G_M^n Data Analysis and Thesis Writing Update

Anuruddha Rathnayake - UVA

July 18, 2023

Outline

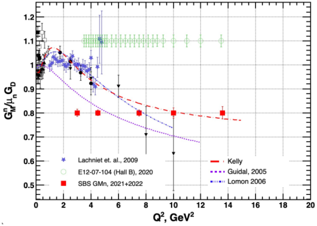
1. My progress on G_M^n physics data analysis

2. Progress towards the thesis

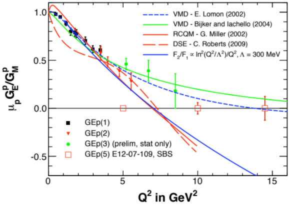
My progress on G_M^n physics data analysis

Super BigBite Spectrometer (SBS) Physics Program at Jefferson Lab

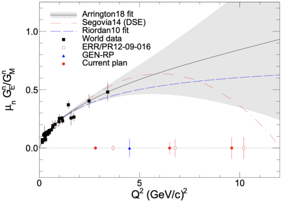
- Measure nucleon EEFFs at the highest Q^2 and precision
- Large *solid angle acceptance* ($\sim$ 75 msr) and *high luminosity*
- G_M^n, nTPE, and G_E^n-II (partially) completed, G_E^n-RP and G_E^p-V coming up soon



← G_M^n word data and the SBS points w/ data:
My thesis experiment E-09-019
Plot credit: P. Datta



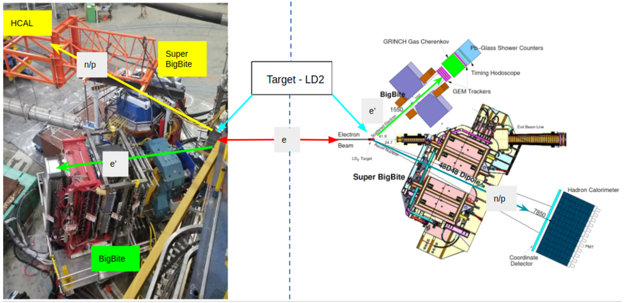
G_E^p world data and expected SBS points



G_E^n world data and SBS points w/ data

G_M^n using "Ratio Method": Coincidence detection of e' and n/p scattered from a Liquid Deuterium (LD2) target

$$R'' = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{d(e,e'n)}}{\left(\frac{d\sigma}{d\Omega}\right)_{d(e,e'p)}}$$



- Electron arm / BigBite spectromenter: Detects the momentum and energy of the scattered e' electrons; i.e identifies the q vector of the reaction
- Hadron arm / SuperBigBite spectrometer: Detects the scattered neutrons and protons and measure their energy and hit position
- Simultaneous measurement of n-tagged, d(e,e'n) and p-tagged, d(e,e'p), quasi-elastic (QE) scattering and form the cross-section ratio, R''

Extracting Neutron Magnetic Form Factor G_M^n from the "Ratio Method"

1) Differential cross-section for elastic e-N scattering from "single-photon-exchange" approx.

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left({G_E}^2 + \frac{\tau}{\epsilon}{G_M}^2\right)\left(\frac{1}{1+\tau}\right)$$

Here, $\tau = Q^2/4M^2_{nucleon}$ and $\epsilon = 1/1 + 2(1+\tau)\tan^2(\theta/2)$

2) e scattering off a deuterium target: close to n target + p target

Detect/count the *quasi-elastically* scattered neutrons and protons and form a ratio

$$\frac{\#n}{\#p} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{d(e,e'n)}}{\left(\frac{d\sigma}{d\Omega}\right)_{d(e,ep)}} = R''$$

3) Convert Quasi-elastic → elastic cross-section ratio

Our theory is for elastic-scattering. Apply certain corrections (ϵ) on quasi-elastic ratio to get to elastic ratio

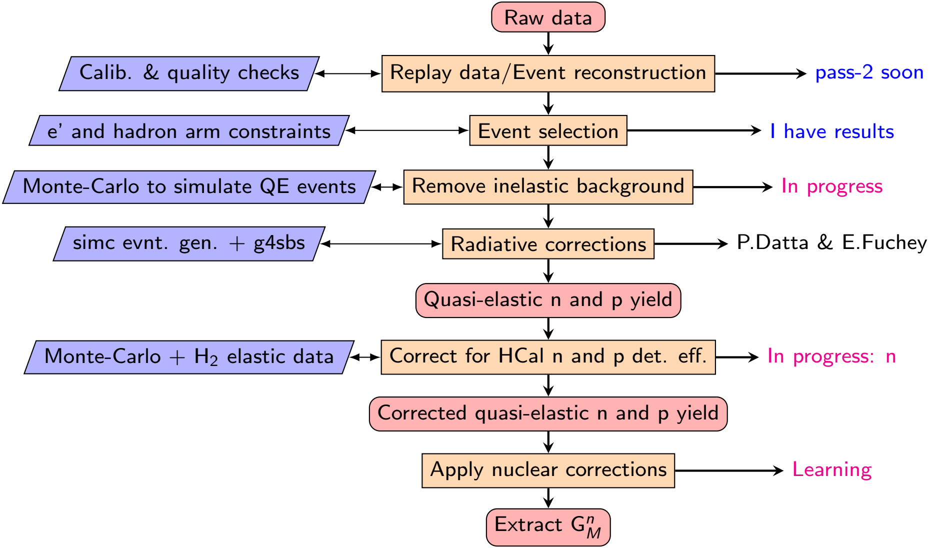
$$\frac{R''}{1+\epsilon} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{n(e,e')}}{\left(\frac{d\sigma}{d\Omega}\right)_{p(e,e')}} = R'$$

4) Extract G_M^n

$$R' = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left((G_E^n)^2 + \frac{\tau}{\epsilon}(G_M^n)^2\right)\left(\frac{1}{1+\tau}\right)}{\left(\frac{d\sigma}{d\Omega}\right)_{p(e,e')}}$$

- $\tau = Q^2/4M^2_{nucleon}$ and $\epsilon = 1/1 + 2(1+\tau)\tan^2(\theta/2)$
- $\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2\cos^2\left(\frac{\theta}{2}\right)}{4E^2\sin^4\left(\frac{\theta}{2}\right)\left[1+(2E/M_{nuc})\sin^2\frac{\theta}{2}\right]}$
- G_E^n - very small w.r.t G_M^n at high Q^2 and can use parameterization techniques to approximate it
- $\left(\frac{d\sigma}{d\Omega}\right)_{p(e,e')}$ - the proton cross-section is well known

G_M^n experiment analysis work-flow



Raw data

Calib. & quality checks ↔ Replay data/Event reconstruction → pass-2 soon

e' and hadron arm constraints ↔ Event selection → I have results

Monte-Carlo to simulate QE events ↔ Remove inelastic background → In progress

simc evnt. gen. + g4sbs ↔ Radiative corrections → P.Datta & E.Fuchey

Quasi-elastic n and p yield

Monte-Carlo + H_2 elastic data ↔ Correct for HCal n and p det. eff. → In progress: n

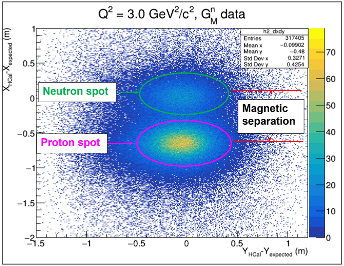
Corrected quasi-elastic n and p yield

Apply nuclear corrections → Learning

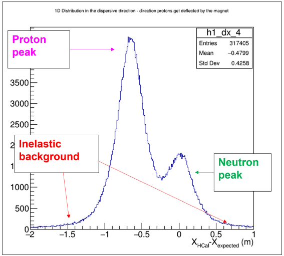
Extract G_M^n

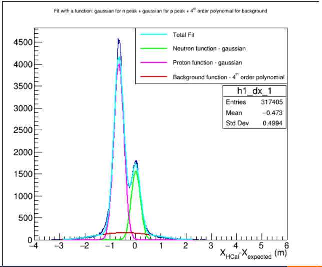
Event selection + n and p separation + background unfolding

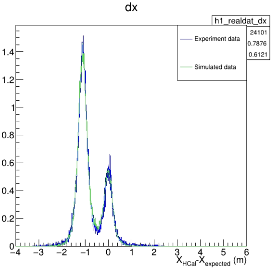
- High luminosity running and open geometry config. → A lot of background events
- Extensive use of constraints on e' arm and hadron arm to clean up
- Use e' arm to find the q vector → predict nucleon hit position in the hadron detector



Vertical 1D projection







HCal *neutron detection efficiency* (NDE) calibration using the "end-point" method

- Current NDE calib. plan: benchmark GENT4 simulations for proton det. eff. by comparing the results from analyzing LH2 data, and use that GENT4 simulation for NDE calib.
- But the above method lacks a direct experimental handle, which is critical for credibility.
- Thus we have started an effort to use tagged neutrons from the reaction $\gamma(p, \pi^+)n$ to calibrate NED of HCal.
- Use SBS-9 LH2 data and analyze down-bending tracks with "end-point" constraints to reject events from many-body pion production channels $\gamma(p, N\pi)n$: cuts on BB track momentum.

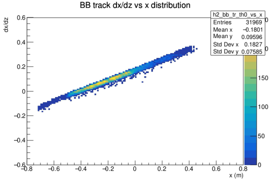


Figure: BigBite track theta vs x pos

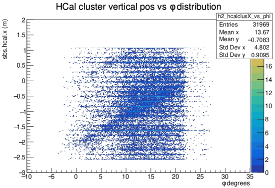


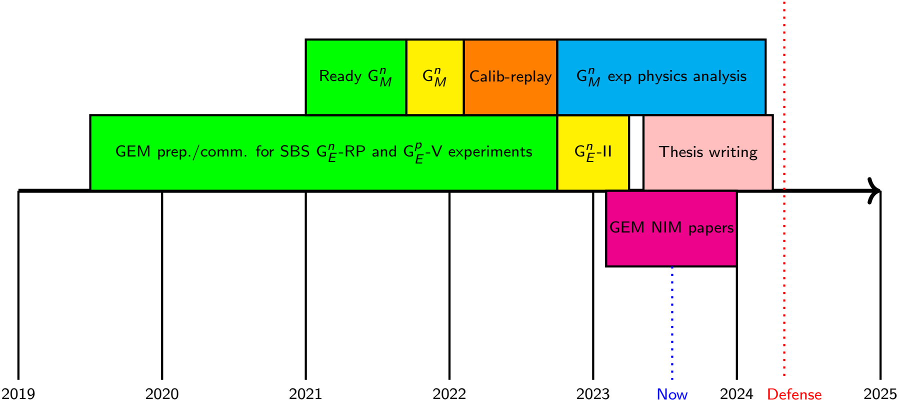
Figure: HCal X pos vs ϕ ang. π^+

- abs(bb.tr.vz[0]) < 0.075 m
- sbs.hcal.e > 0.086 GeV
- BBCal and HCal time corr. cut
- bb.tr.p > 1.6 GeV/c
- More work needed

$$NDE = \frac{\#detected}{\#predicted}$$

Progress towards the thesis

High-level timeline of PhD



Scope of the thesis and progress

1. Formalism of electromagnetic form factors
2. Discussion of the existing data, theories and models being used
3. Introduction to the SBS program at Hall-A of the Jefferson Lab
4. G_M^n experimental setup, describe each subsystem
5. Intro to GEMs, UVA GEM fabrication, commissioning, and performance both with cosmic and beam conditions
6. G_M^n data analysis procedure
7. Discussion of analysis results

- Started writing the chapters about the “Experiment Setup” and “GEM Detectors”
- Analysis details/results can be included as the progress is being made
- Plan is to finish up writing around March, 2024
- Thesis defense planned for May, 2024

Acknowledgements

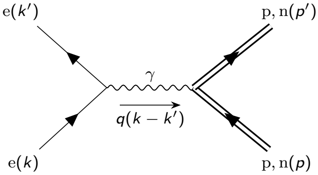
- Our UVA group members: Nilanga Liyanage, Huong Nguyen, Xinzhan Bai, John Boyd, Sean Jeffas, Vimukthi Gamage, and Bhashitha Thuthimal Dharmasena
- Past UVA group members: Kondo Gnanvo, Daning Di, Siyu Jian, and John Matter
- All members of the SBS collaboration
- Jefferson Lab staff members
- Department of Energy for funding; Award number: DE-FG02-03ER41240

Thank You!

Backup

Backup Slides

Elastic Electromagnetic Form Factors (EEFFs)



electron-nucleon scattering under "single-photon-exchange" approx. within QED framework

- Amplitude for electron-nucleon scattering: $-iM = j^{\mu}\frac{-ig_{\mu\nu}}{q^2}J^{\nu}$
- The electron transition current: $j^{\mu} = -e\bar{u}_e(k')\gamma^{\mu}u_e(k)$ is well known
- The nucleon transition current: $J^{\mu} = e\bar{u}(p')\left[F_1(Q^2)\gamma^{\mu} + \frac{\kappa}{2M}F_2(Q^2)i\sigma^{\mu\nu}q_{\nu}\right]u(p)$ is complex and not known
- $F_1(Q^2)$ and $F_2(Q^2)$: *Dirac* and *Pauli* Form Factors
- Scalar functions of $Q^2(= -q^2)$ that parameterize the nucleon's charge and magnetization distribution

Sach's EEFFs and their importance

Sach's electric form factor (G_E) and magnetic form factor (G_M) are defined as:

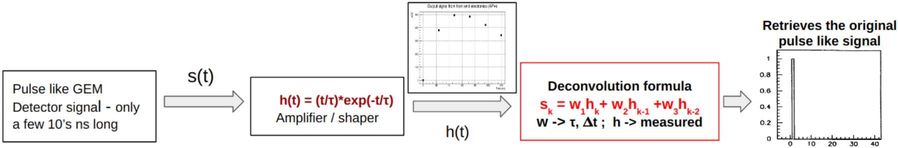
$$G_E = F_1 - \frac{\kappa Q^2}{4M^2}F_2 \qquad G_M = F_1 + \kappa F_2$$

- To calculate isovector form factors $(G^p_{E/M} - G^n_{E/M})$: good test case for lattice QCD
- Extract individual FFs of u and d quarks : constrain sum rules obeyed by the GPDs
- Quark flavor decomposition

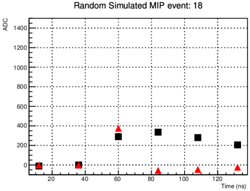
GEM detector specific data analysis projects

- After G_M^n, started to work on a GEM signal decoding technique named "time-deconvolution"
- Intended to be used to "dig out" good signals buried in large background pileup in time

Retrieves the original "pulse" like signal of detector, from output shaped signal →Deconvolution

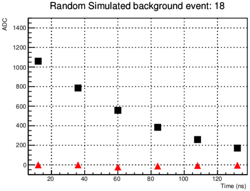


Deconvolution is sensitive to small changes in the signal shape →Can be used to dig out background suppressed events



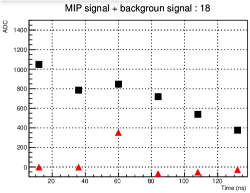
MIP signal Deconvolution - Clear spike indicative of a good signal

+



No spike when deconvolution applied to background

=



Deconvolution applied to sum - Clear spike!

Signal recovered.

Precision Measurement of the Neutron Magnetic Form Factor up to $Q^2 = 13.6\ (GeV/c)^2$ by the Ratio Method

- "Ratio method" will be used to determine G_M^n from quasi-elastic scattering off of deuteron as opposed to historic methods such as
  - "proton subtraction" : single arm measurement technique
  - "proton tagging" : partial coincidence method

  Both techniques inefficient at selectively rejecting inelastic background events which are considerable at high Q^2
- Requires the measurement of both neutron tagged, d(e,e'n) and proton tagged, d(e,e'p), quasi-elastic scattering from the deuteron target

$$R'' = \frac{(\frac{d\sigma}{d\Omega})_{d(e,e'n)}}{(\frac{d\sigma}{d\Omega})_{d(e,e'p)}}$$

- Substantial reduction in the systematic errors (experimental and theoretical) as they cancel in the ratio: Target thickness, beam intensity, dead-time, electron-trigger efficiency, electron acceptance, and the detection and reconstruction efficiency of the scattered electron tracks

Extracting Neutron Magnetic Form Factor G_M^n

Nuclear corrections to derive elastic cross-section ratio

$$R' = \frac{(\frac{d\sigma}{d\Omega})_{n(e,e')}}{(\frac{d\sigma}{d\Omega})_{p(e,e')}} = \frac{R''}{1+\epsilon_{nuc}}$$

From single photon approximation, the cross section for scattering of electrons from a spin - 1/2, non point-like target

$$R' = \frac{\frac{(d\sigma/d\Omega)_{Mott}}{1+\tau}\left((G_E^n)^2 + \frac{\tau}{\epsilon}(G_M^n)^2\right)}{(\frac{d\sigma}{d\Omega})_{p(e,e')}}$$

$$R = R' - \frac{\frac{(d\sigma/d\Omega)_{Mott}}{1+\tau}(G_E^n)^2}{(\frac{d\sigma}{d\Omega})_{p(e,e')}} = \frac{(d\sigma/d\Omega)_{Mott}\frac{\tau/\epsilon}{1+\tau}({\color{red}G_M^n})^2}{(\frac{d\sigma}{d\Omega})_{p(e,e')}}$$

Here, $\tau = Q^2/4M^2_{nucleon}$ and $\epsilon = 1/1 + 2(1+\tau)\tan^2(\theta/2)$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2\cos^2(\frac{\theta}{2})}{4E^2\sin^4(\frac{\theta}{2})\left[1+(2E/M_{nuc})\sin^2\frac{\theta}{2}\right]}$$

Evidence for Existence of Structure in Nucleons

For a simple structure-less *Dirac* particle with spin, the magnetic moment:

$$\mu = \frac{q}{m}|\vec{s}|$$

Nucleon	Predicted - *Dirac* type particle	Measured *Otto Stern* (1933)
Proton	$\frac{e}{2M_p} = \mu_N$	$2.79\mu_N$
Neutron	0	$-1.91\mu_N$

- Electron scattering experiments by *Hofstadter* and others (1950's) gave evidence for Charge and Magnetization distributions inside the proton
- Experimentally determined the charge radius of the proton to be **0.8** *fm*
- The "**Form Factors**" called G_E^p and G_M^p were introduced to parameterize the proton internal structure

The Elastic Scattering Differential Corss Section

From the *Fermi's Golden Rule*, the elastic scattering differential cross section of the electron - nucleon scattering in the single photon approximation

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = |M|^2 \frac{m^2}{4\pi^2} \frac{E'^2}{E^2}$$

Substituting for the amplitude M from single photon approximation and after some algebra

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left[(F_1^2 + \frac{\kappa^2 Q^2}{4M_{nuc}^2} F_2^2) + \frac{Q^2}{2M_{nuc}^2} (F_1 + \kappa F_2 \tan^2 (\frac{\theta}{2}) \right]$$

Where, $F_1 = F_1(Q^2)$ and $F_2 = F_2(Q^2)$

where the Mott corss section,

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2 \cos^2 (\frac{\theta}{2})}{4E^2 \sin^4 (\frac{\theta}{2}) \left[1 + (2E/M_{nuc}) \sin^2 \frac{\theta}{2}\right]}$$

Differential cross section for scattering of an electron (spin 1/2, point like, charge -e particle) off a spin-less, structure-less target of mass M$_{nuc}$

Sach's Electromagnetic Form Factors

Sach's electric form factor (G_E) and magnetic form factor (G_M) are defined as:

$$G_E = F_1 - \frac{\kappa Q^2}{4M^2} F_2 \qquad\qquad G_M = F_1 + \kappa F_2$$

Differential cross section for elastic scattering of electrons off of a nucleon in terms of Sach's form factors

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left(G_E^2 + \frac{\tau}{\epsilon} G_M^2\right) \left(\frac{1}{1+\tau}\right)$$

Here, $\tau = Q^2/4M_{nucleon}^2$ and $\epsilon = 1/1 + 2(1+\tau)\tan^2(\theta/2)$

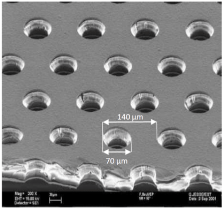
- Very low Q^2, wavelength of the virtual photon is large: insensitive to the nucleon structure, seen like a point particle/extended charged object
- At low Q^2, slope of the G_E distribution at $Q^2 = 0$ gives the nucleon charge radius
- From low to moderate Q^2, wavelength short enough to probe substructure: form factors G_E and G_M interpreted as Fourier transforms of the nucleon charge and magnetization densities
- At high Q^2, relativistic effects complicates the interpretation of form factors

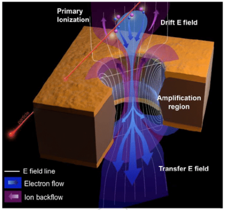
Gas Electron Multiplier Detectors

Gas Electron Multiplier (GEM) Detectors

- A relatively new technology invented in 1997 by CERN physicist *Fabio Sauli*
- GEM is a Micro Pattern Gas Detector (MPGD): micro electronic structures with very small distances (sub-millimeter) between anode and cathode electrodes
- **Very strong electric fields** within a small region
- Utilize gaseous ionization by particles going through
- Charge from this initial ionization alone is not enough for the electronics
- Electrons and ions generated are drifted apart by a “smaller” electric field
- Electrons are guided into regions with very-strong electric fields
- Electrons accelerate (gain energy) and collide with gas atoms creating a large number of electron-ion pairs (*avalanche* process); enough electrons to produce a current/charge large enough for the detection

The GEM foil: A thin (50 μm) polymer foil, metal-coated on both sides and perforated with a high density of holes





A large potential difference across GEM holes: An avalanche of electrons through ionization collisions

Working Principle of a **Triple GEM** Detector

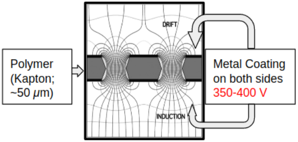


Figure: Cross-section of a GEM foil

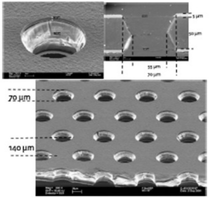


Figure: Microscope image of a GEM foil

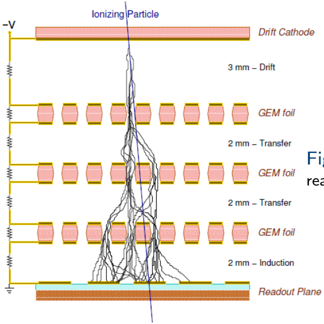


Figure: A cross sectional view of a triple GEM detector: Using 3 GEM foils back to back to increase the gain (roughly 20 per foil →20 X 20 X 20 = 8000)

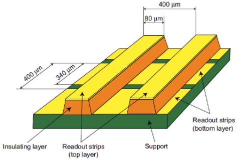


Figure: Schematic of a X-Y strip readout board

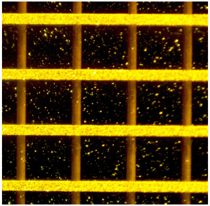
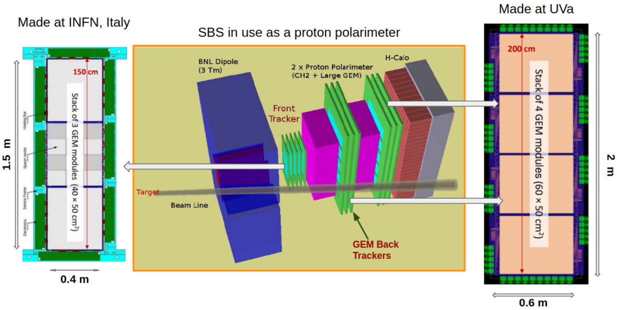


Figure: Electron microscope image of a X-Y strip readout board

The use of Gas Electron Multiplier (GEM) Detectors in the SBS Program

GEMs in SBS

- SBS Program demands from its detectors
  - Support high background rate: 500 KHz/cm^2
  - Large acceptance: 75 msr which means large active area
  - Good angular and momentum resolution: 0.2 $mrad$, 0.5% 4-8 GeV/c
  - Flexibility: use same detectors in different experimental setups
- Available technologies
  - Drift Chambers: cannot sustain high rates
  - Silicon Trackers: Too expensive and less radiation hard
  - Micro Pattern Gas Detectors (MPGD): Good match
- GEMs were chosen from MPGDs due to their higher flexibility and re-usability
  - Capable of high counting rates : 100 MHz/cm^2
  - Exceptional spacial resolution: 70 μm



Made at INFN, Italy

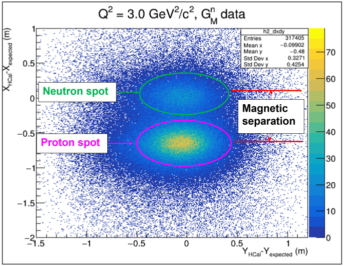
SBS in use as a proton polarimeter

Made at UVa

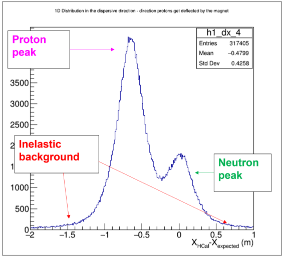
Figure: Caption

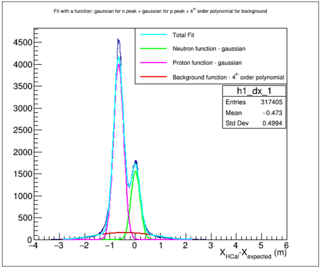
Event selection + n and p separation + background unfolding

- High luminosity running and open geometry config. → A lot of background events
- Extensive use of constraints on e' arm and hadron arm to clean up
- Use e' arm to find the q vector → predict nucleon hit position in the hadron detector



Vertical 1D projection





- Basic fitting technique to extract raw n and p yields
- Gauss func. for n an p peaks, pol func. for backg.
- Integrals of the fit functions gives a reasonable approx. for n and p yields
- Working on using Monte-Carlo simulations to model the QE events' peak shapes
- Via comparing with simulation, most accurate n and p yields can be extracted