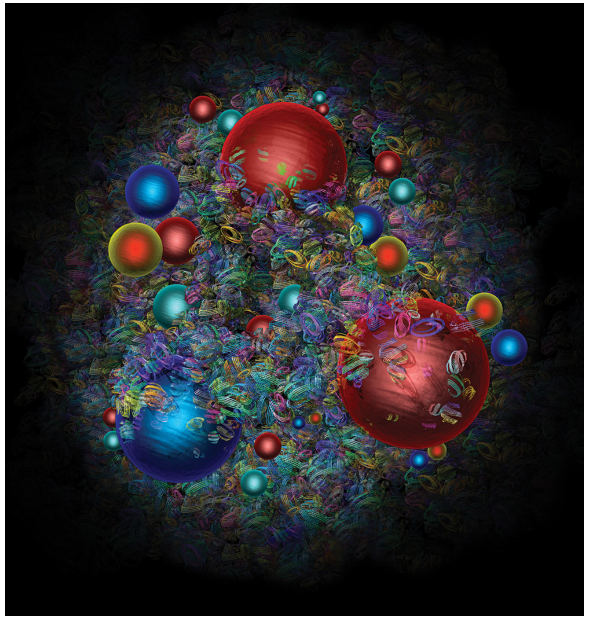
Research Introduction/Overview



Salina Ali

PhD Candidate

CUA Medium Energy Physics Group

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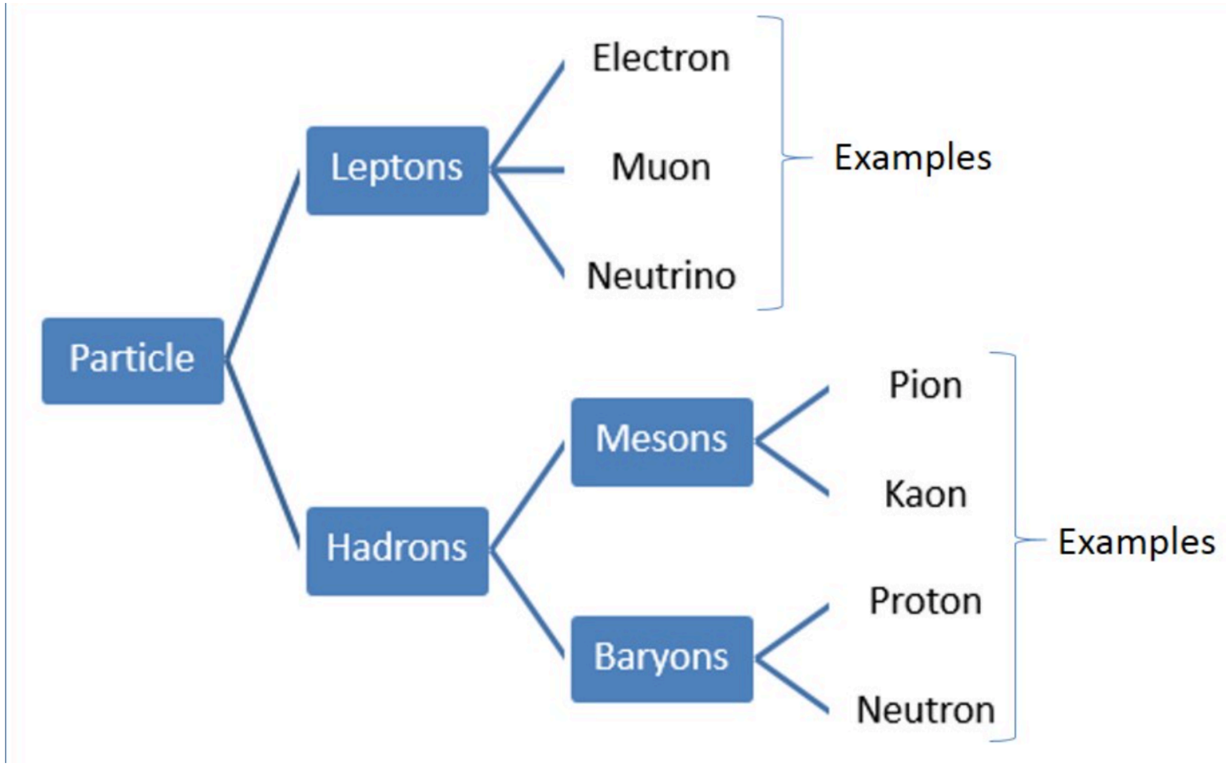
THE CATHOLIC UNIVERSITY OF AMERICA

Jefferson Lab

Definitions/Recap

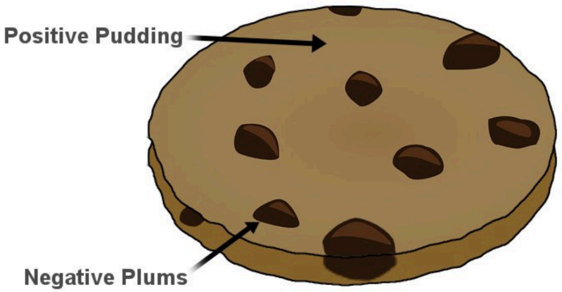
- Quick definitions:
  - **Nucleons** → **protons** and/or **neutrons**
    - Composed of quarks and gluons
  - **Hadrons** → refer to **mesons**, **baryons**
    - *Strong interaction*
  - **Leptons** → **electrons**, **muons**, **neutrinos**
    - *Weak interaction*

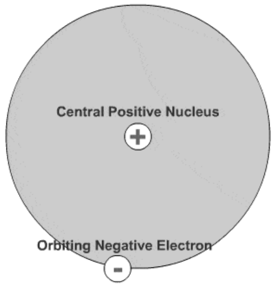


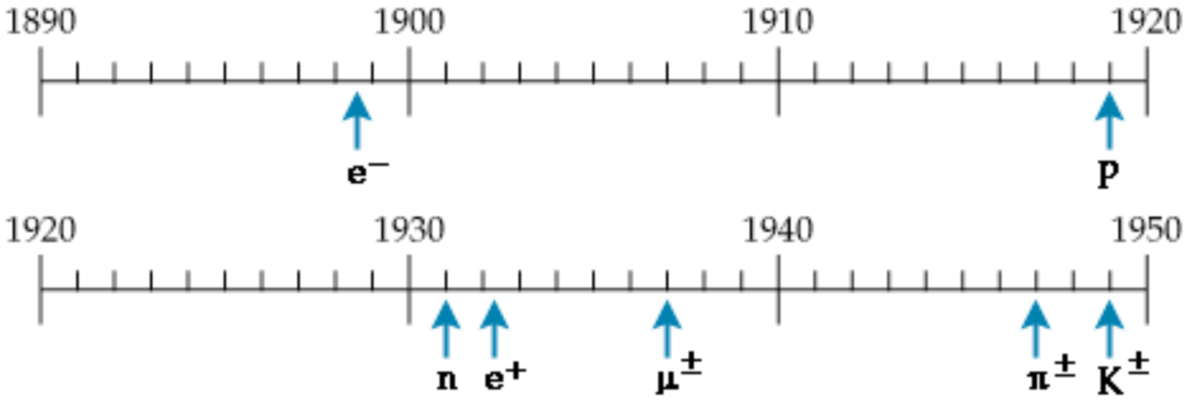
Some history: 19th-20th Centuries

- 1898-1900: **J.J. Thomson** measures the electron and proposes the *"plum-pudding"* model for the atom.
- 1911: **Ernest Rutherford** infers the nucleus as the result of the alpha-scattering experiment performed by **Hans Geiger** and **Ernest Marsden**.
  - Opposes Thomson's plum-pudding model
- 1919: **Rutherford** finds first evidence for the proton via hydrogen nucleus scattering

$$^{14}N + \alpha \to {}^{17}O + p$$



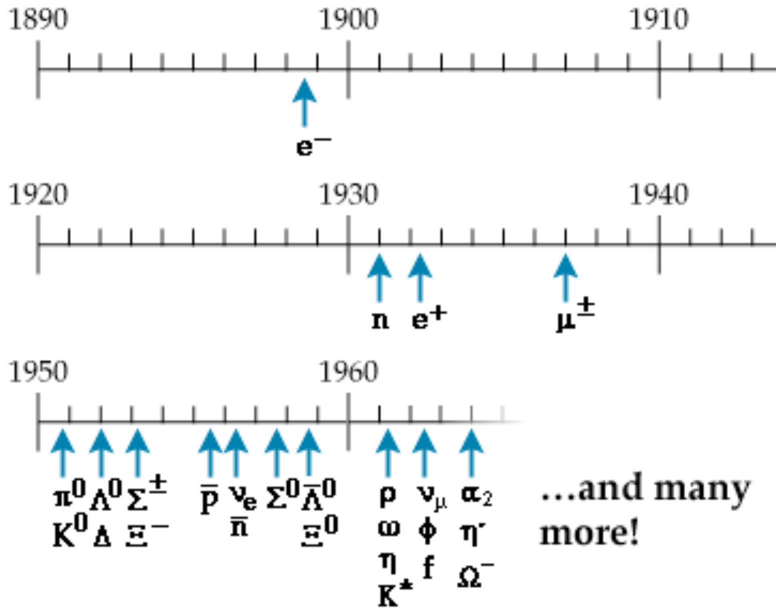


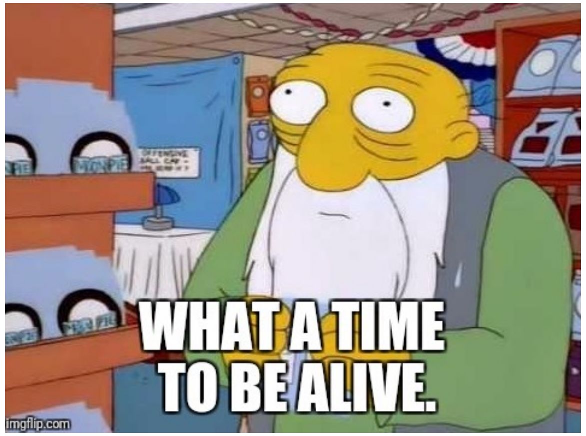


- 1930: Just three fundamental particles are known → *protons*, *electrons*, and *photons.*

Some history: early-mid 20th Century

- 1930: **Wolfgang Pauli** suggests the neutrino to explain the continuous electron spectrum for beta decay.
- 1931:
  - **Paul Dirac** realizes that the positively-charged particles required by his equation are new objects ("positrons").
  - **James Chadwick** discovers the neutron. The mechanisms of nuclear binding and decay become primary problems.
- 1937: muon discovered, first thought to be Yukawa's predicted pion (took a decade to realize this).
- 1947-1949: Strongly interacting Kaon (K^+) and pion (π^+) discovered
- Early 1950s: Splurge of particles and desire to classify them via their reaction mechanisms → need for order and symmetry





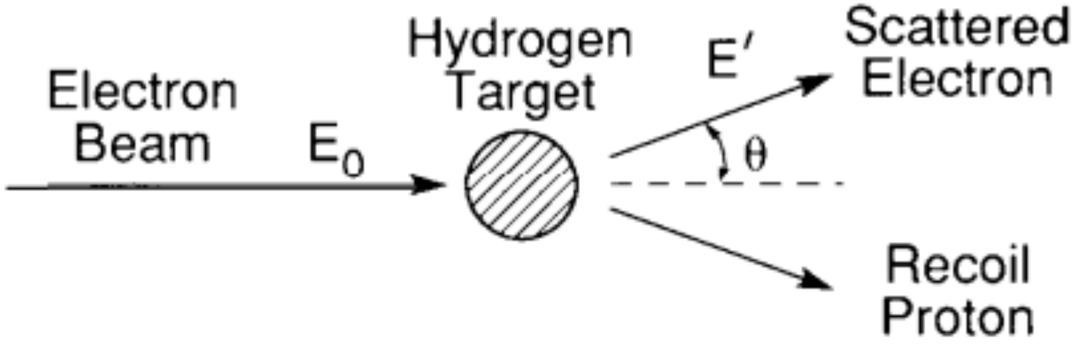
Introduction to Cross Sections: elastic e-p scattering

- 1956: Schiff, Rosenbluth → suggest to use elastic Electron-proton scattering to "probe" the proton, ep→e'p'

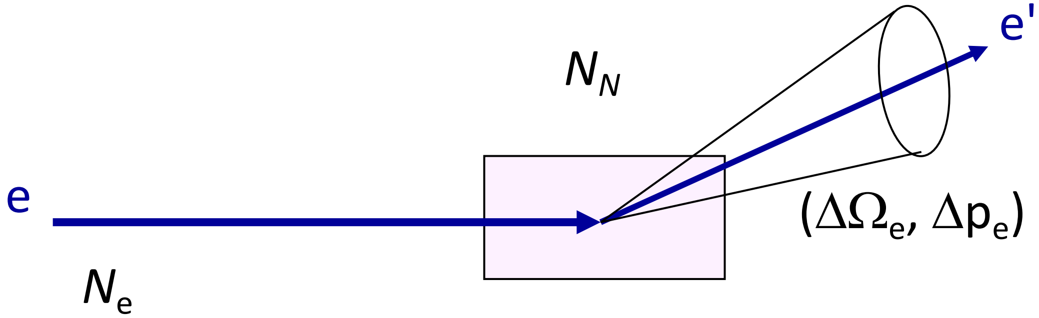
Definitions

$$E' = \frac{E_0}{1 + \frac{2E}{M}\sin^2\frac{\theta}{2}}$$

$$q^2 = -4E_0 E' \sin^2\frac{\theta}{2}$$



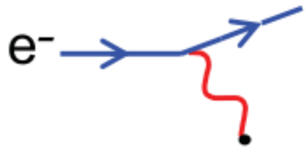
$-q^2 = Q^2$ is the four-momentum transfer squared, e.g. the probe's ability of resolving the structure of the proton



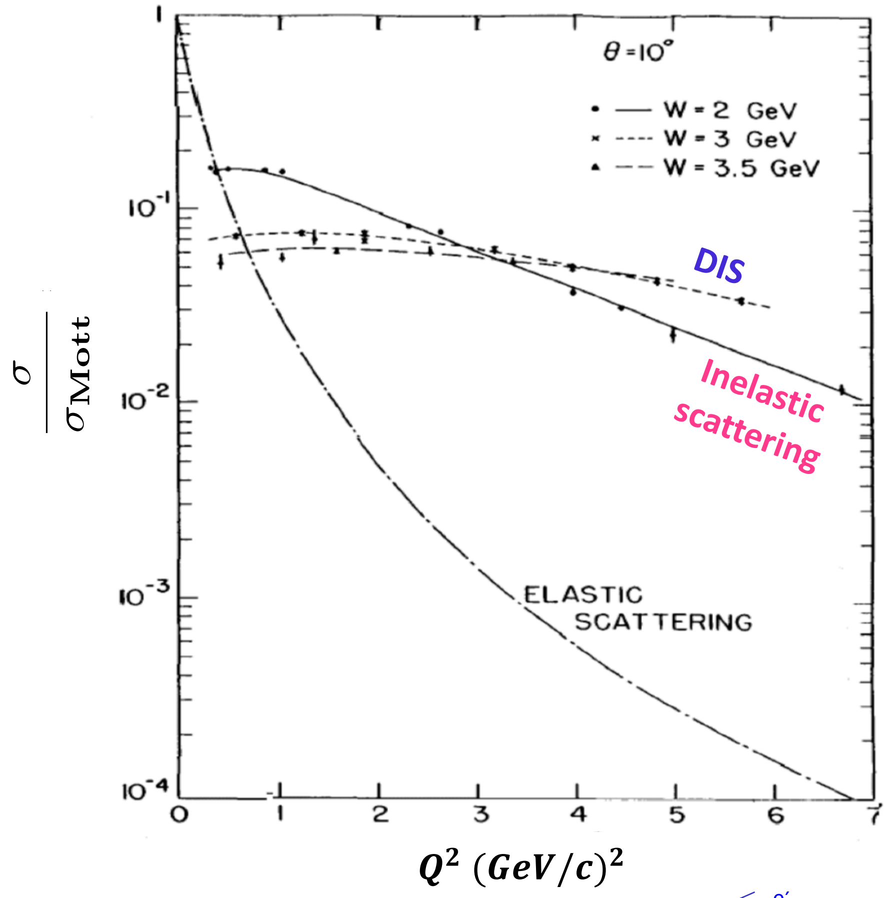
$$\left\langle \frac{d^2\sigma}{d\Omega_e dp_e} \right\rangle = \frac{Counts}{N_e N_N \Delta\Omega_e \Delta p_e}$$

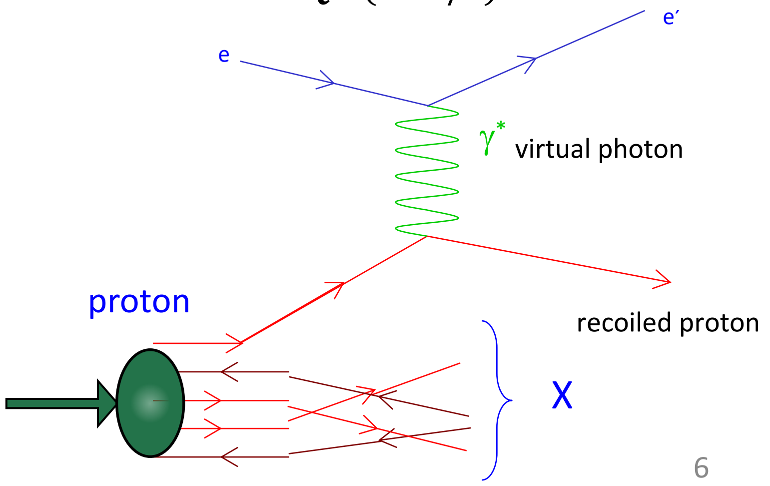
But..what is inside the proton?

- 1968: High energy experiments at Stanford Linear Accelerator Center (SLAC) observe electrons bouncing off small dense objects inside the proton.
- ***Electron scattering experiments*** use high momentum point-like leptons + electromagnetic interactions **(well understood)** to probe the hadronic structure **(which is NOT)** → Great tool to study the hadronic structure!



  - Elastic scattering: proton stays intact
    - Cross section falls off rapidly with Q^2 due to the proton not being point-like
  - Inelastic scattering: proton gets excited, can produce excited states
    - Cross section only weakly dependent on Q^2
  - “Deep” Inelastic scattering (DIS): proton breaks up and we end up with a many-particle final state
    - ***Types of DIS processes → Deeply Virtual Compton Scattering (DVCS), Deeply Virtual Meson Production (DVMP)***

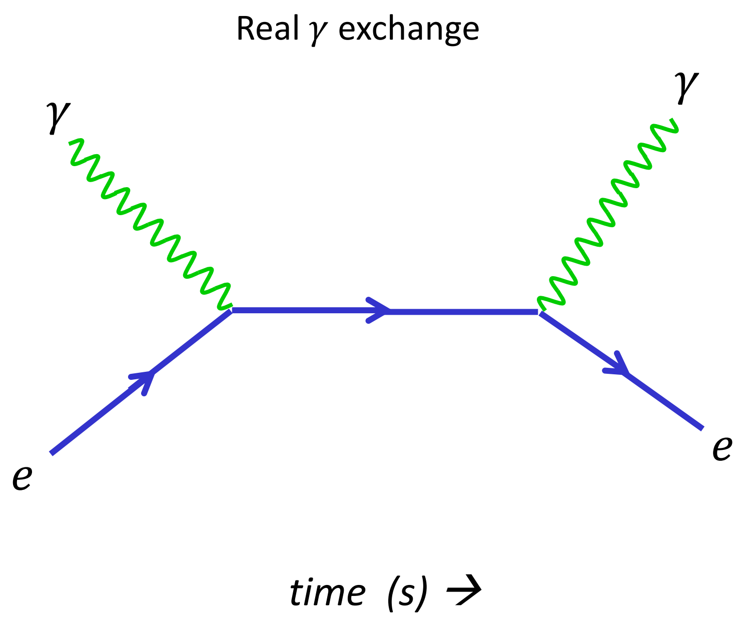


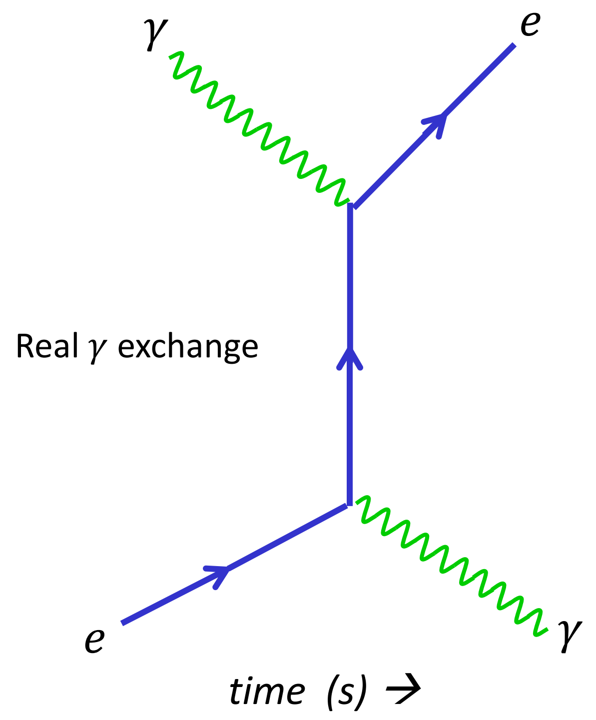


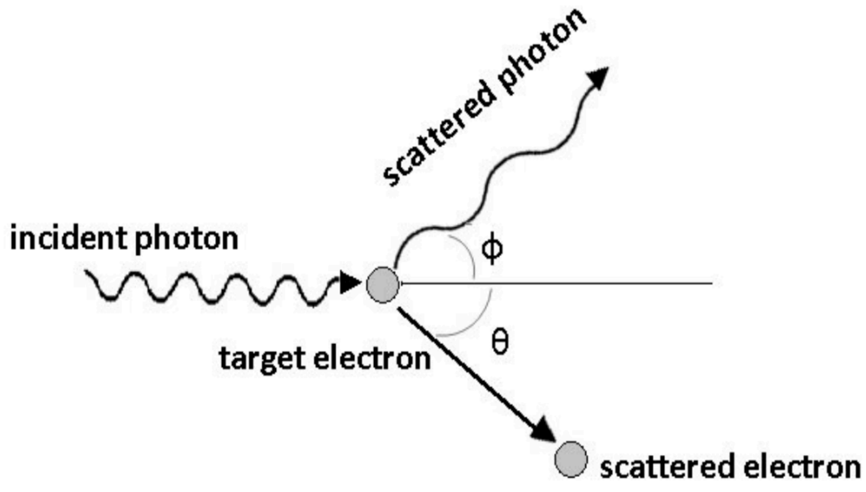
Deeply Virtual Compton Scattering (DVCS)

..but *simple case* first: Compton Scattering i.e. $\gamma e \rightarrow \gamma e$

- Shoot photon at e: scattered photon and electron angles are defined w.r.t the direction of the incident photon → describe Compton scattering with "Feynman drawings" w/ exchange of real photon

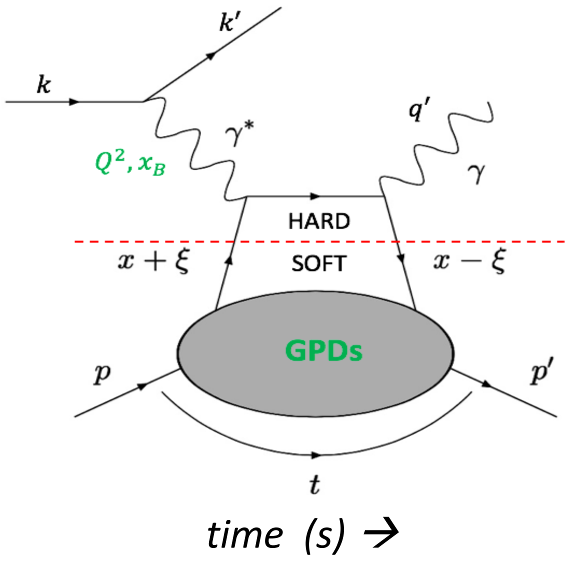




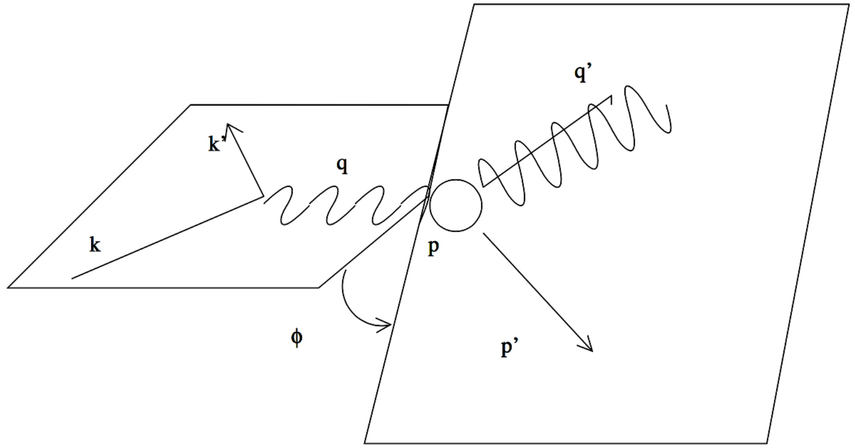


- Elastic to inelastic → virtual photon γ^* can be generated by ***inelastic electron-proton scattering***

Deeply Virtual Compton Scattering (DVCS)

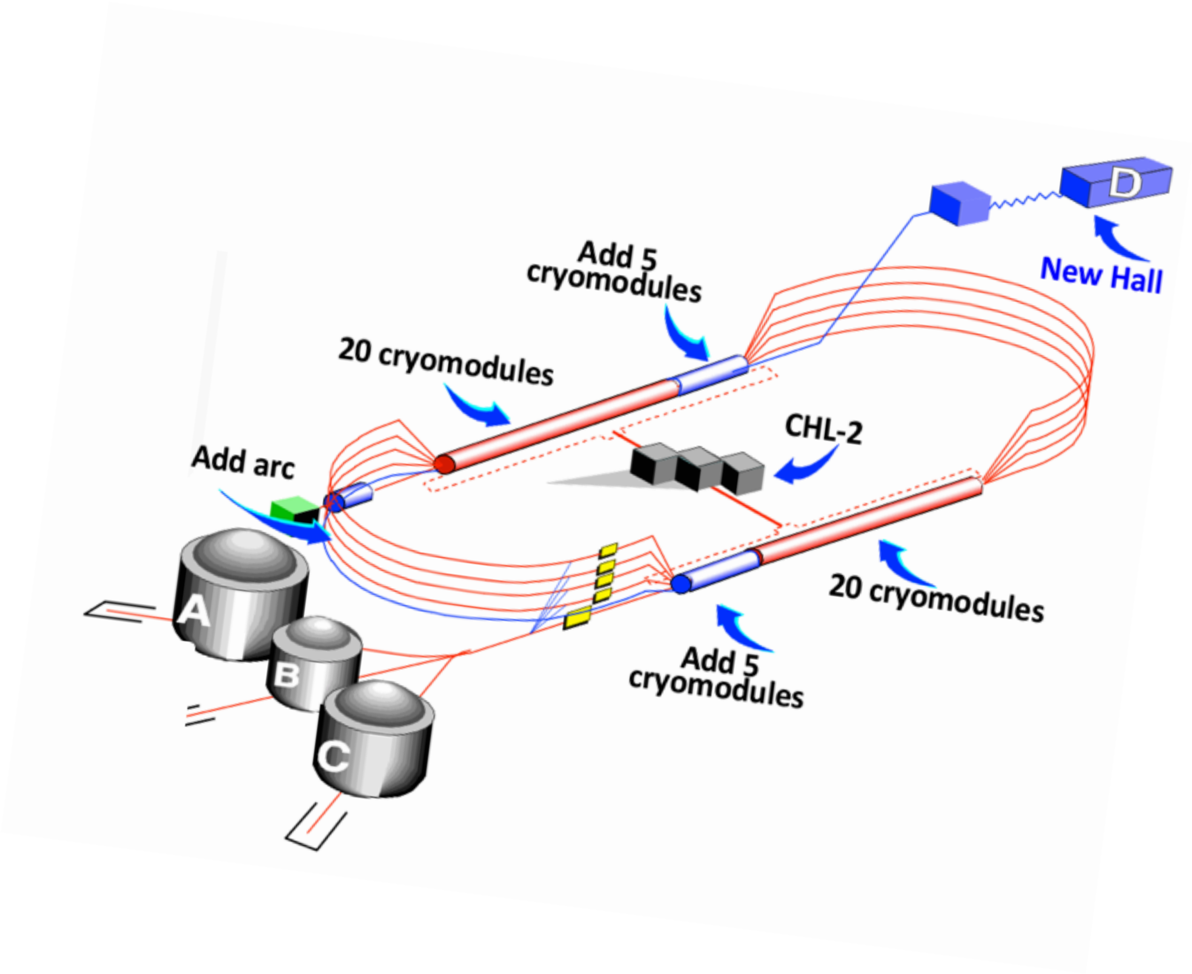


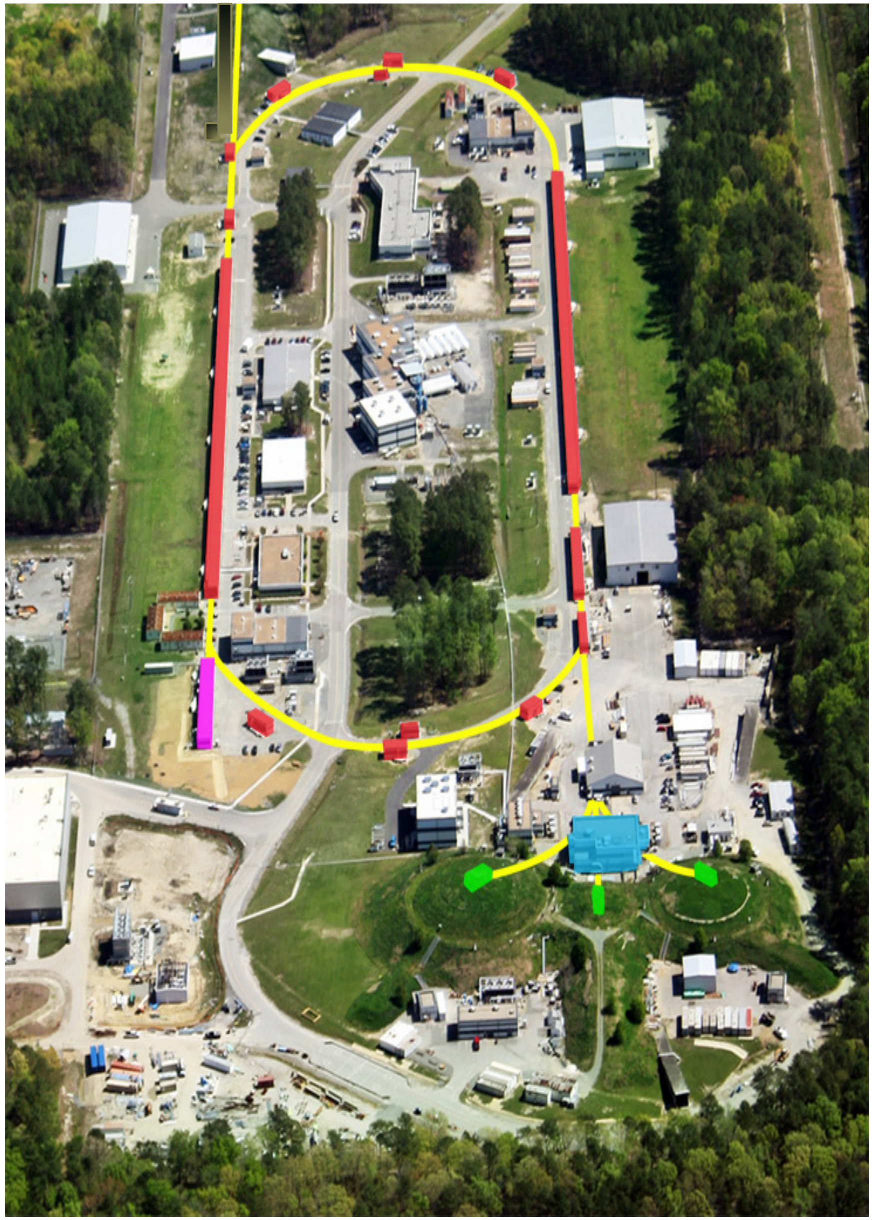
t = four-momentum transfer squared at the nucleon vertex
x = the average longitudinal momenta
ξ = fractional longitudinal momenta
k(k') is the four-vector of the incoming (scattered) electron



- DVCS = The scattering of an electron off a proton via exchange of a virtual photon (of virtuality Q^2) is accompanied by the re-emission of a real photon
- Can generate high energy probe of hadron via "Deeply Virtual" Compton Scattering
  - DVCS = $ep \rightarrow ep\gamma$ ..virtual photon is emitted and re-absorbed, defined by the probe again representing the degree of the photon's "virtuality" Q^2

Continuous Electron Beam Accelerator Facility (@ Jefferson Lab)

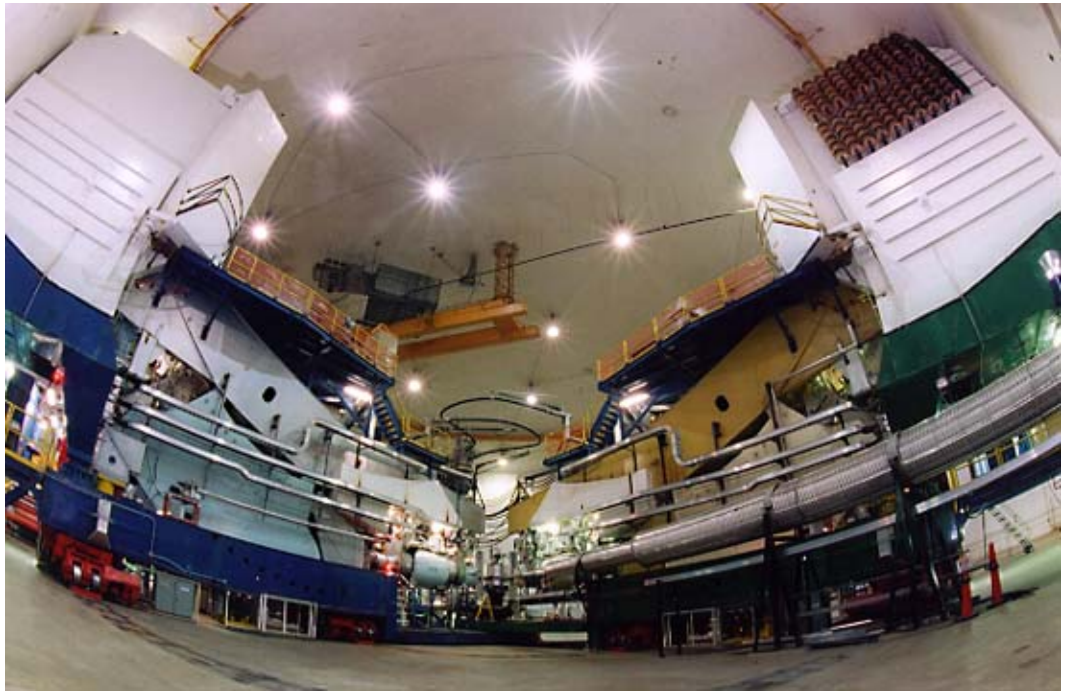


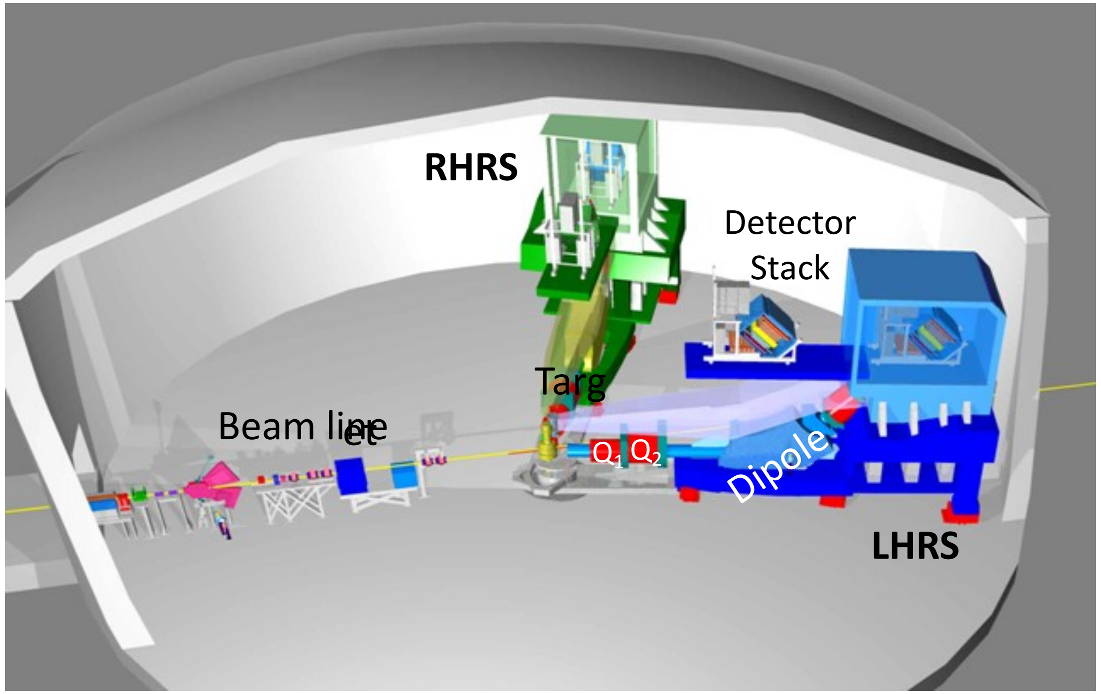


- Halls A, B, C, and D have overlapping interests but own concentration and specialty..with dedicated instrumentation!

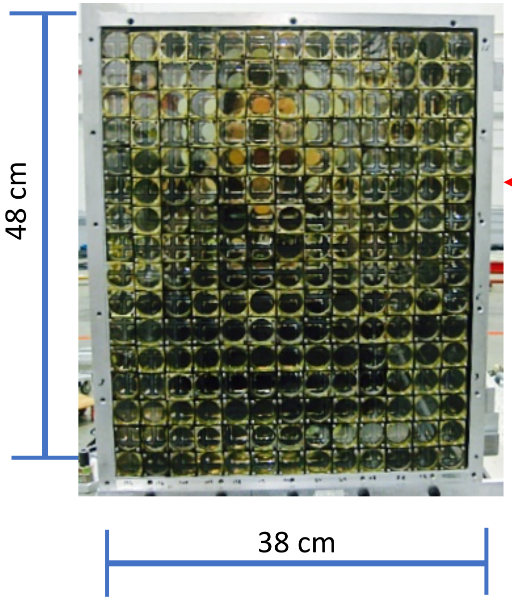
Hall A, Jefferson Lab

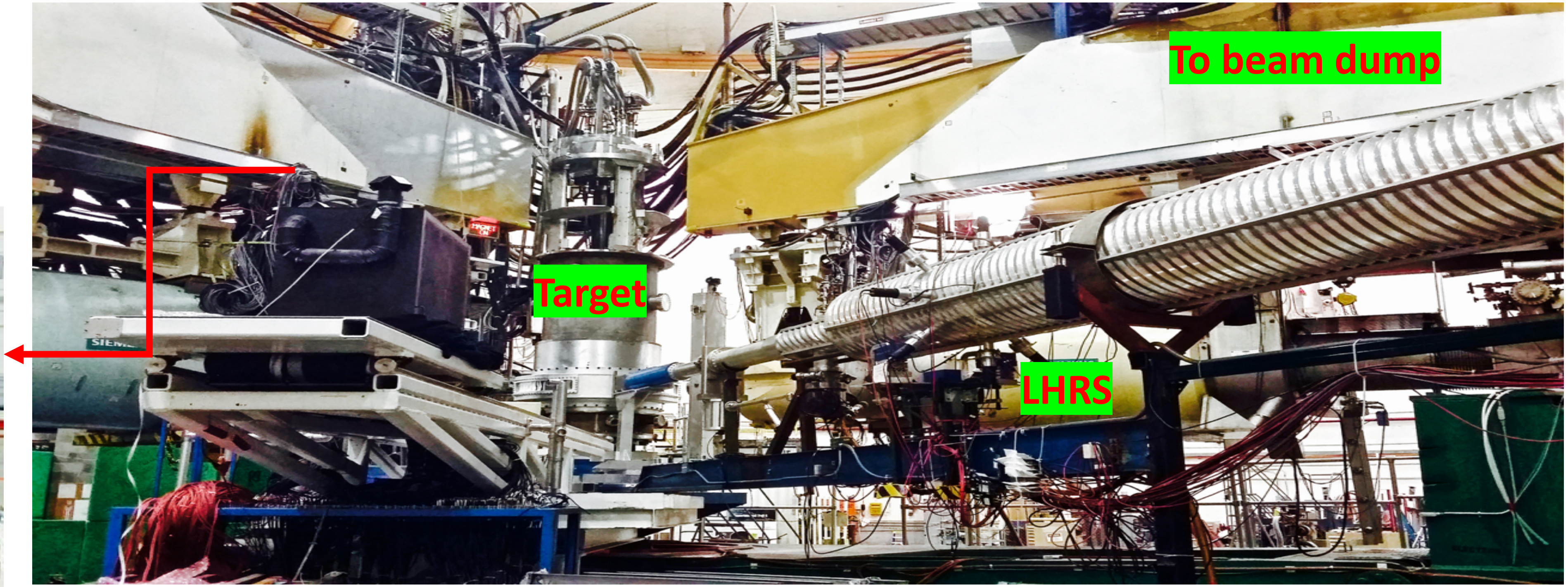
- Specializing in form factors, DIS, GPDs via electron scattering with polarized electron beams
- Matching High Resolution Spectrometers (Left and Right HRS)
  - Specialized in studying inclusive and exclusive reactions via electron scattering (DIS, DVCS, DVMP, SIDIS)..**more on that next**





Experimental Setup for DVCS-3 (E12-06-114) in Hall A





DVCS PbF_2 Calorimeter

- LH_2 target (fixed proton target!)
- **Left High Resolution Spectrometer (LHRS)** – for e' detection
- **DVCS Calorimeter** - used for π^0 and γ detection
    - 208 stacked blocks of PbF_2 crystals (Moliere radius = 2.2 cm)

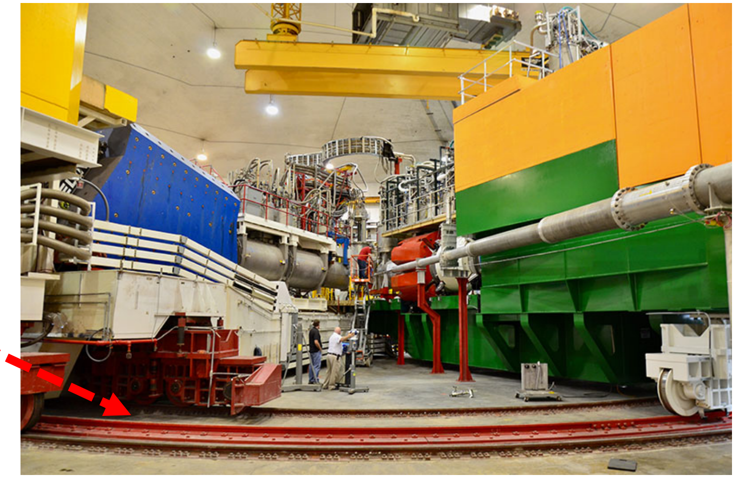
DVCS-3 Experiment Timeline in a nutshell

- 12 GeV Data taking for DVCS-3
  - Complete in 2014 and 2016

$$\boldsymbol{Q^2} = 4EE' \sin^2 \frac{\theta}{2}$$

$$x_B = \frac{Q^2}{2M\nu}$$

E_{beam} = electron beam energy (max 11 GeV in Hall A)



kin	Q^2 (GeV^2)	x_B	E_{beam} (GeV)
36_1	3.1	0.36	7.38
36_2	3.6	0.36	8.520
36_3	4.5	0.36	10.5911
48_1	2.7	0.48	4.480
48_2	4.4	0.48	8.850
48_3	5.3	0.48	8.846
48_4	6.9	0.48	10.97
60_1	5.5	0.60	8.520
60_3	8.4	0.60	10.52
60_2	6.1	0.60	8.5
60_4	9.0	0.60	10.6
48_x	TBD	TBD	TBD

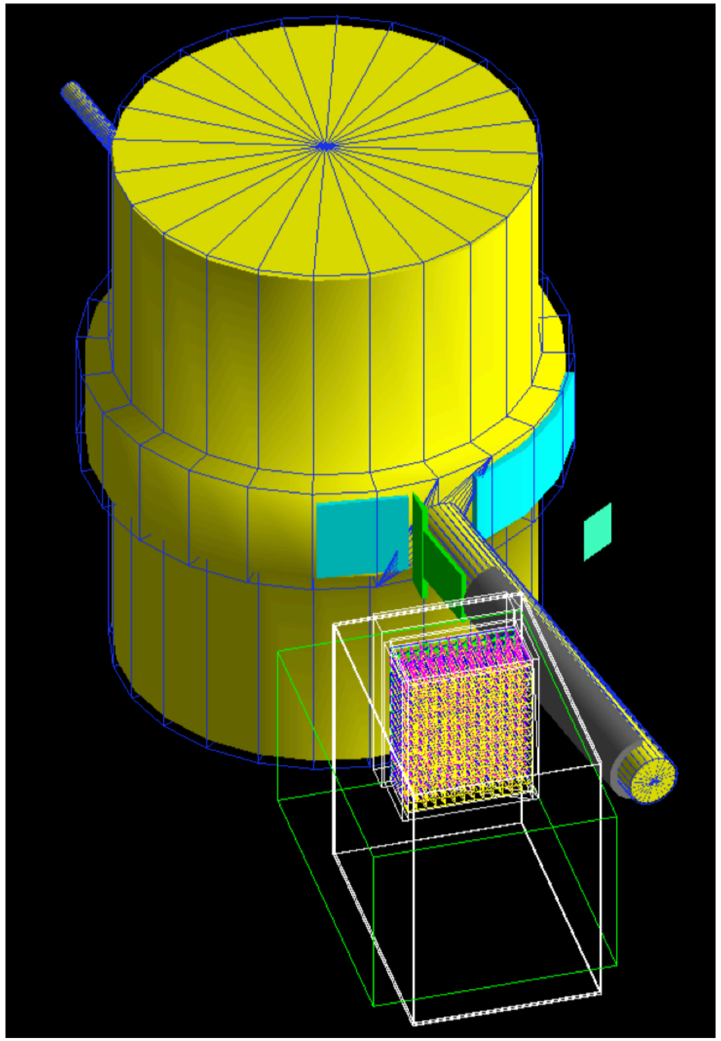
Green: Data taken by DVCS-3: π^0 cross section analysis is complete – still preliminary, systematic studies ongoing

Red: Data to be taken in Hall C with NPS: more points in x_B @ 0.48, 0.60 and higher Q^2.

- Aside: ***how do you set the kinematics for the experiment?***
  - Some parts of the desired kinematic required by the experiment, e.g. θ_e, Q^2, are set by moving the huge spectrometers in the Hall on tracks with the corresponding beam energies and currents.
  - Beam energies for the experiment are requested by shift leaders, and determined by Hall personnel assigned on experiment.

Monte Carlo (MC) Simulation

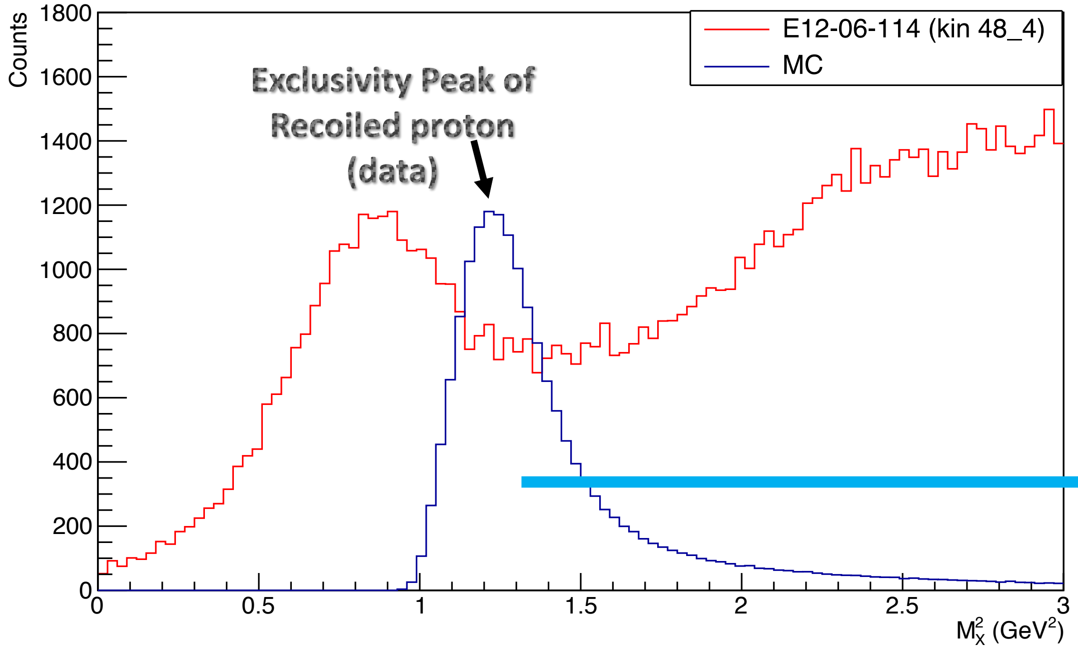
- Experimental cross section is calculated from the # of experimental events detected over total acceptance of detector *BUT*:
  - The detector in experiment (DVCS Electromagnetic calorimeter) is not sensitive to all locations in acceptance.
  - **Monte Carlo (MC) simulation is used to estimate the total acceptance.**
- MC depends on **geometry of detector** and is used to estimate acceptance over the phase space of particles detected and radiative effects.
- Limitations of the simulation:
  - To match the MC exclusivity peak to the data, **apply a local "smearing" and calibration procedure to** the components of the photon's energy and momentum in the MC.



Geometry of the experimental setup implemented in the GEant4 simulation.

Tuning of Monte Carlo Simulation for DVCS-3

- MC is limited in reconstructing the resolution of the photon's energy DVCS calorimeter, so we need to match the MC exclusivity peak to the data
- **<u>We apply a local "smearing" and calibration procedure to</u>** the components of the photon's energy and momentum in the MC

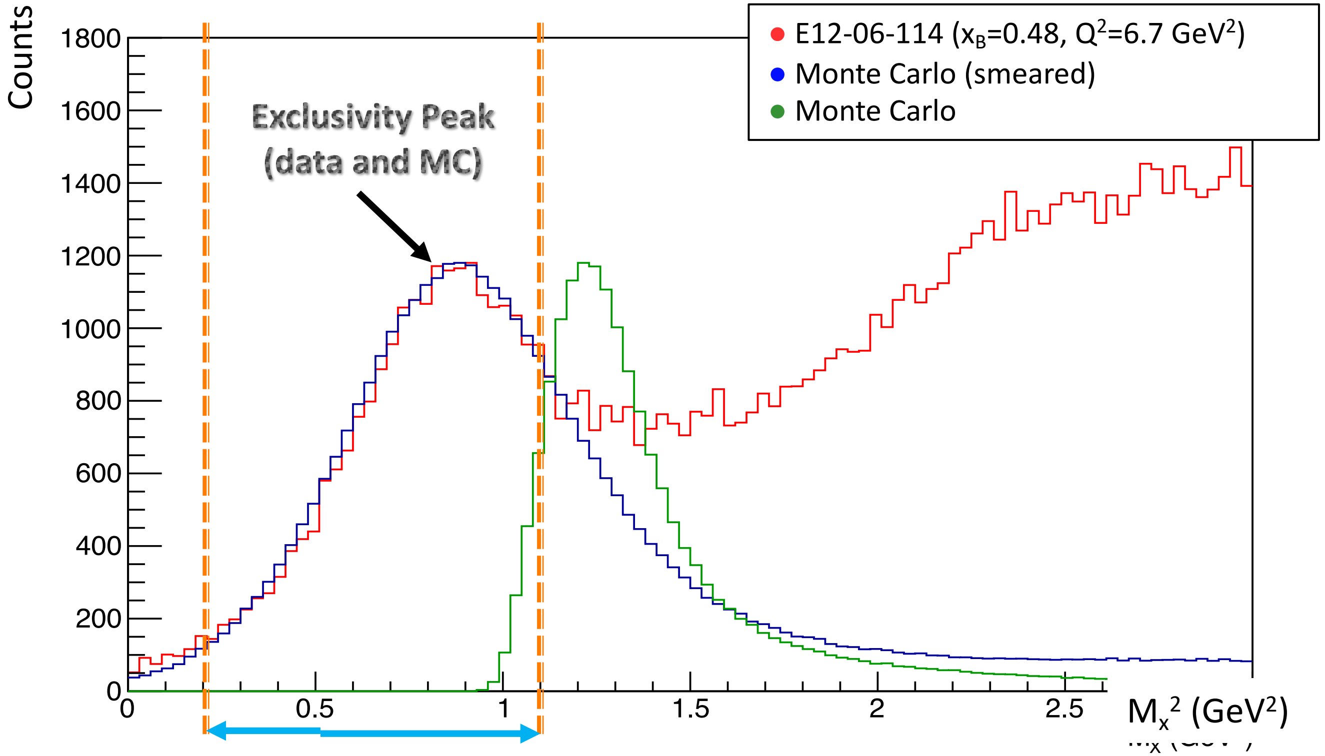


$$\begin{bmatrix} q_x \\ q_y \\ q_z \\ E \end{bmatrix} = gaus(\mu, \sigma) \times \begin{bmatrix} q_x \\ q_y \\ q_z \\ E \end{bmatrix}$$

<u>"detection" of proton from experiment</u>

→ Reconstructed missing mass squared M_x^2 with peak at (0.938 GeV)^2=0.88 GeV^2

Selection of π^0 events: M_x^2 cut



Lower bound < $(M_X)^2$ < Upper bound

- Apply $(M_x)^2$ cut where data and MC diverge → vary $(M_x)^2$ cut to determine systematic uncertainty on cross section.
  - 0.5% uncertainty contribution is expected.

Summary

- Overview of history of e-p scattering
- Introduction to Cross sections; Elastic scatterings, inelastic scattering, and Deep Inelastic Scattering (DIS)
- Introduction to Deeply Virtual Compton Scattering (DVCS) process
- Overview of DVCS-3 Experiment in Hall A (my PhD thesis experiment)
  - DVCS-3 in Hall A of Jefferson Lab (Newport News, VA) took data for nine kinematics in 2014, 2016 → analyzed π^0 electroproduction data within DVCS kinematics.
- DVCS-3 Data Analysis introduction
  - Monte Carlo Simulations
  - Detection of proton in experiment (exclusivity peak of missing mass squared)
  - Smearing of MC exclusivity peak to data
- Potential topics to discuss next time:
  - Introduction to Generalized Parton Distributions (GPDs), DVMP
  - π^0 electroproduction cross section extraction procedure
  - Other projects: Work on kaon aerogel Cherenkov detector for kaonLT experiment
  - Other projects: Lead tungstate crystal characterization @ CUA