12th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon May 31-June 4, 2010, College of William and Mary, Williamsburg, Virginia, USA

# Status of the OLYMPUS Experiment at DESY*

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**Hampton University, VA 23668 and Jefferson Lab, VA 23606, USA**

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* Supported by NSF grants 0855473 and 0959521

# OLYMPUS

pOsitron-proton and

eLectron-proton elastic scattering to test the

hYpothesis of

Multi-

Photon exchange

Using

DoriS

(inofficial logo)


**2008 – Full proposal**
**2009 – Technical review**
**2010 – Funding approval**
**2010/11 – Transfer of BLAST**
**2012 – OLYMPUS Running**

DESY inFORM.

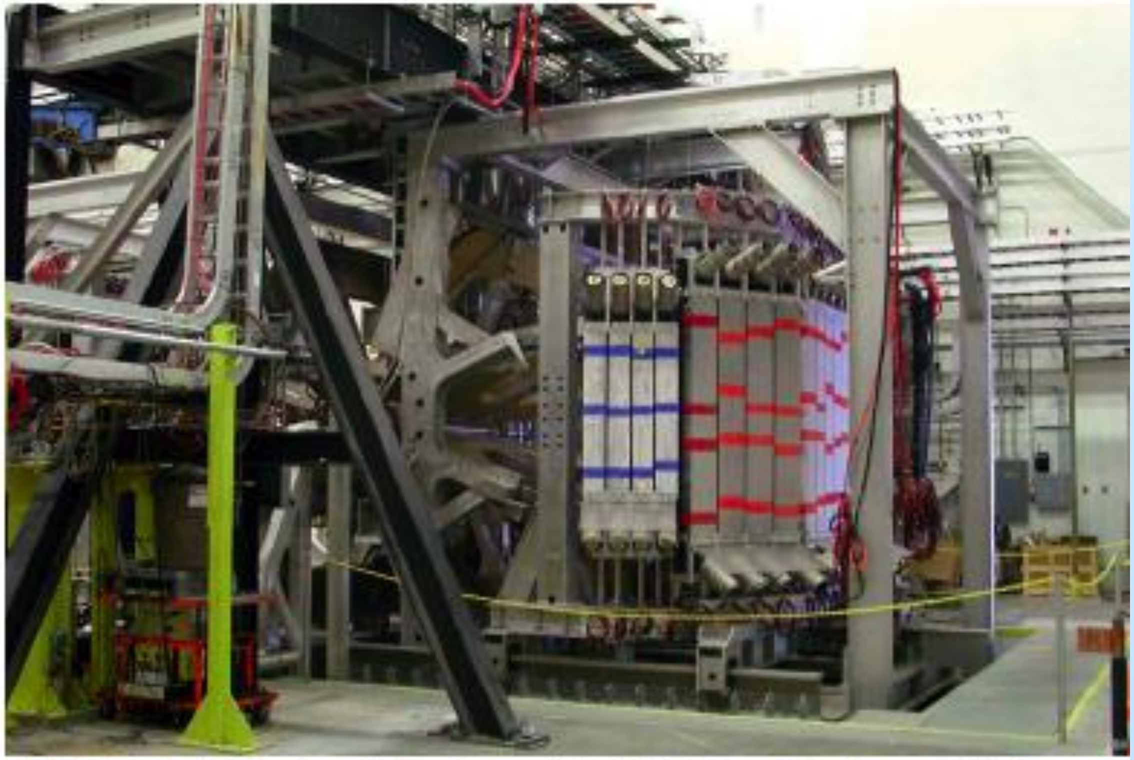
04/2010
Newsletter of the Research Centre DESY

# From the home of the gods into the proton

## With OLYMPUS scientists try to solve the mystery of the proton

What does it look like inside the proton? This is a question that scientists at DESY have been concerned with for a long time. For 15 years, HERA offered the possibility to look inside the proton. Now, there is a new experiment – this time at DORIS – that took up this question: OLYMPUS.

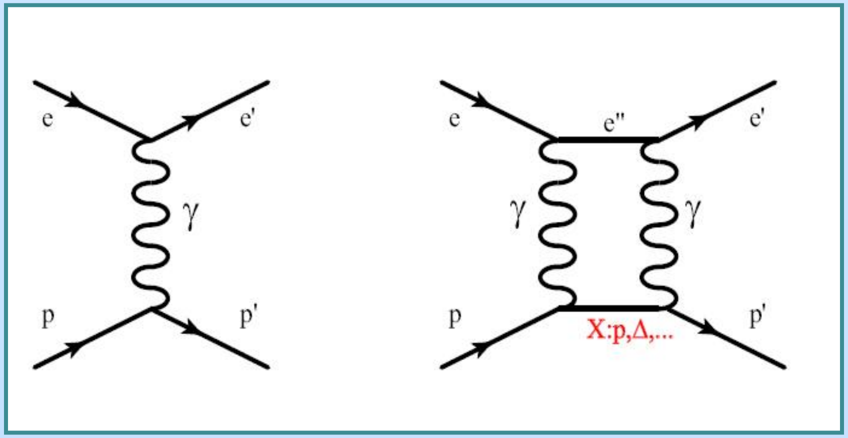
OLYMPUS is a comparatively small experiment. The complete detector weighs only about 50 tons – a lightweight, compared to, for example, the 3600 tons of the HERA experiment ZEUS. "Apart from its size, this is due to the fact that the detector has no iron yoke," Uwe Schneekloth, one of two technical coordinators of the experiment, explains. Moreover, the area surrounding the interaction point is not completely equipped with electronics, as this is the case in large detectors.

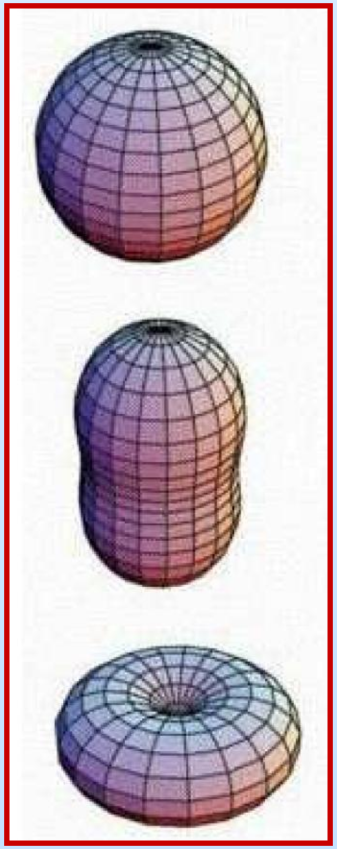


The BLAST detector of MIT's accelerator BATES will be reassembled at DESY to a large extent and become OLYMPUS.

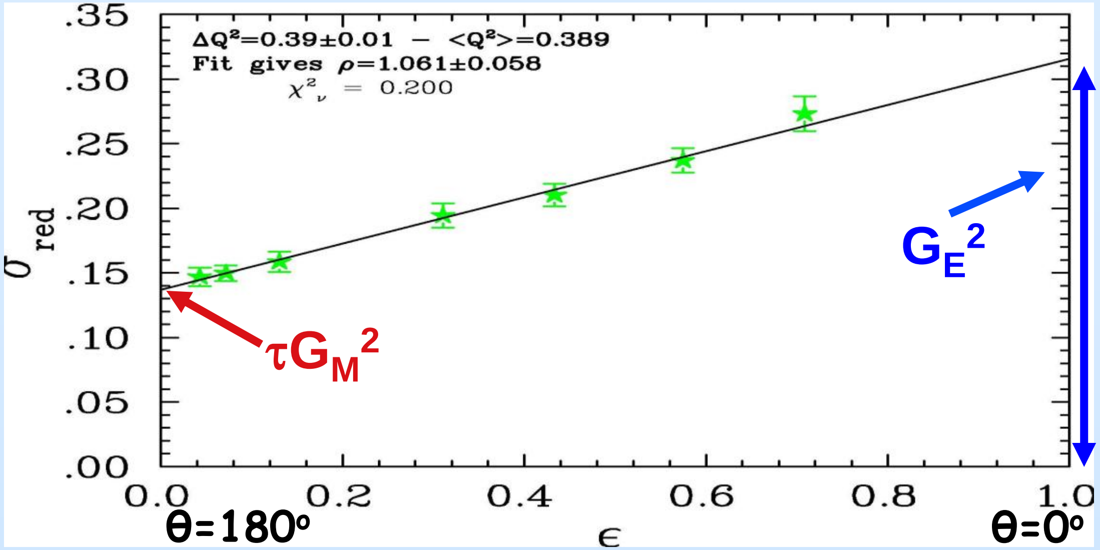
# Outline

- Review of the physics case
- The limit of one-photon exchange or:
  - What is $G^p_E(Q^2)$?
  - What is the nature of lepton scattering?
- Description of the OLYMPUS experiment
- Status and timeline



# Form Factors from Rosenbluth Method




➔ **Determine** $|G_E/G_M|$

- **In One-photon exchange approximation above form factors are observables of elastic electron-nucleon scattering**

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

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

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

# 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

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

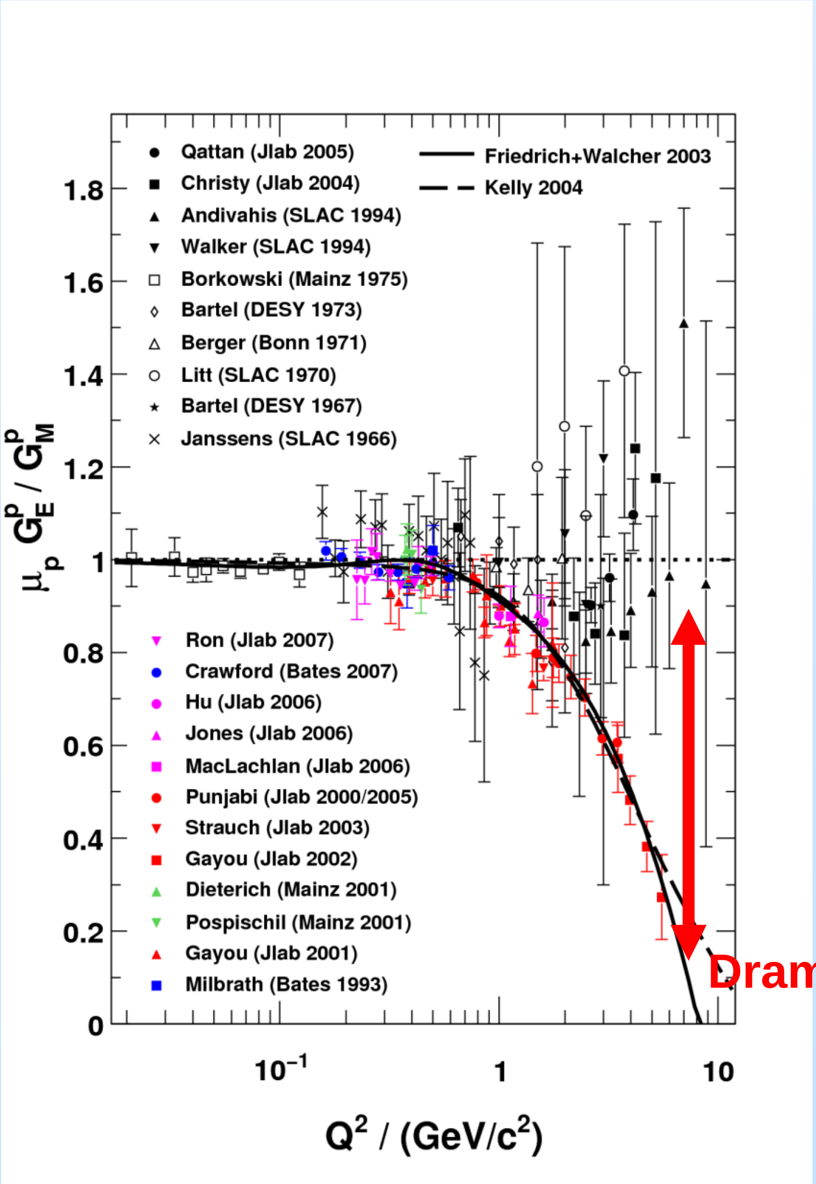
- Double spin asymmetry = spin correlation

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

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

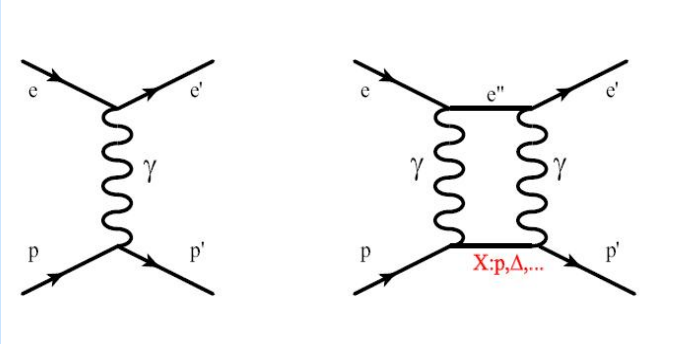
  independent of polarization or analyzing power

# Proton Form Factor Ratio




## Jefferson Lab 2000–

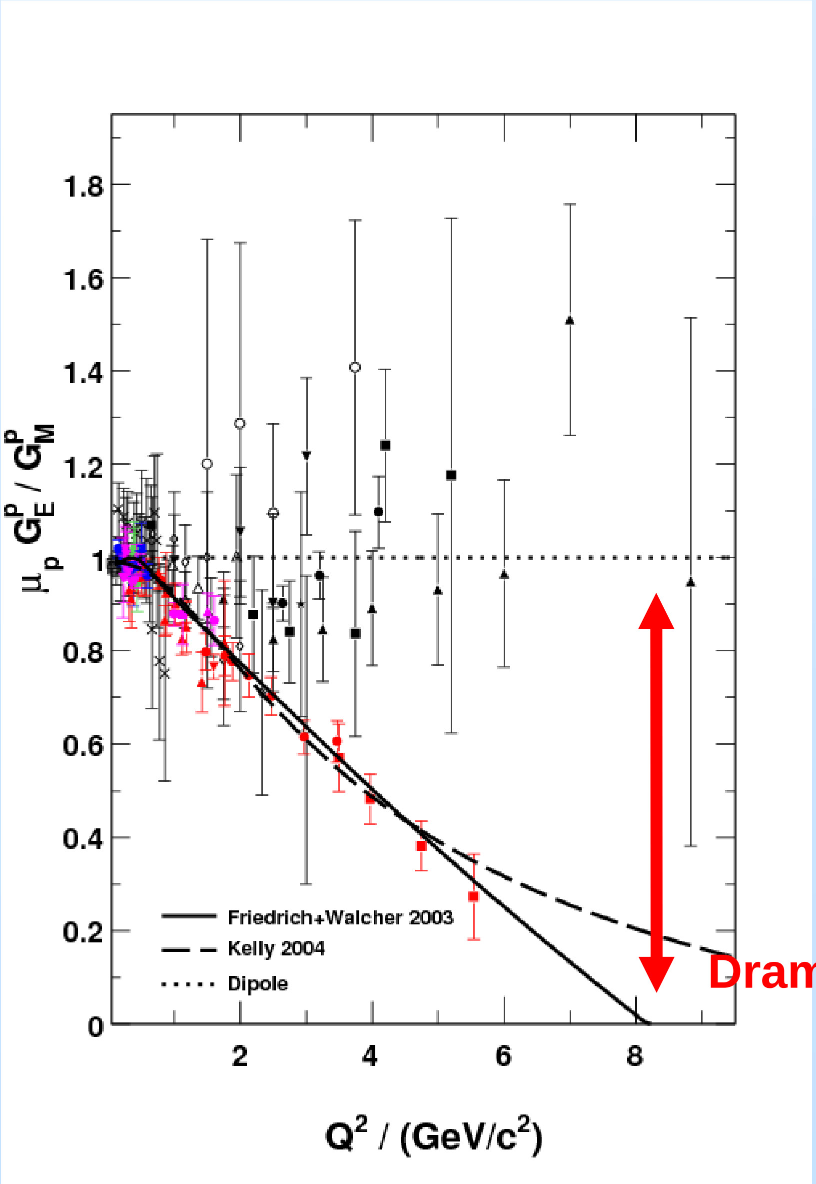
- All Rosenbluth data from SLAC and Jlab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Multi-photon exchange considered best candidate




Dramatic discrepancy!

>900 citations

# Proton Form Factor Ratio

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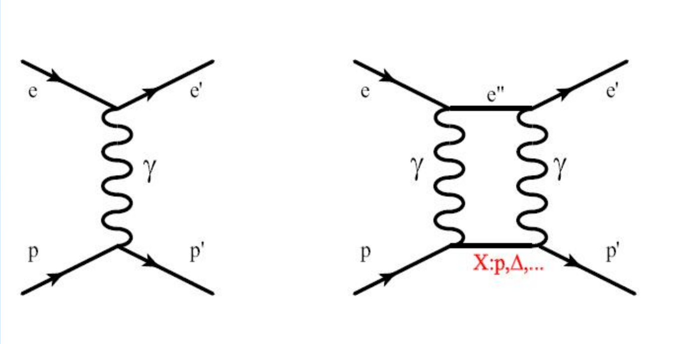
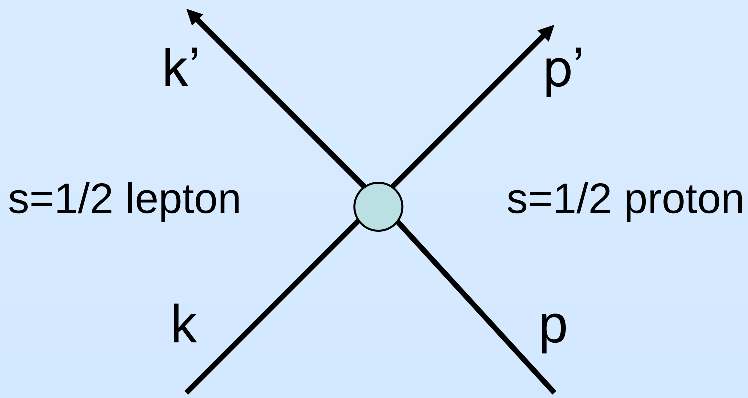



**Dramatic discrepancy!**

**>900 citations**

# Elastic ep Scattering Beyond OPE




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

**Kinematical invariants :**

$$\begin{aligned} Q^2 &= -(p-p')^2 \\ \nu &= K \cdot P = (s-u)/4 \end{aligned}$$

**Next-to Born approximation:**

$$\begin{aligned} T^{non-flip}_{h'\lambda'_N, h\lambda_N} &= \frac{e^2}{Q^2} \bar{u}(k', h') \gamma_\mu u(k, h) \\ (m_e = 0) \quad & \times \quad \bar{u}(p', \lambda'_N) \left( \tilde{G}_M \gamma^\mu - \tilde{F}_2 \frac{P^\mu}{M} + \tilde{F}_3 \frac{\gamma . K P^\mu}{M^2} \right) u(p, \lambda_N) \end{aligned}$$

**The T-matrix still factorizes, however a new response term $F_3$ is generated by TPE**
**Born-amplitudes are modified in presence of TPE**

$$\begin{aligned} \tilde{G}_M(\nu, Q^2) &= G_M(Q^2) + \delta \tilde{G}_M \\ \tilde{F}_2(\nu, Q^2) &= F_2(Q^2) + \delta \tilde{F}_2 \\ \tilde{F}_3(\nu, Q^2) &= 0 + \delta \tilde{F}_3 \end{aligned}$$

$$\tilde{G}_E \equiv \tilde{G}_M - (1+\tau)\, \tilde{F}_2$$

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

**Three new complex amplitudes dep. on ε & $Q^2$ !**

# 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

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

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

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

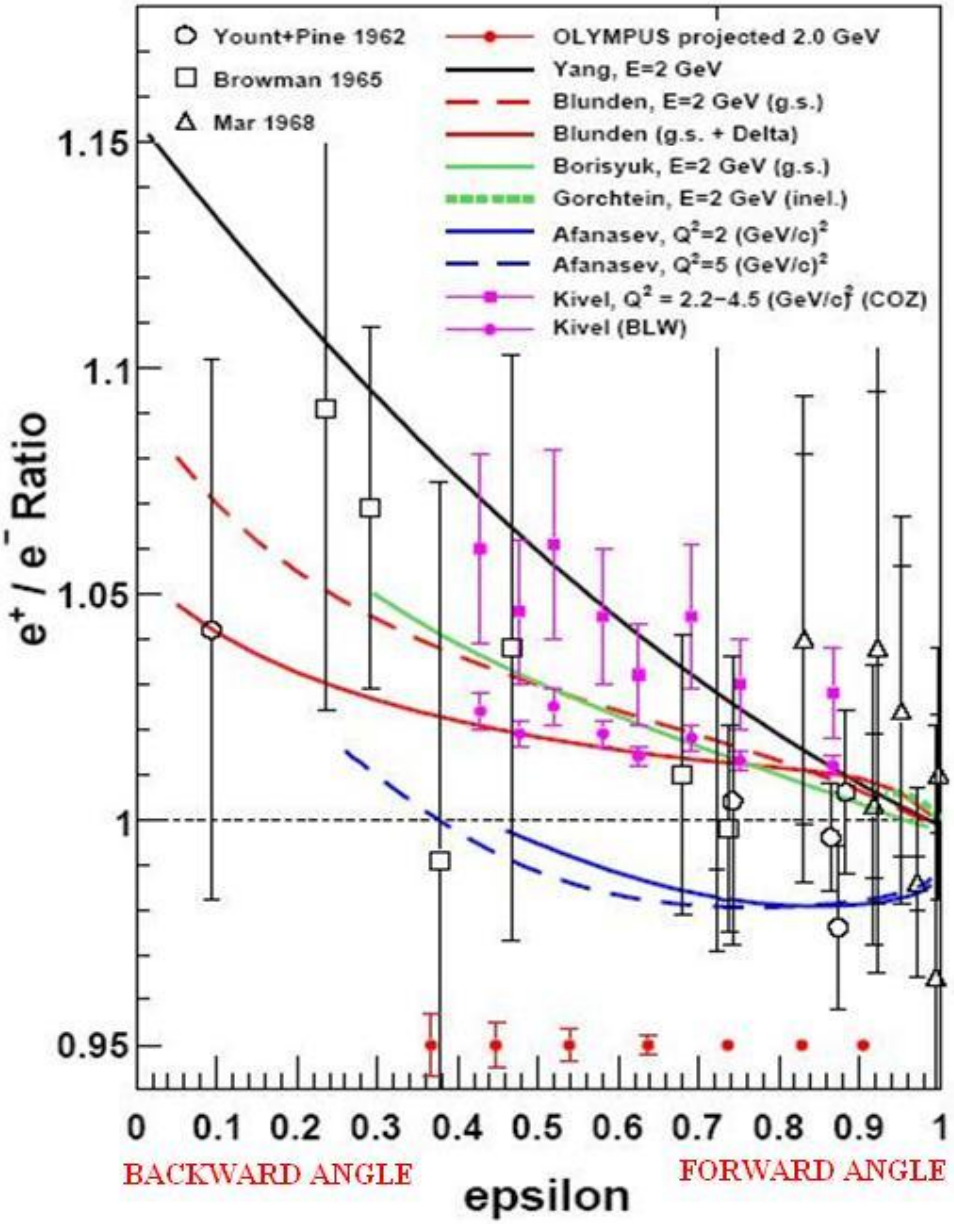
**Born Approximation** | **Beyond Born Approximation**

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

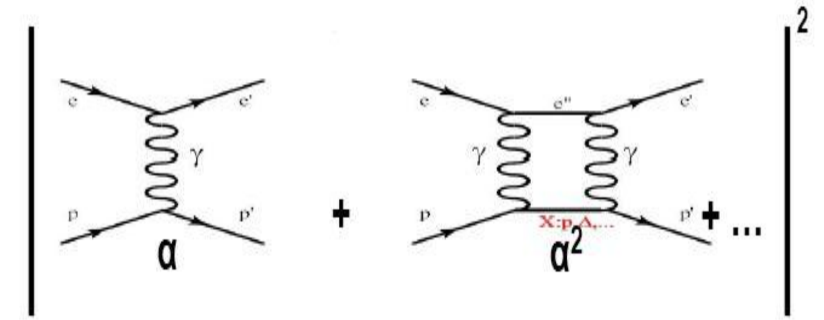
*M.P. Rekalo and E. Tomasi-Gustafsson, E.P.J. A 22, 331 (2004)*

Slide idea:
L. Pentchev

# Elastic Positron-to-Electron Ratio




**Two-photon exchange involving interference of one- and two-photon amplitudes**

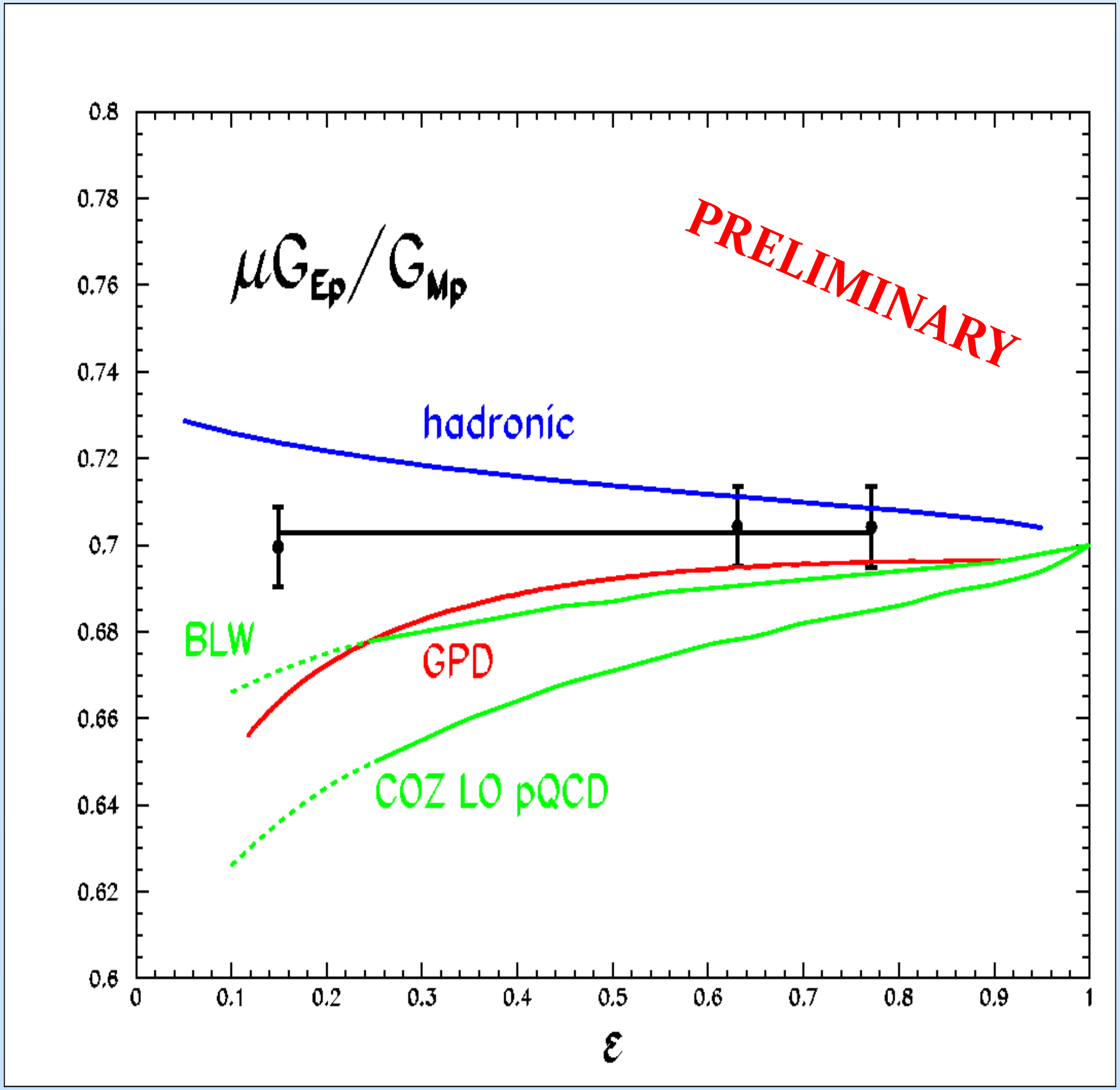



$$\sigma = (1\gamma)^2\alpha^2 + (1\gamma)(2\gamma)\alpha^3 + \ldots..$$

$$e^- \Longleftrightarrow e^+ \Rightarrow \alpha \Longleftrightarrow -\alpha$$

→ **Measure unpolarized cross section ratio to 1% precision!**

# E04-019 (Two-gamma)



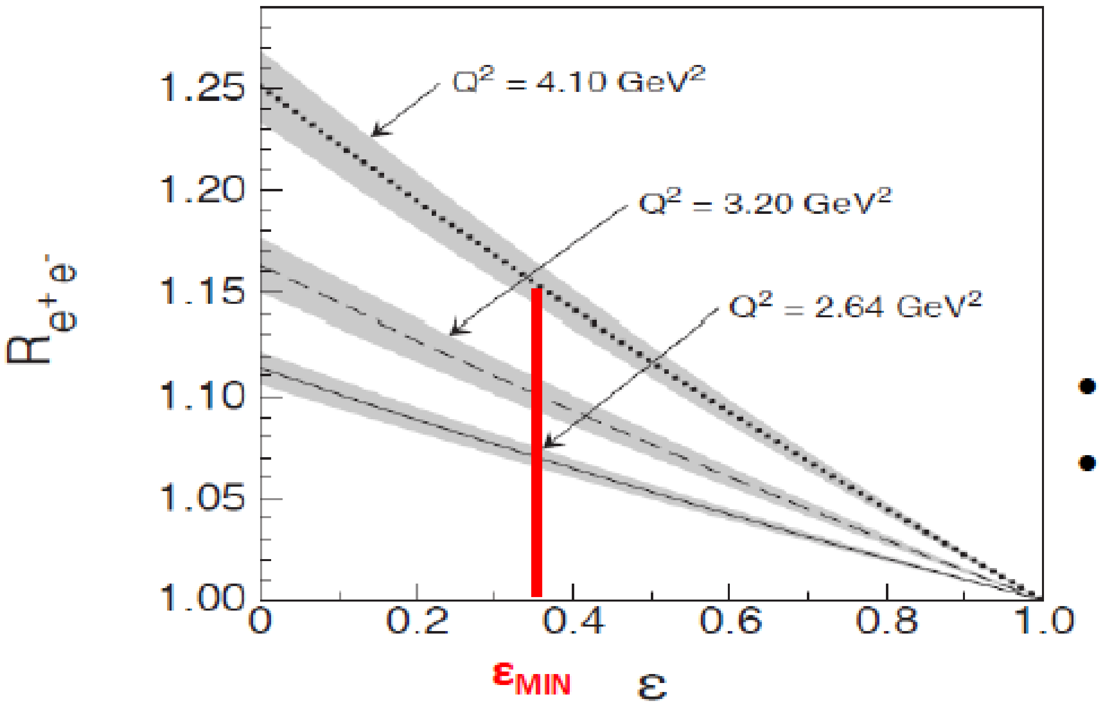

$G_E/G_M$ from $P_t/P_l$ constant vs. ε

➔ $(1–2\varepsilon R/(1+\varepsilon))\ Y_{2\gamma}$ constant
➔ with $Y_{2\gamma}$ = const. ➔ $Y_{2\gamma}$ = 0?

**M. Meziane, Sess. 5C (Wed.)**
**( = this session)**

# Empirical extraction of TPE amplitudes

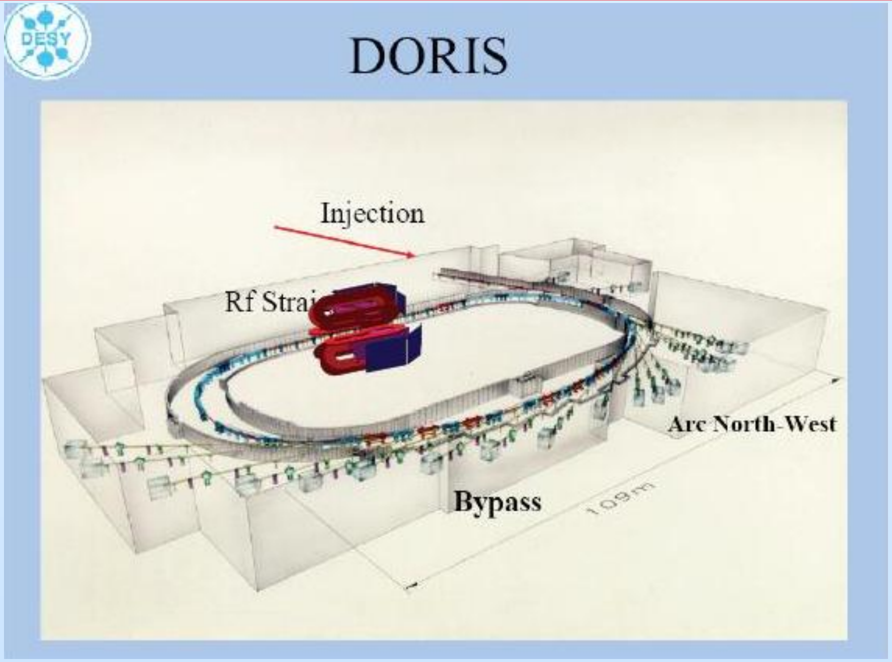
J. Guttmann, N. Kivel, and M. Vanderhaeghen, Mainz preprint MKPH-T-10-06

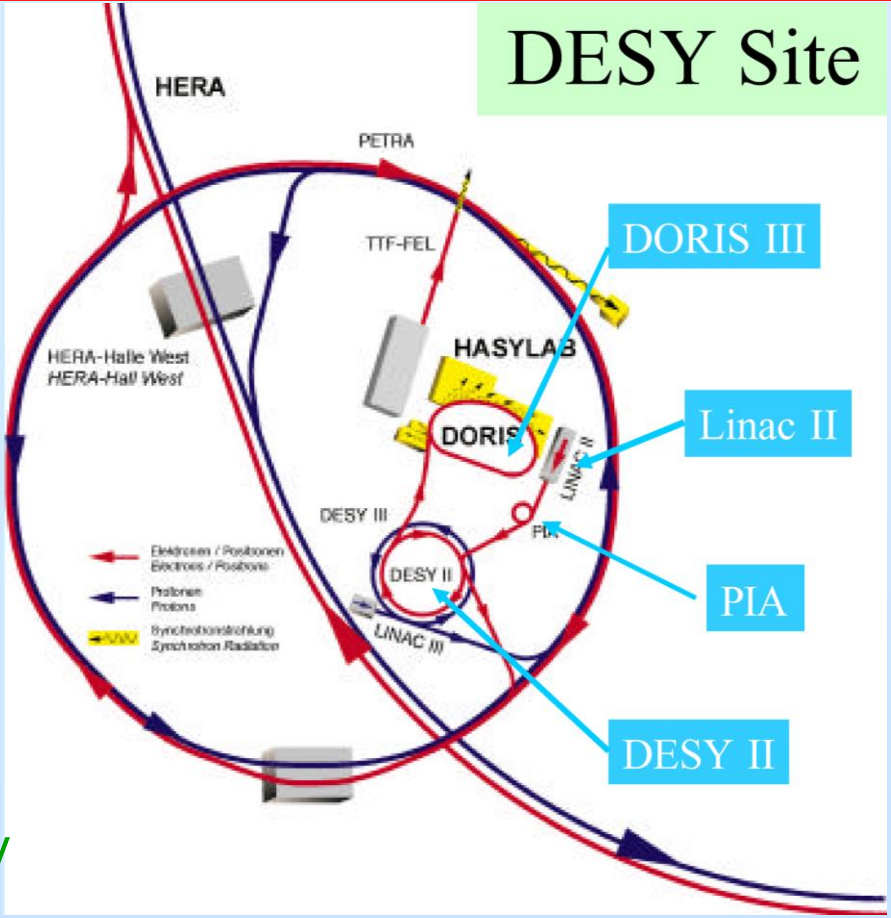



- 6% effect for OLYMPUS
- Grows with $Q^2$!

FIG. 5: Predictions for the $e^+p/e^-p$ elastic cross section ratio $R_{e+e-}$ as a function of $\varepsilon$, together with their $1\sigma$ error bands. The results are based on the fits of the JLab/Hall A cross section data [6], together with the $P_t/P_l$, and $P_l/P_l^{Born}$ data from Ref. [12] at $Q^2 = 2.5$ GeV$^2$.

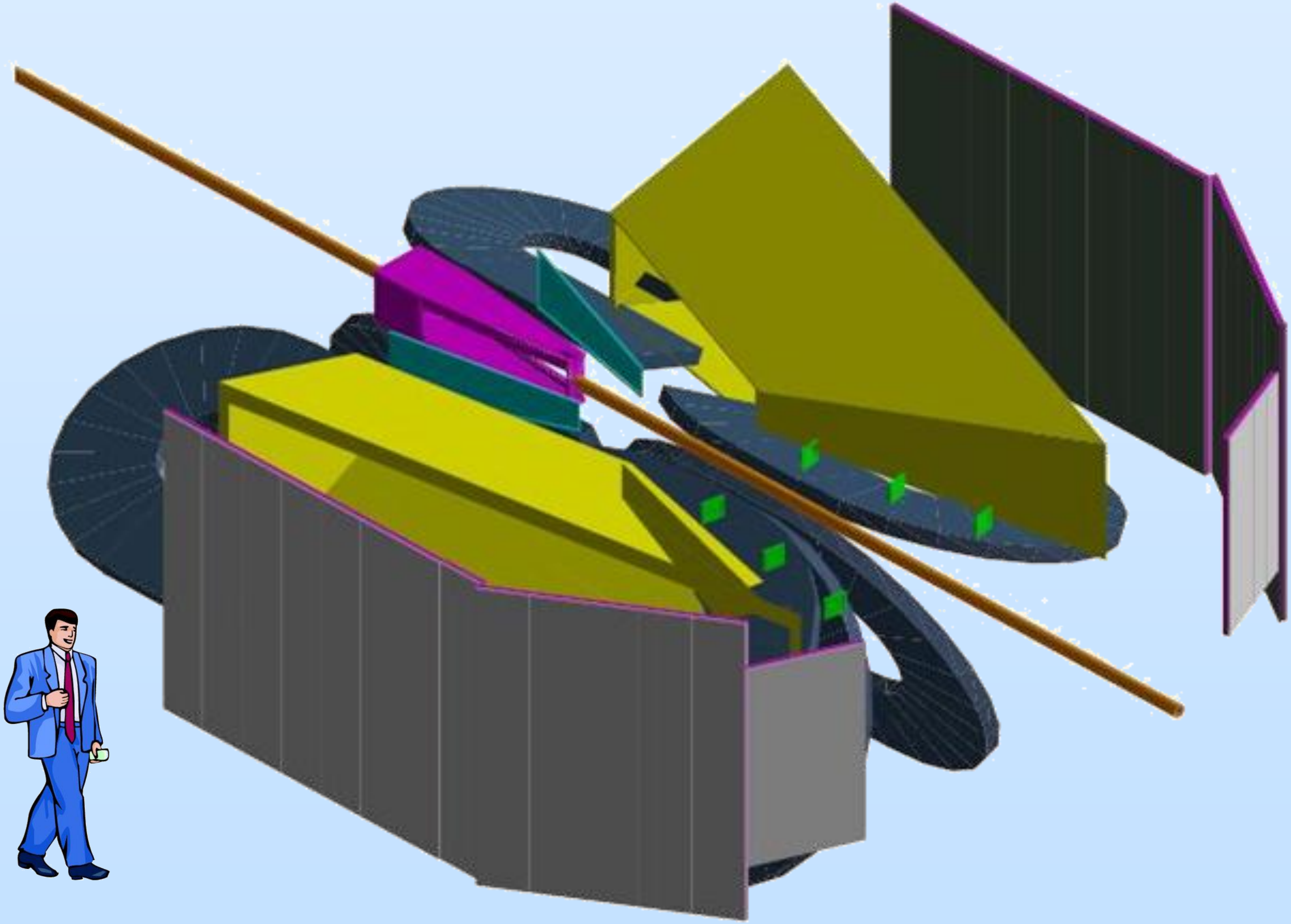
# OLYMPUS: BLAST@DESY/DORIS




- Electrons/positrons (>100mA) in multi-GeV storage ring DORIS at DESY, Hamburg, Germany
- Unpolarized internal hydrogen target storage cell with buffer system
- Large acceptance detector for e-p in coincidence BLAST detector from MIT-Bates available

# The Proposed OLYMPUS Detector



# Collaboration organization

- **Nov 2006 – Idea first formulated (D. Hasell, M.K., R. Milner)**
- **Jun 2007 – Letter of Intent**
- **Sept 2008 – Full Proposal**
- **Technical review Sept 2009, officially approved since Jan 2010**
- **Three collaboration meetings since technical review**
  **Nov 30 – Dec 1, 2009 Feb 23 – 24, 2010 Apr 26 – 27, 2010**
- **Elected management of OLYMPUS at Dec 2009 meeting:**
  **Spokesman: Richard Milner (MIT)**
  **Deputy spokesman: Reinhard Beck (U. Bonn)**
  **Technical coordinator: Douglas Hasell (MIT)**
  **Project manager: Uwe Schneekloth (DESY)**
- **Appointed coordinators:**
  **Tracking – D. Hasell (MIT)**
  **Scintillators – I. Lehmann (U. Glasgow)**
  **Luminosity Monitor – M. Kohl (Hampton U.)**
  **Symmetric Moller Monitor – F. Maas (U. Mainz)**
  **Target – R. Milner (MIT)**
  **Data Acquisition – C. Funke (U. Bonn)**
  **Slow Controls – A. Izotov (PNPI)**

# Institutional Responsibilities

- **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 Kentucky:** Simulations
- **University of New Hampshire:** TOF scintillators
- **Yerevan:** Removal of ARGUS, TOF system

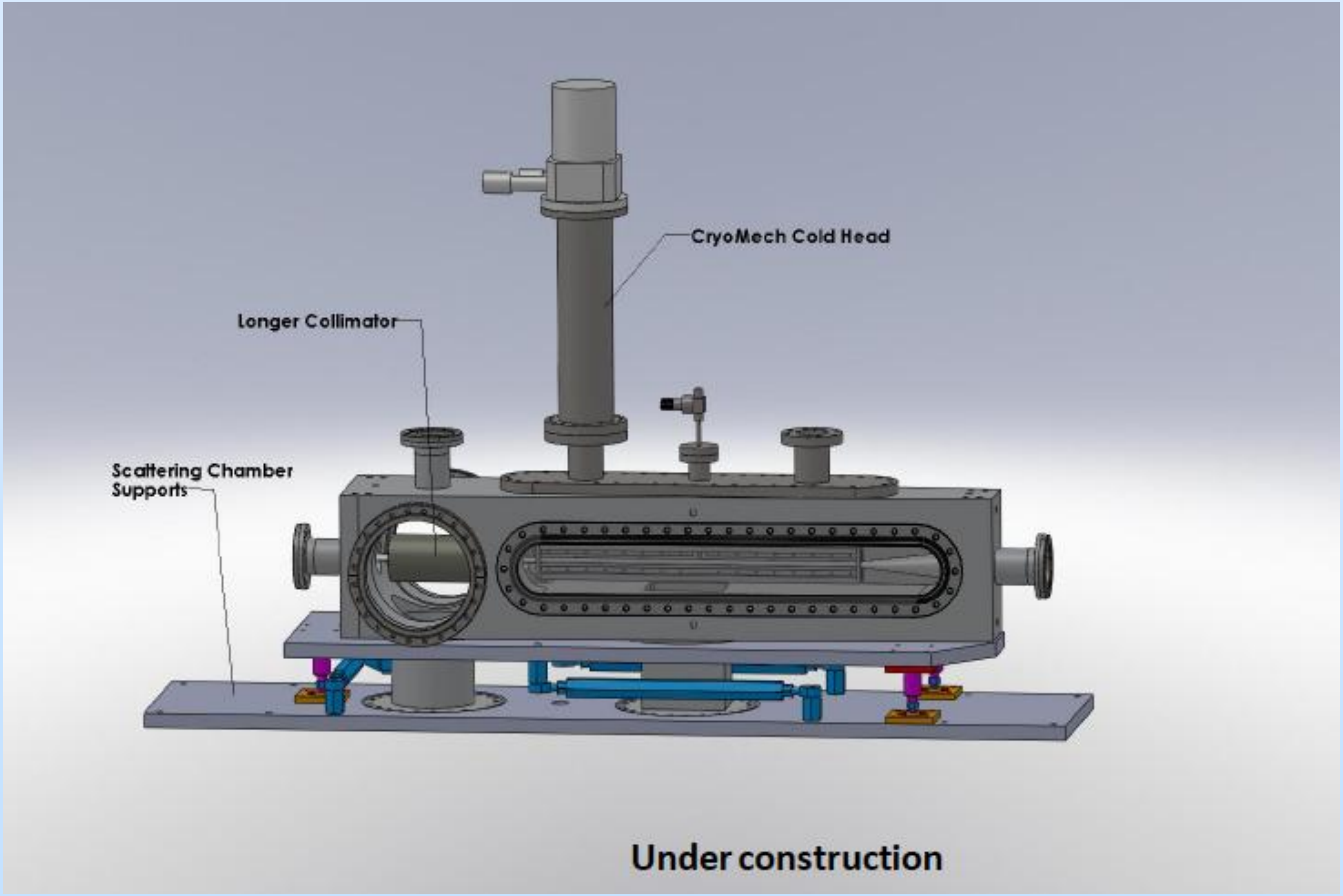
# Disassembly and Preparations at Bates

- **Disassembly completed in May 2010; shipped 3 oversea containers**
- **Drift chambers to be rewired at DESY**

# Preparation of the Experiment

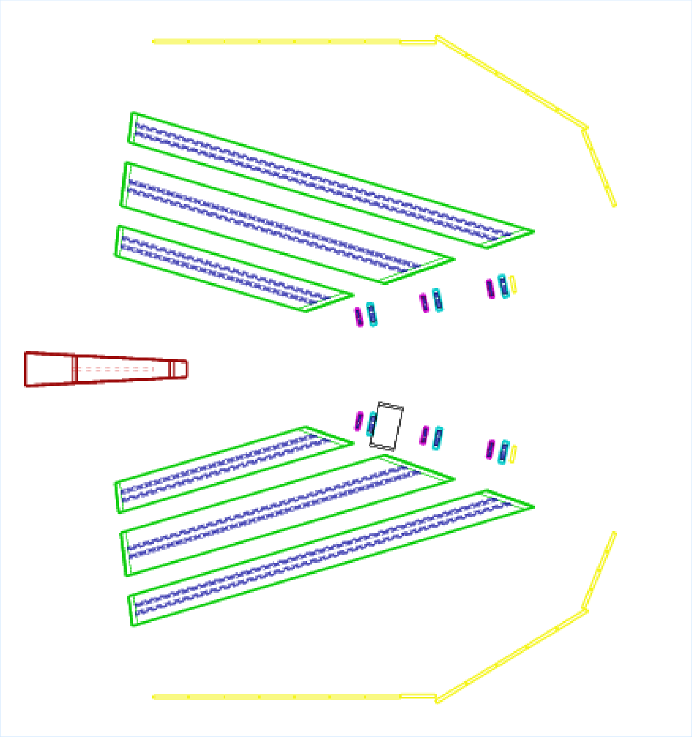
- BLAST disassembly completed and shipped; ARGUS removal completed
- Target and vacuum system
  - Full design completed, target chamber ordered
  - Heat loads determined and accounted for in design
  - Target cells under construction in Ferrara
  - Moller/Bhabha monitor fully integrated in design
  - Control system development to start in May 2010
- Drift Chambers
  - Decided to rewire drift chambers at DESY in summer 2010
  - Materials and personnel in place
- TOFs
  - TOFs tested and calibrated at Bates in January 2010
  - U. Glasgow coordinating
  - Supports to be redesigned
- Luminosity Monitoring
  - Both 12-degree elastic (Hampton&PNPI) and symmetric Moller/Bhabha (Mainz) monitors being developed
- GEMs
  - Hampton group at MIT in summer 2010
  - Readout system for STAR/FGT developed for GEM tracker
  - Hampton pursuing readout from INFN/Rome/Jlab for GEM luminosity monitor
- DAQ
  - University of Bonn coordinating
  - System will be brought into operation at DESY in summer 2010

# Target and Vacuum System



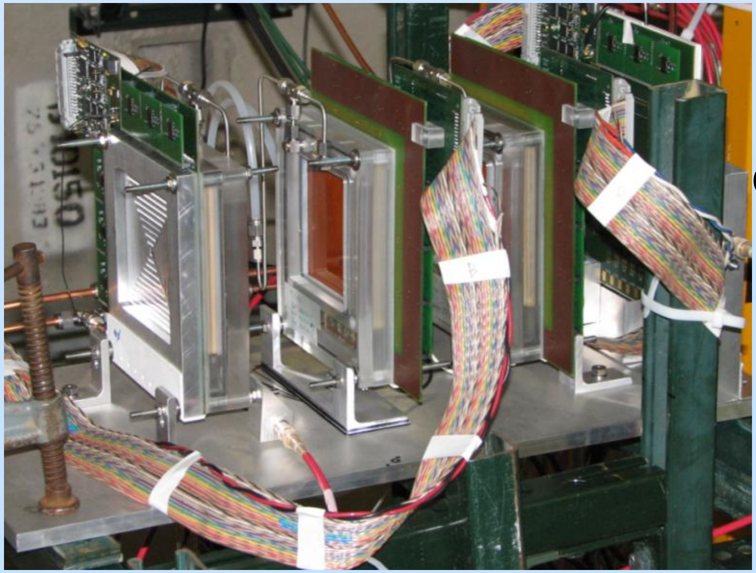
# Luminosity Monitors: GEM + MWPC

- Forward elastic scattering at 12 degrees
- Two GEM + MWPC telescopes with interleaved elements operated independently
- Scintillator for triggering and timing
- High redundancy – alignment, efficiency
  No interference
  Two independent groups (Hampton, PNPI)

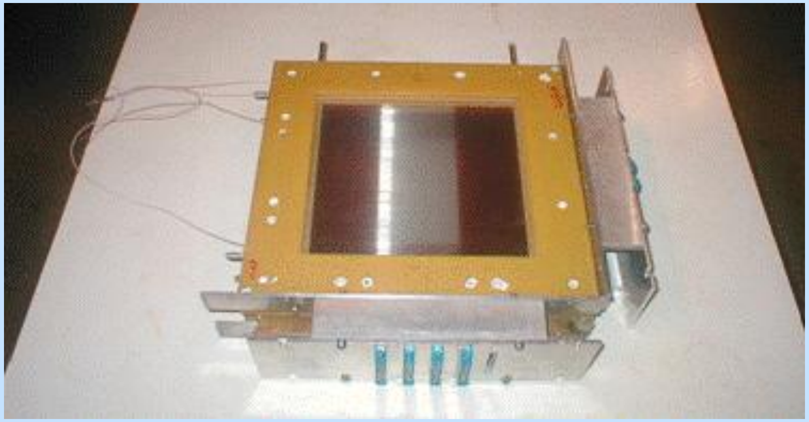


Prototypes:

GEM

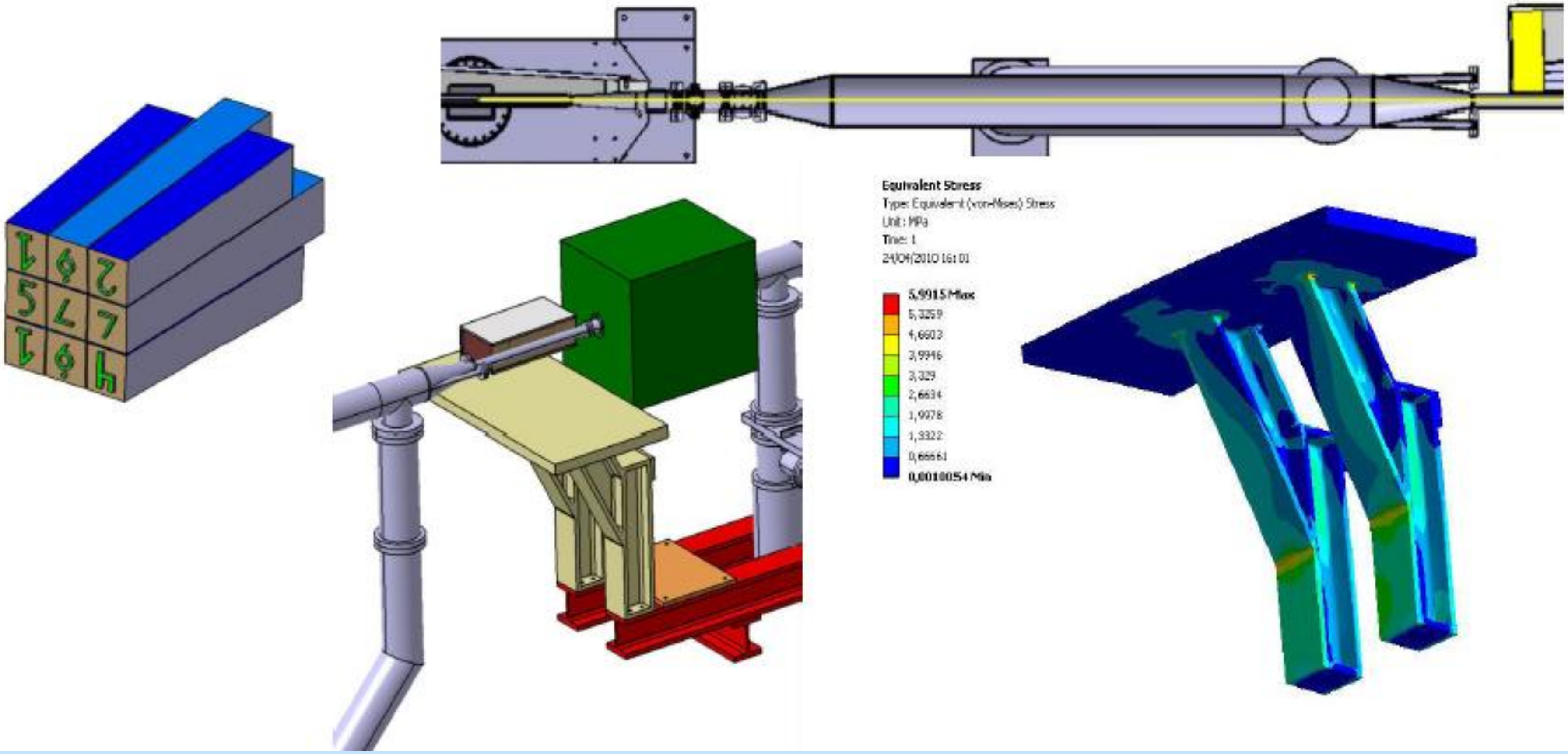


MWPC

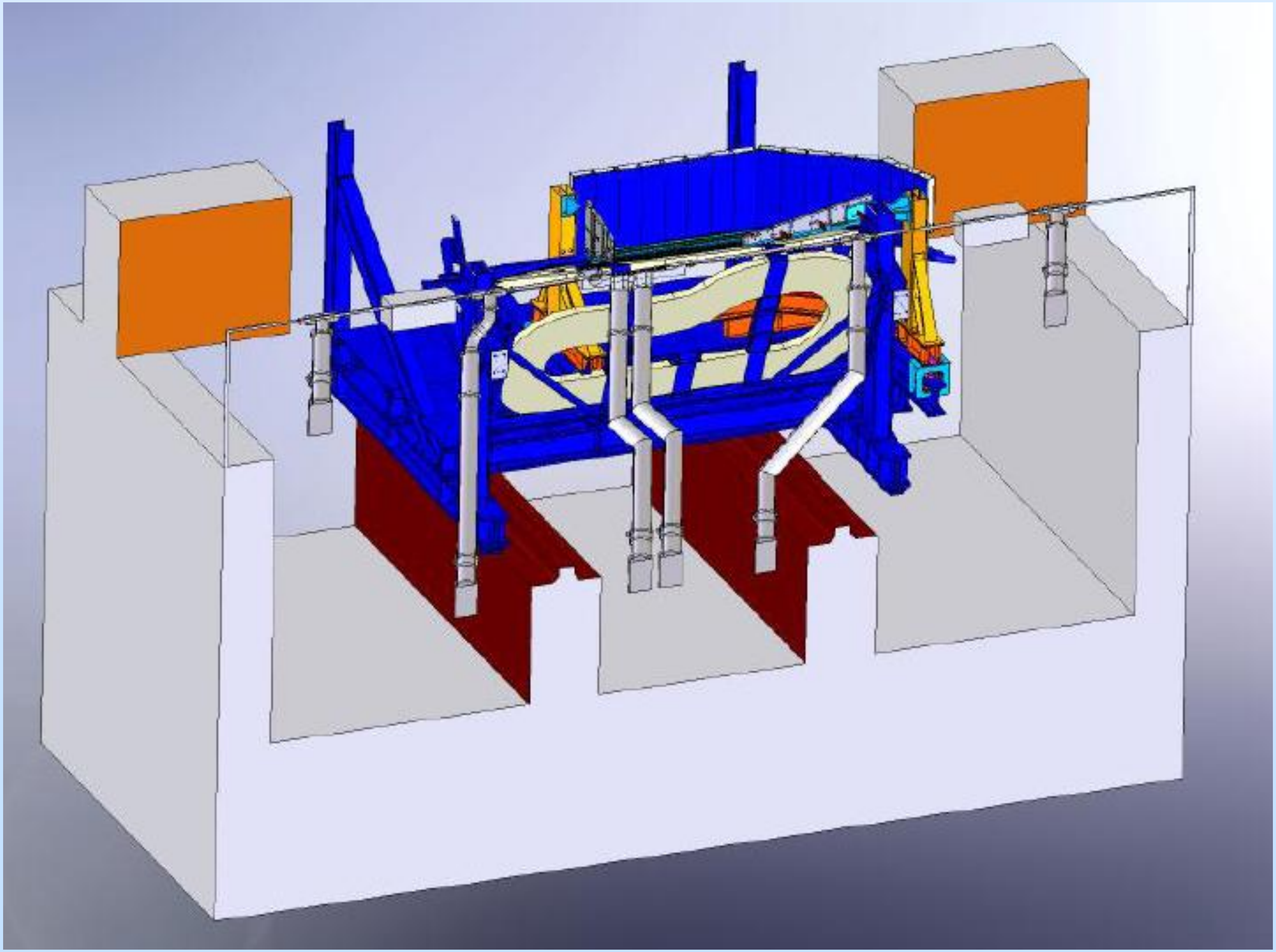


# Symmetric Møller/Bhabha Lumi Monitor

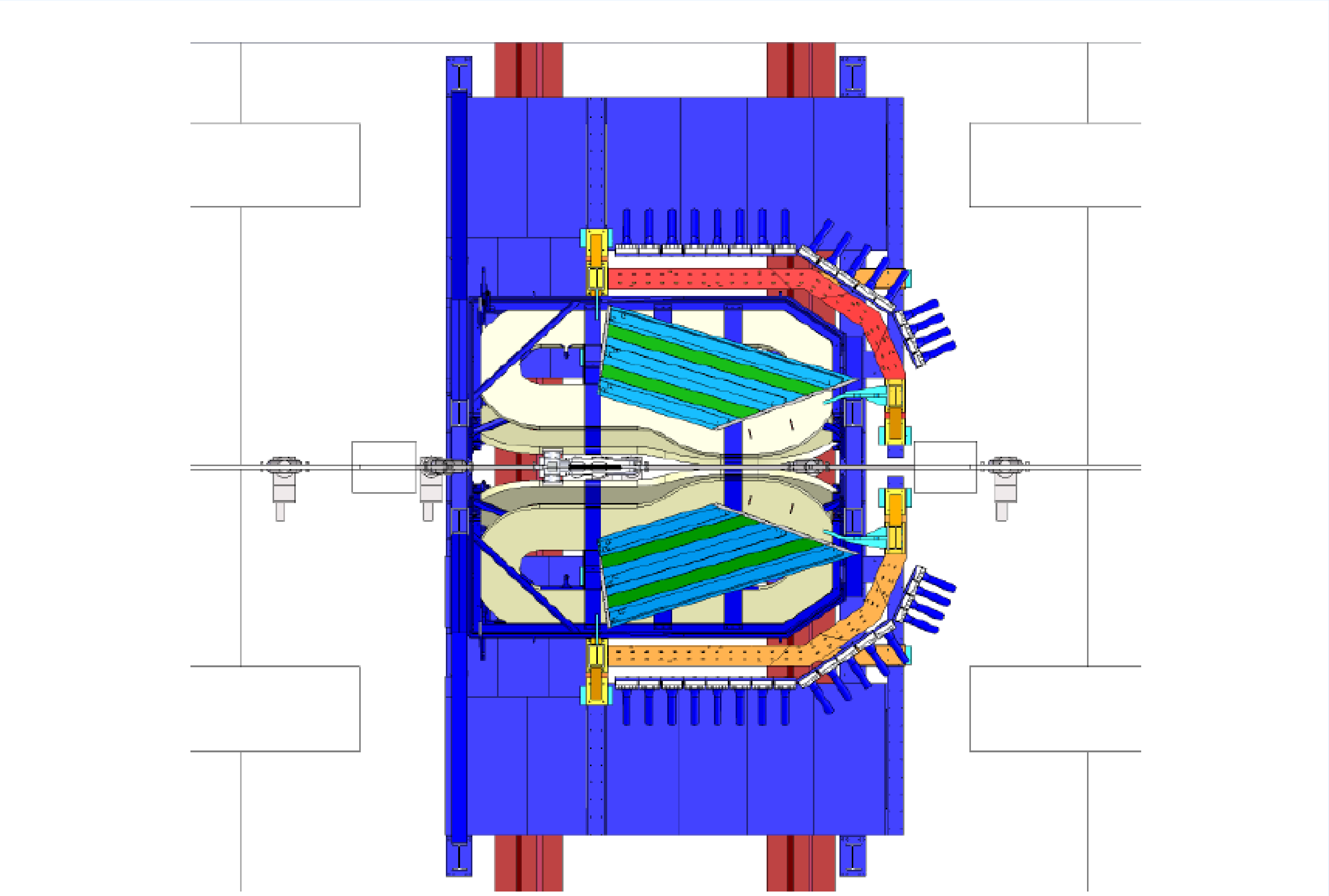
- Existing radiation hard $PbF_2$ crystals at U. Mainz
- 560 kHz rate expected at 2 GeV
- 26 X 26 X 160 $mm^3$
- Needs to operate from 2 to 4.5 GeV



# Quarter Section at DORIS Interaction R.



# OLYMPUS@DORIS Top View



# Schedule

- BLAST disassembly completed and shipped
  - Magnet, TOF, wire chambers, detector subframes
  - All detector components to be at DESY end of July 2010
  - Restringing of wire chambers July – October 2010
  - TOF preparation, toroid assembly (on rails in DORIS hall), DAQ
- Assembly and testing of target at MIT-Bates through October 2010
  - Target chamber ordered, expect delivery in July
  - Commissioning of gas system underway
  - Target cells under construction in Ferrara to arrive in June 2010
  - Control system development to start in May 2010
  - Complete system to be tested at MIT-Bates August – September 2010
  - Ship to DESY October 2010, install in Dec 2010 – Feb 2011 shutdown
- Luminosity Monitoring
  - Hampton group to be at MIT-Bates June – August 2010
  - Assembly of GEM detector elements at Bates
  - New INFN readout system to be available August 2010
  - Testing of GEMs at Hampton U. August – October 2010 with cosmic rays
  - Ship to DESY end of 2010, install in Feb 2011
- Install test experiment Dec 2010 – Feb 2011, establish internal target operation
- Install OLYMPUS experiment in interaction region in August 2011
- Commission in fall 2011
- Take data in two running blocks in 2012

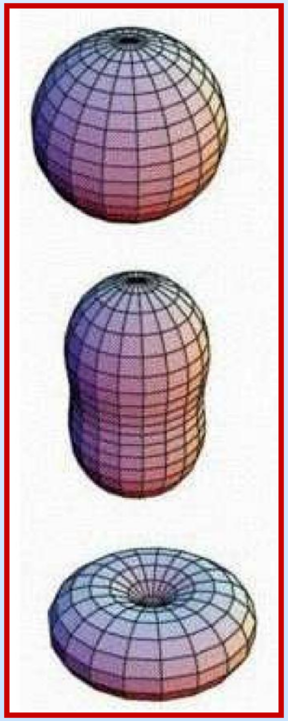
# Summary

- 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
  - Scattering of positrons
- Need both positron and electron beams for a definitive test of TPE
  OLYMPUS, CLAS, VEPP-3
- Improved precision and extension of "standard" methods to high $Q^2$
- A comprehensive and rich program underway and/or proposed is expected to be conclusive within a few years
- Broader Impact:
  gamma-Z box in PVES; TPE effects in Fewbody Structure and DIS

# 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)

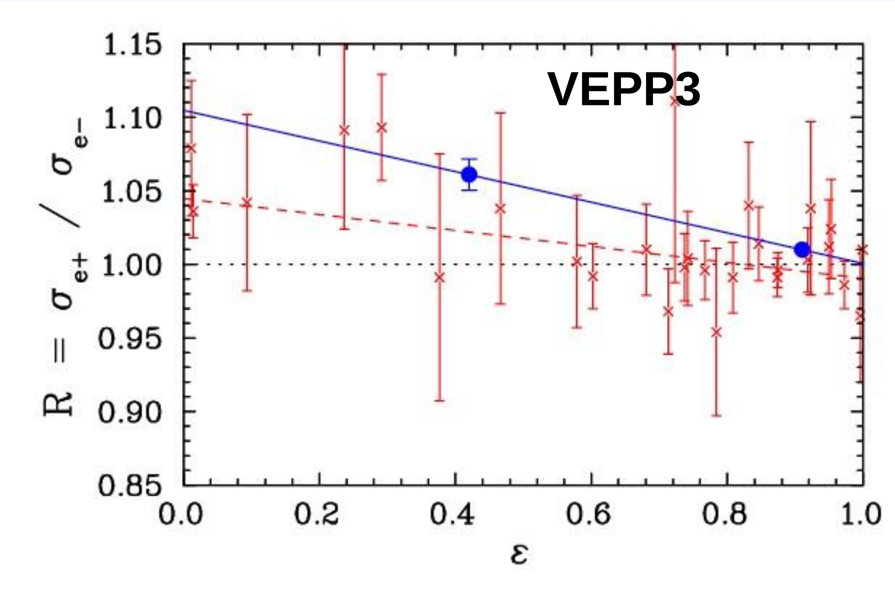
**We have made big investments in lepton scattering facilities to explore hadron structure**

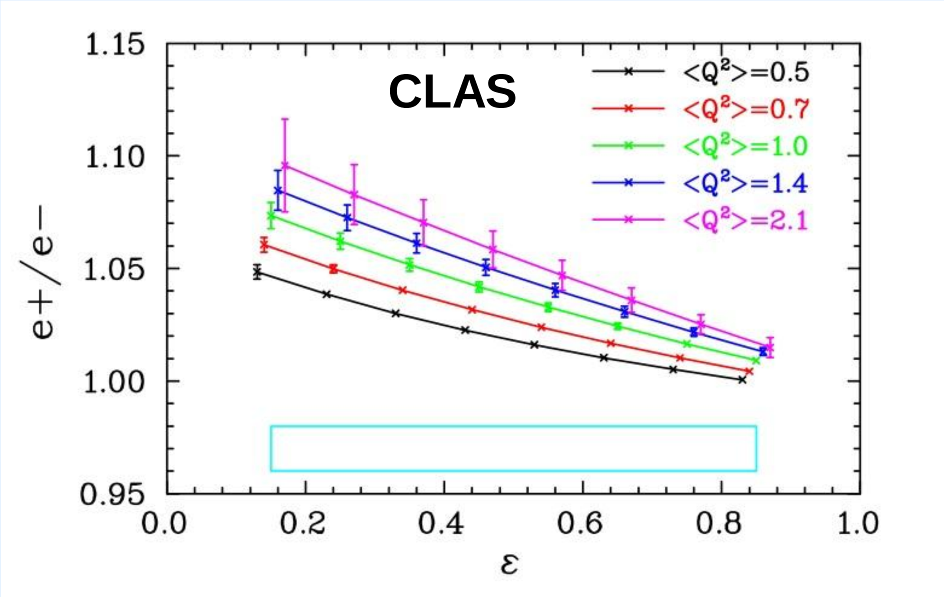
**The elastic form factors characterize the simplest process in nuclear physics, namely elastic scattering**
(straightforward, one should think)

**We have to understand the elastic form factors before we can claim to have understood anything else**

# Backup slides

# e+/e- cross section ratio to verify TPE




**Experiment proposals to verify TPE hypothesis:**

| | | | |
|---|---|---|---|
| **e+/e- ratio:** | **CLAS/PR04-116** | **secondary e+/e- beam** | **– 2011/12** |
| | **Novosibirsk/VEPP-3** | **storage ring / intern. target** | **– 2009-?** |
| | **OLYMPUS@DESY** | **storage ring / intern. target** | **– 2012** |

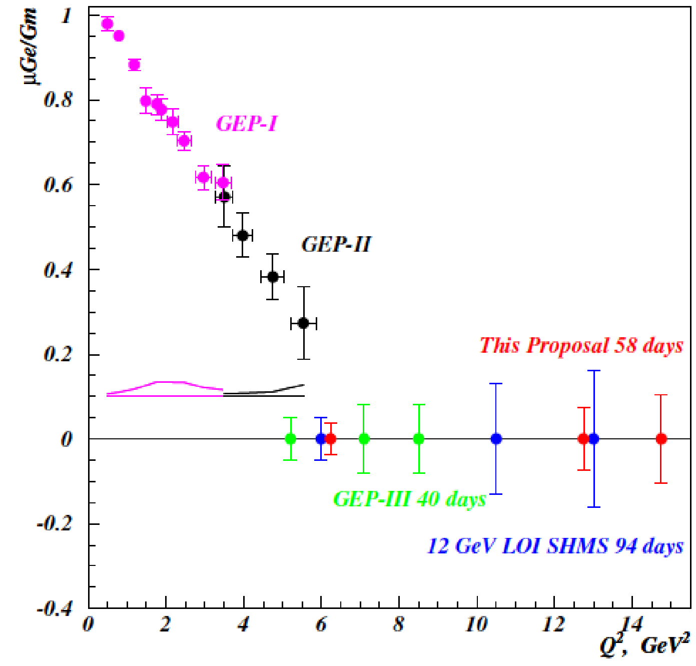
# New Proton Measurements at High $Q^2$

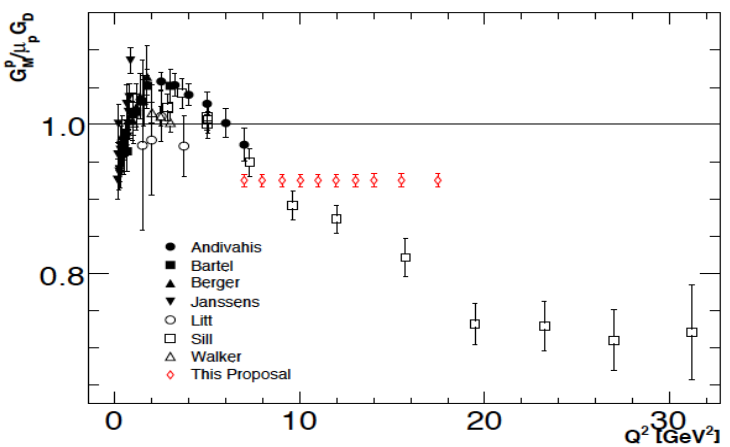
## High-$Q^2$ measurements at Jefferson Lab

- **Hall C E05-017: Super-Rosenbluth**
  $Q^2 = 0.9 – 6.6\ (GeV/c)^2$
  Completed in summer 2007
- **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
- **SANE /Hall C E05-017: Polarized Target**
  $Q^2 = 5 – 6\ (GeV/c)^2$
  Completed in spring 2009

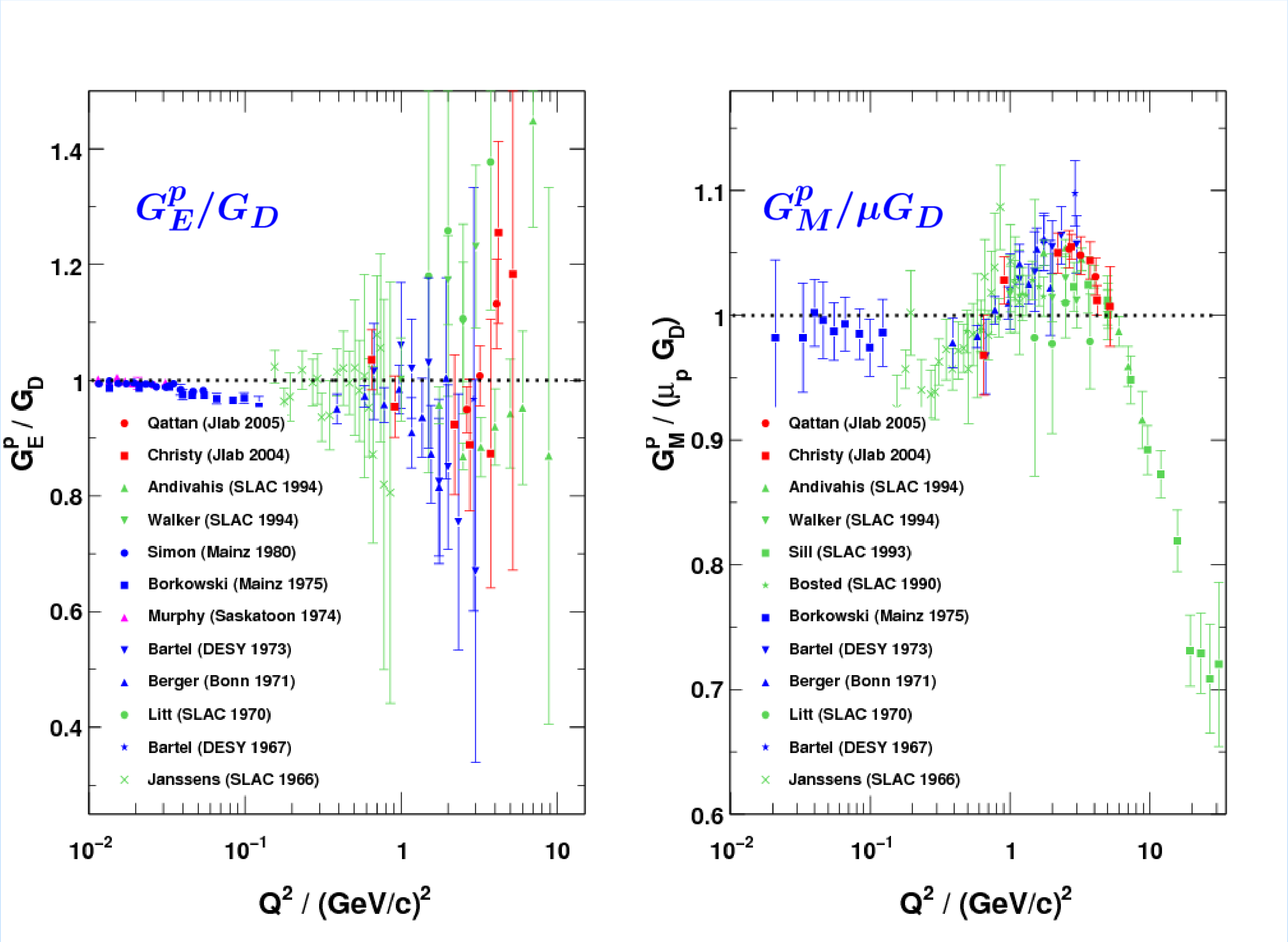
## Proposed experiments

- 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
- 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 $(GeV/c)^2$: Conditionally approved

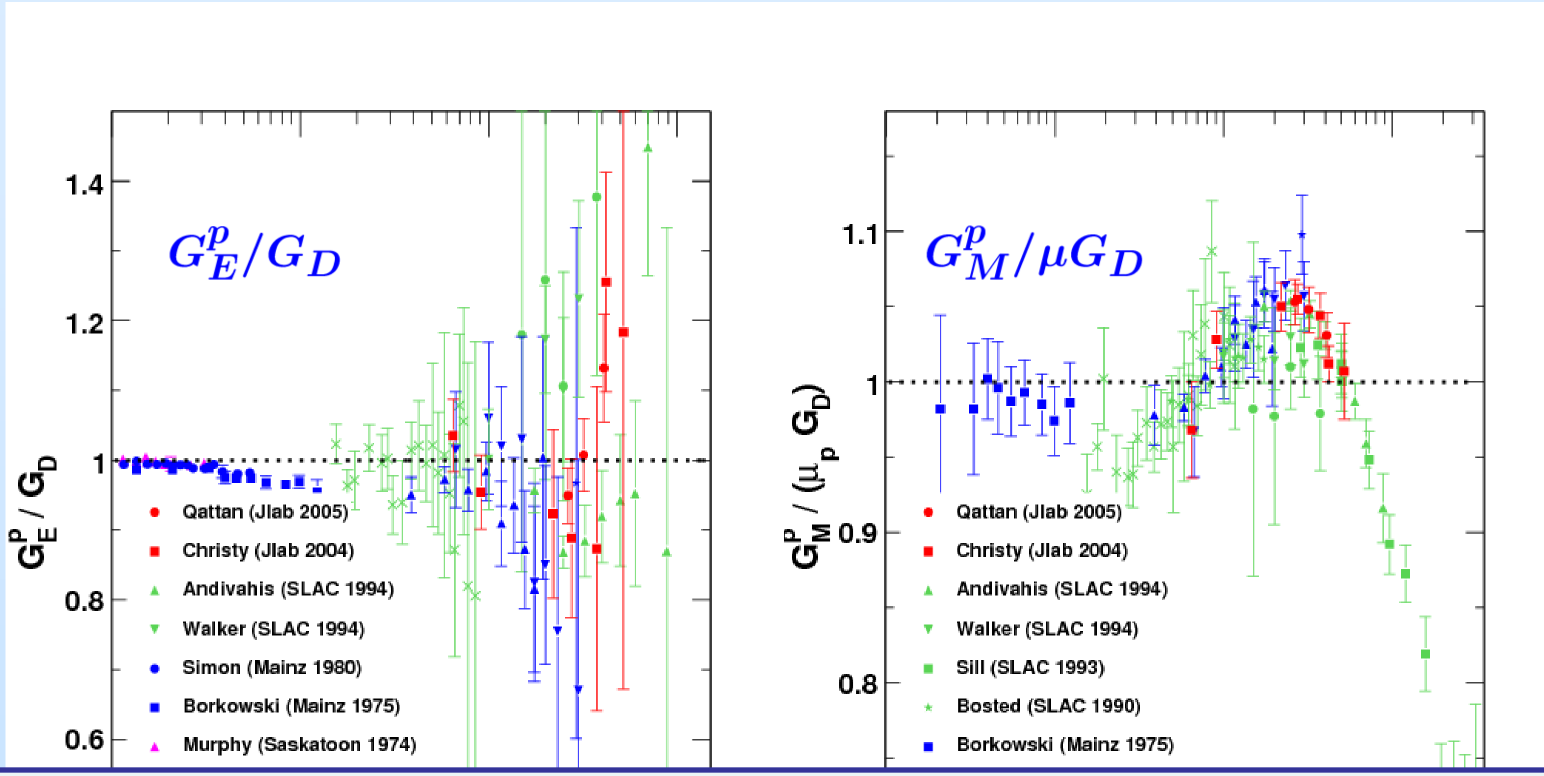


# $G^p_E$ and $G^p_M$ from Unpolarized Data



# $G^p_E$ and $G^p_M$ from Unpolarized Data




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

# 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

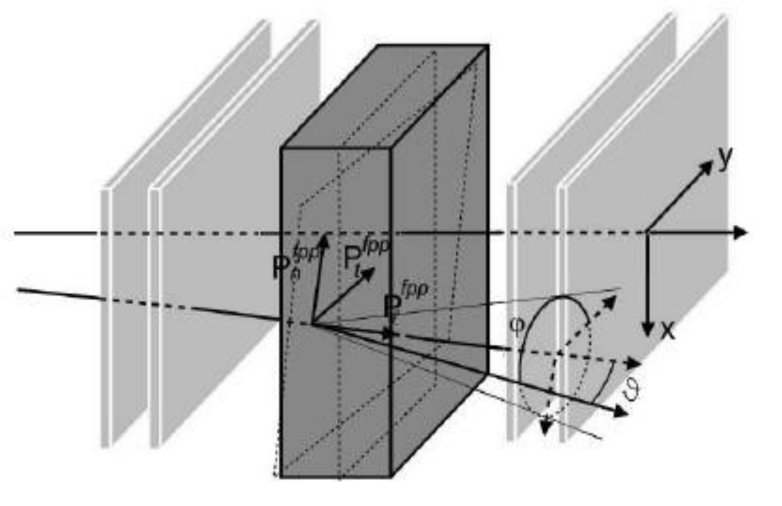



FIG. 9: Schematic of the polarimeter chambers and analyzer, showing a non-central trajectory; $\vartheta$ is the polar angle, and $\varphi$ is the azimuthal angle from the $y$-direction counterclockwise.

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

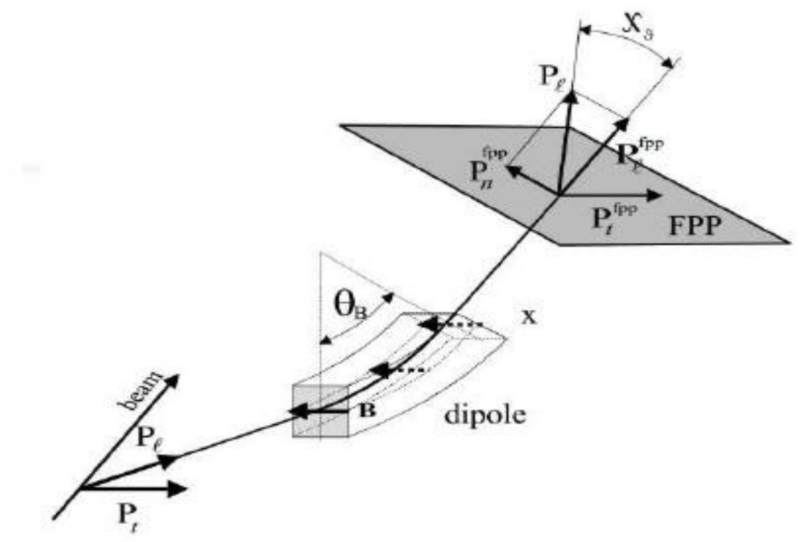
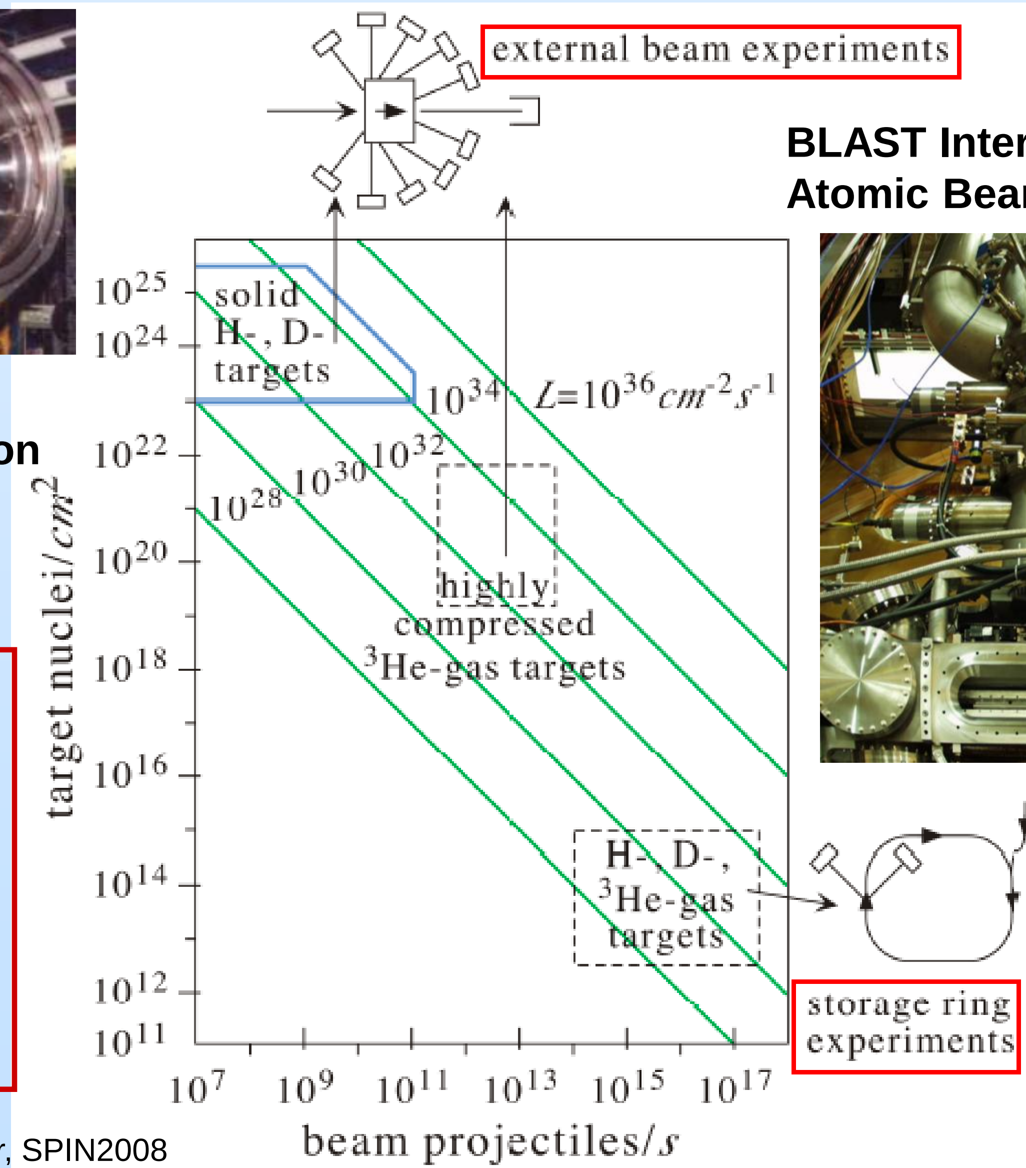



FIG. 15: Schematic drawing showing the precession by angle $\chi_\theta$ of the $P_\ell$ component of the polarization in the dipole of the HRS.

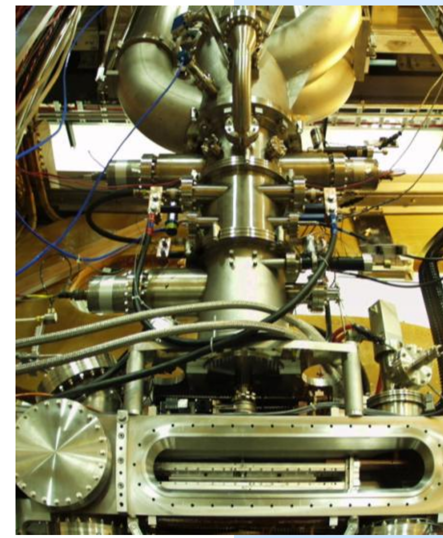
**Spin transfer formalism** to account for spin precession through spectrometer

# Polarized Targets

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




**BLAST Internal Target:**
**Atomic Beam Source**

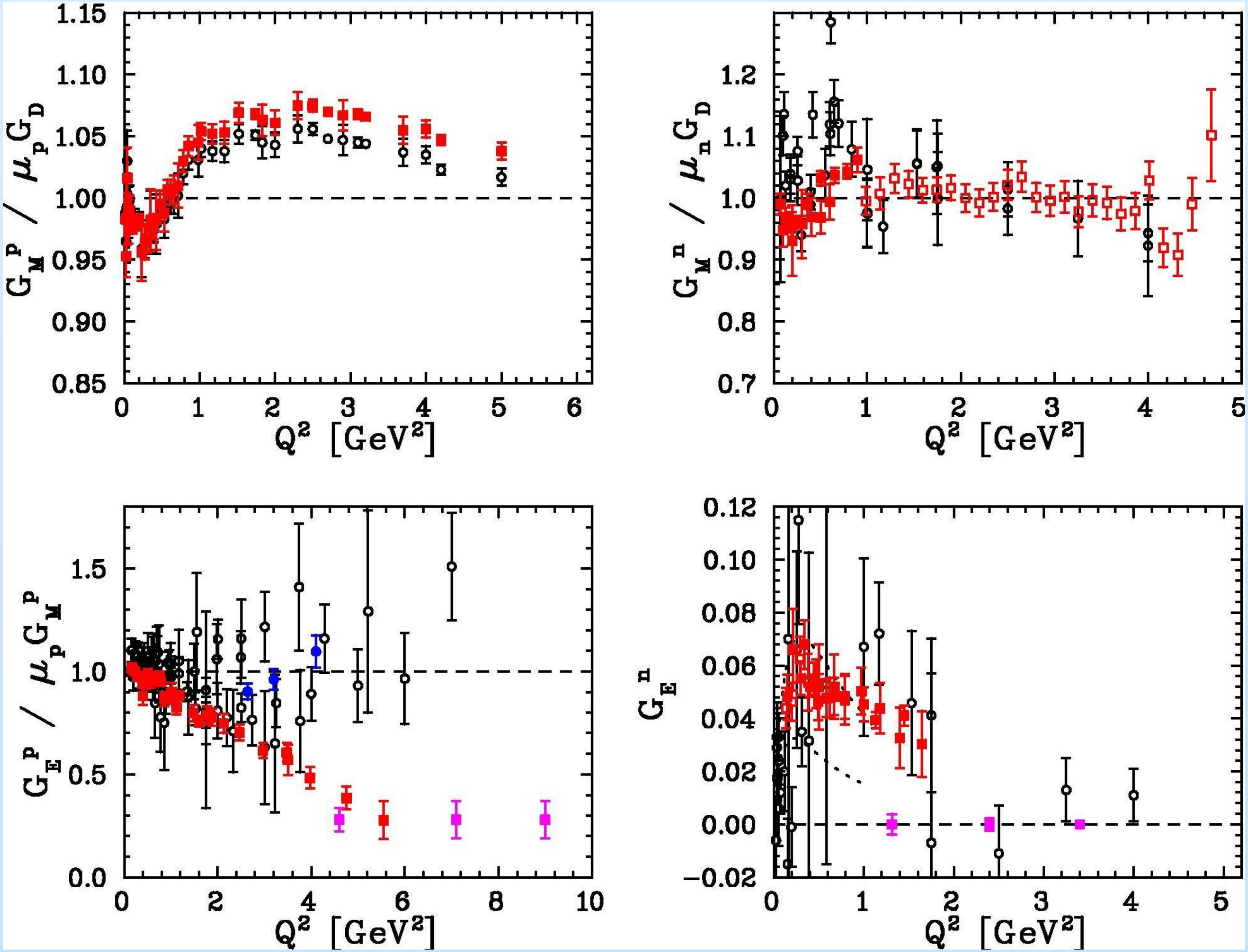


**Limited luminosity for polarized hydrogen/deuterium targets,**

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

from W. Meyer, SPIN2008

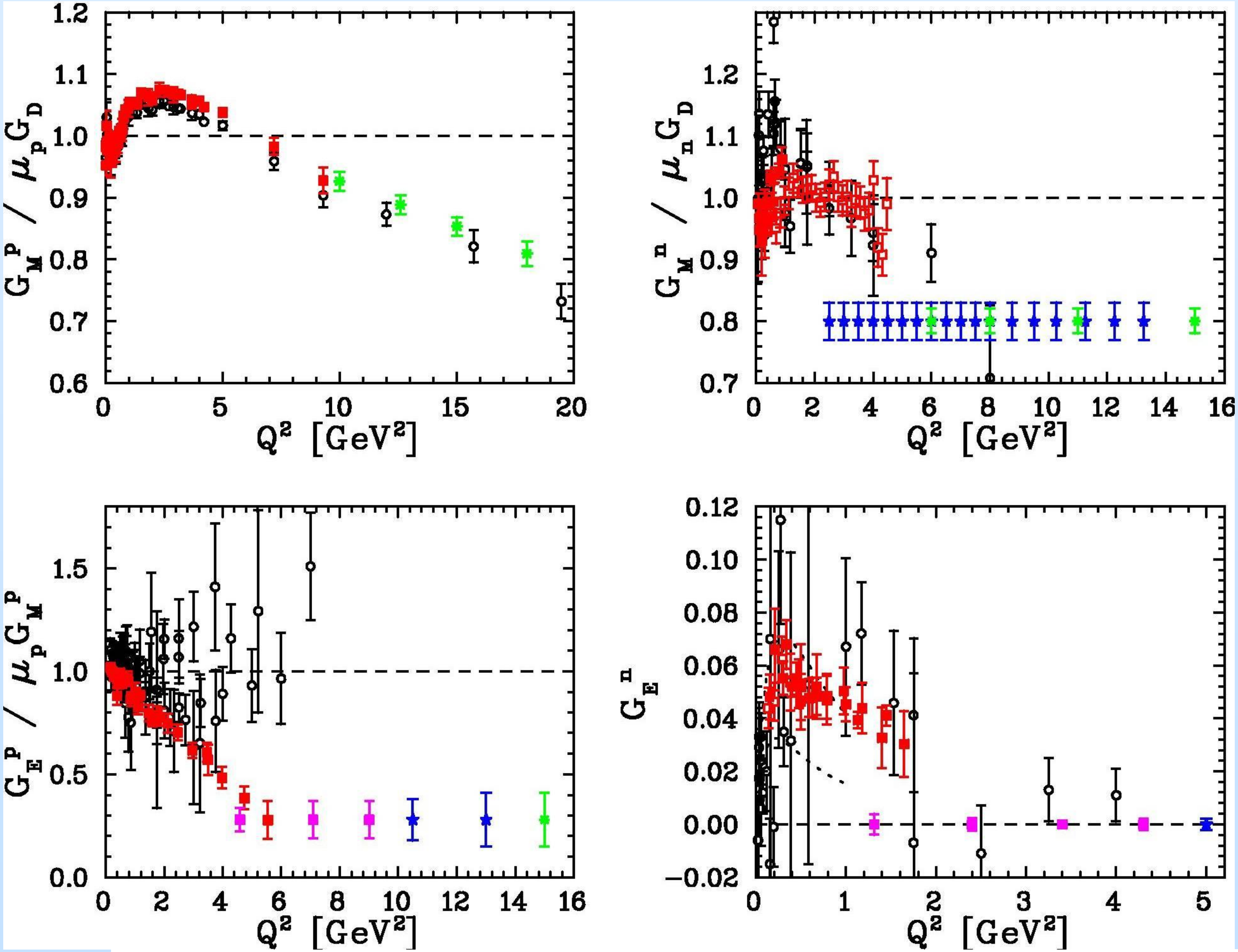
# Nucleon Form Factors: Last Ten Years



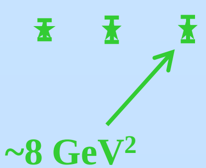

J. Arrington
PANIC08

**Magenta: underway or approved**

# Extensions with Jlab 12 GeV Upgrade



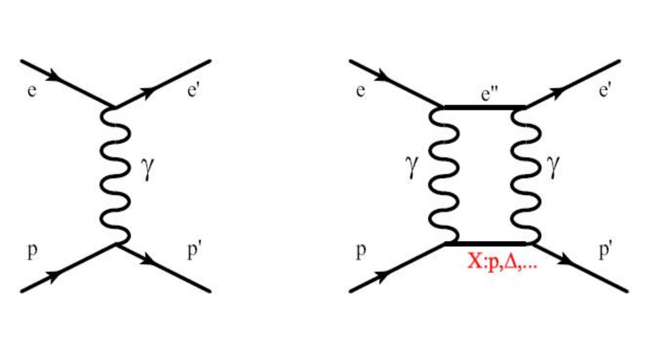

J. Arrington
PANIC08




- **BLUE = CDR or PAC30 approved, GREEN = new ideas under development**

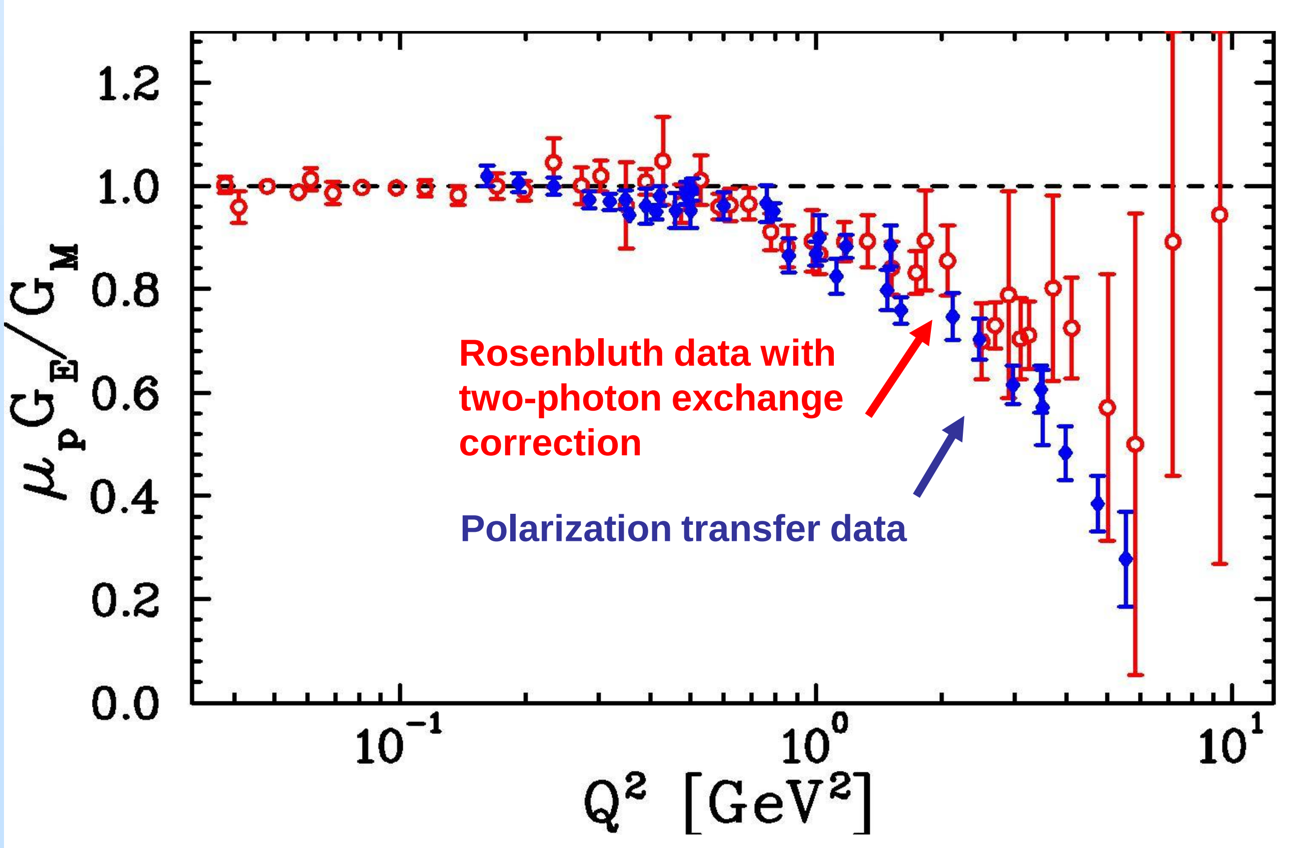
# Two-Photon Exchange: Exp. Evidence

**Two-photon exchange theoretically suggested**

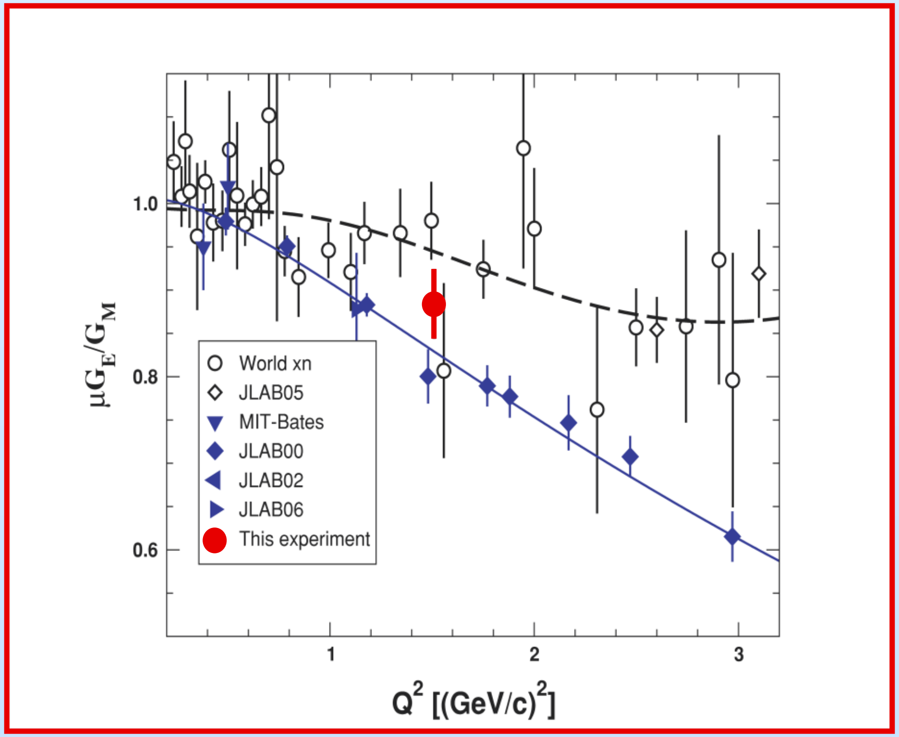



**TPE can explain form factor discrepancy**

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



# 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

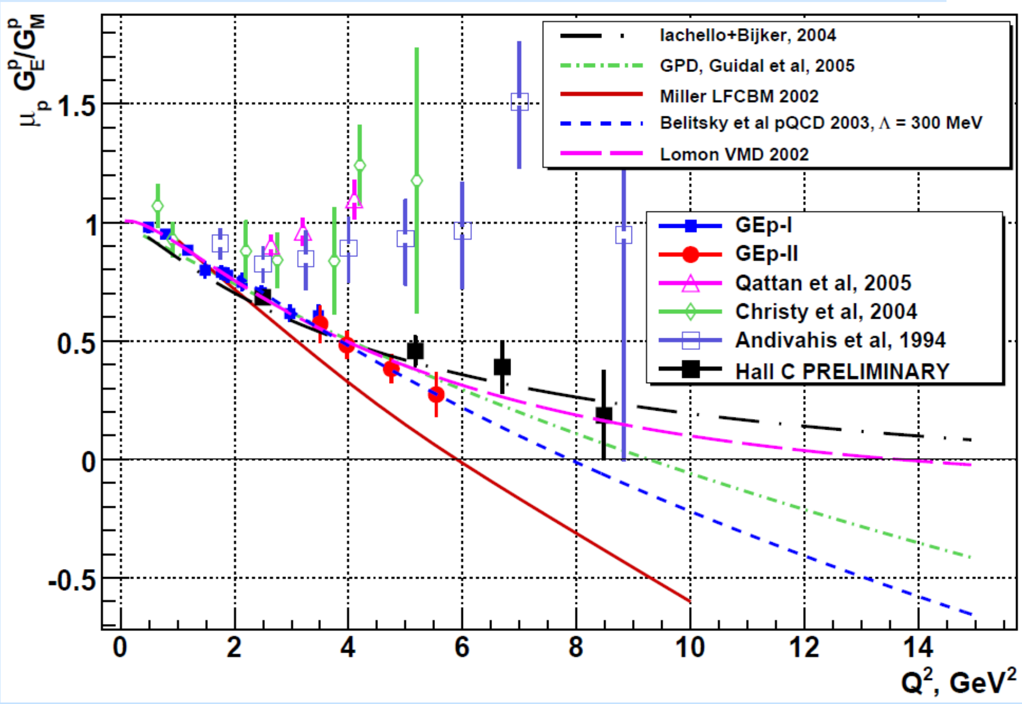
**RSS /Hall C: $Q^2 \approx 1.5$ (GeV/c)$^2$**

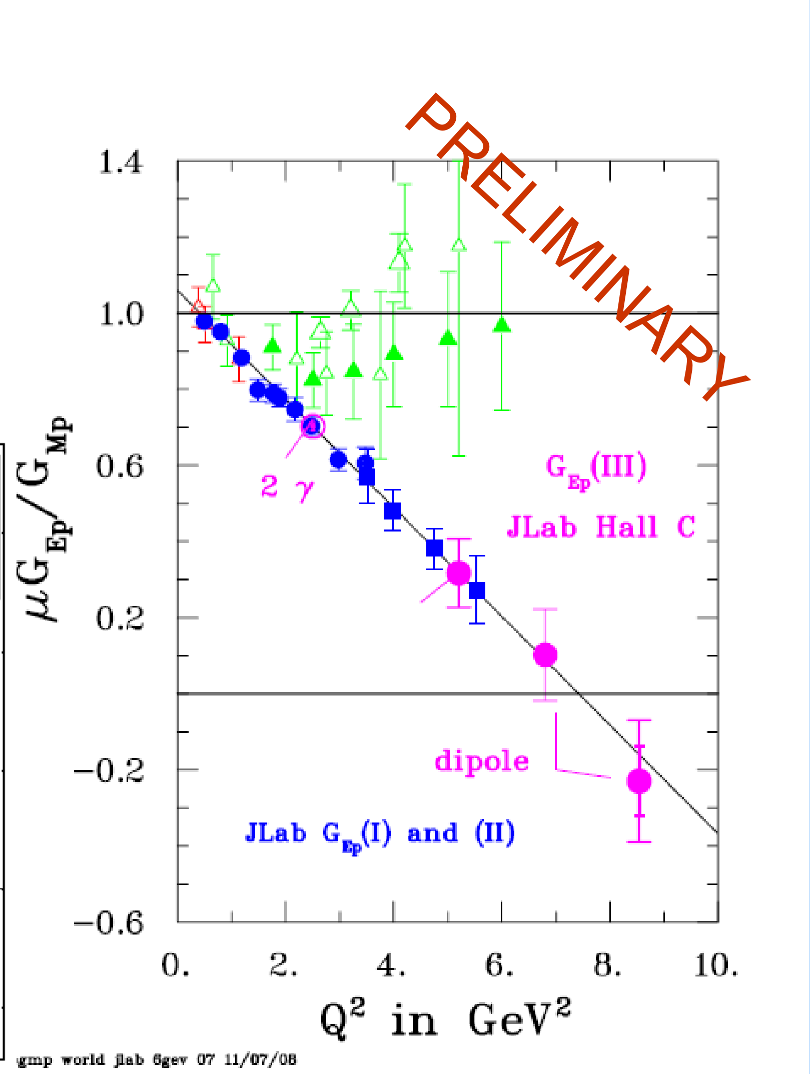
**SANE/Hall C: completed March 2009**
**BigCal electron detector**
**Recoil protons in HMS parasitically**
**Extract $G_E/G_M$ to <5% at $Q^2 \approx$5-6 (GeV/c)$^2$**

# New Proton Measurements at High $Q^2$

**Extension to higher $Q^2$ at Jefferson Lab**

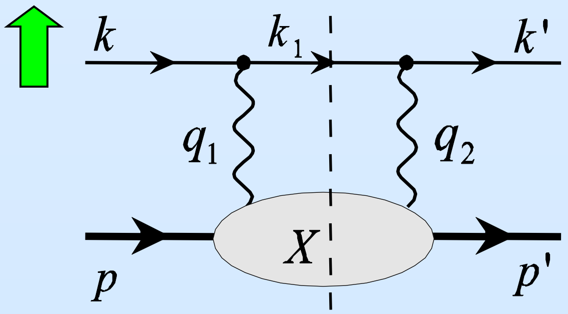
- **GEp-III /Hall C: PR04-108/PR04-019**
  Completed in spring 2008
- Sign change of $G_E/G_M$ observed
  **(preliminary, C. Perdrisat @ PANIC08)**
- **Or maybe not (preliminary, CIPANP09)**



# Imaginary part of TPE: SSA's

spin of beam OR target
NORMAL to scattering plane




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

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

$$A_n = -\frac{1}{(2\pi)^3}\frac{e^2(1-\varepsilon)}{8\,Q^2}\int_{M^2}^{s} dW^2 \frac{|\vec{k}_1|^2}{4\sqrt{s}}\int d\Omega_{k1}\frac{1}{Q_1^2\,Q_2^2}\,\mathcal{I}\left(L_{\alpha\mu\nu}H^{\alpha\mu\nu}\right)$$

**lepton** $\quad L_{\alpha\mu\nu} = \bar{u}(k',h')\gamma_\mu(\gamma\cdot k_1 + m_e)\gamma_\nu u(k,h)\cdot[\bar{u}(k',h')\gamma_\alpha u(k,h)]^*$

**hadron** $\quad H^{\alpha\mu\nu} = W^{\mu\nu}\cdot\left[\bar{u}(p',\lambda'_N)\left(G_M\gamma^\alpha - F_2\frac{P^\alpha}{M}\right)u(p,\lambda_N)\right]^*$

$$W^{\mu\nu} = \sum_X (2\pi)^4\delta^4(p+q_1-p_X)\,\langle p'\lambda'_N|J^\mu(0)|X\rangle\,\langle X|J^\nu(0)|p\lambda_N\rangle$$

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

BF-06 (Wed.) BF-07 (Wed.)

# Target normal spin asymmetry

- general formula, of order $e^2$

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

- involves the imaginary part of two-photon exchange amplitudes