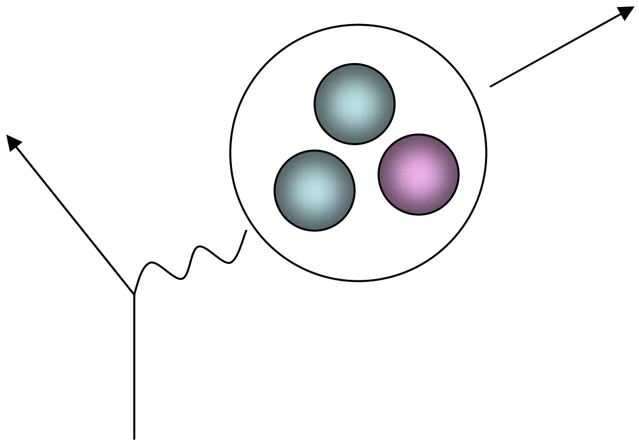

Few body Form Factors

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Hall A Jefferson Laboratory

EINN 2007

10 September 2007

Outline

- Few body form factors
- Deuterium
  - Models
  - Comparison with data
  - New measurements
- Helium 3 and Helium 4
  - Models
  - Comparison He3/He4 data
  - E04-018
- Conclusion

Few body form factors

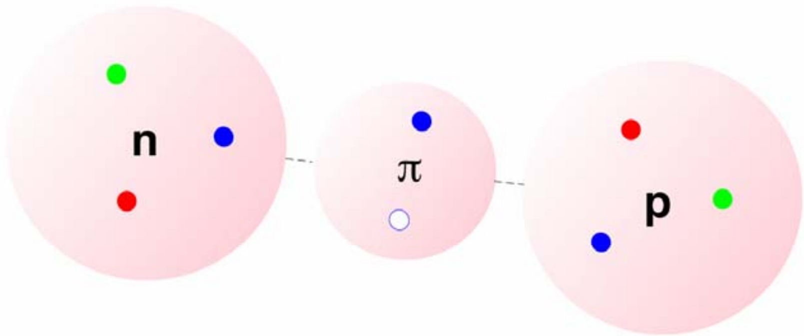
- Few body form factors
  - Study of the nuclear forces within the nucleus
    - 2 nucleon forces with deuterium
    - 3 nucleon forces ^{3}He

- 'ab initio' ("exact") calculations of the structure of few- body nuclei possible:
  - Nucleus has (2,3) nucleons interacting via force described by V_{NN}
  - V_{NN} fit to N-N phase shifts
  - Exchange currents and leading relativistic corrections in V_{NN} and nucleus

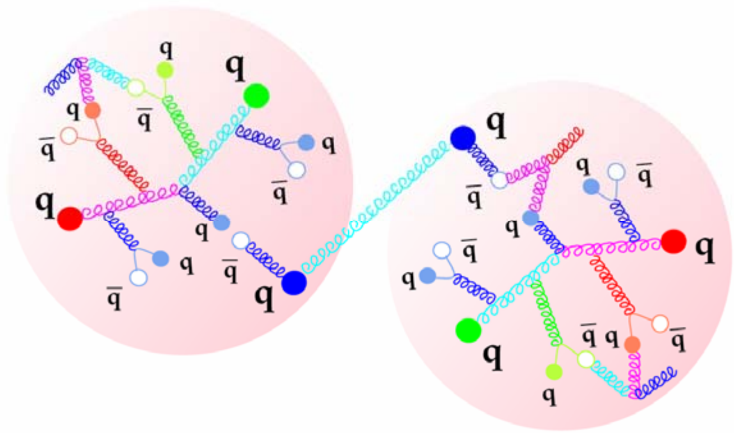
Direct comparison of the data with calculations

- Deuteron:
  - A, B, t_{20} form factors
- He form factors to high Q^2
  - ^{3}He
  - ^{4}He

Case of A=2
Deuteron Structure



Two nucleons interacting via the (pion-mediated) NN force



Two multi-quark systems interacting via the residue of the (gluon-mediated) QCD color force

Deuteron form factors

- Deuteron form factors

$$\frac{d\sigma}{d\Omega} = \sigma_M \left[A(Q^2) + B(Q^2)\tan^2\left(\frac{\theta}{2}\right) \right]$$

$$\sigma_M = \frac{\alpha^2 E' \cos^2\left(\frac{\theta}{2}\right)}{4E^3 \sin^4\left(\frac{\theta}{2}\right)} \qquad Q^2 = 4EE' \sin^2\left(\frac{\theta}{2}\right)$$

$$A(Q^2) = F_C^2(Q^2) + \frac{8}{9}\tau^2 F_Q^2(Q^2) + \frac{2}{3} F_M^2(Q^2)$$

$$B(Q^2) = \frac{4}{3}\tau F_M^2(Q^2) \qquad \textit{with} \qquad \tau = Q^2 / 4M_d^2$$

Polarizabilities observables

$$\sigma(\theta,\phi)=\sigma_0(\theta)\left(1+t_{20}T_{20}+2t_{21}T_{21}\cos\phi+2t_{22}T_{22}\cos 2\phi\right)$$

$$S=A+B\tan^2(\theta/2)$$

$$f(\theta)=1+2(1+\tau)\tan^2(\theta/2)$$

$$\tau=Q^2/4M_d^2$$

$$t_{20}=\frac{1}{\sqrt{2}S}\left[\frac{8}{3}\tau F_C F_Q+\frac{8}{9}\tau^2F_Q^2+\frac{1}{3}\tau f(\theta)F_M^2\right] \qquad t_{21}=\frac{1}{\sqrt{6}S}\tau\sqrt{\tau(1+f(\theta))}F_M F_Q\sec\frac{\theta}{2}$$

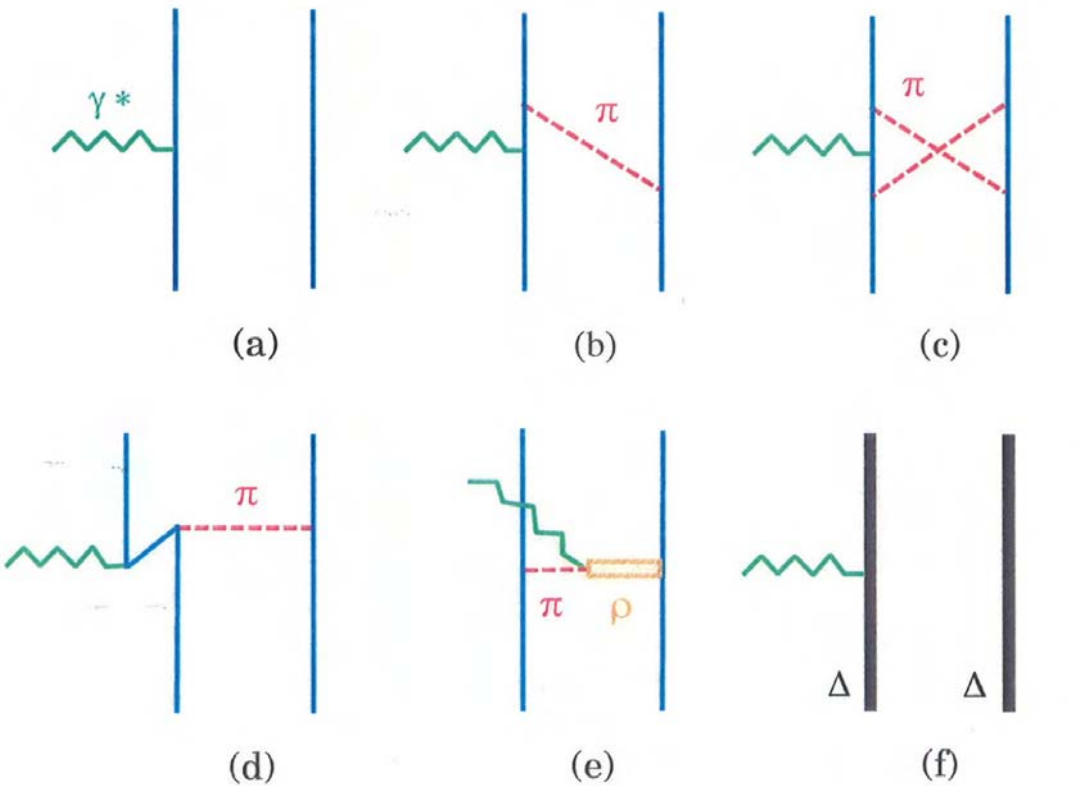
$$t_{22}=\frac{1}{2\sqrt{3}S}\tau F_M^2$$

$$\boxed{\tilde{t}_{20}=\sqrt{2}\,\frac{y(2+y)}{1+2y^2}} \quad with \quad y=\frac{2\tau F_Q}{3F_C}$$

- Neglect angular dependence and F_M contribution in t_{20}
- t_{20} measurement allows to extract the form factors

Deuterium factors non relativistic

- Impulse approximation (IA)
- Meson exchange current (MEC)

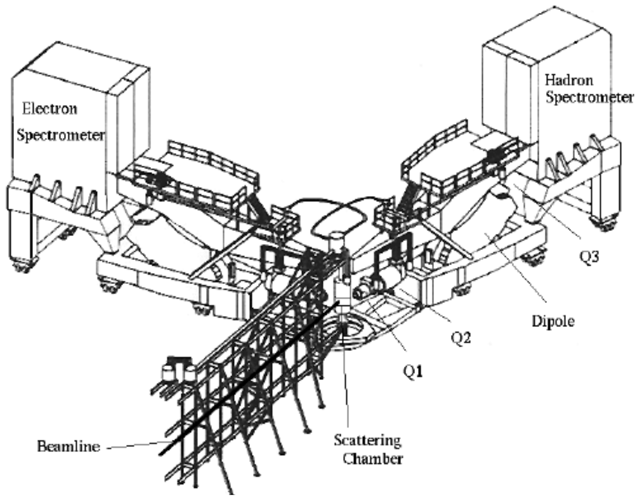


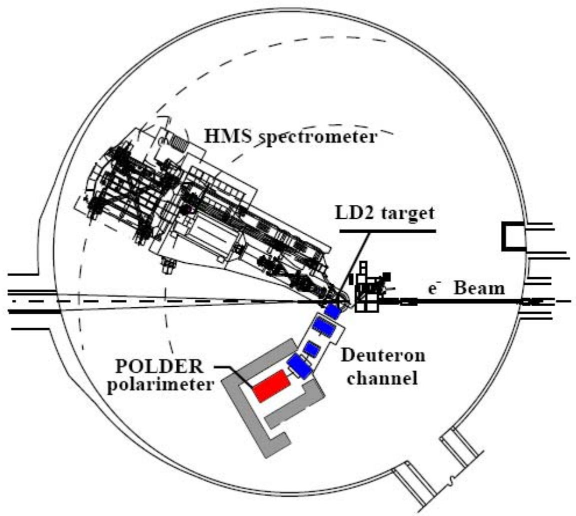
- Models based on the IA and MEC only do not reproduce the data

⇒ Relativistic calculations

Deuterium experimental data

- Deuterium
  - Saclay
  - Bonn
  - Stanford
  - NIKHEF
  - Bates
  - JLAB Hall A
  - JLAB Hall C
    - Polder experiment
  - Mainz





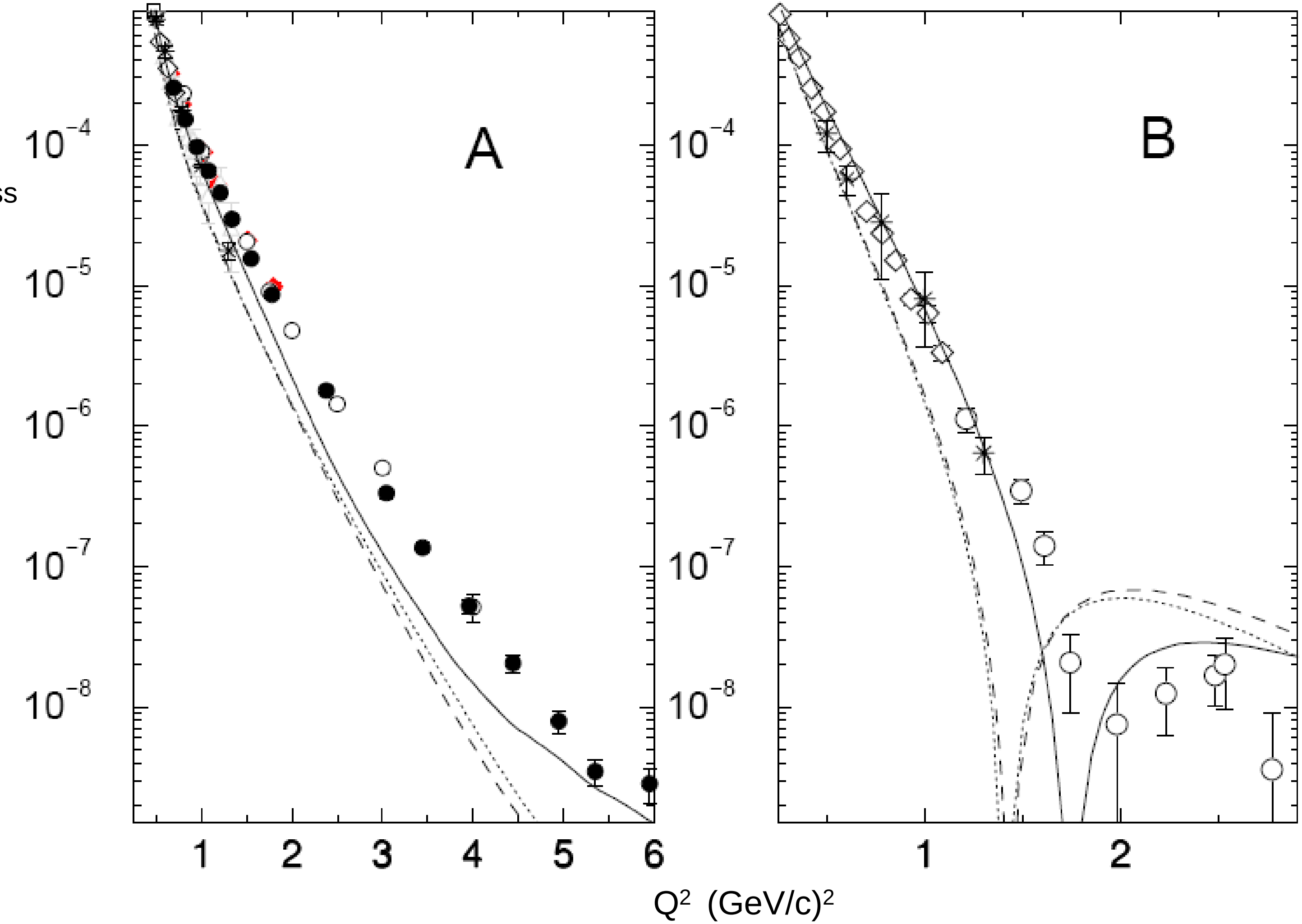
Comparison with models

- Relativistic calculations

Van orden, Devine, Gross (VDG)

Hummel, Tjon (HT)

Phillips, Wallace, Devine (PWD)



Comparison with models

- Relativistic calculations

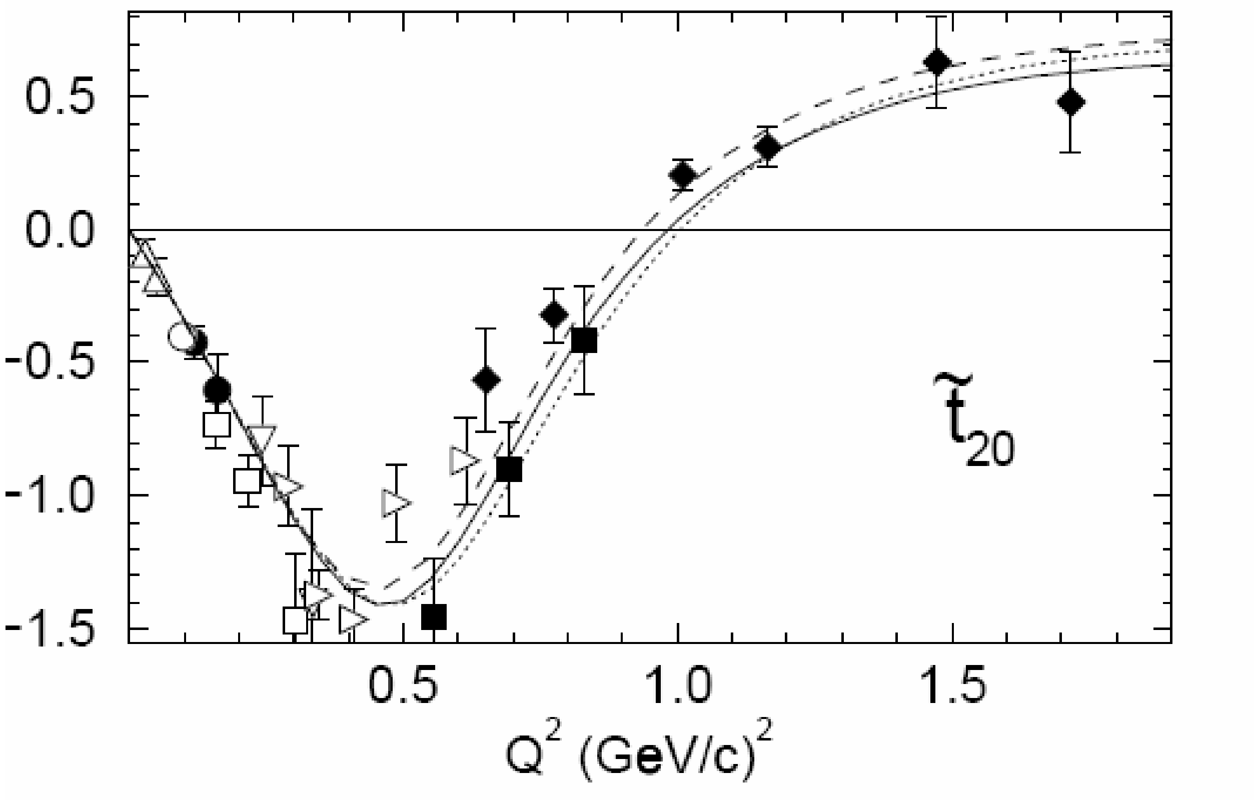
VDG

HT

PWD

Jlab POLDER

Bates



Comparison with models

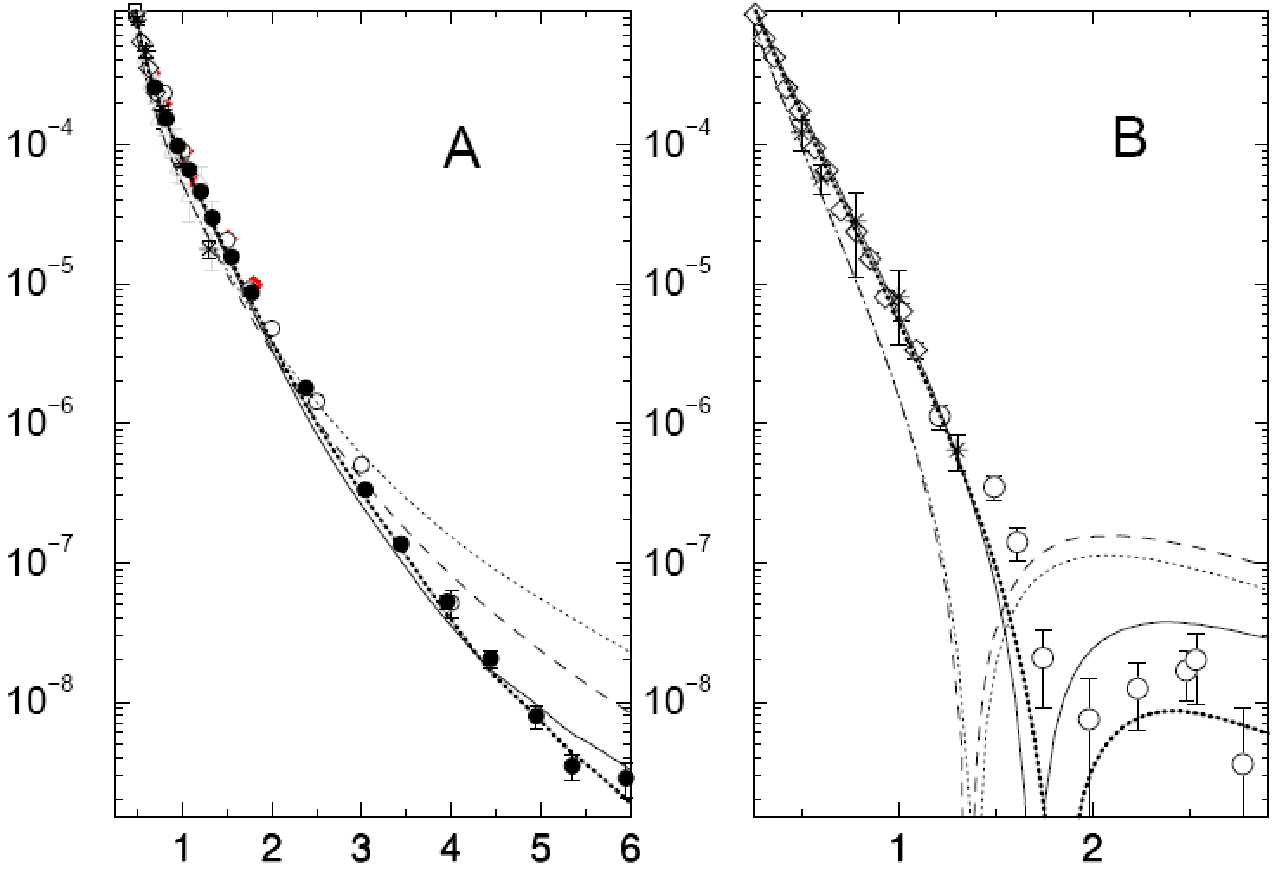
- Relativistic models with MEC

VDG

HT

PWD

Alternate VDG



Comparison with model

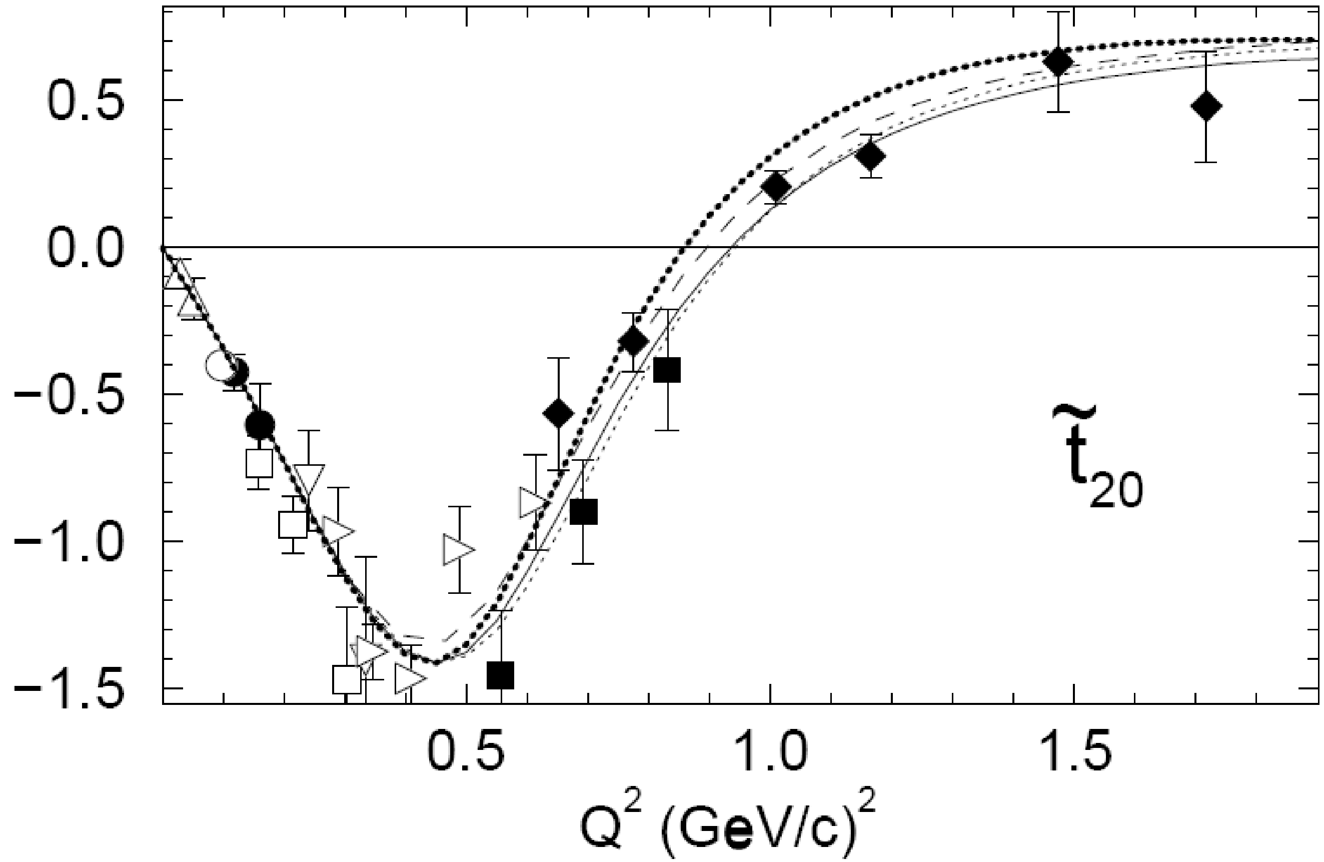
- With MEC

VDG

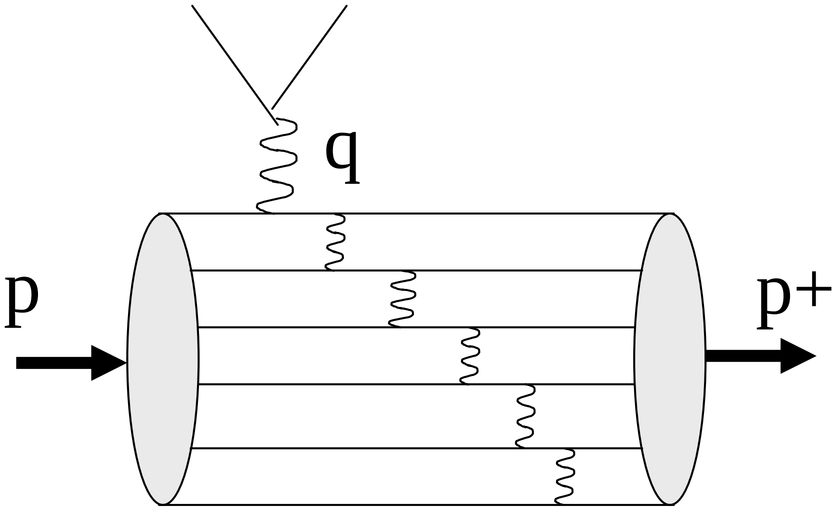
HT

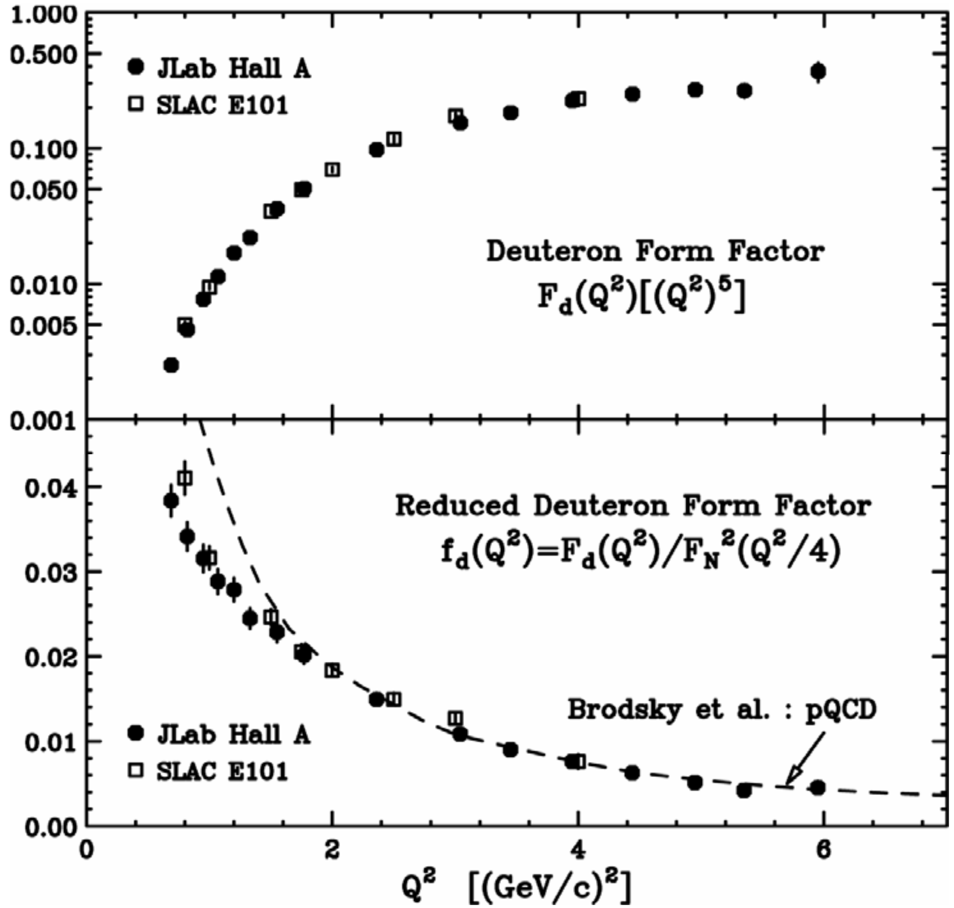
PWD

Alternate VDG



pQCD Counting Rules





Dimensional Scaling Quark Model

$$\sqrt{A} \sim (Q^2)^{-(n-1)} \qquad n = 6 \quad \text{quarks}$$

Perturbative QCD

$$\sqrt{A} = \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5 \sum_{m,n} d_{mn} \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-\gamma_n-\gamma_m}$$

Data indicate that pQCD scaling is fulfilled for $Q^2 > 5$ GeV^2

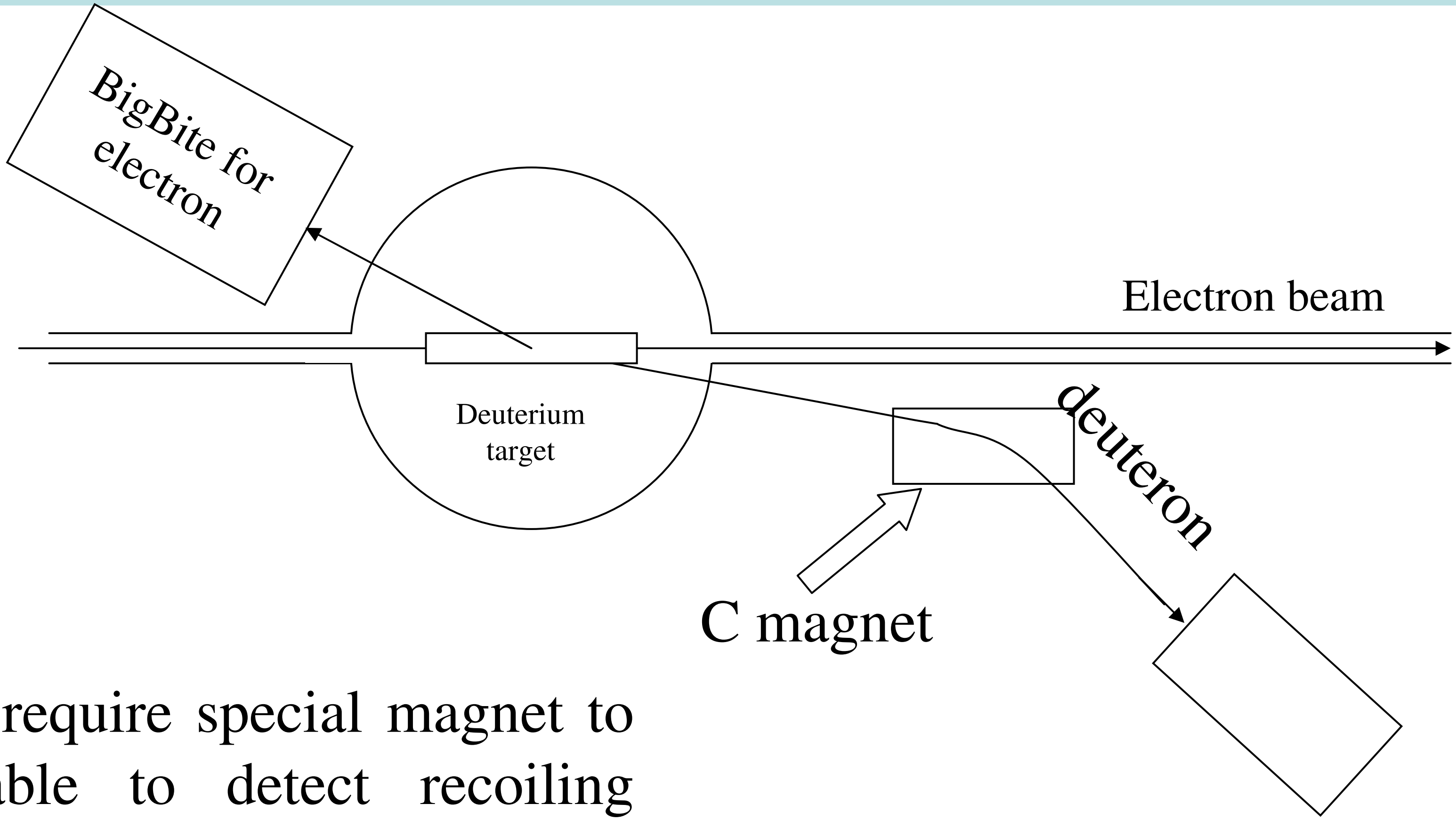
Deuteron form factors

- Models successfully predict $A(Q^2)$
- T_{20} measurement allows separation
- $B(Q^2)$ discrepancy with the models and poor statistical accuracy and larger Q^2 range is very sensitive to models

⇒

New proposal in Hall A
for large Q^2

Deuteron form factors

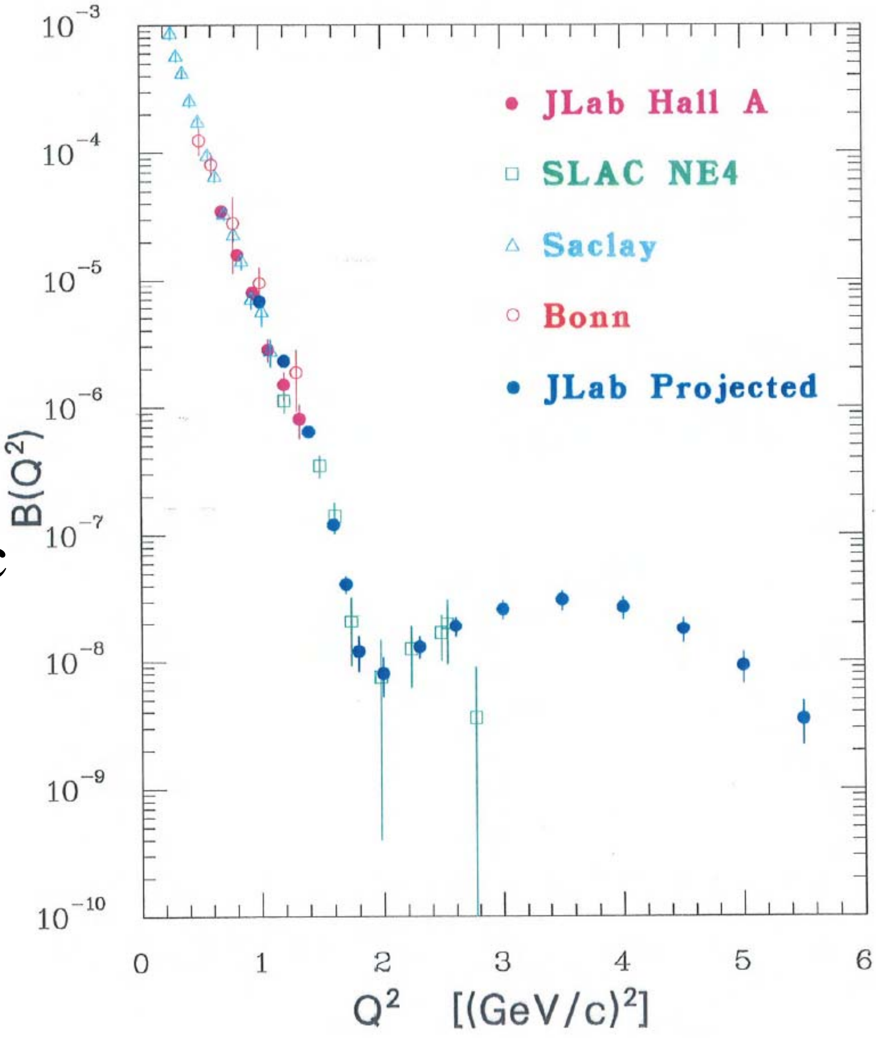


Will require special magnet to be able to detect recoiling nucleus at very forward angles

High resolution spectrometer

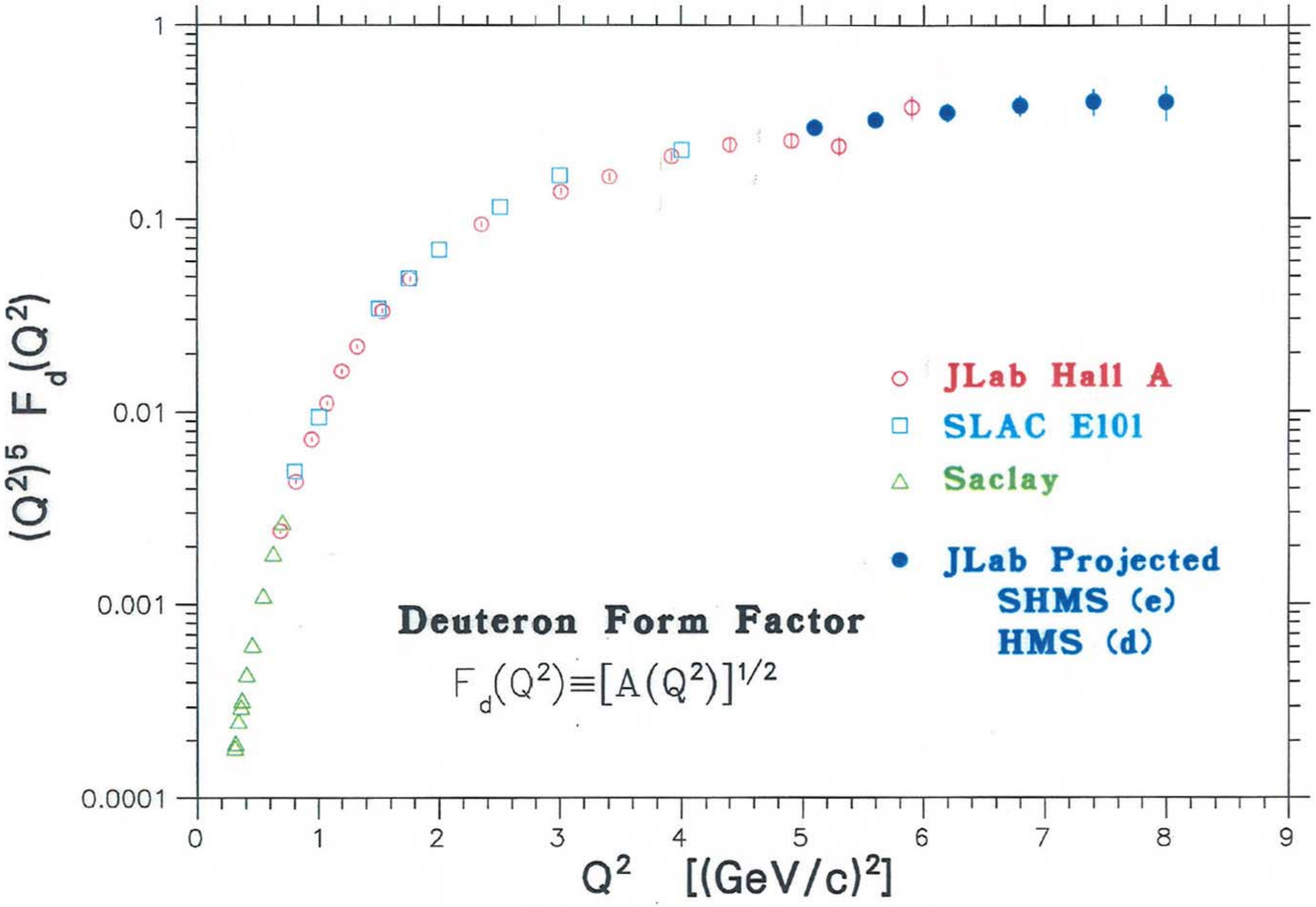
Deuteron form factors

New proposal will be submitted to upcoming JLab PAC to more than double the available Q^2-range for the deuteron magnetic form factor



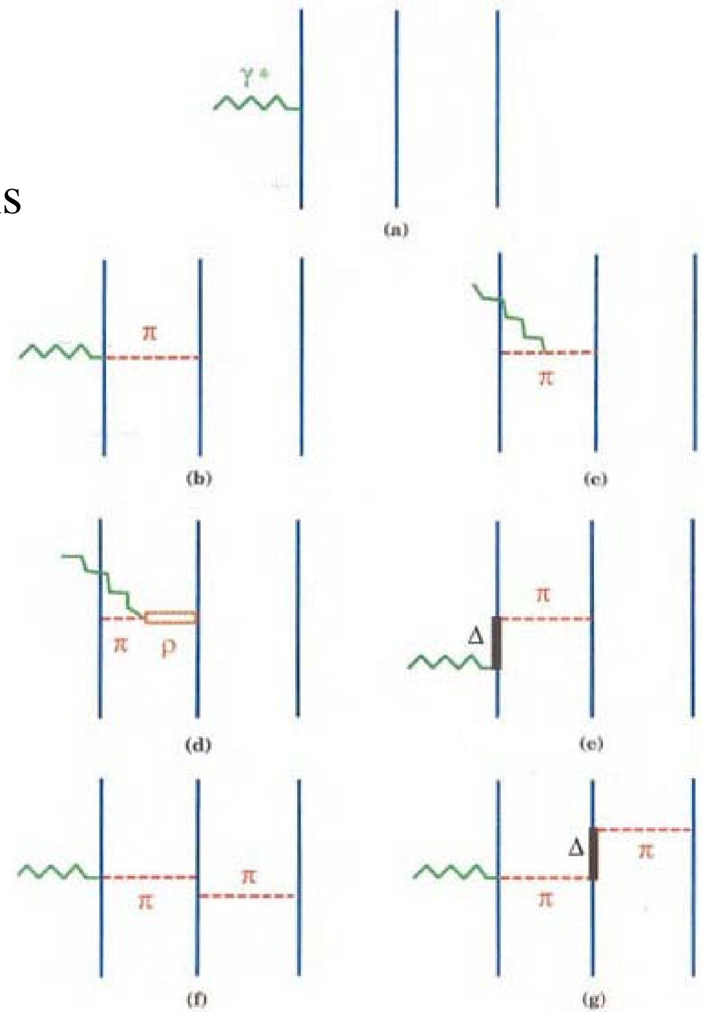
Deuteron form factors

- 12 GeV upgrade Hall C



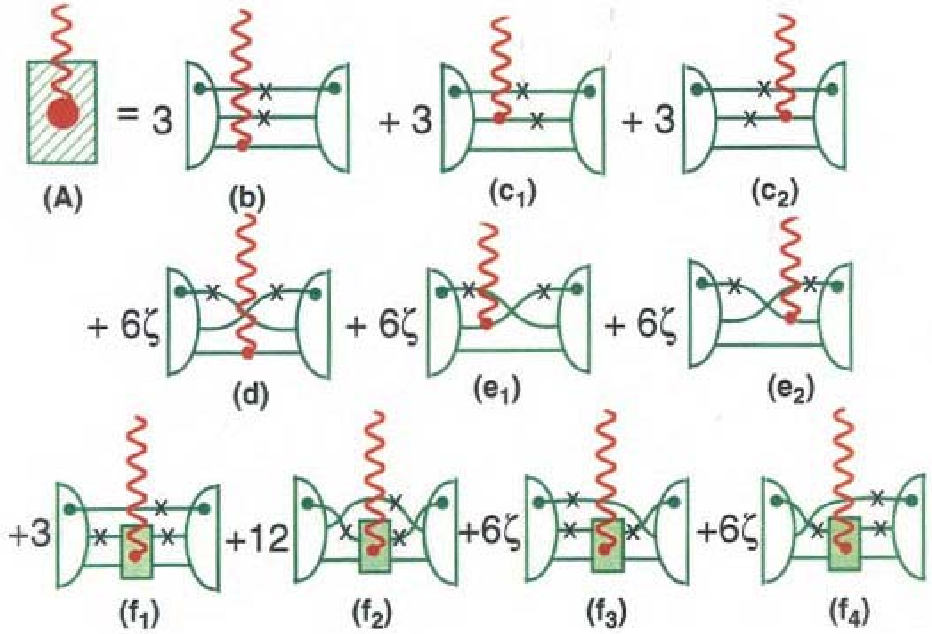
Case A=3,4
The Three- and Four-Body "Standard Model"

- Non-Relativistic Impulse Approximation
- Solve the nuclear ground state using:
  - Numerical solutions of Faddeev equations
  - Correlated Hyperspherical Harmonics
  - Monte Carlo methods
    - Variational Monte Carlo (VMC)
    - Green's Function Monte Carlo (GFMC)
- Relativistic corrections
  - Darwin-Foldy
  - Spin-orbit
- "Standard Model" to be challenged soon by the three-body covariant Bethe-Salpeter relativistic model by Gross and collaborators



Beyond the Impulse Approximation

- IA alone can not describe the few-body form factor data
- Position of first diffraction minimum and height of second maximum
- 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 at low Q^2
- Multi-quark admixtures in nuclear wave function



Few body form factors for He

- ^{3}He

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

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

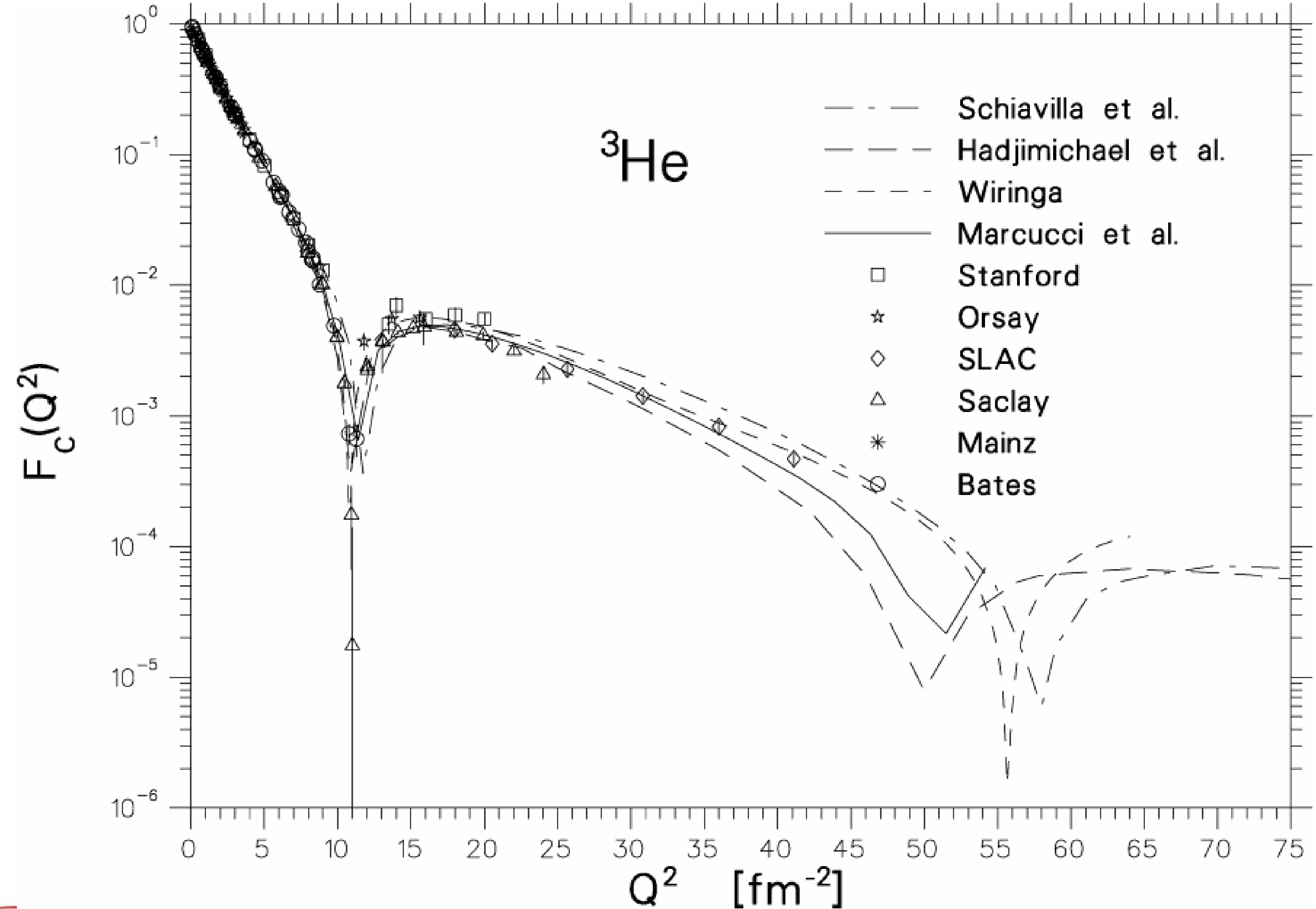
$$B(Q^2) = 2\tau\mu^2 F_M^2(Q^2)$$

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

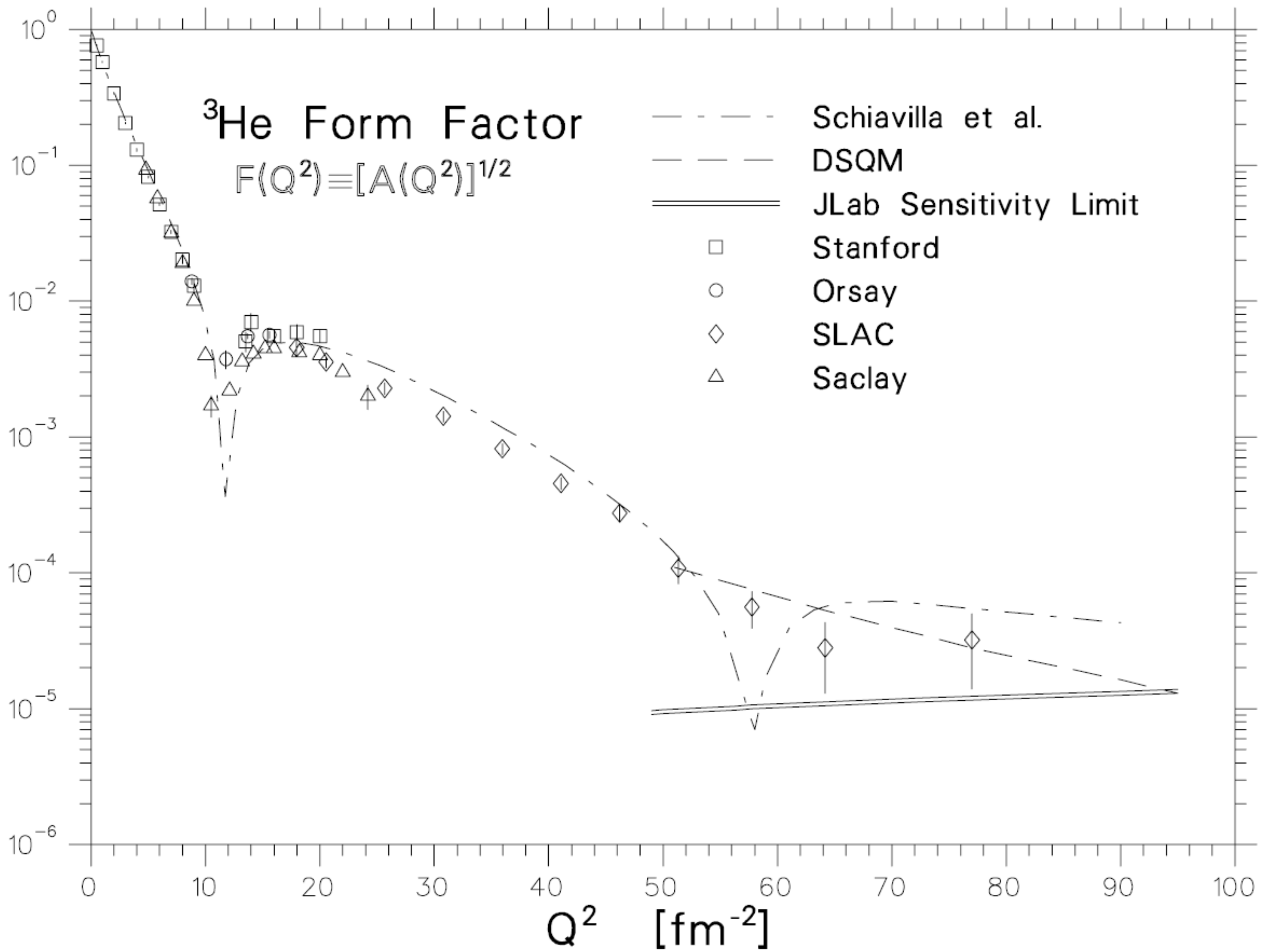
- ^{4}He

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

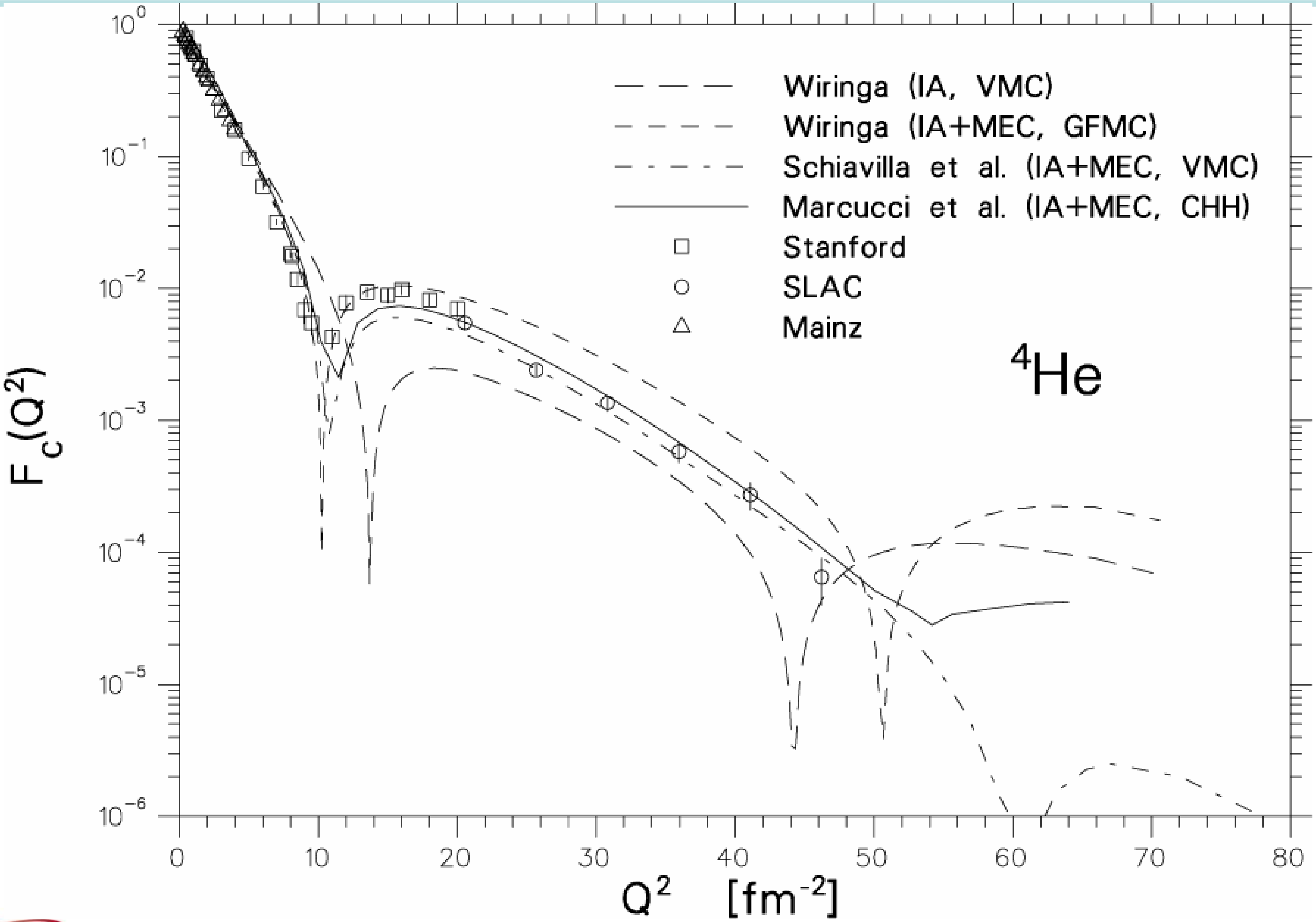
Existing data



Existing data



Existing data



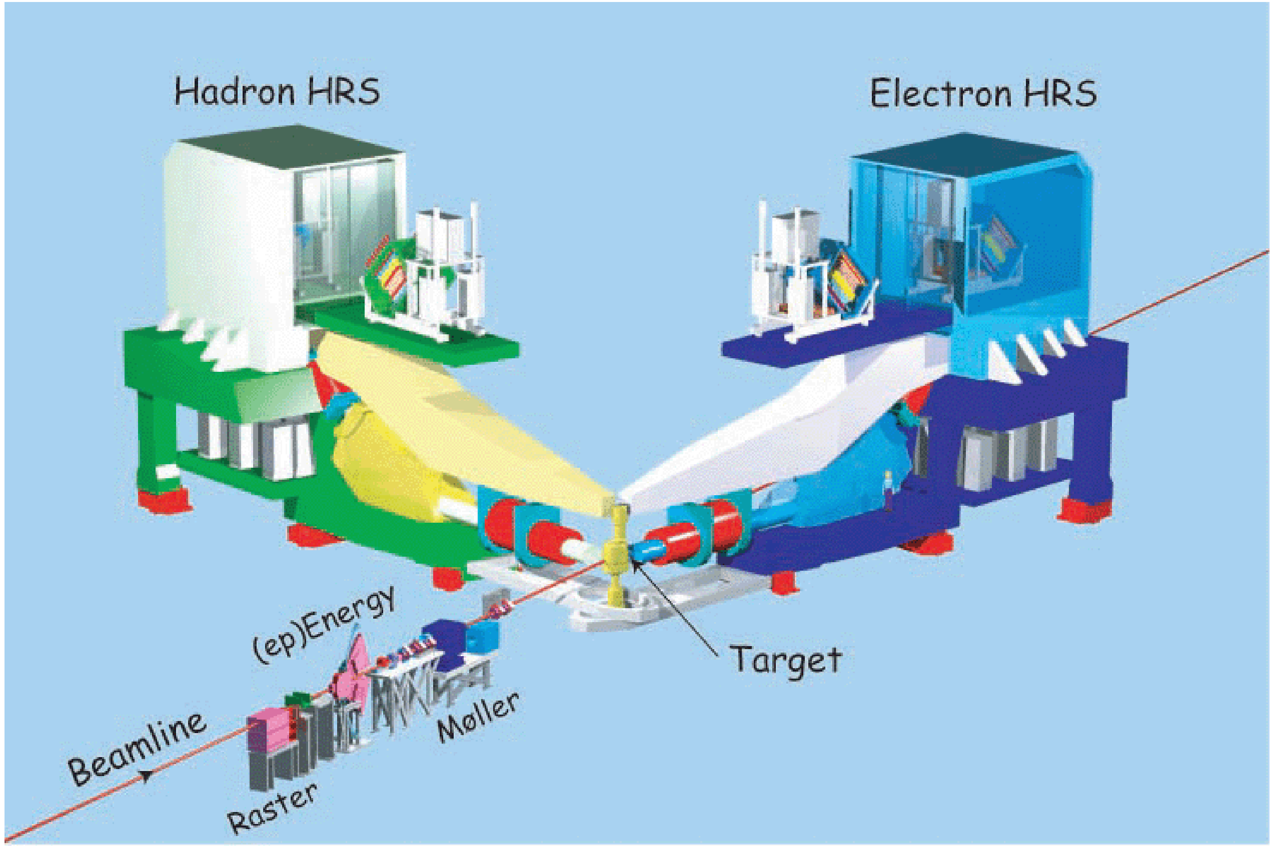
Few body for factors

- E04018 experiment in Hall A 2006/2007
- Forward and backward measurement to separate
- High luminosity
- ^{3}He and ^{4}He measurement
- Use both HRS in coincidence to get elastic signal out of background
  - Time of flight
  - Energy loss in scintillator
  - Kinematical correlation

JLab Hall A

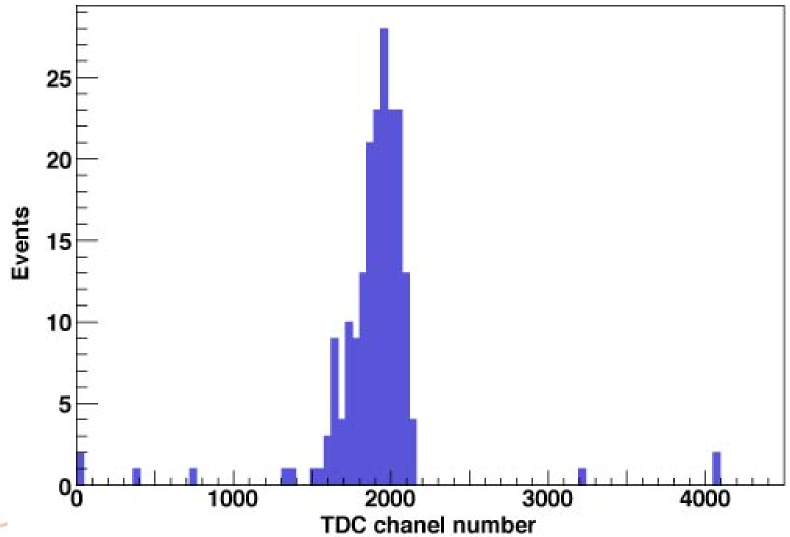
Two High Resolution Spectrometers

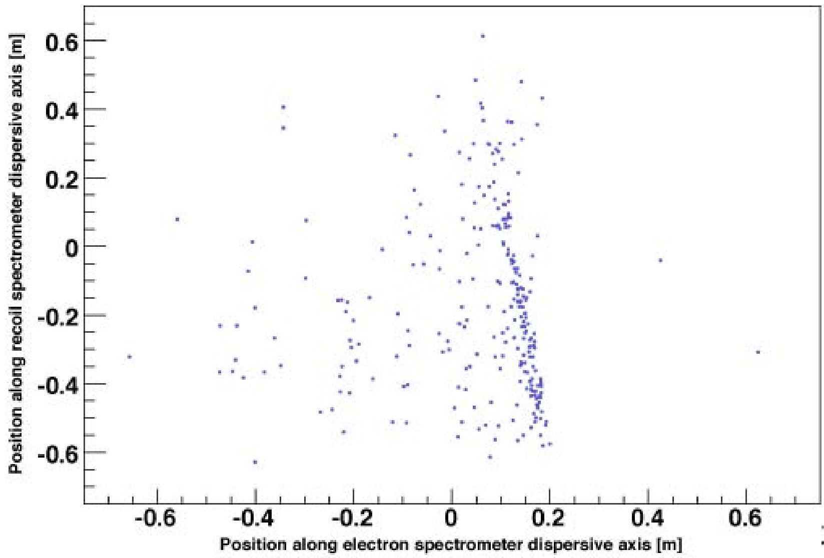
p_{max}	4 GeV/c
momentum resolution	10^{-4}
solid angle	6 msr



Experimental Details

- 20 cm long targets operated at 8K
- Beam current of up to 100 μA, corresponding to luminosity of 2.10^{38} nuclei/cm^2/s
- Allowing cross section to be measured as small as 2.10^{-41} cm^2/sr
- Beam energy from 0.7 to 4.4 GeV, covering Q^2 from 1.5 (0.6) to 4 (5) GeV^2 for ^{3}He (^{4}He) with 3 angle settings for Rosenbluth separation on ^{3}He
- Scattered electron and recoiling nucleus detected in coincidence

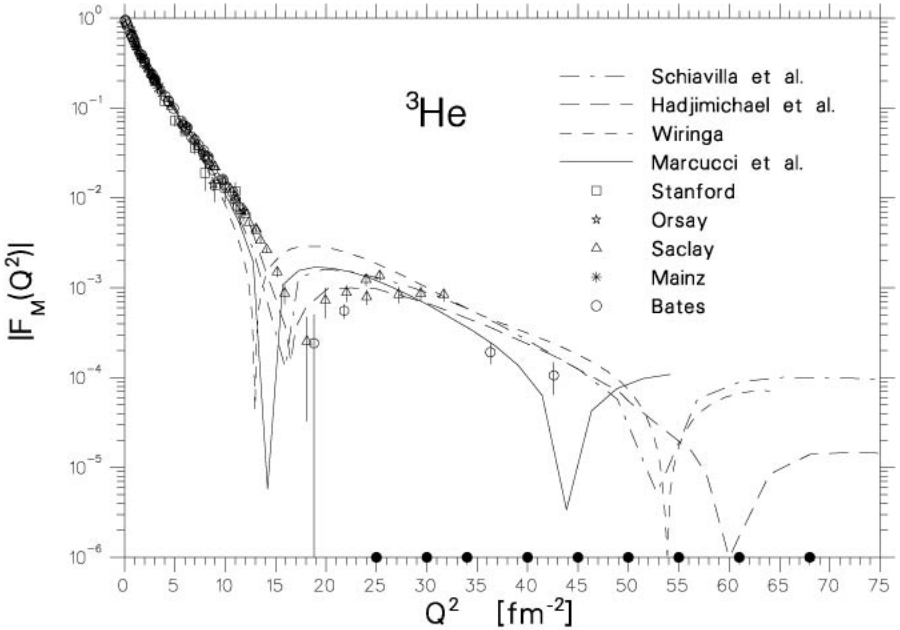


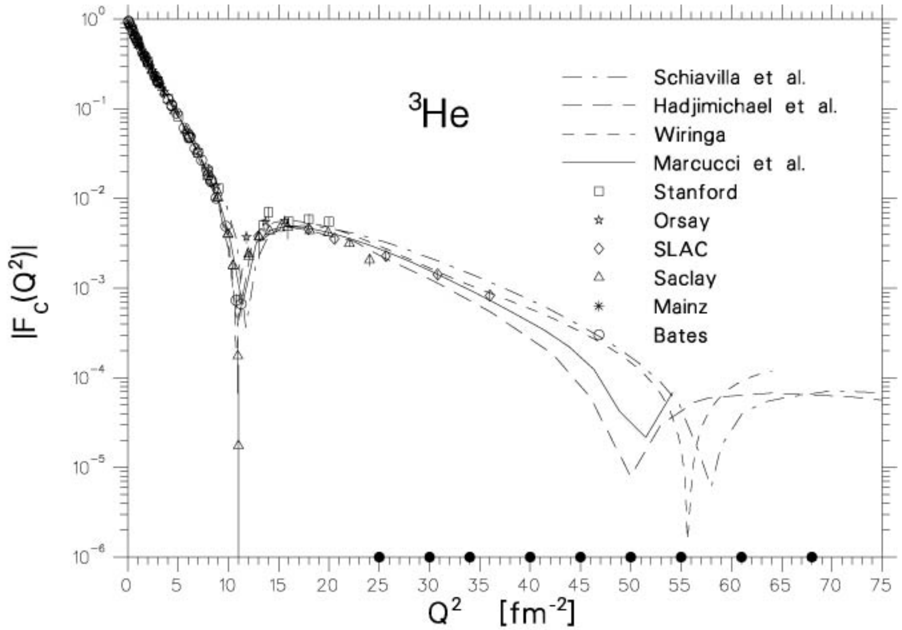


Jefferson Lab

JSA

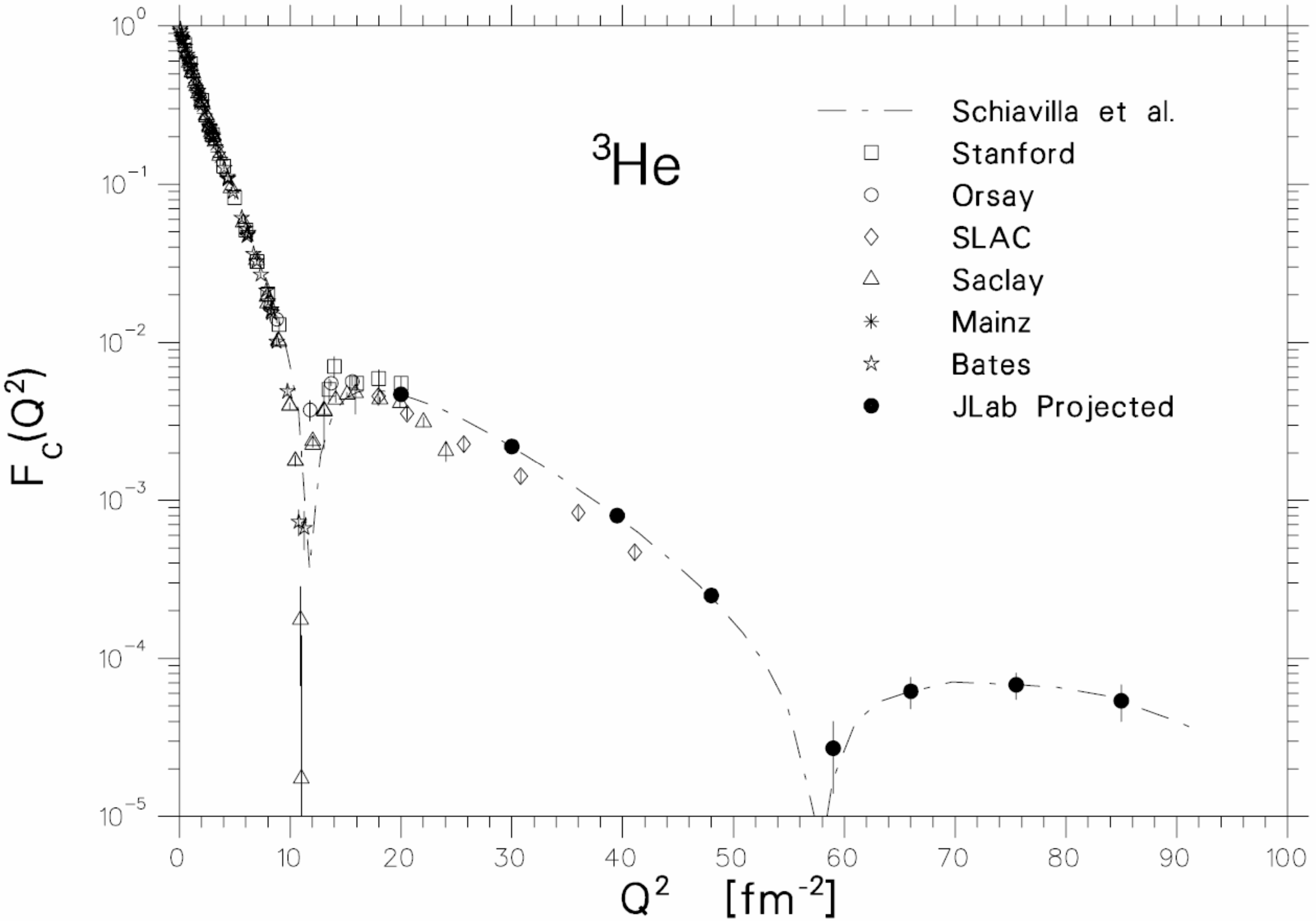
Results for ^{3}He





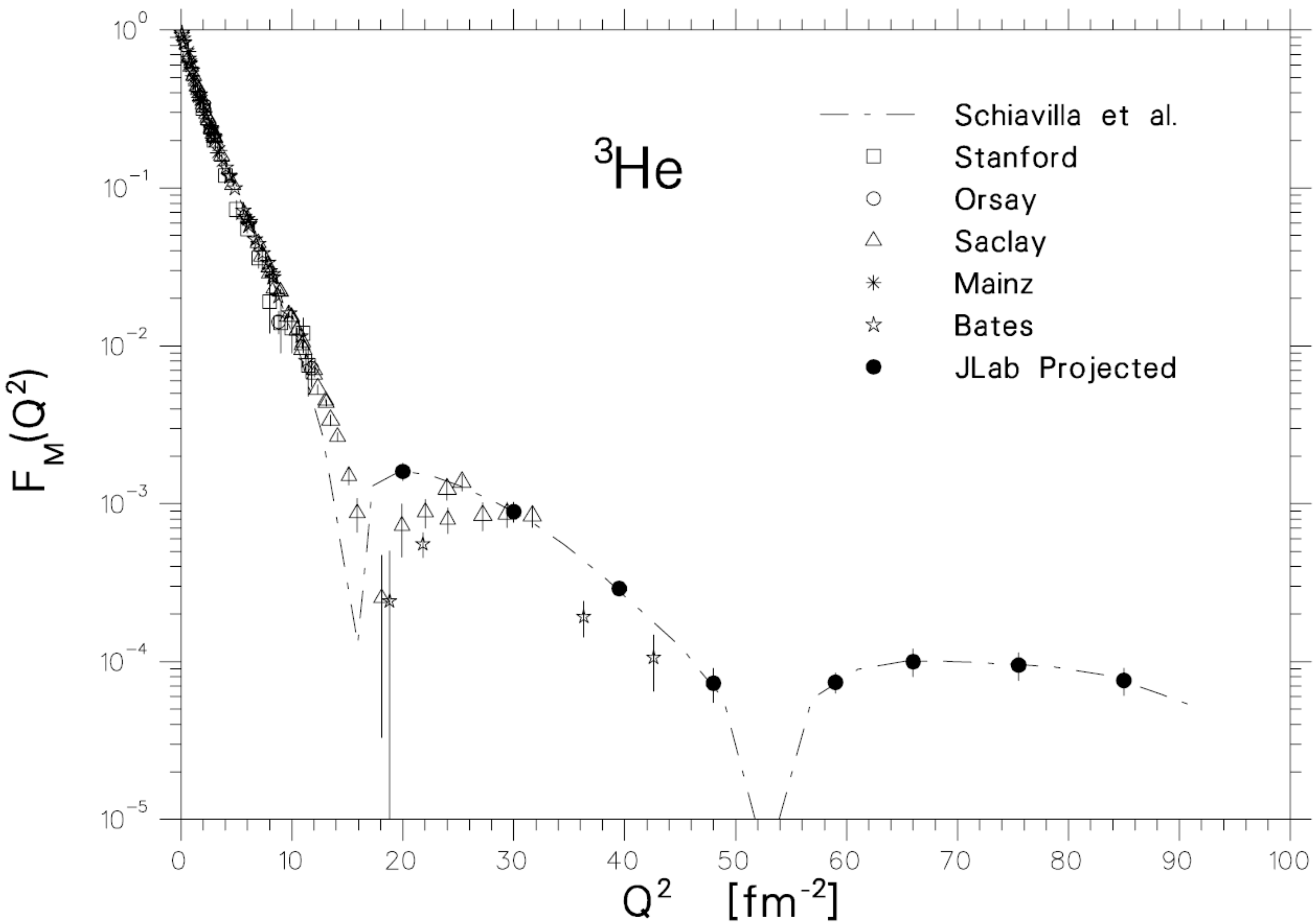
- New data nearly double the available Q^2-range
- Preliminary data indicate diffraction minimum at ~ 55 fm^{-2}
- Will provide sensitive tests to available model calculations
  - Schiavilla IA + MEC - Wiringa VMC
  - Hadjimichael IA + MEC - Marcucci CHH variational method

^{3}He E04-018



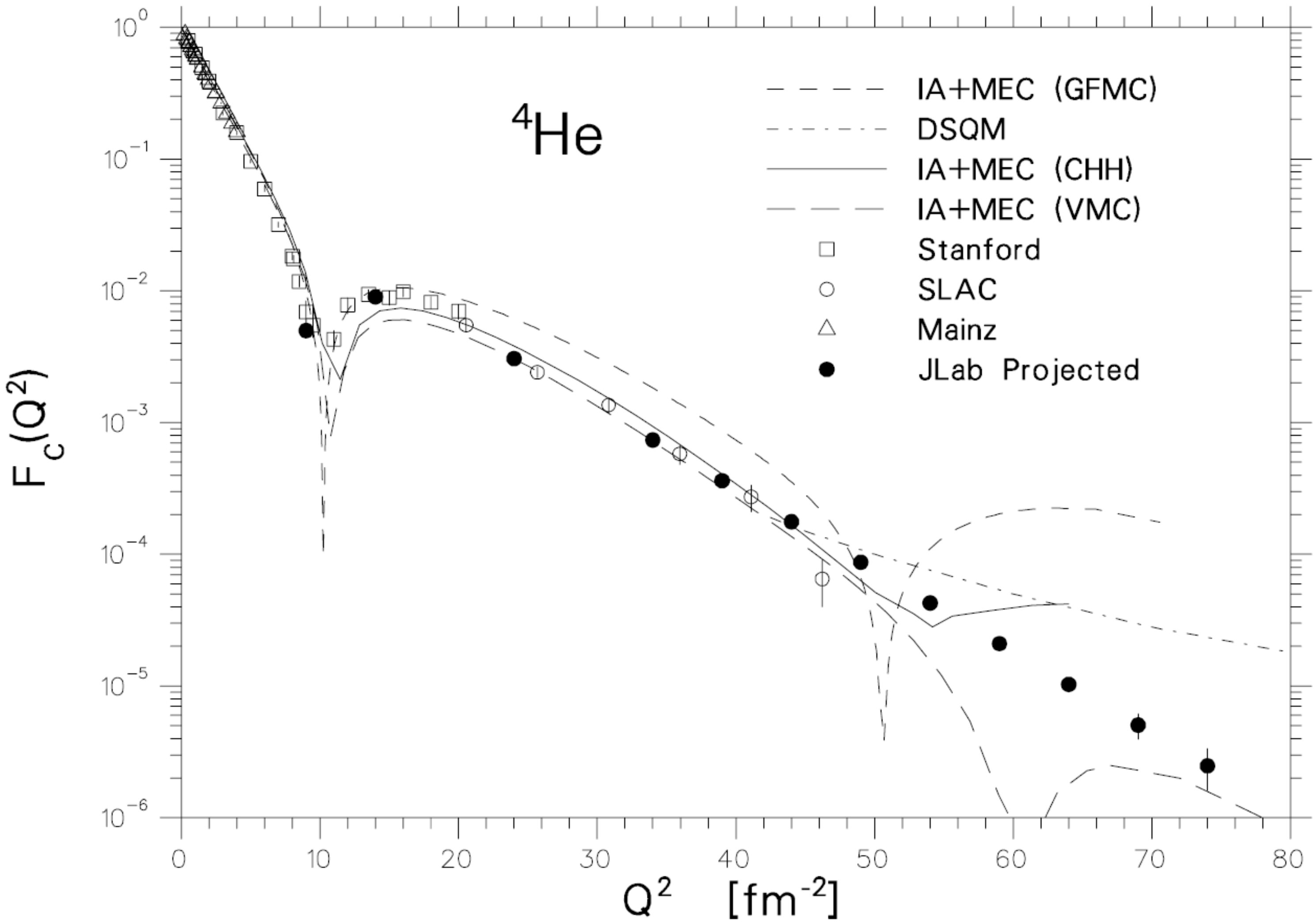
³He
Schiavilla et al.
Stanford
Orsay
SLAC
Saclay
Mainz
Bates
JLab Projected
F_c(Q²)
Q² [fm⁻²]
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0
10
20
30
40
50
60
70
80
90
100

^{3}He E04-018



^{3}He
Schiavilla et al.
Stanford
Orsay
Saclay
Mainz
Bates
JLab Projected
$F_M(Q^2)$
Q^2 [fm^{-2}]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
10
20
30
40
50
60
70
80
90
100

^{4}He E04-018



^{4}He
IA+MEC (GFMC)
DSQM
IA+MEC (CHH)
IA+MEC (VMC)
Stanford
SLAC
Mainz
JLab Projected
$F_C(Q^2)$
Q^2 [fm^{-2}]

Summary

- Extensive program to study elastic electron scattering on few-body systems is a great tool to understand the nuclear structure by comparing experiment with full calculations
- Results have shown that the elastic form-factor data can be adequately described by hadron-based models up to large Q^2-values, although the data at the highest Q^2 support pQCD scaling
- Recently, a scattering experiment has been completed on $^{3,4}He$ that extends the existing data set to large Q^2-values
- Very preliminary results have indicated the observation of a second diffraction minimum in both nuclei
- More experiments to come to fully understand the nuclear structure