University of Glasgow

ePIC

Past and Present Research: Hadron Structure and Electron Scattering

Jefferson Lab

CFNS Postdoc Monthly Meeting

Gary Penman*
University of Glasgow

28th August 2025

*gary.penman@glasgow.ac.uk

WORLD CHANGING GLASGOW

A WORLD TOP 100 UNIVERSITY

Introduction

Research History

PhD (2021-2025): University of Glasgow + Hall A Jefferson Lab - SBS Form Factor Program.

Several EIC related projects during this time

Viva passed March 2025.

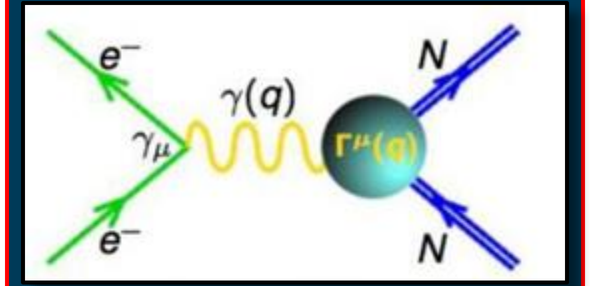
Now Joint Postdoctoral Fellow, CFNS + Glasgow.

Studying TCS (+ other interesting EIC physics) and working on development of the ePIC Low-Q2 Tagger.

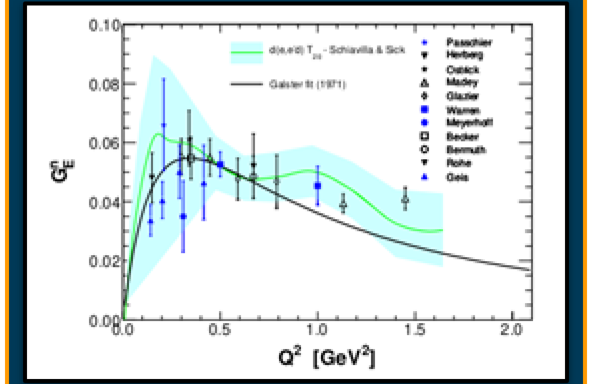
PhD Research:
GEn – Electric Form Factor of the Neutron

GEN-II: Neutron Electric Form Factor at High Q^2

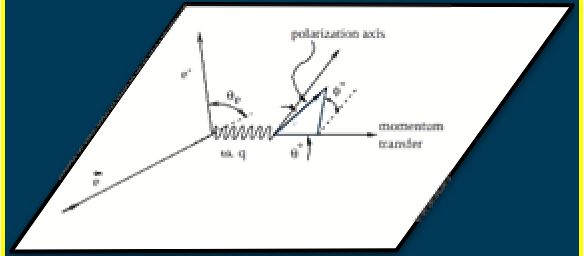
Double polarized semi-exclusive 3He(e,e'n)pp quasi-elastic scattering



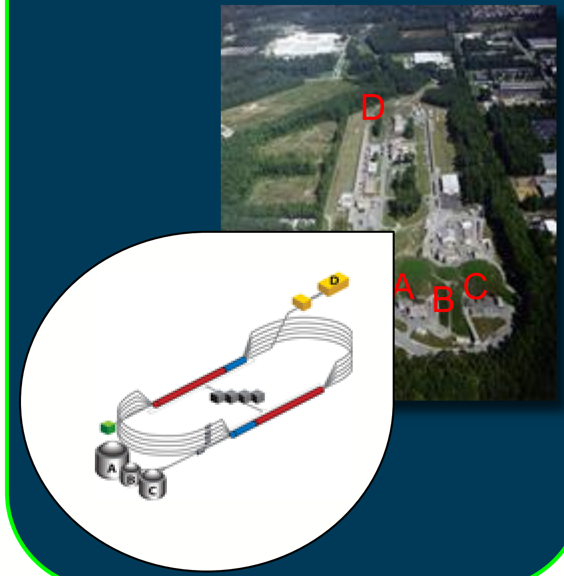
Extract Sachs Form Factor GEn with precise high Q2 GMn data.

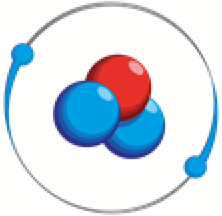


Measure transverse asymmetry $A_\perp$ of cross section



Hall A - Thomas Jefferson National Accelerator Facility

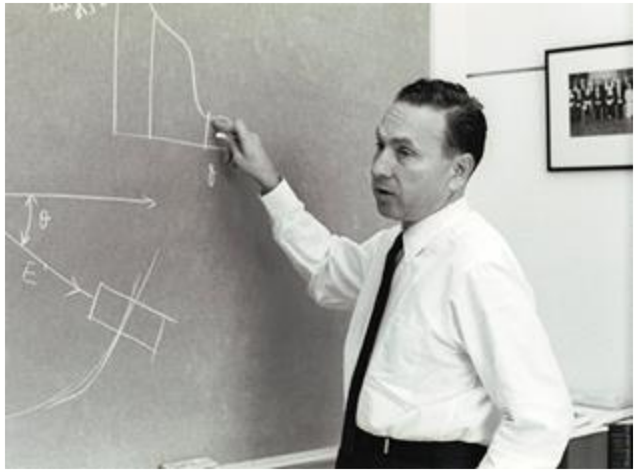


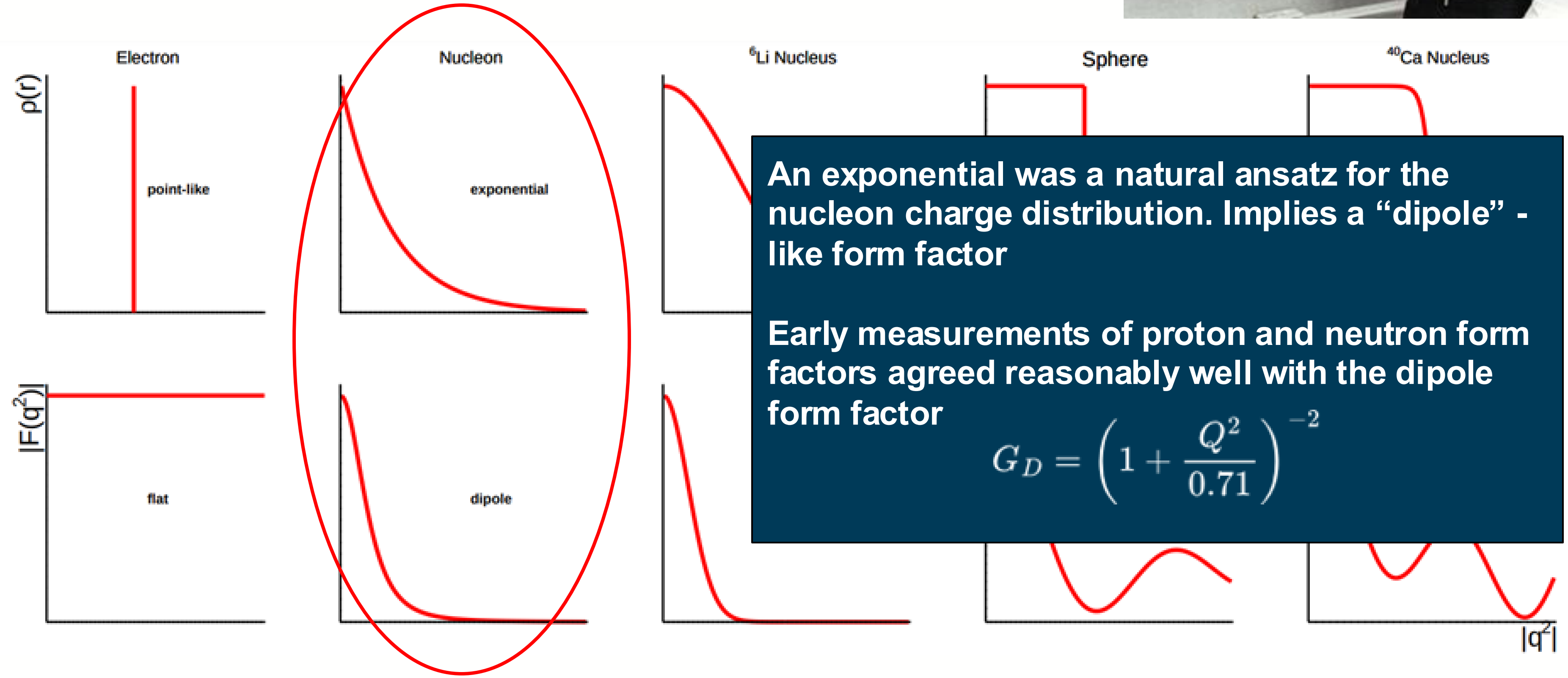


Nucleon Structure - Form Factors

R. Hofstadter et al. (1950s) demonstrated that the elastic scattering cross section could be described by the cross section of point particle scattering from QED and a “Form Factor” of the form

$$\sigma(\theta_e) = \sigma_M \left| \int \rho(r) e^{iq.r} d^3r \right|^2 = \sigma_M \left| F(q) \right|^2$$



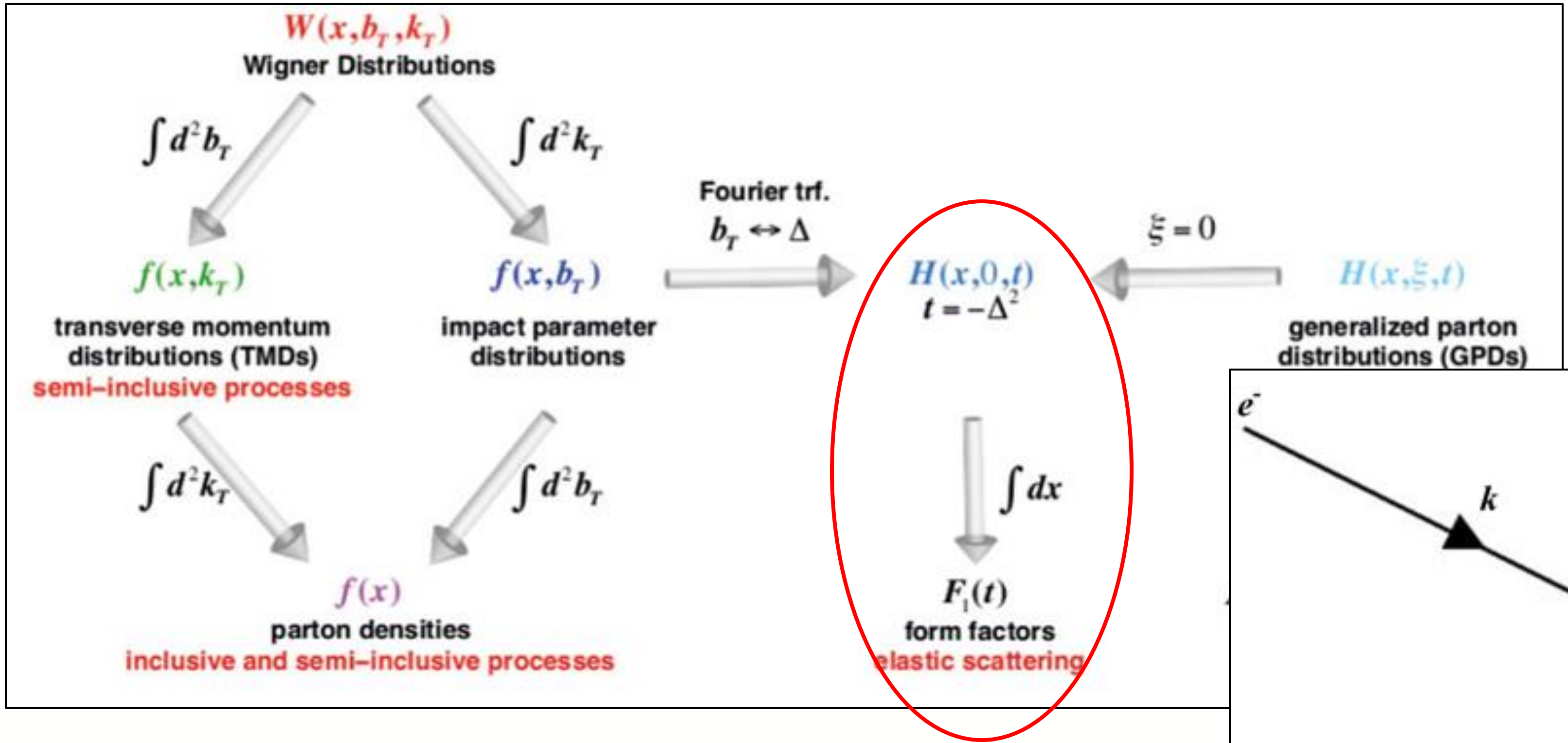


An exponential was a natural ansatz for the nucleon charge distribution. Implies a “dipole” - like form factor

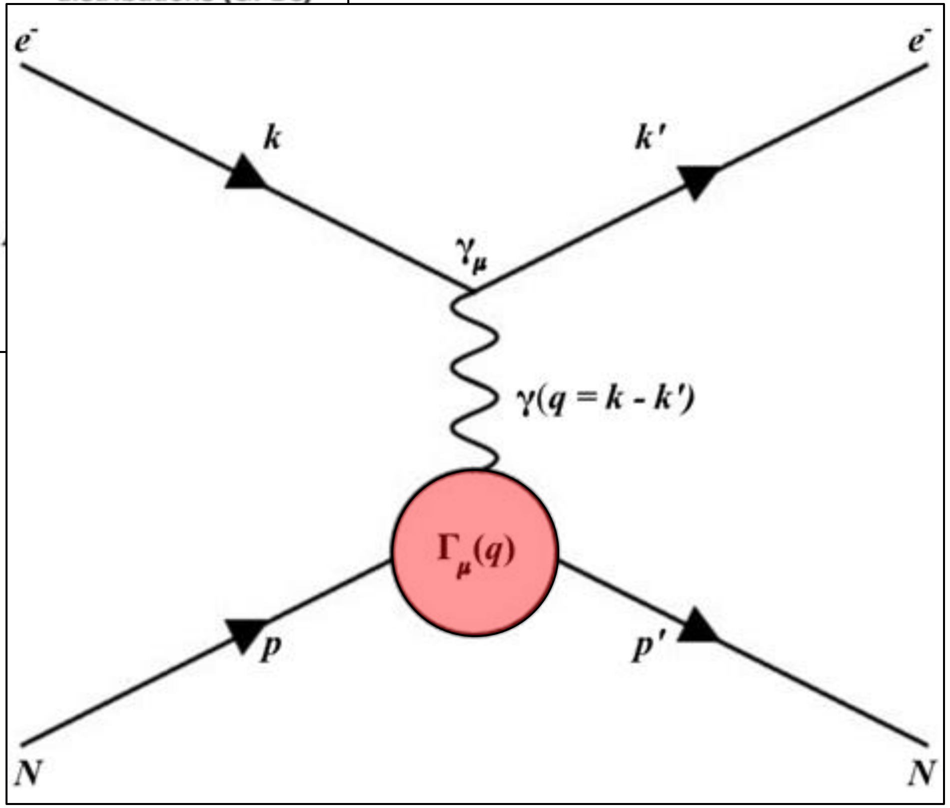
Early measurements of proton and neutron form factors agreed reasonably well with the dipole form factor

$$G_D = \left(1 + \frac{Q^2}{0.71}\right)^{-2}$$

Probing Nucleon Structure with Electrons



$$\Gamma_\mu(p,p') = \gamma_\mu F_1(Q^2) + \frac{i\sigma_{\nu\mu}}{2M} F_2(Q^2)$$



Pauli, Dirac FFs

$$F_{1p}(0) = 1$$
$$F_{2p}(0) = \mu_p - 1$$
$$F_{1n}(0) = 0$$
$$F_{2n}(0) = \mu_n$$

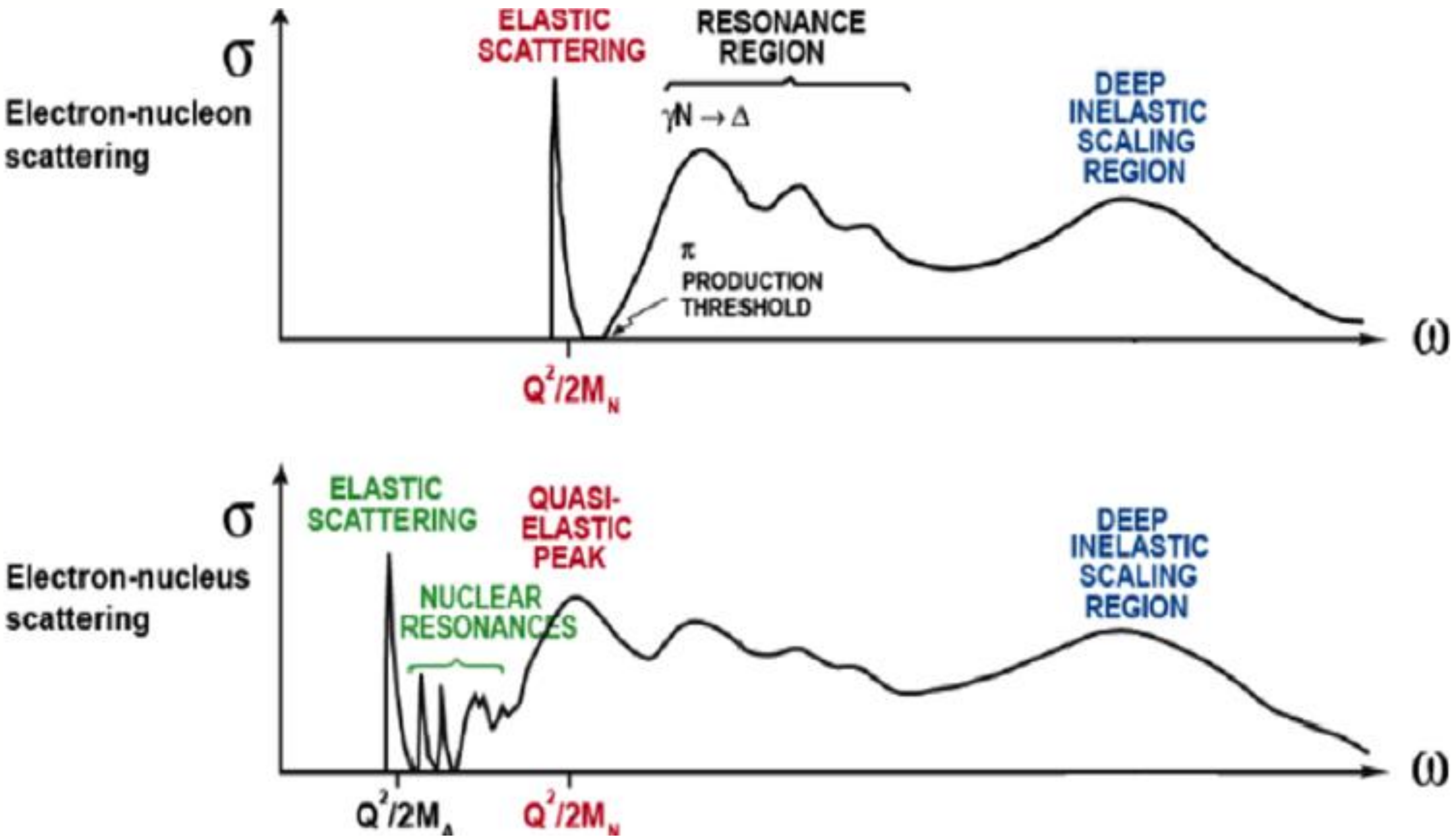
Sach's EMFFs

$$G_E^{p(n)} = F_1^{p(n)} - \tau F_2^{p(n)}$$
$$G_M^{p(n)} = F_1^{p(n)} + F_2^{p(n)}$$

$$\tau \equiv \frac{Q^2}{4M^2}$$

Nucleon structure is revealed in the Q^2 evolution of the form factors

Quasi-elastic eN Scattering



Elastic scattering on hydrogen provides a clean probe of proton EM Form Factors

No free neutron targets! Neutron structure explored by quasielastically scattering neutrons out of light nuclei.

The motion within a nucleus "smears" out kinematics with respect to elastic electron-proton scattering.

Electric form-factor

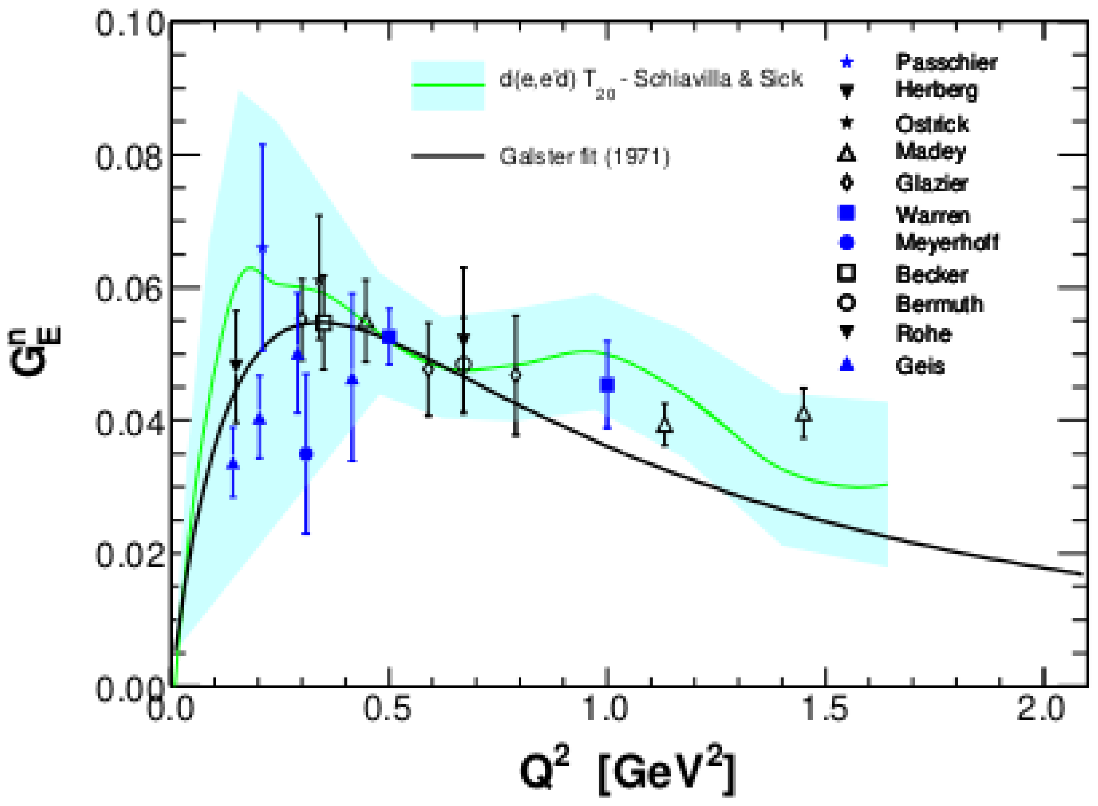
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4 \theta/2} \frac{E}{E'} \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} \cos^2 \theta/2 + 2\tau G_M^2 \sin^2 \theta/2 \right]$$

point-like target

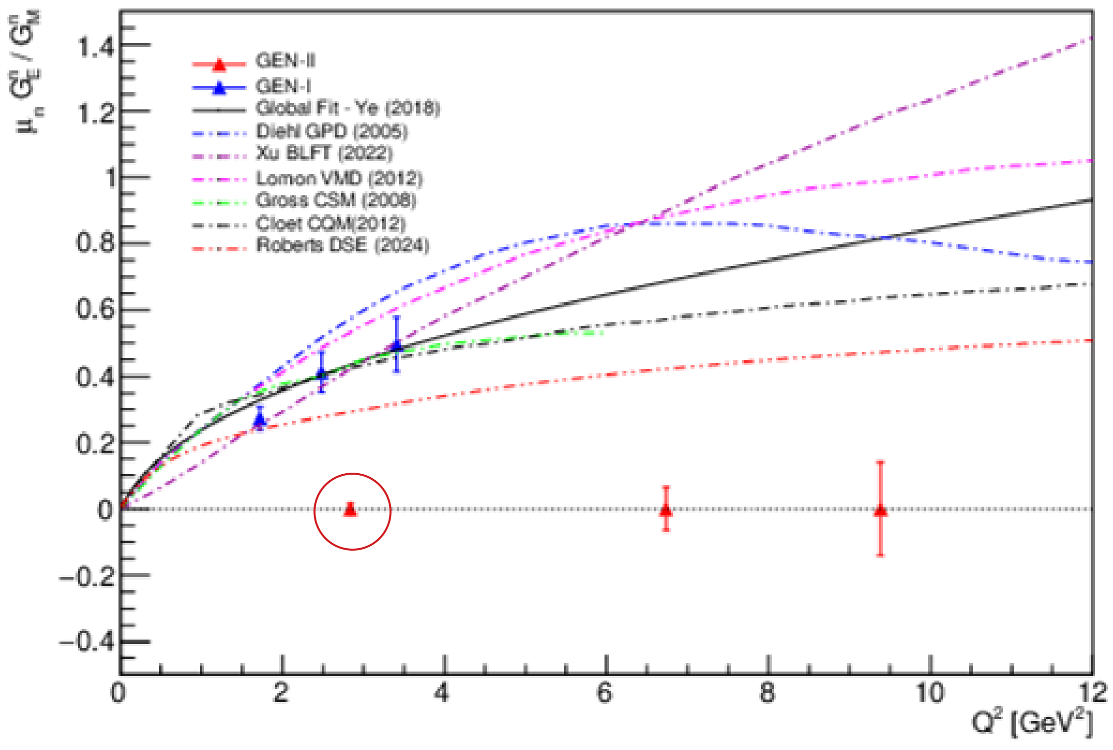
Magnetic form-factor

$$\tau \equiv \frac{Q^2}{4M^2}$$

Electric Form Factor of the Neutron G_E^n



Pre-JLab GEn world data from polarisation measurements.

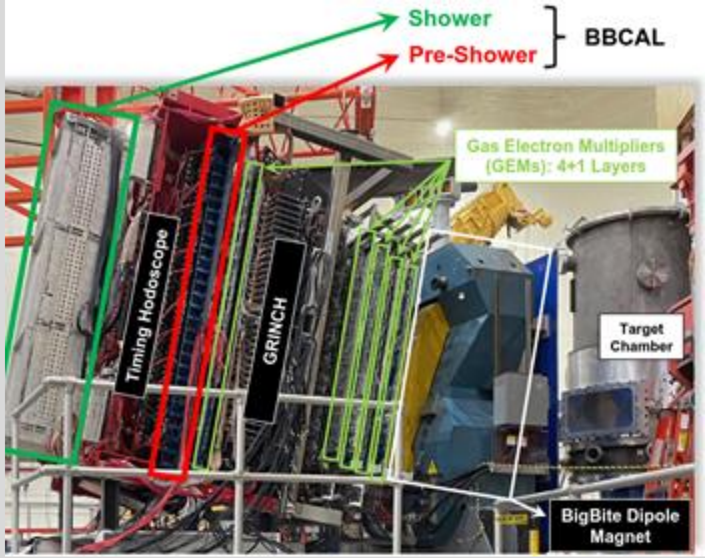


GEN-I results (blue triangles) and GEN-II statistical projections (red triangles), plotted with various nucleon form factor parameterisations.

Hall A Experimental Setup: Super Bigbite Spectrometer

Electron Arm: Bigbite

- 750A Dipole Magnet
- Full Detector Stack
  - Calo Trigger
  - GEM Tracking
  - Cherenkov
  - Timing Hodoscope



Nucleon Arm: SBS

- 2100A Dipole Magnet
- Hadron Calorimeter

Polarised ^{3}He Target

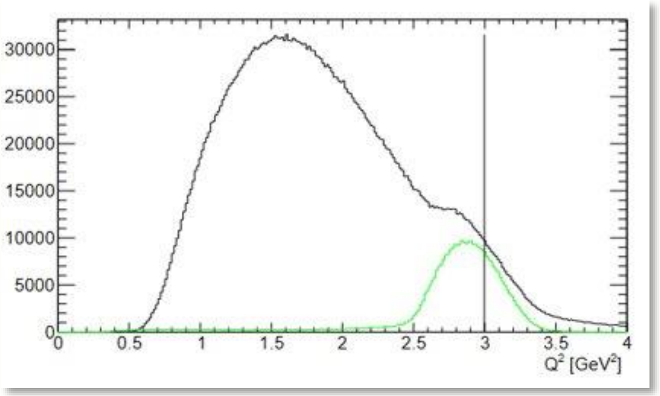
GEN-II polarised target installation, Summer 2022.

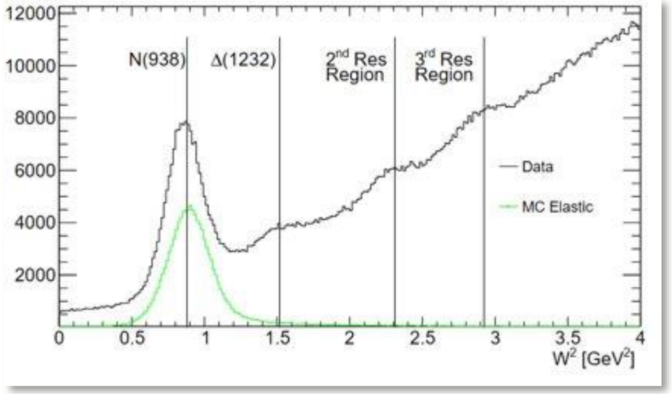
(Simplified) Data Analysis

1. Kinematic Reconstruction:

$$Q^2 = -q^2 = -(k-k')^2 = 2E_i E_f(1-\cos\theta_e)$$

$$W^2 = P^\mu P_\mu = (q+T)^2$$

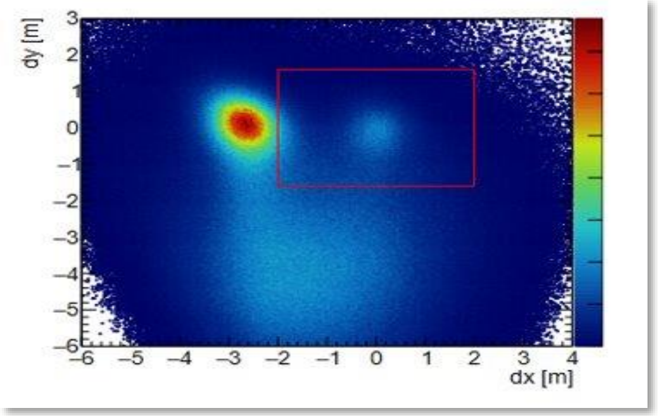


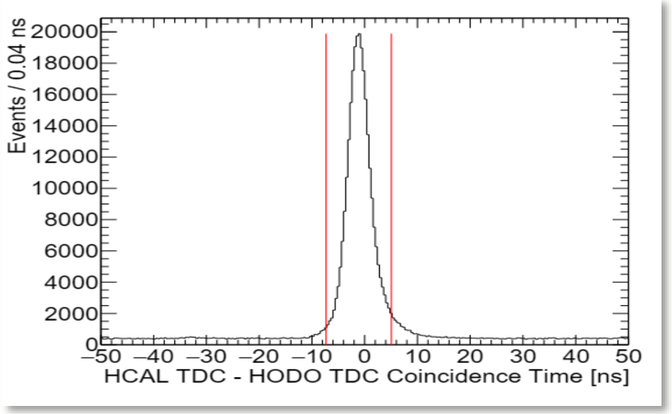


2. Quasielastic event selection:

$$\Delta x = x_{\mathrm{HCAL}} - x_{\mathrm{expect}}$$

$$\Delta y = y_{\mathrm{HCAL}} - y_{\mathrm{expect}}.$$





3. Rejection of timing accidentals: 3 sigma coincidence time cut between electron in hodoscope and neutron in hadron calorimeter.

4. Final asymmetry analysis:

What we measure: Asymmetry between +,- helicity states for events.

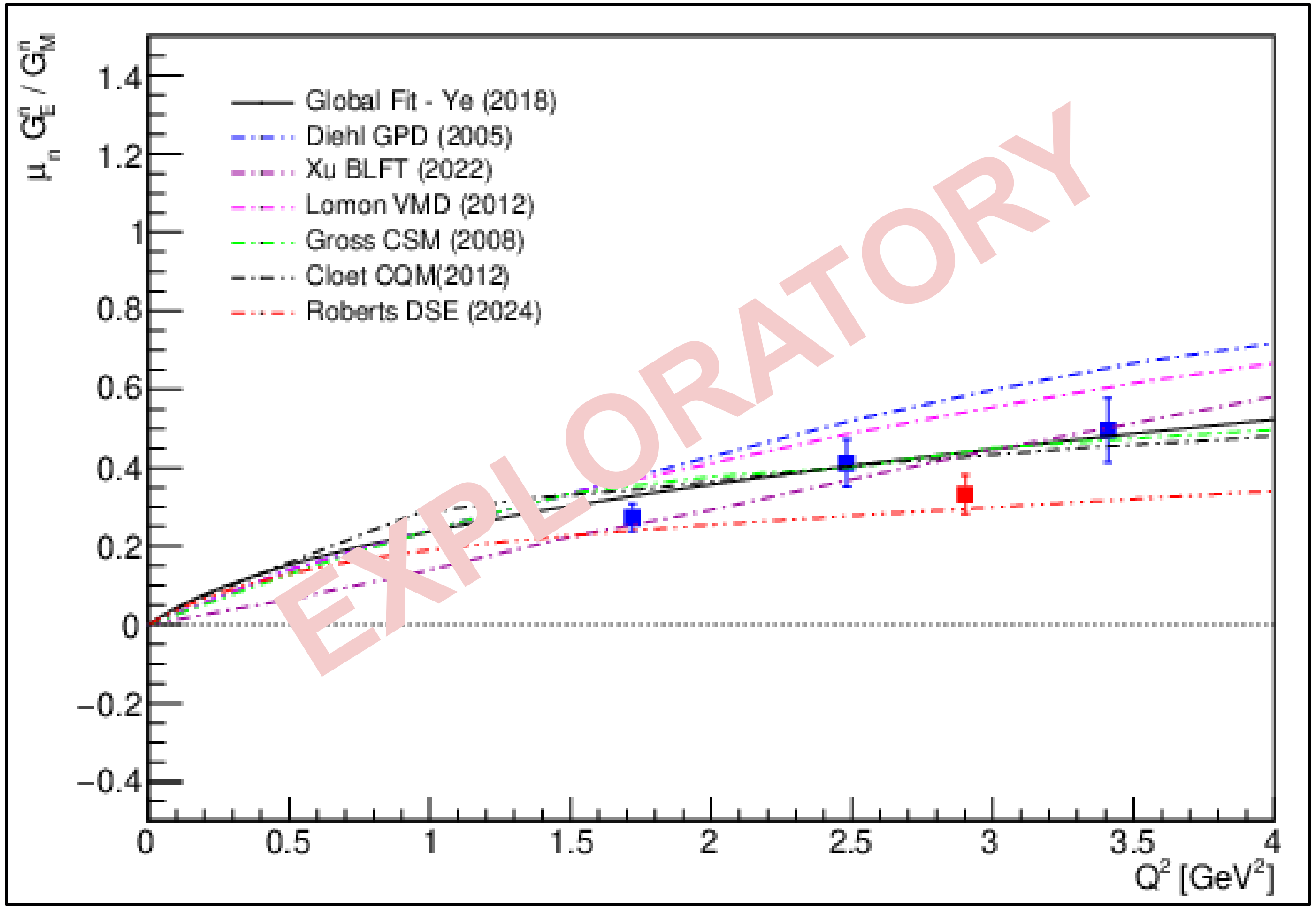
The sum of background modifications to the raw asymmetry:

$$A_{\mathrm{phys}} = \frac{A_{\mathrm{raw}} - \Sigma_\chi f_\chi A_\chi}{P_{\mathrm{He^3}} P_{\mathrm{n}} P_{\mathrm{beam}} (1 - \Sigma_\chi f_\chi)}$$

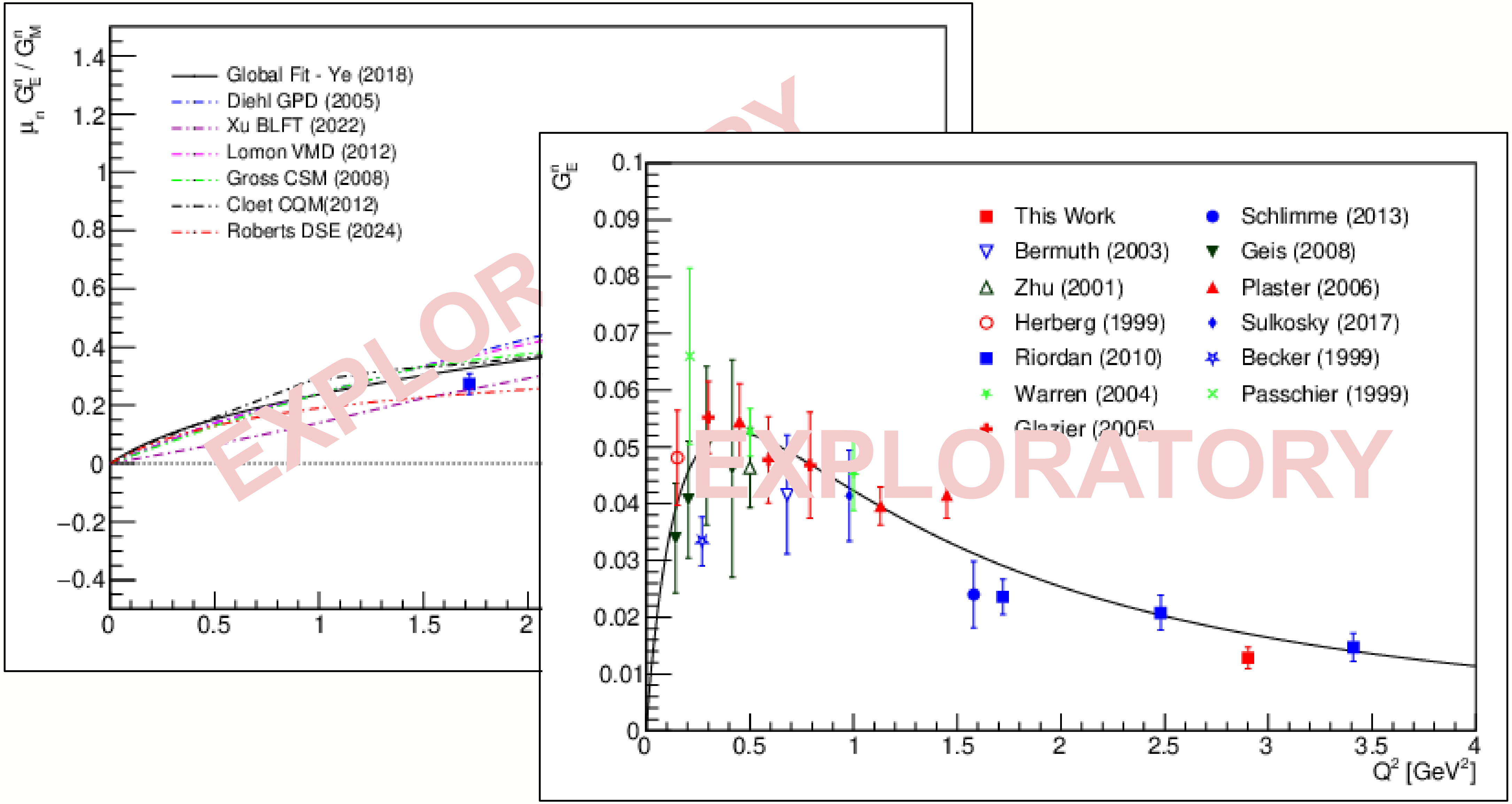
Polarisation of the target, beam and neutron within ^{3}He

Fraction of event sample as a result of purely QE scattered neutrons

Exploratory Results (Circa Dec 2024)



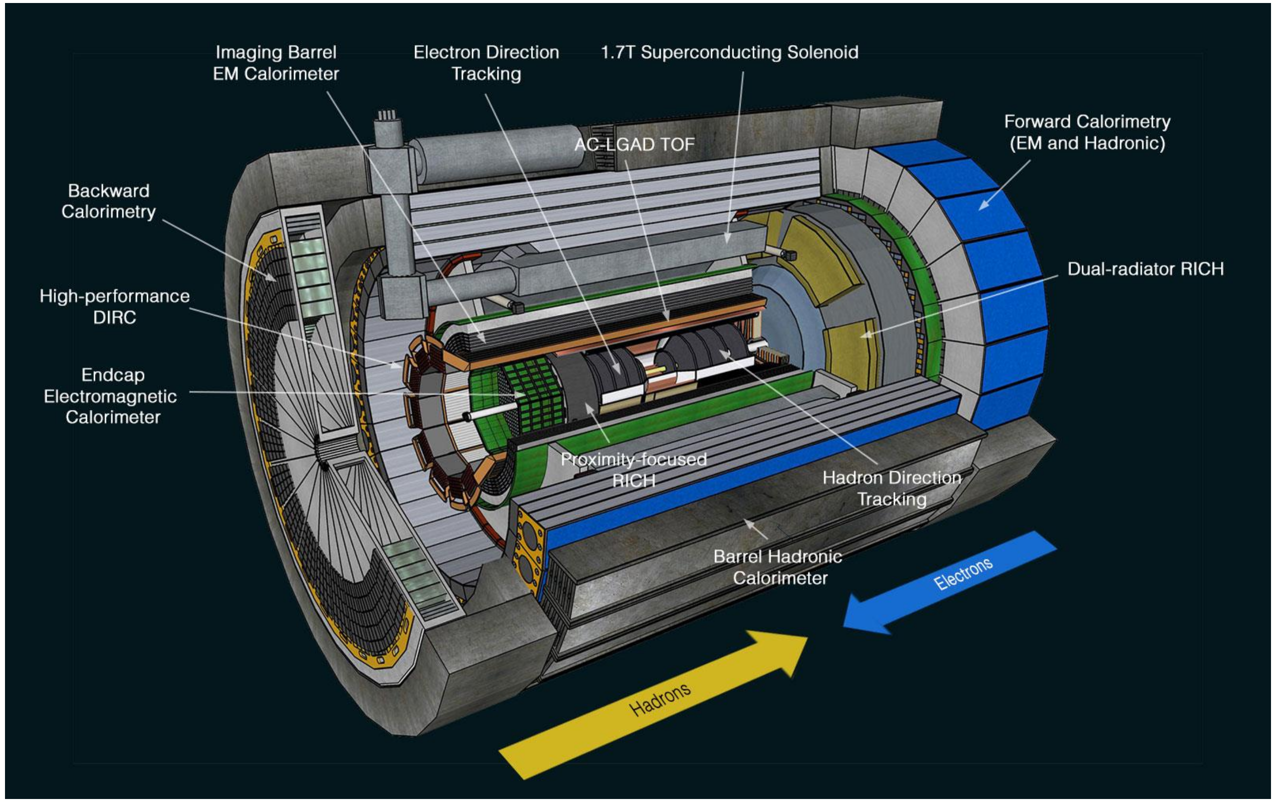
Exploratory Results (Circa Dec 2024)



Current Research:
Timelike Compton Scattering
and the ePIC Low-Q^2 tagger

ePIC Detector

- ePIC will be the first detector of the future Electron Ion Collider (EIC).
- EIC will collide electrons and protons/ions, at the central interaction point (IP6) of ePIC.
- This will enable a fantastic physics regime, with measurements of Structure, Spin Structure functions, Gluon density, GPDs, TMDs, Nuclear PDFs... and more!
- However, many of the detection requirements of the physics processes which provide access to these topics are limited by only a central hermitic detector – forward hadron / backward electron detection required!
- This has motivated the development of the far backward and far forward detector packages.



Cutaway view of the ePIC detector.

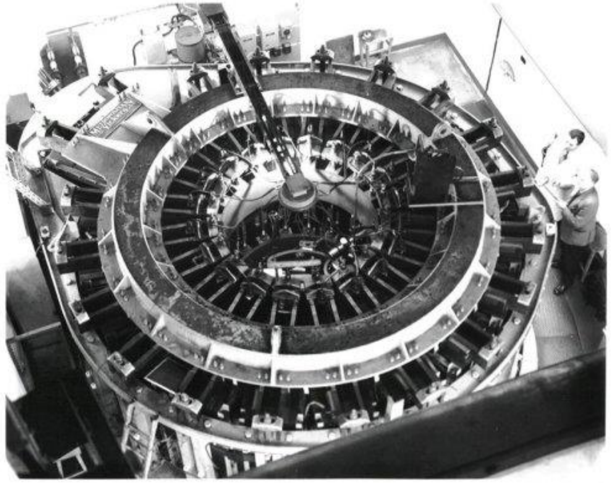
Photon Tagging at Glasgow

Glasgow group have a long history with photon tagging, spanning decades since the construction of the 300 MeV Synchrotron in the 1950's.

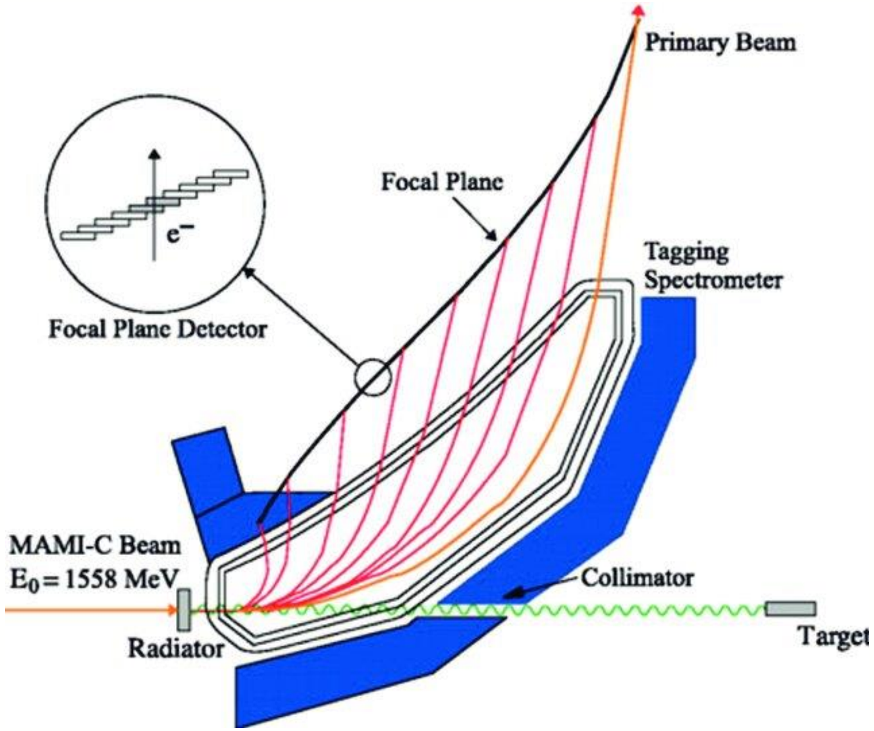
Experience in using Timepix3 detectors to develop pair spectrometer/polarimeter in Mainz

Recent role in developing Low-Q^2 tagger for CLAS12 – NIM A. 2020 163419, NIM A. 2020 163475.

Rochester Conference, first operation of synchrotron, 1954.



300 MeV Synchrotron in the Kelvin Building Basement.



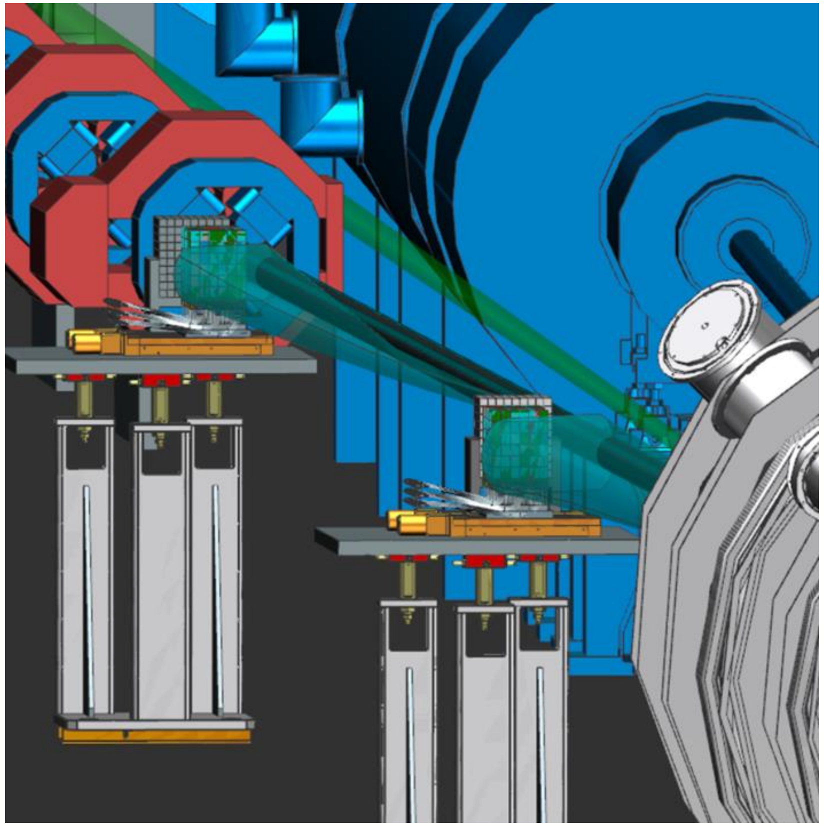
The Glasgow-Mainz photon tagging spectrometer at MAMI – EPJConf 20147200024.

Low-Q^2 Tagger

Future Concept with ePIC

- For precise measurements of photoproduction and vector mesons.
- The ePIC Low-Q^2 Tagger extends the reach of the central detector down to effectively $Q^2 = 0$ GeV^2.
- Located after the first group of beamline steering and focusing magnets.
- Scattered electrons follow a unique path through the magnetic optics, resulting in a unique measured electron vector.
- Electrons with reduced energy are steered away from the main beam.
- Transforming the vector back through the magnetic optics accesses the original scattered vector.
- 4-momentum of the virtual photon interaction can be inferred.

ePIC Low-Q^2 Tagger in Far Backward region.

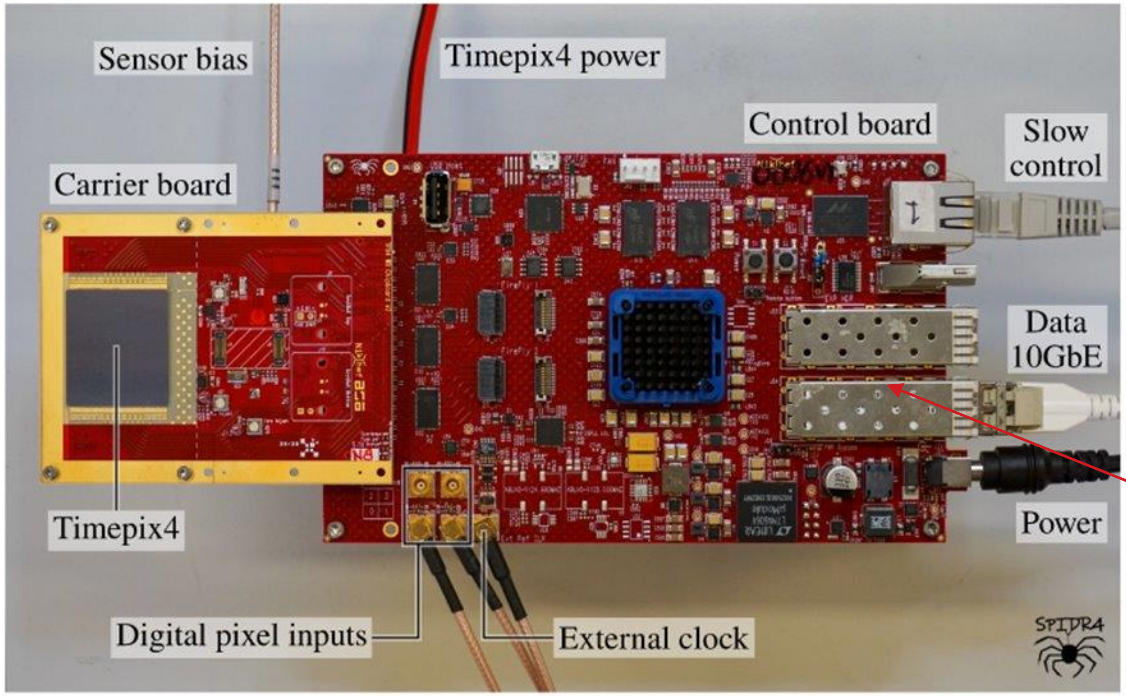


Low-Q^2 Tagger stations placed beside the outgoing electron beamline.

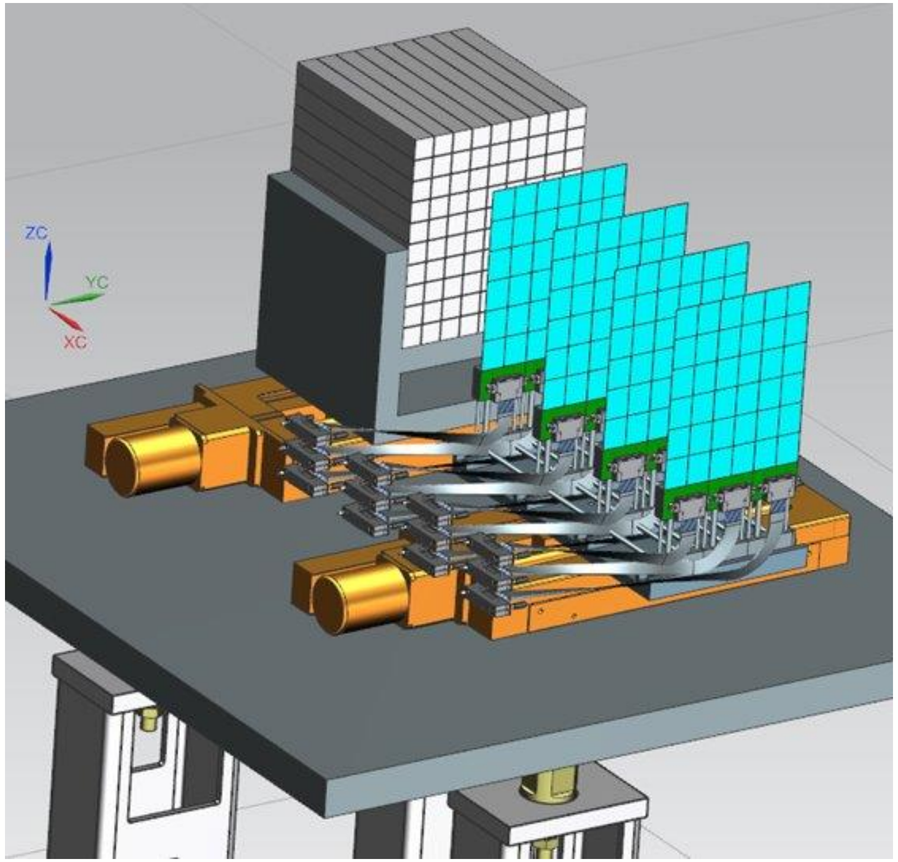
ePIC Low-Q^2 Tagger - Design

Tagger Design

- Two tagger stations covering different energy ranges.
- Tracker consisting of 4 layers of Timepix4 detectors.
- Detector layer consisting of tiled Timepix4 ASICs using TSV.
- SPIDR4 readout (exploring different future readout options)
- Calorimeter based on the luminosity systems design for high rates.



SPIDR4 readout - K. Heijhoff et al 2022 JINST 17 P07006



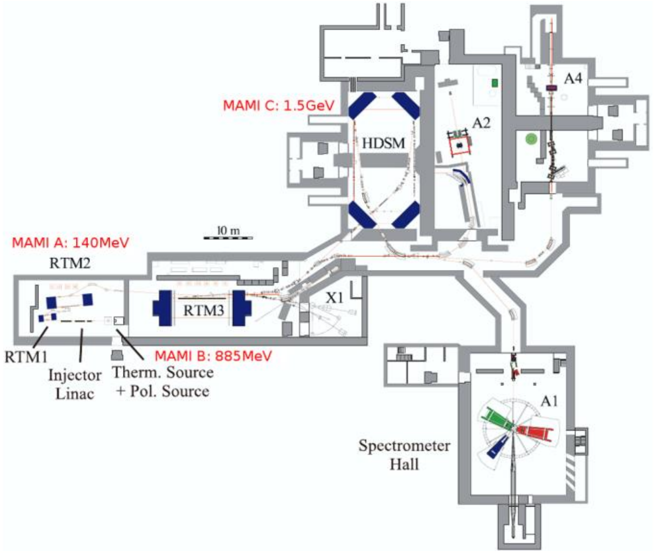
CAD model of a tagger station.

Prototyping Setup!

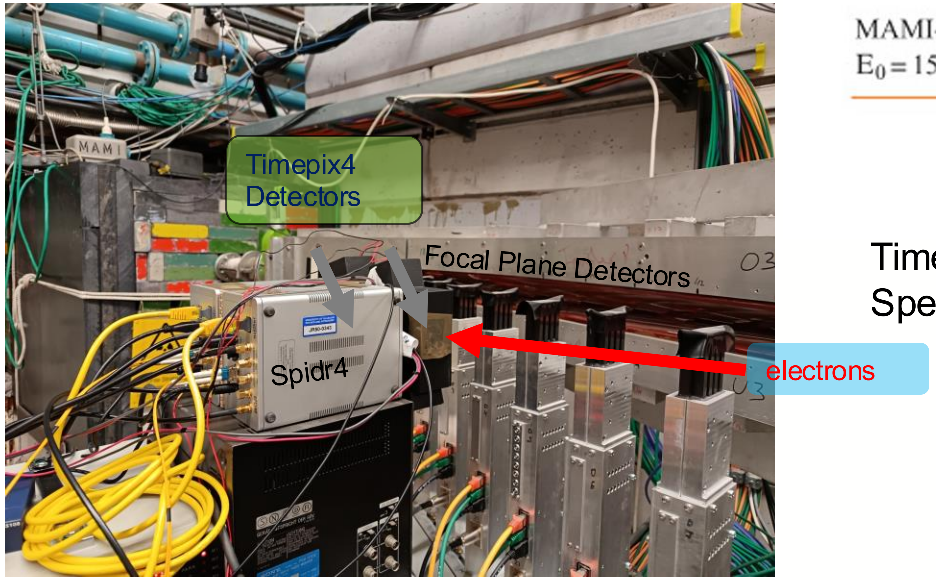
Timepix Beam Test at Mainz (Feb 2025)

Test Setup

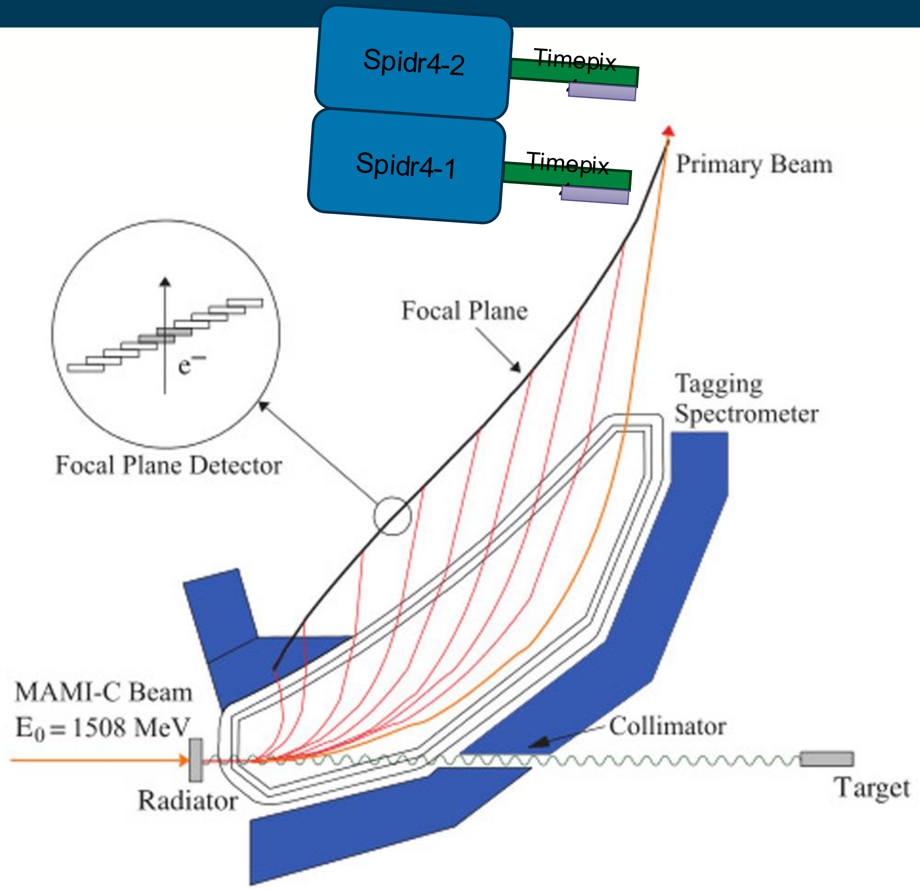
- A2 Hall at MAMI
- Continuous (max) 1.6 GeV electron beam
- Timepix4 placed at high electron energy to maximize flux.
- Signal from plastic scintillators on focal plane fed directly into Timepix4



[The Mainz Microtron MAMI]



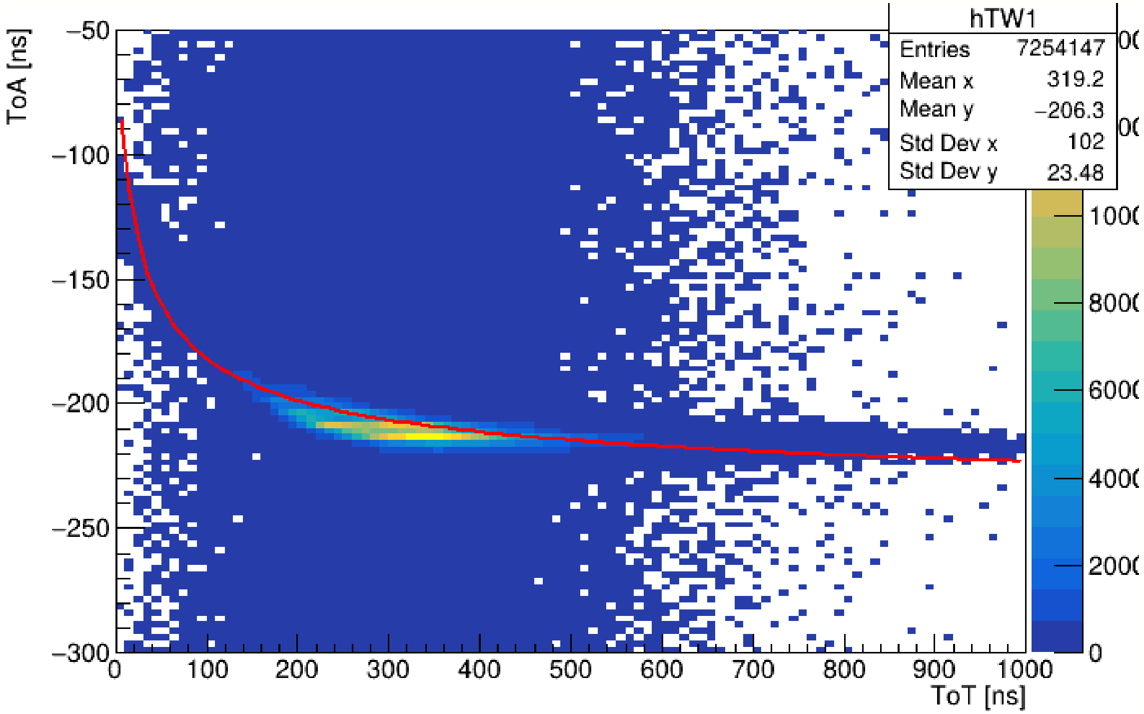
Timepix4 detector setup in A2 Hall, and Glasgow Photon Tagging Spectrometer.



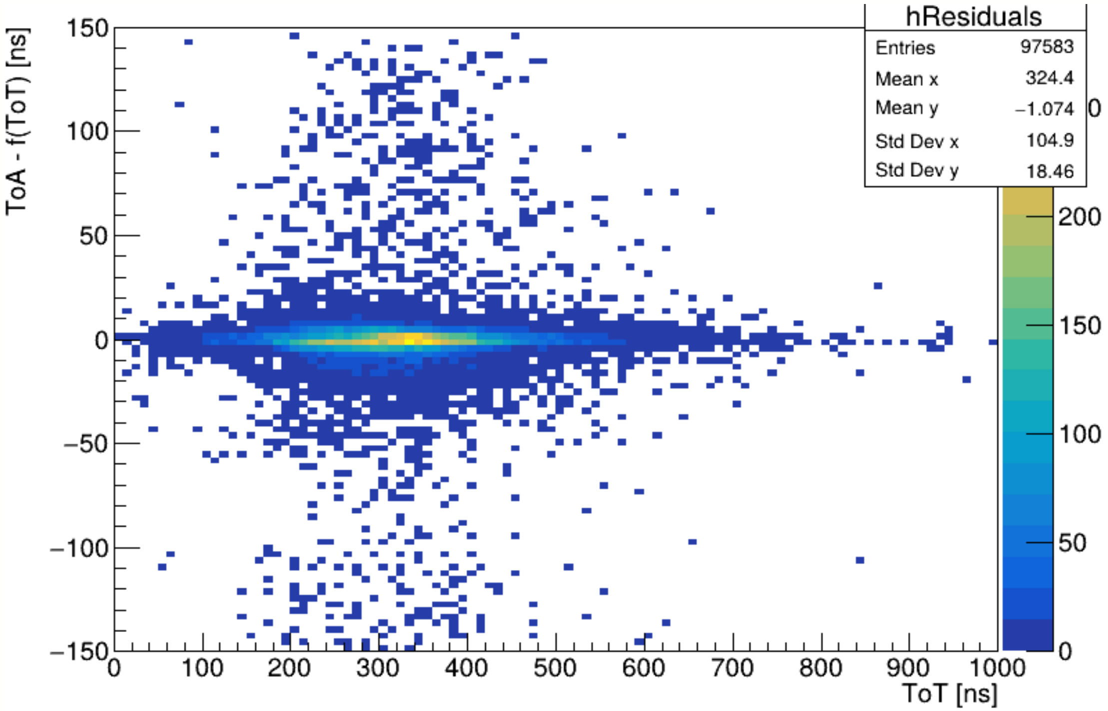
Timepix4 detectors and Glasgow Photon Tagging Spectrometer diagram (not to scale).

Ongoing Work: Timepix4 Timewalk Calibration

Timepix data from Mainz beam test is being analysed. By using the Mainz focal plane tagger as a reference channel, we can look at the walk effect arising from different time over threshold (TOT) of signals.



Raw cluster time – focal plane input time



Cluster time – focal plane input time, corrected for Timepix timewalk.

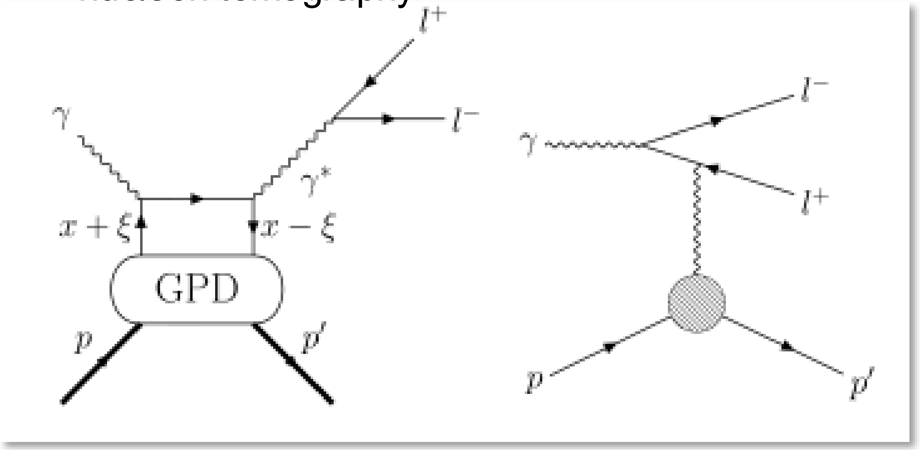
Need to extend this to a pixel by pixel calibration (requires a huge number of statistics) and compare final resolution to that of rough global fift, above.

Next steps will include extracting time resolution before and after.

Low-Q^2 Physics

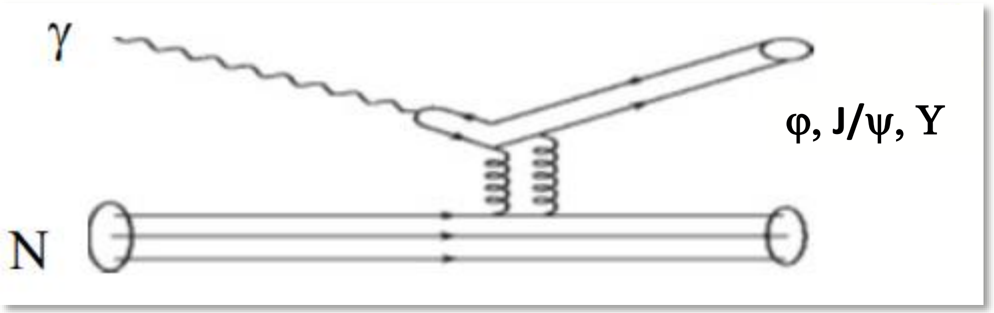
Time-like Compton Scattering (TCS)

- TCS is the hard exclusive photoproduction of a lepton pair. Analogous to DVCS electroproduction.
- Provides access to nucleon Generalized Parton Distributions (PDFs) - crucial ingredient in nucleon tomography



(Left) leading order TCS diagram and (right) BH term

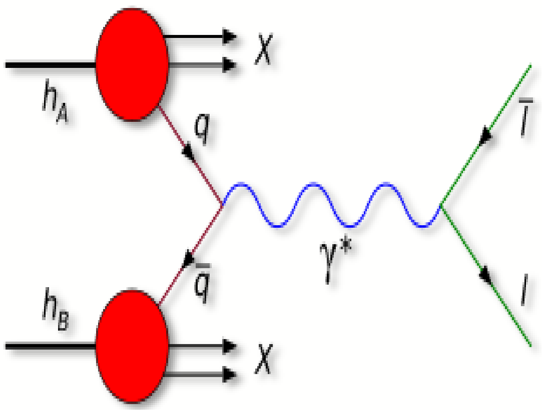
Vector Meson Production



Leading order VM production via pomeron exchange.

- Exclusive VM production might shed light on bound meson-nucleon systems
- Provides access to gluonic GPDs and quarkonium distribution amplitudes

Drell Yan Production



- Resolved photoproduction: incoming photon acts as qqbar pair
- Provides access to quark PDF of the photon!
- Cross section surprisingly not that small!
- Similar signal to TCS, but experimentally more challenging due to jets in the final state

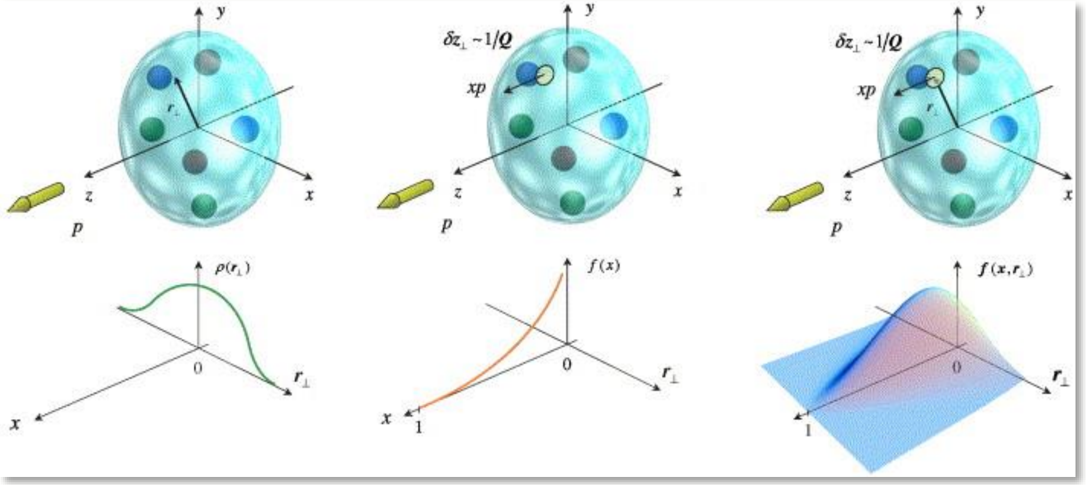
TCS with ePIC at EIC

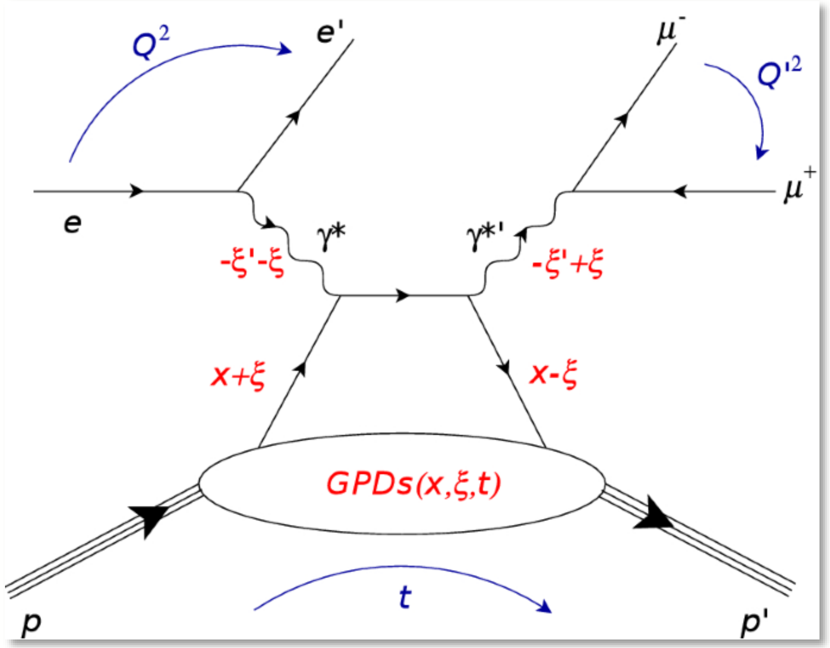
TCS is the time-reversal symmetric process to DVCS: the incoming photon is *real,* and the outgoing photon has large timelike virtuality.

At EIC we will study quasi-real TCS from very Low-Q2 photons produced from electron-proton collisions.

In this sense, what we will be measuring is the lowest accessible region in Q^2 of Double Deeply Virtual Compton Scattering!

FFs describe 1D transverse distribution, PDFs describe 1D longitudinal momentum, but no correlation!
GPDs directly correlate longitudinal momentum and transverse position of partons.





"DDVCS ...the virtuality of the final state photon indeed decouples the experimental x- and ξ-dependences opening off-diagonal investigation of the GPDs... " –*Eur. Phys. J. A* 57, 240 (2021).

TCS with ePIC at EIC

Event Generator: EpIC

EpIC: Monte Carlo generator for exclusive processes

https://pawelsznajder.github.io/epic/index.html

```
<!-- Kinematic limits -->
<kinematic_range>
    <param name="range_y" value="0.05|1.0" />
    <param name="range_Q2" value="0.0|5." />
    <param name="range_t" value="-2.|-0.0001" />
    <param name="range_Q2Prim" value="2.|10." />
    <param name="range_phi" value="0.0|6.28318" />
    <param name="range_phiS" value="0.0|6.28318" />
    <param name="range_phiL" value="0.0|6.28318" />
    <param name="range_thetaL" value="0.0|3.14159" />

    <param name="range_xB" value="0.000001|1." />
</kinematic_range>
```

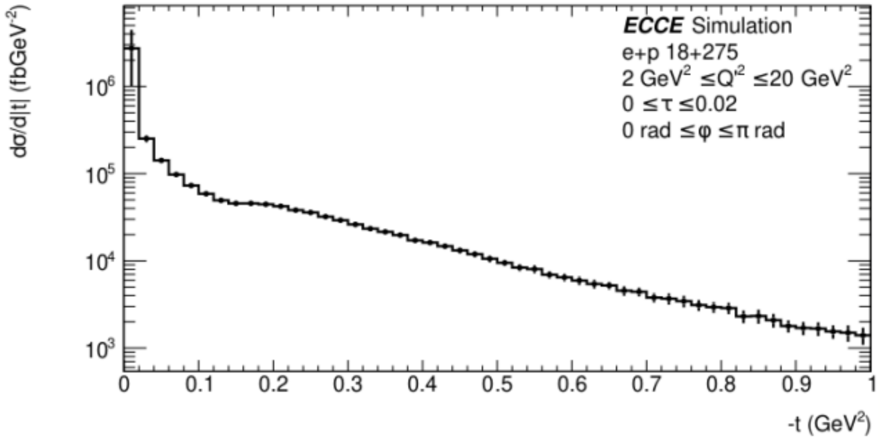
Generated 1M h=+1, 1M h=-1 DDVCS events.
Ymin = 0.05 results in minimum photon energy of ~1GeV (@18x275)
Q2min=0 provides natural transition to QR TCS.
Q'2min>=2 GeV^2 provides hard scale ($t \ll Q'^2/4M^2$).
Full range in decay angles.

Analysis Machinery

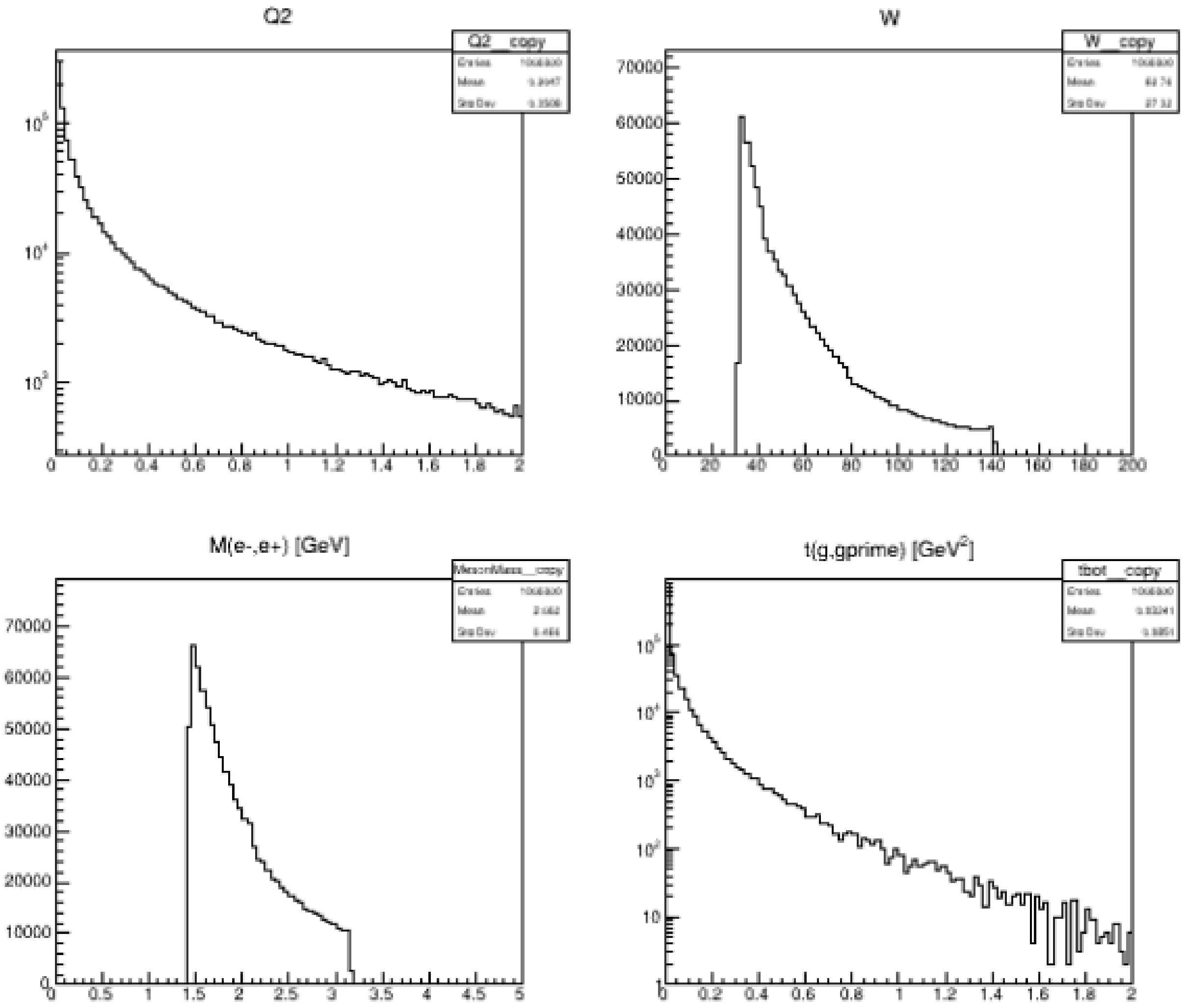
- DDSIM/NPSIM - simulating hepmc3 MC with full ePIC geant4 geometry.
- EICRecon - full detector reconstruction of particles after simulation.
- RAD - under development analysis framework for fast RDataFrame based physics analysis.
- Brufit - roofit based fitting machinery for extracting amplitudes and asymmetries (among many other uses).

Ongoing Work

Checking basic kinematics distributions. In particular, making sure |t| shape is consistent with existing studies and known BH differential cross section, and final integrated cross section for process is sensible.

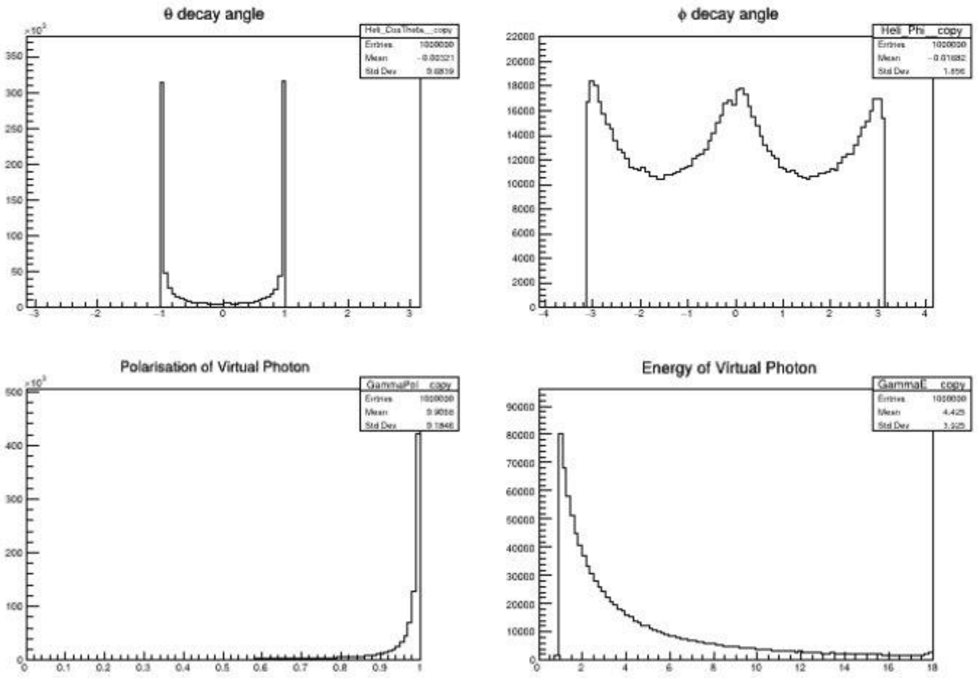


18x275 pure TCS EpIC generator module (2022). [K. Gates ISMD2022]



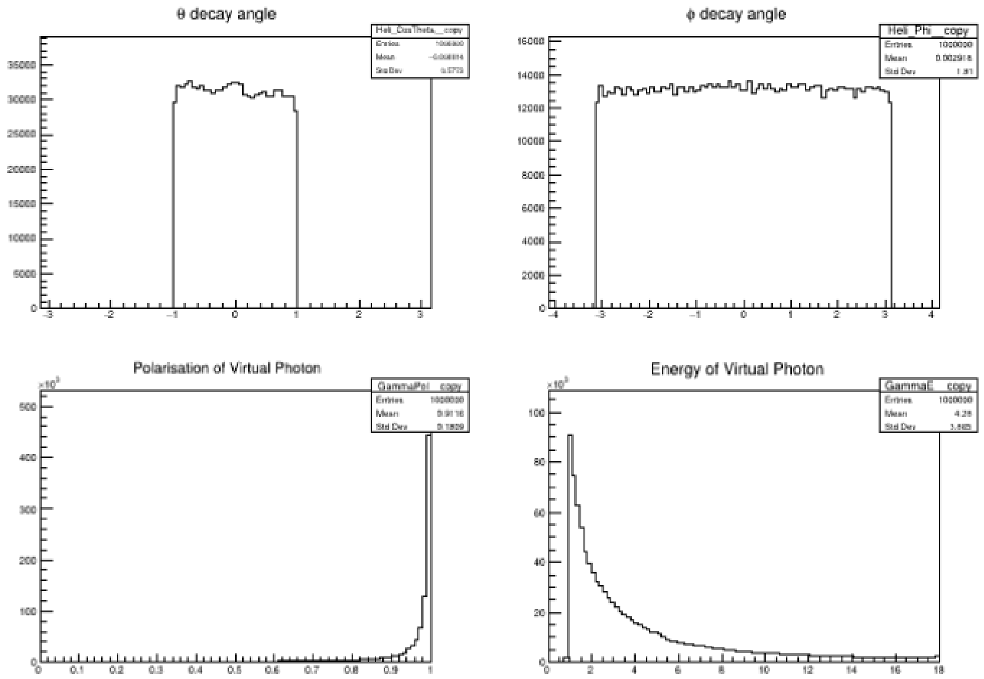
MC Truth level kinematic distributions from EpIC DDVCS generator, 18x275 energy configuration, with aforementioned generation limits.

Ongoing Work: Re-producing flat angular distributions



RAD::ParticleGenerator

GenerateTwoBody()



Input: HepMC3 events with physical decay angular distributions, from generator.

Output: Randomly generated "flat" decay angles

Importantly, we implemented methods to alter the HepMC3 event data, and rewrite each "flat" event out to a new MC file. This means we can simulate both physical and flat angular distributions, for the purposes of acceptance correcting in asymmetry analysis'.

Future Work / Next Steps:

Hardware Timepix4

- Pixel level timewalk calibration
- Extract best (in beam) timing resolutions
- Rate and DAQ tests
- 4(+) Layer Telescope, future beam tests

Software & Physics Analysis

- Final validation of TCS / DDVCS events
- Integration with ePIC monthly simulation campaigns
- Benchmarking acceptance of channel
- Possible integration with Pre-TDR
- Amplitudes and Asymmetry analysis of simulated events with Brufit
- Continuing RAD framework development

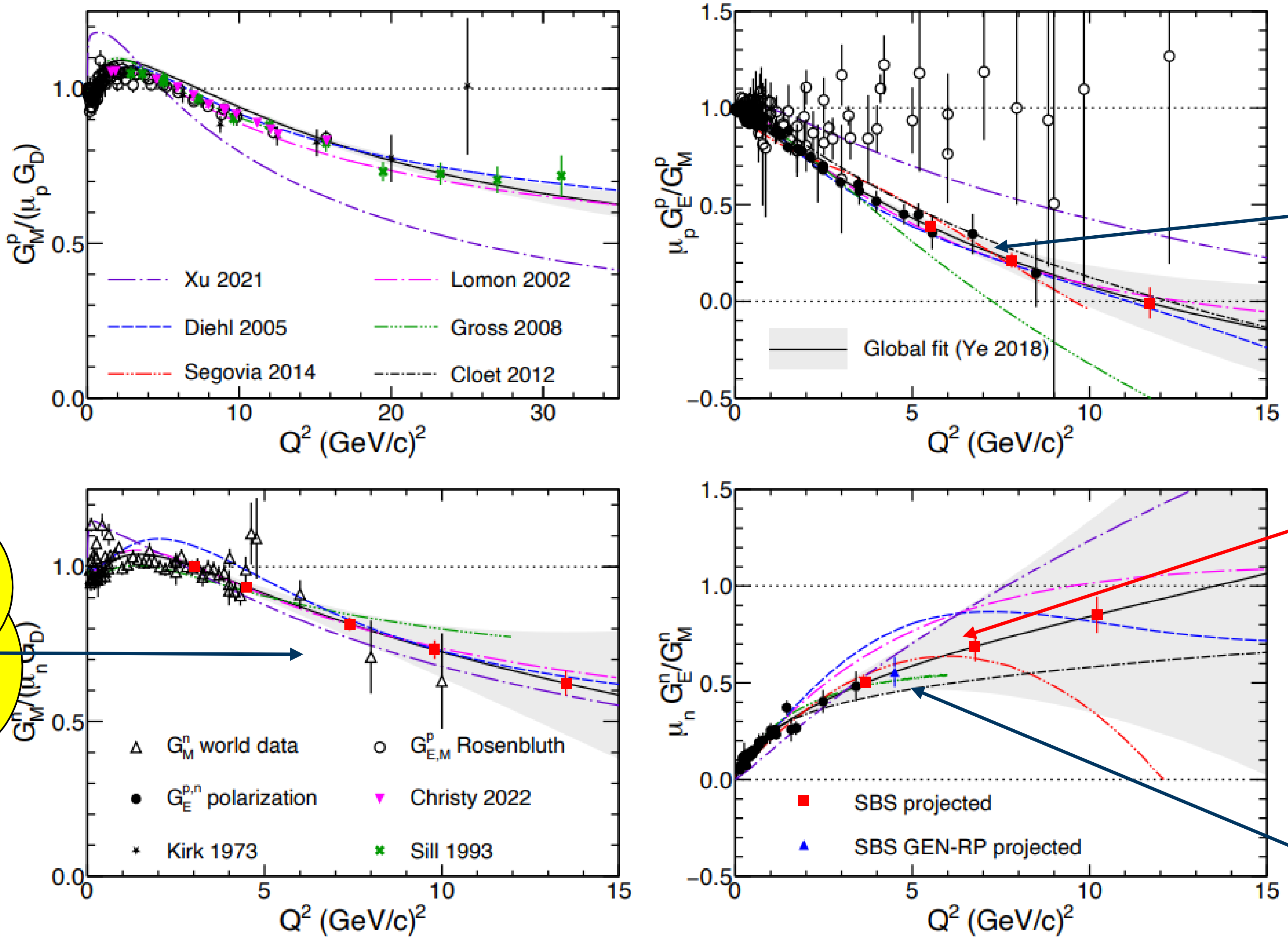
Thank You!


BACKUP

SBS Form Factor Program

GMp: Well measured up to large Q2 in 2000's. Not measured by SBS (atleast for now)

SBS GMn: Neutron magnetic form factor via Durand Ratio method. Ran Fall 2021- Spring 2022. First experiment following Summer 2021 installation.



GEp: Proton electric form factor via recoil polarimetry. Ran Spring – Summer 2025

SBS GEN-II: Measurement of GEn in double polarisation asymmetry measurement. Topic of my thesis!

GEN-RP: Measurement of GEn via recoil polarimetry. Ran Spring 2025.

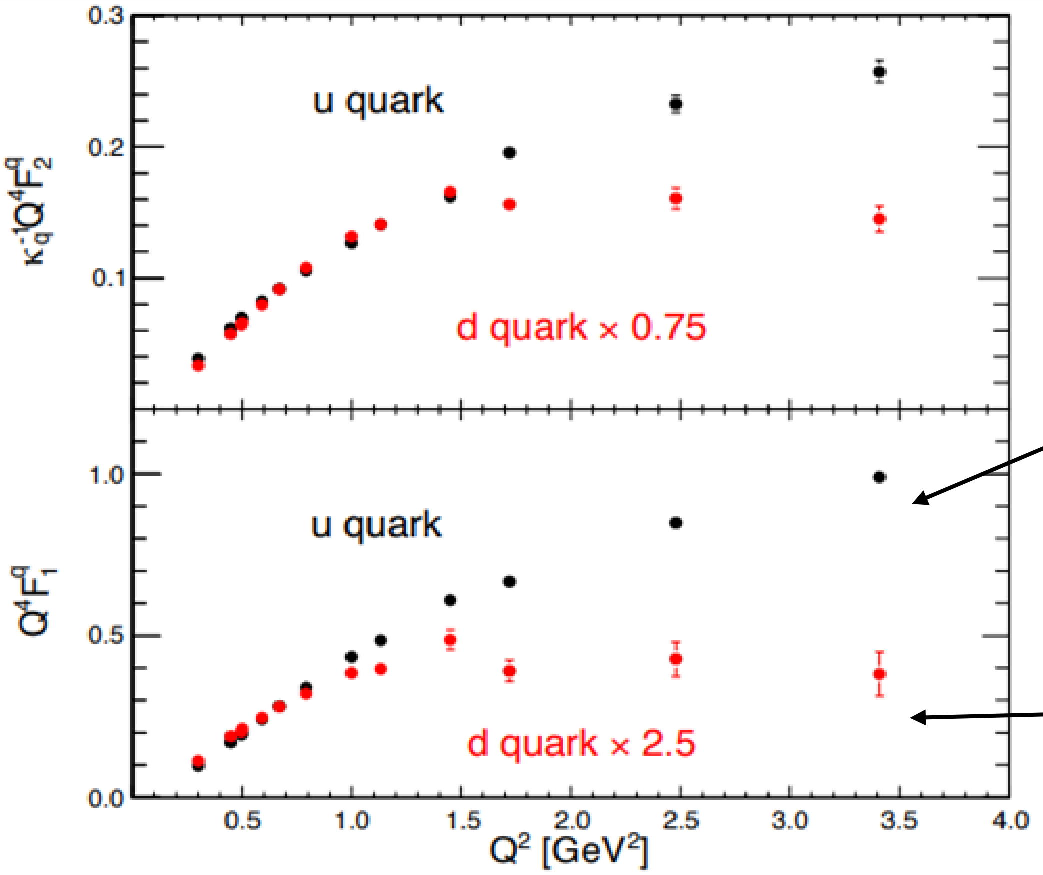
Figure lifted from A. Puckett, *50 Years of QCD*, EPJ C 83, 1125 (2023)

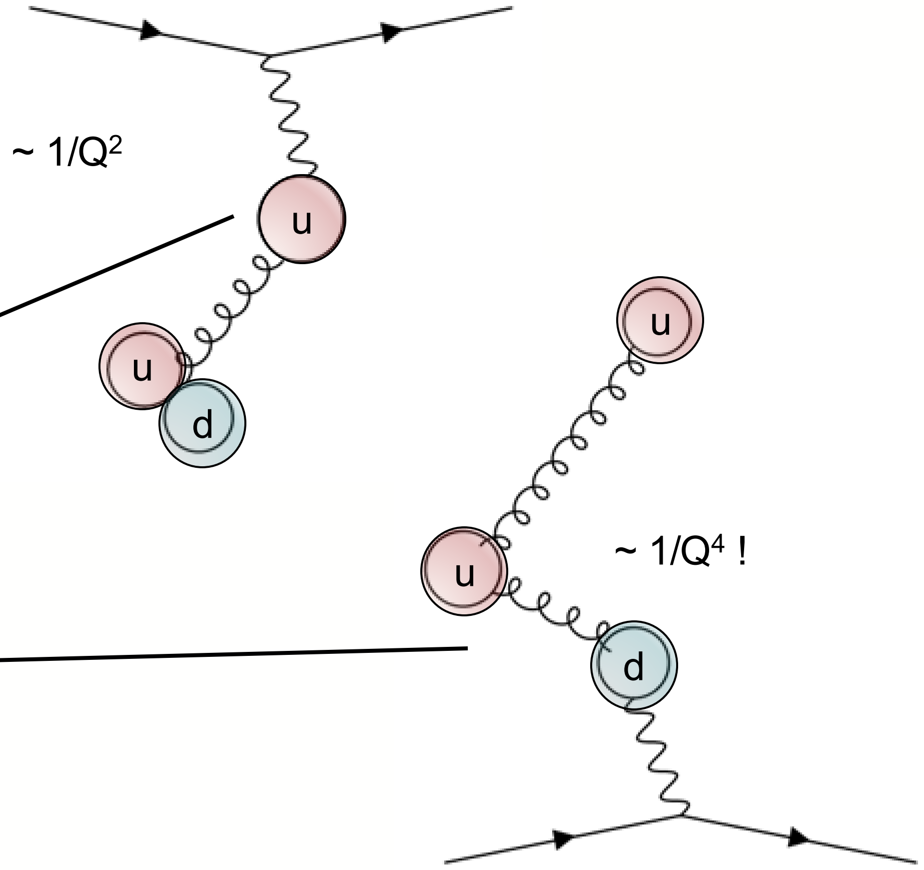
Form Factor Flavour Separation

Extracted G_E and G_M can be decomposed as: $F_1 = \frac{G_E + \tau G_M}{1+\tau}$ $F_2 = -\frac{G_E - G_M}{1+\tau}$

$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)} \quad \text{and} \quad F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$

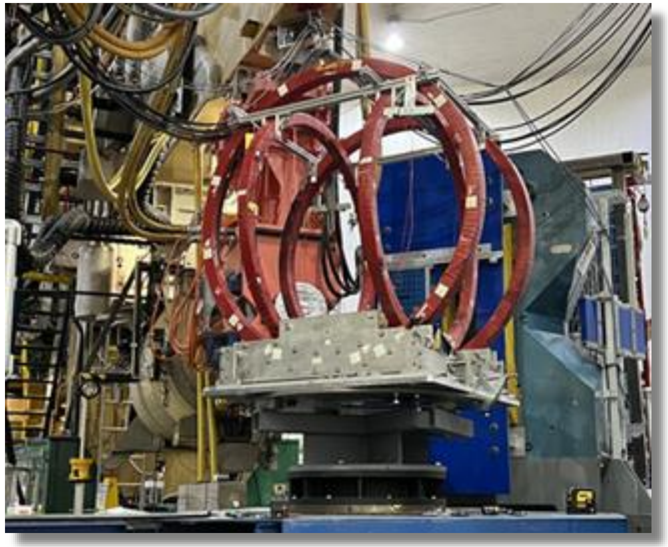
Different behaviour of u and d quarks may indicate **<u>diquark correlations!</u>**



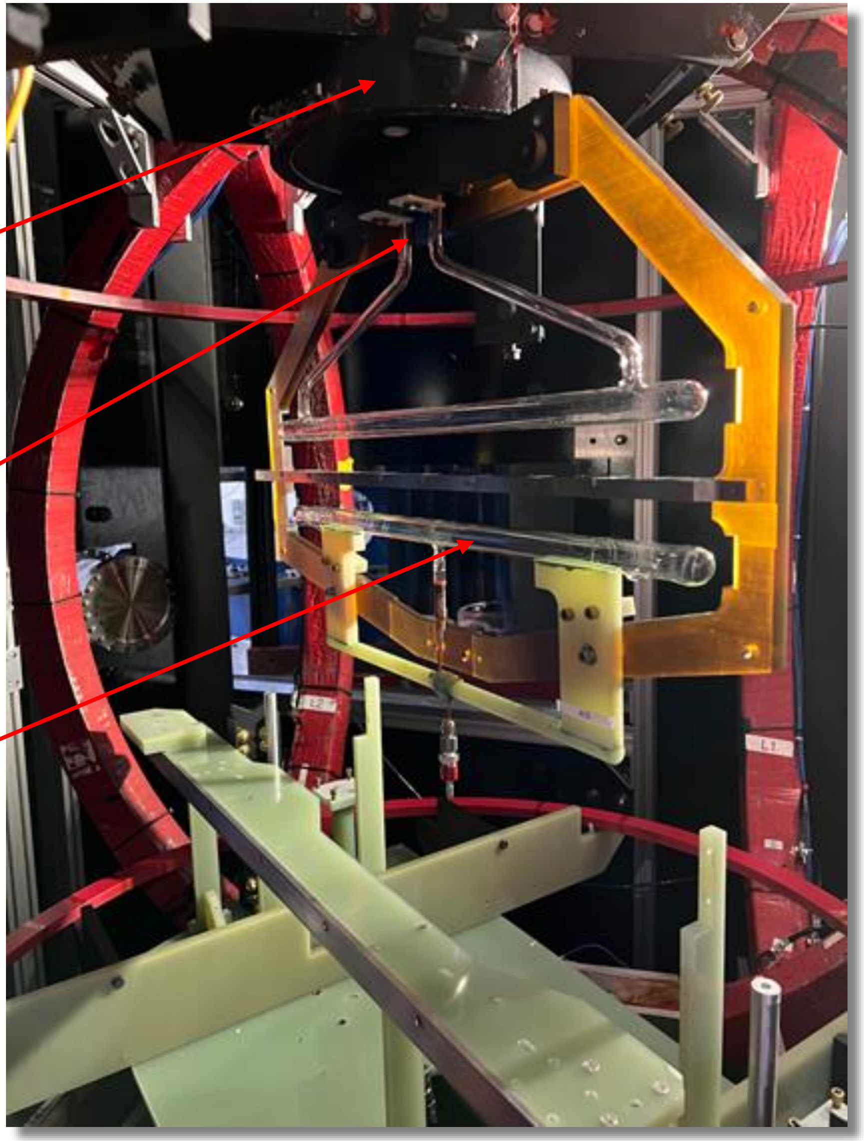


Q^2 dependence for *u* and *d* contributions to the proton form factors.
Cates et. al 2011, PRL 106, 252003

Polarised ^{3}He Target



The entire system is placed within a set of Helmholtz coils, which rotate to provide a target polarisation perpendicular to the momentum transfer



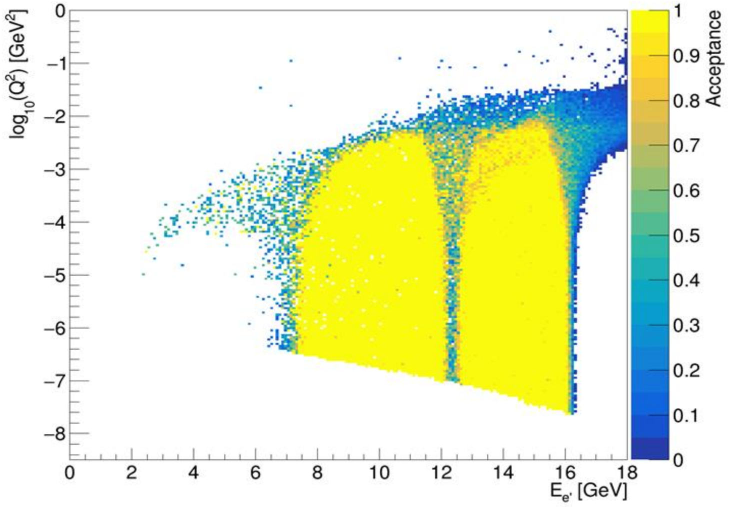
Pumping Chamber resides inside ceramic 'oven' at around 260 degrees C. High power narrow band lasers directed onto the alkali vapour within.

The downstream TT has a heater strip which induces convection around the cell. RTDs are placed on cells for Temp monitoring

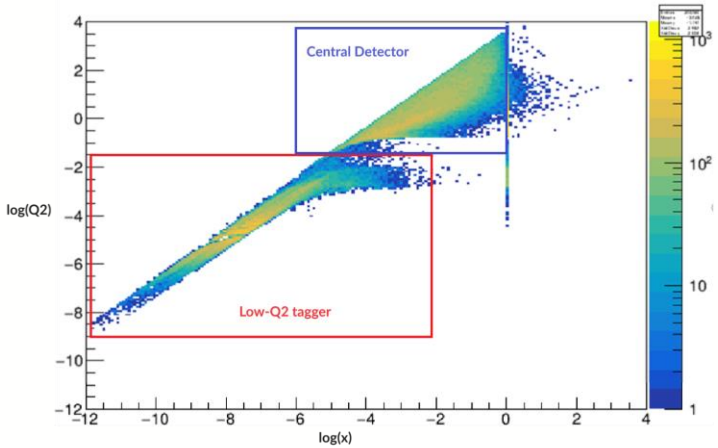
Reference cell installed further down the ladder to take H2 runs Carbon targets between H2 and He3 cells.

^{3}He gas polarised via spin exchange optical pumping (SEOP).

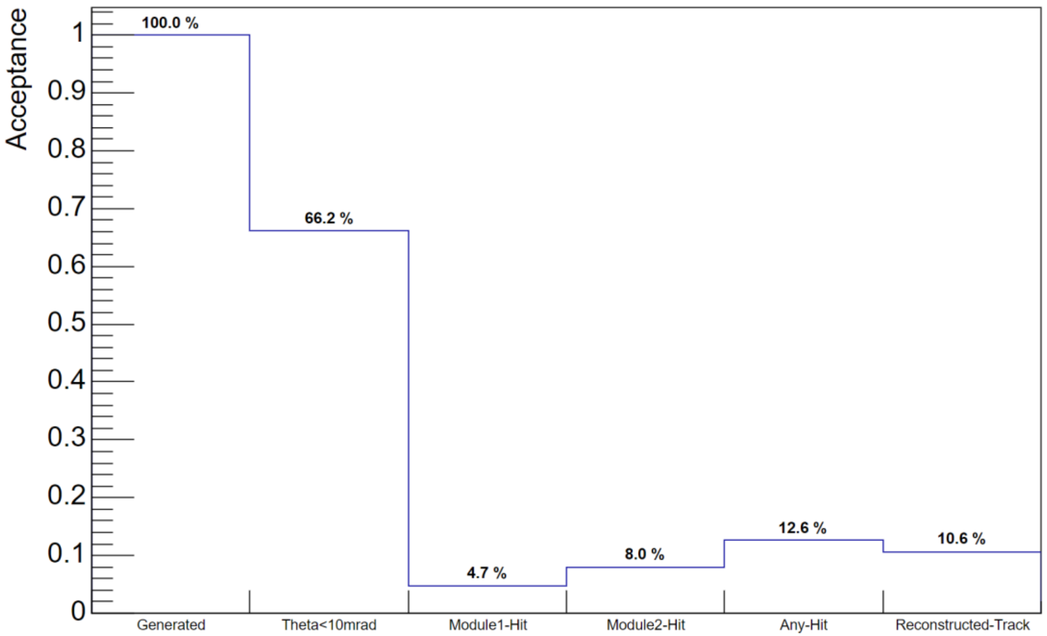
ePIC Low-Q^2 Tagger - Acceptance



Acceptance of reconstructed low-Q^2 tagger electrons as a function of energy and Q^2



x-Q^2 acceptance showing central and low-Q^2 tagger.

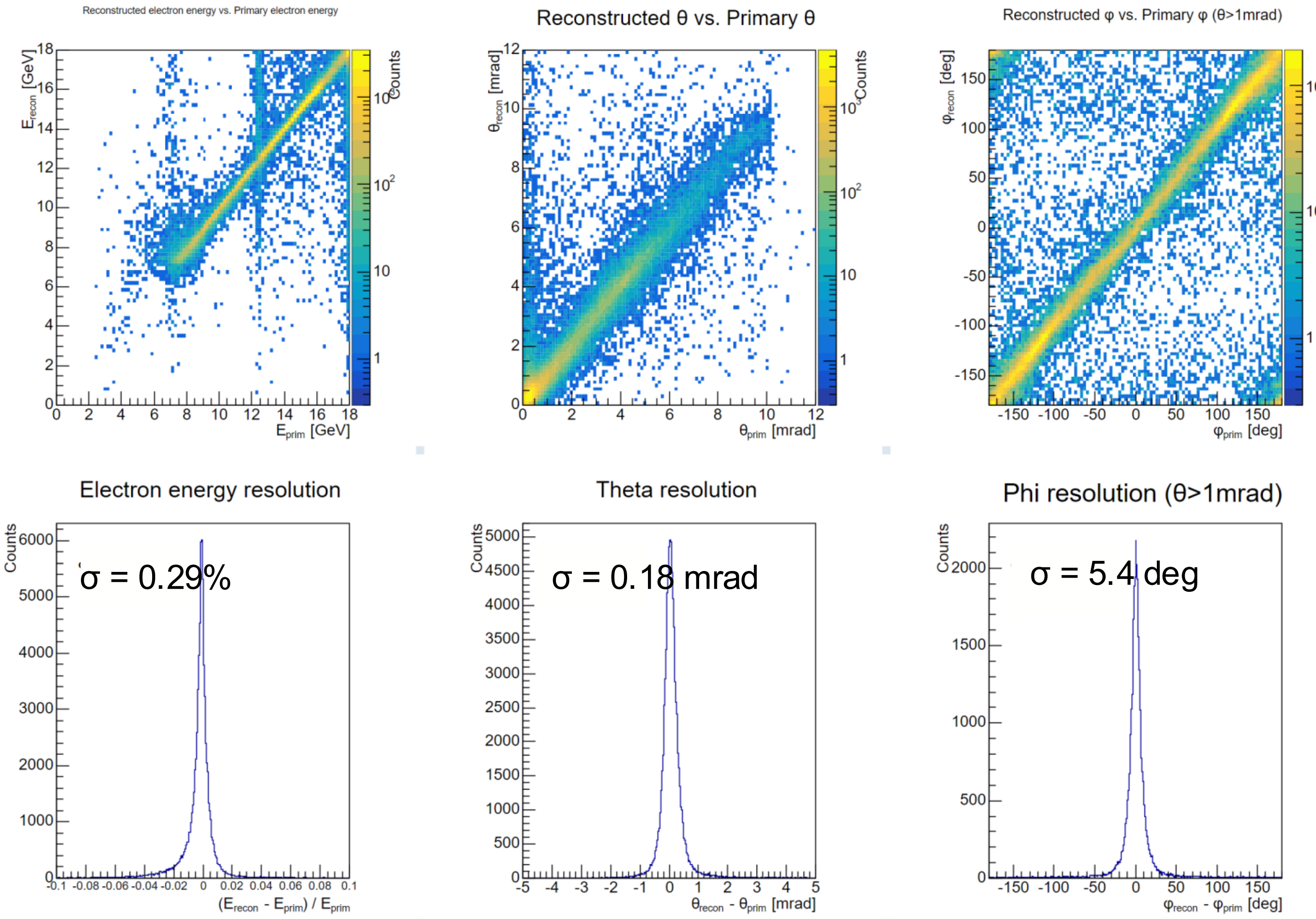


Integrated acceptance at various stages of track reconstruction.

Limitations

- Integrated acceptance of Quasi-real photoproduction events.
- Most events are produced at the highest energy, too close to the electron beam.
- Low energy lost in beamline magnets
- Q^2 gap between central detector due to beamline magnet configuration

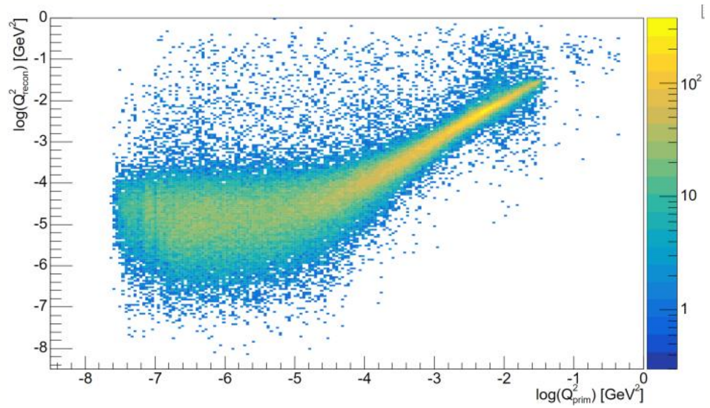
ePIC Low-Q^2 Tagger - Resolution



Reconstructed kinematics and resolution of Quasi-real photoproduction electrons. ϕ has been limited to where θ>1 mrad.

Limitations

- Fundamentally limited by the beam divergence
- ϕ can never be extracted below the beam divergence limit
- Limited acceptance where polarization will be possible



Reconstruction of Q^2 vs truth (generated) Q^2