Charge-Exchange Neutron Scattering:
Extending Recoil-Polarimetry measurements of G_{En}/G_{Mn} to high values of Q^2

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Facilities where ElectroMagnetic Form Factors (EMFF) can be measured in the space-like domain

Double-polarised measurements are the best way to access G_E the Sachs electric form factor at moderate → high Q^2 for both p and n

- Exclusive $(e,e'N)$ on ^{1}H, ^{2}H, ^{3}He targets.
- High intensity continuous-wave (CW) electron beam
- Highly polarised electron beam $P_e > 80\%$ (strained GaAs cathode)
- High power cryogenic LH_2, LD_2 targets
- Highly polarised ^{3}He gas targets ($P_{He} > 60\%$) capable of maintaining polarisation at high ($\geq$50 μA) incident electron beam current
- Recoil proton or neutron polarimeters
- Facilities capable of double-polarised experiments:
  MAMI, Mainz, Germany, $E_{max} = 1.6\ GeV$
  CEBAF, Jefferson Lab, Virginia, USA, $E_{max} = 11.0\ GeV$

Nucleon EMFF from Differential Cross Section

$$\sigma(\theta) = \sigma_M \left\{ \left[F_1^2(Q^2) + \frac{Q^2}{4M_N^2} F_2^2(Q^2) \right] + \frac{2Q^2}{4M_N^2} \left[F_1(Q^2) + F_2(Q^2) \right] \tan^2 \frac{\theta_e}{2} \right\}$$

$$= \sigma_M \left\{ \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} \right] + 2\tau G_M^2(Q^2) \tan^2 \frac{\theta_e}{2} \right\} \qquad \tau = Q^2/4M_N^2$$

$$G_E = F_1 - \tau F_2$$

$$G_M = F_1 + F_2$$

$$G_E^p(0) = Z_p = 1 \qquad G_M^p(0) = \mu_p = 2.79$$

$$G_E^n(0) = Z_n = 0 \qquad G_M^n(0) = \mu_n = -1.79$$

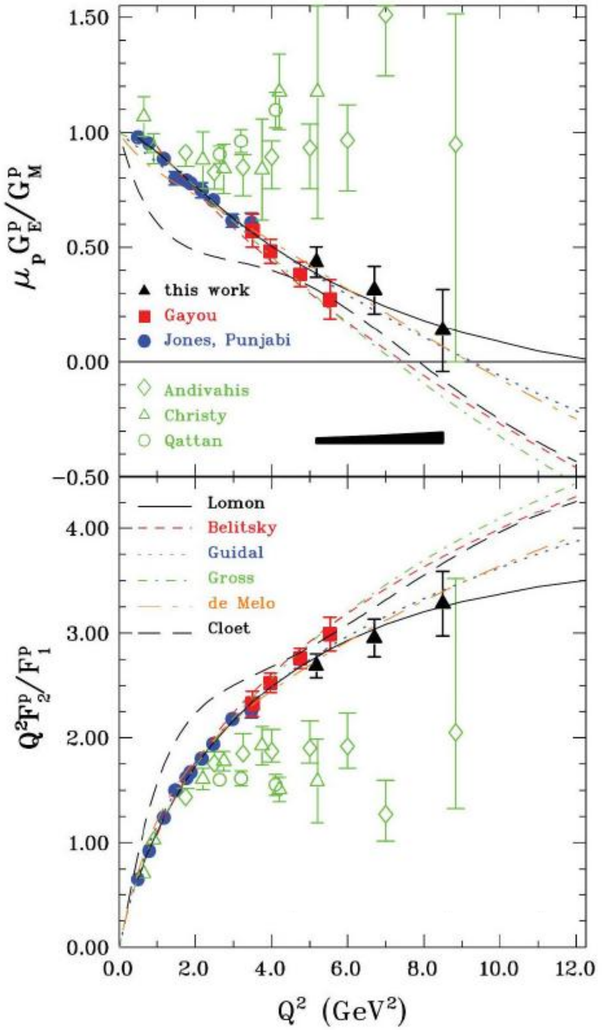
- The structure of a spin-½ particle can be cast in terms of F_2 (Pauli: spin flip) and F_1 (Dirac: non spin flip) form factors
- Often recast in terms of the Sachs form factors $G_E(Q^2)$ and $G_M(Q^2)$
- The elastic scattering differential cross section decomposes into 2 terms
- Separate by measuring at fixed Q^2, but different combinations of $E_{e'}$ and θ_e

  EMFF measurements for > 60 years... R. Hofstadter, Rev. Mod. Phys. 28 (1956), 214.
- Rosenbluth Separation technically challenging (normalisation and acceptance issues)
- If there is a large disparity in the strength of electric and magnetic amplitudes the uncertainties in the weaker component can be large
- More recently the single photon exchange approximation in electron scattering at $Q^2 > 1$ (GeV/c)^2 has been questioned...although size of possible two-photon effects not yet demonstrated conclusively. Also radiative correction effects?

Polarised Elastic EMFF Mesaurements

Proton Data

A. Pucket et al., PRL 104(2010),242301



- Q^2 dependence G_{Ep}/G_{Mp} measured by ${}^1H(\vec{e}, e'\vec{p})$ behaves differently to older Rosenbluth measurements as Q^2 increases >> 1 $(GeV/c)^2$
- Radiative Corrections ?
- Two-photon exchange effects ?
  Rosenbluth sensitive to two-photon
  JLab double polarised G_{Ep}/G_{Mp} @ fixed Q^2 insensitive to ε
  (viz. E. Brash talk)
- 2-photon effects probed by comparison of elastic electon/positron-proton scattering (e.g. CLAS, Olympus, VEPP-3).
  (viz. M. Kohl talk)

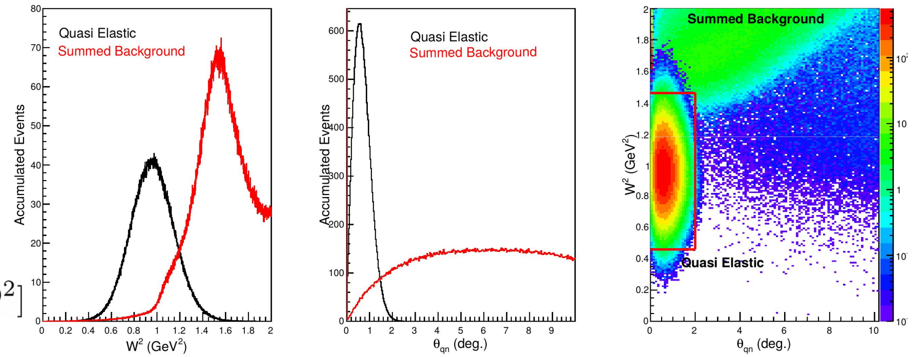
- Around 1990, when suitable high-duty-factor, polarised electron beams became available, double polarised measurements of G_{En}/G_{Mn} started:
  Bates, Mainz, NIKHEF and continuing at JLab.
  Pioneering ${}^2H(\vec{e}, e'\vec{n})$ Recoil Polarisation (RP) @ Bates:
  T. Eden et al., Phys. Rev. C50 (1994), R1749
- So far no RP measurement of G_{En}/G_{Mn} beyond $Q^2 = 1.5$ $(GeV/c)^2$ (Hall C, JLab)
- JLab Hall-A ${}^3\vec{H}e(\vec{e}, e'n)$ G_{En}/G_{Mn} data extend to $Q^2 = 3.4$ $(GeV/c)^2$
  ~90% of ^{3}He polarisation carried by unpaired neutron

The Need for G_{En}/G_{Mn} Data at Higher Q^2

- In terms of Q^2 range and precision, neutron measurements still lag way behind proton measurements
- JLab: E12-09-016 G_{En}/G_{Mn} with polarized electron beam & ^{3}He target up to $Q^2 \sim 10$ (GeV/c)^2
- Alternative RP method with polarized electron beam, unpolarized ^{2}H target and polarimeter to measure polarisation transfer to recoiling neutron. JLab: E12-17-004
- QE signal much cleaner with ^{2}H target compared to ^{3}He

MC simulation separation QE signal from non-elastic background $d(e,e'n)$, $Q^2 = 4.5\ (GeV/c)^2$

$$W = [M_n^2 + 2M_n(E - E') - Q^2]$$



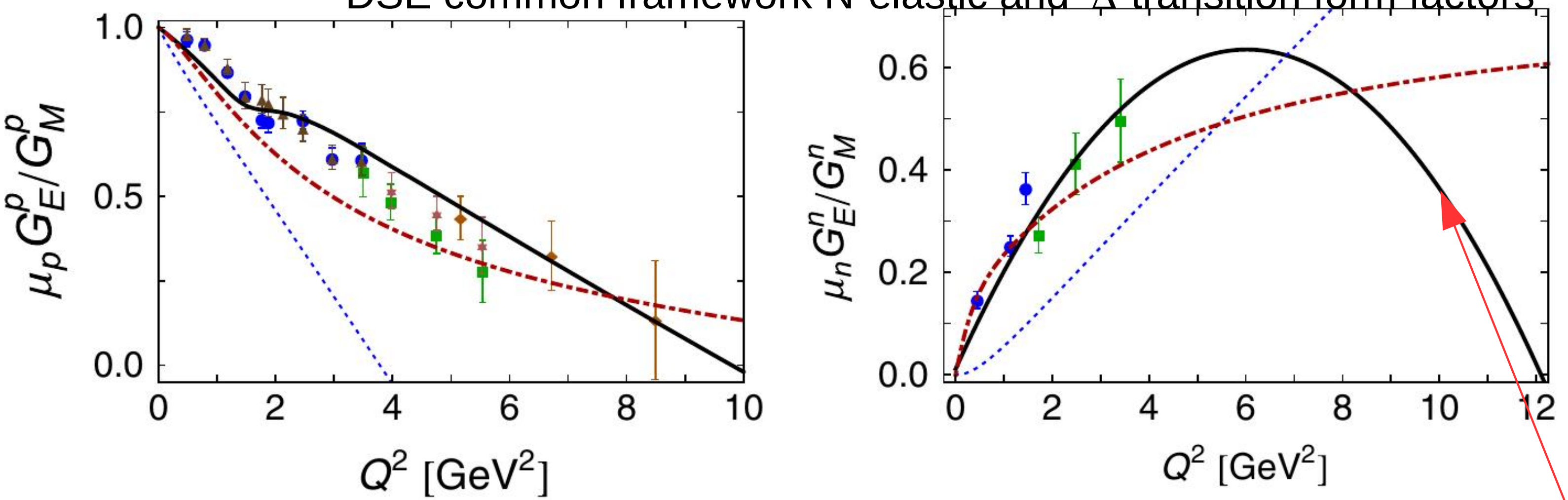
Red box: 98.5% QE events accepted. Non-elastic contamination 1.5% of accepted QE

- Much higher luminosity possible with unpolarised (liquid) target
- **BUT** in general ^{3}He target polarisation $P_{3He} >> A_y$ the analysing power of a neutron recoil polarimeter
- Efficiency of polarimeter in RP experiment generally comparatively low
- ^{2}H RP experiment should, as far as possible, match kinematic range and precision of ^{3}He experiment. Currently approved up to $Q^2 = 4.5\ (GeV/c)^2$
  Up to now no recoil polarimetry measurement at $Q^2 > 1.5\ (GeV/c)^2$

Theoretical Predictions for G_E/G_M ...

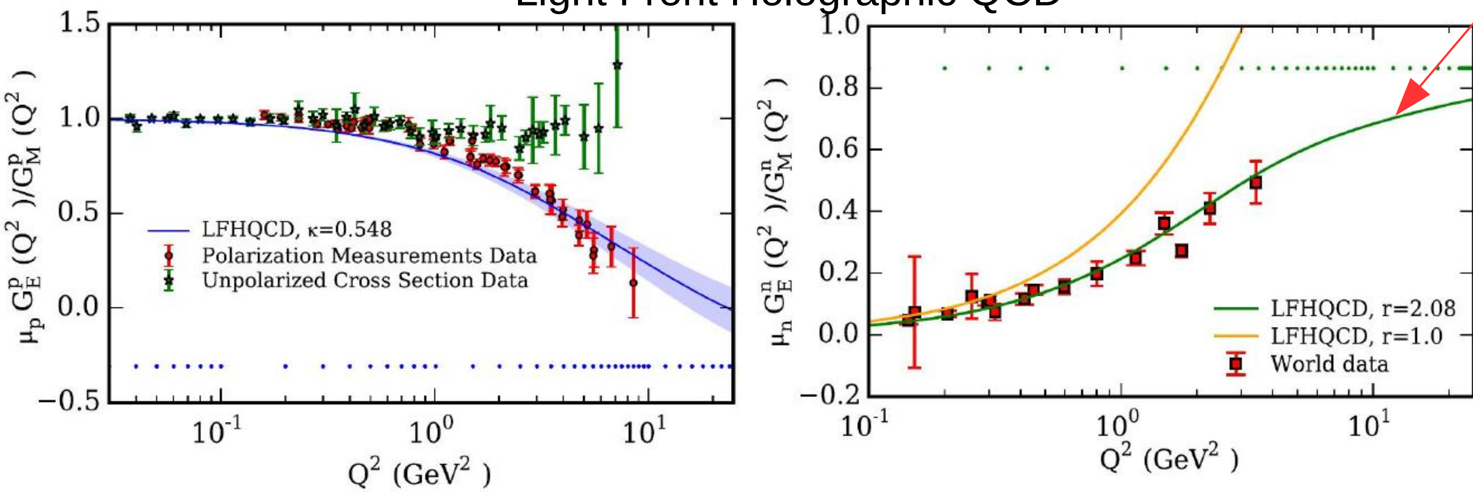
diverge hugely where there is no data

J. Segovia et al., Few-Body Syst. 55 (2014), 1185.
DSE common framework N-elastic and Δ-transition form factors



Different theoretical frameworks...
Very different predictions for $\mu_n G_{En}/G_{Mn}$
Vital to have new data

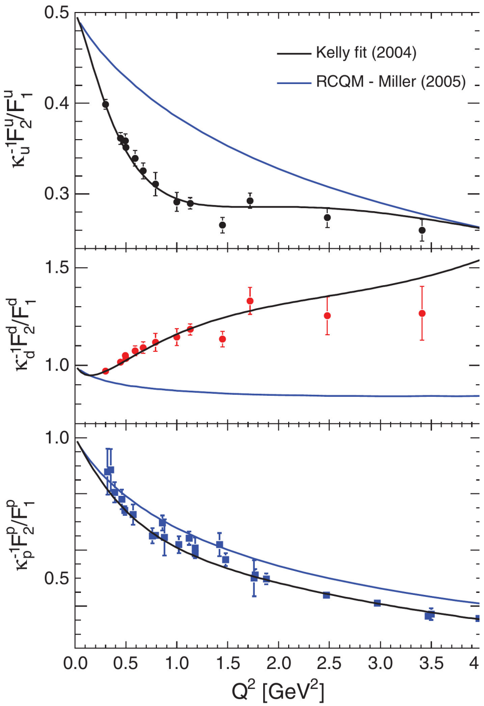
R. S. Sufian et al., Phys. Rev. D95(2017),014011.
Light Front Holographic QCD

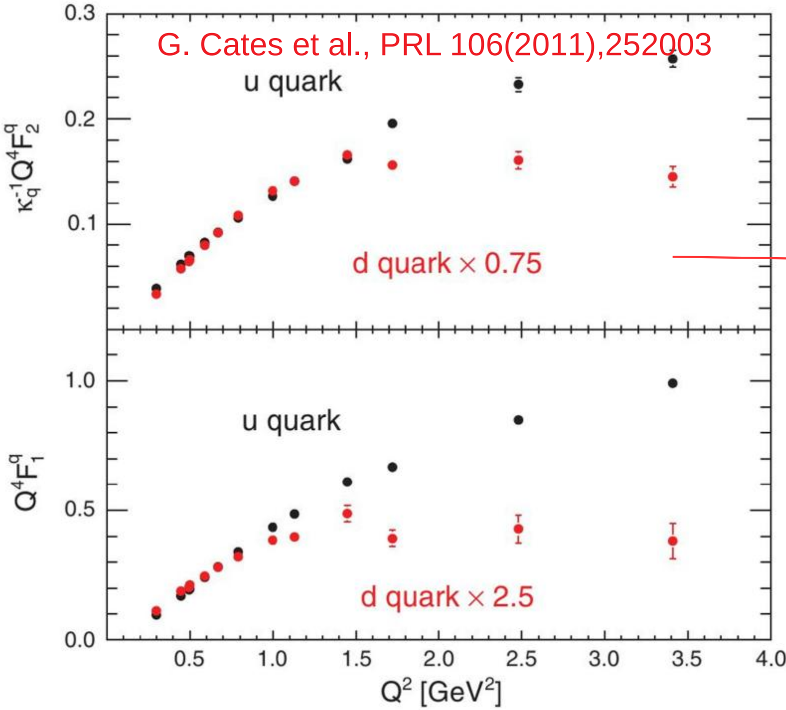


Scaling of Flavour-Separated F_1, F_2 Form Factors

$$G_E = F_1 - \tau F_2 \qquad G_M = F_1 + F_2$$

Flavour-separated u/d distributions … all 4 p,n Sachs form factors necessary





If non-u/d nucleon content small @ moderate Q^2

$$\kappa_u = 2\kappa_p + \kappa_n = +1.67$$
$$\kappa_d = \kappa_p + 2\kappa_n = -2.03$$
$$F^u_{1,2}(Q^2) = F^n_{1,2} + 2F^p_{1,2}$$
$$F^d_{1,2}(Q^2) = 2F^n_{1,2} + F^p_{1,2}$$

New RP measurement E12-17-004 will extend separation to $Q^2 = 4.5 (GeV/c)^2$

4.5

No RP data with ^{2}H target $Q^2 > 1.5 (GeV/c)^2$

- u/d flavour separation: range of Q^2 is determined by range of G_{En} data
- quite different u,d dependence on Q^2
- diquark configuration?

G_E/G_M using Recoil Polarimetry

A.I.Akhiezer et al., JEPT 33 (1957),765
R.G.Arnold, C.E.Carlson and F.Gross, Phys.Rev. C23(1981),363

$$P_x = -hP_e\frac{2\sqrt{\tau(1+\tau)}\tan\frac{\theta_e}{2}G_E G_M}{G_E^2+\tau G_M^2(1+2(1+\tau)\tan^2\frac{\theta_e}{2}}$$

$$P_y = 0$$

$$P_z = hP_e\frac{2\tau\sqrt{1+\tau+(1+\tau)^2\tan^2\frac{\theta_e}{2}}\tan\frac{\theta_e}{2}G_M^2}{G_E^2+\tau G_M^2(1+2(1+\tau)\tan^2\frac{\theta_e}{2})}$$

$$\frac{P_x}{P_z} = \frac{1}{\sqrt{\tau+\tau(1+\tau)\tan^2\frac{\theta_e}{2}}}\cdot\frac{G_E}{G_M}$$

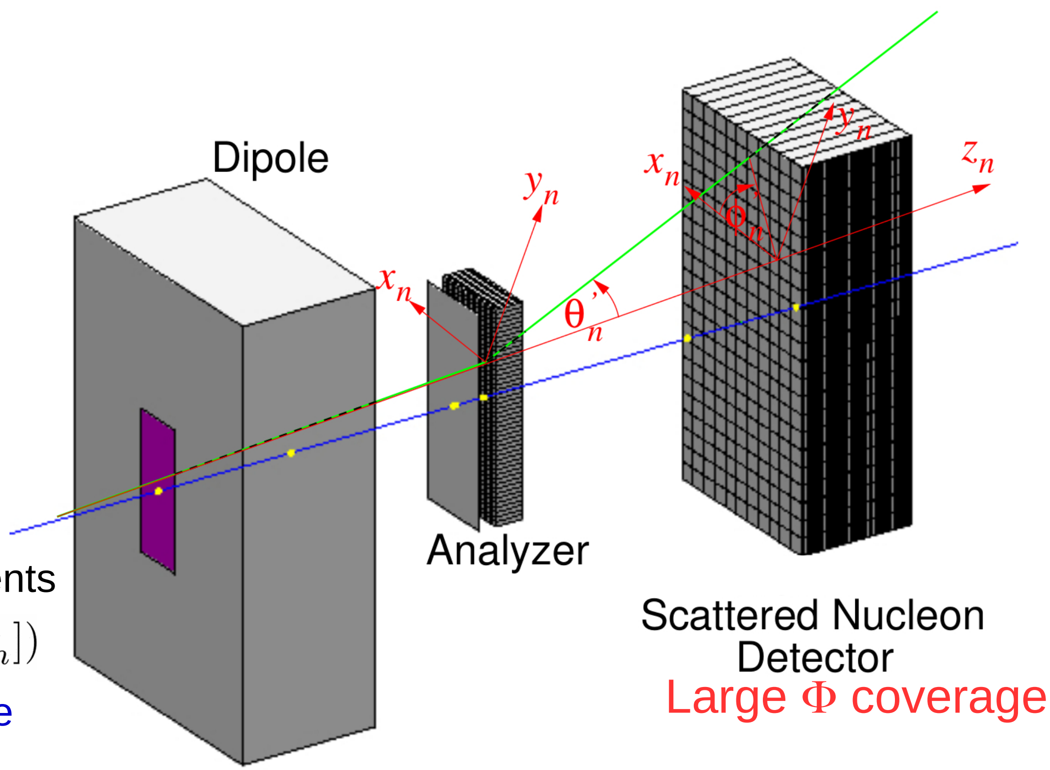
Recoil Polarimetry...
N-N scattering $V_{so}(\boldsymbol{l.s})\rightarrow$
ϕ dependence → transverse polarisation components

$$\sigma(\theta_n', \phi_n') = \sigma_0(1+P_e A_y^{eff}[P_x^n\sin\phi_n' + P_y^n\cos\phi_n'])$$

Precession angle of nucleon $P_z \rightarrow P_y$ through dipole

$$\chi = \frac{2\mu_N}{\hbar c\beta_N}\int_L B.dl$$

Integrated Field ~2 Tm: $\chi\rightarrow 70°$ as $\beta_n\rightarrow 1$



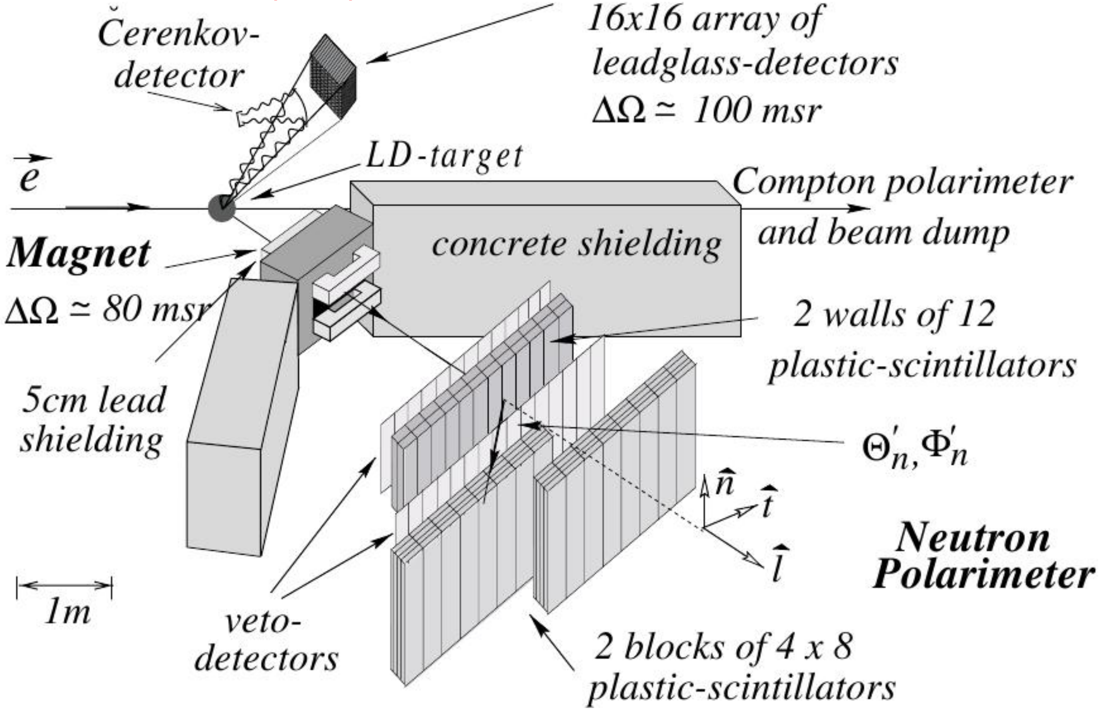
Large Φ coverage

P_e *and* A_y cancel in ratio but should be as high as possible to achieve good precision

G_{En}/G_{Mn} Measurements at MAMI-A3

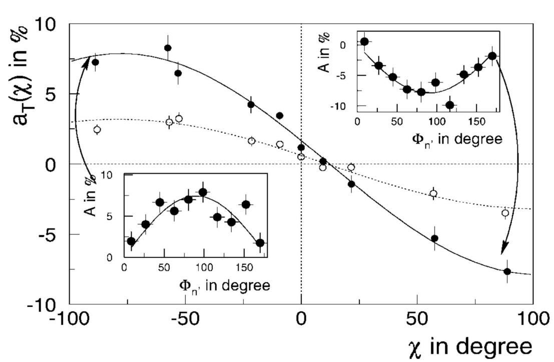
...Started ~ 1990

M. Ostrick et al., PRL 83(1999),276



- 1st Double Polarisation Measurements with CW polarised electron beam: Mainz A3
- Large solid angle $(e,e'n)$ detection
- Both ^{2}H$(e,e'n)$ and ^{3}He$(e,e'n)$ QE scattering measured
- Corrections for binding effects @ Q^2~0.3 $(GeV/c)^2$ Large
- Angular uncertainty in q vector (e' detector) limited the achievable systematic uncertainties
- Polarimeter consisted of
  Front Wall: n-scattering analyser
  1.8 m Glasgow TOF Bars
  Rear Walls: n-scattering Asymmetry Detector
  3m Glasgow/Tübingen TOF Bars

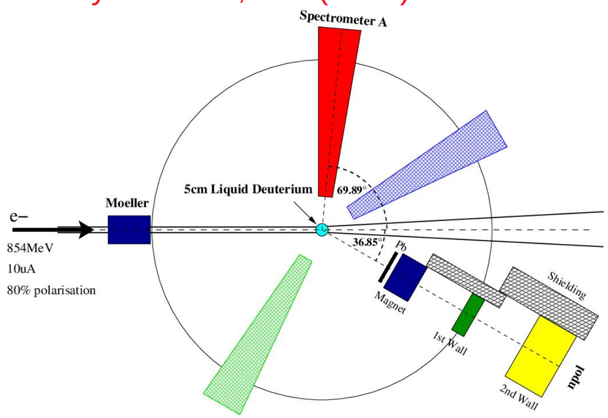
R.Watson Ph.D. Thesis
University of Glasgow, 1997

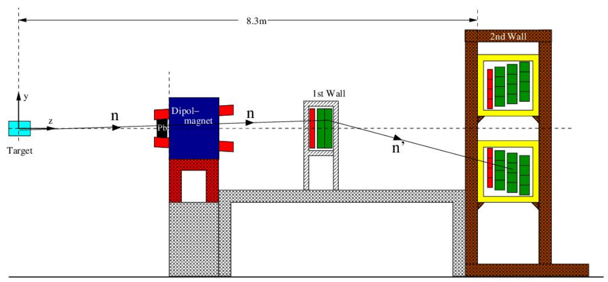


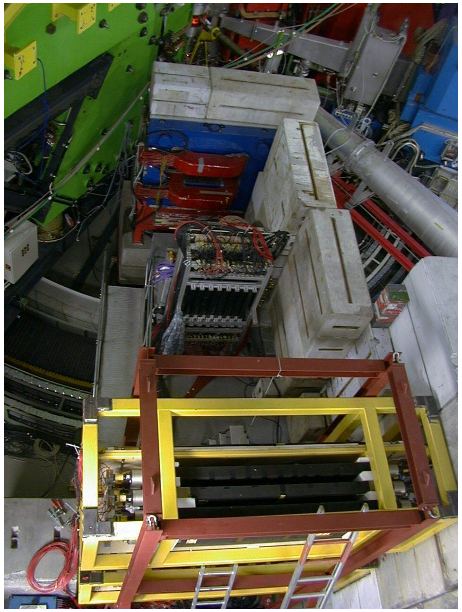
Vary dipole magnetic field to change n-spin precession angle $\tan\chi_0 = P_e A_y^{eff} P_x / P_e A_y^{eff} P_z$

G_{En}/G_{Mn} at Mainz A1

D. I. Glazier et al.,
Eur. Phys. J. A 24, 101 (2005).



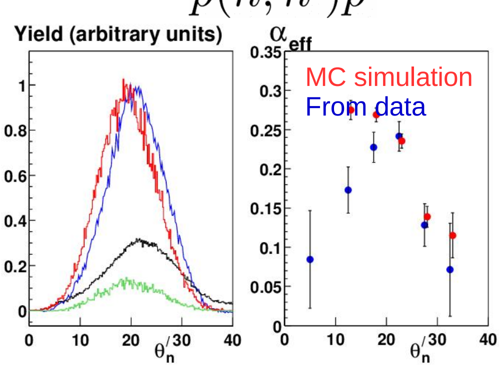




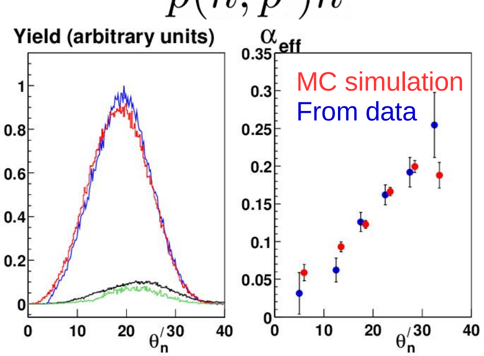
- High-resolution A1 spectrometer A.
- CH plastic scint. polarimeter
  Mainz segmented analyser wall
  Glasgow 1.8 m TOF asymmetry wall
- D.G. developed polarised nucleon scattering model for Geant-4
- Adaptation of DG's framework to higher momentum situation in Hall-A

Derek Glazier Ph.D. Thesis, University of Glasgow, 2004

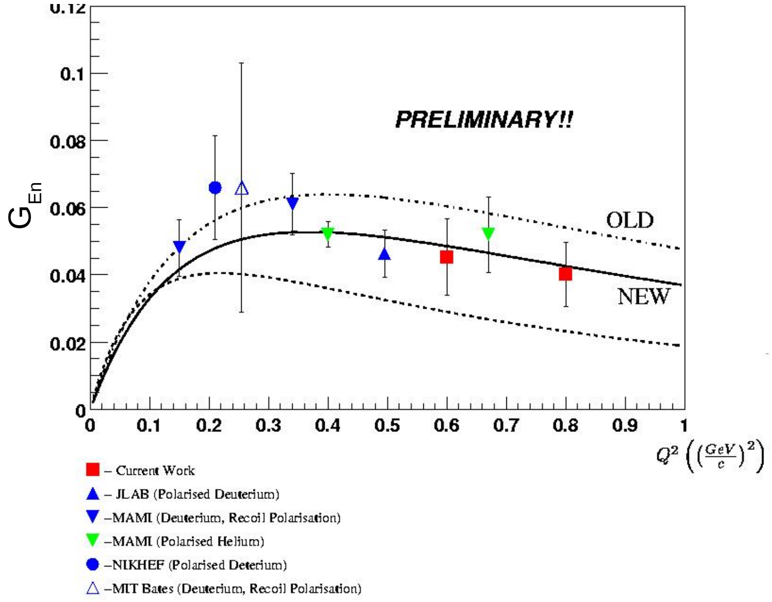
$$p(n,n')p'$$



$$p(n,p')n'$$



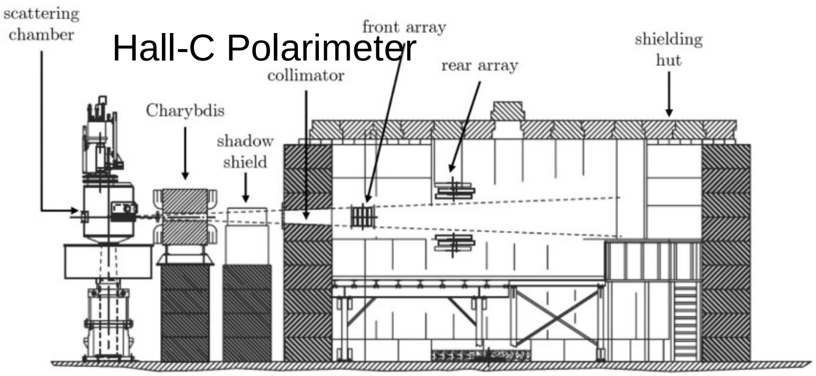
The Situation early 2000's

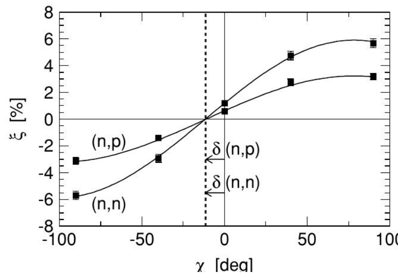


G_{En}/G_{Mn} in Hall-C JLab

B. Plaster et al. PRC 73 (2006),025205

Hall-C Polarimeter

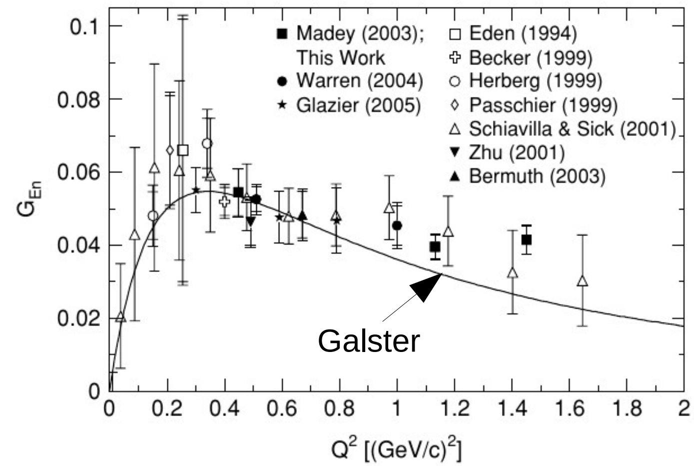




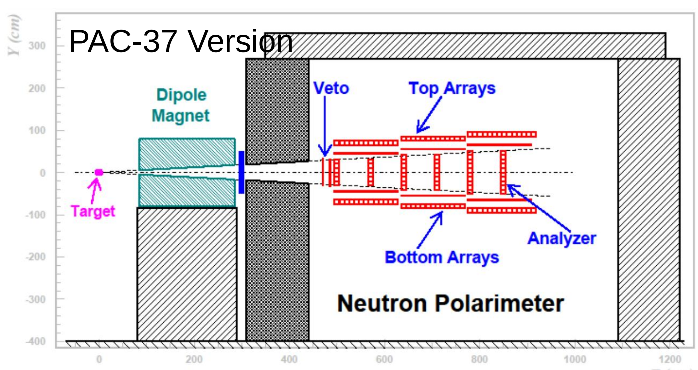
In common with Mainz RP, measured P_x/P_z as function of spin precession angle

Inferred Effective A_y

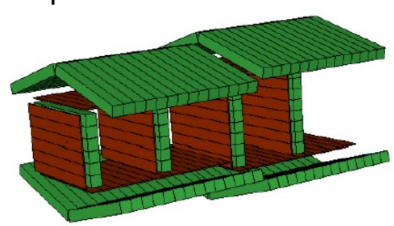
Event type	$\langle Q^2 \rangle$ [(GeV/c)^2] 0.447	1.132	1.450
(n, n)	0.141 ± 0.004	0.137 ± 0.010	0.144 ± 0.013
(n, p)	0.103 ± 0.005	0.075 ± 0.007	0.071 ± 0.011



New experiment proposed for upgraded JLab: E12-11-009, C-Gen Collaboration
SHMS + new neutron polarimeter



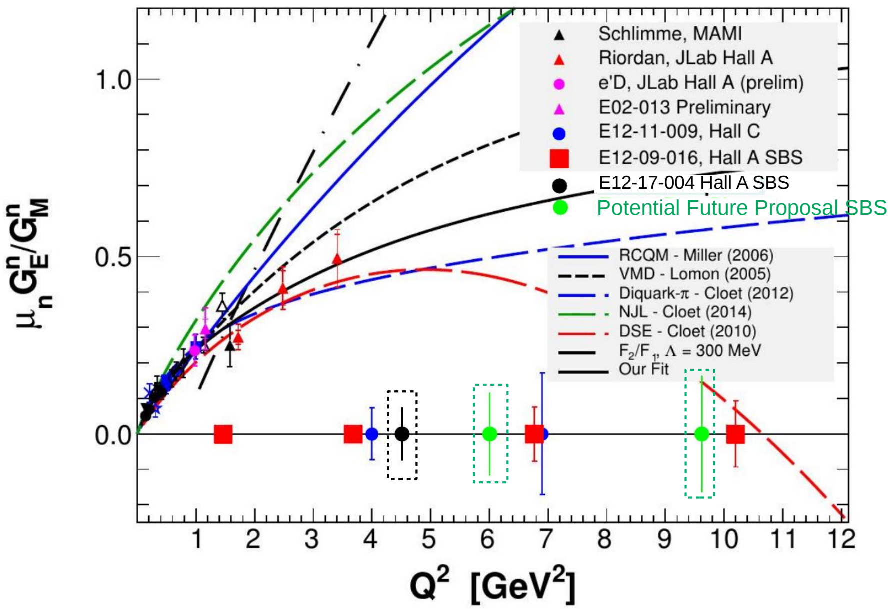
Updated version

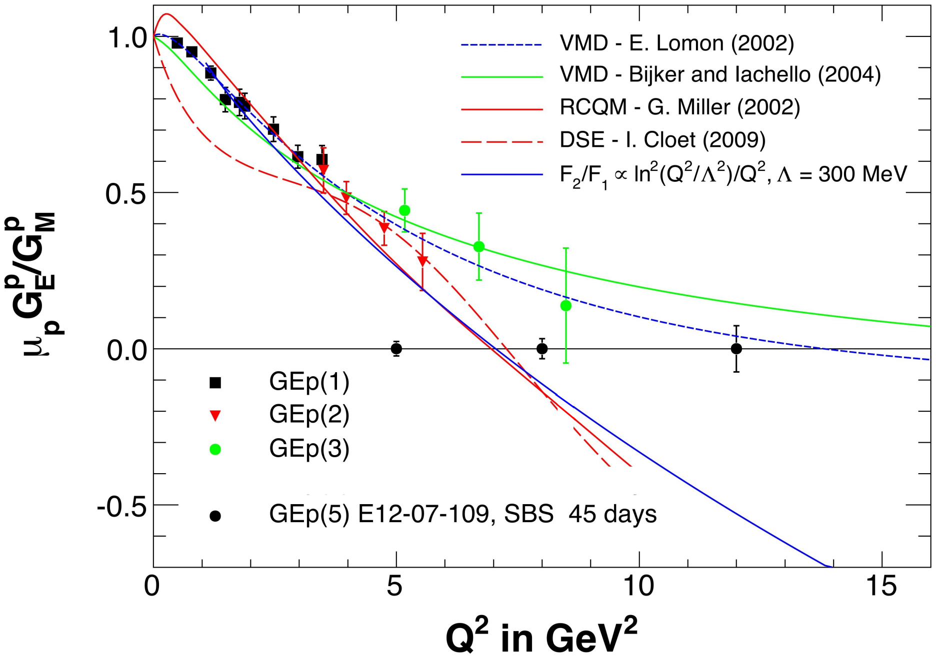


- 80 μA beam on 40 cm LD_2
- Polarimeter constructed CH plastic scintillator bars
  Detects low momentum, large-angle recoil p
- Q^2 = 3.95, 6.88 (GeV/c)^2
- Detection efficiency ~ 6%
- A_y = ??

New EMFF Experiments in JLab Hall A
Super BigBite Spectrometer (SBS)

Hall A all 4 Nucleon Sachs form factors.





E12-07-108 G_{Mp} elastic *p(e,e')p* cross section (2%) using High Resolution Spectrometer, max $Q^2 = 16\ (\mathrm{GeV}/c)^2$

Cross Section

$$\sigma_{ep} \propto \frac{E^2}{Q^{12}}$$

Polarimetry

$$A_y \propto \frac{1}{p_p} \sim \frac{M}{Q^2}$$

$$FOM \propto N A_y^2 \sim \frac{E^2}{Q^{16}}$$

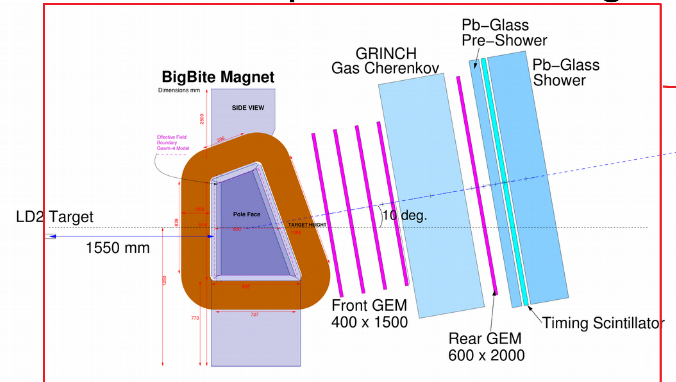
SBS programme of nucleon EMFF measurements

- E12-09-019 G_{Mn}/G_{Mp} (by ratio *d(e,e'n)/d(e,e'p)* method)
- E12-09-016 G_{En}/G_{Mn} (with polarized beam & target)
- E12-07-109 G_{Ep}/G_{Mp} (with polarized beam & recoil polarimetry)
- E12-17-004 G_{En}/G_{Mn} (with polarized beam & recoil polarimetry)

Luminosity up to ~10^{39} cm^{-2}s^{-1}

Experimental Components E12-09-019/E12-17-004

Electron Spectrometer BigBite



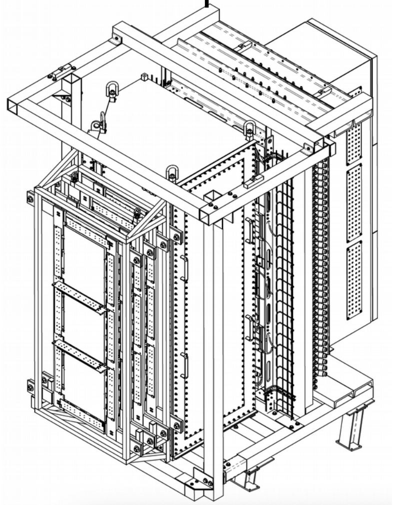
Ω ~ 55 msr

$\delta p/p$ ~ 0.5%

$\delta\theta$ ~ 1 mr

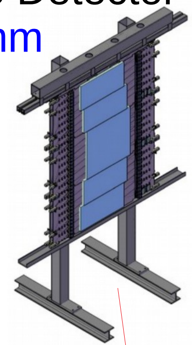
δz ~ 2 mm @ target

δt ~ 150 ps



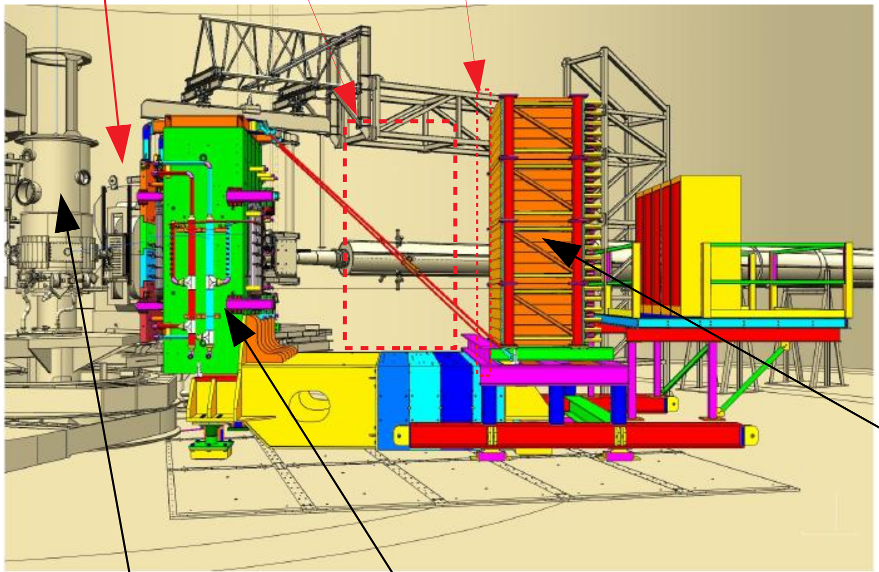
Coordinate Detector CDet

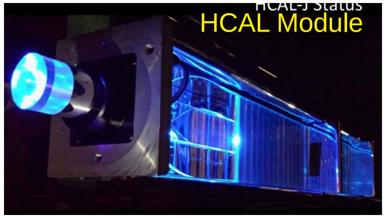
δx, δy ~2 mm



E12-17-004 G_{En}/G_{Mn} (RP) will "piggy-back" on the longer E12-09-019 G_{Mn}/G_{Mp} experiment

Neutron Polarimeter





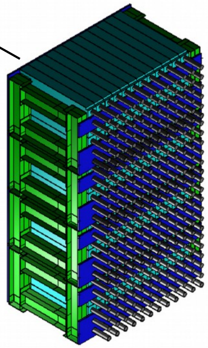
Hadron Calorimeter

80 – 90% efficiency

multi-GeV p and n

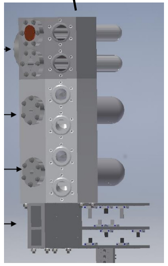
Effective suppression soft background

~0.5 ns timing resolution



48D48 Dipole

~2 Tm integrated field

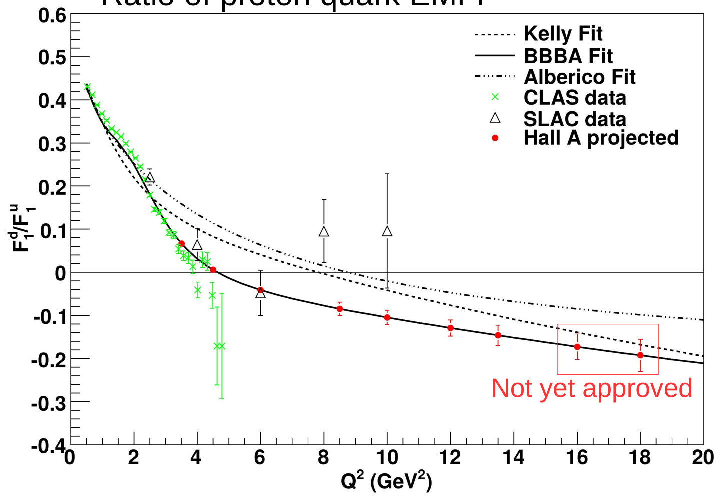


Hall-A Target

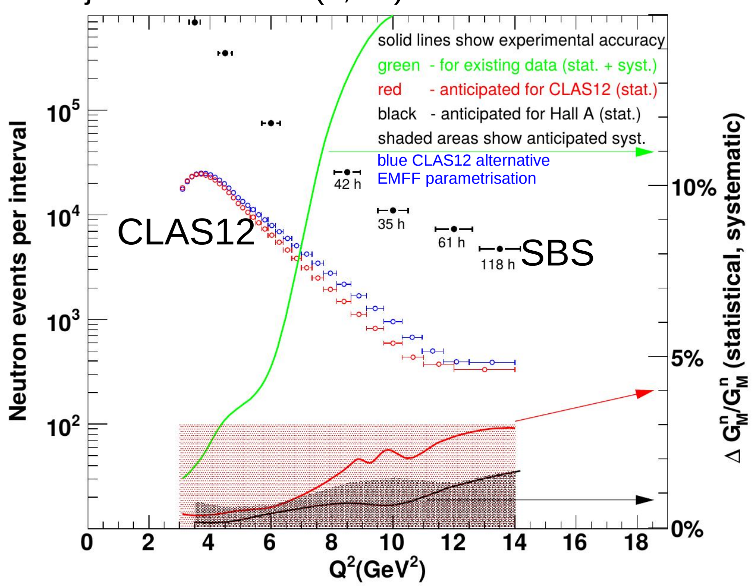
LH_2, LD_2, C-foil

E12-09-019 G_{Mn}/G_{Mp} Motivation

Ratio of proton quark EMFF



Projected numbers (e,e'n) events & uncertainties



- Assuming very small nucleon strange content ... G_{Mn} (+ the other 3 Sachs FF) enables iso-spin analysis of EMFF, ie $F_{1(2)}^{u(d)}$
- Also gives info on neutron transverse charge density down to scale ~0.05 fm
- Approved experiment will measure at Q^2 = 3.5 – 13.5 (GeV/c)^2
- Smaller statistical and systematic uncertainties at each Q^2 bin than CLAS12 experiment E12-07-104 CLAS12 experiment has finer Q^2 granularity
- SBS could measure up to Q^2 = 18 (GeV/c)^2 but not yet approved.

Approved kinematic points
BigBite e' spectrometer...
Min. $\theta_{e'}$ ~ 30 deg   Max. $E_{e'}$ ~ 3.8 GeV

Beam and Spectrometer Configurations for "Golden" Settings

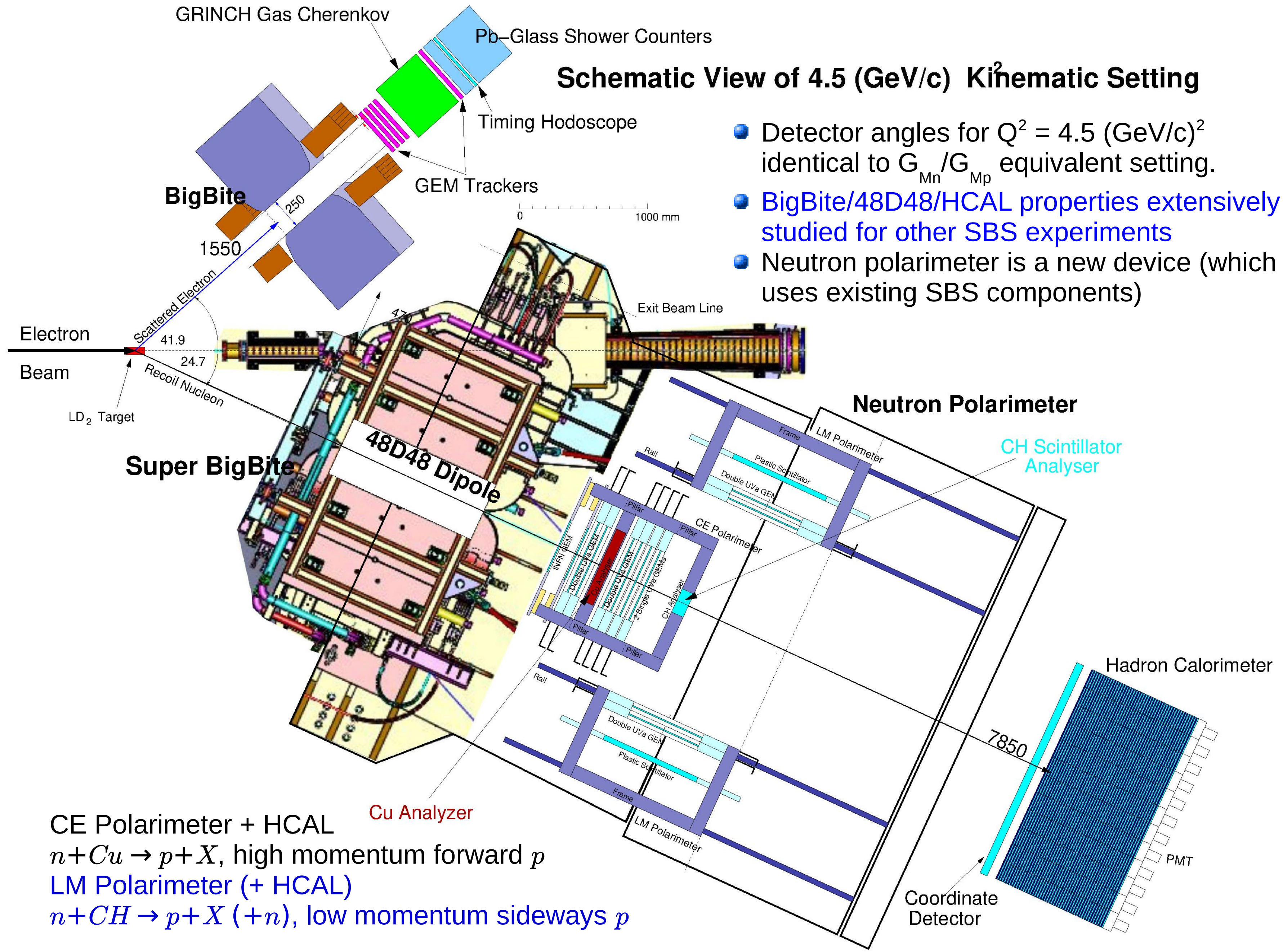
Kin	Q^2 [GeV^2]	E_{beam} [GeV]	θ_{bb} [°]	θ_{sbs} [°]	d_{bb} [m]	d_{mag} [m]	d_{hcal} [m]	∫Bdl [Tm]	$P_{e'}$ [GeV/c]	$P_{h'}$ [GeV/c]
1	3.5	4.40	32.50	31.10	1.80	2.00	7.20	1.71†	2.54	2.64
2	4.5	4.40	41.90	24.70	1.55	2.25	8.50	1.71†	2.00	3.20
3	5.7	4.40	58.40	17.50	1.55	2.25	11.00	1.71†	1.36	3.86
4	8.1	6.60	43.00	17.50	1.55	2.25	11.00	1.65	2.28	5.17
5	10.2	8.80	34.00	17.50	1.75	2.25	11.00	1.60	3.38	6.29
6	12.0	8.80	44.20	13.30	1.55	2.25	14.00	1.50	2.41	7.27
7	13.5	11.00	33.00	14.80	1.55	3.10	17.00	0.97	3.80	8.08

†SBS Field integral is at maximum.

E12-17-004 G_{En}/G_{Mn} Experiment Layout

Schematic View of 4.5 $(GeV/c)^2$ Kinematic Setting

- Detector angles for Q^2 = 4.5 $(GeV/c)^2$ identical to G_{Mn}/G_{Mp} equivalent setting.
- BigBite/48D48/HCAL properties extensively studied for other SBS experiments
- Neutron polarimeter is a new device (which uses existing SBS components)



CE Polarimeter + HCAL

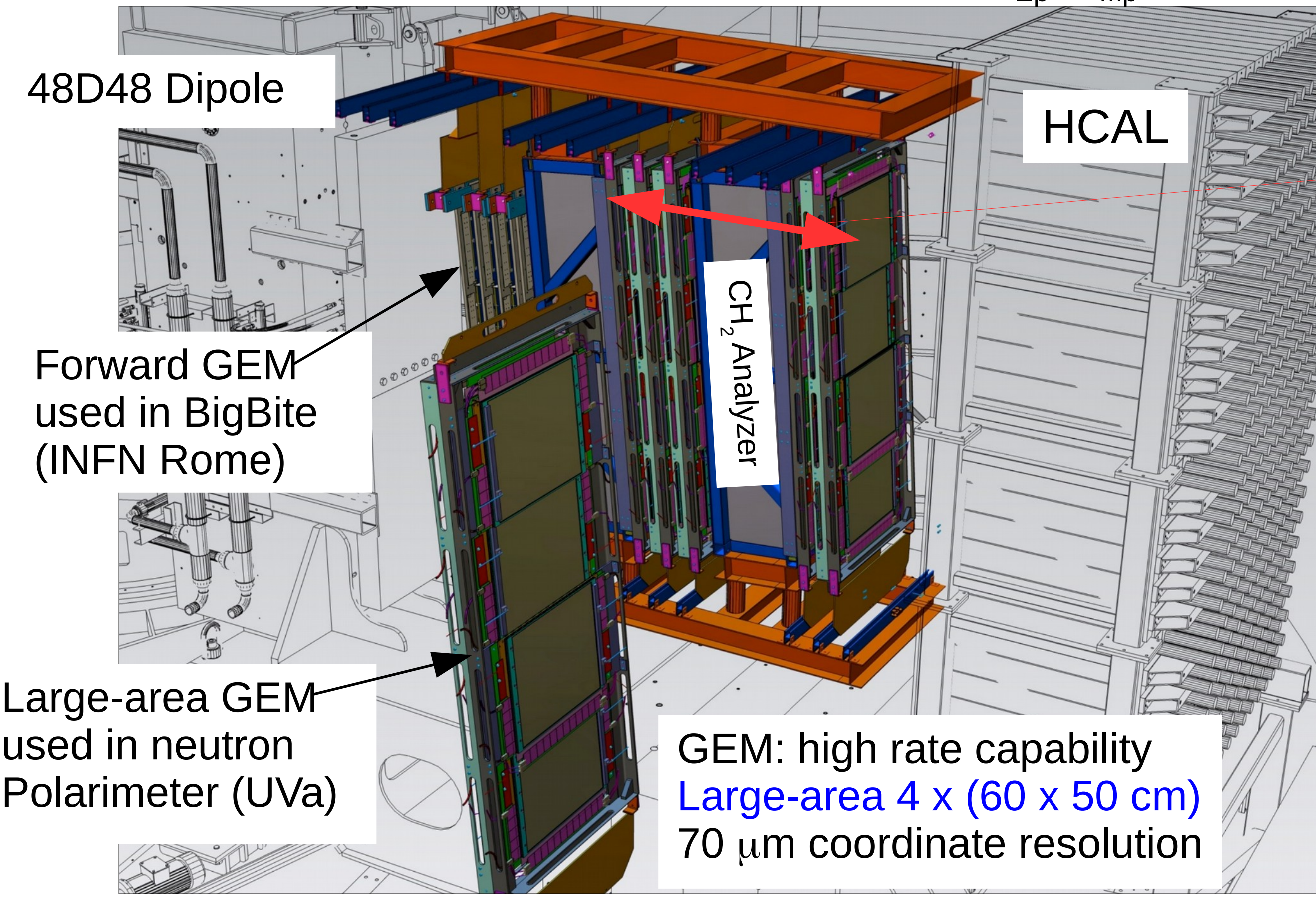
$n+Cu \rightarrow p+X$, high momentum forward p

LM Polarimeter (+ HCAL)

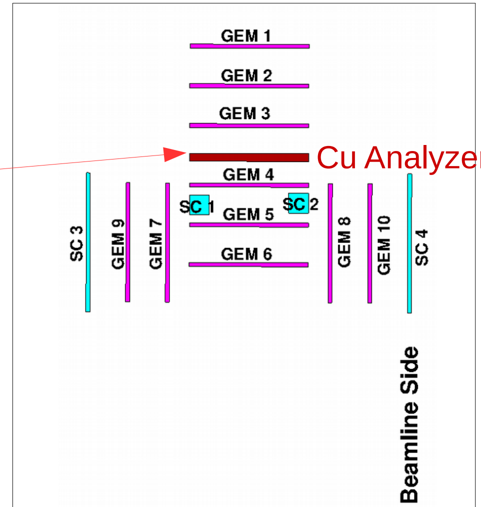
$n+CH \rightarrow p+X\ (+n)$, low momentum sideways p

Neutron Polarimeter (GEM) Chambers

Proton polarimeter for E12-07-109 G_{Ep}/G_{Mp}



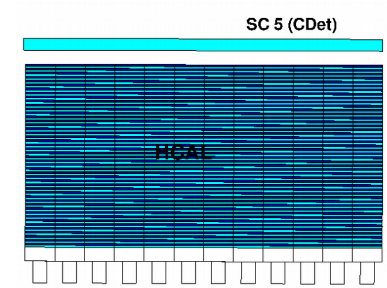
Plan view of neutron polarimeter



Analyzer block(s) removed for G_{Mn}/G_{Mp} cross-section run

Separate run for G_{En}/G_{Mn}

GEMs can be slid in/out of detector acceptance...possibly useful for G_{Mn}/G_{Mp}



Neutron polarimeter employs charge exchange $np \rightarrow pn$ scattering

Cu analyzer, compact longitudinally, high A_y

Use same GEM and HCAL as E12-07-109 (G_{Ep}/G_{Mp})

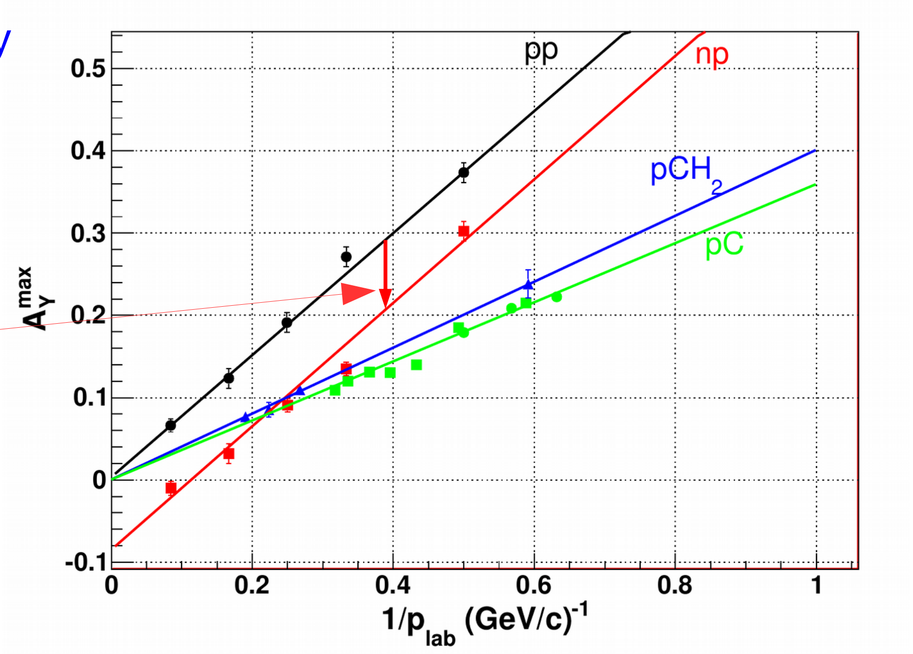
Polarimeter geometry will be somewhat different to E12-07-109

Nucleon Polarimetry
A_y Elastic (-like) N-N Scattering

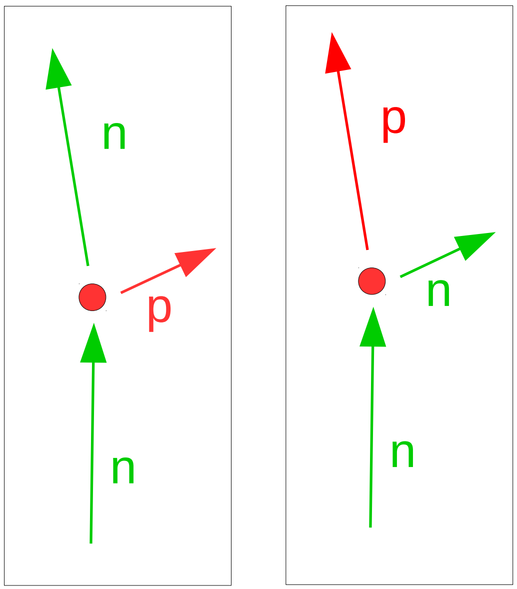
- Elastic $np \rightarrow np$ or $pp \rightarrow pp$ for highest A_y value. LH_2 analyser possibly not feasible technically at JLab
- Proton A_y measurements C, CH_2: detect forward proton + X undetected
  This does not select elastic or quasi-elastic exclusively
- Empirical $p+C$ value of A_y ~ 0.5 of free elastic p-p scattering
  Fermi-motion smearing of the elastic signal
  Inelastic contamination
- A_y for $pp \rightarrow pp$ scales as $1/p_{lab}$
  $np \rightarrow np$ has similar slope but negative offset
- Up to recently **no data on $n+C \rightarrow n+p+X$** at p_{lab}~ several GeV/c (nor for any complex nucleus)

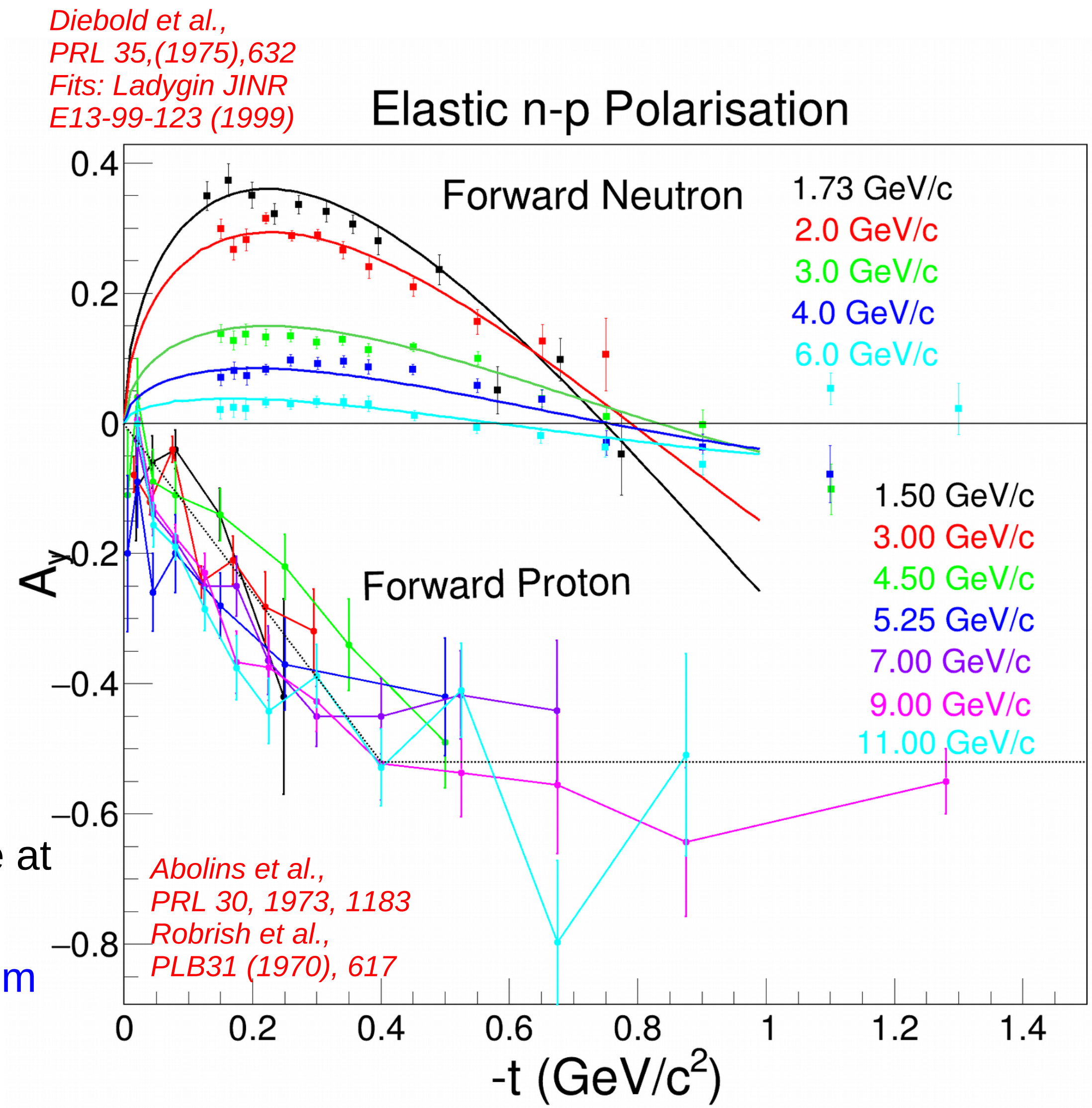
Peak Analysing Power of N-N Scattering
A_y^{max} @ $p_\perp$ ~ 300 - 400 MeV/c

R. Diebold et al., PR. 35(1975), 632.
S.L. Kramer et al., PRD17(1978), 1709.
L.S. Azhgirey et al., NIM A538(2005), 431.
N.E. Cheung et al., NIM A363(1995), 561.
I.G. Alekseev et al., NIM A434(1999), 254.



n-p Elastic: Forward Neutron vs. Forward Proton

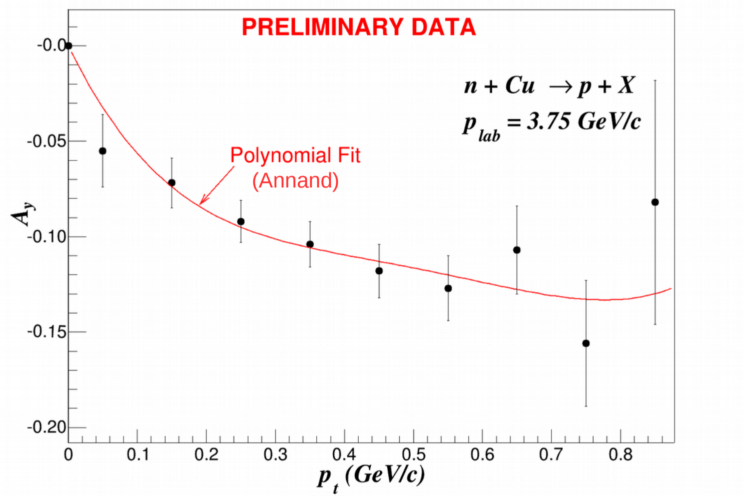




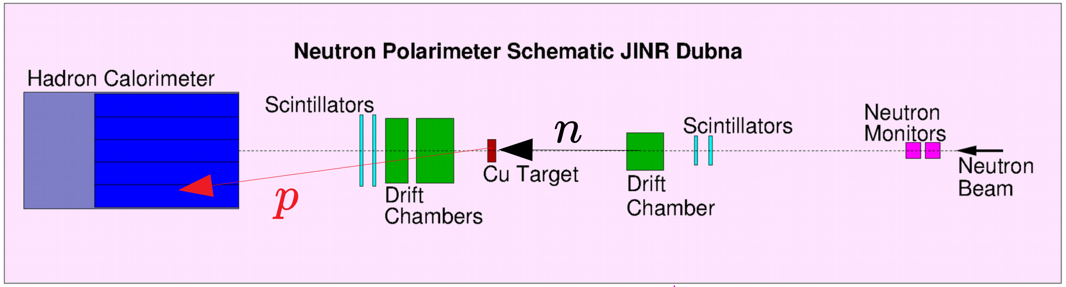
- Measurements from 1970's
- A_y for $np \rightarrow np$ falling rapidly with increasing neutron momentum
- A_y for charge-exchange $np \rightarrow pn$ large at sufficiently large t (θ_p ~ few deg.)
- No apparent strong incident momentum dependence for charge-exchange A_y
- $\sigma_{np\rightarrow np}$ factor ~10 higher than $\sigma_{np\rightarrow pn}$

Polarised (N,N) Scattering at JINR Dubna
viz. Presentation N. Piskunov

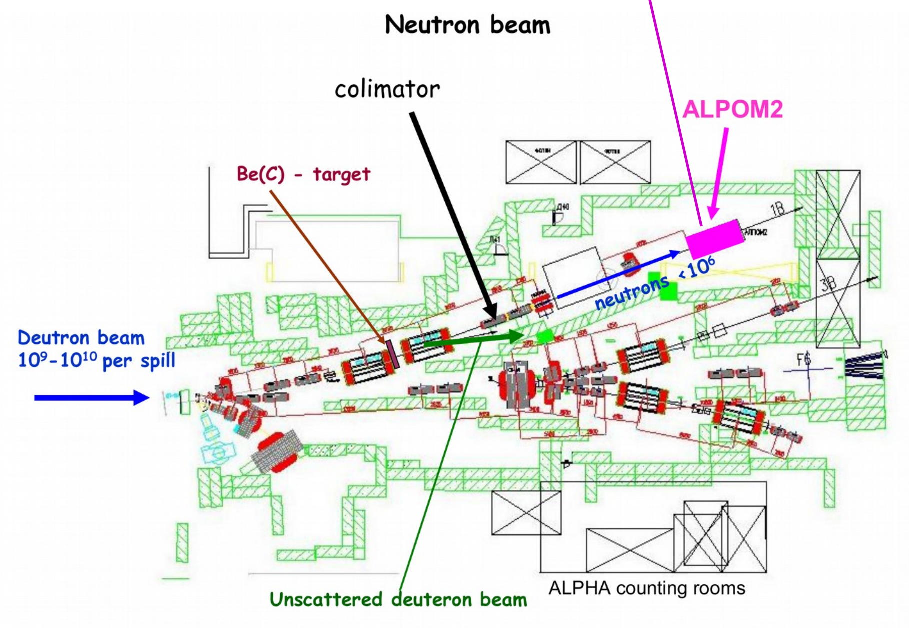
Analysis: I. Sitnik (high energy protons selected by hadron calorimeter)



Conceptually the Dubna polarimeter is very similar to the JLab SBS neutron polarimeter



- JINR Dubna Nov 16 – Feb 17.
- Measure asymmetries polarized $np \rightarrow pn$ C, CH, CH_2, Cu Target
- p_{lab}: 3.0 – 4.2 GeV/c
- Extract A_y as a function of $p_t = p_{lab} sin\theta$
- Cu asymmetry similar to C
- Use polynomial fit to Cu data to calculate FoM of JLab neutron polarimeter

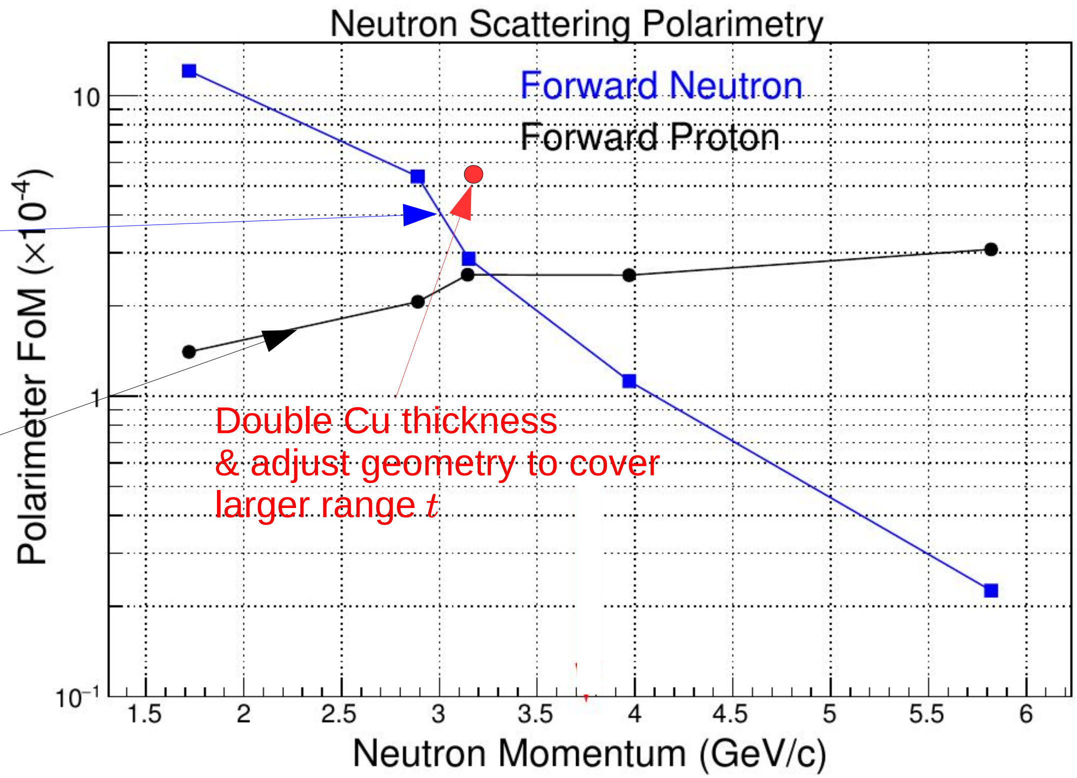


Polarimeter Figure of Merit

$$\mathcal{F}^2(p_n) = \int \varepsilon(p_n, \theta_n') \, A_y^2(p_n, \theta_n') d\theta_n'$$

Plastic scintillator analyzer
$np \rightarrow np$ (forward neutron)

Cu analyzer
$np \rightarrow pn$ (forward proton)



- Calculate efficiency of polarimeter as function of p_n,θ_N by Monte Carlo
- A_y for free $np \rightarrow np$: JINR fit to $\boldsymbol{p_n}$ and $\boldsymbol{t}$ dependence. Scale A_y by 0.5 for ^{12}C scattering
- A_y for $np \rightarrow pn$ on Cu: Preliminary analysis new measurement from JINR
  Assume A_y depends on p_t (or t) only, as observed for free $np \rightarrow pn$ scattering
- To be tested at JINR if the maximum polarised neutron energy is increased to ~ 6 GeV.

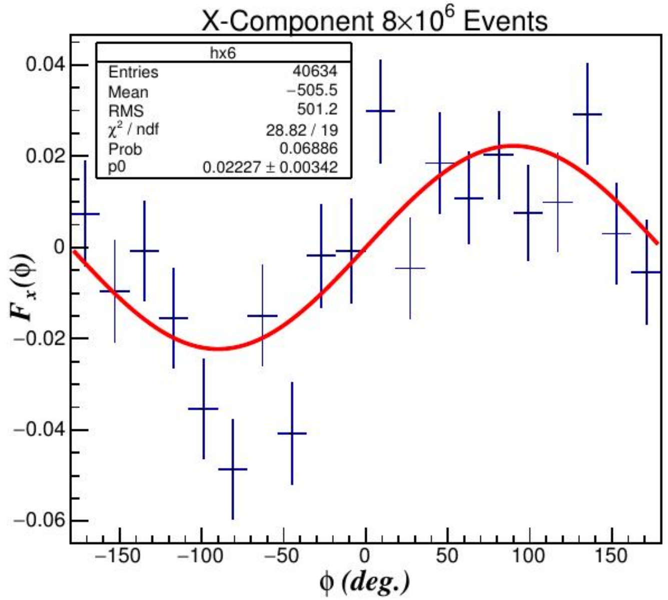
Obtaining Polarisation Components $P_x P_y$

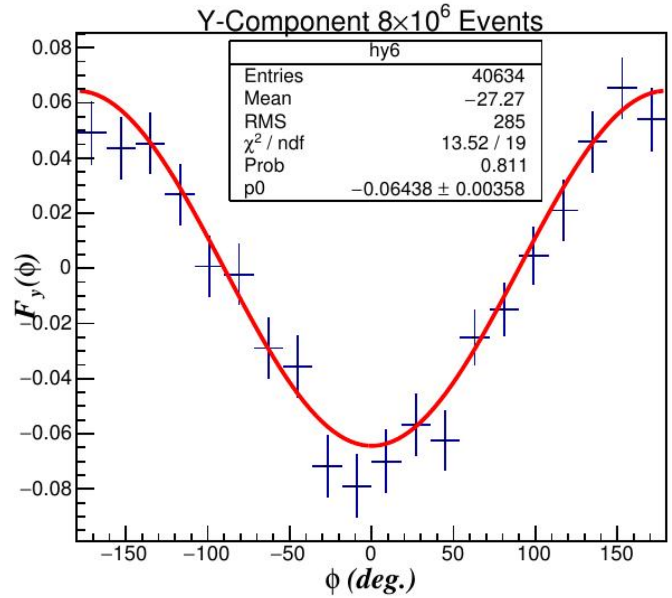
$$\sigma(\theta_n, \phi_n) = \sigma(\theta_n)\left\{1 + P_e A_y^{eff}(P_x \sin\phi_n + P_y \cos\phi_n)\right\}$$

P_x, $P_y = P_z sin 70^o$ from
J.J. Kelly, PRC70(2004), 068202

8 x 10^6 simulated events, p_{lab} = 3.15 GeV/c (Q^2 = 4.5 (GeV/c)^2)

Proposed data point: 3 $\times$ 10^7 incident neutrons





- 4 Comb. beam helicity, SBS dipole polarity $F(\phi_n) = C\{1 \pm |P_x^*| \sin\phi_n \pm |P_y^*| \cos\phi_n\}$
- Unpolarized Distribution $C = F_{++} + F_{--} + F_{+-} + F_{-+}$
- Polarized Distributions $F_x = (F_{++} - F_{-+} + F_{+-} - F_{--})/C$

  $F_y = (F_{++} - F_{+-} + F_{-+} - F_{--})/C$
- Effective analyzing power A_y of polarimeter ~0.9 $\times$ A_y for $np \to pn$ scattering
  Dilution not increased significantly if Cu analyzer thickness increased 4 → 8 cm
  Dilution independent of p_{lab}
- A_y is the same for x and y polarisation components

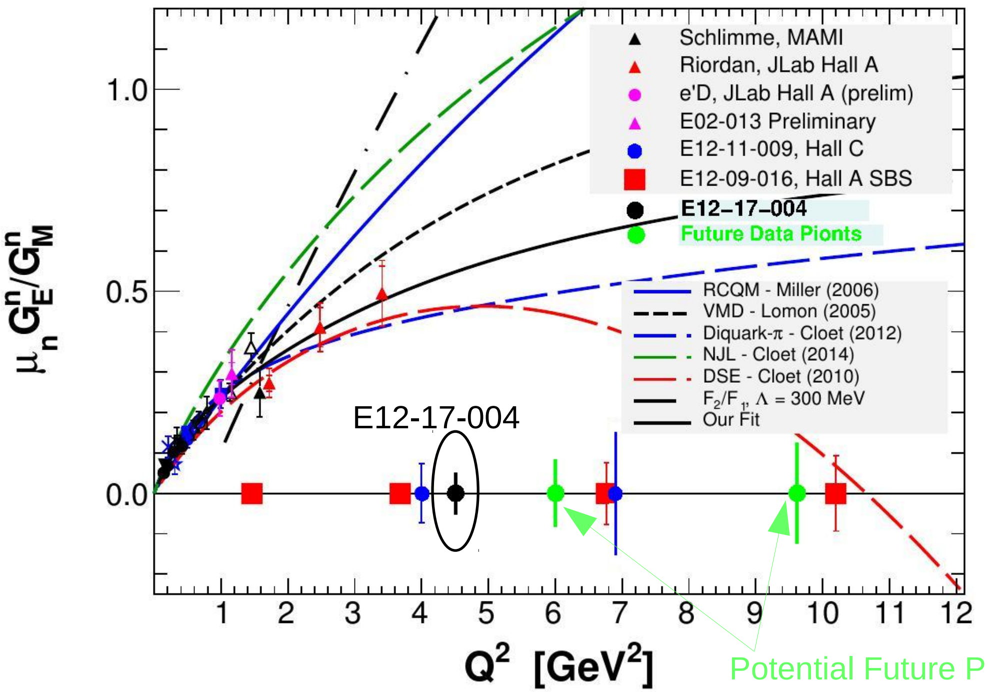
Precision @ L = 1.26 × 10^{38} cm^{-2}s^{-1}

Charge exchange np→pn on Cu Analyzer

$$\delta P = \sqrt{\frac{2}{N_{inc}\mathcal{F}^2}} \qquad R = \mu_n G_E^n / G_M^n$$

E_{beam} (GeV)	Q^2 (GeV/c)^2	p_n (GeV/c)	Rate (Hz)	FoM × 10^{-4}	Time (hr)	δP	δR
4.4	**4.5**	**3.15**	**48.8**	**5.39**	**100**	**0.013**	**0.053**
6.6	6.0	3.97	26.0	5.39	150	0.016	0.082
8.8	9.3	5.82	2.9	5.39	750	0.022	0.13

L_n = 1.5 × 10^{38} cm^{-2} s^{-1}



Potential Future Proposal

- Approved data point @ Q^2 = 4.5 (GeV/c)^2
- Estimates from Geant-4 Monte Carlo model + Dubna measurement
- δR based on Glaster G_{En} and Kelly G_{Mn} EMFF parametrisation
- Expect overall systematic error to be ~3.0%
- Return to request time for higher Q^2 when polarimetry technique proven

Summary

- New high precision measurement of **G_{En}/G_{Mn} at Q^2 = 4.5 (GeV/c)^2**
- Method QE $^2\mathrm{H}(\vec{e},e'\vec{n})$ measure recoil neutron polarization
- BigBite and SBS (configured as a polarimeter) are highly suited to a double polarised, recoil-nucleon polarimetry measurement of G_{En}/G_{Mn}
- Experiment rated A-, allocated 100 hr of beam....running together with E12-09-019 G_{mn}/G_{mp}. **Expect to run in 2020**
- Data will provide comparison of $np \rightarrow pn$ and $np \rightarrow np$ scattering as a neutron polarization analyzer
- Return to future PAC with proposal for higher Q^2 points once polarimetry method established

Gateway to New Experiments?
JLab PAC45 Report, July 2017

Summary: The PAC is excited at the prospect of neutron polarimetry via the charge exchange reaction as it opens the door to measurements of the neutron form factor ratio at high momentum transfer via recoil polarimetry. We are also glad to see that there has been close interaction with E12-11-009 as shown by the fact that some members of that experiment have joined the present proposal. The PAC is optimistic that the proposed experiment will make a significant contribution to the program with recoil polarimetry at JLab.

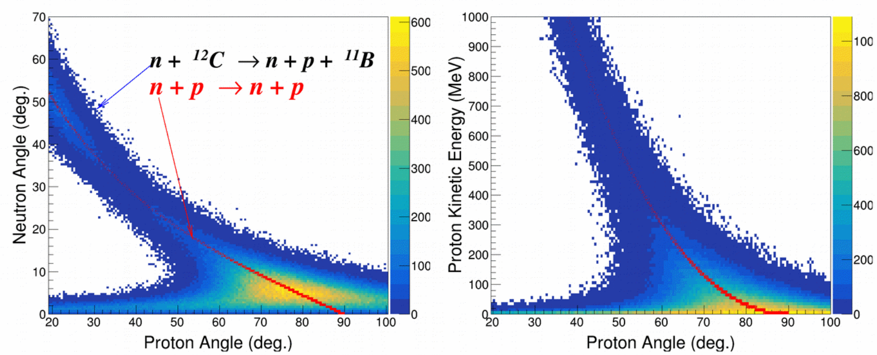
Thanks for your attention

Backup

Large-Angle-Proton Polarimetry

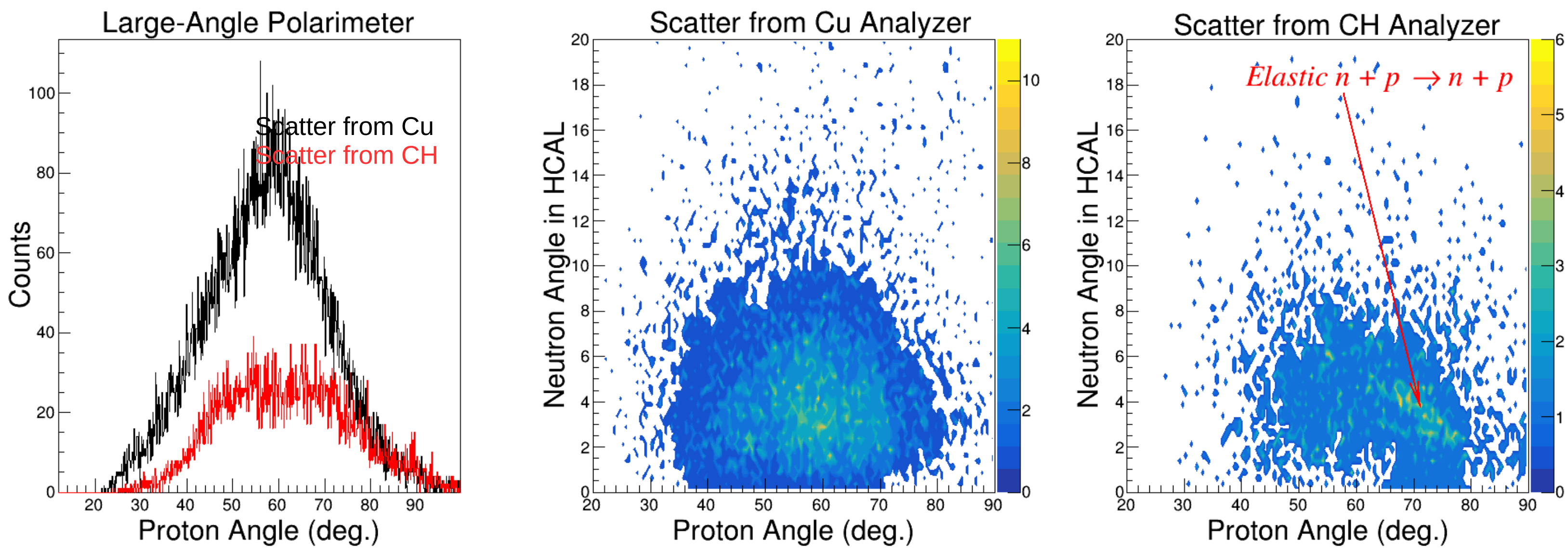
Very Preliminary

Incident Neutron Momentum 3.15 GeV/c
Fermi smearing of proton angle



- QE n-p scattering from ^{12}C or ^{57}Cu
  Fermi smearing of large-angle recoiling proton
- ~1% incident neutrons scatter in Cu making detected large angle proton track
- ~0.4% neutrons scatter in CH making detected large angle proton track
- ~25% of detected large-angle protons have coincident energetic neutron in HCAL

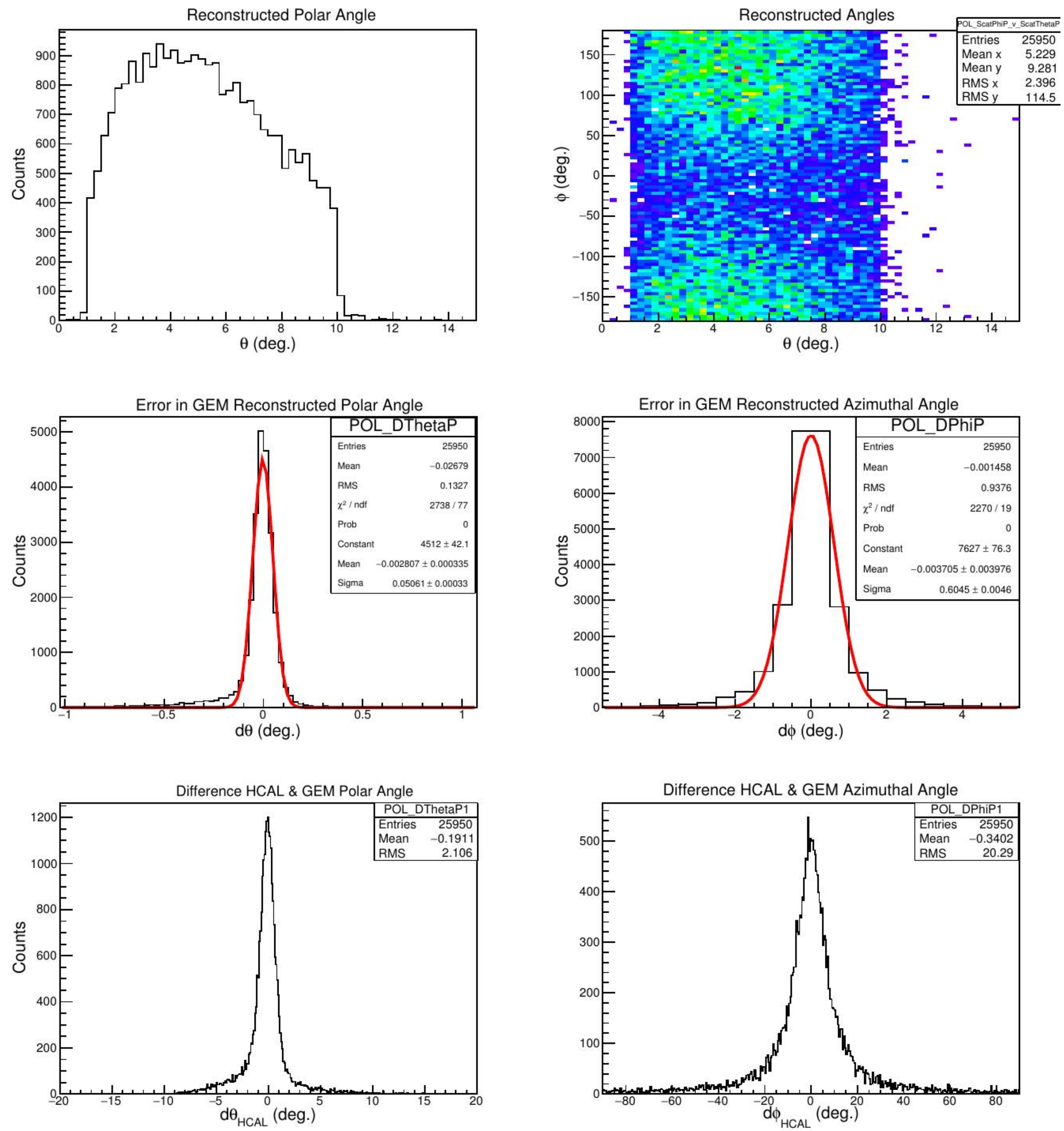
Geant-4 Calculation 3.15 GeV/c Incident Neutrons



Contamination of large-angle proton events by non-elastic processes
How does that affect A_y??

Forward Proton Angle Reconstruction by GEM

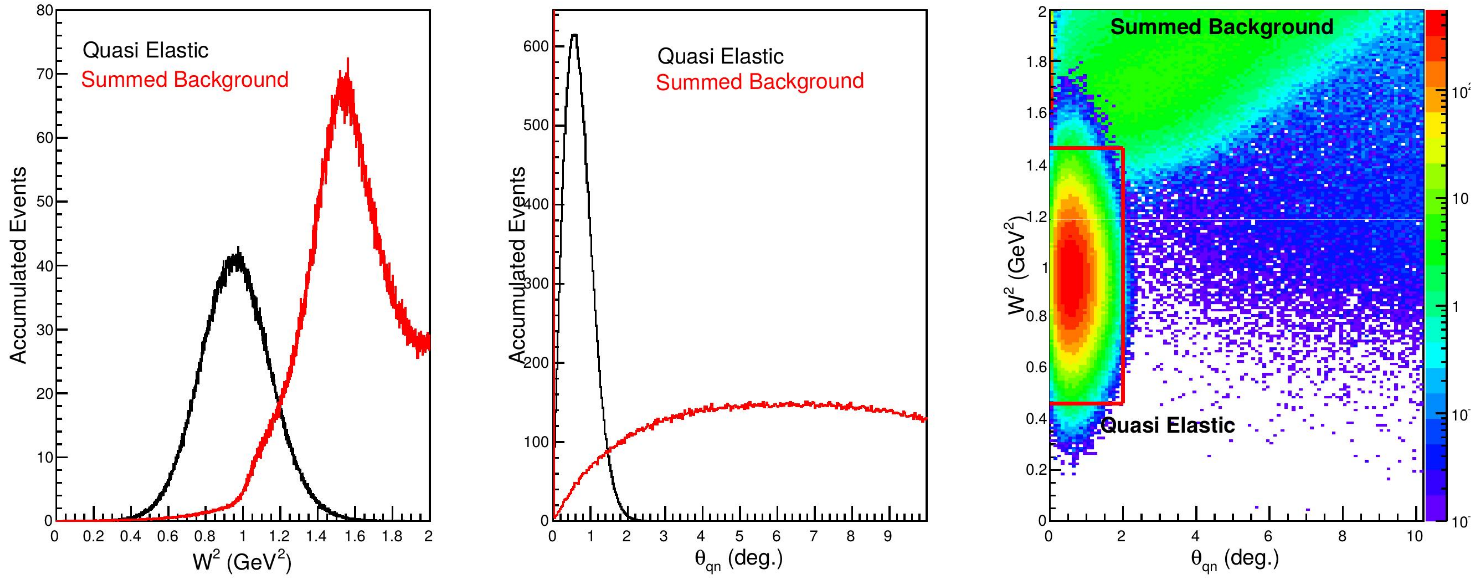
- Reconstruct analyzer hit position and proton angle using GEM position info.
  σ_θ ~ 0.05 deg.
  σ_ϕ ~ 0.6 deg.
- Select polar scattering angle... optimum range depends on p_{lab}
- Select calorimeter energy deposit > ½ peak channel
- Polarimeter detection efficiency ~3%
- Polarimeter similar to Dubna setup...expect similar effective analyzing power



University of Glasgow

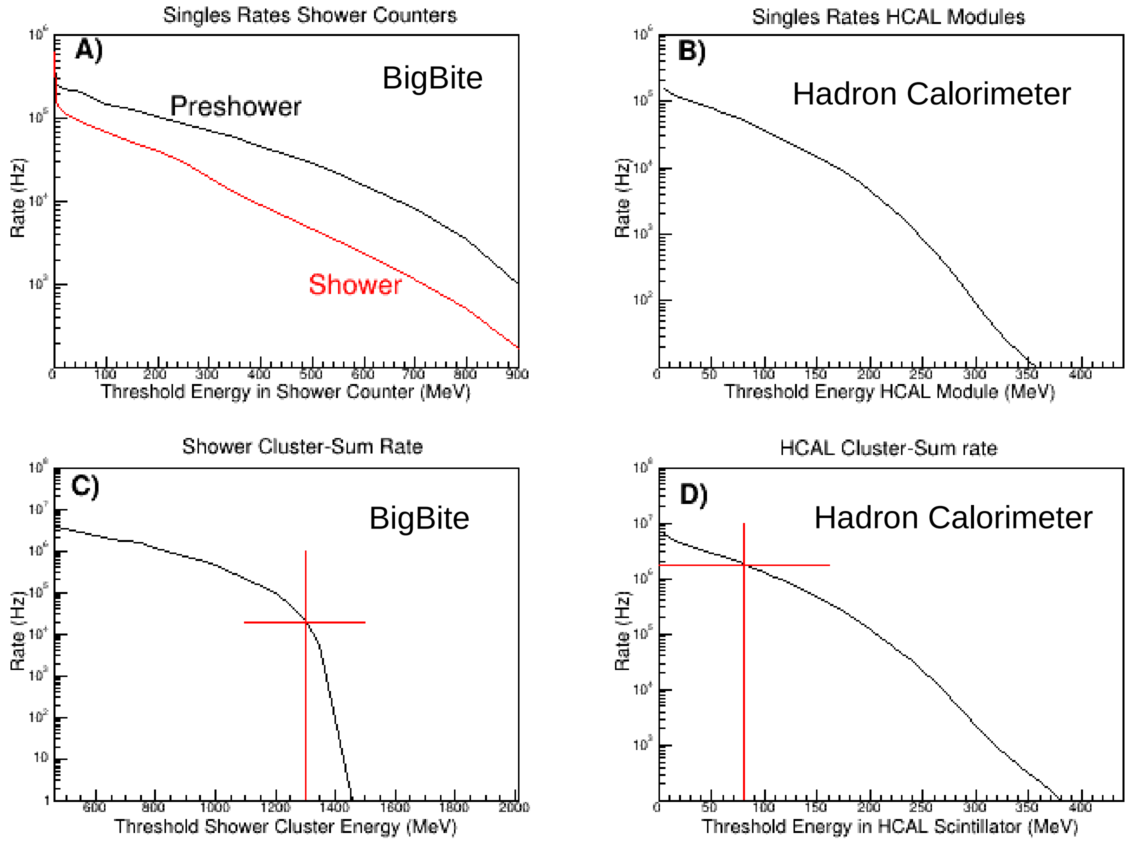
d(e,e'n) QE Signal Separation

QFS: J. W. Lightbody and J. S. O'Connell, Computers in Physics 2(1988),57



- BigBite: clean separation of electrons from π^- (GRINCH and Preshower/Shower)
- Polarimeter: clean separation of d(e,e'n) from d(e,e'p) (front GEM & deflection in dipole)
- *d(e,e'n)* QE signal has some contamination, mainly from pion electroproduction
- Use QFS code to calculate QE and non-elastic cross sections
  MC procedure folds in detector resolution effects
- Combination of W^2 and θ_{qn} to separate QE from non-elastic
- "Red-box" cut: 98.5% QE events accepted, non-elastic background 1.5% of QE strength
- Cleaner separation of QE for *d(e,e'n)* compared to $^3He(e,e'n)$ (polarized target G_{En}/G_{Mn})

Trigger Rates @ 40 μA on 10 cm LD_2



- Cluster-sum rate in BigBite Pb-Glass
  ~ 20 kHz at threshold of 1.3 GeV (65% $E_{e'}$)
- Cluster-sum rate in HCAL
  ~ 1.7 MHz at threshold of 0.5 E_{peak} for 3 GeV/c nucleons
- BigBite-HCAL coincidence rate for Δt ~ 50 ns: **1.7 kHz**
- DAQ should handle 5 kHz comfortably

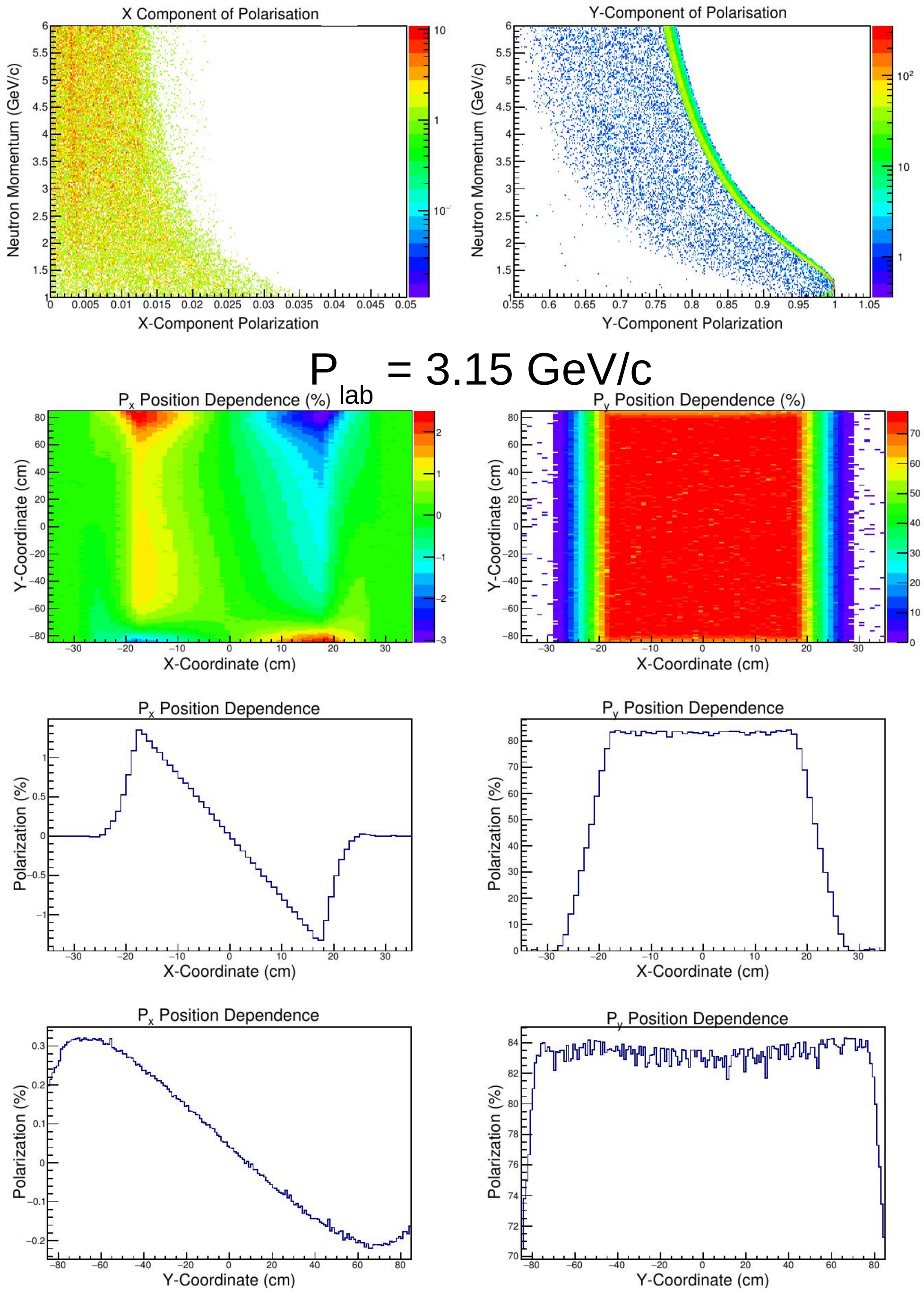
Hadron Arm Tracking Detector Rates

4.4 GeV electrons 10 cm D_2 target

Detector	Rate kHz/cm^2
GEM 1	62
GEM 2	63
GEM 3	62
GEM 4	11
GEM 5	11
GEM 6	14
GEM 7	9
GEM 8	27
GEM 9	5
GEM 10	19
CDet 5	30

- GEM rates mainly from soft photons
  Rates factor ~10 lower than G_{Ep}/G_{Mp}
- Beamline shield reduces rates in side detectors
- Well defined ***q*** vector from BigBite
  Fermi-smeared QE nucleon "spot" @ analyzer area ~ 100 cm^2 →
  GEM rate within spot ~1.5 MHz
- ~5% chance GEM accidental hit
  if Δt ~ 35 ns (GEM σ_t ~ 6 ns)
- Clean track reconstruction expected

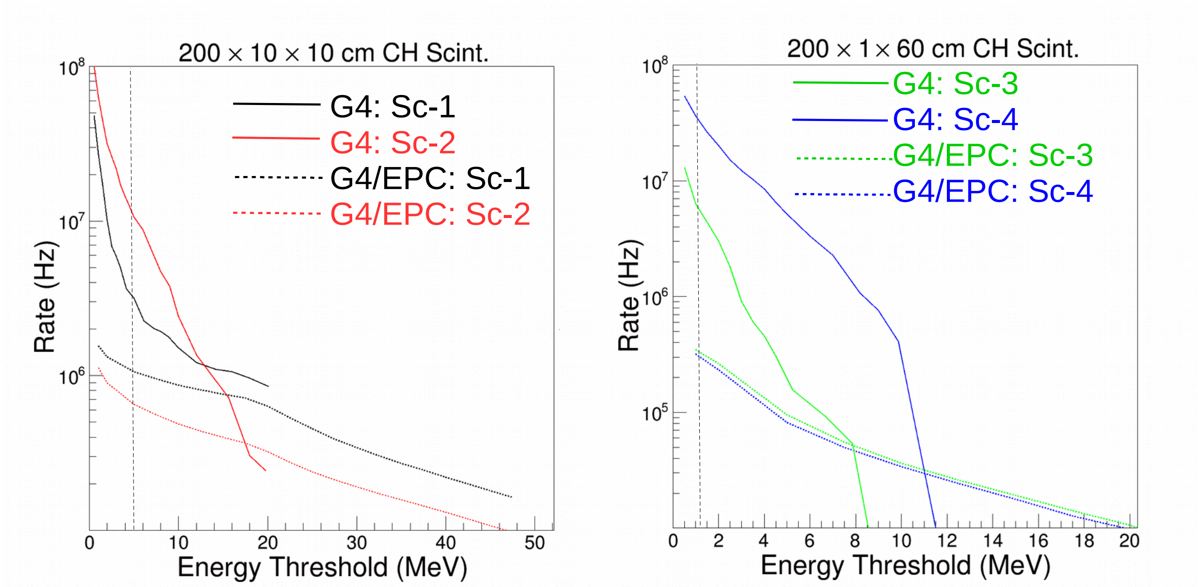
Spin Precession in 48D48 Dipole



- Nucleon spin precession calculated in Geant-4.10 Earlier G4 have problems with neutron spin precession
- TOSCA field map, no field clamps fitted
- Start neutrons with spin (0,0,1) at target, track through dipole field, record spin components at analyser
- Max spin transfer z→ x ~3%
- Smoothly varying, can be corrected, polarimeter has good position resolution
- Max sys. error to P_x/P_z ~ 1%

Preliminary: Large Angle Polarimeter Rates

Polarimeter: Large-Angle Scintillators



Scintillators will require to be segmented finely

- Calculations made with Geant-4
- 4.4 GeV electrons on 10 cm D_2, use G4 electromagnetic and hadronic physics models to sample produced particle types and 4-momenta
  Need huge number of events to obtain reasonable hadron sample
- Use code EPC to calculate differential cross section $\sigma(p,\theta)$ for p,n,π^0,π^-,π^+ electro production
  In G4 use these to generate particles at the target position and then track through BB/SBS

EPC: J. W. Lightbody and J. S. O'Connell,
Computers in Physics 2(1988),57

Summary of Experimental Method

Obtain G_{En}/G_{Mn} for Q^2 of 4.5…..eventually up to ~ 9 $(GeV/c)^2$

Measure double-polarised $^2H(\vec{e},e'\vec{n})p$

As opposed to E12-09-016 $\overrightarrow{^3He}(\vec{e},e'n)pp$

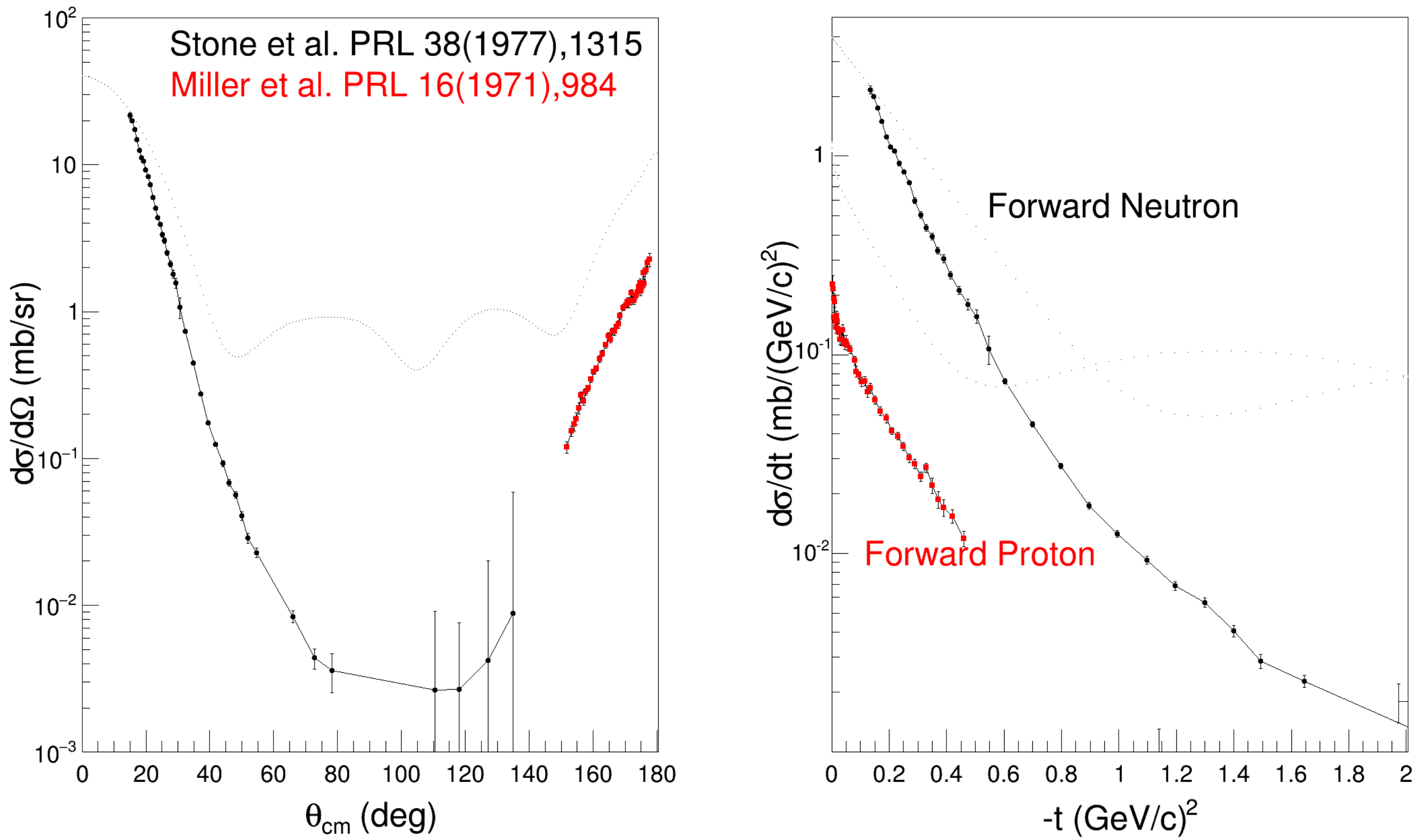
- Polarization ratio of final-state neutron $P_x/P_z \rightarrow G_{En}/G_{Mn}$
  (precess $P_z \rightarrow P_y$ in dipole magnetic field)
- Cryogenic D_2 Target 10 cm long
- 40 μA 80% polarized electron beam, L = 1.26×10^{38} $cm^{-2}s^{-1}$
- BigBite e' detector (same configuration as E12-09-019 G_{Mn}/G_{Mp})
- SBS Neutron polarimeter: acceptance well matched to electron arm
  Polarimeter detects high-momentum, small angle protons
  produced by np→pn **AND** low-momentum large-angle protons produced by np→np scattering
- **Apart from polarimeter very similar to G_{Mn}/G_{Mp} E12-09-019 setup**

Systematic Uncertainties

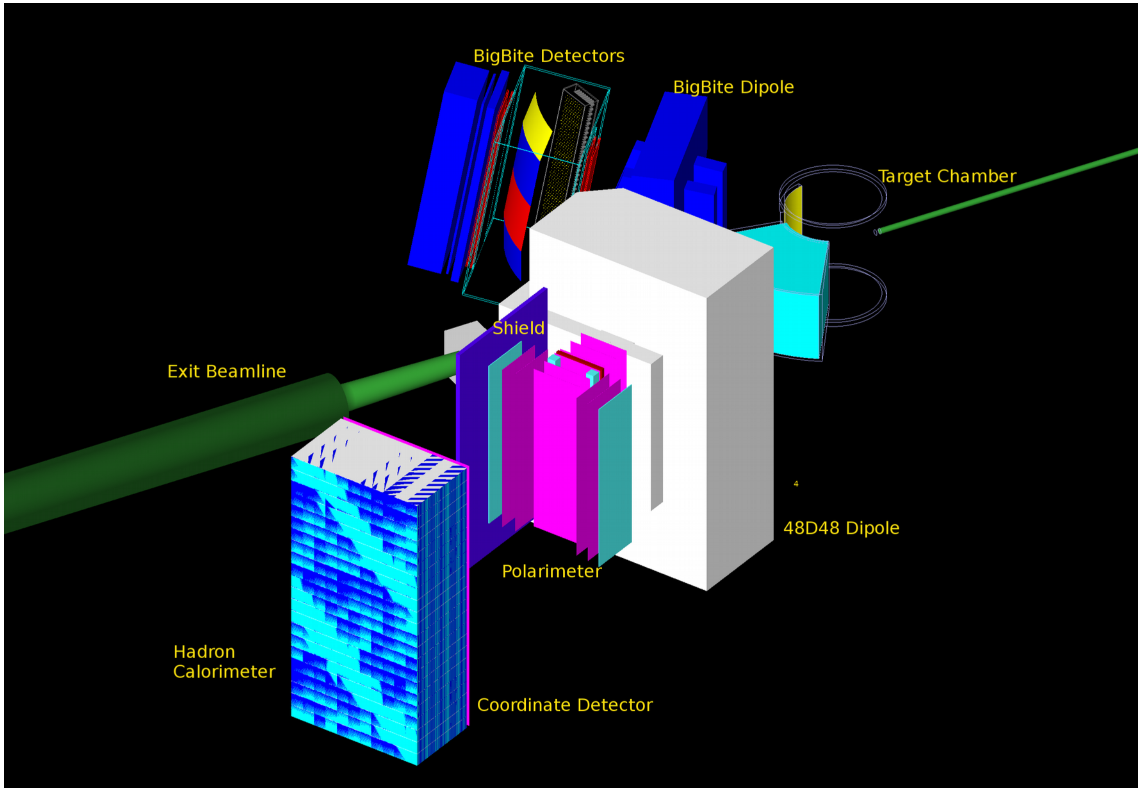
- Non-equal values A_y for P_x and P_y. Simulations show no significant variations. Max. size of error of the P_x/P_y ratio is $\sim$ 1%.
- Azimuthal angle acceptance non-uniformity...Simulations consistent with cancellation after beam helicity flip and precession angle reversal (reversal of 48D48 field). Max. size of error $\sim$ 1%.
- Non-uniformity of the magnetic field results in a small $P_z \rightarrow P_x$ mixing. Neutron path through the dipole reconstructed accurately. After correction an overall uncertainty of 1% estimated
- Reproducibility of the spin precession angle after polarity reversal. At a precession angle of 60°, a 2% difference in integrated field would give 1% difference in rotated component $P_z \rightarrow P_y$.
- Variation in the angle of spin precession through the dipole magnet. Correction factor can be evaluated event by event. The estimated uncertainty is 0.25%.
- Dilution of the asymmetry by accidental background. The background is estimated to be at the 1% level which can be subtracted without significant error.
- Contamination of the quasi-elastic signal by inelastic processes. A deuteron measurement will have clean rejection of the inelastic background. Estimated 1.5% contribution
- **Total systematic uncertainty ~ 3%**

n-p Elastic Cross Section

p_{lab} = 5 GeV/c



The Geant-4 Model



- Geant4.10.03: add ϕ dependence polarised nucleon elastic and QE scattering
- Record signal amplitude and time from each detector element.
- Analyse simulated data as in real experiment.
- Calculate element rates 4.4, 6.6, 8.8 GeV, 40 μA on 10 cm LD_2 ($\mathfrak{L}$ = 1.26 x 10^{38} $cm^{-2}s^{-1}$)
- Simulate n-p scattering processes in polarimeter….angle resolution, acceptance efficiency
- Reconstruct polar, asimuthal angles….ϕ distributions give effective analyzing power of polarimeter

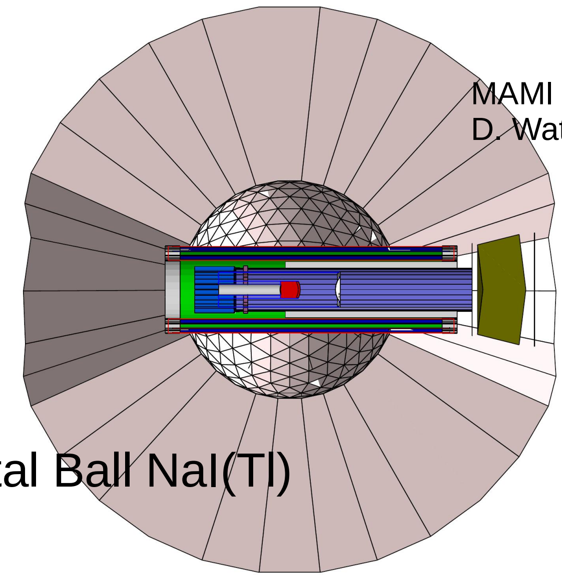
RP in Meson Electro/Photo-production

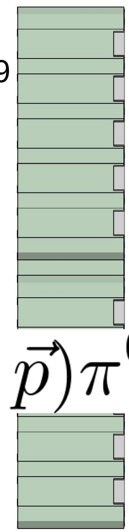
JLab γ+p→ p+π^0, Focal-plane polarimeter installed on recoil-proton spectrometer
K.Wijsooriya et al., PRC 66(2002),034614
Polarimetry with a ~4π detector system
Glasgow/Mainz Tagger at MAMI
Crystal-Ball + TAPS 4π EM calorimer

TAPS BaF2

M. Sikora et al.
PRL 112 (2014),022501

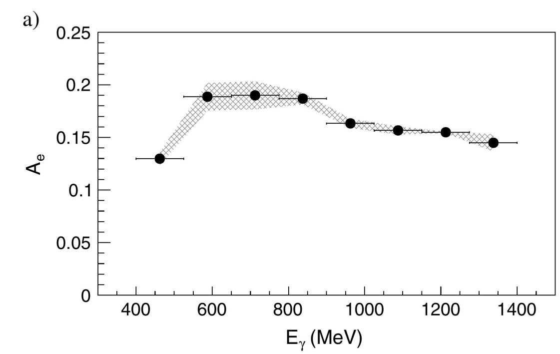
MAMI Experiment A2-03/09
D. Watts et al.

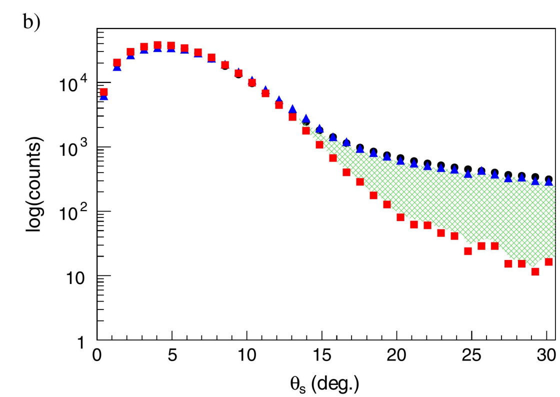


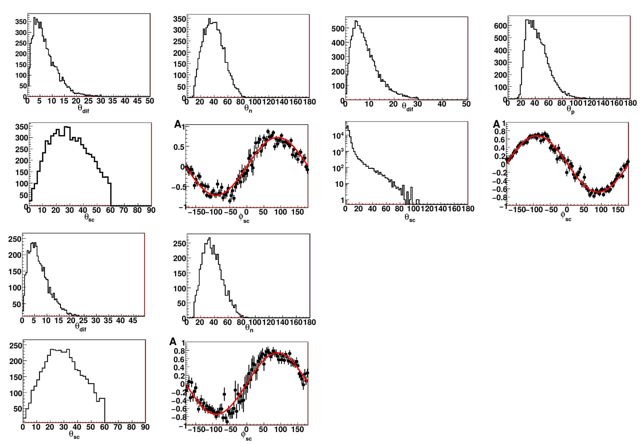


$$^{1}H(\vec{\gamma},\vec{p})\pi^{0}$$

Crystal Ball NaI(Tl)

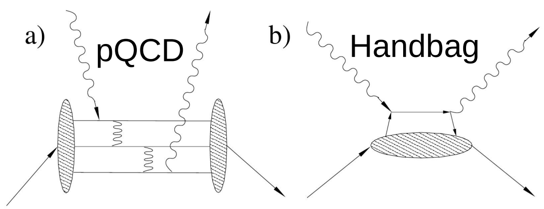




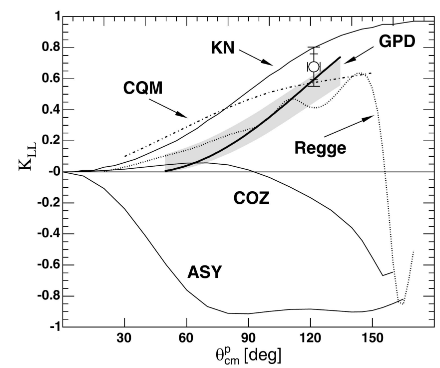


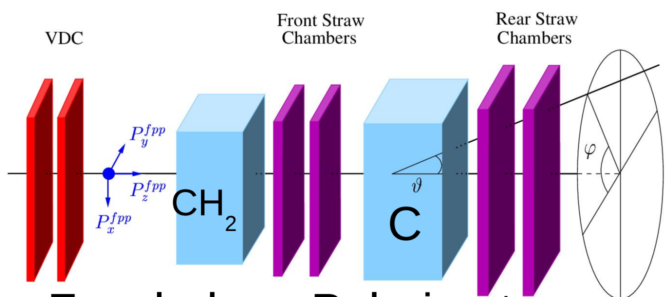
RP in High-s, High-t Compton Scattering

- JLab experiment E99-114
  $p(\vec{\gamma}, \gamma' \vec{p})$
- Measure K_{LL}, K_{LT}
  s = 6.9 GeV^2, t = -4.0 (GeV/c)^2
  Scaling of $d\sigma/s$ and $d\sigma/dt$
- Reaction mechanism

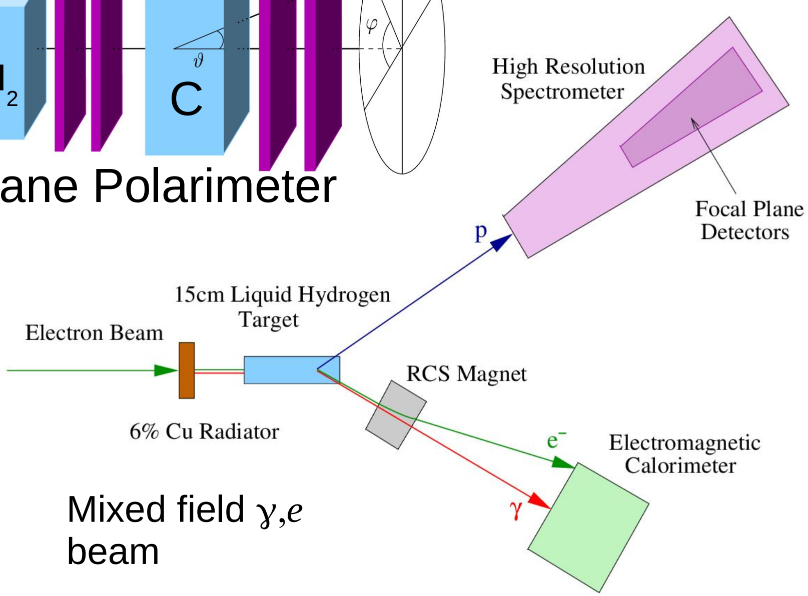


D.J. Hamilton et al.,
PRL 94 (2005), 242001



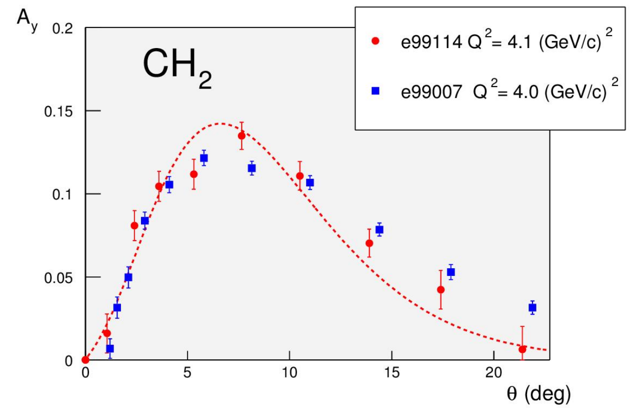


Focal-plane Polarimeter

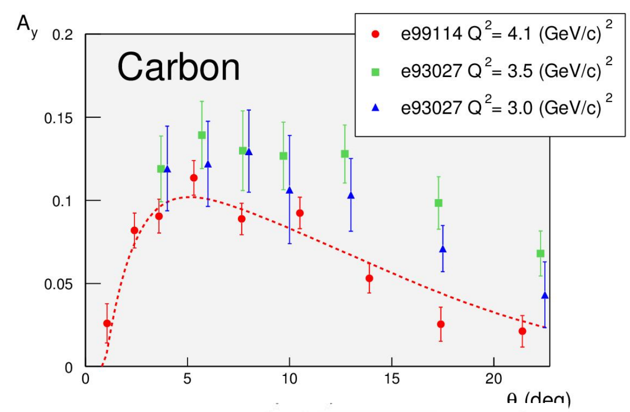


Mixed field γ,e beam

Analysing Power from
$p(\vec{e}, e'\vec{p})$



Proton momentum ~ 2.9 GeV/c



$$P'_z = \frac{\frac{E+E'}{M}\sqrt{\tau(1+\tau)}\tan^2\frac{\theta}{2}}{\left(\frac{G_E}{G_M}\right)^2 + (\tau/\epsilon)},$$

Compare measured $hA_yP'_z$