U.S. Programs for the Study of Nucleon Structure

- OLYMPUS at DESY **web.mit.edu/OLYMPUS/**
- Electron-Ion Collider
- Polarized ^{3}He Source Development **he3.lns.mit.edu**

Elastic electron-proton scattering cross section

In the one-photon exchange approximation, the cross section is a product of the Mott cross section and the form factor functions

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2}{4E^2}\frac{1}{\sin^4\frac{\theta}{2}}\cdot\cos^2\frac{\theta}{2}\cdot\frac{E'}{E}$$

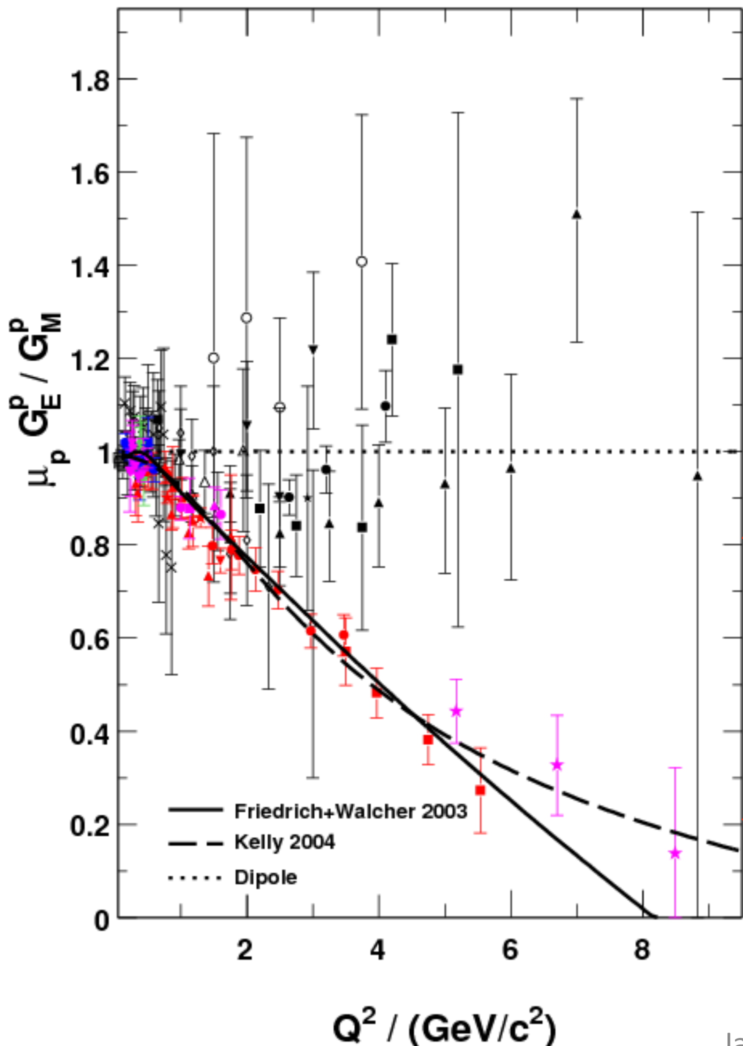
$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = S_0 = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2} \qquad \tau = \frac{Q^2}{4M_p^2}$$

$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$

$$= \frac{\epsilon\, G_E^2 + \tau G_M^2}{\epsilon\,(1+\tau)}, \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

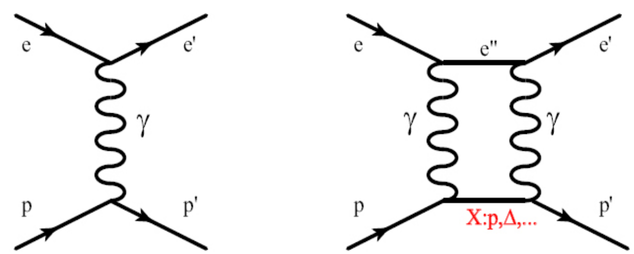
ε =relative flux of longitudinally polarized virtual photons

Proton Form Factor Ratio



Jefferson Lab 2000

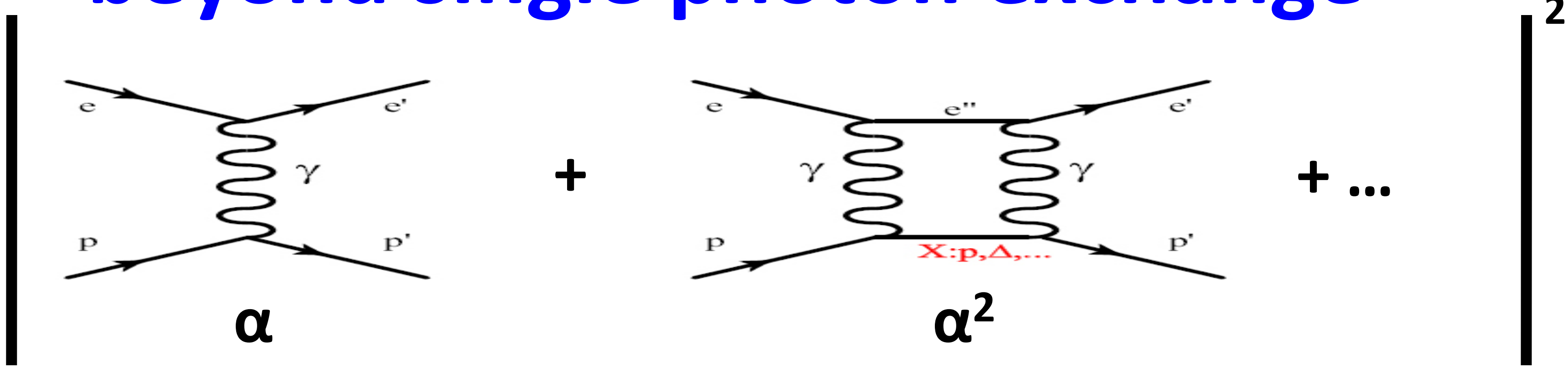
- All Rosenbluth data from SLAC and JLab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Contribution of multi-photon exchange widely accepted explanation of discrepancy



Dramatic discrepancy!

>800 citations

Definitive determination of contributions beyond single photon exchange



$$\sigma(e^- p) = |M_{1\gamma}|^2 \alpha^2 - 2\,|M_{1\gamma}|\,|M_{2\gamma}|\,\alpha^3 + \ldots$$

$$\sigma(e^+ p) = |M_{1\gamma}|^2 \alpha^2 + 2\,|M_{1\gamma}|\,|M_{2\gamma}|\,\alpha^3 + \ldots$$

Cross section ratio for elastic e^+ and e^- proton scattering:

$$R = \frac{\sigma(e^+ p)}{\sigma(e^- p)} = 1 + \frac{4\,\Re(M^\dagger_{1\gamma} M_{2\gamma})}{|M_{1\gamma}|^2}$$

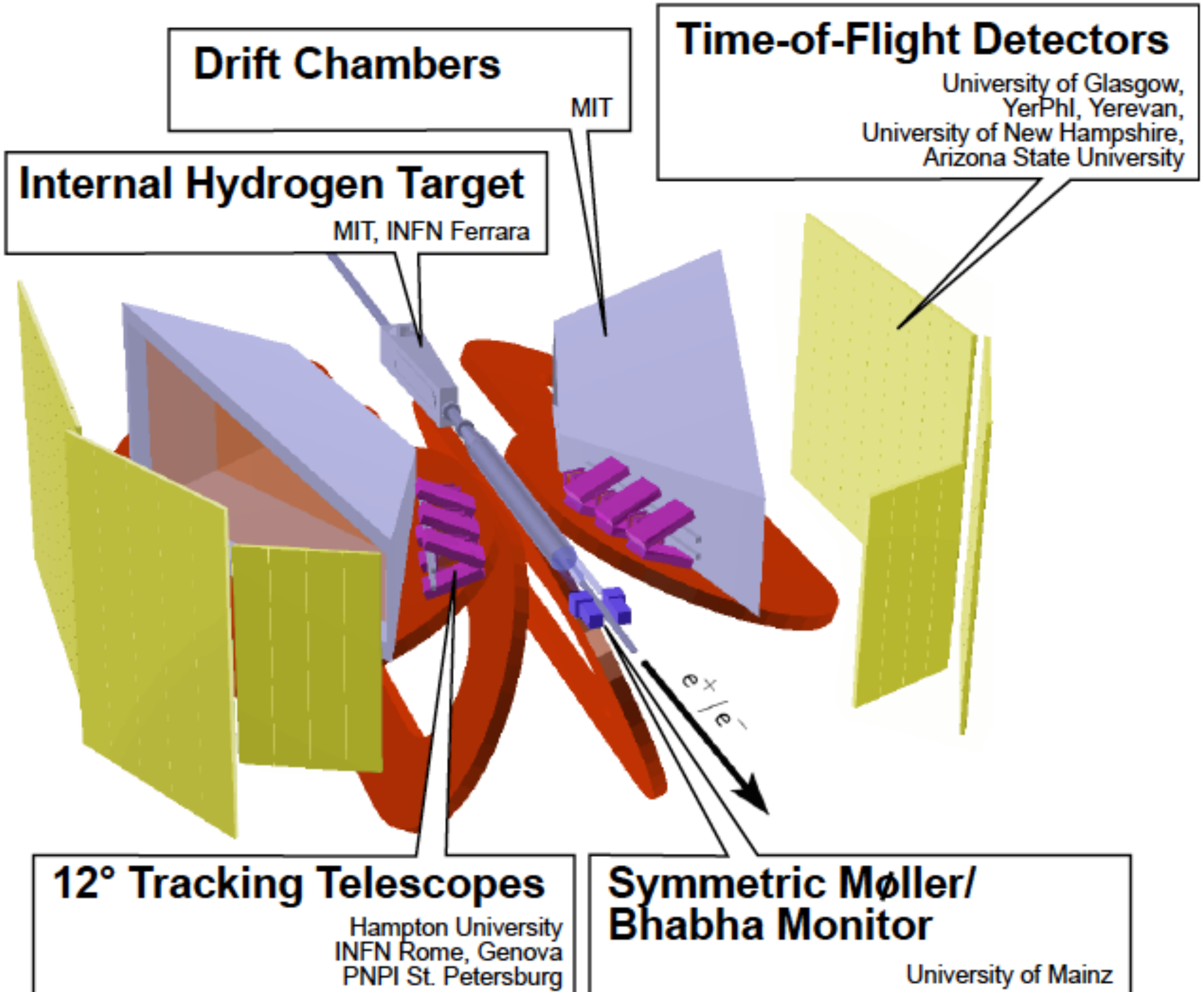
Arizona State University, USA
DESY, Hamburg, Germany
Hampton University, USA
INFN, Bari, Italy
INFN, Ferrara, Italy
INFN, Rome, Italy
Massachusetts Institute of Technology, USA
Petersburg Nuclear Physics Institute, Russia
Universität Bonn, Germany
University of Glasgow, United Kingdom
Universität Mainz, Germany
University of New Hampshire, USA
Yerevan Physics Institute, Armenia

The OLYMPUS Experiment

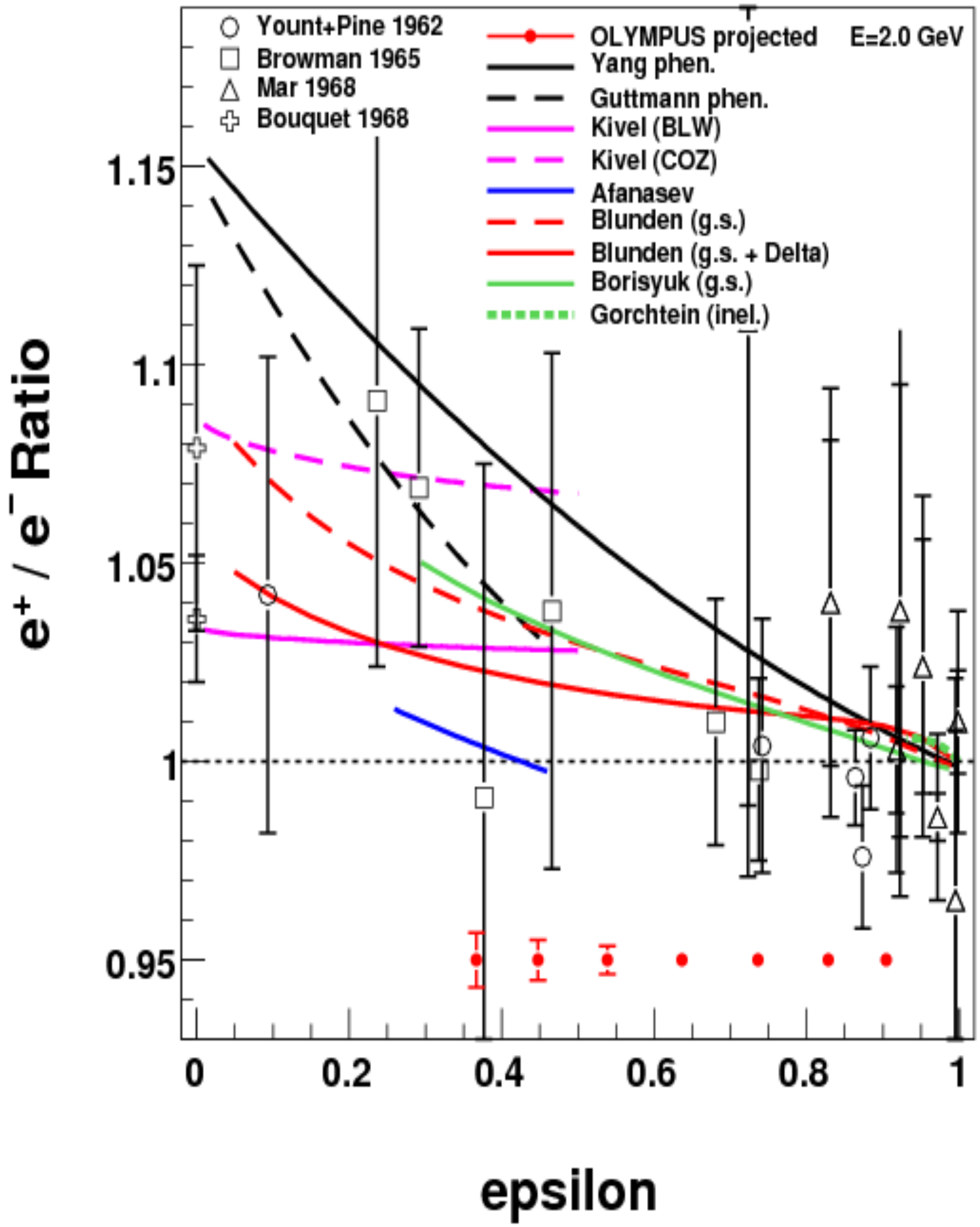
- Electrons/positrons (100mA) in multi-GeV storage ring DORIS at DESY, Hamburg, Germany
- Unpolarized internal hydrogen target (buffer system) 3×10^{15} at/cm^2 @ 50 mA → $L = 10^{33}$ / (cm^{2}s)
- Large acceptance detector for e-p in coincidence: utilized existing BLAST detector from MIT-Bates
- Redundant monitoring of luminosity:
  Pressure, temperature, flow, current measurements
  Small-angle elastic scattering at high epsilon / low Q^2
  Symmetric Moller/Bhabha scattering

- **Measured ratio of positron-proton to electron-proton unpolarized elastic scattering with goal of ≈1% stat.+sys.**

The OLYMPUS Experiment

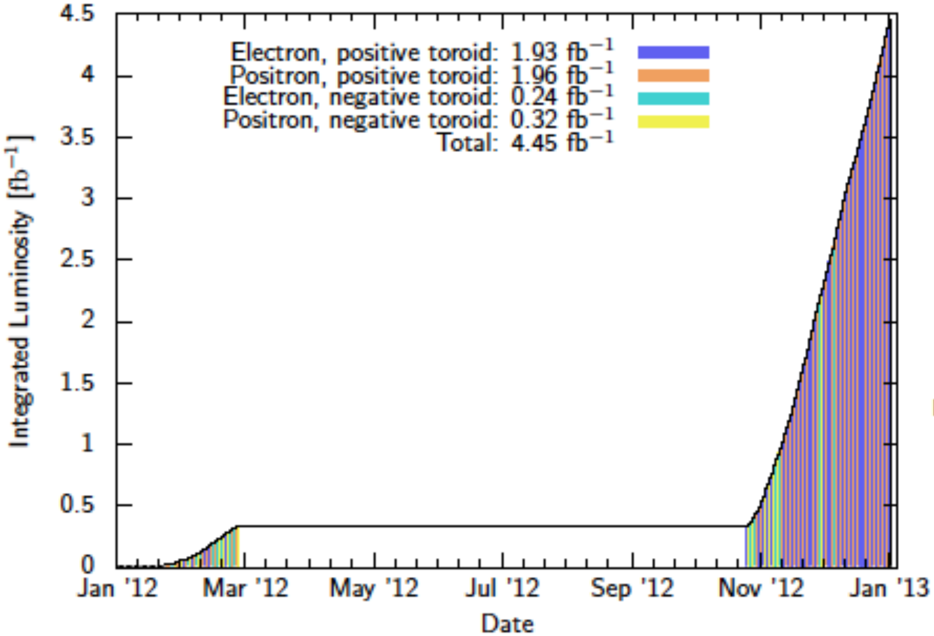


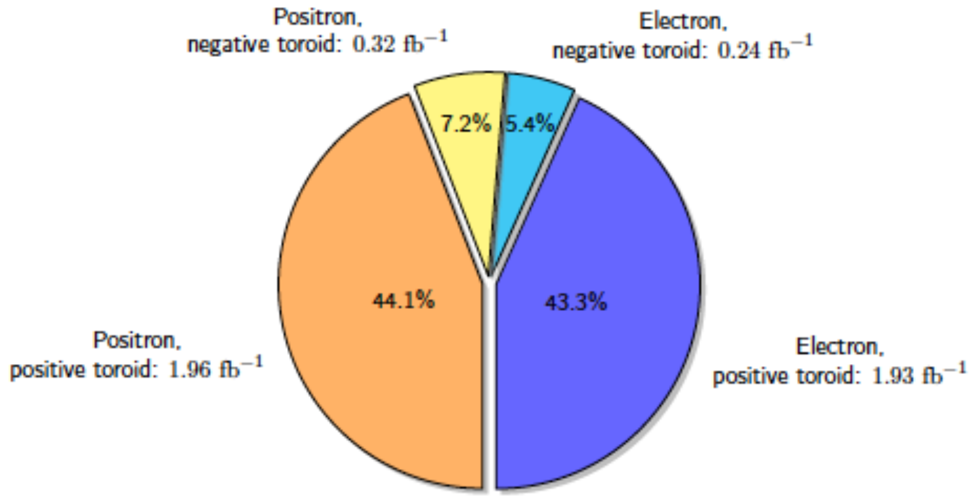
Projected OLYMPUS uncertainties



- 2 GeV incident beam energy
- Luminosity = 2 x 10^{33} cm^{-2} s^{-1}
- 500 hours each for e+ and e-
- 3.6 fb^{-1} integrated luminosity

Data taking



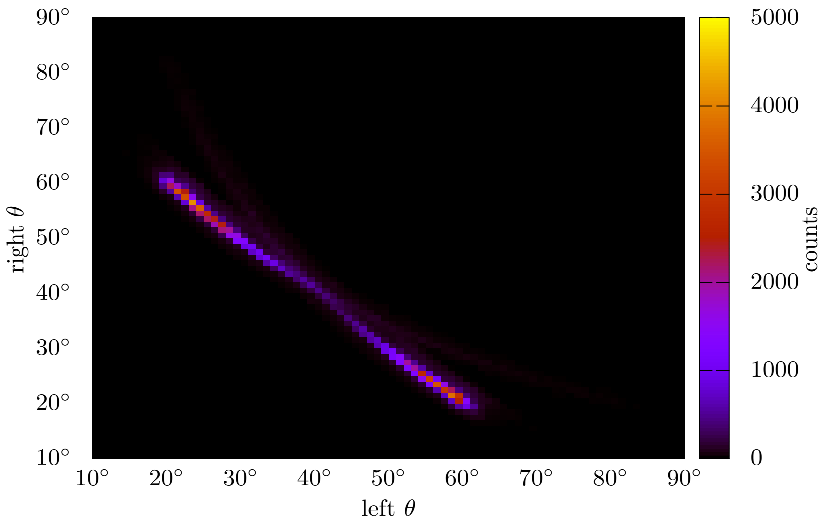


J. Bernauer

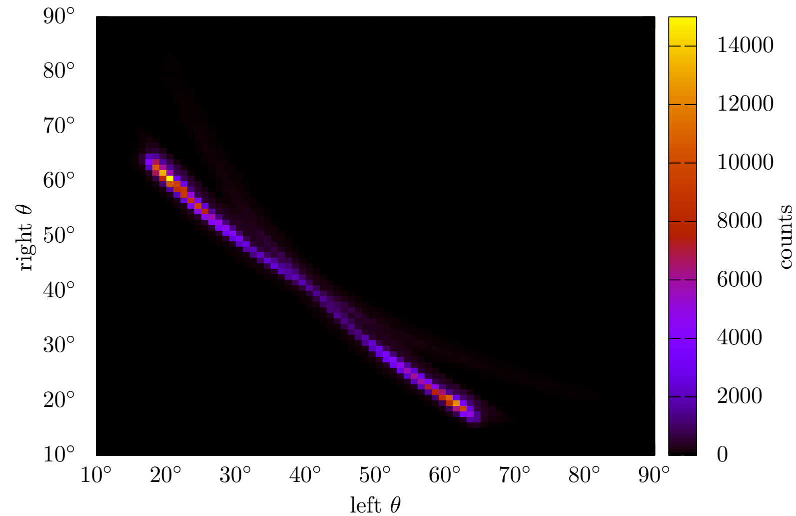
- well-balanced e^+, e^- data sets
- additional negative toroid data (systematics!)
- $\mathcal{L}_{int}$ goal of 4 fb^{-1} exceeded!

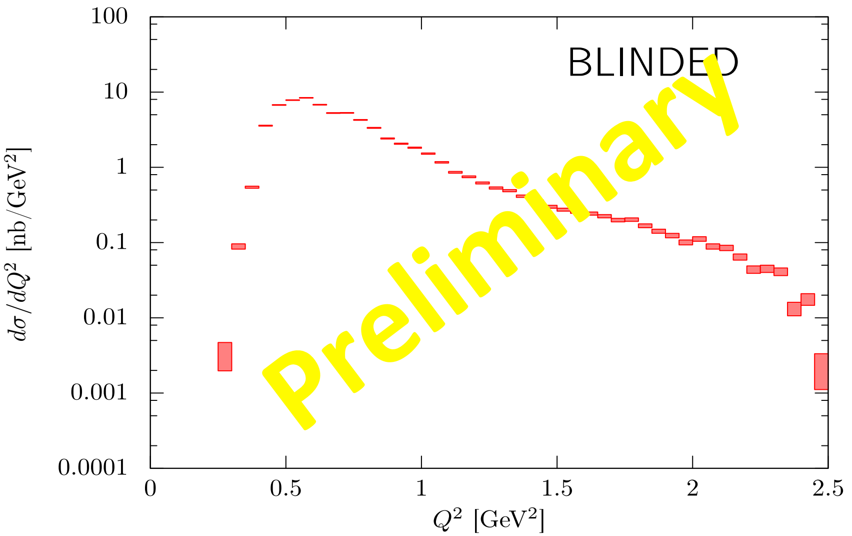
Coincident elastic (e,e'p) events

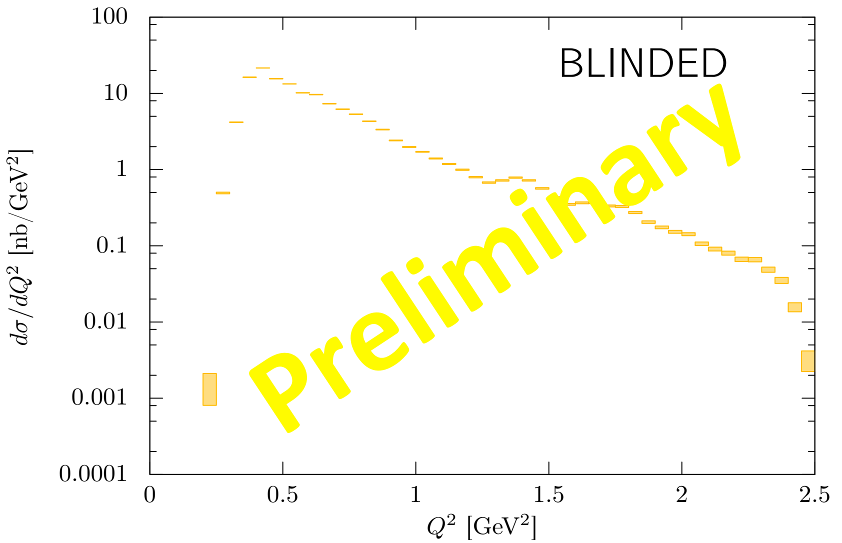
e- beam



e+ beam







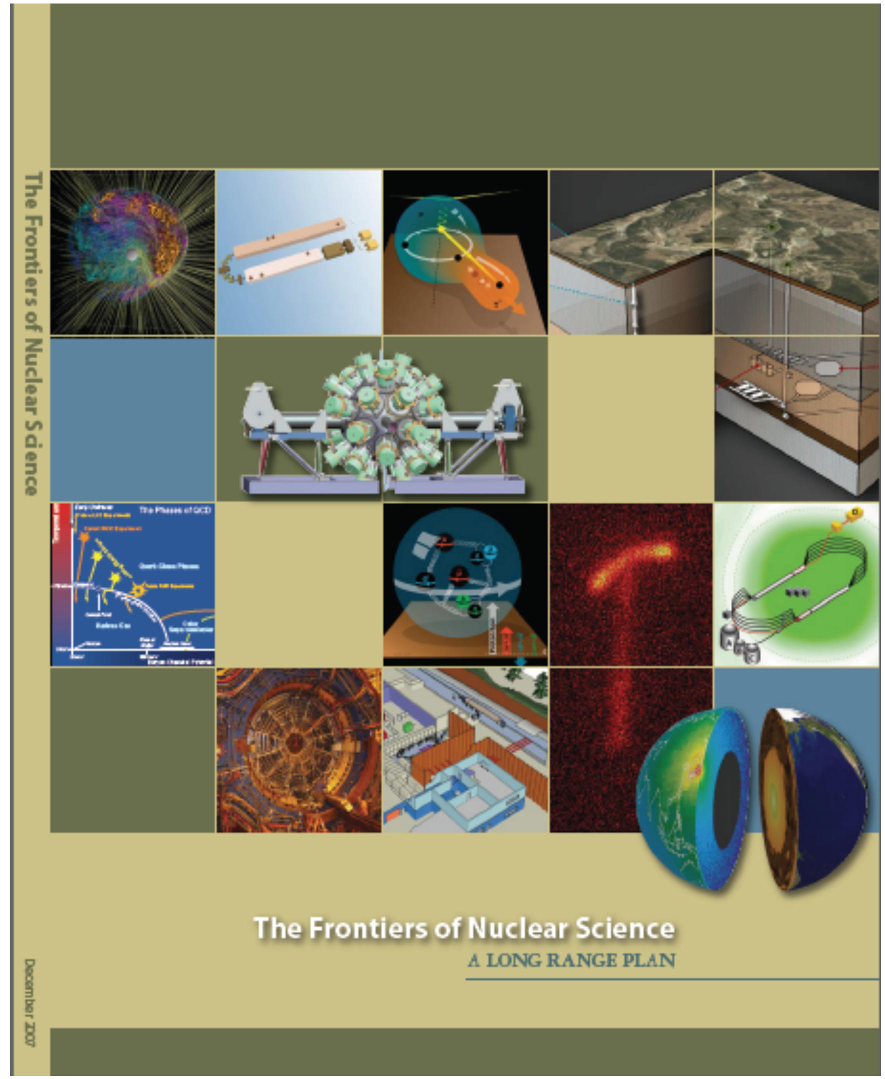
Schedule

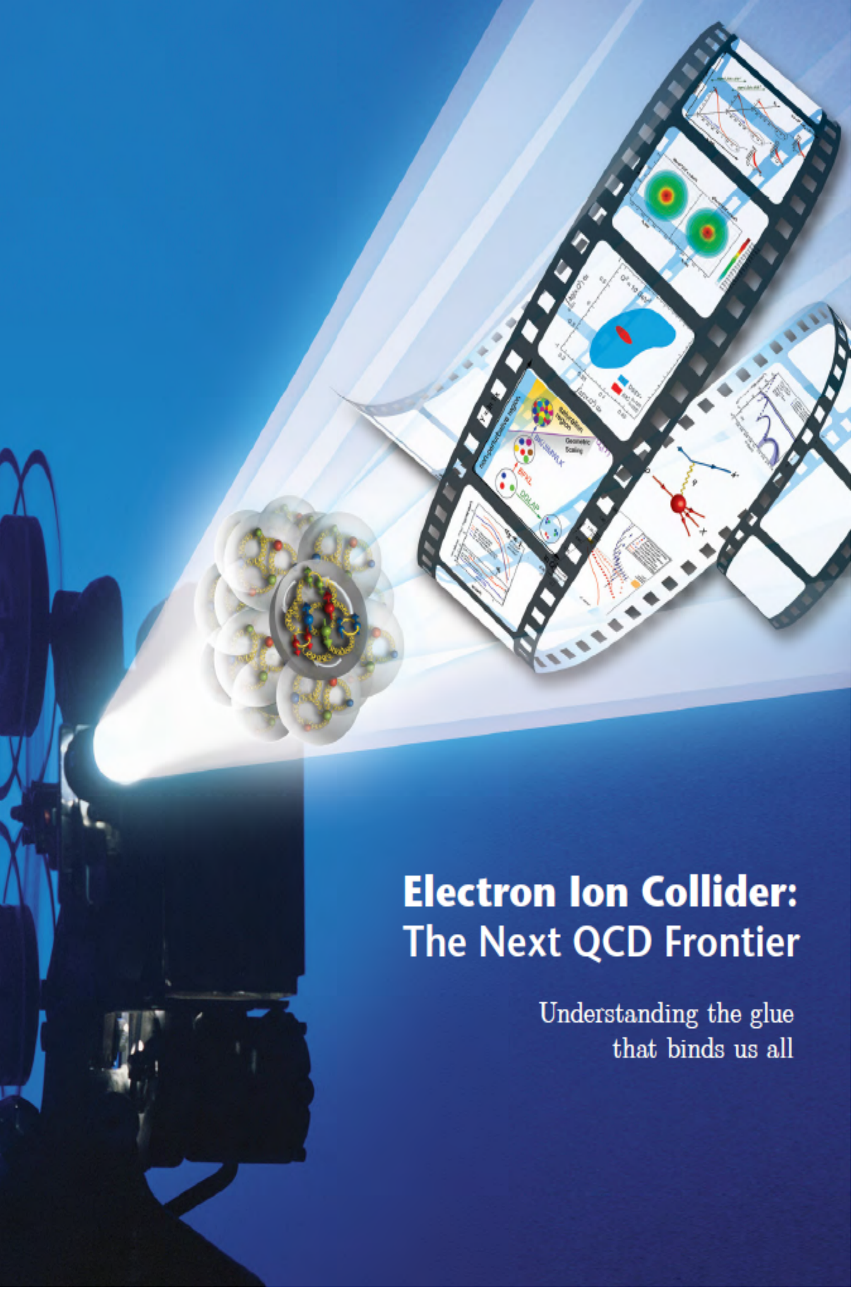
• OLYMPUS proposed	09/2008
• OLYMPUS approved and funded	01/2010
• Experiment roll-in	07/2011
• First data taking run	02/2012
• Second data taking run	10-12/2012
• Post-experiment survey and field mapping	02-04/2013
• Data analysis	in progress

NSAC 2007 Long Range Plan

"An **Electron-Ion Collider (EIC)** with polarized beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia. In support of this new direction:

We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton."



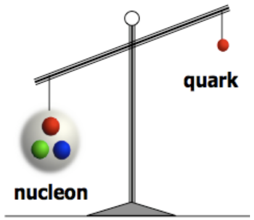


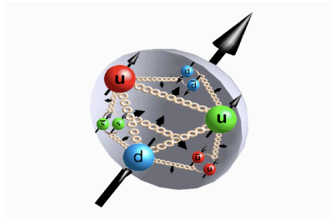
EIC will be a precision electron microscope to study the smallest constituents of matter with the highest precision.

As physicists, we make measurements on hadrons. QCD is a theory of quarks and gluons. How can we understand this?

How are elementary properties of the nucleon understood in terms of the quarks and gluons of QCD?

Mass, Spin





Is there a universal distribution of the partonic constituents of all nuclei when viewed at high energy?

Why study QCD?

- Understanding the fundamental structure of matter in the world we live in demands that we provide an explanation of hadron properties and structure in terms of quarks and gluons.
- QCD is a fully consistent theory that we are certain describes the real world: in the limit $m_q \rightarrow 0$ there are no free parameters.
- All the interactions are a consequence of deep symmetry principles like gauge invariance and chiral symmetry.
- Most of the visible phenomena are emergent, i.e. the electrically charged and colored quarks and the gluon color force-carriers are not seen.
- This makes QCD a unique laboratory for exploring the dynamics of a non-trivial, consistent relativistic theory.
- The recent discovery of the quark gluon plasma at RHIC demands an understanding of QCD well beyond that currently possible.

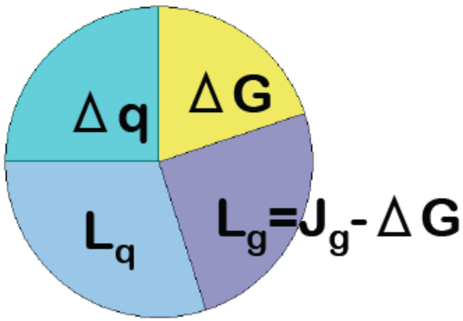
Exploring the glue that binds us all

arXiv: 1212.1701, Eds. A. Deshpande, Z.-E. Meziani, J.-W. Qiu

- **Nucleon Spin and its 3D Structure and Tomography**
  - The Spin and Flavor Structure of the Nucleon
  - The Confined Motion of Partons Inside the Nucleus
  - The Tomography of the Nucleon: Spatial Imaging of Gluons and Sea Quarks
- **The Nucleus, a QCD Laboratory**
  - QCD at Extreme Parton Densities
  - The Tomography of the Nucleus
  - Propagation of a Color Charge in QCD
  - The Distribution of Quarks and Gluons in the Nucleus
- **Physics at the Intensity Frontier**

What is the origin of spin-½ of the proton?

- Goal: disentangle the different quark and gluon contributions to the spin-½ proton via lepton scattering experiments



$$\tfrac{1}{2} = \Sigma + L_q + J_g$$

- To date we know that
  - contribution of quarks Σ is about 25%
  - contribution of gluons is comparable to that of quarks, with considerable uncertainty
  - measured contribution of sea quarks is zero, with considerable uncertainty
- Measurements on the neutron and proton can be combined to provide a fundamental test of the Standard Model, known as the Bjorken Sum Rule.
- While, JLab@12GeV in the valence region and RHIC-spin with proton beams can continue to make progress, EIC would provide a dramatic new capability to experimentally access and disentangle all the contributions to the proton's spin.

EIC will answer the question: what is the origin of nucleon spin?

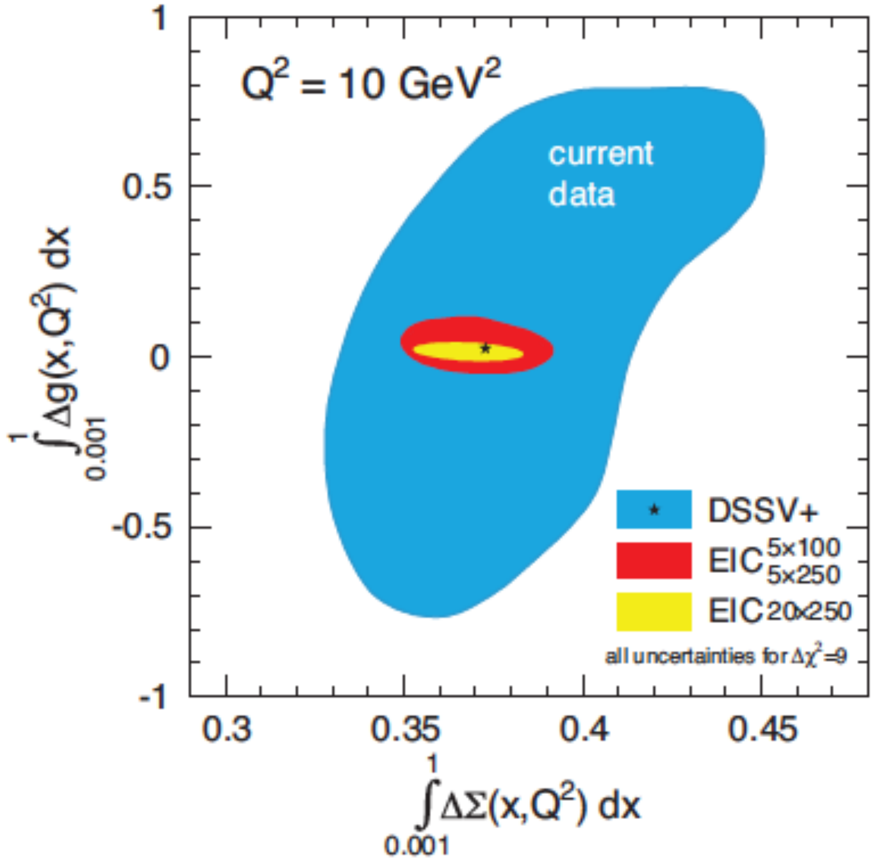


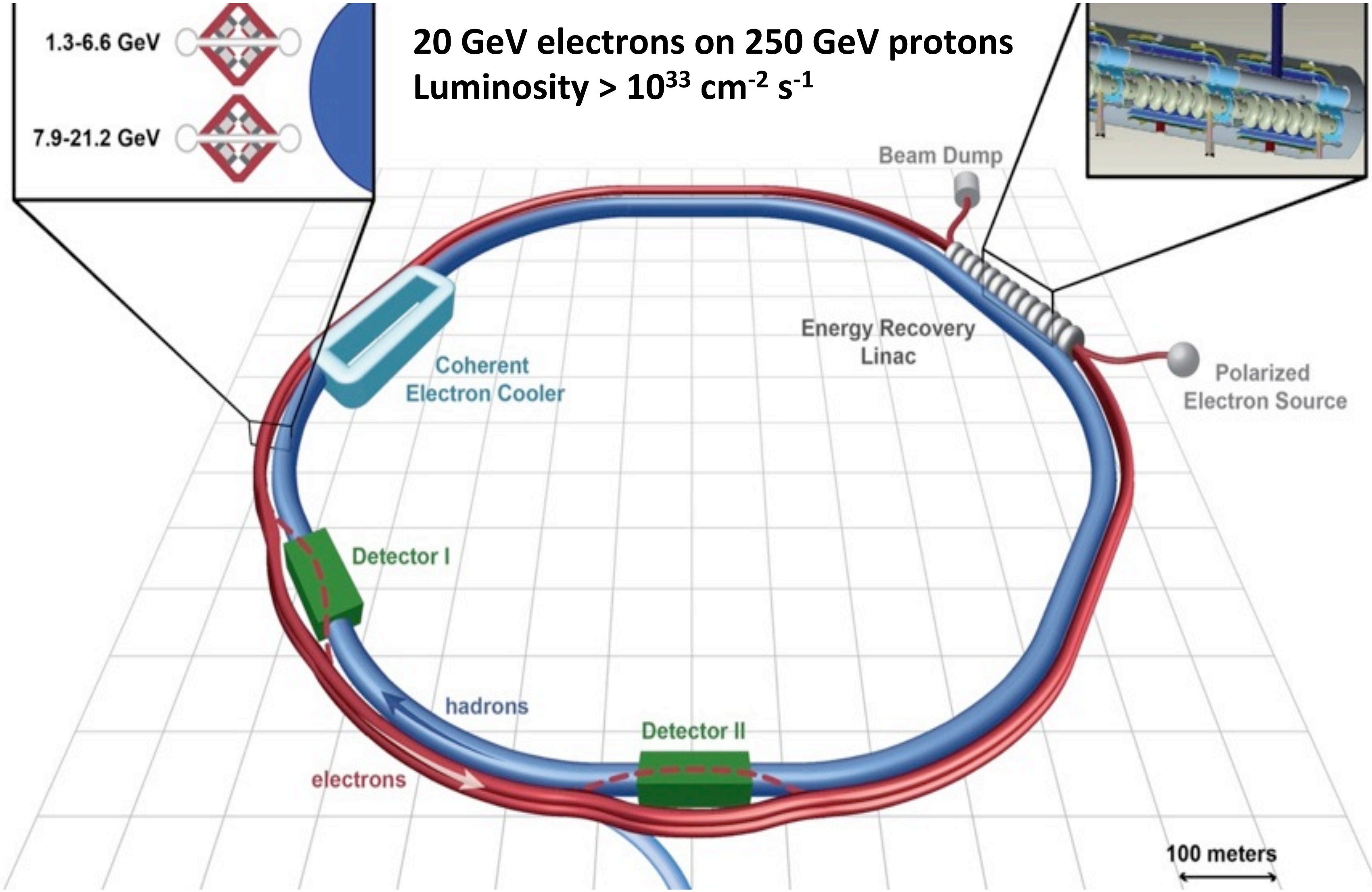
Figure 2.9: Present (outer area) and projected (inner area) accuracies for the correlated truncated integrals of $\Delta\Sigma$ and Δg over $0.001 \leq x \leq 1$ [66].

EIC: Design Parameters

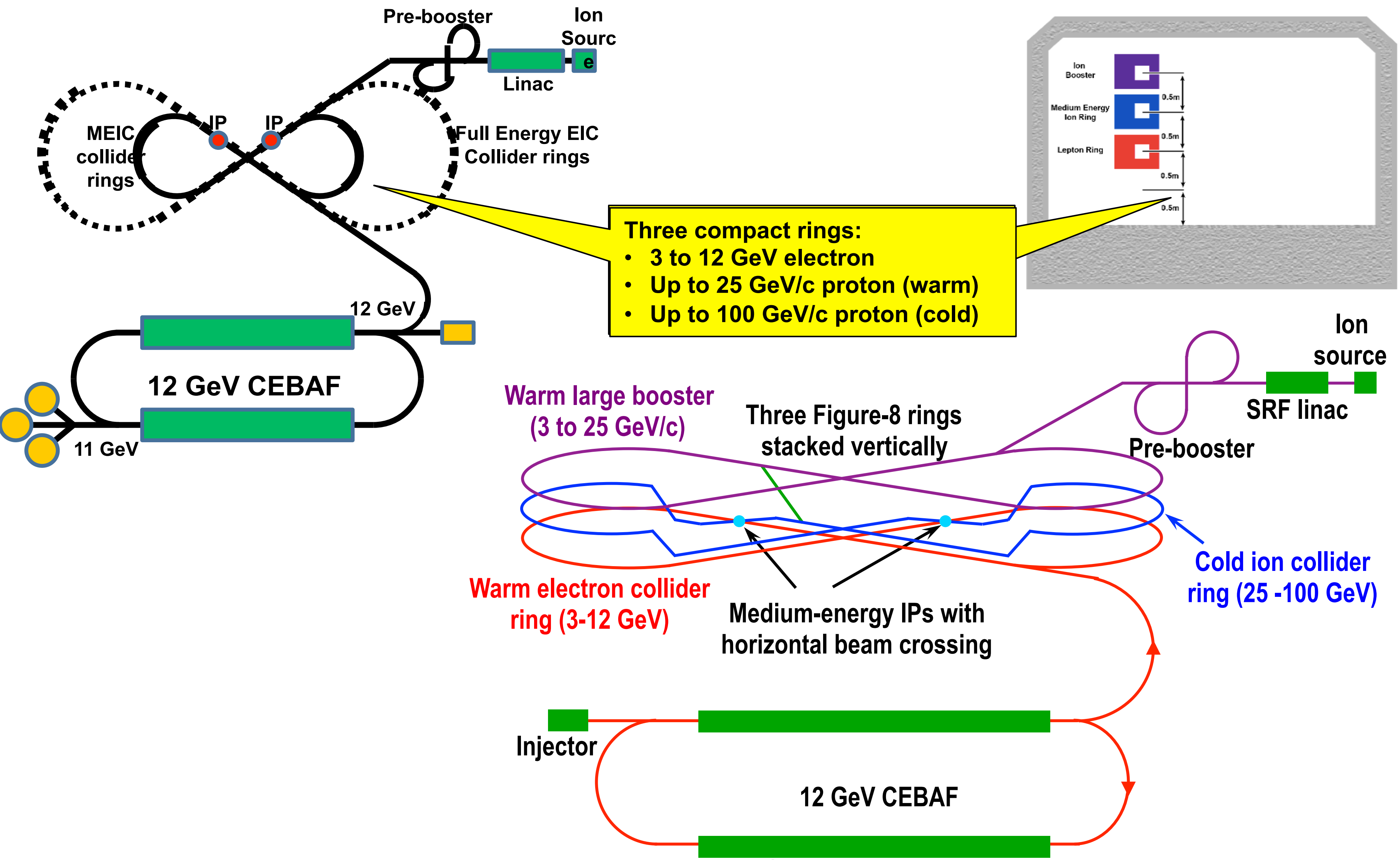
- Highly polarized (>70%) electron and nucleon beams
- Ion species from deuterium to A = 200 or so
- Center-of-mass energies from $\sqrt{s} \approx 20$ to $\sqrt{s} \approx 70$ GeV & variable
- Upgradeable to center-of-mass energy of about $\sqrt{150}$ GeV
- High luminosity $\approx 10^{34}$ e-nucleons cm^{-2} s^{-1}
- Multiple interaction regions
- Integrated detector/interaction region
- Positron beam desirable
- Two designs: **eRHIC@BNL**
  MEIC@JLab

eRHIC Design

20 GeV electrons on 250 GeV protons
Luminosity > 10^{33} cm^{-2} s^{-1}



MEIC Design



Pre-booster
Ion Source
Linac
IP
IP
MEIC collider rings
Full Energy EIC Collider rings
12 GeV
12 GeV CEBAF
11 GeV
Ion Booster
Medium Energy Ion Ring
Lepton Ring
0.5m
0.5m
0.5m
0.5m
Three compact rings:
• 3 to 12 GeV electron
• Up to 25 GeV/c proton (warm)
• Up to 100 GeV/c proton (cold)
Ion source
SRF linac
Pre-booster
Warm large booster (3 to 25 GeV/c)
Three Figure-8 rings stacked vertically
Cold ion collider ring (25 -100 GeV)
Warm electron collider ring (3-12 GeV)
Medium-energy IPs with horizontal beam crossing
Injector
12 GeV CEBAF

Fastest Possible Schedule

- US Nuclear Physics Long Range Planning exercise expected in 2015
- U.S. QCD community will seek approval from broad Nuclear Physics community to propose EIC for construction
- If granted, site selected by 2017
- If funded, construction begins in 2020
- EIC begins operation in 2025

Development of a Source of Polarized ^{3}He for RHIC

BNL-MIT Collaboration

J. Maxwell, C. Epstein, E. Mace, R. Milner

MIT

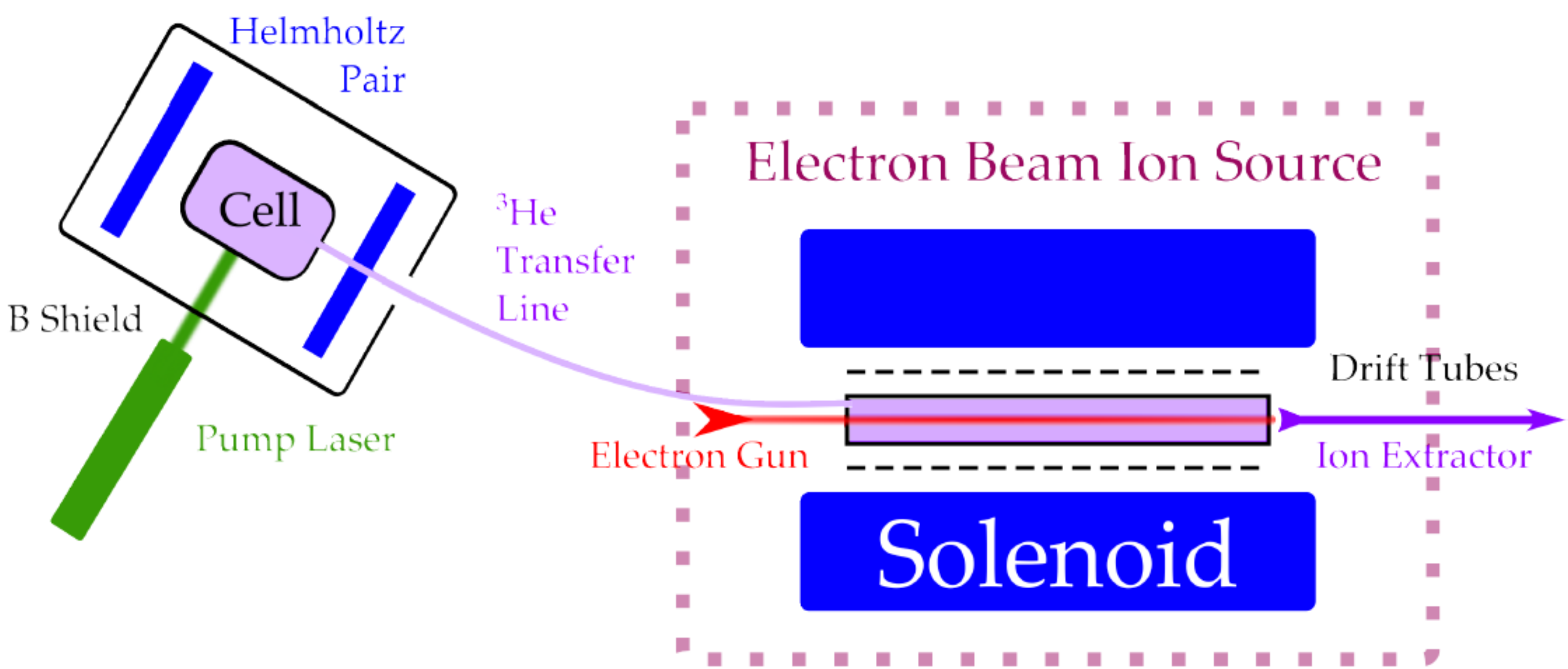
J. Alessi, E. Beebe, J. Farrell, A. Pikin, J. Ritter, A. Zelenski

BNL

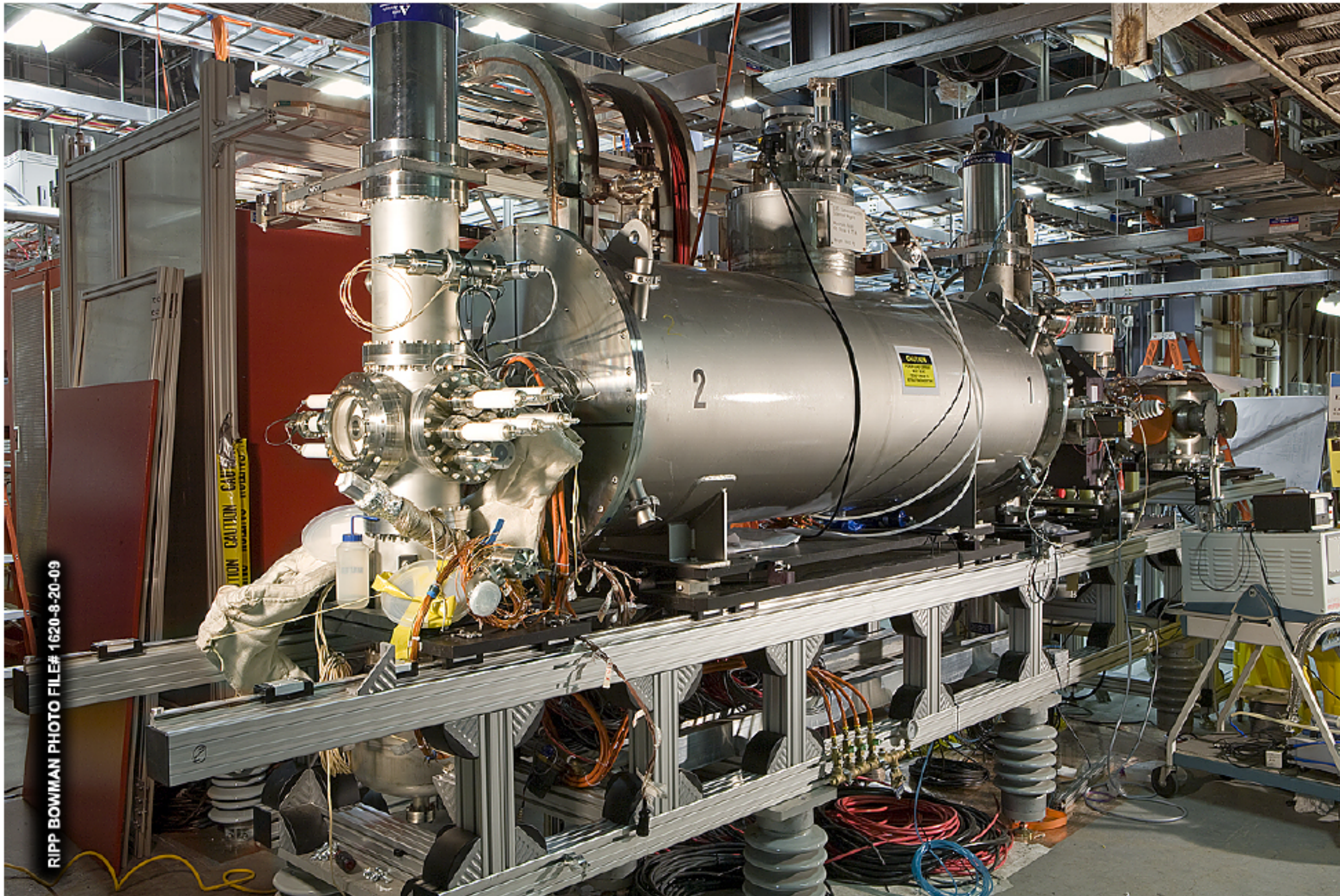
Proposed by J. Alessi and A. Zelenski in 2003

Source Design Goals

- Polarize to ~70% at 30 G & 1 torr with 10 W laser
- Transfer to EBIS at 5 T & 10^{-7} torr
- Deliver 1.5×10^{11} $^3He^{++}$ ions per 20 μsec pulse



RHIC's Electron Beam Ion Source



RHIC's Electron Beam Ion Source

- 5 T Solenoid B Field; 1.5 m Ion Trap
- 20 keV electrons up to 10 A, 575 A/cm^2 Current Density
- **Any** species, switch between species in 1 sec

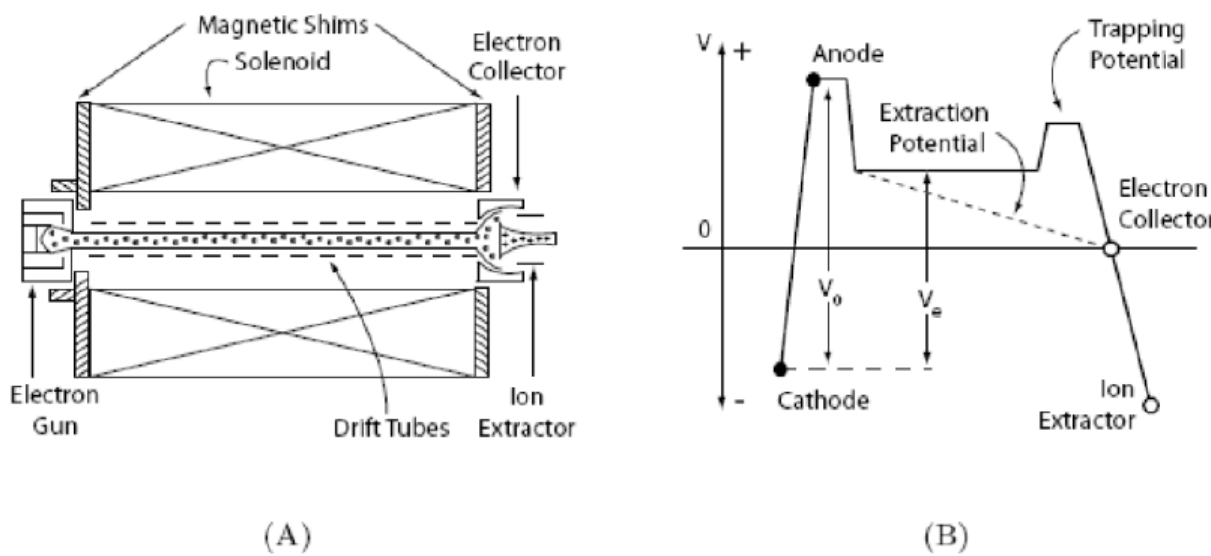
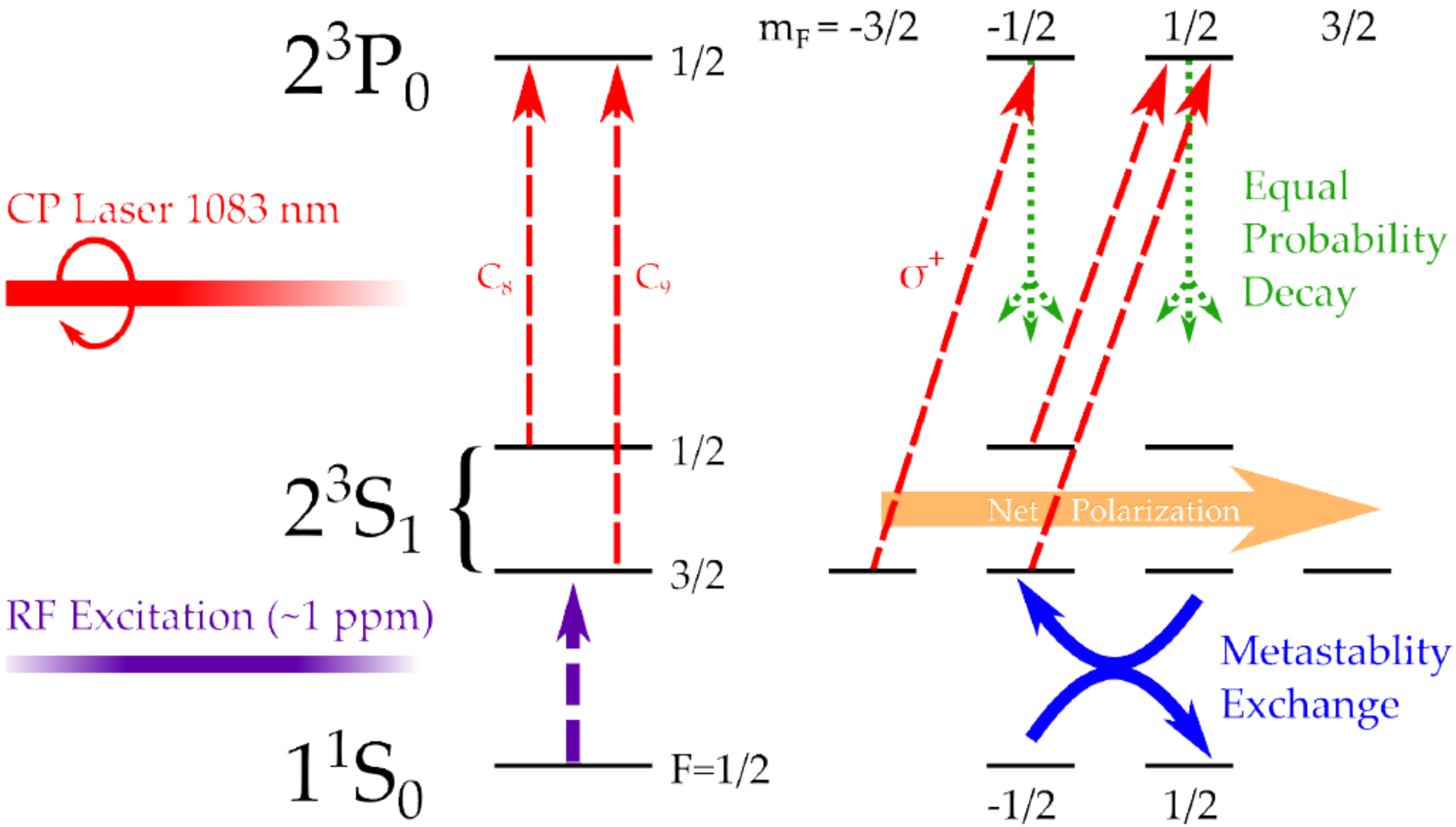


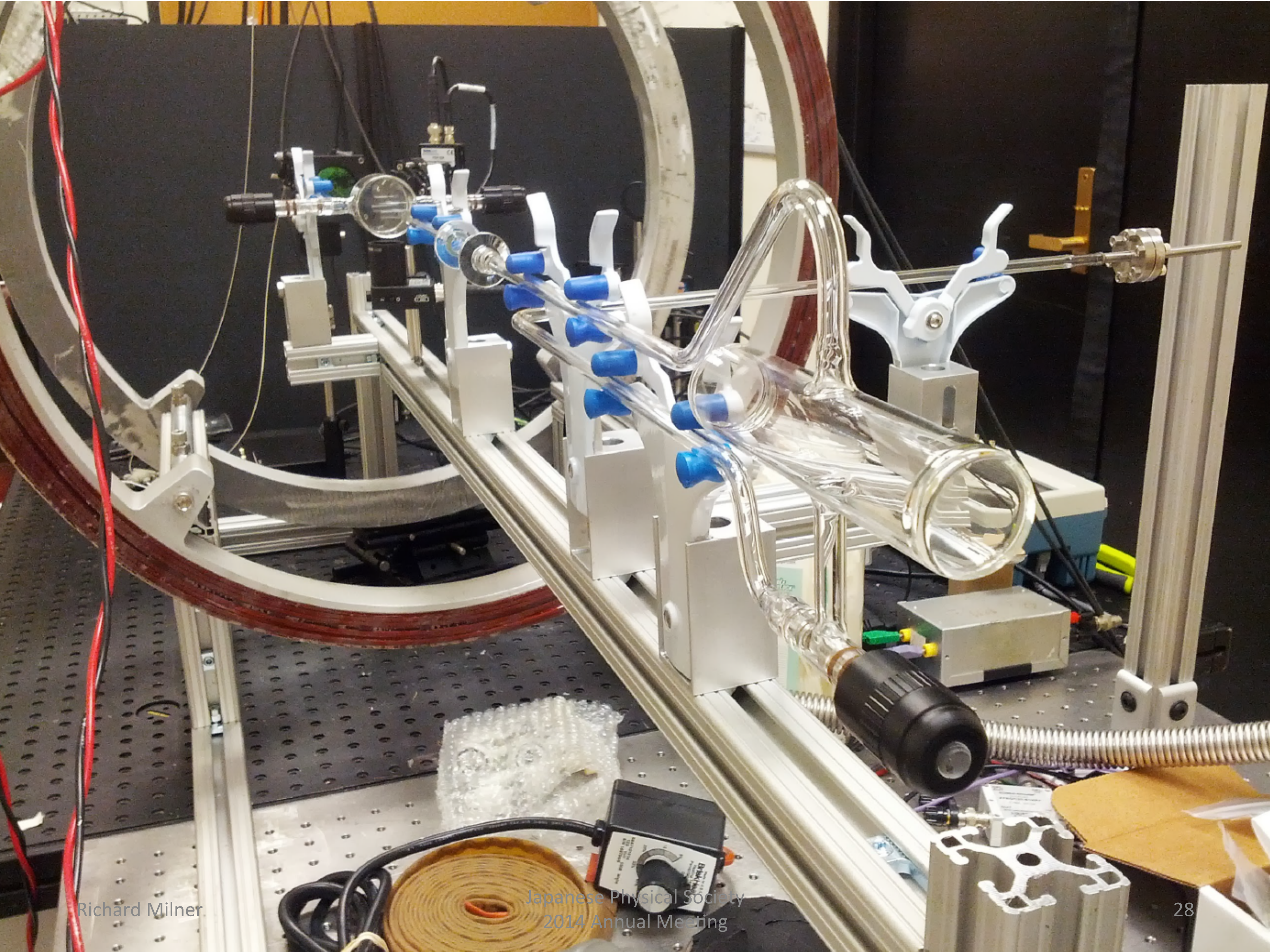
Figure 4. (A) A schematic of the EBIS course. (B) The electric potential along the axis of the source.

MEOP Mechanism

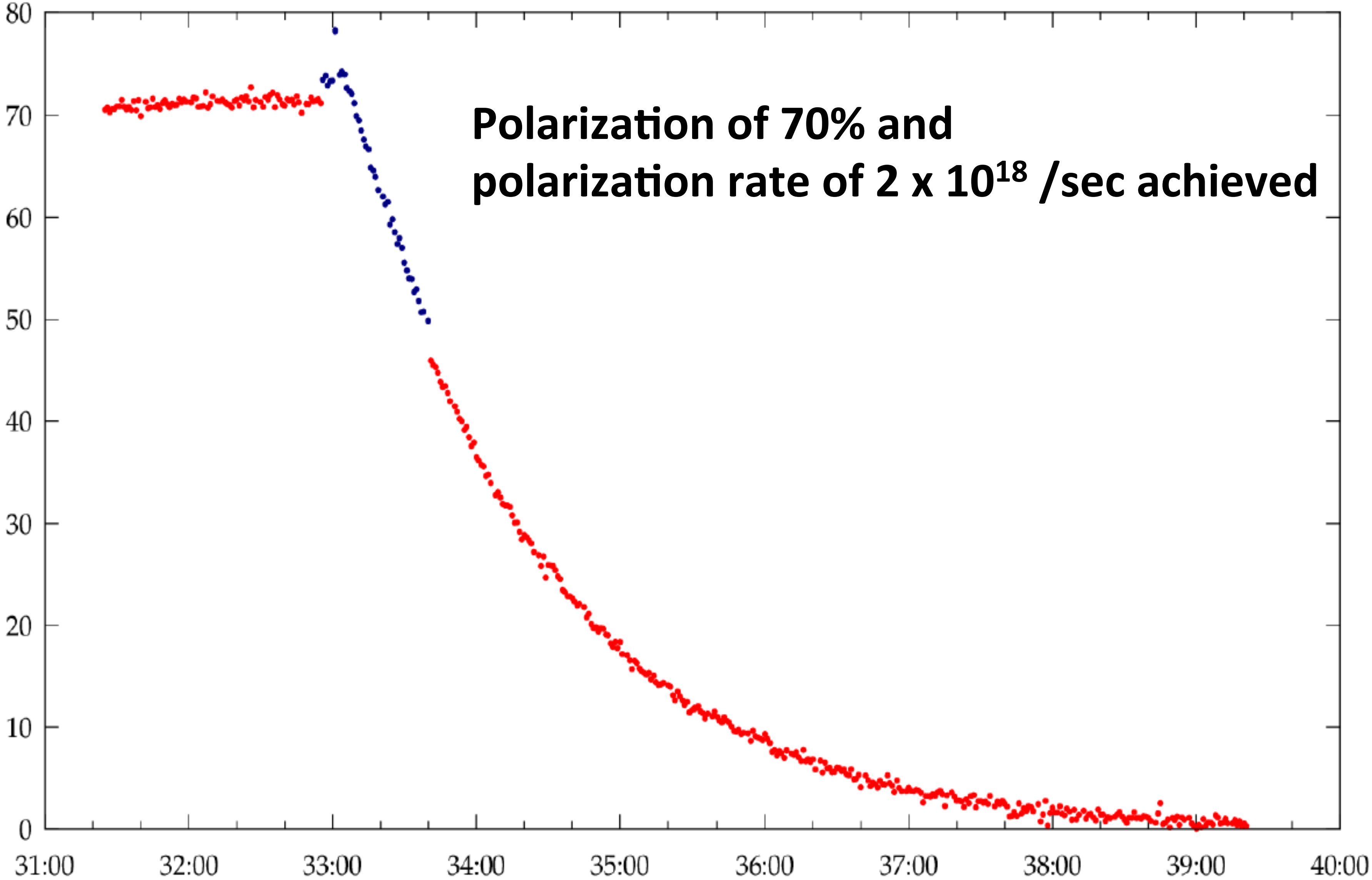


Depolarization Contributions

- Wall Bounces
  - 3 mm long, 0.1mm diameter leak: 1 torr to 10^{-7} torr
  - 1m long, 2mm diameter tube: $\approx 10^6$ bounces, ≈ 1 msec
  - Negligible depolarization with glass walls
- Magnetic field gradients from EBIS stray field
  - Hinder Polarization
  - Depolarization During Transport to EBIS
- Small Contributions During Ionization:
  - Charge Exchange: $^3\text{He}^+ + {}^3\text{He}^{++} \rightarrow {}^3\text{He}^{++} + {}^3\text{He}^+$
  - Recombination: $e^- + {}^3\text{He}^{++} \rightarrow {}^3\text{He}^+$
  - Spin Exchange from Beam

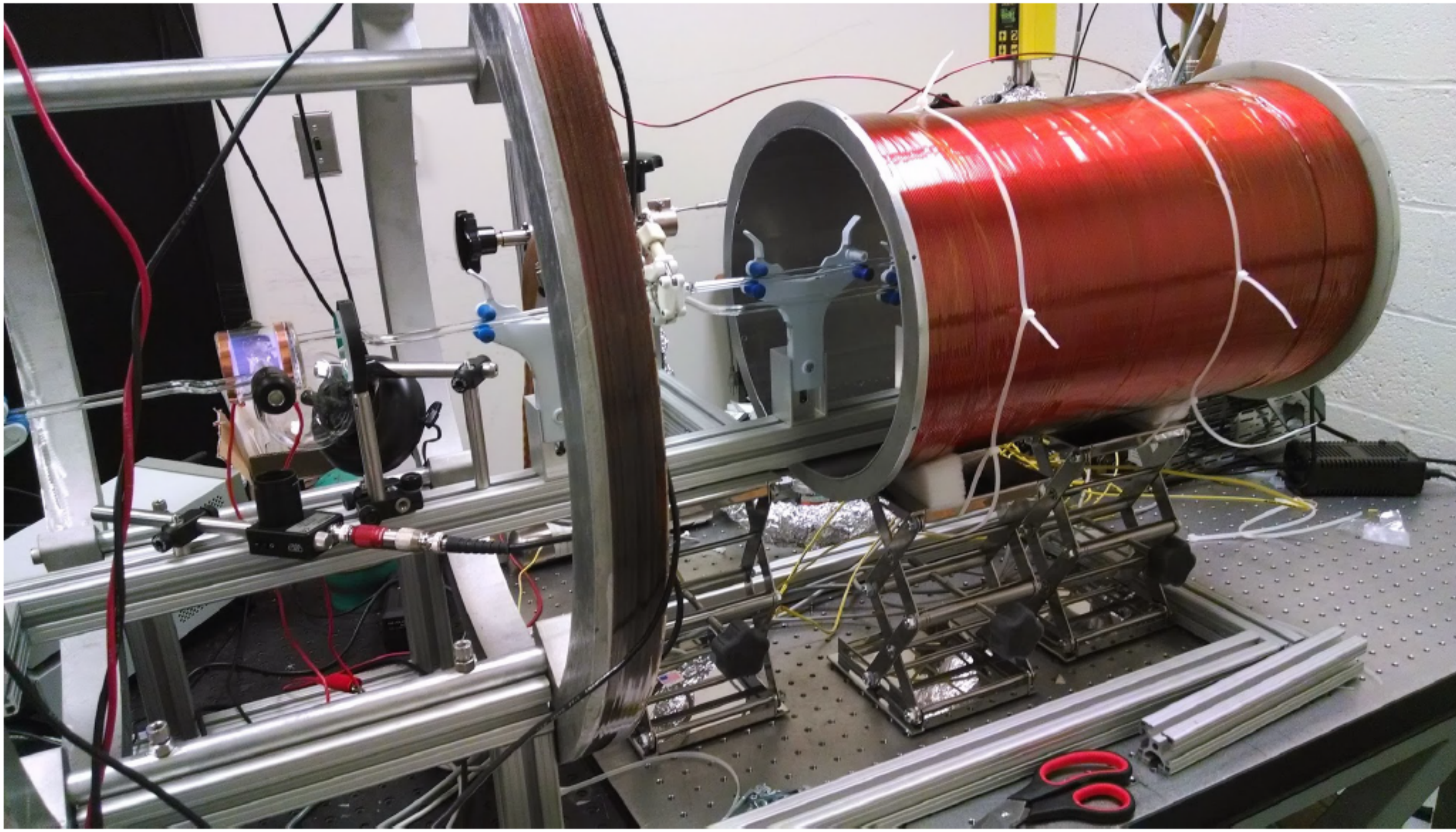


Polarization of 100 cm^3 pump cell



Polarization of 70% and polarization rate of 2 x 10^{18} /sec achieved

Test experiment at MIT: spin transfer between pump cell in Helmholtz coil and test cell in solenoid



Schedule

- Setting up polarized ^3He atom source at BNL
- Summer 2014: carry out depolarization tests with spare EBIS solenoid
- Design optimized transfer system of polarized ^3He gas into EBIS.
- Summer 2015: extract polarized $^3He^{++}$ from EBIS at 5.3 MeV and measure the polarization using a nuclear reaction.
- If polarization is significant, then inject in AGS

EIC Users Group Meeting at Stony Brook

June 24-27, 2014

http://skipper.physics.sunysb.edu/~eicug/meetings/SBU.html

Wang Center Of Asian Arts & Hilton Hotel At Stony Brook

Aim:

- Organize EIC users → NSAC Long Range Plan
- Presentation & Discussions on: Science Case, Machine & Detector
- EIC in the international context: presentations from Europe, Asia
- Encourage & help build collaborations in physics, detectors and technology

Contact: abhay.deshpande@stonybrook.edu