International School of Nuclear Physics
Erice - Italy, Sep16-24 2011

The Jefferson Lab program: from 6 GeV operations to 12 GeV upgrade

M. Battaglieri
INFN - GE
Italy

Outline

- JLab scientific mission
- The facility today and progress on the 12 GeV upgrade
- JLab physics today and the 12 GeV era
- Status and summary

JLab scientific mission

- Understand how hadrons are constructed from the quarks and gluons of QCD
- Understand the QCD basis for the nucleon-nucleon force
- Explore the limits of our understanding of nuclear structure
  - high precision
  - short distances
  - the transition from the nucleon-meson to the QCD description
- To make progress in these areas we must address critical issues in "strong QCD":
  - What is the mechanism of confinement?
  - Where does the dynamics of the q-q interaction make a transition from the strong (confinement) to the perturbative (QED-like) QCD regime?
- Probe potential new physics through high precision tests of the Standard Model

The CEBAF parameters

- Primary Beam: Electrons
- Beam Energy: 4 GeV (original)
  - $10 > \lambda > 0.1$ fm

    nucleon → quark transition

    baryon and meson excited states
- 100% Duty Factor (cw) Beam
  - coincidence experiments ⇒ excite system and observe its evolution
  - Three Simultaneous Beams with Independently Variable Energy and Intensity
    - complementary, long experiments
- Polarization (beam and reaction products)
  - spin degrees of freedom
  - weak neutral currents

The CEBAF parameters

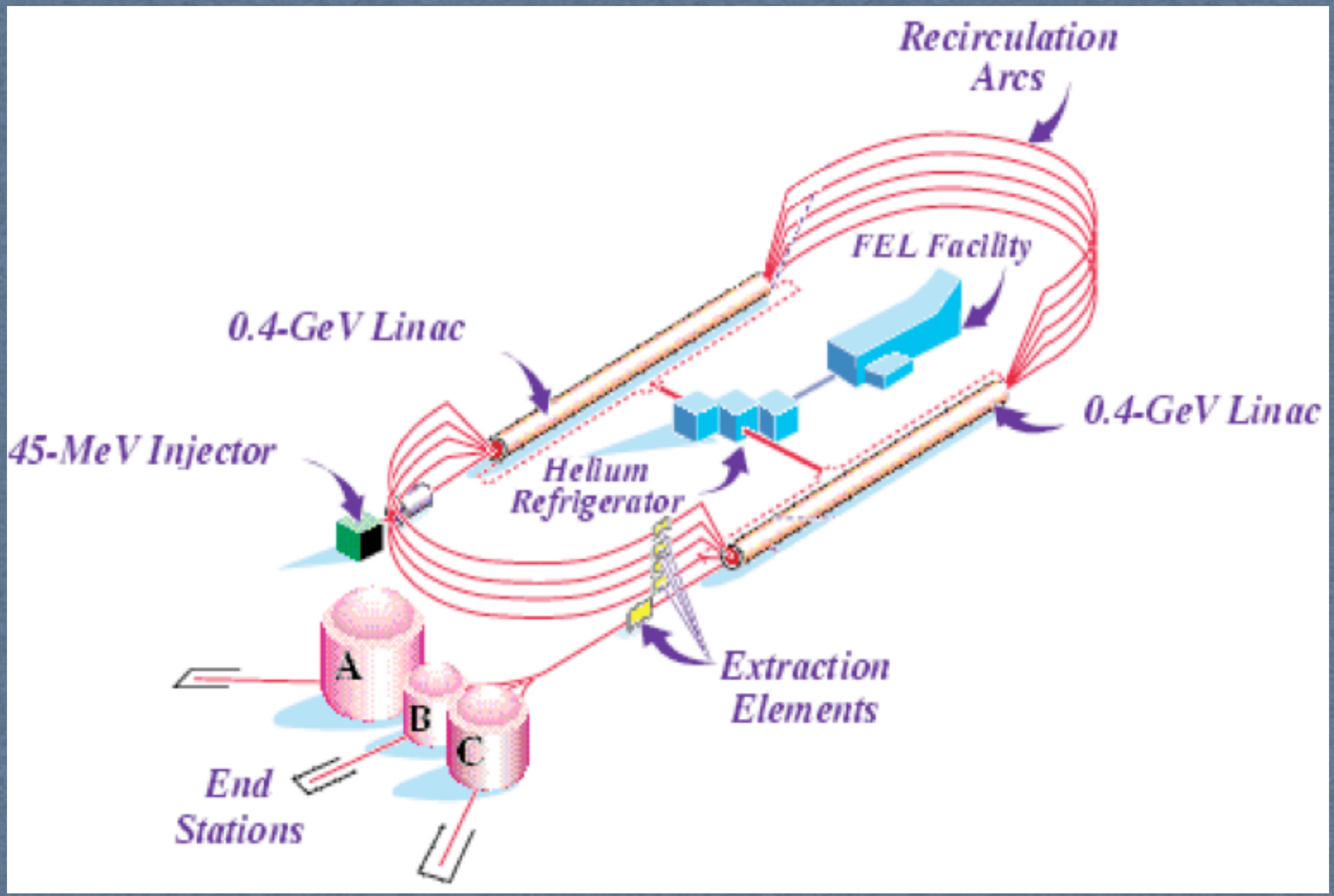
- ✳ Primary Beam: Electrons
- ✳ Beam Energy: 4 GeV (original)
  - 10 > λ > 0.1 fm
    nucleon → quark transition
    baryon and meson excited states

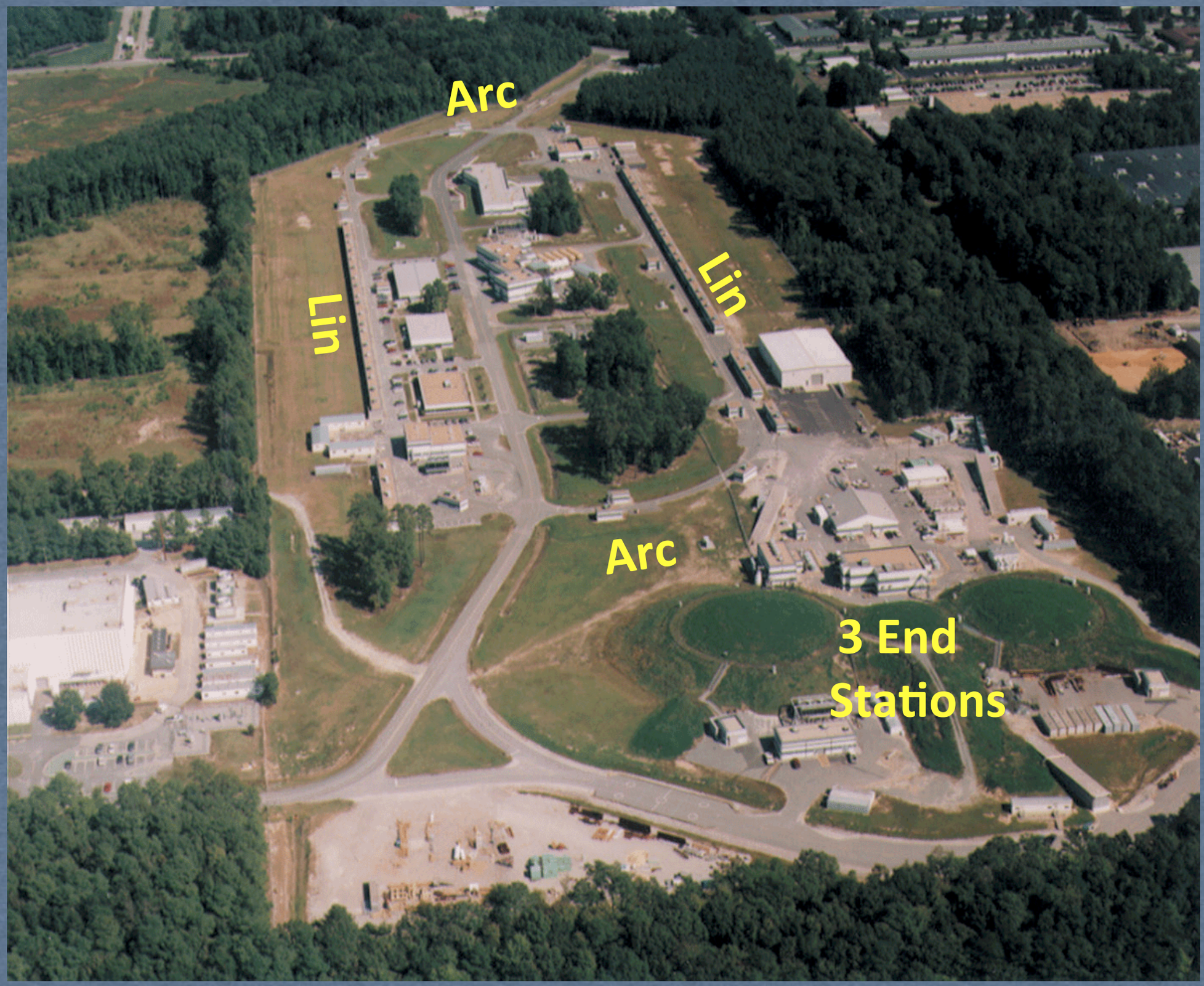
6 GeV now
12 GeV soon

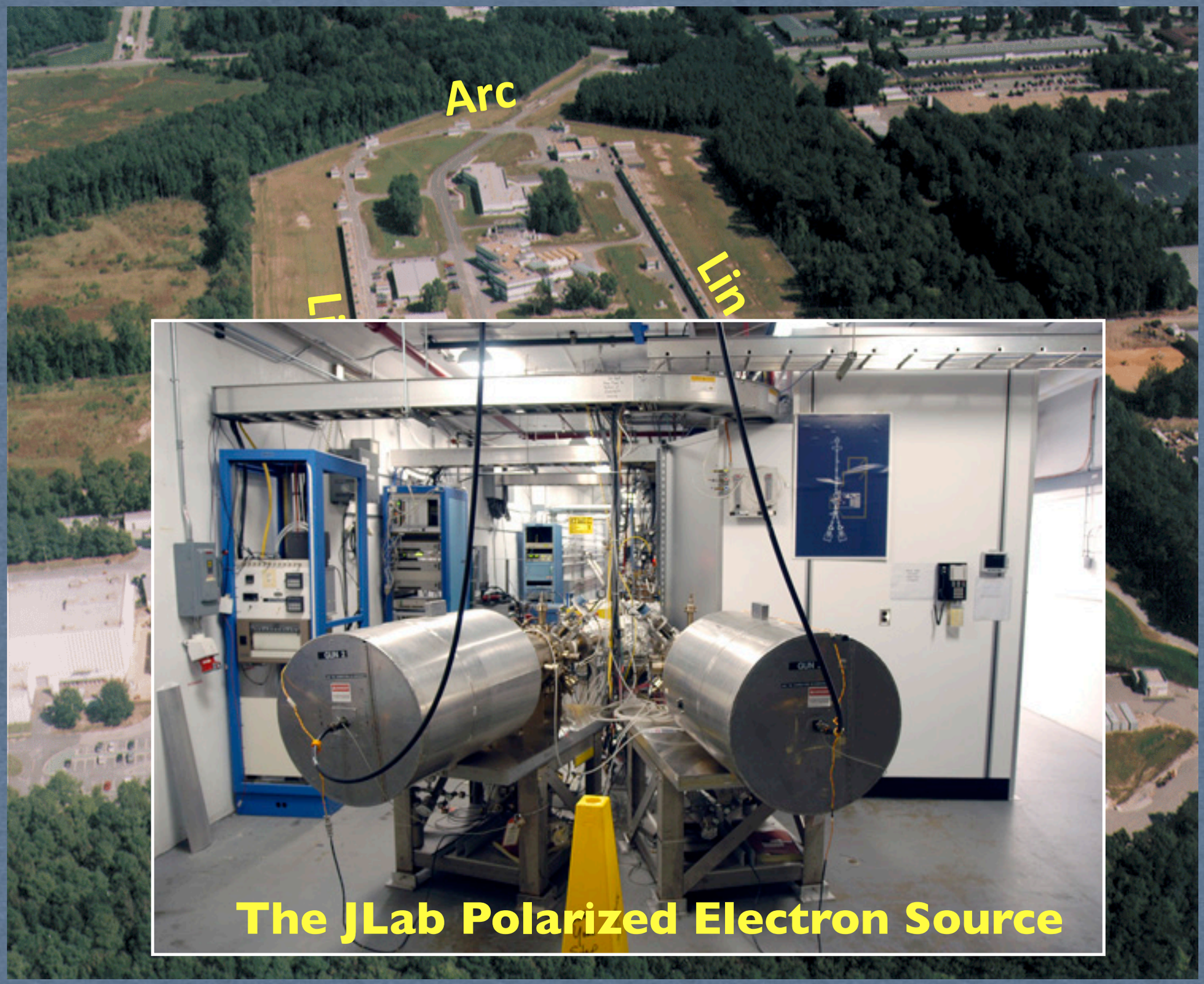
- ✳ 100% Duty Factor (cw) Beam
  - coincidence experiments
  - Three Simultaneous Beams with Independently Variable Energy and Intensity
    - complementary, long experiments
- ✳ Polarization (beam and reaction products)
  - spin degrees of freedom
  - weak neutral currents

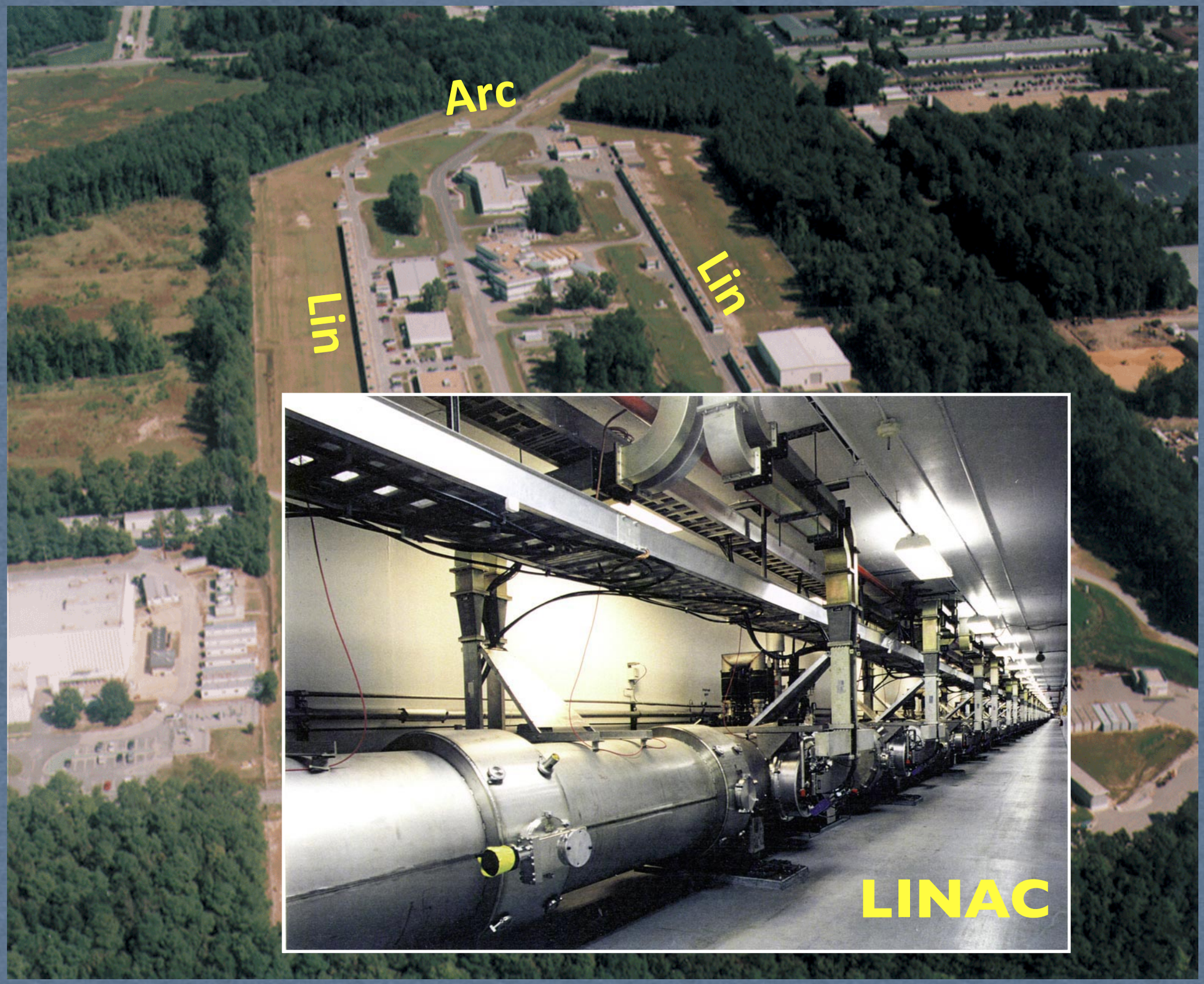
L > 10^6 x SLAC at the time of the original DIS experiments!
JLab12 luminosity will increase by 10 x

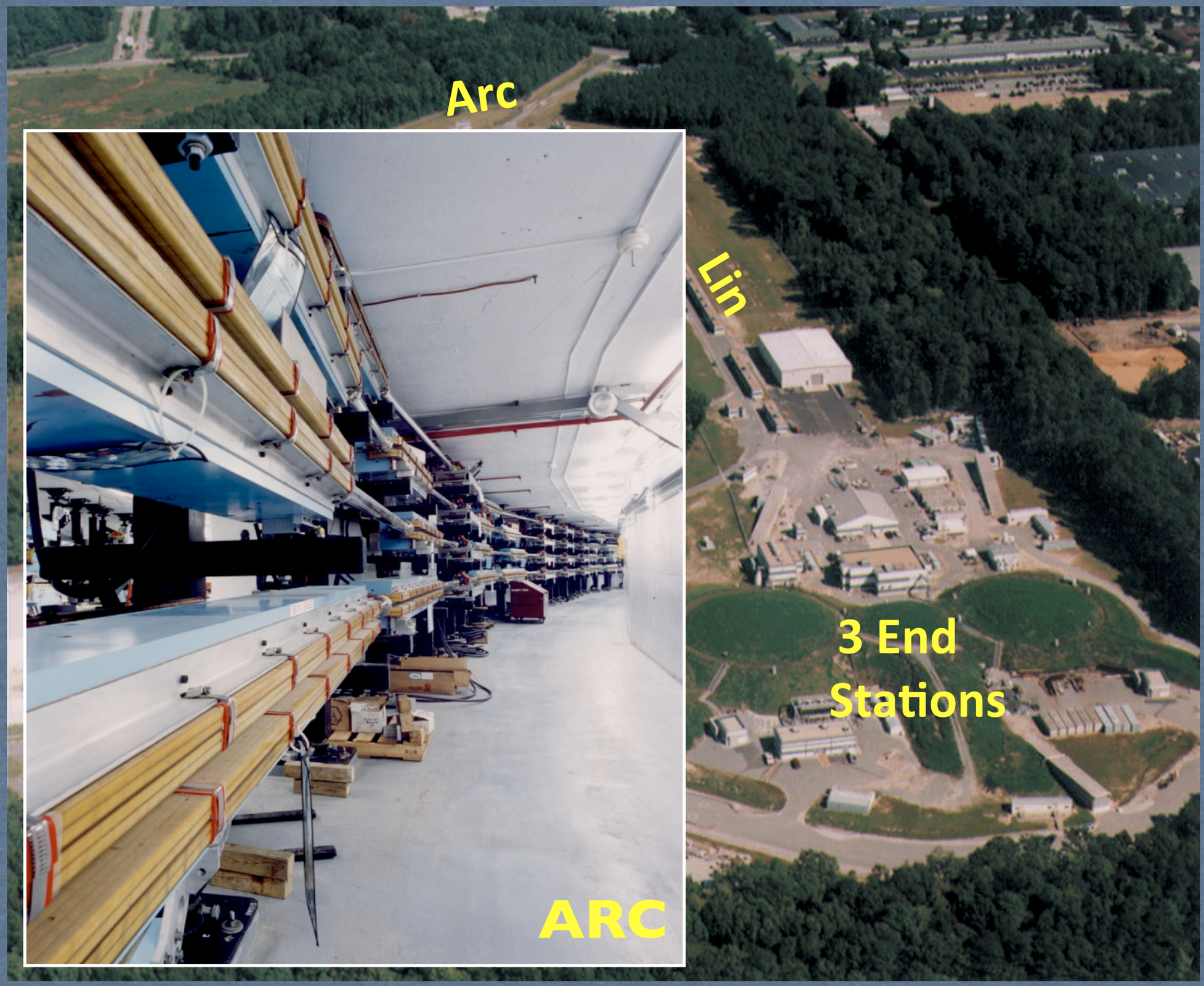
Jefferson Lab today (6 GeV)



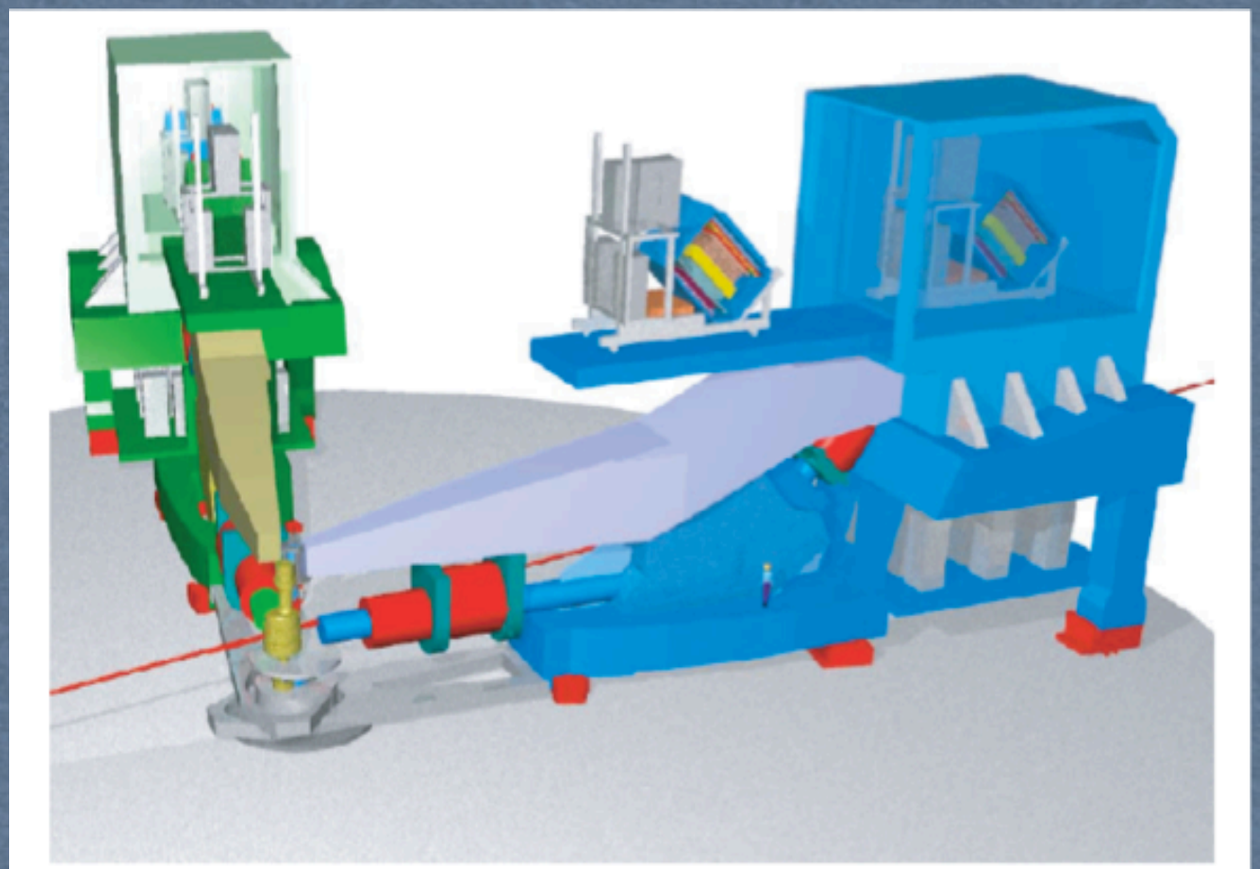

Arc
Lin
Lin
Arc
3 End
Stations


Arc
Lin
The JLab Polarized Electron Source


Arc
Lin
Lin
LINAC

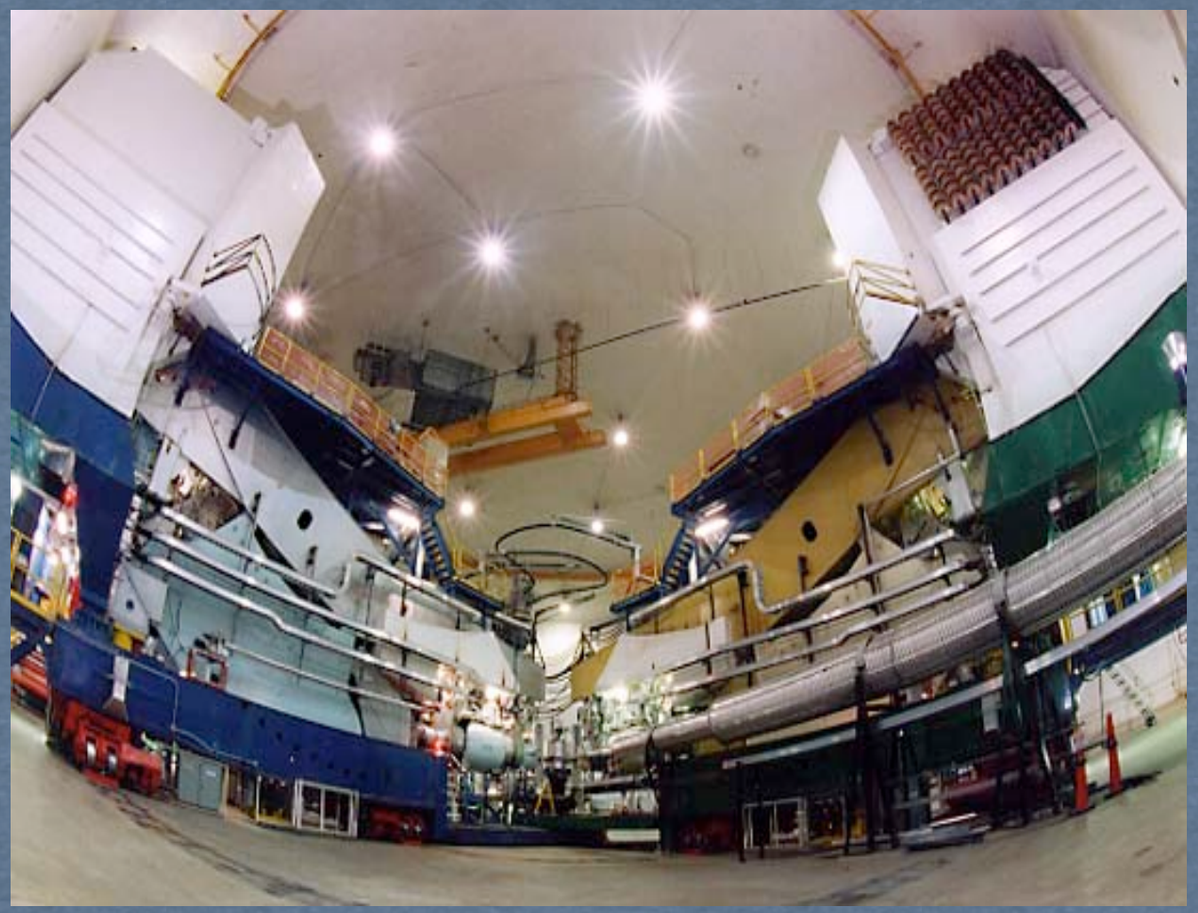

Arc
Lin
ARC
3 End
Stations

Hall A Spectrometers



High Resolution Spectrometers (HRS)

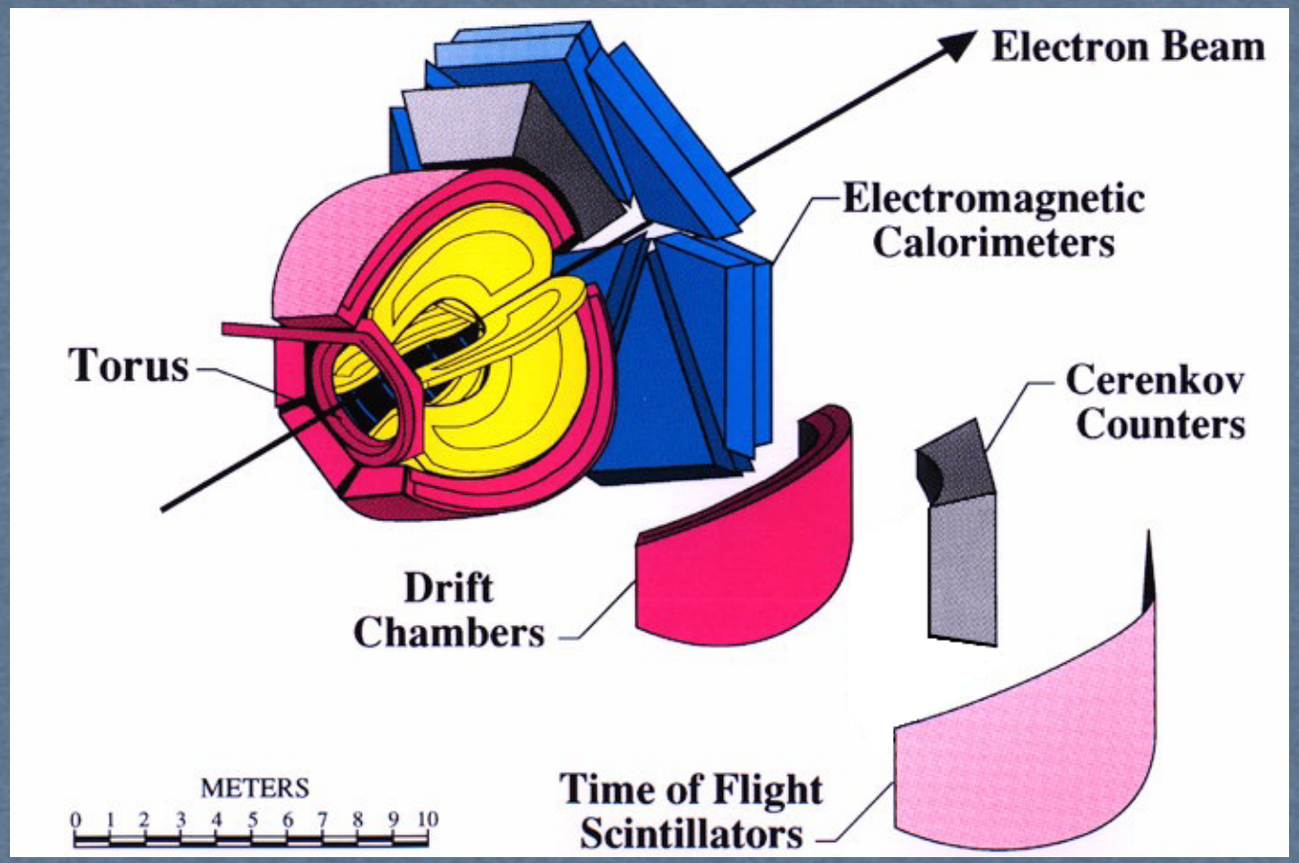
- Resolution $1x10^{-4}$ FWHM
- Large momentum range (0.3-4.3 GeV, 0.3-3.3 GeV)
- Max luminosity $10^{38}cm^{-2}s^{-1}$
- Proton Polarimeter



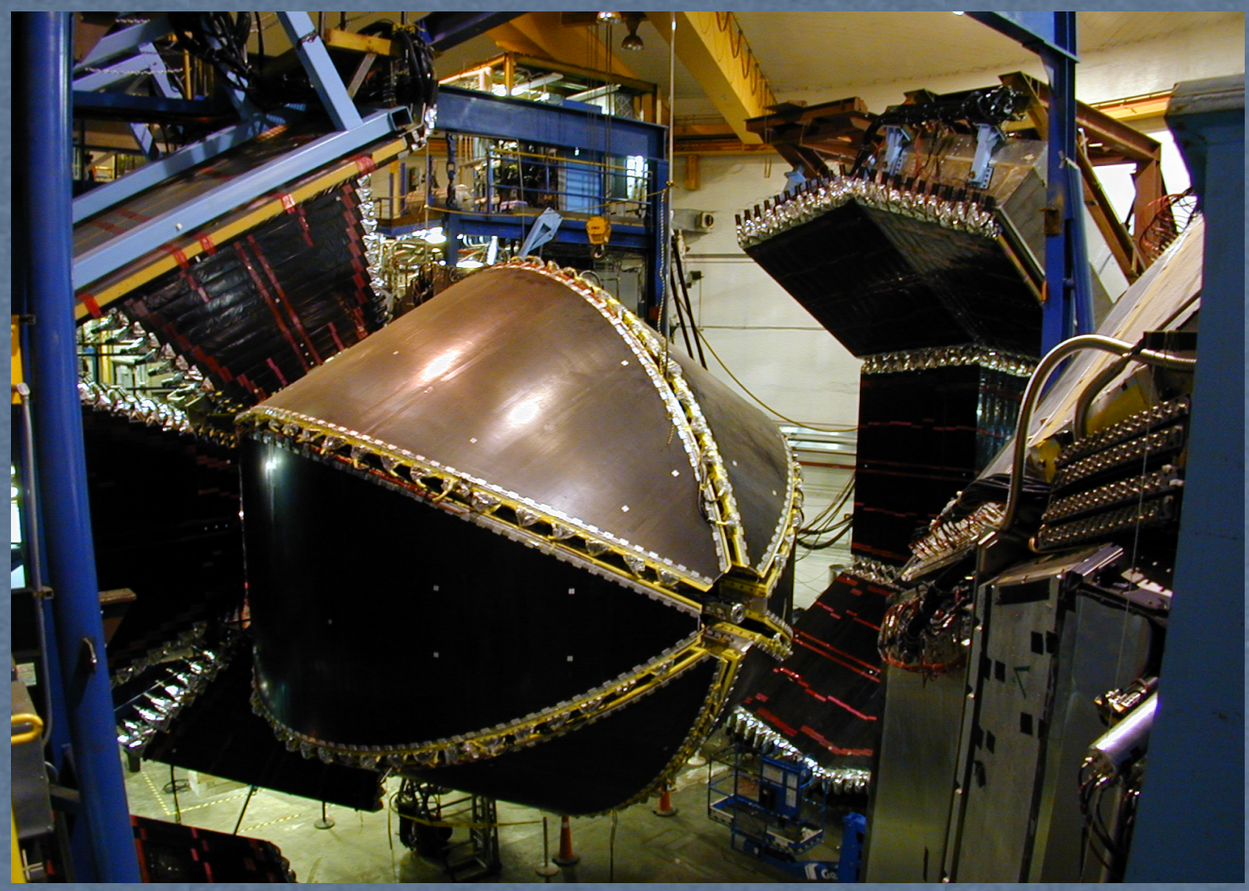
New dedicated detectors recently installed:

- Neutron detector for form factor measurement
- Big Bite spectrometer
- DVCS calorimeter

Hall B experimental setup

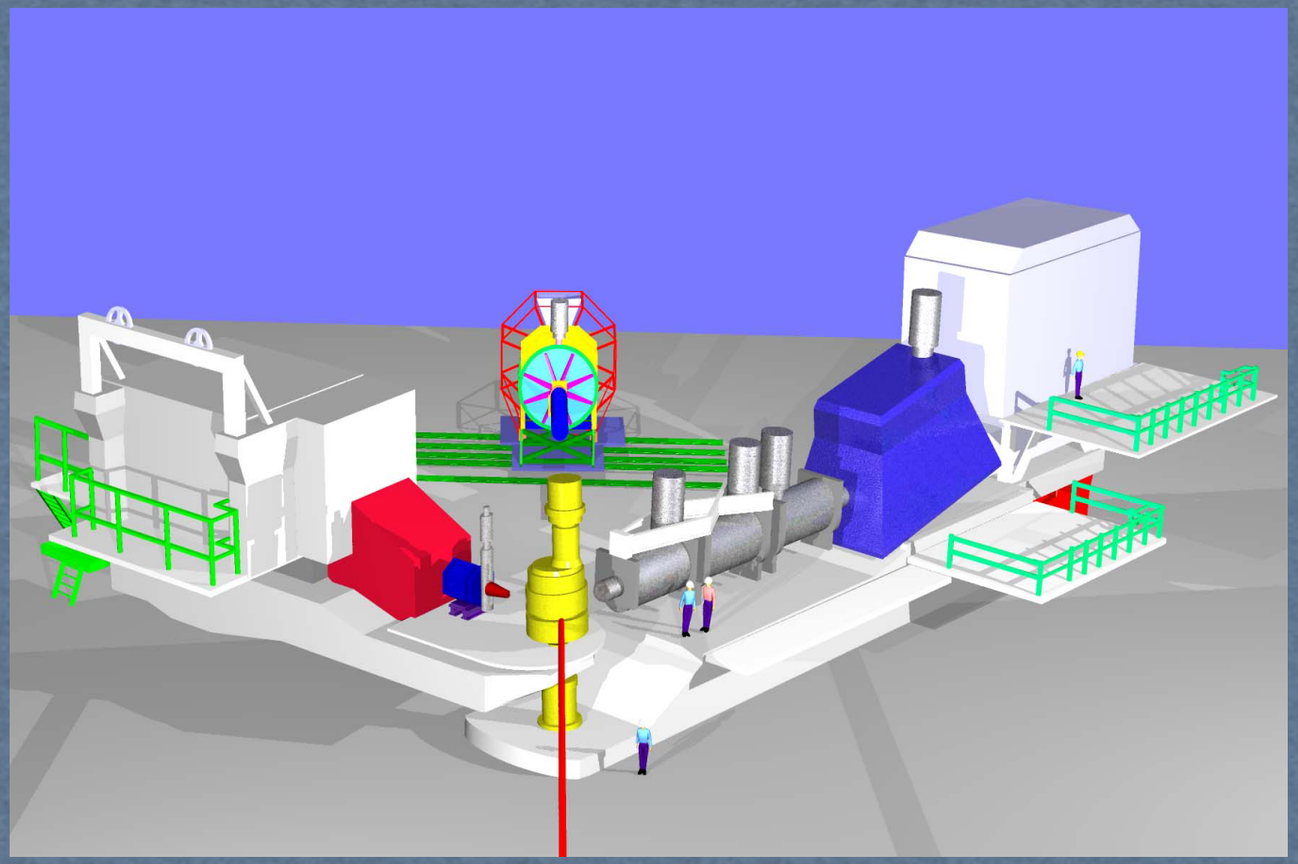


CEBAF Large Acceptance Spectrometer



- magnetic spectrometer based on six-coil toroidal field
- large kinematical coverage + high luminosity $10^{34}cm^{-2}s^{-1}$
- simultaneous measurement of exclusive and inclusive reactions
- central field-free region well suited for the insertion of a polarized target

Hall C equipment



High Momentum Spectrometer (HMS)

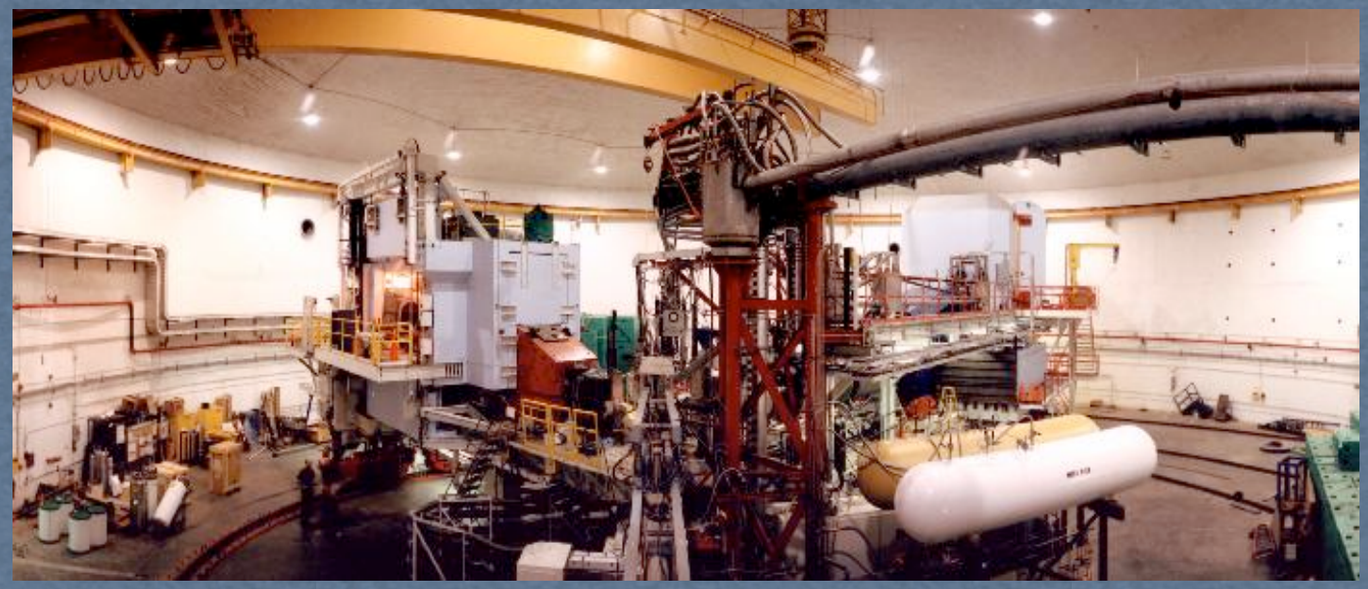
- Max momentum 7.5 GeV
- Resolution 10^{-3}
- 18% momentum acceptance
- Angular acceptance > 6msr

Short Orbit Spectrometer (SOS)

- Max momentum 1.8 GeV
- Resolution 10^{-3}
- 40% momentum acceptance

Experimental Hall used for large installations:

- **G0**: parity violation
- **Qweak**: measurement of the weak charge
- ...



The 12 GeV upgrade

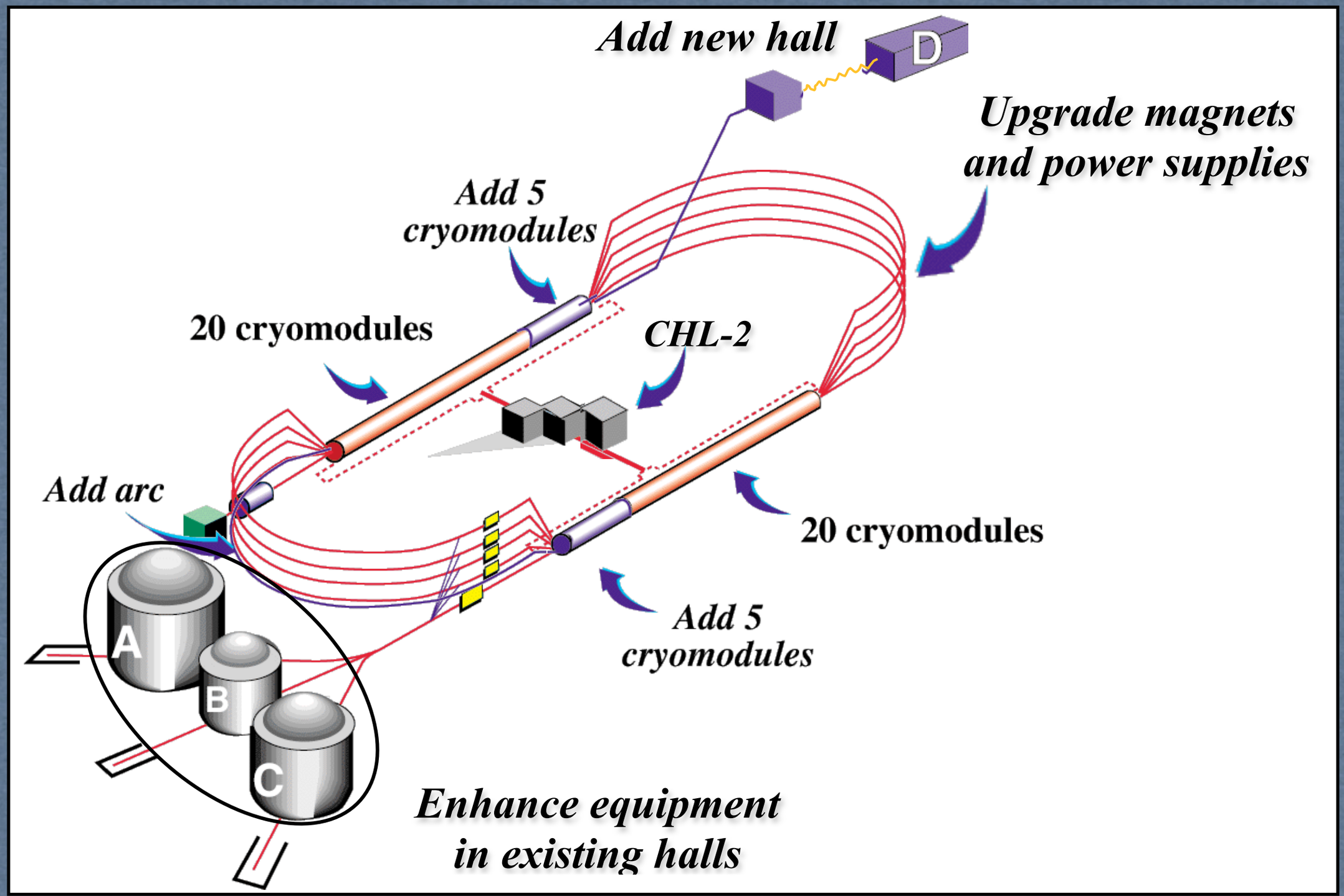
- CEBAF design and performance make easy the energy upgrade
  - CEBAF RF cavities exceeded the designed specification by 50%
  - Maximum beam energy of 6 GeV routinely achieved (4 GeV max nominal energy)
  - ARCS can accommodate an electron beam up to 24 GeV
- Upgrade of the accelerator
- Construction of new equipment for Hall A, B and C
- Construction of a new experimental hall (Hall D)

The Upgrade of CEBAF to 12 GeV (the highest priority of the 2007 NSAC Long Range Plan) is now well underway

- Project is "**on cost and on schedule**" and over half complete as of today
- Initial beam operation to begin in Hall A in Oct 2014 and full operation by Jun 2015

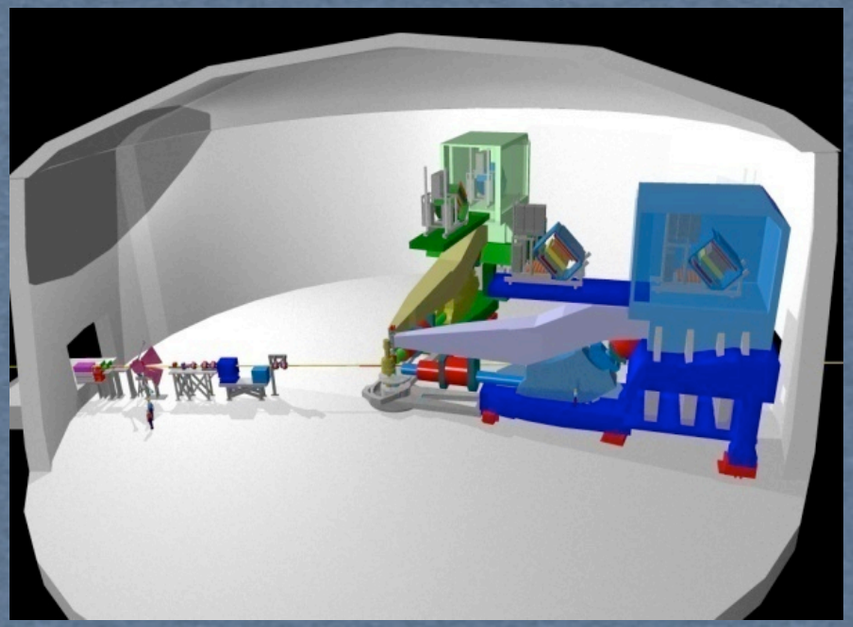
The 12 GeV Research Program is Evolving Rapidly

CEBAF @12 GeV

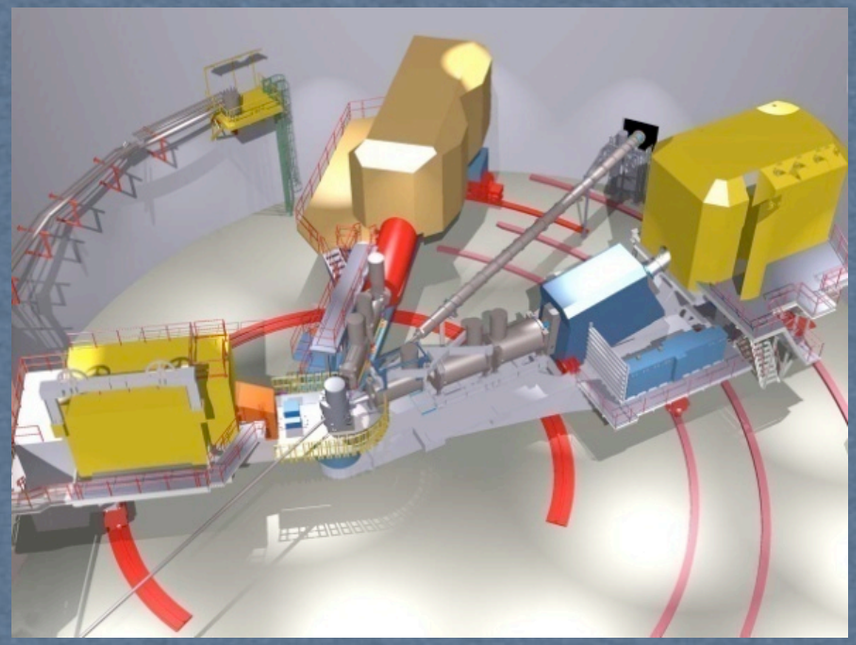

Add new hall
D
Upgrade magnets
and power supplies
Add 5
cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5
cryomodules
A
B
C
Enhance equipment
in existing halls

The 12 GeV equipment

Hall A – High Resolution Spectrometers and new multipurpose large acceptance detector



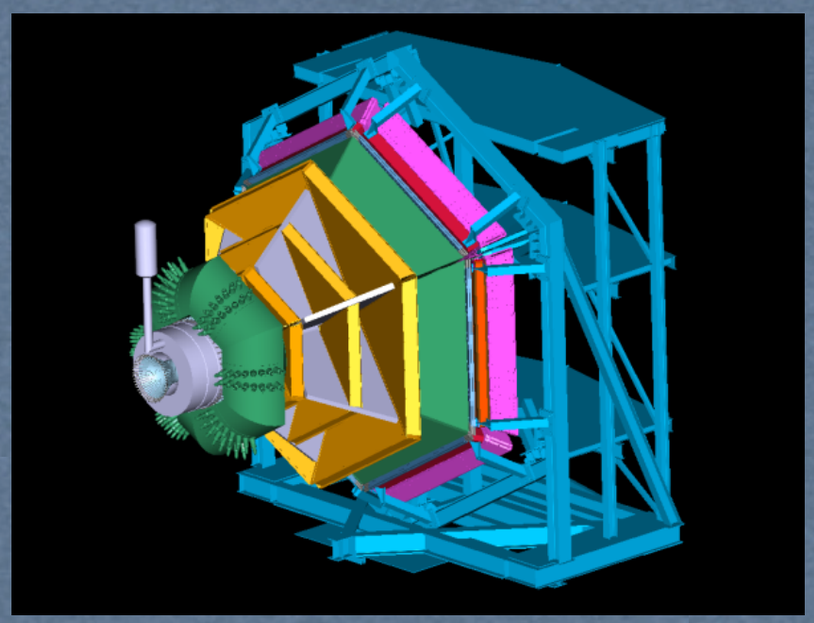
✳ short range correlations, form factors, and future new experiments: SOLID, MOELLER, SBS



Hall C – Super High Momentum Spectrometer (SHMS)

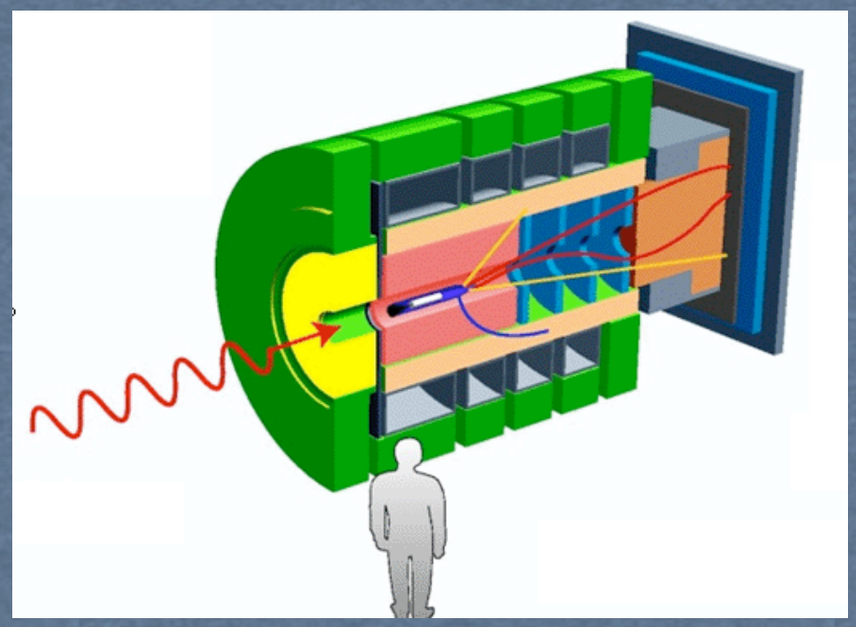
✳ precise determination of valence q properties in nucleons and nuclei

Hall D – GLUEx detector for photoproduction experiments



Hall B – Large acceptance detector CLAS12 for high luminosity measurements ($10^{35}cm^{-2}s^{-1}$)

✳ Understanding nucleo structure via GPDs



✳ explore origin of confinement by studying hybrid mesons

JLab science: today and in the 12 GeV era

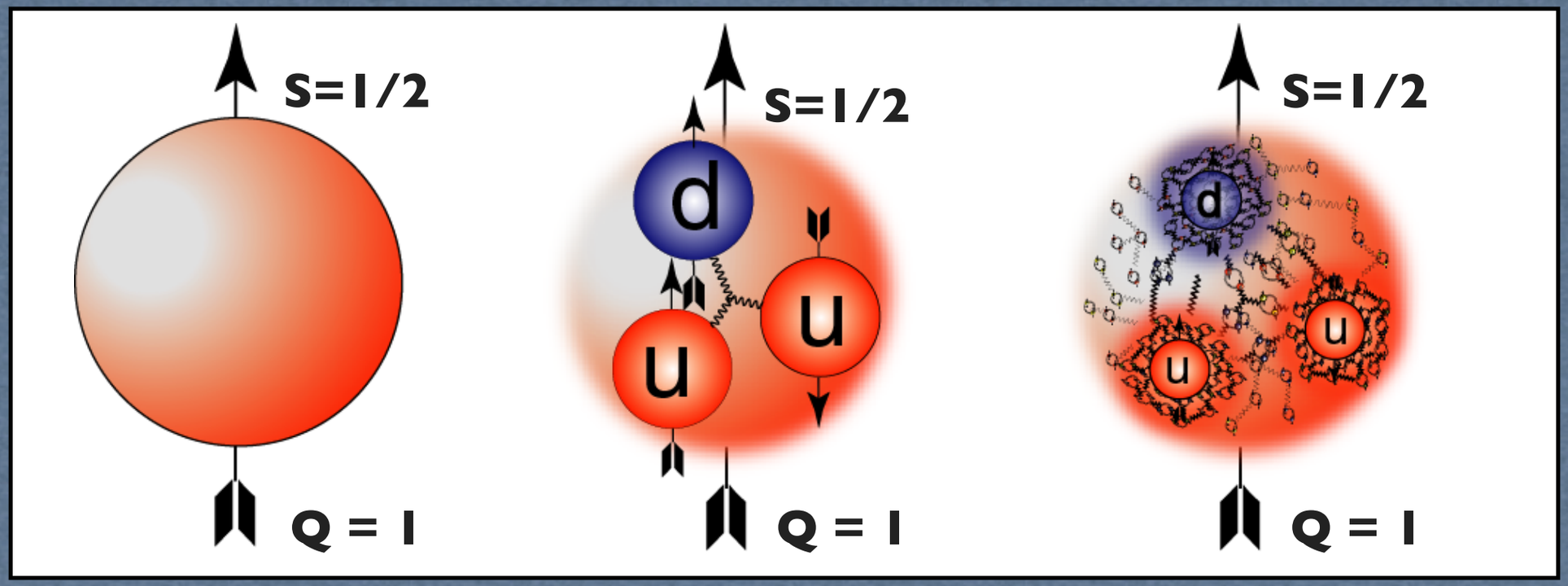
- **Nucleon Structure**
  - EM, EW, and Flavor-Separated Form Factors
  - Structure Functions and Extensions to $x \rightarrow 1$
  - Generalized Parton Distributions
  - N* s and Transition Form Factors
- **Quark Electro-Weak Couplings and Standard Model Tests**
- **The Physics of Confinement – the Search for Hybrid Mesons**
- **Nuclear Structure and the Quark Structure of Nuclei**
  - N-N Short Range Correlations and the EMC Effect
  - Hypernuclear Physics
  - High-p Structure and Nucleons in medium

NUCLEON STRUCTURE
from elastic form factors to GPDs

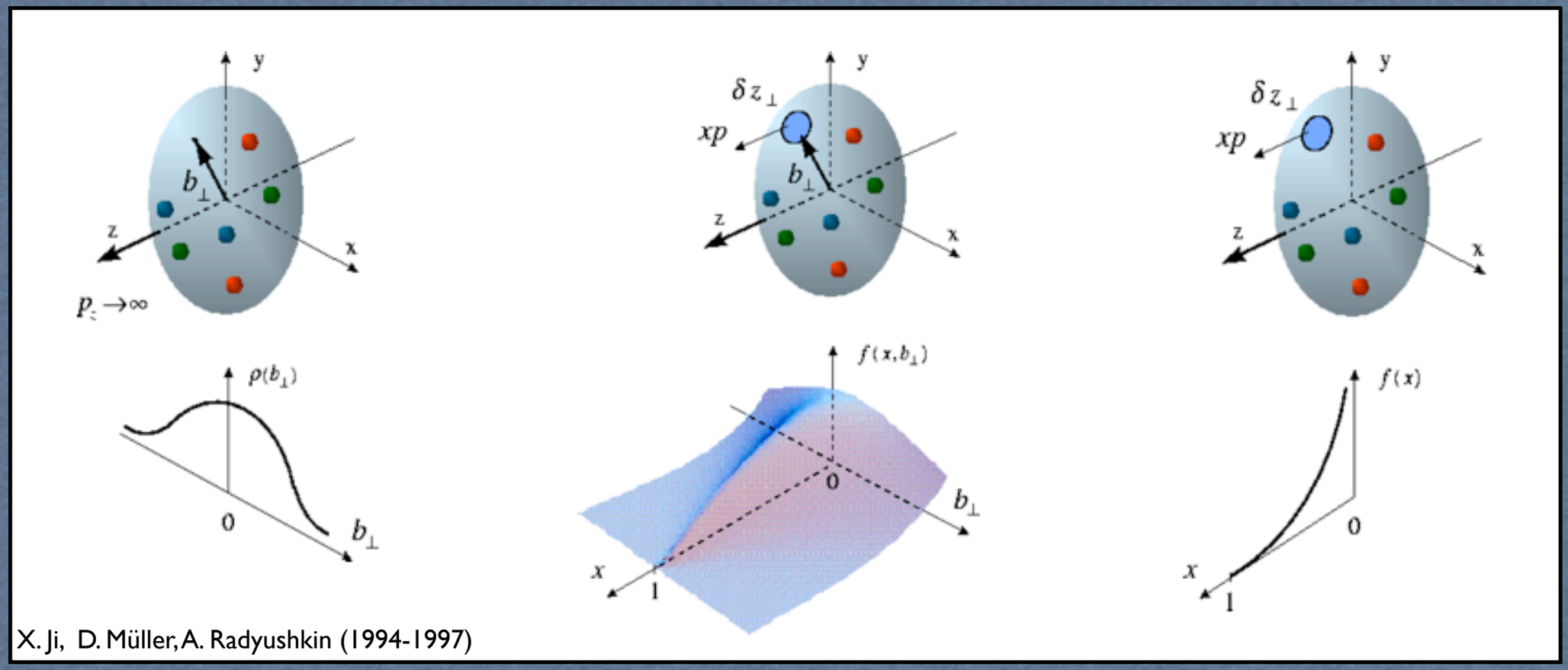
The Proton and Neutron are the "Hydrogen Atoms" of QCD

What we "see" changes with spatial resolution

>1 fm	0.1 — 1 fm	< 0.1 fm
Nucleons	Constituent quarks and glue	"bare" quarks and glue



NUCLEON STRUCTURE
from elastic form factors to GPDs



X. Ji, D. Müller, A. Radyushkin (1994-1997)

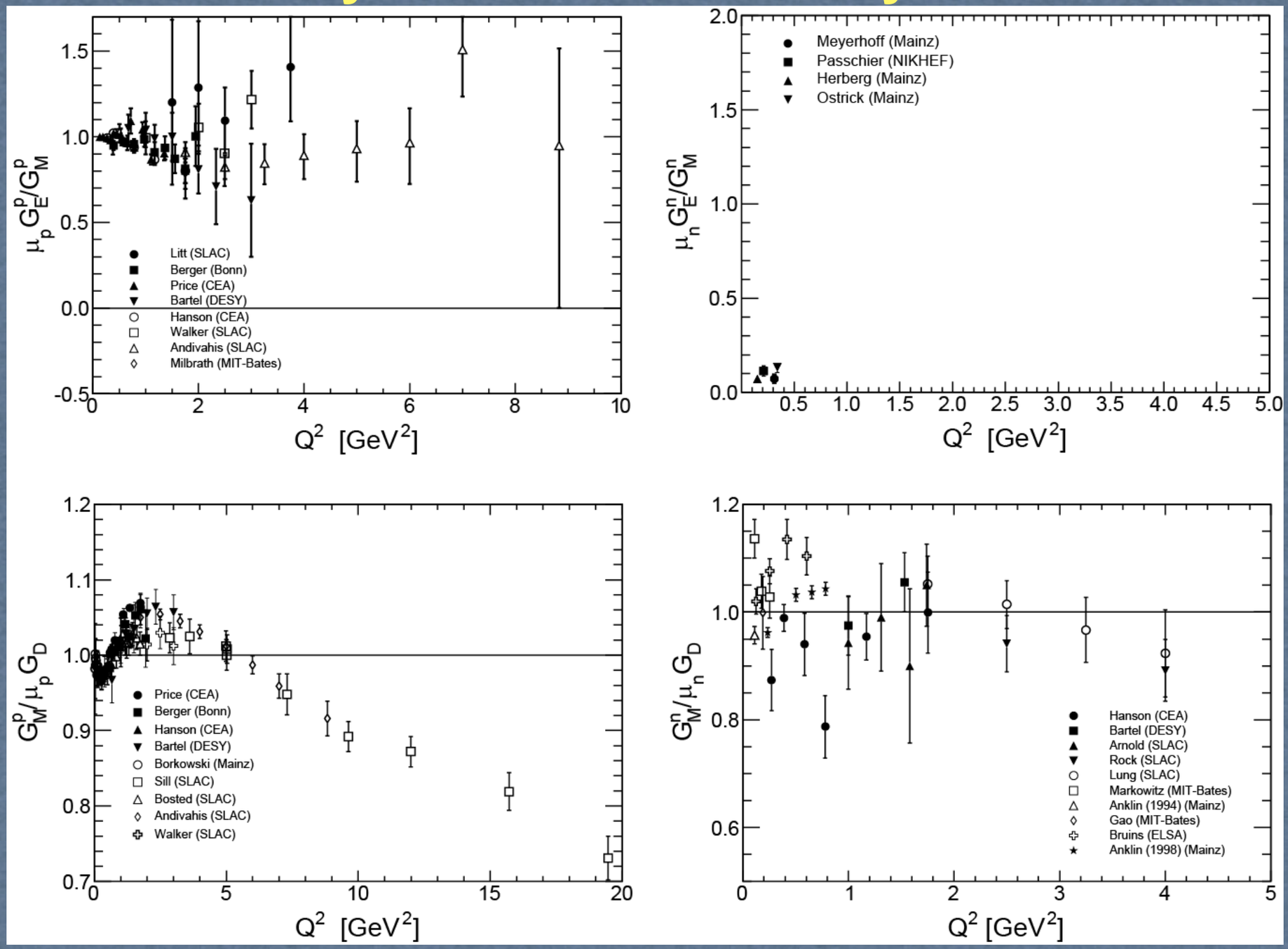
Elastic Scattering
transverse quark distribution in Coordinate space (charge and current densities)

Deep Exclusive Scattering
fully-correlated quark distribution in both coordinate and momentum space (**Generalized Parton Distributions**)

Deep Inelastic Scattering
longitudinal quark distribution in momentum space (momentum and helicity distributions)

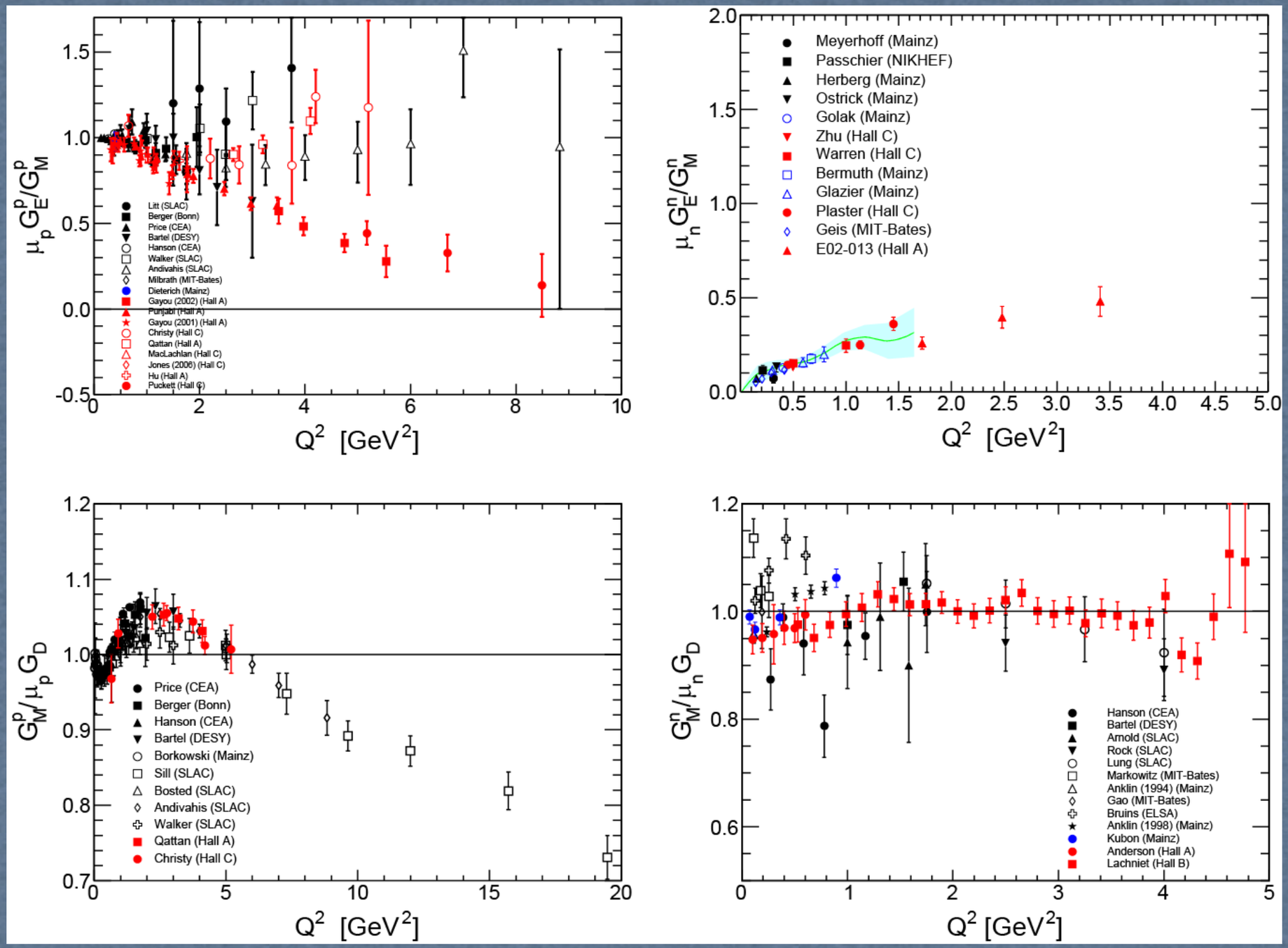
JLab data on the EM form factors provide a testing ground for theories constructing nucleons from quarks and glue

Before JLab and Recent non-JLab Data



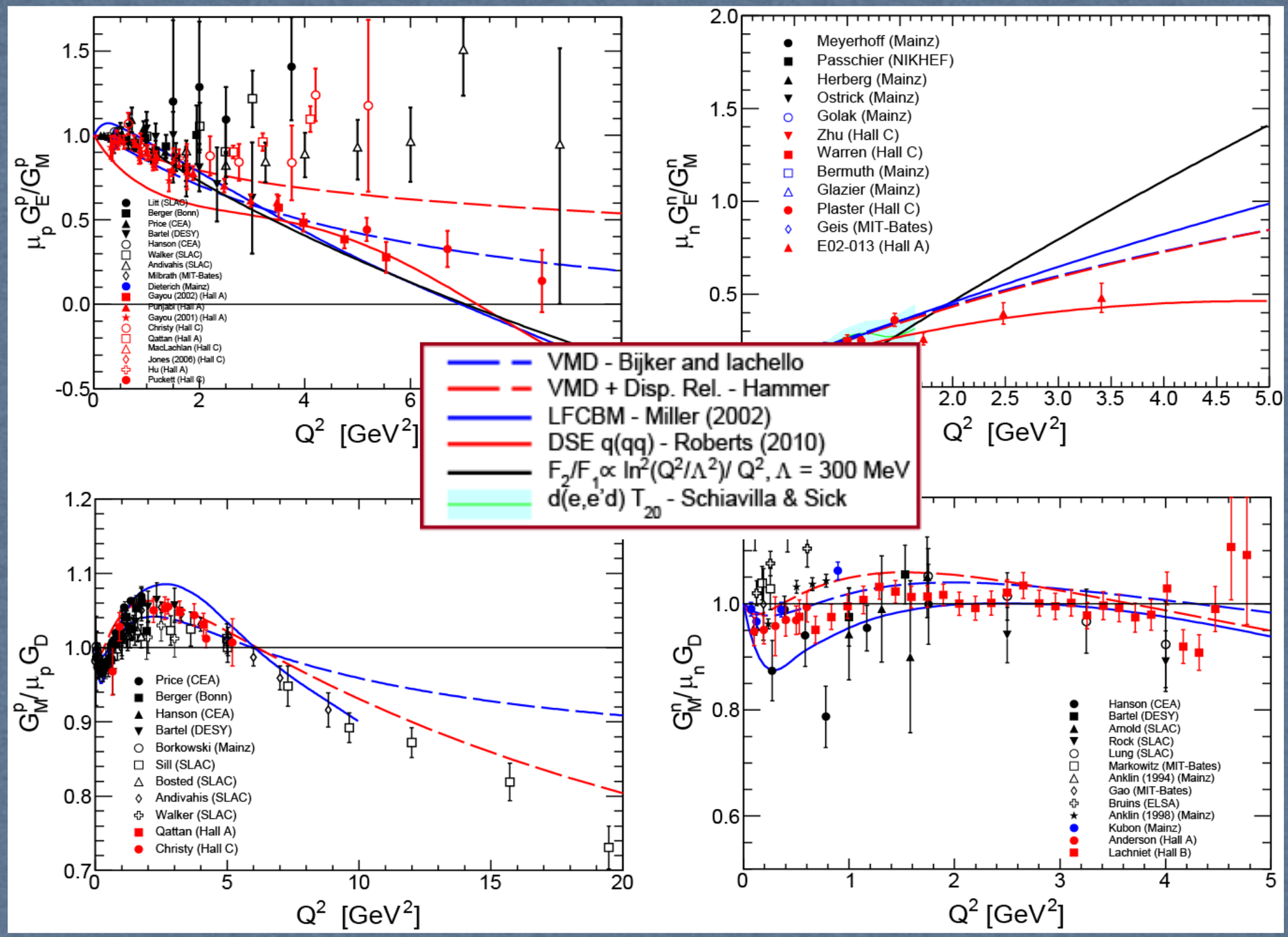
JLab data on the EM form factors provide a testing ground for theories constructing nucleons from quarks and glue

Today, including new JLab Data



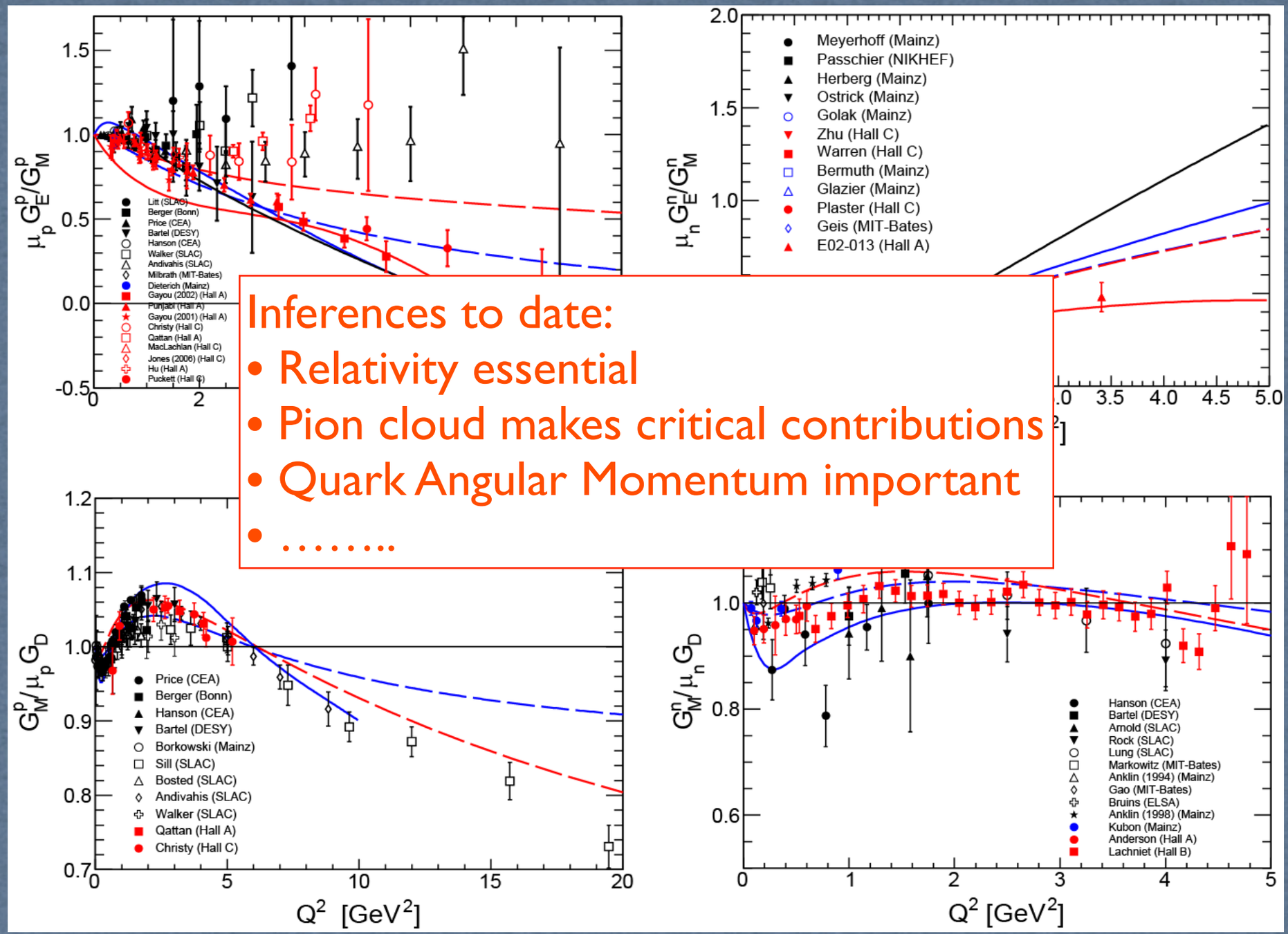
JLab data on the EM form factors provide a testing ground for theories constructing nucleons from quarks and glue

Today, including new JLab Data, compared to theory



JLab data on the EM form factors provide a testing ground for theories constructing nucleons from quarks and glue

Today, including new JLab Data, compared to theory



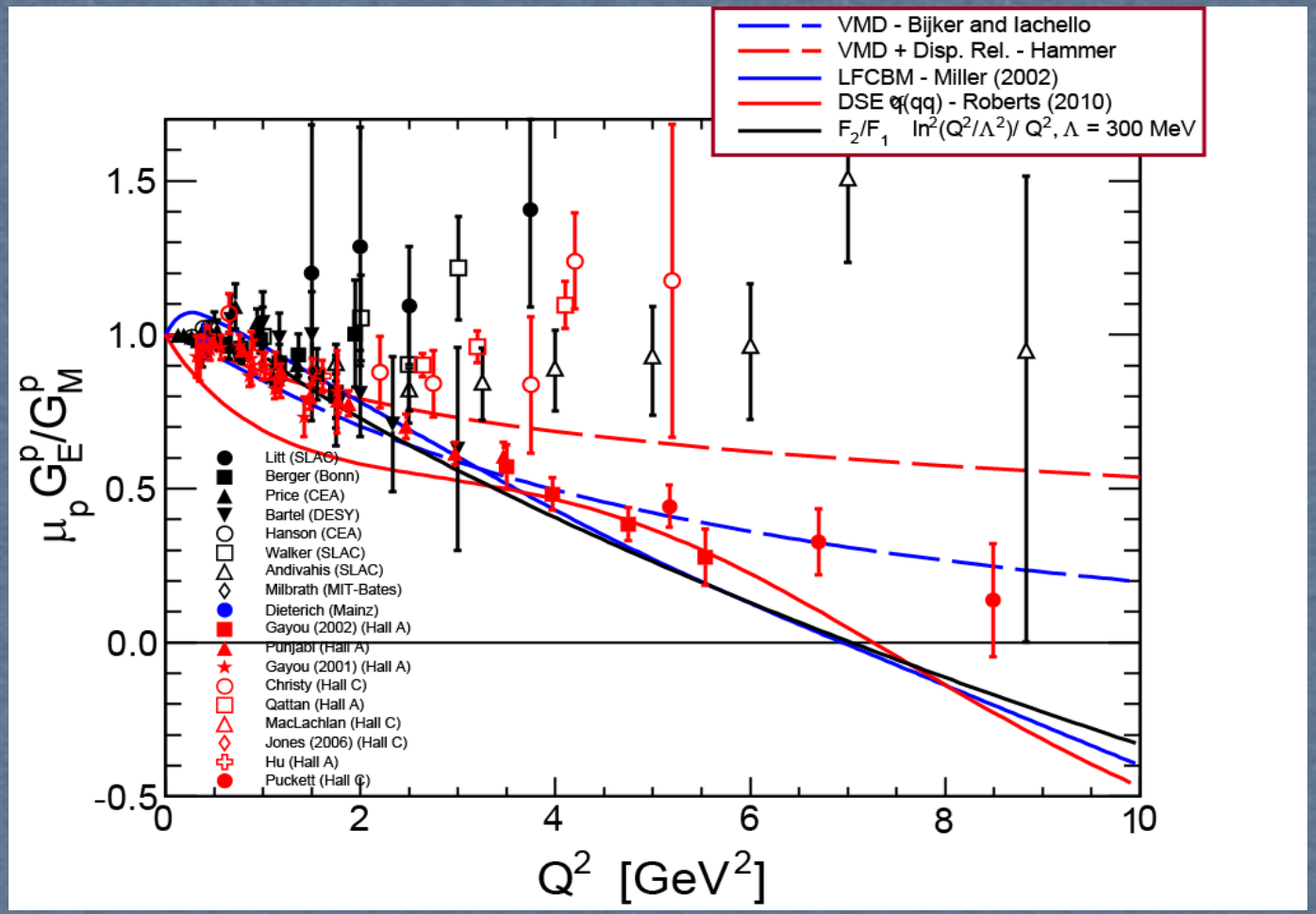
Inferences to date:

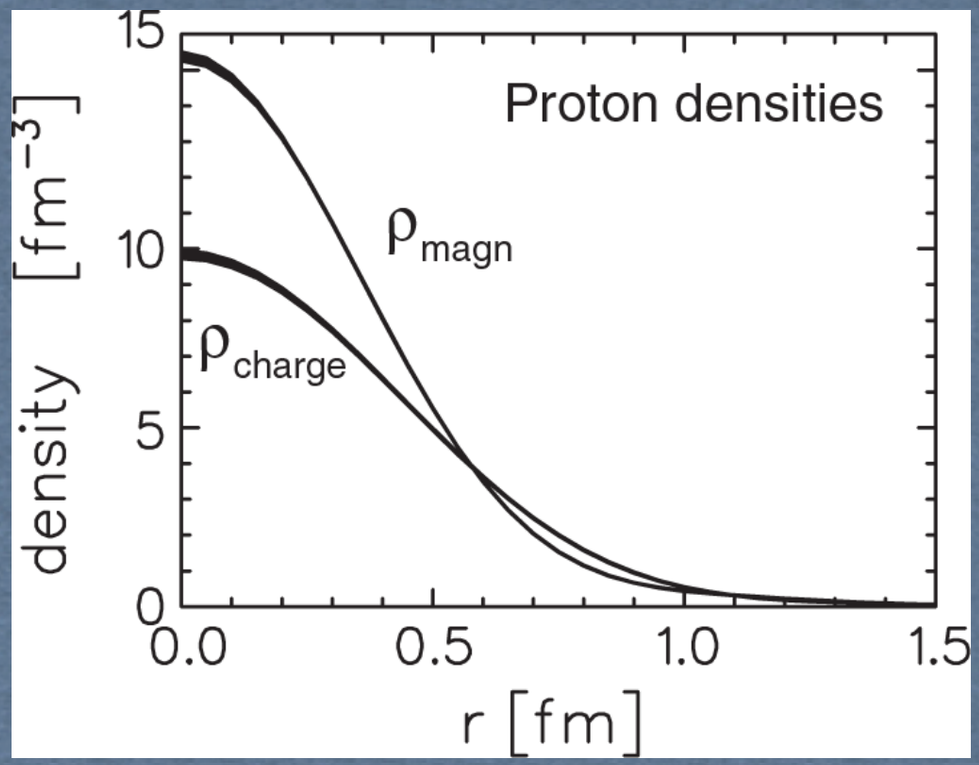
- Relativity essential
- Pion cloud makes critical contributions
- Quark Angular Momentum important
- ……..

These data are elucidating the nucleon's structure

The inequality of G_E^p and μG_M^p was a surprise.

- Rosenbluth separation - polarization transfer are incompatible
- Reconciliation: radiative corrections, TPE, ...
- Demonstrated that a proper treatment of quark orbital angular momentum and relativity + pion cloud is essential in describing nucleon structure

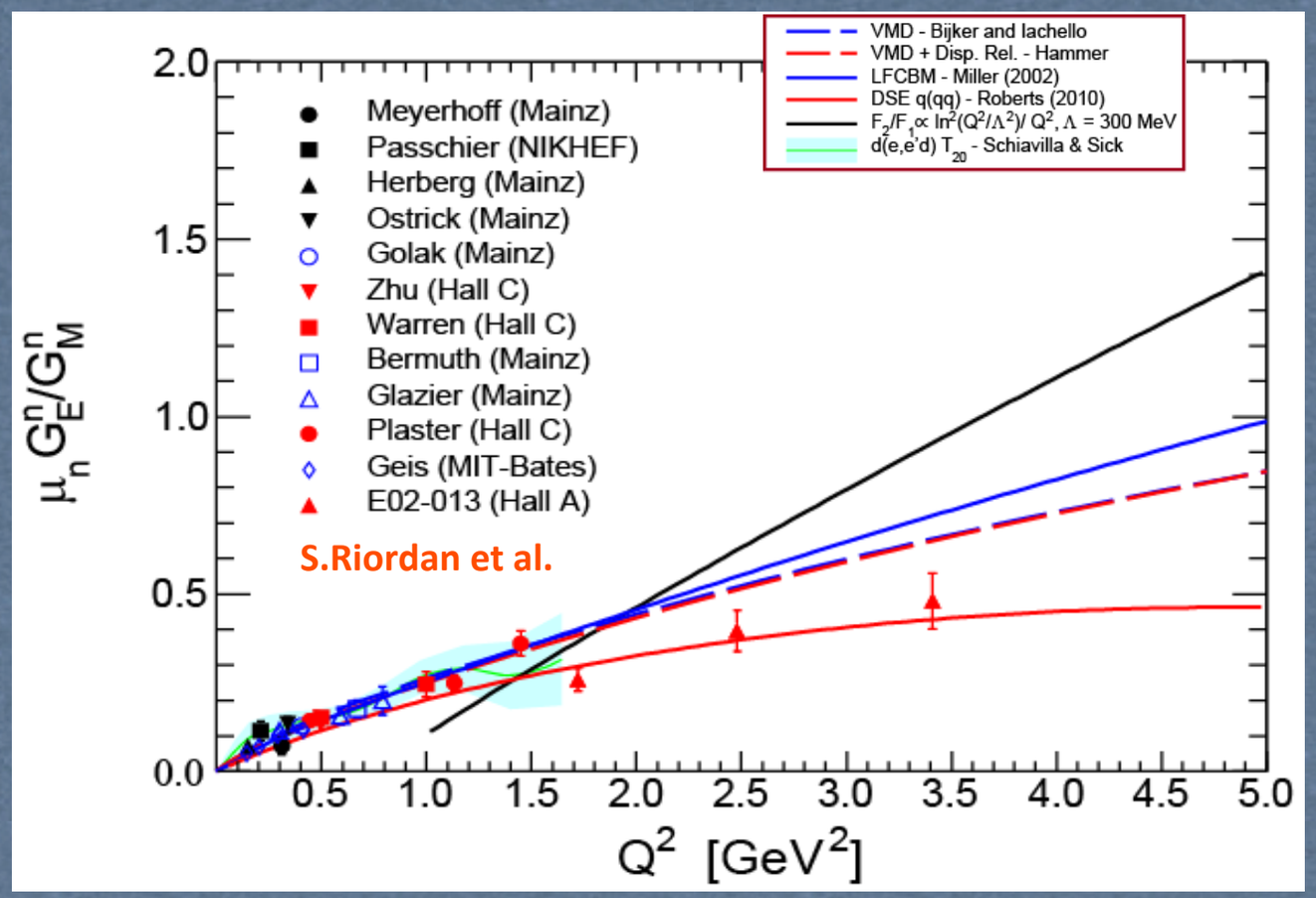


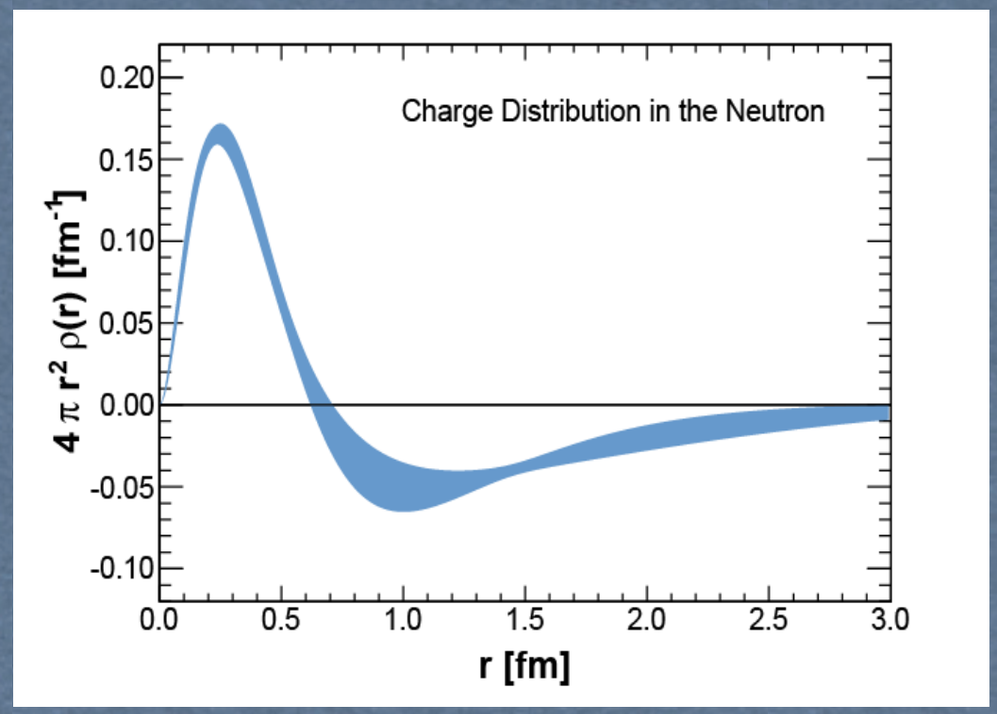


These data are elucidating the nucleon's structure

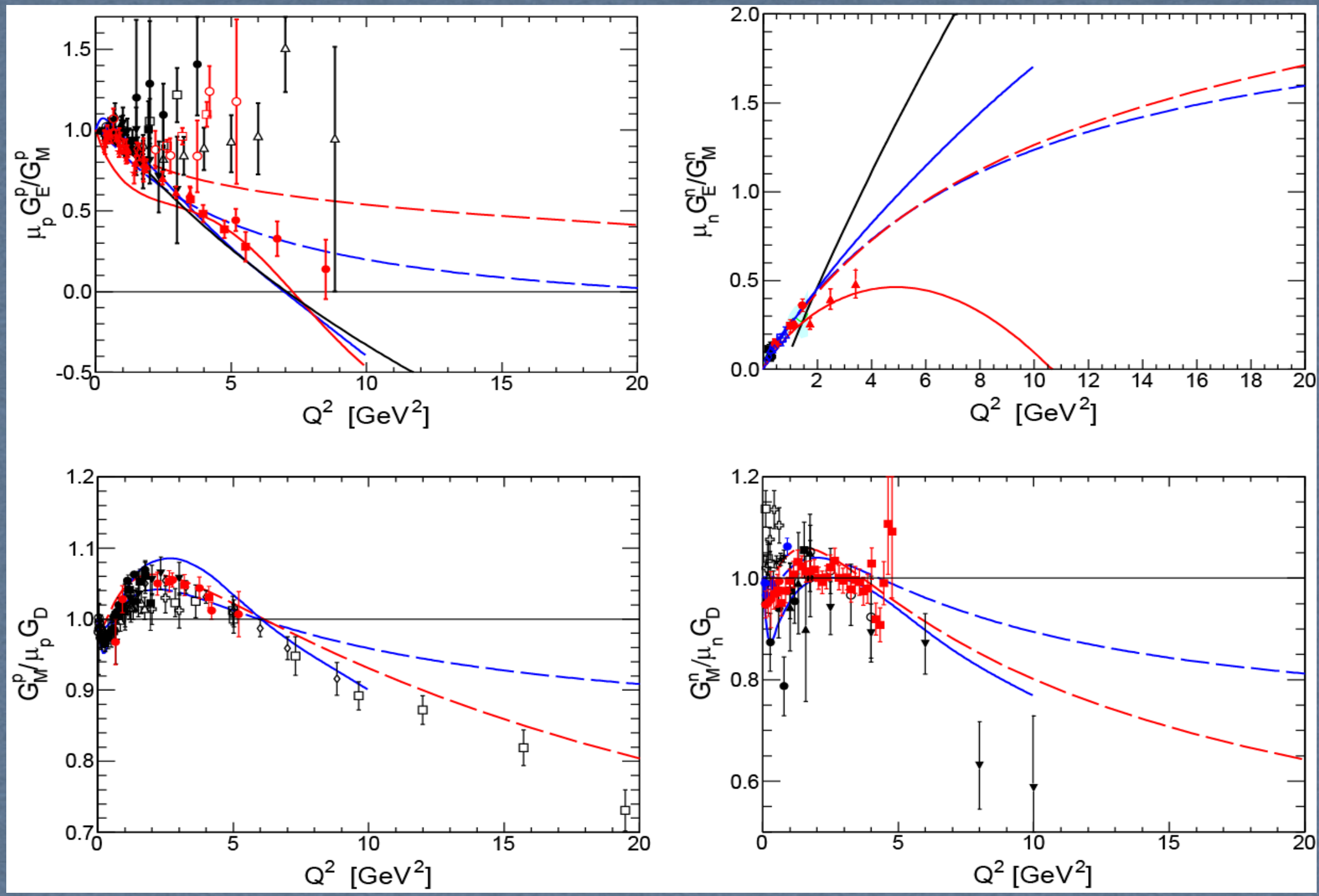
The charge form factor of the neutron is particularly interesting

- Neutron electric form factor data reveal the shape of the charge distribution
- Confirm the importance of relativistic effects and pion cloud in nucleon structure
- Dressed quark-diquark model using the Dyson-Schwinger and Faddeev equations in good agreement



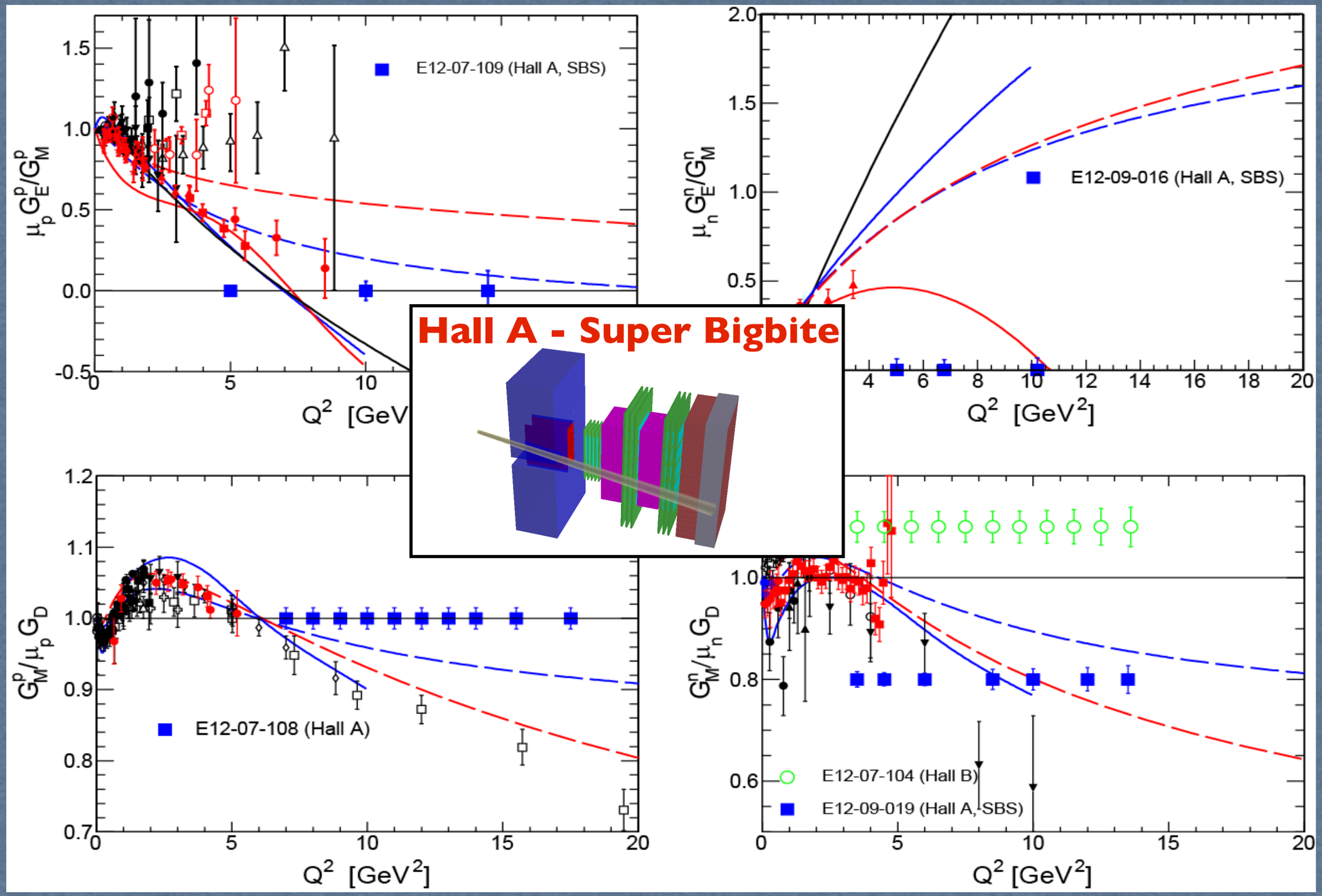


Form Factors – Plans for 12 GeV



Today

Form Factors – Plans for 12 GeV

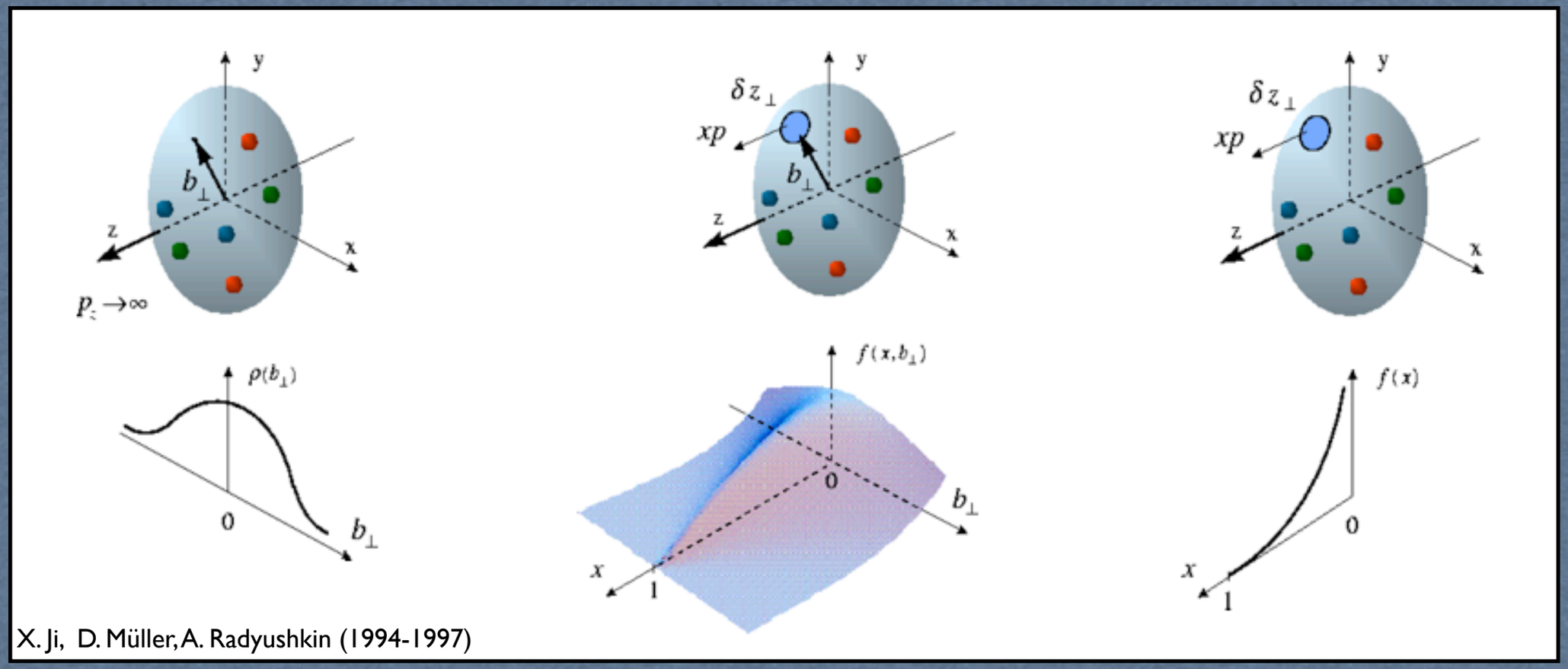


JLab at 12 GeV

JLab science: today and in the 12 GeV era

- **Nucleon Structure**
  - EM, EW, and Flavor-Separated Form Factors
  - Structure Functions and Extensions to $x \rightarrow 1$
  - Generalized Parton Distributions
  - N* s and Transition Form Factors
- **Quark Electro-Weak Couplings and Standard Model Tests**
- **The Physics of Confinement – the Search for Hybrid Mesons**
- **Nuclear Structure and the Quark Structure of Nuclei**
  - N-N Short Range Correlations and the EMC Effect
  - Hypernuclear Physics
  - High-p Structure and Nucleons in medium

NUCLEON STRUCTURE
from elastic form factors to GPDs



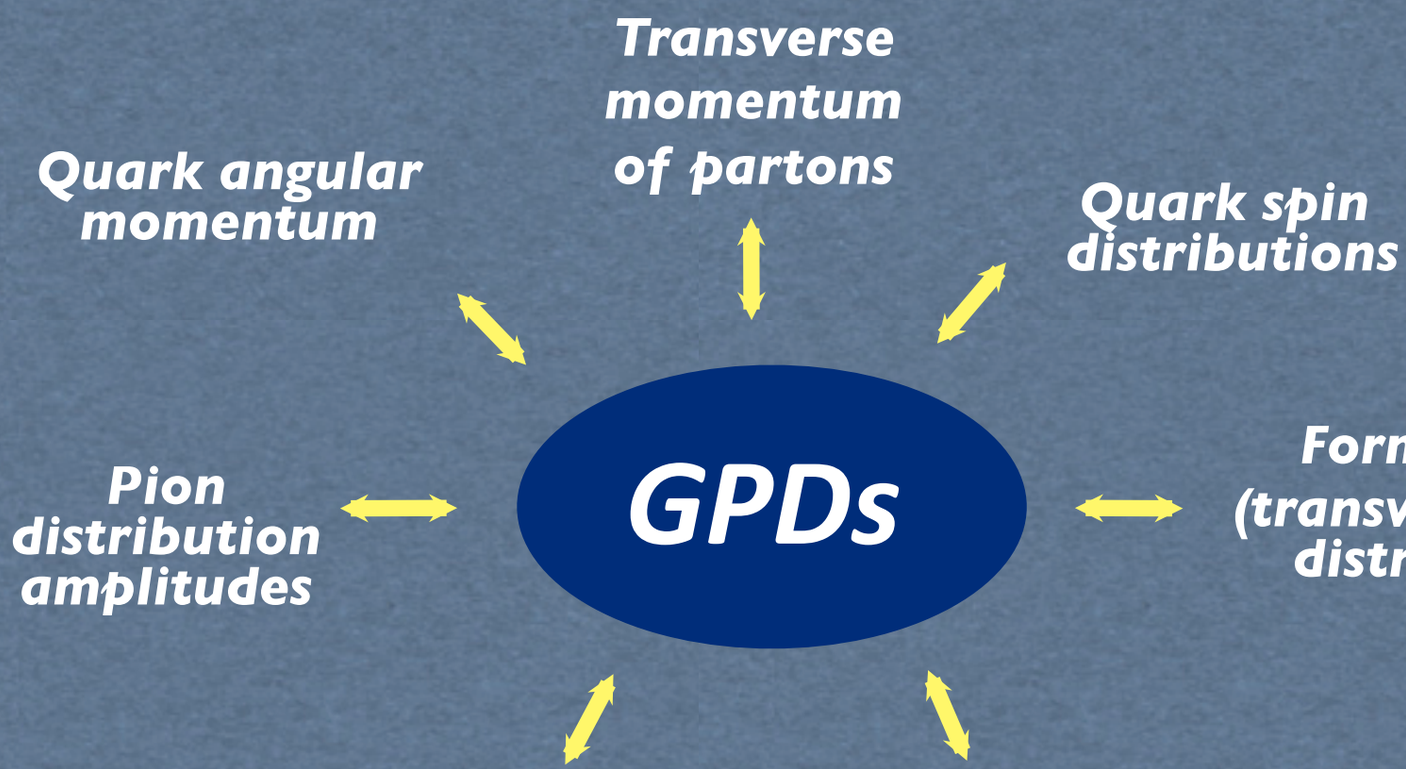
X. Ji, D. Müller, A. Radyushkin (1994-1997)

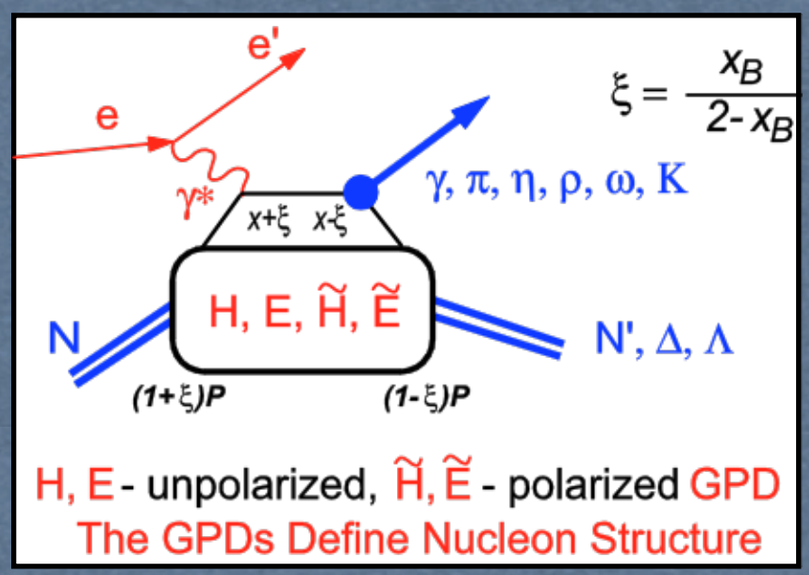
Elastic Scattering
transverse quark distribution in Coordinate space (charge and current densities)

Deep Exclusive Scattering
fully-correlated quark distribution in both coordinate and momentum space (**Generalized Parton Distributions**)

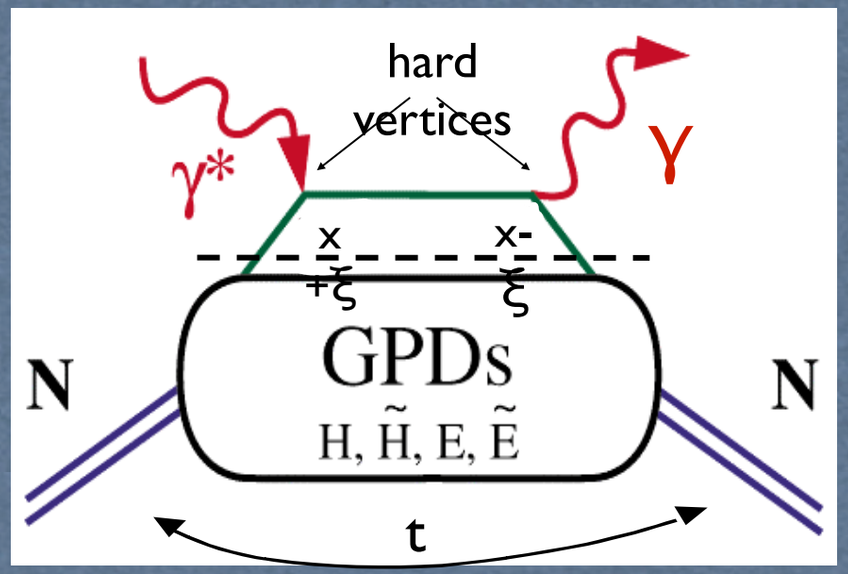
Deep Inelastic Scattering
longitudinal quark distribution in momentum space (momentum and helicity distributions)

Developing a Unified Description of Hadron Structure via the Recently Devised Generalized Parton Distributions





Deeply Virtual Compton Scattering (DVCS) is 'gold channel'

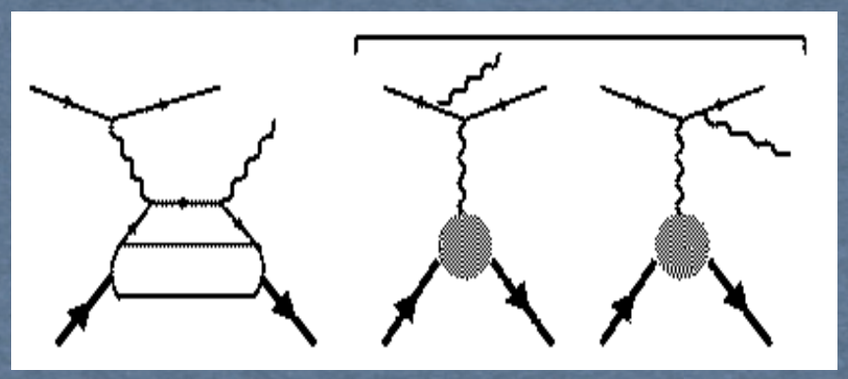


x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

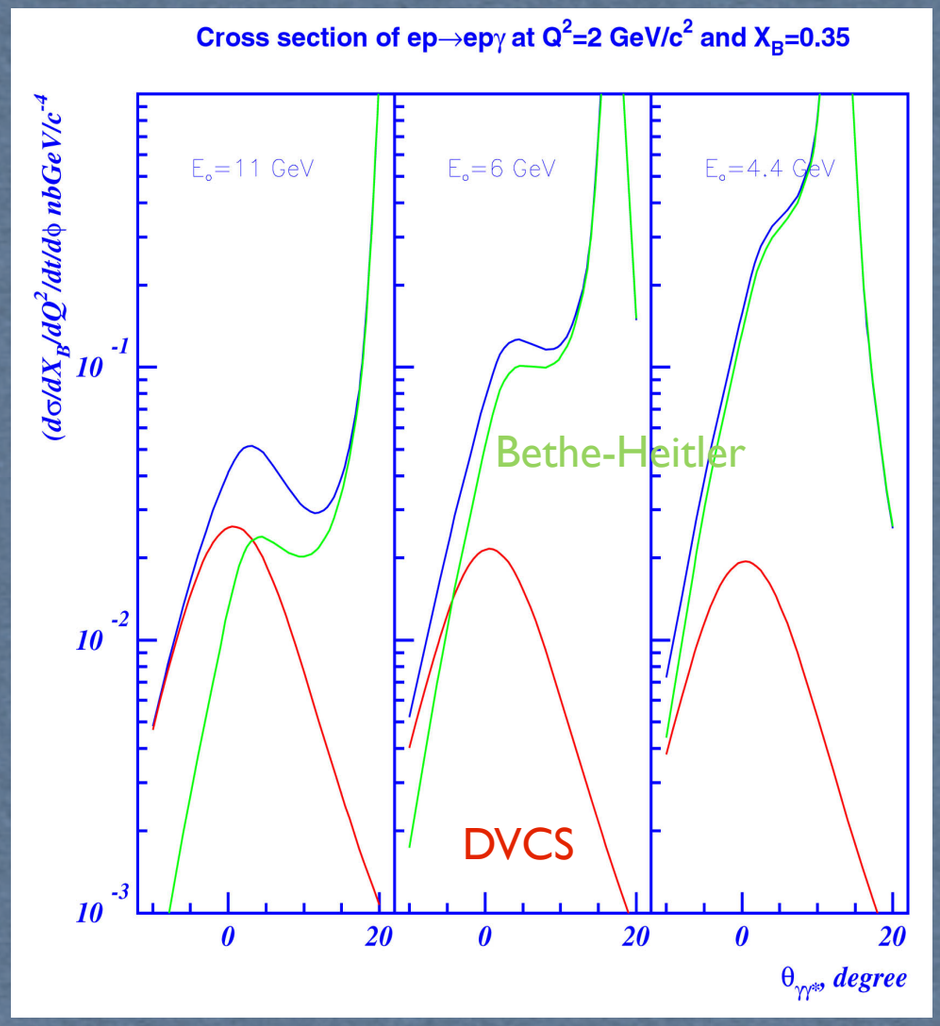
$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\varphi} \sim |T^{DVCS} + T^{BH}|^2$$



T^{BH}: given by elastic form factors

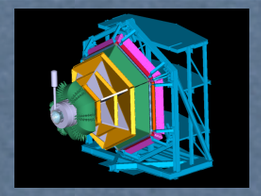
T^{DVCS}: determined by GPDs

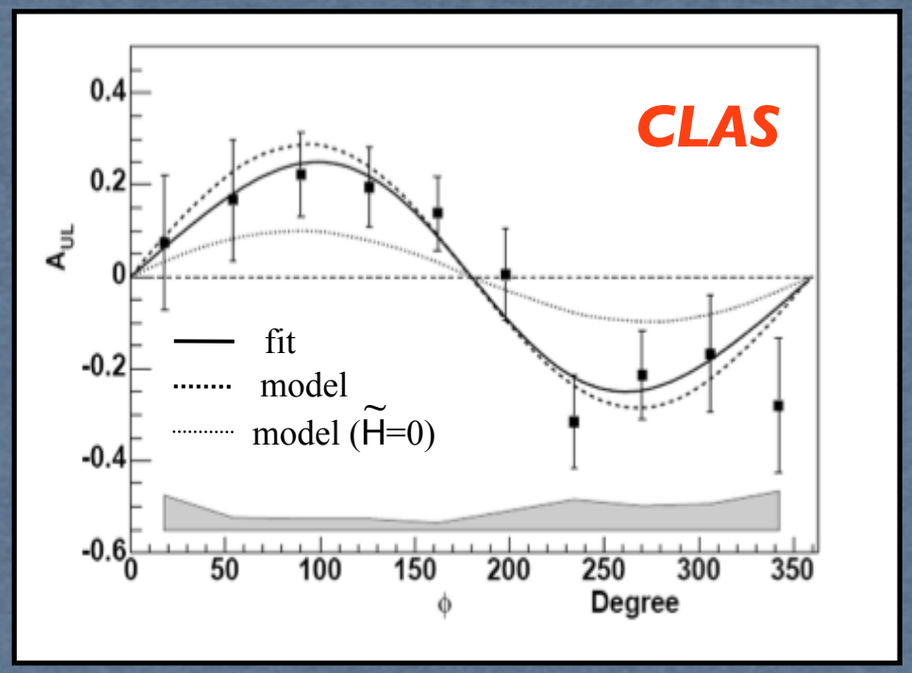


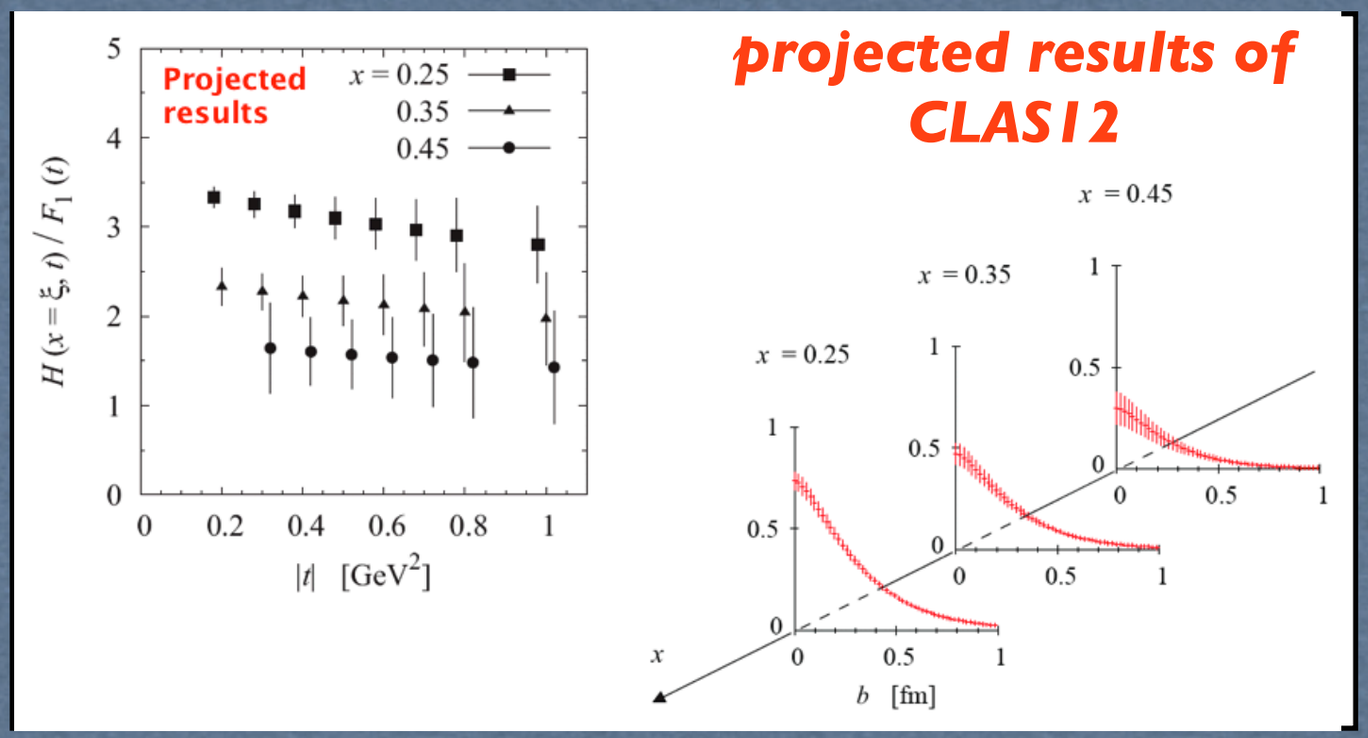
BH-DVCS interference generates **beam and target asymmetries** that carry the nucleon structure information.

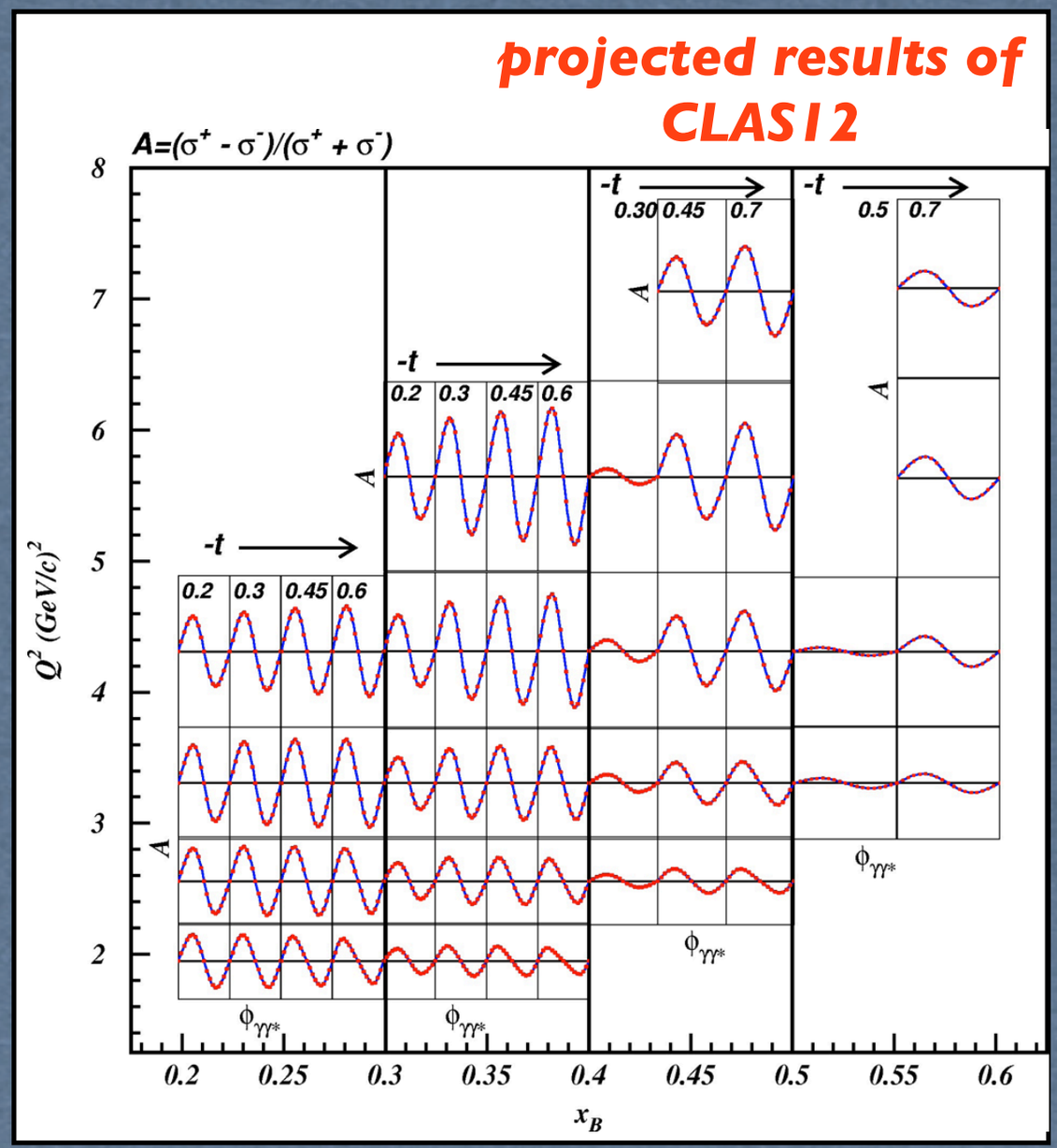
$$\Delta\sigma_{UL} \sim \sin\varphi \, \mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)H + \ldots\} d\varphi$$

From pioneering results of CLAS to full kinematic coverage of CLAS12

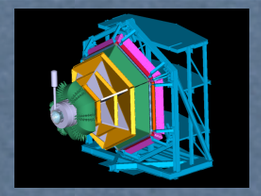


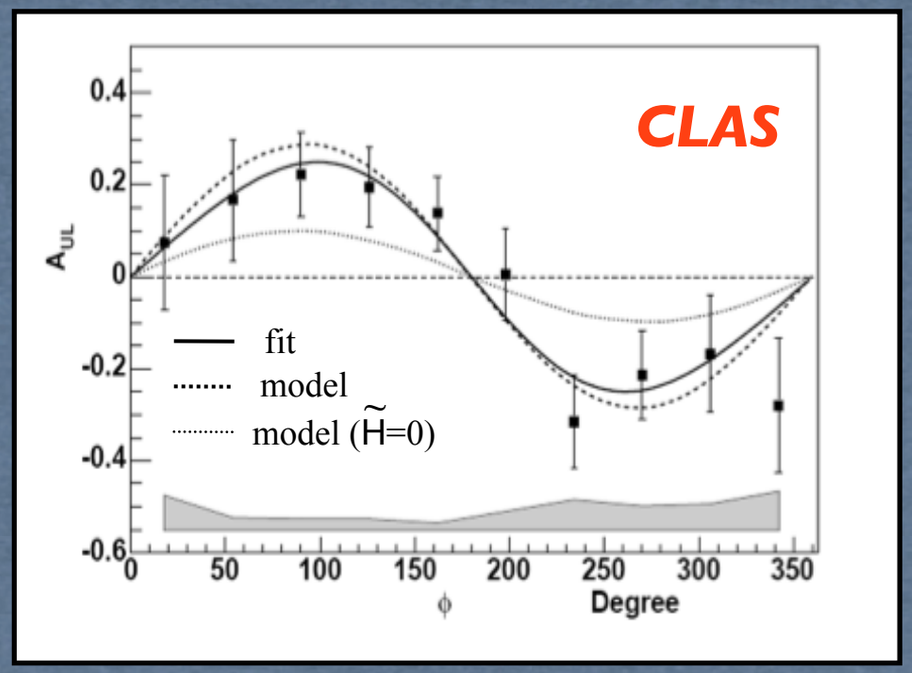


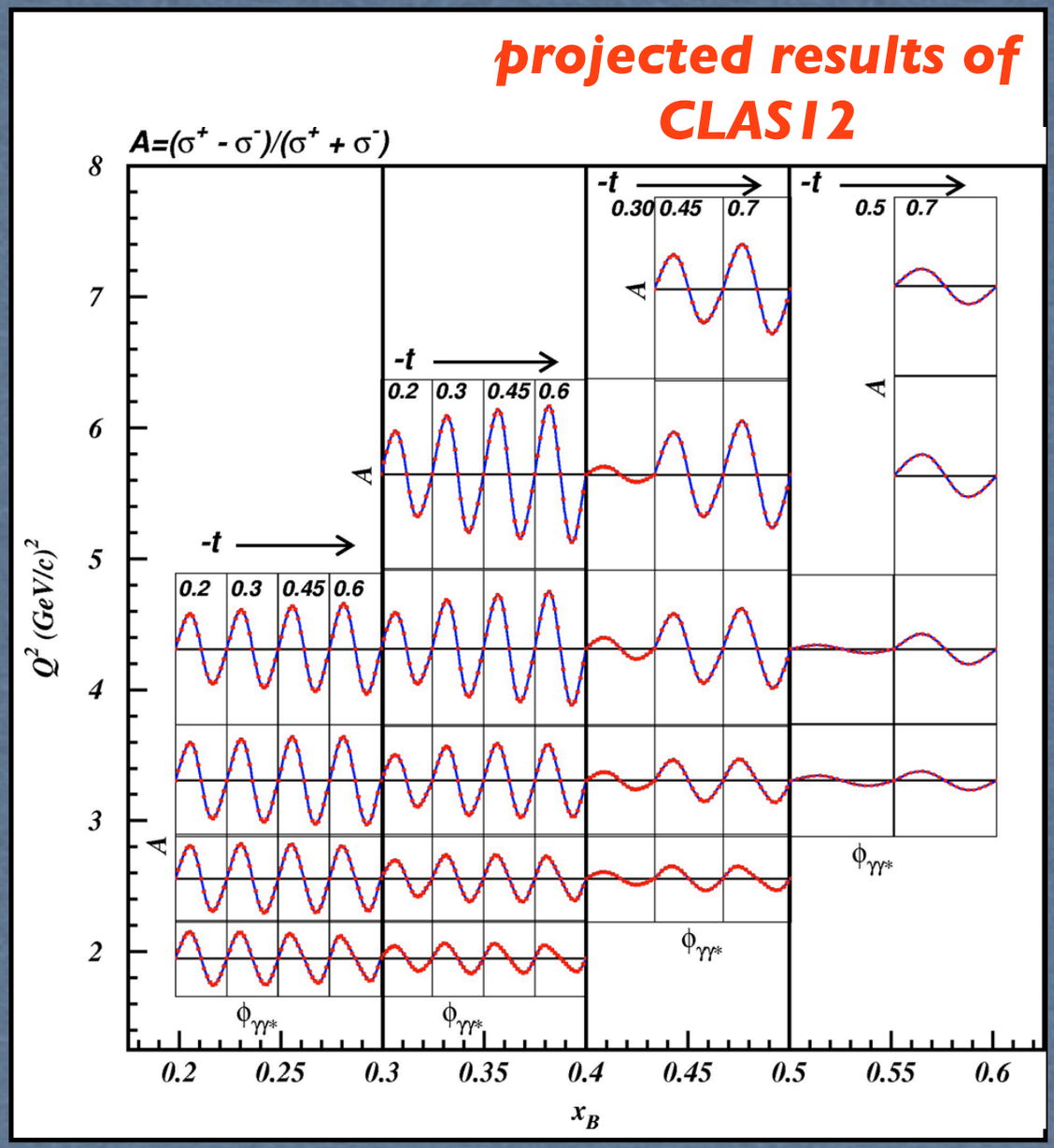


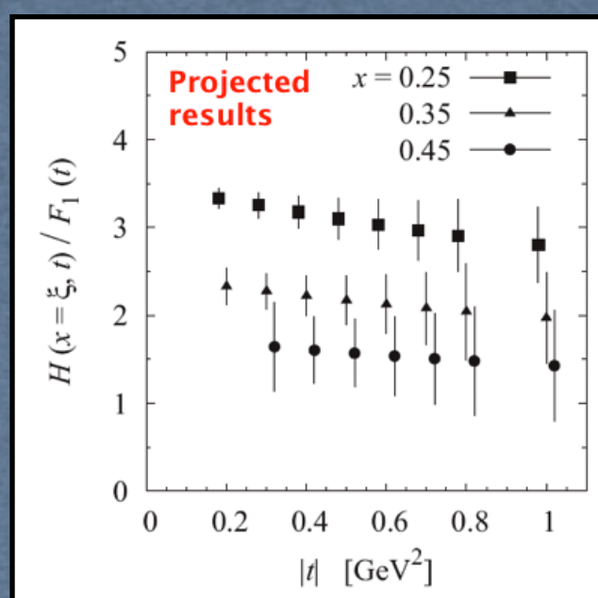


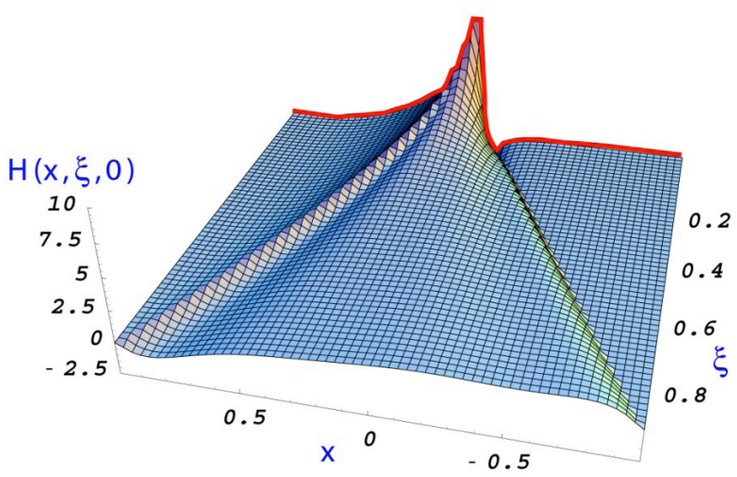
From pioneering results of CLAS to full kinematic coverage of CLAS12











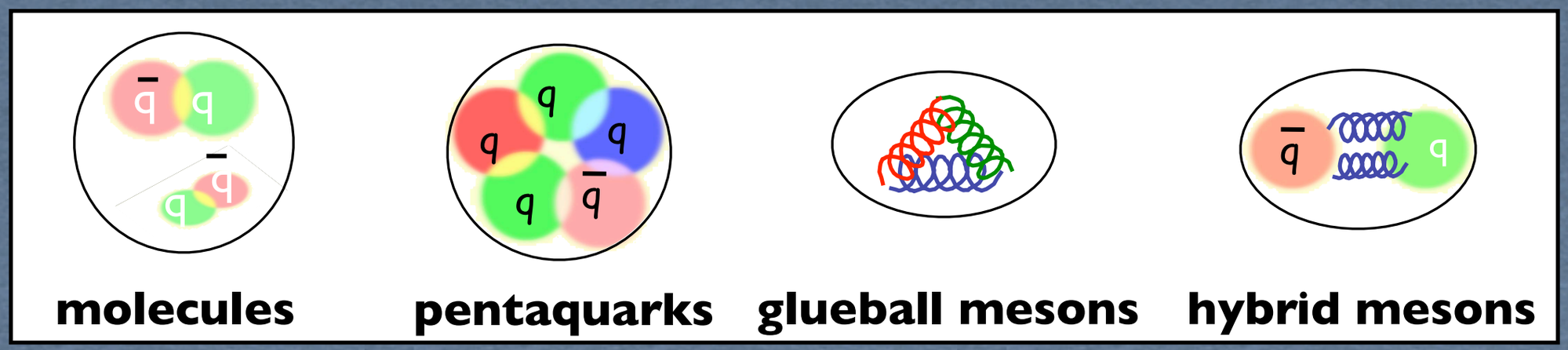
JLab science: today and in the 12 GeV era

- **Nucleon Structure**
  - EM, EW, and Flavor-Separated Form Factors
  - Structure Functions and Extensions to $x \rightarrow 1$
  - Generalized Parton Distributions
  - N* s and Transition Form Factors
- **Quark Electro-Weak Couplings and Standard Model Tests**
- **The Physics of Confinement – the Search for Hybrid Mesons**
- **Nuclear Structure and the Quark Structure of Nuclei**
  - N-N Short Range Correlations and the EMC Effect
  - Hypernuclear Physics
  - High-p Structure and Nucleons in medium

Beyond the quark model: hybrids and exotics

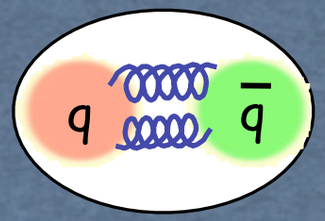
Quarks are confined inside colorless hadrons
they combine to 'neutralize' color force

Other quark-gluon configuration can give colorless objects



QCD does not prohibit such states but not yet unambiguously observed

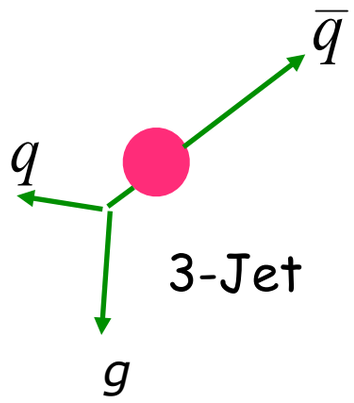
Meson spectroscopy with photons at JLab

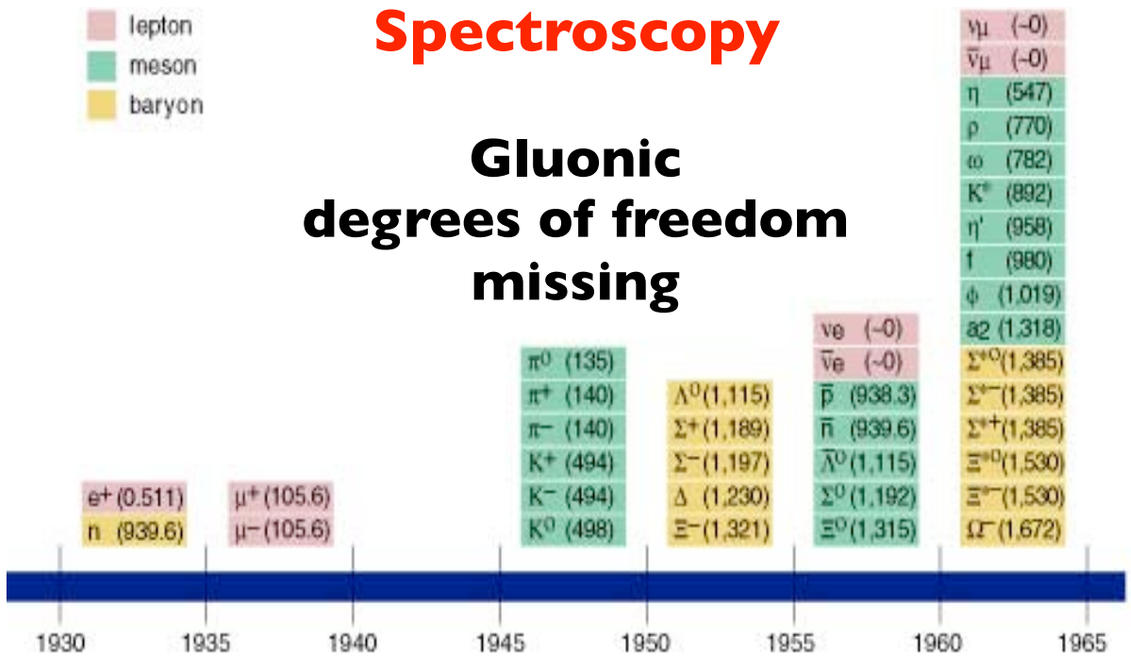


hybrid mesons

Understanding gluonic excitations of mesons and the origin of confinement

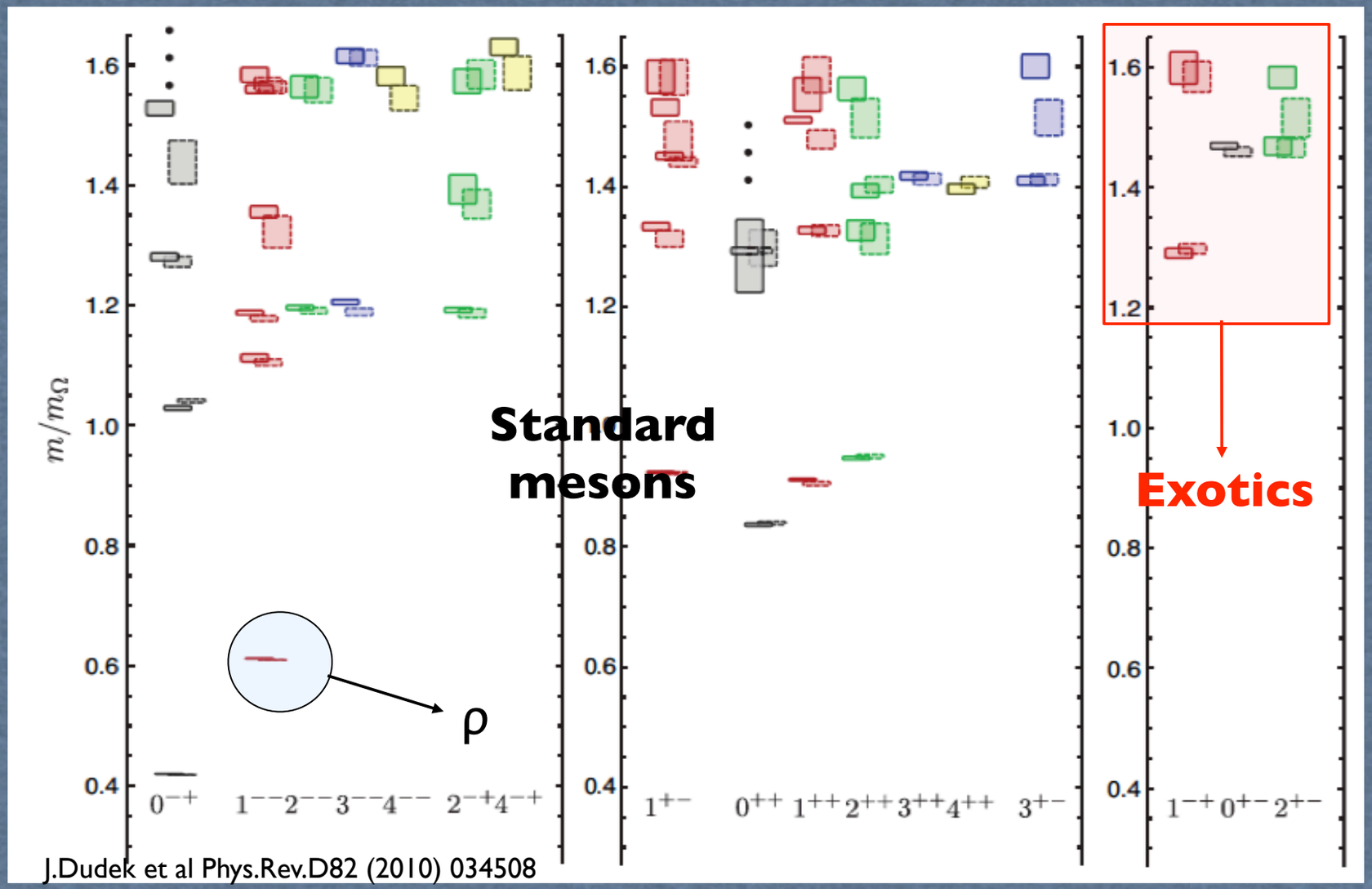
Gluon jets observed at high energy





one of the most important issue in hadron physics and main motivation for the JLab 12 GeV upgrade (GlueX program in Hall-D)

QCD Lattice calculations



J.Dudek et al Phys.Rev.D82 (2010) 034508

Lattice-QCD predictions for the lowest hybrid states

0^{+-} 1.9 GeV
1^{-+} 1.6 GeV

Hybrid mesons and glueballs mass range:

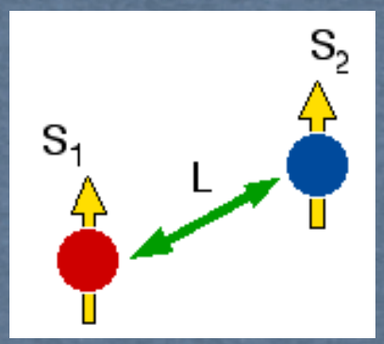
1.4 GeV - 3.0 GeV

This mass range is accessible in photoproduction experiments with a beam energy in the range 5 GeV < E_γ <12 GeV

Perfectly matched to JLab12 energy!

Meson spectroscopy with photons at JLab

Search for mesons with 'exotic' quantum numbers
(not compatible with quark-model)

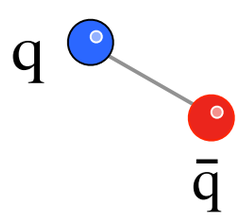


$S=S_1+S_2$ $J= L+S$ $P = (-1)^{L+1}$ $C= (-1)^{L+S}$

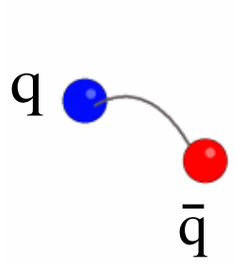
Not-allowed: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$ ...

Unambiguous experimental signature for the presence of gluonic degrees of freedom in the spectrum of mesonic states

Normal meson:
flux tube in
ground state
m=0
$CP=(-1)^{S+1}$

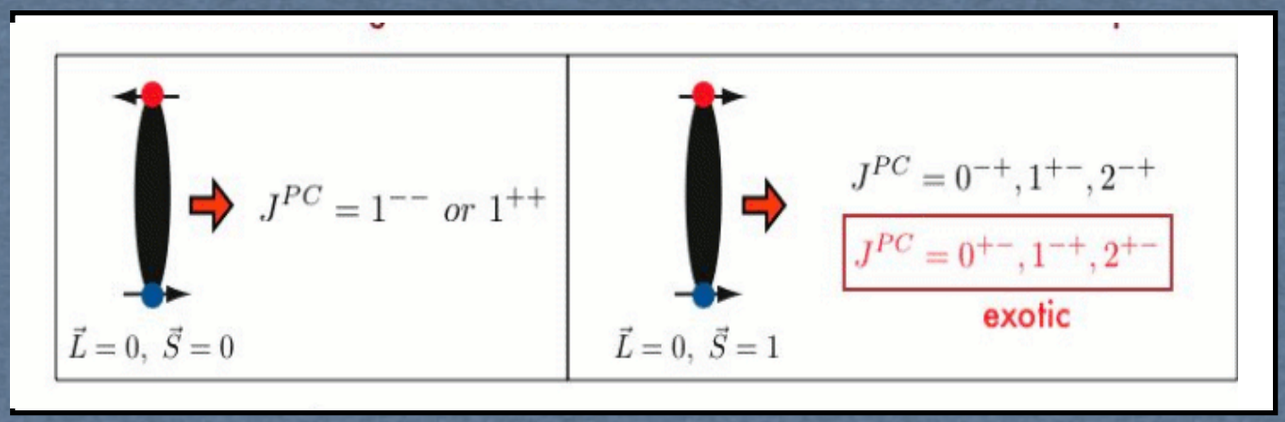


Hybrid meson:
flux tube in
excited state
m=1
$CP=(-1)^{S}$



Flux tube
J^{PC} 1^{-+}, 1^{+-}

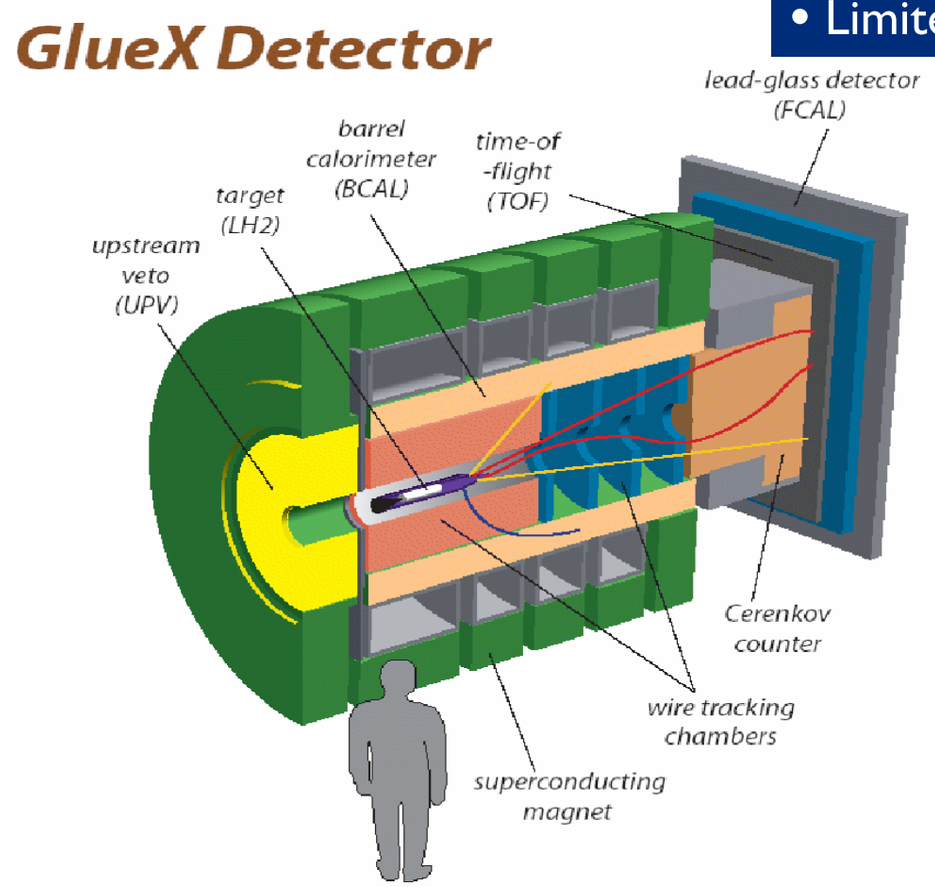
Combine excited glue quantum number with those of the quarks



Meson spectroscopy with photons at JLab-12 GeV

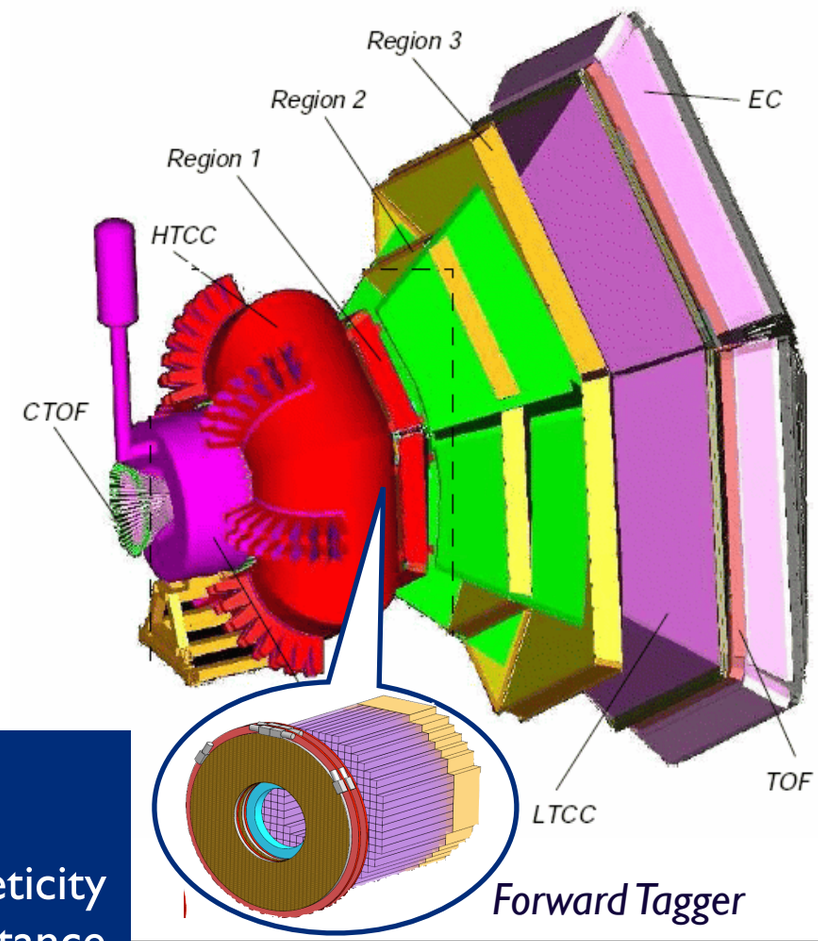
- Determination of JPC of meson states requires PWA
- Decay and production of exclusive reactions
- Good acceptance, energy resolution, particle identification

Hall-D - GlueX Detector



- Good hermeticity
- Uniform acceptance
- Limited resolution
- Limited pID

Hall-B - CLAS12 Detector

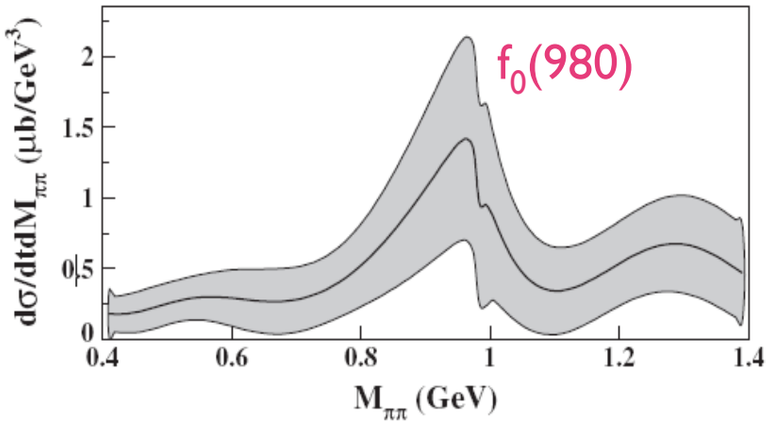


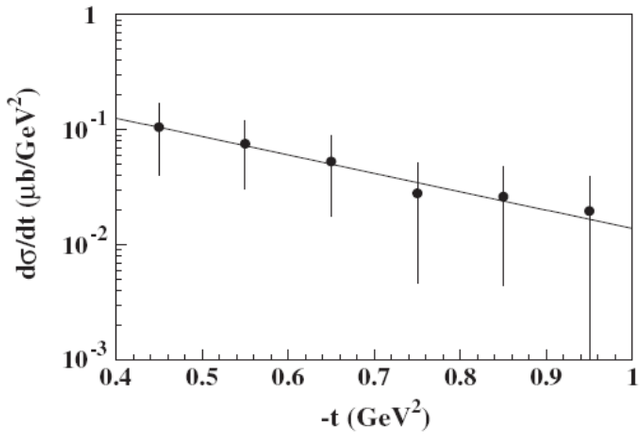
- Good resolution
- Good pID
- Reasonable hermeticity
- Un-uniform acceptance

From CLAS@6GeV to GlueX and MesonEx

CLAS@6GeV

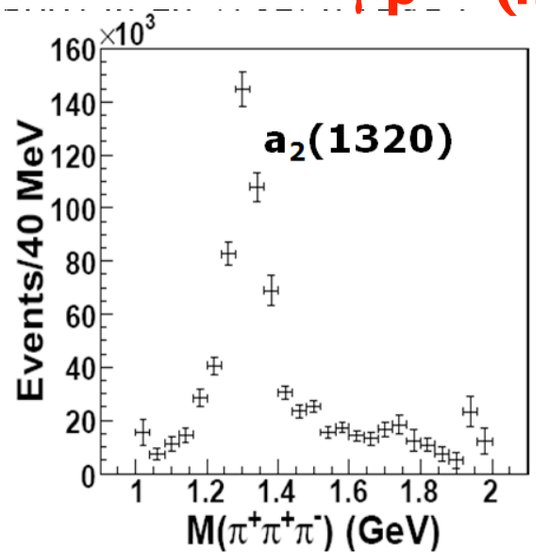
$\gamma\, p \rightarrow p\, \pi^+ \pi^-$

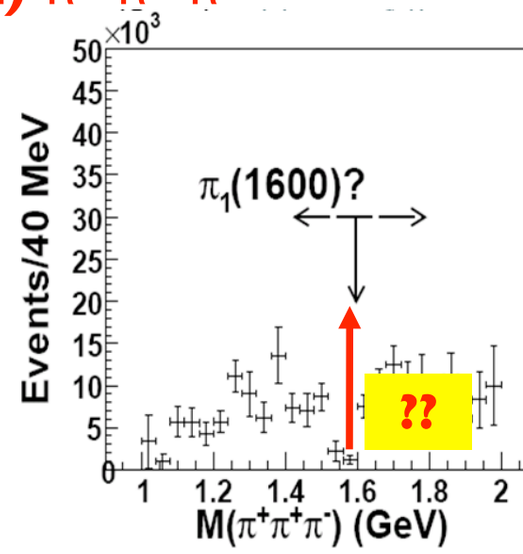




First observation of the $f_0(980)$ in a photoproduction experiment

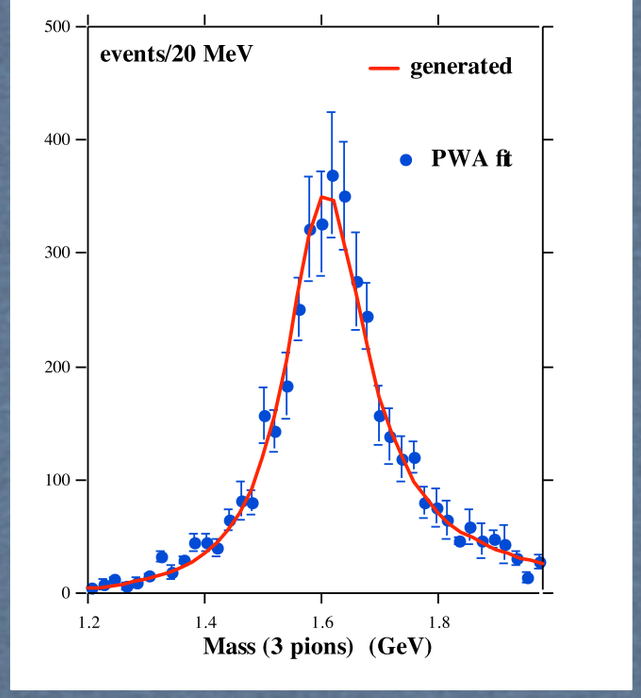
$\gamma\, p \rightarrow (n)\, \pi^+ \pi^+ \pi^-$



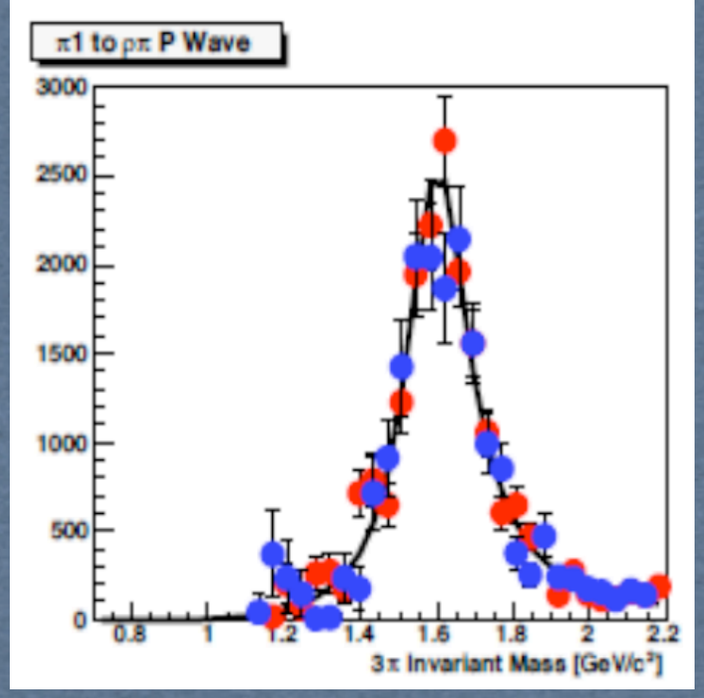


No-evidence of exotic 1^{-+} state $\pi_1(1600)$

GlueX - Hall D



MesonEx - Hall B



Benchmark reaction:
$\gamma\, p \rightarrow (n)\, \pi^+ \pi^+ \pi^-$

An exotic wave ($J^{PC} = 1^{-+}$) was generated at level of 2.5 % with 7 other waves. Events were smeared, accepted, passed to PWA fitter
Statistics correspond to few days of running

X (exotic) $\rightarrow \rho\, \pi^+ \rightarrow \pi^+ \pi^+ \pi^-$

JLab science: today and in the 12 GeV era

✳**Nucleon Structure**

- EM, EW, and Flavor-Separated Form Factors
- Structure Functions and Extensions to x→1
- Generalized Parton Distributions
- N* s and Transition Form Factors

Tomorrow:
16:30 Vincenzo Bellini (Catania)
New trends in hadronic physics at JLab

Today, Parallel Session A
16:00 Silvia Niccolai (Orsay)
GPDs with CLAS and CLAS12

Today, Parallel Session A
16:35: Mauro Taiuti (Genova)
Transition form factors in CLAS and CLAS12

✳**Quark Electro-Weak Couplings and Standard Model Tests**

✳**The Physics of Confinement – the Search for Hybrid Mesons**

✳**Nuclear Structure and the Quark Structure of Nuclei**

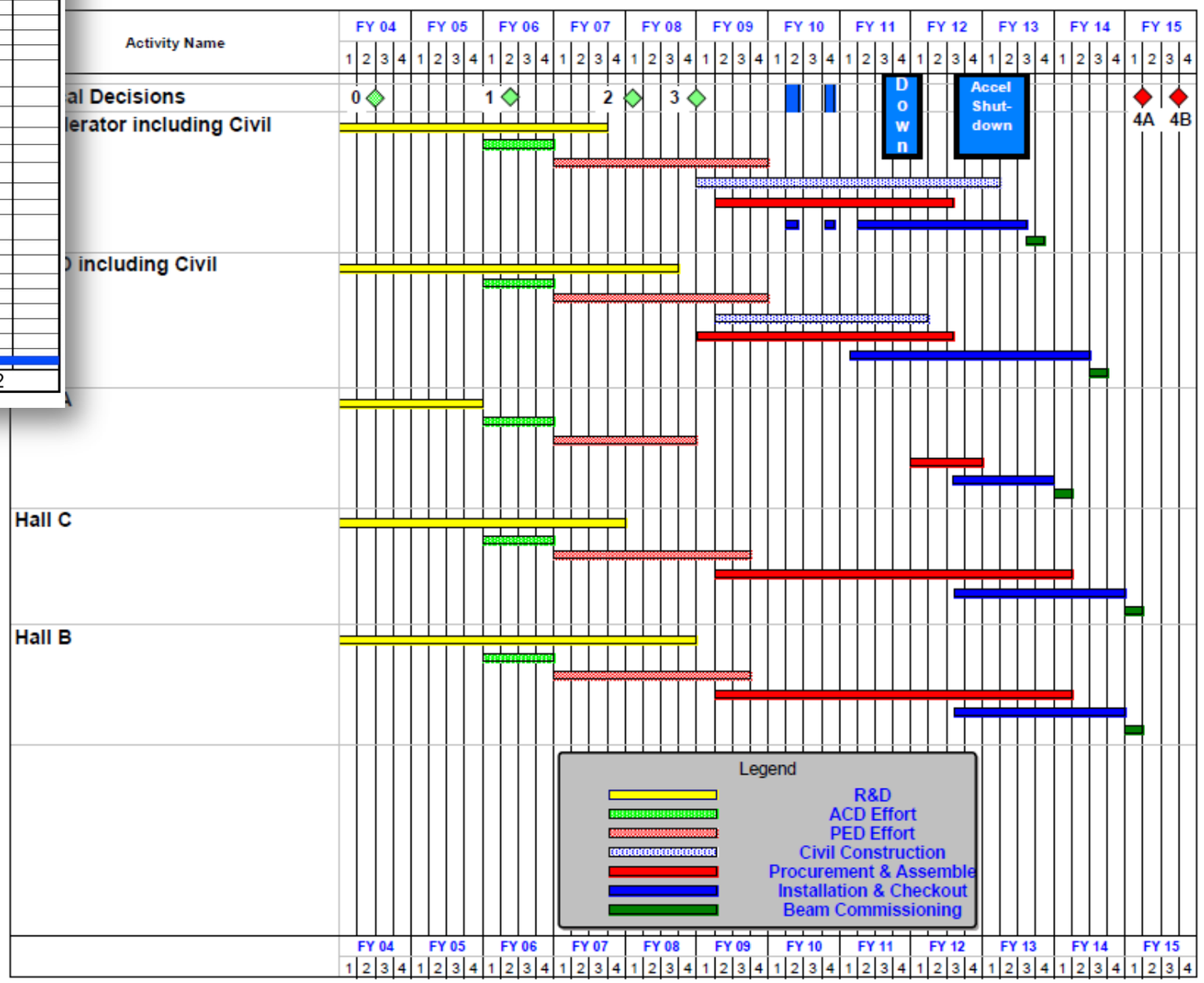
- N-N Short Range Correlations and the EMC Effect
- Hypernuclear Physics
- High-p Structure and Nucleons in medium

Timeschedule and conclusions

	Experiment	FY2009	FY2010	FY2011	FY2012
1	Hall A				
2	Tranversity & SSA-He3				
3	d2n (E06-014)				
4	3He SSA (E05/015/E08-005)				
5	3He AxAz (E05-102)				
6	HAPPEx-III (E05-109)				
7	PV-DIS (E08-011)				
8	PREx (E06-002)				
9	A' Tests				
10	DVCS (E07-007/E08-025)				
11	N-Delta (E08-010)				
12	D-Threshold (E08-008)				
13	SRC (E07-006)				
14	E08-009(4He)				
15	x>2 (E08-014)				
16	g2p (E08-027)				
17	Proton FF DSA (E08-010)				
18	~~Hypernuclear (E07-012)~~				
19					
20	Hall B				
21	eg1-dvcs				
22	eg6 (DVCS and Meson Spect.)				
23	g9-Frost (N* w/ Pol. Target)				
24	PRIMEx II (E08-023)				
25	eg5 (e+/e- TPE)				
26	HD ICE				
27					
28	Hall C				
29					
30	SANE(E07-003)				
31	~~g1d (E07-011)~~				
32	HKS-HES				
33	Q-Weak-I				
34	Q-Weak-II				
35					
36	Accelerator Major Downs				
		2009	2010	2011	2012

6-month installation
May – Dec 2011

12-month installation
May 2012 – May 2013



Hall A commissioning start
October 2013

Hall D commissioning start
April 2014

Halls B/C commissioning start
October 2014

Project Completion
June 2015

Timeschedule and conclusions

CEBAF@JLab is fulfilling its scientific mission:

- To understand how hadrons are constructed from the quarks and gluons of QCD
- To understand the QCD basis for the nucleon-nucleon force
- To explore the limits of our understanding of nuclear structure

  high precision
  short distances
  the transition from the nucleon-meson to the QCD description

The 12 GeV Upgrade will greatly enhance the scientific“reach” of the facility, supporting an exciting program of fundamental research