Jefferson Lab *Super Bigbite Spectrometer* Program to Measure Nucleon Elastic Electromagnetic Form Factors at High Q^2 and *Gas Electron Multiplier* Detectors

Anuruddha Rathnayake

HUGS - 2021

June 18, 2021

Outline

1. Jlab Hall-A SBS Program
   - SBS-G_M^n Experiment
2. Gas Electron Multiplier Detectors
3. The use of Gas Electron Multiplier (GEM) Detectors in the SBS Program
   - GEM Fabrication at UVa
4. GEM Commissioning and Characterization for SBS program at Jlab
   - Assembly of GEM Layers
   - Characterization of Detectors via Cosmic-Ray Testing

SBS Physics Program in Jefferson Lab, Hall-A

- Measuring elastic electromagnetic Form Factors (G_M^n, G_E^n, G_M^p, and G_E^p) of the nucleons at the highest 4-momentum transfer (Q^2) and precision achieved so far
- Utilizing large *solid angle acceptance* ($\sim$ 75 msr) and *high luminosity*: good statistics

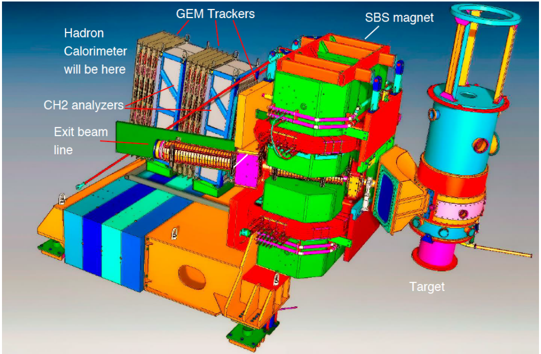


Figure: Super Bigbite Spectrometer in GEp-V experiment

SBS-GMn experiment will extend the Q^2 range by close to a factor of 3!

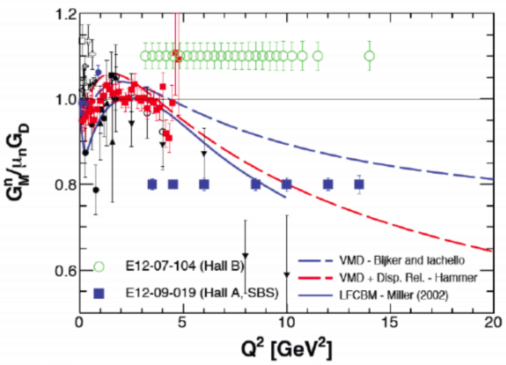


Figure: Previous and upcoming GMn results; $G_D(Q^2) = 1/(1 + Q^2/\Delta)^2$, $\Delta = 0.71\ (GeV/c)^2$

- From knowing the elastic magnetic form factor of the neutron
  - Can calculate isovector form factors $(G^p_{E/M} - G^n_{E/M})$; good test case for lattice QCD
  - Can extract individual FFs of up and down quarks which; used to constrain Generalized Parton Distribution (GPD) functions

G_M^n Experiment Layout

Bigbite Detector: Detects the momentum and angle of the scattered electrons

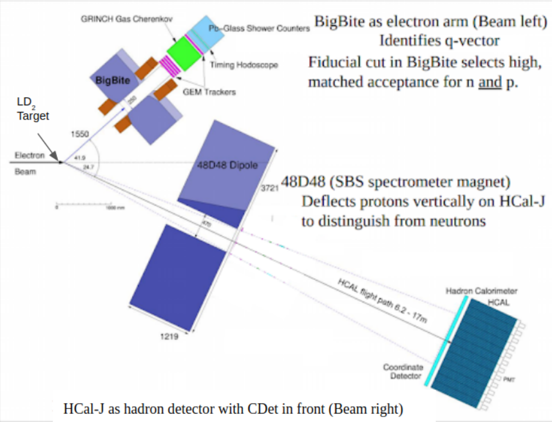


Figure: Schematic layout of the GMn experimental apparatus

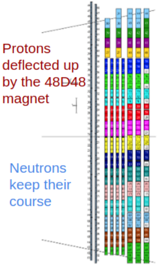
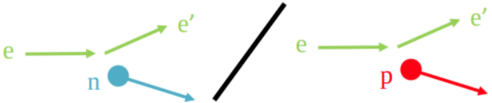


Figure: Nucleon Detector

HCAL: Detects the scattered neutrons and protons and measures their energy

Precision Measurement of the Neutron Magnetic Form Factor up to $Q^2 = 13.5\ (GeV/c)^2$ by the Ratio Method

- "Ratio method" will be used to determine G_M^n from quasi-elastic scattering off of deuteron
- 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



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

- Substantial reduction in the systematic errors (experimental and theoretical) as they cancel in the ratio: Target thickness, beam intensity, and many more...

Extracting Neutron Magnetic Form Factor G_M^n

Nuclear corrections to derive elastic cross-section ratio

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

From single photon approximation

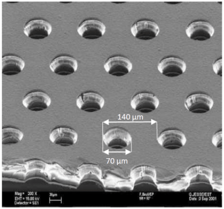
$$R' = \frac{\frac{(d\sigma/d\Omega)_{Mott}}{1+\tau}\left((G_E^n)^2 + \frac{\tau}{\epsilon}(G_M^n)^2\right)}{\left(\frac{d\sigma}{d\Omega}\right)_{p(e,e')}}$$

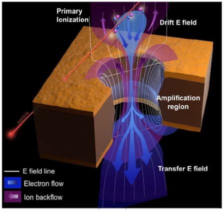
$$R = R' - \frac{\frac{(d\sigma/d\Omega)_{Mott}}{1+\tau}(G_E^n)^2}{\left(\frac{d\sigma}{d\Omega}\right)_{p(e,e')}} = \frac{(d\sigma/d\Omega)_{Mott}\frac{\tau/\epsilon}{1+\tau}(G_M^n)^2}{\left(\frac{d\sigma}{d\Omega}\right)_{p(e,e')}}$$

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

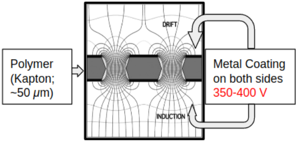


Figure: Cross-section of a GEM foil

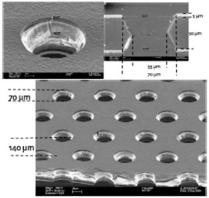


Figure: Microscope image of a GEM foil

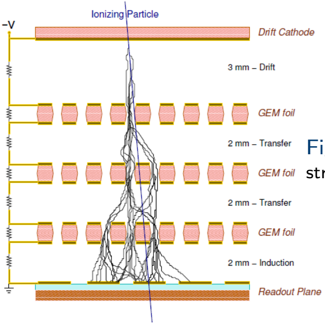


Figure: A cross sectional view of a triple GEM detector: Using 3 GEM foils back to back to increase the gain (roughly 20 per foil $\rightarrow$20 X 20 X 20 = 8000)

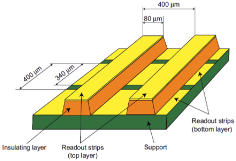


Figure: Schematic of a X-Y strip readout board

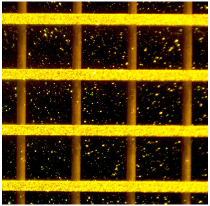
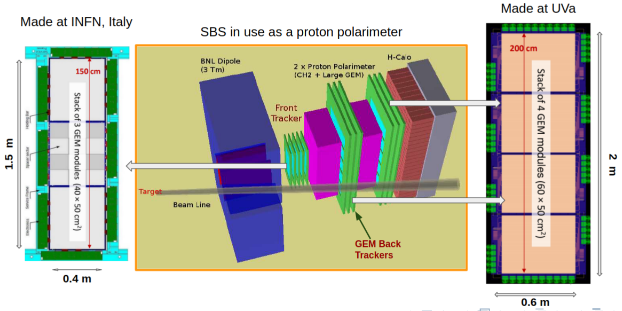


Figure: Electron microscope image of a X-Y strip readout board

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



GEM Production at UVa

Gas used: A mixture of 70% Argon and 30% Carbon dioxide

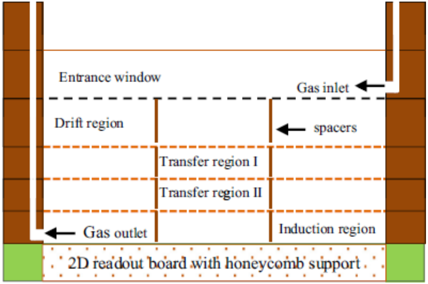


Figure: Schematic Cross-sectional view of a GEM module made at UVa

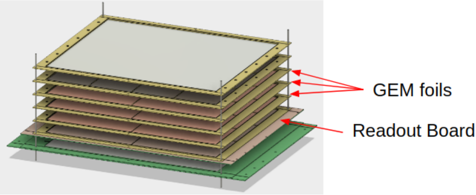


Figure: An exploded CAD diagram

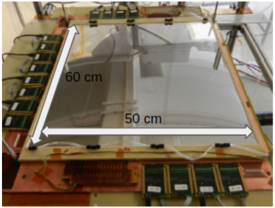


Figure: A completed GEM module inside UVa detector lab clean room

GEM Commissioning and Characterization at Jlab

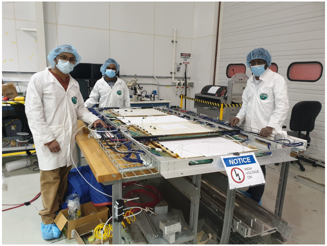


Figure: During a GEM layer assembly

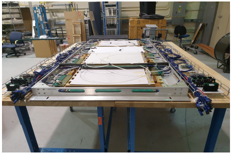


Figure: A completely tested GEM layer

Figure: Cosmic stand and the crew

Figure: Inserting a GEM layer into the Bigbite electron spectrometer

Assembly of GEM layers

- Put four 60 cm X 50 cm GEM chambers on an Aluminum frame; get a one very large active area of 60 cm X 200 cm
- The four modules are overlapped so that there is no dead area in between

Figure: Green: Active area; Red: Outer edge

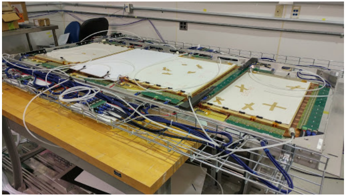


Figure: A completed GEM layer with the protective covers on

- A single such GEM layer has 11,264 channels: lots of cabling...!
- Power for readout electronics, HV for the detectors, readout HDMI cables, and gas connections are all arranged so that a GEM layer is an independent unit
- We need to assemble **11** of these layers;have finished the assembly 9 of them by now

Cosmic Stand Setup

- Test all the GEM layers assembled with cosmics extensively
- Characteristics such as gain, position resolution, and efficiency are studied
- Scitillators on the top and bottom of the stand; set-up so that a cosmic particle going right through the stack will generate a trigger event
- In such trigger event, the charge collected by any strip/channel along with a strip ID will be recorded: this will be our raw data
- After cleaning up for noise, clean "HITS" are obtained
- A "track based analysis" is performed to study different characteristics

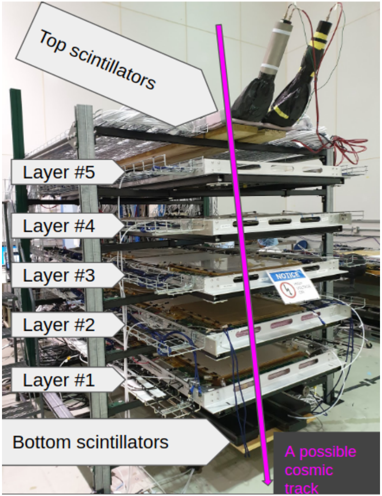


Figure: Cosmic stand with 5 GEM layers; trigger in coincidence with top and bottom scintillators

- A set of 2-D histograms with coarse X-Y bins
- The bin count of a given bin increases by one, if for a particular event, there is a hit within that bin
- All the hits shown in here are hits that have participated in a cosmic track re-construction
- No dead areas in any of the 20 GEM modules here

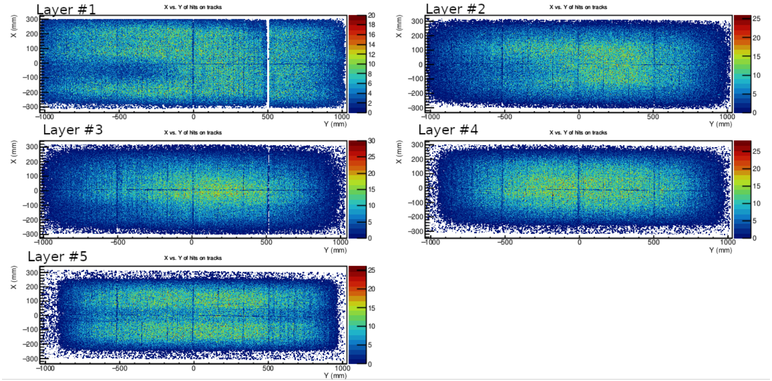


Figure: 2-D cluster position map of cosmic data taken Nov 2020

2-D "Track Based Efficiency" Maps

- How efficient a given GEM module/portion of a GEM module is at detecting particles
- A tracking algorithm finds out possible tracks which are re-constructed out of the 5 layers cosmic data, per each event
- Then calculate the number of tracks that went through a given small 2-D bin ("should hit" histogram)
- Separately calculate the number of times when an actual hit was registered in that bin ("did hit" histogram)
- The ratio between "did hit" and "should hit" is defined as the efficiency

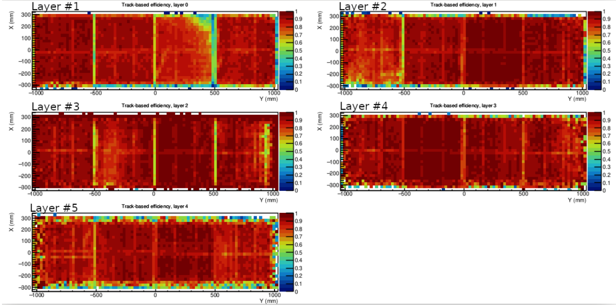


Figure: 2-D efficiency map of cosmic data taken Nov 2020

Efficiency Plateau Studies

- Efficiency plateau studies to find out the optimal operational HV for a given GEM module: The smallest voltage at which a GEM module starts to give the peak/plateau efficiency
- Don't want to operate the module above this "operational voltage"
- A single number for a GEM module is calculated by taking the ratio of the sums of "did hit" and "should hit" histograms: Thus the entire active area of the GEM module is considered

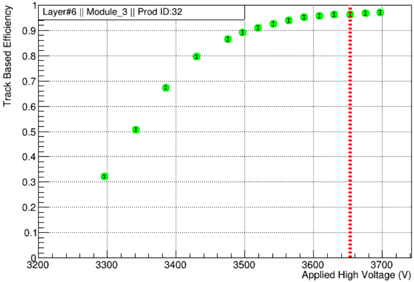
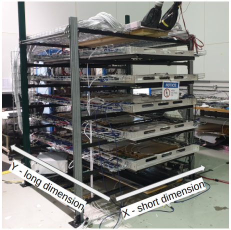
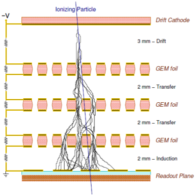


Figure: "Track based efficiency vs HV in GEM": The GEM module has reached above 95% efficiency (and plateaued) by the usual operation voltage of 3653 V

Position Resolution

- "Tracking residuals" are studied to find the position resolution of GEMs
- The distance between a fitted track and the actual hit location in a GEM detector is calculated: do this for all the events and put it into a histogram
- We get an histogram that is centered around 0 as can be seen
- The standard deviation is interpreted as the resolution
- The resolution in X direction is always higher than the resolution in Y direction. More angular tracks are present in Y as that is the longer direction in our cosmic stand





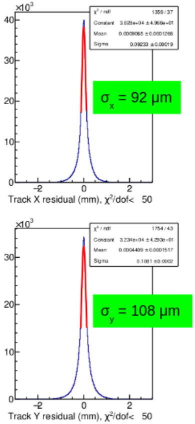
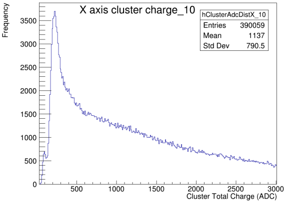


Figure: Tracking residuals in X/Y

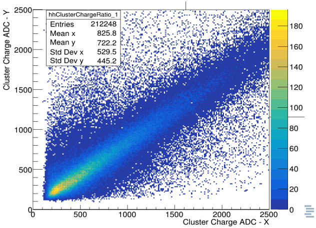
Signal Gain

- When a charge is deposited on read-out strips, the analog signal is digitized (Analog to Digital Converter - ADC) and is recorded in "ADC" units
- Thus the number of ADCs we get from an incoming charge particle is proportional to the gain of the GEM detector
- For each event, the number of ADCs collected is recorded and put into a histogram like the one shown in the right
- We use the mean of the distribution to quantify the gain
- Charge correlation between X strips and Y strips is used to extract an event of interest out of multiple hits

X - axis ADC distribution



X-Y charge correlation



Summary

- Studying elastic electromagnetic form factors of the nucleons is important to expand our knowledge of the structure of nucleons and push forward the theory frontiers
- SBS physics program in Jlab focuses on measuring elastic electromagnetic form factors of the nucleons at the highest four-momentum transfer and precision achieved so far
- The GEM detectors will be used as tracking detectors in the SBS program to do tracking under high rate conditions
- We carry out extensive cosmic-ray testing to characterize the detectors in Jlab right now
- We are at the final stages of the commissioning activities of our GEM detectors for the experiment
- The first run of the program is expected to start this fall in September

Thank You!

Backup

Why Know Nucleon Form Factors?

- Nucleons (protons and neutrons) are most of what ourselves and things around us are made of; form factors help us to probe into the nucleons
- Provide very stringent tests for models of hadron structure: Quark models, pertabative QCD, lattice QCD, effective field theories, and etc
- Used to constrain Generalized Parton Distribuion Functions (GPD) : which allows us to do "3D imaging" of the nucleon

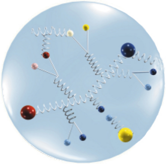


Figure: A "3-D Cartoon" of a nucleon representing its complexity: a "sea" of quarks and gluons

Evidence for Existence of Structure in Nucleons

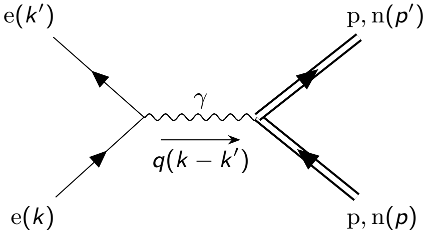
For a simple structure-less *Dirac* particle with spin, the magnetic moment:

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

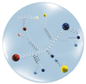
Nucleon	Predicted - *Dirac* type particle	Measured *Otto Stern* (1933)
Proton	$\frac{e}{2M_p} = \mu_N$	$2.79\mu_N$
Neutron	0	$-1.91\mu_N$

- 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

electron-nucleon Scattering within the QED Framework: Single Photon Approximation



- 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 $F_2(Q^2)$ are Known as *Dirac* and *Pauli* Form Factors; **only unknowns**
- Scalar functions of $Q^2(= -q^2)$ that parameterize the internal structure of the nucleon unknown to us

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

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

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

where the Mott corss section,

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

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