Hauptvortrag at DPG2013, Dresden, March 4-8, 2013

Investigating the charge of the proton

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Outline

Proton electric and magnetic form factors G_E and G_M

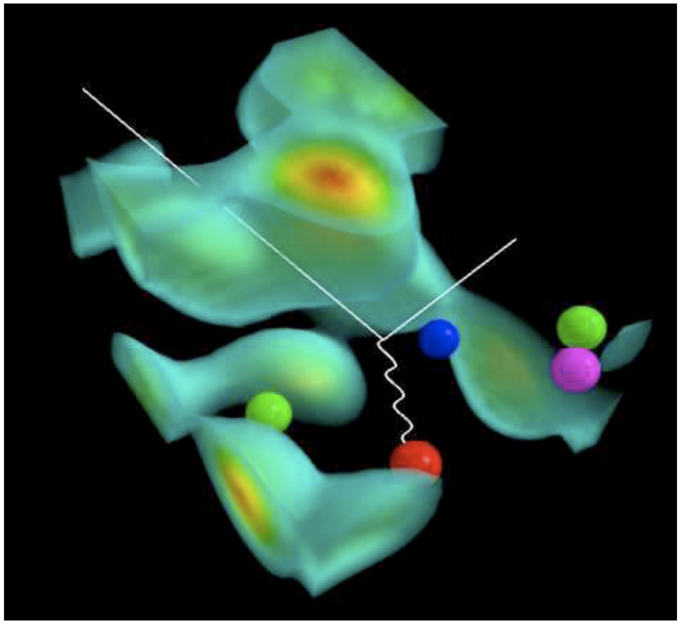
- Introduction, motivation and formalism
- Traditional and new techniques
- Overview of experimental data

High Q^2: Energy frontier

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

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-IV (& GMp) – high Q^2 at Jlab-12	– proposed

Rosenbluth separation

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

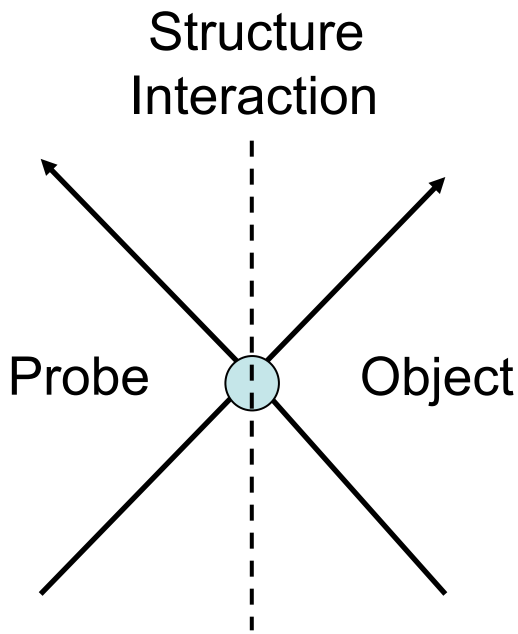
Positron-electron comparisons

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

Proton radius measurements

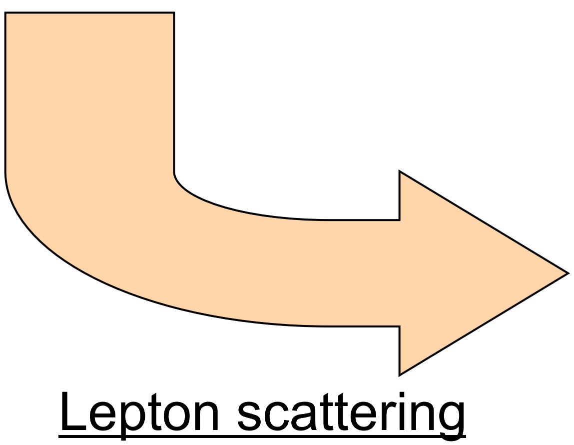
PSI / (muonic hydrogen Lamb shift, HFS)	– published (2010+2013)
MAMI / A1 (e-scattering)	– published (2010)
Jlab / PrimEx (e-scattering)	– proposed
PSI / MUSE (muon scattering experiment)	– proposed

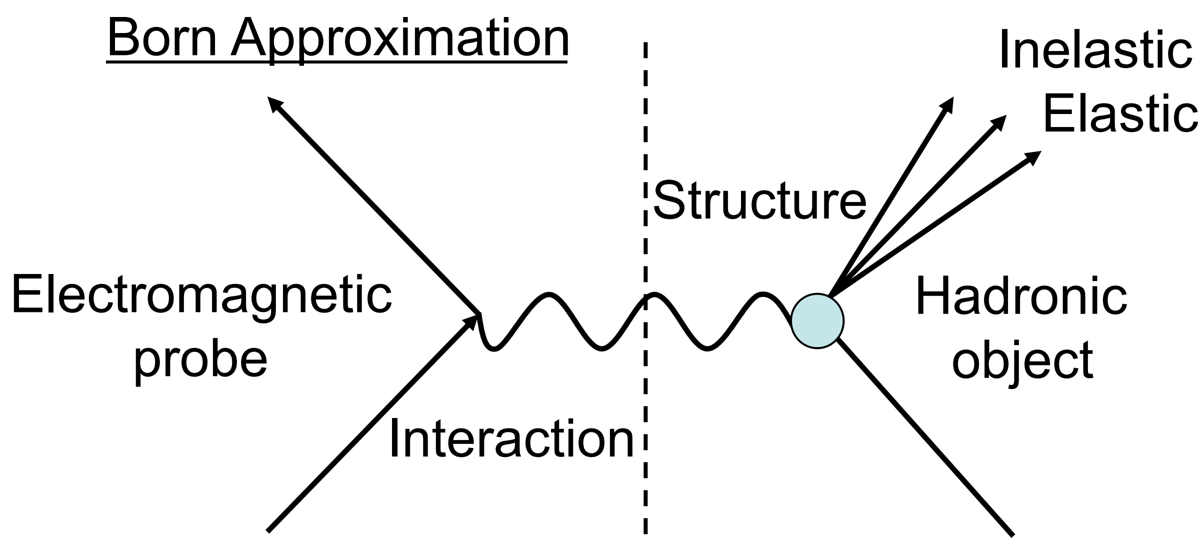
Hadronic structure and EW interaction



Factorization!

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





One-Photon Exchange Approximation

The beginnings

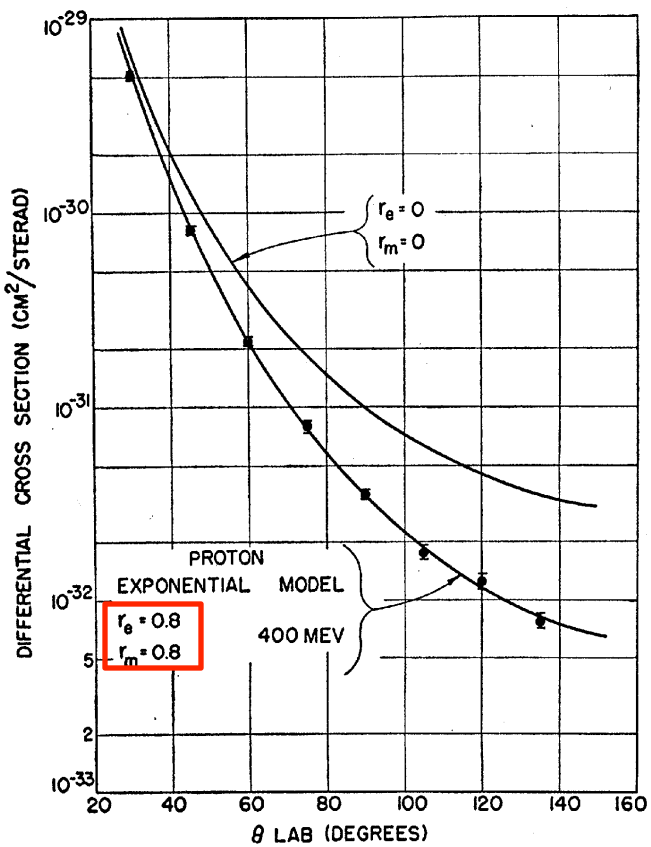


FIG. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with rms radii = 0.80×10^{-13} cm.

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

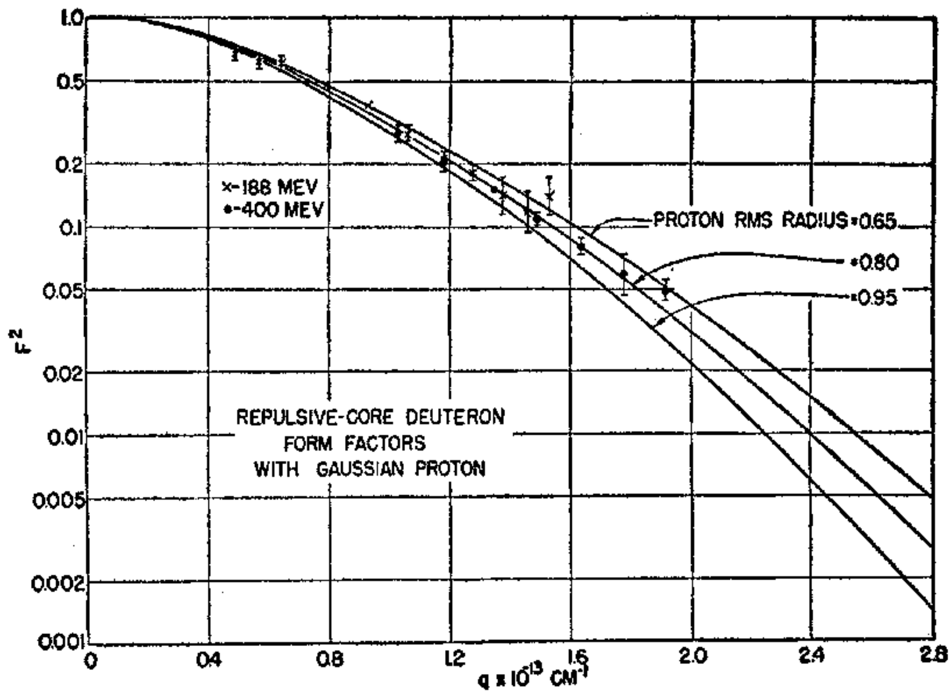
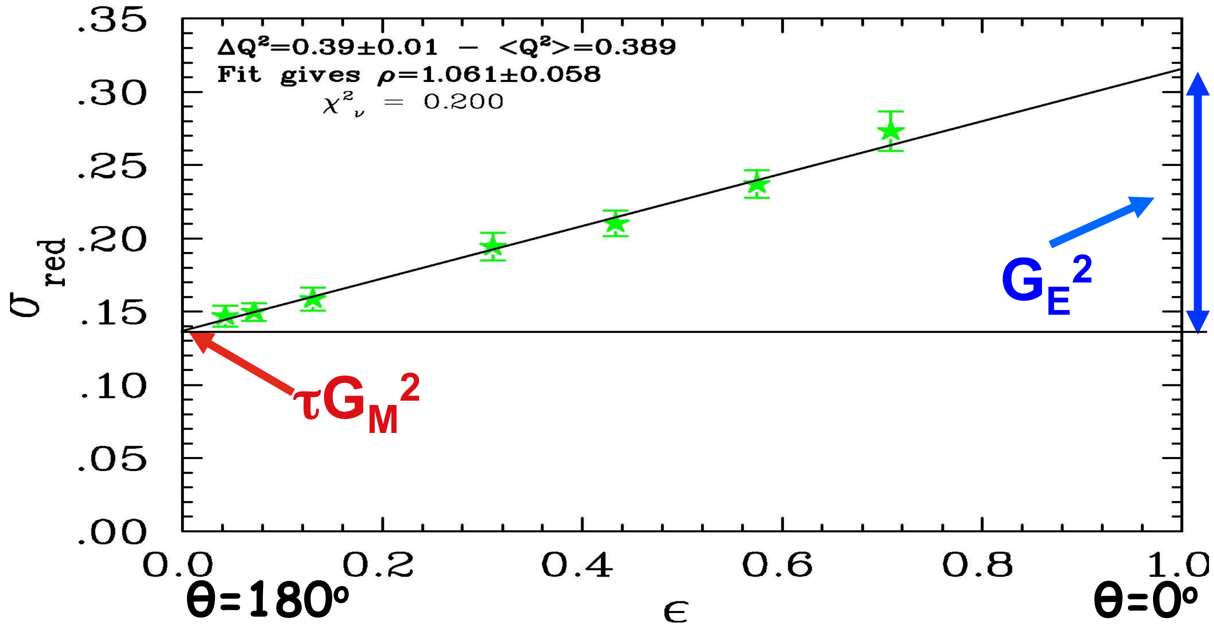


FIG. 31. Introduction of a finite proton core allows the experimental data to be fitted with conventional form factors (McIntyre).

ed-elastic
Finite size + nuclear structure

Form factors from Rosenbluth method



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

➔ **Determine**

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

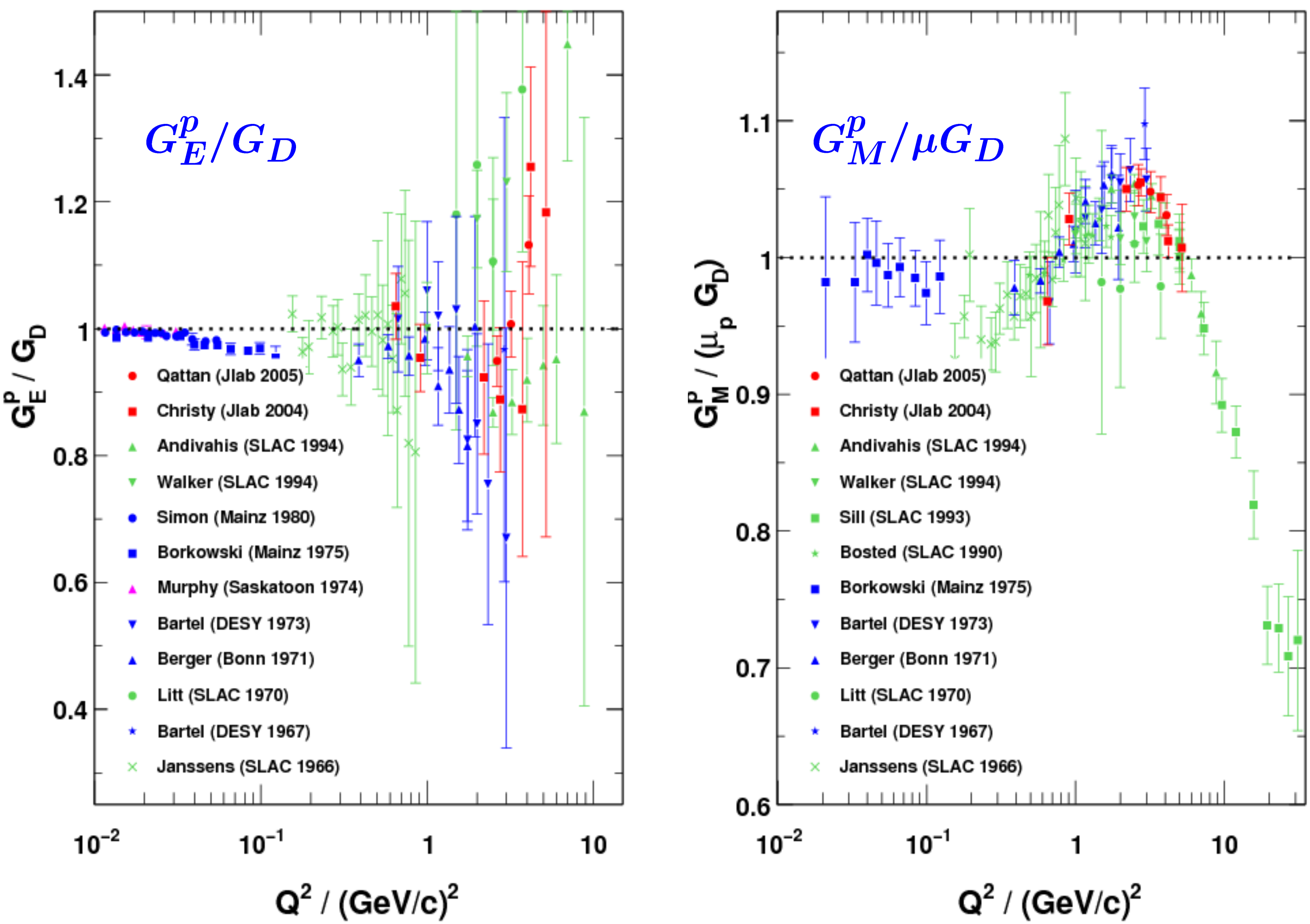
- **In One-photon exchange, form factors are related to radiatively corrected elastic electron-proton scattering cross section**

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

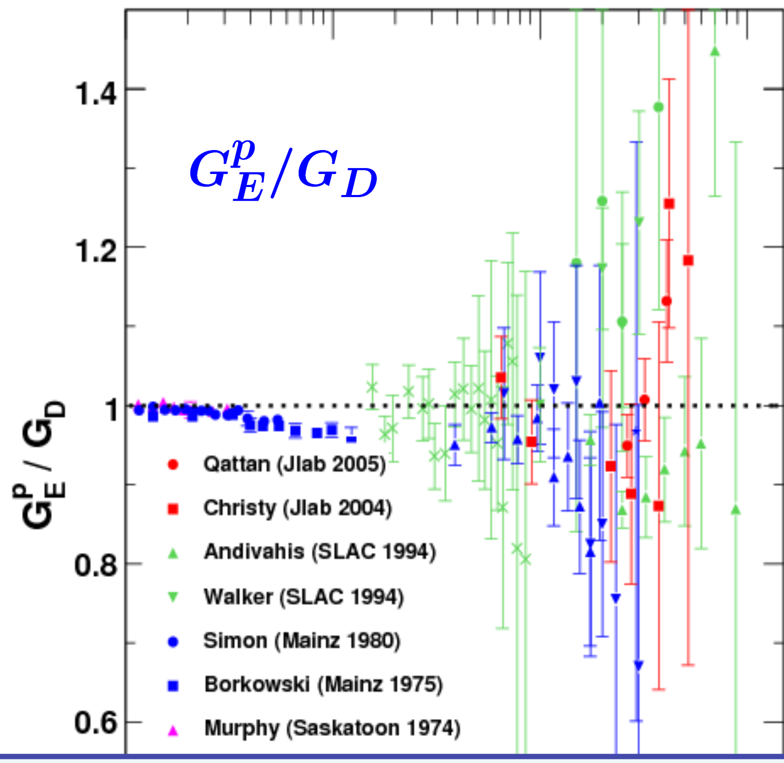
$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$

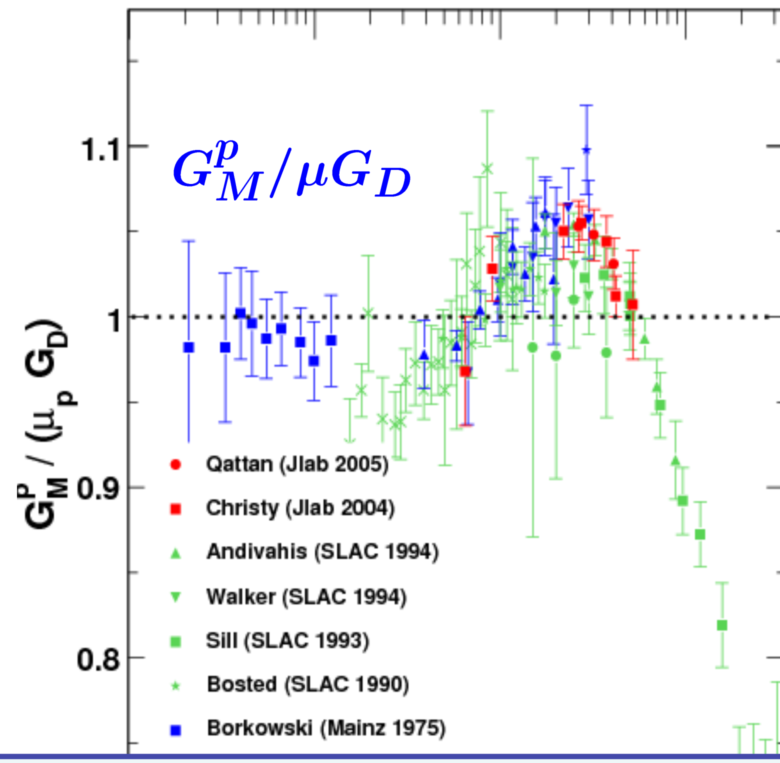
$$= \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)}, \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

G^p_E and G^p_M from unpolarized data



G^p_E and G^p_M from unpolarized data



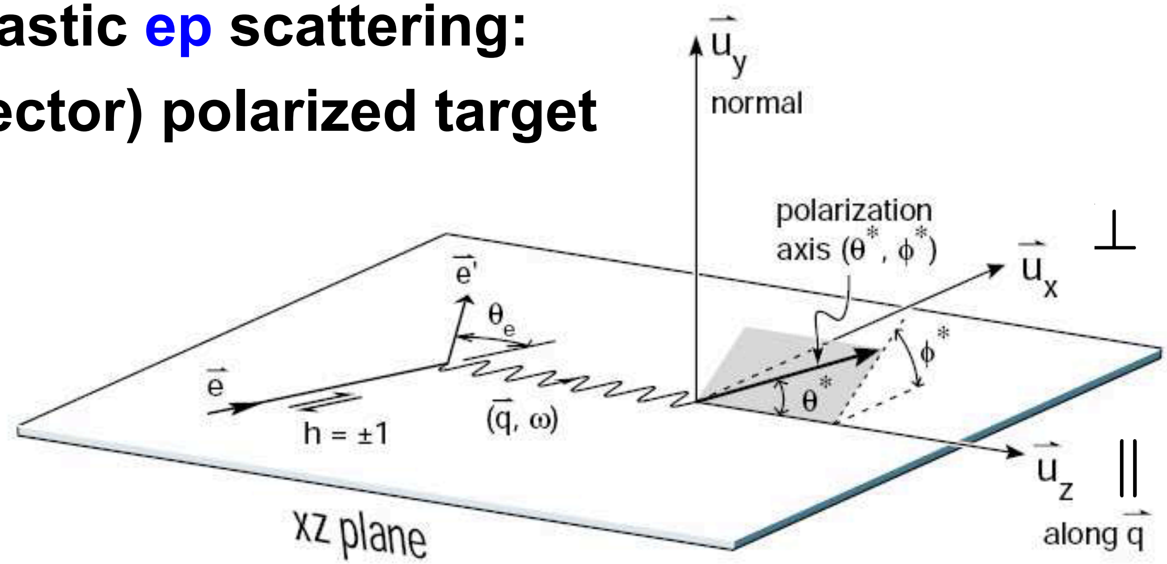


- $G(Q^2) \overset{\text{Fourier}}{\longleftrightarrow} \rho(r)$ **charge and magnetization density (Breit fr.)**
- **Dipole form factor** $G_D = \frac{1}{\left(1+\frac{Q^2}{0.71}\right)^2} \longleftrightarrow \rho_D(r) = \rho_0\, e^{-\sqrt{0.71}r}$
- $G_E^p \approx G_M^p/\mu_p \approx G_M^n/\mu_n \approx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

Nucleon form factors and polarization

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

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



- **Polarized cross section**

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

- **Double spin asymmetry = 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

Recoil polarization technique

- Pioneered at MIT-Bates
- Pursued in Halls A and C, and MAMI A1
- In preparation for Jlab @ 12 GeV

V. Punjabi et al.,
Phys. Rev. C71 (2005) 05520

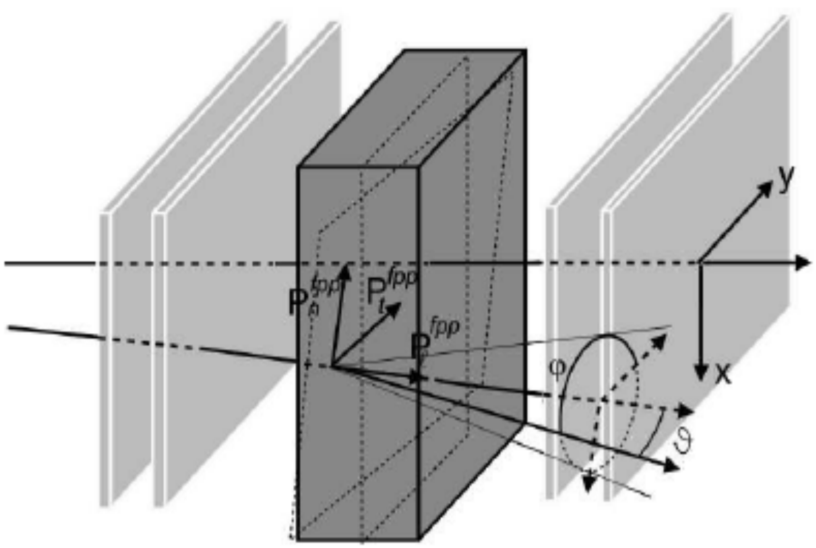


FIG. 9: Schematic of the polarimeter chambers and analyzer, showing a non-central trajectory; ϑ is the polar angle, and φ is the azimuthal angle from the y-direction counterclockwise.

Focal-plane polarimeter
Secondary scattering of polarized proton from unpolarized analyzer

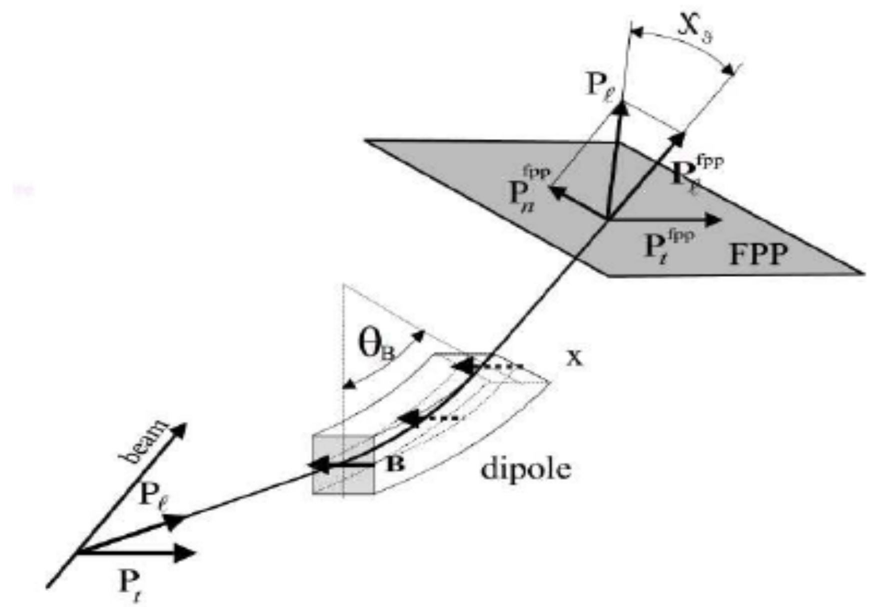
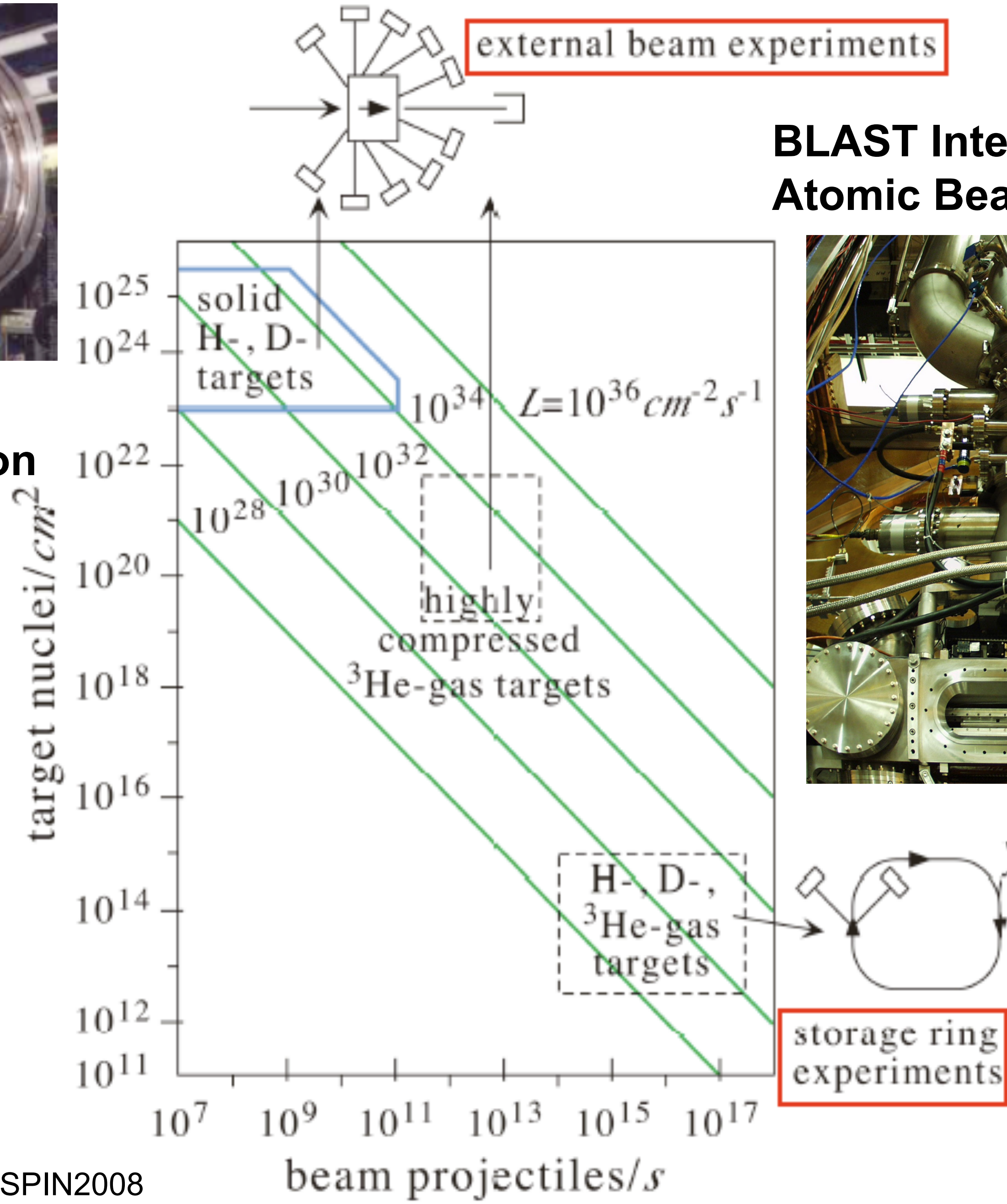


FIG. 15: Schematic drawing showing the precession by angle χ_θ of the P_ℓ component of the polarization in the dipole of the HRS.

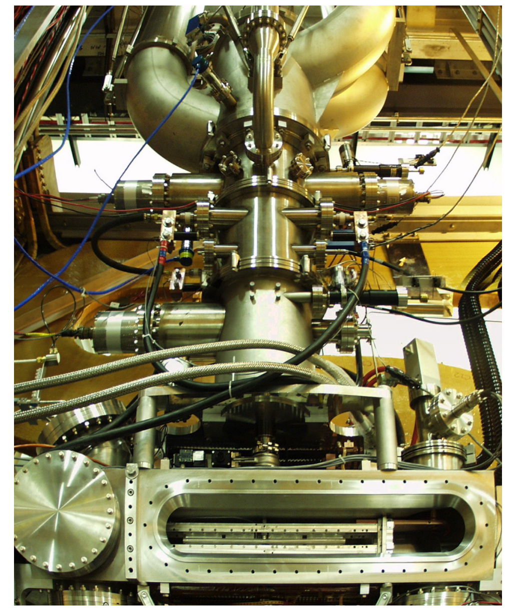
Spin transfer formalism to account for spin precession through spectrometer

Polarized targets

UVA / “SLAC”-Target:
Dynamic Nuclear Polarization



BLAST Internal Target:
Atomic Beam Source

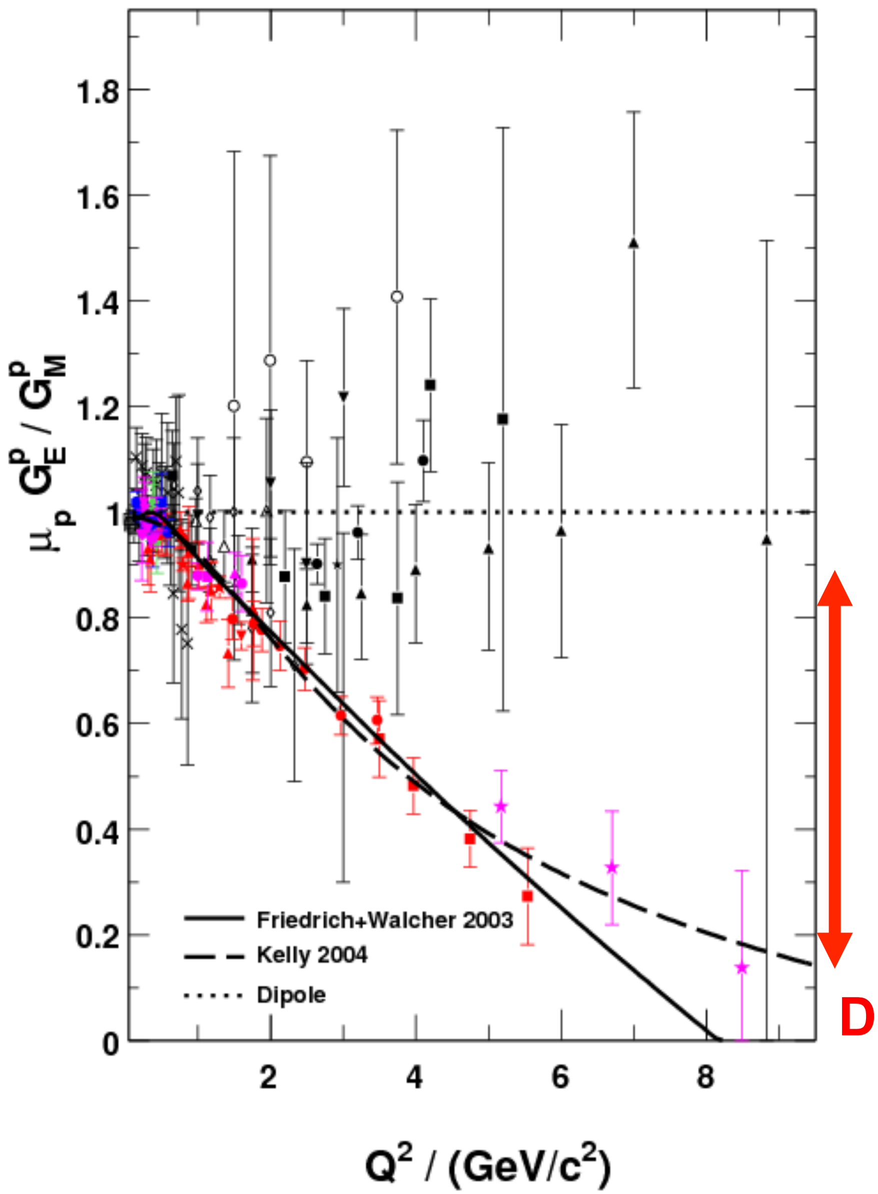


Limited luminosity for polarized hydrogen/ deuterium targets

Very precise at low to moderately high Q^2

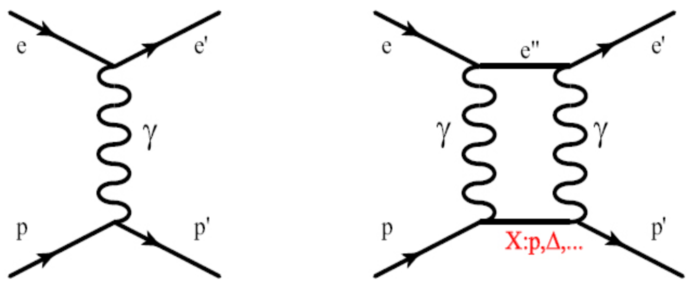
from W. Meyer, SPIN2008

Proton form factor ratio



Jefferson Lab 2000–

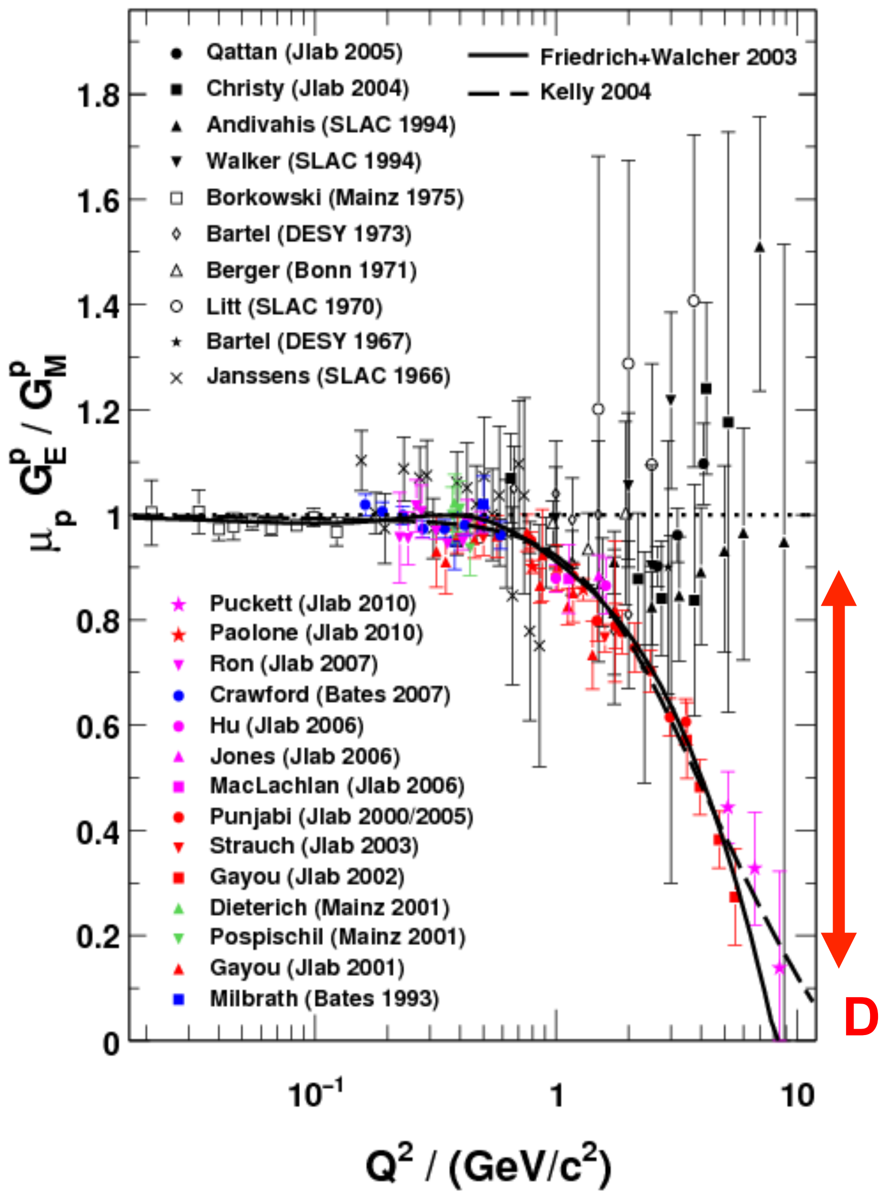
- All Rosenbluth data from SLAC and Jlab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Multi-photon exchange considered best candidate



Dramatic discrepancy!

>800 citations

Proton form factor ratio



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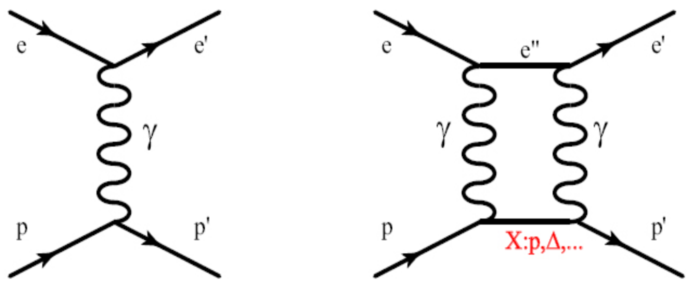
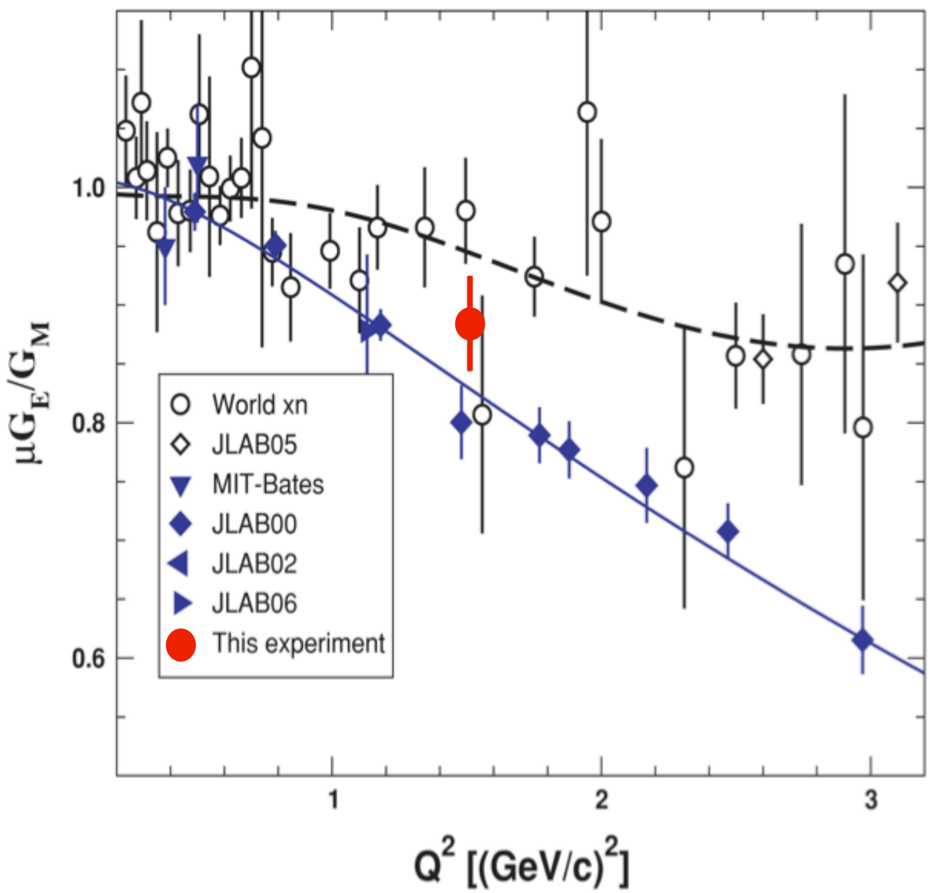


Dramatic discrepancy!

>800 citations

Polarized target experiments 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

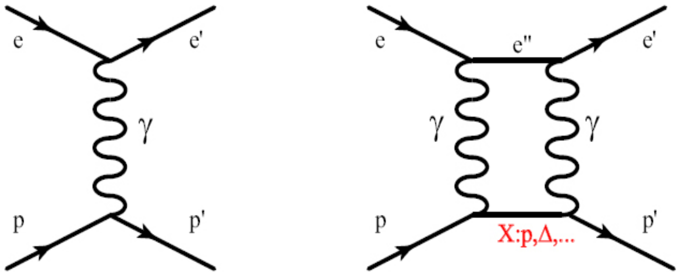
RSS /Hall C: $Q^2 \approx 1.5$ $(GeV/c)^2$

SANE/Hall C: completed March 2009
BigCal electron detector
Recoil protons in HMS parasitically
Extract G_E/G_M at $Q^2 \approx 2$ and 6 $(GeV/c)^2$

Future precision measurements at high Q^2 are feasible

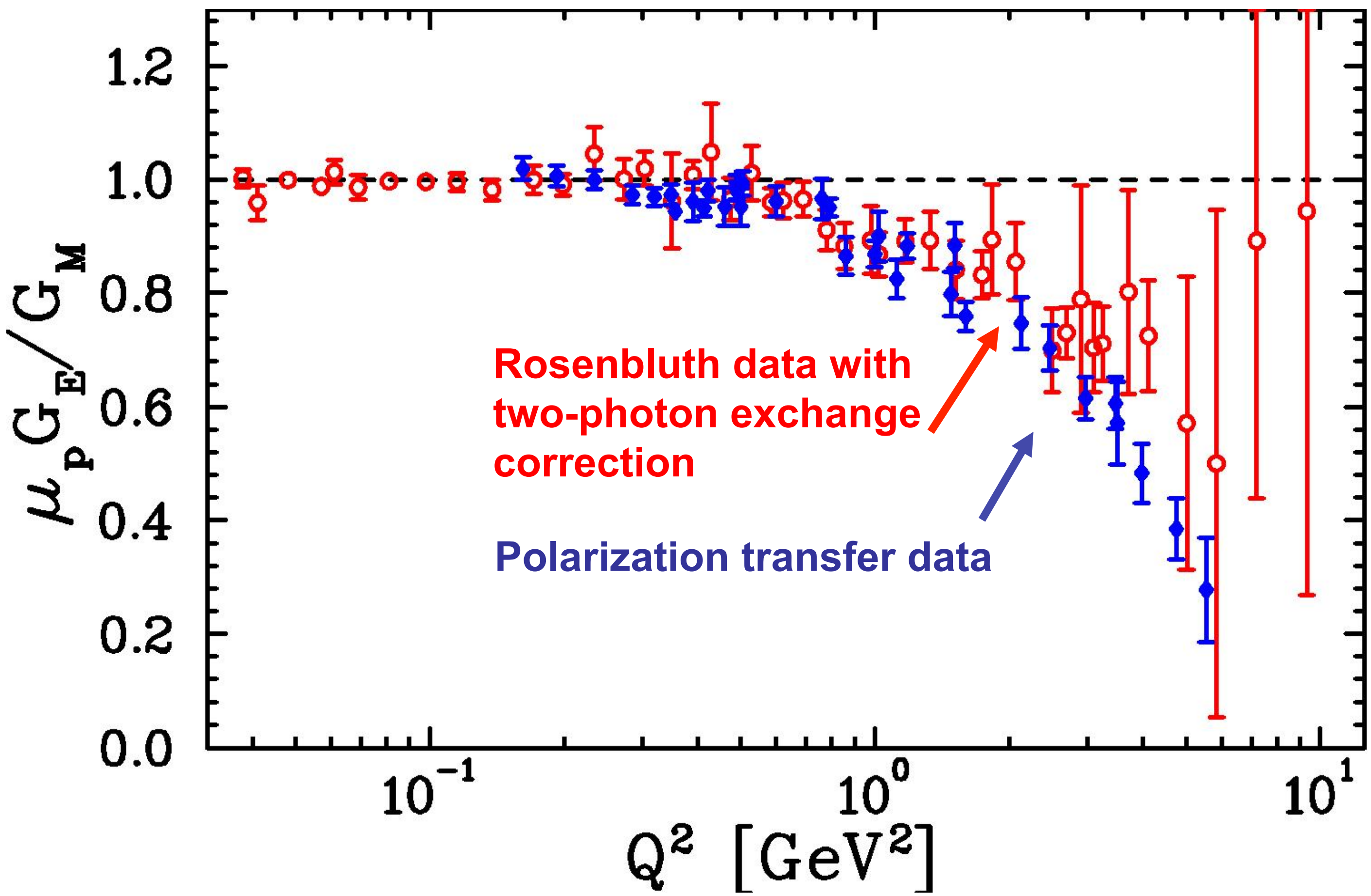
Two-photon exchange: exp. evidence

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)

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

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

Rosenbluth non-linearity E05-017

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

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

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

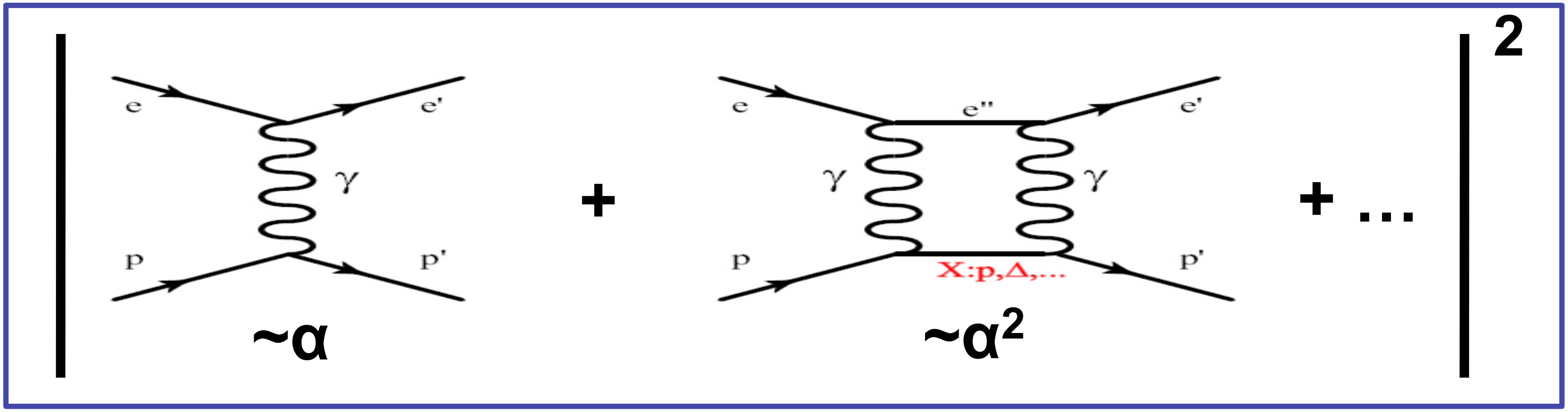
Born Approximation | **Beyond Born Approximation**

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)

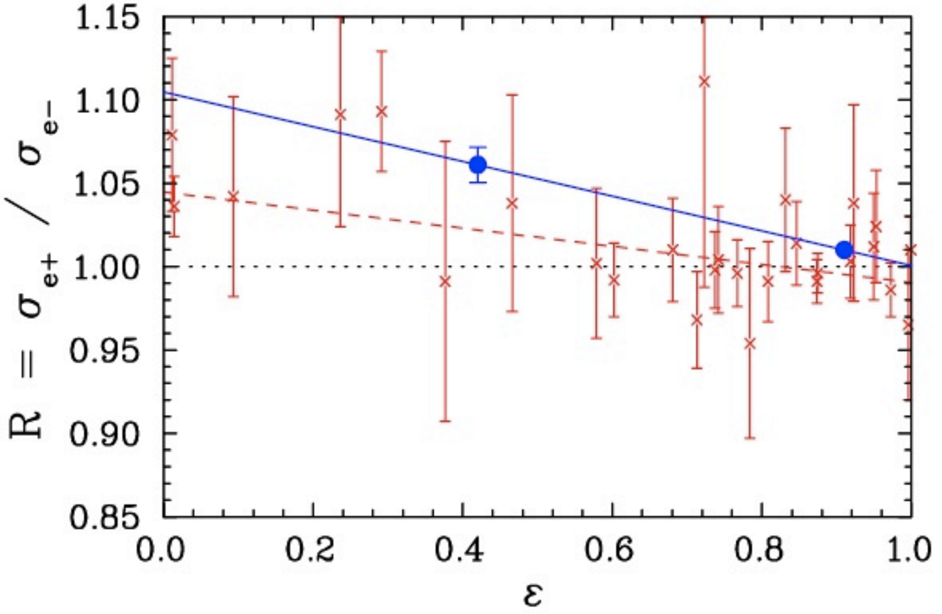
$$\sigma_{e^\pm p} = |\mathcal{M}_{1\gamma}|^2 \pm 2\Re\{\mathcal{M}_{1\gamma}^\dagger \mathcal{M}_{2\gamma}\} + \cdots$$

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

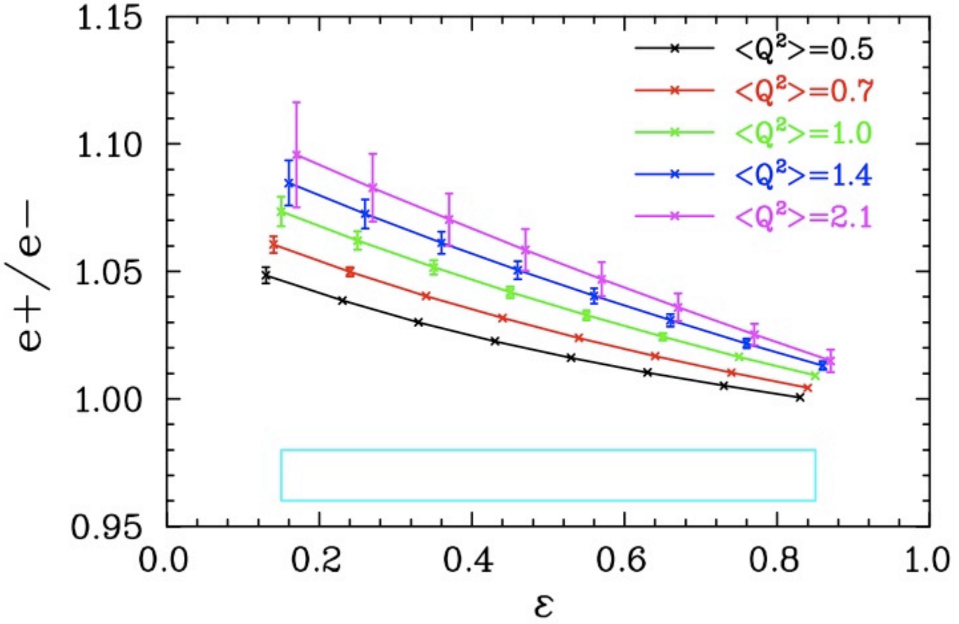
$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx 1 + 4\frac{\Re\{\mathcal{M}_{1\gamma}^\dagger \mathcal{M}_{2\gamma}\}}{|\mathcal{M}_{1\gamma}|^2}$$

Experiments to verify TPE (real part)

VEPP3 (proposed)



CLAS (proposed)



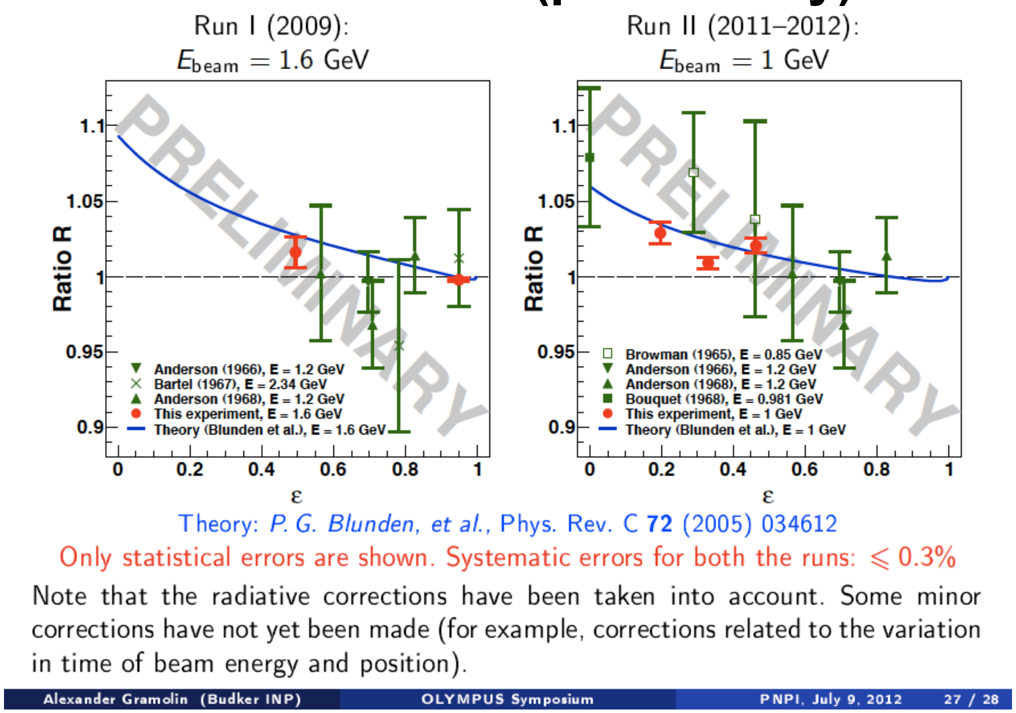
Experiments to verify TPE hypothesis:

e+/e- ratio:	**CLAS/PR04-116**	**secondary e+/e- beam / ext. target (2011)**
	Novosibirsk/VEPP-3	**storage ring / intern. target (2009-2011)**
	OLYMPUS/DESY	**storage ring / intern. target (2012)**

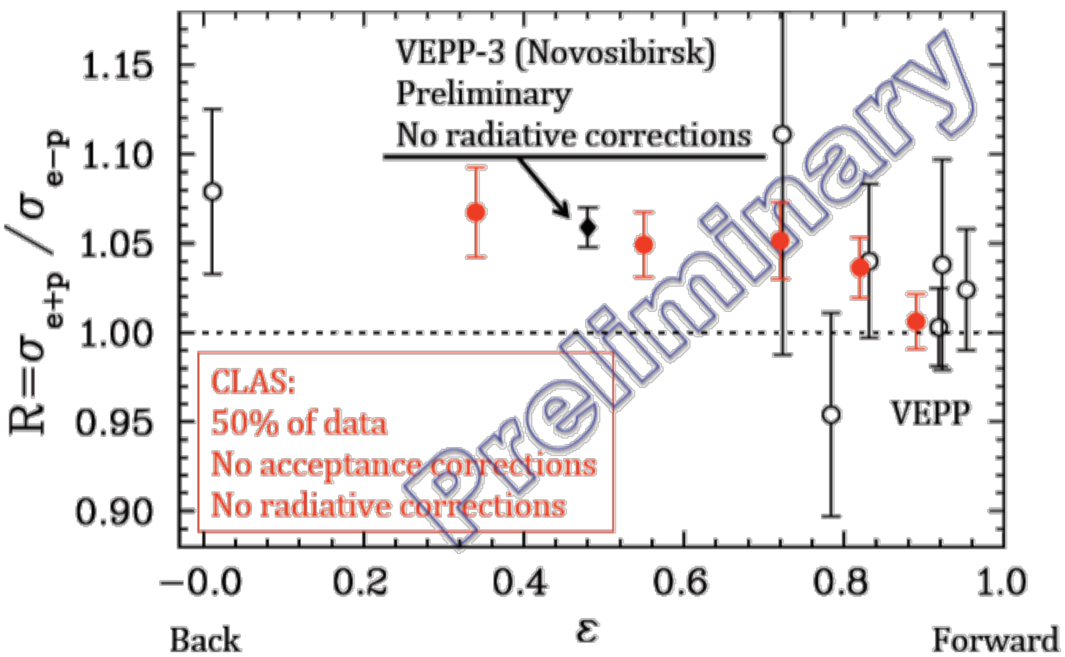
ε-dependence: **E04-019 ("Two-Gamma", recoil polarization)**
E05-017 ("Super-Rosenbluth", unpolarized)

Experiments to verify TPE (real part)

VEPP3 (preliminary)



CLAS (preliminary)



Experiments to verify TPE hypothesis:

e+/e- ratio: CLAS/PR04-116 — secondary e+/e- beam / ext. target (2011)
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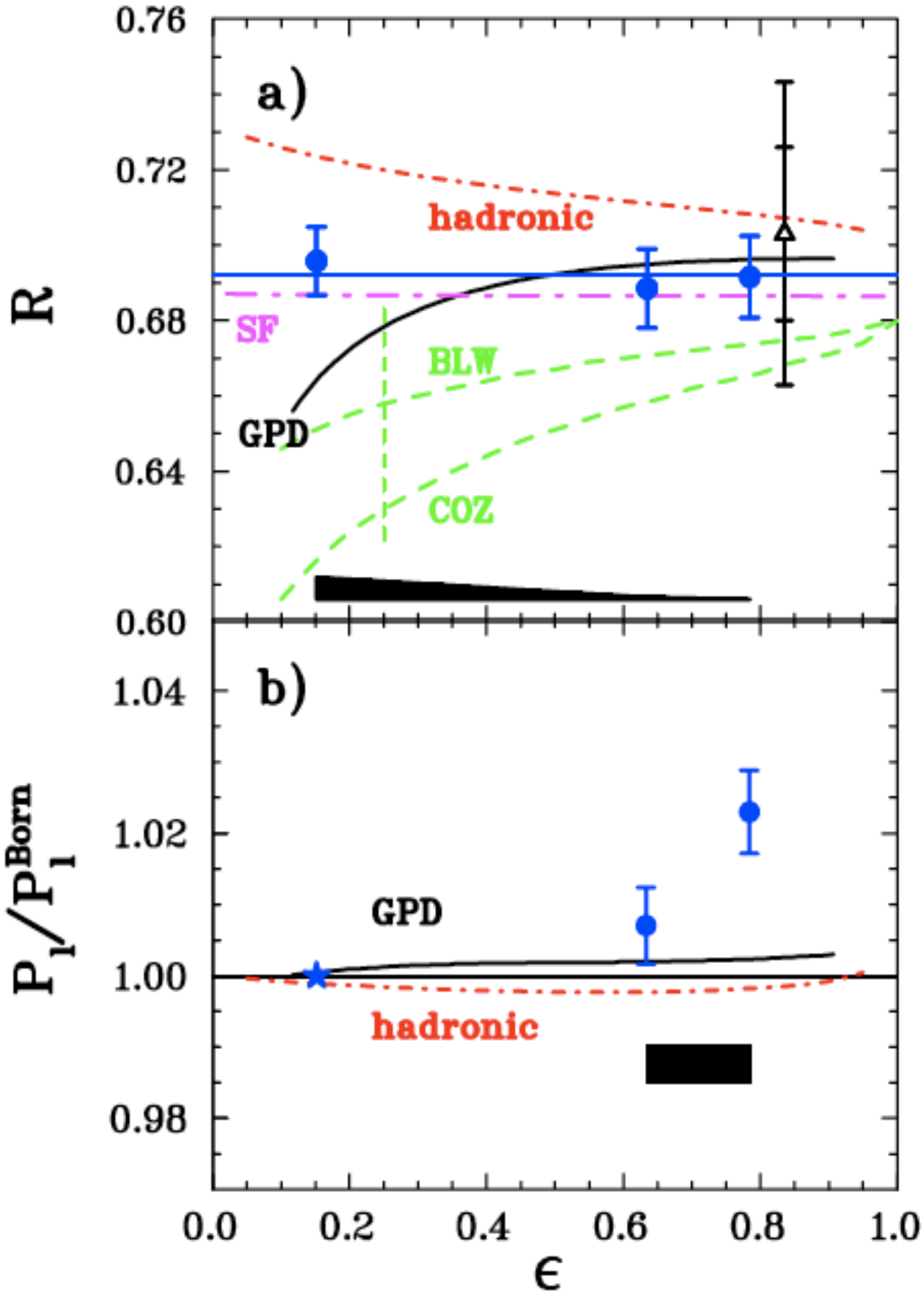
OLYMPUS/DESY — storage ring / intern. target (2012)

ε-dependence: E04-019 ("Two-Gamma", recoil polarization)
E05-017 ("Super-Rosenbluth", unpolarized)

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

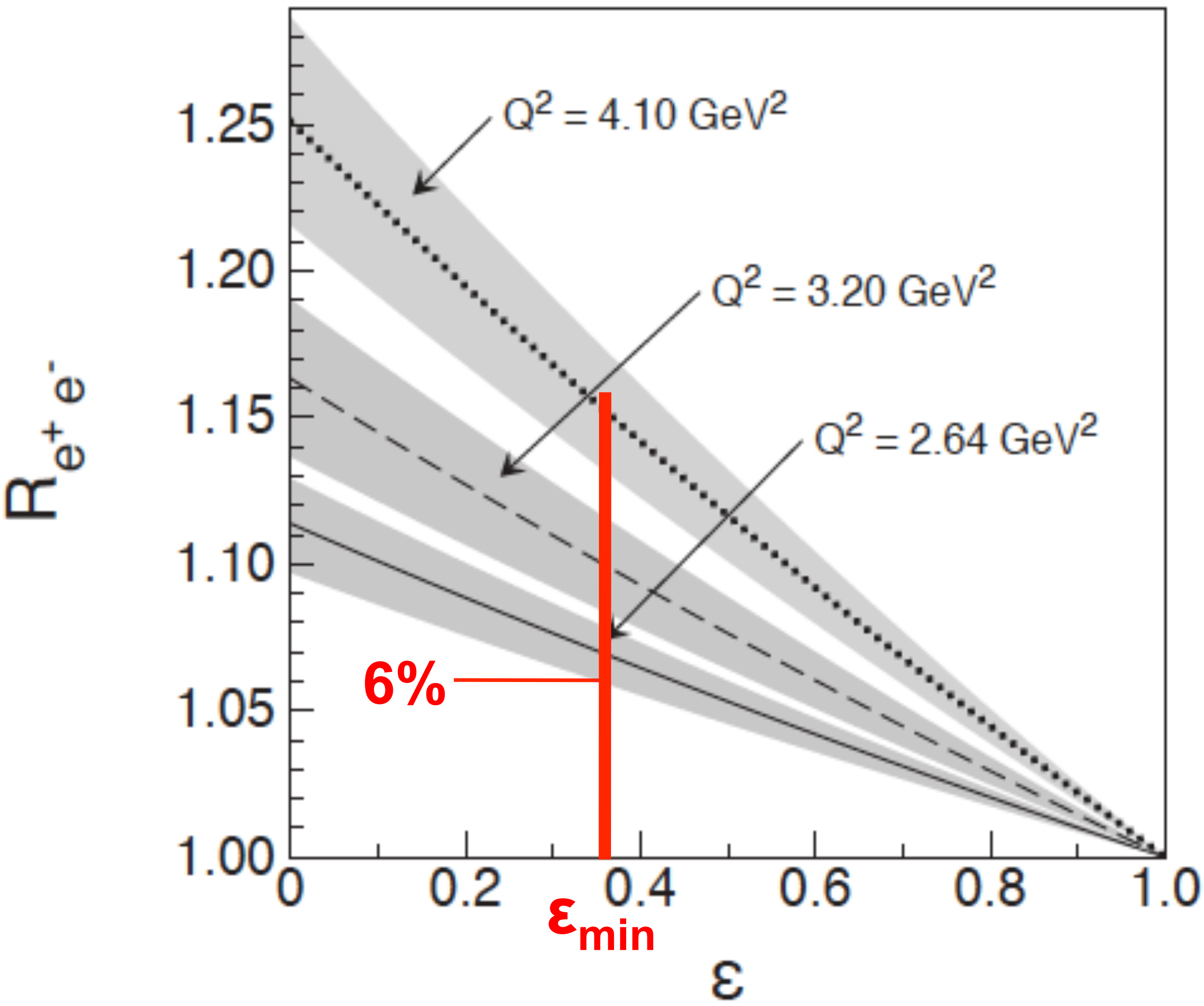
- ➔ **no effect in P_t/P_l**
- ➔ **some effect in P_l**

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

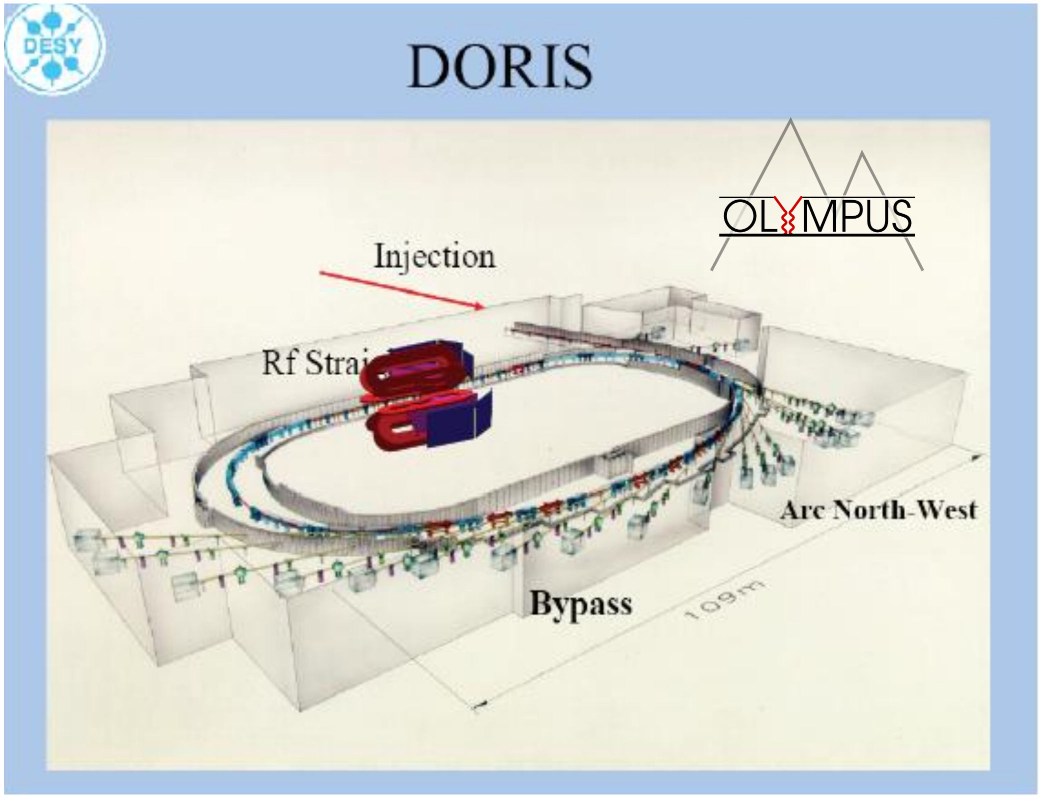
J. Guttmann, N. Kivel, M. Meziane, and M. Vanderhaeghen, EPJA 47 (2011) 77

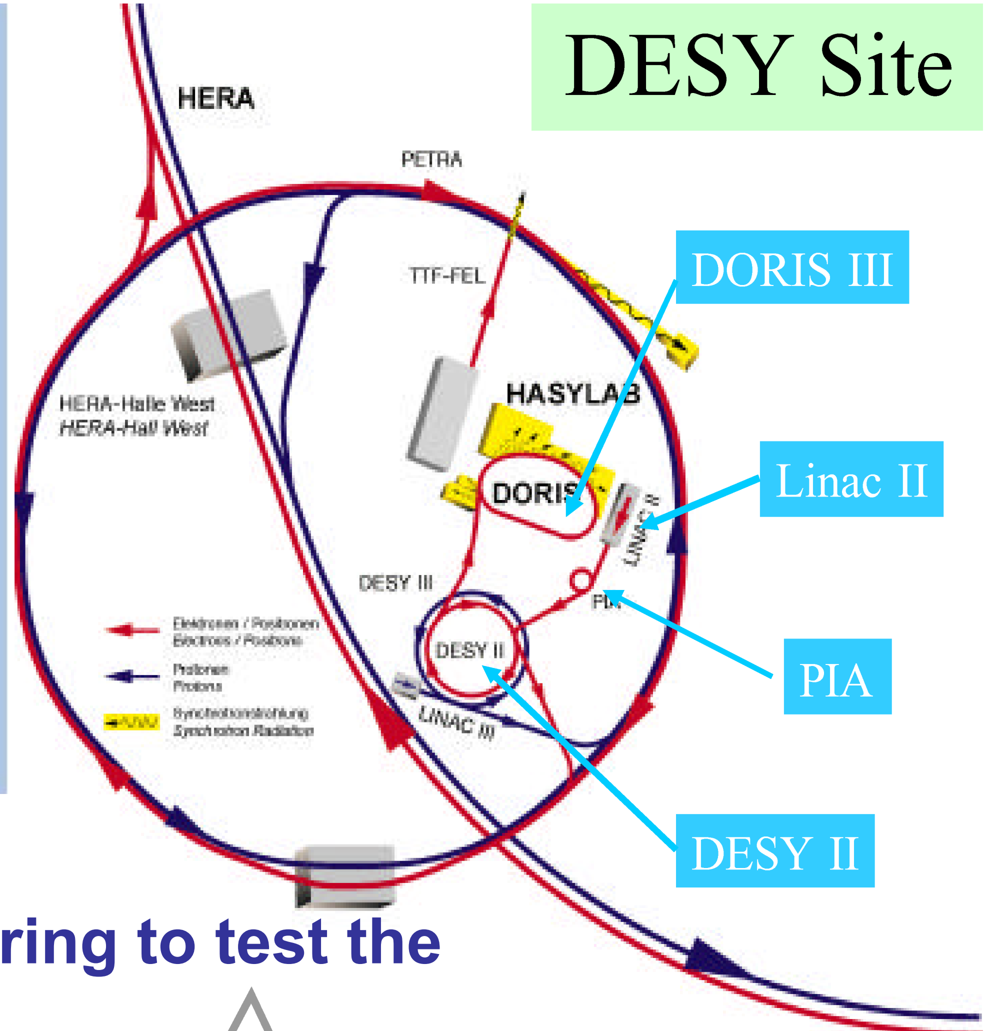


grows with Q^2!

Expect ~6% effect for OLYMPUS@2.0GeV

OLYMPUS @ DORIS/DESY





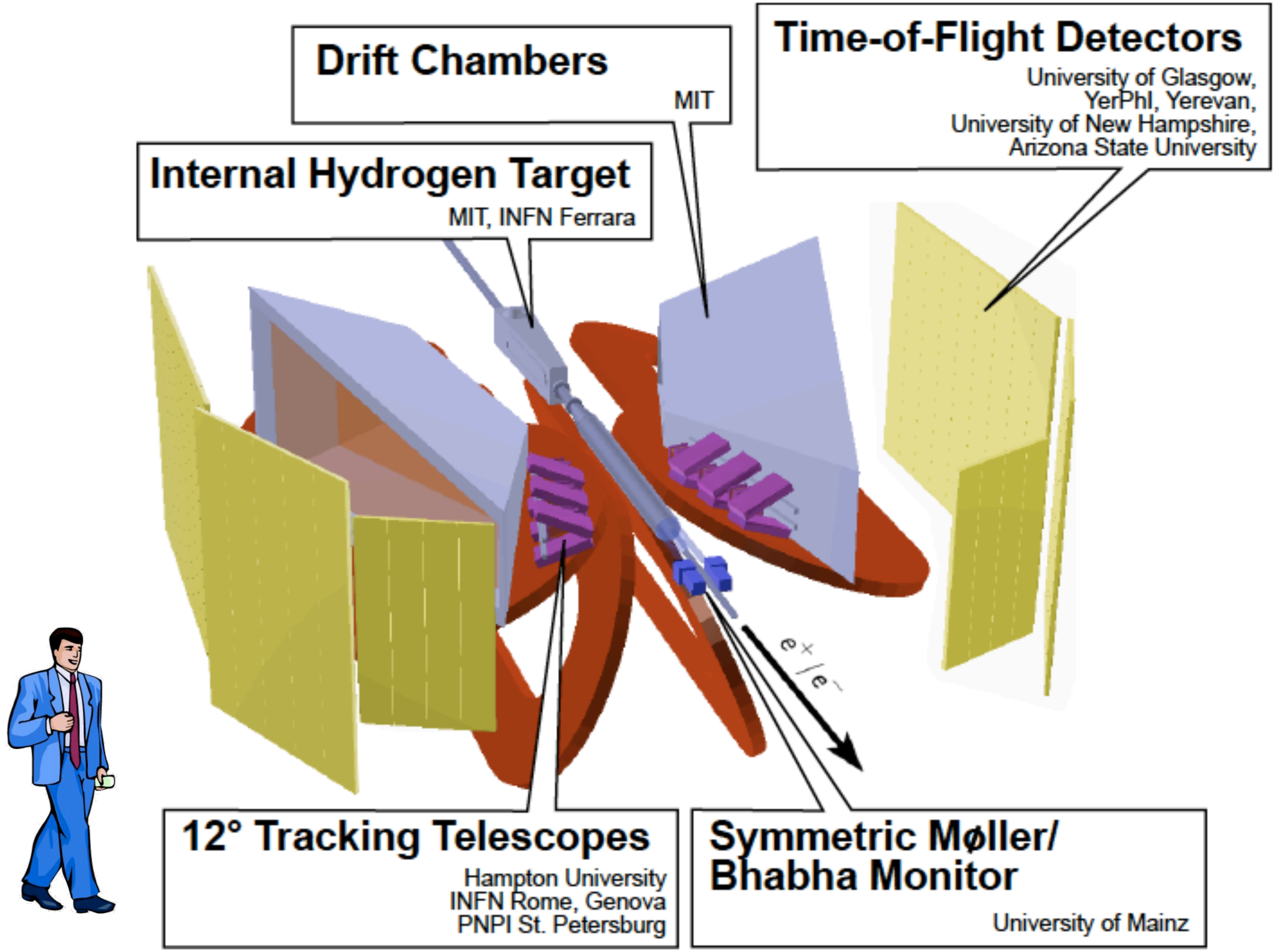
pOsitron-proton and
eLectron-proton elastic scattering to test the
hYpothesis of
Multi-
Photon exchange
Using
DoriS

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)
  3×10^{15} at/cm^2 @ 100 mA $\rightarrow$ $L = 2 \times 10^{33}$ / (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.

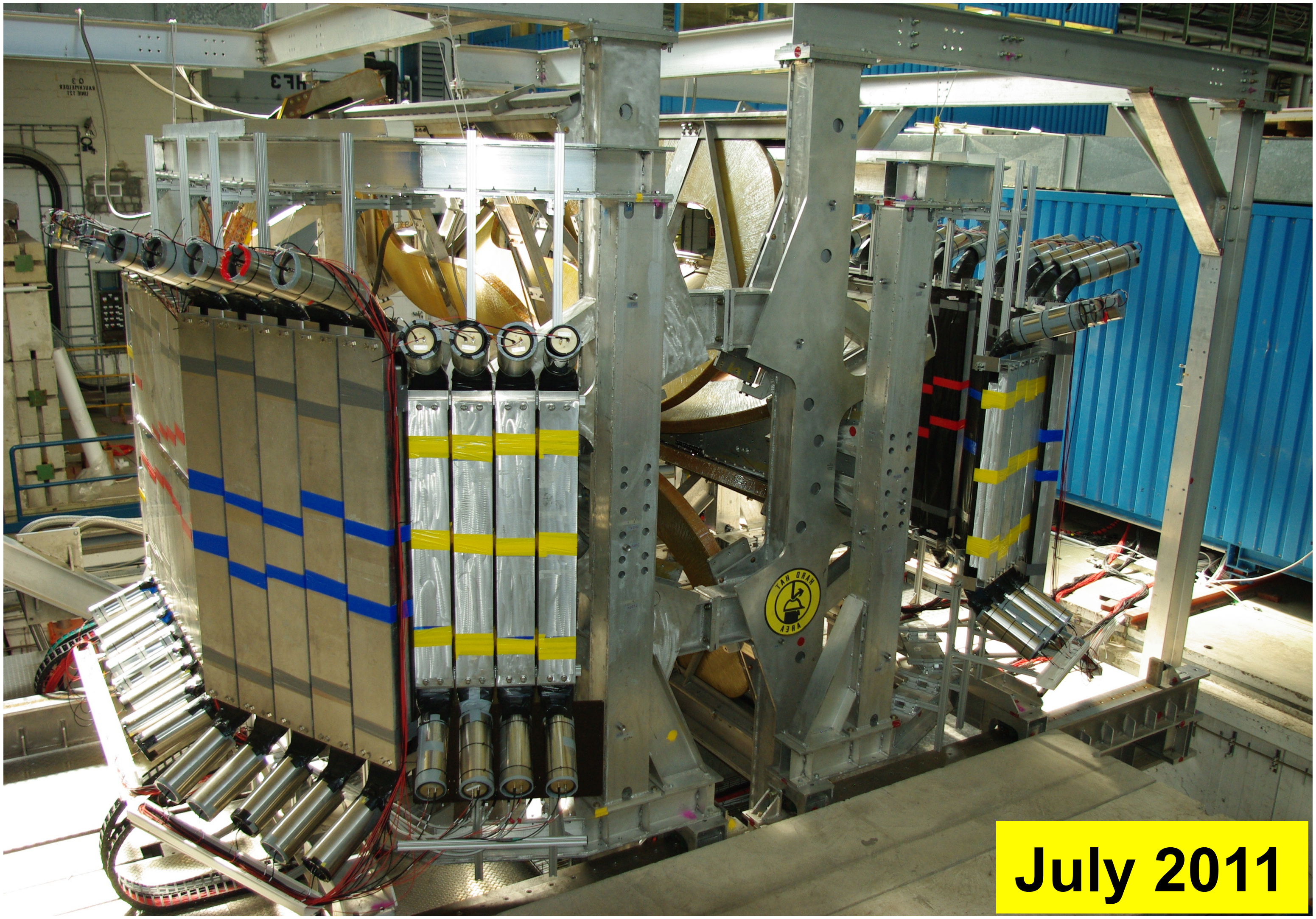
The designed OLYMPUS detector



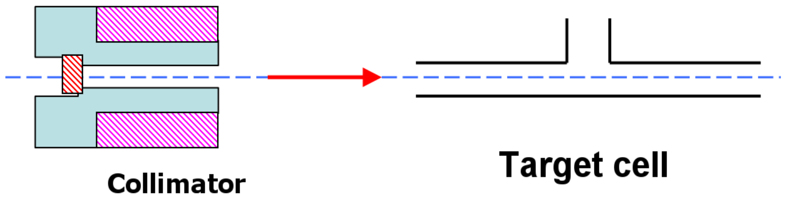
based on a figure by R. Russell

The realized OLYMPUS detector

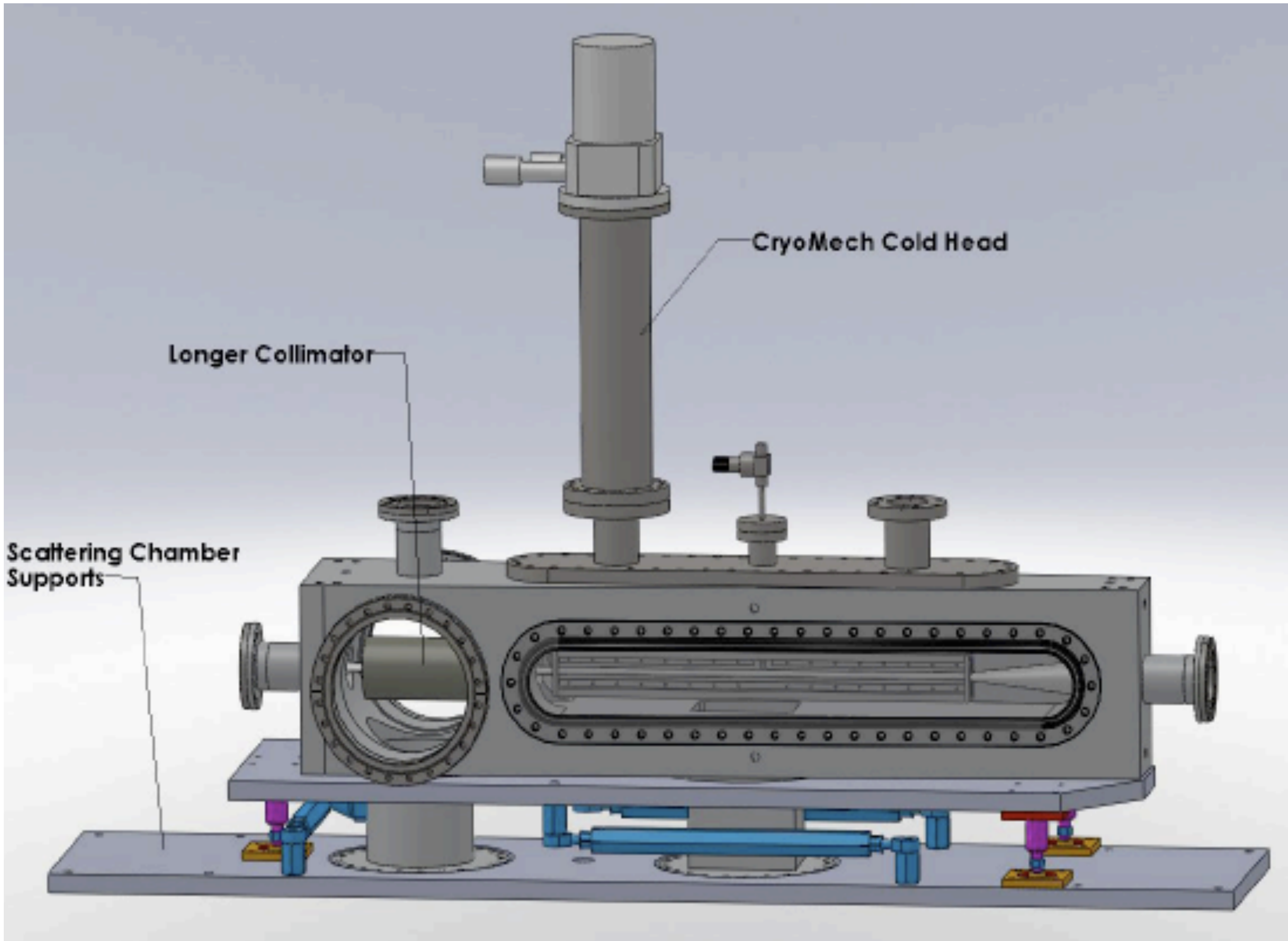
OLYMPUS

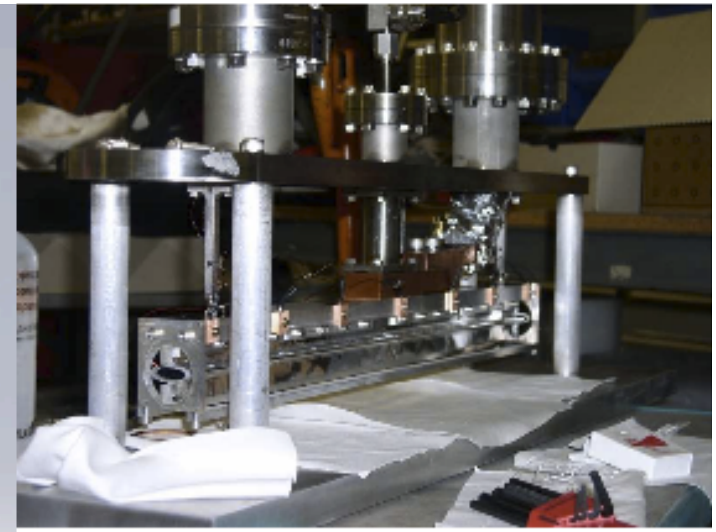


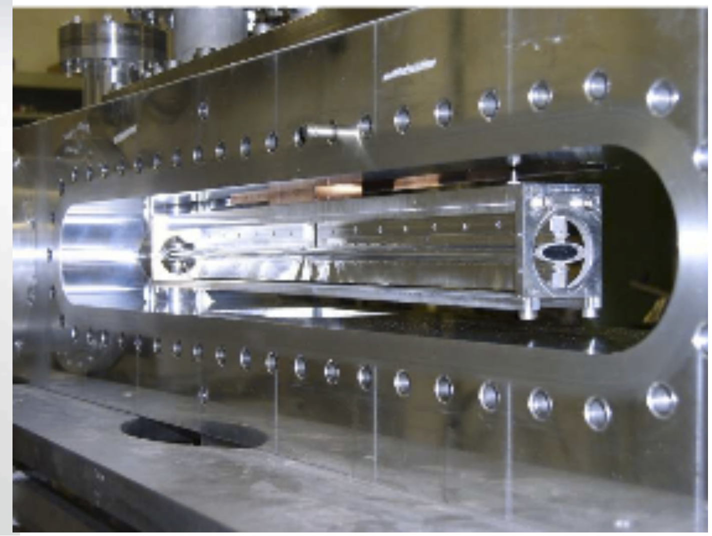
Target and vacuum system



MIT
INFN Ferrara



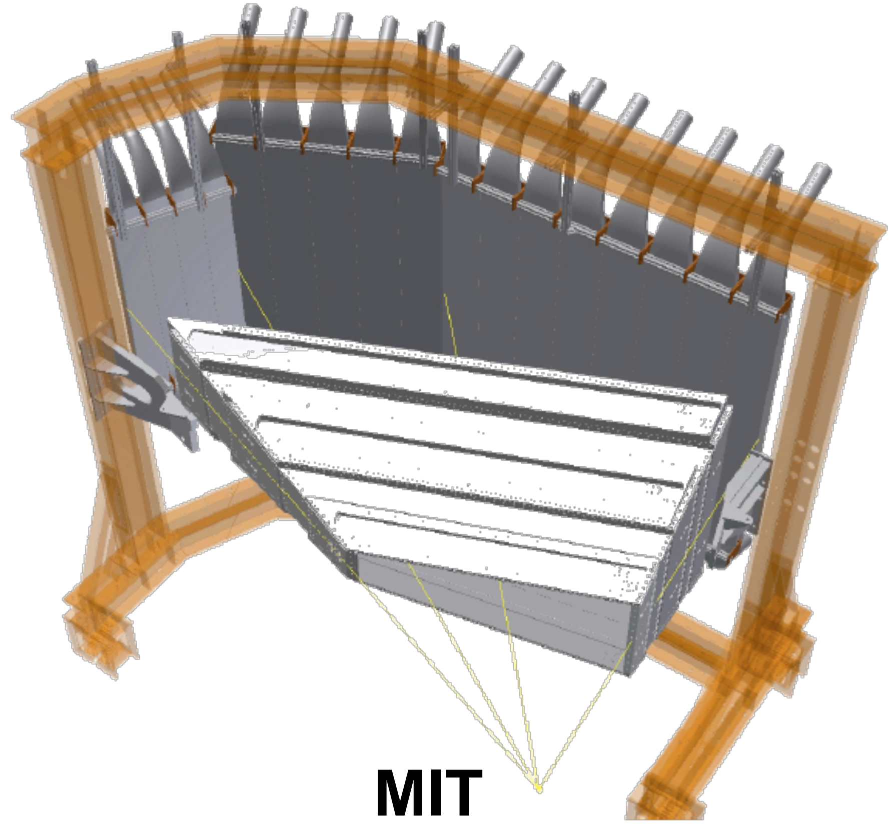




Designed and built in 2010
Very stable operation after repairs

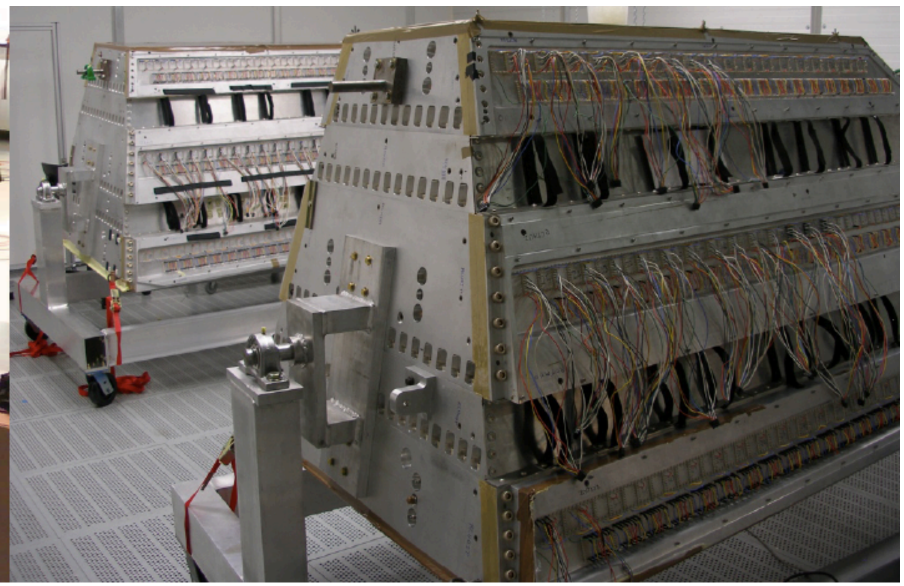
Wire chambers and TOF scintillators

- 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



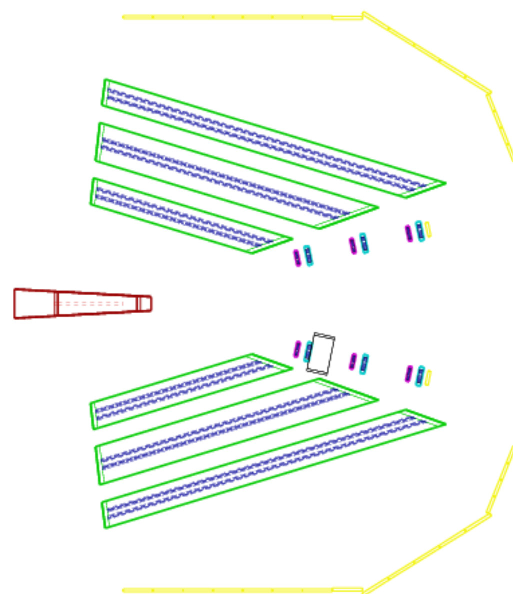
Glasgow, Yerevan, UNH, ASU

MIT

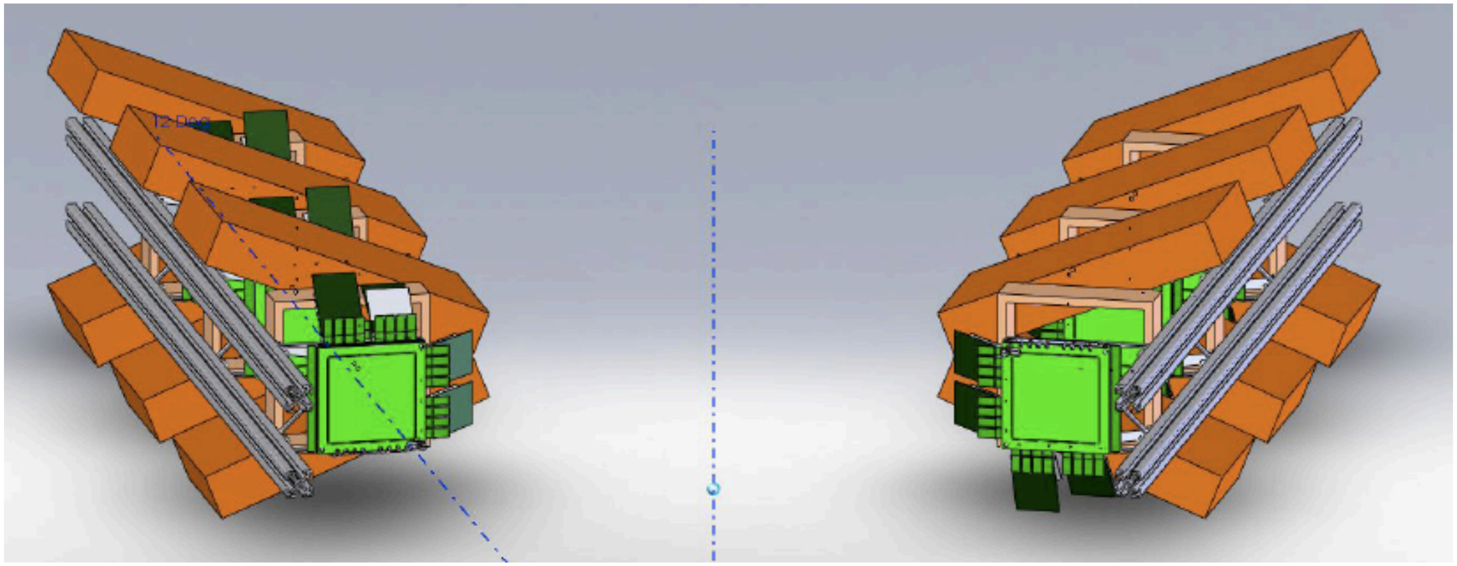


Luminosity monitors: GEM + MWPC

- 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)



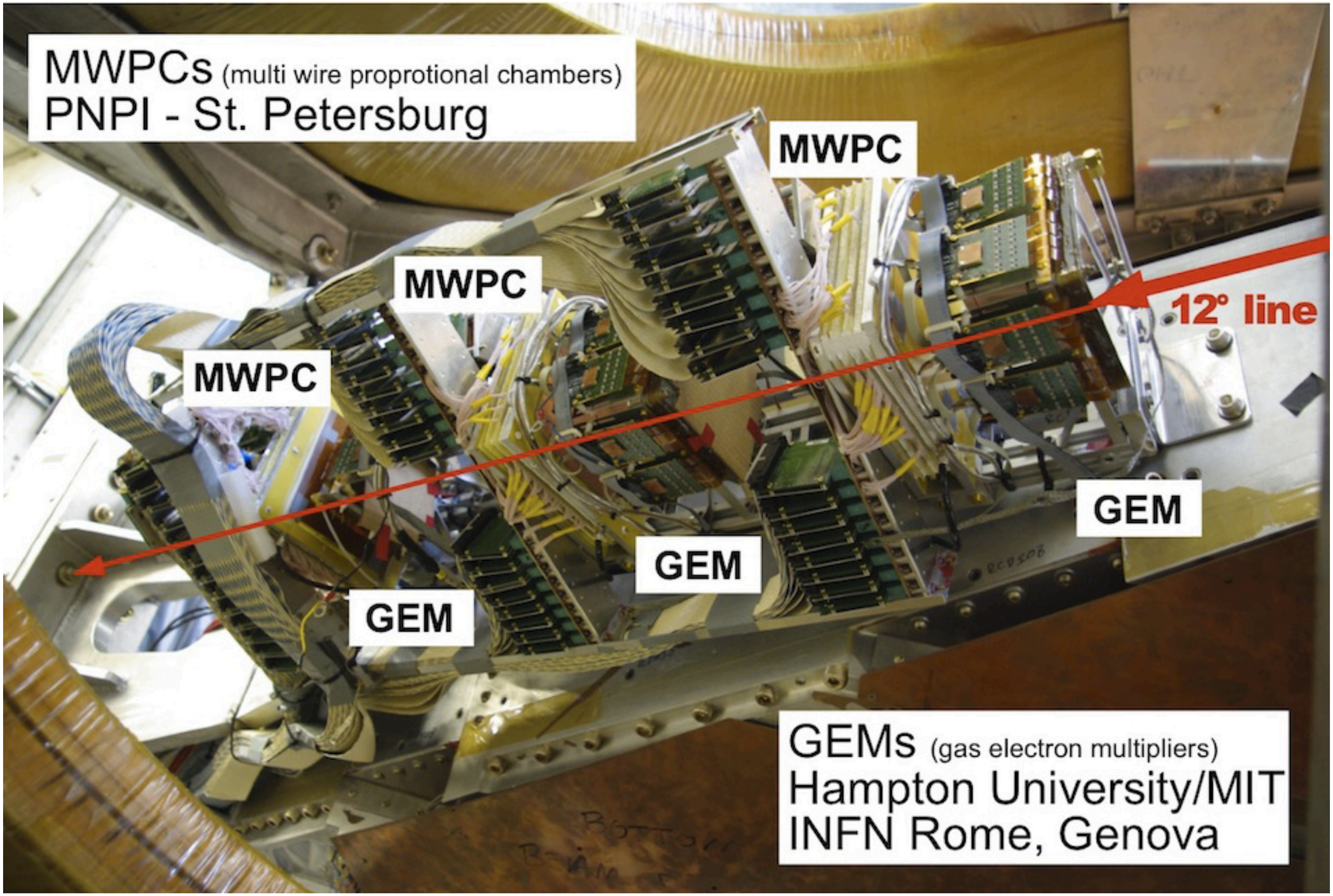
Ozgur Ates
HK 42.6
(Di 18:15)



Designed to fit into forward cone

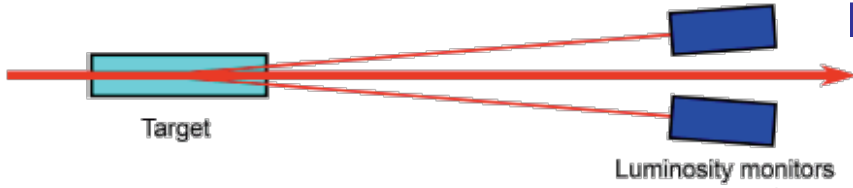
Luminosity monitors: GEM + MWPC

OLYMPUS

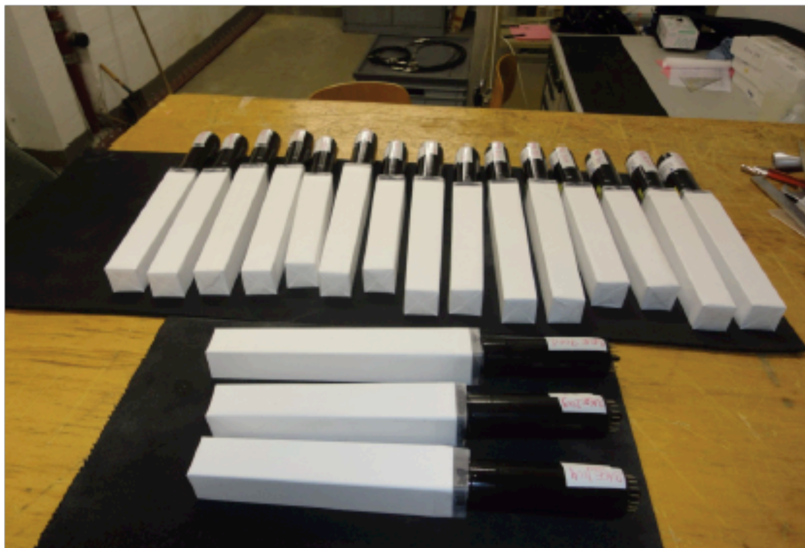


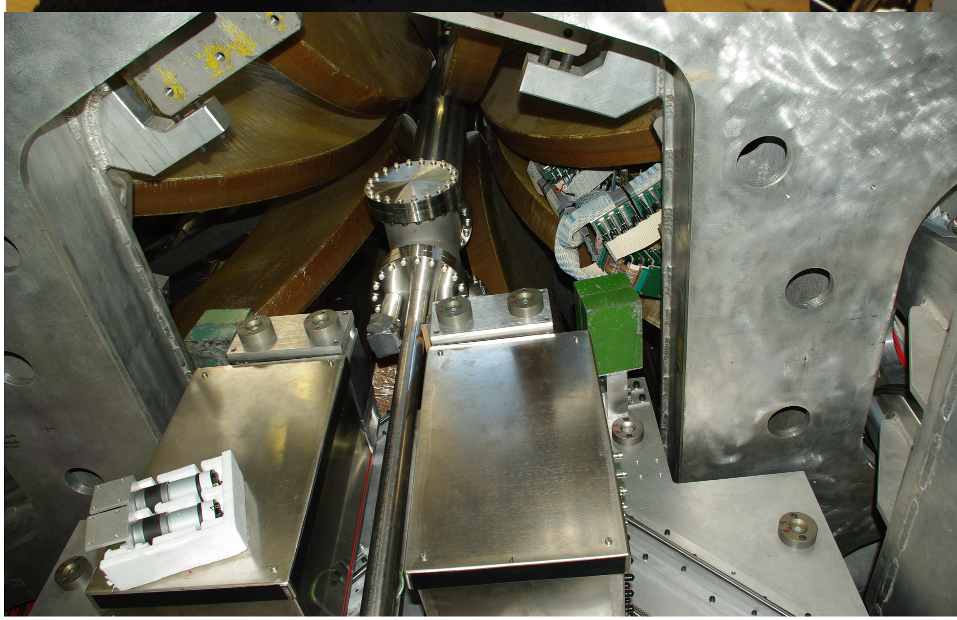
Telescopes of three GEMs and MWPCs interleaved
Mounted on wire chamber forward end plate
Extensively tested at DESY test beam facility

Symmetric Møller/Bhabha monitor



Mainz University

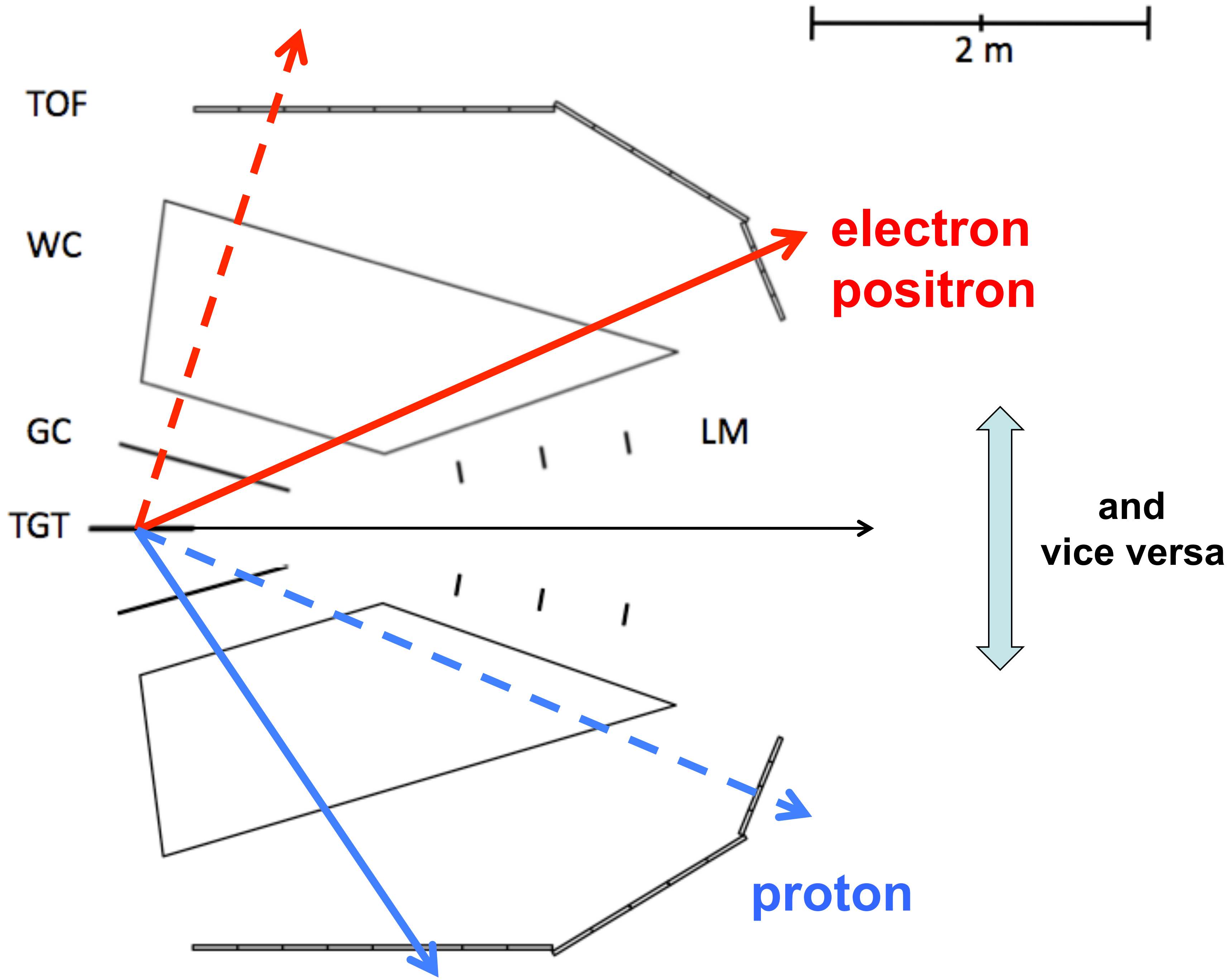




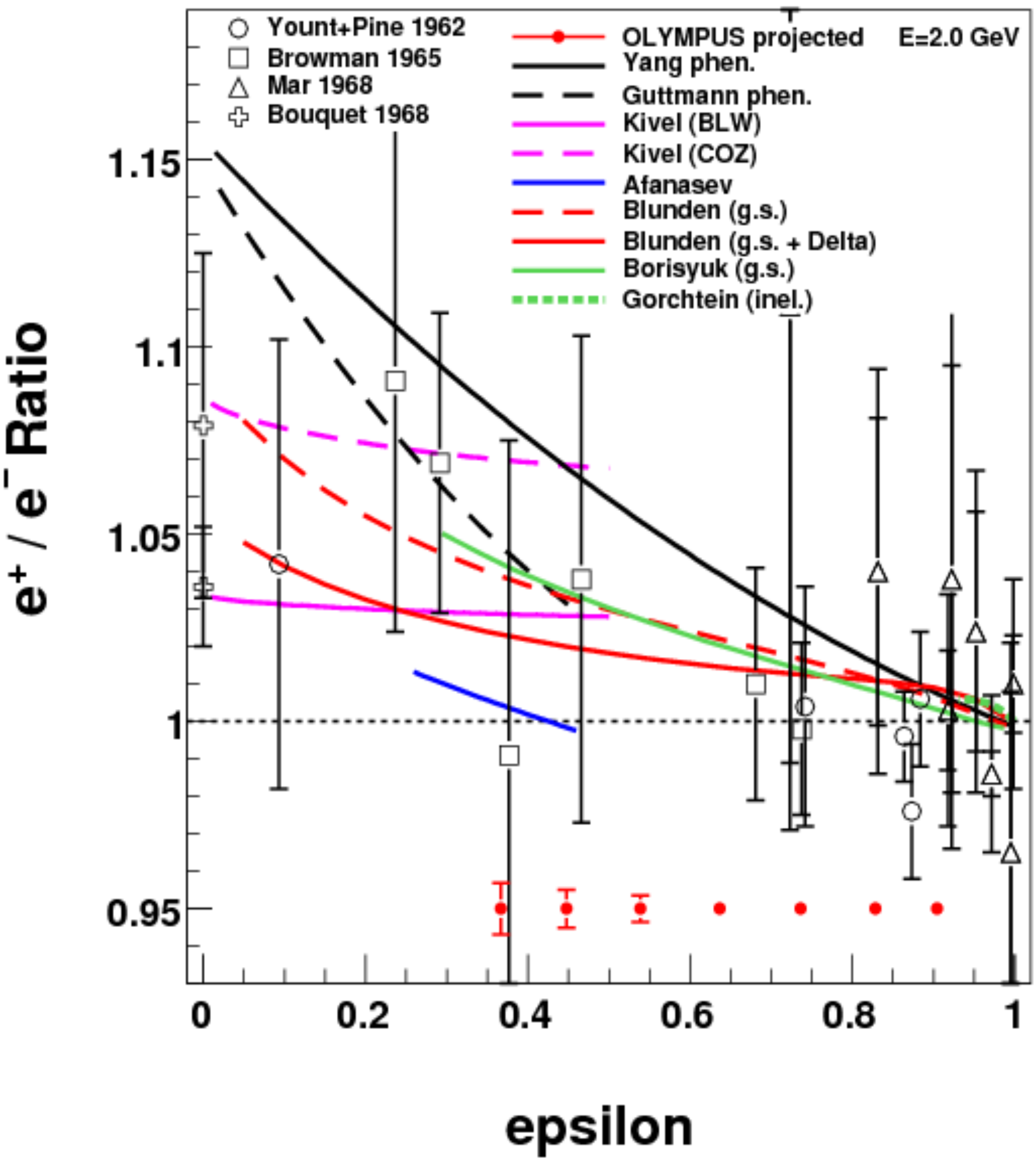
- **Symm. angle 1.3° @ 2.0 GeV**
- **Matrix of 3x3 PbF_2 crystals**
- **Tested at DESY and MAMI**

Roberto Pérez Benito
HK 42.5 (Di 18:00)

OLYMPUS kinematics at 2.0 GeV



Projected results for OLYMPUS



Data from 1960's

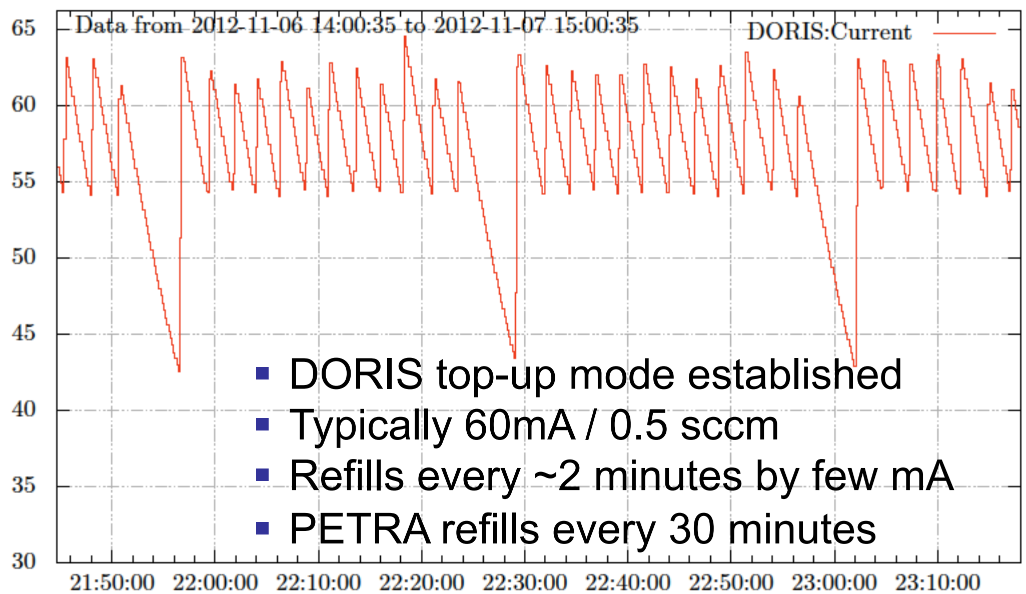
Many theoretical predictions with little constraint

OLYMPUS:

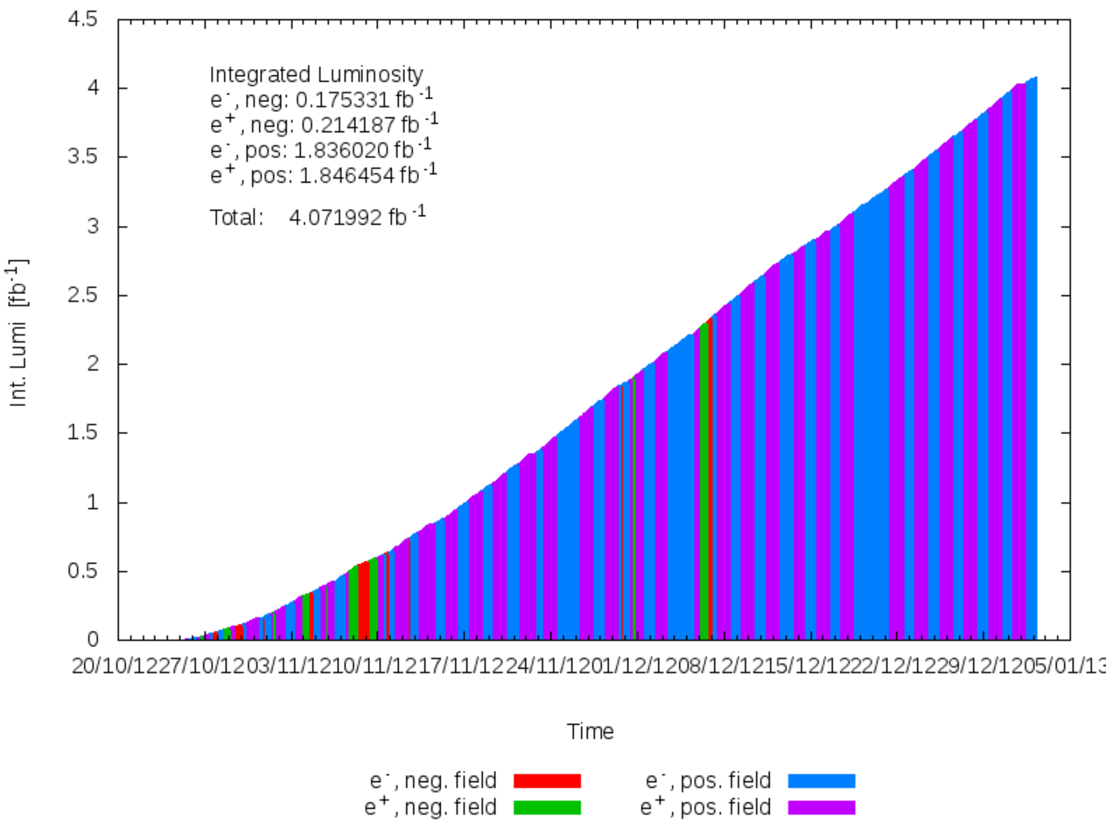
- **E= 2.0 GeV**
- **$0.6 < Q^2/(GeV/c)^2 < 2.2$**
- **Acquire 3.6 fb^{-1} for <1% projected uncertainties**

Data taken in 2012

Timeline of OLYMPUS



- DORIS top-up mode established
- Typically 60mA / 0.5 sccm
- Refills every ~2 minutes by few mA
- PETRA refills every 30 minutes



- 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}

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

- Smooth performance of machine, target, detector

Expect results by 2014

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	(elected 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, simulations
- **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
- **Petersburg Nuclear Physics Institute:** Slow controls, MWPC luminosity monitor
- **University of Bonn:** Trigger and data acquisition
- **University of Mainz:** Trigger, DAQ, Symmetric Moller monitor
- **University of Glasgow**: Particle Identification, TOF scintillators
- **University of New Hampshire:** TOF scintillators
- **Yerevan:** Removal of ARGUS, TOF system

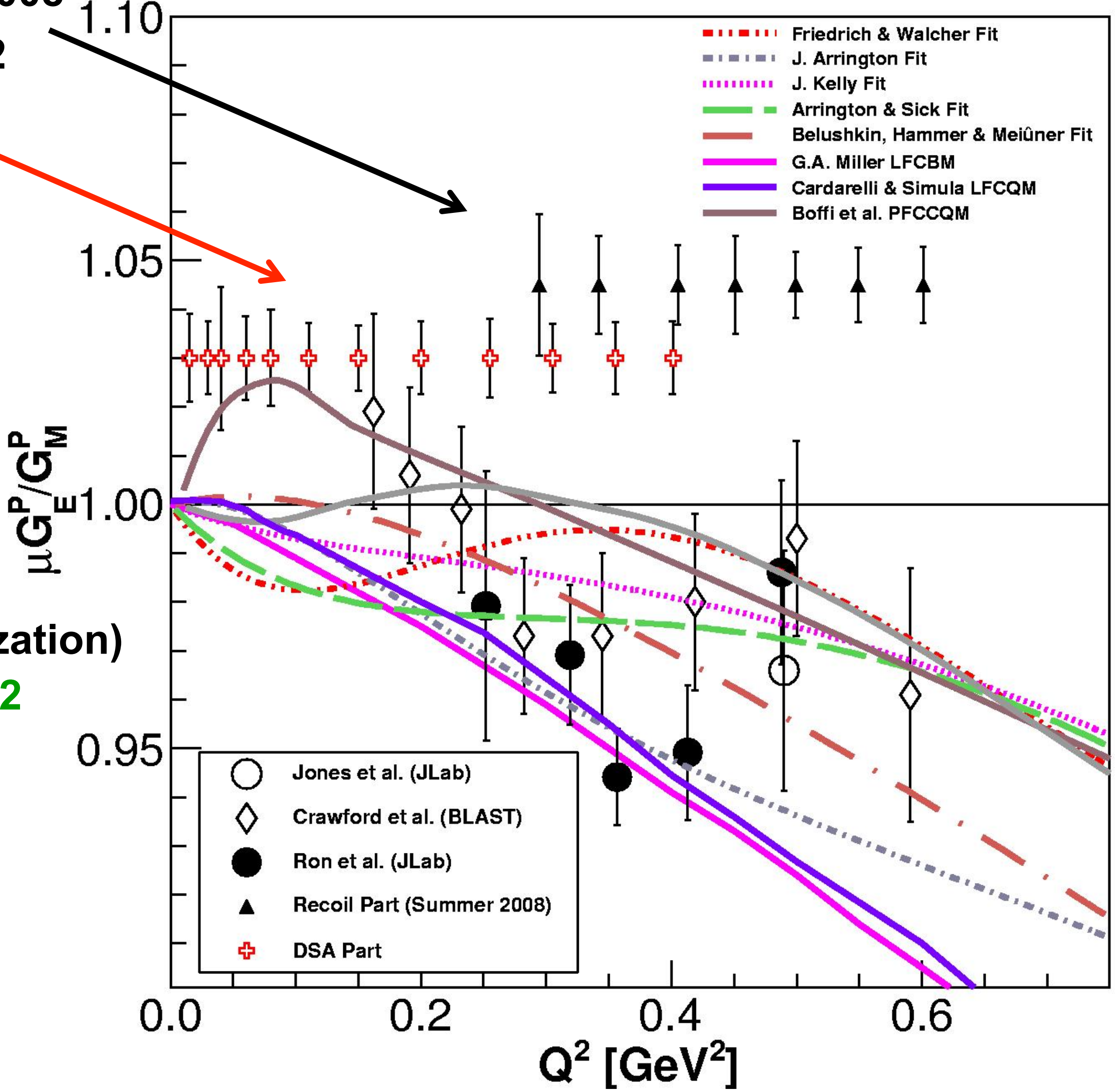
New proton measurements at low Q^2

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

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

◇ **BLAST (polarized target)**
C. Crawford et al., PRL98 (2006) 052301

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



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

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

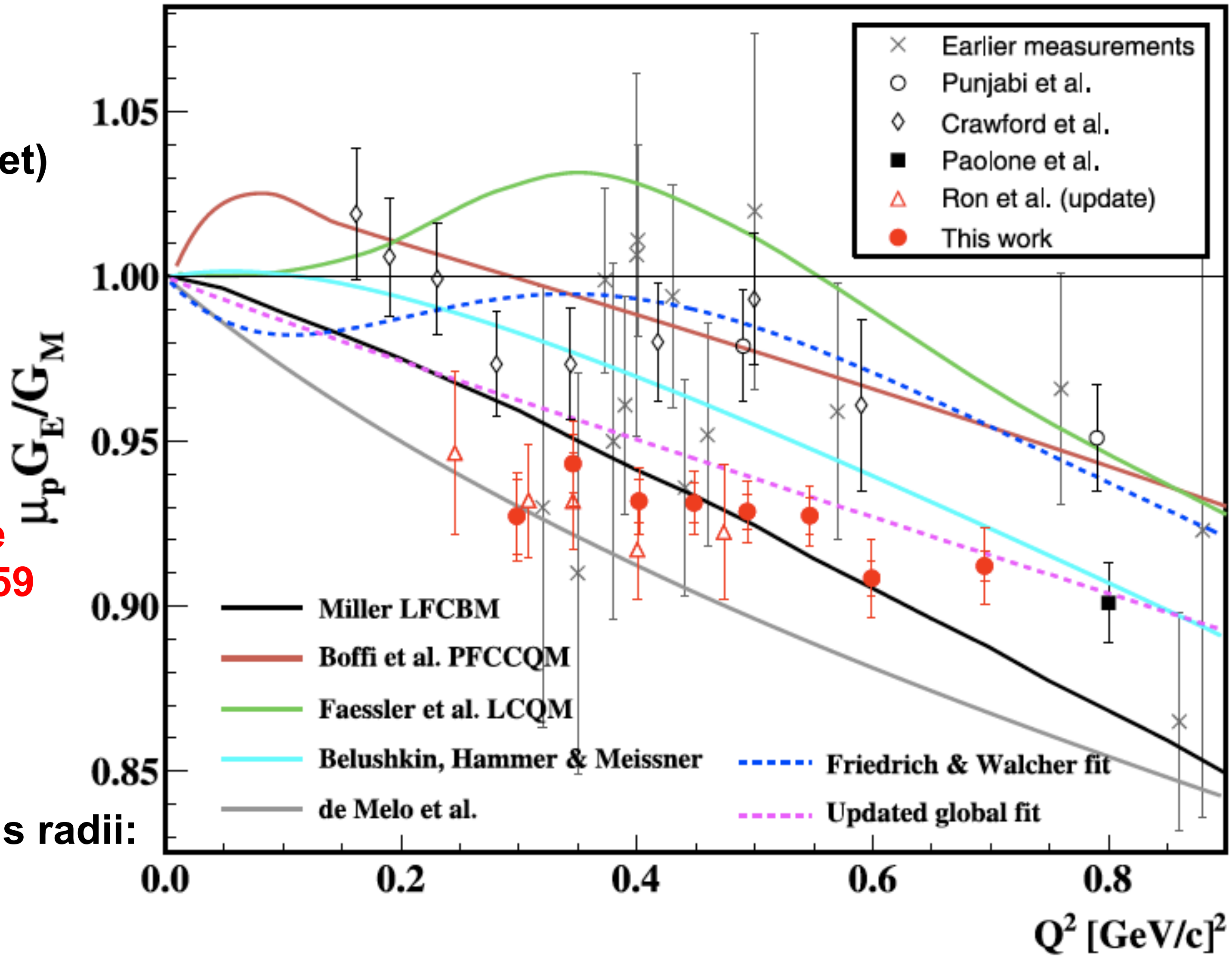
X. Zhan, E08-007 + LEDEX update Phys. Lett. B 705 (2011) 59

2-sigma difference lower than BLAST

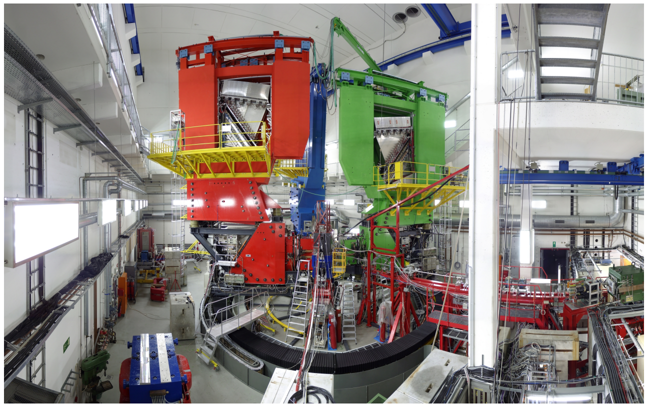
Charge and magnetic rms radii:

$R_E = 0.875 \pm 0.010$ fm

$R_M = 0.867 \pm 0.020$ fm

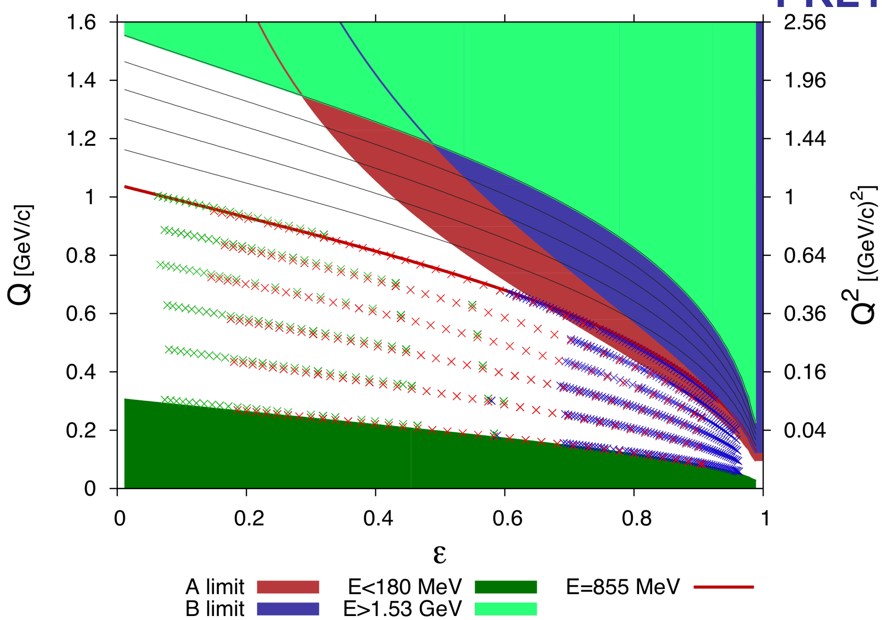


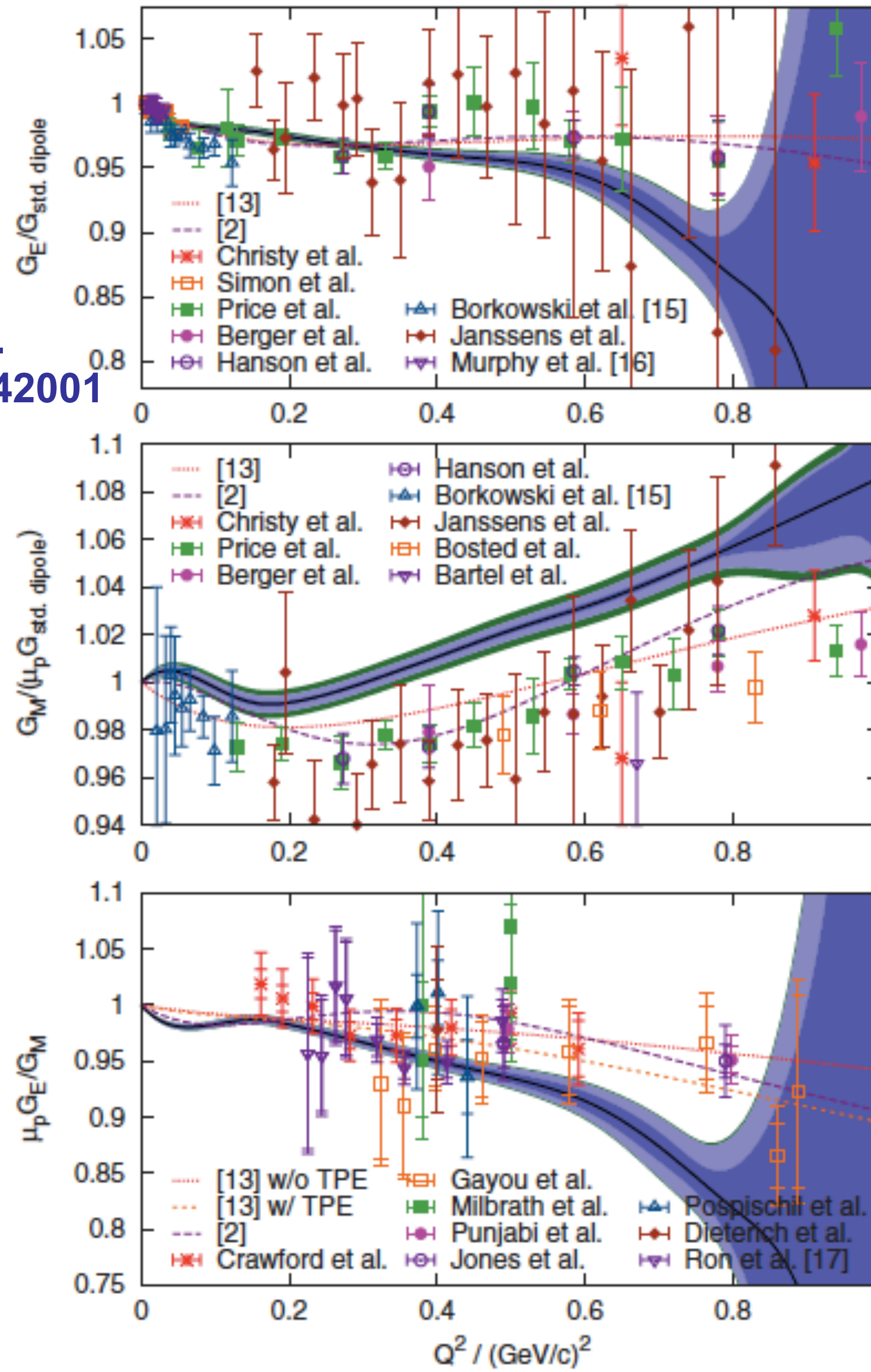
New proton measurements at low Q^2



MAMI A1

J. Bernauer et al.
PRL105 (2010) 242001





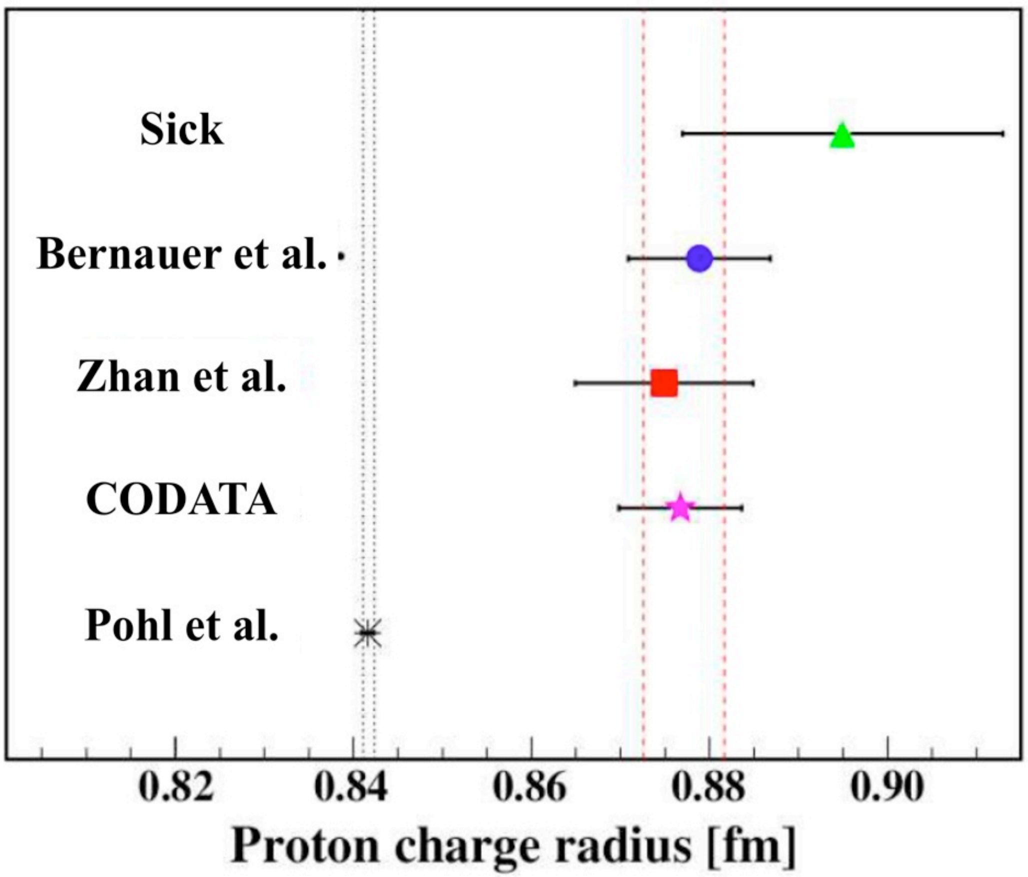
Rosenbluth separation at low Q^2
Precise charge and magnetic rms radii:

$R_E = 0.879 \pm 0.008$ fm

$R_M = 0.777 \pm 0.017$ fm

The proton radius puzzle

- 7σ discrepancy between muonic hydrogen Lamb shift and combined electronic Lamb shift and electron scattering
- High-profile articles in Nature, NYTimes, etc.
- Special feature at many conferences



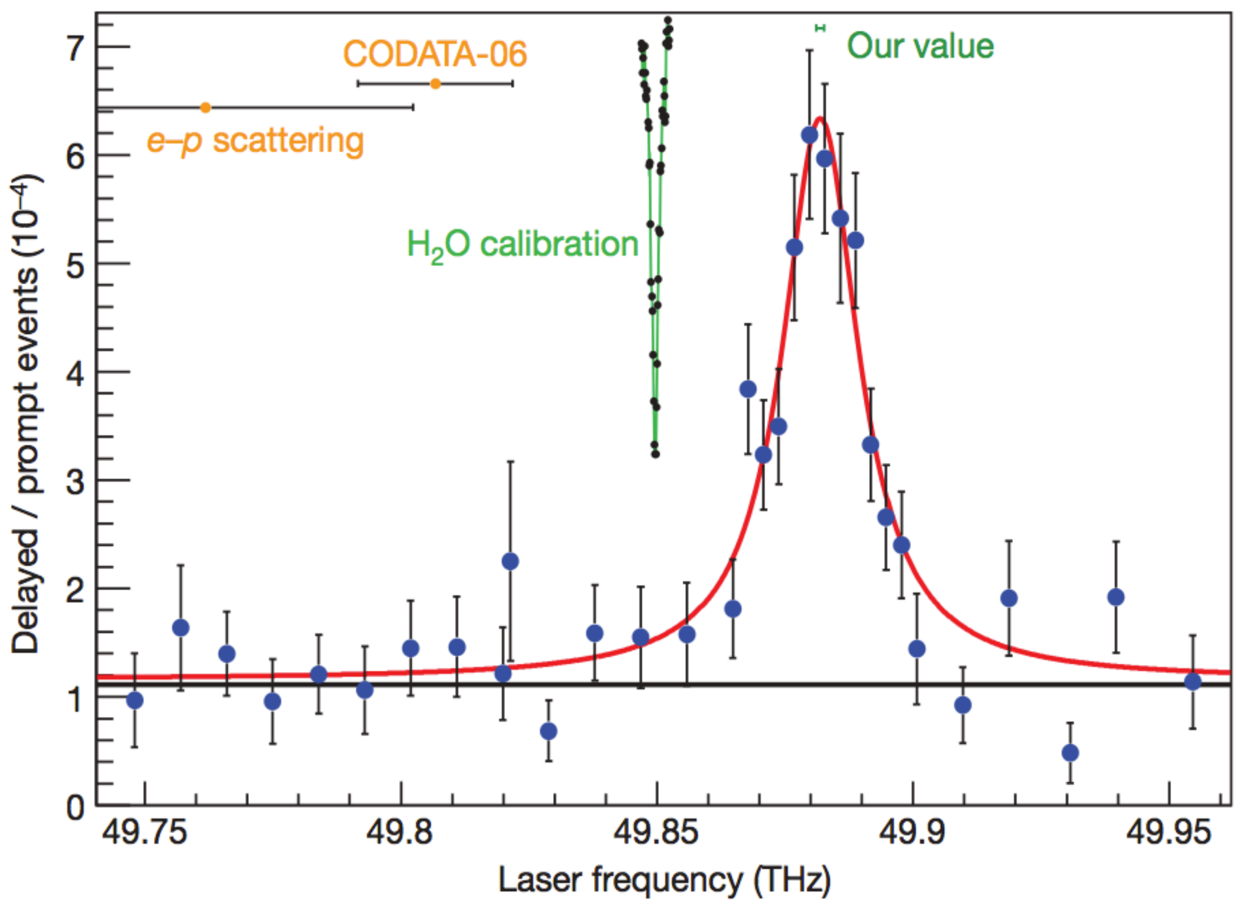
#	Extraction	$<r_E>^2$ (fm)
1	Sick	0.895±0.018
2	Bernauer Mainz	0.879±0.008
3	Zhan JLab	0.875±0.010
4	CODATA	0.877±0.007
5	Combined 2-4	0.876±0.005
6	Muonic Hydrogen	0.842±0.001

PSI muonic hydrogen measurements

- **R. Pohl et al., Nature 466, 09259 (2010):** **2S➩2P Lamb shift**
  $\Delta E(meV) = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3$ ➩ $r_p =$ 0.842 ± 0.001 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±0.00039 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

- **Physics beyond Standard Model differentiating μ and e**
  Lepton universality violation
  Light massive gauge boson
  Existing constraints on new physics

More insights from comparison of ep and μp scattering

Motivation for μp scattering

Electronic hydrogen

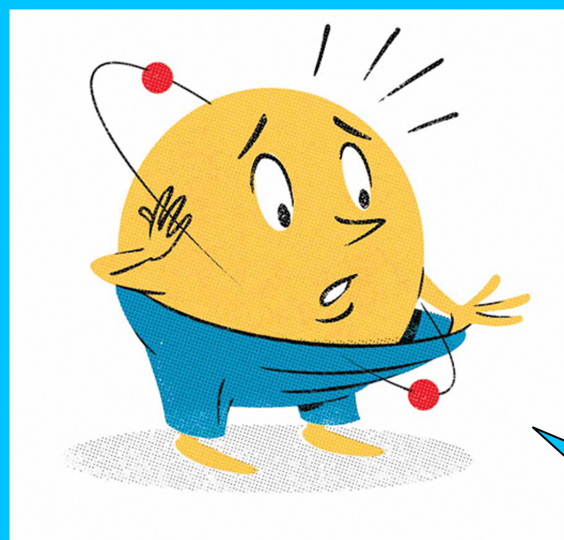
0.877±0.007

Lamb shift

Muonic hydrogen

0.842±0.001

0.84087±0.00039



Electron scattering

0.875±0.006

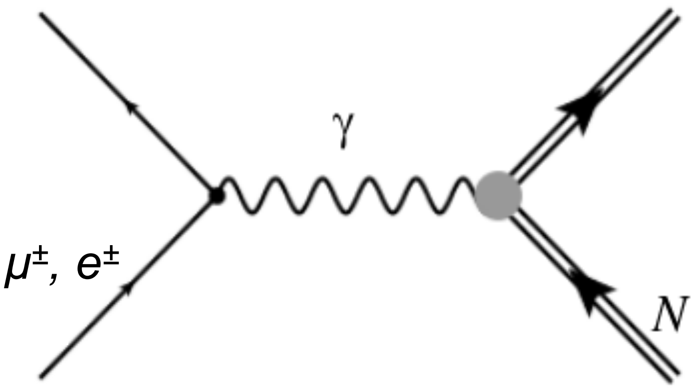
Elastic scattering

Muon scattering

???

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:

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

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

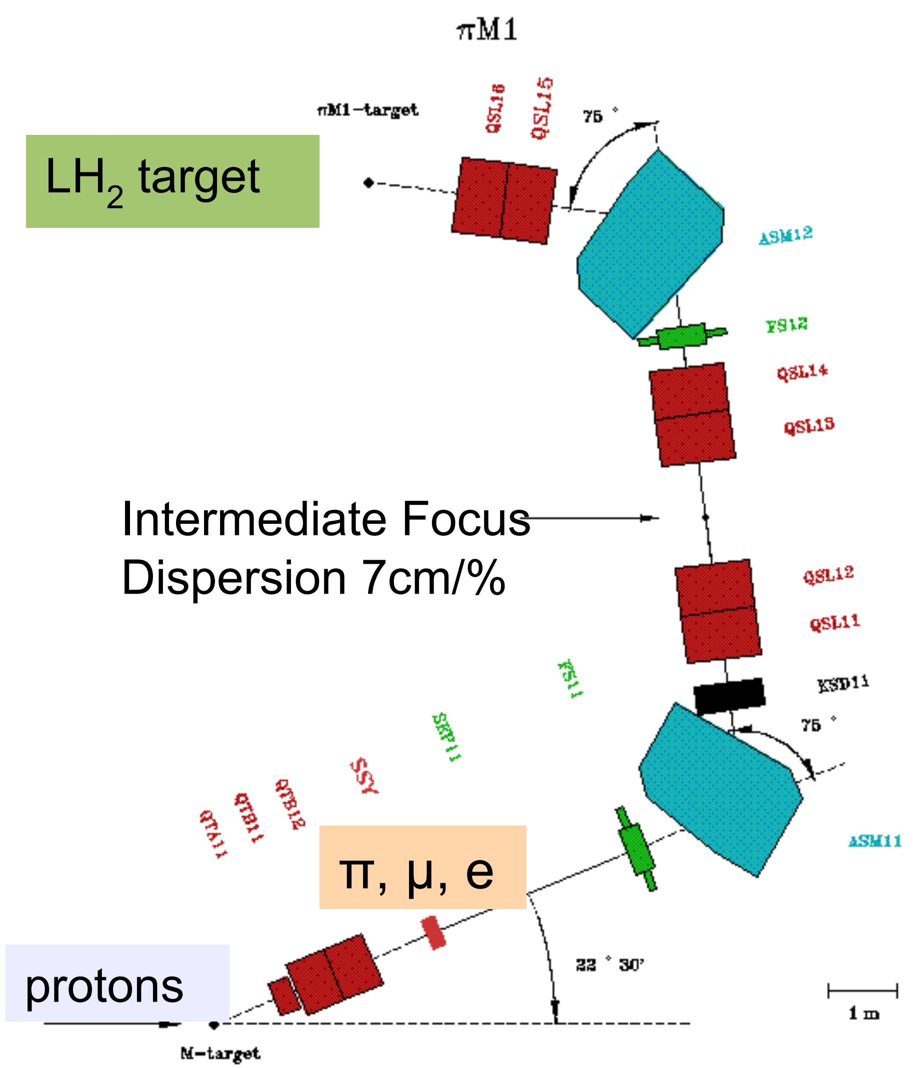
Expect identical form factors and radii for ep and μp scattering

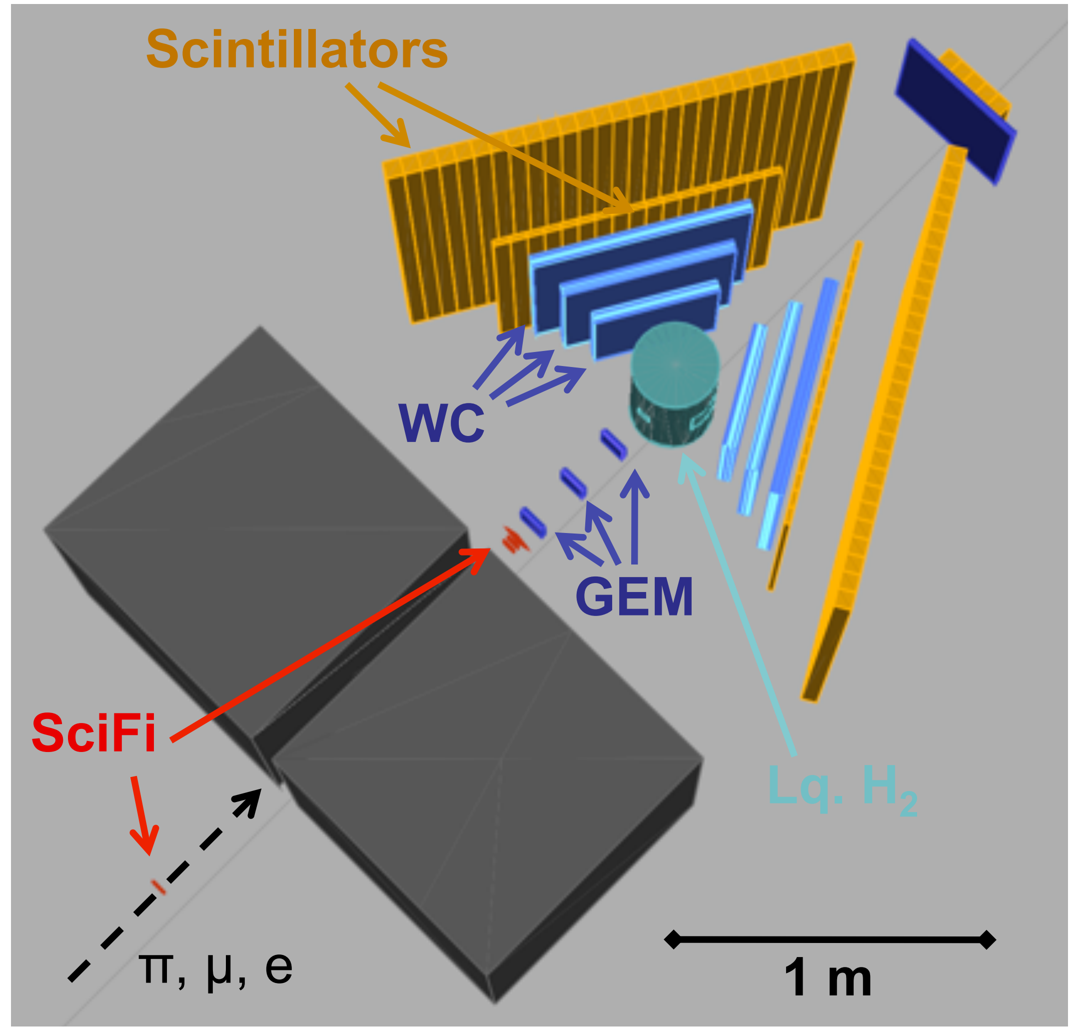
Proposal for muon scattering at PSI

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

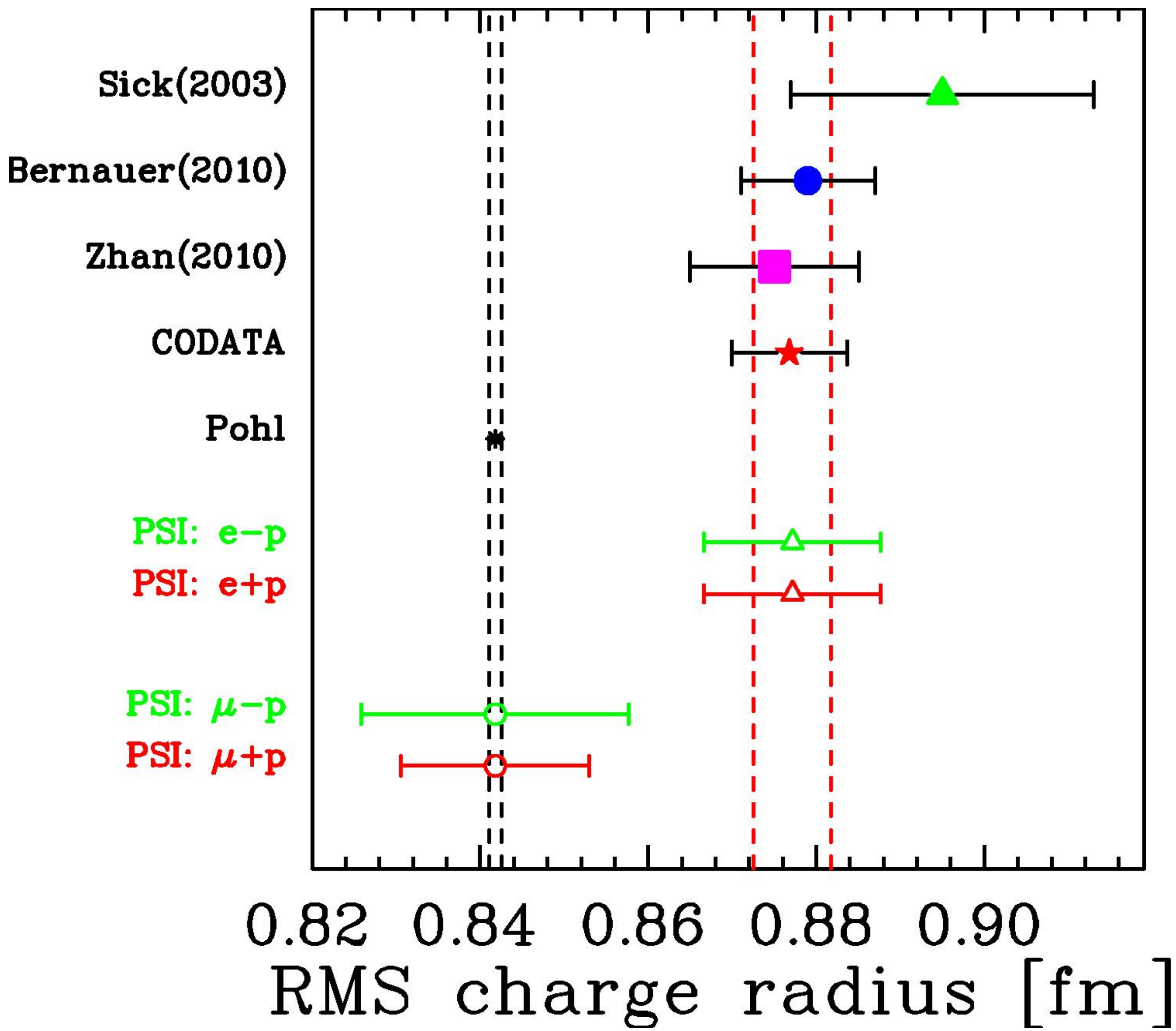
Beam particle tracking
Liquid hydrogen target
Scattered lepton detection

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

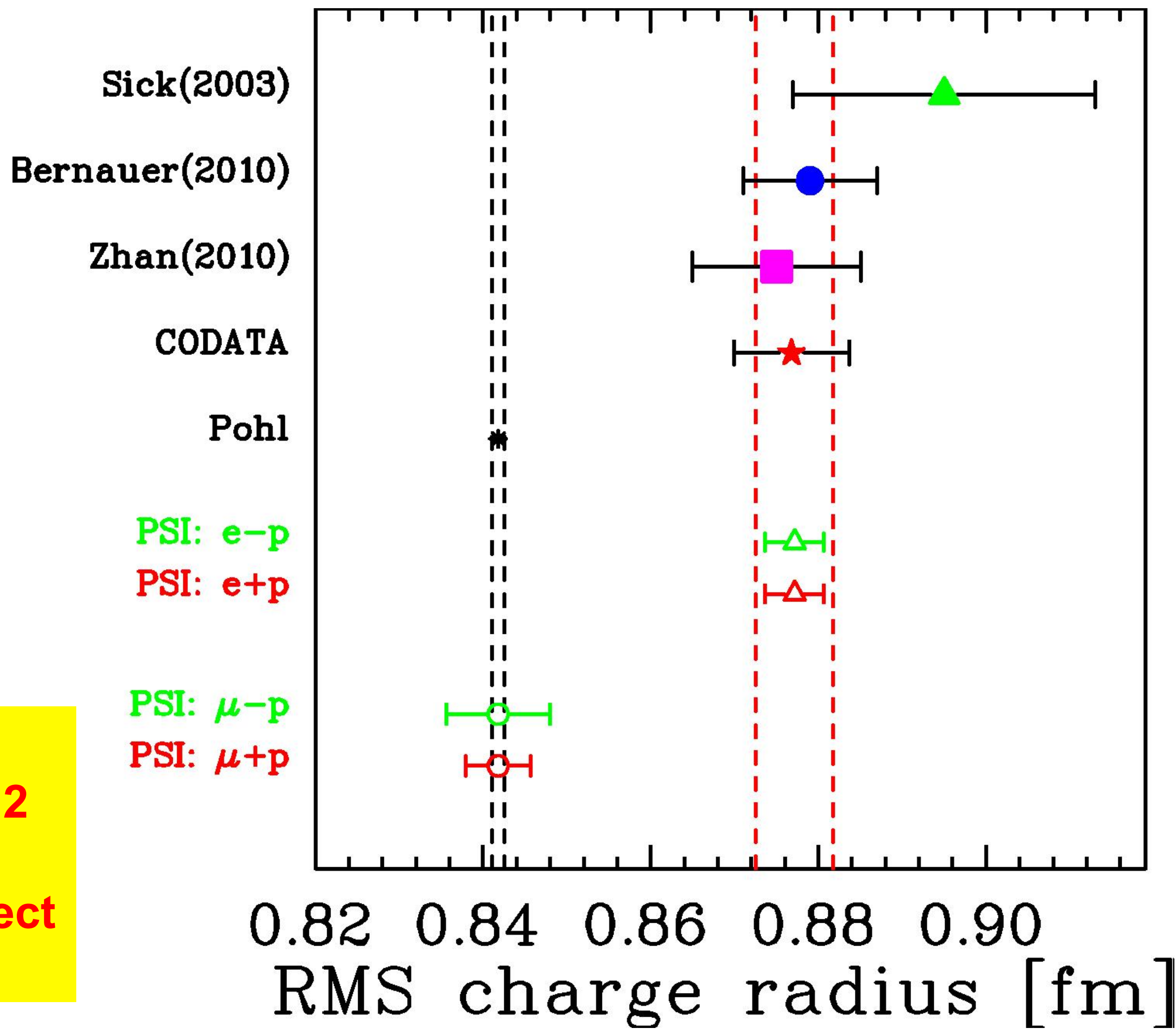
Charge radius extraction limited by systematics, fit uncertainties

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 2013–2015
  - Production running ~2016
- **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 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
  - MUon Scattering Experiment MUSE
  - New Physics remains a possibility

The nine muses

Backup

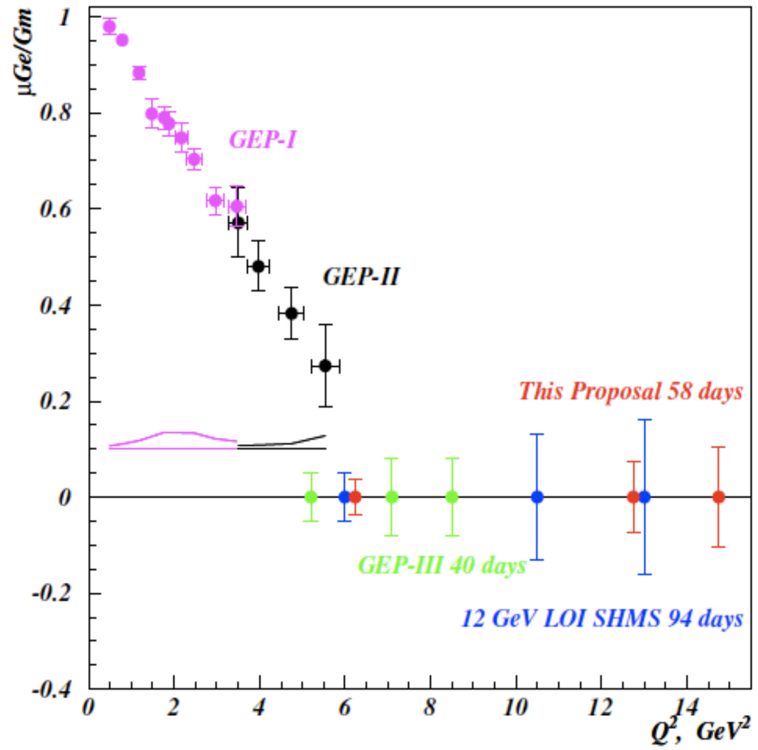
New proton measurements at high Q^2

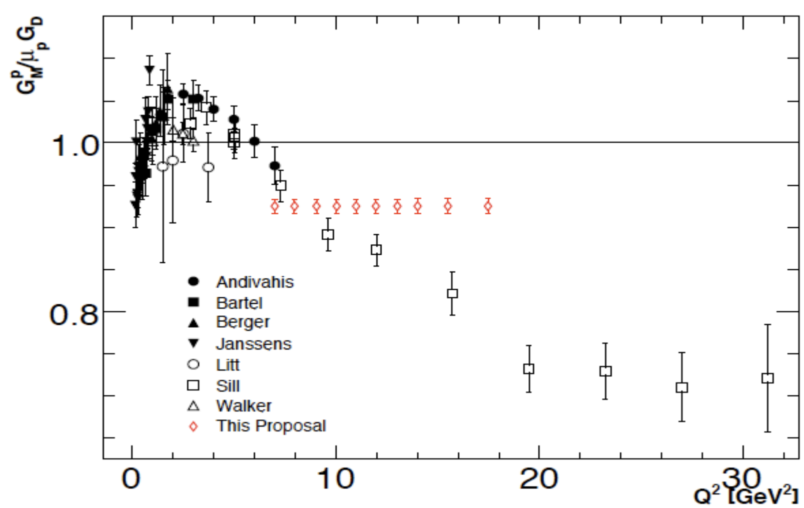
New High-Q^2 measurements at Jefferson Lab

- **Hall C E05-017: Super-Rosenbluth**
  Q^2 = 0.9 – 6.6 $(GeV/c)^2$
  Completed in summer 2007 – analysis underway
- **GEp-III /Hall C: E04-108/E04-019**
  Q^2 = 2.5, 5.2, 6.8, 8.5 $(GeV/c)^2$
  Completed in spring 2008, PRL**104** (2010) 242301
- **SANE /Hall C E07-003: Polarized Target**
  Q^2 = 2 and 6 $(GeV/c)^2$
  Completed in spring 2009, analysis near completion

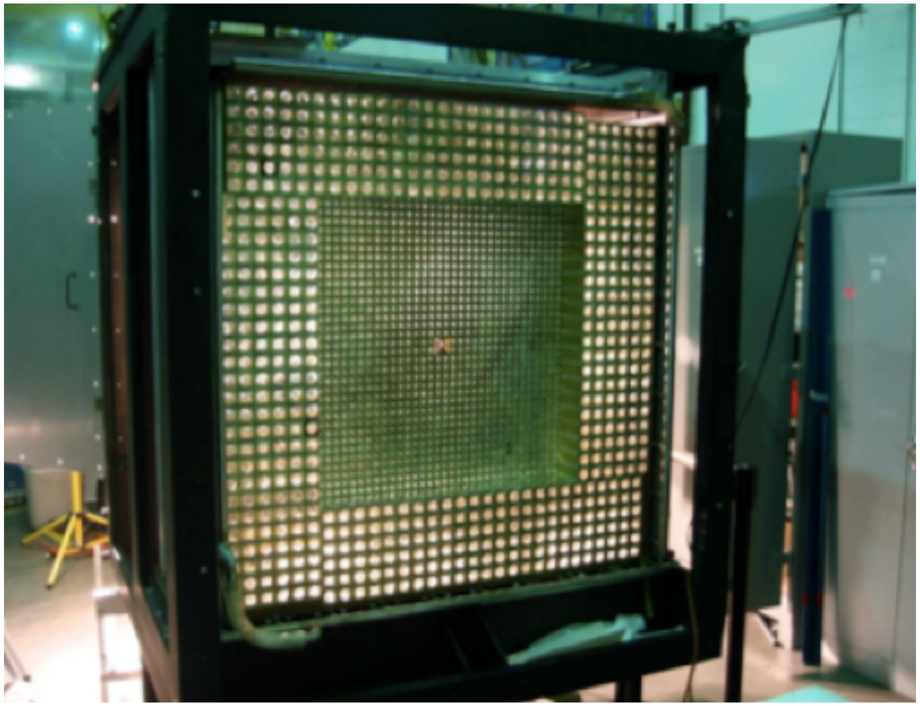
Proposed experiments

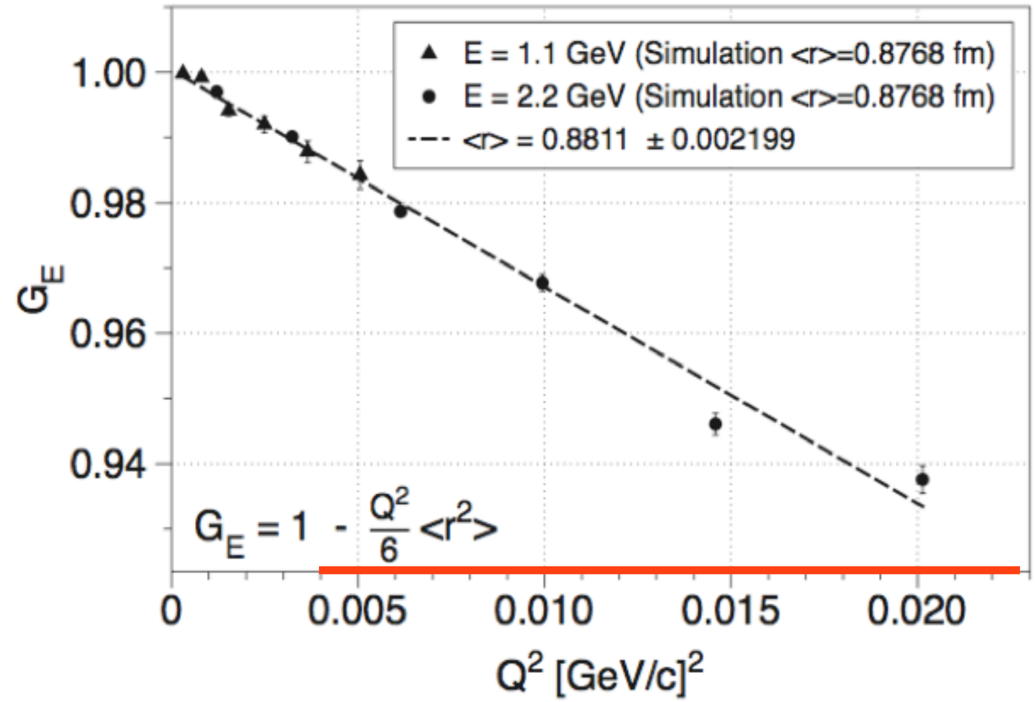
- PAC32: **PR12-07-109 /Hall A (GEp-IV)**
  L. Pentchev, C.F. Perdrisat, E. Cisbani,
  V. Punjabi, B. Wojtskhowski, M. Khandaker et al.
  Q^2=13,15 $(GeV/c)^2$: Approved
- PAC32: **PR12-07-108 /Hall A (high-Q^2 x-sec.)**
  S. Gilad, B. Moffit, B. Wojtsekhowski, J. Arrington et al.
  Q^2 =7-17.5 $(GeV/c)^2$: Approved, to run 2014/15
- PAC34: **PR12-09-001 /Hall C (GEp-V)**
  E.J. Brash, M. Jones, C.F. Perdrisat, V. Punjabi et al.
  Q^2=6,10.5,13 $(GeV/c)^2$; (deferred by PAC 37)





The "PrimEx" proton radius proposal



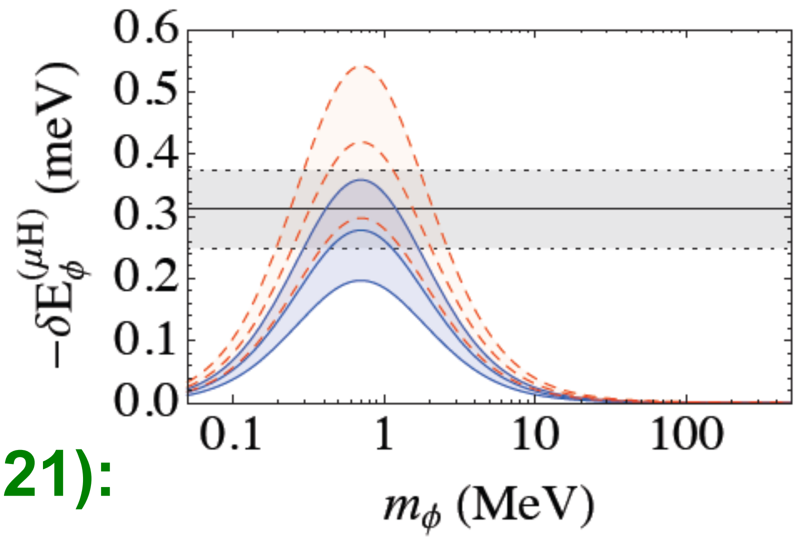


- Low intensity beam in Hall B @ Jlab into windowless gas target.
- Scattered ep and Moller electrons into HYCAL at 0^o.
- Lower Q^2 than Mainz. Very forward angle, insensitive to 2γ, G_M.
- Conditionally approved by PAC38 (Aug 2011): ``Testing of this result is among the most timely and important measurements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

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)

- 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

LFU and the proton radius puzzle

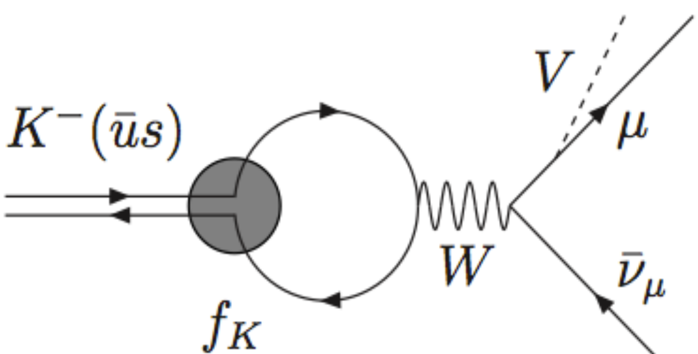
Batell, McKeen, Pospelov (arXiv:1103.0721):

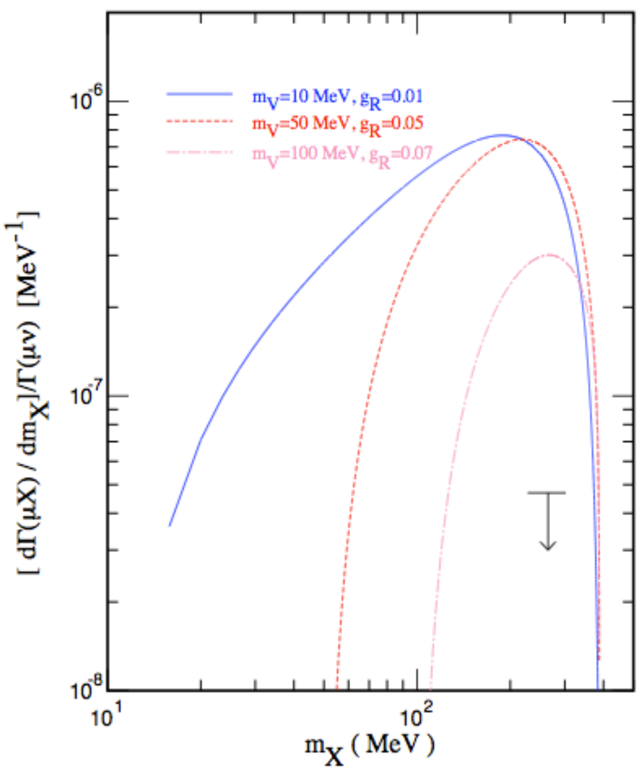
can solve proton radius puzzle

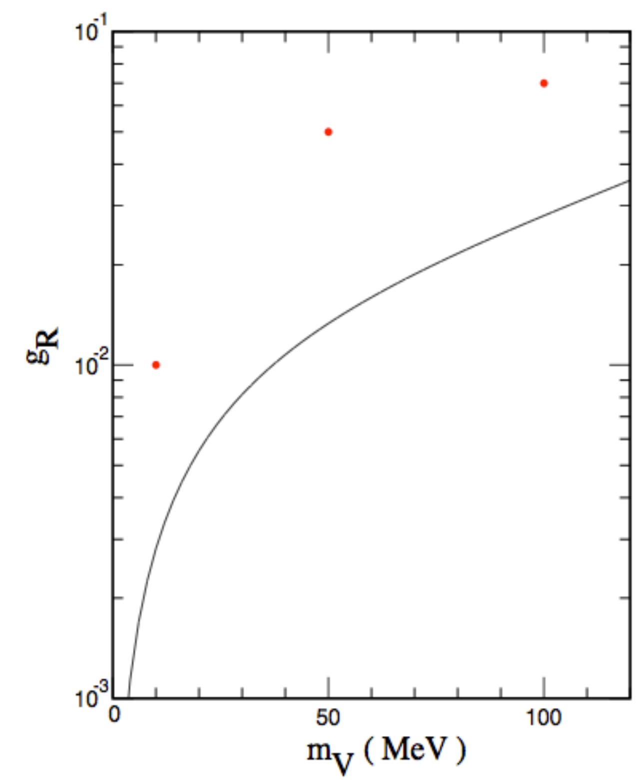
- new e/μ differentiating force consistent with g_μ-2
- <100 MeV gauge boson V or dark photon
- resulting in large PV μp scattering

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

- constrained by K → μν decay (invisible only)

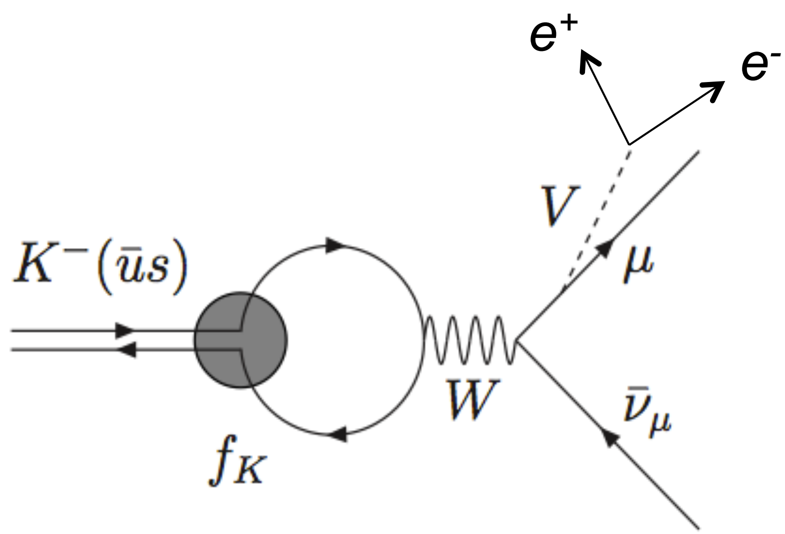






LFU and the proton radius puzzle

Indirectly: Search for violation of lepton universality in K_{l2}
Directly: Search for a light gauge boson (V), coupling to the muon leg, by full reconstruction of final state



Measure

$K_{\mu 2}$: $K^+ \rightarrow \mu^+ + \nu$ (expect ~10^{11} events)

$K_{\mu 2\gamma}(SD)$: $K^+ \rightarrow \mu^+ + \gamma + \nu$ (~10^9 events)

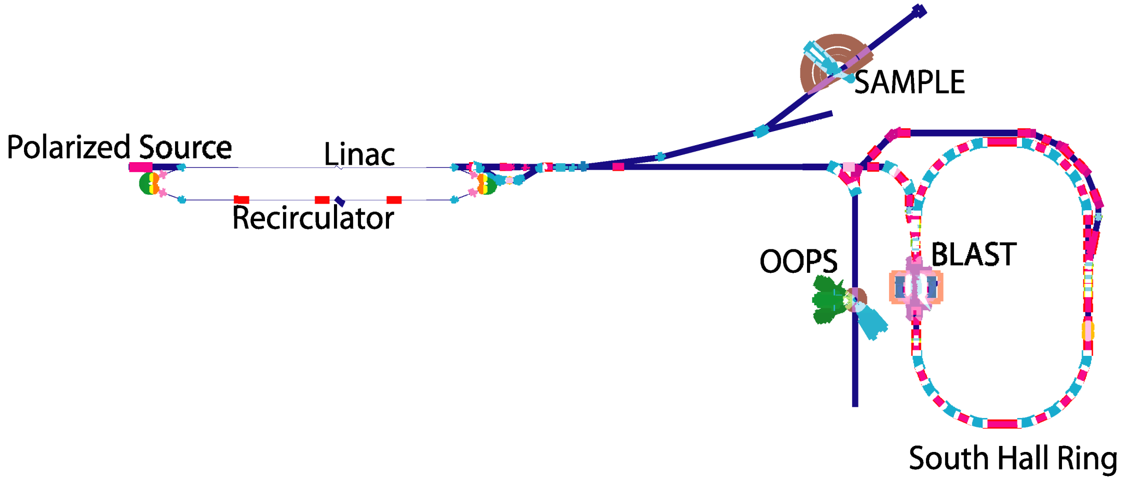
V: $K^+ \rightarrow \mu^+ + e^+ + e^- + \nu$ with $V \rightarrow e^+ + e^-$

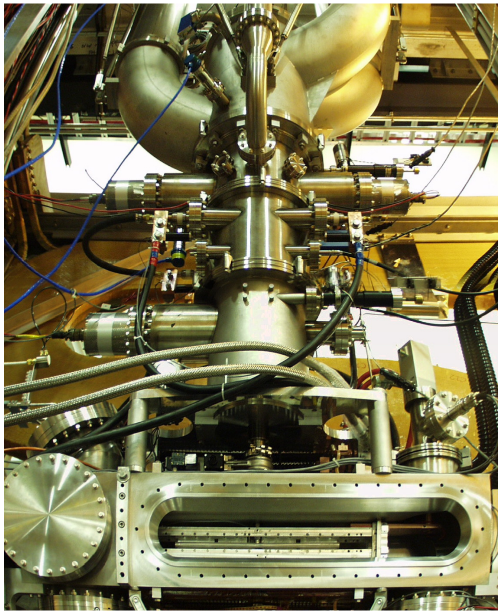
Low Q^2: BLAST at MIT-Bates

Bates Large Acceptance Spectrometer Toroid

- Symmetric, large acceptance, general purpose detector
  Detection of $e^{\pm}$, $\pi^{\pm}$, p, d, n

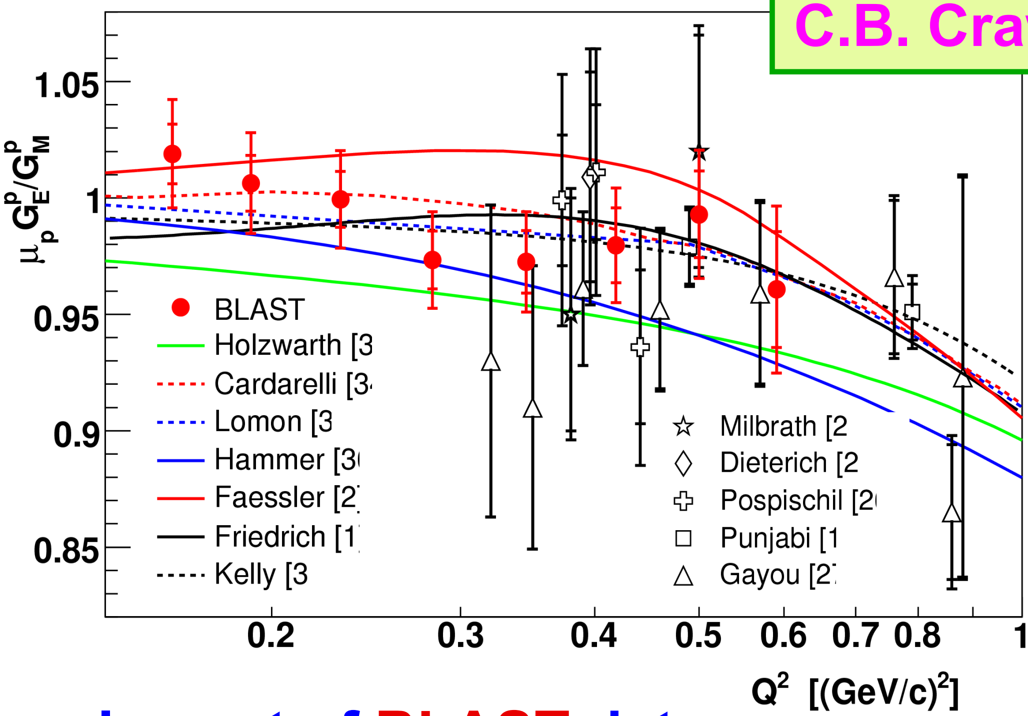
- Longitudinally polarized electrons in SHR
  850 MeV, 200 mA, P_e = 65%



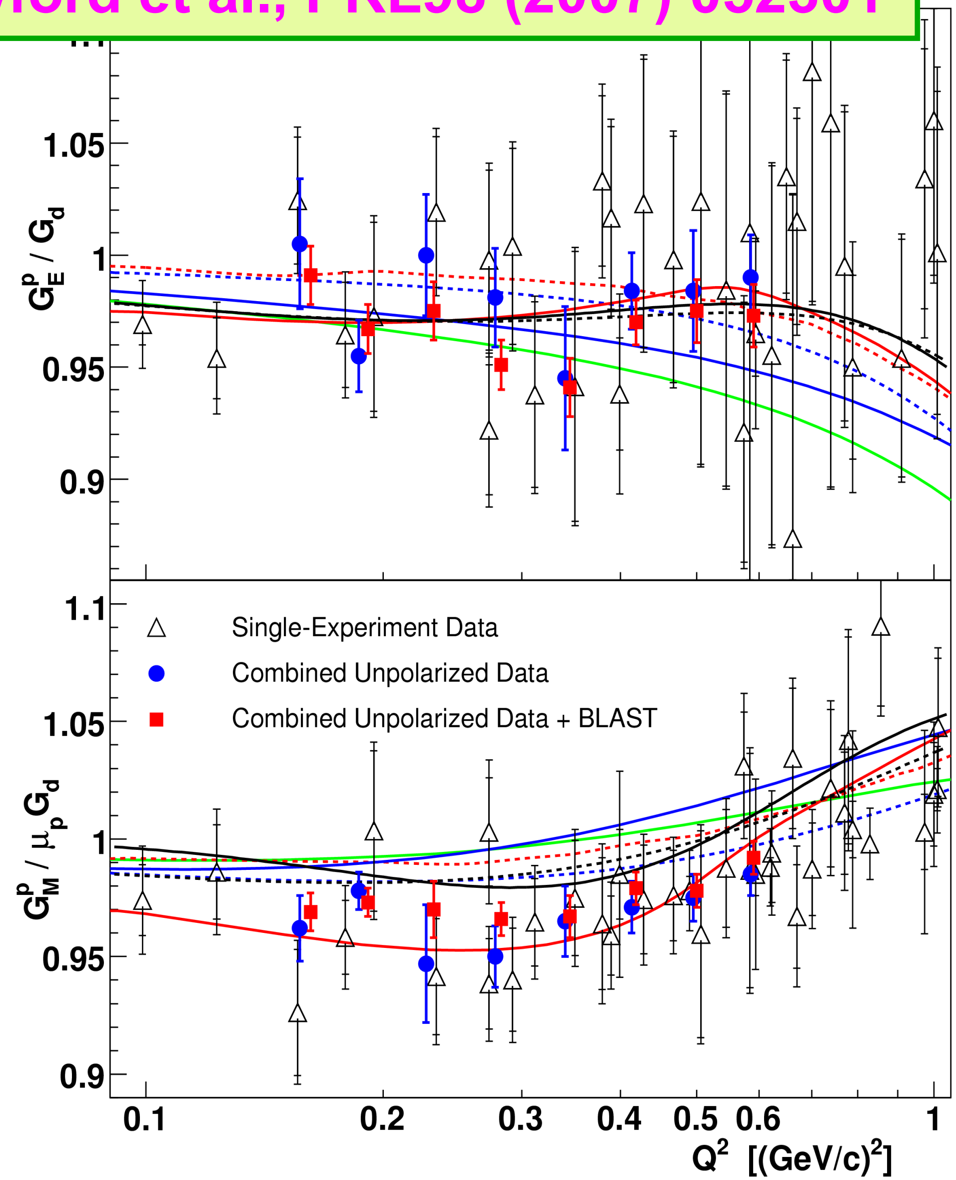


- Highly polarized internal gas target of pure H and D (Atomic Beam Source)
  6×10^{13} atoms/cm^2, $L = 6 \times 10^{31}/(\mathrm{cm}^2\mathrm{s})$, $P_{H/D}$ = 80%

Proton form-factor ratio $\mu_p G^p_E / G^p_M$



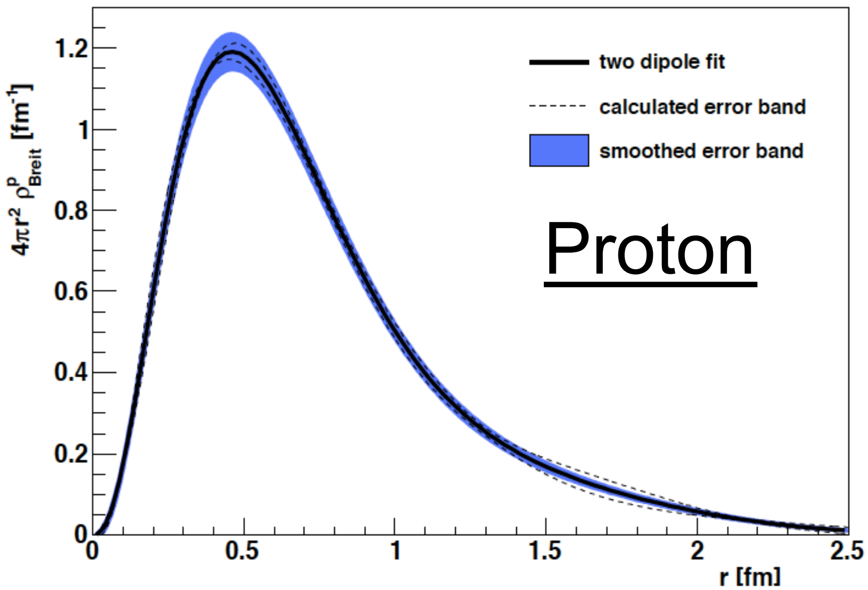
C.B. Crawford et al., PRL98 (2007) 052301

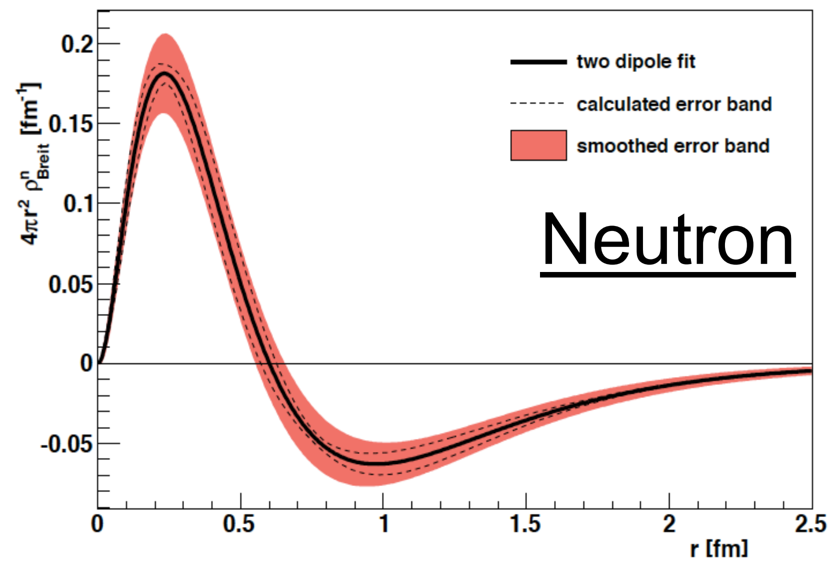


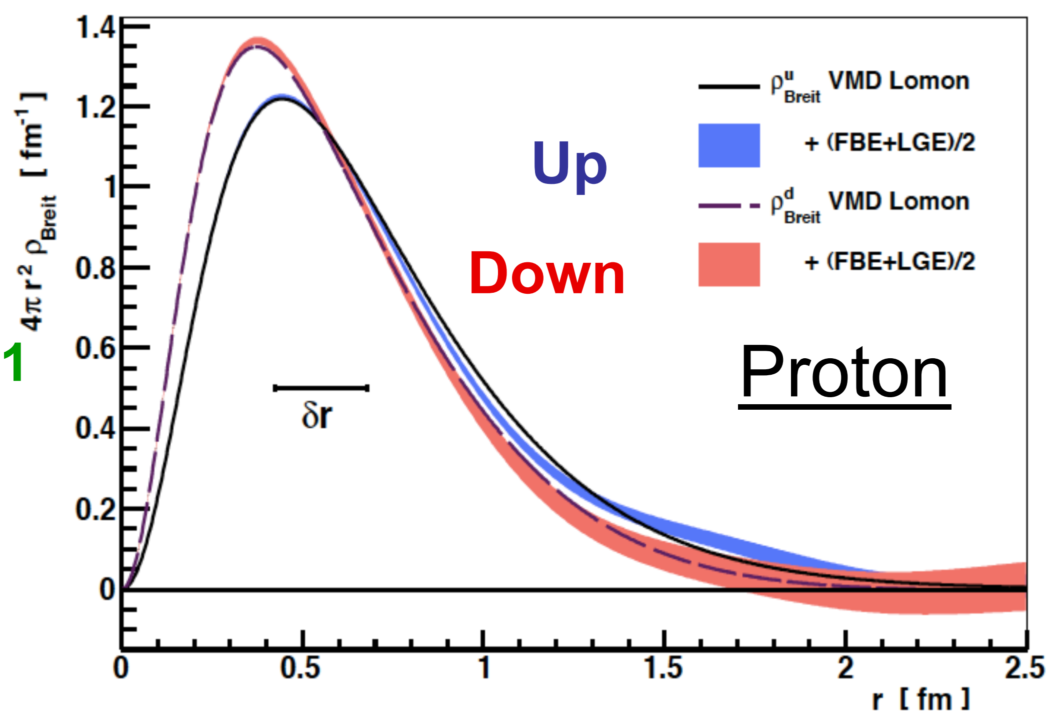
- **Impact of BLAST data combined with cross sections on separation of G^p_E and G^p_M**
- **Errors factor ~2 smaller**
- **Reduced correlation**
- **Deviation from dipole at low Q^2!**

Ph.D. work of C. Crawford (MIT) and A. Sindile (UNH)

Spatial distributions in Breit frame







C. Crawford et al.
PRC 82 (2010) 045211