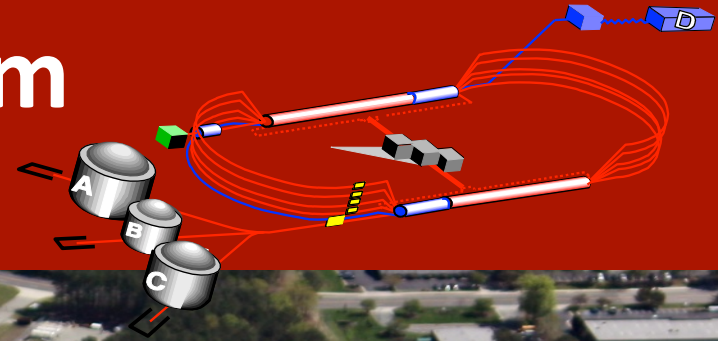
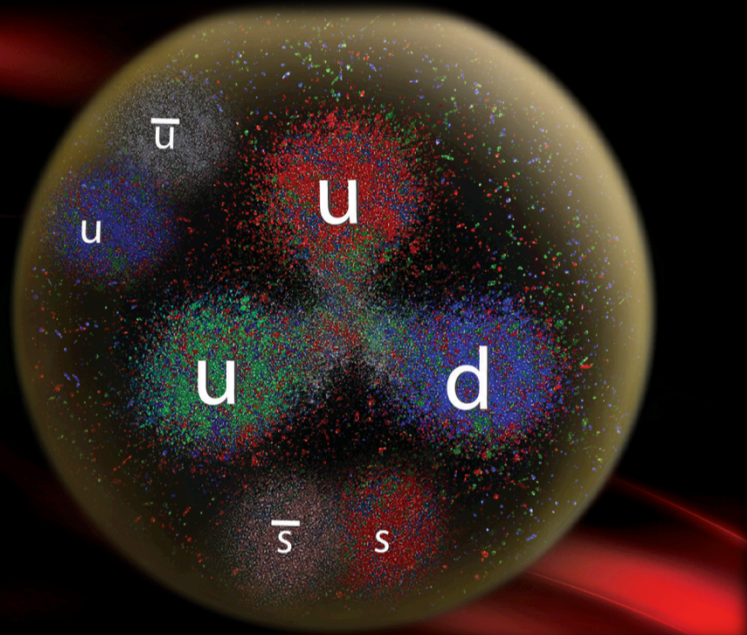


# The Jefferson Lab Program at 12 GeV



# Jefferson Lab Mission



## Address critical issues in “strong” QCD

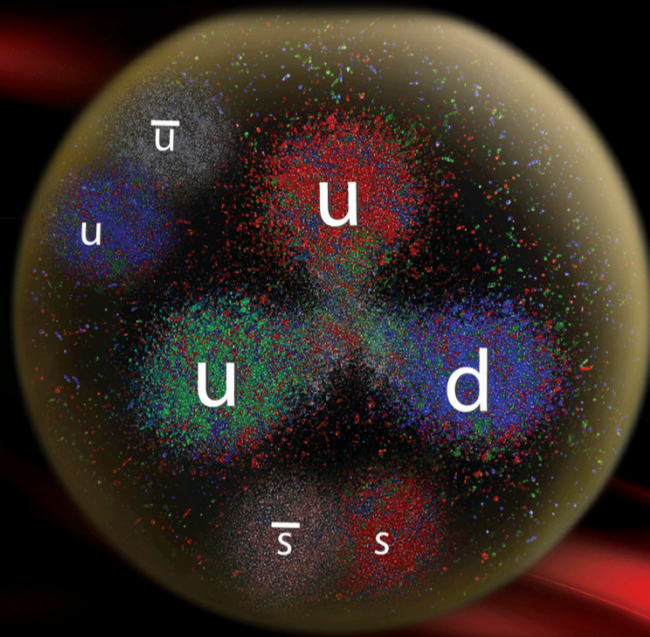
- What is the mechanism of confinement
- How are hadrons constructed from quarks and gluons
- What is the QCD basis for the nucleon-nucleon force

# Jefferson Lab Mission

Address critical issues  
in “strong” QCD

- 
- 1987 The proton spin crisis
  - 2000 The proton form factor crisis
  - 2012 The proton size crisis

# Jefferson Lab Mission



**Discover evidence for physics beyond the standard model**

Superb beam characteristics:

- high intensity
- high polarization
- high resolution
- high stability

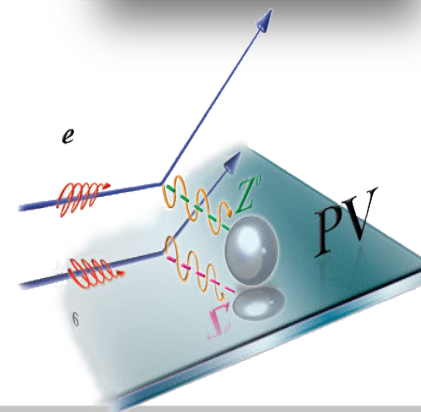
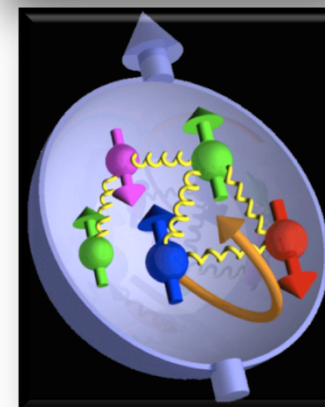
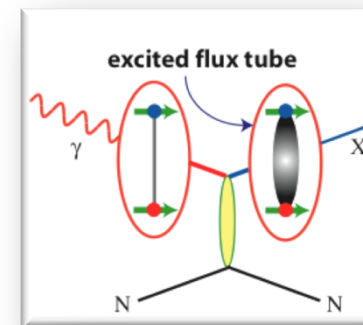
**Address critical issues in “strong” QCD**

- What is the mechanism of confinement
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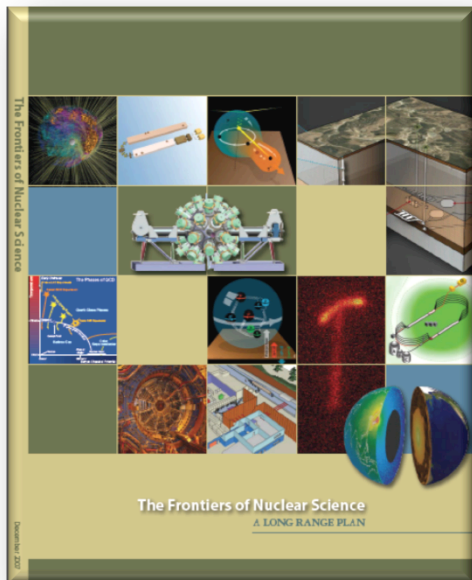


# The 21<sup>st</sup> Century Science Questions

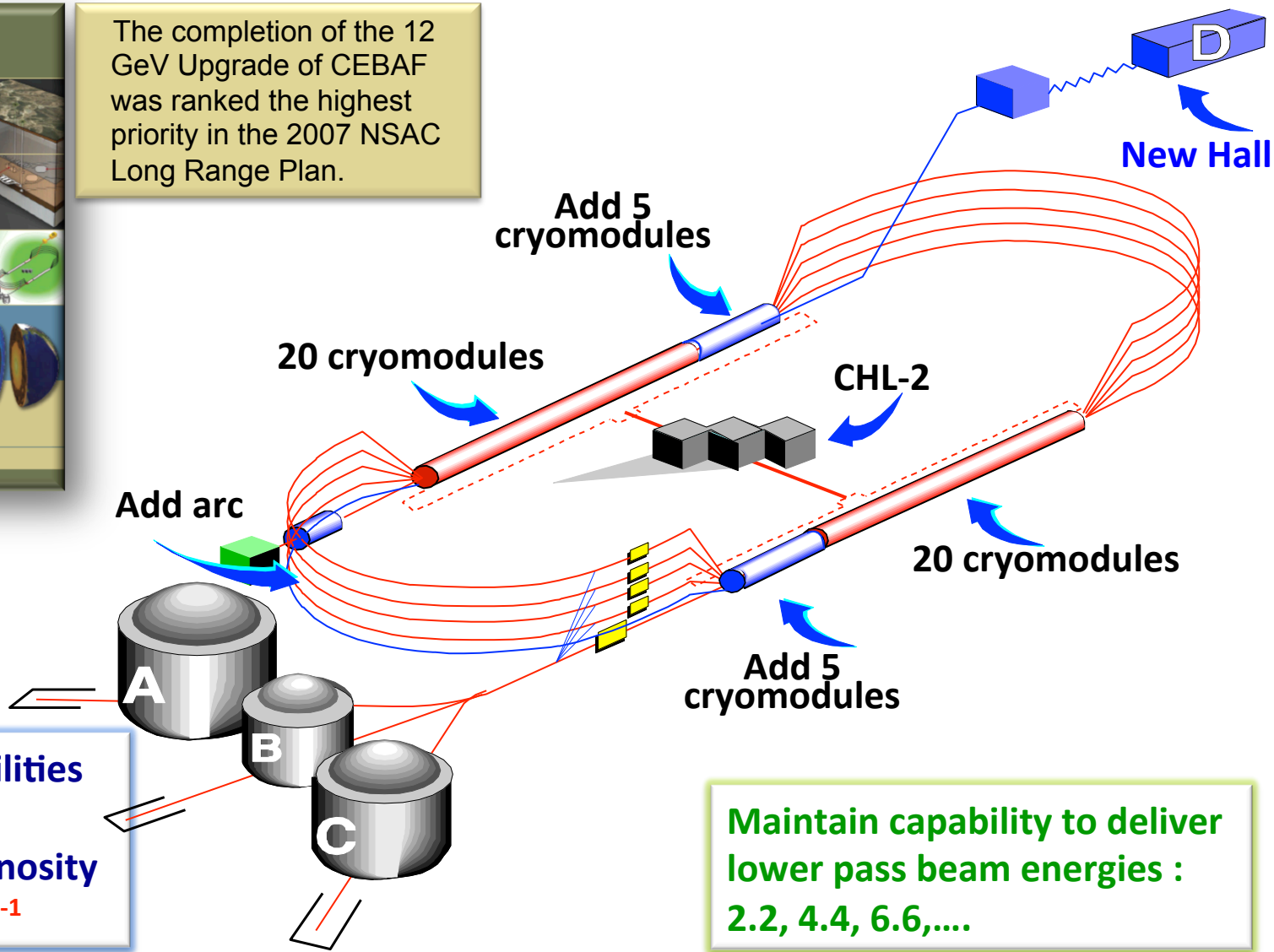
- What is the role of gluonic excitations in the spectroscopy of light mesons?
- Where is the missing spin in the nucleon?  
What is the role of orbital angular momentum?
- Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?
- What is the relation of short-range nuclear structure and parton dynamics?
- Can we discover evidence for physics beyond the standard model of particle physics?



# 12 GeV Upgrade



The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

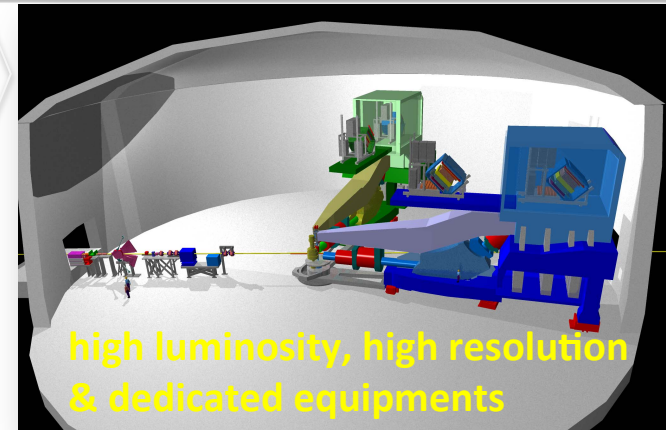
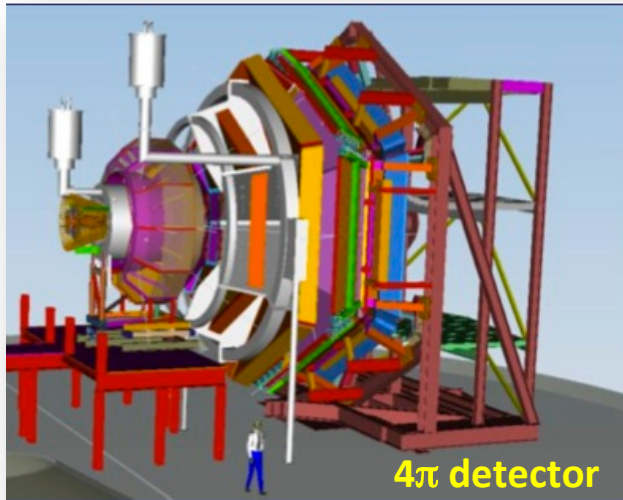


- Enhanced capabilities in existing Halls
- Increase of Luminosity  $10^{35} - \sim 10^{39} \text{ cm}^{-2}\text{s}^{-1}$

Maintain capability to deliver lower pass beam energies : 2.2, 4.4, 6.6,....

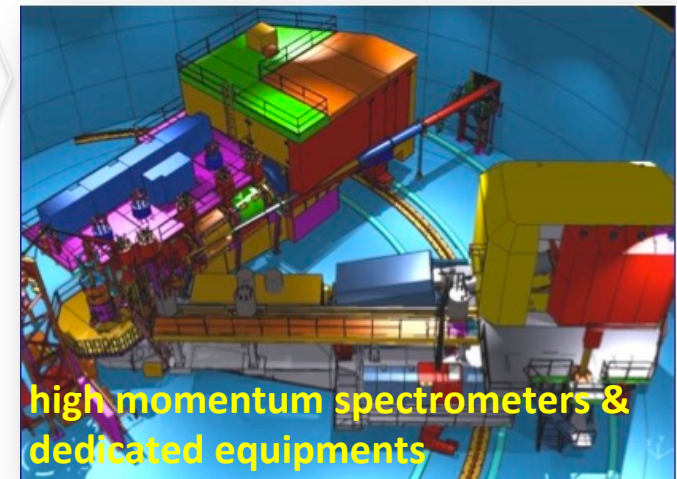
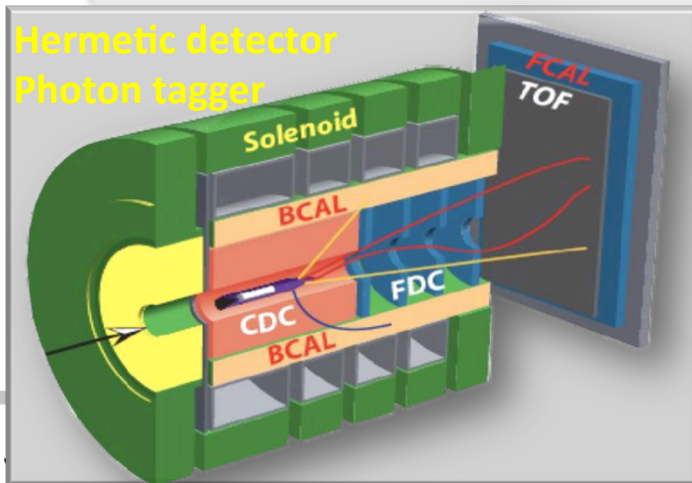
# JLab Physics Program at 12 GeV

**Hall A** – form factors, GPDs & TMDs, SRC  
Low-energy tests of the SM and Fund. Symmetry Exp.



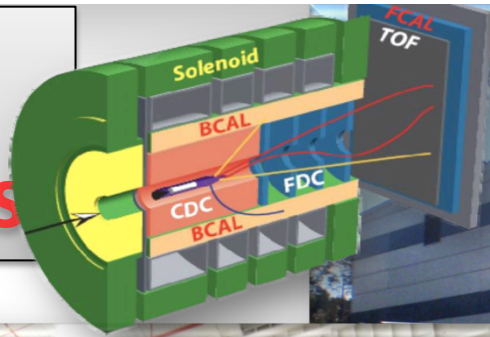
**Hall B** - 3-D nucleon structure via GPDs & TMDs  
Search new form of hadron. matter via Meson Spectr.

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



**Hall D** - exploring origin of confinement by studying *exotic mesons* using real photons

# Hall D Highlights



Hall D & Counting House



Hall D Interior



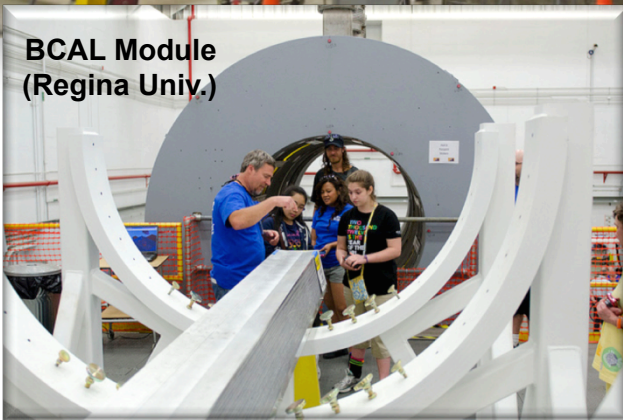
Central Drift Chamber  
(Carnegie Mellon)



Forward Drift Chamber  
(Jlab)



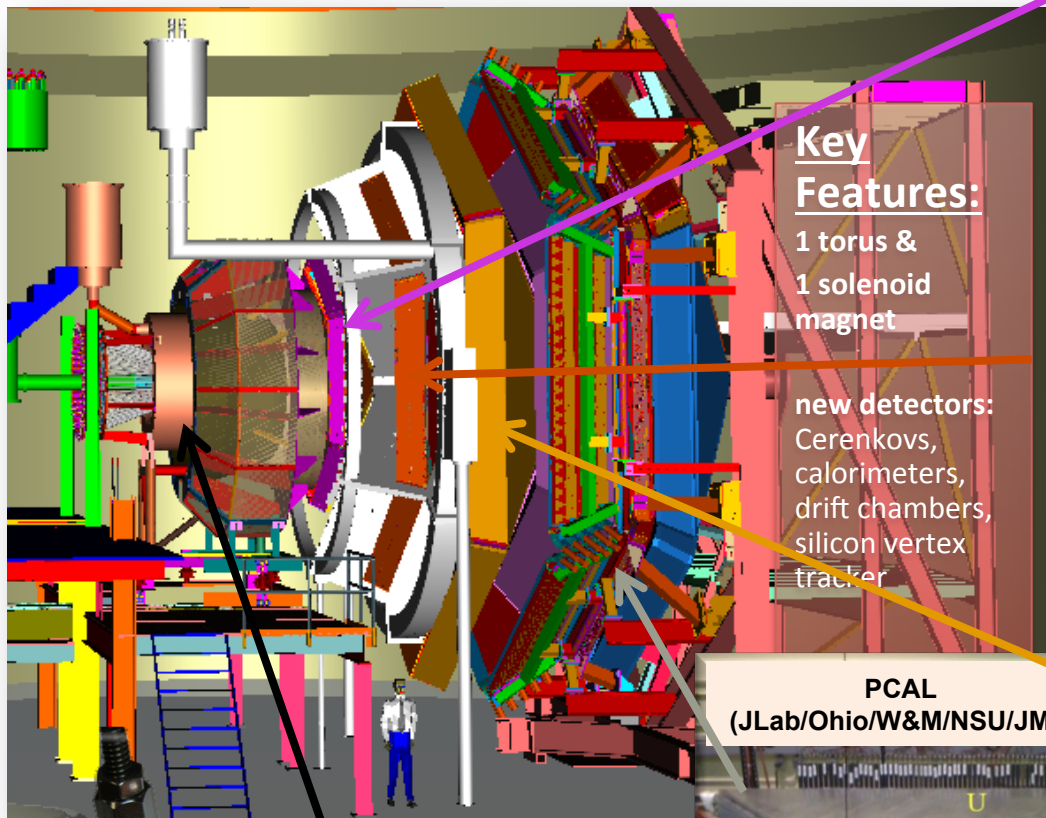
BCAL Module  
(Regina Univ.)



Mini-BCAL



# Hall B - CLAS12 Highlights



**Key Features:**

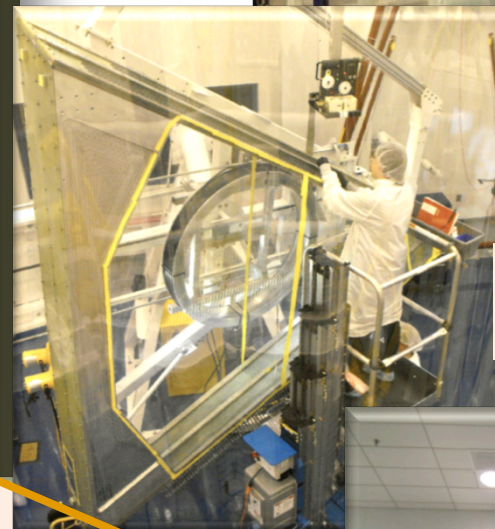
1 torus & 1 solenoid magnet

new detectors: Cerenkovs, calorimeters, drift chambers, silicon vertex tracker

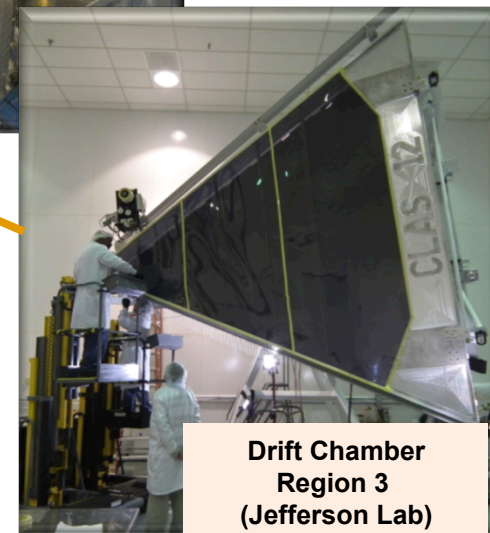
**PCAL**  
(JLab/Ohio/W&M/NSU/JMU)



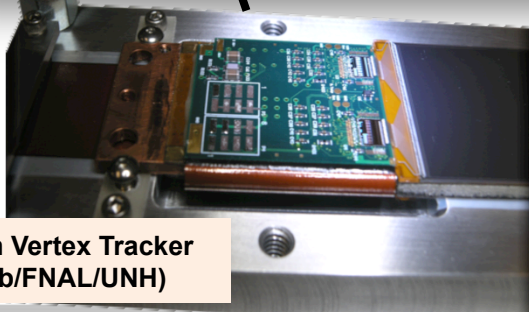
**Drift Chamber Region 1**  
(Idaho State U)



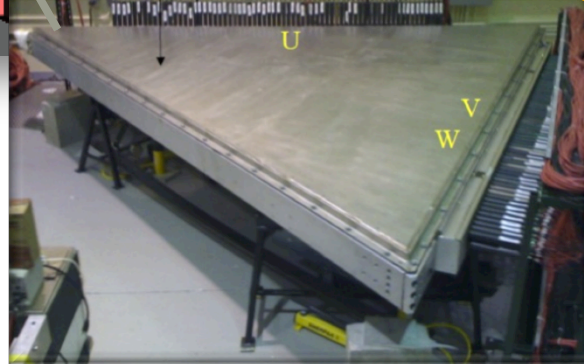
**Drift Chamber Region 2**  
(Old Dominion U)



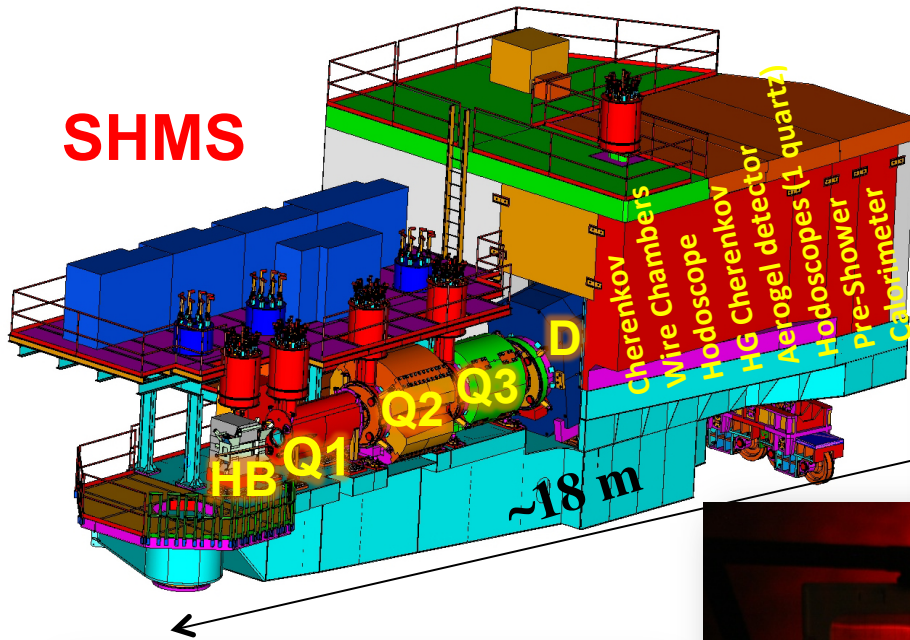
**Drift Chamber Region 3**  
(Jefferson Lab)



**Silicon Vertex Tracker**  
(JLab/FNAL/UNH)



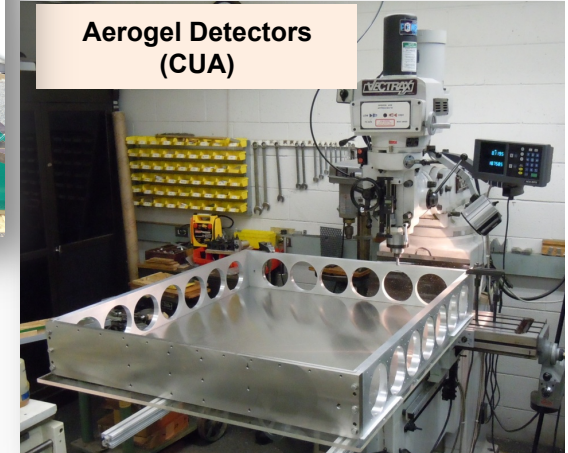
# Hall C Highlights



Spectrometer Carriage Parts



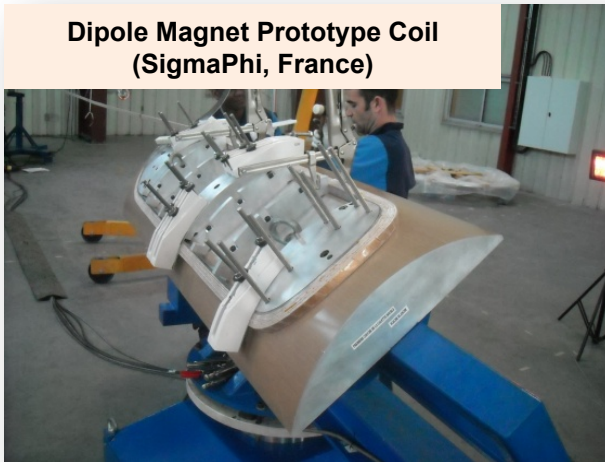
Aerogel Detectors (CUA)



HGC Mirror (U Regina)



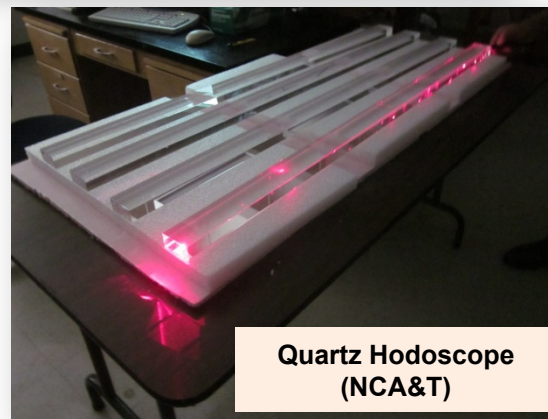
Dipole Magnet Prototype Coil (SigmaPhi, France)



PreShower (Yerevan/NSL)



Quartz Hodoscope (NCA&T)



All detectors but one from user contributions

# Planning for Future Equipments

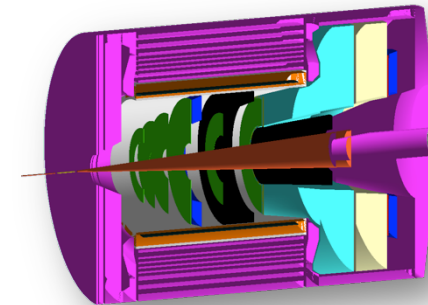
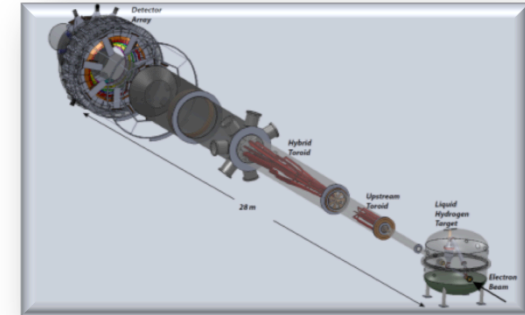
## Future Hall A Large Installation Programs:

- **MOLLER**

- Parity Violating (PV) e-e scattering
- Precise Standard Model test
- Submitted to DOE-ONP Sep. 2011

- **SoLID (PV  $e^-$  -  $q$  scattering + SIDIS)**

- PV e-quark + High Precision TMD Studies
- Chinese collaboration still developing
- CLEO solenoid under negotiation
- Directors review in Fall 2012?

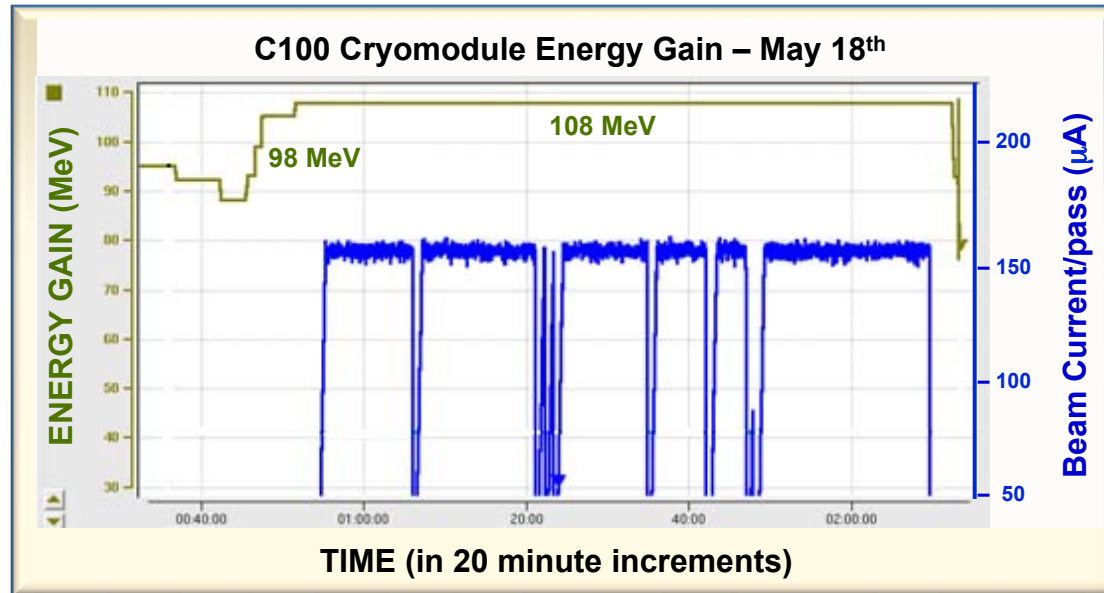


## Also ongoing:

- SBS spectrometer
- $\pi^0$  spectrometer (off SHMS carriage)
- Windowless target for proton charge radius exp.
- Forward Tagger for CLAS12
- 1 sector RICH detector for CLAS12

# 12 GeV Upgrade – Recent Progress

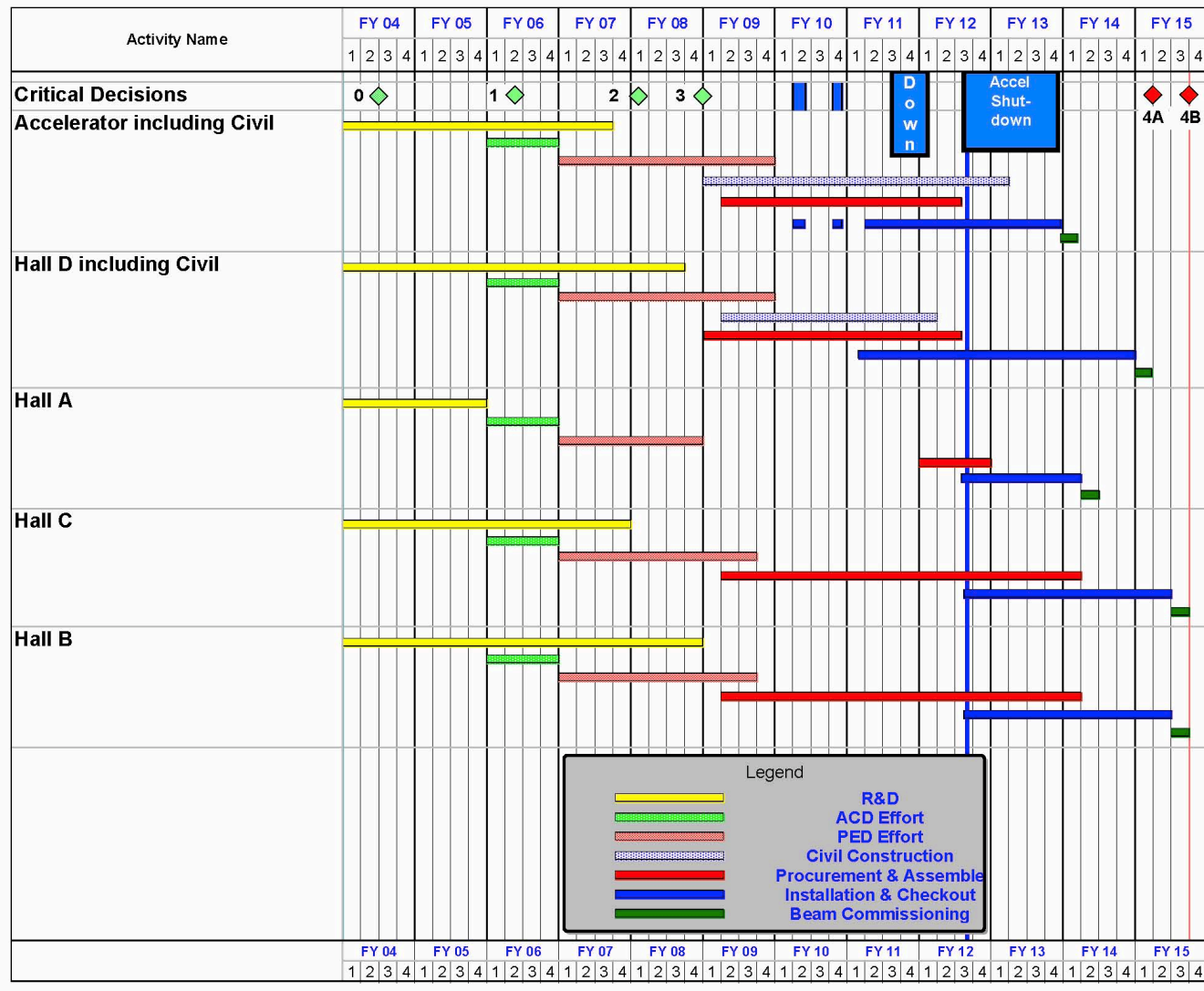
- High gradient cryomodule performance demonstrated in tunnel  
→ Met research beam spec. of **108 MeV @ 465  $\mu\text{A}$**



- Central Helium Liquefier-2 equipment in place
- Hall D – equipment installation in progress
- Superconducting magnets under construction
- All major detector systems under construction



# 12 GeV Upgrade Project Schedule



**FY12: reduction of \$16M**

- ~~12~~ 16-month installation  
May 2012 - ~~May~~ Sept 2013
- Hall A commissioning start  
~~Oct 2013~~ Feb 2014
- Hall D commissioning start  
~~April 2014~~ Oct 2014
- Halls B & C commissioning start  
~~Oct 2014~~ Apr 2015

**Project Completion:**

**June 2015**

# 12 GeV Approved Experiments by Physics Topics

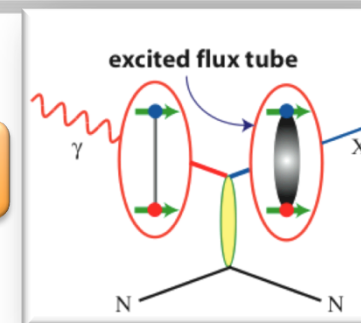
Topic	Hall A	Hall B	Hall C	Hall D	Total
The Hadron spectra as probes of QCD (GluEx and heavy baryon and meson spectroscopy)		1		1	2
The transverse structure of the hadrons (Elastic and transition Form Factors)	4	3	2		9
The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions)	2	2	5		9
The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)	5	10	3		18
Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, F N-N correlations, hypernuclear spectroscopy, few-body experiments)	3	2	6		11
Low-energy tests of the Standard Model and Fundamental Symmetries	2			1	3
<b>Total</b>	<b>16</b>	<b>18</b>	<b>16</b>	<b>2</b>	<b>52</b>

**The approved program equals well beyond 6 years**

# The 21<sup>st</sup> Century Science Questions

- **What is the role of gluonic excitations in the spectroscopy of light mesons?**

M. Battaglieri's talk



Where is the missing spin in the nucleon?

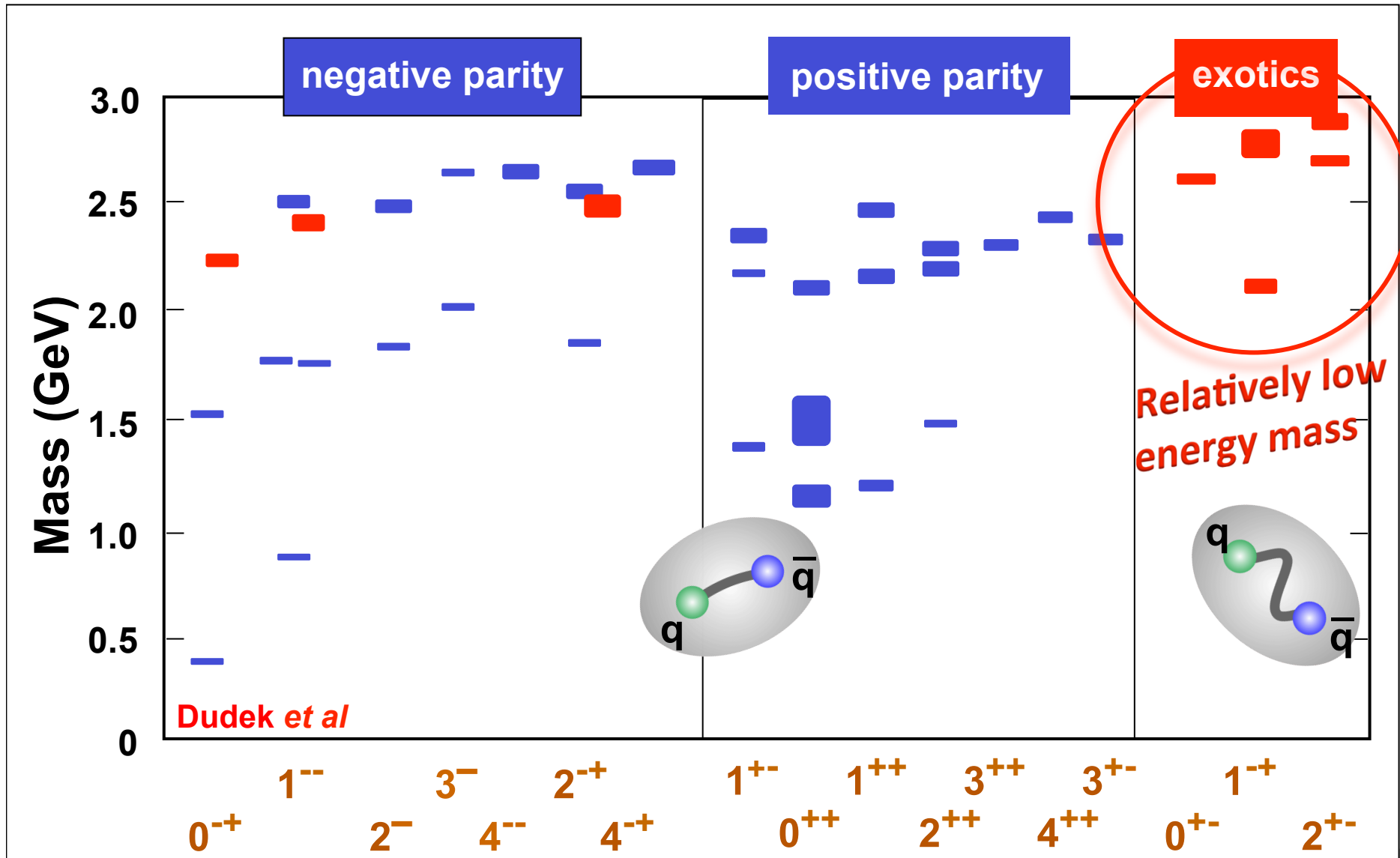
What is the role of orbital angular momentum?

Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?

What is the relation of short-range nuclear structure and parton dynamics?

Can we discover evidence for physics beyond the standard model of particle physics?

# Meson Spectrum





# GlueX-Hall D: strategy for hybrid meson search

- Use 8-9 GeV polarized photons (12 GeV electron beam)
  - The expectation from the flux tube model is that hybrids will be produced at a rate comparable to normal mesons
- Use hermetic detector with large acceptance
  - Decay modes expected to have multiple particles
  - hermetic coverage for charged and neutral particles
  - high data acquisition rate to enable amplitude analysis
- Perform amplitude analysis
  - identify quantum numbers as a function of mass
  - check consistency of results in different decay modes

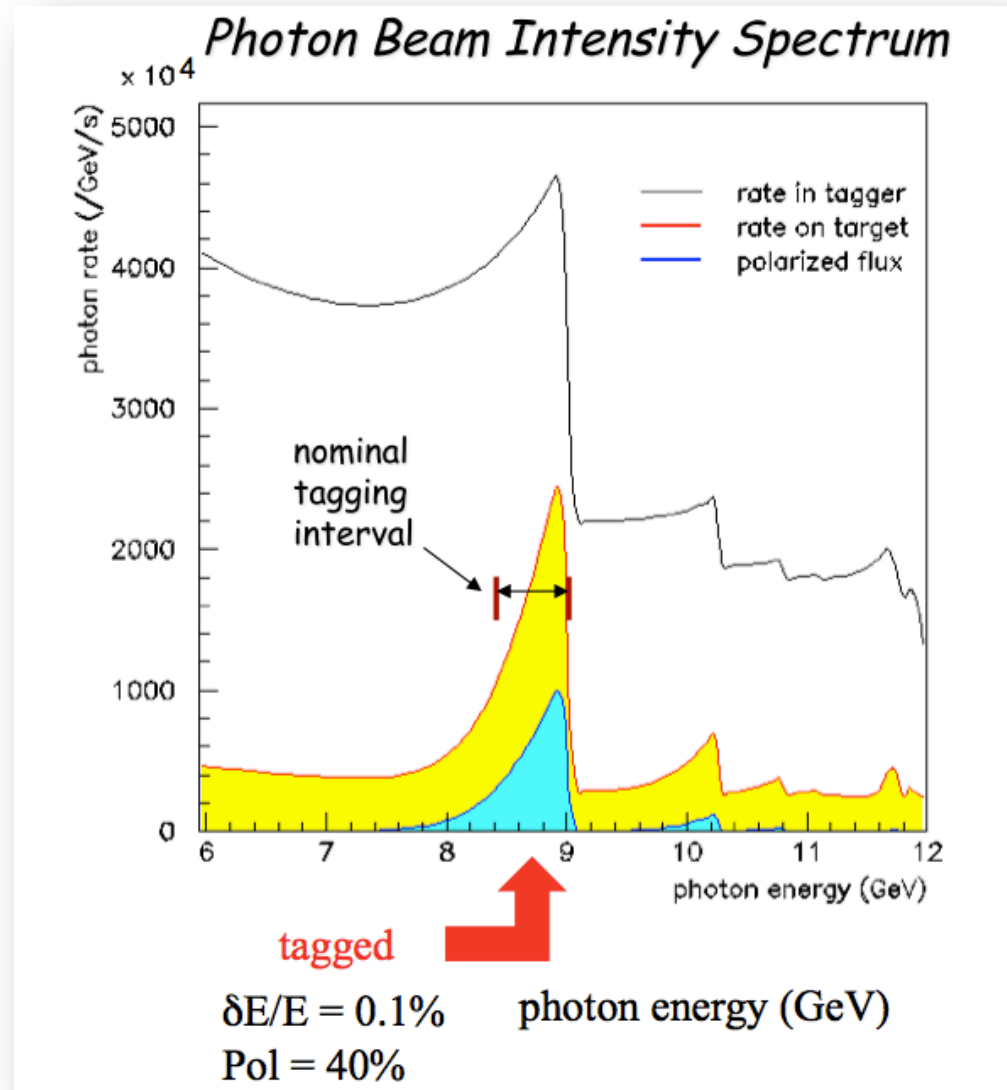
# Linearly Polarized Photon Beam

## Rates are based on

- 12 GeV electron beam
- 20  $\mu\text{m}$  diamon crystal
- 300 nA electron beam
- Collimator diam.: 3.5 mm

→  $10^7$   $\gamma/\text{s}$  on target

Design is expandable to  $10^8$   $\gamma/\text{s}$



# New Hall D – Photon Beam

Hermetic detection of charged and neutral particles in solenoid magnet

Angular coverage :

Charged particles:  $1^\circ < \theta < 140^\circ$

Neutral particles:  $2^\circ < \theta < 170^\circ$

Photon energy resolution :

BCAL:  $\sigma(E)/E = (3.6 + 7.3/\sqrt{E})\%$

FCAL:  $\sigma(E)/E = (2 + 5/\sqrt{E})\%$

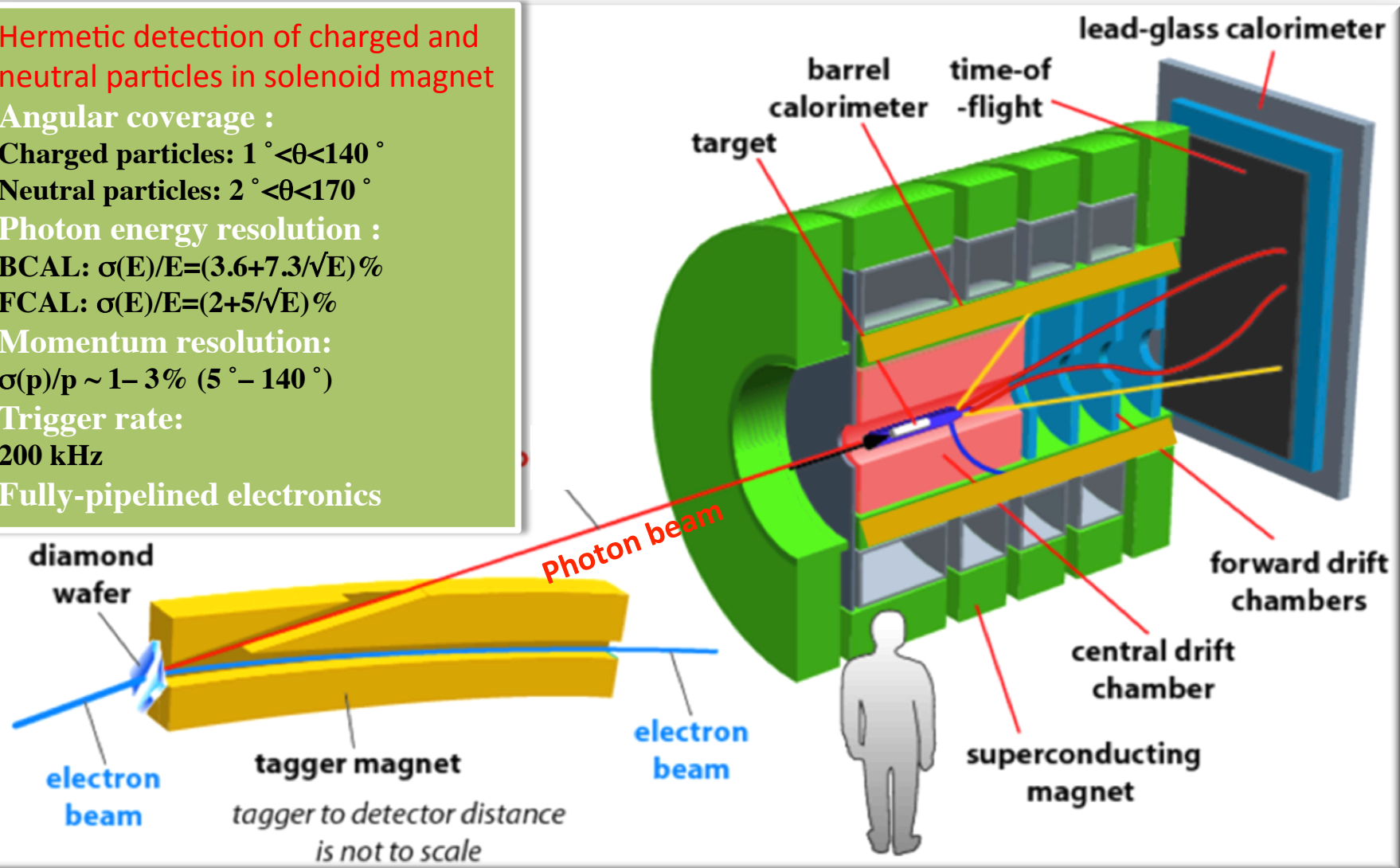
Momentum resolution:

$\sigma(p)/p \sim 1-3\%$  ( $5^\circ - 140^\circ$ )

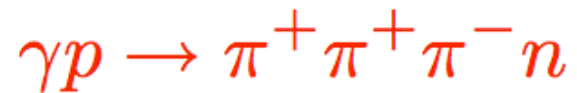
Trigger rate:

200 kHz

Fully-pipelined electronics



# Sample Amplitude Analysis with GlueX



generated waves

$$a_1(1260) \rightarrow \rho\pi \quad (\text{S - wave})$$

$$a_2(1320) \rightarrow \rho\pi \quad (\text{D - wave})$$

$$\pi_1(1600) \rightarrow \rho\pi \quad (\text{P - wave})$$

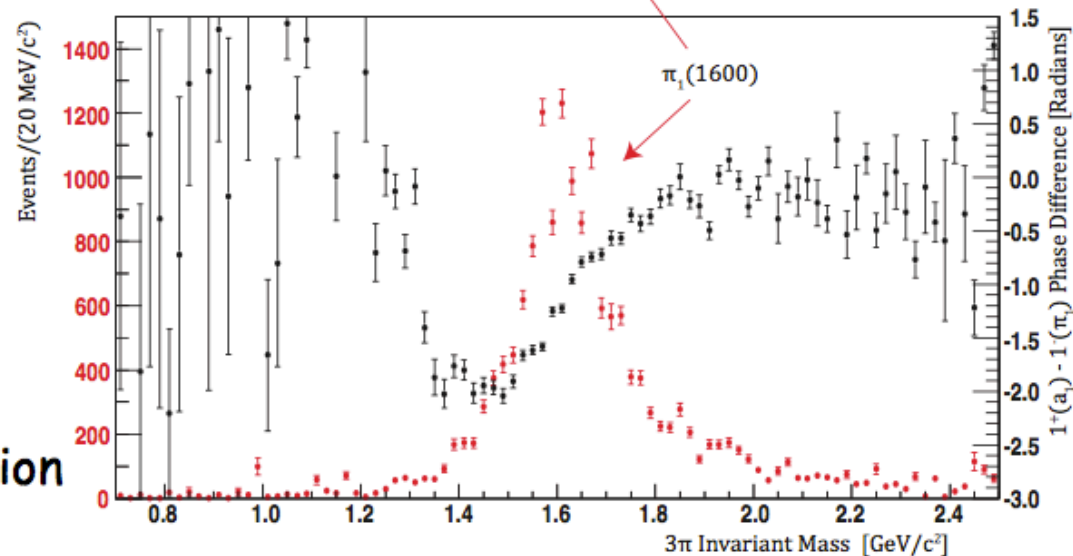
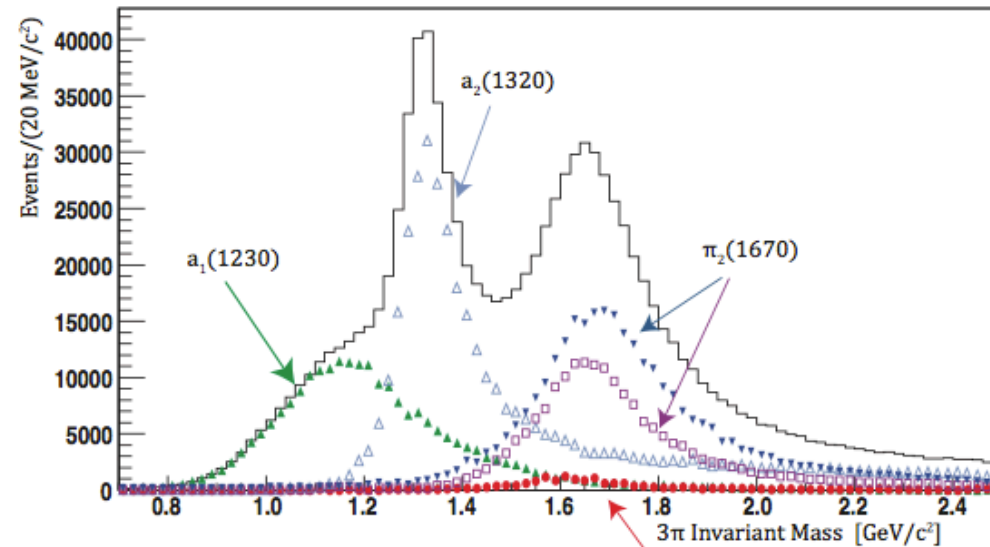
$$\pi_2(1670) \rightarrow f_2\pi \quad (\text{S - wave})$$

$$\pi_2(1670) \rightarrow \rho\pi \quad (\text{P - wave})$$

$1^+$  exotic wave  
generated with 1.6%  
relative strength

Corresponds to 3.5 hours  
GlueX data, full detector  
simulation and reconstruction

Courtesy of E. Smith/MESON2012



# The 21<sup>st</sup> Century Science Questions

What is the role of gluonic excitations in the spectroscopy of light mesons?

- **Where is the missing spin in the nucleon?  
What is the role of orbital angular momentum?**
- **Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?**

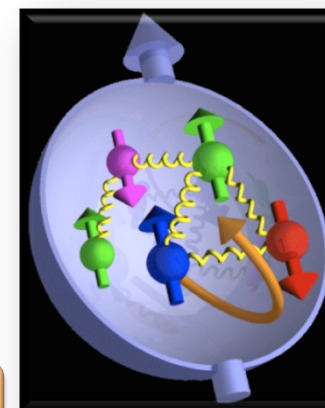
What is the relation of short-range nucleon-nucleon interactions and parton dynamics?

Can we discover evidence for physics beyond the standard model of particle physics?

M. Contalbrigo's talk

S. Niccolai's talk

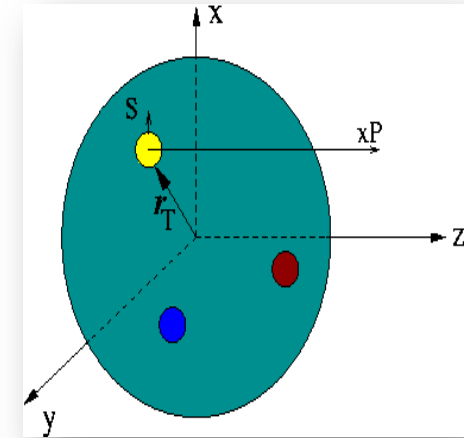
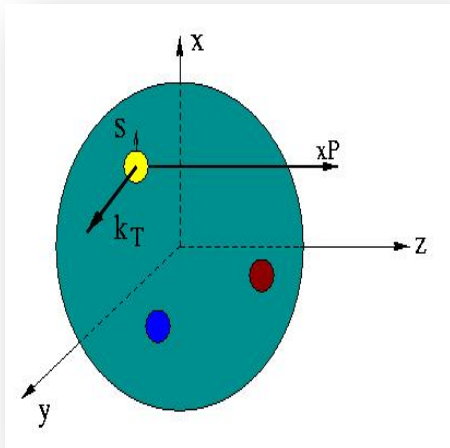
A. Bacchetta's talk



# Unified View of the Nucleon

## 6D Dist.

$W_p^u(x, k_T, \mathbf{r})$  Wigner distributions



$d^3r$

$d^2k_T dr_z$

TMD PDFs

$f_1^u(x, k_T), ..$

$h_1^u(x, k_T)$

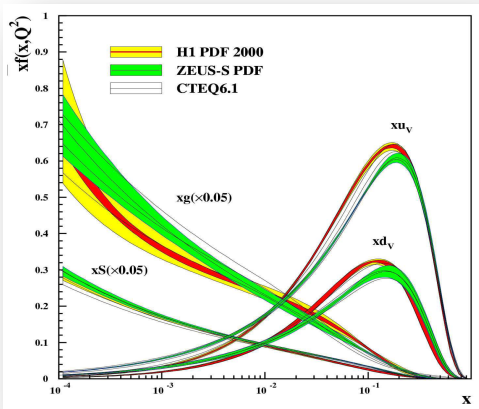
GPDs/IPDs

## 3D imaging

$d^2k_T$

$d^2r_T$

dx & Fourier Transformation

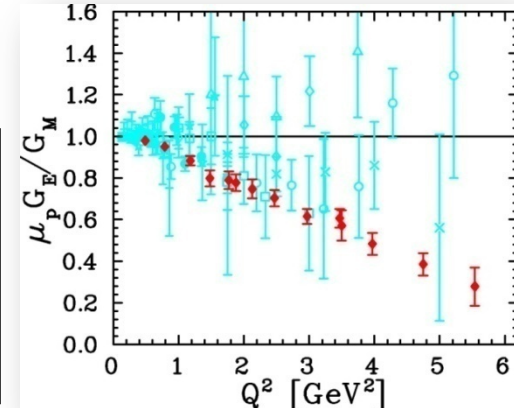


PDFs

$f_1^u(x), .. h_1^u(x)$

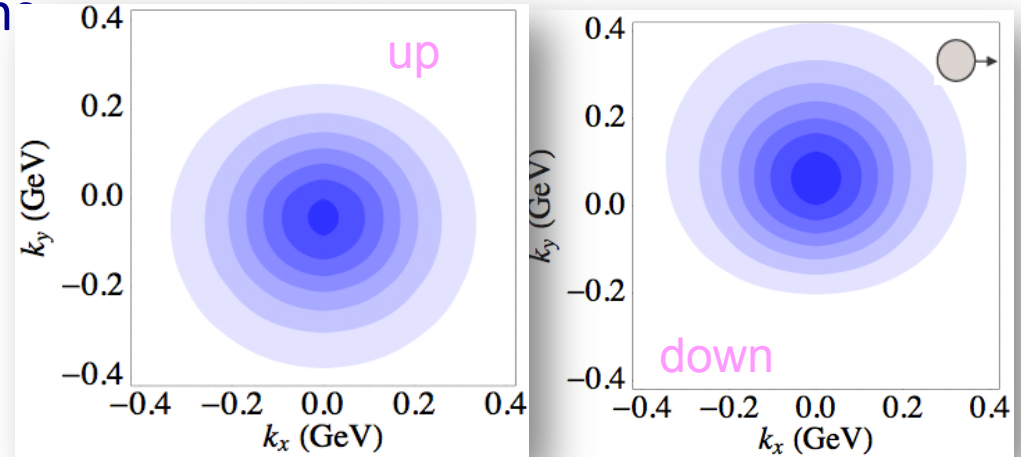
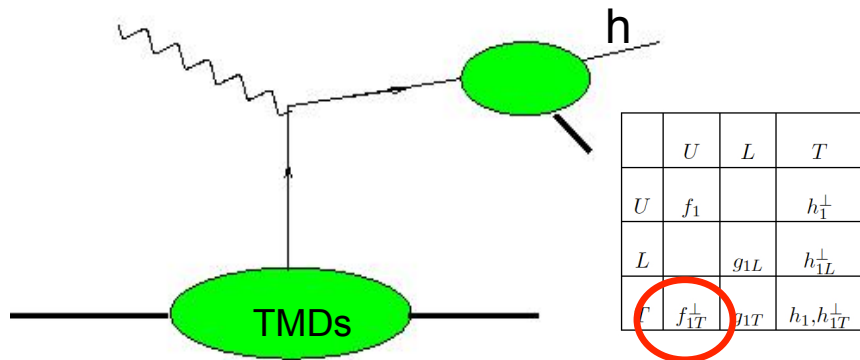
## 1D

Form Factors  
 $G_E(Q^2), G_M(Q^2)$



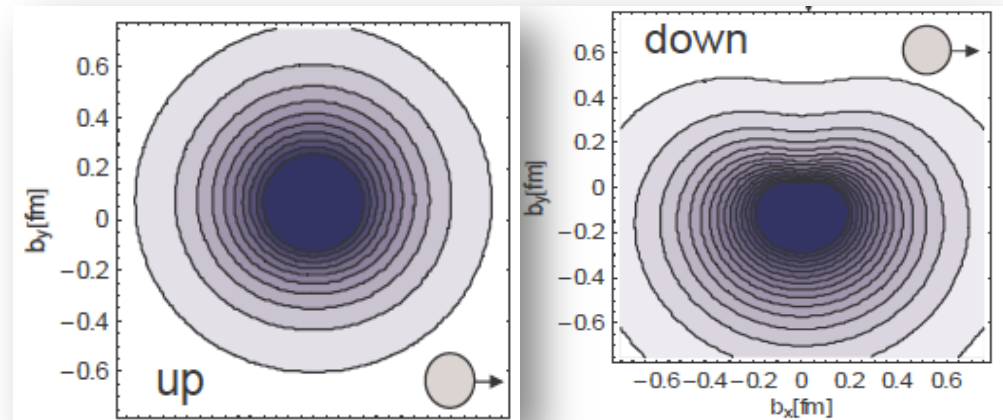
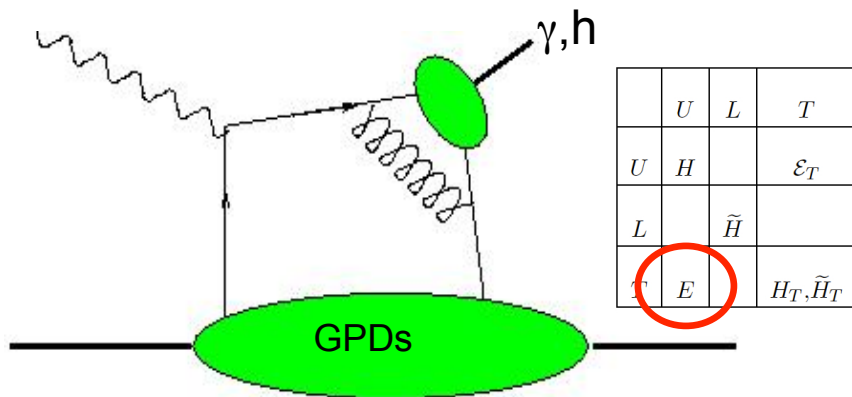
# 3D structure of the Nucleon

Semi-Inclusive processes:  
transverse momentum distribution



Pasquini & Yuan

Hard exclusive processes  
spatial distributions of partons



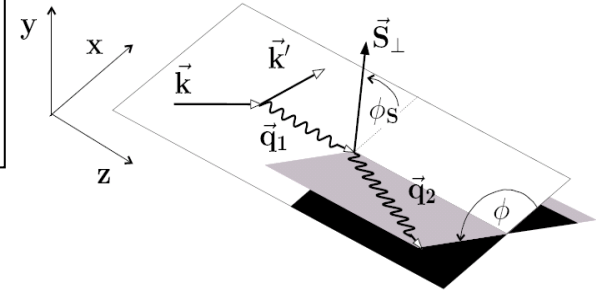
(QCDSF)

# DVCS: the cleanest process

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$$\xi \sim x_B/(2-x_B)$$

$$k = t/4M^2$$



Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi \{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$



$H(\xi, t)$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi \{F_1\tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)\}d\phi$$



$\tilde{H}(\xi, t)$

Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s - \phi) \{k(F_2 H - F_1 E)\}d\phi$$



$E(\xi, t)$

**GPDs extraction possible ONLY through models/parameterizations**



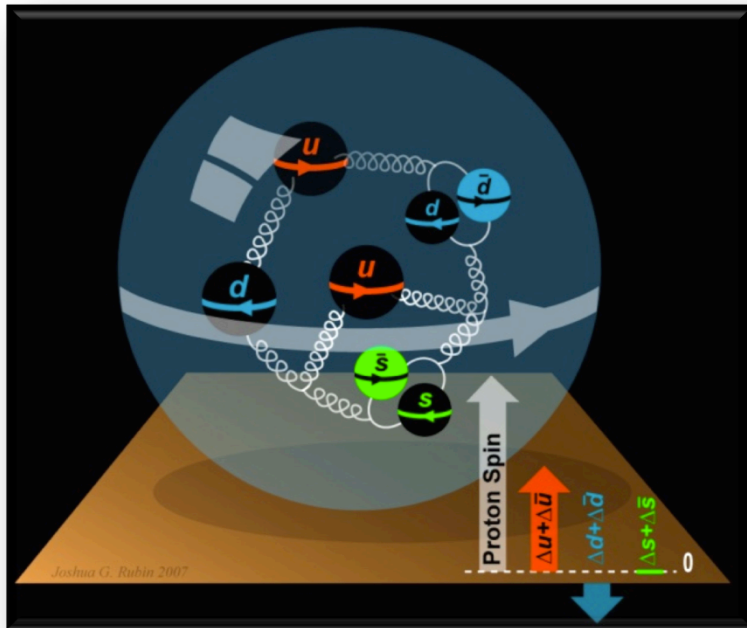
# GPDs in DVCS experiments at 12 GeV

Nucleon polarization	Sensitivity to GPDs	Experiments
Unpolarized	$H, \tilde{H}, E$	E12-06-114: proton (A) E12-06-119: proton (B) E12-11-003: neutron (B)
Long. Polarized	$\tilde{H}, H, E$	E12-06-119: proton NH3 (B)
Transv. Polarized	$E, H$	E12-12-010: proton HD (B)

The JLab DVCS program will be carried out in two experimental Halls: **A & B (CLAS12)**

# Transverse Momentum Distributions

## The Incomplete Nucleon



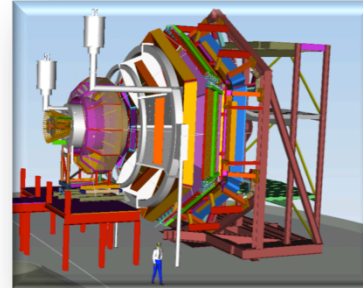
- DIS  $\rightarrow \Delta\Sigma \approx 0.25$
- RHIC + DIS  $\rightarrow \Delta G \ll 1$
- $\rightarrow L_q$

		quark polarization		
		U	L	T
nucleon polarization	U	$f_1$		$h_1^\perp$ Boer-Mulders
	L		$g_1$ helicity	$h_{1L}^\perp$ worm-gear
	T	$f_{1T}^\perp$ Sivers	$g_{1T}$ worm-gear	$h_{1T}^\perp$ $h_{1T}^\perp$ pretzelosity
		transversity		

# SIDIS Program at JLab: a unified effort

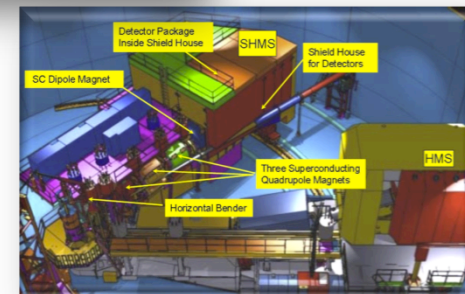
- **CLAS12 in Hall B**

General survey, medium lumi



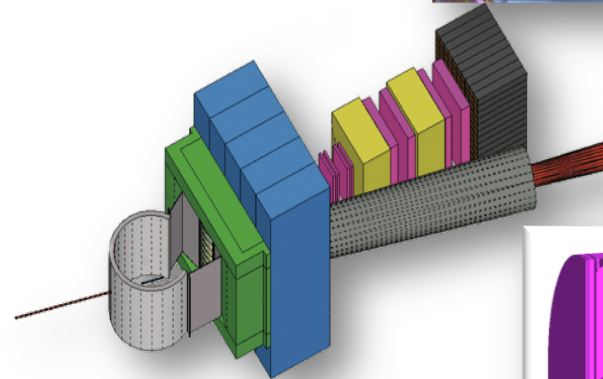
- **SHMS- HMS in Hall C**

L-T studies, precise  $\pi^+/\pi^-$  ratios



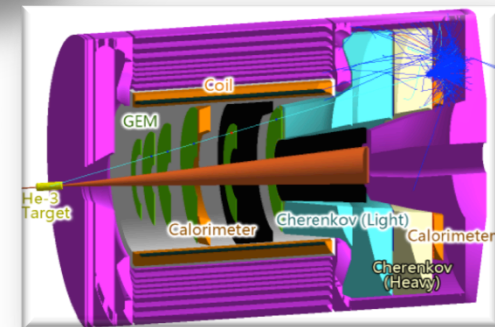
- **SBS in Hall A**

High x, High  $Q^2$ , 2-3D



- **SOLID in Hall A**

High Lumi and acceptance – 4D



# SIDIS @ 12 GeV

Hall B  
CLAS12

E12-06-112:  $\pi^+, \pi^-, \pi^0$   
E12-09-008  $k^+, k^-, k^0$

E12-07-107:  $\pi^+, \pi^-, \pi^0$   
E12-09-009  $k^+, k^-, k^0$

E12-11-111:  $\pi^+, \pi^-, \pi^0$   
 $K^+, K^-$

$H_2, NH_3, D_2, ND_3$

HD

Quark spin polarization

Nucleon polarization		Quark spin polarization		
		U	L	T
Nucleon polarization	U	$f_1$		$h_1^\perp$
	L		$g_1$	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}$	$h_1, h_{1T}^\perp$

Hall A  
SBS/SOLID

HALL C  
HMS+SHMS

E12-09-017:  $\pi^+, \pi^-, K^+, K^-$   
E12-06-104:  $\pi^+, \pi^-$   
E12-09-002:  $\pi^+, \pi^-$

E12-07-007:  $\pi^+, \pi^-$

E12-09-018:  $\pi^+, \pi^-, K^+, K^-$   
E12-10-006  $\pi^+, \pi^-$   
E12-11-108:  $\pi^+, \pi^-$

$^3He$

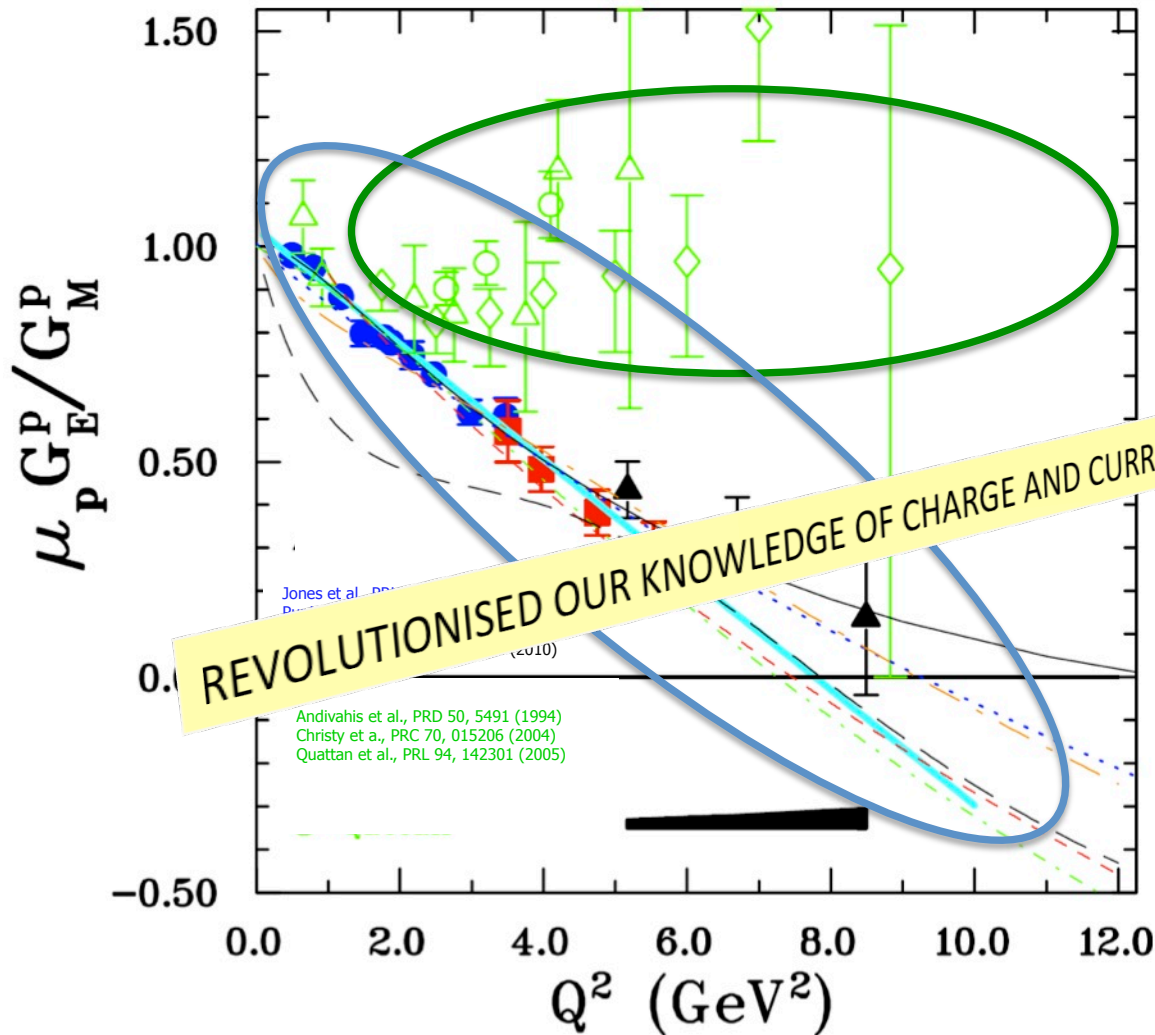
$NH_3$

$H_2, D_2$

Large variety of targets and different species of detected hadrons will be fundamental for flavor separation

# 1D view: Nucleon Form Factors

spatial distributions of electric charge and current



$$\frac{d\sigma}{d\Omega} \propto G_{Ep}^2 + \frac{\tau}{\epsilon} G_{Mp}^2$$

OPE assumption used in the **Bluth separation**

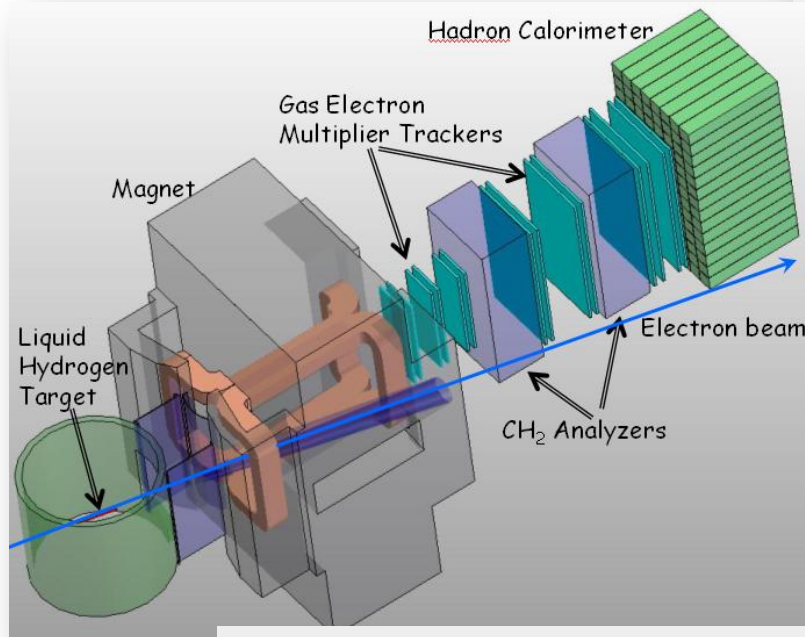
$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t (E_{beam} + E_e)}{P_l 2M_p} \tan \frac{\vartheta_e}{2}$$

**Polarization transfer** technique gives different results!

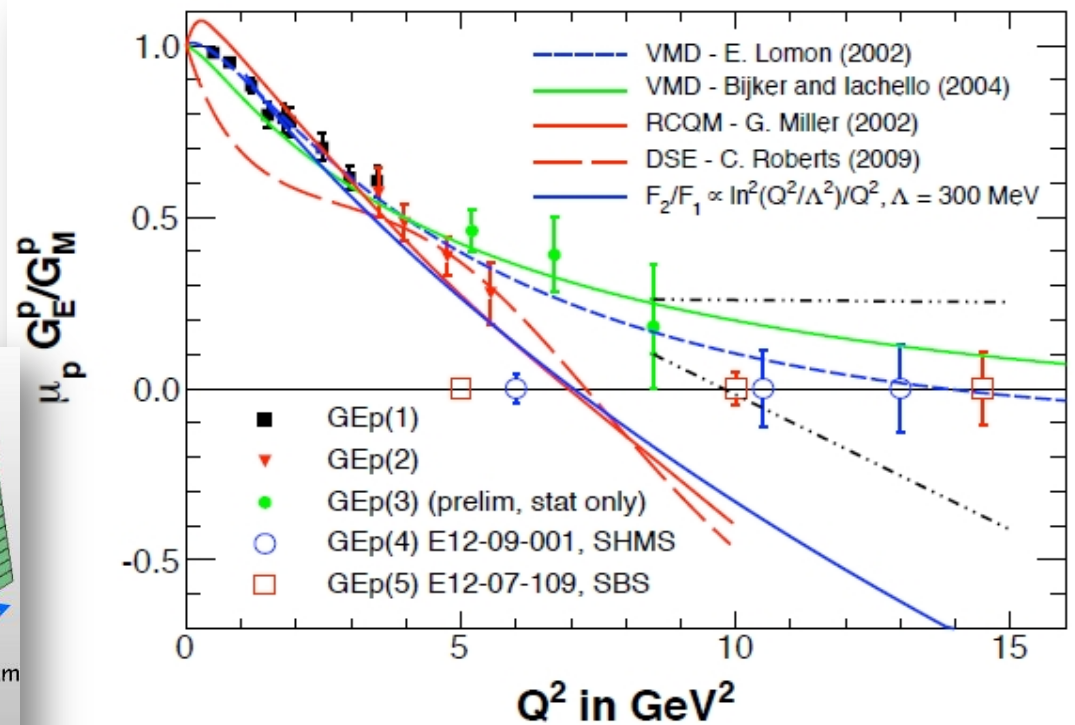
Double polarization experiments only possible with **high intensity, high polarized** beam

# Nucleon FF Measurements @ 12 GeV

- 6 new experiments, of which 3 with SBS, approved to measure proton and neutron  $G_E$  &  $G_M$  at high  $Q^2$



- High Luminosity ( $\sim 10^{39}$ )
- Forward angle (down to 7 degree)
- Equipment flexibility



- Tests for phenomenological models: **New focus on role of relativity and orbital motions**
- Constraint of the GPDs H and E

# The 21<sup>st</sup> Century Science Questions

What is the role of gluonic excitations in the spectroscopy of light mesons?

Where is the missing spin in the nucleon?  
What is the role of orbital angular momentum?

Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?

What is the relation of short-range nuclear structure and parton dynamics?

- **Can we discover evidence for physics beyond the standard model of particle physics?**

J. Birchall's talk

K. Kumar's talk

G. Urciuoli's talk

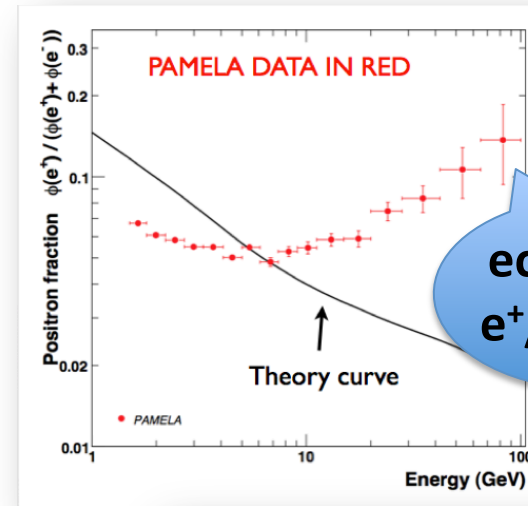
# Search for Dark Forces

A wealth of anomalies can be explained by a new, dark force

- **BNL “g-2” expt:**

$$\Delta a_\mu(\text{expt-thy}) = (295 \pm 88) \times 10^{-11} \quad (3.4 \sigma)$$

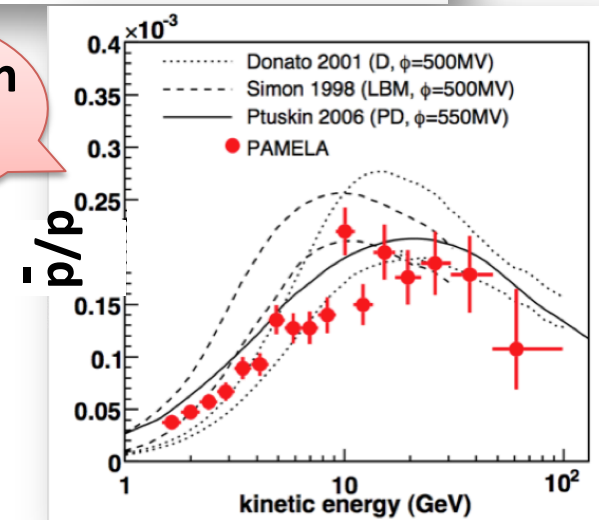
↑  
A dark force carrier in the 10-100 MeV range can explain the difference



- **Hints from astrophysics:**

- Hard leptons/no antiprotons for PAMELA/Fermi
- DAMA annual modulation signal

...but not in  $\bar{p}/p$  ratio

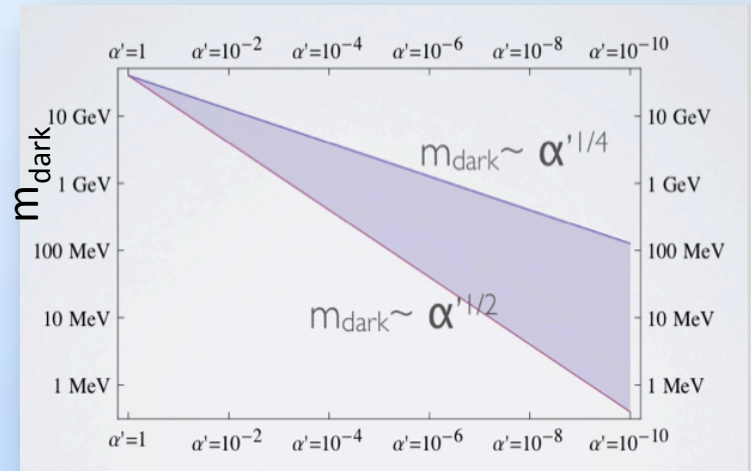




# Search for Dark Forces

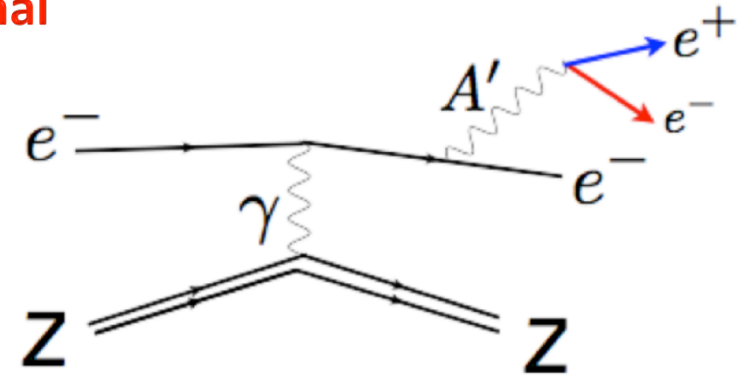
## Vector boson $A'$

- kinematically mixes with  $\gamma$
- $\alpha' = \epsilon \alpha_{e.m}$     $\epsilon = 10^{-2} - 10^{-6}$
- Mass in the **MeV-GeV** region

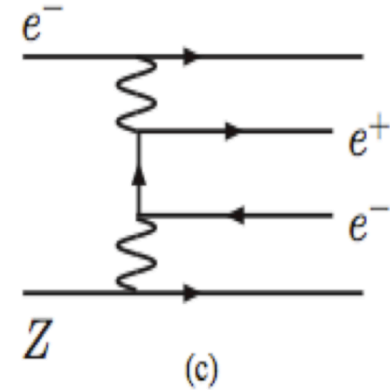
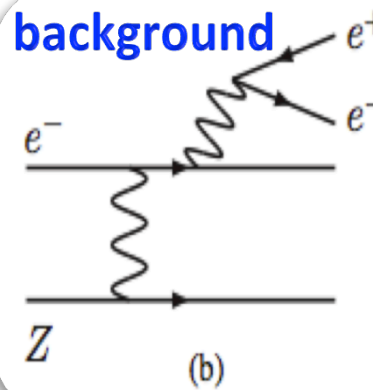


$$\alpha' = \epsilon \alpha_{e.m}$$

signal

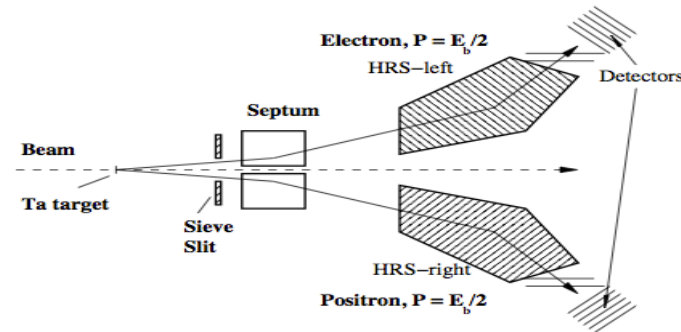
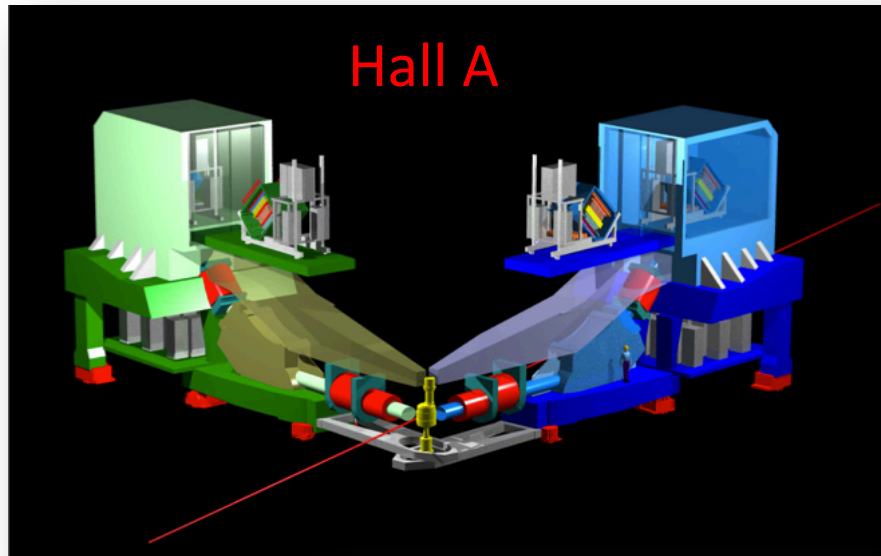


background



3 Jefferson Lab proposals

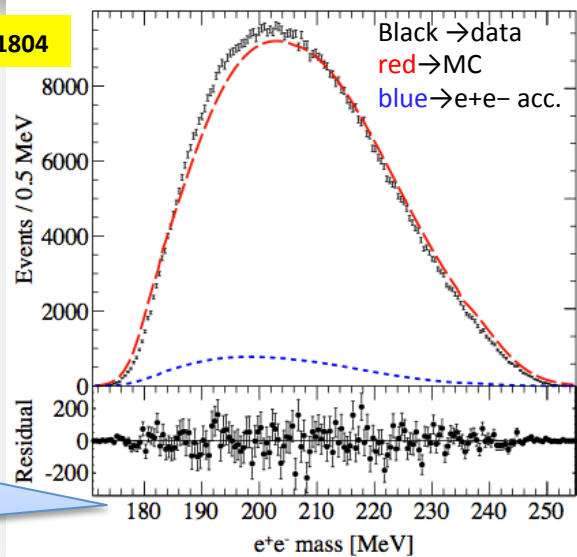
# A Prime Experiment in Hall A



APEX uses the HALL A dual arms spectrometers to reconstruct the  $e^+e^-$  pair

- ➔ DC (tracking), gas Cherenkov (PID), hodoscopes(trigger)
- ➔ great mass resolution ( $\sim$ MeV), small acceptance ( $\sim$ 0.1%)
- ➔ mass resolution dominated by angular resolution

PRL 107 (2011) 191804



small mass range... reflects small acceptance

In July 2010, APEX completed successful test run

- Primary goal was to confirm calculated BKG rates
- Physics data taken at 2.2 GeV
- Excellent Mass Resolution  $\sigma(M) \sim 1$  MeV

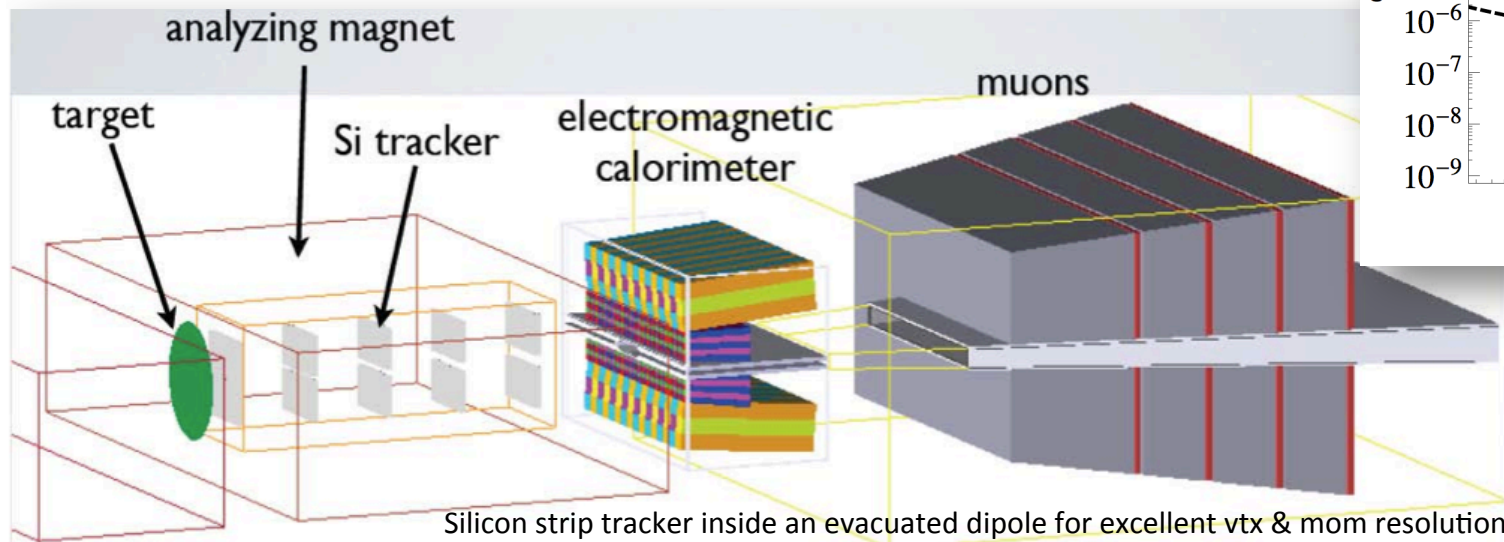
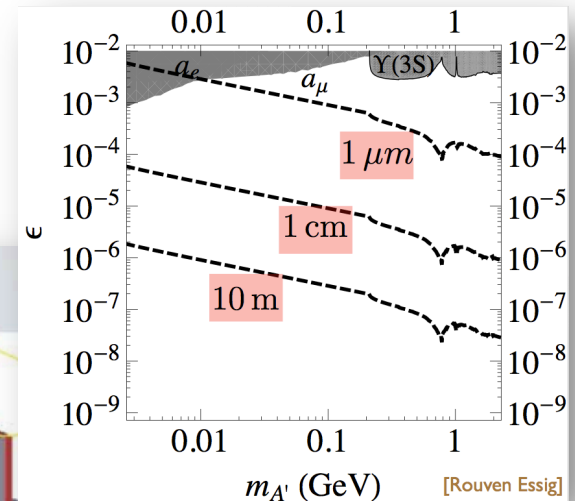
In January 2011, PAC approved APEX to run in 12 GeV era

# Heavy Photon Search @ Hall B

low rate  $\Rightarrow$  intense beam

high background  $\Rightarrow$  high resolution  $\Rightarrow$  **measure displaced vertex**

$$\epsilon < 10^{-4} ; \text{mass } 20\text{-}200 \text{ MeV}$$

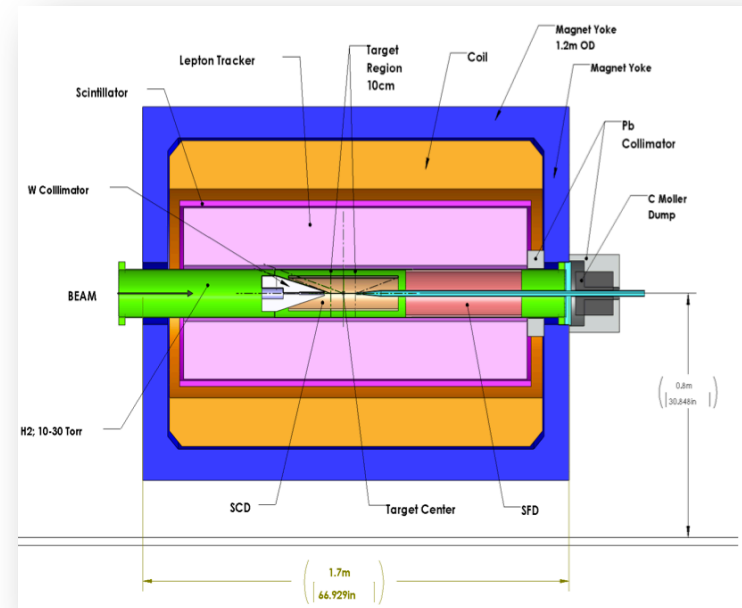
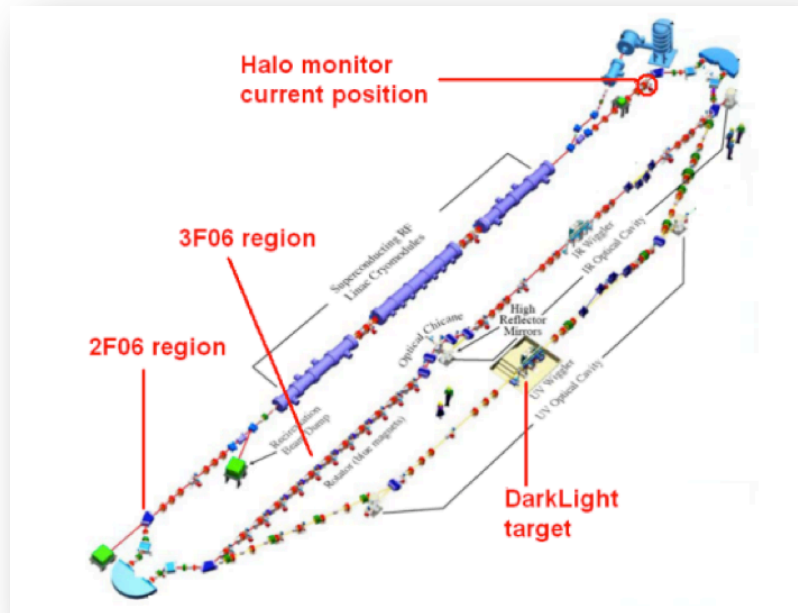


High rate  
High acceptance  
High mass & Vertex  
Resolution detector

**HPS parasitic photon run in April- May 2012: First clean beam and successful data taking for the last 8 hours of CEBAF 6 GeV !**

**Last week PAC recommended to run HPS for 15 days as soon as 12 GeV beam will be available**

# DarkLight @ JLab FEL

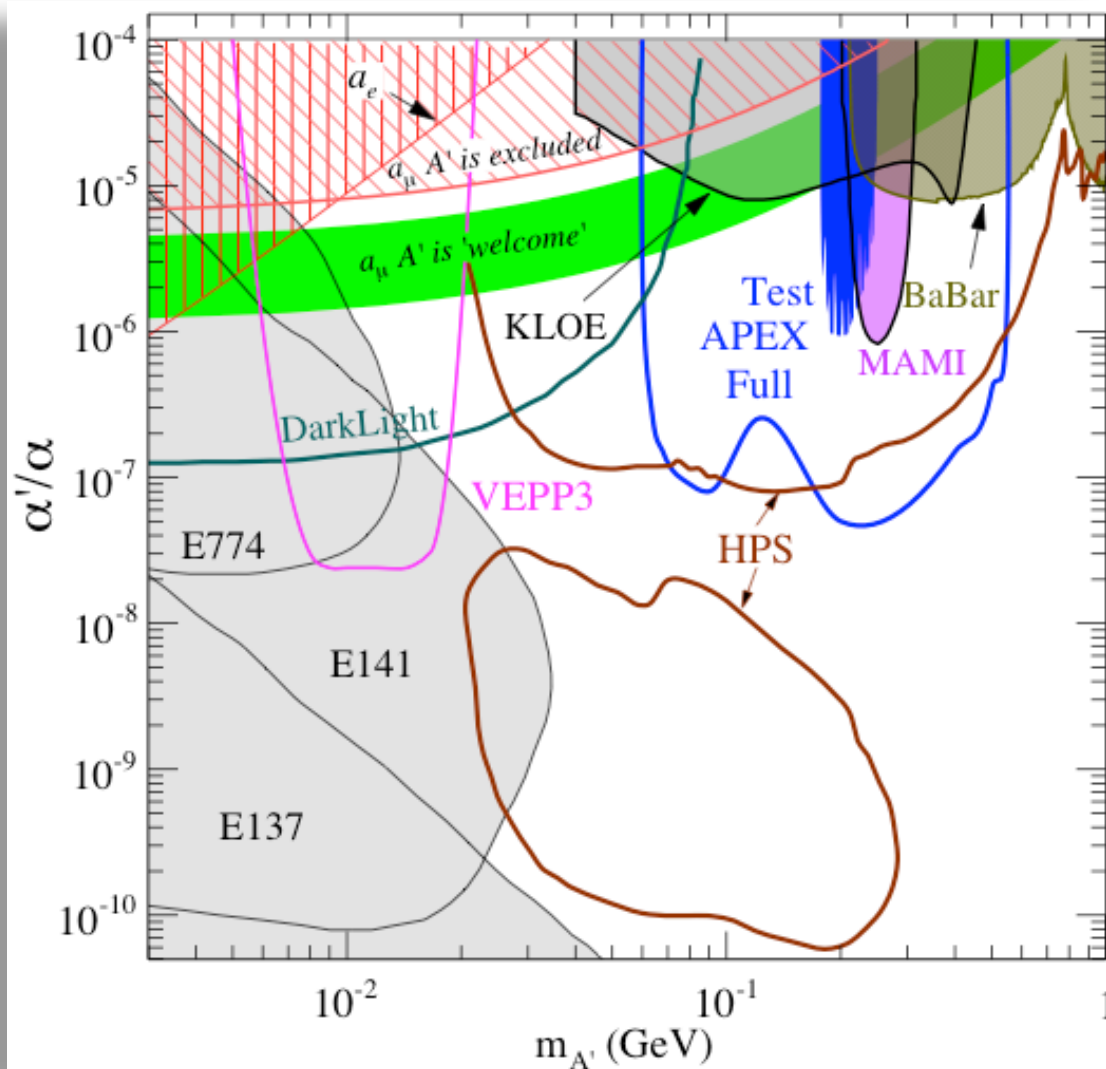


- Use the FEL beam ( $\sim 1\text{mA}$ , 100 MeV) incident on a **H2 gas jet target**. Collect  $1/\text{ab}$  in  $\sim 60$  days of beam time
- High acceptance detector inside a 6-coil toroid: **gas TPC** for recoil proton detection, **GEMs** for vertexing and low momentum lepton recon, outer **drift chambers** for lepton momentum, **scintillator hodoscopes** for triggering

**Beam test in FEL planned in July 2012**

**Last week PAC recommended to run DarkLight experiment as soon as 12 GeV beam will be available if test run will succeed**

# A' Search Summary



**APEX (Hall A)** ~ forward spectrometers

**HPS (Hall B)** ~ compact Si-based vertex-tracker

**DarkLight (JLab FEL)** ~ high acceptance, H2 gas target

Many experiments in the world to look for heavy photons

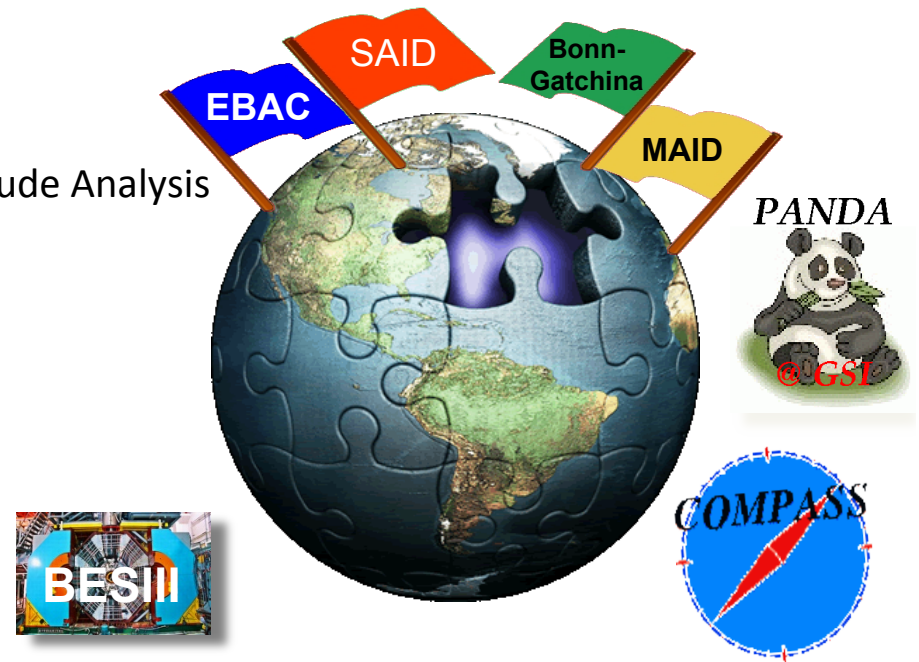
# JLab Physics Analysis Center

Physics from high quality data demands precision analysis tools



- Pool world theoretical/phenomenological expertise
- Common, robust methodologies, especially in Amplitude Analysis
- Train generation of experimentalists and theorists

**global networking**  
to be led by Jefferson Lab



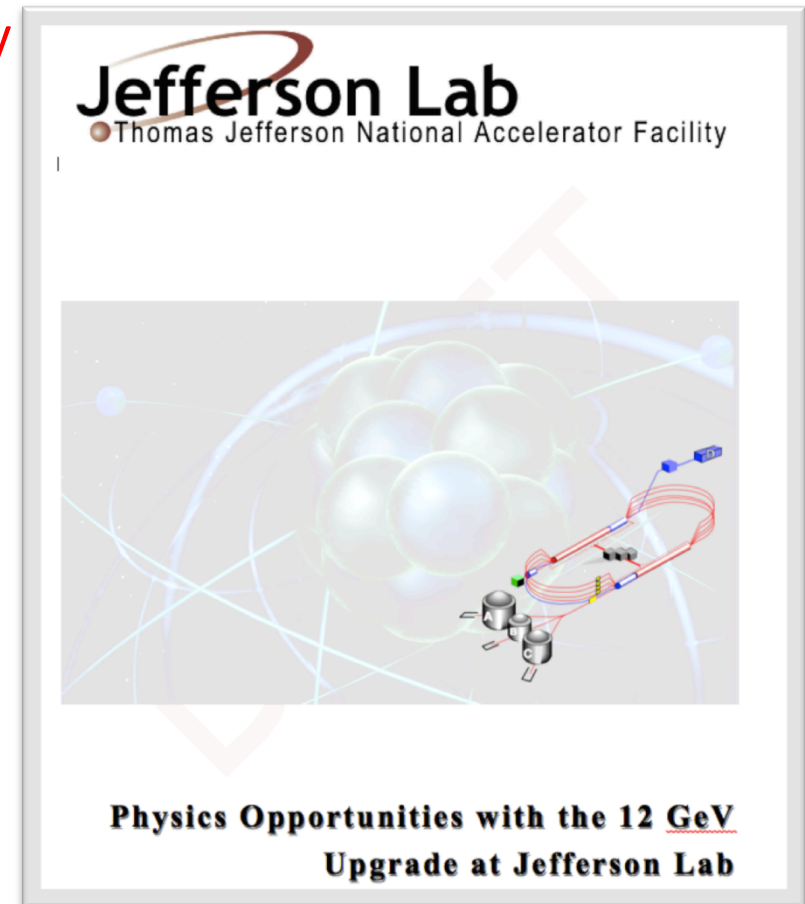
# 12 GeV White Paper under construction

## Physics Opportunities with the 12 GeV Upgrade at Jefferson Lab

- Preparation for NSAC subcommittee activity
- Update Physics Case for “NSAC” Audience

- Overview
- Meson Spectroscopy and Structure
- Nucleon Structure and Spectroscopy
- QCD and Nuclei
- The Standard Model and Beyond
- Appendix A: Experimental Equipment

Complete draft (~50 pages), now being circulated amongst wider audience



# The potential of JLab @ 12 GeV

- Opportunity to discover and study new exotic mesons to elucidate the mechanism of confinement.
- Open a new landscape of nucleon tomography, with potential to identify the missing angular momentum.
- Establish the quantitative foundation for the short-distance behavior in nuclei, underpinning the development of precision nuclear structure studies.
- Provide stringent new tests of the standard model and extensions, complementing the information obtained at LHC.