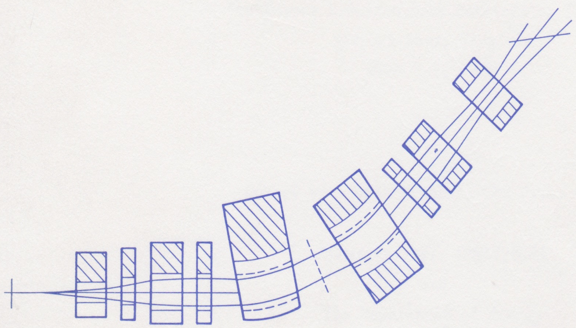
Precision Study of the Standard Model at Low Energies

In honor of Roy Holt's contributions to Nuclear Physics

- Early, formative interactions with Roy
- Some present activities:

SURA SOUTHEASTERN UNIVERSITIES RESEARCH ASSOCIATION, INC.



CONTINUOUS
ELECTRON
BEAM
ACCELERATOR
FACILITY

1985 Summer Workshop

June 3-7, 1985
CEBAF
Newport News, Virginia

REPORT OF THE INTERNAL TARGET WORKING GROUP*

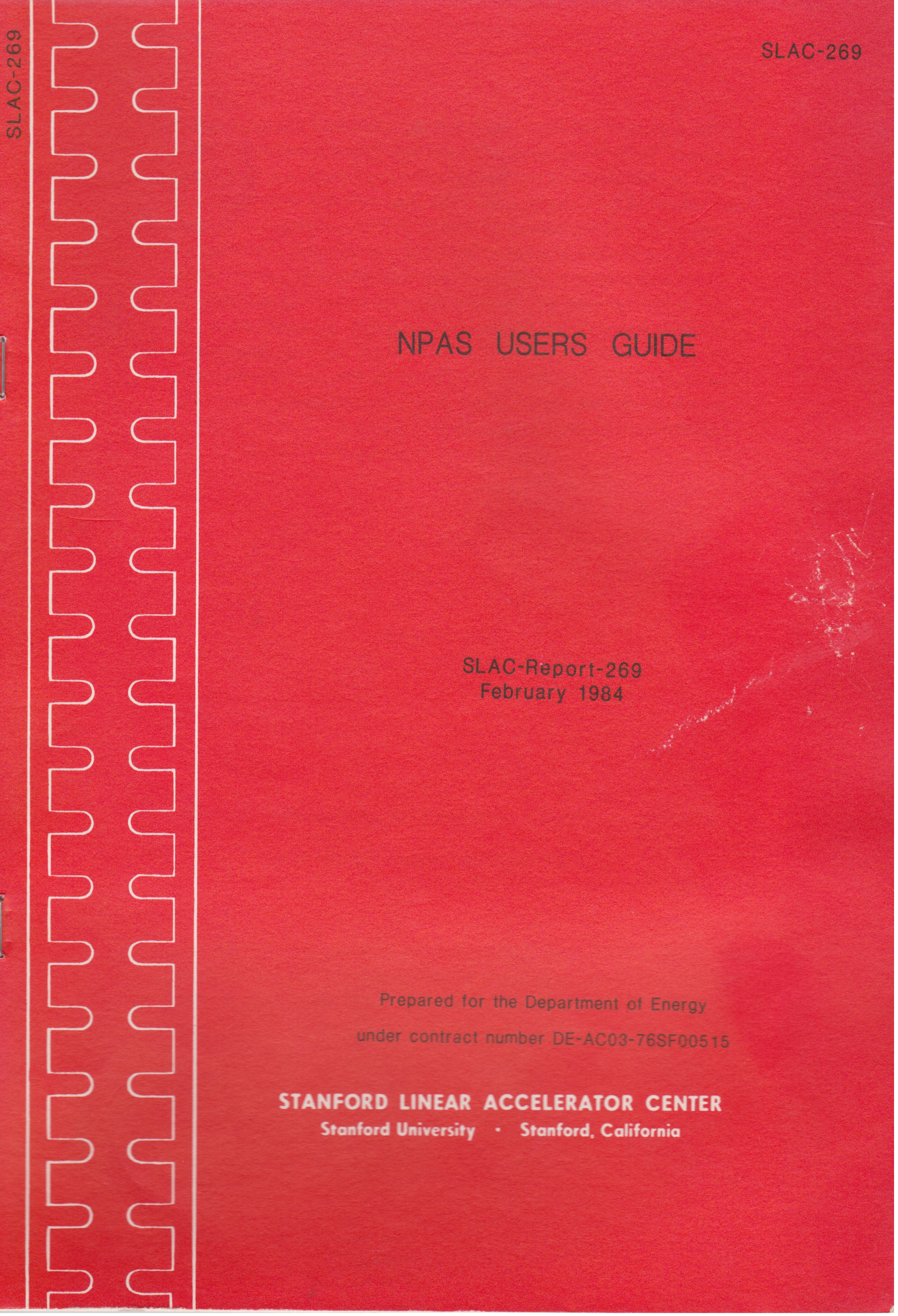
R. J. Holt

Argonne National Laboratory, Argonne, IL 60439

Appendix A

List of Participants

H. E. Conzett	LBL
Martin Epstein	Cal State University
Michael Finn	MIT
Carlo Guaraldo	Frascati
Roy J. Holt (Chairperson)	ANL
R. McKeown	Cal Tech
Hans-Otto Meyer	Indiana University
Richard Miner	Cal Tech
Blaine Norum	CEBAF
Costas Papanicolas	University of Illinois
J. E. Spencer	SLAC
Tom Wise	University of Wisconsin



Nuclear Physics At SLAC

- Where I learned to do experimental electron scattering
- Collaborator with ANL group: scaling in exclusive processes (Holt)
- NE17+NE18

  Very productive final running
- Outstanding young people now leaders in our field:

  N. Makins, R. Ent, W. Lorenzon

My Research Trajectory (1985-2014)

- Early interactions with Roy established a line of research extending over three decades: identify important problems, typically in hadron structure, which are studied using lepton beams

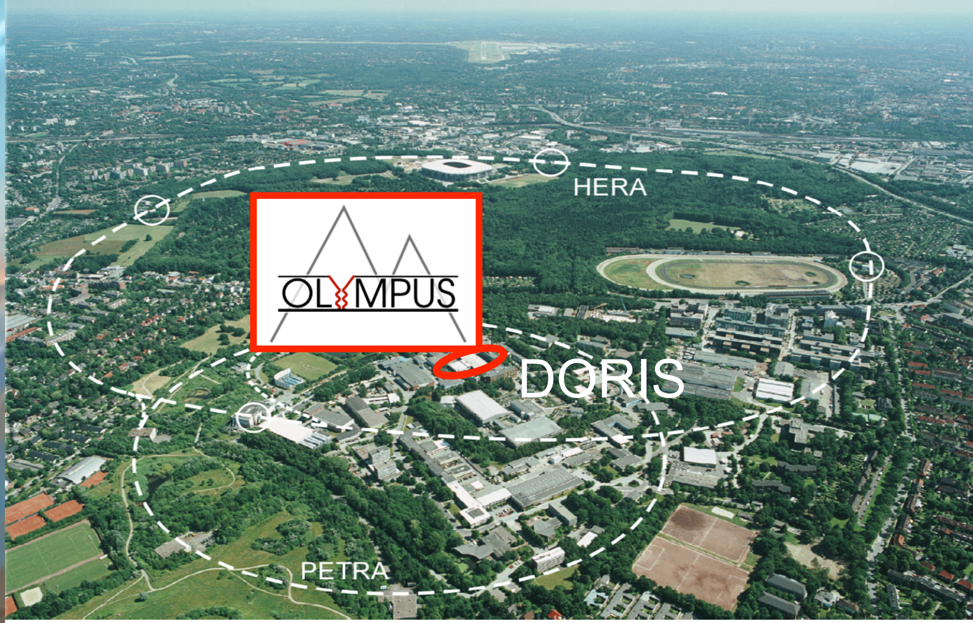
- spin structure of ^{3}He (CE-25 at IUCF)
- spin structure of nucleon (hermes at DESY)
- spin-dependent electron scattering from polarized ^{1}H and ^{2}H (BLAST at MIT- Bates)
- contributions beyond single photon exchange in elastic electron-proton scattering (OLYMPUS at DESY)
- search for a dark photon (DARKLIGHT at JLab ERL)

Technical advantages of windowless gas targets

- Precision of electron probe is fully realized when scattering only from the target of interest.
- This is of particular importance in scattering from a polarized target. Scattering from extraneous material dilutes the asymmetry.
- Polarized internal gas targets realized in full glory in both:

hermes : 27 GeV DIS scattering from quarks

BLAST : 0.85 GeV scattering from polarized ^2H



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

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

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

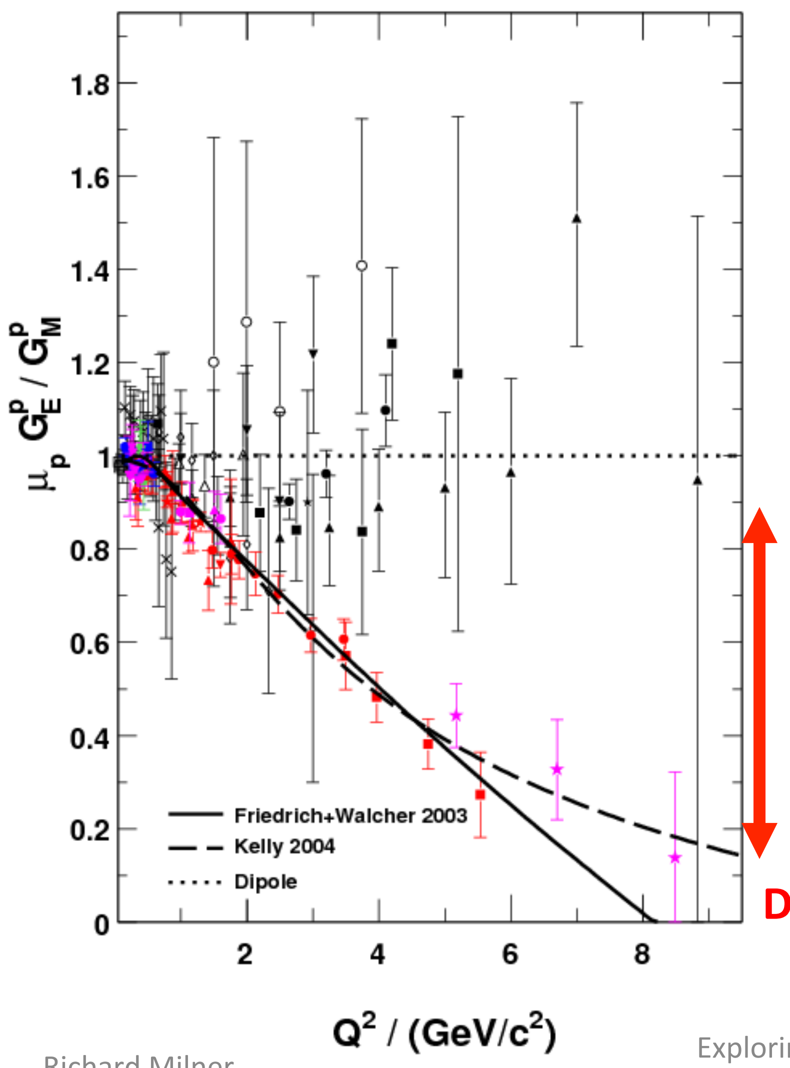
$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = S_0 = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2} \qquad \tau = \frac{Q^2}{4M_p^2}$$

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

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

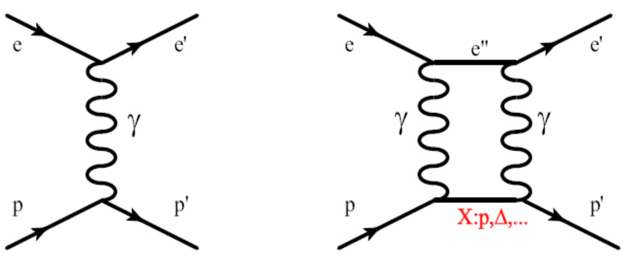
ε =relative flux of longitudinally polarized virtual photons

Proton Form Factor Ratio



Jefferson Lab 2000

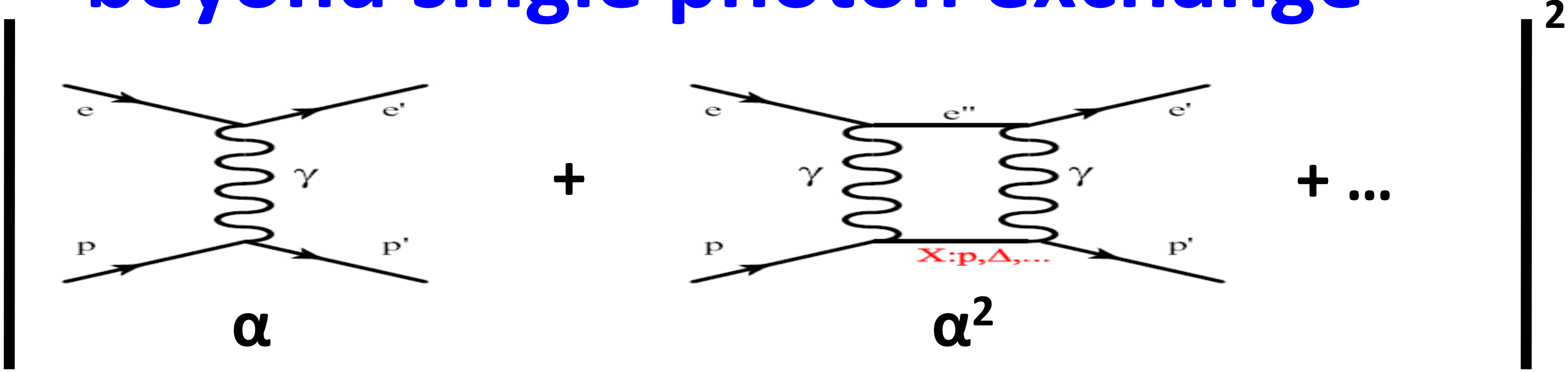
- All Rosenbluth data from SLAC and JLab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Contribution of multi-photon exchange widely accepted explanation of discrepancy



Dramatic discrepancy!

>1000 citations

Definitive determination of contributions beyond single photon exchange



$$\sigma = (1\gamma)^2\alpha^2 + (1\gamma)(2\gamma)\alpha^3 + ...$$

$$e^- \Longleftrightarrow e^+ \Rightarrow \alpha \Longleftrightarrow -\alpha$$

$$\sigma(\text{electron-proton}) = (1\gamma)^2\alpha^2 - (1\gamma)(2\gamma)\alpha^3 + ..$$

$$\sigma(\text{positron-proton}) = (1\gamma)^2\alpha^2 + (1\gamma)(2\gamma)\alpha^3 + ..$$

$$\frac{\sigma(e^+p)}{\sigma(e^-p)} = 1 + (2\alpha)\frac{2\gamma}{1\gamma}$$

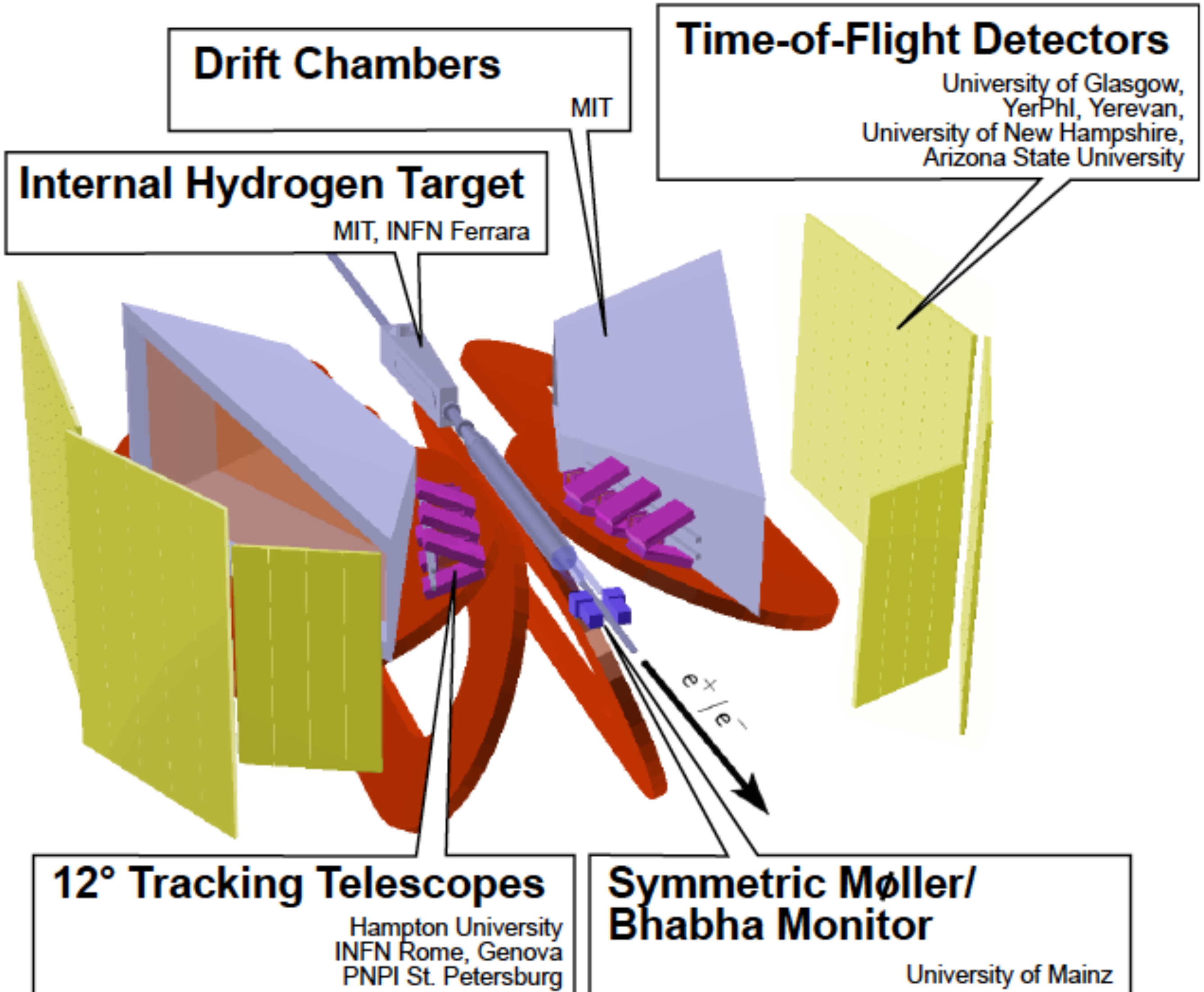
The OLYMPUS Experiment

- 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

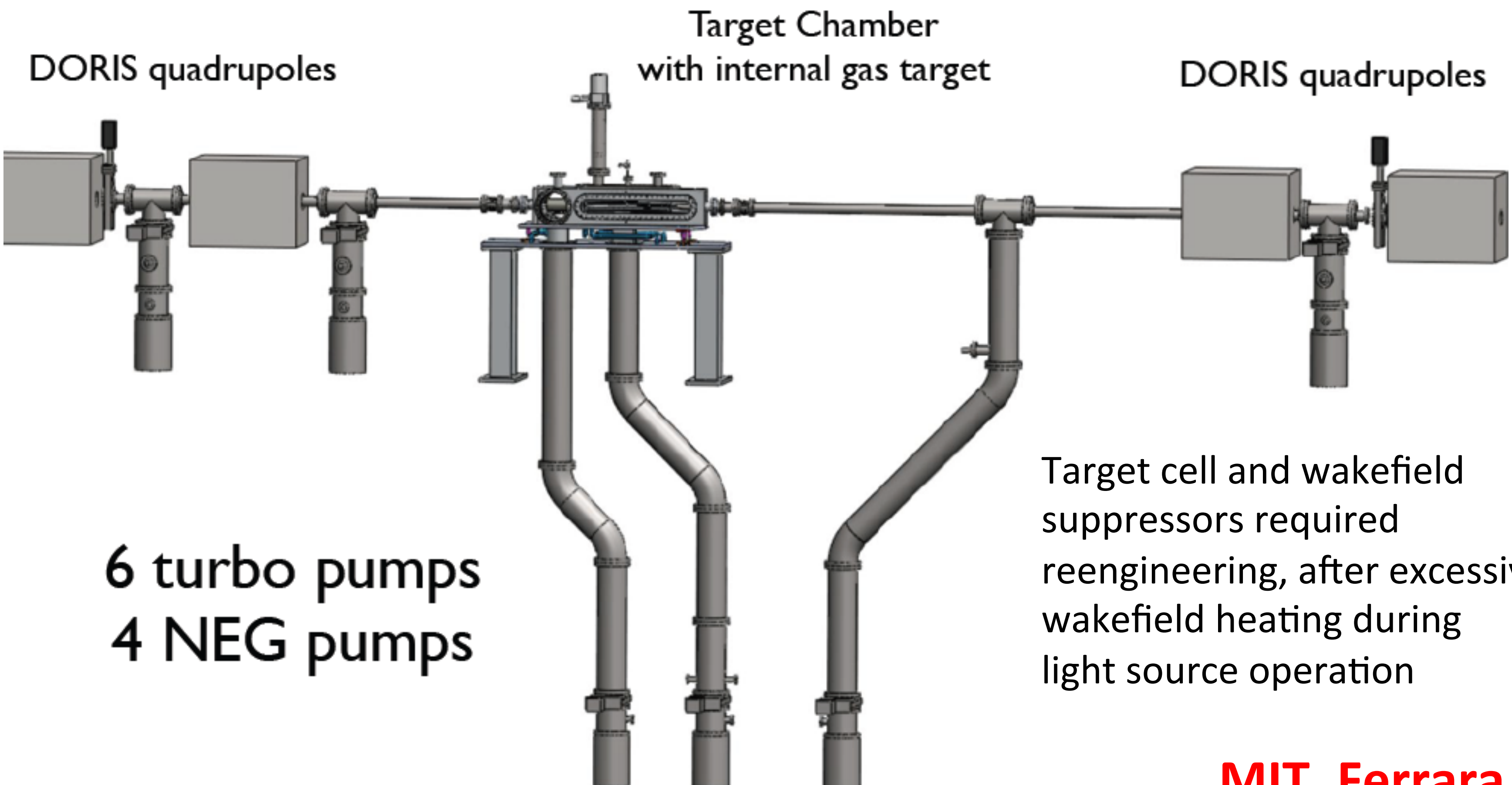
- **Measured ratio of positron-proton to electron-proton unpolarized elastic scattering with goal of ≈1% stat.+sys.**

The OLYMPUS Magnetic Toroid

The OLYMPUS Experiment



target chamber and vacuum system

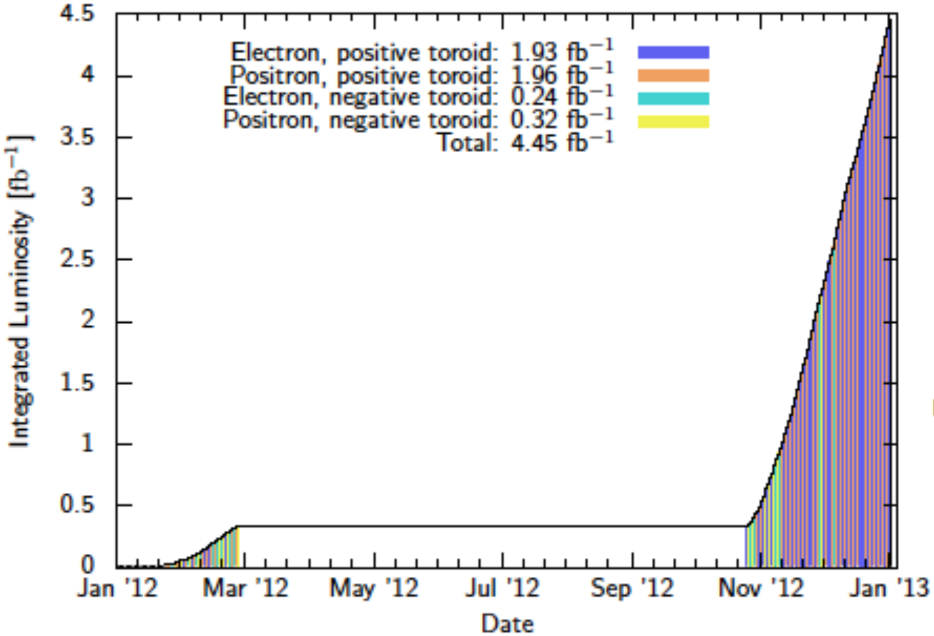


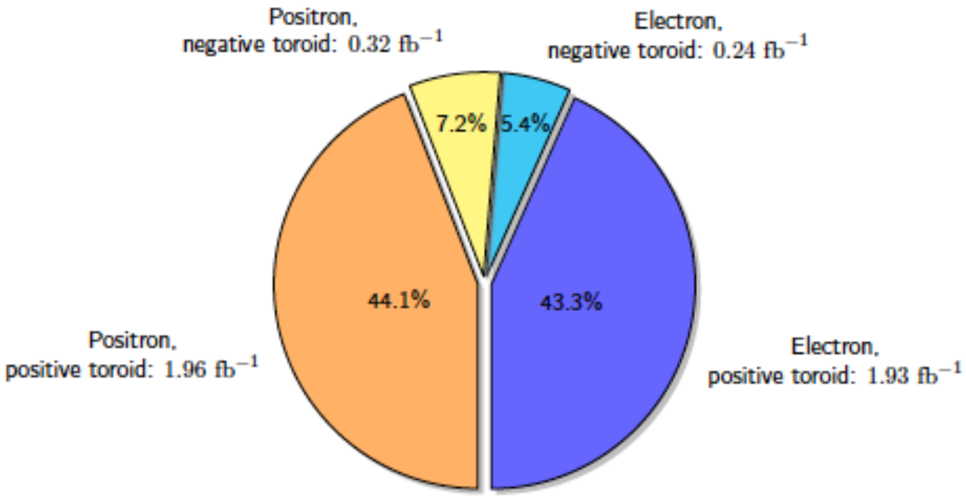
6 turbo pumps
4 NEG pumps

Target cell and wakefield suppressors required reengineering, after excessive wakefield heating during light source operation

MIT, Ferrara

Data taking



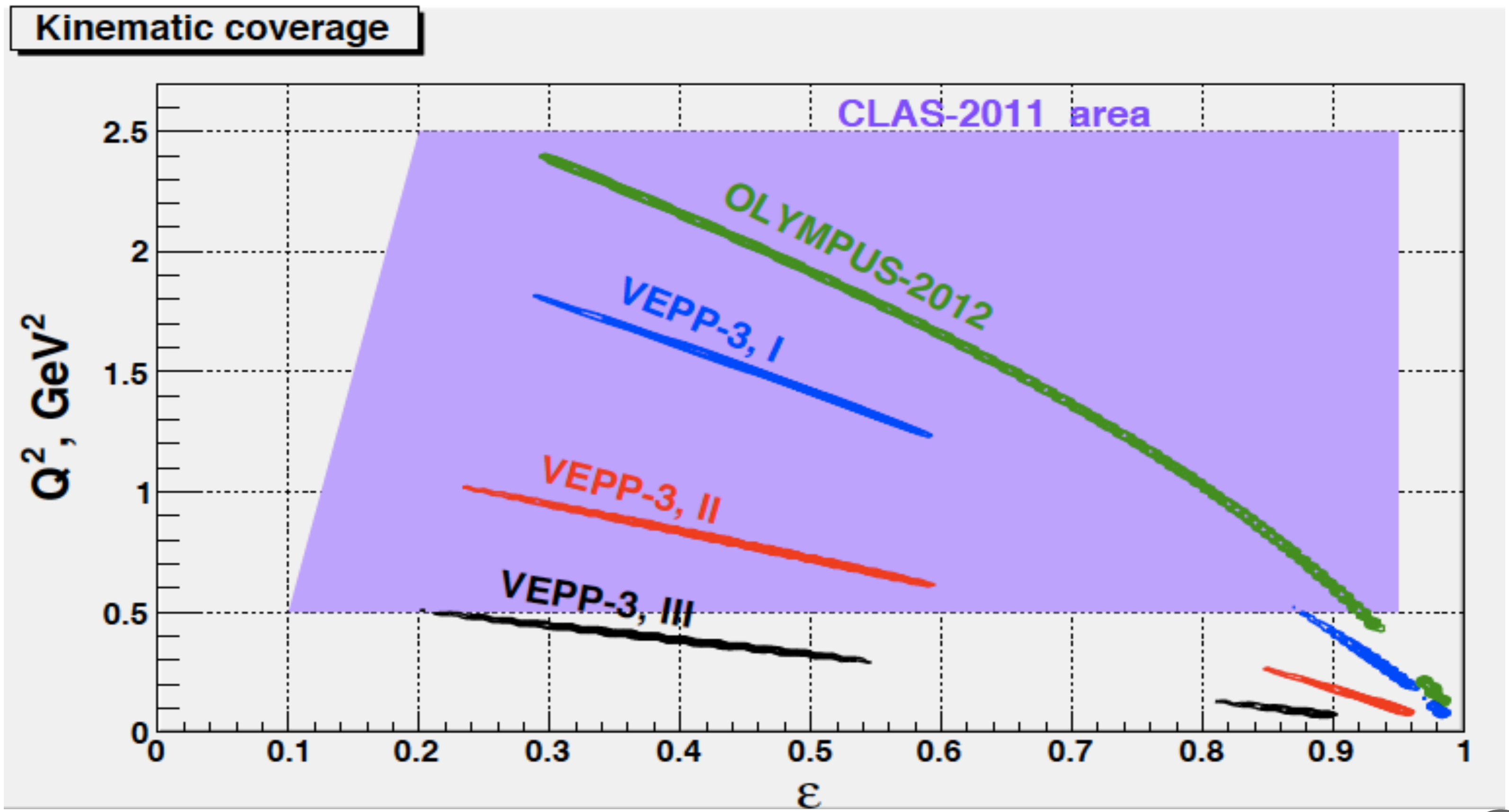


J. Bernauer

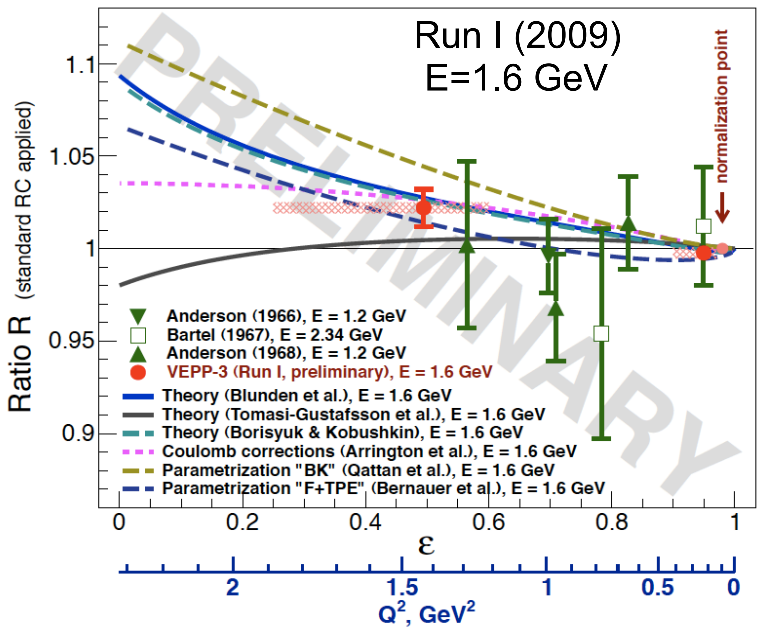
- well-balanced e^+, e^- data sets
- additional negative toroid data (systematics!)
- $\mathcal{L}_{int}$ goal of 4 fb^{-1} exceeded!

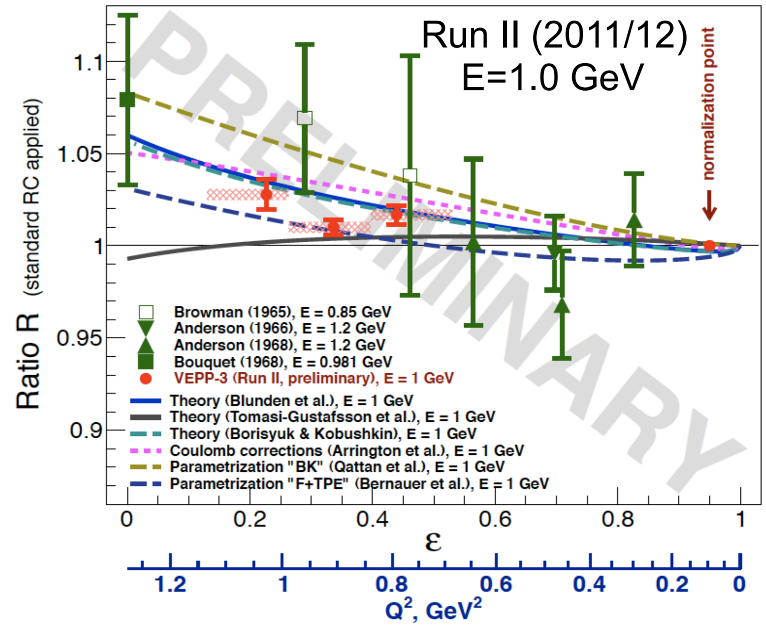
Comparison of Experiments

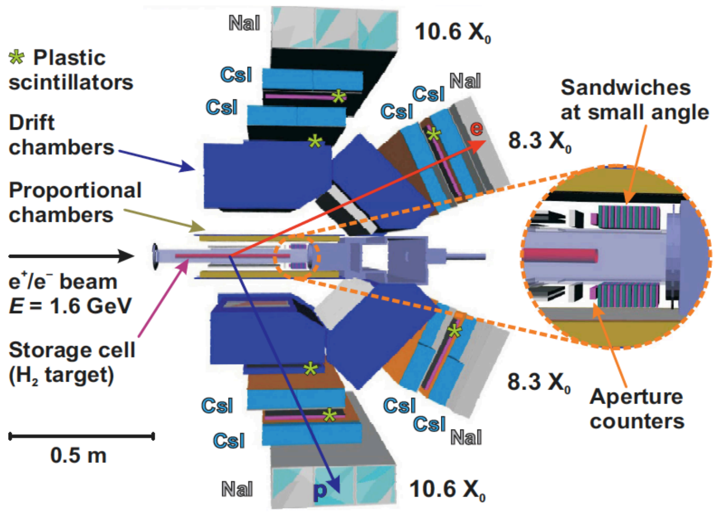
- **VEPP3 @ Novosibirsk: (E_{beam} = 1.6, 1.0, and 0.6 GeV)**
- **CLAS @ JLAB : (E_{beam} = 0.5 – 4.0 GeV continuous)**
- **OLYMPUS @ DESY: (E_{beam} = 2.0 GeV)**

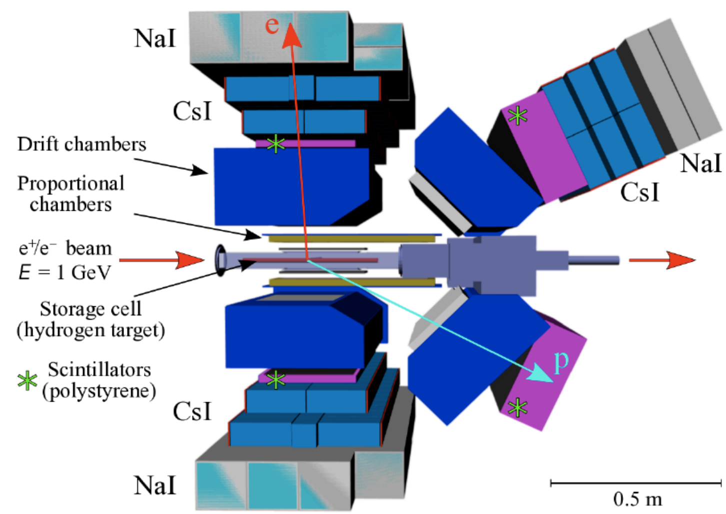


TPE experiments: Novosibirsk/VEPP-3

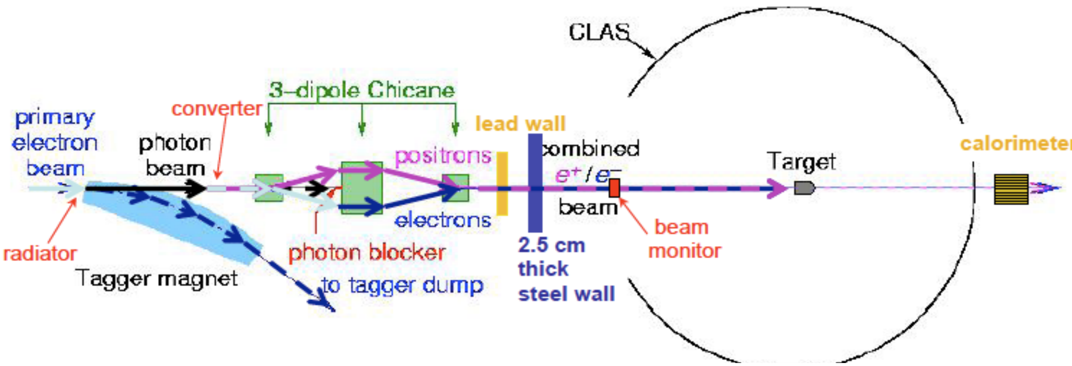


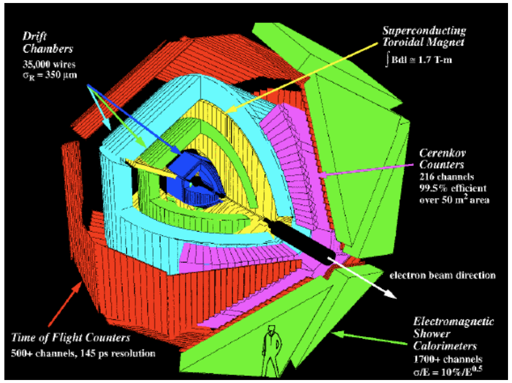


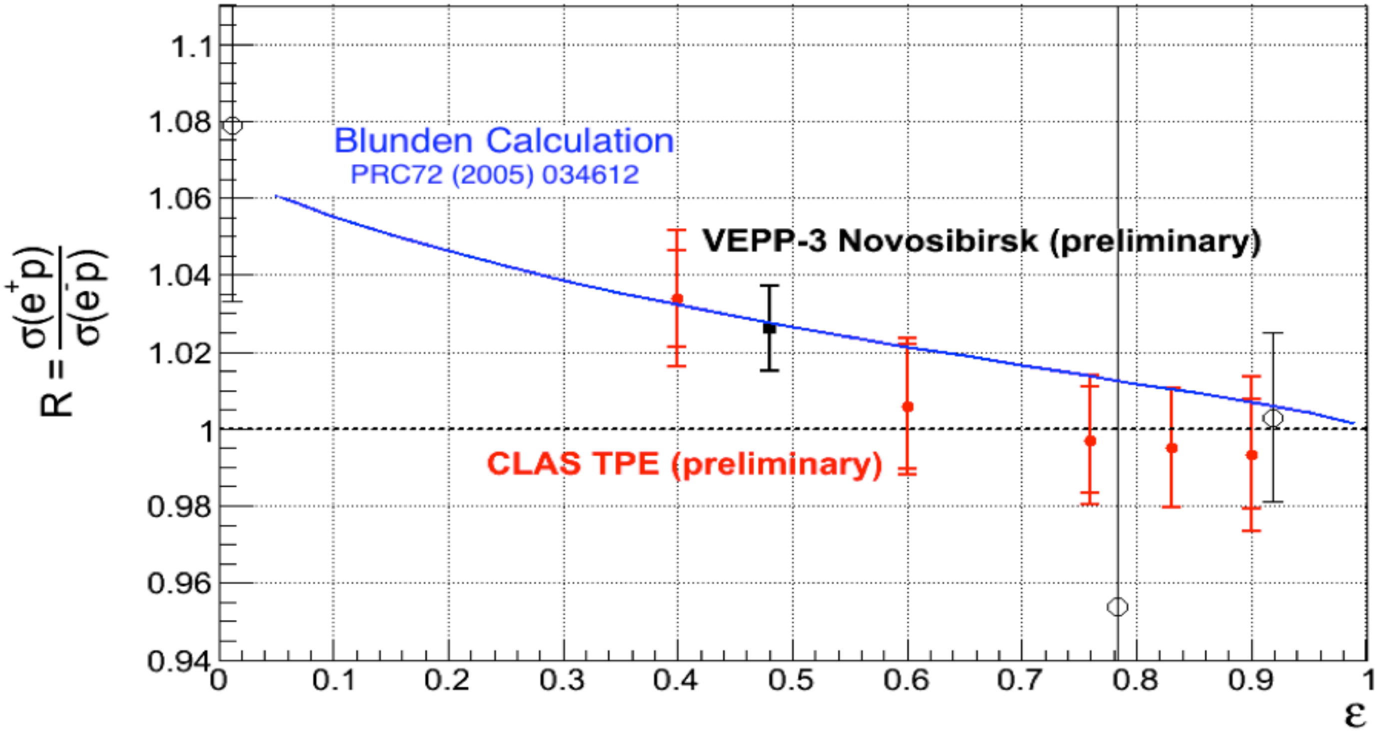




TPE experiments: CLAS (E04-116)



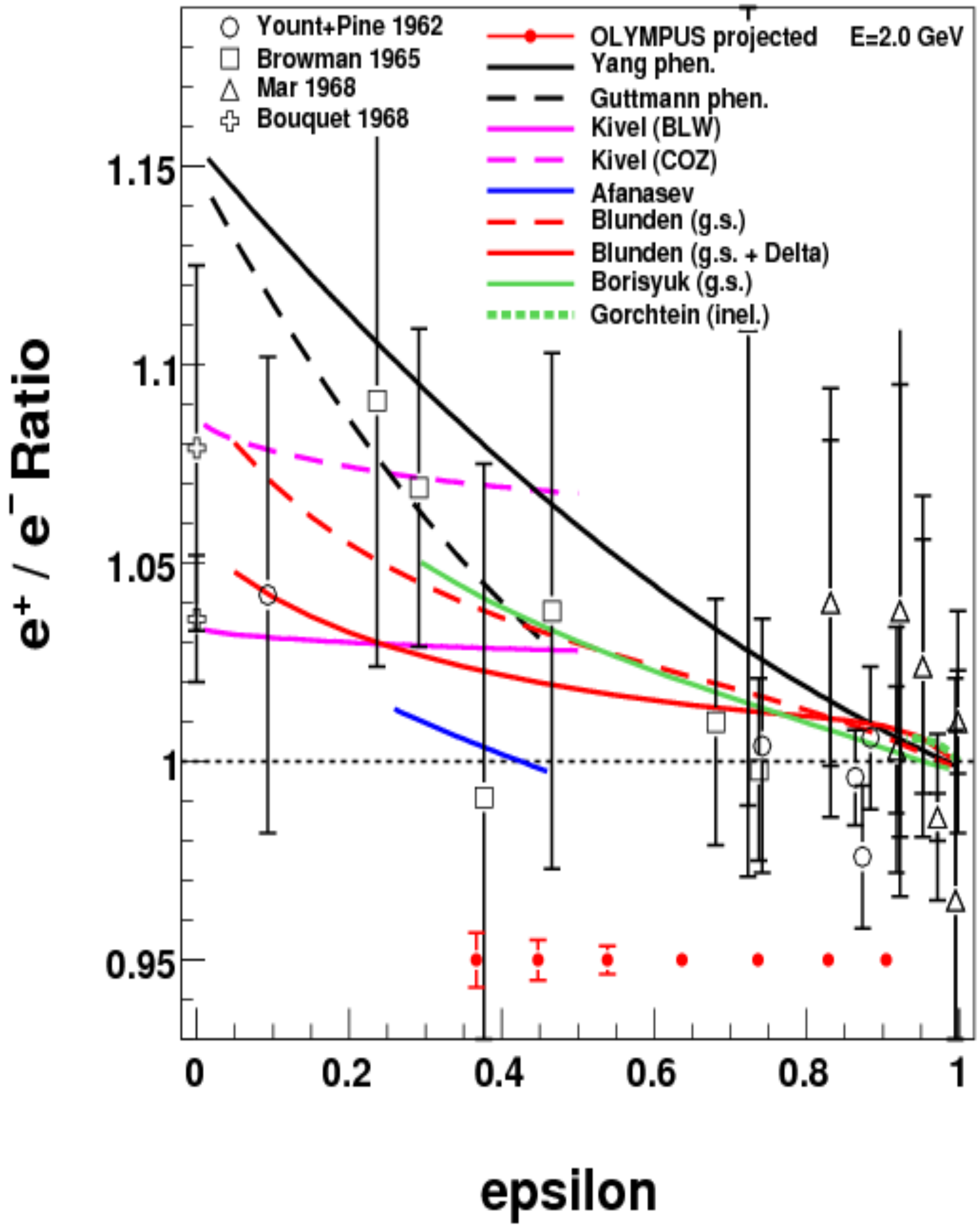




Dasuni Adikaram (ODU)
APS April Meeting, Savannah, GA, Apr ' 14
to be published

Projected uncertainties

OLYMPUS

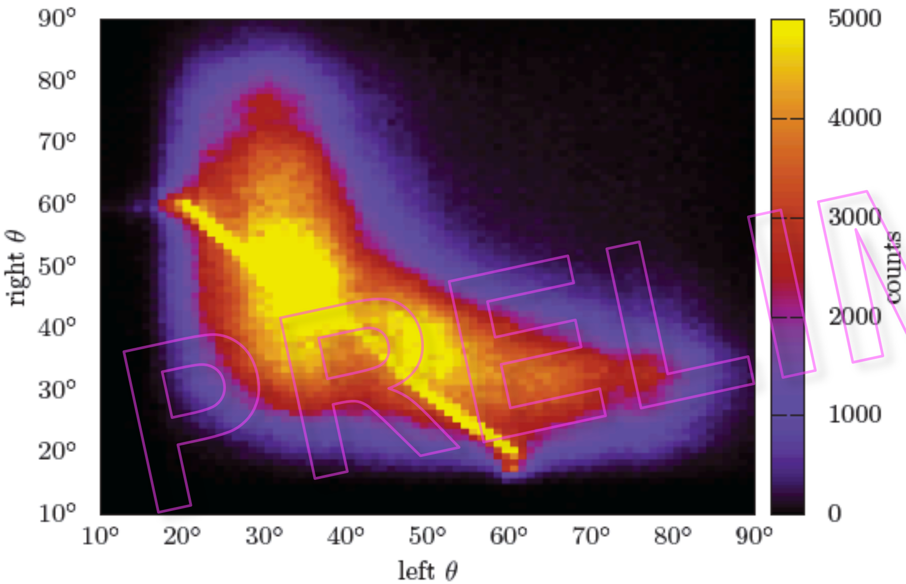


- 2 GeV incident beam energy
- Luminosity = 2 x 10^{33} cm^{-2} s^{-1}
- 500 hours each for e+ and e-
- 3.6 fb^{-1} integrated luminosity

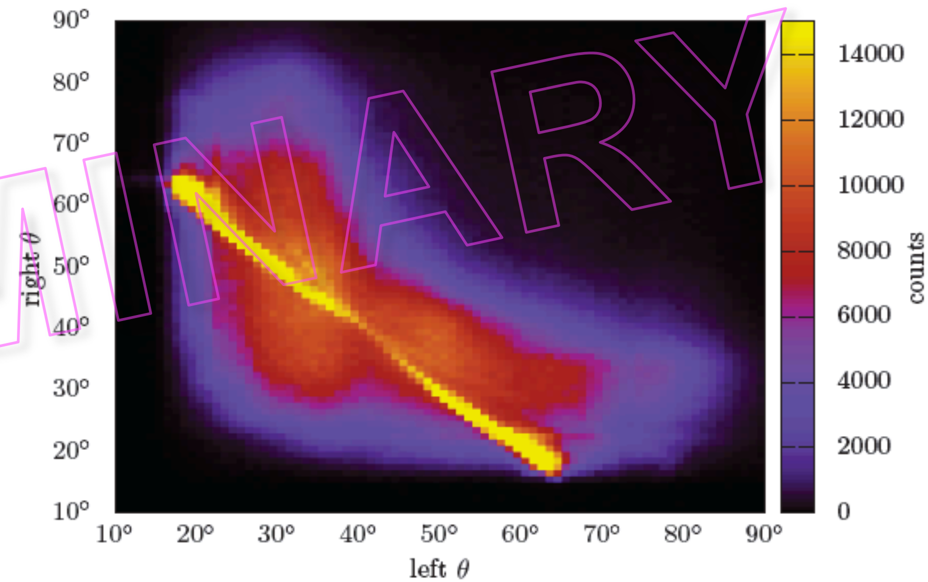
Tracking: very preliminary …

Based on 100 runs (~2% of the data)

Electron beam

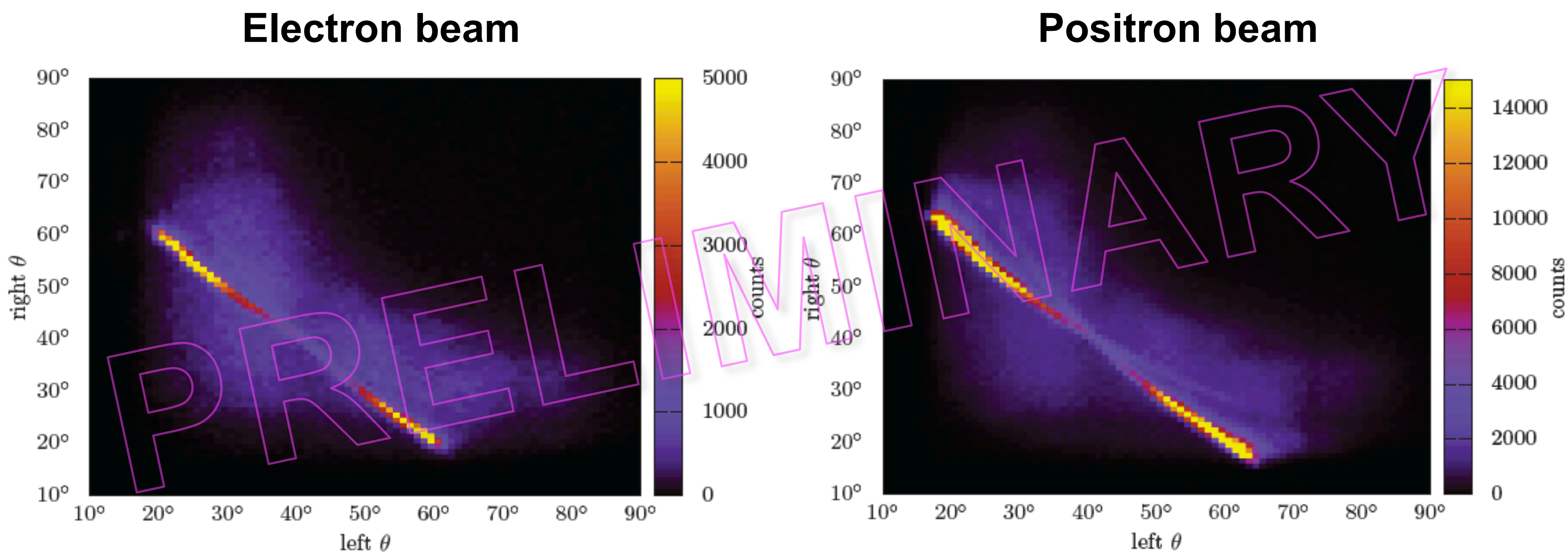


Positron beam



Polar angle in the right sector versus polar angle in left sector

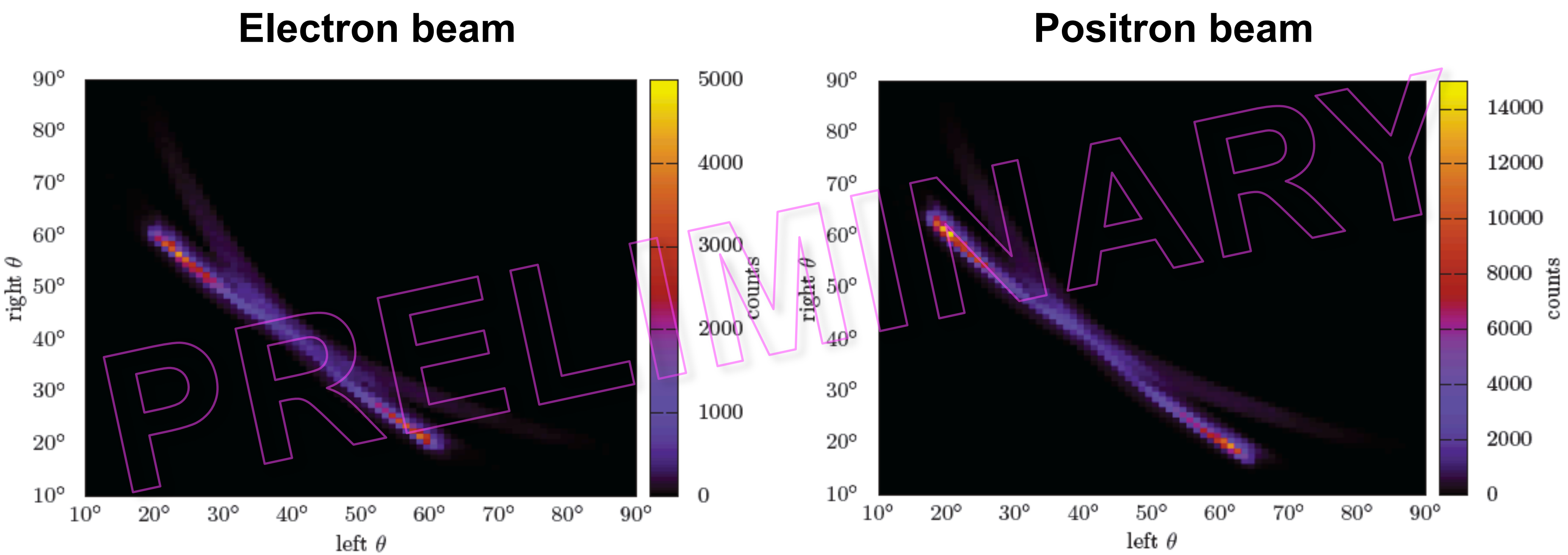
Based on 100 runs (~2% of the data)



Polar angle in the right sector versus polar angle in left sector
Coplanarity cut ±5 degrees

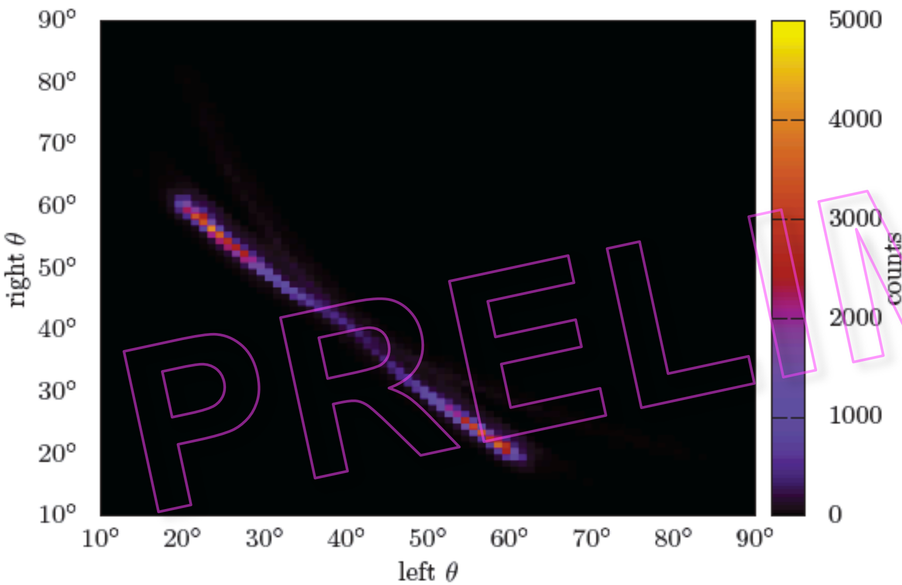
Tracking: very preliminary …

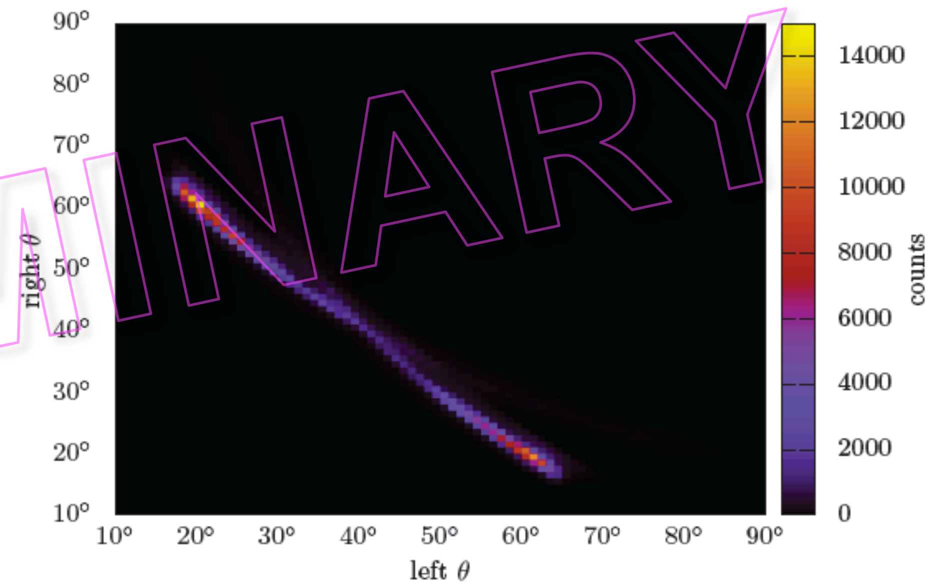
Based on 100 runs (~2% of the data)



Polar angle in the right sector versus polar angle in left sector
Coplanarity cut ±5 degrees
Common vertex ±100 mm

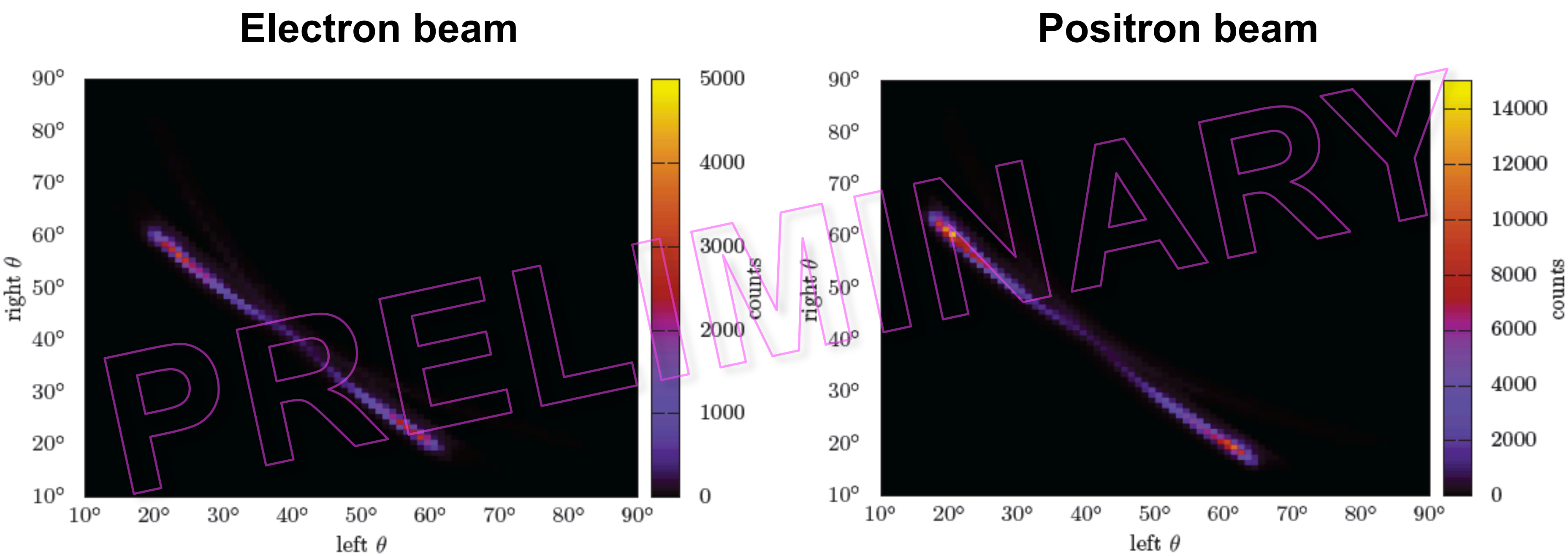
Based on 100 runs (~2% of the data)





Polar angle in the right sector versus polar angle in left sector
Coplanarity cut ±5 degrees
Common vertex ±100 mm
Polar angle kinematic cut $|\theta_l - \theta_l(\theta_p)| < 5$ degrees

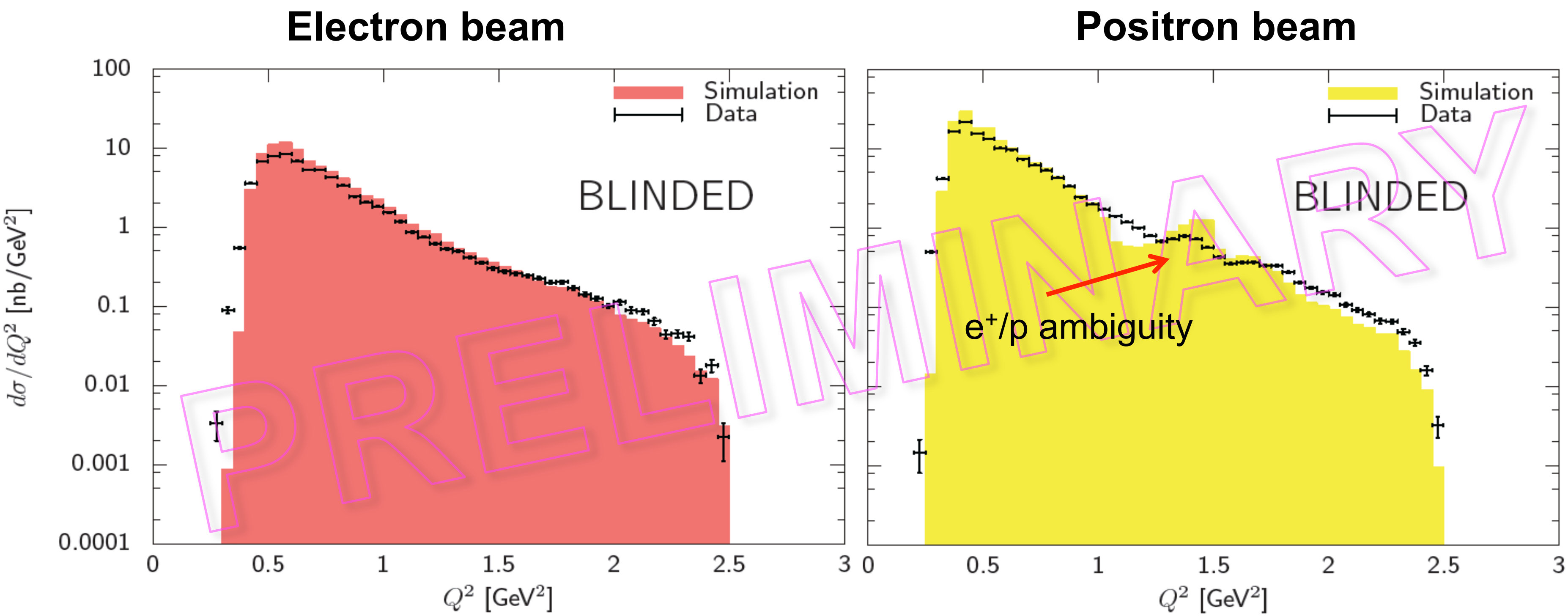
Based on 100 runs (~2% of the data)



Polar angle in the right sector versus polar angle in left sector
Coplanarity cut ±5 degrees
Common vertex ±100 mm
Polar angle kinematic cut $|\theta_l - \theta_l(\theta_p)| < 5$ degrees
Momentum kinematic cut $|P_p - P_p(\theta_p)| < 400$ MeV/c

Yields: very preliminary …

Based on 100 runs (~2% of the data)



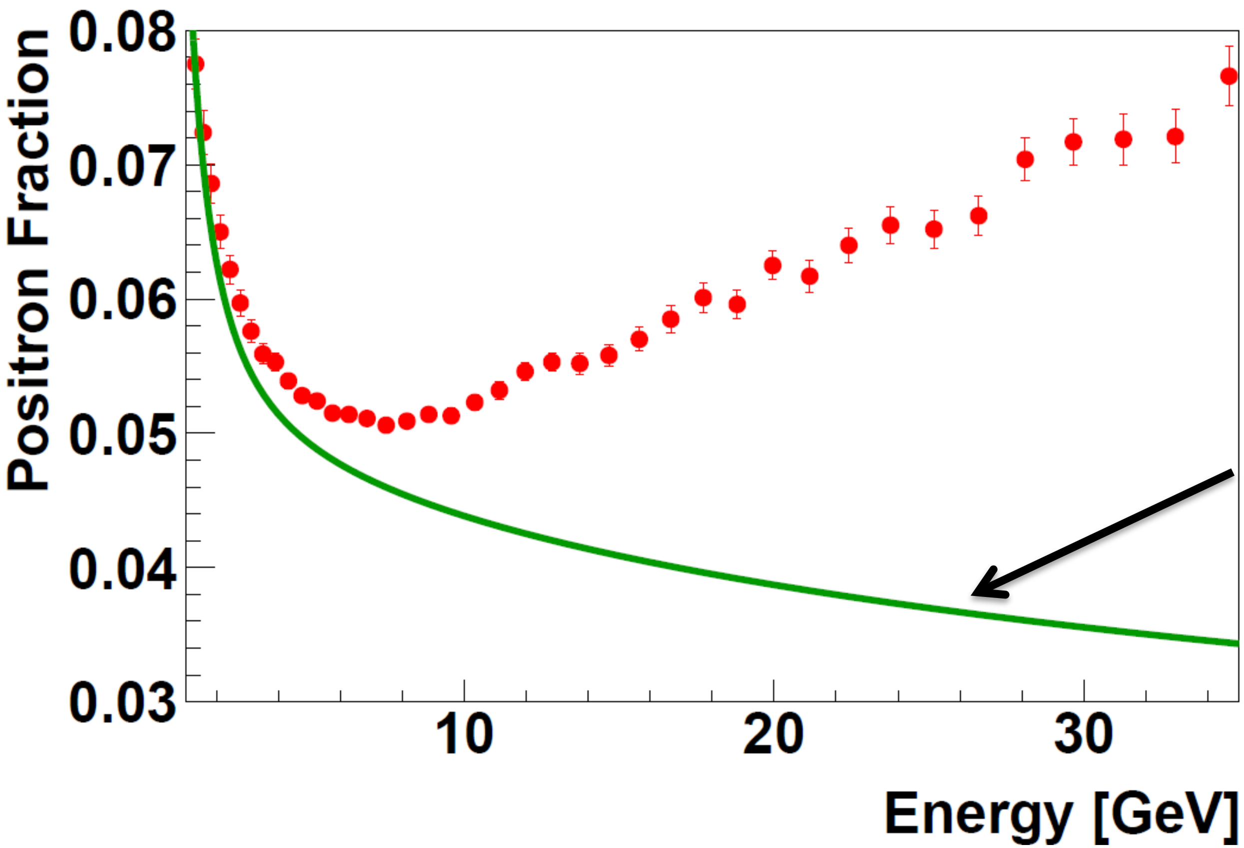
Schedule

• 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
• Results	2015

The Alpha Magnetic Spectrometer Experiment on the International Space Station

AMS is an MIT led International Collaboration
16 Countries, 60 Institutes and 600 Physicists

Recent AMS-02 data: there are new sources of positrons

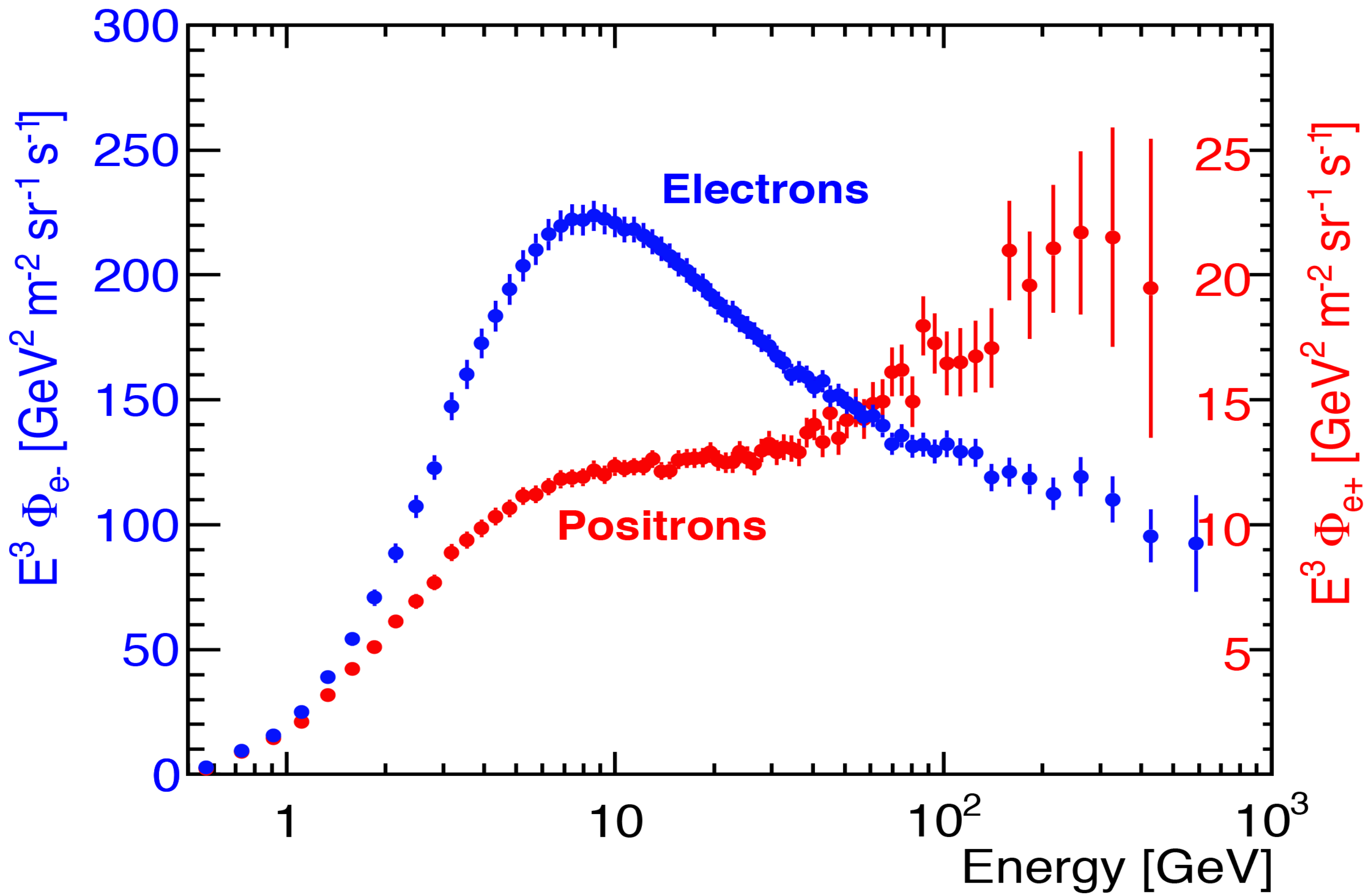


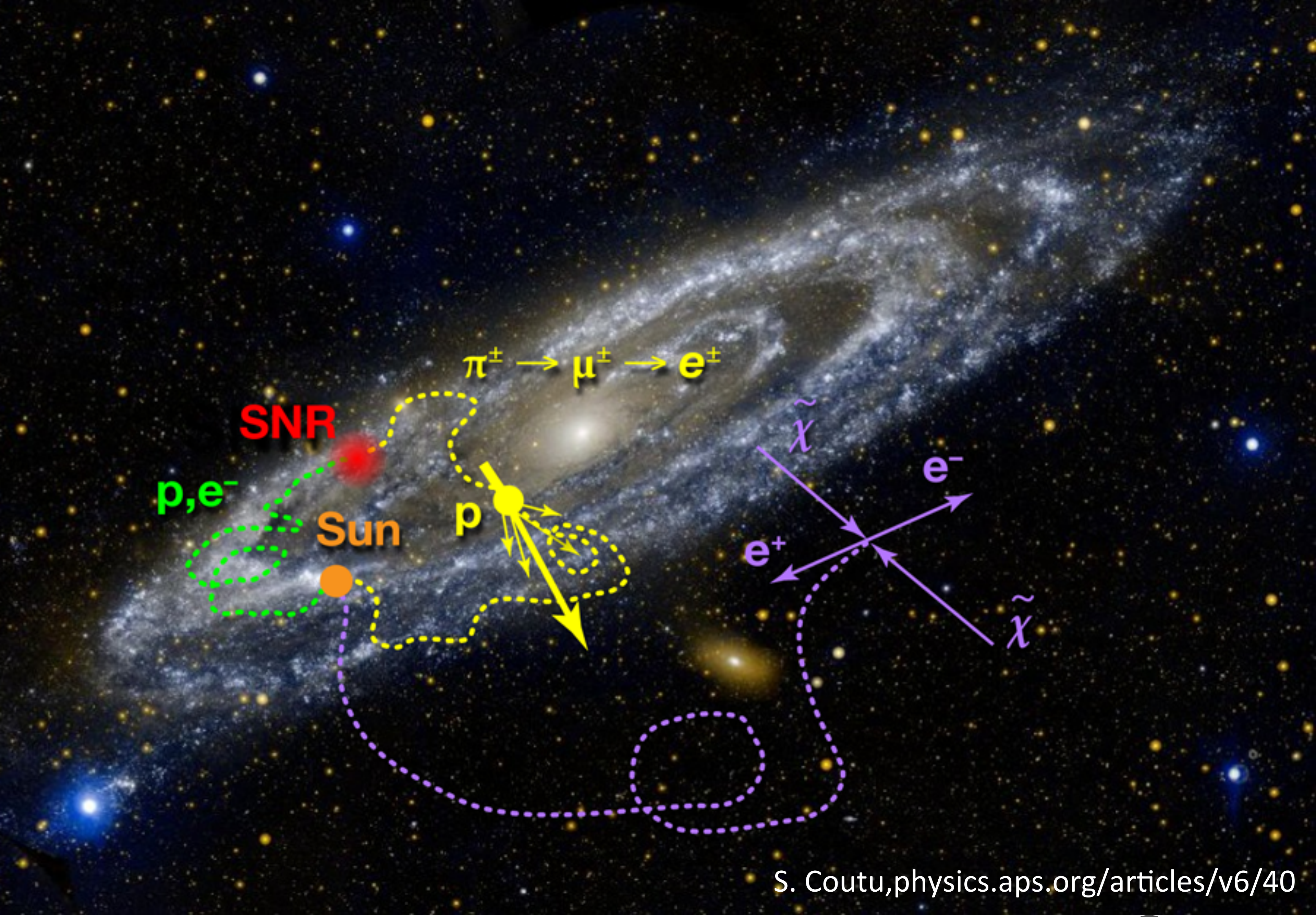
Phys. Rev. Lett. 113, 121101
Phys. Rev. Lett. 113, 121102

Expectation based on collision of ordinary cosmic rays

Recent AMS-02 flux data

Phys. Rev. Lett. 113, 121101
Phys. Rev. Lett. 113, 121102

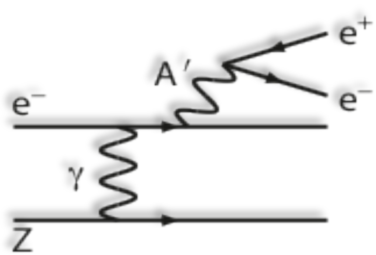




S. Coutu,physics.aps.org/articles/v6/40

New fixed target experiments to search for dark gauge forces

- New dark Abelian forces can couple to the SM hypercharge through the kinetic mixing operator $\frac{\epsilon}{2} F^{Y}_{\mu\nu} F'^{\mu\nu}$, where $F'_{\mu\nu} = \partial_{[\mu} A'_{\nu]}$
- ≈ MeV to GeV scale mass for the A' gauge boson
- A' can be produced in collisions with charged particles and can decay to electrons or muons
- Production cross-section $\sigma_{A'} \sim 100 \text{ pb} \left(\epsilon/10^{-4}\right)^2 \left(100 \, \text{MeV}/m_{A'}\right)^2$
- Decay length $\gamma c\tau \sim 1 \text{ mm} \left(\gamma/10\right) \left(10^{-4}/\epsilon\right)^2 \left(100 \, \text{MeV}/m_{A'}\right)$
- $\alpha' = \epsilon^2 \alpha_{\text{EM}}$
- Look for evidence of A' in the presence of QED radiation



Searching for a Dark Photon

Kinetic mixing:

$$\frac{\epsilon}{2} F^{Y}_{\mu\nu} F'^{\mu\nu}, \text{ where } F'_{\mu\nu} = \partial_{[\mu} A'_{\nu]}$$

$$\alpha' = \epsilon^2 \alpha_{\rm EM}$$

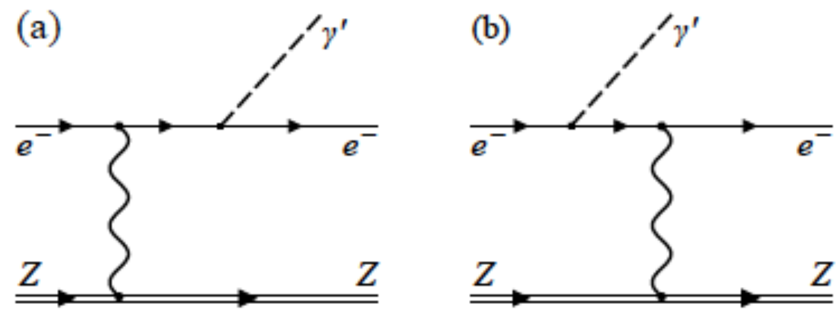


FIG. 1. Radiative production of a γ' in final (a) and initial state (b) on a heavy target nucleus Z. The subsequent decay of the γ' to an electron-positron pair would be the unique signal of such a γ' with a sharp mass distribution.

Warning!
Check variable on vertical axis in sensitivity plots

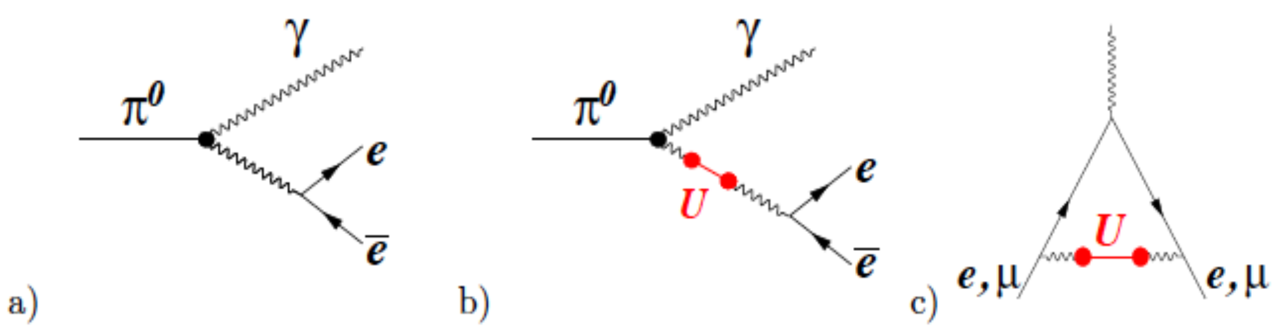


Figure 1: Feynman diagrams for a) the lowest order electromagnetic $\pi^0 \rightarrow e^+e^-\gamma$ decay and a possible contribution of U vector boson to: b) $\pi^0 \rightarrow e^+e^-\gamma$ and c) lepton $g-2$.

BABAR
Search for resonance in dimuon inv. mass distribution in Υ(2S,3S)➔γA' followed by A' ➔μ+μ-

DARKLIGHT Collaboration

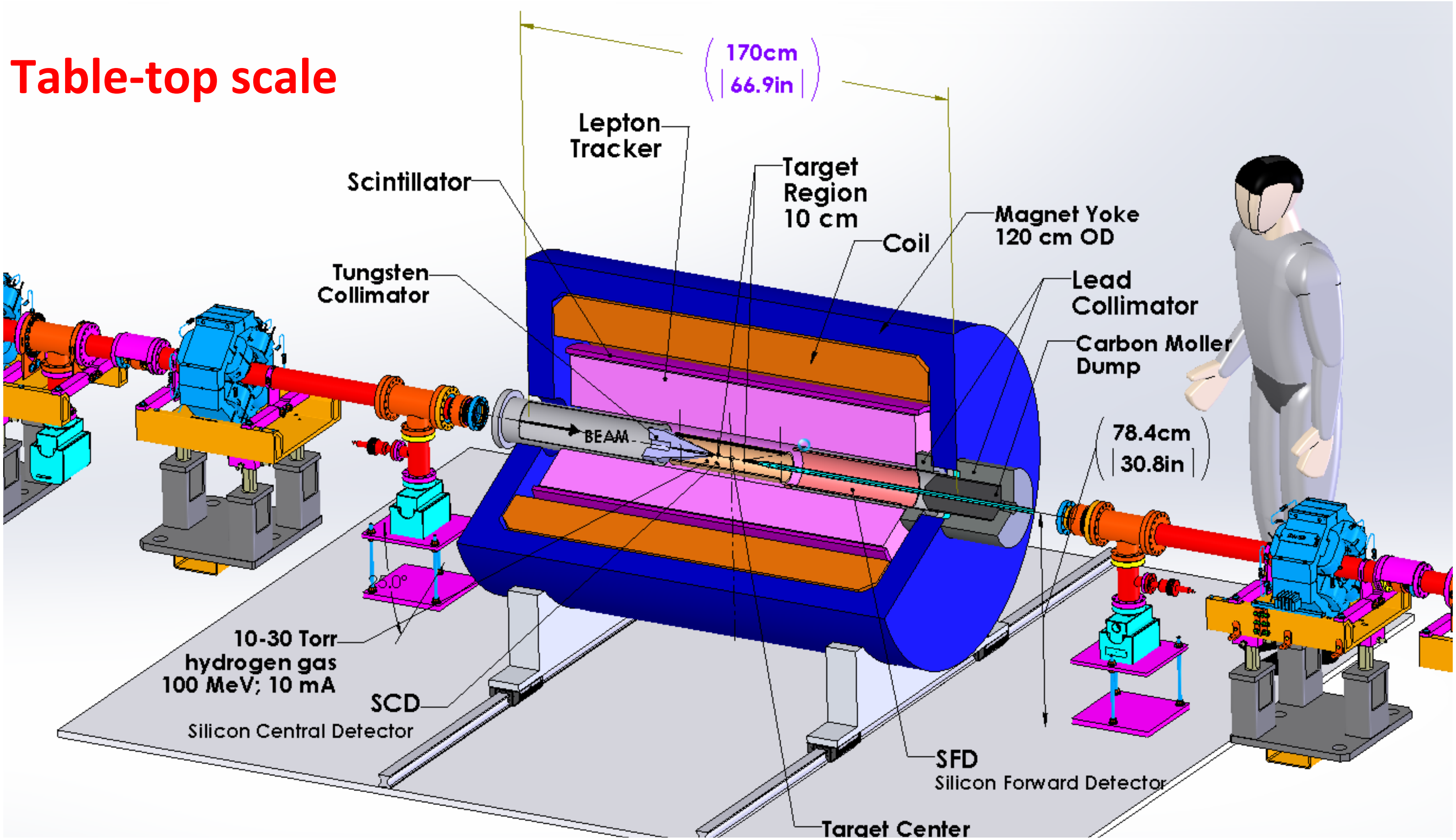
- Arizona State University
- Hampton University
- Jefferson Laboratory
- MIT
- Saclay
- Stony Brook University
- Temple University

Experimental considerations

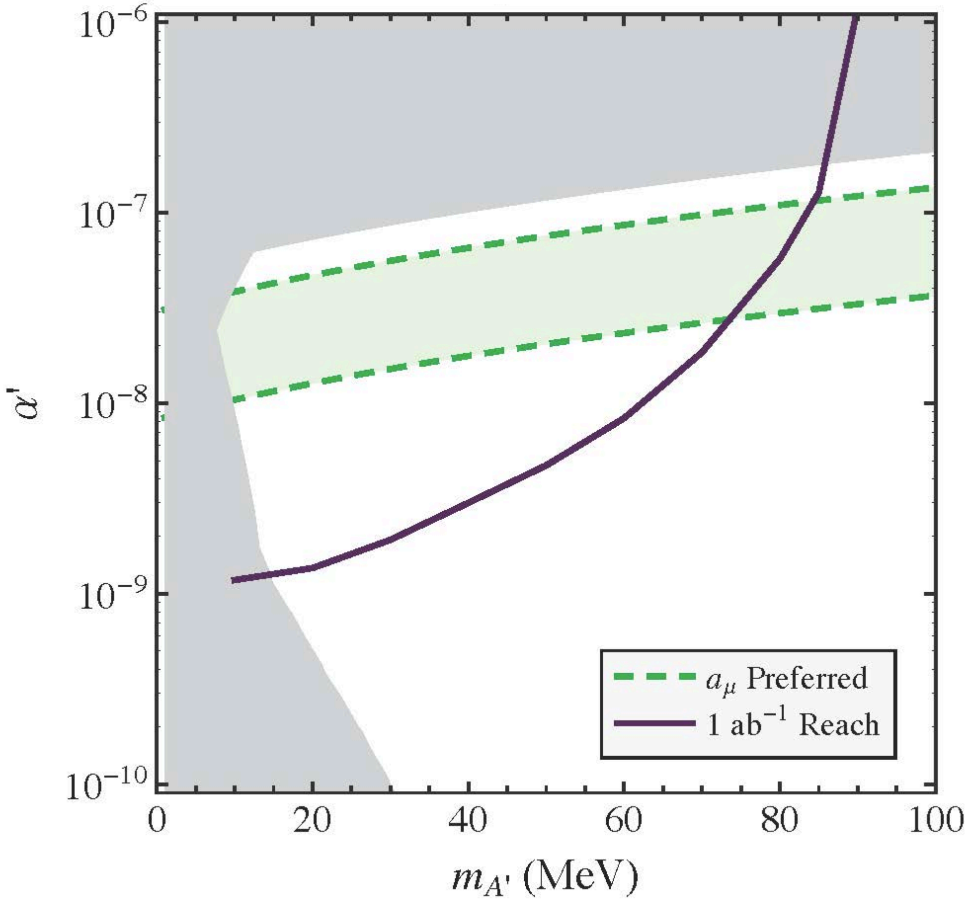
- Elastic electron-proton scattering at about 100 MeV
- Stay below pion threshold to keep final state simplest
- Demand detection of complete final state: scattered electron, recoil proton, and e+e- pair from A' decay => gas target so that the 1-5 MeV recoil proton can escape and be detected
- Require high luminosity: gas target of 10^{19} cm^{-2} and 10 mA of electrons so that one can make a definitive measurement in 1 month
- JLab FEL is world's only such accelerator: 1 MWatt of power
- Energy recovering linac
- Final state leptons have energy from 10 to 100 MeV => multiple scattering dominates resolution => thin material thicknesses
- Gas target of 10^{19} cm^{-2} is challenging; actually pushing to 4 x 10^{19} cm^{-2}

DARKLIGHT Layout

Table-top scale

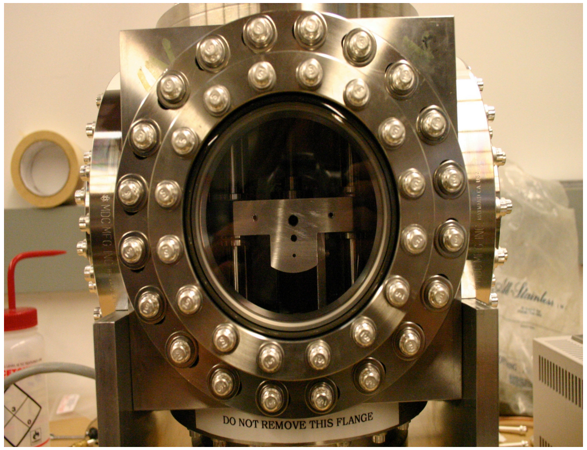


DARKLIGHT Experiment

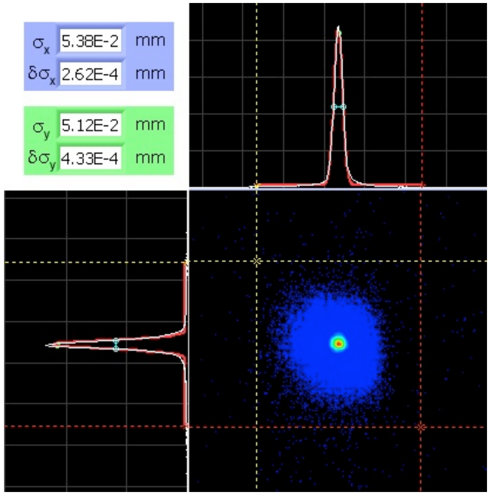


- Precision test of QED radiative processes in electron-proton elastic scattering as $Q^2 \rightarrow 0$
- Search for both e+e- and invisible decays
- Completely calculable
- Complete reconstruction of final-state
- 5σ discovery limit
- 1 ab^{-1} attained in several months of data taking with 10 mA at 100 MeV on 10^{19} cm^{-2} target
- Green region is present muon (g-2) result explained by a dark force
  Freytsis, Ovanesyan, and Thaler
  JHEP **1001**, (2011) 111

Successful beam test in July 2012



Target system designed and constructed at Bates R&E Center

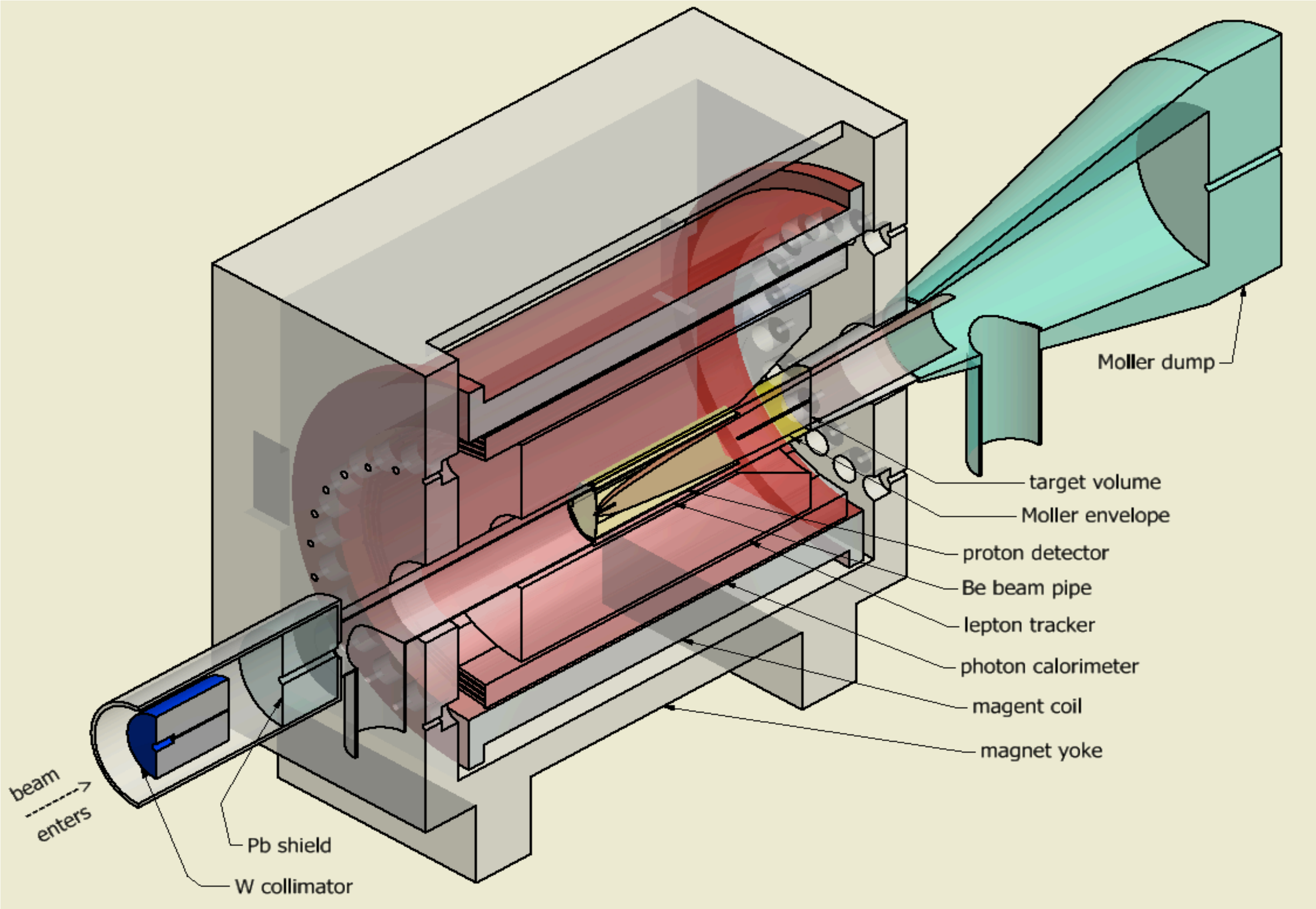


- A test beam of 4.3 mA, 100 MeV (430 kWatt of e-beam power) was successfully transmitted through a 2 mm hole, 127 mm long, with a maximum loss of about 3 ppm for seven hours.
- Halo can be minimized and radiation in vault is manageable.
- The FEL has the stability required for DarkLight.
- Three papers written on test: *Phys. Rev. Lett*. **111**, 164801 (2013)
  Nucl. Instr. Meth. **A729**, 233 (2013)
  Nucl. Instr. Meth. **A729**, 69 (2013)

Existing solenoidal magnet from E906 at BNL

- Constructed in Japan: see thesis by J.P. Nakano, U. of Tokyo (2000)
- E906 carried out at AGS D6 line
- 0.5 Tesla maximum field
- Inner diameter 712 mm
- Magnet with power supply now located at Stony Brook University

Optimized design in progress



Design process

- Full Geant4 computer simulation coordinated by Jan Balewski (MIT)
- Physics processes:
  - elastic electron-proton scattering
  - Moller scattering
  - their associated radiative processes
- Detailed experimental geometry:
  - windowless gas target
  - existing solenoidal magnet
  - realistic 3 D magnetic field map from OPERA
  - Moller dump
  - lepton tracker
  - recoil proton detector
  - photon veto detector
- Simulations are used to optimize the design of the experiment.

Development of a Radiative Møller Generator

- Under development by Charles Epstein (MIT) :
  a Monte Carlo event generator for the radiative corrections to Møller scattering
- Improves understanding of background processes
  - Møller rate is exceptionally high and must be understood

- Produces two types of events:
  - Elastic e-e events with cross-section corrected for the emission of soft photons (Tsai, 1960)
  - Hard single-photon bremsstrahlung events (exact first-order calculation)

Goals of phase-I DarkLight

- Realize full luminosity: 10 mA on 10^{19} cm^{-2} of hydrogen
- Realize solenoidal magnet for complete experiment
- Realize prototype detectors and readout systems for complete experiment which enable three science goals

- Science Goal 1: Accelerator Studies with the ERL (2 days)
- Science Goal 2:Measurement of Standard Model Processes (2 days)
- Science Goal 3: Search for the A' (16 days)

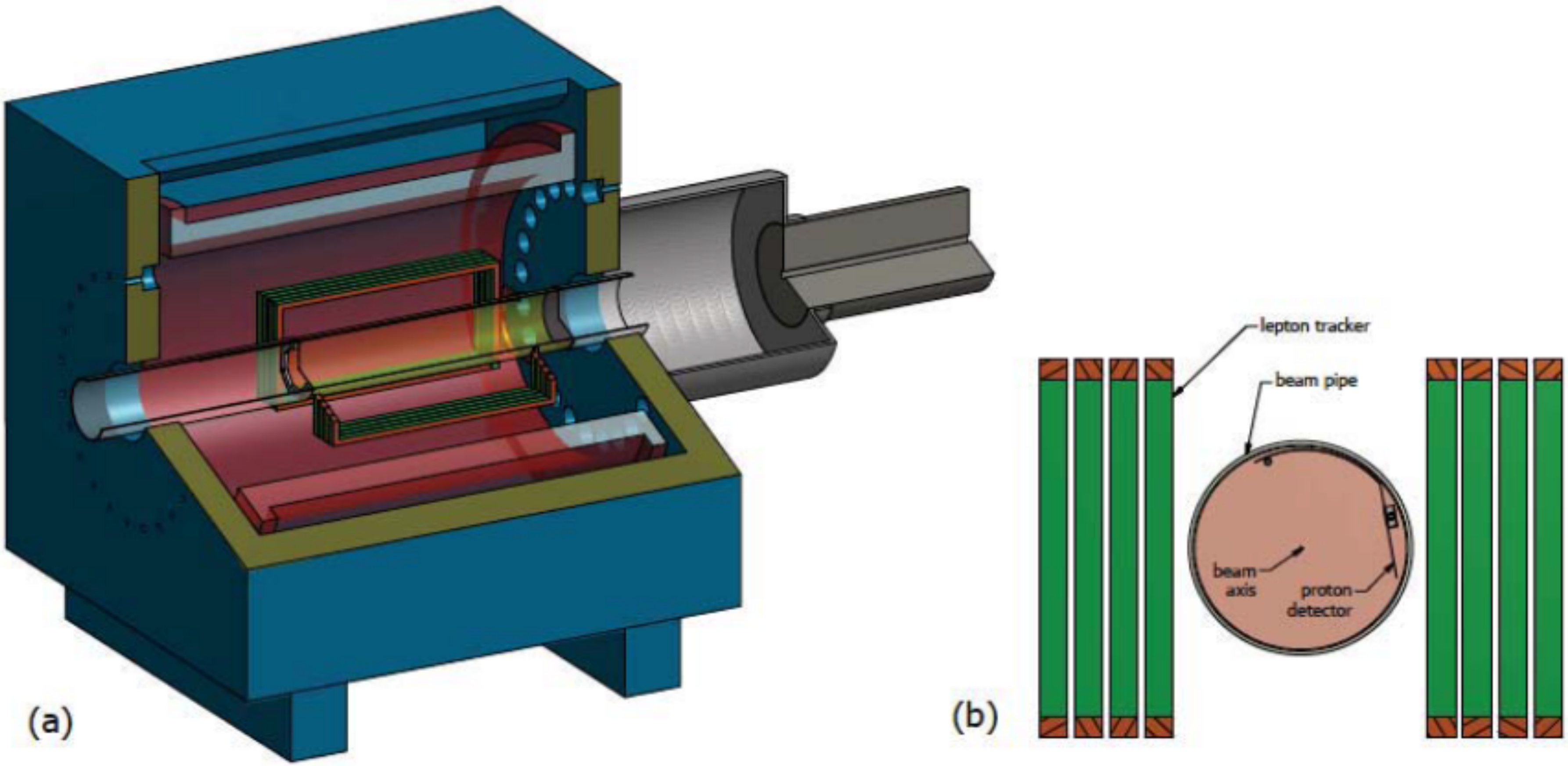


Fig 4. (a) Schematic cutout figure of the phase-I DarkLight instrument showing the solenoidal magnet, GEM trackers, and Møller dump. (b) Schematic transverse section of the proposed detectors for the phase-I DarkLight instrument.

Complete (phase-II) Experiment

- Use phase-I solenoidal magnet
- Use modified phase-I target
- Micromegas are the leading candidate for the lepton tracker technology
- Use phase-I proton detector technology instrumented for full acceptance
- Finish phase-II design as phase-I is finalized over the next 3-6 months
- Seek funding for phase-II in parallel with mounting phase-I

DARKLIGHT Schedule

- DarkLight proposal approved at JLab PAC 39 in June 2012 with “A” scientific rating, conditional upon successful test being completed
- Test successfully completed in July 2012
- Full scientific approval granted in May 2013
- Phase-I experiment funded by NSF MRI July 2014
- Detailed simulations in progress to finalize design: lepton tracker, trigger and readout
- OLYMPUS target was shipped back to MIT in summer 2013 to allow start on development of DarkLight target
- Existing 0.5 T solenoid at Stony Brook University (A. Deshpande)
- Anticipate it will take about 2 years to carry out phase-I experiment
- In parallel, finish design of complete (phase-II) experiment and pursue funding

Summary

- Working in the CEBAF Internal Target Working Group with Roy and others in 1985 strongly influenced my research career.
- The use of intense (p, e-, e+) beams from 100 MeV to 27 GeV on windowless gas targets has helped me address a series of varied and important questions in hadron physics throughout my career.
- I was fortunate to enjoy Roy's advice and counsel in the early, formative years of my career.
- I offer Roy warm congratulations on an outstanding career.
- I wish Roy continued professional success and many long, years of health and happiness with his family.