International Workshop “Experimental and theoretical aspects of the proton form factors”
St. Petersburg, July 9-11, 2012

Summary on Experiments

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Experimental talks

Gramolin, Alexander	Status of the Novosibirsk two-photon exchange experiment
Russell, Rebecca	OLYMPUS experiment at DESY
Puckett, Andrew	Polarization Transfer Measurements of GEp at Large Momentum Transfer
Bennett, Robert	Measuring TPE at CLAS
Perdrisat, Charles	Search for two-photon exchange in elastic ep
Kohl, Michael	Proton radius at PSI
Gasparian, Ashot	High Precision Measurement of the Proton Charge Radius
Gramolin, Alexander	Radiative corrections in the Novosibirsk two-photon exchange experiment
Ramstein, Beatrice	Proton time-like form factor measurements with PANDA

Experiments to determine FFs and TPE

Positron-electron comparisons

Novosibirsk/VEPP-3 – close to publication
CLAS/Jlab – analysis in progress
OLYMPUS/DESY – data taking in progress

Recoil polarization

Gep-II+III – high-Q^2 recoil polarization – published
2-Gamma – ε dependence of recoil pol. – published
Gep-V (& GMp) – high Q^2 at Jlab-12 – proposed
Another ε dependence of recoil pol. – considered

Rosenbluth separation

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

Proton radius measurements

Proton radius puzzle established by Lamb shift in muonic hydrogen
Jlab / PrimEx – proposed
PSI / muon scattering – proposed

The Beginnings

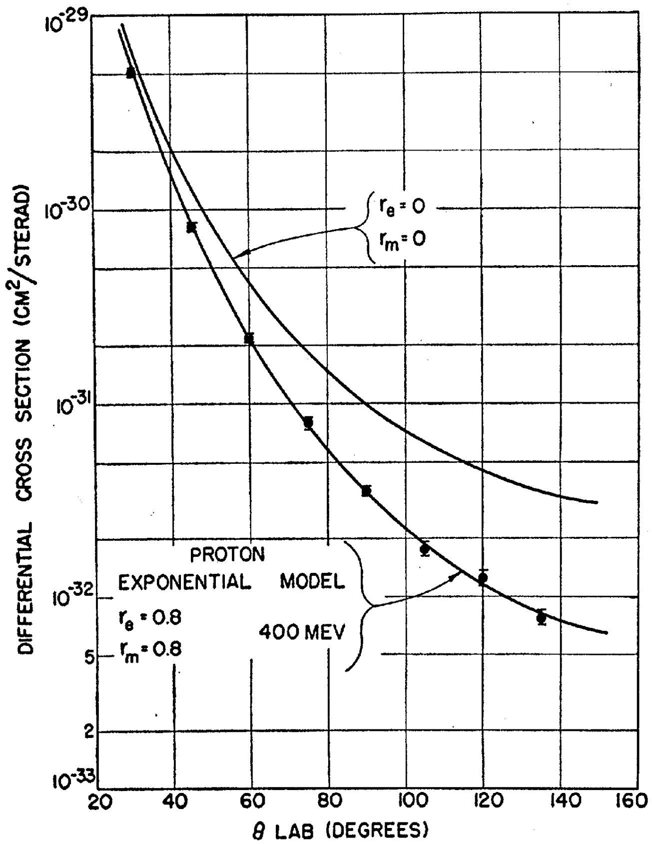


FIG. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with rms radii $=0.80\times10^{-13}$ cm.

Robert Hofstadter
Nobel prize 1961

ep-elastic
Finite size of the proton

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

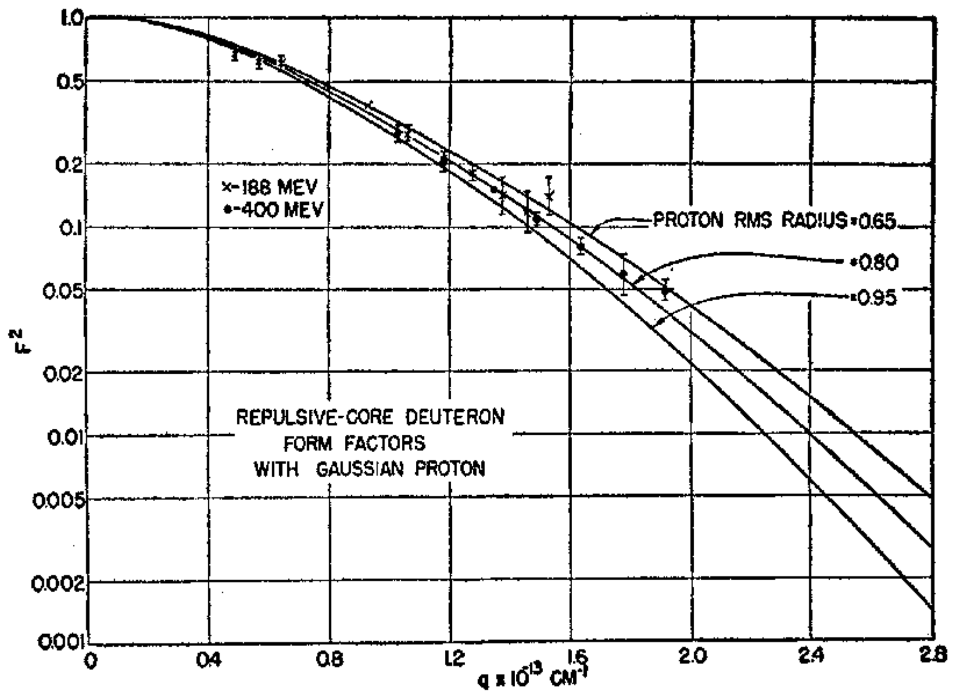


FIG. 31. Introduction of a finite proton core allows the experimental data to be fitted with conventional form factors (McIntyre).

ed-elastic
Finite size + nuclear structure

Proton form factors

- Study with elastic *ep* scattering
- The Rosenbluth separation method at constant Q^2

Rosenbluth Formula

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \frac{G_E^2 + \frac{\tau}{\varepsilon} G_M^2}{1+\tau}$$

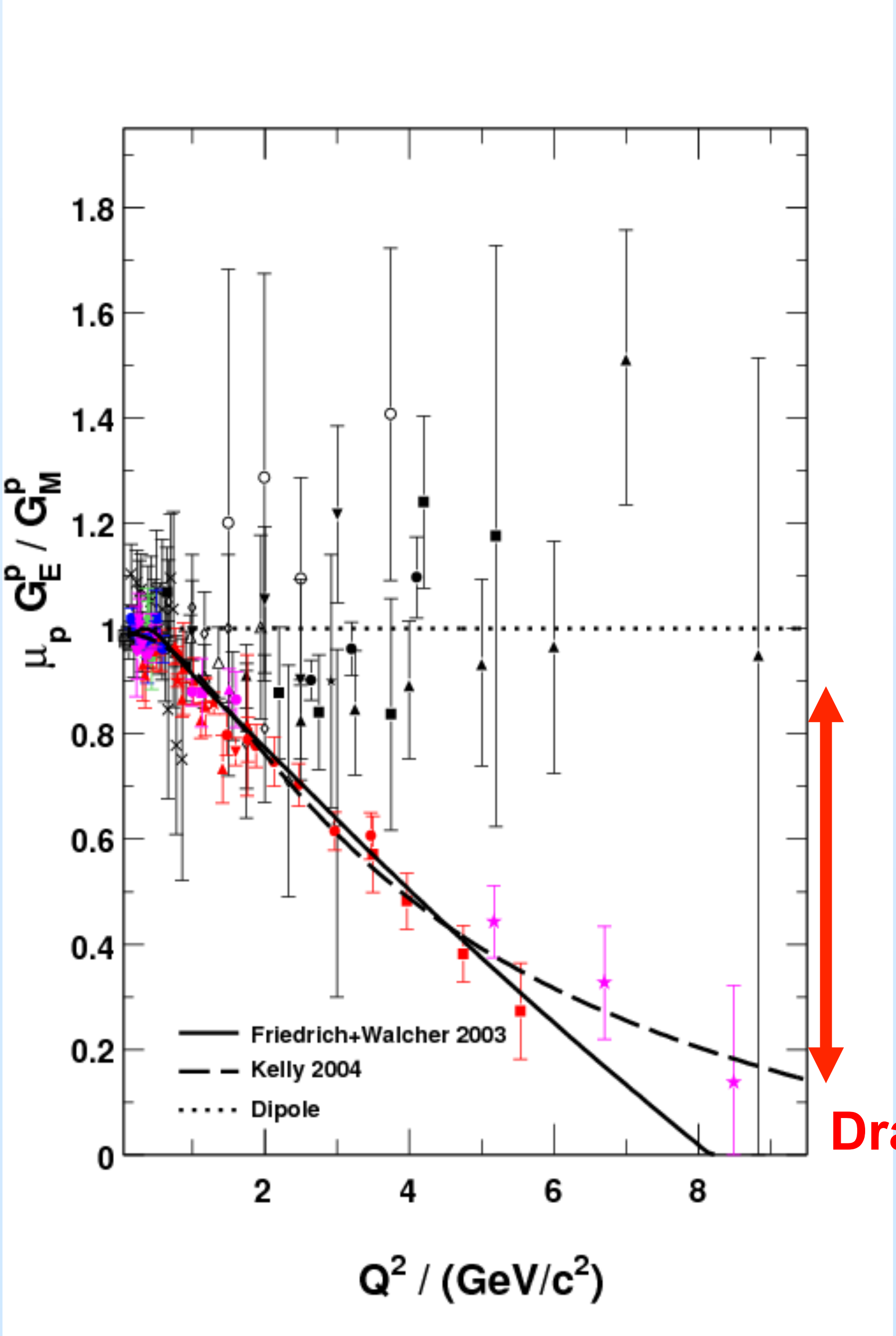
where $\tau = Q^2/4M^2$ and $\varepsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}$

- New techniques with polarized beams and targets

Form factor ratio from polarization transfer

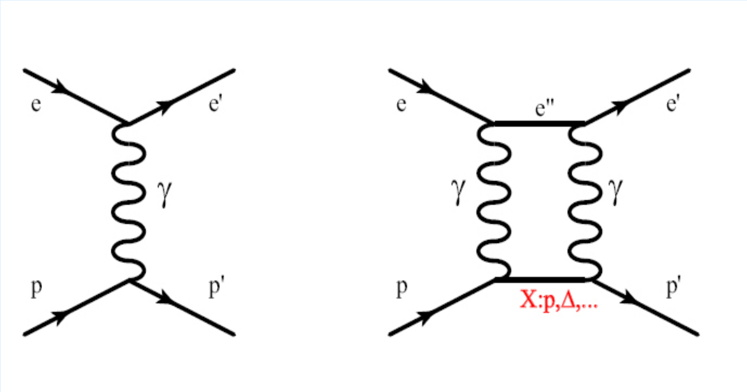
$$\frac{G_E}{G_M} = \frac{\mathcal{P}_t}{\mathcal{P}_\ell} \times (\text{kinematic factor})$$

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

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**

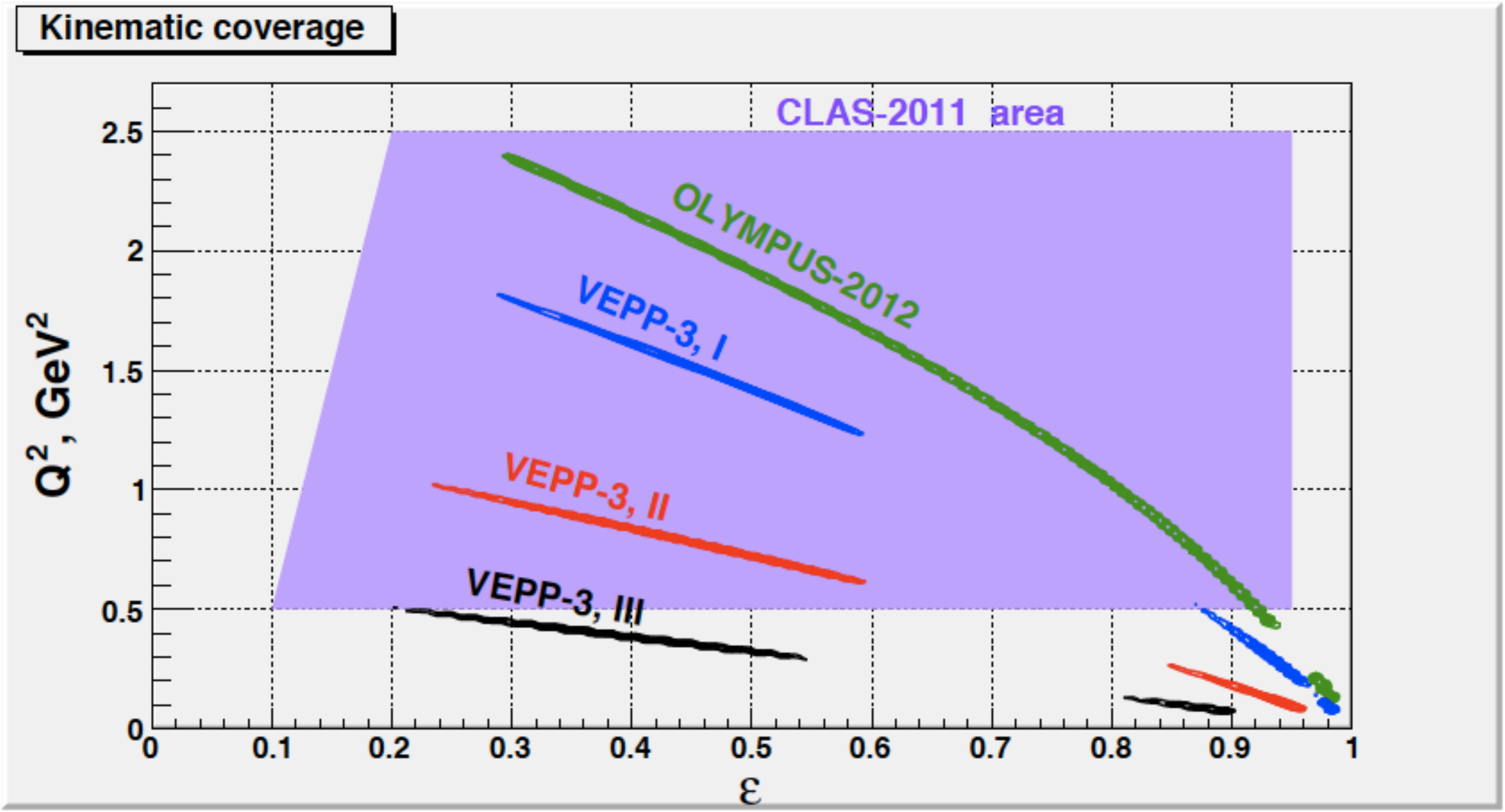
P.A.M. Guichon and M.Vanderhaeghen, Phys.Rev.Lett. 91, 142303 (2003)

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

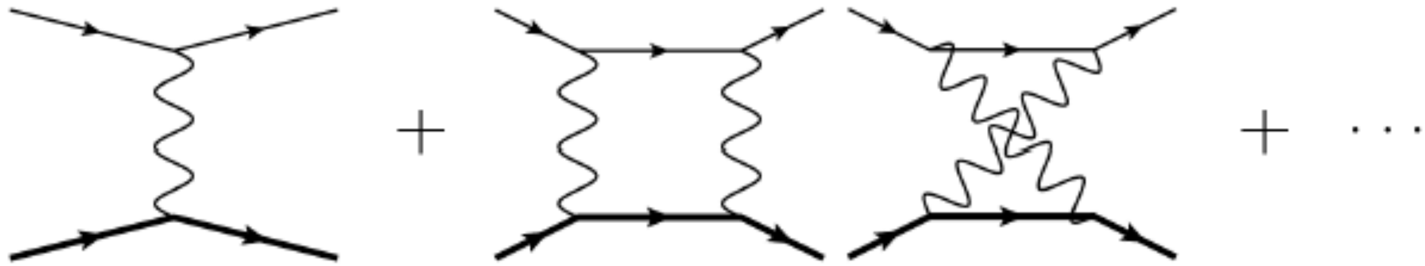
Slide idea: L. Pentchev

Three experiments aimed at measuring the ratio R

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



Measuring the two-photon effect



- Odd lepton-sign power in interference term

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

- e^+/e^- ratio sensitive to two-photon contribution

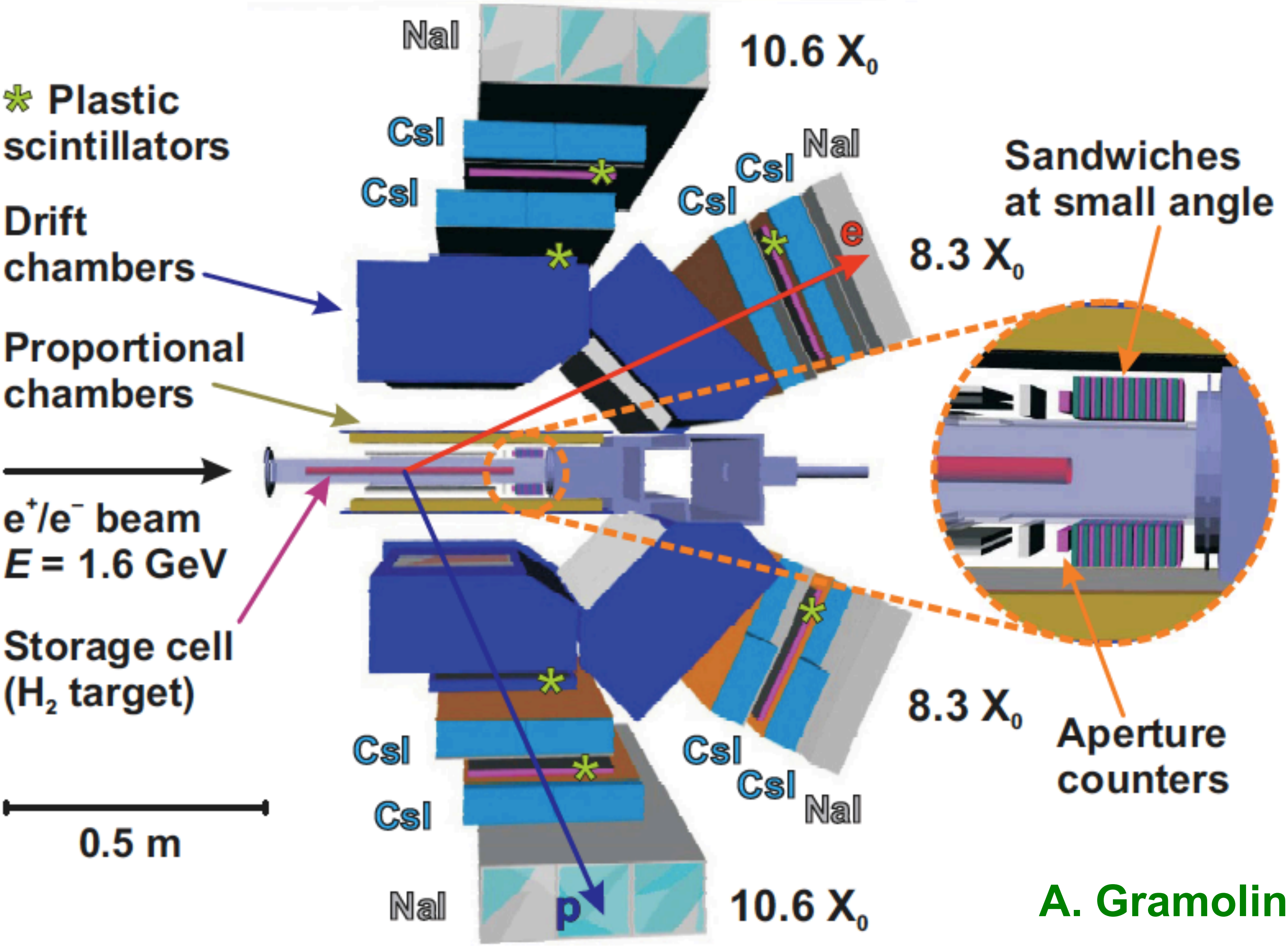
$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx 1 + 4\frac{\Re\{\mathcal{M}_{1\gamma}^{\dagger}\mathcal{M}_{2\gamma}\}}{|\mathcal{M}_{1\gamma}|^2}$$

Comparison of the three experiments

	VEPP–3 Novosibirsk	OLYMPUS DESY	EG5 CLAS JLab
beam energy	3 fixed	1(+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}

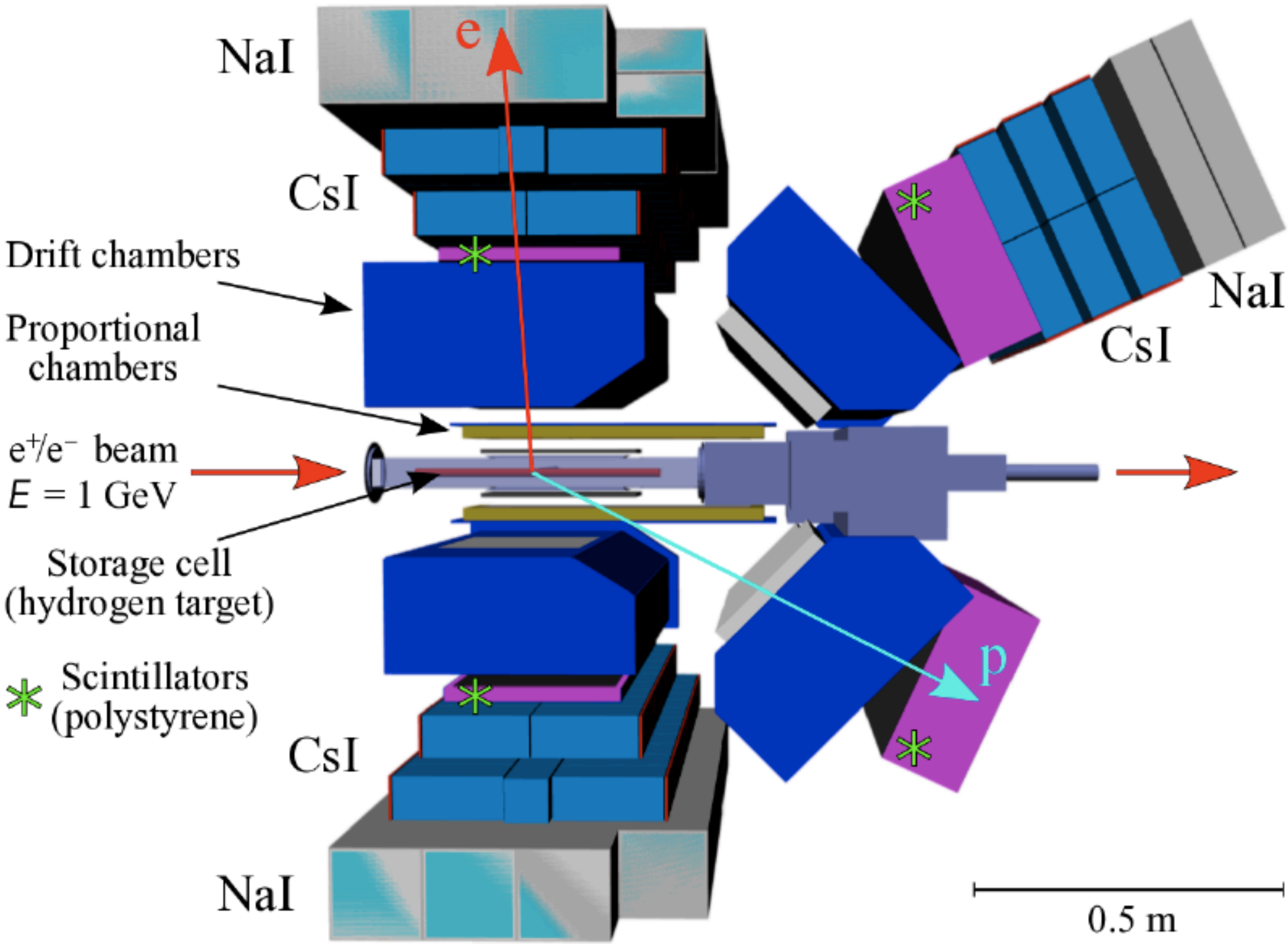
- Novosibirsk experiment is inferior to the other two in experimental luminosity and in quality of particle ID.
- However, the detector performance is sufficient for reliable identification of elastic scattering events.
- Non-magnetic detector, measurement of beams energy, frequent swapping of e^{+}/e^{-} beams allow us to obtain lowest systematic error.

Novosibirsk TPE experiment (run I)



A. Gramolin

Novosibirsk TPE experiment (runs II, III)



Milestones of the Novosibirsk experiment

- The proposal was published (Aug 2004): nucl-ex/0408020

Two-photon exchange and elastic scattering of electrons/positrons on the proton. (Proposal for an experiment at VEPP-3).
J. Arrington, V.F. Dmitriev, R.J. Holt, D.M. Nikolenko, I.A. Rachek, Yu.V. Shestakov, V.N. Stibunov, D.K. Toporkov, H. de Vries. Aug 2004. 13 pp.
e-Print: **nucl-ex/0408020** [nucl-ex] PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 45 records

- Data taking:

Run	Duration	E_{beam}, GeV	Number of e^++e^- cycles	$\int$ luminosity, pb^{-1}
Engineering run	May–Jul 2007	1.6	90	12
Run I	Sep–Dec 2009	1.6	1100	324
Run II	Sep 2011 – Mar 2012	1.0	2350	600
Run III	Apr 2012	0.6	220	18

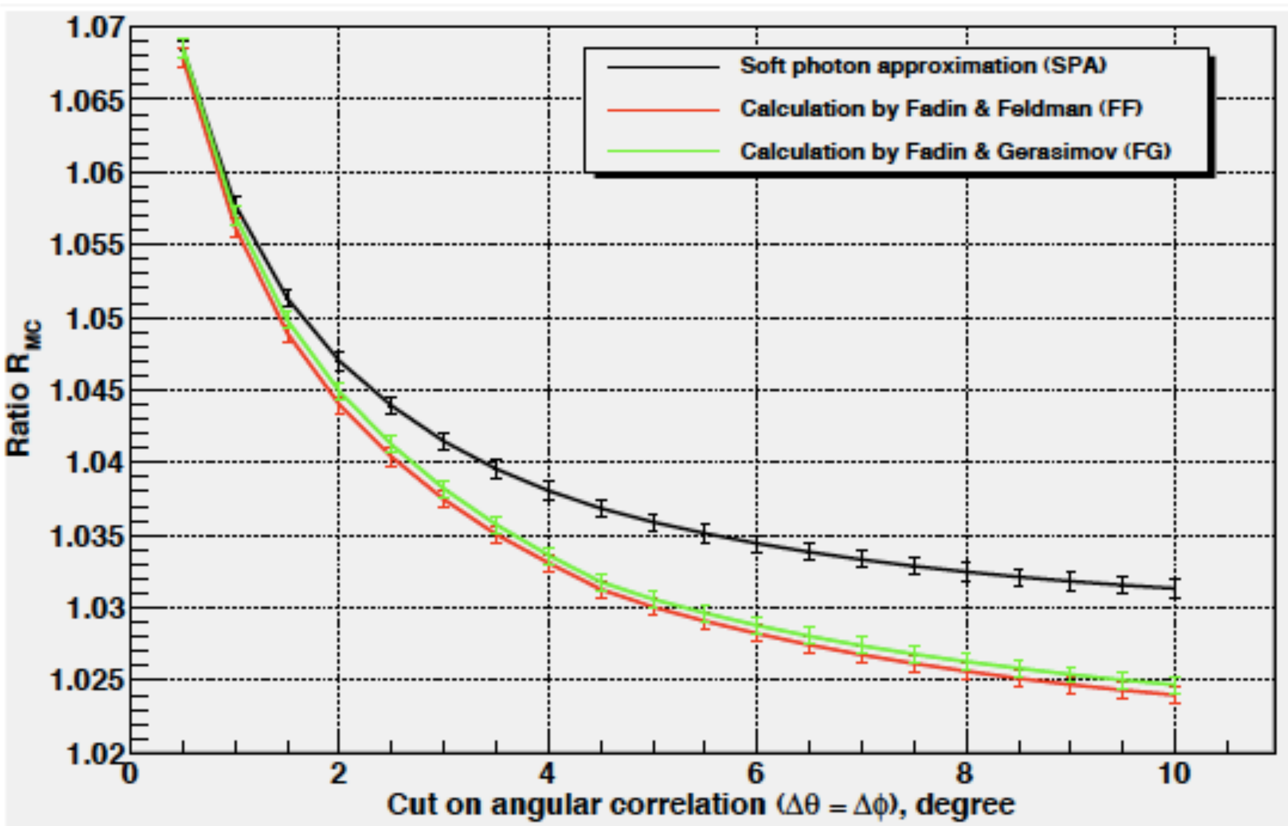
- Some preliminary results were published (Dec 2011): arXiv:1112.5369

Measurement of the two-photon exchange contribution in elastic ep scattering at VEPP-3.
A.V. Gramolin (Novosibirsk, IYF), J. Arrington (Argonne), L.M. Barkov (Novosibirsk, IYF), V.F. Dmitriev (Novosibirsk, IYF & Novosibirsk State U.), V.V. Gauzshtein (Tomsk Polytechnic U.), R.A. Golovin (Novosibirsk, IYF), R.J. Holt (Argonne), V.V. Kaminsky, B.A. Lazarenko, S.I. Mishnev (Novosibirsk, IYF) *et al.*. Dec 2011. 5 pp.
Published in **Nucl.Phys.Proc.Suppl. 225-227 (2012) 216**
To appear in the proceedings of Conference: C11-09-19
e-Print: **arXiv:1112.5369** [nucl-ex] PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 1 record

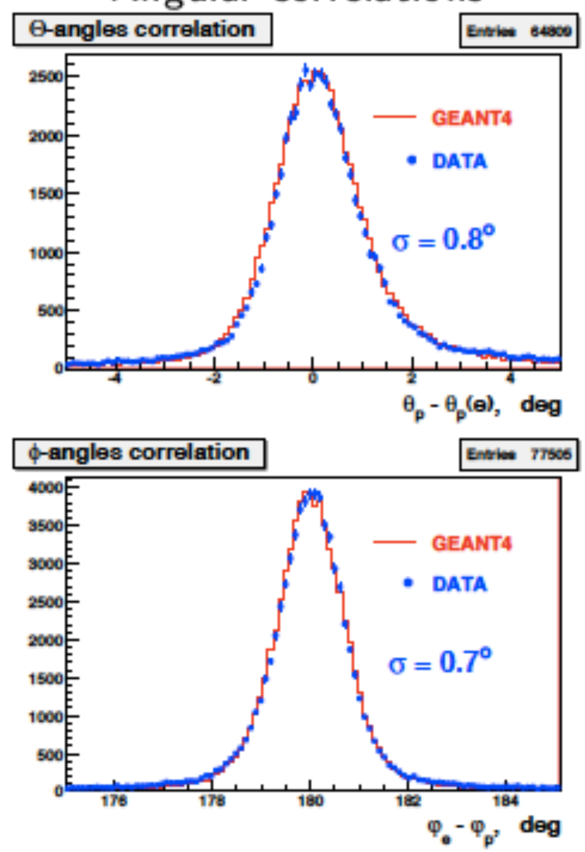
- Final results of the experiment: expected in 2013

MC simulation of the radiative corrections

- The first-order bremsstrahlung: calculation by Fadin & Feldman instead of the simplified soft-photon one.
- Calculation by Fadin & Gerasimov to account for bremstrahlung with Δ-isobar excitation.
- New event generator ESEPP is applied to the Monte-Carlo detector simulation using the Geant4 software package.

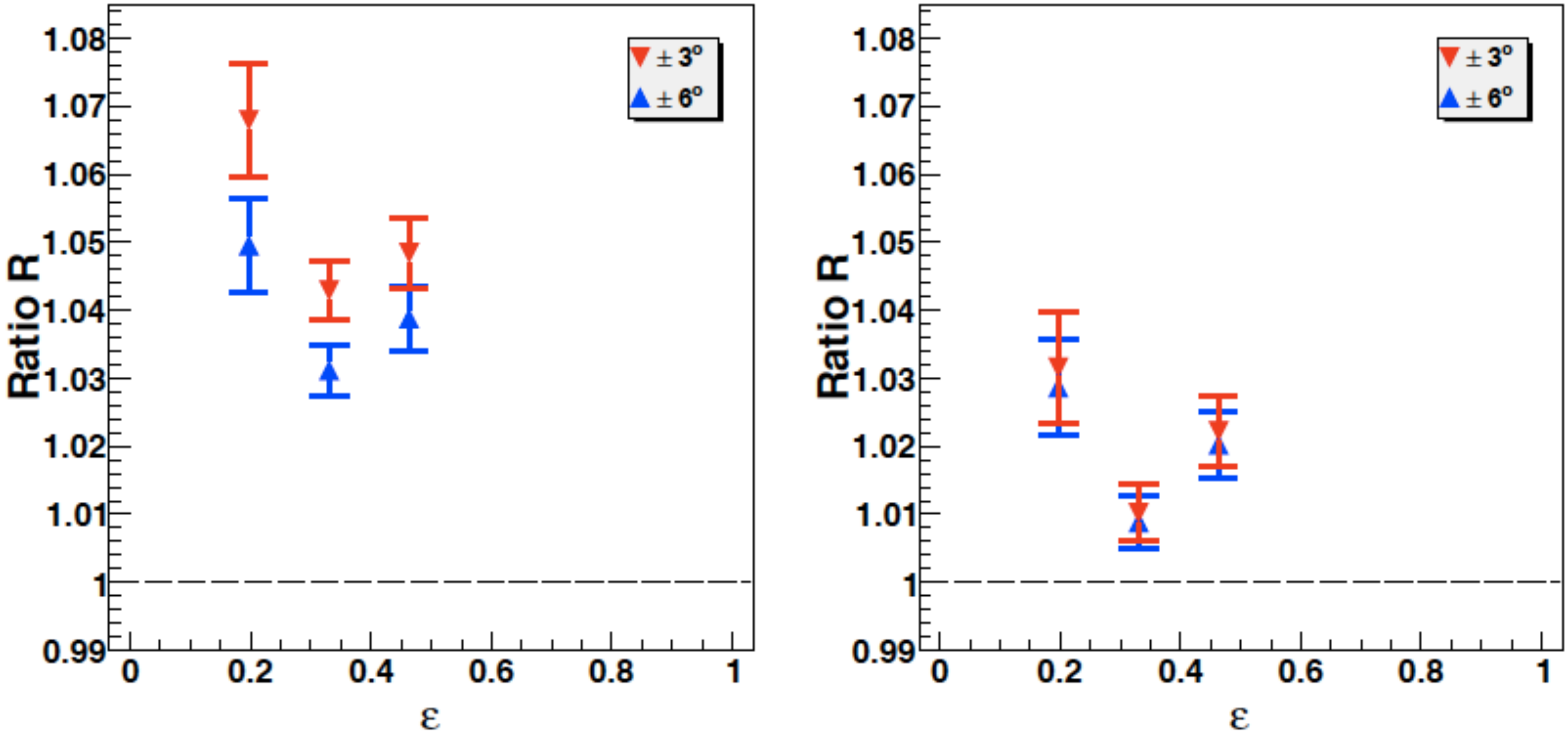


Angular correlations



Ratio R and RC depend both on the kinematic cuts used

Raw data for the ratio R: | Radiatively corrected ratio R:

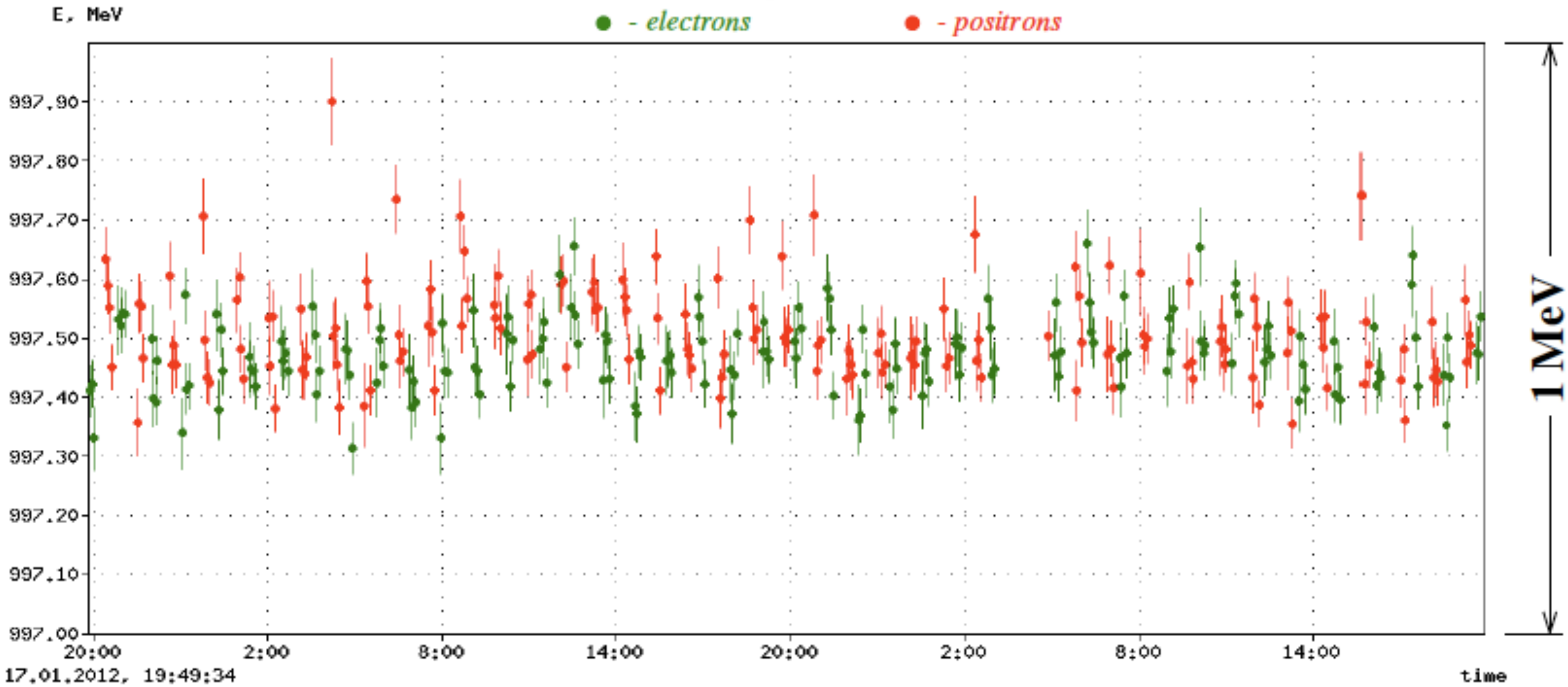


Experimentally measured ratio R is shown before (left figure) and after (right figure) taking into account the radiative corrections (FF model). Red markers correspond to the cut $\Delta\theta = \Delta\phi = 3°$ on the angular correlations, blue markers correspond to the cut $\Delta\theta = \Delta\phi = 6°$ (data for LA range of the run II).

Suppression of the systematics: beam energy

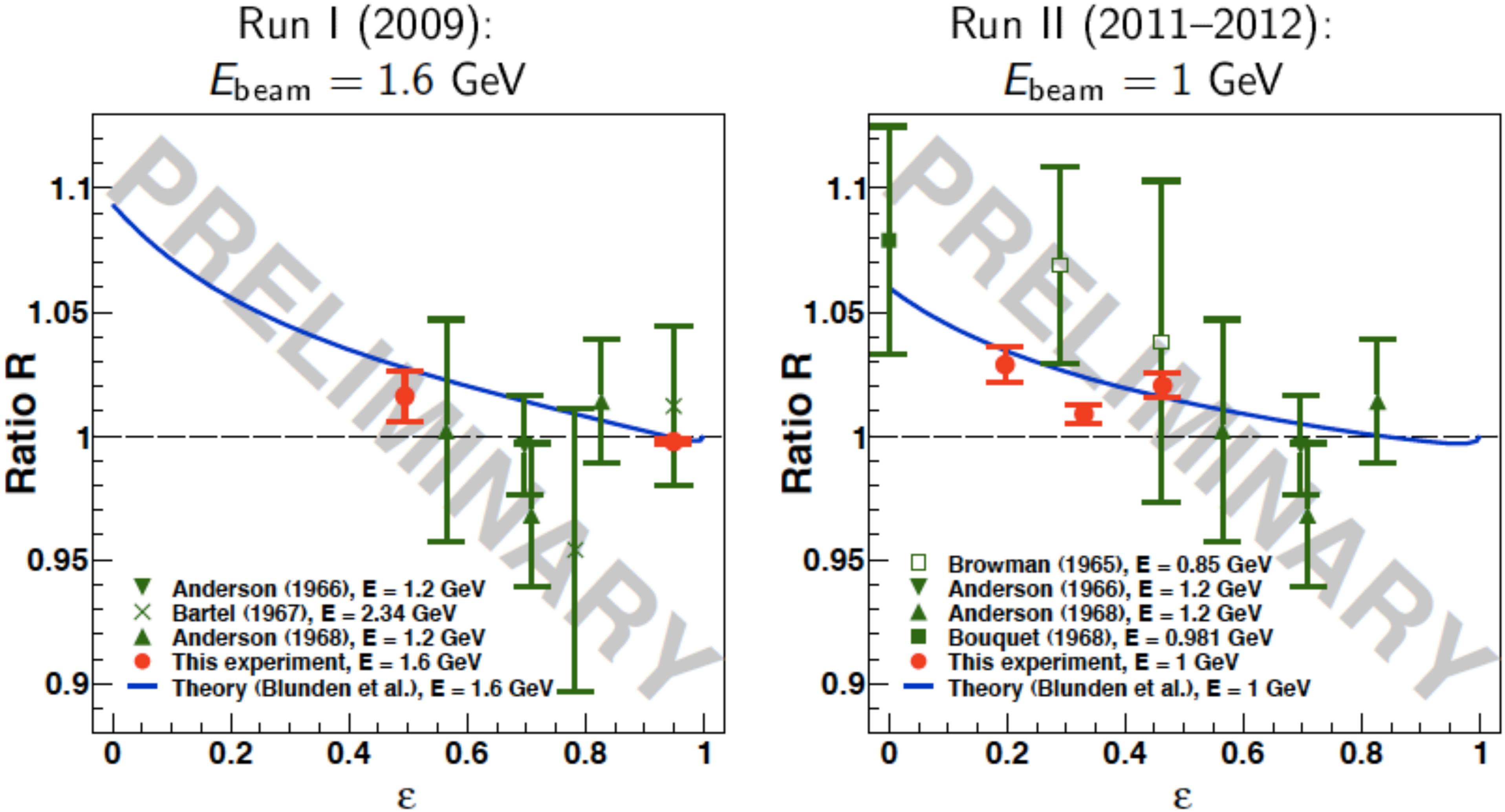
- Method of measuring the energy of the laser photons back-scattered by the VEPP–3 beam is used.
- This allows us to tune the VEPP–3 operation regimes and to monitor the beams energy during the experiment.

VEPP–3 energy measurement



Contribution to the systematic error: $< 0.1\%$

Preliminary results of the Novosibirsk experiment



Theory: *P. G. Blunden, et al.*, Phys. Rev. C **72** (2005) 034612

Only statistical errors are shown. Systematic errors for both the runs: $\leqslant 0.3\%$

Note that the radiative corrections have been taken into account. Some minor corrections have not yet been made (for example, corrections related to the variation in time of beam energy and position).

The OLYMPUS Collaboration

Members from. . .

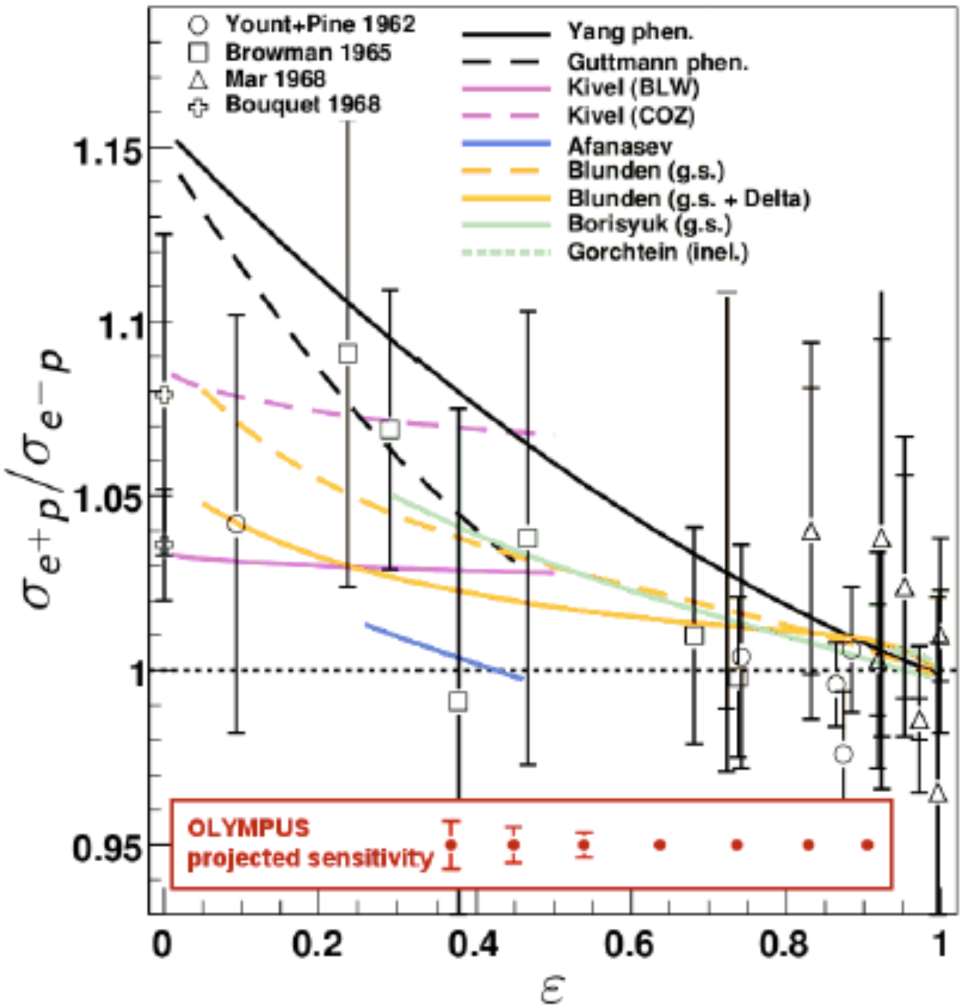
- Arizona State University, USA
- DESY, Hamburg, Germany
- Hampton University, USA
- INFN Bari, Ferrara, and Rome, Italy
- MIT and MIT-Bates, USA
- Petersburg Nuclear Physics Institute, Russia
- University of Bonn, Germany
- University of Glasgow, United Kingdom
- University of Mainz, Germany
- University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

Status of measurements

- No precise measurements at low ε or high Q^2

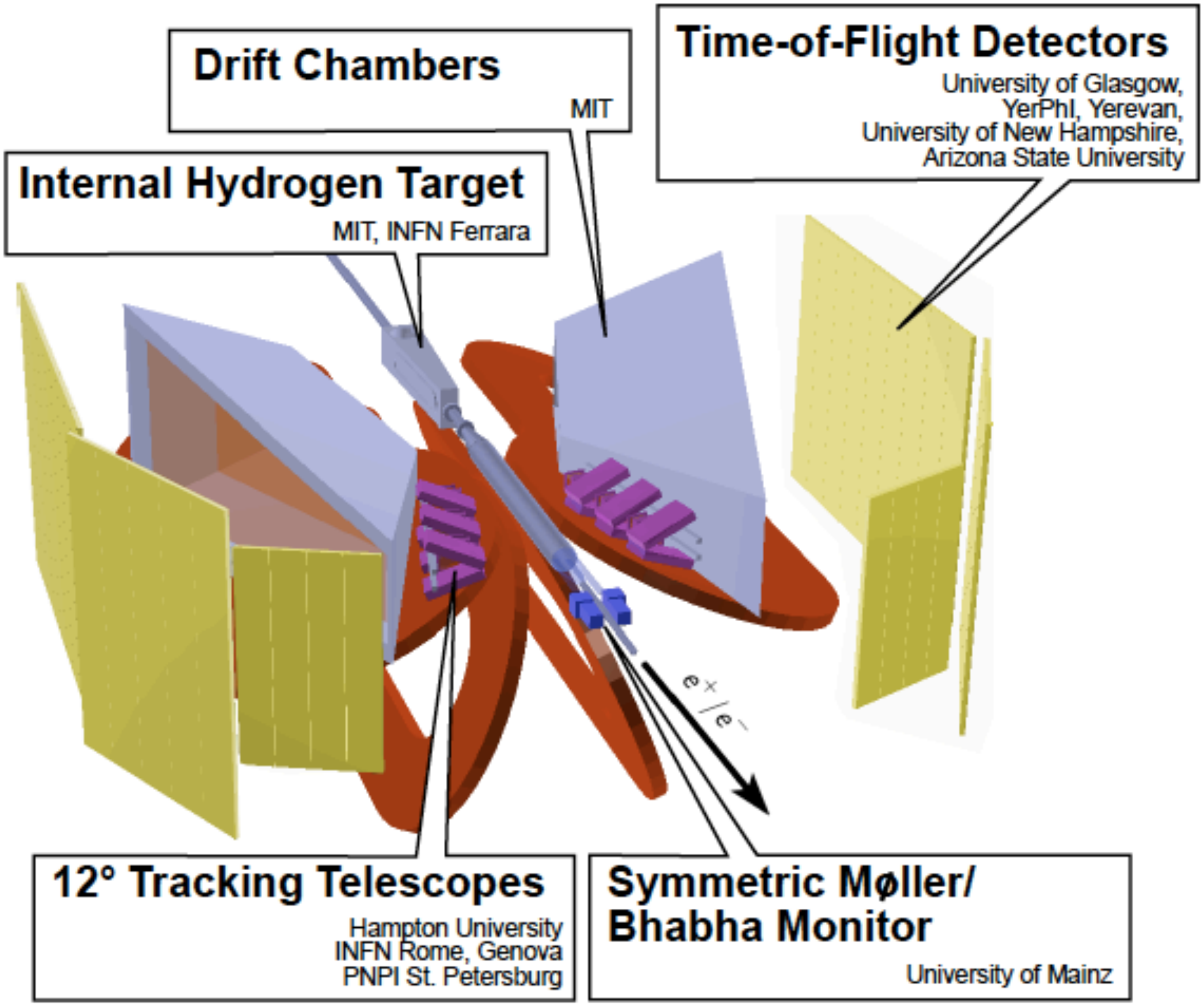
The OLYMPUS experiment

$$E = 2\ \text{GeV}$$
$$0.6\ \text{GeV}^2 \leq Q^2 \leq 2.2\ \text{GeV}^2$$
$$0.3 \leq \varepsilon \leq 0.9$$
Measure ratio to $< 1\%$



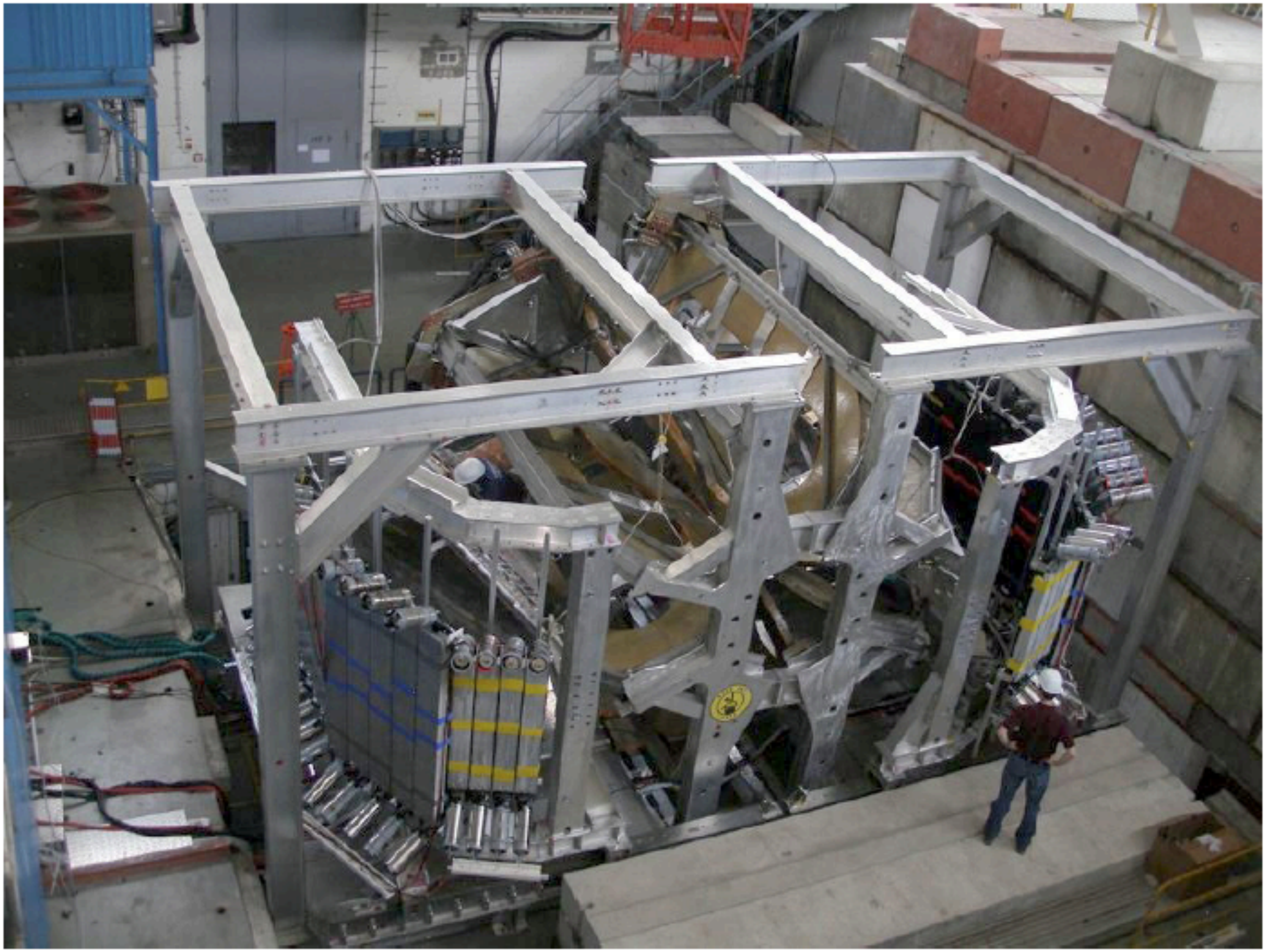
- Two other ongoing experiments: at JLab and Novosibirsk

OLYMPUS setup overview



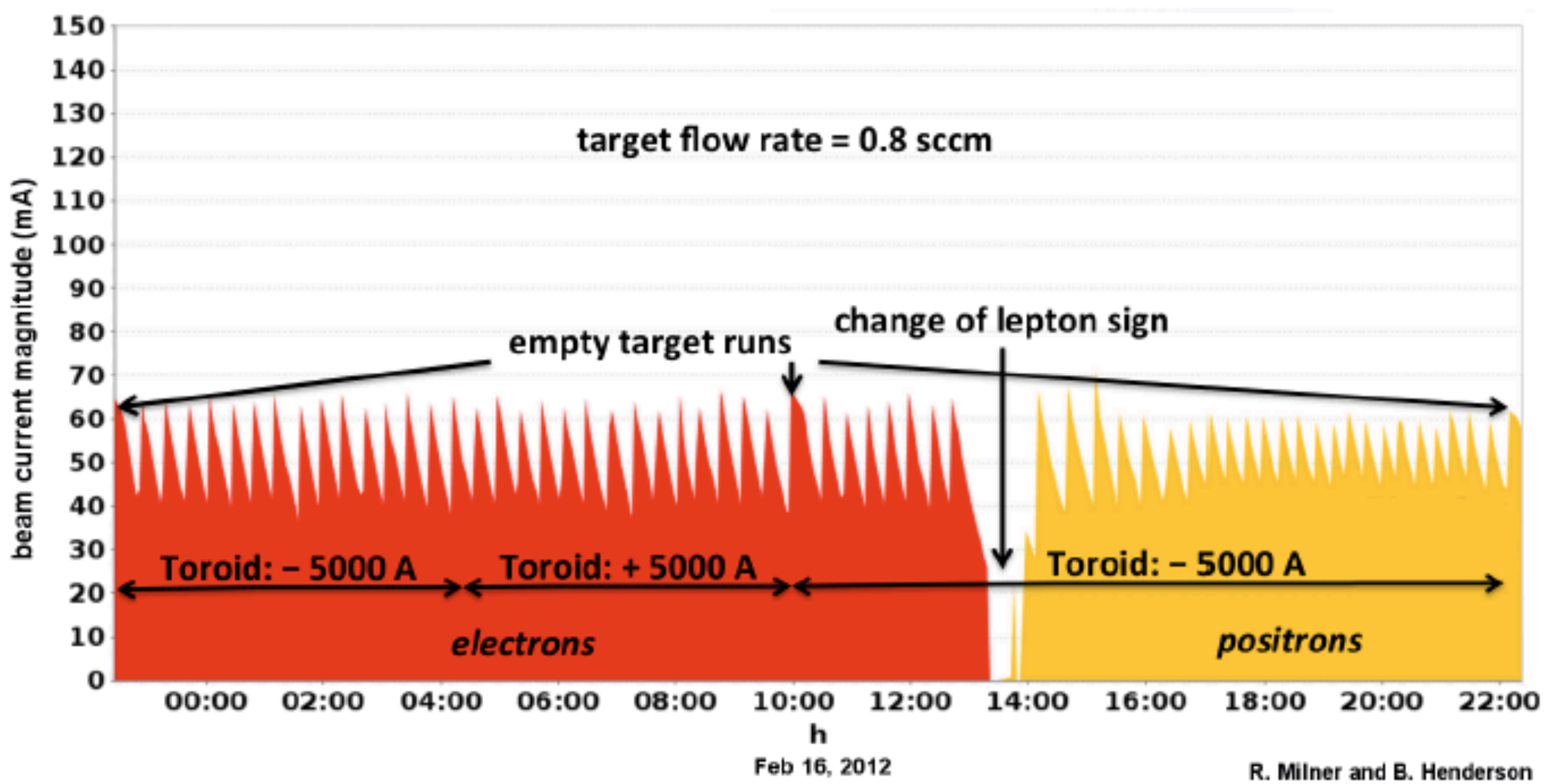
based on a figure by R. Russell

OLYMPUS setup overview – reality



OLYMPUS first run

- Month-long run in February 2012
- Successful start of data collection



- Analysis underway
- Another two months of running Oct. 22- Dec 22, 2012

Radiative Corrections

- Maximon and Tjon estimate:

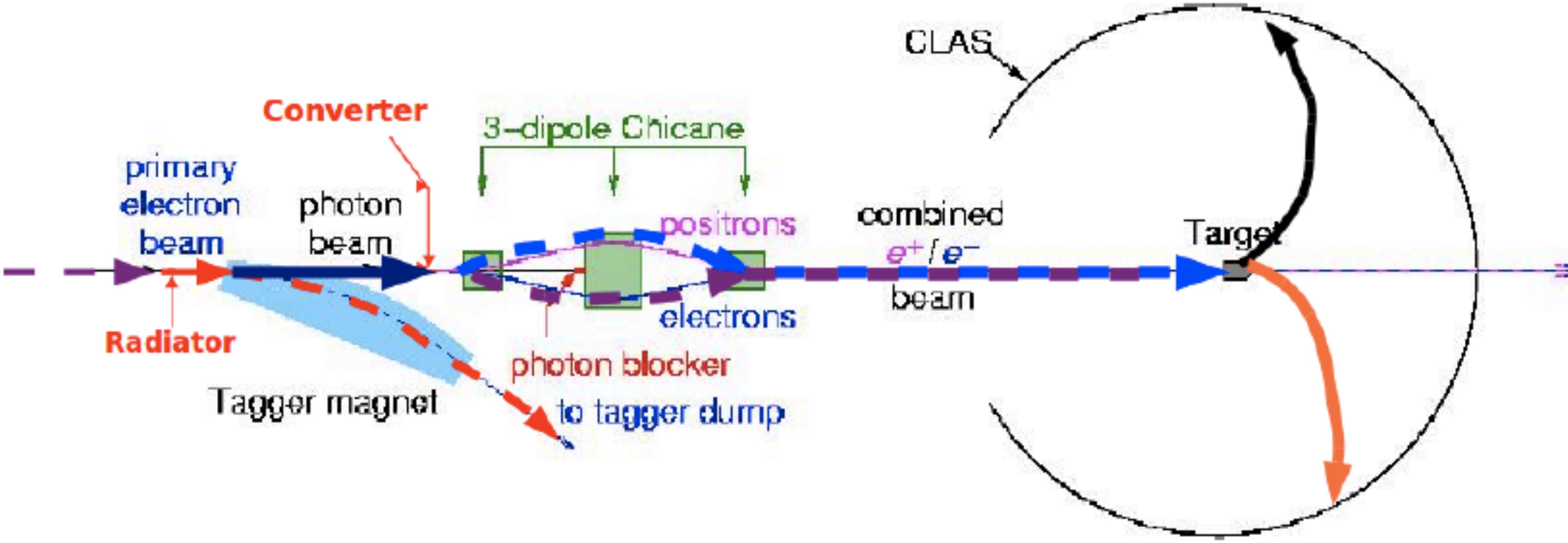
  Ratio just from radiative corrections is 1.08 at large angles

- Larger correction with higher resolution

Two important things to take away:

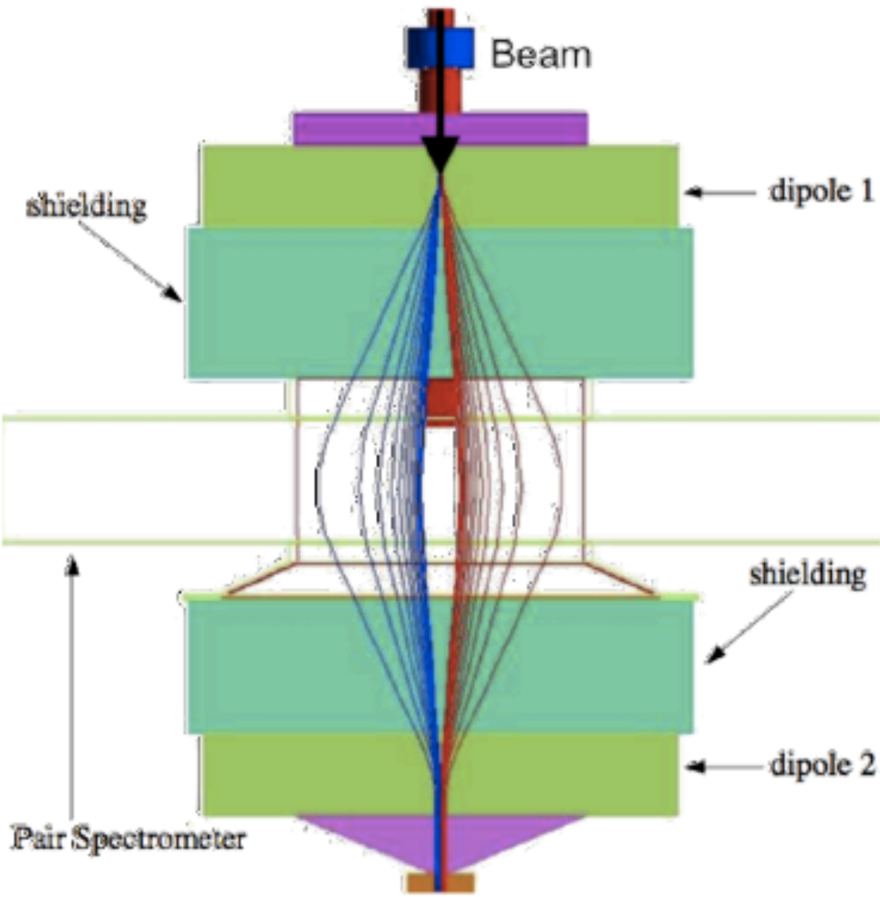
- Radiative corrections will be different for each experiment and can't be easily implemented by third parties
- Radiative corrections for all experiments must be consistent so results are comparable

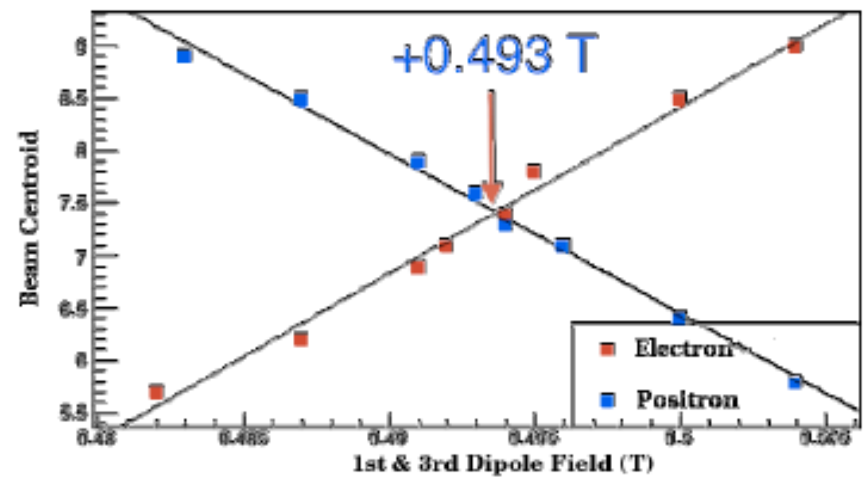
Making Positrons at CLAS

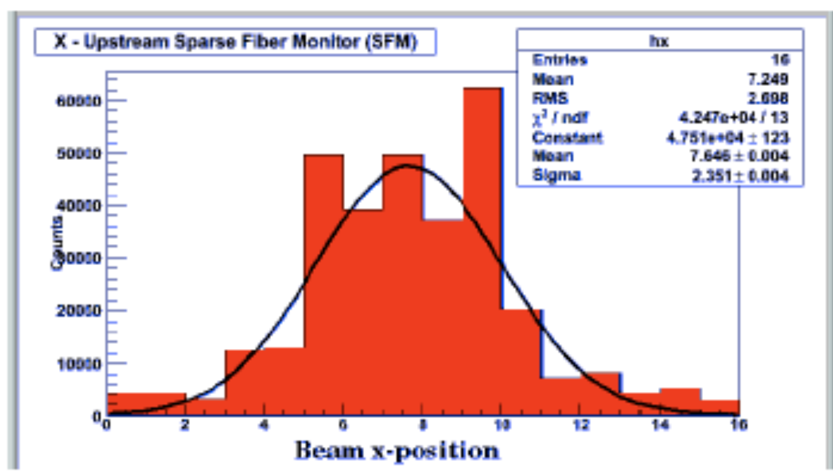


- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 0.9% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 9% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
  - Remaining photons are stopped at the photon blocker
  - e^+ and e^- beams are then recombined and continue to the target
- Target: liquid hydrogen: length = 18cm (30 cm) & diameter = 6cm (6 cm)
- Detector: CLAS (DC, TOF)

Systematic Beam Checks

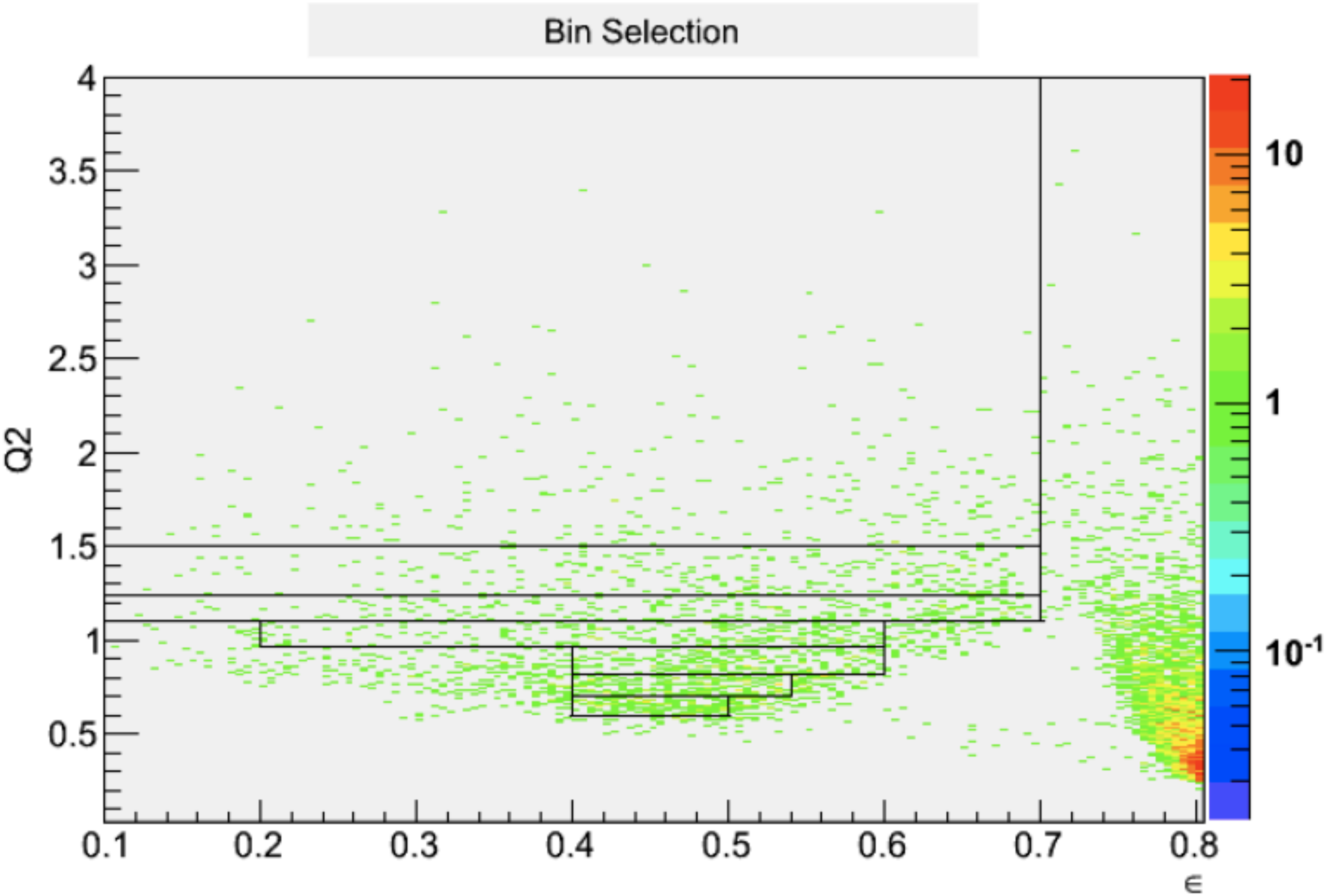




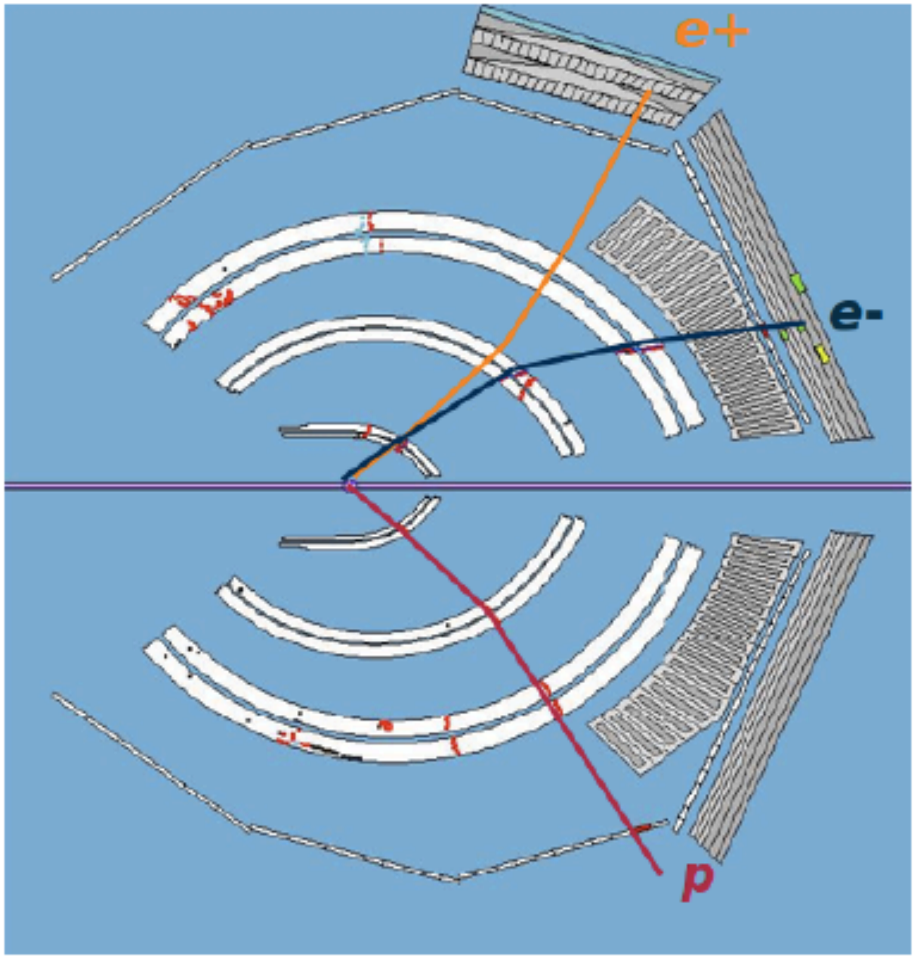


- Flipped chicane polarity about once a week
- Check for geometric alignment of e^-/e^+ on target – Varied steering magnet currents and measured individual beam positions at sparse fiber monitor
- Reproducible crossing for all chicane flips

Low ε Bins



Ratios



1. Apply fiducial cuts to select regions where both e^- and e^+ can both be detected
2. Measure Elastic Scattering Ratio : Proton acceptance cancels in the ratio

$$R = \frac{Y(e^+P)}{Y(e^-P)}$$

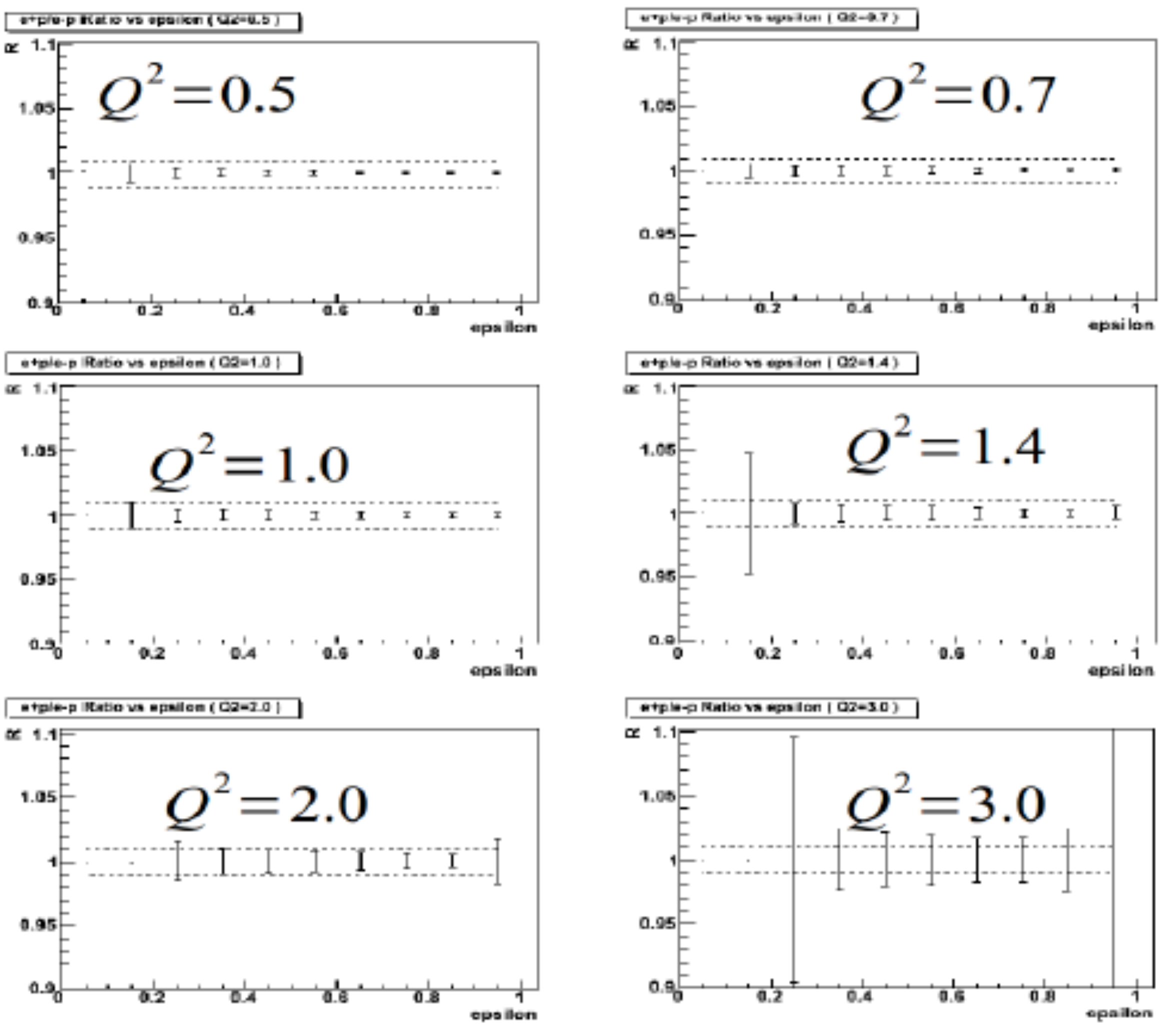
3. Flip torus polarity : Lepton acceptance cancels in double ratio

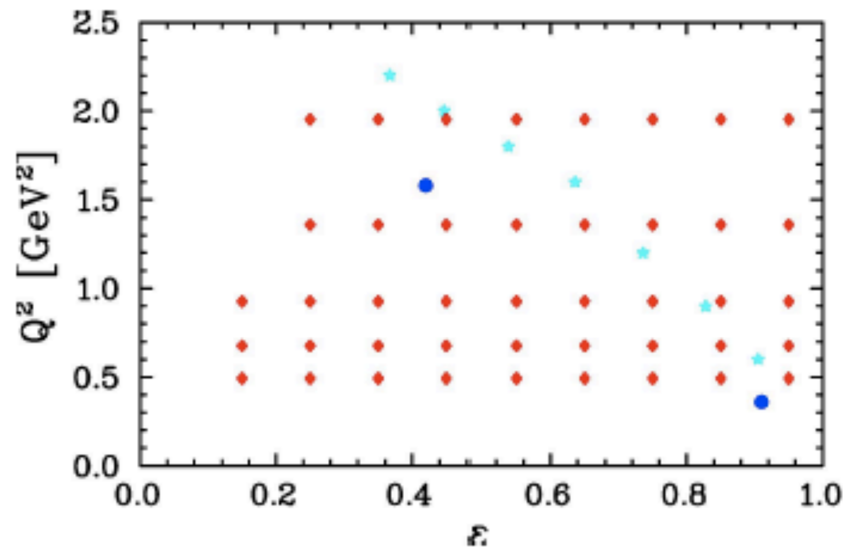
$$R_2 = \sqrt{\left[\frac{Y_{e^+P}}{Y_{e^-P}}\right]^+ \times \left[\frac{Y_{e^+P}}{Y_{e^-P}}\right]^-}$$

4. Flip chicane polarity: Beam asymmetries cancel in quadruple ratio

$$R_4 = \sqrt{R_2^+ \times R_2^-}$$

Projections





- CLAS will map out the TPE effect over large areas of Q^2 and ϵ
- Not the only game in town: Olympus at DESY and VEP-III at Novosibirsk
- CLAS experiment will be able to obtain $< 1\%$ statistical and systematic uncertainties out to $Q^2 = 2GeV^2$

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., PRC71 (2005) 05520
A. Puckett et al., PRL104 (2010) 242301
M. Meziane et al., PRL106 (2011) 132501
A. Puckett et al., PRC85 (2012) 045203

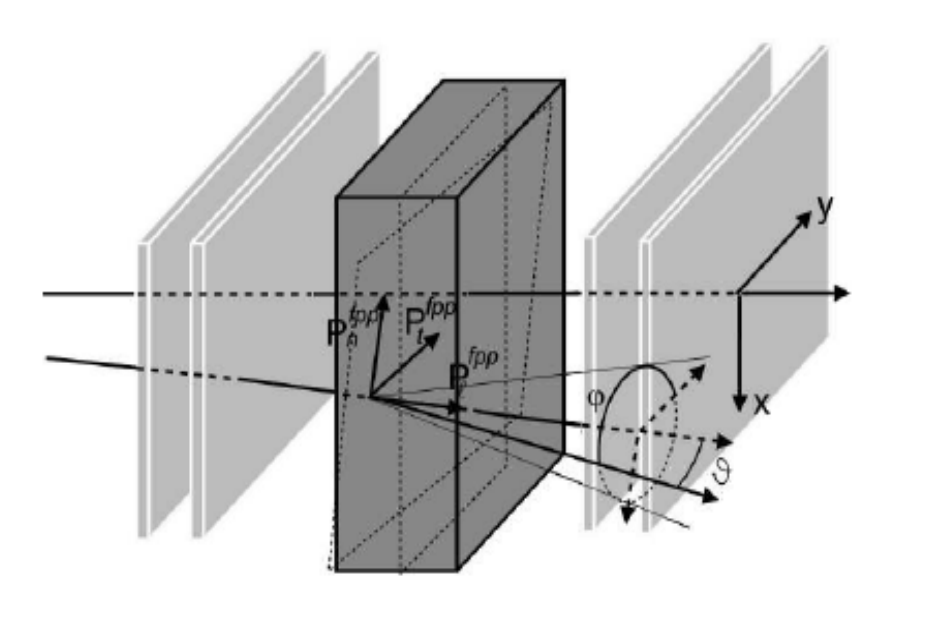


FIG. 9: Schematic of the polarimeter chambers and analyzer, showing a non-central trajectory; ϑ is the polar angle, and φ is the azimuthal angle from the y-direction counterclockwise.

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

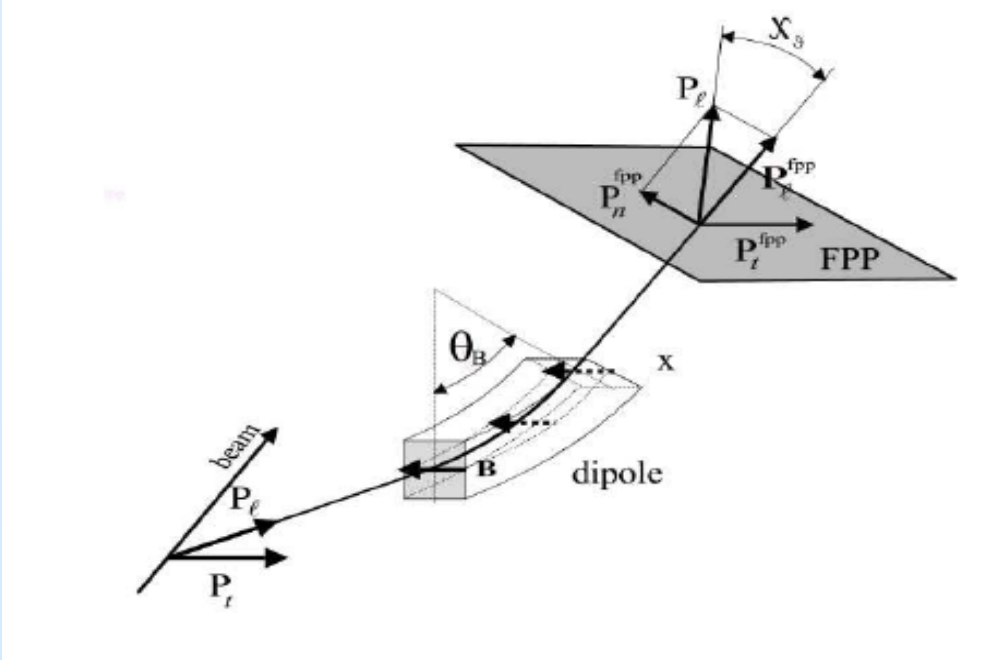
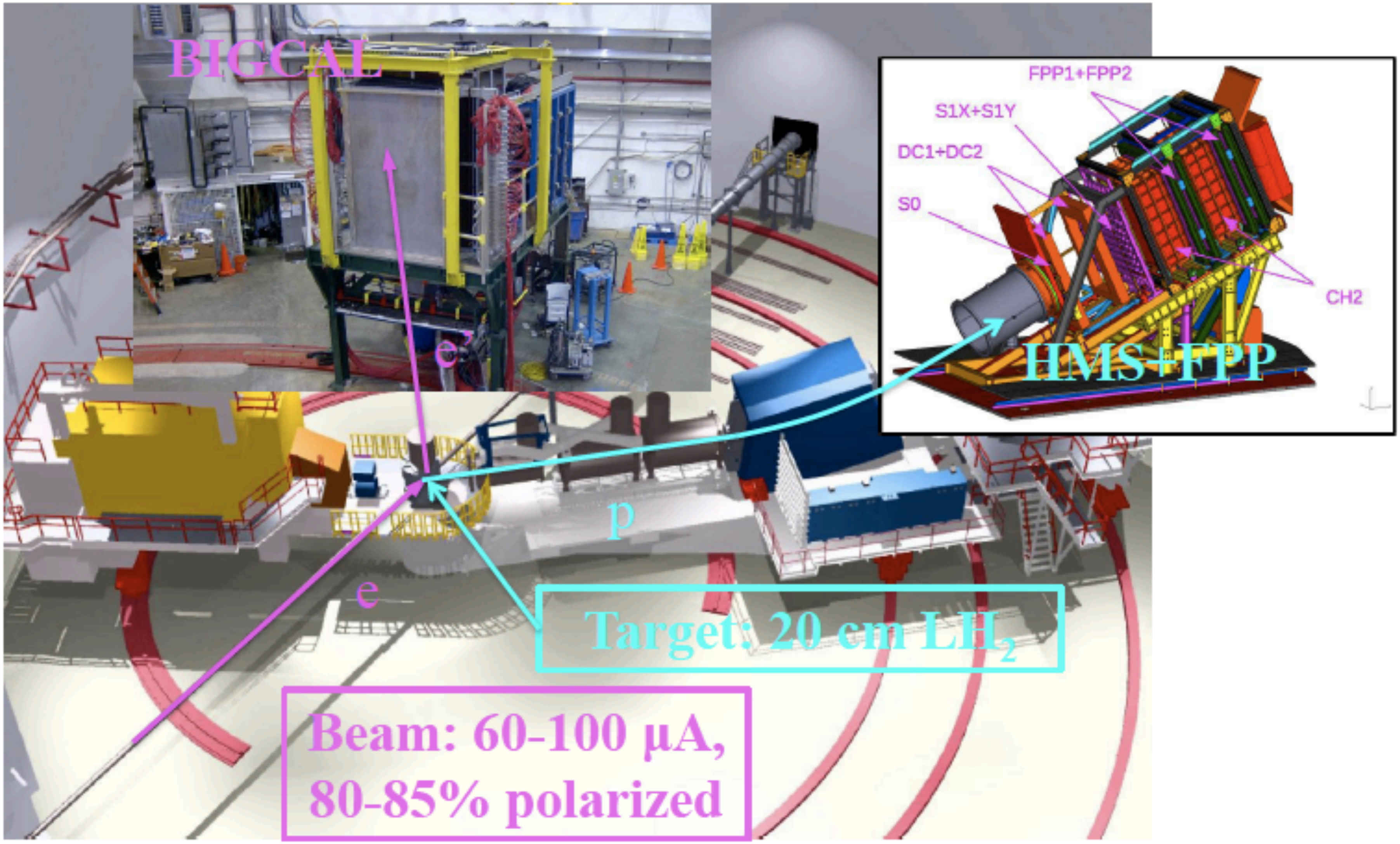


FIG. 15: Schematic drawing showing the precession by angle χ_θ of the P_ℓ component of the polarization in the dipole of the HRS.

Spin transfer formalism to account for spin precession through spectrometer

The GEp-III and GEp-2γ Experiments



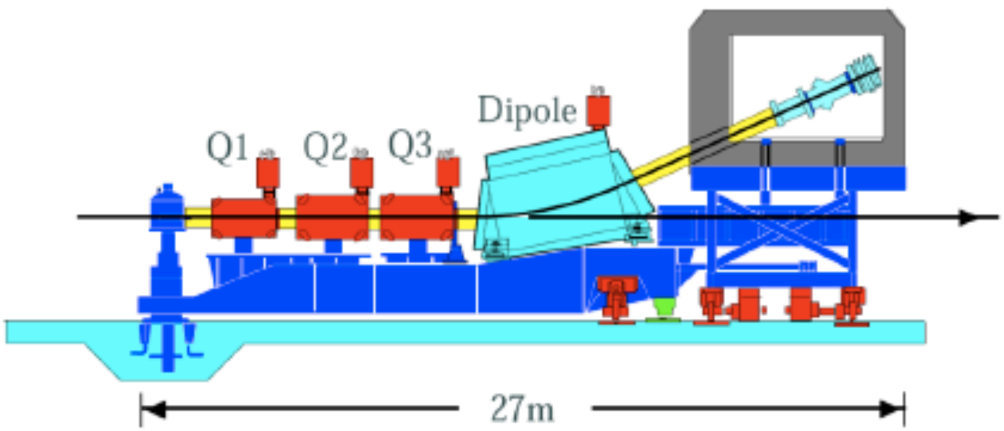
Polarization Transfer in ^{1}H(**e**,e'**p**):
Nominal *ep* luminosity ~4 × 10^{38} Hz/cm^2

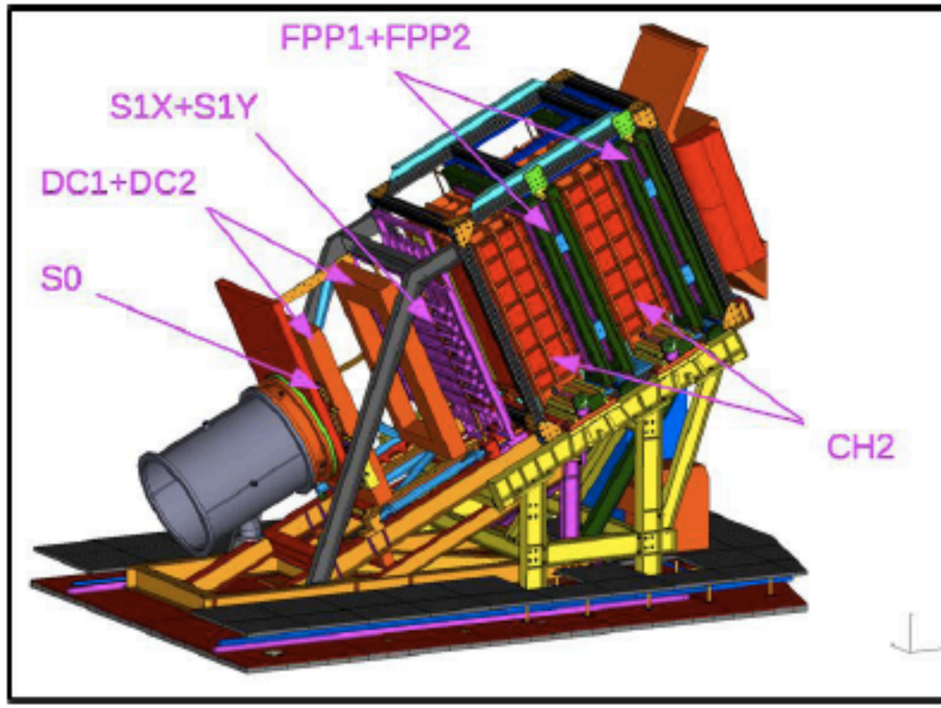
GEp-III/2γ Kinematics

Q^2, GeV^2	ε	E_{beam}, GeV	θ_p, °	p_p, GeV	E_e, GeV	θ_e,°
2.5	0.154	1.873	14.495	2.0676	0.532	105.2
2.5	0.633	2.847	30.985	2.0676	1.51	44.9
2.5	0.789	3.680	36.10	2.0676	2.37	30.8
5.2	0.377	4.053	17.94	3.5887	1.27	60.3
6.8	0.507	5.714	19.10	4.4644	2.10	44.2
8.5	0.236	5.714	11.6	5.407	1.16	69.0

- GEp-2γ: High-precision measurements of ε-dependence of PT ratio at $Q^2 = 2.5$ GeV^2
- GEp-III: Three new measurements at high Q^2
- Collected data from Oct. 2007-June 2008 in Hall C at JLab.

High Momentum Spectrometer (HMS)





- QQQD superconducting, 25° vertical bend magnetic spectrometer
- Acceptance:
  - 6.74 msr solid angle (~2:1 vertical/horizontal aspect ratio)
  - ±9% momentum bite
  - ±5 cm/sin ϑ extended target acceptance
- Resolution:
  - $\delta p/p \sim 0.1\%$
  - Angular resolution ~1 mrad
  - Vertex resolution ~2 mm

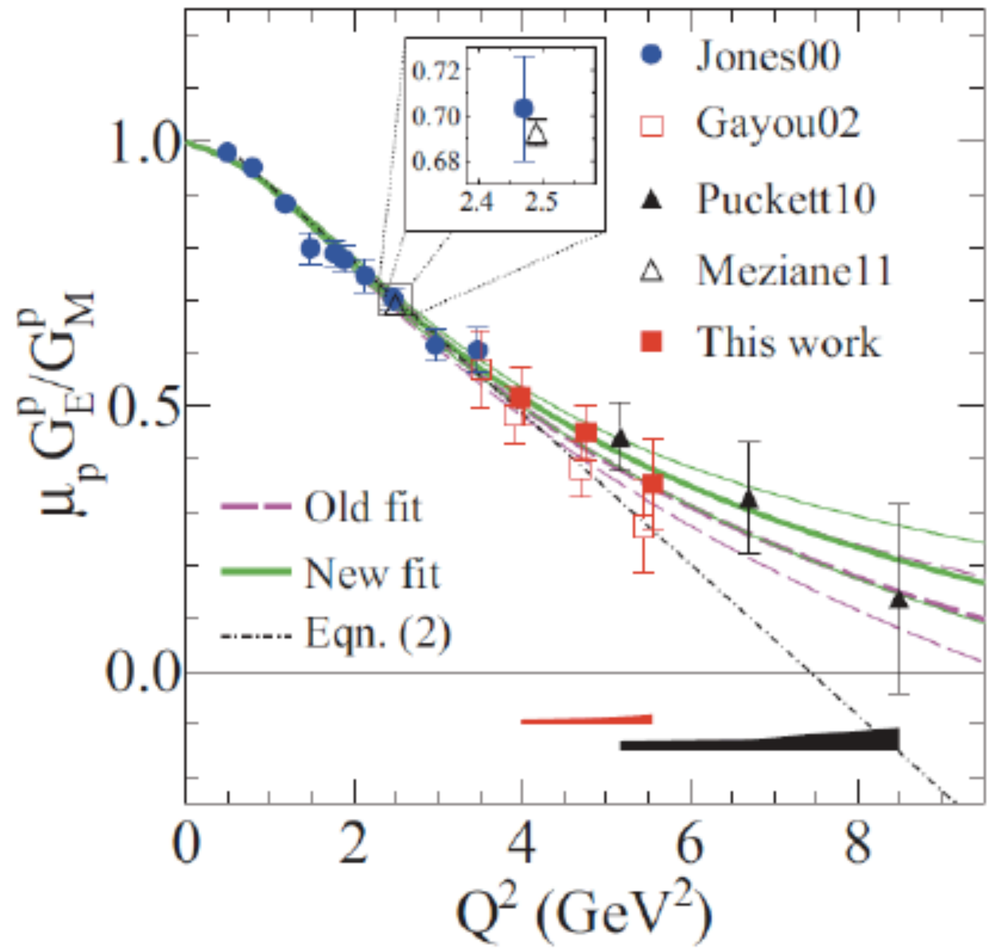
Detector package for GEp-III

- Drift chambers: track scattered protons for kinematics reconstruction and incident FPP track definition
- Scintillator hodoscopes: trigger and timing (resolution ~250 ps)
- FPP: measure proton polarization

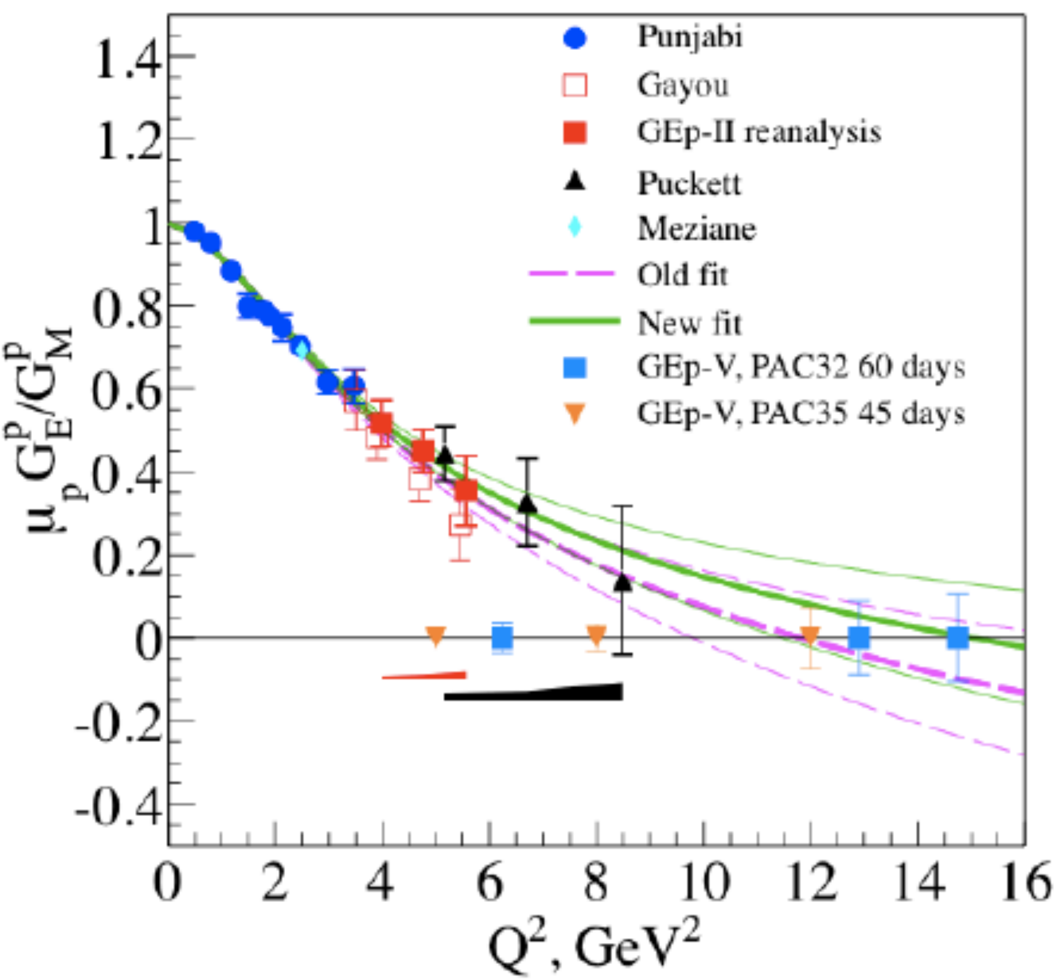
Final Results of GEp-II

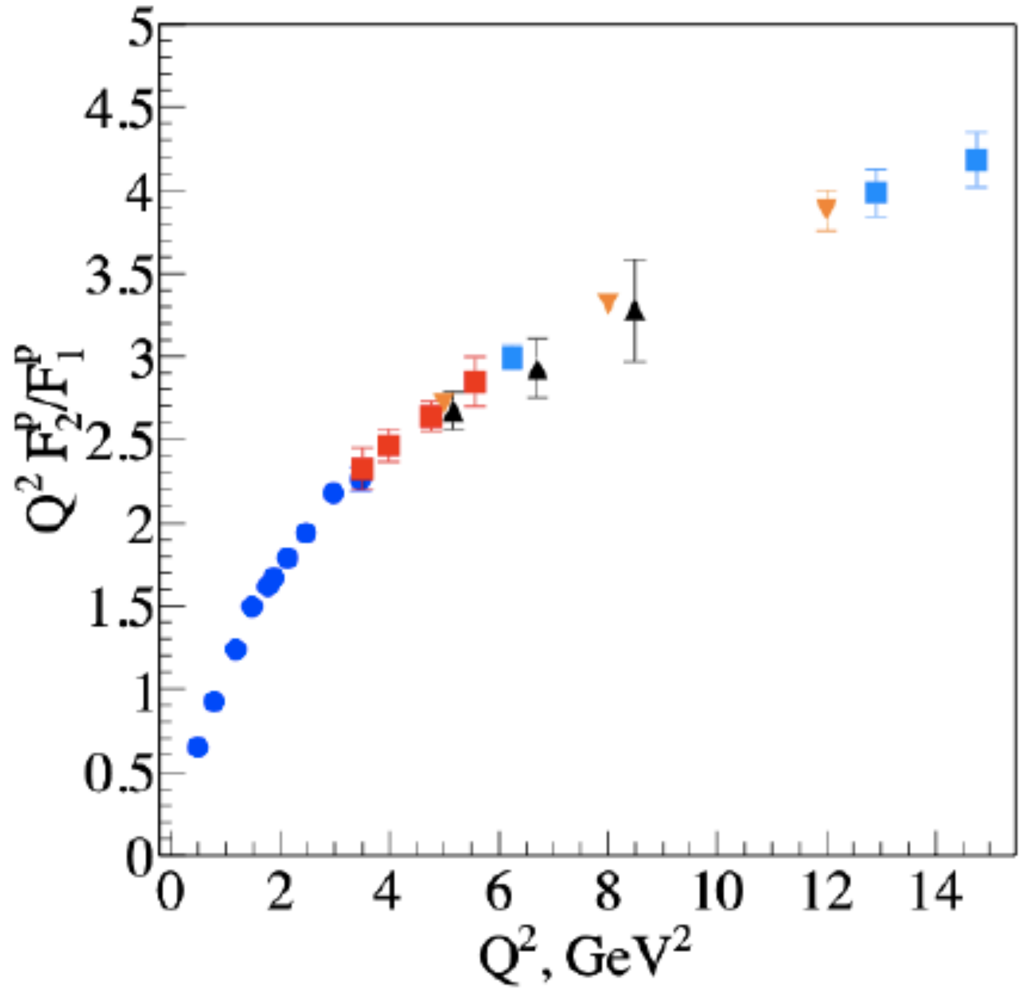
Summary of results

- Reanalyzed three highest-Q^2 points (electron detected in calorimeter)
- Lowest $Q^2 = 3.5$ GeV^2 not reanalyzed (electron detected in HRSR).
- Three highest-Q^2 R values systematically increase, by several times the originally quoted systematics.
- ***Increase mainly due to previously underestimated background***
- Addition of $p(\theta) - p$ cut suppresses background to <0.4%, remaining correction and uncertainty small
- Consistency of GEp-I/II/III/2γ data (Hall A vs. Hall C) is now excellent in a wide Q^2 range
- ***Updated analysis and results now published in Phys. Rev. C, PRC 85, 085, 045203***



Projected Results Approved by JLab PAC





Projected results as $\mu G_E/G_M$

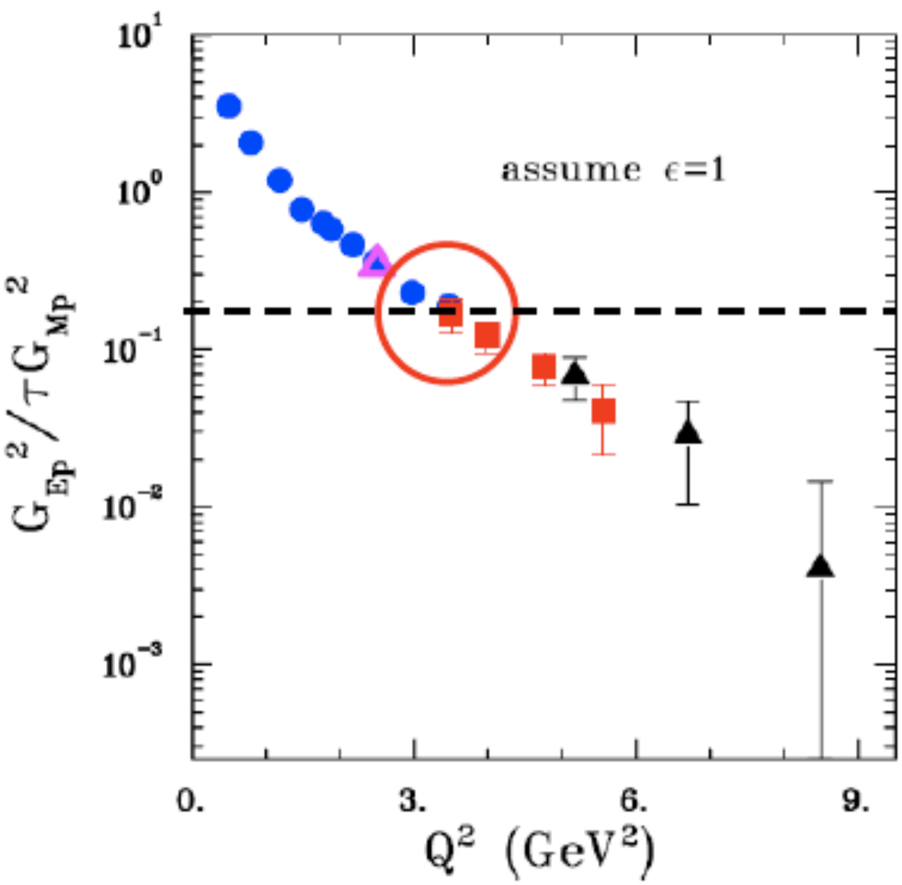
Projected results as $Q^2\ F_2/F_1$

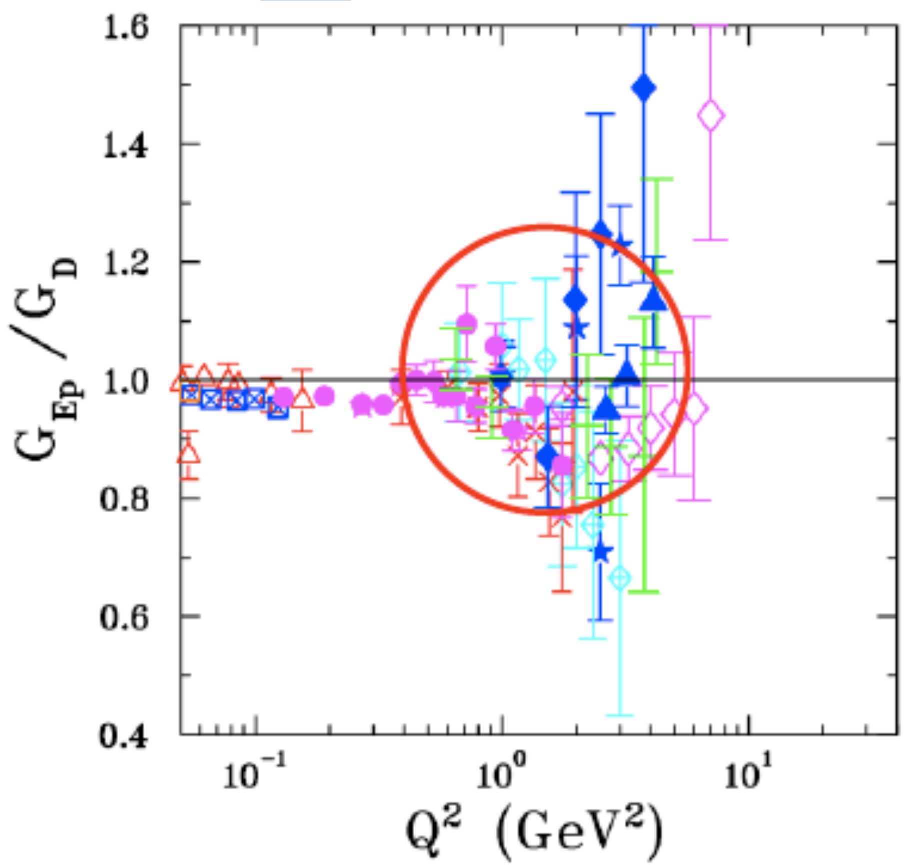
Additional measurements at CLAS12 with HD-Ice for Q2 ~ 2-14 (GeV/c)^2

The relative contribution of G_{Ep} to the cross section becomes of order of the experimental uncertainty (10-20%) by $Q^2 \approx 3.5$ GeV². Which is where the LT data for G_{Ep} seem to loose track of G_{Ep}! Coincidence?

C. Perdrisat

$$\frac{d\sigma}{d\Omega} \approx \frac{\tau G_M^2}{\varepsilon(1+\tau)} \left[1 + \frac{\varepsilon}{\tau} \frac{G_E^2}{G_M^2}\right]$$





In Fact…

If G_{Ep} approaches zero, or the error bar on the cross section becomes large, then G_{Ep}/G_D becomes 1, (to the extend that GM≈GD).

Hence the behavior of the G_{Ep}/G_D ratio obtained from cross section measurements does not necessarily imply inaccurate or incomplete radiative corrections, in particular does not *a priori* require a significant two-photon contribution.

Never-the-less, of course relevant data will provide the final answer, as to whether two-photon exchange is an important effect in proton form factor measurements.

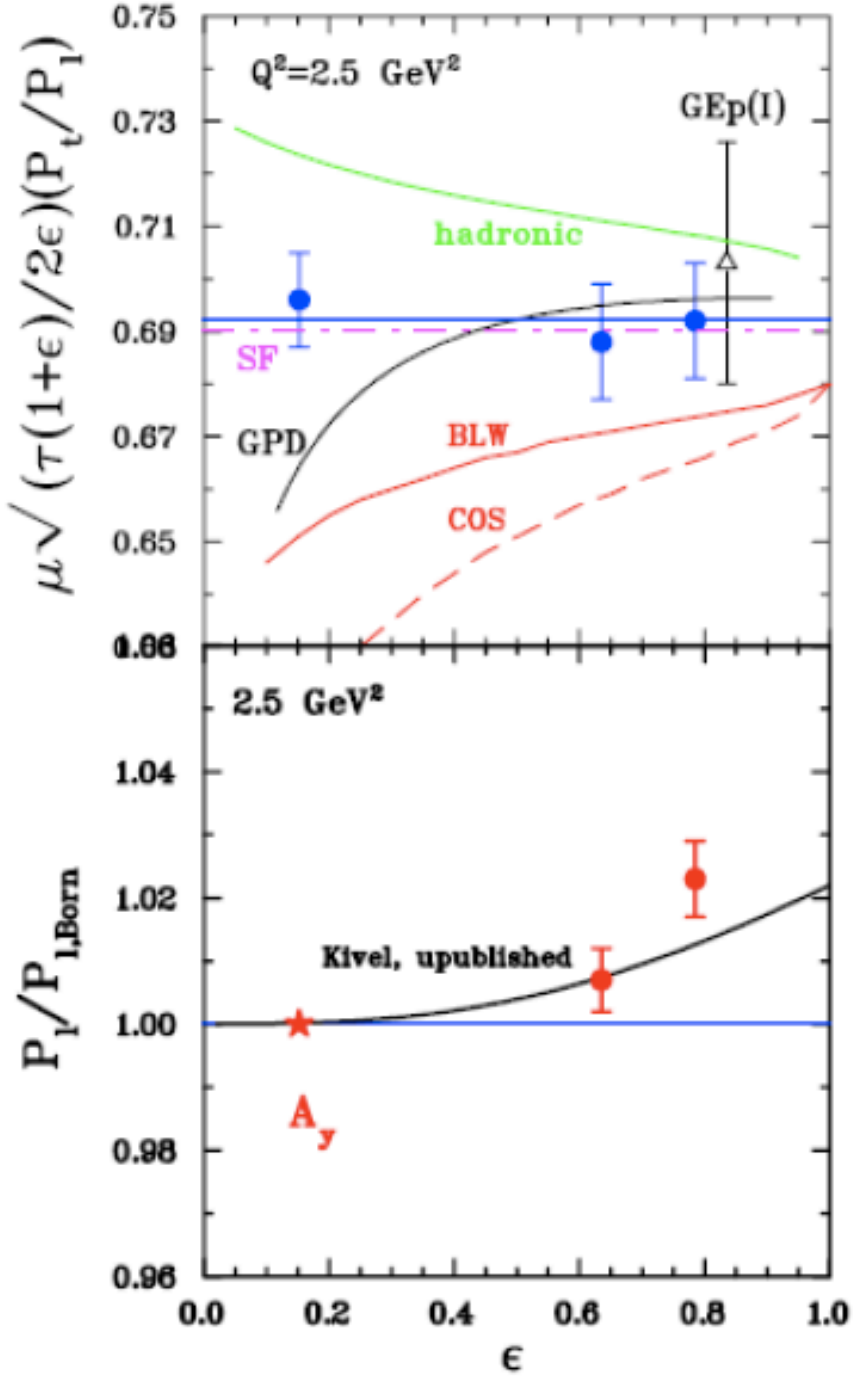
Currently a large effort is being invested in direct detection of two-photon effects from the ratio $d\sigma^+/d\,\sigma^-$.

Double-polarization Jlab 2-gamma expt.

Measured G_{Ep}/G_{Mp} at Q^2=2.5 GeV2
3 values of ε, unprecedentedly small error bars. $R=\mu\sqrt{[\tau(1+\varepsilon)/2\varepsilon]}(P_t/P_\ell)$.

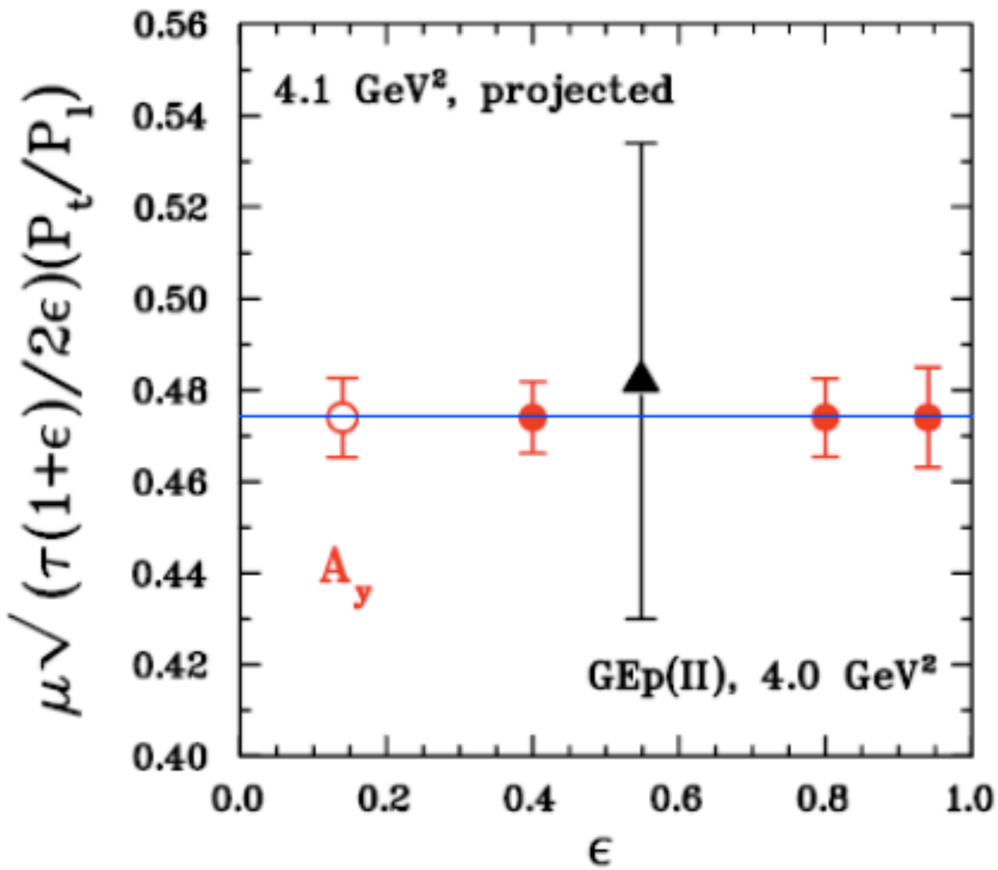
Obtained P_ℓ for two values of ε, the third being used to determine the analyzing power.
Data published:
M. Meziane et al.
PRL 106, 132501 (2011)
COZ BLW nuclear distribution amplitudes: Kivel and Vanderhaeghen
GPD Afanasev et al.
Hadronic Blunden et al.
SF Bystritskiy et al, shifted down.

Soft-colinear effective field theory: Kivel, unpub. 2012



A second two-gamma experiment at Jlab 12 GeV?

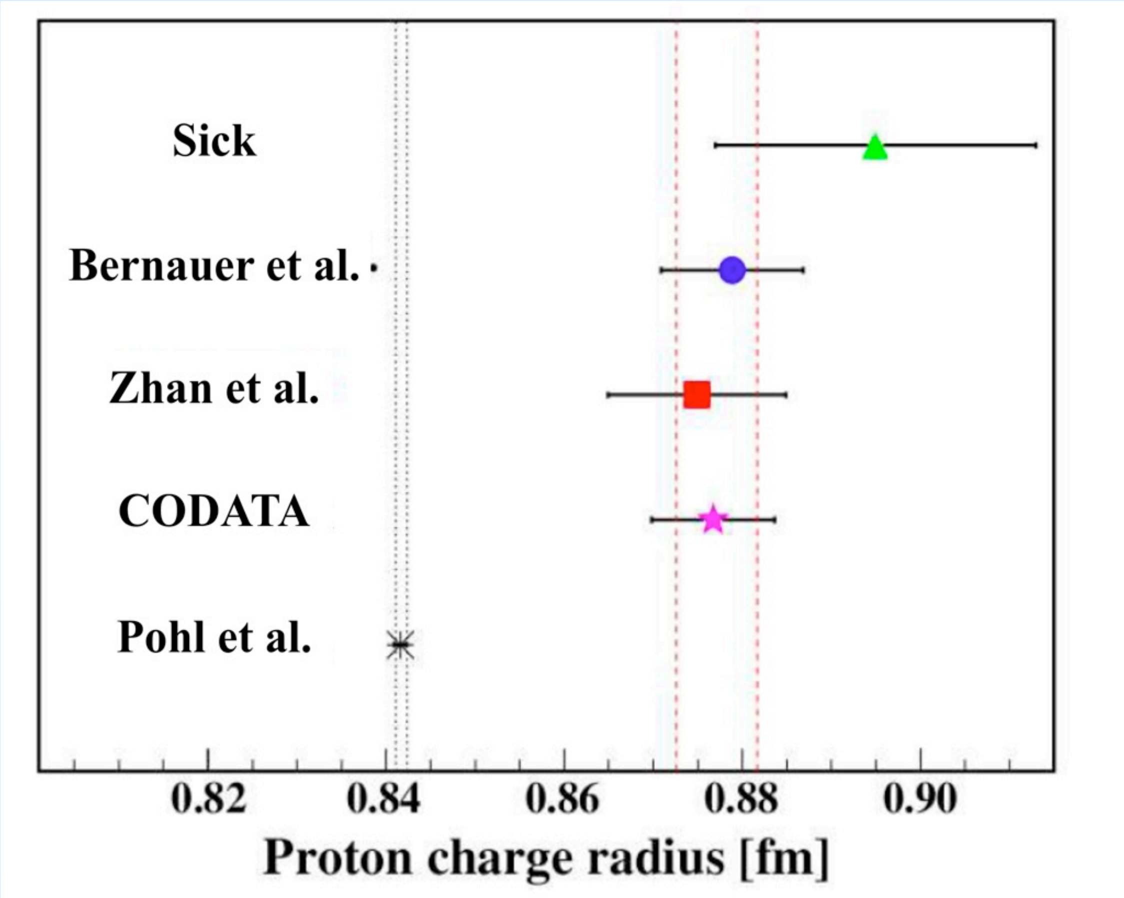
Choose 4.1 GeV^2 because 0.01 statistics possible in 10 days per point.



Cross section with small uncertainty at 4.1 GeV^2 available: I.A. Qattan et al, PRL 94 (2005), 142301.

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	$\langle r_E \rangle^2$ (fm)
1	Sick	0.895±0.018
2	Bernauer Mainz	0.879±0.008
3	Zhan JLab	0.870±0.010
4	CODATA	0.877±0.007
5	Combined 2-4	0.876±0.005
6	Muonic Hydrogen	0.842±0.001

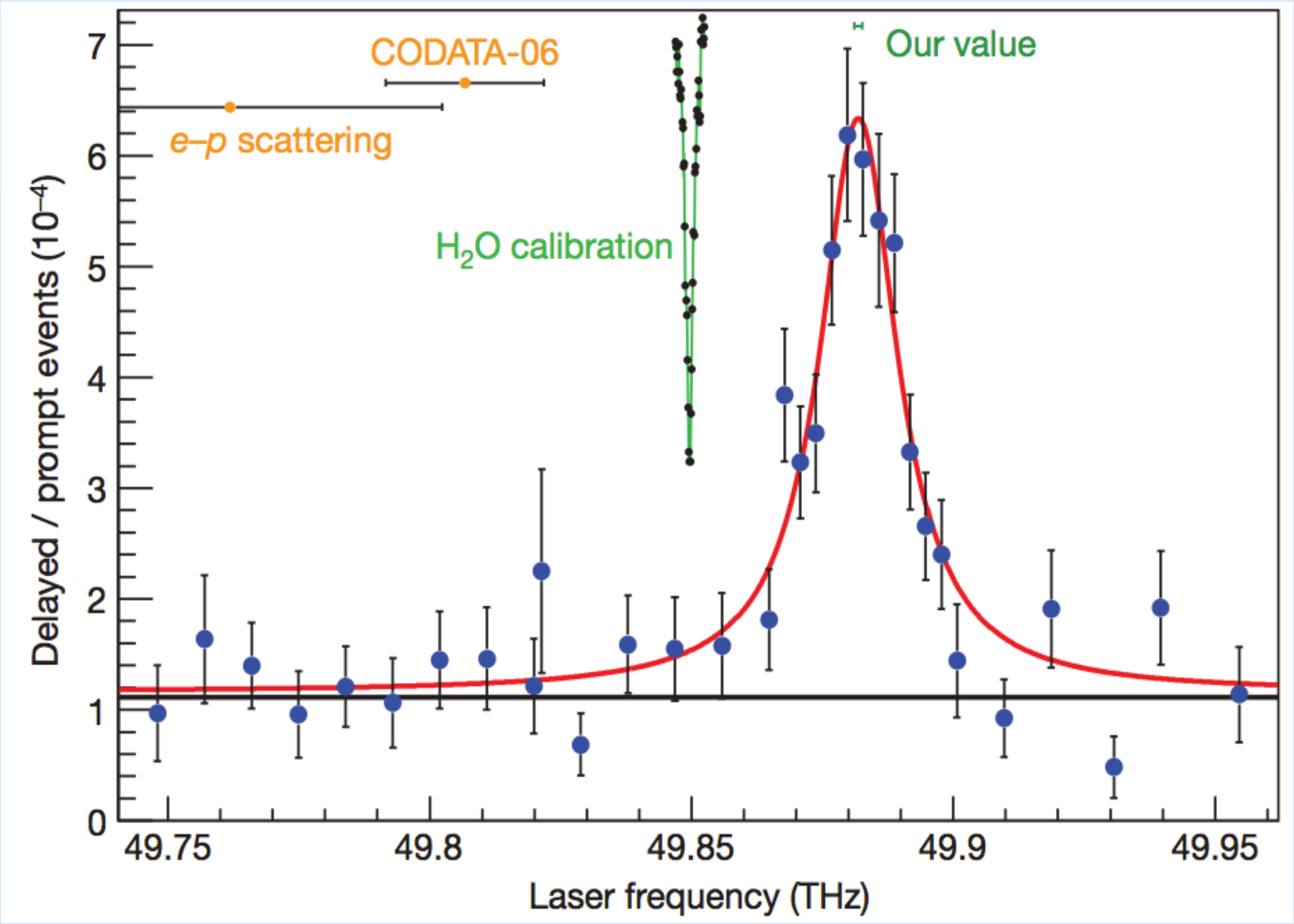
PSI muonic hydrogen measurements

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

ΔE (meV) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3

⇨ r_p = 0.842 ± 0.001.

Possible issues: atomic theory & proton structure



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
  Existing constraints on new physics

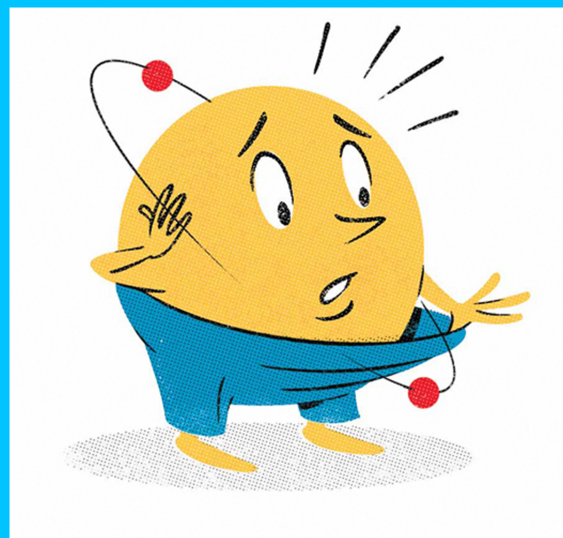
More insights from comparison of ep and μp scattering

Motivation for µp scattering

Electronic hydrogen

Muonic hydrogen

Lamb shift



Electron scattering

Elastic scattering

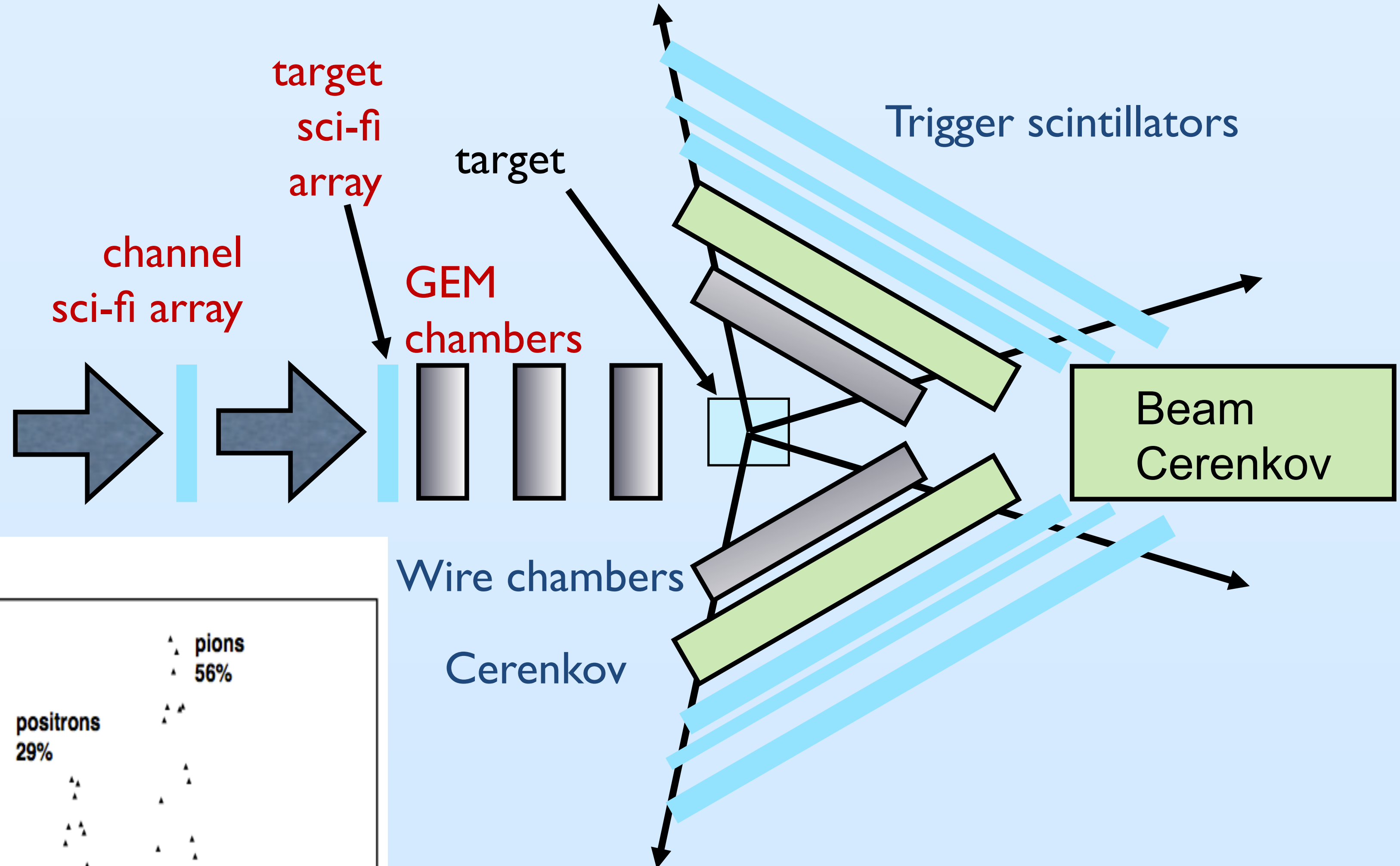
Muon scattering

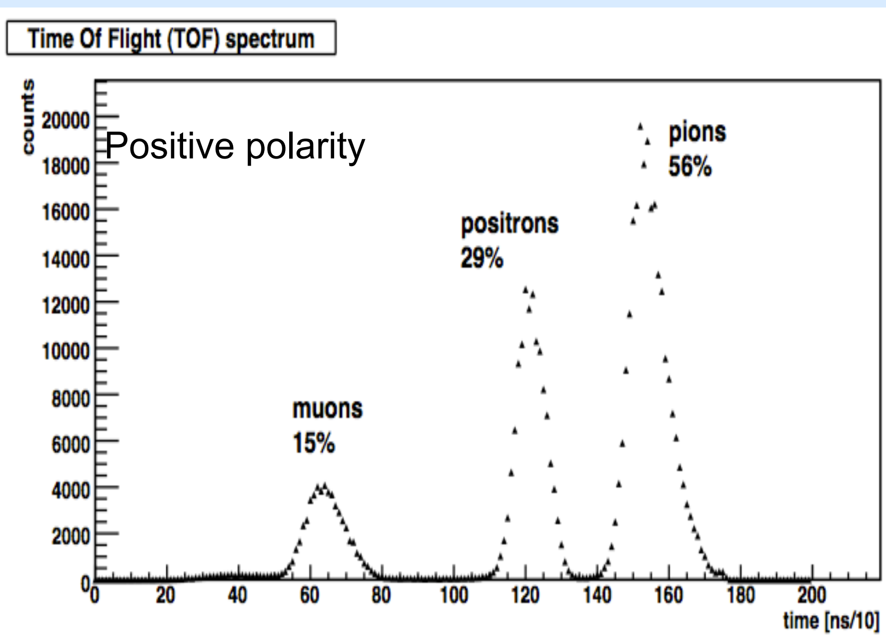
Proposal for $\mu^{\pm}p/e^{\pm}p$ scattering at PSI

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

- Measure absolute cross section for μp scattering and cross section ratios to other species
- Simultaneously measure ep scattering
  → μ/e ratio to cancel certain systematics
  → If radii differ by 4%, form factor slope differs by 8%, and cross section slope differs by 16%
- Measure e+, e- and μ+, μ- on target
  → Directly extract information on two-photon exchange (TPE) effect and compare for e, μ
- Use multiple beam energies
  → separate G_E and G_M with the Rosenbluth method

Schematic layout



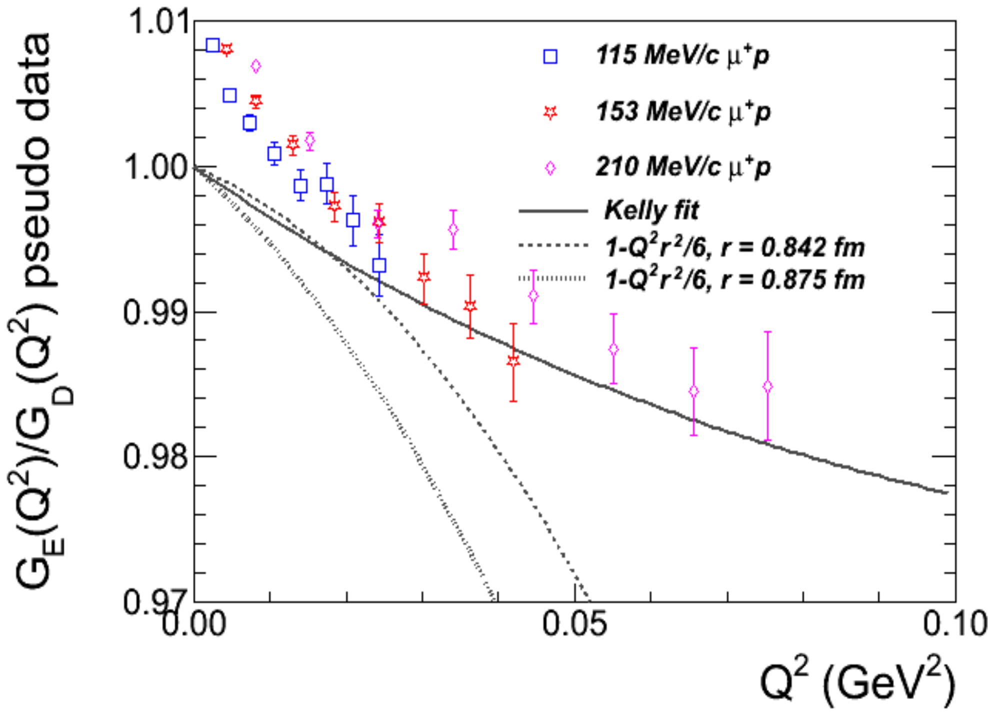


Momentum acceptance: 3%, resolution: 0.1%

Beam spot (nominal): 1.5 cm X x 1 cm Y
35 mr X' x 75 mr Y'

Projected sensitivity

Pseudo-random data with errors:



→ 30 days of running at each energy
→ sub 1% statistical uncertainty (μ^+p)
→ slightly worse for μ^-p, but sufficient for comparison of TPE

Estimate of systematic uncertainties for μ^+p:

Systematic Uncertainty	Absolute (%)	Point-to-point (%)
$x\rho_{target}$	1.0	-
Beam flux (π / μ / e misidentification)	small	-
Radiative correction	0.3	0.1
Solid angle	0.2	0.2
Efficiencies - triggering, analysis, etc.	0.5	0.1
Beam energy	0.2	0.1
Averaging over beam energies	small	small
Knowledge of angle	0.45	0.3
Averaging over angles / multiple scattering	0.2	0.2
Cell wall subtraction	small	small
Cosmic ray subtraction	small	small
π / μ decay corrections	small	small
TOTAL	1.3	0.5

$\Delta r \approx 0.01$ fm for μ^+, $e^\pm$,
but about 0.015 fm for μ^-

Systematics: ~1.3% absolute precision, 0.5% pt-to-pt

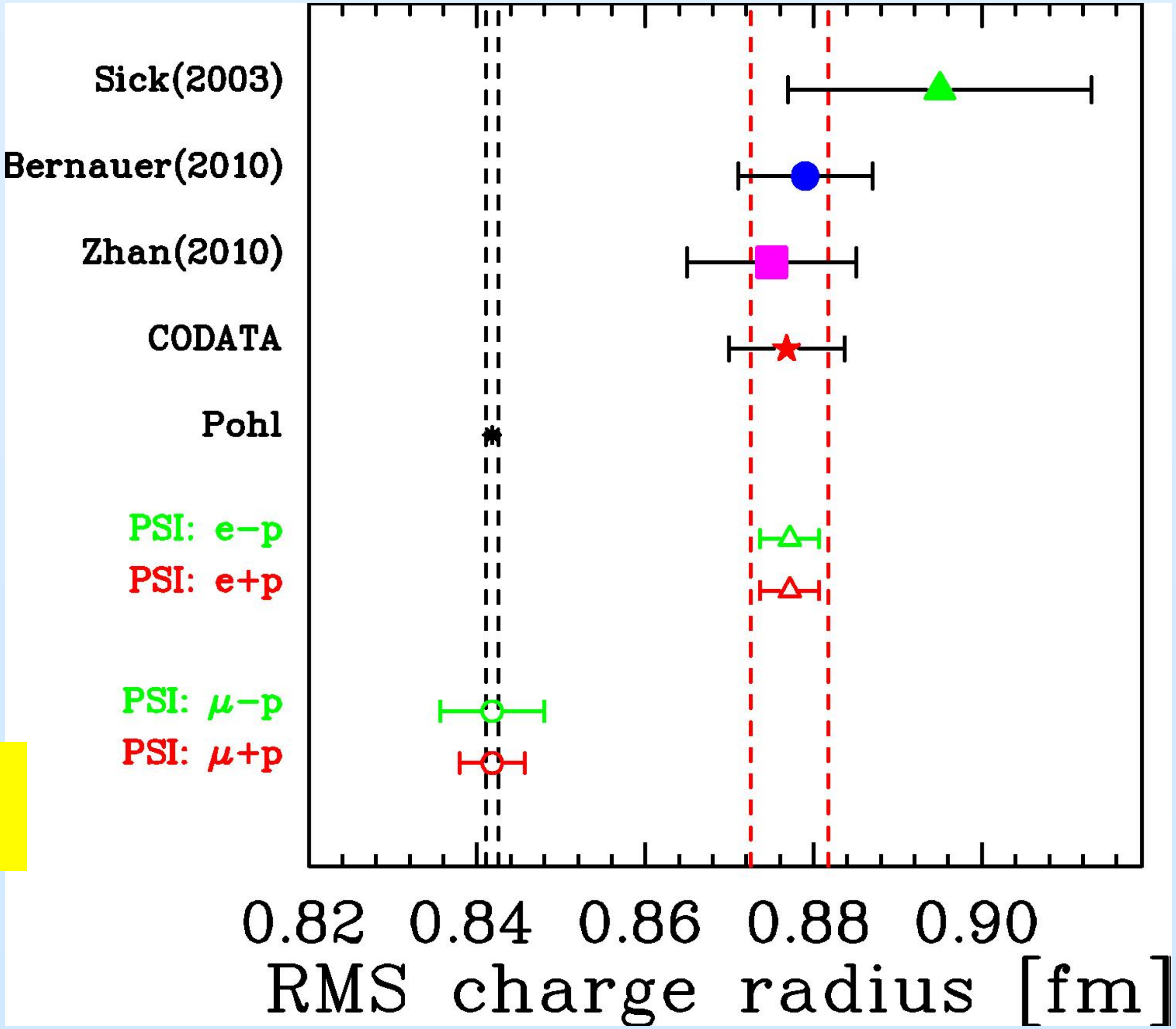
Projected sensitivity

Charge radius extraction limited by systematics, fit uncertainties

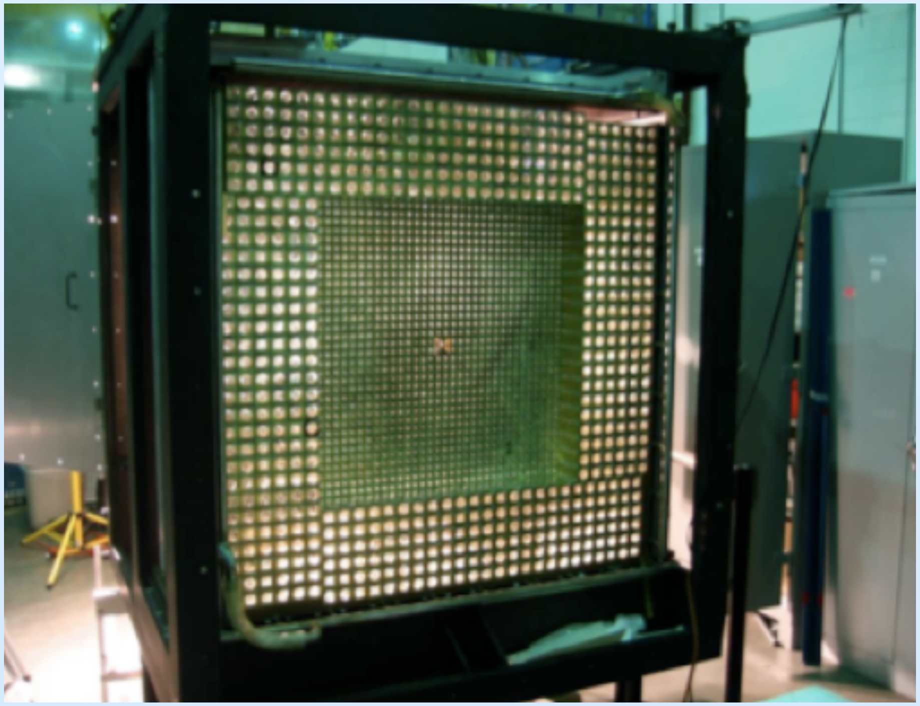
Comparable to existing e-p extractions, but not better

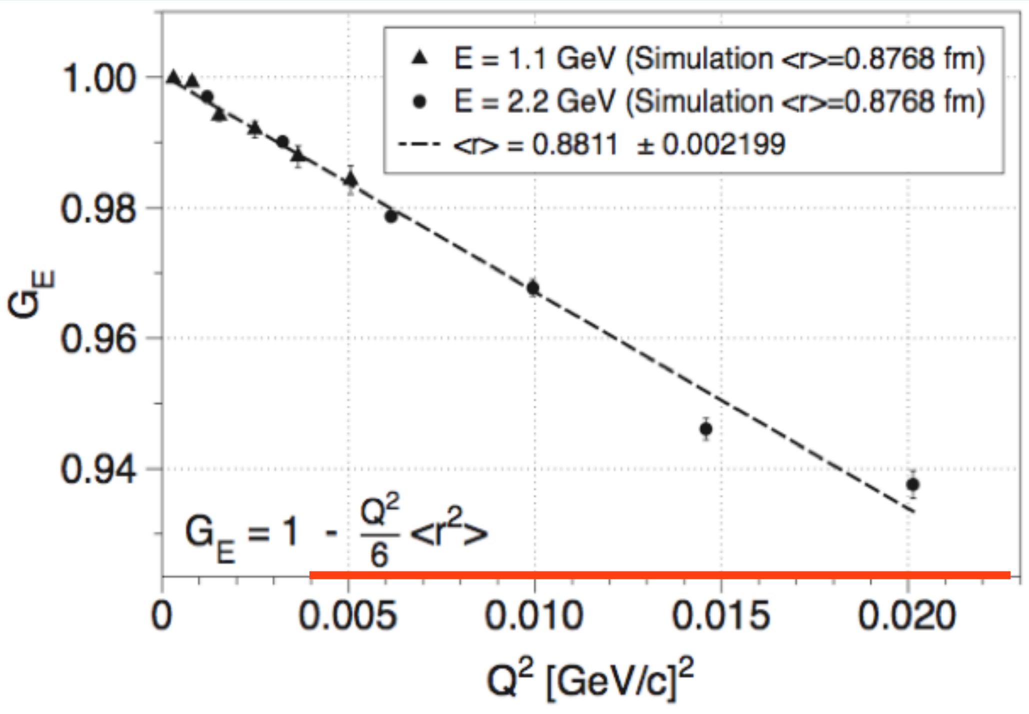
Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, μ+/μ-, and μ/e comparisons

Relative comparison reduces errors by factor of 2



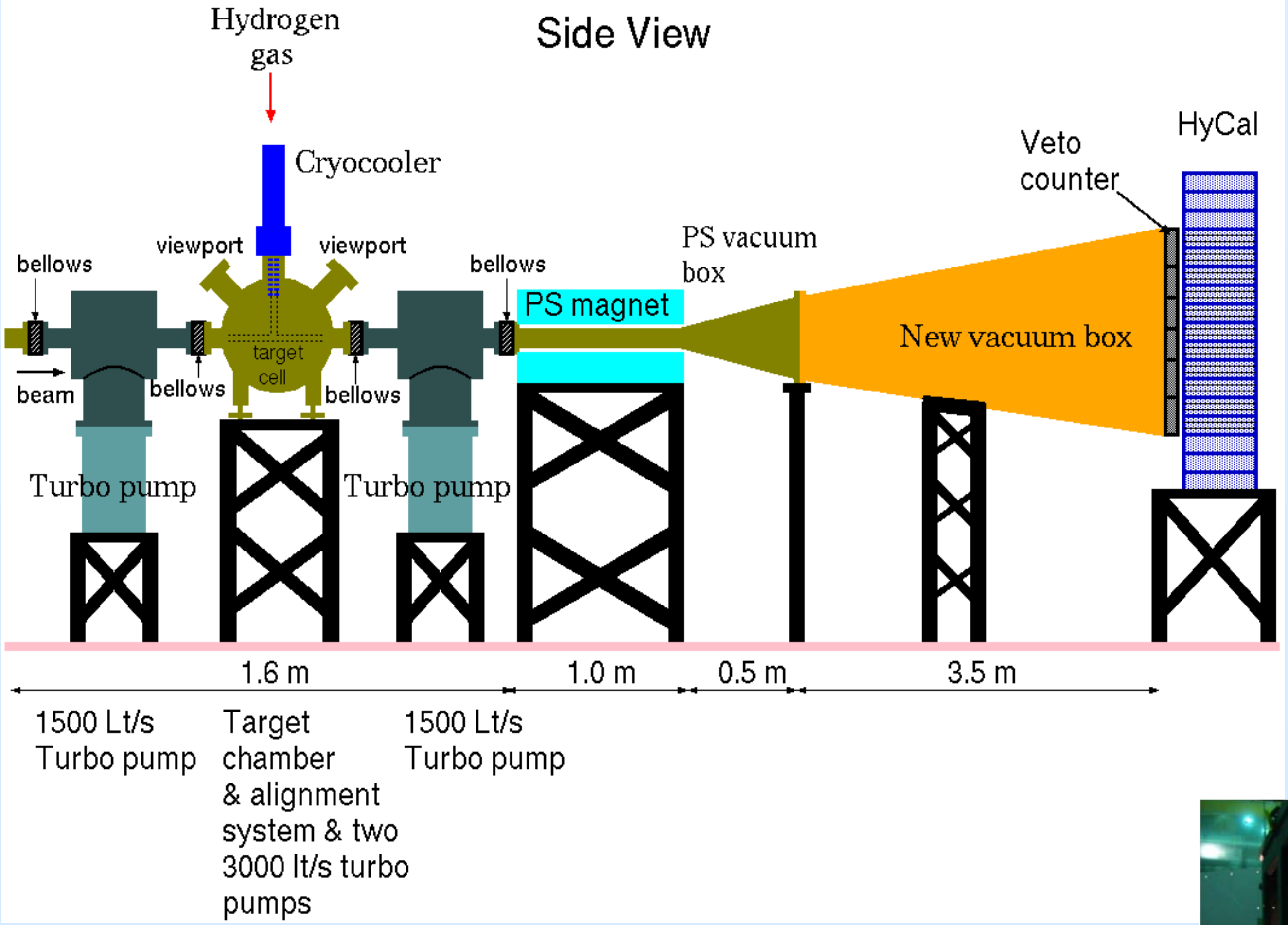
The “PrimEx” proton radius proposal





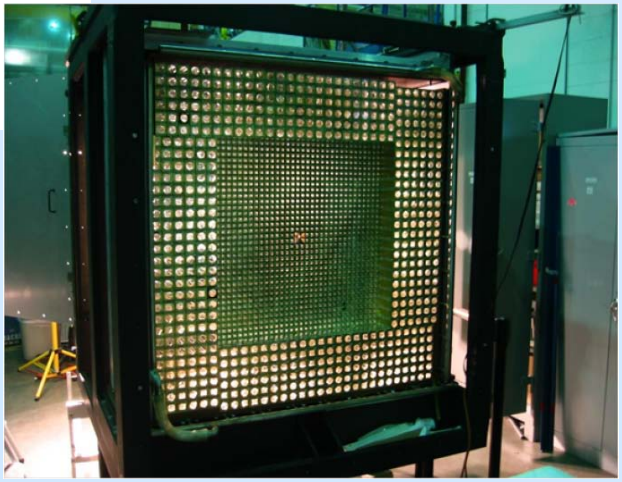
- Low intensity beam in Hall B @ Jlab into windowless gas target.
- Scattered ep and Moller electrons into HYCAL at 0º.
- Lower Q^2 than Mainz. Very forward angle, insensitive to 2γ, G_M.
- Conditionally approved by PAC38 (Aug 2011): ``Testing of this result is among the most timely and important measurements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

Proposed Experimental Setup in Hall B



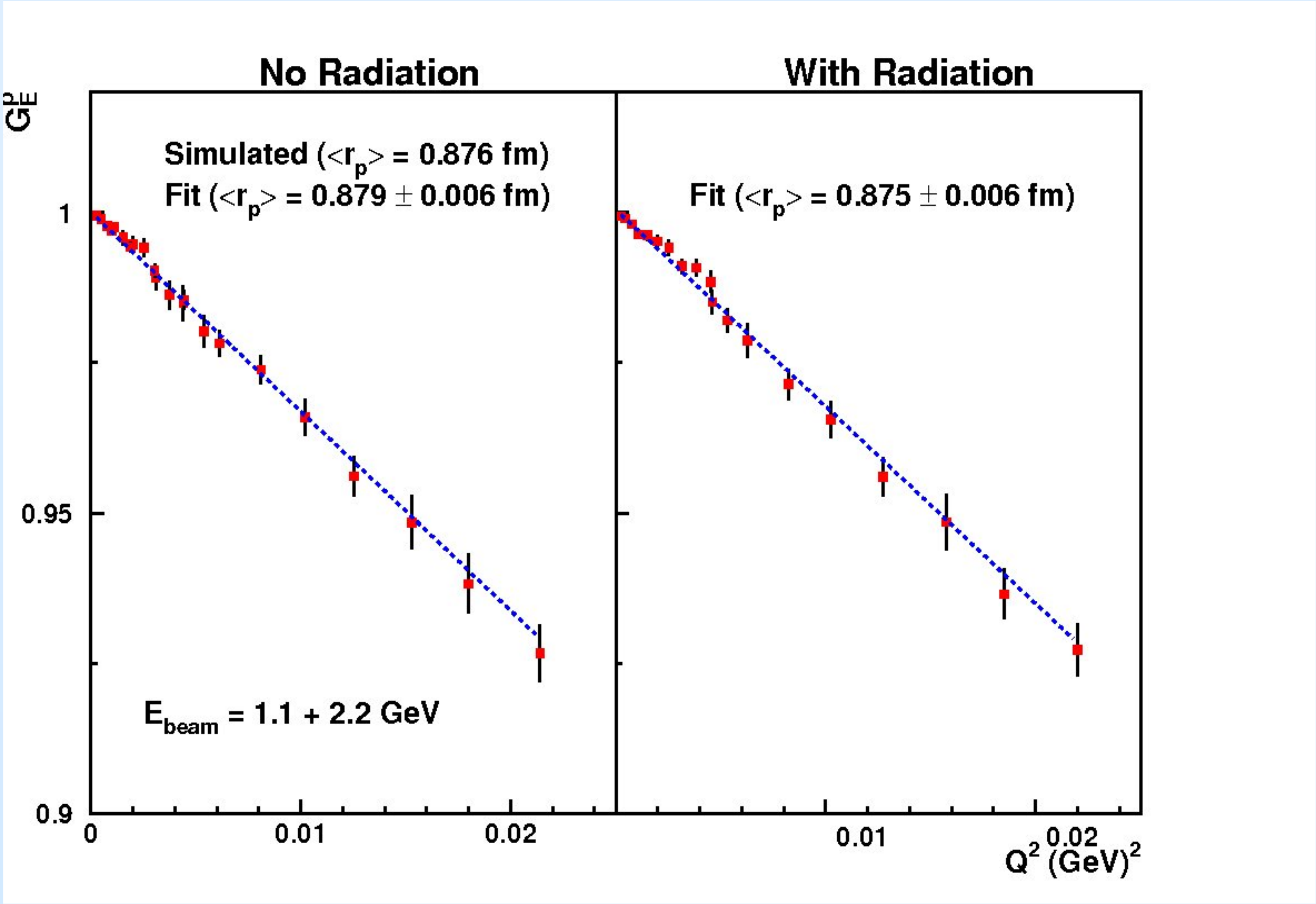
Ashot Gasparian

- High resolution, large acceptance HyCal calorimeter ($PbWO_4$ part only)
- Windowless H_2 gas flow target
- XY – veto counters
- Vacuum box, one thin window at HyCal only



HyCal

Extraction of Proton Charge Radius



- Extraction of r_p from MC simulations with and without radiation
- Estimated systematic uncertainty < 0.3%

Beam Time Request and Error Budget

- target thickness: N_{tgt} = 1x10^{18} H atoms/cm^2
  I_e : ~10nA ($N_e = 6.25 \times 10^{10}$ e^-/s)

- for E_0= 1.1 GeV, Total rate for *ep* → *ep*
  $N_{ep} = N_e \times N_{tgt} \times \Delta\sigma \times \varepsilon_{geom} \times \varepsilon_{det}$
  ≈ 150 events/s ≈ 12.8 M events/day

Rates are high, however, for 0.5% stat. error for the last Q^2= 5x10^{-3} (GeV/c)^2 bin, 2 days are needed

	Time (days)
Setup checkout, calibration	3.5
H_2 gas target commission	5
Statistics at 1.1 GeV	2
Energy change	0.5
Statistics at 2.2 GeV	2
Empty target runs	2
Total	15

- Beam time

Contributions	Estimated Error (%)
Statistical error	0.2
Acceptance (including Q^2 determination)	0.4
Detection efficiency	0.1
Radiative corrections	0.3
Background and PID	0.1
Fitting error	0.2
Total Systematics	0.6%

- Estimated error budget (added quadratically)

Summary

- A novel experiment for the proton size measurement with an independent method is required to address the current "proton charge radius crisis". Jlab is in a position to make a long lasting impact on this important quantity in a timely and unique way

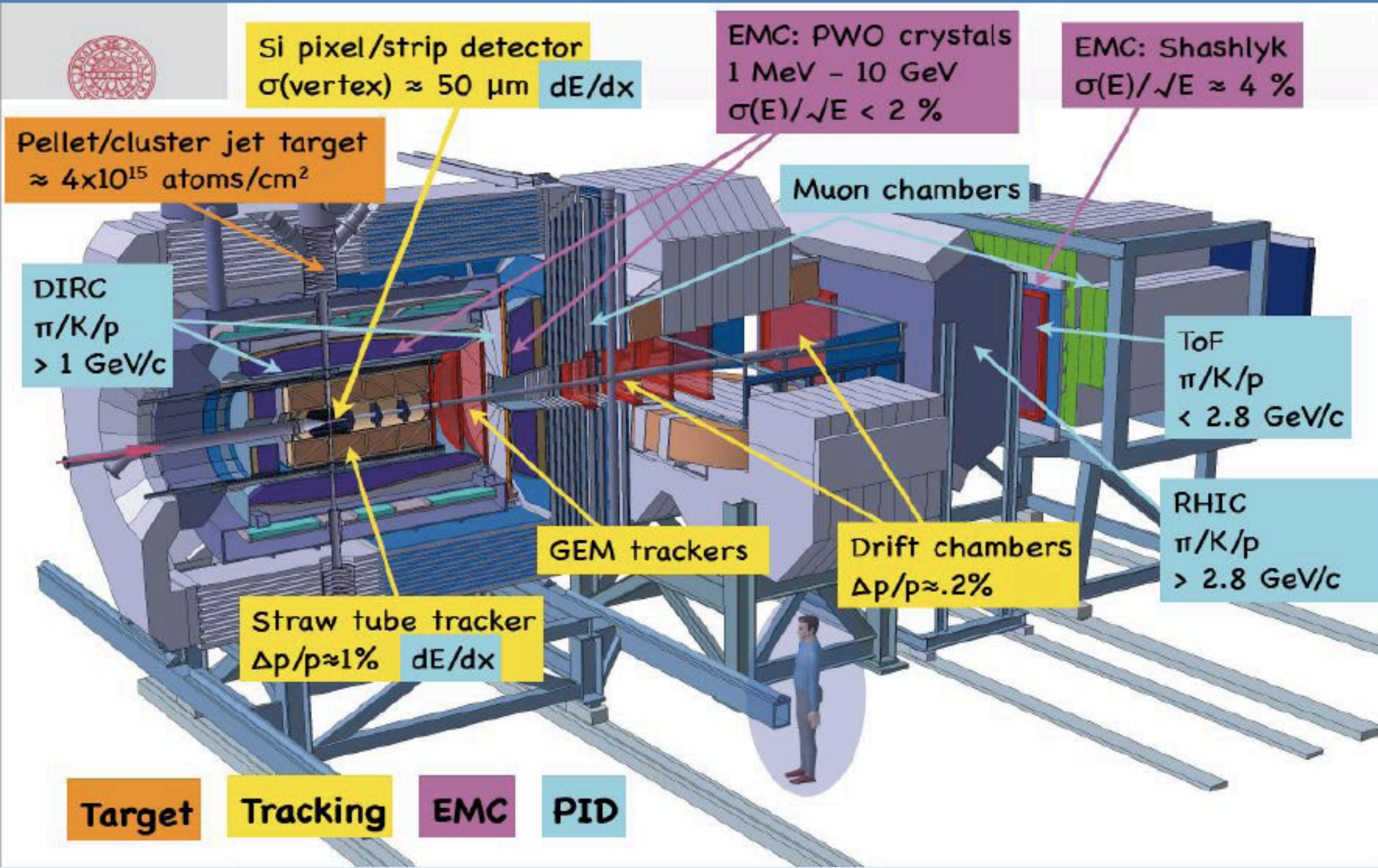
- New magnetic-spectrometer-free experiment with tight control of systematic errors:
  - ✓ ep→ep cross sections normalized to Moller scattering
  - ✓ reach very low Q^2 range: $[2\times10^{-4} - 2\times10^{-2}]$ GeV^2
  - ✓ windowless hydrogen gas flow target

- Current developments:
  - ✓ Pre-engineering design of the new target is completed, MRI proposal is submitted to NSF
  - ✓ Radiative correction codes improved at this Q^2 to provide less than 0.3% uncertainty
  - ✓ Full Monte Carlo simulation code developed for the experiment. Backgrounds are at percent level

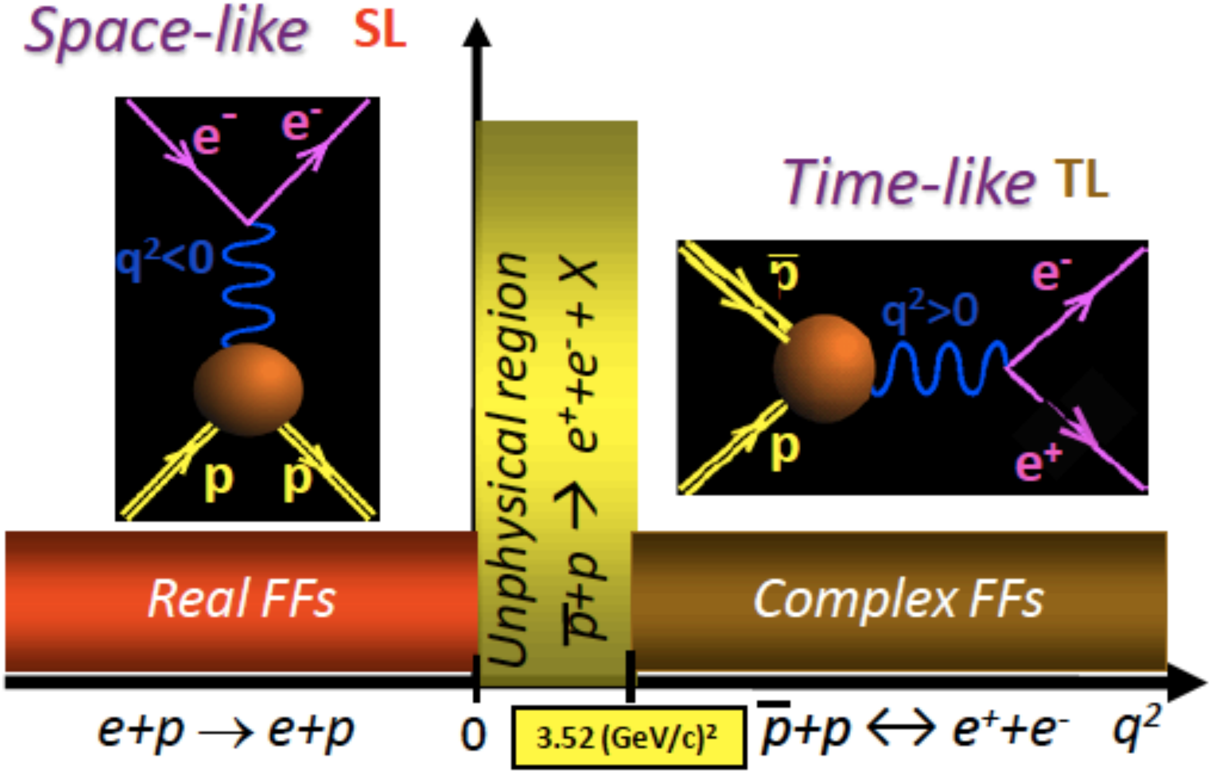
- Only 15 days of beam time is required to measure r_p with sub-percent precision

- The experiment (E12-11-106) is approved by the recent PAC39 with highest scientific rating (A)

The PANDA experimental set-up



Time-Like and Space-Like electromagnetic form factors (1)



Constraints:

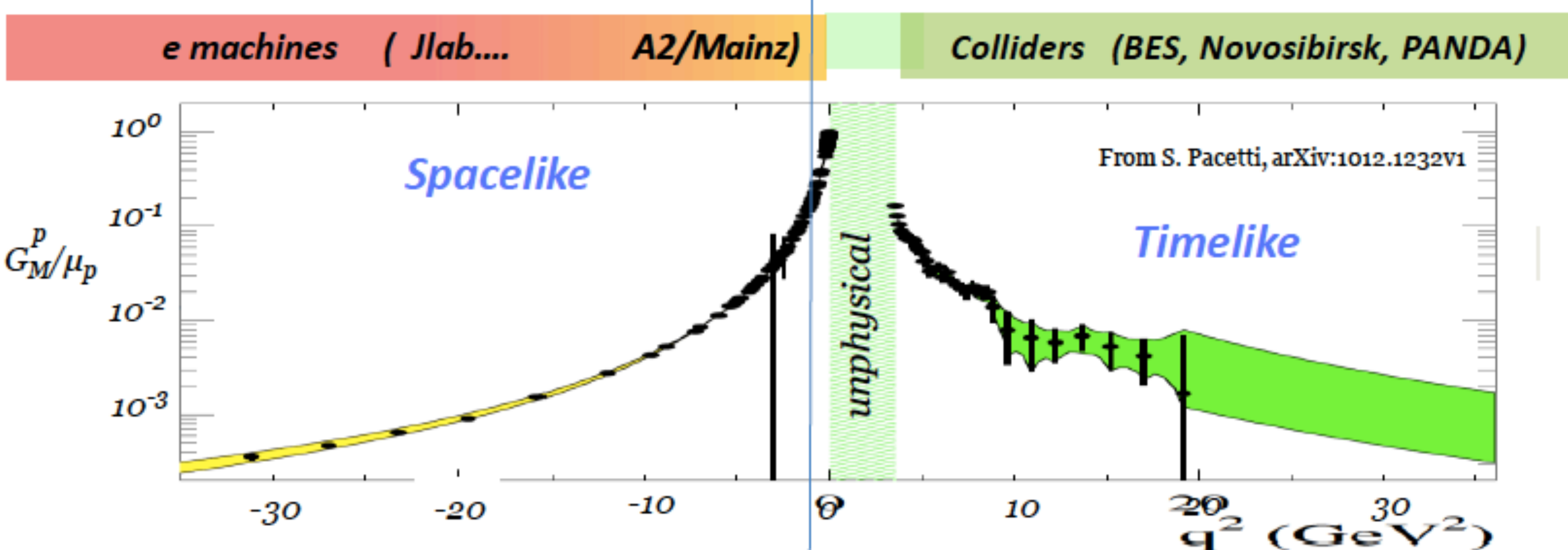
- $G_E^p(0)=1$
- $G_M^p(0)=\mu_p$
- $G_E^p(4m_p^2)= G_M^p(4m_p^2)$

Asymptotics

- $|G_{E,M}(q^2)| \sim (q^2)^{-2}$

- $\lim_{q^2 \to -\infty} G_{E,M}^{SL}(q^2) = \lim_{q^2 \to +\infty} G_{E,M}^{TL}(q^2)$ (Phragmén-Lindelhöf theorem)
- Imaginary part of Time-Like form factors vanishes for $q^2 \to +\infty$

Time-Like and Space-Like electromagnetic form factors (2)



Dispersion relations:

$q^2 < 0$

$$\boxed{G(q^2)} = \frac{1}{\pi}\left[\boxed{\int_{4m_\pi^2}^{4m_p^2}\frac{\mathrm{Im}\;G(s)\,ds}{s-q^2}} + \boxed{\int_{4m_p^2}^{\infty}\frac{\mathrm{Im}\;G(s)\,ds}{s-q^2}}\right]$$

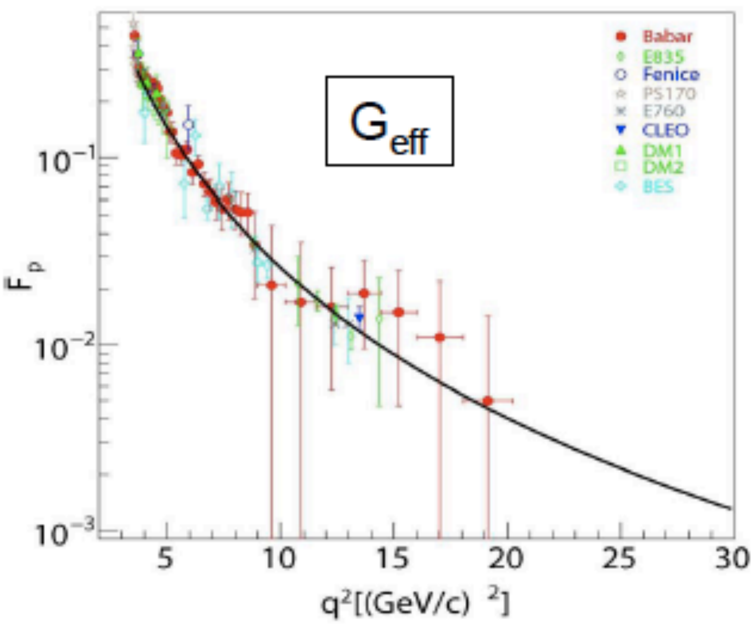
proton electromagnetic form factors in Time-Like region

Cross-sections: $\bar{p}p \rightarrow e^+e^-$

$$\boxed{\sigma_{tot} \sim \left|G_{eff}\right|^2} \qquad \tau = \frac{q^2}{4M_p^2}$$

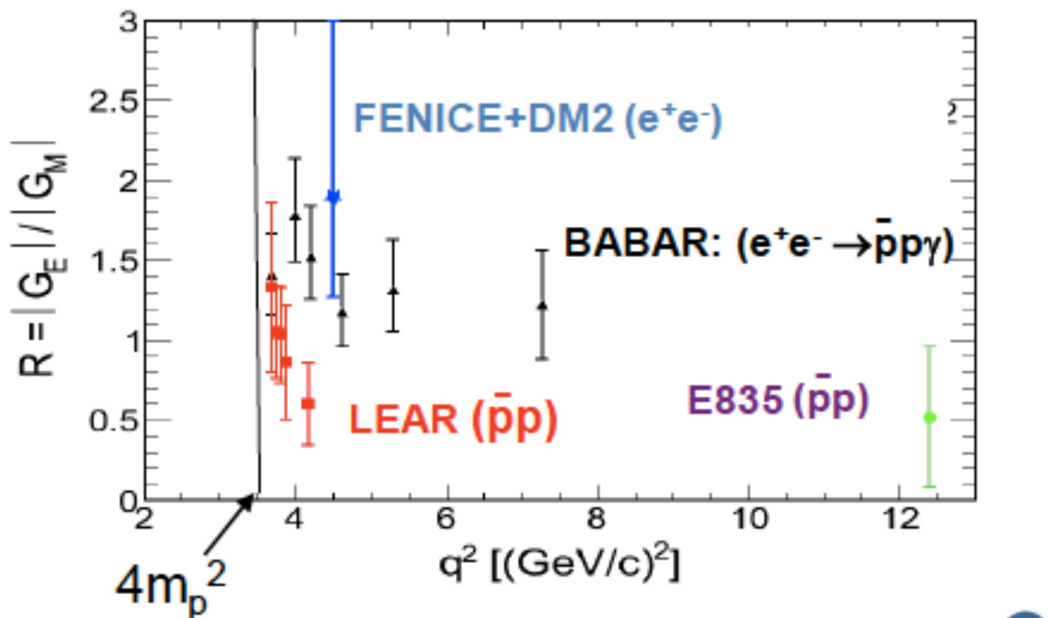
$$\boxed{G_{eff} = |G_M| \quad if \quad |G_E| = |G_M| \quad or \quad \tau >> 1}$$

$$|G_{eff}|^2 = \frac{2\tau |G_M|^2 + |G_E|^2}{2\tau + 1}$$



angular distributions: $\bar{p}p \rightarrow e^+e^-$

$$\frac{d\sigma}{d(\cos\theta_{CM})} = \frac{\pi\alpha^2}{8M_p^2\sqrt{\tau(\tau-1)}}\left[\tau\left|G_M^{TL}\right|^2(1+\cos^2\theta_{CM}) + \left|G_E^{TL}\right|^2\sin^2\theta_{CM}\right]$$



- ✓ G_{eff} : large error bars above 13 $(GeV/c)^2$
- ✓ $|G_E/G_M|$:
  - Inconsistent data above threshold
  - Lack of precise data above 5 $(GeV/c)^2$

Goal of PANDA measurements

Extract Time-Like $|G_E|$ and $|G_M|$ for proton up to 14 $(GeV/c)^2$ from lepton angular distributions in $\bar{p}p \to e^+e^-$ reaction and measure G_{eff} up to 30 $(GeV/c)^2$

Two major challenges:

✓ Decrease of sensitivity to G_E with increasing q^2

✓ Huge hadronic background $\sigma(\bar{p}p \to \pi^+\pi^-) / \sigma(\bar{p}p \to e^+e^-) \sim 10^6$

Interpreting Electron Scattering …

"[…] most of what we know and everything we believe about hadron structure is based on electron scattering" (W. Turchinetz)

"The electromagnetic probe is well understood, hence …"
(a common phrase in many articles)

The elastic form factors characterize the simplest process in nuclear physics, namely elastic scattering (straightforward, one should think)

If we don't understand the elastic form factors [and proton charge radius] we will not have understood anything.

Let's solve these puzzles!