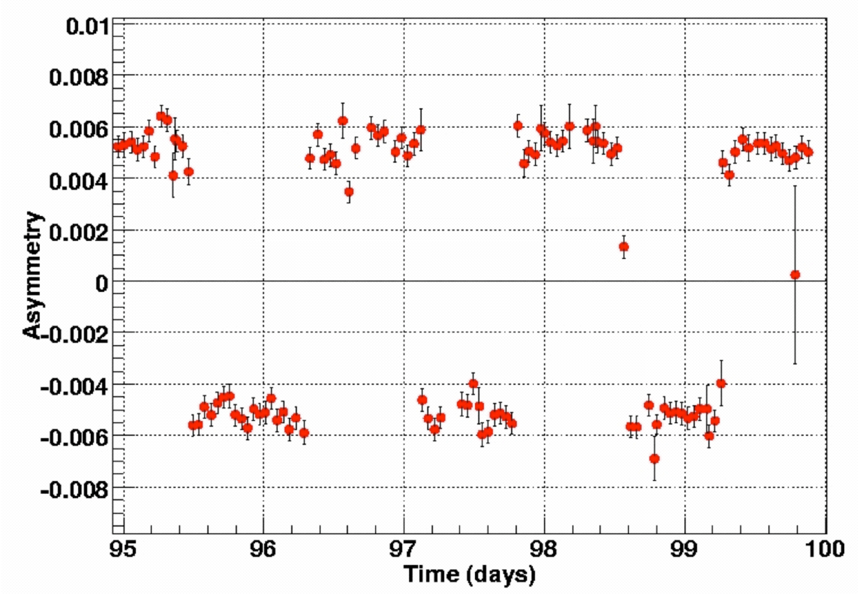
small value of $A_{obs} = A_{\|} + A_{\perp} \approx 2 - 5\%$

smaller is better for reduction of the systematic errors

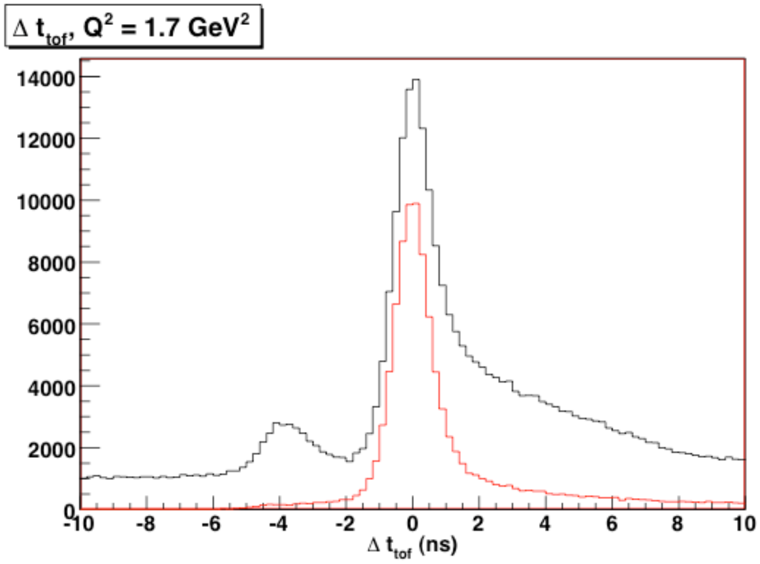
Observed Asymmetry for Quasi-elastic Neutrons

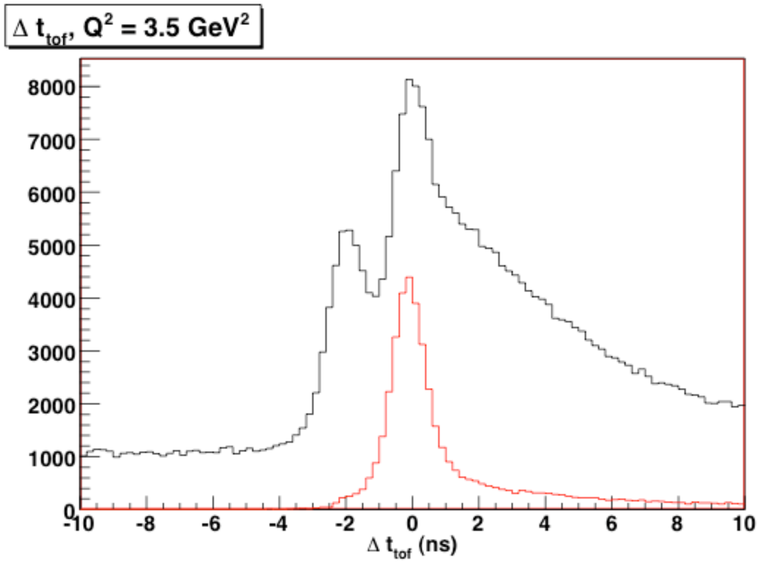


Single arm rate (neutral pions)



Data analysis: step 1 - Time-of-Flight



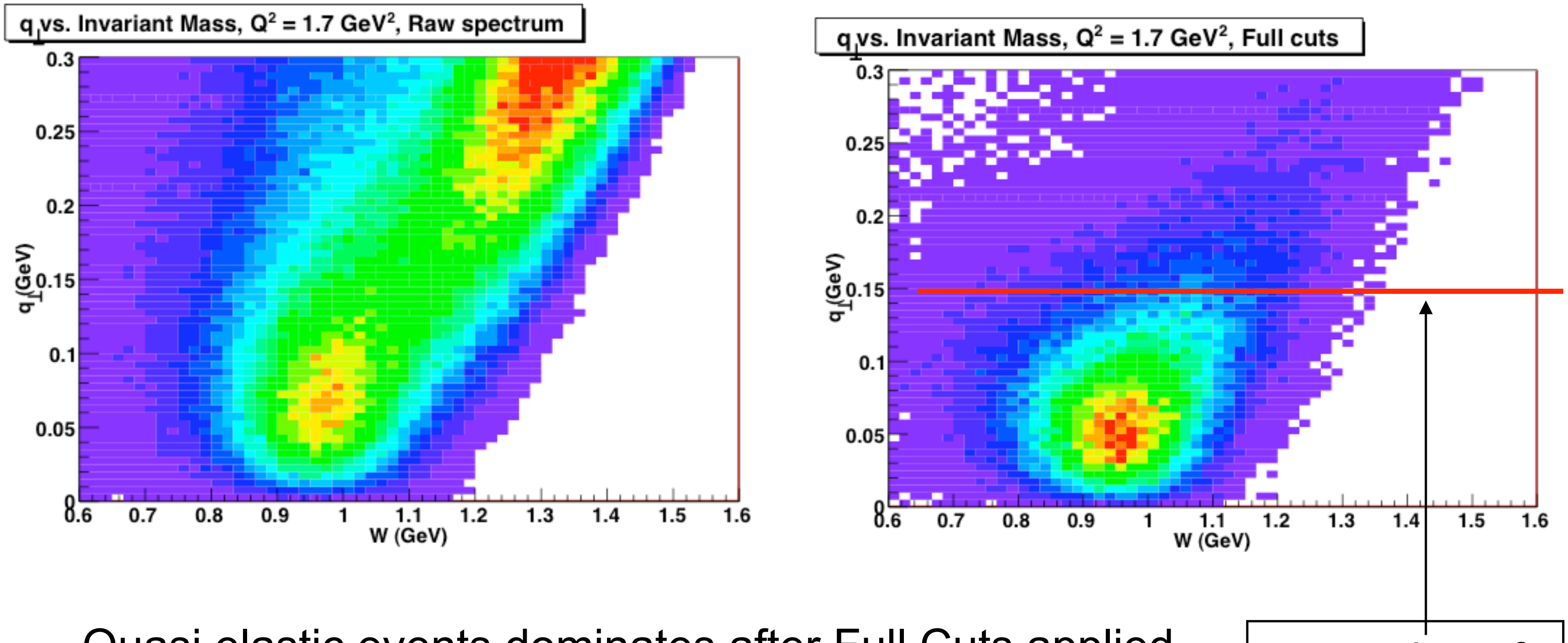


Raw events (BLACK lines) have significant accidental level and large tail for slower protons

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

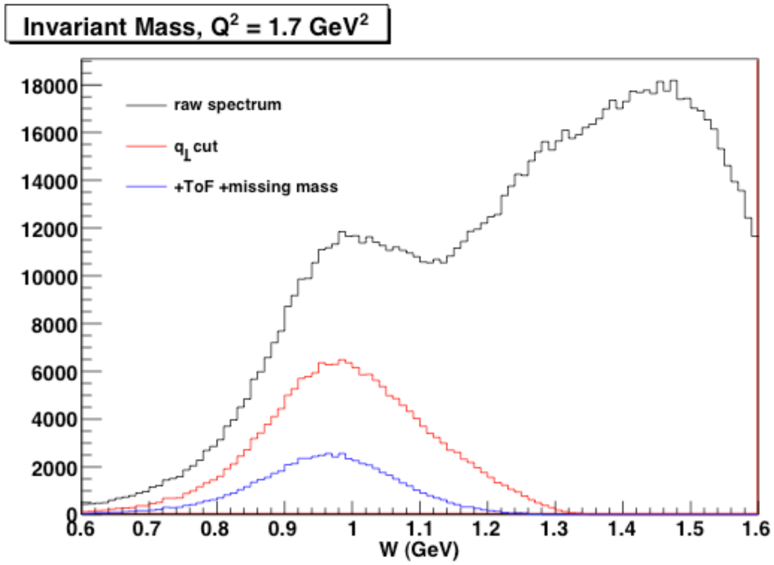
perpendicular "q" = q × $\tan(\theta_{qh})$; $W^2 = M^2 + 2M(E-E') - Q^2$

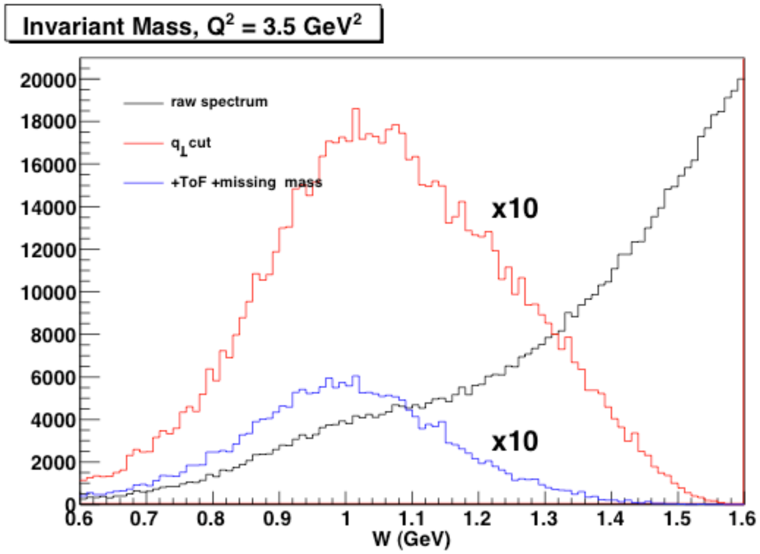


Quasi elastic events dominates after Full Cuts applied

max value of
used perp. q

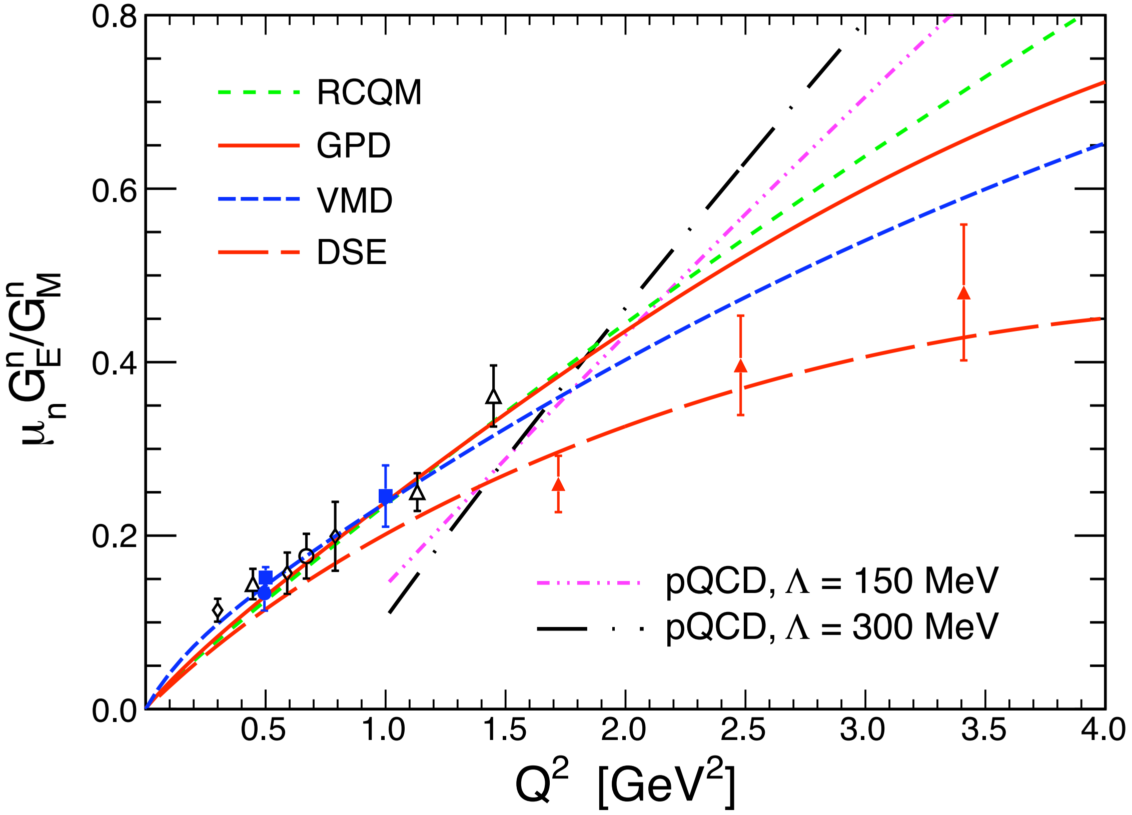
Analysis: step 3 - W distribution





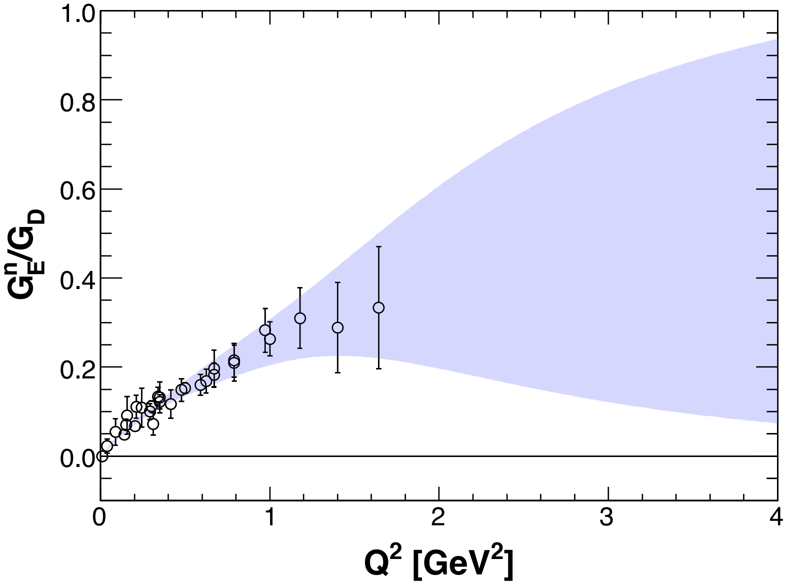
for 3.5 GeV^2 quasi-elastic signal very small in e,e’
after angular correlation cut peak is just as suppose to be

The results G_E^n experiment

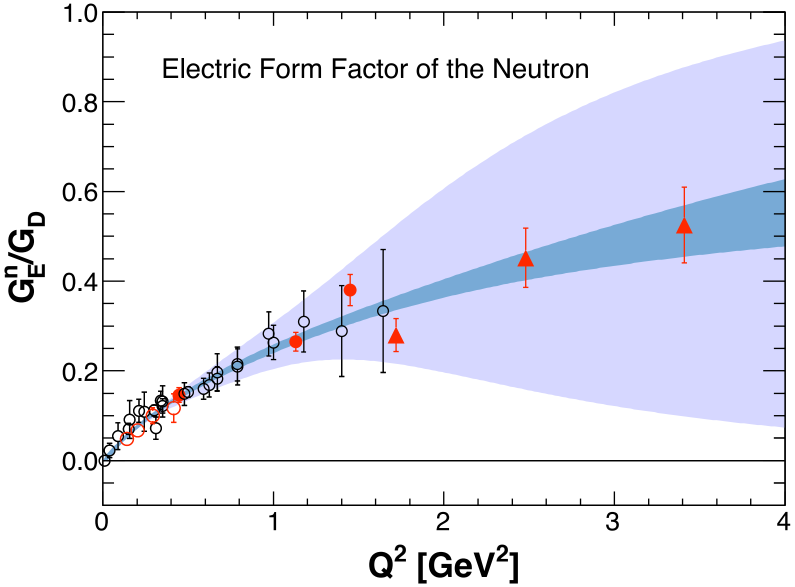


The JLab G_E^n experiments

without JLab GEn
experiments

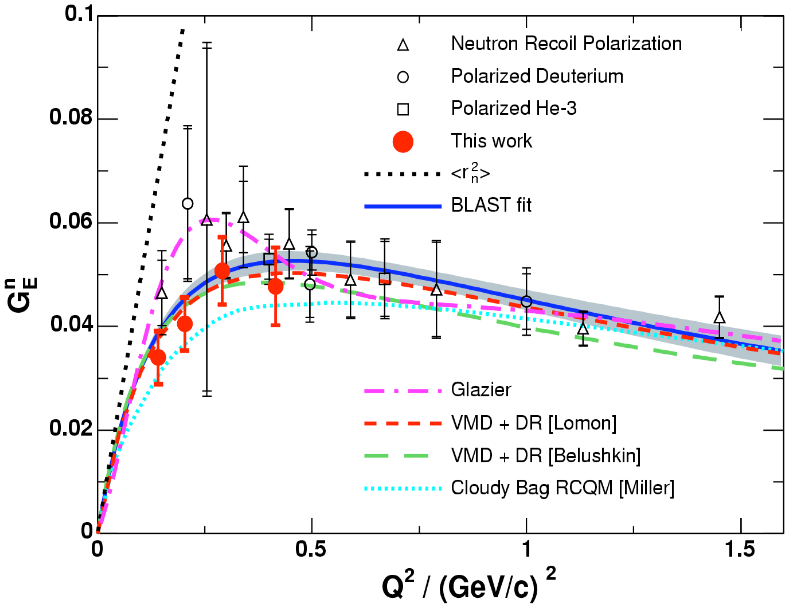


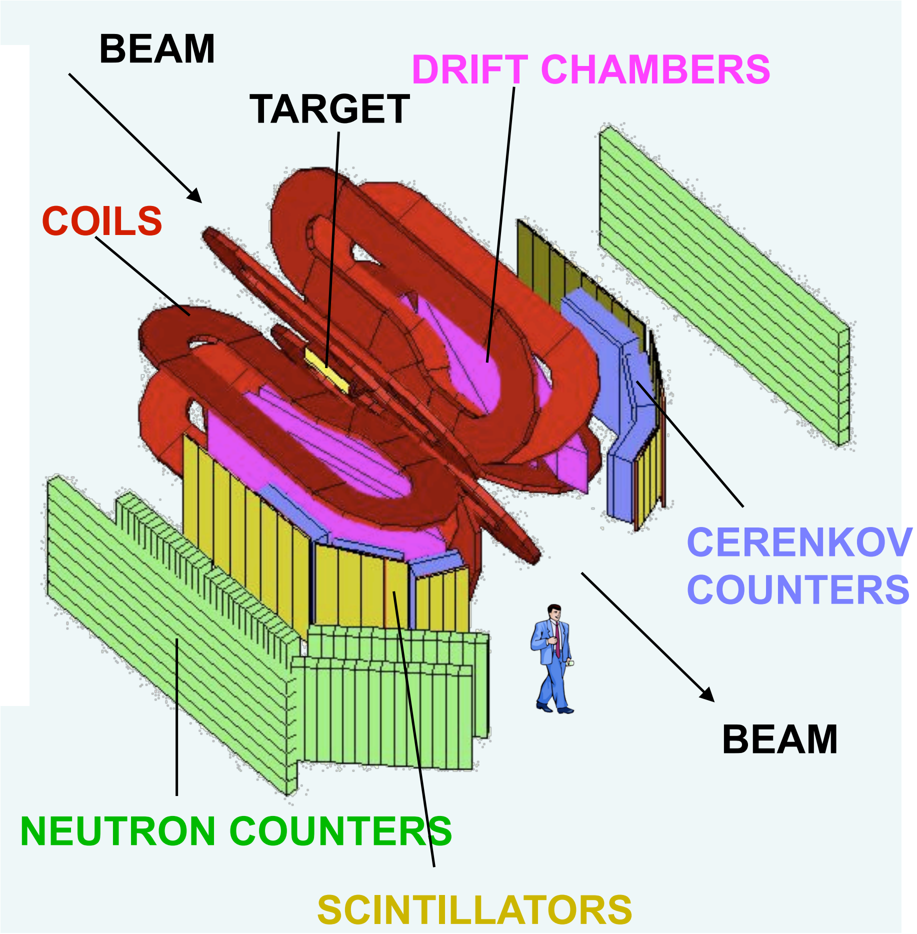
significantly better
accuracy for high Q^2



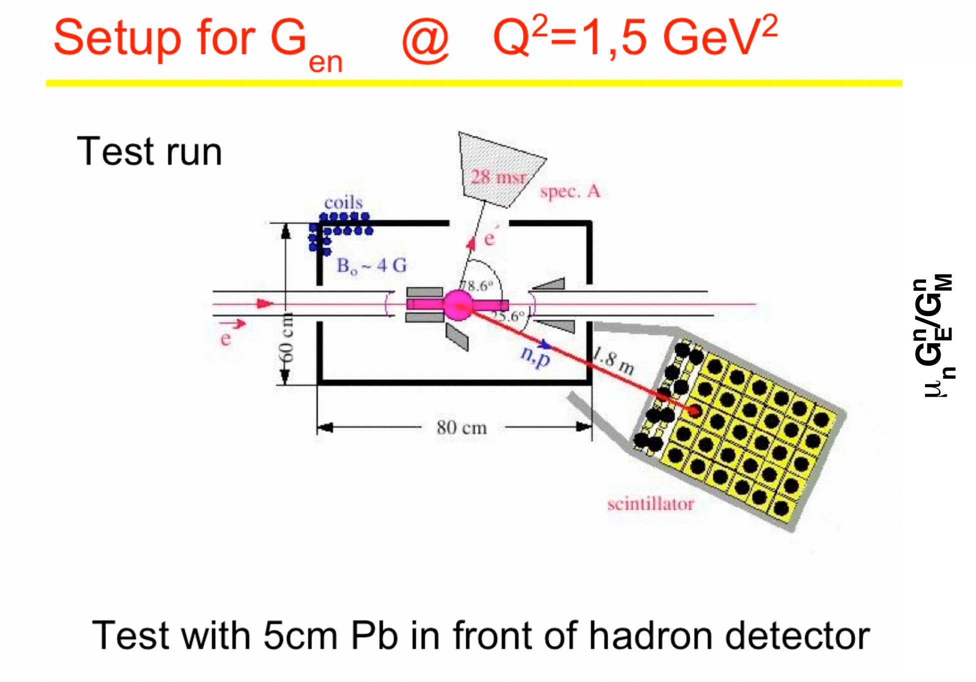
Recent experiment at Bates

$\vec{D}(\vec{e},e'n)$





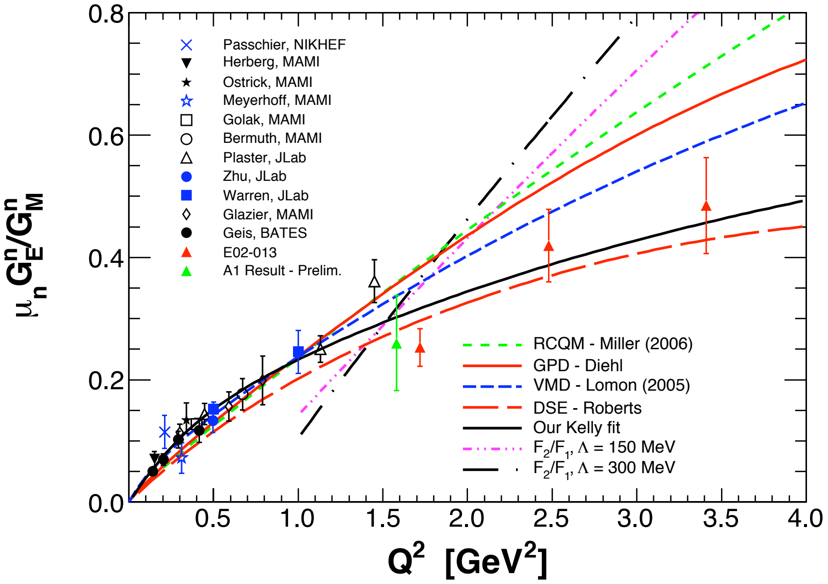
Running experiment at Mainz



Setup for G_{en} @ Q^2=1,5 GeV^2

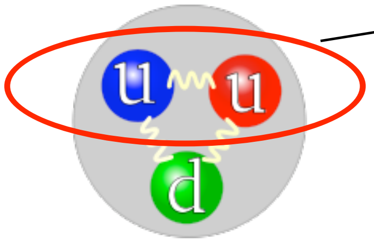
Test run

Test with 5cm Pb in front of hadron detector



Flavor view with EMFFs

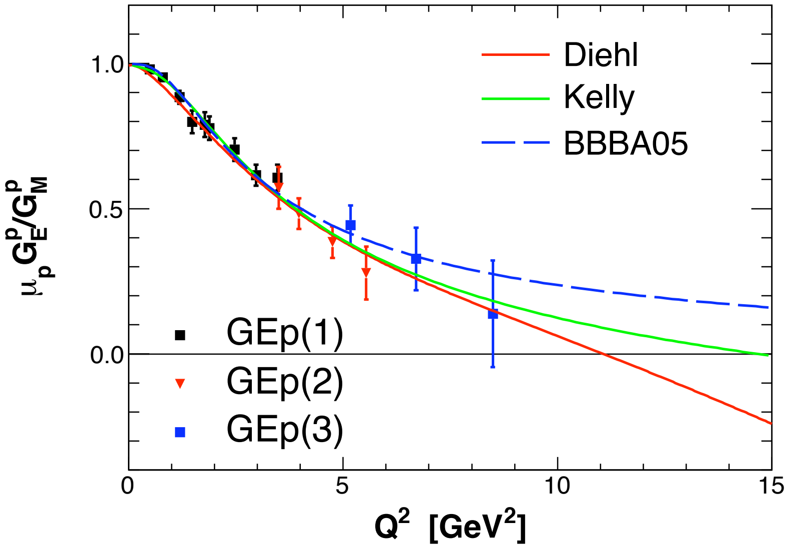
The goal is understanding of the nucleon

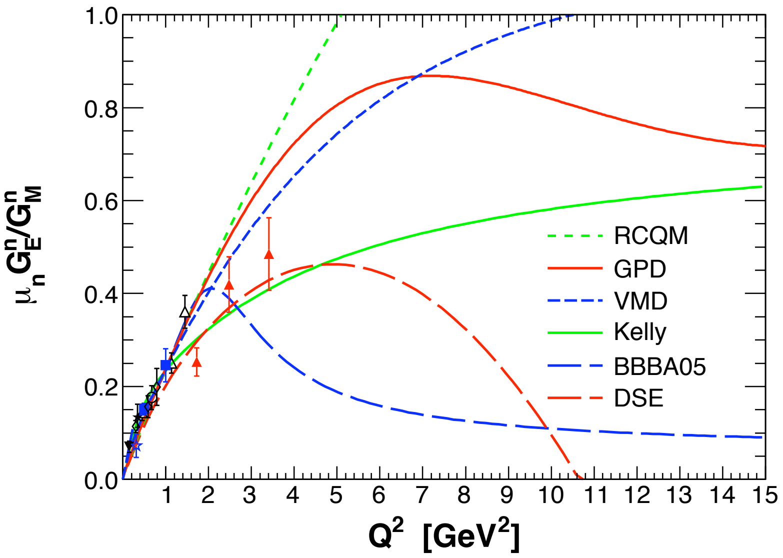


$$F_p = \frac{+2}{3} F_{dual} + \frac{-1}{3} F_{lone}$$

$$F_n = \frac{-1}{3} F_{dual} + \frac{+2}{3} F_{lone}$$

$$F_{1,dual} = F_1^{u,p} = 2\, F_{1p} + F_{1n} \qquad F_{1,lone} = F_1^{d,p} = 2\, F_{1n} + F_{1p}$$





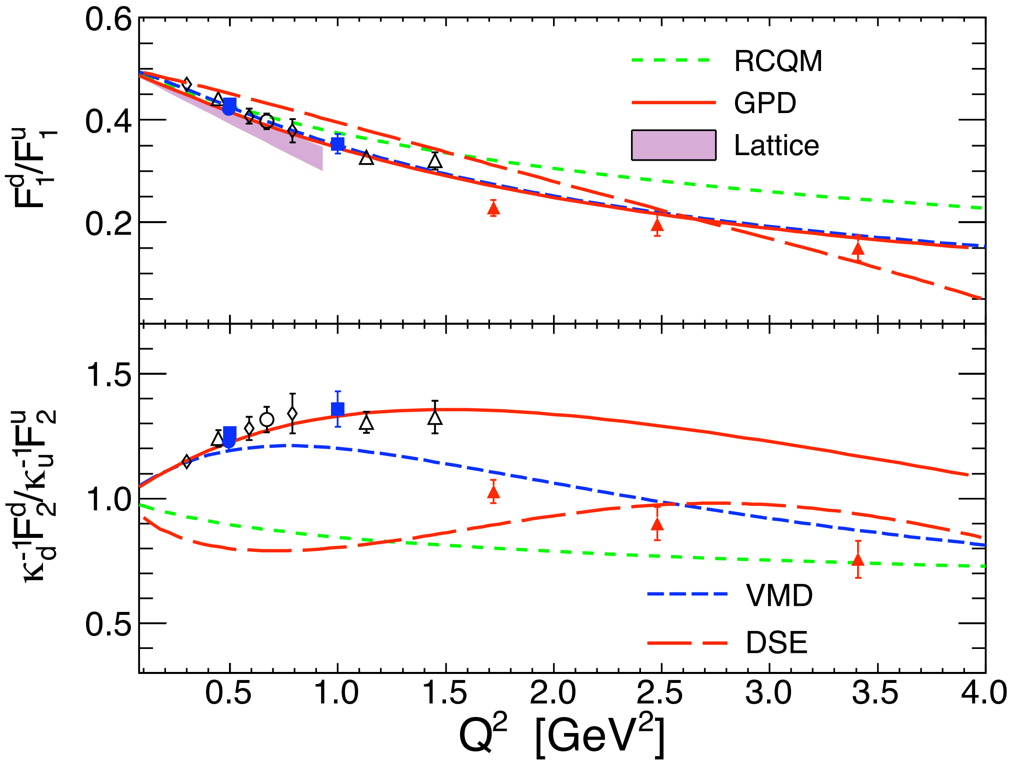
$F_{1\,(2)}^{d}/F_{1\,(2)}^{u}$ with proton and neutron FFs

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

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

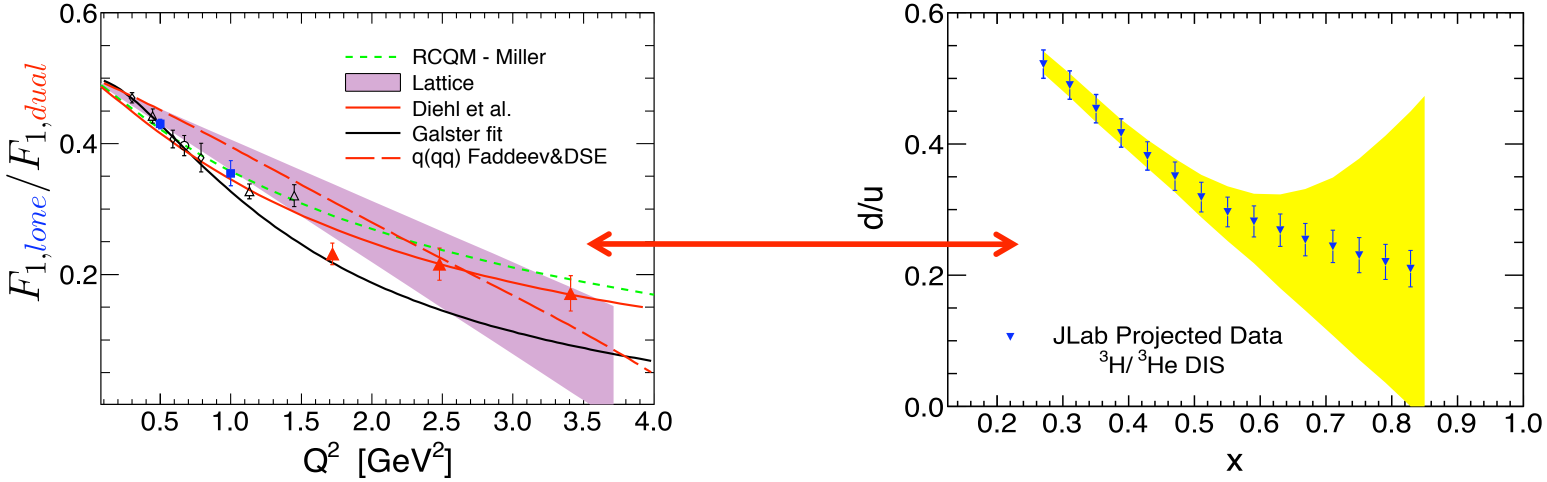
$$F_1^u = 2\,F_{1p} + F_{1n}$$

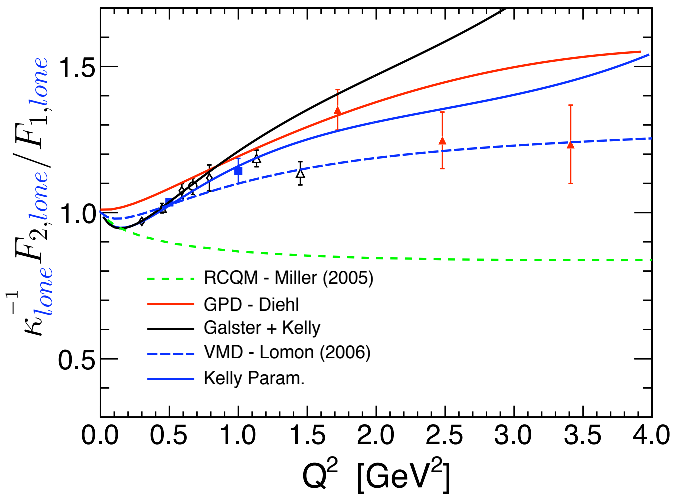
$$F_1^d = 2\,F_{1n} + F_{1p}$$

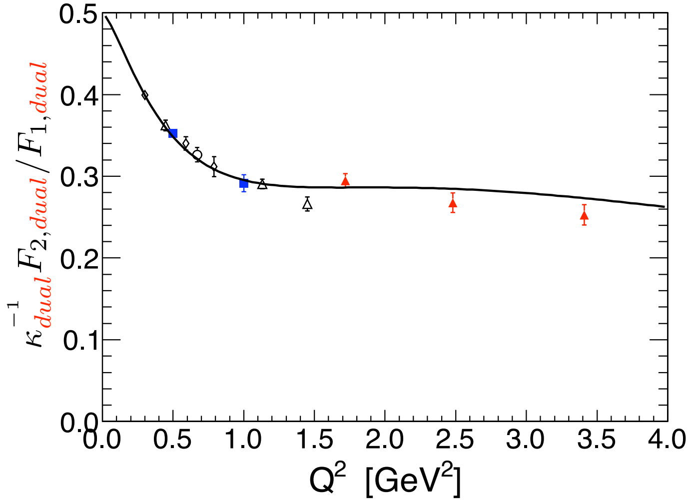


Lattice calculation => very good agreement with the trend, need accuracy
DSE (ANL) => good, possibly a signature of dominant degrees of freedom
Our data will require a new fit of E_d and E_u GPDs

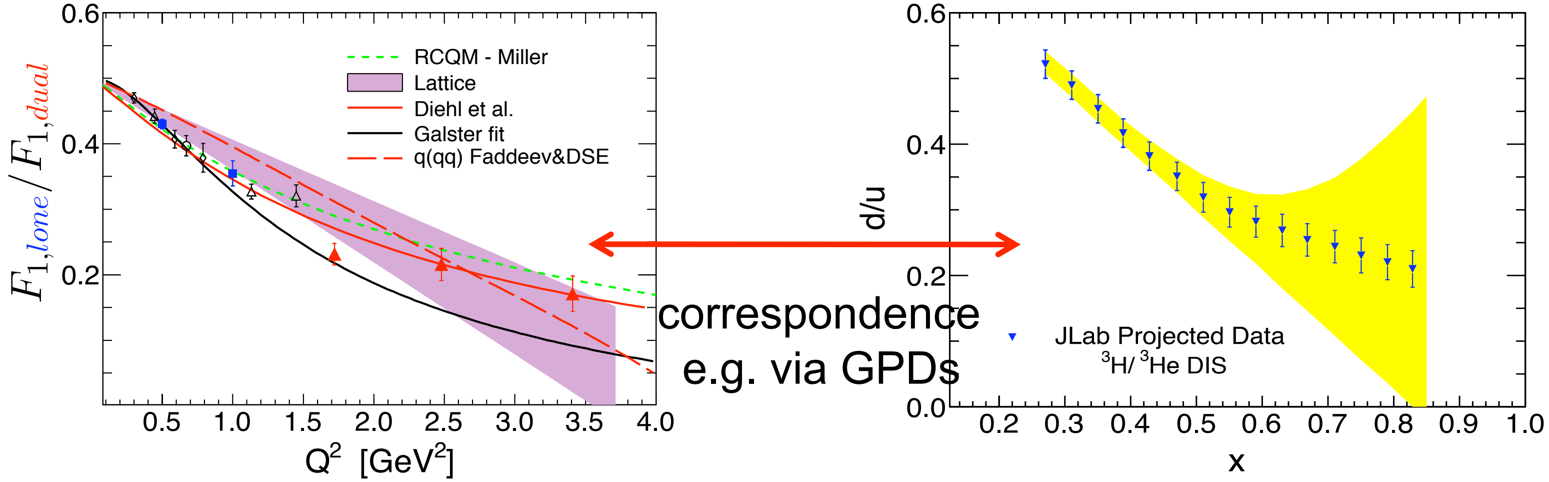
Form Factors ratios



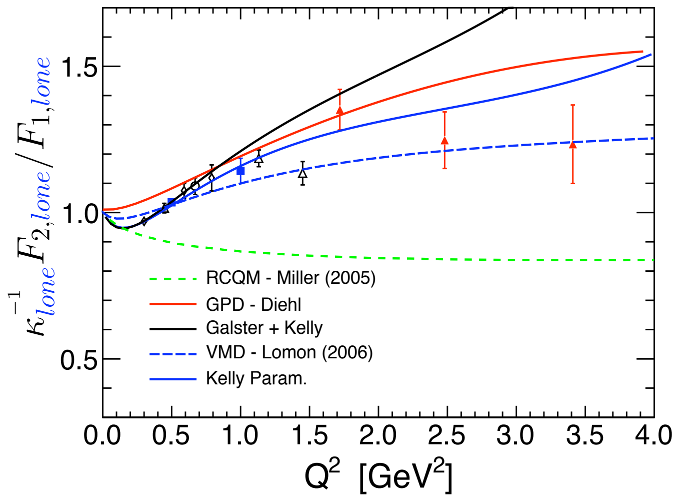


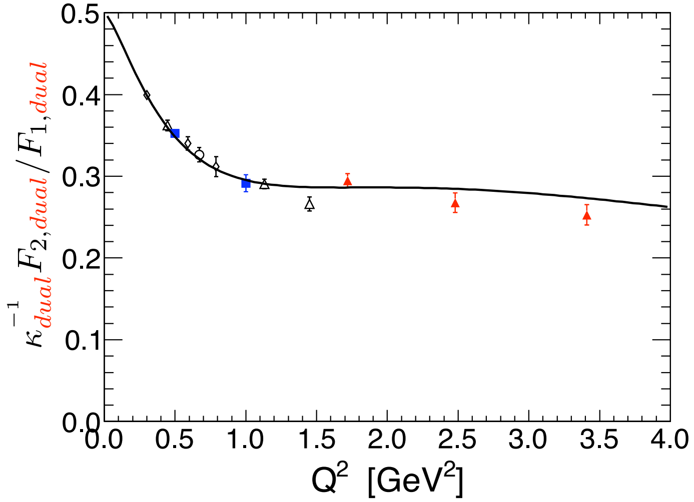


Form Factors ratios

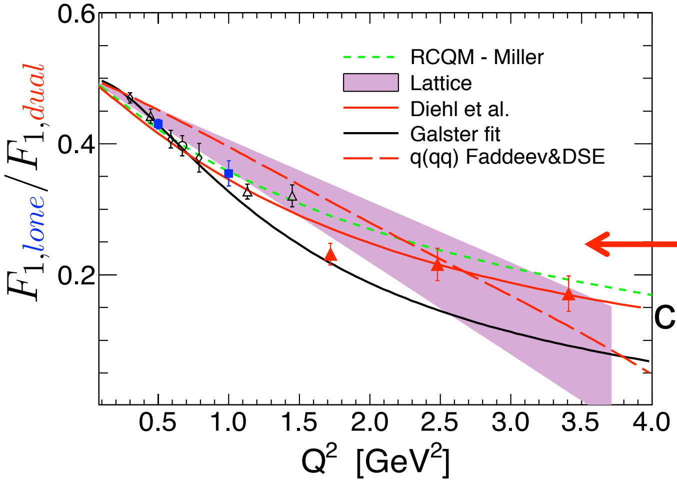


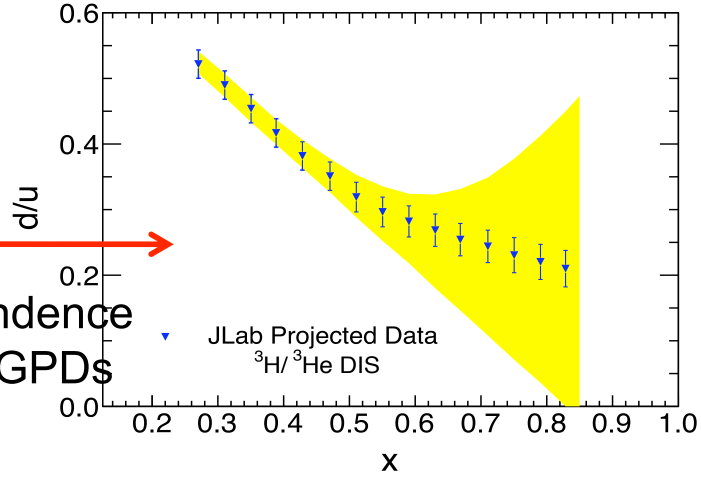
correspondence
e.g. via GPDs





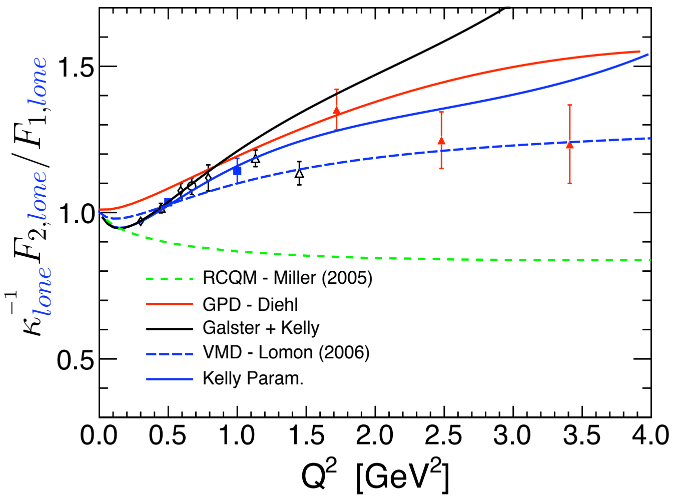
Form Factors ratios

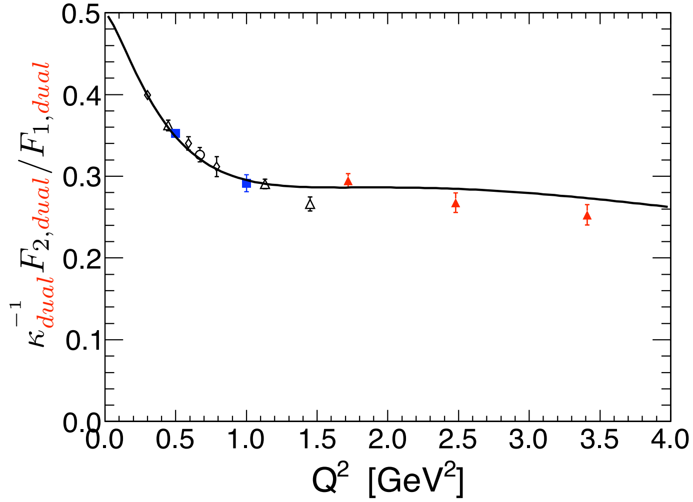




correspondence
e.g. via GPDs

Dual and Lone quark distribution FFs





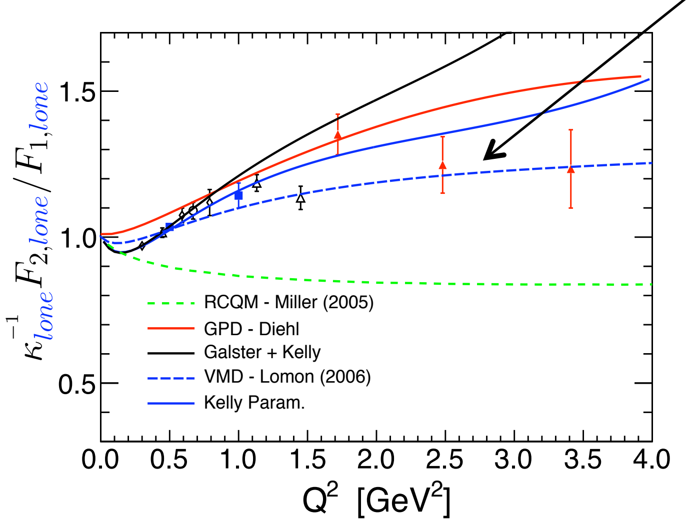
The goal is understanding of the nucleon

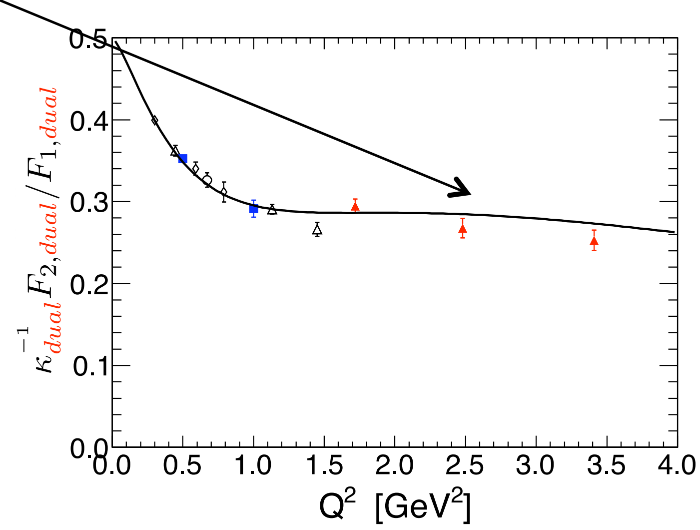
- What is a unique signature of the diquark configuration?

$$F_p = \frac{+2}{3} F_{dual} + \frac{-1}{3} F_{lone}$$

$$F_n = \frac{-1}{3} F_{dual} + \frac{+2}{3} F_{lone}$$

Results of E02-013 Hall A GEn



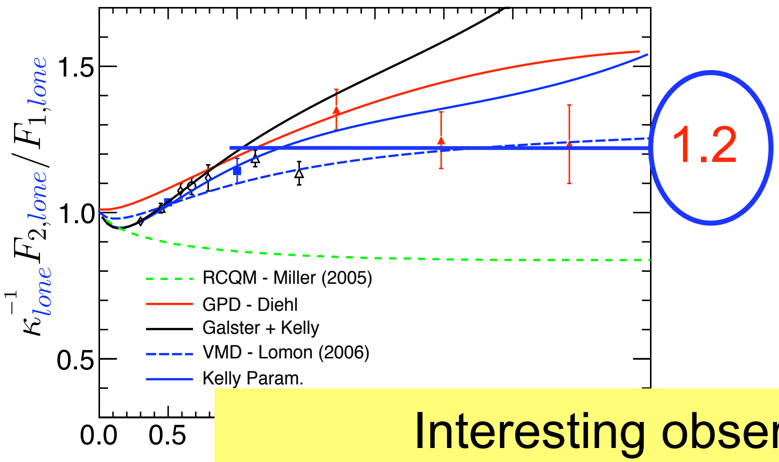


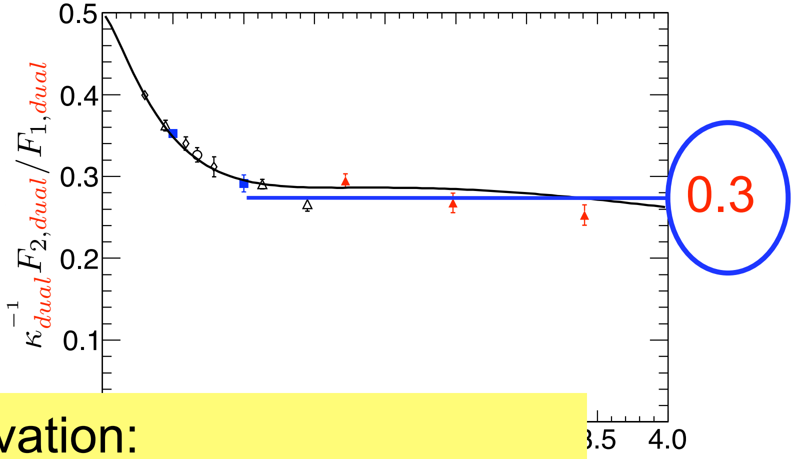
The goal is understanding of the nucleon

- A diquark configuration?
- An effect of orbital motion?

$$F_{1,dual} = F_1^{u,p} = 2\,F_{1p} + F_{1n} \qquad F_{1,lone} = F_1^{d,p} = 2\,F_{1n} + F_{1p}$$

Results of E02-013 Hall A GEn





Interesting observation:
F2/F1 = R is constant in the Q^2-range 1 - 3.5 GeV^2

EMFFs and GPDs

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

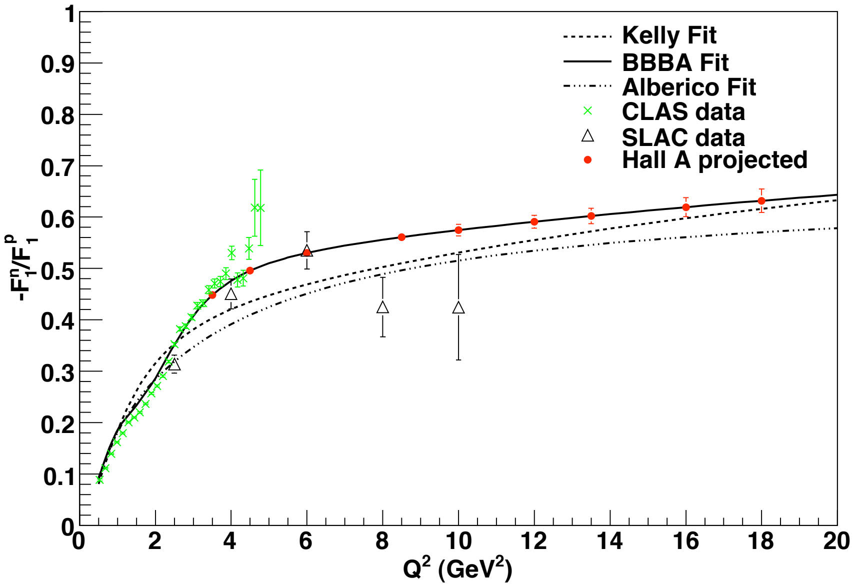
$$H^q(x, \xi = 0, t = 0) = q(x)$$

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

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

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

GMn/GMp and GPDs

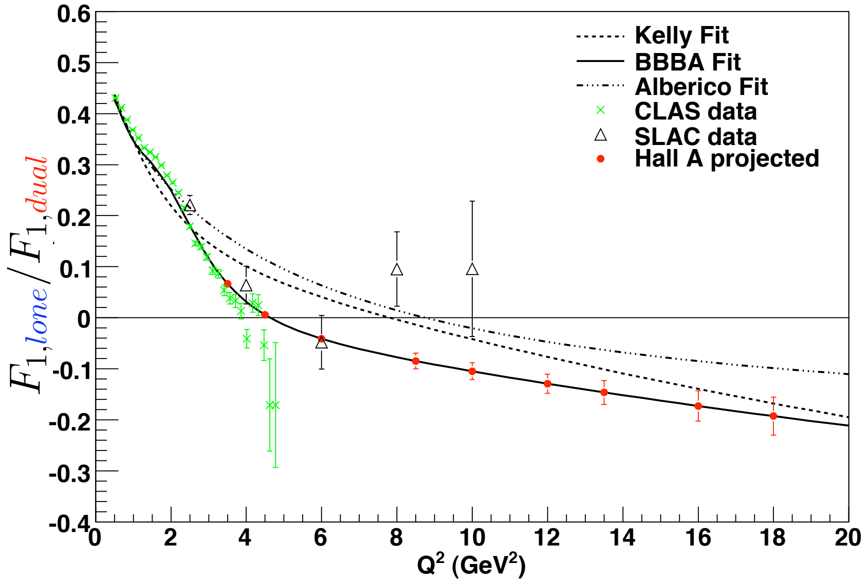


GPD model (Guidal etal):

$$F_1^u(t) = \int_0^1 dx u_v(x) e^{-t\alpha' \ln x},$$

$$F_1^d(t) = \int_0^1 dx d_v(x) e^{-t\alpha' \ln x}.$$

$F_1^d < 0$ presents an interesting challenge to such a model



The transverse neutron densities

Impact parameter GPDs

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

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

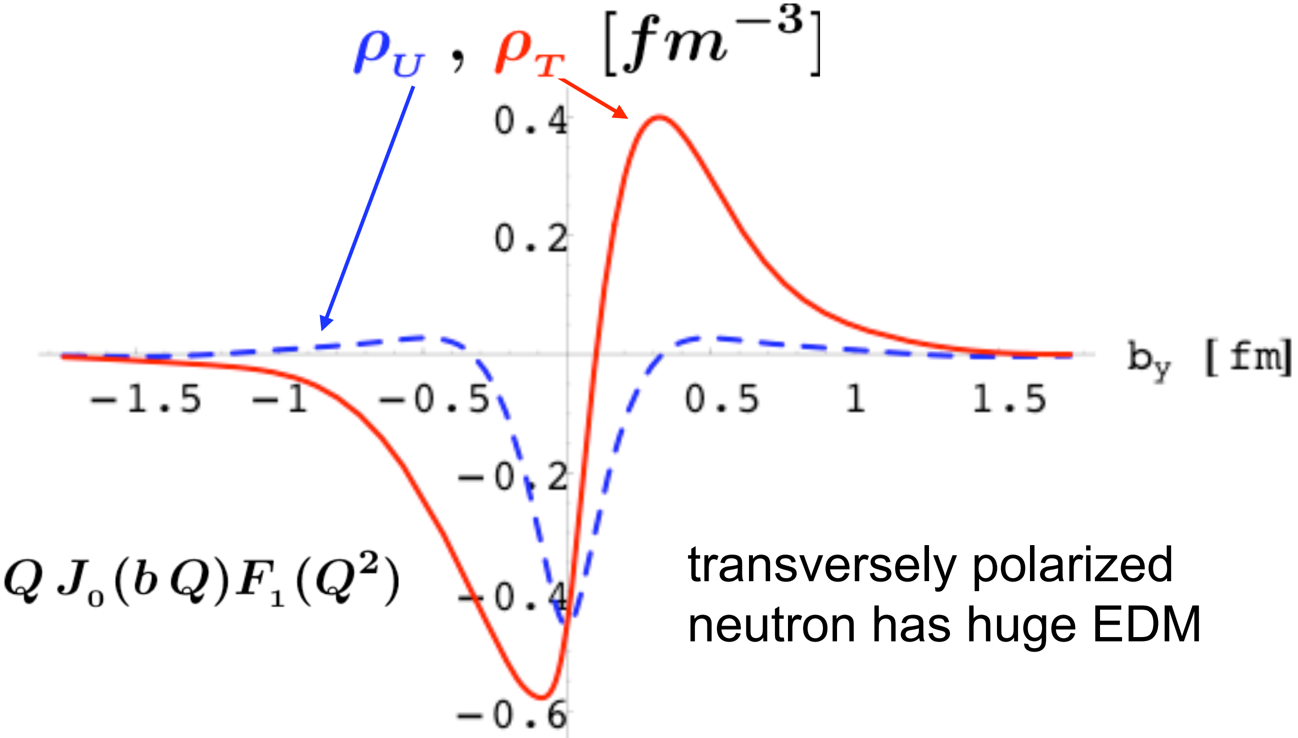
center of momentum $\boldsymbol{R}_\perp = \sum_i x_i \cdot \boldsymbol{r}_{\perp,i}$

$\boldsymbol{b}$ is defined relative to $\boldsymbol{R}_\perp$

Transverse densities

$$\rho_T(\vec{b}) \;=\; \rho_U(b) \;-\; \sin(\phi_b - \phi_S)\int_0^\infty \frac{dQ}{2\pi}\frac{Q^2}{2M} J_1(b\,Q)F_2(Q^2)$$

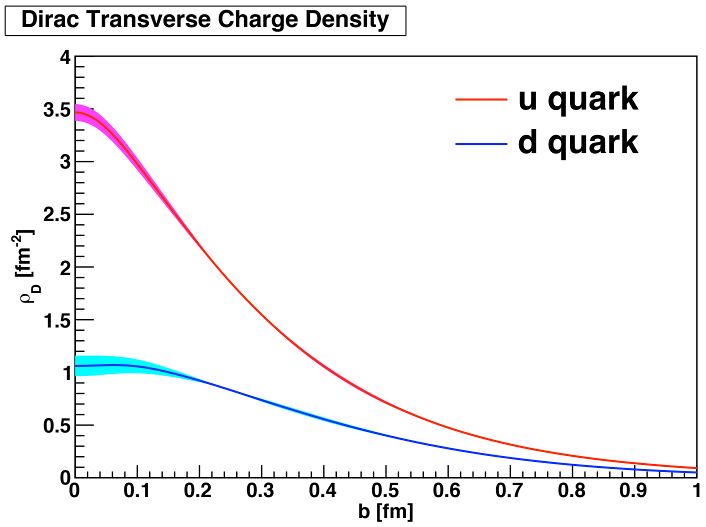
C.Carlson &
M.Vaderhaeghen

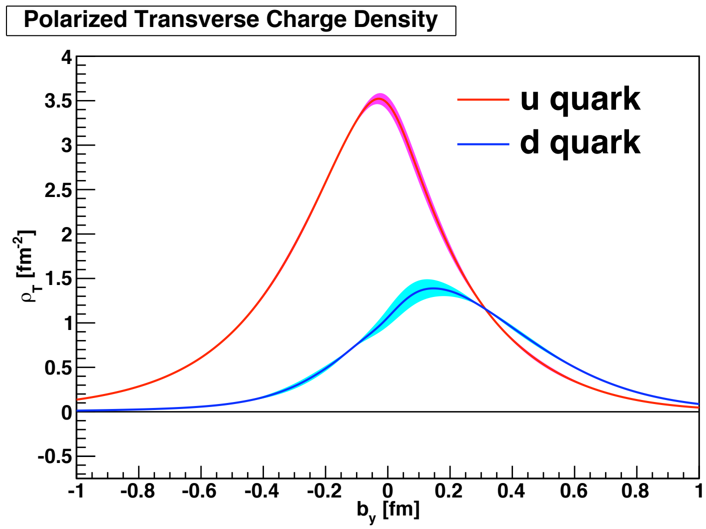


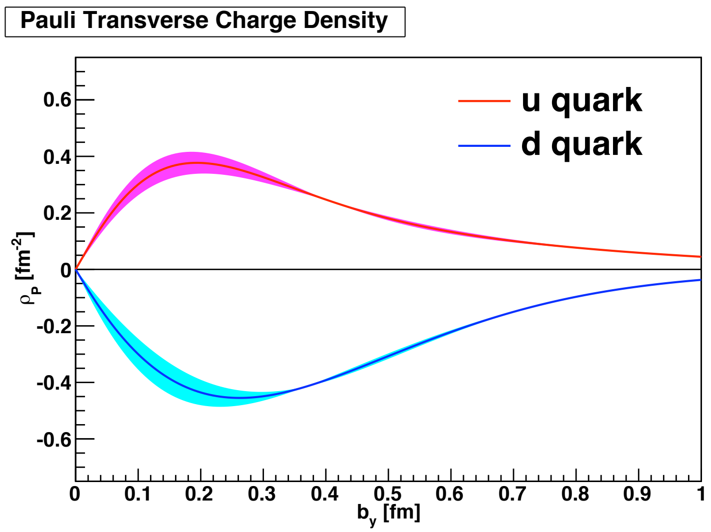
$$\rho_U(b) = \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(b\,Q)F_1(Q^2)$$

transversely polarized
neutron has huge EDM

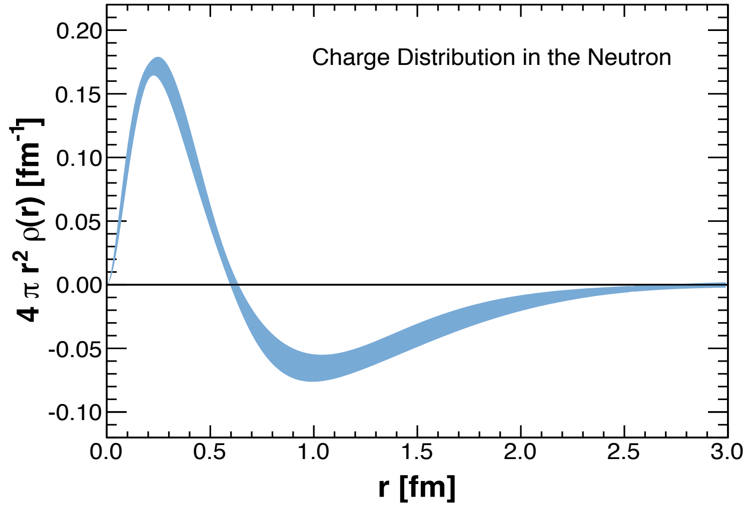
Flavor decomposition of IMF densities


Dirac Transverse Charge Density


Polarized Transverse Charge Density


Pauli Transverse Charge Density

Ordinary charge density

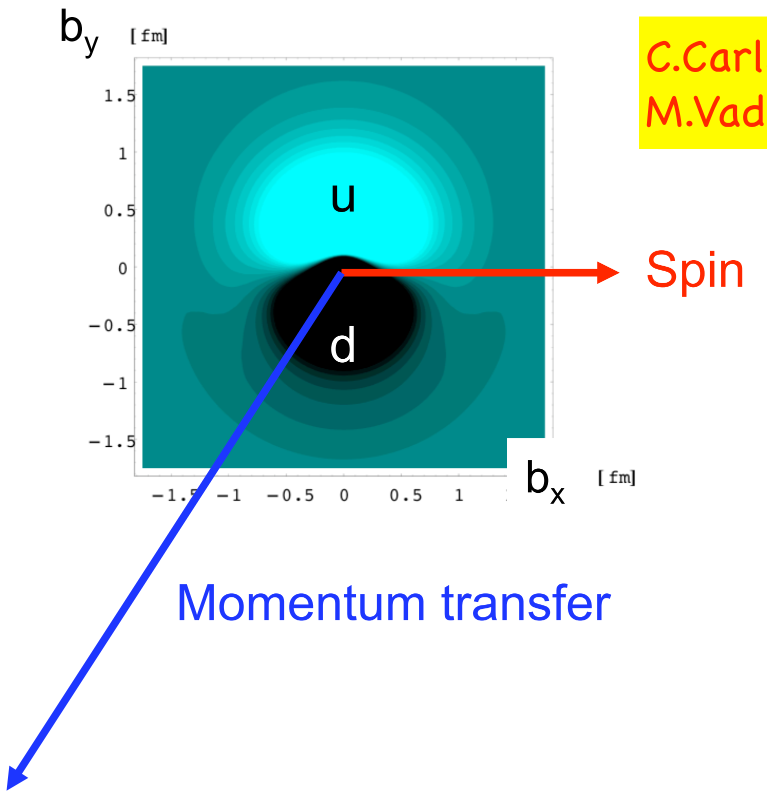


Density in polarized neutron

Transversity effects in

$$\vec{n}(e,e'\pi^-)X$$

$$\vec{n}(e,e'\pi^+)X$$

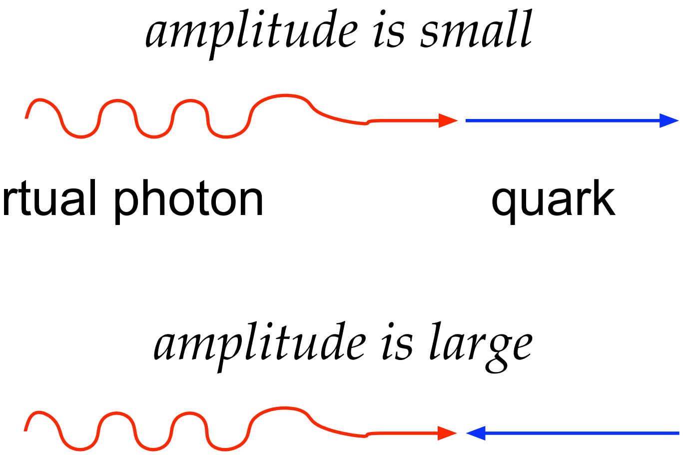


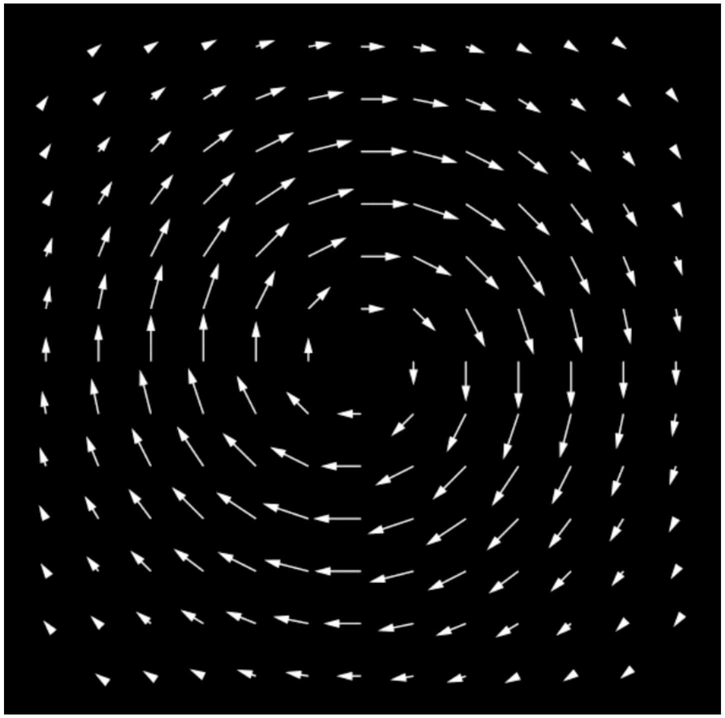
C.Carlson &
M.Vaderhaeghen

Rotation of u/d quarks in neutron

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

M.Burkardt (2003)



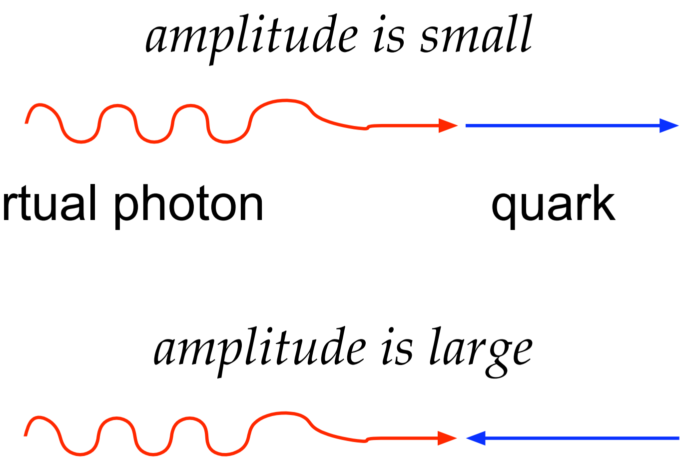


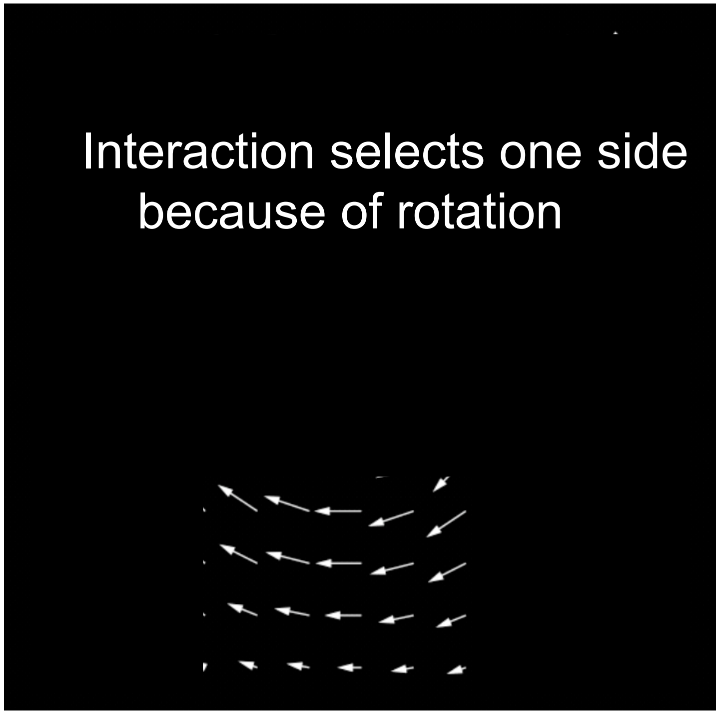
motion inside nucleon

Rotation of u/d quarks in neutron

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

M.Burkardt (2003)

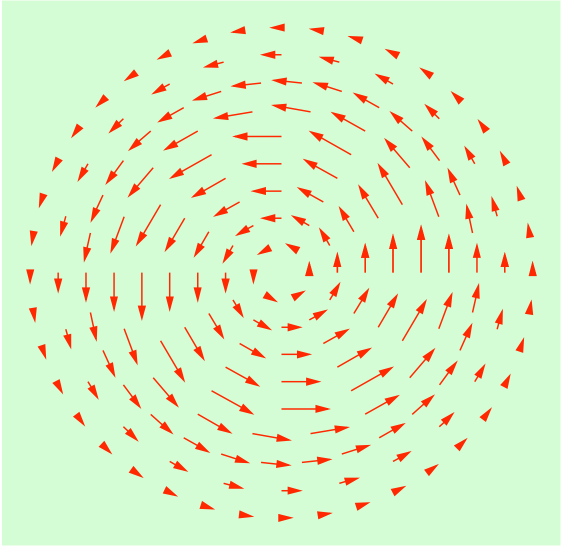




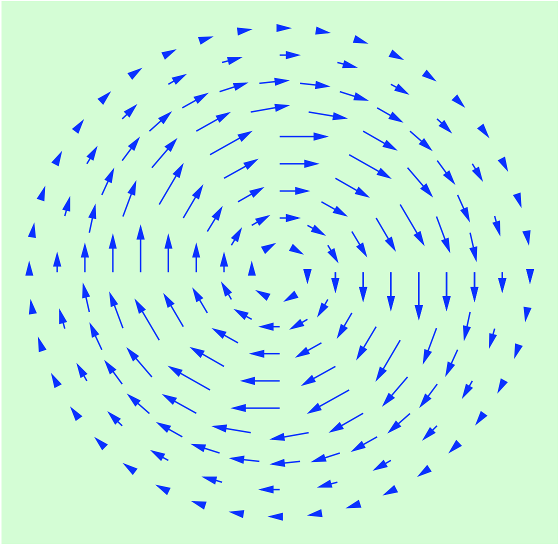
Interaction selects one side because of rotation

Rotation of u/d quarks in neutron

u-quark

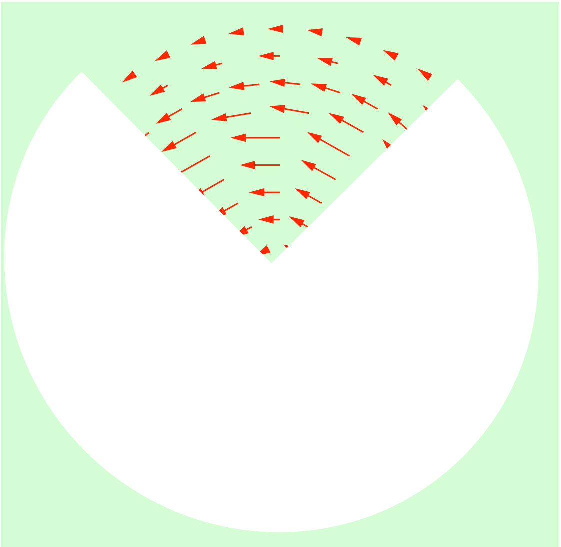


d-quark



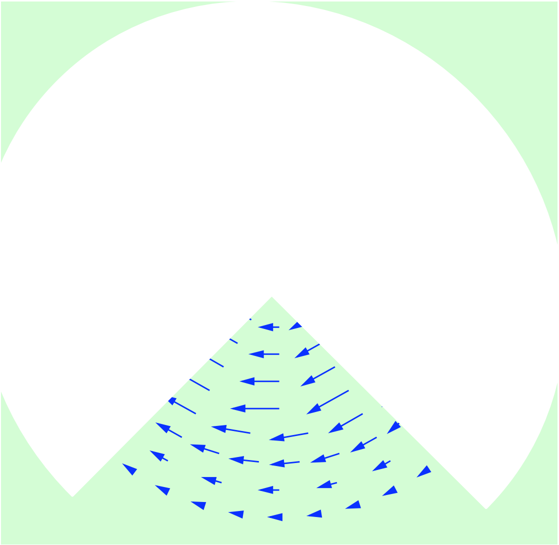
Rotation of u/d quarks in neutron

u-quark



interaction
selects

d-quark



The u/d “separation”, observed in Form Factor data, is likely a result of

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

Future neutron FFs experiments

Future neutron FFs experiments

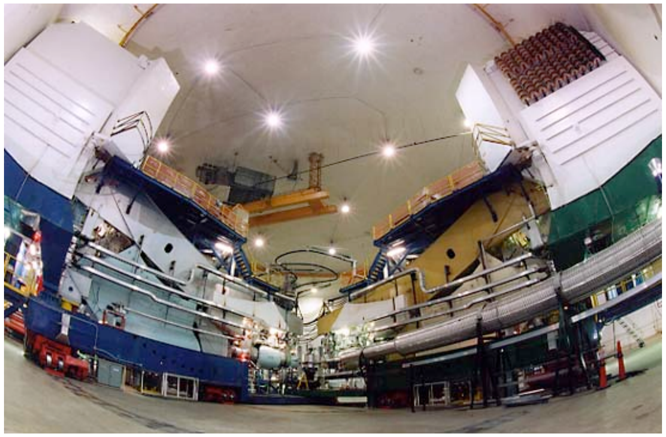
D(e,e’n)p / D(e,e’p)n – under preparation

Double pol. He-3(e,e’n)pp – under preparation

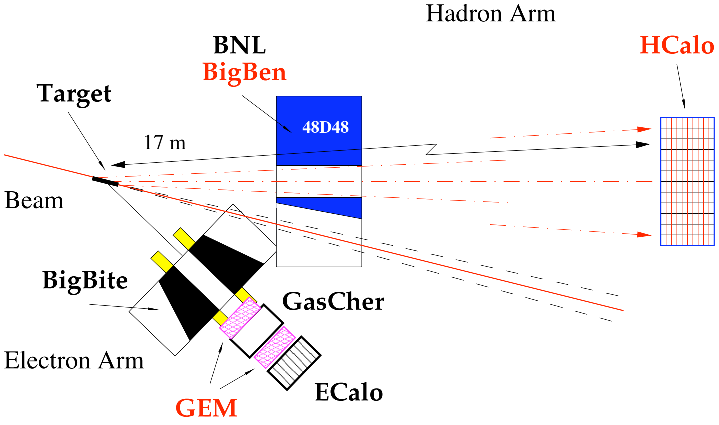
D(e,e’n)p – requires a new A_Y data from JINR
(talk by J. Annand)

Optimization of the experimental setup

Proton magnetic form factor: E12-07-108



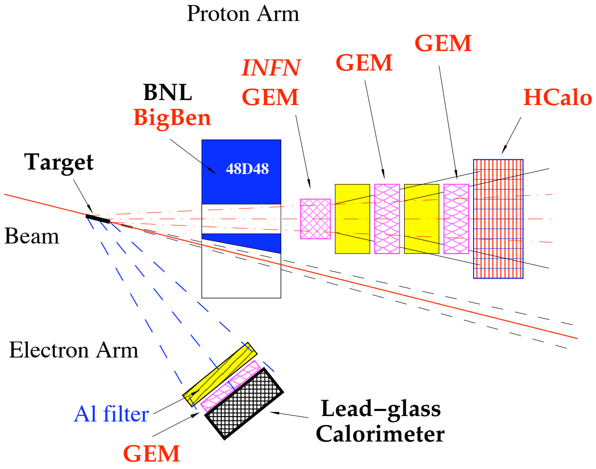
Neutron/proton form factors ratio: E12-09-019



Hadron Arm

BNL
BigBen
HCalo
Target
48D48
17 m
Beam
BigBite
GasCher
Electron Arm
ECalo
GEM

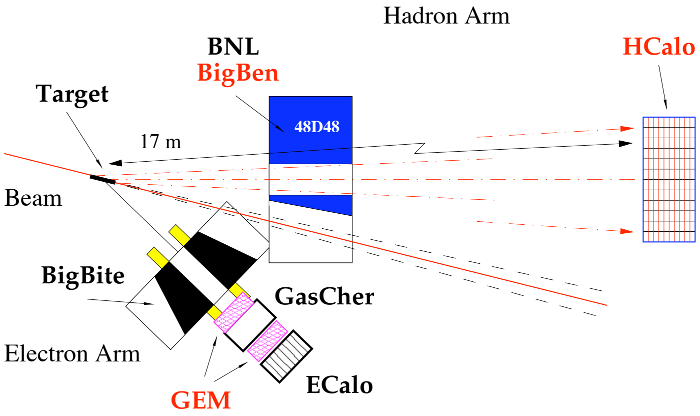
Proton form factors ratio, GEp(5): E12–07–109



Proton Arm

GEM
INFN
GEM
GEM
BNL
BigBen
HCalo
Target
48D48
Beam
Electron Arm
Al filter
GEM
Lead–glass
Calorimeter

Neutron form factors ratio, GEn(2):E12-09-016

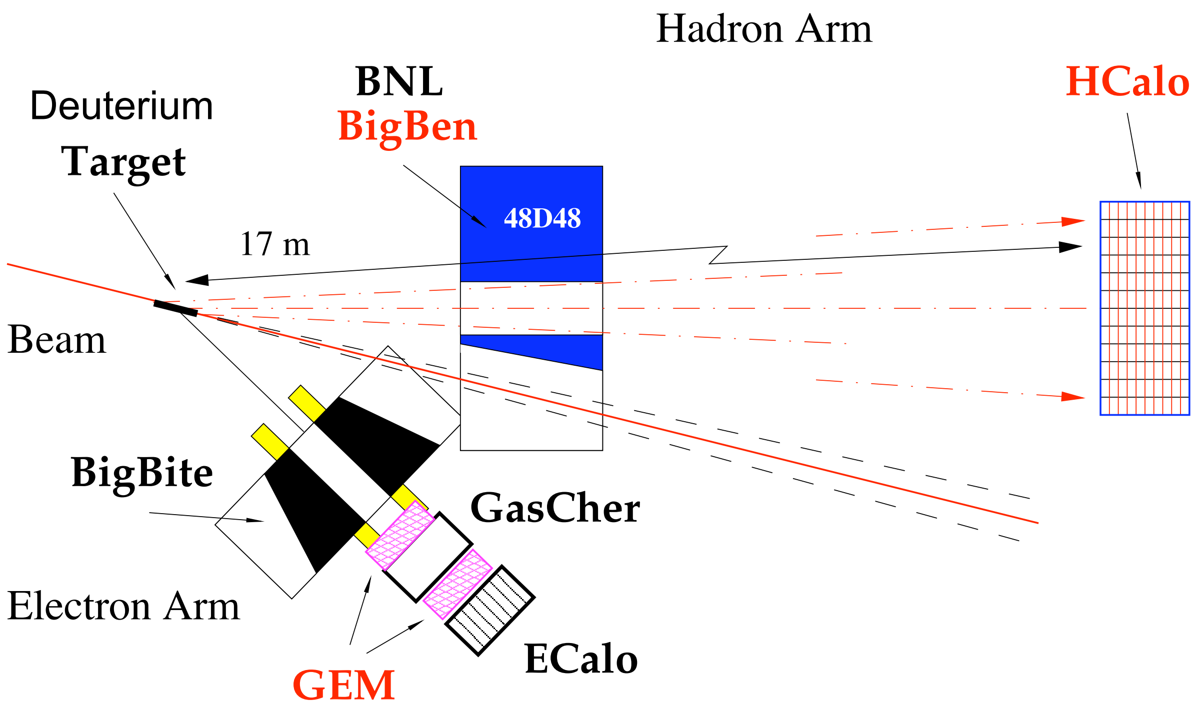


Hadron Arm

BNL
BigBen
HCalo
Target
48D48
17 m
Beam
BigBite
GasCher
Electron Arm
ECalo
GEM

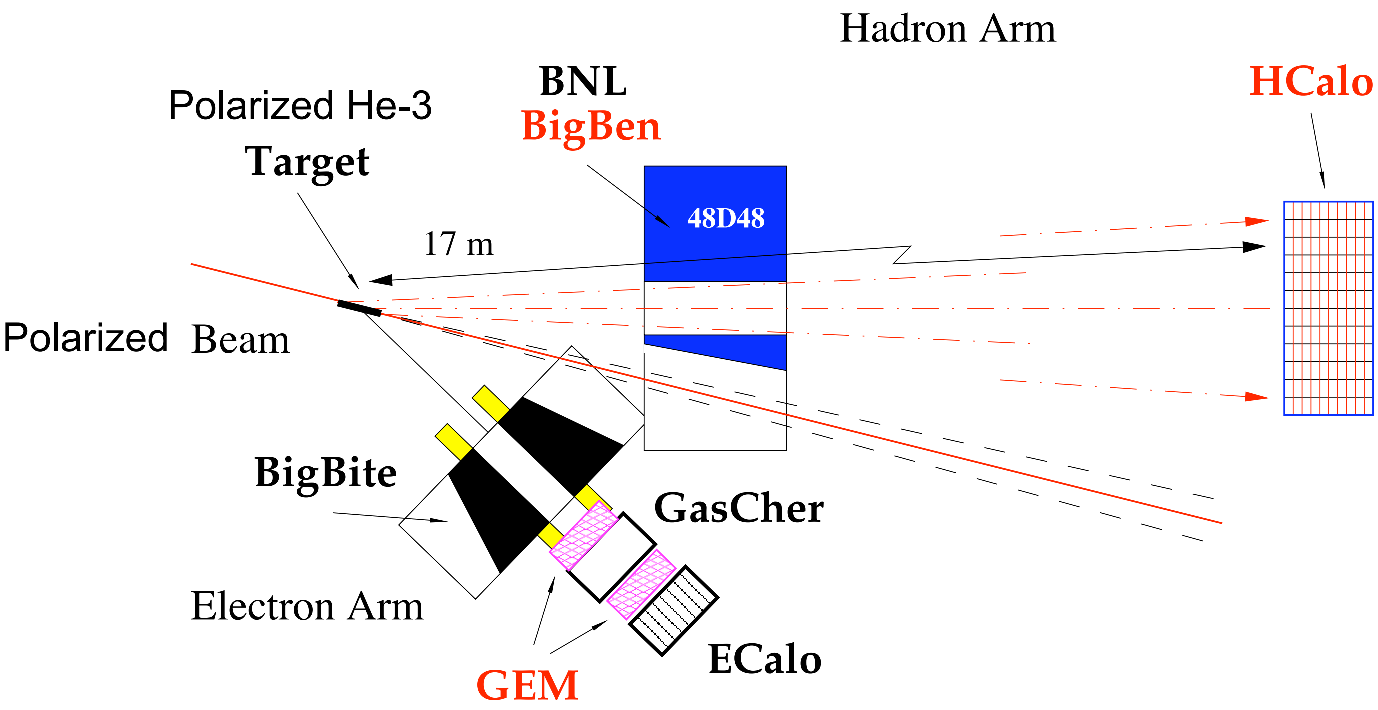
Neutron/proton form factors ratio: E12-09-019

D(e,e’n)p / D(e,e’p)n



Neutron form factors ratio, GEn(2):E12-09-016

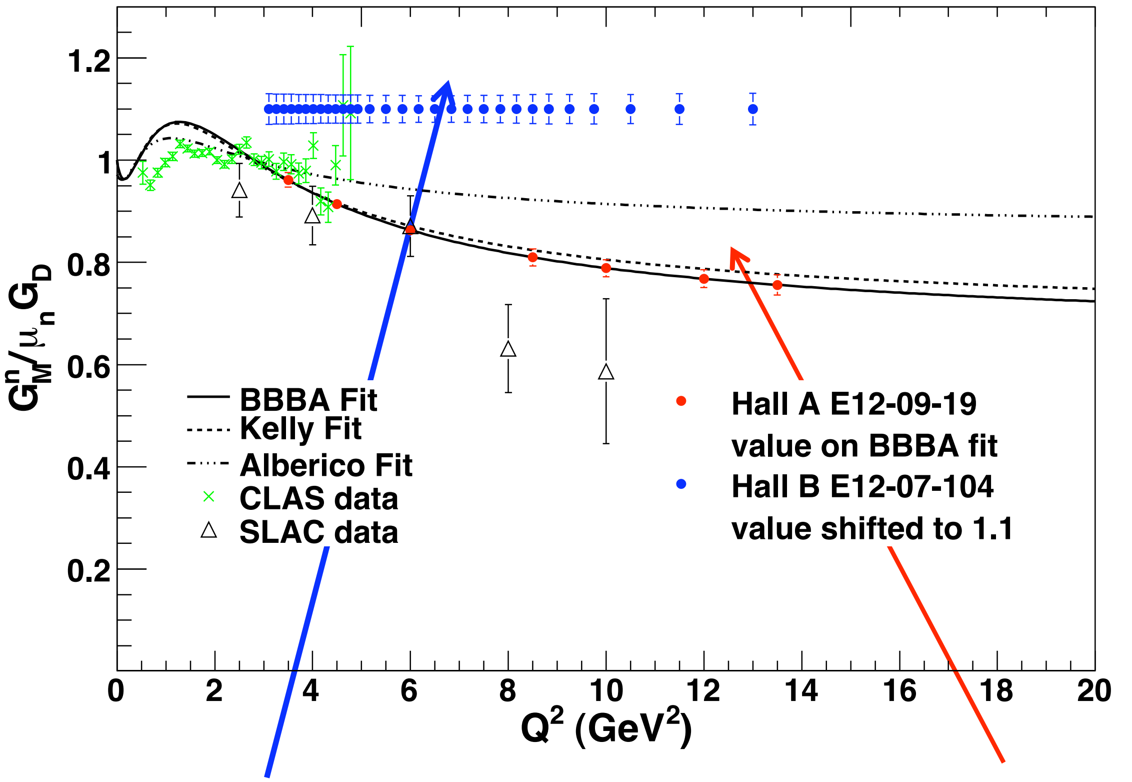
Double polarized He-3(e,e’n)pp



12 GeV GMn experiment

Gilman, Quinn,
and BW

W.Brook etal

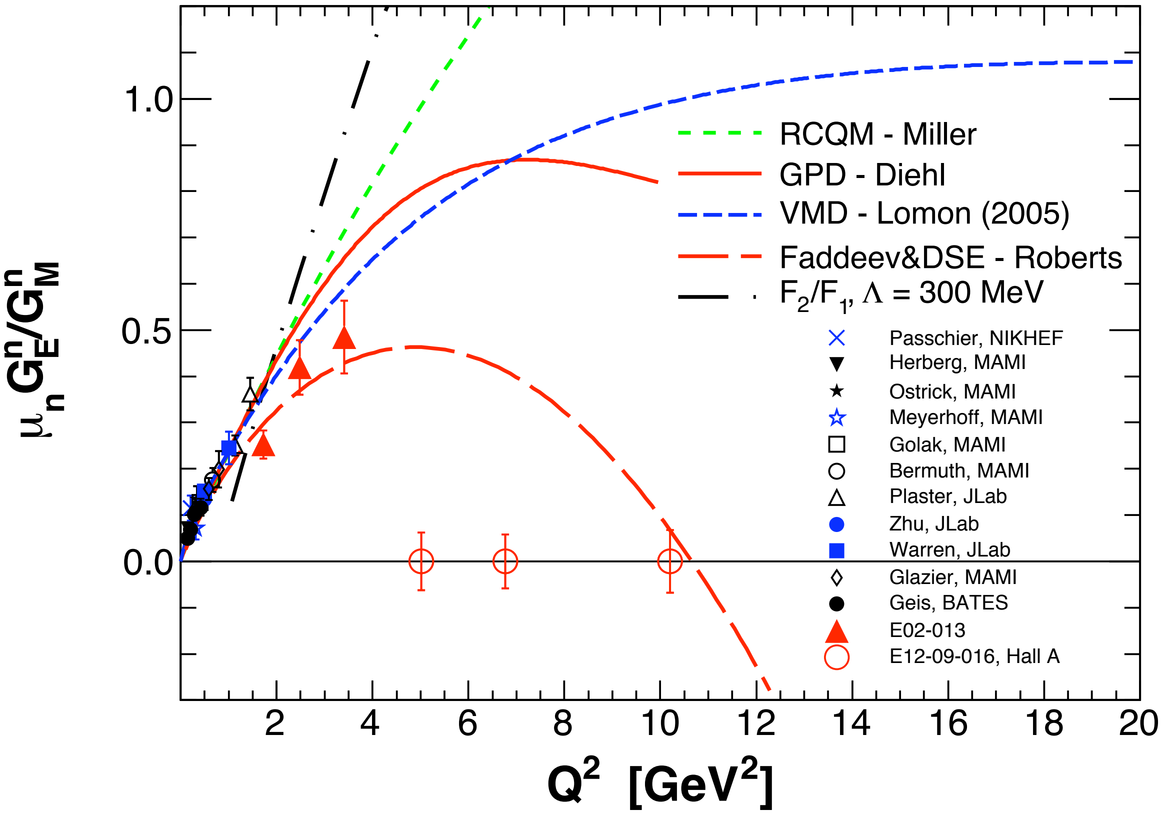


CLAS 12

BigBite + SBS

12 GeV GEn experiment

Cates, Riordan,
and BW



CEBAF electron beam in 2013(4)

• Beam energy	11/12 GeV
• Beam power	1 MW
• Beam current (Hall A/D)	85/5 μA
• Beam polarization	85%
• Emittance @ 12 GeV	10 nm-rad
• Energy spread @ 12 GeV	0.02%
• Beam spot	~ 0.1mm
• Simultaneous beam delivery	Up to 3 halls

Hall A will be the first hall which will get the beam

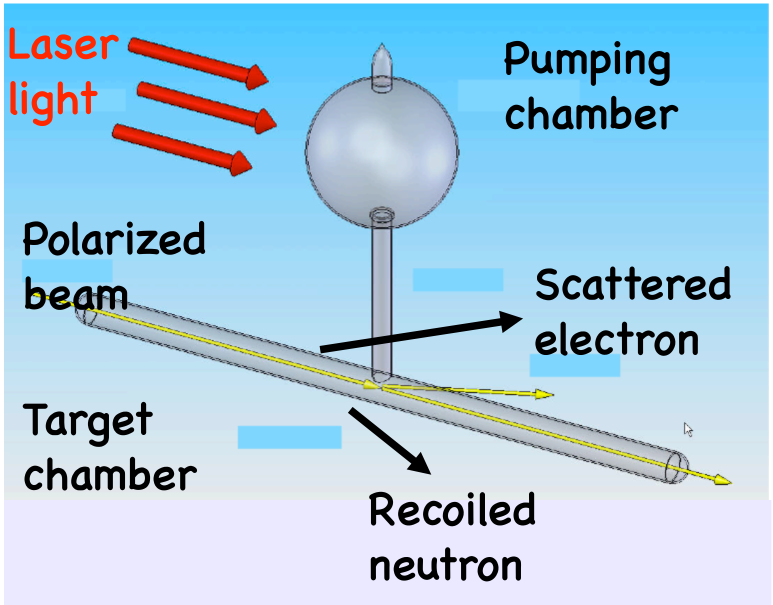
THANKS

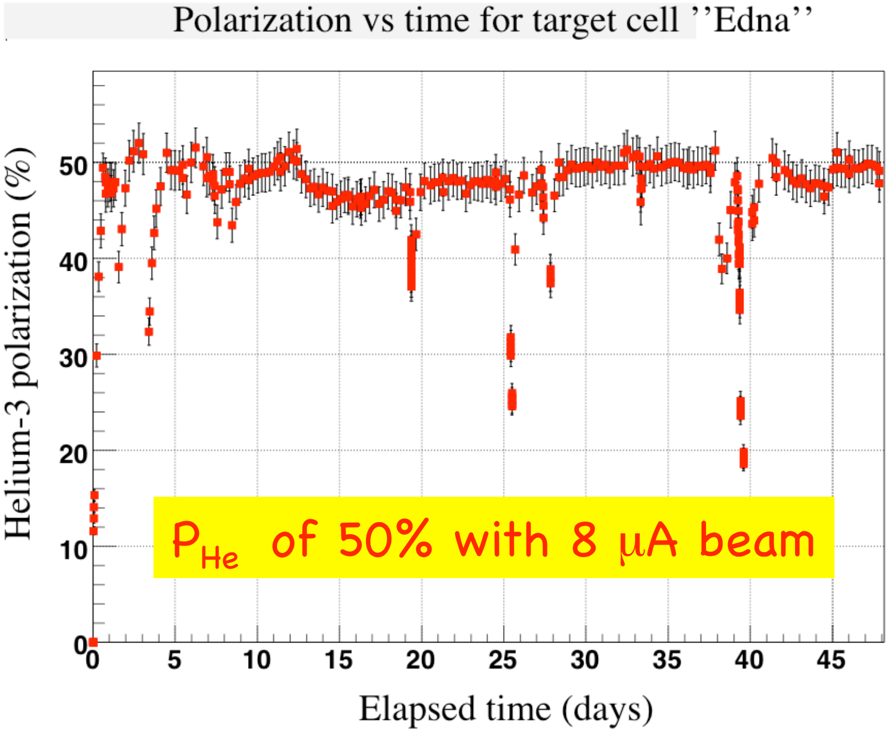
Polarized target

$^{3}He = p + p + n$

S + S′ + P waves

$P_n = 0.86\ P_{He}$





P_{He} of 50% with 8 μA beam

Rb + K mixture has shortened spin-up time to 5-8 hours. The hybrid method of optical pumping was used here for the first time in the nuclear target.