Measurements of the Charge and Magnetic Form Factors of the Triton at Large Momentum Transfers

Makis Petratos*
Kent State University

* For the Jefferson Lab Hall A Tritium Collaboration

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Jefferson Lab Experimental Proposal - May 2015

Jefferson Lab Triton Collaboration

J. Arrington, D. F. Geesaman, K. Hafidi, R. J. Holt, D. Potterveld, P. Reimer
Argonne National Laboratory, Argonne, Illinois, USA

K. A. Aniol, D. J. Margaziotis
California State University, Los Angeles, California, USA

A. Puckett
University of Connecticut, Storrs, Connecticut, USA

G. Fanourakis
Demokritos National Center for Scientific Research, Athens, Greece

J. R. M. Annand,D. Hamilton, D. I. Glazier, D. G. Ireland, K. Livingston, I. J. D. MacGregor, B. McKinnon, B. Seitz, D. Sokhan
University of Glasgow, Scotland, UK

E. Cisbani, S. Frullani, F. Garibaldi, L. Lagamba, R. De Leo, G. Salmè, G. M. Urciuoli
Istituto Nazionale di Fisica Nucleare, Rome and Bari, Italy

A. Camsonne, J.-P. Chen, S. Covrig Dusa, E. Chudakov, J. Gomez, J.-O. Hansen, D. W. Higinbotham, M. Jones, C. Keppel, D. Meekins, L. Meyers, R. Michaels, B. Sawatsky, B. Wojtsekhowski
Jefferson Lab, Newport News, Virginia, USA

W. Alahmade, S. Alsalmi, B. D. Anderson, T. Hague, A. T. Katramatou, D. M. Manley, S. Margetis, M. Nycz, G. G. Petratos, T. Su, W.-M. Zhang
Kent State University, Kent, Ohio, USA

W. Korsch
University of Kentucky, Lexington, Kentucky, USA

X. Jiang
Los Alamos National Laboratory, Los Alamos, New Mexico, USA

E. Beise
University of Maryland, College Park, Maryland, USA

J. R. Calarco, K. Slifer, P. Solvignon
University of New Hampshire, Durham, New Hampshire, USA

C. Ciofi degli Atti, S. Scopetta
University of Perugia, Perugia, Italy

A. Kievsky, L. Marcucci, M. Viviani
University of Pisa/INFN Pisa, Pisa, Italy

R. Gilman, R. D. Ransome
Rutgers, The State University of New Jersey, New Brunswick, New Jersey, USA

M. N. Olson
St. Norbert College, De Pere, Wisconsin, USA

A. Blomberg, S. Joosten, Z.-E. Meziani, M. Paolone, N. Sparveris
Temple University, Philadelphia, Pennsylvania, USA

E. Pace
University of Rome Tor Vergata, Rome, Italy

D. Day, O. Rondon
University of Virginia, Charlottesville, Virginia, USA

Co-spokespersons: A. Camsonne, A. T. Katramatou, G. G. Petratos, N. Sparveris
Contact person: G. G. Petratos (gpetrato@kent.edu)

JLab Proposal P12-15-007

Experiment using the two HRS systems to detect scattered electrons and recoil tritons with Jlab's tritium cryo-target system under development.

Unique opportunity in 30 years since the last electron-tritium scattering experiment.

Important "*for the understanding of nuclear physics*"

Elastic Electron - ^3H (and ^3He) Scattering

- Triton/Helion Charge F_C and Magnetic F_M Form Factors:

$$\frac{d\sigma}{d\Omega} = \frac{Z^2\alpha^2 E'}{4E^3\sin^4\left(\frac{\theta}{2}\right)}\left[A\left(Q^2\right)\cos^2\left(\frac{\theta}{2}\right) + B\left(Q^2\right)\sin^2\left(\frac{\theta}{2}\right)\right]$$

$$A(Q^2) = \frac{F_C^2(Q^2) + \tau\mu^2 F_M^2(Q^2)}{1+\tau} \qquad B(Q^2) = 2\tau\mu^2 F_M^2(Q^2)$$

$$Q^2 = 4EE'\sin^2(\theta/2) \qquad \tau = Q^2/4M^2$$

- *E* : incident electron energy, *E´* : scattered electron energy, *α* : fine structure constant, *Z* : nuclear charge, *θ* : scattered electron angle, *μ* : nuclear magnetic moment, Q^2 : four momentum transfer squared

- Half a century of experimental and theoretical work!

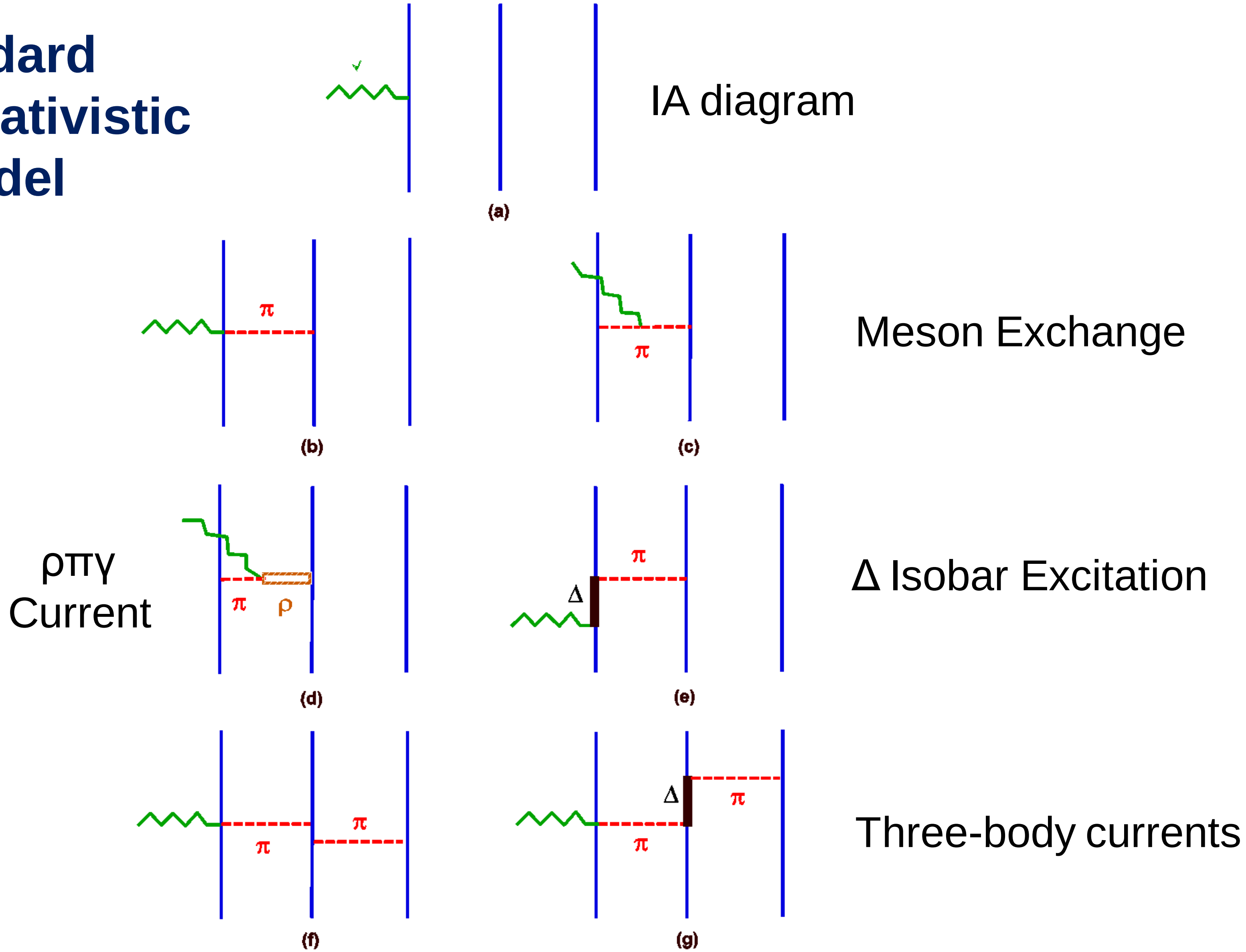
Few-Body Form Factors (FFs)

- Extracted from cross section measurements of elastic electron scattering from light nuclei (A = 2,3,4).
- FFs determine the nuclear charge and magnetization distributions and their associated radius.
- Are sensitive probes of:
  - Nucleon-nucleon potential
  - Meson-exchange currents (MEC)
  - Multi-quark component in nuclear wave function
  - Three-body force effects (A = 3,4)
- Expected to uncover, at large Q^2, a possible transition in the description of elastic scattering, from meson-nucleon to quark-gluon degrees of freedom.
- Subject of “eternal” strong intellectual interest, with many recent reviews (see selected list).

Impulse Approximation (IA) Field Theory

- Few-Body Form Factors are, in the non-relativistic Impulse Approximation, convolutions of the nuclear wave functions with the nucleon form factors.
  - Ground state is solved using the coupled Faddeev equations with a realistic *N-N* potential, **or**
  - Variational or Green's Functions Monte Carlo Methods.
  - All calculations are complemented by MEC and selected diagrams of Three-Body Force Effects (3BFE).
- Relativistic (IA) Covariant calculation was recently completed, no inclusion of $\rho\pi\gamma$ current yet.
- Relativistic Light-Front Hamiltonian Dynamics has been done, no inclusion of two-body currents yet.

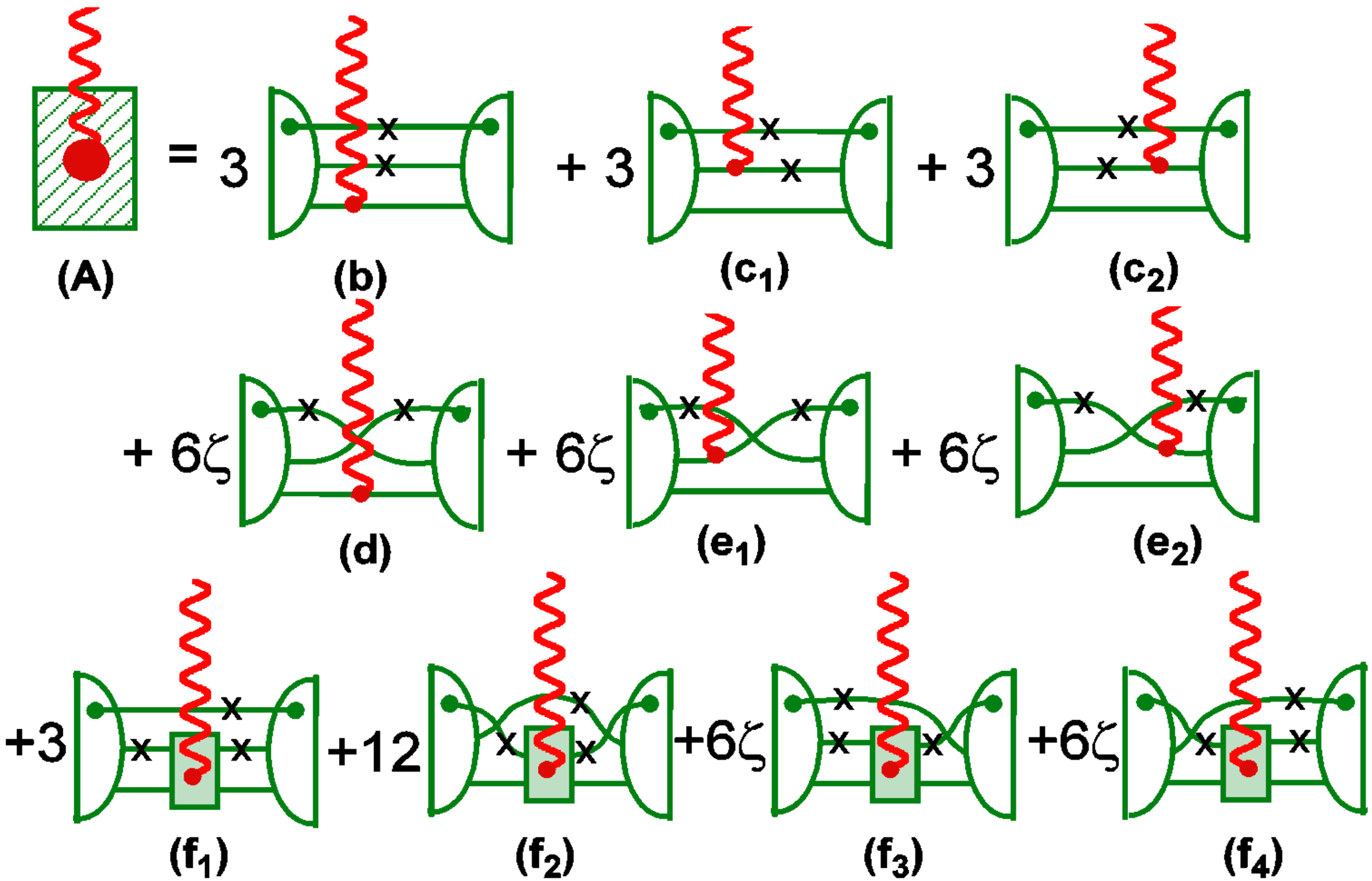
Standard Non-Relativistic Model



“Few-body form factors are the observables of choice for testing the *N-N* interaction and the associated current operator” (Laura Marcucci et al.)

Relativistic “Spectator Model” with Gross Equation

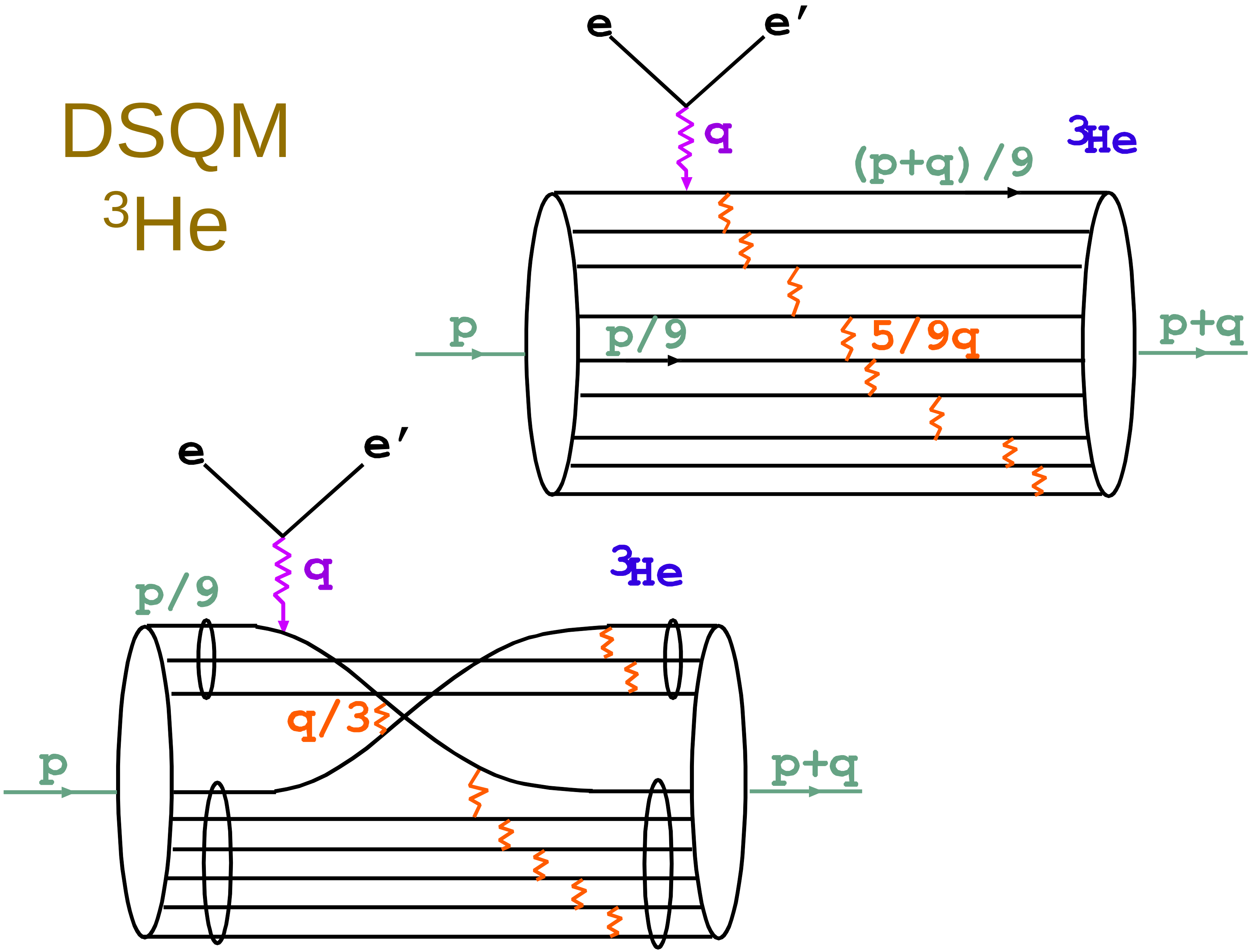
Tri-nucleon System



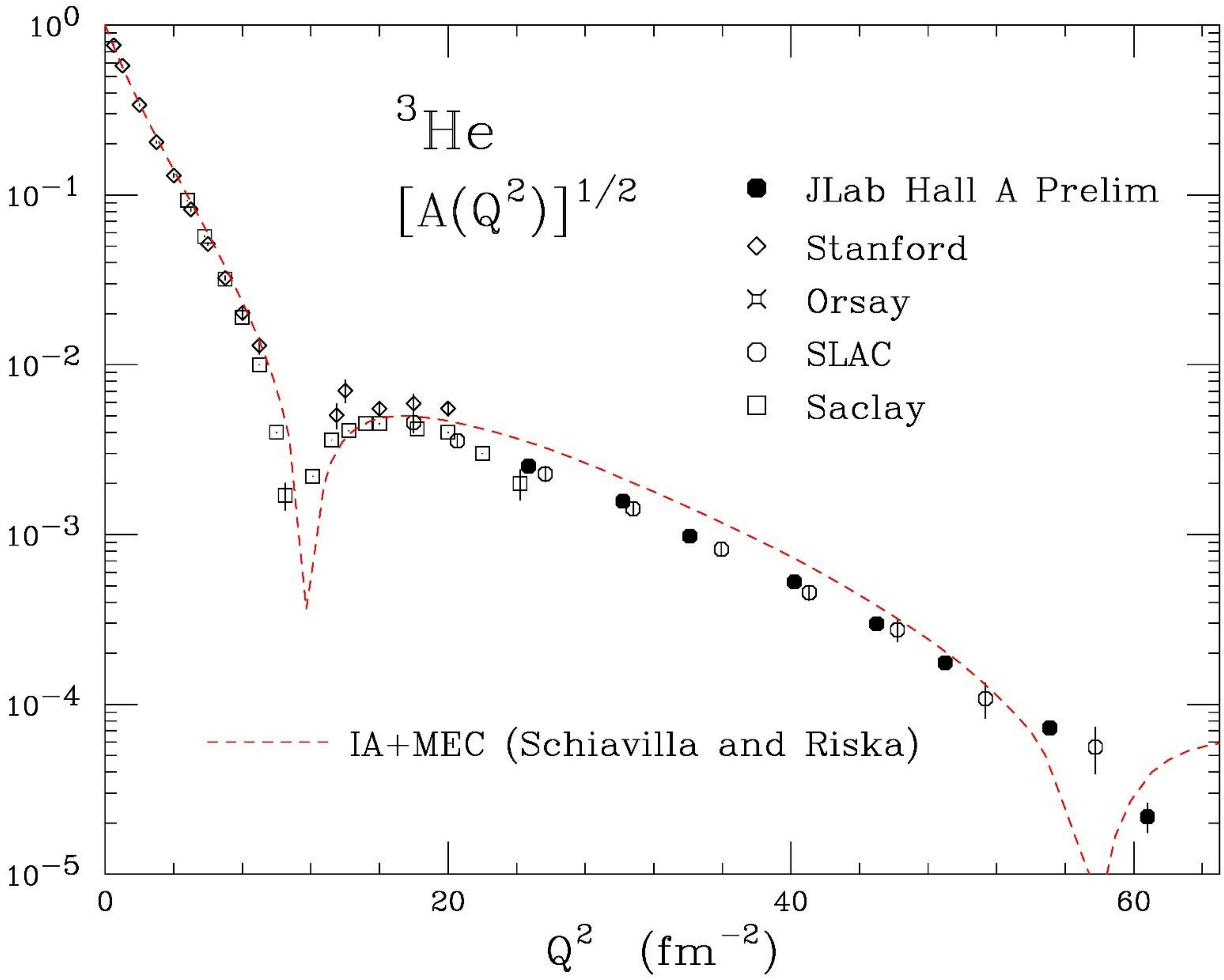
Quark-Gluon Approaches

- Addition of multi quark-cluster admixtures in the tritium/helium ground-state nuclear wave function (unfortunately still in a purely phenomenological approach). Can make sizable contributions to form factors.
- Dimensional-Scaling Quark Model (DSQM):
  - $^3H/^3He$ "Form Factor" prediction: $[A(Q^2)]^{1/2} \sim (Q^2)^{-8}$
  - ^4He "Form Factor" prediction: $[A(Q^2)]^{1/2} \sim (Q^2)^{-11}$
- There is no explicit formula for the *A=3,4* "Form Factor" from perturbative QCD like one for the Deuteron $A(Q^2)$ "Form Factor".
- Recent few-body form factor data rule out applicability of DSQM in the JLab-accessible Q^2 range.

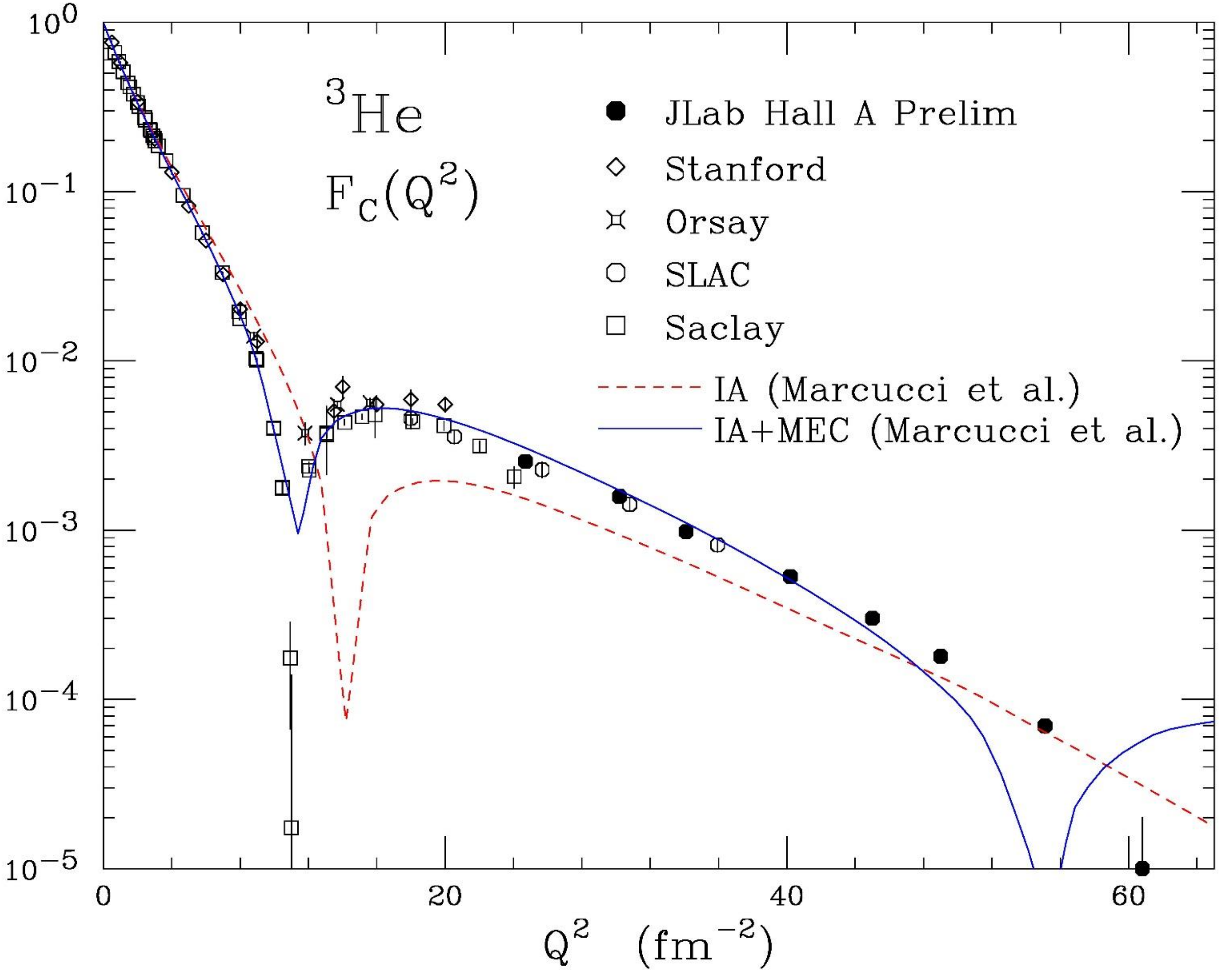
DSQM
^{3}He



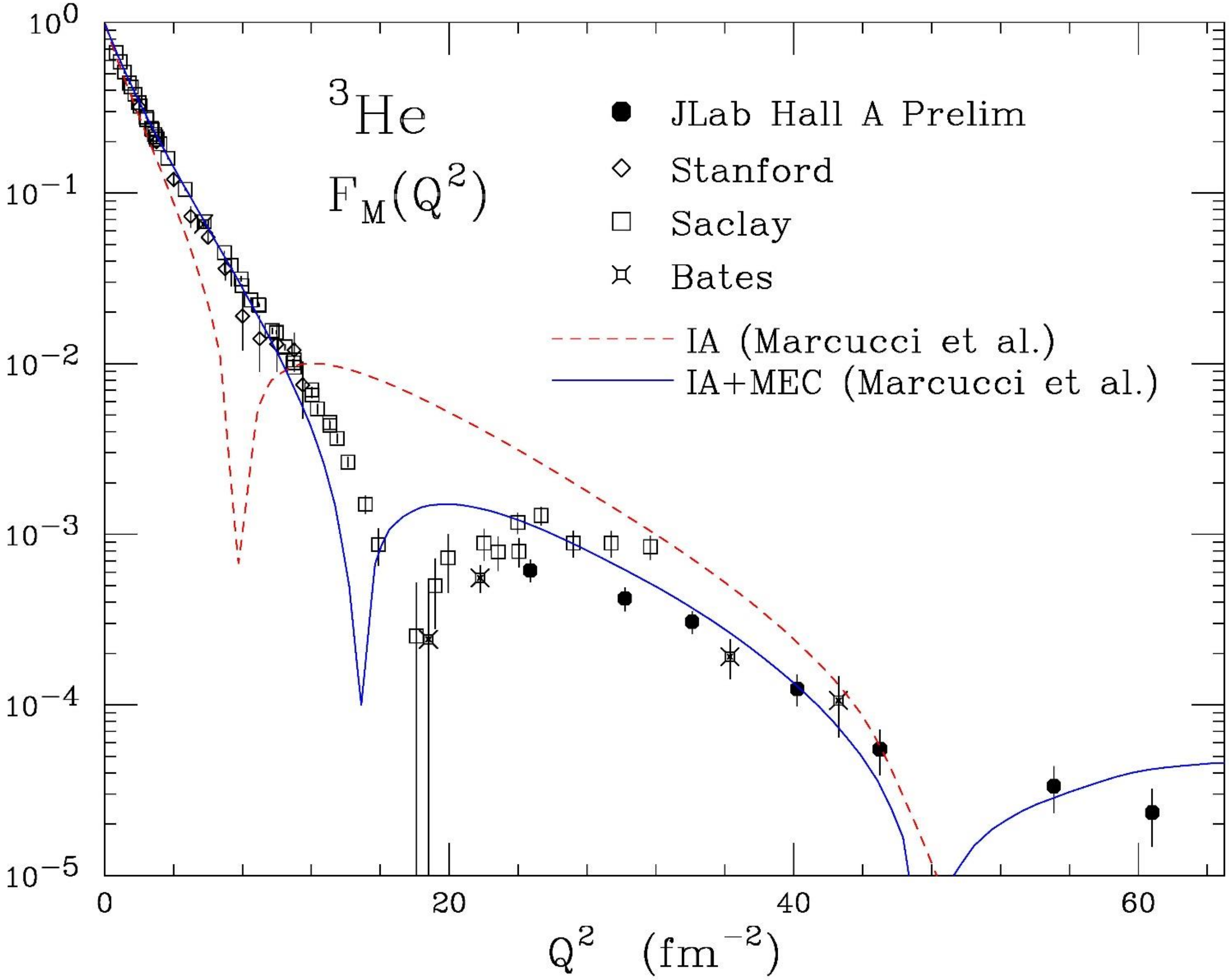
^{3}He "Form Factor" Data – JLab vs SLAC



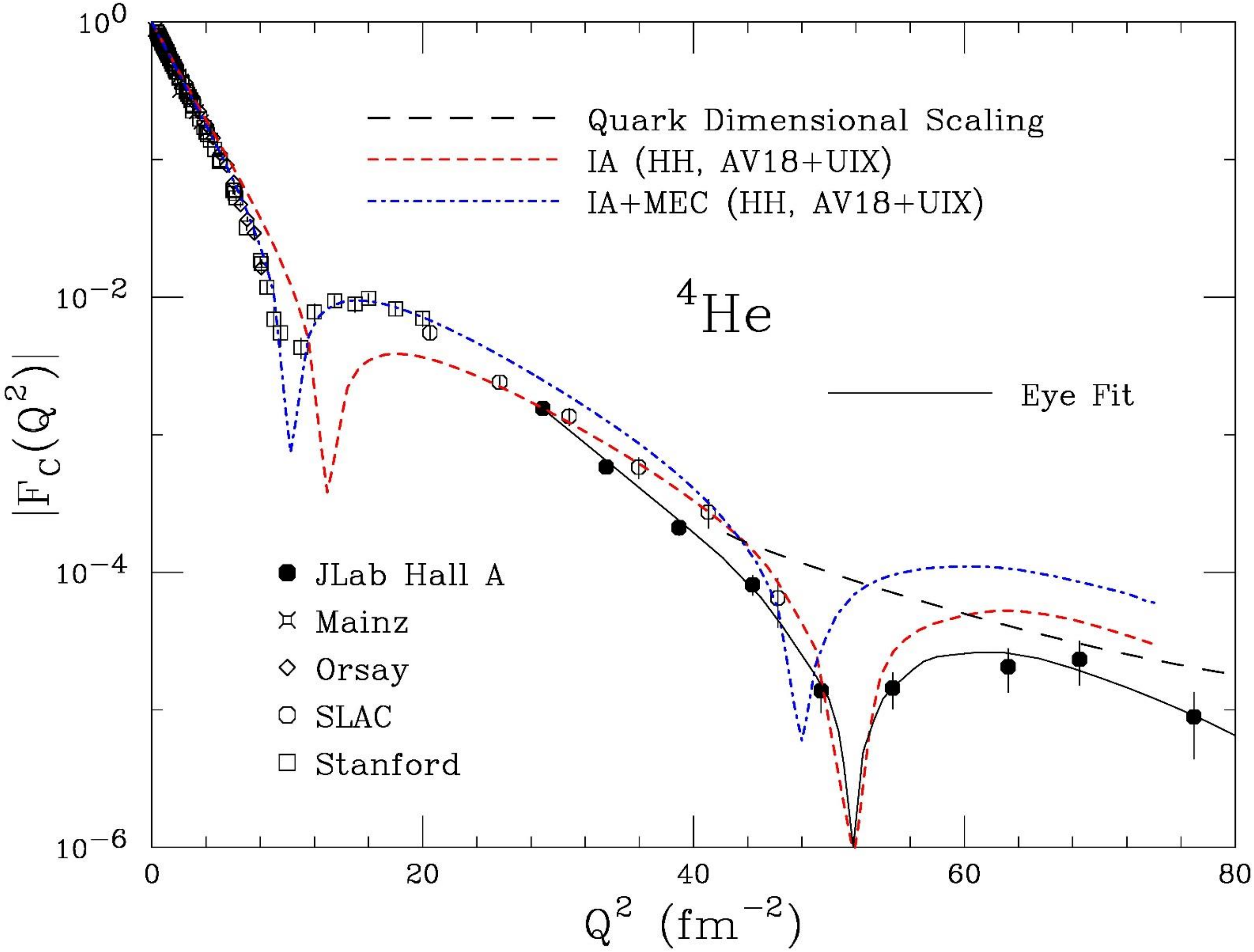
^{3}He Charge Form Factor World Data



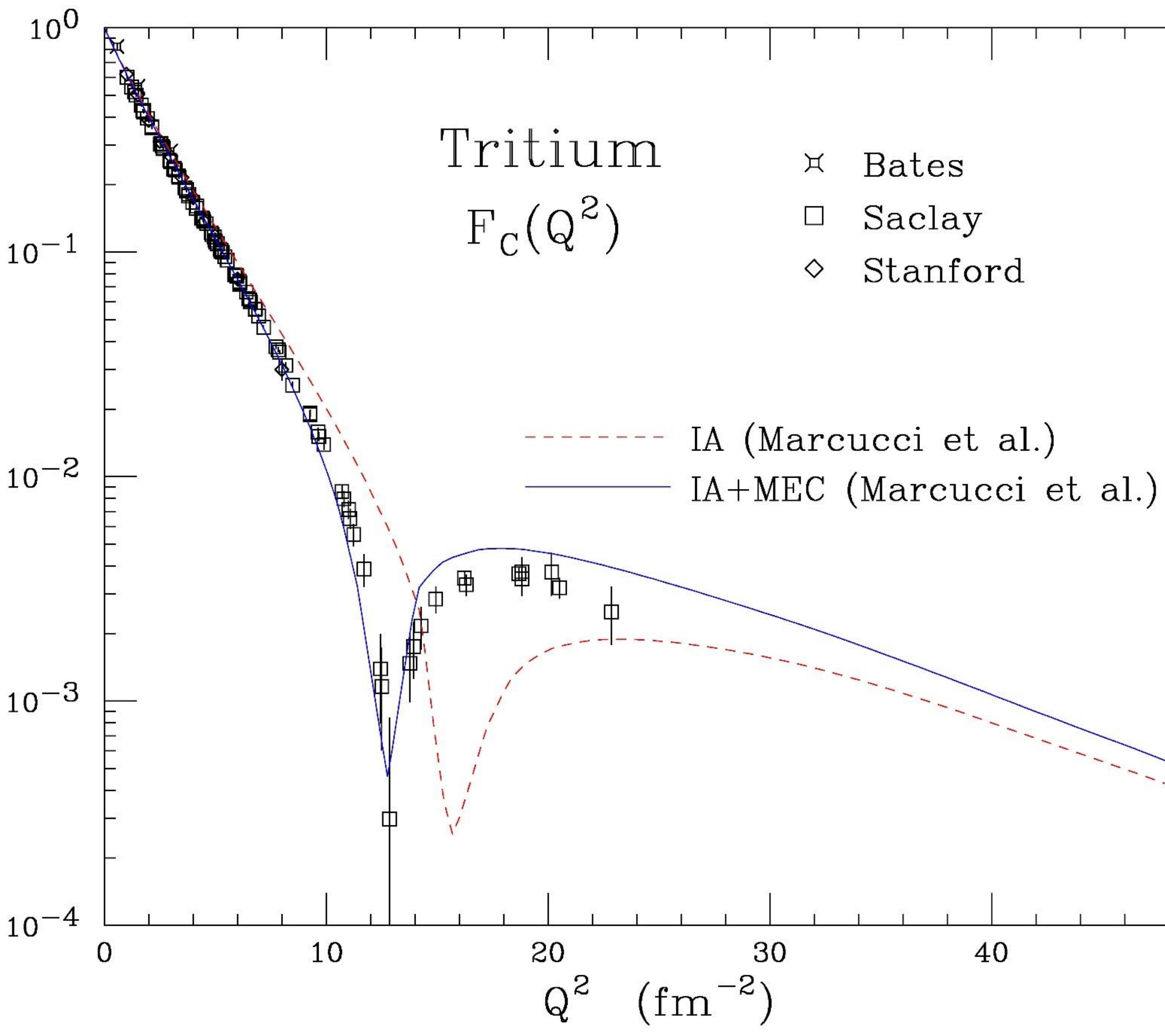
^{3}He Magnetic Factor World Data



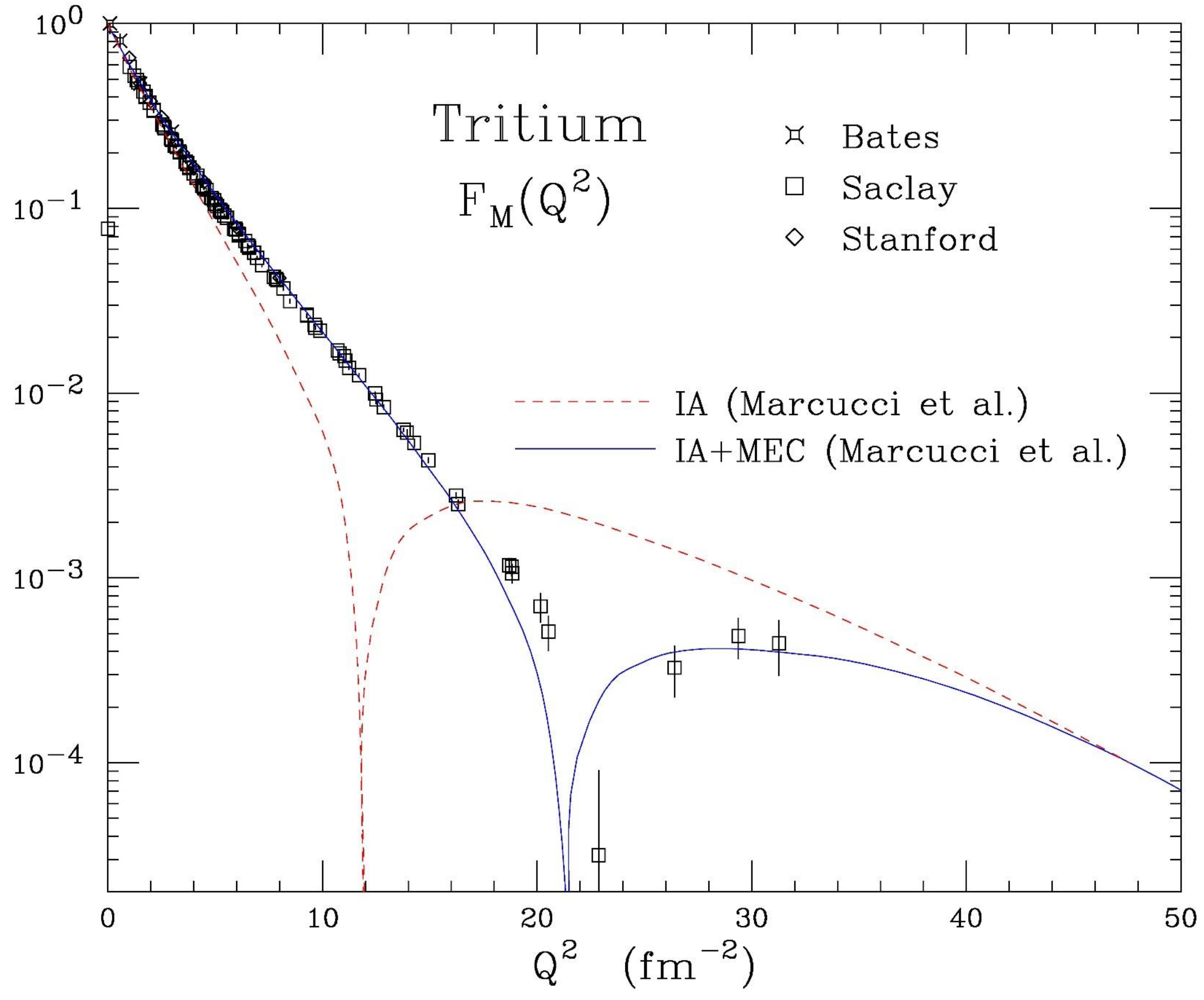
^{4}He Charge Form Factor World Data



^3H Charge Form Factor World Data



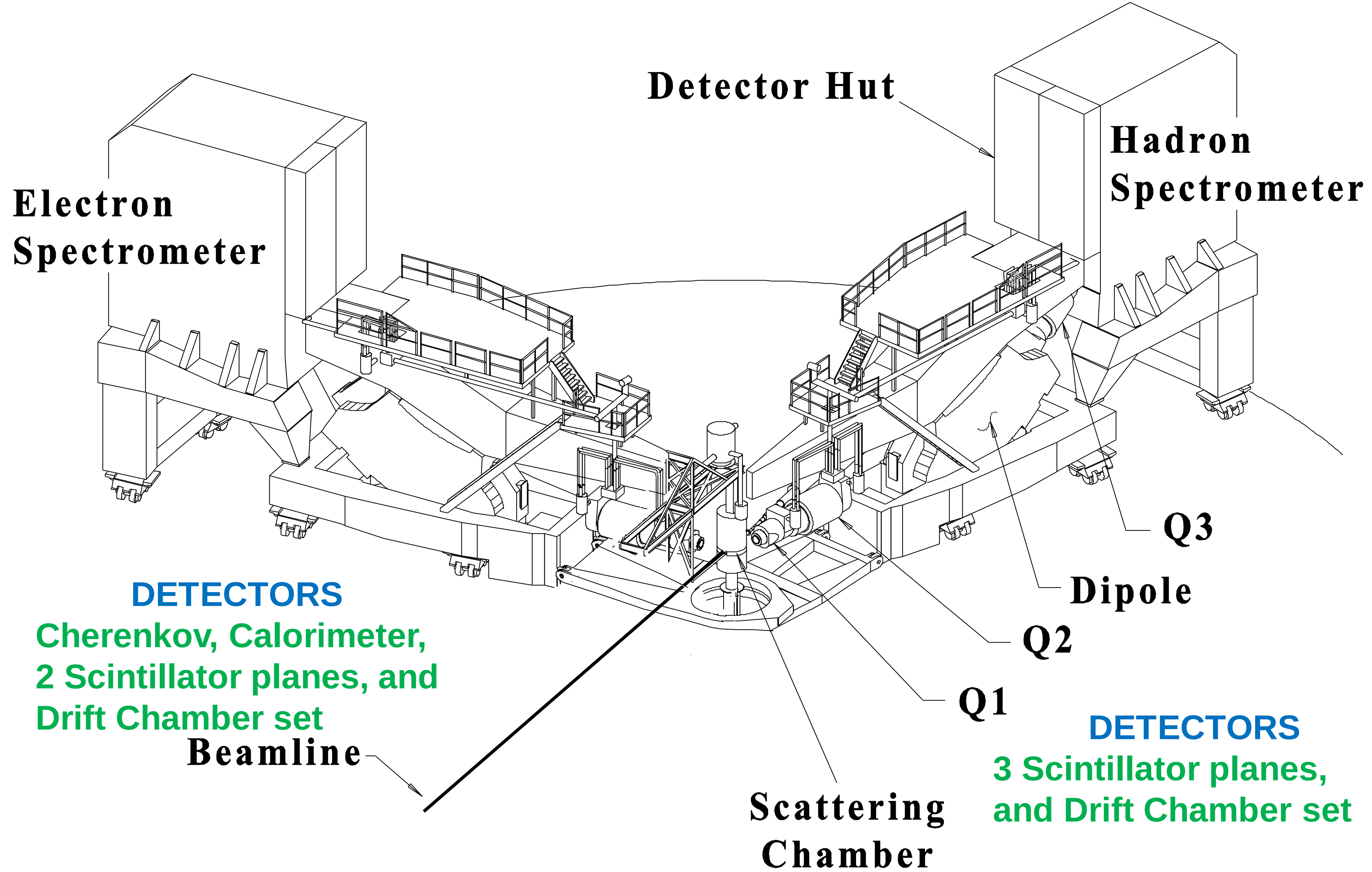
^{3}H Magnetic Form Factor World Data



Jefferson Lab Triton Elastic Experiment

- Use the two Hall A High Resolution Spectrometers (HRS) to detect scattered electrons and recoil tritium nuclei.
- Electron detection will rely on a gas threshold Cherenkov counter, a lead-glass electromagnetic Calorimeter, and a wire drift chamber system.
- Triton detection will rely on a three-plane scintillator package and a wire drift chamber system.
  - First plane is a new single scintillator with two phototubes, to be constructed by St. Norbert College.
- Overall normalization will be checked with single-arm and double-arm (coincidence) elastic electron-proton scattering.
- A full Monte Carlo simulation of the experiment will provide the single- and double-arm solid angle, which will include radiative and Landau energy losses, multiple scattering, etc.

JLab Hall A Triton Form Factor Setup
(with the Tritium target system under development)



Triton Elastic Experiment Strategy

- Triton form factors will be extracted, at each Q^2, from a reliable Rosenbluth Separation between scattering at one very forward and one very backward electron scattering angle.
- Optimum configuration for the forward-electron case is a double-arm (coincidence) measurement using time-of-flight (TOF) between the electron HRS and recoil HRS triggers.
- Optimum configuration that minimizes statistical error for the backward-electron case is a single-arm measurement of only forward recoiling tritons using the right HRS system.
- For the backward-electron case, for consistency checks with triton detection, coincidence data will be taken at the same time at a reduced rate (due to a reduced solid angle) by also detecting backward electrons with the left HRS.

Experimental Apparatus Parameters Overview

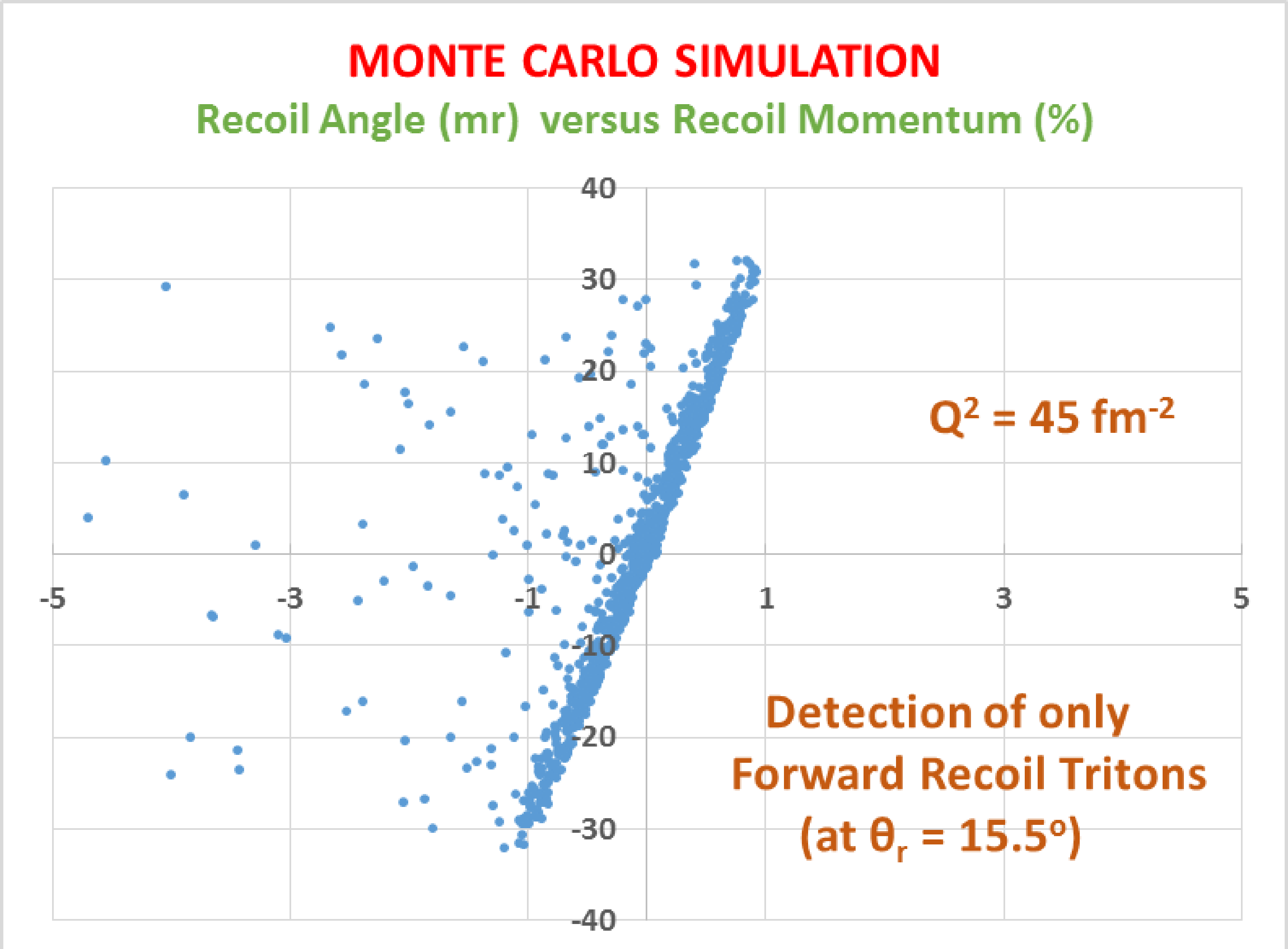
- Beam Energy and Current
  - 2.2 and 4.4 GeV for forward-electron scattering
  - 0.63, 0.78, and 0.88 GeV for backward-electron scattering
  - Beam current 20 µA (as set by target safety specs)
- Tritium target
  - 200 psi gas cell, 1090 Ci activity, 0.0032 g/cm^3 density
  - 500 psi gas Hydrogen cell for calibrations/normalization
  - Cells compatible with needs of elastic measurements
- Left (electron) High Resolution Spectrometer
  - Angular range: 14 to 140 deg
  - Momentum Range 0.5 to 4.1 GeV/c
- Right (recoil) High Resolution Spectrometer
  - Angular range: 15 to 72 deg
  - Momentum Range 1.0 to 1.4 GeV/c

Triton Identification – Separation from Background

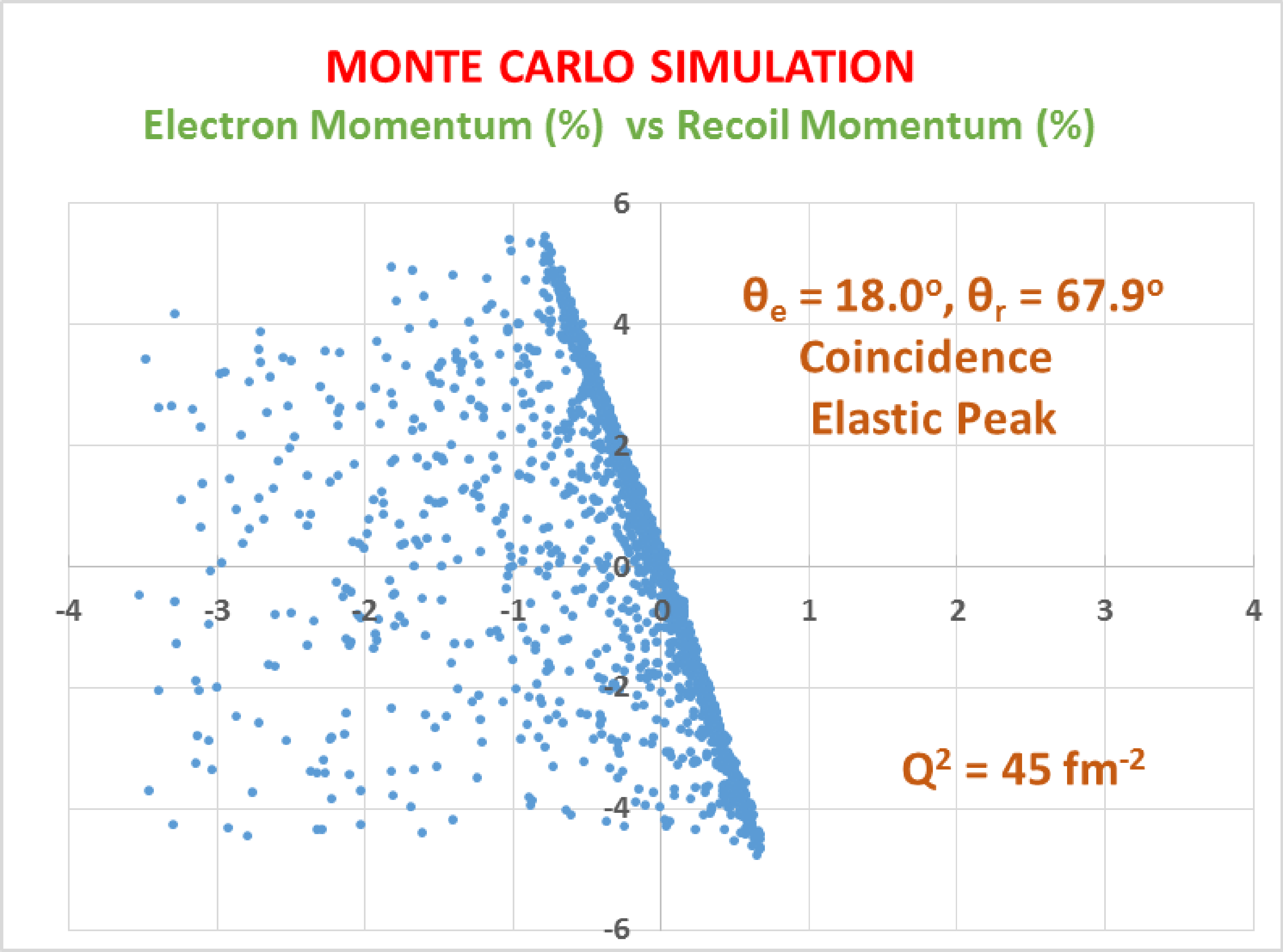
- Triton separation from background will rely on
  - Recoil signal TOF from target to detectors through HRS, using as TDC start the ***31 MHz beam pulse mode*** signal
  - Recoil TOF from the first to the third scintillator plane
  - Recoil scintillator ADC signals
- Recoil HRS setting will be above the beam momentum. There can be no background from light-mass particles
  - Positrons and muons
  - Pions and kaons
- Only particle background from target can be protons and deuterons, separable primarily by TOF
- Punch-through room background cannot produce
  - Physical tracks in time with a triple scintillator coincidence
  - Large ADC signals in all three scintillator planes

Tritons From the Target-Cell End Cups?

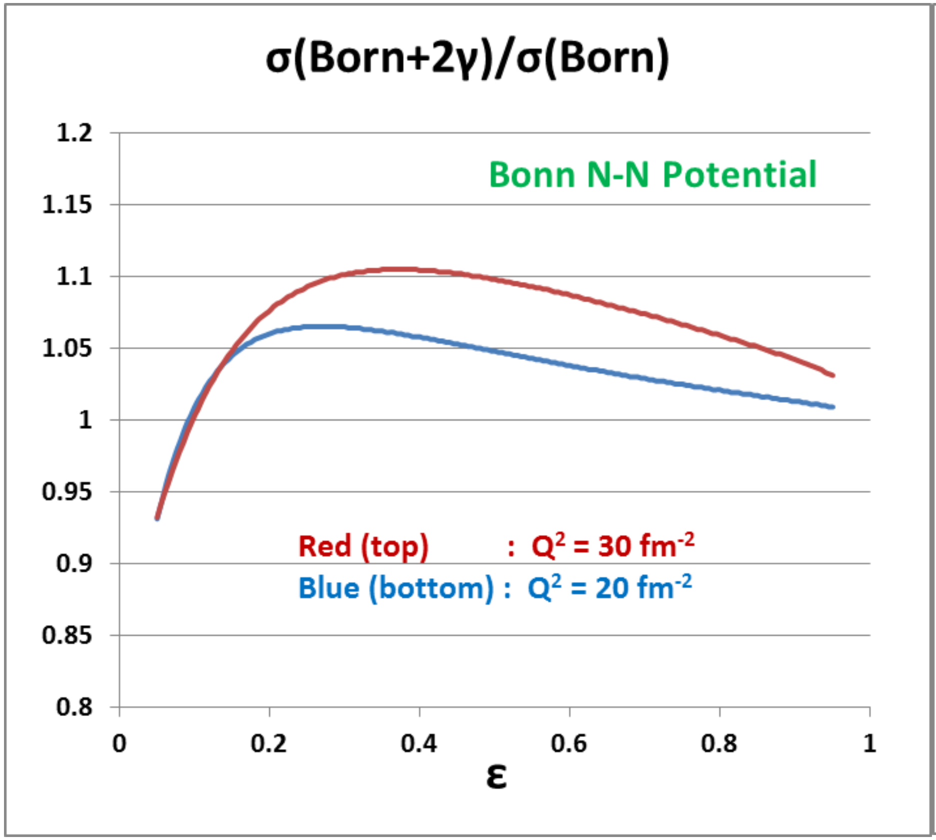
- There should be no tritons originating from the Aluminum end-cups of the target cell *in the momentum acceptance of the elastic spectrometer setting:*
- No deuterons from Aluminum target cell end-cups have been observed in elastic electron-deuteron scattering experiments at SLAC and Jefferson Lab, at both forward and backward angles.
- No helium nuclei from Aluminum target cell end-cups have been observed at SLAC and Jefferson Lab in i) elastic electron-^{3}He scattering experiments at both forward and backward angles, and ii) electron-^{4}He scattering experiments at forward angles.
- Special runs will the empty-replica cell are planned as in previous experiments for each kinematics.

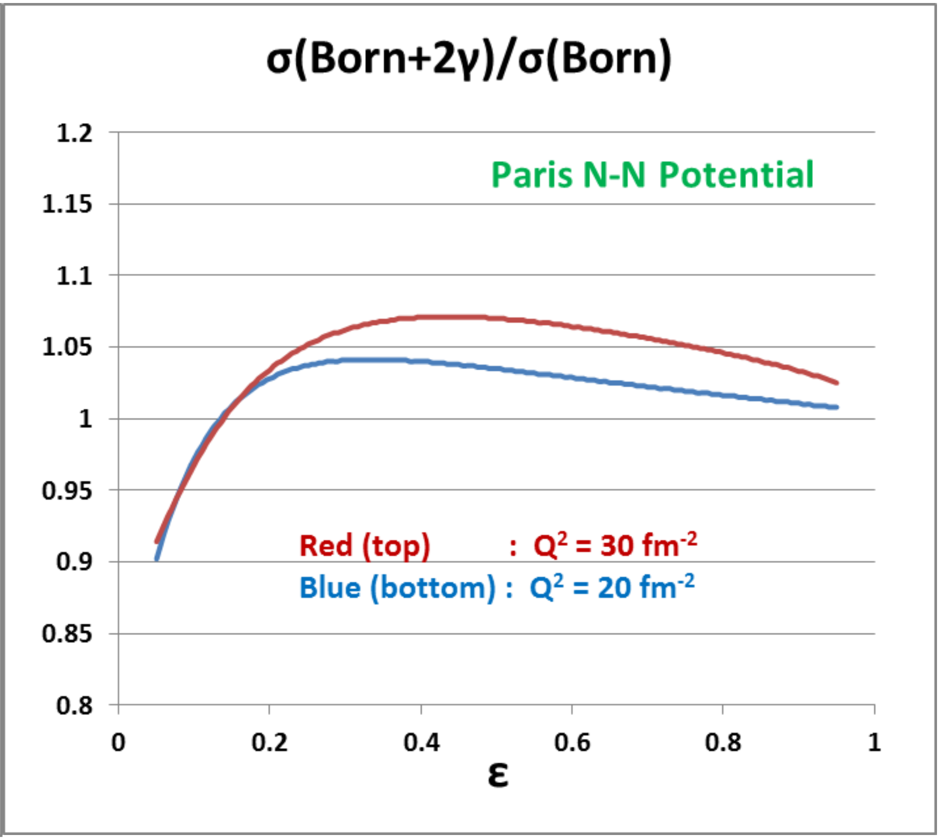


MONTE CARLO SIMULATION
Recoil Angle (mr) versus Recoil Momentum (%)
40
30
20
10
0
-10
-20
-30
-40
-5
-3
-1
1
3
5
Q² = 45 fm⁻²
Detection of only
Forward Recoil Tritons
(at θr = 15.5°)


MONTE CARLO SIMULATION
Electron Momentum (%) vs Recoil Momentum (%)
$\theta_e = 18.0^o, \theta_r = 67.9^o$
Coincidence
Elastic Peak
$Q^2 = 45\ fm^{-2}$
6
4
2
0
-2
-4
-6
-4
-3
-2
-1
0
1
2
3
4

Elastic Electron-Triton Scattering – 2γ Effect

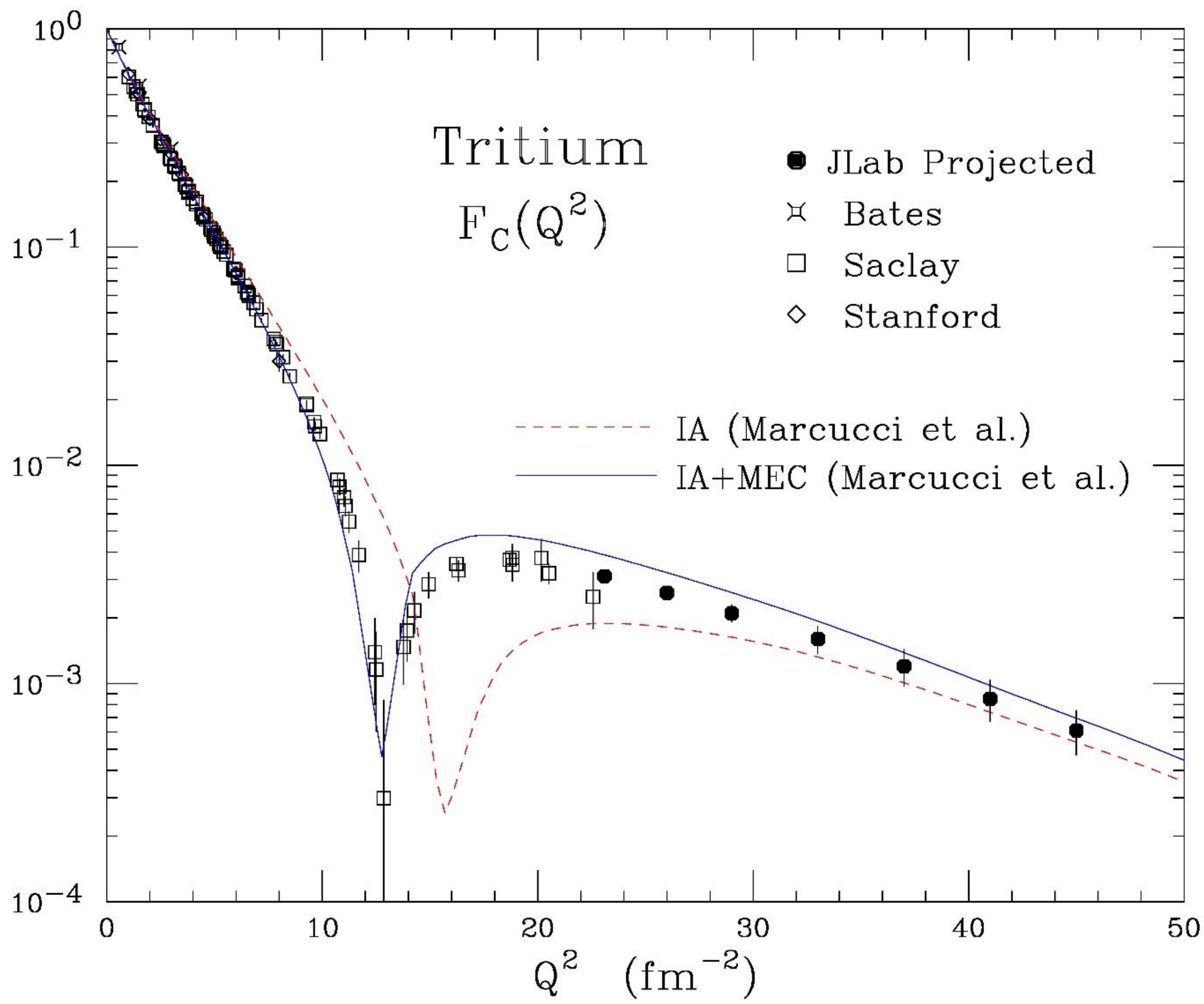




Very recent calculation of the 2-photon exchange contribution to the elastic cross section by **A. P. Kobushkin and Ju. V. Timoshenko** (private com)

Effect appears to be small and correctable with small systematic uncertainty

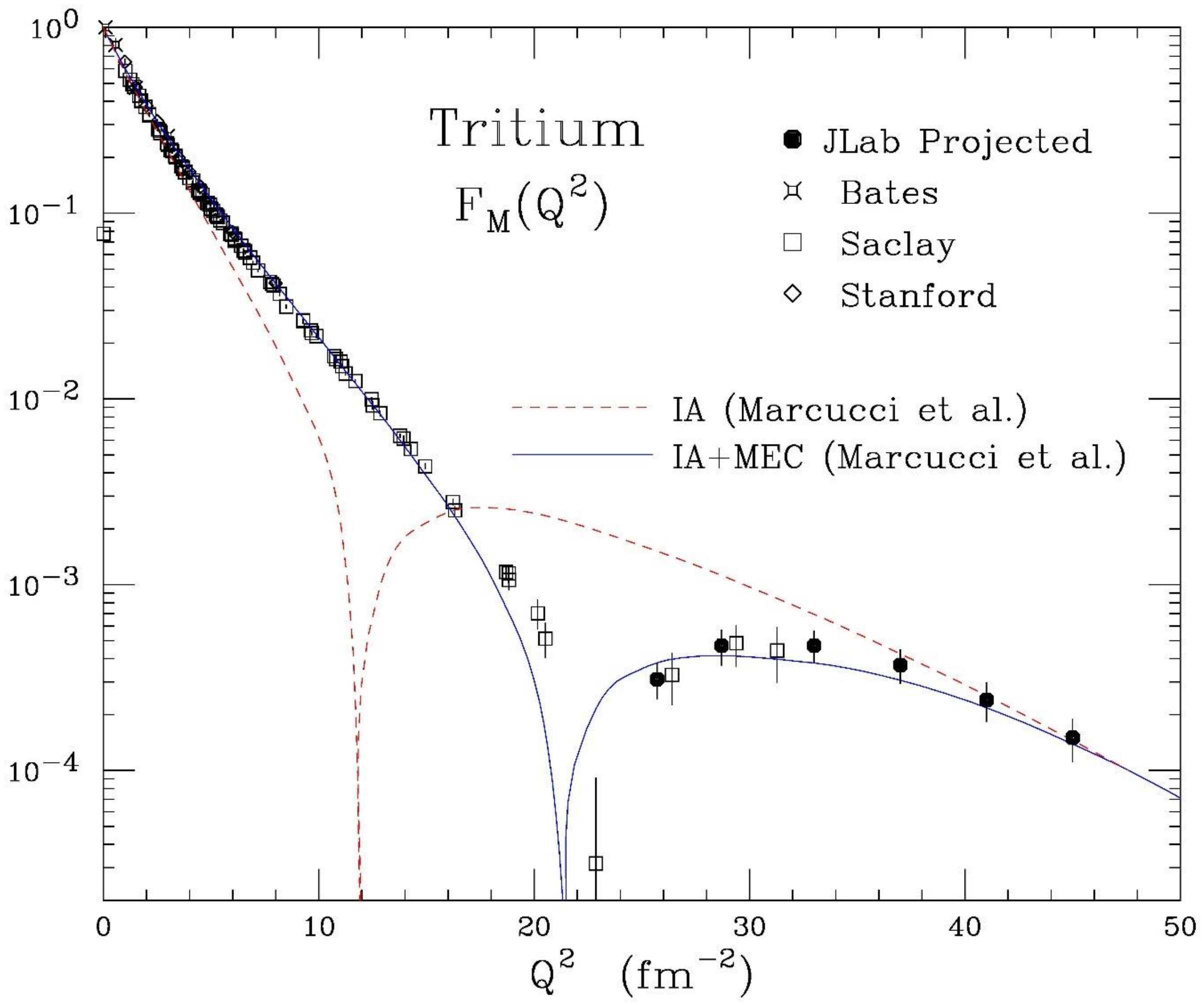
Projected Data for Triton Charge Form factor



8 days of tritium running at 20 µA

2 days of hydrogen calibrations and empty-target replica running

Projected Data for Triton Magnetic Form factor



8 days of tritium running at 20 µA
2 days of hydrogen calibrations and empty-target replica running

Summary

- Availability of a tritium target at JLab offers a unique opportunity for precision measurements of the triton form factors at large momentum transfers, in just 10 days.
- Measurements will be highly complementary to the recent JLab measurements on the other few-body form factors.
- New JLab experiment will be able to i) double the four-momentum transfer range of the existing data, ii) provide new, very precise data with state-of-the-art apparatus.
- New data will be pivotal for the establishment of a canonical model describing the structure and dynamics of the few-body nuclear systems and for understanding isoscalar and isovector MEC mechanisms.
- The Collaboration has a long experience with similar measurements.

Selected Review Papers – Few-Body Form Factors

- L. E. Marcucci *et al*., submitted to J. Phys. G (April 2015).
- S. Bacca and Pastore, J. Phys. G **31**, 123002 (2014).
- W. N. Polyzou *et al*., Few Body Syst. **49**, 129 (2011).
- A. Stadler and F. Gross, Few Body Syst. **49**, 91 (2011).
- V. R. Garsevanishvili *et al*., Phys. Rept. **458**, 247 (2008).
- R. Gilman and F. Gross, J*. Phys. G* **28**, 37 (2002).
- S. G. Bondarenko *et al*., *Prog. Part. Nucl. Phys*. **48**, 449 (2002).
- I. Sick, *Prog. Part. Nucl. Phys*. **47**, 245 (2001).
- M. Garcon and J. W. Van Orden, *Adv. Nucl. Phys*. **26**, 293 (2001).
- J. Carlson and R. Schiavilla, *Rev. Mod. Phys*. **70**, 743 (1998).
- C. E. Carlson, J. R. Miller and R. J. Holt, *Ann. Rev. Nucl. Part. Sci.* **47**, 395 (1997).

Monte Carlo Simulation Model

- Complete simulation of elastic electron-nucleus experiments with the two HRS systems. Includes all physical processes involved.
- Landau Ionization energy loss for incident electrons, scattered electrons and recoil nuclei.
- Internal and external bremsstrahlung radiation energy loss for incident and scattered electrons (Mo and Tsai formalism).
- Multiple scattering for incident electrons, scattered electrons and recoil nuclei.
- Ray-tracing of scattered electrons and recoil nuclei in the two HRS systems using optics models based on magnetic measurements and position surveys of magnets and vacuum apertures.
- Model weights scattering events with their cross section probability.
- Program calculates effective single- and double-arm (coincidence) solid angle for cross section determination.
- **Details**: A. T. Katramatou, Kent State University preprint KSU-CNR-14-11, December 2011.

Elastic e-Triton Cross Section Determination

$$\frac{d\sigma}{d\Omega}(E,\theta_e)=\frac{N_{e'r}}{N_e N_t (\Delta\Omega)_{eff} F(Q^2)} \prod_i C_i$$

- Standard Terms
  - Number of electron-nucleus TOF coincidence events
  - Number of incident electrons
  - Number of target nuclei
  - Effective Monte Carlo solid angle with radiative corrections
  - Q^2-only-dependent part of radiative corrections
- Multiplicative Corrections C_i
  - Computer dead time
  - Detector inefficiencies
  - Absorption of recoil nuclei in target and windows
  - Beam-induced target density reduction

ELECTRON-TRITON FORWARD ELASTIC KINEMATICS

Q^2 (fm^{-2})	E (GeV)	E' (GeV)	Θ (deg.)	P_r (GeV/c)	Θ_r (deg)	β_r	$d\Omega_e/d\Omega_r$
23.0	2.2	2.041	25.81	0.960	67.78	0.323	0.585
26.0	2.2	2.020	27.62	1.022	66.34	0.342	0.638
29.0	4.4	4.199	14.20	1.082	72.27	0.359	0.218
33.0	4.4	4.171	15.21	1.156	71.09	0.381	0.237
37.0	4.4	4.143	16.16	1.227	69.98	0.400	0.256
41.0	4.4	4.116	17.08	1.295	68.93	0.419	0.275
45.0	4.4	4.088	17.96	1.360	67.93	0.436	0.295

Table 1: Forward elastic electron-triton kinematics in the Q^2 range from 23 to 45 fm^{-2}, where E is the incident electron energy, E' and Θ are the scattered electron energy and angle, and Θ_r, P_r and β_r are the angle, momentum and speed of the recoil triton. The last column is the Jacobian transformation ratio of the scattered electron and recoil triton solid angles.

ELECTRON-TRITON BACKWARD ELASTIC KINEMATICS

Q^2 (fm^{-2})	E (GeV)	E' (GeV)	Θ (deg.)	P_r (GeV/c)	Θ_r (deg)	β_r	$d\Omega_e/d\Omega_r$
23.0	0.633	0.474	119.6	0.960	25.41	0.323	4.54
26.0	0.633	0.453	140.0	1.022	16.54	0.342	5.32
29.0	0.780	0.579	104.5	1.082	31.21	0.359	4.08
33.0	0.780	0.551	119.7	1.156	24.45	0.381	4.84
37.0	0.780	0.523	140.0	1.267	15.90	0.400	5.72
41.0	0.877	0.593	122.3	1.295	22.79	0.419	5.17
45.0	0.877	0.566	140.0	1.360	15.50	0.436	6.00

Table 2: Backward elastic electron-triton kinematics in the Q^2 range from 23 to 45 fm^{-2}, where E is the incident electron energy, E' and Θ are the scattered electron energy and angle, and Θ_r, P_r and β_r are the angle, momentum and speed of the recoil triton. The last column is the Jacobian transformation of the ratio of the scattered electron and recoil triton solid angles.

FORWARD ELECTRON SCATTERING RUN PLAN

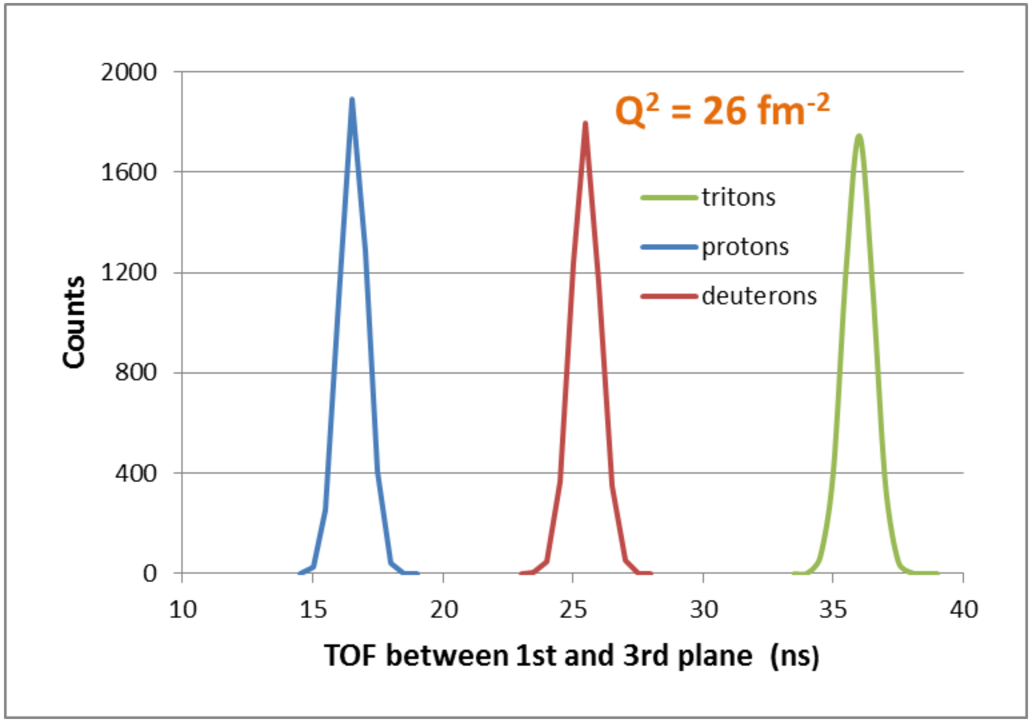
Q^2 (fm^{-2})	F_C	F_M	Cross Section (cm^2/sr)	Time (hr)	Counts	ΔF_C ($\pm$%)
23.0	3.1×10^{-3}	2.7×10^{-5}	3.6×10^{-36}	4.8	136	6.4
26.0	2.5×10^{-3}	3.1×10^{-4}	1.8×10^{-36}	7.2	117	6.4
29.0	2.1×10^{-3}	4.7×10^{-4}	5.3×10^{-36}	7.2	116	8.8
33.0	1.6×10^{-3}	4.7×10^{-4}	2.6×10^{-36}	4.8	41	14.3
37.0	1.2×10^{-3}	3.6×10^{-4}	1.1×10^{-36}	4.8	19	20.0
41.0	8.5×10^{-4}	2.4×10^{-4}	4.6×10^{-37}	9.6	17	21.5
45.0	6.1×10^{-4}	1.5×10^{-4}	1.9×10^{-37}	14.4	11	23.1
Total				52.8		

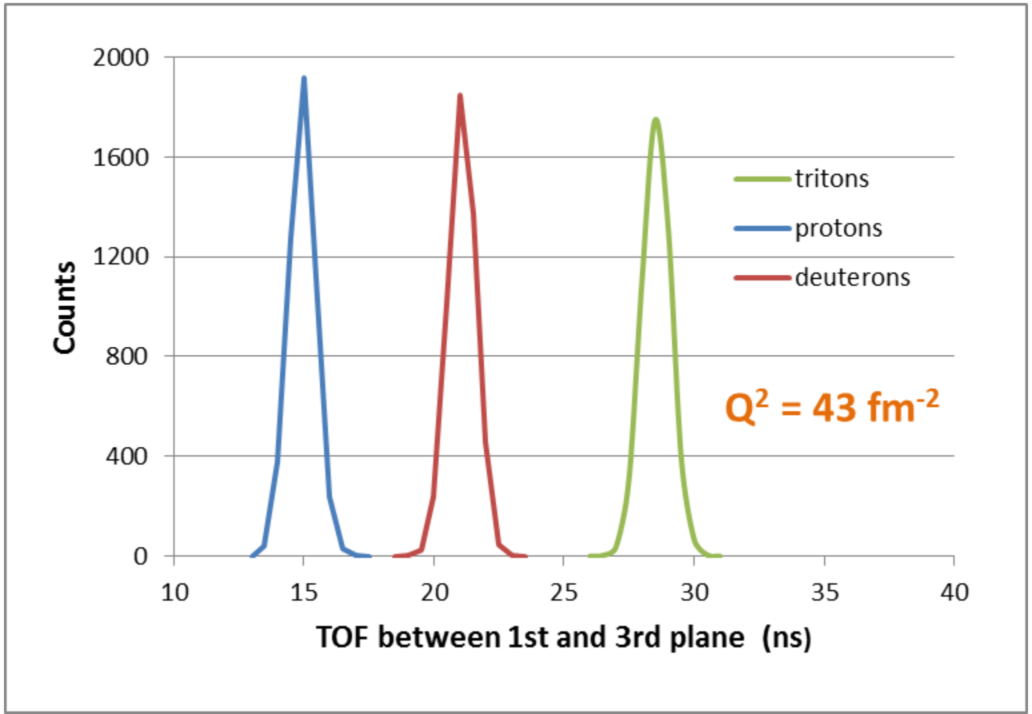
Table 3: Run plan scenario with cross section and counting rate estimates for the forward electron-triton scattering measurements, using the two HRS systems to detect both scattered electrons and recoil tritium nuclei in coincidence. The rate estimates assume a 25 cm long gas tritium target with density 0.00325 g/cm^3, a beam current of 20 μA, a nominal solid angle of 5.0 msr for HRS, and a radiative correction factor of 0.8. Also given is the total uncertainty in the extraction of the charge form factor F_C.

BACKWARD ELECTRON SCATTERING RUN PLAN

Q^2 (fm^{-2})	F_C	F_M	Cross Section (cm^2/sr)	Time (hr)	Counts	ΔF_M ($\pm$%)
23.0	3.1×10^{-3}	2.7×10^{-5}	1.9×10^{-37}	9.6	52	NM
26.0	2.5×10^{-3}	3.1×10^{-4}	7.4×10^{-38}	31.2	68	21.5
29.0	2.1×10^{-3}	4.7×10^{-4}	1.7×10^{-37}	28.8	146	21.7
33.0	1.6×10^{-3}	4.7×10^{-4}	9.8×10^{-38}	9.6	27	19.6
37.0	1.2×10^{-3}	3.6×10^{-4}	4.4×10^{-38}	7.2	9	22.0
41.0	8.5×10^{-4}	2.4×10^{-4}	2.3×10^{-38}	22.8	15	23.5
45.0	6.1×10^{-4}	1.5×10^{-4}	7.8×10^{-39}	33.6	8	25.1
Total				142.8		

Table 4: Run plan scenario with cross section and counting rate estimates for recoil triton detection measurements using the Right HRS system. The rate estimates assume a 25 cm long gas tritium target with density 0.00325 g/cm^3, a beam current of 20 μA, a spectrometer nominal solid angle of 5.0 msr, and a radiative correction factor of 0.8. Also given is the total uncertainty in the extraction of the charge form factor F_M (NM means not measurable).



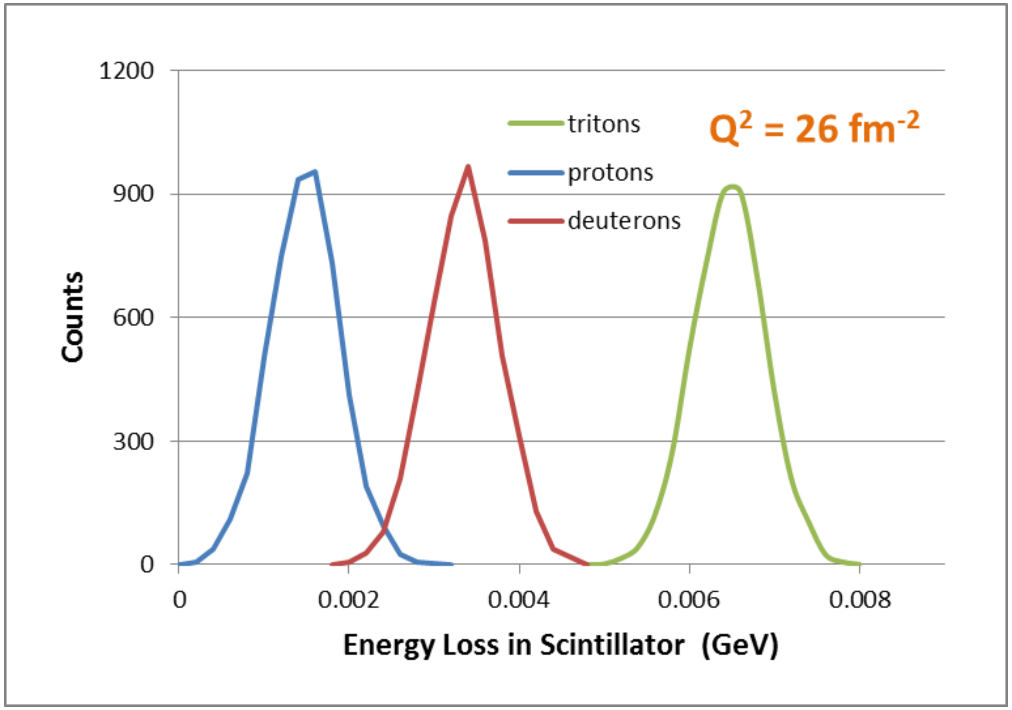


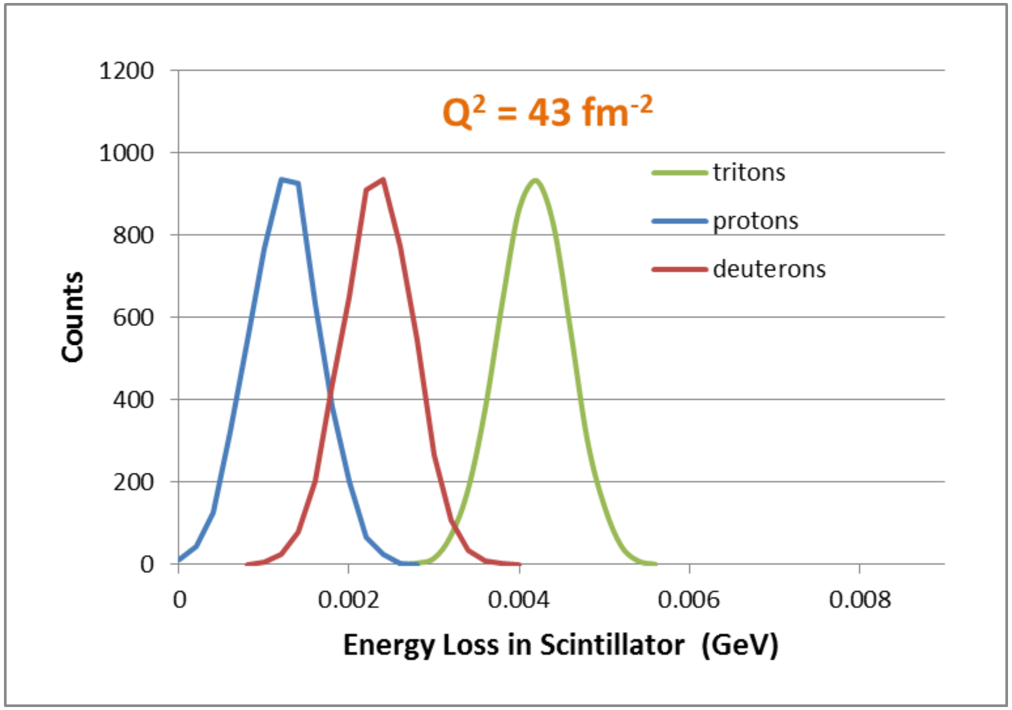
MONTE CARLO SIMULATION

TOF between front and back planes of scintillators

Elastic triton events

Uniform proton and deuteron background





MONTE CARLO SIMULATION

Ionization energy loss in front scintillator

Elastic triton events

Uniform proton and deuteron background