The CLAS12 Physics Program

Raffaella De Vita
INFN – Genova
on behalf of the CLAS Collaboration

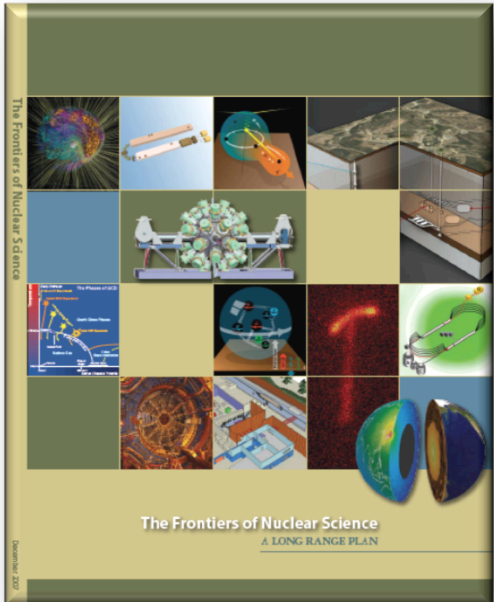
MENU 2016
Kyoto, 30 July 2016

Jefferson Lab

Continuous Electron Beam Accelerator Facility (CEBAF)

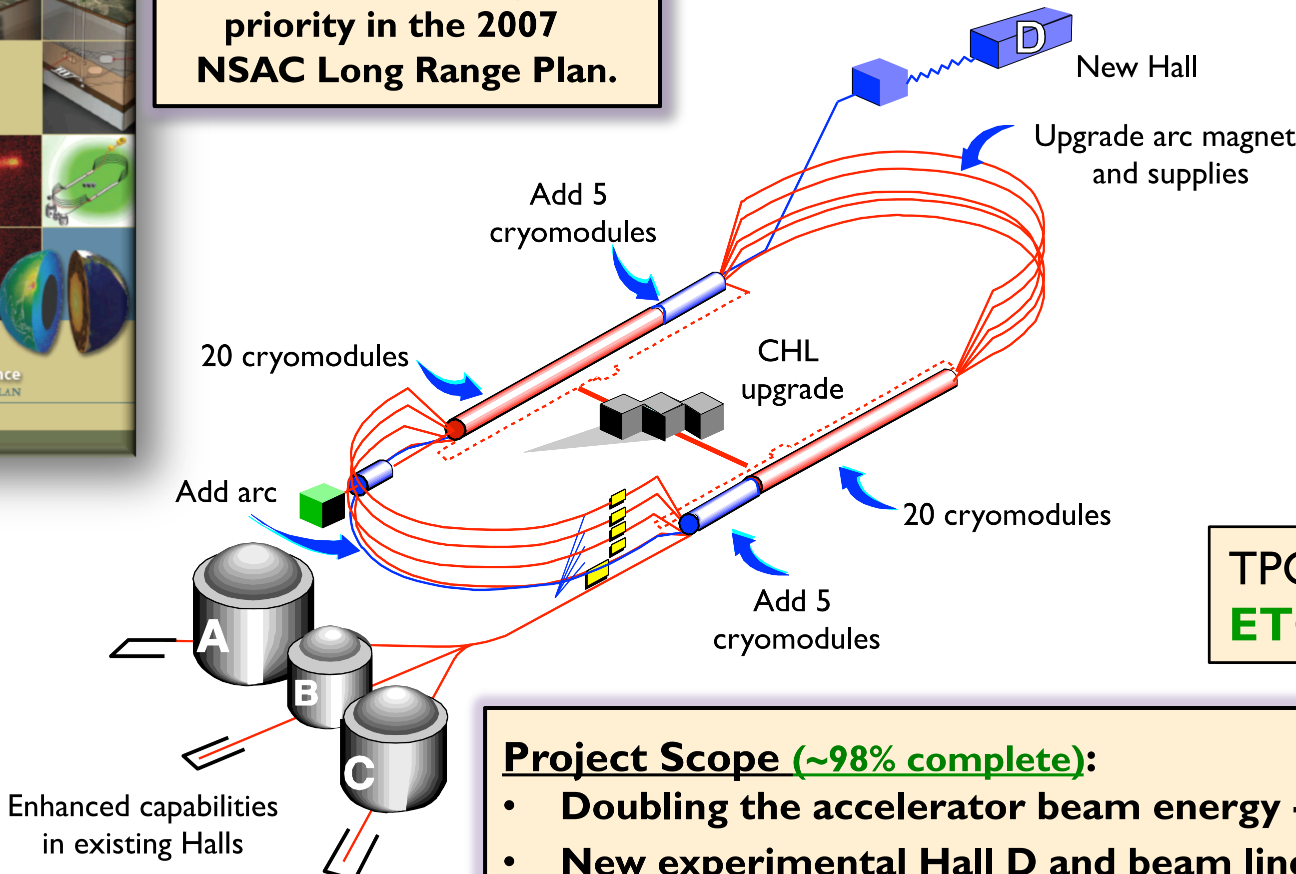
- A superconducting electron machine based on two Linacs in racetrack configuration
- Simultaneous distribution to 4 experimental Halls
- Beam energy up to 11 & 12 GeV
- Beam current I_B = 100 pA – 100 μA
- Electron beam polarization > 85%

The 12 GeV upgrade



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

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use.



TPC = $338M
ETC = ~$8M

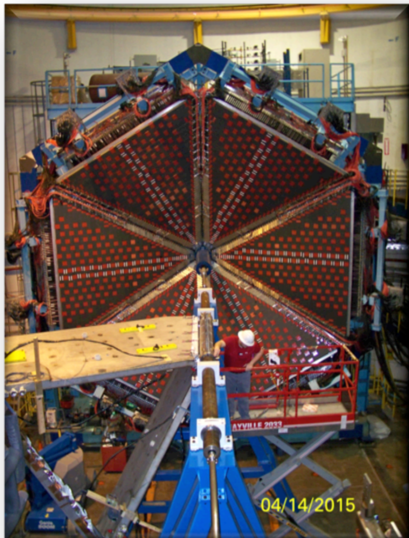
Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6….

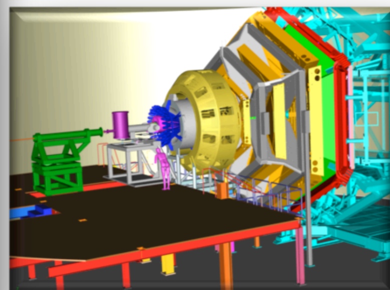
Project Scope (~98% complete):

- **Doubling the accelerator beam energy - DONE**
- **New experimental Hall D and beam line - DONE**
- **Civil construction including Utilities - DONE**
- **Upgrades to Experimental Halls B & C - ~96%**

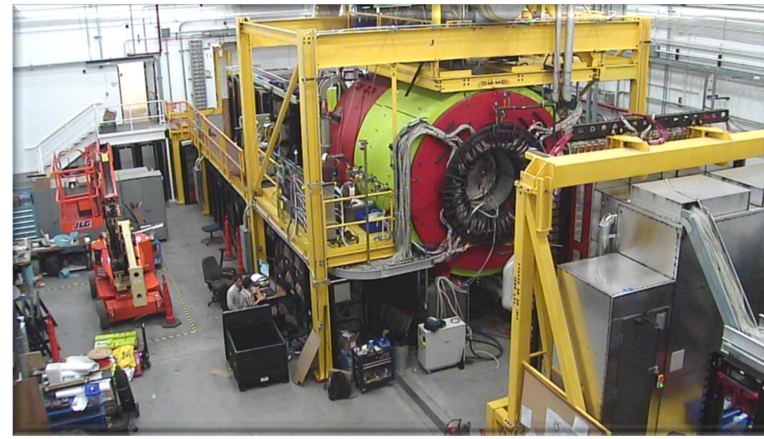
12 GeV scientific capabilities

Hall B **– understanding nucleon structure via generalized parton distributions**

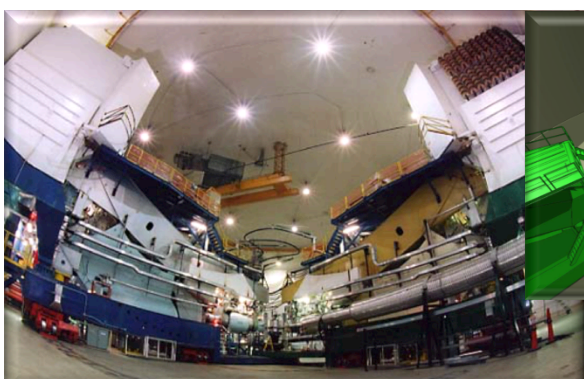


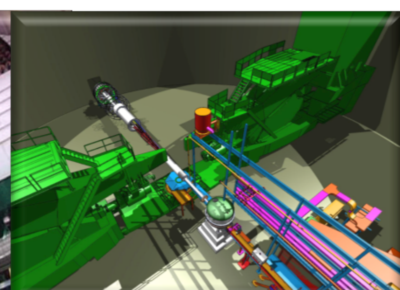


Hall D **– exploring origin of confinement by studying exotic mesons**

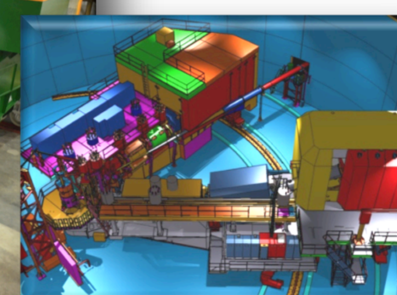


Hall A **– form factors, future new experiments (e.g., SoLID and MOLLER)**





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



The CLAS12 Science Program Outline

- Overview
- Gluonic hadrons
- Nucleon structure
- Nucleon tomography
- Summary

CLAS12 technical scope

Forward Detector:

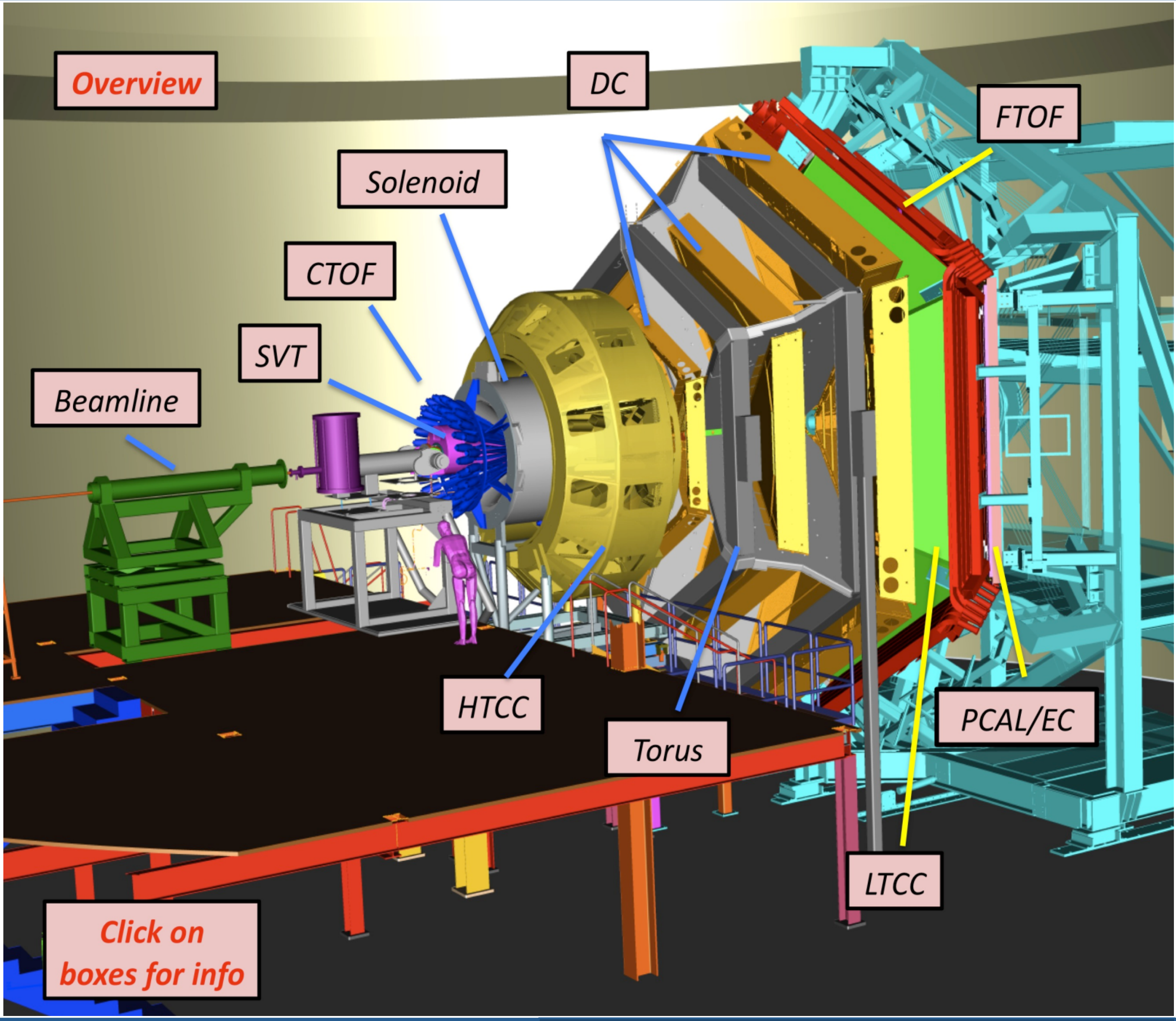
- *TORUS magnet*
- *HT Cherenkov Counter*
- *Drift chamber system*
- *LT Cherenkov Counter*
- *Forward ToF System*
- *Preshower calorimeter*
- *E.M. calorimeter (EC)*

Central Detector:

- *SOLENOID magnet*
- *Barrel Silicon Tracker*
- *Central Time-of-Flight*

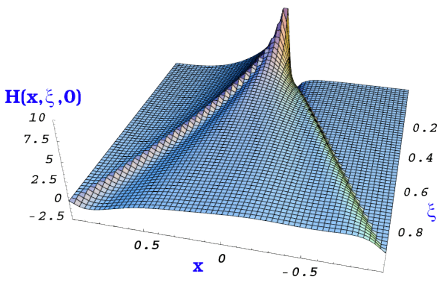
Proposed upgrades:

- *Micromegas (CD)*
- *Neutron detector (CD)*
- *RICH detector (FD)*
- *Forward Tagger (FD)*

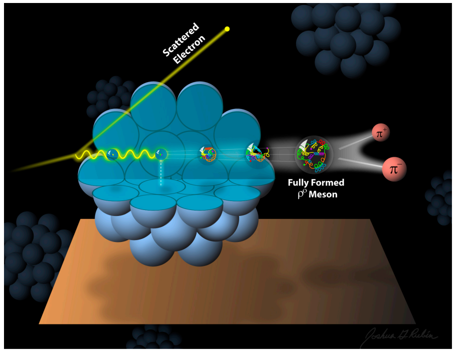


The CLAS12 science program

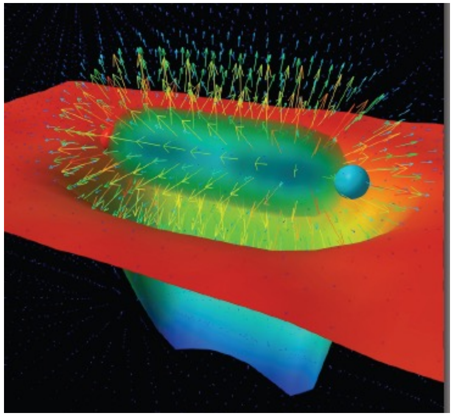
- The 3D structure of the nucleon – from form factors and PDFs to GPDs and TMDs



- The strong interaction in nuclei – evolution of quark hadronization, nuclear transparency of hadrons



- Quark confinement and the role of the glue in meson and baryon spectroscopy



Understanding the meson spectrum

Predictions of the light quark meson spectrum now available from lattice QCD

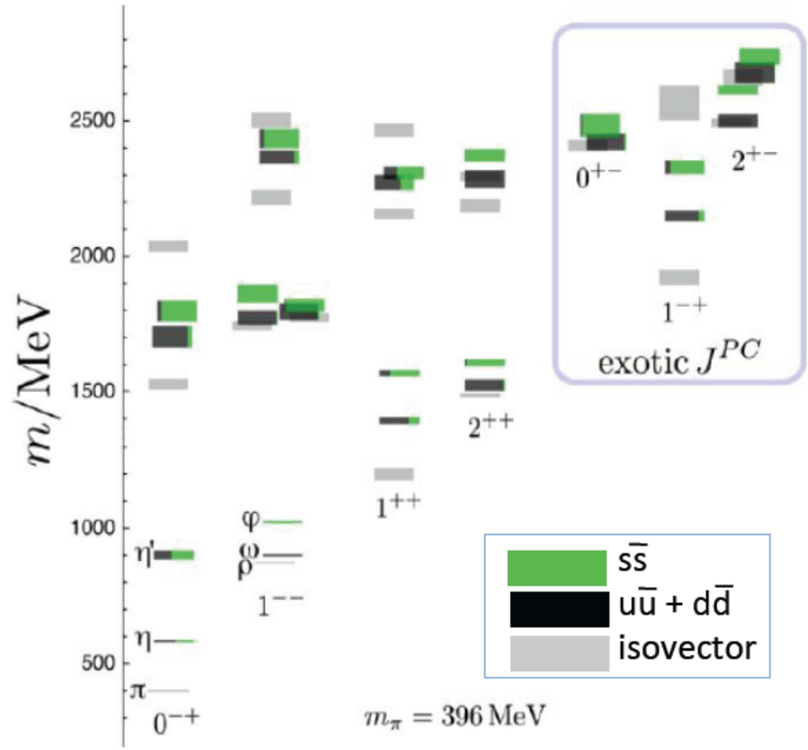
Spectrum includes meson state with large gluonic content (hybrids) with both regular and exotic quantum numbers

Experimental signature: a multiplet of gluonic mesons with exotic J^{PC}, i.e. non quark-antiquark

Searches with hadron beams are underway at COMPASS. Dedicated searches witih photon beams are beginning at JLab with GlueX

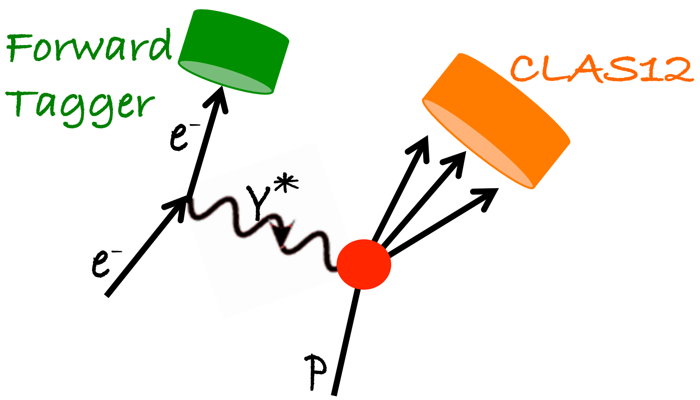
In Hall B, CLAS12 will be used in quasi-real photo-production to search for hybrid meson states

Meson Spectrum in LQCD



Dudek, Edwards, Guo and Thomas, PRD 88, 094505 (2013)

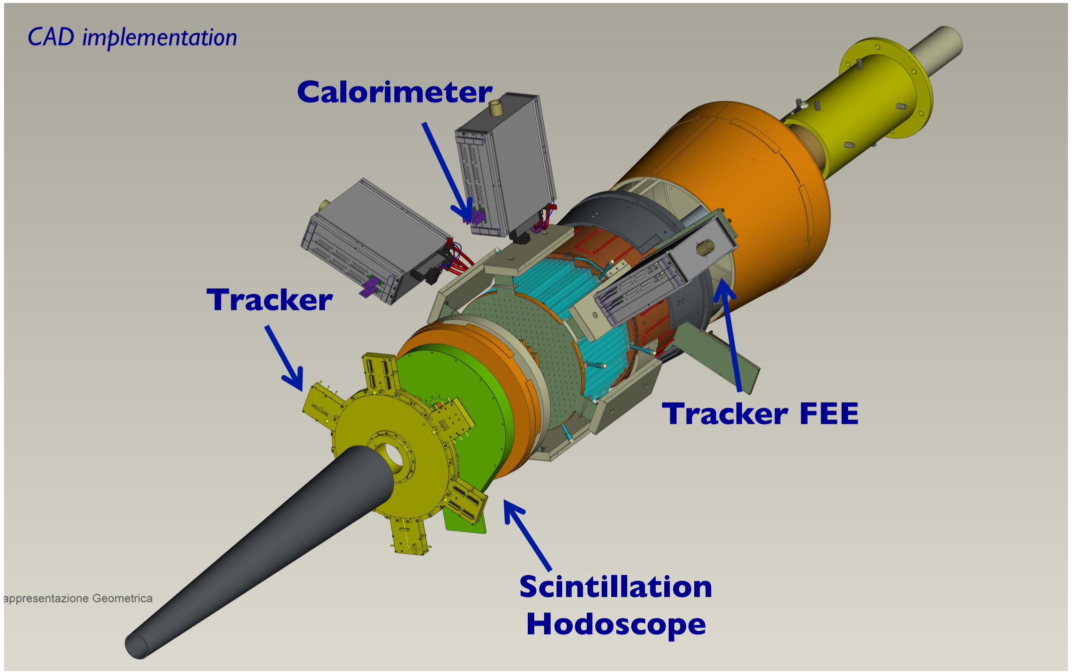
Quasi-real photon Forward Tagger



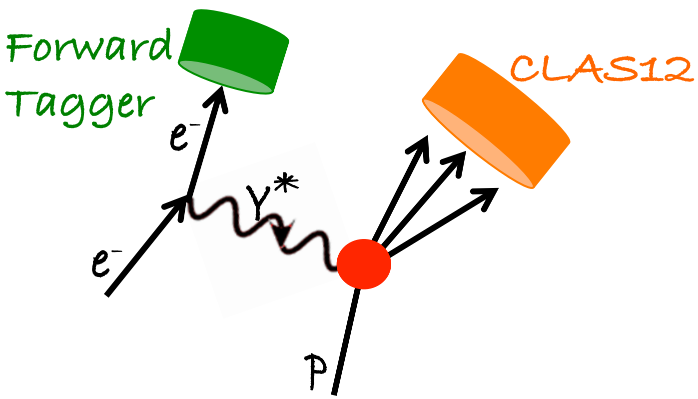
Quasi-real photoproduction on proton target:

- Detection of multiparticle final state from meson decay in the large acceptance spectrometer CLAS12
- Detection of the scattered electron for the tagging of the quasi-real photon in the novel Forward Tagger

Forward Tagger	
E'	0.5-4.5 GeV
ν	7-10.5 GeV
θ	2.5-4.5 deg
Q^2	0.007 – 0.3 GeV^2
W	3.6-4.5 GeV
Photon Flux	5×10^7 γ/s @ $L_e=10^{35}$



Quasi-real photon Forward Tagger

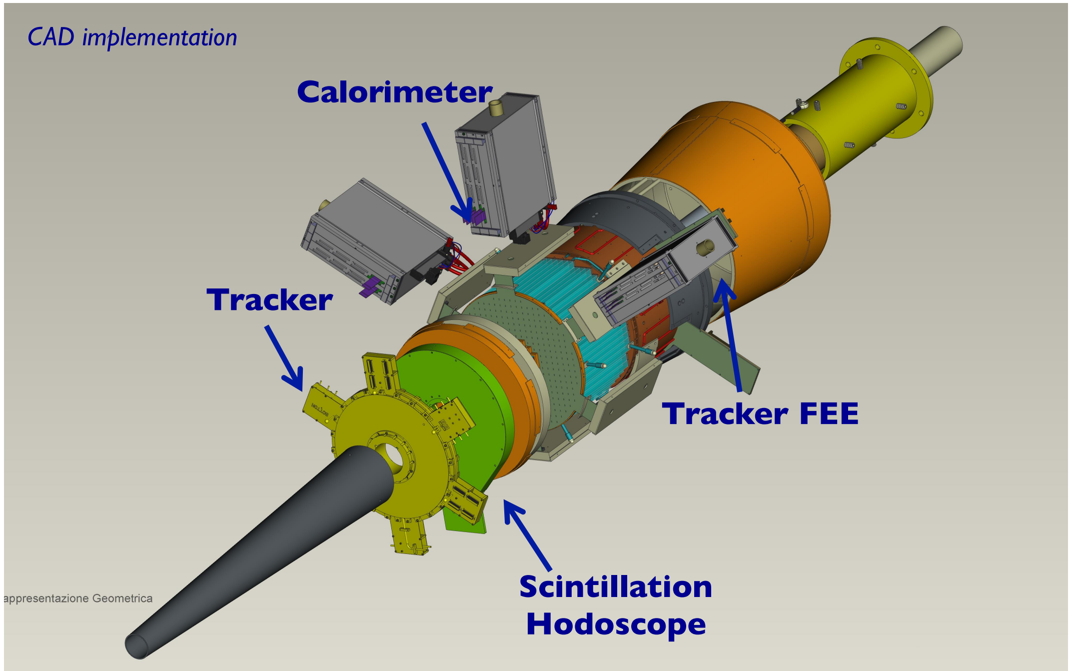


Quasi-real photoproduction on proton target:

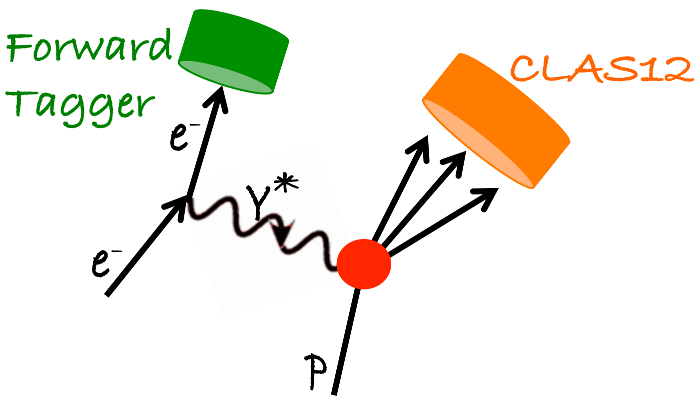
- Detection of multiparticle final state from meson decay in the large acceptance spectrometer CLAS12
- Detection of the scattered electron for the tagging of the quasi-real photon in the novel Forward Tagger

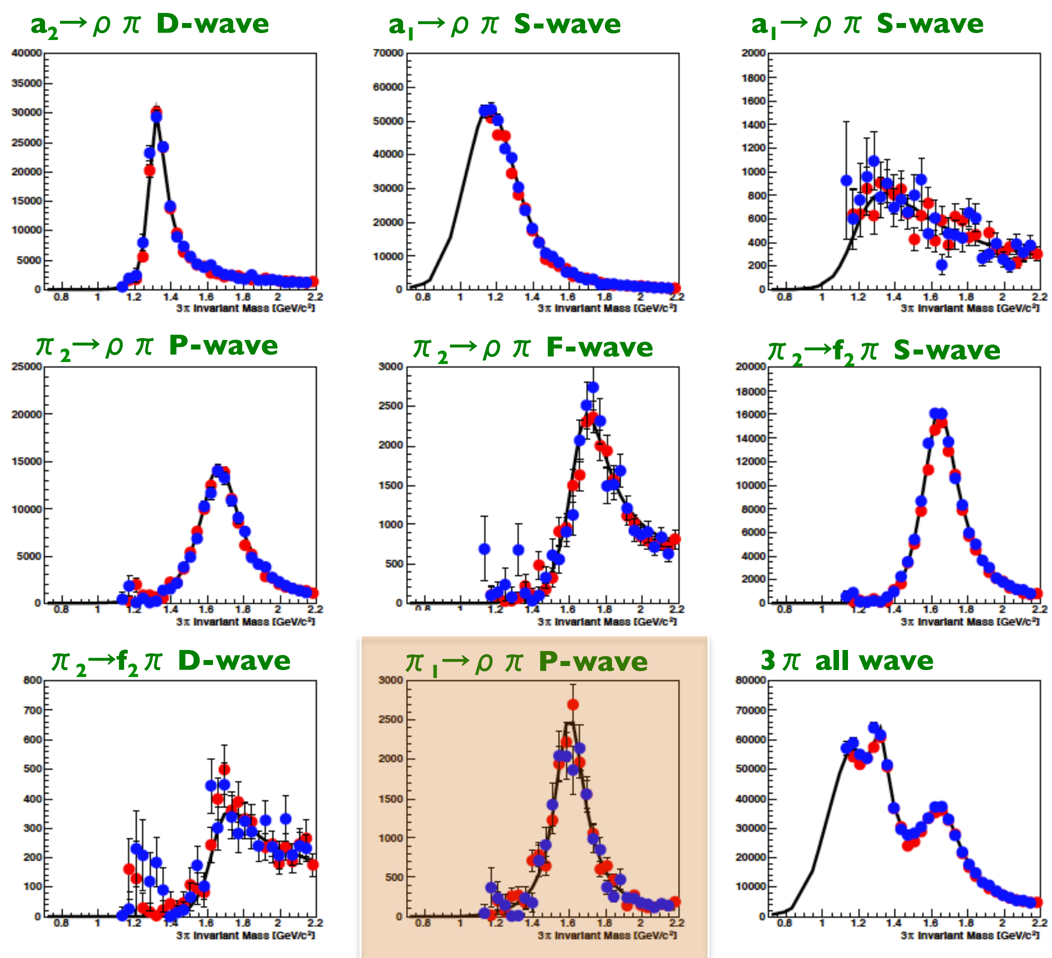
Detector Layout

- *calorimeter* to determine the electron energy with few % accuracy
  → homogenous $PbWO_4$ crystals
- *tracker* to determine precisely the electron scattering plane and the photon polarization → micromegas
- *veto* to distinguish photons from electrons → scintillator tiles with WLS fiber readout



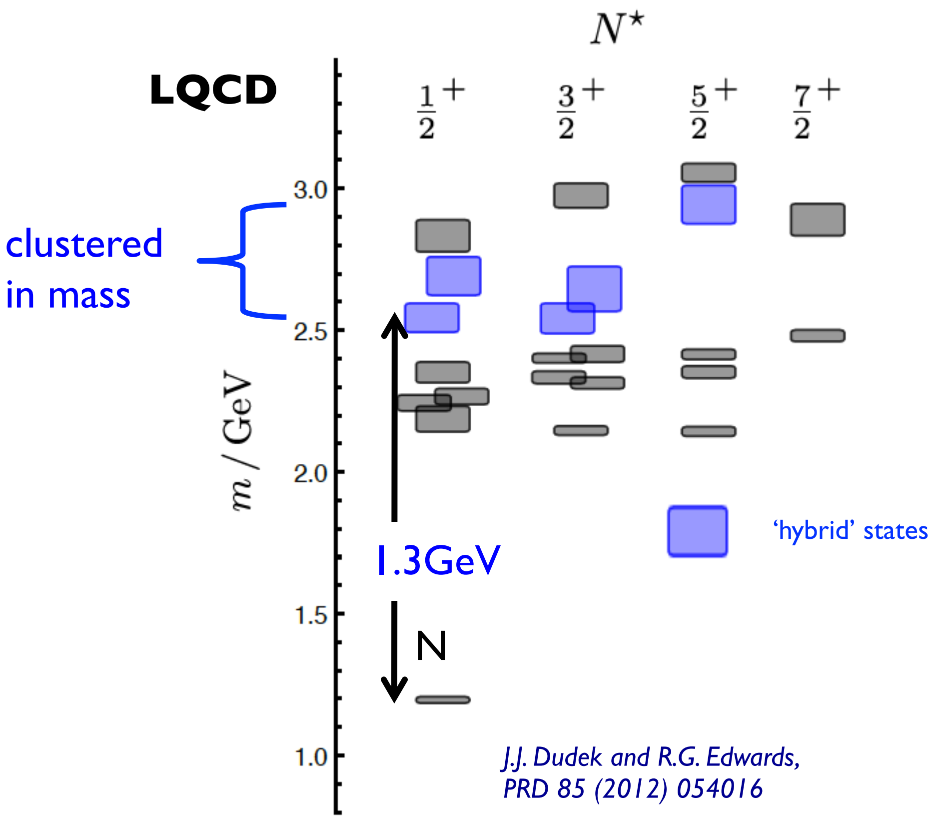
Search for exotic mesons

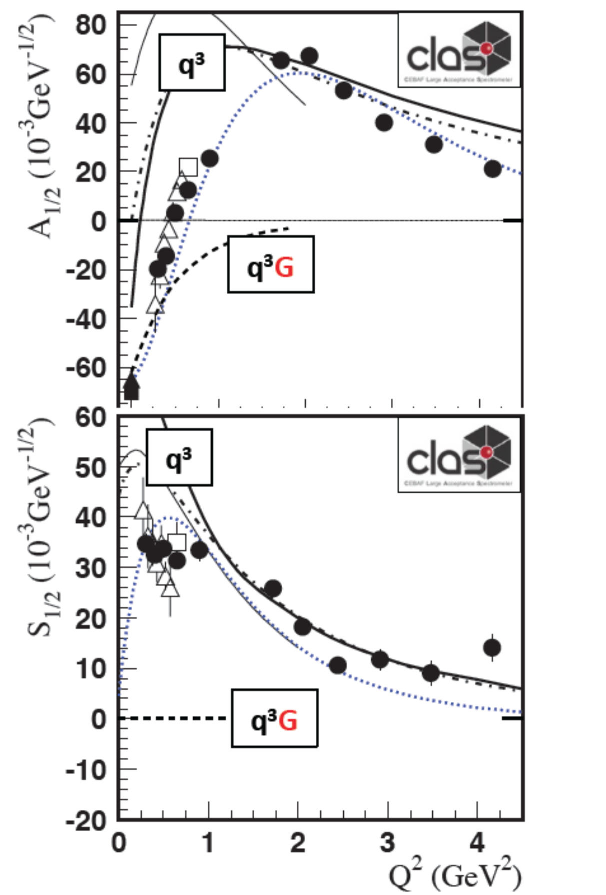




Events generated in specific partial waves, tracked through detector system and reconstructed, retain their initial partial wave contents…

Search for gluonic baryons





q^3G baryons have same J^P values as q^3 baryons, but are more extended objects

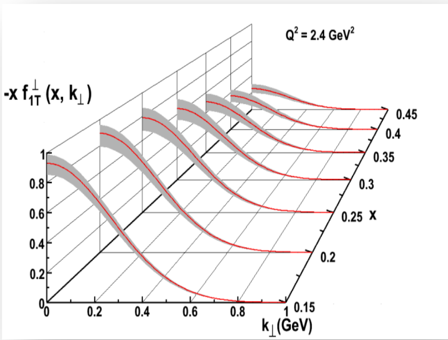
Measurement of the Q^2 dependence of transition form factors can allow us to distinguish between "ordinary" and "hybrid" states

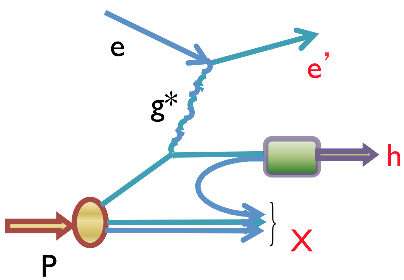
New proposal to search for hybrid baryons with CLAS12 submitted to JLab PAC

3D mapping of the nucleon

TMDs: Longitudinal momentum fraction x and transverse momentum k

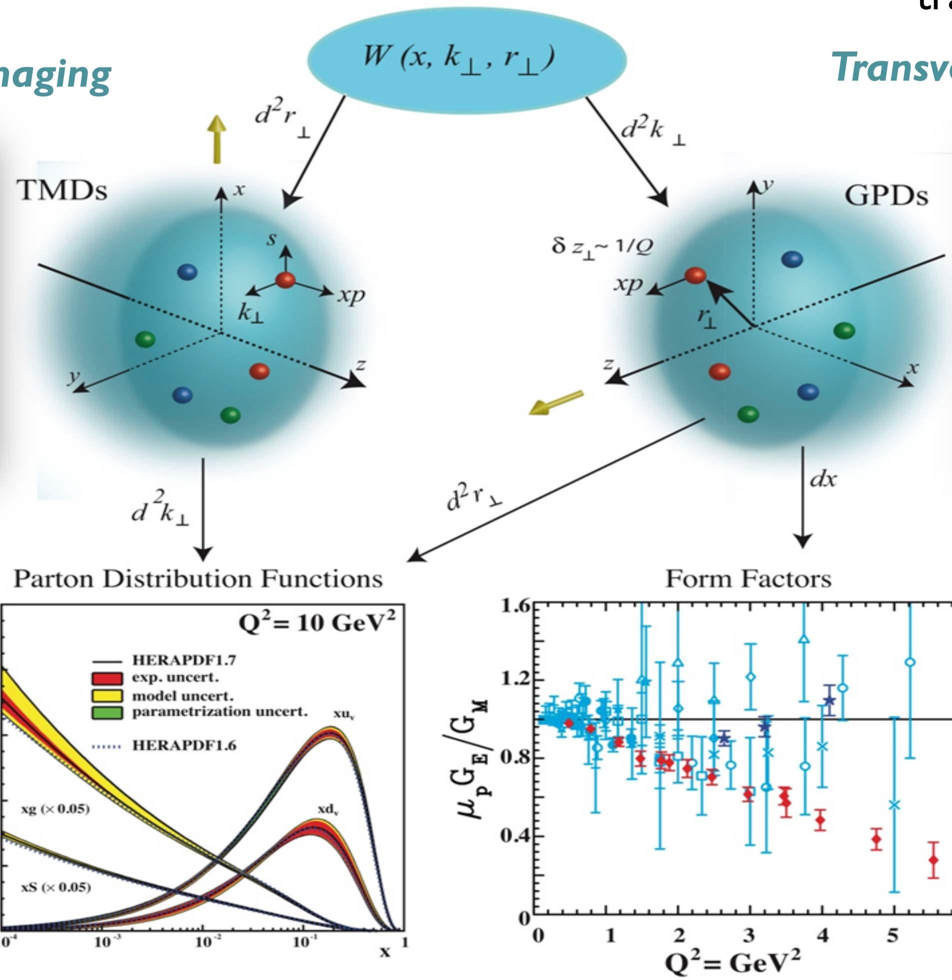
Transverse Momentum Imaging

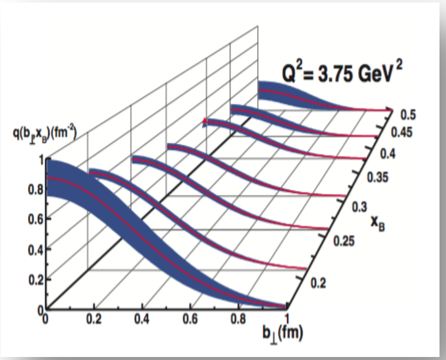


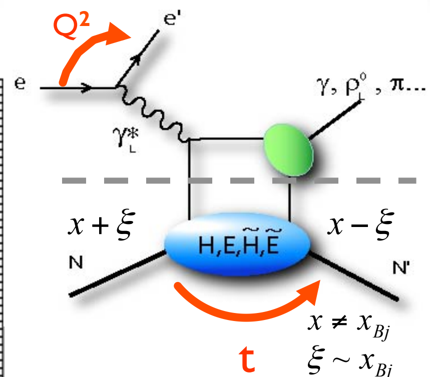


GPDs: Longitudinal momentum fraction x at transverse location b

Transverse Spatial Imaging

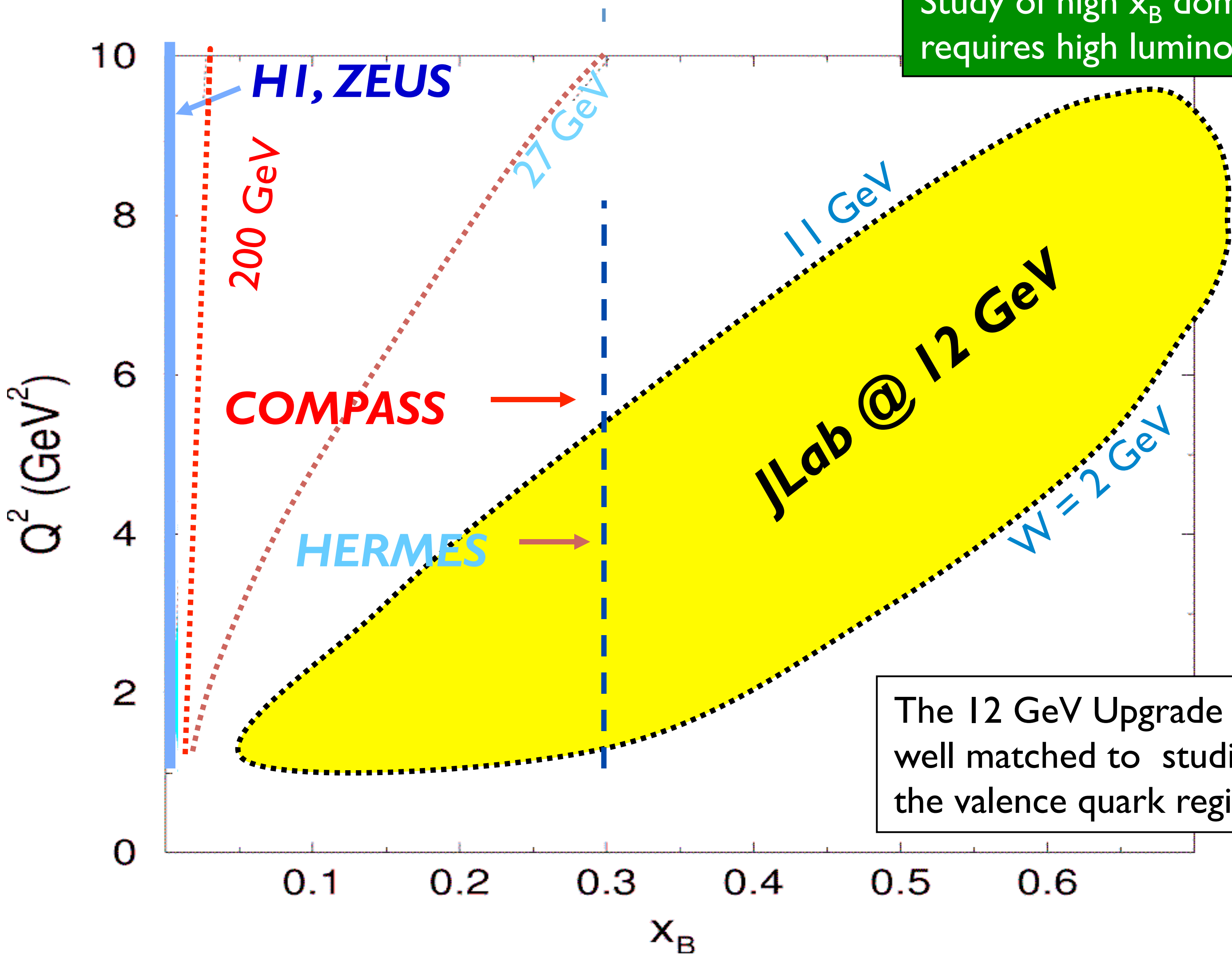






Kinematic coverage

Study of high x_B domain requires high luminosity



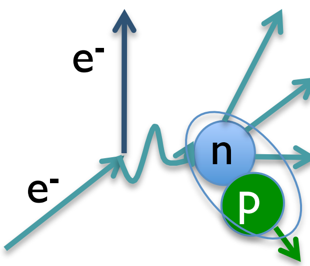
The 12 GeV Upgrade is well matched to studies in the valence quark regime.

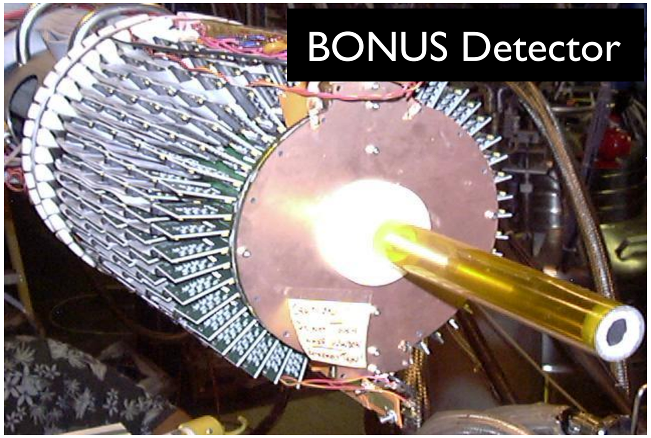
The neutron structure and d/u

F_2^n/F_2^p ratio by tagging almost unbound neutrons using detection of low momentum protons in a radial TPC

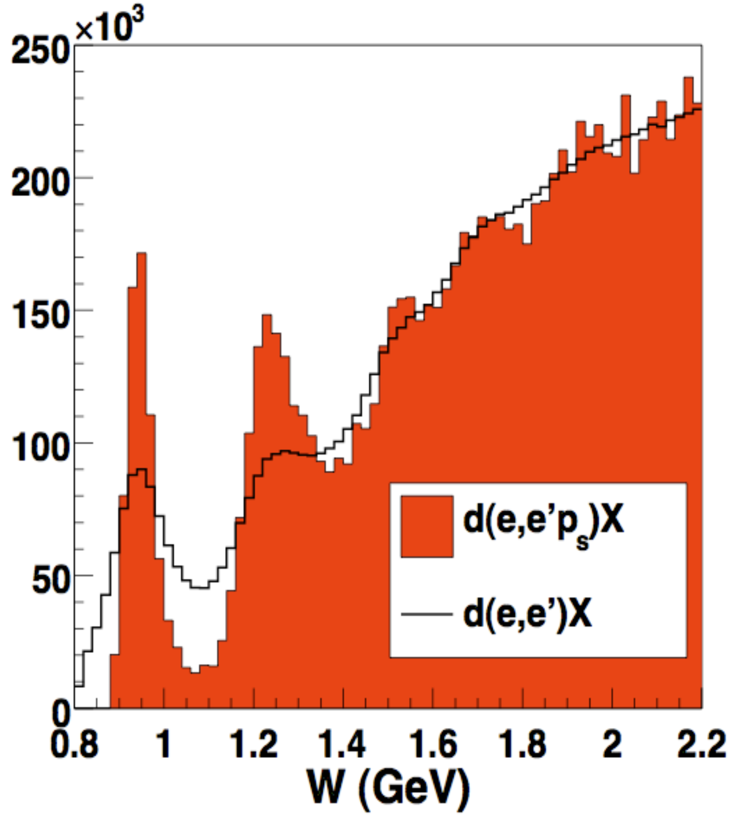
E12-06-113: S. Bueltman et al.

$e^- D \rightarrow e^- p_s X$





5 Tesla mag. field

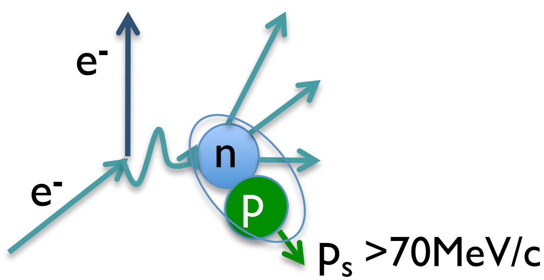


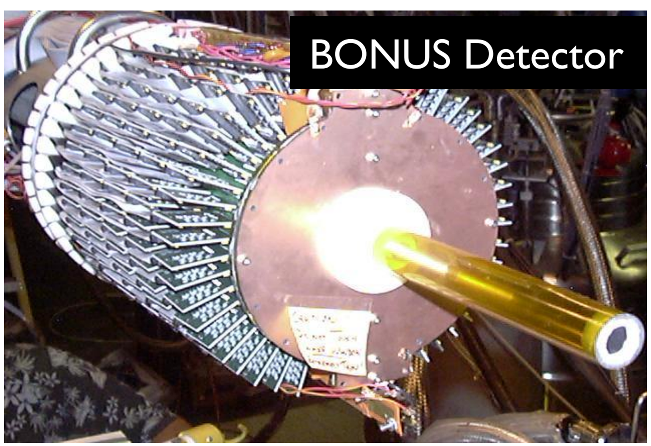
The neutron structure and d/u

F_2^n/F_2^p ratio by tagging almost unbound neutrons using detection of low momentum protons in a radial TPC.

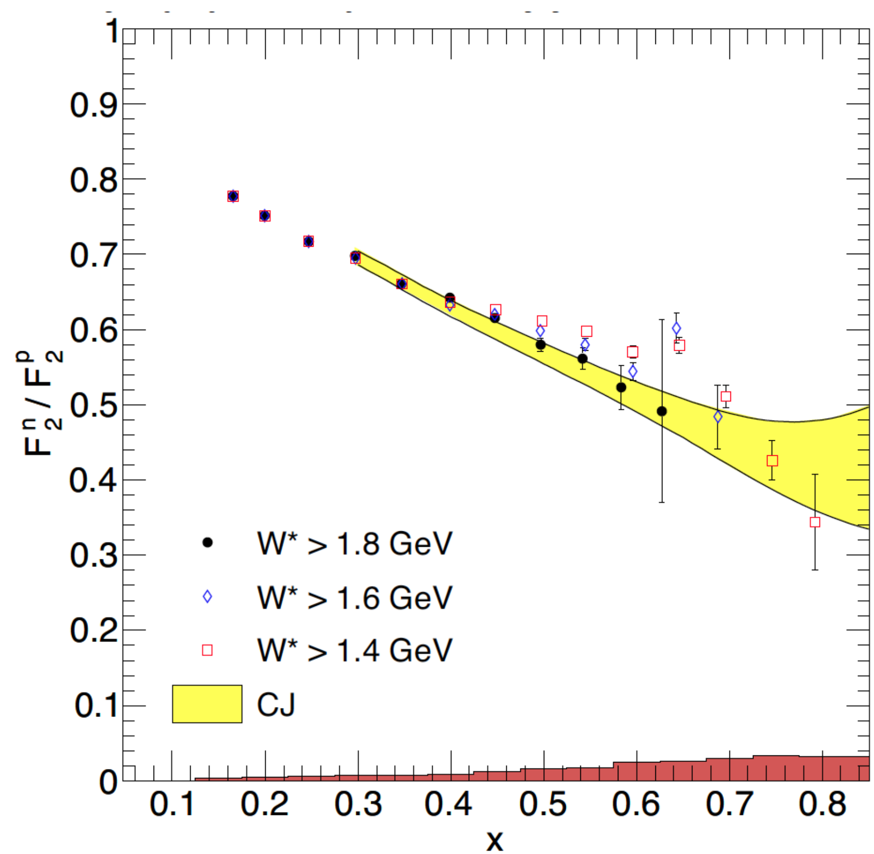
E12-06-113: S. Bueltman et al.

$e^- D \rightarrow e^- p_s X$





5 Tesla
mag. field



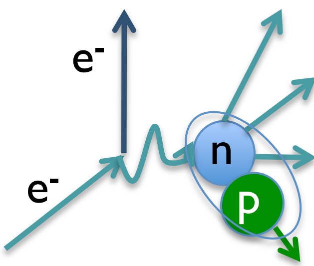
First model-independent measurement of F_2^n/F_2^p

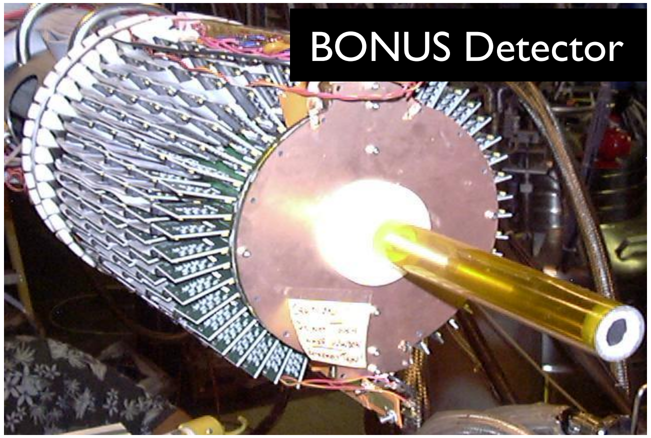
The neutron structure and d/u

F_2^n/F_2^p ratio by tagging almost unbound neutrons using detection of low momentum protons in a radial TPC.

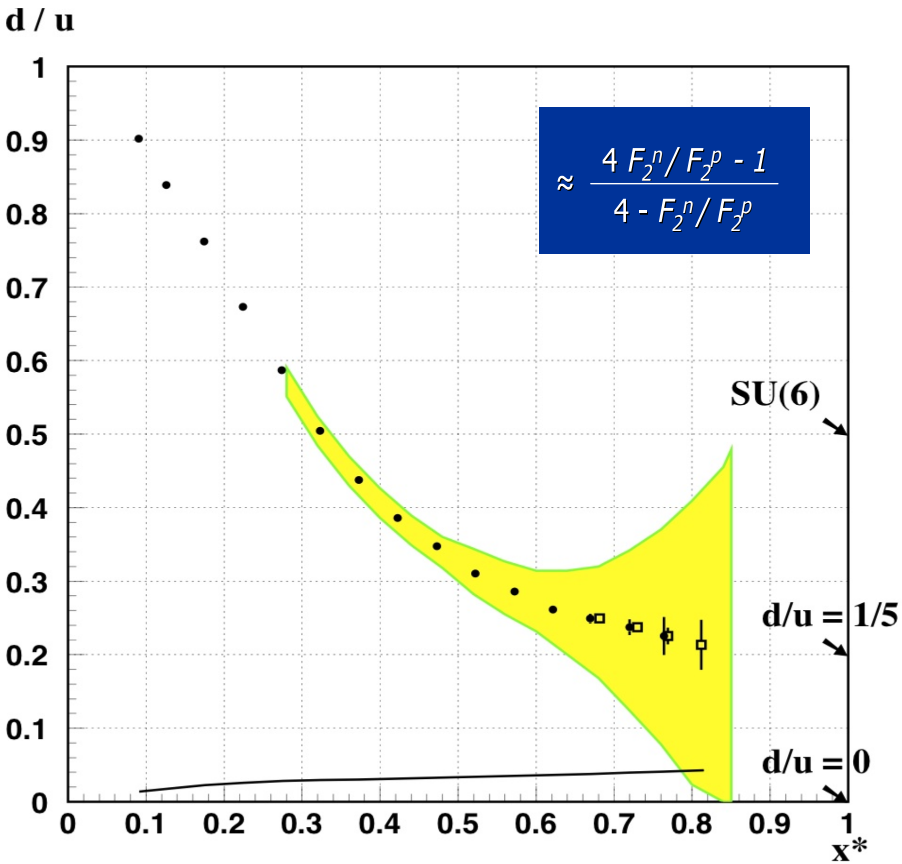
E12-06-113: S. Bueltman et al.

$e^- D \rightarrow e^- p_s X$





5 Tesla mag. field



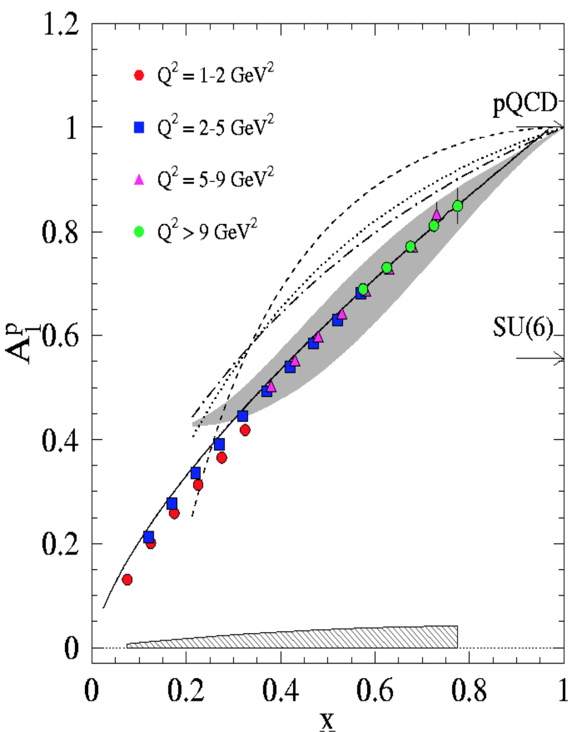
Projected results for d(x)/u(x) for 12 GeV experiment

Polarized PDFs at 12 GeV

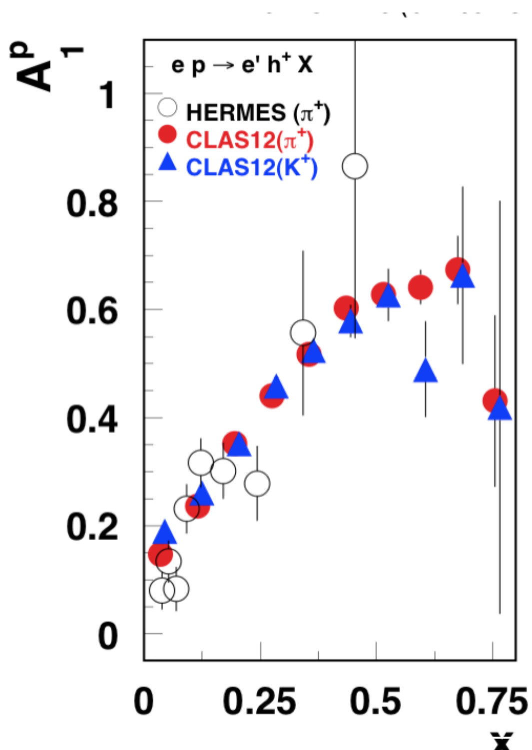
Precise information on $A_1(x,Q^2)$ with flavor tag reduced uncertainties in quark helicity distributions

Q^2 dependence and evolution provides access to $\Delta G(x)$

$$g_1(x,Q^2)_{\mathrm{pQCD}} = \frac{1}{2}\sum_q^{N_f} e_q^2[(\Delta q + \Delta\bar{q}) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi}\delta C_q) + \frac{\alpha_s(Q^2)}{2\pi}\boxed{\Delta G} \otimes \frac{\delta C_G}{N_f}]$$

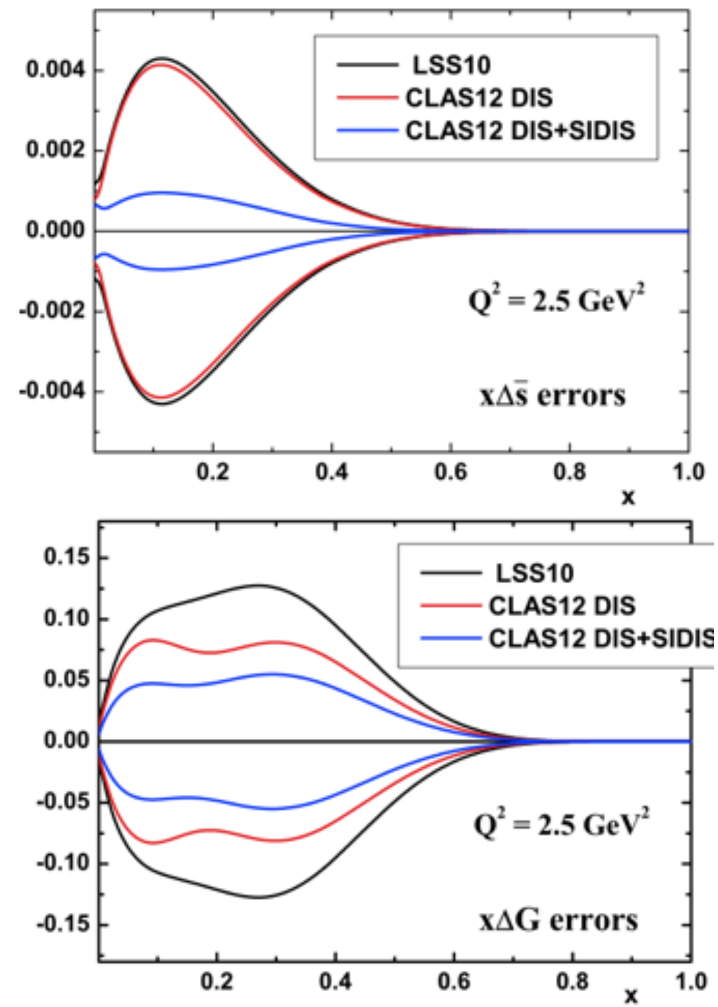


E12-06-109: S. Kuhn et al.

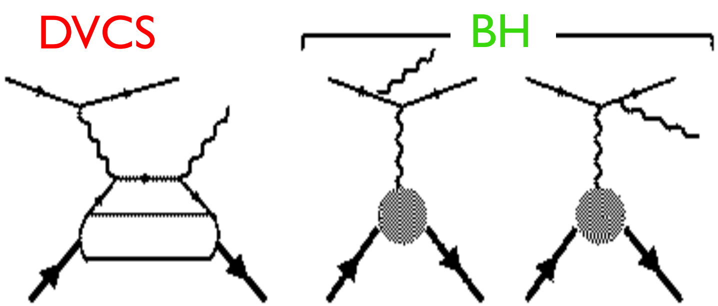


E12-09-007: K. Hafidi et al.

Improved PDFs from NLO analyses

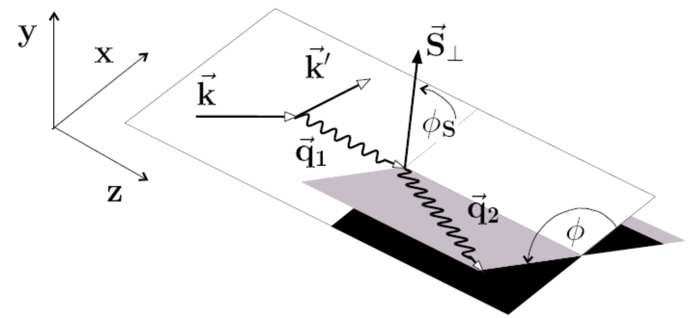


DVCS: a path toward extracting GPDs



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

$k = t/4M^2$



Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi\,\mathrm{Im}\{F_1\mathcal{H} + \xi\,(F_1+F_2)\tilde{\mathcal{H}} + \xi F_2\mathcal{E}\}d\phi \quad\Rightarrow\quad \mathcal{H}$$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi\,\mathrm{Im}\{F_1\tilde{\mathcal{H}} + \xi\,(F_1+F_2)(\mathcal{H} + \xi/(1+\xi)\,\mathcal{E}) - \ldots\}d\phi \quad\Rightarrow\quad \tilde{\mathcal{H}}$$

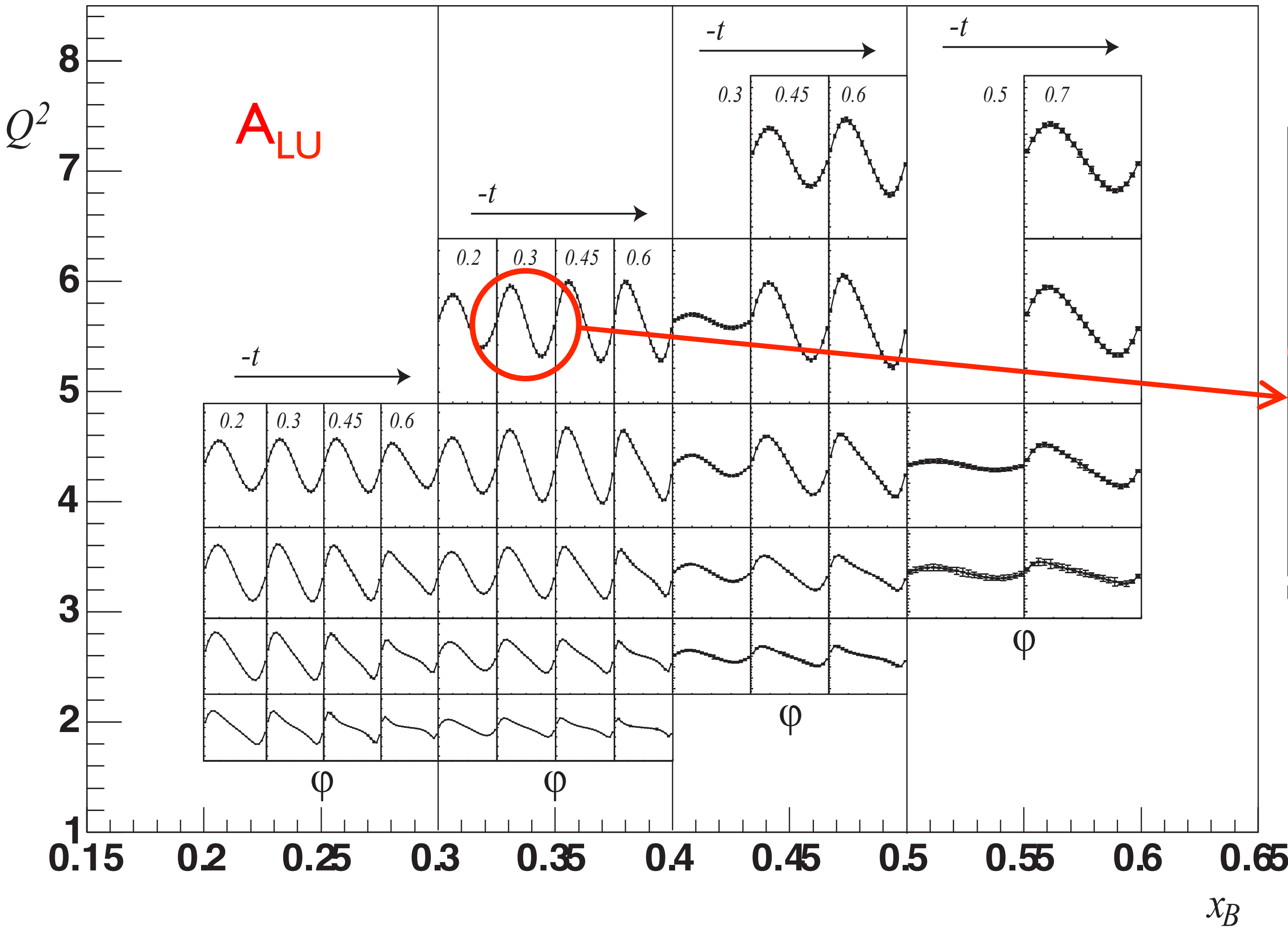
Unpolarized beam, transverse target:

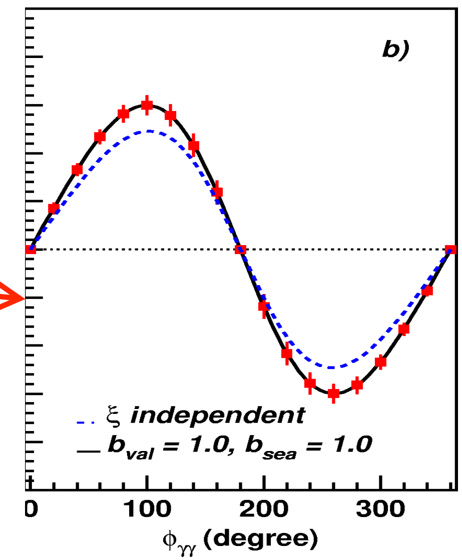
$$\Delta\sigma_{UT} \sim \cos\phi\,\mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi \quad\Rightarrow\quad \mathcal{H}, \mathcal{E}$$

A_{LU} projections on proton at 12 GeV

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

$\vec{e}p \rightarrow ep\gamma$





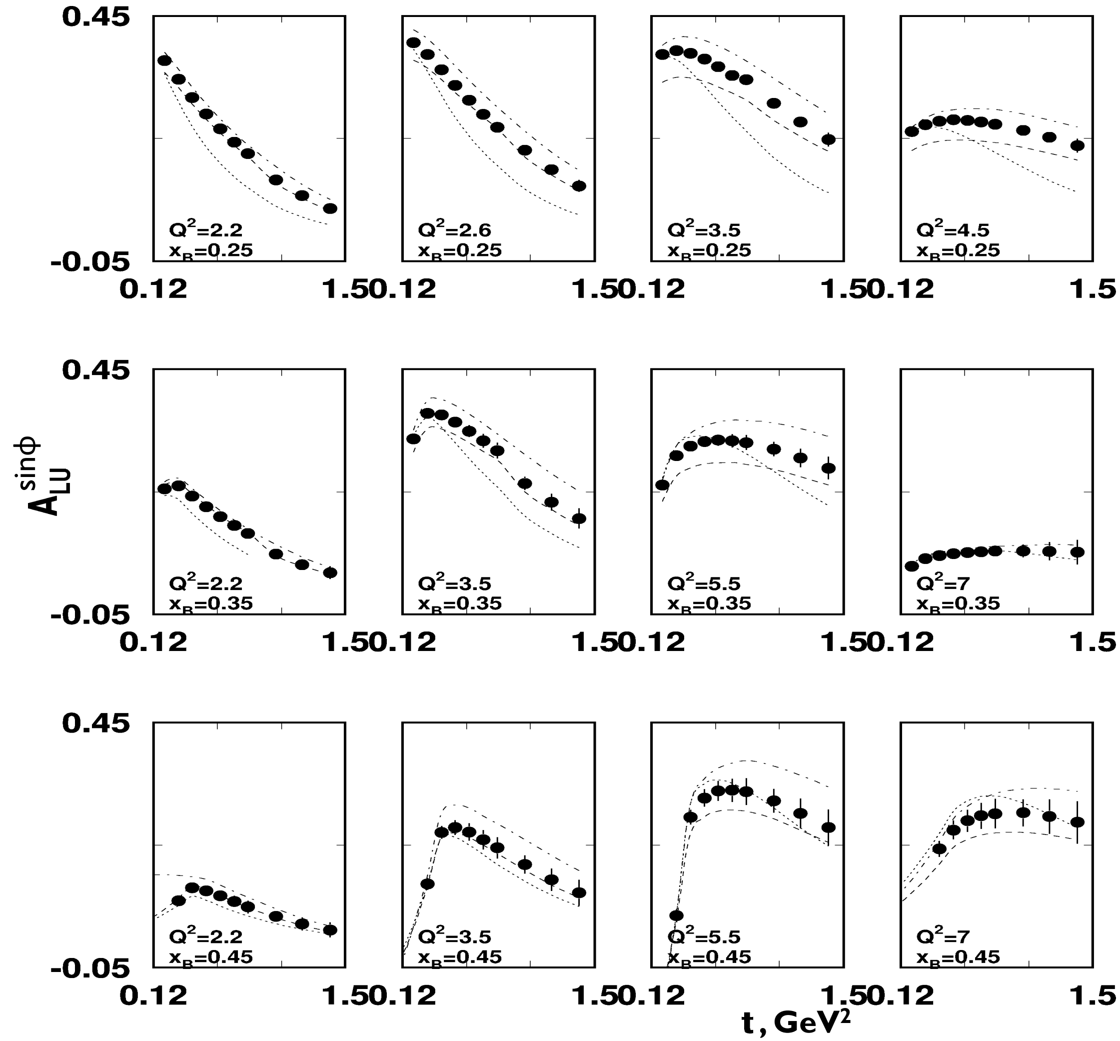
E12-06-119: F. Sabatié et al.

A_{LU} projections on proton at 12 GeV

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

$\vec{e}p \rightarrow ep\gamma$

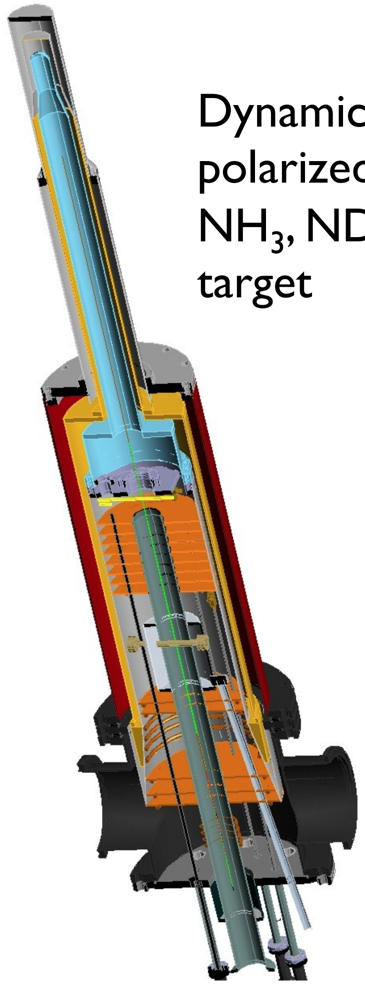
$E_e = 11 GeV$



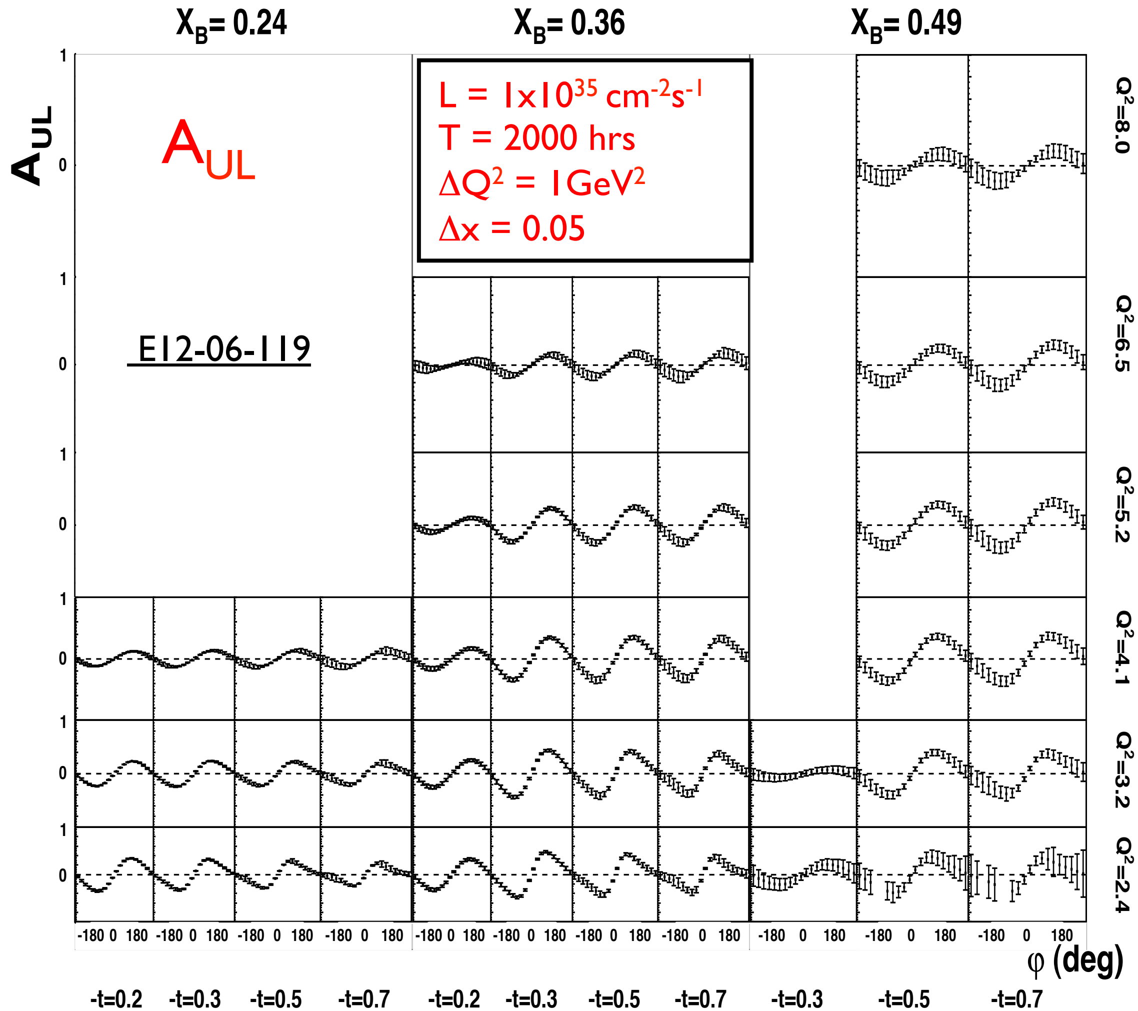
A_{UL} projections on proton at 12 GeV

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

$\vec{e}p \rightarrow ep\gamma$



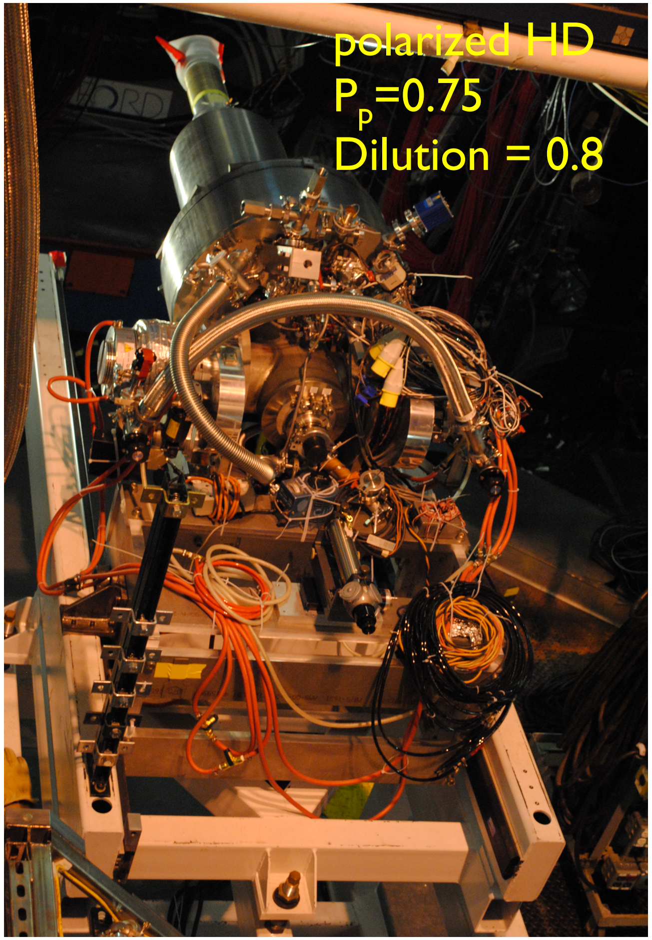
Dynamically polarized NH_3, ND_3 target

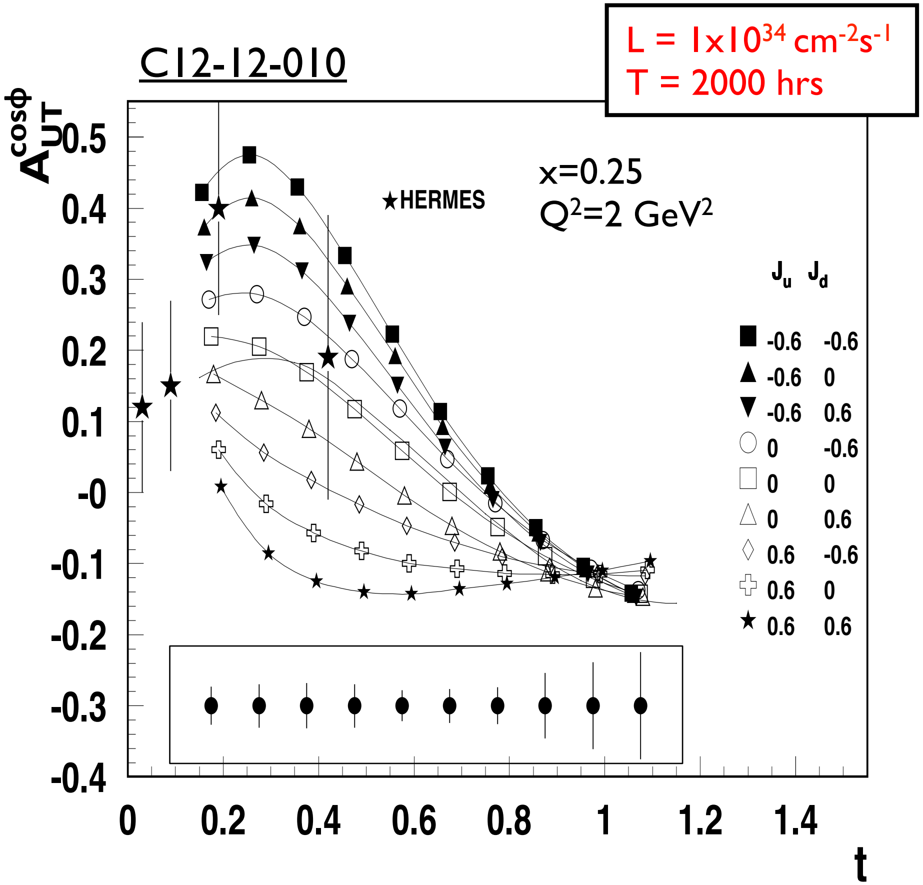


A_{UT} projections on proton at 12 GeV

$\Delta\sigma_{UT} \sim \cos\phi \, \mathrm{Im}\{k(F_2 \mathit{H} - F_1 \mathit{E}) + \ldots\} d\phi$

$ep^{\uparrow} \rightarrow ep\gamma$

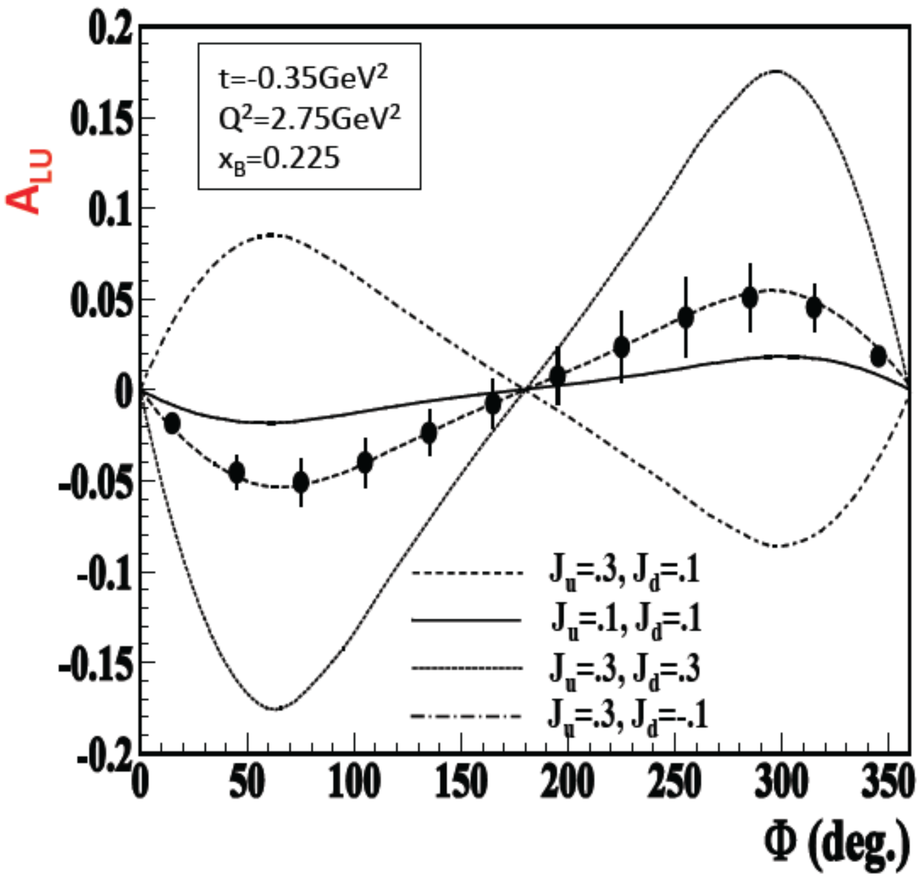




A_{UT} and A_{LT} are sensitive to the u and d-quark contributions to the proton spin

DVCS A_{LU} asymmetries on neutron

Total of 588 bins, in t, Q^2, x_B, ϕ



E12-11-003: S. Niccolai et al.

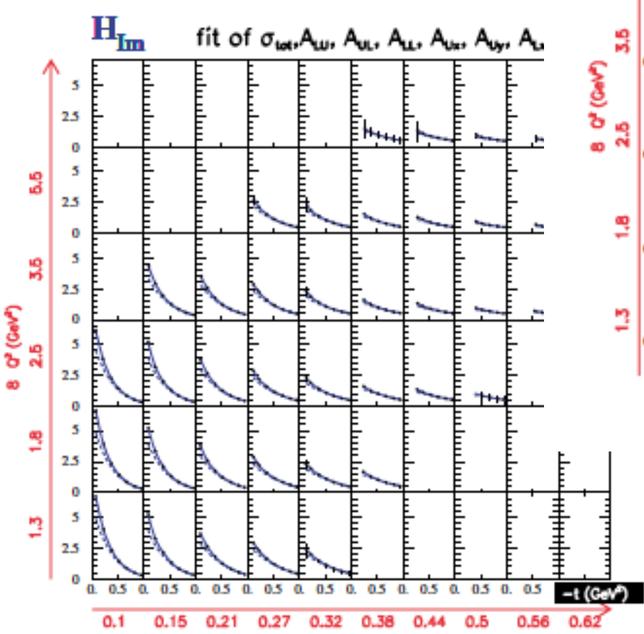
Neutron counter for CLAS12 Central Detector built at IPN-Orsay

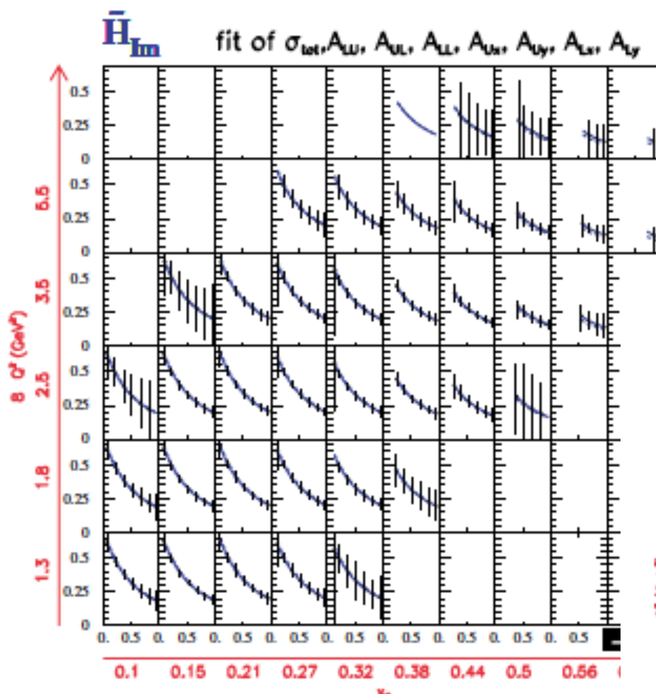
A_{LU} is sensitive to the d-quark spin content of the neutron

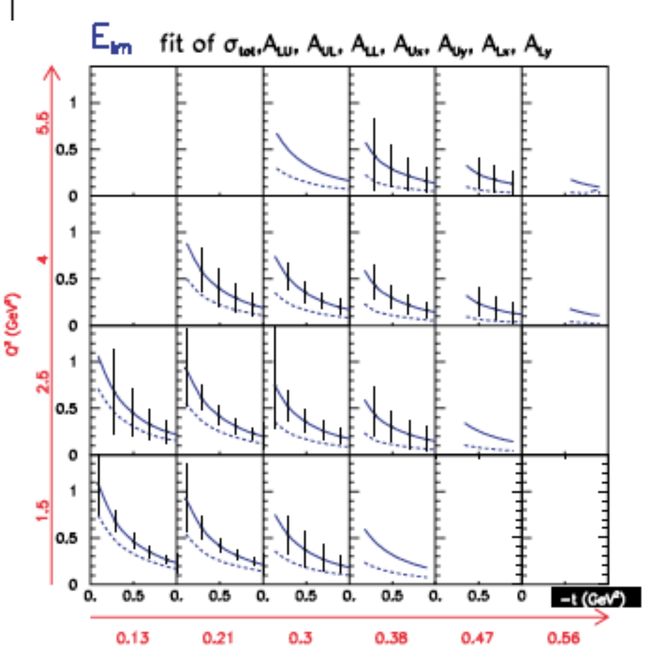
GPDs from projected CLAS12 data

Review article: M. Guidal, H. Moutarde, M.Vanderhaeghen, Rept.Prog.Phys. 76 (2013) 066202

Reconstructed CFF/GPDs in leading order twist-2 approximation

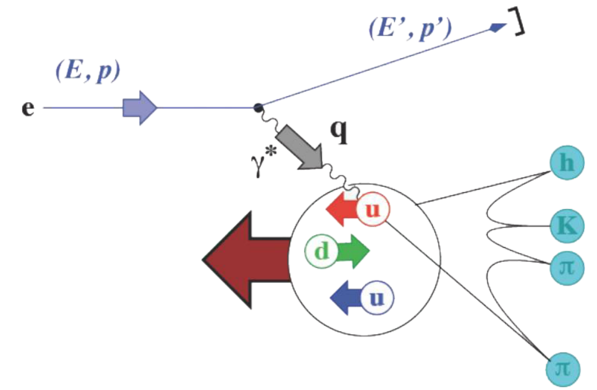






CLAS12 TMD program on proton

Leading twist TMD parton distributions: information on correlations between **quark orbital** momentum and **spin**



Quark spin polarization

Nucleon polarization

	N \ q	U	L	T	
IH_2	U	f_1		$h_1^\perp$	E12-06-112: π^+, π^-, π^0 E12-09-008: K^+, K^-, K^0
NH_3	L		g_1	$h_{1L}^\perp$	E12-07-107: π^+, π^-, π^0 E12-09-009: K^+, K^-, K^0
HD	T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$	C12-11-111: π^+, π^-, π^0 K^+, K^-

Semi-inclusive meson production in DIS

The TMD program will map the 4D phase space in Q^2, x, z, P_T

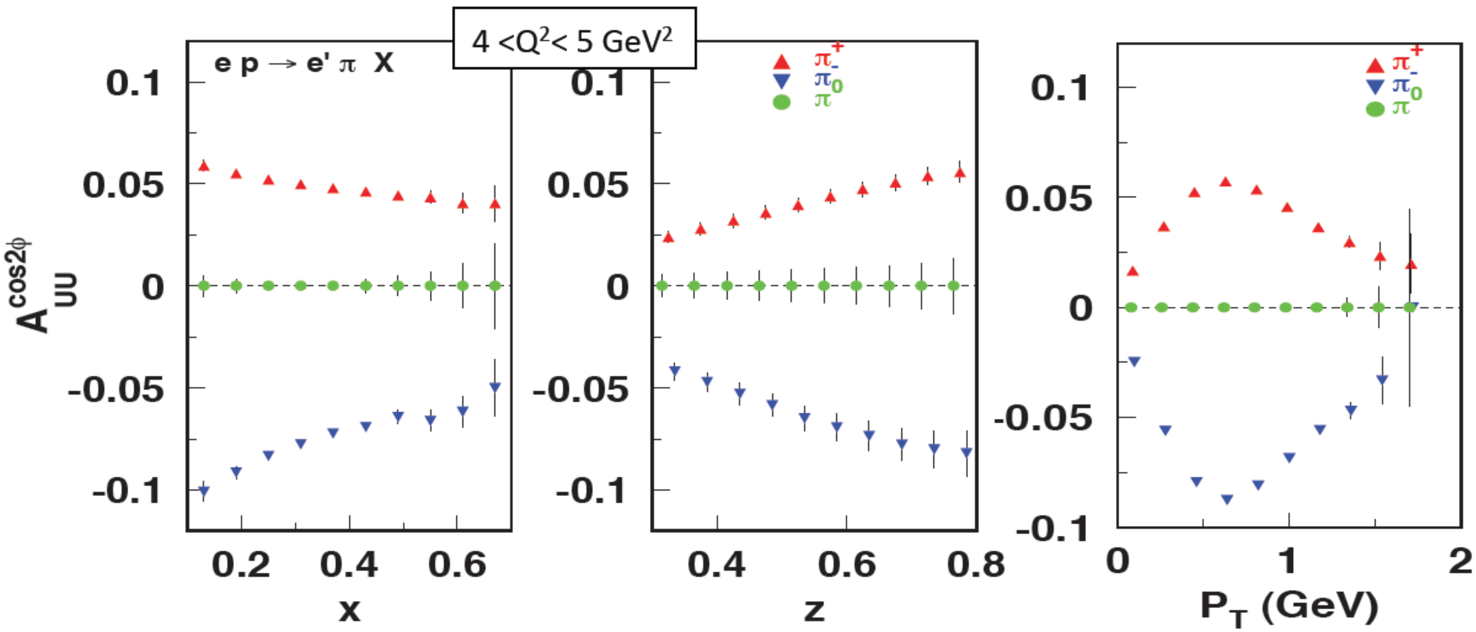
A_{UU} projections for pions

N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

E12-06-112: H. Avakian et al.

$$\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h}\Big\},$$

Measure momentum distribution of transversally polarized quarks in unpolarized nucleon



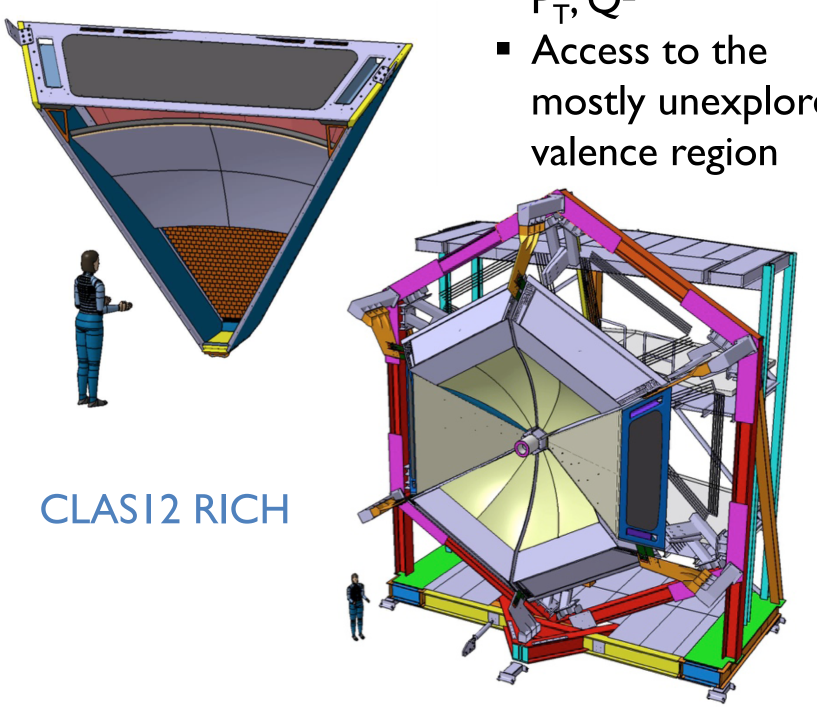
Wide x and P_T range needed to map out phase space in longitudinal and transverse quark momentum

Transversity from SIDIS

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

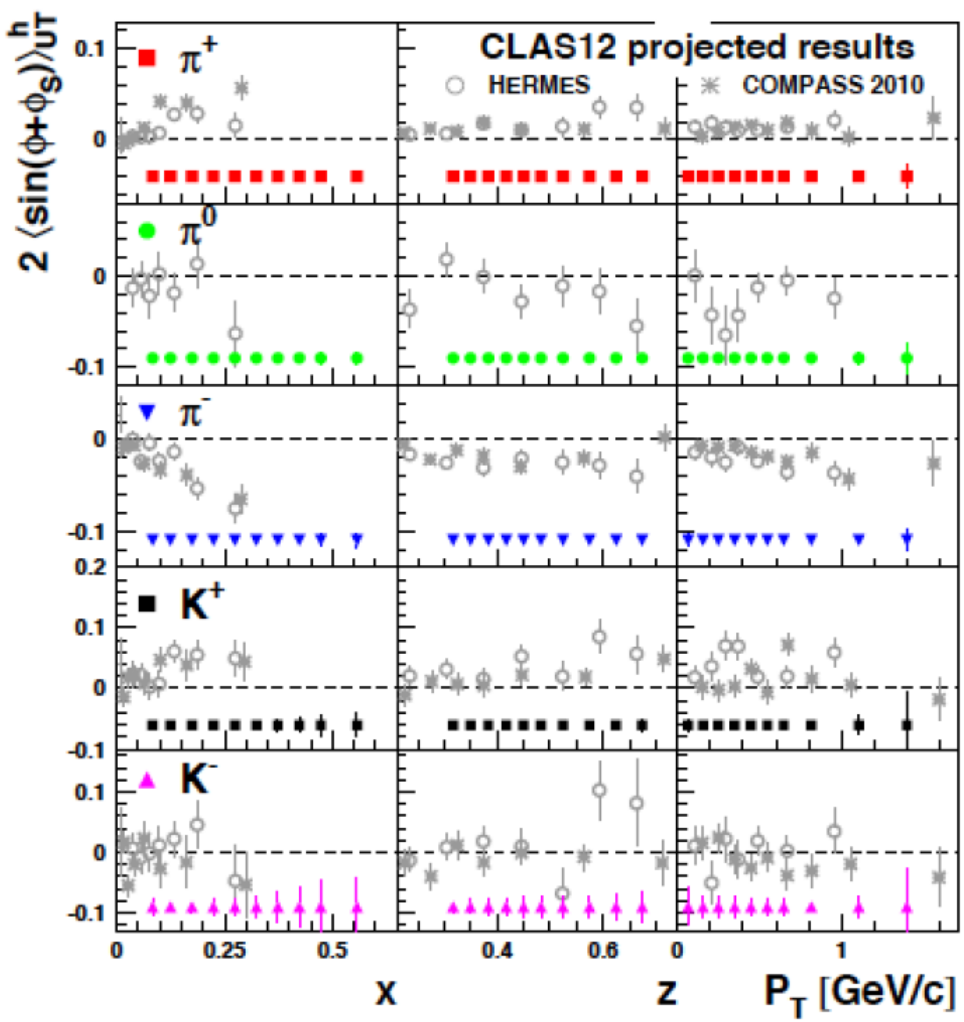
Combined used of **RICH** detector for enhanced PID and transversally **polarized HD target**

- 4D mapping: x, z, P_T, Q^2
- Access to the mostly unexplored valence region



CLAS12 RICH

C12-11-111: M. Contalbrigo et al.

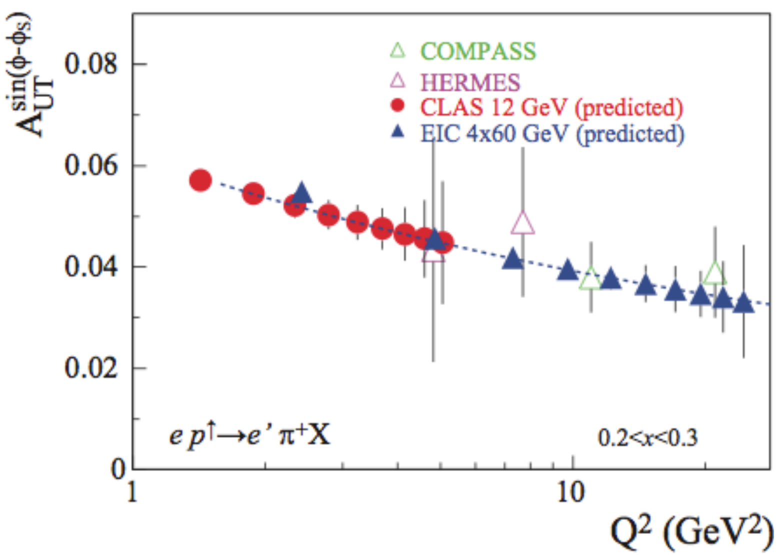


A_{UT}: Sivers function from SIDIS

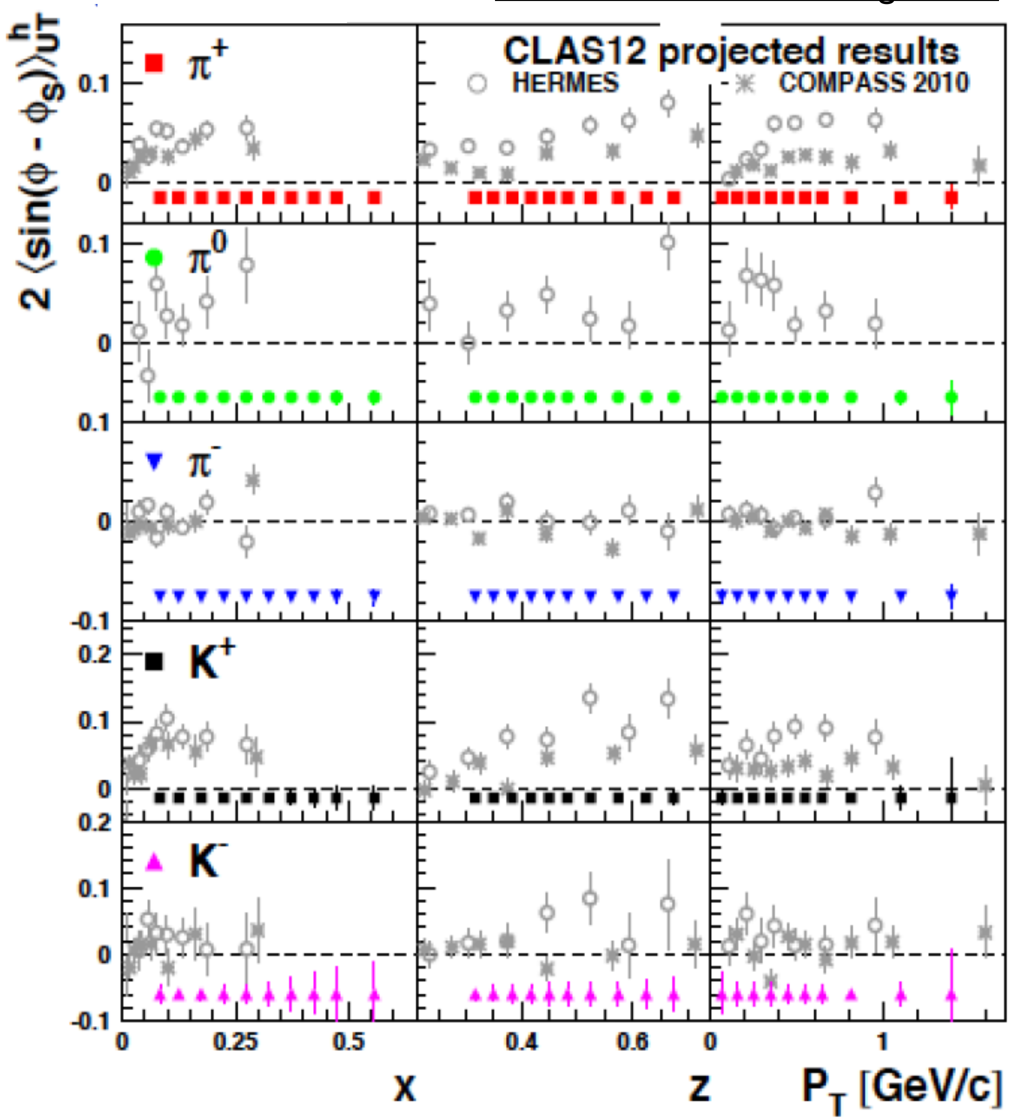
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Detailed mapping of the **Sivers** function

- 4D mapping: x, z, P_T, Q^2
- Access to the mostly unexplored valence region



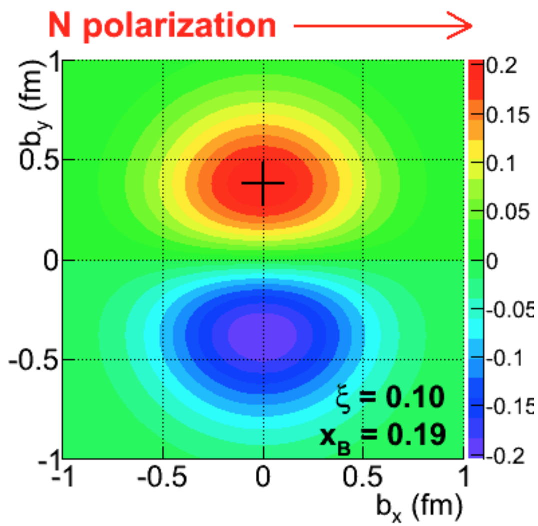
C12-11-111: M. Contalbrigo et al.



From GPDs and TMDs to nucleon imaging

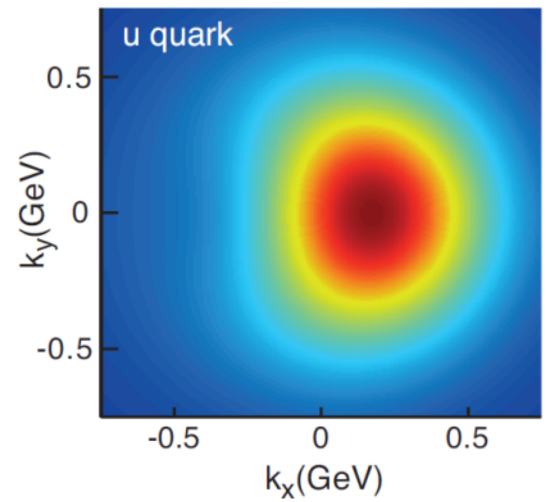
An ambitious and very extensive program to precisely map out GPDs and TMDs within a broad kinematic range…

Spatial Imaging



Contribution of
GPD E

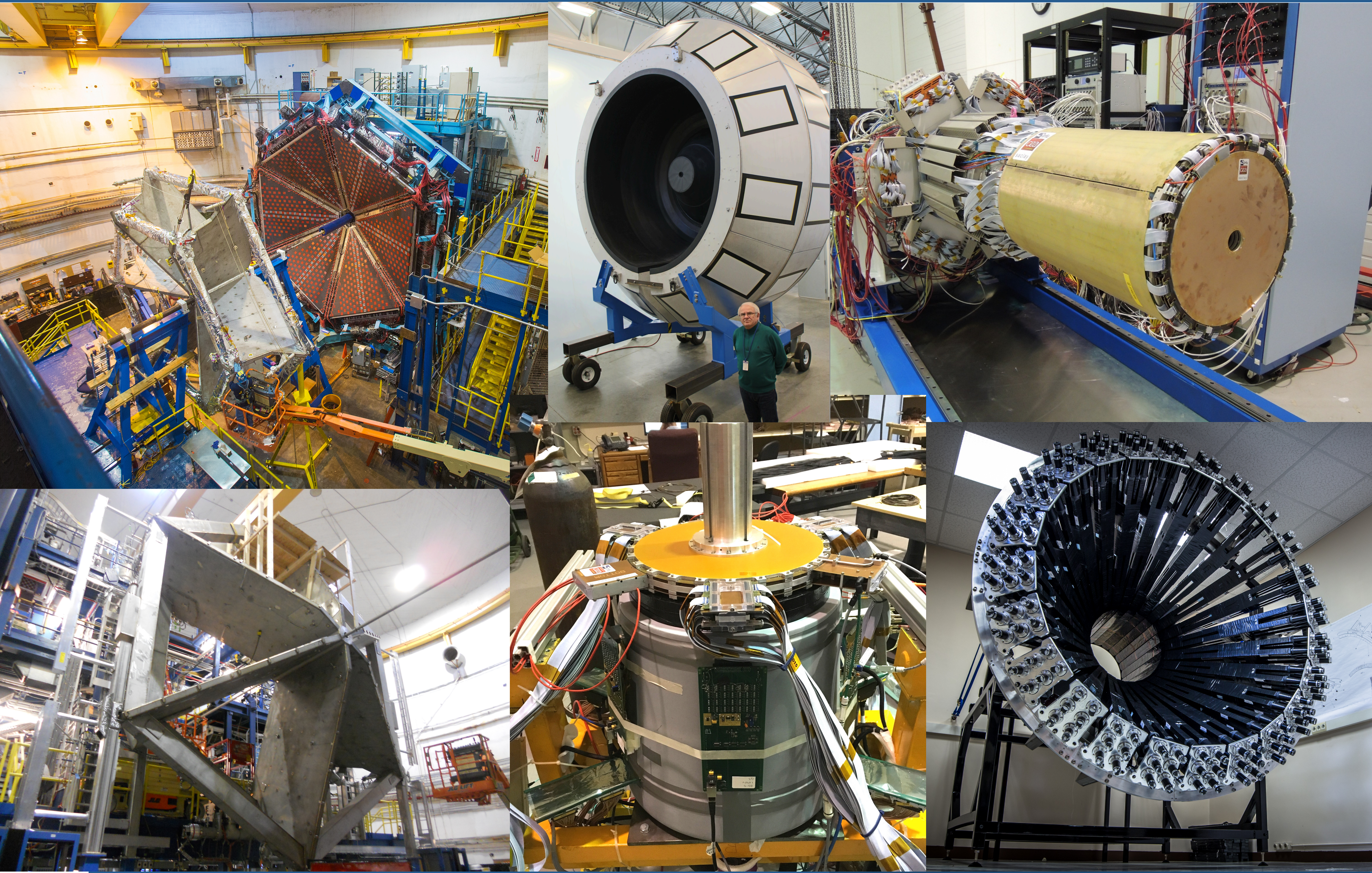
Momentum Imaging



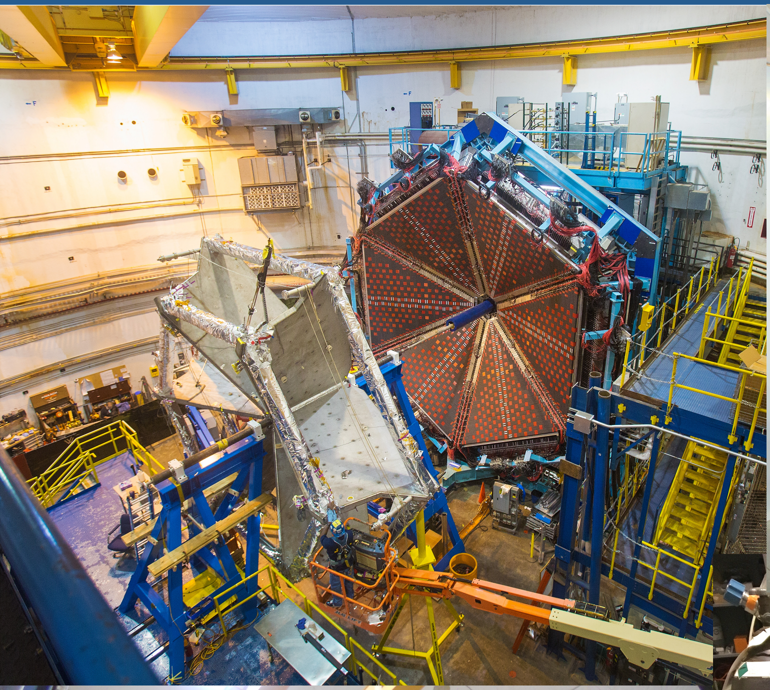
Contribution of
TMD f_{1T}

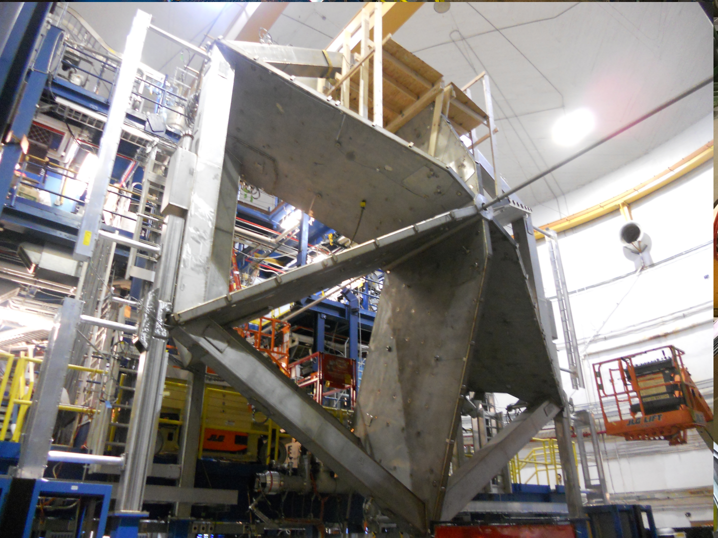
…providing input to obtain a "quark tomography" of the nucleon

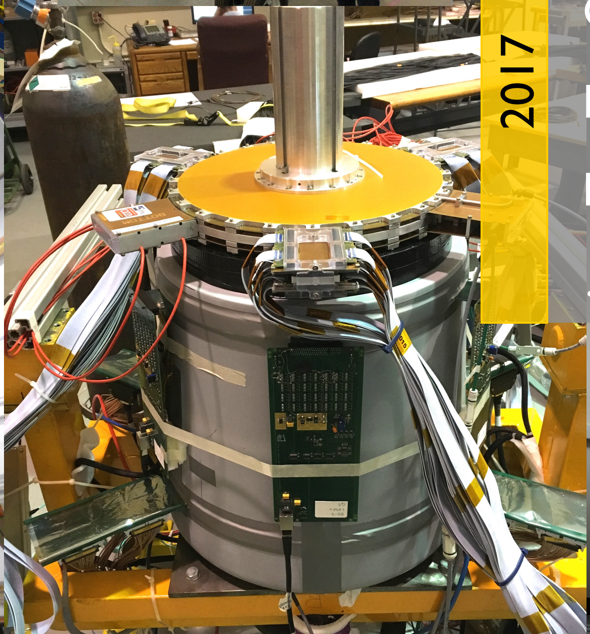
CLAS12 status and schedule



CLAS12 status and schedule



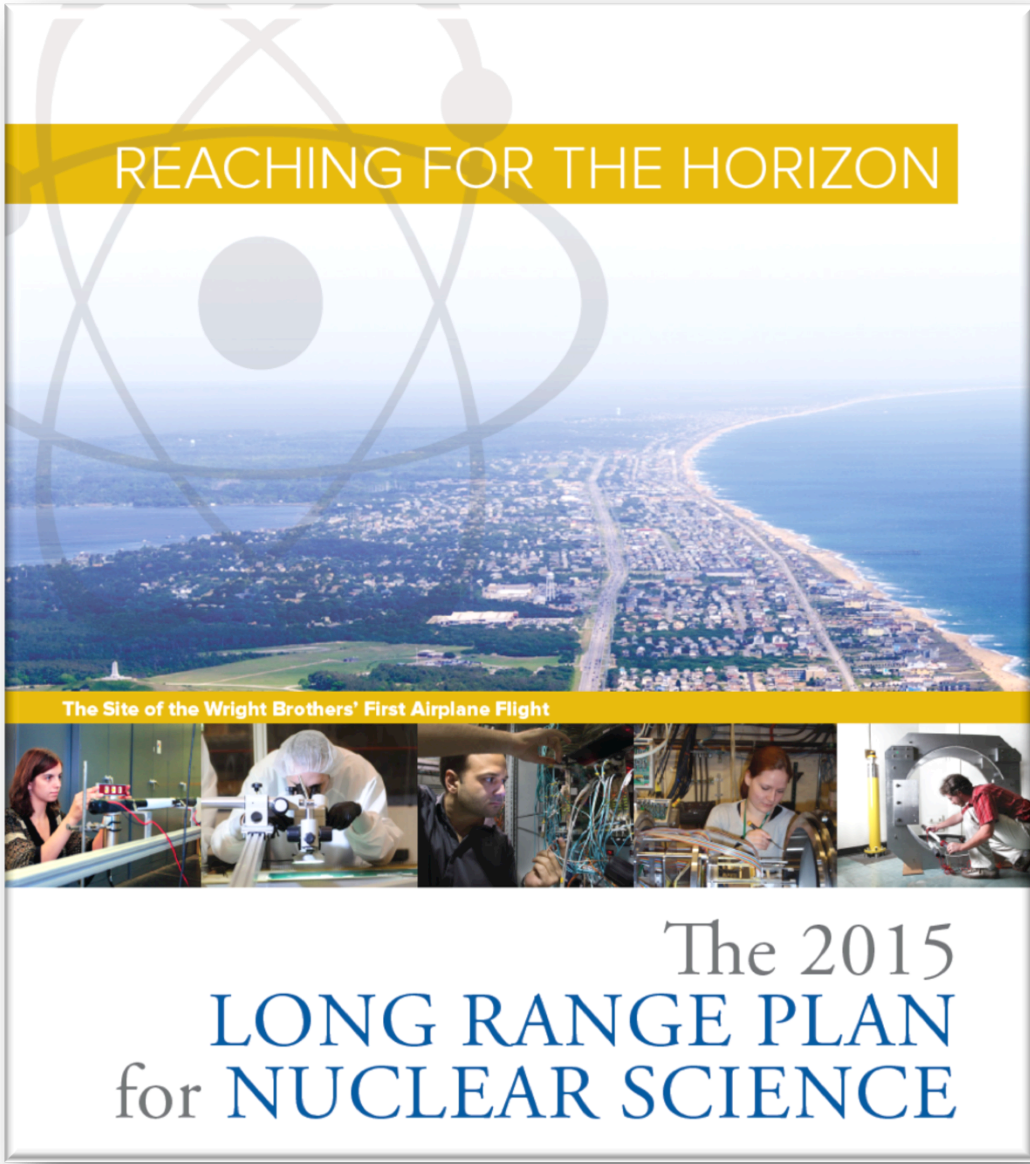




2016
- Torus pump- and cool-down
- Forward detector installation
- Solenoid installation and test
- Central detector installation

2017
- Commissioning run
- RICH installation
- Engineering run
- … PHYSICS

2015 NSAC Longe Range Plan



- NSAC = Nuclear Science Advisory Committee
- Advise DOE and NSF on future of Nuclear Physics program every 5-7 years
- Four recommendations
- RECOMMENDATION I:
  The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.
  - *With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.*
  - …

CLAS Collaboration

Arizona State University, Tempe, AZ
University Bari, Bari, Italy
University of California, Los Angeles, CA
California State University, Dominguez Hills, CA
Carnegie Mellon University, Pittsburgh, PA
Catholic University of America
CEA-Saclay, Gif-sur-Yvette, France
Christopher Newport University, Newport News, VA
University of Connecticut, Storrs, CT
Edinburgh University, Edinburgh, UK
University of Ferrara, Ferrara, Italy
Florida International University, Miami, FL
Florida State University, Tallahassee, FL
George Washington University, Washington, DC
University of Genova, Genova, Italy
University of Glasgow, Glasgow, UK

University of Grenoble, Grenoble, France
Idaho State University, Pocatello, Idaho
INFN, Laboratori Nazionali di Frascati, Frascati, Italy
INFN, Sezione di Genova, Genova, Italy
INFN, Sezione di Ferrara, Ferrara, Italy
INFN, Sezione di Torino, Torino, Italy
Institut de Physique Nucléaire, Orsay, France
Institut fur Kernphysik, Jülich
ITEP, Moscow, Russia
James Madison University, Harrisonburg, VA
Kyungpook University, Daegu, South Korea
University of Massachusetts, Amherst, MA
Moscow State University, Moscow, Russia
University of New Hampshire, Durham, NH
Norfolk State University, Norfolk, VA

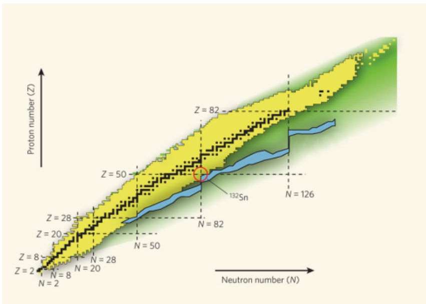
Ohio University, Athens, OH
Old Dominion University, Norfolk, VA
Rensselaer Polytechnic Institute, Troy, NY
Rice University, Houston, TX
University of Richmond, Richmond, VA
University of Rome Tor Vergata and INFN, Italy
University of South Carolina, Columbia, SC
Thomas Jefferson National Accelerator Facility, Newport News, VA
Union College, Schenectady, NY
University Santa Maria, Valparaiso, Chile
Virginia Polytechnic Institute, Blacksburg, VA
University of Virginia, Charlottesville, VA
College of William and Mary, Williamsburg, VA
Yerevan Institute of Physics, Yerevan, Armenia
Brazil, Morocco and Ukraine,
, have individuals or groups involved with CLAS,
but with no formal collaboration at this stage.

Summary

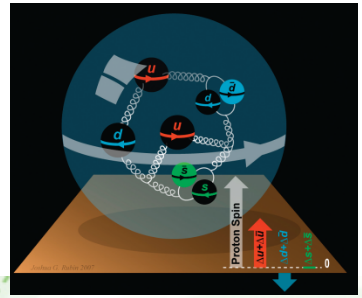
- CLAS12 with JLab 12 GeV upgrade has a broad science program covering many facets of hadron physics and addressing fundamental questions in QCD
- Extending knowledge of PDFs to high x in measurements of (un)polarized structure functions using tagging. Addresses part of the nucleon "spin-puzzle" and extend knowledge of quark density distribution at high x
- Precision studies of DVCS and SIDIS in polarization measurements give access to GPDs TMDs and enable quark multidimensional imaging of the nucleon
- Study of hadron spectroscopy and search for hybrid states provide insight on the origin of hadron mass, the role of gluons and confinement
- Many topics not discussed, nucleon resonances, hyperon production, nucleon e.m. form factors, QCD and nuclei, ….

Backup

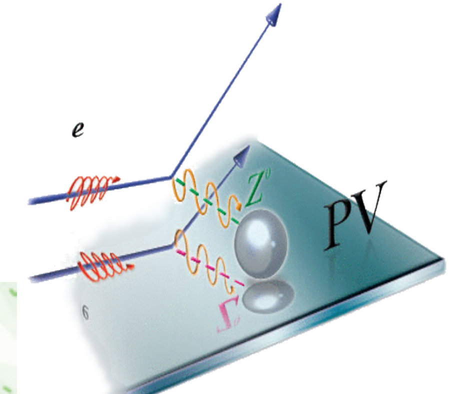
JLab: a laboratory for nuclear science



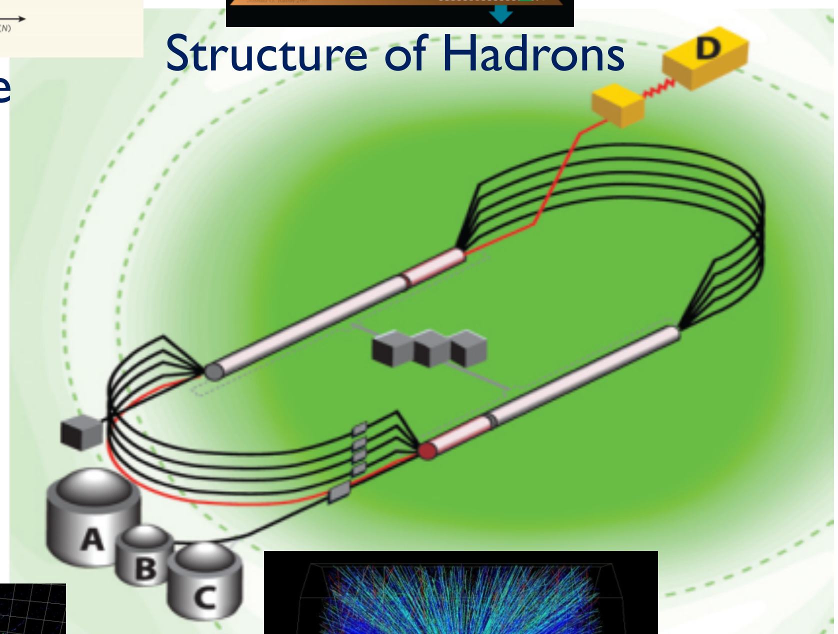
Nuclear Structure



Structure of Hadrons

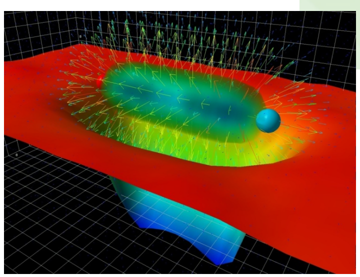


Fundamental
Forces & Symmetries

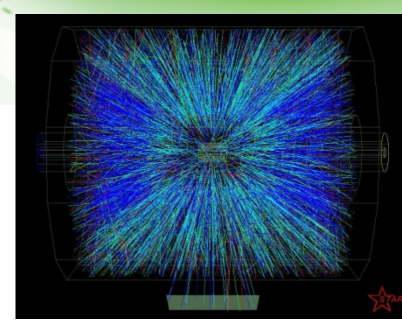


Medical Imaging

Accelerator S&T



Quark Confinement



Hadrons from Quarks

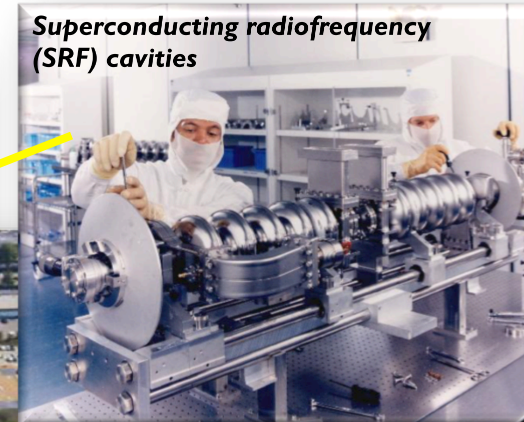
Theory and Computation

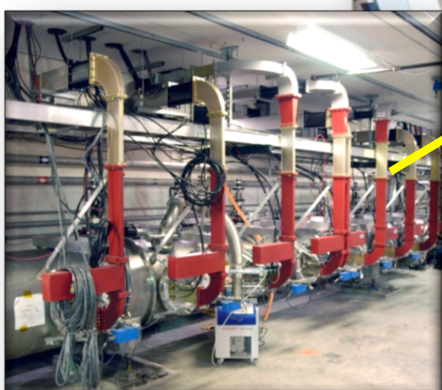
Jefferson Lab Accelerator Complex

Hall D (new construction)

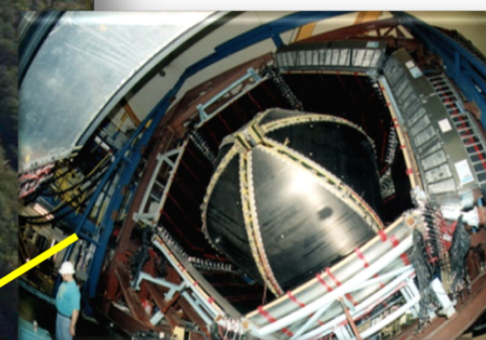
Cryomodules in the accelerator tunnel

Superconducting radiofrequency (SRF) cavities





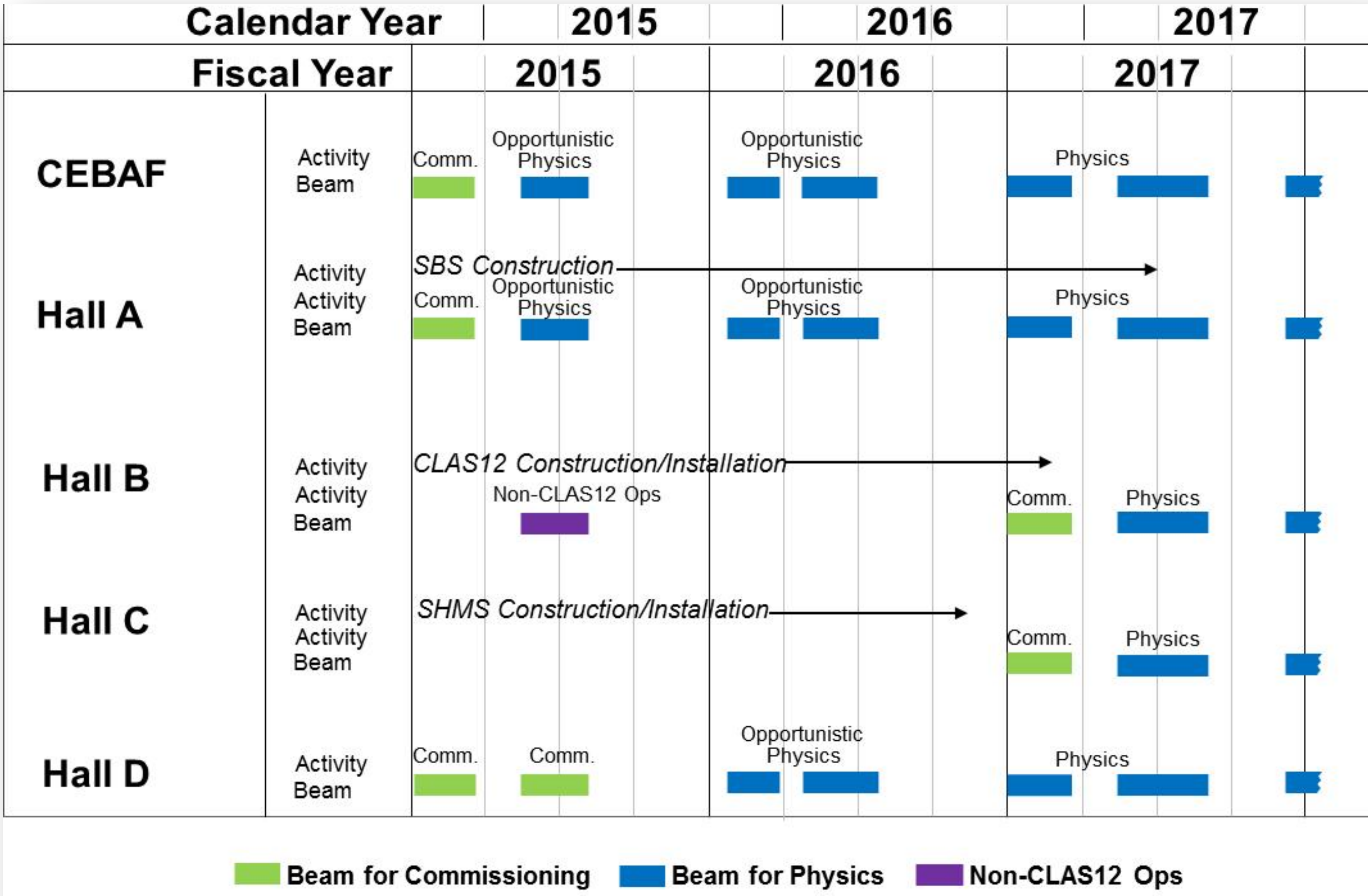
Free Electron Laser (FEL)



CEBAF Large Acceptance Spectrometer (CLAS) in Hall B

An aerial view of the recirculating linear accelerator and 4 experimental halls

JLab 3-years schedule



NSAC 2015 LRP

RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

- *With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.*
- *Expeditiously completing the Facility for Rare Isotope Beams (FRIB) construction is essential. Initiating its scientific program will revolutionize our understanding of nuclei and their role in the cosmos.*
- *The targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model must be sustained.*
- *The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.*

The ordering of these four bullets follows the priority ordering of the 2007 plan.