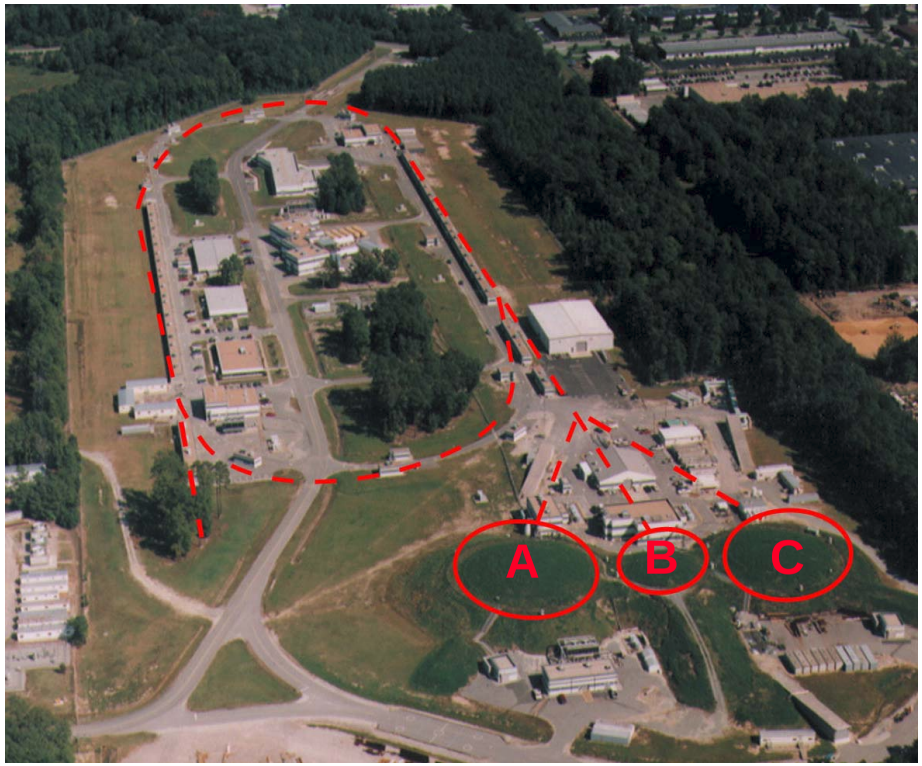
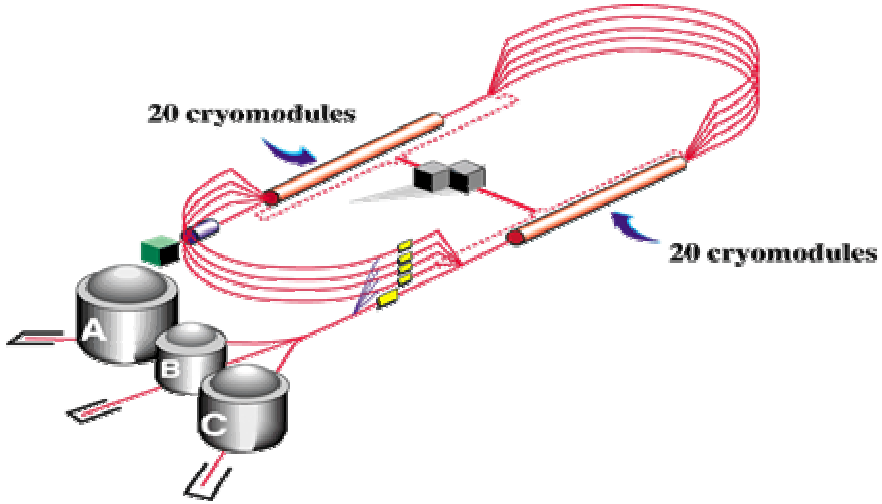
Physics Potential of the Jefferson Lab 12 GeV Upgrade

Garth Huber

UNIVERSITY OF REGINA

CAP Congress, Laval University, Quebec City, June 11, 2008.





Two Cold Superconducting Linacs

Continuous Polarized Electron Beam

E → 6 GeV

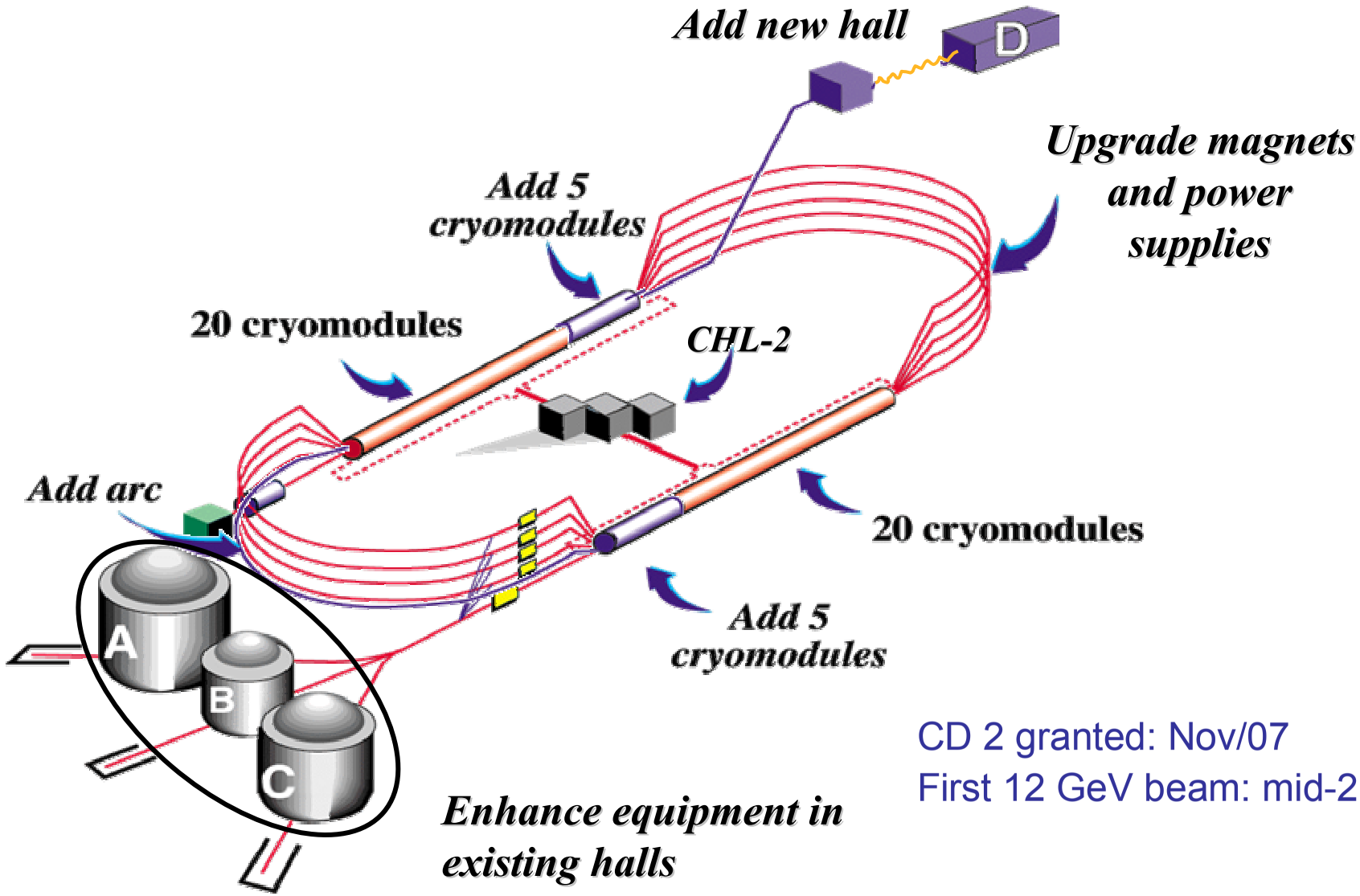
> 100 μA

up to 80% polarization

concurrent to 3 Halls

First beam delivered in 1994

JLab 12 GeV Upgrade

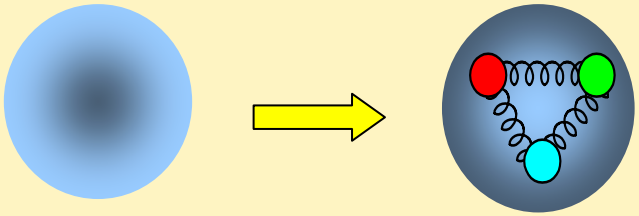


CD 2 granted: Nov/07
First 12 GeV beam: mid-2013

The Physics Issue in Brief

Our ability to answer the question:

How do the nucleon's properties (mass, spin, charge radius, etc.) arise from its quark and gluon constitutents?



requires that we develop a quantitative (as opposed to qualitative) understanding of non-perturbative QCD.

	u	+	u	+	d	=	proton
mass:	0.003	+	0.003	+	0.006	$\neq$	0.938

98% of the proton's mass is not due to the "rest mass" of its valence constituents, and hence does not rise directly from the Higgs mechanism.

$\Rightarrow$ The proton's mass arises dynamically through the quark and gluon interactions of Quantum Chromo-Dynamics (QCD).

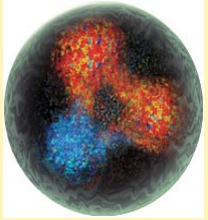
Why electron scattering experiments?

Transition from pQCD to Strong QCD needs data with high precision for a quantitative understanding of confinement.

Ongoing Advancements:
Intense CW electron beams.
Polarized targets/polarimetry.
Improvement in polarized e^- sources.

Luminosity:
(SLAC, 1978) ~ 8 x 10^{31} cm^{-2}-s^{-1}
(JLab, 2000) ~ 4 x 10^{38} cm^{-2}-s^{-1}

$$d = 1 \rightarrow 0.1\,\text{fm} \quad \Leftrightarrow \quad Q^2 = 0.1 - 10\ \text{GeV}^2$$



- JLab 12 GeV Upgrade will play a crucial role towards our better understanding of hadron structure.
- On world scene, JLab program complements the work at J-PARC and GSI as well as radioactive beam facilities.

12 GeV Approved Experiments to Date

EXOTIC MESONS	NUCLEAR EFFECTS DUE TO QCD
Mapping the Spectrum of Light Quark Mesons and Gluonic Excitations with Linearly Polarized Photons (E12-06-102, Hall D)	Inclusive Scattering from Nuclei at x>1 in the Quasi-elastic and Deeply-Inelastic Regimes (E12-06-105, Hall C)
NUCLEON AND MESON ELECTROMAGNETIC STRUCTURE	Color Transparency in Exclusive Vector Meson Electroproduction (E12-06-106, Hall B)
Charged Pion Form Factor to High Q^2 (E12-06-101, Hall C)	Color Transparency in $A(e,e'p)$ and $A(e,e'\pi)$ (E12-06-107, Hall C)
σ_L/σ_T Ratio in Semi-Inclusive Deep Inelastic Scattering (E12-06-104, Hall C)	Quark Propagation and Hadron Formation (E12-06-117, Hall B)
Probing the Proton's Quark Dynamics in Semi-Inclusive Pion Production (E12-06-112, Hall B)	F_2^n/F_2^p, d/u and A=3 EMC Effect in Deep Inelastic Scattering off ^{3}H and ^{3}He Mirror Nuclei (E12-06-118, Hall A)
F_2^n/F_2^p at Large x_{Bj} via $^2H(e,e'p)X$ (E12-06-113, Hall B)	Hadronization in Nuclei by Deep Inelastic Scattering (E12-07-101, Hall B)
Neutron Magnetic Form-Factor at High Q^2 Using the Ratio Method on ^{2}H (E12-07-104, Hall B)	A-dependence of J/Ψ Production Near Threshold (E12-07-106, Hall C)
Proton Magnetic Form Factor from Q^2=7-17.5 GeV^2 (E12-07-108, Hall A)	**GENERALIZED PARTON DISTRIBUTIONS**
Proton Form Factor Ratio Measurements at Q^2=13,15 GeV^2 (E12-07-109, Hall A)	Hard Exclusive Electroproduction of π^0 and η (E12-06-108, Hall B)
NUCLEON SPIN STRUCTURE	Electron-Helicity Dependent Deeply Virtual Compton Scattering (E12-06-114, Hall B)
Longitudinal Spin Structure g_1 of p,d (E12-06-109, Hall B)	Deeply Virtual Compton Scattering (E12-06-119, Hall B)
Neutron Spin Asymmetry A_1^n in the Valence Quark Region using Polarized ^{3}He Target (E12-06-110, Hall C)	$1/Q^n$ Scaling Test of the L-T Separated Pion Electroproduction Cross Section (E12-07-105, Hall C)
"Color Polarizabilities" in the Neutron: Measurement of g_2^n, d_2^n at High Q^2 (E12-06-121, Hall C)	**PHYSICS BEYOND THE STANDARD MODEL**
Neutron Asymmetry A_1^n in the Valence Quark Region (E12-06-122, Hall A)	Parity-Violating Asymmetry in Deep Inelastic Scattering off Deuterium (E12-07-102, Hall C)
Spin-Orbit Correlations with Longitudinally Polarized Target (E12-07-107, Hall B)	

NUCLEON AND MESON ELECTROMAGNETIC STRUCTURE

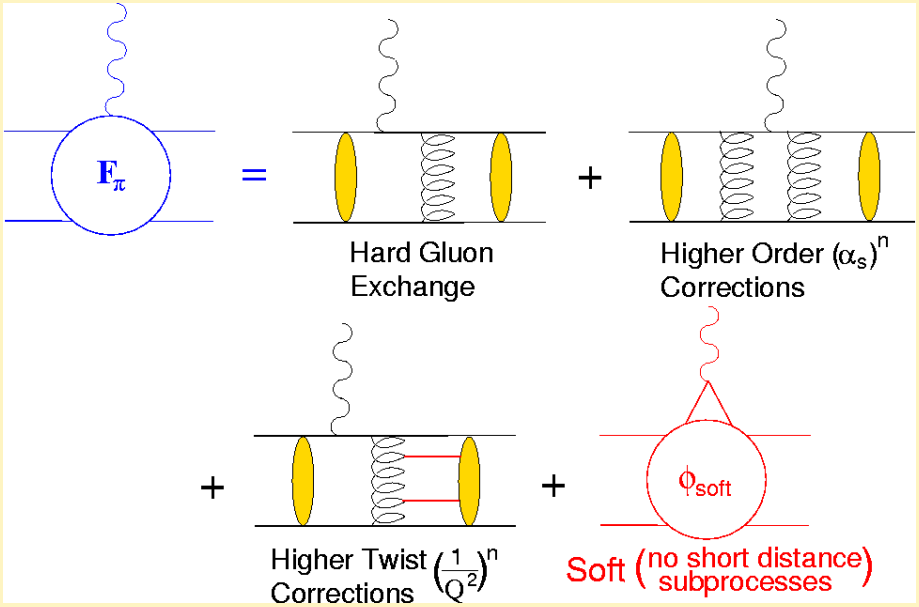
e.g. Charged Pion Form Factor to High Q^2
(E12-06-101, Hall C)

π^+ Electric Form Factor and QCD

- The simple $q\bar{q}$ valence quark structure of mesons presents the ideal laboratory for testing our understanding of bound quark systems.

→ all hadronic structure models use the π^+ as a test case.

"The positronium atom of QCD"



Excellent opportunity for studying the **QCD transition** from the **strong QCD** regime to the **hard QCD** regime.

Jefferson Lab is the only facility capable of the necessary measurements.

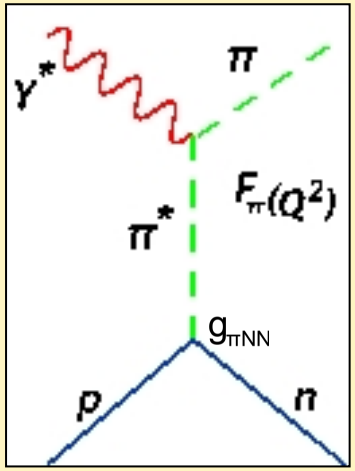
Determination of F_π via Pion Electroproduction

At low Q^2<0.3 GeV^2, the π^+ form factor can be measured exactly using high energy π^+ scattering from atomic electrons.

$\Rightarrow F_\pi$ determined by the pion charge radius 0.657±0.012 fm.

To access higher Q^2, one must employ the $p(e,e'\pi^+)n$ reaction.

- the t-channel process dominates σ_L at small $-t$<0.02 GeV^2.



$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)} g_{\pi NN}^2(t) F_\pi^2(Q^2,t)$$

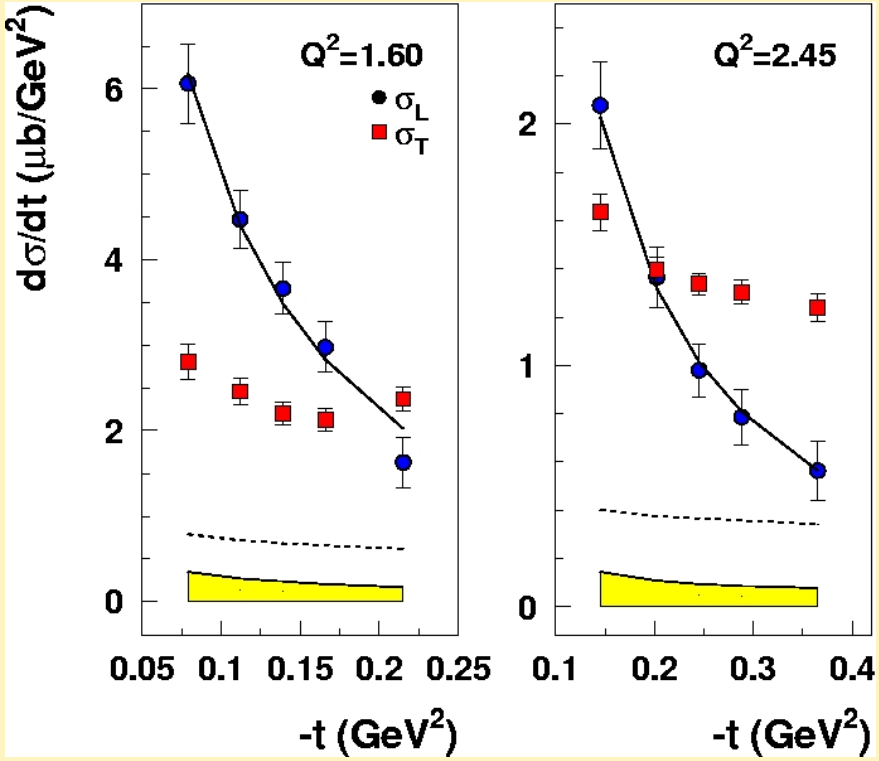
In the actual analysis, a model incorporating the π^+ production mechanism and the `spectator' nucleon is used to extract F_π from σ_L.

Extraction of F_π from JLab *6 GeV* Data

Technique: $$\frac{d\sigma}{dt} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \ldots$$

- Rosenbluth separation required to isolate σ_L.
  - Measure cross section at fixed ($W, Q^2, -t$) at 2 beam energies.
  - Simultaneous fit at 2 ε values to determine σ_L, σ_T, and interference terms.

- **Control of point-to-point systematic uncertainties crucial due to $1/\Delta\varepsilon$ error amplification in L/T separation.**
- Careful attention must be paid to spectrometer acceptance, kinematics, efficiencies, …



Fit of VGL Regge model to σ_L gives F_π at each Q^2.

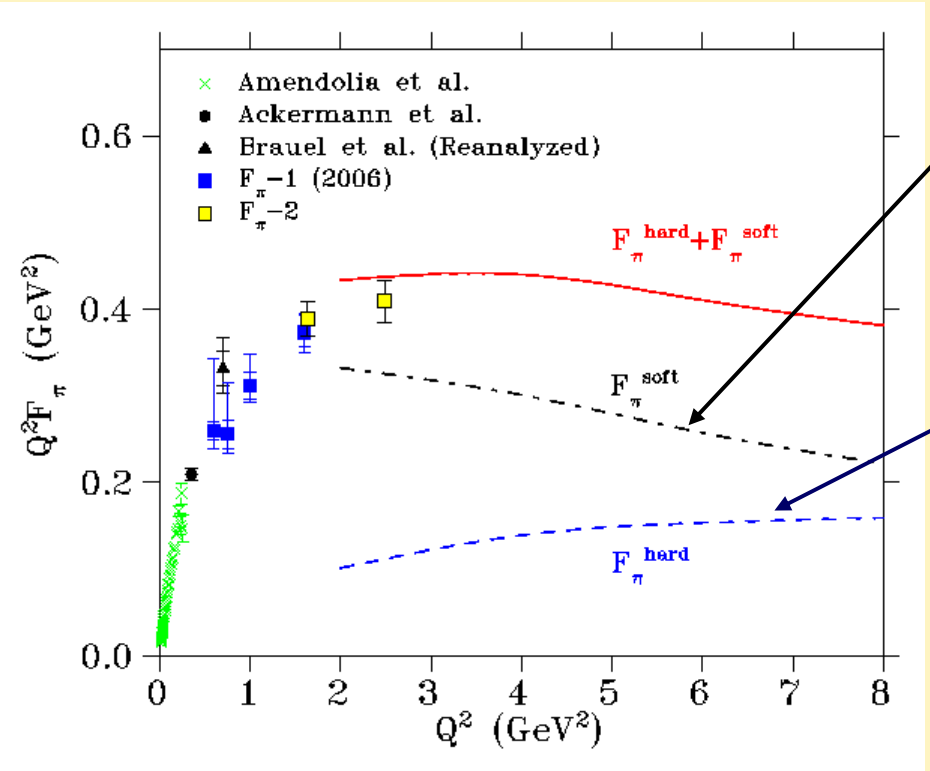
$$F_\pi = \frac{1}{1 + Q^2/\Lambda_\pi^2}$$

The role of Soft and Hard QCD in F_π

pQCD LO+NLO Calculation:

Analytic perturbation theory at the parton amplitude level.

*A.P. Bakulev, K. Passek-Kumericki, W. Schroers, & N.G. Stefanis, PRD **70** (2004) 033014.*



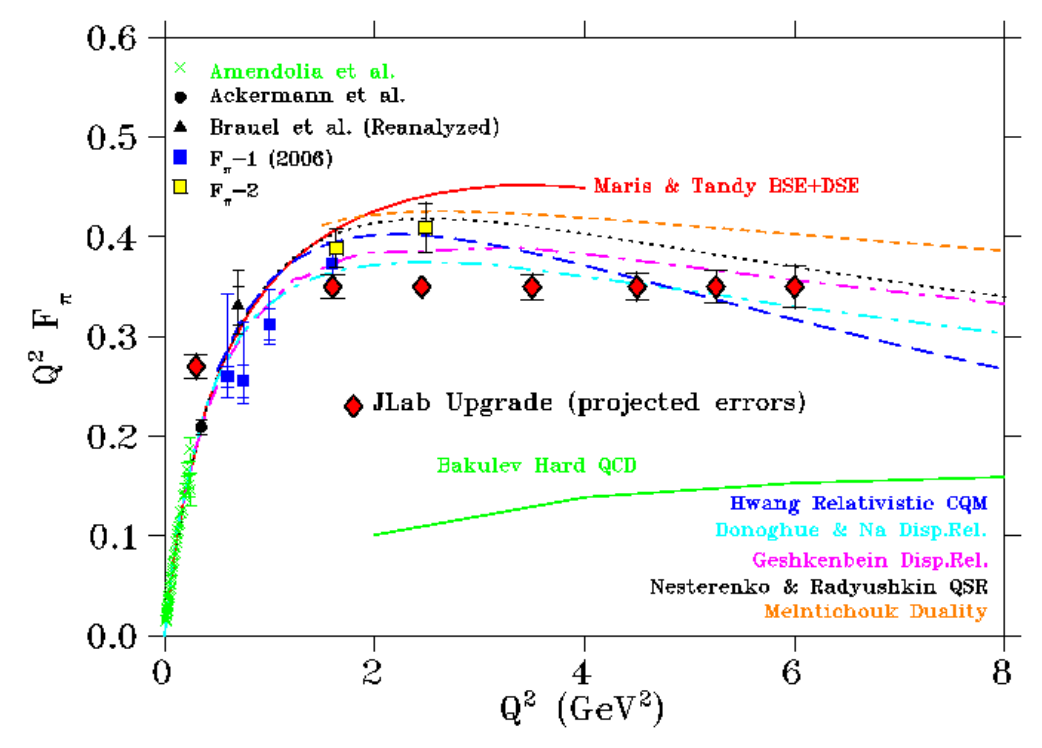
SOFT QCD:

- Extra piece needed to describe data.
- Model-dependent.
- Estimated from local quark-hadron duality model.

HARD QCD: pQCD LO+NLO

- JLab 6 GeV F_π results are far from the values predicted by pQCD.
- At the distance scales probed by the experiment (0.15<r<0.30 fm), the π^+ structure is not governed by the two valence quarks.
- Virtual quarks and gluons dominate.

$F_{\pi^+}(Q^2)$ after JLab 12 GeV Upgrade



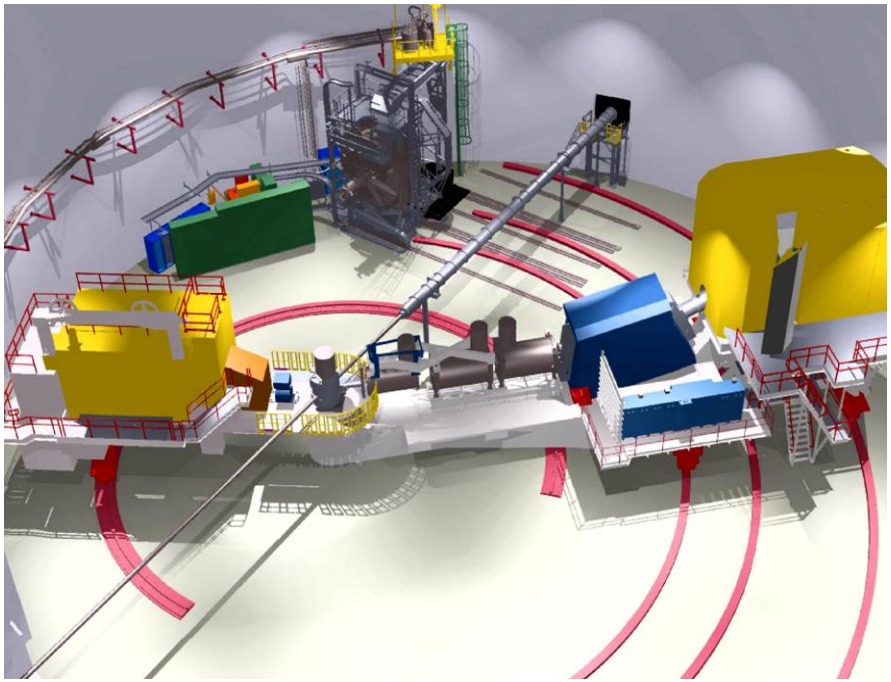
E12-06-101: G. Huber and D. Gaskell spokespersons

JLab Upgrade will allow our measurements to be extended shorter distance scales to discover the scale where valence quarks dominate pion's structure.

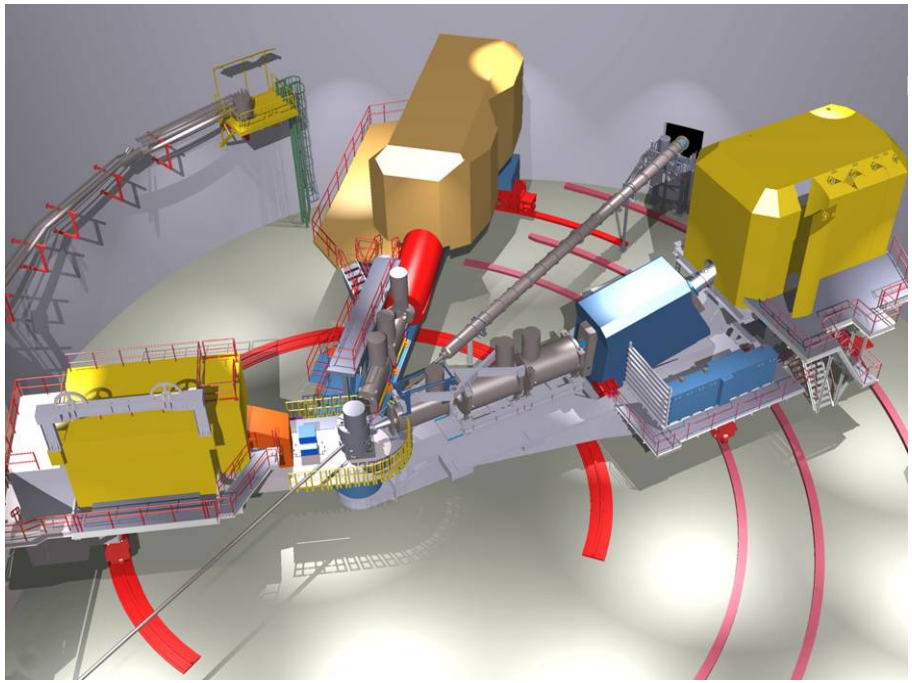
→ **Different theoretical viewpoints on whether higher-twist mechanisms dominate until very large momentum transfer or not.**

Experimental Hall C

At the present 6 GeV Beam Energy



After the 12 GeV Upgrade



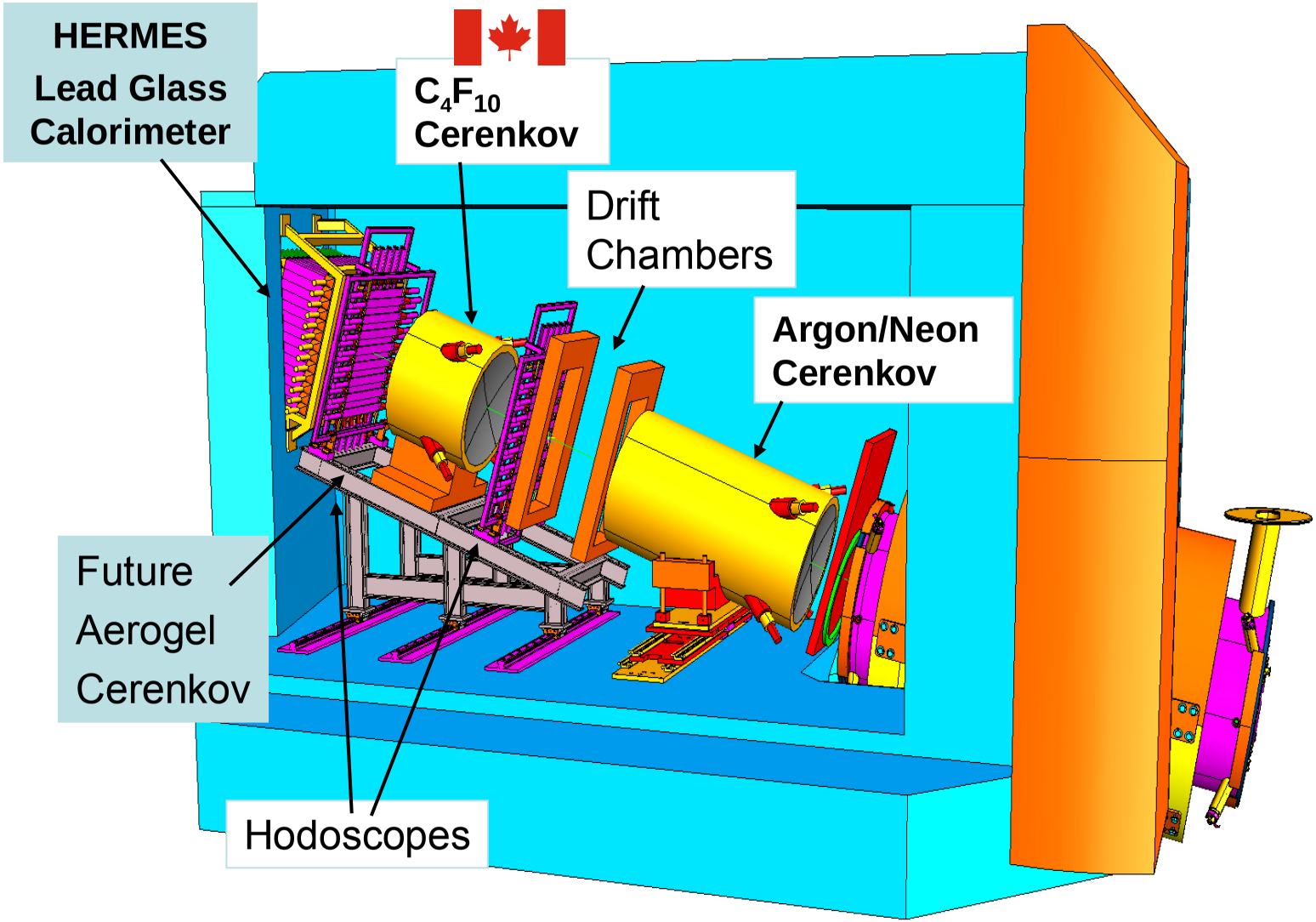
Hall C's High Momentum Spectrometer, Short Orbit Spectrometer and specialized equipment for studying:

- The strange quark content of the proton.
- Form factors of simple quark systems.
- The transition from hadrons to quarks.
- Nuclei with a strange quark embedded.

Add a Super- High Momentum (12 GeV) Spectrometer for studying:

- Super-fast (high x_B) quarks.
- Form factors of simple quark systems.
- The transformation of quarks into hadrons.
- Quark-quark correlations.

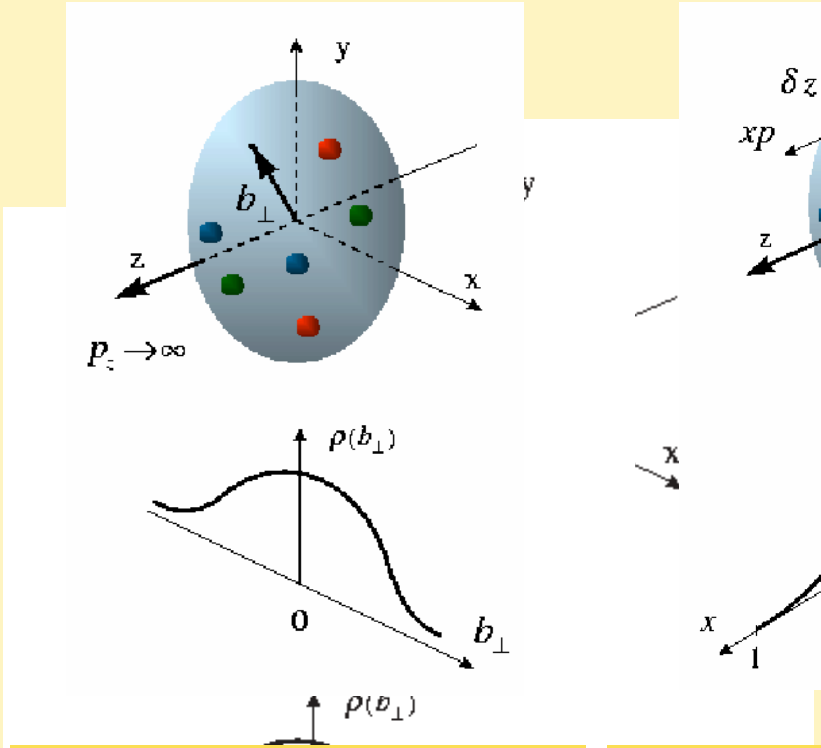
Super-High Momentum Spectrometer (SHMS) Focal Plane Detectors

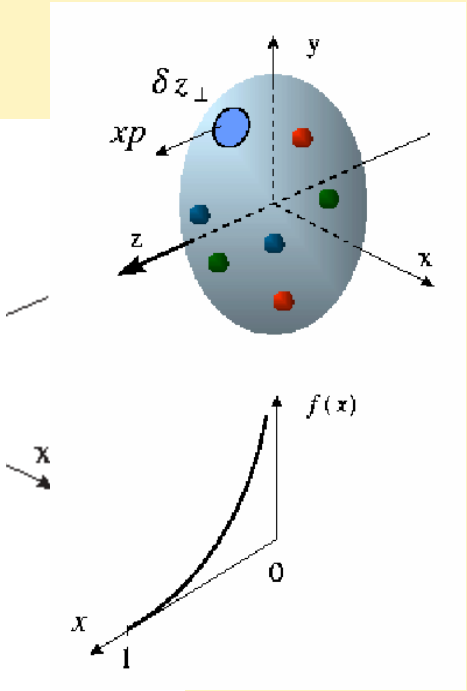


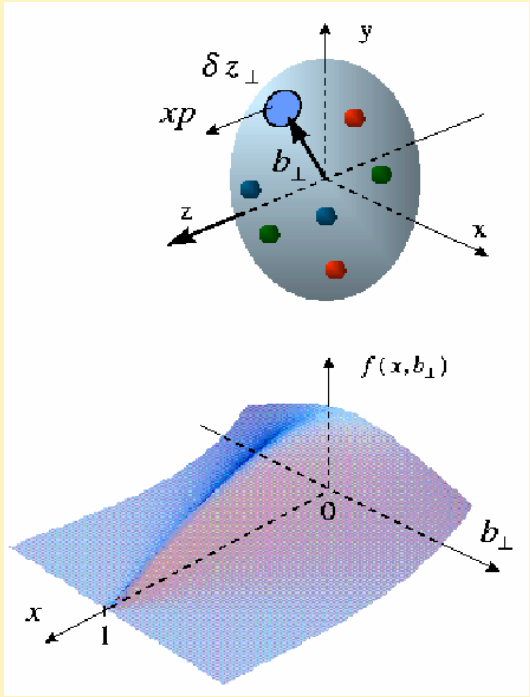
GENERALIZED PARTON DISTRIBUTIONS

e.g. $1/Q^n$ Scaling Test of the L-T Separated Pion Electroproduction Cross Section (E12-07-105, Hall C)

Generalized Parton Distributions offer a 3D description of hadron structure







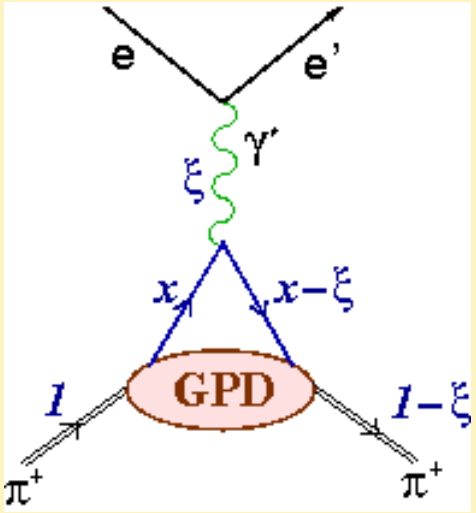
Elastic Scattering
(form factors)
transverse parton distribution in Coordinate space

DIS
(structure functions)
longitudinal parton distribution in momentum space

DES (GPDs)
Fully-correlated parton distribution in both coordinate and momentum space

Generalized Parton Distributions (GPDs)

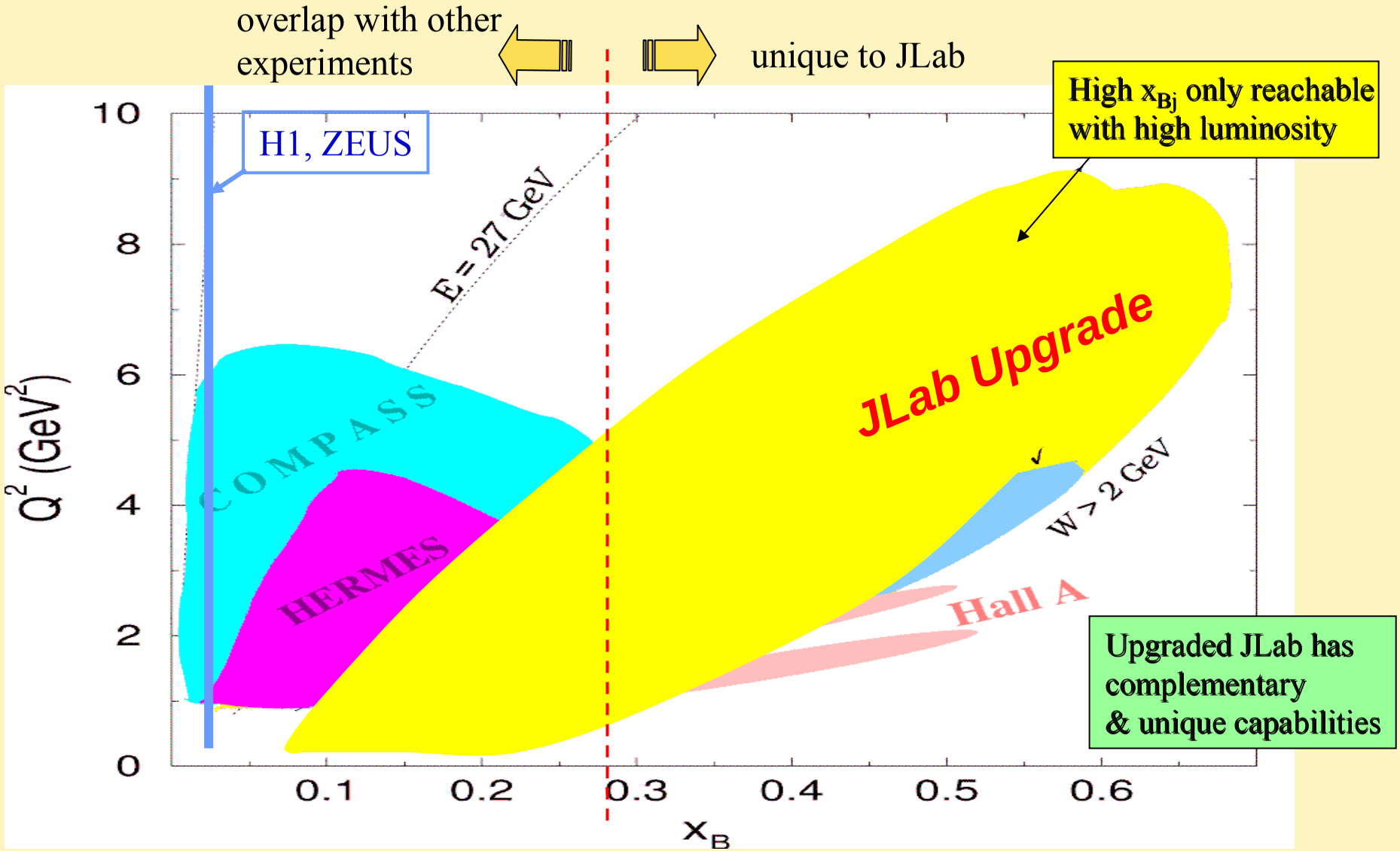
- GPDs are universal quantities and reflect the structure of the hadron independently of the probing reaction.



- GPD picture applies strictly to the hard-scattering regime, where the interaction can be clearly separated into perturbative (pQCD) and non-perturbative factors.
  - GPD contains the non-perturbative part of the interaction and represents the interference of parton wave functions, differing by momentum fraction ξ.

$$F_\pi(Q^2) = \int_0^1 \sum_q H_\pi^q(\xi, x, Q^2)\,dx$$

Deeply Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade

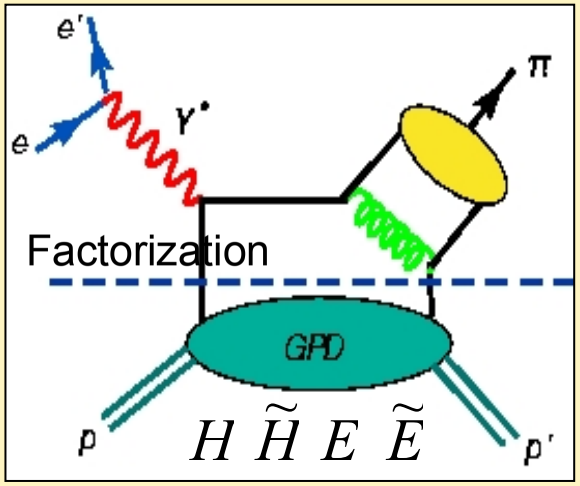


Hard-Soft Factorization

- **To access physics contained in GPDs, one is limited to the kinematic regime where hard-soft factorization applies.**
  - Determining the applicability of the GPD mechanism at higher x_{Bj} is a high priority for the JLab 12 GeV program.
  - Only if hard-soft factorization applies can GPDs be extracted.

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: $\sigma_L >> \sigma_T$.

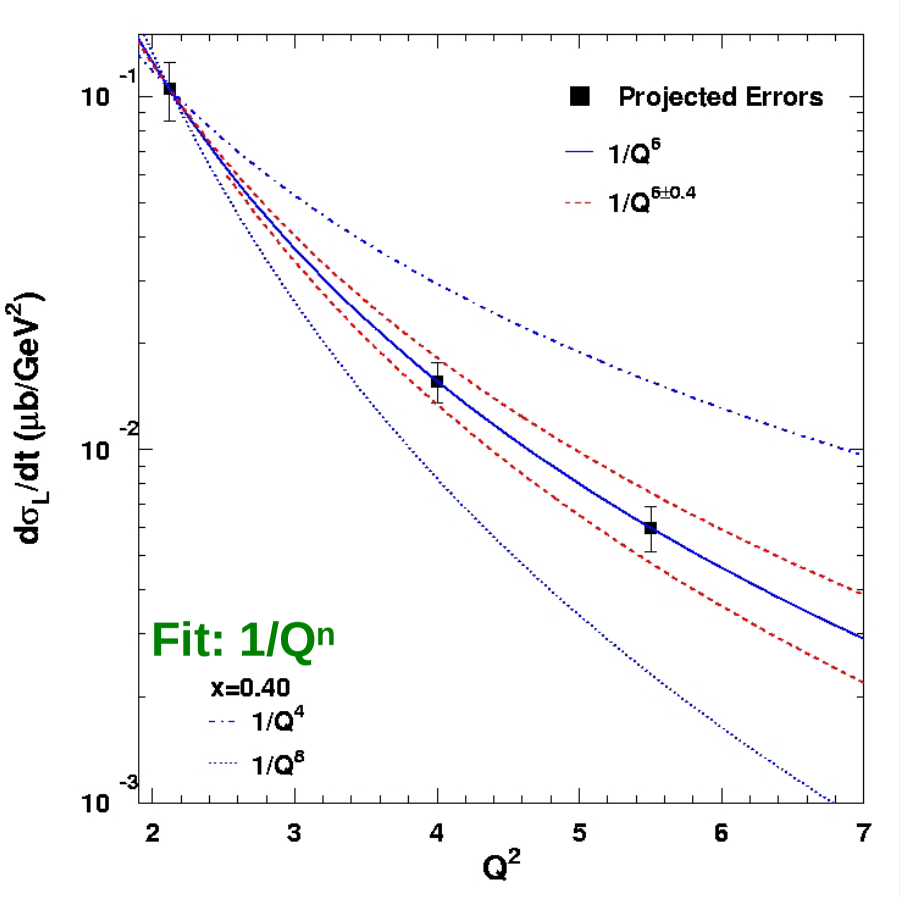


$1/Q^n$ Scaling Test after JLab 12 GeV Upgrade

- Measure separated cross sections for the $p(e,e'\pi^+)n$ reaction at three values of x_{Bj}.
- QCD scaling predicts $\sigma_L \sim Q^{-6}$ and $\sigma_T \sim Q^{-8}$.
- The Q^2 coverage is a factor of 3-4 larger compared to 6 GeV.

"A detailed study to determine whether or not meson electroproduction can provide information on GPDs is important."

-- JLab PAC32



E12-07-105:
T. Horn and G. Huber and spokespersons

EXOTIC MESONS

Mapping the Spectrum of Light Quark Mesons and Gluonic Excitations with Linearly Polarized Photons

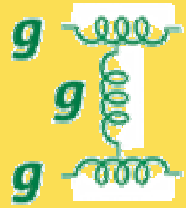
(E12-06-102, Hall D)

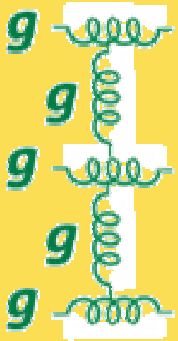
Mesons in QCD

Conventional Meson

$$3 \otimes \bar{3} = 1 \oplus 8$$

Glueball Meson

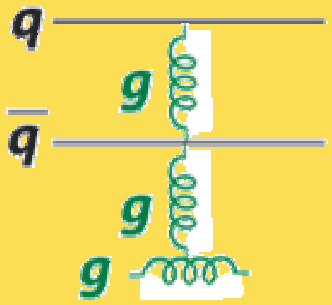




$$8 \otimes 8 = 1 \oplus 8 \oplus \cdots$$

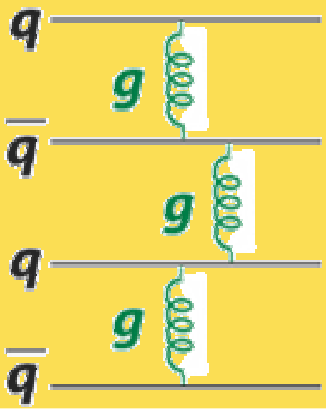
$$(8 \otimes 8)_8 \otimes 8 = 1 \oplus \cdots$$

Hybrid Meson



$$(3 \otimes \bar{3})_8 \otimes 8 = 1 \oplus \cdots$$

4-quark Meson or Molecule

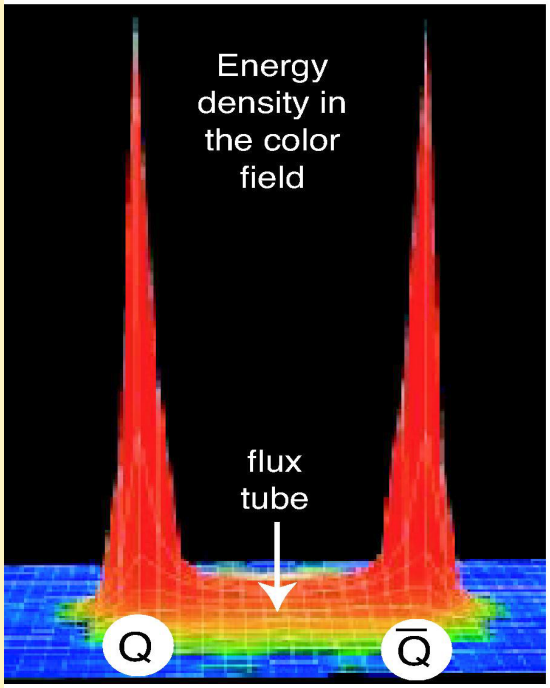


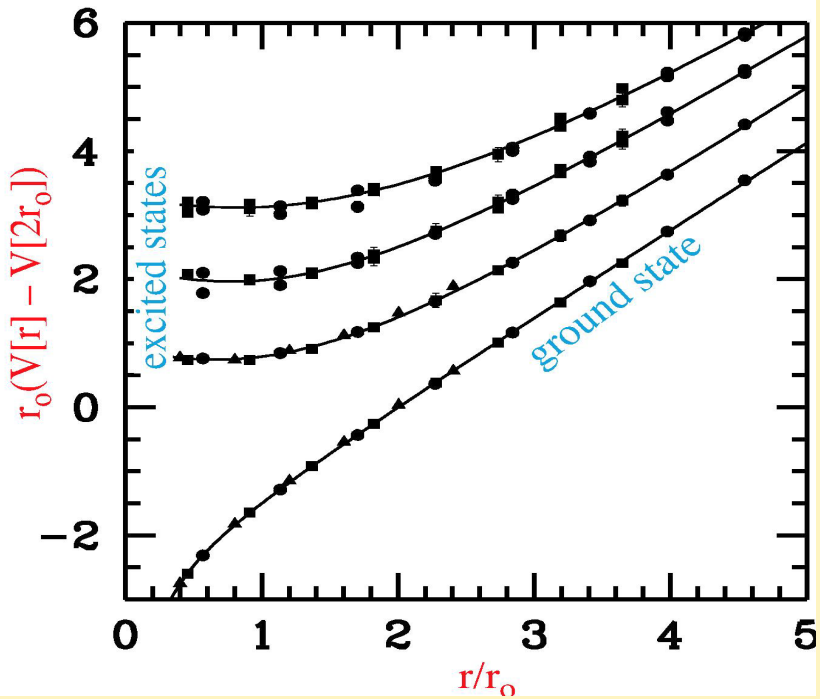
Hybrid Meson Mass Prediction

Lattice QCD computations in heavy-quark sector:

- Insight into excitations of gluon string binding the $q\bar{q}$
- For heavy quarks, energy associated with "excited string" of around 1 GeV.
  - Lowest 1^{-+} state around 1.8-2.0 GeV:

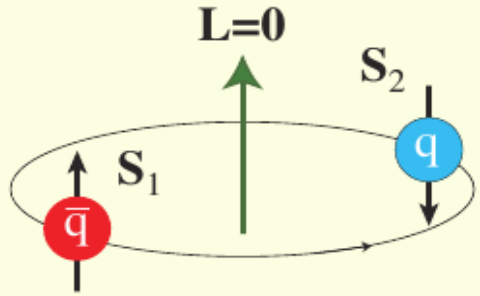
    plus chiral correction ~ -0.1 to -0.2 GeV.



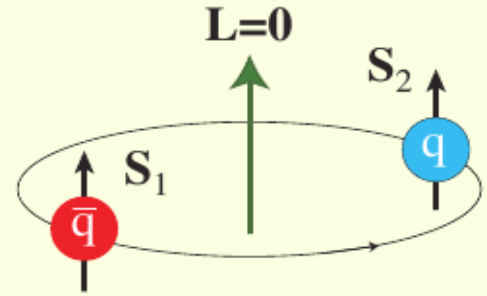


Conventional Light Mesons

$$\vec{J} = \vec{L} + \vec{S}$$
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$



$J^{PC} = 0^{-+}: \ \pi, \ K$

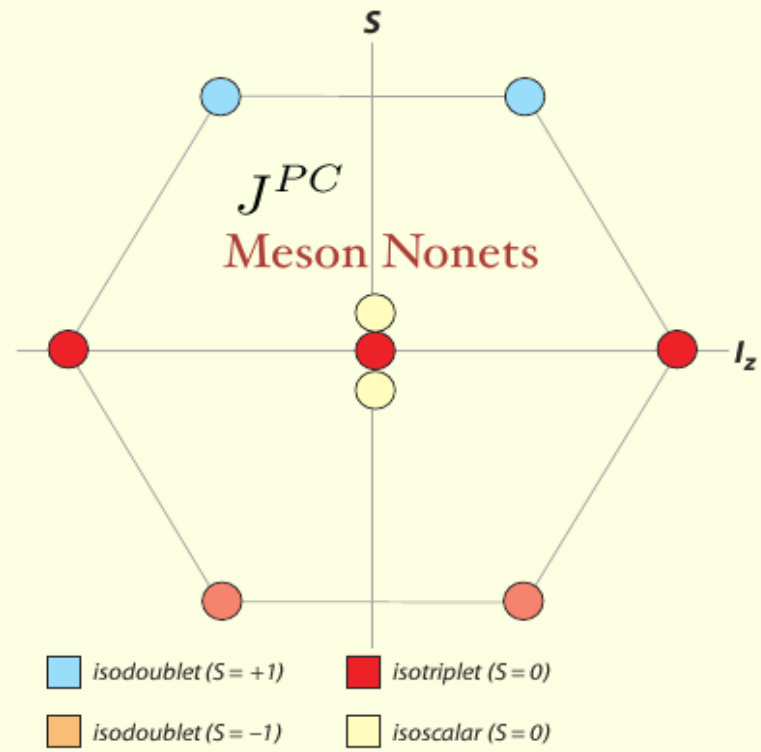


$J^{PC} = 1^{--}: \ \rho, \ K^*, \ \gamma$

Certain spin-parity combinations are not allowed - exotic:

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

For light quarks (u, d, s) and fixed J, P and C we expect nonets of mesons:

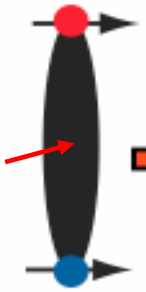


Production of Hybrid Mesons

Combine excited glue QN $J^{PC} = 1^{+-}$ *or* 1^{-+} with those of the quarks:

$J^{PC} = 1^{--}$ *or* 1^{++}

$\vec{L} = 0, \ \vec{S} = 0$



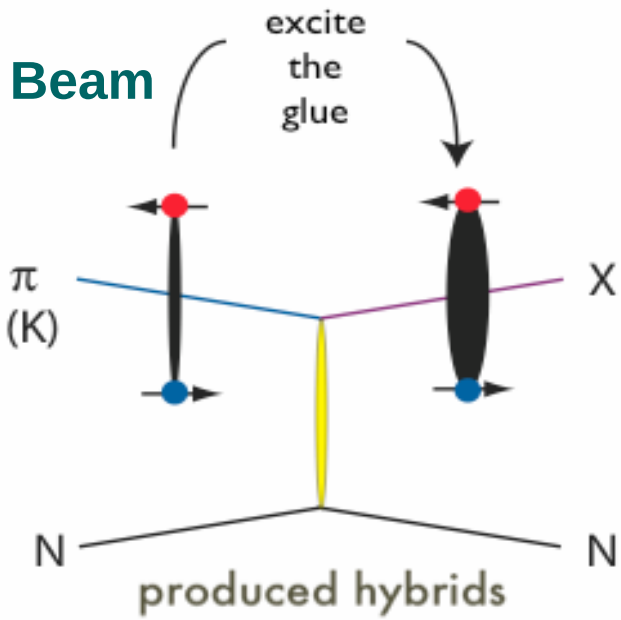
$J^{PC} = 0^{-+}, 1^{+-}, 2^{-+}$

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

exotic

$\vec{L} = 0, \ \vec{S} = 1$

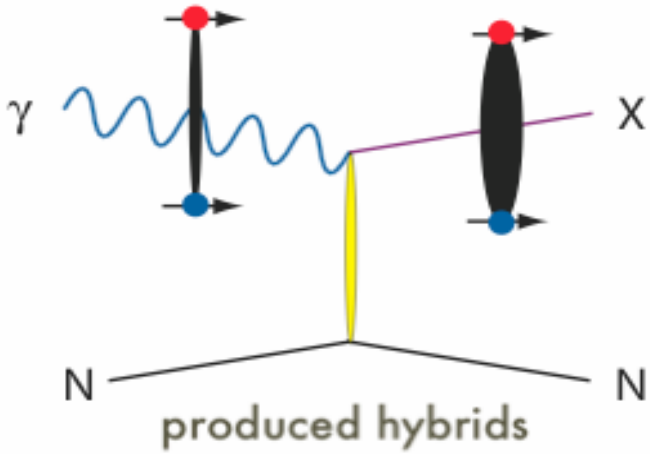
π/K Beam



produced hybrids

are not expected to be exotic

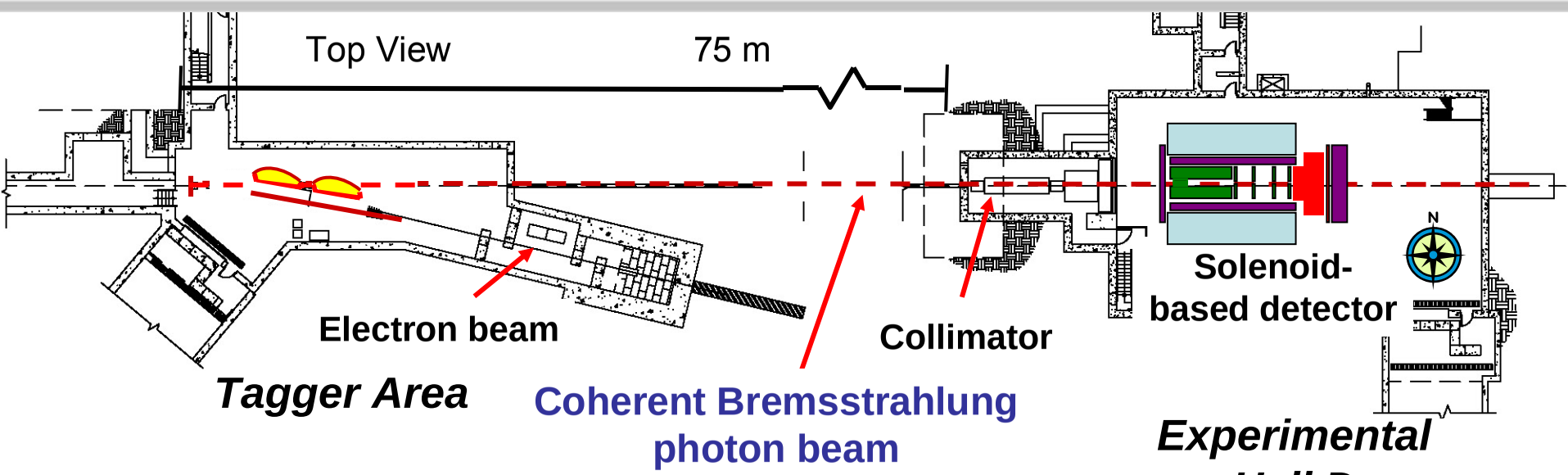
Photon Beam

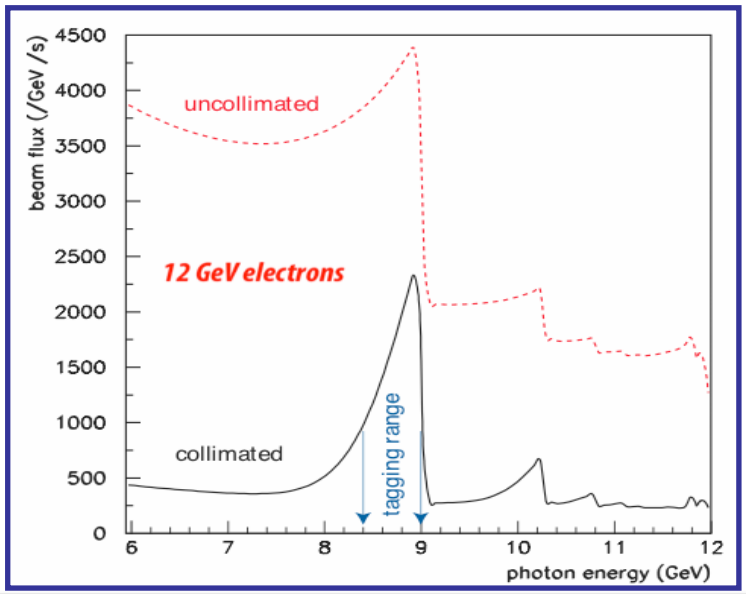


produced hybrids

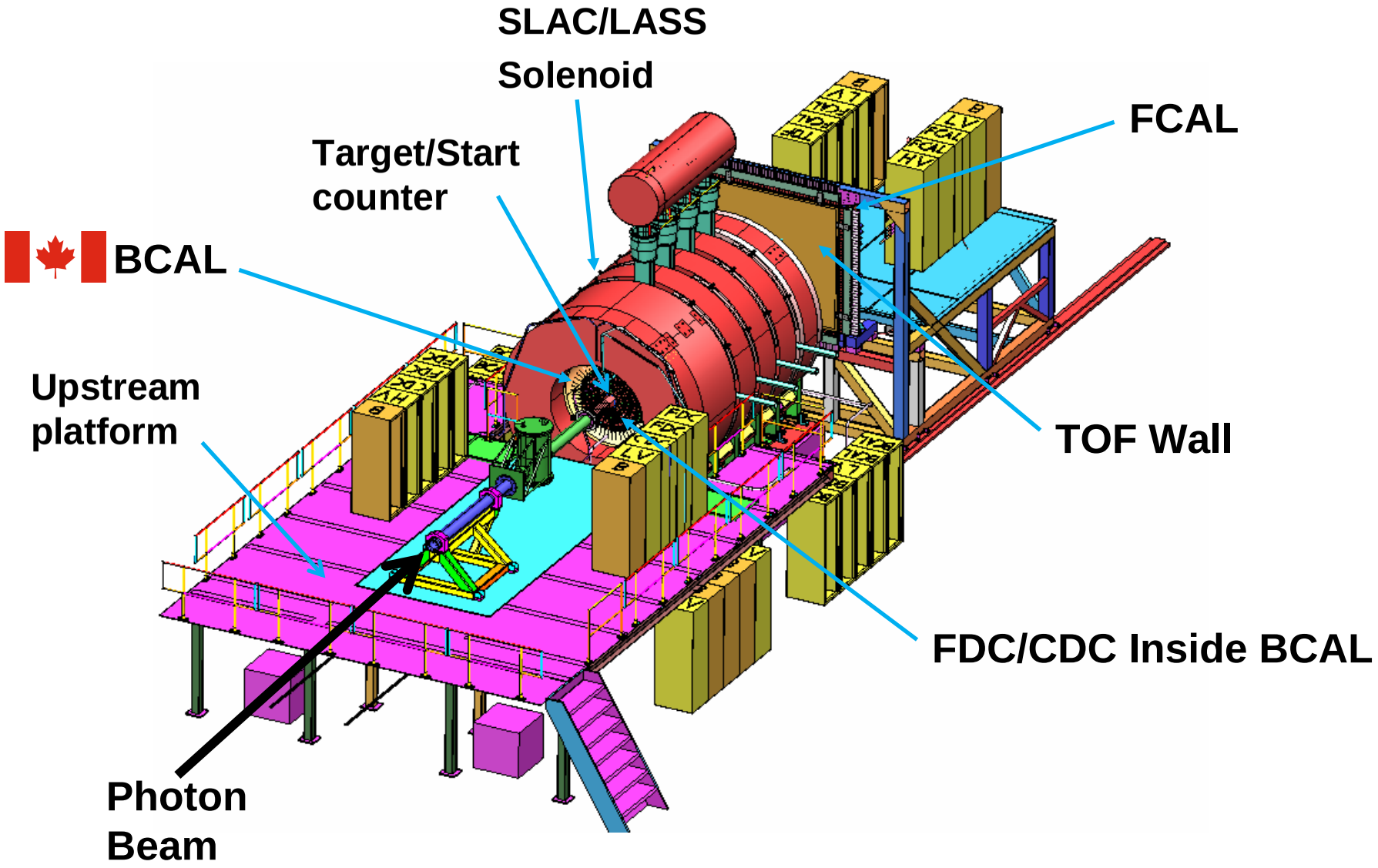
can be exotic

Coherent Photon beam and Experimental Hall D





Hall D: *GlueX* Detector



GlueX Experiment Goals

FIRST 5 YEARS:

- Establish the existence of a $J^{PC}=1^{-+}$ or 2^{+-} exotic meson in several decay channels if it is present at a level of a few % of conventional mesons.
  - If exotics are not present, the few % level exclusion limit would indicate problems with the QCD-based models made to date.
- Measure branching modes for established exotic states to validate QCD predictions.
- Add to the knowledge of conventional meson spectroscopy that straddles the light and heavy quark sectors.

12 GeV Upgrade: Phases and Schedule

(based on funding guidance provided by DOE-NP in June-2007)

- **2009-2013 Construction** – ***starts in ~6 months!***
  - ***Parasitic machine shutdown – May 2011 through Oct 2011 (6 months)***
  - ***Accelerator shutdown start mid-May 2012***
  - ***Accelerator commissioning mid-May 2013***

- **2013-2015 Pre-Operations** (beam commissioning)
  - ***Hall A commissioning start ~October 2013***
  - ***Hall D commissioning start ~April 2014***
  - ***Halls B and C commissioning start ~October 2014***