High Q^2 Few-Body Form Factors

Makis Petratos
Kent State University

Contributors

J. Gomez, M. Katramatou, M. Petratos, R. Suleiman

PAC 18
Jefferson Lab
July 15, 2000

Few-Body Form Factors

- Elastic scattering from the deuteron and few-body systems has been a major part of the experimental program of every electron machine
- Bates, NIKHEF, Saclay and SLAC (HEP and NPAS) have had highly successful programs
- Physics importance justified development of tritium targets at Bates and Saclay
- Papers on subject are among the highest cited in electronuclear physics
- Subject is integral part of every electronuclear conference
- Fundamental information on the structure of the deuteron and the three- and four-body systems.

Elastic Electron-Deuteron Scattering

- Cross Section

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

$$\begin{aligned} A(Q^2) &= F_C^2(Q^2) + \frac{8}{9}\tau^2 F_Q^2(Q^2) + \frac{2}{3}\tau F_M^2(Q^2) \\ B(Q^2) &= \frac{4}{3}\tau(\tau+1)F_M^2(Q^2) \end{aligned}$$

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

- F_C, F_Q, F_M: Charge, Quadrupole, Magnetic form factors
- Forward angle scattering $\longrightarrow A(Q^2)$
- Backward angle scattering $\longrightarrow B(Q^2)$

Polarized e-d Elastic Scattering

- To separate F_C, F_Q, F_M form factors must measure a polarization observable.
- Measure the target deuteron analysing power (polarized target, unpolarized beam).
- Measure the recoil deuteron tensor polarization (unpolarized beam and target).

$$t_{20} =$$

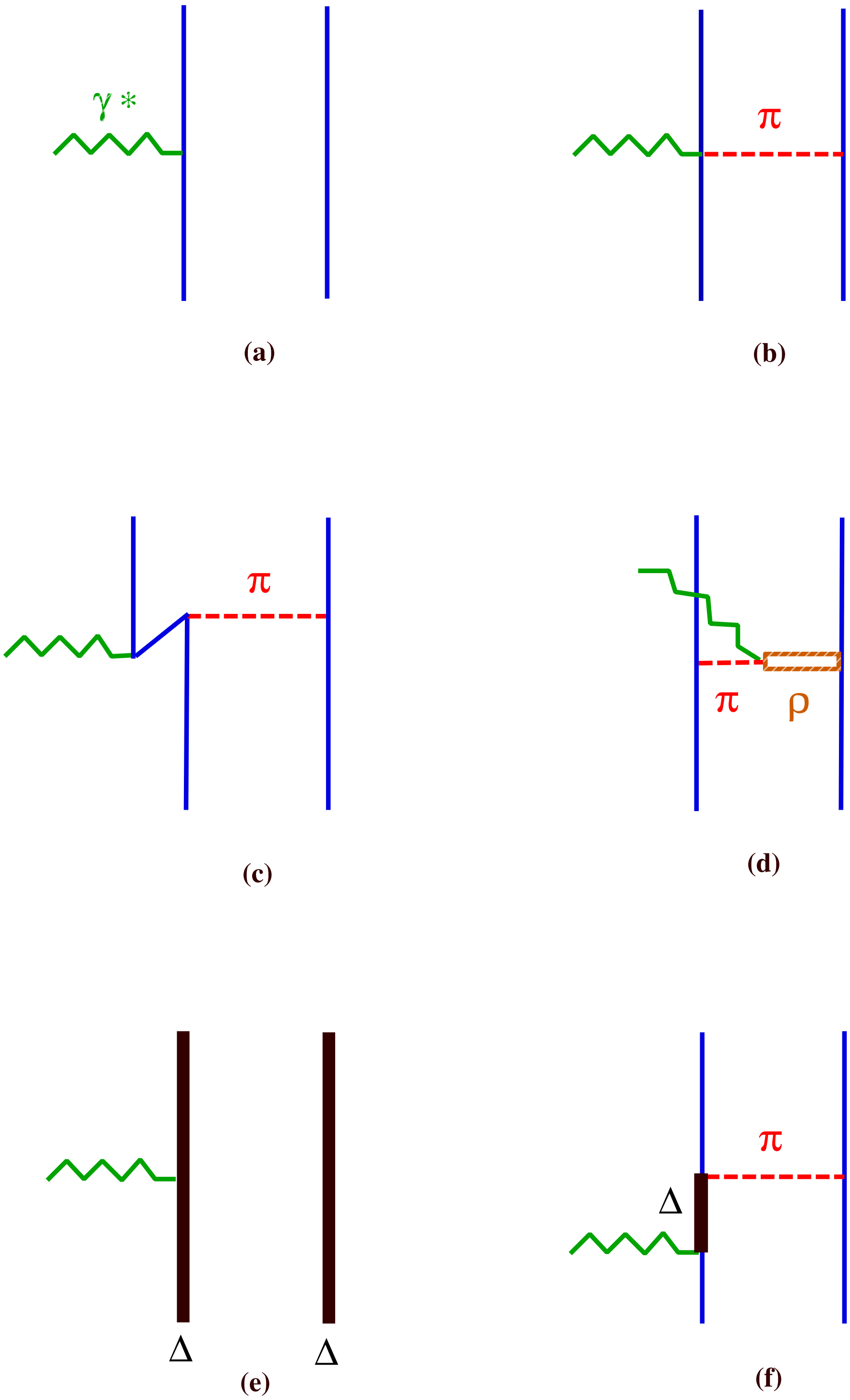
$$-\frac{1}{\sqrt{2}S}\left[\frac{8}{3}\tau F_C F_Q + \frac{8}{9}\tau^2 F_Q^2 + \frac{1}{3}\tau[1 + 2(1+\tau)\tan^2\frac{\theta}{2}]G_M^2\right]$$

$$S = A + B\tan^2\frac{\theta}{2}$$

Deuteron Non-Relativistic Approach

- Impulse Approximation
- Two-body bound state solved with Schrödinger equation using a realistic NN potential
- Darwin-Foldy and spin-orbit Relativistic Corrections
- Meson-Exchange Currents
- Isobar Configurations
- Six-Quark Admixtures
- Total Form Factor:

$$F = F_{IA} + F_{RC} + F_{MEC} + F_{IC} + F_{6q}$$


γ *
(a)
π
(b)
π
(c)
π
ρ
(d)
Δ
Δ
(e)
π
Δ
(f)

Deuteron Relativistic Approaches

- Manifestly Covariant Dynamics using 3-D reductions of Bethe-Salpeter equation
  - Lorentz transformations are kinematic
  - Inclusion of negative energy states is dynamic
  - Quasi-potential approximation
    - Gross equation$^{(\mathrm{VDG})}$
    - Blackenbeckler-Sugar equation$^{(\mathrm{HT})}$
  - Equal-time approximation
    - Wallace-Mandelweig equation$^{(\mathrm{PW})}$

- Light Front Dynamics using field theories quantized on the light cone
  - Conventional quantum mechanics
  - Some Lorentz transformations include the interaction

VDG : Van Orden, Devine and Gross
HT : Hummel and Tjon
PW : Phillips and Wallace

Deuteron Quark-Gluon Approaches

- Dimensional Scaling Quark Model (DSQM)

$$\sqrt{A(Q^2)} \sim (Q^2)^{-5}$$
$$\sqrt{B(Q^2)} \sim (Q^2)^{-6}$$

- Perturbative QCD

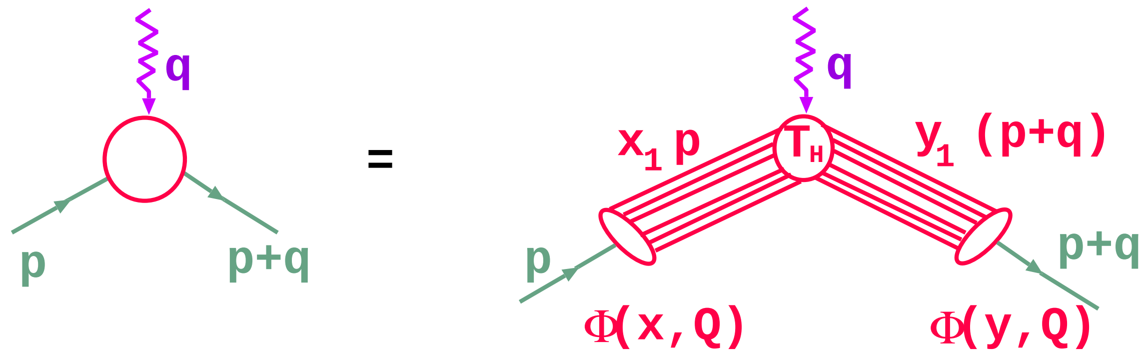
$$\sqrt{A(Q^2)} = \int_0^1 \int_0^1 dx dy \Phi_d^\dagger(y,Q) T(x,y,Q) \Phi_d(x,Q)$$

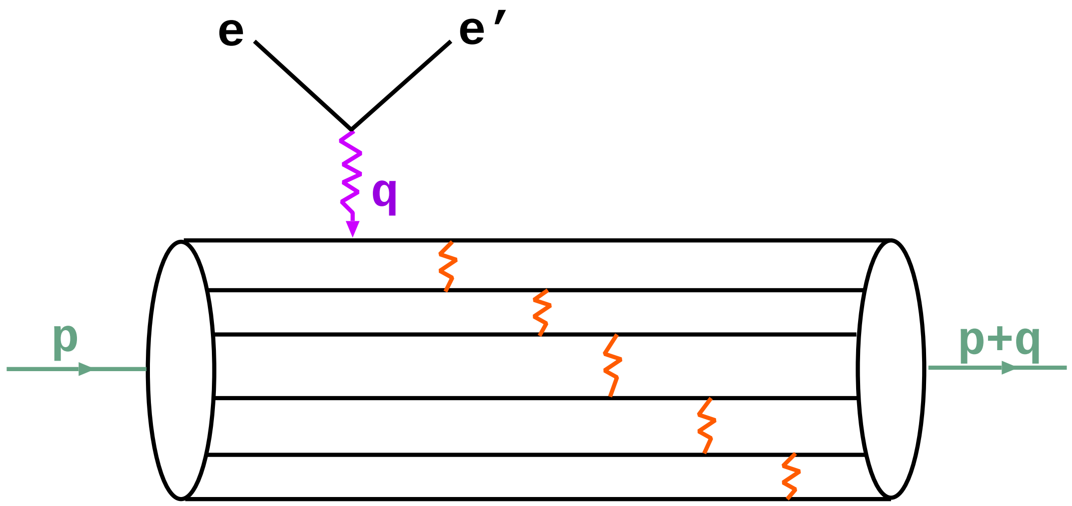
- Deuteron Form Factor

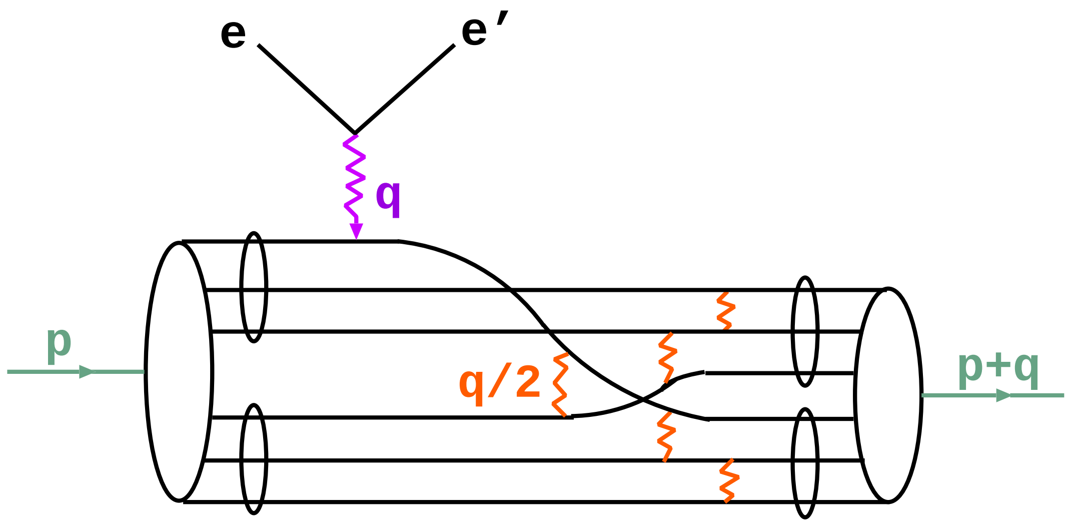
$$\begin{aligned} F_d(Q^2) &\equiv \sqrt{A(Q^2)} = \\ &= \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5 \sum_{m,n} d_{mn} \left[\ln\left(\frac{Q^2}{\Lambda^2_{QCD}}\right)\right]^{-\gamma_n-\gamma_m} \end{aligned}$$

- Reduced Deuteron Form Factor

$$f_d(Q^2) = \frac{F_d(Q^2)}{F_N^2(Q^2/4)} \sim \left[\frac{\alpha_s(Q^2)}{Q^2}\right] \left[\ln\left(\frac{Q^2}{\Lambda^2_{QCD}}\right)\right]^{-\Gamma(n_f,n_c)}$$


q
p
p+q
=
q
x_1 p
T_H
y_1 (p+q)
p
p+q
Φ(x,Q)
Φ(y,Q)


e
e'
q
p
p+q


e
e'
q
p
q/2
p+q

Elastic Electron-Helium/Tritium Scattering

- ^{3}He/^{3}H charge and magnetic form factors:

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

$$\begin{aligned} A(Q^2) &= \frac{F_C^2(Q^2) + \mu^2 \tau F_M^2(Q^2)}{1+\tau} \\ B(Q^2) &= 2\tau\mu^2 F_M^2(Q^2) \end{aligned}$$

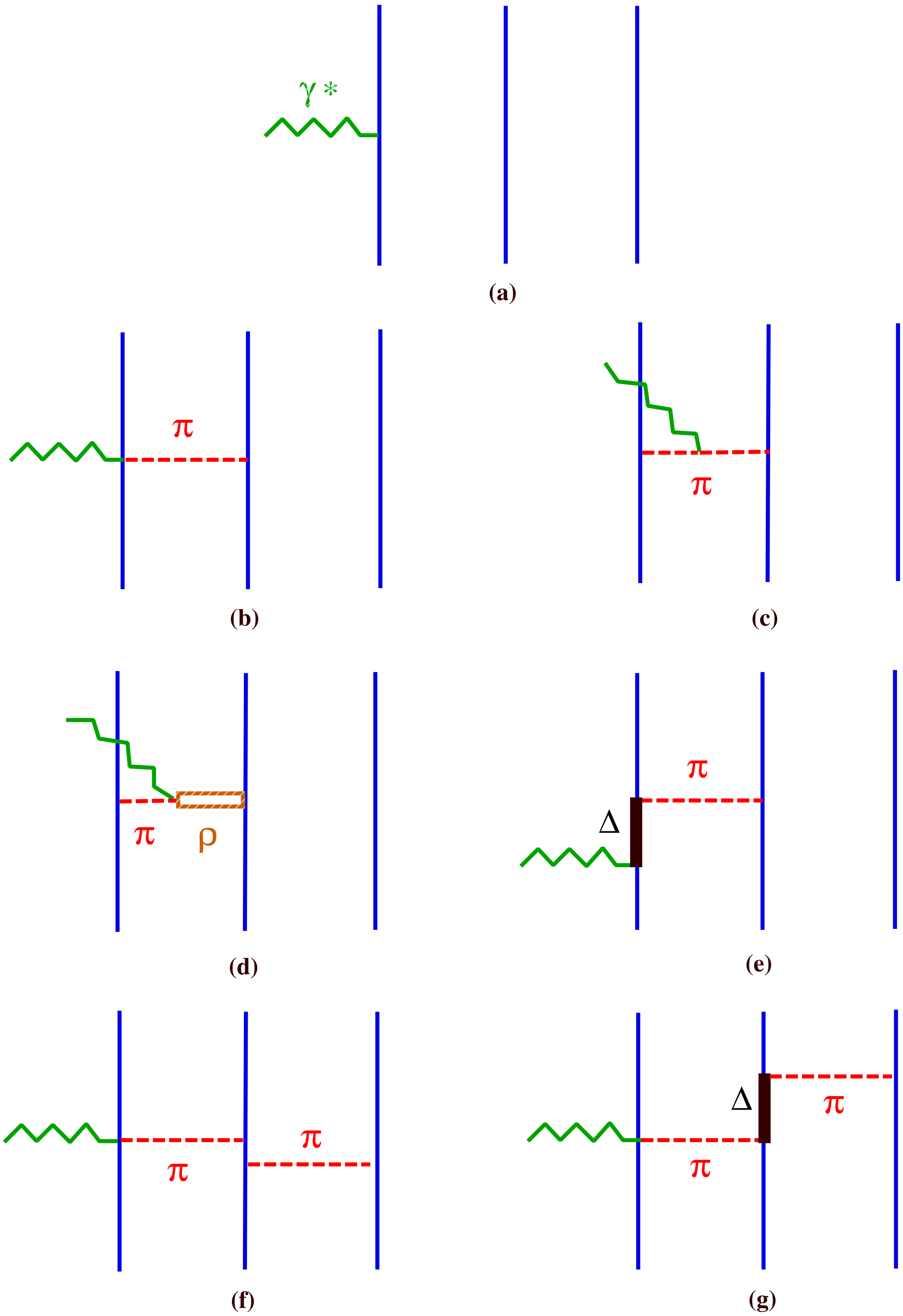
$$Q^2 = 4EE' \sin^2(\tfrac{\theta}{2}) \qquad \tau = Q^2/4M^2$$

- ^{4}He charge form factor

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

The Three- and Four-Body Standard Model

- Impulse Approximation (IA)
- Solve the nuclear ground state using:
  - Numerical solutions of Faddeev equations
  - Correlated Hyperspherical Harmonics (CCH)
  - Monte Carlo methods
    - Variational Monte Carlo (VMC)
    - Green's Function Monte Carlo (GFMC)
- Relativistic Corrections
  - Darwin - Foldy
  - Spin - orbit


γ *
(a)
π
(b)
π
(c)
π
ρ
(d)
π
Δ
(e)
π
π
(f)
Δ
π
π
(g)

Beyond the Impulse Approximation

- IA alone cannot describe the few-body form factor data
- Position of first diffraction minimum and height of secondary maximum either overestimated or underestimated
- Inclusion of Meson-Exchange Currents (MEC) brings theory in better agreement with data
  - Model-independent (pion-like exchanges)
  - Model-dependent (transition currents)
- Isobar Configurations calculated to have small effects
- Three-Body Force effects have been shown to be small
- Multi-Quark Admixtures in nuclear wave function

Constituent Counting Rules

- Dimensional scaling of high energy amplitudes using quark counting

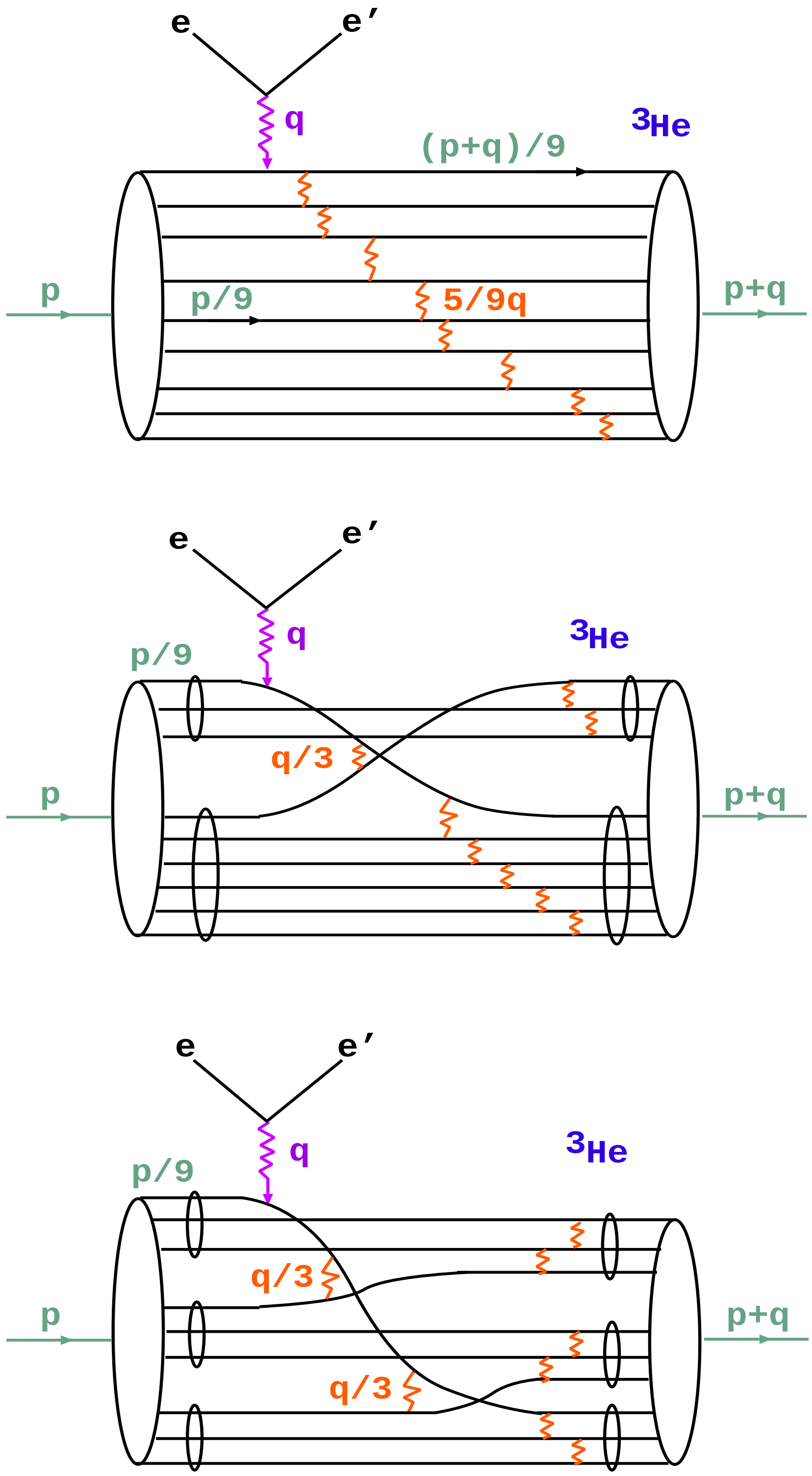
- Prediction for Helium Form factor:

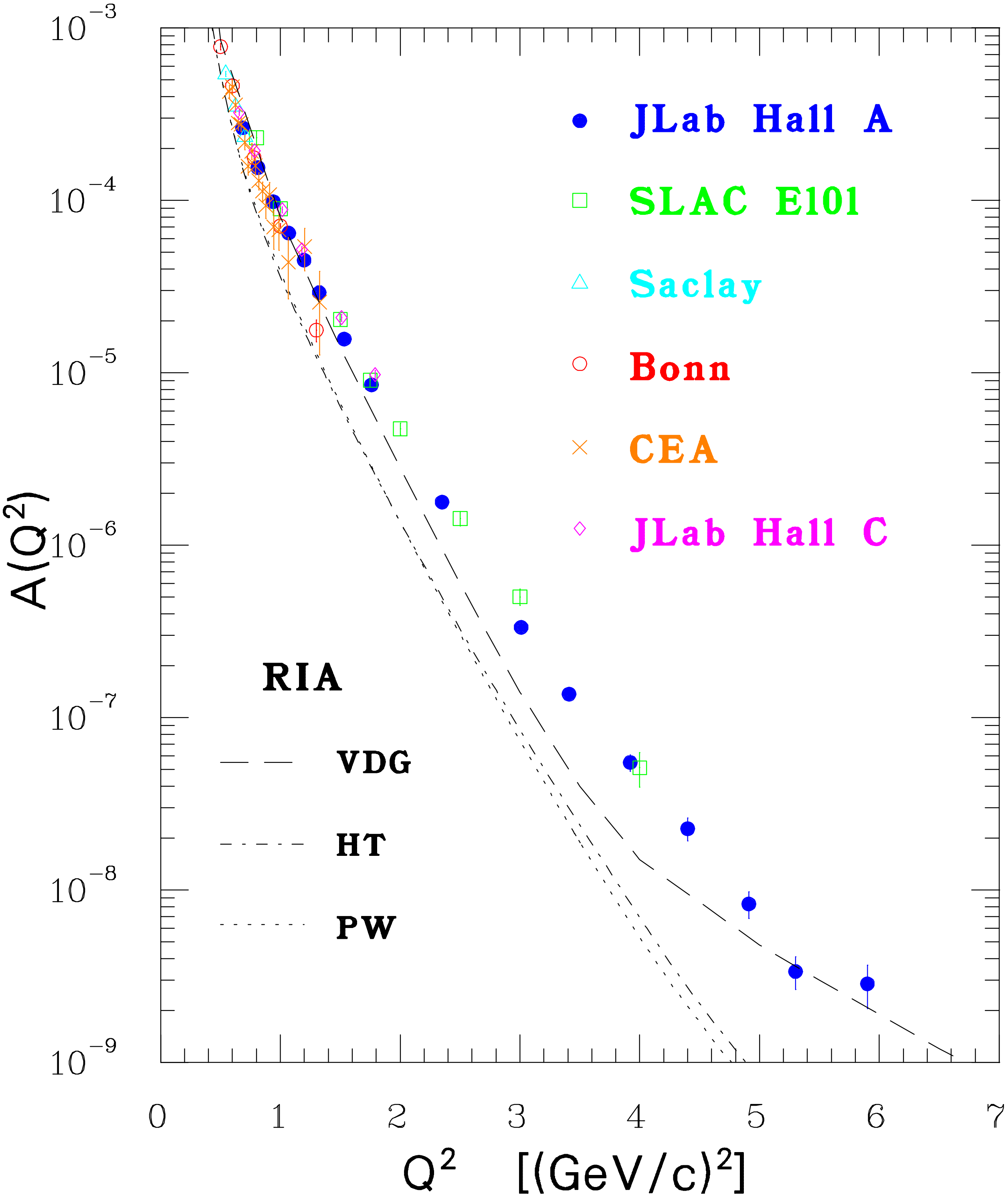
$$F_{\mathrm{He}}(Q^2) \equiv \sqrt{A_{\mathrm{He}}(Q^2)} \sim (Q^2)^{1-3A}$$

$$A = 3 \text{ for } {}^3\mathrm{He}, \quad A = 4 \text{ for } {}^4\mathrm{He}$$

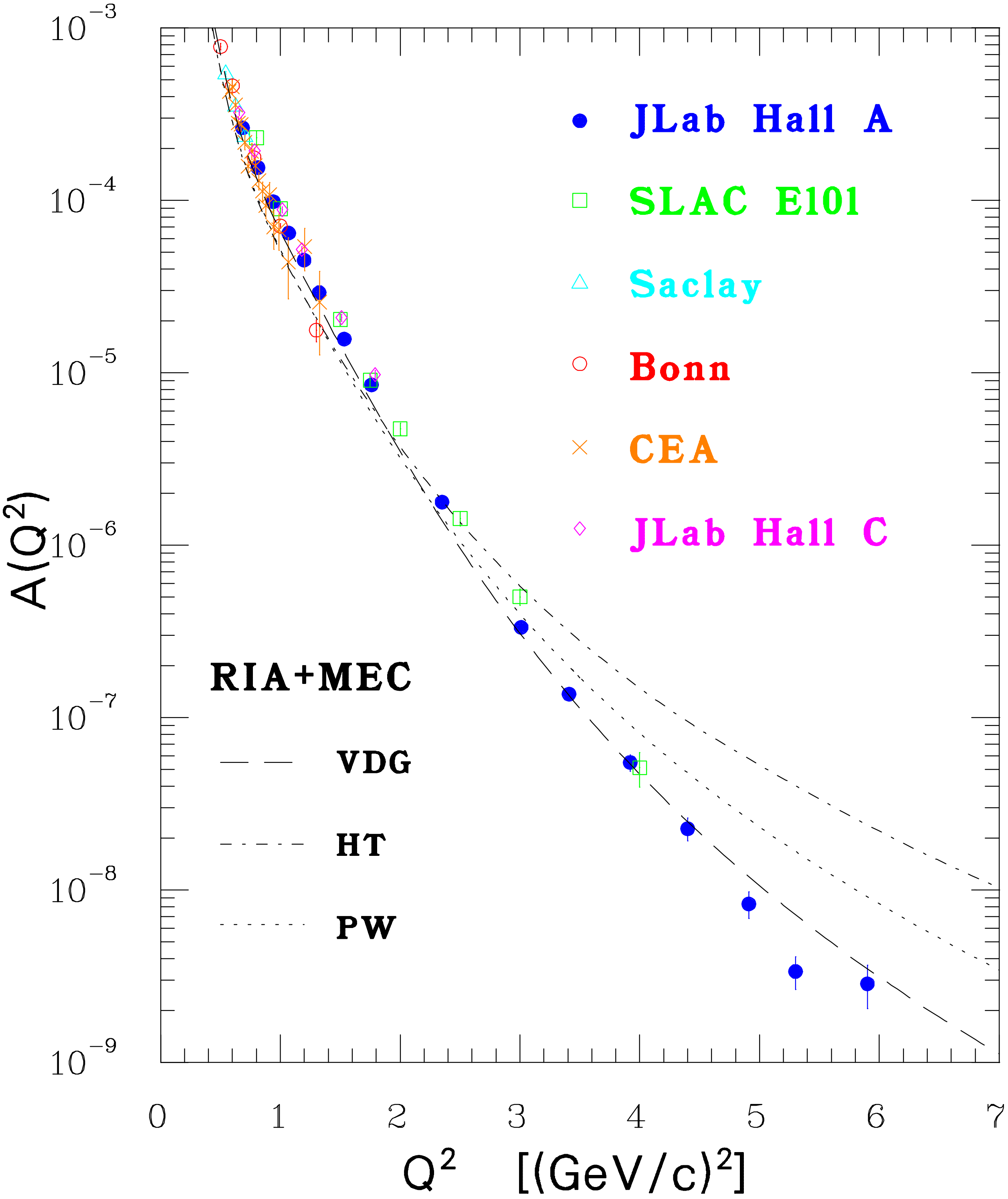
- Dominance of the constituent-interchange force between quarks of different nucleons to share Q/A

- Can this be applicable to the Q^2 range accessible by JLab?

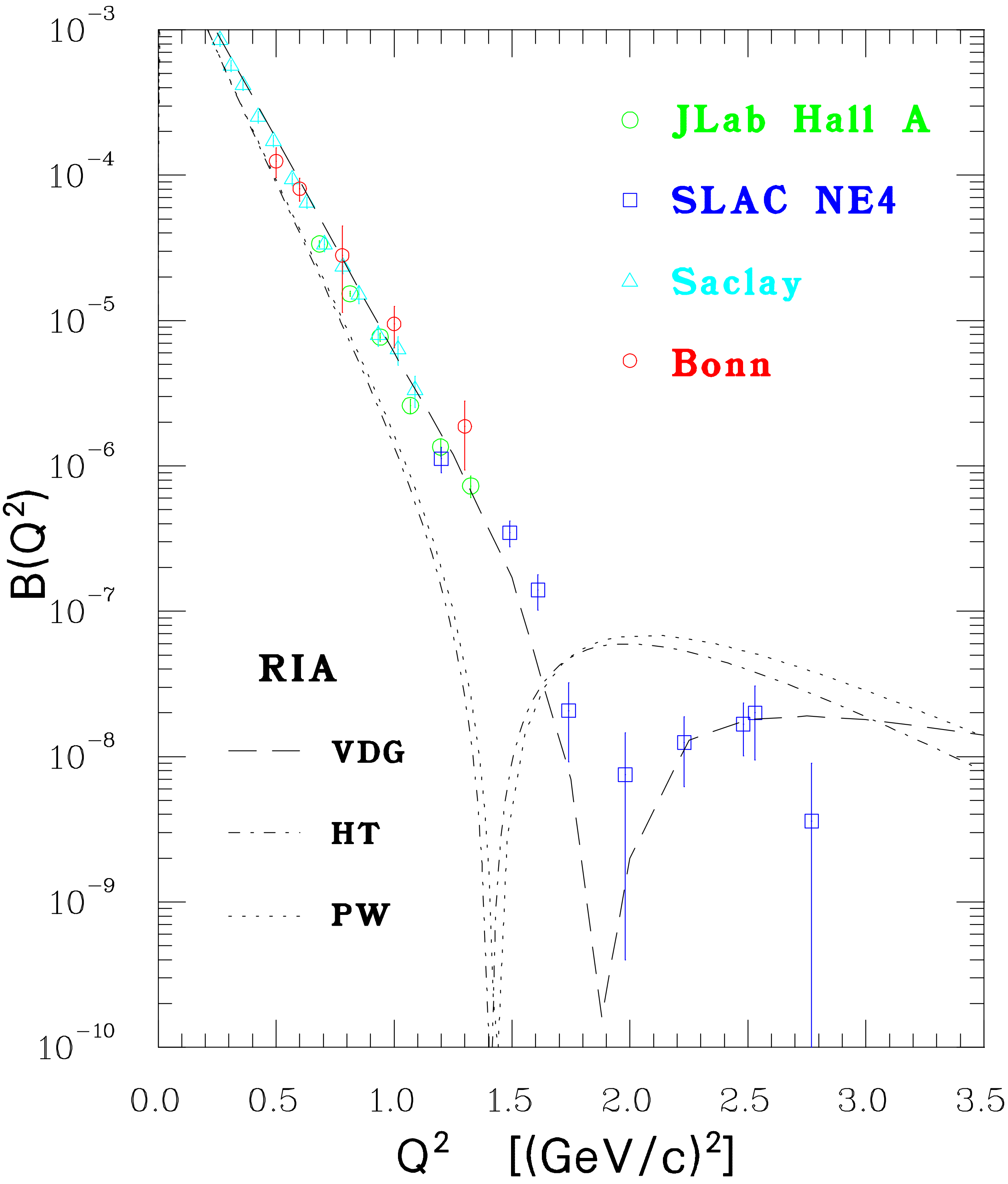

e
e′
q
^{3}He
(p+q)/9
p
p/9
5/9q
p+q
e
e′
q
^{3}He
p/9
q/3
p
p+q
e
e′
q
^{3}He
p/9
q/3
p
q/3
p+q

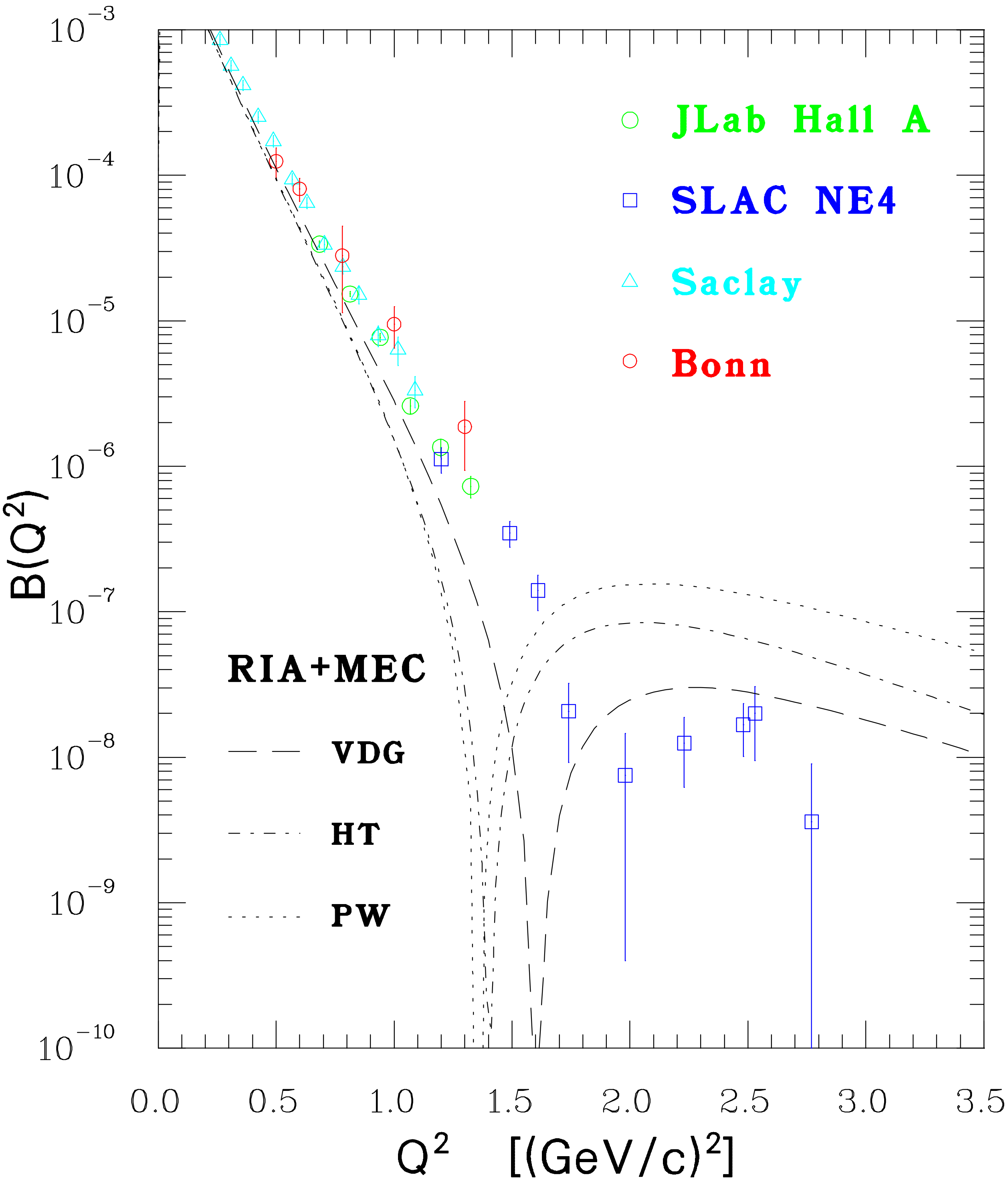


JLab Hall A
SLAC E101
Saclay
Bonn
CEA
JLab Hall C
RIA
VDG
HT
PW
$A(Q^2)$
Q^2 [(GeV/c)^2]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0
1
2
3
4
5
6
7

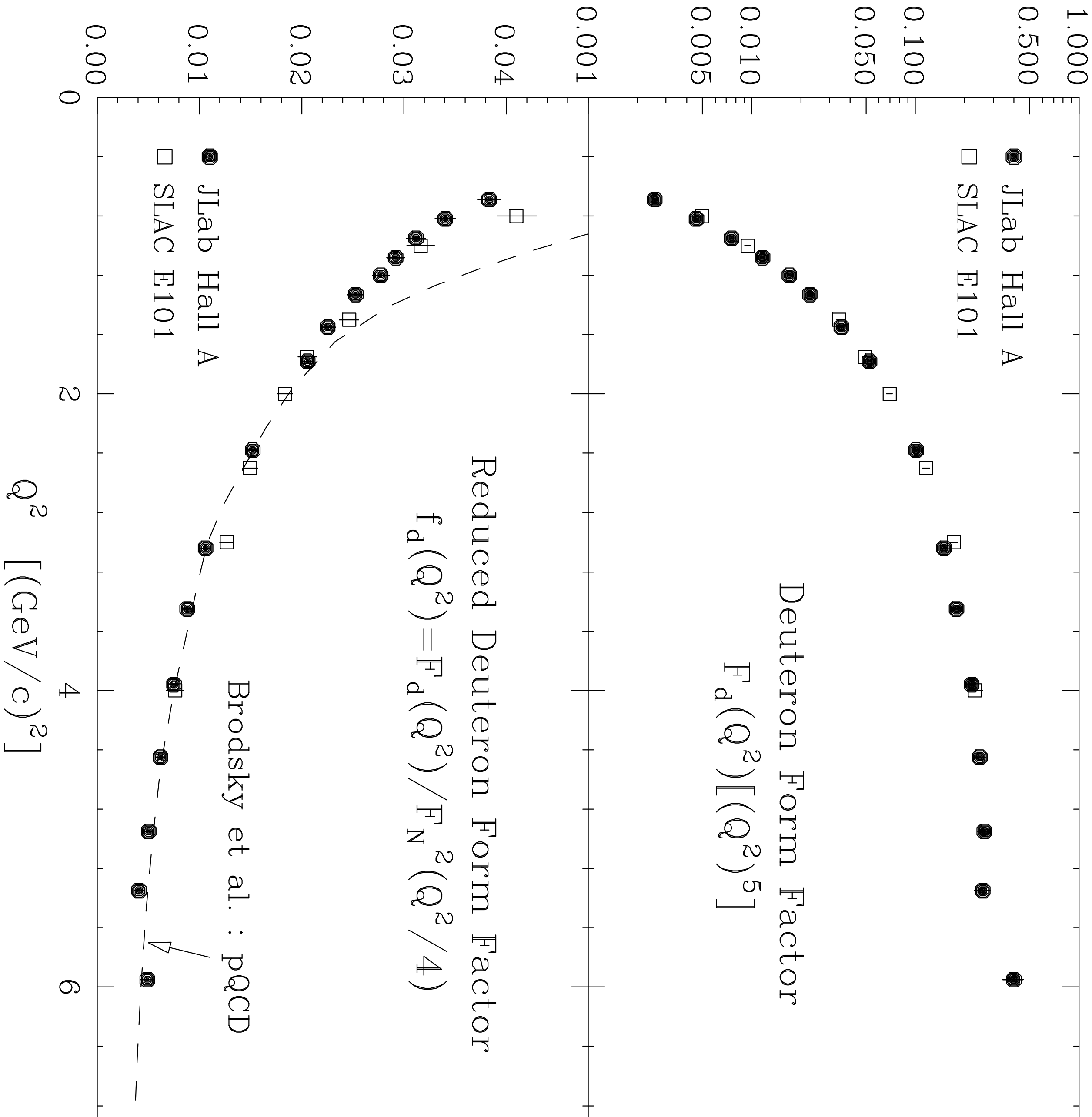


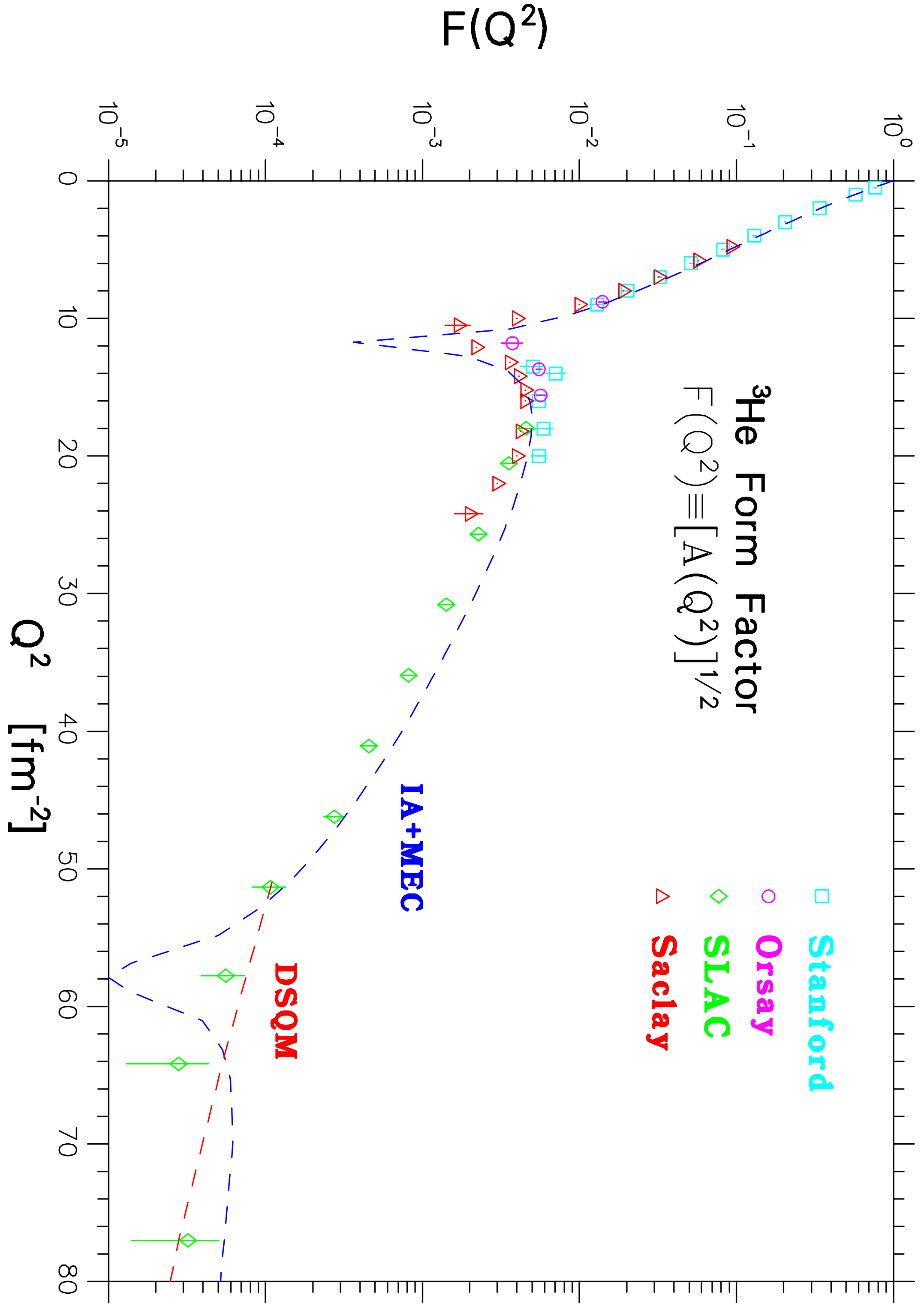
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$A(Q^2)$
0 1 2 3 4 5 6 7
Q^2 [(GeV/c)^2]
JLab Hall A
SLAC E101
Saclay
Bonn
CEA
JLab Hall C
RIA+MEC
VDG
HT
PW


JLab Hall A
SLAC NE4
Saclay
Bonn
RIA
VDG
HT
PW
B(Q^2)
Q^2 [(GeV/c)^2]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

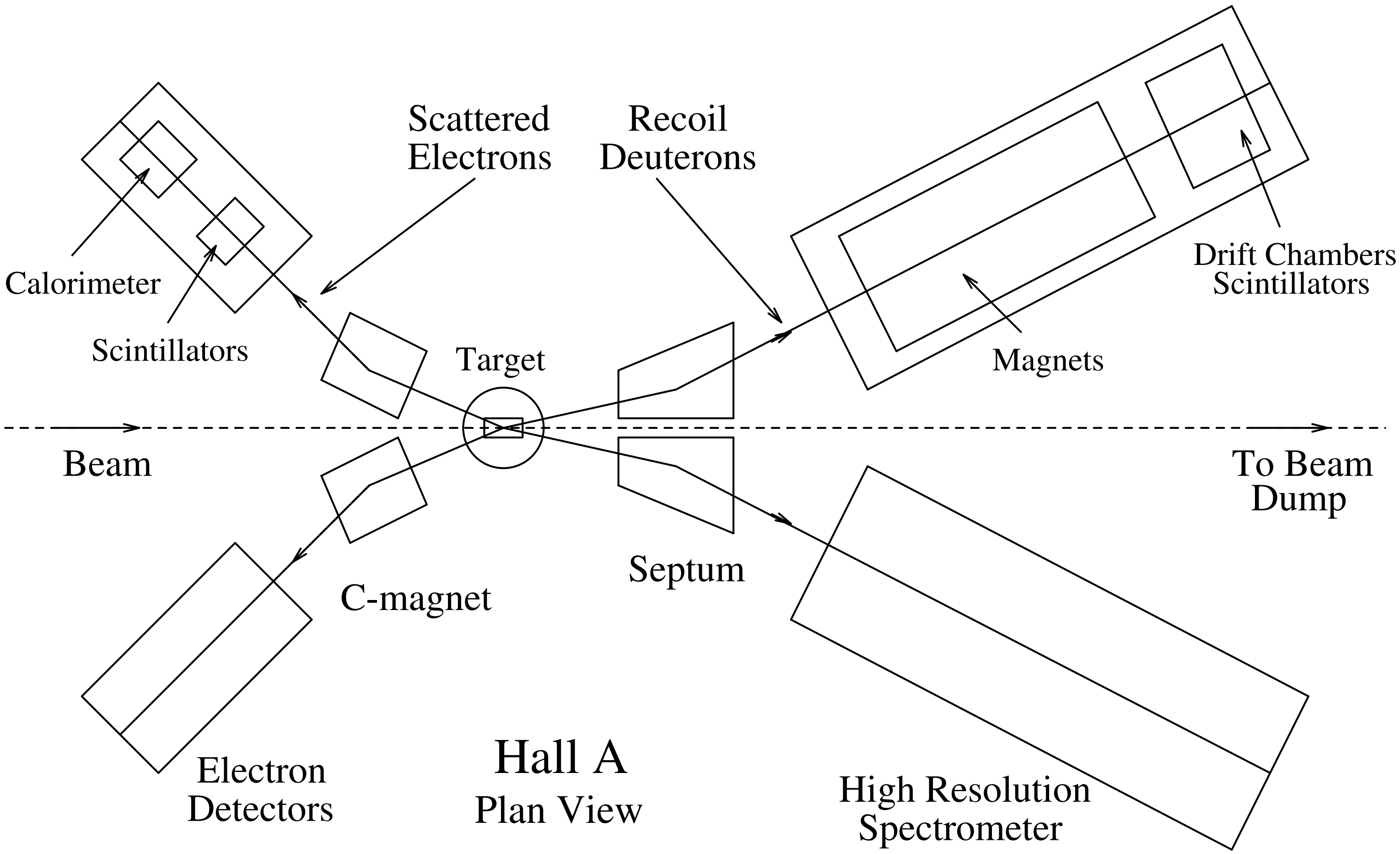


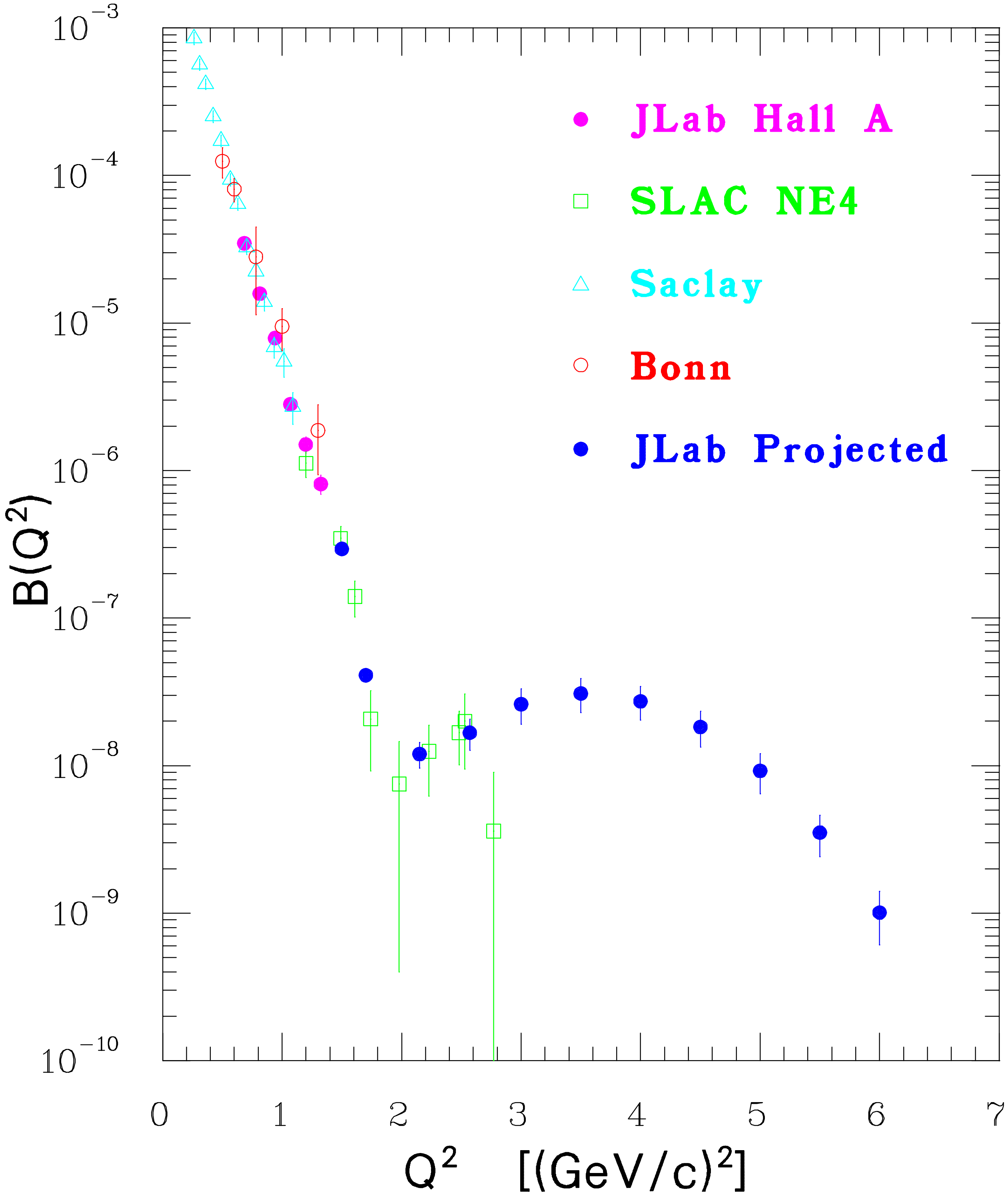
JLab Hall A
SLAC NE4
Saclay
Bonn
RIA+MEC
VDG
HT
PW
B(Q2)
Q2 [(GeV/c)2]


1.000
0.500
0.100
0.050
0.010
0.005
0.001
0.04
0.03
0.02
0.01
0.00
0
2
4
6
JLab Hall A
SLAC E101
Deuteron Form Factor
$F_d(Q^2)[(Q^2)^5]$
JLab Hall A
SLAC E101
Reduced Deuteron Form Factor
$f_d(Q^2)=F_d(Q^2)/F_N^2(Q^2/4)$
Brodsky et al. : pQCD
Q^2 $[(\mathrm{GeV}/c)^2]$



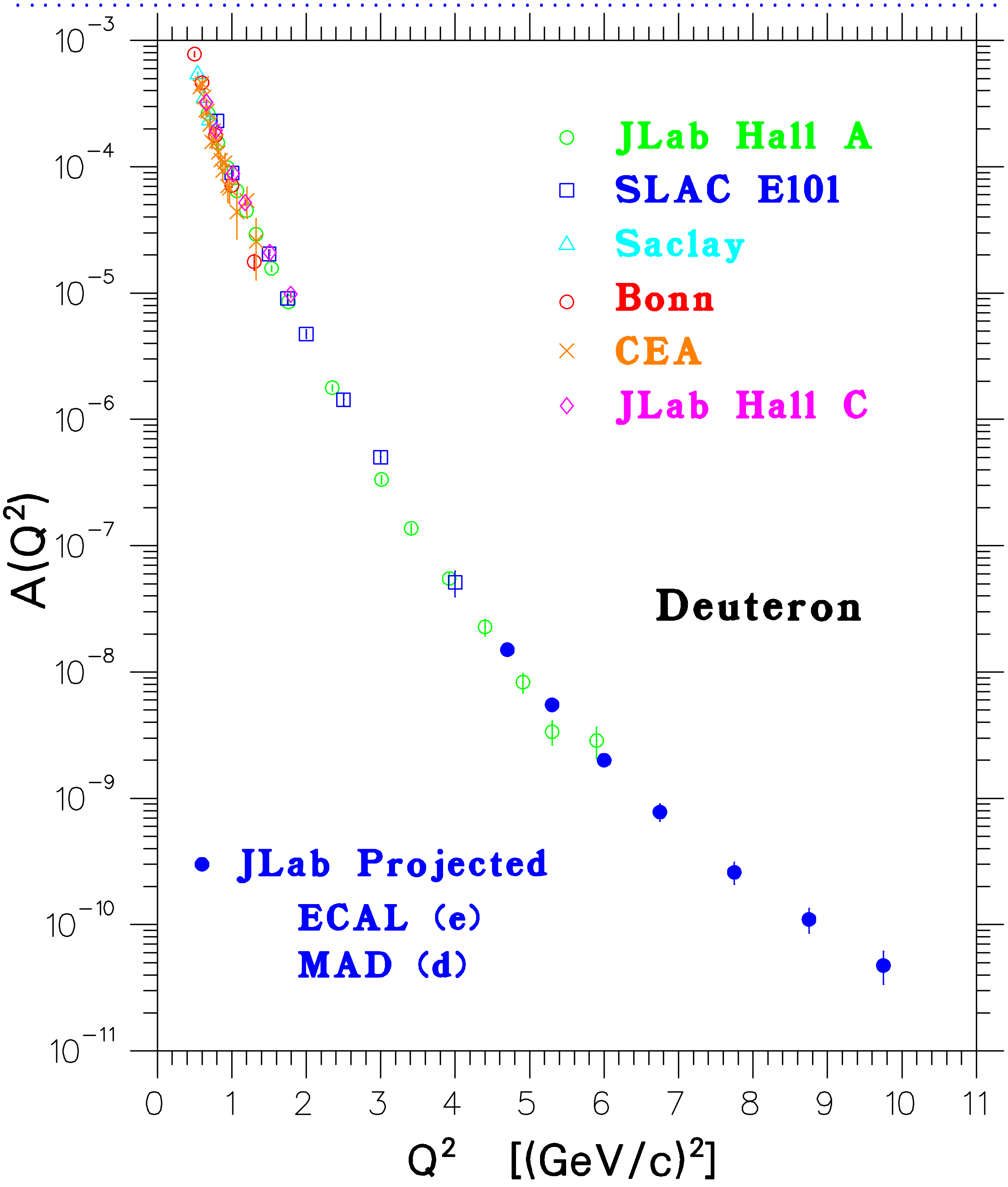
^{3}He Form Factor
$F(Q^2) \equiv [A(Q^2)]^{1/2}$
Stanford
Orsay
SLAC
Saclay
IA+MEC
DSQM
$F(Q^2)$
Q^2 [fm^{-2}]


Scattered
Electrons
Recoil
Deuterons
Calorimeter
Scintillators
Drift Chambers
Scintillators
Magnets
Target
Beam
To Beam
Dump
C-magnet
Septum
Electron
Detectors
Hall A
Plan View
High Resolution
Spectrometer

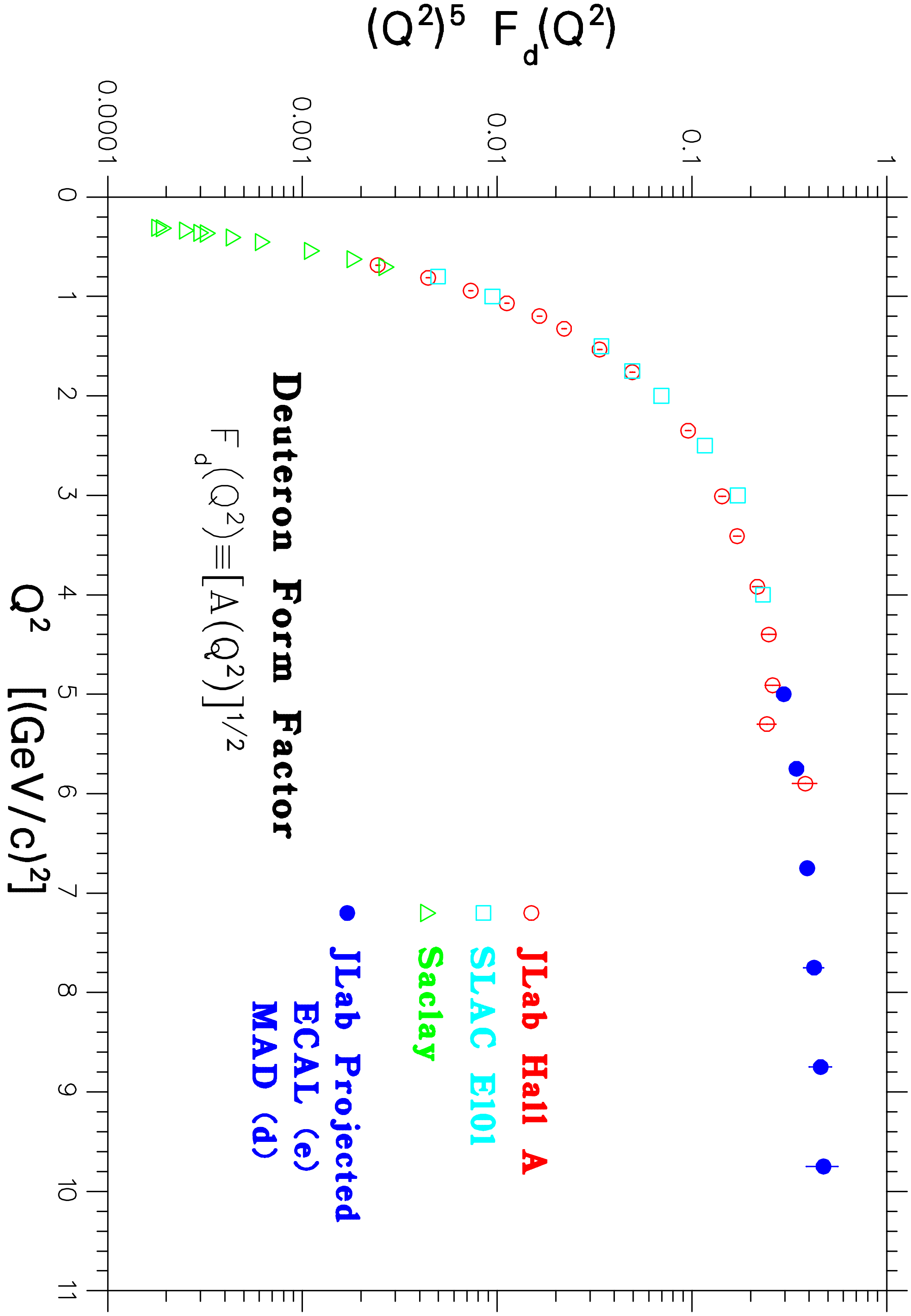

JLab Hall A
SLAC NE4
Saclay
Bonn
JLab Projected
B(Q²)
Q² [(GeV/c)²]
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
0
1
2
3
4
5
6
7

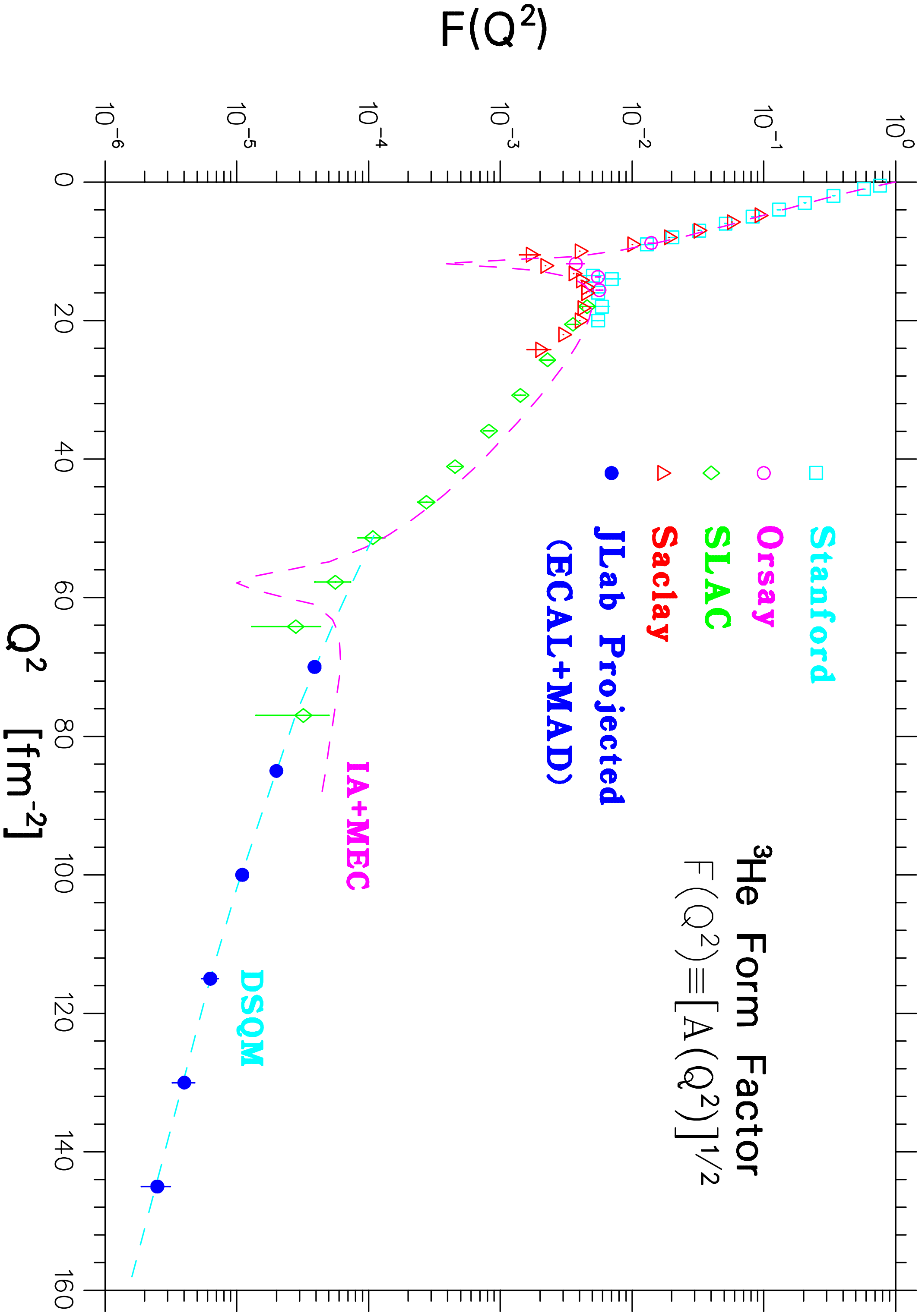
Experimental Apparatus

- Coincidence experiments
- Assume 20 cm targets and 70 μA current
- Assume one month of beam time for deuteron and one month for ^{3}He
- Scenario (1): Hall C
  - Detect electrons in SHMS
  - Detect recoil nuclei in HMS
- Scenario (2): Hall A
  - Detect electrons in electromagnetic calorimeter (ECAL)
  - Detect recoil nuclei in MAD



JLab Hall A
SLAC E101
Saclay
Bonn
CEA
JLab Hall C
Deuteron
JLab Projected
ECAL (e)
MAD (d)
$A(Q^2)$
Q^2 [(GeV/c)^2]


Deuteron Form Factor
$F_d(Q^2) \equiv [A(Q^2)]^{1/2}$
$(Q^2)^5\ F_d(Q^2)$
$Q^2\ [(GeV/c)^2]$
JLab Hall A
SLAC E101
Saclay
JLab Projected
ECAL (e)
MAD (d)
0.0001
0.001
0.01
0.1
1
0
1
2
3
4
5
6
7
8
9
10
11



^{3}He Form Factor
$F(Q^2) \equiv [A(Q^2)]^{1/2}$
Stanford
Orsay
SLAC
Saclay
JLab Projected
(ECAL+MAD)
IA+MEC
DSQM
$F(Q^2)$
Q^2 [fm^{-2}]

Elastic ^{3}H/^{3}He Comparison

- Differences
  - Target density ($F_C,\ F_M$)
  - Magnetic moment (F_M)
  - Atomic number ($F_C,\ F_M$)
  - Beam energy (F_C)
- Figure of merit for ^{3}H:
  - F_M : $\sim$ same as ^{3}He
  - F_C : $\sim 1/5$ of ^{3}He
- Luminosity is sufficient to discover the predicted second diffraction minima of F_C and F_M

Conclusions

- JLab upgrade to 12 GeV ideal to significantly extend the deuteron and ^{3}He form factors at higher Q^2
- A tritium target for DIS measurements will also provide world class data on the tritium form factors* at large Q^2
- MAD and an electromagnetic calorimeter are highly desirable for coincidence measurements
- Test limits of the standard model of the deuteron and three-body systems
- Explore a possible break-down and transition to a quark-gluon description

*J. Calarco, C. Jones, R. Ransome