Exploring the Nature of Matter

Jefferson Lab and its plans

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September 2009

Acknowledgements

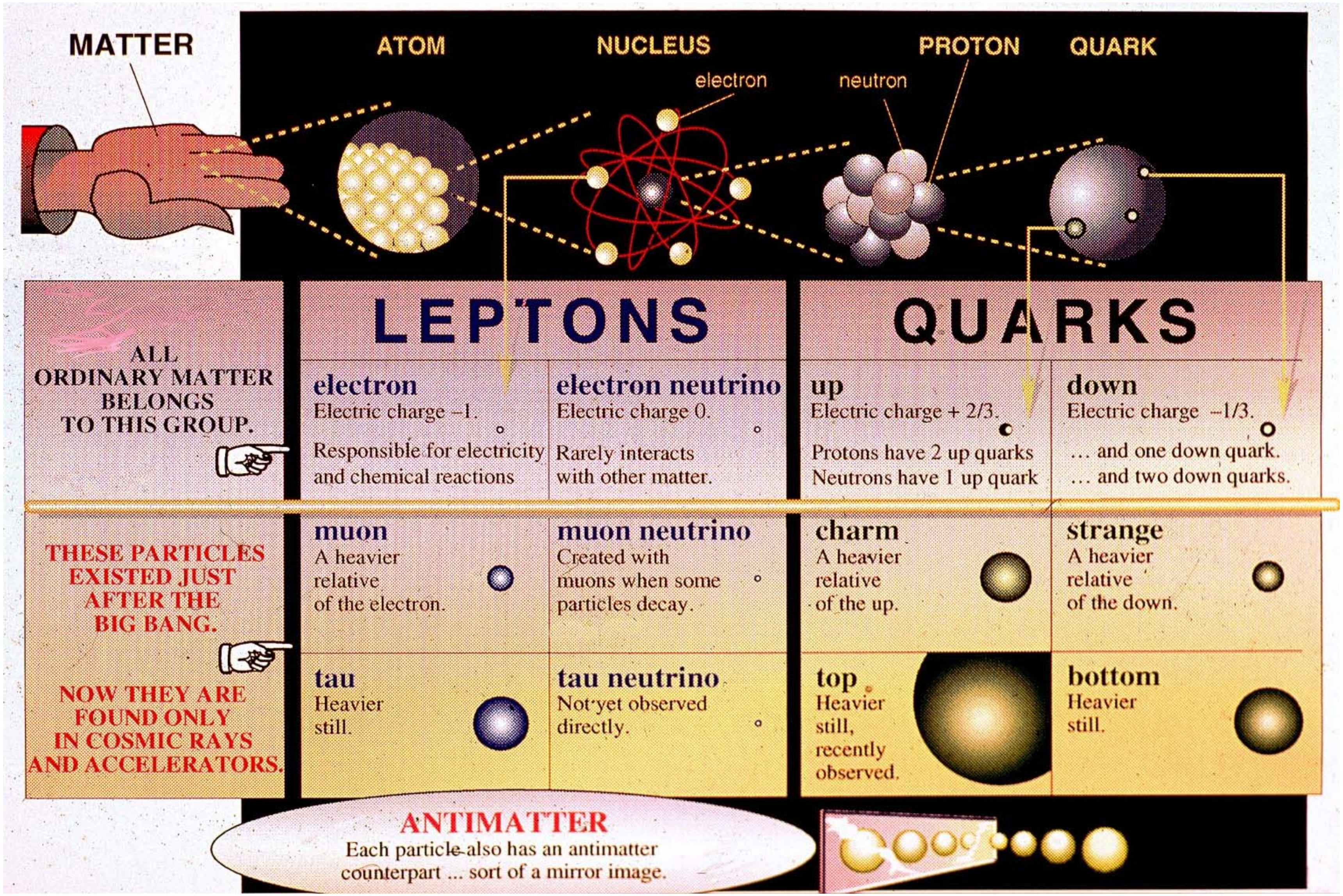
This talk was compiled from the work of many others. In particular I have liberally used several transparencies from talks presented by my colleagues at Jefferson Laboratory and others from whom they in turn have "borrowed".

I have also made use of the Nuclear Science Advisory Committee (NSAC) long range plan from 2007.

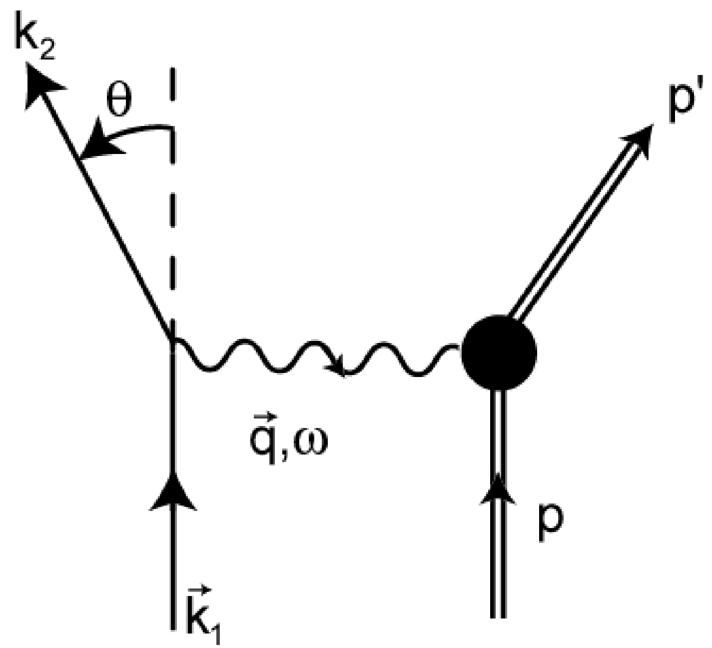
The Talk

- Introduction
  - Electron as a Probe of Nuclei and Nucleons
  - Quarks, Partons and Gluons
  - Technologies of Jefferson Laboratory
  - 12 GeV Upgrade Project
- Hadron (Nuclear and Nucleon) Structure
- Precision Electroweak Measurements
- Hadron Spectroscopy
- A Future Machine?
- Conclusions

The Ultimate Constituents



Electron Scattering: Microscope for Nuclear Physics



- Electrons are point-like
- The interaction (QED) is well-known
- The interaction is weak
- Vary q to map out Fourier Transforms of charge and current densities:
  $\lambda \cong 2\pi/q$ **(1 fm ⇔ 1 GeV/c)**

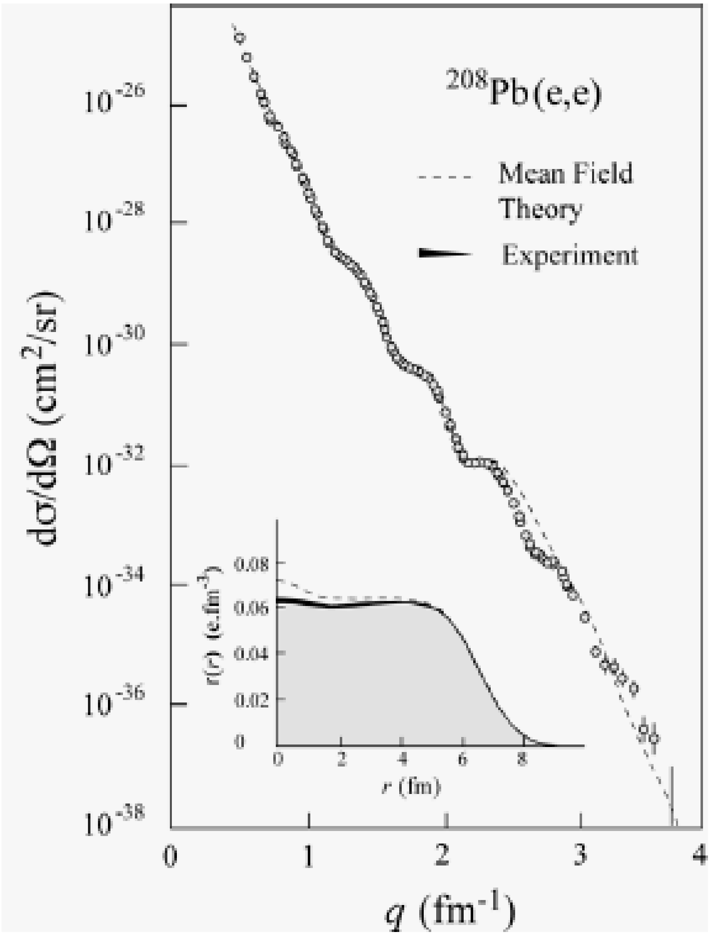
$$S_{fi} = \frac{-e^2}{\Omega}\,\bar{u}(k_2)\,\gamma^{\mu}\,u(k_1)\frac{1}{q^2}\int e^{iq\cdot x}\langle f|\hat{J}_{\mu}(x)|i\rangle d^4x$$

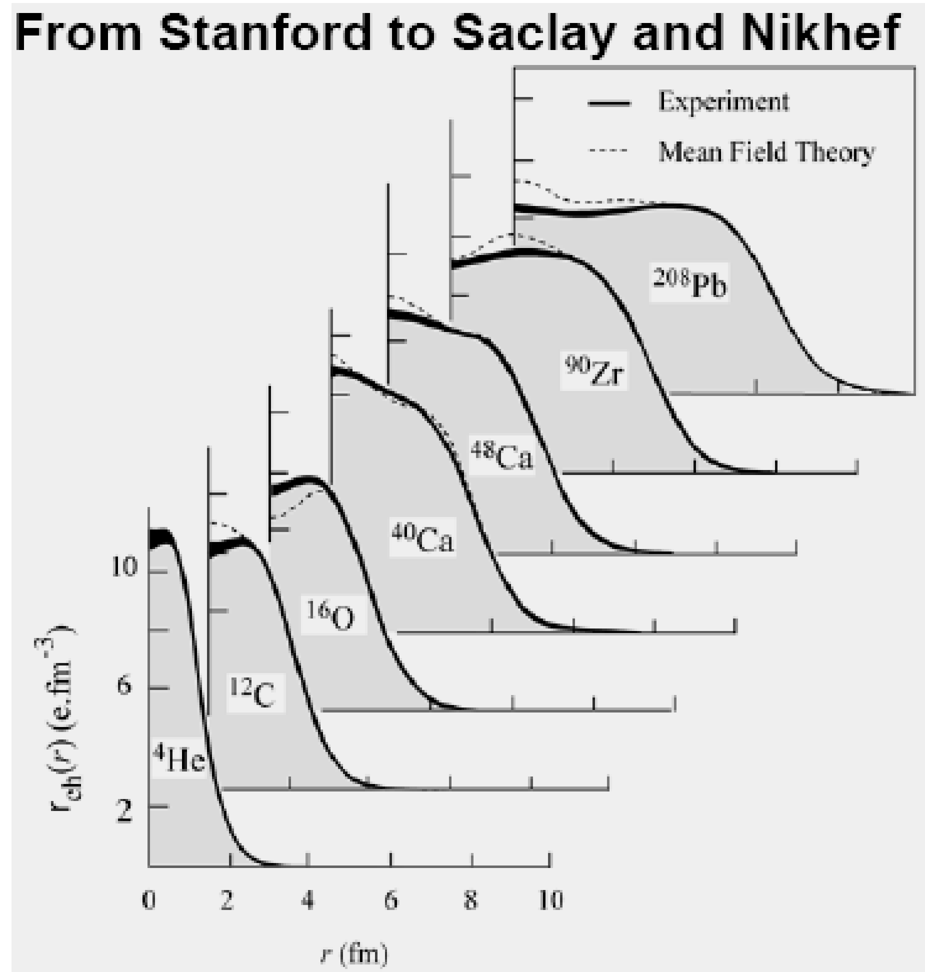
$\vec{q} = \vec{k}_1 - \vec{k}_2 =$ Momentum Transfer

$\omega = E_p - E_{p'} =$ Energy Transfer

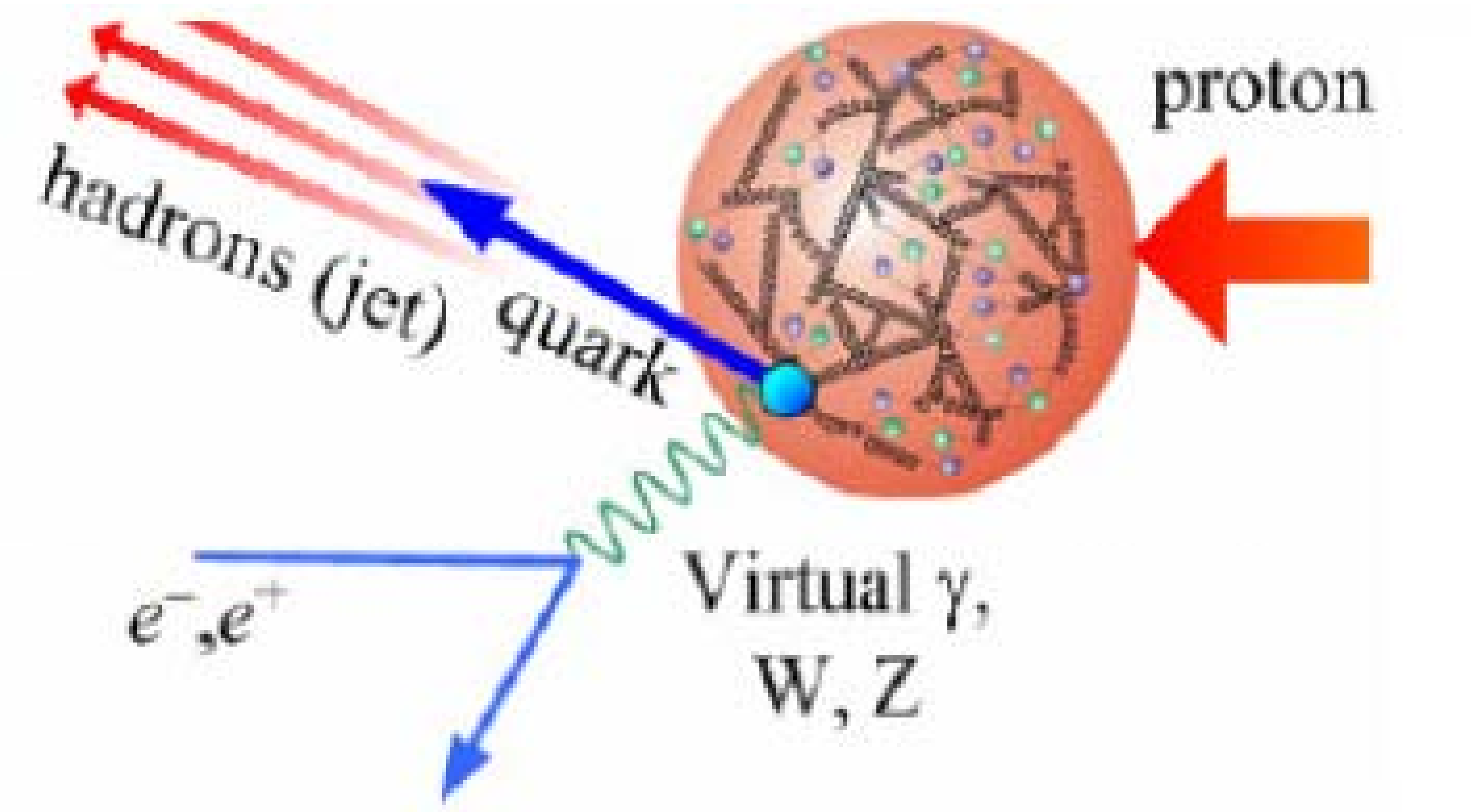
$Q^2 = -q^2 =$ 4-Momentum Transfer

Nuclear Charge Distributions





Electron Scattering: A picture



Nucleon Structure Functions

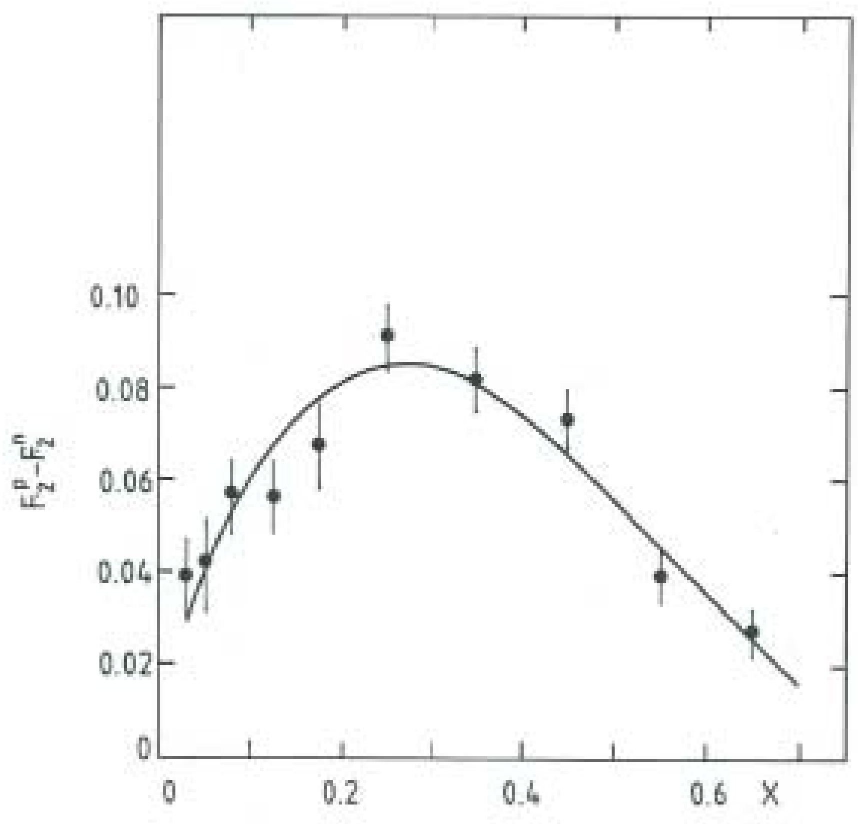
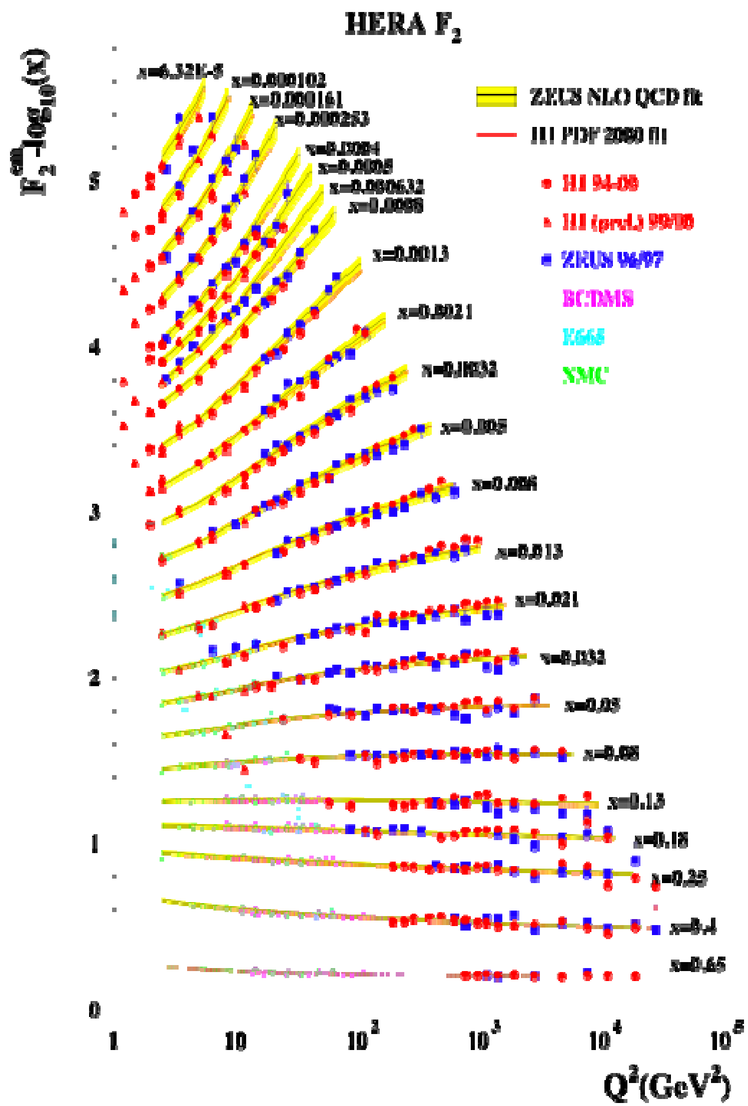


FIG. 2



Jefferson Lab

A Surprise: The EMC Effect

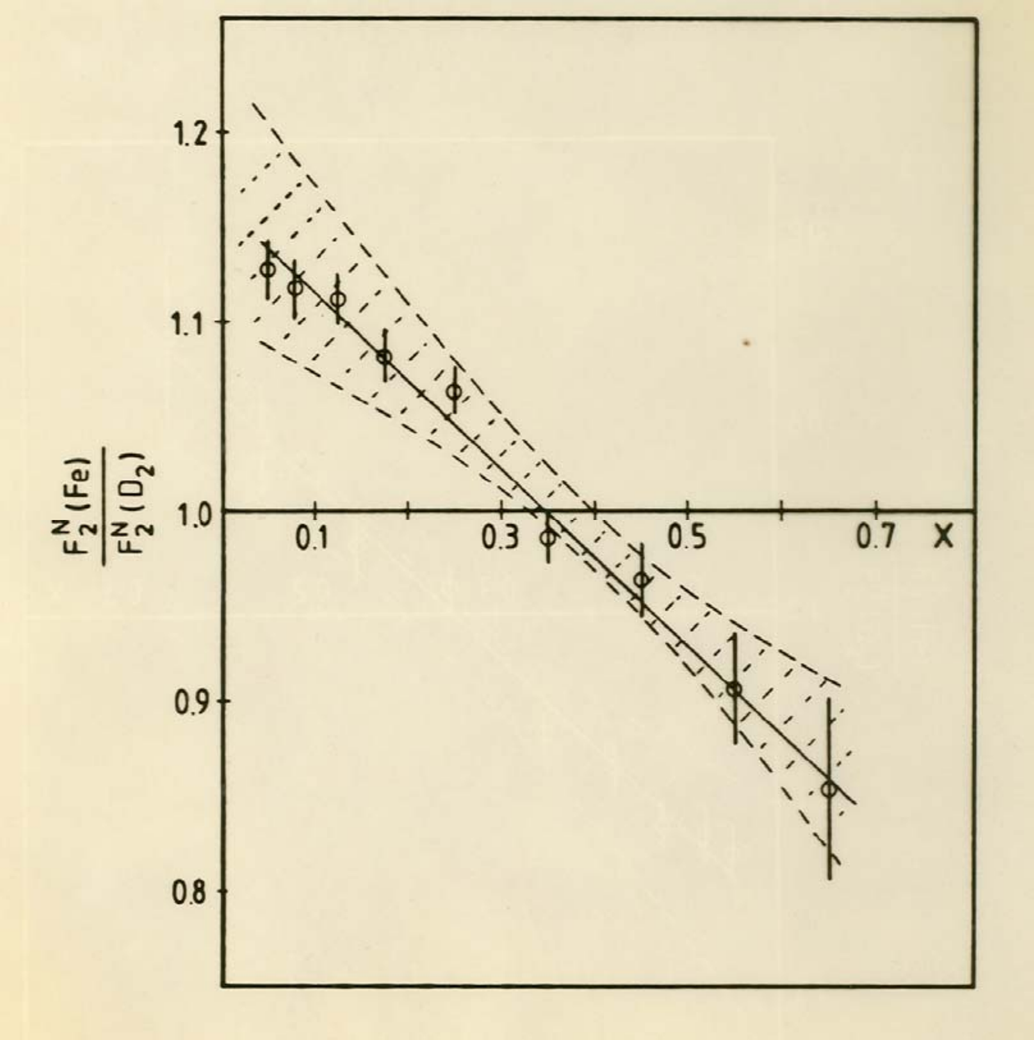
Unexpected

Despite the high momentum transfers involved

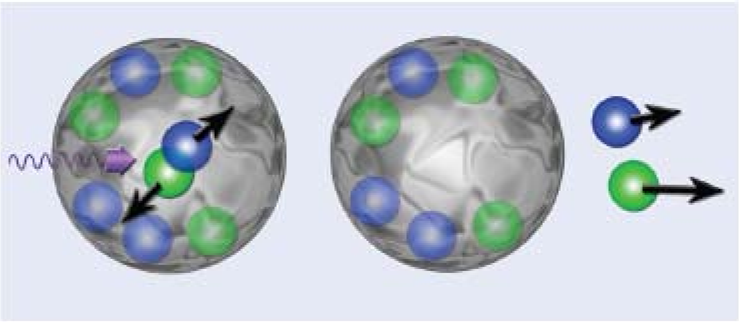
the measured F_2^N depends on the nucleus!!!!!

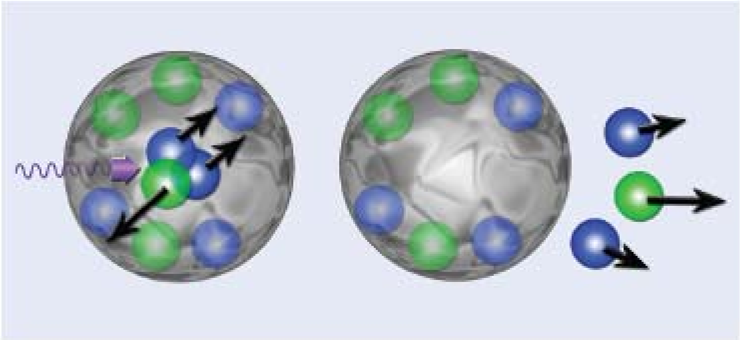
Lots of post-data wisdom from theorists!!

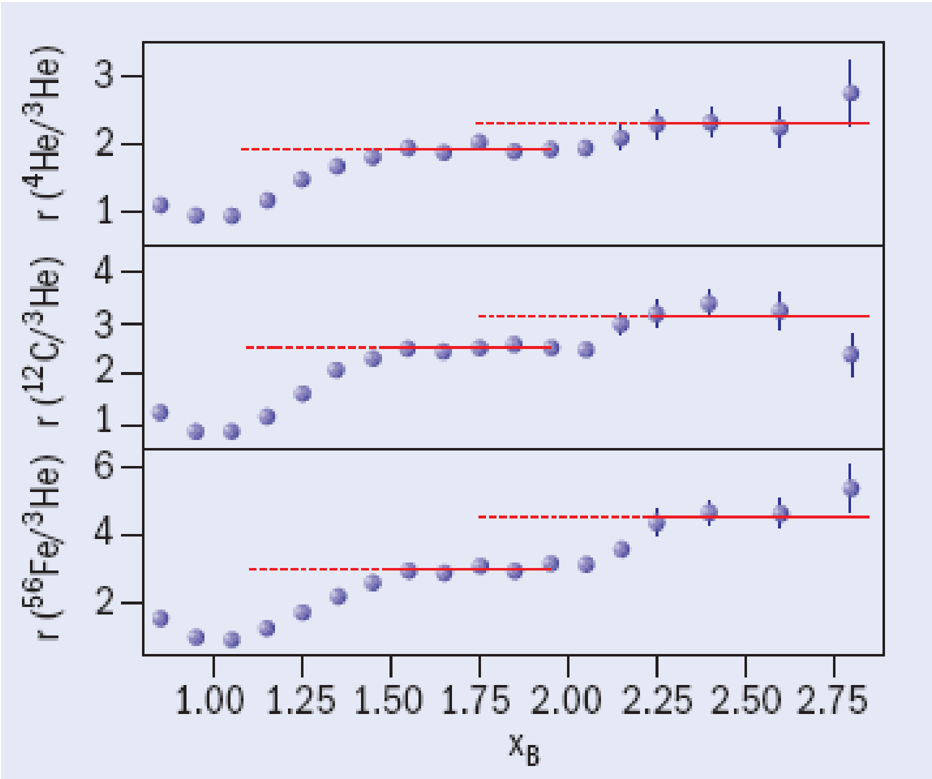
Also from experimentalists (Arie Bodek)



Nucleon Nucleon Correlations





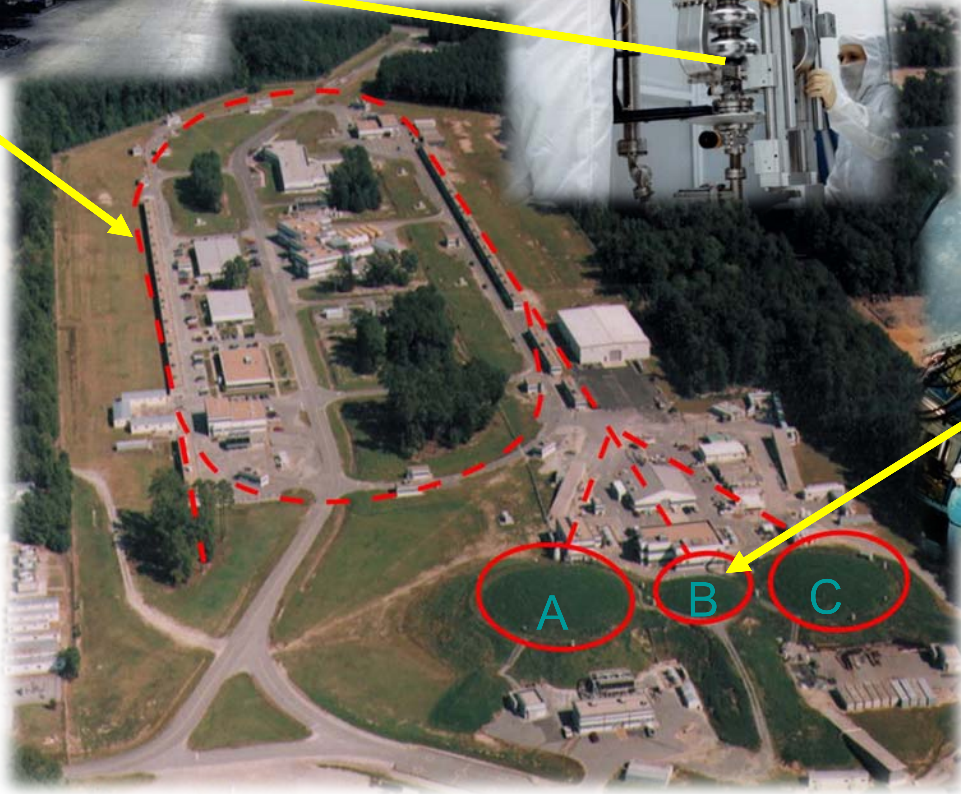


Experiment from Jefferson Lab
Graphics from CERN Courier

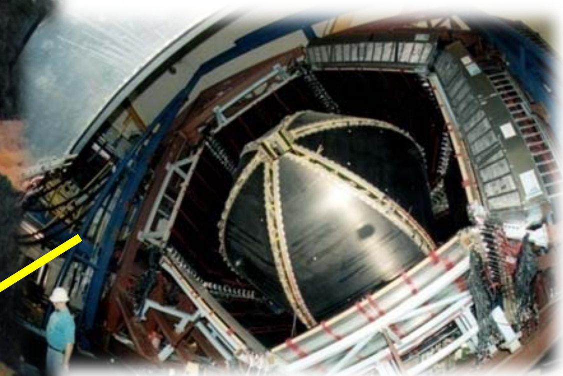
Jefferson Lab

Superconducting radiofrequency (SRF) cavities undergo vertical testing.

Cryomodules in the accelerator tunnel

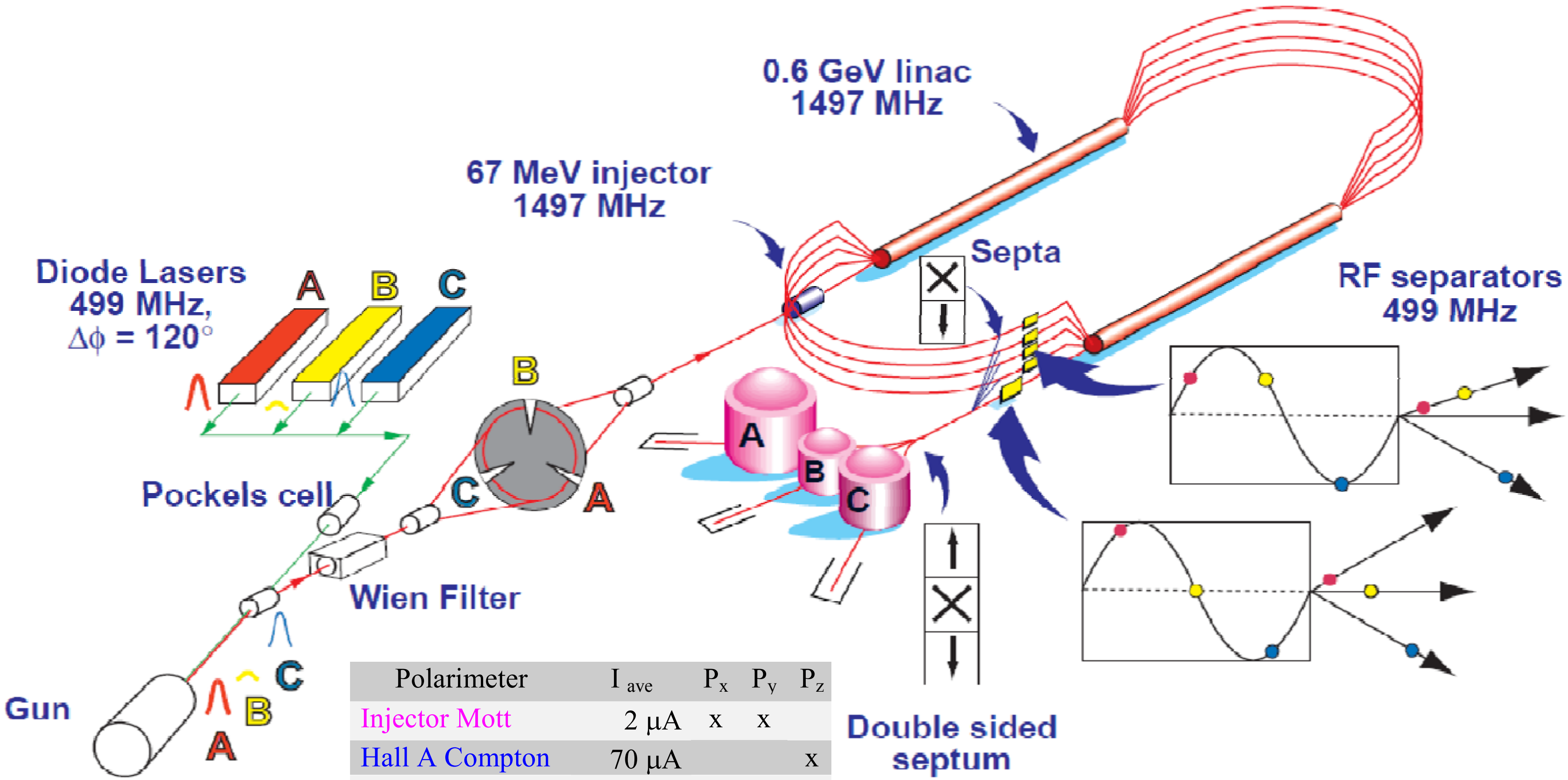


An aerial view of the recirculating linear accelerator and 3 experimental halls.



CEBAF Large Acceptance Spectrometer (CLAS) in Hall B

Spin, Current, and Beam Delivery @CEBAF



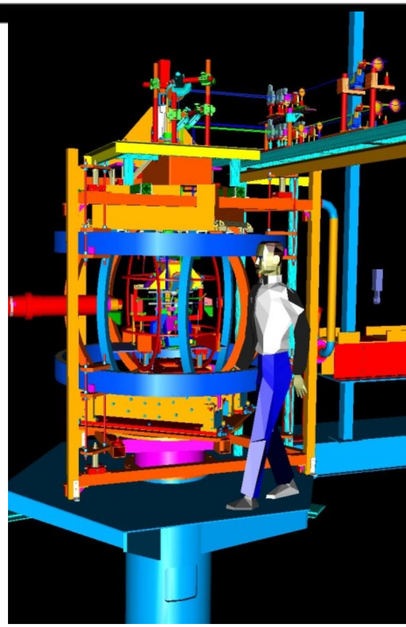
Polarimeter	I_{ave}	P_x	P_y	P_z
Injector Mott	2 µA	x	x	
Hall A Compton	70 µA			x
Hall A Moller	1 µA	x		x
Hall B Moller	10 nA		x	x
Hall C Moller	1 µA			x

Under development
<0.5% Atomic Beam Polarimeter (Hall A)
<1% Compton Polarimeter (Hall C)

Polarized Targets at JLab

Hall A: $^{3}\overrightarrow{\text{He}}$

G_E^n, SSAs
Transversity



Hall B: eg1

Dynamically polarized NH_3 ND_3,

Q^2 evolution of Nucleon Spin Structure, DVCS

Hall B: FROST

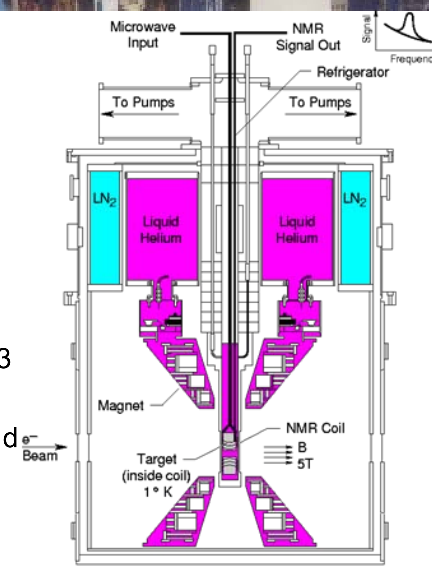
Frozen Spin Target, Butanol

"Missing" N* Search.

Hall C:

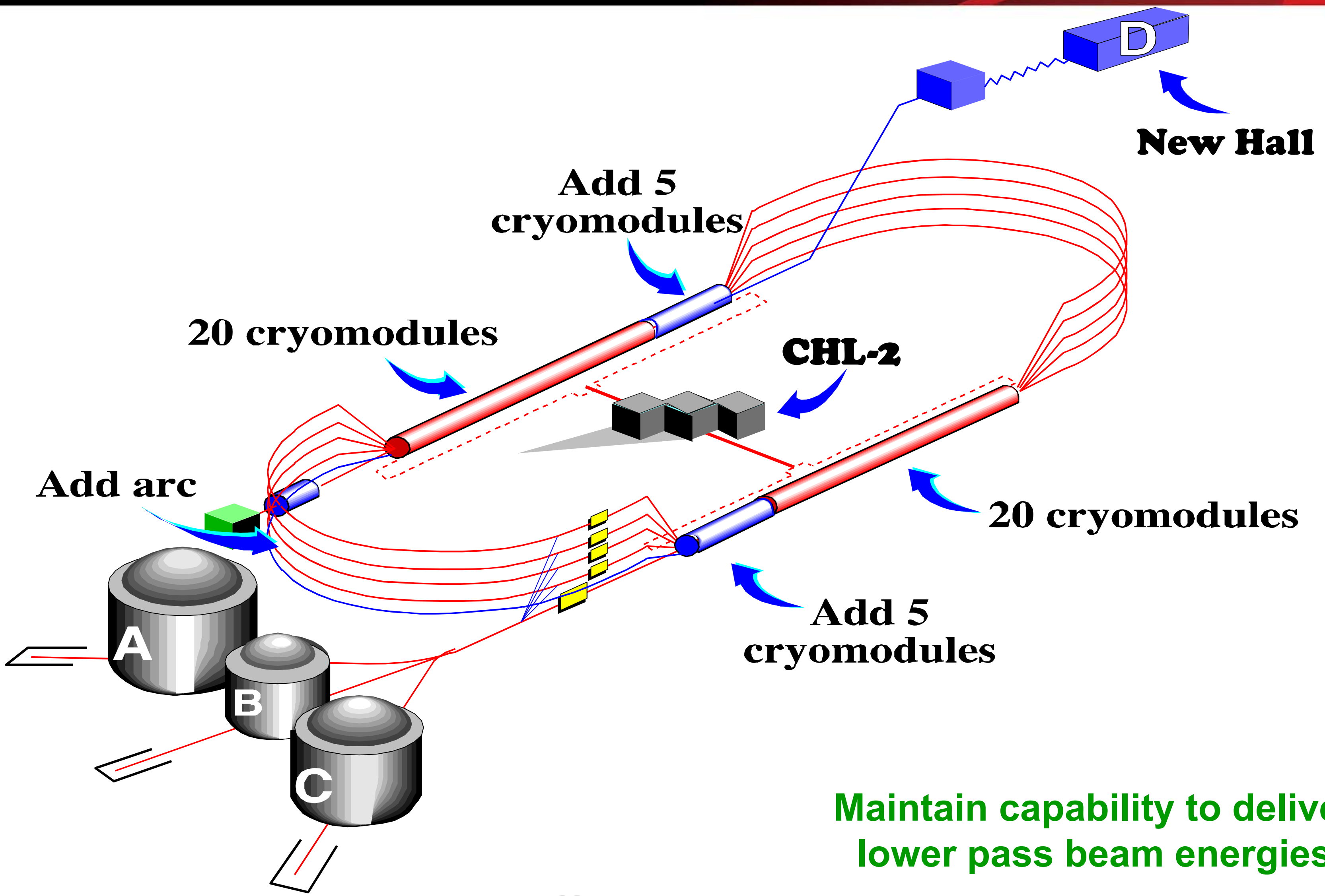
Dynamically polarized, NH_3 ND_3

G_E^n, SANE, g_1^p, g_1^d



HDIce from BNL under development: Polarized neutron target for N* expts.

12 GeV Upgrade

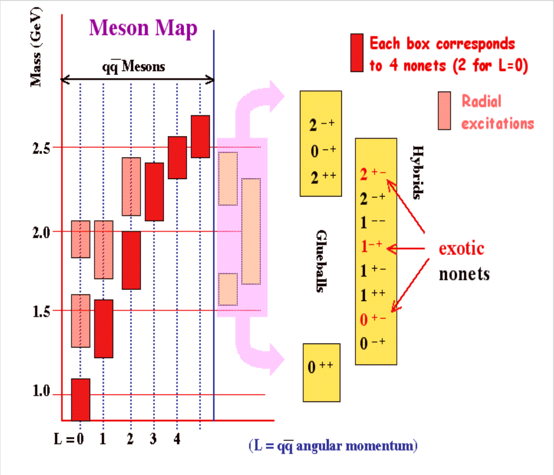


Maintain capability to deliver lower pass beam energies

Enhanced capabilities in existing Halls

12 GeV Upgrade

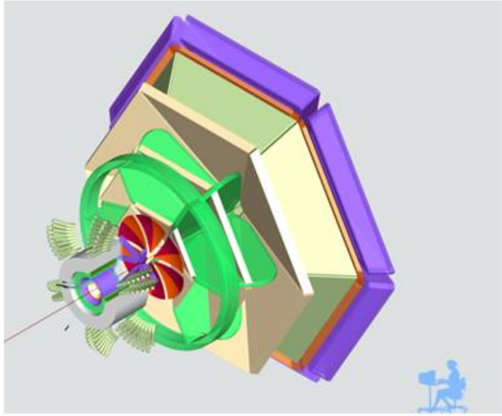
Exciting new scientific opportunities – continue world leadership

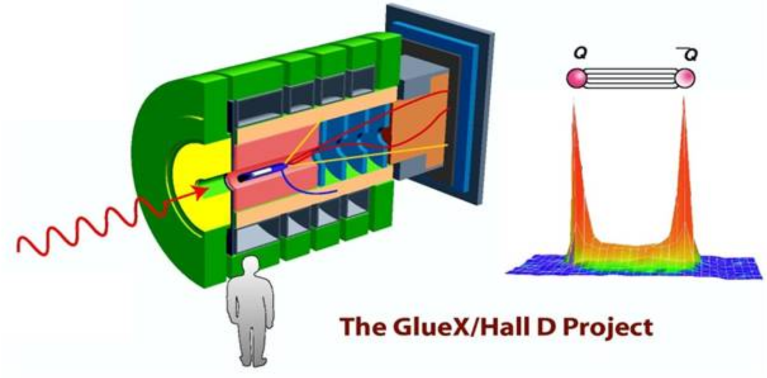


- **Discover the spectrum and properties of exotic mesons in mass range 1.5-2.6 GeV** in order to explore the physical origins of quark confinement
- **Define the spin and flavor structure of the nucleon in the valence region**, hence test theories of di-quarks, pQCD….
- Determine the orbital angular momentum carried by up and down quarks and **explore potential of Generalized Parton Distributions for tomographic imaging**
- Exploit the unique capabilities of CEBAF at 12 GeV **to explore the structure of nuclei at the level of quarks and gluons** – understand the EMC effect
- **Probe potential new physics** (beyond the Standard Model) through precise test of evolution of $\sin^2 \theta_W$ from Z-pole

Four Halls

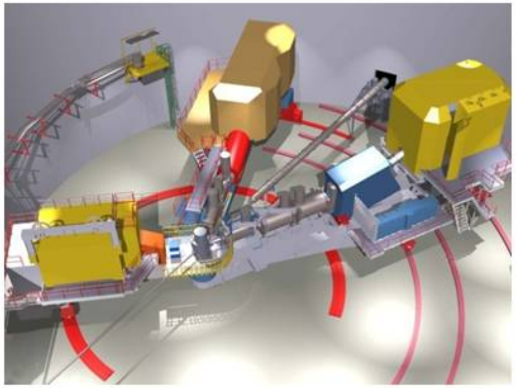
Hall D – exploring origin of confinement by studying exotic mesons

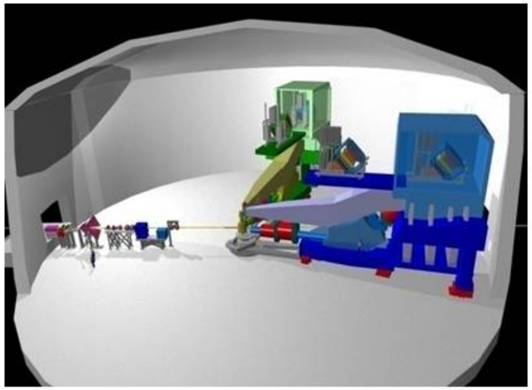




Hall B – understanding nucleon structure via generalized parton distributions

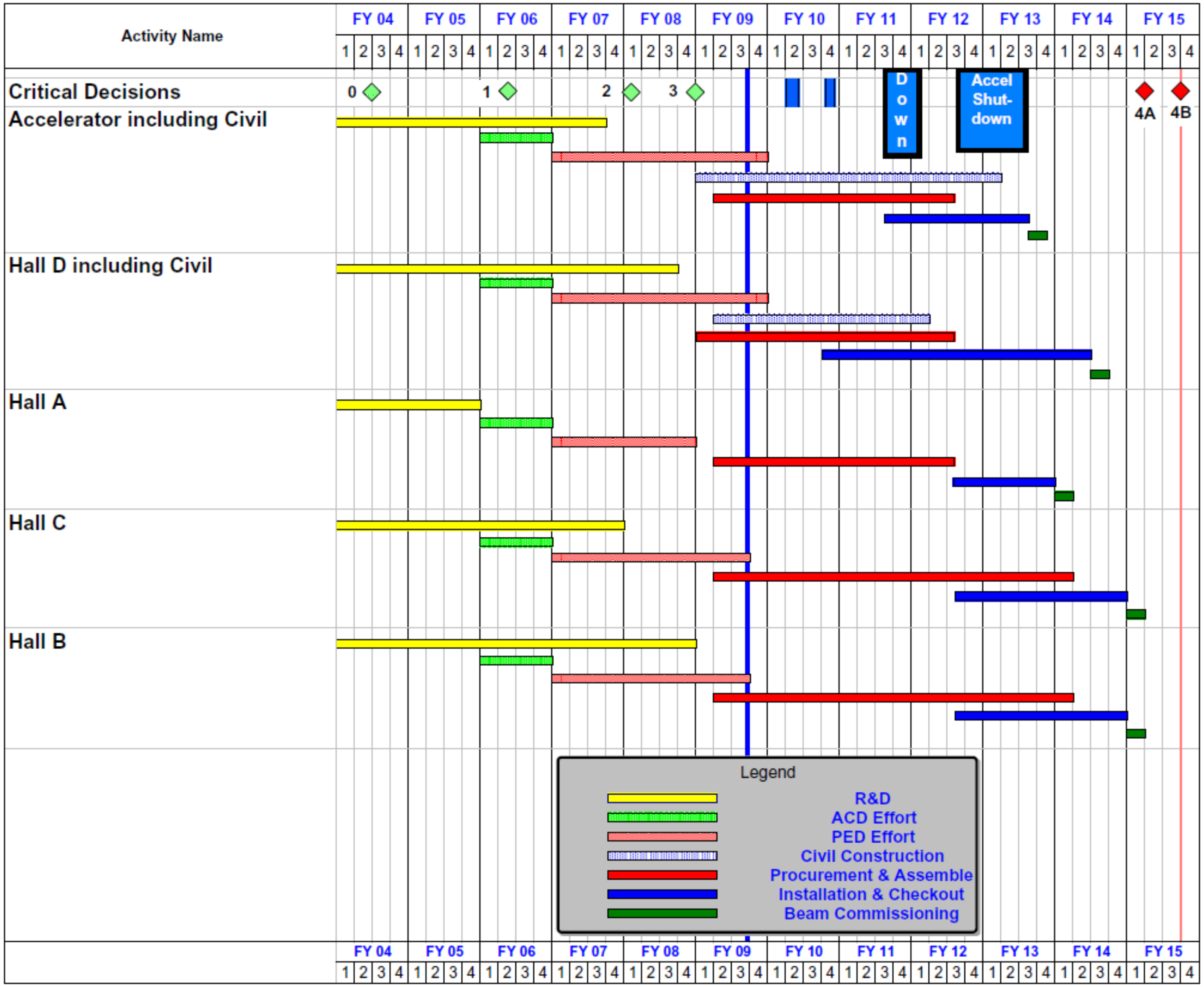
Hall C – precision determination of valence quark properties in nucleons and nuclei





Hall A – short range correlations, form factors, hyper-nuclear physics, future new experiments

12 GeV SCHEDULE



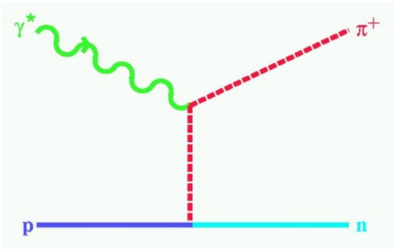
Charged Pion Electromagnetic Form Factor

Where does the dynamics of the q-q interaction make a transition from the strong (confinement) to the perturbative (QED-like) QCD regime?

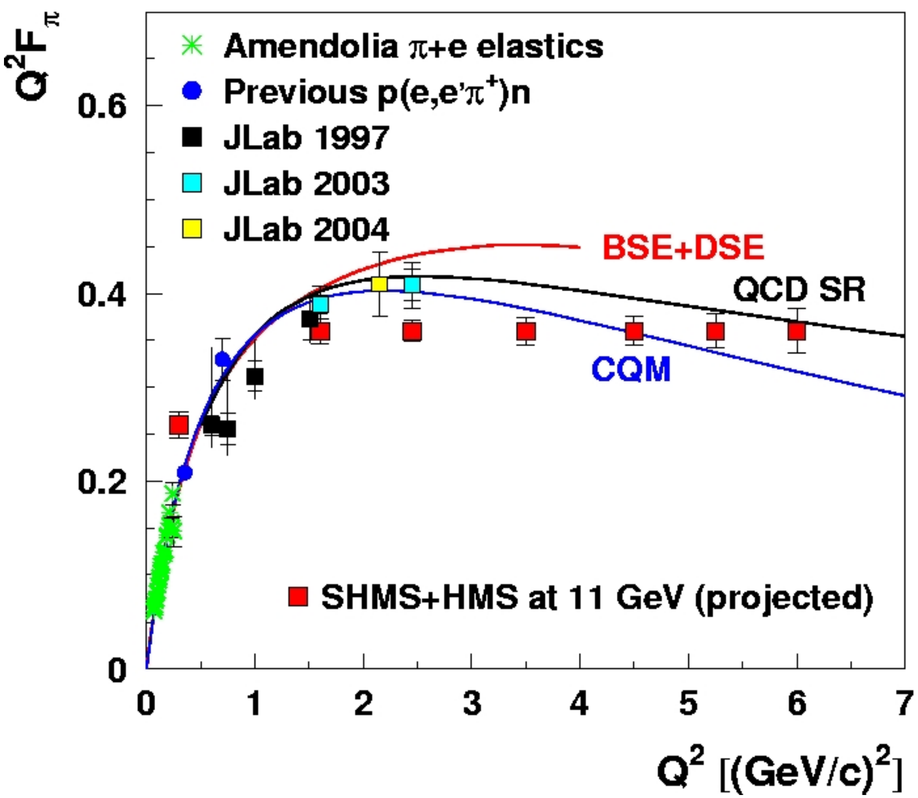
- It will occur earliest in the simplest systems
  → the pion form factor $F_\pi(Q^2)$ provides our best chance to determine the relevant distance scale experimentally

To measure $F_\pi(Q^2)$:

- At low Q^2 (< 0.3 $(GeV/c)^2$): use π + e scattering → R_{rms} = 0.66 fm
- At higher Q^2: use $^1H(e,e'\pi^+)n$



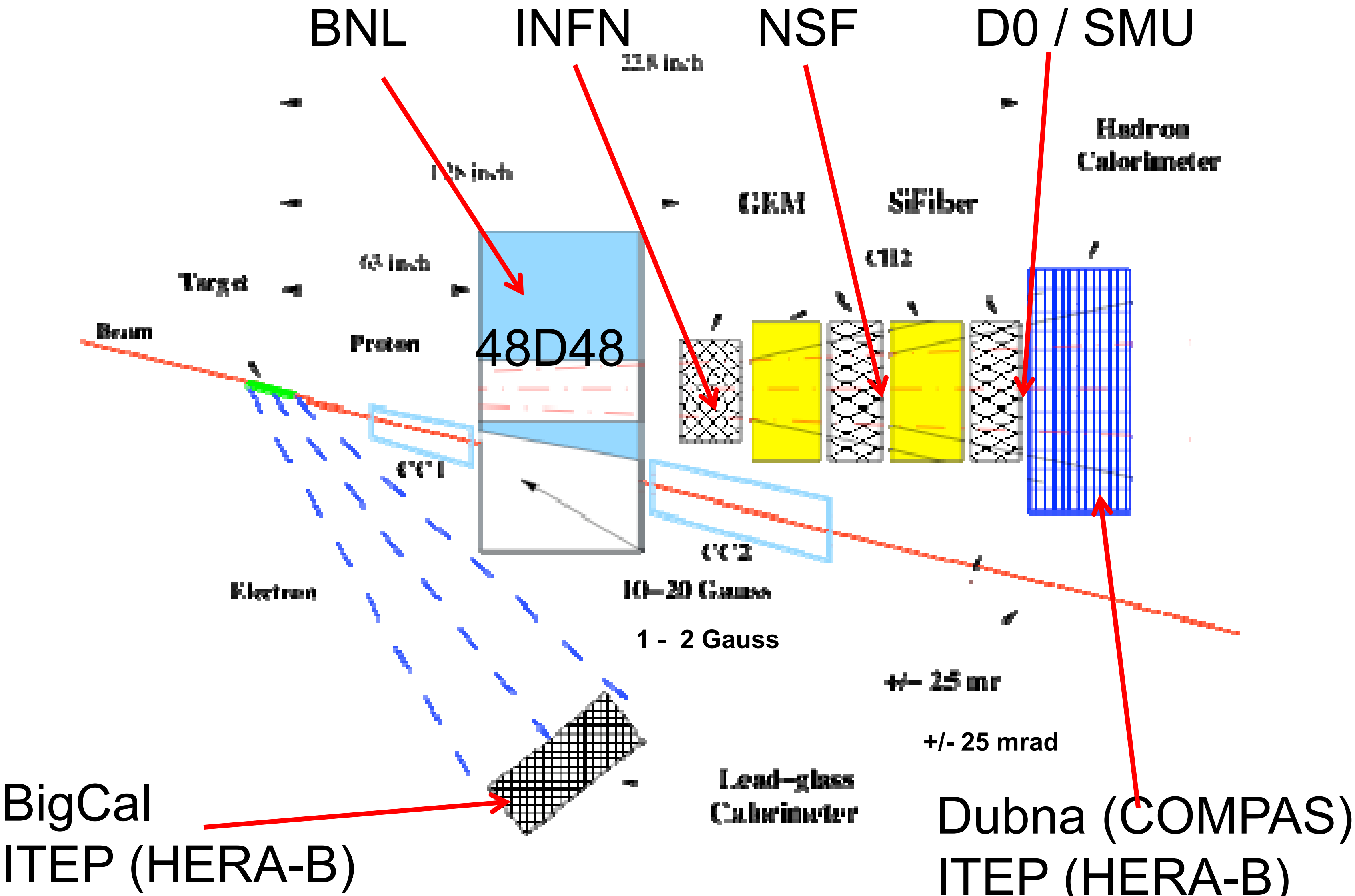
Scatter from a virtual pion in the proton and 1) extrapolate to the pion pole
→ large uncertainty
2) use a realistic pion electroproduction model



- In asymptotic region, $F_\pi \to 8\pi\alpha_s f_\pi^2 Q^{-2}$

Jefferson Lab

Super BigBite Spectrometer



12 GeV in Hall A:Scientific Plans

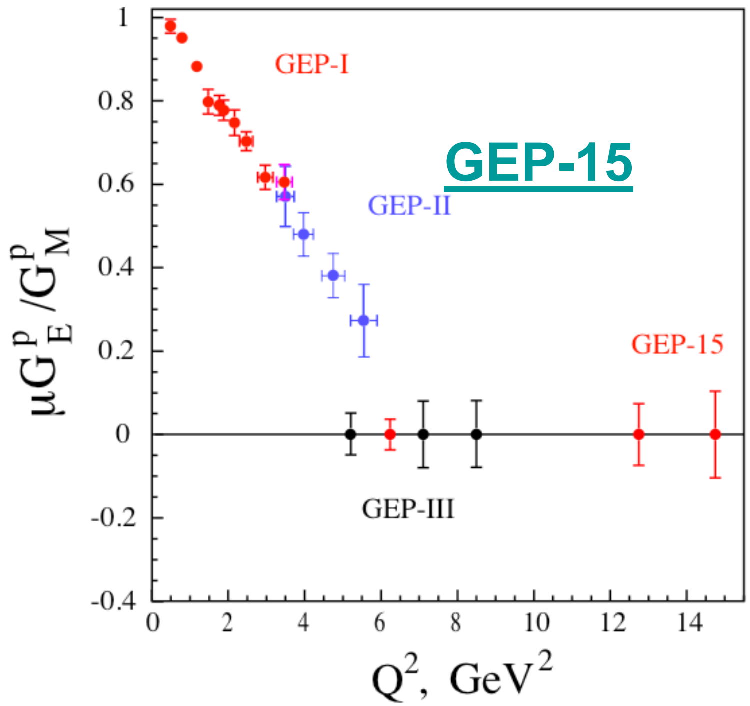
GEP-15 Experiment (approved by August PAC32):

Goal: Measure F_2/F_1 on proton up to Q^2 = 15 GeV^2
Method: Recoil Polarization on elastic ep scattering
Expected Result: Relative accuracy ~ 3%
Physics Impact:

- Study spin flip part of the hadron current
- Constrain Generalized Parton Distributions at high t
- Critical test of Form Factor models and reaction dynamics

Requires a new spectrometer

$$\left(G_E^p / G_M^p \propto -P_x / P_z\right)$$



Other relevant physics experiments

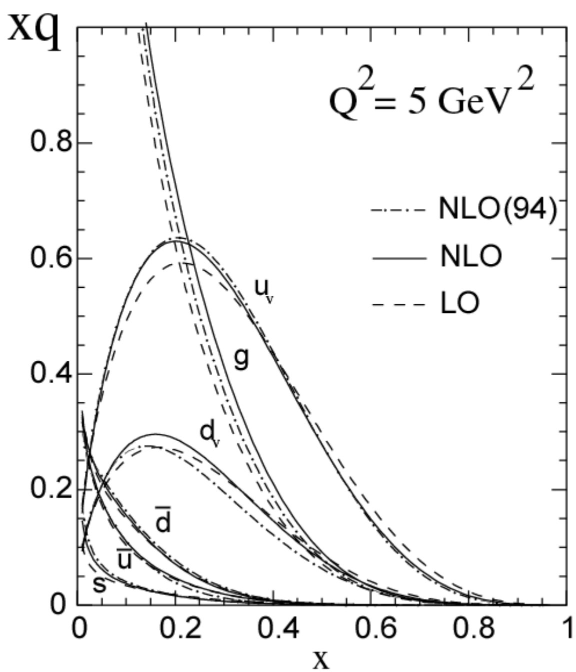
(same detectors as G_E^P, different configurations):

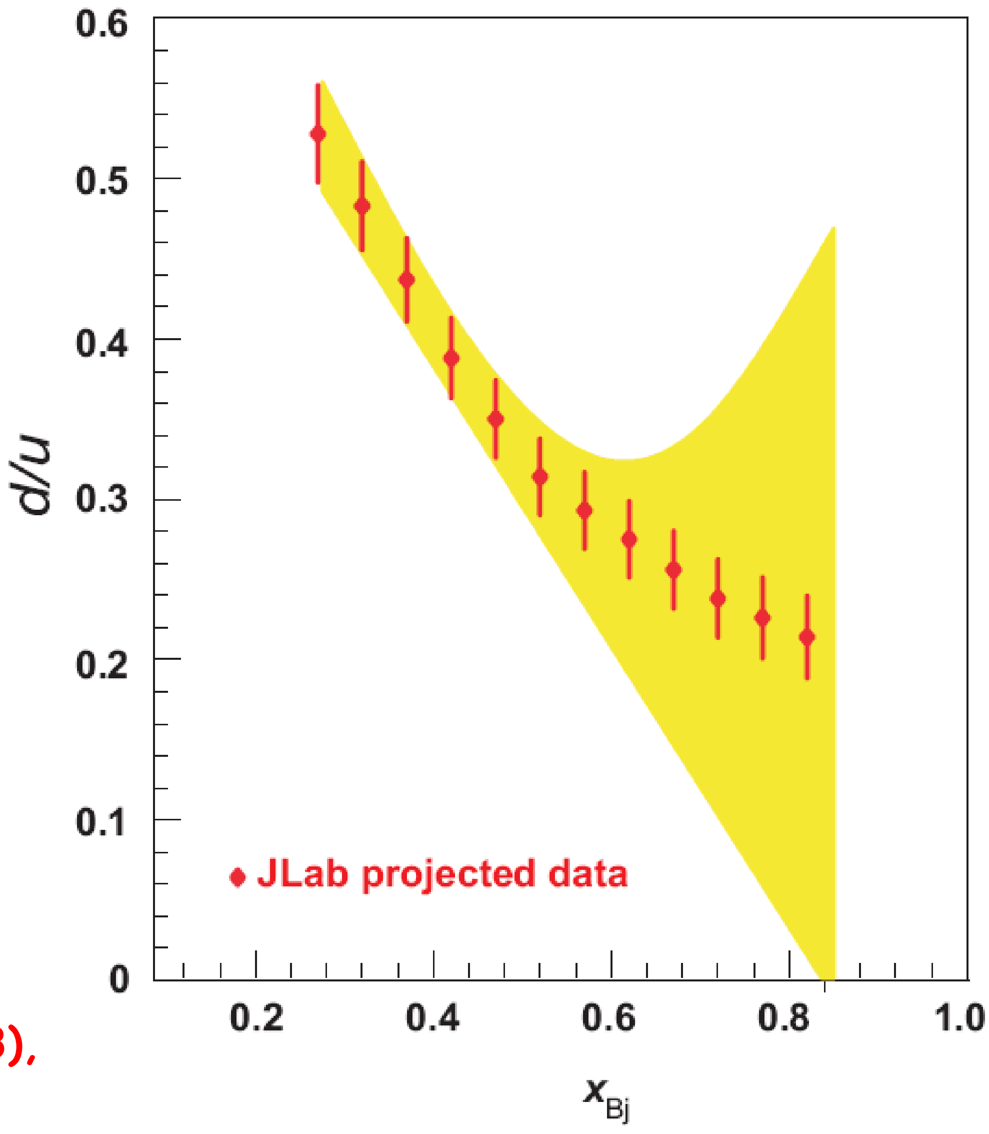
- G_E^n to 7 GeV^2 (double present knowledge)
- Nucleon Spin structure via Deep Inclusive and Semi-Inclusive Deep Inelastic Scattering
- J/Ψ photo-production

Measuring High-x Structure Functions

REQUIRES:

- High beam polarization
- High electron current
- High target polarization
- Large solid angle spectrometers





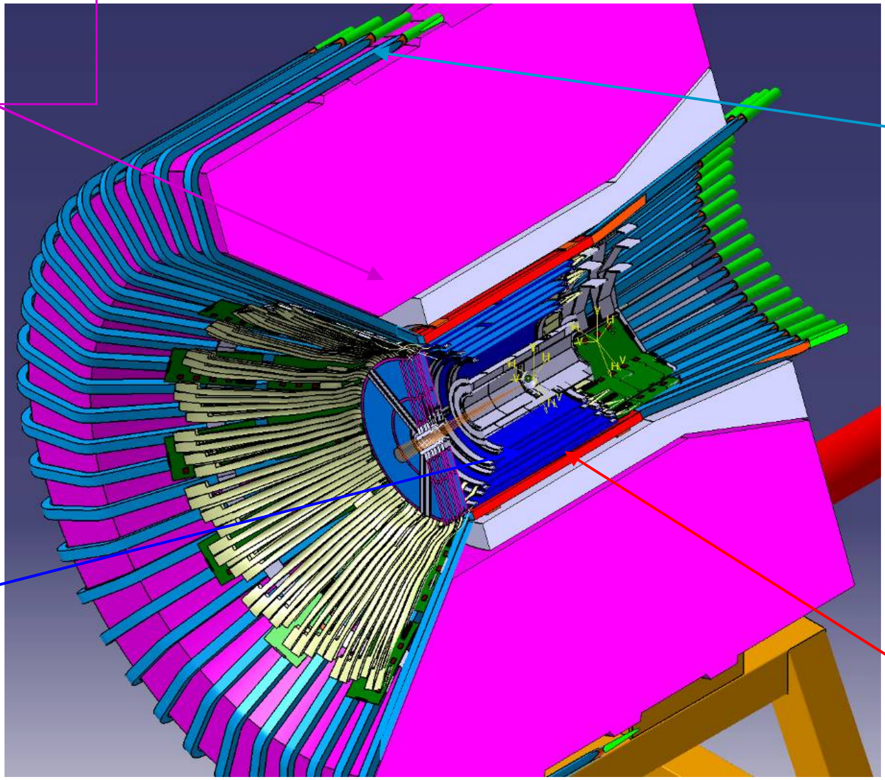
12 GeV will access the regime (x > 0.3), where valence quarks dominate

Hall B: The CEBAF Large Acceptance Spectrometer (*CLAS*)

CLAS12 Central Detector

European collaboration:
INFN Frascati,
INFN Genova,
U. Glasgow
LPSC Grenoble
IPN Orsay,
CEA-Irfu Saclay

Solénoïde 5 T:
Saclay?



Light guides TOF
IN2P3/Glasgow

Central
Tracker:
Si JLab
MM Saclay

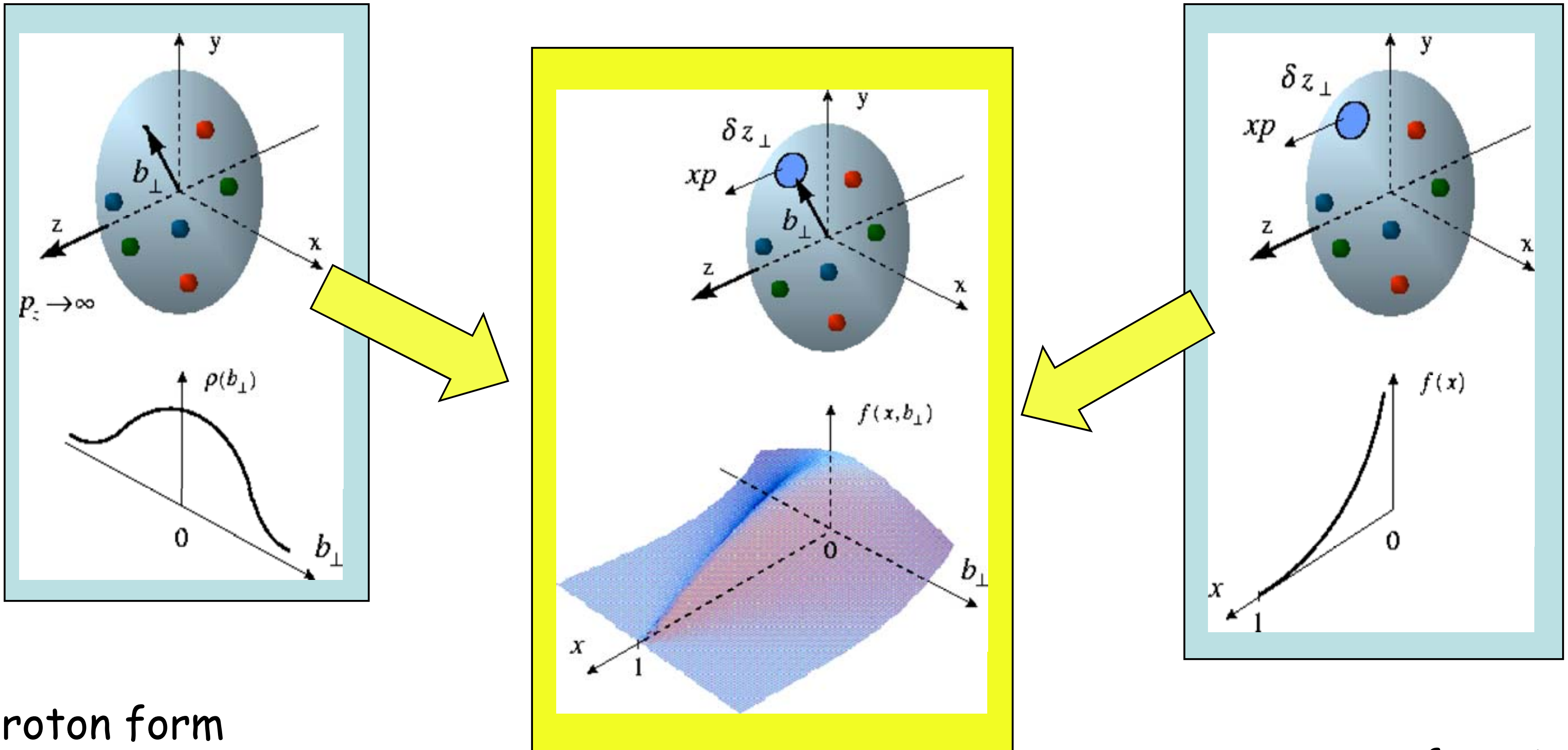
Neutron
counters

IN2P3/INFN

(All subsystems under R&D or conceptual phase)

Generalized Parton Distributions (GPDs)

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

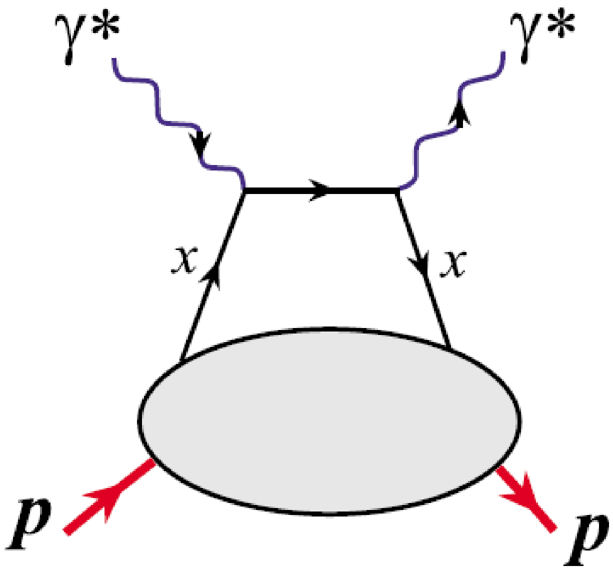


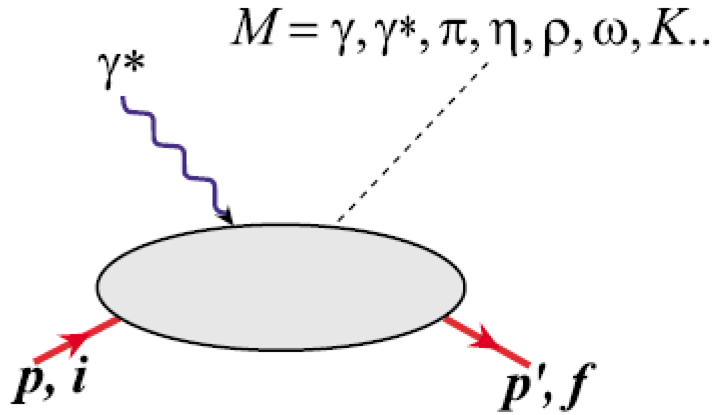
Proton form factors, transverse charge & current densities

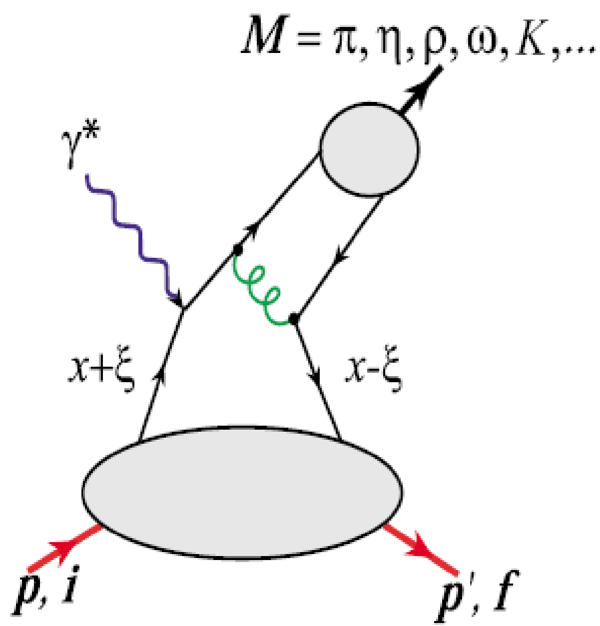
Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Deep Inelastic and Deep Exclusive Scattering

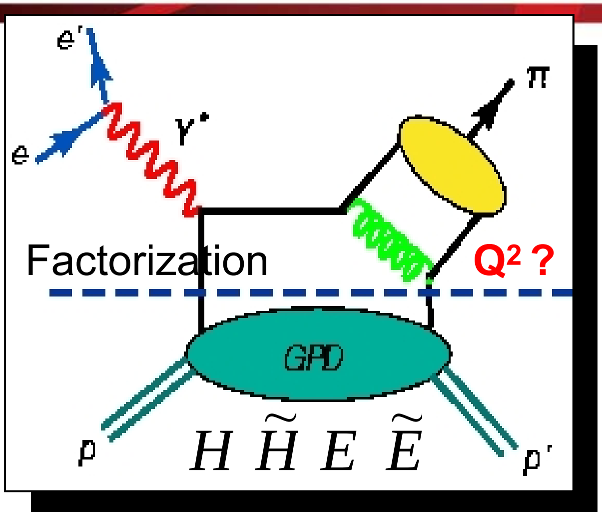


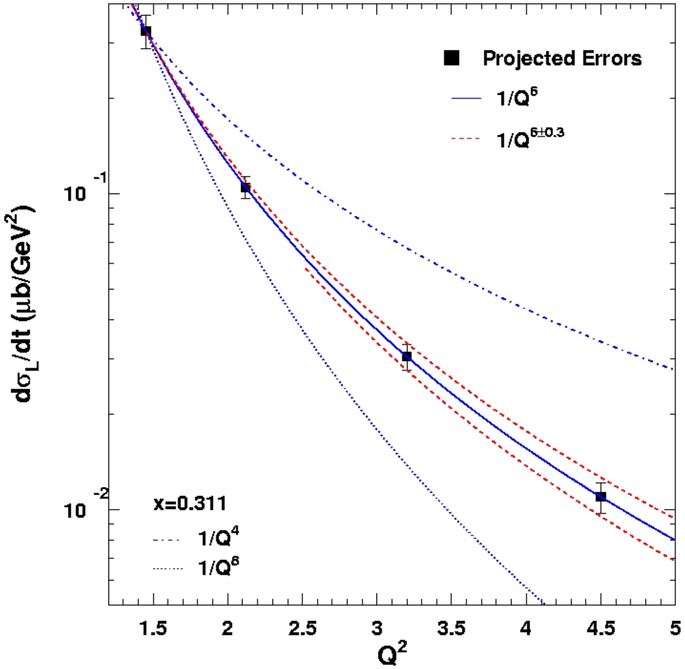




Tests of the Handbag Dominance

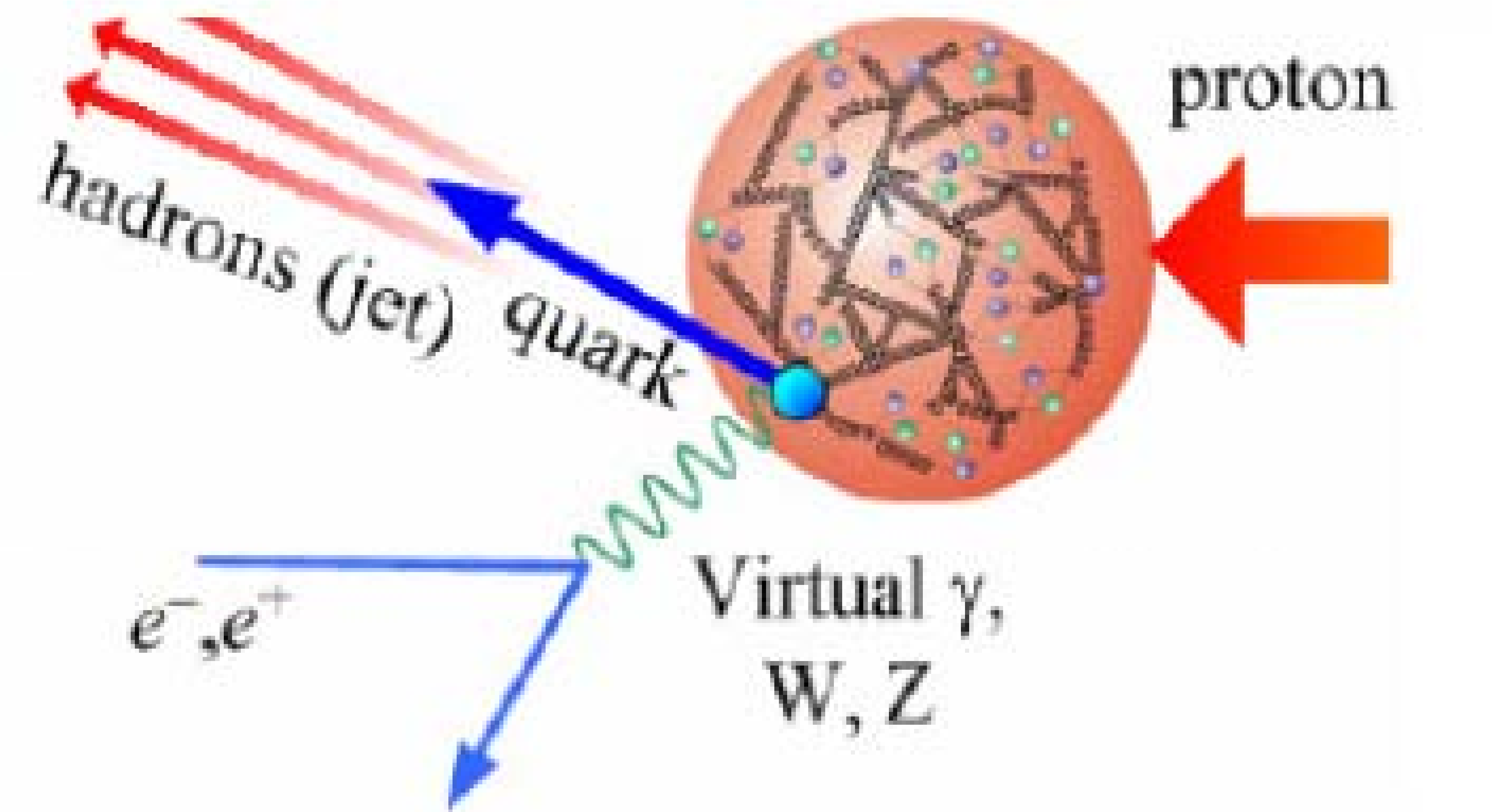
- To study the combined spatial and momentum distributions, need to measure GPDs
  - But must demonstrate that the conditions for factorization apply!
- One of the most stringent tests of factorization is the Q^2 dependence of the π electroproduction cross section
  - **σ_L scales to leading order as Q^{-6}**
  - σ_T scales as Q^{-8}
  - As Q^2 becomes large: $\sigma_L >> \sigma_T$
- Factorization theorems for meson electroproduction have been proven rigorously only for longitudinal photons *[Collins, Frankfurt, Strikman, 1997]*





$$2\pi \frac{d\sigma}{dt d\phi} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(1+\varepsilon)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$

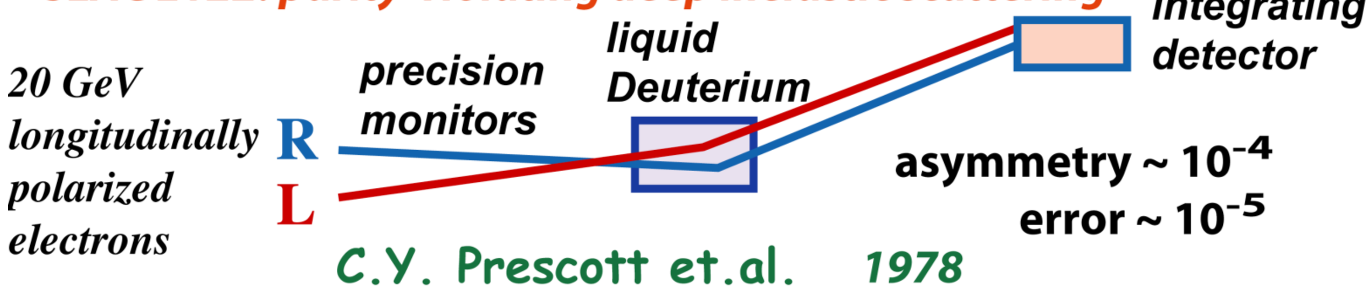
Electron Scattering: A picture

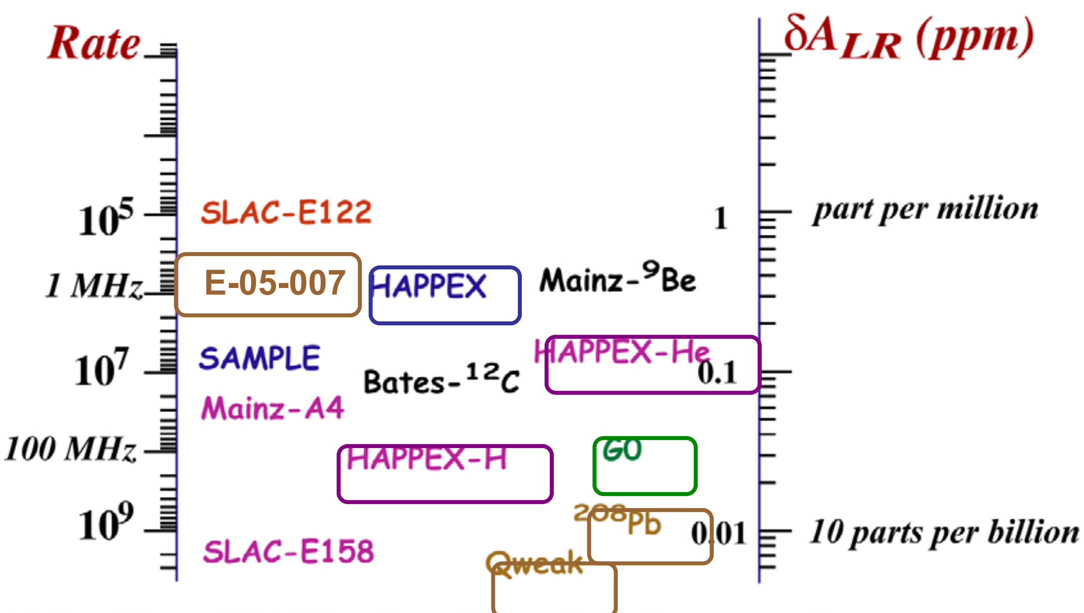


Parity Violating Asymmetries

$A_{PV} \sim 8 \times 10^{-5}\, Q^2$ → 0.1 to 100 ppm

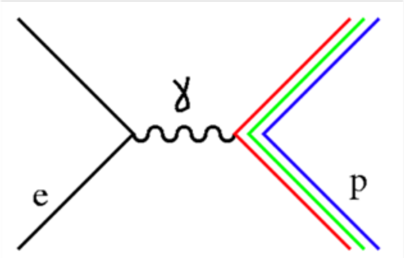
SLAC E122: parity-violating deep inelastic scattering



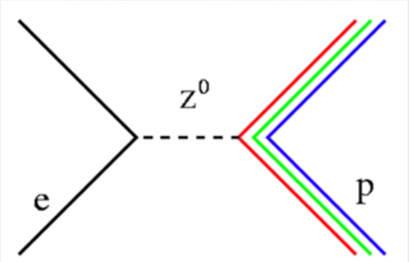


- *Steady progress in technology*
- *part per billion systematic control*
- *1% normalization control*
- *JLab now takes the lead*
  - *-New results from HAPPEX*
  - *-Photocathodes*
  - *-Polarimetry*
  - *-Targets*
  - *-Diagnostics*
  - *-Counting Electronics*

Extraction of Q^p_{weak}



As $Q^2 \to 0$



measures Q^p - proton's electric charge

measures Q^p_{weak} - proton's weak charge

The Q_{weak} experiment measures the parity-violating analyzing power A_z

$$A_z = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \simeq -3 \times 10^{-7}$$

(-300 ppb)

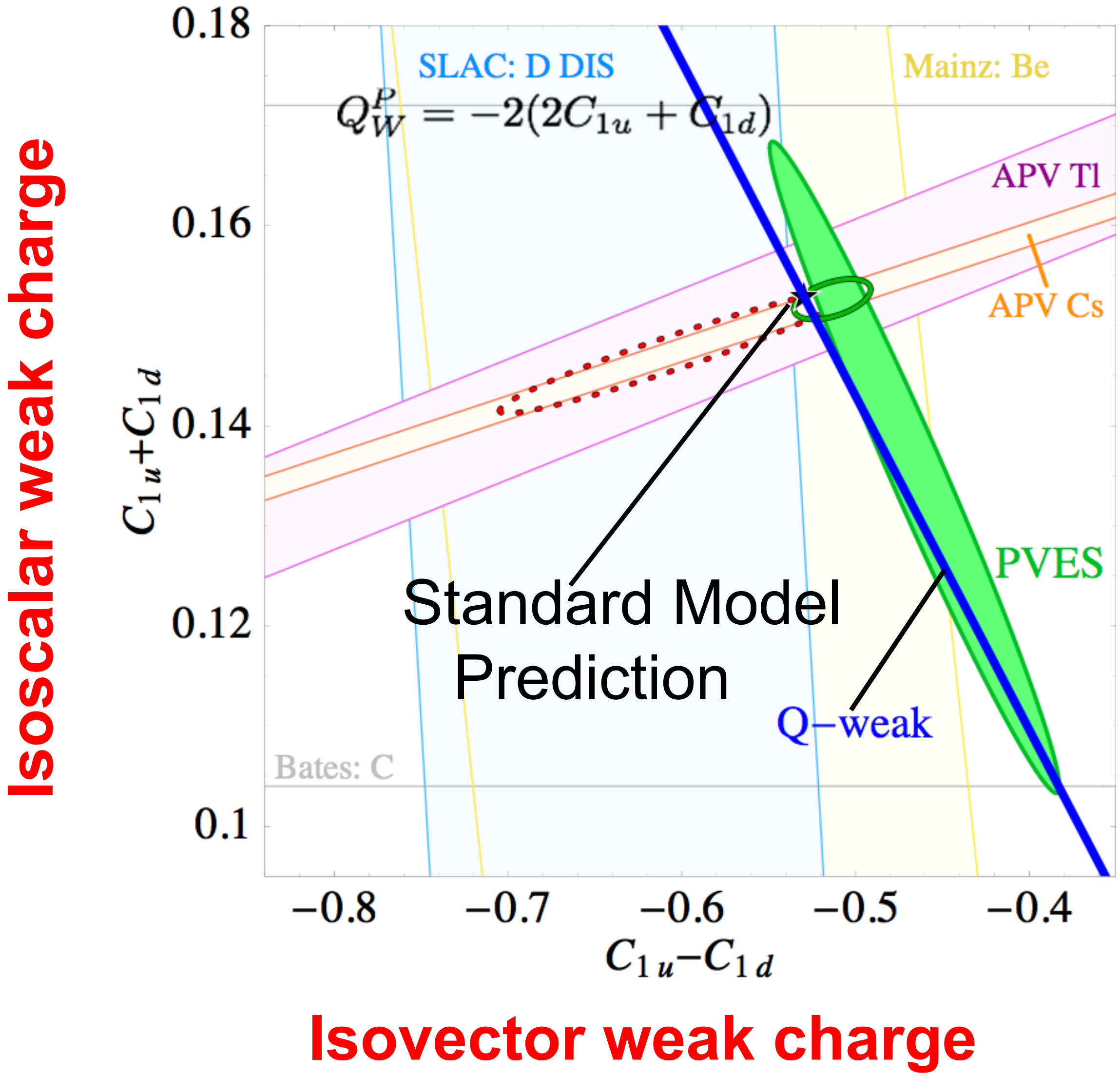
$$A_z \xrightarrow[\substack{Q^2 \to 0 \\ \theta \to 0}]{} \frac{-G_F}{4\pi\alpha\sqrt{2}}[Q^2 Q^p_{weak} + Q^4 B(Q^2)]$$

Contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$,
Extracted using global fit
of existing PVES experiments!

$$Q^p_{weak} = 1 - 4\sin^2\theta_W \sim 0.072 \text{ (at tree level)}$$

- Q^p_{weak} is a well-defined experimental observable
- Q^p_{weak} has a definite prediction in the electroweak Standard Model

Weak Couplings

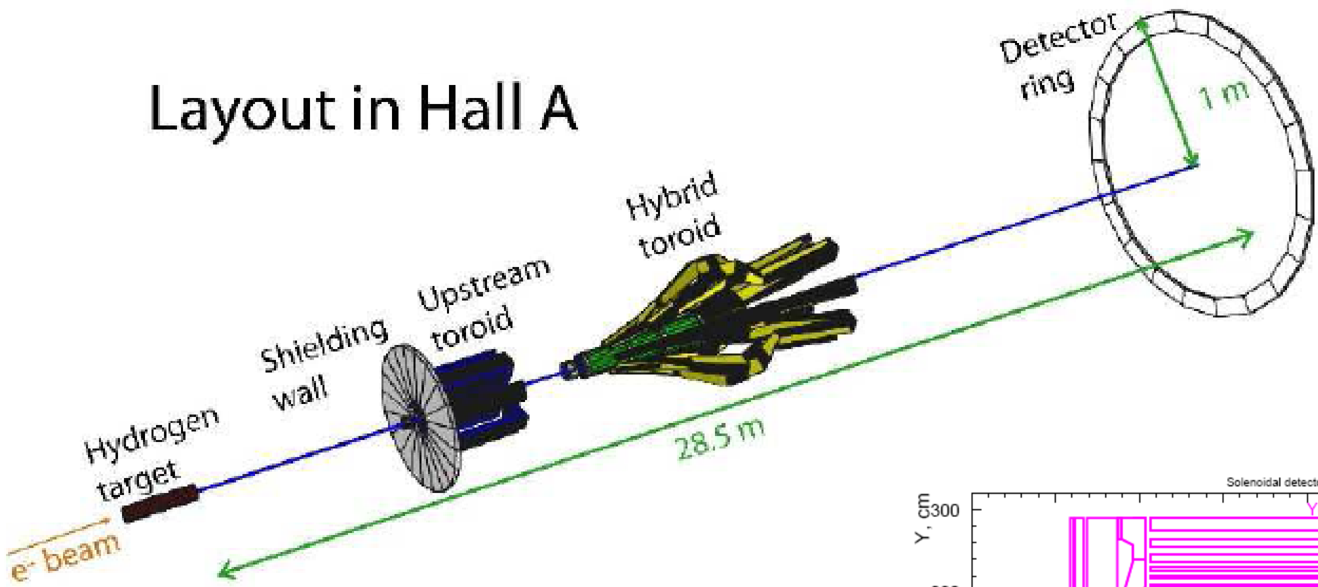


All Data & Fits Plotted at 1 σ

HAPPEx: H, He
G^0: H,
PVA4: H
SAMPLE: H, D

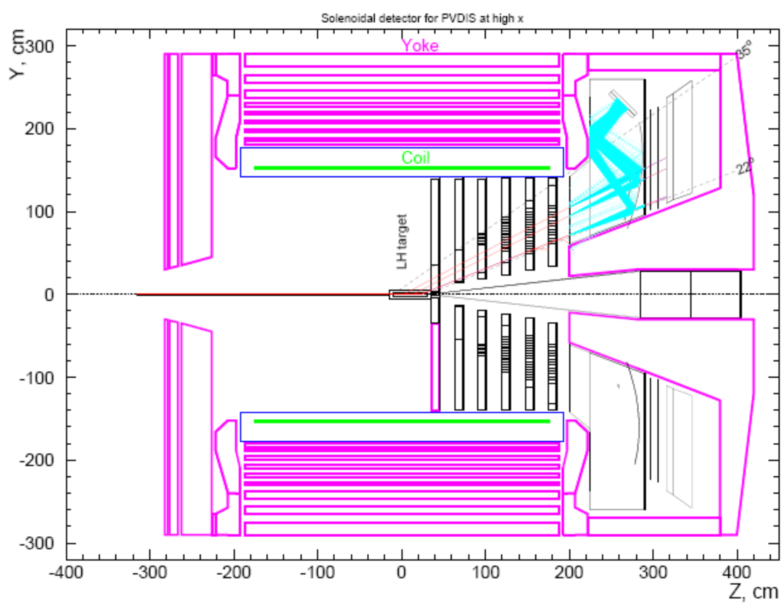
Q-weak expected precision

Møller & Deep Inelastic Scattering Parity Violation

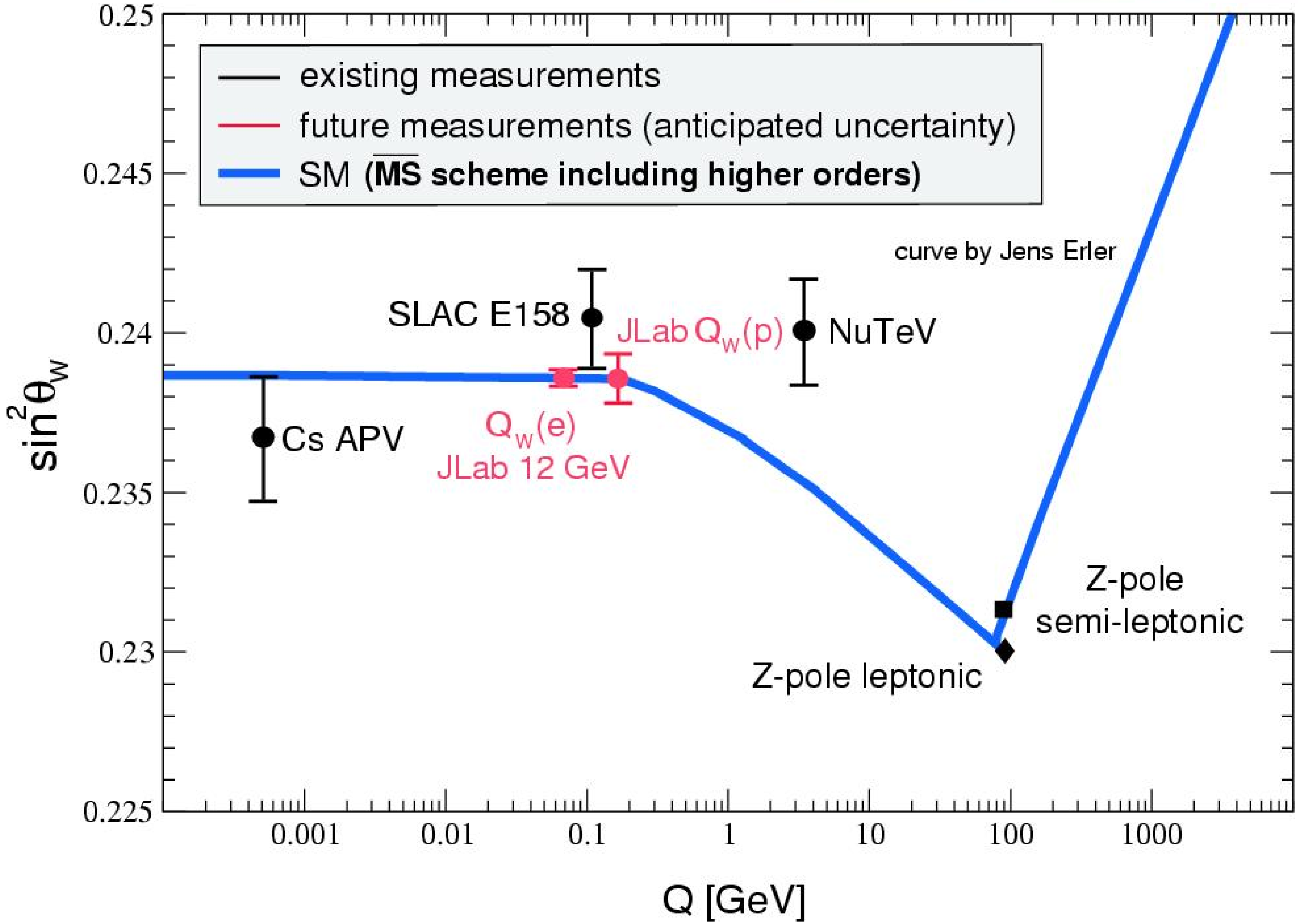


- Dedicated Møller Experiment with toroids

- SoLID general purpose deep inelastic parity violating experiment with solenoid
  - Semi-Inclusive Program?

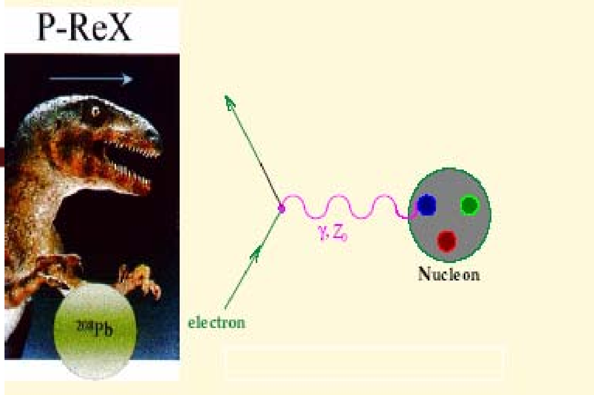


$\sin^2\theta_W$



existing measurements
future measurements (anticipated uncertainty)
SM ($\overline{MS}$ scheme including higher orders)
curve by Jens Erler
SLAC E158
JLab $Q_W(p)$
NuTeV
Cs APV
$Q_W(e)$
JLab 12 GeV
Z-pole
semi-leptonic
Z-pole leptonic
$\sin^2\theta_W$
0.25
0.245
0.24
0.235
0.23
0.225
0.001
0.01
0.1
1
10
100
1000
Q [GeV]

PREX : ^{208}Pb Radius Experiment



Low Q^2 elastic e-nucleus scattering

(E = 850 MeV, $\Theta = 6^o$)

Z^0 (Weak Interaction) : couples mainly to neutrons

$$\frac{dA}{A} = 3\% \rightarrow \frac{dR_n}{R_n} = 1\%$$

Measure a Parity Violating Asymmetry

$$A = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_P(Q^2)} \right]$$

- Fundamental check of Nuclear Theory
- Input to Atomic PV Expts
- Neutron Star Structure

Asymptotic Freedom

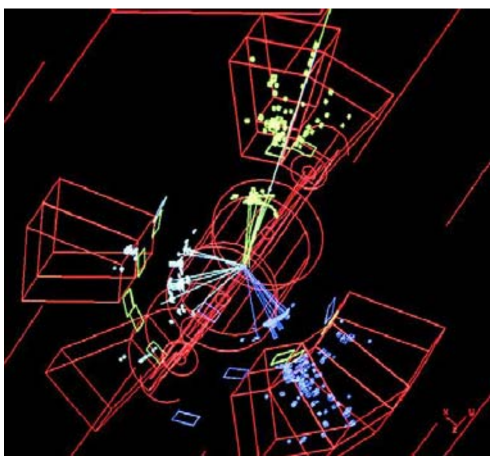
Small Distance
High Energy

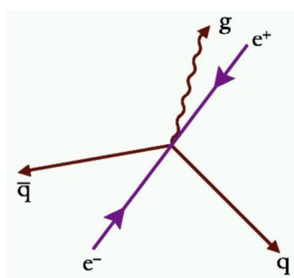
Confinement

Large Distance
Low Energy

Perturbative QCD

High Energy Scattering

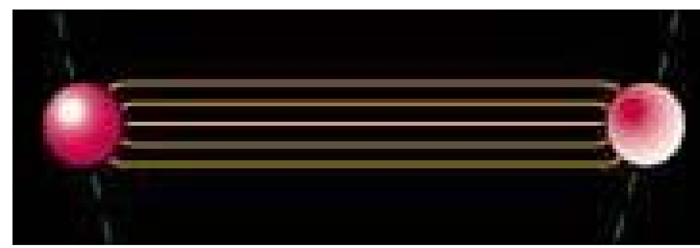




Gluon
Jets
Observed

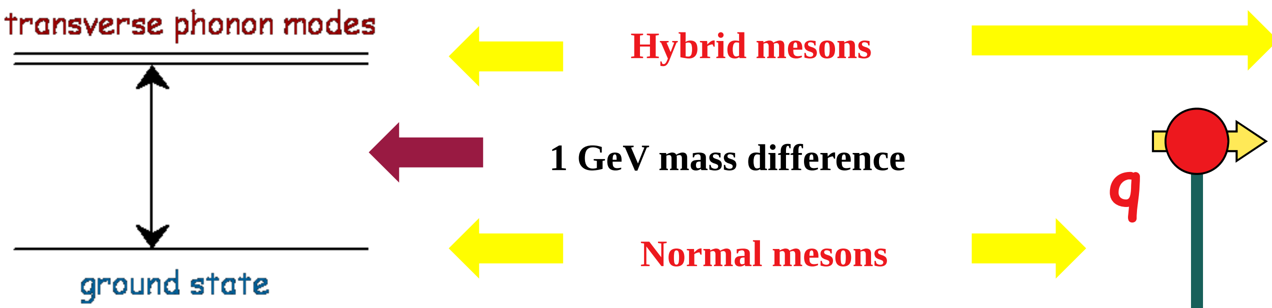
Strong QCD

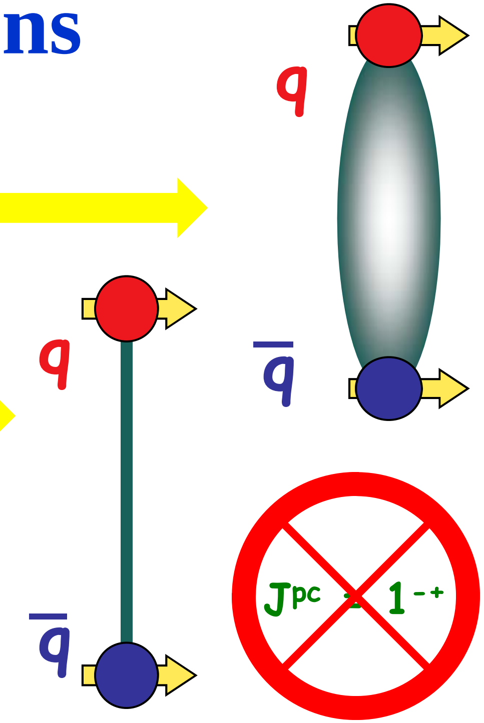
Spectroscopy

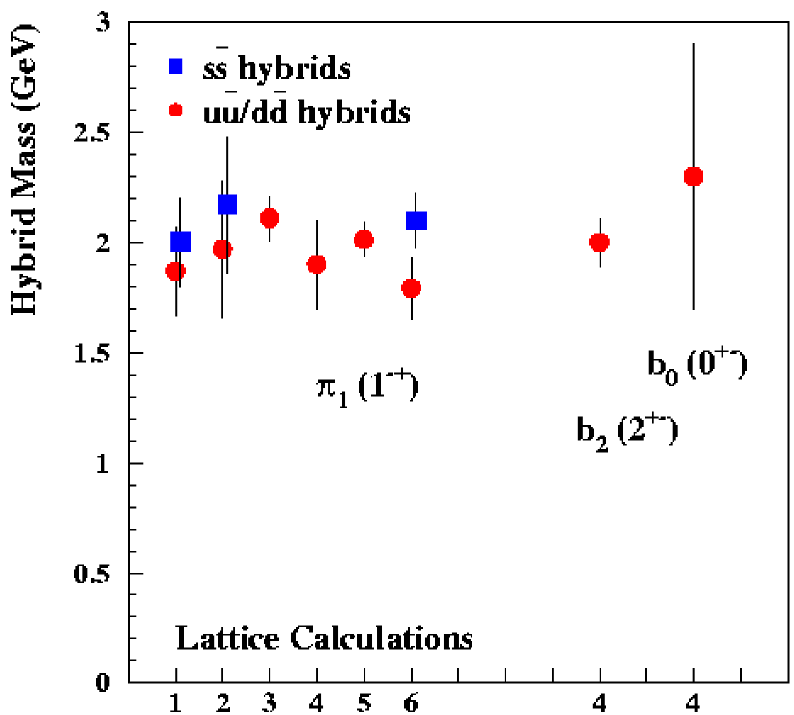


Gluonic
Degrees of Freedom
Missing

Hybrid mesons and mass predictions







Lattice

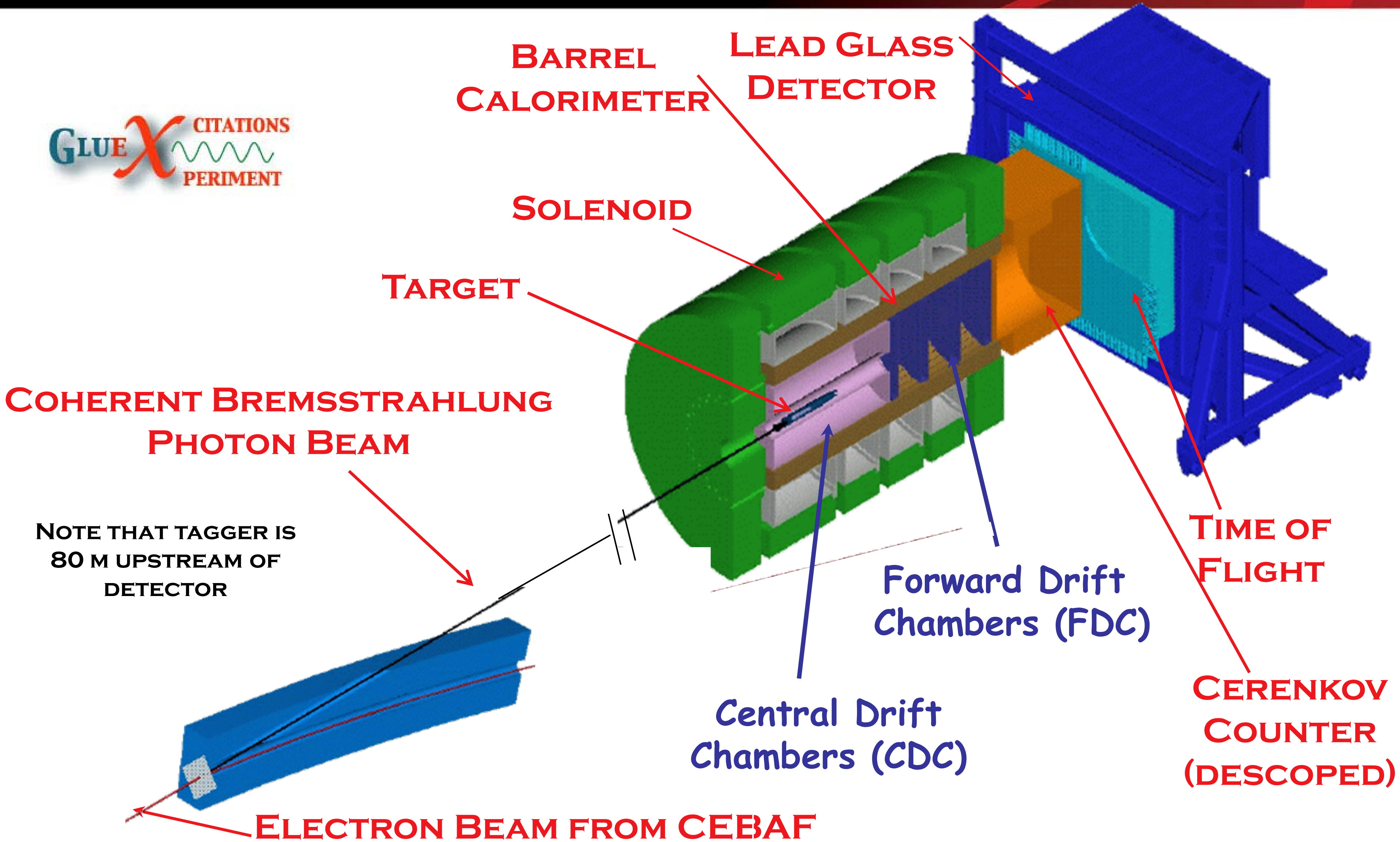
1^{-+} 1.9 GeV

2^{+-} 2.1 GeV

0^{+-} 2.3 GeV

Lowest mass expected to be $\pi_1(1^{-+})$ at 1.9±0.2 GeV

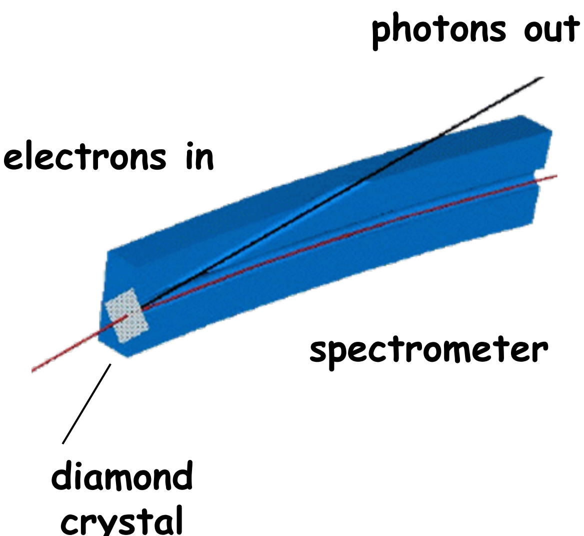
Glueχ

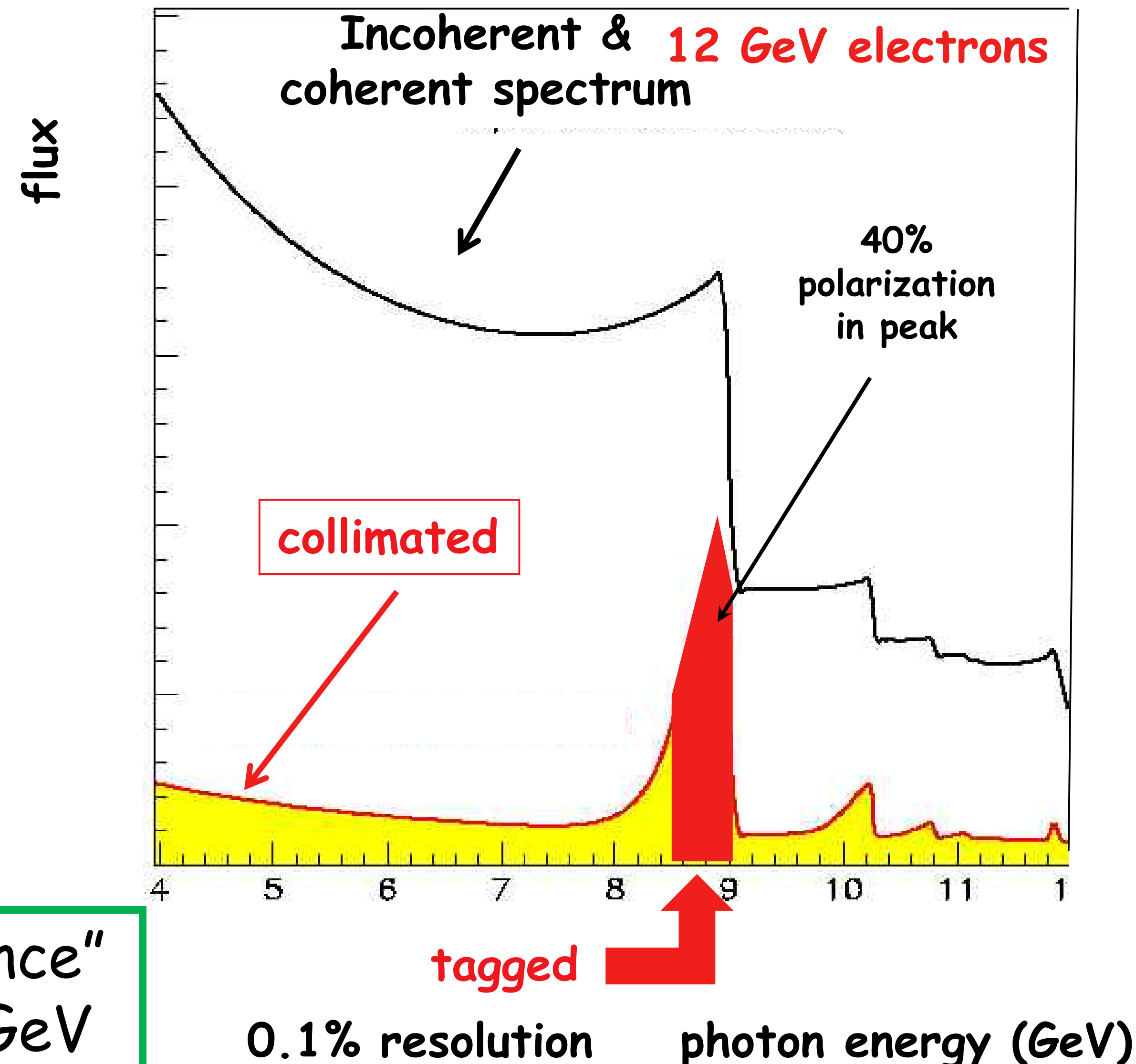


GlueX
Citations
Periment
Lead Glass Detector
Barrel Calorimeter
Solenoid
Target
Coherent Bremsstrahlung Photon Beam
Note that tagger is 80 m upstream of detector
Forward Drift Chambers (FDC)
Central Drift Chambers (CDC)
Time of Flight
Cerenkov Counter (descoped)
Electron Beam from CEBAF

GlueX uses Coherent Bremsstrahlung

This technique provides requisite energy, flux and polarization





Good "acceptance" up to M ~ 2.5 GeV

Finding the Exotic Wave

$\gamma \rightarrow$ V(ector Meson) S = 1 (Double-blind M. C. exercise)

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.

$$X(\text{exotic}) \rightarrow \rho\pi \rightarrow 3\pi$$

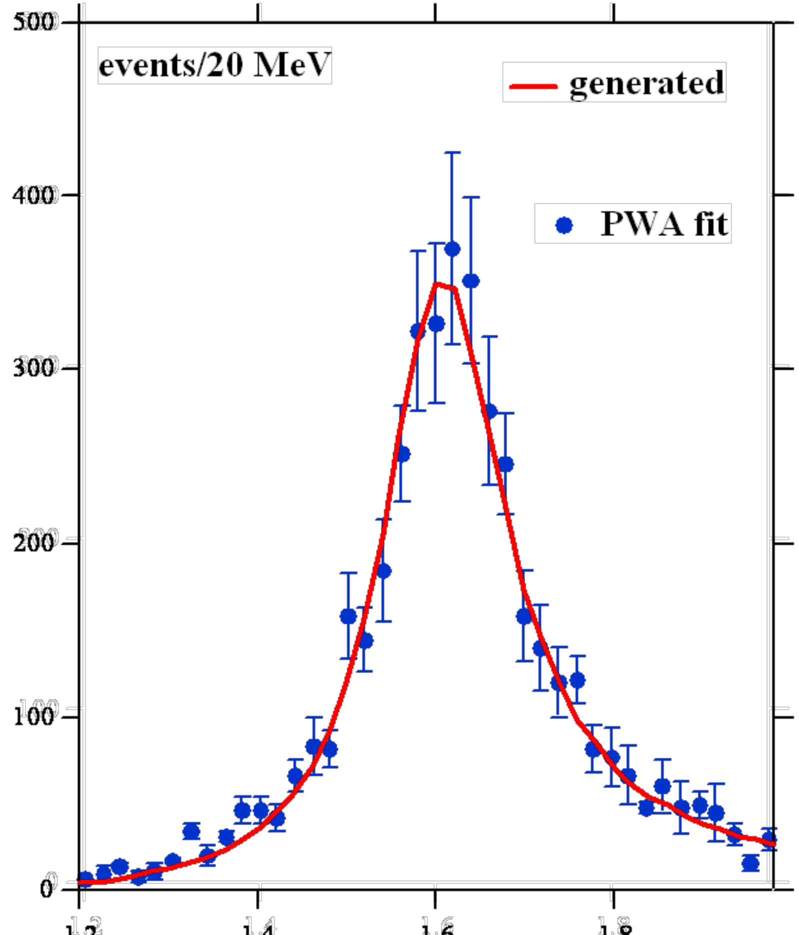
Mass

Input: 1600 MeV
Output: 1598 +/- 3 MeV

Width

Input: 170 MeV
Output: 173 +/- 11 MeV

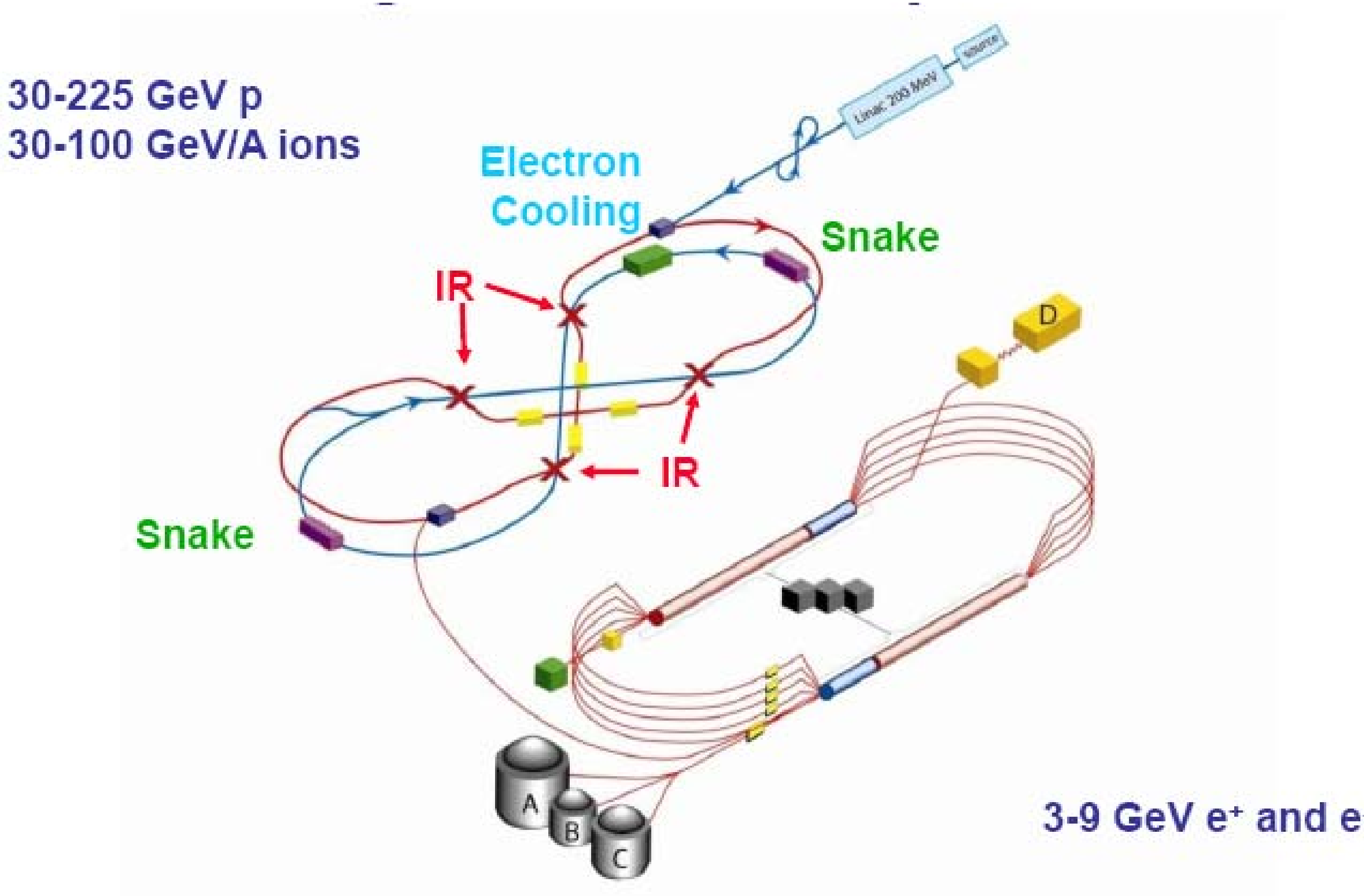
Statistics shown here correspond to a few days of running.



Electron Ion Collider

- **Recommended as a generic capability** by:
  - **NSAC Long Range Report**
  - **IUPAP WG9 Working Group on world-wide nuclear facilities**
- **Candidate Facilities with different key characteristics**
  - **LHeC at CERN**
  - **eRHIC at Brookhaven National Laboratory**
  - **ELIC – ELectron Ion Collider at Jlab**
  - **MANUEL at FAIR-GSI**
  - **Plus several new ideas!!!!**
- **Natural Extension of Jlab nuclear physics agenda**
- **Issues**
  - **Physics Case(s) not yet broadly accepted**
  - **Cost scale is thought to be large**
- **Jefferson Lab and BNL: Joint EIC Advisory Committee reports to Laboratory Directors**

ELectron Ion Collider

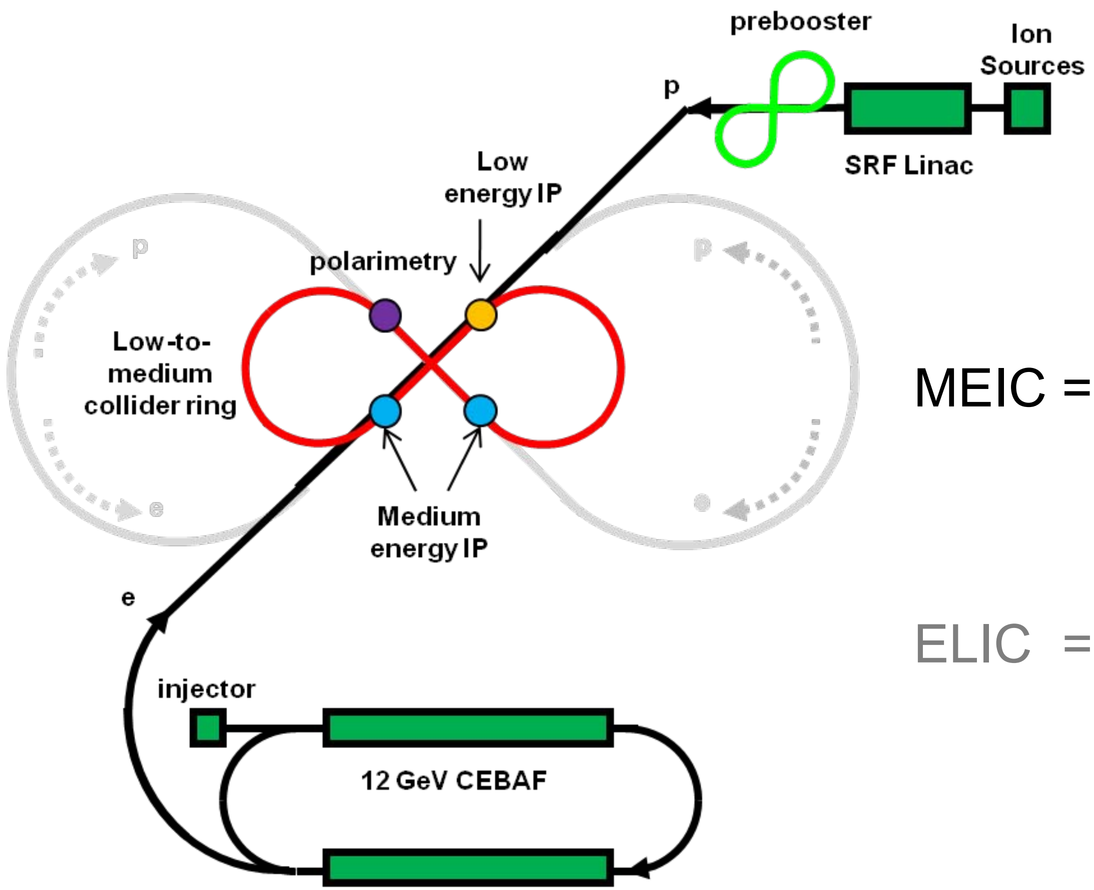


Medium Energy Electron Ion Collider

Map the spin and 3D quark-gluon structure of protons

Discover the role of gluons in atomic nuclei

Understand the creation of the quark-gluon matter around us



MEIC = EIC@JLab
1 low-energy IR (s ~ 200)
3 medium-energy IRs (s < 2600)

ELIC = high-energy EIC@JLab (s = 11000)
(limited by JLab site)

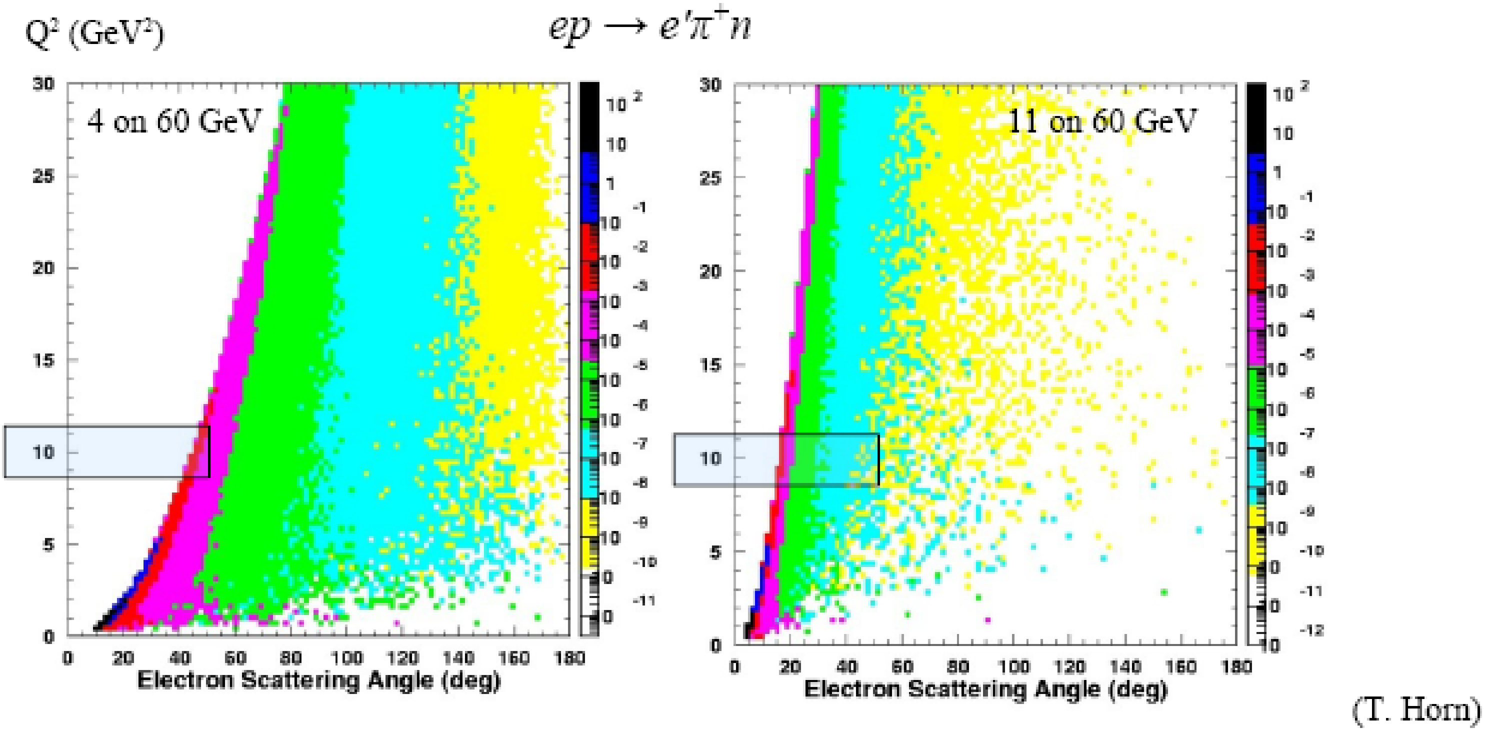
Potential Physics Program Elements

- Inclusive DIS
  - **Unpolarized:** EMC effect, gluons in nuclei
  - **Polarized:** ΔG, Δq
- Semi-Inclusive DIS
  - **Unpolarized:** flavor decomposition of sea, strangeness
  - **Polarized:** orbital angular momentum in TMDs, flavor separation of Δq
- Exclusive (GPDs: transverse spatial distributions, orbital angular momentum)
  - **Diffractive:** gluons from DVCS and J/ψ; DVCS on nuclei
  - **Non-diffractive:** sea quarks from light mesons

Experimental requirements

MEIC Exclusive Process Kinematics

$ep \rightarrow e'\pi^+ n$



(T. Horn)

- Electrons scattering angles are large compared with fixed-target kinematics.
- Large *e-p* momentum asymmetry would require e/π discrimination at large angles in order to reach $Q^2 \sim 10$ GeV^2 (ensuring factorization).
- Small-angle coverage only needed for symmetric collisions and photoproduction.

EIC Working Group/Initiative at Jefferson Lab

- **Coordinators**
  - UGBOD Chair - **Zein-Eddine Meziani**
  - Jefferson Lab AD for Accelerators - **Andrew Hutton**
  - Jefferson Lab AD for Physics - **Larry Cardman**
- **Goals**
- **Physics/Detectors**
- **Explore the case for a high luminosity** (10^{34} -- 10^{35} cm^{-2} sec^{-1}, High Polarization (80% e, 70%p) collider with moderate energy reach.
- **Delineate those physics goals** which can be achieved, and enumerate those which are not addressed. Concentrate on key experiments, the real physics drivers.
- **Explore at least one concept** study and propose solutions for high luminosity.

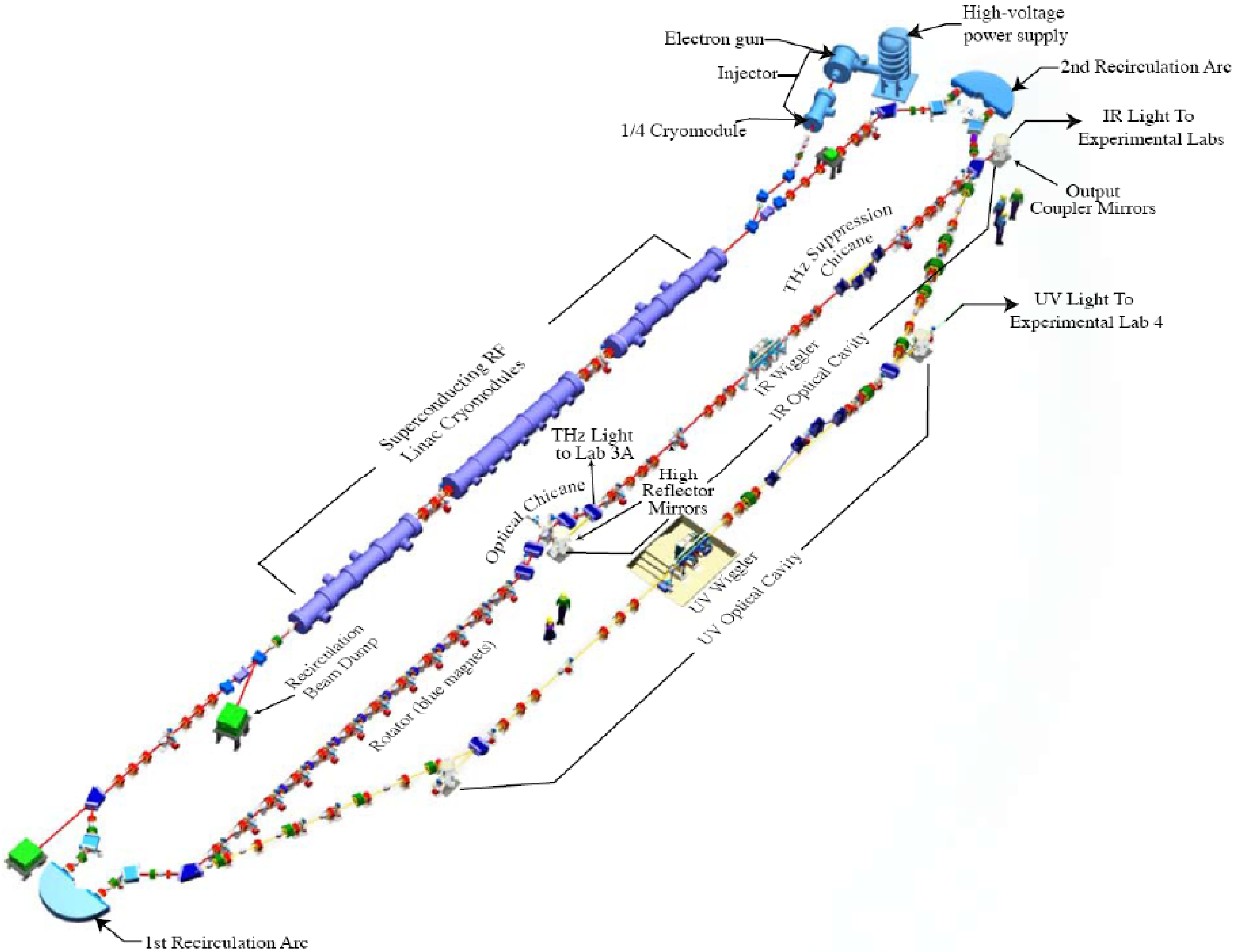
- **Machine**
- A concept for a machine with high luminosity, high polarization and moderate energy has been developed. The machine is somewhat novel:
- Validate the existing conceptual design of the machine.
- Develop ideas and an R&D program which will address any deficiencies.
- **Report**
- **Write a white paper** which documents the physics case and which describes the machine and detectors.
- **Timescale**
- To be maximally useful, the report should be available by the **beginning of summer 2010**. It would then permit a rational discussion of the potential for such a machine

Exploring the Nature of Matter

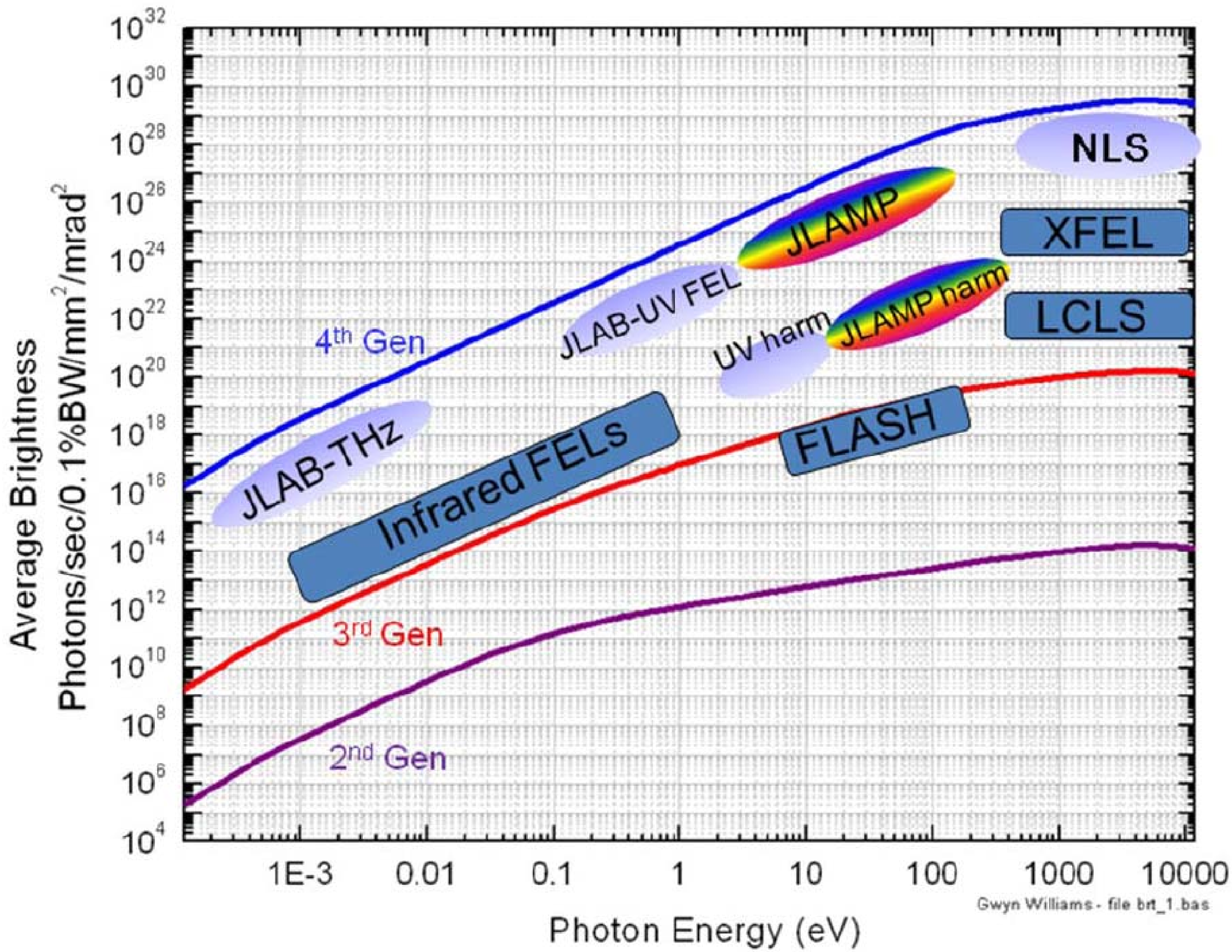
JLAMP Spares

- JLAMP Follows

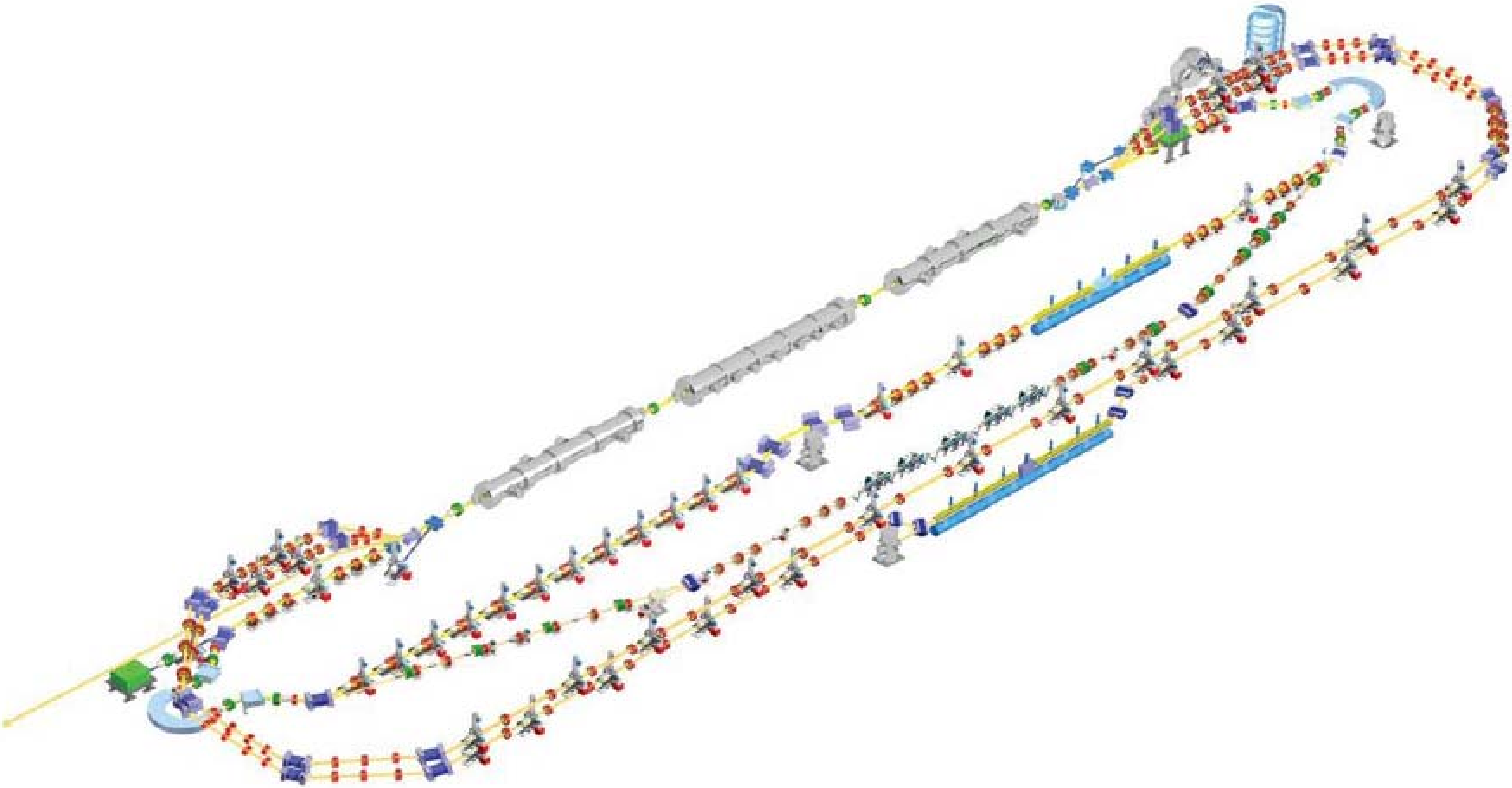
Jefferson Lab Free Electron Laser



JLAMP


Average Brightness
Photons/sec/0.1%BW/mm²/mrad²
10^32
10^30
10^28
10^26
10^24
10^22
10^20
10^18
10^16
10^14
10^12
10^10
10^8
10^6
10^4
1E-3
0.01
0.1
1
10
100
1000
10000
Photon Energy (eV)
Gwyn Williams - file brt_1.bas
4th Gen
3rd Gen
2nd Gen
NLS
JLAMP
XFEL
JLAB-UV FEL
UV harm
JLAMP harm
LCLS
JLAB-THz
Infrared FELs
FLASH

JLAMP Layout



Spares Follow

Abstract

Thomas Jefferson National Accelerator Facility (Jefferson Lab) is one of the premier facilities for nuclear and hadronic physics in the world. With high luminosity and high polarization continuous wave electron beams, the 6 GeV physics program has produced exciting results during the past decade. Currently the laboratory is executing an upgrade of the accelerator from 6 GeV to 12 GeV: this project was recommended as the top priority in the most recent US nuclear physics long-range plan. The upgrade, which also includes changes to the experimental facilities, will open new avenues of investigation. Beyond this upgrade Jefferson Lab is preparing the case for a future Electron Ion Collider.

Electron Scattering

- 1950: Does the proton have finite size and structure?
  - Elastic electron-proton scattering
    - ⇨ the proton is not a point-like particle but has finite size
      - charge and current distribution in the proton, G_E/G_M
- Nobel prize 1961- R. Hofstadter
- 1960-1980: What is the internal structure of the proton?
  - Deeply inelastic scattering
    - ⇨ discover quarks in ‘scaling’ of structure functions
      - quark longitudinal momentum distribution
      - quark helicity distribution
- Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor