What is so puzzling about the electric charge of the proton?

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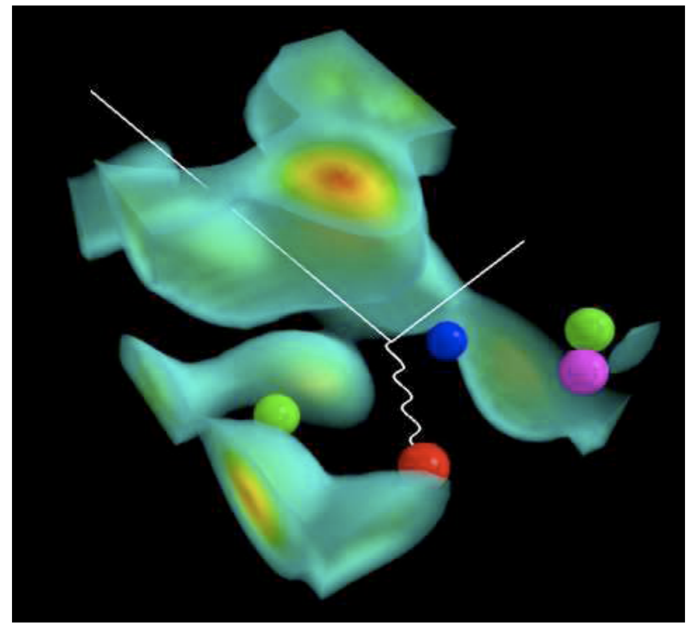
* **Supported by NSF grant PHY-1207672, and DOE Early Career Award DE-SC0003884**

Outline

Proton electric and magnetic form factors G_E and G_M describe the charge and magnetization

- Introduction, motivation and formalism
- Traditional and new techniques
- Overview of experimental data



A. Thomas, W. Weise,
The Structure of the Nucleon (2001)

High Q^2: Energy frontier

- Proton form factor ratio
- Transition to pQCD
- Two-photon exchange: $G_E(Q^2)$ uncertain

Low Q^2: Precision frontier

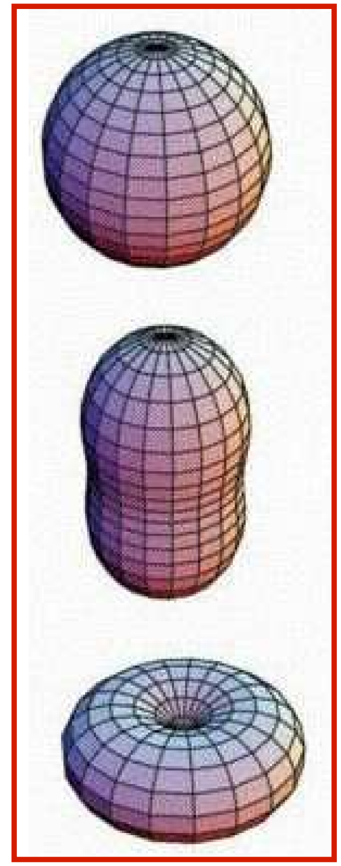
- Pion cloud effect
- Deviations from dipole form
- The Proton Radius Puzzle: 7σ discrepancy

Nucleon elastic form factors …

- Fundamental quantities
- Defined in context of single-photon exchange

- Describe internal structure of the nucleons
- Related to spatial distribution of charge and magnetism

- Rigorous tests of nucleon models
- Determined by quark structure of the nucleon
- Role of orbital angular momentum and diquark correlation
- Ultimately calculable by Lattice-QCD
- Input to nuclear structure and parity violation experiments



50 years of ever increasing activity

- Tremendous progress in experiment and theory over last decade
- New techniques / polarization experiments
- Unexpected results

Present form factor and TPE experiments

Recoil polarization and polarized target

GEp-II+III – high-Q^2 recoil polarization	– published (2010)
2-Gamma – ε dependence of recoil pol.	– published (2011)
E08-007 – low-Q^2 recoil polarization	– published (2011)
E08-007 – low-Q^2 polarized target	– analysis in progress
SANE – high-Q^2 polarized target	**– to be published**
GEp-V (& GMp) – high Q^2 at Jlab-12	– proposed

Rosenbluth separation

Super-Rosen – high-Q^2 Rosenbluth	– analysis in progress

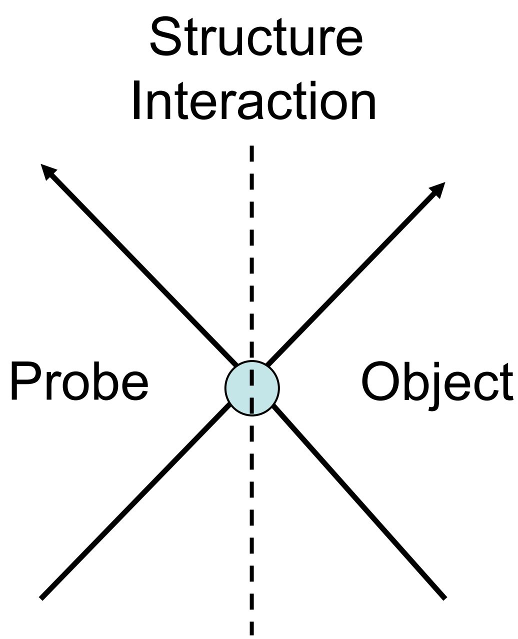
Positron-electron comparisons

Novosibirsk/VEPP-3	– analysis in progress
CLAS/Jlab	– analysis in progress
OLYMPUS/DESY	**– completed, analysis started**

Proton radius measurements

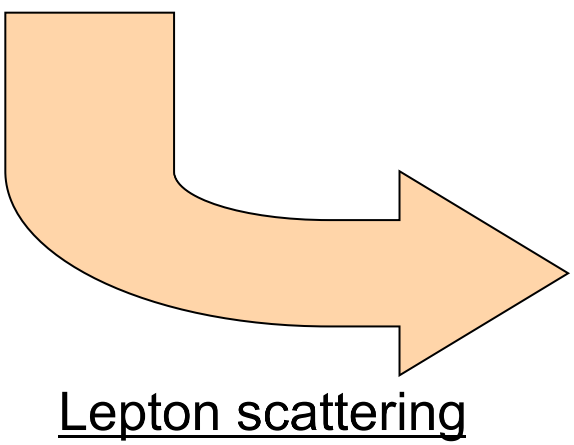
PSI / (muonic hydrogen Lamb shift, HFS)	– published (2010, 2013)
MAMI / A1 (e-scattering)	– published (2010) + proposed
Jlab / PRad (e-scattering)	– proposed
PSI / MUSE ($e^{\pm}$, $\mu^{\pm}$ scattering)	**– proposed**

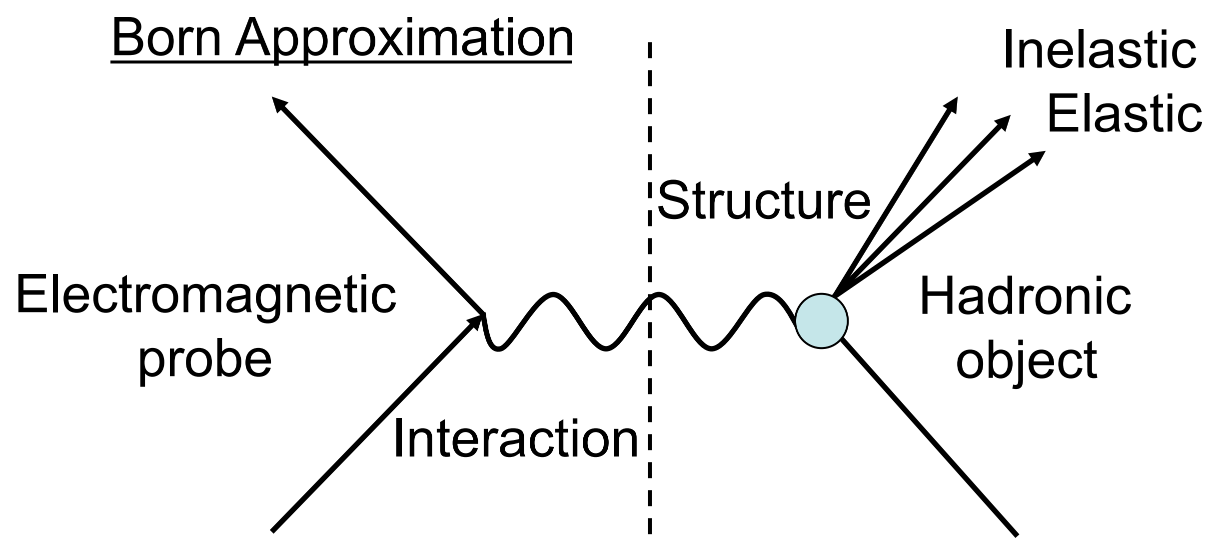
Hadronic structure and EM interaction



Factorization!

$$|\text{Form factor}|^2 = \frac{\sigma(\text{structured object})}{\sigma(\text{pointlike object})}$$

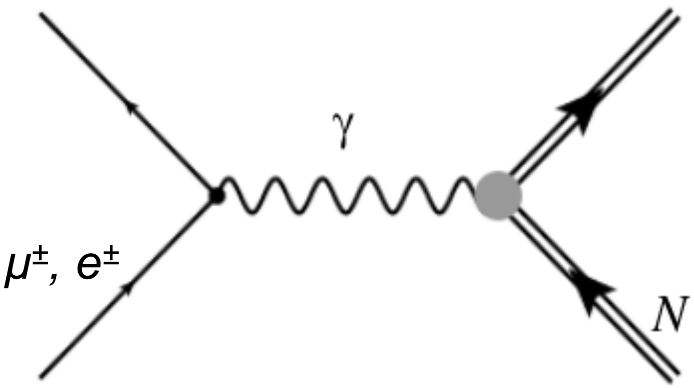




One-Photon Exchange Approximation

Lepton scattering and charge radius

Lepton scattering from a nucleon:



Vertex currents:

$$J_e^\mu = -e\overline{u}_e \gamma^\mu u_e$$

$$J_N^\mu = \overline{\psi}_N \left[F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M_N} \right] \psi_N$$

F_1, F_2 are the Dirac and Pauli form factors

Sachs form factors:

$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \tau F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + F_2(Q^2) \end{aligned}$$

Fourier transform (in the Breit frame) gives spatial charge and magnetization distributions

Derivatives in $Q^2 \to 0$ limit: Radii

$$\begin{aligned} \langle r_E^2 \rangle &= -6 \frac{dG_E^p(Q^2)}{dQ^2}\bigg|_{Q^2\to 0} \\ \langle r_M^2 \rangle &= -6 \frac{dG_M^p(Q^2)/\mu_p}{dQ^2}\bigg|_{Q^2\to 0} \end{aligned}$$

The beginnings

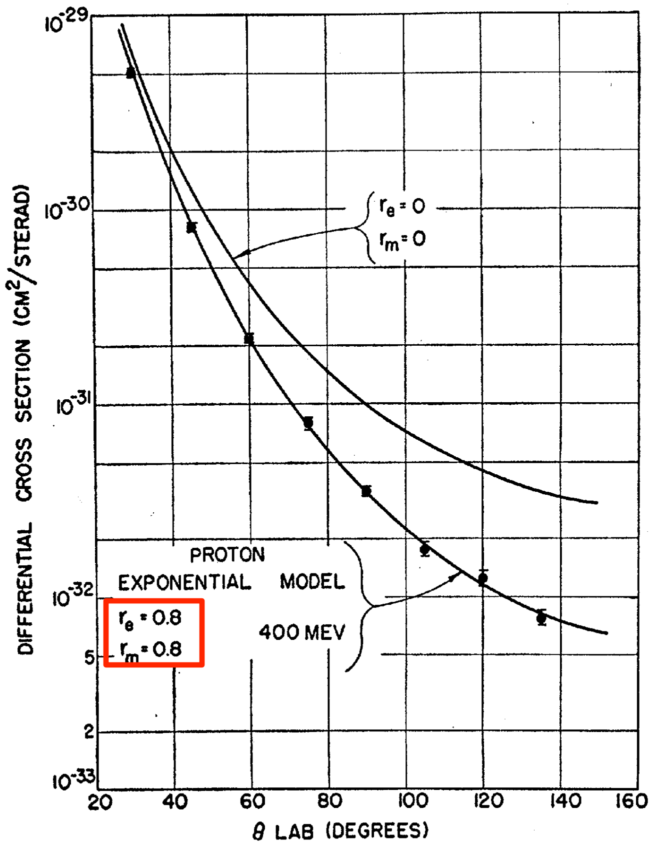


FIG. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with rms radii $=0.80\times10^{-13}$ cm.

R. Hofstadter, Rev. Mod. Phys. 56 (1956) 214

Robert Hofstadter
Nobel prize 1961

ep-elastic
finite size of the proton
$R_p \sim 0.8$ fm

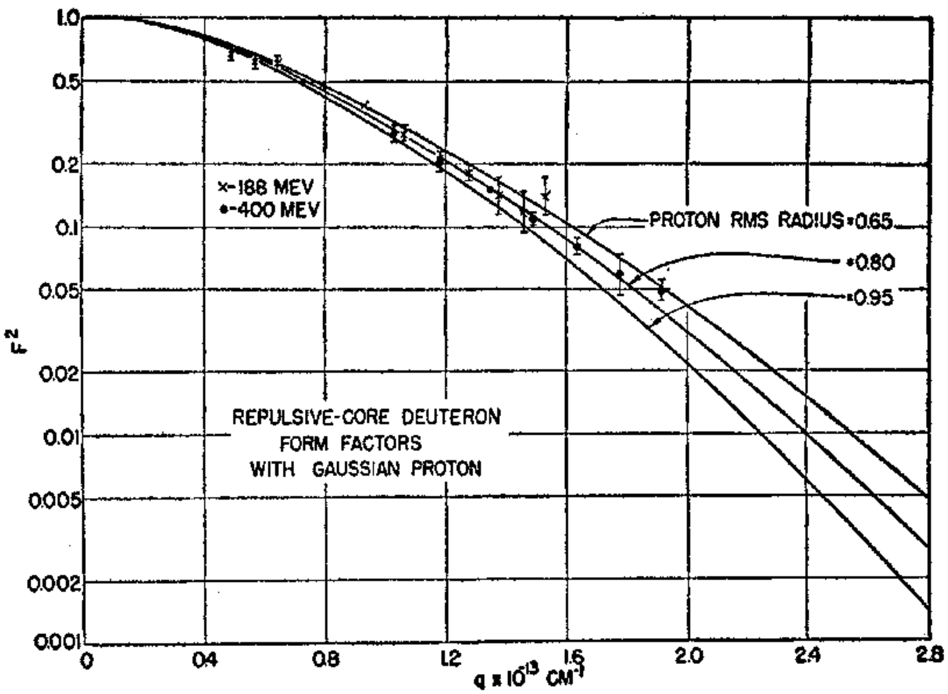
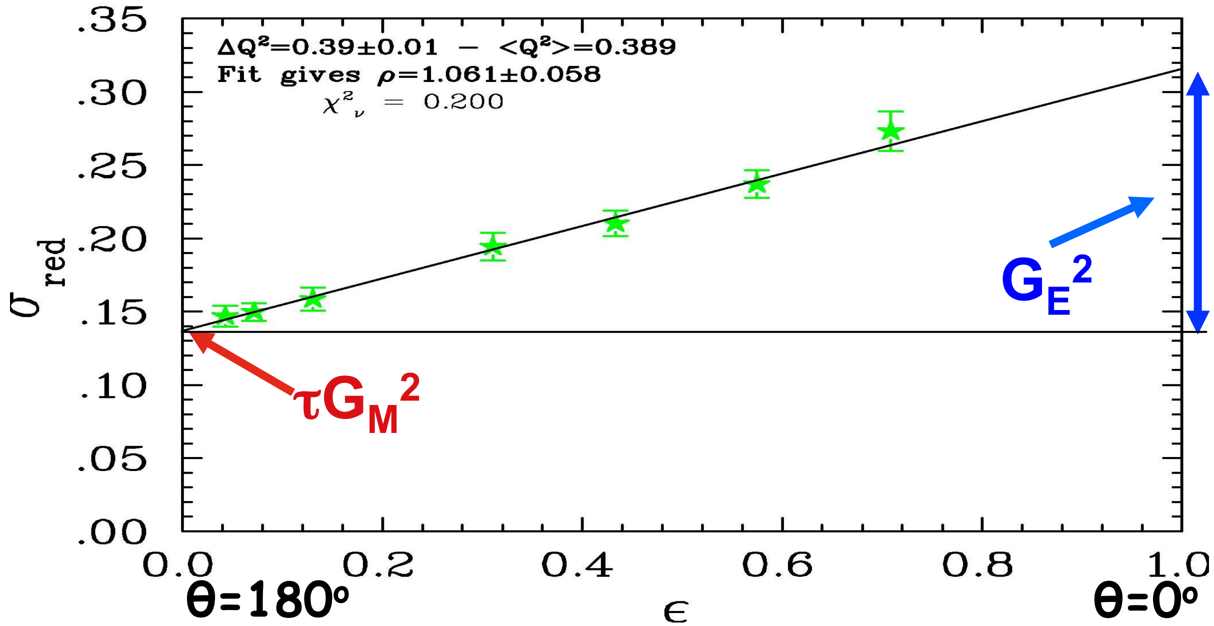


FIG. 31. Introduction of a finite proton core allows the experimental data to be fitted with conventional form factors (McIntyre).

ed-elastic
Finite size + nuclear structure

Form factors from Rosenbluth method



$\sigma_{red} = \varepsilon G_E{}^2 + \tau G_M{}^2$

➔Determine

$|G_E|$, $|G_M|$,

$|G_E/G_M|$

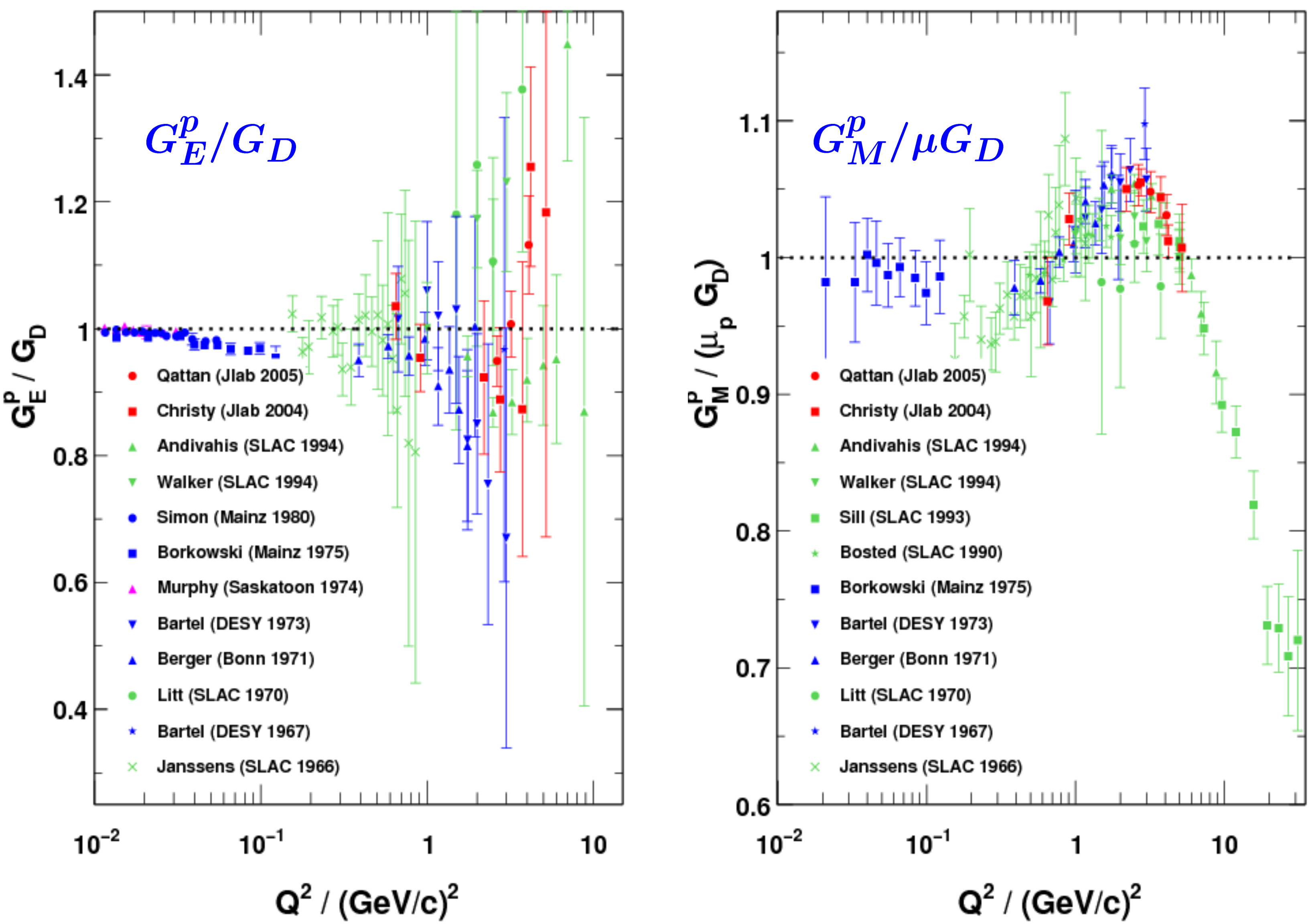
- **In One-photon exchange, form factors are related to radiatively corrected elastic electron-proton scattering cross section**

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

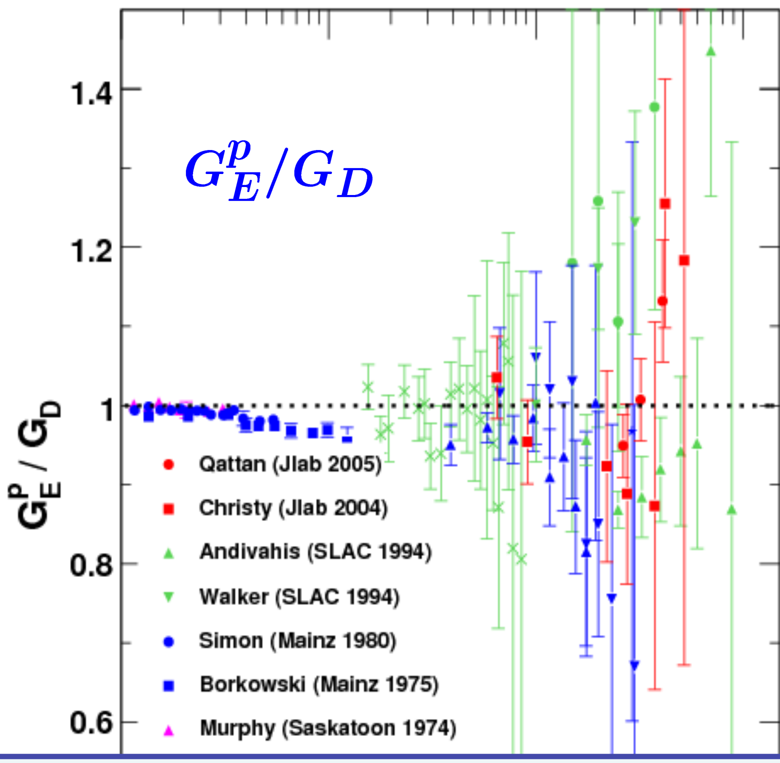
$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$

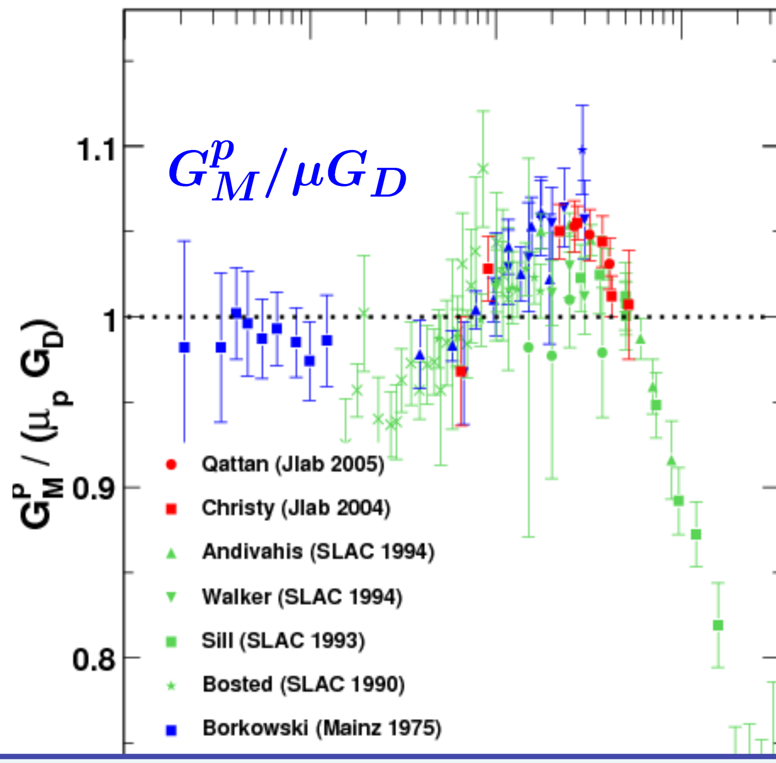
$$= \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)}, \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

G^p_E and G^p_M from unpolarized data



G^p_E and G^p_M from unpolarized data



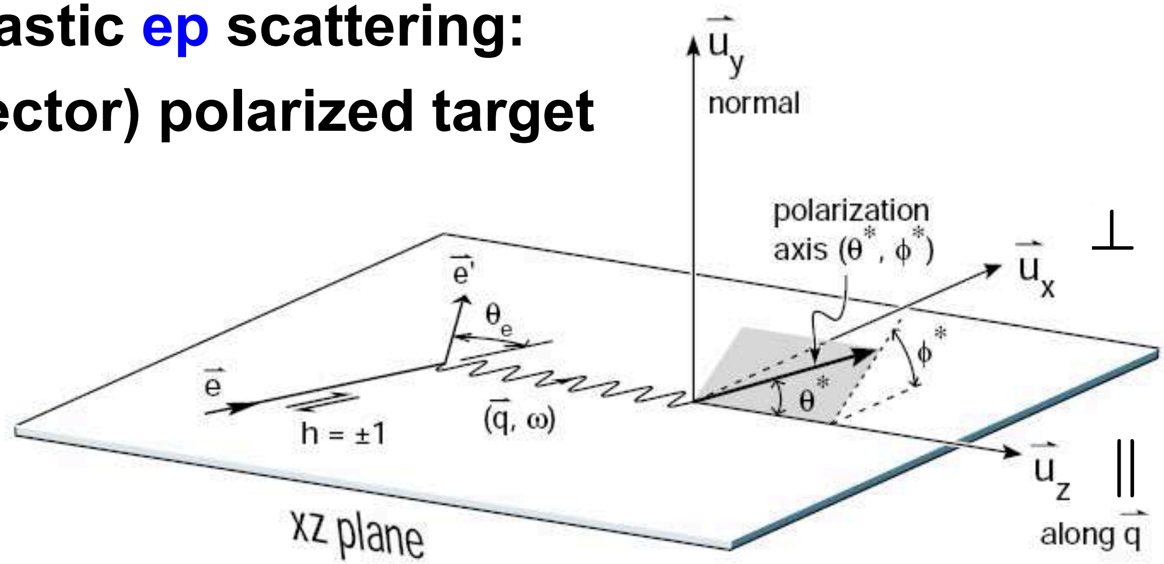


- $G(Q^2) \overset{\text{Fourier}}{\longleftrightarrow} \rho(r)$ **charge and magnetization density (Breit fr.)**
- **Dipole form factor** $G_D = \frac{1}{\left(1+\frac{Q^2}{0.71}\right)^2} \leftrightarrow \rho_D(r) = \rho_0\, e^{-\sqrt{0.71}r}$
- $G^p_E \approx G^p_M/\mu_p \approx G^n_M/\mu_n \approx G_D$ **within 10% for $Q^2 < 10$ $(GeV/c)^2$**

Nucleon form factors and polarization

- **Double polarization in elastic ep scattering:**
  Recoil polarization or (vector) polarized target

  $^{1}H(\vec{e},e'\vec{p})$, $^{1}\vec{H}(\vec{e},e'p)$



- **Polarized cross section**

$$\sigma = \sigma_0 \left(1 + P_e \vec{P}_p \cdot \vec{A}\right)$$

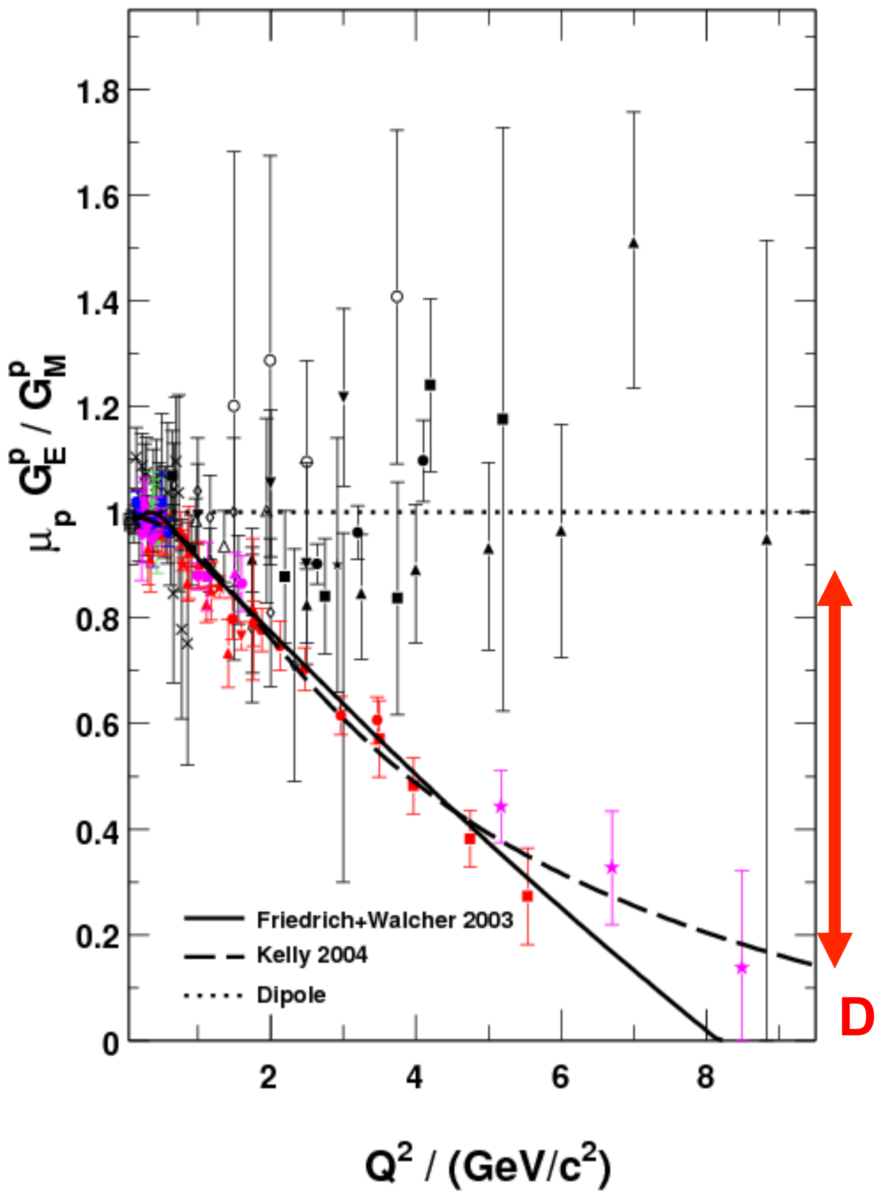
- **Double polarization observable = spin correlation**

$$-\sigma_0 \vec{P}_p \cdot \vec{A} = \sqrt{2\tau\epsilon(1-\epsilon)} G_E G_M \sin\theta^* \cos\phi^* + \tau\sqrt{1-\epsilon^2} {G_M}^2 \cos\theta^*$$

- **Asymmetry ratio ("Super ratio")** $\frac{P_\perp}{P_\parallel} = \frac{A_\perp}{A_\parallel} \propto \frac{G_E}{G_M}$

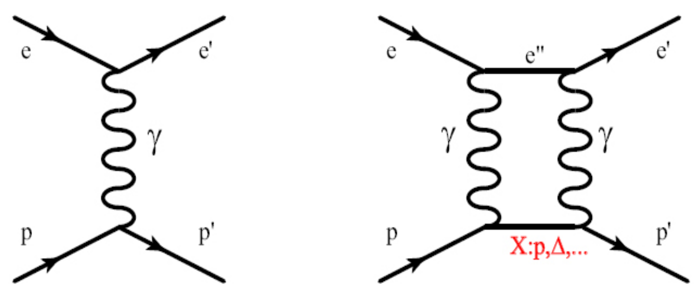
  independent of polarization or analyzing power

Proton form factor ratio



Jefferson Lab 2000–

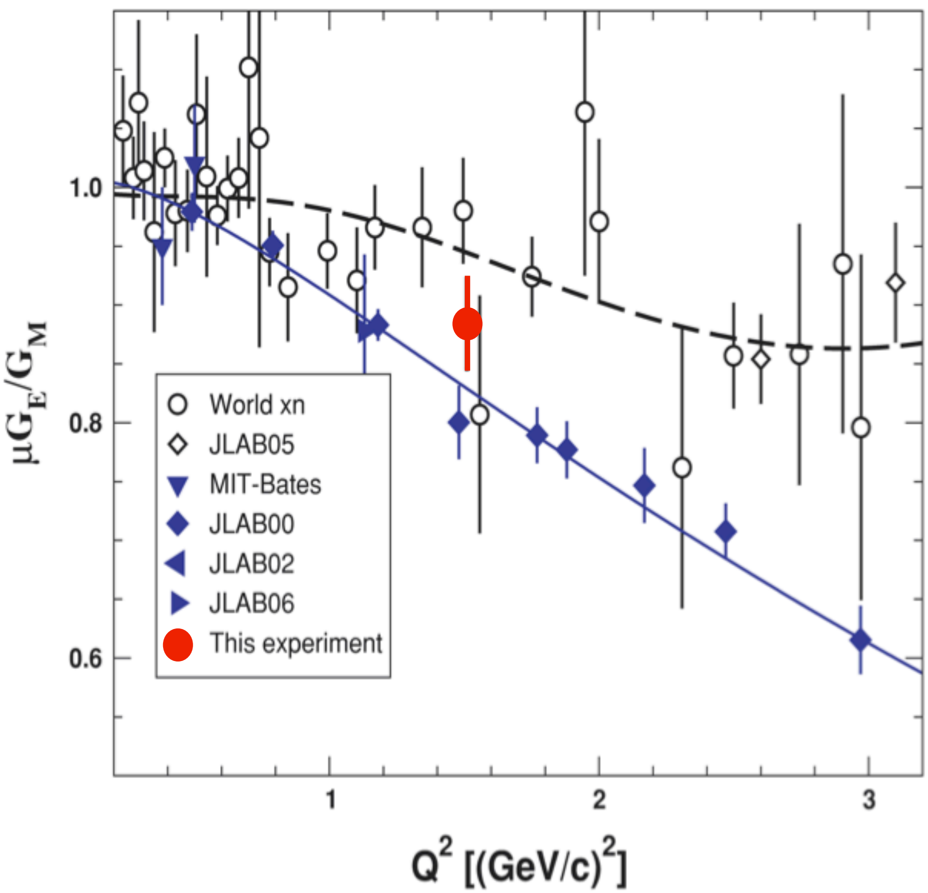
- All Rosenbluth data from SLAC and Jlab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Multi-photon exchange considered best candidate



Dramatic discrepancy!

>800 citations

Polarized target data at high Q^2



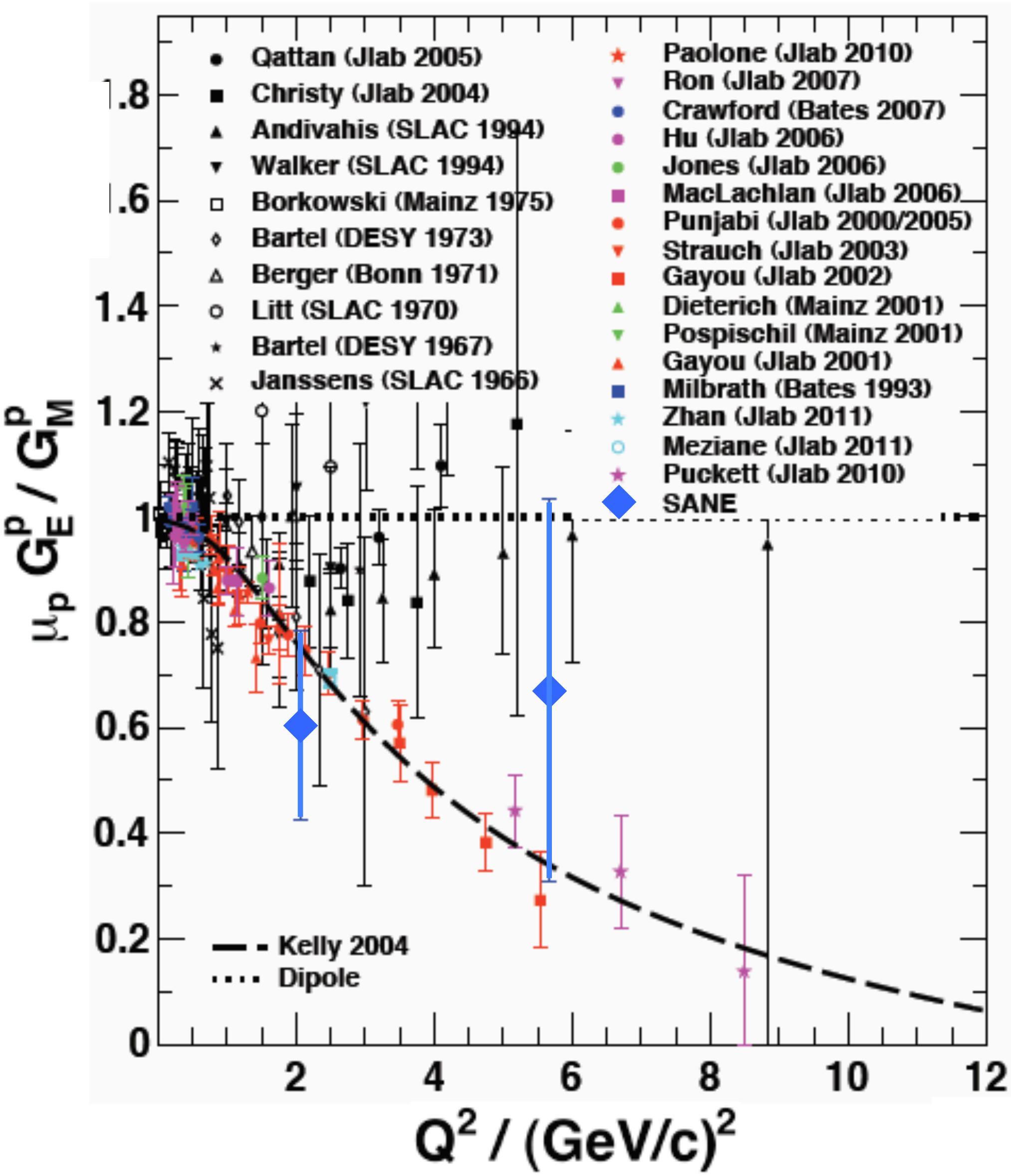
M.K. Jones et al., PRC74 (2006) 035201

Polarized Target:
Independent verification of recoil polarization result is crucial

Polarized internal target / low Q^2: **BLAST**
Q^2<0.65 (GeV/c)^2 not high enough to see deviation from scaling

RSS /Hall C: $Q^2 \approx 1.5$ (GeV/c)^2

Polarized target data at high Q^2



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RSS /Hall C: $Q^2 \approx 1.5$ (GeV/c)^2

SANE/Hall C: completed March 2009
BigCal electron detector
Recoil protons in HMS parasitically
G_E/G_M at $Q^2 \approx 2.1$ and 5.7 (GeV/c)^2

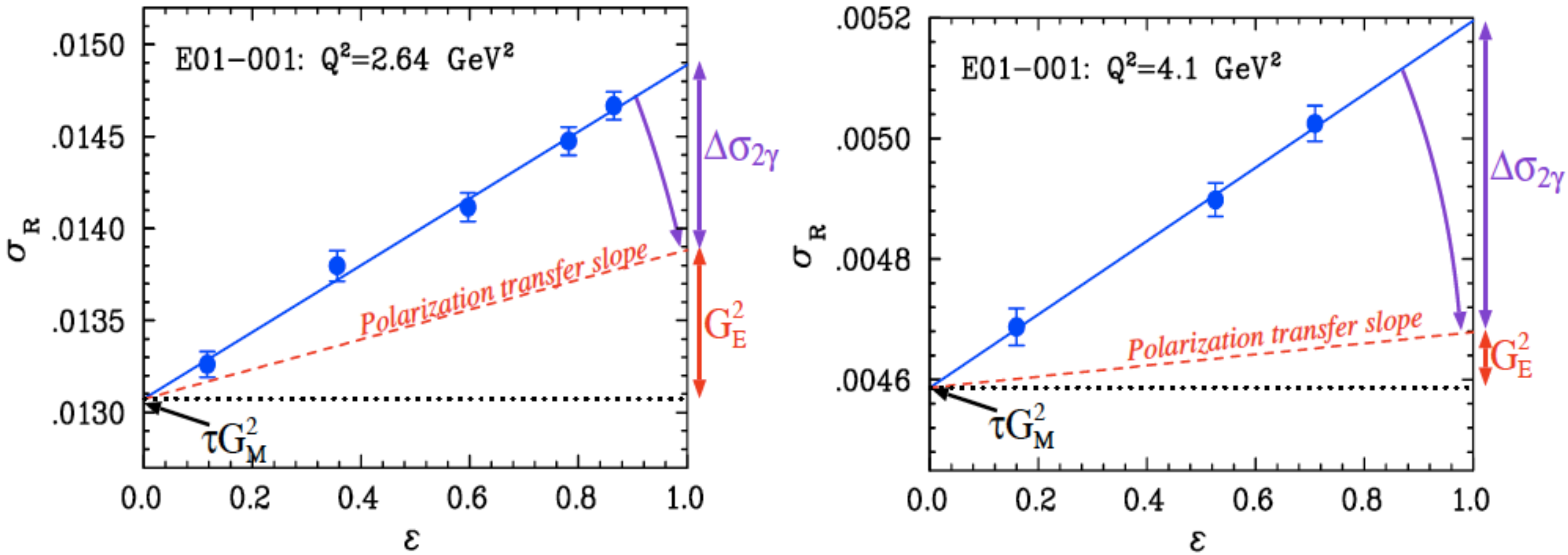
Decline of G_E/G_M has been confirmed!

Future precision measurements at high Q^2 are feasible

A. Liyanage, M.K. et al., to be published
DNP2013 DH.00004

Effect of two-photon exchange

J. Arrington

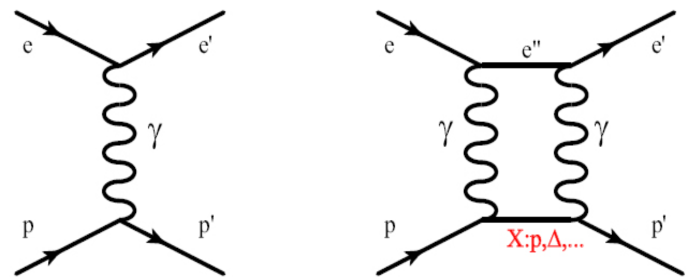


per constructionem, theorists sought mechanism that affects the "slope" in the Rosenbluth plot

At high Q^2 , the contribution of G_E to the cross section is of similar order as the TPE effect (few %)

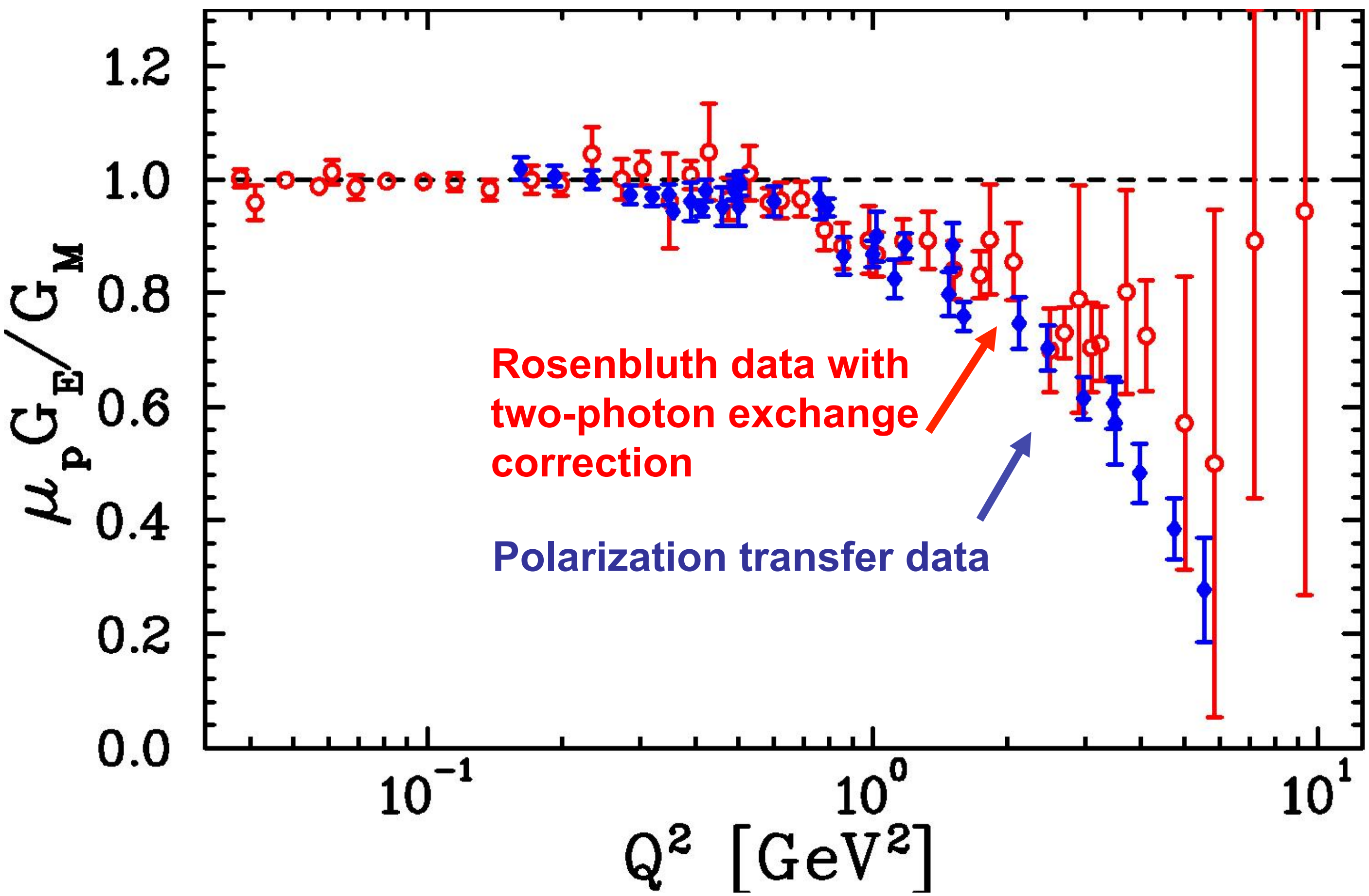
Two-photon exchange: exp. evidence

Two-photon exchange theoretically suggested

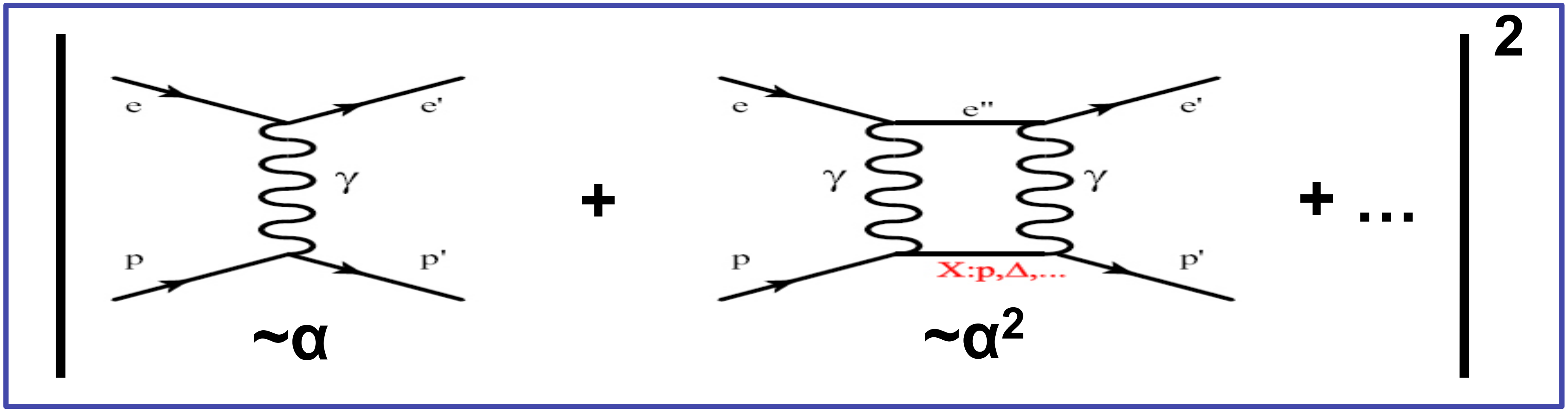


TPE can explain form factor discrepancy

J. Arrington, W. Melnitchouk, J.A. Tjon,
Phys. Rev. C 76 (2007) 035205



Lepton-proton elastic scattering



- **Interference term depends on lepton charge sign (C-odd)**

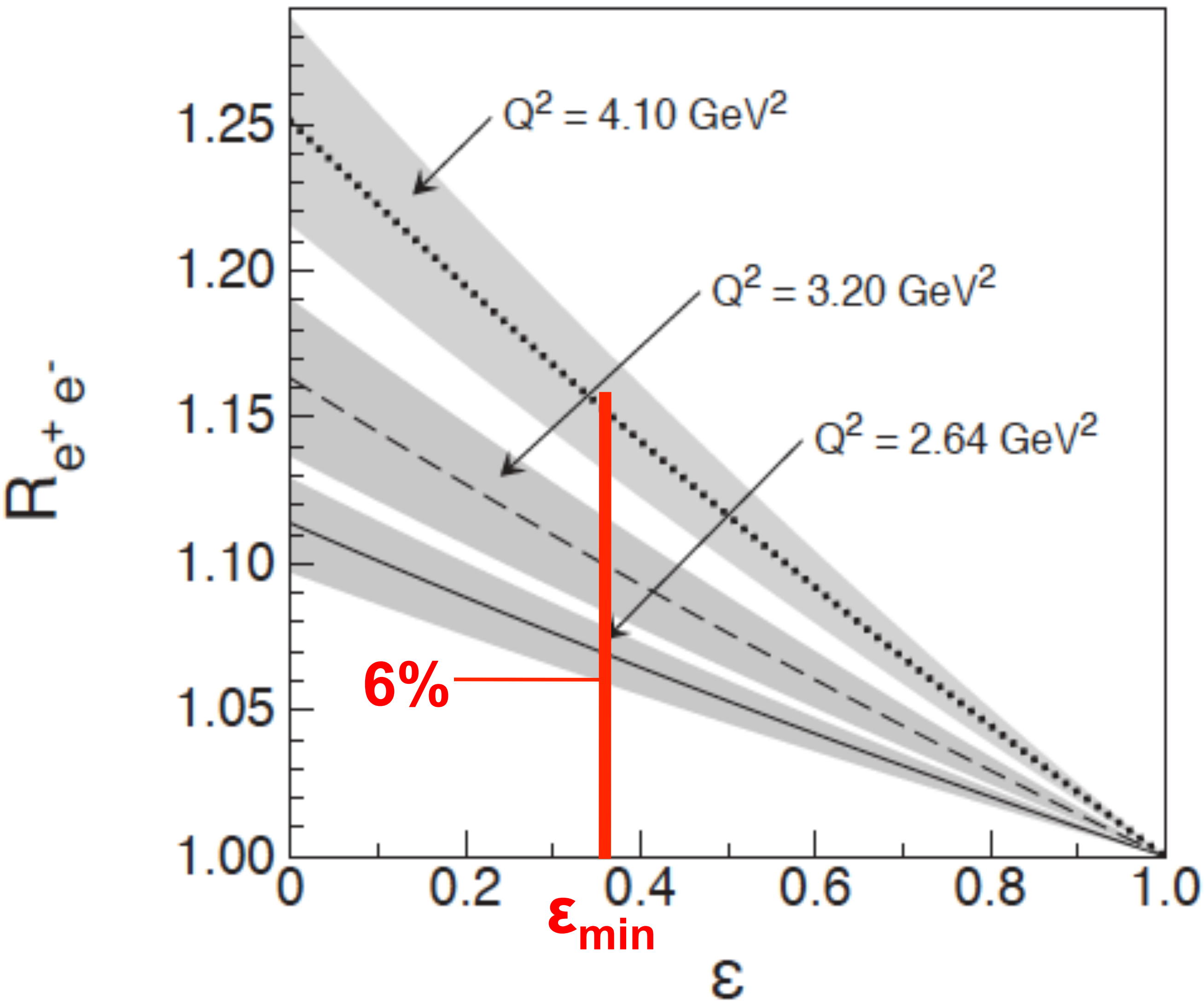
$$\sigma_{e^\pm p} = |\mathcal{M}_{1\gamma}|^2 \pm 2\Re\{\mathcal{M}_{1\gamma}^\dagger \mathcal{M}_{2\gamma}\} + \cdots$$

- **e^+/e^- ratio deviates from unity by two-photon contribution**

$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx 1 + 4\frac{\Re\{\mathcal{M}_{1\gamma}^\dagger \mathcal{M}_{2\gamma}\}}{|\mathcal{M}_{1\gamma}|^2}$$

Empirical extraction of TPE amplitudes

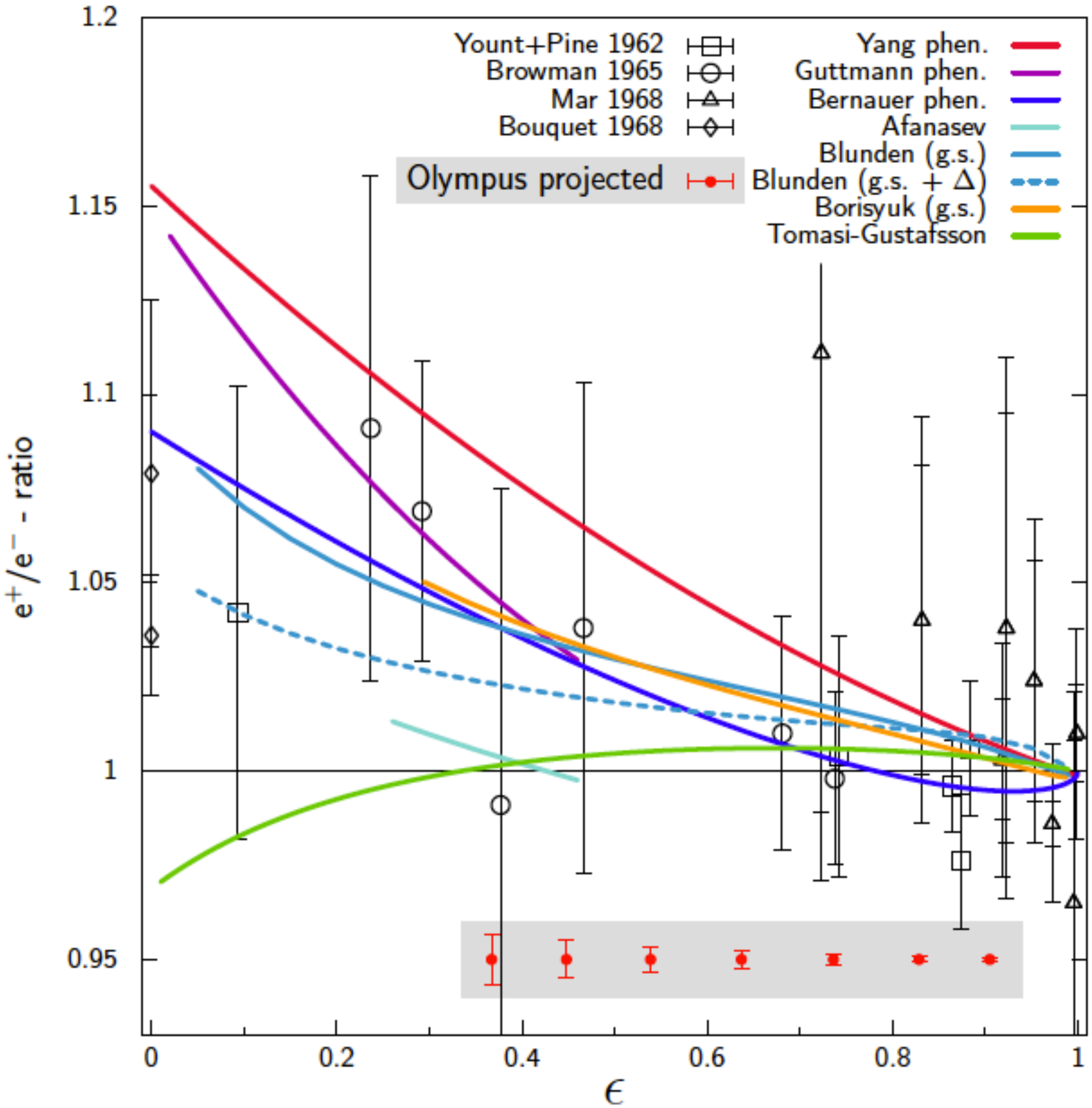
J. Guttmann, N. Kivel, M. Meziane, and M. Vanderhaeghen, EPJA 47 (2011) 77



grows with Q^2!

Expect ~6% effect for OLYMPUS@2.0GeV Q^2 ~ 2.2 $(GeV/c)^2$

Projected results for OLYMPUS



OLYMPUS

Data from 1960's

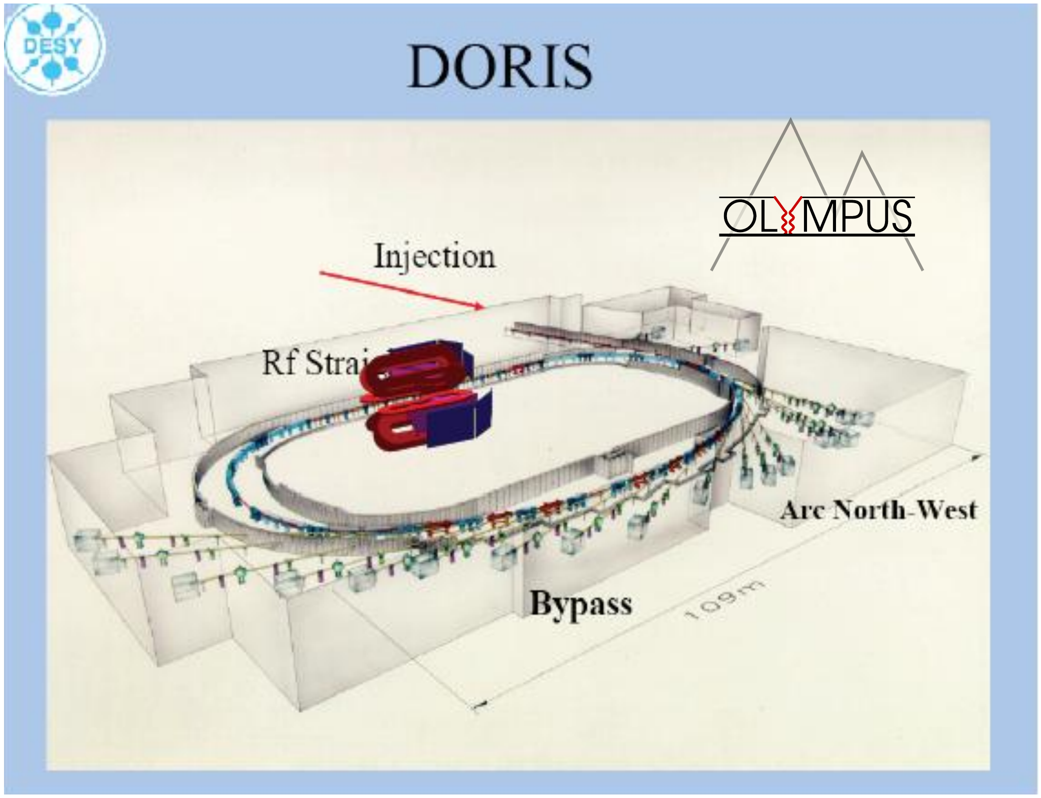
Many theoretical predictions with little constraint

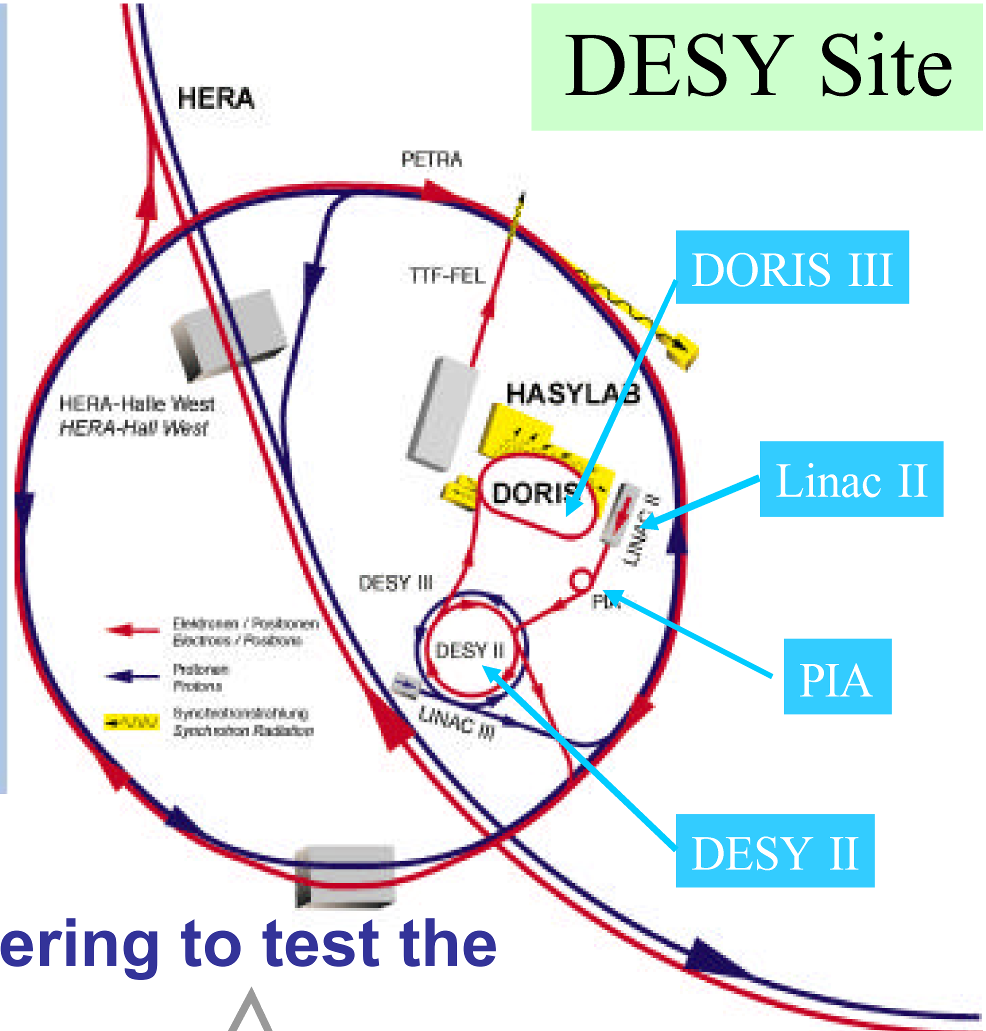
OLYMPUS:

- **E= 2.0 GeV**
- **$0.4 < Q^2/(GeV/c)^2 < 2.2$**
- **Acquire 3.6 fb^{-1} for <1% projected uncertainties**

Data taking completed in 2012

OLYMPUS @ DORIS/DESY





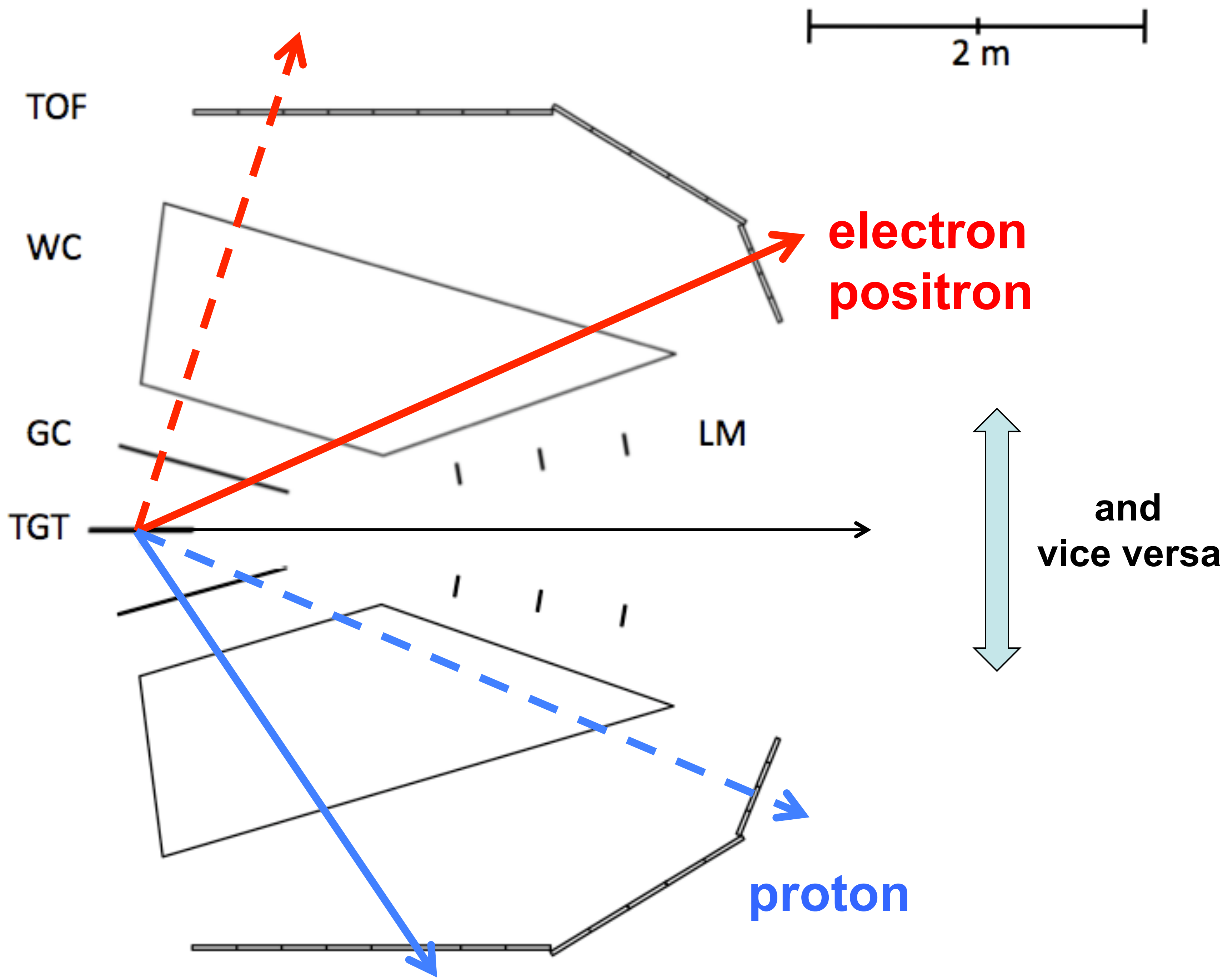
pOsitron-proton and
eLectron-proton elastic scattering to test the
hYpothesis of
Multi-
Photon exchange
Using
DoriS

The OLYMPUS experiment

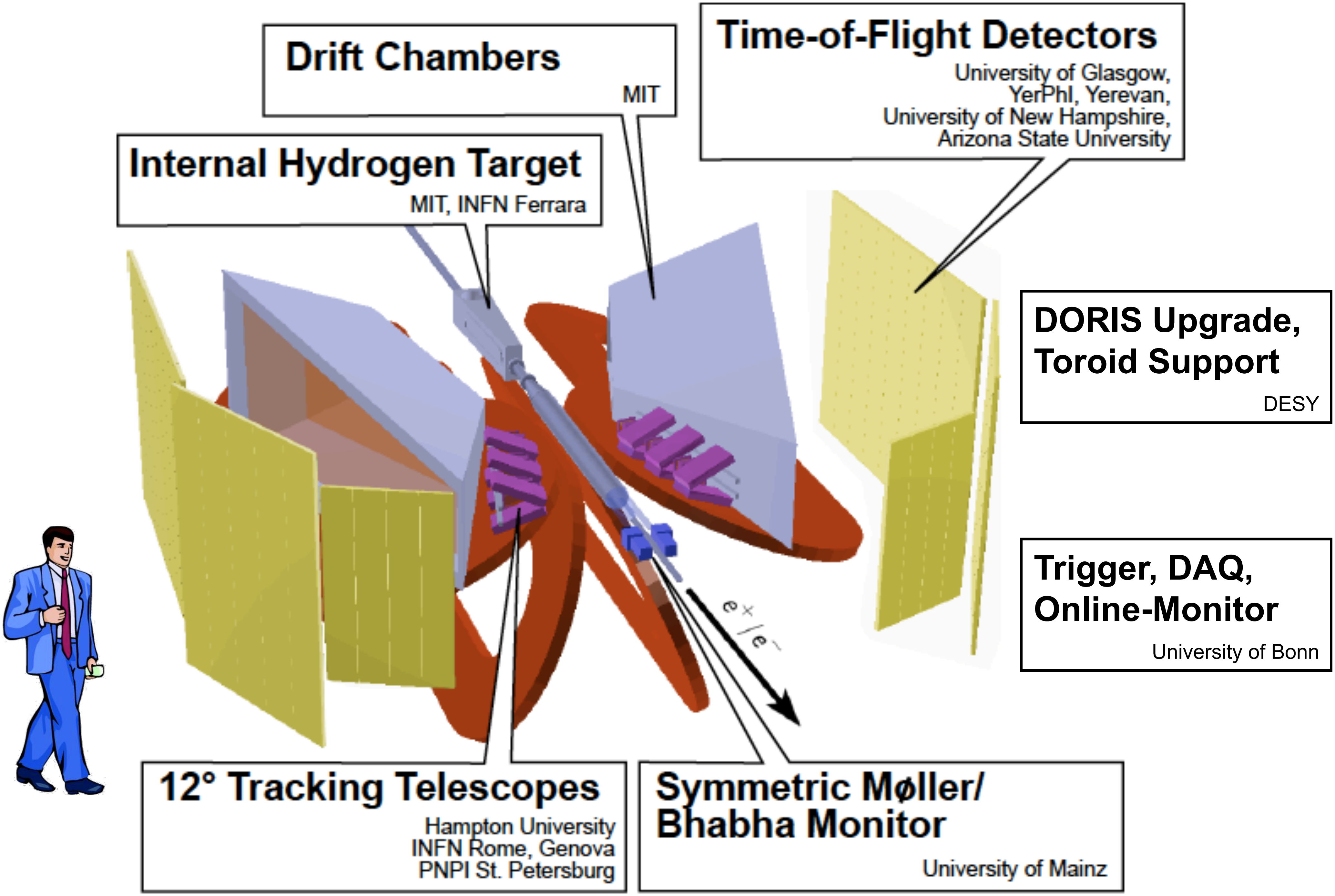
- Electrons/positrons (100mA) in 2.0–4.5 GeV storage ring
  DORIS at DESY, Hamburg, Germany
- Unpolarized internal hydrogen target (buffer system)
  $3x10^{15}$ at/cm^2 @ 100 mA → L = $2x10^{33}$ / (cm^{2}s)
- Large acceptance detector for e-p in coincidence
  BLAST detector from MIT-Bates available
- Redundant monitoring of luminosity
  Pressure, temperature, flow, current measurements
  Small-angle elastic scattering at high epsilon / low Q^2
  Symmetric Moller/Bhabha scattering

- Measure ratio of positron-proton to electron-proton unpolarized elastic scattering to 1% stat.+sys.

OLYMPUS kinematics at 2.0 GeV

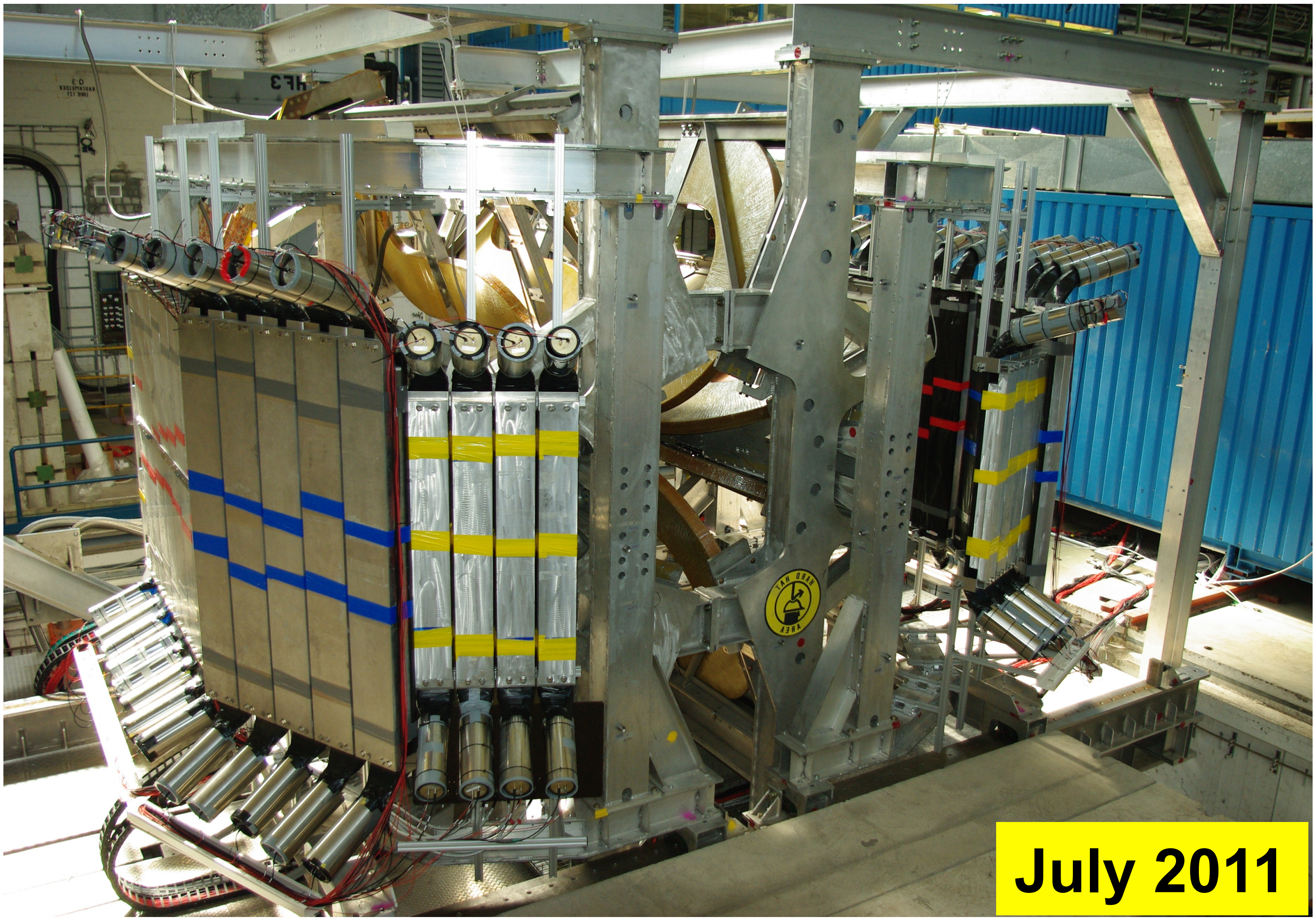


The designed OLYMPUS detector

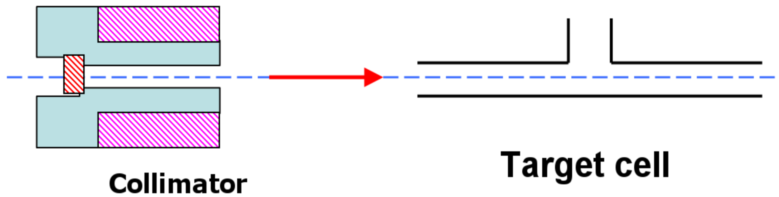


based on a figure by R. Russell

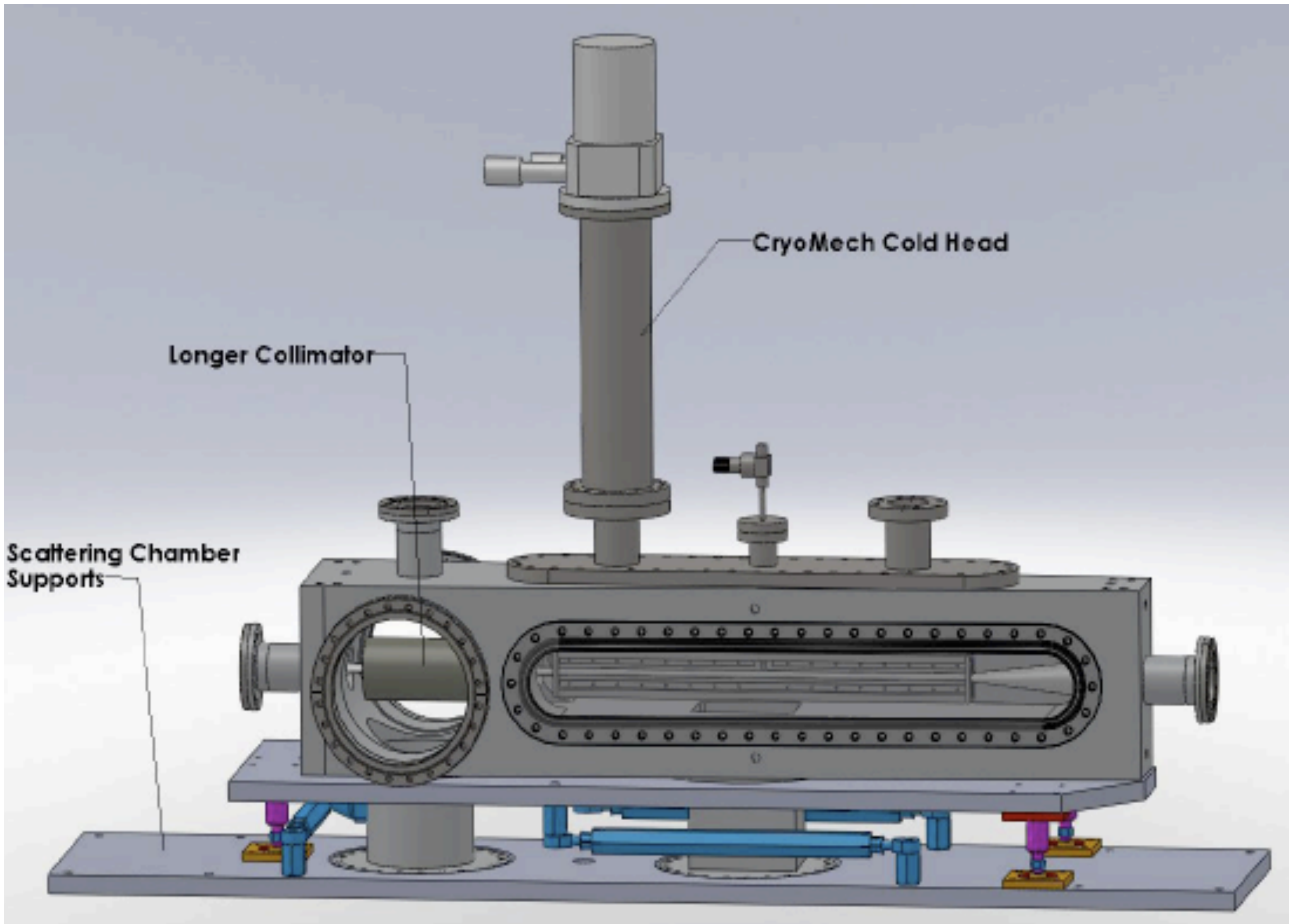
The realized OLYMPUS detector

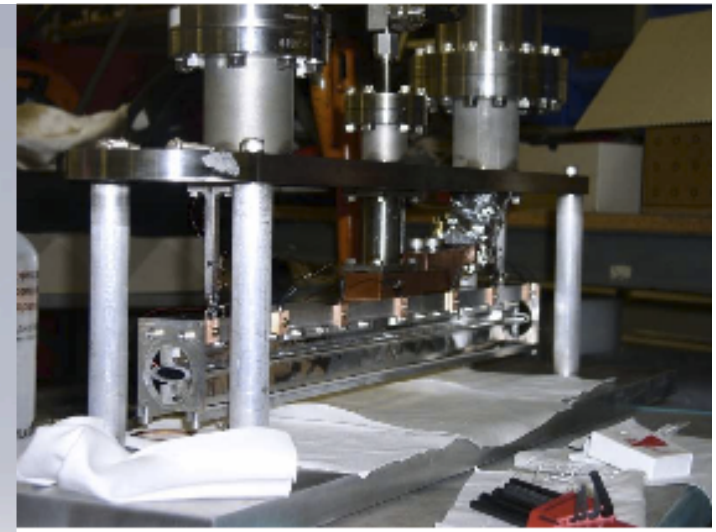


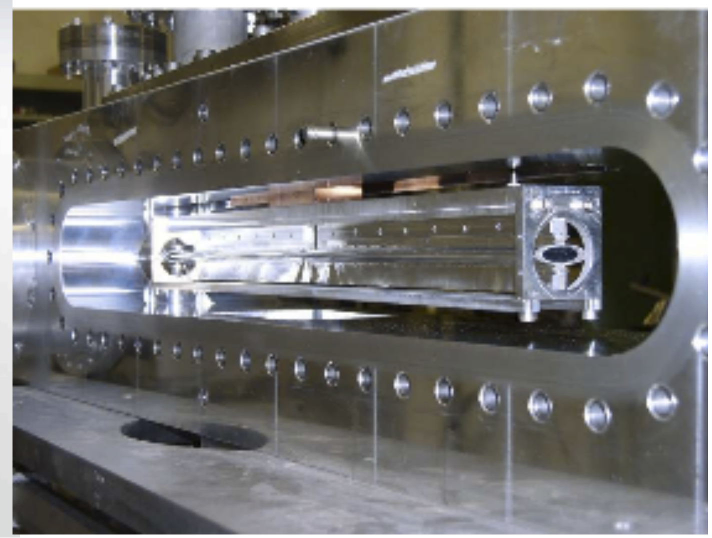
Target and vacuum system



MIT
INFN Ferrara



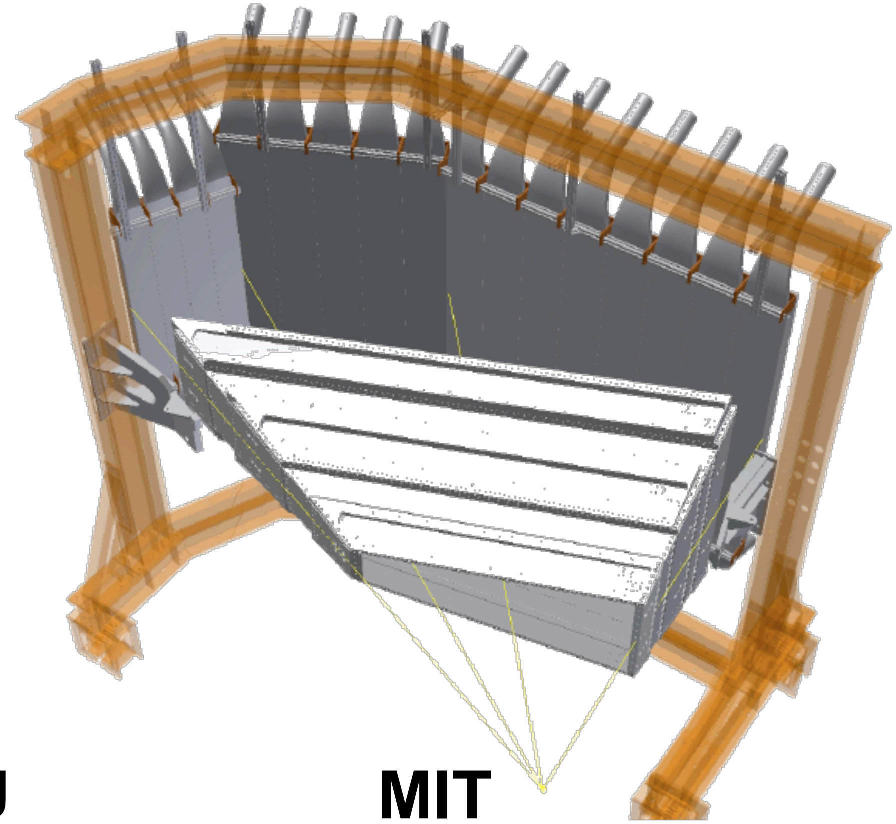




Designed and built in 2010
Very stable operation after repairs

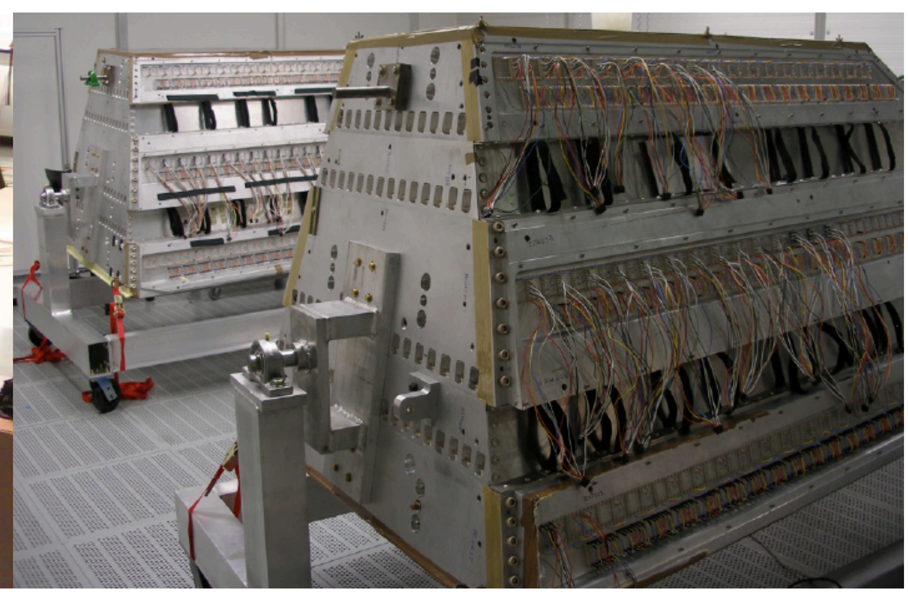
Wire chambers and TOF scintillators

- 2x18 TOFs for PID, timing and trigger
- 2 WCs for PID and tracking (z,θ,φ,p)
- WC and TOF refurbished from BLAST
  WC re-wired at DESY
  TOF rewrapped, efficiency tested
- Installed in OLYMPUS Apr-May 2011
- Stable operation



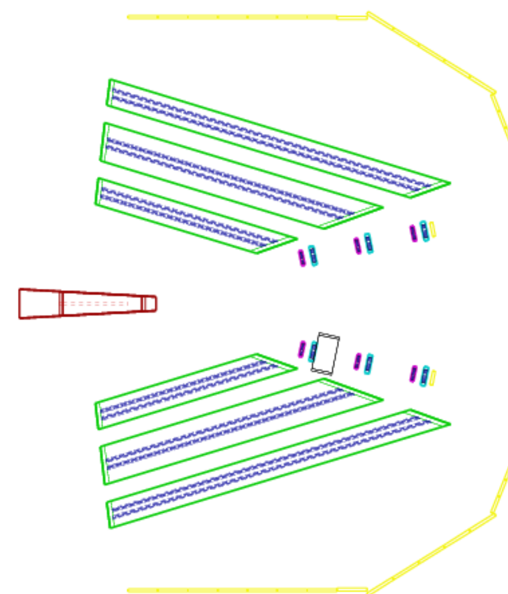
Glasgow, Yerevan, UNH, ASU

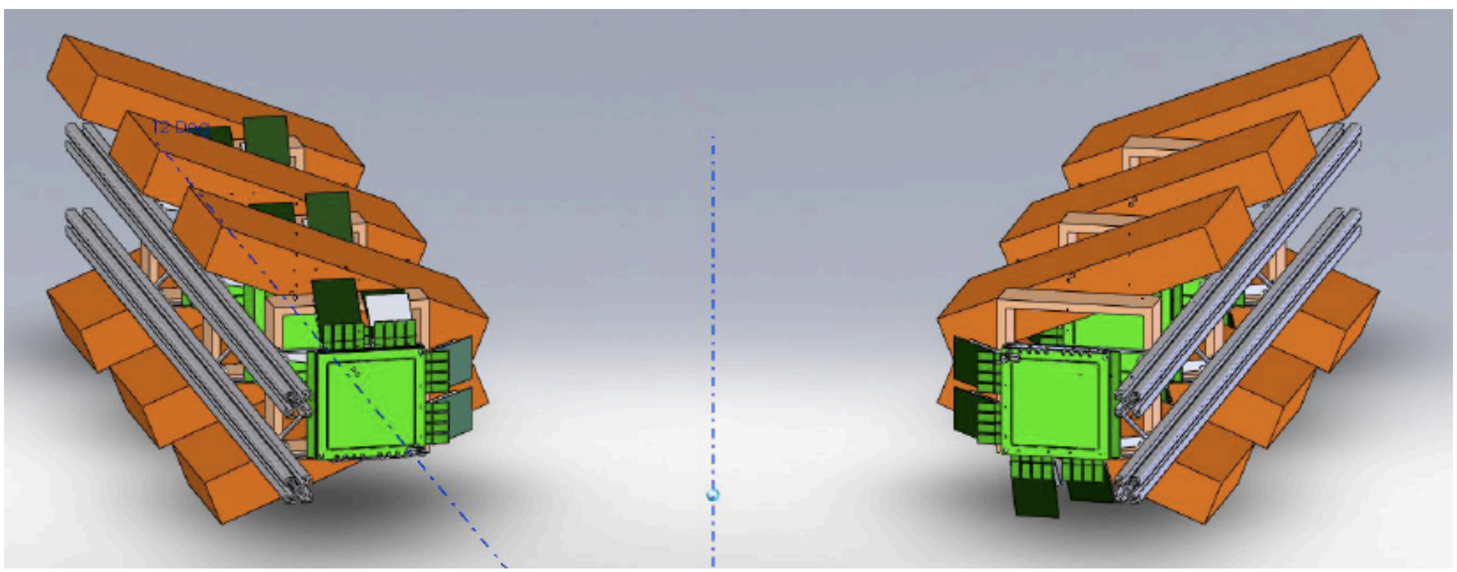
MIT



Luminosity monitors: GEM + MWPC

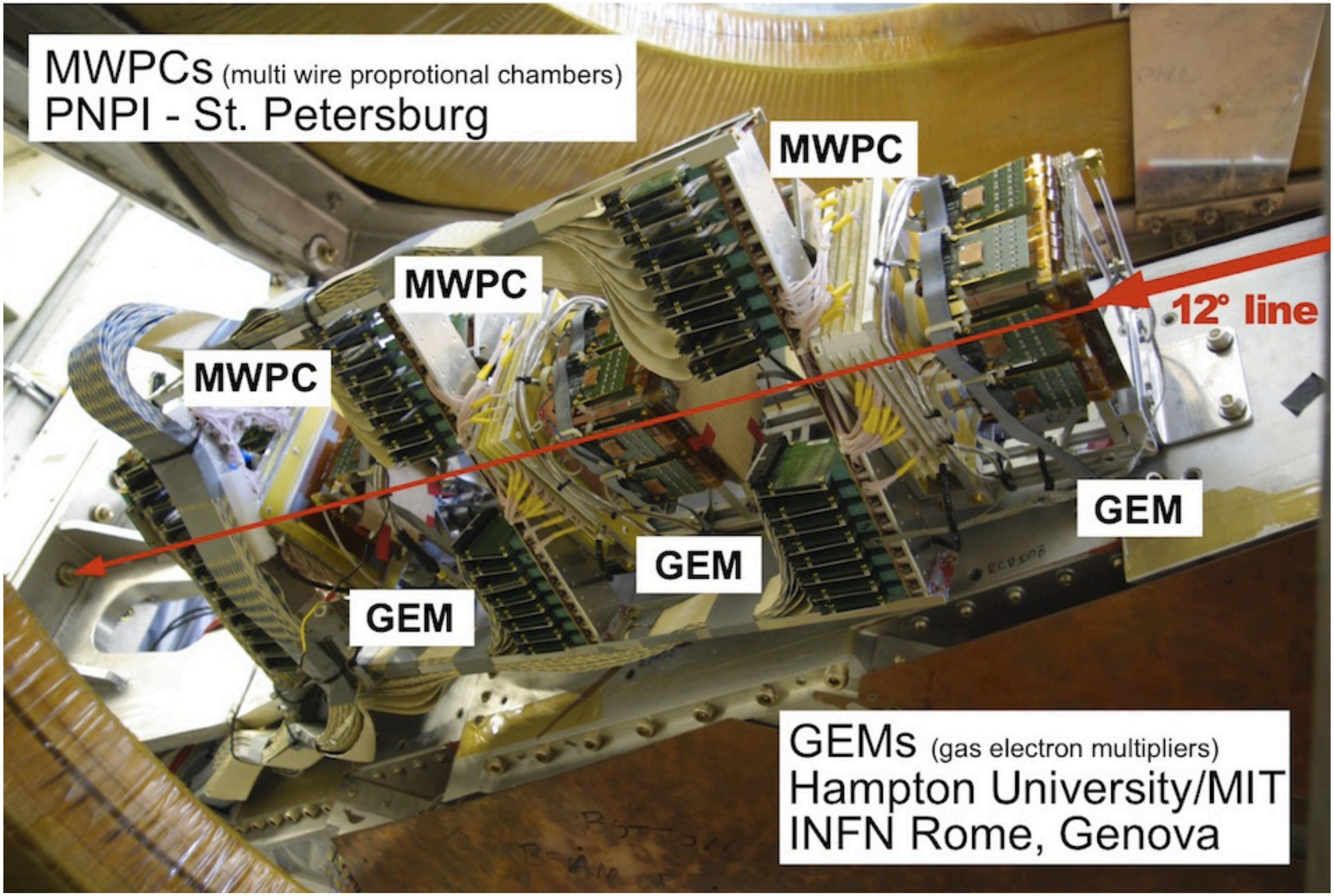
- Forward elastic scattering of lepton at 12°
  in coincidence with proton in main detector
- Two GEM + MWPC telescopes with
  interleaved elements operated independently
- SiPM scintillators for triggering and timing
- Sub-percent (relative) luminosity measurement
  per hour at 2.0 GeV
- High redundancy – alignment, efficiency
  Two independent groups (Hampton/INFN, PNPI)





Designed to fit into forward cone

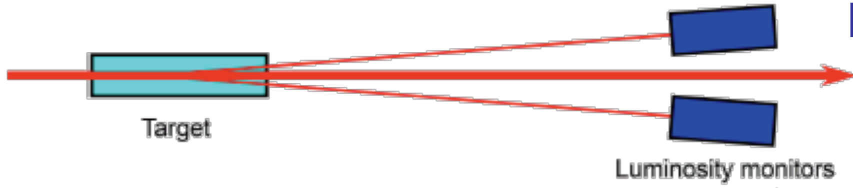
Luminosity monitors: GEM + MWPC



O. Ates
J. Diefenbach

Telescopes of three GEMs and MWPCs interleaved
Mounted on wire chamber forward end plate
Extensively tested at DESY test beam facility

Symmetric Møller/Bhabha monitor

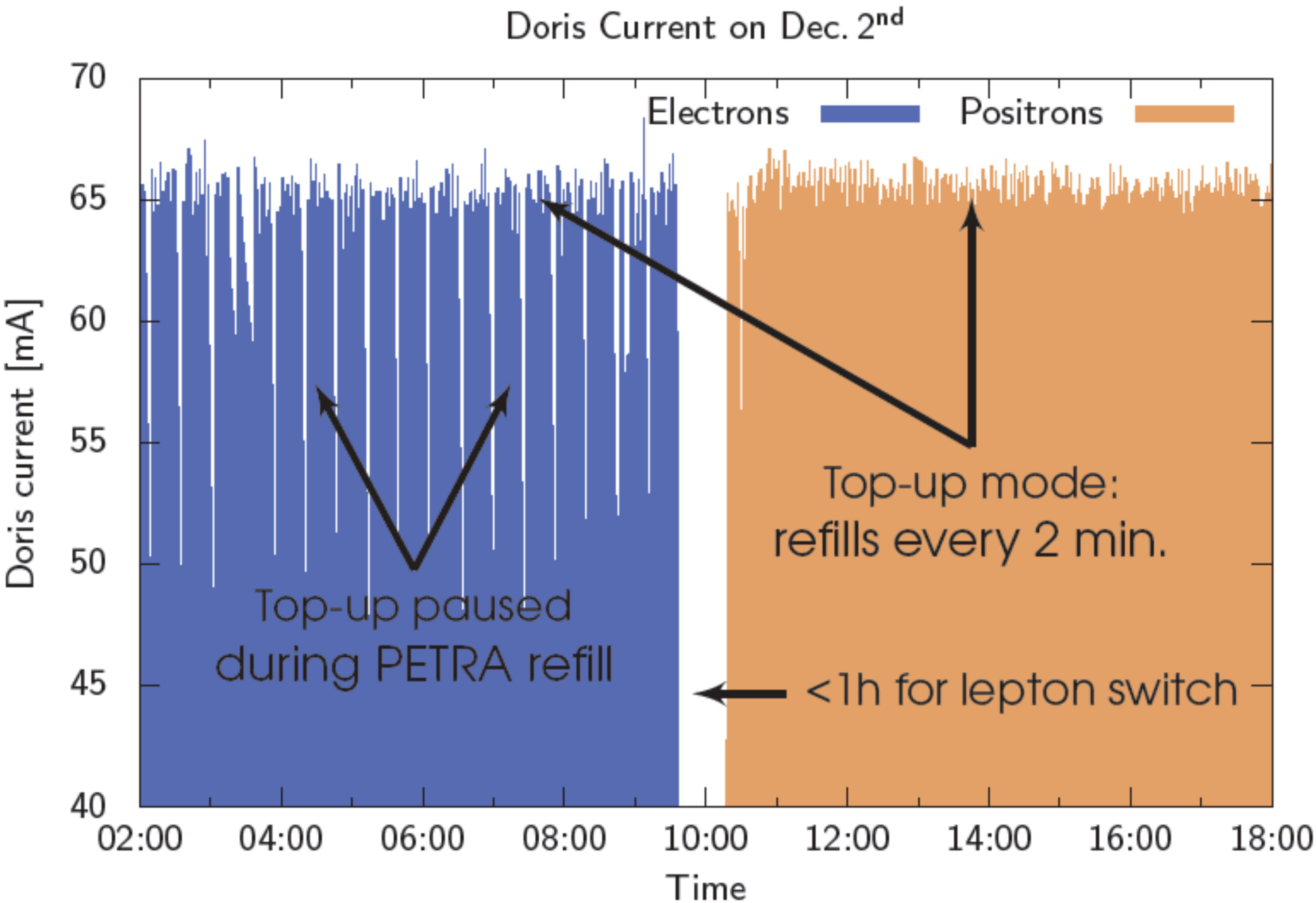


Mainz University

- Symm. angle 1.3° @ 2.0 GeV
- Matrix of 3x3 PbF_2 crystals
- Tested at DESY and MAMI

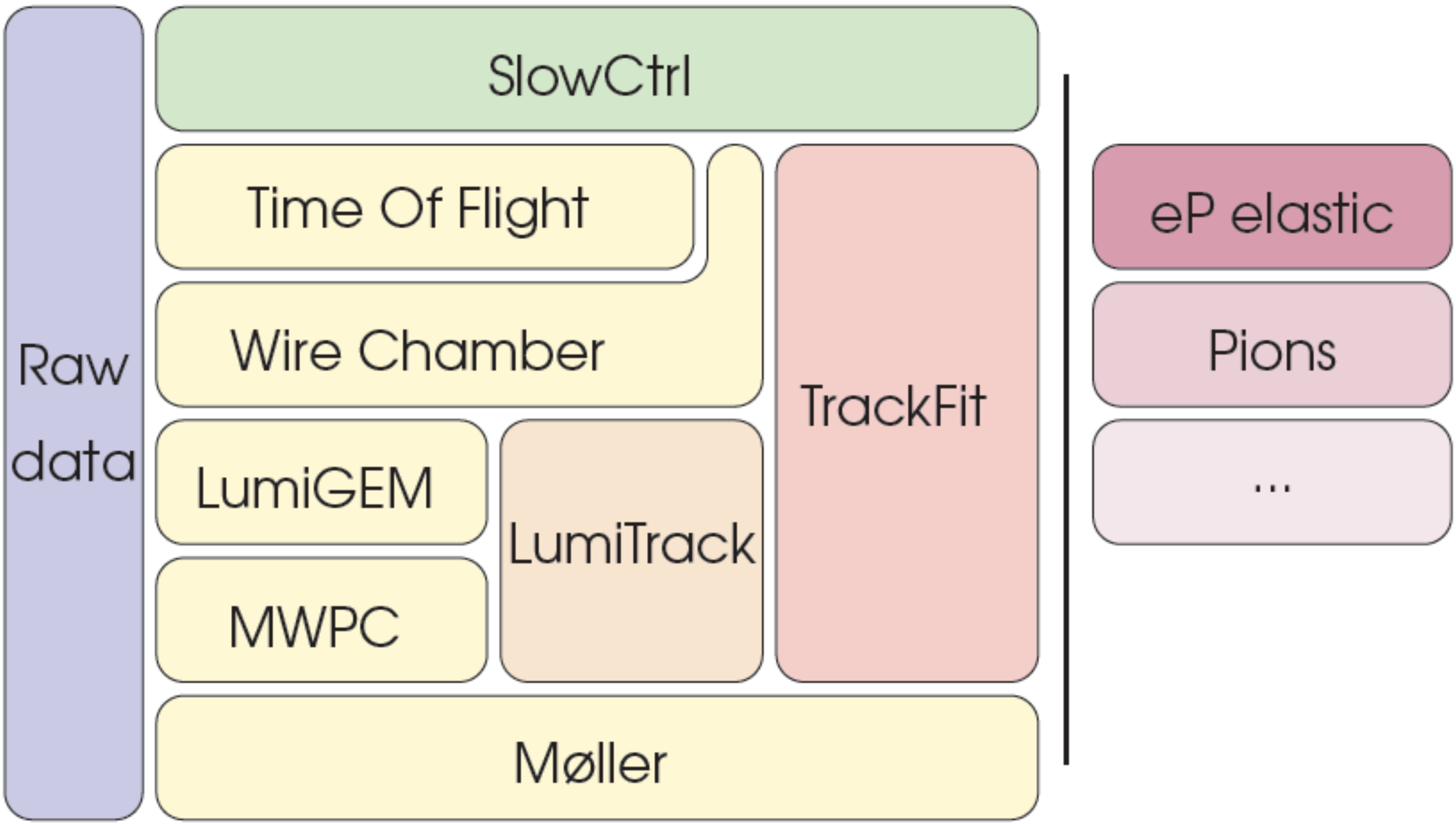
Performance of DORIS

- DORIS top-up mode established
- Typically 65mA / 0.5 sccm
- Refills every ~2 minutes by few mA
- PETRA refills every 30 minutes

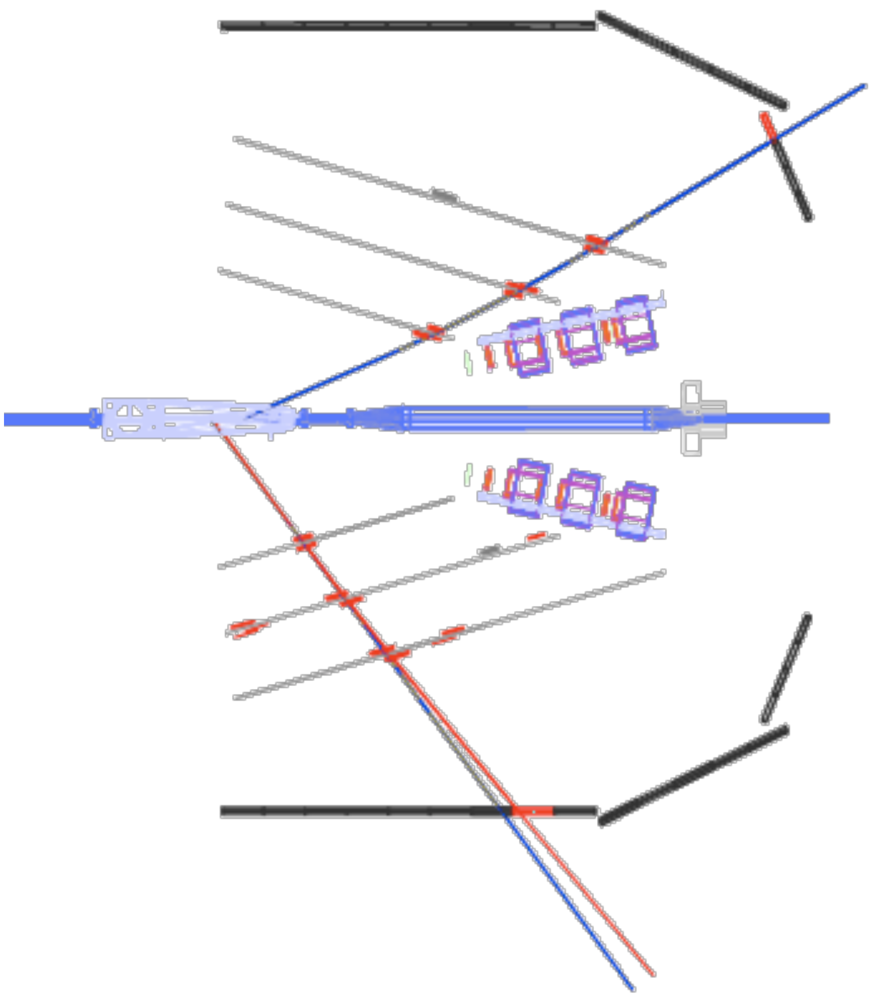


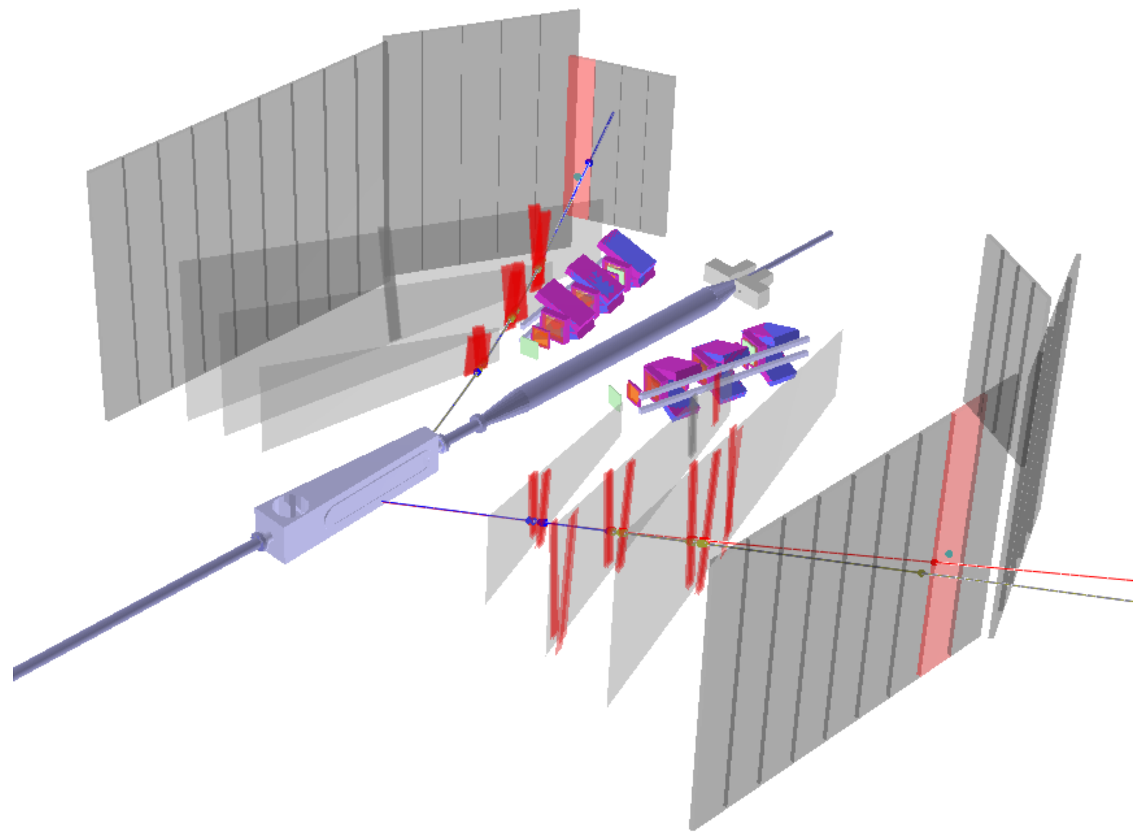
Analysis framework

ROOT based C++ analysis framework ("cooker")
with plug-ins and recipes (J. Bernauer)
and full MC integration



Event display (3D)

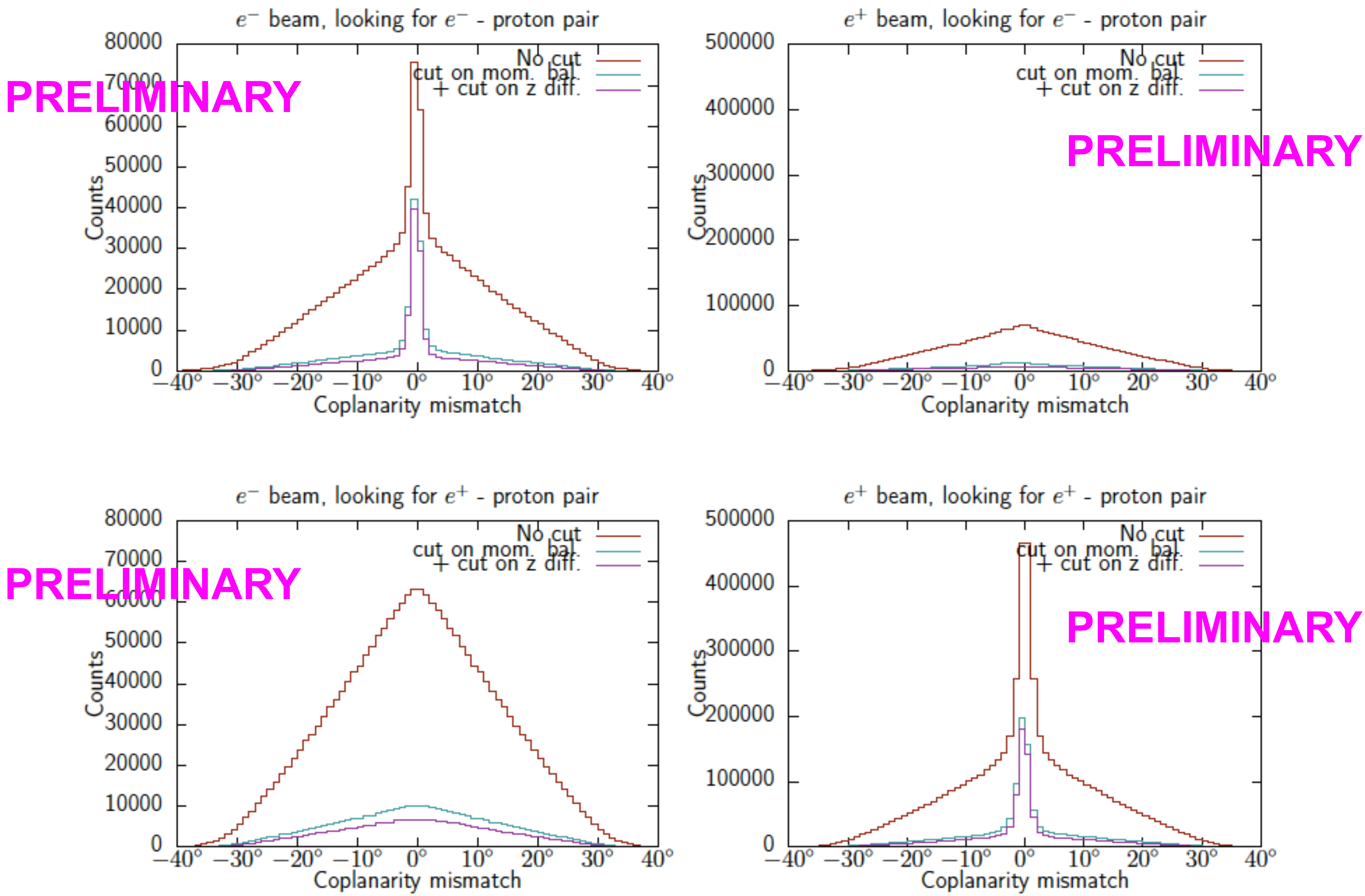




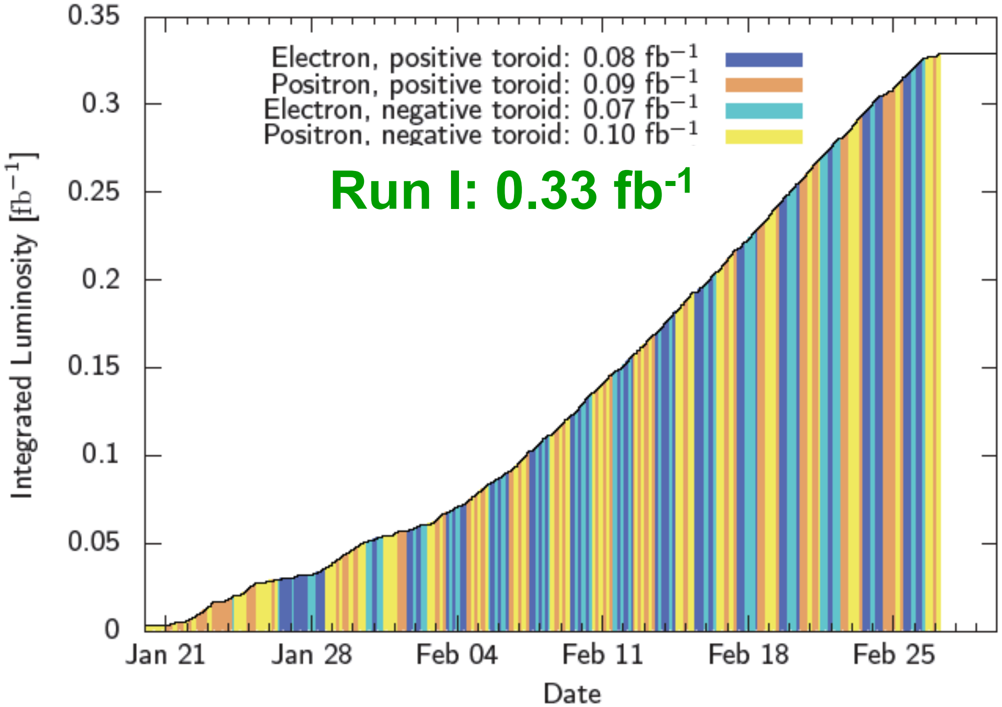
Run 4975, event 78

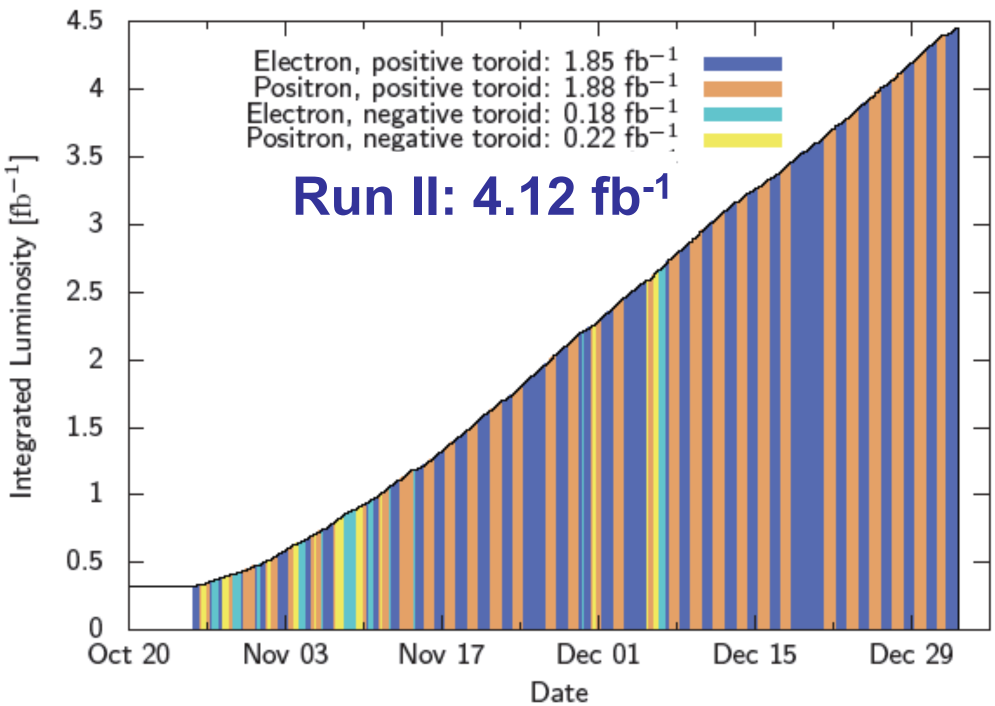
Very preliminary …

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



Timeline of OLYMPUS





- 2007 Letter of Intent
- 2008 Proposal
- 2009 Technical review
- 2010 Approval and funding
- Summer 2010 BLAST transfer
- Spring 2011 Target test run
- Summer 2011 Detector installed
- Fall 2011 Commissioning

First run Jan 30 – Feb 27, 2012
… acquired < 0.3 fb-1

- Summer 2012 Repairs and upgrades

Second run Oct 24, 2012 – Jan 2, 2013
… acquired > 4.0 fb-1

- Spring 2013 Survey & field mapping
- Smooth performance of machine, target, detector
- **Analysis underway**

OLYMPUS collaboration

OLYMPUS

~50 physicists from 13 institutions in 6 countries

Elected spokesmen / deputy:	**R. Milner / R. Beck**	**(2009–2011)**
	M.K. / A. Winnebeck	**(2011–2013)**
	D. Hasell / U. Schneekloth	**(2013–)**

- **Arizona State University:** TOF support, particle identification, magnetic shielding
- **DESY:** Modifications to DORIS accelerator and beamline, toroid support, infrastructure, installation
- **Hampton University:** GEM luminosity monitor
- **INFN Bari:** GEM electronics
- **INFN Ferrara:** Target
- **INFN Rome:** GEM electronics
- **MIT:** BLAST spectrometer, wire chambers, tracking upgrade, target and vacuum system, transportation to DESY, simulations, slow control, analysis framework
- **Petersburg Nuclear Physics Institute:** MWPC luminosity monitor
- **University of Bonn:** Trigger, data acquisition, and online monitor
- **University of Mainz:** Trigger, DAQ, Symmetric Moller monitor
- **University of Glasgow**: TOF scintillators
- **University of New Hampshire:** TOF scintillators
- **A. Alikhanyan National Laboratory (AANL), Yerevan:** TOF scintillators

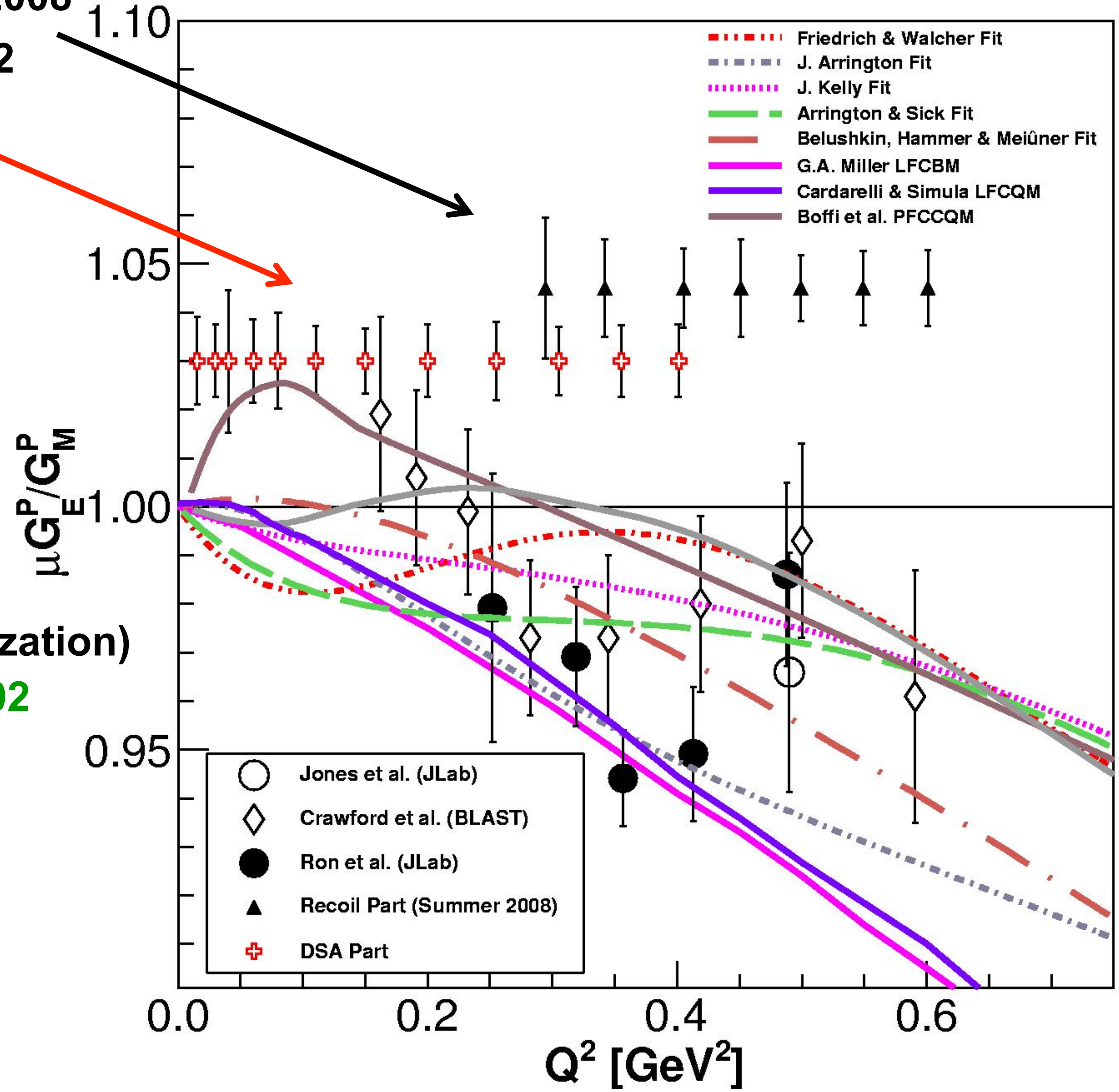
New proton measurements at low Q^2

Hall A PR07-004, PR08-007 (PAC31/33)

- **Recoil polarization, completed 2008**
- **Polarized target, completed 2012**

◇ **BLAST (polarized target)**
C. Crawford et al., PRL98 (2007) 052301

● **LEDEX PR05-004 (recoil polarization)**
G. Ron et al., PRL99 (2007) 202002



New proton measurements at low Q^2

Hall A PR07-004, PR08-007 (PAC31/33)

- **Recoil polarization, completed 2008**
- **Polarized target, completed 2012**

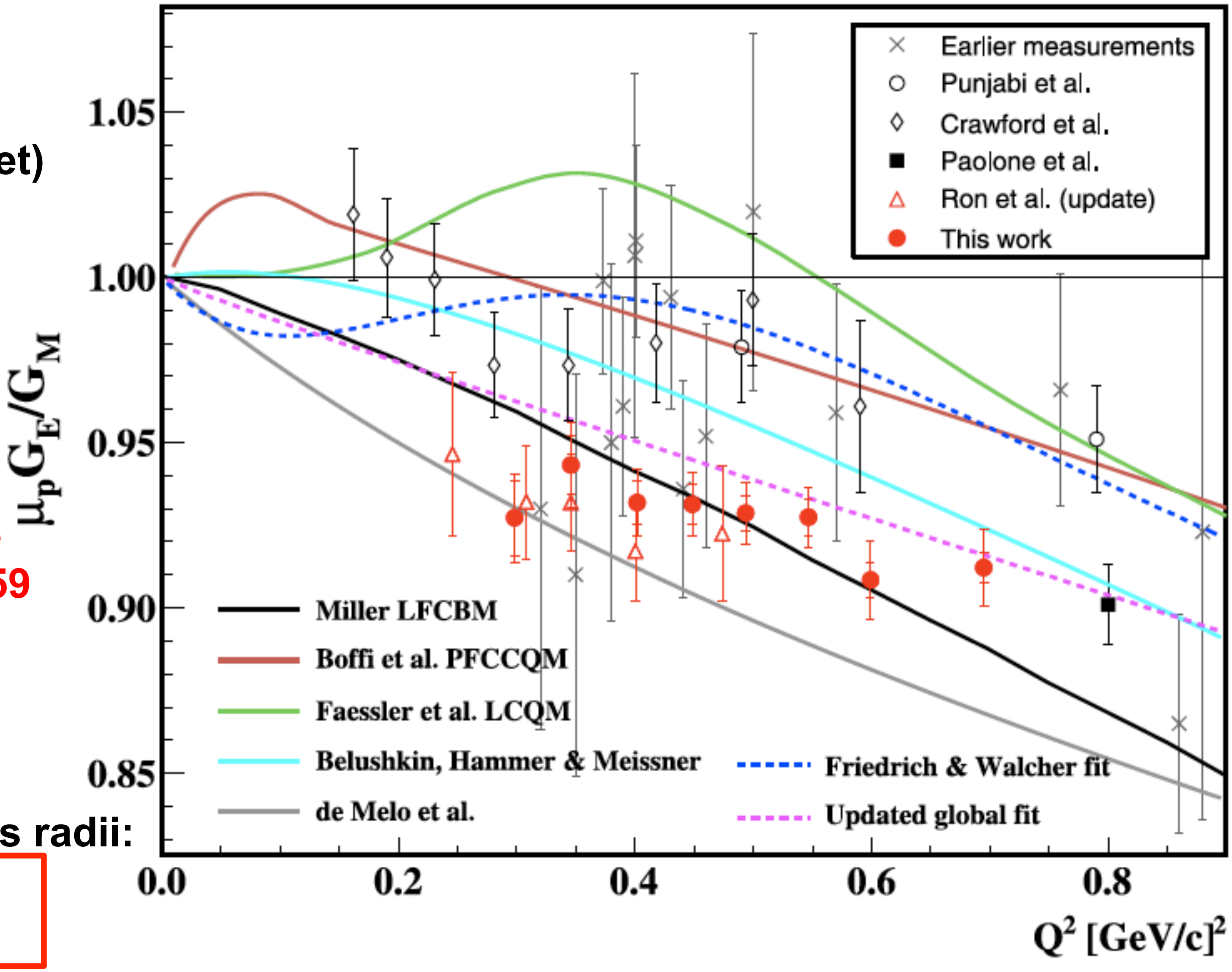
◇ **BLAST (polarized target)**
C. Crawford et al., PRL98 (2007) 052301

X. Zhan,
E08-007 + LEDEX update
Phys. Lett. B 705 (2011) 59

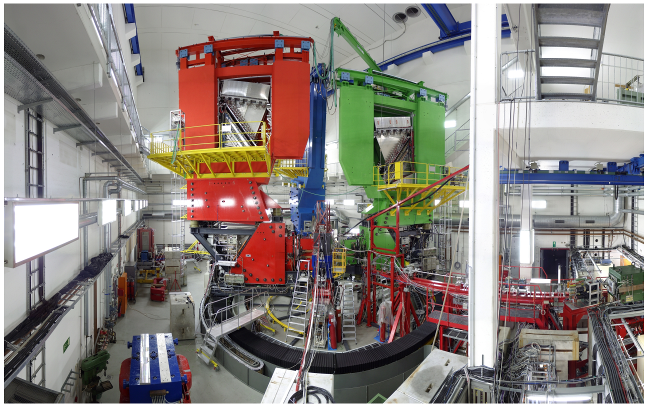
2-sigma difference lower than BLAST

Charge and magnetic rms radii:

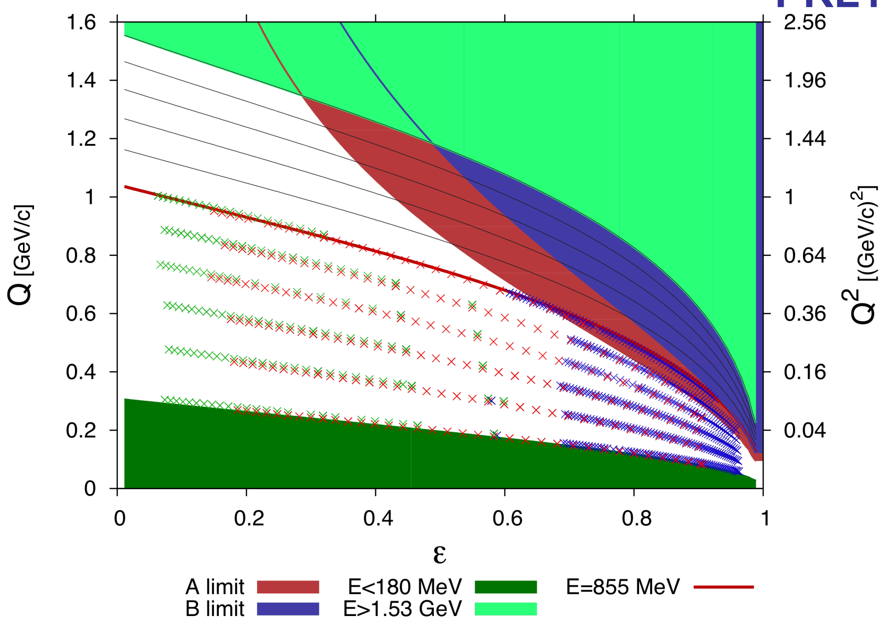
$R_E = 0.875 \pm 0.010$ fm
$R_M = 0.867 \pm 0.020$ fm



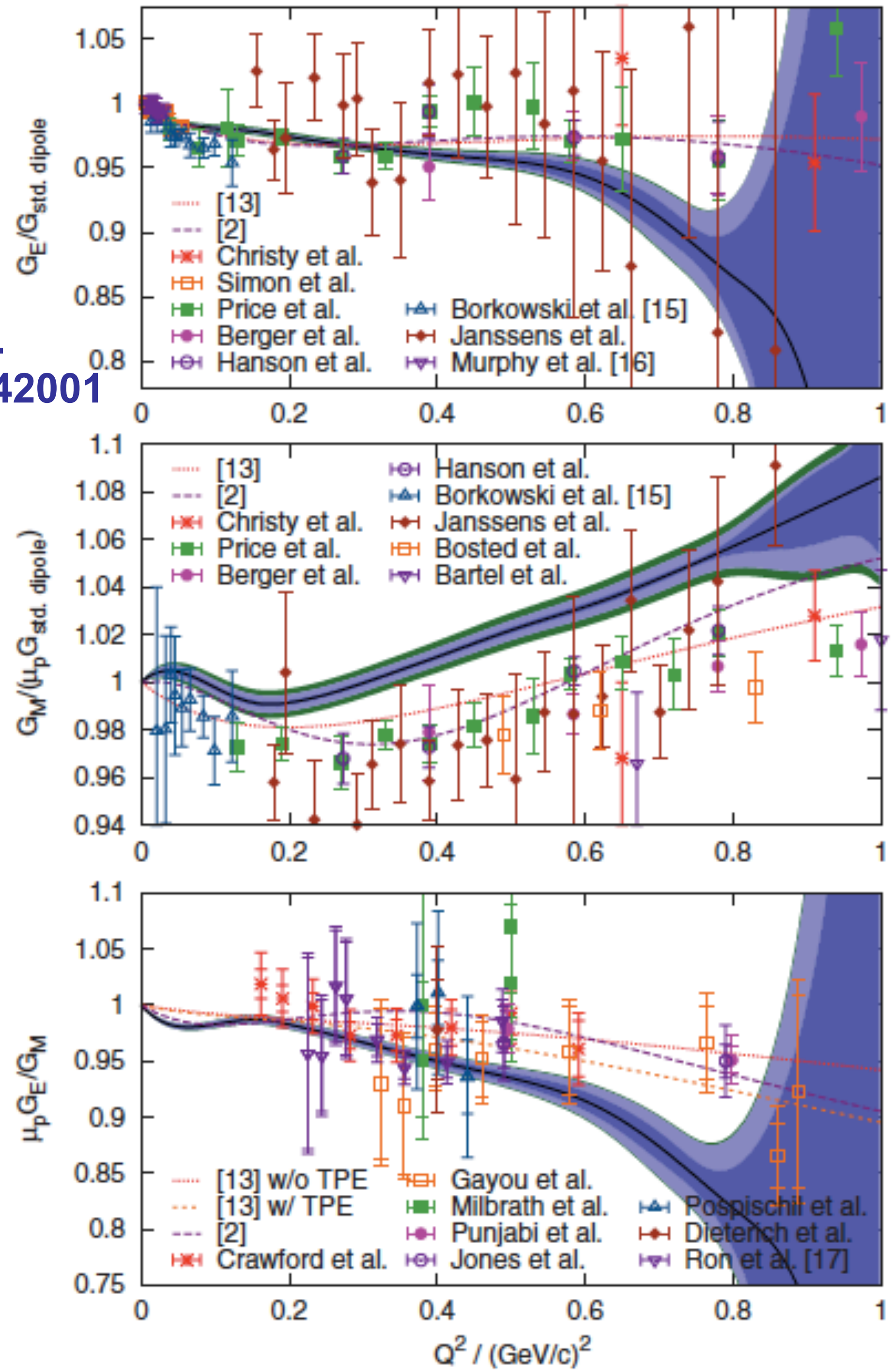
New proton measurements at low Q^2



MAMI A1



J. Bernauer et al.
PRL105 (2010) 242001



Rosenbluth separation at low Q^2
Precise charge and magnetic rms radii:

R_E = 0.879 ± 0.008 fm
R_M = 0.777± 0.017 fm

PSI muonic hydrogen measurements

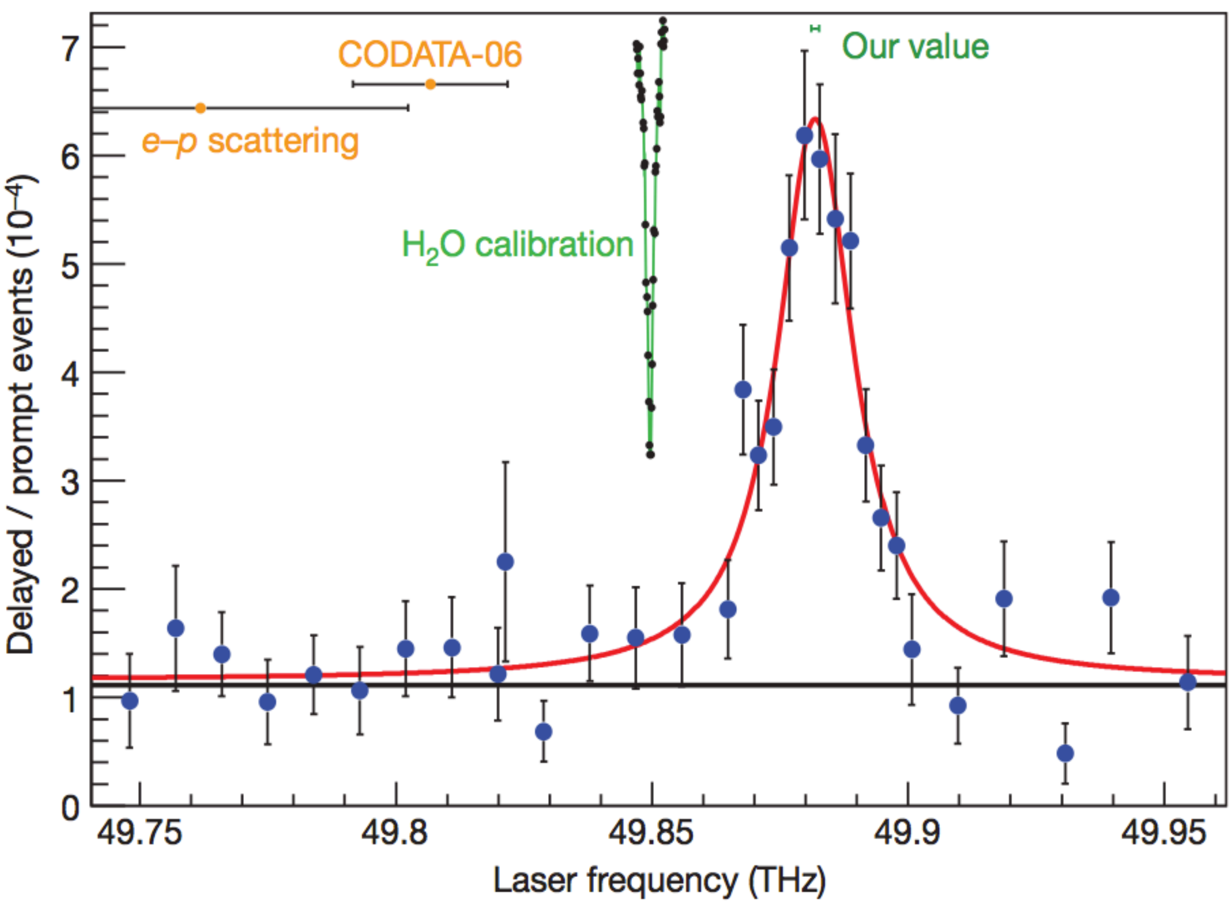
- R. Pohl et al., Nature 466, 09259 (2010): 2S➪2P Lamb shift

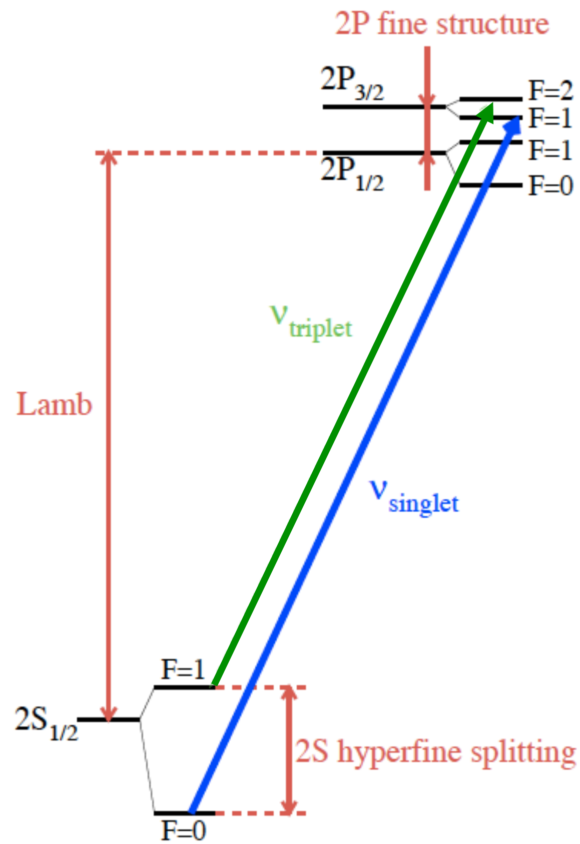
  $\Delta E(meV) = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3$ ➪ $r_p = 0.84184 \pm 0.00067$ fm

  Possible issues: atomic theory & proton structure

- UPDATE: A. Antognini et al., Science 339, 417 (2013): 2S➪2P Lamb + 2S-HFS

  $\Delta E_L(meV) = 206.0336(15) - 5.2275(10) r_p^2 + 0.0332(20)_{TPE}$ ➪ $r_p = 0.84087 \pm 0.00039$ fm



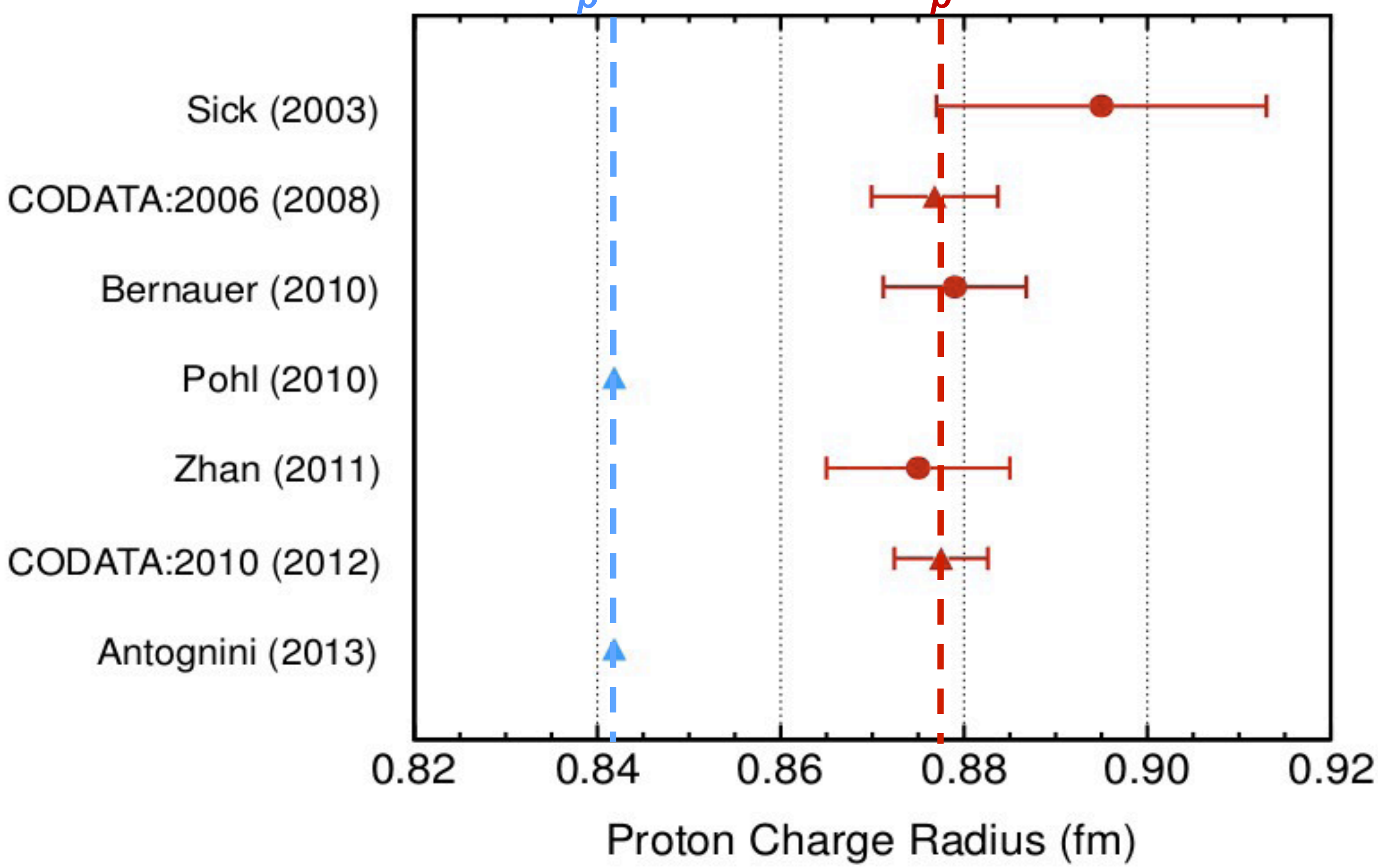


The proton radius puzzle

- >7σ discrepancy between **muonic** and **electronic** measurements
- High-profile articles in Nature, NYTimes, etc.
- Puzzle unresolved, possibly New Physics

Muonic R_p = 0.84 fm

Electronic R_p = 0.88 fm



▲ Spectroscopy

● Scattering

R_P = 0.84184(67) fm

R_P = 0.875(10) fm

R_P = 0.8775(51) fm

R_P = 0.84087(39) fm

The proton radius puzzle in the media

R. Pohl et al., Nature 466, 09259 (2010)

The proton radius puzzle in the media

July 2010

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The New York Times

Space & Cosmos

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS | OPINION

ENVIRONMENT | **SPACE & COSMOS**

For a Proton, a Little Off the Top (or Side) Could Be Big Trouble

By DENNIS OVERBYE
Published: July 12, 2010

RECOMMEND
TWITTER
LINKEDIN
E-MAIL
PRINT
REPRINTS
SHARE

For most of us, 4 percent off around the waist — a couple of belt notches — would be a great triumph.

Enlarge This Image

Chris Gash

Not so for the proton, the subatomic particle that anchors atoms and is the building block of all ordinary matter, of stars, planets and people. Physicists announced last week that a new experiment had shown that the proton is about 4 percent smaller than they thought.

Instead of celebration, however, the result has caused consternation. Such a big discrepancy, say the physicists, led by Randolf Pohl of the Max Planck Institute for Quantum Optics in Garching, Germany, could mean that the most accurate theory in the history of physics, quantum electrodynamics, which describes how light and matter interact, is in trouble.

"What you have is a result that actually shocked us," said Paul Rabinowitz, a chemist from Princeton University, who was a member of Dr. Pohl's team.

January 2013

ars technica

SCIENTIFIC METHOD / SCIENCE & EXPLORATION

Hydrogen made with muons reveals proton size conundrum

A measurement that's off by 7 standard deviations may hint at new physics.

by John Timmer - Jan 24 2013, 2:01pm EST

PHYSICAL SCIENCES 102

The proton accelerator at the Paul Scherrer Institute, which was used to create the muons used in this experiment.
Paul Scherrer Institute

Proton Mass Mystery Could Mean New Physics

APR 15, 2013 08:35 PM ET // BY STEPHANIE PAPPAS, LIVESCIENCE

The proton radius puzzle in the media

April 2013

The proton radius puzzle in the media

July 2013

The proton radius puzzle in the media

January 2014

Possible resolutions to the puzzle

- **The ep (scattering) results are wrong**
  Fit procedures not good enough
  Q^2 not low enough, structures in the form factors
- **The ep (spectroscopy) results are wrong**
  Accuracy of individual Lamb shift measurements?
  Rydberg constant could be off by 5 sigma
- **The μp (spectroscopy) result is wrong**
  Discussion about theory and proton structure for extracting the proton radius from muonic Lamb shift measurement
- **Proton structure issues in theory**
  Off-shell proton in two-photon exchange leading to enhanced effects differing between μ and e
  Hadronic effects different for μp and ep:
  e.g. proton polarizability (*effect* $\propto m_l^4$)
- **Physics beyond Standard Model differentiating μ and e**
  Lepton universality violation, light massive gauge boson
  Constraints on new physics from kaon decays

New measurements are on their way

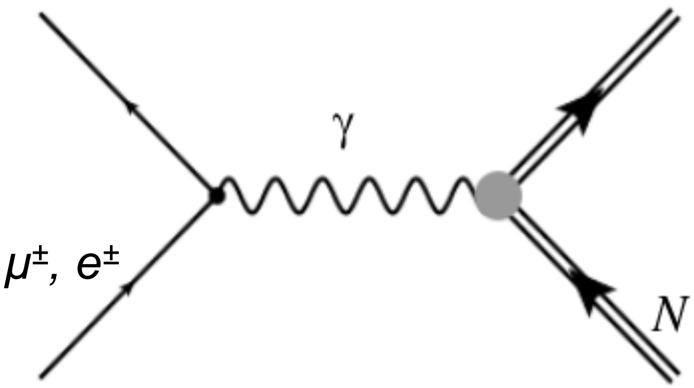
- **Additional measurements needed / in preparation**
  - Spectroscopy with μD, μHe, and regular H; Rydberg constant
  - ep-, ed-scattering
    (PRad at Jlab, ISR-ep and ed elastic at MAMI; MESA)
  - $\mu^{\pm}$p- and $e^{\pm}$p-scattering in direct comparison at PSI (MUSE)
  - Searches for lepton universality violating light bosons
    (e.g kaon decay such as TREK/E36 at J-PARC)

r_p (fm)	ep	μp
Spectroscopy	**0.8758 ± 0.077**	**0.84087 ± 0.00039**
Scattering	**0.8770 ± 0.060**	**???**

Need more precision for extraction from scattering
More insights from comparison of ep and μp scattering

Lepton scattering and charge radius

Lepton scattering from a nucleon:



Vertex currents:

$$J_e^\mu = -e\bar{u}_e\gamma^\mu u_e$$

$$J_N^\mu = \bar{\psi}_N\left[F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M_N}\right]\psi_N$$

F_1, F_2 are the Dirac and Pauli form factors

Sachs form factors:

$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \tau F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + F_2(Q^2) \end{aligned}$$

Fourier transform (in the Breit frame) gives spatial charge and magnetization distributions

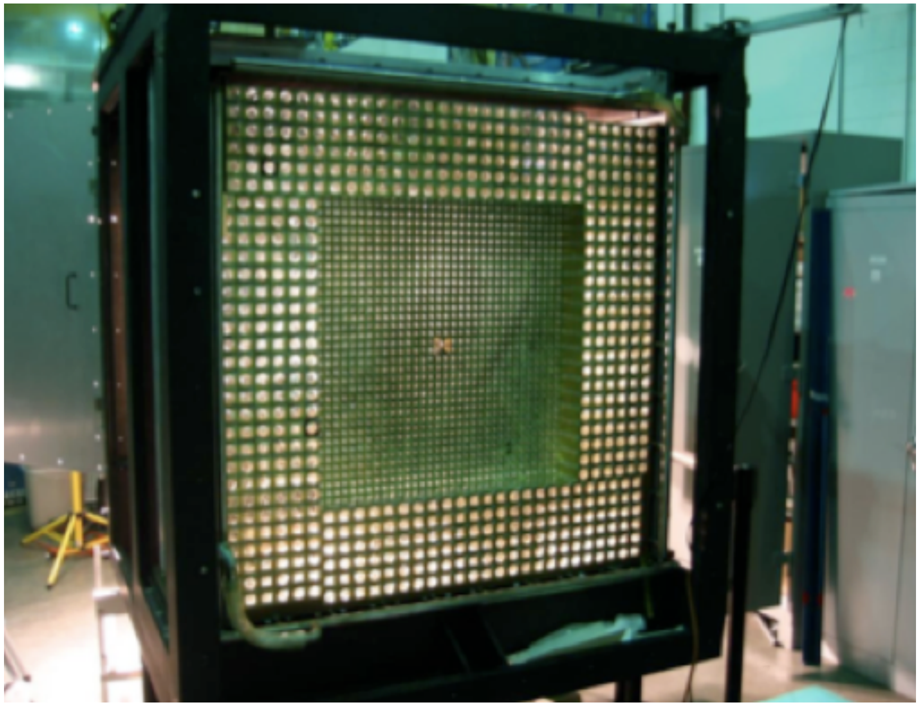
Derivative in $Q^2 \rightarrow 0$ limit:

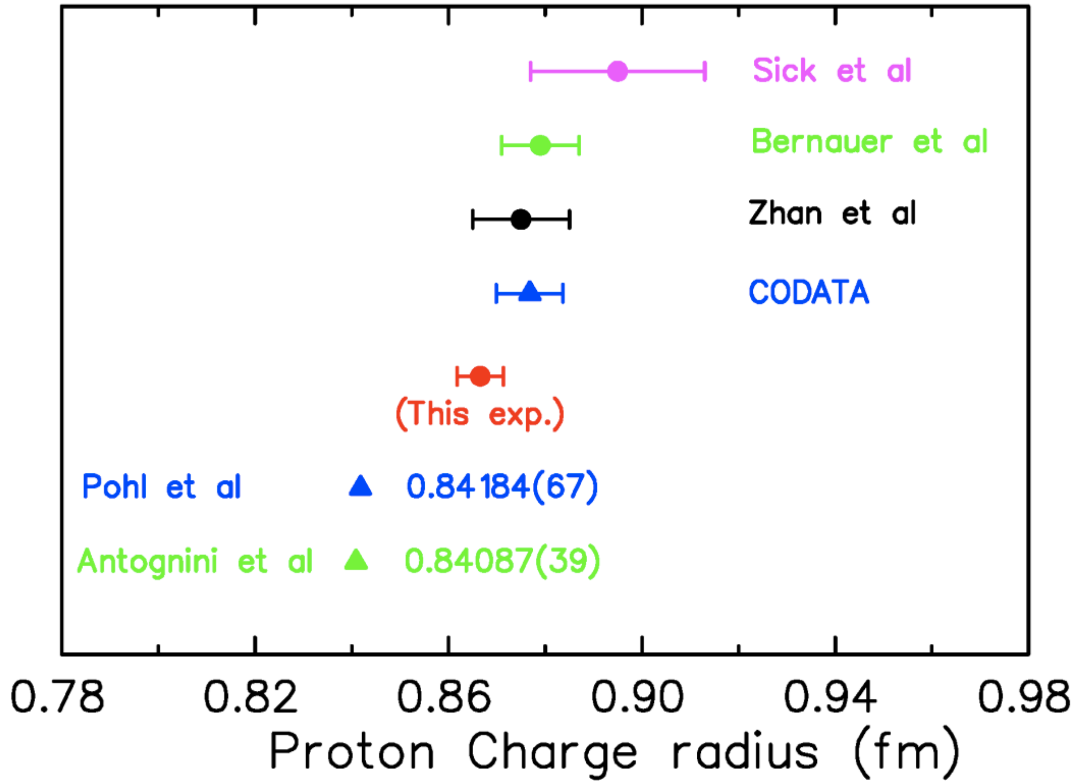
$$\langle r_E^2 \rangle = -6\frac{dG_E^p(Q^2)}{dQ^2}\bigg|_{Q^2\rightarrow 0}$$

$$\langle r_M^2 \rangle = -6\frac{dG_M^p(Q^2)/\mu_p}{dQ^2}\bigg|_{Q^2\rightarrow 0}$$

Expect identical result for ep and μp scattering

The PRad proton radius proposal (JLAB)





- Low intensity beam in Hall B @ Jlab into windowless gas target
- Scattered ep and Moller electrons into HYCAL at 0°
- Lower Q^2 than Mainz. Very forward angle, insensitive to 2γ, G_M
- Conditionally approved by PAC38 (Aug 2011): ``Testing of this result is among the most timely and important measurements in physics.''
- Approved by PAC39 (June 2012), graded "A"
- Could run in Hall B in 2015

Motivation for μp scattering

Electronic hydrogen

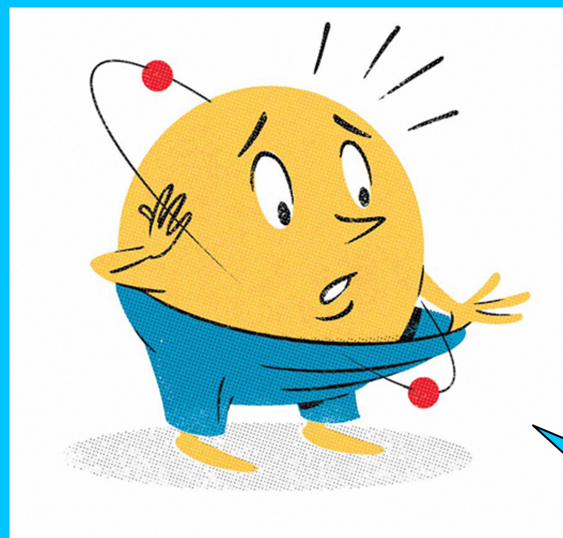
0.877±0.007

Lamb shift

Muonic hydrogen

0.842±0.001

0.84087±0.00039



Electron scattering

0.875±0.006

Elastic scattering

Muon scattering

???

MUon Scattering Experiment (MUSE) at PSI

Use the world's most powerful low-energy separated e/π/μ beam for a direct test if μp and ep scattering are different:

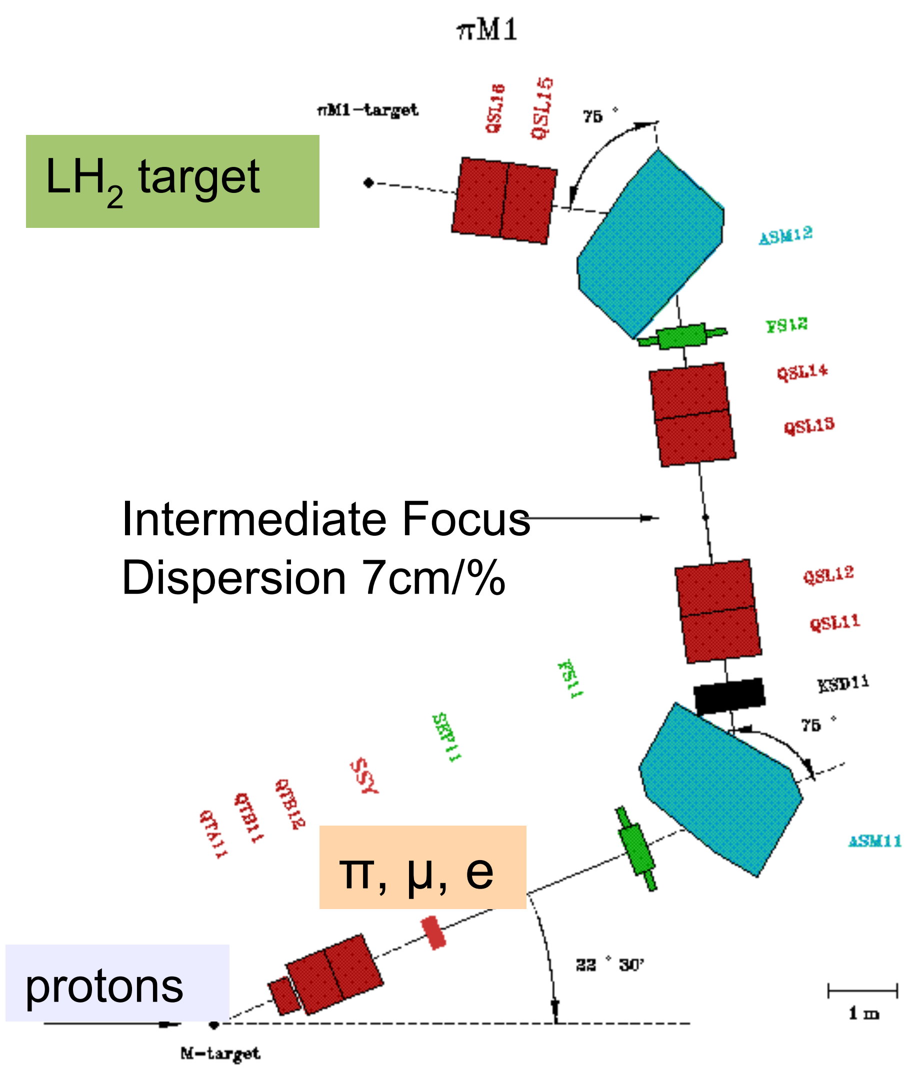
- **Simultaneous, separated beam of (e+/π+/μ+) or (e-/π-/μ-) on liquid H_2 target**
  - → **Separation by time of flight**
  - → **Measure absolute cross sections for ep and μp**
  - → **Measure e+/μ+, e-/μ- ratios to cancel certain systematics**
- **Directly disentangle effects from two-photon exchange (TPE) in e+/e-, μ+/μ-**
- **Multiple beam momenta 115-210 MeV/c to separate G_E and G_M (Rosenbluth)**

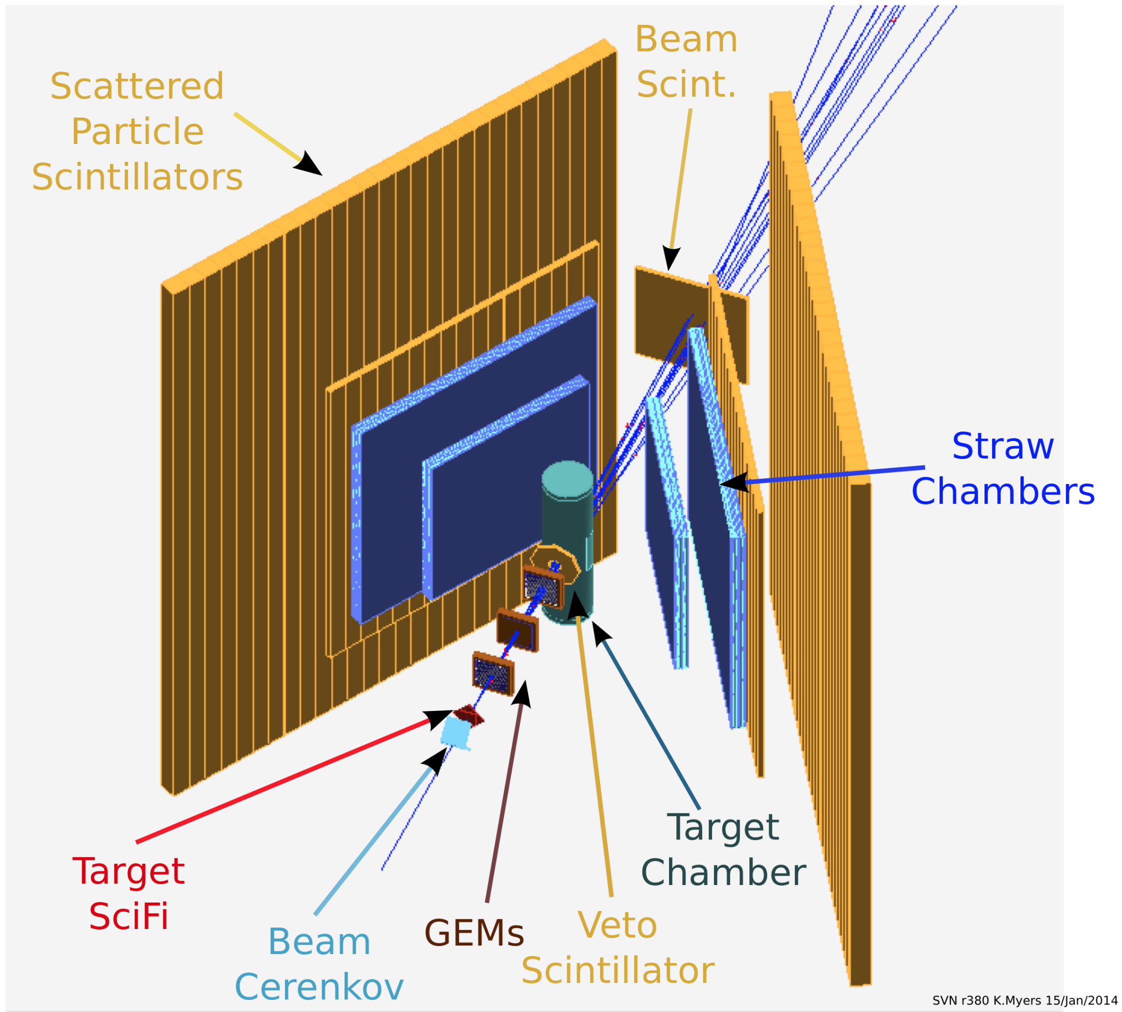
MUon Scattering Experiment (MUSE) at PSI

PAUL SCHERRER INSTITUT
PSI

Appollo and the nine muses

MUSE beamline and experiment layout



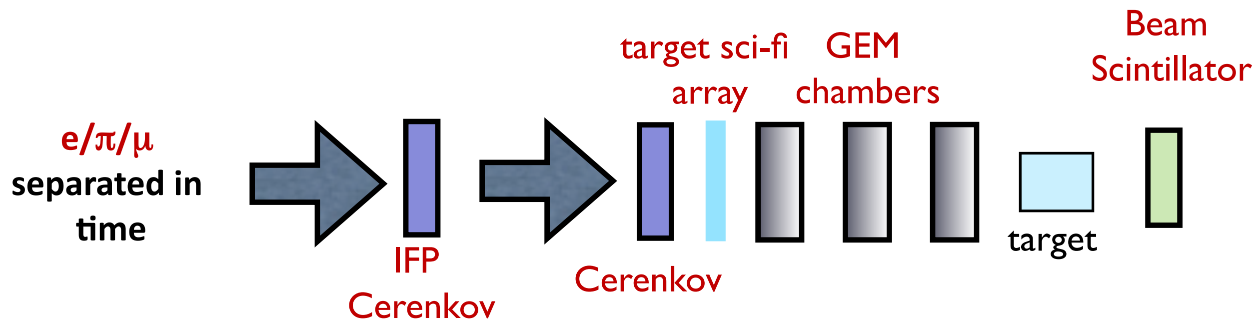


πM1: 100-500 MeV/c
Momentum measurement
RF+TOF separated π, μ, e

Beam particle tracking
Liquid hydrogen target
Scattered lepton detection

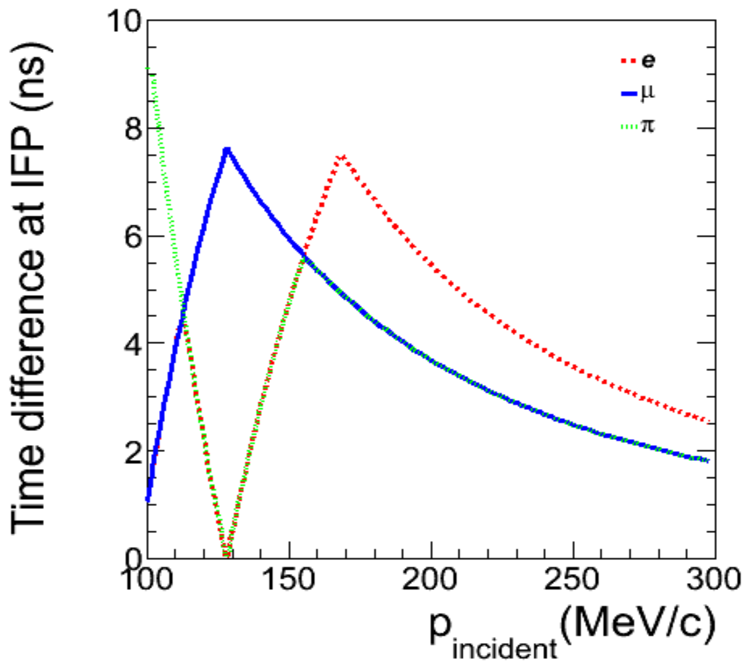
Requirements for beamline detectors

Beamline Elements:

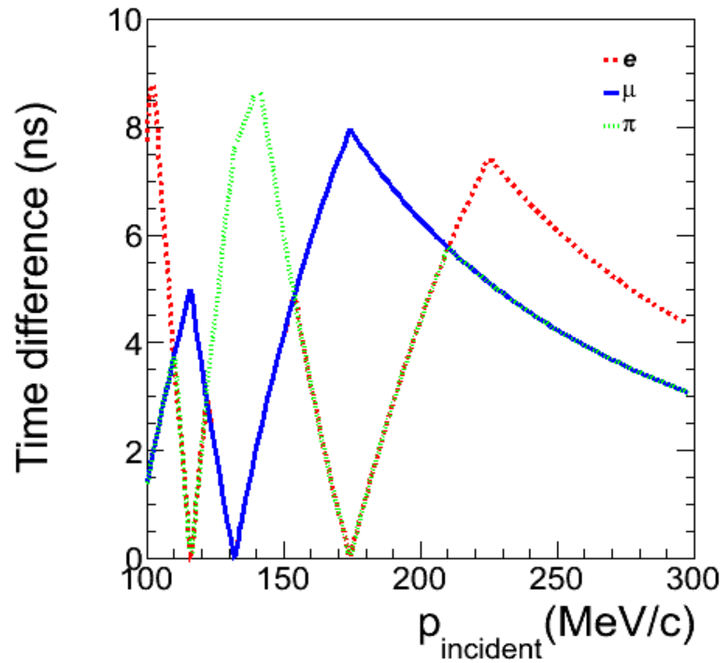


- Precise time-of-flight measurements for e/π/μ PID at trigger level
- TOF for beam momentum measurement to 0.1-0.2%
- Suppression of background from in-flight decay
- Beam particle tracking to 0.5 mr for accurate scattering angle

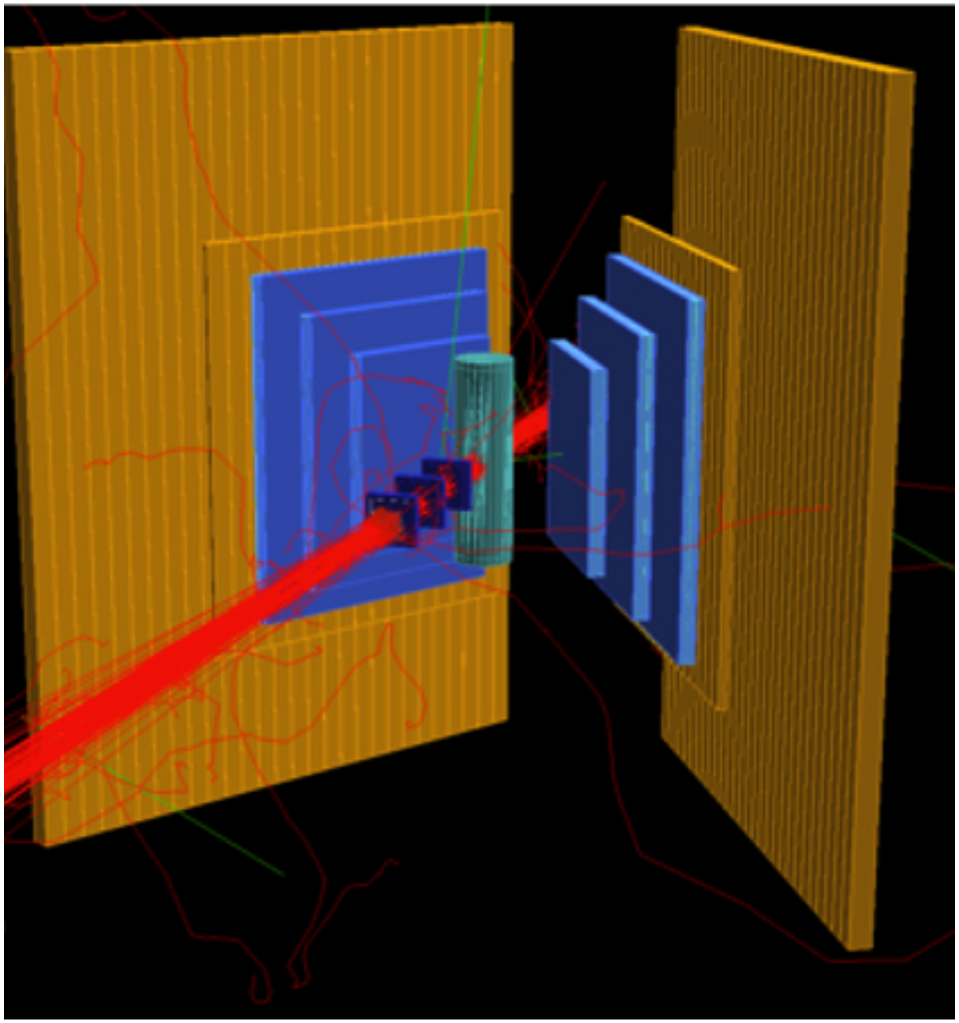
Particles are well separated at IFP

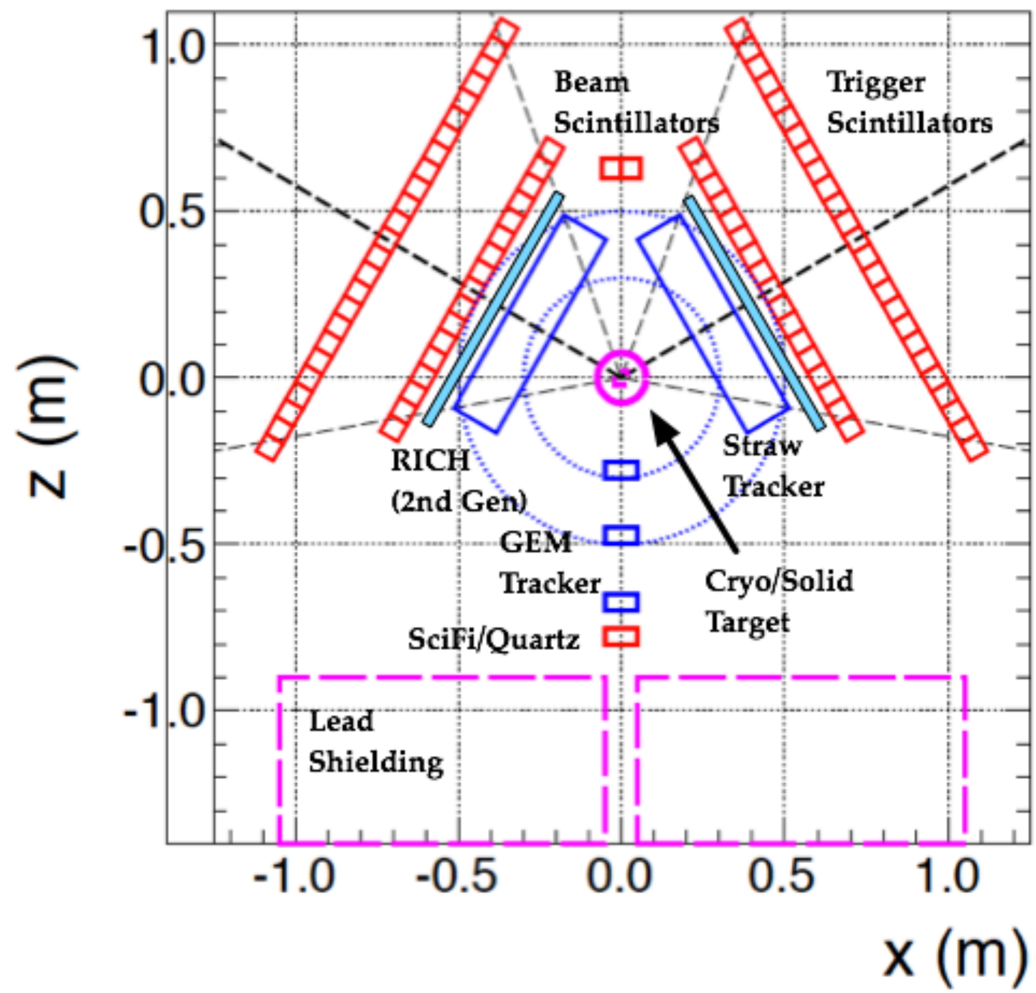


and at target



Reference design

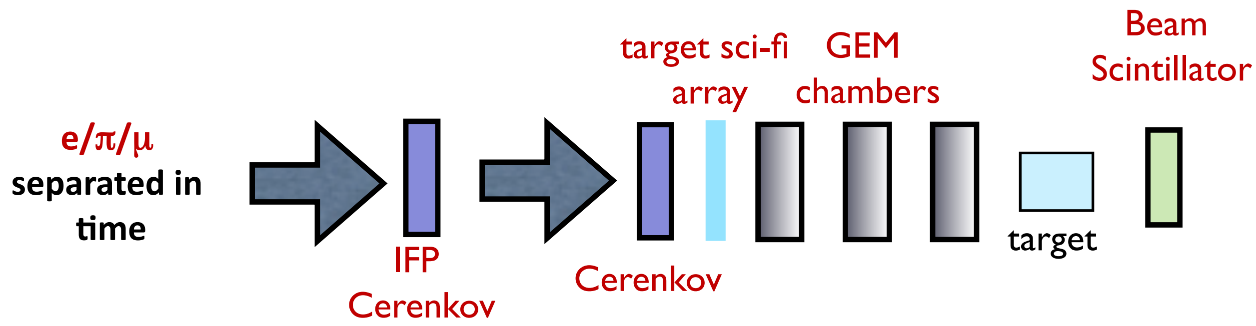




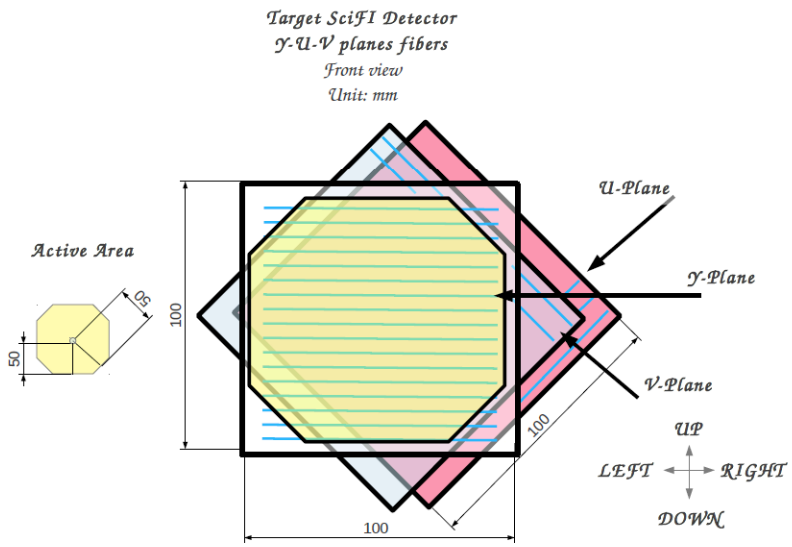
- Limited beam flux (5 MHz) → Large angle, non-magnetic detectors
- Secondary beam → Tracking of beam particles to target
- Mixed beam → Identification of beam particle in trigger

Beamline instrumentation

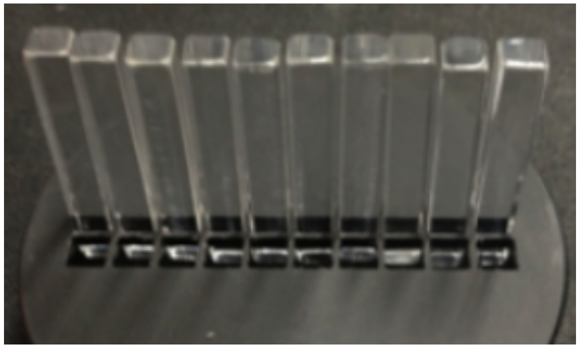
Beamline Elements:



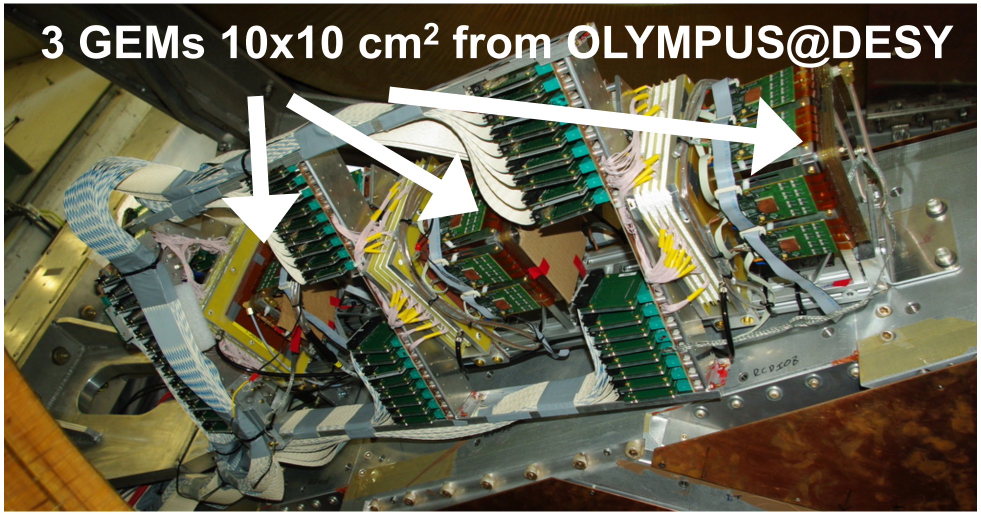
Target sci-fi array and scintillator:
→ Flux, PID, Trigger, TOF, momentum



Beam Cerenkov
(quartz or sapphire)
→ Timing, PID, trigger:
beam TOF, momentum,
scattered particle TOF

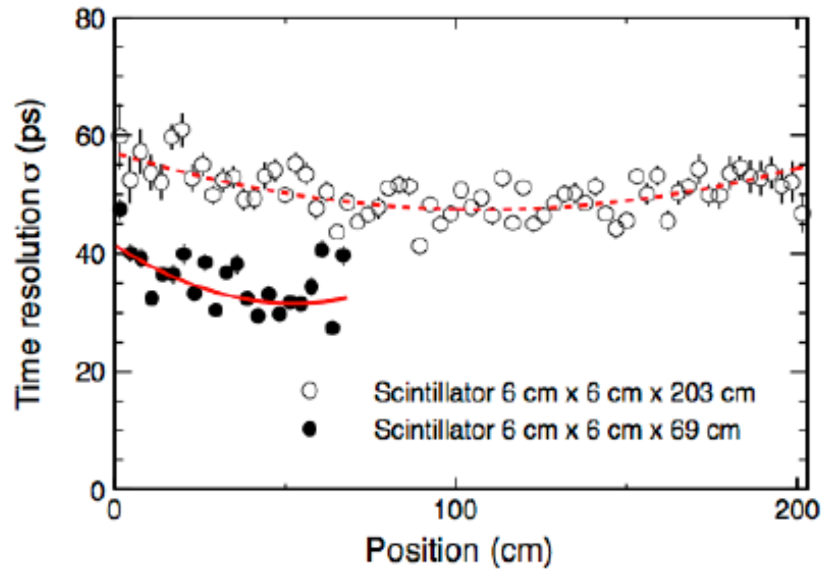


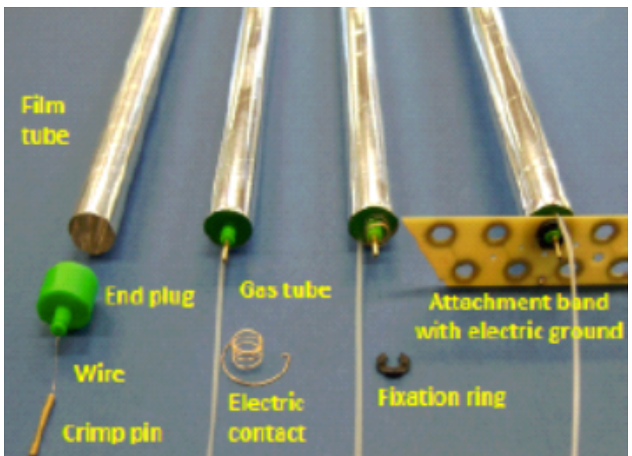
GEM telescope
→ Determine incident angle to 0.5 mr
→ Third GEM to reject ghost tracks
→ Existing chambers from OLYMPUS

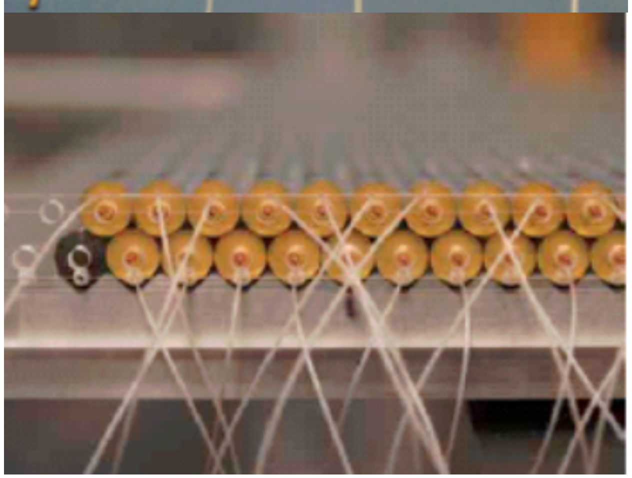


Main detector instrumentation

- 2 planes of scintillators (CLAS12 design)
- 94 bars (2 sides + beam)
- High precision (40-50ps) timing
- PID and trigger, background rejection



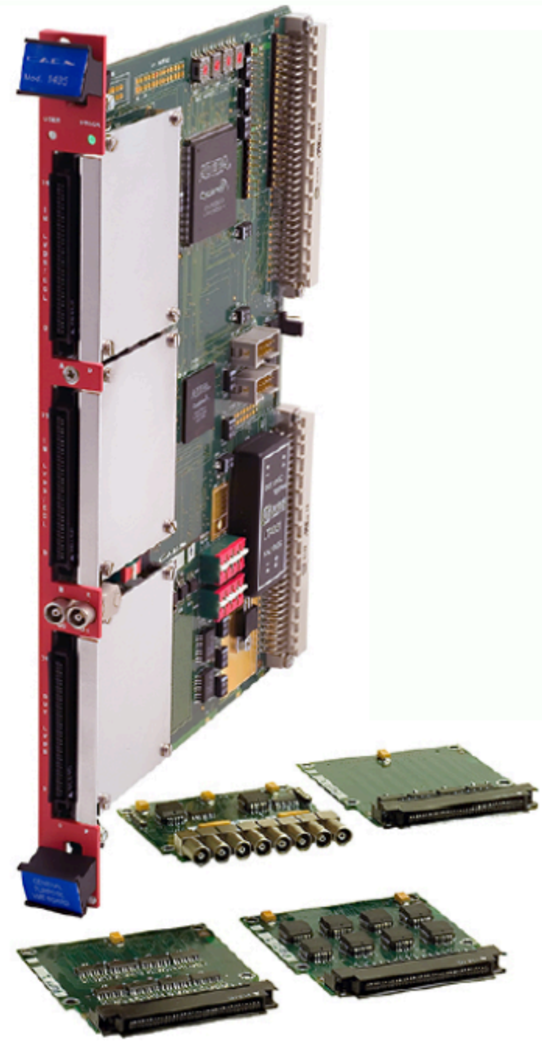


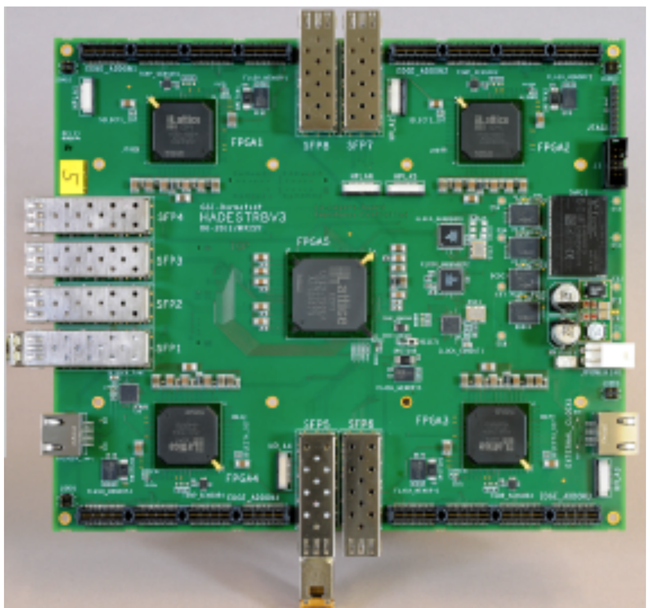


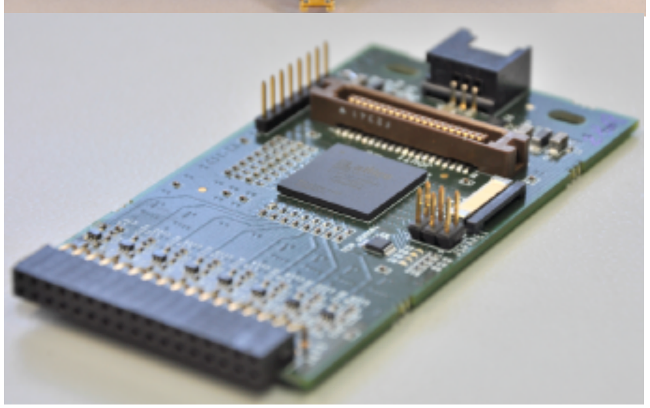
- Straw Tube Tracker (STT), ~3000 straws
- Determine scattered particle trajectory
- Existing PANDA design - 140μm resolution
- Thin walled (25μm), overpressured (2 bar)
- Directly coupled to fast readout boards

Trigger and DAQ

- FPGA design for beam PID (custom or v1495)
- SciFi + Beam RF + Cerenkov -> Beam PID
- Count particles and reject pions
- Need 99.9% pion rejection efficiency





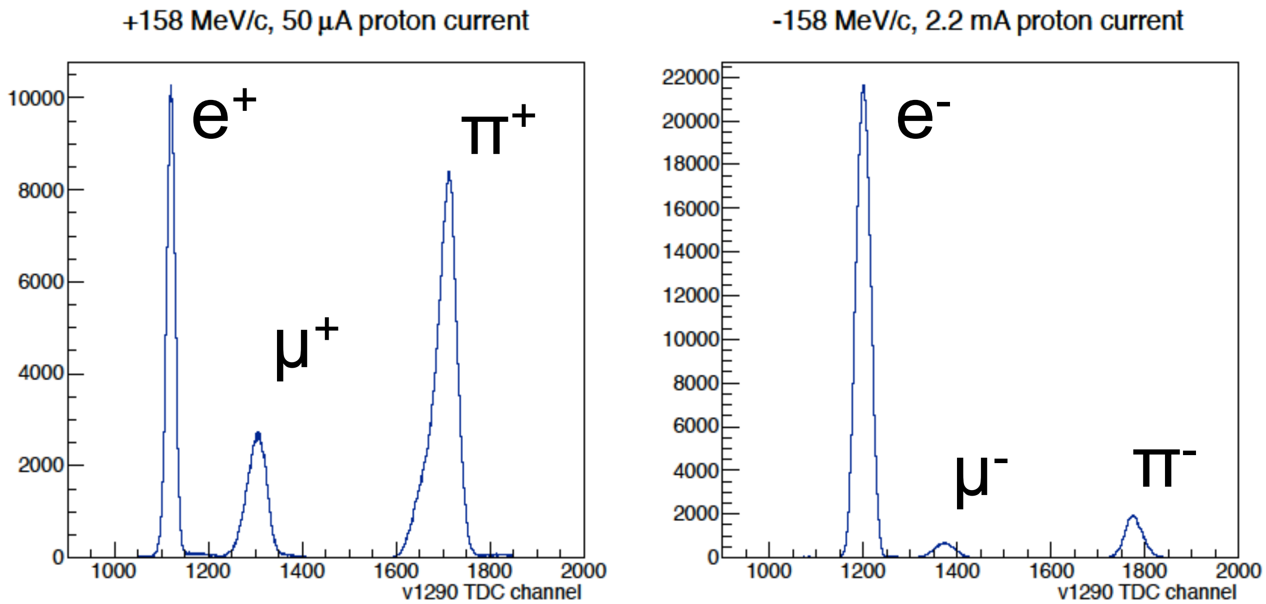


- Custom signal splitters
- FPGAs as front end discriminator/amplifier, custom designed TDCs (PADIWA/TRB3)
- High channel density (256ch/board).
- Standard CAEN ADCs

Responsibilities for new equipment

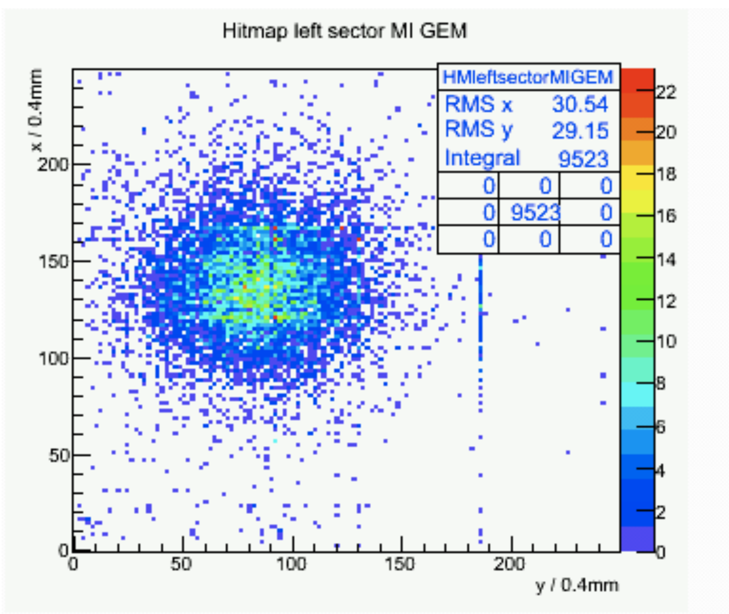
Detector	Who	Technology
Beam SciFi	Tel Aviv	conventional
GEMs	Hampton	detector exists
Sapphire Cerenkov	Rutgers	prototyped (Albrow et al)
FPGAs	Rutgers	conventional
Target	George Washington	conventional - very low power
Straw Tube Tracker	Hebrew U	copy existing system (PANDA)
scintillators	South Carolina	copy existing system
DAQ	George Washington	conventional, except TRB3

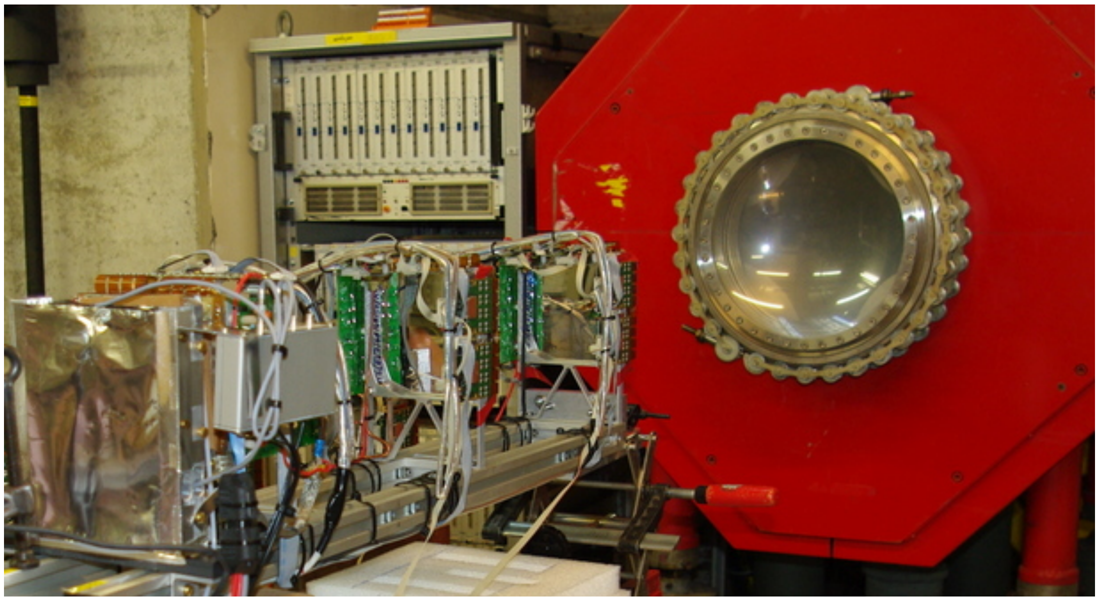
First beam tests



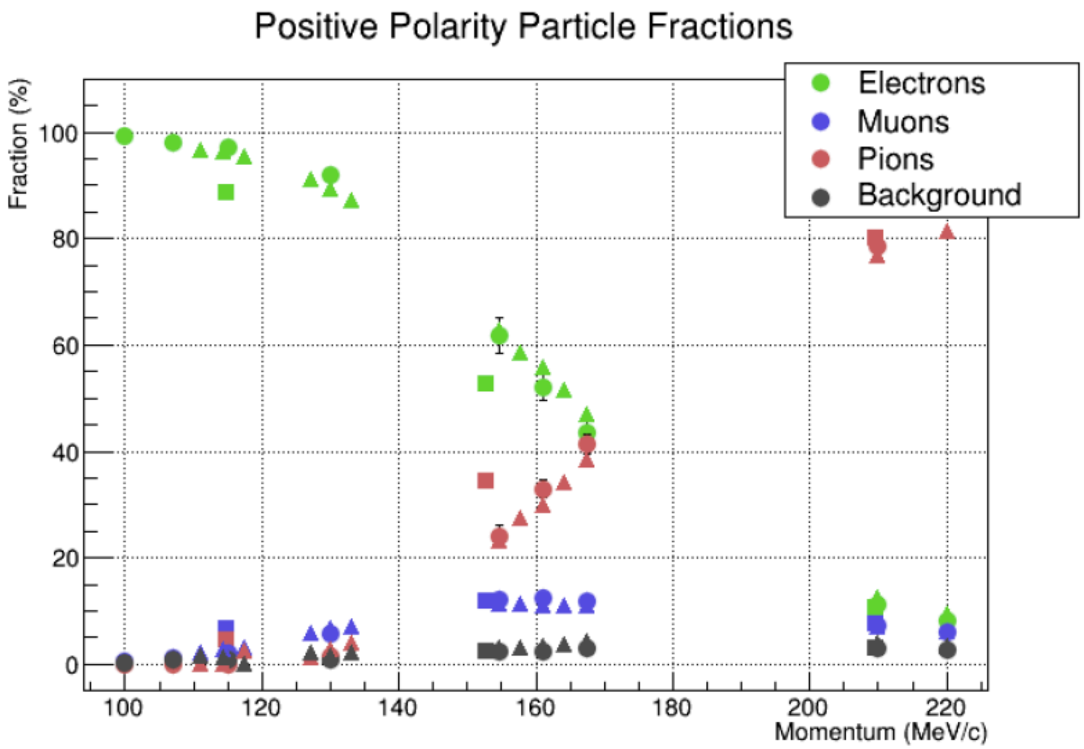
Time of flight relative to RF time (Fall 2012)

Beam spot with GEM telescope – May 23, 2013

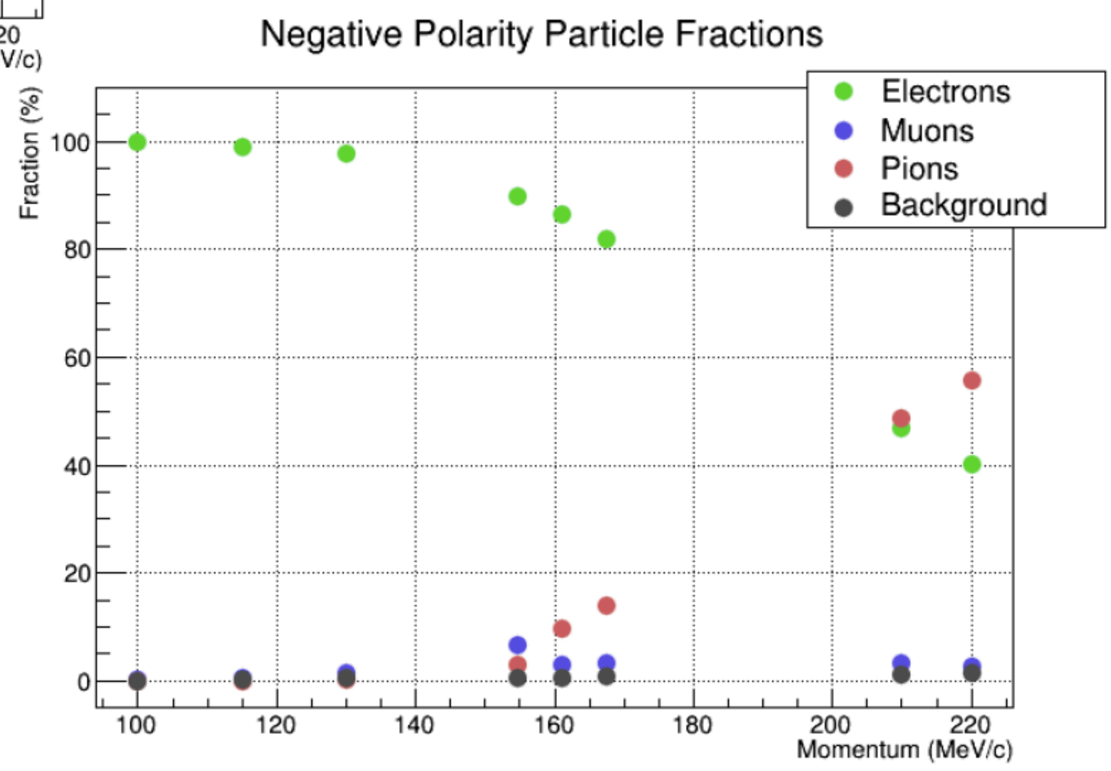




Composition of the πM1 secondary beam



Beam test result from December 2013

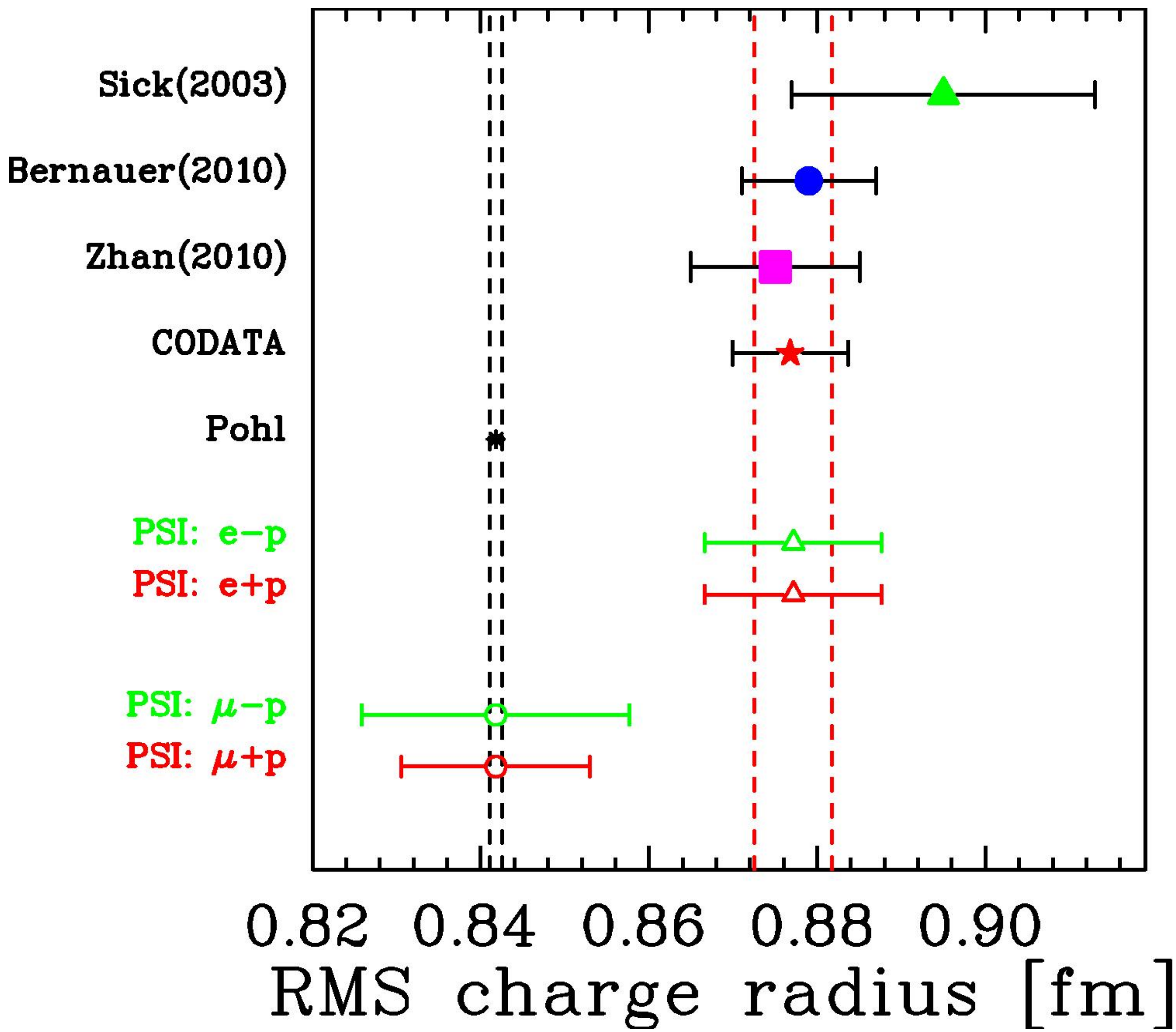


Projected sensitivity

Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing e-p extractions, but not better

Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, μ+/μ-, and μ/e comparisons



Projected sensitivity

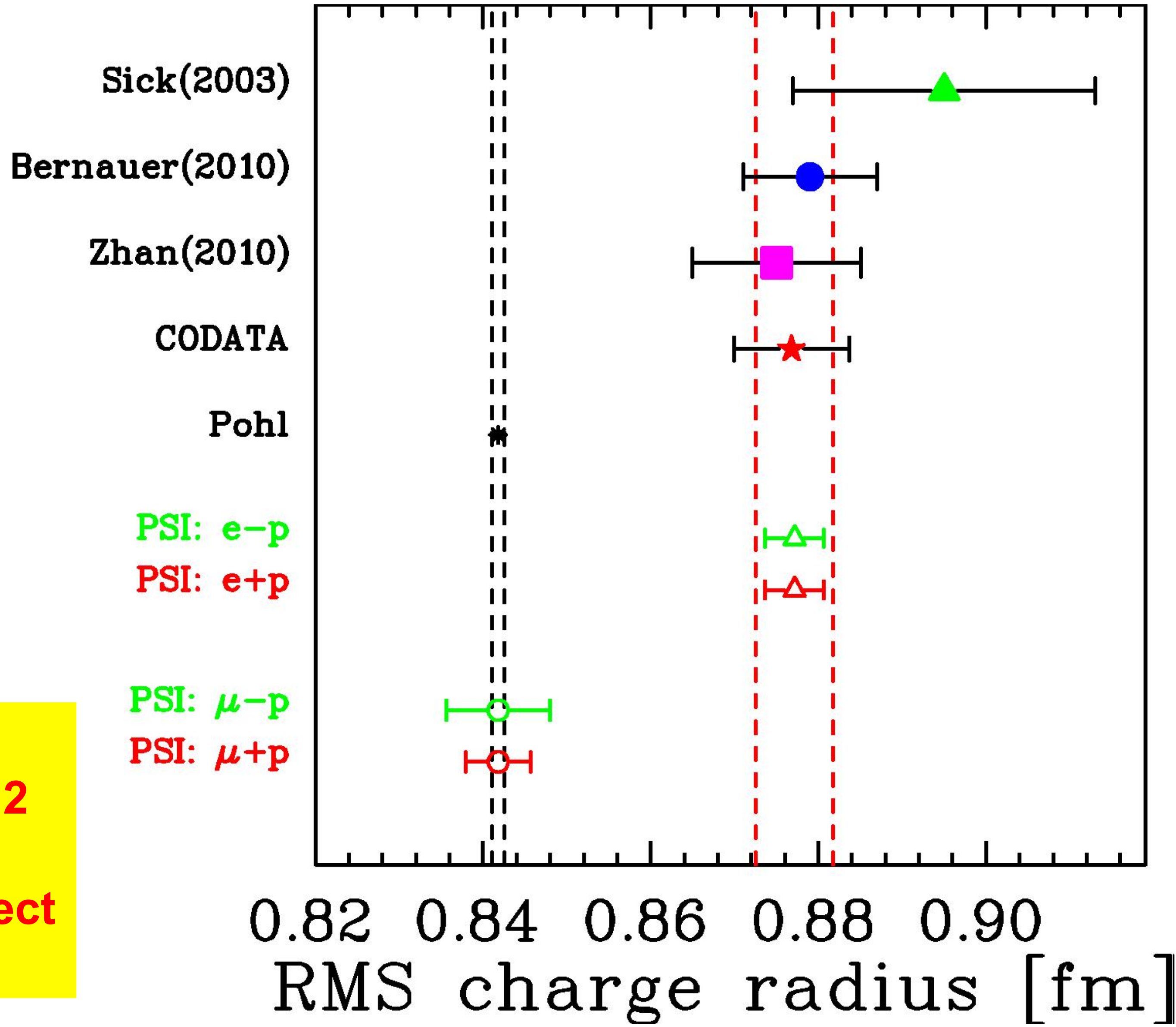
Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing e-p extractions, but not better

Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, μ+/μ-, and μ/e comparisons

Relative comparison reduces errors by factor of 2

MUSE suited to verify 7σ effect with similar significance



MUon Scattering Experiment – MUSE

- **Proton Radius Puzzle – still unresolved ~4 years later**
- **MUSE Experiment at PSI**
  - Measure μp and ep scattering and compare μ+/e+ and μ-/e- directly
  - Measure e+/e- and μ+/μ- to study/constrain TPE effects
- **Technical Challenges**
  - PID, timing, background rejection, momentum and flux determination
- **Timeline**
  - Initial proposal February 2012
  - Technical review July 2012
  - First beam tests in fall 2012
  - **PAC-approved in January 2013**
  - Further beam tests in summer and December 2013
  - Funding & construction 2014–2015
  - Production running 2016–2017 (2x 6 months)

MUon Scattering Experiment – MUSE

47 MUSE collaborators from 24 institutions in 6 countries:

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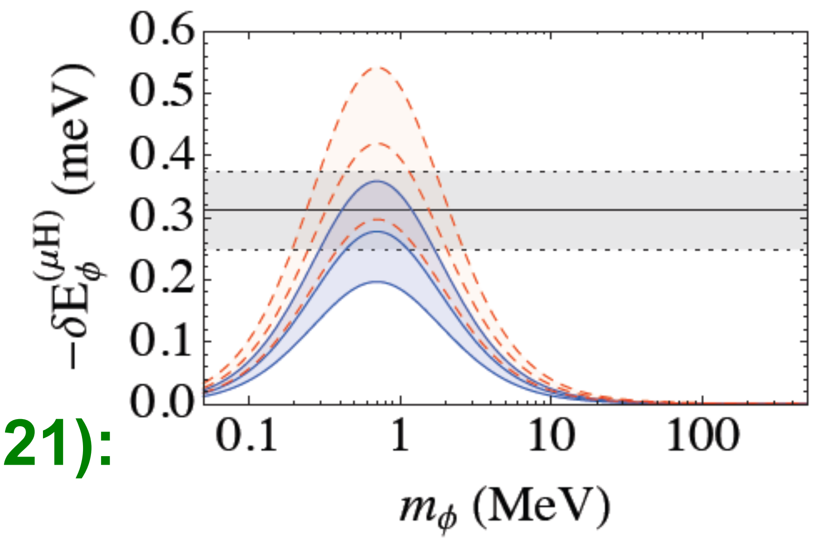
A dark photon and the proton radius puzzle

Jaeckel, Roy (arXiv:1008.3536)

- Hidden U(1) photon can decrease charge radius for muonic hydrogen, however even more so for regular hydrogen



Tucker-Smith, Yavin (arXiv:1011.4922)

can solve proton radius puzzle

- MeV particle coupling to p and μ (not e) consistent with g_{μ}-2

Batell, McKeen, Pospelov (arXiv:1103.0721):

can solve proton radius puzzle

- new e/μ differentiating force consistent with g_{μ}-2
- <100 MeV vector or scalar gauge boson V (poss. dark photon)
- resulting in large PV μp scattering

Carlson, Rislow (arXiv:1310.2786):

can solve proton radius puzzle

- new e/μ differentiating force consistent with g_{μ}-2
- Two fine-tuned scalar/pseudoscalar or vector/axial gauge bosons

Barger, Chiang, Keung, Marfatia (arXiv:1109.6652):

- Should be constrained by K → μν decay

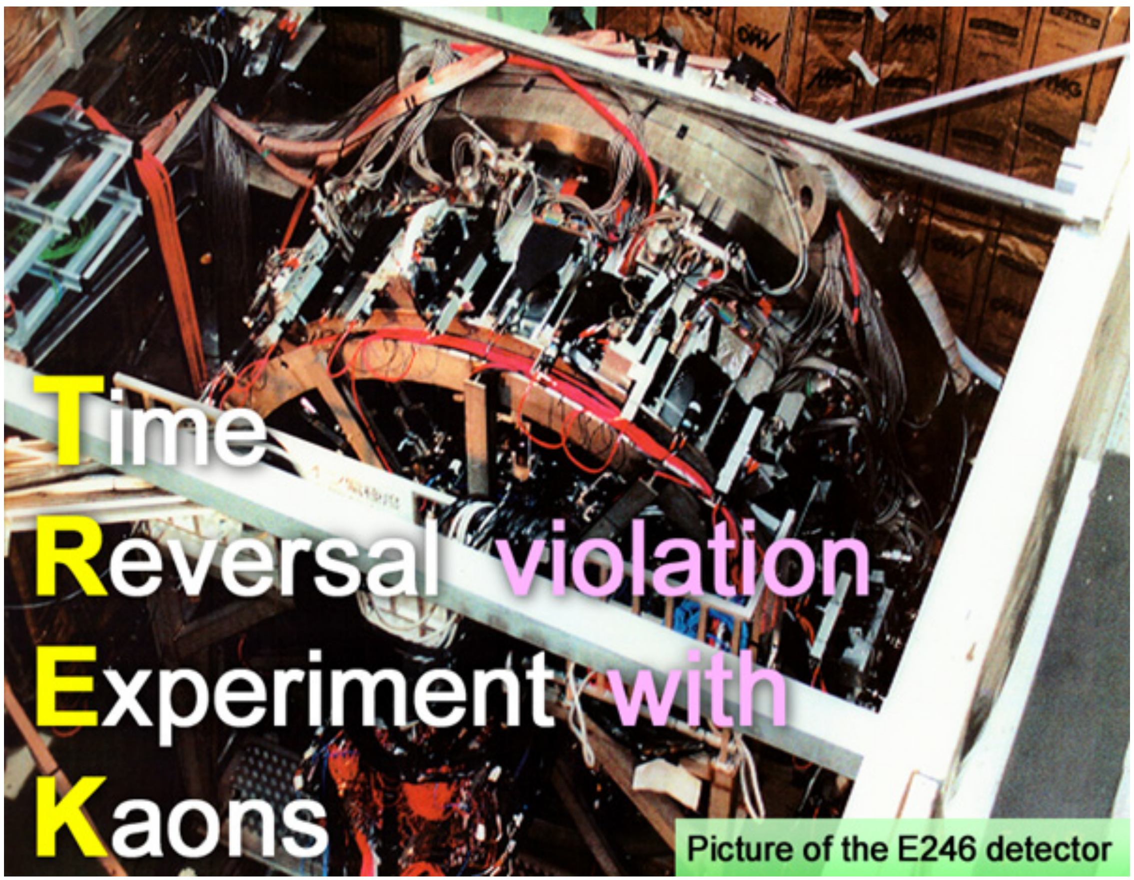
TREK (E36) at J-PARC

Measurement of $\Gamma(K^+ \rightarrow e^+\nu)/\Gamma(K^+ \rightarrow \mu^+\nu)$

and

Search for heavy sterile neutrinos

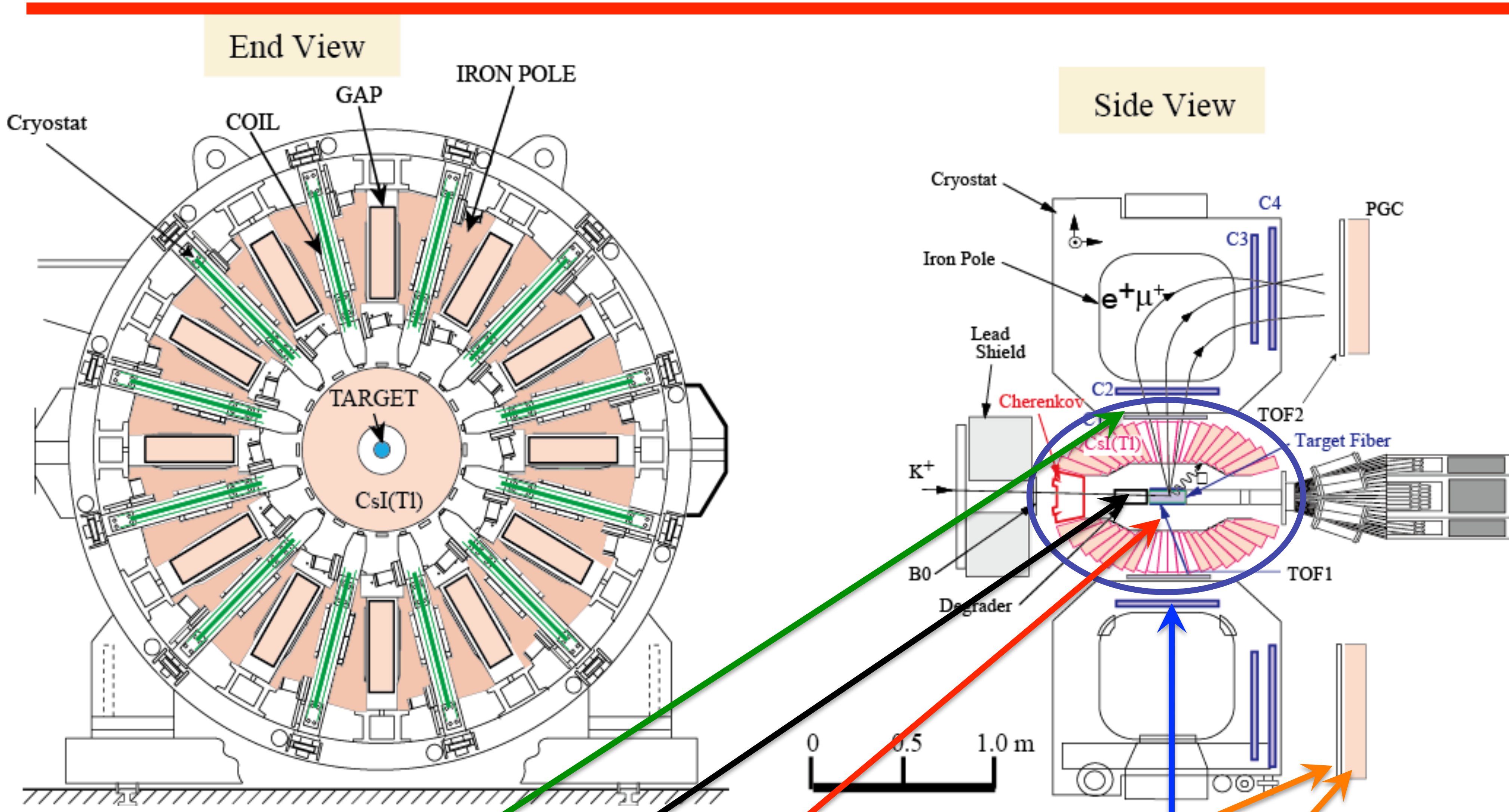
using the TREK detector system



Official website:
http://trek.kek.jp

Scheduled to run beginning of 2015

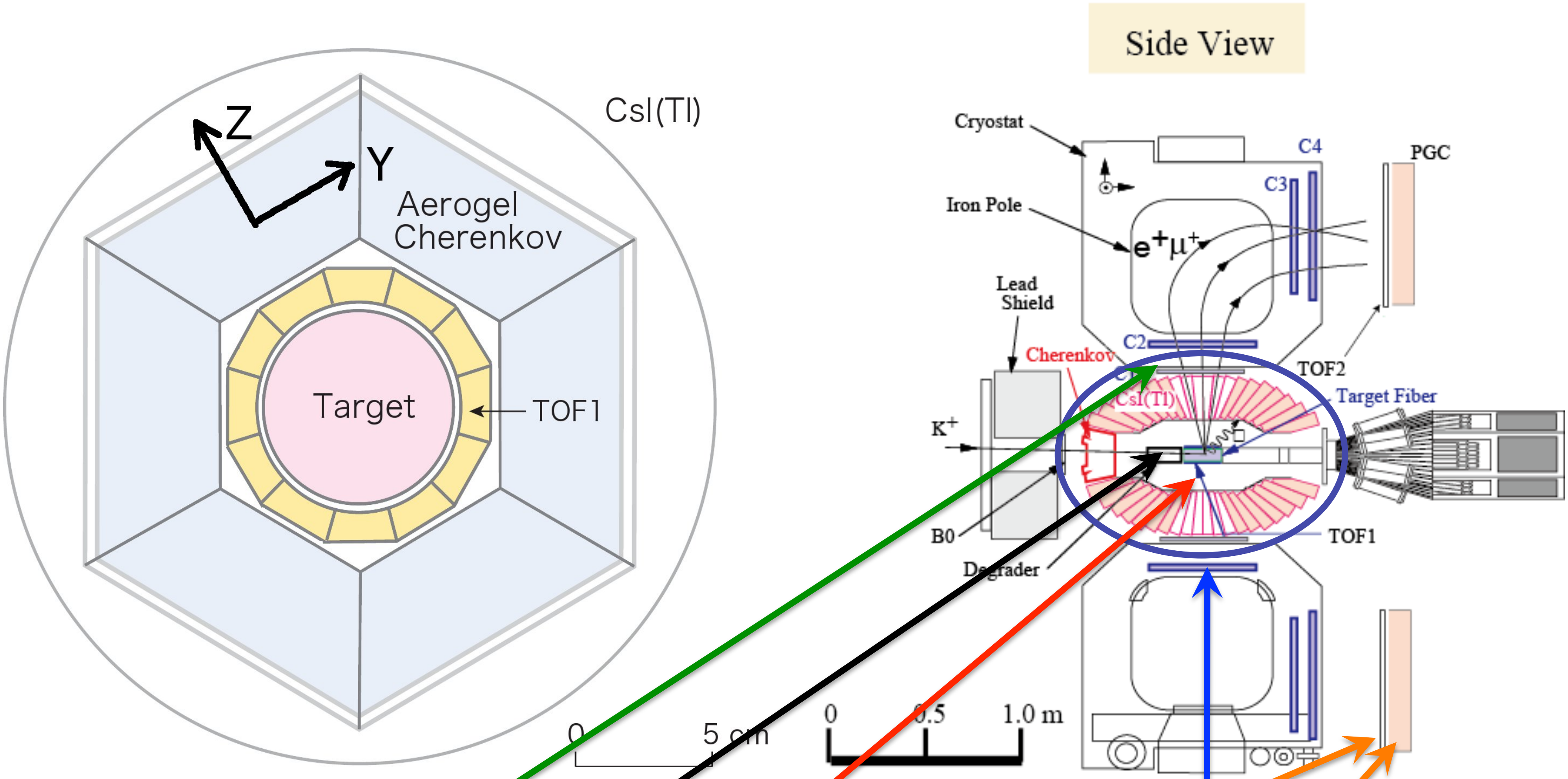
Target & E246/TREK detector upgrade



- C1 GEM
- Target
- Aerogel Cerenkov

- TOF, Leadglass
- CsI(Tl) readout

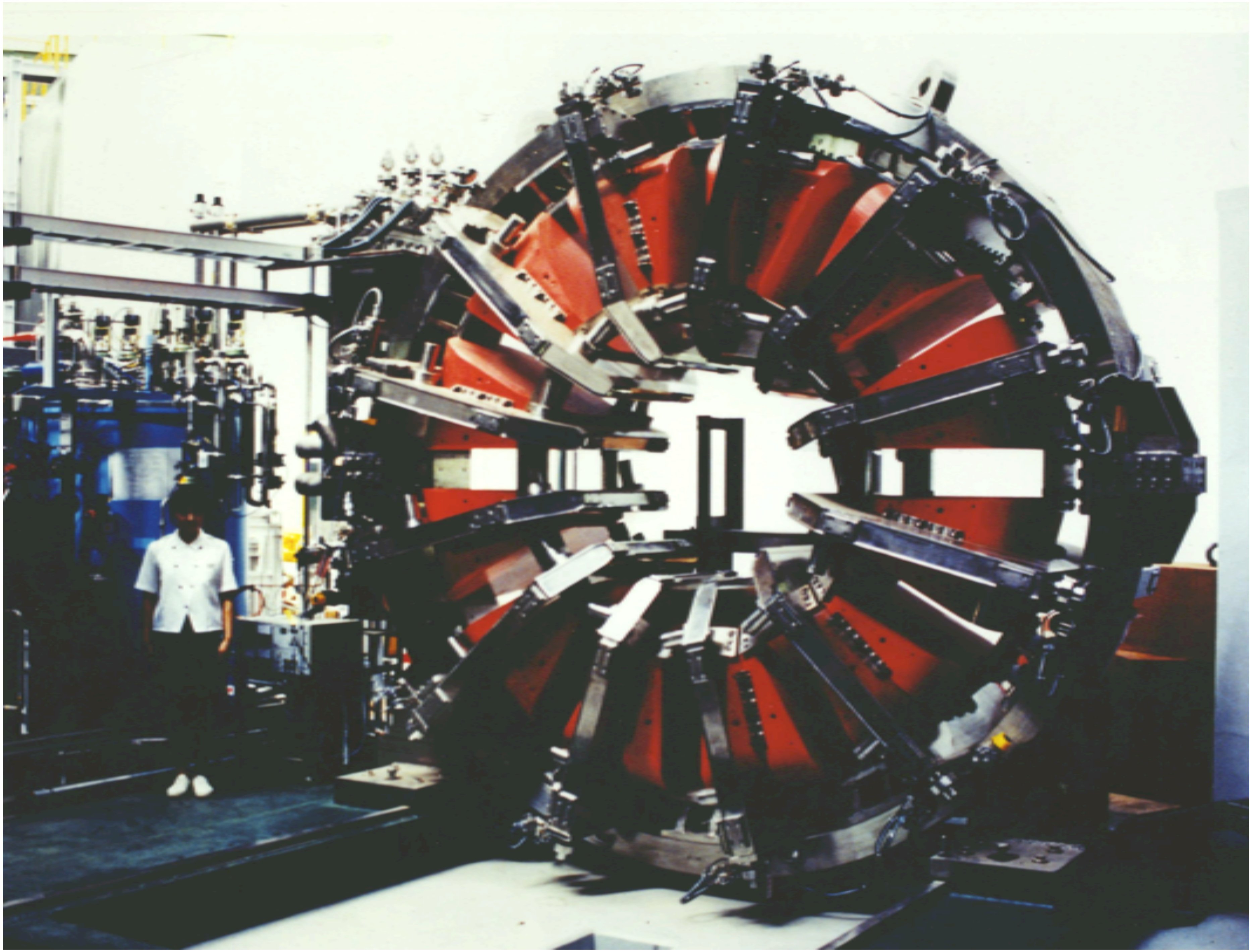
Target & E246/TREK detector upgrade



- C1 GEM
- Target
- Aerogel Cerenkov

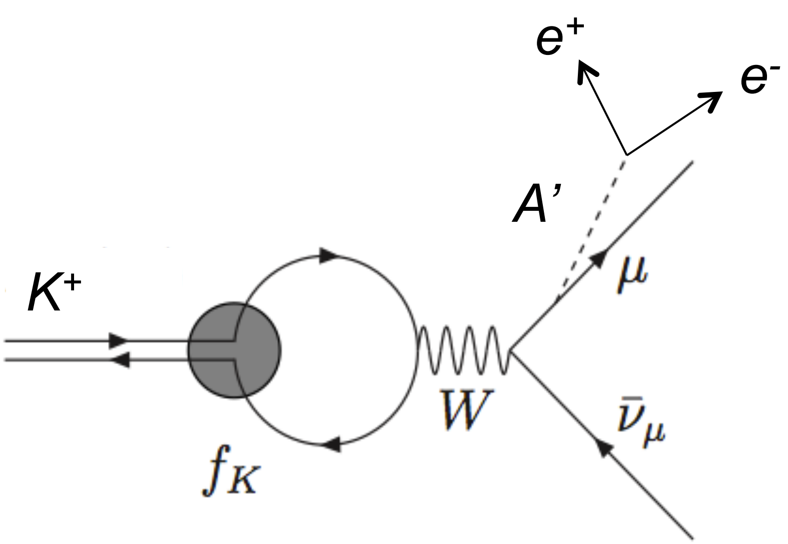
- TOF, Leadglass
- CsI(Tl) readout

E246: Superconducting toroidal magnet



Search for a new particle in $K^+ \to \mu^+ \nu e^+ e^-$

- Light mediator of dark force U(1) coupled to SM via kinetic mixing; motivated by astrophysics, $g_\mu - 2$, (and proton radius puzzle R_p)
- Possibly enhanced coupling to muons, not probed by electroproduction
- Measure all charged decay particles and search for peak in the e^+e^- invariant mass spectrum in the range 0-380 MeV



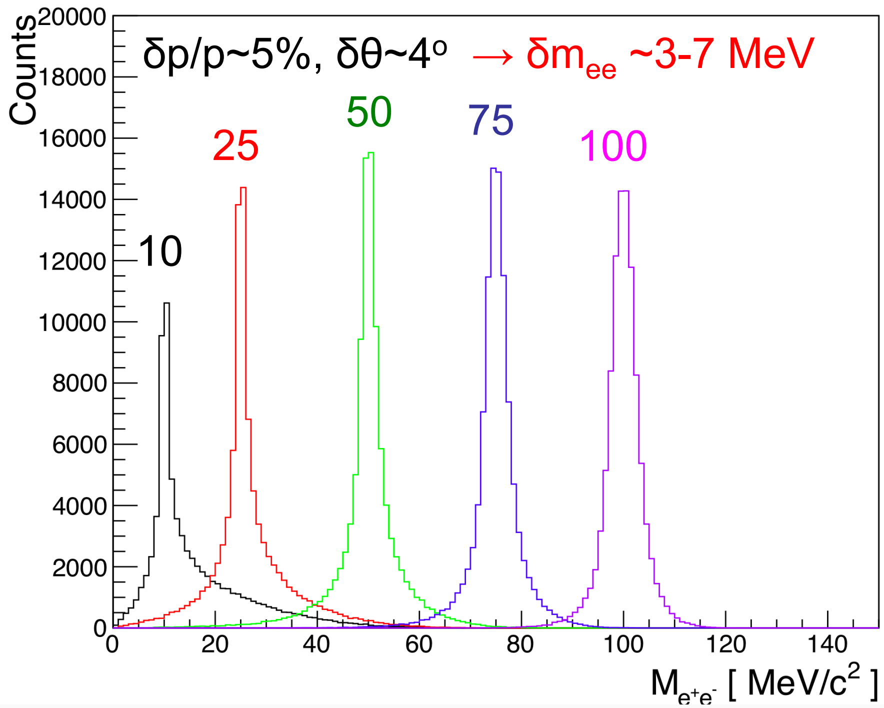
$K_{\mu 2}$: $K^+ \to \mu^+ \nu$ (~10^{10} events)

$K_{\mu 2\gamma}$: $K^+ \to \mu^+ \nu \gamma$ (~10^7 events)

Signal: BR($K^+ \to \mu^+ \nu A'$) ~10^{-8}
$A' \to e^+e^-$ (~100 events)

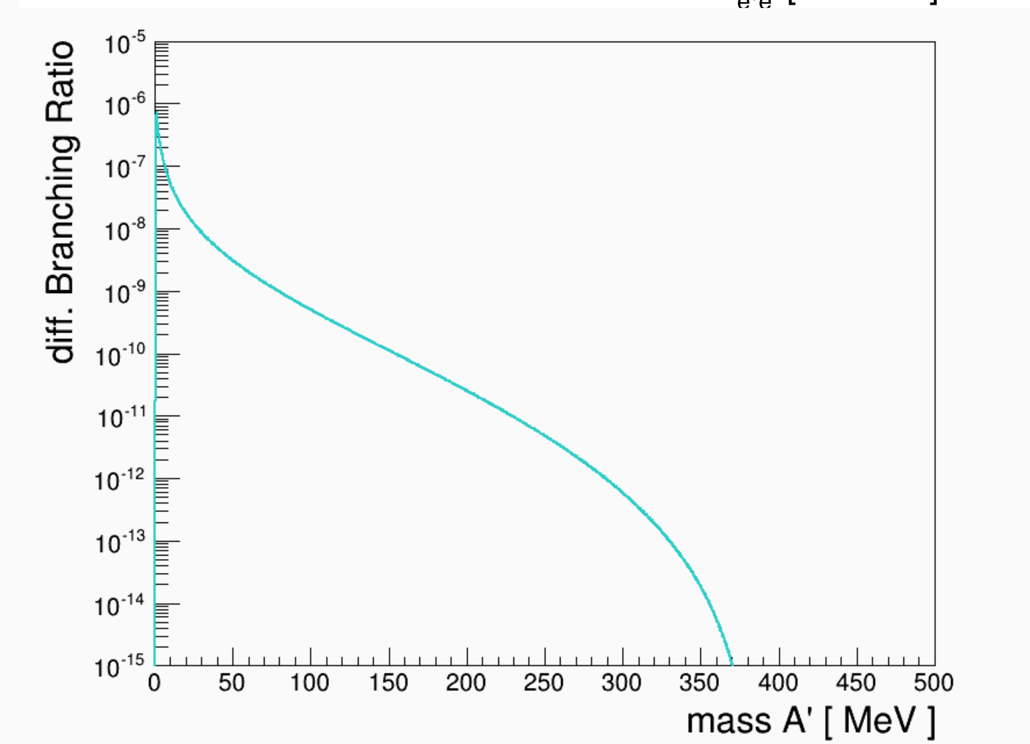
Background:
BR($K^+ \to \mu^+ \nu e^+ e^-$) ~ 2.5 x 10^{-5}

Search for a new particle in $K^+ \rightarrow \mu^+ \nu e^+ e^-$



Investigated for E36:

- Detect μ^+ in toroid, e^+e^- in CsI(Tl)
- Simulate achievable resolution for invariant mass m_{ee}

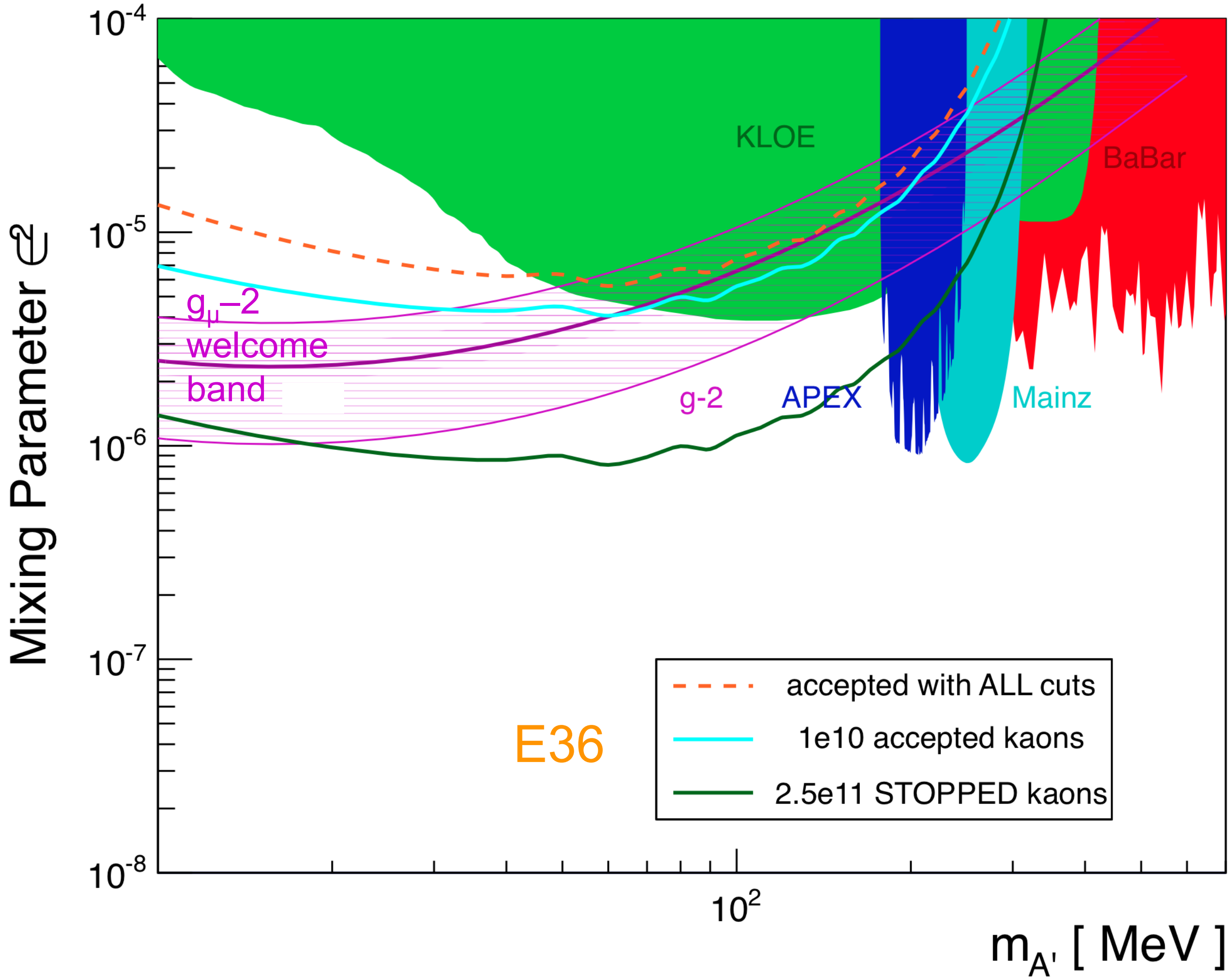


- Simulate QED background (radiative decay $K^+ \rightarrow \mu^+ \nu\ e^+ e^-$)
- Sensitivity from background fluctuation

→ Exclusion limits for ε^2 versus m_{ee}

P. Monaghan, B. Dongwi

Dark photon exclusion limit $K^+ \rightarrow \mu^+ \nu e^+ e^-$



P. Monaghan

TREK/E36:

Kaons delivered: 1.0×10^{12}

&& stopped: 2.5×10^{11}

&& μ^+ accepted: 1.8×10^{10}

&& e^+e^- accepted: 1.0×10^{10}

- Mixing parameter: dark photon framework, universal coupling
- Simulated signal channel $K^+ \rightarrow \mu^+ \nu A'$ for resolution
- Simulated background distribution with BR($K^+ \rightarrow \mu^+ \nu e^+ e^-$)=2.5e-5
- Obtain exclusion limit for signal > 2x background fluctuation
- Exclusion limit dependent on resolution and number of accepted K^+

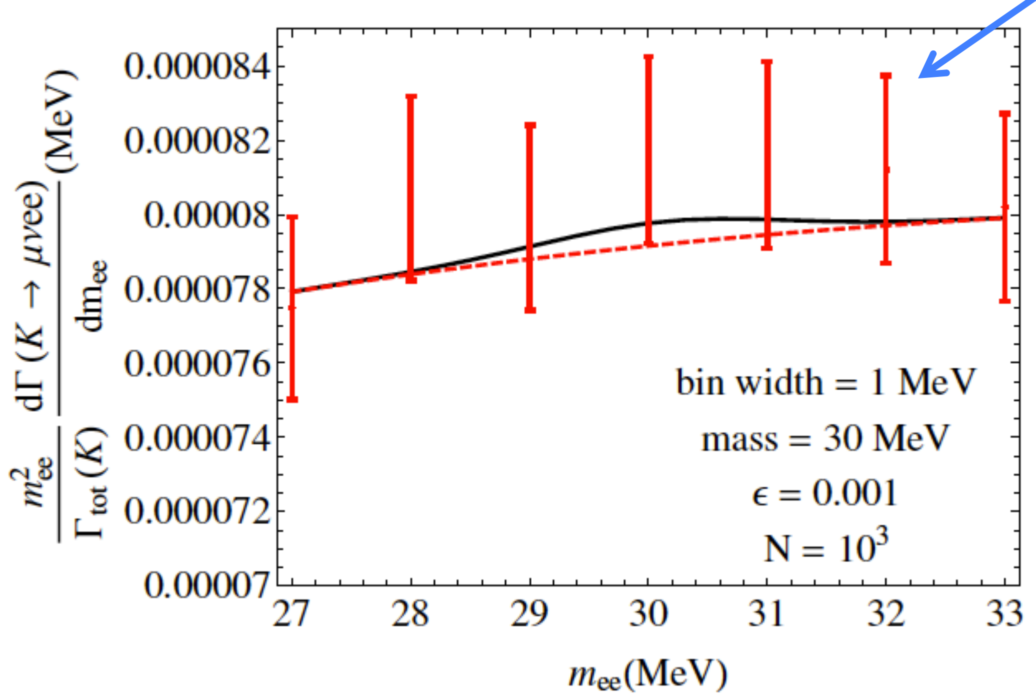
Search for a new particle in $K^+ \to \mu^+ \nu e^+ e^-$

QED background: $K^+ \to \mu^+ \nu e^+ e^-$
- $\Gamma(K^+ \to \mu^+ \nu ee) \sim 2.5 \times 10^{-5}$
- *Expect 10^{10} stopped K^+ in E36*
- *250k QED evts or ~1000 / MeV*

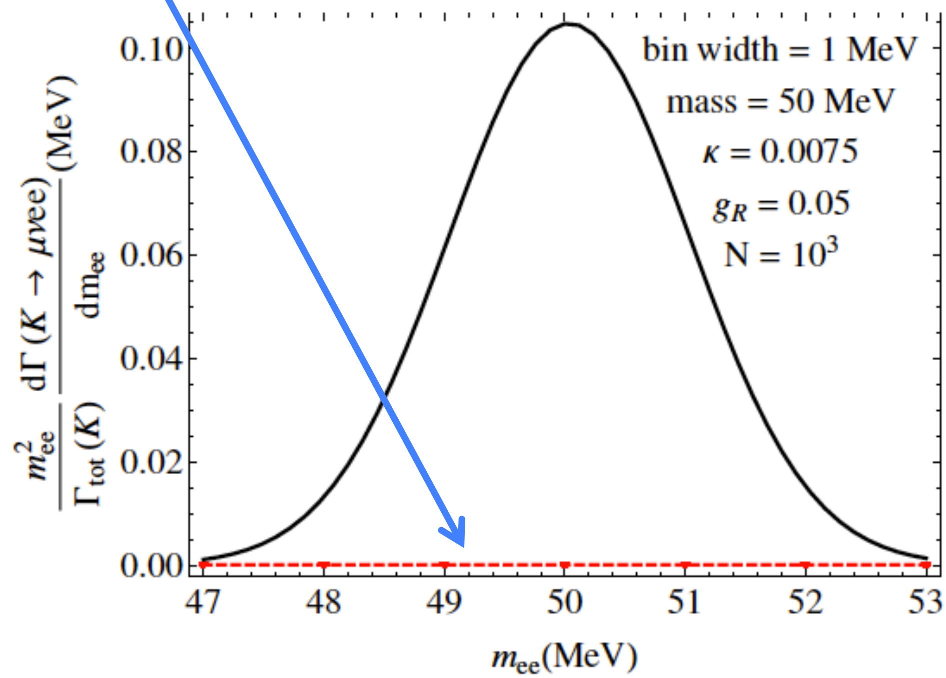
Signal: $K^+ \to \mu^+ \nu A', A' \to e^+ e^-$

C. Carlson, B. Rislow, hep-ph/1310.2786

same background!



Dark photon model
(universal coupling)
$\Gamma(K^+ \to \mu^+ \nu A') \sim 10^{-9}$



Batell model
(univ.-violating, right-handed muons)
$\Gamma(K^+ \to \mu^+ \nu A') \sim 10^{-4} - 10^{-1}$

B. Batell, D. McKeen, and M. Pospelov, PRL107, 011803 (2011), 1103.0721

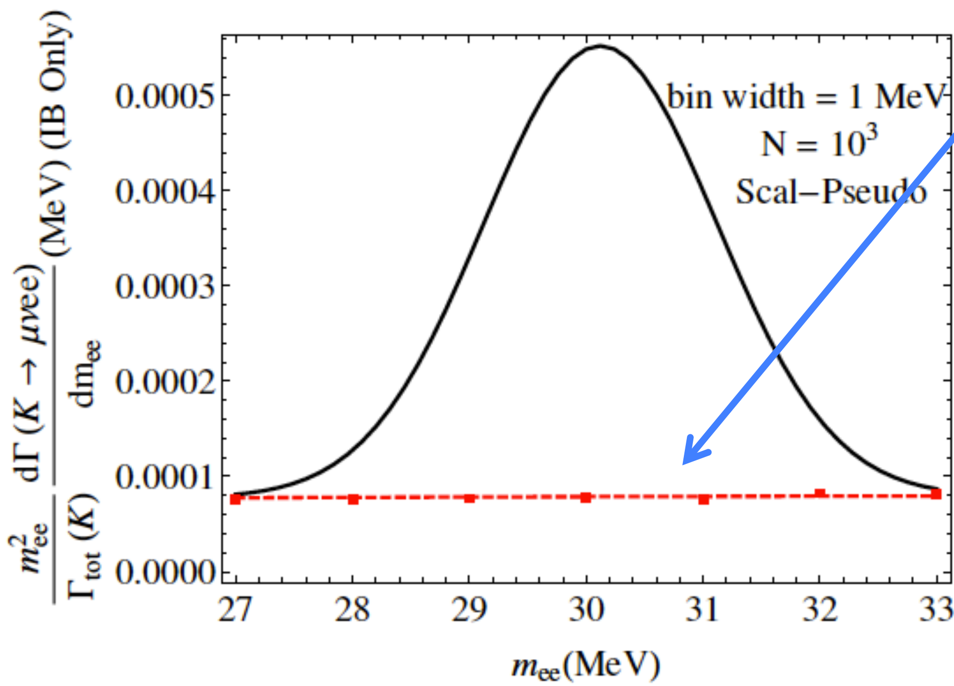
Search for a new particle in $K^+ \to \mu^+ \nu e^+ e^-$

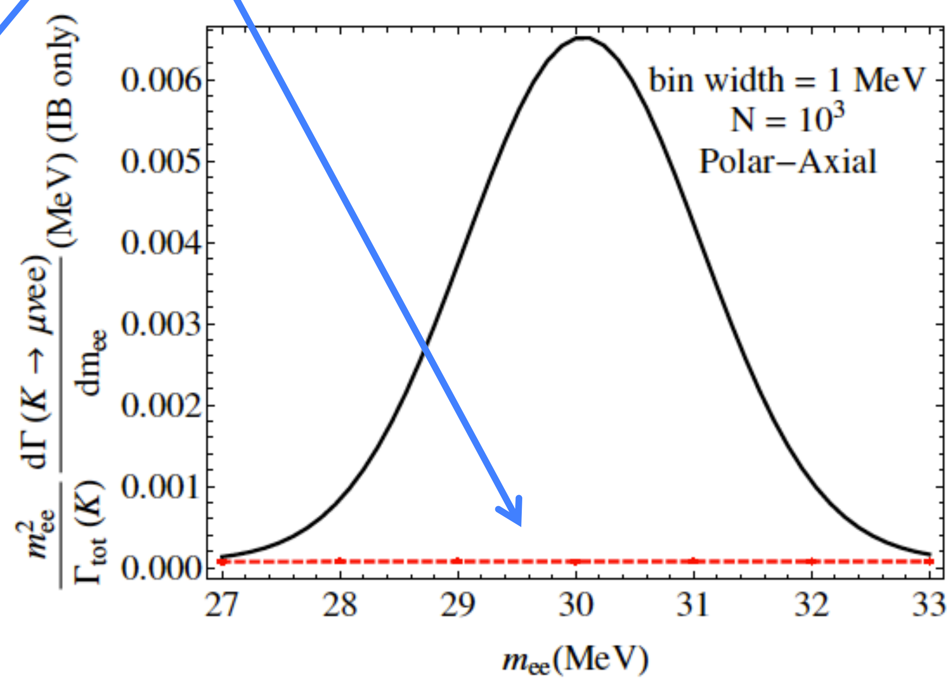
QED background: $K^+ \to \mu^+ \nu e^+ e^-$
- $\Gamma(K^+ \to \mu^+ \nu ee) \sim 2.5 \times 10^{-5}$
- *Expect 10^{10} stopped K^+ in E36*
- *250k QED evts or ~1000 / MeV*

Signal: $K^+ \to \mu^+ \nu A', A' \to e^+ e^-$

C. Carlson, B. Rislow, hep-ph/1310.2786

same background!





Carlson&Rislow model
(universality-violating, fine tuned); $\Gamma(K^+ \to \mu^+ \nu A') \sim 10^{-6} - 10^{-5}$

HUGE signals predicted, E36 very stringent test

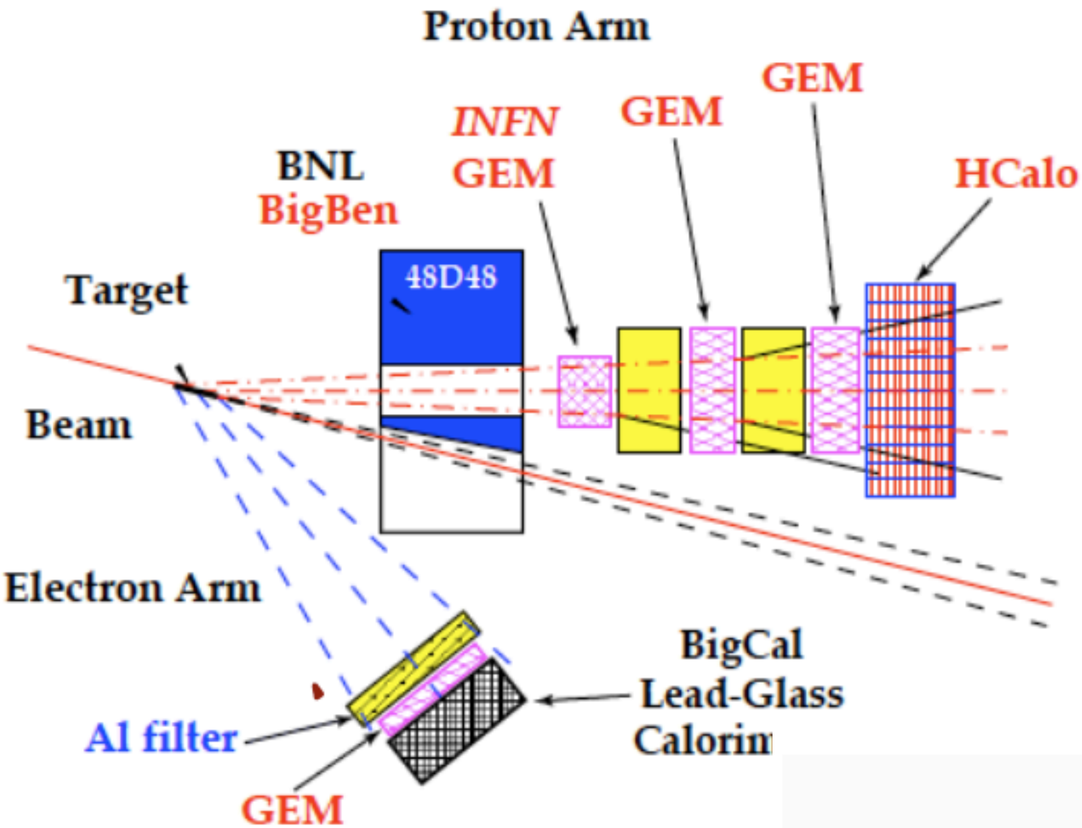
Summary

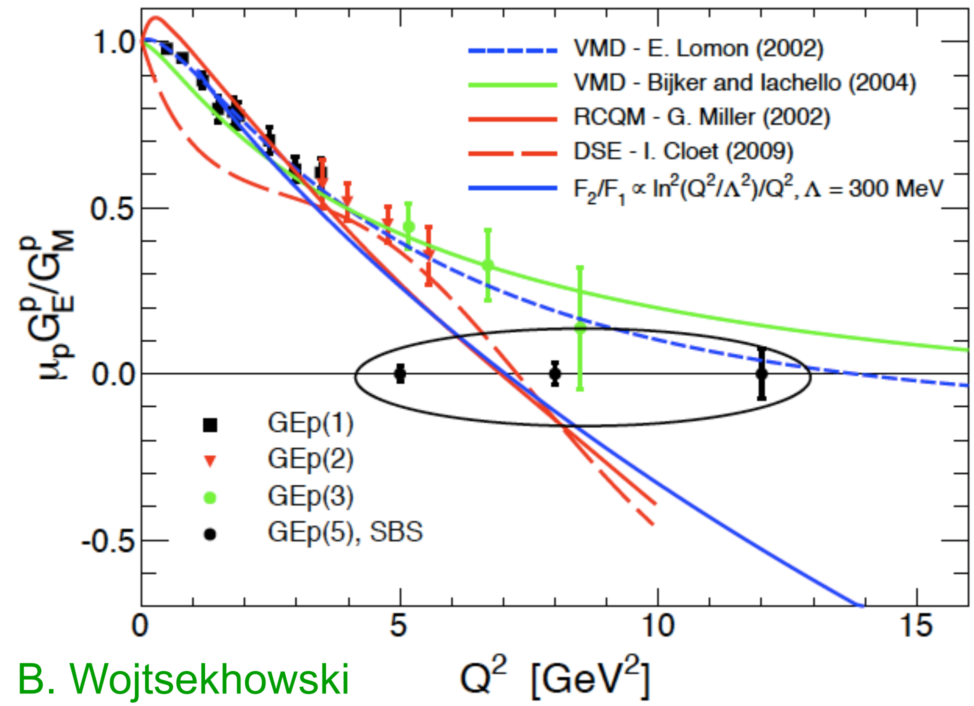
- The limits of OPE have been reached with available today's precision
  ➔ Nucleon elastic form factors, particularly G_E^p under doubt
- The TPE hypothesis is suited to remove form factor discrepancy, however calculations of TPE are model-dependent
- Experimental probes: Real part of TPE –
  - ε-dependence of polarization transfer
  - ε-nonlinearity of cross sections
  - Comparison of positron and electron elastic scattering
- The Proton Radius Puzzle has been standing since 2010
  - Muonic hydrogen Lamb shift: Proton rms radius 7σ smaller than with electronic hydrogen and electron scattering
  - PRad at JLab
  - MUon Scattering Experiment MUSE
  - New Physics tested with TREK/E36

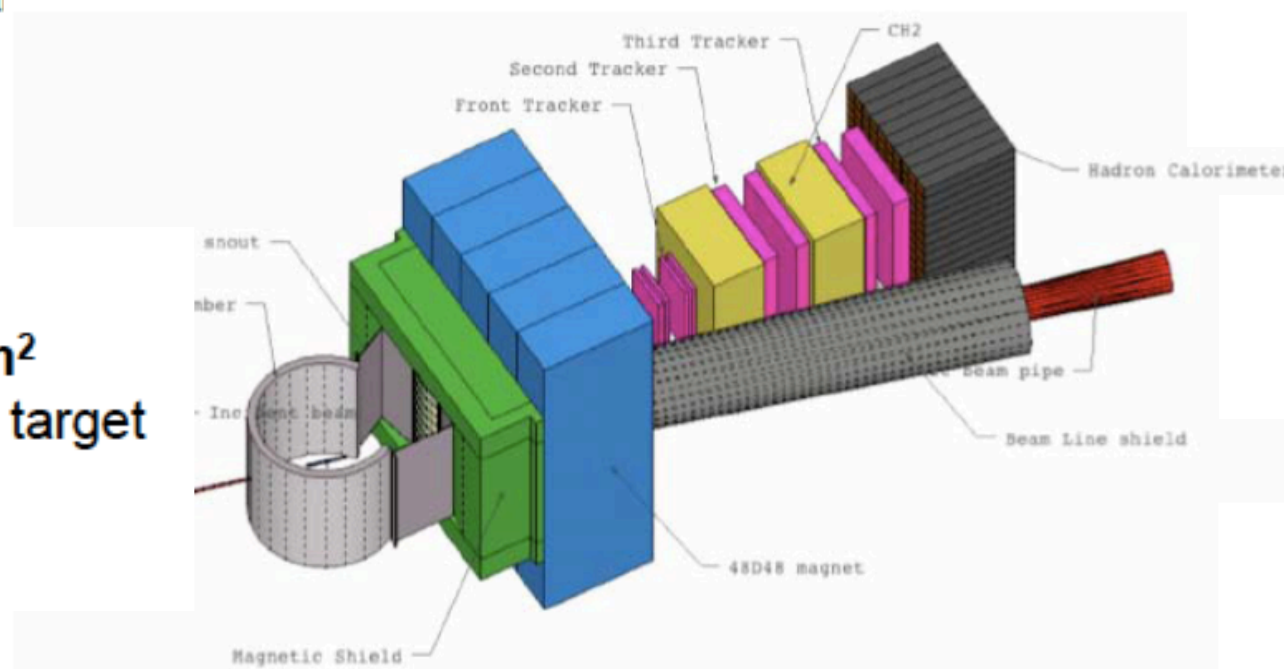
The nine muses

Backup

The proposed GEp-V experiment in Hall A







- Luminosities up to
  8×10^{38} e/s × nucleon/cm^2
- Full acceptance for 40cm long target
- v.good angular resolution
- good momentum resolution

Observables involving real part of TPE

$$P_t = -\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}} \frac{G_M^2}{d\sigma_{red}} \left\{ R + R\frac{\Re\left(\delta\tilde{G}_M\right)}{G_M} + \frac{\Re\left(\delta\tilde{G}_E\right)}{G_M} + Y_{2\gamma} \right\}$$

$$P_l = \sqrt{(1+\varepsilon)(1-\varepsilon)} \frac{G_M^2}{d\sigma_{red}} \left\{ 1 + 2\frac{\Re(\delta\tilde{G}_M)}{G_M} + \frac{2}{1+\varepsilon}\varepsilon Y_{2\gamma} \right\}$$

$$\frac{P_t}{P_l} = -\sqrt{\frac{2\varepsilon}{(1+\varepsilon)\tau}} \left\{ R - R\frac{\Re\left(\delta\tilde{G}_M\right)}{G_M} + \frac{\Re\left(\delta\tilde{G}_E\right)}{G_M} + 2\left(1 - R\frac{2\varepsilon}{1+\varepsilon}\right) Y_{2\gamma} \right\}$$

E04-019 (Two-gamma) ε dependence of recoil polarization

$$d\sigma_{red} / G_M^2 = 1 + \frac{\varepsilon R^2}{\tau} + 2\frac{\Re(\delta\tilde{G}_M)}{G_M} + 2R\frac{\varepsilon\Re(\delta\tilde{G}_E)}{\tau G_M} + 2\left(1 + \frac{R}{\tau}\right)\varepsilon Y_{2\gamma}$$

Rosenbluth non-linearity E05-017

e^+/e^- x-section ratio CLAS, VEPP3, OLYMPUS

$$\Re(\tilde{G}_E) = G_E(Q^2) + \Re(\delta\tilde{G}_E(Q^2,\varepsilon))$$

$$\Re(\tilde{G}_M) = G_M(Q^2) + \Re(\delta\tilde{G}_M(Q^2,\varepsilon))$$

$$R = G_E / G_M \qquad Y_{2\gamma} = 0 + \sqrt{\frac{\tau(1+\tau)(1+\varepsilon)}{1-\varepsilon}} \frac{\Re(\tilde{F}_3(Q^2,\varepsilon))}{G_M}$$

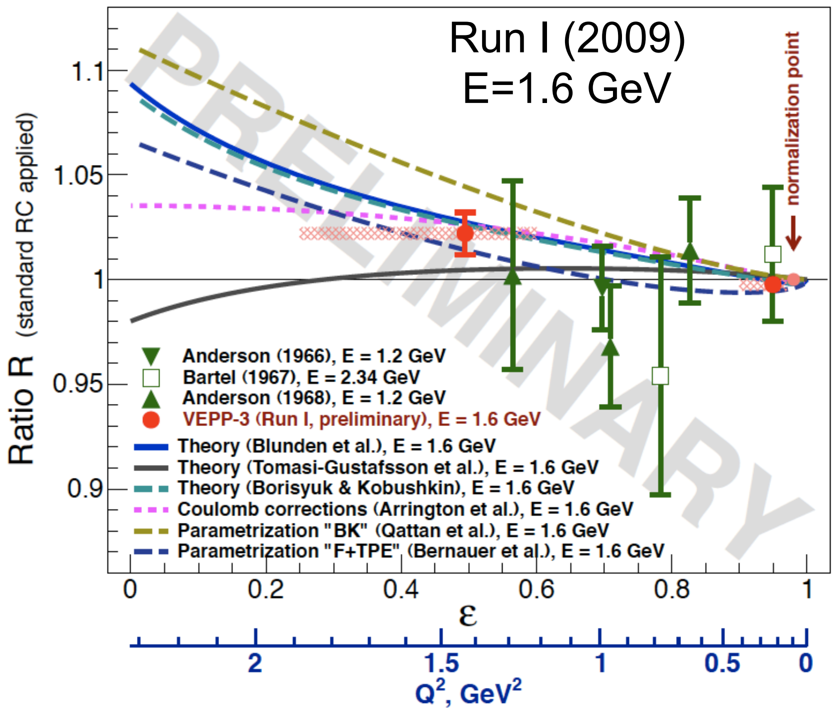
Born Approximation | **Beyond Born Approximation**

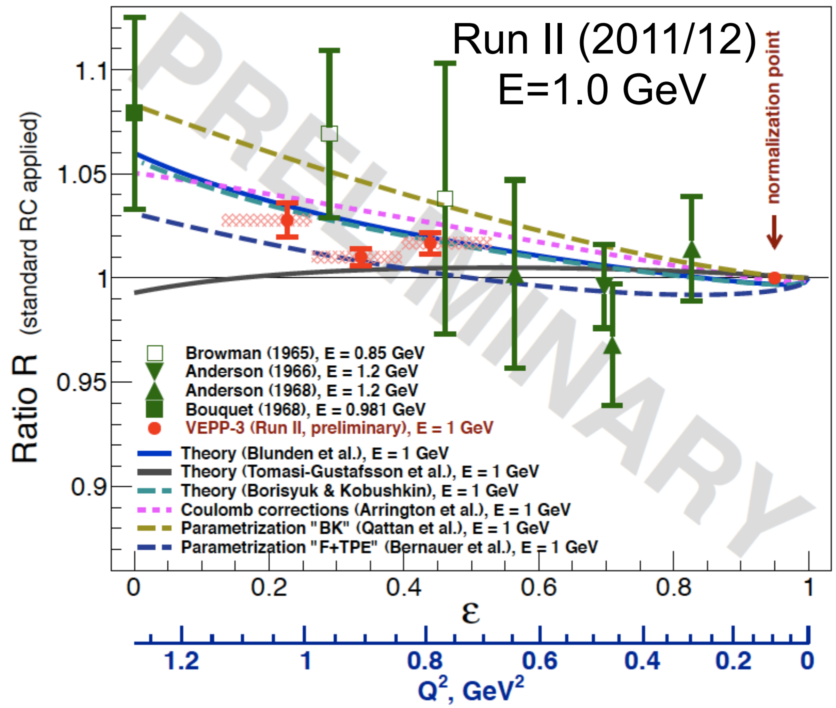
P.A.M. Guichon and M.Vanderhaeghen, Phys.Rev.Lett. 91, 142303 (2003)

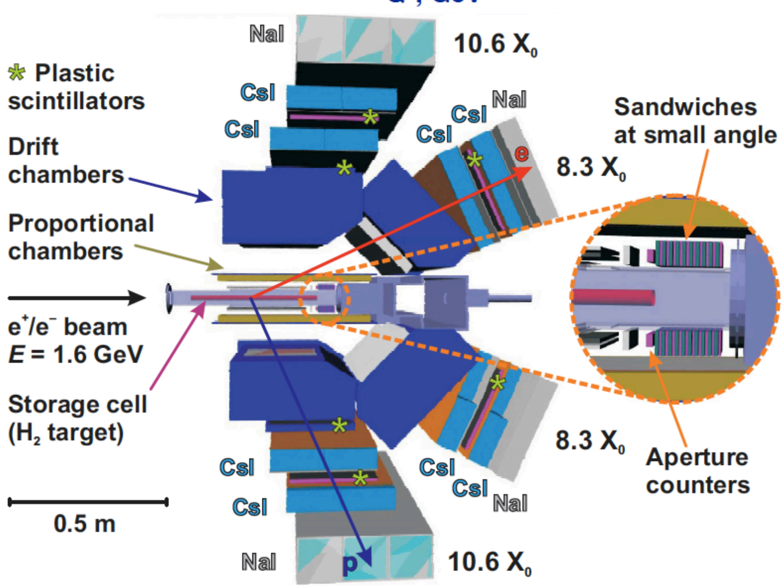
M.P. Rekalo and E. Tomasi-Gustafsson, E.P.J. A 22, 331 (2004)

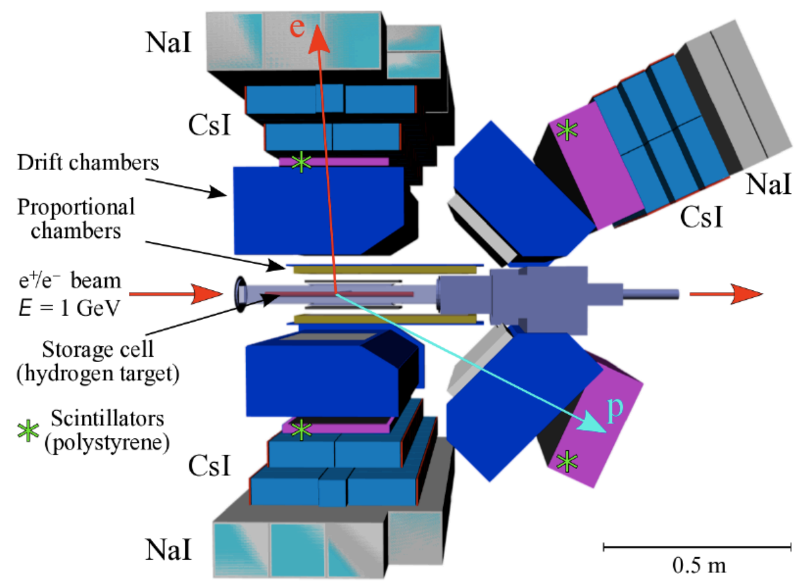
Slide idea: L. Pentchev

TPE experiments: Novosibirsk/VEPP-3



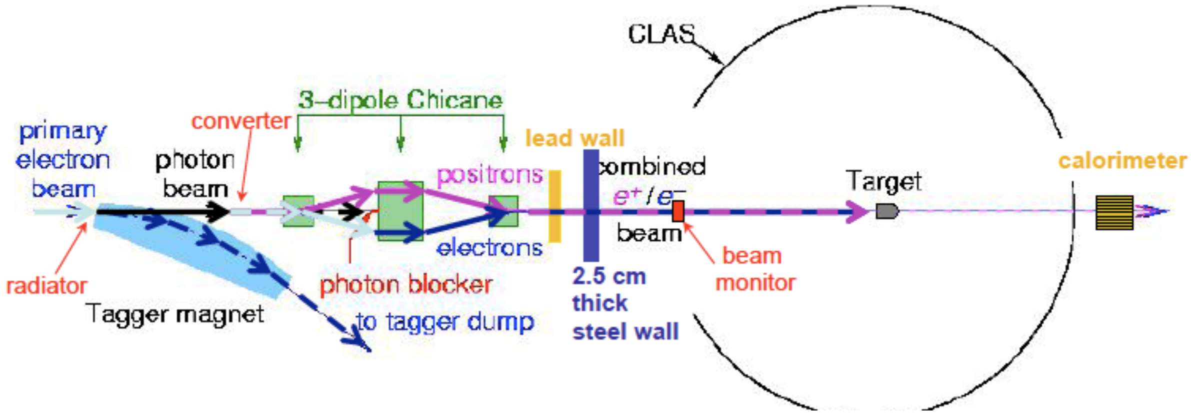


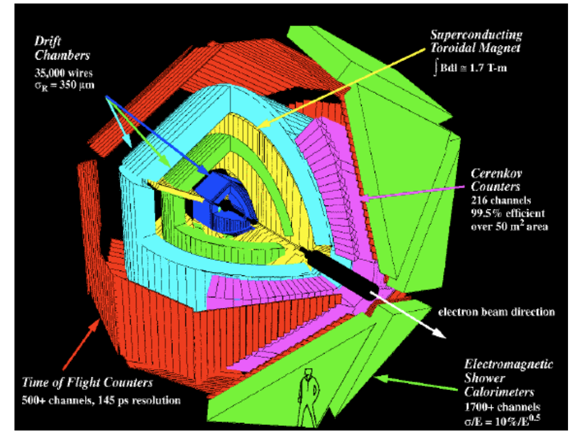


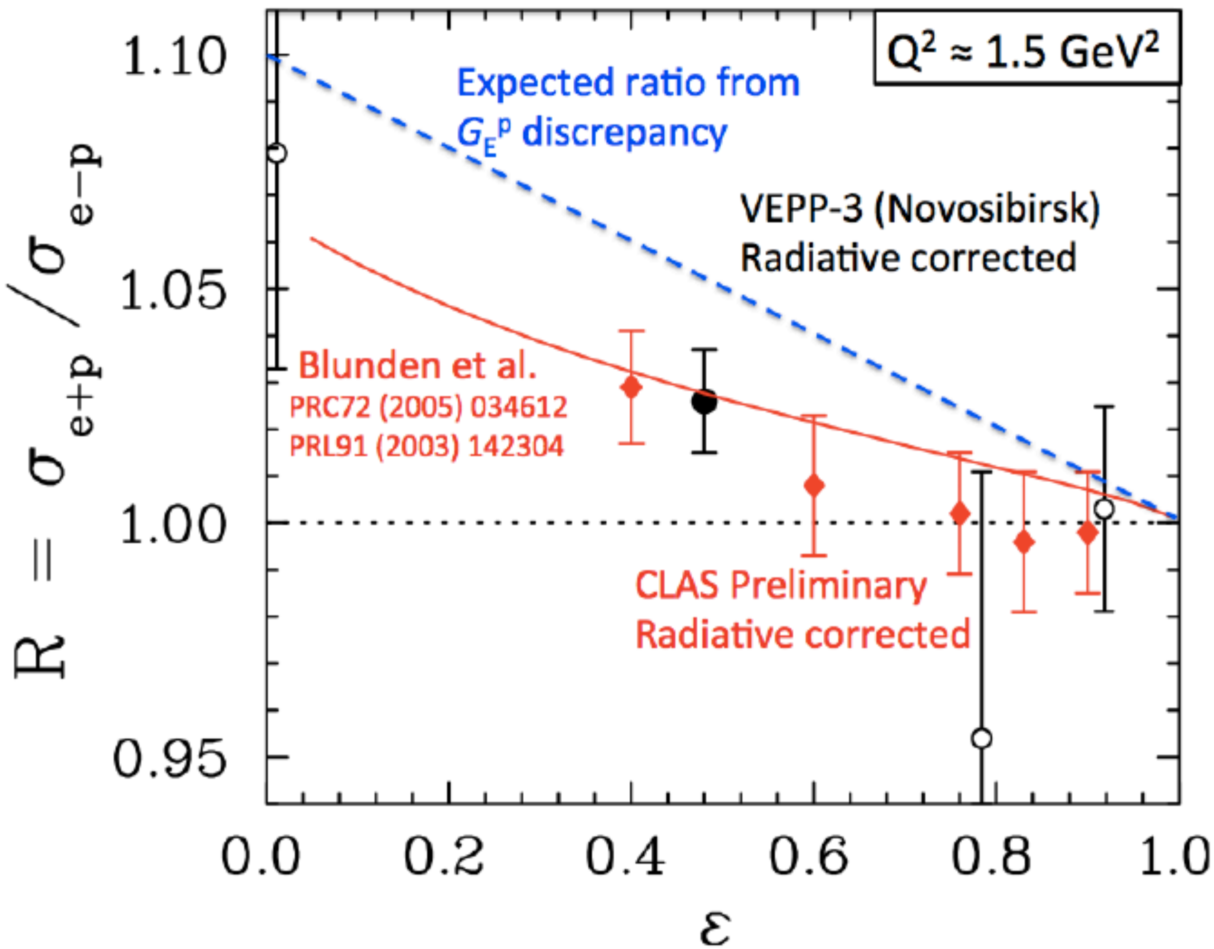


A. Gramolin, Workshop on Radiative Corrections in Annihilation and Scattering Experiments, Orsay, October 7-8, 2013

TPE experiments: CLAS (E04-116)



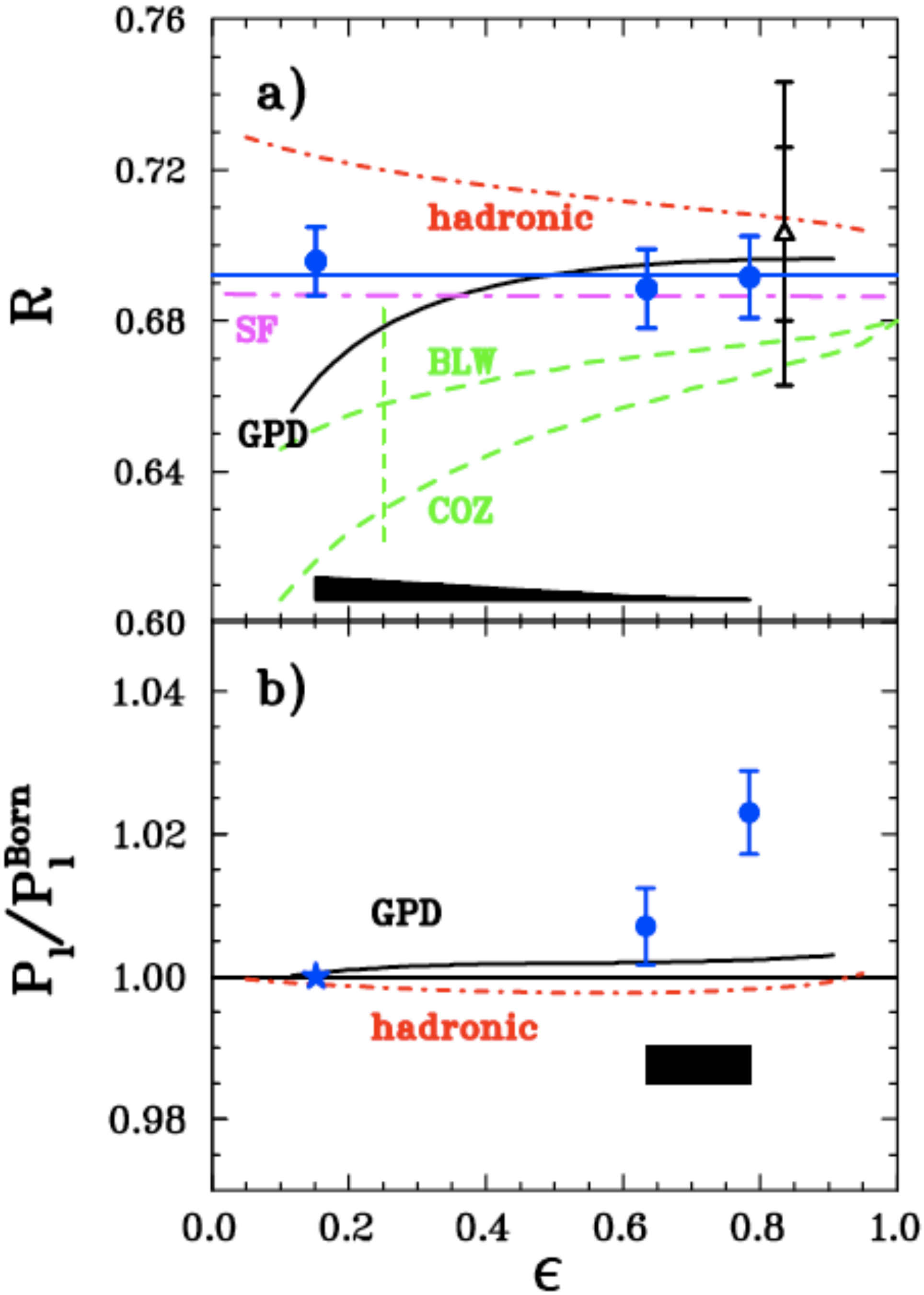




Dasuni Adikaram (ODU), DH.00005

Dipak Rimal (FIU) DH.00006

Jefferson Lab E04-019 (Two-gamma)



Jlab – Hall C
Q^2 = 2.5 (GeV/c)^2

G_E/G_M from P_t/P_l constant vs. ε

➔ **no effect in P_t/P_l**
➔ **some effect in P_l**

Expect larger effect in e+/e-!

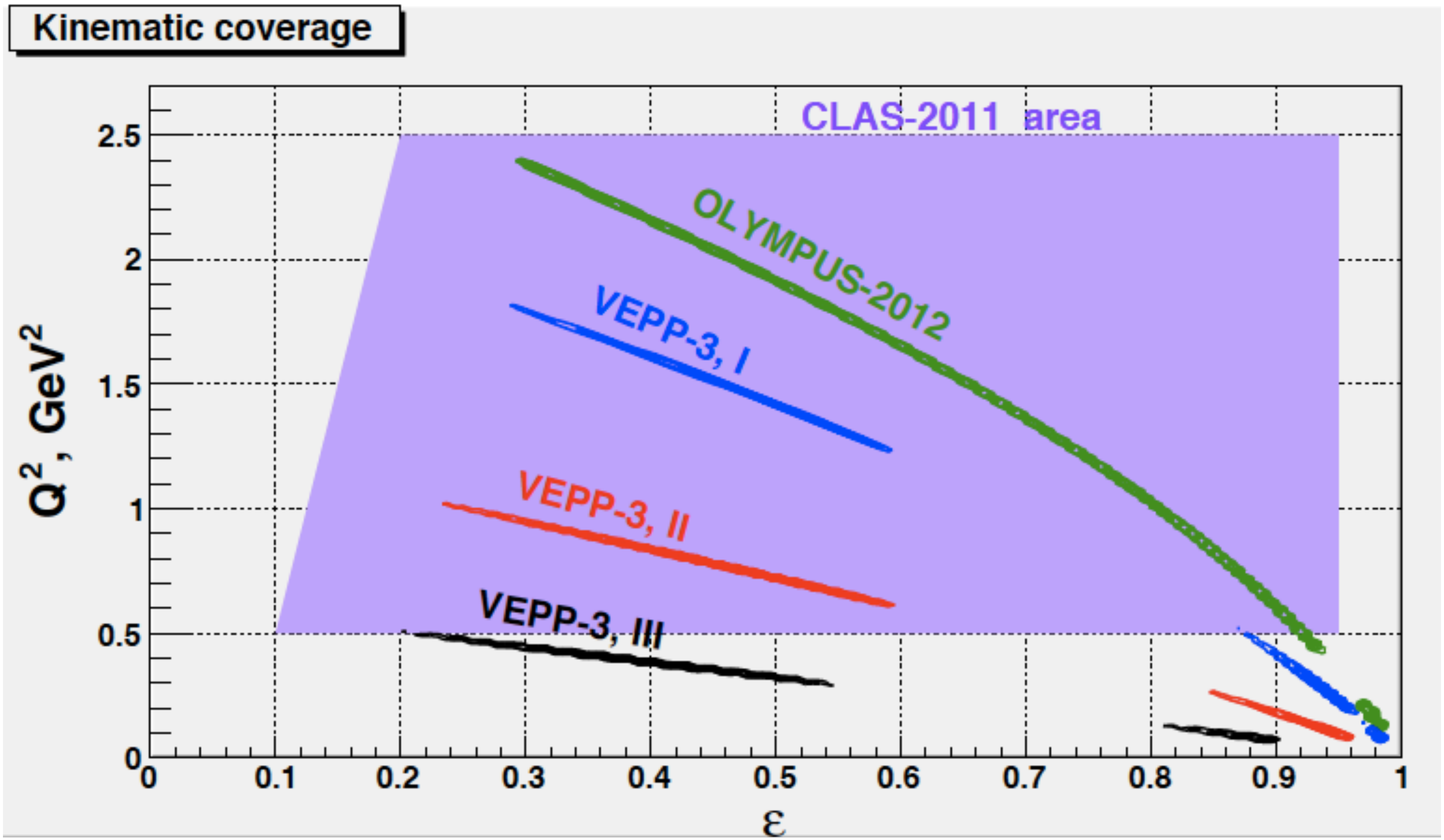
M. Meziane et al., hep-ph/1012.0339v2
Phys. Rev. Lett. 106, 132501 (2011)

Comparison of e^+/e^- experiments

	VEPP–3 Novosibirsk	OLYMPUS DESY	EG5 CLAS JLab
beam energy	3 fixed	1 fixed	wide spectrum
equality of $e^{\pm}$ beam energy	measured	measured	reconstructed
e^+/e^- swapping frequency	half-hour	8 hours	simultaneously
e^+/e^- lumi monitor	elastic low-Q^2	elastic low-Q^2, Möller/Bhabha	from simulation
energy of scattered $e^{\pm}$	EM-calorimeter	mag. analysis	mag. analysis
proton PID	$\Delta E/E$, TOF	mag. analysis, TOF	mag. analysis, TOF
e^+/e^- detector acceptance	identical	big difference	big difference
luminosity	1.0×10^{32}	2.0×10^{33}	2.5×10^{32}
beam type	storage ring	storage ring	secondary beam
target type	internal H target	internal H target	liquid H target
data taken	2009, 2011-12	2012	2011

Comparison of e^+/e^- experiments

- Novosibirsk experiment ($E_{beam} = 1.6$, 1 and 0.6 GeV)
- CLAS @ JLab experiment ($E_{beam} = 0.5 \div 4$ GeV)
- OLYMPUS @ DESY experiment ($E_{beam} = 2$ GeV)

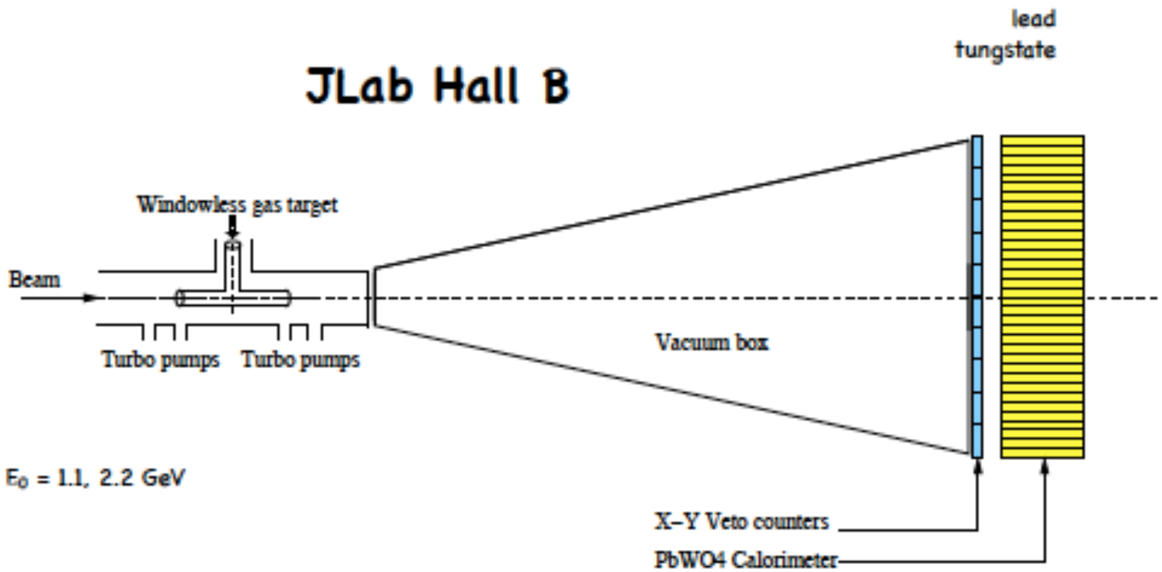


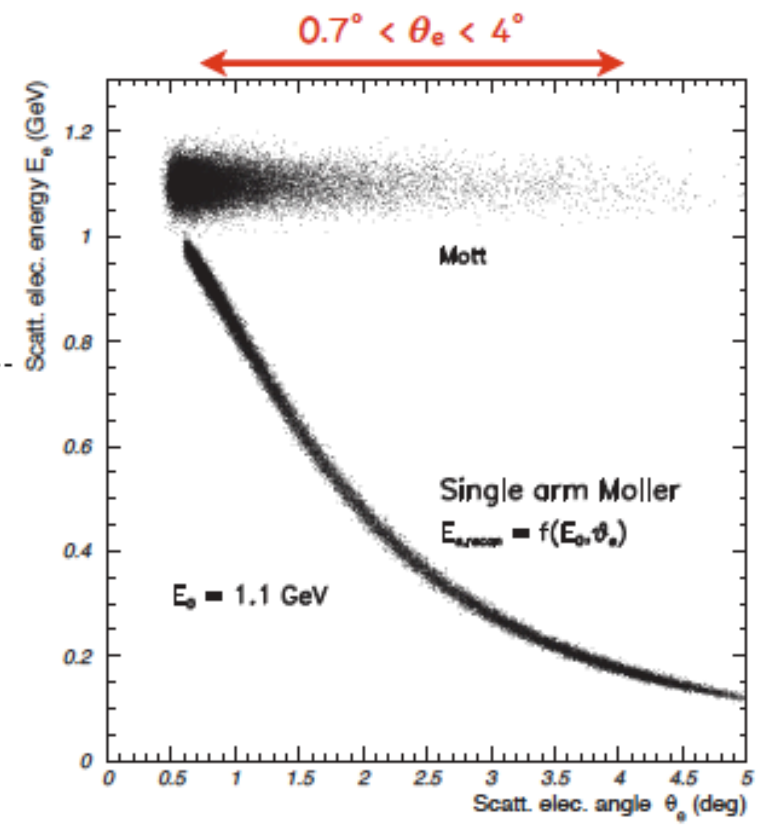
The PRad proton radius proposal (JLAB)

E12-11-106: Experimental method

(1) minimize experimental background:
high density windowless H_2 gas flow target

(3) Effective separation of Møller events from the ep elastic scattered events for angles $\theta_e > 0.7°$.



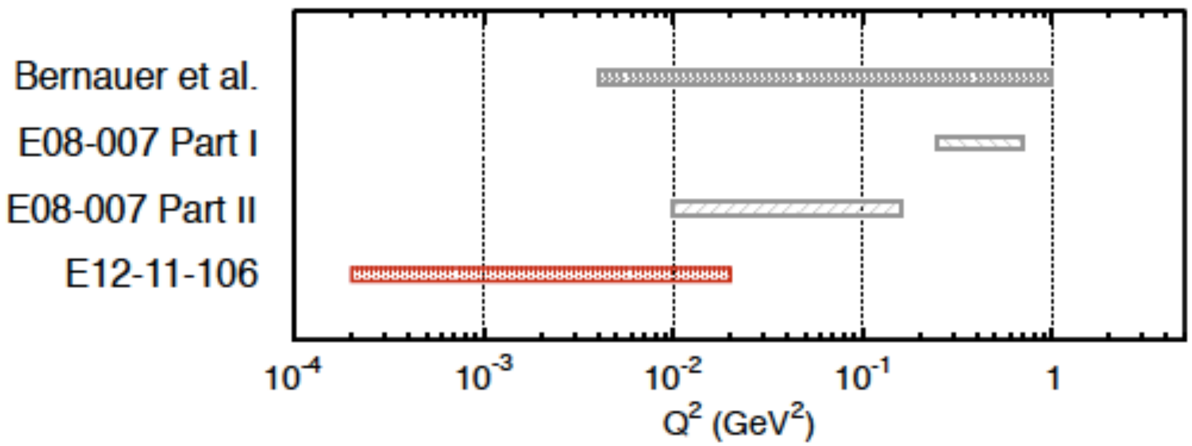


(2) Non-magnetic-spectrometer method:
high resolution, high acceptance crystal calorimeter

Jefferson Lab Experiment E12-11-106, A. Gasparian, H. Gao, and D. Dutta spokespeople.

The PRad proton radius proposal (JLAB)

E12-11-106: Very-low Q^2 elastic ep-scattering



Jefferson Lab Experiment E12-11-106, A. Gasparian, H. Gao, and D. Dutta spokespeople.

Very low Q^2 range: $2\text{x}10^{-4}$ to $2\text{x}10^{-2}$ GeV^2 → Model independent r_p extraction

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep}(Q_i^2)=\left[\frac{N(ep\to ep \text{ in } \theta_i\pm\Delta\theta)}{N(e^-e^-\to e^-e^-)}\cdot\frac{\epsilon_{geom}^{e^-e^-}}{\epsilon_{geom}^{ep}}\cdot\frac{\epsilon_{\text{det}}^{e^-e^-}}{\epsilon_{\text{det}}^{ep}}\right]\left(\frac{d\sigma}{d\Omega}\right)_{e^-e^-}$$

Møller scattering – well known QED process

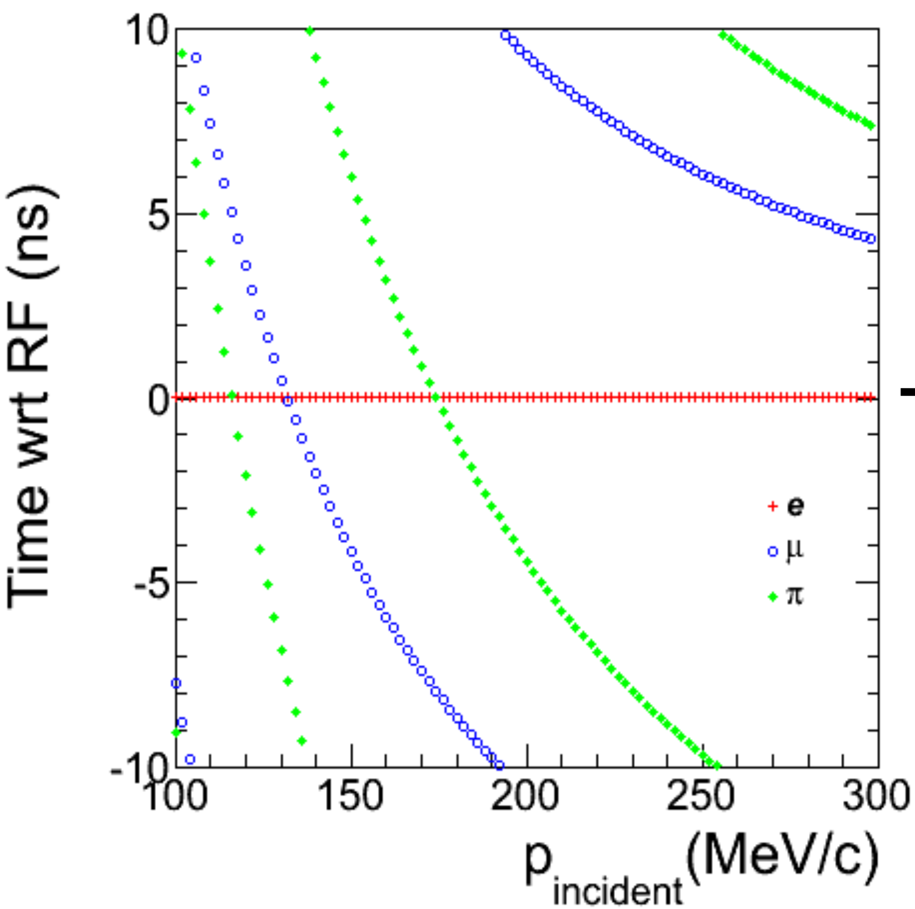
Simultaneous detection of two processes → N_e and N_{tgt} cancel

- ep → ep
- ee → ee (Møller scattering)

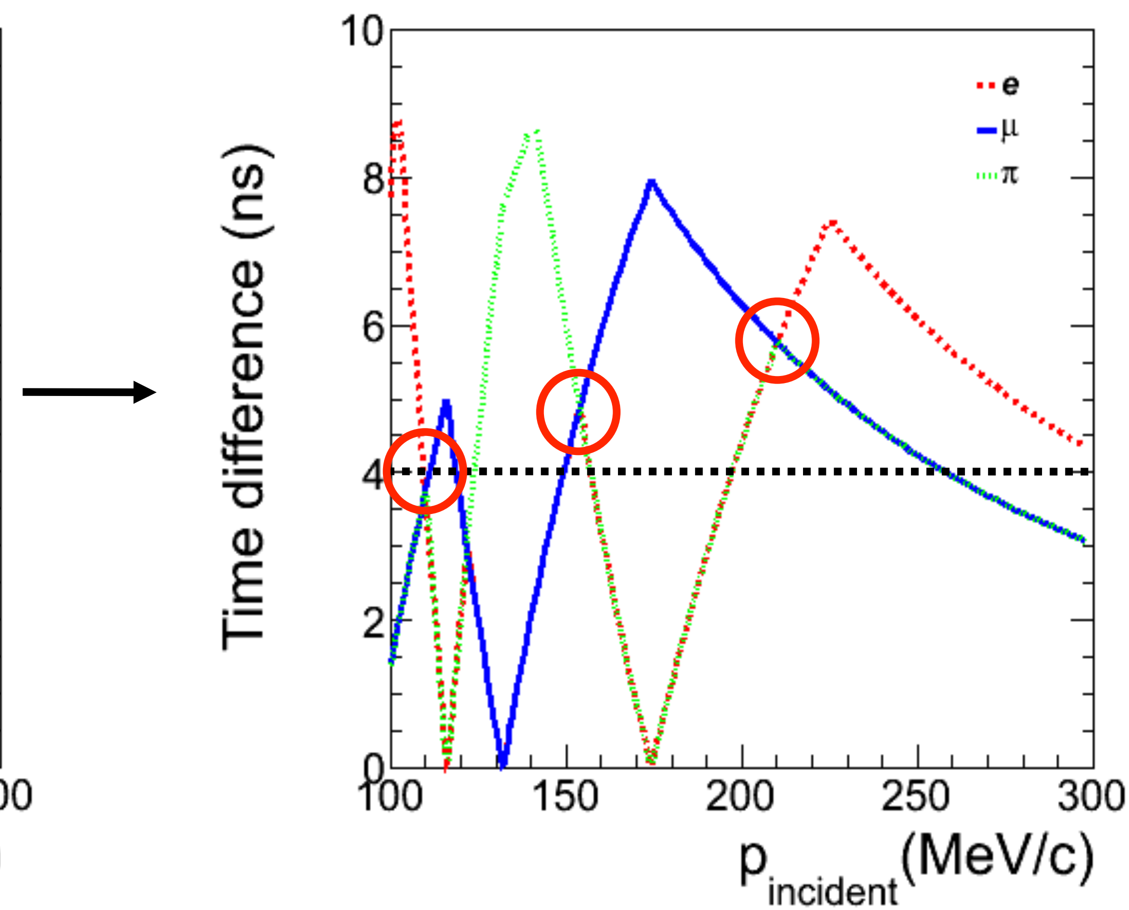
Separation of e, π, μ by RF time

Requirement: particle separation in time for PID
50 MHz RF → 20 ns between bunches

Timing of particles in target region
wrt electron (β = 1)



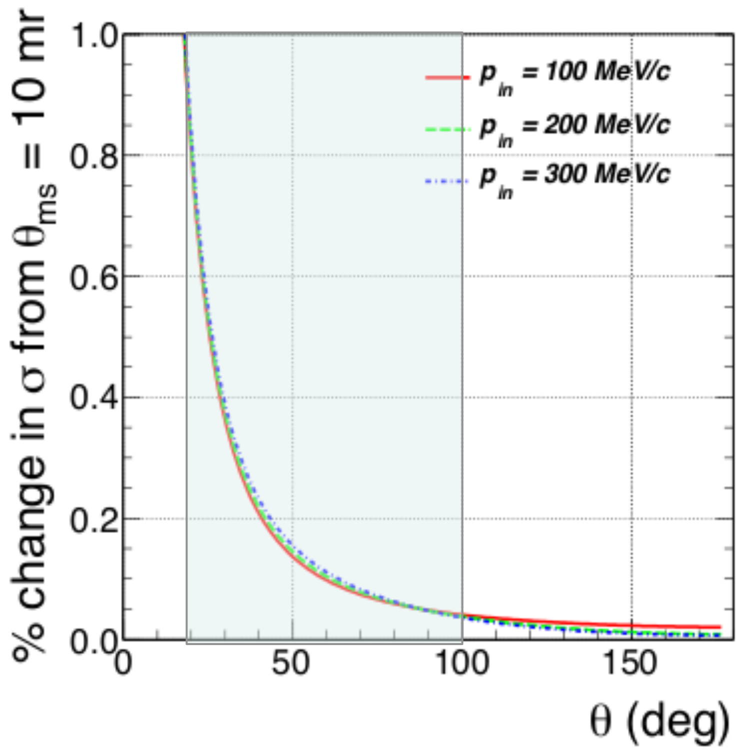
Minimum time separation of particles
in target region



p = 115, 153, and 210 MeV/c

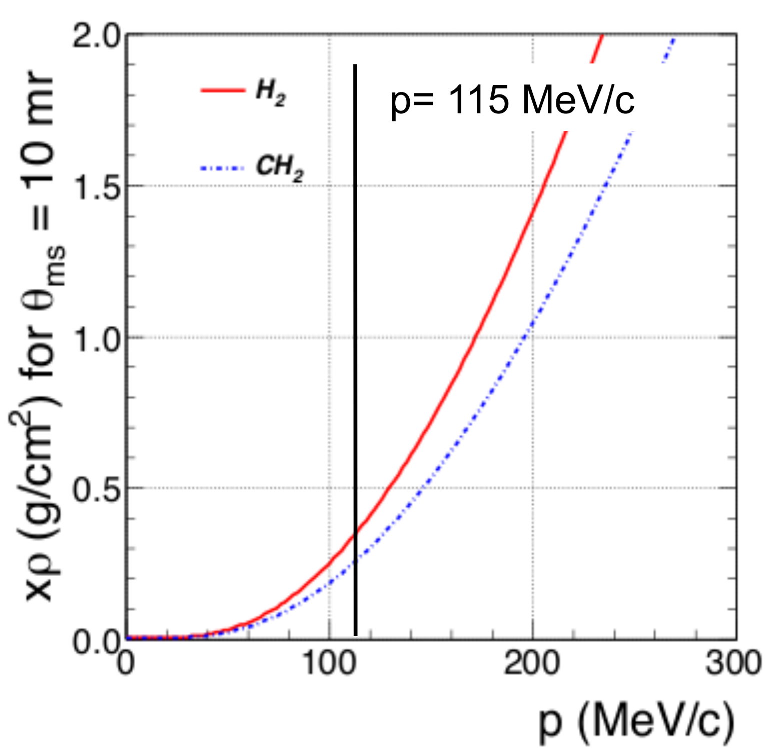
Beamline and target considerations

Target: → 4 cm LH2, thickness constrained by effects of multiple scattering



% change in cross section for θ_{ms} = 10 mr

→ Limits acceptance to > 20°



Target thickness giving θ_{ms} = 10 mr

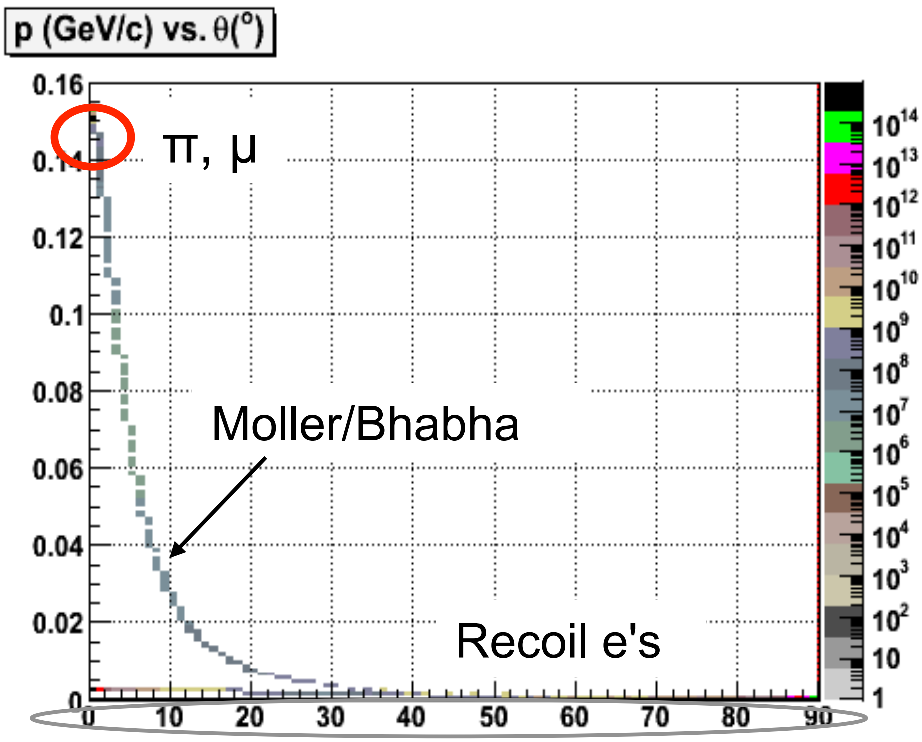
→ Limits target thickness to 0.3 g/cm^2

Beamline Cerenkov: provide redundant PID, and provide cross check for RF timing calibration

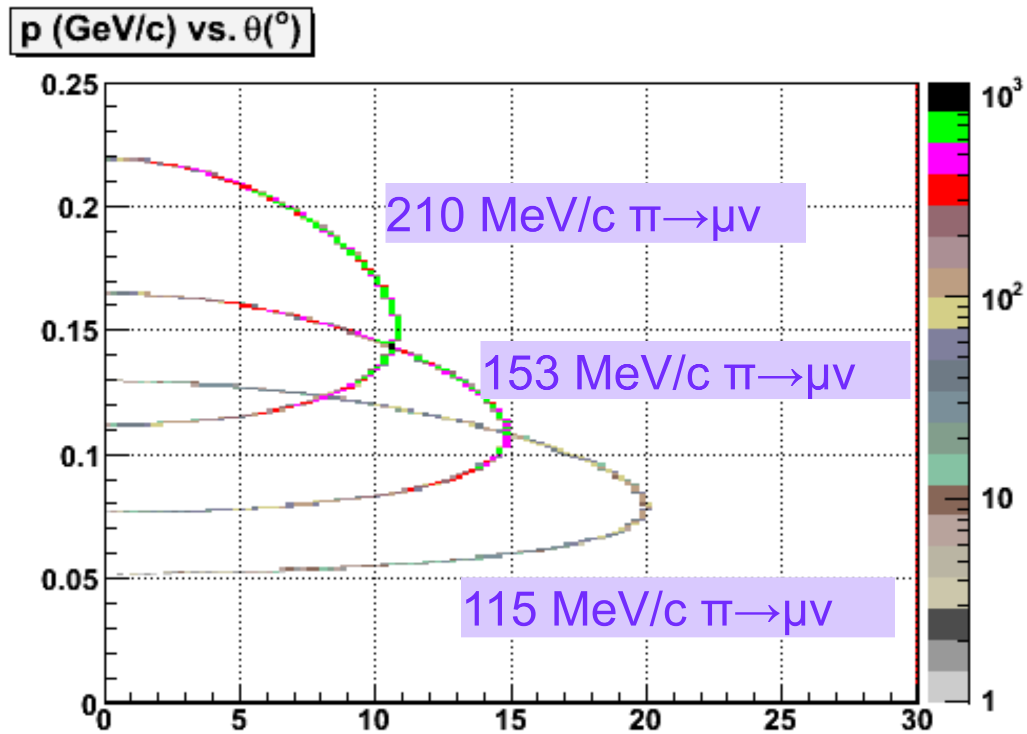
Background considerations

Requirement: low backgrounds or background rejection

Scattering from electrons:



Muons from π decays

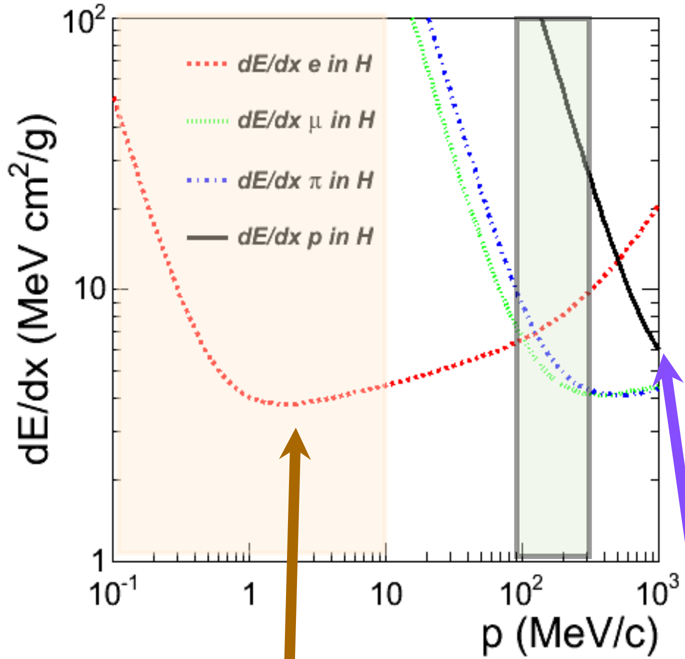


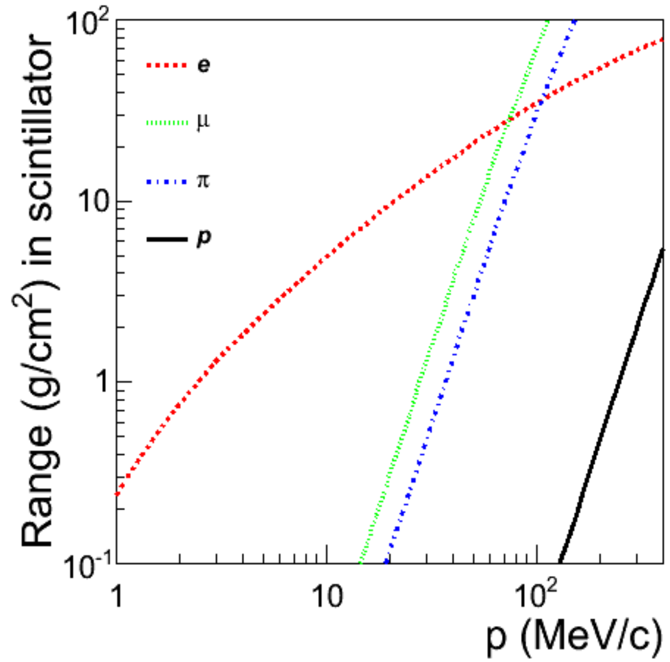
→ π, μ at forward angles
→ e-,e+ <10 MeV above 15°
→ Recoil e's low momentum

→ Will have π RF time
(3 orders of magnitude suppression)
→ Track will not point back to the target

Suppression of **μ → eνν background** with offline time-of-flight (8-20 σ)

Scattered particle considerations





Large angle, very low energy Moller / Bhabha e's lose large fraction of energy in target

Recoil protons E loss so large that all except forward angle recoil protons stopped in target

All the low-energy electron and proton backgrounds are ranged out in the first scintillator layer

Possible kaon decay channels in E36

K^+ decays ~ 10^{10}

Signal: $K^+ \rightarrow \pi^+ A'$, $A' \rightarrow e^+e^-$

Background: BR($K^+ \rightarrow \pi^+ e^+ e^-$) ~ 2.9 x 10^{-7} ~ 2,900 ev.

Signal: $K^+ \rightarrow \mu^+ \nu A'$, $A' \rightarrow e^+e^-$

Background: BR($K^+ \rightarrow \mu^+ \nu\ e^+ e^-$) ~ 2.5 x 10^{-5} ~ 250,000 ev.

Add. background from $K^+ \rightarrow \mu^+ \nu \pi^0 \rightarrow \mu^+ \nu\ e^+ e^- (\gamma)$

π^0 decays ~ 1) 3x10^8; 2) 2x10^9

π^0 production: 1) $K^+ \rightarrow \mu^+ \nu \pi^0$ (3.27%); 2) $K^+ \rightarrow \pi^+ \pi^0$ (21.13%)

Signal: $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow e^+e^-$

Background: BR($\pi^0 \rightarrow \gamma\ e^+ e^-$) ~ 1.2% ~ 0.3 (2.3) x$10^7$ ev.

P. Adlarson et al., 1304.0671 [hep-ex] (WASA/COSY): "World's largest sample" 5x10^5