Nucleon form factors experiments with 12 GeV CEBAF

Nucleon FFs in 12 GeV era and Large Acceptance Large Luminosity Spectrometer for Hall A TJNAF

Bogdan Wojtsekhowski, Jefferson Lab

Outline of the talk

- status of FFs, connection FFs and GPDs, and calculation of the transverse densities

- 12 GeV program: GMP-18, GEP-15, GMN-17, and GEN-7.5 GeV^2

- New spectrometer concept and applications

- Road map of construction

Highlights of electromagnetic FFs

- Direct observation of the nucleon structure: Hofstadter 1950th
- Rosenbluth: L/T separation in 1950, Akhiezer: A_{LT} in 1957

- SLAC measurement of G^p_M up to 30 GeV^2
- pQCD dimensional scaling: F1 ~ $1/t^2$ and F2/F1 ~ 1/t

- Polarized electron beam era: Sinclair's electron source in 1977
- CEBAF with polarimeter and polarized targets in 1990th

- Unification of DIS/FF/DVCS in GPDs by Muller, Ji, Radyushkin
- G^p_E/G^p_M vs Q^2 dependence, discovery by Perdrisat etal
- G^n_M/G^p_M precision measurement by Brooks etal
- G^n_E/G^n_M measurements at NIKHEF, Mainz, JLab, BATES

- Transverse densities by Burkardt, Diehl@C, Miller, Boffi&Pasquini ..

Perspectives of the field in 12 GeV era

Electro-Magnetic Form Factors

One-photon approximation, α_{em} = 1/137, hadron current

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

Rosenbluth (1950)

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

Guichon & Vanderhaeghen

$$\mathcal{M} = \frac{4\pi\alpha}{Q^2}\bar{u}'\gamma_{\mu}u \cdot \bar{N}'\left(\tilde{F}_1\gamma^{\mu} - \tilde{F}_2[\gamma^{\mu},\gamma^{\nu}]\frac{q_{\nu}}{4M} + \tilde{F}_3 K_{\nu}\gamma^{\nu}\frac{P^{\mu}}{M^2}\right)N$$

Afanasev et al.

Blunden et al.

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

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

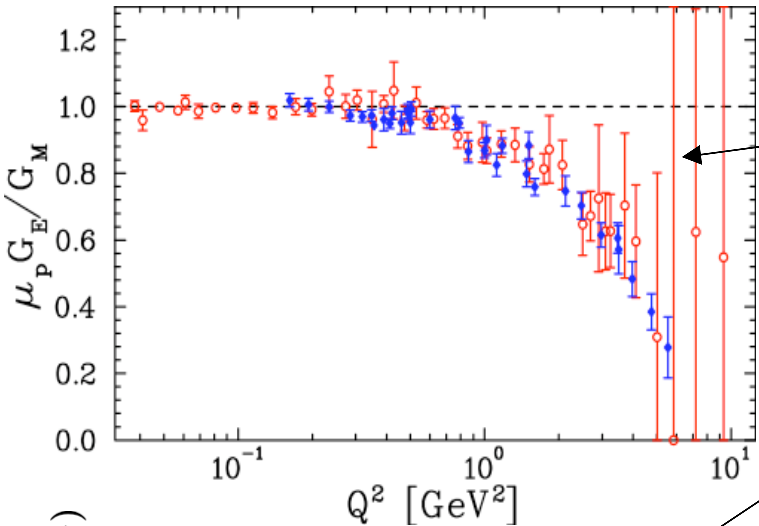
$$d\sigma = d\sigma_{NS}\left\{\varepsilon(\tilde{G}_E + \frac{s-u}{4M^2}\tilde{F}_3)^2 + \tau(\tilde{G}_M + \varepsilon\frac{s-u}{4M^2}\tilde{F}_3)^2\right\}$$

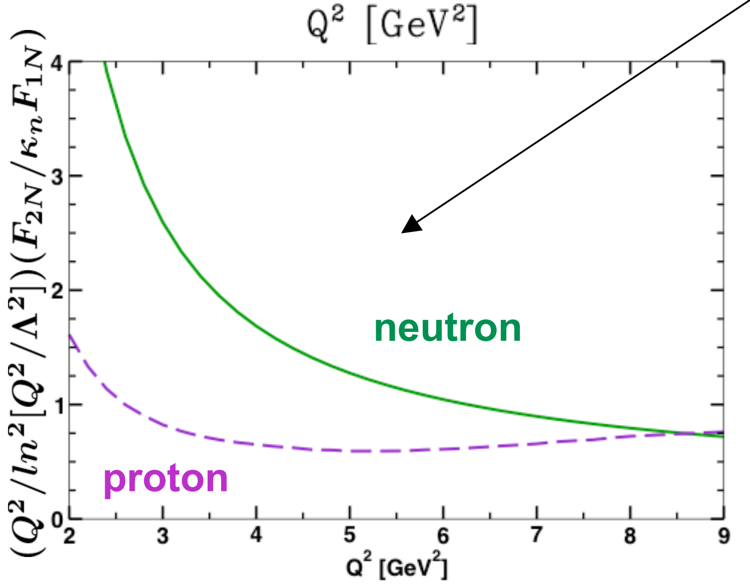
old $G_{E,M}$ are real functions of $t=-Q^2$

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

Extra terms contribute less than few % to σ_R

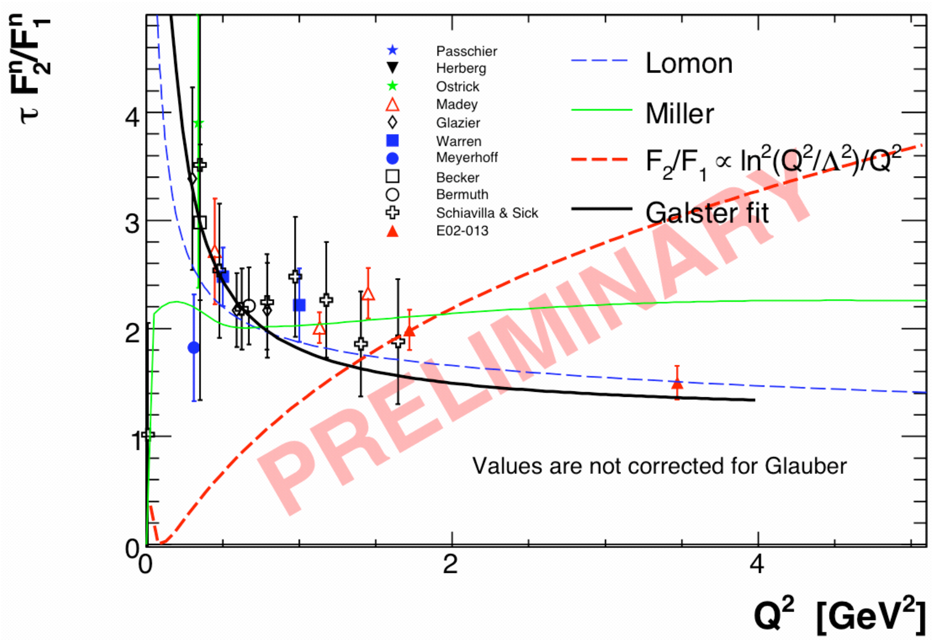
Recent development





- Rosenbluth analysis with 2–γ terms
  Arrington etal, nucl-ex:0707.1861
  E.Tomasi-Gustafsson etal,
  PRC 75 (2007)
- FFs from DSE approach in QCD
  C.Roberts, arXiv:0712.0633
- Confirmation of GEP at Q^2 ~ 4 GeV^2 with Focal Plane Polarimeter in HMS
  Perdrisat etal, [GEP-III]
- Constrain on 2–γ terms with ε scan at fixed Q^2 = 2.5 GeV^2 with FPP in HMS
  It was reported today by L.Pentchev

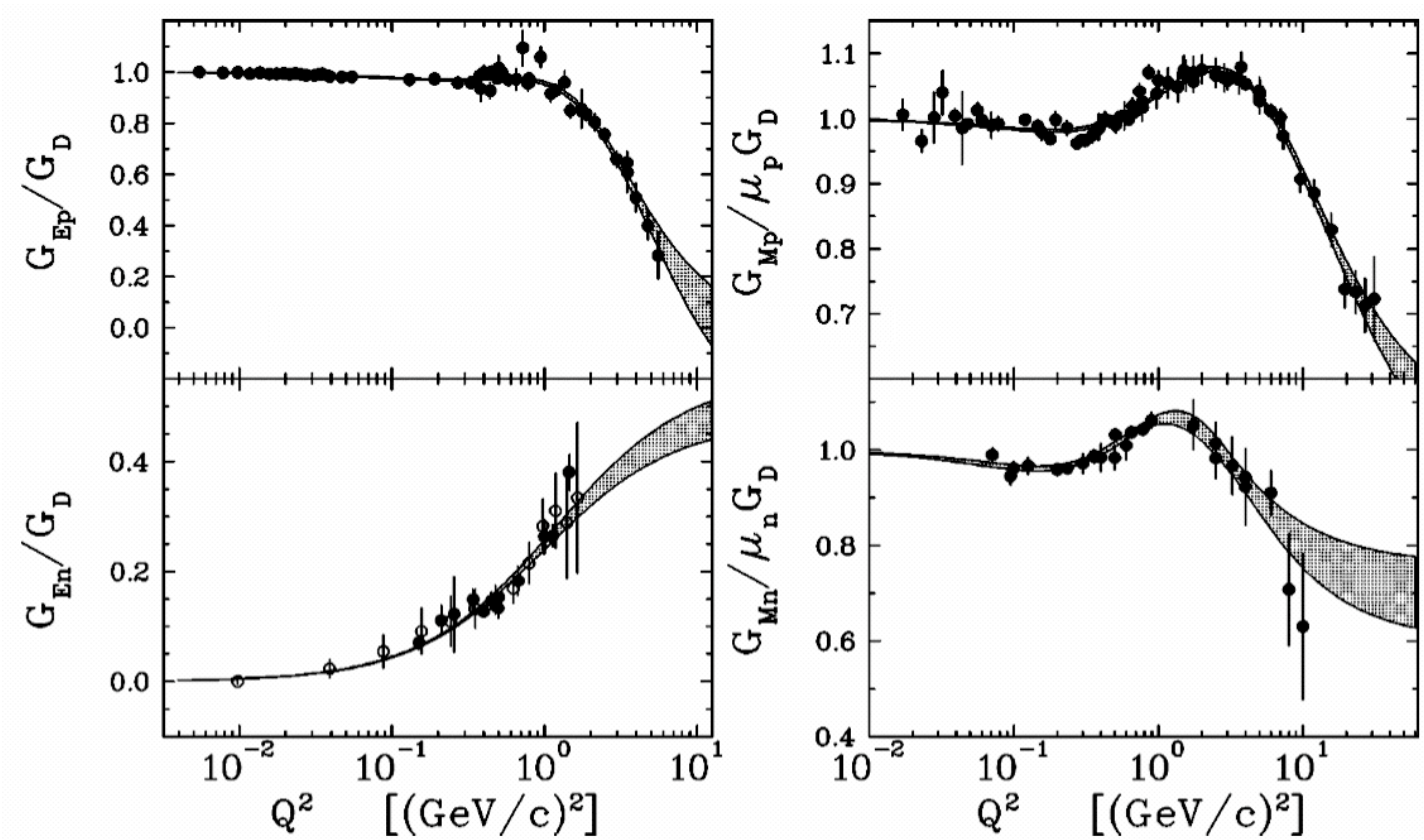
Last month news



- Preliminary result from JLab He-3(e,e'n) experiment for GEN/GMN at 1.7 and 3.5 GeV^2.
  more will be in June "Neutron FFs", Elba-X

- GEP-III is taking data for GEP/GMP at 8.5 GeV^2. E.Brash report in Trento

Kelly's parameterization



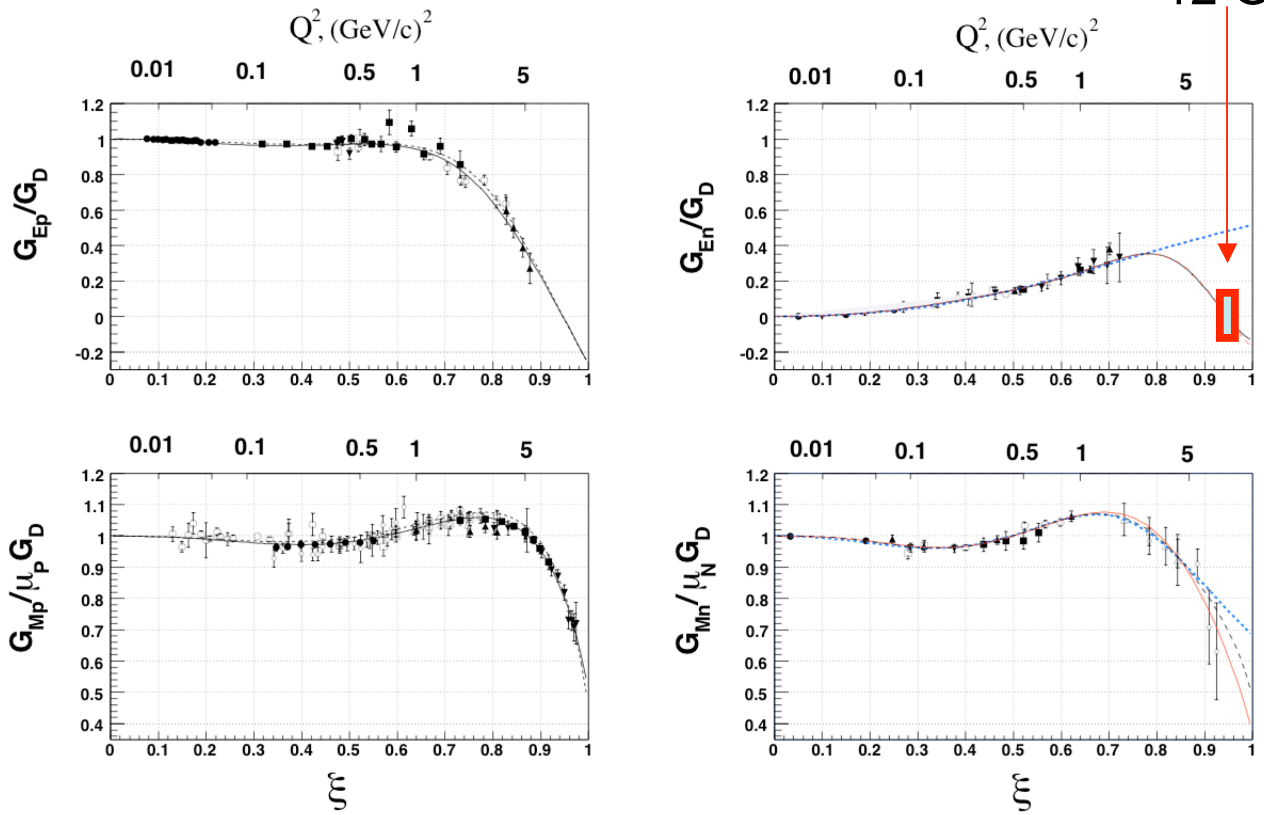
J. Kelly, PRC 70, 068202 (2004)

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

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

New parameterization

12 GeV



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

ξ is Nachtman scaling variable

Two constraints QCD motivated

Kelly's

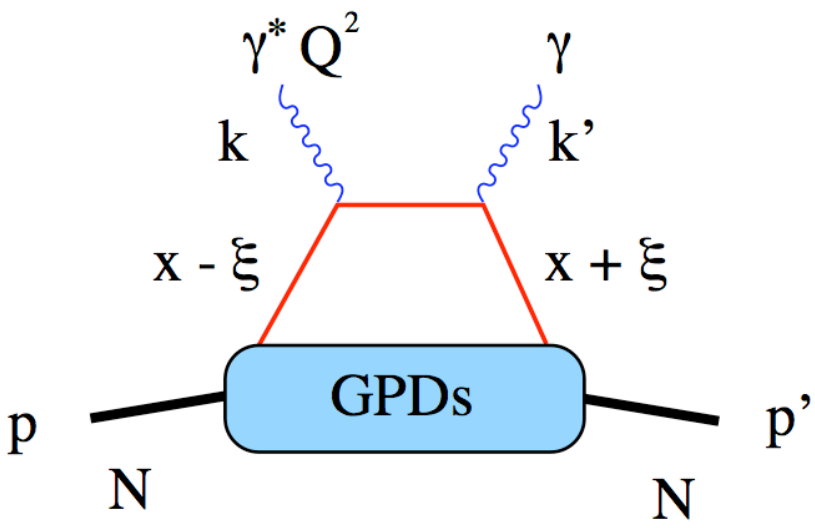
(d/u) = 0, 0.2

$$\xi^{p,n} = 2/(1+\sqrt{1+\tau_{p,n}^{-1}}) \qquad G_{BABB} = A(\xi)\times G_{Kelly}(Q^2)$$

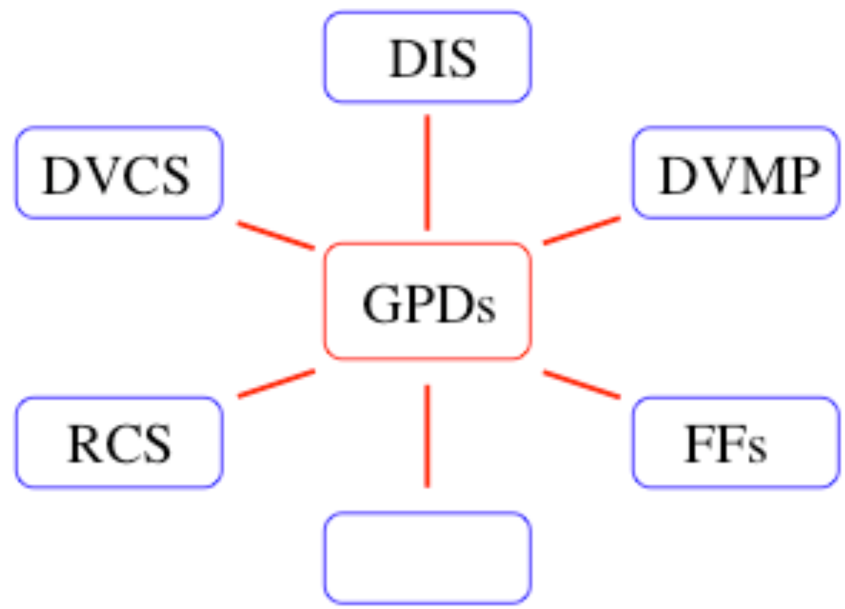
$$\text{constrains: at } \xi \to 1 \quad 1)\ \frac{G^2_{Mn}}{G^2_{Mp}} = \frac{1+4(d/u)}{4+(d/u)} \quad 2)\ \frac{G^2_{En}}{G^2_{Mn}} = \frac{G^2_{Ep}}{G^2_{Mp}}$$

GPDs of nucleon

Müller (94), Ji (97), Radyushkin (97)



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



Quark dynamics of nucleon encoded in GPD functions

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

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

GPDs information

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

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

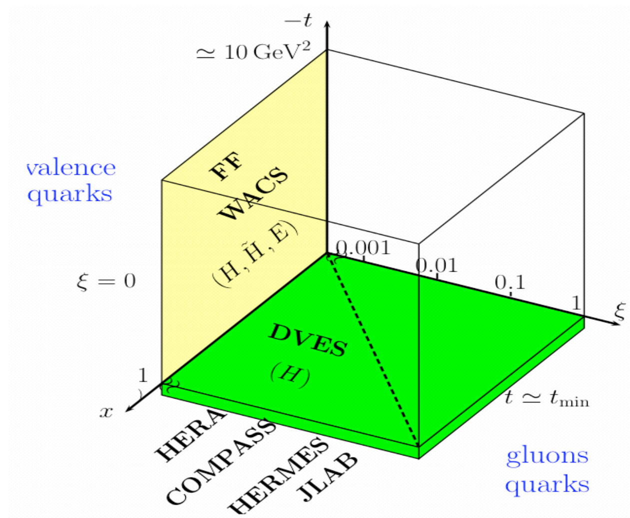
$$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$$

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

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

P.Kroll, Excl.-07

a lot to measure



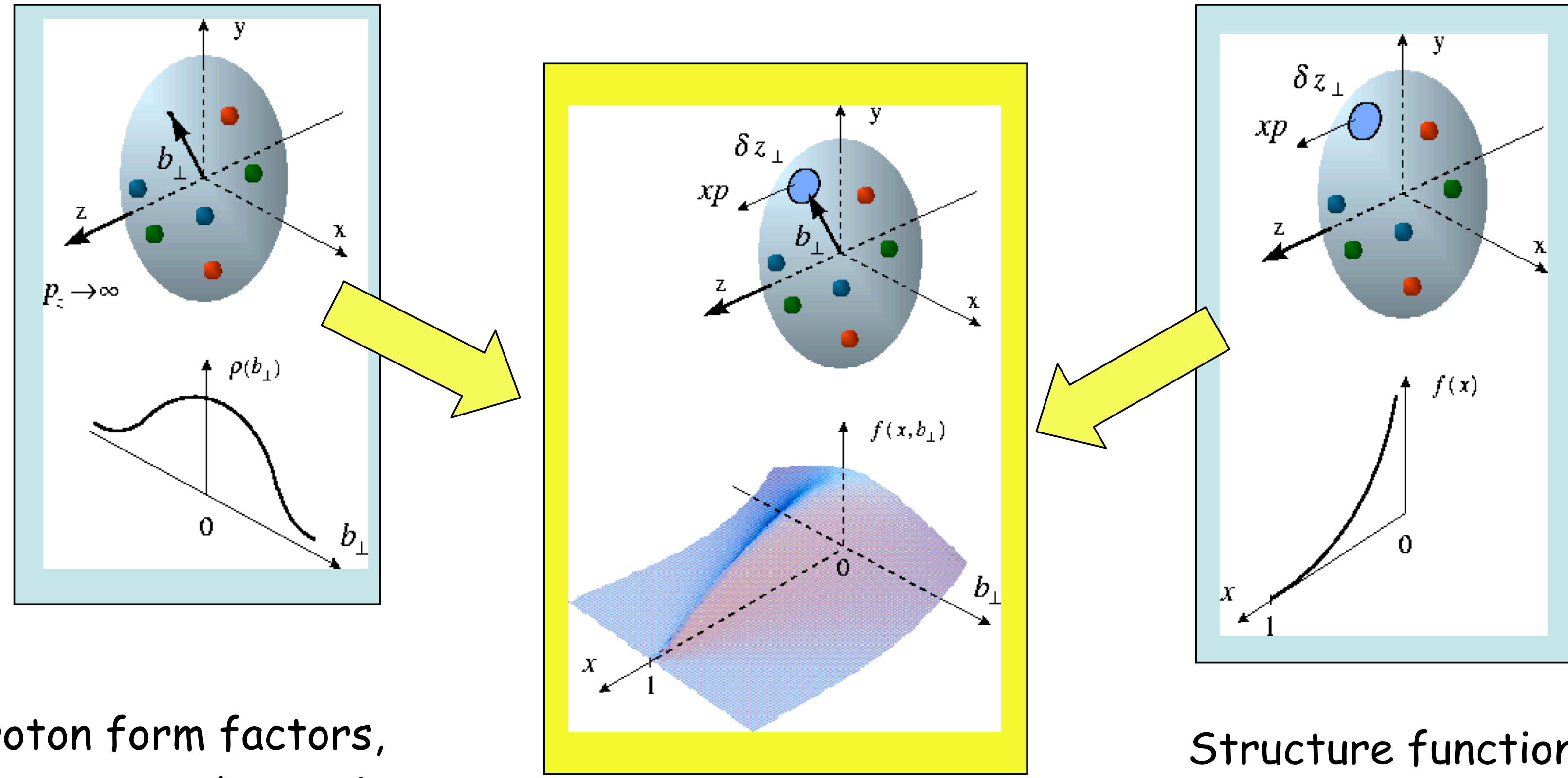
Ji's sum rule for quark orbital momentum

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

DVCS will access low t, large Q^2 kinematics

FFs presently are the main source for E_v^q

3-d picture of the nucleon



Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Impact parameter and densities

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

Muller, Ji, Radyushkin

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

M.Burkardt

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

P.Kroll: u/d segregation

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

G.Miller

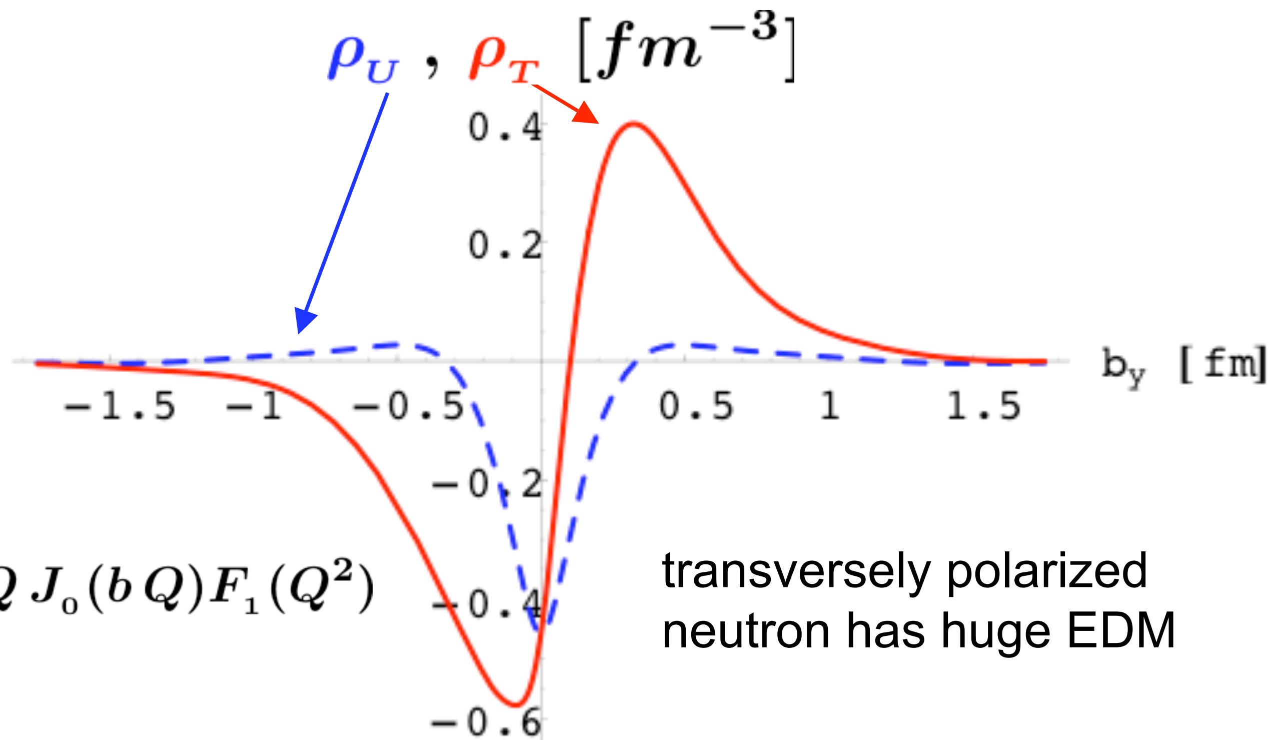
center of momentum $R_\perp = \sum_i x_i \cdot r_{\perp,i}$

b is defined relative to $R_\perp$

Transverse densities

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

C.Carlson &
M.Vaderhaeghen



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

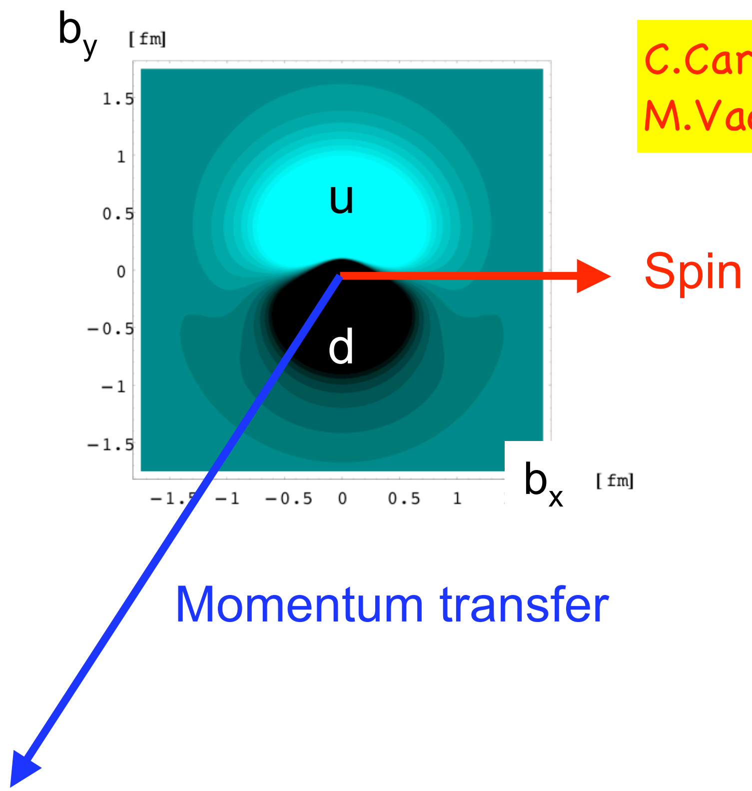
transversely polarized
neutron has huge EDM

Density in polarized neutron

Transversity effects in

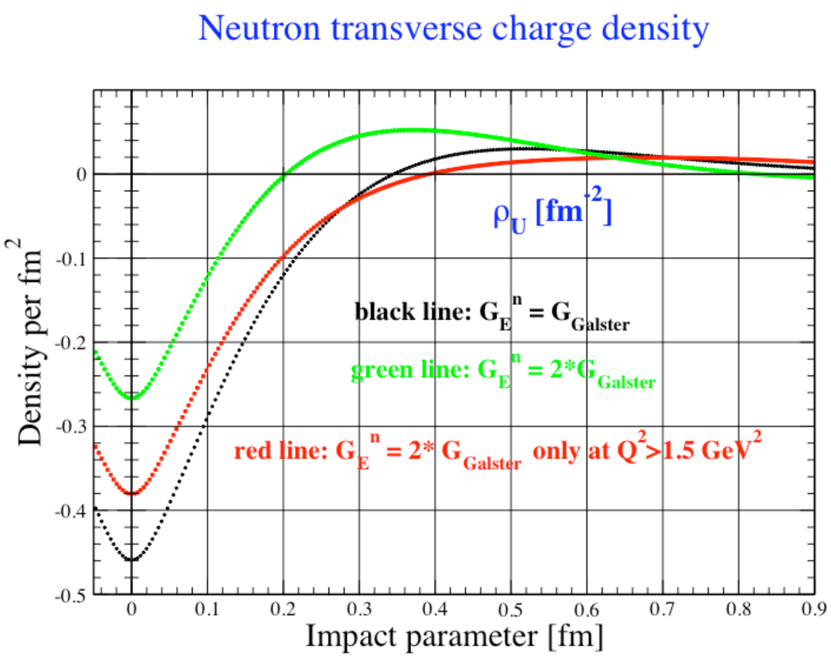
$$\vec{n}(e, e'\pi^-)X$$

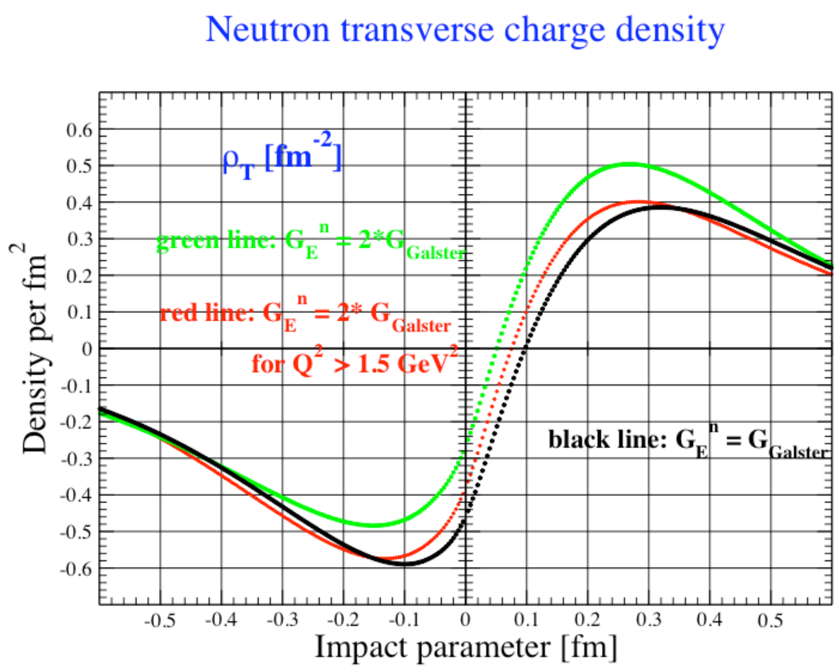
$$\vec{n}(e, e'\pi^+)X$$



C.Carlson & M.Vaderhaeghen

Effect of GEN





- Negative density at low **b** in a neutron => d quarks dominate
- High Q^2 elastic process in Feynman mechanism requires a large x quark, so d quarks dominate at large x, in agreement with DIS

CEBAF electron beam in 2013(4)

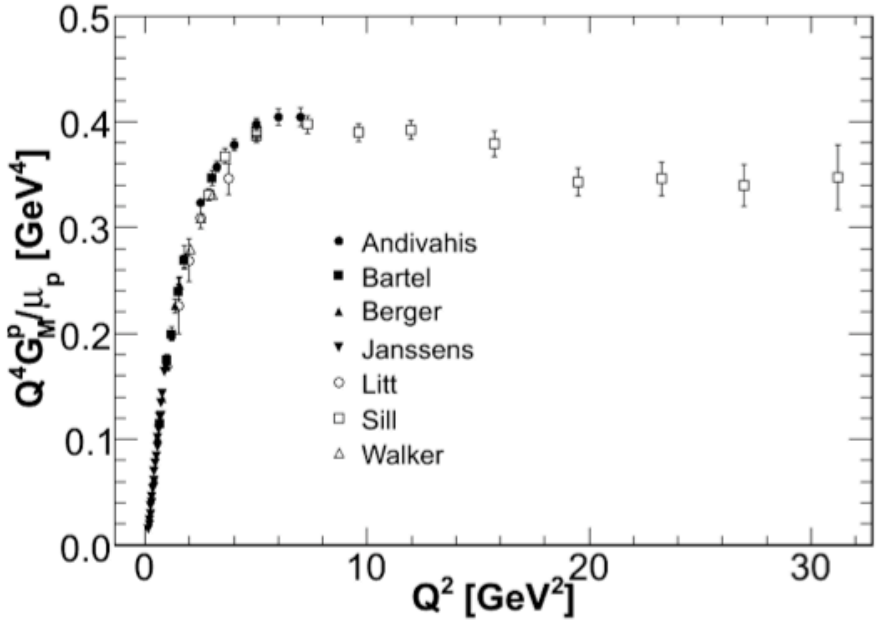
• Beam energy	11/12 GeV
• Beam power	1 MW
• Beam current (Hall A/D)	85/5 μA
• Beam polarization	85%
• Emittance @ 12 GeV	10 nm-rad
• Energy spread @ 12 GeV	0.02%
• Beam spot	~ 0.1mm
• Simultaneous beam delivery	Up to 3 halls

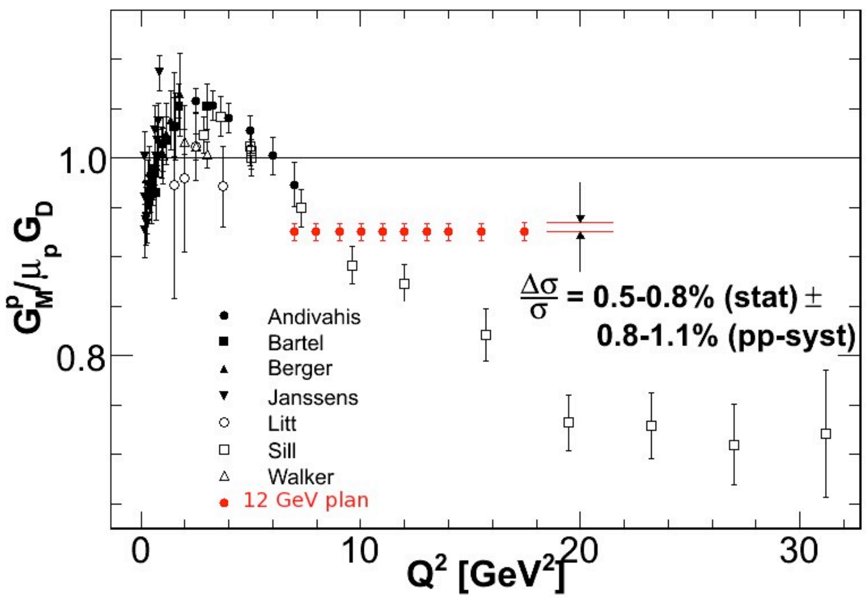
Hall A will be the first hall which will get the beam

GMP at high Q^2

precision data for GMP with HRS at 11 GeV

B.Moffit, S.Gilad, J.Arrington & BW





GMP is the base for all other form factor measurements

Approved single arm measurement will use existing HRSs of Hall A, high luminosity, well understood optics, enhanced detector packages

GMP with HRS

E_{beam}, GeV	Q^2, GeV^2	θ_e degree	$E_{e'}$, GeV	Time, days	Events
6.6	7.0	35	2.87	0.1	40k
	8.0	42	2.35	0.2	40k
	9.0	52	1.78	0.5	40k
	10.0	67	1.25	1.5	40k
8.8	9.0	29	4.00	0.2	40k
	10.0	33	3.47	0.5	40k
	11.0	38	2.95	0.5	40k
	12.0	44	2.42	1.5	40k
	13.0	53	1.86	3.0	28k
11	13.0	31	4.07	1	28k
	14.0	35	3.53	2	24k
	15.5	42	2.74	2.5	20k
	17.5	58	1.69	12	16k

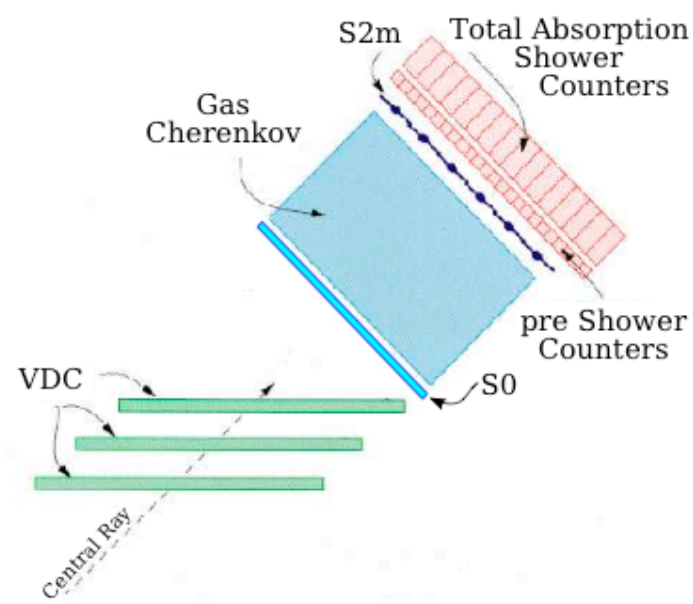


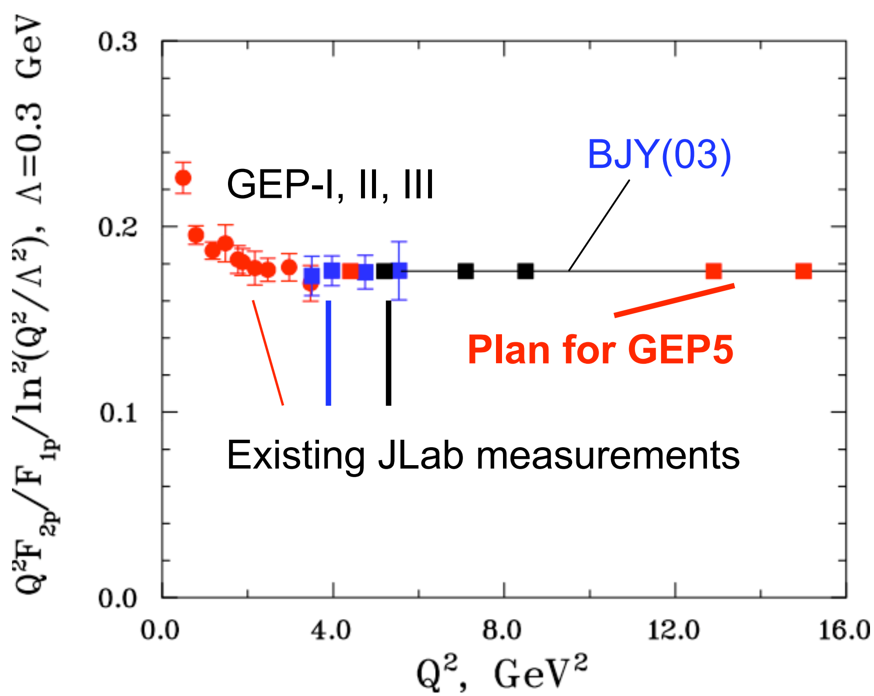
Table of kinematics
Systematical uncertainties
Advanced optics analysis

Improved track reconstruction

GEP/GMP for max Q^2

Pentchev, Perdrisat, Punjabi, Cisbani & BW

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



- Up to max Q^2 = 15 GeV^2
- Study the spin flip part of the hadron current
- Constrain GPDs at high t
- Provide critical test of the FF models and reaction dynamics

$\Delta(F_2/F_1)/(F_2/F_1)$ accuracy will be 3%

compare to $\frac{ln^2(Q^2=10/\Lambda^2)}{ln^2(Q^2=15/\Lambda^2)} = 0.85$

Challenges at high Q^2

$$\text{Form factor} \propto Q^{-4}$$

$$\text{Cross section} \propto E^2/Q^4 \times Q^{-8}$$

$$\text{Figure-of-Merit } \epsilon A_Y^2 \times \sigma \times \Omega$$

$$\propto E^2/Q^{16}$$

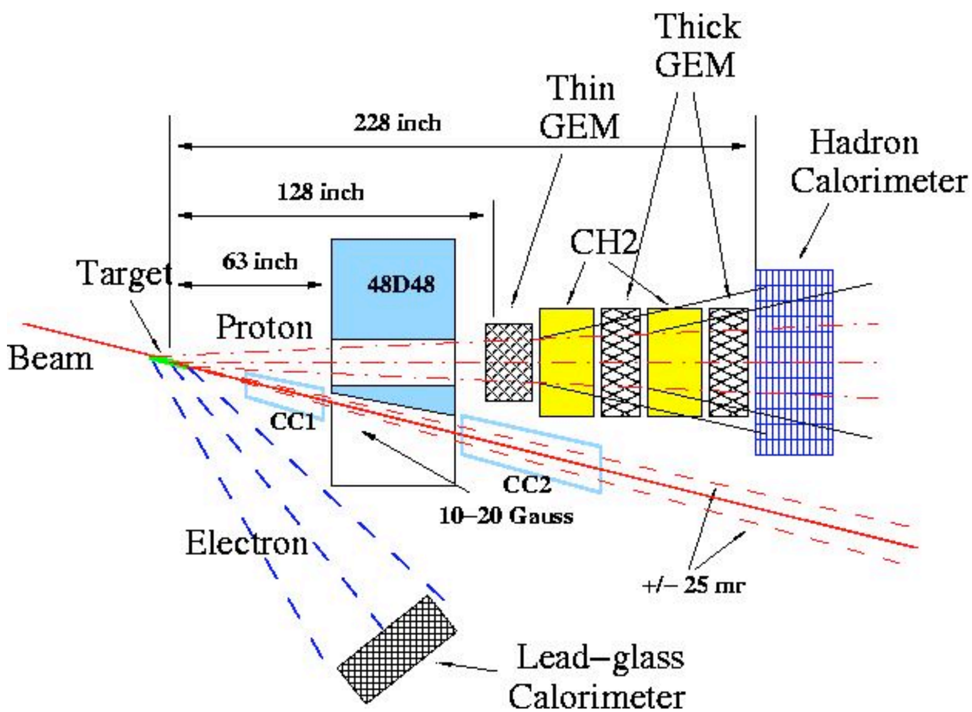
Need large statistics → max luminosity and solid angle

Max luminosity → large background
Large solid angle → small bend → huge background

Solution is a modern tracking detector based on
Gas Electron Multiplier (F.Sauli, 1997)

Experiment: Layout and Parameters

$$H(\vec{e}, e'\vec{p})$$



Beam: 75 μA, 85% polarization
Target: 40 cm liquid H_2
Electron arm at 37^o, covers Q^2 range from 12.5 to 16 GeV^2
Proton arm at angle 14^o, with Ω = 35 msr ,
Spin precession angle is ~ 90^o (it is optimum)

Event rate is 15 times higher than with standard spectrometer

From 58 days of production time resulting accuracy (for each of two data points):

$$\Delta(\mu G_E^p / G_M^p) = \pm 0.10$$

New in GEP5 experiment

1. Large solid angle in the proton arm at a small scattering angle achieved with single dipole magnet. Beam line will go through a hole in magnet pole.

2. Gas Electron Multiplier chambers to handle high rate of the background. Similar counting rates handled in COMPASS; rate will be much higher in LHCb.

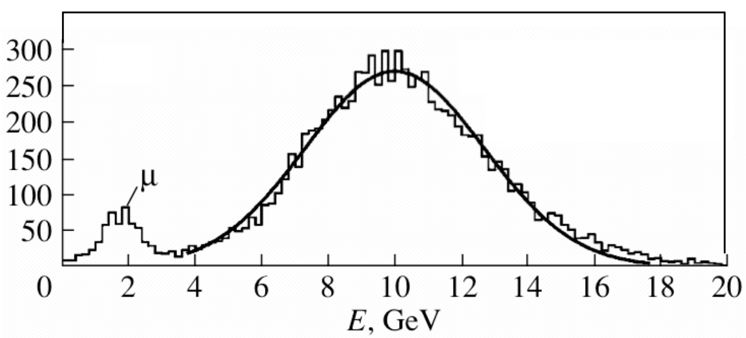
3. High threshold trigger with hadron calorimeter.

Proton Arm

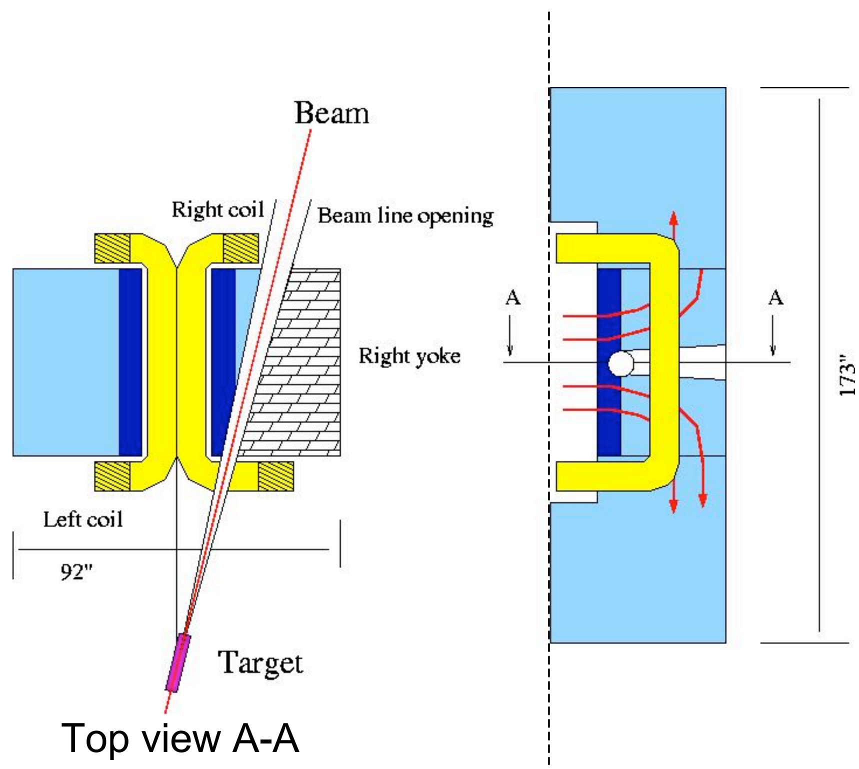
- Magnet: 48D48 - 46 cm gap, 3 Tm field integral, 100 ton
- solid angle is 35 msr for GEP, could be ~70 msr

GEM chambers for tracking with 70 μm resolution

- momentum resolution is 0.5% for 8.5 GeV/c proton
- angular resolution is 0.2-0.3 mrad
- trigger threshold is 4 GeV from hadron calorimeter



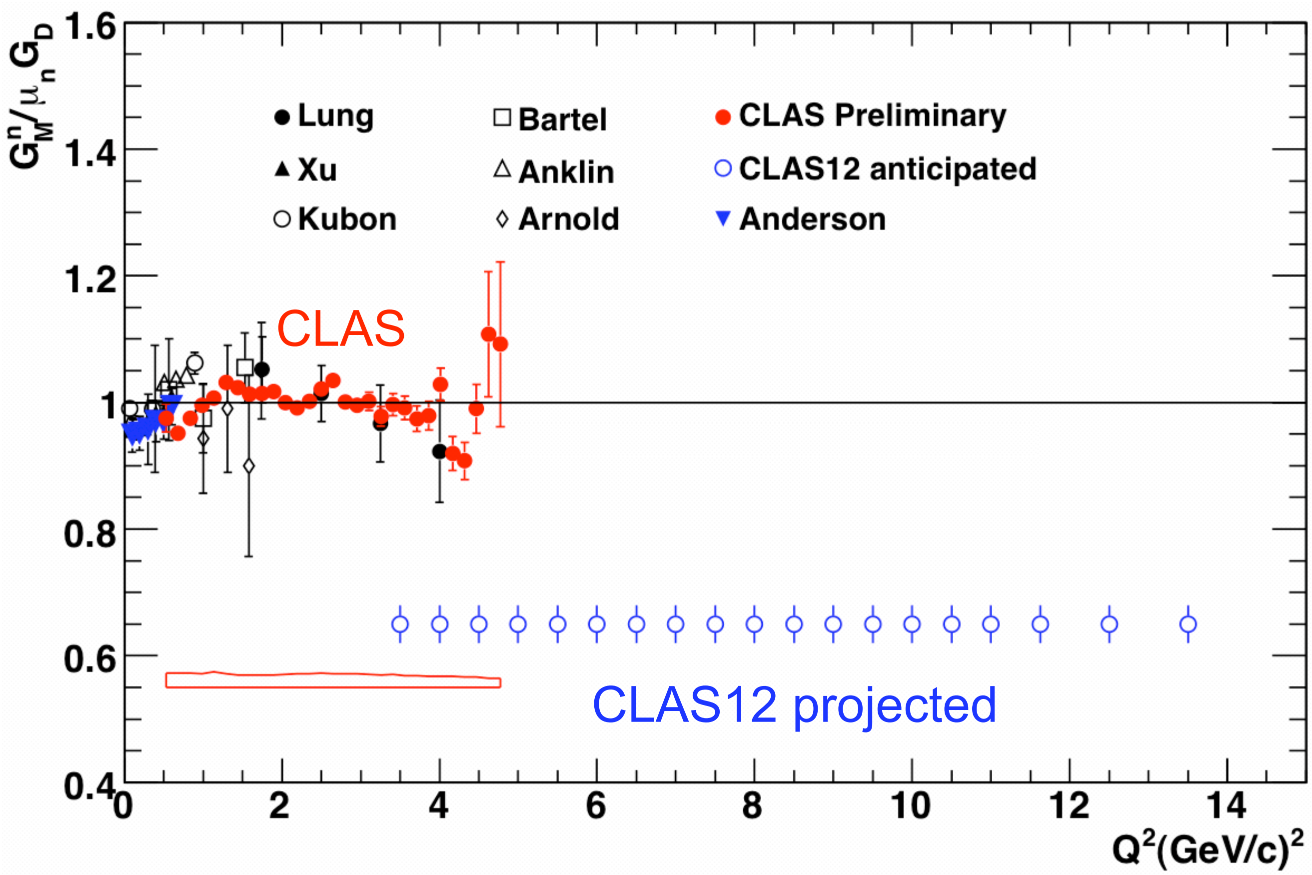
Calorimeter response for 10 GeV protons from test for Compass experiment



Top view A-A

GMN/GMP at high Q^2

Brooks, Gilfoyle, Fafidi, Lachniet, Vineyard

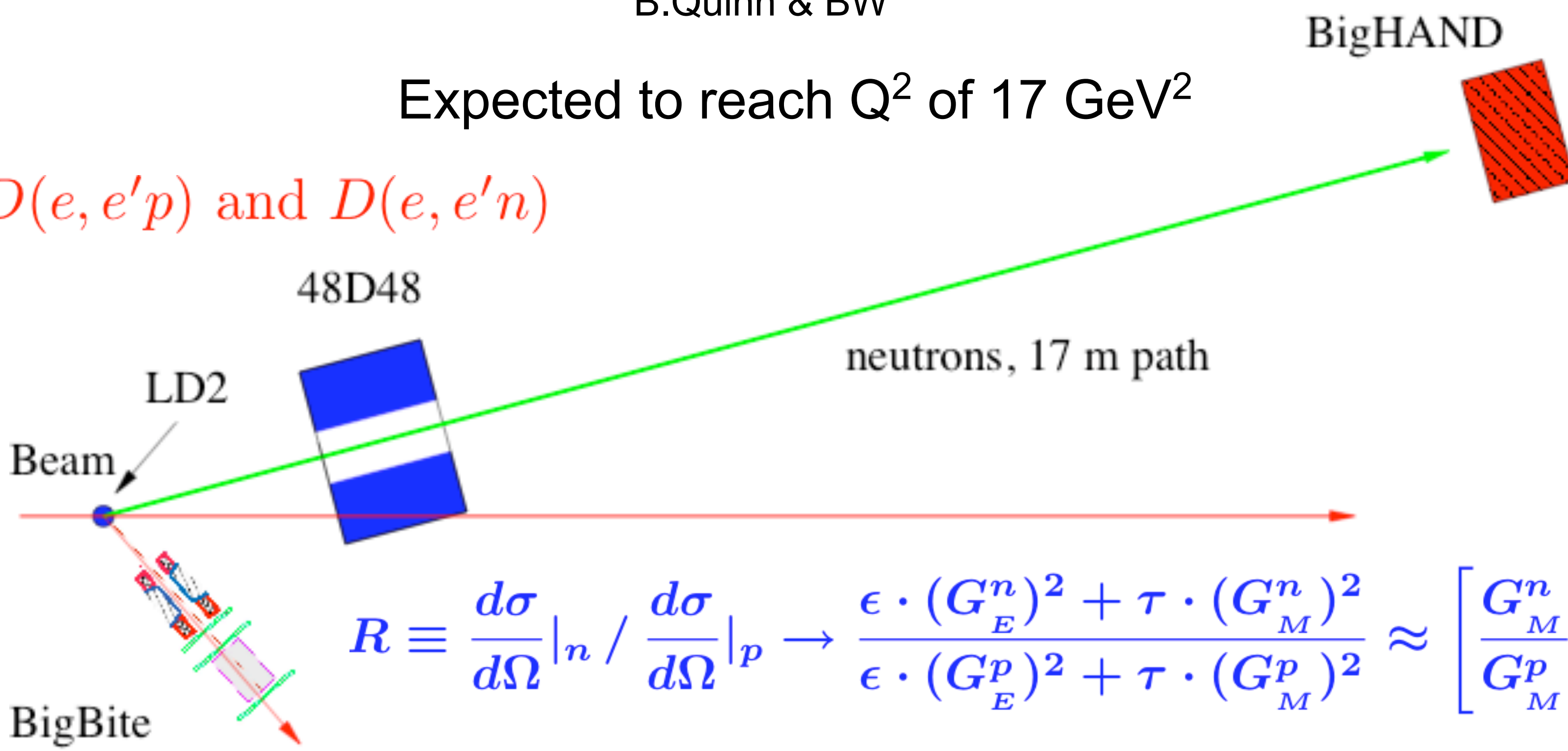


GMN concept for max Q^2

B.Quinn & BW

Expected to reach Q^2 of 17 GeV^2

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

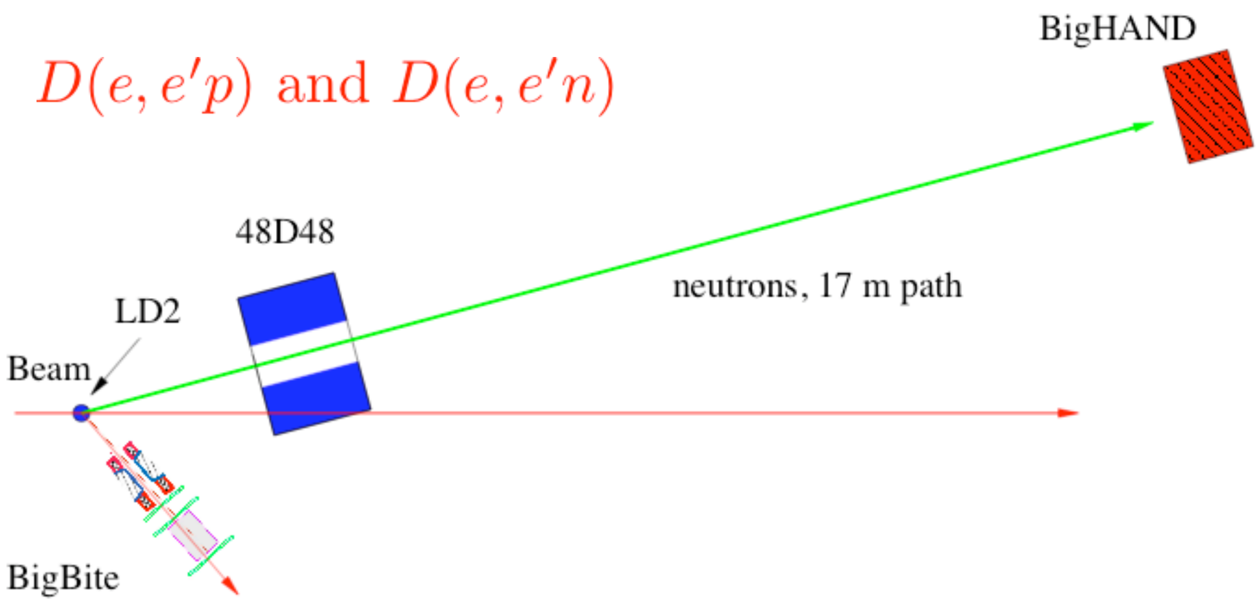


$$R \equiv \frac{d\sigma}{d\Omega}\Big|_n \Big/ \frac{d\sigma}{d\Omega}\Big|_p \rightarrow \frac{\epsilon\cdot(G_E^n)^2 + \tau\cdot(G_M^n)^2}{\epsilon\cdot(G_E^p)^2 + \tau\cdot(G_M^p)^2} \approx \left[\frac{G_M^n}{G_M^p}\right]^2$$

$$\text{luminosity } \mathcal{L}_{eN} = 1\cdot 10^{38}\ cm^{-2}/s$$

$$\text{accuracy for } G_M^n/G_M^p \sim 1-2\% \text{ in 50 days run}$$

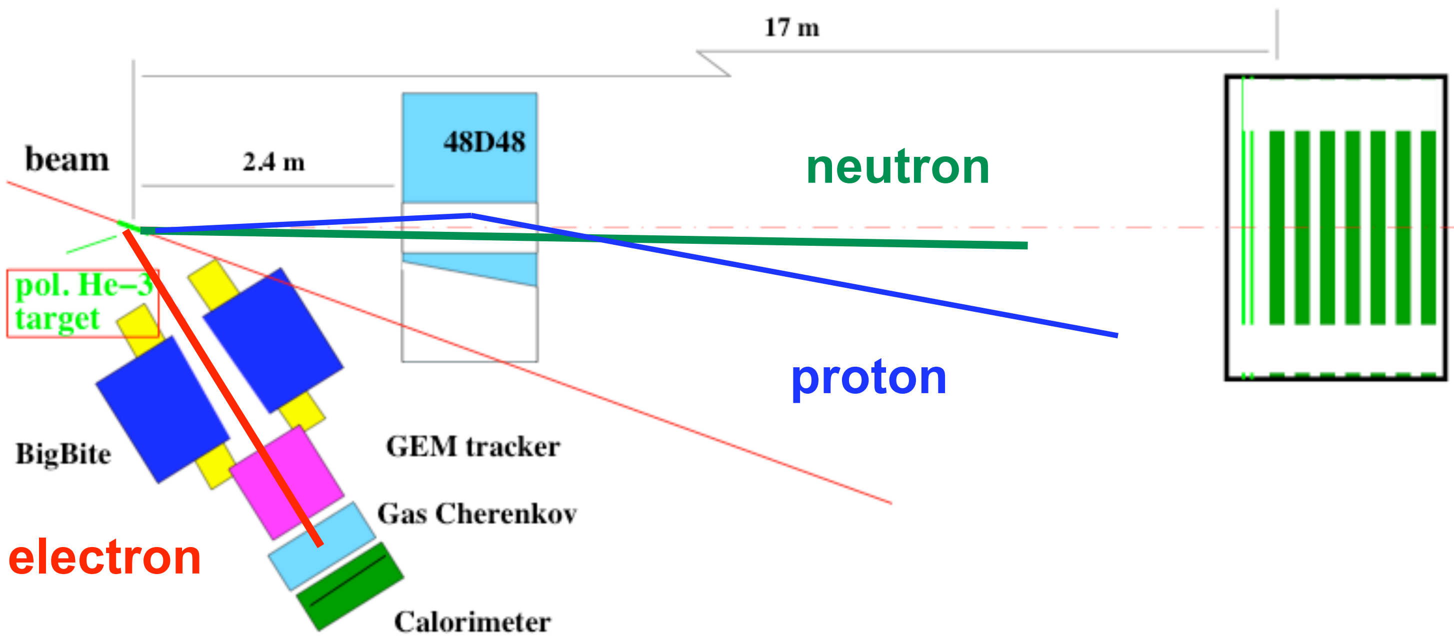
Scheme for GMN/GMP in details



- Long neutron path: angular resolution ~ 2 mr, ToF ~ 0.3 ns
- BigBite with GEM tracker: easy handle 10^{38} cm^{-2}/s luminosity, resolution of 0.1% at 1 GeV electron momentum
- 48D48 OFF/ON for protons: measurement of N(n+p)/N(n) in the same detector

GEN/GMN at 7.5 GeV^2

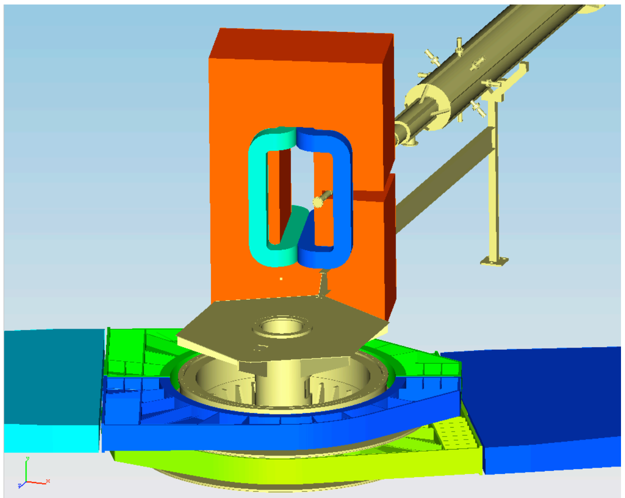
Cates & BW

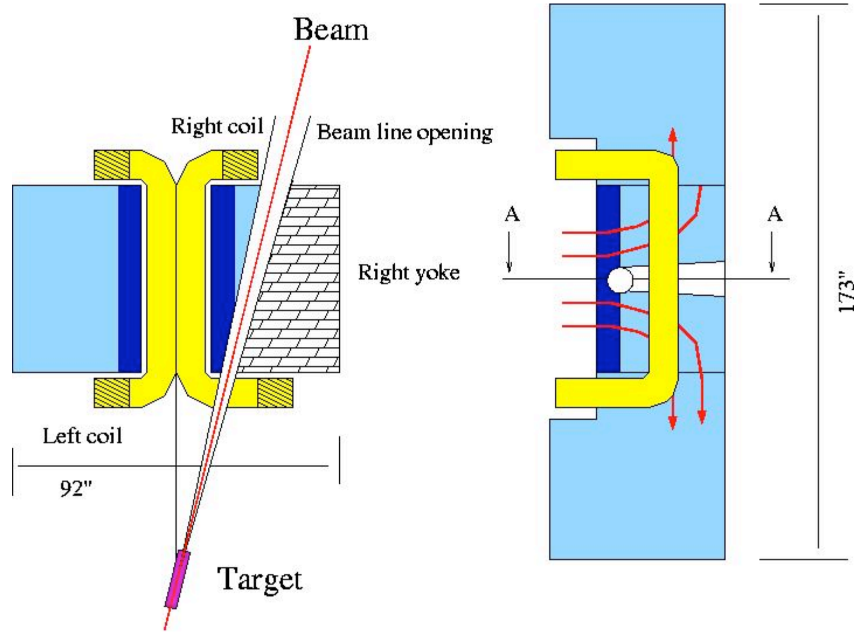


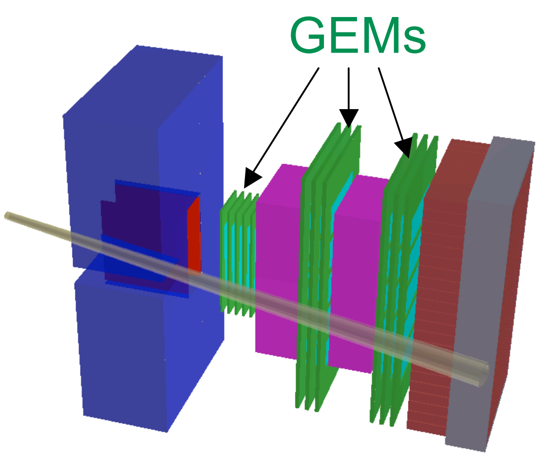
Beam energy of 6.6 GeV, 30 mkA. Target: He-3, polarization 70%, 30 days

G_E^n at 7.5 GeV^2 with uncertainty of 20% * $G_{Galster}$ (or 0.06 G_{Dipole}).

Multi Purpose Spectrometer







- Magnet: 48D48 - 46 cm gap, 2-3 Tesla*m
- Solid angle is 70 msr at angle 15 deg.
- GEM chambers with 70 μm resolution
- momentum resolution is 0.5% for 5 GeV/c
- angular resolution is 0.3 mr

Parameters of MPS

$\theta_{central}$, degree	Ω, msr	D, meter	Hor. range, degree	Vert. range, degree
3.5	5	9.5	$\pm$ 1.3	$\pm$3.3
$\boxed{5.0}$	$\boxed{12}$	5.8	$\pm$ 1.9	$\pm$4.9
7.5	30	3.2	$\pm$ 3	$\pm$8
15	72	1.6	$\pm$ 4.8	$\pm$12.2
30	76	1.5	$\pm$ 4.9	$\pm$12.5

Solid angle

Resolution:

Momentum =>

$$\frac{\sigma_p}{P} = 0.001 \cdot P[GeV]$$

Angular =>

$$\sigma_\theta = 0.2 - 0.3 \text{ mr}$$

Momentum acceptance =>

$$P \text{ range } 2 - 10 \text{ GeV/c}$$

Physics experiments with MPS

Exclusive processes

Nucleon FFs (GEP,GMP,GMN)
DVCS, WACS
Single pion production
Phi meson production
J/Psi photo-production
e,e'π and e,e'η at large Q^2 & low W

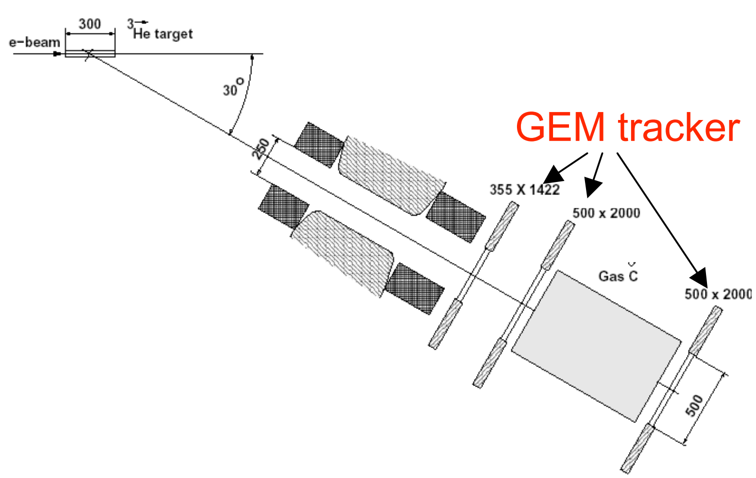
Polarized and exotic targets

GEN with He-3
Pol. DIS
Pol. SIDIS
T/He-3 for u/d
ALL-WACS

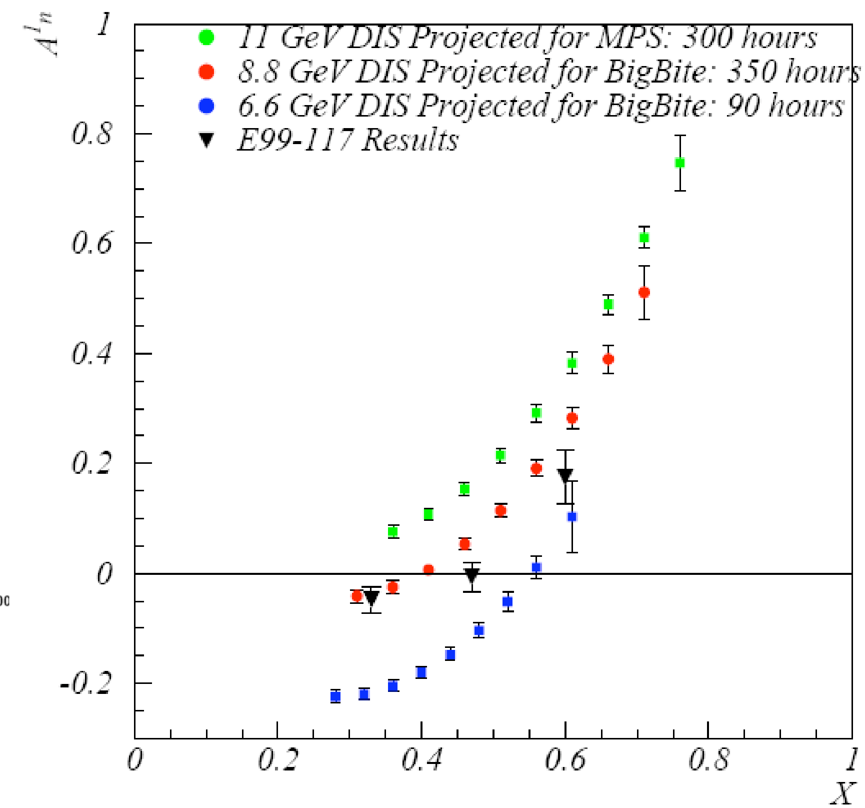
Polarized DIS with MPS

Cates, Liyanage, Meziani,
Rosner, Zheng, and BW

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



Total ~1000 h



MPS advantage over HMS+SHMS ~ 12

MPS advantage over BigBite ~ 6

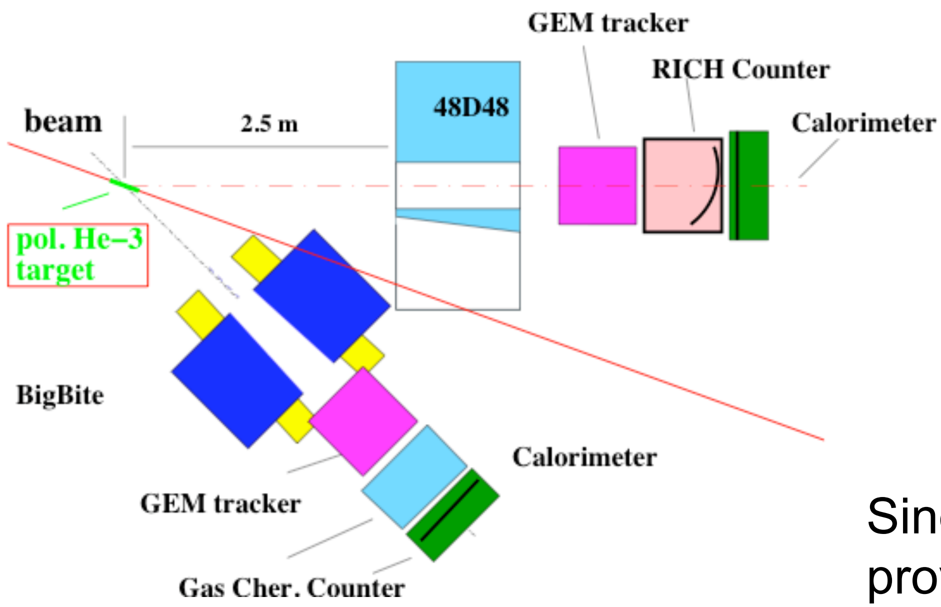
very good accuracy, x up to 0.75
first test of Q^2 dependence

Neutron Transversity with MPS

MPS at 20 deg, BigBite at 25 deg

40 msr x 50 msr

Cisbani & BW



In one month 30,000 times more events than in all transv. data collected by HERMES

Single run of MPS will provide full coverage for all $P_{\perp} >$ 1/6 of $P_{||}$

Road map and time line

GEP5 experiment was approved in Aigust 2007

• INFN approved (September 2007) a startup GEM funding
• INFN funding is needed: 5 years grant for the front tracker of the MPS spectrometer, expected in September 2008
• NSF funding is needed: $1.8M MRI grant for the FPP trackers including electronics, expected in summer 2009
• UK funding is needed for GEM DAQ and trigger construction

Time line for the construction project:

- ❑ First telescope GEM tracker in 2008: test in Hall A
- ❑ Project technical review in 2008
- ❑ BNL magnet in 2010
- ❑ First full size tracking device by 2011
- ❑ Front tracker by 2012
- ❑ FPP trackers by 2013
- ❑ Hadron calorimeter/electronics in 2013

Summary

- 12 GeV CEBAF will provide precision nucleon Form Factors values:

  - ✓ G^p_E @ 15 GeV^2
  - ✓ G^p_M @ 17.5 GeV^2
  - ✓ G^n_E @ 7.5+ GeV^2
  - ✓ G^n_M @ 14+ GeV^2

- MPS spectrometer will be a universal tool for experiments in hadron physics at large Q^2