Recoil-Nucleon Polarimetry in Hadron Physics (with γ, γ^* Probes)

J.R.M. Annand
Department of Physics and Astronomy

Polarised Nucleon Scattering

Spin-orbit component of nucleon-nucleus potential $V_{so}(\boldsymbol{l}.\boldsymbol{s})$ produces an azimuthal modulation of the scattering process from which the (transverse components of the) spin polarisation of the incident nucleon may be deduced.

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

Nucleon polarimeters, which infer incident spin polarisation from a azimuthal scattering distribution, are typically constructed from

An analyser (scattering block). Various materials have been used:

- H (e.g. HARP, NIKHEF for protons. MWPC tracking), Measurements of A_y pp and np available up to ~6 GeV/c
- ^{4}He active analyser...high-pressure gas or liquid scintillates
- ^{12}C, CH_2, Plastic scintillator: A_y for p + ^{12}C (CH_2) determined up to p_p ~ 6 GeV/c. n + ^{12}C (CH_2) A_y measurements confined to relatively low momenta.

A position sensitive rear detector of the nucleon azimuthal scattering distribution

- Position-sensitive organic scintillator arrays. Good time-of-flight (TOF) resolution.
- Fe-scintillator Hadron Calorimeter. High efficiency, insensitive to soft background.
- Calorimeters designed primarily for EM...e.g. TAPS BaF_2. Reasonable neutron. efficiency ($\boldsymbol{p}_n$ > 300 MeV/c) good TOF resolution and good granularity..
- Proton: stacks of tracking detectors, e.g. GEM

Applications of Recoil Polarimetry in EM Hadron Physics

Polarised observables vital to untangle the processes contributing to a reaction

- Interference terms between contributing amplitudes
  facilitate separation and identification of small amplitudes
- *Polarised (e,e') observables can be relatively insensitive to >1-photon exchange effects (e.g. compared to Rosenbluth separation)*

Recoil-Polarisation in Experiments with γ or γ^* probes

- *Investigation of the Nucleon excitation spectrum*
- Photo and electro production of pseudo-scaler mesons $N(\vec{\gamma},\pi^0\vec{N})$ etc.
- Constrain PWA, help determine helicity amplitudes unambiguously

- *Nucleon elastic form factor measurements $N(\vec{e},e'\vec{N})$*
- Double-polarised experiments yield G_E/G_M
- Beam - target-nucleon or Beam - recoil-nucleon polarised
- Extend range of Q^2 explored... does G_{Ep}/G_{Mp} continue to fall with Q^2.
- How does G_{En}/G_{Mn} behave?

- *π^+ Charge form factor from $p(\vec{e},e'\pi^+\vec{n})$*
- Extract longitudinal response from recoil n polarisation.
- Can extract charge form factor with model dependence under control.
  If -t is small (< 0.2 GeV^2)...limits the Q^2 available. Neutron momenum is low
- Independent method to Rosenbluth Separation. Either is highly challenging

Pseudo Scalar Meson Photo Production
4 Complex Amplitudes

Polarised: Beam Target Recoil-N

		Beam	Target	Recoil-N	
1.	$\{d\sigma/d\Omega\}/\mathcal{N}$				$=\lvert b_1\rvert^2+\lvert b_2\rvert^2+\lvert b_3\rvert^2+\lvert b_4\rvert^2$
	Single polarization				
2.	P			y'	$=\lvert b_1\rvert^2-\lvert b_2\rvert^2+\lvert b_3\rvert^2-\lvert b_4\rvert^2$
3.	Σ	p			$=\lvert b_1\rvert^2+\lvert b_2\rvert^2-\lvert b_3\rvert^2-\lvert b_4\rvert^2$
4.	T		y		$=\lvert b_1\rvert^2-\lvert b_2\rvert^2-\lvert b_3\rvert^2+\lvert b_4\rvert^2$
	Double polarizaton Beam-target				
5.	E	c	z		$=2\,\mathrm{Re}(b_1b_3^*+b_2b_4^*)$
6.	F	c	x		$=2\,\mathrm{Im}(b_1b_3^*-b_2b_4^*)$
7.	G	t	z		$=2\,\mathrm{Im}(b_1b_3^*+b_2b_4^*)$
8.	H	t	x		$=-2\,\mathrm{Re}(b_1b_3^*+b_2b_4^*)$
	Beam-recoil				
9.	C_x	c		x'	$=-2\,\mathrm{Im}(b_1b_4^*-b_2b_3^*)$
10.	C_y	c		z'	$=2\,\mathrm{Re}(b_1b_4^*+b_2b_3^*)$
11.	O_x	t		x'	$=2\,\mathrm{Re}(b_1b_4^*-b_2b_3^*)$
12.	O_z	t		z'	$=2\,\mathrm{Im}(b_1b_4^*+b_2b_3^*)$
	Target-recoil				
13.	T_x		x	x'	$=2\,\mathrm{Re}(b_1b_2^*-b_3b_4^*)$
14.	T_z		x	z'	$=2\,\mathrm{Im}(b_1b_2^*-b_3b_4^*)$
15.	L_x		z	x'	$=-2\,\mathrm{Im}(b_1b_2^*+b_3b_4^*)$
16.	L_z		z	z'	$=2\,\mathrm{Re}(b_1b_2^*+b_3b_4^*)$

8 **properly chosen** observables
for unambiguous determination of $b_{1,2,3,4}$

(W-T.Chiang & F.Tabakin, PRC 55(1997),2054).

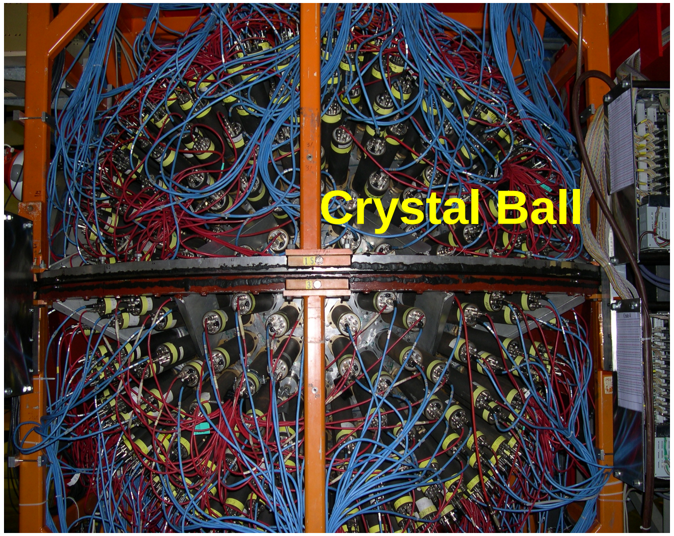
(L.S.Barker, A.Donnachie & J.K.Storrow, NP B95(1975),347)

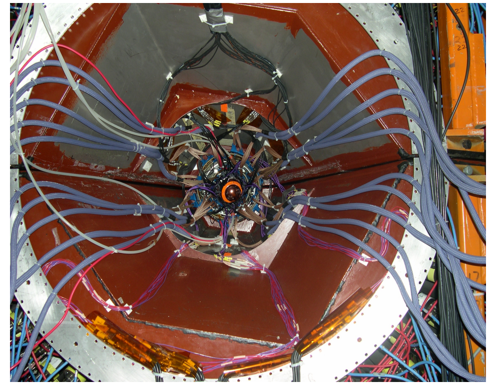
MAMI-C @ Mainz

- High intensity, CW, 1604 MeV electron beam
- Linearly or circularly polarised γ beam
- Tagged Photons E_γ = 80 – 1500 MeV
- Logitudinal and transverse polarised frozen-spin target...^{1}H & ^{2}H
- Polarised ^{3}He target
- 4π Calorimeter Crystal Ball + TAPS
- Recoil nucleon polarimeter.
- So far have dσ, P, Σ, T, E, F, G, C_x, O_x
- π^0,π^+,η and κ photoproduction proton and neutron (*d*, ^{3}He)

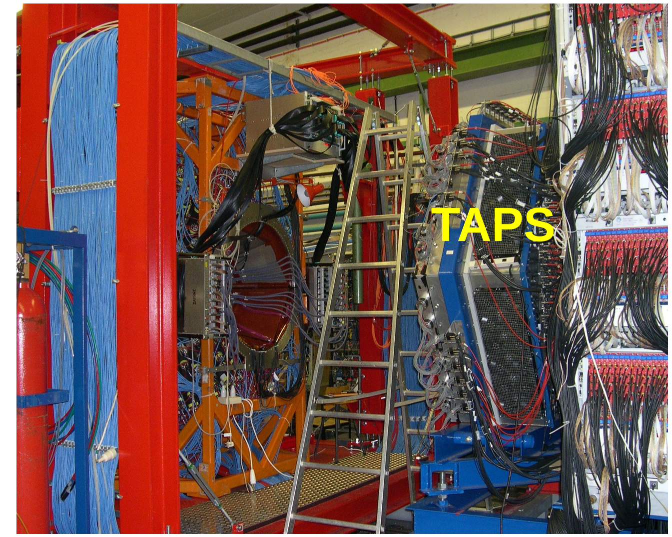
Similar physics at
Crystal Barrel @ ELSA Bonn
CLAS @ Hall-B Jefferson Lab
Hall-A: K.Wijesooriya et al PRC66(2002),034614

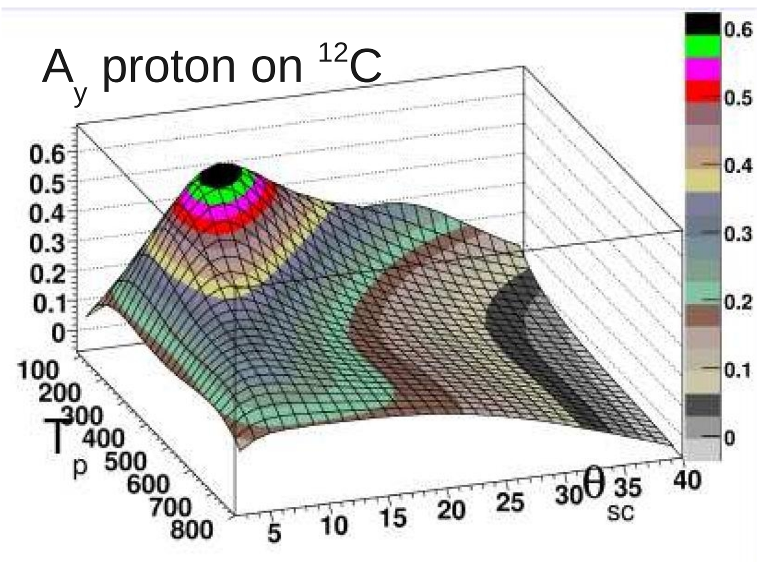
Crystal Ball @ MAMI





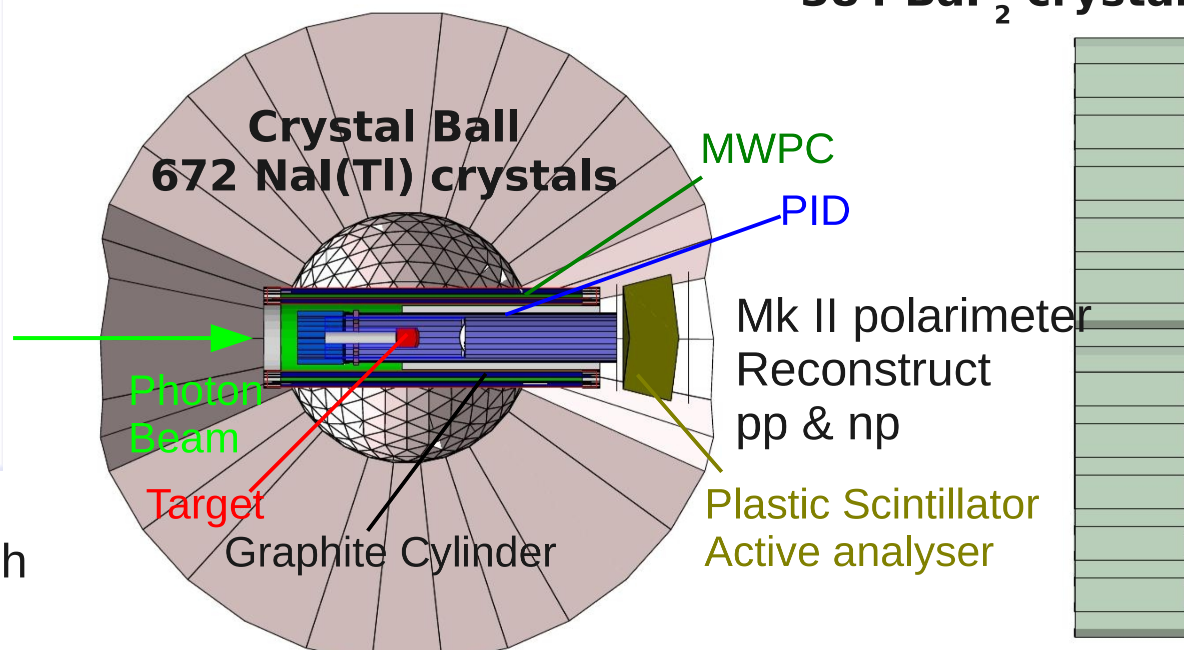
Central Tracking and Particle ID





Approved: MAMI-A2/03-09
D. Watts, D. Glazier, Uni. Edinburgh
J.R.M.A., Uni. Glasgow

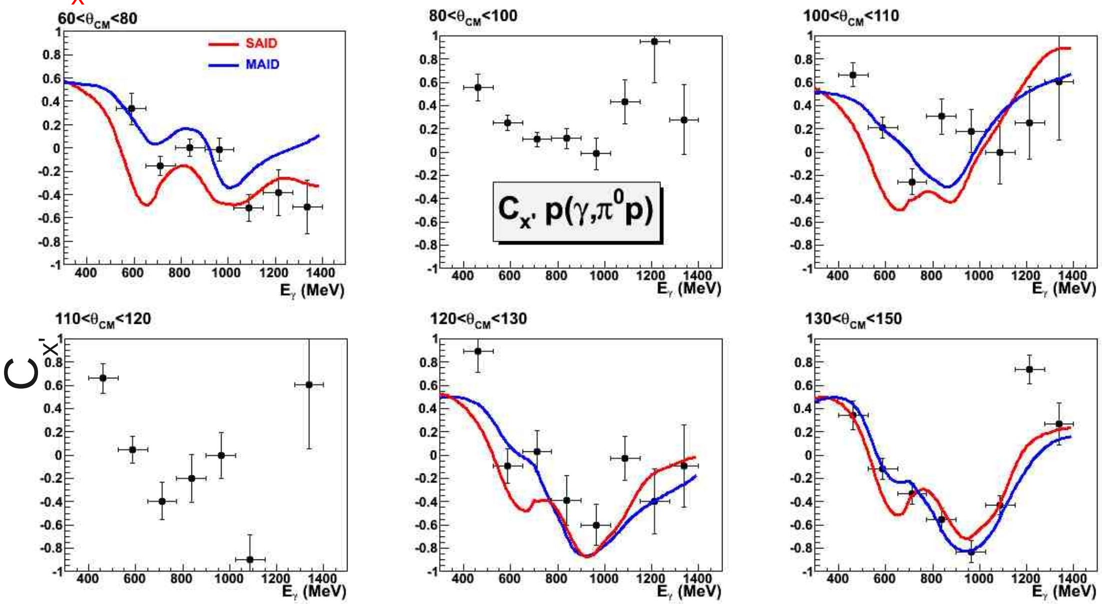
TAPS forward wall
384 BaF_2 crystals



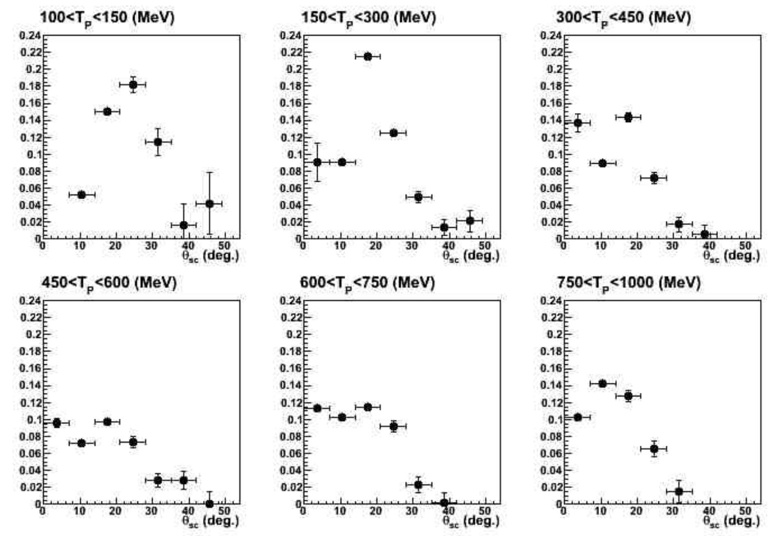
Mk II polarimeter
Reconstruct
pp & np

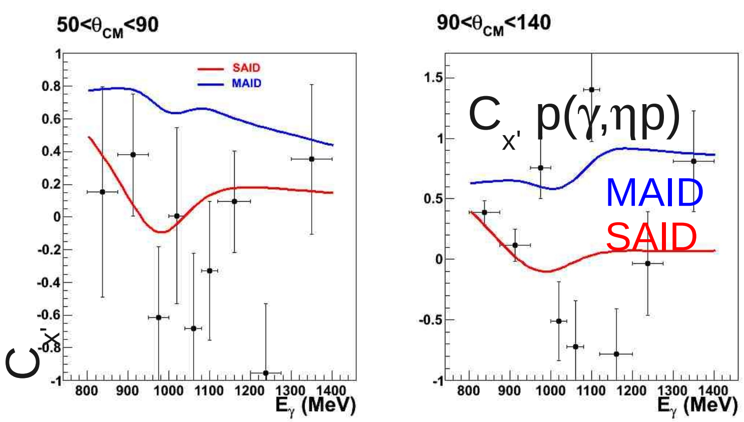
Preliminary Mainz Measurements C_x and O_x

C_x: *Mark Sikora, Uni. Edinburgh*

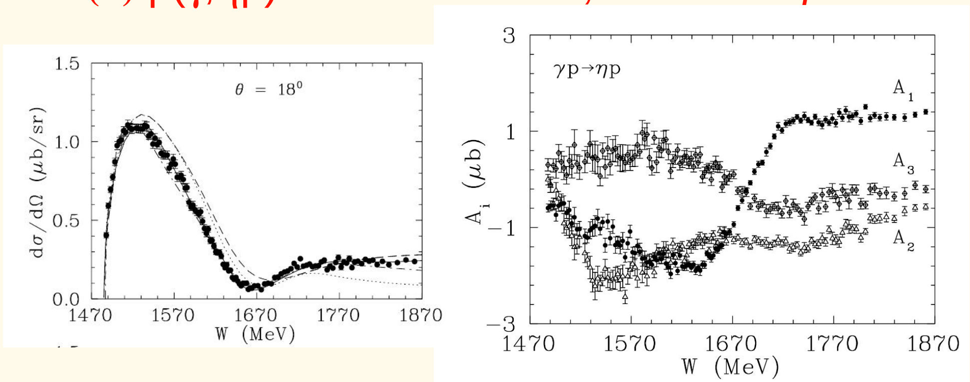


Analysing Power





σ(θ) p(γ,ηp) *E.McNicoll et al, PRC Accepted*



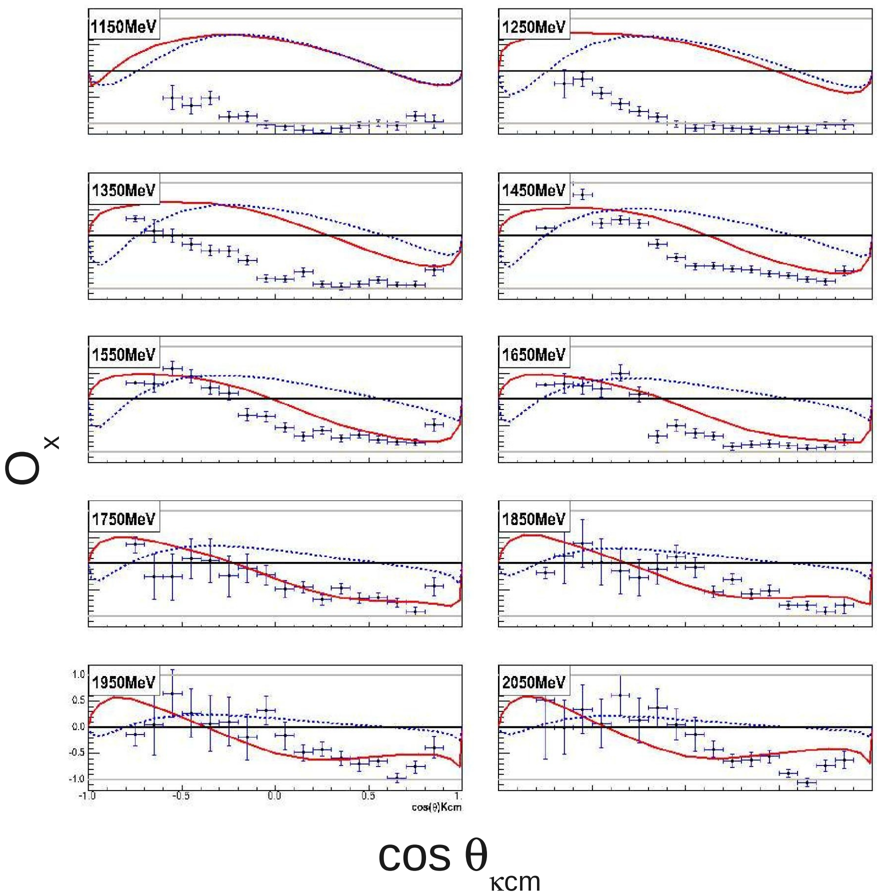
$$\rho_f \frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_0}\left[1 - P_\gamma^{lin}\Sigma\cos 2\phi_m + \sigma_{x'}\left(P_\gamma^{circ}C_{x'} + P_\gamma^{lin}O_{x'}\sin 2\phi_m\right) + \sigma_{y'}\left(P - P_\gamma^{lin}T\cos 2\phi_m\right) + \sigma_{z'}\left(P_\gamma^{circ}C_{z'} + P_\gamma^{lin}O_{z'}\sin 2\phi_m\right)\right]$$

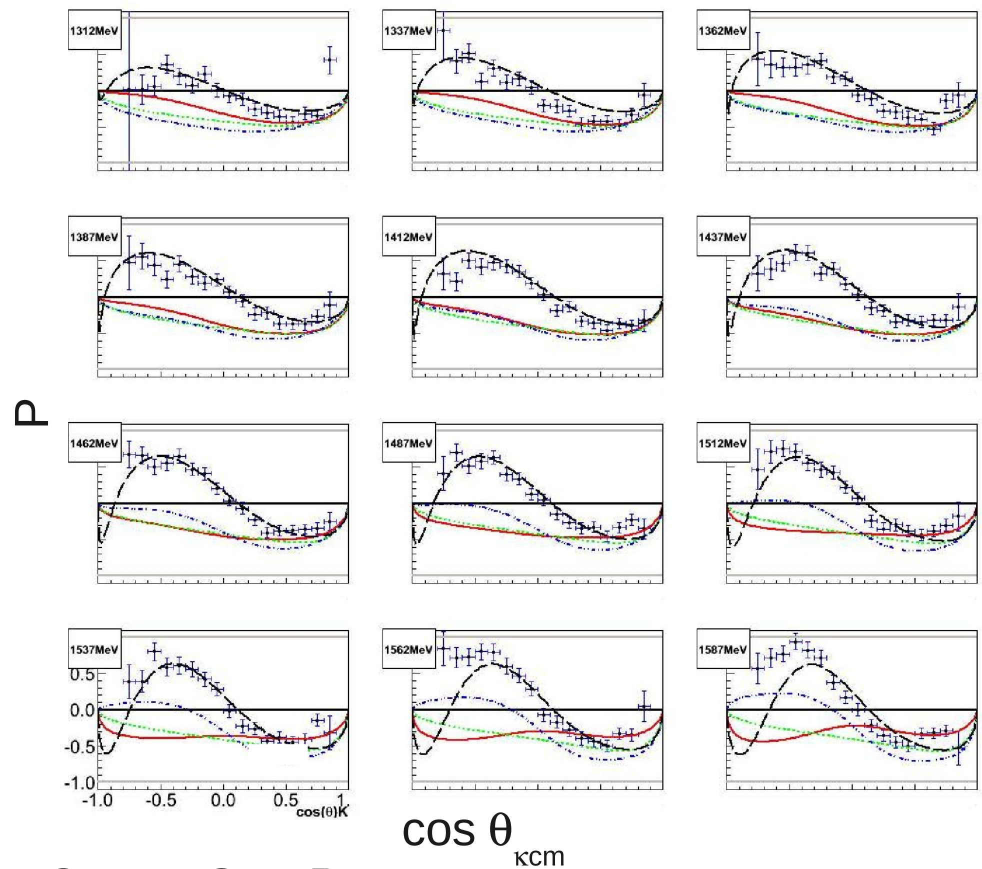
$$\hat{z}' = \hat{p}_p \quad \hat{y}' = \frac{p_\gamma \times p_m}{|p_\gamma \times p_m|} \quad \hat{x}' = \hat{y}' \times \hat{z}'$$

$\gamma + N \to K^{+}\Lambda^{0}$ Photoproduction @ CLAS

Recoil hyperon "self analysing"...distribution of decay products depends on the initial spin orientation.

Craig Patterson Ph.D. Uni.Glasgow, 2008, free proton





Curves: Mainz Kaon-MAID

F.X. Lee et al, N.P. A695 (2001) 237

S_{11}(1650), P_{11}(1710), P_{13}(1720) blue-dash;

+ D13(1900) red;

Curves: Gent Regge + resonance:

T. Corthals et al., PR C73 (2006), 045207

dotted green Regge background;

+ S_{11}(1650), P_{11}(1710), P_{13}(1720) blue dot-dash;

+ D_{13}(1900) red; + P_{11}(1900) black dashed

Quasi-free neutron, proton Neil Hassal Ph.D. Uni.Glasgow, 2010,

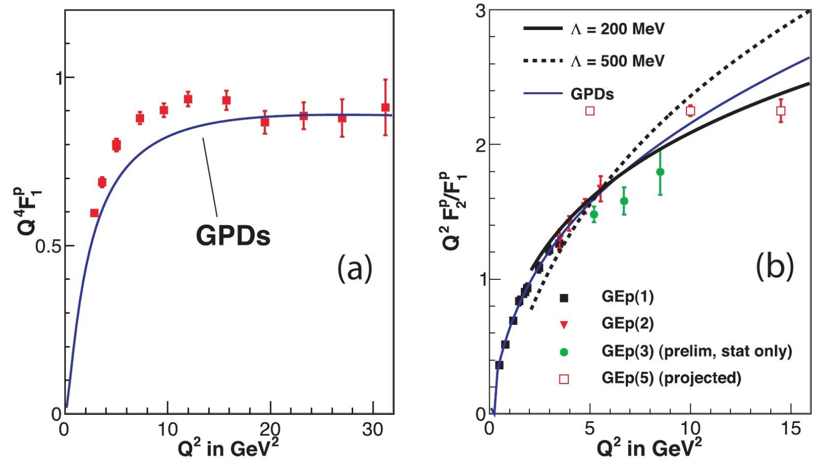
Nucleon Elastic Form Factors... Still Important

University of Glasgow

- Q^2 dependence G_{Ep}/G_{Mp} a major surprise. pQCD scaling *(S.J.Brodsky & G.R.Farar, PRD 11(1975),1309.)* F_1/F_2 does not scale as $1/Q^2$. Quark orbital angular mom.

Belitsky, Ji & Yuan PRL 91 (2003),092003
Scaling with $L_z = 1$
Hadron helicity not conserved

- Disparities in the predictions of theoretical models at Q^2 > few $(GeV/c)^2$. Interplay of analytical and LQCD predictions and FF experiment vital.

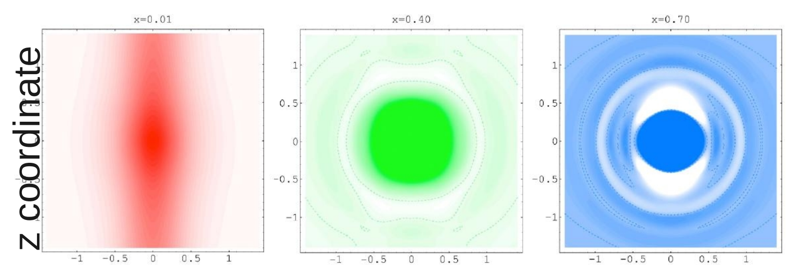


- Dyson-Schwinger Equ. → solution to any field theory. Infinite DSE series truncated in practise...use ansatz Calculate dynamical generation of mass of "dressed quarks" (dq). Use dq as d.o.f. in Faddeev calc. of FF. Include di-quark config. *(Cloët et al, F.B. Sys. 46(2009),1)*

- LQDC light quark predictions becoming more quantitative. Strong dependence on π mass. Extrapolation to chiral limit by χPT, χEFT. Calculations to ~ 4 $(GeV/c)^2$ New FF data will guide extension to ~ 10 $(GeV/c)^2$

X.Ji et al.,
Ann. Rev. Nucl. Part. Sci. 54 (2004), 413

x = 0.01 *x = 0.4* *x = 0.7*



u-quark radial coord

- GPD: unified framework connects DIS structure functions and Elastic form factors. Correlate spatial and momentum d.o.f. 3D images of nucleon. Need FF for constraint of GPD

$$\int_{-1}^{+1} H^q(x,\xi,Q^2)dx = F_1^q(Q^2) \qquad \int_{-1}^{+1} E^q(x,\xi,Q^2)dx = F_2^q(Q^2)$$

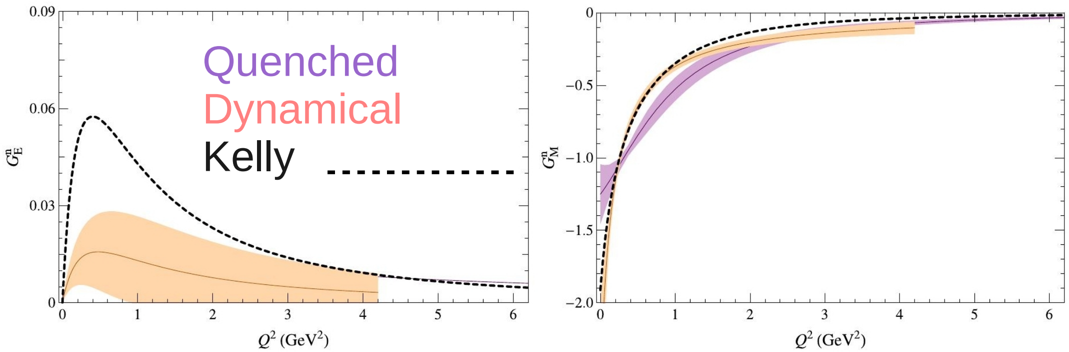
.

- Ji Sum Rule *(X.Ji, PRD 59(1999),014013)* total quark ang. mom. related to sums over GPDs. FF constrains GPD fits....

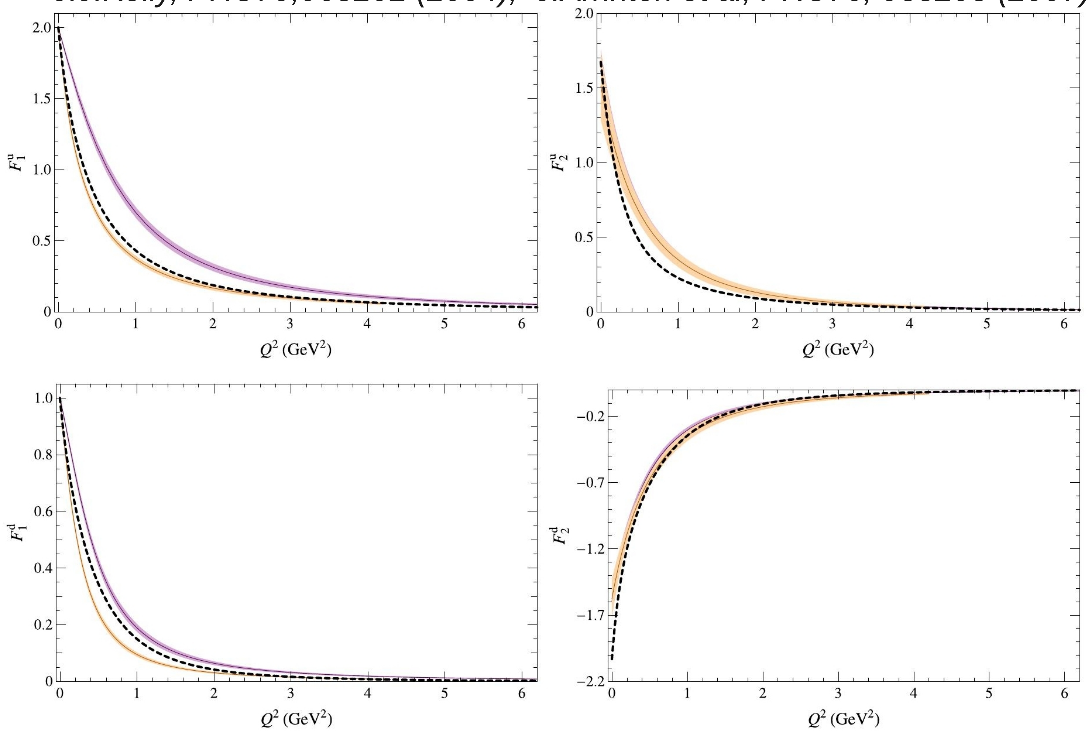
University of Glasgow

Need Both Proton and Neutron Measurements

LQCD: H.-W. Lin et al. arXiv.1005.0799v1 5th May 2010



Exp. Fit:
J.J.Kelly, PRC70,068202 (2004); J.Arrinton et al, PRC76, 035205 (2007)

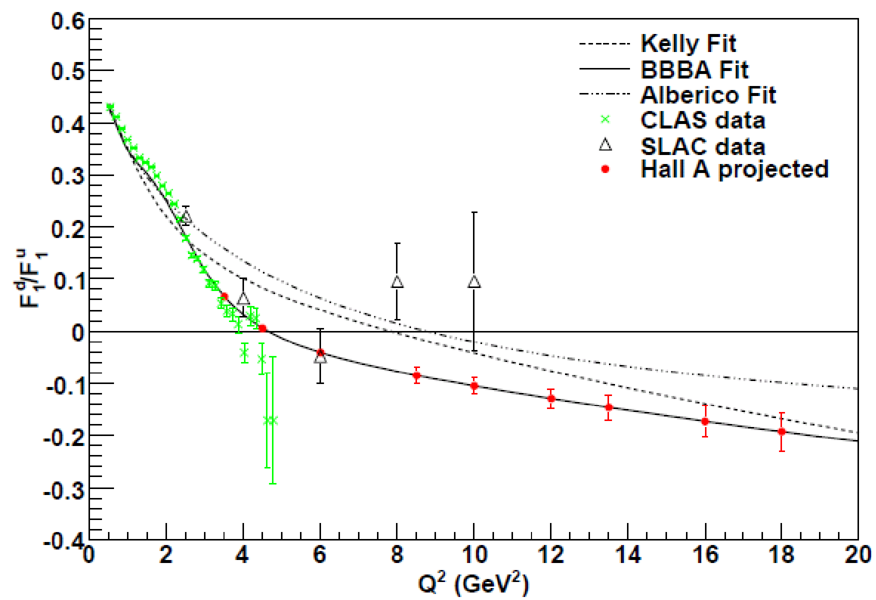


Isovector relatively accessible to LQCD
$F^v = F^p - F^n$
LQCD progresses to higher Q^2

Flavour decomposition possible
Assuming small strange contribution

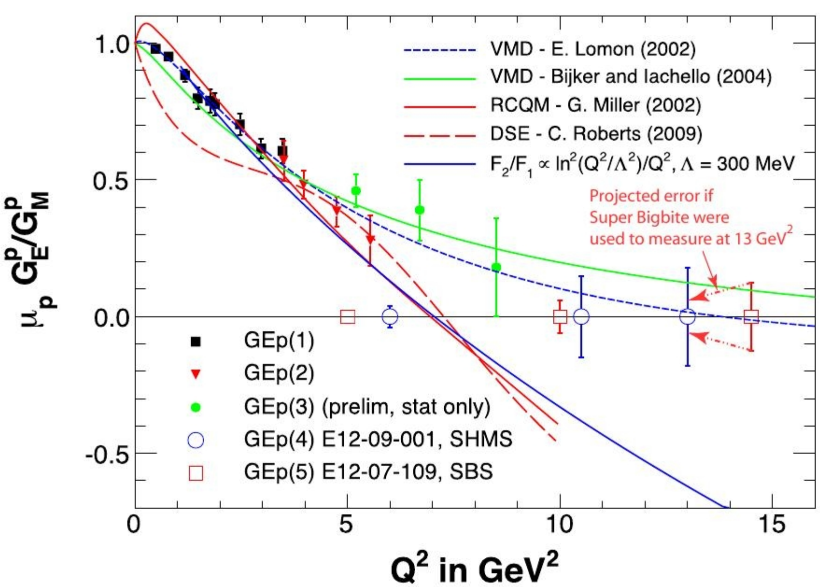
$$F_1(Q^2) = \frac{G_E + G_M}{1+\tau} \qquad F_2(Q^2) = \frac{-G_E + G_M}{1+\tau}$$

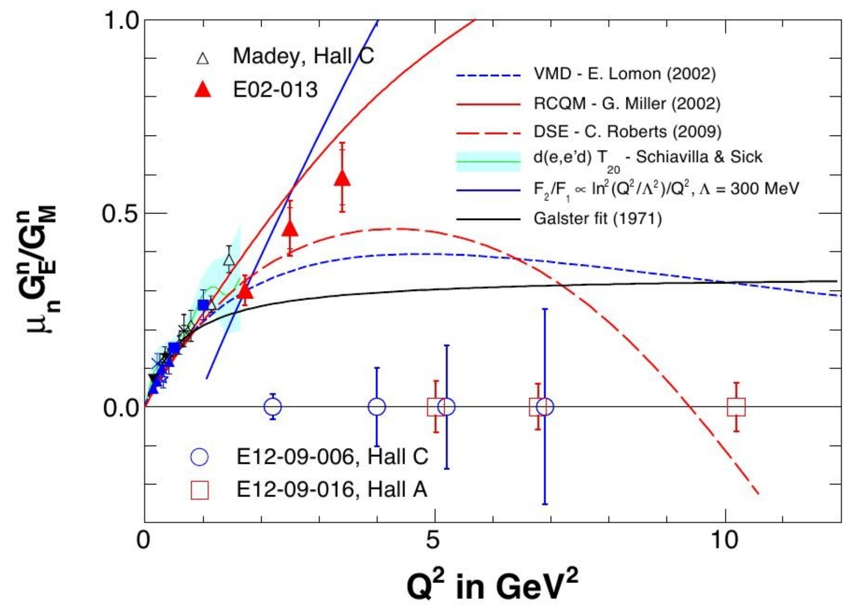
$$F^u_{1,2} = F^n_{1,2} + 2F^p_{1,2} \qquad F^d_{1,2} = 2F^n_{1,2} + F^p_{1,2}$$



University of Glasgow

Hall-A Nucleon Elastic Form Factor Measurements



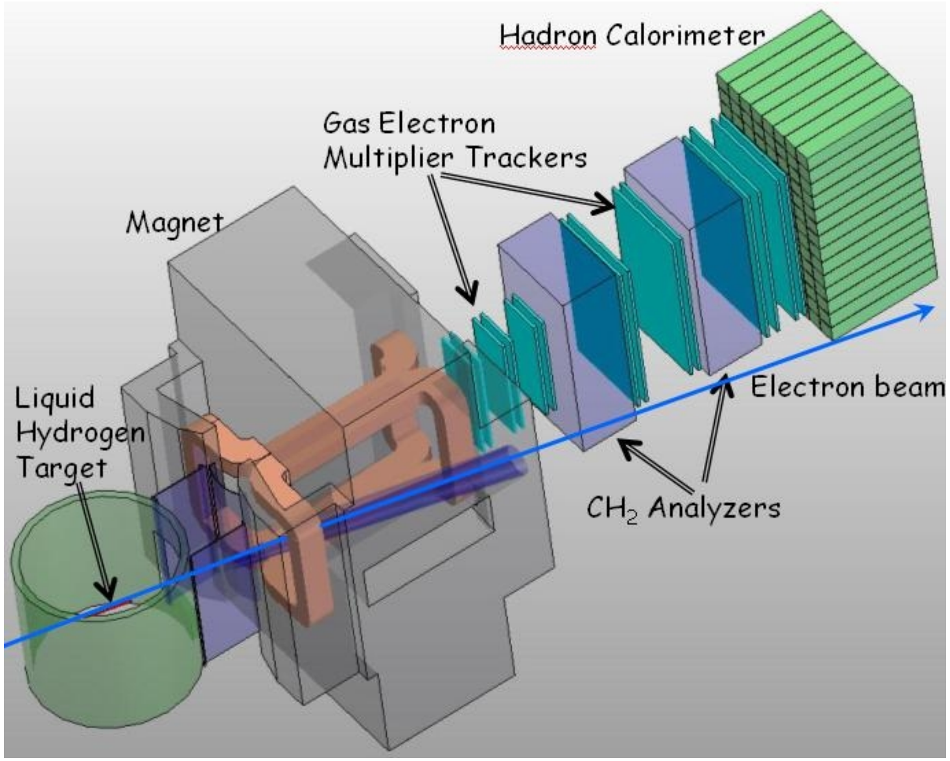


Measure all 4 Nucleon Sachs form factors G_{Mp}, $G_{Mn/}G_{Mp}$, G_{ep}/G_{Mp}, G_{en}/G_{Mn} .

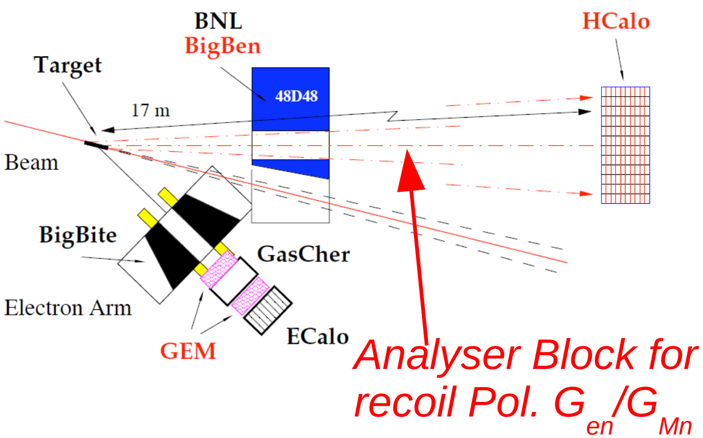
- E12-07-108: G_{Mp} to high precision using the HRS
- E09-019: G_{Mn}/G_{Mp} up to 18 $(GeV/c)^2$ (eventually)
- E12-07-109: G_{Ep}/G_{Mp} up to ~15 (GeV/c)2
- E09-016: G_{En}/G_{Mn} up to 10 $(GeV/c)^2$ SBS precess n-spin and sweeps background
- How would recoil neutron polarimetry compare for G_{en}/G_{Mn}
- np, nn analysing power at high momentum ?
- Independent G_{en}/G_{Mn} measurement highly desirable

Common Modular Apparatus for 11-GeV Experiments

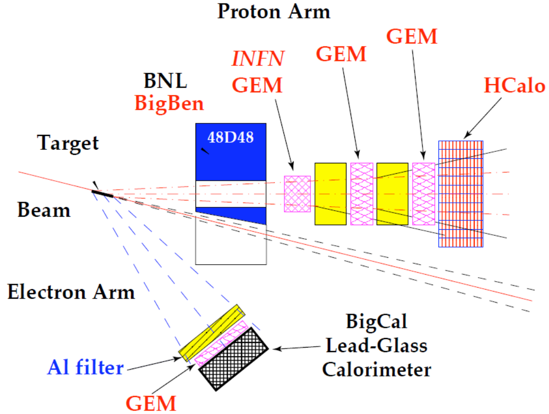
G_{Ep}/G_{Mp} from p(e,e'p) Recoil polarimetry



G_{En}/G_{Mn}, G_{Mp}/G_{Mn}



G_{Ep}/G_{Mp}



- Jefferson Lab Hall A 11 GeV Current up to 80mA CW
- High Resolution Spectrometers
- SBS Dipole
- GEM Trackers
- Hadron Calorimeter
- CH_2 polarisation analysers, Plastic scintillator array?
- BigBite Spectrometer (e') BigCal Pb-Glass Cherenkov (e')

University of Glasgow

G_{En}/G_{Mn} using Recoil Neutron Polarimetry

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

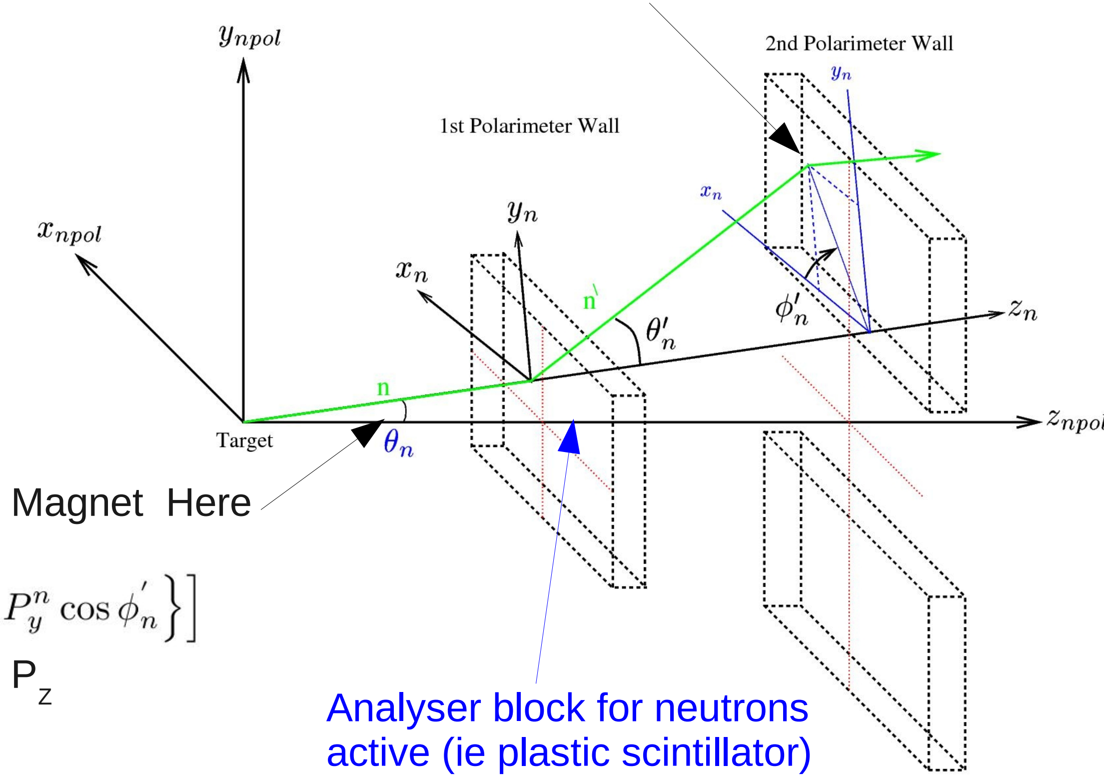
$$P_x = -hP_e \frac{2\sqrt{\tau(1+\tau)}\tan\frac{\theta_e}{2} G_E G_M}{G_E^2 + \tau G_M^2(1+2(1+\tau)\tan^2\frac{\theta_e}{2}}$$

$$P_y = 0 \quad \text{(free target nucleon)}$$

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

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

Scattering asymmetry blocks detect neutrons or protons...
typically plastic scintillator bars



Dipole Magnet Here

Analyser block for neutrons active (ie plastic scintillator) and position sensitive. Use both n-N and QF n-N from ^{12}C

Recoil Polarimetry...

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

Precess nucleon spin through dipole to access P_z

Measure ϕ modulation vs precession angle

$\rightarrow G_{en}/G_{Mn}$ independently of A_y

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

$$A(\chi) = \alpha P_e \sqrt{P_x^2 + P_z^2}\sin(\chi - \chi_0)$$

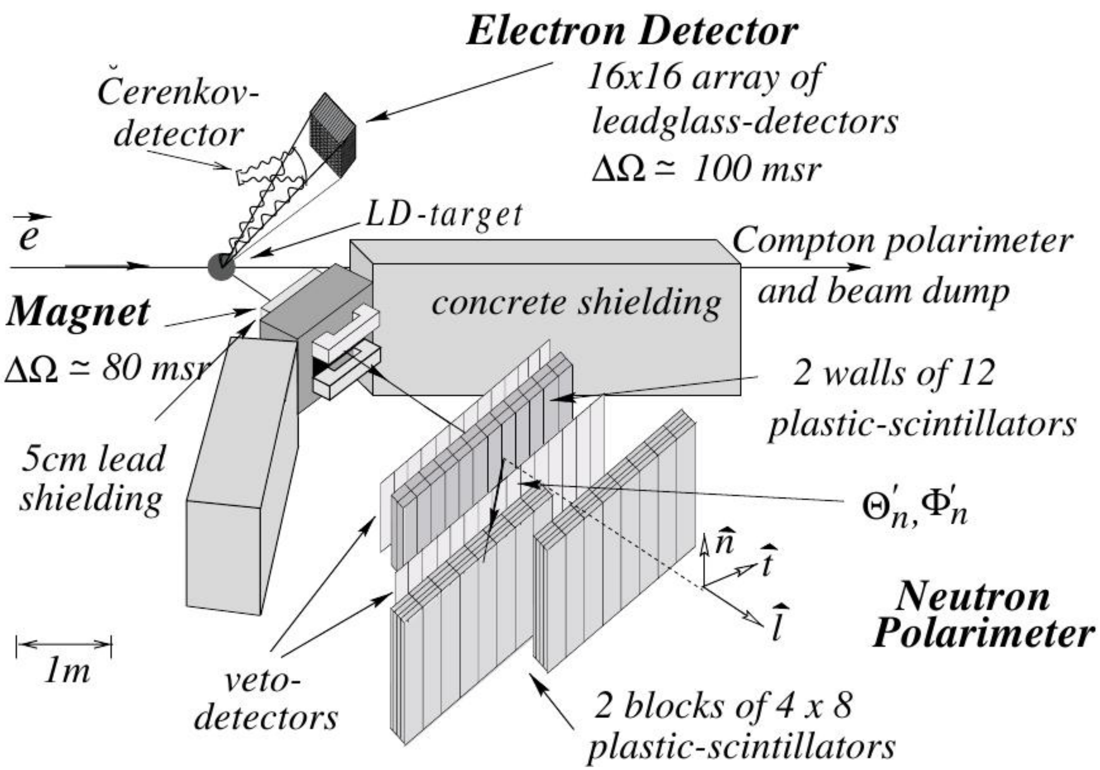
$$\tan\chi_0 = P_x/P_z \propto G_E/G_M$$

BUT!

Polarimeter Figure of Merit

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

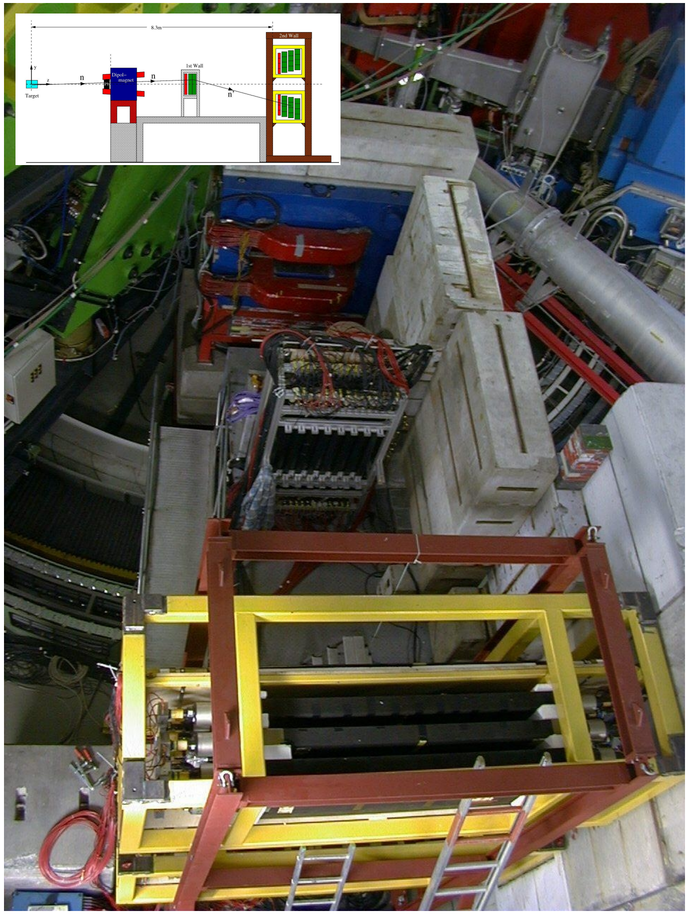
G_{En}/G_{Mn} at MAMI-A3
Started ~ 1990

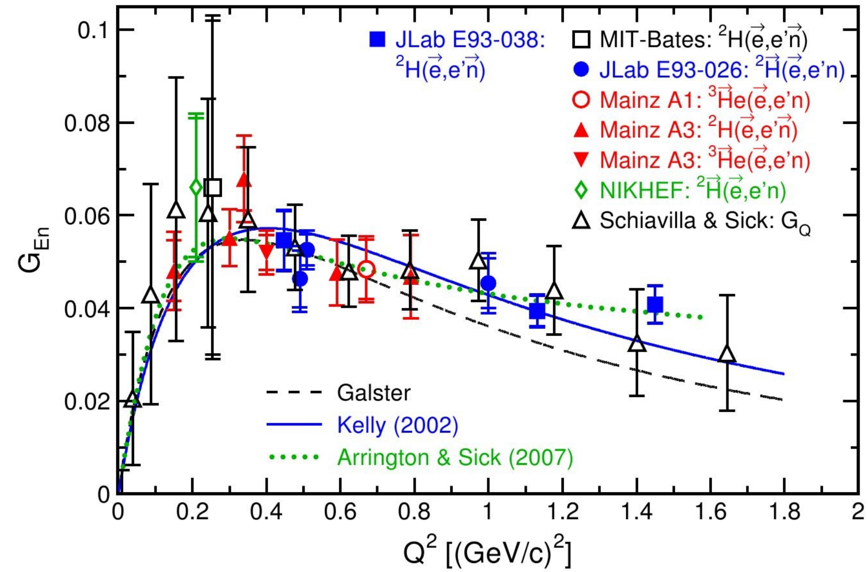


1st G_{En}/G_{Mn} measurement using variable n-spin precession angle in a dipole magnetic field

- 1st Double Polarisation Measurement
  MIT Bates
- 1st Double Polarisation
  Measurements with "Challenging" Error Bars Mainz A3
- Large solid angle setup
- Both ^{2}H(e,e'n) and ^{3}He(e,e'n) QE scattering
- Corrections for binding effects @ Q^2 ~0.3 $(GeV/c)^2$ Large
- Angular Uncertainty in ***q*** vector limited the achievable systematic uncertainties
- 3m Glasgow/Tübingen TOF Bars
  Rear Walls: n-scattering Asymmetry Detector
- 1.8 m Glasgow TOF Bars
  Front Wall: n-scattering analyser
- *R.Watson Ph.D.*
  University of Glasgow, 1998

G_{En}/G_{Mn} Recoil Polarimetry MAMI A1

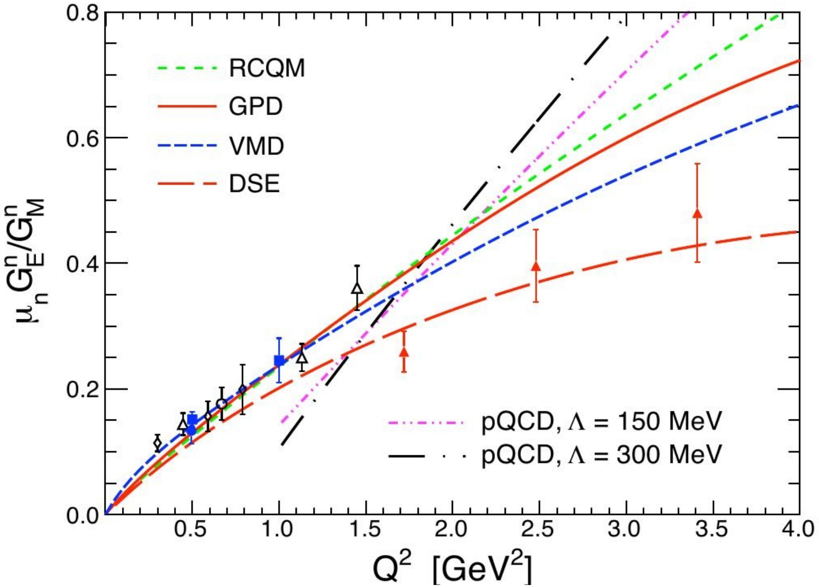


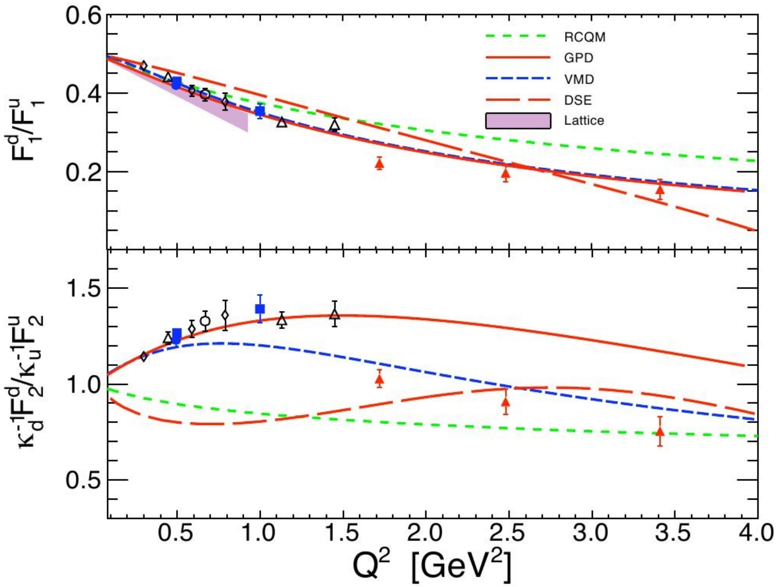


- High-resolution spectrometer A for e'.
  accurate determination of ***q***
- Dipole precesses n spin z $\rightarrow$ x. G_{En}/G_{Mn} from up-down asymmetry as fn of precession angle.
- Highly segmented Mainz analyser wall
  1-2 MHz rates in front scintillators
  5 cm Pb in pole gap of dipole
- Glasgow 1.8 m TOF scattering ϕ–asymmetry wall
  detectors moved out of direct line of sight from target
  measure up-down asymmetry
  also used in JLab Hall-A Big-HAND
- Monte Carlo (Geant-4) simulations of the effective analysing power...basis of new Hall-A studies.

Derek Glazier Ph.D. Uni.Glasgow 2004
Michael Seimetz Ph.D. Uni. Mainz
D.G Monte Carlo modelling of n-polarimetry...polarised nucleon scattering in Geant-4 simulation

JLab Hall-A G_{En}/G_{Mn} Polarised ^{3}He Target





Measurements of the Electric Form Factor of the Neutron up to $Q^2 = 3.4$ GeV^2 using the Reaction $^3\vec{He}(\vec{e},e'n)pp$, *S. Riordan et al., arXiv:1008,1738.*

New experiment E09-016 $Q^2 \rightarrow 10$ GeV^2

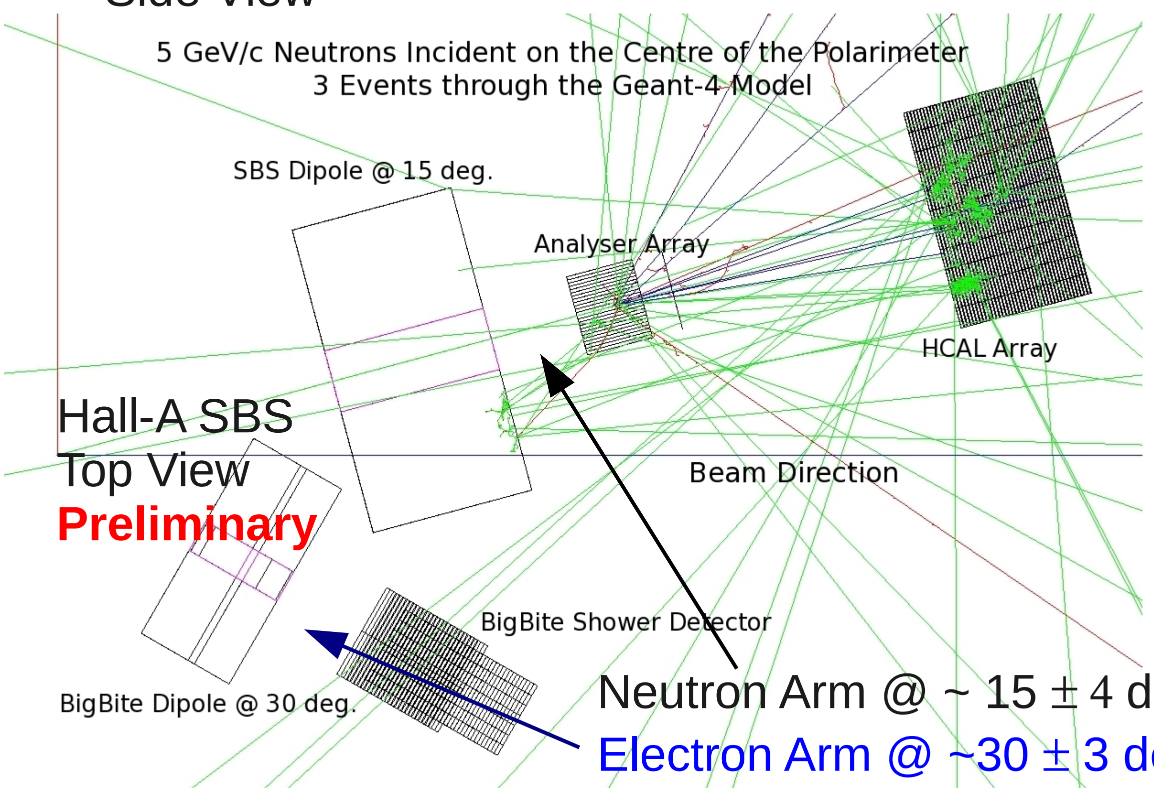
$^3\vec{He}(\vec{e},e'n)$ New $^3\vec{He}$ Target (U.Virginia), High Luminosity

Polarimeter for High Q^2 Measurements at JLab D($\vec{e}$,e'$\vec{n}$)

- Neutron measurements difficult
- No free target... use ^{2}H or ^{3}He
  Bound-nucleon effects, FSI?
- Different experimental technique, with different target nucleus highly desirable

- Currently highest Q^2 pt G_{En}/G_{Mn} by recoil pol. Hall-C JLab 1.4 GeV^2
- SBS precesses n-spin z → y
  sweeps low-momentum background
  differentiates n and p hit positions
- Analyser array of plastic scintillator
  20 x 50 of 30 x 30 x 250 mm bars
  aligned || incident neutrons
  Pb curtain necessary ?
- HCAL is the ϕ asymmetry detector
  11 x 22 of 150 x 150 x 1000 mm
  Fe-Plastic modules
  insensitive to low-energy background
  "full" ϕ coverage
  very high neutron efficiency
- GEM chambers pre/post analyser?
  np channel, QF d(e,e'p)

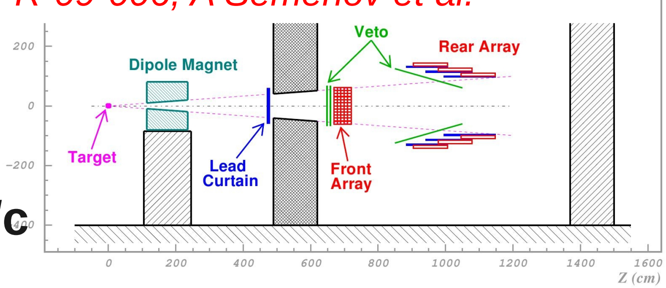
Side View



Hall-A SBS
Top View
Preliminary

Neutron Arm @ ~ 15 ± 4 deg.
Electron Arm @ ~30 ± 3 deg.
Q^2 = up to 7 – 8 (GeV/c)^2
Neutron momentum 5.5 – 7 GeV/c

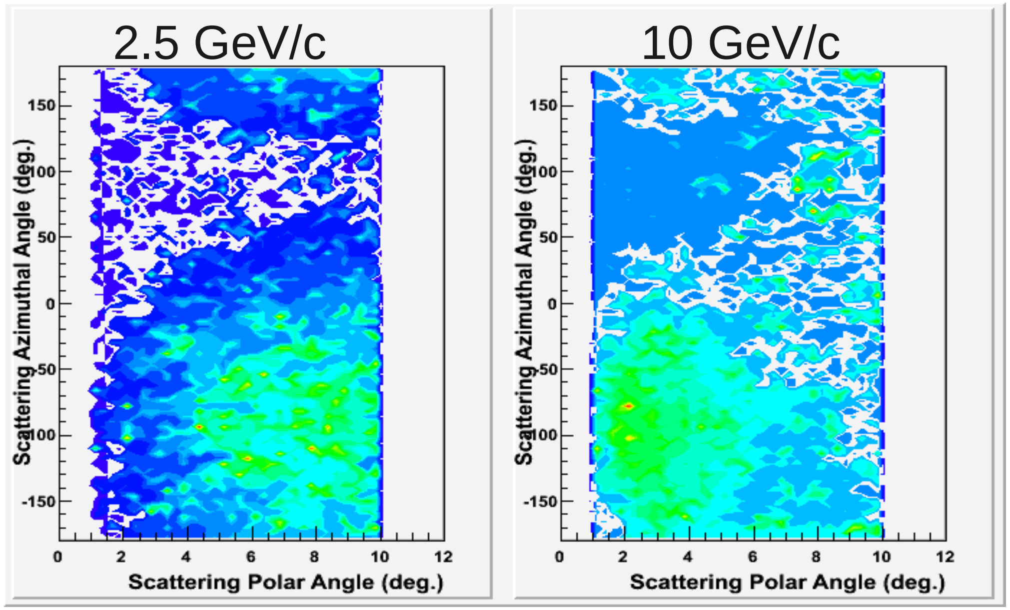
JLab Hall-C Polarimeter Q^2 → 7 GeV^2
PR-09-006, A Semenov et al.



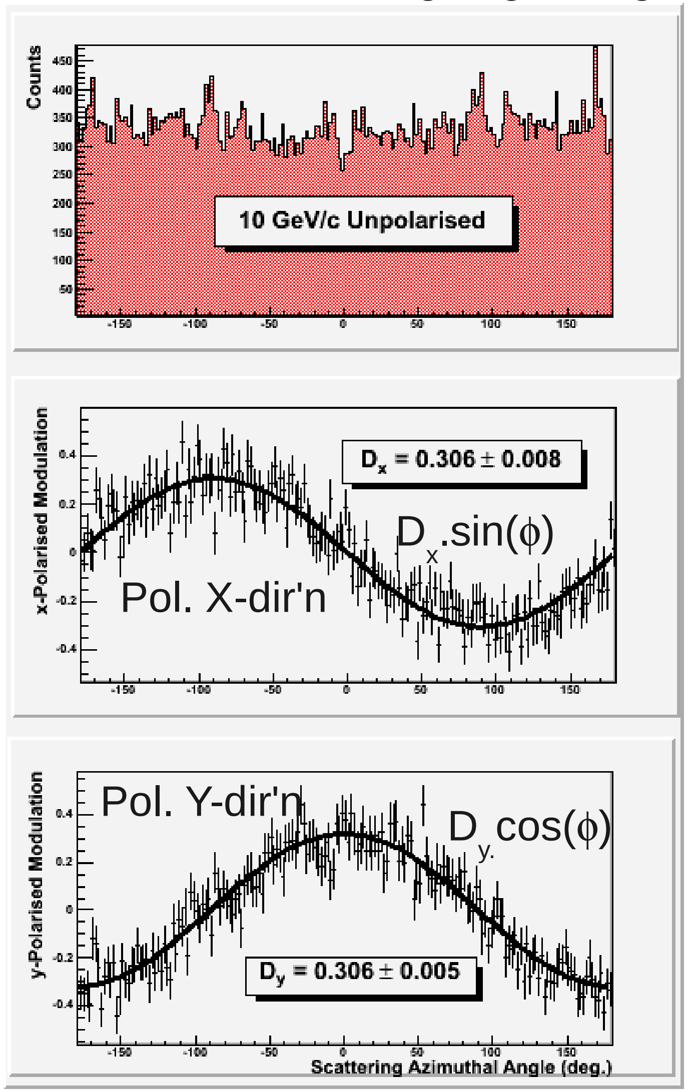
Polarimetry Monte Carlo (Geant-4)

P_n	T(mm)	Dx	Dy	Events
2.5	250	0.612 ± 0.014	0.630 ± 0.006	20304
2.5	500	0.560 ± 0.010	0.565 ± 0.005	39835
5.0	250	0.468 ± 0.009	0.479 ± 0.005	43348
5.0	500	0.373 ± 0.006	0.378 ± 0.004	91363
7.5	250	0.364 ± 0.008	0.369 ± 0.005	55917
7.5	500	0.294 ± 0.005	0.295 ± 0.004	119700
10.0	250	0.306 ± 0.008	0.306 ± 0.005	60255
10.0	250	0.621 ± 0.013	0.621 ± 0.006	21090
10.0	500	0.240 ± 0.005	0.237 ± 0.004	130656

$1.0 < \theta_n < 10^\circ$; $1.0 < \theta_n < 6^\circ$



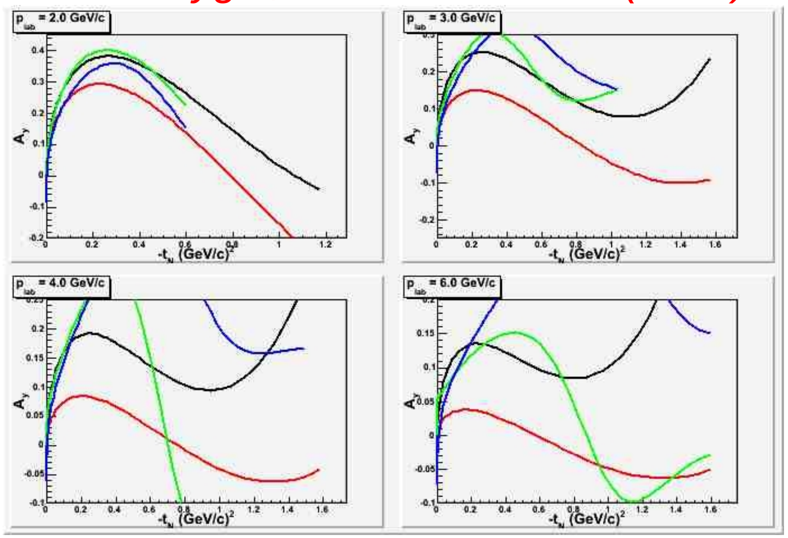
Monte Carlo Simulation of Polarimeter
Include pol-nucleon scattering model
Incident polarisatiom and A_y set to 1.0
Effecftive A_y dependence on analyser thickness and scattering angle range



A_y Free pp & np Scattering

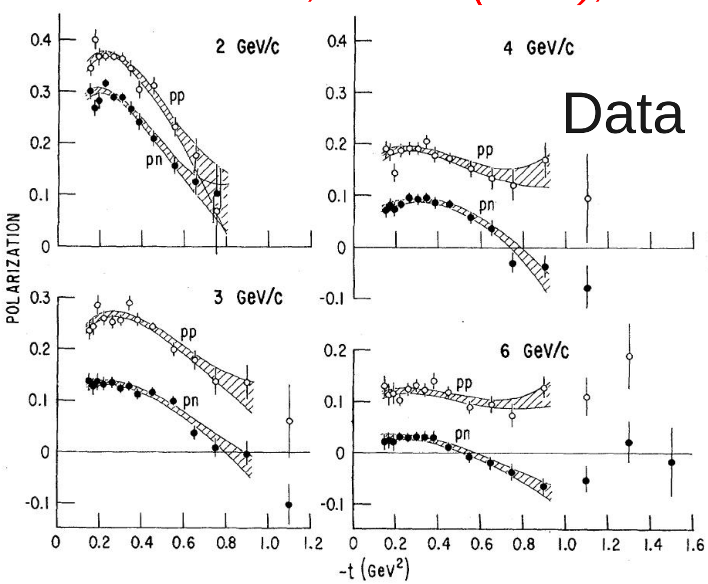
FoM ~ A^2_y . dσ/dΩ

V.P. Ladygin, JINR E12-99-123(1999)



- Ladygin fit pp
- Ladygin fit np
- SAID PWA pp
- SAID PWA np

R. Diebold et al., PRL 35(1975),632



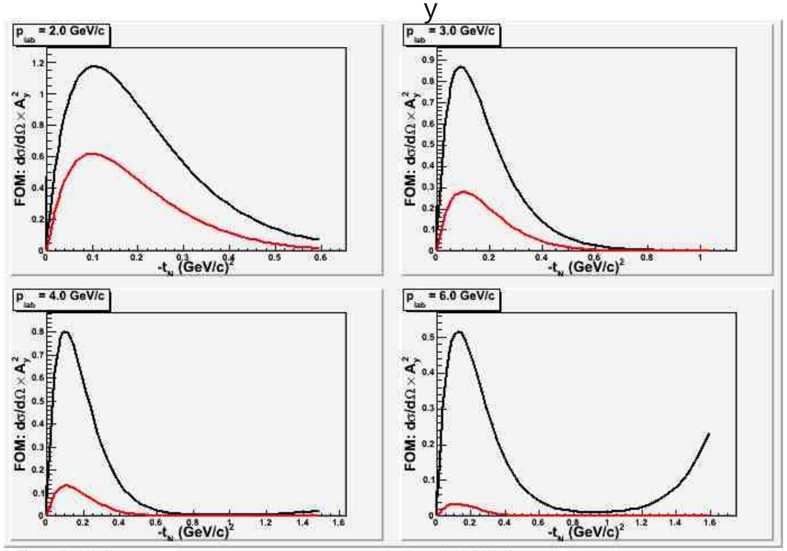
Data

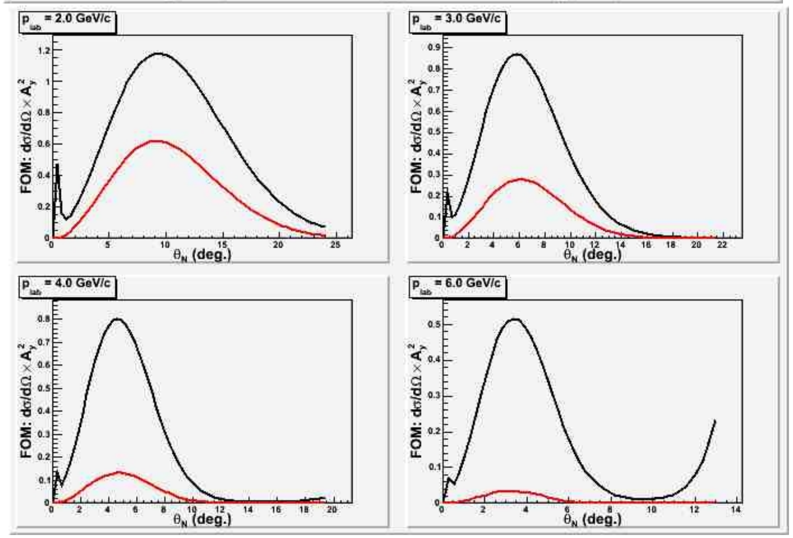
Fits & PWA

Predicted np FoM poor at high p_n...

How does nn behave?

$$\Delta P = \sqrt{\frac{2}{N_{inc}\mathcal{F}^2}}$$





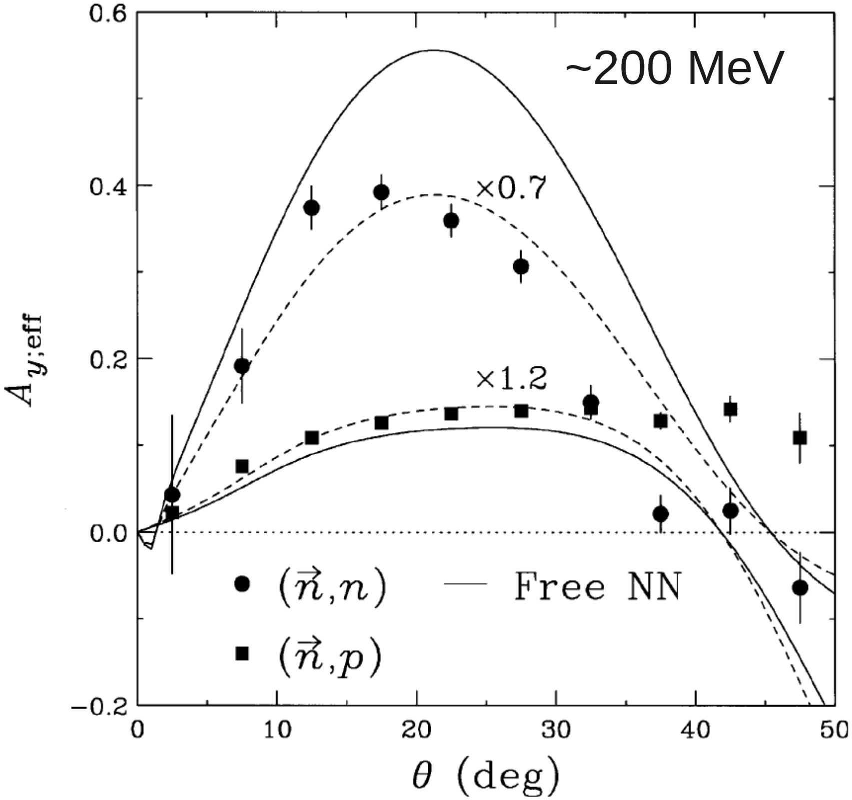
Extraction G_E/G_M without knowledge of A_y... BUT!!

Counts to obtain specific precision depends on FoM

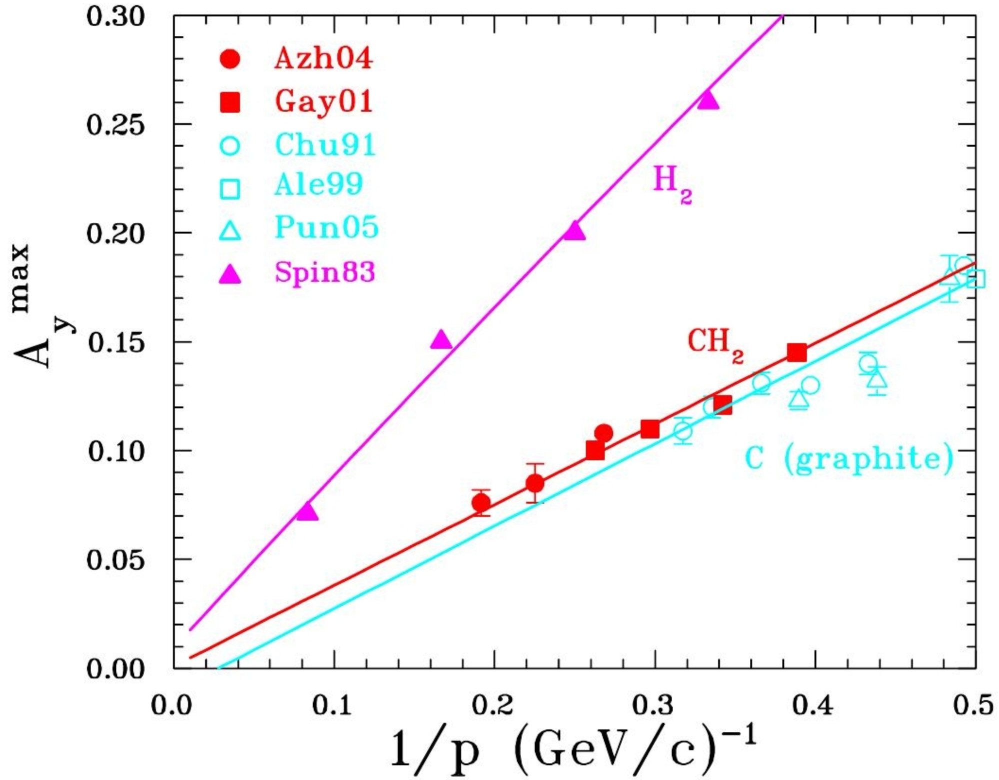
FoM ~ $\mathcal{F}^2(p_n) = \int \varepsilon(p_n, \theta_n^{'}).A_y^2(p_n, \theta_n^{'})d\theta_n$

Effective A_y Free vs Bound Nucleons

T.Wasaka et al., NIM A547 (2005), 569



L.S.Azhgirey et al., NIM A538 (2005), 431
and JLab proposal PR-09-016 (Gep(V))



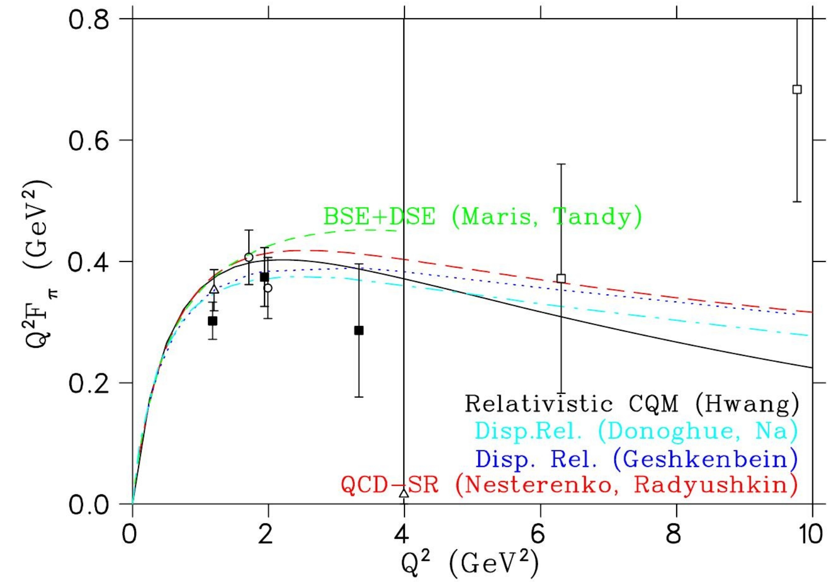
QF n-n ~ 0.7 Free n-n
n-p rather poorer....
What happens at higher momenta

QF p-p ~ 0.5 Free p-p

Extend n-n, n-p measurements to several GeV/c?...Dubna (as for p-p)?

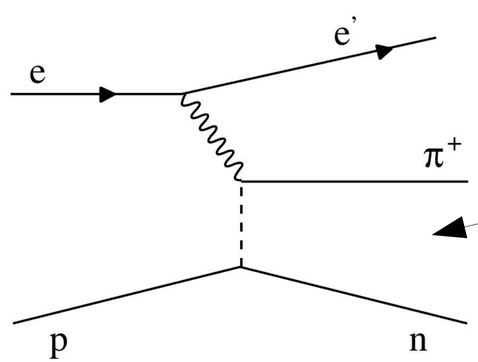
π^+ Electric Form Factor

- Asymtotic $F_\pi(Q^2 \to \infty) \to 8\pi\alpha_s f_\pi^{+}/Q^2$
- Where does asymtotic regime set in?
- $Q^2 \sim 20\ GeV^2$?
- BABAR $\gamma\gamma^* \to \pi^0$
  Transition form factor $F(Q^2)$
  B.Aubert et al., arXiv:0905.4778
- Elastic π-e scattering limited to low Q^2
- Electron scattering from virtual π cloud on proton to access higher Q^2



Spectrometer acceptance issues mean that Rosenbluth is highly challenging
Alternatives to Rosenbluth...Recoil N Pol.
J.J. Kelly et al, Phys. Rev. C75(2007),025201

- JLab PR-07-014 $p(\vec{e},e'\vec{p})\pi^0$ evaluate non-pole background $-t > 0.2\ GeV^2$...
- extend JLab kinematic reach?



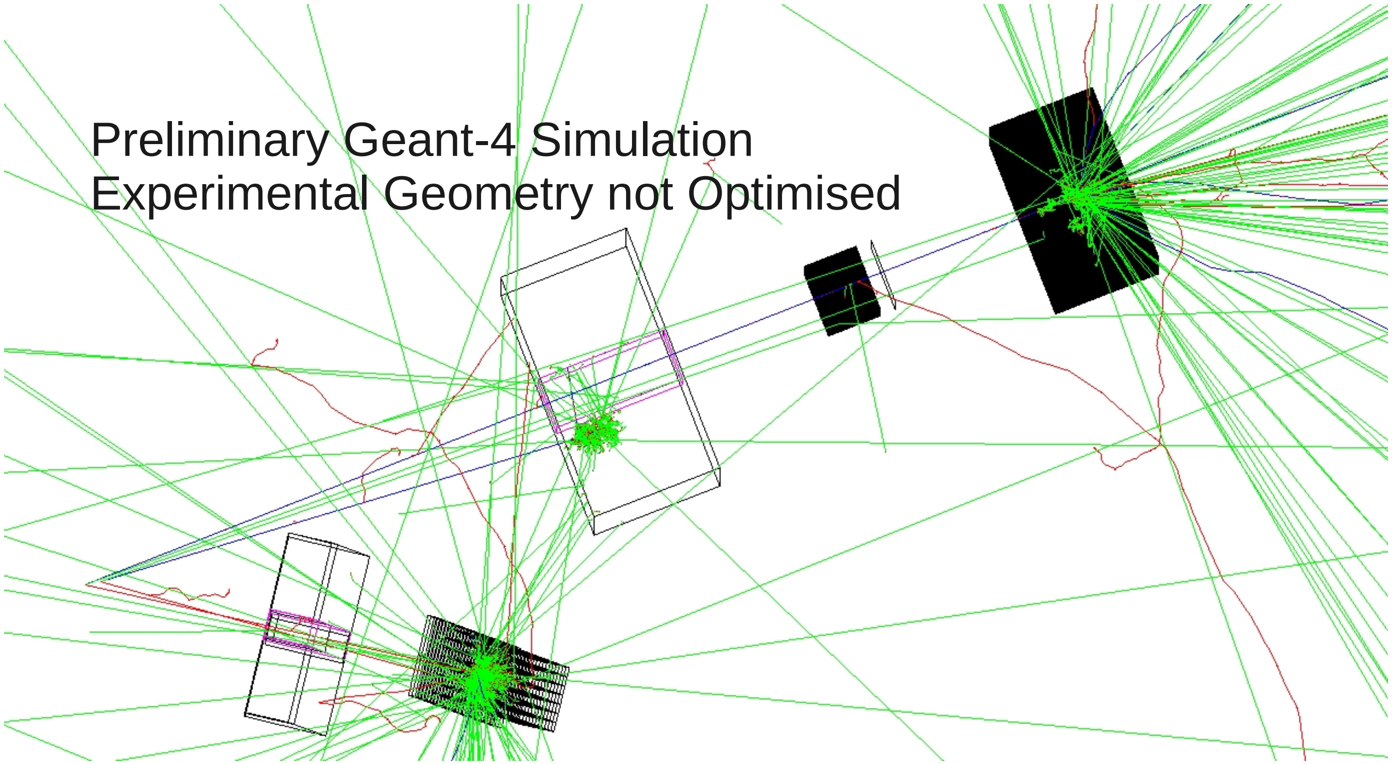
Jefferson Lab. π^+ Electric Form Factor $F_\pi(Q^2)$

- $\gamma^*+p \to \pi^+ + n$. Parallel kinematics,
  $t < 0.2\ (GeV/c)^2$, $W \sim 3$ GeV

$$\frac{d\sigma_L}{dt} \sim \frac{-tQ^2}{(t-m_\pi^2)^2} g_{\pi NN}^2(t) F_\pi^2(Q^2)$$

- Maximise t-channel contribution and t-channel separation from other processes
- Hall-C $p(e,e'\pi^+)n$ Rosenbluth
  E12-06-101 G.Huber et al.
- Kinematic constraints limit $Q^2 < 6\ GeV^2$

Speculative $p(\vec{e},e'\pi^+\vec{n})$ Experiment @ JLab



Longitudinal/Transverse Separation
Parallel Kinematics

$$\sigma_0 P_x = hc^- \frac{R^t_{LT'}}{R_T + \epsilon R_L}$$

$$\sigma_0 P_y = c^+ \frac{R^n_{LT}}{R_T + \epsilon R_L}$$

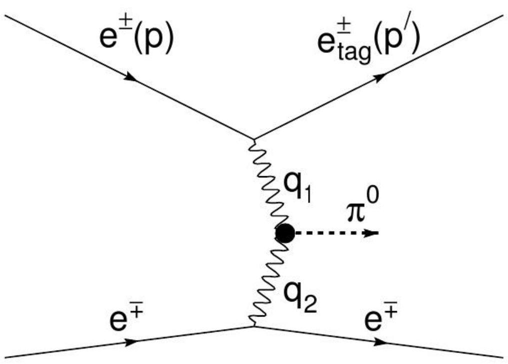
$$\sigma_0 P_z = hc^0 \frac{R^l_{TT'}}{R_T + \epsilon R_L} \qquad R^l_{TT'} = R_T \quad \|_{kinematics}$$

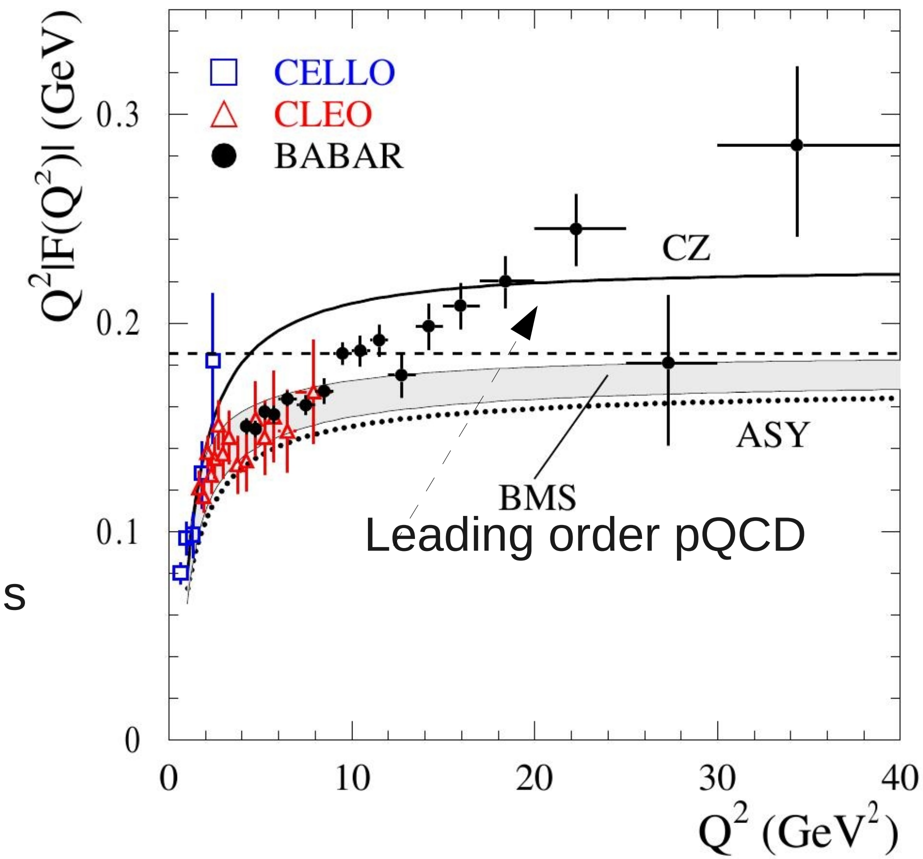
$$R = \frac{\sigma_L}{\sigma_R} = \frac{1}{\varepsilon}\left[\frac{h\sqrt{1-\varepsilon^2}}{P_z} - 1\right] \qquad \sigma_L = \frac{\sigma_0}{(1/R + \varepsilon)}$$

- Laboratory angle of π^+ and n similar
- Both pass through dipole aperture
- $-t < 0.2$ GeV$^2 \Rightarrow p_n \sim 200$ MeV/c
- Expect huge background radiation field
- HCAL not sensitive $p_n \sim 200$ MeV/c
- Need π^+ to tagg reaction process cleanly

Thank you for your attention

Pion Form Factors



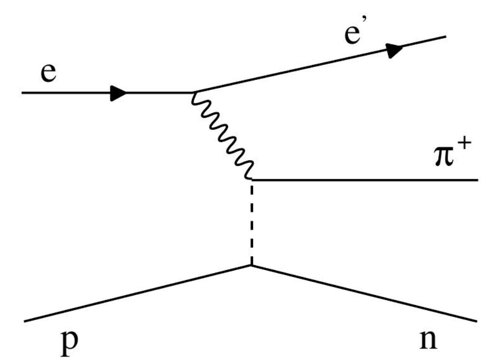


- Even the simplest light hadronic systems continue to spring surprises
- BABAR $\gamma\gamma^* \rightarrow \pi^0$
  Transition form factor $F(Q^2)$
  $Q^2 = 4 - 40\ (\mathrm{GeV}/c)^2$
- $F(Q^2)$ extraction some model dependence

B.Aubert et al., arXiv:0905.4778 [hep-ex] 2009

Jefferson Lab. π^+ Charge Form Factor $F_\pi(Q^2)$

- $\gamma^*+p \rightarrow \pi^+ + n$. Parallel kinematics, $t < 0.2\ (\mathrm{GeV}/c)^2$
- Hall-C $p(e,e'\pi^+)n$ Rosenbluth E12-06-101 G.Huber et a

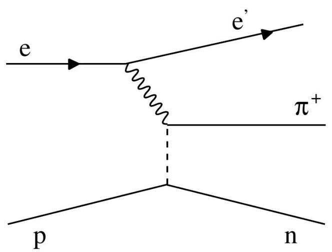


t-channel dominant

π^+ Electric Form Factor from γ^*+p → n+π^+

- No free pion target
- Asymtotic region ($Q^2 \approx 20$ (GeV/c)^2 not accessible. $F_\pi(Q^2 \to \infty) \to 8\pi\alpha_s f_\pi^{+}/Q^2$
- Work in gap region between soft and hard regimes
- Scatter from the "pion cloud" around the nucleon
- Similar idea employed pion polarisability (Compton scattering) measurement at Mainz

$$\frac{d\sigma_L}{dt} \sim \frac{-tQ^2}{(t-m_\pi^2)^2} g^2_{\pi NN}(t) F^2_\pi(Q^2)$$

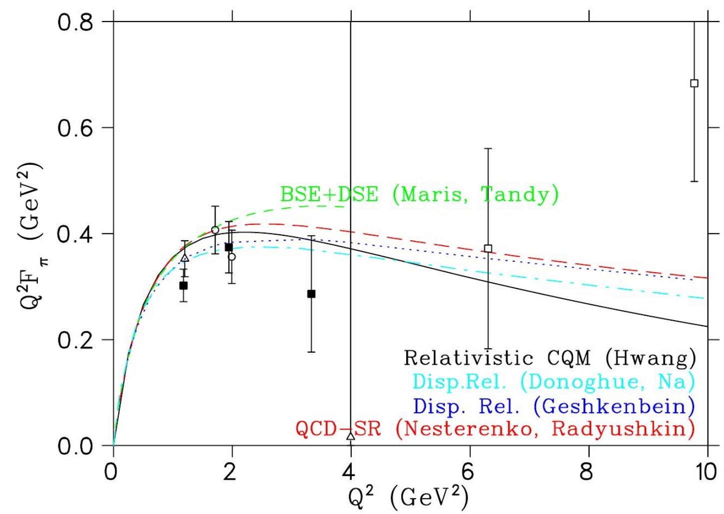


$$\sigma_0 P_x = hc^- \frac{R^t_{LT'}}{R_T + \epsilon R_L}$$

$$\sigma_0 P_y = c^+ \frac{R^n_{LT}}{R_T + \epsilon R_L}$$

$$\sigma_0 P_z = hc^0 \frac{R^l_{TT'}}{R_T + \epsilon R_L}$$

$$R = \frac{\sigma_L}{\sigma_T} = \frac{1}{\epsilon}\left(\frac{1}{\chi_z} - 1\right)$$

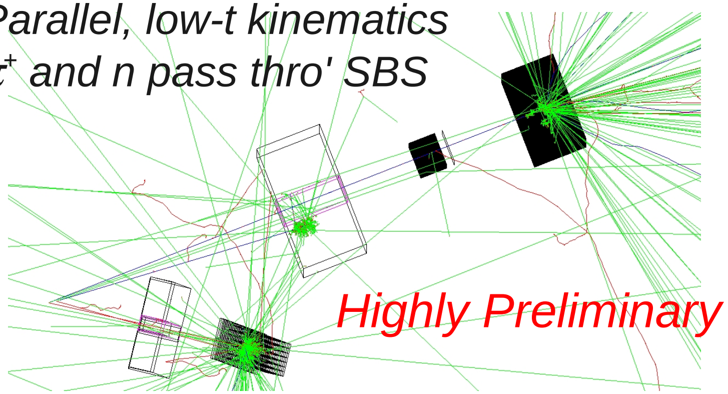


- Maximise t-channel contribution and t-channel separation from other processes
- Keep |t| < 0.2 (GeV/c)"
- W large, above resonance region
- How to separate σ_L ?

  Rosenbluth, Recoil Polarisation?

  See J.J. Kelly et al, Phys. Rev. C75(2007),025201

Parallel, low-t kinematics
π^+ and n pass thro' SBS



Status for Nucleon Recoil Polarimetry

Nucleon resonance spectroscopy

- Recoil measurements P, O_x, C_x continue at Mainz Mk-II polarimeter
- Preliminary results already impacting strongly on SAID PWA

Gen/GMn

- Jefferson Lab. Proposal 2011
- How high in Q^2, before beam-time request impractical
- Plan to measure CH_2 (plastic scint.) neutron analysing power necessary
- G_{Ep}/G_{Mp} measurement by recoil pol. already approved

π^+ electric form factor

- Rosenbluth separation of longitudinal response difficult.
- Independent measurement by n-polarimetry would be desirable
- Small t, hence low p_n... 200-300 MeV/c very challenging

Neutron analysing power measurements at high momentum

- Possible at Dubna
- Polarised d source $\rightarrow$ polarised p or n
- Nuclotron accelerator p_d up to ~12.8 GeV/c
- Measurement of analysing power of CH_2 (plastic scintillator) using reduced version of JLab polarimeter under discussion (N. Piskunov)

Motivation for Extending G_{Mn} to high Q^2

Theory Review: The theoretical interest in extending this measurement to to the highest possible Q^2 is very general and unassailable.

- Among the simplest, most fundamental of hadronic observables
- Provides a definitive test of any theory
- Elastic form factors provide anchoring base for GPD fits and prediction
- Comparison of G_{Mn} and G_{Mp} of particular interest

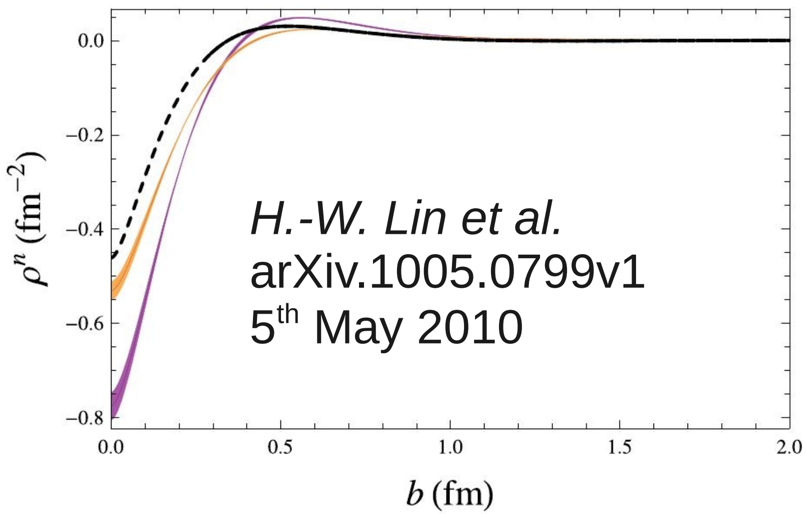
  Compare high-Q^2 scaling behavior

  From G_{Mn} and G_{Mp} access isovector form factor, "more doable" by LQCD to high Q^2

  Extract G_{Mn} for u and d quarks

  Quark transverse charge density of neutron related to G_{Mn}

$$\rho(b) = \int_0^\infty \frac{QdQ}{2\pi} J_0(bQ) F_1(Q^2) \qquad F_1 = \frac{G_E + G_M}{1+\tau}$$



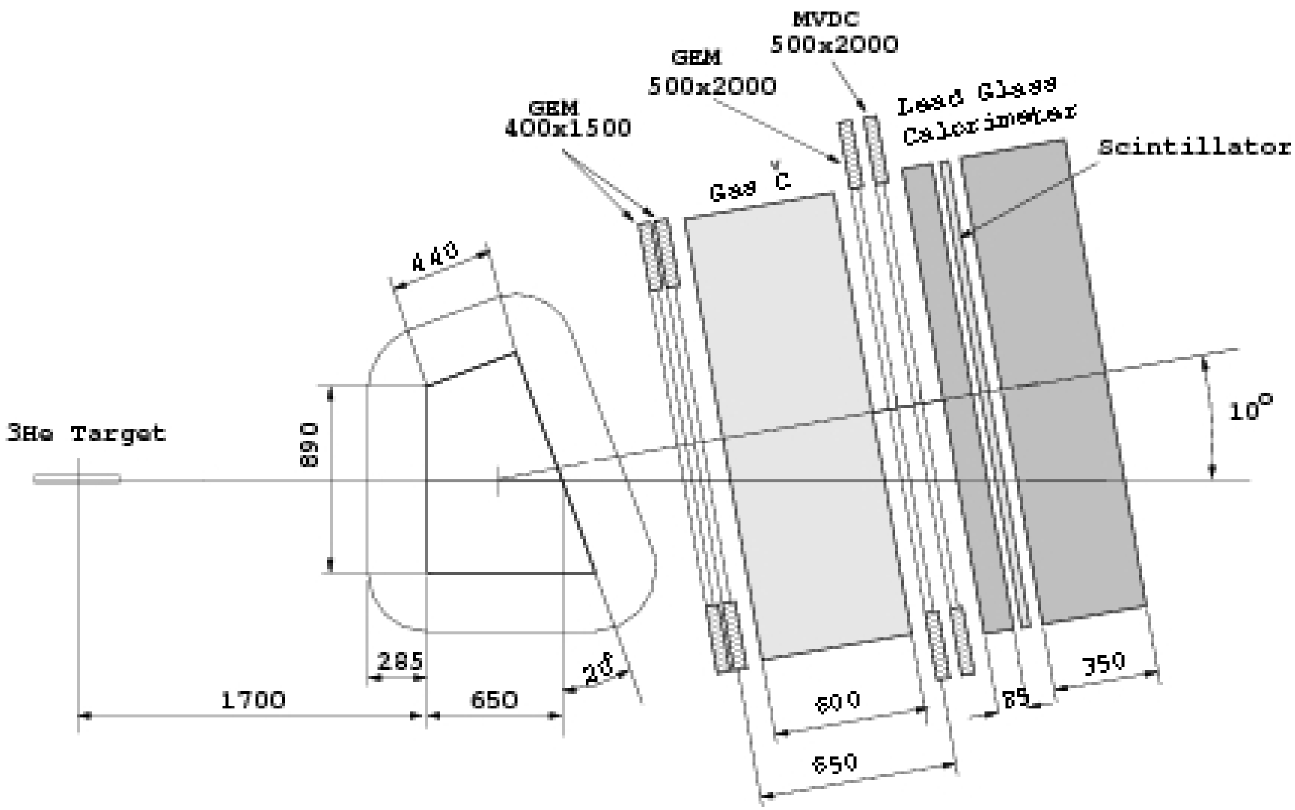
H.-W. Lin et al.
arXiv.1005.0799v1
5th May 2010

Backup II: G_{Mn} Systematic Errors

Table 3: Estimated contributions (in percent) to systematic errors on R.

Q^2 (GeV/c)^2	3.5	4.5	6.0	8.5	10.	12.	13.5	16.	18.
proton cross-section	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	4.
G^n_E	1.8	1.4	0.67	0.81	2.0	1.28	0.74	.929	.42
Nuclear correction,	-	-	-	-	-	-	-	-	-
Accidentals	-	-	-	-	-	-	-	-	-
Target windows	.2	.2	.2	.2	.2	.2	.2	.2	.2
Acceptance losses	0.1	0.07	0.2	0.16	0.1	0.16	0.13	0.16	.11
Inelastic contamination	0.16	0.7	2.3	2.5	2.5	2.7	4.6	4.6	5.4
Nucleon mis-identification	1.	0.3	0.6	1.	0.3	0.3	0.3	0.3	0.3
HCal calibration	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Without proton err.									
Syst. error on G^n_M/G^p_M	1.07	0.84	1.32	1.36	1.62	1.47	2.34	2.52	2.74
With proton err.									
Syst. error on G^n_M	1.37	1.19	1.57	1.6	1.83	1.70	2.49	2.66	3.39

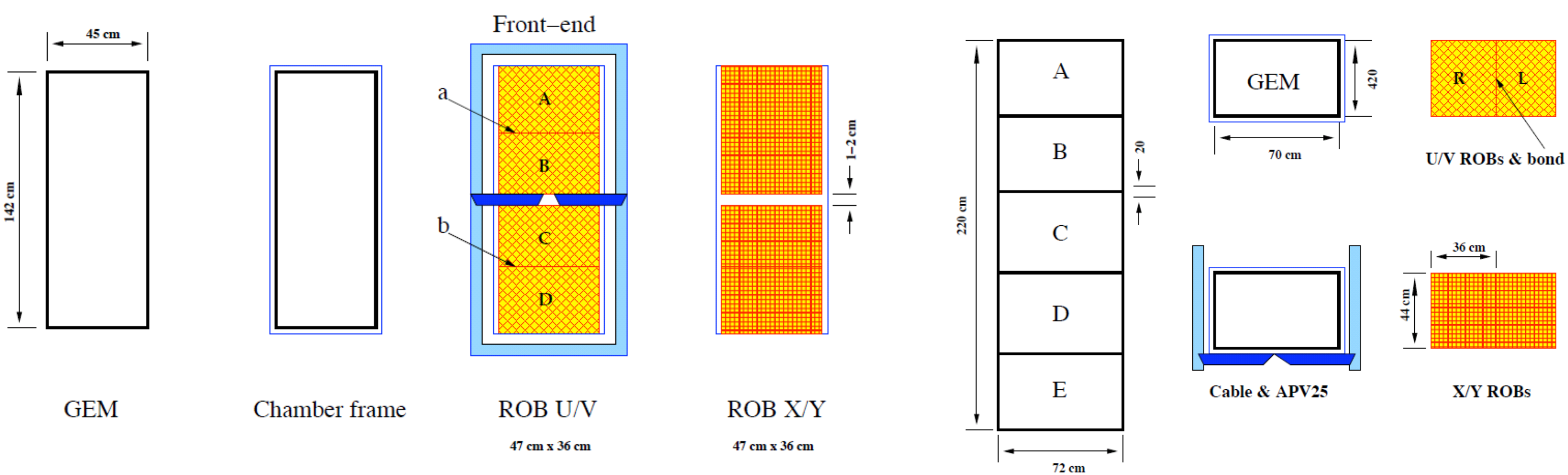
Common Apparatus: BigBite e' Detector



BigBite Spectrometer

Instrumented with
GEM planes from SBS
GAS Čerenkov
Shower Counter

GEM gives
increased luminosity
w.r.t. VDC tracker

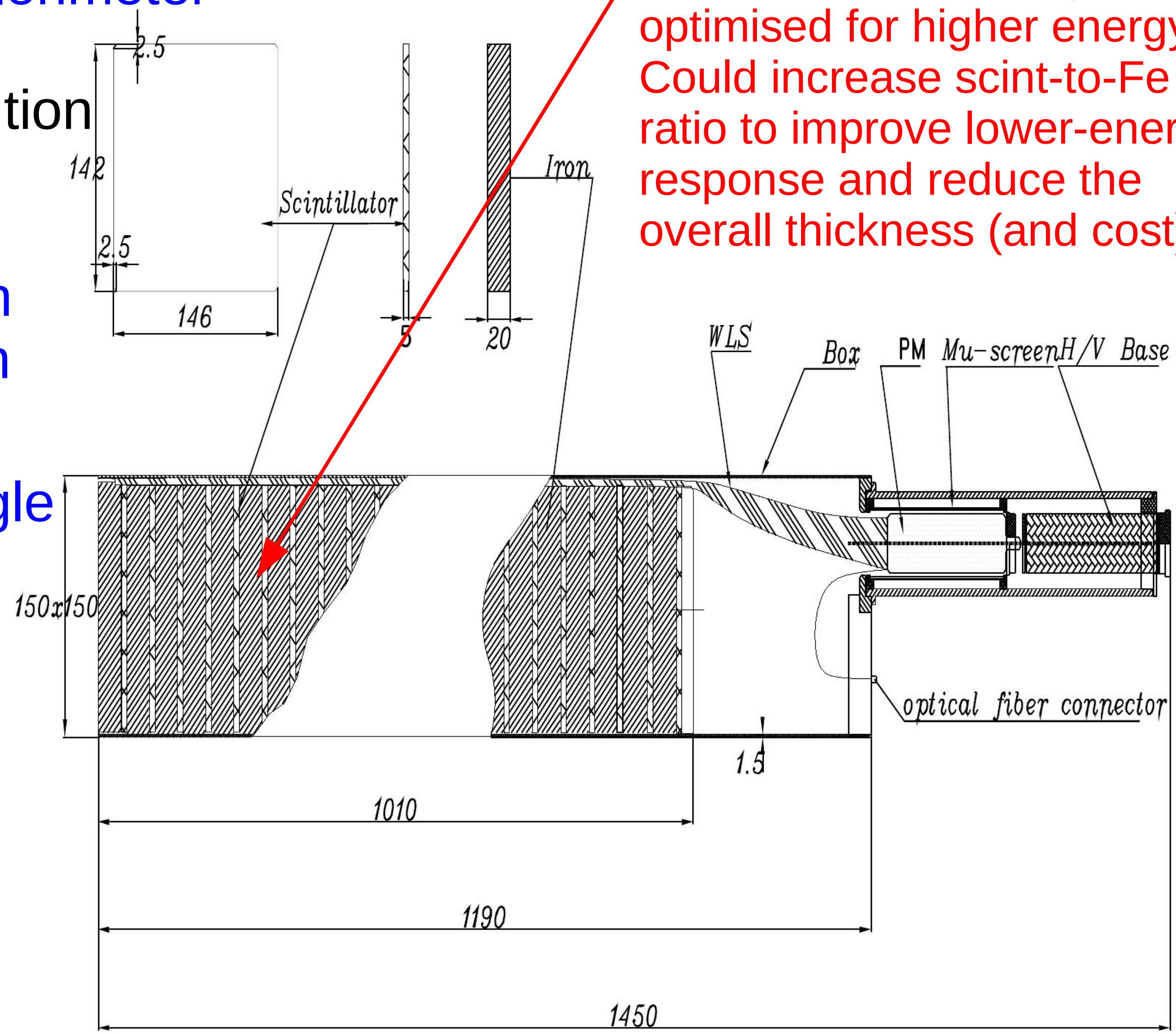


Common Apparatus: HCal

Hadron Calorimeter (HCal) to be built (CMU lead) for SBS

- Replacement for BigHAND stack
- Fe/scintillator sampling calorimeter
- 11 x 22 identical modules
- Reasonable energy resolution
- High threshold
- High Luminosity
- Excellent spatial resolution
  - G_{Mn} Tight cut on nucleon direction (wrt q-vector)
  - G_{En} Good scattering-angle determination
- High efficiency for n and p
  - $\varepsilon_p \sim \varepsilon_n$ (cancel in ratio)

COMPASS Modules (Dubna) optimised for higher energy
Could increase scint-to-Fe ratio to improve lower-energy response and reduce the overall thickness (and cost)



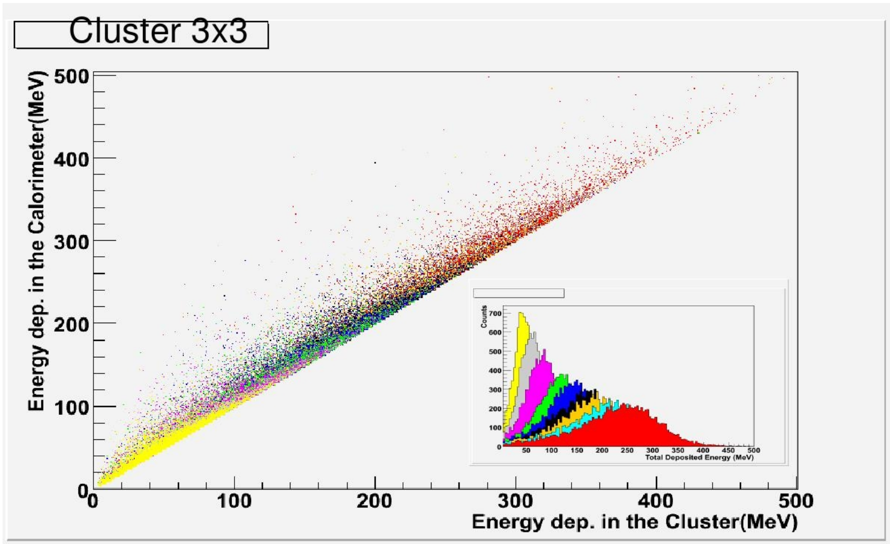
Monte Carlo Studies for G_{En} & G_{Mn}

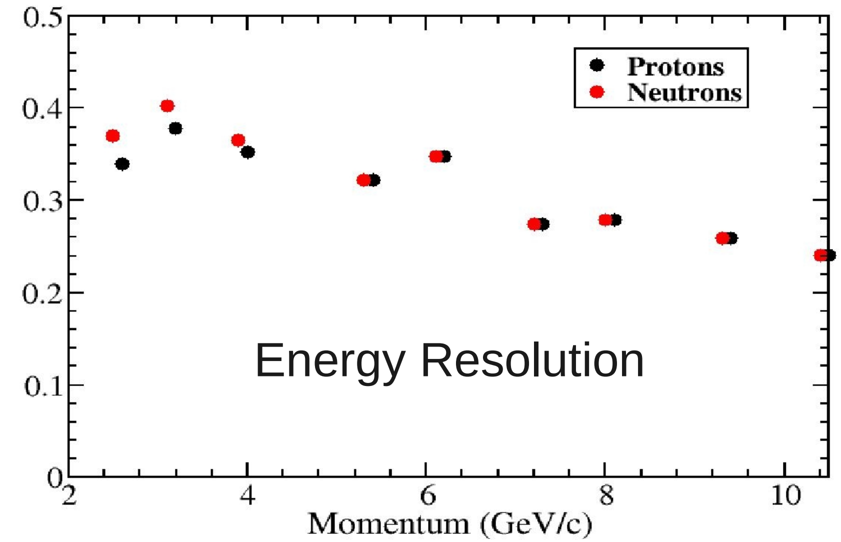
- JRMA Geant-4 + ROOT. ROOT based event generator and analyser of MC simulated output. Geant-4 based model of BigBite, SBS, analyser array and HCAL. Simplistic representation of tracking detectors
- CMU (Fatiha Benmokhtar) studies of HCAL (using JRMA code)
- JLab (Sergey Abrahamyan) Geant-3.21 model + DINREG. (P.Degtiarenko) estimate counting rates in detectors
- Dubna (I. Savin, N.Vlasov and V.Krivokhizhin) Geant-4
- JRMA method: Event-by-event output also saved as a ROOT tree
  Energies, Hit times, Hit coordinates detector elements
  4-momenta of original generated particles
- Analyse output from G4 simulation (as would be done for real data)
  Add Gaussian smearing energies, times etc at this stage
  Use energies, times and central coordinates of detector elements to analyse clusters of struck elements.
  Compare with actual hit positions and kinematics of original particle(s)

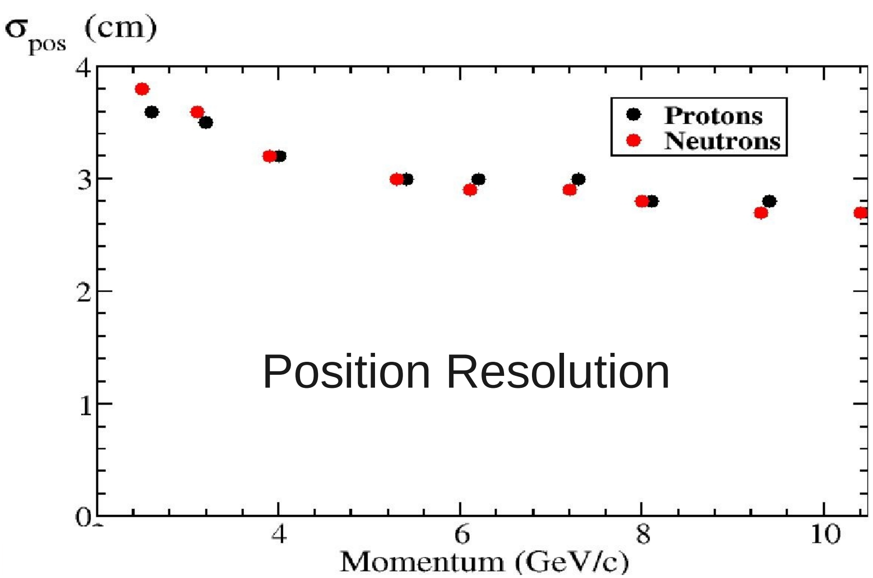
University of Glasgow

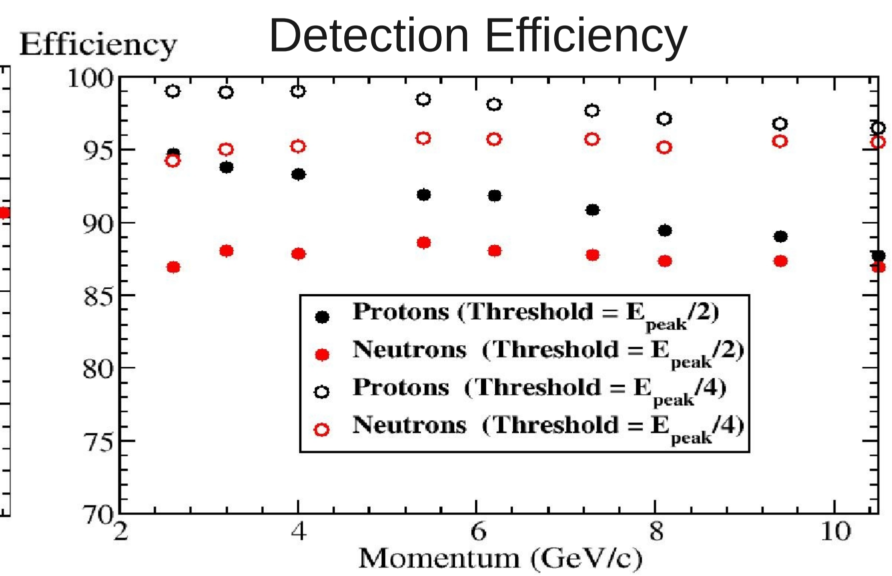
HCal Response: Calculations by F.Benmokhtar

The response to several-GeV protons and neutrons is very similar
Minimise systematic effects in determining G_{Mn} by the ratio method

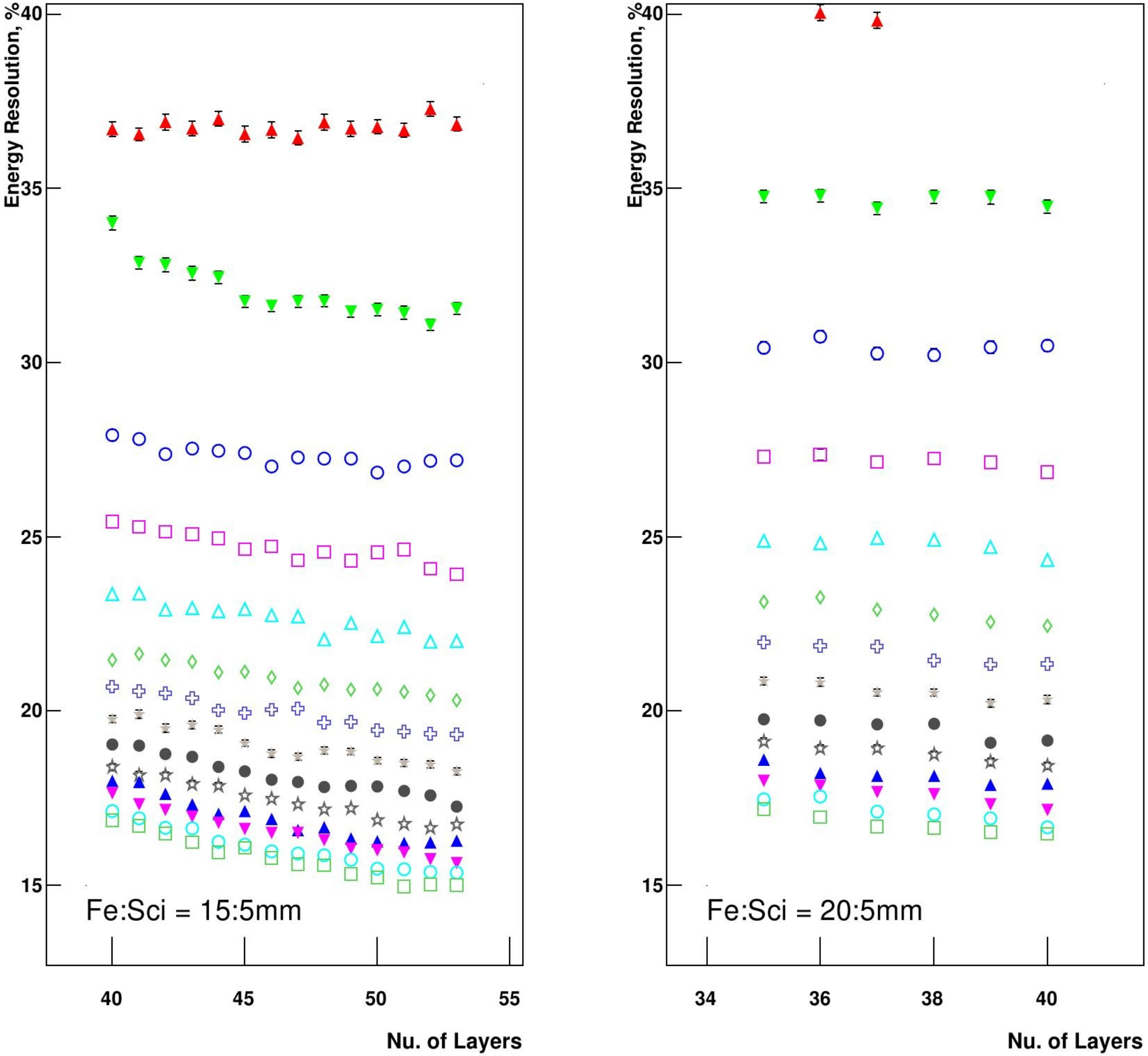








Dubna Calculations, I.Savin et al.

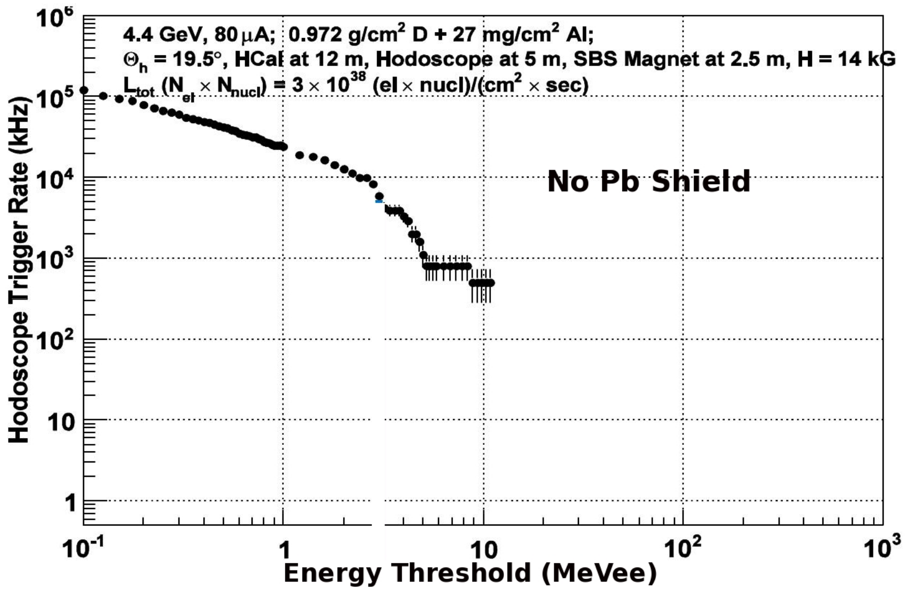


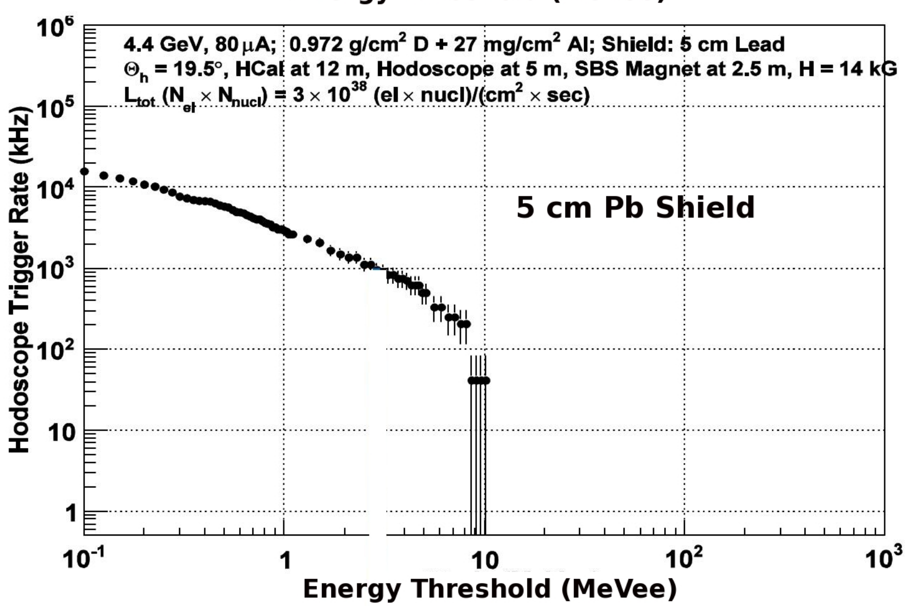
- **Incident Protons**
- Geant-4.9.3
- LHEP Hadronic Interaction Package
- Energy 1 – 15 GeV
- 2 Fe-Scintillator ratios
  15mm Fe/5mm Scint
  20mm Fe/5mm Scint
- Vary number Fe-Sci layers.

Should confirm these... also for neutrons
Check the influence of different hadronic interaction models (e.g Bertini Binary Cascade in nuclei)

The Polarisation-Analyser Array

DINREG Rate Predictions





Analyser Array of Plastic Scintillator bars

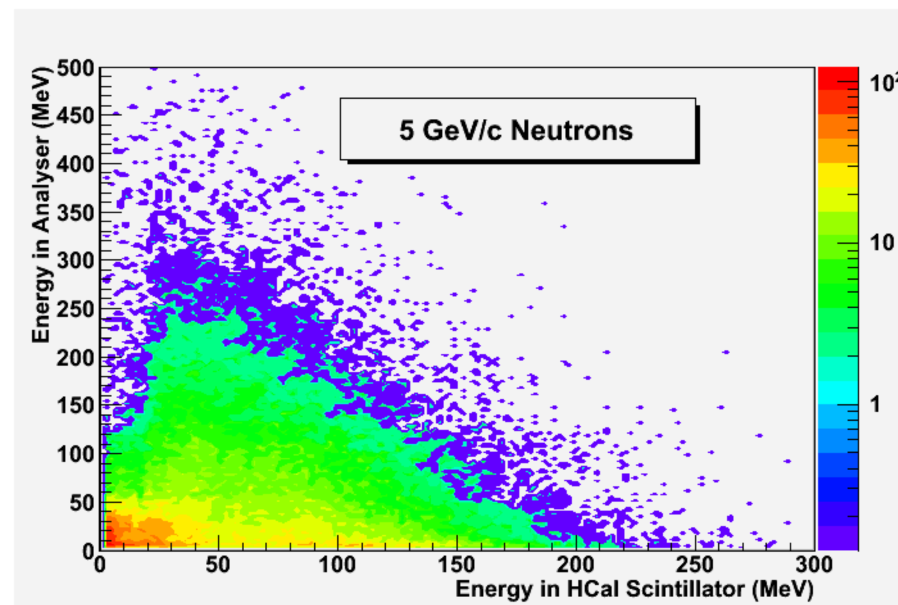
- Aligned long-axes parallel to the direction of incident neutrons.
- Rate calculation by Sergey Abrahamyan

  $Q^2 = 5.4\ GeV^2$, $L = 3x10^{38}\ Hz.cm^{-2}$

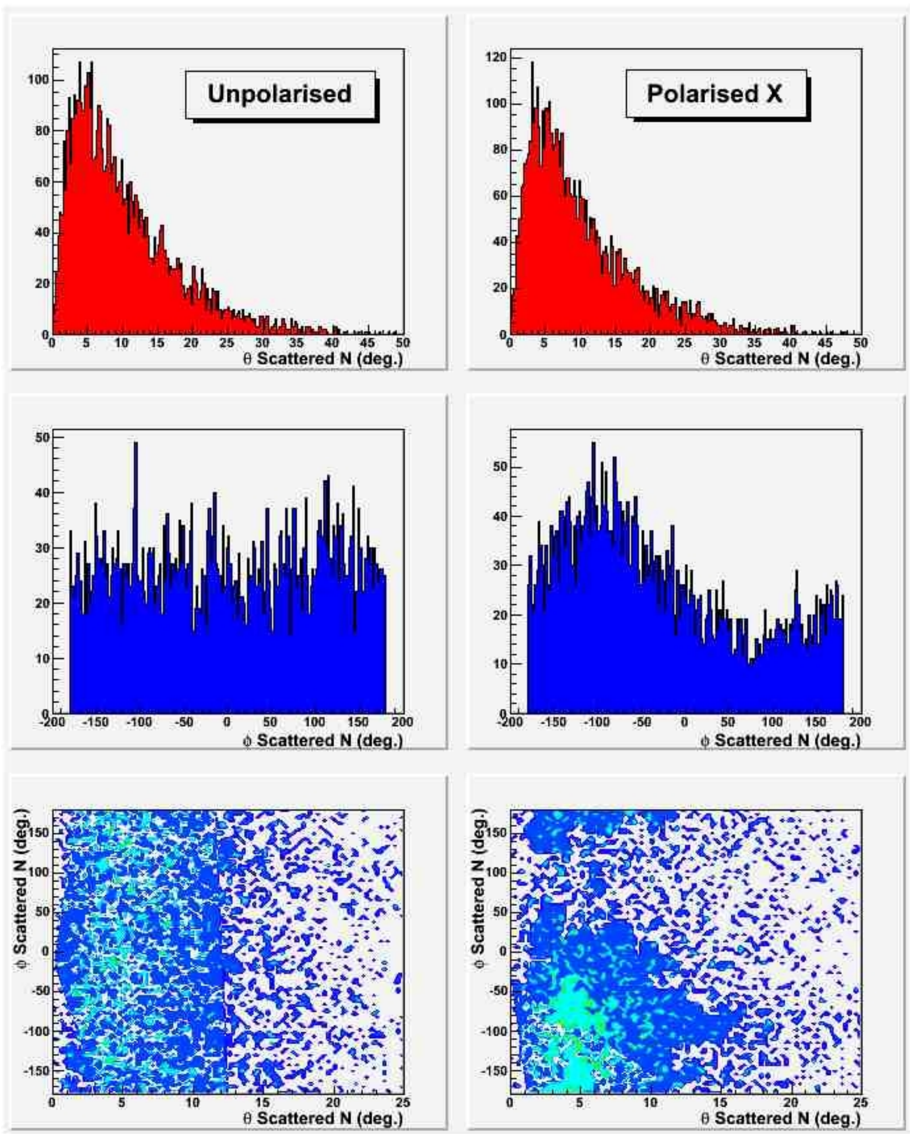
  Ee = 4.4 GeV

  5 x 5 x 20 cm bars
- Rate as a function of applied threshold
- With/without 5cm Pb shield wall

JRMA has assumed 2.5 x 2.5 cross section 25 or 50 cm length polarimetry simulation



Preliminary Polarimetry Analysis II



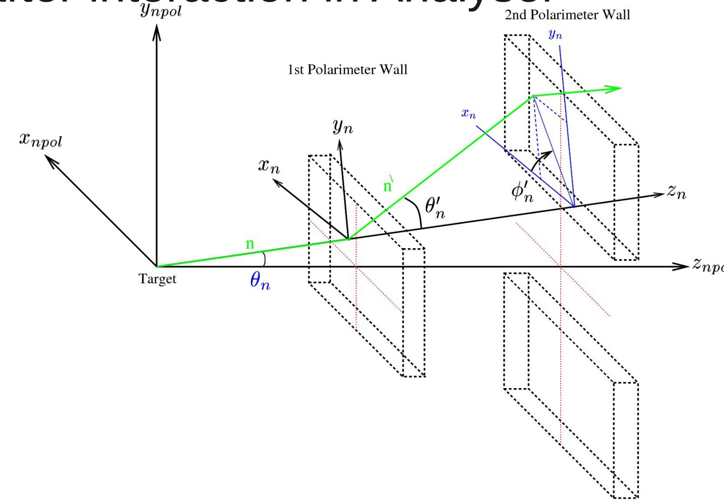
2 – 9 GeV Neutrons incident
on a 250 mm thick analyser block

Neutron either unpolarised or
Polarised along x-direction (horizontal)

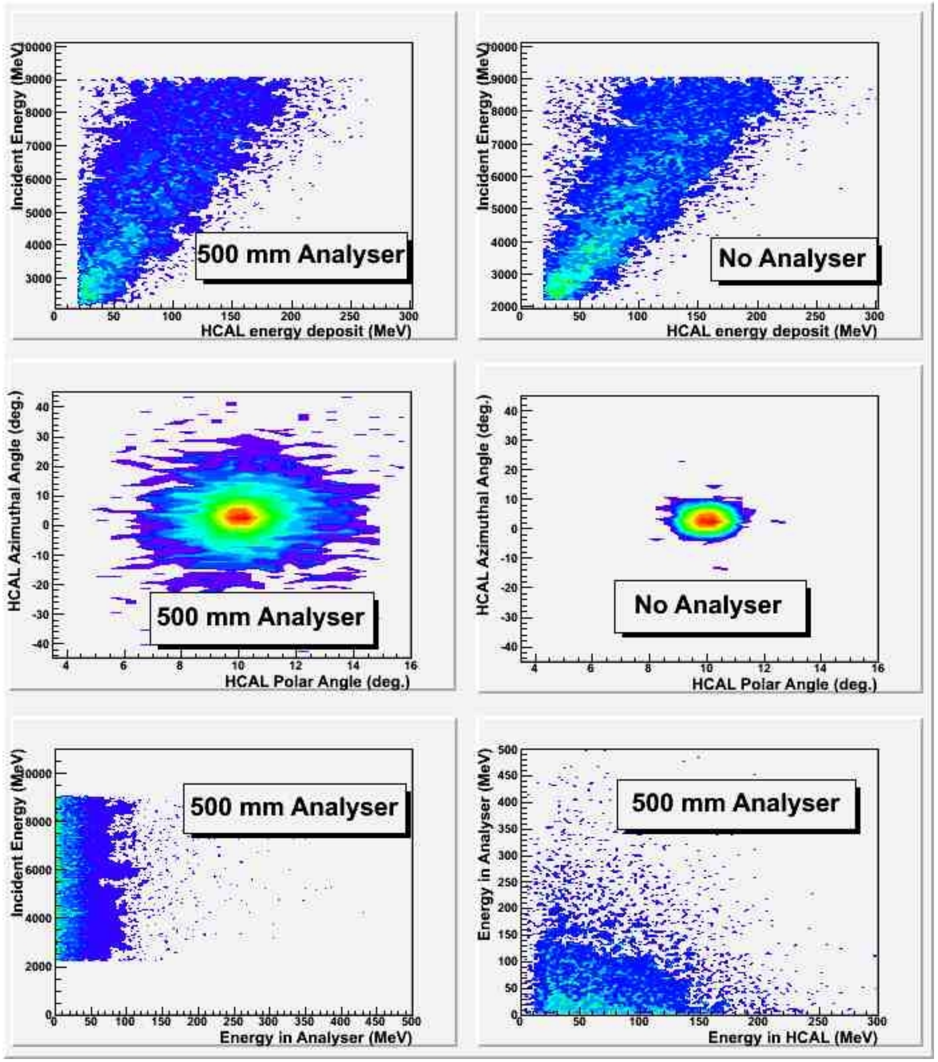
Analysing powers set to 1.0

Analysis of MC-generated date
Requiring that the scattering events
are prompt.

No differentiation of type of particle
after interaction in Analyser

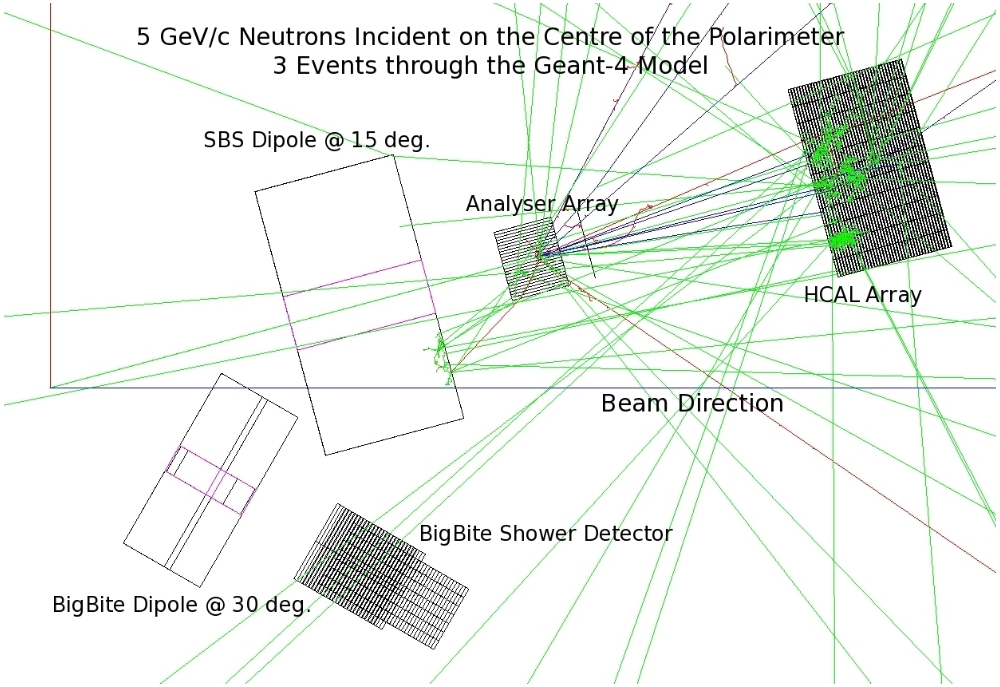


Preliminary Polarimetry Analysis



Fire neutrons 2 – 9 GeV
at the center of the analyser block and record the energies times positions etc. of the signals in the Analyser and HCAL arrays

Reconstruct energy deposited and hit positions through a cluster analysis



Some Ancient History
Q: What is a form factor?

$$\sigma_M(\theta) = \left(\frac{Ze^2}{2mc^2}\right)^2 \left(\frac{1-\beta^2}{\beta^4}\right) \frac{1-\beta^2 \sin^2 \frac{\theta_e}{2}}{\sin^4 \frac{\theta_e}{2}}$$

$$\sigma_N(\theta) = \sigma_M \left| \int_{vol} \rho(r) e^{i\boldsymbol{q}.\boldsymbol{r}} d\tau \right|^2$$

$$= \sigma_M \left| \int_0^\infty \rho(r) \frac{\sin qr}{qr} 4\pi r^2 dr \right|^2$$

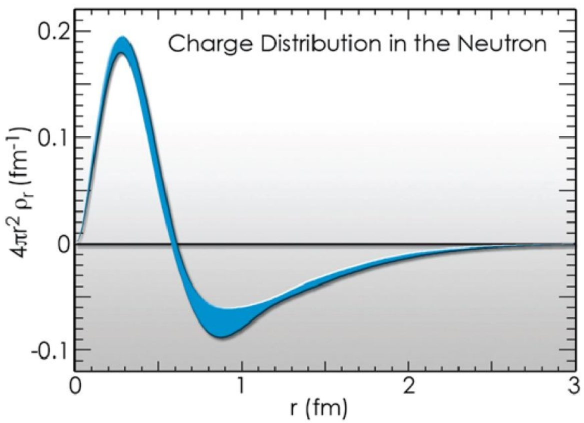
$$F = \frac{4\pi}{q} \int_0^\infty \rho(r) \sin(qr) r\, dr$$

1st Born approximation used to calculate:

- The differential cross section for elastic electron scattering
- Contains the Mott term σ_M (scattering from a point object)
- + An integral dependent on the charge density ρ(r) and momentum transfer **q**.
- $\sigma_N \sim \sigma_M.|F|$

A: a form factor (FF) describes the extended, non point-like structure of a non-elementary particle. Sometimes also called “structure factor”.
Hofstadter started the nuclear electron-scattering industry rolling around 1953, using elastic scattering to measure the sizes and shapes of atomic nuclei (and subsequently nucleons).
R.Hofstadter, Rev. Mod. Phys. 28 (1956)

At low Q^2 FFs ~ Fourier transforms of charge and current distributions



Nucleon Electromagnetic Form Factors

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

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

$$G_E = F_1 - \tau F_2$$

$$G_M = F_1 + F_2$$

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

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

- 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 these are recast in terms of the Sachs form factors G_E and G_M $\tau = Q^2/4M_N^2$
- 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
- Rosenbluth Separation in 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 are large
- More recently the single photon exchange approximation in electron scattering has been questioned. Seems invalid for precision measurements of differential cross sections at high Q^2
- Polarisation variables are much less sensitive to multi-photon exchange effects
- They also provide a means to extract a weak amplitude with good precision