Research Perspectives at Jefferson Lab: 12 GeV and Beyond

SPIN2002
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CEBAF @ 12 GeV, WHY?(As Presented to NSAC)

Key new physics:

- Understanding Confinement (via meson spectroscopy)

  (defines E_{max} and requires the addition of "Hall D")
- Detailed mapping of the quark and gluon wave functions of the nucleons via measurements of:
  - Deep Exclusive Scattering, and
  - Deep Inelastic Scattering as $x \rightarrow 1$ over a large range of Q^2

  (MAD in Hall A, CLAS upgrade to £ $=10^{35}$, SHMS in Hall C)

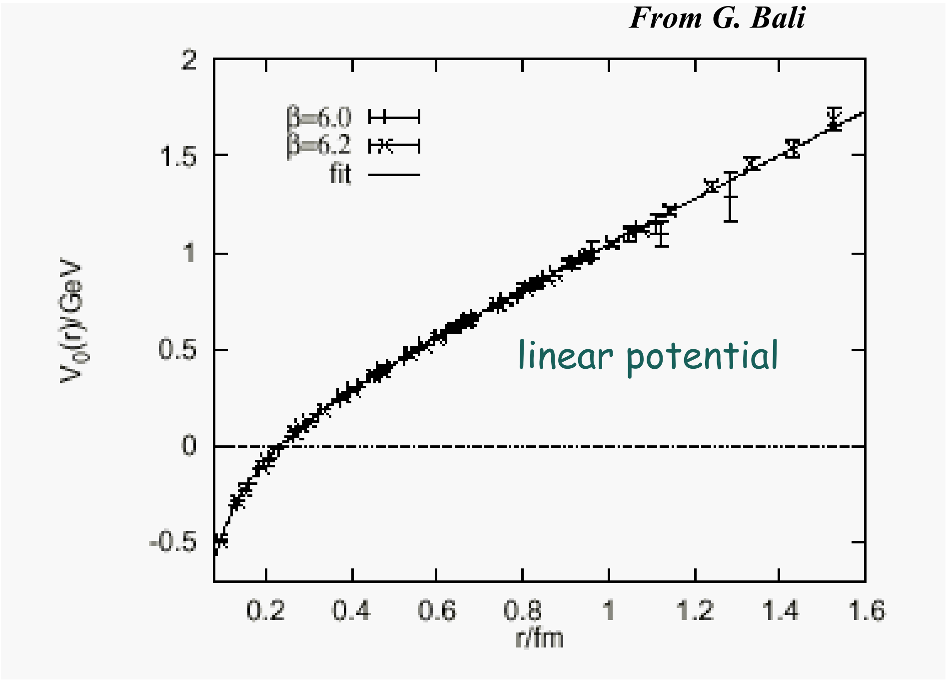
Enhancements to our present physics program:

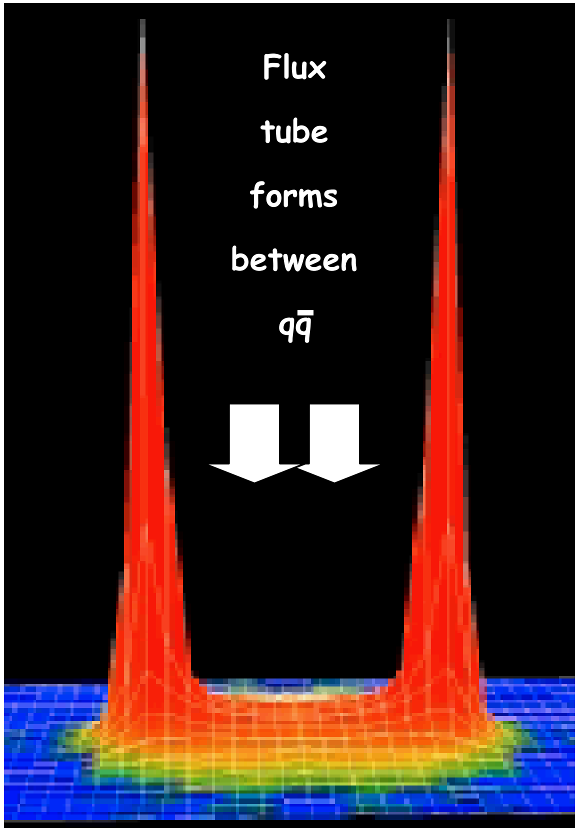
- Extension of the present program of spin, hadron and nuclear microscopy to higher Q^2

  (Higher energies also increase throughput for many experiments now run with 6 GeV beams)

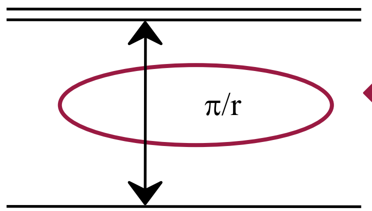
Lattice QCD

Flux tubes realized





transverse phonon modes



ground state

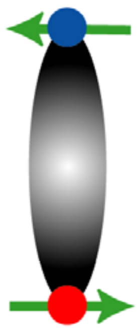
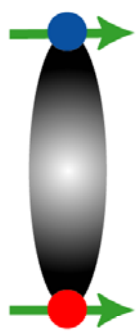
Hybrid mesons

1 GeV mass difference

Normal mesons

Confinement arises from flux tubes and their excitation leads to a new spectrum of mesons

Quantum Numbers for Hybrid Mesons

Quarks	$\oplus$	Excited Flux Tube	$\Rightarrow$	Hybrid Meson
$S=0$ $L=0$ $J^{PC}=0^{-+}$ **like** π, K		$J^{PC}=\begin{cases}1^{+-}\\1^{-+}\end{cases}$		$J^{PC}=\begin{cases}1^{--}\\1^{++}\end{cases}$
$S=1$ $L=0$ $J^{PC}=1^{--}$ **like** γ, ρ		$J^{PC}=\begin{cases}1^{+-}\\1^{-+}\end{cases}$		**Exotic** $J^{PC}=\begin{cases}0^{-+} & 1^{-+} & 2^{-+}\\0^{+-} & 1^{+-} & 2^{+-}\end{cases}$

Flux tube excitation (and parallel quark spins) lead to exotic J^{PC}

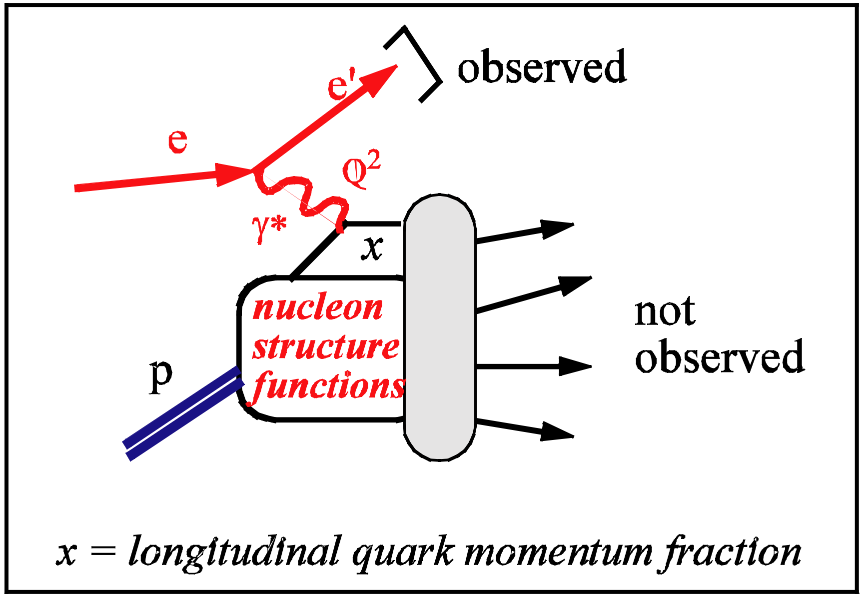
Strategy for Exotic Meson Search

- Use photons to produce meson final states
  - tagged photon beam with 8 – 9 GeV
  - linear polarization to constrain production mechanism
- Use large acceptance detector
  - hermetic coverage for charged and neutral particles
  - typical hadronic final states:

$f_1\eta$	$KK\eta$	$KKppp$
b_1p	$\omega\bar{p}$	$pp\bar{p}p$
ρp	ppp	

  - high data-acquisition rate
- Perform partial-wave analysis
  - identify quantum numbers as a function of mass
  - check consistency of results in different decay modes

Exploring Nucleon Structure via DIS

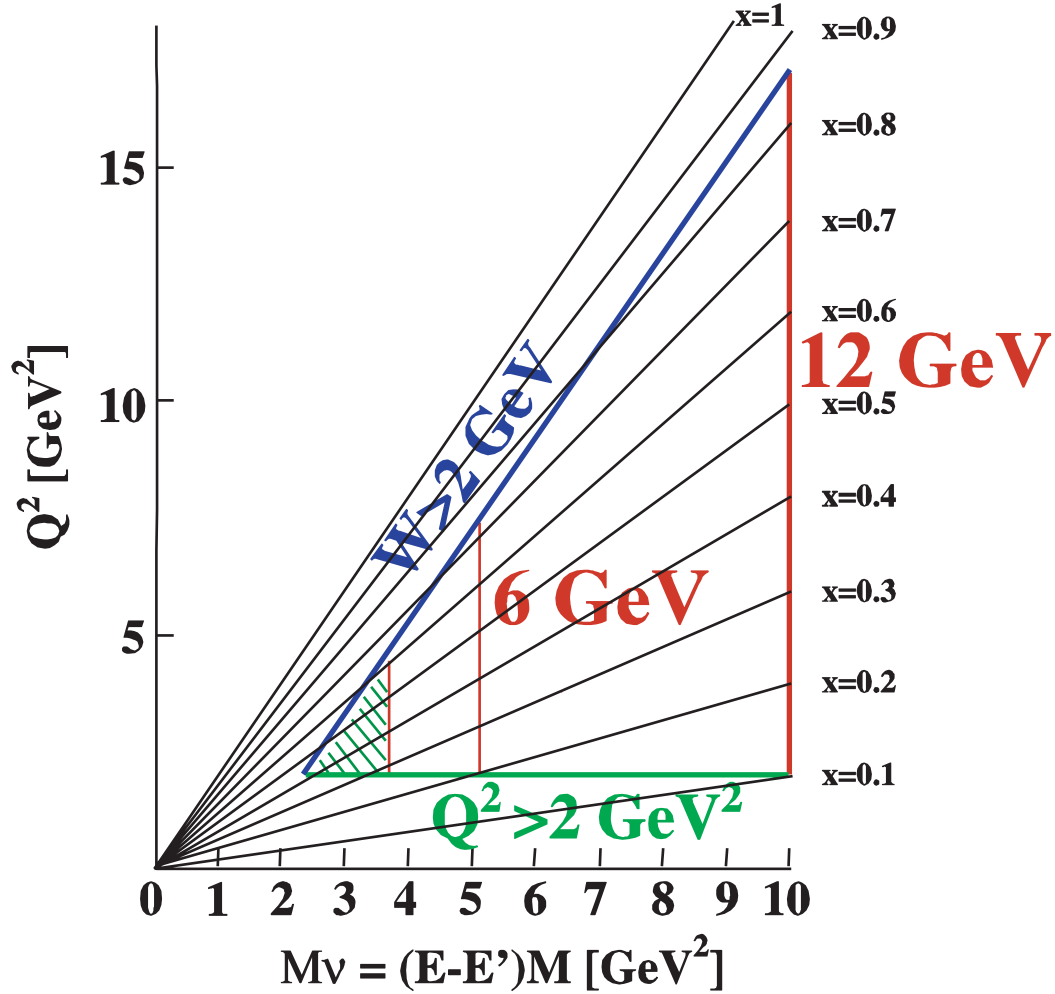


What have we learned?

- Quarks as point-like objects discovered in DIS
- 50% of the nucleon's momentum is carried by quarks, the remainder by gluons
- Quarks are spin-1/2 objects
- 25% of the nucleon's spin is carried by the quarks' spin

There is still much to be learned by extending DIS measurements into the valence regime ($x \to 1$)

12 GeV Provides Substantially Enhanced Access to the DIS Regime



12 GeV will access the valence quark regime (x > 0.3), where constituent quark properties are not masked by the sea quarks

Valence Quark Structure of the Nucleon

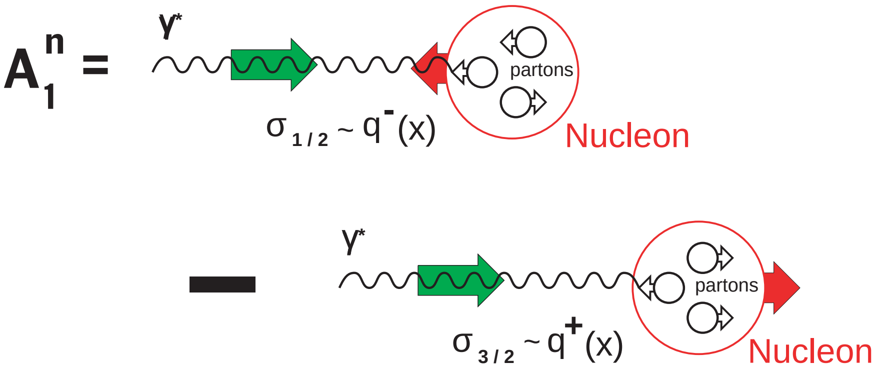
Key Unanswered Questions:

- How are the constituent quarks (quasi-particles) constructed from bare quarks and glue?
- What is the flavor structure of the nucleon?
- What is the spin flavor structure of the nucleon?

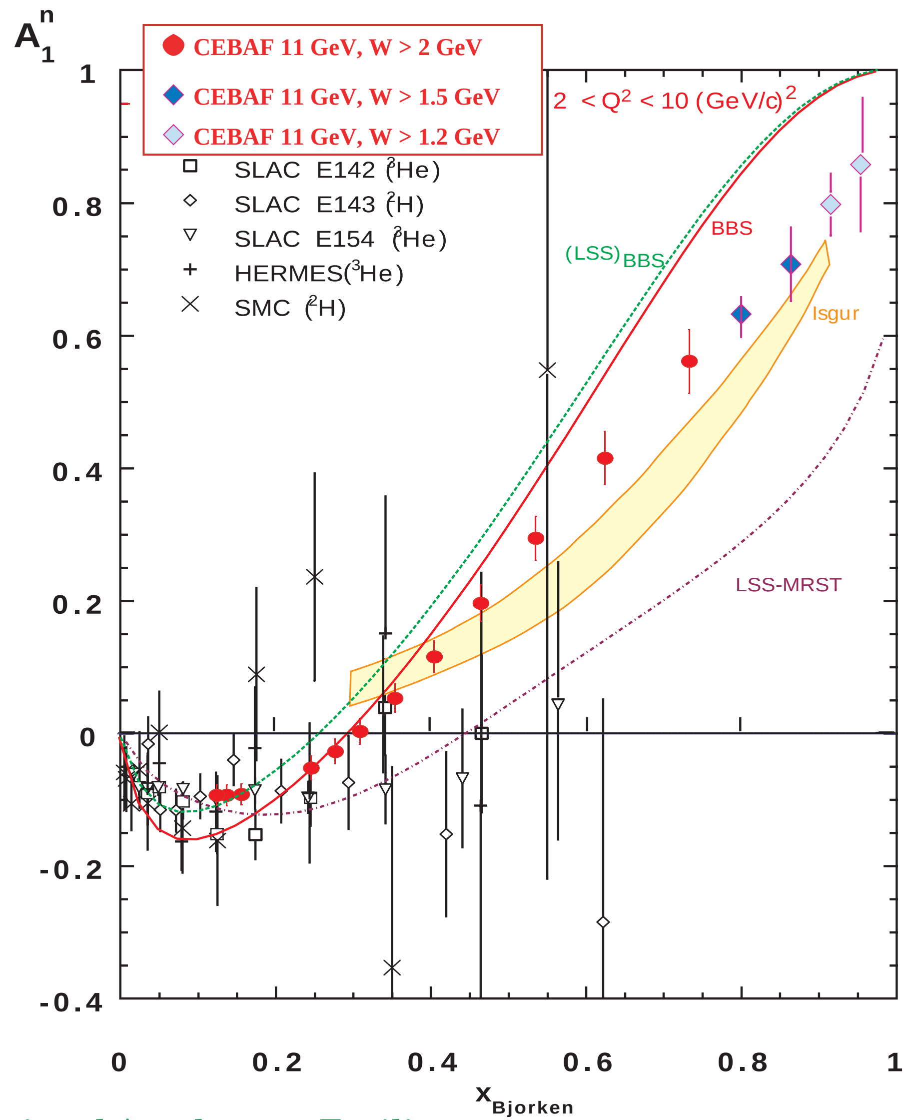
See, e.g. predictions for structure functions as $x \to 1$

Nucleon Model	F_{2n}/F_{2p}	d/u	A_{1n}	A_{1p}
SU(6)	2/3	1/2	0	5/9
Valence Quark	1/4	0	1	1
pQCD	3/7	1/5	1	1

The Neutron Asymmetry A_1^n



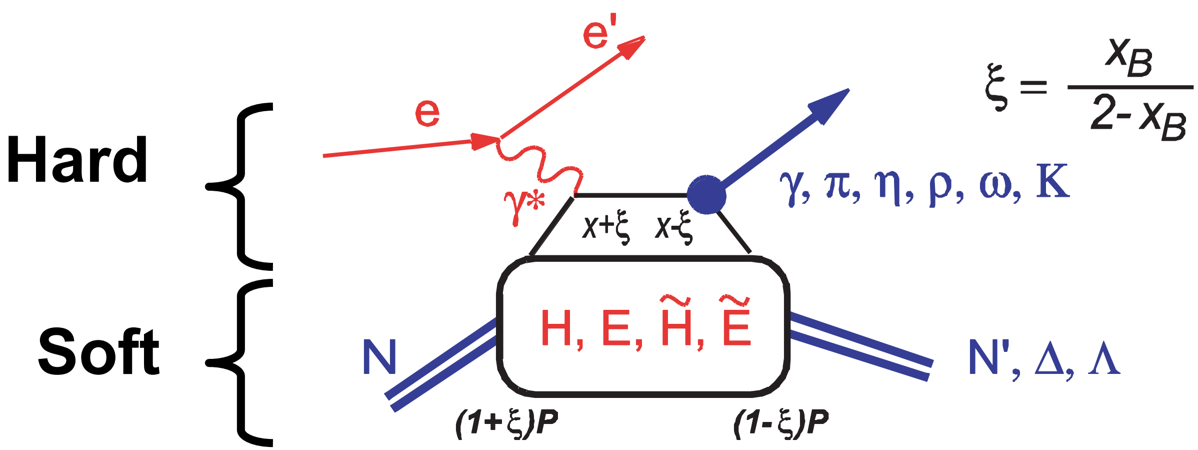
- Study of spin structure functions has been limited to the low-x region
- JLab at 12 GeV with its high luminosity is a prime facility for measurements at large x



Generalized Parton Distributions

- Key Theoretical Insight - Factorization of the Reaction:
  - a "**hard**" part (calculable in pQCD), that characterizes the probe, and
  - a "**soft**" part (the Generalized Parton Distributions) that contains the structure and dynamics of the nucleon

⇒ Separate reaction from nucleon structure and characterize nucleon structure using GPD's

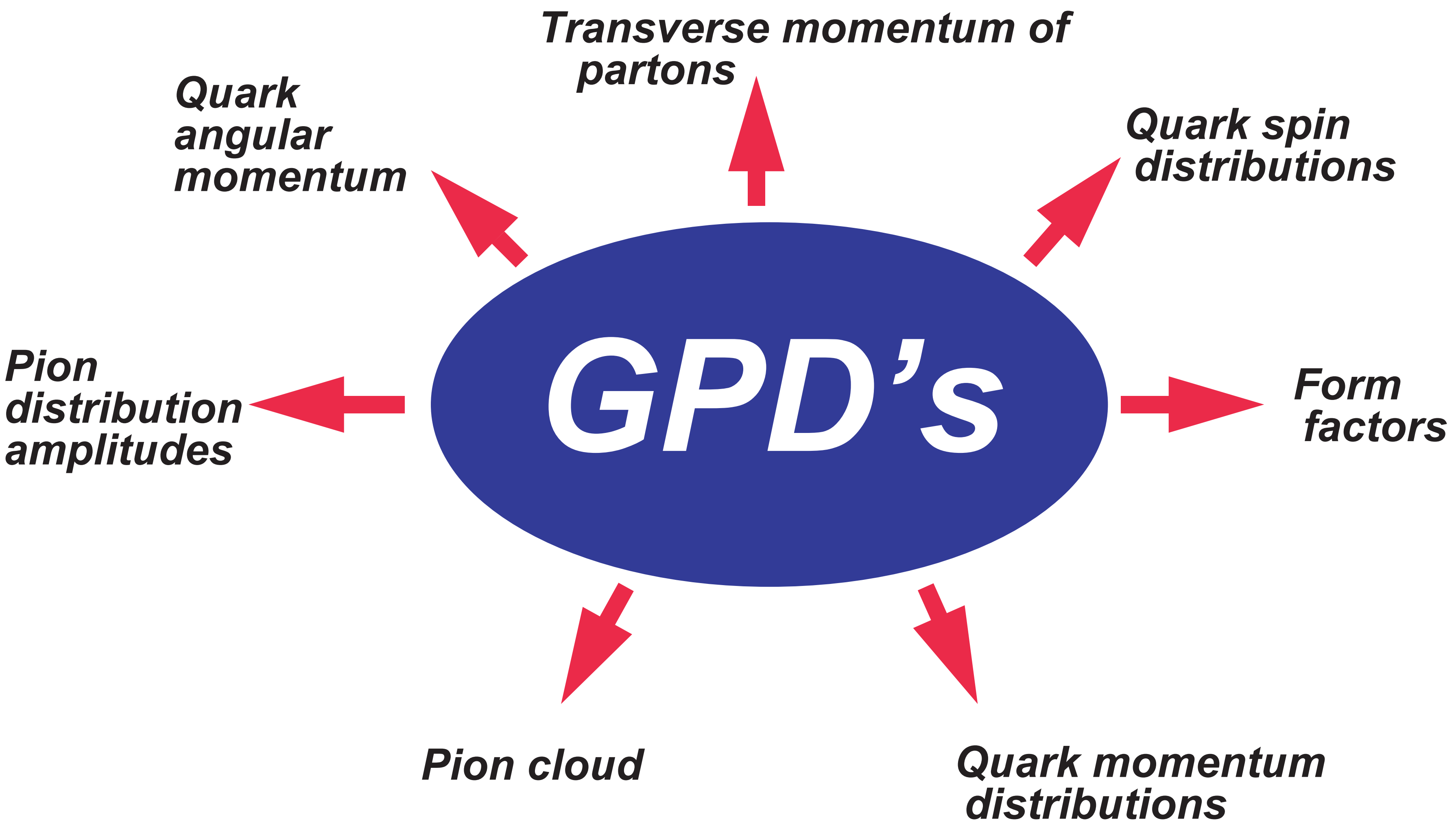


H, E - unpolarized, H̃, Ẽ - polarized GPD

The GPDs Define Nucleon Structure

1996-98
Mueller
Ji
Radyushkin
Collins

Unified Framework for Understanding Nucleon Structure



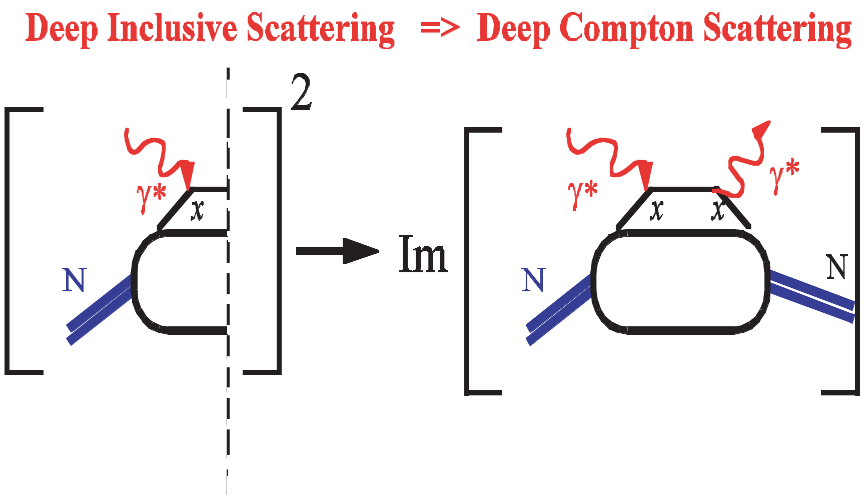
Measuring the GPD's

- Key experimental capabilities include:
  - CW (100% duty factor) electron beams
    (permits fully exclusive reactions)
  - modern detectors
    (permit exclusive reactions at high luminosity)
  - adequate energy
    (~10 GeV to access the valence quark regime)

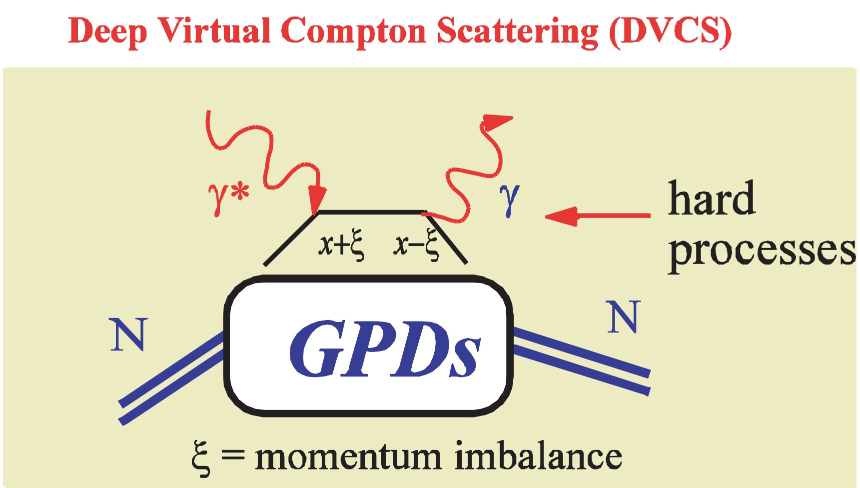
$\Rightarrow$Measurements of the GPD's are now feasible

Deep Virtual Compton Scattering

DIS is limited by the fact that it can only measure longitudinal distributions averaged over all quarks in the nucleon

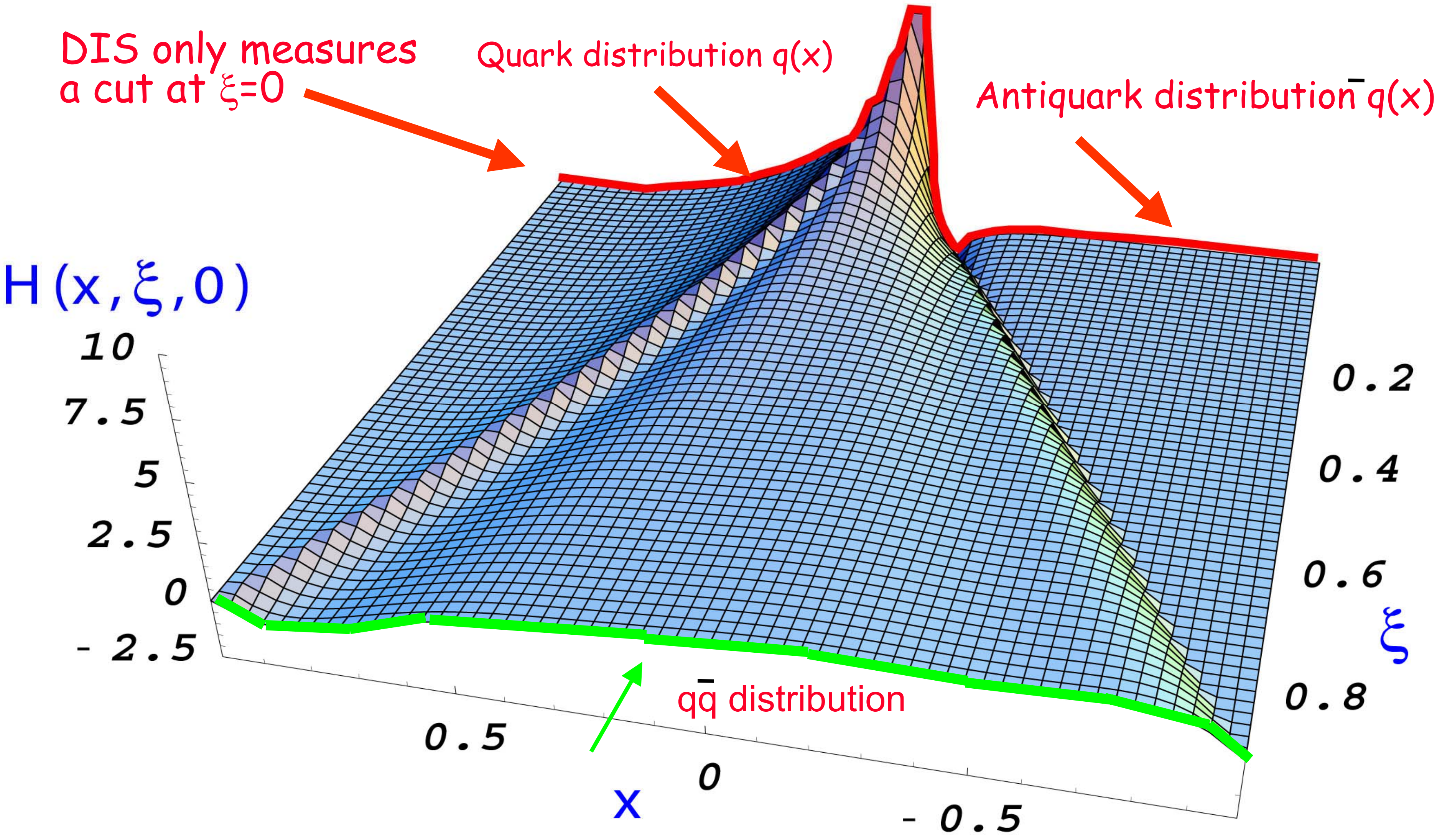


- DIS corresponds exactly to the imaginary part of the Deep Compton Scattering amplitude



- Add determination of the final state (by exclusive reactions such as DVCS) and we can (finally!) probe nucleon quark structure and correlations at the amplitude level

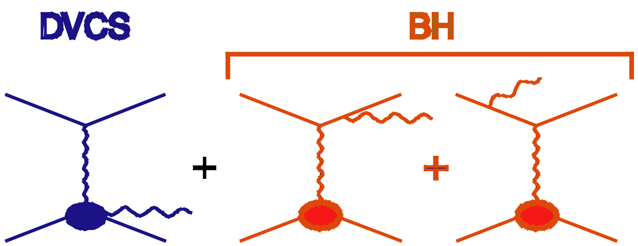
GPD's Contain Much More Information than DIS

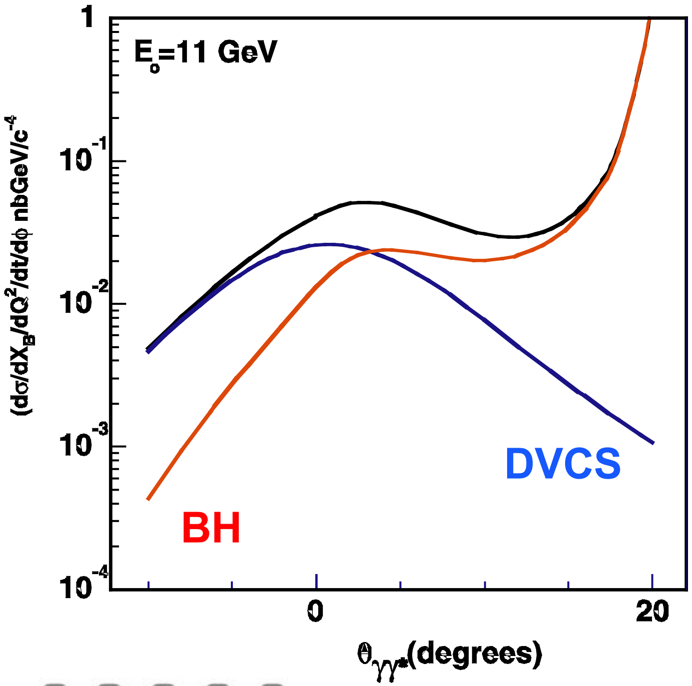


DVCS

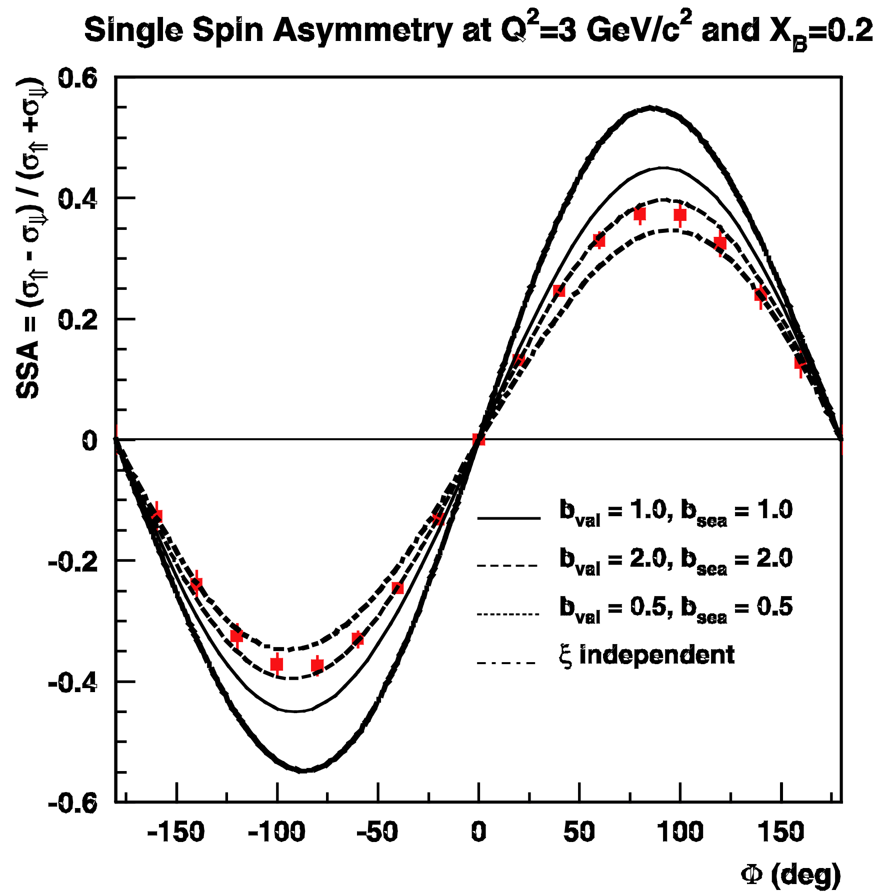
Single-Spin Asymmetry in $e\vec{p} \rightarrow ep\gamma$ Measures phase and amplitude directly

DVCS and Bethe-Heitler are coherent $\Rightarrow$ can measure amplitude AND phase





DVCS at 11 GeV can cleanly test correlations in nucleon structure



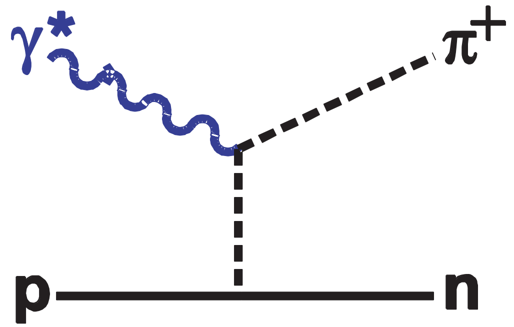
The Pion Form Factor

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

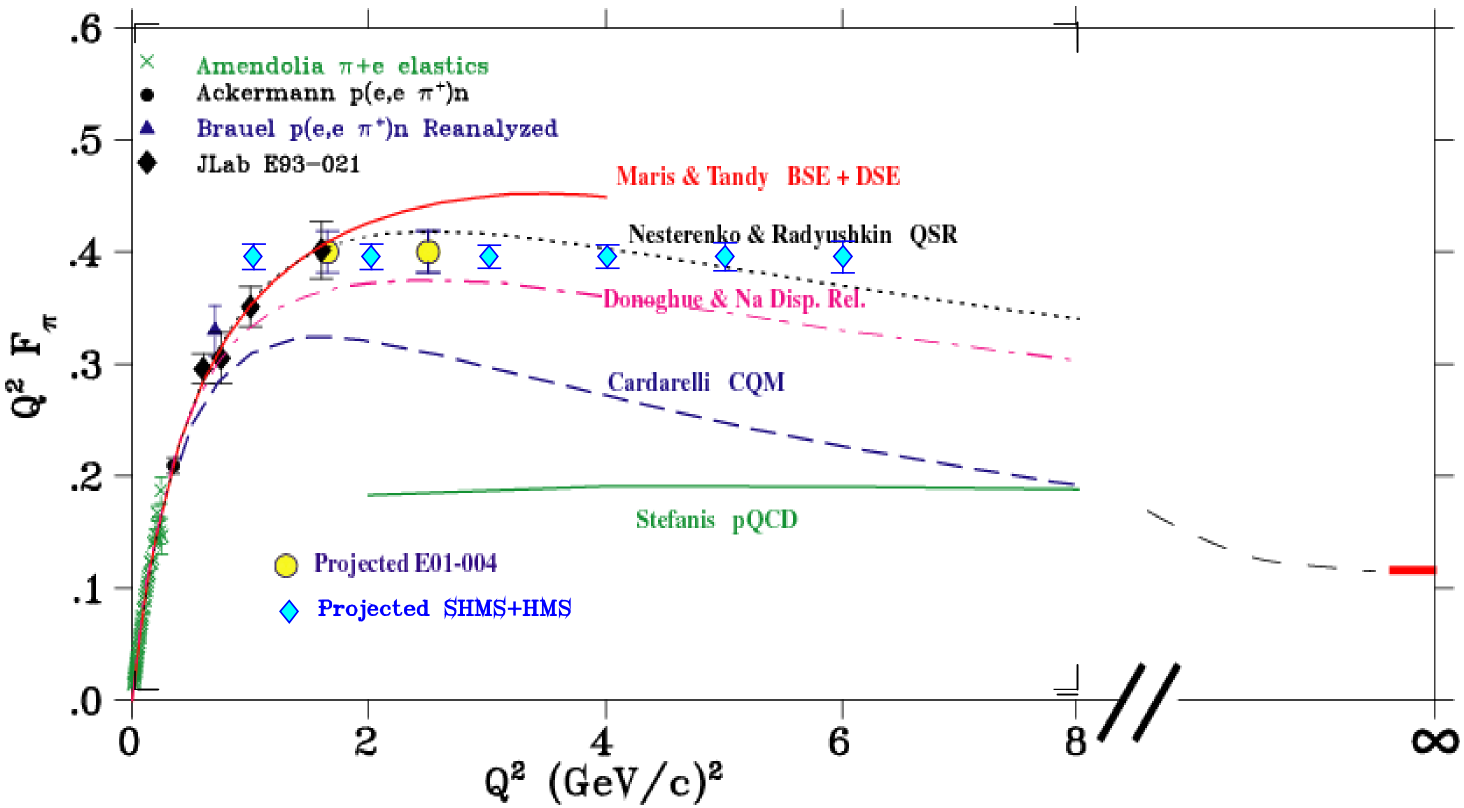
- It will occur earliest in the simplest systems; the pion form factor provides our best chance to determine the relevant distance scale experimentally

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

- At low Q^2 (<0.3 $(GeV/c)^2$): use π e^- scattering $\Rightarrow R_{rms}=0.66$ fm
- At higher Q^2: use $^1H(e,e'\pi^+)n$ (scatter from a virtual pion in the proton and extrapolate to the pion pole)



Pion Form Factor



FF of lightest hadron is expected to start scaling at lowest Q^2

12 GeV Upgrade supports Continuation of the Present Program

- Higher energies support more efficient experiments addressing the current physics problems:
  - Enhanced counting rates (σ ” E^2 at fixed Q^2)
    (also $\Rightarrow$ can reach higher Q^2)
  - Dramatically improved experiment design flexibility and signal-to-noise ratio

- Note: 5-pass recirculator design naturally provides 2.2, 4.4, and 6.6 GeV beams to support experiments best done at the present machine energies

Formal Construction Recommendation of the 2001 NSAC LRP

NSAC 2001 Long Range Plan (3/01):

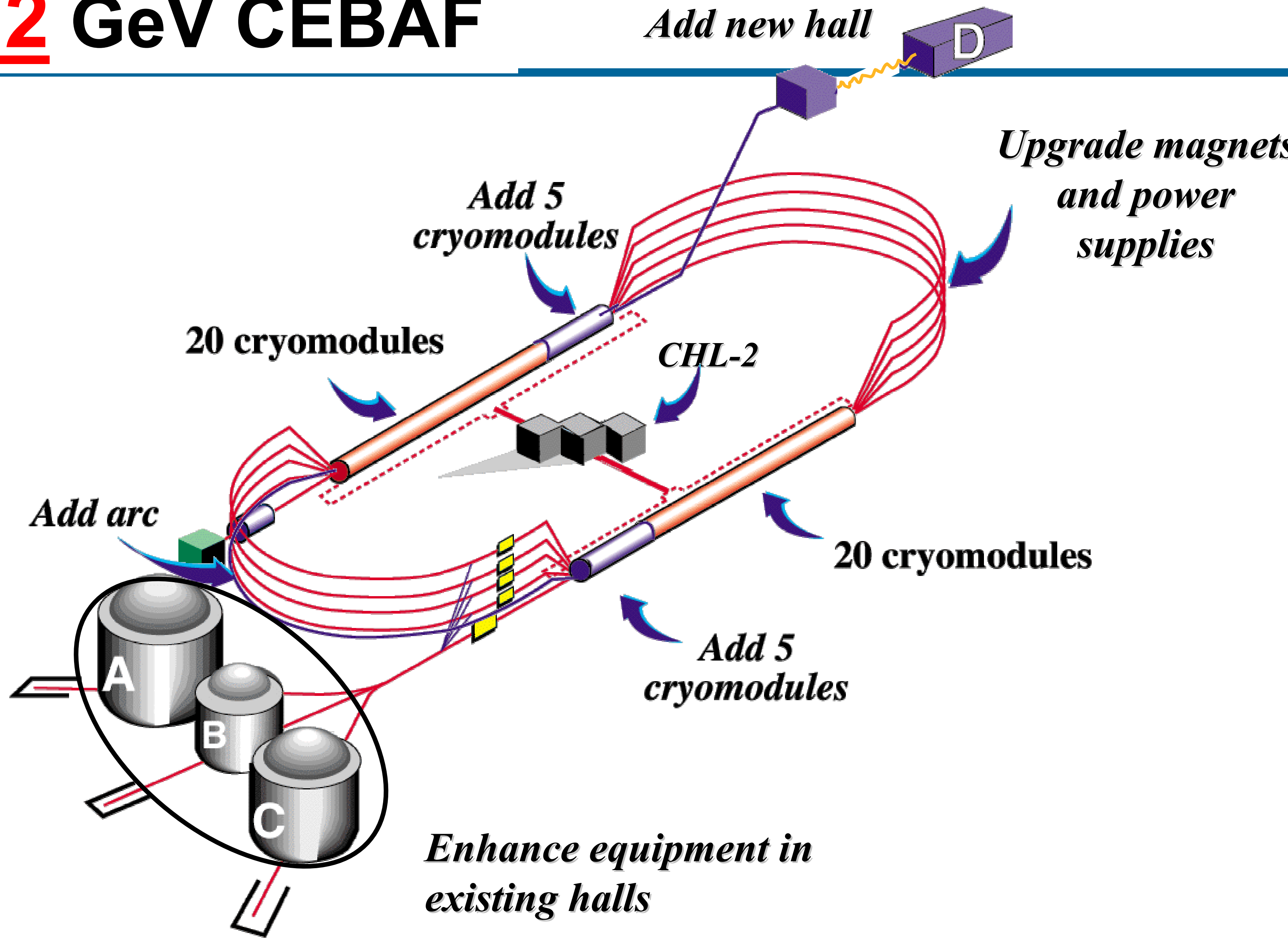
"We strongly recommend the upgrade of CEBAF at Jefferson Laboratory to 12 GeV as soon as possible."

"The 12 GeV upgrade of the unique CEBAF facility is critical for our continued leadership in the experimental study of hadronic matter. This upgrade will provide new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon description of matter, and the nature of quark confinement."

CEBAF @ Higher Energies How?

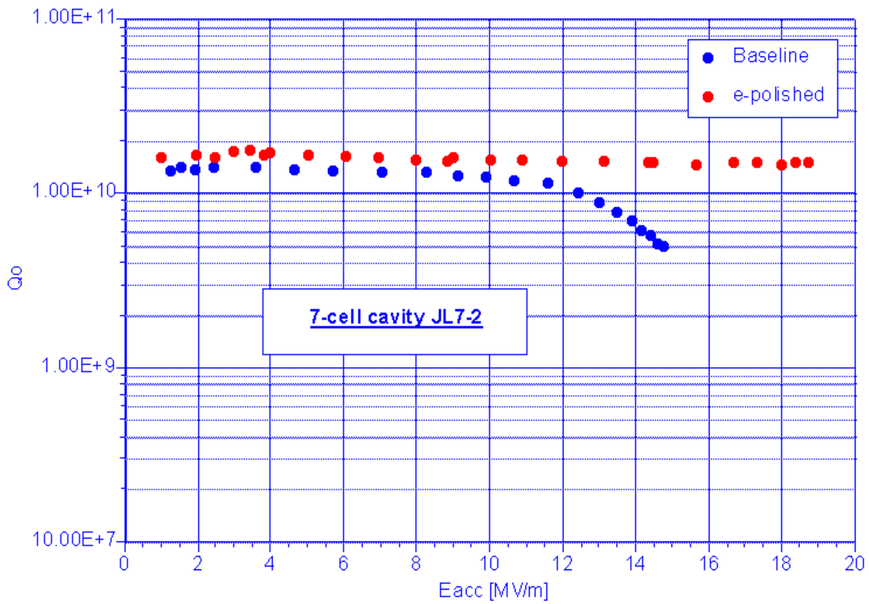
- Design choices for CEBAF's construction make tripling the original energy to 12 GeV remarkably cost effective.
- The extraordinary performance of the original SRF cavities has already brought us to 6 GeV, and further advances in SRF make 12 GeV straightforward.
- Much of the existing experimental equipment can be upgraded for use at higher energies, minimizing equipment costs.

12 GeV CEBAF



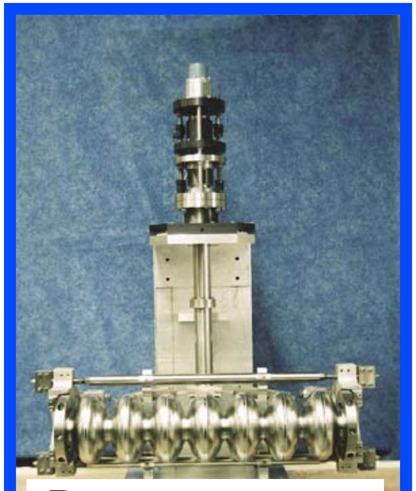
Add new hall
D
Upgrade magnets and power supplies
Add 5 cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5 cryomodules
A
B
C
Enhance equipment in existing halls

New 7-Cell Cavity Design Exceeds Specs for 12 GeV



Performance of 7-cell electropolished cavity (red) exceeds design specs.

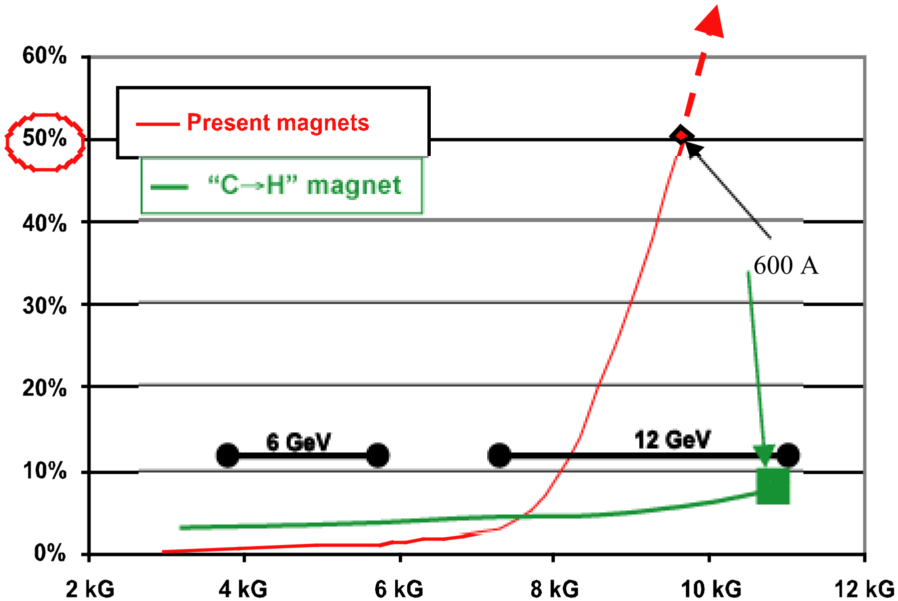
Prototype 7-cell cavity



Prototype tuner

Beam Transport - Recirculation Dipoles

- Need more field
- Simplest solution is to turn up current, but leads to saturation
- Simple and cheap solution is to add return iron (H-type magnet)



The Experimental Halls Today

- Hall C (operational since mid '95) £ ~10^{38} $cm^{-2}s^{-1}$
  - Two medium-resolution spectrometers HMS and SOS
  - High-Momentum Spectrometer / Short-Orbit Spectrometer

	High-Momentum Spectrometer	Short-Orbit Spectrometer
. dp/p	~ 10^{-3}	~ 10^{-3}
. p_{max}	~ 7 GeV/c	~ 1.5 GeV/c
. $\Delta\Omega$	~ 7 msr	~ 9 msr

- Hall A (operational since May '97) £ ~10^{39} $cm^{-2}s^{-1}$
  - Two identical high-resolution spectrometers (HRS)
    - dp/p ~ 10^{-4}
    - p_{max} ~ 4 GeV/c
    - $\Delta\Omega$ ~ 6 msr

- Hall B (operational since December '97) £ ~10^{34} $cm^{-2}s^{-1}$
  - CEBAF Large Acceptance Spectrometer (CLAS)
  - Based on six-sector superconducting toroidal magnetic field

CEBAF Upgrade: Experimental Equipment

Hall	Physics Goal	Measurement Technique	Instrumentation (new and upgraded)
A	Map out the valence quark distribution	Inclusive electron scattering at high x	Medium Acceptance Detector (MAD) at high luminosity and intermediate angles **(keep both HRS spectrometers)**
B	Determine the Generalized Parton Distributions	Multi-particle final states in exclusive electron scattering	CLAS upgraded to higher (10^{35}) luminosity and coverage **(reuse CLAS coil and major detector elements)**
C	Understand form factors of simple quark systems	Exclusive meson production at large momentum transfer (one arm at full beam momentum)	Super High Momentum Spectrometer (SHMS) at high luminosity and forward angles **(keep HMS)**
D	Understand confinement	Photo-production of mesons with exotic quantum numbers	9 GeV tagged polarized photons and 4π hermetic detector **(refurbish SC solenoid, lead glass array)**

Hall A Upgrade: Medium Acceptance Spectrometer

- Design Objectives:

  Two combined-function superconducting magnets

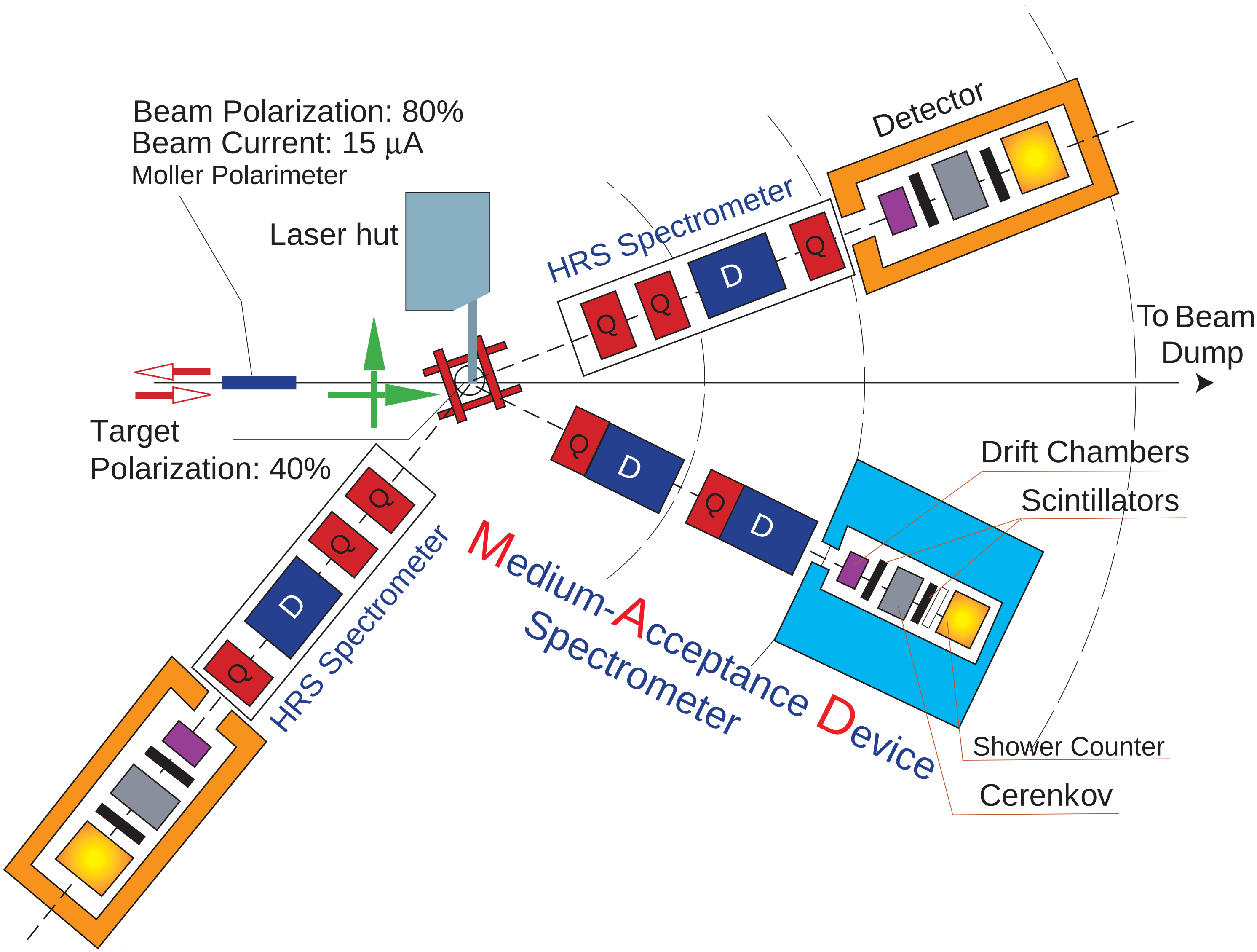
  Magnet characteristics (each)

  - Weight: 180 t Bend angle: 10° + 20°
  - Dipole field: 1.5 T Gradient: 4.2 T/m

- Spectrometer properties (acceptance linear between 15° and 35°)

Spectrometer Angle	35°		15°
	Acceptance	Resolution(σ)	Acceptance
Angular	30 msr		15 msr
Horizontal	± 37 mrad	0.5 mrad	± 31 mrad
Vertical	± 206 mrad	4.3 mrad	± 120 mrad
Momentum	± 15 %	0.07 %	
Target coordinate	± 6 cm @ 90°	0.25 cm	

Hall A Floor Plan with MAD Spectrometer



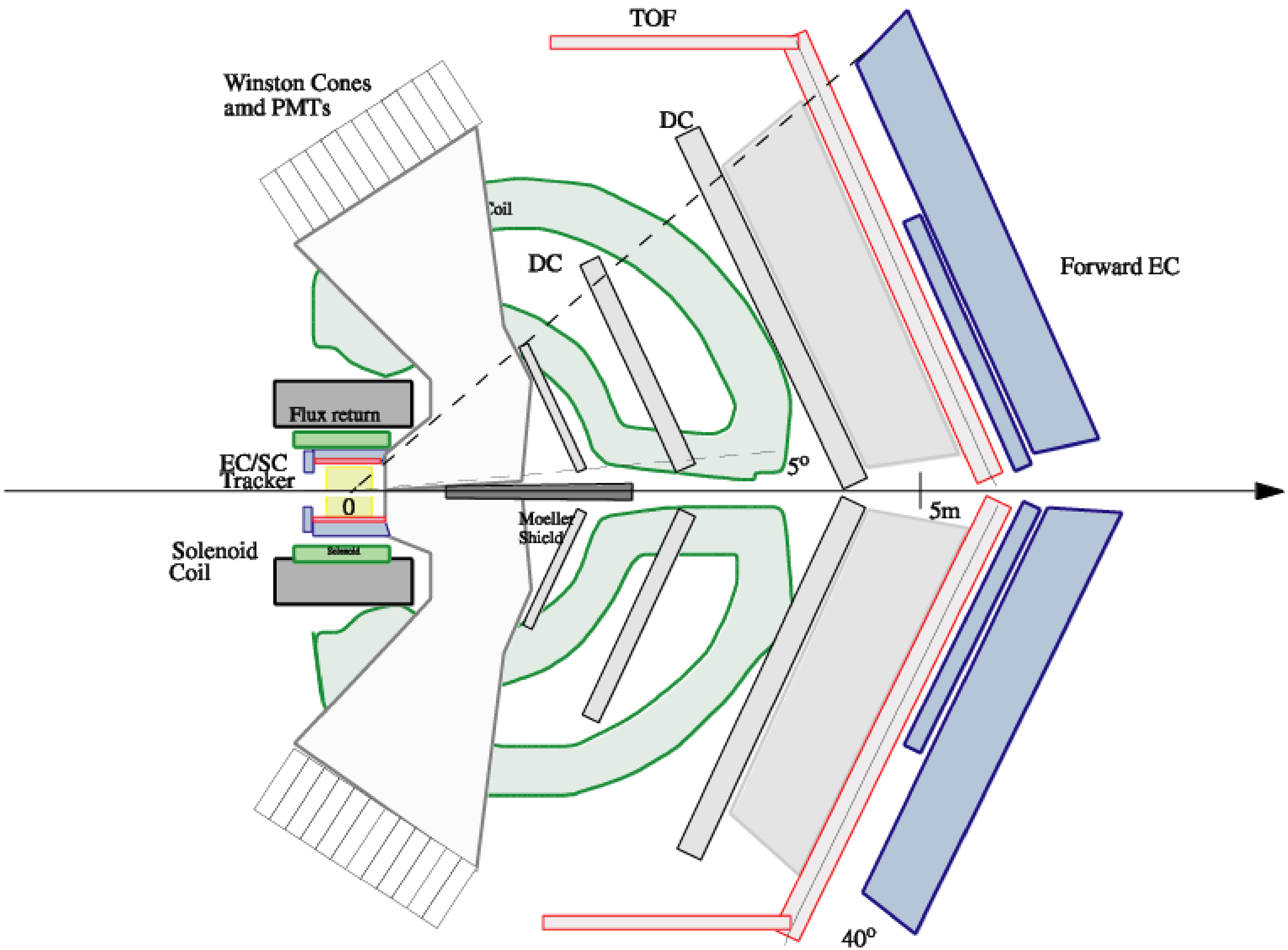
Hall B: CLAS++ Design Features

- CLAS now, at full specs:

luminosity	10^{34} cm^{-2}s^{-1}
tagged photons	10^{7} s^{-1}
event rate	3000 s^{-1}

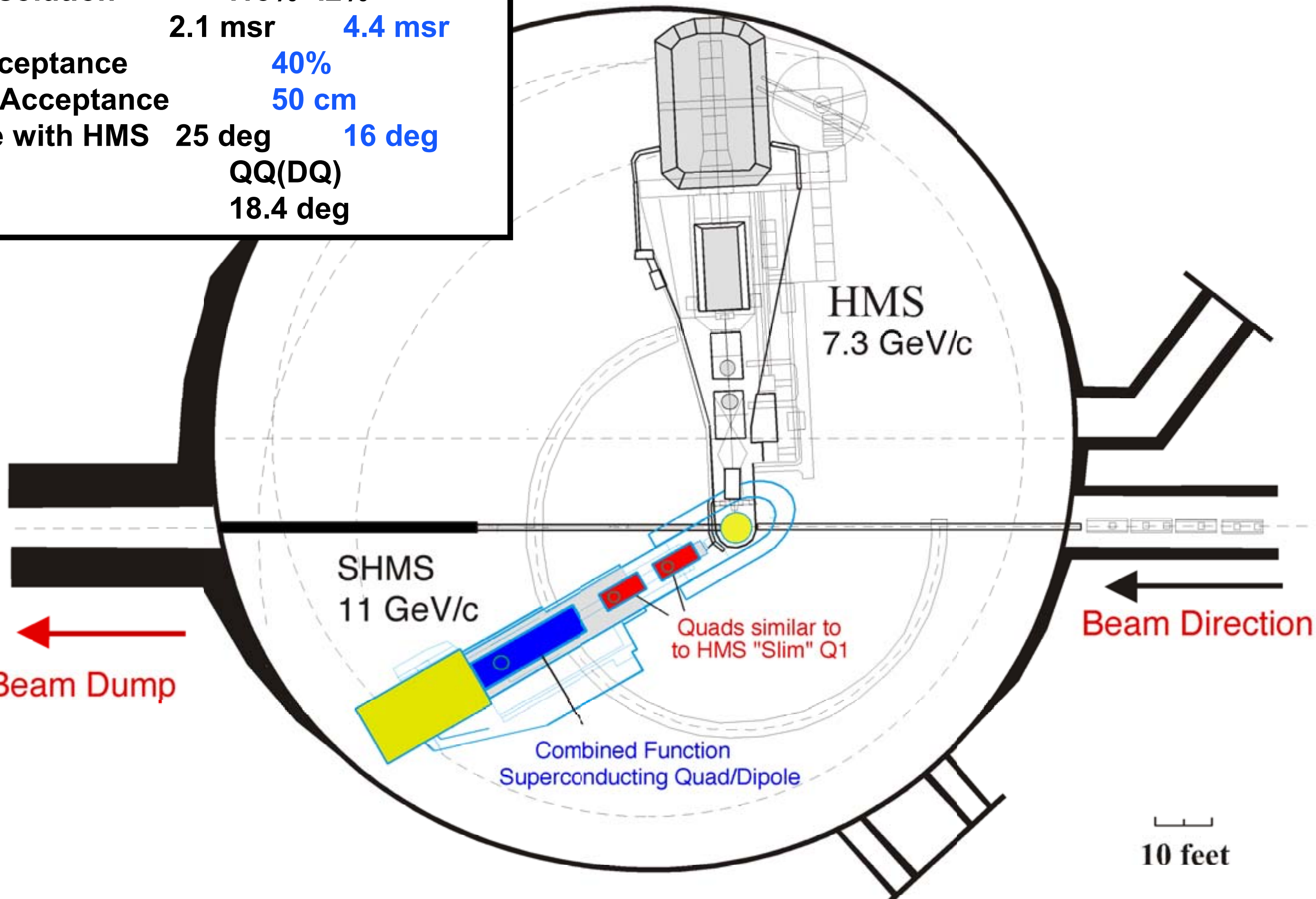
- Limitations at higher energies: use of missing-mass technique
  angular coverage due to torus coils
  e^-/π^- separation (PID)
  luminosity
- CLAS Upgrade
  - Add new central detector (40° < θ < 135°)
    move target upstream by 1 m
    SC solenoid for Møller shielding and momentum analysis
    drift-cell tracker, microstrip and calorimeter
  - Complete azimuthal coverage
    with forward tracker and inner calorimeter
  - Finer-grained drift chambers to reach luminosity of 10^{35} cm^{-2}s^{-1}
  - Very limited use of tagged photons (Hall D)

Hall B Upgrade: CLAS++



SHMS - HMS Spectrometers

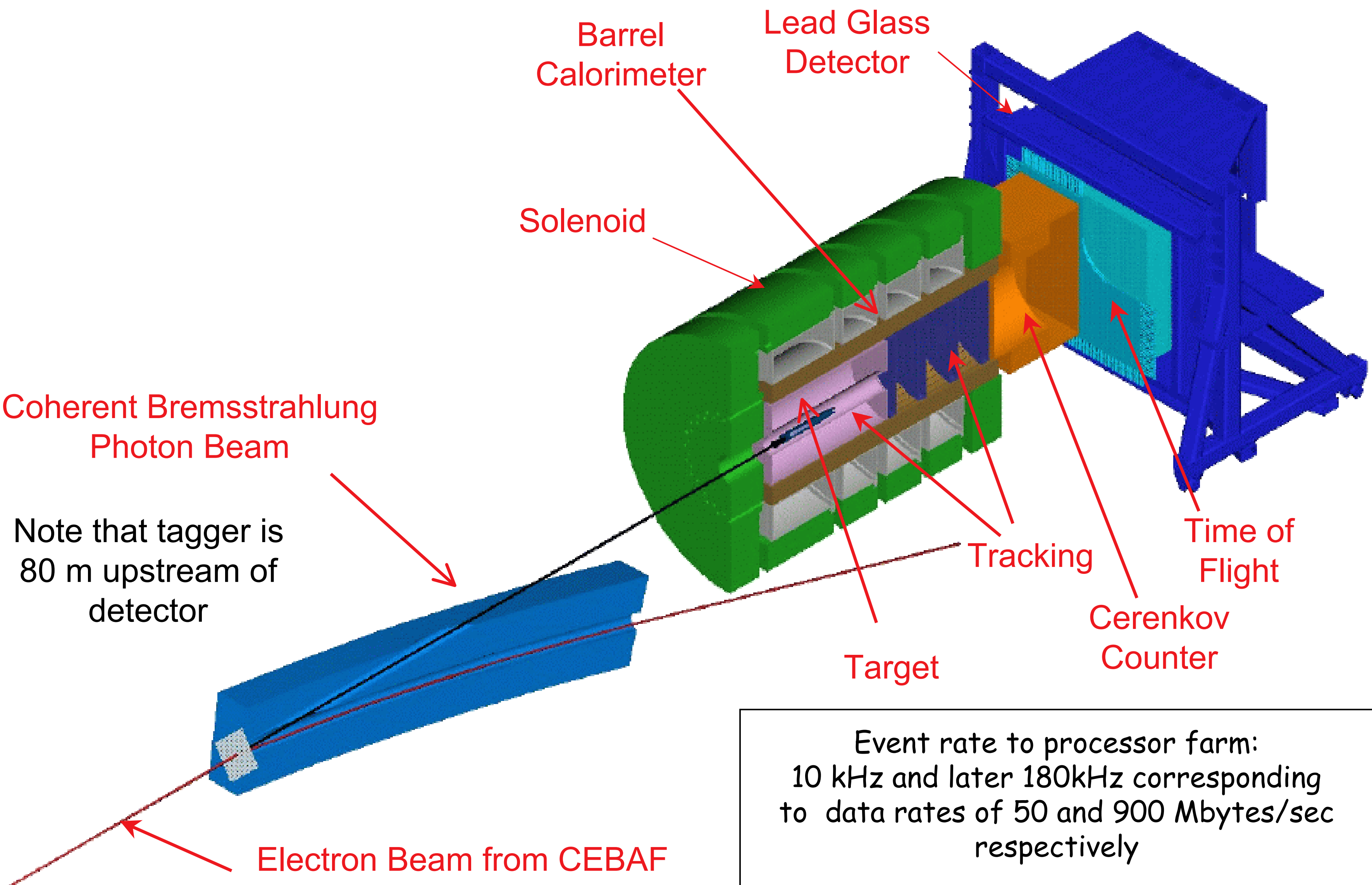
Max. Central Momentum	11 GeV/c	9 GeV/c
Min. Scattering Angle	5.5 deg	10 deg
Momentum Resolution	.15% -.2%	
Solid Angle	2.1 msr	4.4 msr
Momentum Acceptance		40%
Target Length Acceptance		50 cm
Opening Angle with HMS	25 deg	16 deg
Configuration	QQ(DQ)	
Bend Angle	18.4 deg	



Physics Requirements for Hall D Detector

- Acceptance between 1° and 130° to allow reconstruction of exclusive final states with multiple charged and neutral particles
- Momentum resolution ~ 1% (MEGA magnet)
- Calorimeter energy resolution $\sigma/E \sim 5\%/\sqrt{E}$
- Particle Identification using TOF and Cerenkov counters
- High DAQ rate with a software Level 3 trigger

Hall D Detector



Note that tagger is 80 m upstream of detector

Event rate to processor farm:
10 kHz and later 180kHz corresponding to data rates of 50 and 900 Mbytes/sec respectively

Next Steps

CD	DOE Meaning	Implications
CD-0	Approve Mission Need	Formal CDR work begins using program funds R&D for CDR begins PED Funds can be requested Serious search for non-DOE/NP funds
CD-1	Approve Preliminary Baseline Range	CDR done and reviewed Acquisition plan developed PED funds can be spent
CD-2	Approve Performance Baseline	"Lehman Review" – Budget Extablished Request construction funding
CD-3	Approve Start of Construction	Construction project begins in earnest
CD-4	Approve start of operations or project closeout	Science Begins!

Long-Term Future @ JLab

Investigations underway for Electron-light Ion Collider that could simultaneously provide 25 GeV external beams for fixed target experiments

New Tool to Investigate
- (Semi-Inclusive) DIS
- Deep Exclusive Reactions (GPD's)

I. 3-5 GeV Electrons & 30-50 GeV light ions in Collider Mode
- Luminosity $\leq 6 \times 10^{34}$ cm^{-2}
- (Substantial overlap with EIC/eRHIC for Light Ions)

II. 25 GeV External Beams
- Luminosity ~10^{38} cm^{-2} s^{-1}
- (≈ ELFE Project)

Basis of Proposal

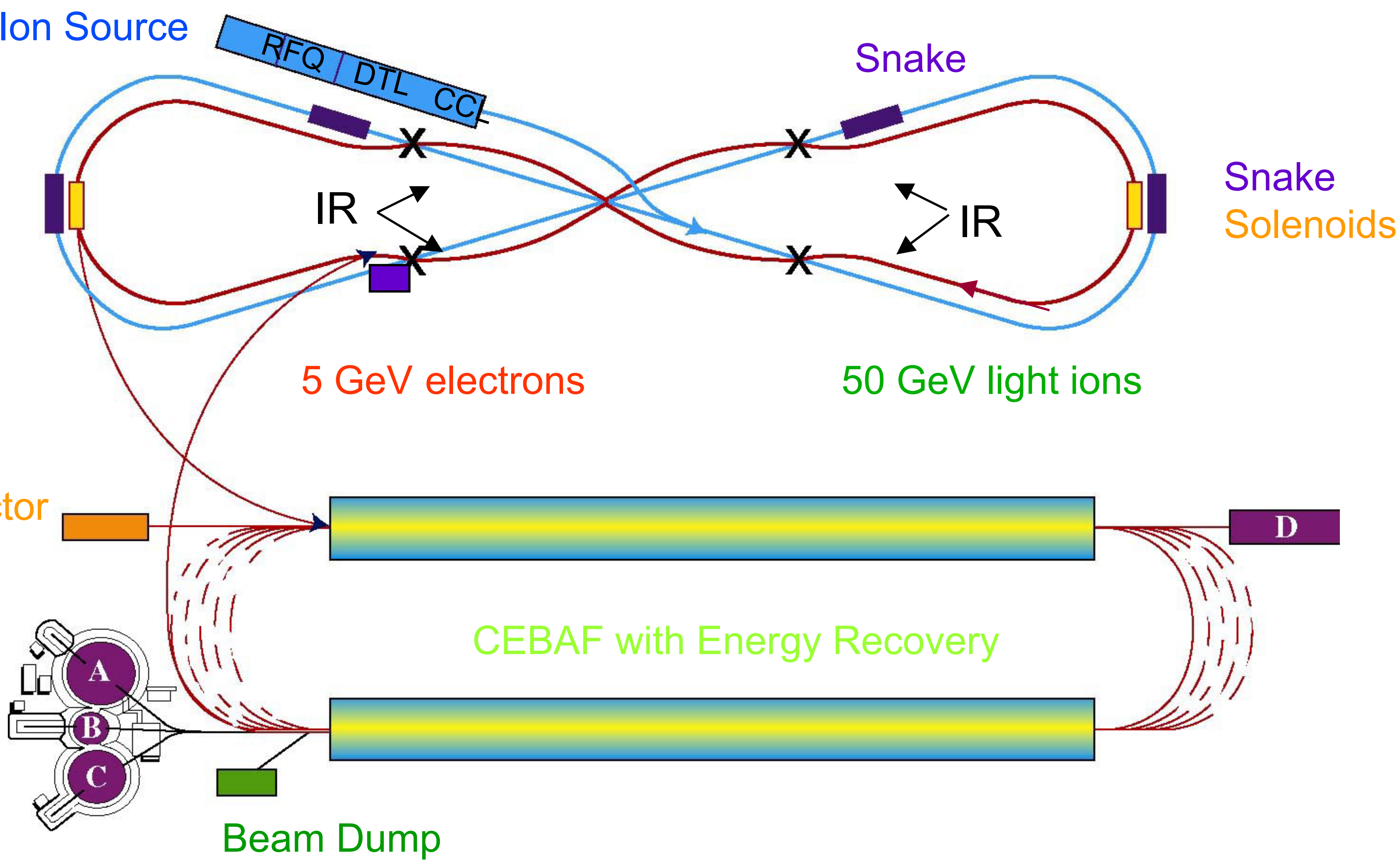
- Further Upgraded CEBAF is used for the acceleration of electrons
- Energy recovery is used for RF power savings and beam dump requirements
- "Figure-8" storage ring is used for the ions for flexible spin manipulations of all light-ion species of interest
- Circulator ring for the electrons may be used to ease high-current polarized photoinjector requirements
- Antiparallel linacs can also be used in full acceleration mode rather than deceleration mode to get 25 GeV High Luminosity beam

Parameter Choices

- Self-consistent parameters developed for 4 point designs (PD's):
  - PD0: No electron cooling
    Parameters based on demonstrated performance to date
    Max luminosity of 1×10^{32} cm^{-2} sec^{-1}
  - PD1: Add Electron cooling
    Max luminosity of 1×10^{33} cm^{-2} sec^{-1}
  - PD2: Add short ion bunches, Circulator Ring, Crab Crossing
    Max luminosity of 1×10^{34} cm^{-2} sec^{-1}
  - PD3: Add traveling focus
    Max achievable luminosity 6×10^{34} cm^{-2} sec^{-1}
- Assumptions:
  - E_e=5 GeV, E_i = 50 GeV,
  - Equal beam sizes for electrons and ions are assumed at the IP

EIC@JLab (Electron-Light Ion Collider Layout)

One accelerating and one decelerating pass through CEBAF

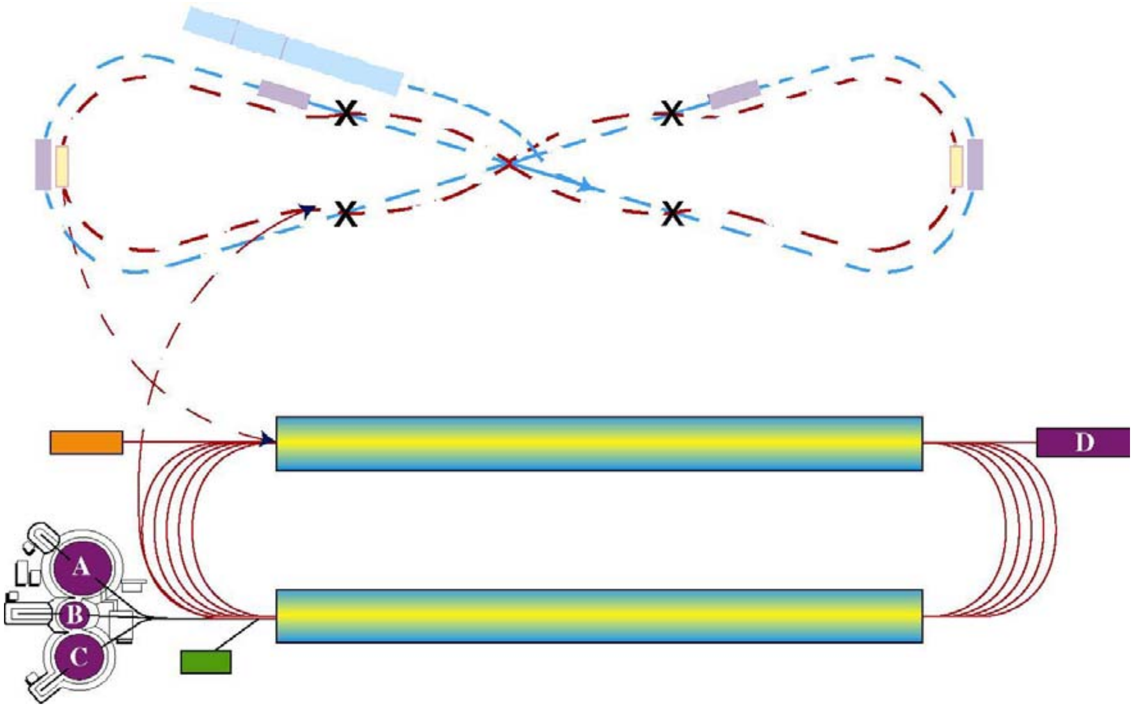


ELFE@JLab (25 GeV Fixed Target Program Layout)

Five accelerating passes through CEBAF ⇒
25 GeV Fixed Target Program

(30 GeV CM Collider Program ⇒
One accelerating and one decelerating pass through CEBAF)

Exploring whether collider and fixed target modes can run simultaneously



Summary and Perspectives

- CEBAF accelerator is running reliably at 5.7 GeV with (80%, 100 μA) polarized beam supporting a broad program of fundamental research in nuclear and nucleon structure.
- The 12 GeV JLab upgrade, a formal recommendation of the NSAC Long Range Plan, will permit a major step forward in the study of "strong" QCD and hadron structure
- Substantial progress has been made toward refining the experimental program and equipment designs presented to the Community during the NSAC LRP
- International involvement is essential to move this exciting project forward rapidly
- Even as we take the step toward 12 GeV, we are beginning to think about the future beyond 12 GeV w/ ELFE- and EIC-type capabilities