HA.00002

Investigating the charge of the proton

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* Supported by NSF grants PHY-0855473, 0959521, and 1207672, and by DOE Early Career Award DE-SC0003884

Outline

Proton electric and magnetic form factors G_E and G_M

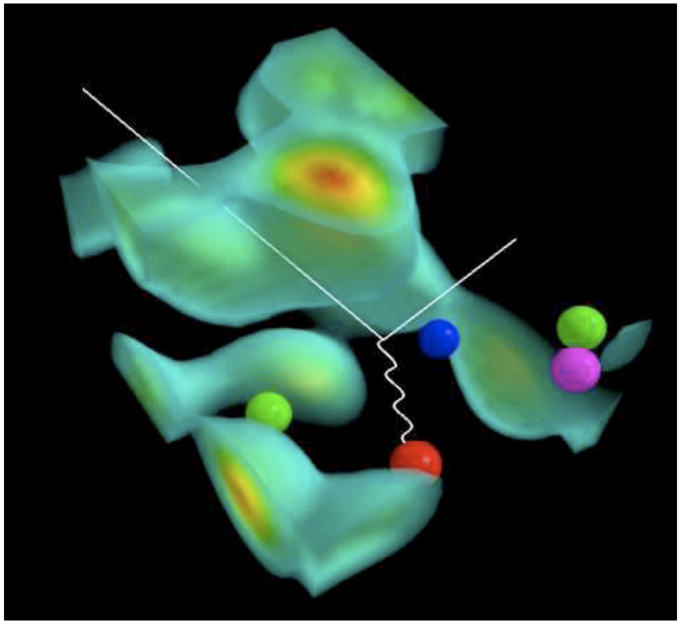
- Introduction, motivation and formalism
- Traditional and new techniques
- Overview of experimental data

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



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

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 – analysis in progress
GEp-V (& GMp) – high Q^2 at Jlab-12 – proposed

Rosenbluth separation

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

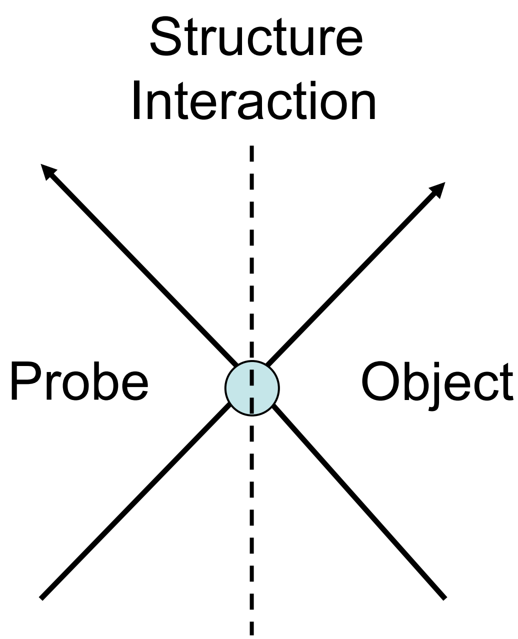
Positron-electron comparisons

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

Proton radius measurements

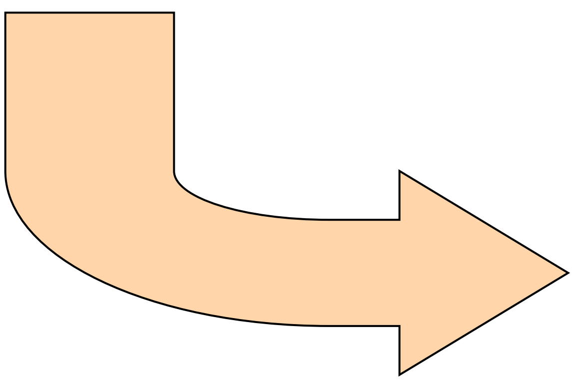
PSI / (muonic hydrogen Lamb shift, HFS) – published (2010, 2013)
MAMI / A1 (e-scattering) – published (2010)
Jlab / PRad (e-scattering) – proposed
PSI / MUSE ($e^{\pm}$, $\mu^{\pm}$ scattering) – proposed

Hadronic structure and EM interaction



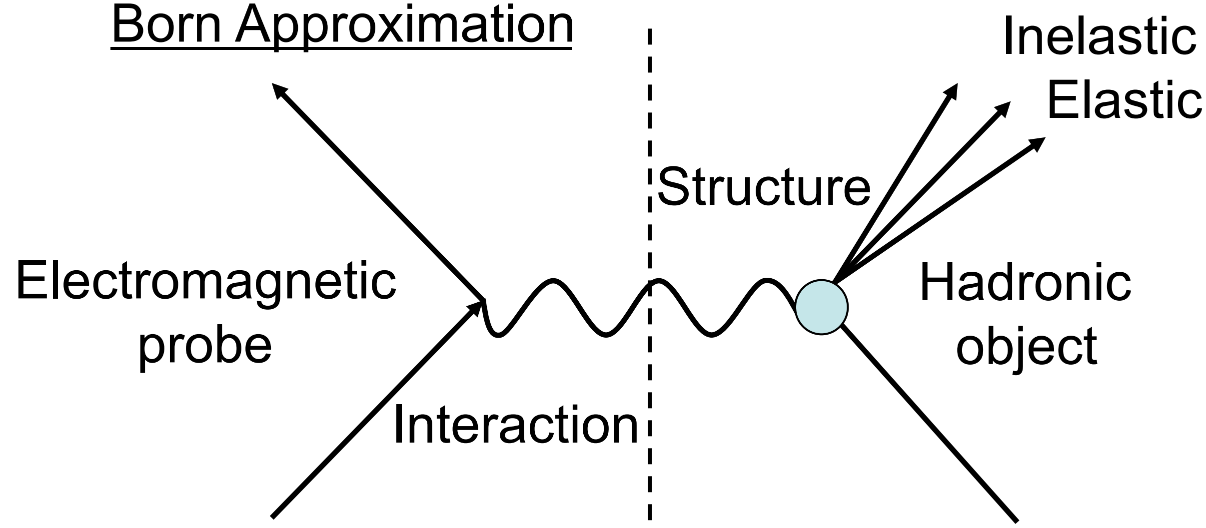
Factorization!

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



Lepton scattering

Born Approximation



One-Photon Exchange Approximation

The beginnings

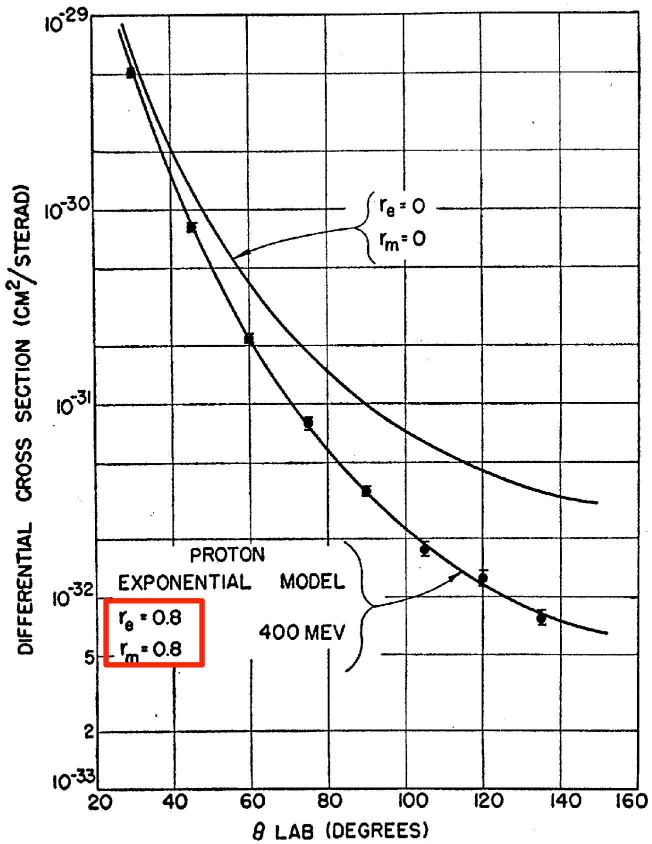


FIG. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with rms radii = 0.80×10^{-13} cm.

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

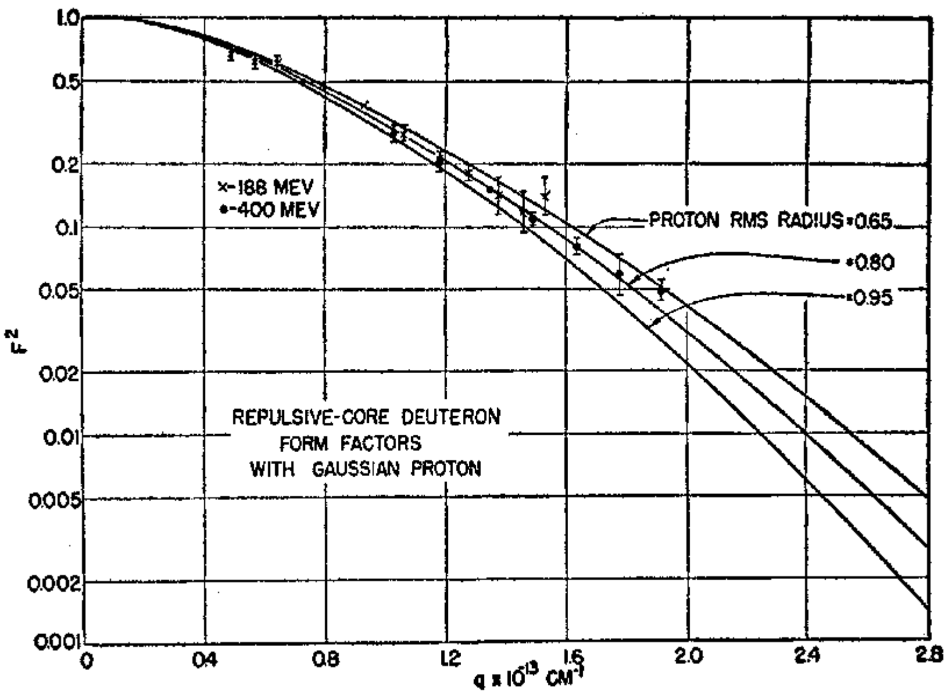
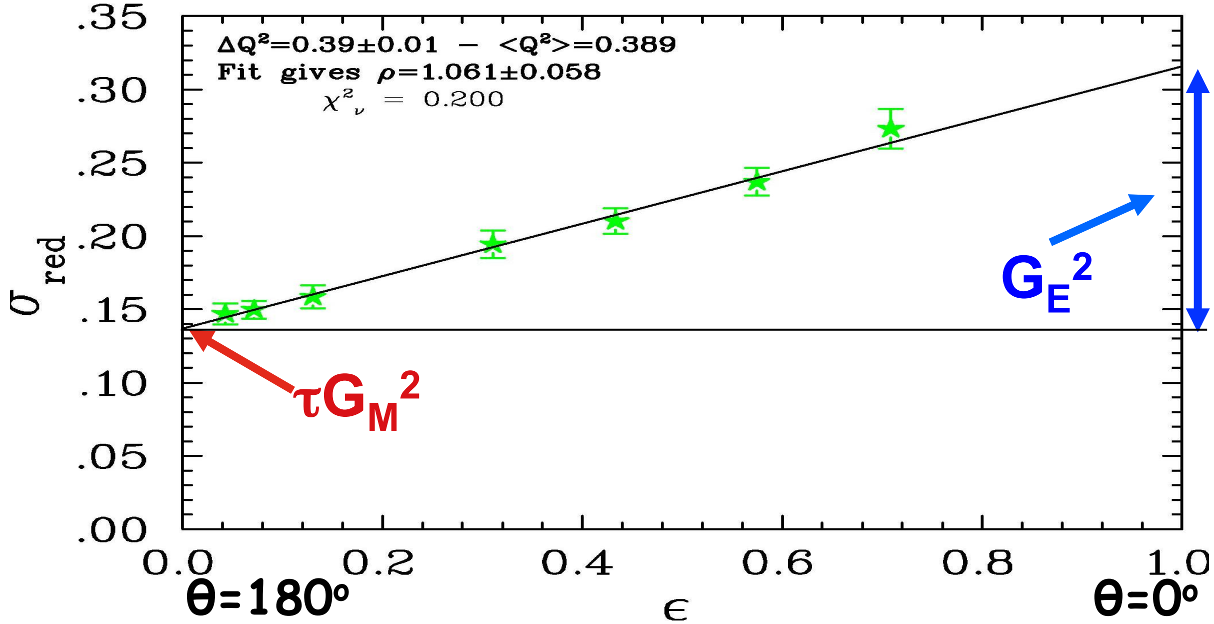


FIG. 31. Introduction of a finite proton core allows the experimental data to be fitted with conventional form factors (McIntyre).

ed-elastic
Finite size + nuclear structure

Form factors from Rosenbluth method



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

→Determine

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

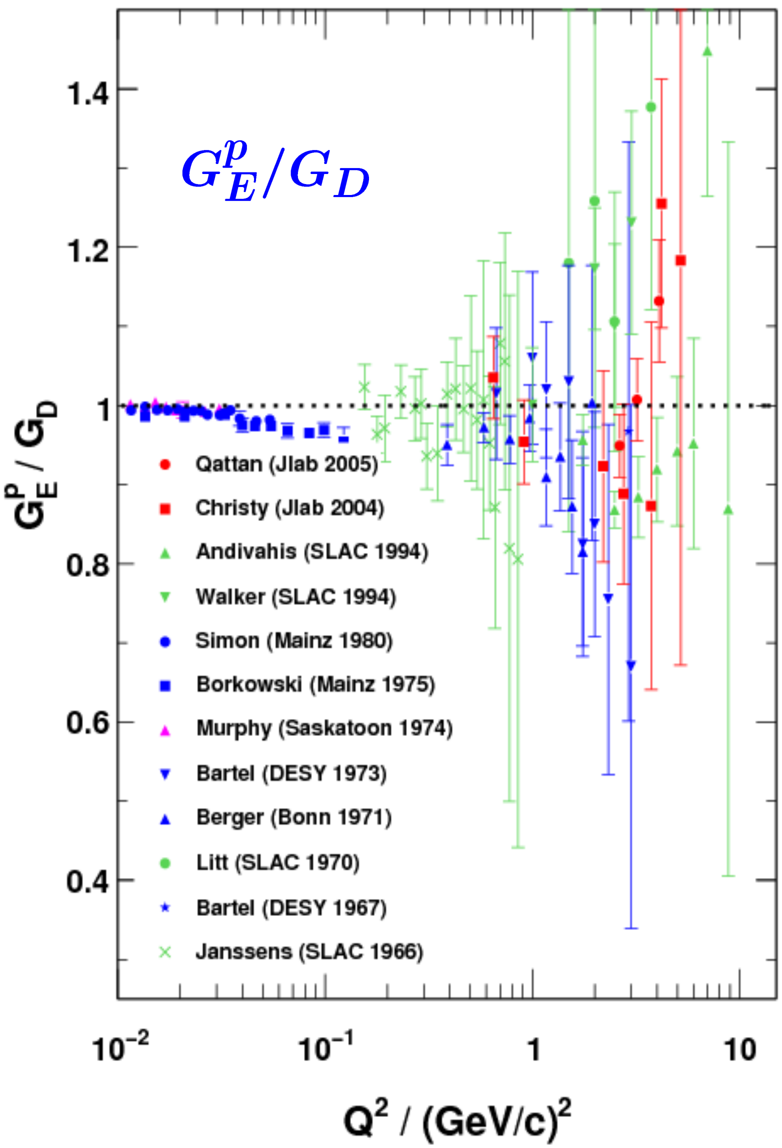
- In One-photon exchange, form factors are related to radiatively corrected elastic electron-proton scattering cross section

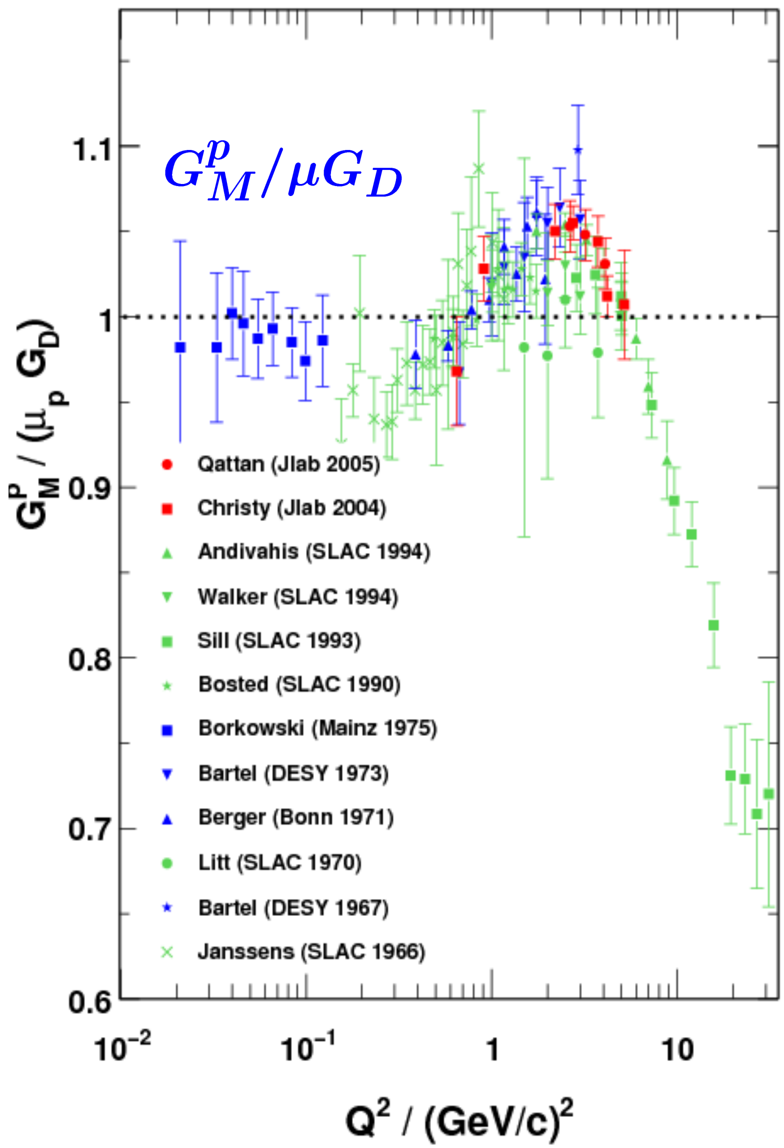
$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = S_0 = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}$$

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

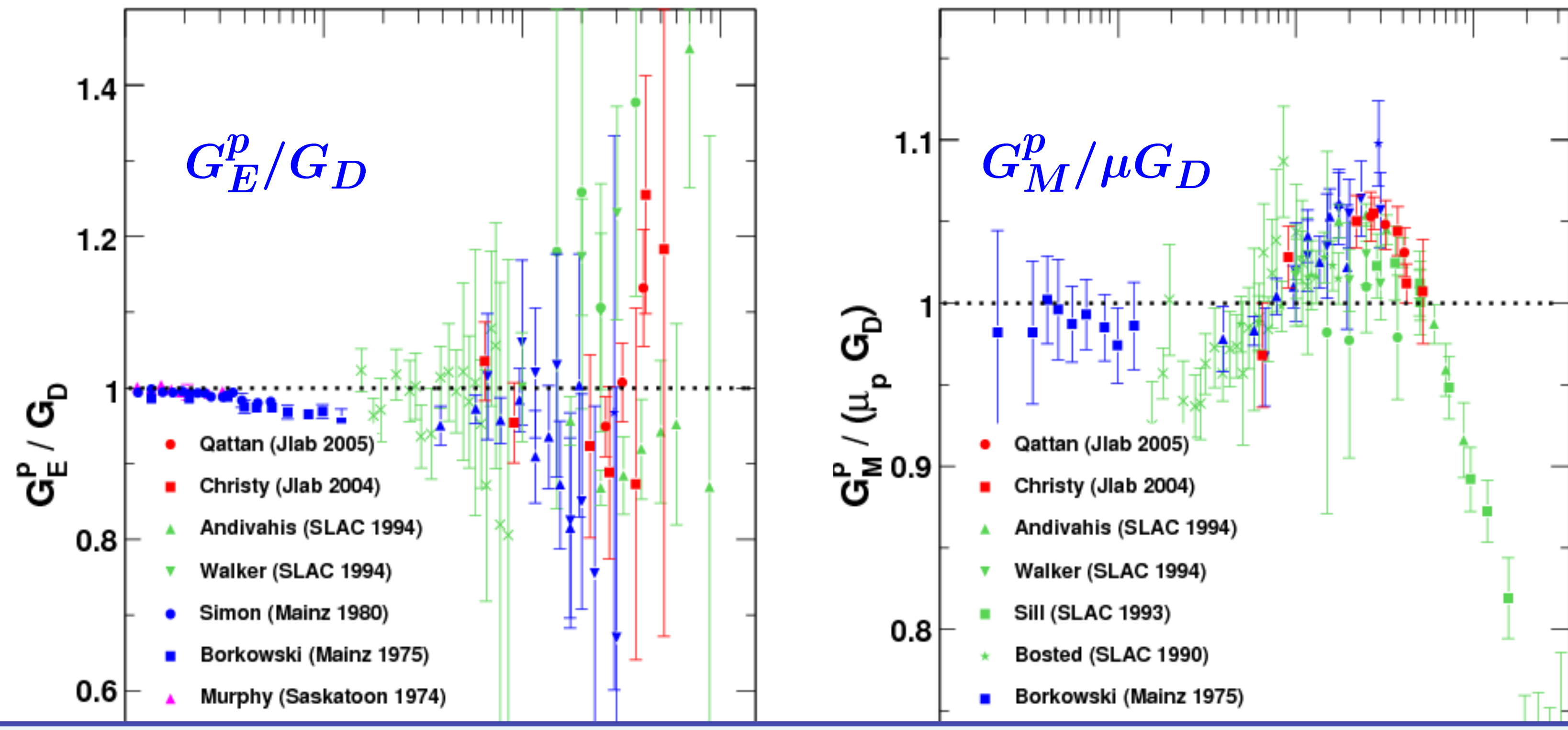
$$= \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)}, \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

G^p_E and G^p_M from unpolarized data





G^p_E and G^p_M from unpolarized data

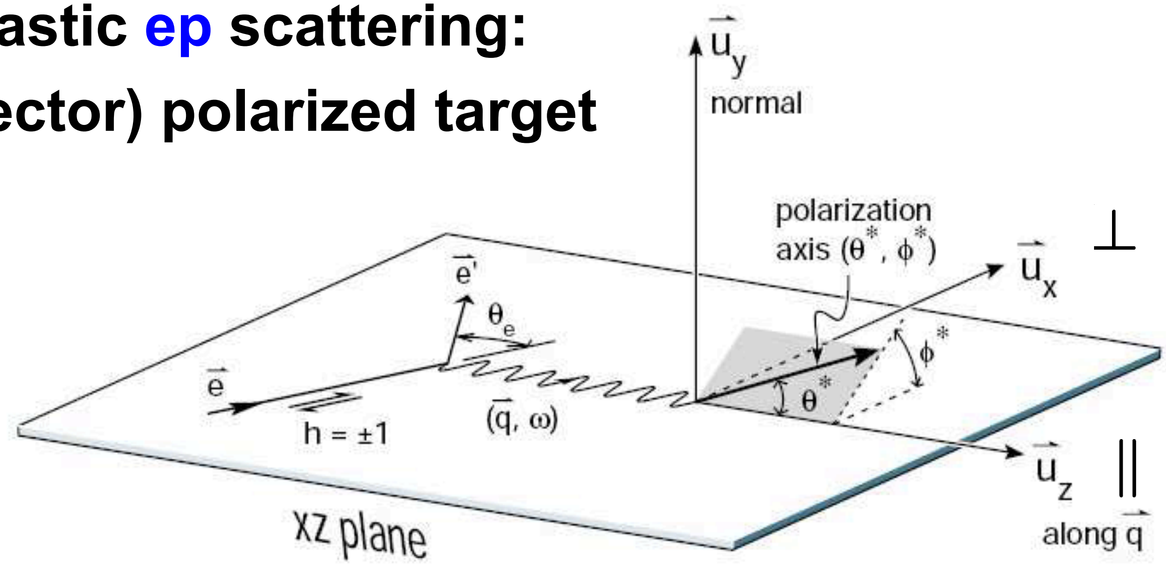


- $G(Q^2) \overset{\text{Fourier}}{\longleftrightarrow} \rho(r)$ **charge and magnetization density (Breit fr.)**
- **Dipole form factor** $G_D = \frac{1}{\left(1+\frac{Q^2}{0.71}\right)^2} \longleftrightarrow \rho_D(r) = \rho_0\, \mathrm{e}^{-\sqrt{0.71}r}$
- $G_E^p \approx G_M^p/\mu_p \approx G_M^n/\mu_n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

Nucleon form factors and polarization

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

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



- **Polarized cross section**

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

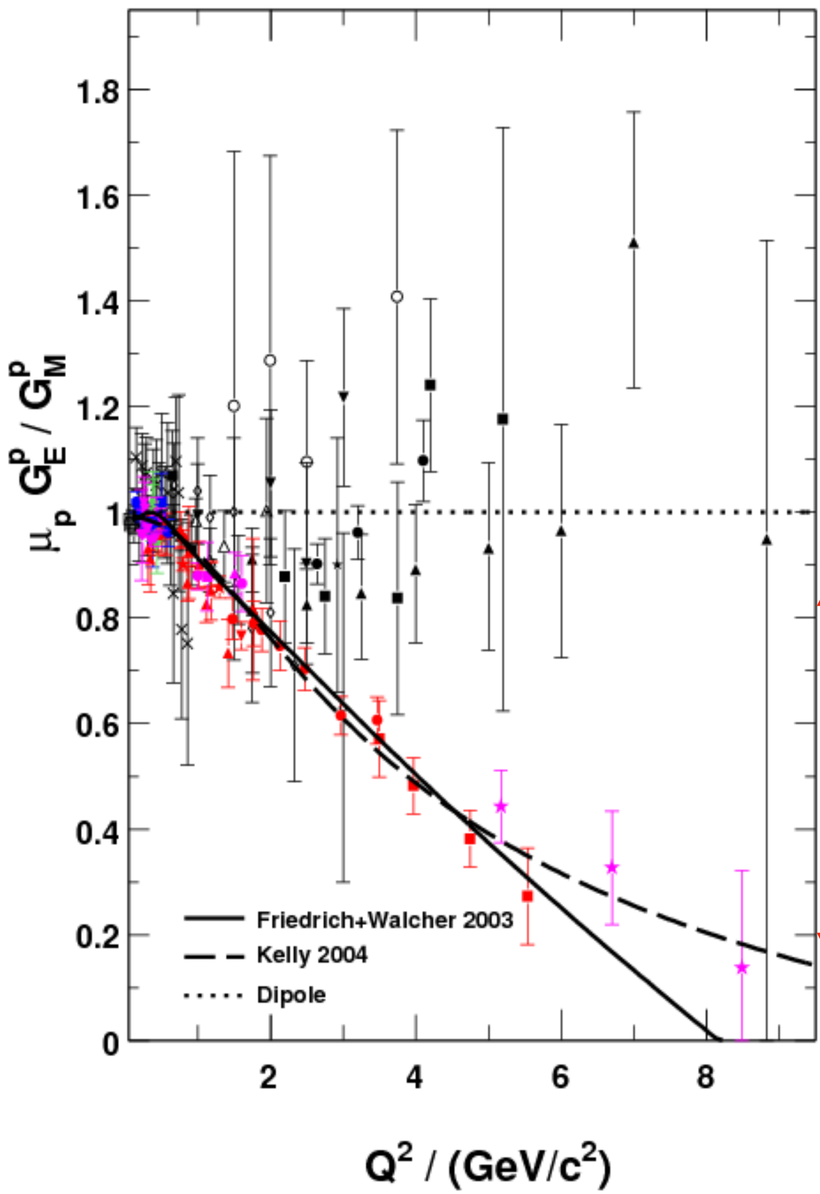
- **Double polarization observable = spin correlation**

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

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

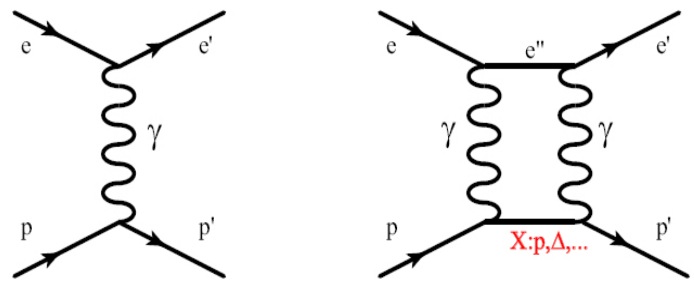
  independent of polarization or analyzing power

Proton form factor ratio



Jefferson Lab 2000–

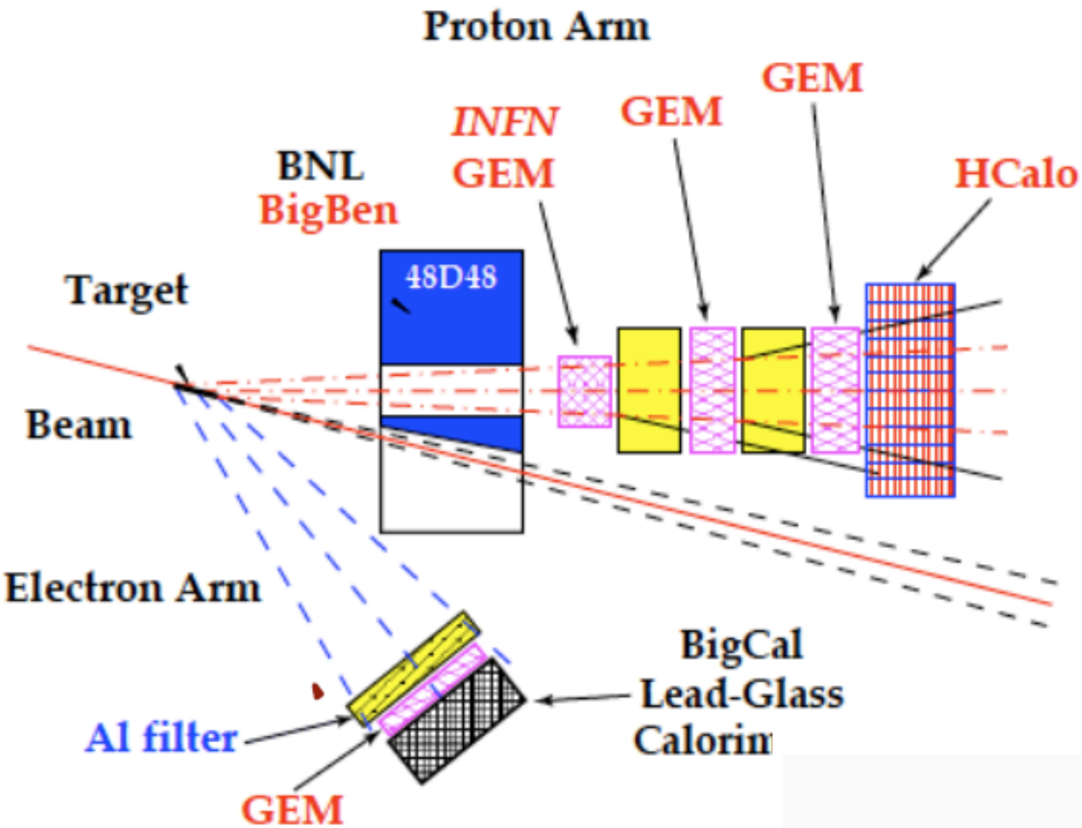
- All Rosenbluth data from SLAC and Jlab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Multi-photon exchange considered best candidate

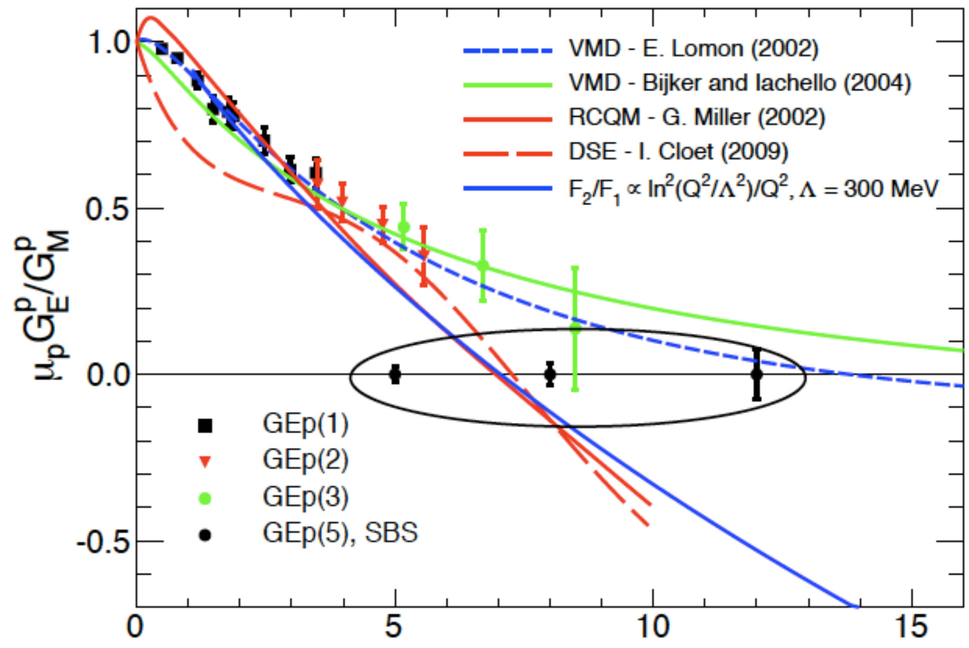


Dramatic discrepancy!

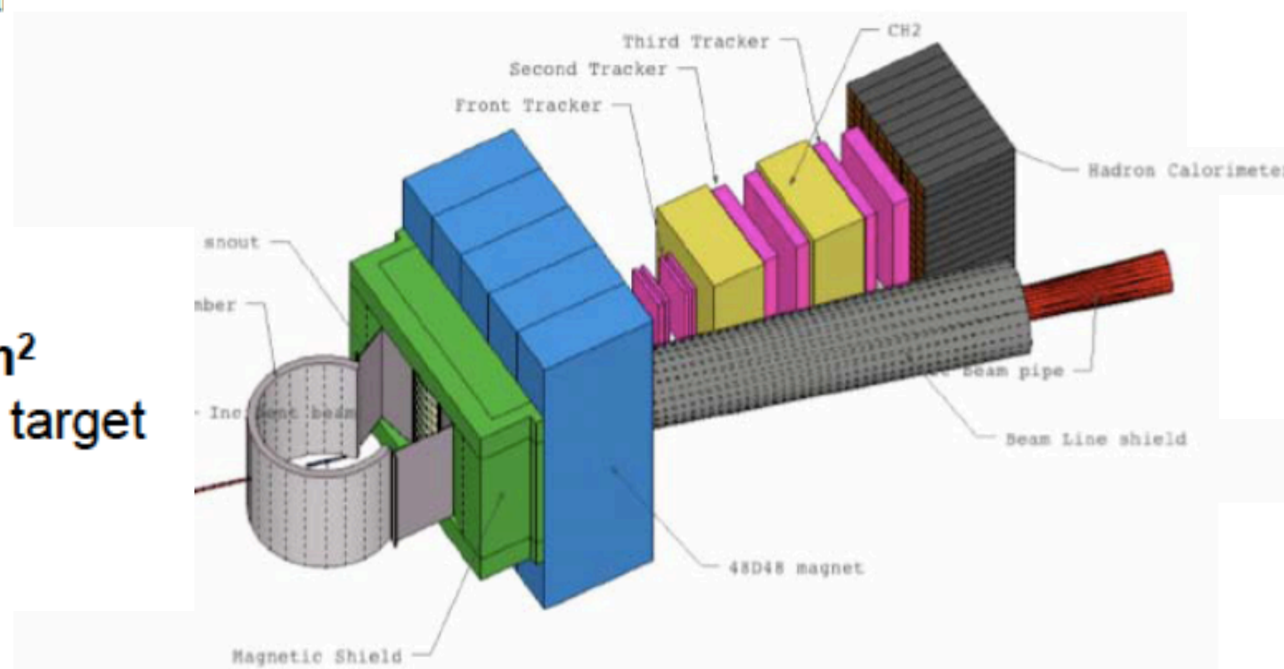
>800 citations

The proposed GEp-V experiment in Hall A



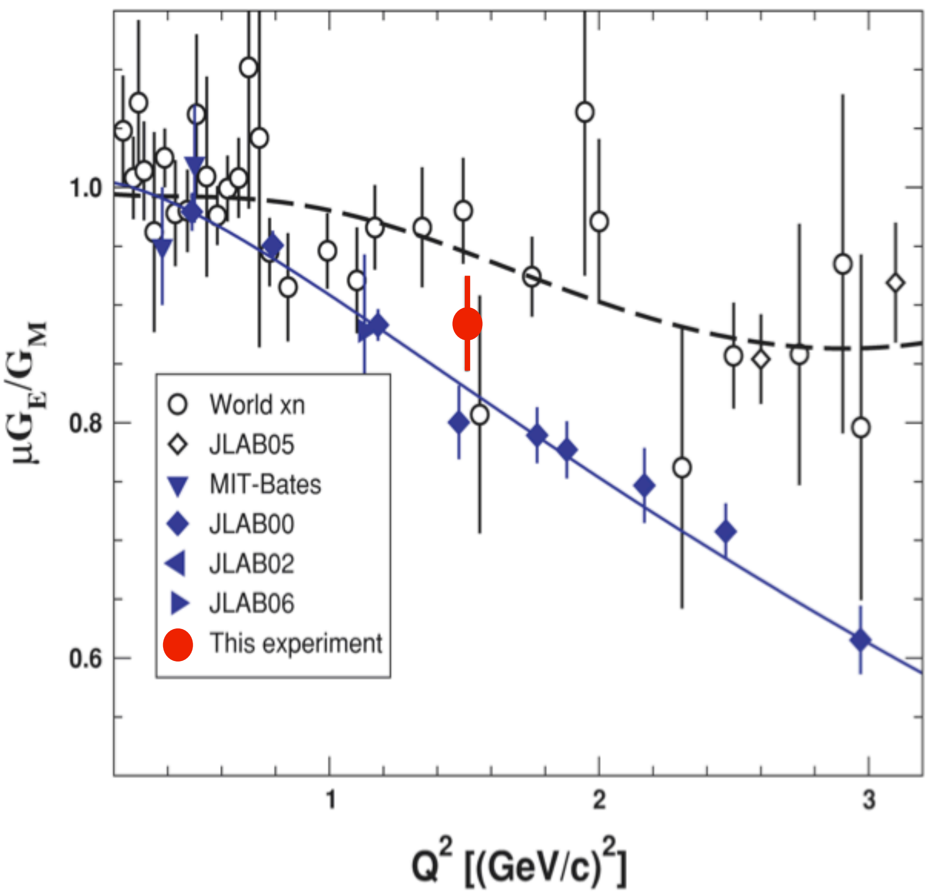


B. Wojtsekhowski



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

Polarized target data at high Q^2



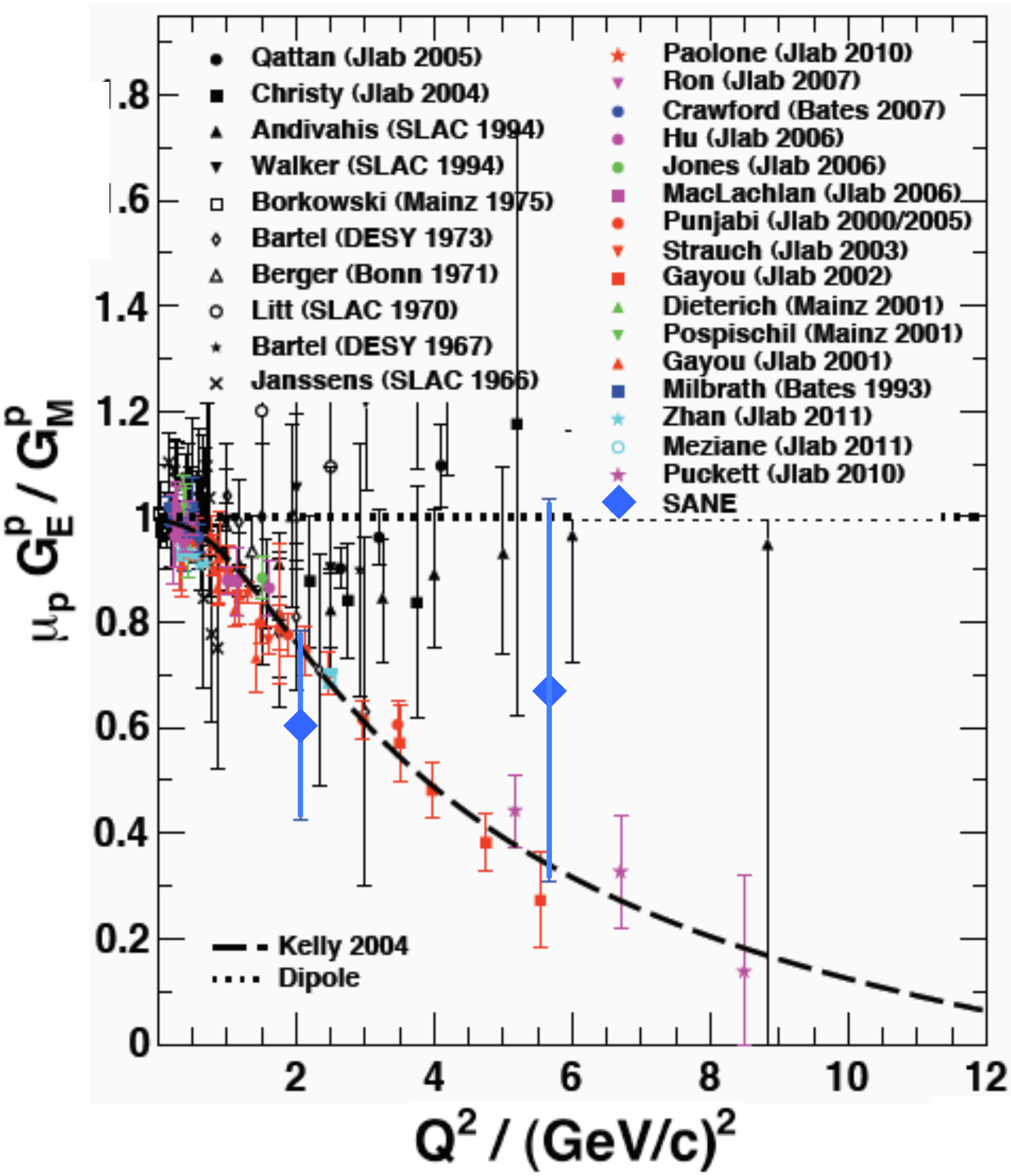
M.K. Jones et al., PRC74 (2006) 035201

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



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

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

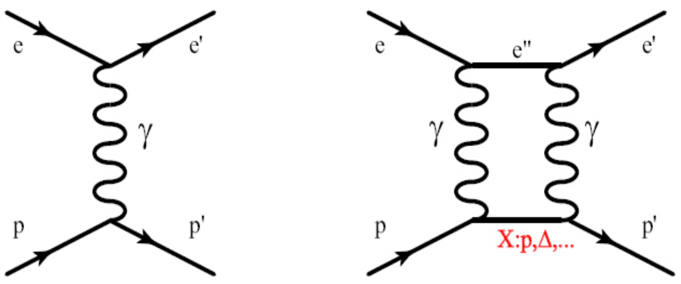
SANE/Hall C: completed March 2009
BigCal electron detector
Recoil protons in HMS parasitically
G_E/G_M at $Q^2 \approx 2.1$ and 5.7 (GeV/c)^2

Decline of G_E/G_M has been confirmed!

Future precision measurements at high Q^2 are feasible

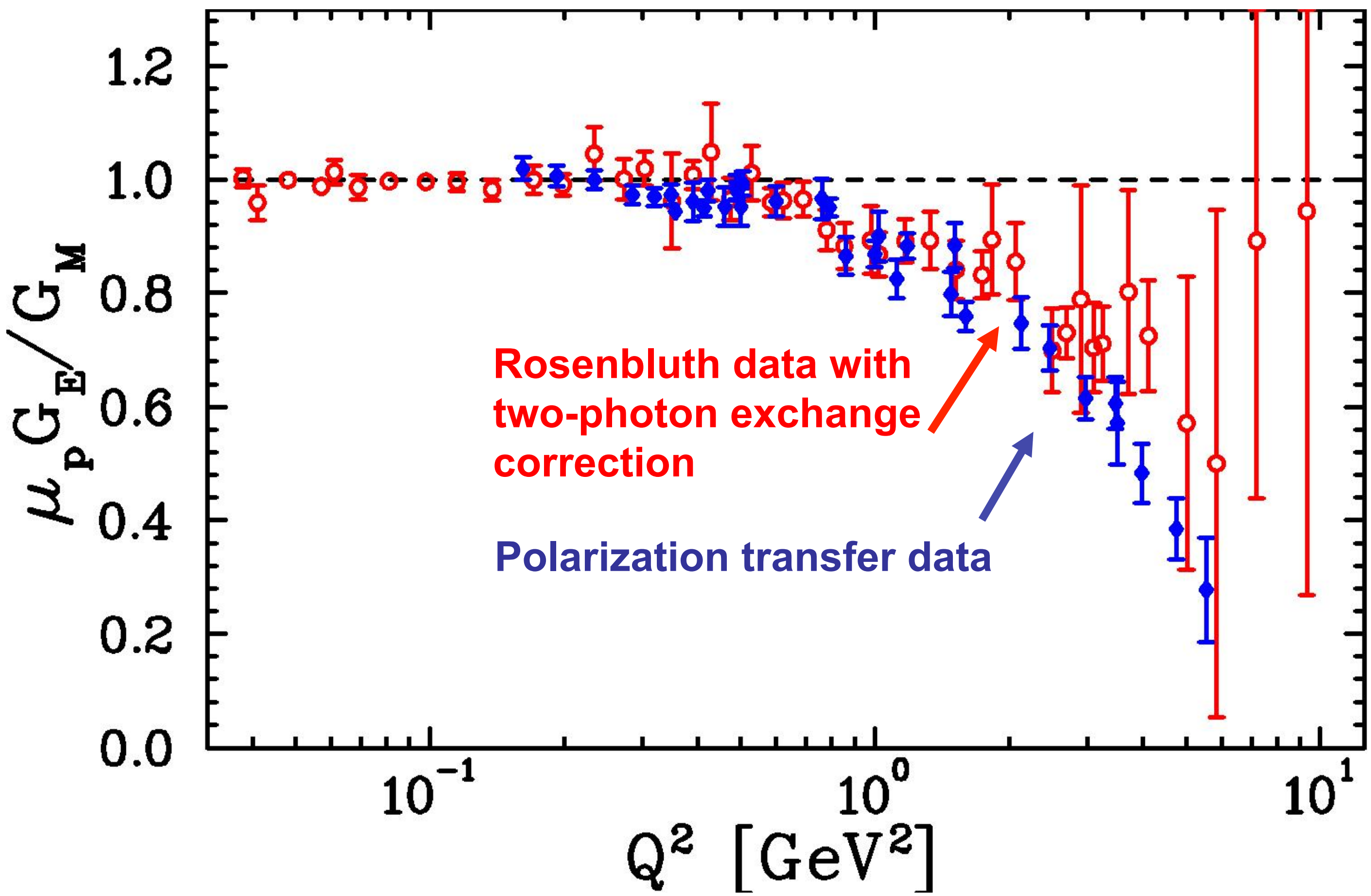
Two-photon exchange: exp. evidence

Two-photon exchange theoretically suggested



TPE can explain form factor discrepancy

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



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

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

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

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

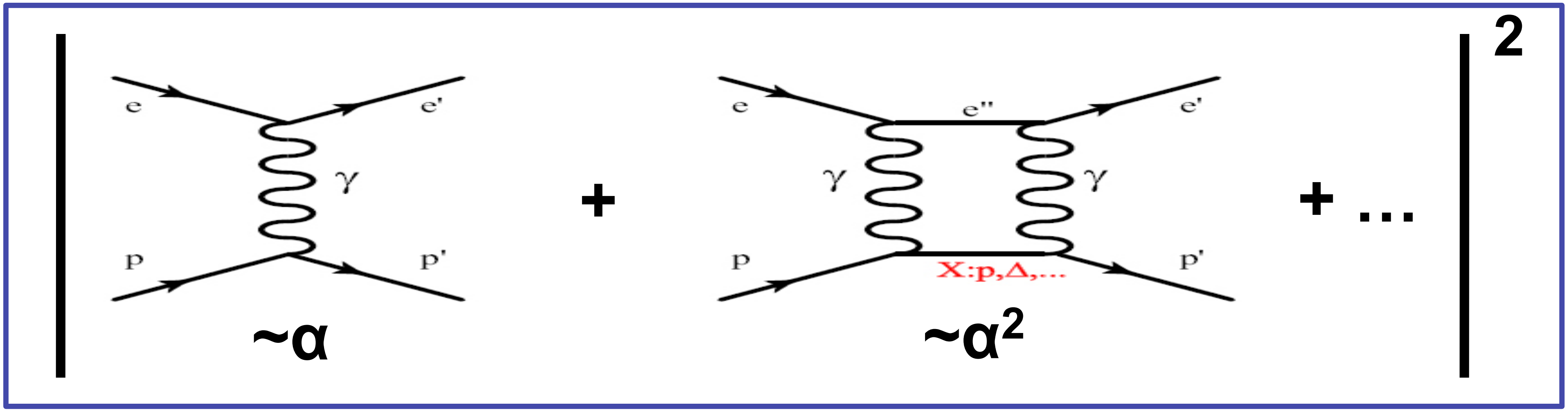
Born Approximation | **Beyond Born Approximation**

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

Lepton-proton elastic scattering



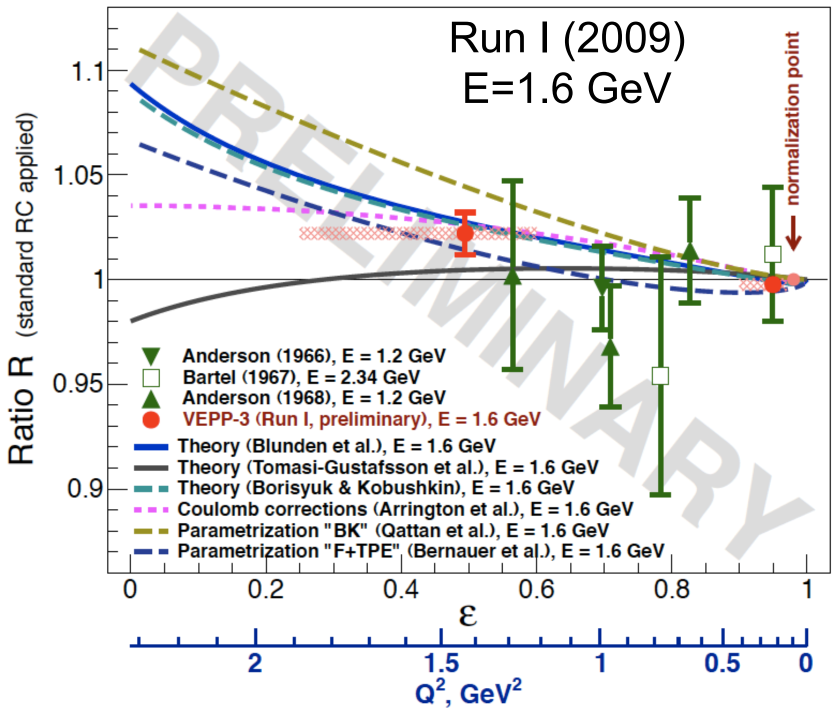
- **Interference term depends on lepton charge sign (C-odd)**

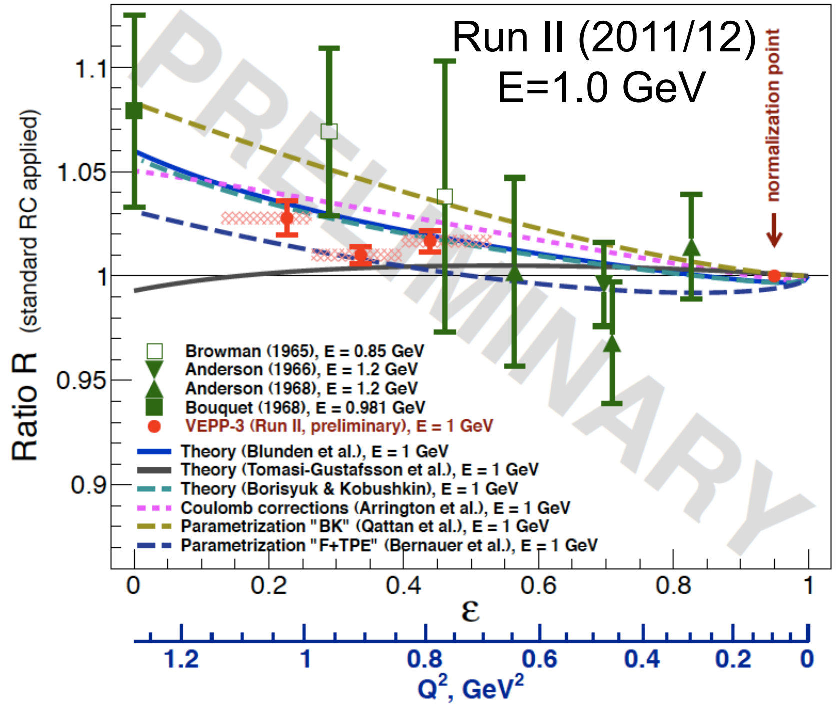
$$\sigma_{e^{\pm}p} = |\mathcal{M}_{1\gamma}|^2 \pm 2\Re\{\mathcal{M}_{1\gamma}^{\dagger}\mathcal{M}_{2\gamma}\} + \cdots$$

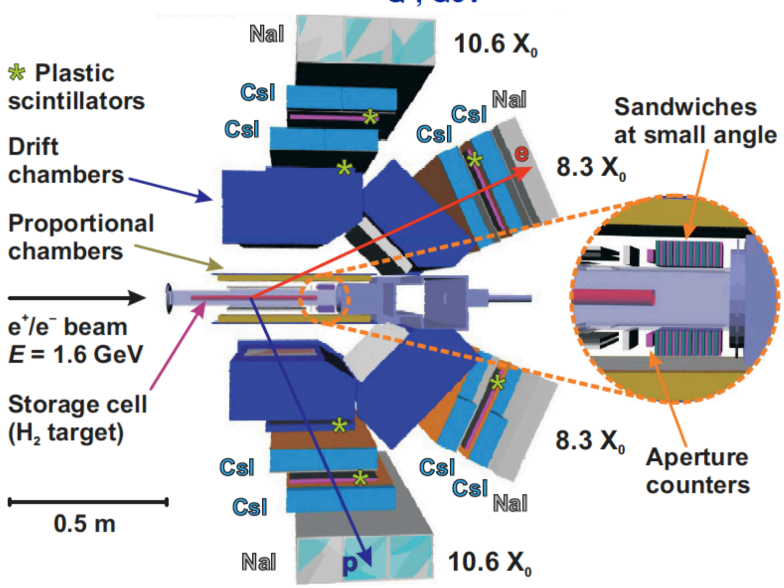
- **e^+/e^- ratio deviates from unity by two-photon contribution**

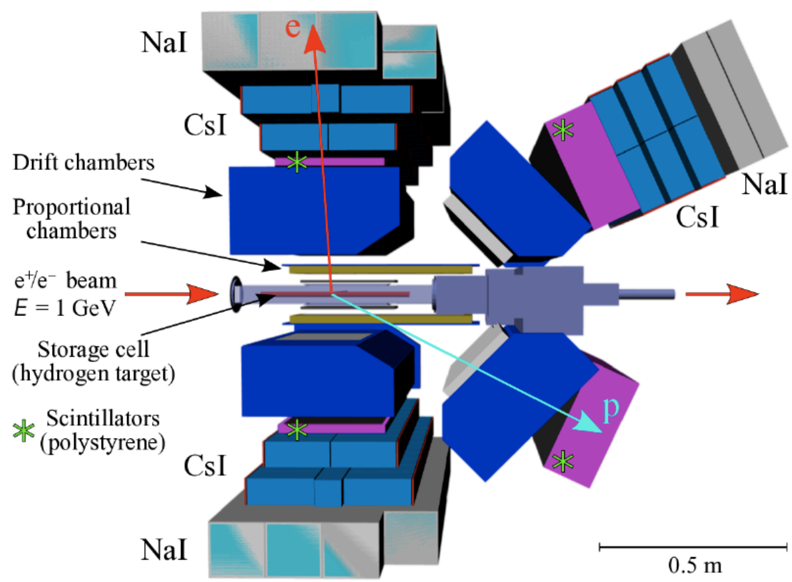
$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx 1 + 4\frac{\Re\{\mathcal{M}_{1\gamma}^{\dagger}\mathcal{M}_{2\gamma}\}}{|\mathcal{M}_{1\gamma}|^2}$$

TPE experiments: Novosibirsk/VEPP-3



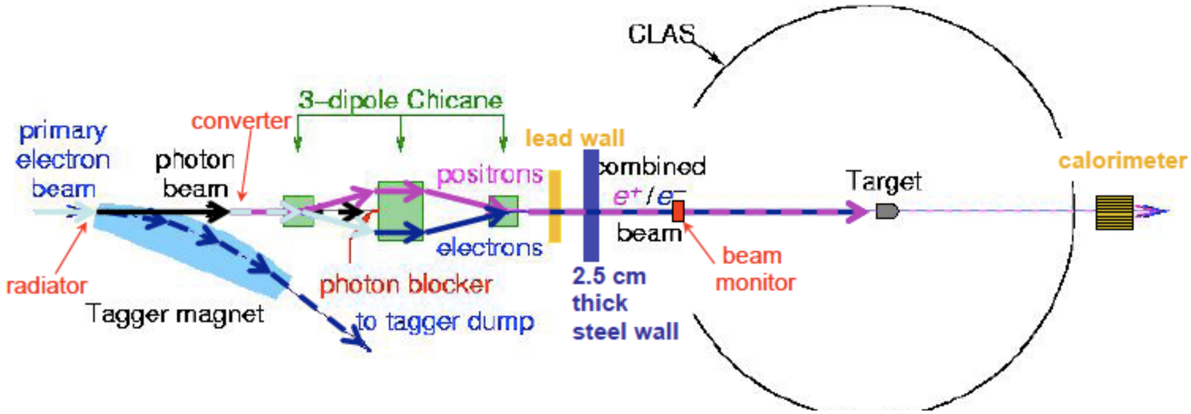


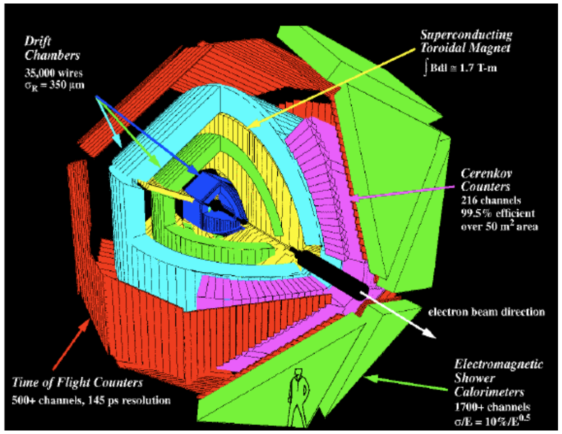


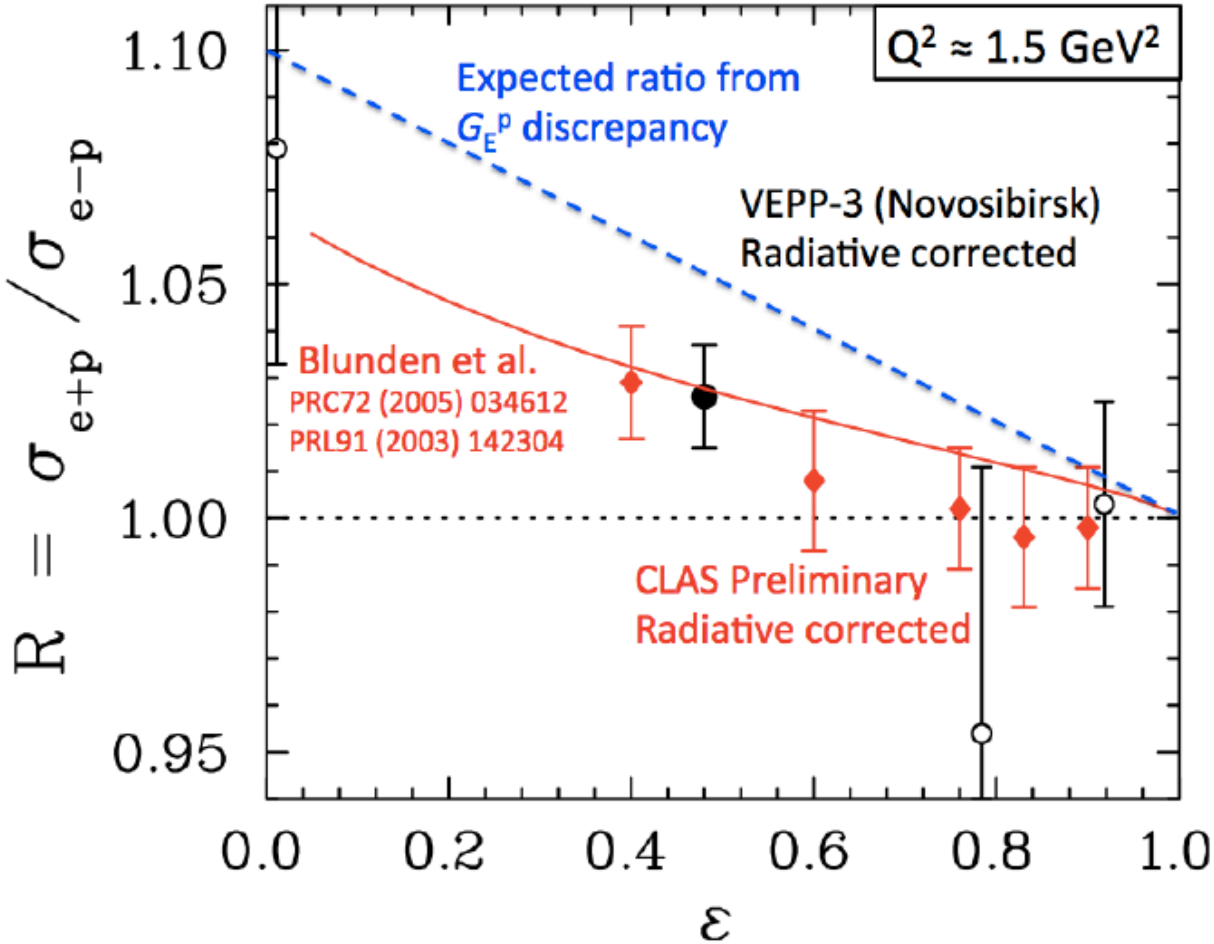


A. Gramolin, Workshop on Radiative Corrections in Annihilation and Scattering Experiments, Orsay, October 7-8, 2013

TPE experiments: CLAS (E04-116)



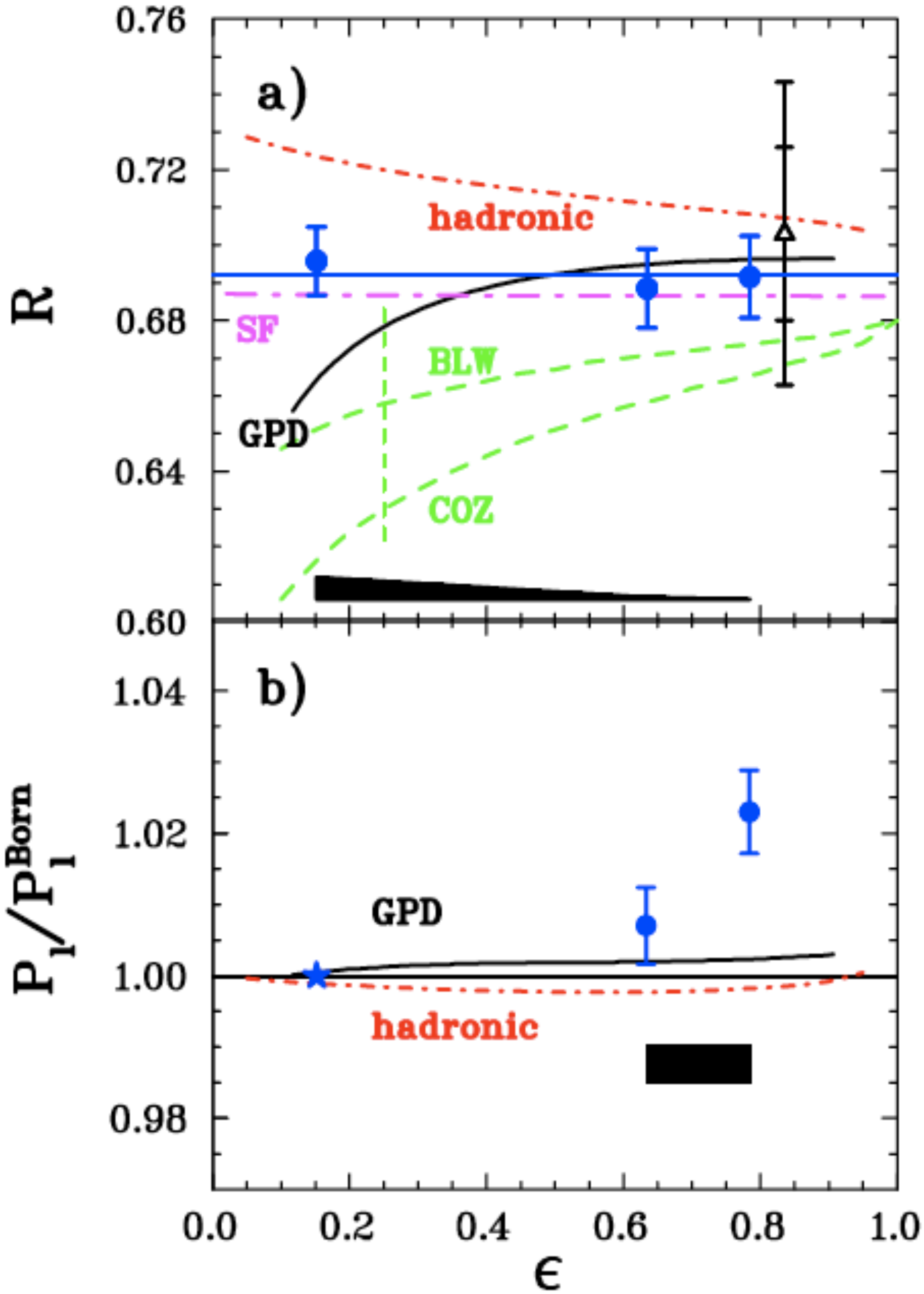




Dasuni Adikaram (ODU), DH.00005

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

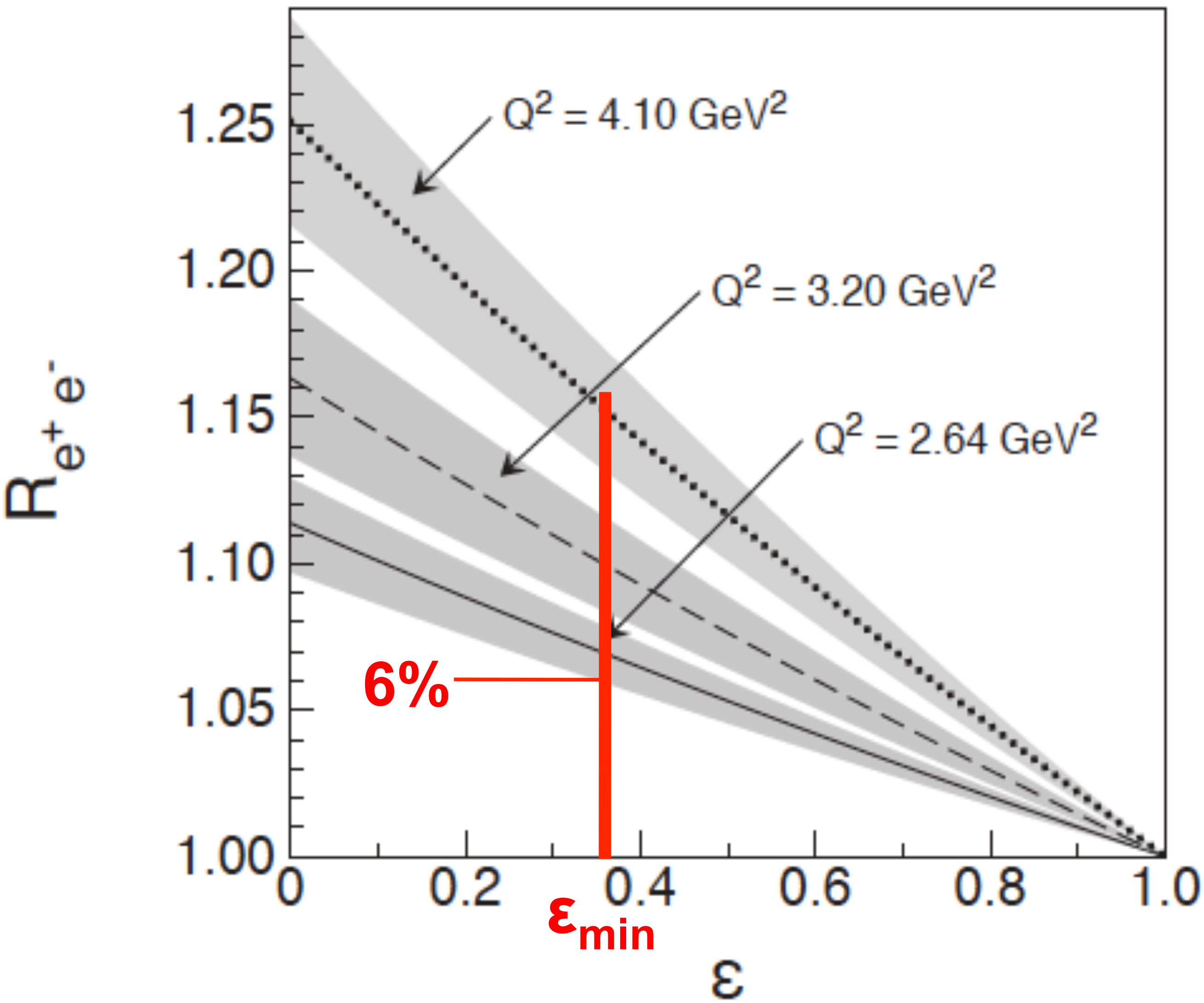
- ➔ **no effect in P_t/P_l**
- ➔ **some effect in P_l**

Expect larger effect in e+/e-!

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

Empirical extraction of TPE amplitudes

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

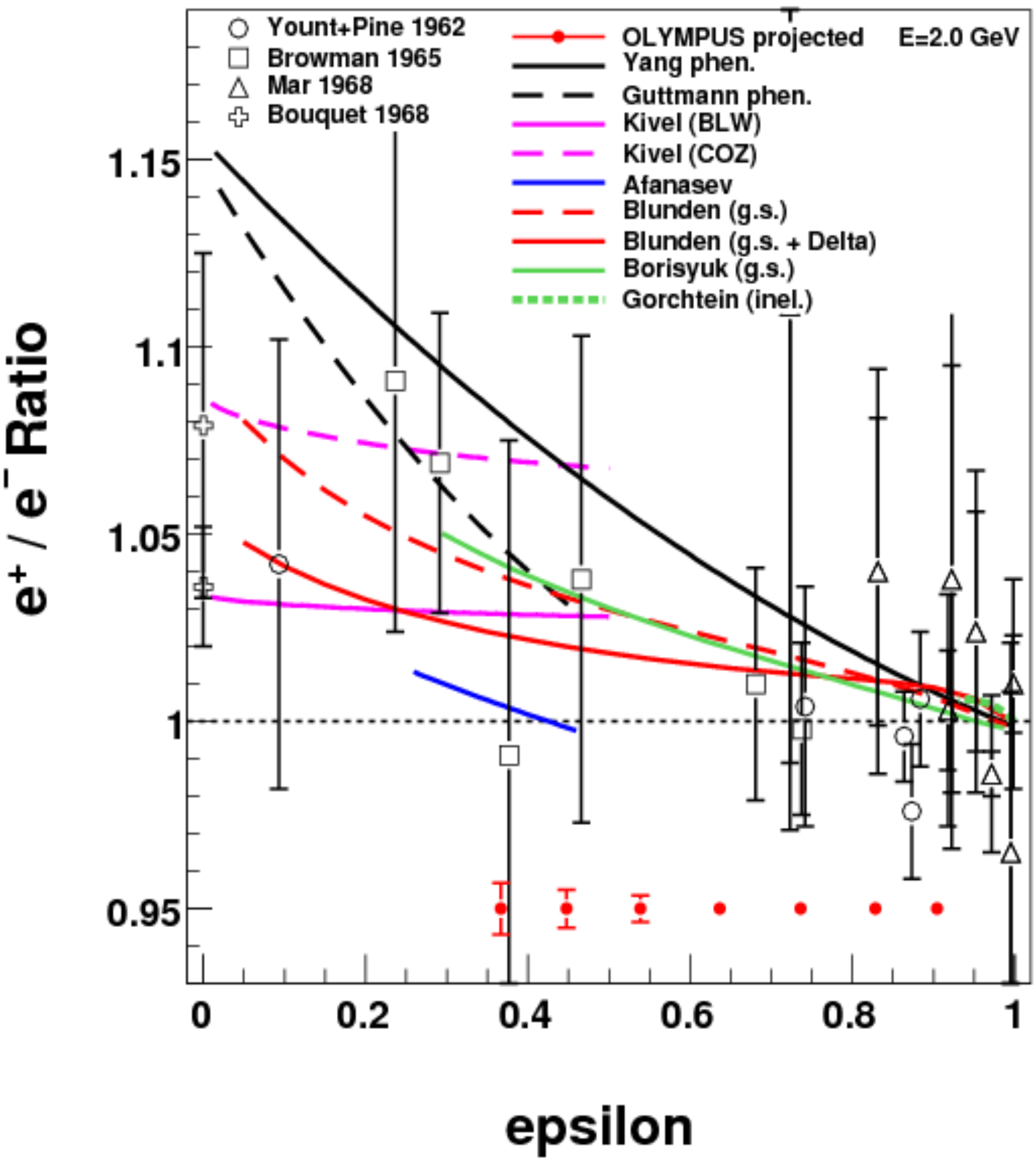


grows with Q^2!

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

OLYMPUS

Projected results for OLYMPUS



Data from 1960's

Many theoretical predictions with little constraint

OLYMPUS:

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

Data taking completed in 2012

Presentations on OLYMPUS

Thursday

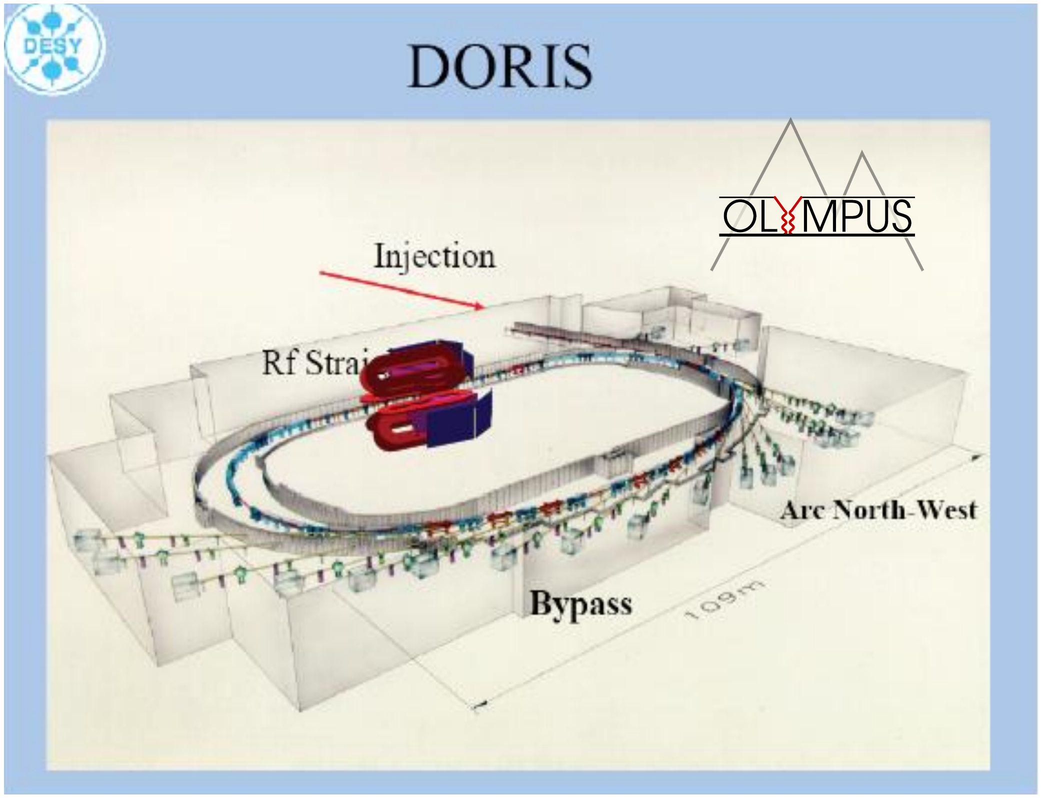
08:30-08:42 CH.00001 : Status of the OLYMPUS experiment
Michael Kohl (Hampton University)

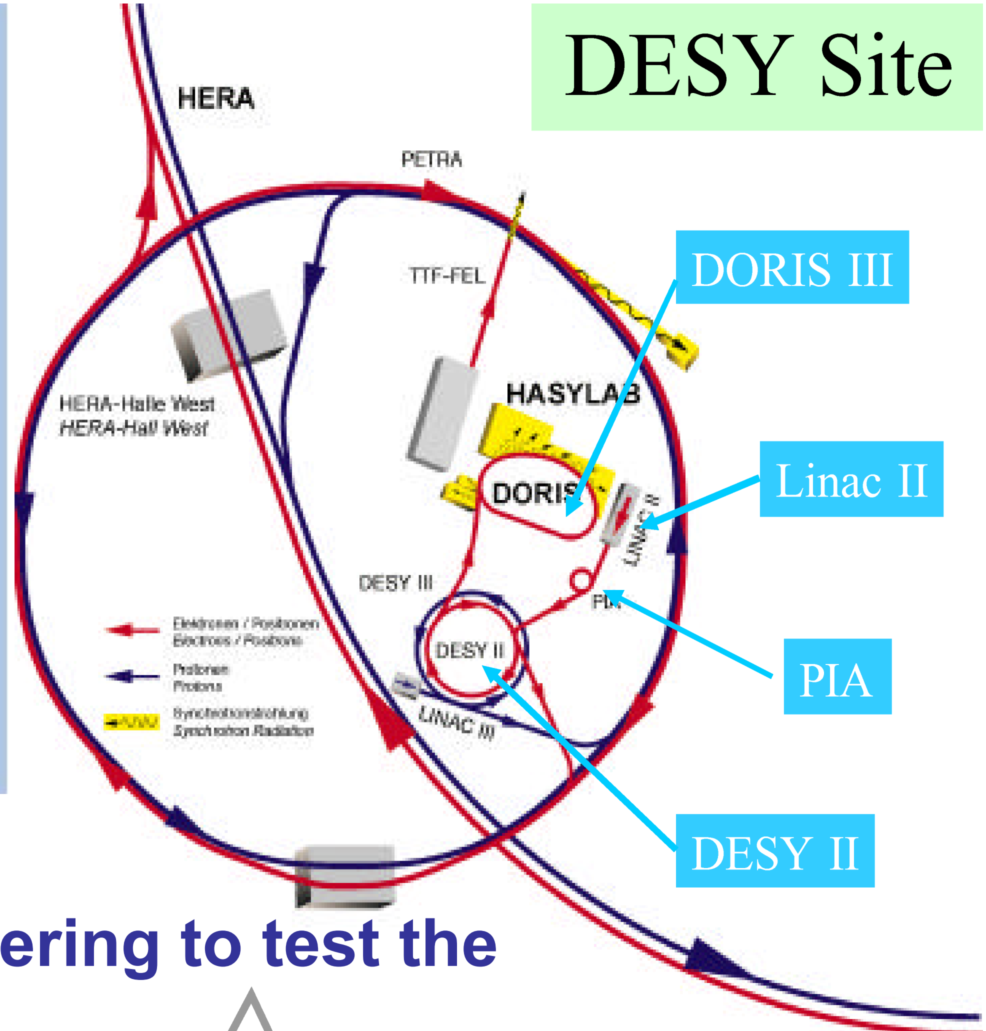
08:42-08:54 CH.00002 : Status of the OLYMPUS Analysis
Brian Henderson (MIT)

08:54-09:06 CH.00003 : Luminosity monitoring at OLYMPUS with forward-angle elastic scattering
Ozgur Ates (Hampton University)

09:06-09:18 CH.00004 : Radiative corrections for the OLYMPUS experiment
Rebecca Russell (MIT)

OLYMPUS @ DORIS/DESY





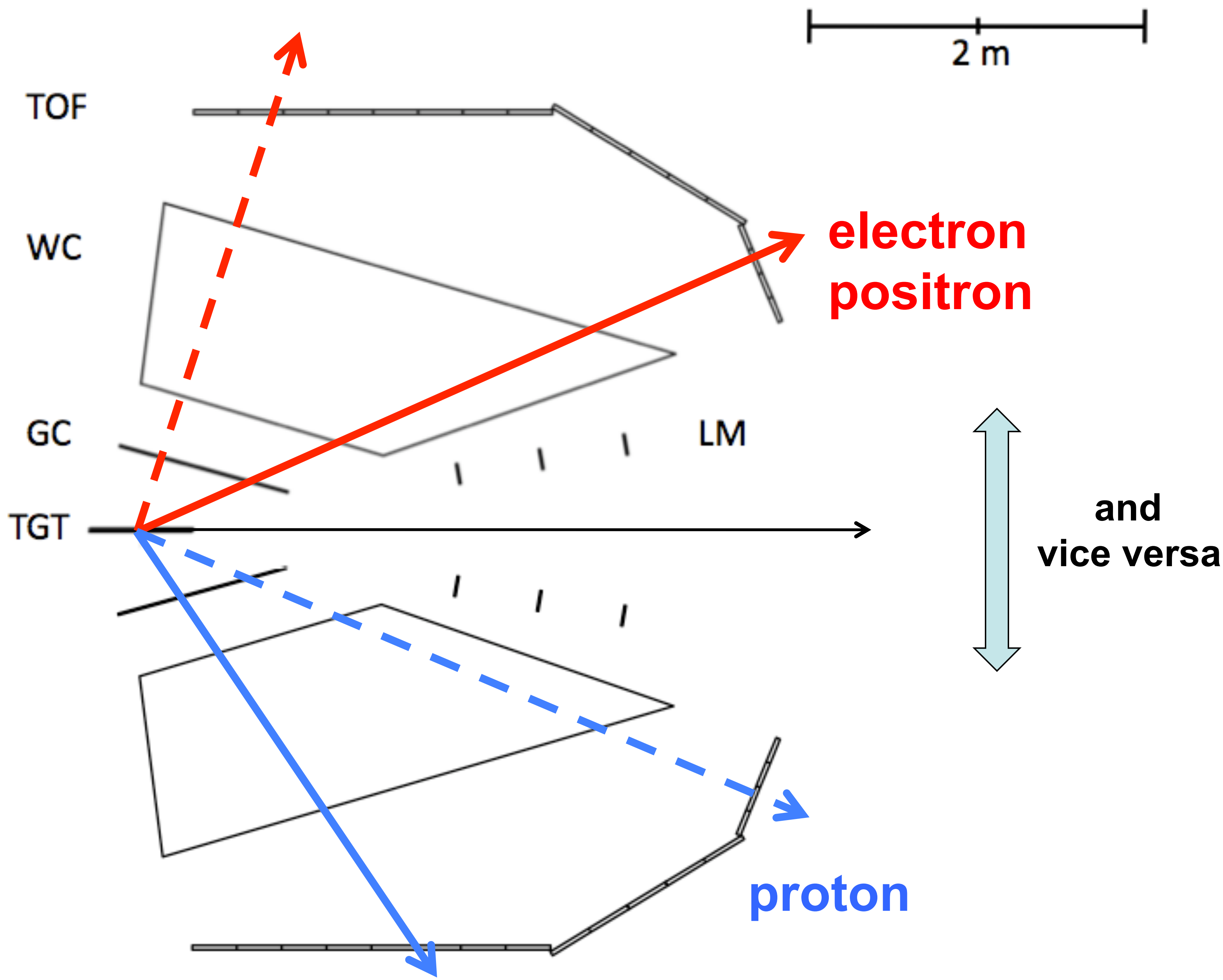
pOsitron-proton and
eLectron-proton elastic scattering to test the
hYpothesis of
Multi-
Photon exchange
Using
DoriS

The OLYMPUS experiment

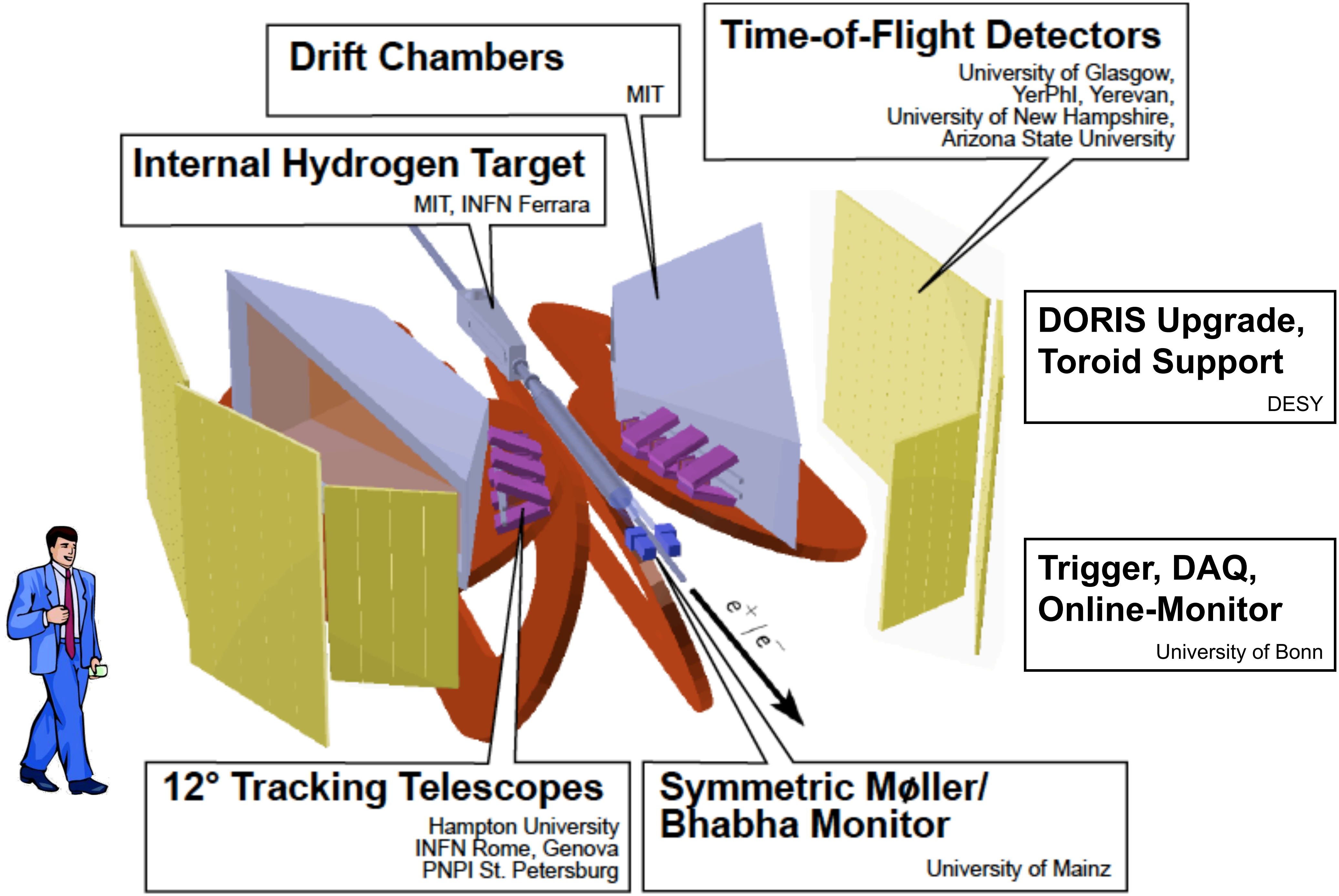
- Electrons/positrons (100mA) in 2.0–4.5 GeV storage ring
  DORIS at DESY, Hamburg, Germany
- Unpolarized internal hydrogen target (buffer system)
  $3x10^{15}$ at/cm^2 @ 100 mA → L = $2x10^{33}$ / (cm^2s)
- Large acceptance detector for e-p in coincidence
  BLAST detector from MIT-Bates available
- 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

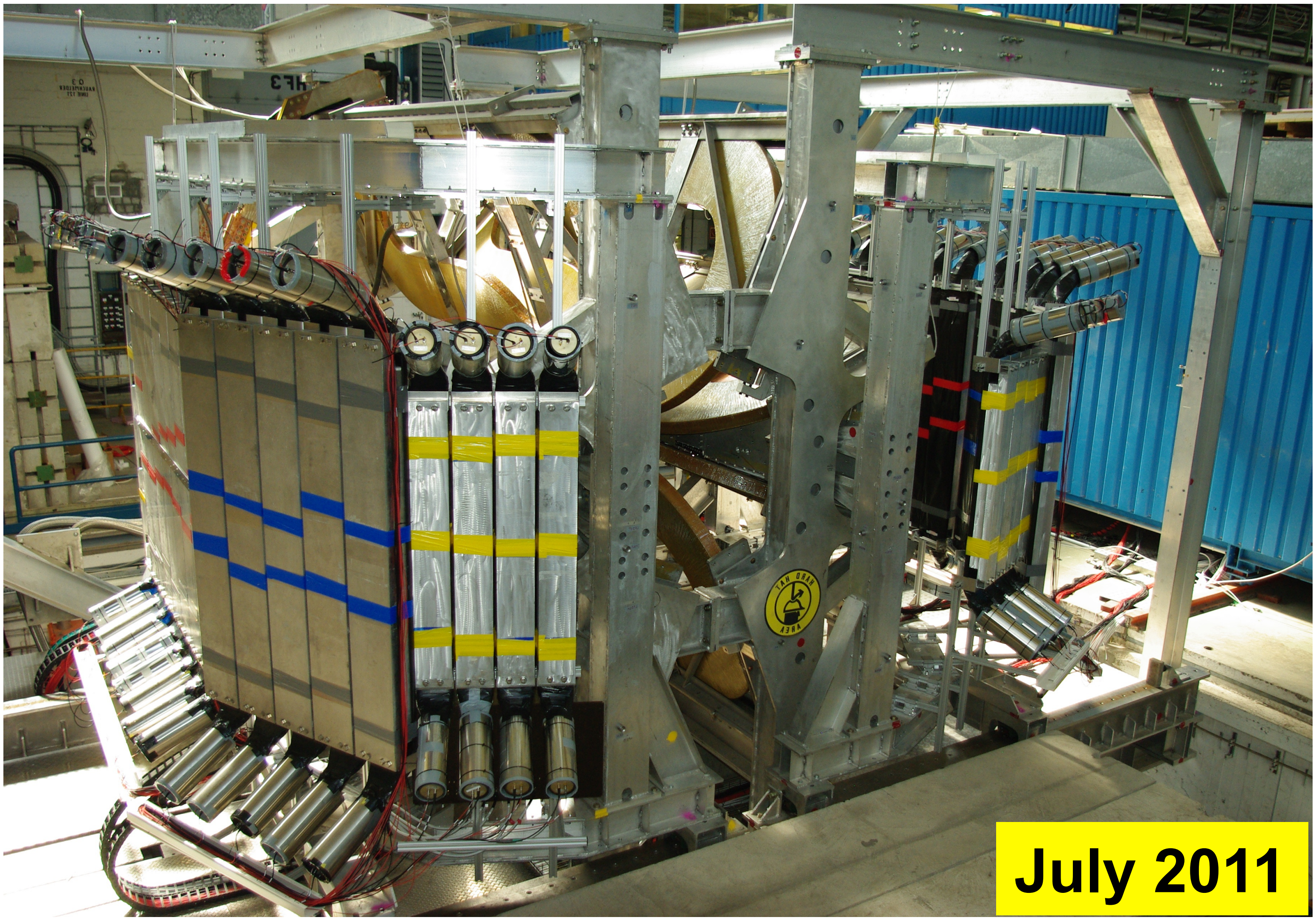


The designed OLYMPUS detector



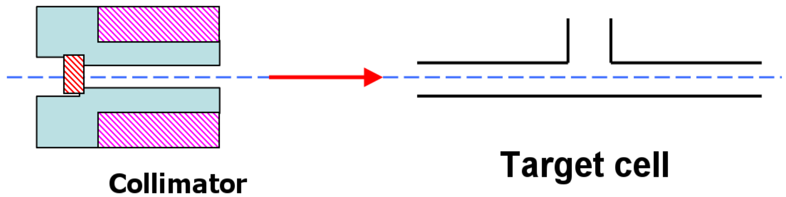
based on a figure by R. Russell

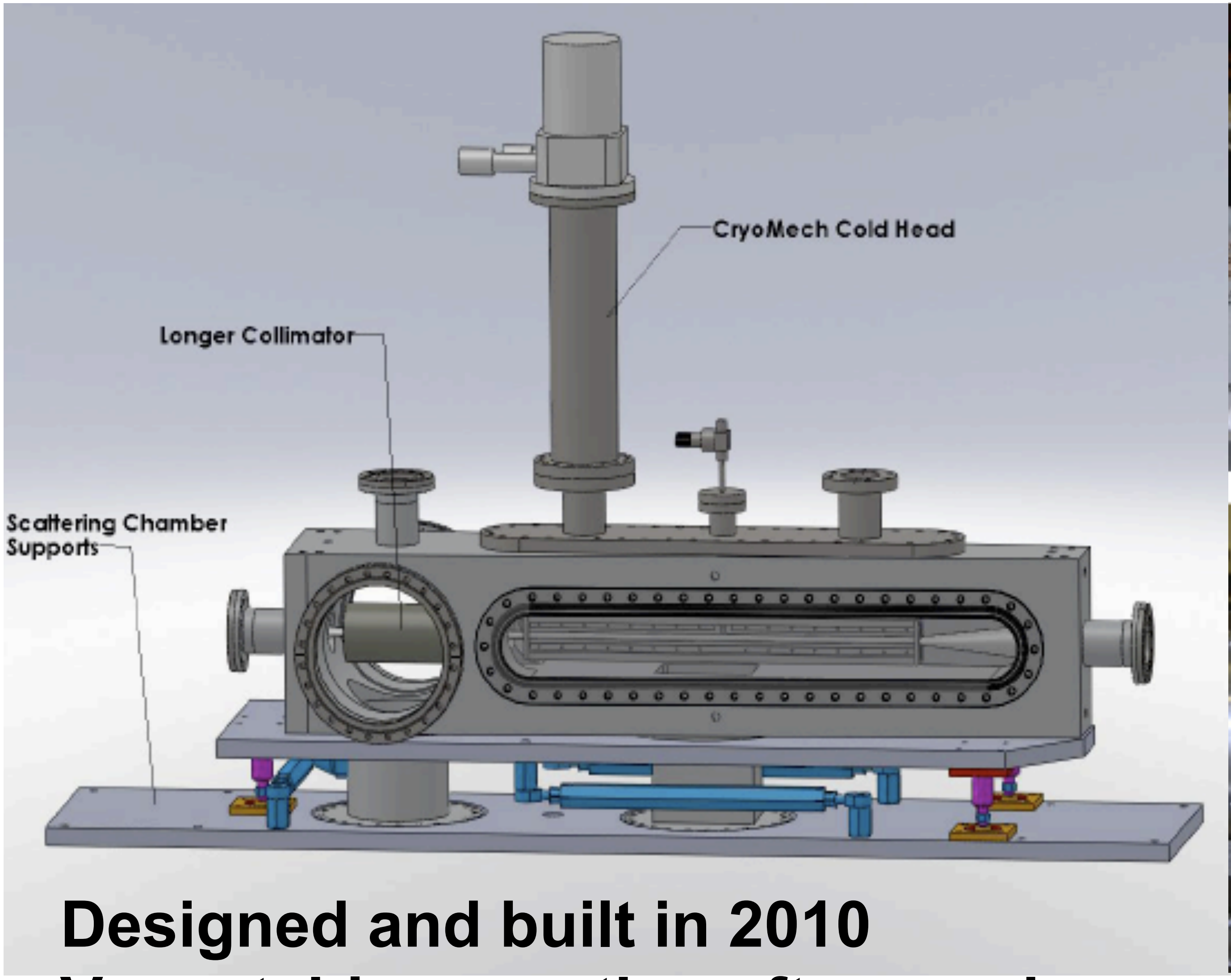
The realized OLYMPUS detector

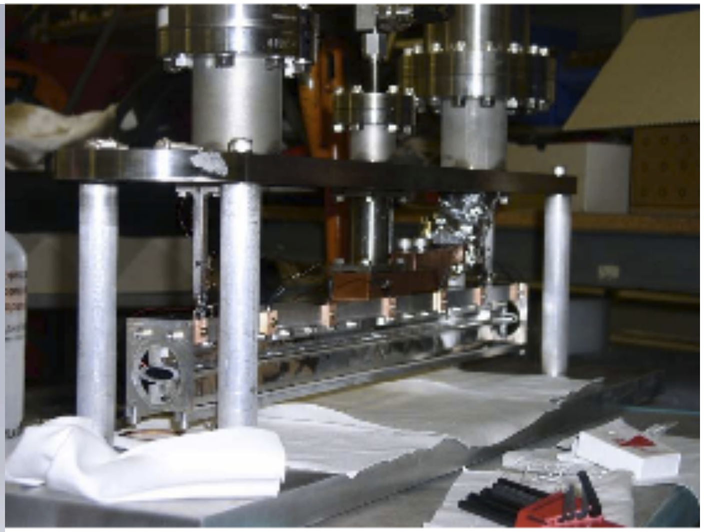


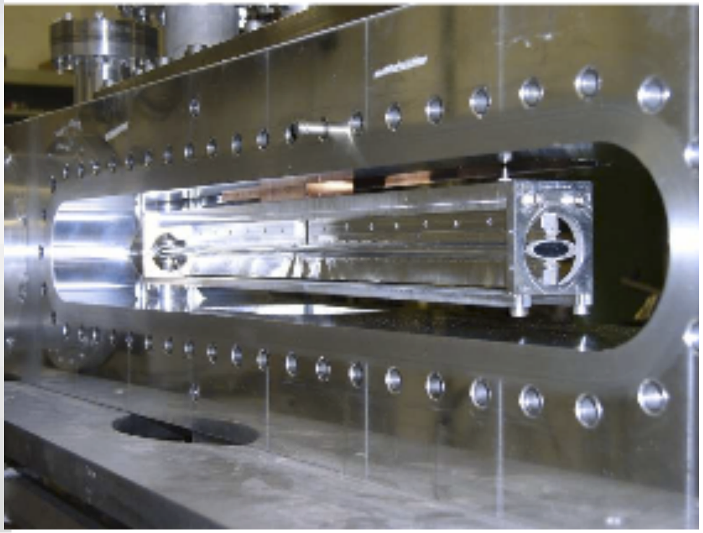
Target and vacuum system

MIT
INFN Ferrara





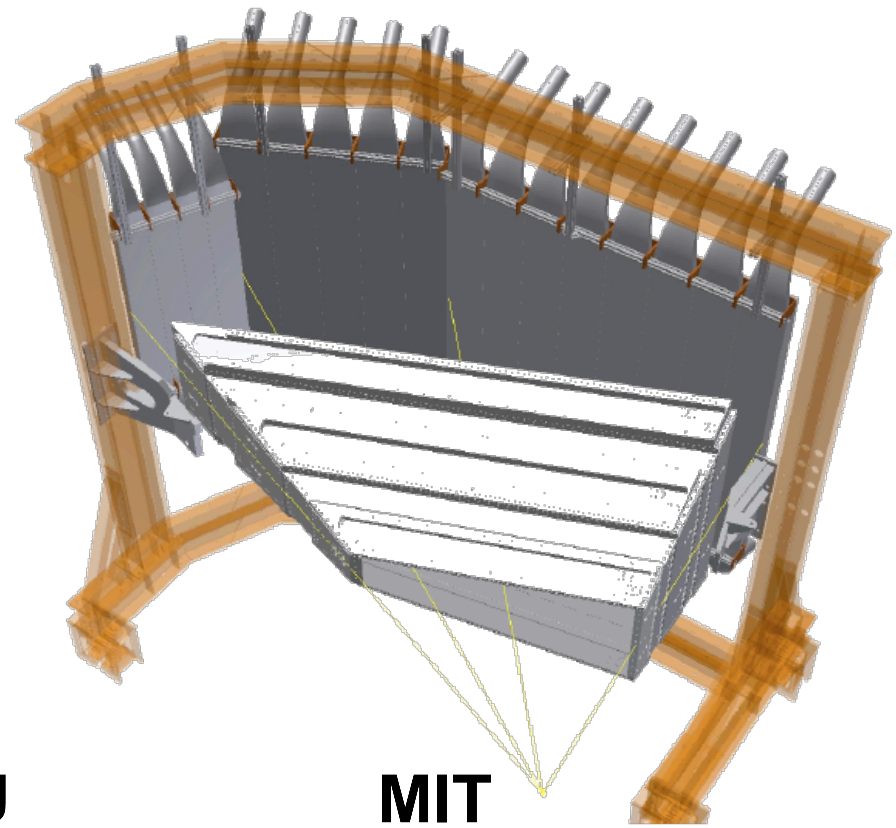




Designed and built in 2010
Very stable operation after repairs

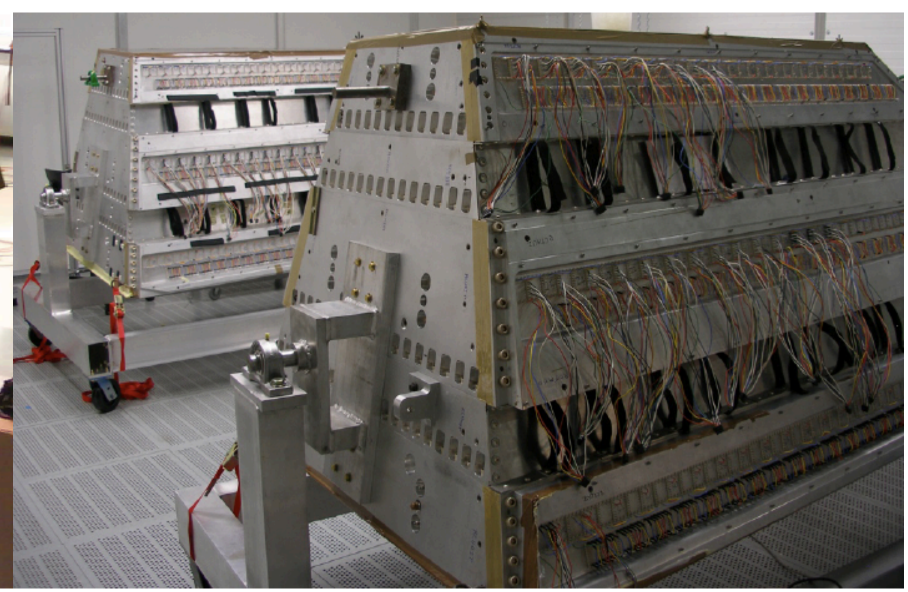
Wire chambers and TOF scintillators

- 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



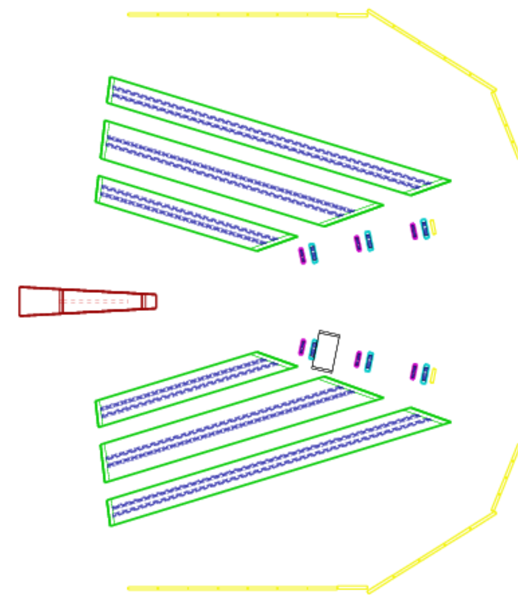
Glasgow, Yerevan, UNH, ASU

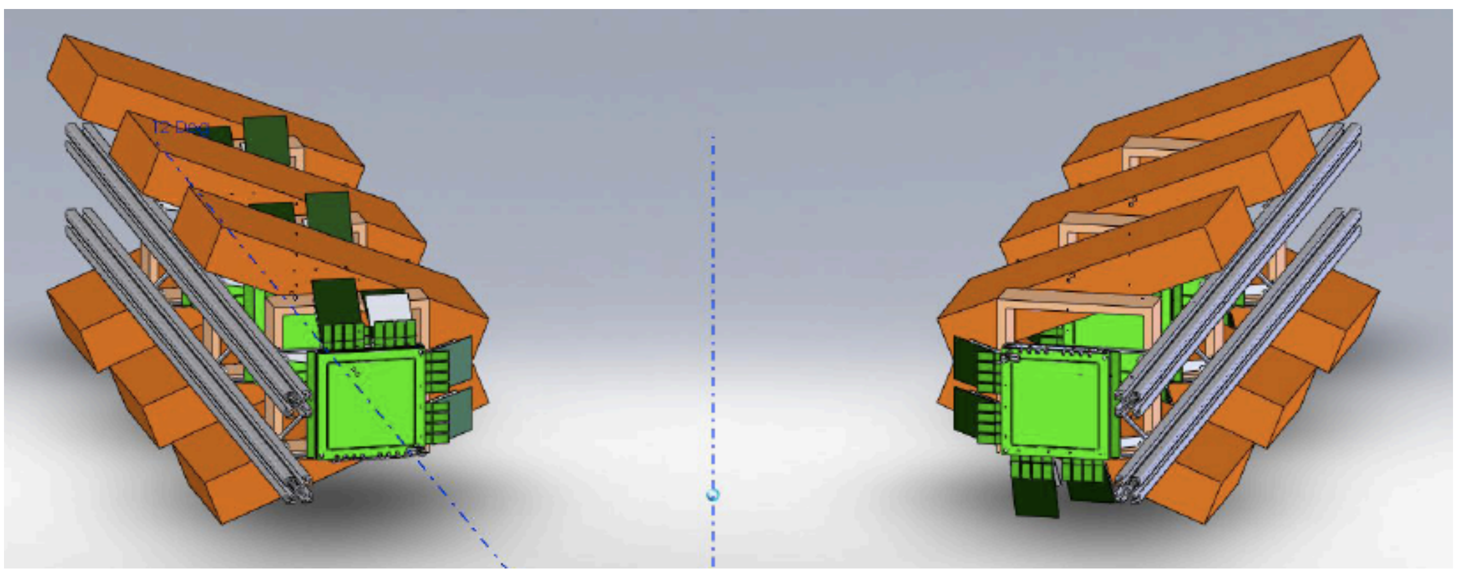
MIT



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)

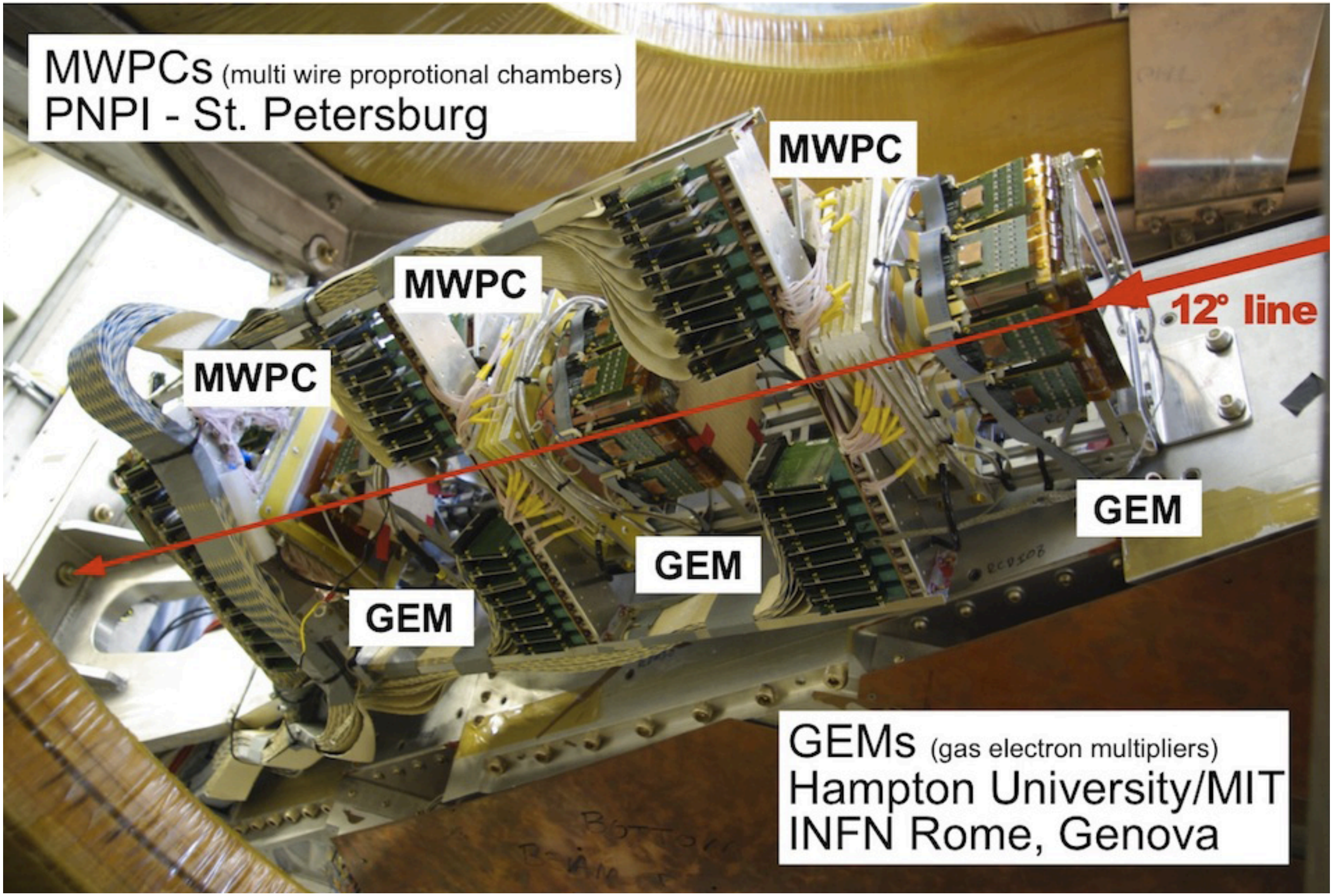




Designed to fit into forward cone

Luminosity monitors: GEM + MWPC

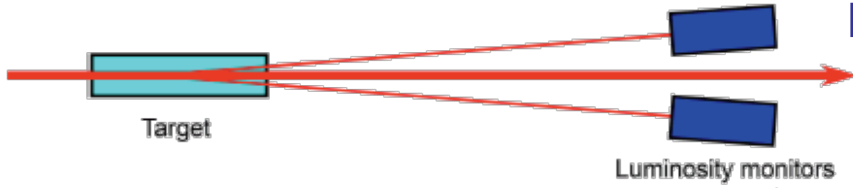
OLYMPUS

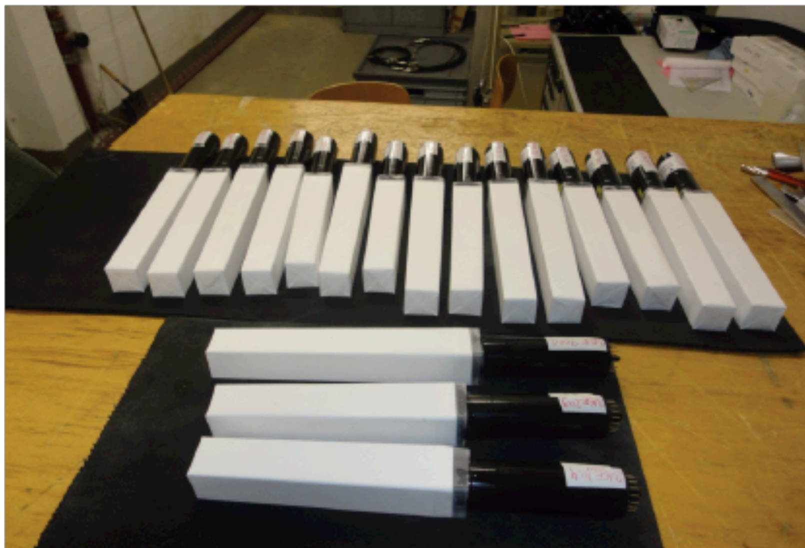


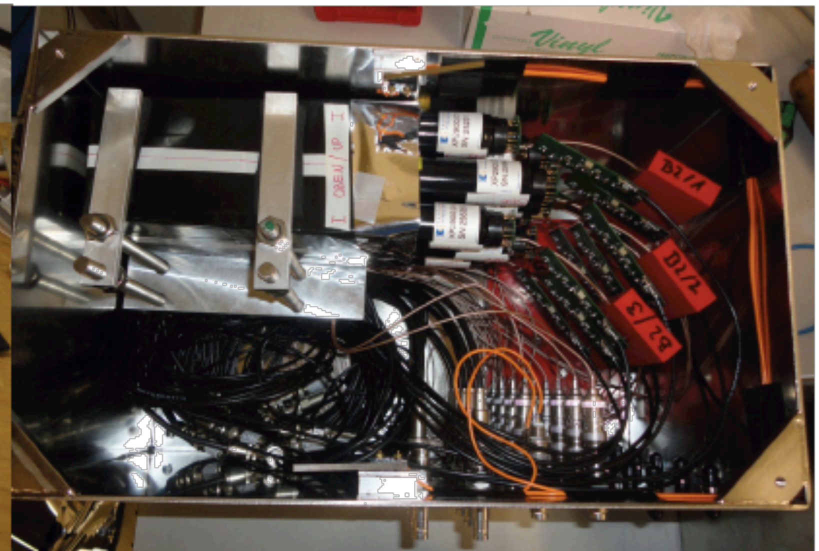
Telescopes of three GEMs and MWPCs interleaved
Mounted on wire chamber forward end plate
Extensively tested at DESY test beam facility

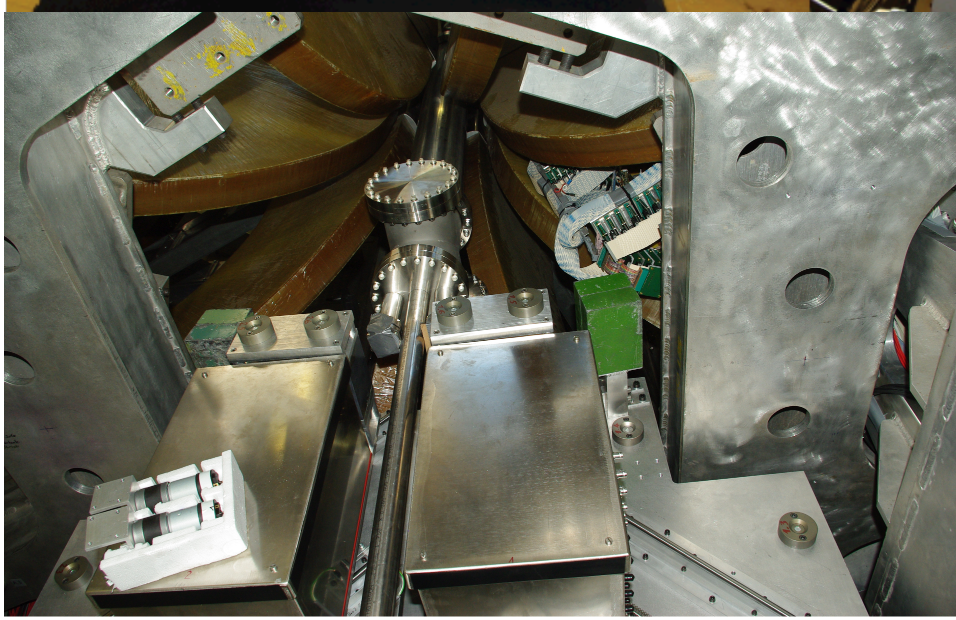
Symmetric Møller/Bhabha monitor

Mainz University





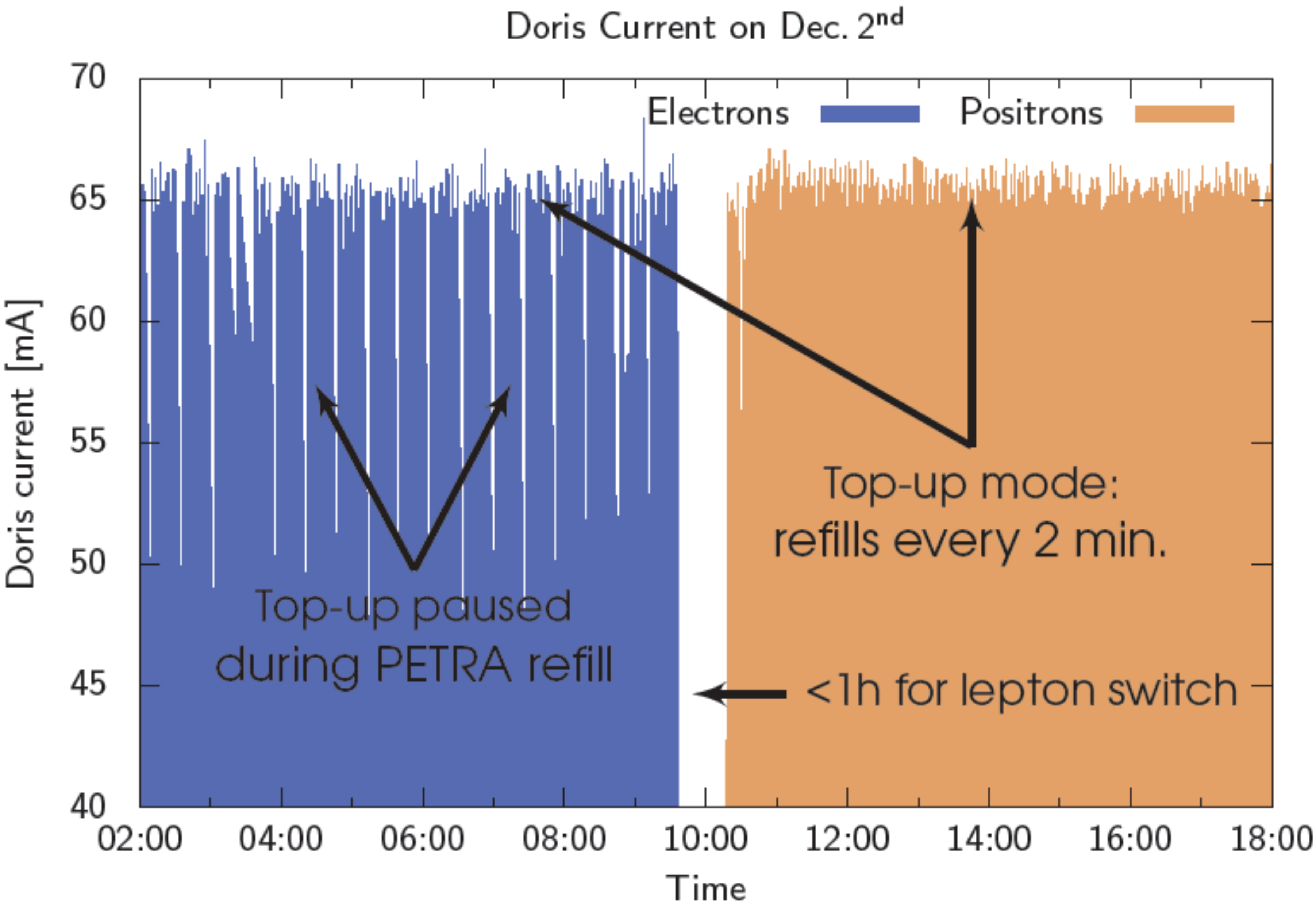




- **Symm. angle 1.3° @ 2.0 GeV**
- **Matrix of 3x3 PbF_2 crystals**
- **Tested at DESY and MAMI**

Performance of DORIS

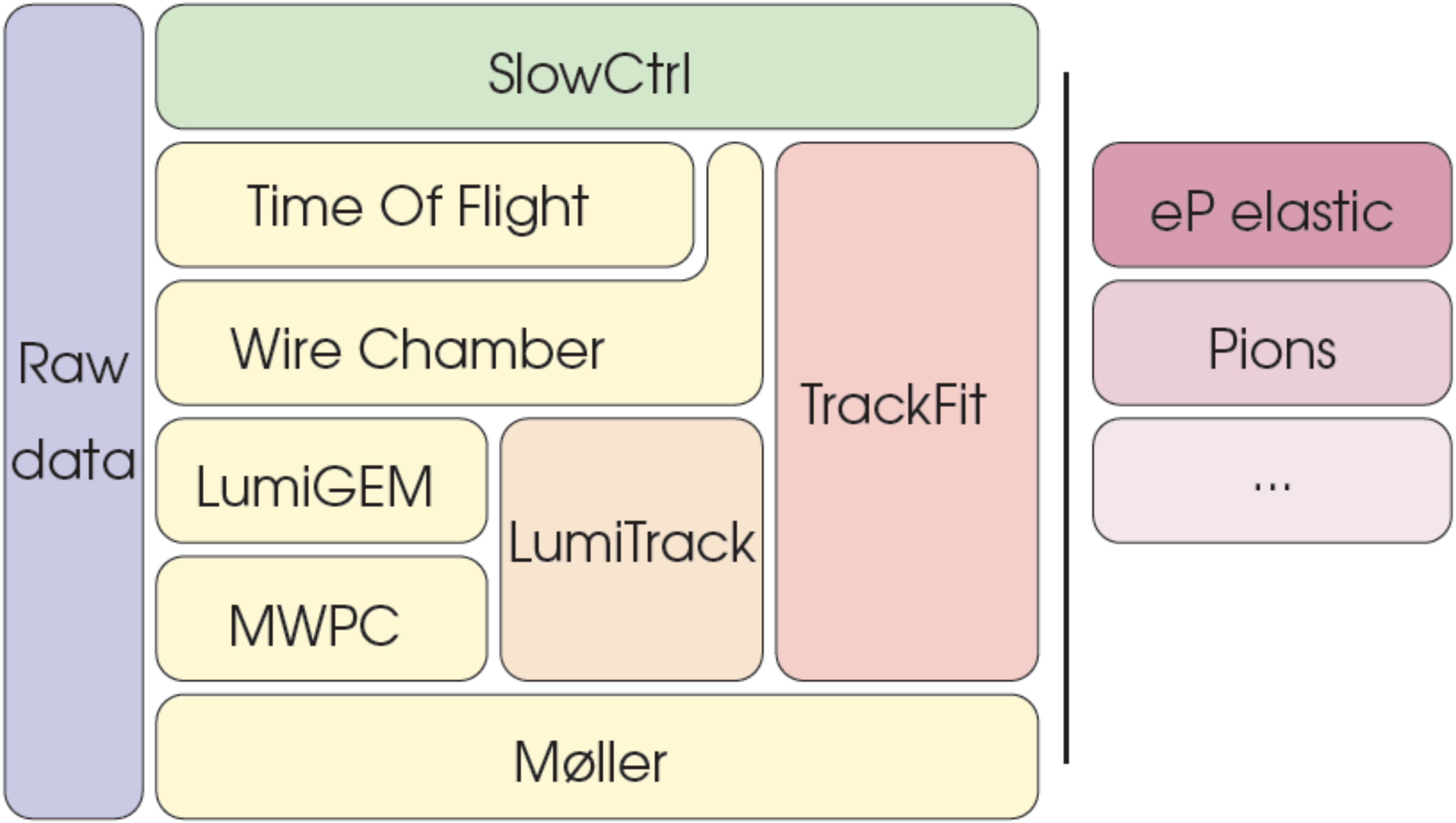
- DORIS top-up mode established
- Typically 65mA / 0.5 sccm
- Refills every ~2 minutes by few mA
- PETRA refills every 30 minutes



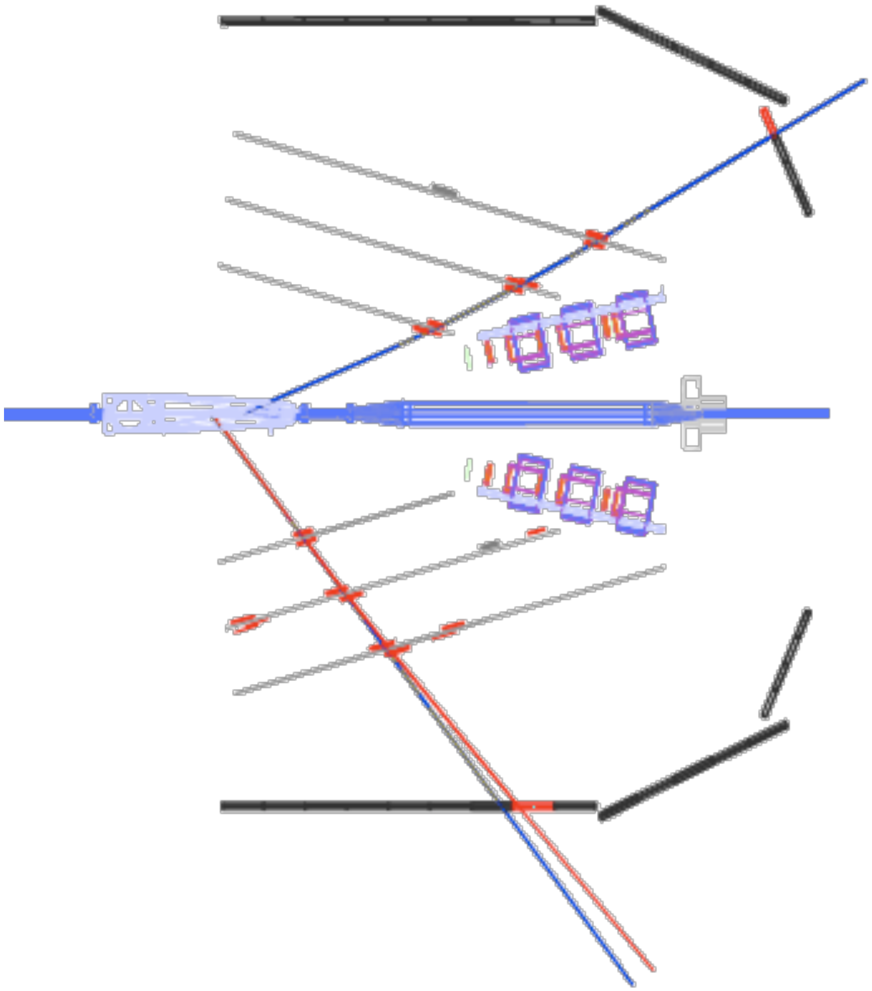
Analysis framework

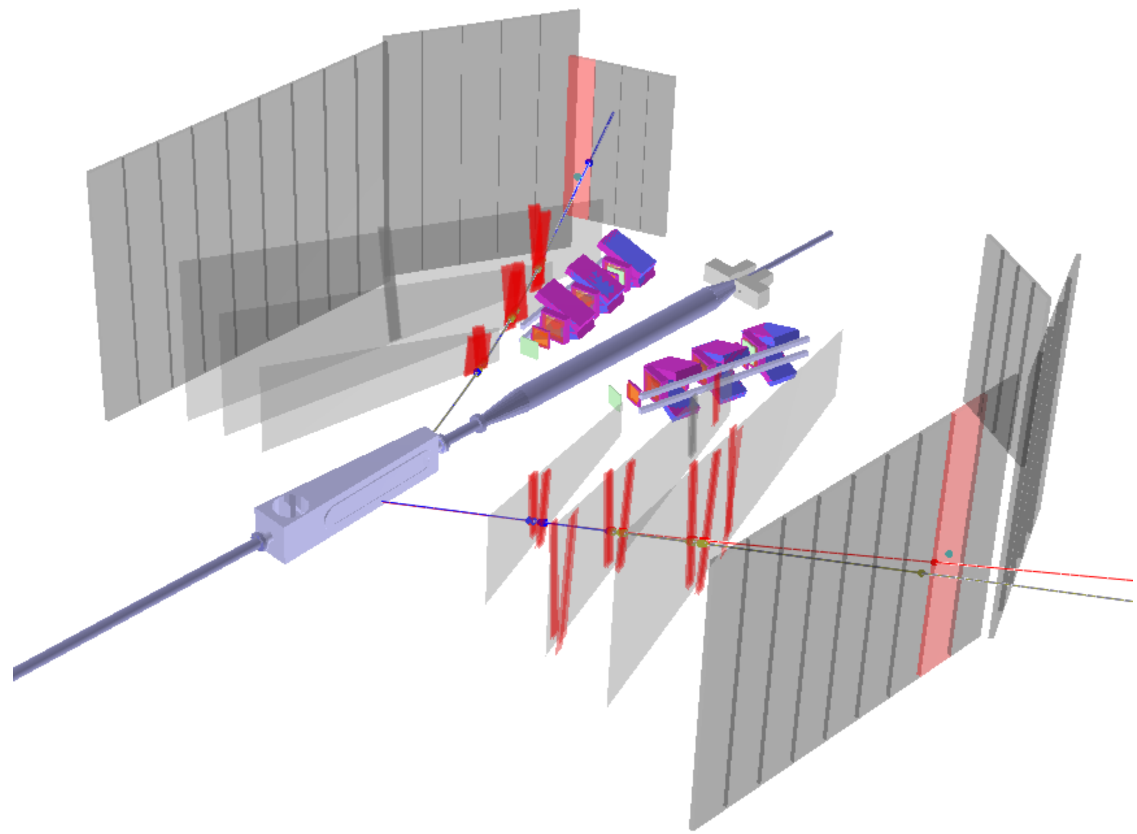
OLYMPUS

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



Event display (3D)

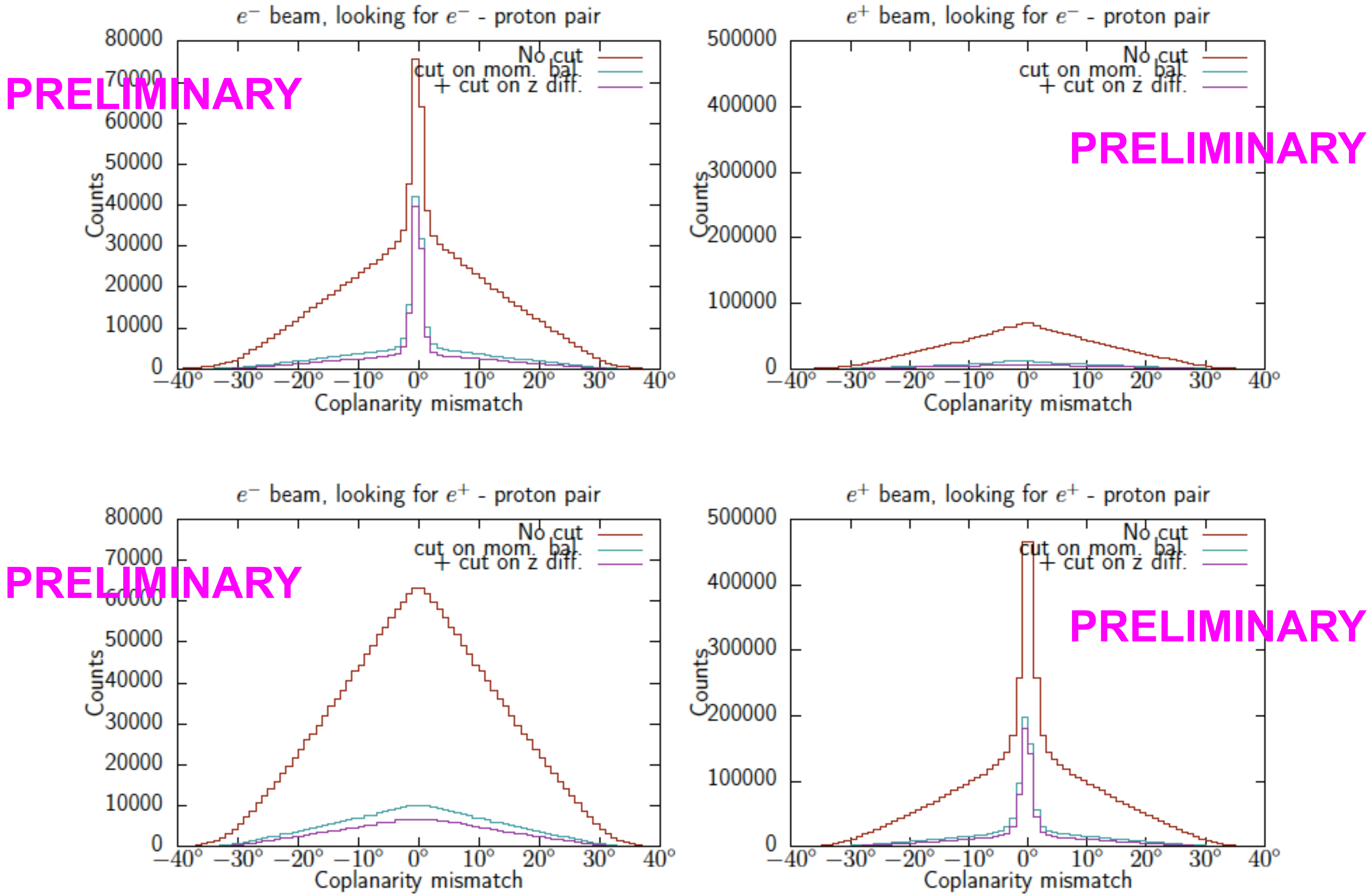




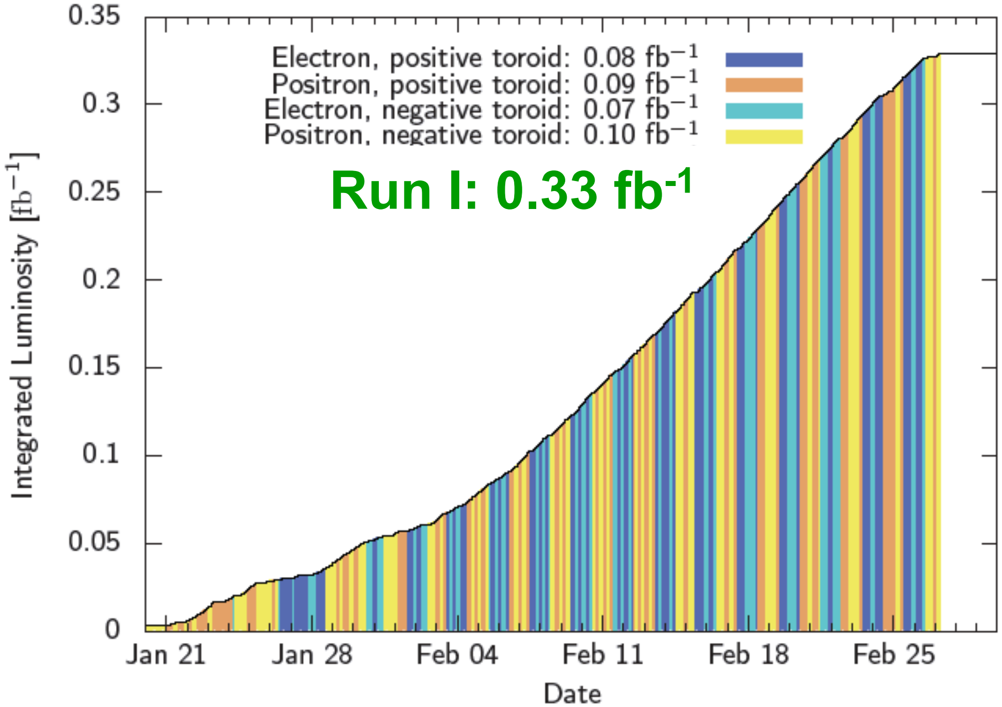
Run 4975, event 78

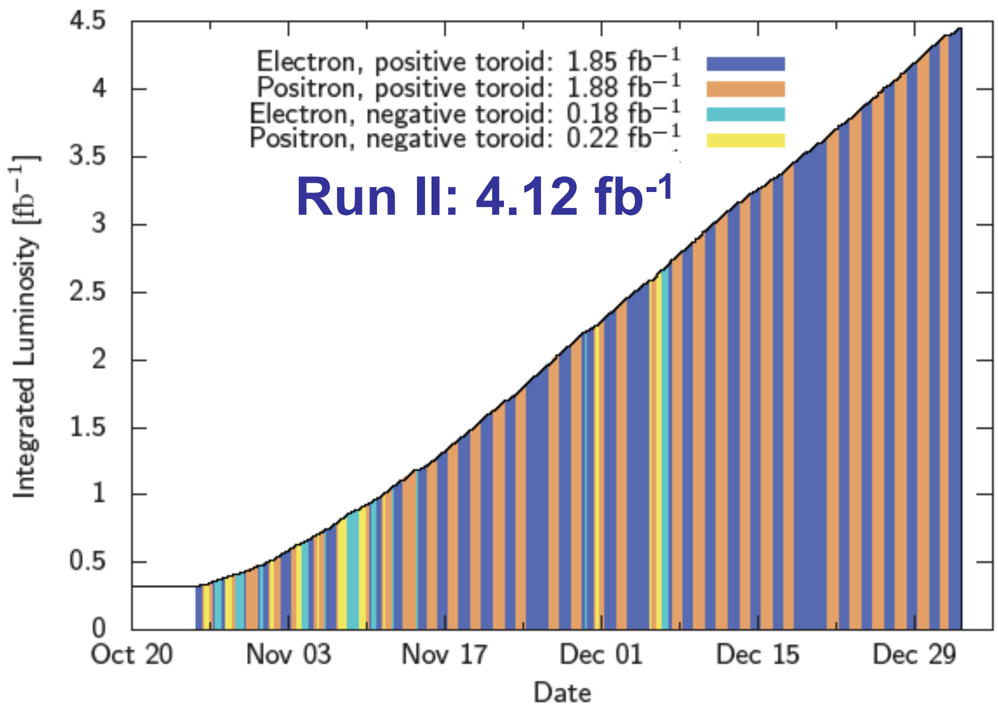
Very preliminary …

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

~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

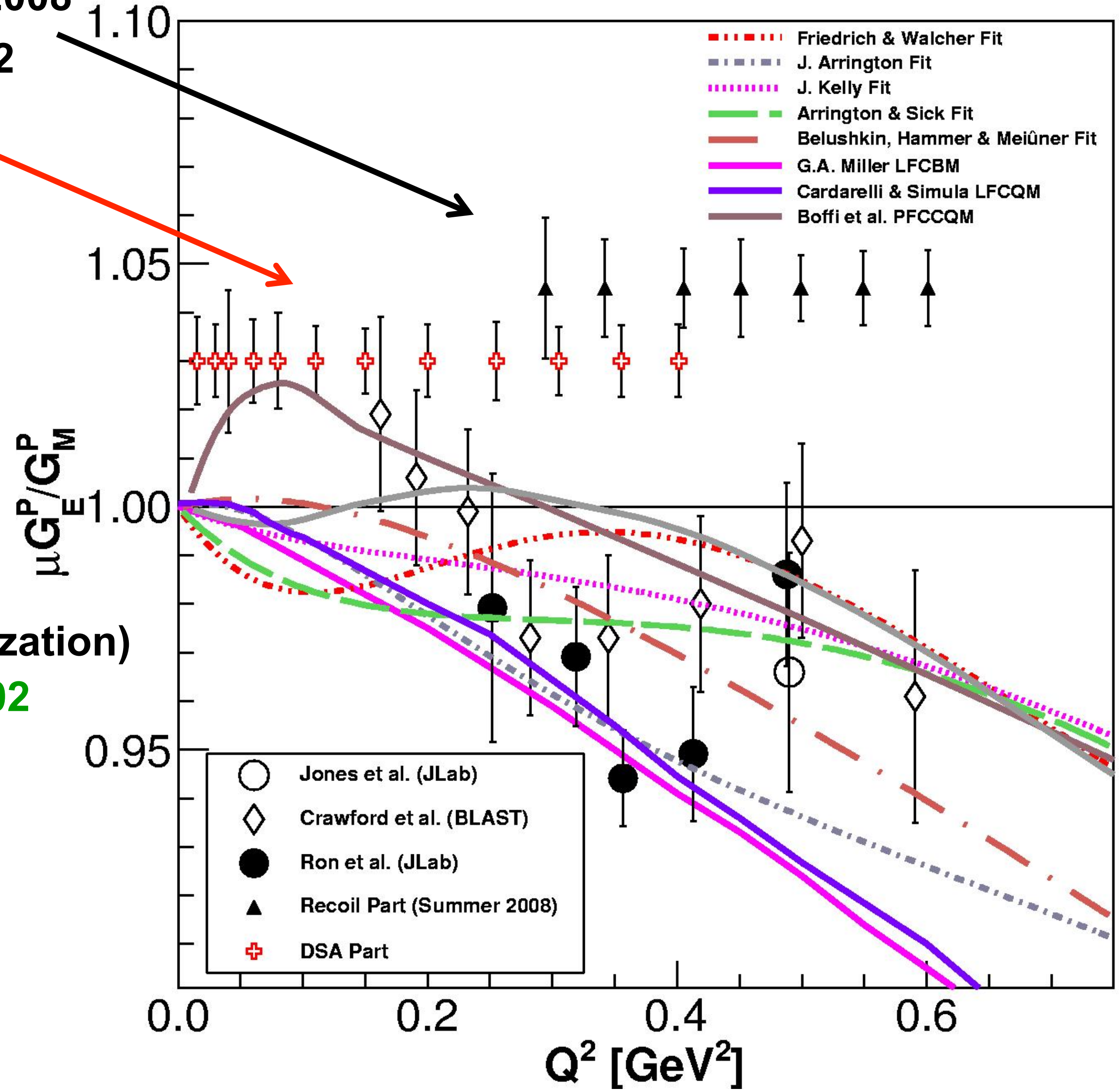
New proton measurements at low Q^2

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**

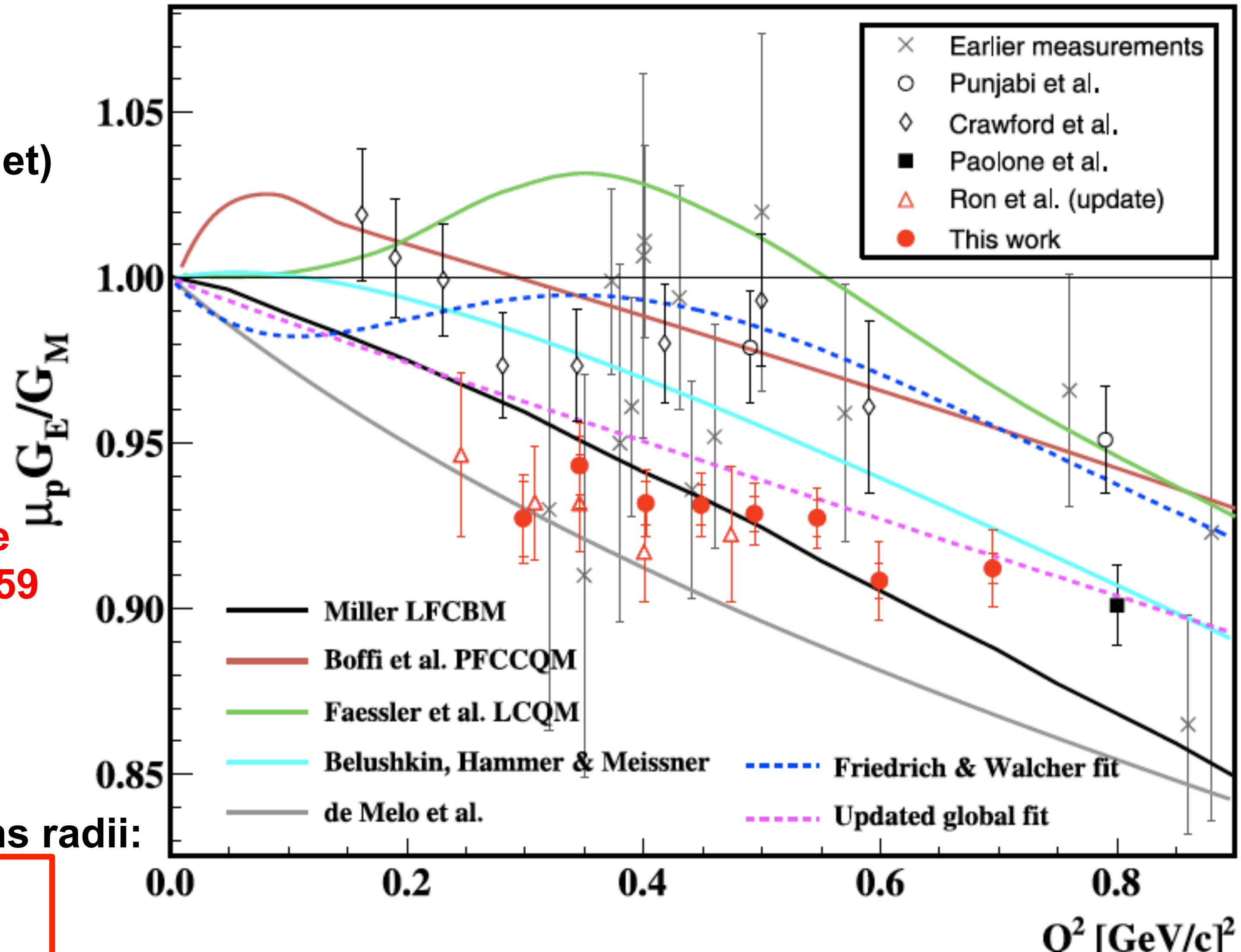
◇ **BLAST (polarized target)**
C. Crawford et al., PRL98 (2007) 052301

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

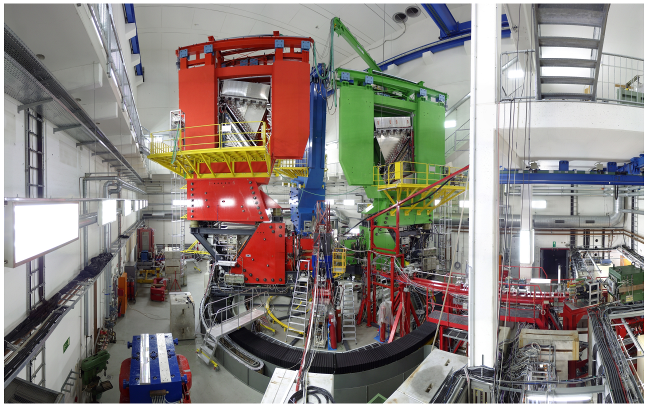
2-sigma difference lower than BLAST

Charge and magnetic rms radii:

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

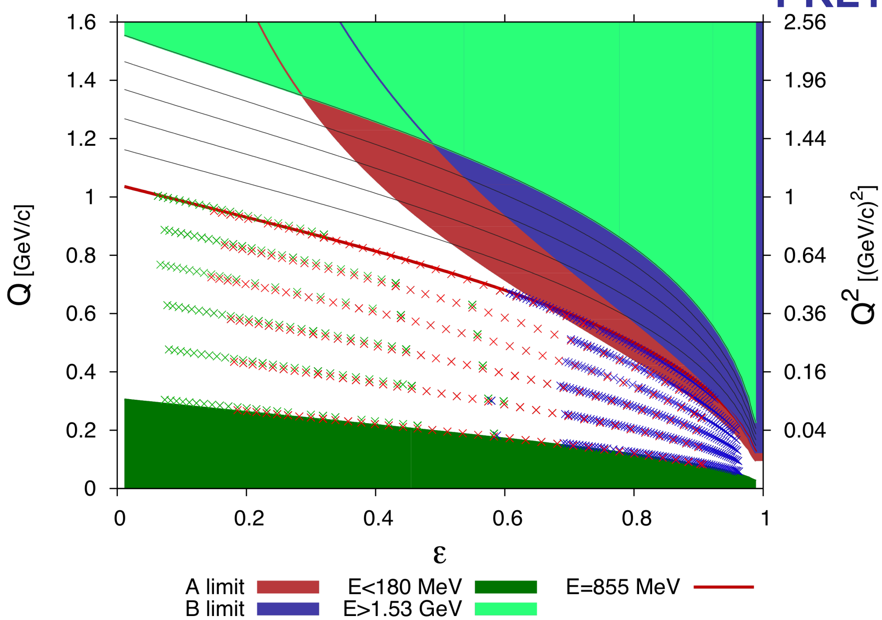


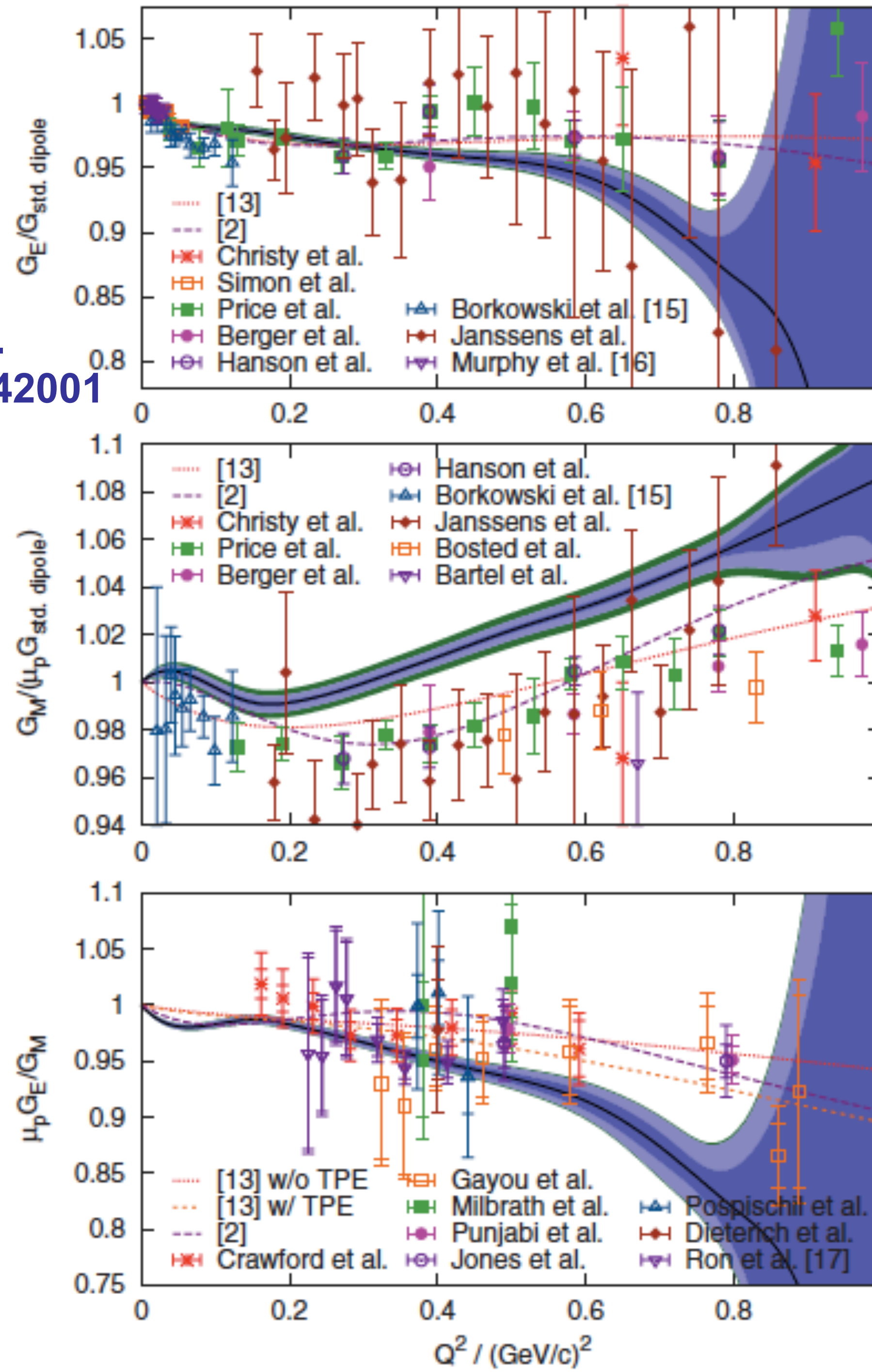
New proton measurements at low Q^2



MAMI A1

J. Bernauer et al.
PRL105 (2010) 242001





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

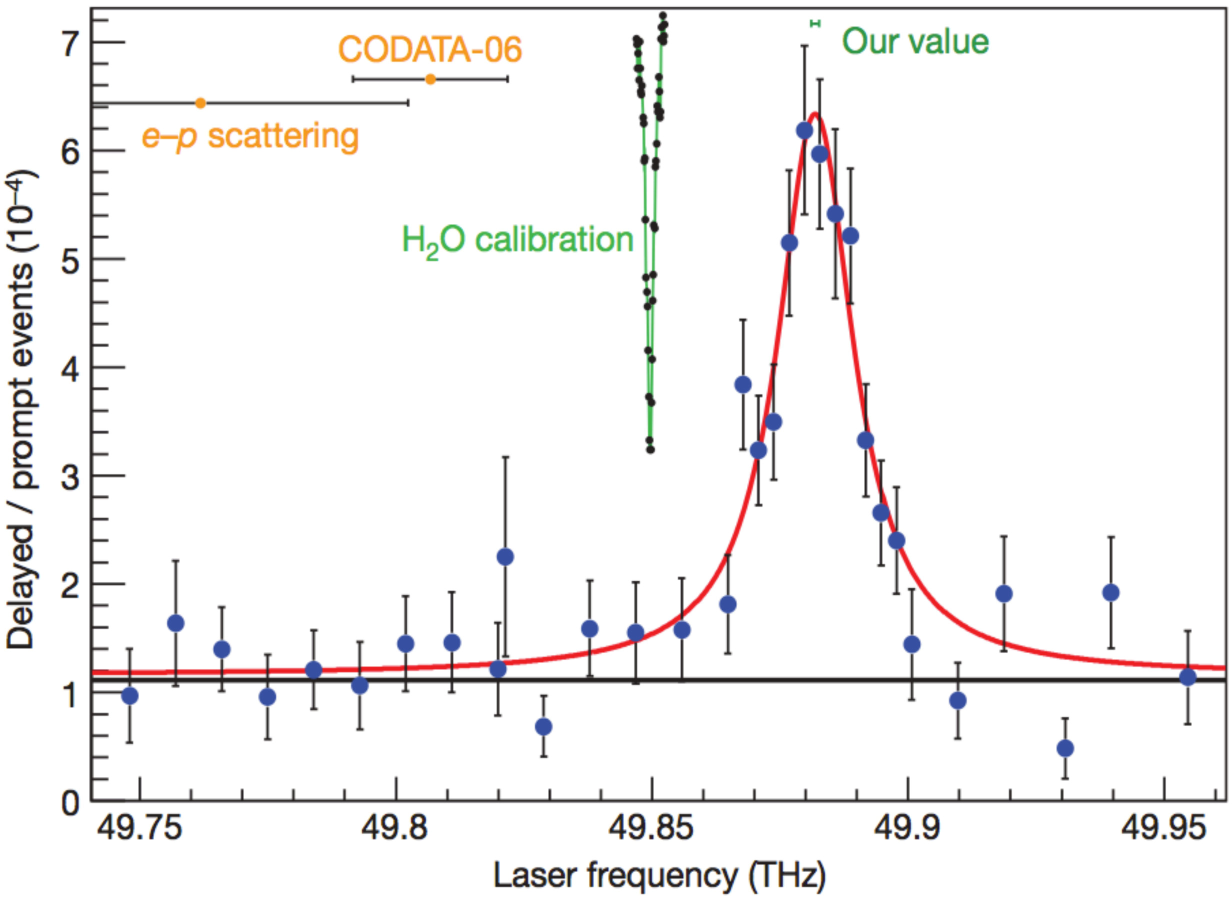
$R_E = 0.879 \pm 0.008$ fm
$R_M = 0.777 \pm 0.017$ fm

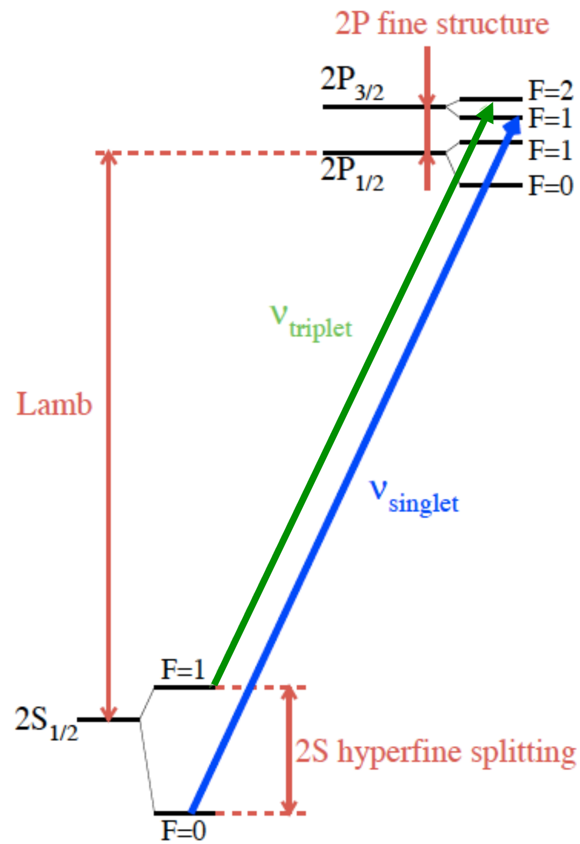
PSI muonic hydrogen measurements

- 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

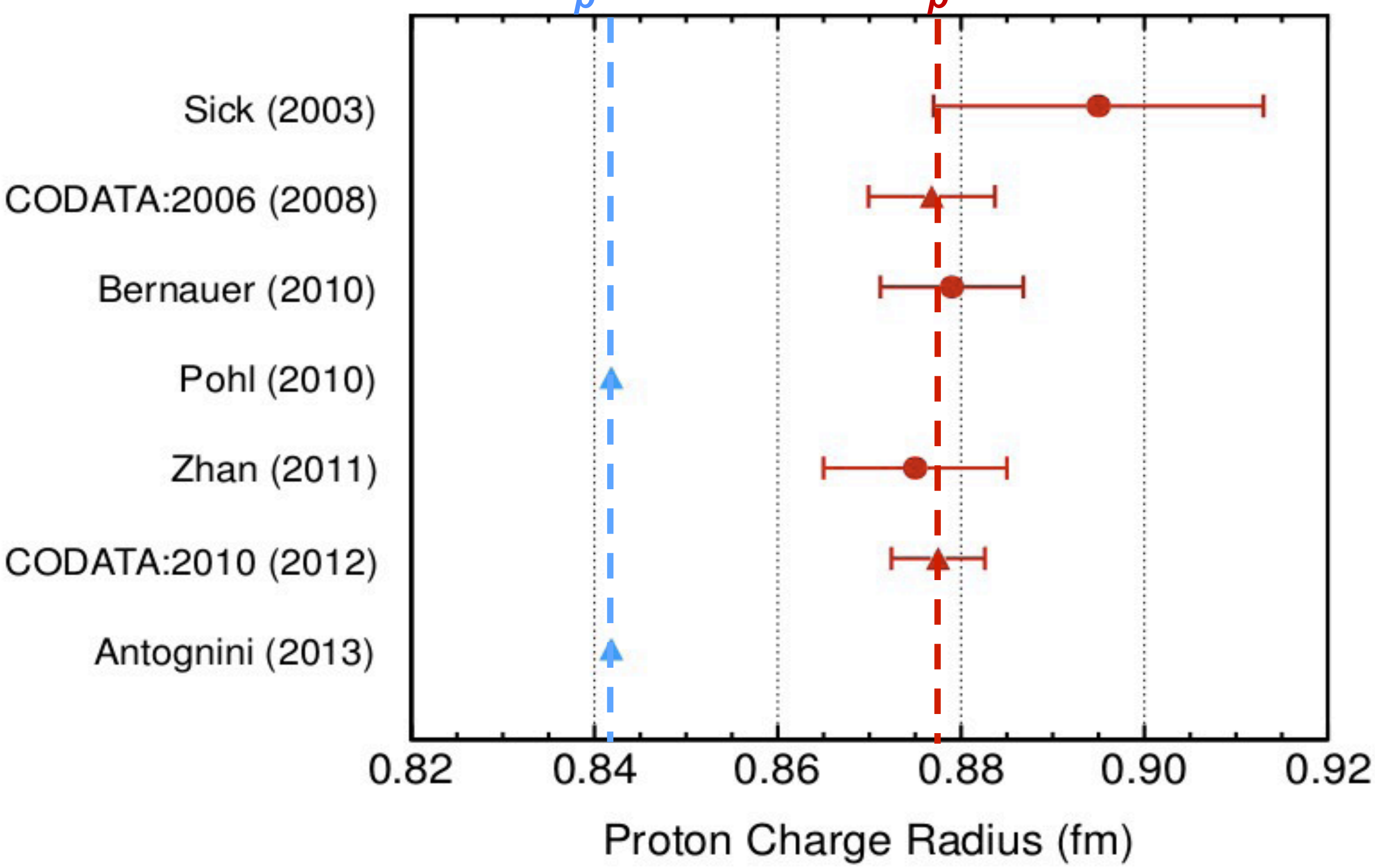




The proton radius puzzle

- >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

Possible resolutions to the puzzle

- **The μp result is wrong**
  Discussion about theory and proton structure for extracting the proton radius from Lamb shift measurement

- **The ep (scattering) results are wrong**
  Fit procedures not good enough
  Q^2 not low enough, structures in the form factors

- **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
  Existing constraints on new physics

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 at MAMI)
  - $\mu^{\pm}$p- and $e^{\pm}$p-scattering in direct comparison at PSI (MUSE)

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

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

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

A full session dedicated to the proton radius

Thursday Oct. 24, 2013

4:00-4:12 FD.00001: The PRad Experiment at JLab
Dipangkar Dutta

4:12-4:24 FD.00002: Target Simulation for the PRad Experiment
Yang Zhang

4:24-4:36 FD.00003: Radiative corrections beyond the ultra-relativistic approximation for PRad – Mehdi Meziane

4:36-4:48 FD.00004: The MUSE Measurement of the Proton Radius at PSI πM1: Overview – Bill Briscoe

4:48-5:00 FD.00005: Simulation study for the PRad experiment
Chao Peng

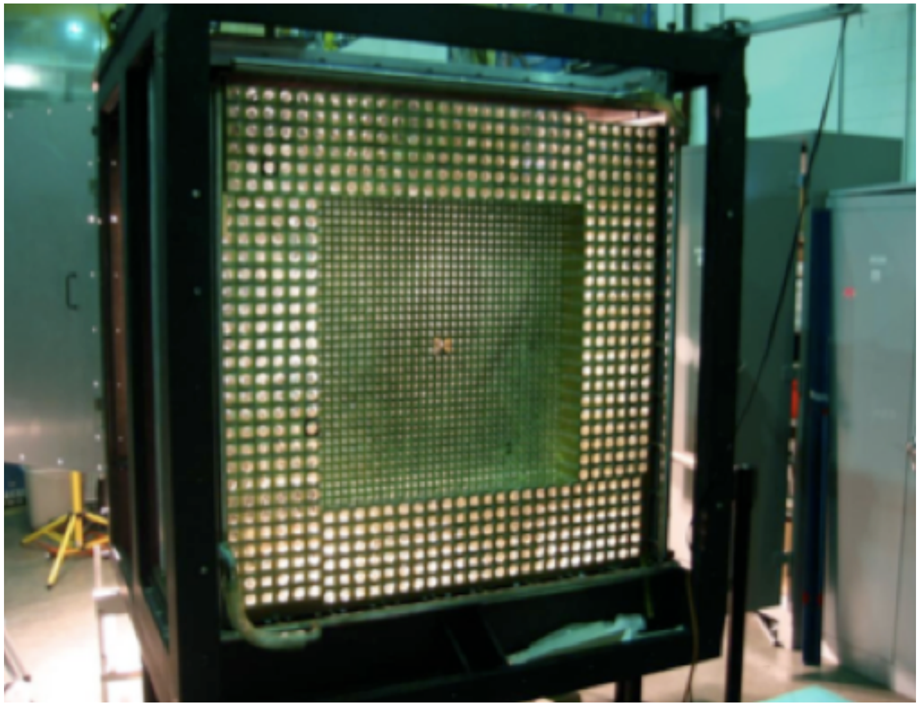
5:00-5:12 FD.00006: The MUSE Measurement of the Proton Radius at PSI πM1: Simulations – Katherine Myers

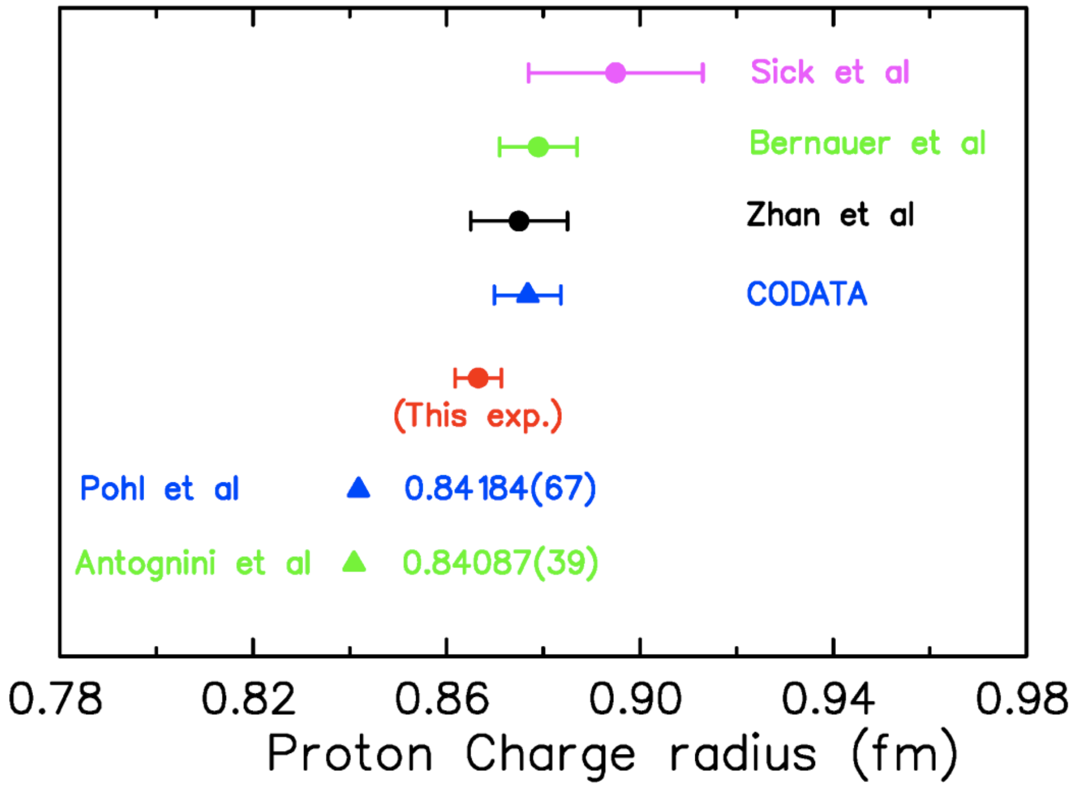
5:12-5:24 FD.00007: The MUSE Measurement of the Proton Radius at PSI πM1: Scattering test – Ron Gilman

5:24-5:36 FD.00008: The MUSE Measurement of the Proton Radius at PSI πM1: Radiative Corrections and Two-photon Exchange
Andrei Afanasev

5:36-5:48 FD.00009: The MUSE Measurement of the Proton Radius at PSI πM1: Beam Studies – Vincent Sulkosky

The PRad proton radius proposal (JLAB)



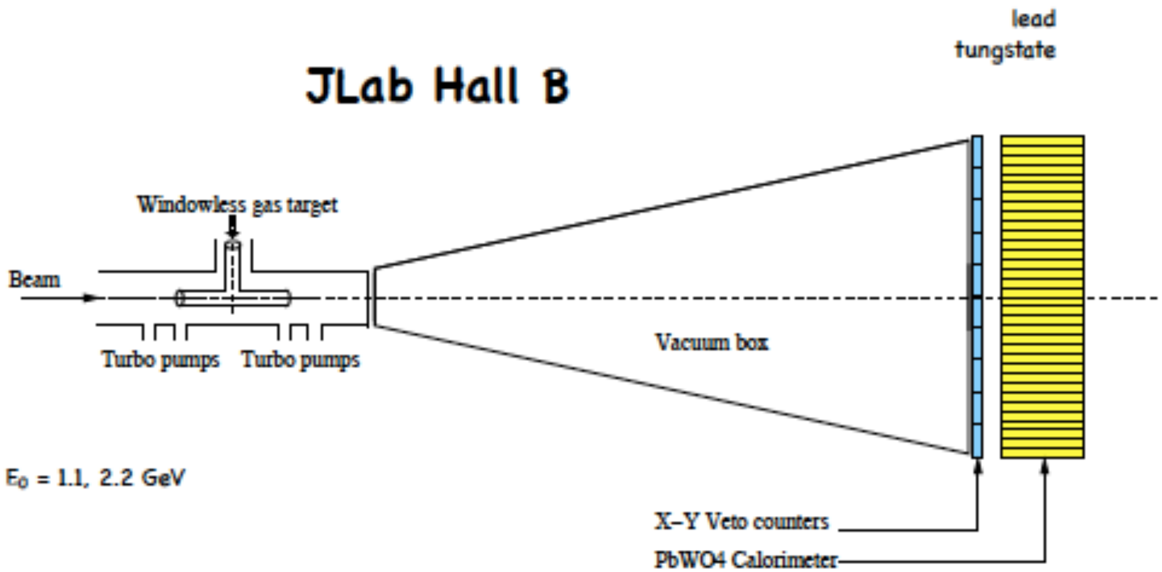


- Low intensity beam in Hall B @ Jlab into windowless gas target.
- Scattered ep and Moller electrons into HYCAL at 0º.
- Lower Q^2 than Mainz. Very forward angle, insensitive to 2γ, G_M.
- Conditionally approved by PAC38 (Aug 2011): ``Testing of this result is among the most timely and important measurements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

The PRad proton radius proposal (JLAB)

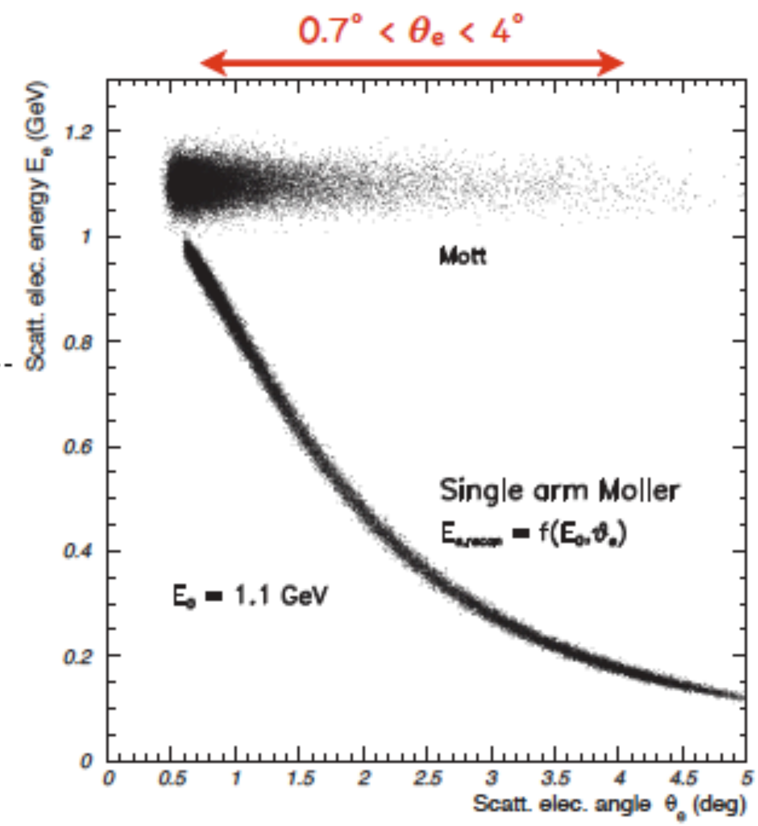
E12-11-106: Experimental method

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



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

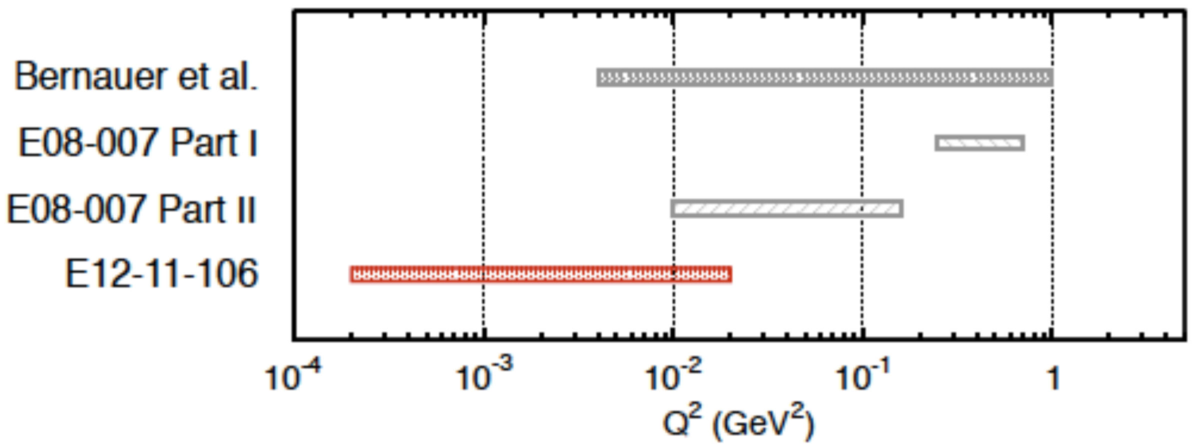
(3) Effective separation of Møller events from the ep elastic scattered events for angles $\theta_e > 0.7°$.



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: 2×10^{-4} to 2×10^{-2} GeV^2 → Model independent r_p extraction

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

Møller scattering – well known QED process

Simultaneous detection of two processes

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

→ N_e and N_{tgt} cancel

Motivation for μp scattering

Electronic hydrogen

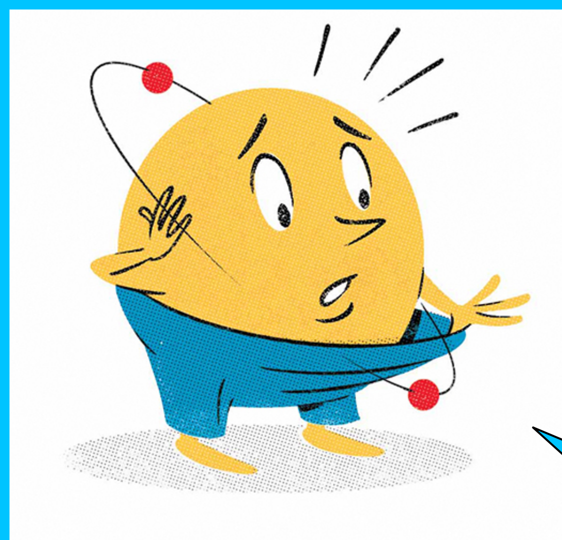
0.877±0.007

Lamb shift

Muonic hydrogen

0.842±0.001

0.84087±0.00039



Electron scattering

0.875±0.006

Elastic scattering

Muon scattering

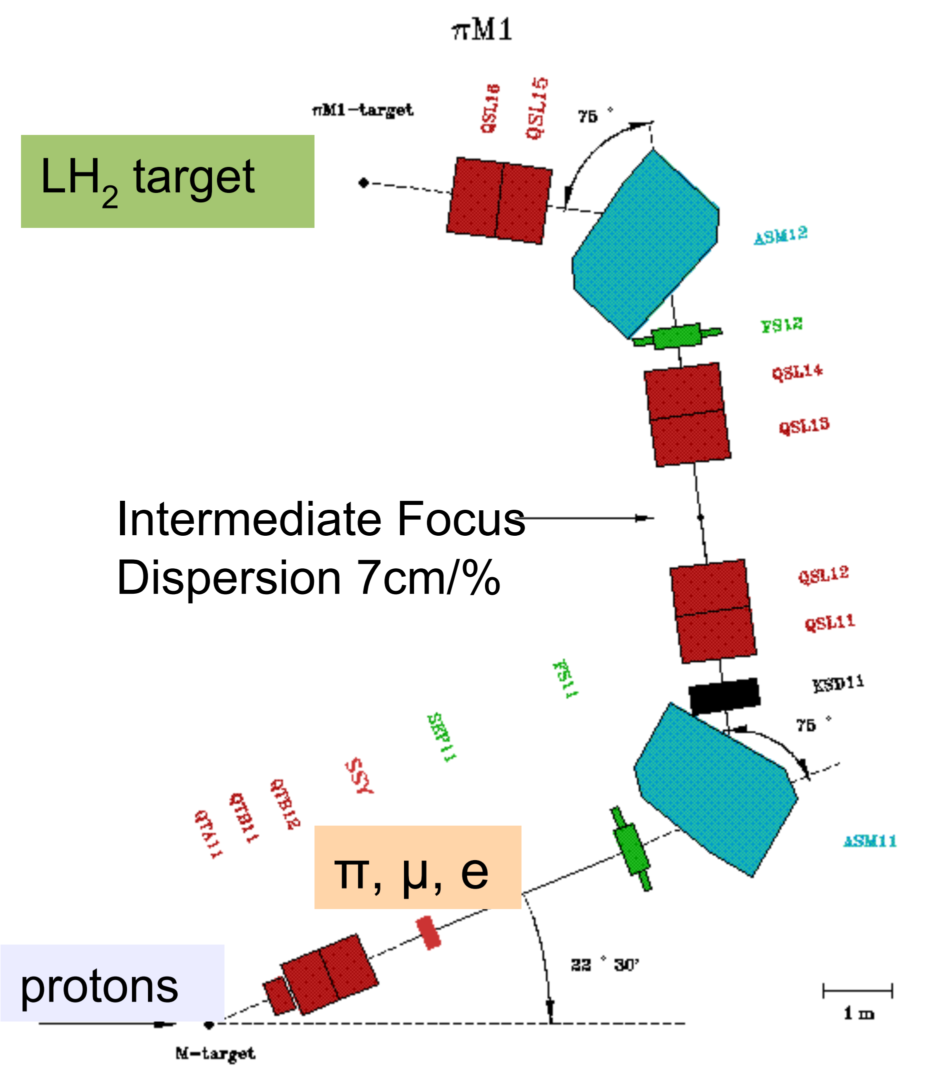
???

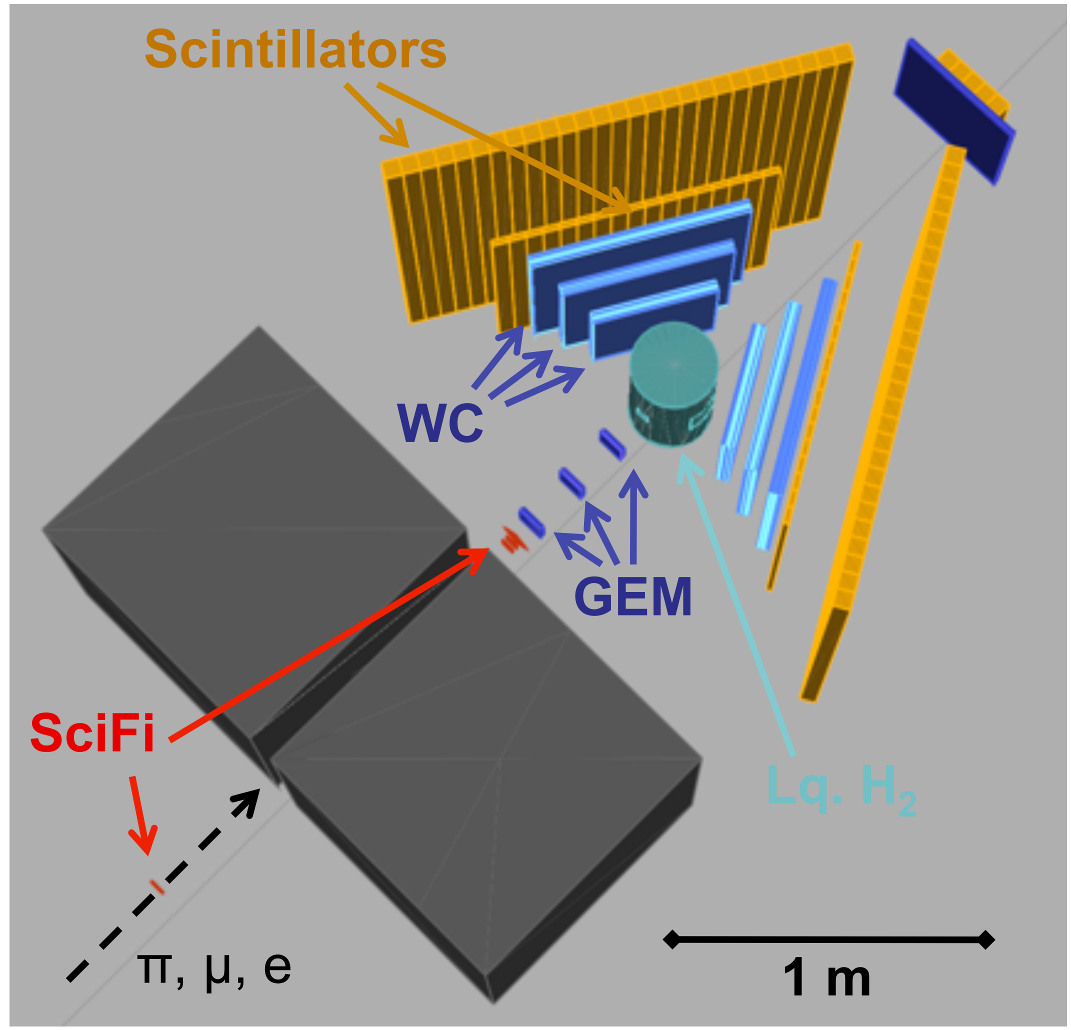
MUon Scattering Experiment (MUSE) at PSI

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)

MUSE beamline and experiment layout

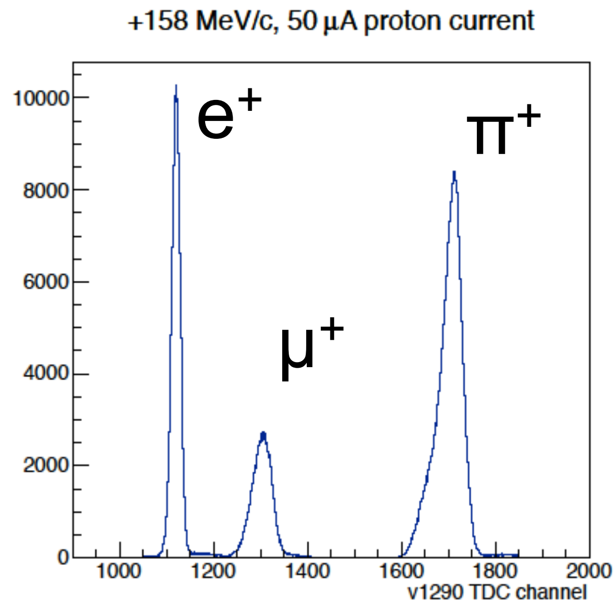


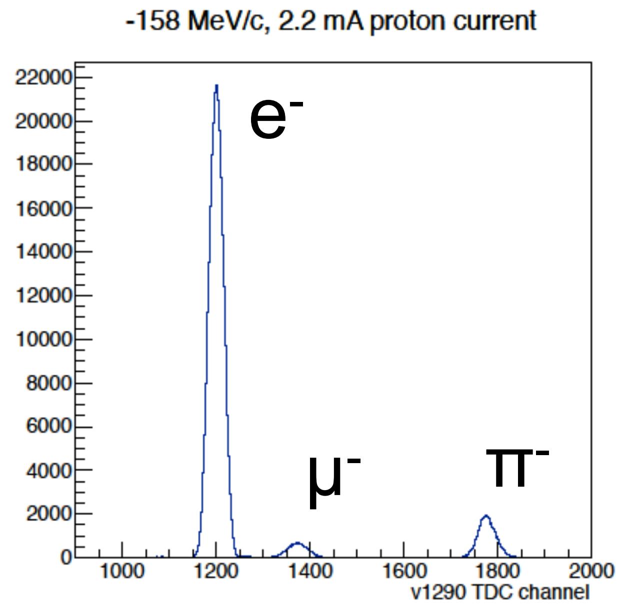


πM1: 100-500 MeV/c
Momentum measurement
RF+TOF separated π, μ, e

Beam particle tracking
Liquid hydrogen target
Scattered lepton detection

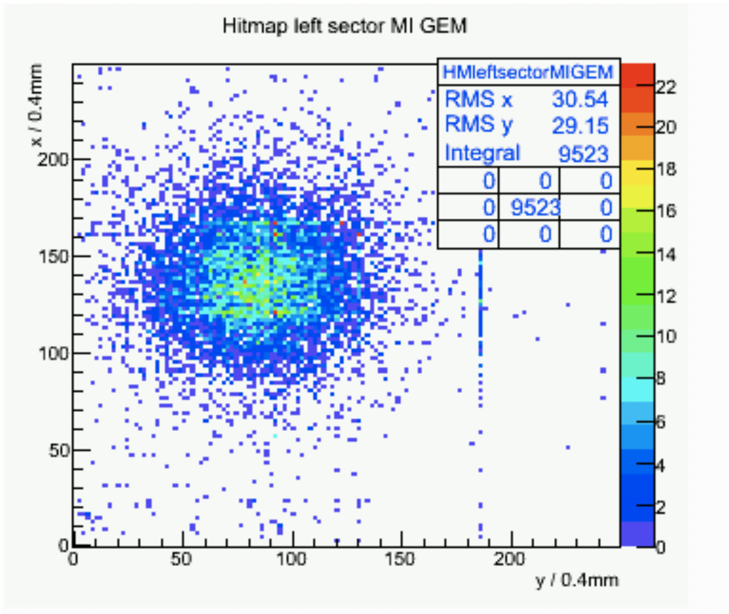
First beam tests

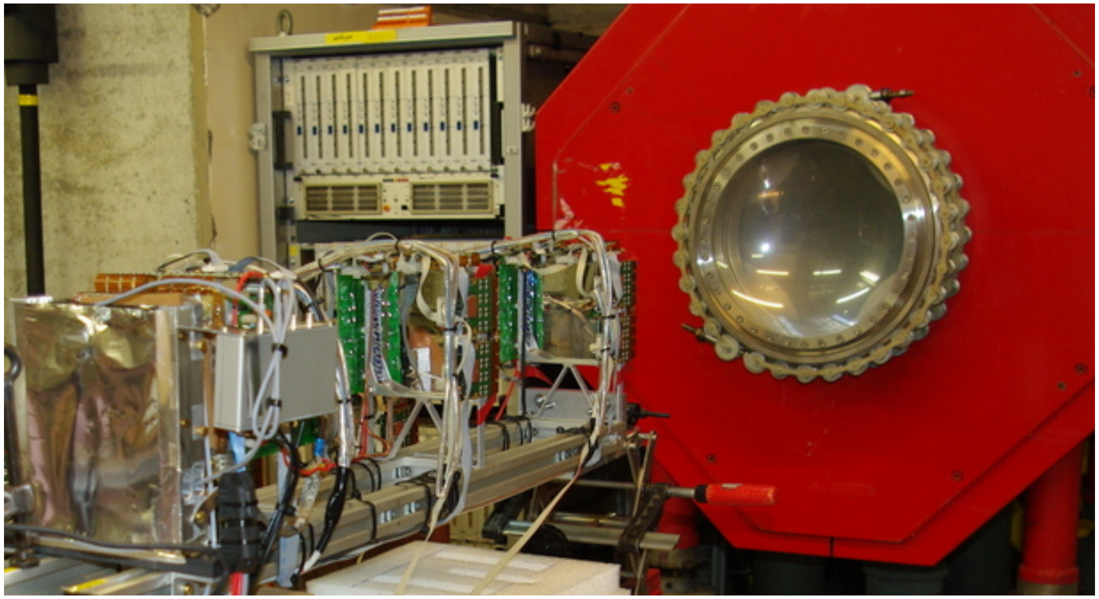




Time of flight relative to RF time (Fall 2012)

Beam spot with GEM telescope – May 23, 2013



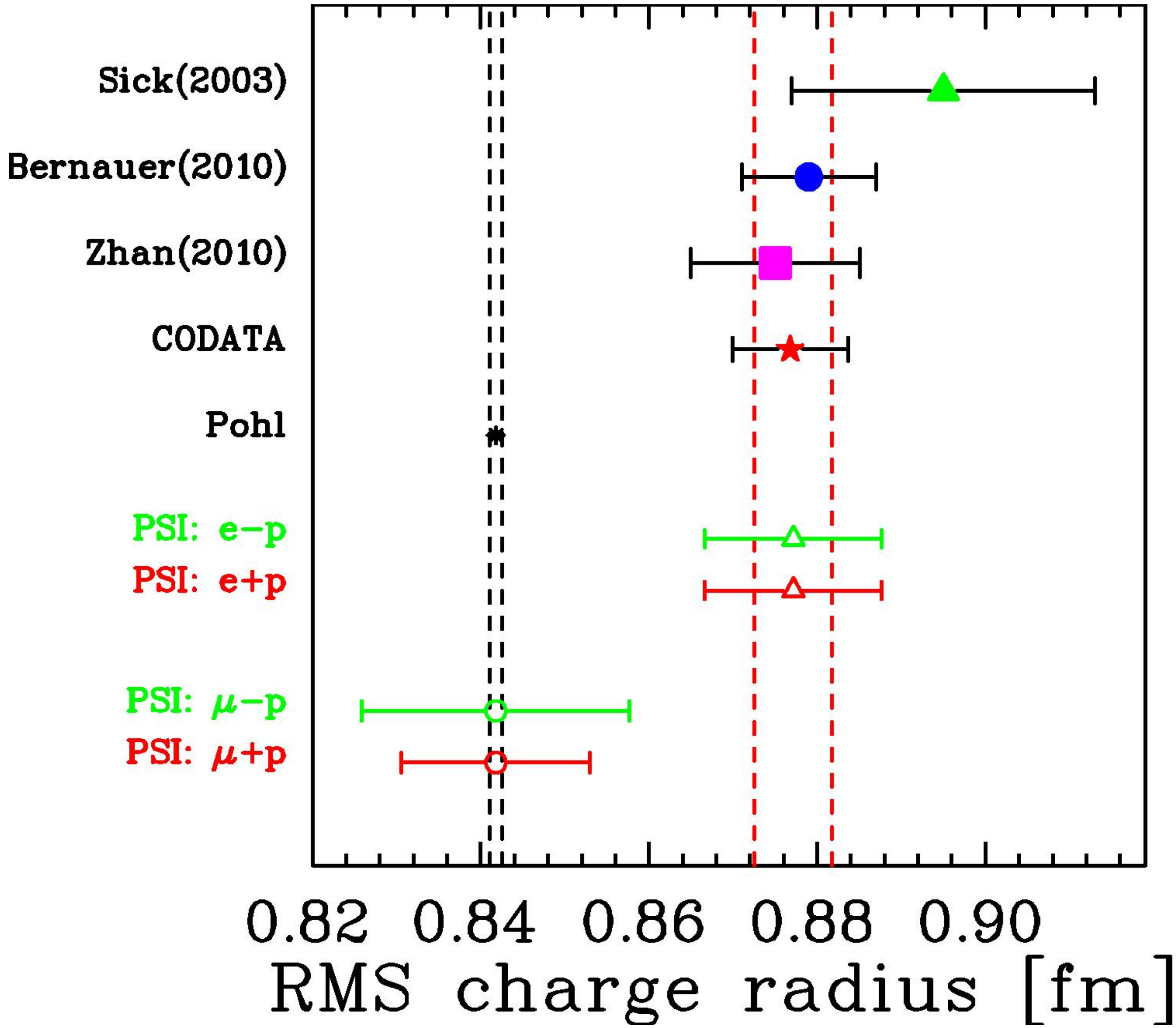


Projected sensitivity

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

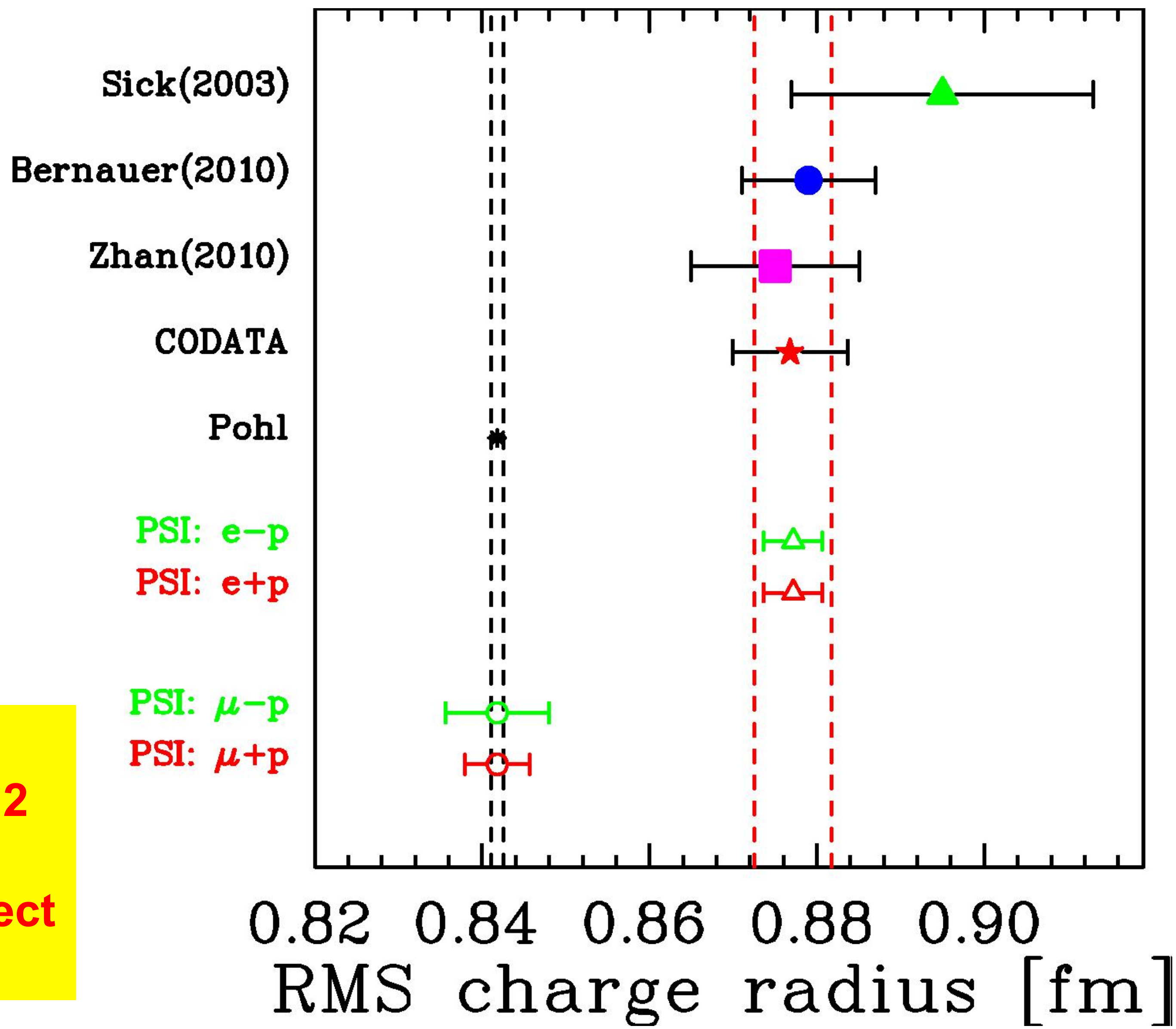
Charge radius extraction limited by systematics, fit uncertainties

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 ~3 years later**

- **MUSE Experiment at PSI**
  - Measure μp and ep scattering and compare directly
  - Measure e+/e- and μ+/μ- to study/constrain TPE effects

- **Timeline**
  - Initial proposal February 2012
  - Technical Review July 2012
  - **Approved in January 2013**
  - Engineering runs 2012–2013
  - Funding & Construction 2014–2015
  - Production running 2016–2017

- **48 MUSE collaborators from 23 institutions in 6 countries:**

  Argonne National Lab, Christopher Newport University, Technical University of Darmstadt, Duke University, Duquesne University, George Washington University, Hampton University, Hebrew University of Jerusalem, Jefferson Lab, Massachusetts Institute of Technology, Norfolk State University, Old Dominion University, Paul Scherrer Institute, Rutgers University, University of South Carolina, Seoul National University, St. Mary's University, Soreq Nuclear Research Center, Tel Aviv University, Temple University, University of Virginia, Weizmann Institute, College of William & Mary

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**

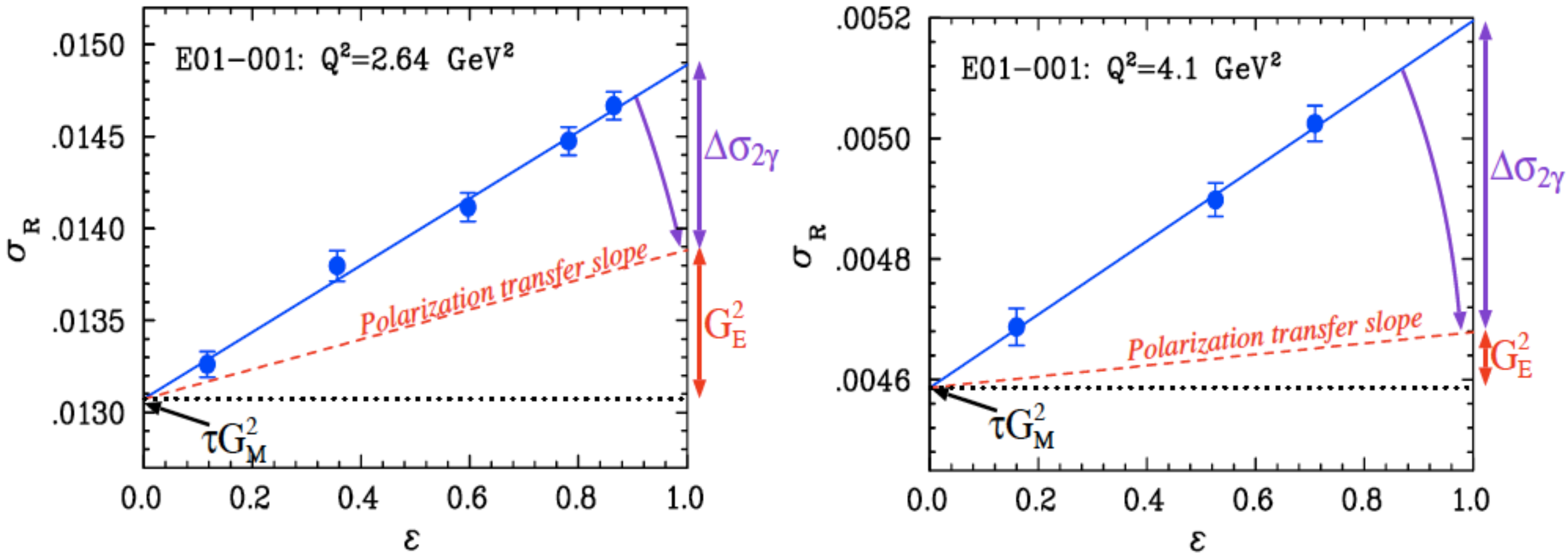
- **The Proton Radius Puzzle has been standing since 2010**
  - **Muonic hydrogen Lamb shift: Proton rms radius 7σ smaller than with electronic hydrogen and electron scattering**
  - **PRad at JLab**
  - **MUon Scattering Experiment MUSE**
  - **New Physics remains a possibility**

The nine muses

Backup

Effect of two-photon exchange

J. Arrington



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

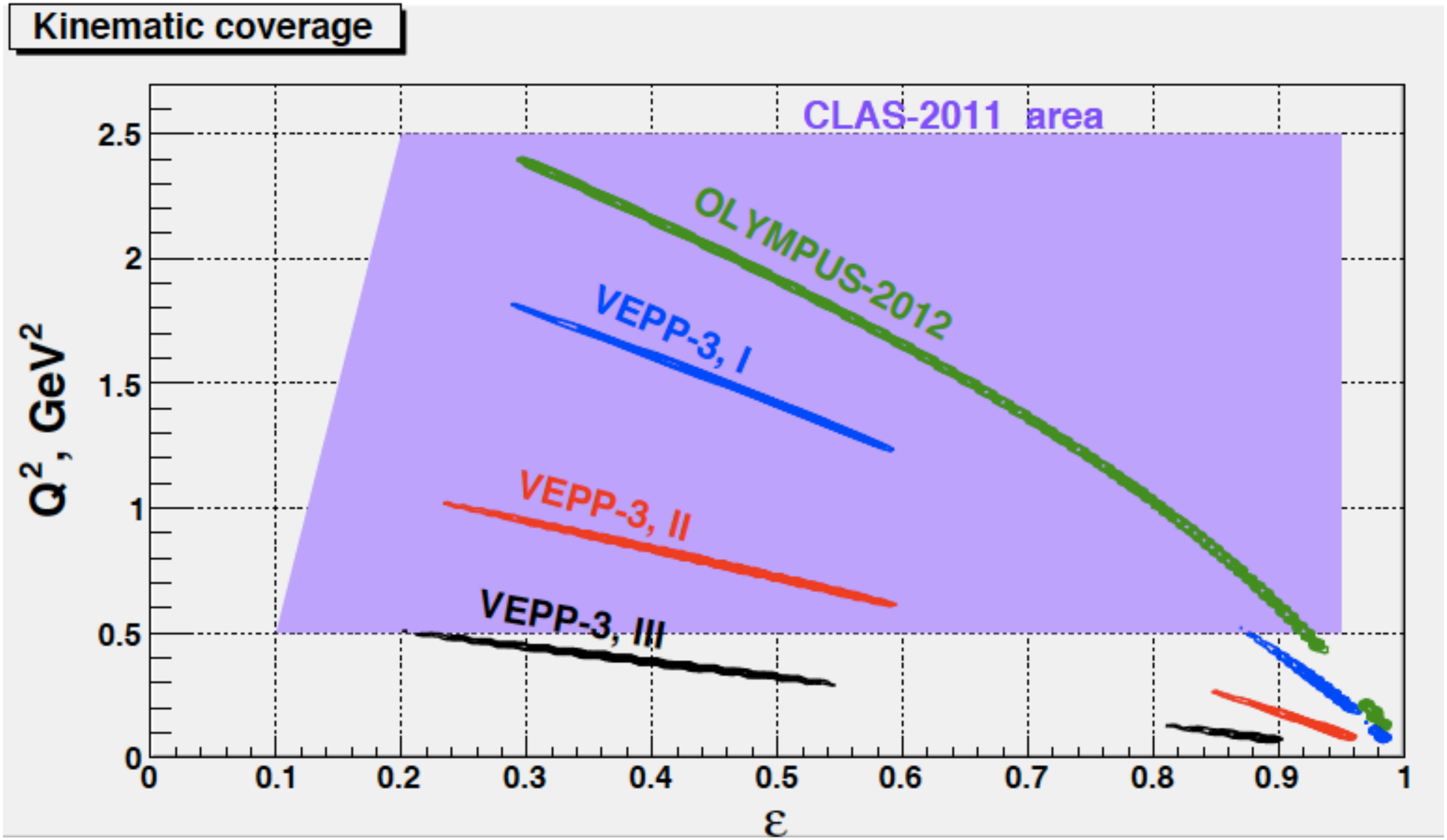
At high Q^2 , the contribution of G_E to the cross section is of similar order as the TPE effect (few %)

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)



A dark photon and the proton radius puzzle

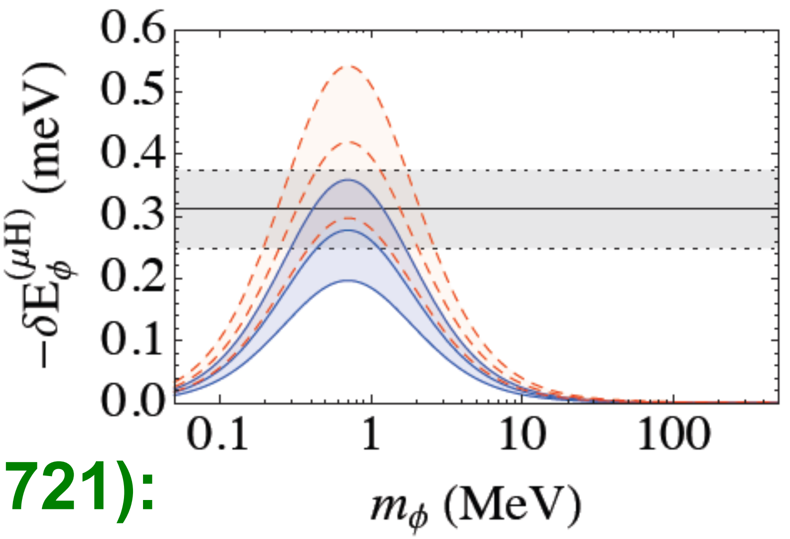
Jaeckel, Roy (arXiv:1008.3536)

- 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

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

- constrained by K → μν decay