

EM Form Factors and OLYMPUS

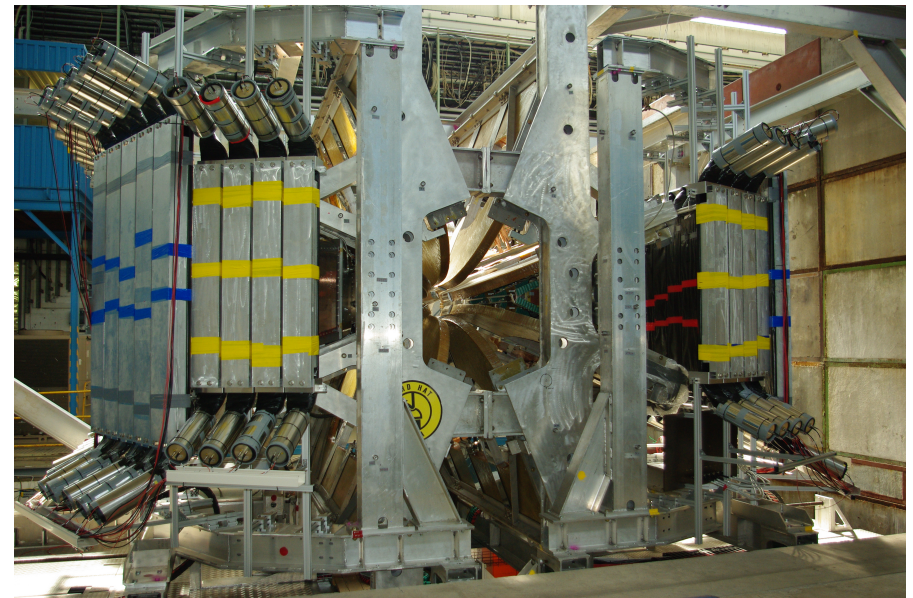
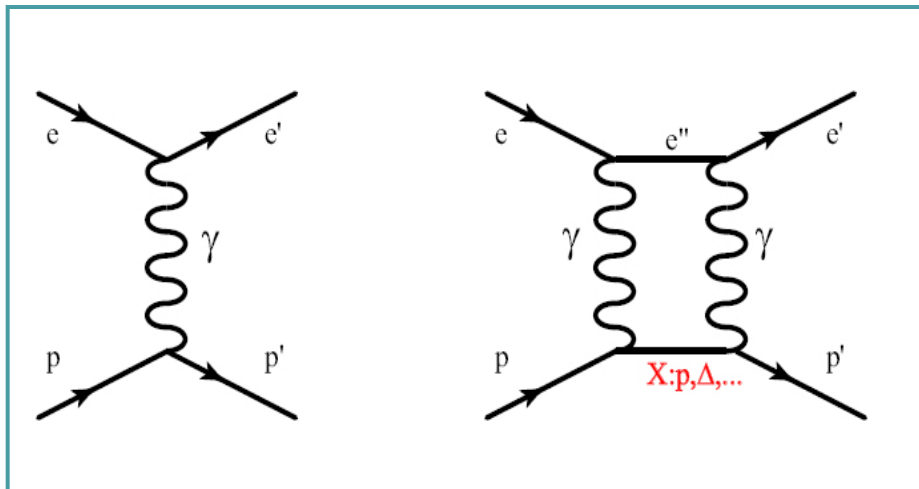
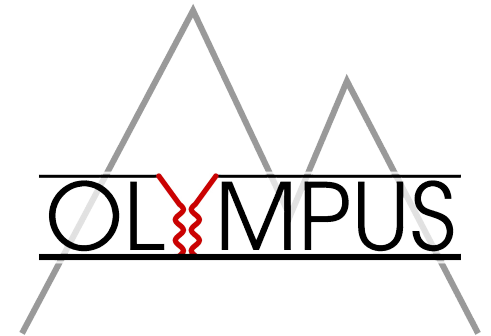
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Outline

- Proton form factors in the context of one-photon exchange (OPE)
- The limit of OPE or:
 - What is G_E^p ?
 - What is the nature of lepton scattering?
- Two-photon exchange (TPE): New observables
- Current and future experiments to probe TPE
 → **OLYMPUS & more**



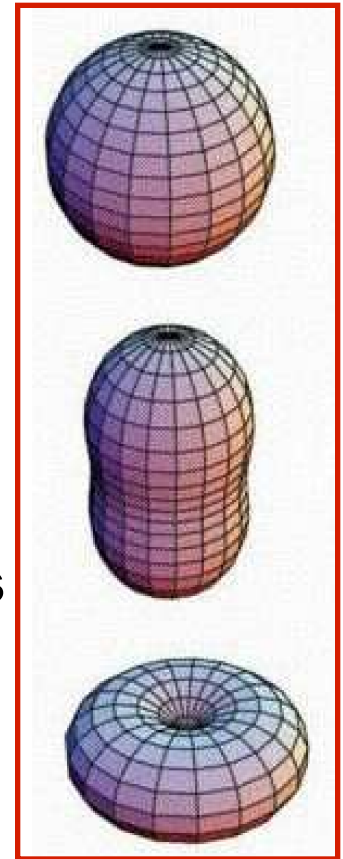
OLYMPUS @ DESY

Nucleon elastic form factors ...

- Fundamental quantities
- Defined in context of single-photon exchange
- Describe internal structure of the nucleons
- Related to spatial distribution of charge and magnetism
- Rigorous tests of nucleon models
- Determined by quark structure of the nucleon
- Role of orbital angular momentum and diquark correlation
- Ultimately calculable by Lattice-QCD
- Input to nuclear structure and parity violation experiments

50 years of ever increasing activity

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



Present form factor and TPE experiments

Recoil polarization and polarized target (Jlab)

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

Rosenbluth separation (Jlab)

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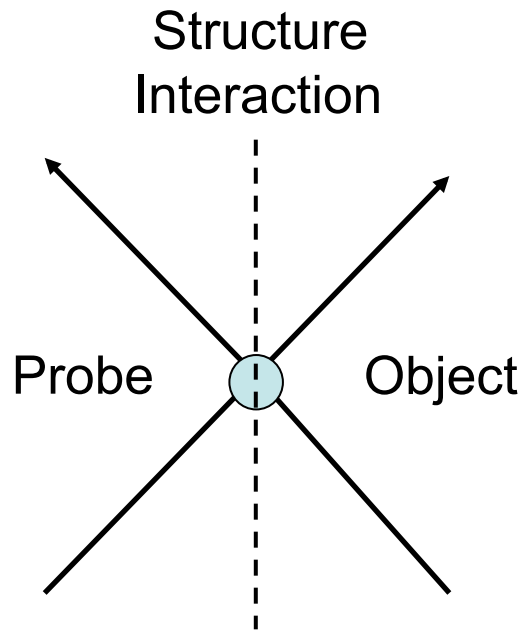
Positron-electron comparisons

Novosibirsk/VEPP-3	– to be published
CLAS/Jlab	– to be published
OLYMPUS/DESY	– analysis in progress

Proton radius measurements

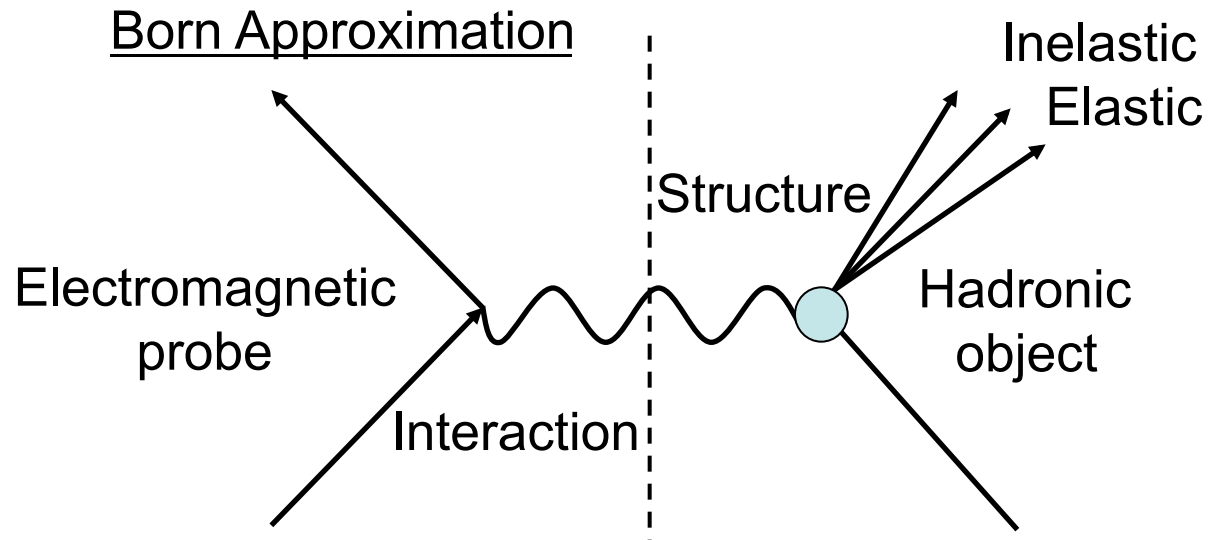
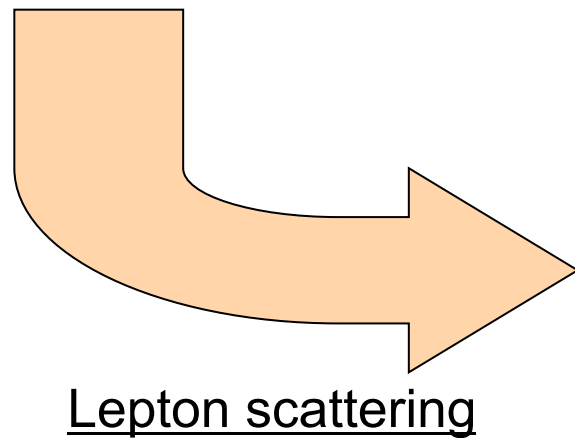
PSI / (muonic hydrogen Lamb shift, HFS)	– published (2010, 2013)
MAMI / A1 (e-scattering)	– published (2010)
MAMI / A1 (ISR)	– analysis in progress
Jlab / PRad (e-scattering)	– proposed
PSI / MUSE (e^\pm , μ^\pm scattering)	– proposed

Hadronic structure and EM interaction



Factorization!

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



One-Photon Exchange Approximation

The beginnings

Robert Hofstadter
Nobel prize 1961



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

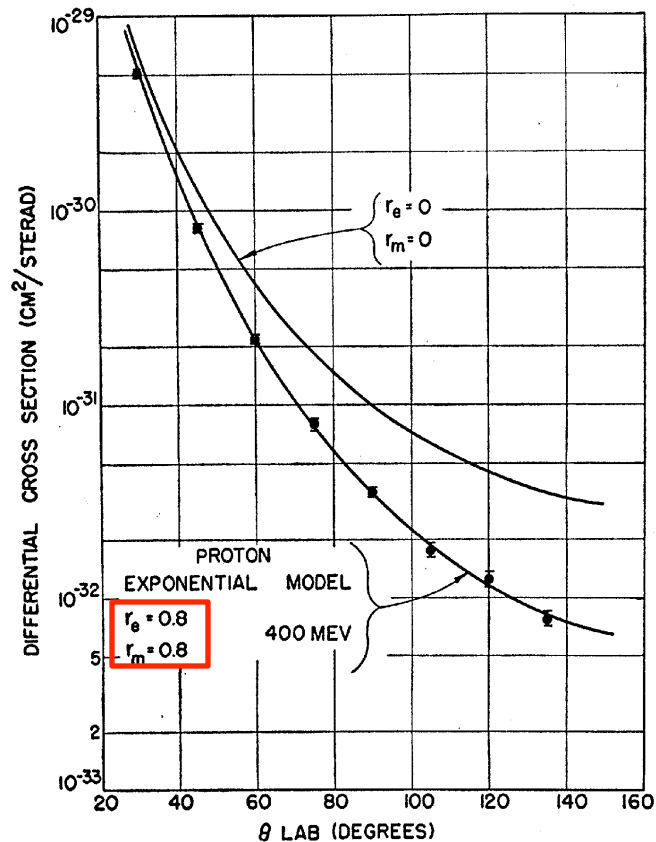


FIG. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with rms radii = 0.80×10^{-13} cm.

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

ed-elastic
Finite size + nuclear structure

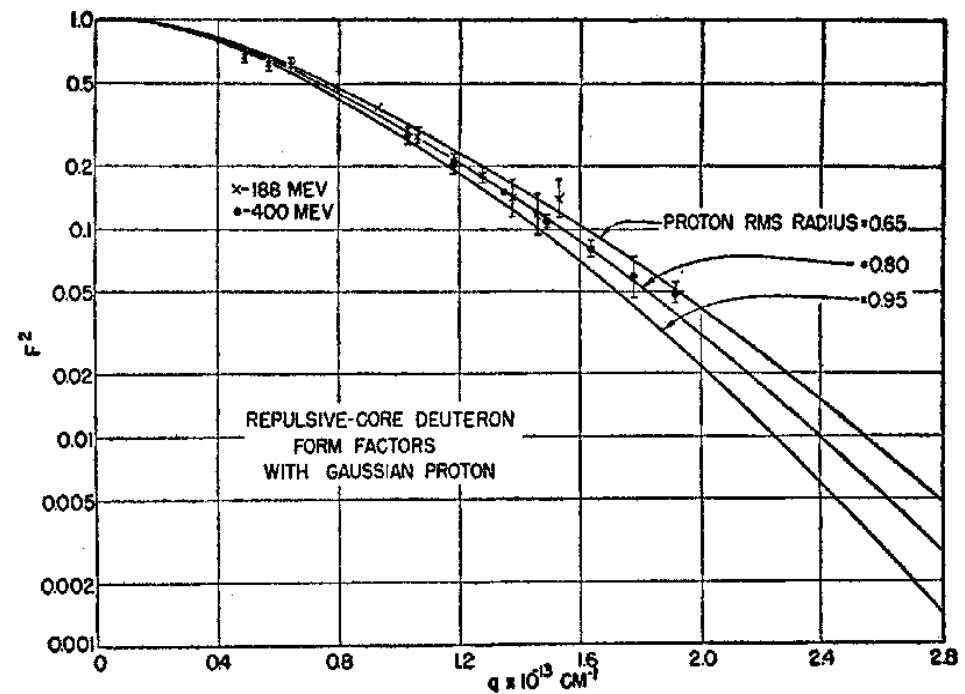
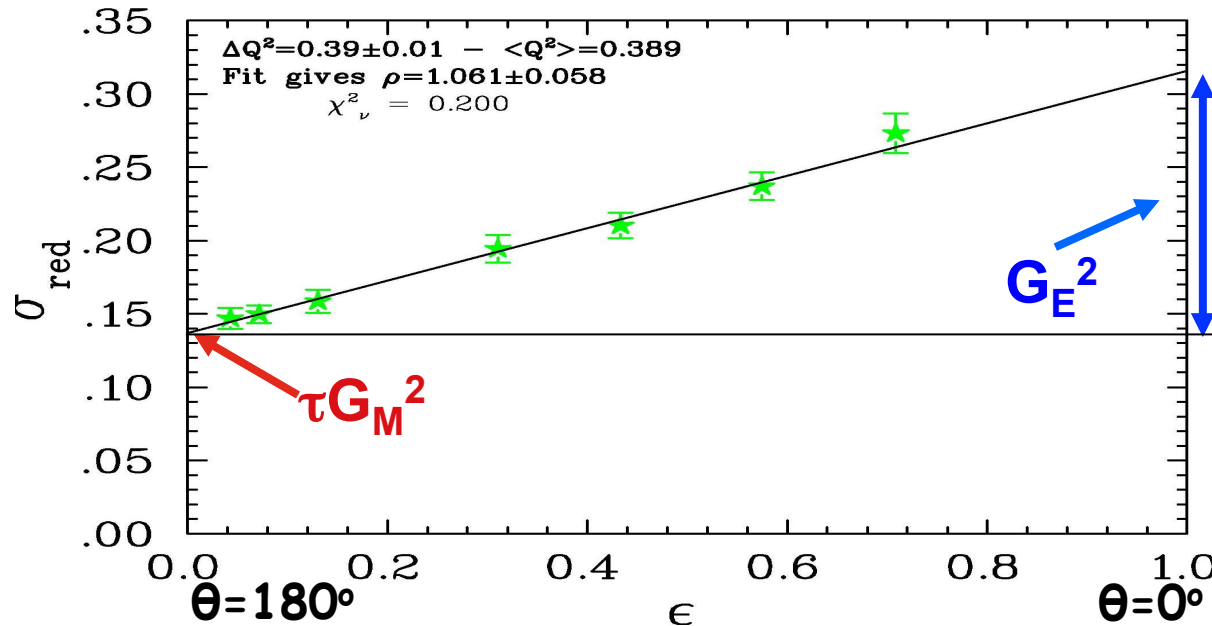


FIG. 31. Introduction of a finite proton core allows the experimental data to be fitted with conventional form factors (McIntyre).

Form factors from Rosenbluth method



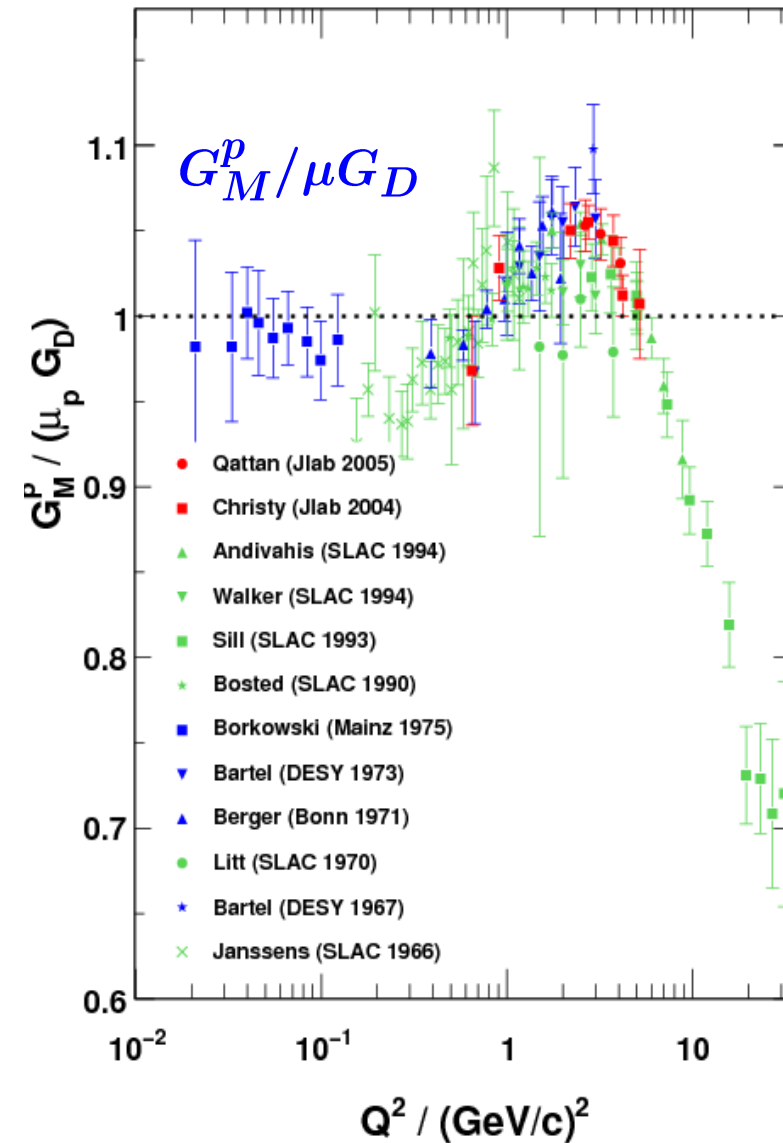
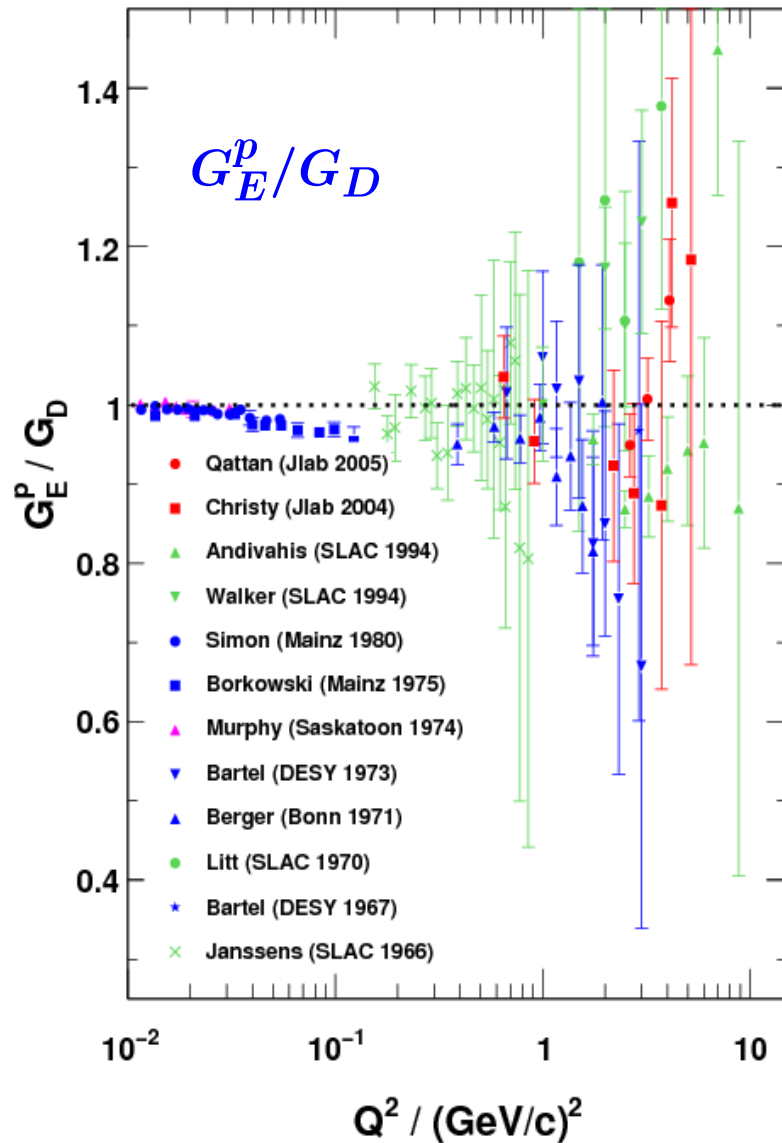
$$\sigma_{\text{red}} = \epsilon G_E^2 + \tau G_M^2$$

→ Determine
 $|G_E|$, $|G_M|$,
 $|G_E/G_M|$

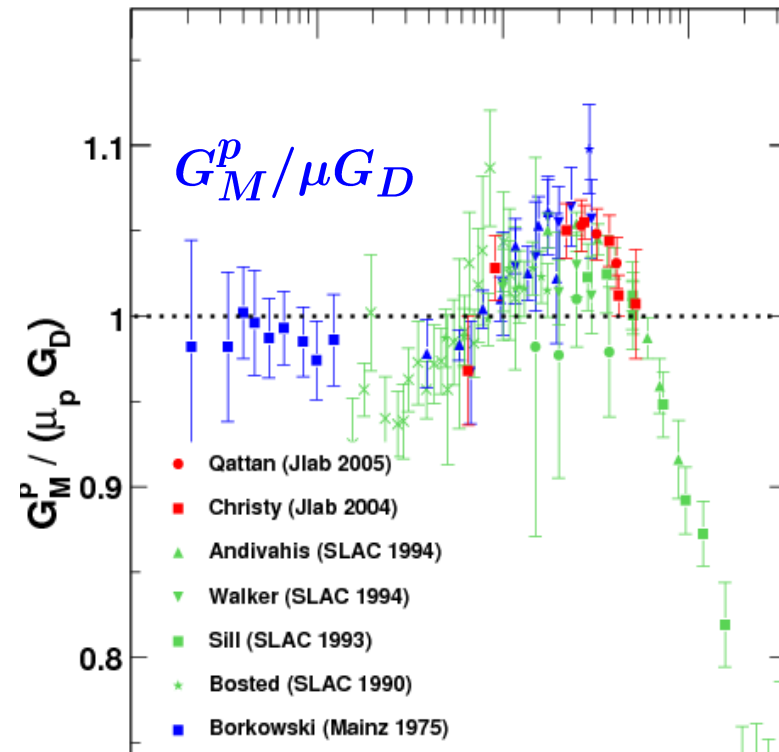
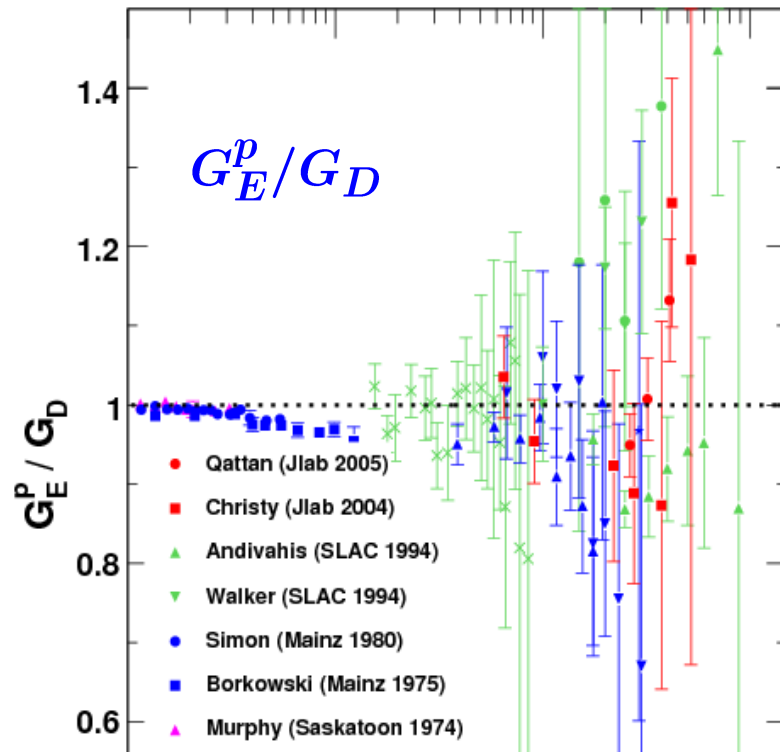
- In One-photon exchange, form factors are related to radiatively corrected **elastic electron-proton** scattering cross section

$$\begin{aligned} \frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{\text{Mott}}} &= S_0 = A(Q^2) + B(Q^2) \tan^2 \frac{\theta}{2} \\ &= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1 + \tau} + 2\tau G_M^2(Q^2) \tan^2 \frac{\theta}{2} \\ &= \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1 + \tau)}, \quad \epsilon = \left[1 + 2(1 + \tau) \tan^2 \frac{\theta}{2} \right]^{-1} \end{aligned}$$

G_E^p and G_M^p from unpolarized data



G_E^p and G_M^p from unpolarized data



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

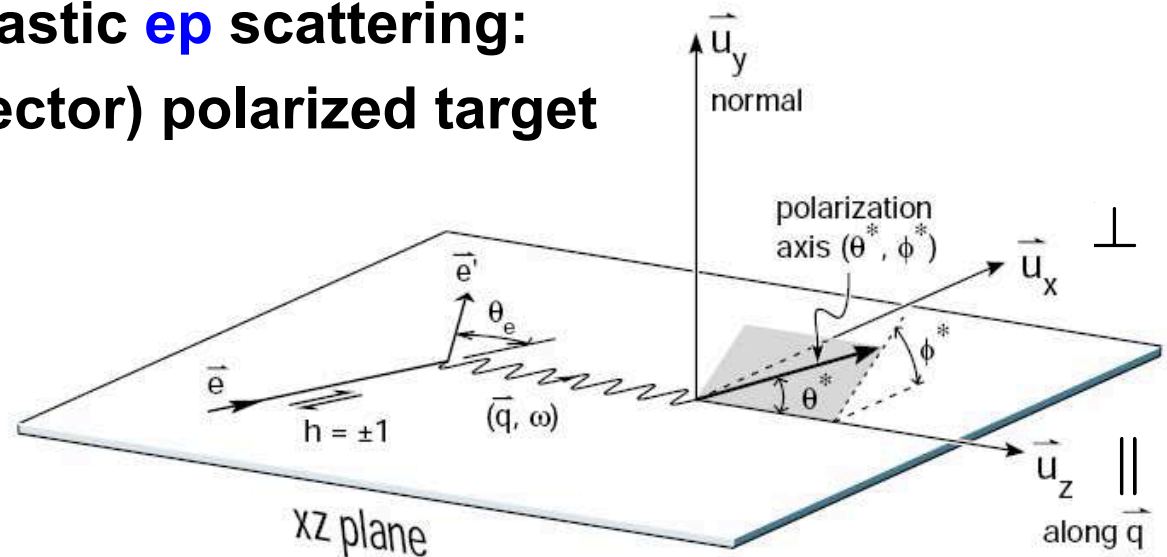
Nucleon form factors and polarization

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

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

- Polarized cross section

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



- Double polarization observable = spin correlation

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

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

independent of
polarization or analyzing power

Dombey (1969)
Donnelly and Raskin (1986)

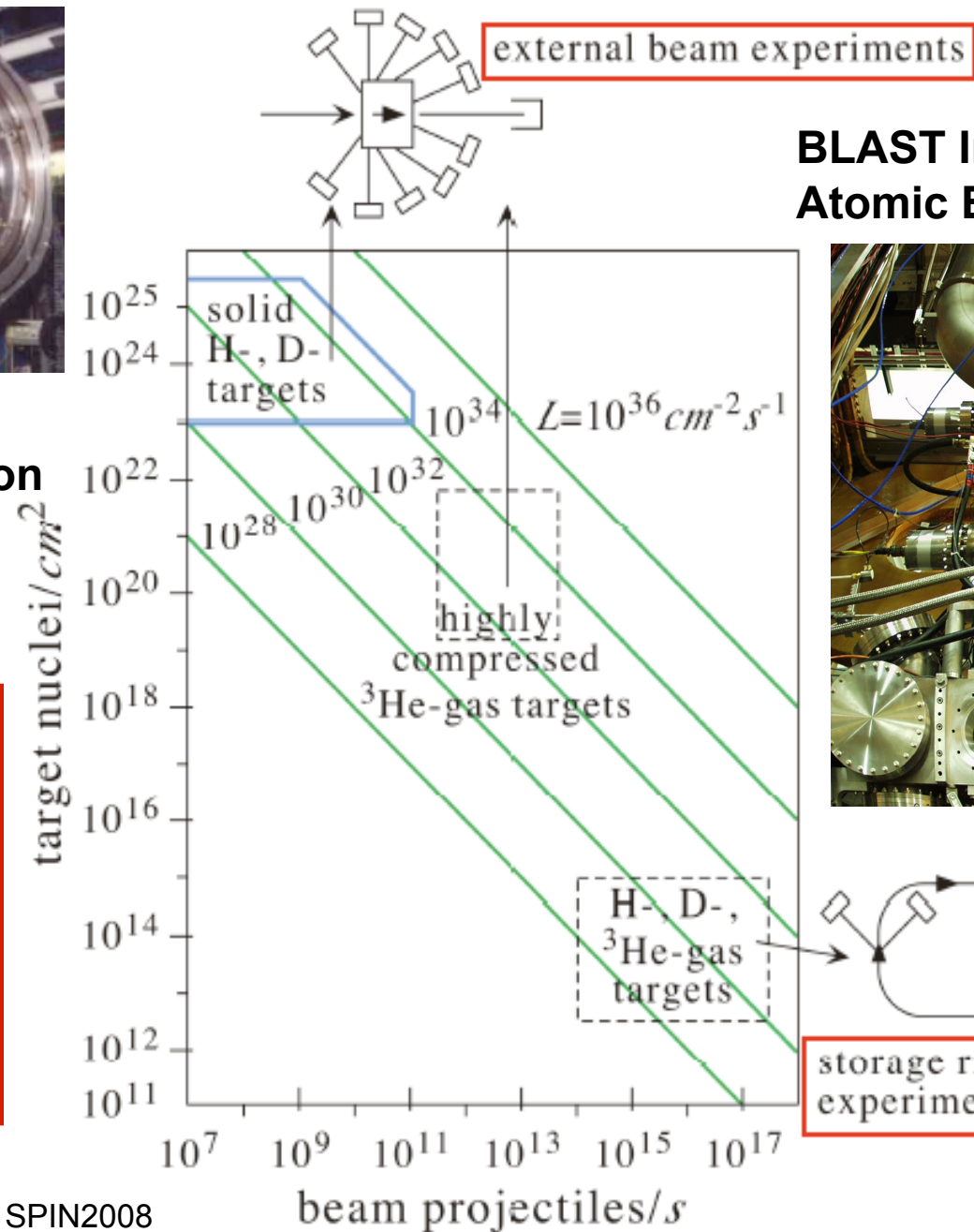
Polarized targets



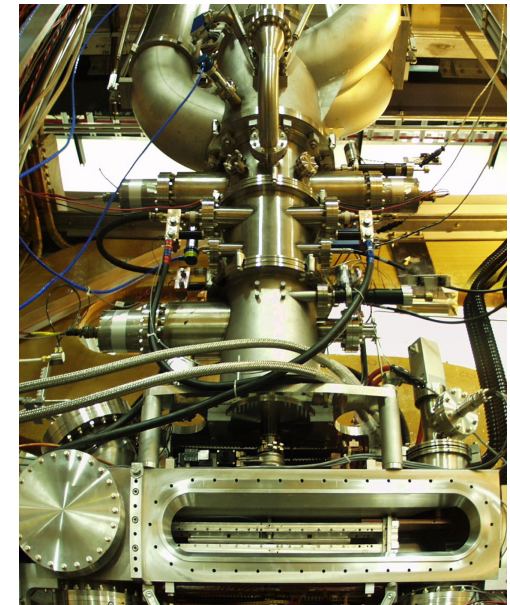
**UVA / "SLAC"-Target:
Dynamic Nuclear Polarization**

**Limited luminosity for
polarized hydrogen/
deuterium targets**

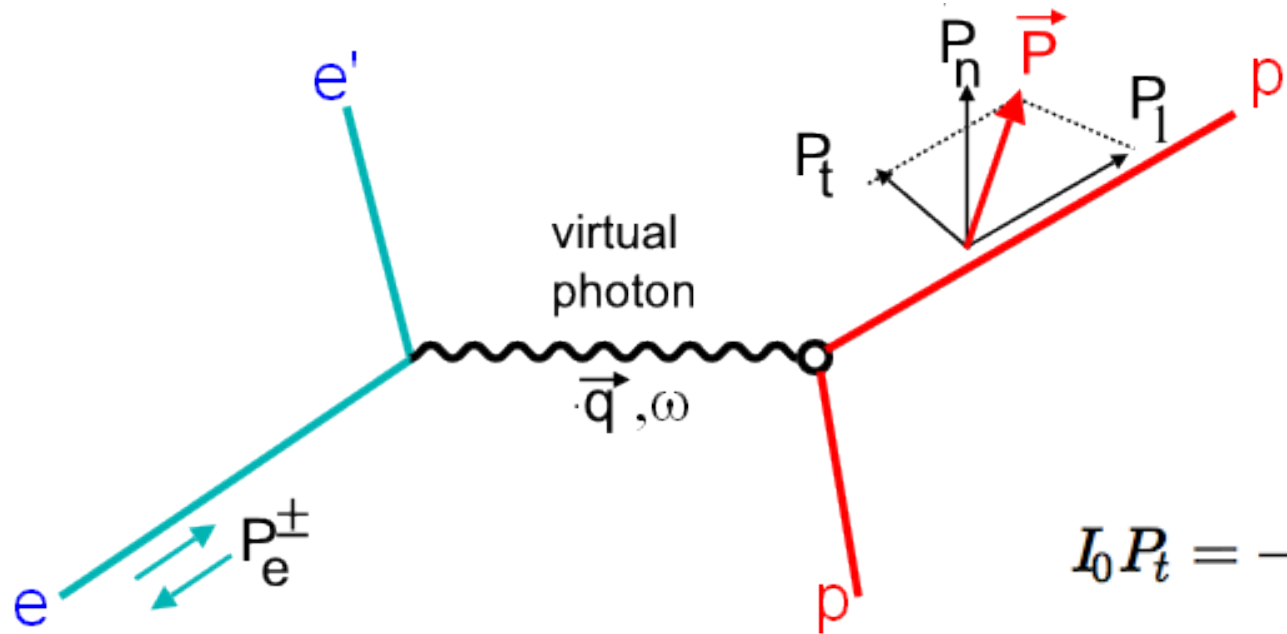
**Very precise at low to
moderately high Q^2**



**BLAST Internal Target:
Atomic Beam Source**



Recoil polarization technique



$$I_0 P_t = -2\sqrt{\tau(1+\tau)} G_E G_M \tan \frac{\theta_e}{2}$$

$$I_0 P_l = \frac{1}{M} (E_e + E_{e'}) \sqrt{\tau(1+\tau)} G_M^2 \tan^2 \frac{\theta_e}{2}$$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l} \frac{(E_e + E_{e'})}{2M_p} \tan\left(\frac{\theta_e}{2}\right)$$

$$I_0 \propto G_E^2 + \frac{\tau}{\epsilon} G_M^2$$

Applicable to protons and neutrons

Akhiezer and Rekalov (1968+1974)
Arnold, Carlson and Gross (1981)

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

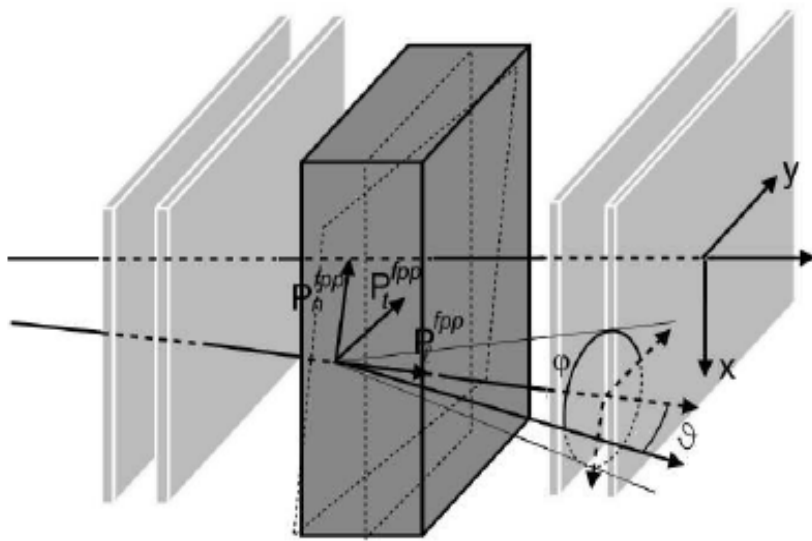


FIG. 9: Schematic of the polarimeter chambers and analyzer, showing a non-central trajectory; ϑ is the polar angle, and φ is the azimuthal angle from the y -direction counterclockwise.

Focal-plane polarimeter

Secondary scattering of polarized proton from unpolarized analyzer

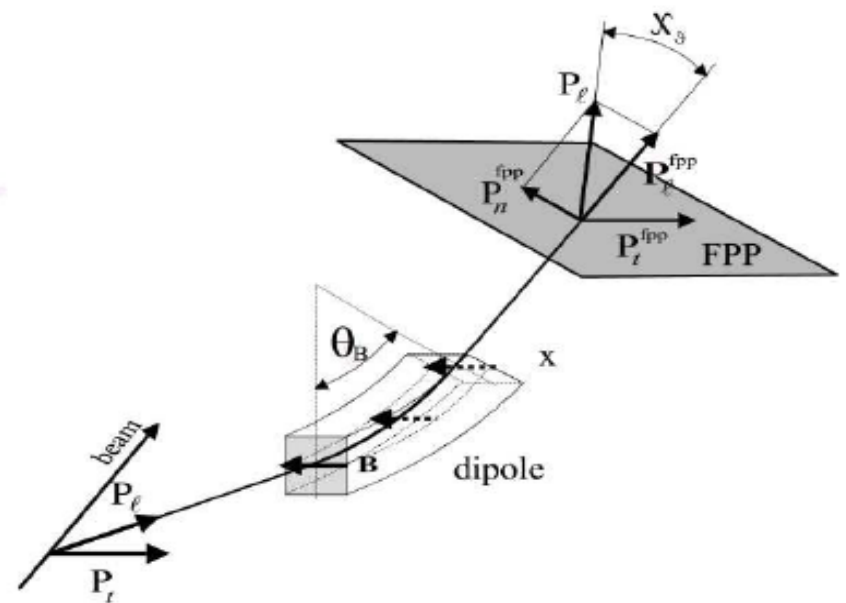
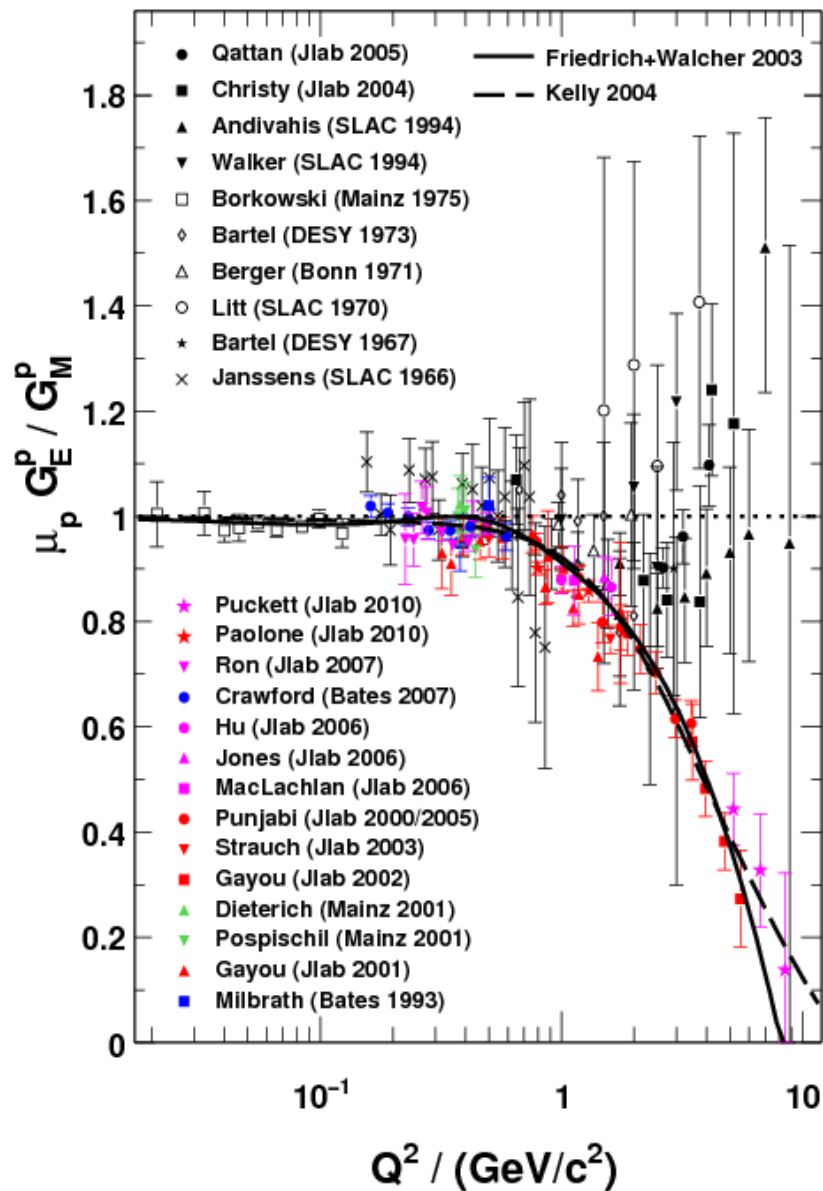


FIG. 15: Schematic drawing showing the precession by angle χ_θ of the P_e component of the polarization in the dipole of the HRS.

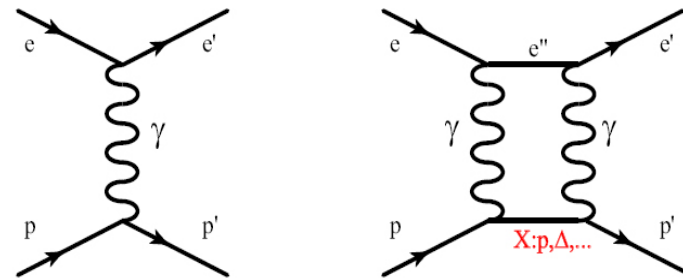
Spin transfer formalism to account for spin precession through spectrometer

Proton form factor ratio



Jefferson Lab 2000–

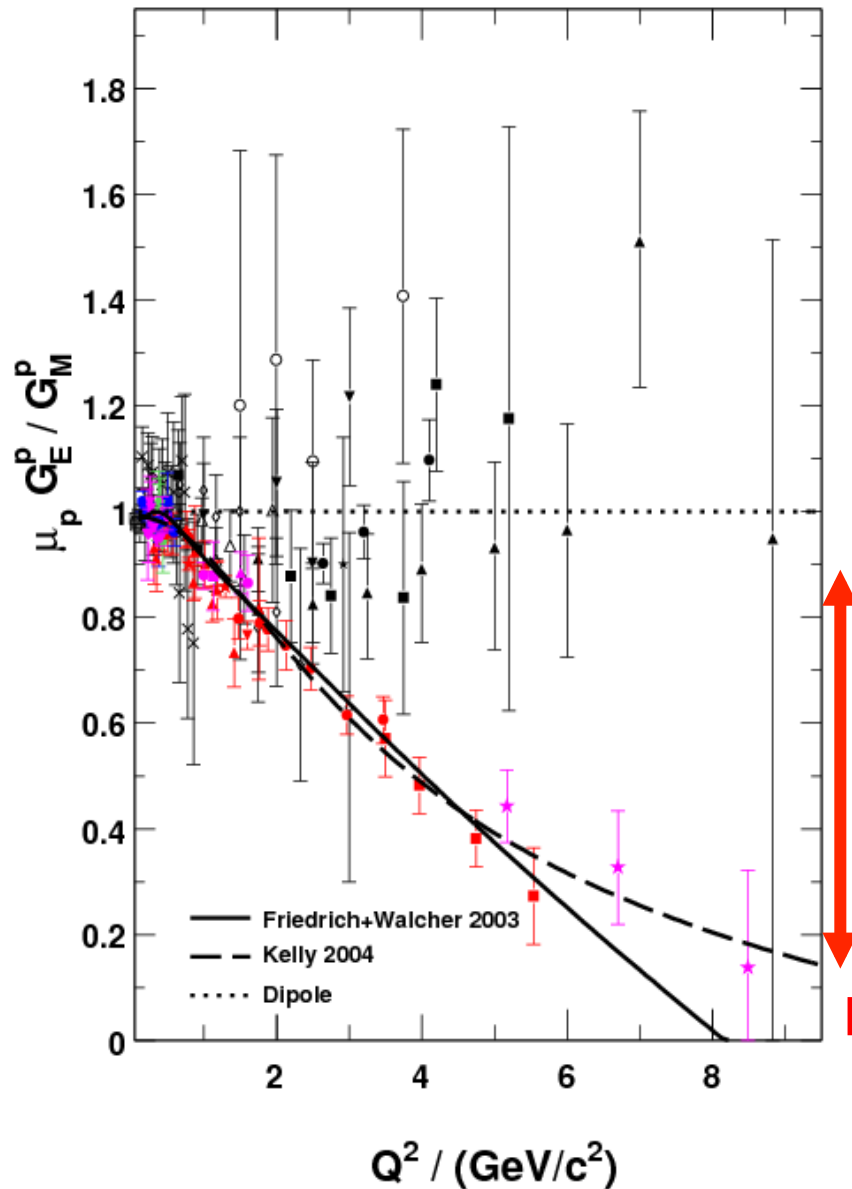
- All Rosenbluth data from SLAC and Jlab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Multi-photon exchange considered best candidate



Dramatic discrepancy!

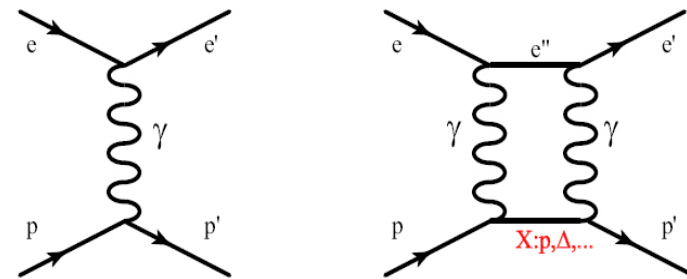
>800 citations

Proton form factor ratio



Jefferson Lab 2000–

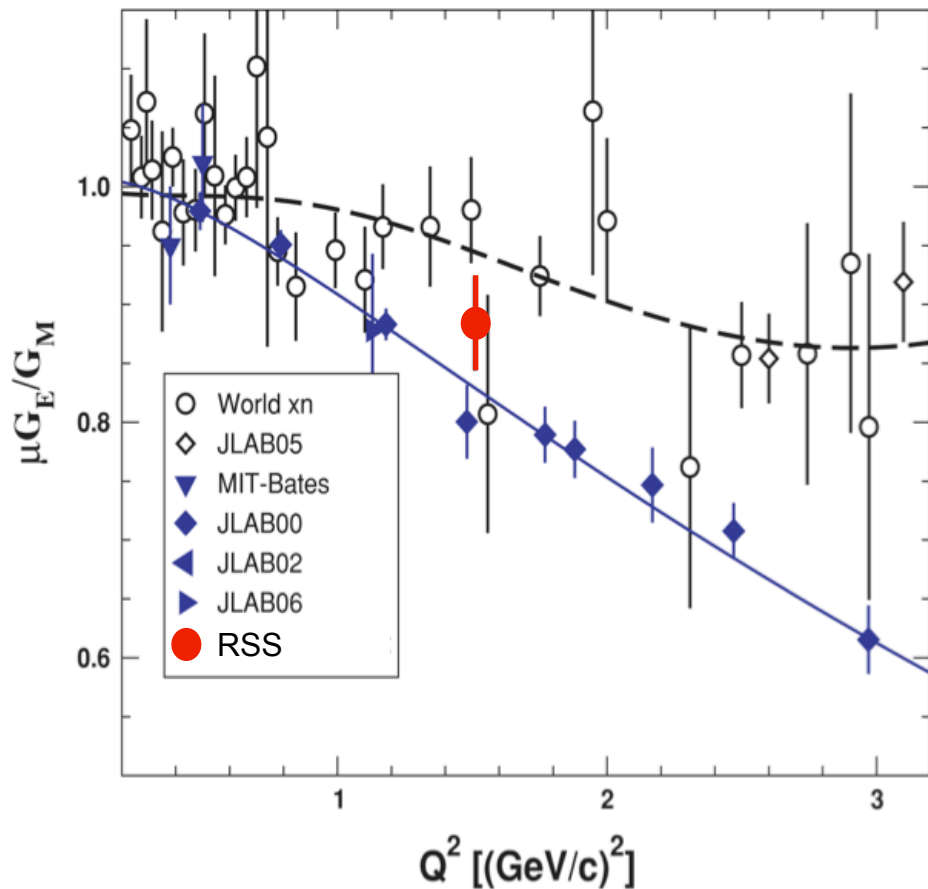
- All Rosenbluth data from SLAC and Jlab in agreement
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Dramatic discrepancy!

>800 citations

Polarized target data at high Q^2



Polarized Target:

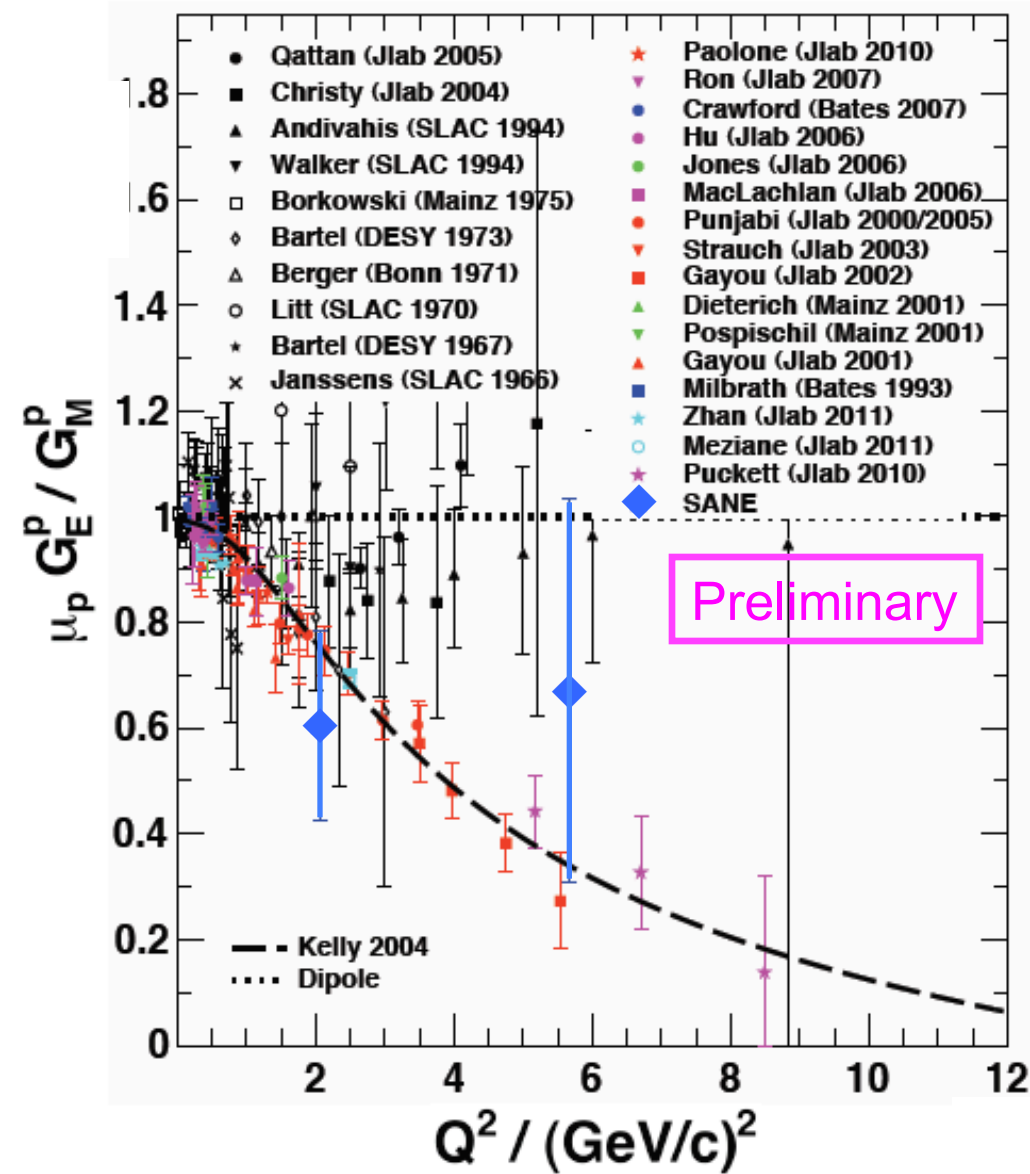
Independent verification of recoil polarization result is crucial

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

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

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

Polarized target data at high Q^2



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

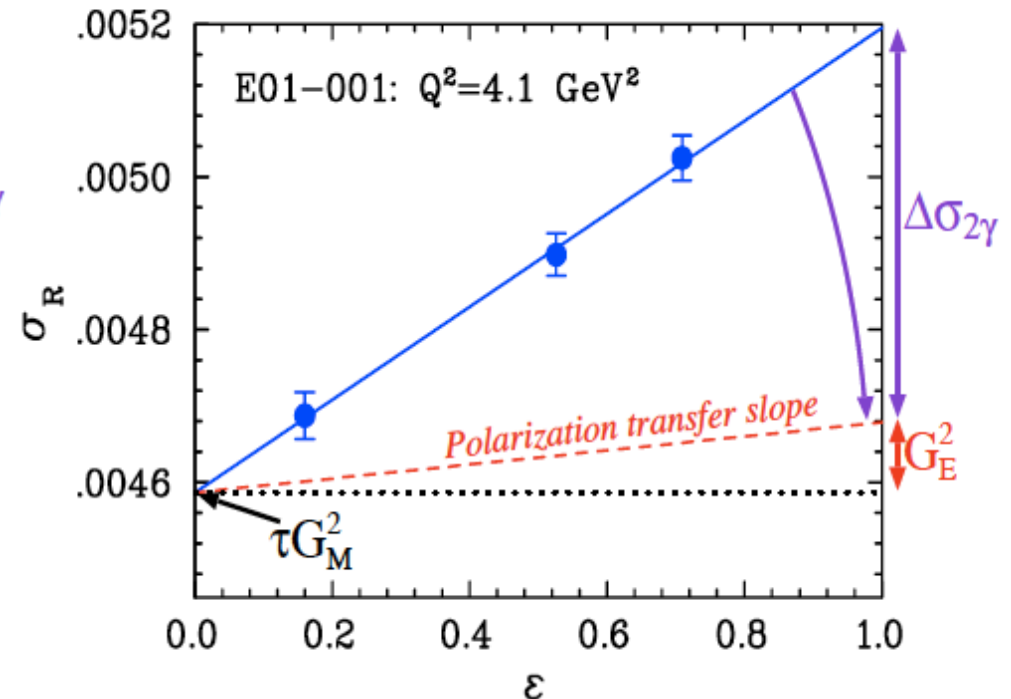
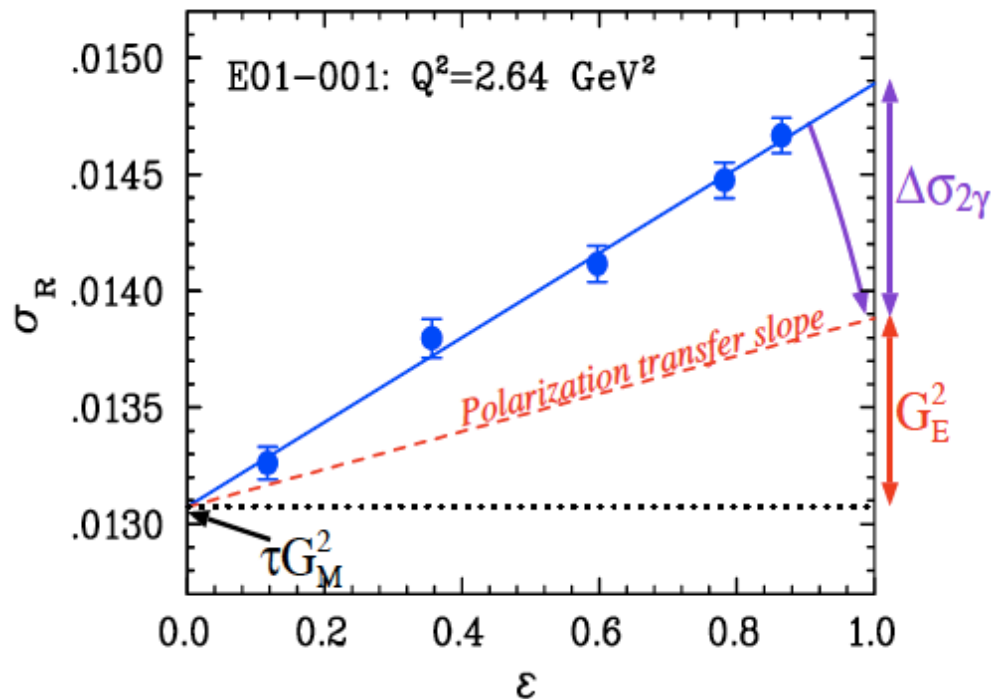
Decline of G_E/G_M has been confirmed!

Future precision measurements at high Q^2 are feasible

A. Liyanage, M.K. *et al.*, to be published

Effect of two-photon exchange

J. Arrington, P. Blunden, W. Melnitchouk, Prog. Part. Nucl. Phys. 66, 782 (2011)



per constructionem, theorists sought mechanism that affects the “slope” in the Rosenbluth plot (ϵ -dependence)

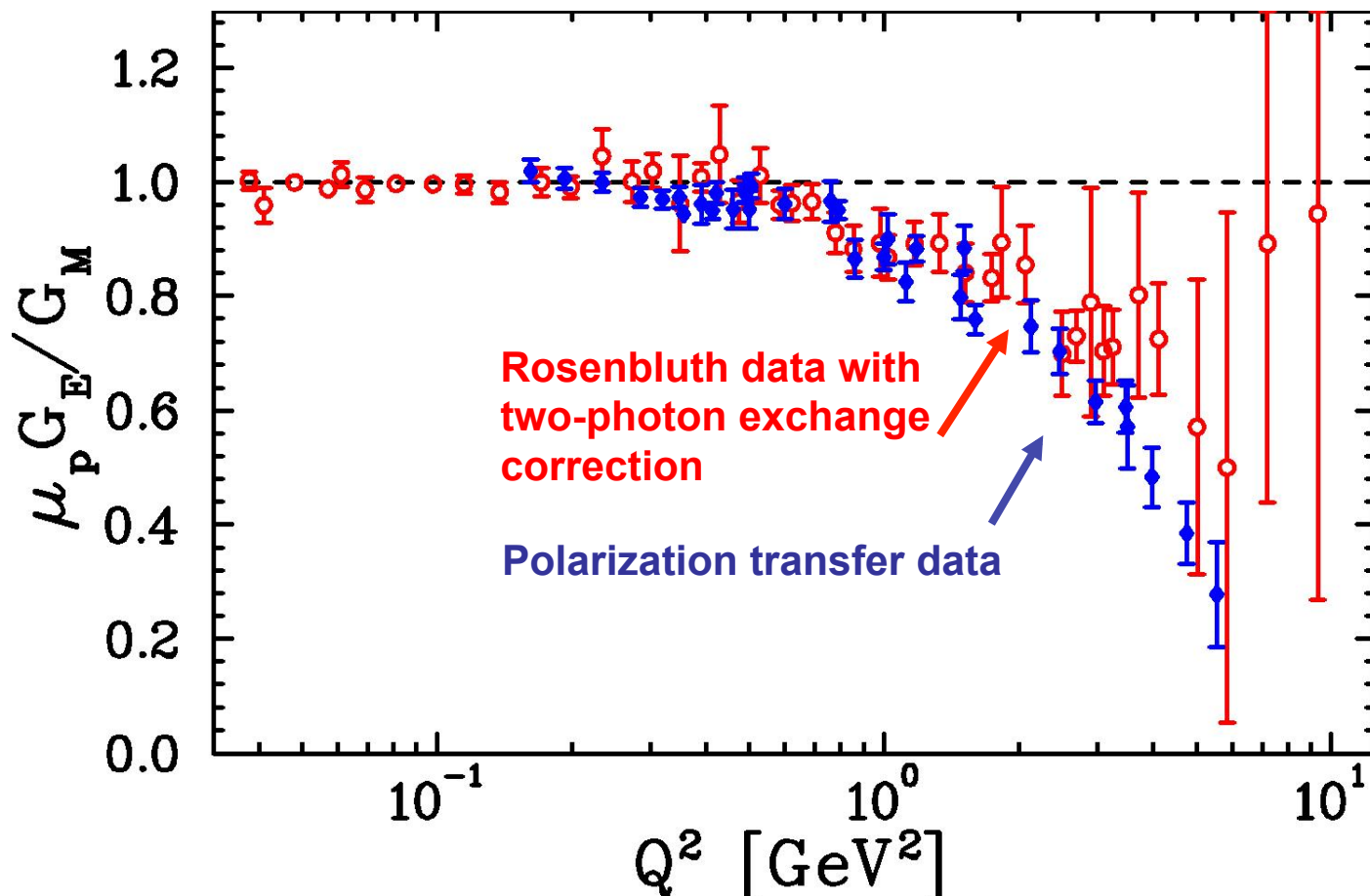
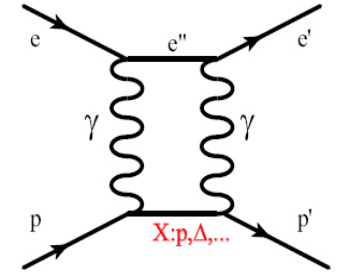
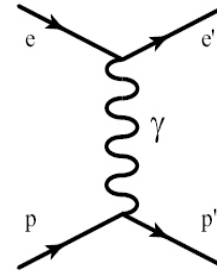
At high Q^2 , the contribution of G_E to the cross section is of similar order as the TPE effect (few %)

Two-photon exchange: exp. evidence

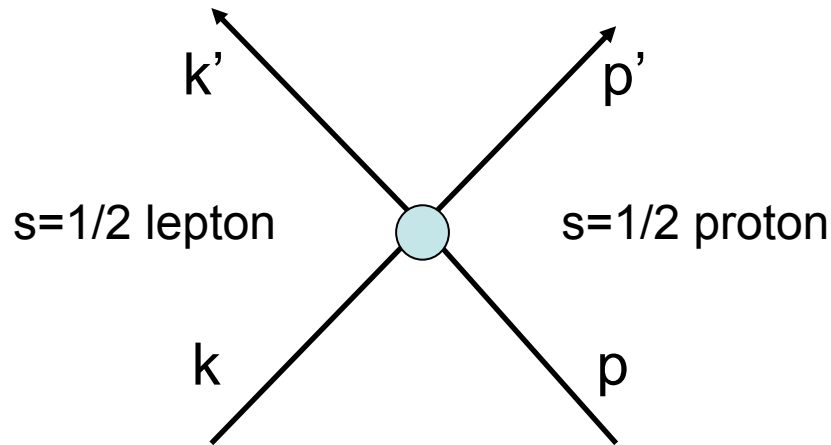
Two-photon exchange theoretically suggested

TPE can explain form factor discrepancy

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



Elastic ep scattering beyond OPE



$$P \equiv \frac{p + p'}{2}, \quad K \equiv \frac{k + k'}{2}$$

Kinematical invariants :

$$Q^2 = -(p - p')^2$$

$$\nu = K \cdot P = (s - u)/4$$

Next-to Born approximation:

$$T_{h' \lambda'_N, h \lambda_N}^{non-flip} = \frac{e^2}{Q^2} \bar{u}(k', h') \gamma_\mu u(k, h)$$

$$\times \bar{u}(p', \lambda'_N) \left(\tilde{G}_M \gamma^\mu - \tilde{F}_2 \frac{P^\mu}{M} + \tilde{F}_3 \frac{\gamma \cdot K P^\mu}{M^2} \right) u(p, \lambda_N)$$

$(m_e = 0)$

The T-matrix still factorizes, however a new response term F_3 is generated by TPE
Born-amplitudes are modified in presence of TPE; modifications $\sim \alpha^3$

$$\tilde{G}_M(\nu, Q^2) = G_M(Q^2) + \delta \tilde{G}_M \quad \tilde{G}_E \equiv \tilde{G}_M - (1 + \tau) \tilde{F}_2$$

$$\tilde{F}_2(\nu, Q^2) = F_2(Q^2) + \delta \tilde{F}_2 \quad \tilde{G}_E(\nu, Q^2) = G_E(Q^2) + \delta \tilde{G}_E$$

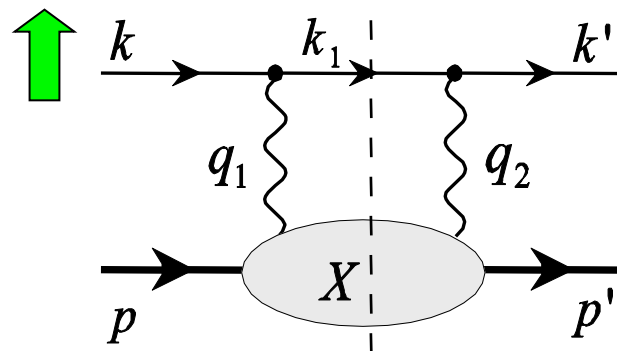
$$\tilde{F}_3(\nu, Q^2) = 0 + \delta \tilde{F}_3$$

New amplitudes are complex!

Inherited from M. Vanderhaeghen

Imaginary part: Single-spin asymmetries

spin of **beam OR target**
NORMAL to scattering plane



$$s = (k + p)^2$$

on-shell intermediate state ($M_X = W$)

$$A_n = -\frac{1}{(2\pi)^3} \frac{e^2 (1 - \varepsilon)}{8 Q^2} \int_{M^2}^s dW^2 \frac{|\vec{k}_1|^2}{4\sqrt{s}} \int d\Omega_{k_1} \frac{1}{Q_1^2 Q_2^2} \mathcal{I}(L_{\alpha\mu\nu} H^{\alpha\mu\nu})$$

E.g. target normal spin asymmetry

$$A_n = \sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}} \frac{1}{\sigma_R} \left\{ -G_M \mathcal{I} \left(\delta\tilde{G}_E + \frac{\nu}{M^2} \tilde{F}_3 \right) + G_E \mathcal{I} \left(\delta\tilde{G}_M + \left(\frac{2\varepsilon}{1+\varepsilon} \right) \frac{\nu}{M^2} \tilde{F}_3 \right) \right\},$$

↑ **Beam:** PVES at Bates, MAMI and Jlab; ↑ **Target:** PR05-015, PR08-005

Observables involving real part of TPE

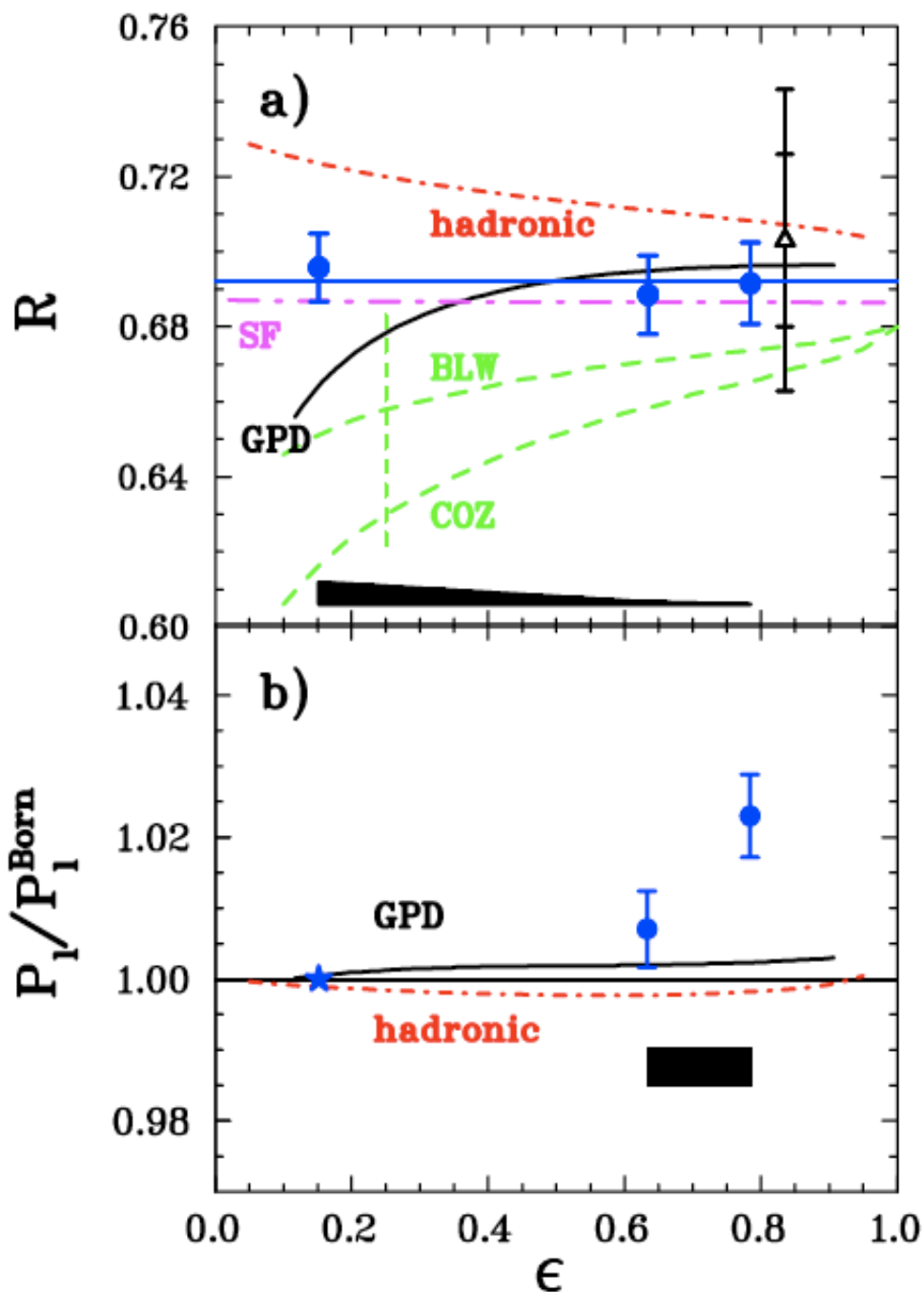
$P_t = -\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}} \frac{G_M^2}{d\sigma_{red}} \left\{ R + \right.$ $P_l = \sqrt{(1+\varepsilon)(1-\varepsilon)} \frac{G_M^2}{d\sigma_{red}} \left\{ 1 + 2 \frac{\Re(\delta\tilde{G}_M)}{G_M} + \frac{2}{1+\varepsilon} \varepsilon Y_{2\gamma} \right\}$ $\frac{P_t}{P_l} = -\sqrt{\frac{2\varepsilon}{(1+\varepsilon)\tau}} \left\{ R - \right.$	$\left. R \frac{\Re(\delta\tilde{G}_M)}{G_M} + \frac{\Re(\delta\tilde{G}_E)}{G_M} + Y_{2\gamma} \right\}$	}	E04-019 (Two-gamma)		
$d\sigma_{red} / G_M^2 = 1 + \frac{\varepsilon R^2}{\tau} + 2 \frac{\Re(\delta\tilde{G}_M)}{G_M} + 2R \frac{\varepsilon \Re(\delta\tilde{G}_E)}{\tau G_M} + 2 \left(1 + \frac{R}{\tau} \right) \varepsilon Y_{2\gamma}$	$\left. R \frac{\Re(\delta\tilde{G}_M)}{G_M} + \frac{\Re(\delta\tilde{G}_E)}{G_M} + 2 \left(1 - R \frac{2\varepsilon}{1+\varepsilon} \right) Y_{2\gamma} \right\}$			}	e ⁺ /e ⁻ x-section ratio CLAS, VEPP3, OLYMPUS Rosenbluth non-linearity E05-017
$\Re(\tilde{G}_E) = G_E(Q^2) + \Re(\delta\tilde{G}_E(Q^2, \varepsilon))$ $\Re(\tilde{G}_M) = G_M(Q^2) + \Re(\delta\tilde{G}_M(Q^2, \varepsilon))$	$R = G_E / G_M \quad Y_{2\gamma} = 0 + \sqrt{\frac{\tau(1+\tau)(1+\varepsilon)}{1-\varepsilon}} \frac{\Re(\tilde{F}_3(Q^2, \varepsilon))}{G_M}$				
<p style="color: blue; margin: 0;">Born Approximation</p>	<p style="color: red; margin: 0;">Beyond Born Approximation</p>				

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

Jefferson Lab E04-019 (Two-gamma)



Jlab – Hall C
 $Q^2 = 2.5 \text{ (GeV/c)}^2$

G_E/G_M from P_t/P_l constant vs. ϵ

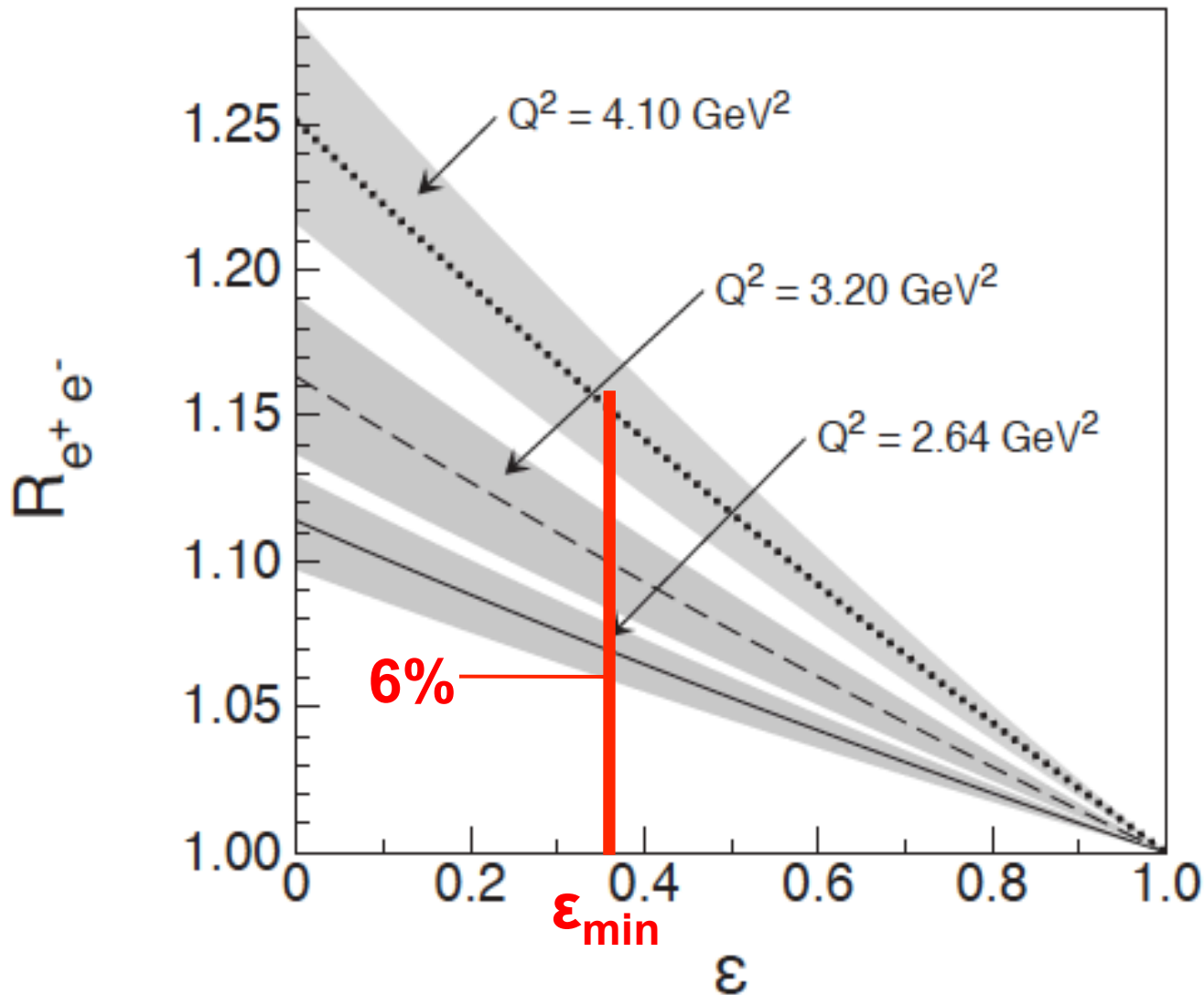
- no effect in P_t/P_l
- some effect in P_l

Expect larger effect in $e^+/e^-!$

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

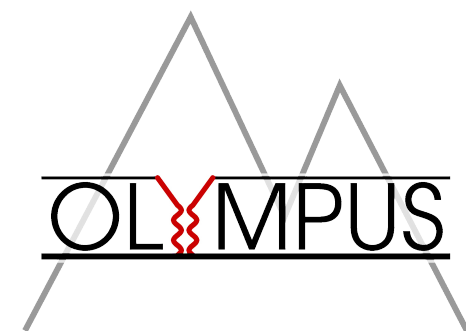
Empirical extraction of TPE amplitudes

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

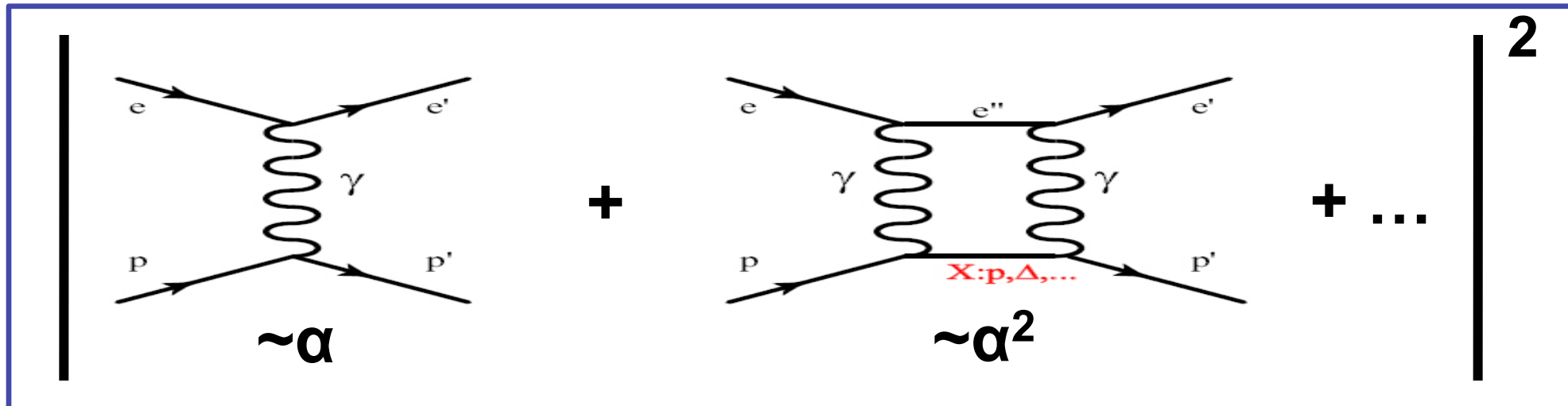


grows with Q^2 !

Expect $\sim 6\%$ effect for OLYMPUS@2.0GeV



Lepton-proton elastic scattering



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

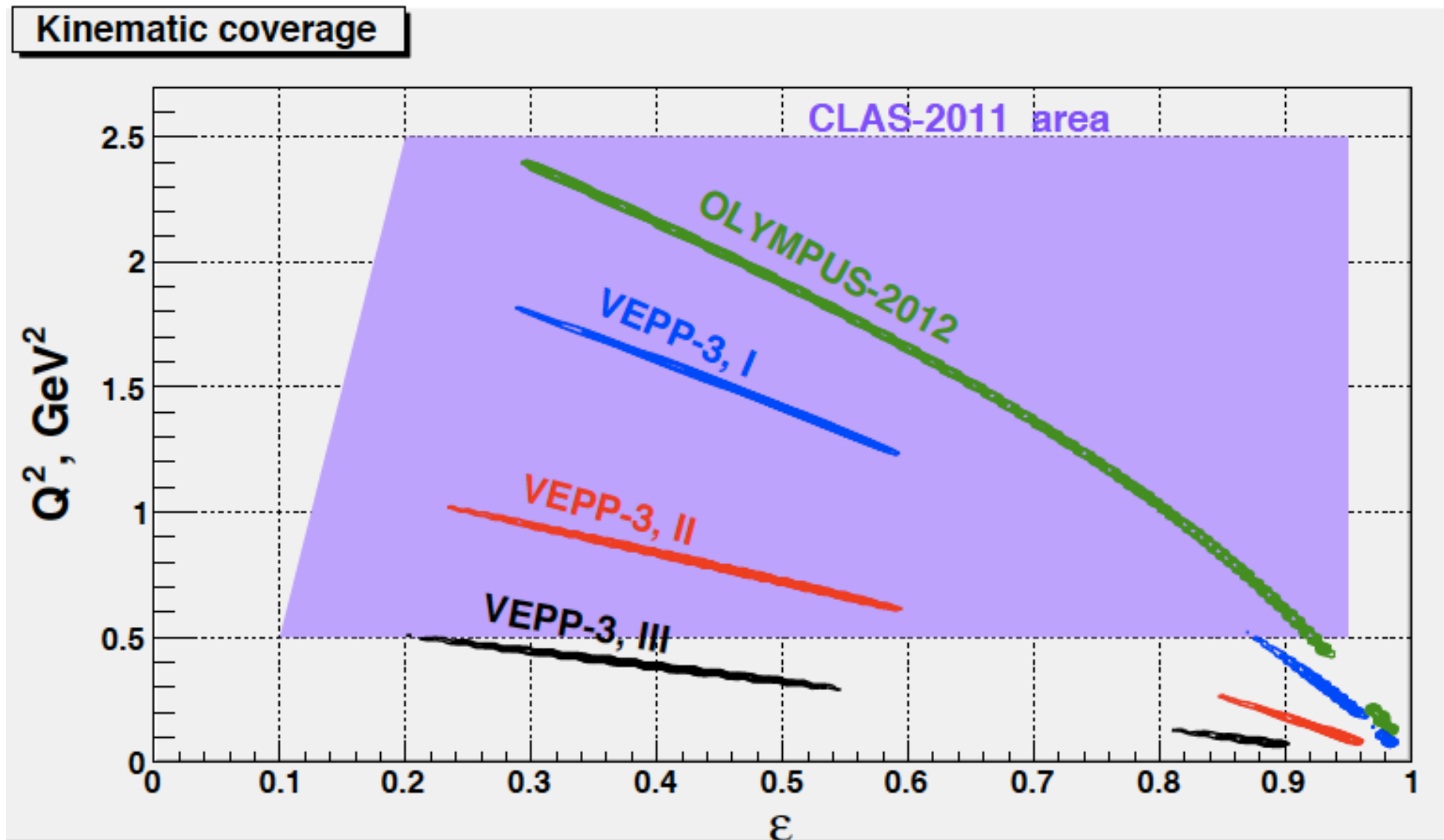
$$\sigma_{e^\pm p} = |\mathcal{M}_{1\gamma}|^2 \pm 2\Re\{\mathcal{M}_{1\gamma}^\dagger \mathcal{M}_{2\gamma}\} + \dots$$

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

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

Comparison of e^+/e^- experiments

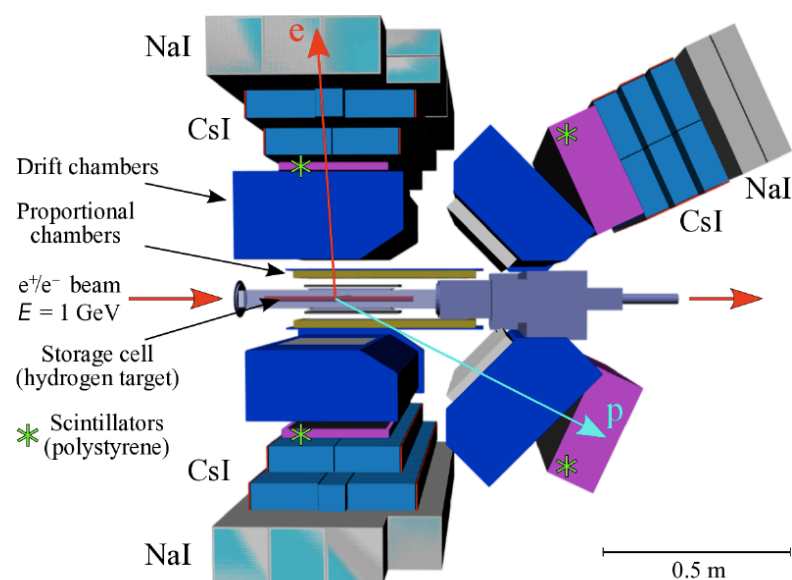
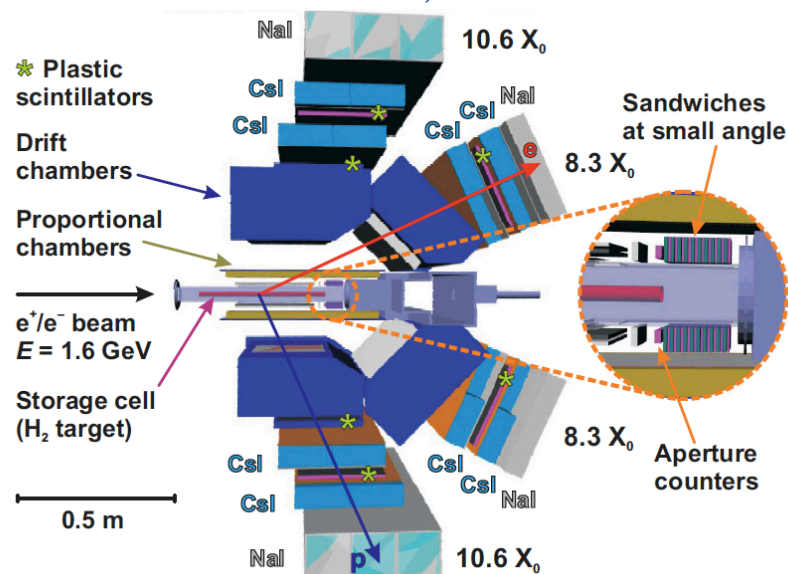
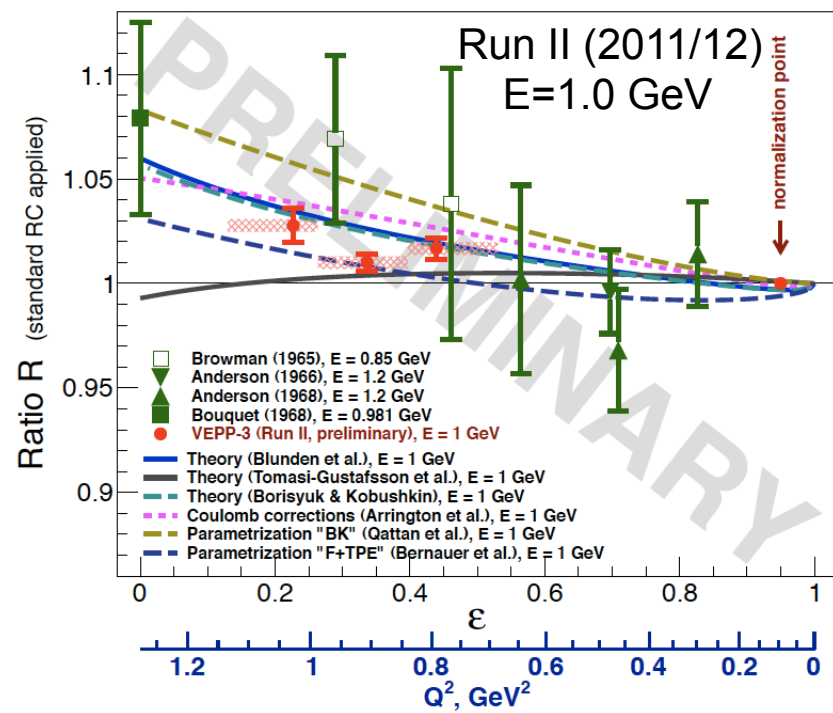
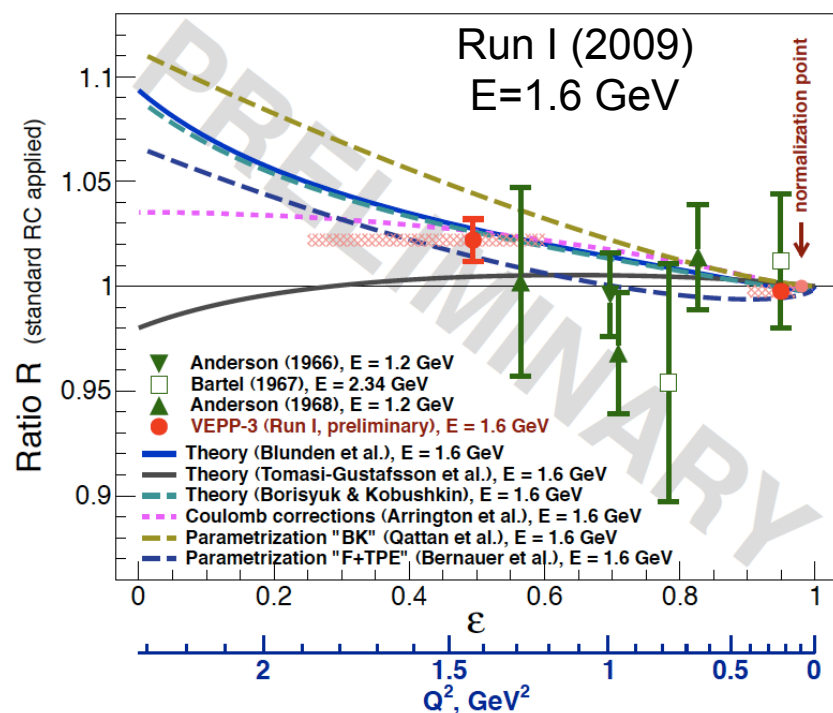
- Novosibirsk experiment ($E_{\text{beam}} = 1.6, 1$ and 0.6 GeV)
- CLAS @ JLab experiment ($E_{\text{beam}} = 0.5 \div 4$ GeV)
- OLYMPUS @ DESY experiment ($E_{\text{beam}} = 2$ GeV)



Comparison of e^+/e^- experiments

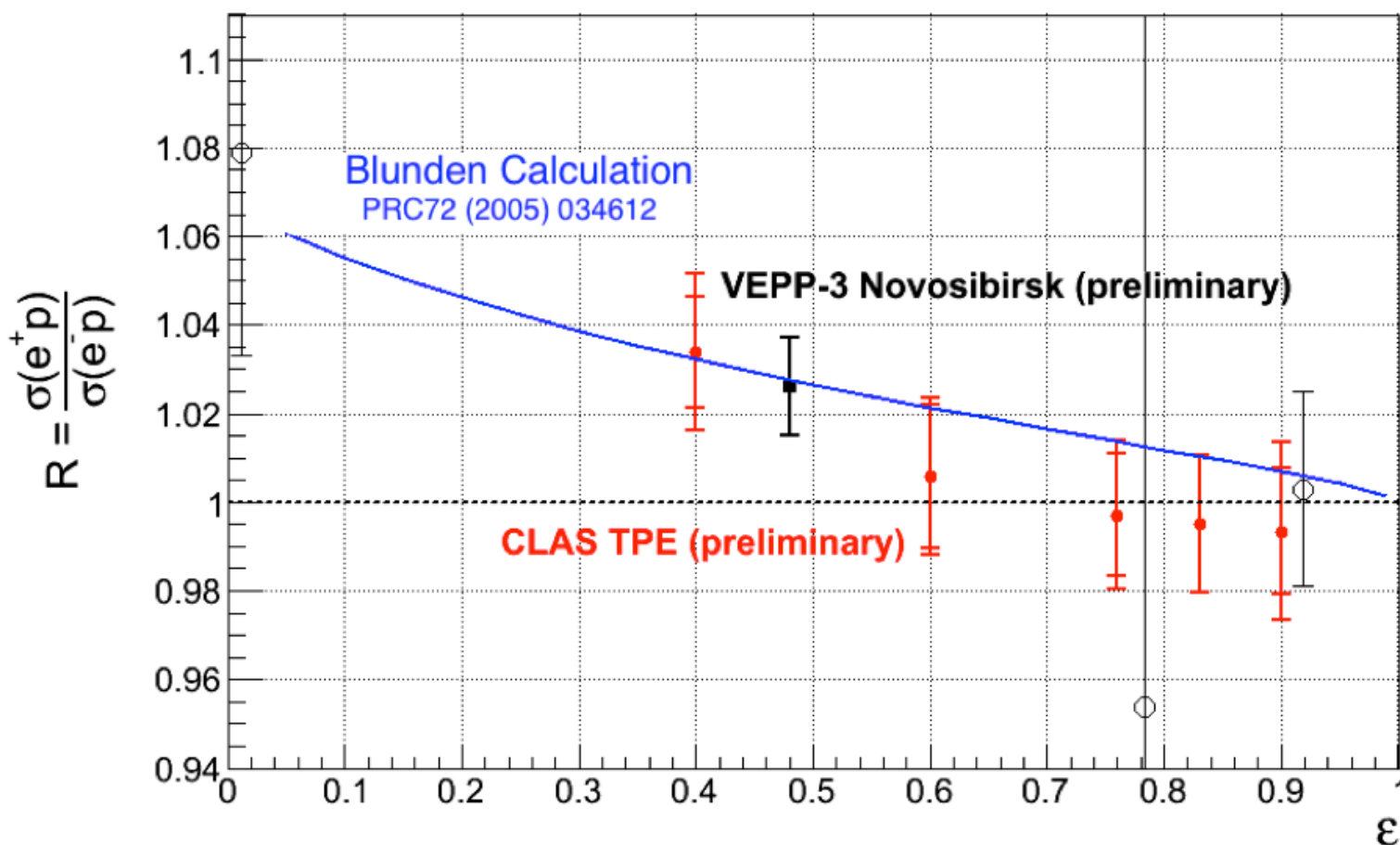
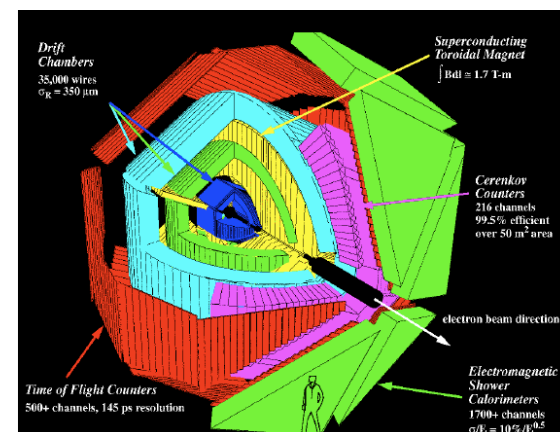
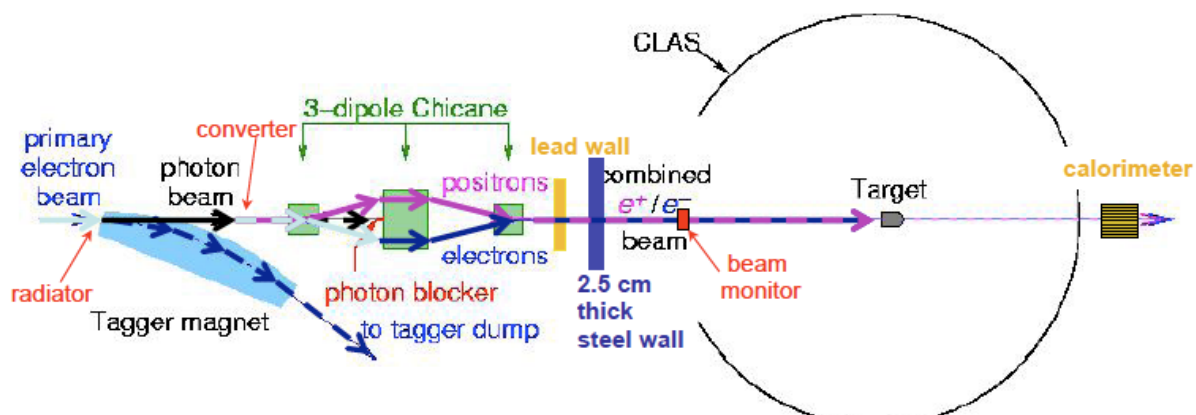
	VEPP-3 Novosibirsk	OLYMPUS DESY	EG5 CLAS JLab
beam energy	3 fixed	1 fixed	wide spectrum
equality of e^\pm beam energy	measured	measured	reconstructed
e^+/e^- swapping frequency	half-hour	24 hours	simultaneously
e^+/e^- lumi monitor	elastic low- Q^2	elastic low- Q^2 , Möller/Bhabha	from simulation
energy 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

TPE experiments: Novosibirsk/VEPP-3



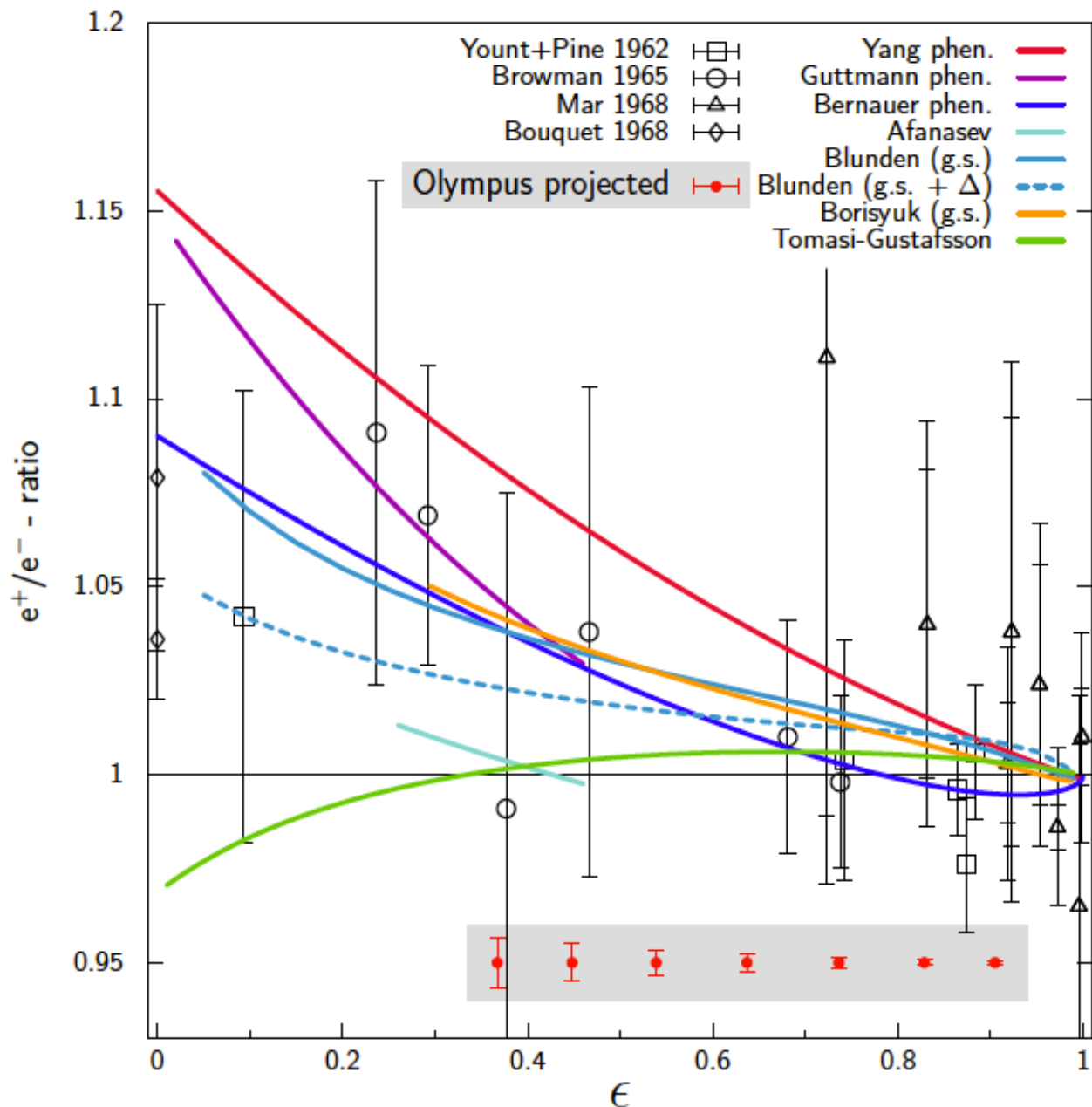
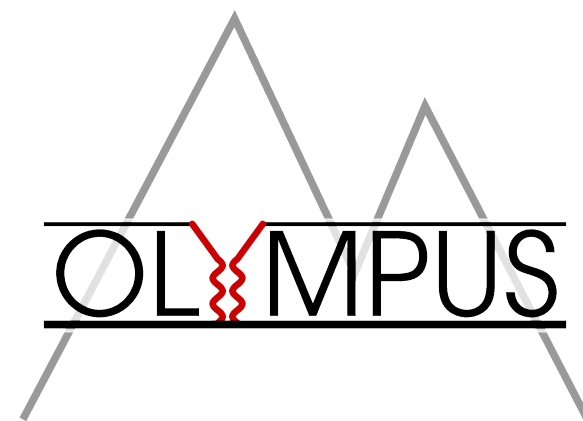
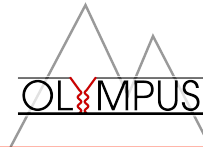
A. Gramolin, Workshop on Radiative Corrections in Annihilation and Scattering Experiments, Orsay, October 7-8, 2013

TPE experiments: CLAS (E04-116)



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

Projected results for OLYMPUS



Data from 1960's

Many theoretical predictions
with little constraint

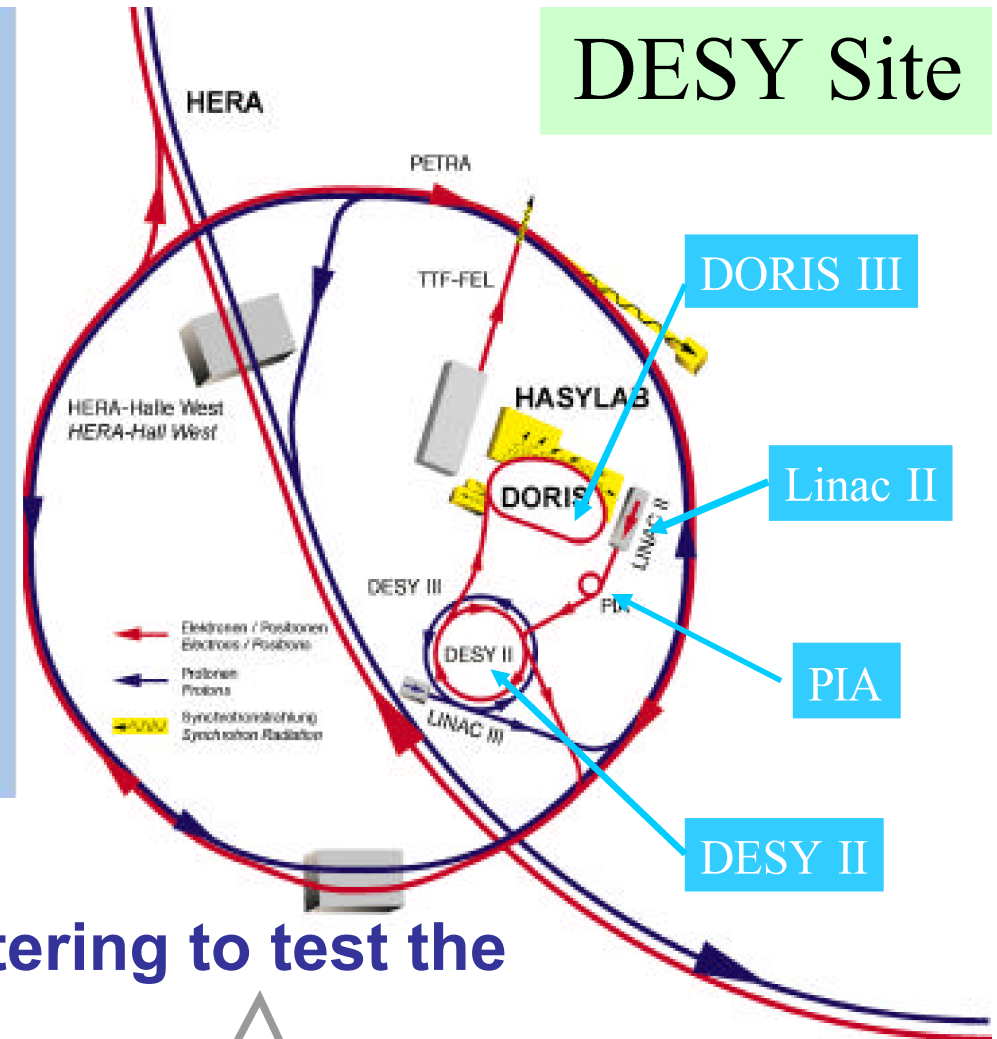
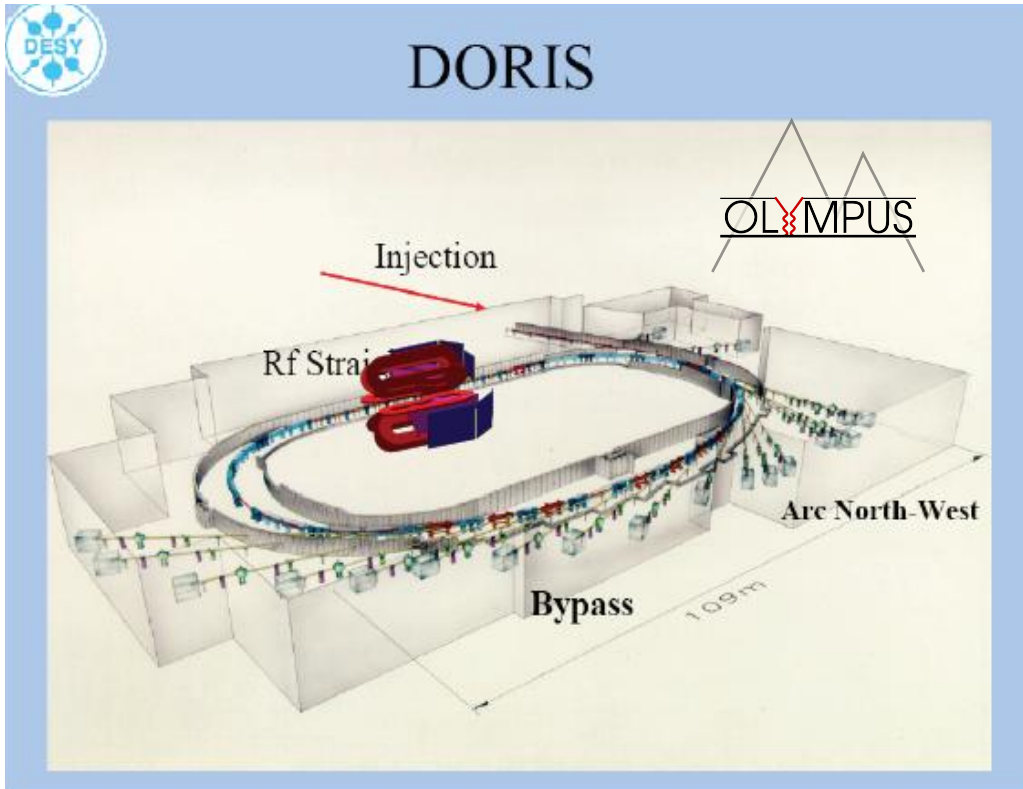
OLYMPUS:

E= 2.0 GeV

$0.4 < Q^2/(\text{GeV}/c)^2 < 2.2$

**Acquire 3.6 fb^{-1} for $<1\%$
projected uncertainties**

Data taking completed in 2012



positron-proton and
electron-proton elastic scattering to test the
hypothesis of

Multi-

Photon exchange

Using

Doris

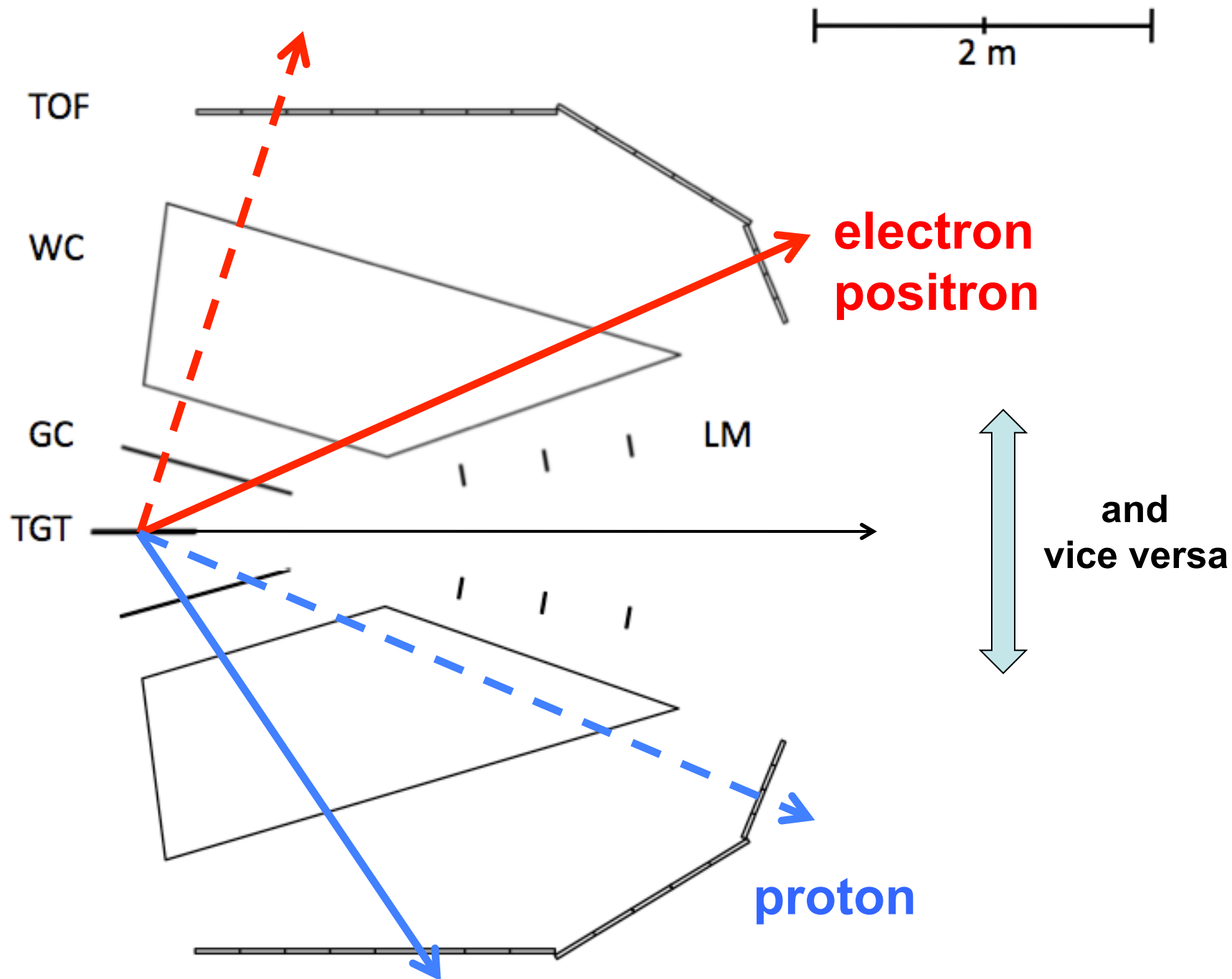
OLYMPUS

The OLYMPUS experiment

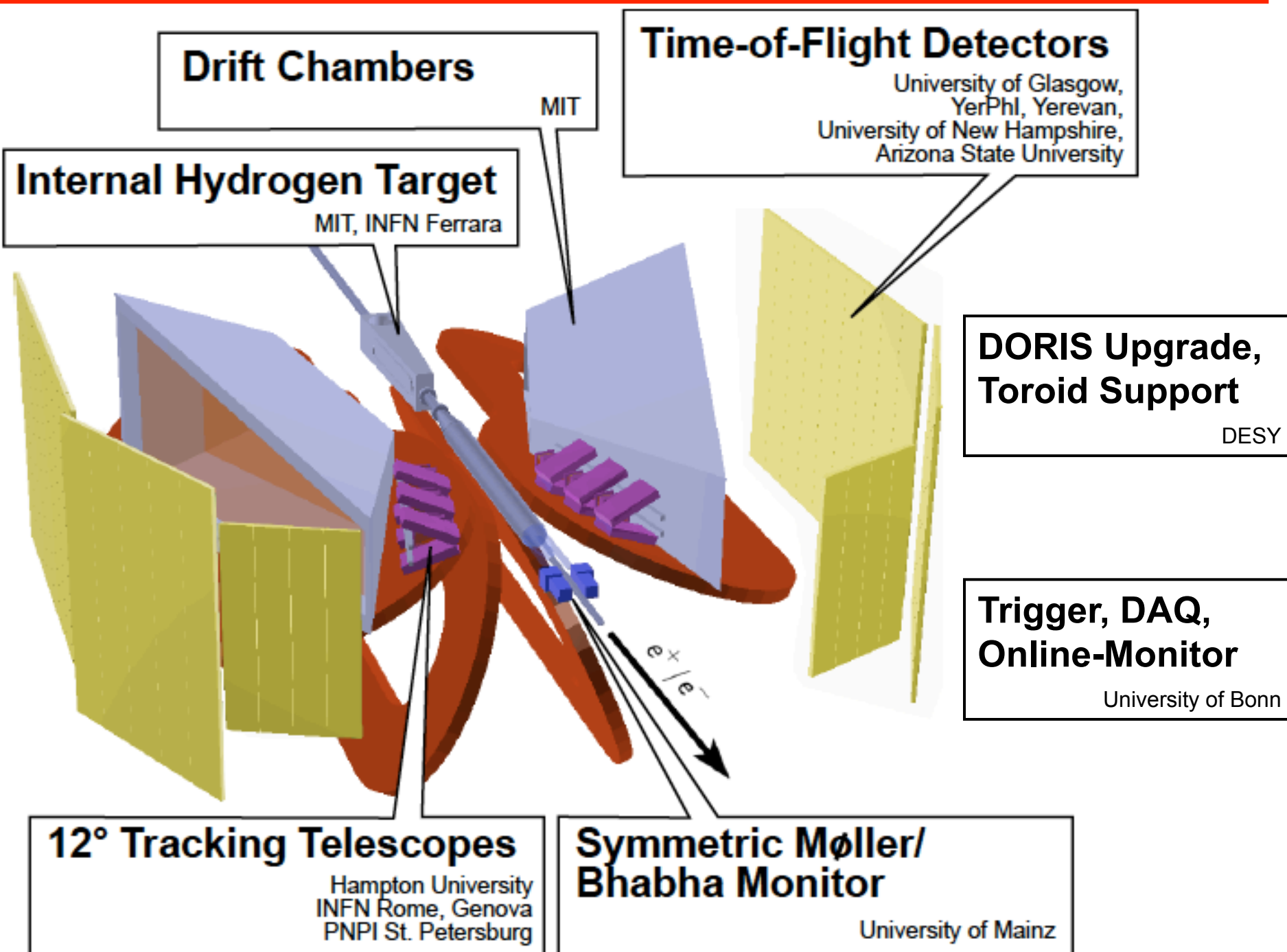
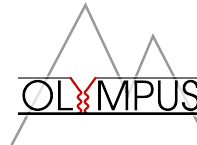


- **Electrons/positrons (100mA) in 2.0–4.5 GeV storage ring
DORIS at DESY, Hamburg, Germany**
- **Unpolarized internal hydrogen target (buffer system)
 3×10^{15} at/cm² @ 100 mA \rightarrow $L = 2 \times 10^{33}$ / (cm²s)**
- **Large acceptance detector for e-p in coincidence
BLAST detector from MIT-Bates available**
- **Redundant monitoring of luminosity
Pressure, temperature, flow, current measurements
Small-angle elastic scattering at high epsilon / low Q²
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

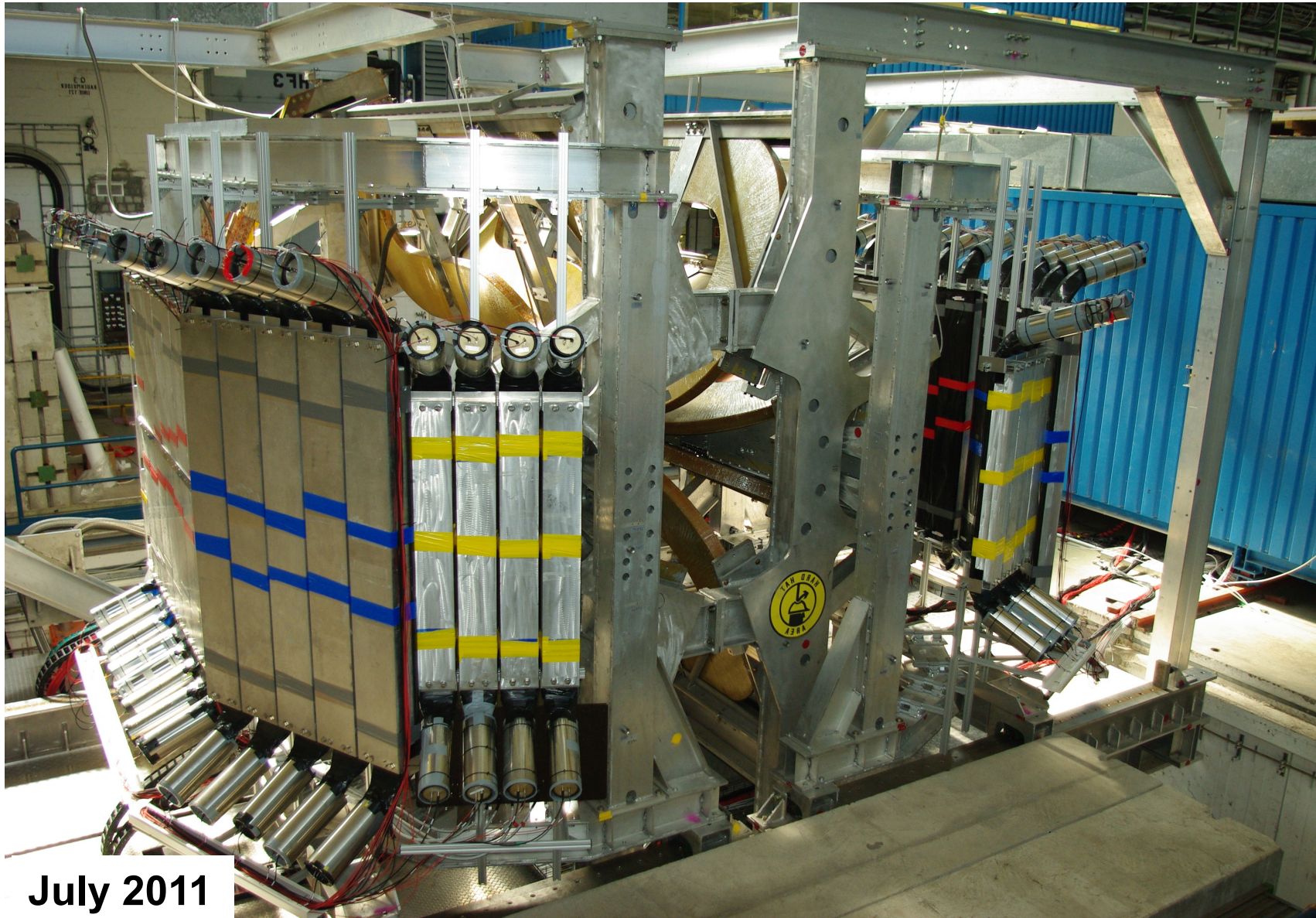


The designed OLYMPUS detector



based on a figure by R. Russell

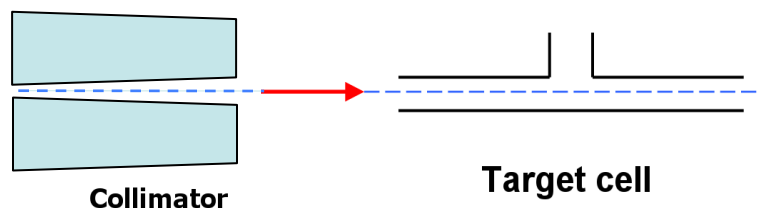
The realized OLYMPUS detector



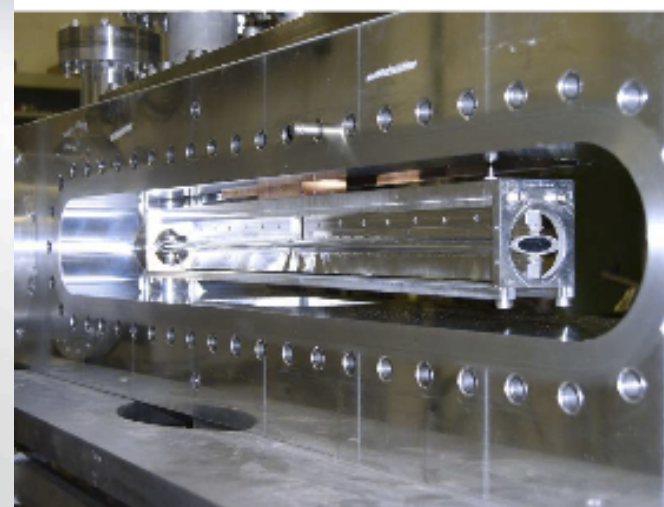
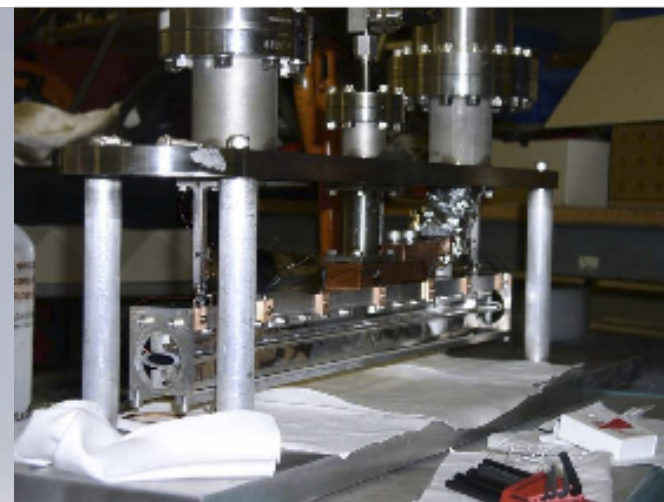
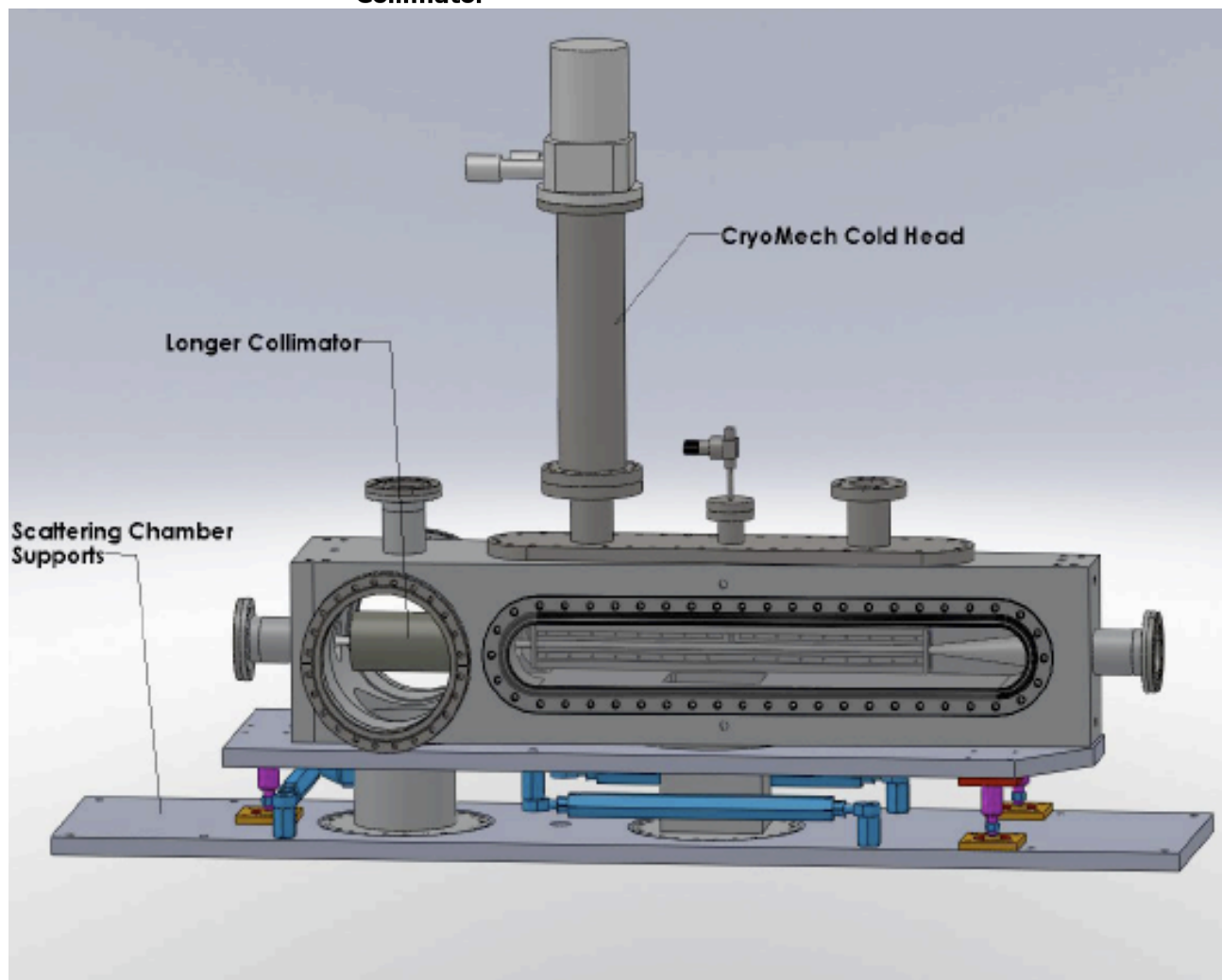
July 2011

“The OLYMPUS Experiment”, R. Milner *et al.*, NIMA 741, 1 (2014)

Target and vacuum system



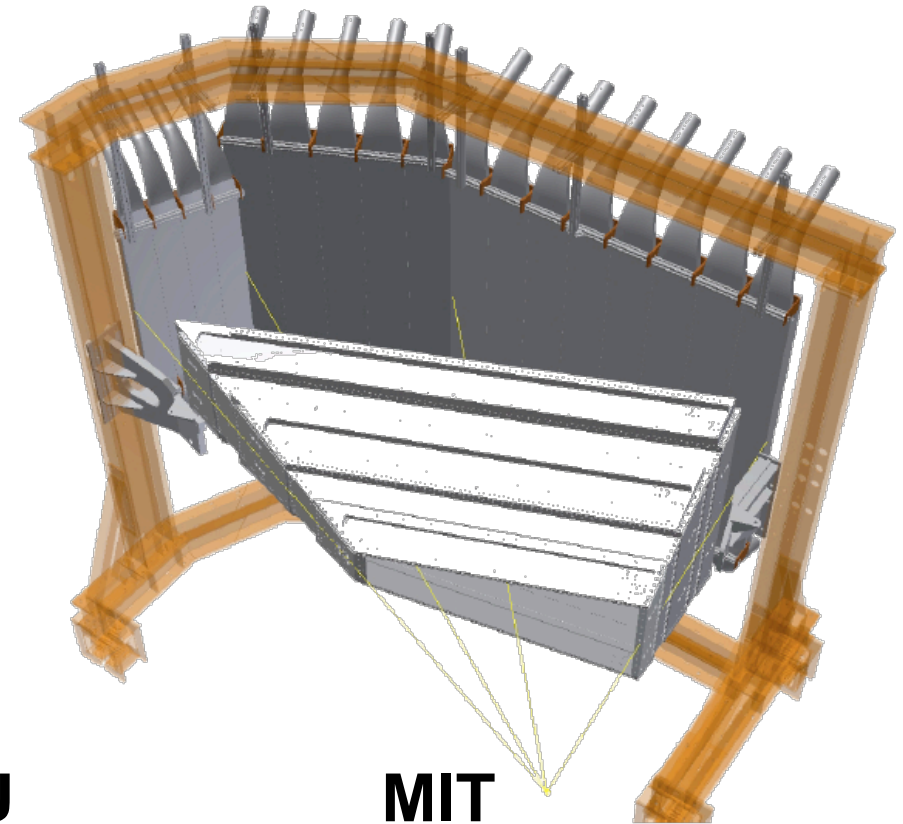
MIT
INFN Ferrara



Designed and built in 2010
Very stable operation after repairs

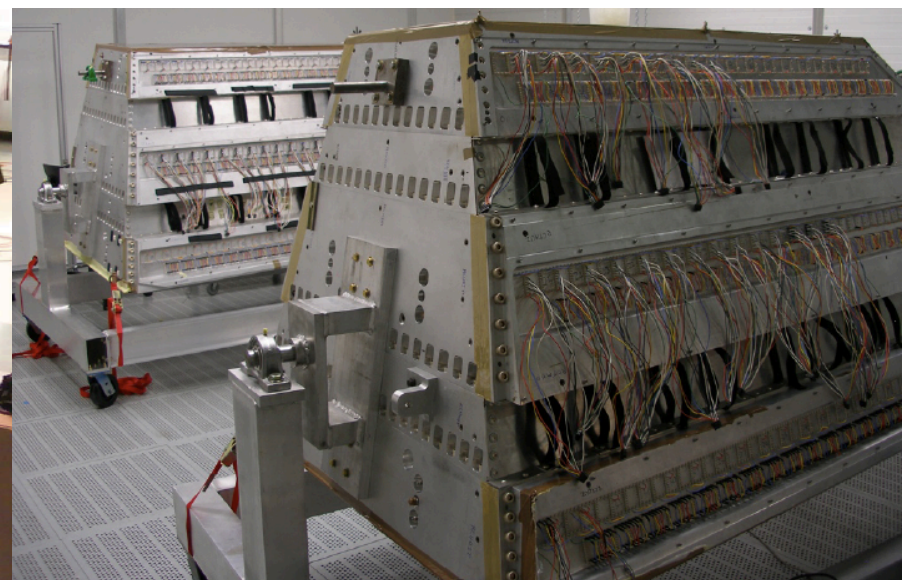
J.C. Bernauer *et al.*,
NIMA 755, 20 (2014)

- **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



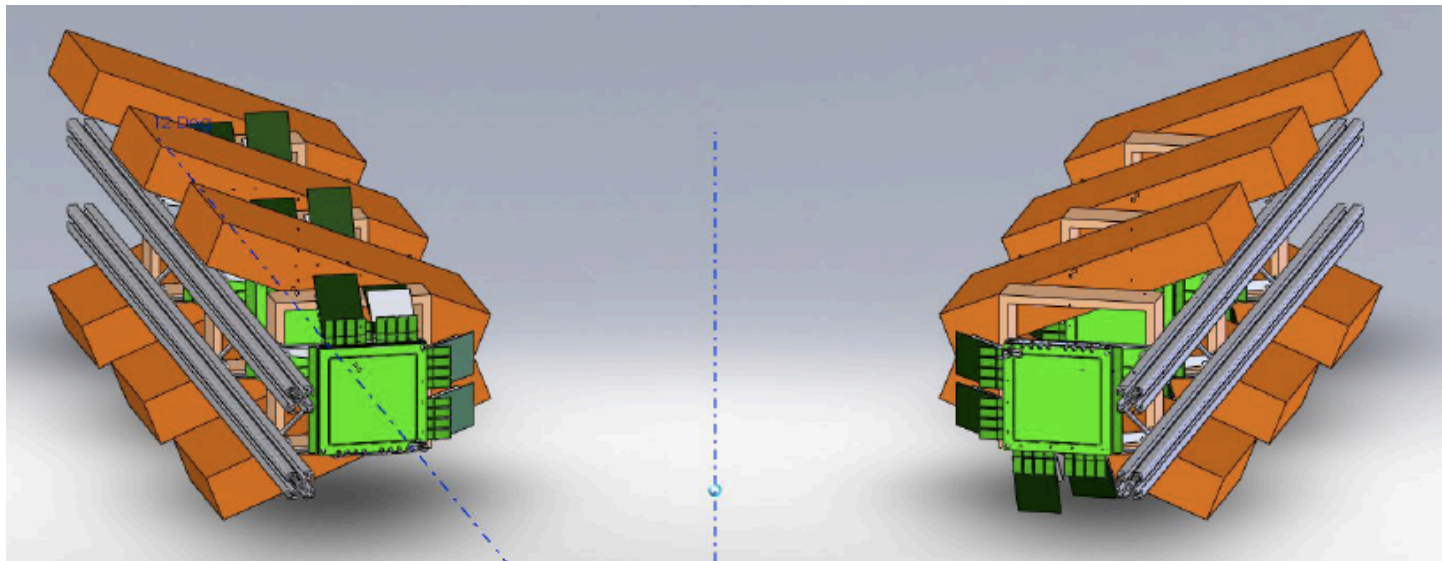
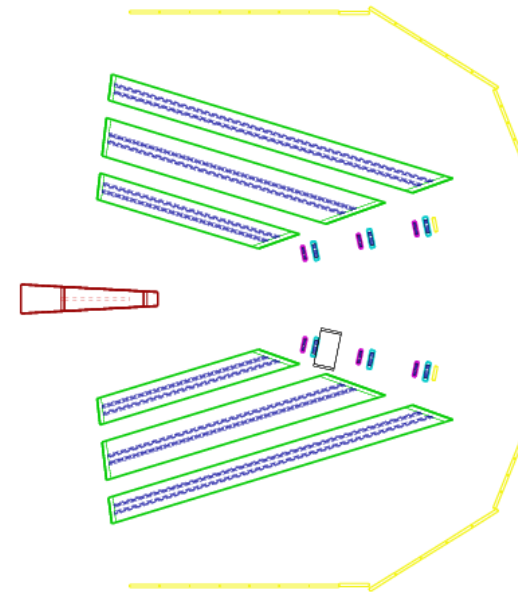
Glasgow, Yerevan, UNH, ASU

MIT



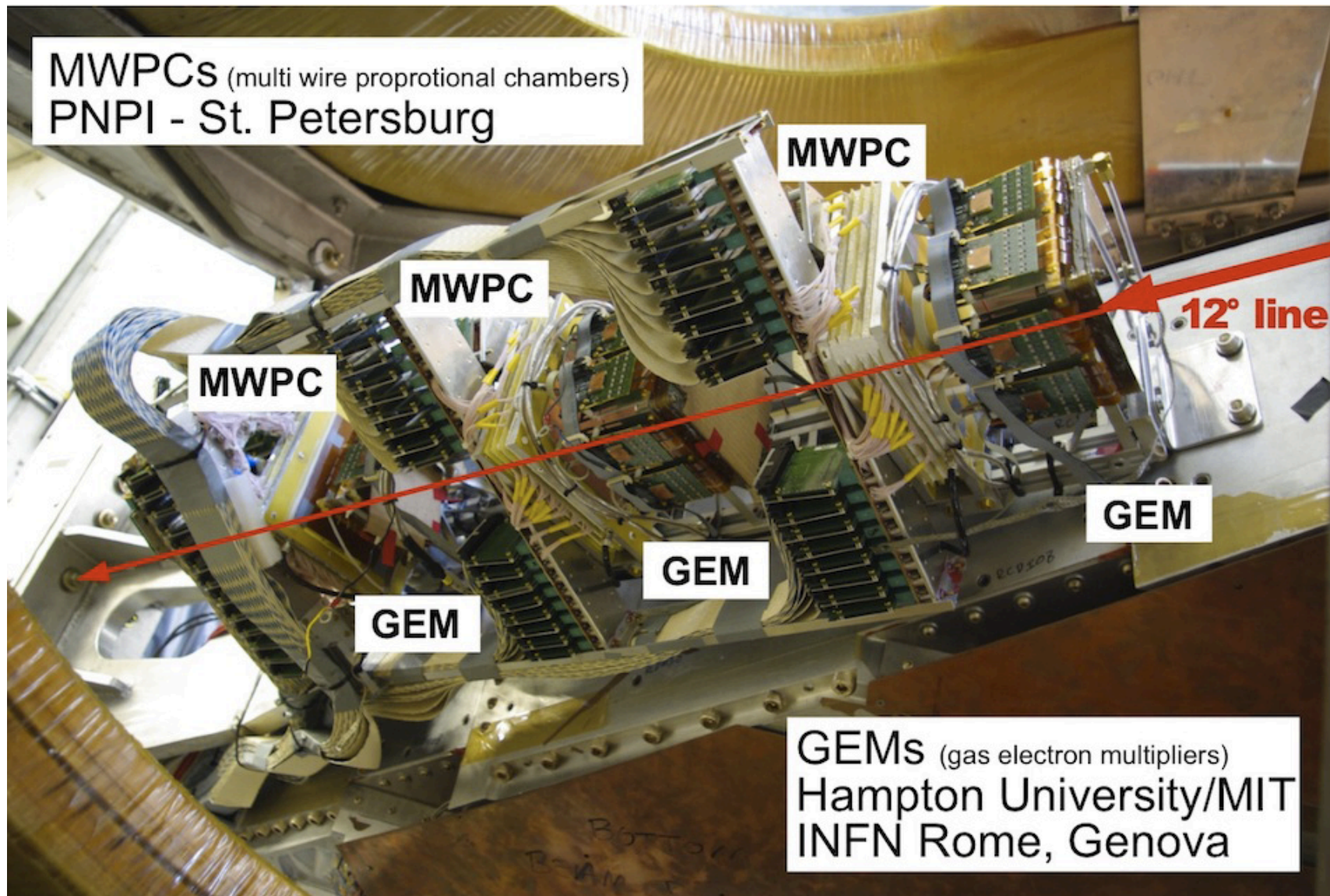
Luminosity monitors: GEM + MWPC

- 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**)



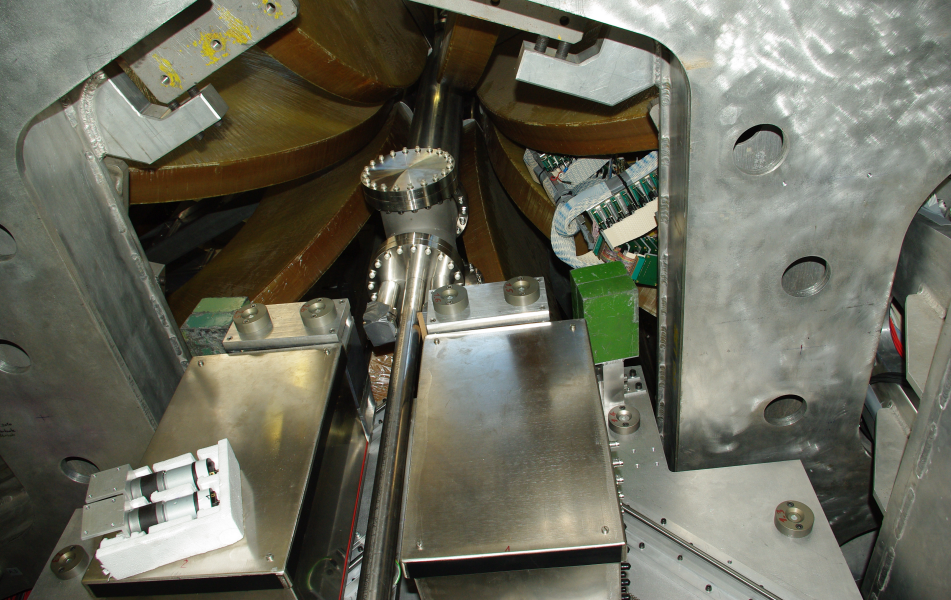
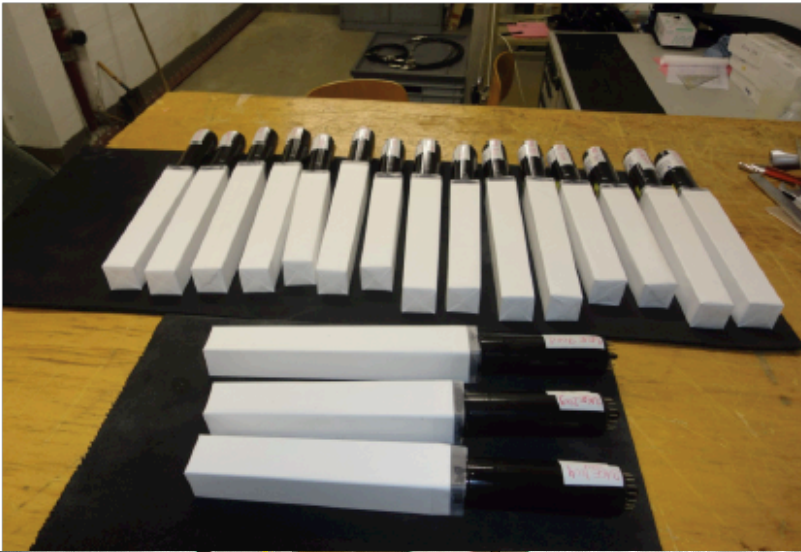
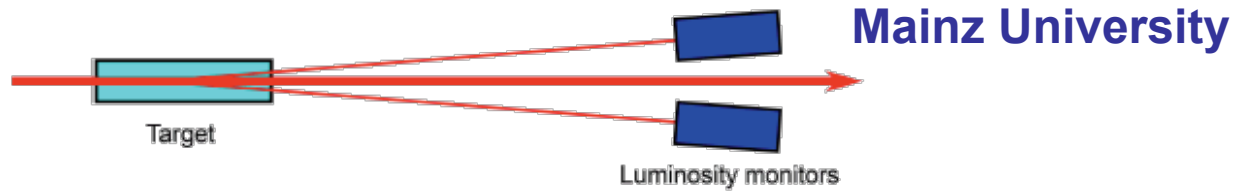
Designed to fit into forward cone

Luminosity monitors: GEM + MWPC



**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

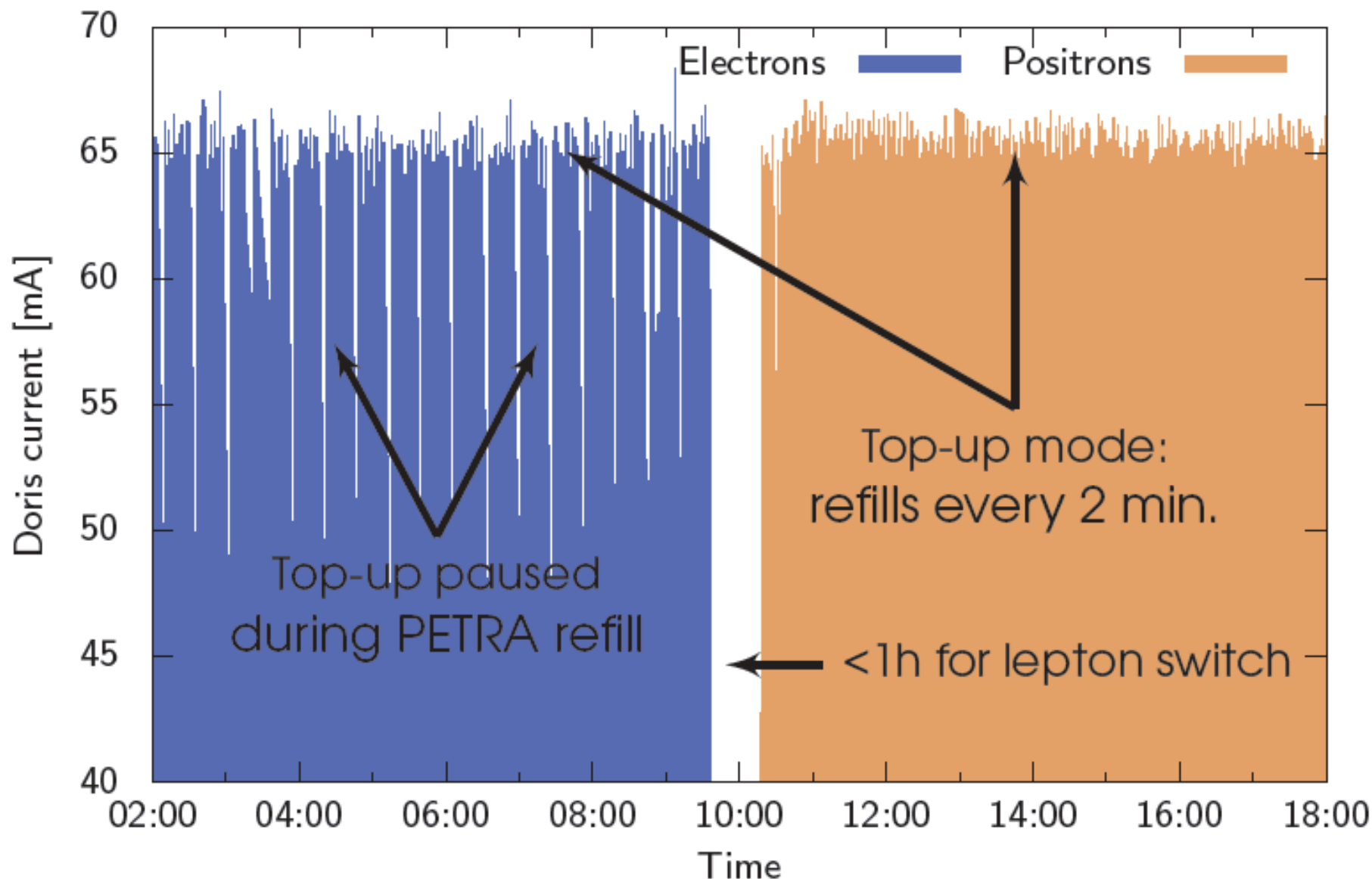


- **Symm. angle 1.3° @ 2.0 GeV**
- **Matrix of 3x3 PbF₂ crystals**
- **Tested at DESY and MAMI**

Performance of DORIS

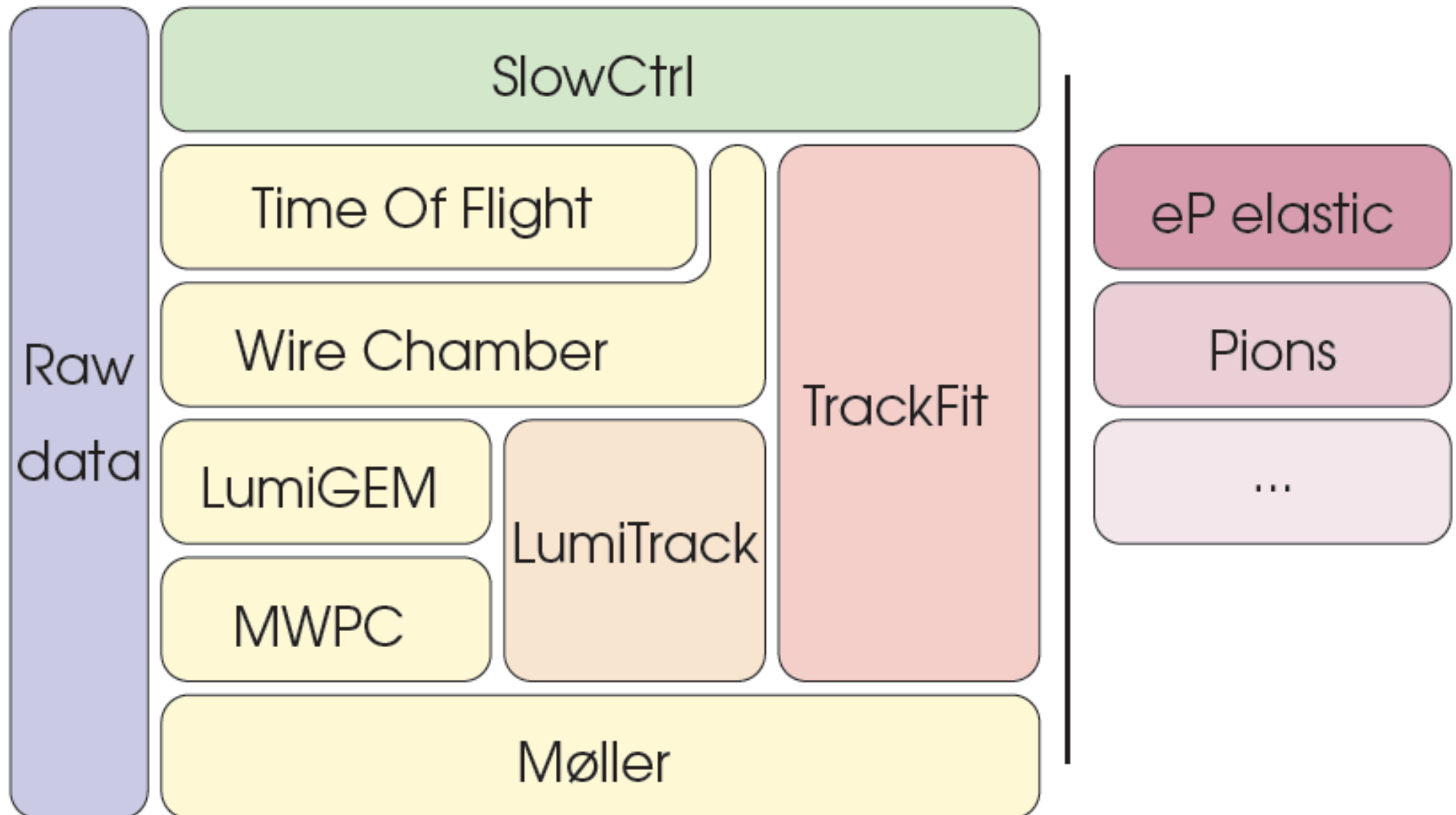
- DORIS top-up mode established
- Typically 65mA / 0.5 sccm
- Refills every ~2 minutes by few mA
- PETRA refills every 30 minutes

Doris Current on Dec. 2nd



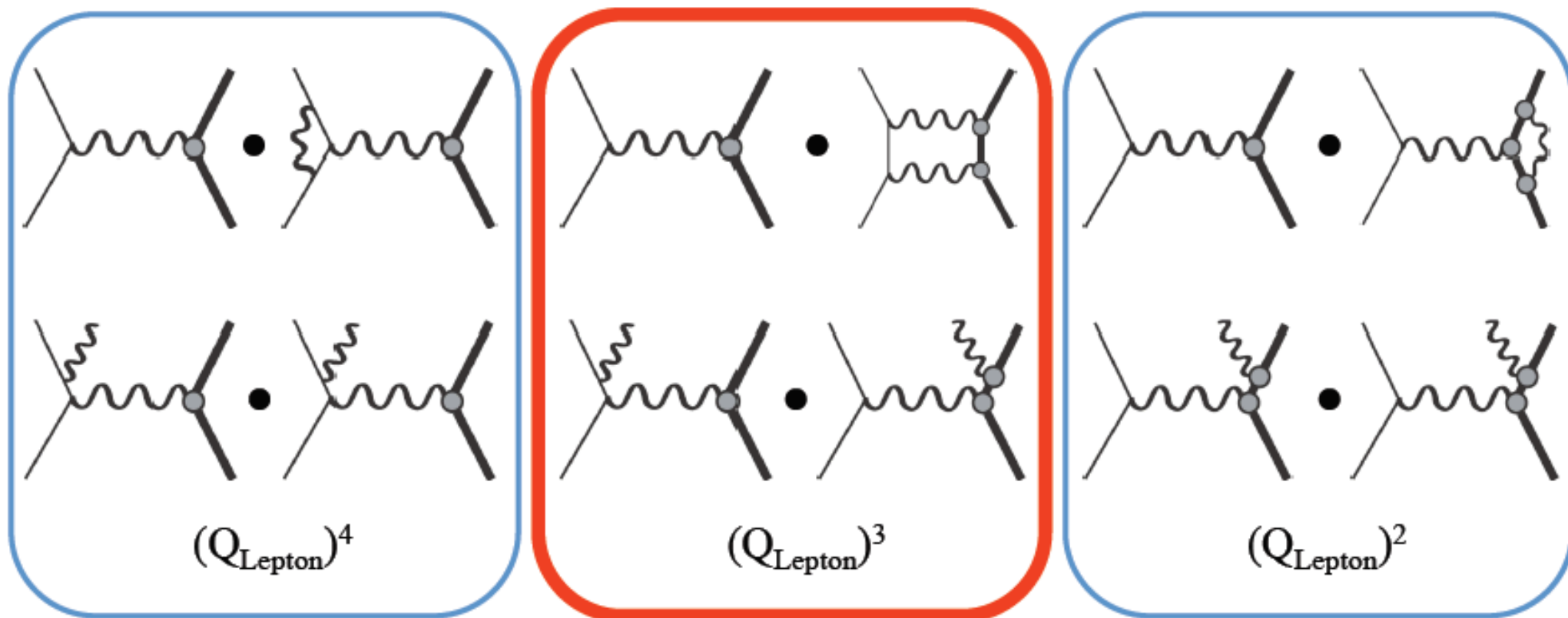
**ROOT based C++ analysis framework (“cooker”)
with plug-ins and recipes
and full MC integration**

(J. Bernauer)



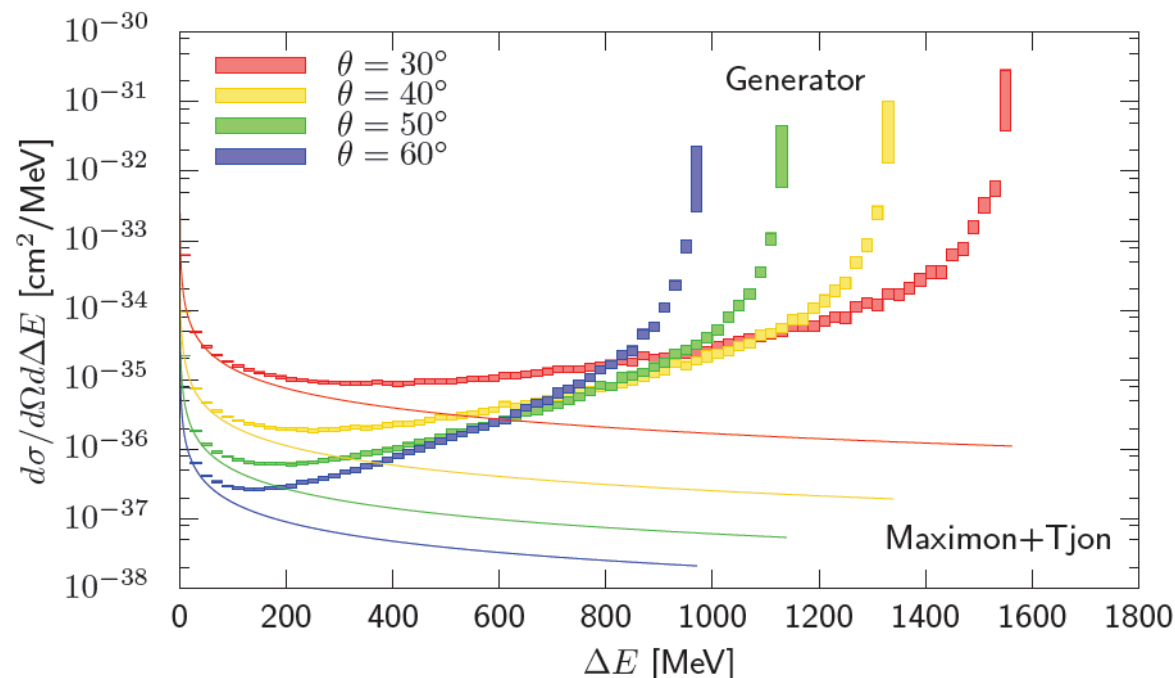
Radiative corrections of order α^3

- Use MC framework to accurately implement all 'standard' RC and to extract effect from hard TPE
- Ensure consistency between different experiments

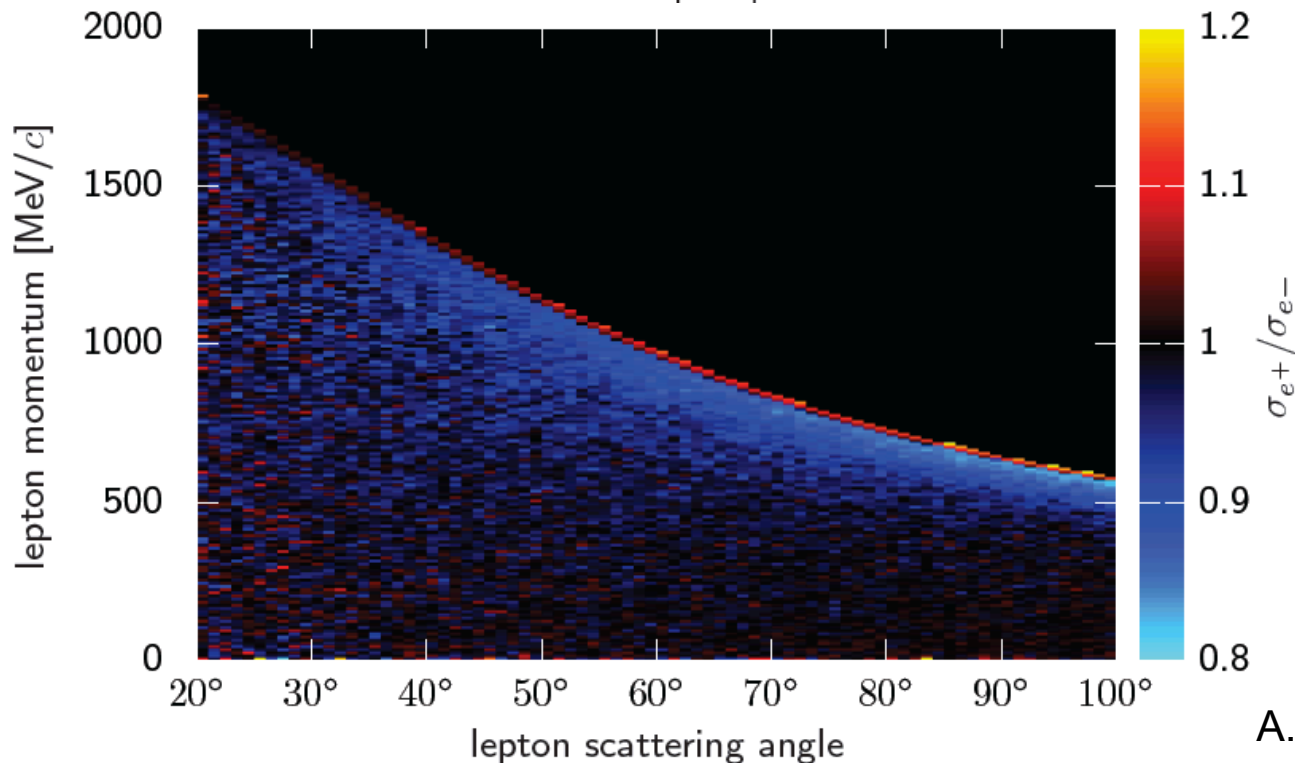


Changes sign with lepton sign

MIT radiative generator

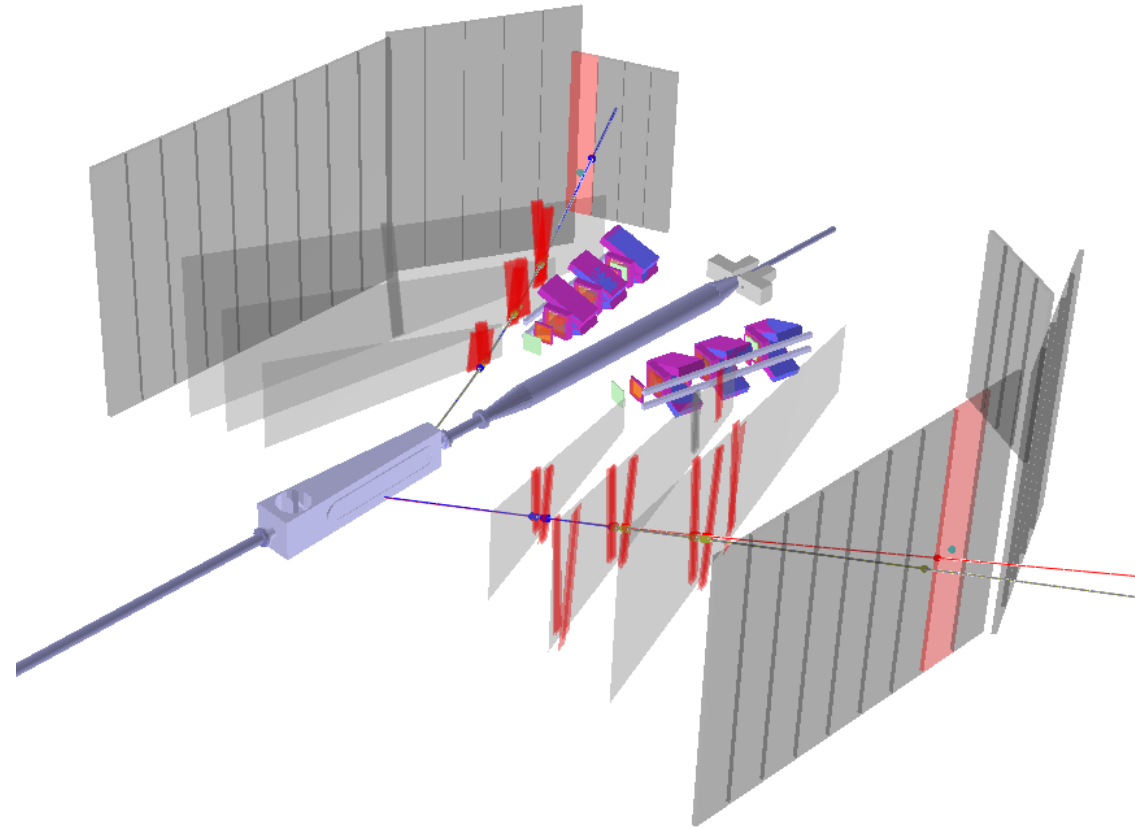
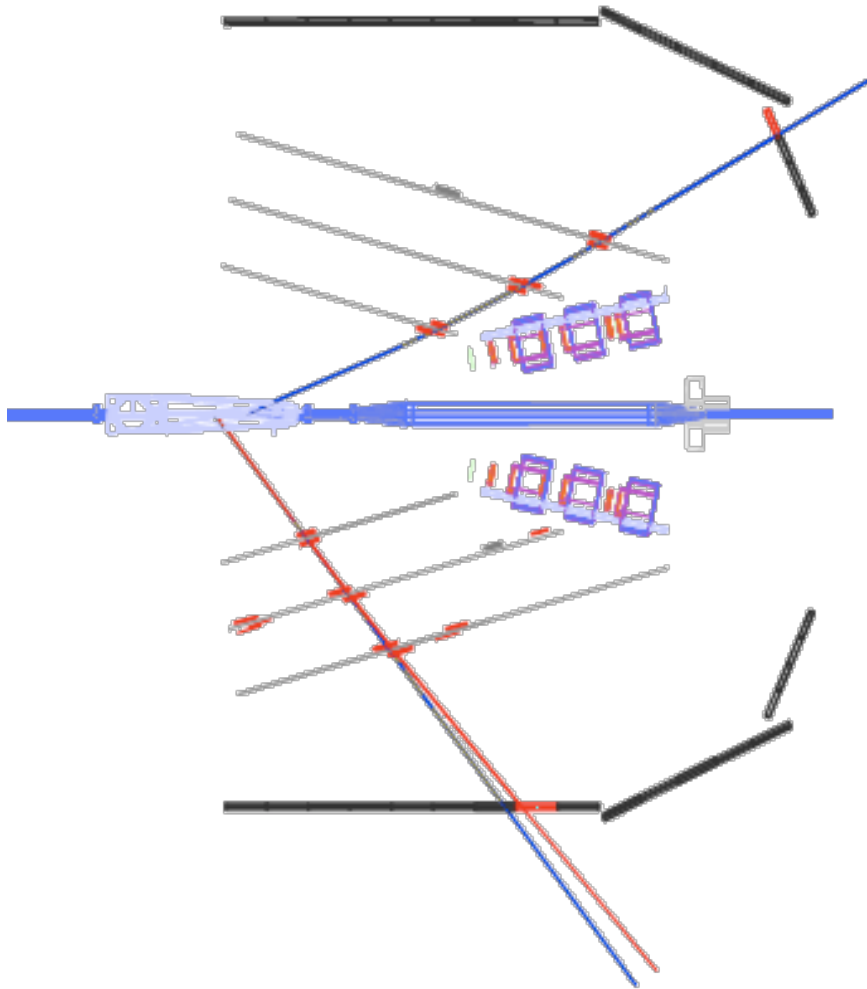


- Avoids approximations
- Agreement with Maximon&Tjon (soft photons) at low ΔE
- Excellent agreement with VEPP-3 generator



Effect on $\sigma_{e^+}/\sigma_{e^-}$

Event display (3D)

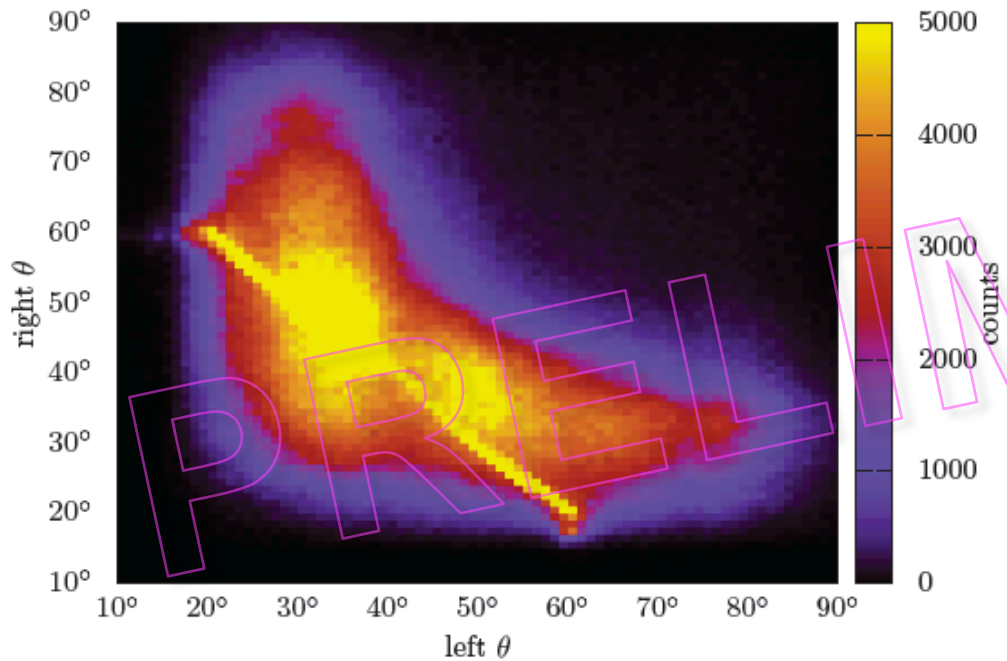


Run 4975, event 78

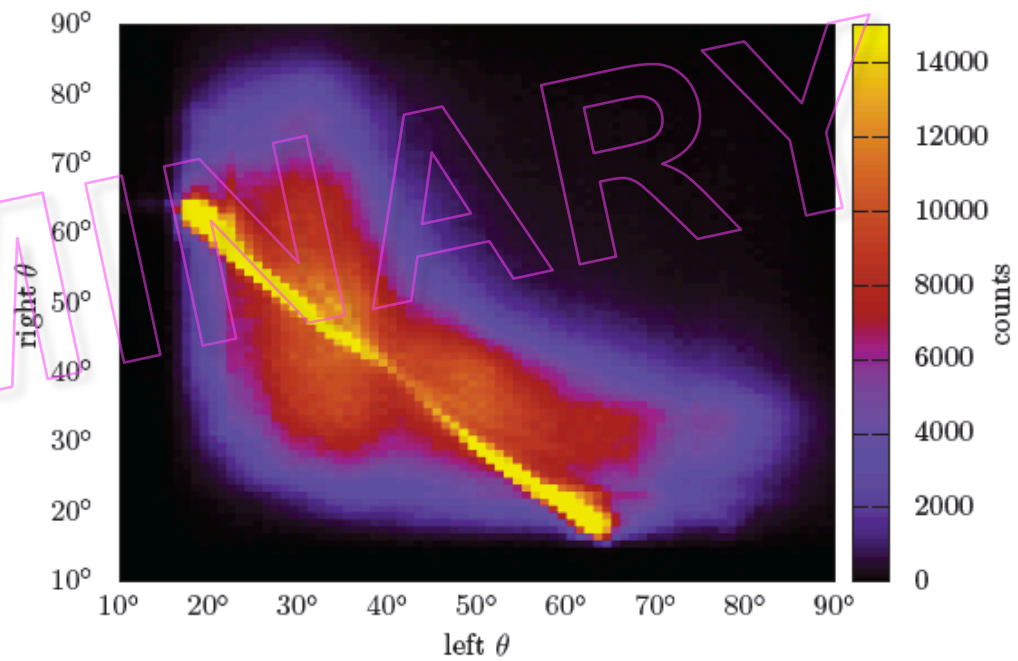
Tracking: very preliminary ...

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

Electron beam



Positron beam

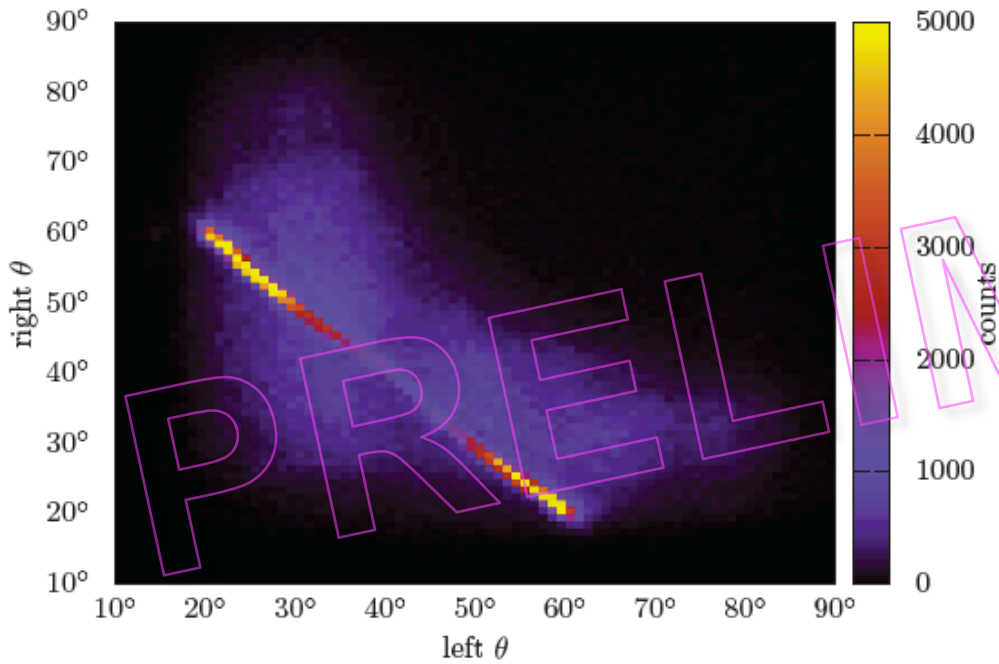


Polar angle in the right sector versus polar angle in left sector

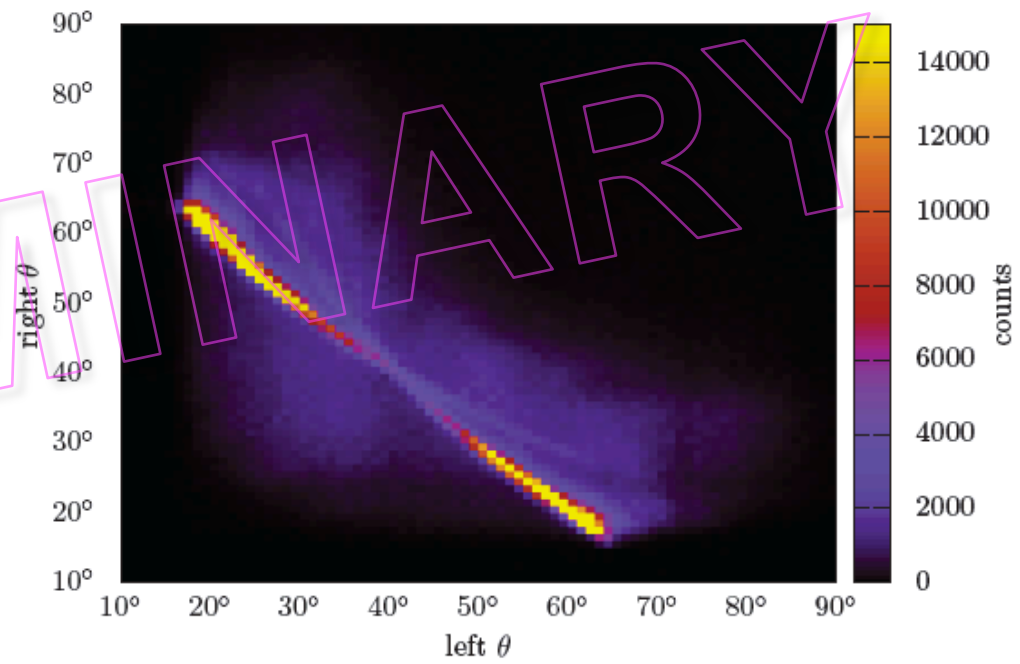
Tracking: very preliminary ...

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

Electron beam



Positron beam

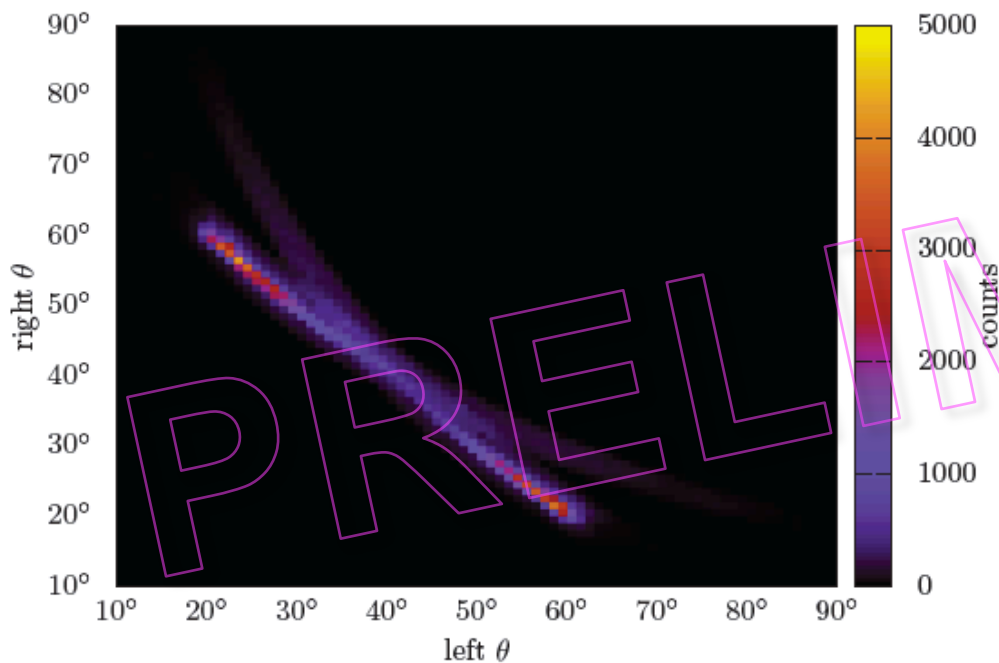


Polar angle in the right sector versus polar angle in left sector
Coplanarity cut ± 5 degrees

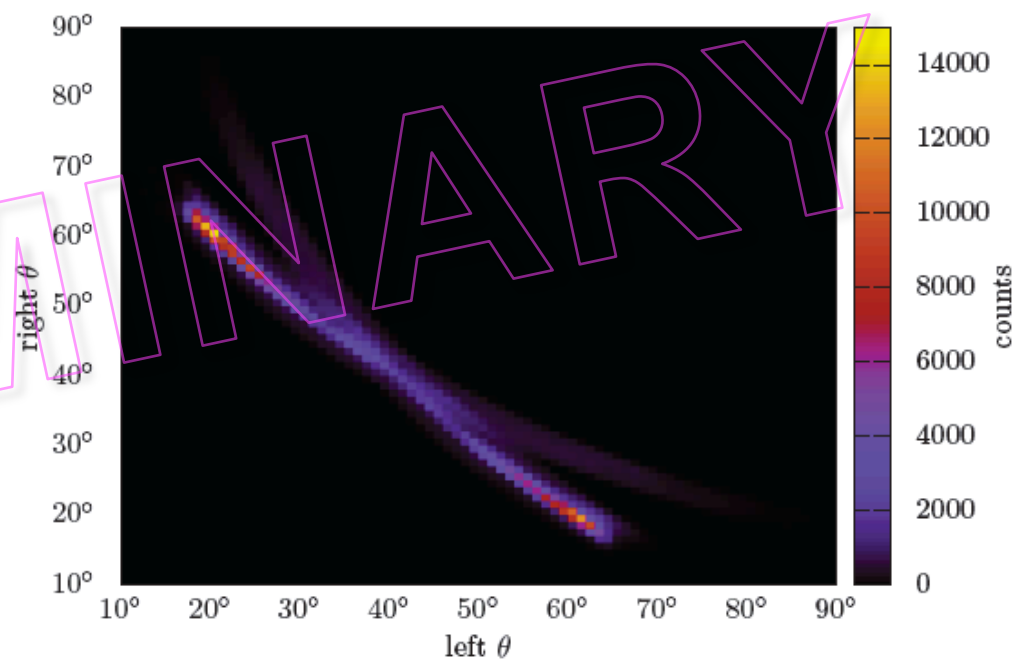
Tracking: very preliminary ...

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

Electron beam



Positron beam



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

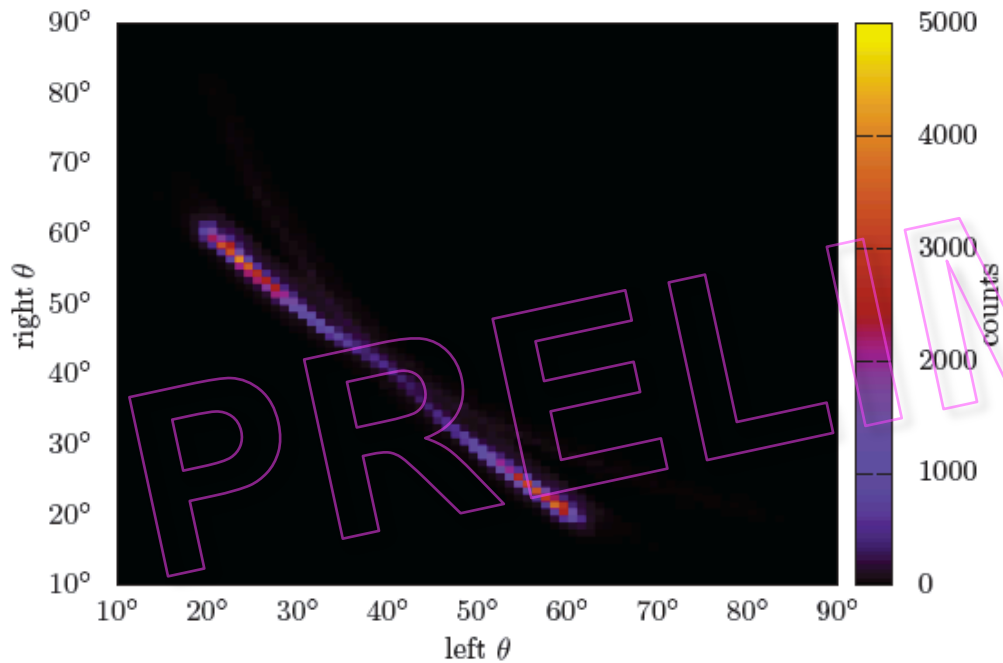
Coplanarity cut ± 5 degrees

Common vertex ± 100 mm

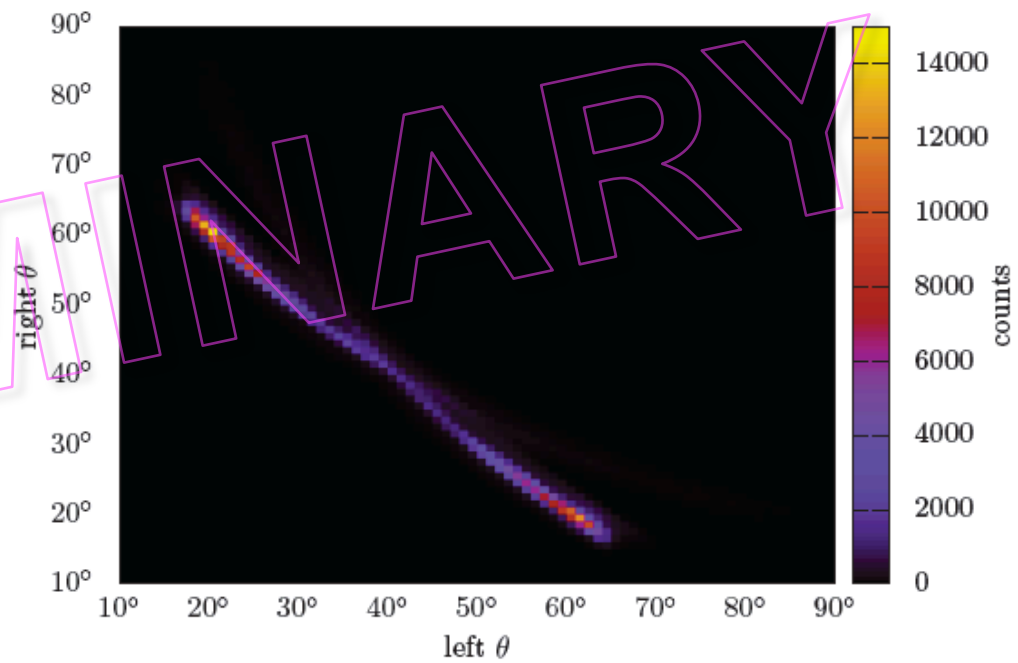
Tracking: very preliminary ...

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

Electron beam



Positron beam



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

Coplanarity cut ± 5 degrees

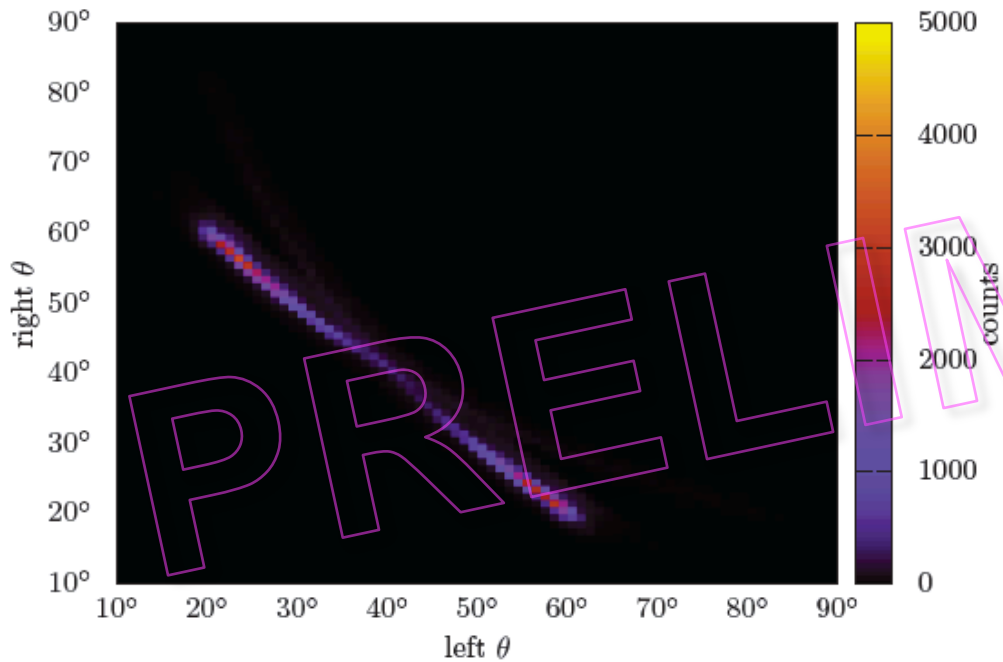
Common vertex ± 100 mm

Polar angle kinematic cut $|\theta_l - \theta_l(\theta_p)| < 5$ degrees

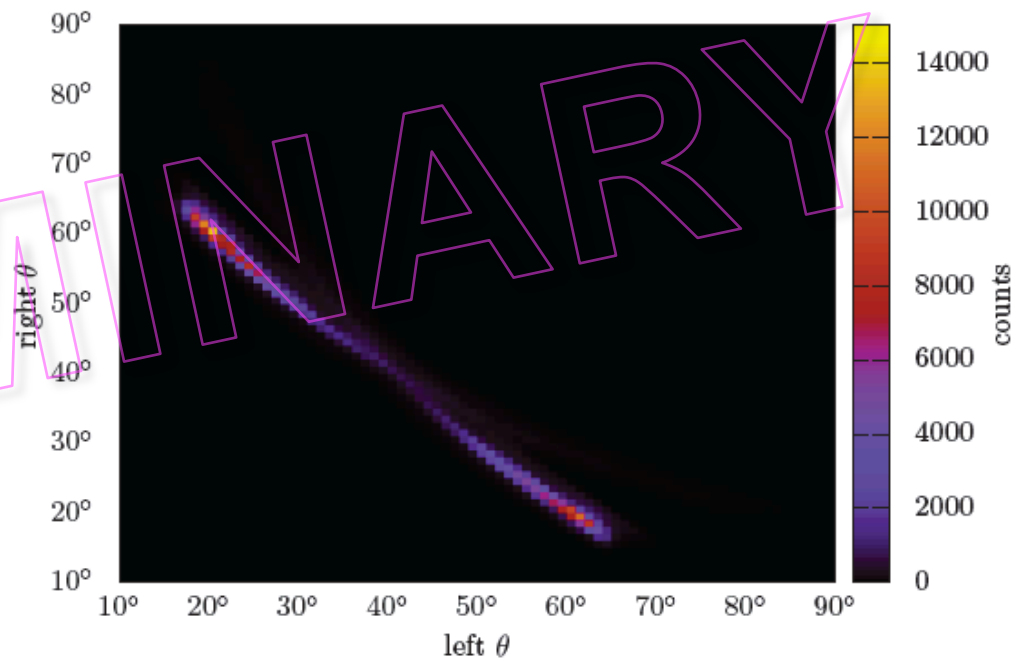
Tracking: very preliminary ...

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

Electron beam



Positron beam



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

Coplanarity cut ± 5 degrees

Common vertex ± 100 mm

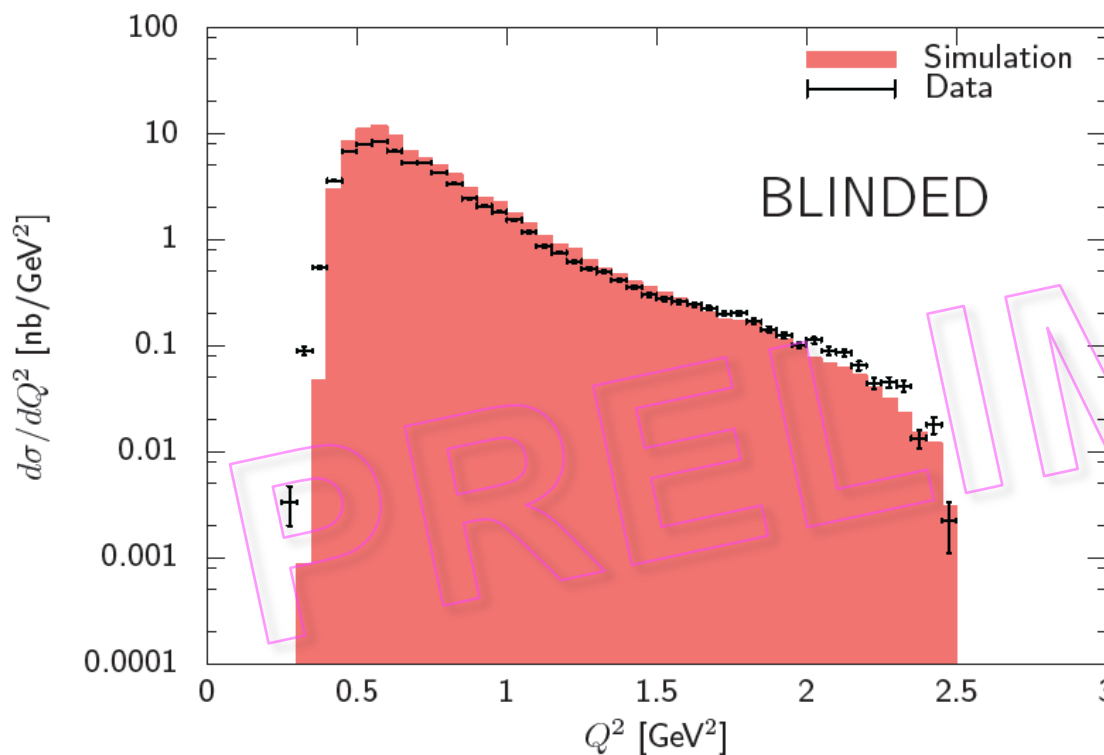
Polar angle kinematic cut $|\theta_l - \theta_r(\theta_p)| < 5$ degrees

Momentum kinematic cut $|P_p - P_p(\theta_p)| < 400$ MeV/c

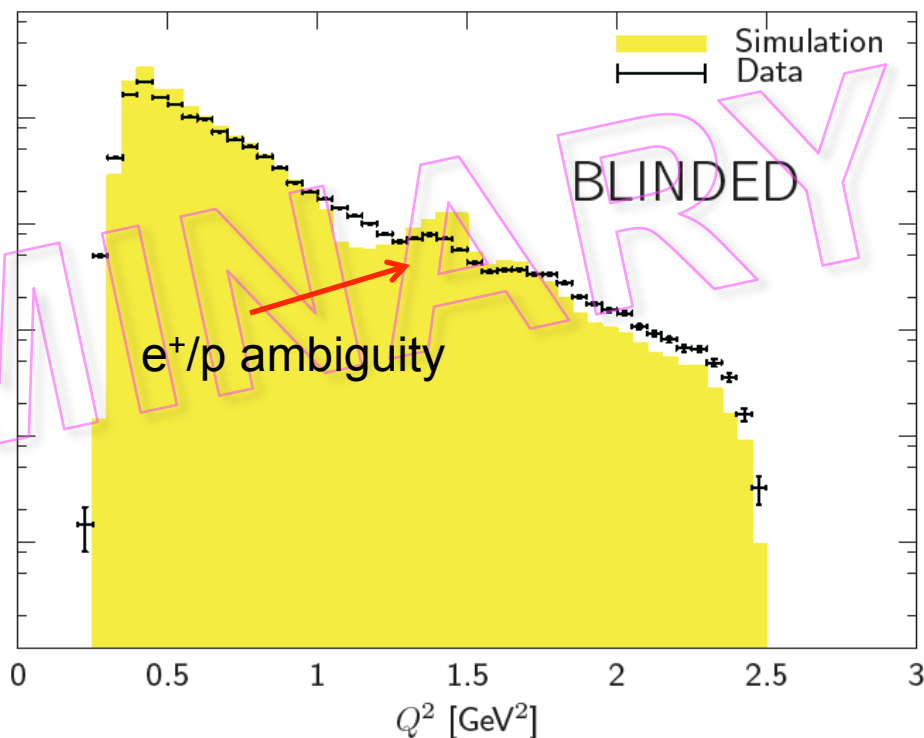
Yields: very preliminary ...

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

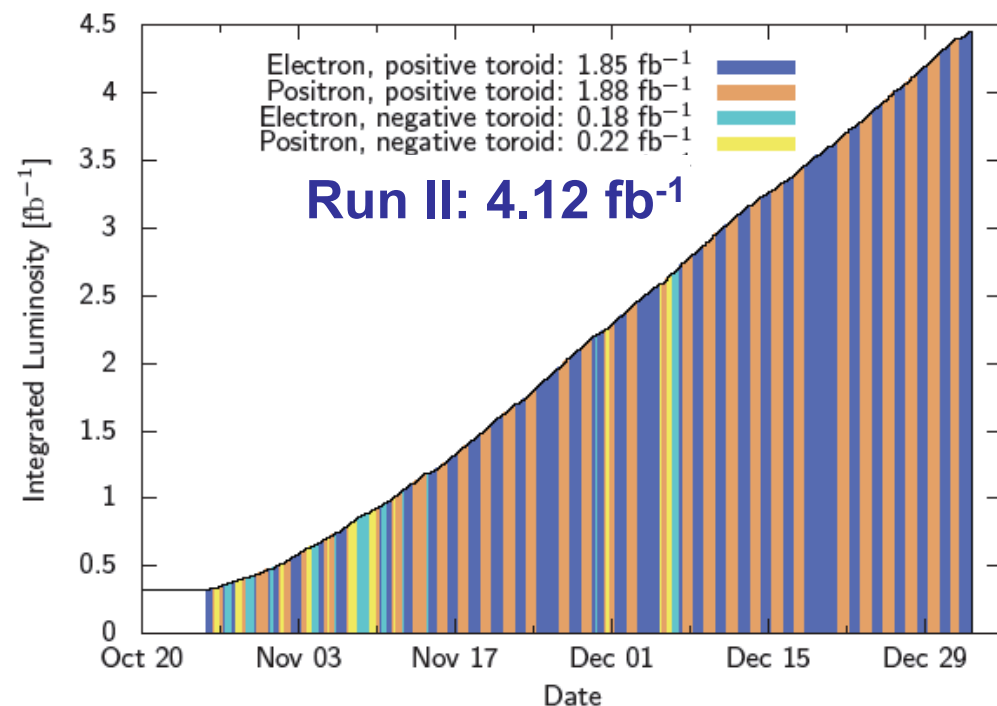
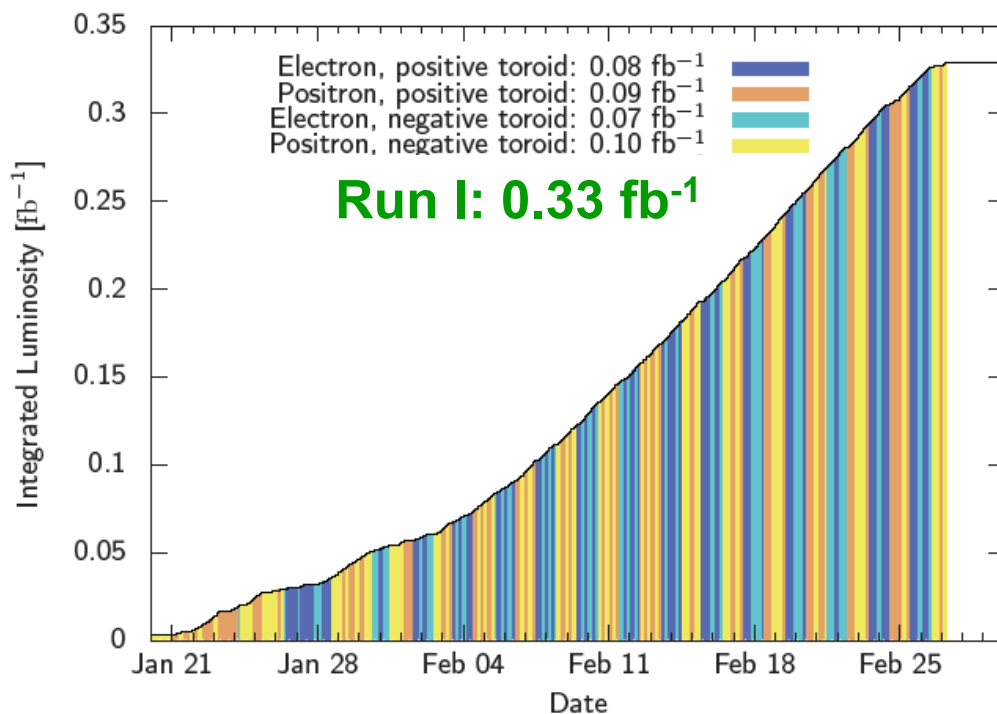
Electron beam



Positron beam



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}

- Smooth performance of machine, target, detector
- Spring 2013 Survey & field mapping
- Analysis progressing – framework, calibrations, tracking, simulations
- **Expect results end of 2014**

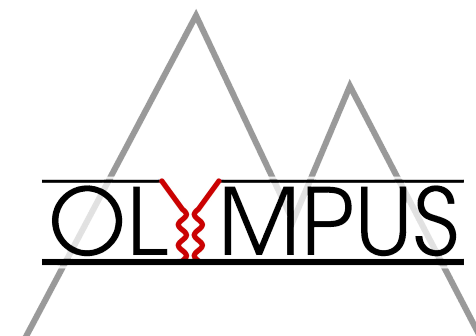
~50 physicists from 13 institutions in 6 countries

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

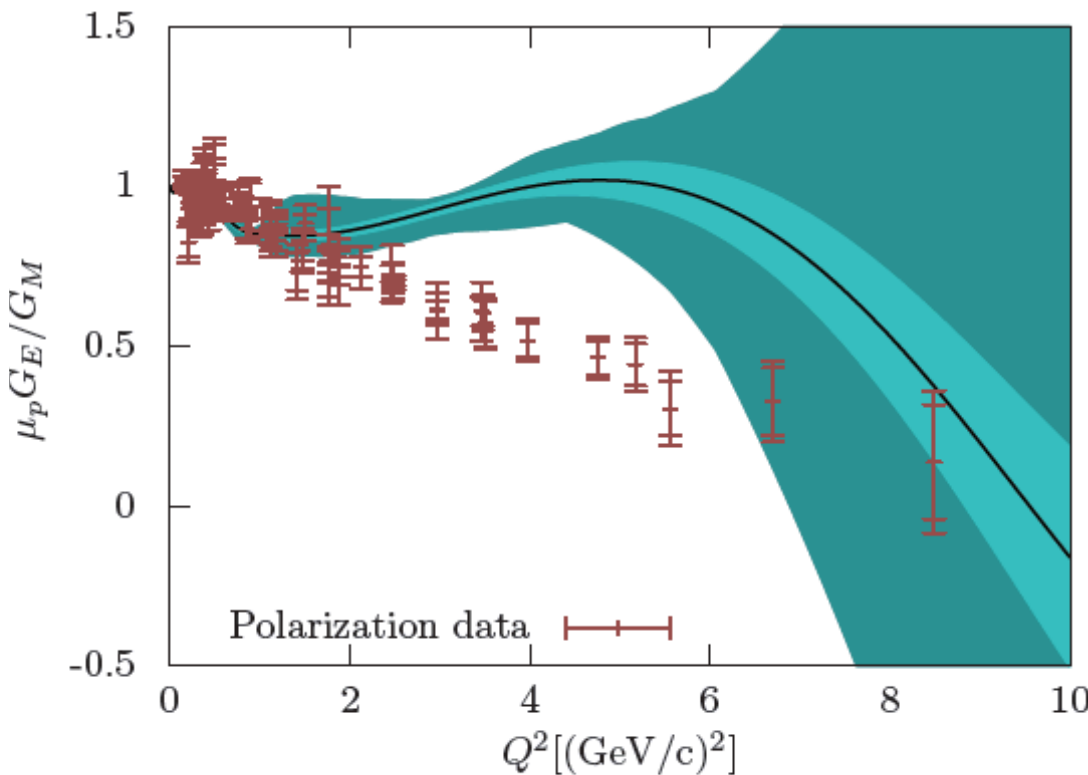
Summary

- **The limits of OPE have been reached with the achieved precision**
 - ➔ Large discrepancy between unpolarized and polarized data
 - ➔ 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**
- **ϵ dependence of polarization transfer, ϵ -nonlinearity of cross sections single-spin asymmetries**
- **Need both positron/electron comparisons for a definitive test of TPE: VEPP-3, CLAS, OLYMPUS**
- **A comprehensive and rich program underway, expected to be conclusive in the near future**
- **Broader Impact:**
gamma-Z box in PVES; TPE effects in DIS; proton radius puzzle

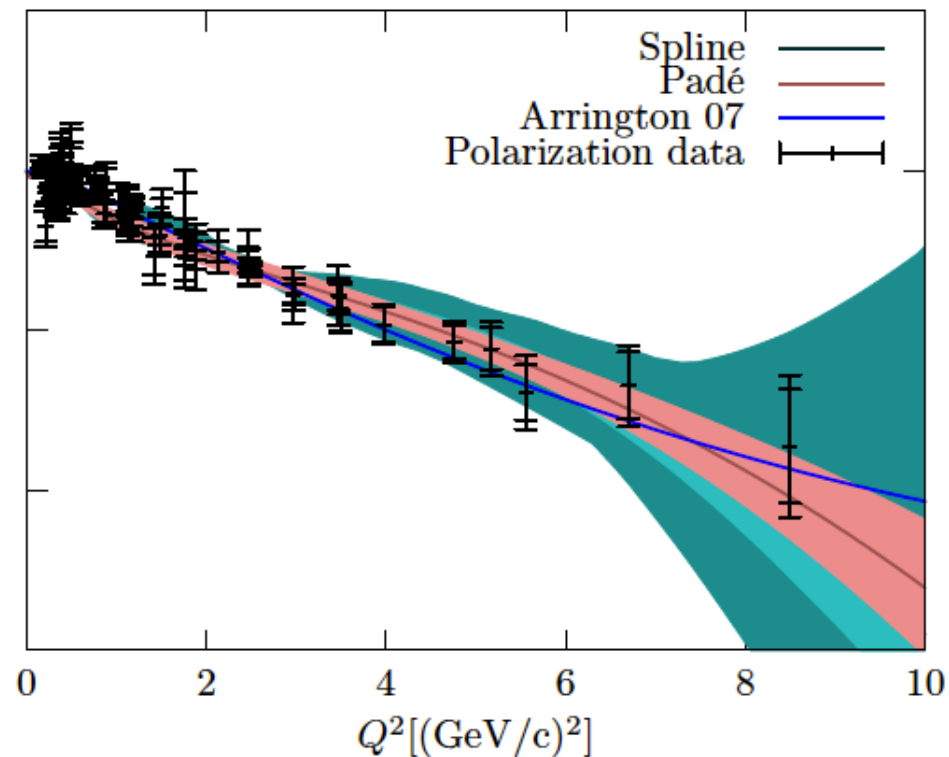


Global analysis

Fit to unpolarized data



Fit including polarized data + TPE parameterization



J.C. Bernauer *et al.*, arXiv:1307.6227v1

Outlook: TPE and the proton radius puzzle



The Muon Scattering Experiment (MUSE) at PSI and the Proton Radius Puzzle

Michael Kohl* for the MUSE Collaboration

Hampton University, Hampton, VA 23668, USA



Abstract

The proton radius puzzle is the disagreement between the much more precise radius determined from muonic hydrogen spectroscopy and the numerous atomic hydrogen and electron scattering determinations. The puzzle has several possible resolutions, including beyond standard model physics, missing conventional physics, and errors or underestimated uncertainties in the extraction of the radius from the data. New experiments are needed to resolve the puzzle. The MUSE Scattering Experiment (MUSE) recently approved at PSI has been designed to help resolve the puzzle by measuring the radius in a way not yet done. Similar to electron scattering, the radius will be extracted from the observed change of the charge form factor with momentum transfer. The experiment uses the *mM1* beamline to provide a mixed secondary muon and electron (and pion) beam of either positive or negative charge. The comparison of muon and electron scattering measured simultaneously determines the consistency of the cross sections, form factors, and extracted radii in the two cases with high precision. Comparison of yields from both charge signs will at the same time disentangle the effects of two-photon exchange which could be different for e and μ . The proton charge radius can be extracted from each set of scattering data. Simultaneous measurement of e - p and μ - p data allows to compare both probes with high precision.

The Proton Radius Puzzle in the Media



Proton Mass Mystery Could Mean New Physics

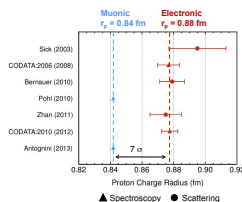


Possible Solutions of the Puzzle

- Error in the ep scattering & atomic extractions**
 - problem with fits, lack of data, underestimated uncertainties
- Proton structure issues in theory (TPE)**
 - enhanced effects differing between e and μ – likely not large enough
- Physics beyond the Standard Model**
 - lepton non-universality, new e/μ differentiating force, constraints by existing and future data
- Additional measurements are needed, in preparation, or already completed**
 - Spectroscopy with μD , μHe , and regular H
 - ep, ed scattering at Jlab and MAMI
 - μp and ep scattering comparison at PSI (MUSE), and for both charge species
 - New physics constraints e.g. from kaon decays (TREK@J-PARC)

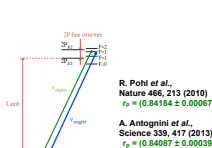
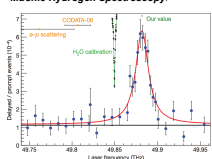
r_p (fm)	μp	ep
Spectroscopy	0.84087 ± 0.00038	0.8758 ± 0.0077
Scattering	???	0.8770 ± 0.0060

The Proton Radius Puzzle

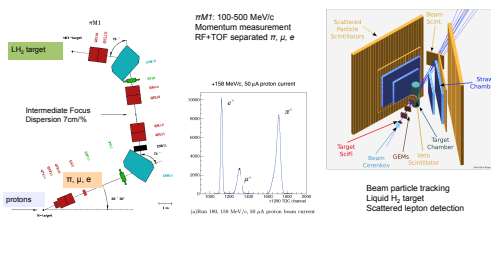


The unexplained discrepancy of 7 standard deviations between the muonic hydrogen result and the CODATA value has existed since 2010.

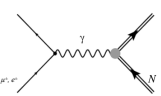
Muonic Hydrogen Spectroscopy



MUSE Scattering Experiment (MUSE)



Lepton scattering from a nucleon:



Electromagnetic current:

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

F_1, F_2 = Dirac and Pauli form factors

Expect identical result for ep and μp scattering

Sachs form factors:

$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$$

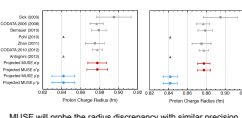
$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

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

$$\left(\frac{dG_E}{dQ^2} \right)_{Q^2=0}$$

$$\left(\frac{dG_M}{dQ^2} \right)_{Q^2=0}$$

MUSE Goal



MUSE will probe the radius discrepancy with similar precision

Collaboration

~60 MUSE collaborators from:
 Argonne National Lab, Christopher Newport University, College of William & Mary, Duke University, Duquesne University, George Washington University, Hampton University, Hebrew University of Jerusalem, Jefferson Lab, Massachusetts Institute of Technology, Miami University, Norfolk State University, Old Dominion University, Paul Scherrer Institut, Rutgers University, Sorbonne Nuclear Research Center, St. Mary's University, Technical University of Darmstadt, Tel Aviv University, Temple University, University of Iowa, University of South Carolina, University of Virginia, Weizmann Institute

Timeline

History:

- Summer 2010**
 - Liquid H_2 target
 - The proton radius puzzle is established
- Fall 2011**
 - First ideas for MUSE to measure the r_p with μp scattering
- February 2012; July 2012**
 - Proposal for MUSE first reviewed by PAC; technical review
- Fall 2012; Summer 2013; Fall 2013**
 - Test runs at the PSI *mM1* beamline to study beam properties, established beam particle ID by time-of-flight and beam particle tracking with GEMs; further tests in 2014
- January 2013; January 2014**
 - Revised proposal for MUSE, approved by PAC
 - Updated proposal, re-endorsed by PAC; technical review
- March 2014**
 - Final funding review by NSF and DOE

Schedule:

- 2012 – 2014: R&D phase**
 - Fundraising, further tests, finalize technical design
- 2015 – 2016: Construction phase**
 - Preparation of experiment at PSI, dry run end of ~2016
- 2017 – 2018: Running phase**
 - 2x6 months for two beam charges, three beam momenta

* Supported by NSF grant PHY-1207072 and DOE Early Career Award DE-SC0003044
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MUSE (poster session on Sat) Muon Scattering Experiment

Use $e/\pi/\mu$ beam at PSI
for a direct test if μp and ep scattering are different:

- Simultaneous, separated beam of $(e^+/\pi^+/\mu^+)$ or $(e^-/\pi^-/\mu^-)$ on liquid H_2 target
- Measure e^+/μ^+ , e^-/μ^- ratios to compare extracted charge
- Disentangle effects from two-photon exchange (TPE) in e^+/e^- , μ^+/μ^-

Backup

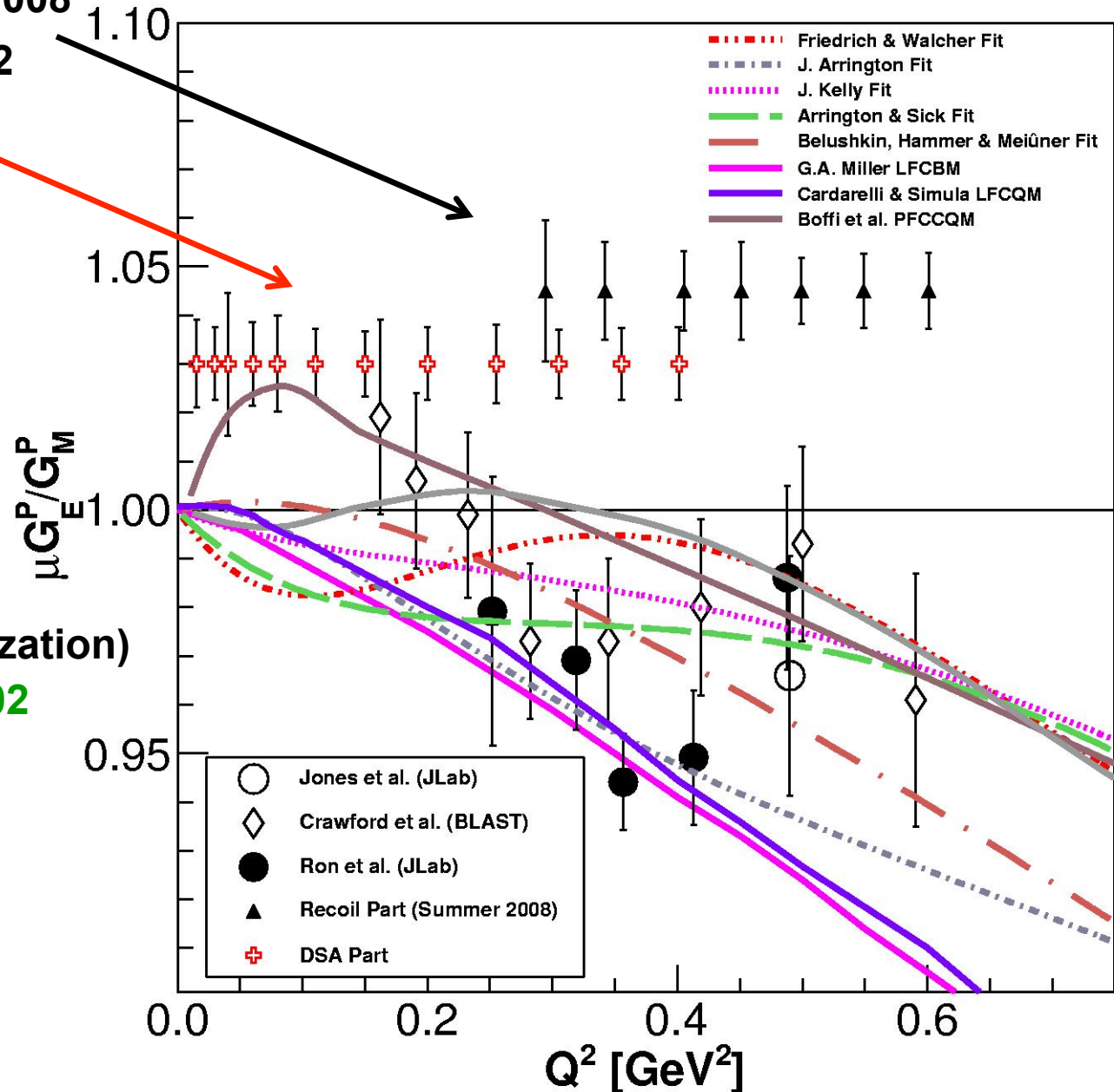
New proton measurements at low Q^2

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

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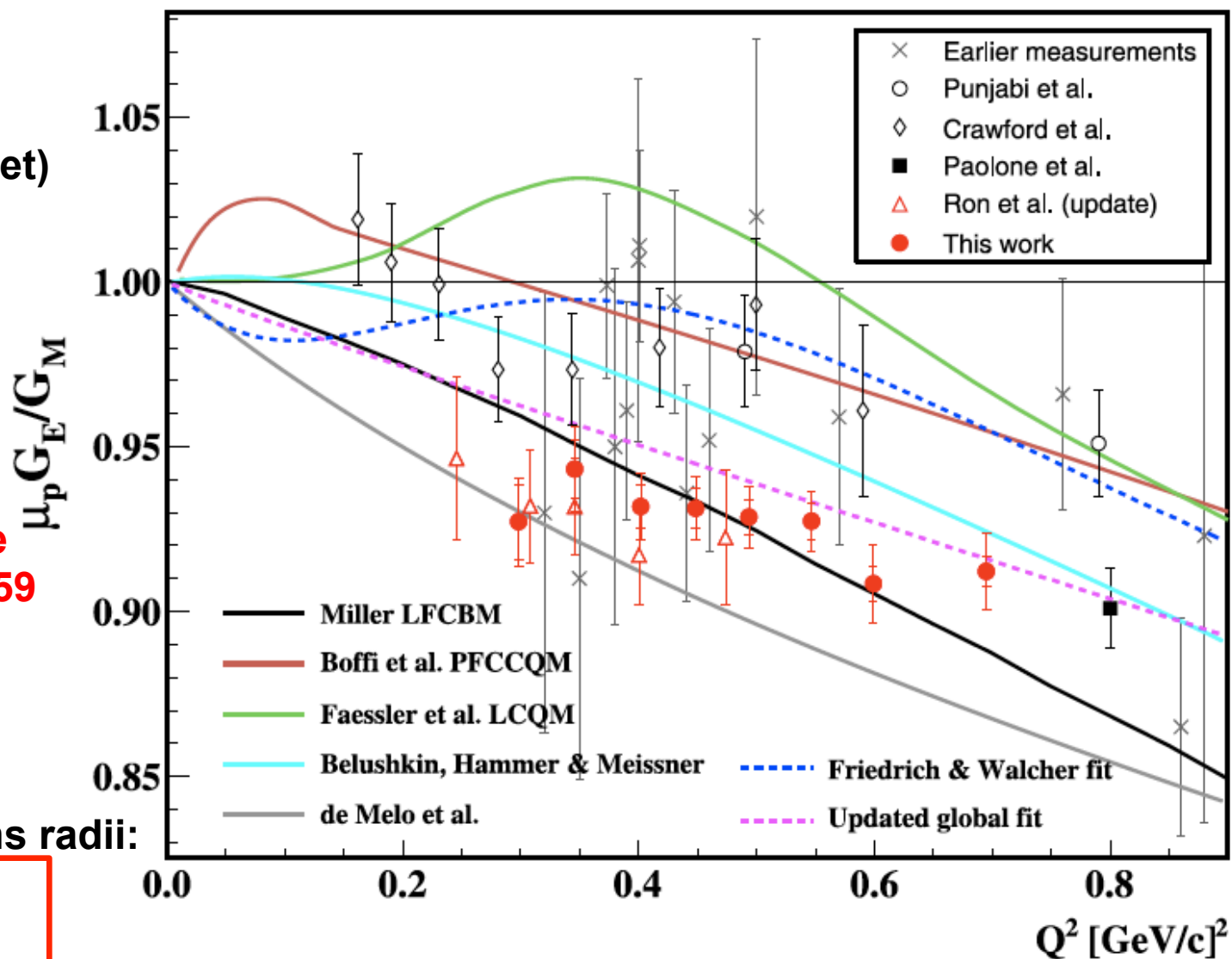
X. Zhan,
E08-007 + LEDEX update
Phys. Lett. B 705 (2011) 59

2-sigma difference
lower than BLAST

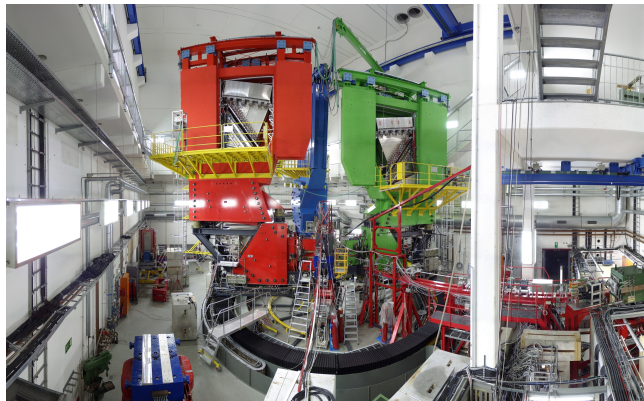
Charge and magnetic rms radii:

$$R_E = 0.875 \pm 0.010 \text{ fm}$$

$$R_M = 0.867 \pm 0.020 \text{ fm}$$

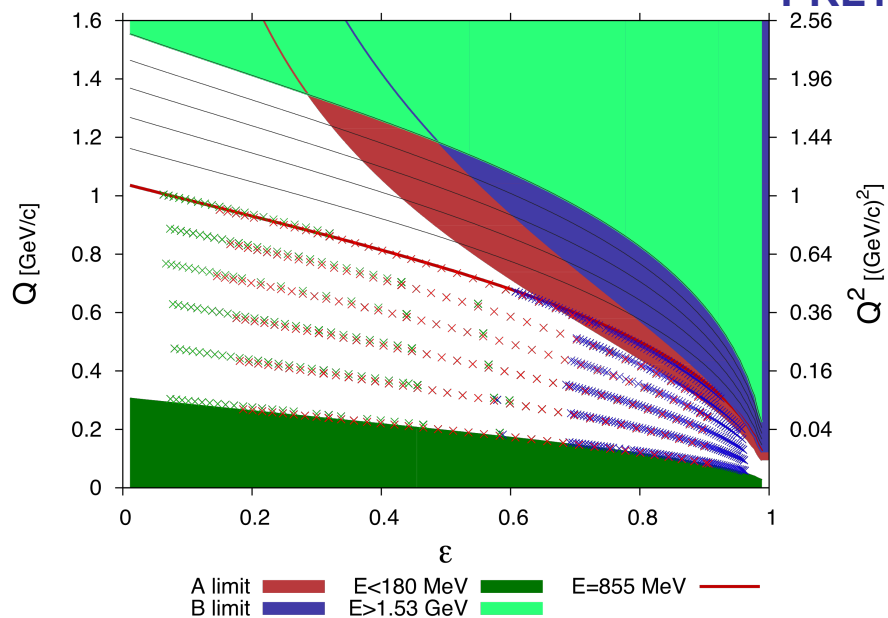


New proton measurements at low Q^2



MAMI A1

J. Bernauer et al.
PRL105 (2010) 242001



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

$$R_E = 0.879 \pm 0.008 \text{ fm}$$

$$R_M = 0.777 \pm 0.017 \text{ fm}$$

