Jefferson Lab with 12 GeV Electrons

Alexei Prokudin for Hugh Montgomery

Spin2012, JINR, Dubna

September 17, 2012

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Message from Mont

"Dear Colleagues,

It was with a lot of regret that I had to cancel my attendance at Spin 2012.

As some of you may know, I collaborated with a strong group from Dubna, led by Gena Alexeev on the DZero Experiment on the Tevatron at Fermilab. If I recall correctly I visited Dubna in 1998 and on several occasions, combinations of Alexeev and Lab Director Kadyshevski and Lab Director Sissakian also visited us in Illinois. But my first visit to Dubna took place much earlier. I visited Protvino, Novosibirsk, Leningrad as it then was, and Dubna, as well as Moscow in 1983, just before I moved from CERN to the states.

At that time Nikolai Nikolaievitch Nikolaev (N-cubed), who is now at Juelich, was my host in Russia and I see that he is attending the conference. Among others, I met with Professor Baldin in Dubna. Of course times have changed in 30 years and I wish I could have seen for myself.

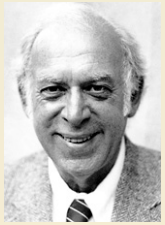
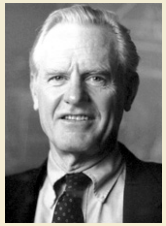
Please accept, again, my apologies, and my best wishes for a very successful conference.

Regards, Mont"

The Talk

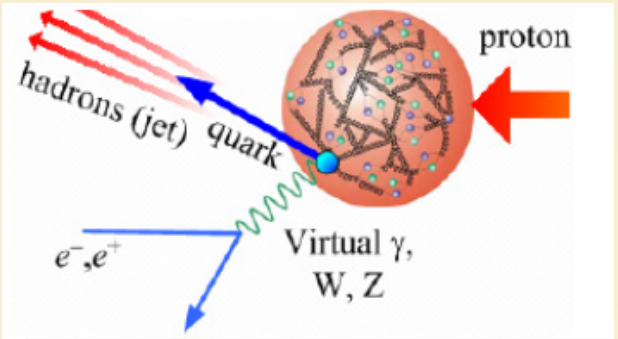
- Jefferson Lab, an introduction
- The 12 GeV Upgrade Project
- The 12 GeV Physics Program
- Conclusions

Electron Scattering

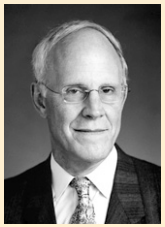




"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"

Friedman, Kendal, Taylor, Nobel Prize 1990

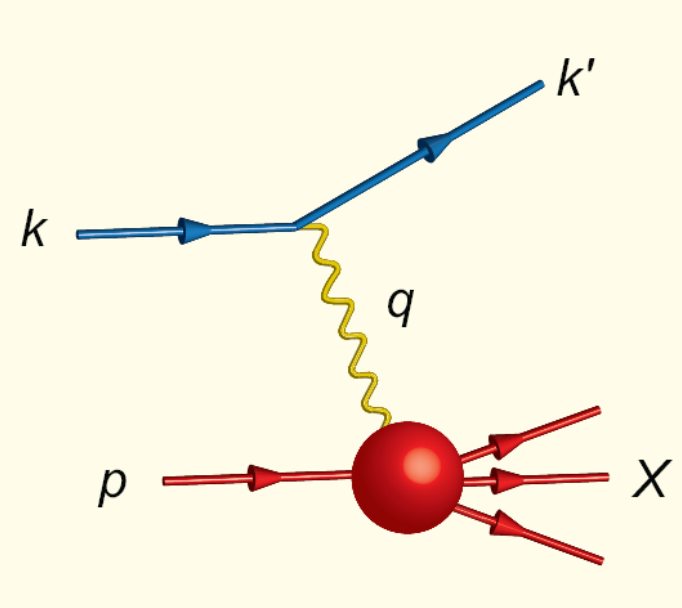


"for the discovery of asymptotic freedom in the theory of the strong interaction"



Gross, Politzer, Wilczek, Nobel Prize 2004

Electron Scattering: Microscope for Nuclear and Particle Physics

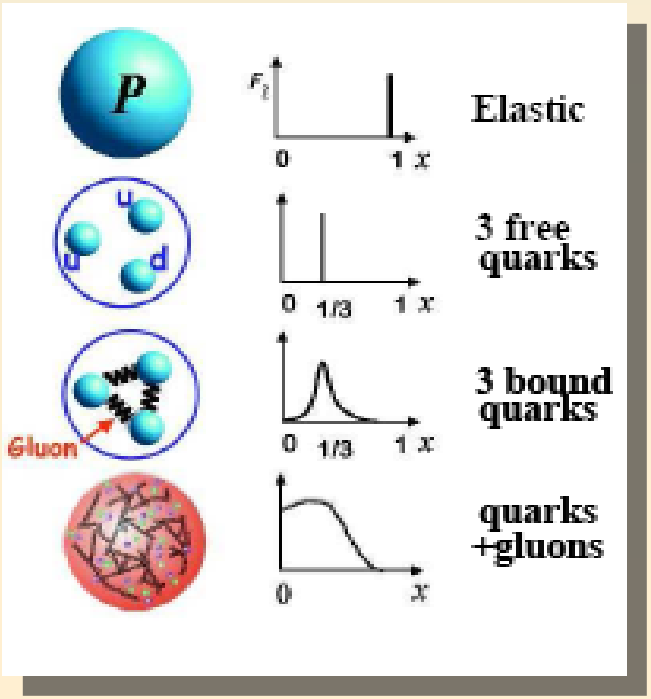


- Electrons are point-like, QED well understood, and is weak.
- Vary *q* to map out Fourier Transform of charge and current densities:

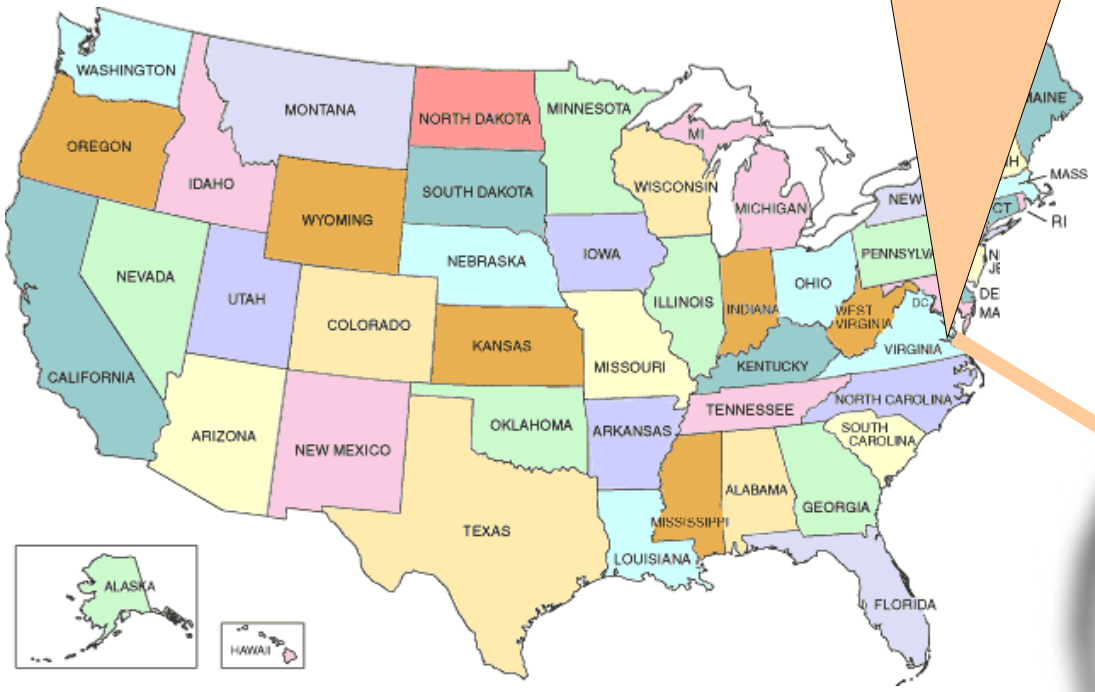
  $\lambda \cong 2\pi / q$ (1 fm ⇔ 1 GeV/c)

$$x_{Bj} = \frac{Q^2}{2P \cdot q}$$

parton momentum fraction



Jefferson Lab



Jefferson Lab: CEBAF

Continuous
Electron
Beam
Accelerator
Facility

Jefferson Lab: CEBAF

HALL A

HALL B

HALL C

Jefferson Lab: CEBAF

HALL D

HALL A

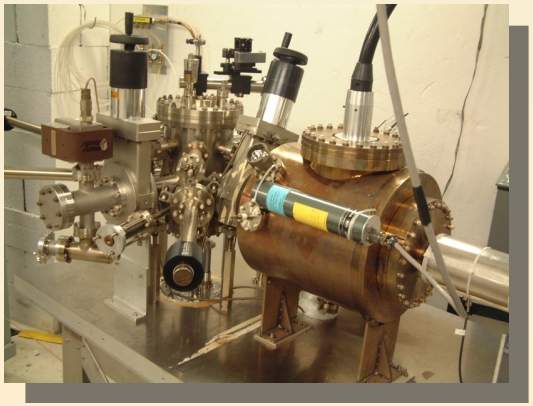
HALL B

HALL C

Polarized Electron Source

B. Matthew Poelker
2011 E. O. Lawrence Award

"For transformative effort to achieve production of electron beams"

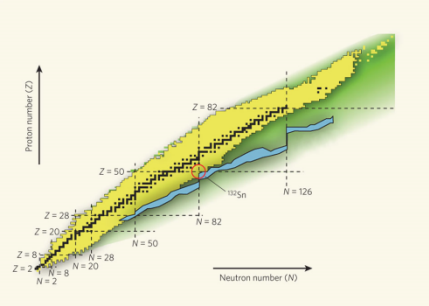


Electron Gun

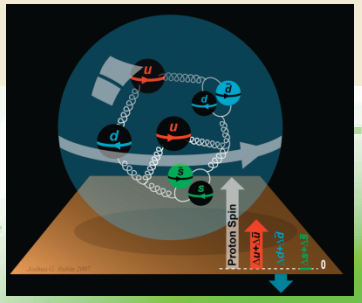
CEBAF is is a powerful electron accelerator with many unique features. See talk of Matt Poelker on Thursday!

Record Performance (2012): 180 μA at 89% polarization

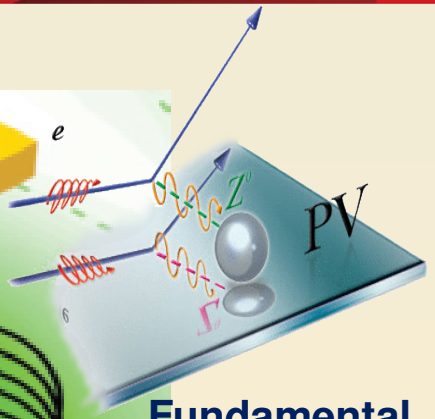
A Laboratory for Nuclear Science



Nuclear Structure



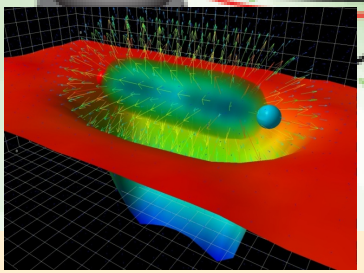
Structure of Hadrons



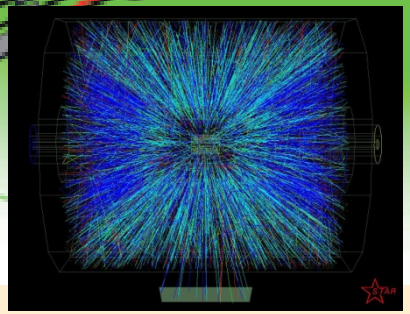
Fundamental Forces & Symmetries

Medical Imaging

Accelerator S&T



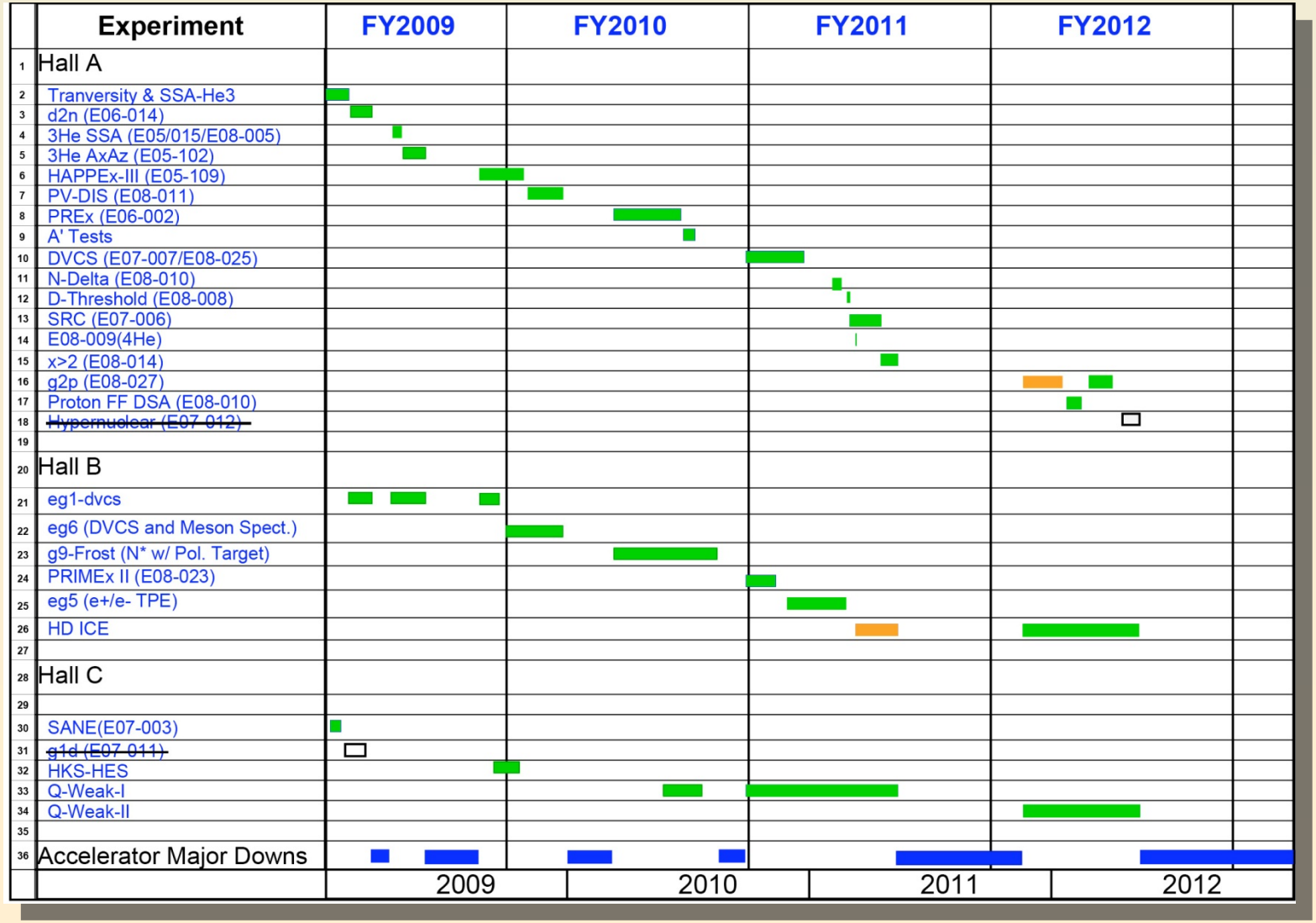
Quark Confinement



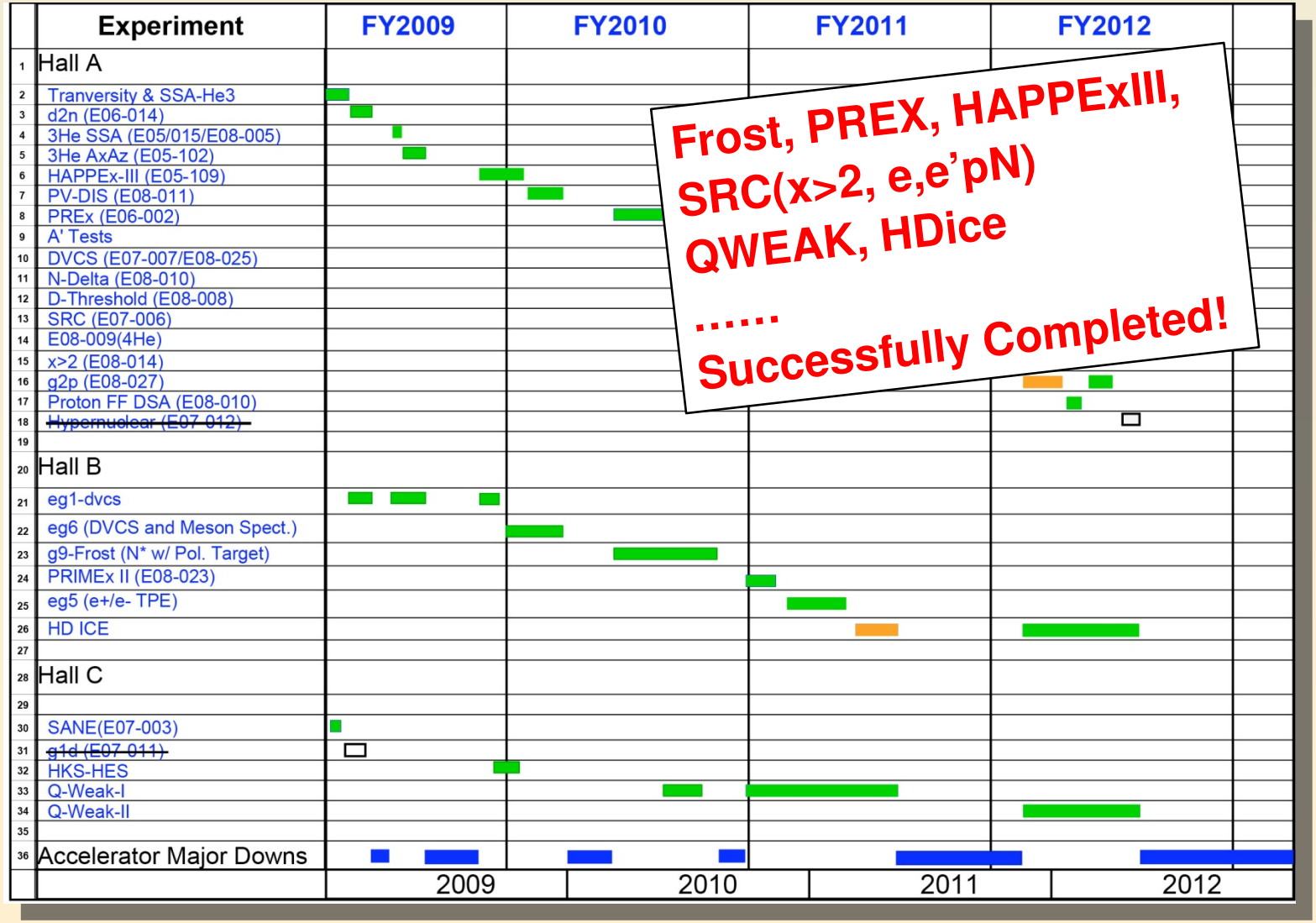
Hadrons from Quarks

Theory and Computation

6 GeV Experimental Nuclear Physics Program (2009-12)



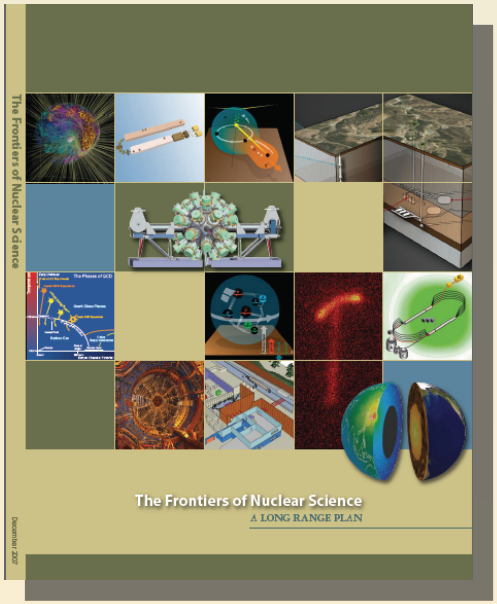
6 GeV Experimental Nuclear Physics Program (2009-12)



JLab: 21st Century Science Questions

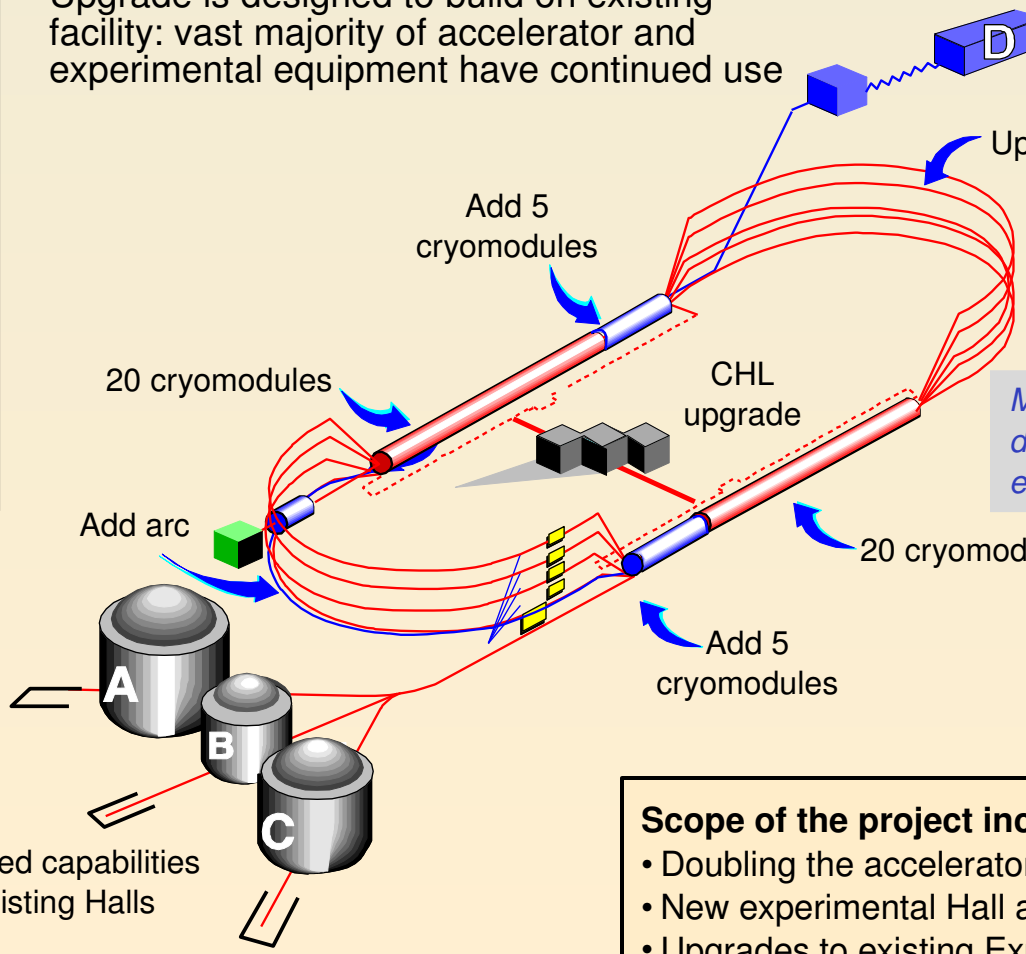
- What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?
- Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?
- Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?
- What is the relation between short-range N-N correlations and the partonic structure of nuclei?
- Can we discover evidence for physics beyond the standard model of particle physics?

12 GeV Upgrade Project



The completion of the 12 GeV Upgrade of CEBAF 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

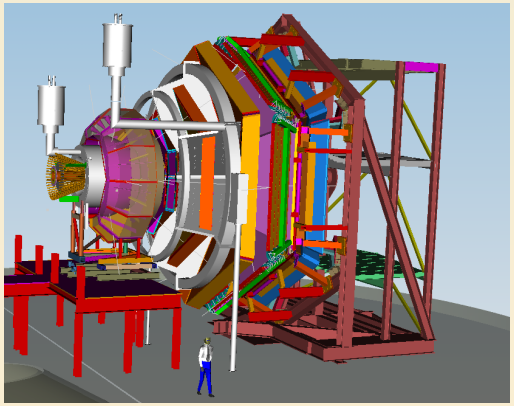


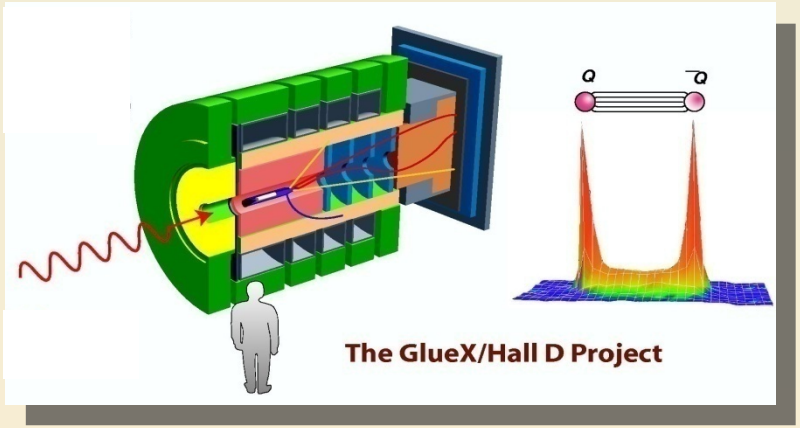
*Maintain capability to deliver lower pass beam energies: **2.2, 4.4, 6.6….***

Scope of the project includes:
- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

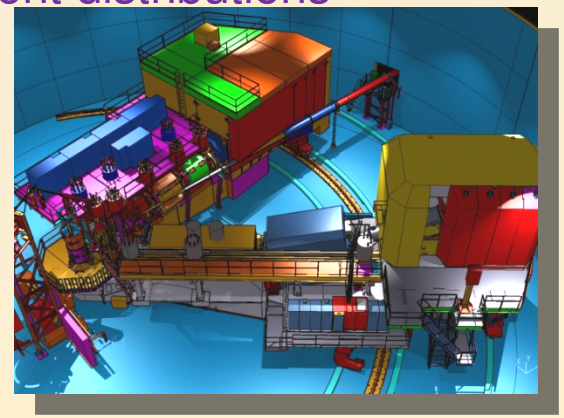
12 GeV Scientific Capabilities

Hall D – exploring origin of confinement by studying exotic mesons

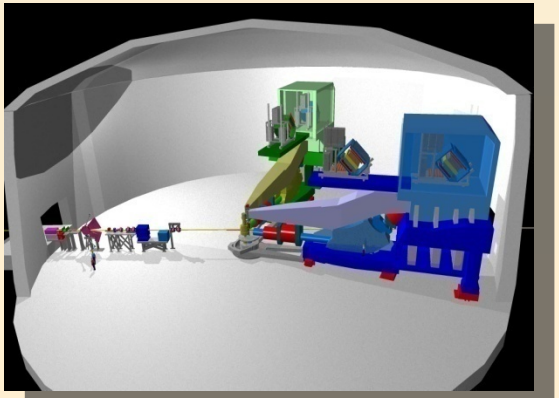




Hall B – understanding nucleon structure via 3D distributions: generalized parton distributions and transverse momentum dependent distributions



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



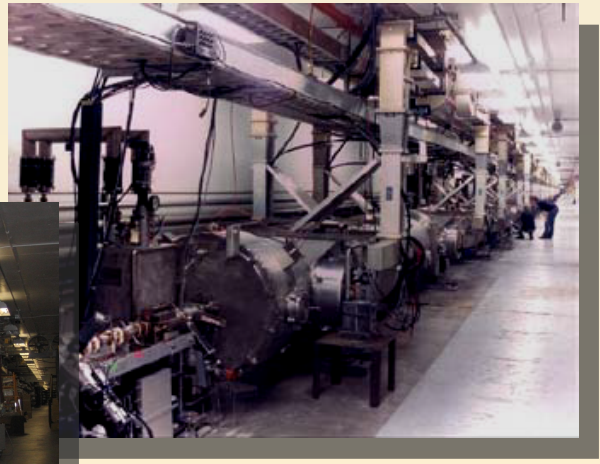
Hall A –form factors, future new experiments (e.g., SoLID and MOLLER)

12 GeV Project Status

Hall D & Counting House

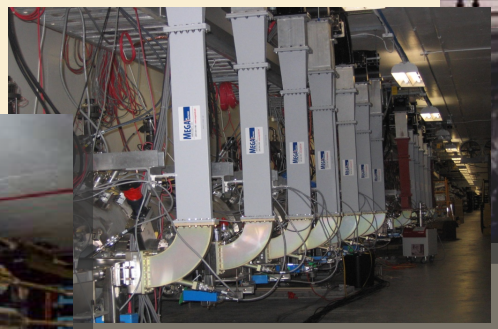
Hall D Interior

12 GeV Cryomodules



Hall D Drift Chamber

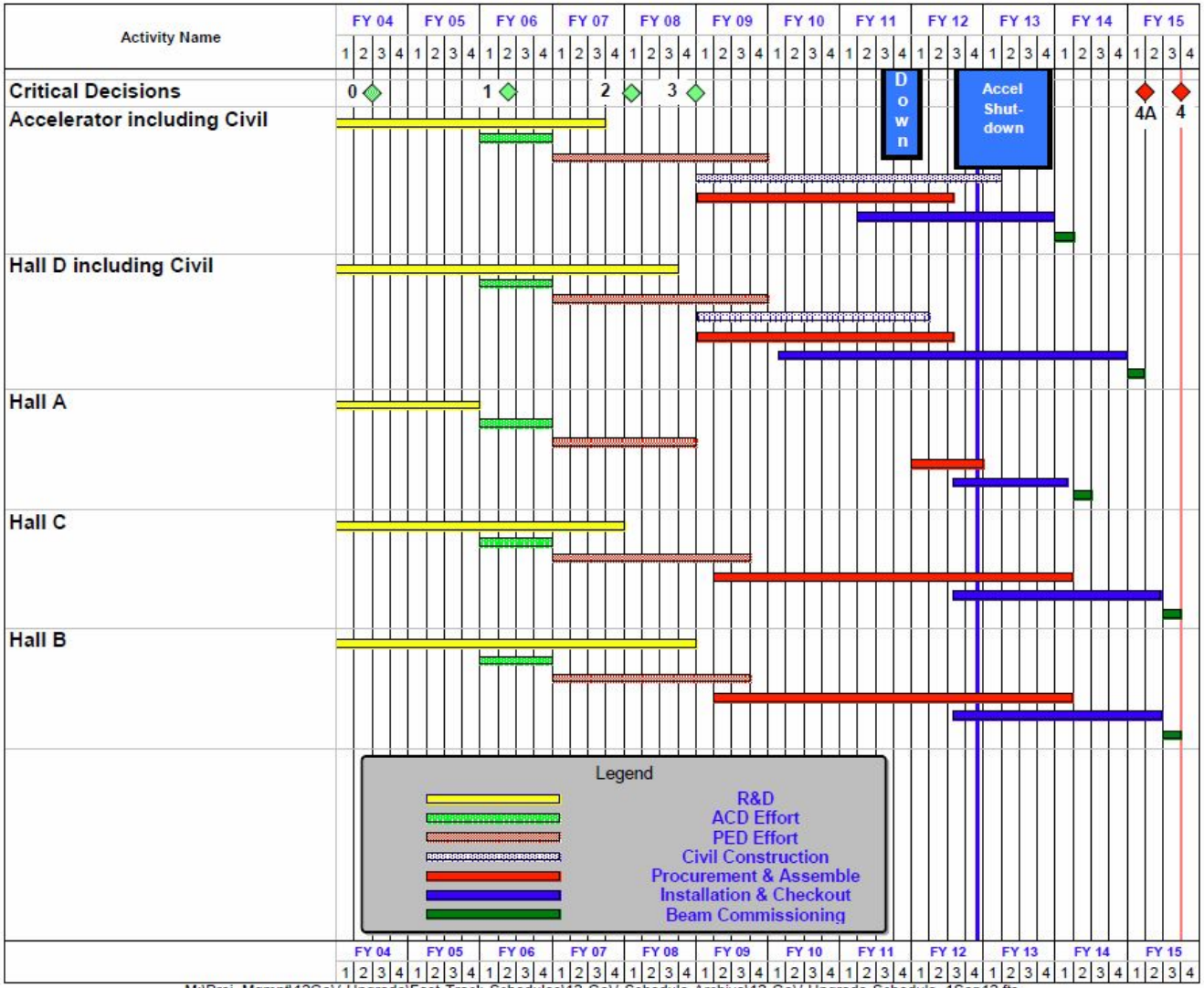
Cryomodule Waveguides



Arc Magnets

- Performance Index: schedule 96%; cost 96%
- Project Construction 58% complete
- Civil 94% complete

12 GeV Upgrade Project Schedule



FY12: reduction of $16M
FY13: Pres Request

~~12~~ 16-month installation
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

Next DOE Project Review
November 27-29, 2012

12 GeV Science Program

- The physical origins of quark confinement (GlueX, meson and baryon spectroscopy)
- The spin and flavor structure of the proton and neutron (PDF's, GPD's, TMD's…)
- The quark structure of nuclei
- Probe potential new physics through high precision tests of the Standard Model

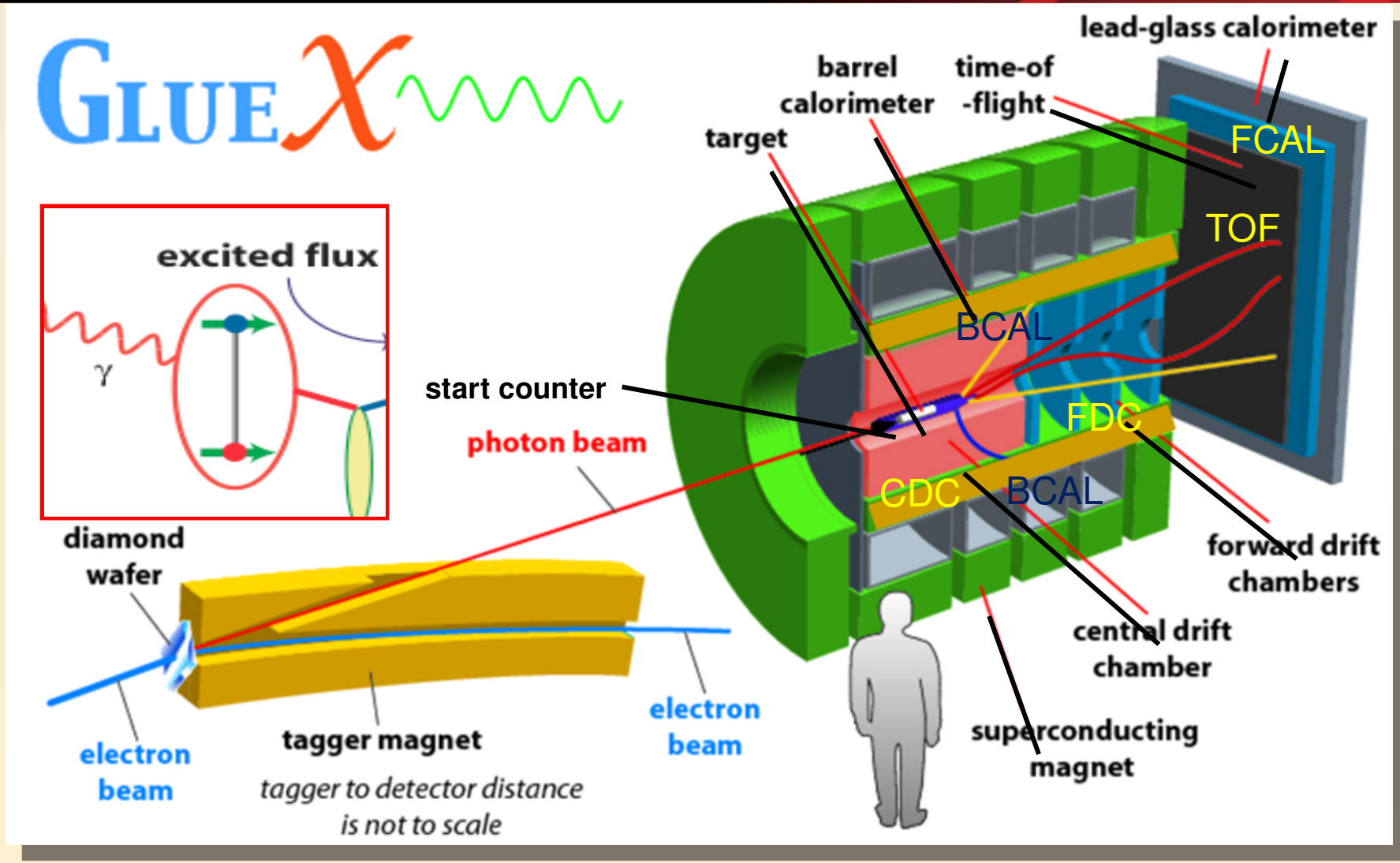
- Defining the Science Program:
  - Eight Reviews: Program Advisory Committees (PAC) - 2006 through 2011
  - Results: *52 experiments approved; 15 conditionally approved*
  - White paper for NSAC subcommittee

Experiments for 4 Halls approved for more than seven years of operation beginning in FY15.

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
Total	**16**	**18**	**16**	**2**	**52**

Hall D



9 GeV photons at a rate of 10^7 photons per second

Quantum Numbers of Hybrid Mesons

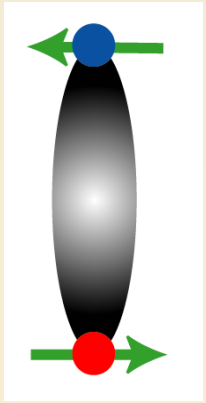
Quarks ⊕ **Excited Gluon Field** → **Hybrid Meson**

$S = 0$

$L = 0$

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

like π, K



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

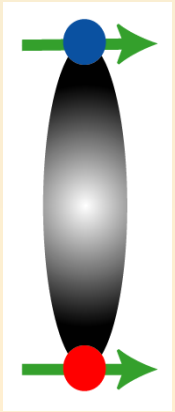
$J^{PC} = \begin{cases} 1^{--} \\ 1^{++} \end{cases}$

$S = 1$

$L = 0$

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

like γ, ρ



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

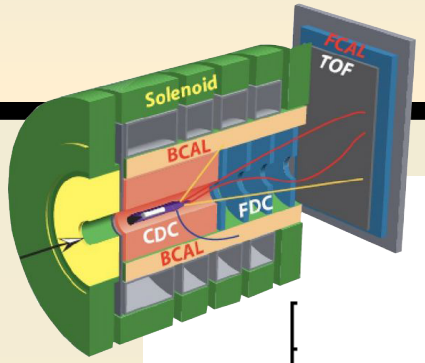
Exotic

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

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

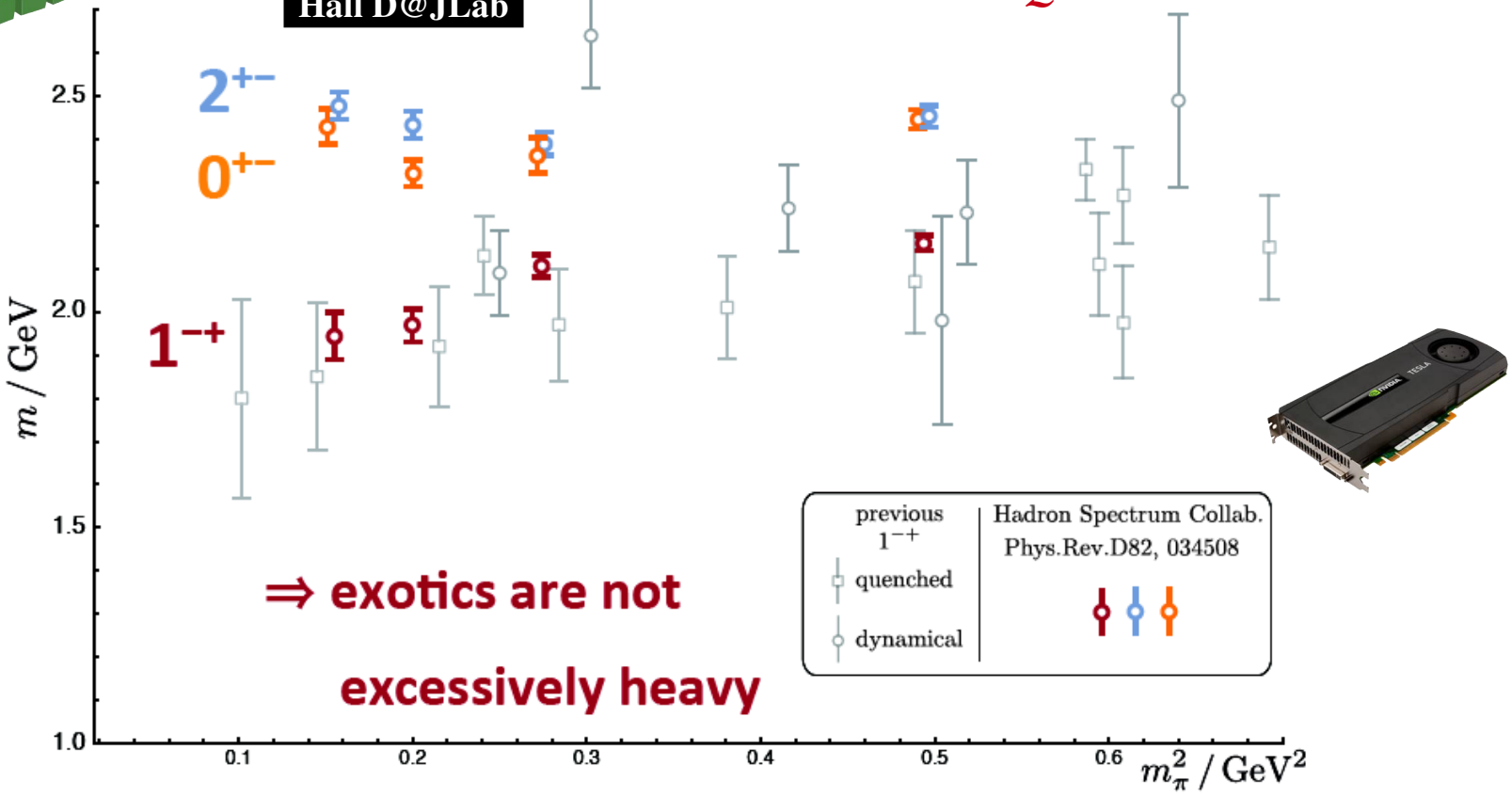
GlueX is optimised for exotics, polarised photon beam

Isovector Meson Spectrum



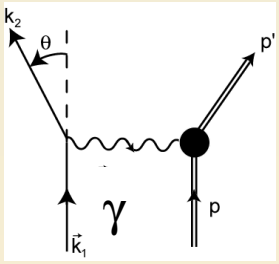
GlueX Collaborations Experiment
Hall D@JLab

States with Exotic Quantum Numbers

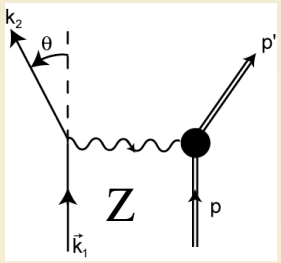


Dudek et al

Parity Violation Experiments



X



$A_{pv} \sim Q^2/M_W^2 \sim 10^{-4}Q^2$

γZ interference term

Sign depends on helicity; ie parity violation Asymmetry

Depends on exquisite control and stability of beams, spin flip at 960 Hz

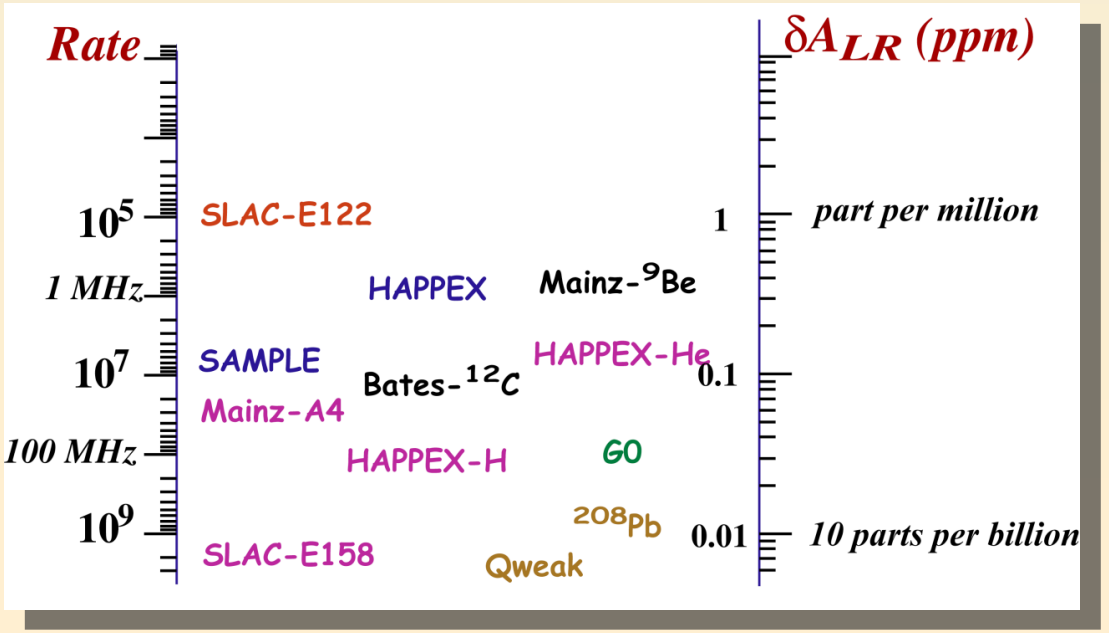
Seminal Demonstration

SLAC E122

Deep Inelastic Scattering deuterium target

C. Y. Prescott et al, 1978

$Q^2 \sim 1\ GeV^2$

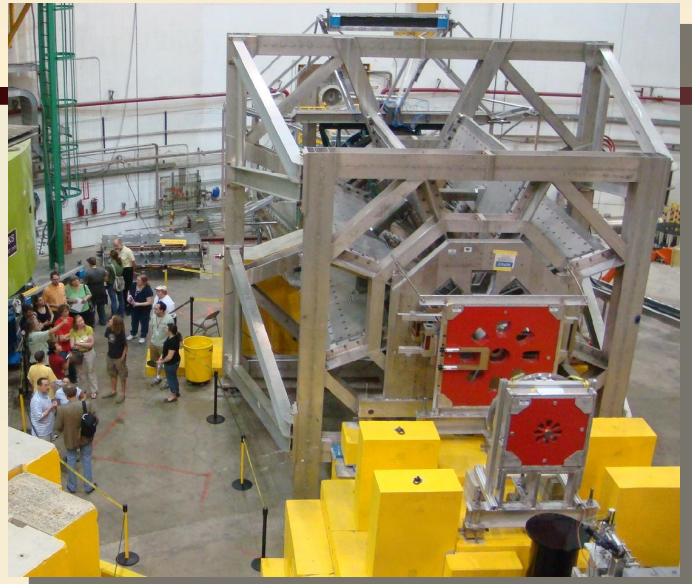


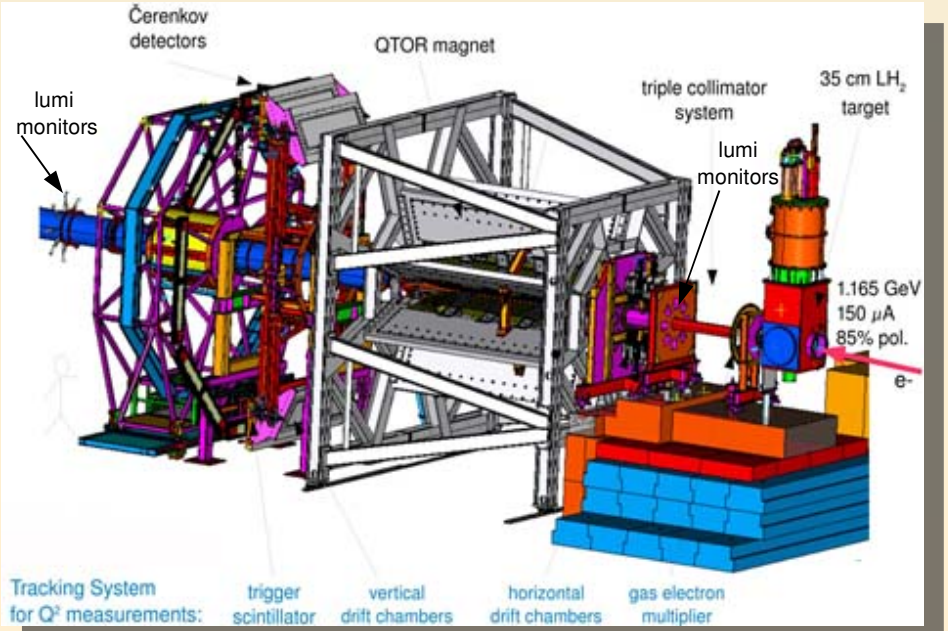
Qweak

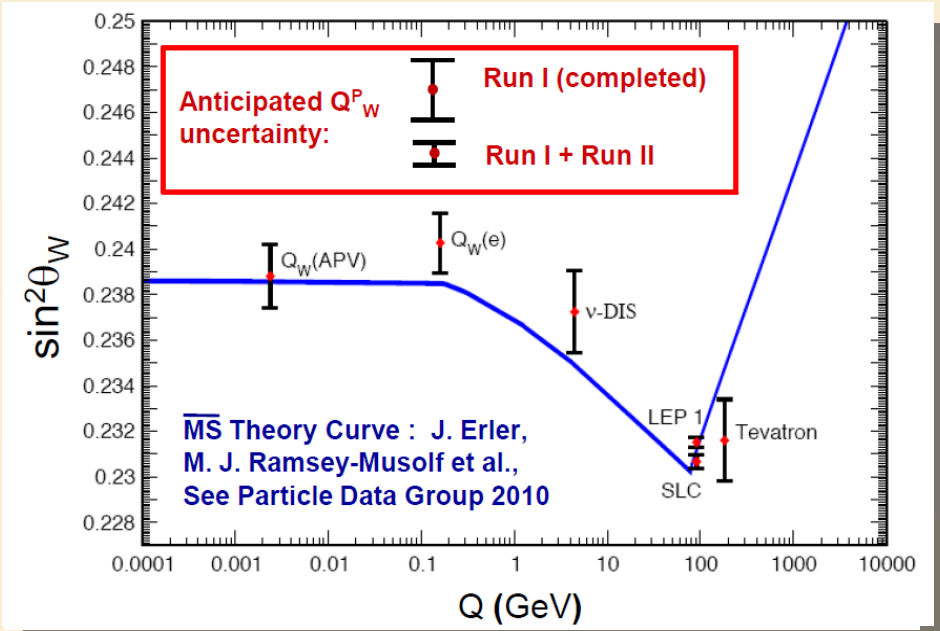
Silviu Covrig
DoE Early Career Award 2012

Precise determination of the weak charge of the proton

$$Q^p_w = (1 - 4 \sin^2 \theta_W)$$



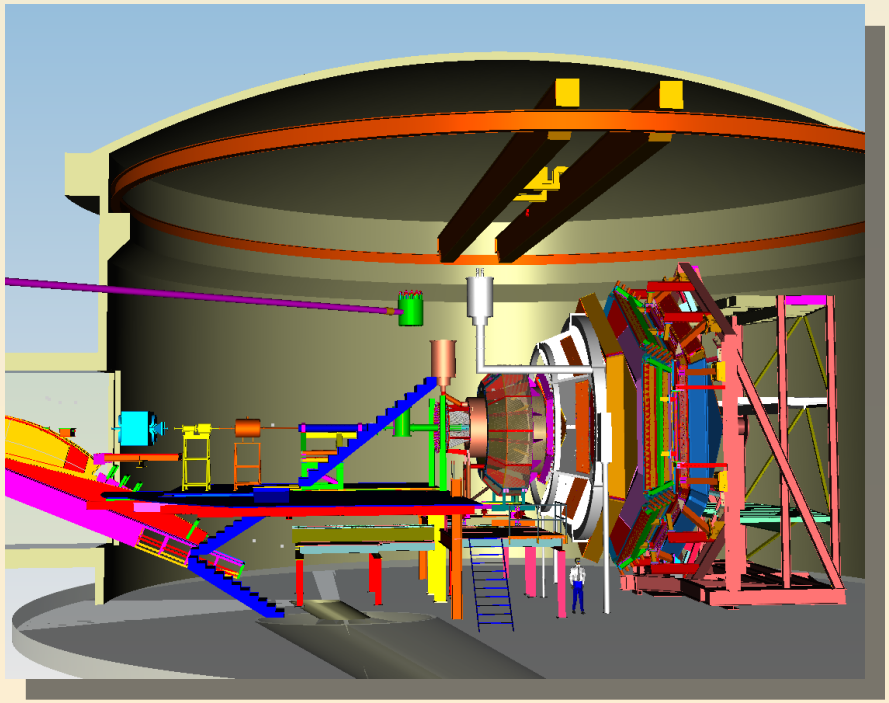




Jefferson Lab

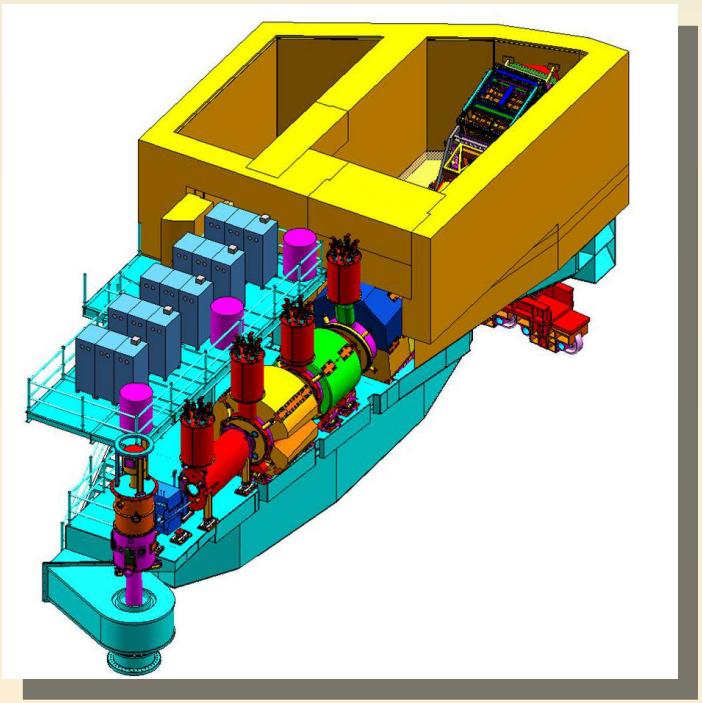
Halls B and C

Hall B
CLAS12 = CEBAF Large Acceptance Spectrometer



- **Key Features:**
  - 1 torus & 1 solenoid magnet
  - new detectors: Cerenkovs, calorimeters, drift chambers, silicon vertex tracker
    - -- re-use some existing detectors
  - hermetic device, low beam current, high luminosity

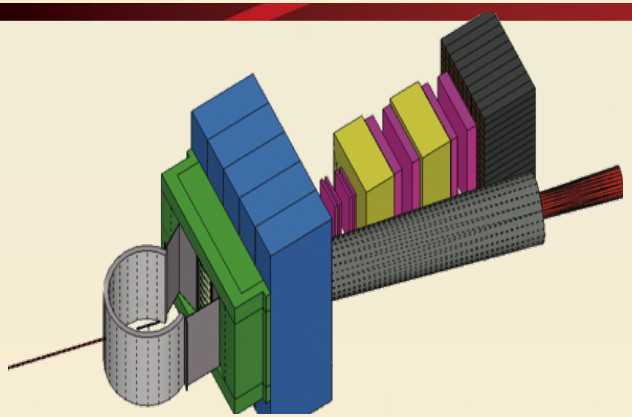
Hall C
SHMS = "Super High Momentum Spectrometer"



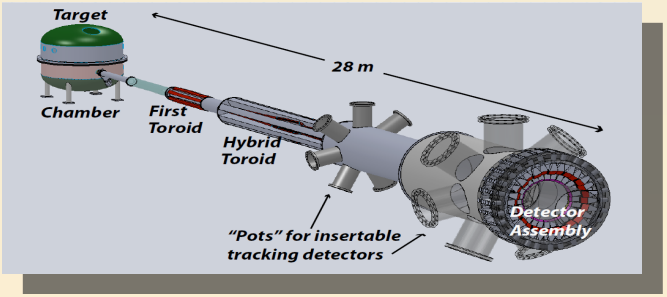
- **Key Features:**
  - 3 quadrupole & 1 dipole & 1 horizontal bend magnet
  - new 6 element detector package
  - complementary to existing spectrometer (HMS)
  - rigid support structure
  - well-shielded detector enclosure

Hall A – New Instrumentation

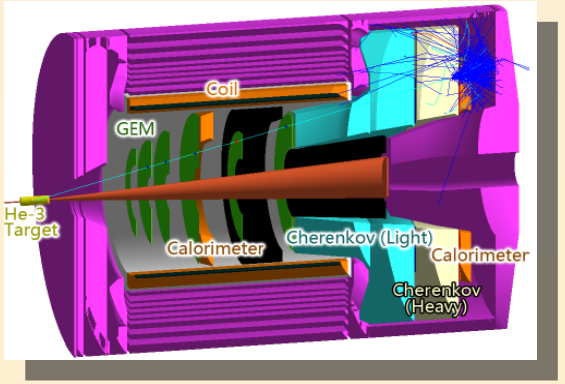
- **Super BigBite Spectrometer**
  - Extend form factors
  - TMD studies



- **MOLLER experiment**
  - PV e-e scattering
  - Precise standard model test

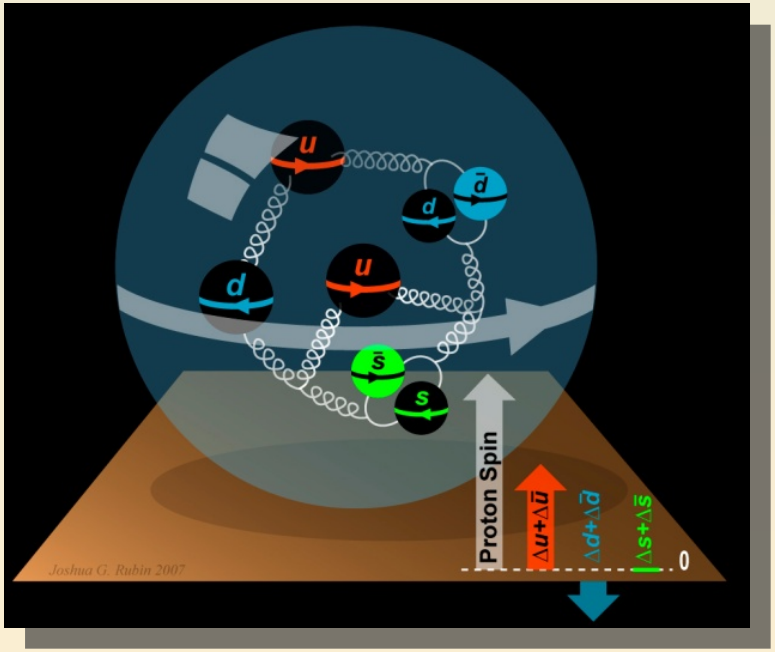


- **SoLID**
  - PV e-quark scattering
  - High precision TMD studies



TMD = Transverse Momentum Dependence
PV = Parity Violating

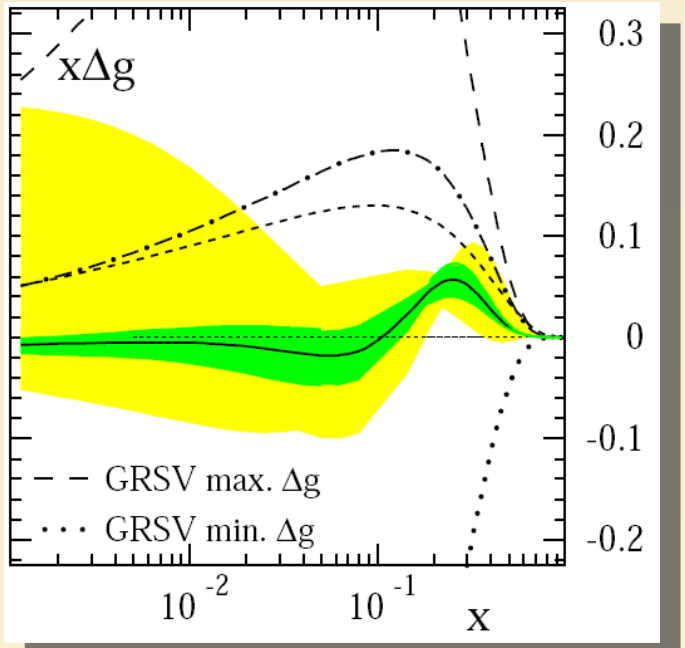
The Incomplete Nucleon: Spin Puzzle



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

[Xiandong Ji, 1997]

See talk by Elliot Leader

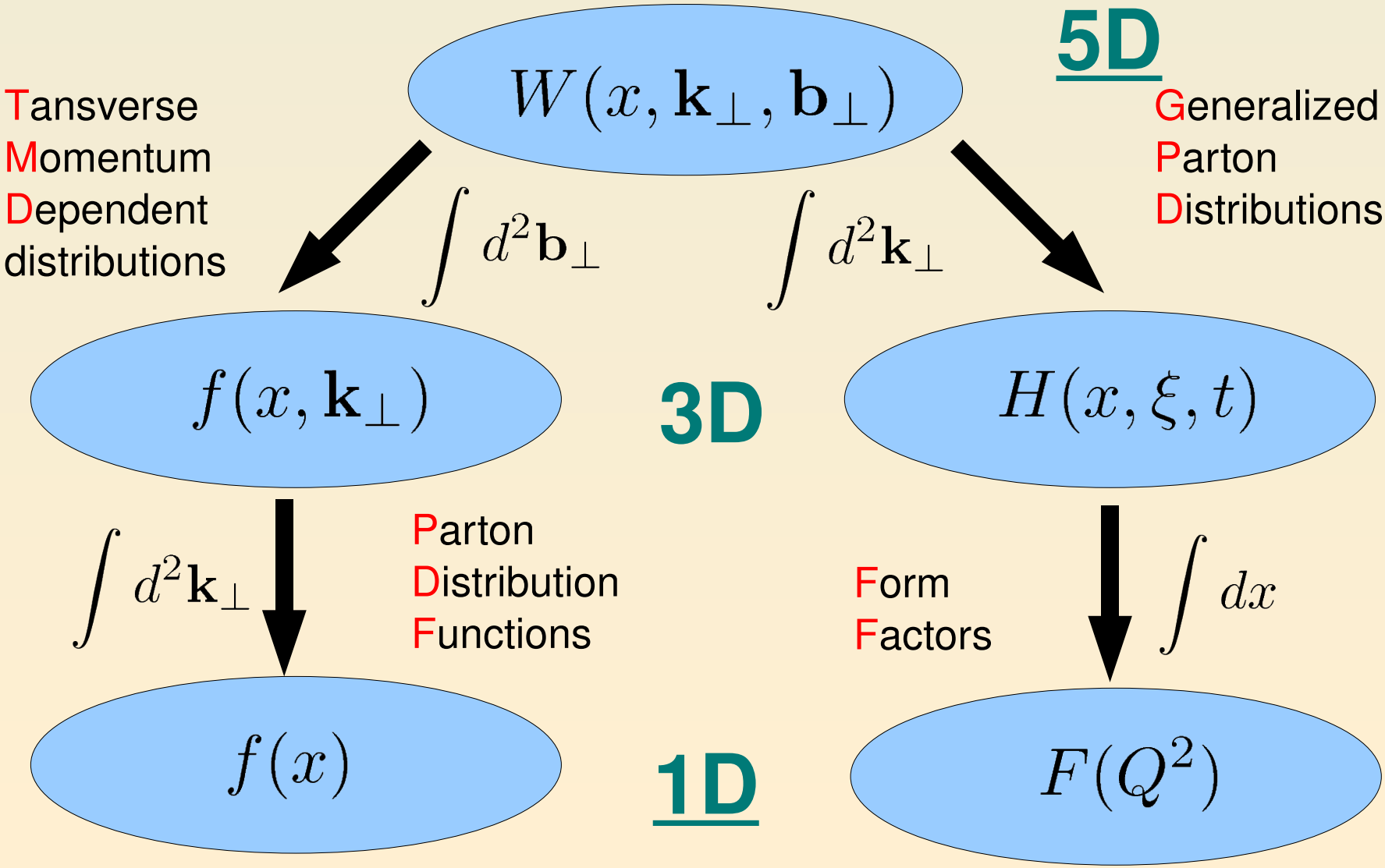


D. de Florian et al., PRL 101 (2008) 072001

- DIS → $\Delta\Sigma \cong$ 0.25
- RHIC + DIS → $\Delta G \ll 1$
- → L_q

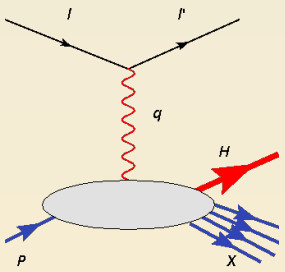
$$J^q = \frac{1}{2}\int_{-1}^{+1} dx\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)] = \Delta\Sigma^q/2 + L^q$$

Unified View of Nucleon Structure



Unified View of Nucleon Structure

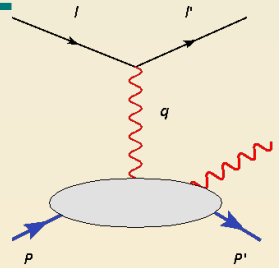
TMD



$W(x, \mathbf{k}_\perp, \mathbf{b}_\perp)$

5D

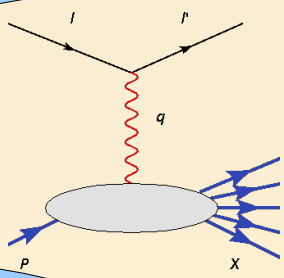
GPD

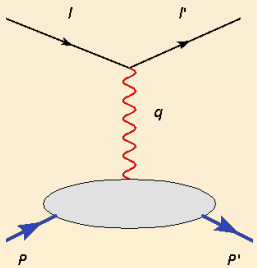


$f(x, \mathbf{k}_\perp)$

3D

$H(x, \xi, t)$





PDF

FF

$f(x)$

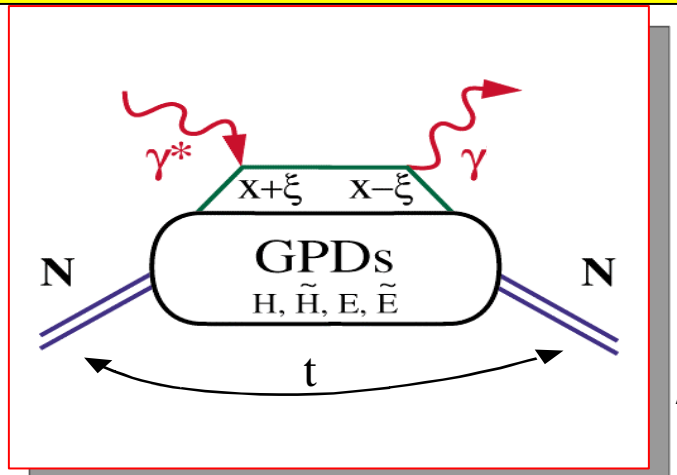
1D

$F(Q^2)$

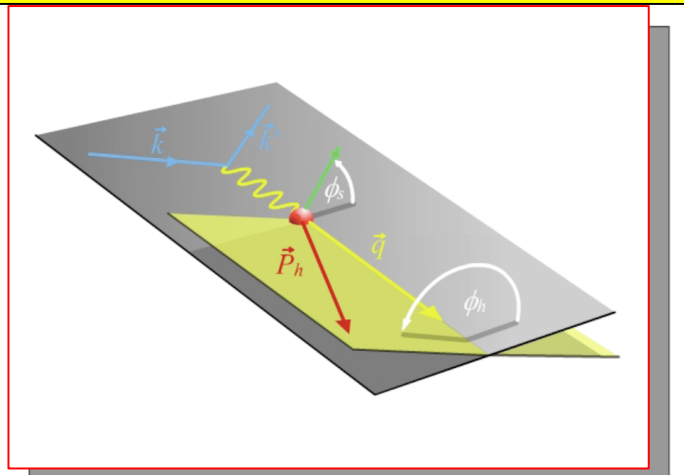
Particular processes to study. Polarization is required!

Extraction of GPDs and TMDs

Deeply Virtual Compton Scattering



Semi Inclusive DIS



Asymmetries

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

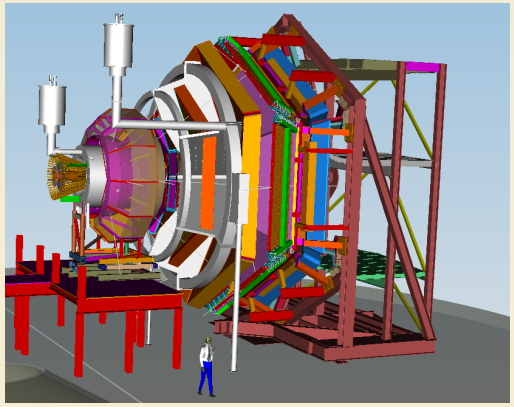
$H(\xi,t)$ $\quad \tilde{H}(\xi,t)$

$E(\xi,t)$ $\quad \tilde{E}(\xi,t)$

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 $h_{1T}^{\perp}$

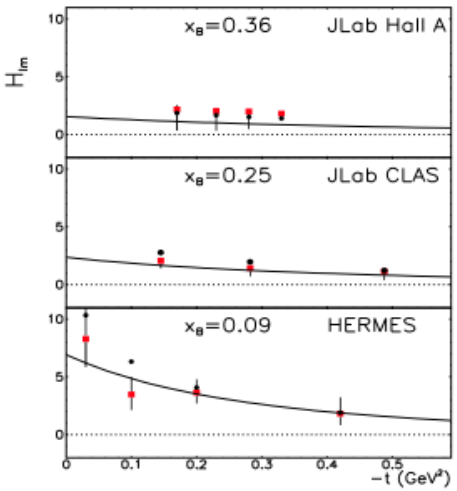
DVCS beam asymmetry at 12 GeV

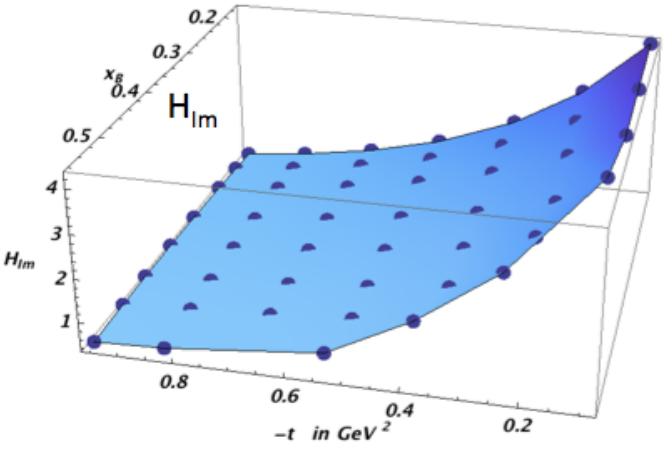
CLAS12

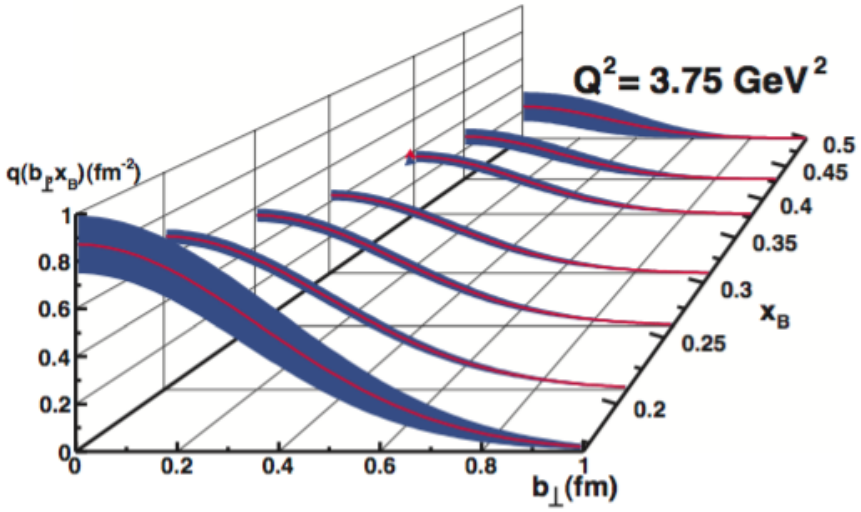


$\vec{e}p \longrightarrow epγ$

High luminosity and large acceptance allows wide coverage in $Q^2 < 8$ GeV^2, $x_B < 0.65$, and $t < 1.5$GeV^2



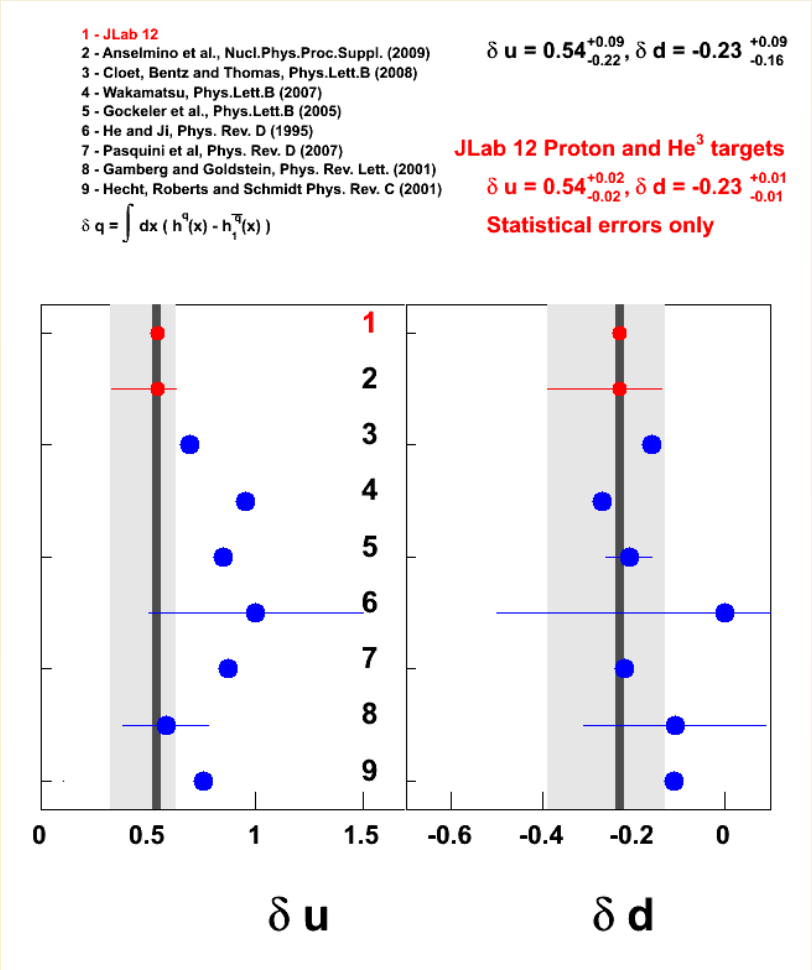


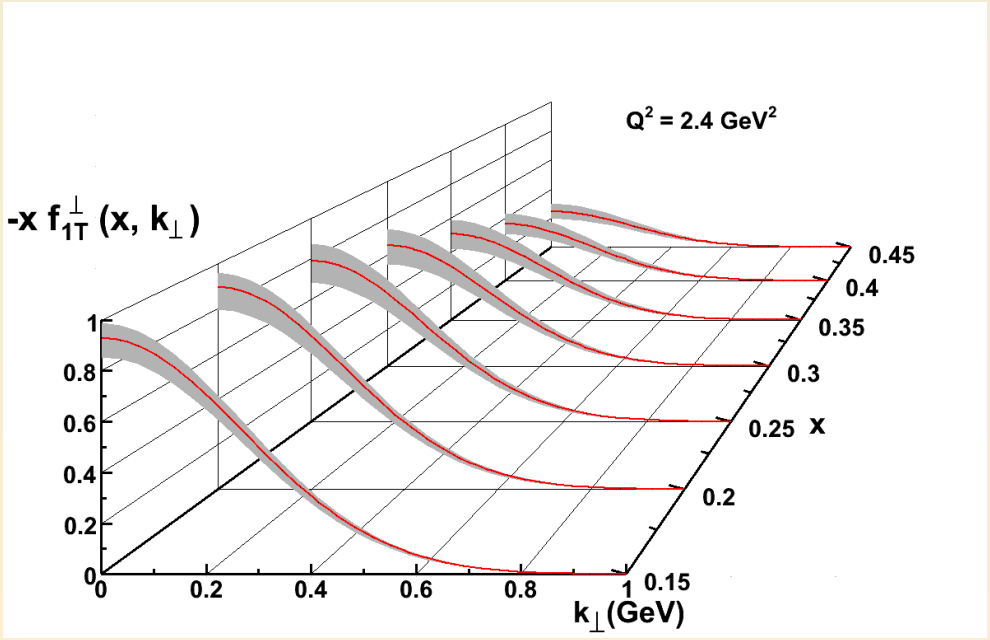


Jefferson Lab

SIDIS Electroproduction of Pions

Expected result for tensor charge extraction:

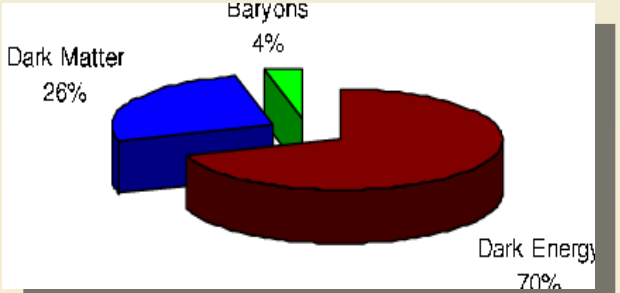


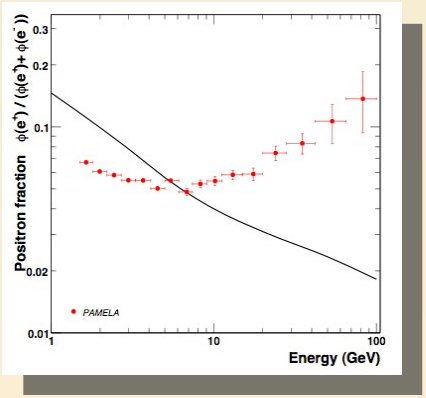


Expected accuracy of TMD profile

Cosmology and Dark Matter

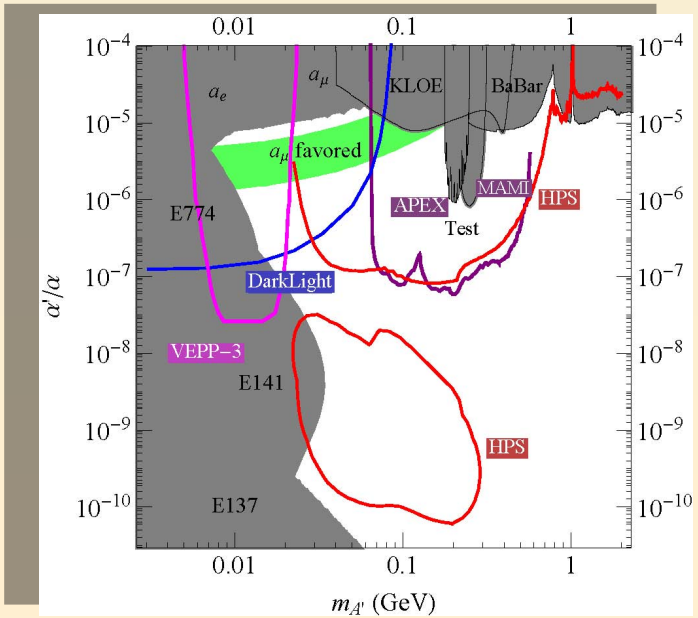
Dark sector is new physics beyond the standard model.
Many direct searches for dark matter interacting with sensitive detectors
(hints, no established signal yet…)





Signal of astrophysical positron excess.

Possible solution: a massive neutral vector boson A’ with low mass ($M_{A'} < 1$ GeV)



3 Jefferson Lab proposals

- APEX (Hall A) – test run published
- HPS (Hall B) – tested with photon beam
- DarkLight (FEL) – test run complete

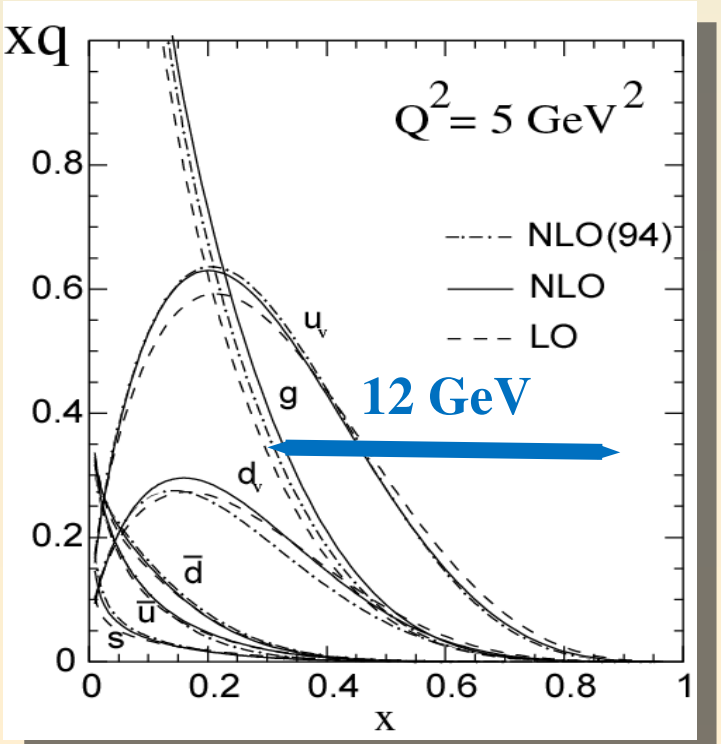
12 GeV JLab – The Potential

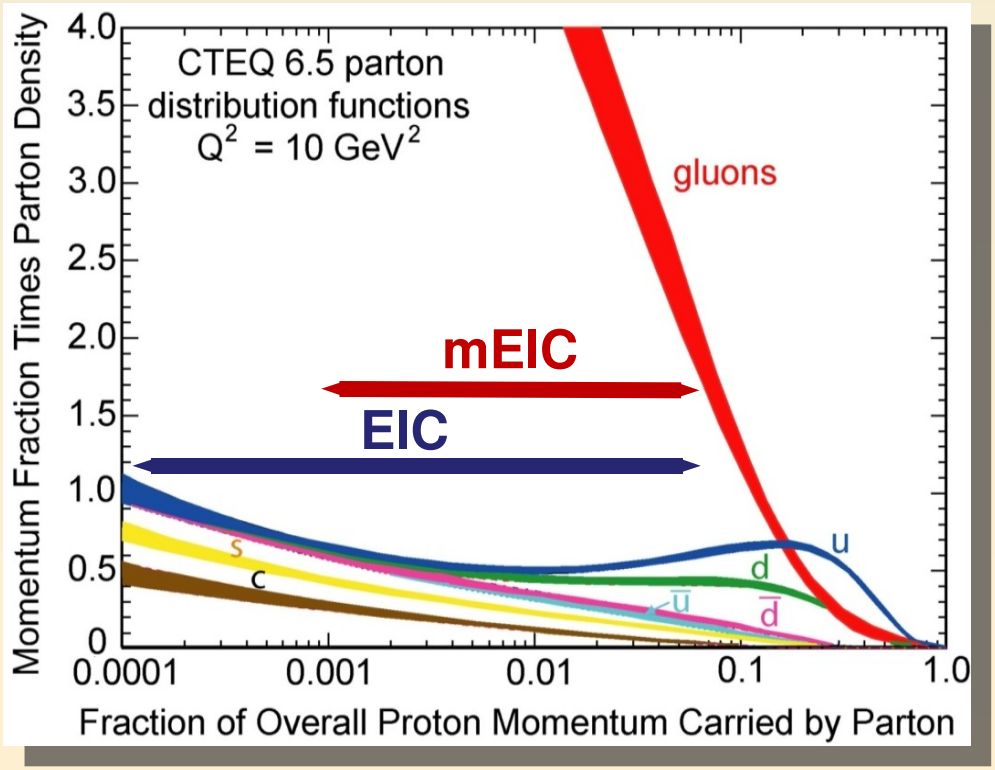
- Opportunity to discover and study new exotic mesons to elucidate the mechanism of confinement.
- Open a new landscape of nucleon tomography, with potential to identify the missing angular momentum.
- Establish the quantitative foundation for the short-distance behavior in nuclei, underpinning the development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

Into the "sea": Electron Ion Collider

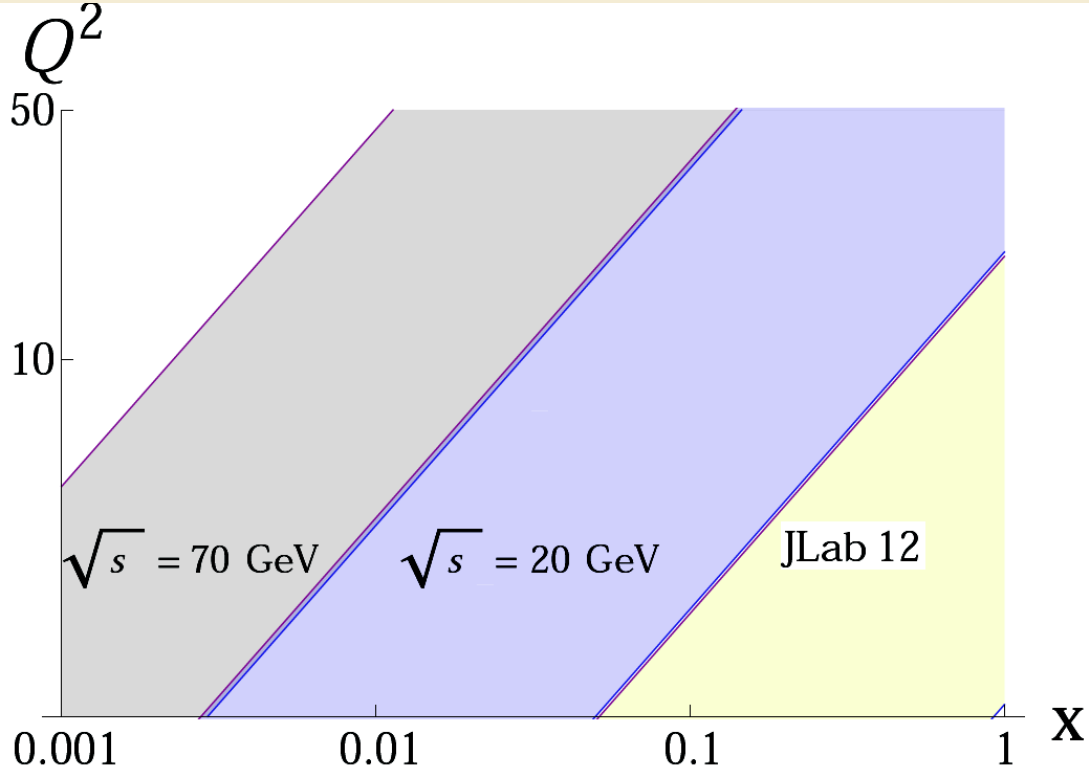
With 12 GeV we study mostly the valence quark component

An EIC aims to study the sea quarks, gluons, and scale dependence.



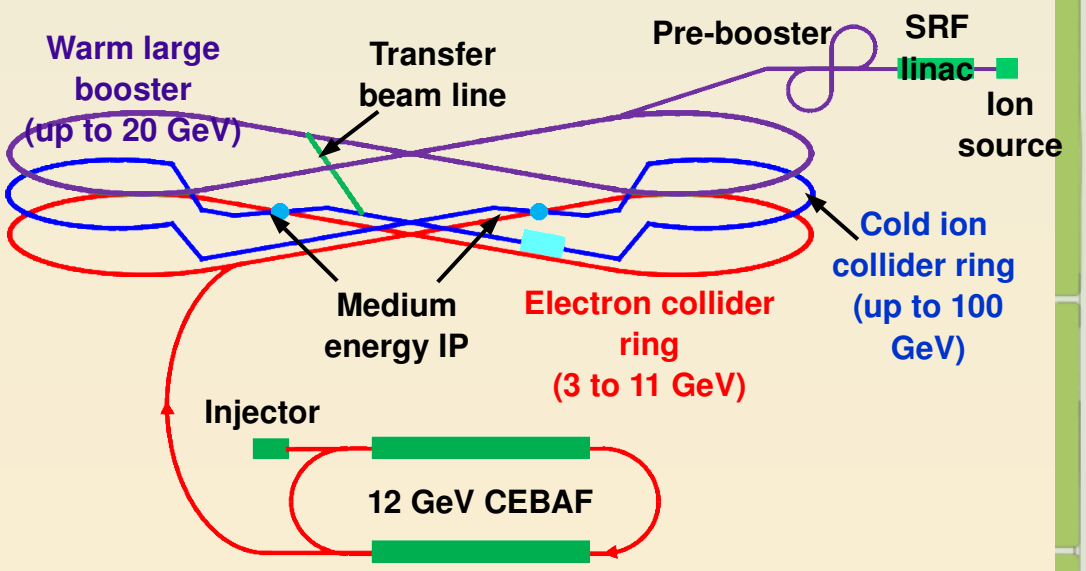


Into the “sea”: Electron Ion Collider



JLab 12 and future Electron Ion Collider are complimentary

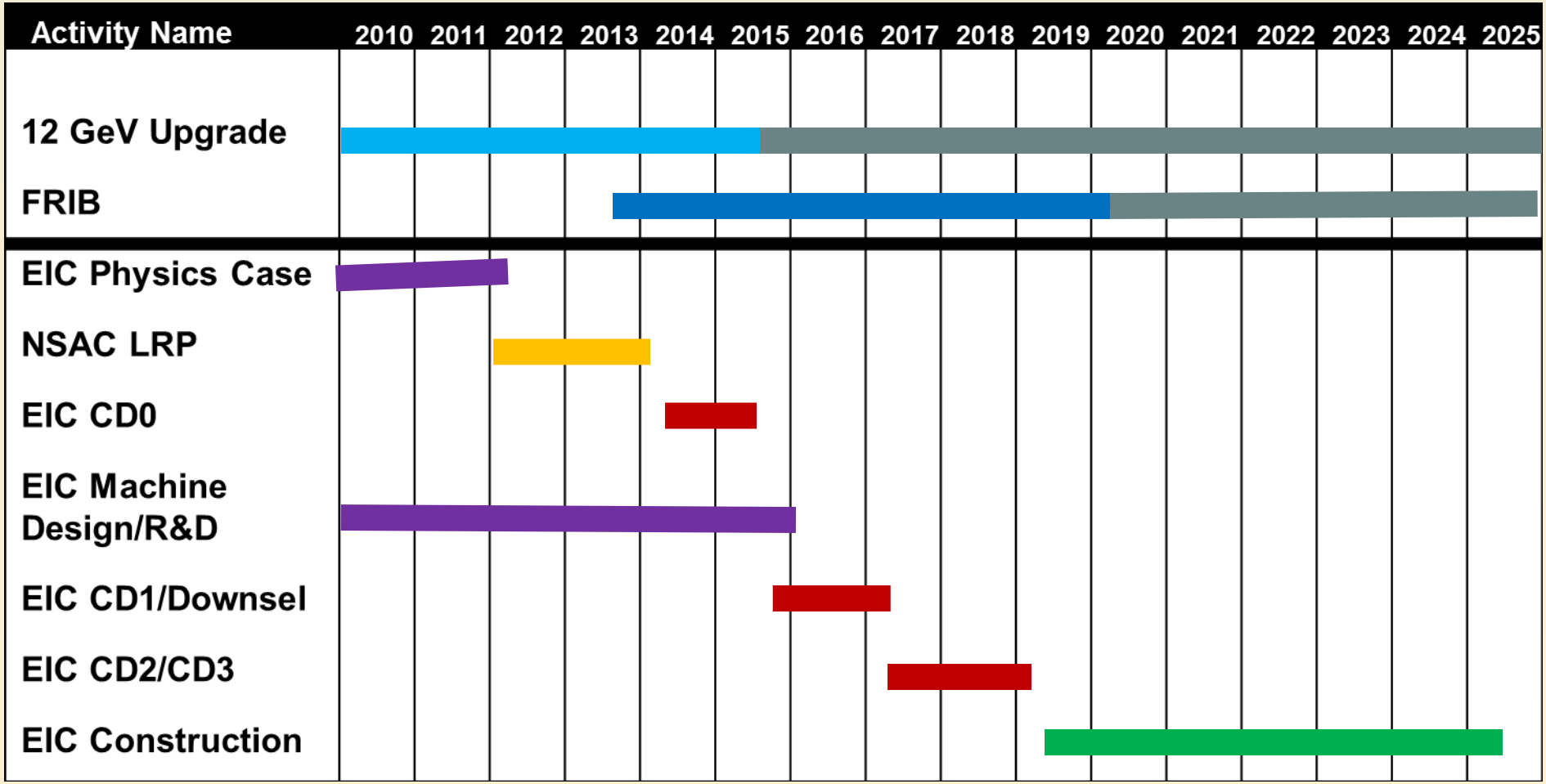
Medium Energy EIC@JLab



JLab Concept

- Initial configuration (MEIC):
  - 3-11 GeV on 20-100 GeV ep/eA collider
  - fully-polarized, longitudinal and transverse
  - luminosity: up to few x 10^{34} e-nucleons cm^{-2} s^{-1}
- Upgradable to higher energies (250 GeV protons)

Jefferson Lab Electron Ion Collider

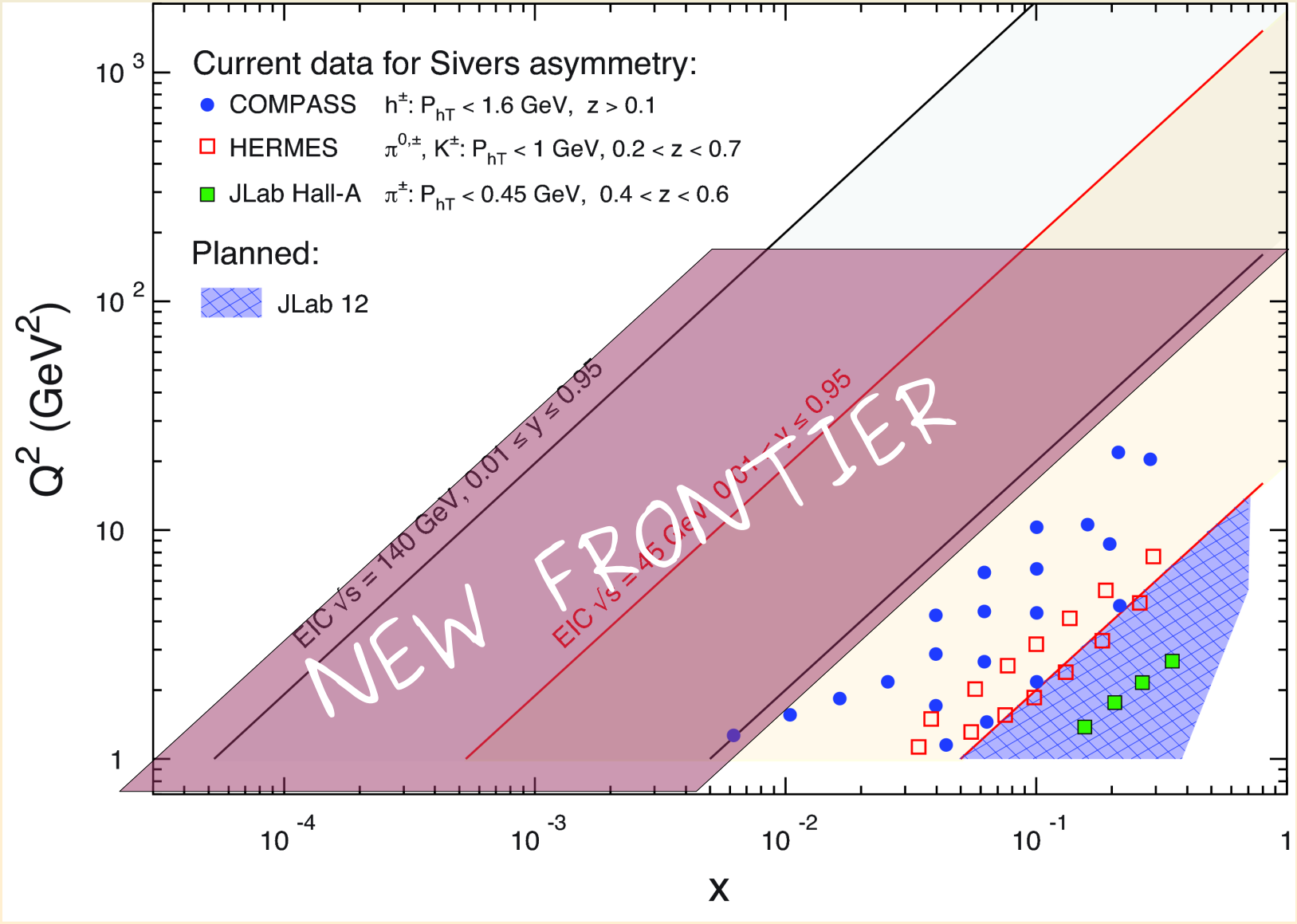


A Laboratory for Nuclear Science

- The Jefferson Lab electron accelerator is a unique world-leading facility for nuclear physics research and related applications
- 12 GeV Upgrade ensures at least a decade of excellent opportunities for discovery
  - New vistas in QCD
  - Growing program Beyond the Standard Model
- EIC moving forward:
  - Strong science case, much builds on JLab 12 GeV program
  - MEIC design well developed – time scale following 12 GeV program is "natural"
- Accelerator Science and Technology
  - JLab: CEBAF and FEL
  - SRF development

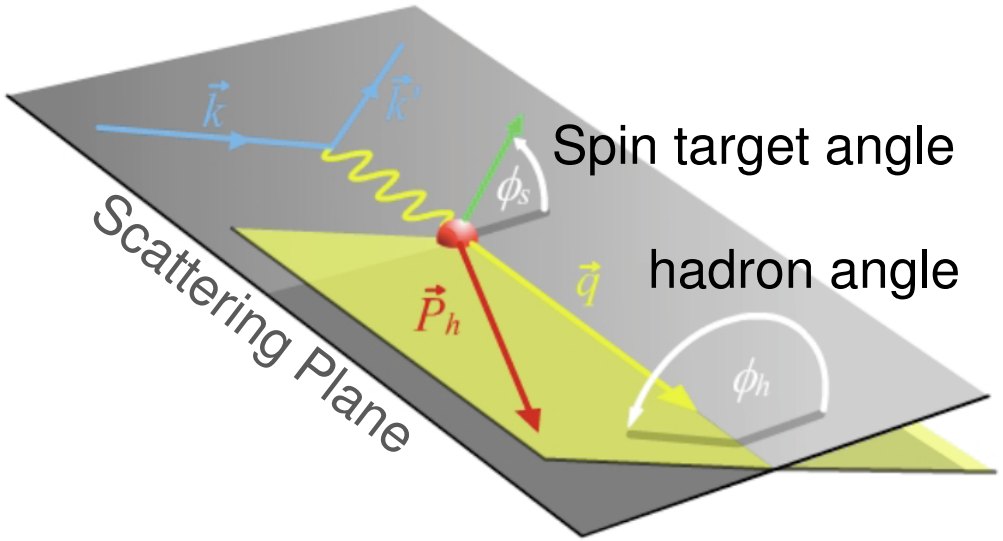
Spares Follow

Into the “sea”: Electron Ion Collider



SIDIS Electroproduction of Pions

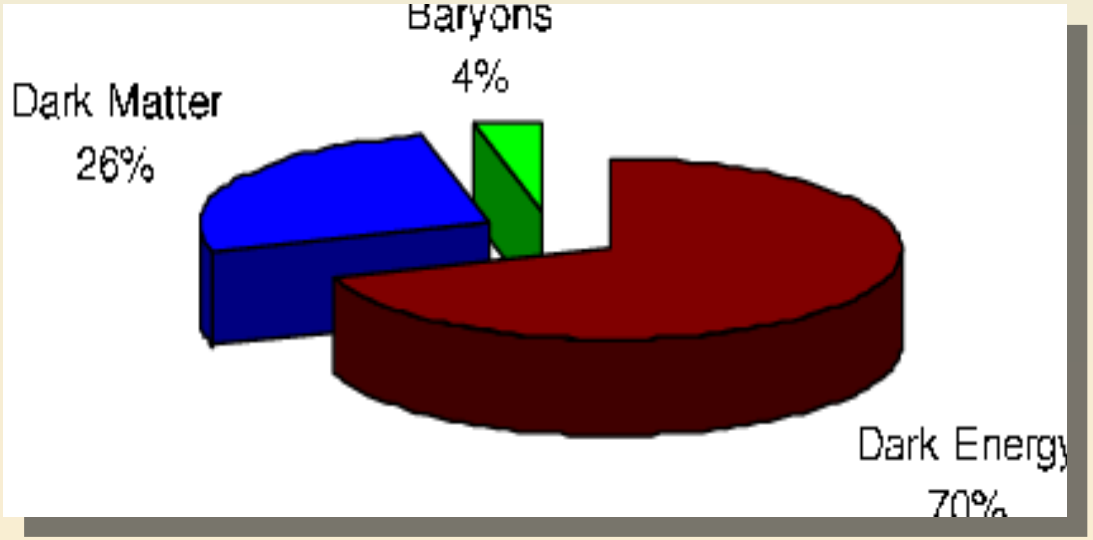
- Separate Sivers and Collins effects



- Previous data from HERMES,COMPASS
- New landscape of TMD distributions
- Access to orbital angular momentum

- **Sivers** angle, effect in distribution function: $(\phi_h - \phi_s)$
- **Collins** angle, effect in fragmentation function: $(\phi_h + \phi_s)$

Cosmology and Dark Matter

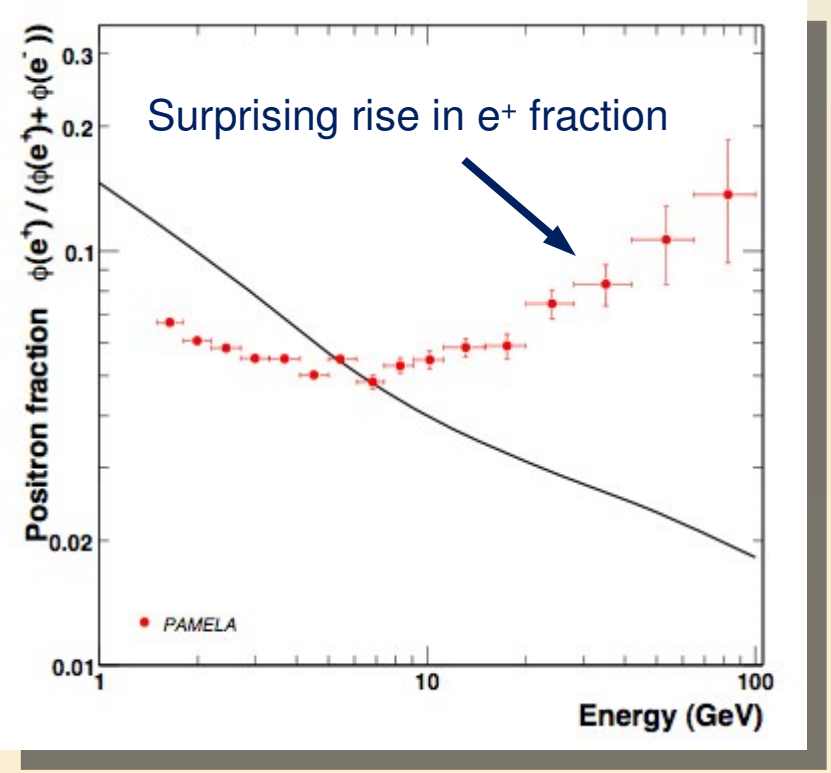


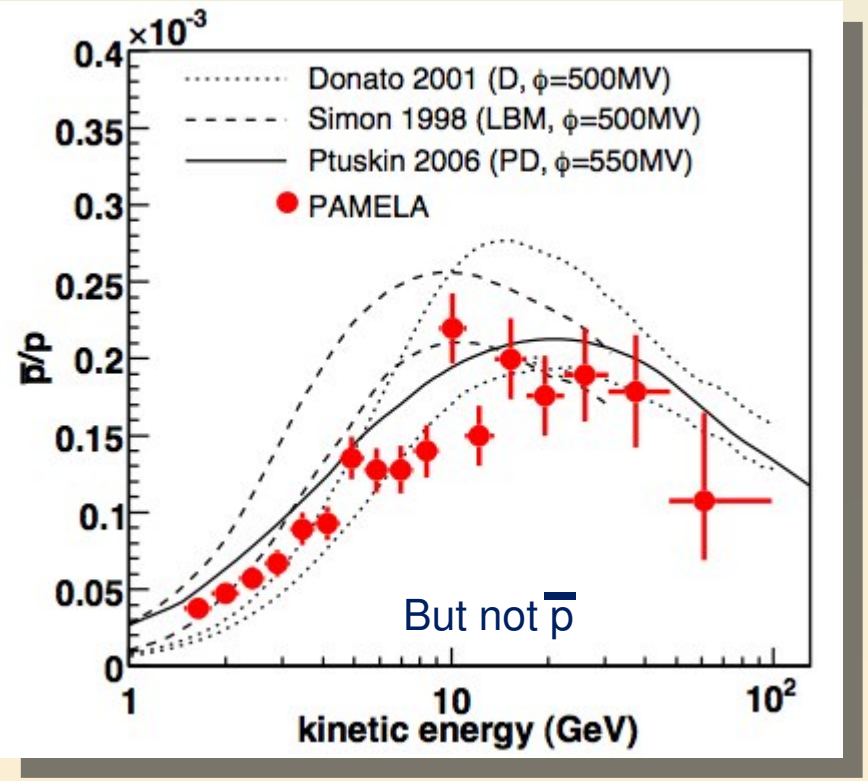
Dark sector is new physics, beyond the standard model

Many direct searches for dark matter interacting with sensitive detectors (hints, no established signal yet…)

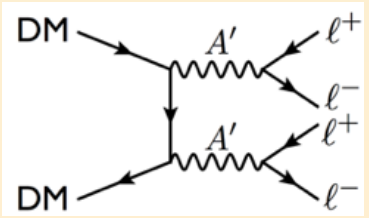
Controversial evidence for excess astrophysical positrons…

PAMELA Data on Cosmic Radiation



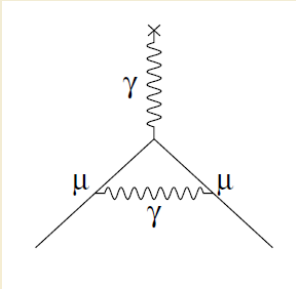


- Could indicate low mass A' ($M_{A'} < 1$ GeV)
  - Or local astrophysical origin??



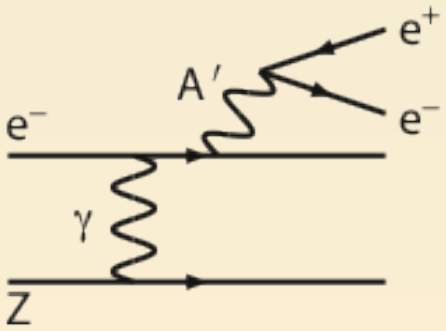
New Opportunity: Search for A' at Jefferson Lab

BNL "g-2" expt: Δa_μ(expt-thy) = (295±88) x 10^{-11} (3.4 σ)

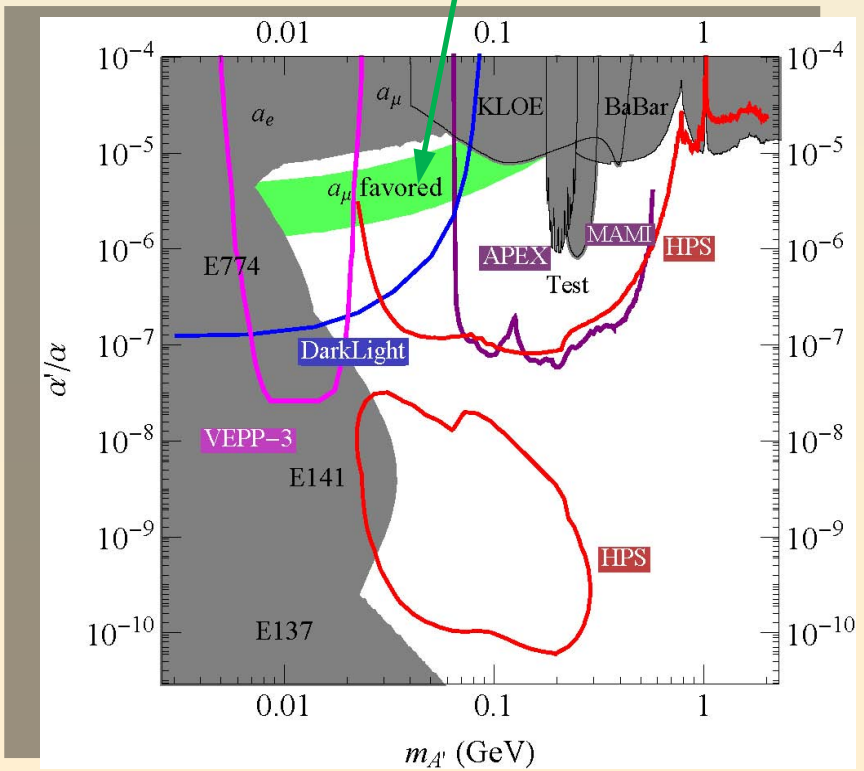


No evidence for SUSY at LHC (yet)

Another solution: A', a massive neutral vector boson



g – 2 preferred!



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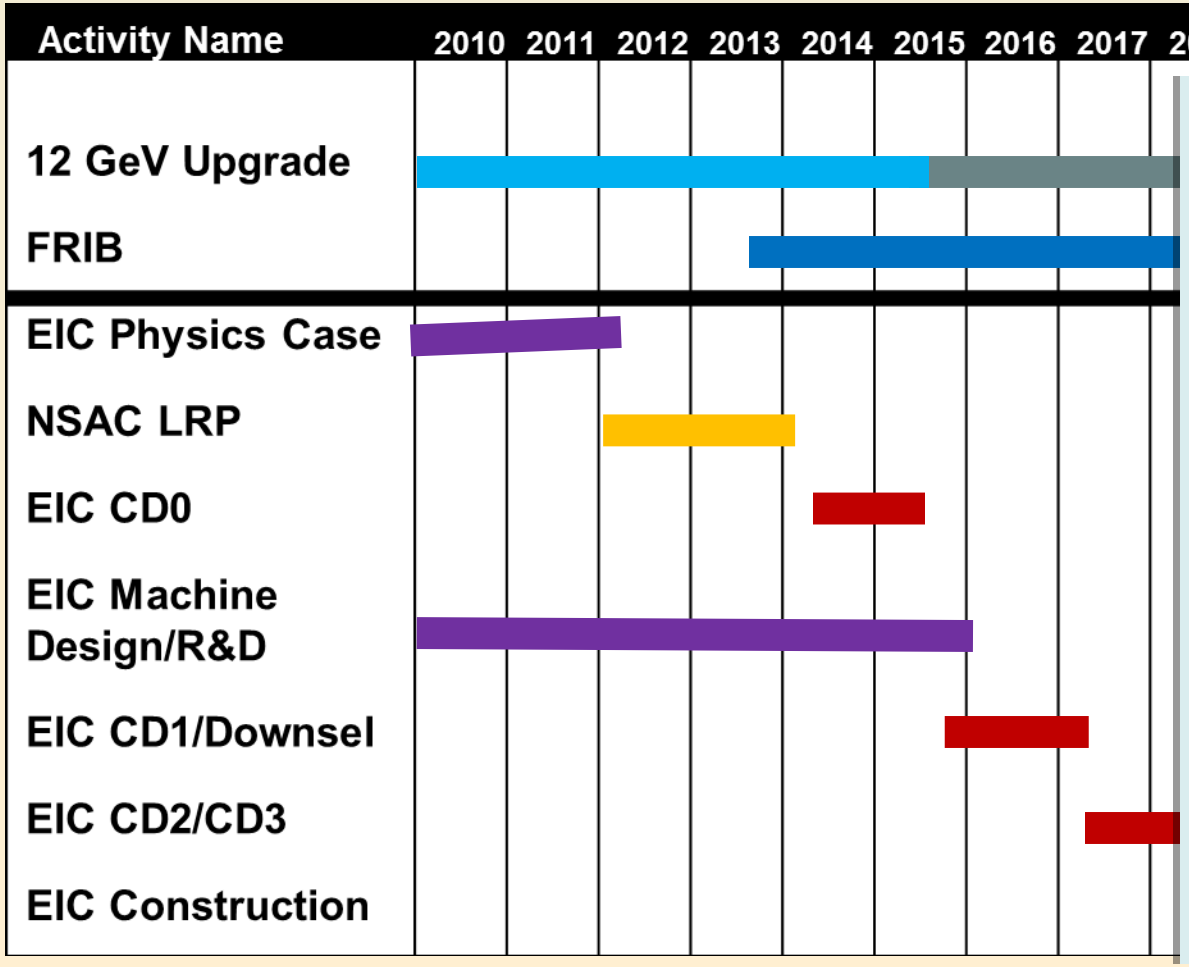
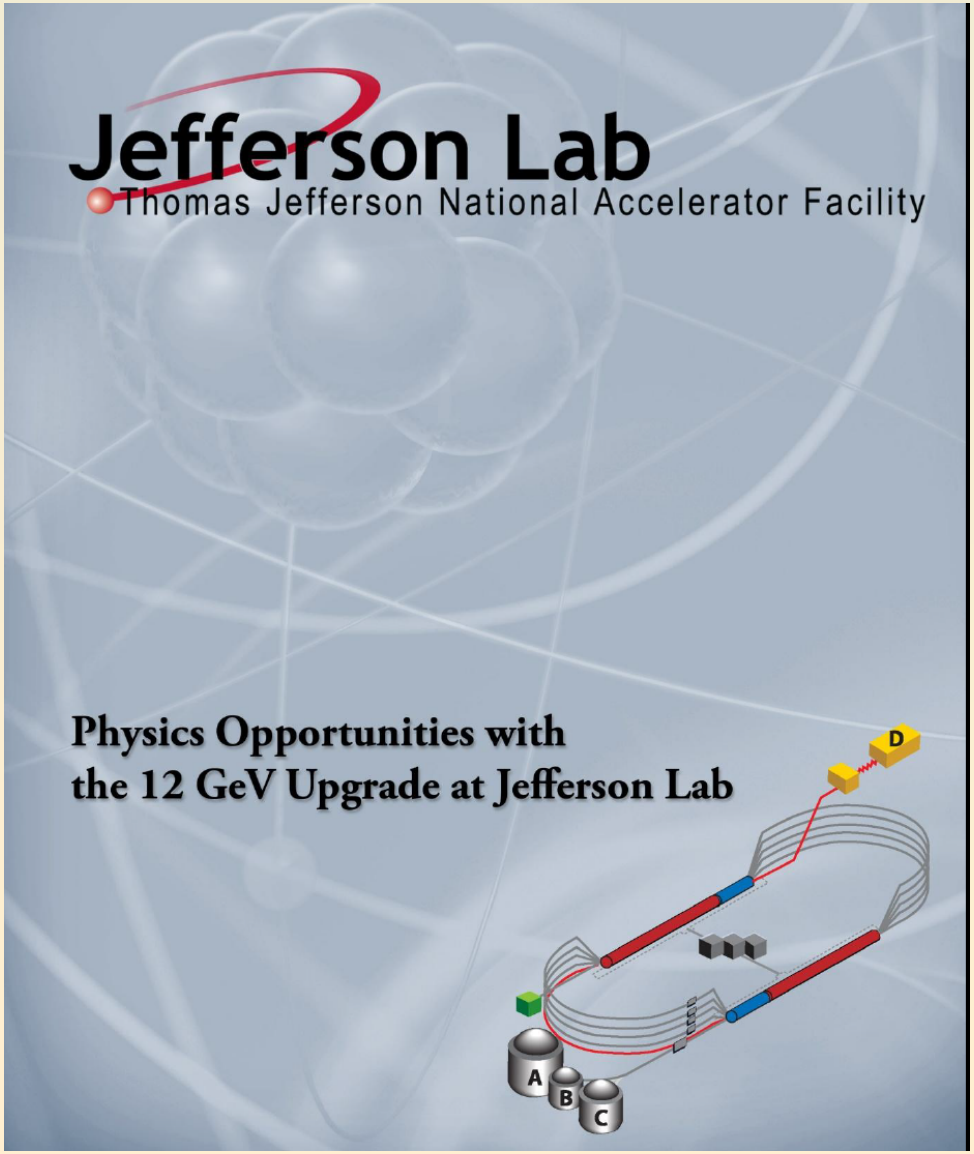
Jefferson Lab Electron Ion Collider



- Initial configuration (MEIC):
  - 3-11 GeV on 20-100 GeV ep/eA collider
  - fully-polarized, longitudinal and transverse
  - luminosity: up to few x 10^{34} e-nucleons cm^{-2} s^{-1}
- Design Maturing
- User Driven Physics Case
- Integrated Detector
- Cost Estimate in progress

White Paper



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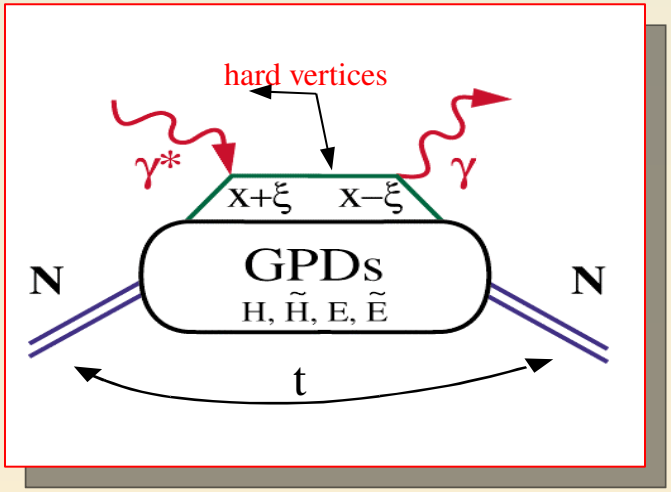
Extraction of GPD's

Cleanest process: Deeply Virtual Compton Scattering

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

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



Polarized beam, unpolarized target:

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

Unpolarized beam, longitudinal target:

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

Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \sin\phi \{k(F_2 H - F_1 E)\} d\phi \Rightarrow E(\xi,t)$$

Transverse Momentum Dependent Distr,TMDs

Leading Twist

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 $h_{1T}^\perp$

8 functions in total (at leading twist)

Each represents different aspects of partonic structure

Each function is to be studied

Kotzinian (1995), Mulders, Tangerman (1995), Boer, Mulders (1998)

Unified View of Nucleon Structure

$W(x,b_T,k_T)$

Wigner Distributions

5D

$\int d^2b_T$ $\int d^2k_T$

Fourier trf.

$b_T \leftrightarrow \Delta$

$\xi = 0$

$f(x,k_T)$ **3D** $f(x,b_T)$ $H(x,0,t)$ $t=-\Delta^2$ $H(x,\xi,t)$

transverse momentum distributions (TMDs)
semi–inclusive processes

impact parameter distributions

generalized parton distributions (GPDs)
exclusive processes

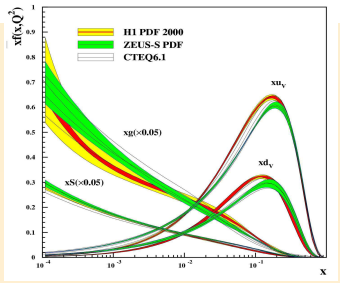
$\int d^2k_T$ $\int d^2b_T$ $\int dx$ $\int dx x^{n-1}$

$f(x)$ $F_1(t)$ $A_{n,0}(t)+4\xi A_{n,2}(t)+....$

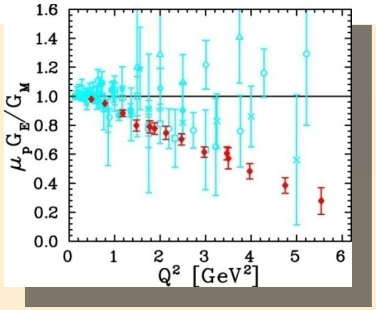
parton densities
inclusive and semi–inclusive processes

form factors
elastic scattering

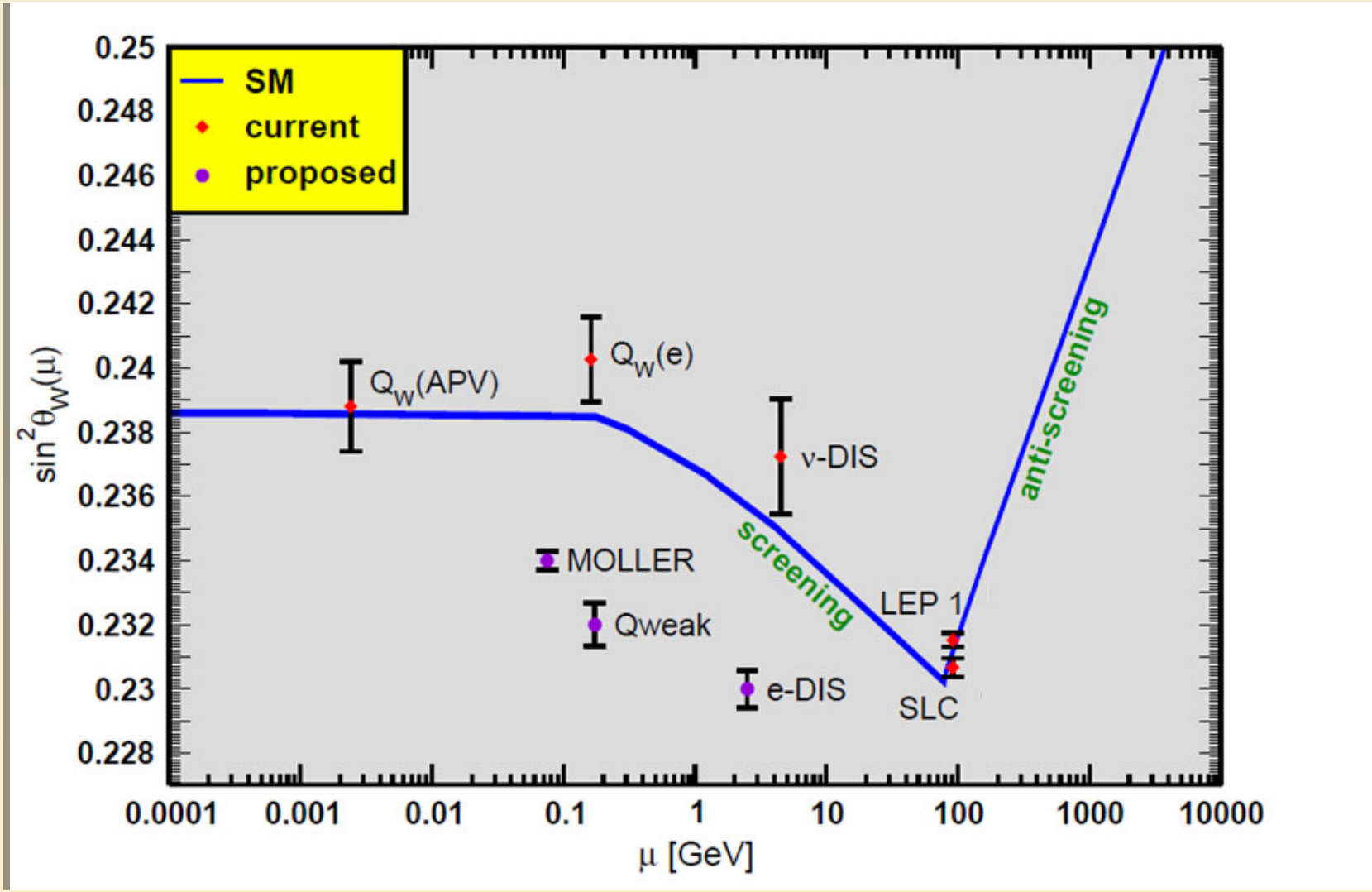
generalized form factors
lattice calculations



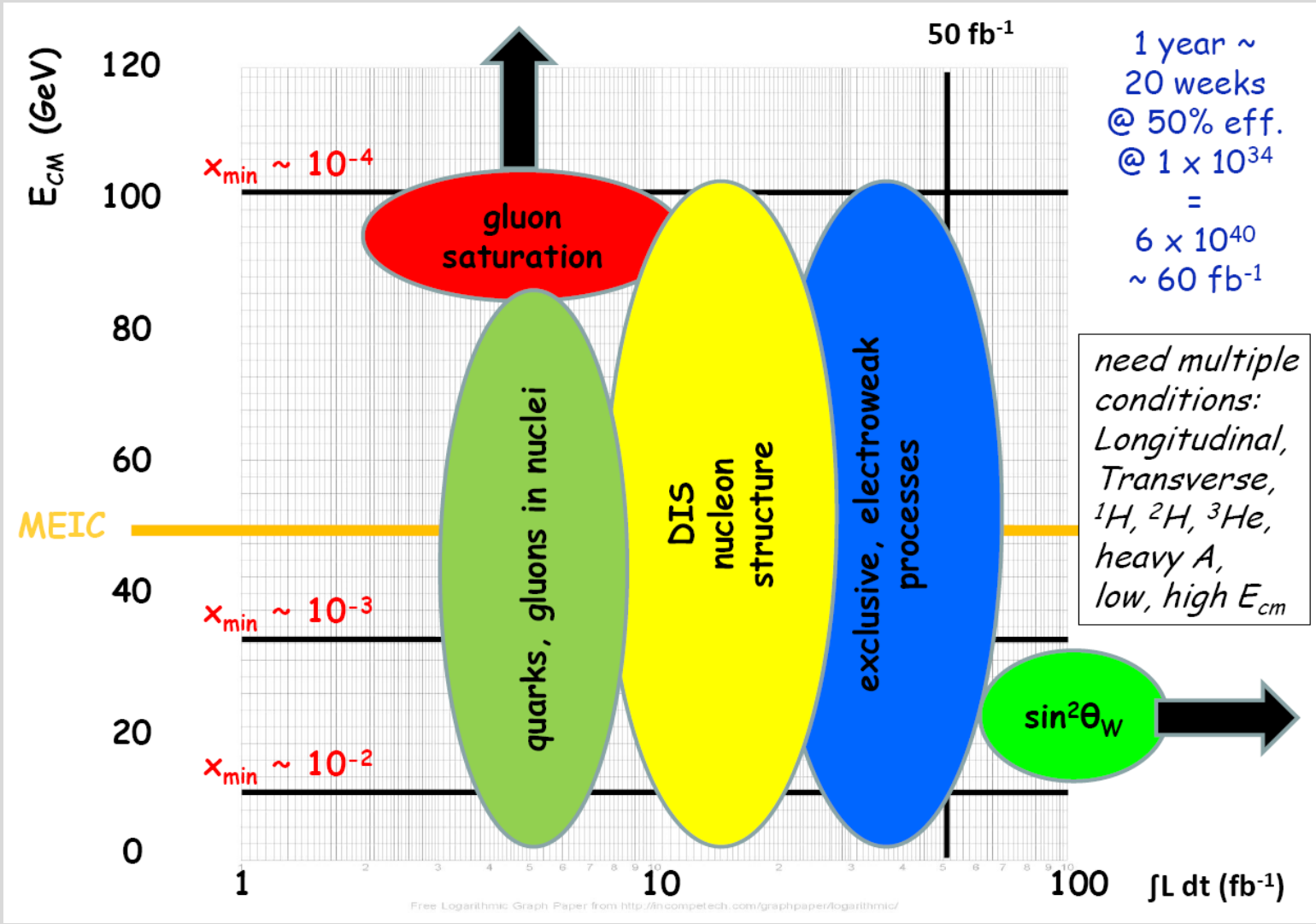
1D



$\sin^2\theta_W$


SM
current
proposed
Q_W(APV)
Q_W(e)
ν-DIS
MOLLER
Qweak
e-DIS
LEP 1
SLC
screening
anti-screening
$\sin^2\theta_W(\mu)$
μ [GeV]
0.25
0.248
0.246
0.244
0.242
0.24
0.238
0.236
0.234
0.232
0.23
0.228
0.0001
0.001
0.01
0.1
1
10
100
1000
10000

EIC Science reach as function of E_{CM} and integrated luminosity



Electron Ion Colliders

Design Goals for Colliders Under Consideration World-wide

	Energies	s	Design Luminosity
(M)EIC@JLab	Up to 11 x 60+	240-3000	Close to 10^{34}
Future ELIC@JLab	Up to 11 x 250 (20? x 250)	11000 (20000?)	Close to 10^{35}
Staged MeRHIC@BNL	Up to 5 x 250	600-5000	Close to 10^{34}
eRHIC@BNL	Up to 20 x 325 (30 x 325)	26000 (39000)	Close to 10^{34}
ENC@GSI	Up to 3 x 15	180	Few x 10^{32}
LHeC@CERN	Up to 150 x 7000	4200000	Close to 10^{33}

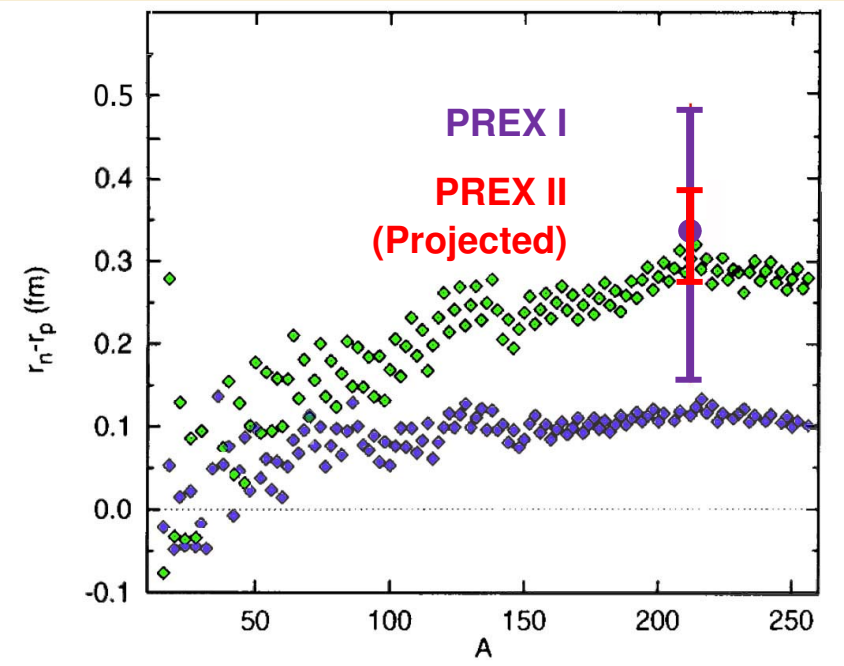
Present focus of interest (in the US) are the (M)EIC and Staged e-RHIC versions, with s up to ~3000 and 5000, resp.

Lead (^{208}Pb) Radius Experiment: PREX

Elastic Scattering Parity-Violating Asymmetry

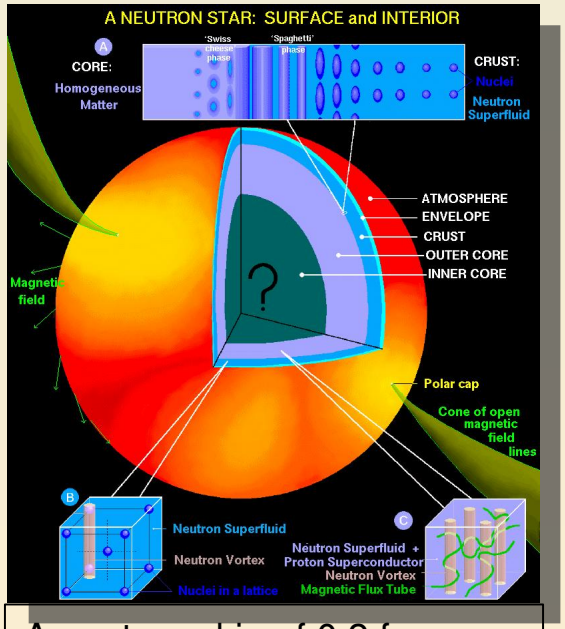
Clean Probe of **Neutron** Distribution

Applications : Nuclear Structure Physics, Neutron Stars,
Atomic Parity, Heavy Ion Collisions



Relativistic mean field

Nonrelativistic skyrme



A neutron skin of 0.2 fm or more has implications for our understanding of neutron stars and their ultimate fate.