The tensor polarized target program at Jefferson Lab and possibilities for polarized deuteron beams at the EIC

Talk By Douglas W. Higinbotham (Jefferson Lab) INT Workshop 16 February 2024

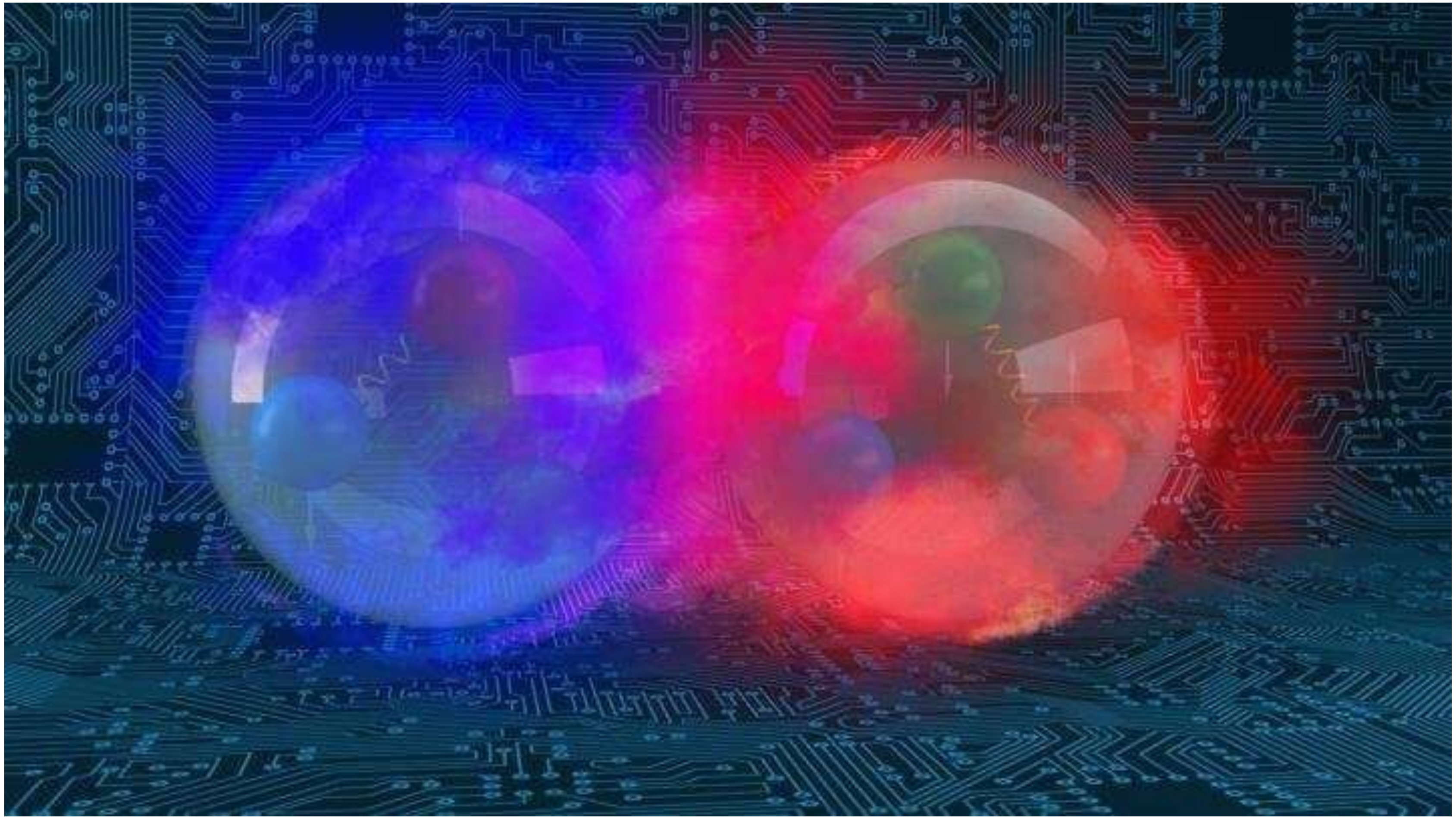


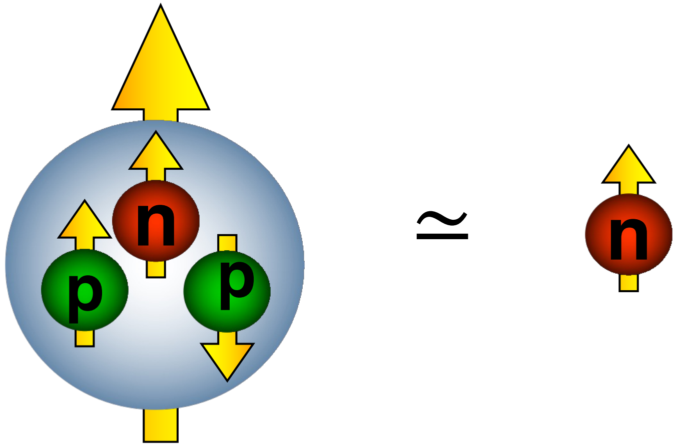
Image by Andrew Sproles, Oak Ridge National Laboratory

Magnetic Moments

- Proton = 2.793 μ_N where $\mu_N = e\hbar/2m_p$
- Neutron = -1.913 μ_N
- Deuteron = 0.857 μ_N (~3% different from p+n)
- ^{3}He = -2.128 μ_N (~10% different from neutron)

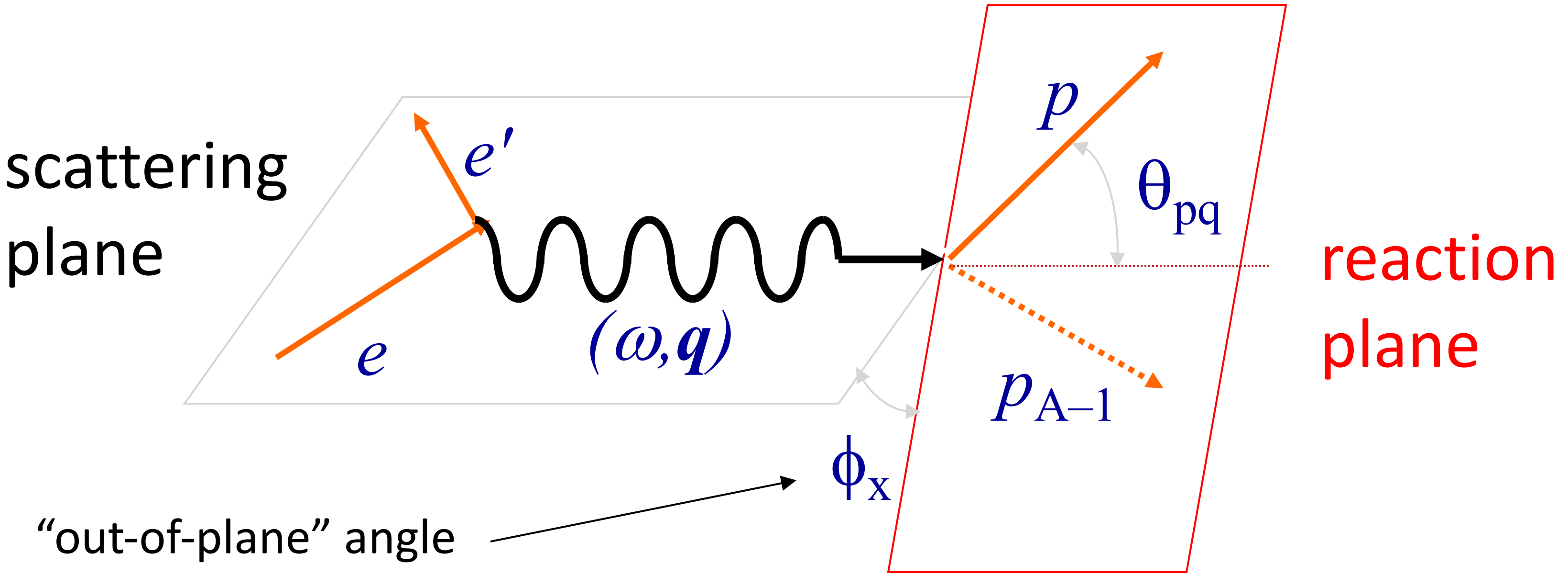
Examples of ^{3}He Magnetic Moment Calculations:

Shell Model = -1.913 μ_N
Quark Model = -2.005 μ_N
QCD Model = -2.291 μ_N



Calculations from https://doi.org/10.1016/j.rinp.2017.07.065

Electron Scattering *Quasi-Elastic* Kinematics



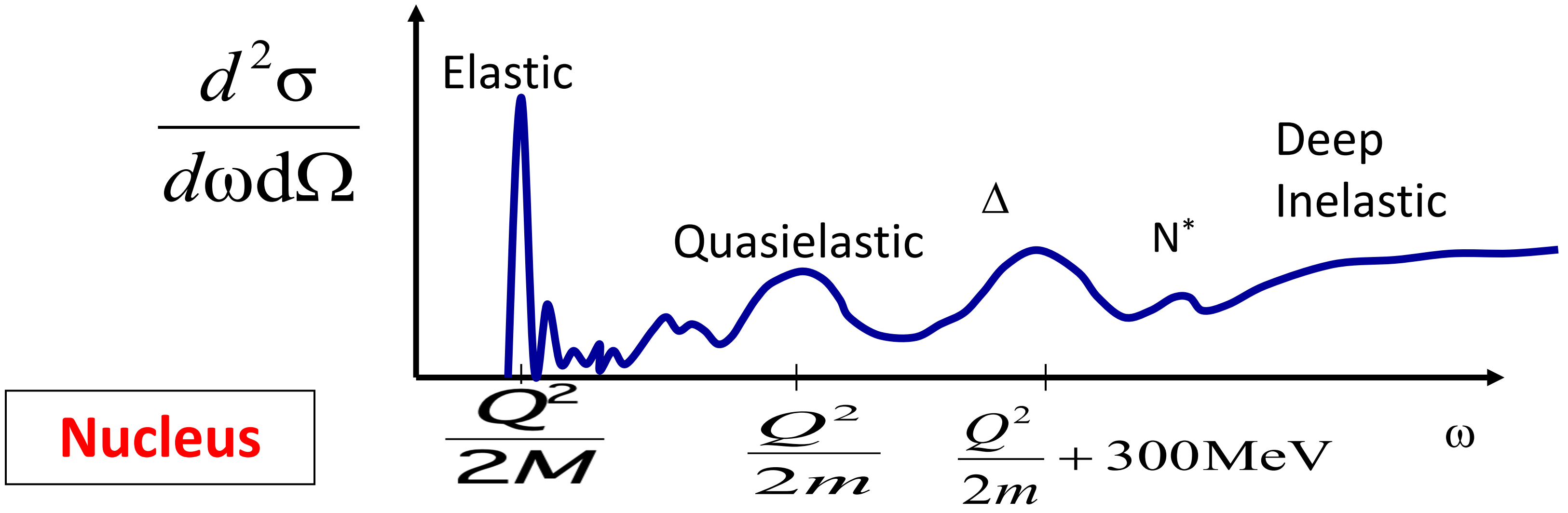
Four-momentum transfer: $Q^2 \equiv -q_\mu q^\mu = \boldsymbol{q}^2 - \omega^2$

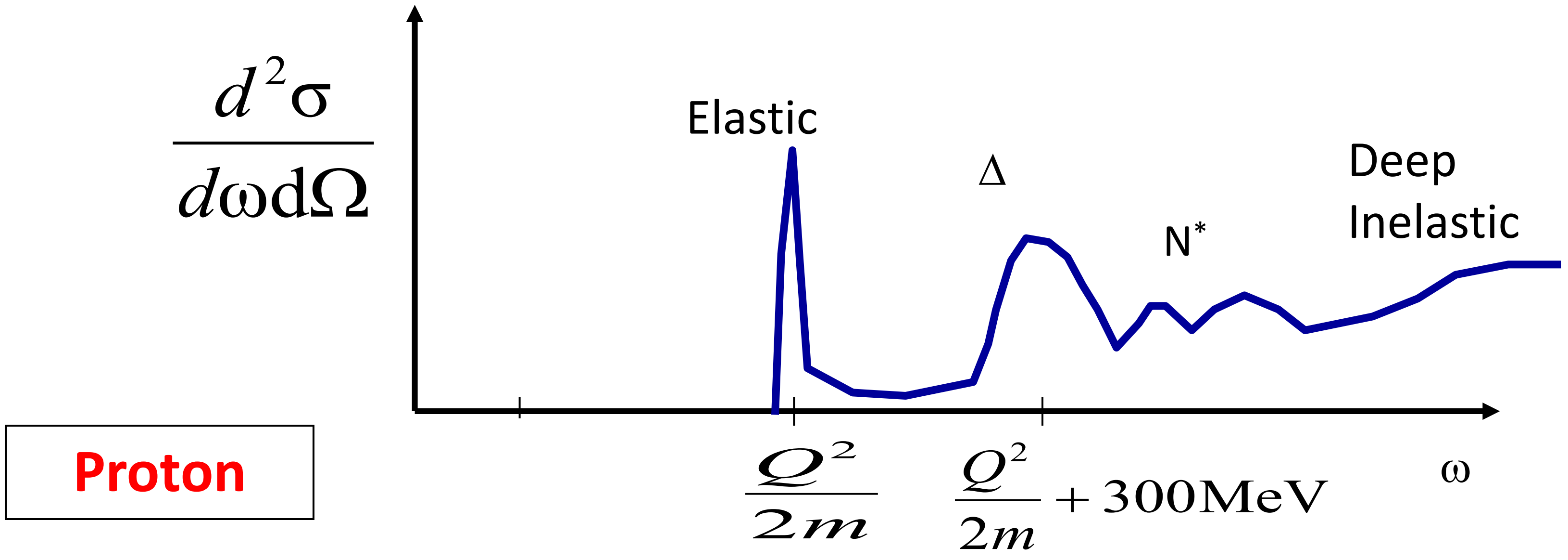
Missing momentum: $\boldsymbol{p}_m = \boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{A-1}$

Missing energy: $\omega = e - e'$

Bjorken x: $x_B = Q^2/2m\omega$

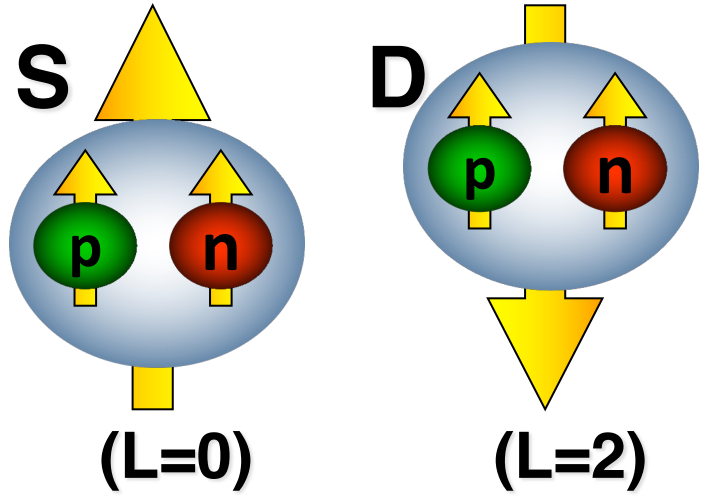
A(e,e') at Fixed Q^2 vs. ω

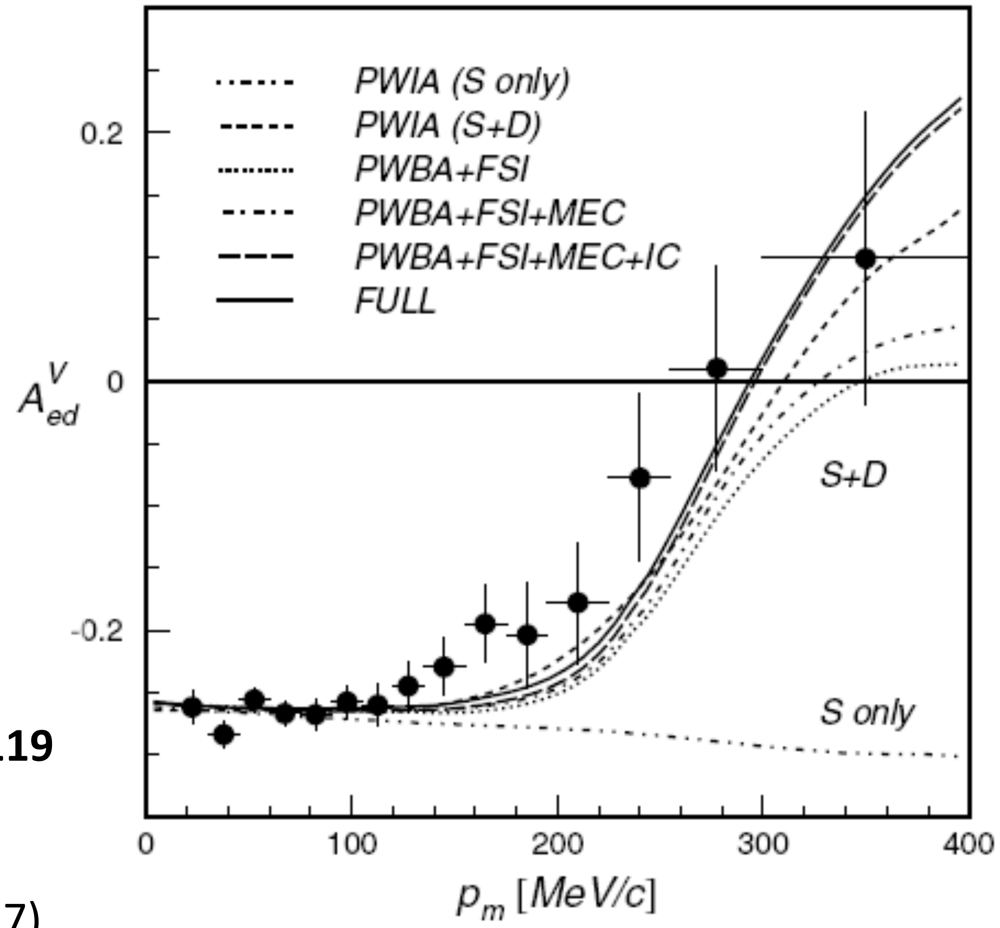




Classic QE $^2\vec{H}(\vec{e},e'p)$ data from NIKHEF

I. Passchier *et al.,* Phys. Rev. Lett. **88** (2002) 102302.





- "The experiment reveals in a most direct manner the effects of the D state in the deuteron ground-state wave."

- BLAST: A. DeGrush *et al.,* Phys. Rev. Lett. **119** (2017) 18250.

- CLAS: M. Mayer *et al.,* Phys. Rev. **C95** (2017) 024005

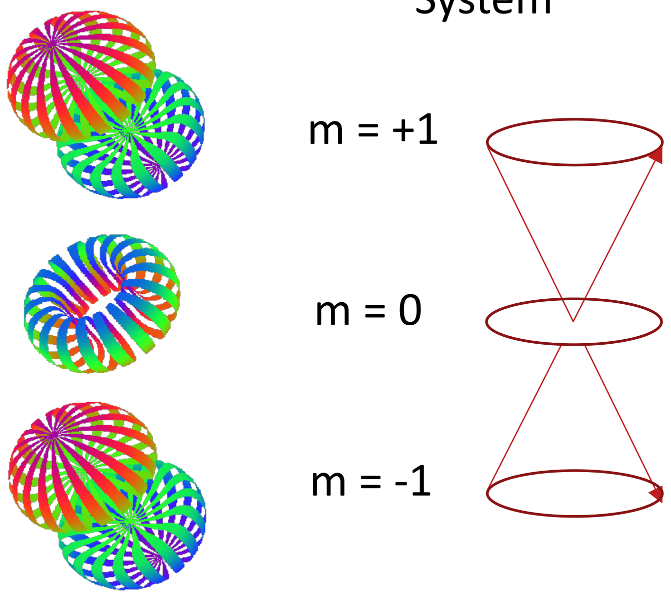
This shows why "neutron" DIS experiments like BONUS tag low P_m protons.

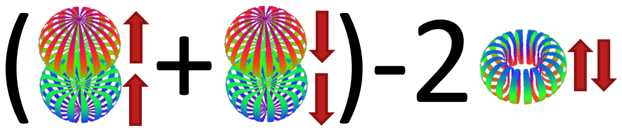
Tensor Polarization

A high-luminosity tensor-polarized target has promise as a **novel probe of nuclear physics**

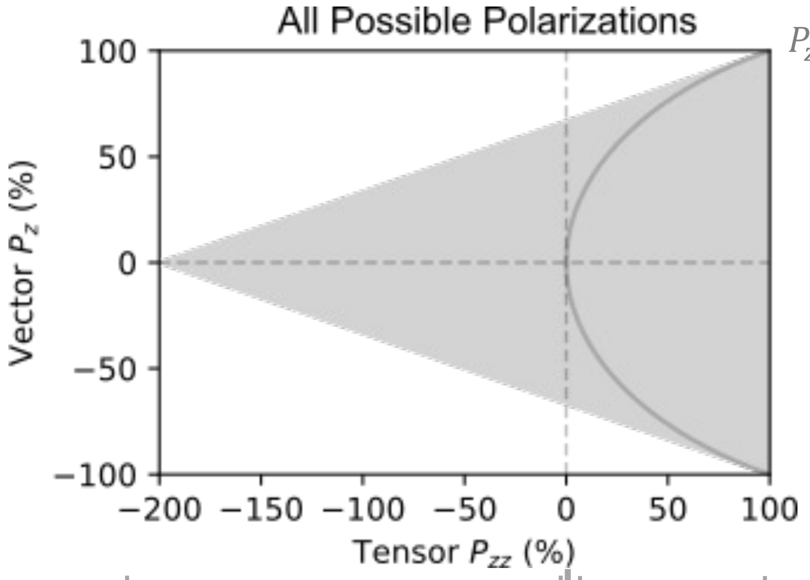
J Forest, *et al*, PRC **54** 646 (1996)

Spin-1 System

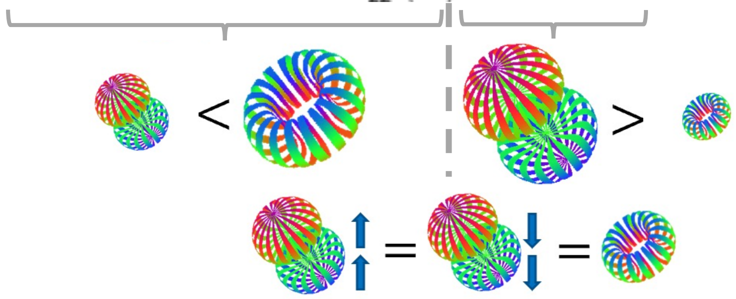




Tensor $P_{zz} = (p_{+}+p_{-}) - 2p_0 = 1 - 3p_0$



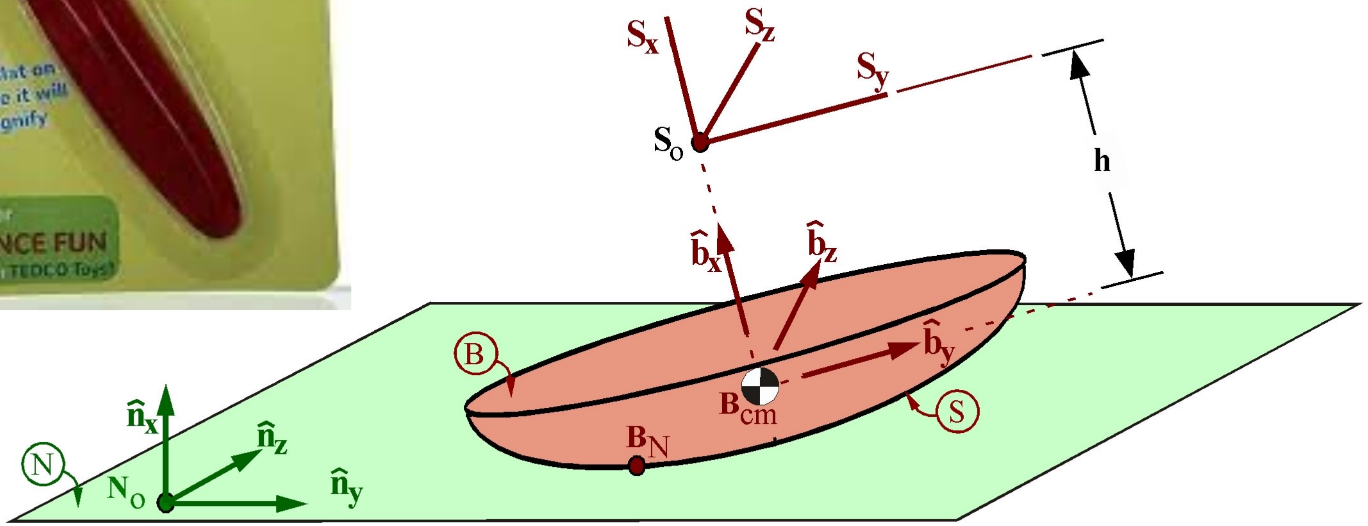
$P_{zz}^{equil} = 2 - \sqrt{4 - 3P_z^2}$
$= \text{Gray Half} - \text{circle}$



Classical Mechanics Example of Tops & Moment of Inertia Tensors

Tippy Top

Rattleback



Accessing The Tensor Observables

- In the polarized deuteron cross section, there are four asymmetry terms
  - $h_e =$ Electron helicity
  - $P = P_z =$ Vector polarization
  - $Q = P_{zz} =$ Tensor polarization

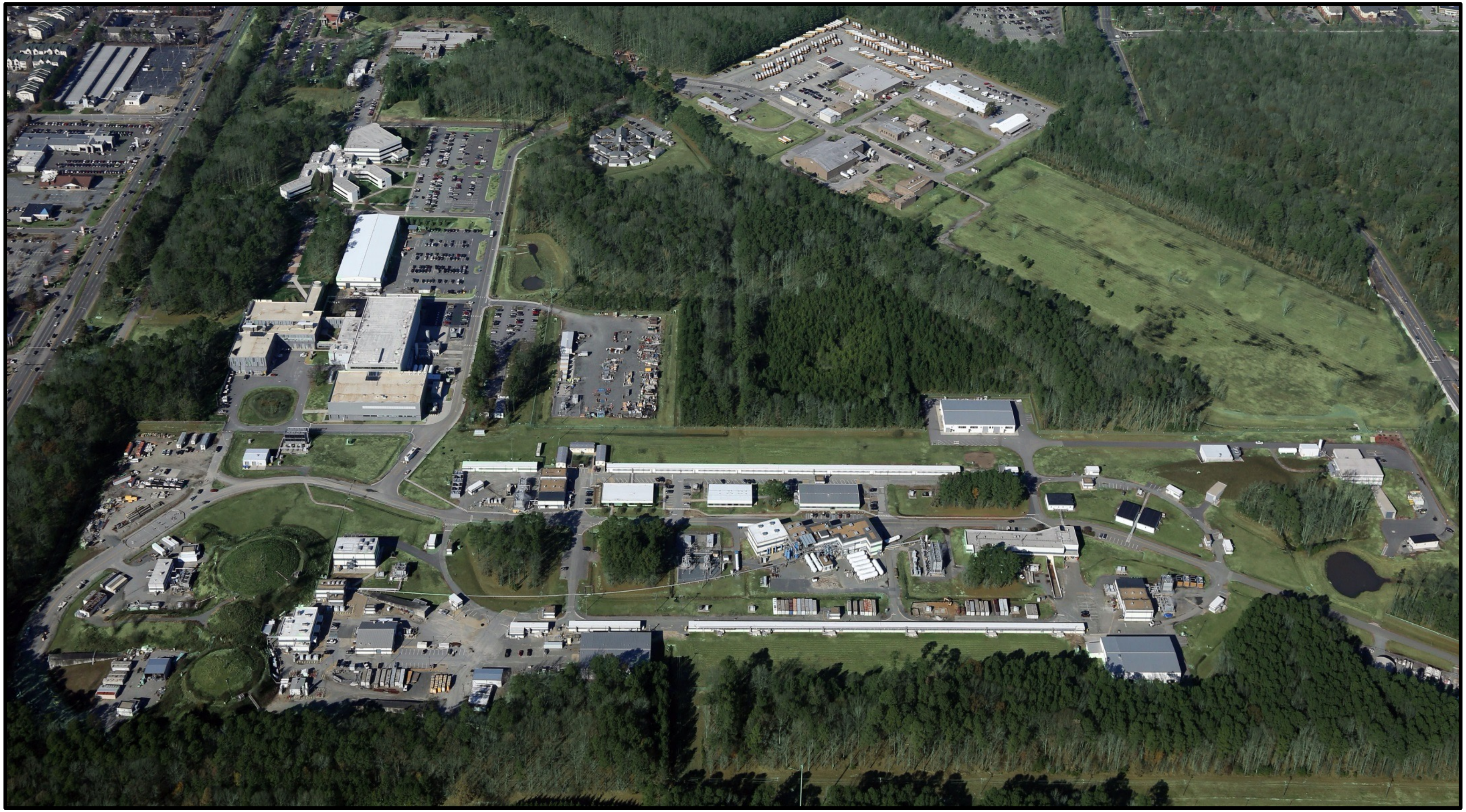
$$\frac{d^2\sigma}{dkd\Omega} = \sigma(h_e, P, Q) = \sigma_0 \left[1 + h_e(PA_{||} + QA_T^{ed}) + PA_V^d + \frac{1}{2}QA_{zz} \right]$$

0 0

  - Integrating electron helicity suppresses $A_{||}$ and A_T^{ed}
  - Switching between positive and negative vector polarizations and integrating suppresses A_V^d

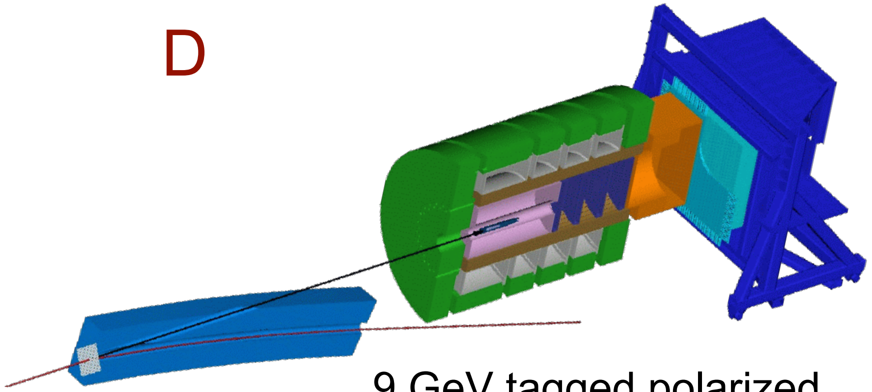
W. Leidemann, E.L. Tomusiak, H. Arenhovel, Phys. Rev. C 43, 1022 (1991)

Jefferson Lab Located In Newport News, VA



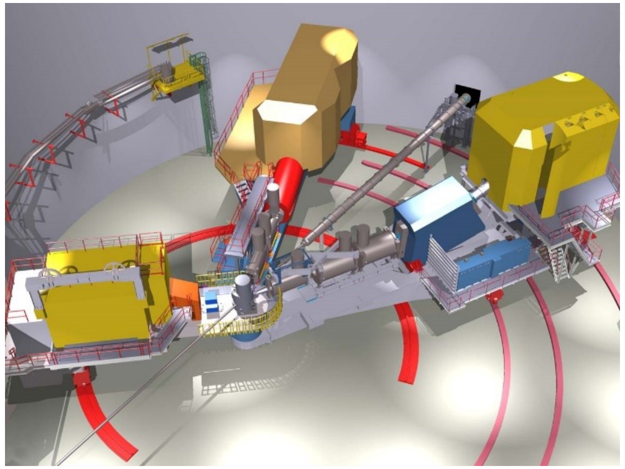
Jefferson Lab's Four Complimentary Experimental Halls

D



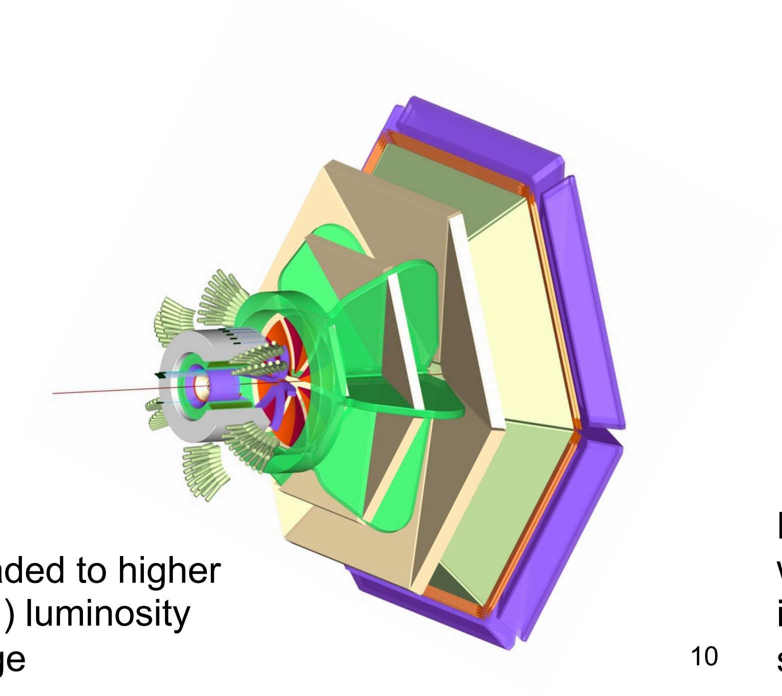
9 GeV tagged polarized photons and a 4π hermetic detector

C



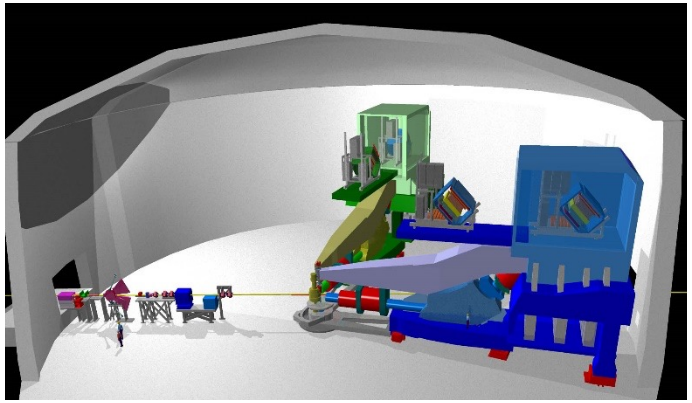
Super High Momentum Spectrometer (SHMS) at high luminosity and forward angles

B



CLAS upgraded to higher (10^{35} $cm^{-2}s^{-1}$) luminosity and coverage

A



Retain HRS Pair for continuation of research in which resolution comparable to nuclear level spacing is essential. Use Hall to stage "one-of-a-kind" specialized experiments requiring unique apparatus.

Approved Tensor Asymmetry Experiments for Hall C @ JLab

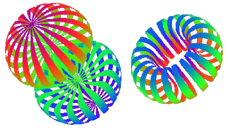
$$b_1 = -\frac{3}{2} F_1 A_{zz}$$

$$A_{zz} = \frac{2}{fQ}\left(\frac{\sigma_Q - \sigma_0}{\sigma_0}\right)$$

$$T_{20} \approx \frac{A_{zz}}{\sqrt{2} d_{20}}$$

DIS	Quasi-Elastic/SRC	Elastic	
< 0.5	$0.8 - 1.8$	2	x

Elastic T_{20}



T_{20}, along with unpol. A & B form factors, gave rise to current deuteron understanding

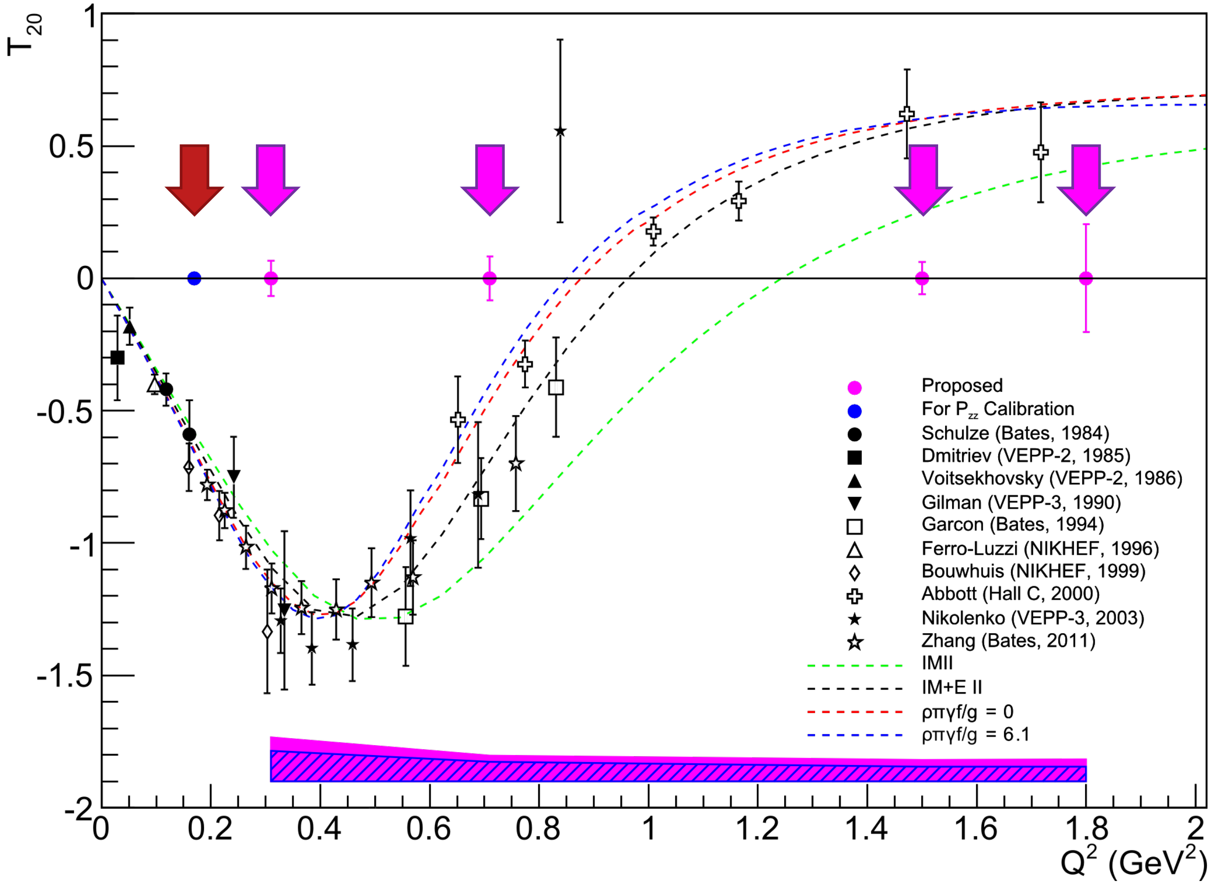
QE Experiment gets T_{20} for free.

At low Q^2,

- T_{20} well known
- P_{zz} can be extracted from T_{20}
- Completely independent P_{zz} measurement from NMR line-shape P_{zz}

T_{20} in the largest and highest Q^2 range ever done in a single experiment

- Important cross-check of Hall C high Q^2 data



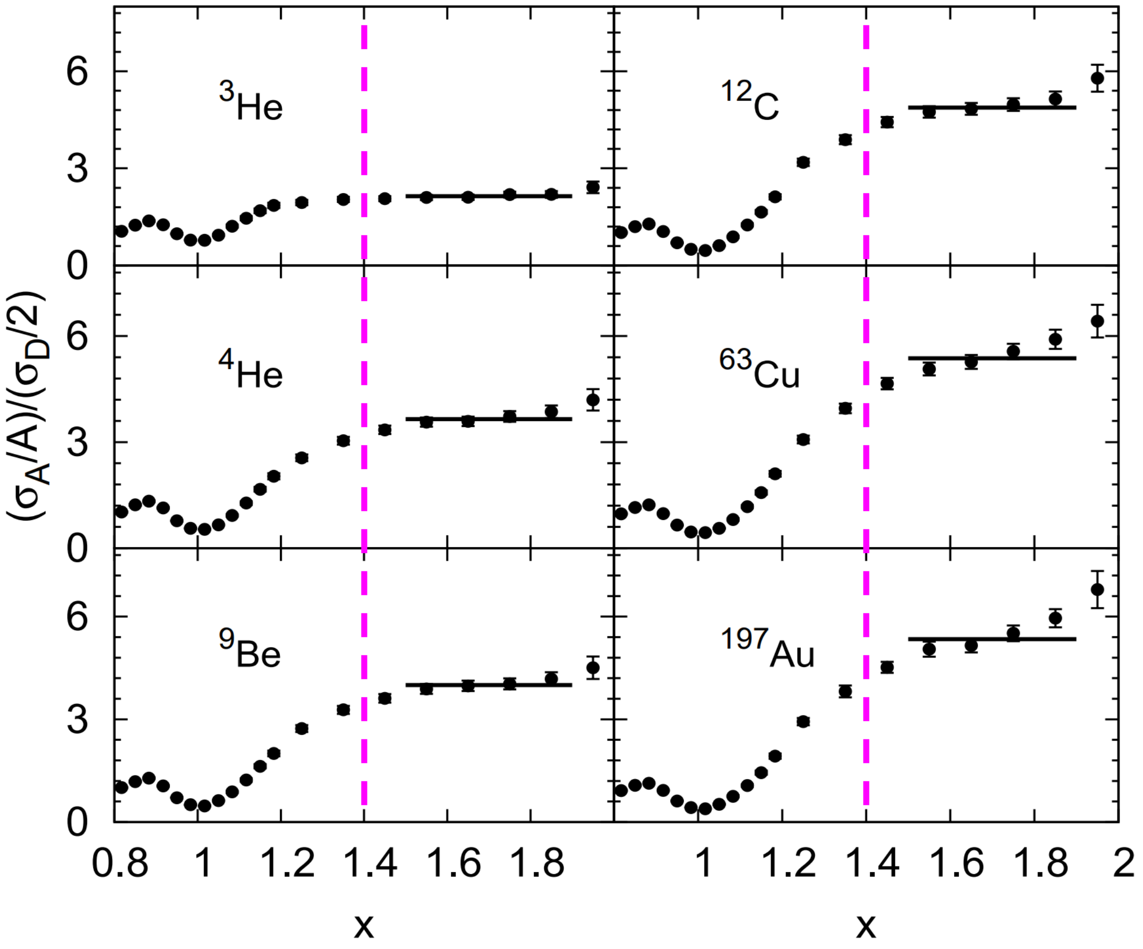
Proposed from E Long, *et al*, JLab C12-15-005

World Data from R Holt, R Gilman, Rept.Prog.Phys. **75** 086301 (2012)

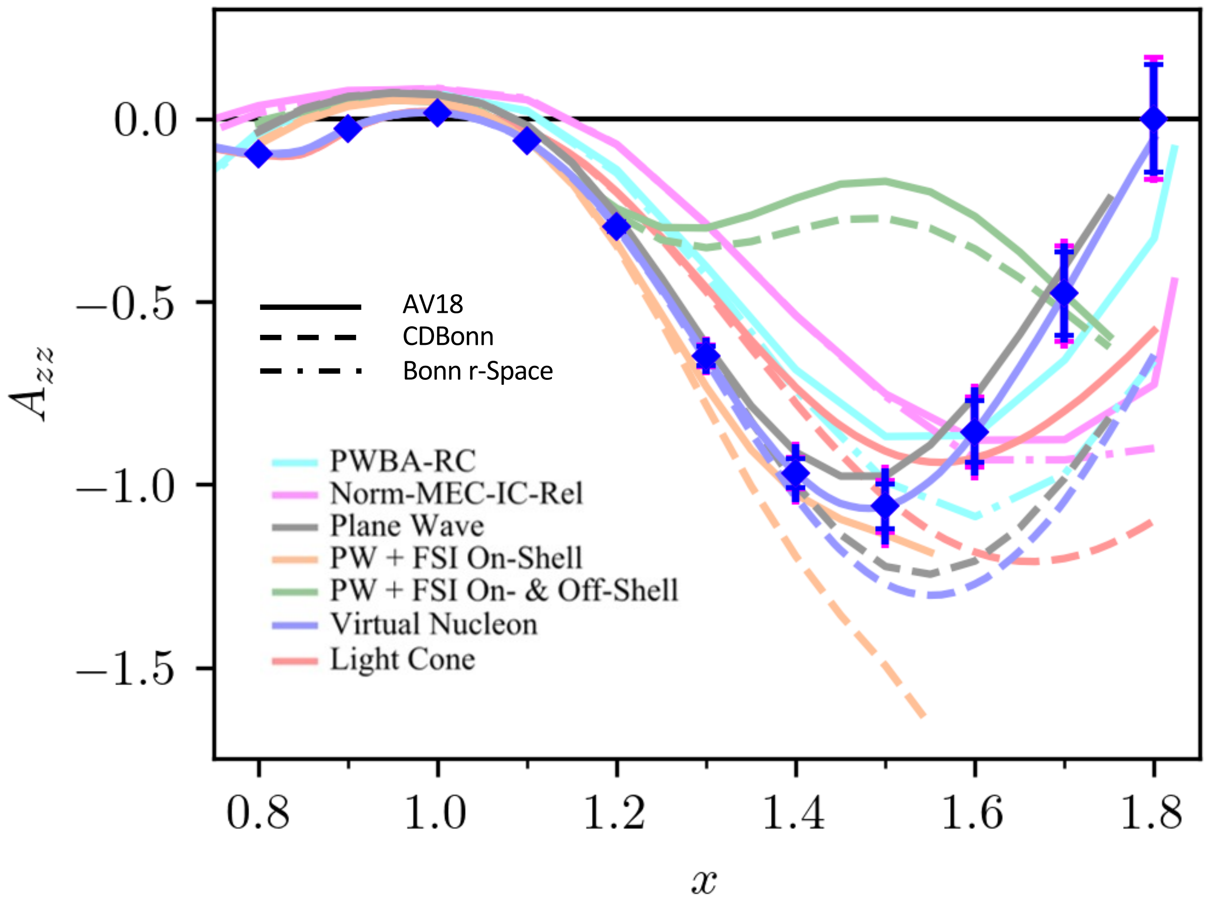
J Forest, *et al*, PRC **54** 646 (1996)

Short Range Correlation Data & Expected A_{zz} Tensor Data

N Foman, *et al*, PRL **108** 092502 (2012)



Blue Points Expected Data

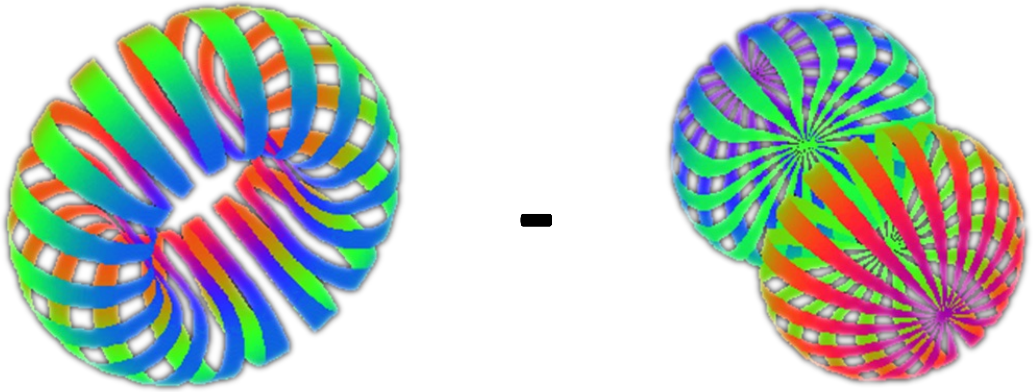


b_1 Structure Function

$$b_1(x) = \frac{q^0(x) - q^1(x)}{2}$$

q^0 : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the *Deuteron* is in state m=0

q^1 : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the *Deuteron* is in state |m| = 1



Interesting mix of nuclear and quark physics

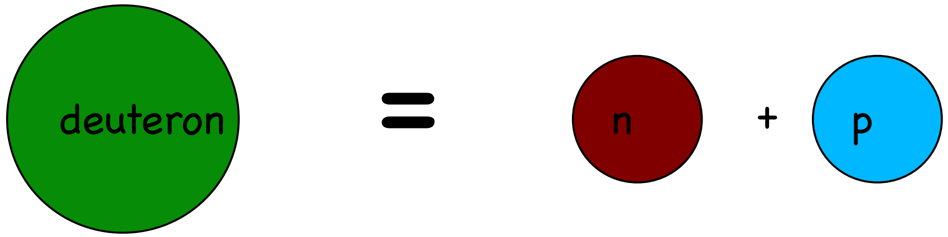
measured in DIS (so probing quarks), but depends solely on the deuteron spin state

b_1 Structure Function

Hoodbhoy, Jaffe and Manohar (1989)

b_1 vanishes in the absence of nuclear effects

i.e. if...



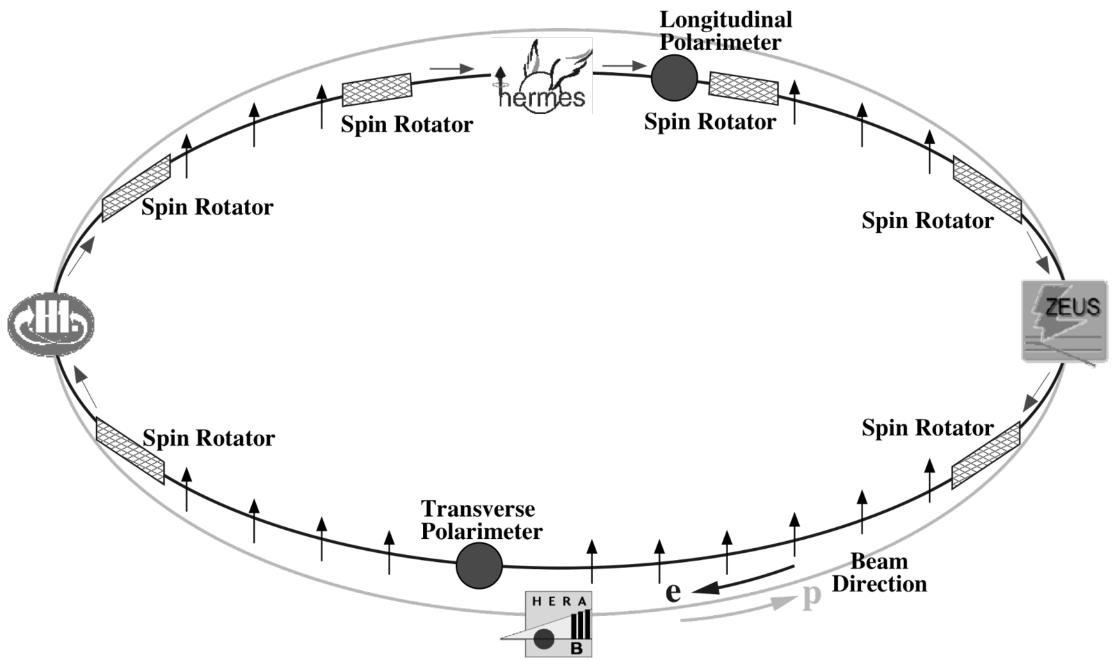
Proton Neutron in relative S-state

Even accounting for D-State admixture **b_1 expected to be vanishingly small**

Khan & Hoodbhoy, PRC 44 ,1219 (1991) : $b_1 \approx O(10^{-4})$
Relativistic convolution model with binding

Umnikov, PLB 391, 177 (1997) : $b_1 \approx O(10^{-3})$
Relativistic convolution with Bethe-Salpeter formalism

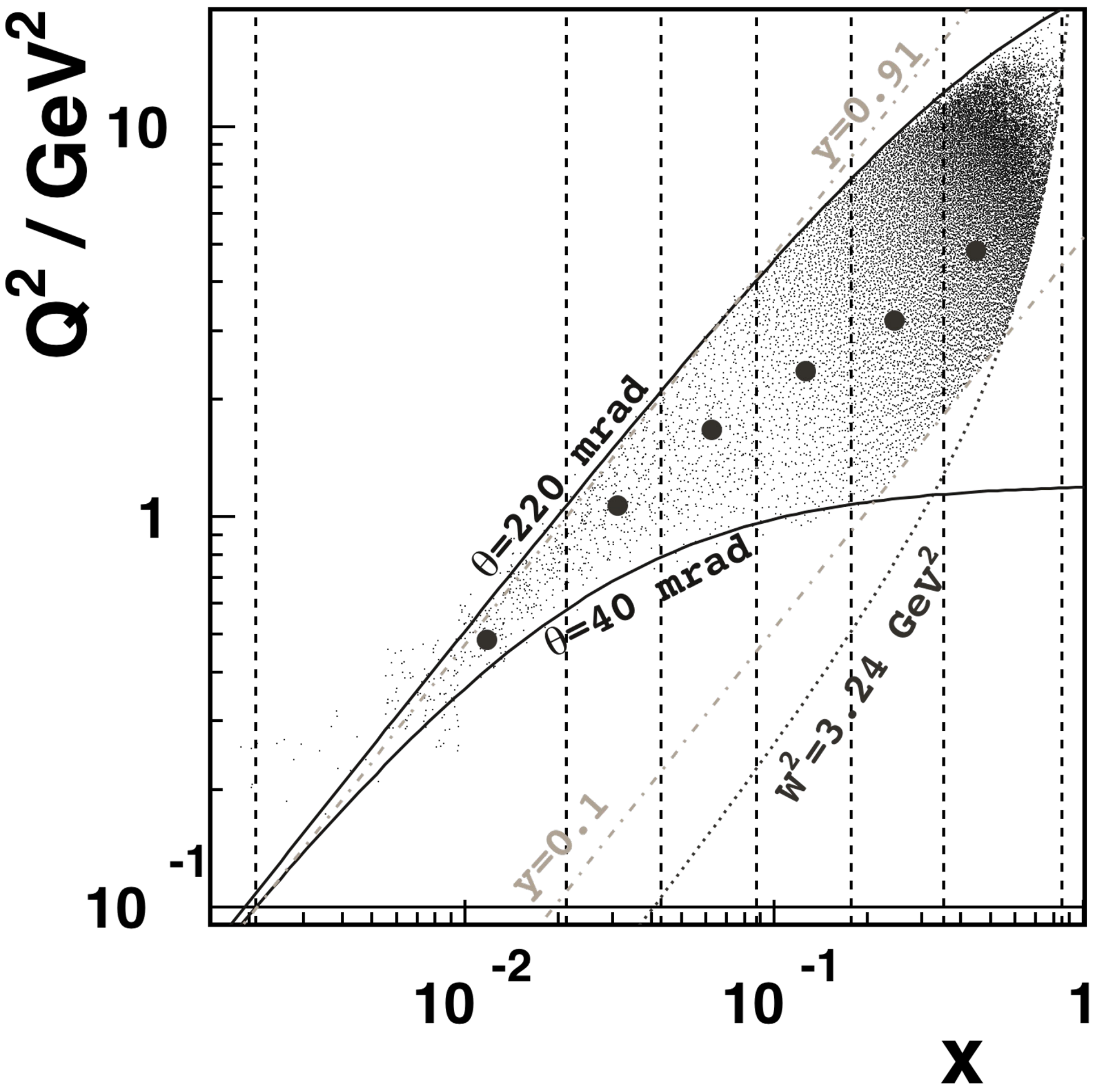
Data from HERMES



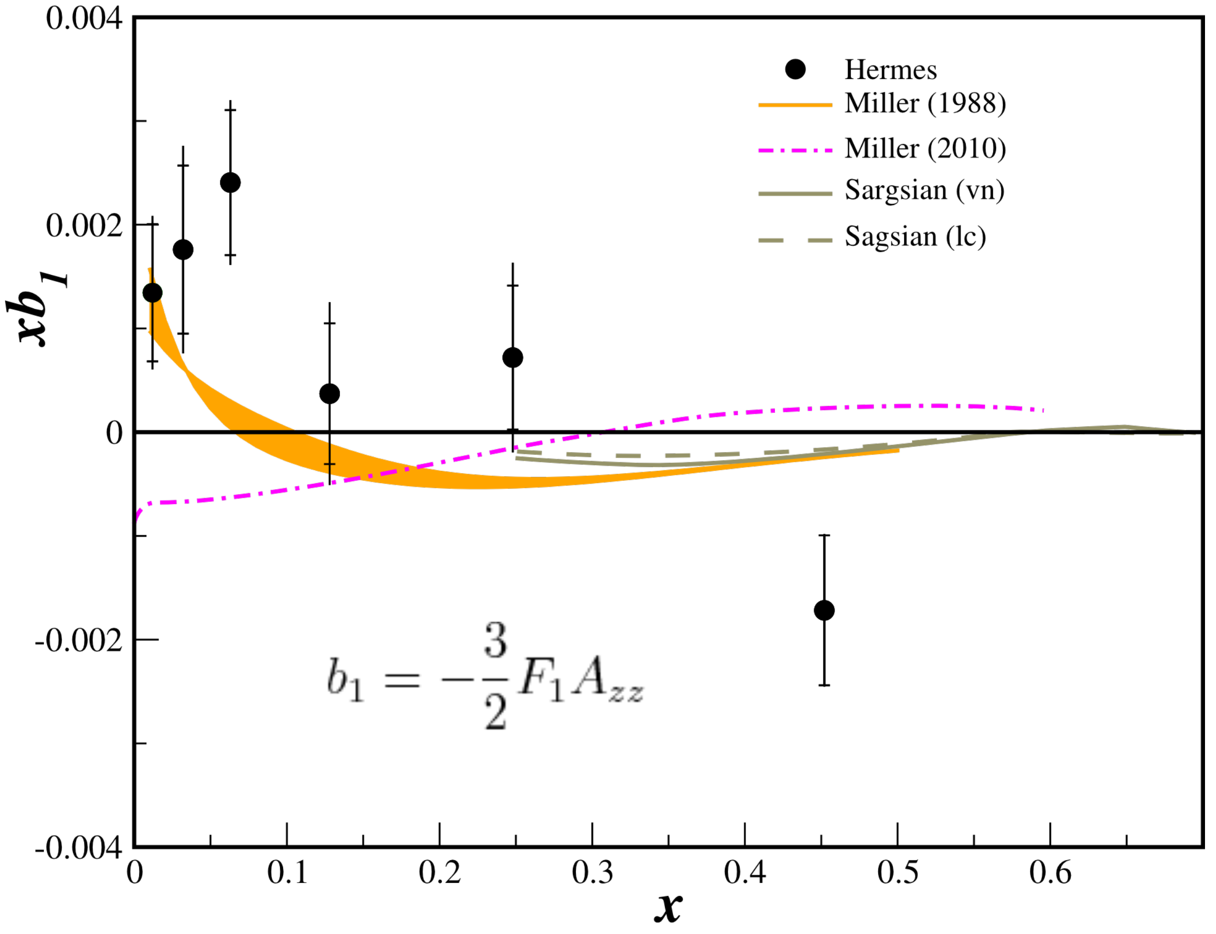
27.6 GeV positrons

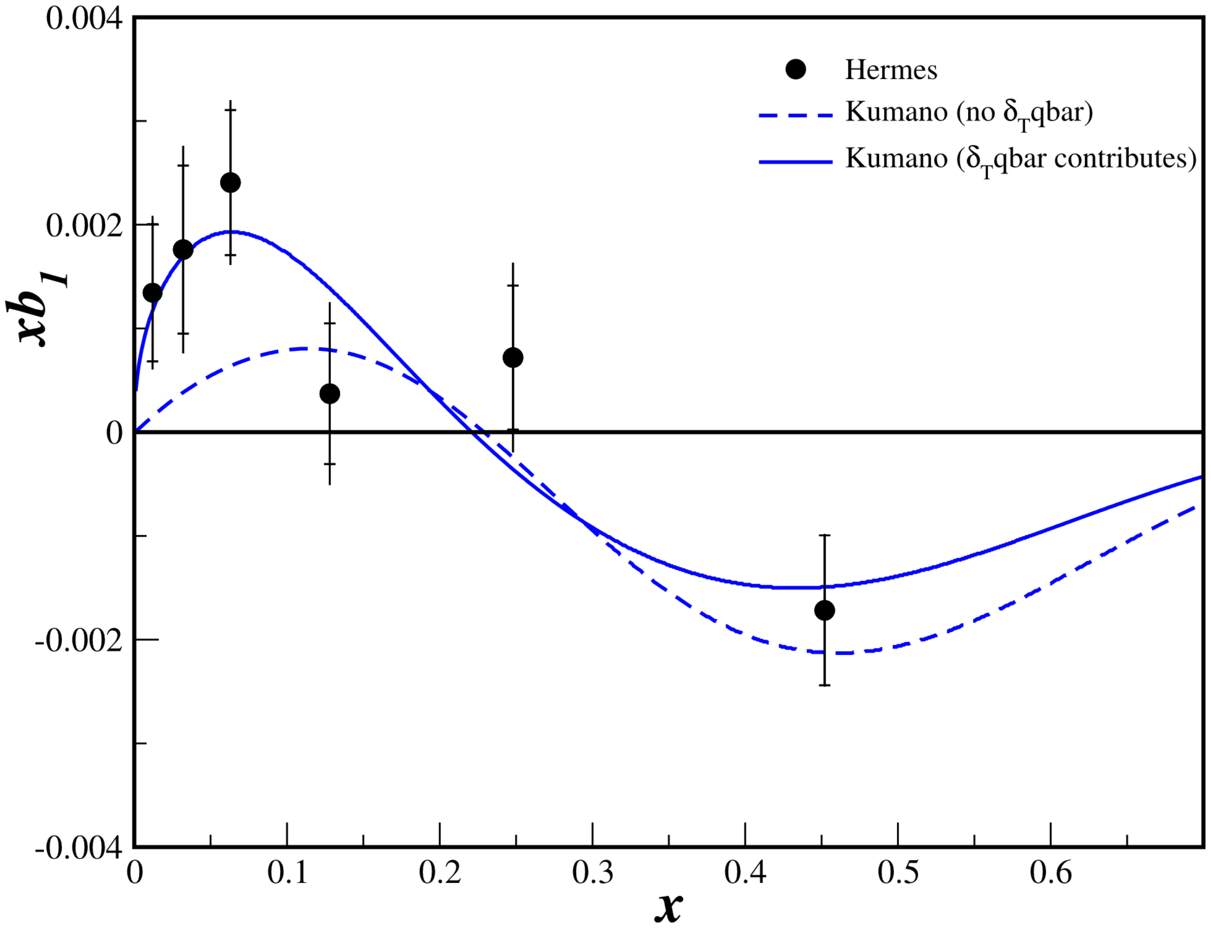
Internal gas target

~Pure tensor polarization with little vector component



b1 Results from HERMES & Comparison to Models



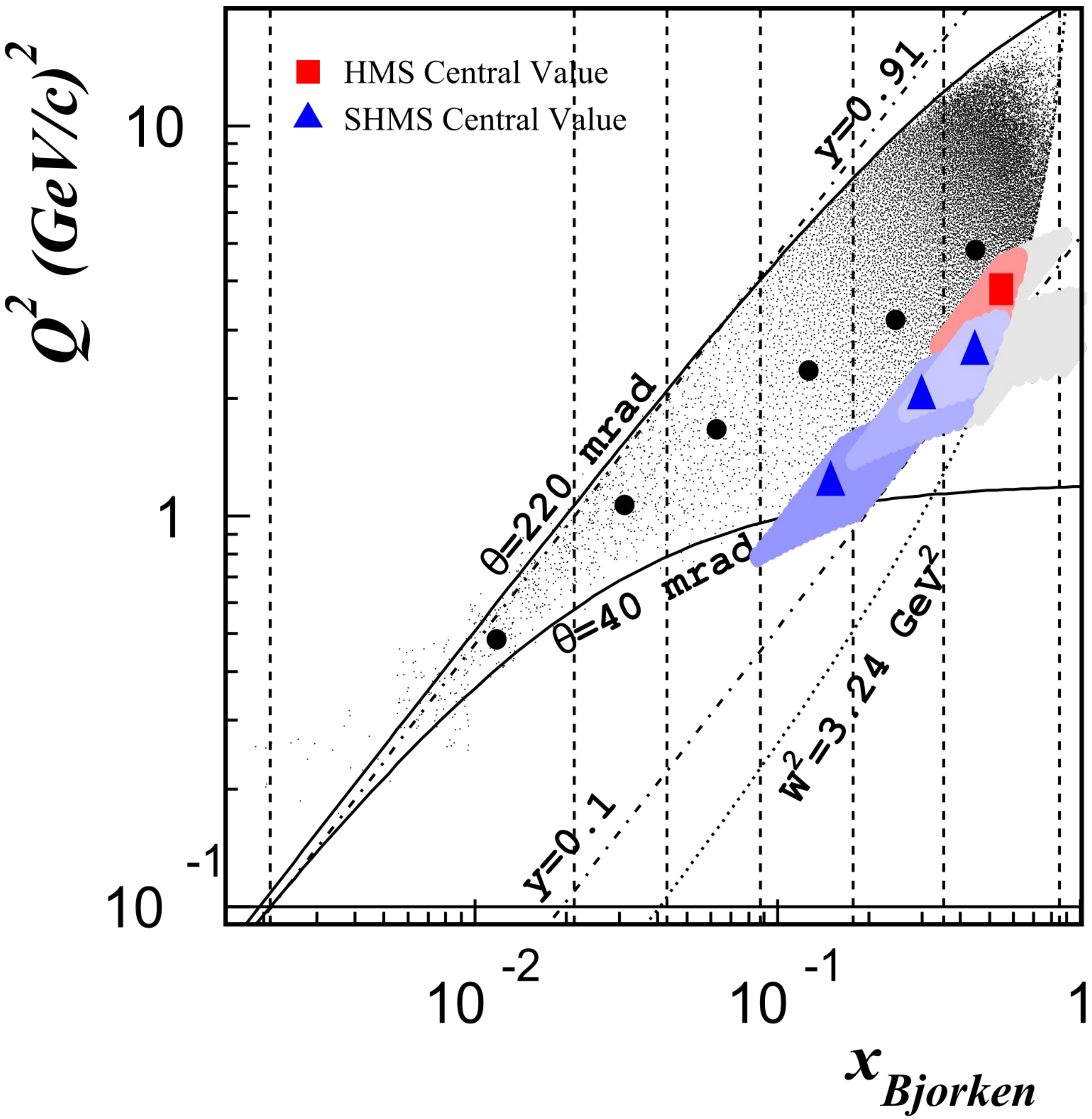


All Conventional Models predict small or vanishing values of b1 in contrast to the HERMES data

Kumano Fit is constrained to agree with the HERMES Data by having a tensor polarized sea.

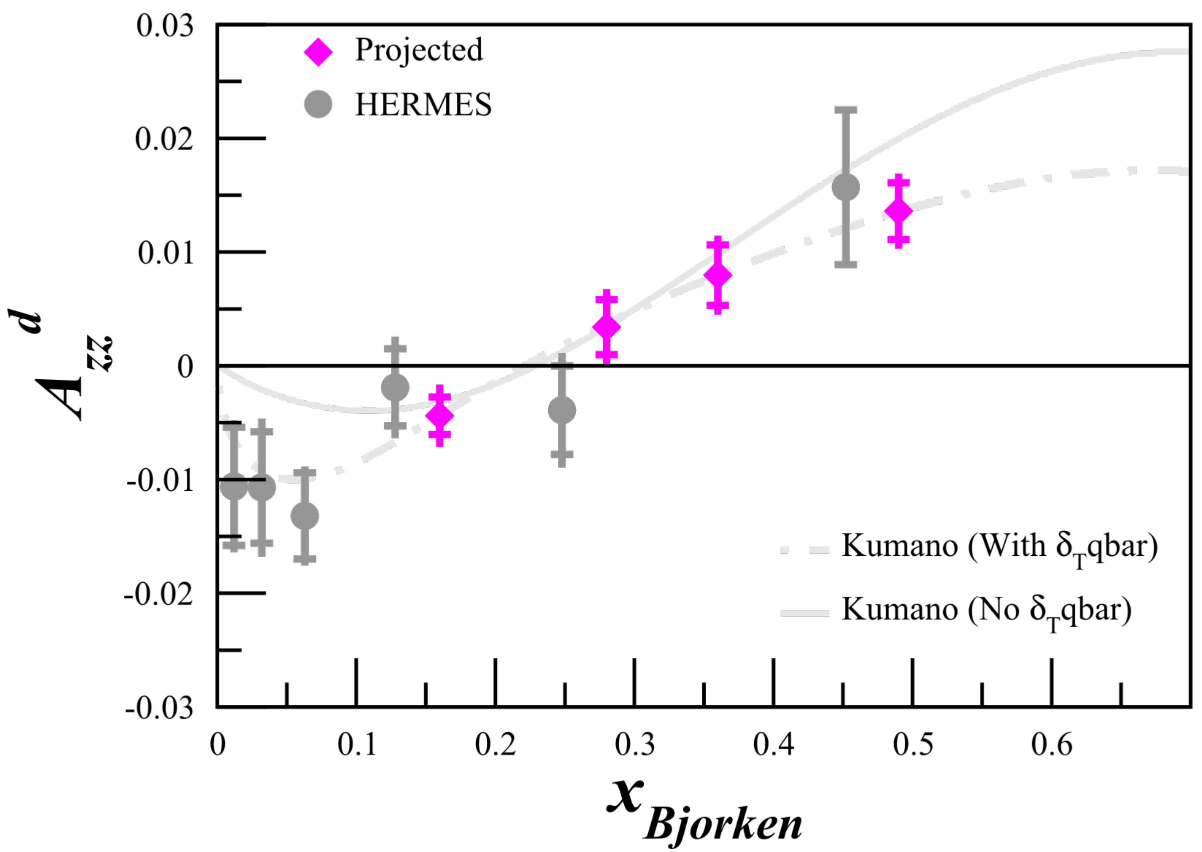
No other model shows such large effects.

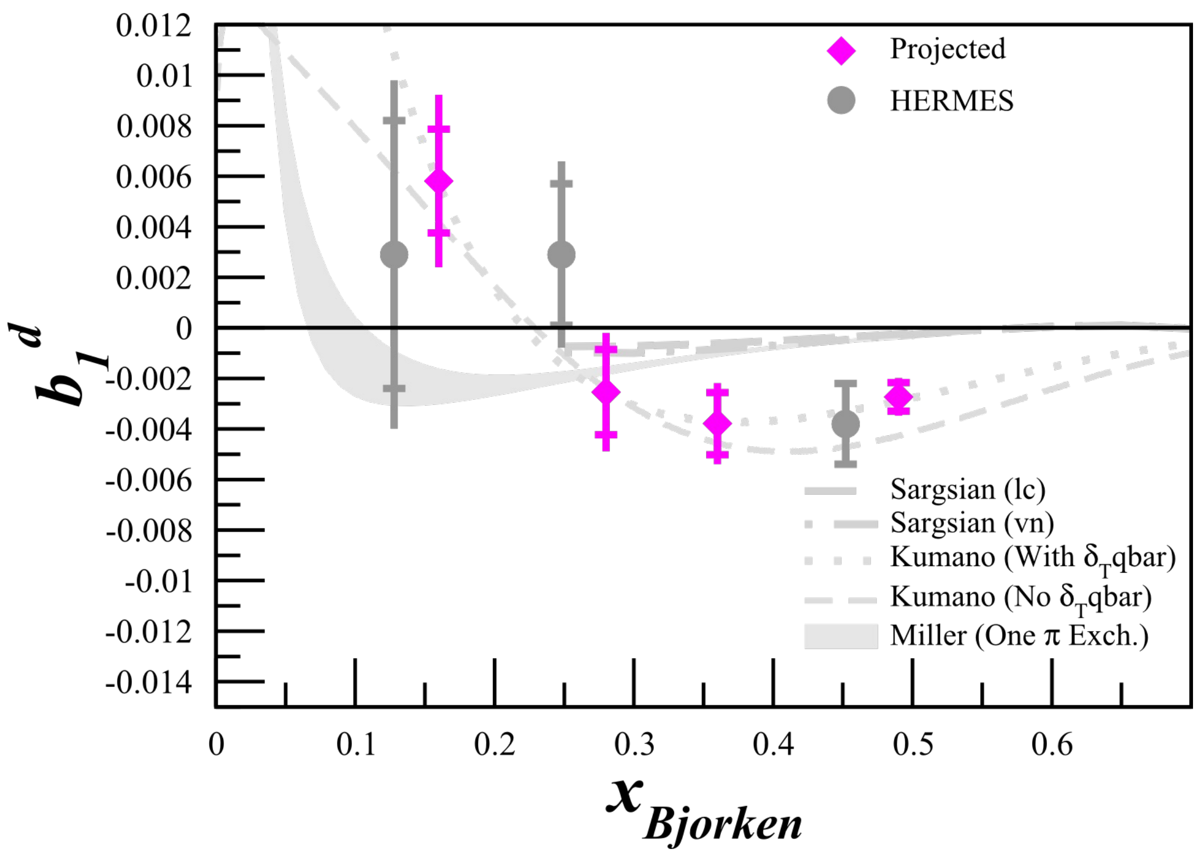
Jefferson Lab Kinematics for the b1 Experiment with 11 GeV Beam



Jefferson Lab is much lower energy than HERMES experiment BUT Jefferson Lab has much higher luminosity.

Projected Results





$$\frac{d^2\sigma}{dkd\Omega} = \sigma(h_e, P, Q) = \sigma_0 \left[1 + h_e(PA_{\parallel} + QA_T^{ed}) + PA_V^d + \frac{1}{2}QA_{zz}\right]$$

Jefferson Lab's beam *is* polarized, leading to 8 helicity states

- Combining these in various ways can give us 4 unique asymmetries
- 4 measurements & 4 unknowns
  - Simultaneously measure all pol. deuteron asymmetries from the upcoming tensor experiments

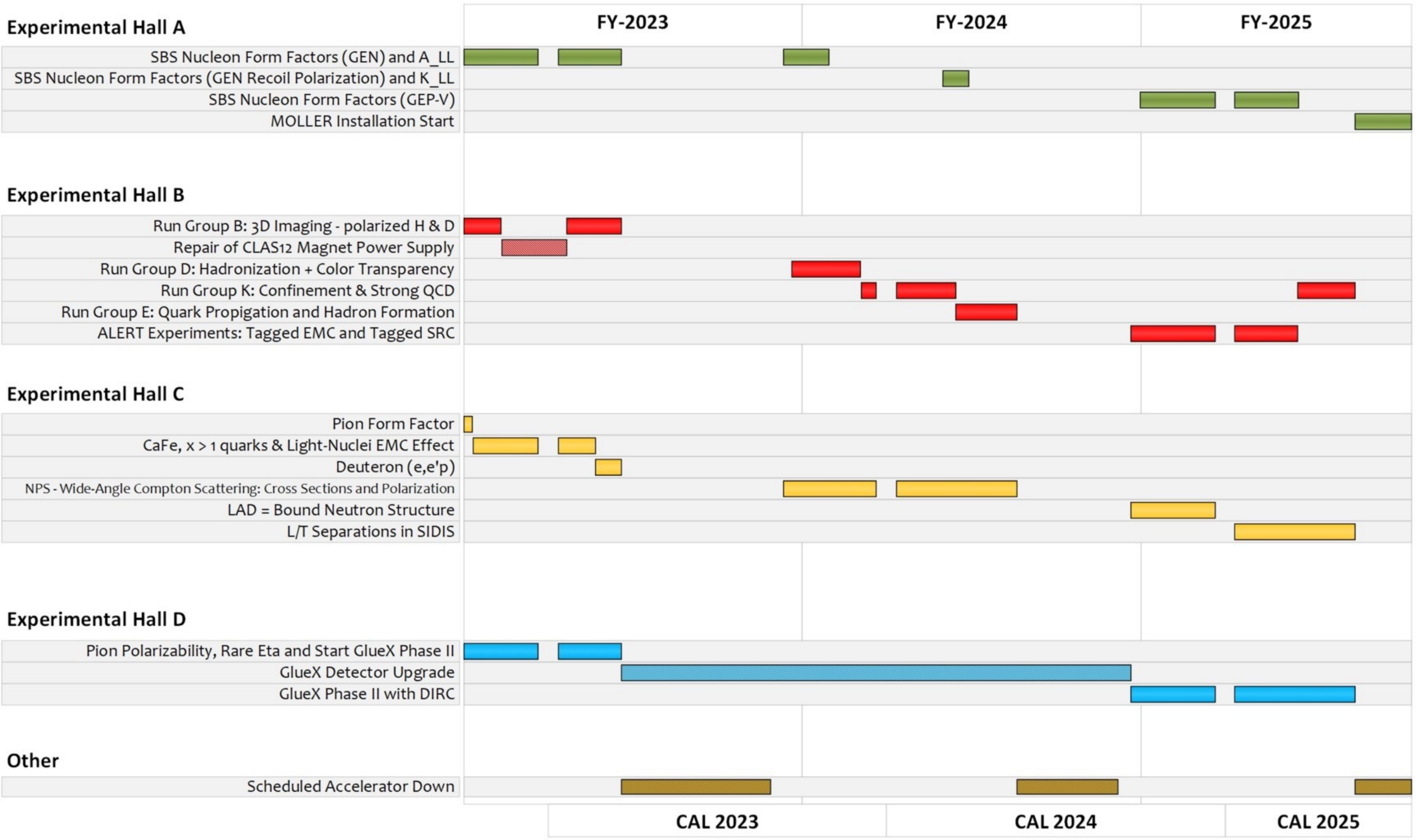
$$\begin{aligned}
\sigma_{1+} &= \sigma(h_e, P_1, Q_1) \rightarrow \sigma(+h_e, +P, Q) \\
\sigma_{1-} &= \sigma(-h_e, P_1, Q_1) \rightarrow \sigma(-h_e, +P, Q) \\
\sigma_{2+} &= \sigma(h_e, P_2, Q_2) \rightarrow \sigma(+h_e, -P, Q) \\
\sigma_{2-} &= \sigma(-h_e, P_2, Q_2) \rightarrow \sigma(-h_e, -P, Q) \\
\sigma_{3+} &= \sigma(h_e, P_3, Q_3) \rightarrow \sigma(+h_e, +P, 0) \\
\sigma_{3-} &= \sigma(-h_e, P_3, Q_3) \rightarrow \sigma(-h_e, +P, 0) \\
\sigma_{4+} &= \sigma(h_e, P_4, Q_4) \rightarrow \sigma(+h_4, -P, 0) \\
\sigma_{4-} &= \sigma(-h_e, P_4, Q_4) \rightarrow \sigma(-h_e, -P, 0)
\end{aligned}$$

Beam Asym w/ Tensor Target: $A_T^{ed} = \left[\frac{1}{hQ_n}\right]\left[\left(\frac{N_{n+} - N_{n-}}{N_{n+} + N_{n-}}\right)\left(1 + fA_V^d P_n + f\frac{1}{2}A_{zz}Q_n\right)\right] - fA_{\parallel}\frac{P_n}{Q_n}$

Beam/Target Vector Asym: $A_{\parallel} = \left[\frac{1}{fPh}\right]\left[\frac{(N_{3+} + N_{4-}) - (N_{4+} + N_{3-})}{(N_{4+} + N_{3-}) + (N_{3+} + N_{4-})}\right]$

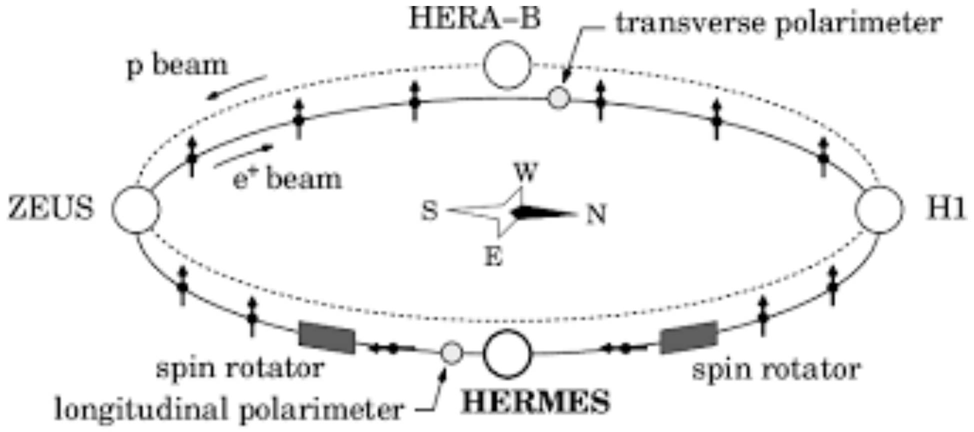
Target Vector Asym: $A_V^d = \left[\frac{1}{fP}\right]\left[\frac{N_3 - N_4}{N_4 + N_3}\right] - A_{\parallel}h$

Near Term Jefferson Lab Experimental Schedule



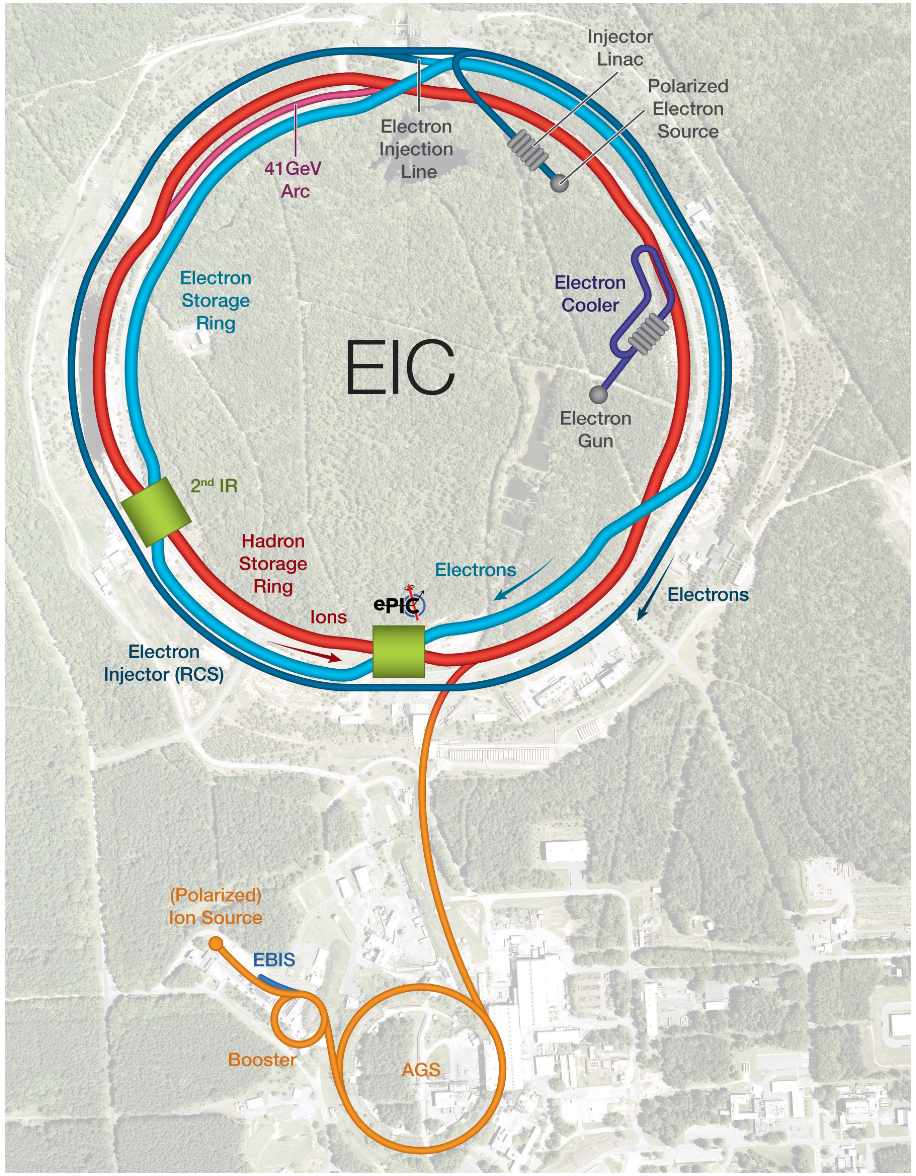
HERA

- HERA (German: Hadron-Elektron-Ringanlage, English: Hadron-Electron Ring Accelerator) was a particle accelerator at DESY in Hamburg.
- 318 GeV center of mass energies: 27.5 GeV e, 920 GeV p
- Electron-proton collider ran from 1992 – 2007
- Electron polarization by Sokolov – Ternov effect.
- Amazing machine and publications are still coming out from the data.
- Luminosity and some design choices limited the physics reach which now naturally lead to next generation machine: the EIC.

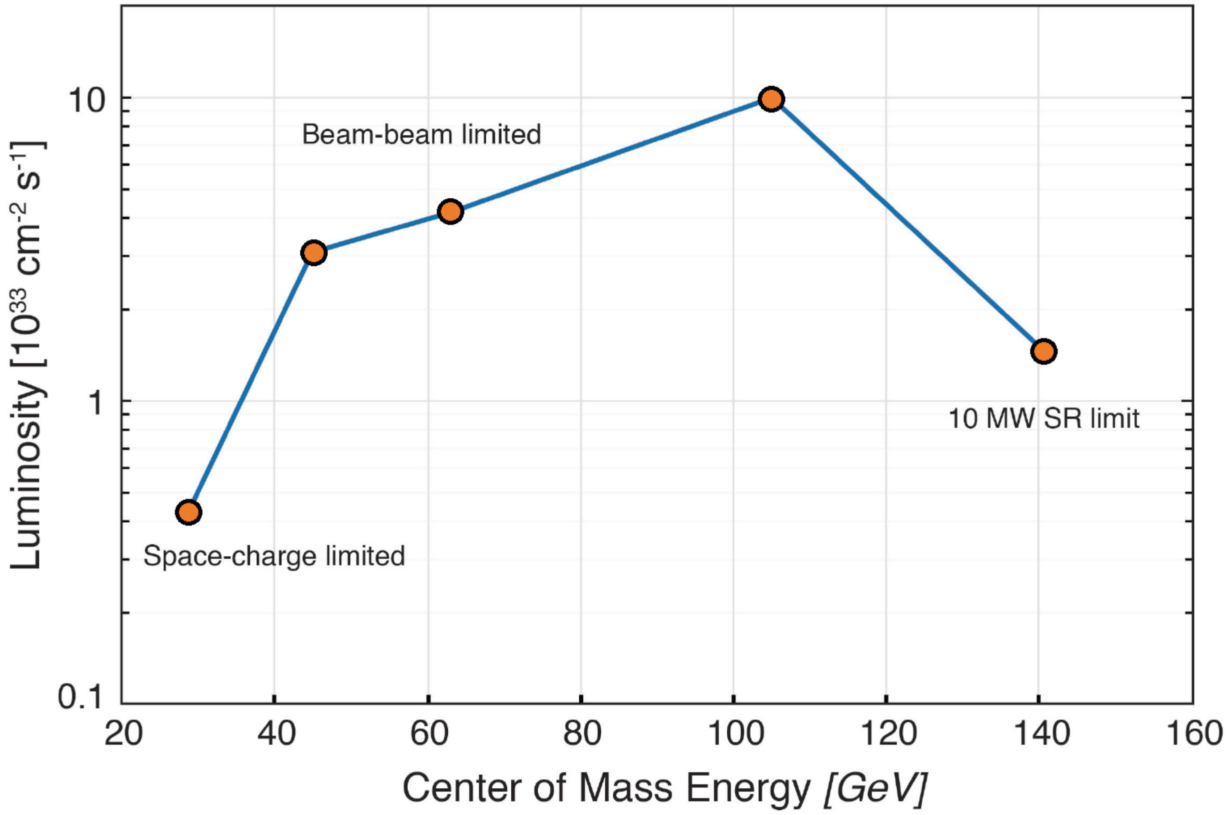


Basic Parameters of the EIC

- For e-N collisions:
  - Polarized beams: e, p, d/^{3}He (effective neutron)
  - e beam 5-10(20) GeV
  - Luminosity ~ 10^{33-34} cm^{-2}sec^{-1}
  - 100-1000 times HERA
  - 20-100 (140) GeV variable center of mass energy
- For e-A collisions:
  - Wide range in nuclei
  - Luminosity per nucleon same as e-p
  - Variable center of mass energy

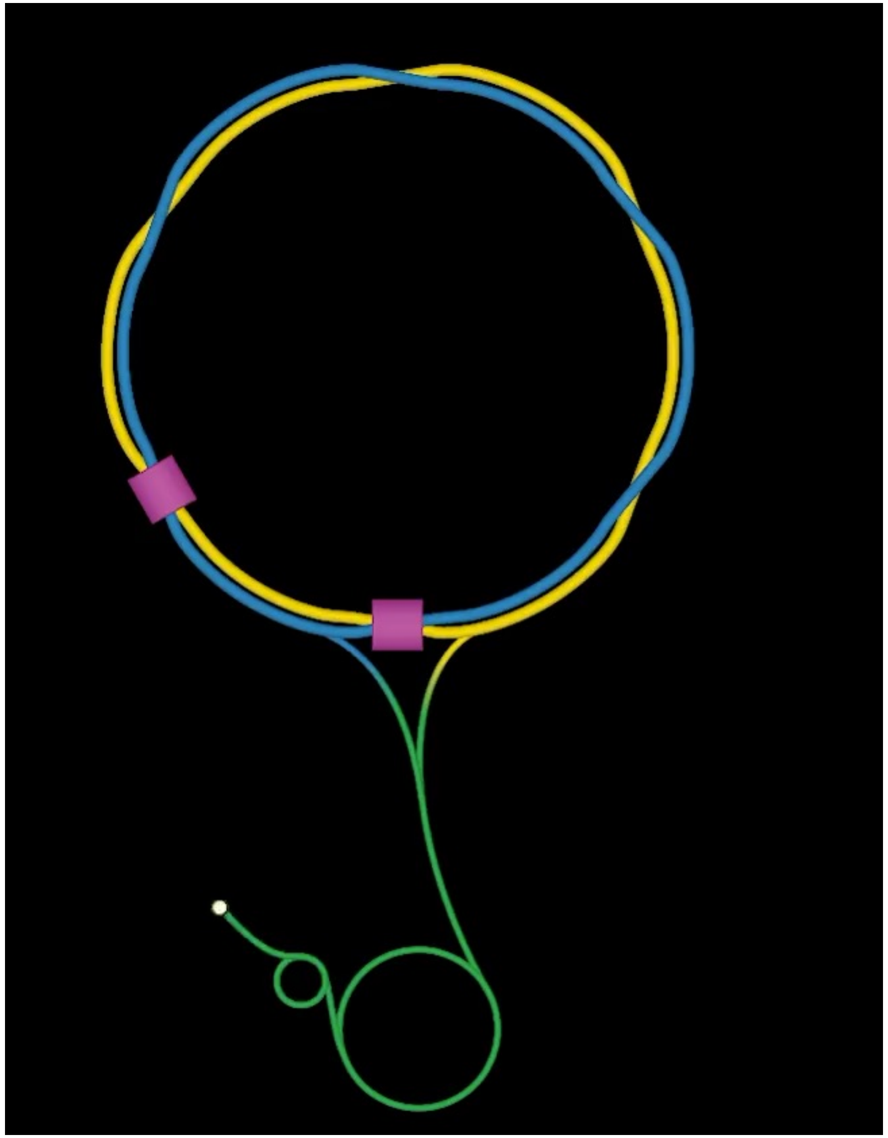


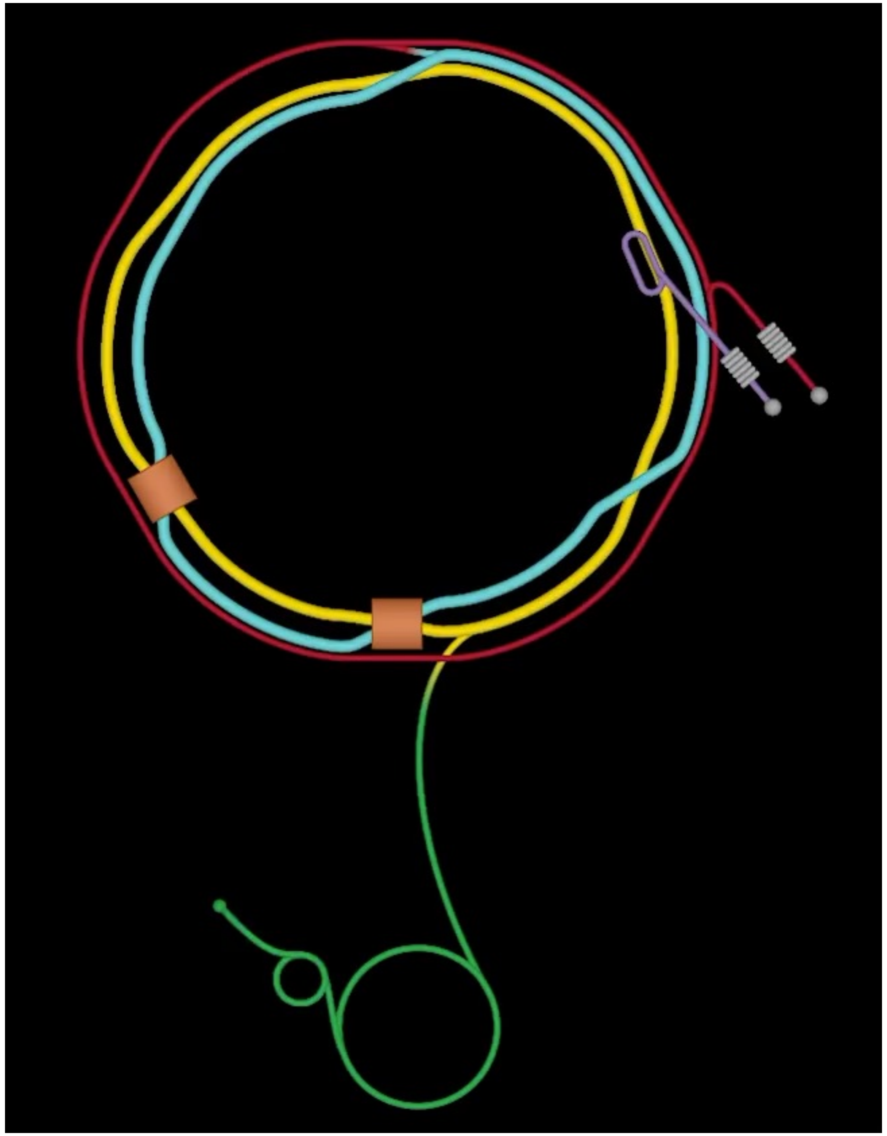
Luminosity vs Center of Mass Energy at the EIC



- Parameter and IR optimization at 105 GeV center-of-mass energy
- Optimization yields $10^{34} cm^{-2} sec^{-1}$ luminosity at 105 GeV
- Requires electron cooling of the hadron beam.
- NOTE: At a collider, it nominally takes years to reach the maximum luminosity with rapid luminosity improvements at first and then a long slow multi-year rise to

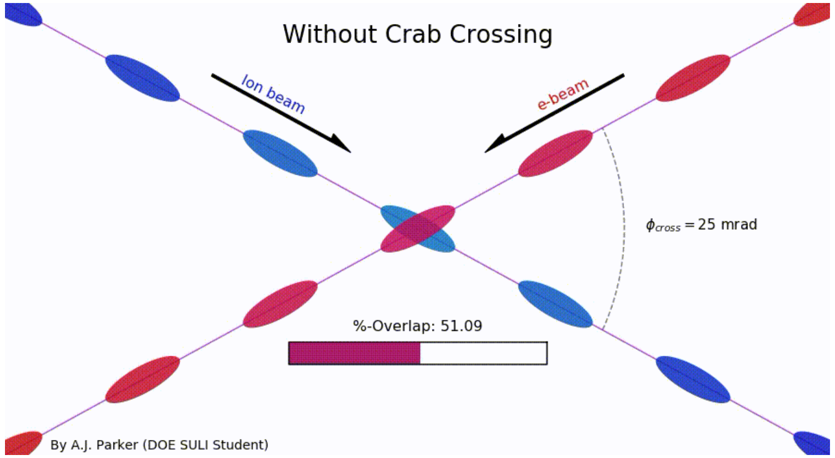
From RHIC to Electron Ion Collider

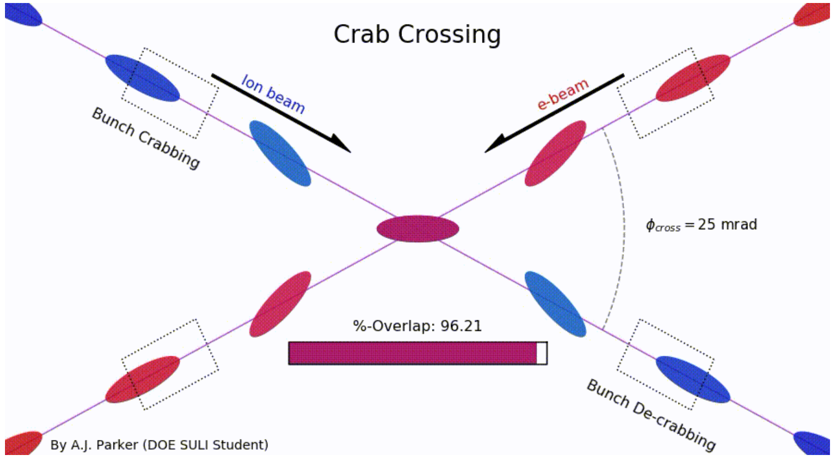




Visualization of The Colliding Beams

- DOE SULI summer student Asia Parker (Duquesne University)
- Showing how crab crossing increases the overlap of the beams
- https://github.com/sherwberry/SULI2020_CrabCrossingAnimation





EIC Yellow Report

Posted to the arXiv on 8 March 2021:
https://arxiv.org/abs/2103.05419

902 pages, 415 authors, and 151 institutions

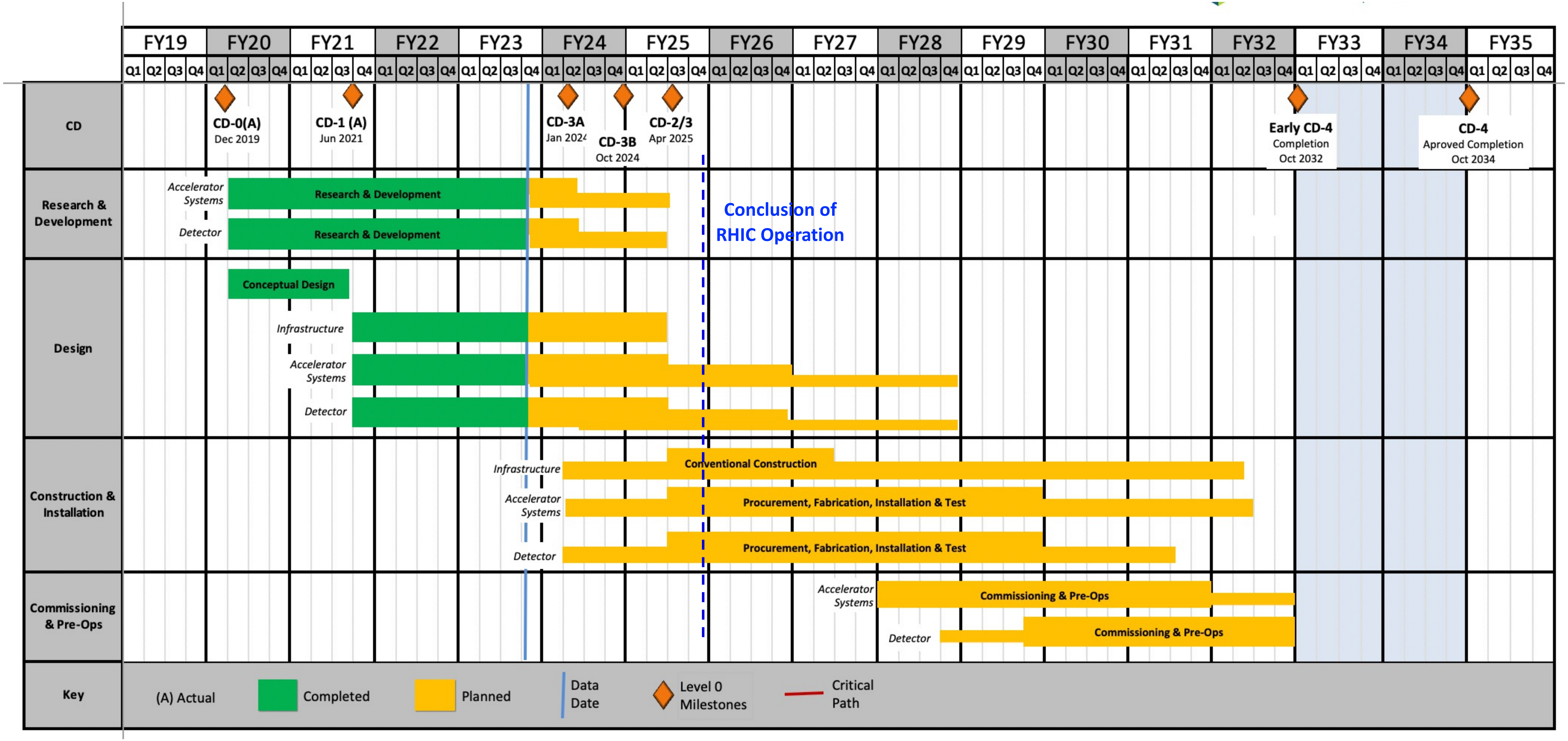
also published in a refereed journal:
Nucl.Phys.A 1026 (2022) 122447

As of 15 February 2024 has 741 citations.

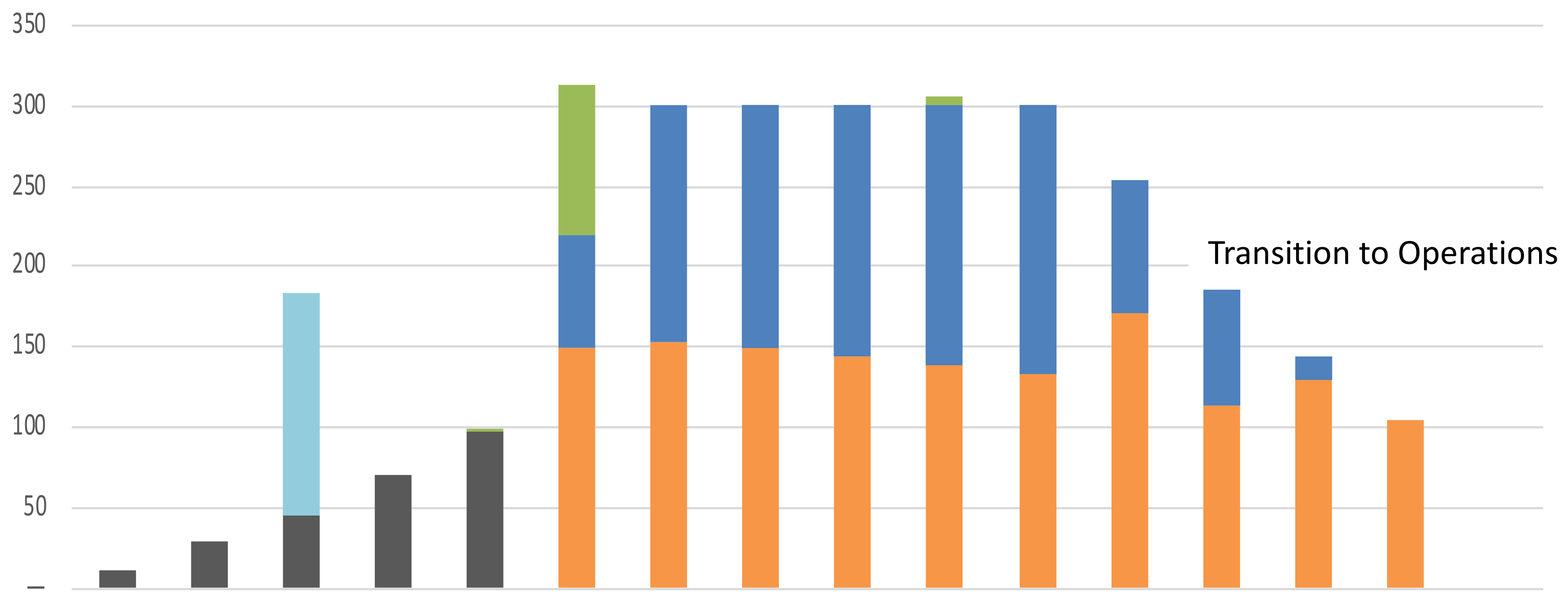
The document is broken into three volumes:
Executive Summary
Physics
Detectors

ePIC collaboration is now getting ready to write the draft Technical design document for the detector package.

Schedule as Shown at Jan. 2024 ePIC Meeting



EIC Reference Funding Profile v4 - FY25 $219M



FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32	FY33	FY34	Total
11	30	183	70	98	219	300	300	300	300	300	254	185	145	105	2,800
					69	147	151	156	161	166	82	72	15		1,108

- This funding profile, V4 (Version 4), is based on actuals through FY23 and forecasts.
- V5 will use FY24 actual and revised forecasts.
- V6 will be the CD-2 Performance Baseline.

~10% Cost of A US Aircraft Carrier

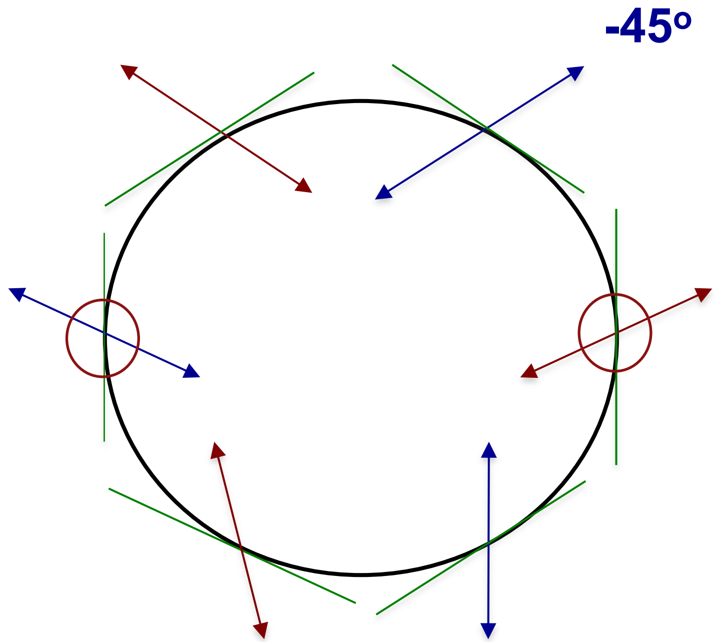
which are all built here in Newport News

Gerald R. Ford-class aircraft carrier

3 billion dollars is a very large amount for a DOE nuclear physics project and budgets in the US are annual so we can expect good years and bad years along the way.

Six Hadron Ring Snakes Planned for the EIC

Being designed for polarized protons and polarized 3He.



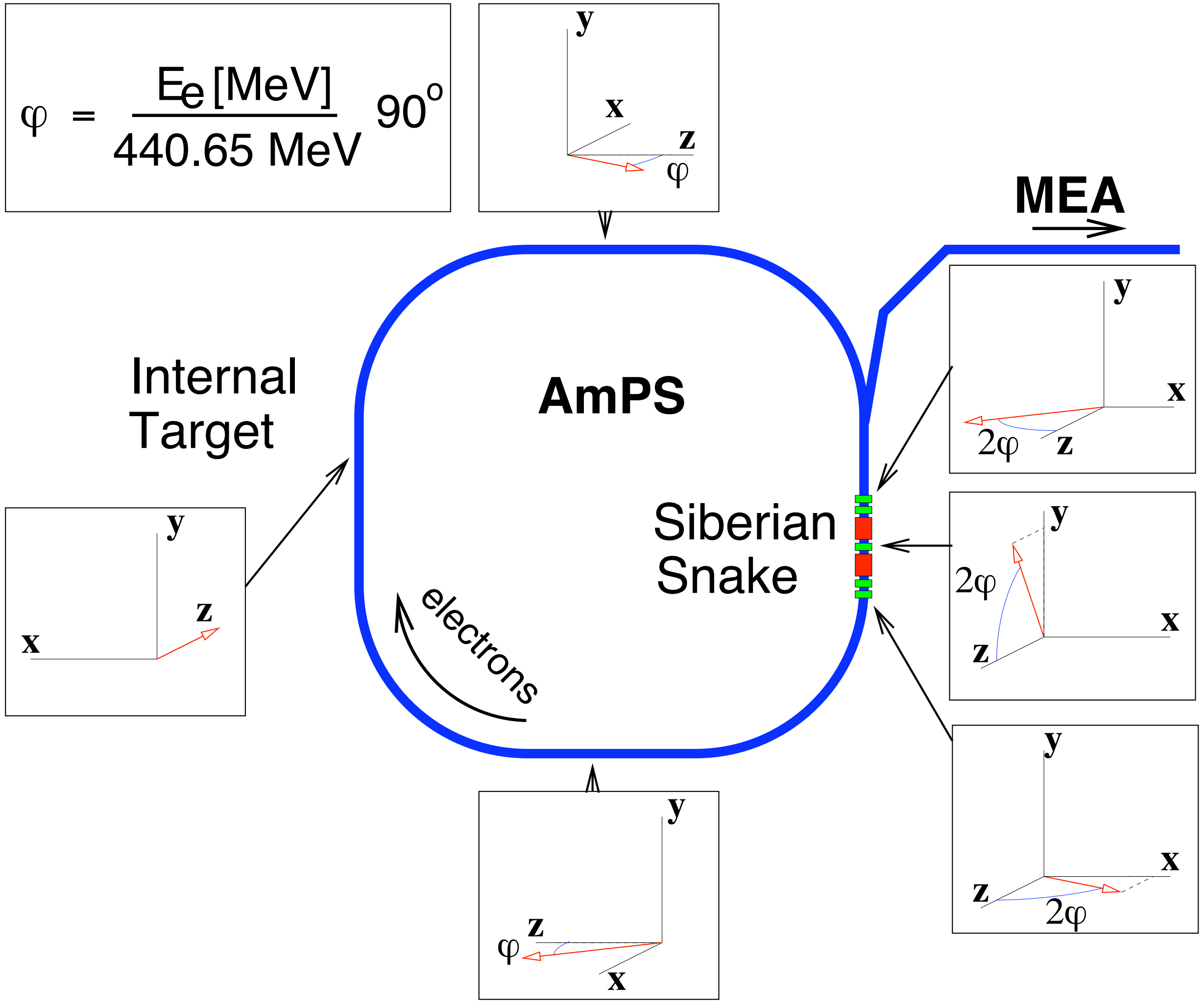
Ideally multiple snake arrangement is perfectly symmetric with 60 degree bending angle between Snakes.

Due to the injection region constraint, the snake at IP6 can not be put into the desired place. The proposed snake locations are as following with counting starting at IP12: snake1 = ϕ, snake2=$\pi/3 - \phi$, snake3 = $2\pi/3-\phi$, snake4 =$\pi+\phi$, snake5 = $4\pi/3-\phi$, snake6= $5\pi/3-\phi$, where ϕ = 0.0435rad.

Electron Polarization @ NIKHEF with a Full and Partial Snake

- The NIKHEF storage ring with a full Siberian Snake could provide stored, longitudinally polarized electrons at any energy.
- When the NIKHEF Snake broke, we were able to continue doing physics by going to 440.65 MeV along with a partial snake.
- https://doi.org/10.1103/PhysRevLett.84.3855

$$\varphi = \frac{E_e\,[\mathrm{MeV}]}{440.65\ \mathrm{MeV}}\ 90^{o}$$



Deuteron Polarization at the EIC

- Magnetic moment of the proton is 2.79 nuclear magnetons, neutron moment is -1.91, 3He is -2.13 (i.e. we already no pol. 3He not equal to pol. n)) BUT the deuteron moment is 0.857 nuclear magnetons making it significantly harder to manipulate with Siberian snakes.

- Assuming the deuterons can be accelerated from an atomic beam source without loosing polarization (this is a non-trivial challenge of depolarizing resonances), the idea of magic energies can be used to allow longitudinal deuteron polarization at an interaction region in the EIC without (hopefully) having to further upgrade the Siberian snakes.

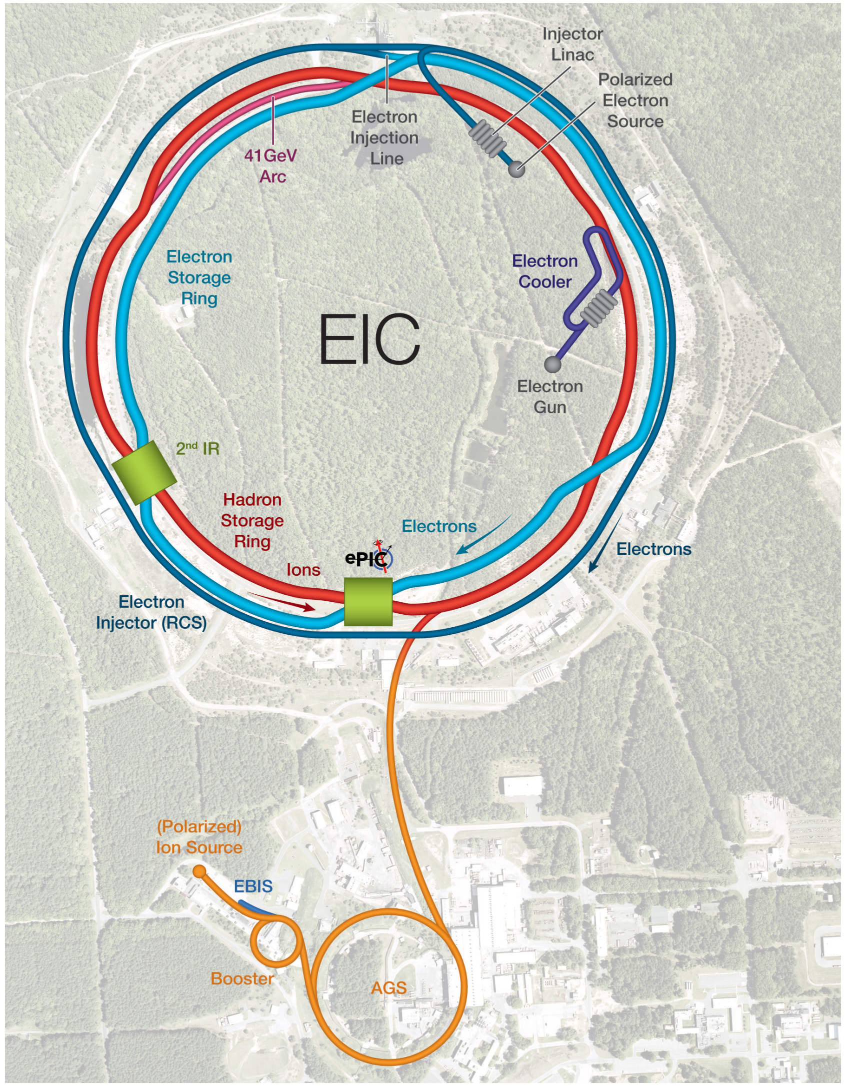
- Assuming an EIC deuteron energy range of 20.5 to 137.5 GeV/nucleon, there are a total of 17 energies where the deuteron polarization can in principle be made longitudinal at least at one interaction point: 26.2, 32.8, 39.4, 45.9, 52.5, 59.0, 65.6, 72.1, 78.7, 85.3, 91.8, 98.4, 104.9, 111.5, 118.1, 124.6, and 131.2 GeV/nucleon.

- Of these energies, there are 5 where the deuteron polarization can be made longitudinal at both interaction points: 39.4, 59.0, 78.7, 98.4, and 118.1 GeV/nucleon.

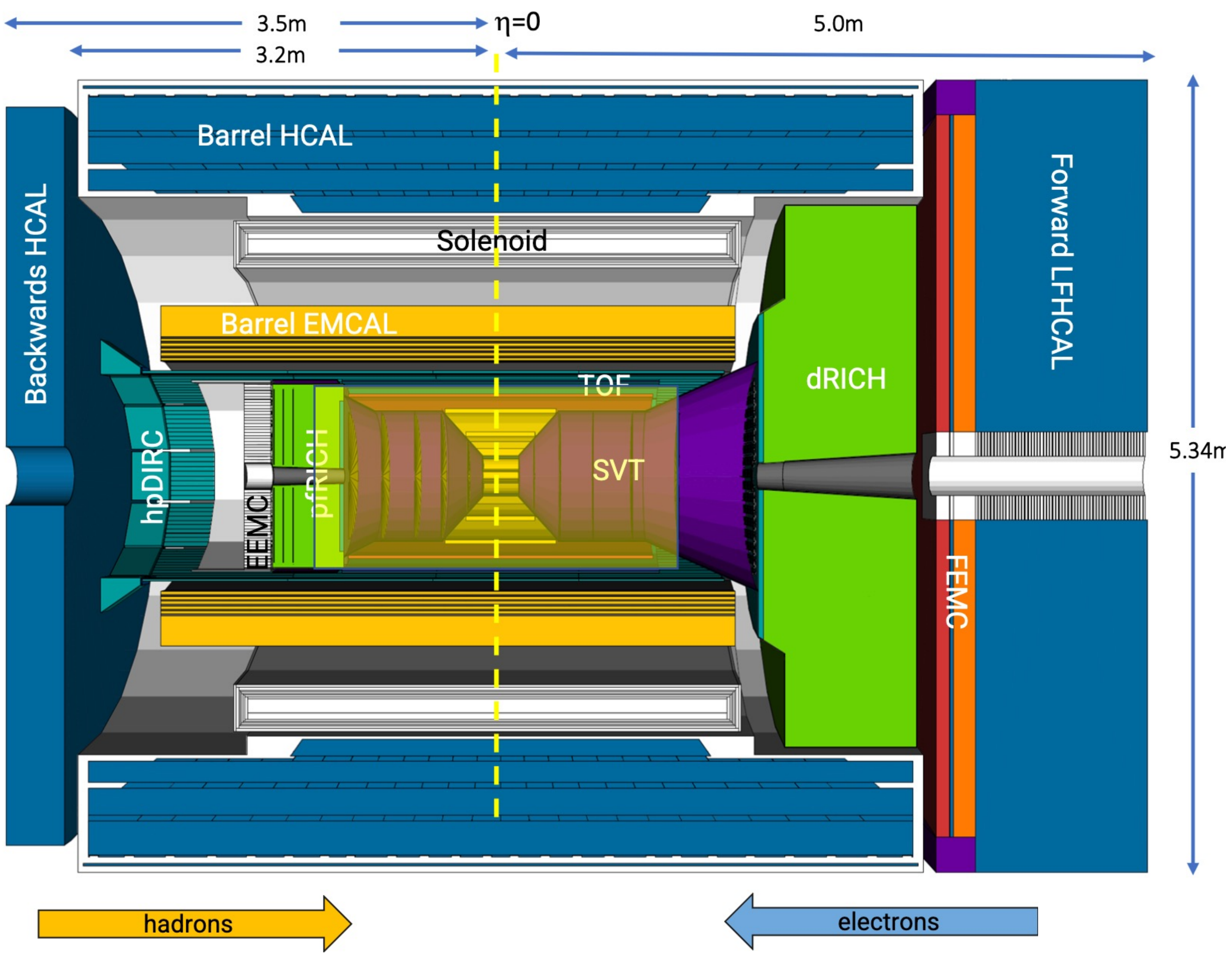
- Two of those are very close to the yellow report energies of 41 and 110 GeV.

Summary

- With much thanks to the UNH and UVA target groups, a new generation of tensor polarized experiments are being planned for Jefferson Lab.
- Are low current and can run with the demanding Moller experiment in Hall A
- Elastic, QE, and DIS measurements will be made to extra T20, Azz, and b1.
- The future EIC is being designed to have polarized electrons and polarized light ions; but due to the small magnetic moment deuterons will be very challenging.
- The “trick” that was demonstrated at NIKHEF is making use of magic energies.

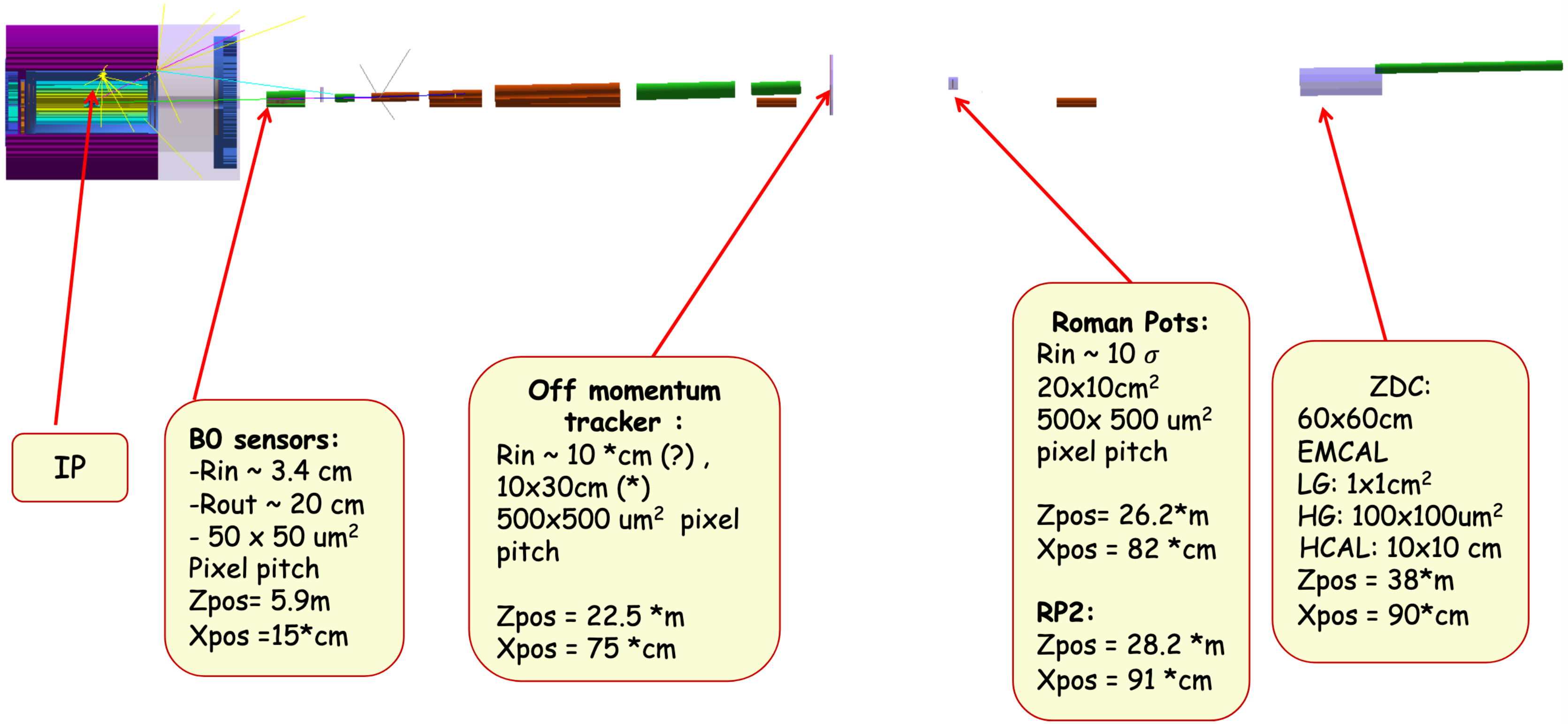


Current Layout (July 2023) of ePIC Detector System



Far Forward Detection Systems (my favorite part of the EIC)

Detectors located tens of meters from the main EIC detector and are small in size.

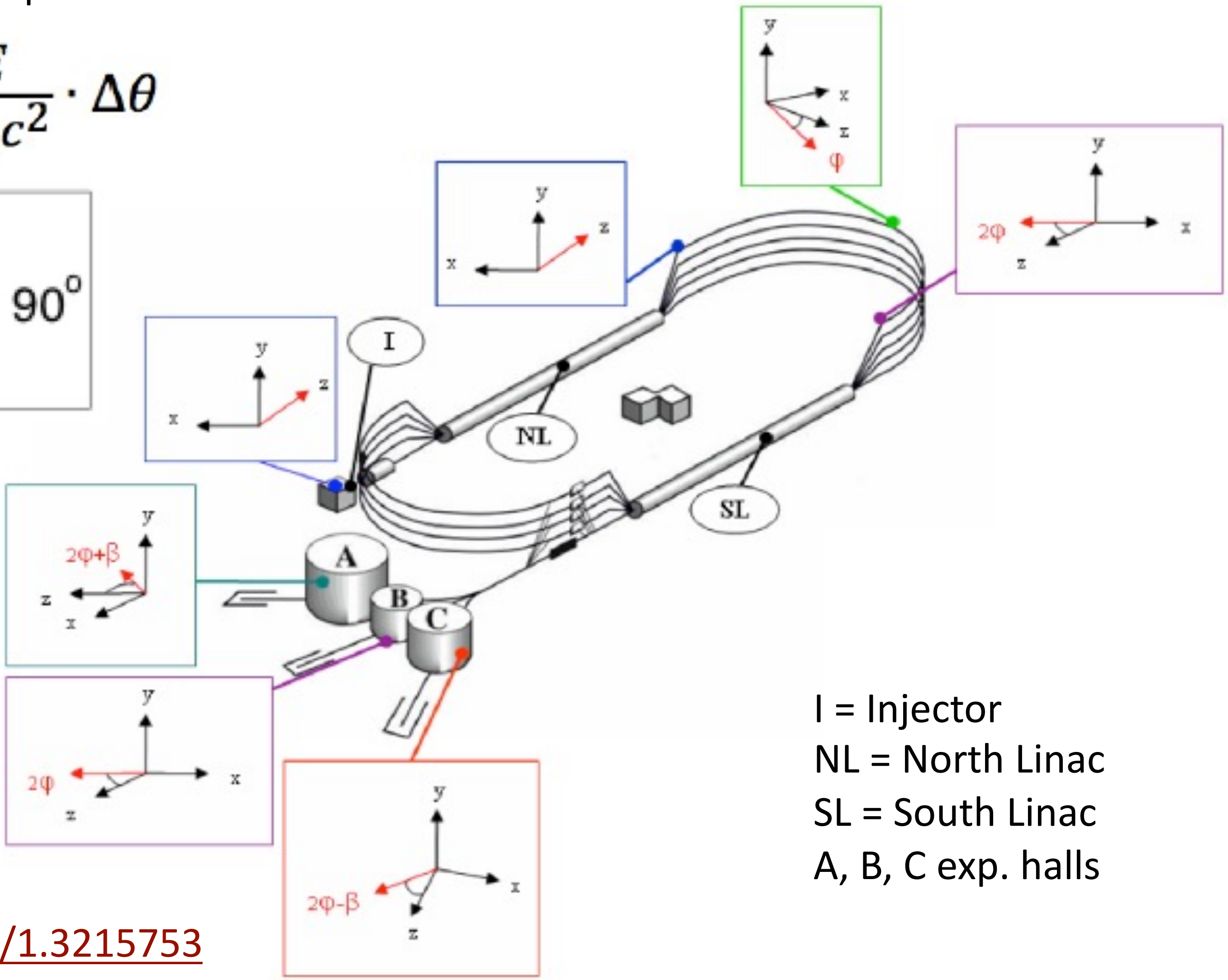


Spin Precession in CEBAF

Like a trick shot, by carefully picking the beam energy, highly polarized electrons can be sent to multiple experimental halls at once.

$$\Delta\varphi = \frac{g-2}{2} \cdot \frac{E}{m_e c^2} \cdot \Delta\theta$$

$$\varphi = \frac{E_e\,[\mathrm{MeV}]}{440.65\ \mathrm{MeV}}\, 90^{\circ}$$

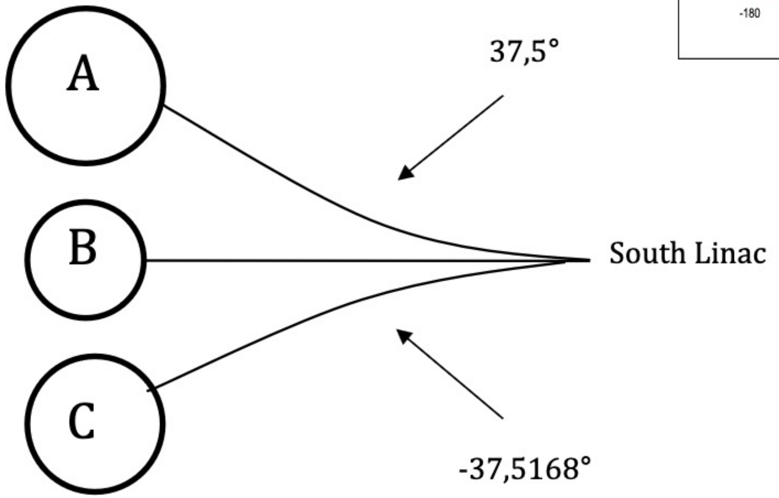


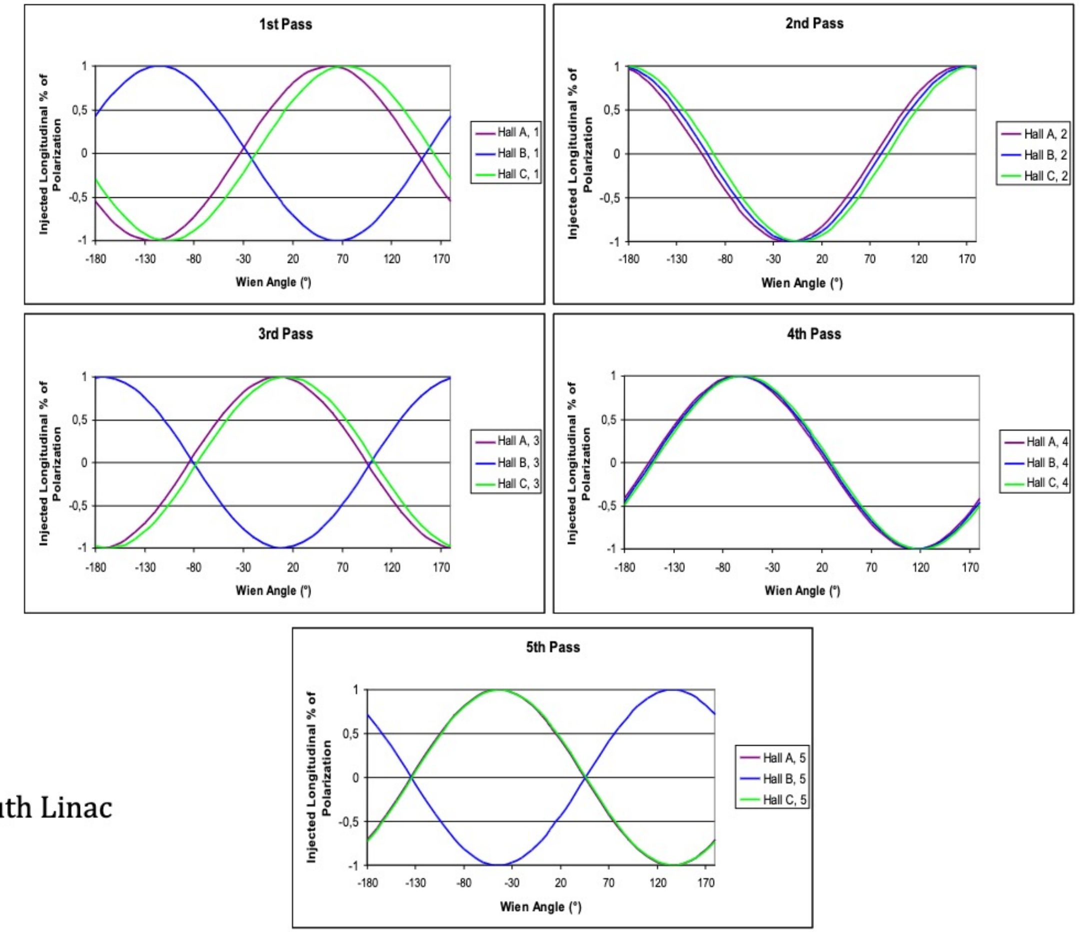
I = Injector
NL = North Linac
SL = South Linac
A, B, C exp. halls

https://doi.org/10.1063/1.3215753

Ma

1st	2.12 GeV
2nd	4.23 GeV
3rd	6.35 GeV
4th	8.46 GeV
5th	10.6 GeV





Last JLab run was very close to this with 1.047 GeV/linac + 0.1 GeV injector energy.

Critical Decision Process

PROJECT ACQUISITION PROCESS AND CRITICAL DECISIONS						
Project Planning Phase		Project Execution Phase			Mission	
Preconceptual Planning	Conceptual Design	Preliminary Design	Final Design	Construction	Operations	
CD-0 Approve Mission Need	CD-1 Approve Preliminary Baseline Range	CD-2 Approve Performance Baseline	CD-3 Approve Start of Construction	CD-4 Approve Start of Operations or Project Closeout		

CD-0	CD-1	CD-2	CD-3	CD-4
Actions Authorized by Critical Decision Approval				
• Proceed with conceptual design using program funds • Request PED funding	• Allow expenditure of PED funds for design	• Establish baseline budget for construction • Continue design • Request construction funding	• Approve expenditure of funds for construction	• Allow start of operations or project closeout

PED: Project Engineering & Design