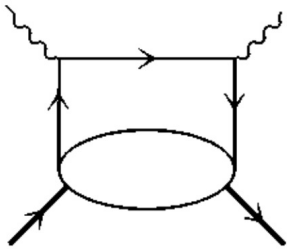
Jefferson Lab
Thomas Jefferson National Accelerator Facility

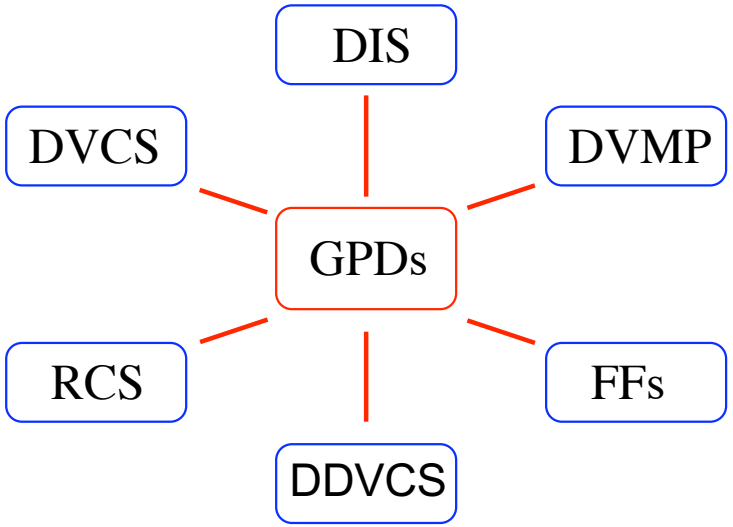
Diquark evidence in elastic scattering processes

Bogdan Wojtsekhowski, Jefferson Lab

The nucleon structure in terms of GPDs



+ …



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

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

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

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

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

Physics of QCD via GPDs

needs best calculations of
the nucleon structure

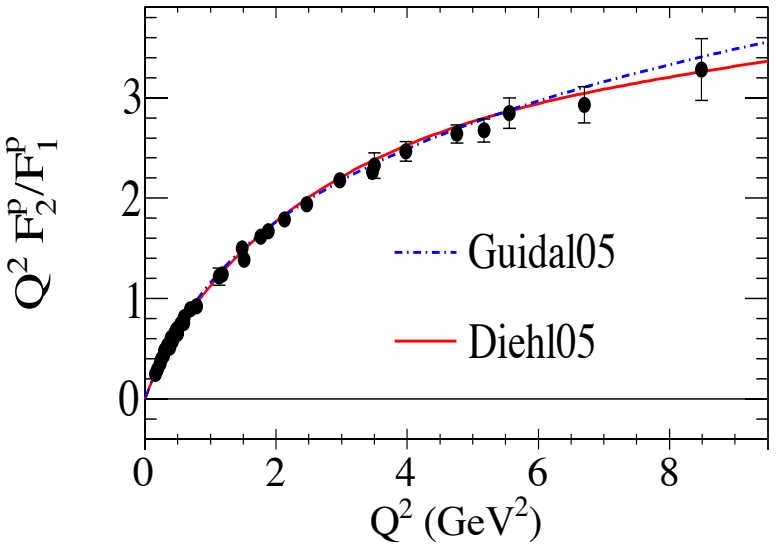
The goal is understanding of the nucleon

from the Sachs FFs to the ratio F2/F1 and the BJY "log" scaling

$$F_1 = \frac{G_E + \tau G_M}{1+\tau} \quad F_2 = -\frac{G_E - G_M}{1+\tau}$$

$$\tau = Q^2/4M^2$$

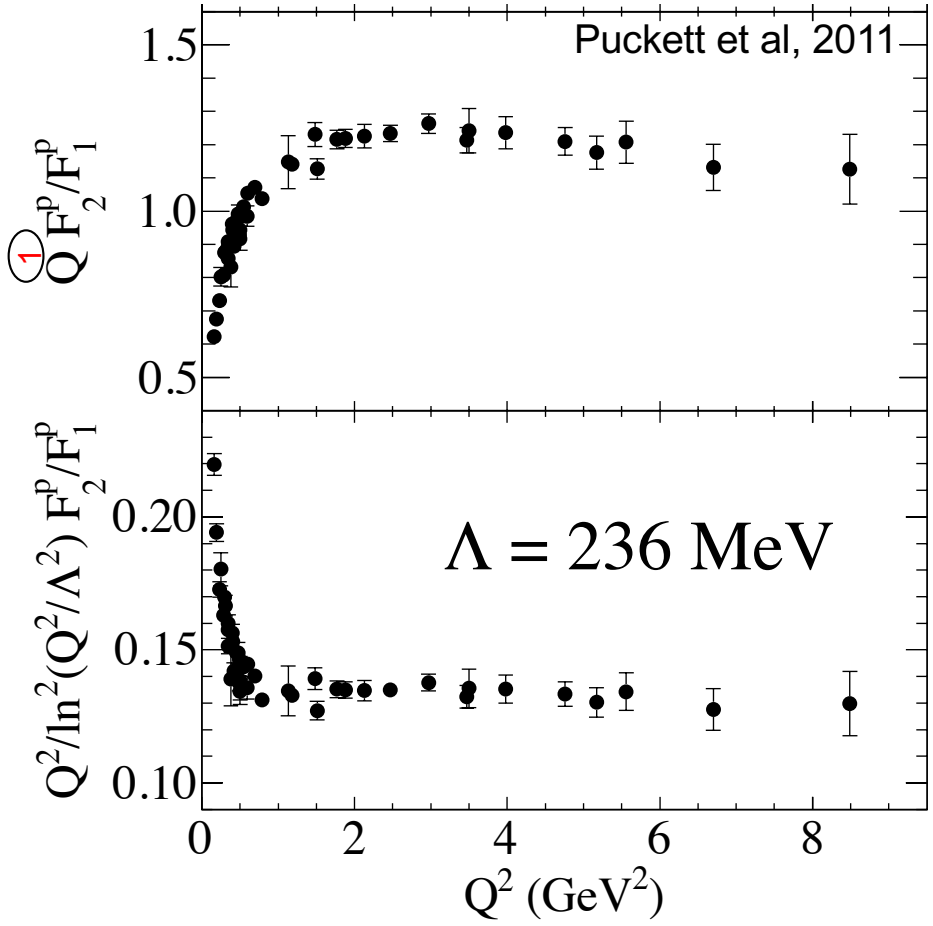
$$Q^2\, F_2/F_1 \propto \frac{1 - G_E/G_M}{1 + [G_E/G_M]/\tau}$$



G.Miller: Orbital moment!

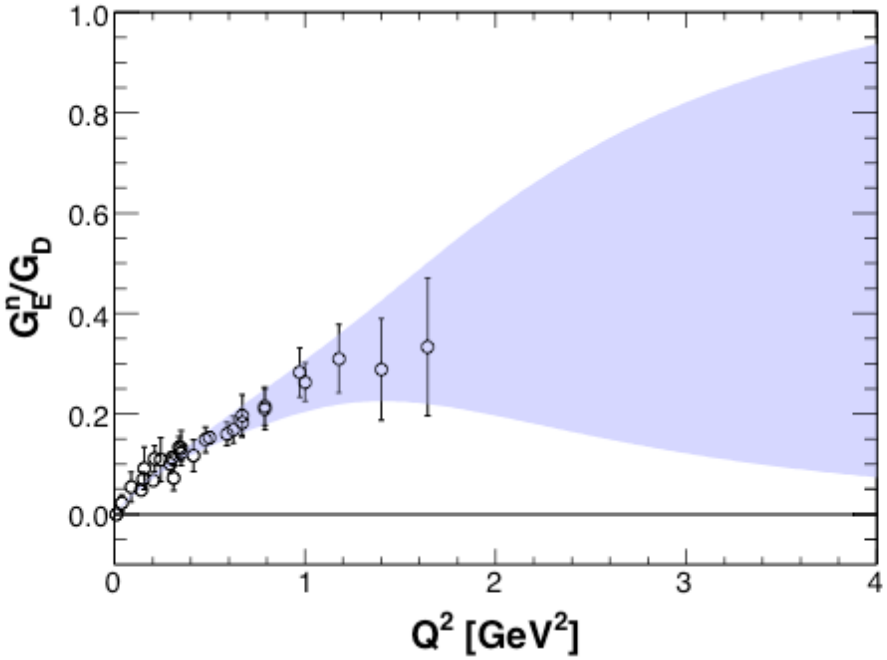
Balitsky-Ji-Yuan: log Q^2 scaling due to the orbital moment w.f.

$$Q^2/\ln^2(Q^2/\Lambda^2)\, F_2^p/F_1^p$$

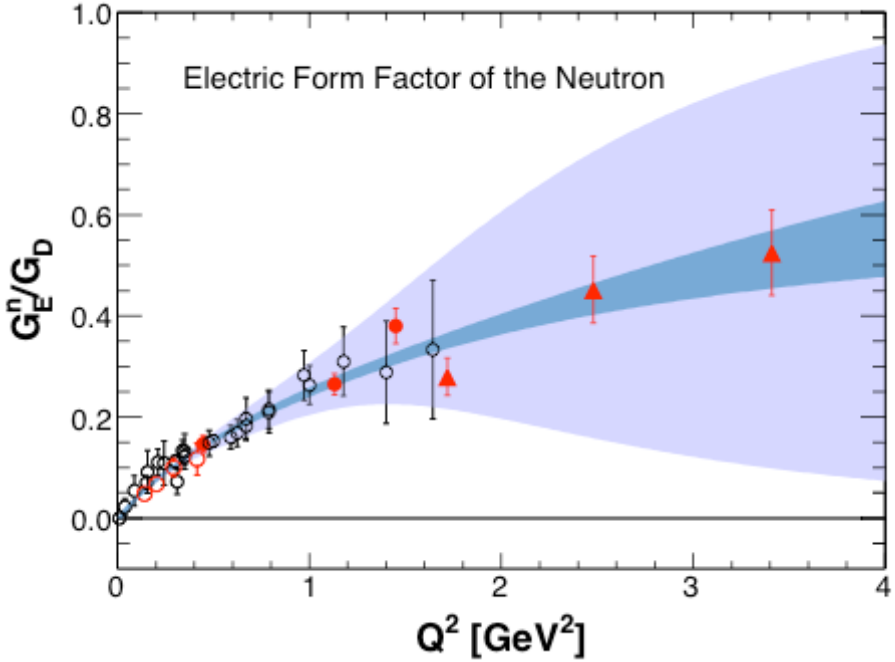


The JLab G_E^n experiments

without JLab GEn experiments



significantly better accuracy and higher Q^2

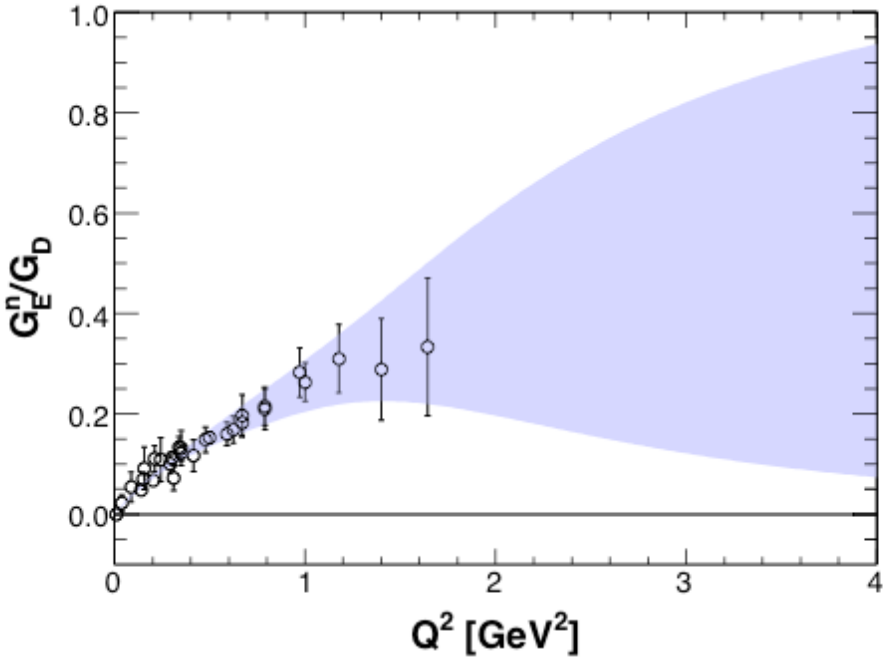


F. Gross, 1987, CEBAF Physics program

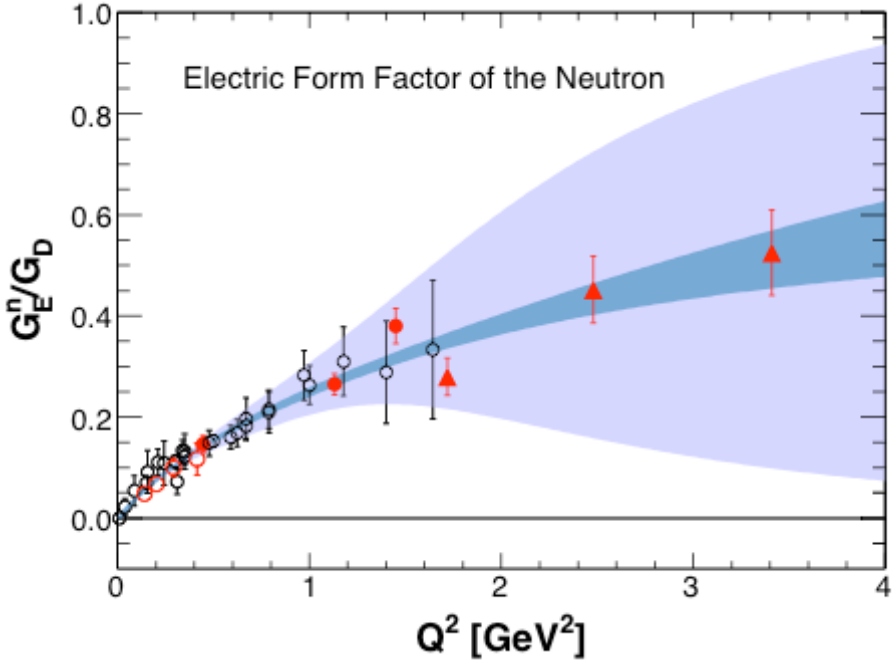
(iv) *Measurement of the charge structure of the neutron and deuteron*. Coincidence techniques must be used to measure these basic quantities, and hence the capabilities of CEBAF will be needed to obtain accurate measurements at high Q^2. These important quantities are sensitive to quark distributions.

The JLab G_E^n experiments

without JLab GEn experiments



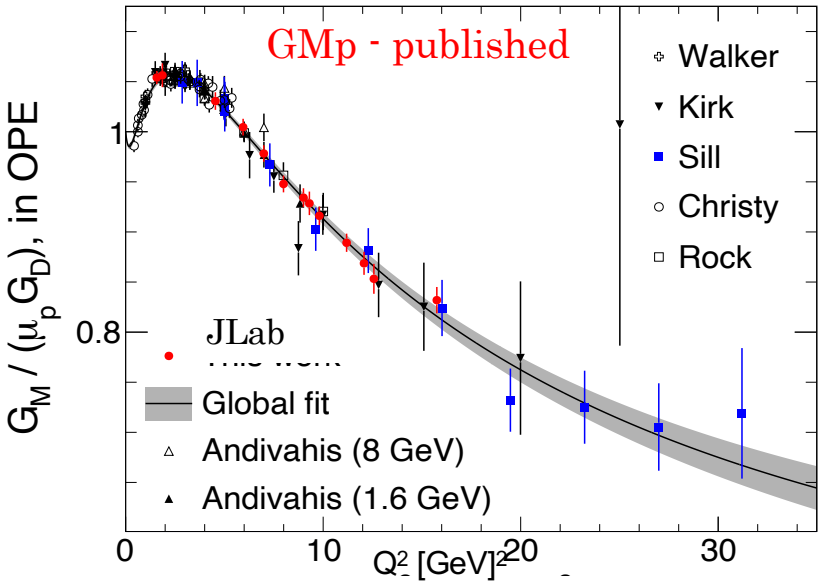
significantly better accuracy and higher Q^2

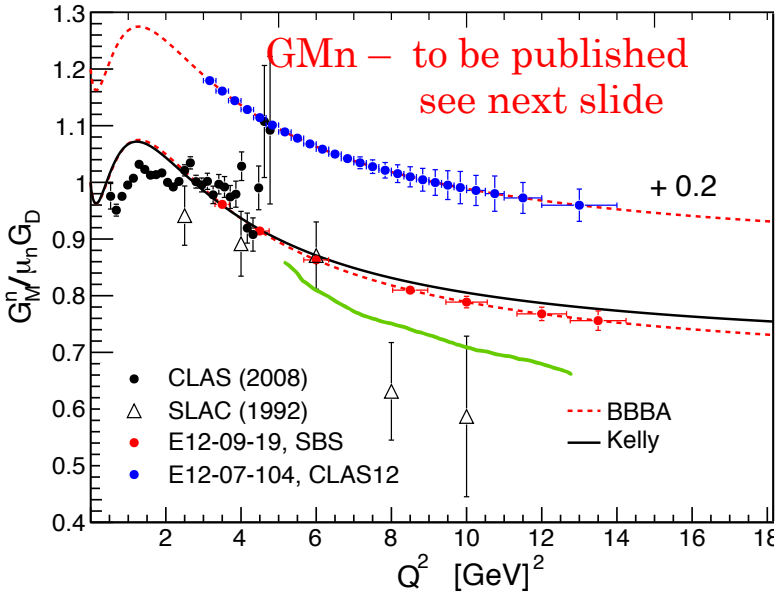


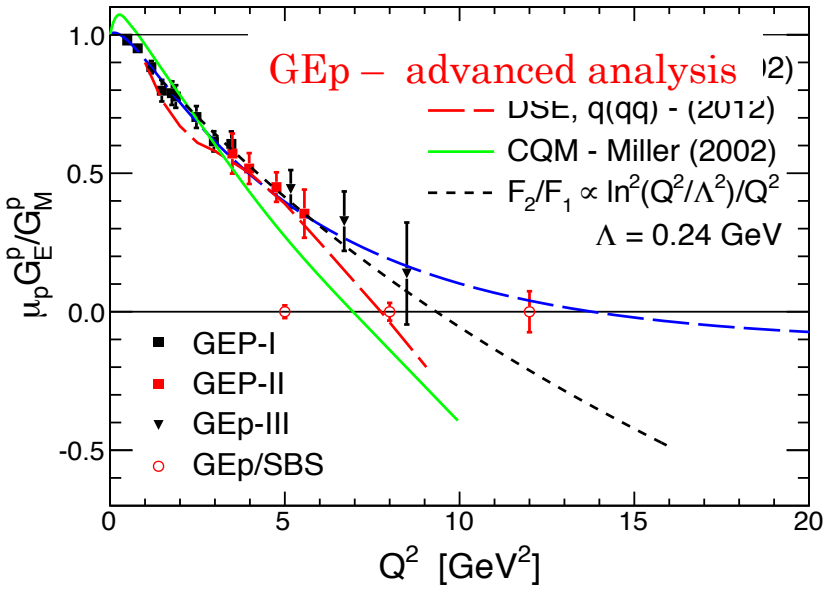
F. Gross, 1987, CEBAF Physics program

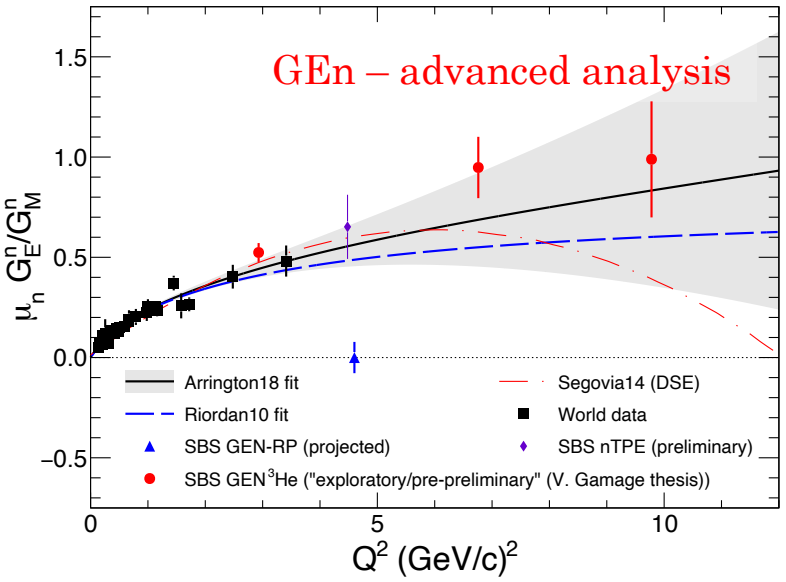
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The nucleon FFs status and plans







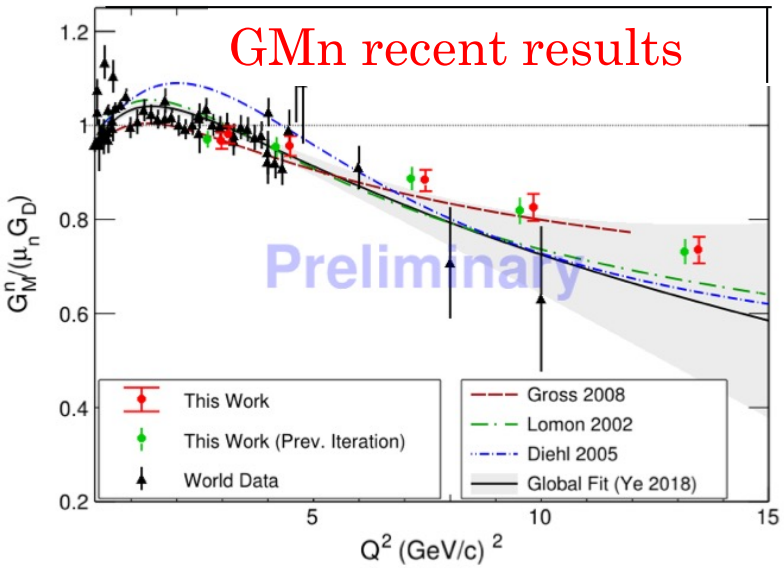


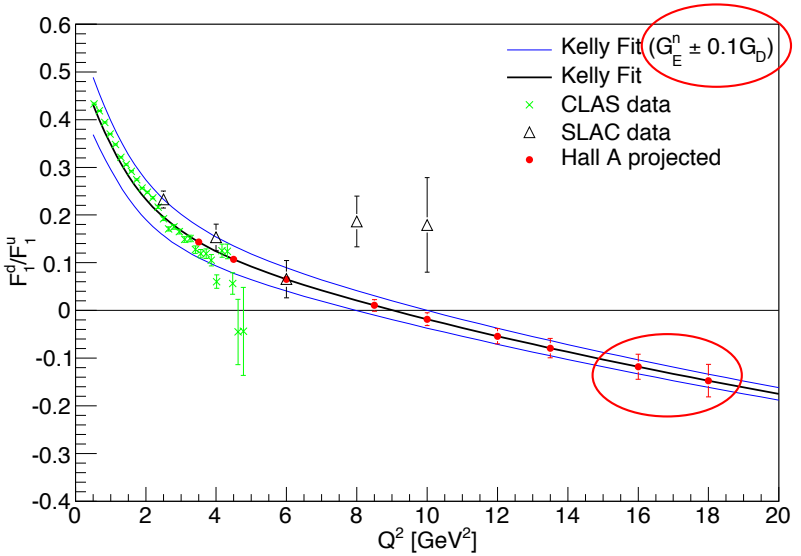
GMn can go to $Q^2 =$ 18 GeV^2

Precision Measurement of the Neutron Magnetic Form Factor at Q^2=16.0 and 18.0 $(GeV/c)^2$ by the Ratio Method

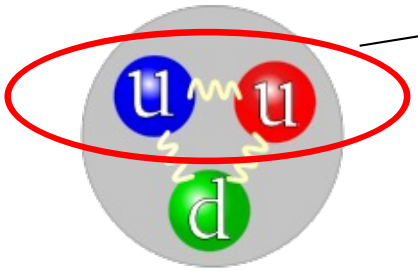
$$F_1 = \frac{G_E + \tau G_M}{1+\tau}$$

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





The goal is understanding of the nucleon

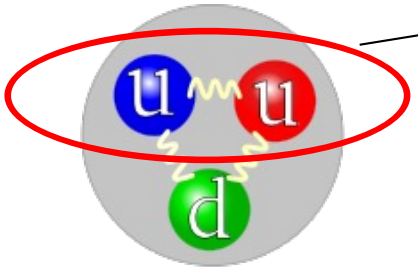


$$F_p = \frac{+2}{3} F_{dual} + \frac{-1}{3} F_{lone}$$

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

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

The goal is understanding of the nucleon

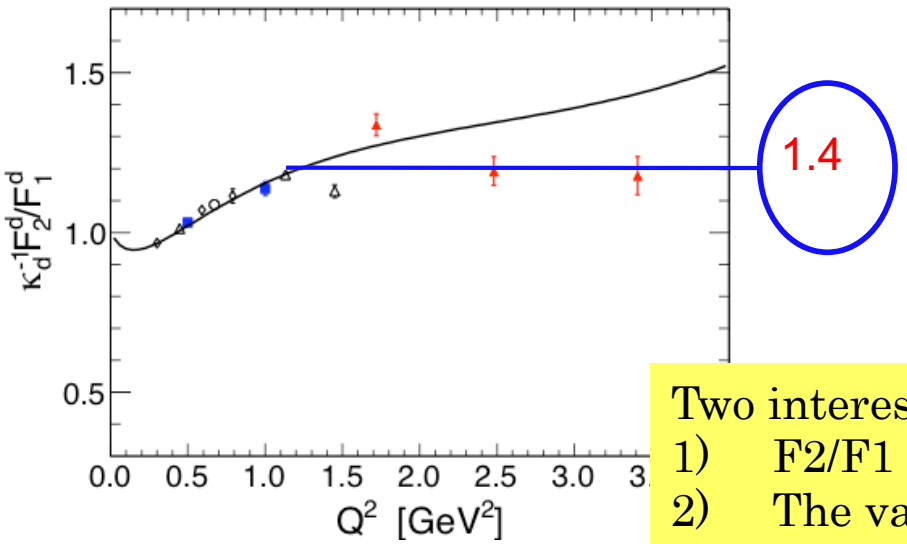


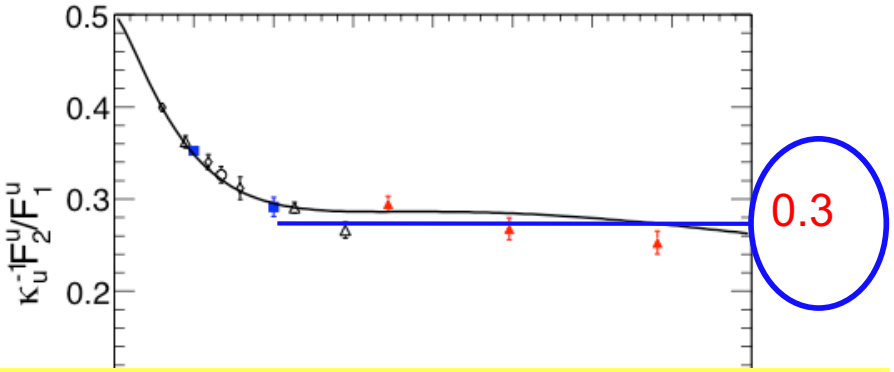
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Results of E02-013 Hall A GEn

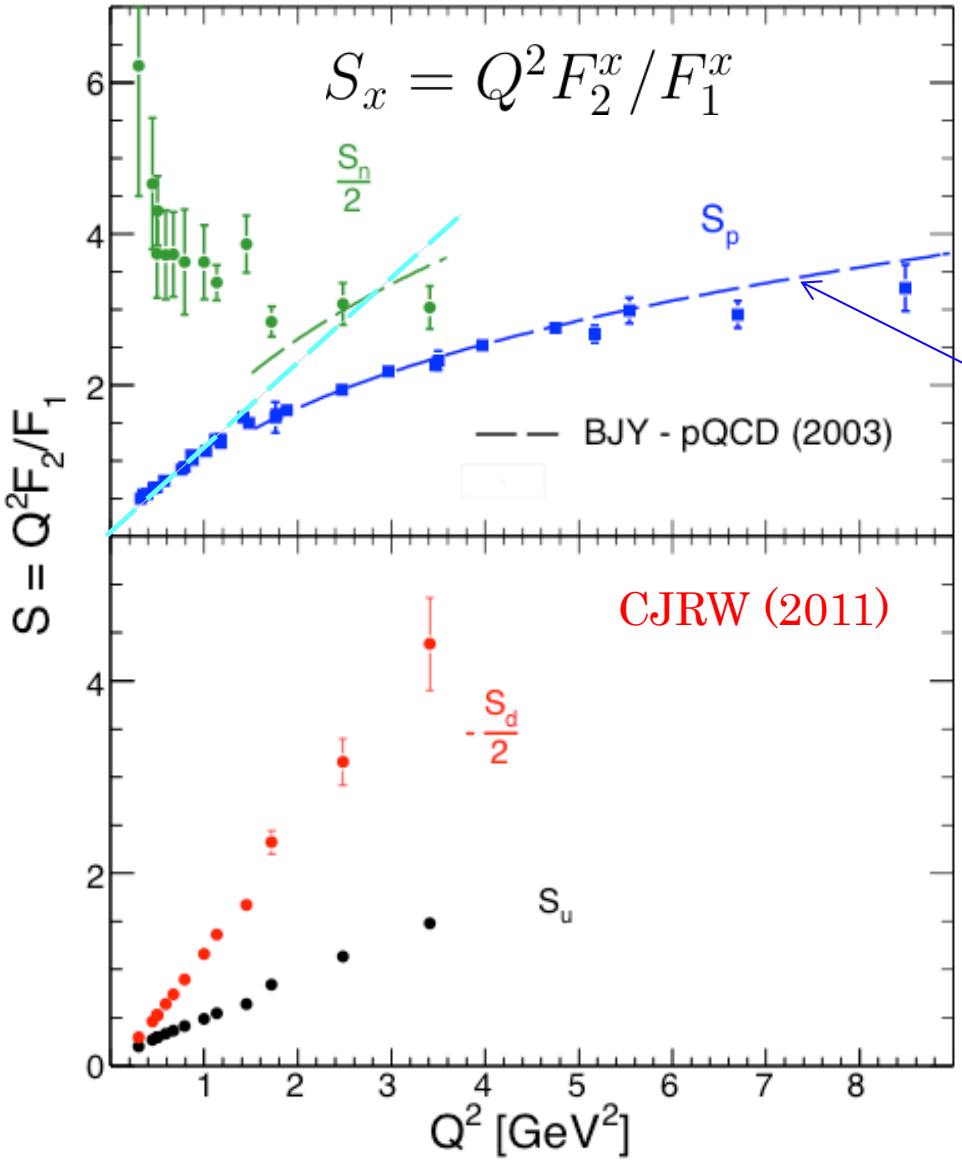




Two interesting observations:

1) F2/F1 = R is constant in the Q^2-range 1 - 3.5 GeV^2
2) The value of R for d-quark >> than R for u-quark

The goal is understanding of the nucleon



pQCD prediction for large Q^2:

$$S \to Q^2 F_2 / F_1$$

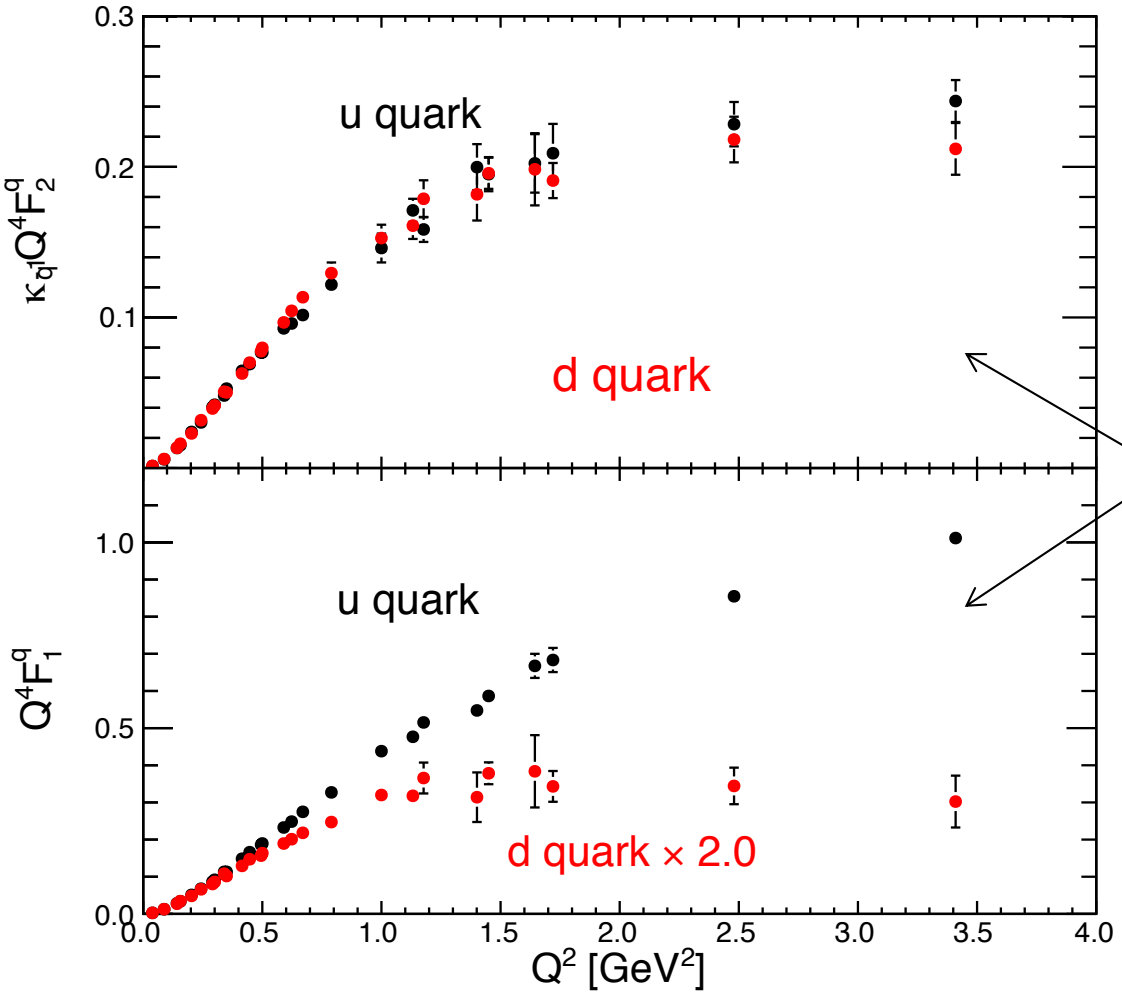
pQCD updated prediction:

$$S \to \left[Q^2 / \ln^2(Q^2/\Lambda^2)\right] F_2/F_1$$

Flavor separated contribution:
The log scaling for the proton
Form Factor ratio at few GeV^2
is "accidental".

The lines for each individual flavor are straight!

Flavor contributions to the nucleon FFs



CJRW (u/d with new GEn data)
Phys. Rev. Lett. 106 (2011)

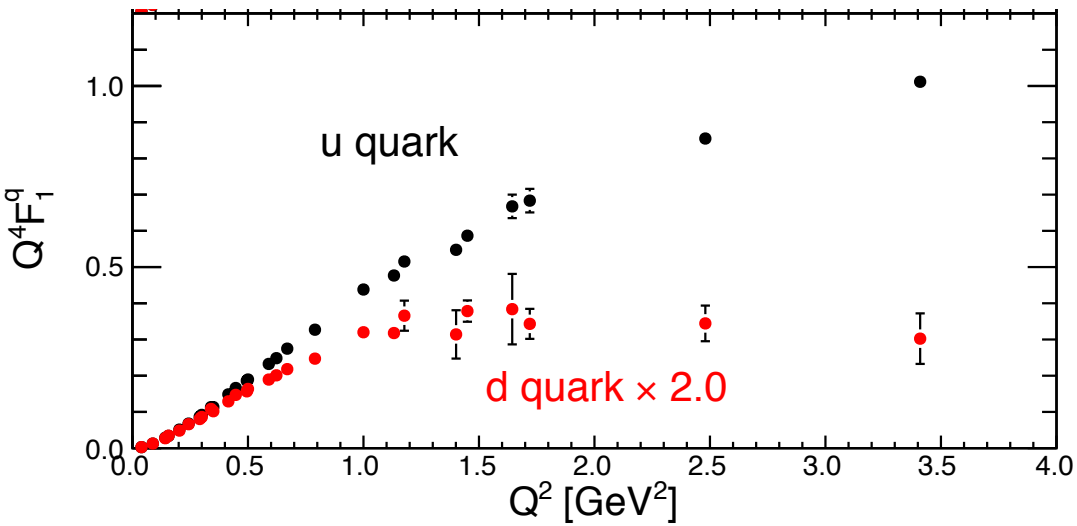
M.Diehl and P.Kroll (GPDs)
Eur.Phys.J. C73 (2013) 2397

Using the D&K table of F^u, F^d

The down quark contribution to the F_1 proton form factor is strongly suppressed at high Q^2

Diquark

Flavor contributions to the nucleon FFs



The experiment suggests that the probability of proton survival after absorption of a massive virtual photon is much higher when the photon interacts with an up quark, which is doubly represented in the proton.

This may be interpreted as an indication of the up-up correlation. At high Q^2 a correlation usually enhances the high momentum component and the interaction cross section.

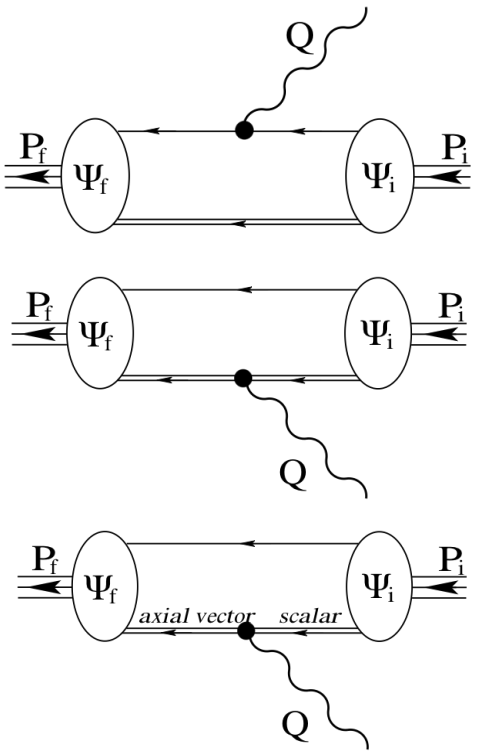
The relatively weak down quark contribution to the F_{1p} indicates a suppression of the up-down correlation or a mutual cancellation of different types of up-down correlations.

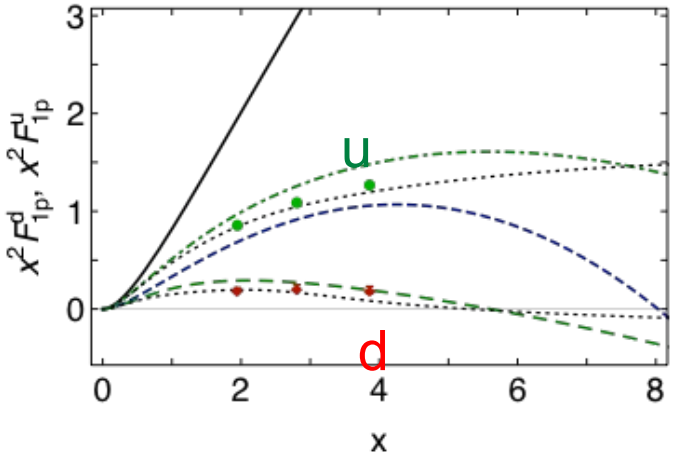
Diquark

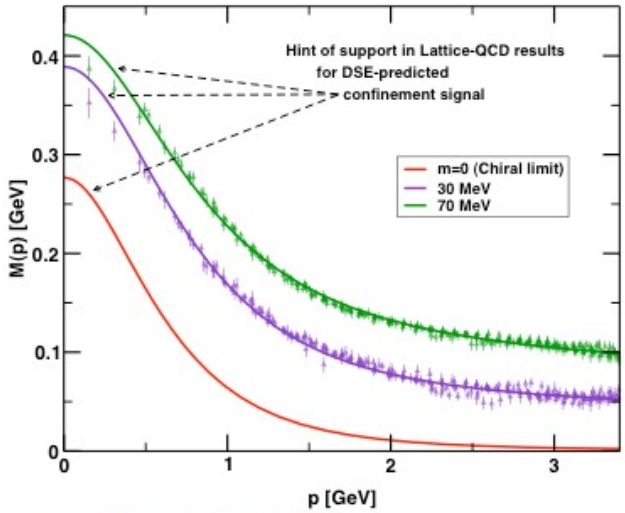
The goal is understanding of the nucleon

Nucleon and Roper electromagnetic elastic and transition form factors

Wilson, Cloet, Chang, Roberts, PRC 85, 025205 (2012)



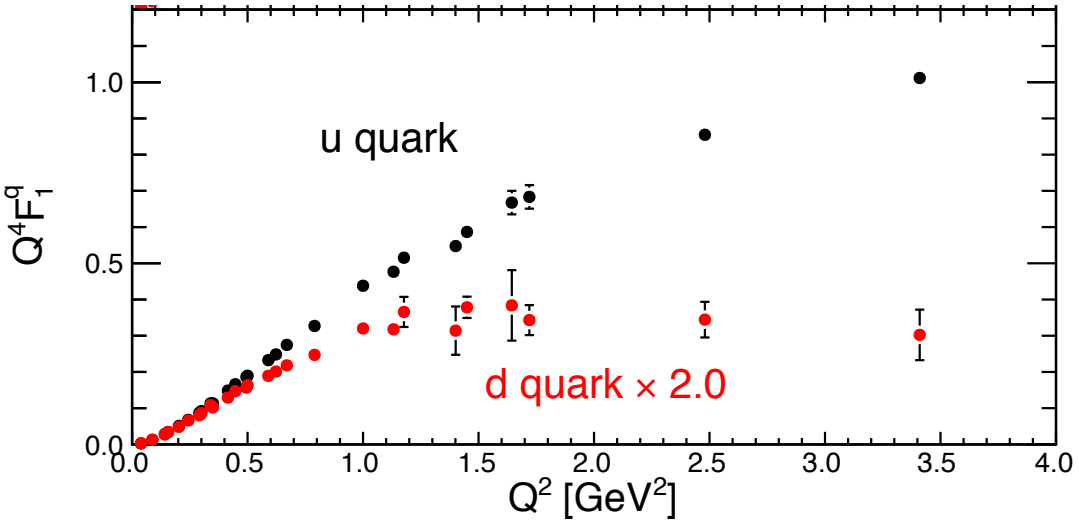


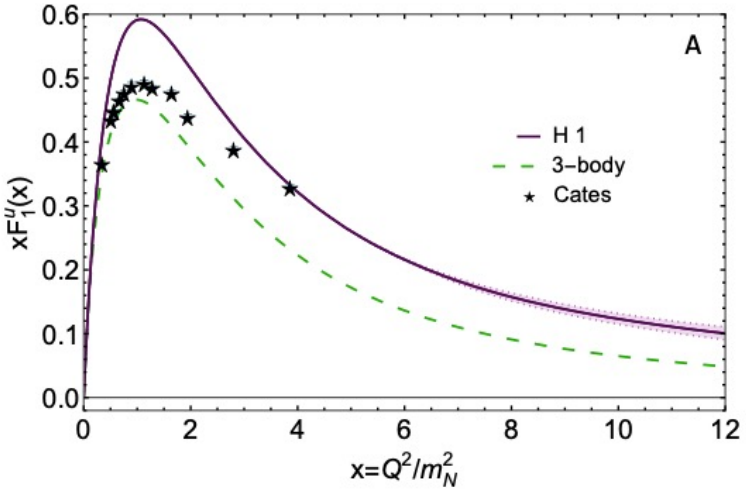


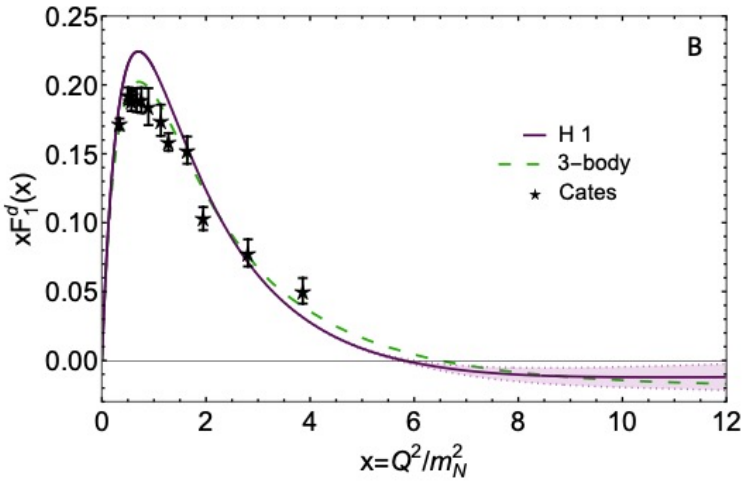
Interplay between the [qq] and {qq} diquarks creates a zero crossing

Could the diquarks produce a flavor dependence of M(p)?

The goal is understanding of the nucleon

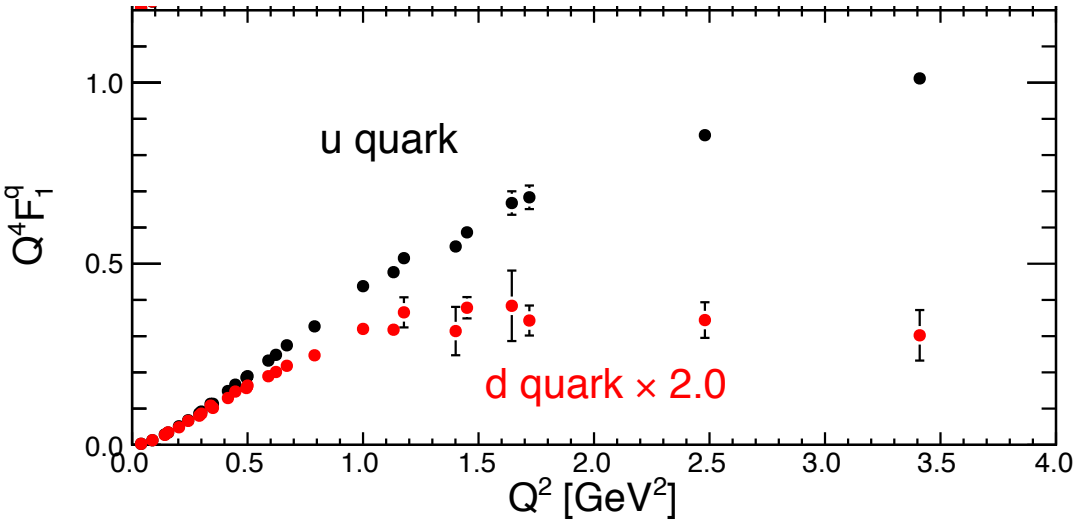






Cheng, Yao, Binosi, Lu, Roberts, EJP-A, 61, 255 (2025)

The goal is understanding of the nucleon



Flavor separated form factors at high Q2 (> 2 (GeV/c)^2) have

a significant enhancement of the diquark effects.

Another elastic process to look at is a Wide Angle Compton Scattering.

WACS from a proton was carefully measured up to s ~ 10 GeV^2 .

Can we do a similar study for a neutron? – next part of this talk

GPDs and form factors of WACS

$$\gamma p \to \gamma p \qquad\qquad ep \to ep$$

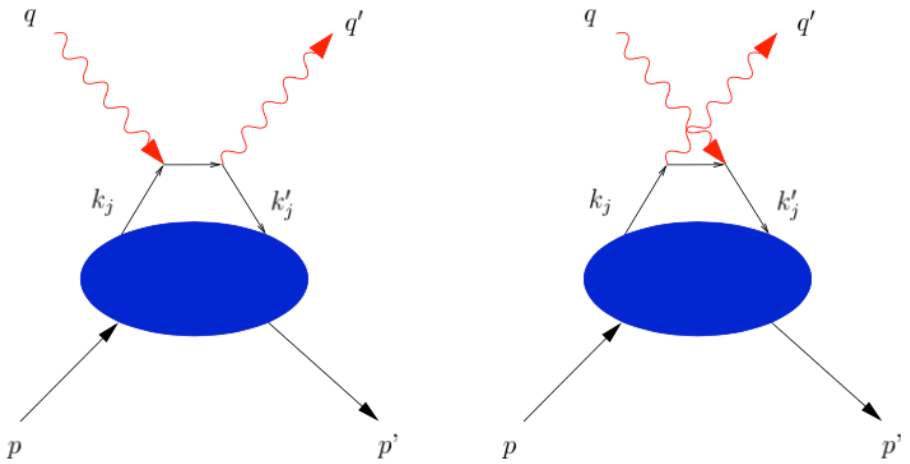
$$R_V(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} H^a(x,0,t), \qquad F_1(t) = \sum_a e_a \int_{-1}^{1} dx\, H^a(x,0,t),$$

$$R_A(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} \,\mathrm{sign(x)}\, \hat{\mathrm{H}}^{\mathrm{a}}(\mathrm{x},0,\mathrm{t}), \qquad G_A(t) = \sum_a \int_{-1}^{1} dx\, \mathrm{sign(x)}\, \hat{\mathrm{H}}^{\mathrm{a}}(\mathrm{x},0,\mathrm{t}),$$

$$R_T(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} E^a(x,0,t), \qquad F_2(t) = \sum_a e_a \int_{-1}^{1} dx\, E^a(x,0,t),$$

GPD	x^{-1} moment	x^0 moment	$t=0$ limit
$H^a(x,0,t)$	$R_V(t)$	$F_1(t)$	$q(x)$
$\hat{H}^a(x,0,t)$	$R_A(t)$	$G_A(t)$	$\Delta q(x)$
$E^a(x,0,t)$	$R_T(t)$	$F_2(t)$	$2J(x)/x - q(x)$

WACS cross section in GPDs



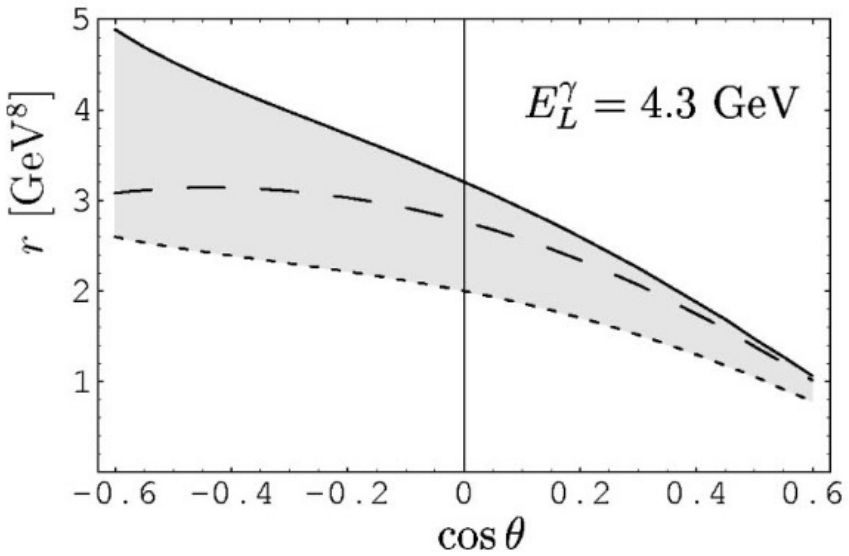
M. Diehl et al.

PRD **67**, 037502 2003

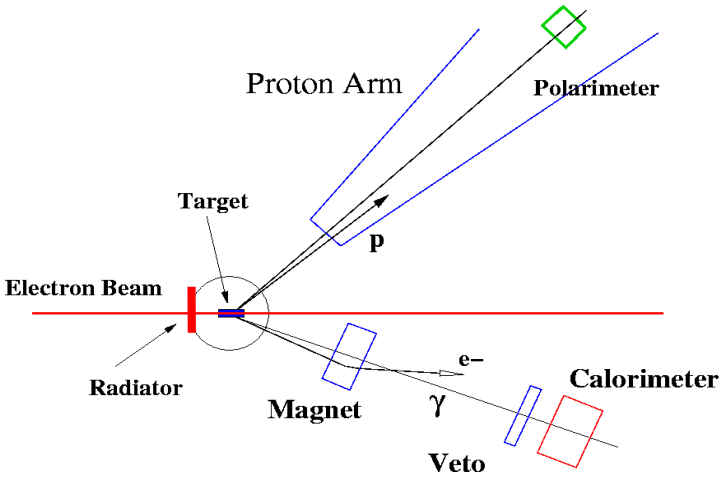
$$r = t^4 \frac{d\sigma/dt}{d\sigma_{\rm KN}/dt},$$

$$\frac{d\sigma_{\rm KN}}{dt} = \frac{2\pi\alpha_{\rm elm}^2}{(s-m^2)^2}$$

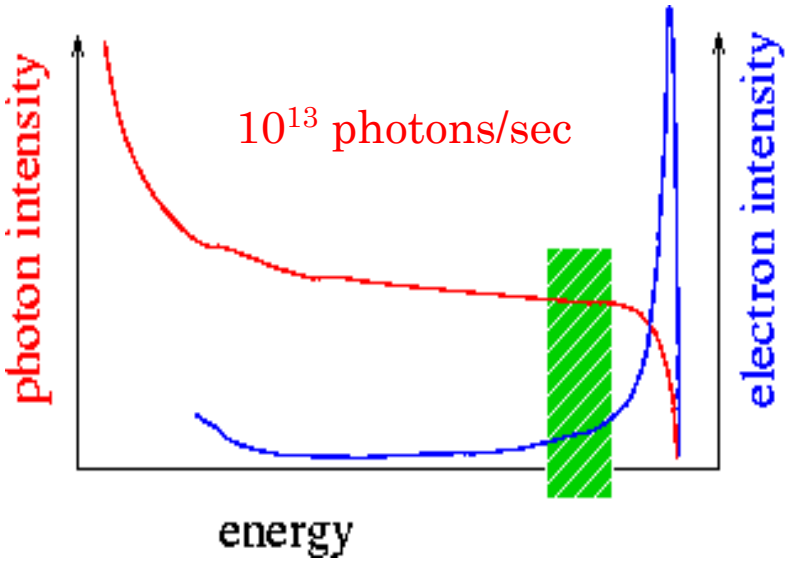
$$\times\left[-\frac{s-m^2}{u-m^2}-\frac{u-m^2}{s-m^2}+\frac{4m^2t(m^4-su)}{(s-m^2)^2(u-m^2)^2}\right]$$



JLab proton WACS experiment - 2002



Two-body kinematics



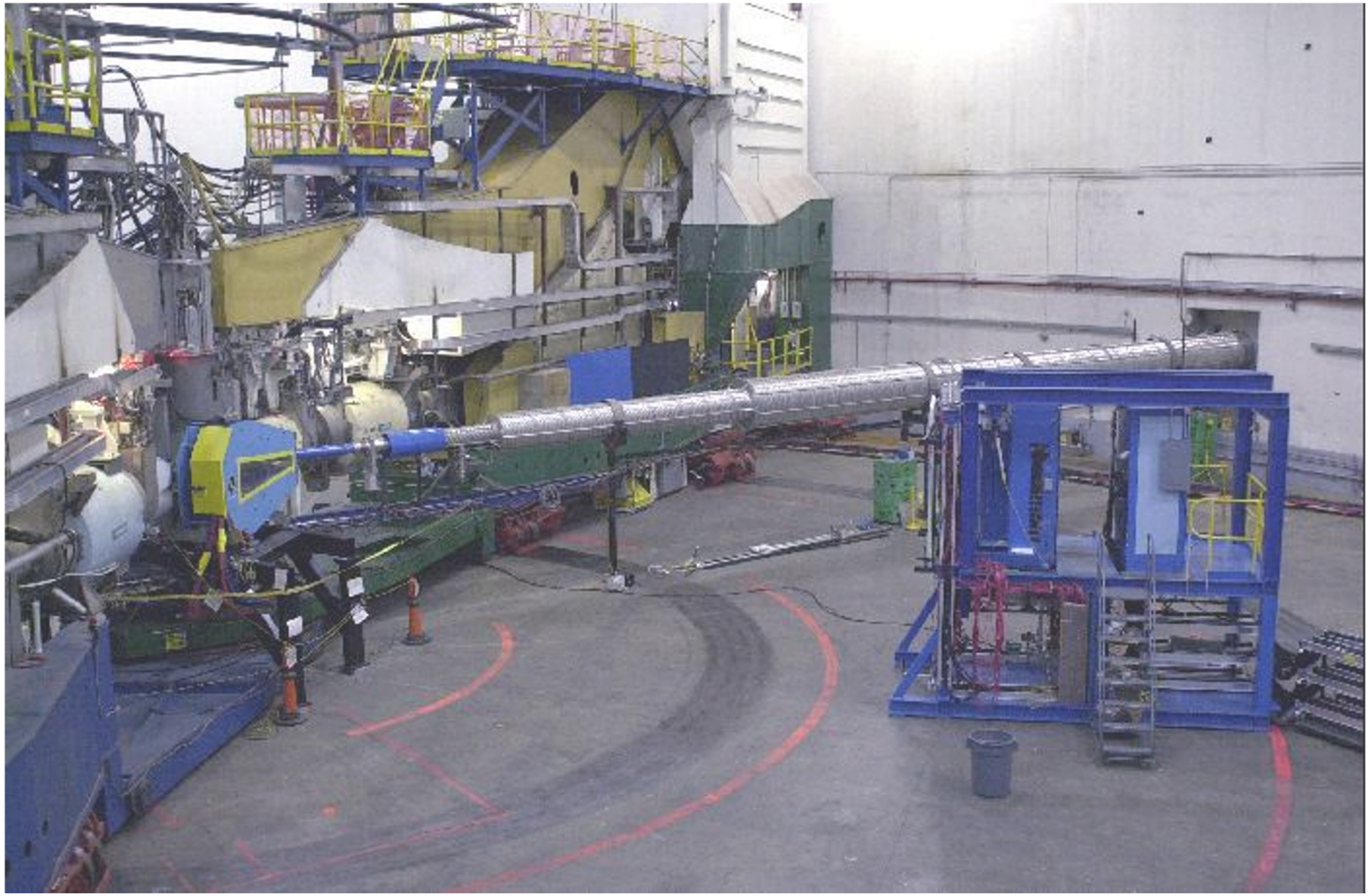
Mixed e/γ beam => photon flux => productivity 1300x "clean" γ

Magnetic separation of p/e and p/γ events

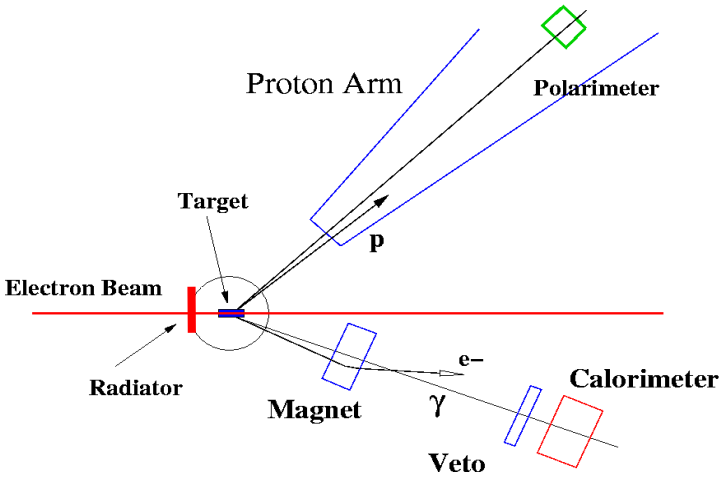
Luminosity was γ–p = 10^{37} Hz/cm^2

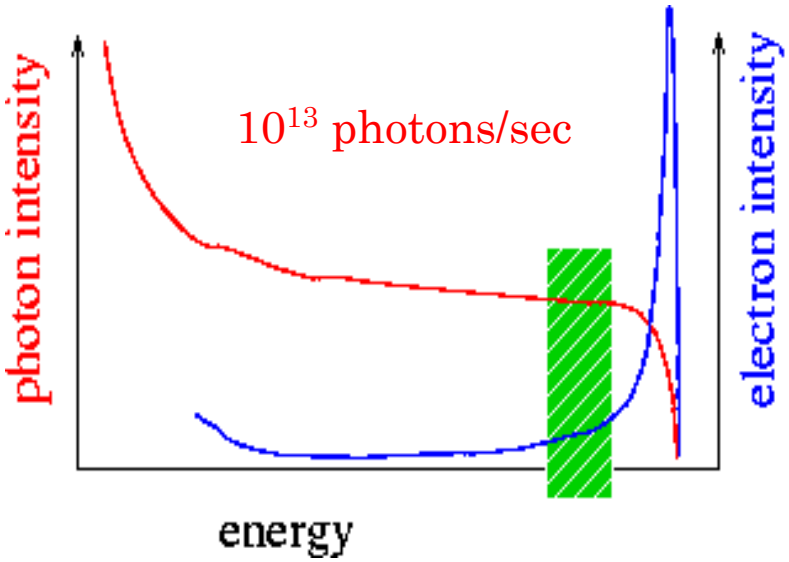
Proton arm had solid angle of 6 msr

JLab proton WACS experiment

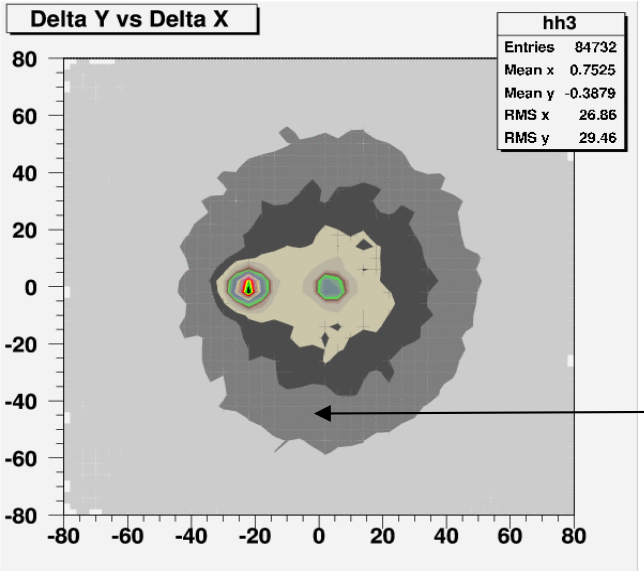


Mixed e/γ beam

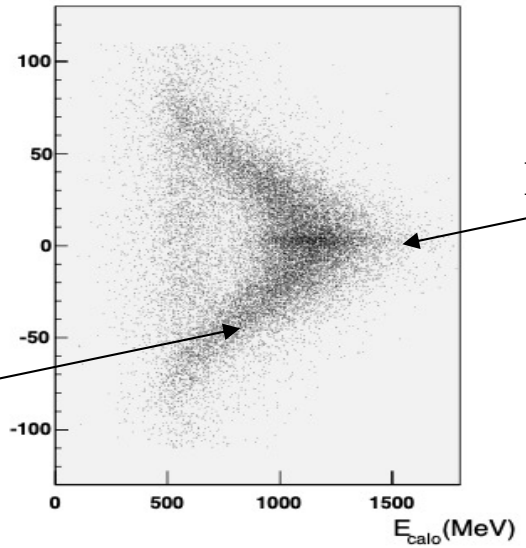




Two-body kinematics

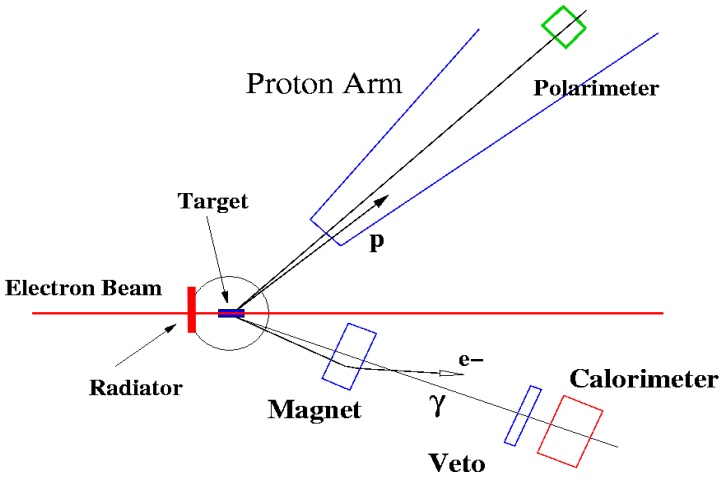


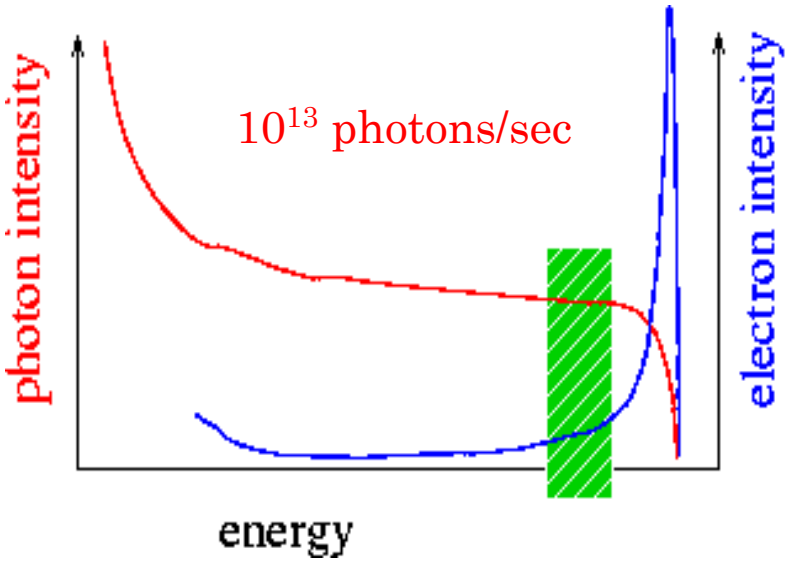
"pion" events



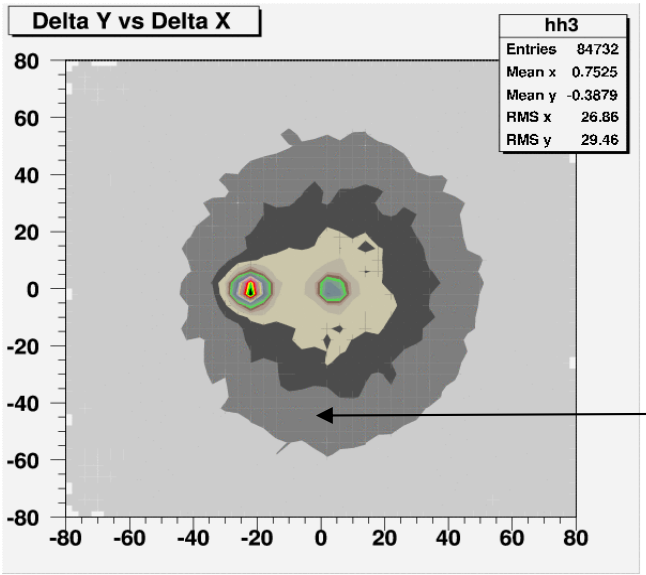
RCS events

Mixed e/γ beam



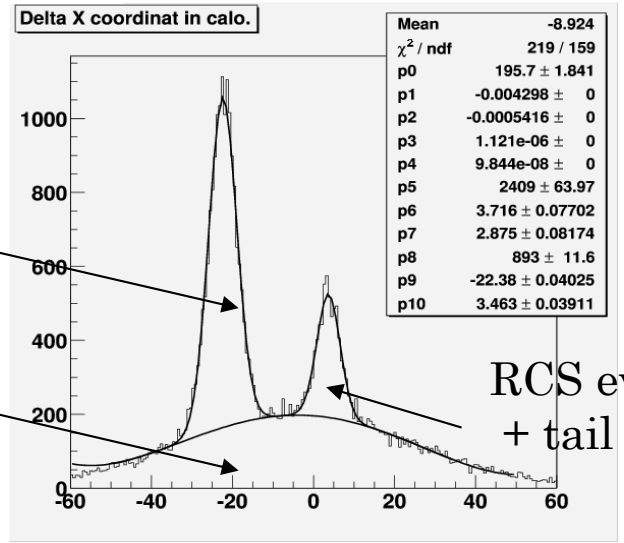


Two-body kinematics



ep events

"pion" events



RCS events
+ tail of epγ

Experimental results: cross section

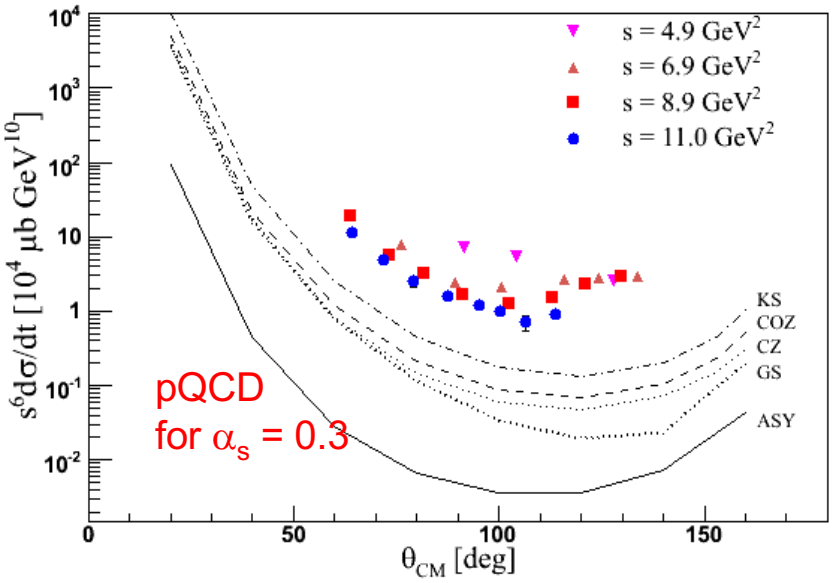
Elastic photon-proton scattering

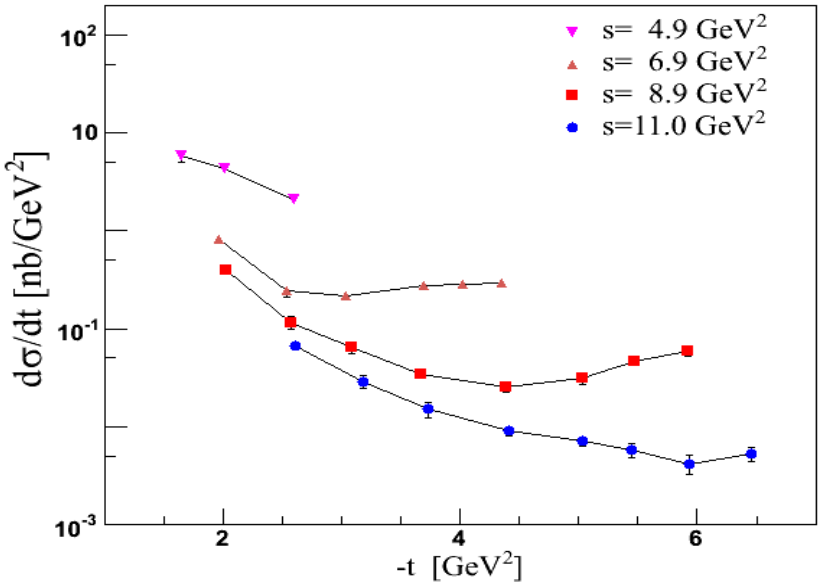
$p\gamma \to p\gamma$

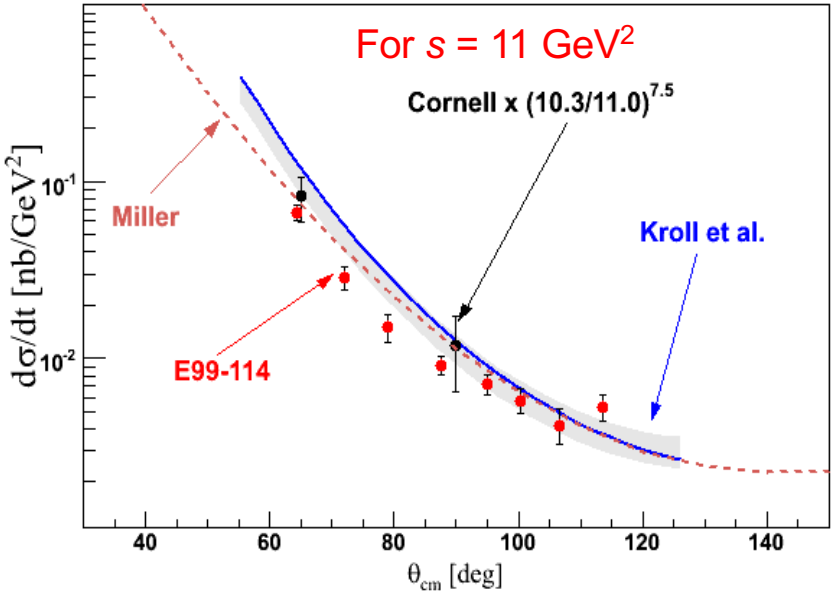
correlations of in-plane angles,

out-of-plane angles,

angle-energy







Results of 6 GeV WACS experiment

Cornell, PR D, 19, 1921 (1979)

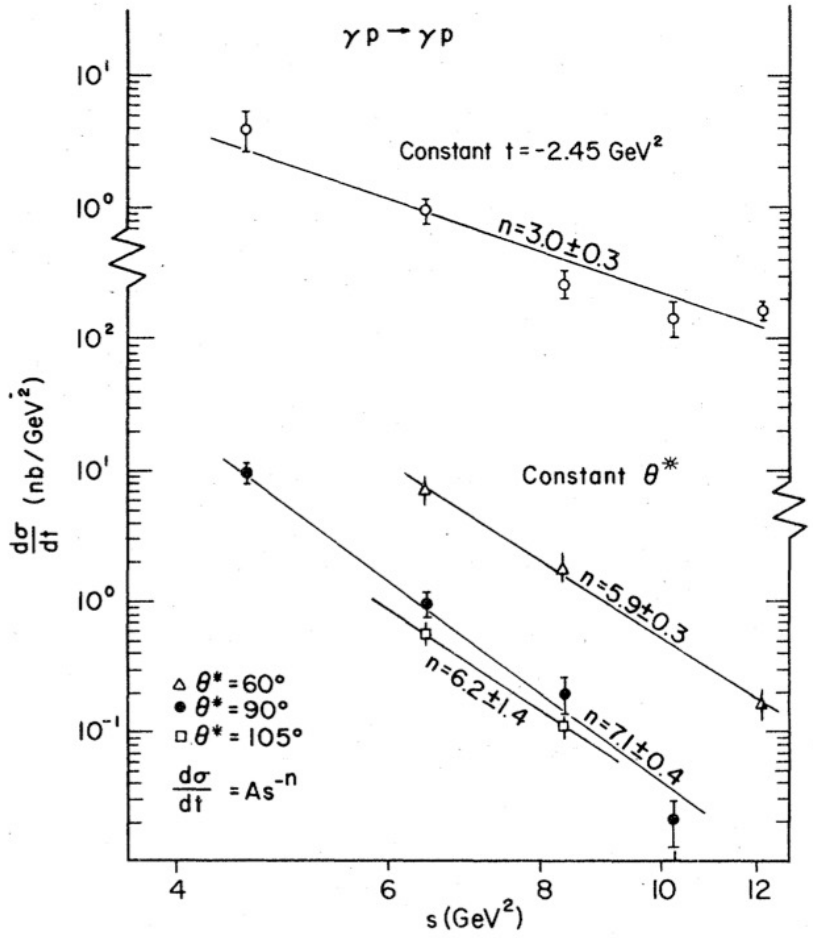
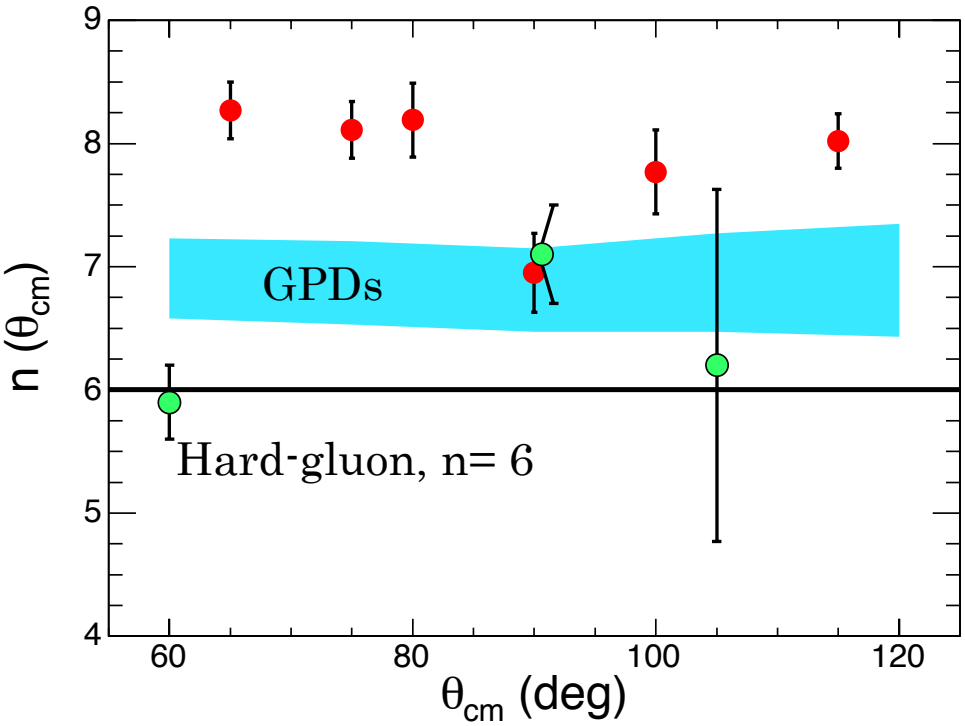


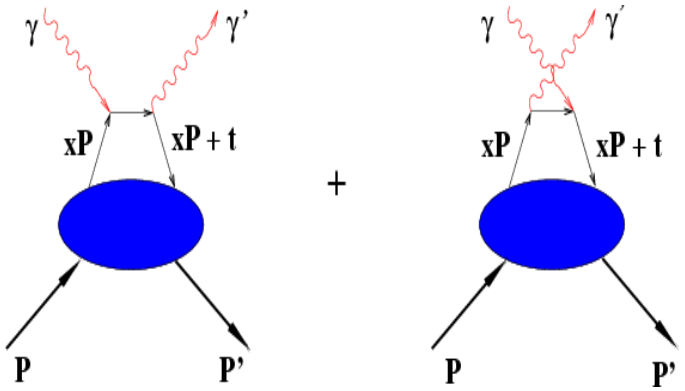
FIG. 6. Compton-scattering cross sections at constant t and at constant θ^*. The straight lines are fits to the data. The fits shown here have no energy cuts.

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n = 8.0 +/- 0.2

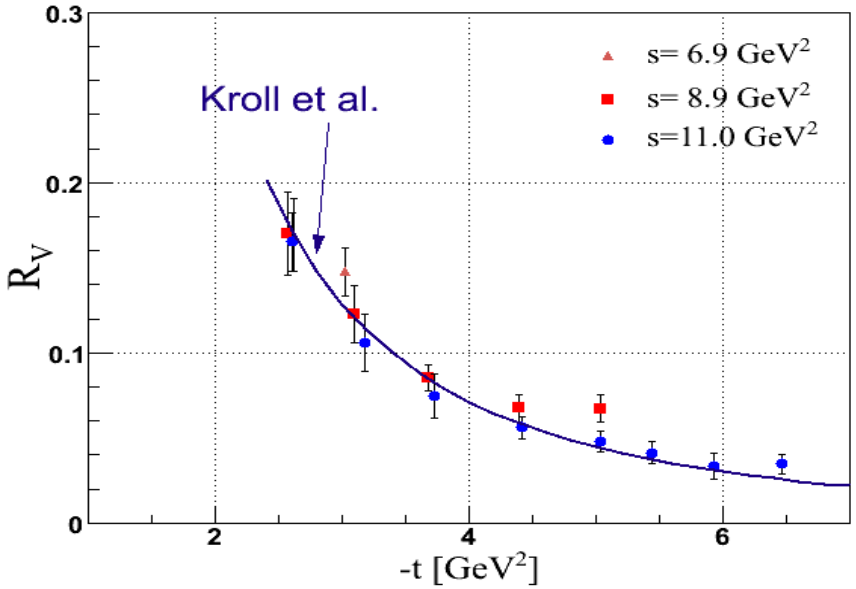
The Compton process from a proton

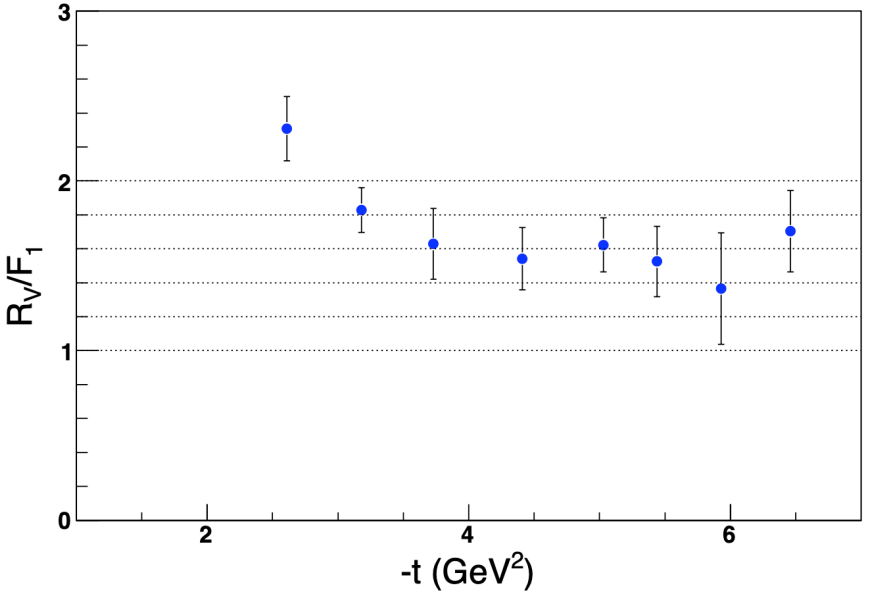


$$\frac{d\sigma_{RCS}}{d\sigma_{KN}} = \frac{(\hat{s}-\hat{u})^2}{\hat{s}^2+\hat{u}^2}R_V^2(t) + \frac{2\hat{s}\hat{u}}{\hat{s}^2+\hat{u}^2}R_A^2(t)$$

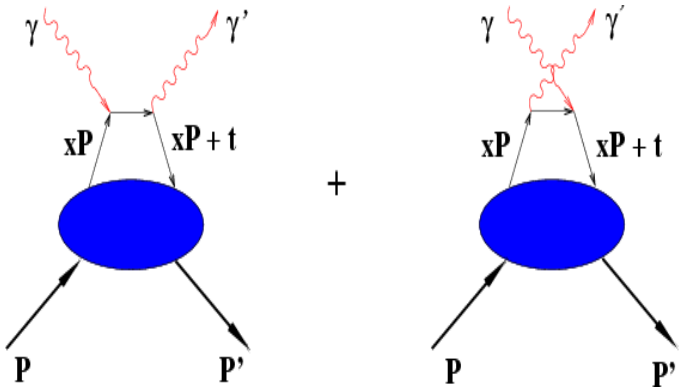
$$R_V(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} H^a(x,0,t),$$

$$F_1(t) = \sum_a e_a \int_{-1}^{1} dx\, H^a(x,0,t),$$





The Compton process from a neutron



$$\frac{d\sigma_{RCS}}{d\sigma_{KN}} = \frac{(\hat{s}-\hat{u})^2}{\hat{s}^2+\hat{u}^2}R_V^2(t) + \frac{2\hat{s}\hat{u}}{\hat{s}^2+\hat{u}^2}R_A^2(t)$$

P. Kroll arXiv: 1703.05000

form factors are therefore strongly suppressed, the valence-quark form factors dominate at large $-t$. Since for $x \to 1$ the $1/x$-factor in the Compton form factors can be neglected, these form factors are also dominated by the valence quark contributions and in particular by the u-valence quark one. This has the following consequences which hold at sufficiently large $-t$:

$$R_V \simeq e_u^2 F_1^u\,, \qquad R_A \simeq e_u^2 \tilde{F}^u\,, \qquad R_T/R_V \simeq 1/|t|^{0.6}\,, \tag{36}$$

and for the ratio of the form factors for Compton scattering off neutrons and off protons one has

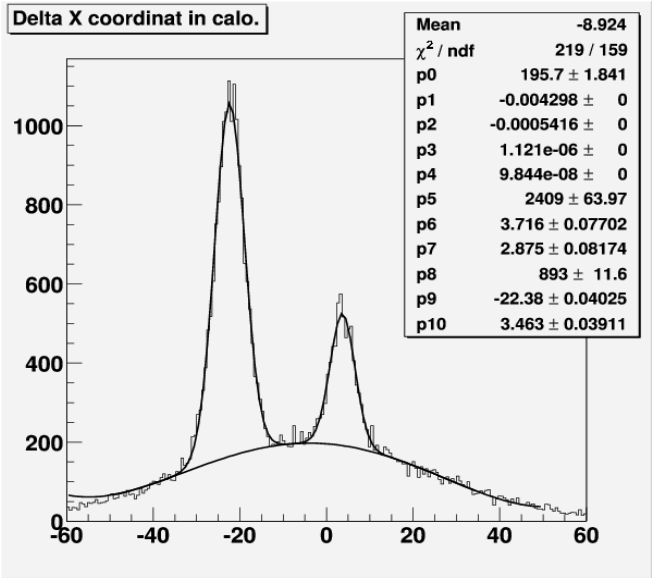
$$R_i^n/R_i^p \simeq e_d^2/e_u^2\,. \tag{37}$$

Event rates ratio - γn/γp depends on d-quark and u-quark GPDs

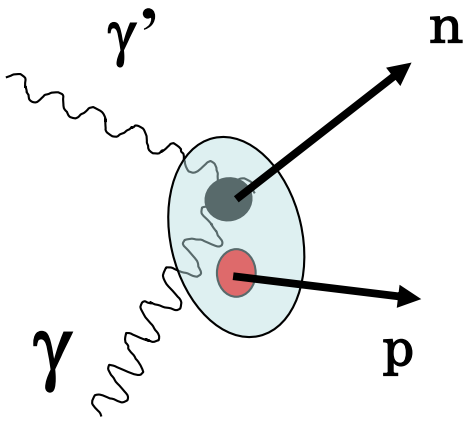
nWACS may also have an effect from d/u reduction at large t

Experiment for the neutron WACS

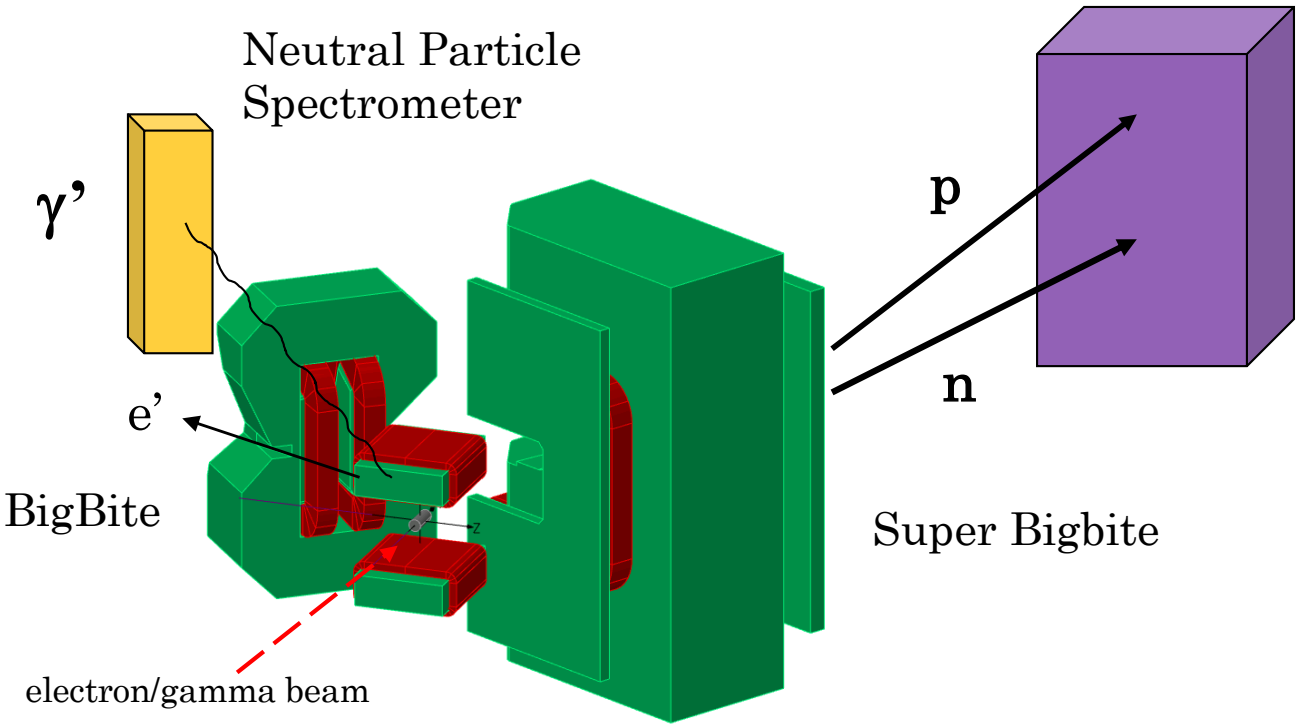
There are π^0 events in the γ-p event sample.
Separation requires good reconstruction of the correlation between the scattered photon and recoiled neutron directions.
The initial neutron momentum is on the same order, the spectator proton should be detected.



Detection of the soft (p > 50 MeV/c) proton puts a limit on the target density and requires a fast accurate detector for such protons.



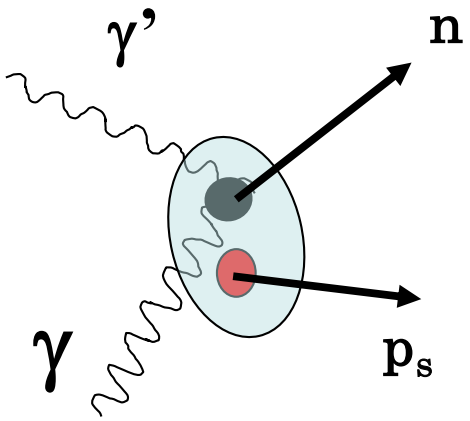
Detector system for the neutron WACS



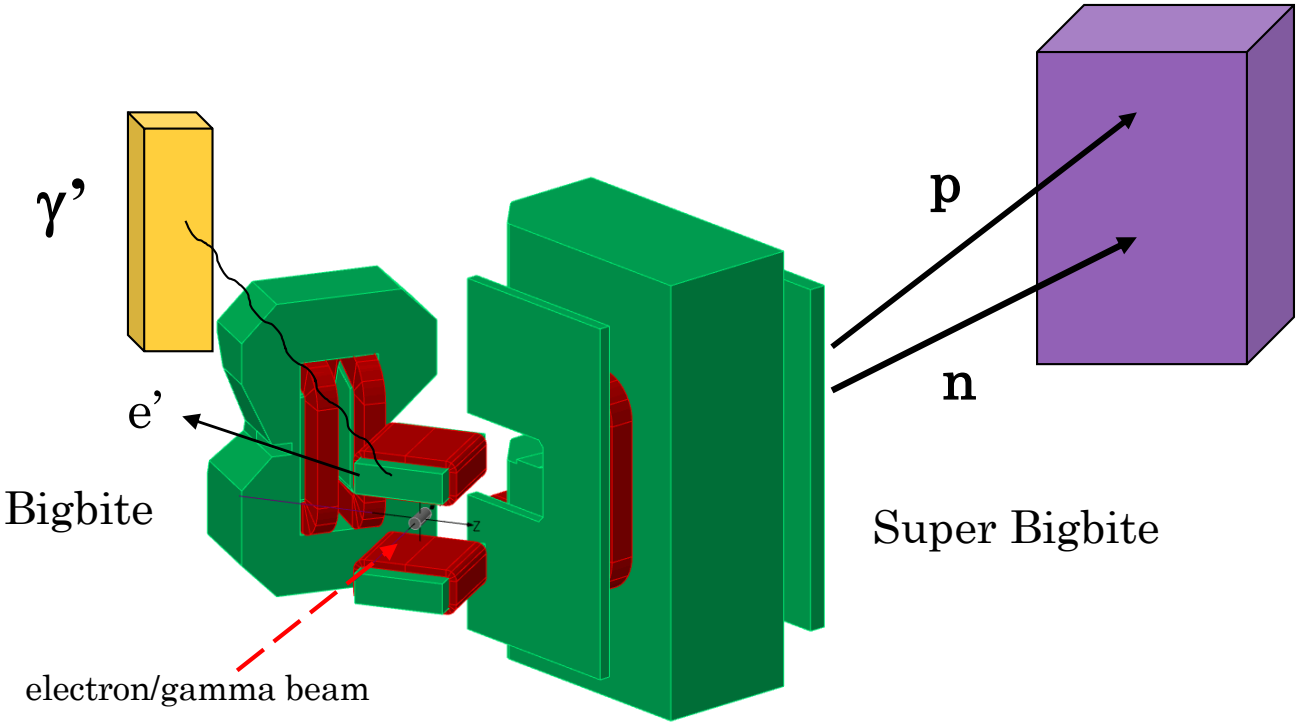
D(e,e'p) and D(e,e'n)

D(γ,γ'p) and D(γ,γ'n)

D(γ,π^op) and D(γ,π^o n)



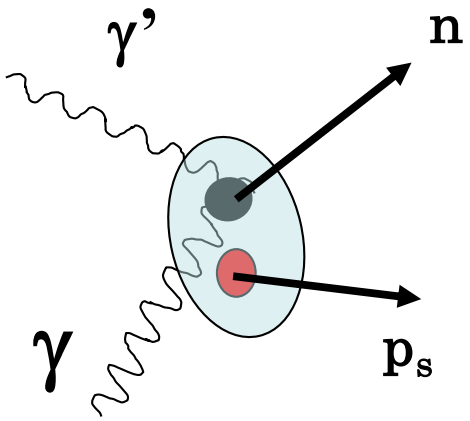
Detector system for the neutron WACS



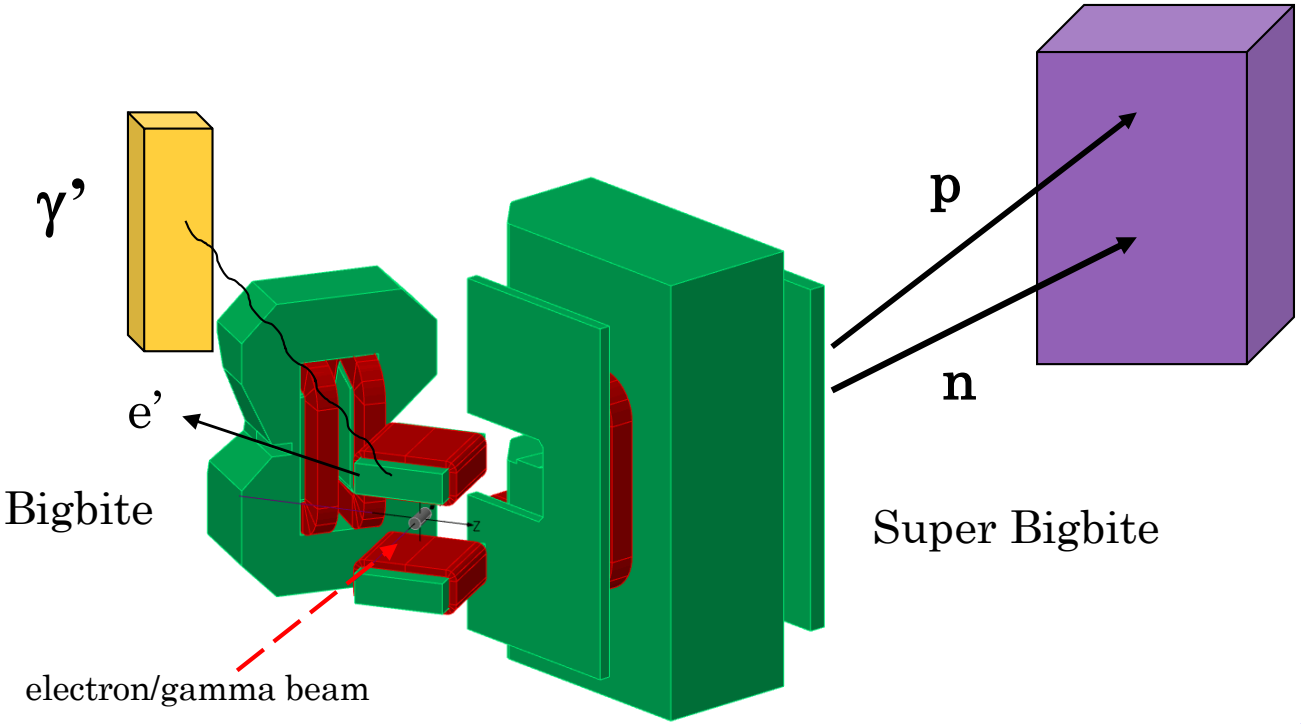
~~D(e,e'p) and D(e,e'n)~~

~~D(γ,γ'p) and D(γ,γ'n)~~

~~D(γ,π°p) and D(γ,π° n)~~



Detector system for the neutron WACS

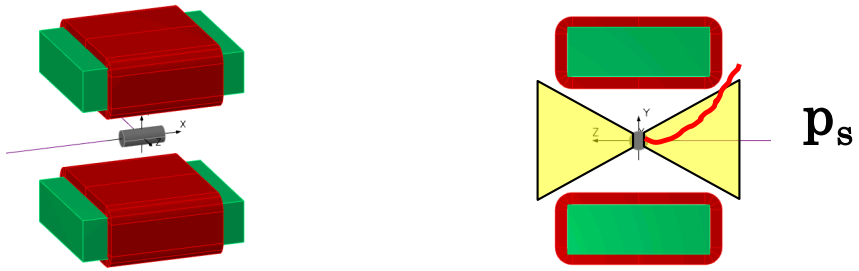


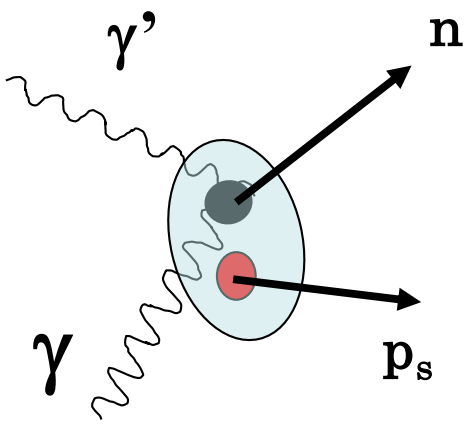
D(e,e'p) and D(e,e'n)

D(γ,γ'p) and D(γ,γ' n p_s)

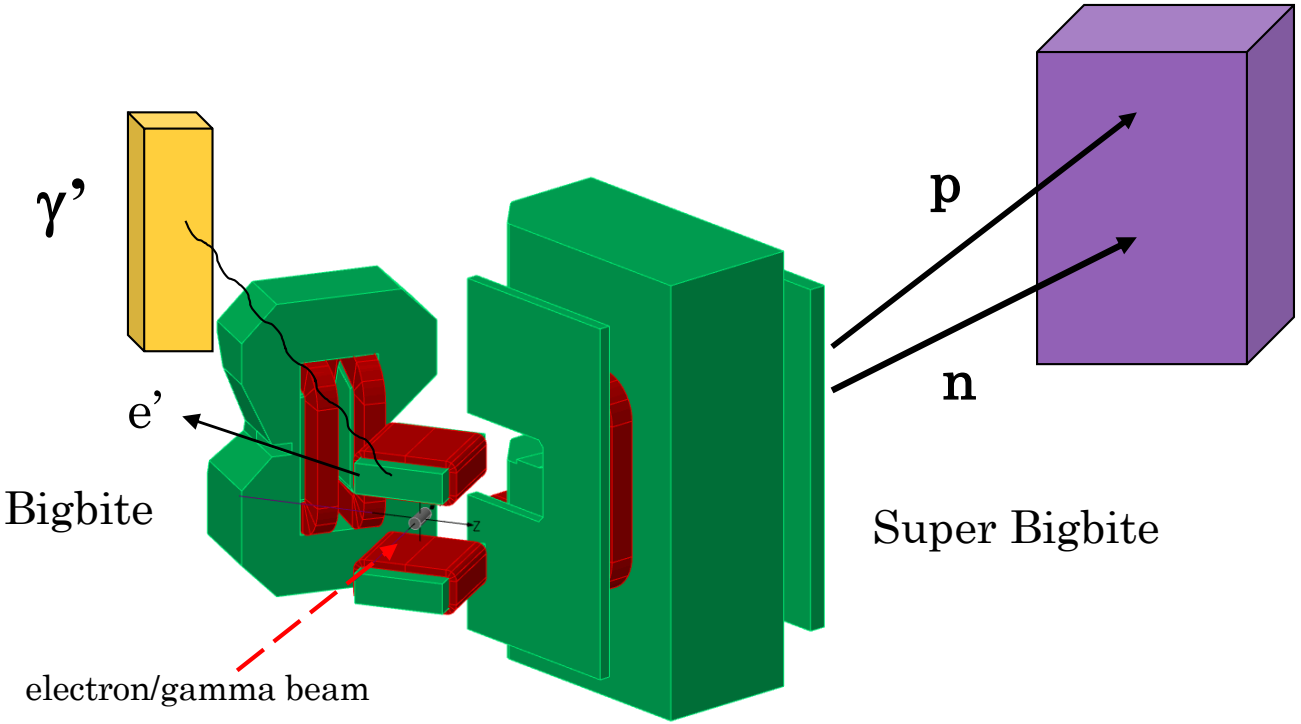
D(γ,π^op) and D(γ,π^o n)

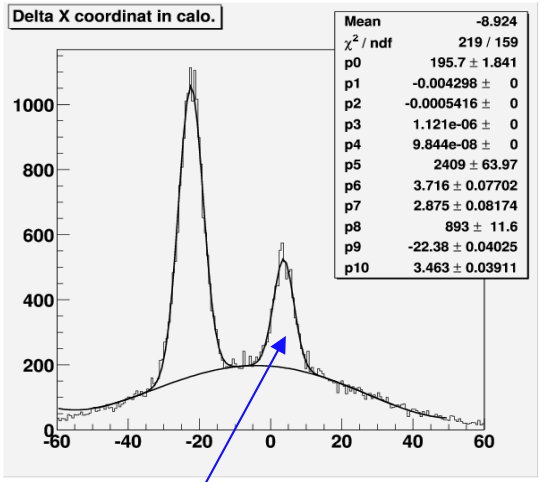
New magnet for the spectator proton





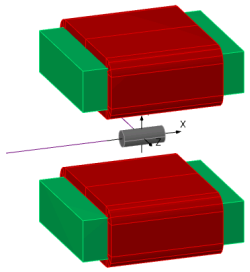
Detector system for the neutron WACS

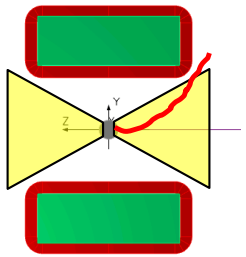


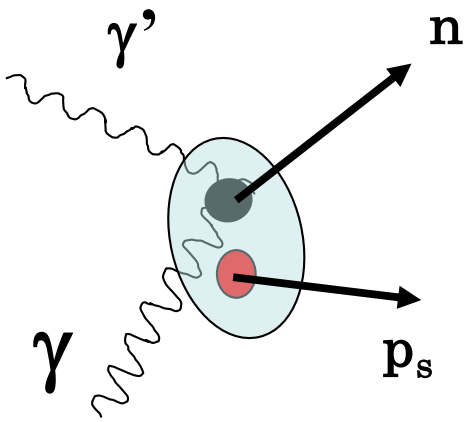


$D(\gamma,\gamma' n p_s)$ $D(\gamma,\pi^o n)$

New magnet for the spectator proton



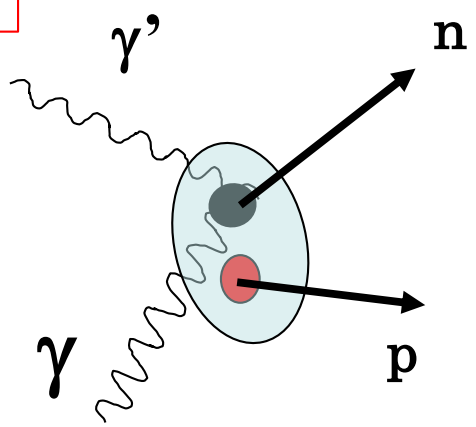




Parameters of the neutron WACS

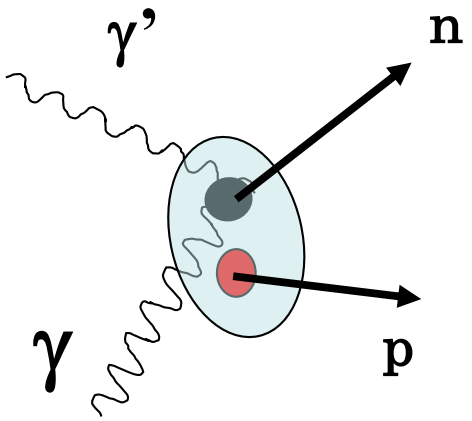
- 25-cm-long 1.5 atm pressure gas deuterium target
- 50 μA 6.6 GeV electron beam
- Electron – neutron luminosity $L_{e\text{-}p} = 5 \times 10^{35}$ Hz/cm^2
- Photon – neutron luminosity ~ 0.1 x $L_{e\text{-}p}$
- Photon energy range ~ 10%
- Neutron arm solid angle 70 msr (SBS + HCAL, n/p separation)
- Photon arm solid angle 70 msr (BB +NPS, γ/e separation)
- Spectator proton arm solid angle 3 sr (3 kG in "fringe solenoid")

$$N_{RCS} = \frac{d\sigma}{dt}_{RCS} \boxed{\frac{(E_\gamma^f)^2}{\pi}\Delta\Omega_\gamma} f_{\gamma p} \boxed{\left(\frac{\Delta E_\gamma^f}{E_\gamma^f}\frac{t_{rad}}{X_o}\right)} \mathcal{L}_{ep}$$



Background in proton spectator arm

- Deuteron target in the mixed e-γ beam
- Effective luminosity gamma-deuteron is 5 x 10^{34} cm^{-2}/s
- D(γ,pn) at 3 MeV has cross section of 3 mbarn
- Total soft proton rate is 1.5 x 10^{8} per second
- In p_s detector acceptance (1/4 of 4π) rate will be ~ 40 MHz
- Quasi elastic e-p scattering also contributes
- Need a detector with time resolution of 1 ns
- MWDC is capable of providing such accuracy

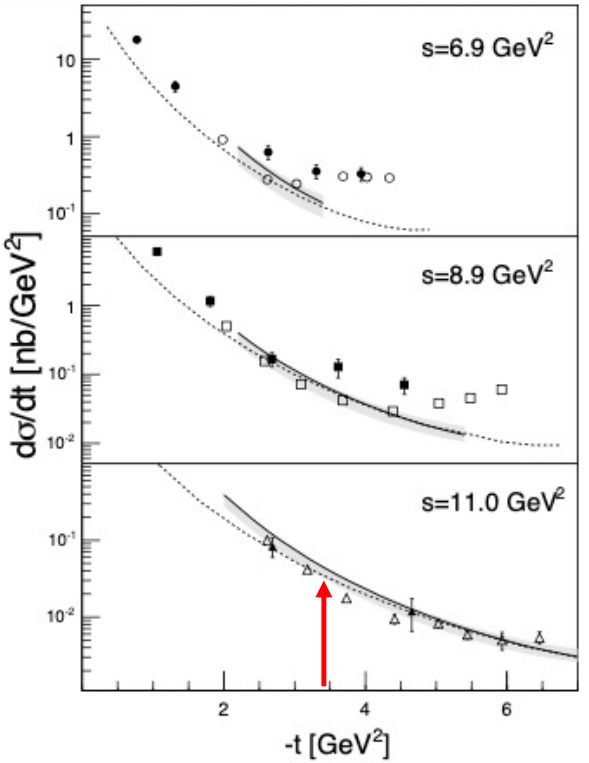


Event rate in the neutron WACS

- Electron beam energy 6.6 GeV
- Incident photon energy 5.4 GeV, s = 11 GeV^2
- Lab gamma angle 25 degrees; t =-3.5, u = -5.7
- Cross section for the proton WACS ~ 0.02 nb/GeV^2
- $\Delta t \sim 0.27$ GeV^2 , $\Delta\sigma \sim 0.5 \times 10^{-35}$ cm^2

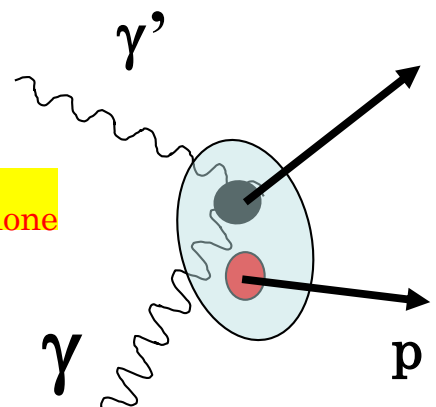
$$N_{RCS} = \frac{d\sigma}{dt}_{RCS} \frac{(E_\gamma^f)^2}{\pi} \Delta\Omega_\gamma f_{\gamma p}\left(\frac{\Delta E_\gamma^f}{E_\gamma^f}\frac{t_{rad}}{X_o}\right)\mathcal{L}_{ep}$$

- Event rate could be 0.025 Hz for the proton WACS
- 10 day run ~ 22,000 proton WACS events of D(γ,γ'p)n
- Spectator proton solid angle ~ ¼ of a full 4π, so ~ 5,400 neutron WACS events of D(γ,γ'n p_s)



$$\frac{d\sigma_{RCS}}{d\sigma_{KN}} = \frac{(\hat{s}-\hat{u})^2}{\hat{s}^2+\hat{u}^2} R_V^2(t) \qquad R_i^n/R_i^p \simeq e_d^2/e_u^2 .$$

- P. Kroll suggested an extra factor of 1/16 for the neutron because the value of $F1_{dual}$ >> $F1_{lone}$



- Neutron WACS could show diquark contribution
- Is the ratio of WACS cross sections (n/p) 2/32 or 18/33 ?

Summary

- The diquark is a natural part of the nucleon structure.
- Elastic scattering from the nucleon allows us to look deep inside.
- Accurate measurements of the Nucleon Form Factors at high Q^2 significantly boost understanding of the nucleon.
- Compton scattering from a neutron could open additional views of a diquark in a nucleon at high s, -t, -u.