Physics Prospects with the JLab 12 GeV Upgrade

Gluonic Excitations

3-dim view
of the Nucleon

Valence Structure
of the Nucleon

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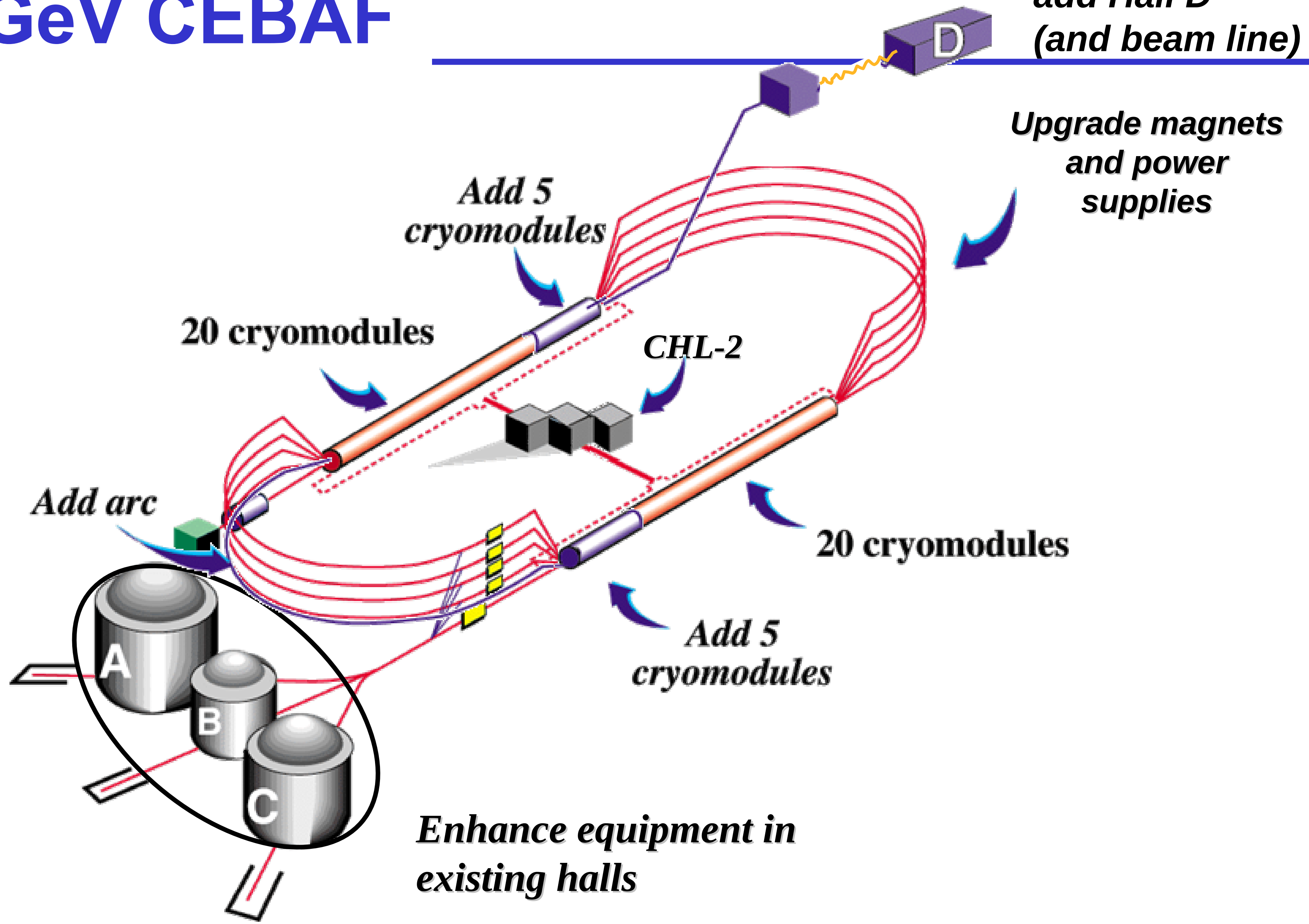
PANIC02
Osaka

CEBAF @ JLab Today

- Main physics programs
  - nucleon electromagnetic form factors (including strange form factors)
  - N $\rightarrow$ N* electromagnetic transition form factors
  - spin structure functions of the nucleon
  - form factors and structure of light nuclei
- Superconducting recirculating electron accelerator
  - max. energy 5.7 GeV
  - max current 200 μA
  - e polarization 80%
- Simultaneous operation in 3 halls — L[$cm^{-2}s^{-1}$]
  - 2 High Resolution Spectrometers (p_{max}=4 GeV/c) — 10^{39}
  - 2 spectrometers (p_{max}=7 and 1.8 GeV/c) + special equipment — 10^{39}
  - Large Acceptance Spectrometer for e and γ induced reactions — 10^{34}

12 GeV CEBAF


add Hall D
(and beam line)
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

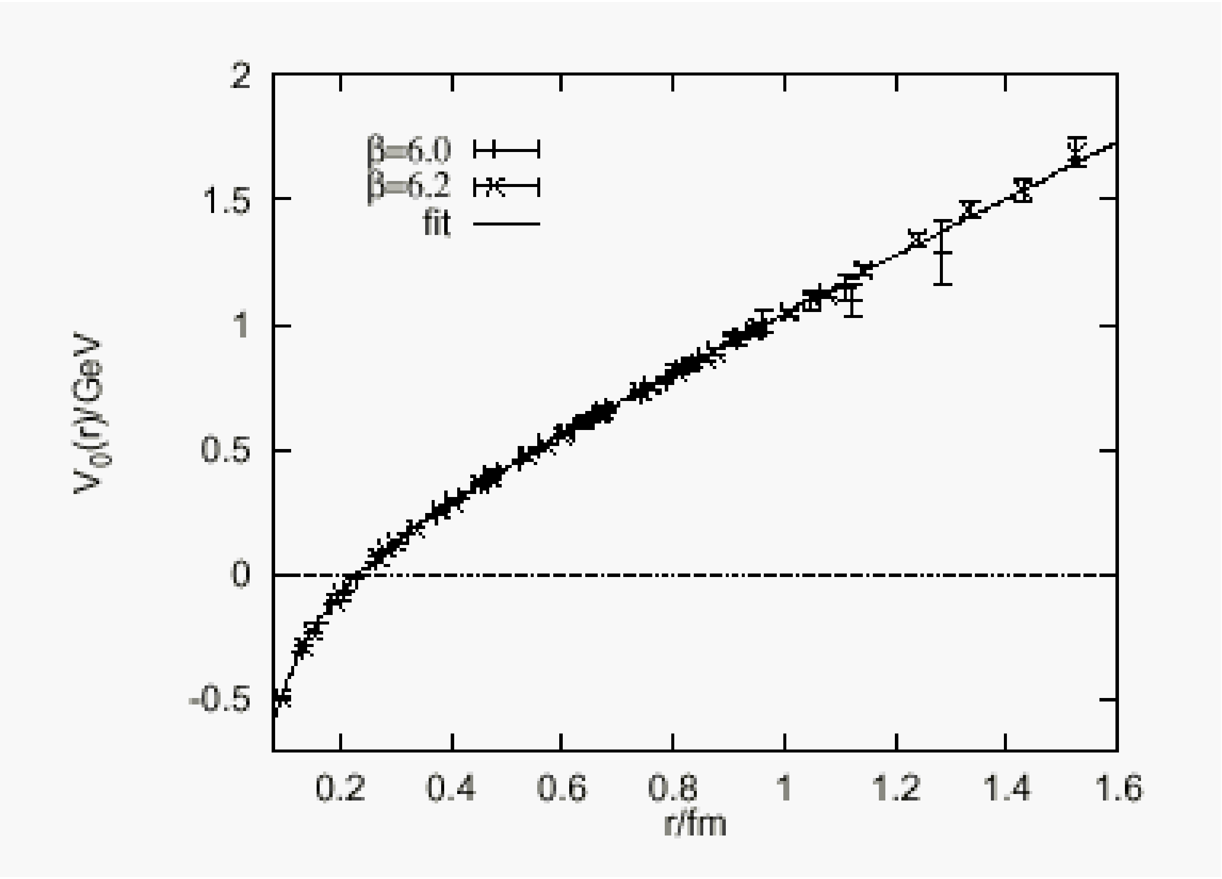
Gluonic Excitations

Hall D at Jefferson Lab
www.gluex.org

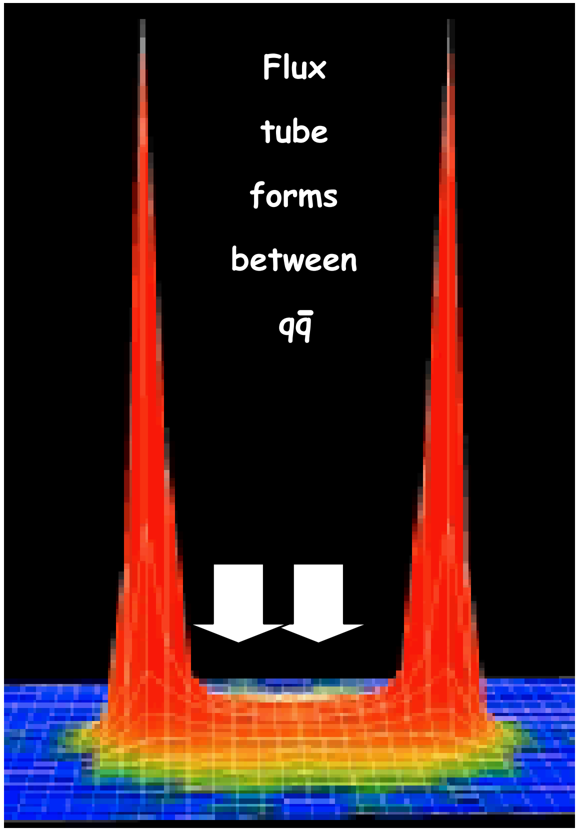
Dynamical role of Glue

Confinement

Lattice QCD



Flux tubes realized



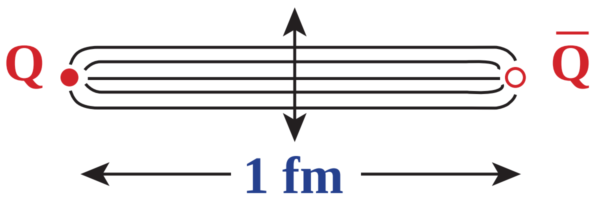
→ Flux Tube Model

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

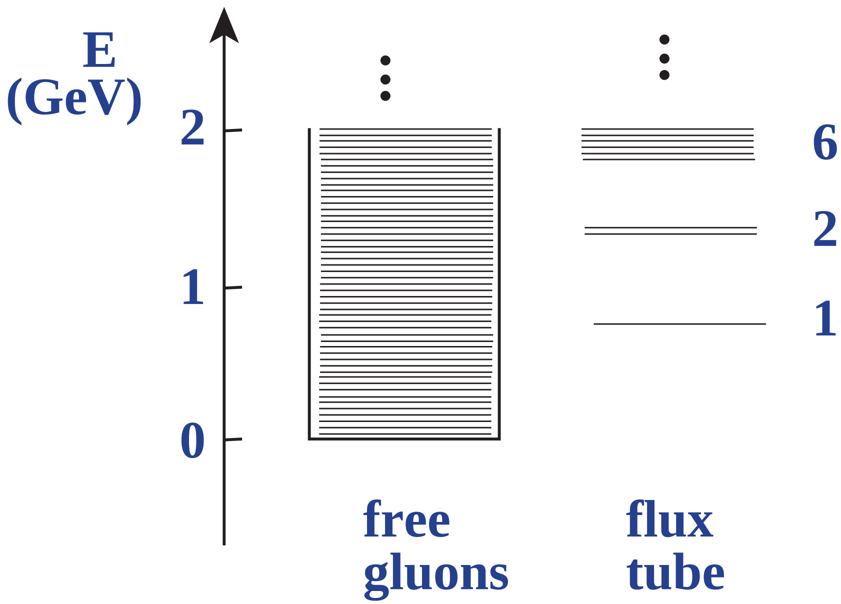
From G. Bali

Understanding Confinement

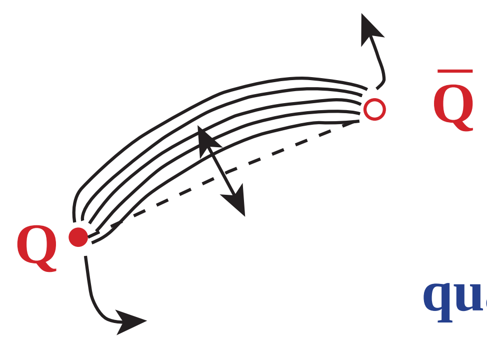
The Ideal Experiment



quarks fixed

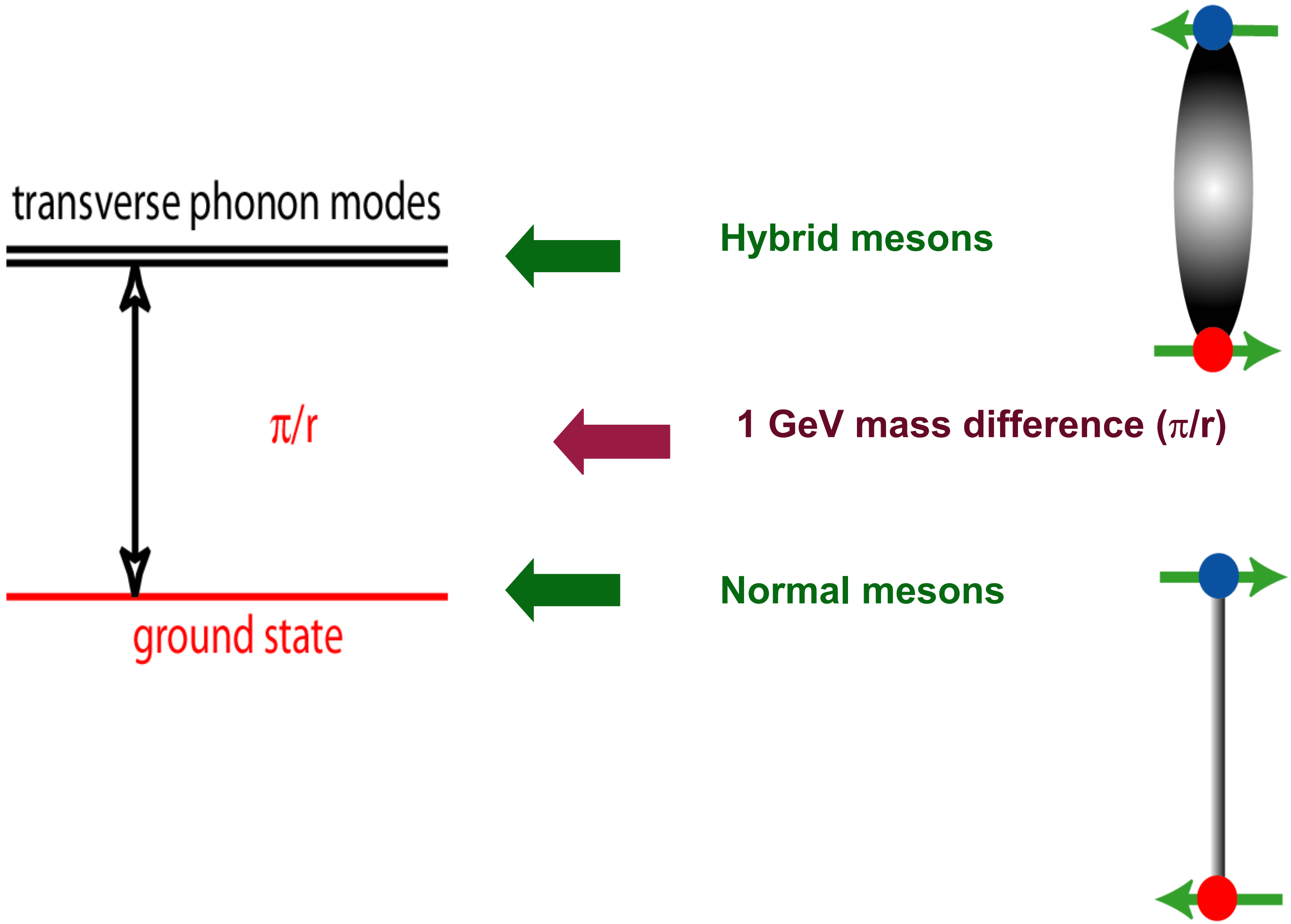


The Real Experiment



quark motion plus
flux tube excitation

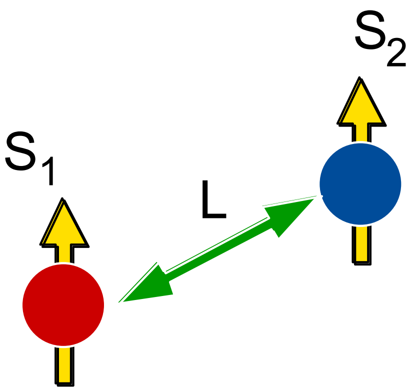
Hybrid Mesons



Normal Mesons – $q\bar{q}$ color singlet bound states

Spin/angular momentum configurations & radial excitations generate our known spectrum of light quark mesons.

Starting with u - d - s we expect to find mesons grouped in nonets - each characterized by a given J, P and C.

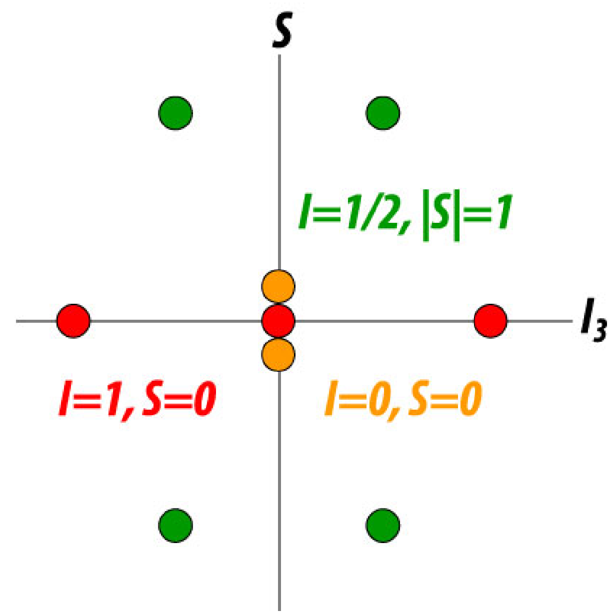


$$S = S_1 + S_2$$

$$J = L + S$$

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$



$$J^{PC} = 0^{-+}\ \ 0^{++}\ \ 1^{--}\ \ 1^{+-}\ \ 2^{++} \ldots$$

Allowed combinations

$$J^{PC} = 0^{--}\ \ 0^{+-}\ \ 1^{-+}\ \ 2^{+-} \ldots$$

Not-allowed: exotic

Quantum Numbers of Hybrid Mesons

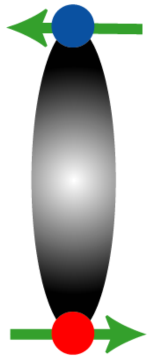
Quarks ⊕ **Excited Flux Tube** → **Hybrid Meson**

$S = 0$

$L = 0$

$J^{PC} = 0^{-+}$

like π, K



$$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$$

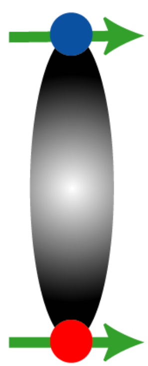
$$J^{PC} = \begin{cases} 1^{--} \\ 1^{++} \end{cases}$$

$S = 1$

$L = 0$

$J^{PC} = 1^{--}$

like γ, ρ



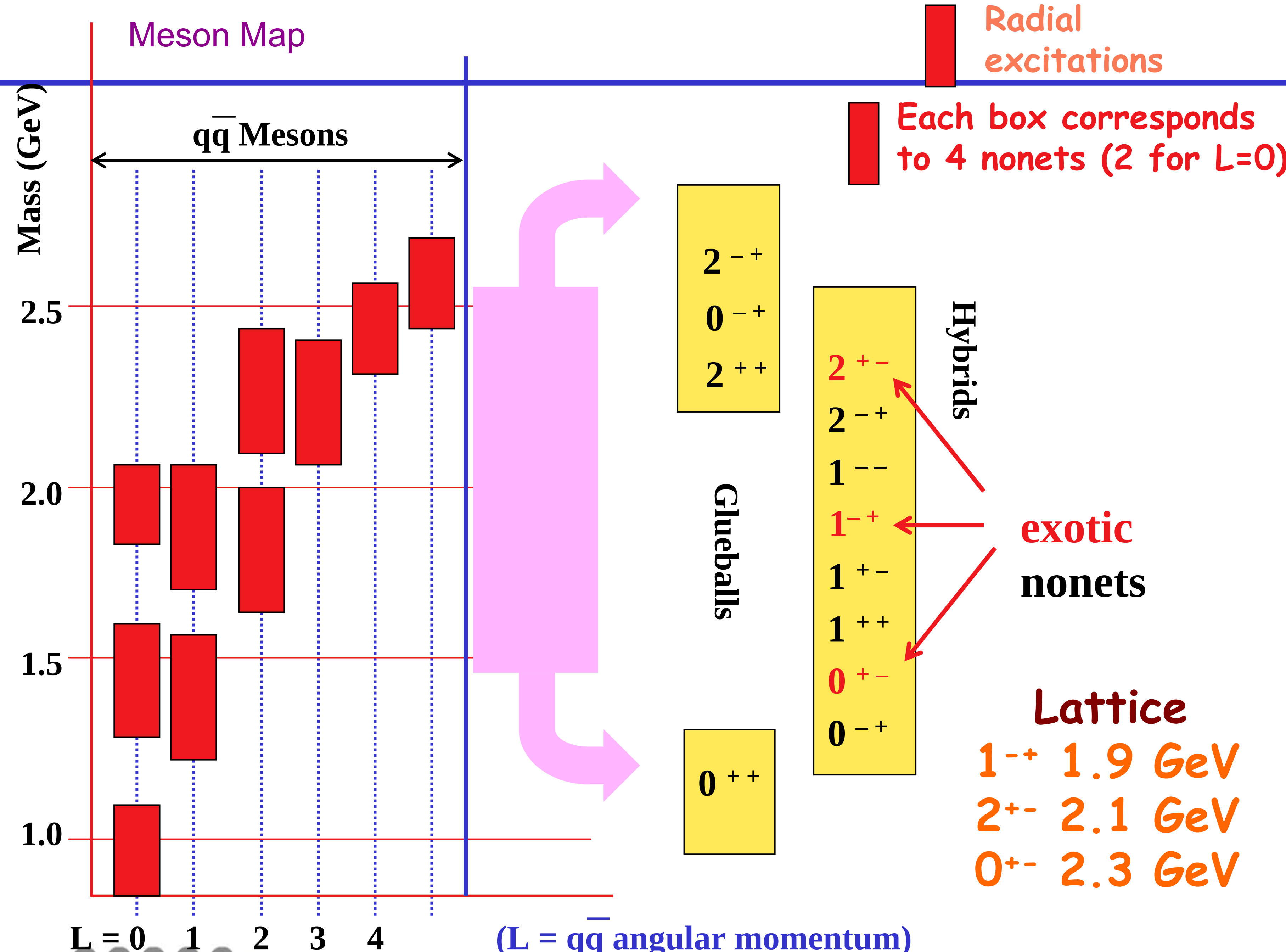
$$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$$

Exotic

$$J^{PC} = \begin{cases} 0^{-+} \quad 1^{-+} \quad 2^{-+} \\ 0^{+-} \quad 1^{+-} \quad 2^{+-} \end{cases}$$

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

Meson Map



Radial excitations
Each box corresponds to 4 nonets (2 for L=0)
Mass (GeV)
$q\bar{q}$ Mesons
2.5
2.0
1.5
1.0
L = 0 1 2 3 4
($L = q\bar{q}$ angular momentum)
Glueballs
2^{-+}
0^{-+}
2^{++}
0^{++}
Hybrids
2^{+-}
2^{-+}
1^{--}
1^{-+}
1^{+-}
1^{++}
0^{+-}
0^{-+}
exotic nonets
Lattice
1^{-+} 1.9 GeV
2^{+-} 2.1 GeV
0^{+-} 2.3 GeV

Exotic Signal $J^{PC}=1^{-+}$

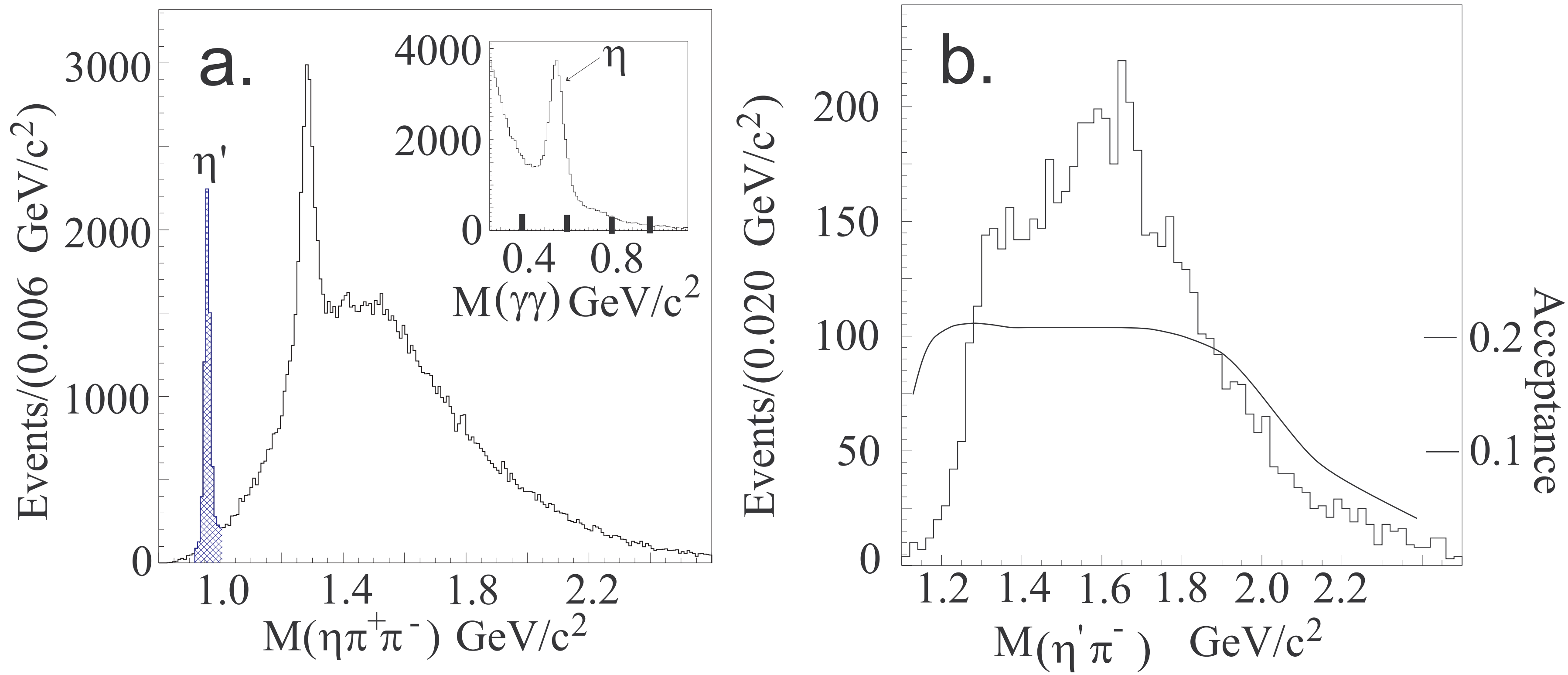
E852 $\pi_1(1600) \rightarrow \eta' \pi^-$

$\hookrightarrow \eta \pi^+\pi^-$

$\hookrightarrow \gamma\gamma$

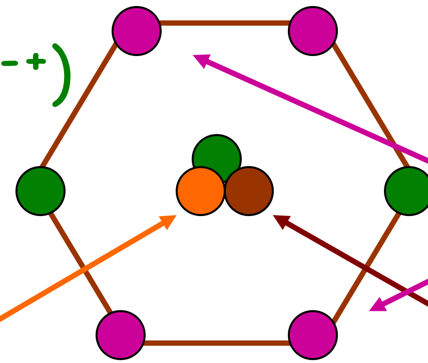
$M = 1.60 \pm 0.05$

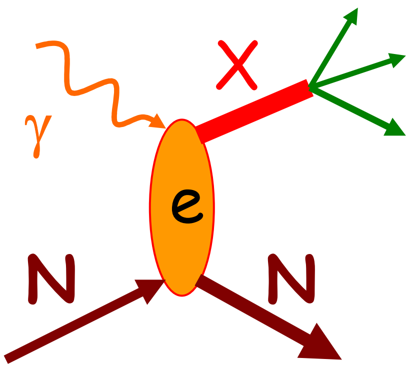
$\Gamma = 0.34 \pm 0.06$



PRL **86**, 3977 (2001)

Families of Exotics





$\gamma \Leftrightarrow \rho, \omega, \phi$

Couple to V.M + e

$\pi_1 \Leftrightarrow \rho\pi$

$\eta_1 \Leftrightarrow \rho b_1\,,\ \omega\phi$

$\eta'_1 \Leftrightarrow \phi\omega$

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:

    $f_1\eta \rightarrow K\bar{K}\eta \rightarrow K\bar{K}\pi\pi\pi$

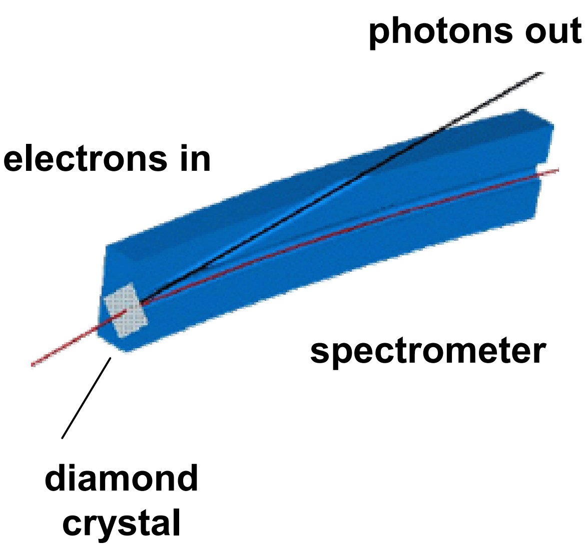
    $b_1\pi \rightarrow \omega\pi \rightarrow \pi\pi\pi\pi$

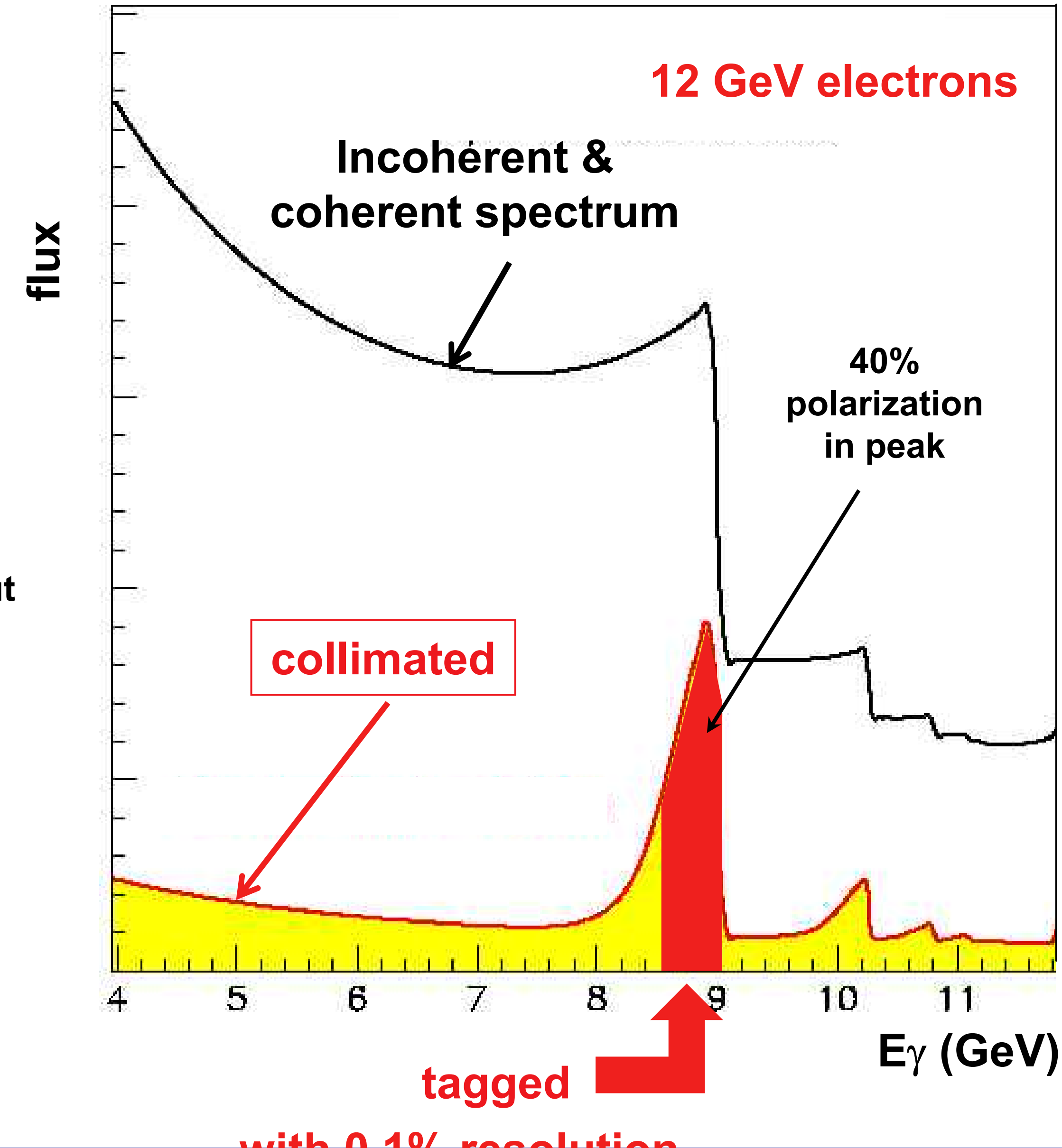
    $\rho\pi \rightarrow \pi\pi\pi$
  - high data acquisition rate

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

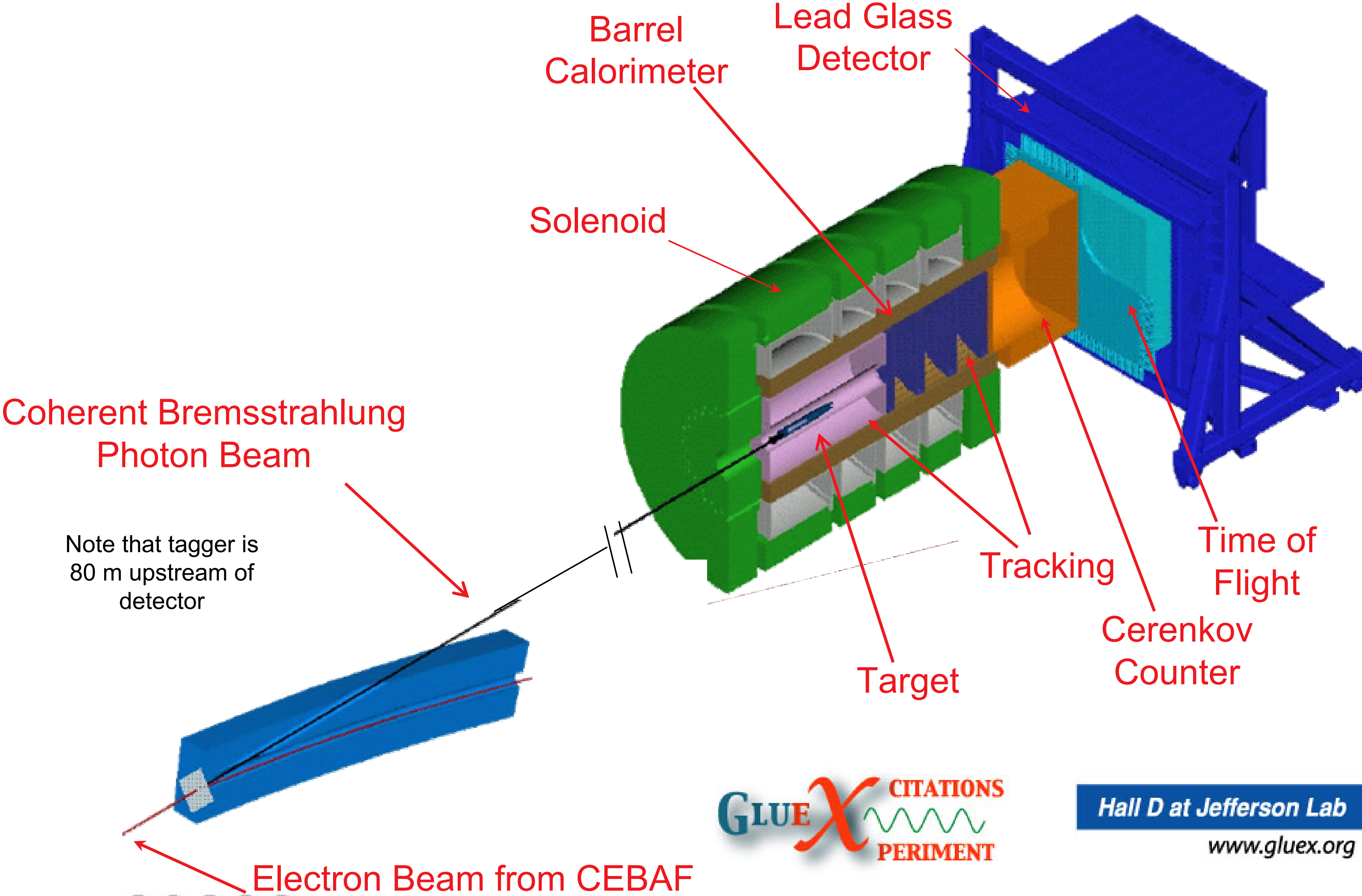
Coherent Bremsstrahlung

This technique provides requisite energy, flux and polarization





GlueX / Hall D Detector



GlueX CITATIONS PERIMENT

Hall D at Jefferson Lab
www.gluex.org

Finding an Exotic Wave

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

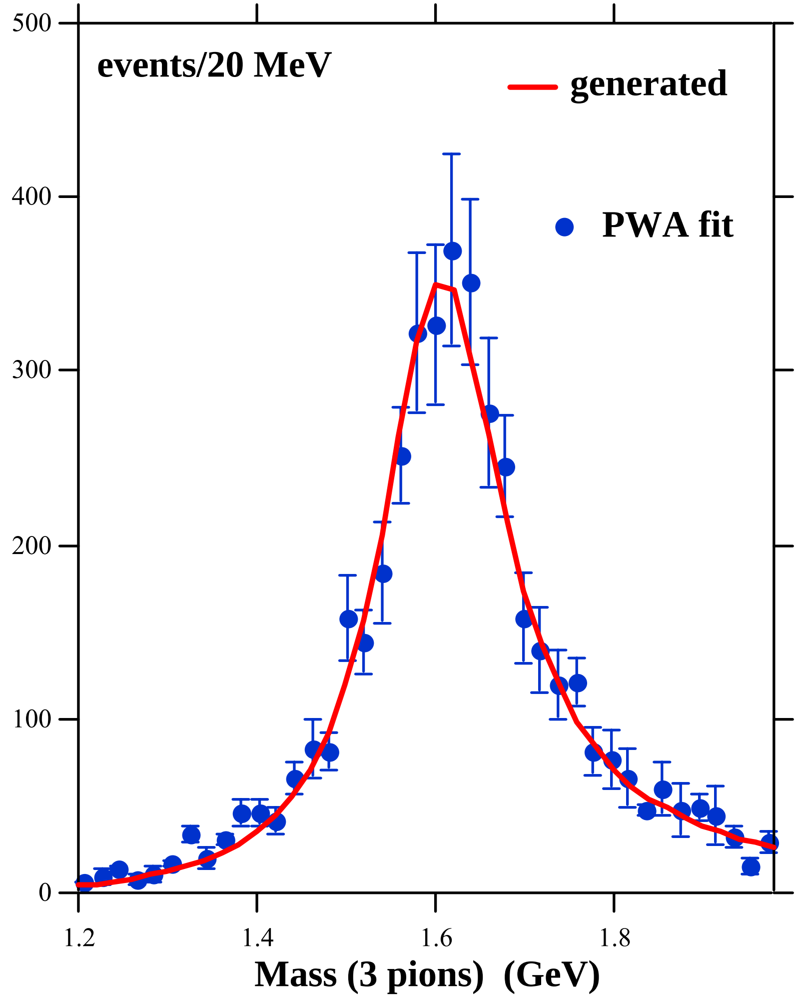
Input: 1600 MeV
Output: 1598 +/- 3 MeV

Width

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

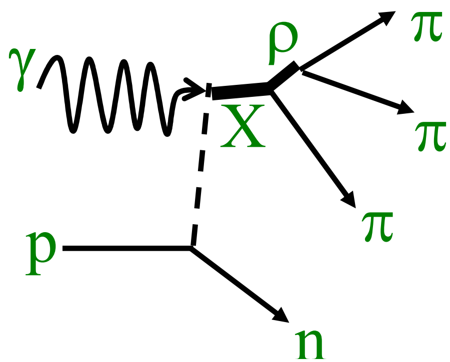
Statistics shown here correspond to a few days of running.

Double-blind M. C. exercise

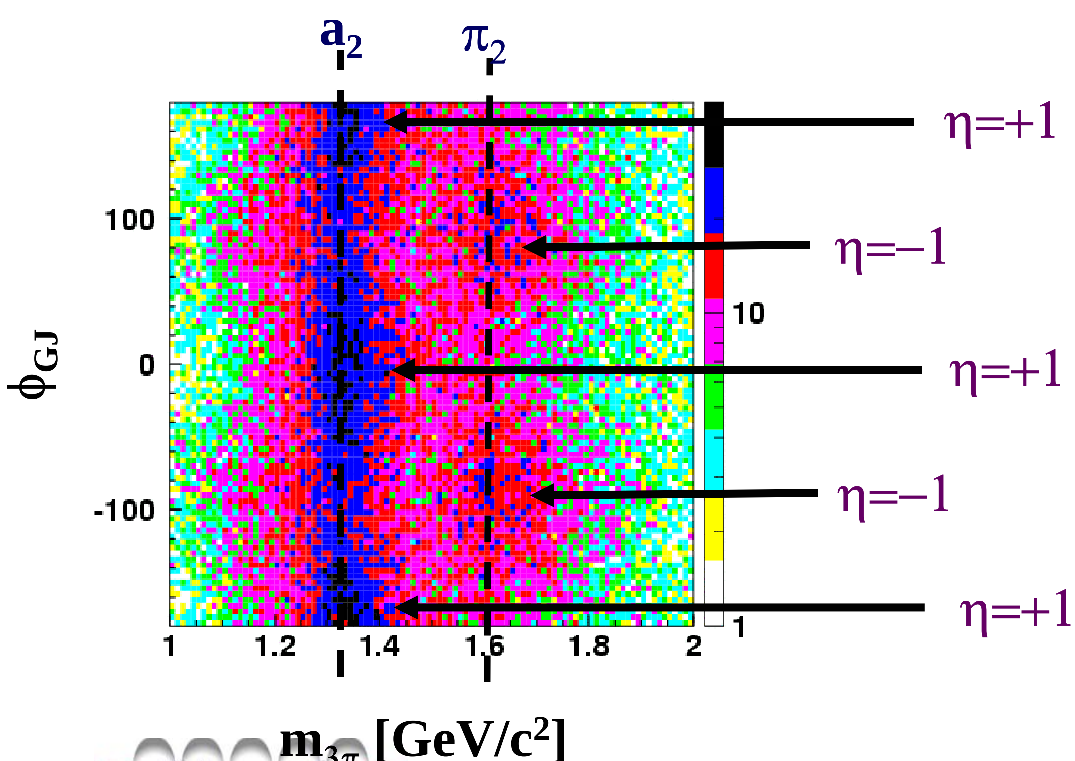


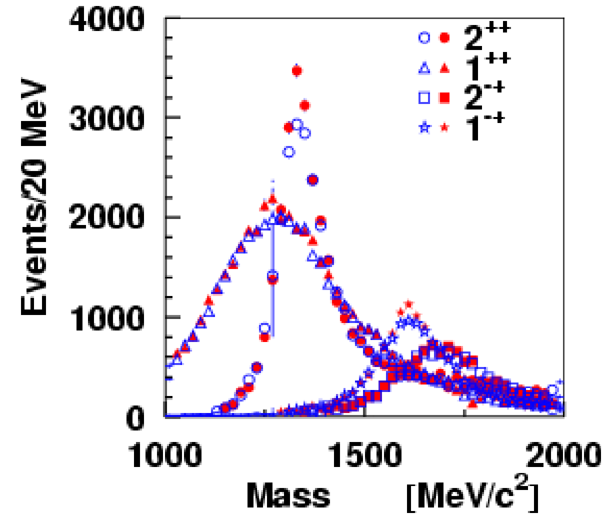
Detector Designed to do Partial Wave Analysis

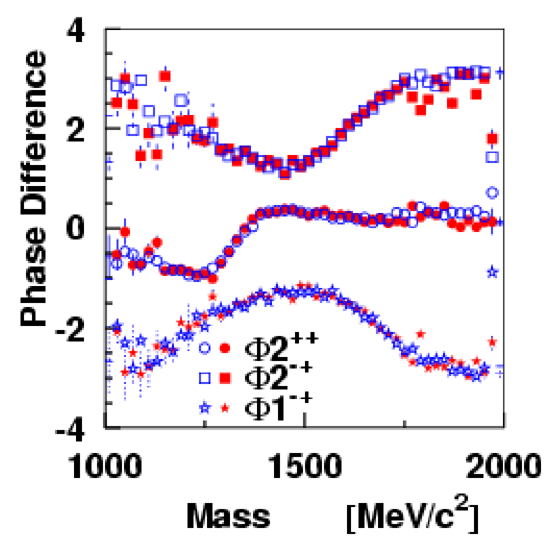
Double blind studies of 3π final states



Linear Polarization



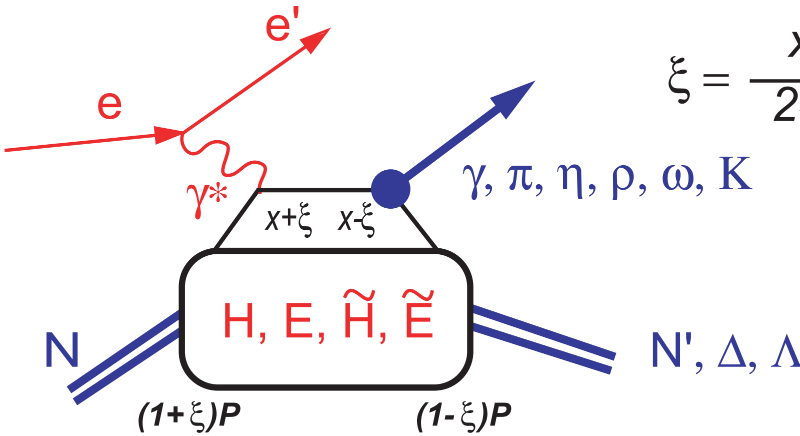




3-dimensional view of the Nucleon

Deep Exclusive Scattering

Generalized Parton Distributions



$$\xi = \frac{x_B}{2 - x_B}$$

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

The GPDs Define Nucleon Structure

- **GPD's provide access to fundamental quantities such as the quark orbital angular momentum that have not been accessible**

$$J_{quark} = \tfrac{1}{2}\Delta\Sigma + L^q = \tfrac{1}{2}\int_{-1}^{+1} dx\, x \left\{ H^q(x,\xi,t=0) + E^q(x,\xi,t=0) \right\}$$

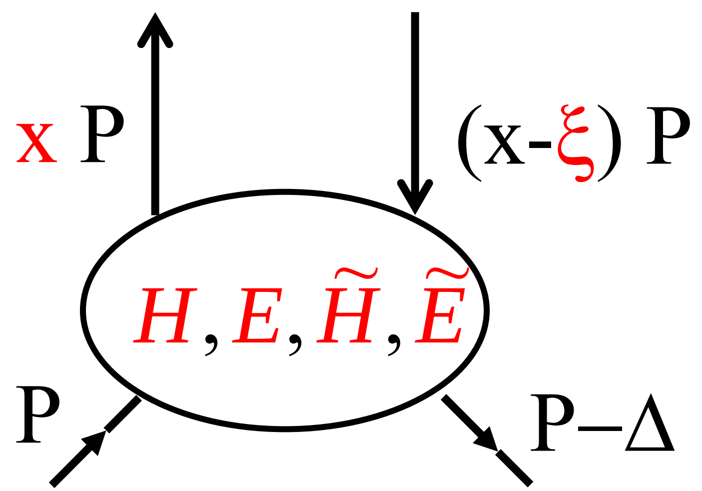
- **and the GPD's unify the description of inclusive and exclusive processes, connecting directly to the "normal" parton distributions:**

$$G_E(-t) = \int_{-1}^{+1} dx \sum_q \left\{ H^q(x,\xi,t) + \frac{t}{4M^2} E^q(x,\xi,t) \right\}$$ **(for example),**

Limiting Cases for GPDs

Ordinary Parton Distributions $(\Delta, t, \xi \rightarrow 0)$

$H_0(x,0) = q(x)$ *unpolarized* $\widetilde{H}_0(x,0) = \Delta q(x)$ *polarized*



$$\xi = \frac{\Delta \cdot z}{P \cdot z} \qquad t = \Delta^2$$

Nucleon Form Factors (Sum Rules)

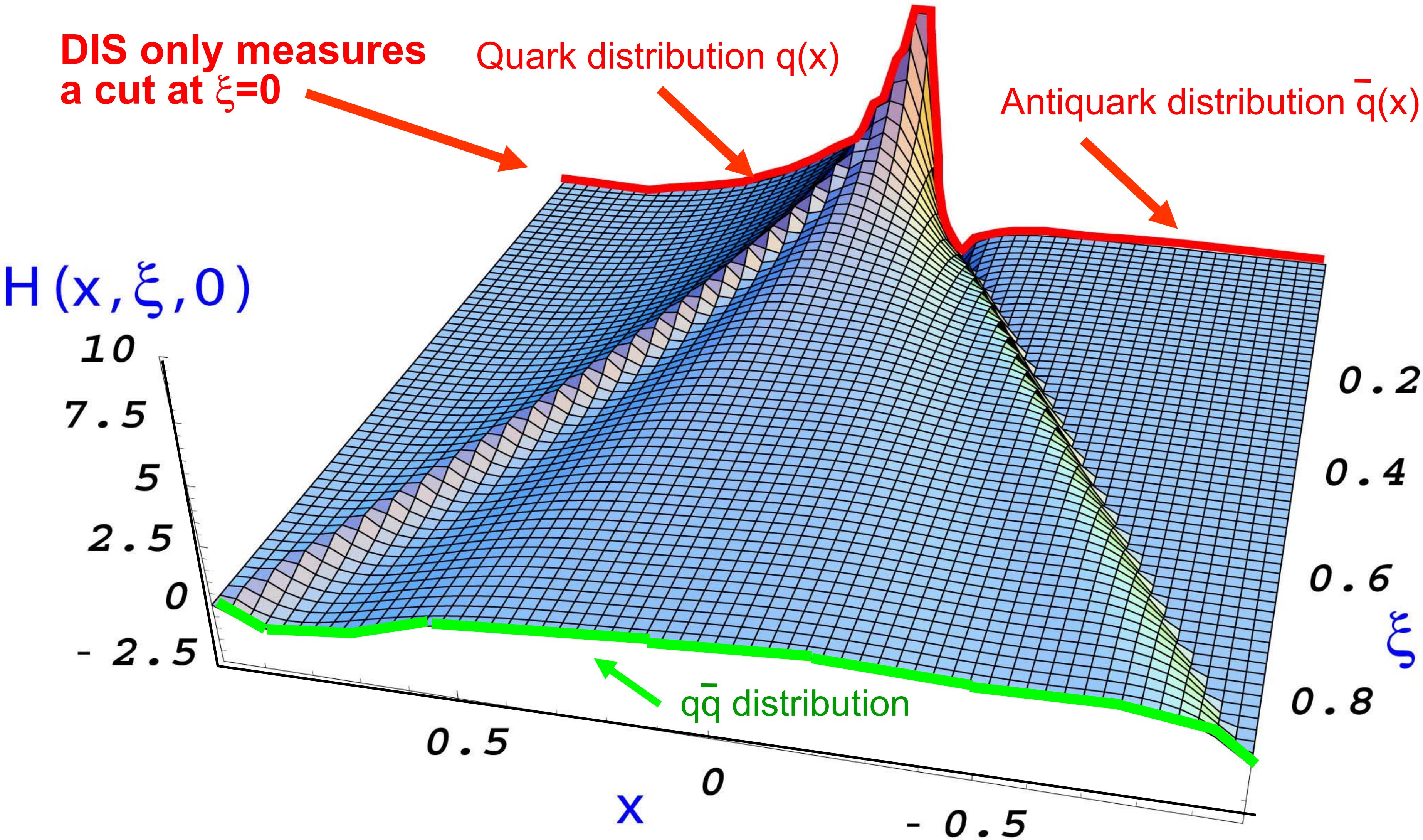
$$\int H_\xi(x,t)dx = F_1(t)$$ Dirac

$$\int \widetilde{H}_\xi(x,t)dx = g_A(t)$$ Axial vector

$$\int E_\xi(x,t)dx = F_2(t)$$ Pauli

$$\int \widetilde{E}_\xi(x,t)dx = h_A(t)$$ Pseudoscalar

GPDs Contain Much More Information than DIS



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)

➔ Measurements of the GPD's are now feasible

Interpretation of the GPD's

Analogy with form factors

$$F(\vec{q}) = \int d^3 r e^{-i\vec{q}\cdot\vec{r}} \rho(\vec{r})$$

Charge $\leftrightarrow$ Form Factor

$$\vec{r} \text{ measured relative to } \vec{R}_{cm} = \sum \frac{m_i r_i}{M}$$

Parton Distribution $\leftrightarrow$ GPD's

$$H(x, q_\perp) = \int d^2 b_\perp e^{-iq_\perp \cdot b_\perp} f(x, b_\perp) \quad @\xi = 0$$

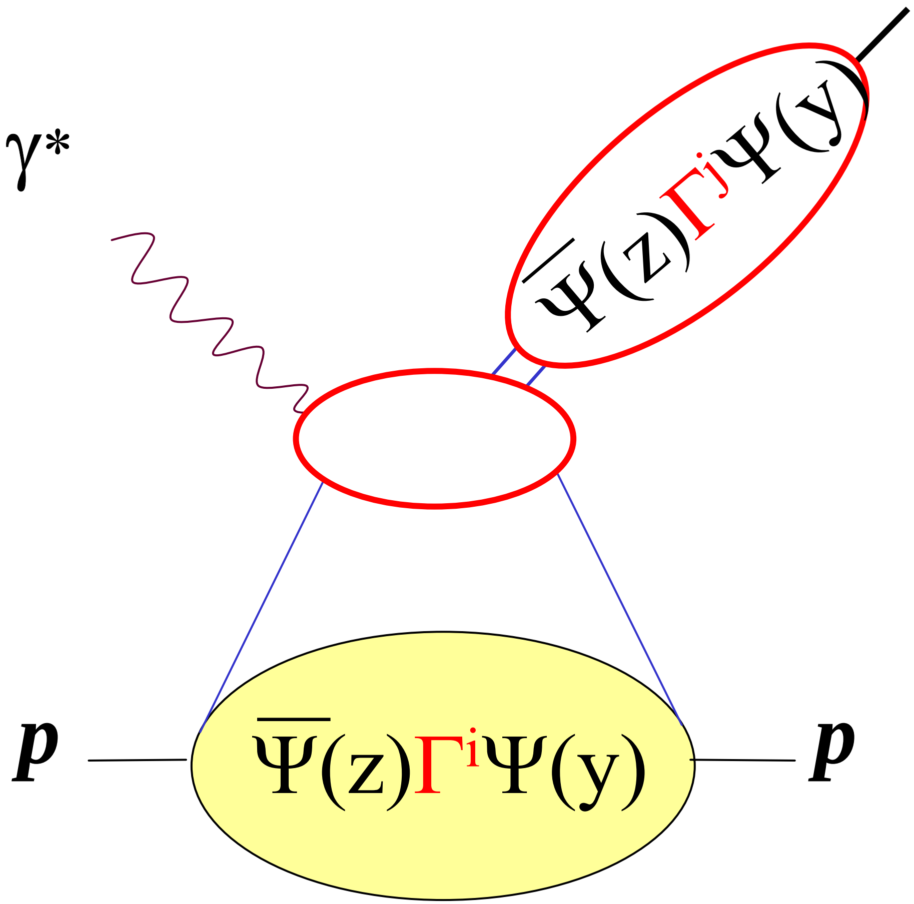
$$b_\perp \text{ measured relative to } R_\perp^{CM} = \sum x_i r_{i\perp}$$

$\textit{where } f(x, b_\perp) \textit{ is a parton density of quarks with}$

$\textit{momentum fraction } x \textit{ at a } \perp \textit{ distance } b_\perp \textit{ from } R_\perp^{CM}$

Ref. Burkardt

Meson Production as a Filter



- Use quantum numbers of meson to select appropriate combinations of parton distributions in nucleon.

Pseudo-scalars (polarized)

π^0: $\Delta u_v - \frac{1}{2}\Delta d_v$

η : $\Delta u_v - \frac{1}{2}\Delta d_v + 2\Delta s_v$

Vector Mesons (unpolarized)

ρ_L^0: $u + \bar{u} + \frac{1}{2}(d + \bar{d})$; g

ω_L^0: $u + \bar{u} - \frac{1}{2}(d + \bar{d})$; g

ϕ_L^0: $s + \bar{s}$; g

Program to determine GPD's

$$ep \to ep\rho^0 \longrightarrow H^2, E^2$$
$$\quad \hookrightarrow \pi^+\pi^-$$

$$en\pi^+ \longrightarrow \tilde{H}^2, \tilde{E}^2$$

$$e\ p\gamma \longrightarrow H^2, E^2, \tilde{H}^2, \tilde{E}^2$$

$$\vec{e}p \to ep\gamma \longrightarrow H, E, \tilde{H}, \tilde{E}$$

$$e\vec{p} \to en\pi^+ \longrightarrow \tilde{H} * \tilde{E}$$

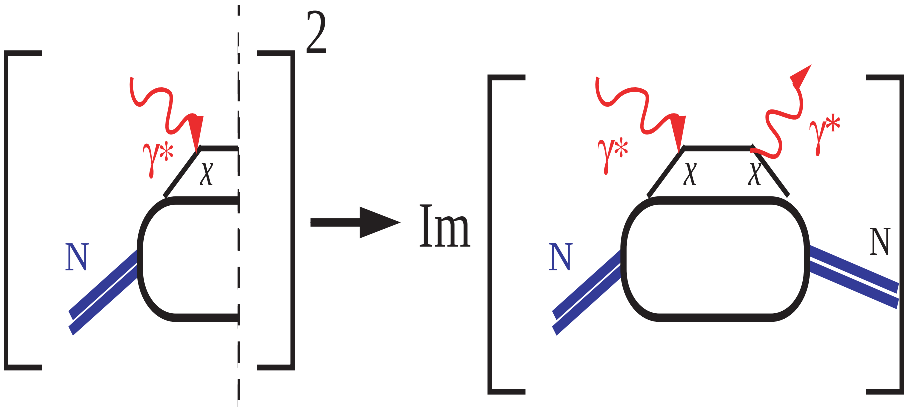
Other Channels

$\vec{e}\ p \to eN\ (\eta,\pi)$ e $\Delta\ \pi$ e Nω e (Λ,Σ) K

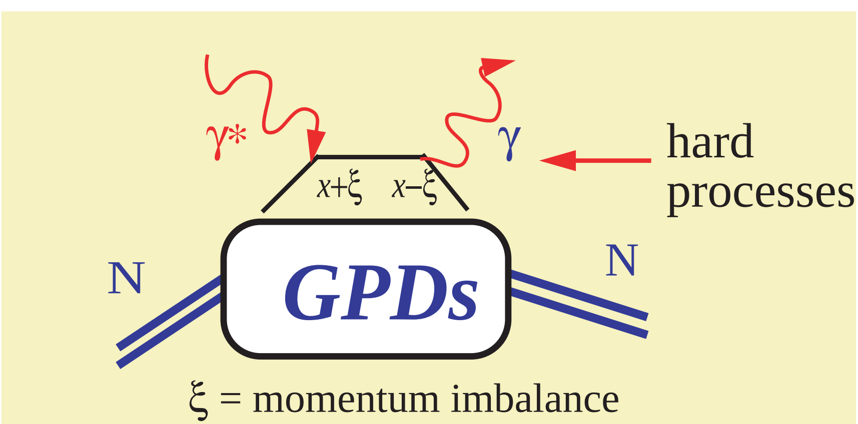
Deep Virtual Compton Scattering:
A Window on Quark Correlations

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

Deep Inclusive Scattering => Deep Compton Scattering



Deep Virtual Compton Scattering (DVCS)

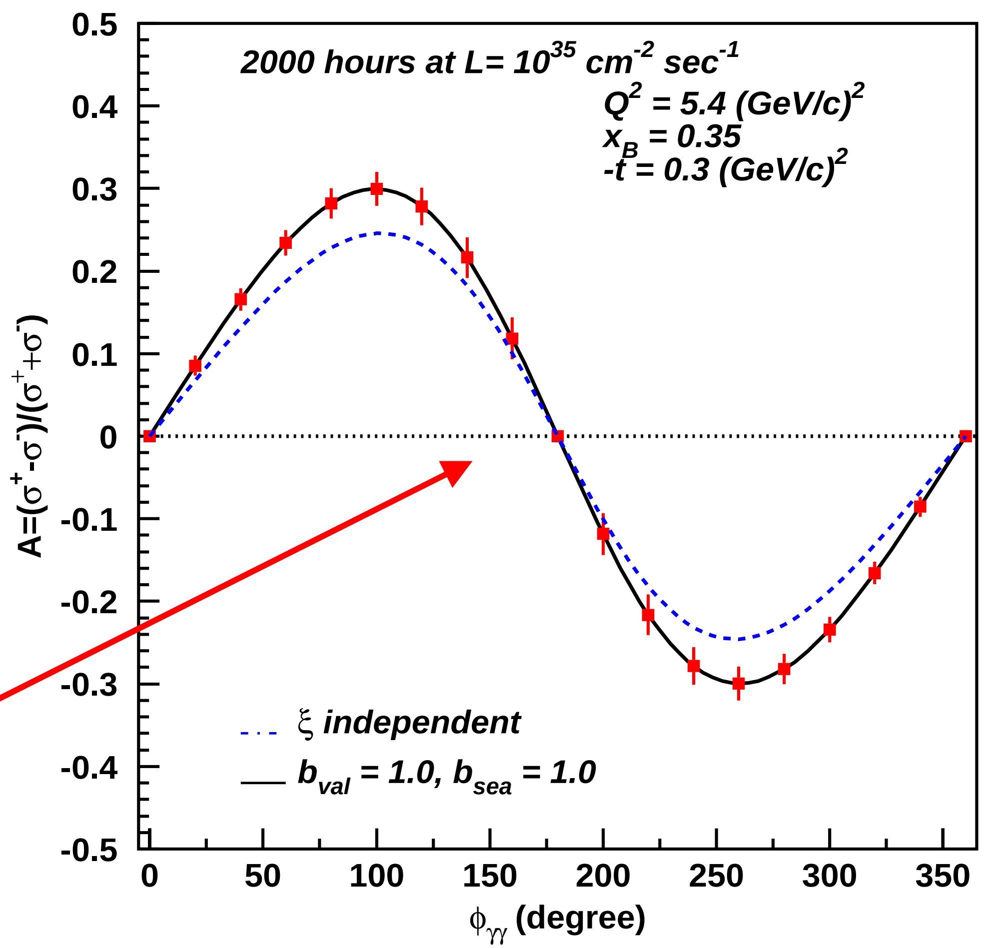


- **DIS corresponds exactly to the imaginary part of the Deep Compton Scattering amplitude**
- **Add determination of the final state (by exclusive reactions such as DVCS) and we can (finally!) probe nucleon quark structure and correlations at the amplitude level**

DVCS Single-Spin Asymmetry

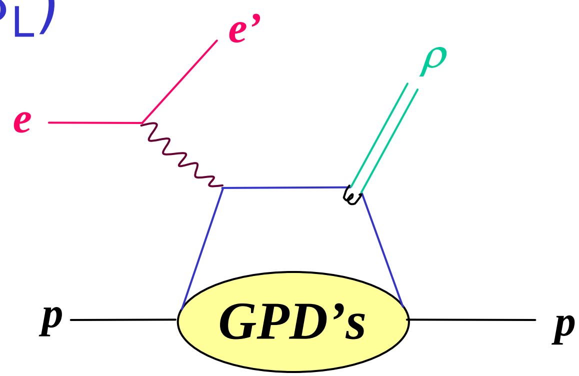
$Q^2 = 5.4\ GeV^2$
$x = 0.35$
$-t = 0.3\ GeV^2$

CLAS experiment
$E_0 = 11$ GeV
$P_e = 80\%$
$L = 10^{35}\ cm^{-2}s^{-1}$
Run time: 2000 hrs



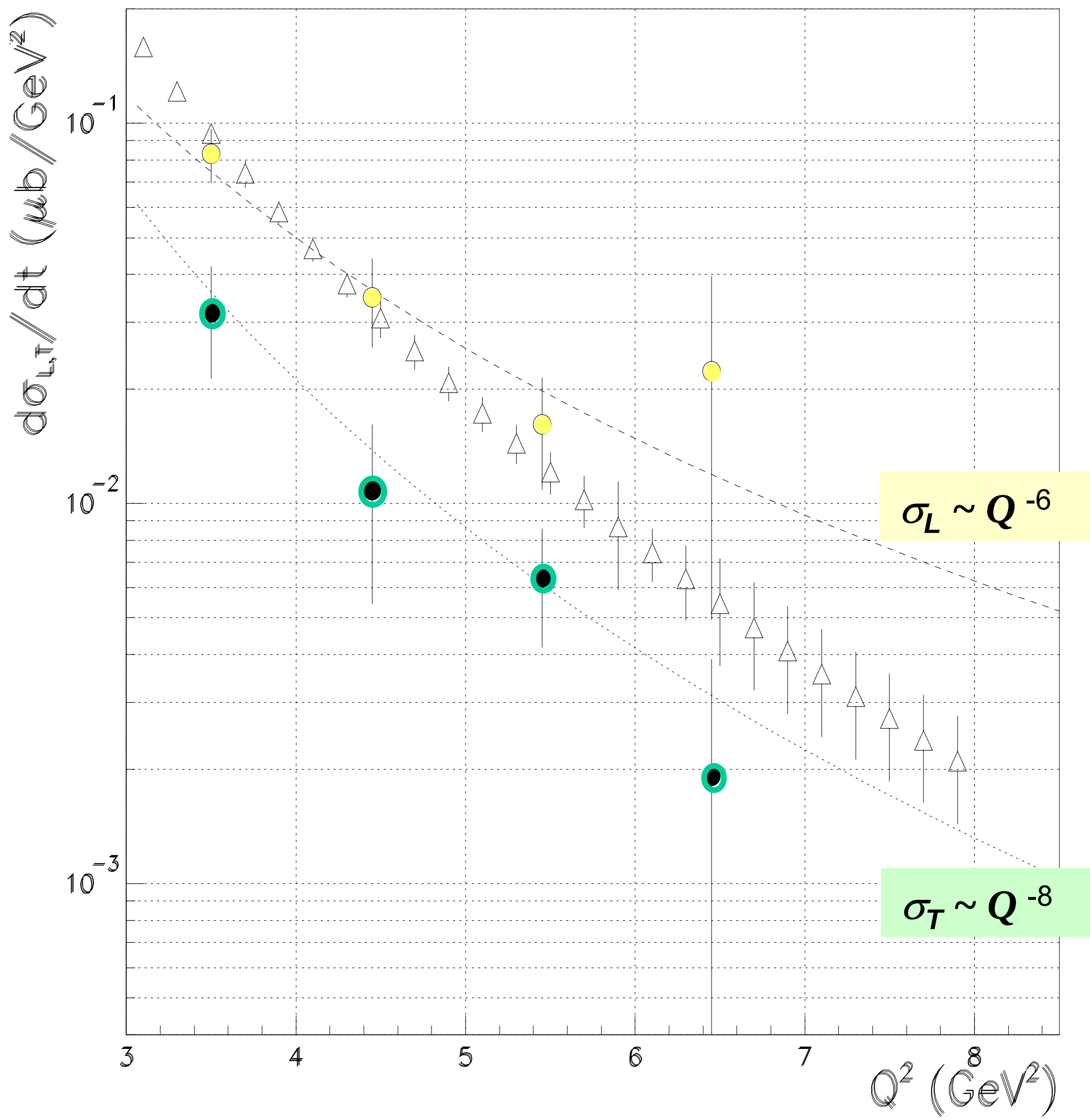
Hard Meson Electroproduction (ρ^o)

- Physics issue: map out GPD's (need to isolate σ_L)



- Technique: determine σ_L from $\rho \rightarrow \pi\pi$ decay angle distribution
- CLAS at 11 GeV

  400 hrs at L = 10^{35} $cm^{-2}s^{-1}$



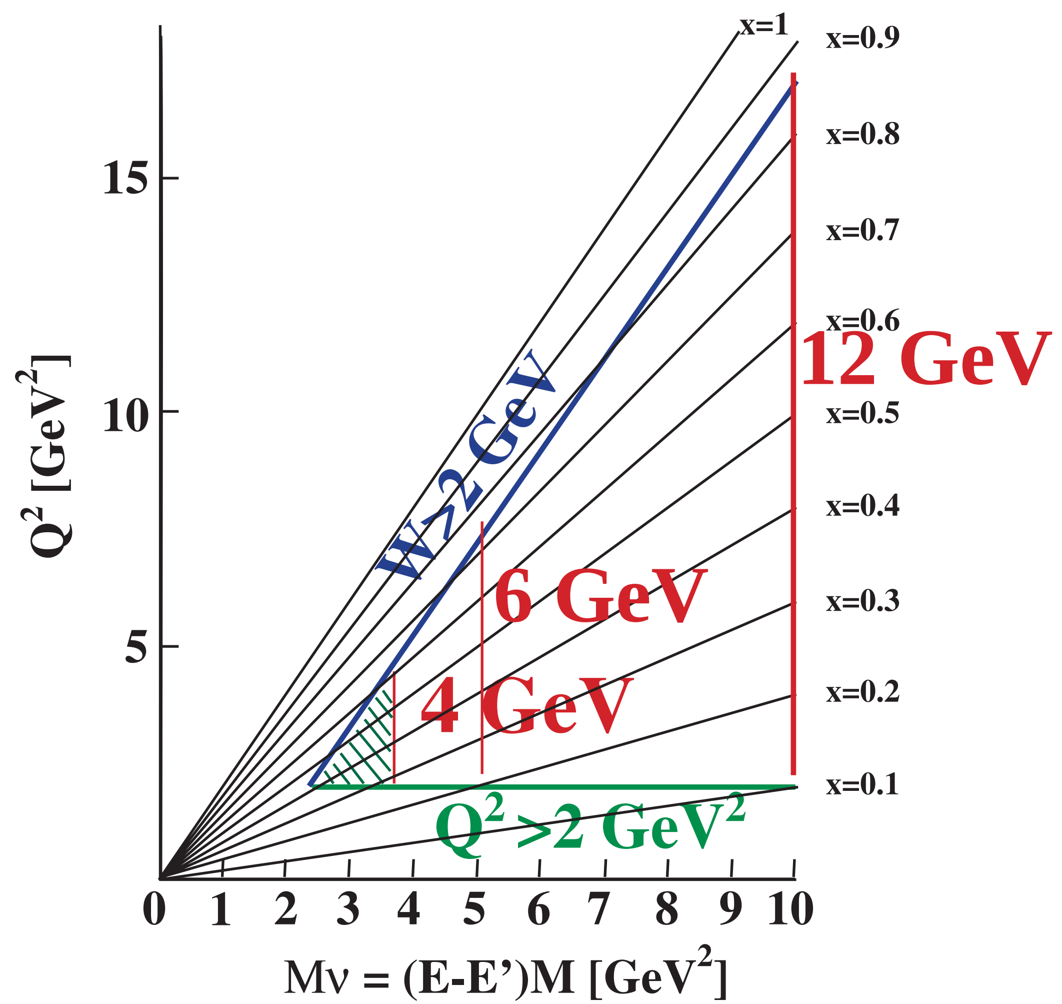
Valence Quark Structure of the Nucleon

Parton Distributions at large x

Enhanced Access to the DIS Regime

- 12 GeV will access the valence quark regime for x > 0.3

- where constituent quark properties are not masked by the sea quarks



Predictions for large x_{Bj}

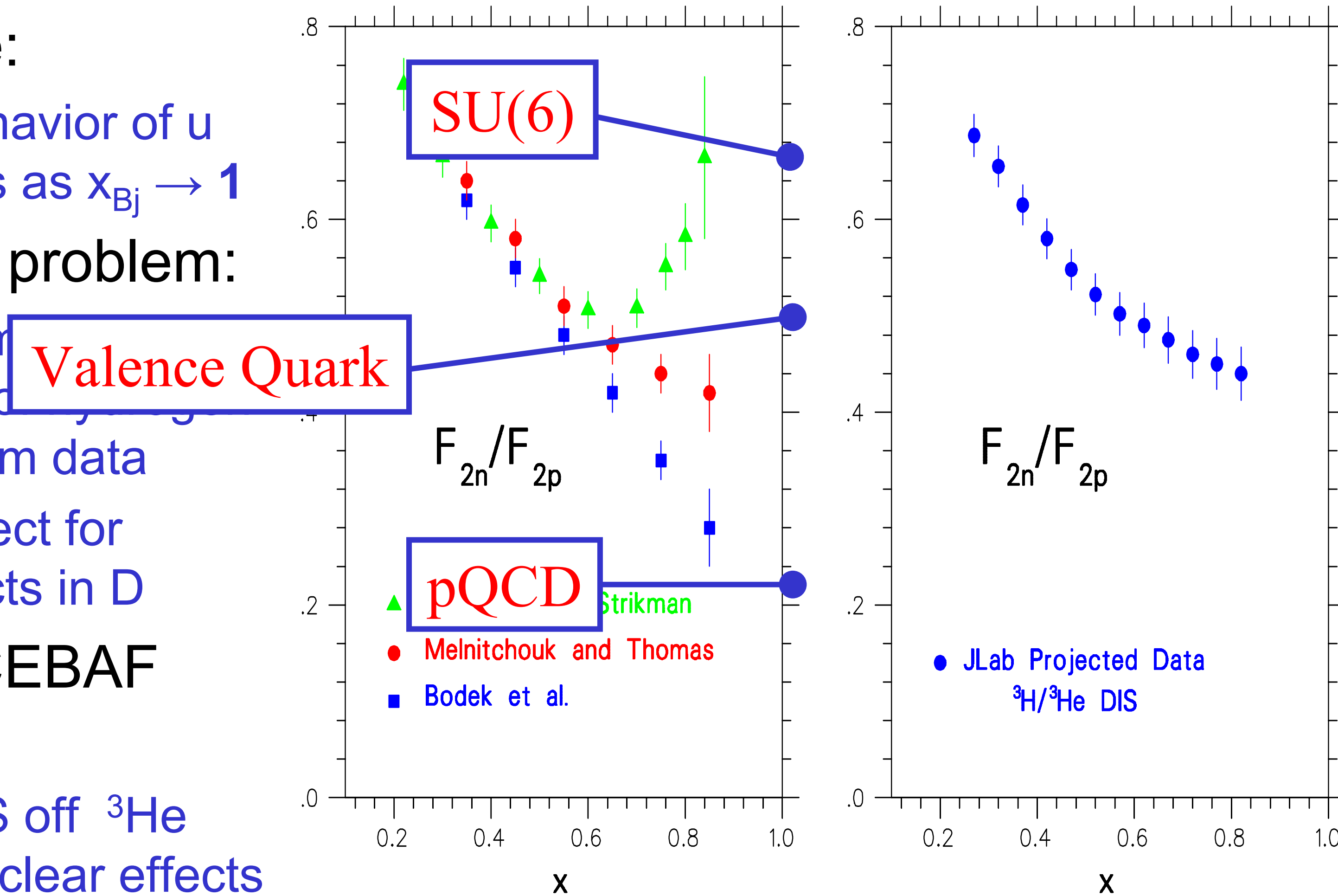
Proton Wavefunction (Spin and Flavor Symmetric)

$$\left|p\uparrow\right\rangle = \frac{1}{\sqrt{2}}\left|u\uparrow(ud)_{S=0}\right\rangle + \frac{1}{\sqrt{18}}\left|u\uparrow(ud)_{S=1}\right\rangle - \frac{1}{3}\left|u\downarrow(ud)_{S=1}\right\rangle - \frac{1}{3}\left|d\uparrow(uu)_{S=1}\right\rangle - \frac{\sqrt{2}}{3}\left|d\downarrow(uu)_{S=1}\right\rangle$$

Nucleon Model	F_2^n/F_2^p	d/u	A_1^n	A_1^p
SU(6)	2/3	1/2	0	5/9
Valence Quark	1/4	0	1	1
pQCD	3/7	1/5	1	1

Valence Quark Distribution

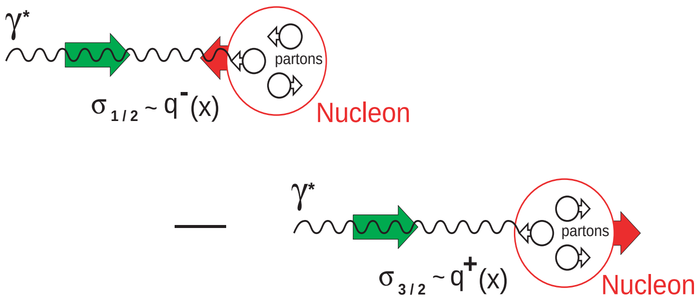
- Physics issue:
  - compare behavior of u and d quarks as $x_{Bj} \rightarrow$ **1**
- Experimental problem:
  - extract inform
    comparison o
    and deuterium data
  - need to correct for nuclear effects in D
- Solution for CEBAF upgrade:
  - compare DIS off ^{3}He and ^{3}H (nuclear effects ~ same)



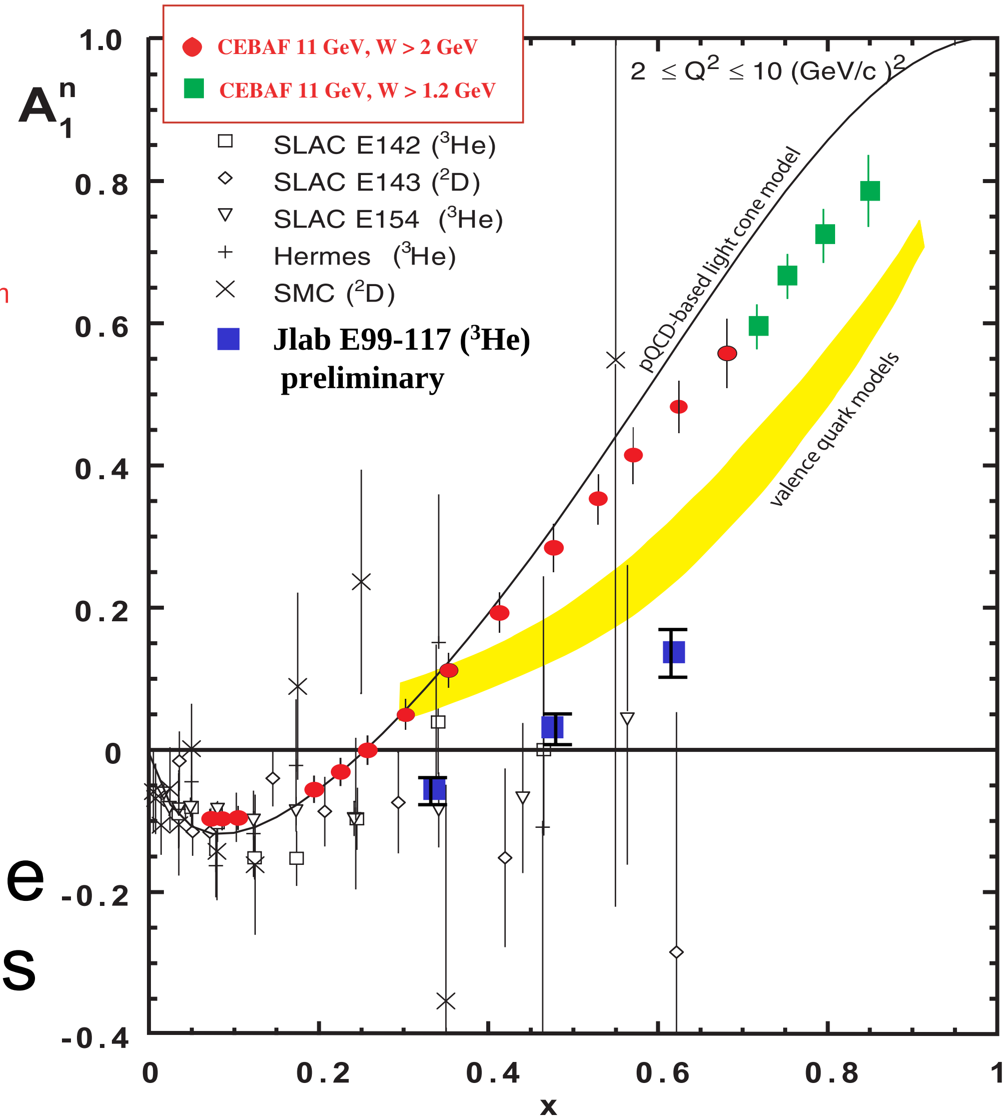
The Neutron Spin Asymmetry A_1^n

A_1^n Measures the Spin Response:

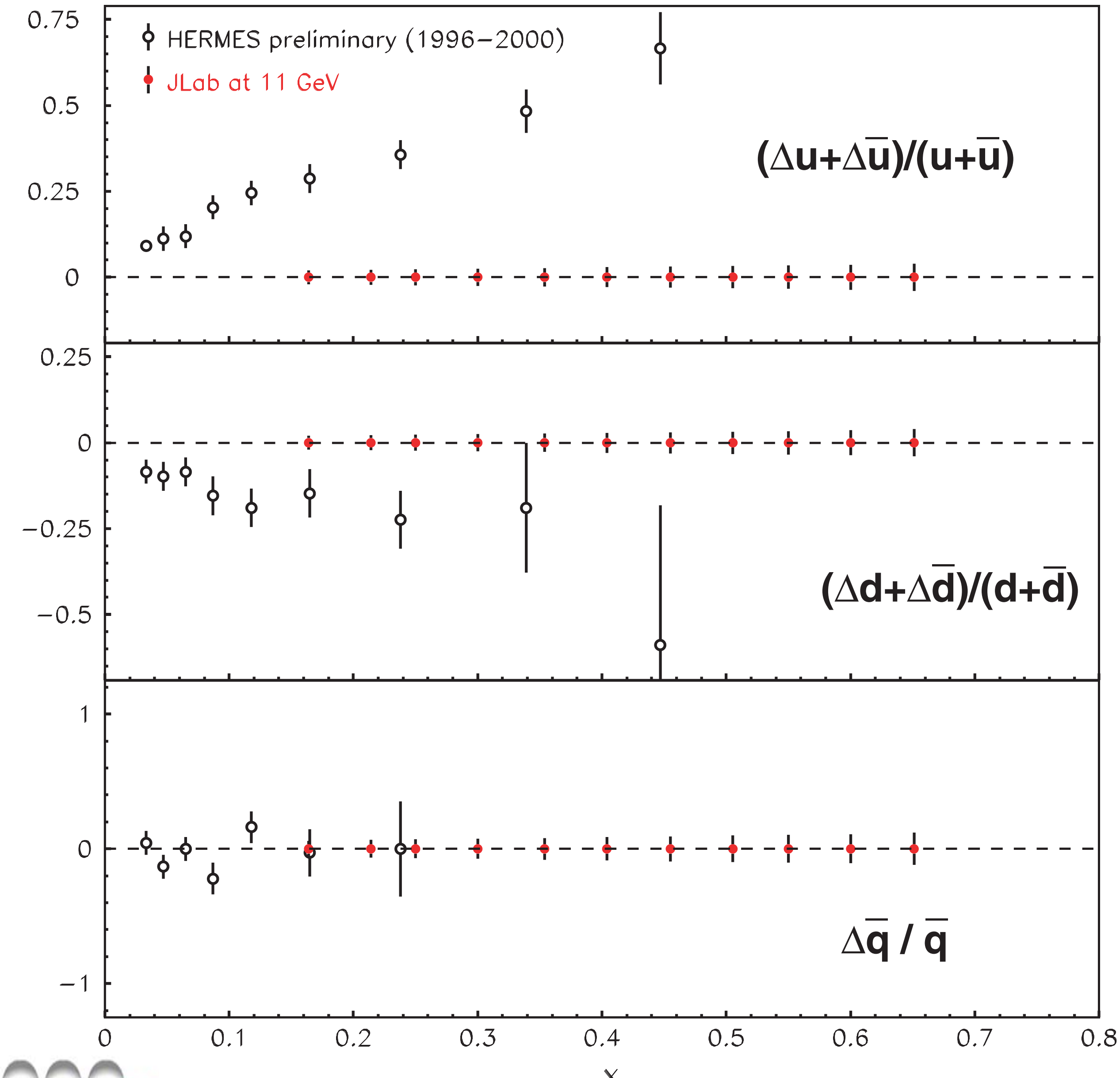
$A_1^n =$



- 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



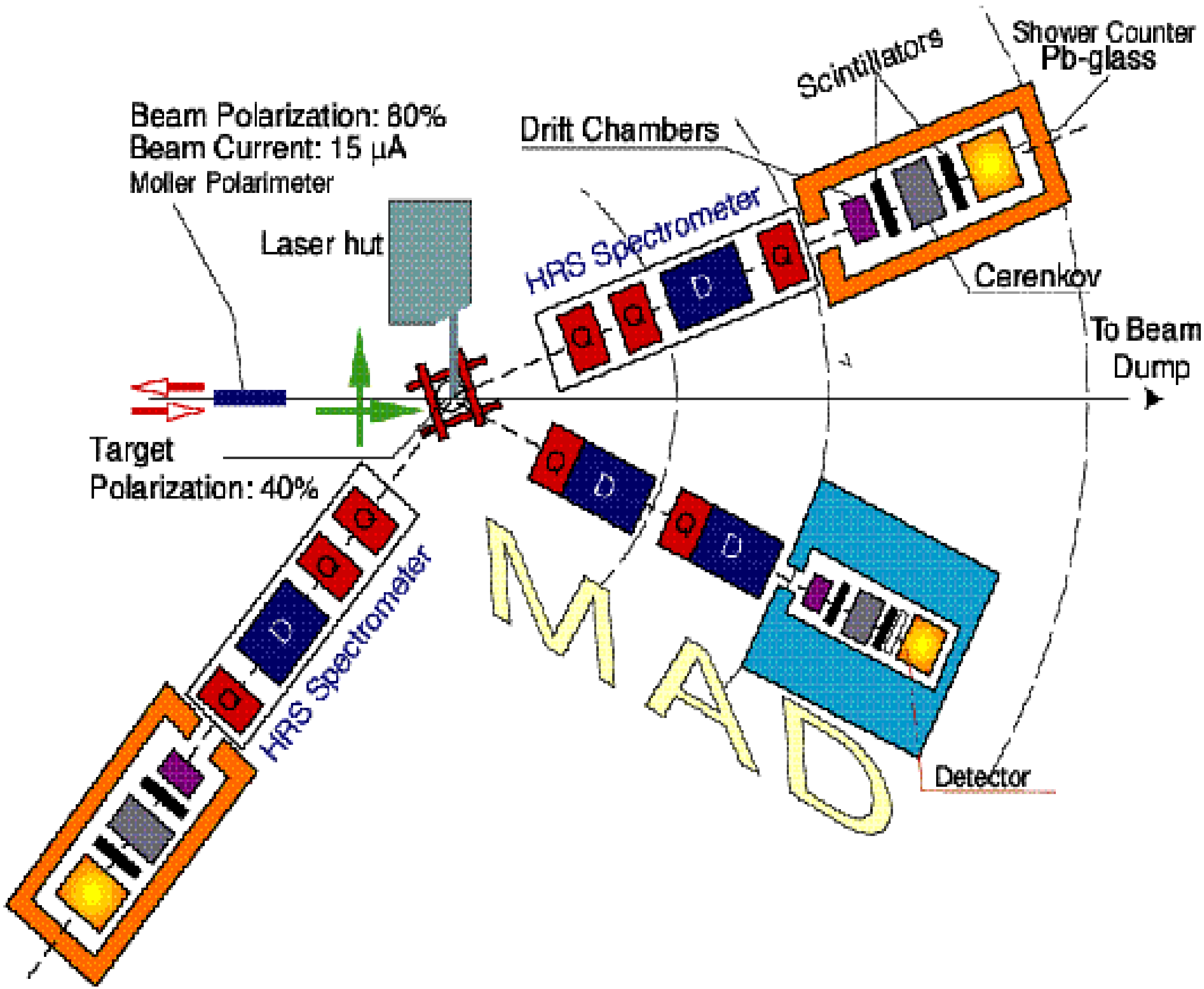
Flavor Decomposition: $(e,e'\pi^+)/(e,e'\pi^-)$



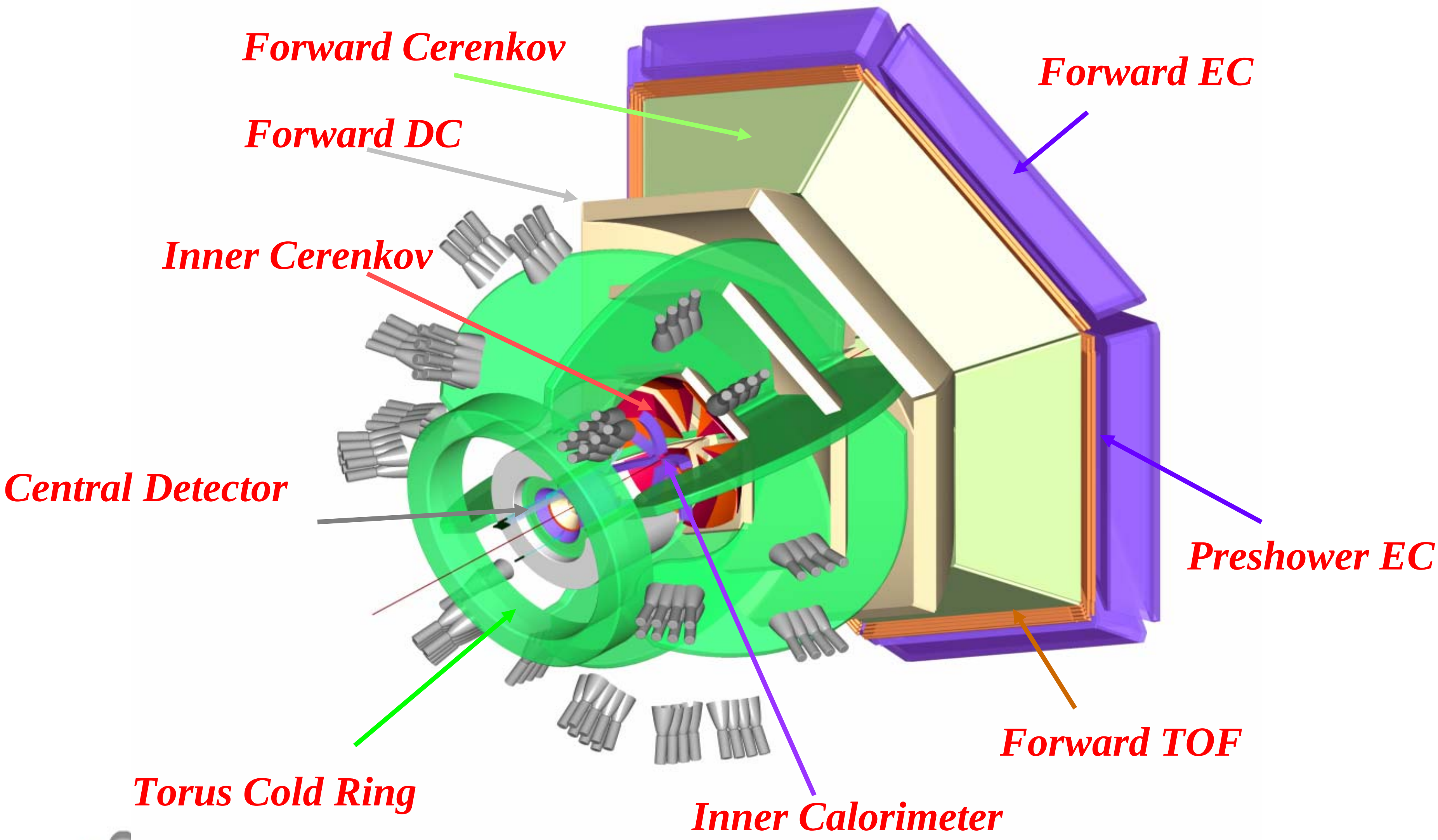
12 GeV Upgrade Project Status

- Developed by CEBAF User Community in collaboration with JLab
- Nuclear Science Advisory Committee, NSAC
  - plan presented during last 5-year Long Range Plan
  - recommended by NSAC for new construction
- Plan presented to Department of Energy
  - presently waiting for CD-0 (determination of 'mission need')
- Detailed report is being prepared to be reviewed by Jlab PAC in January
- Construction
  - construction start expected in FY2007 (October 2006)
  - 3 year construction project

Hall A Floor Plan with MAD Spectrometer

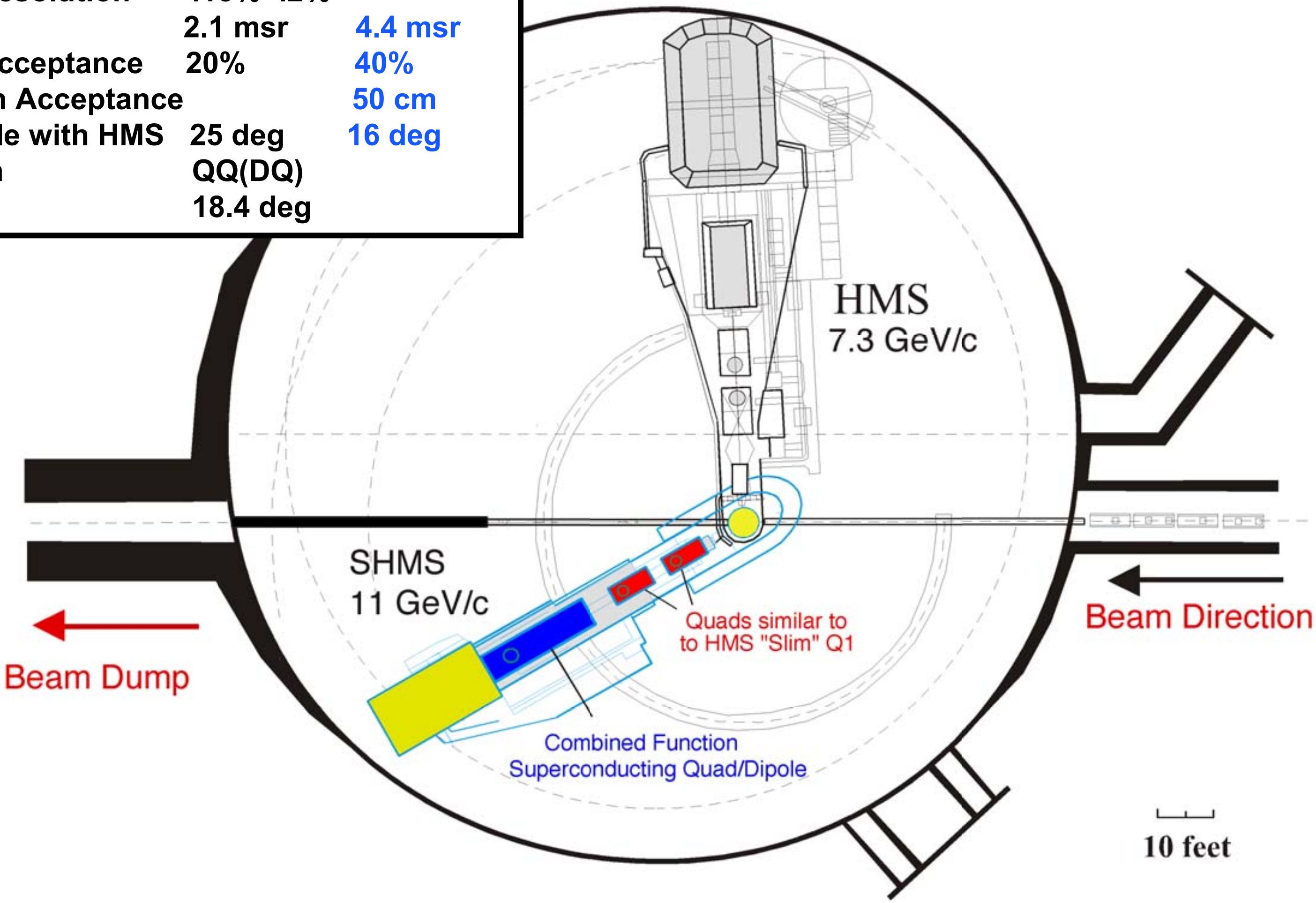


CLAS++ Detector



SHMS - HMS Spectrometers After Upgrade

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	20%	40%
Target Length Acceptance		50 cm
Opening Angle with HMS	25 deg	16 deg
Configuration	QQ(DQ)	
Bend Angle	18.4 deg	



Physics Program at 12 GeV

Gluonic Excitations

Valence Structure
of the Nucleon

3-dim view
of the Nucleon

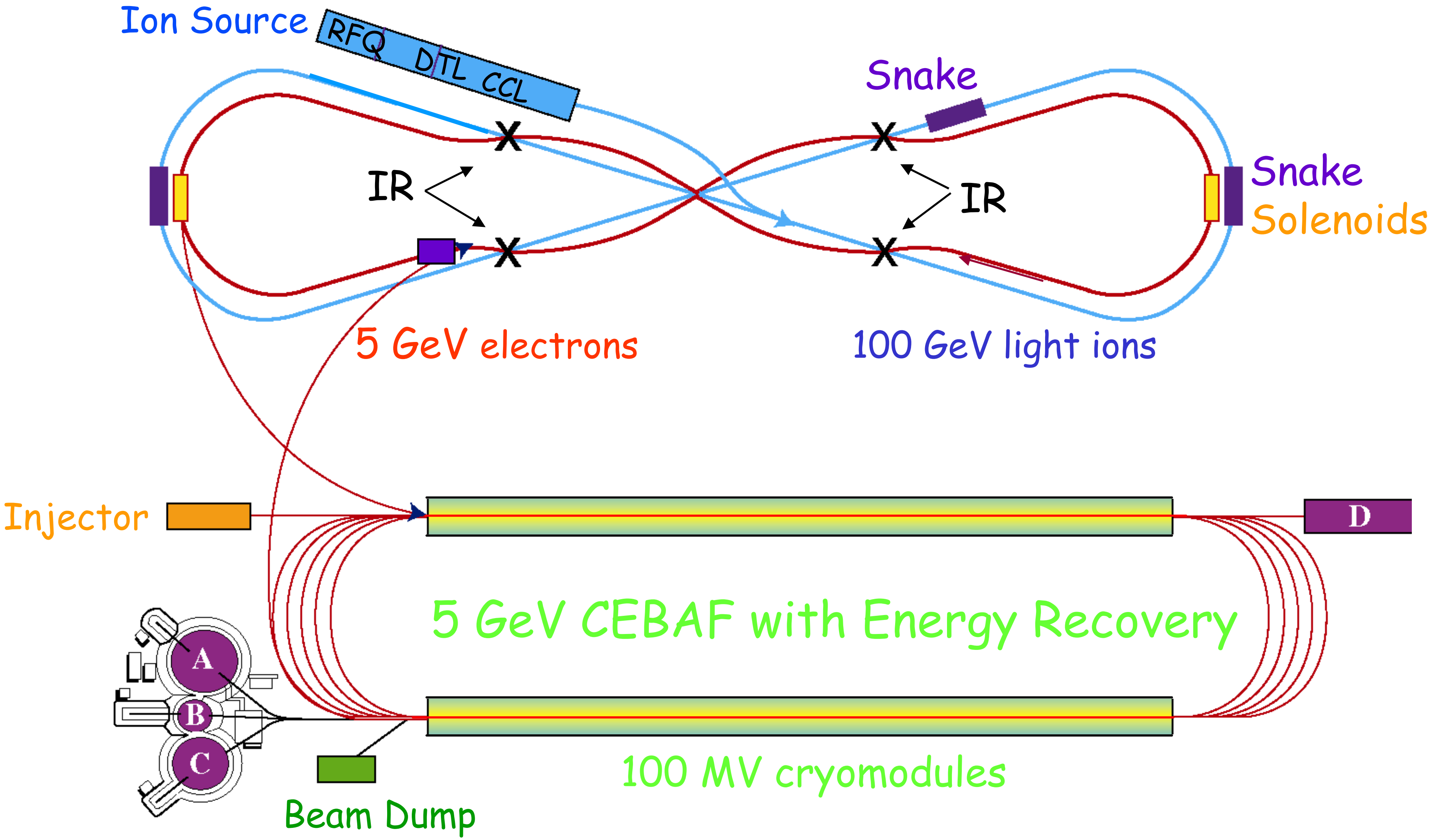
Exciting

Compelling

In view of recent progress
in lattice calculations

Timely

Electron-Light Ion Collider Layout



Luminosity = $10^{35} cm^{-2} s^{-1}$

Lia Merminga