University of Glasgow

# Form factor measurements and the OLYMPUS experiment

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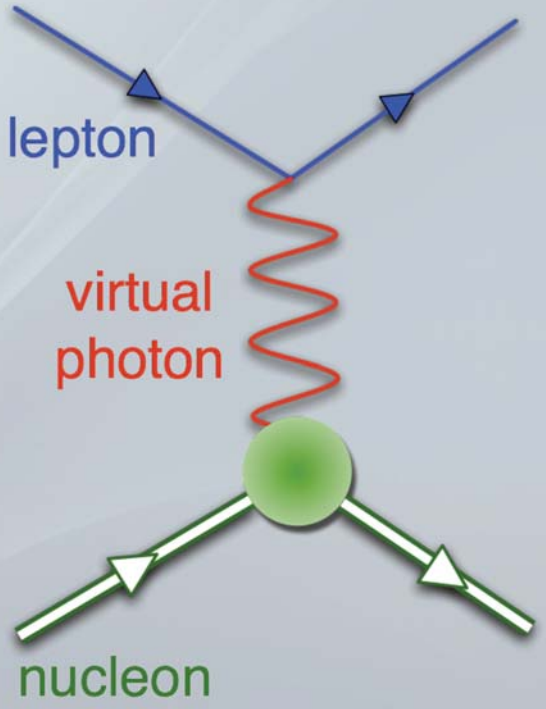
NPE Seminar
23 June 2011

# Form Factors

- Elastic scattering

$$\langle N(P')|J^{\mu}_{\mathrm{EM}}(0)|N(P)\rangle =$$
$$\bar{u}(P')\left[\gamma^{\mu}F_1^N(Q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2M}F_2^N(Q^2)\right]u(P)$$



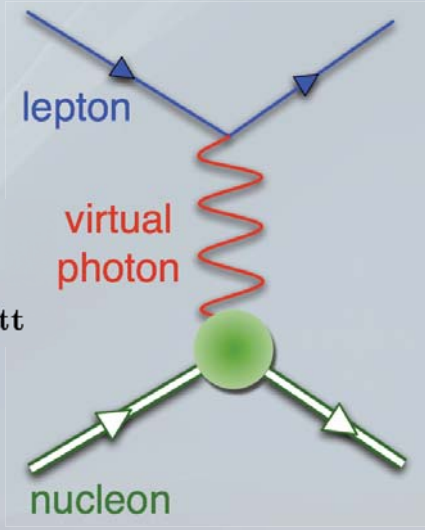

- Electric and magnetic form factors $G_E$ and $G_M$
  - Fourier transforms of resp. distributions

$$G_E = F_1 - \tau F_2; \quad G_M = F_1 + F_2, \quad \tau = \frac{Q^2}{4M^2}$$

# Classical Approach

- Assume single photon exchange – Born approximation
  - Measure cross section (Rosenbluth)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rosenbluth}} = \left[\frac{|G_E|^2 + \tau|G_M|^2}{1+\tau} + 2\tau|G_M|^2 \tan^2\frac{\theta}{2}\right]\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}$$



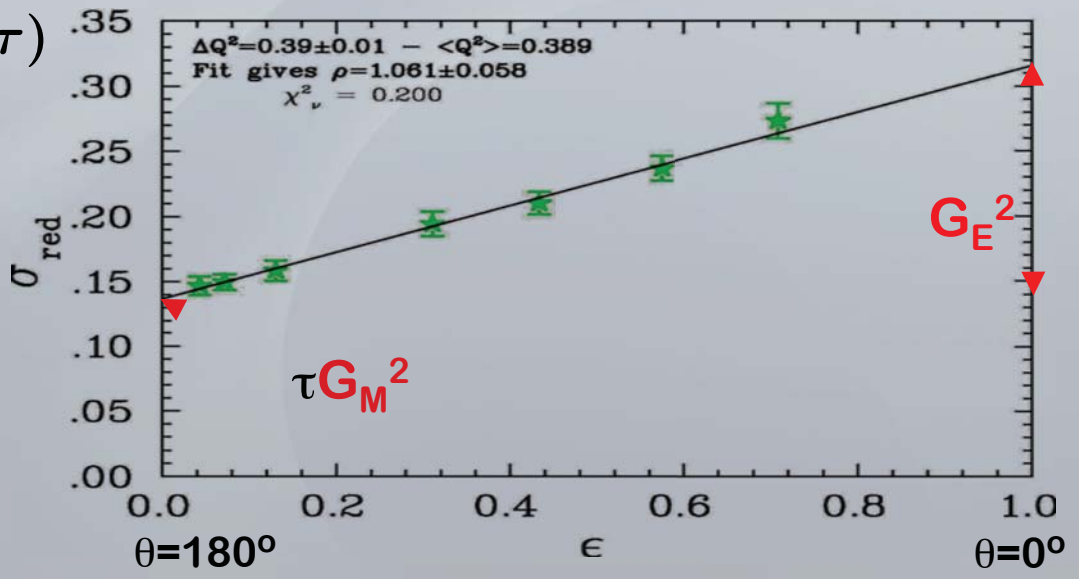

  - Extract $G_E$ and $G_M$

$$\sigma_{\text{red}} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rosenbluth}}}{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}}\epsilon(1+\tau)$$

$$= \epsilon|G_E|^2 + \tau|G_M|^2$$

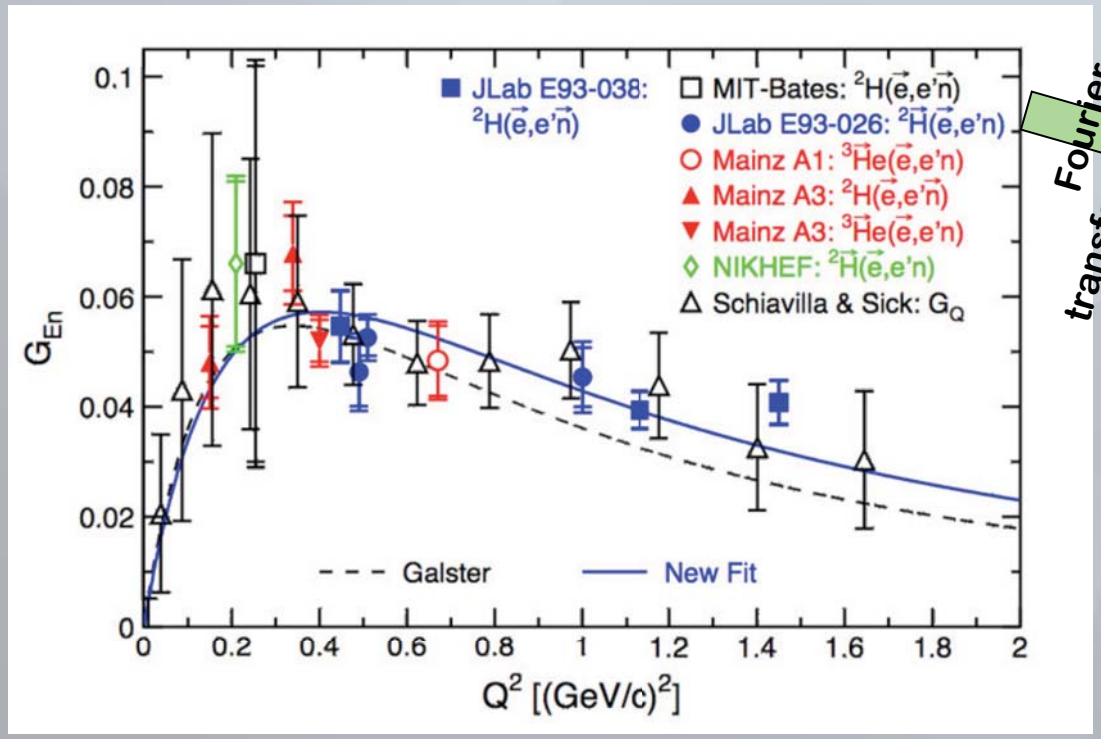
- with $\tau = \frac{Q^2}{4M_p^2}$

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

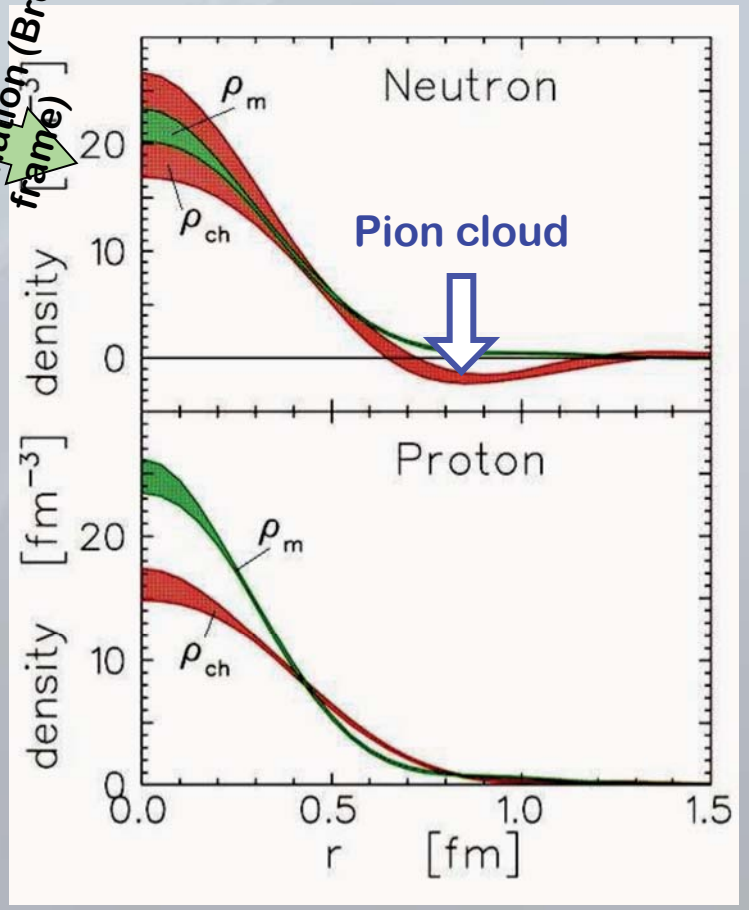


# Successful Approach

- Series of space like form factor measurements
  - access to radial charge and magnetic distributions

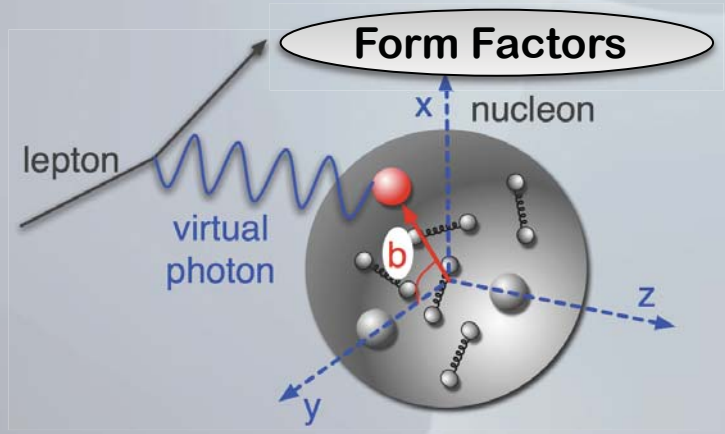


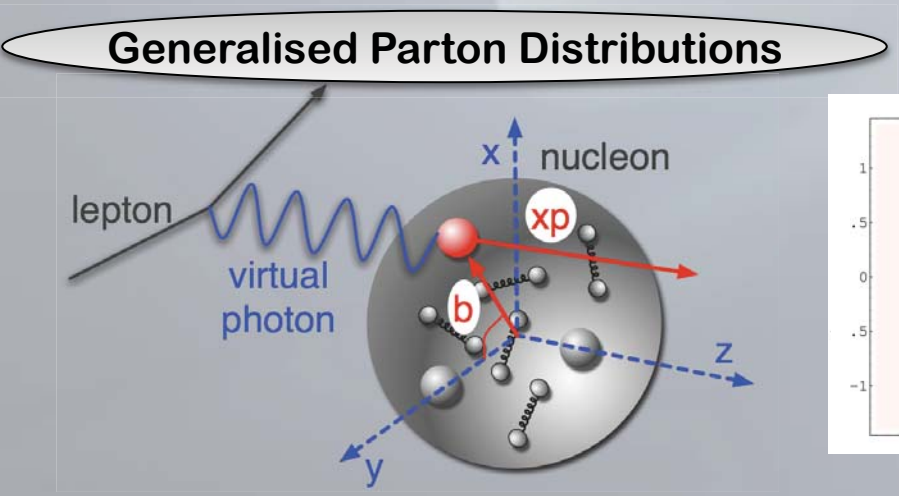

Fourier transformation (Breit frame)



# Aside: Connection to GPDs

- **Form factors are first moments of GPDs**
  - **i.e. constrain GPDs**



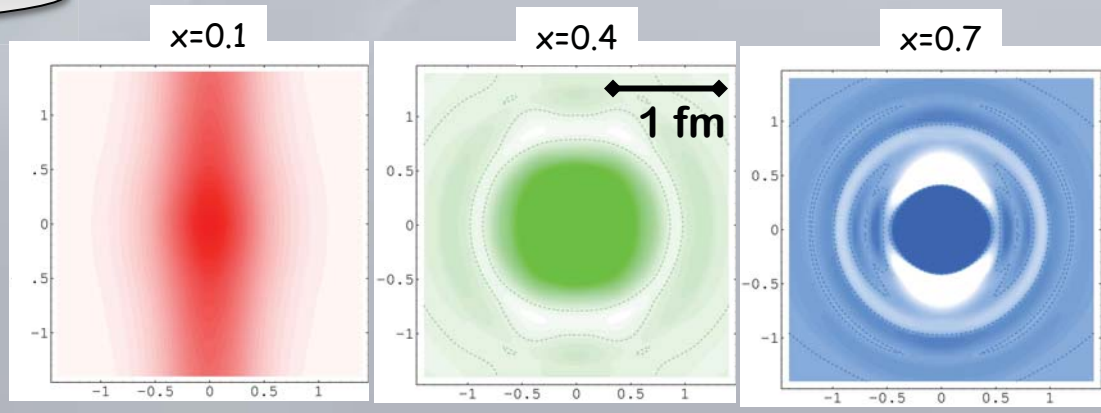




parallel anti-parallel quark spin

proton's shape

G.Miller, PRC 68:022201 (2003)

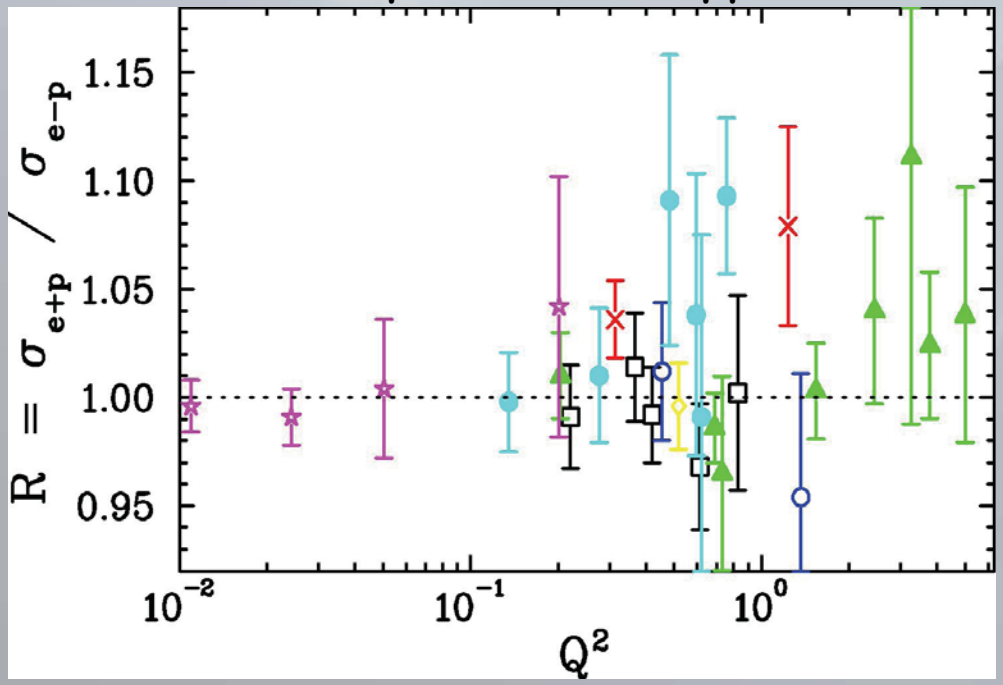
u-quark phase-space charge

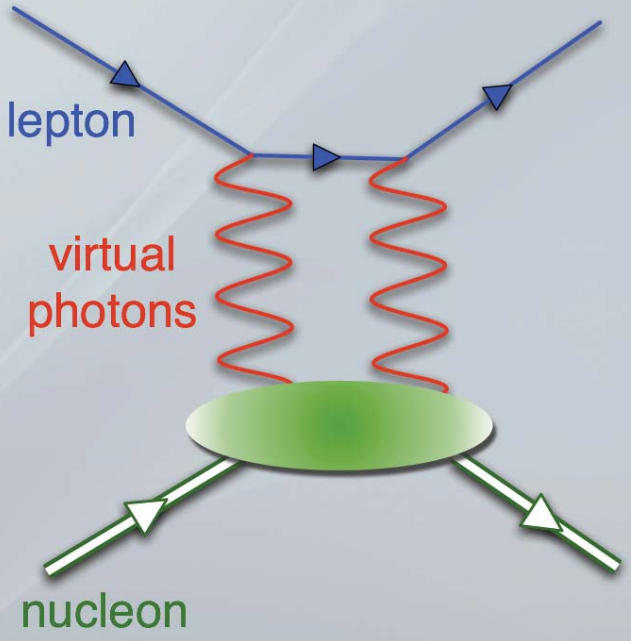



A.Belitsky, X.Ji, F.Yuan, PRD69:074014 (2004)

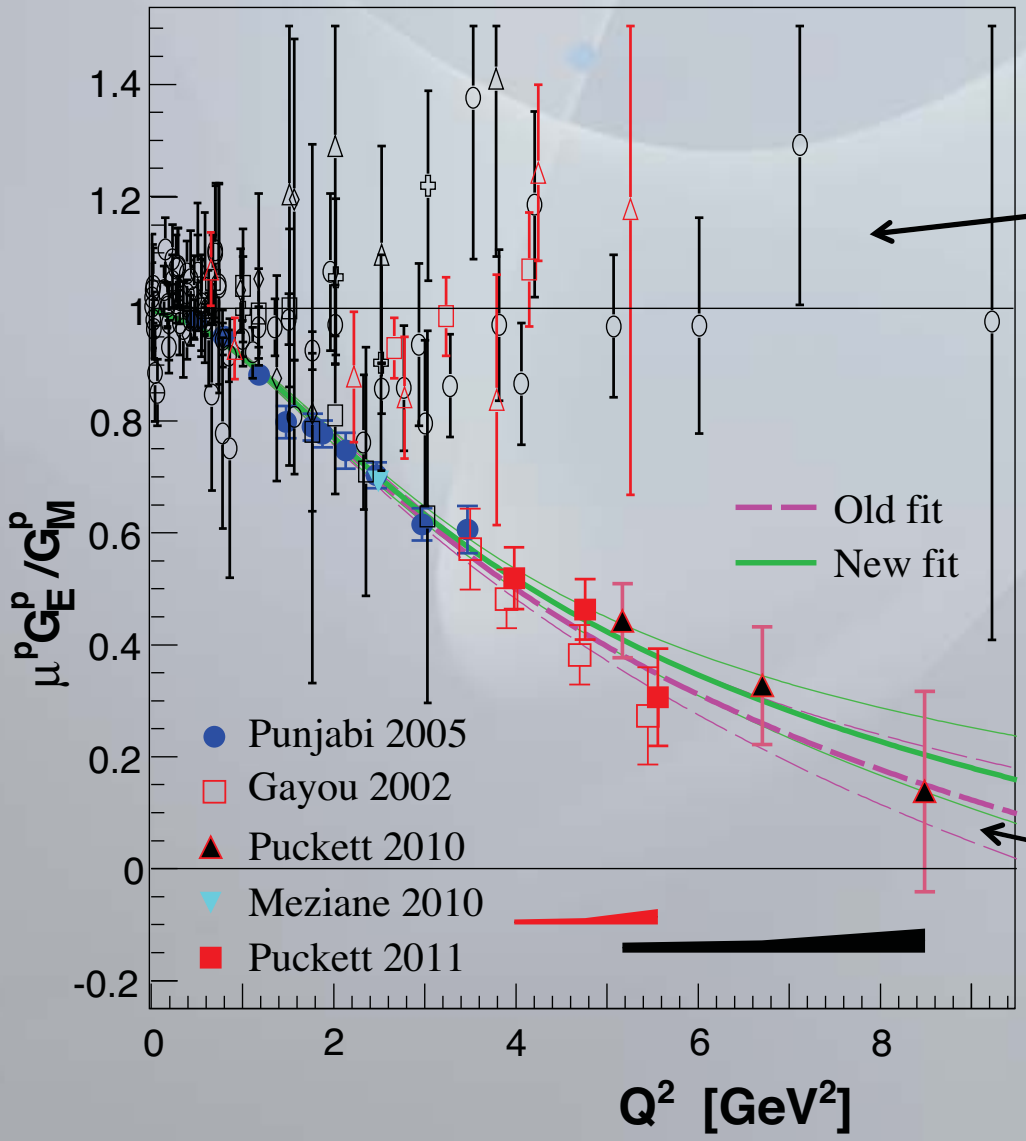
# Multi-Photon Contributions?

- Long standing beliefs:
  - $G_E \sim G_M$
  - Multi-photon contribution 1-2% only
- Experimental arguments
  - Linearity of Rosenbluth plot
  - $e^+/e^-$ (and $\mu^+/\mu^-$) ratio found to be 1
    - as required in Born approximation



# Recent Puzzle in $G_E/G_M$




Rosenbluth separation

Double polarisation measurements

# Recent Puzzle in $G_E/G_M$

- Nobody predicted this effect
- Polarization measurements
  - measure asymmetry ratio

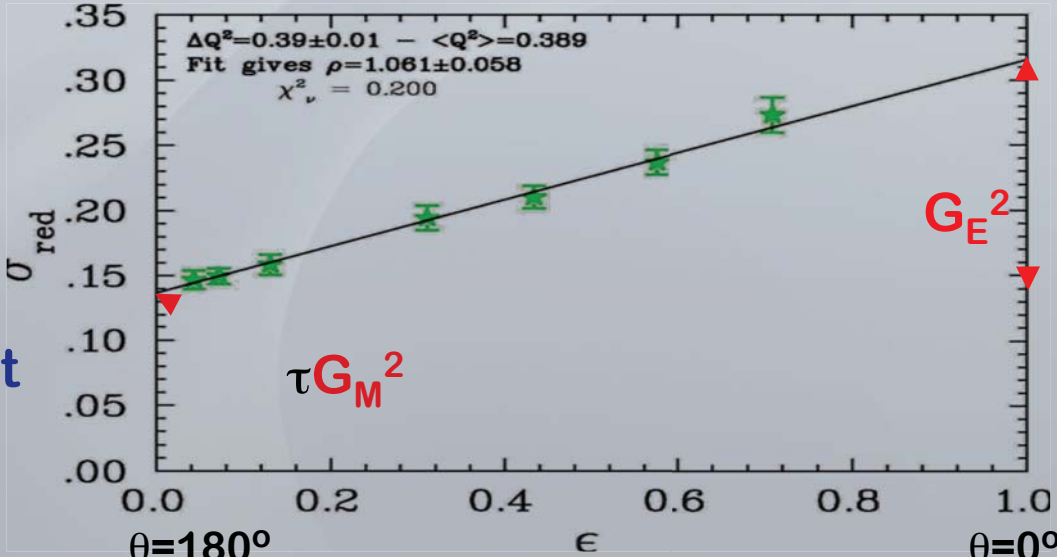
$$\frac{P_\perp}{P_\parallel} = \frac{A_\perp}{A_\parallel} \propto \frac{G_E}{G_M}$$

- Rosenluth separation

$$\sigma_{\mathrm{red}} := \epsilon |G_E|^2 + \tau |G_M|^2$$

at high $Q^2$

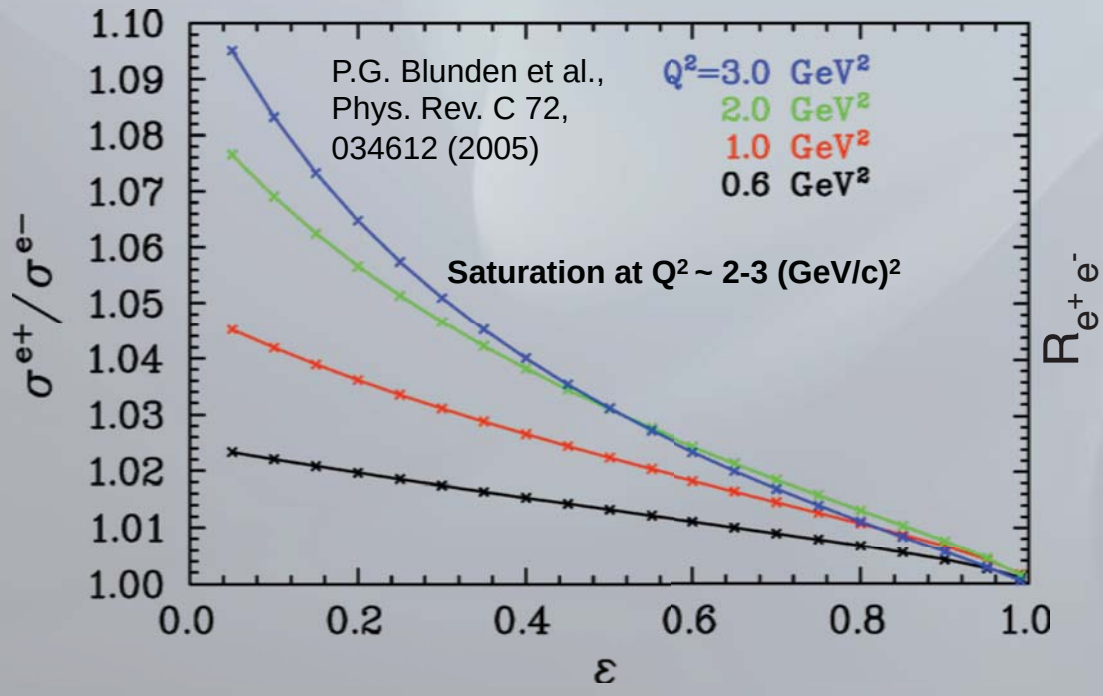
- $G_E$ difficult to extract
- $2\gamma$ corrections large

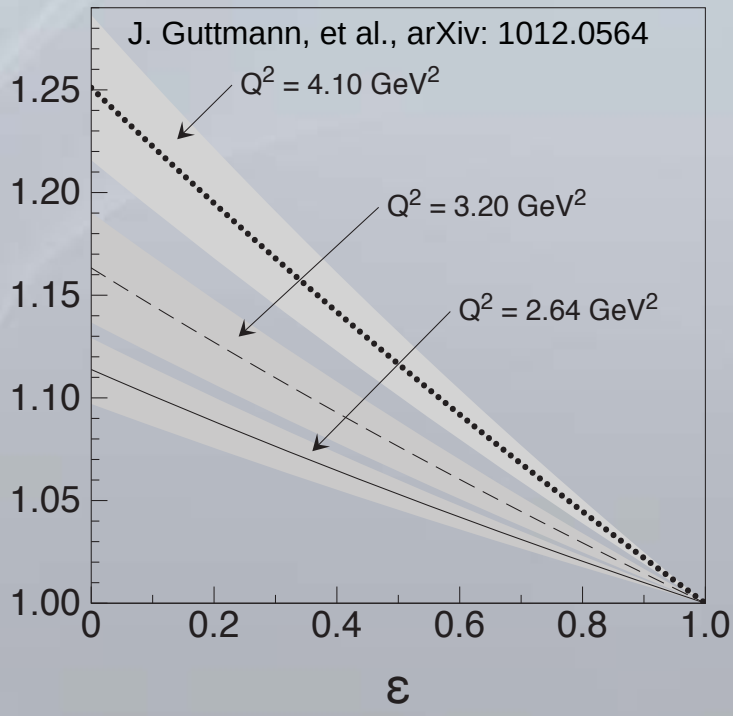


# How to address the issue

- Measure cross section ratio $e^+/e^-$ versus epsilon
  - exactly unity in Born approximation
  - two-photon effects at low epsilon
  - several percent effect at $Q^2 \sim 2$ GeV$^2$
  - 3 experiments: OLYMPUS, CLAS, VEPP3

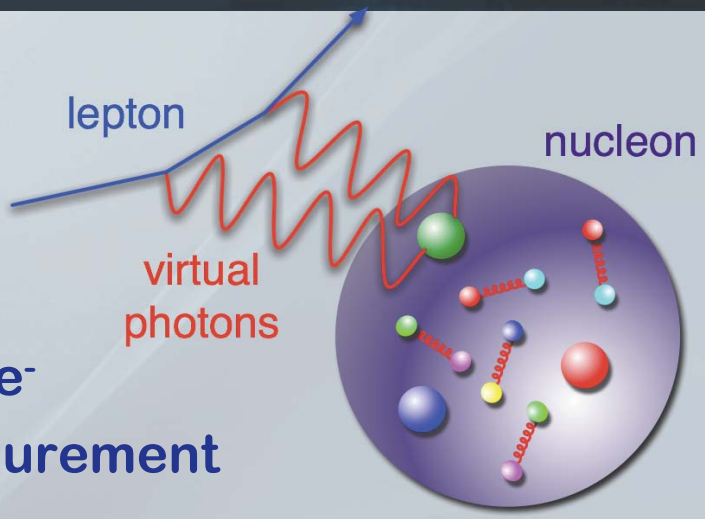
$$\epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$



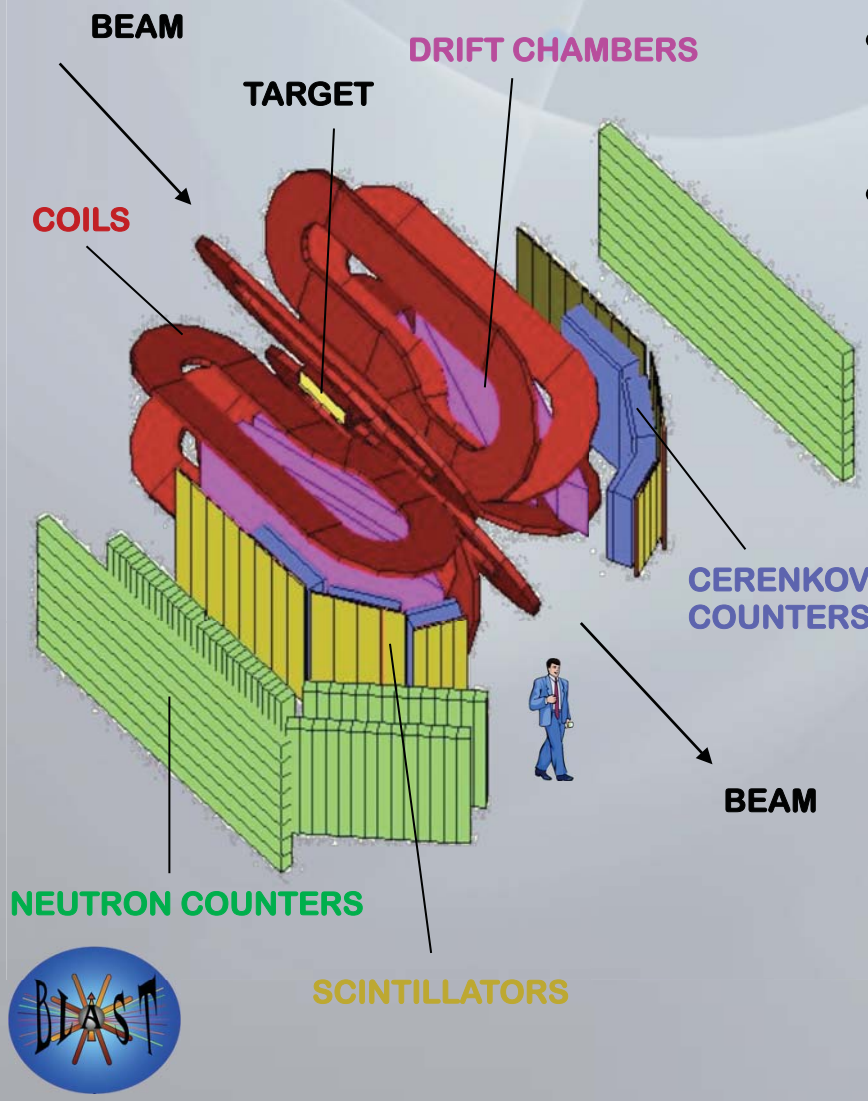
# Measurement Concept

- Electron and positron beams
- Proton target
- OLYMPUS features
  - E ~ 2 GeV
  - Frequent switch between $e^+$ and $e^-$
  - Lepton-proton coincidence measurement
  - Windowless, pure proton target
  - Large theta coverage, i.e. epsilon range
  - Minimal systematic uncertainties
    - symmetric arrangement
    - reversible magn. field
  - Precise luminosity measurement
    - ratio $e^+$ to $e^-$ with precision <1%
  - Redundancy



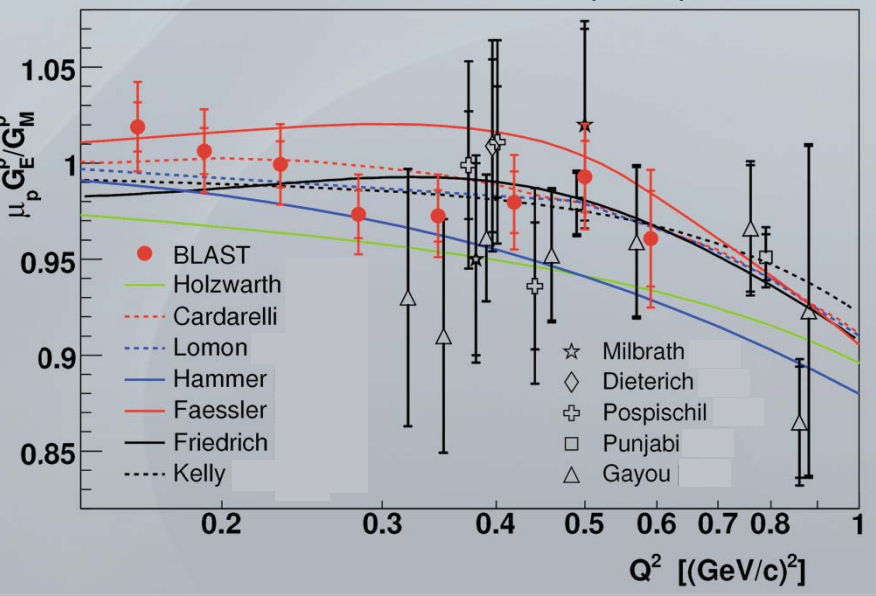

OLYMPUS

# BLAST at MIT-Bates

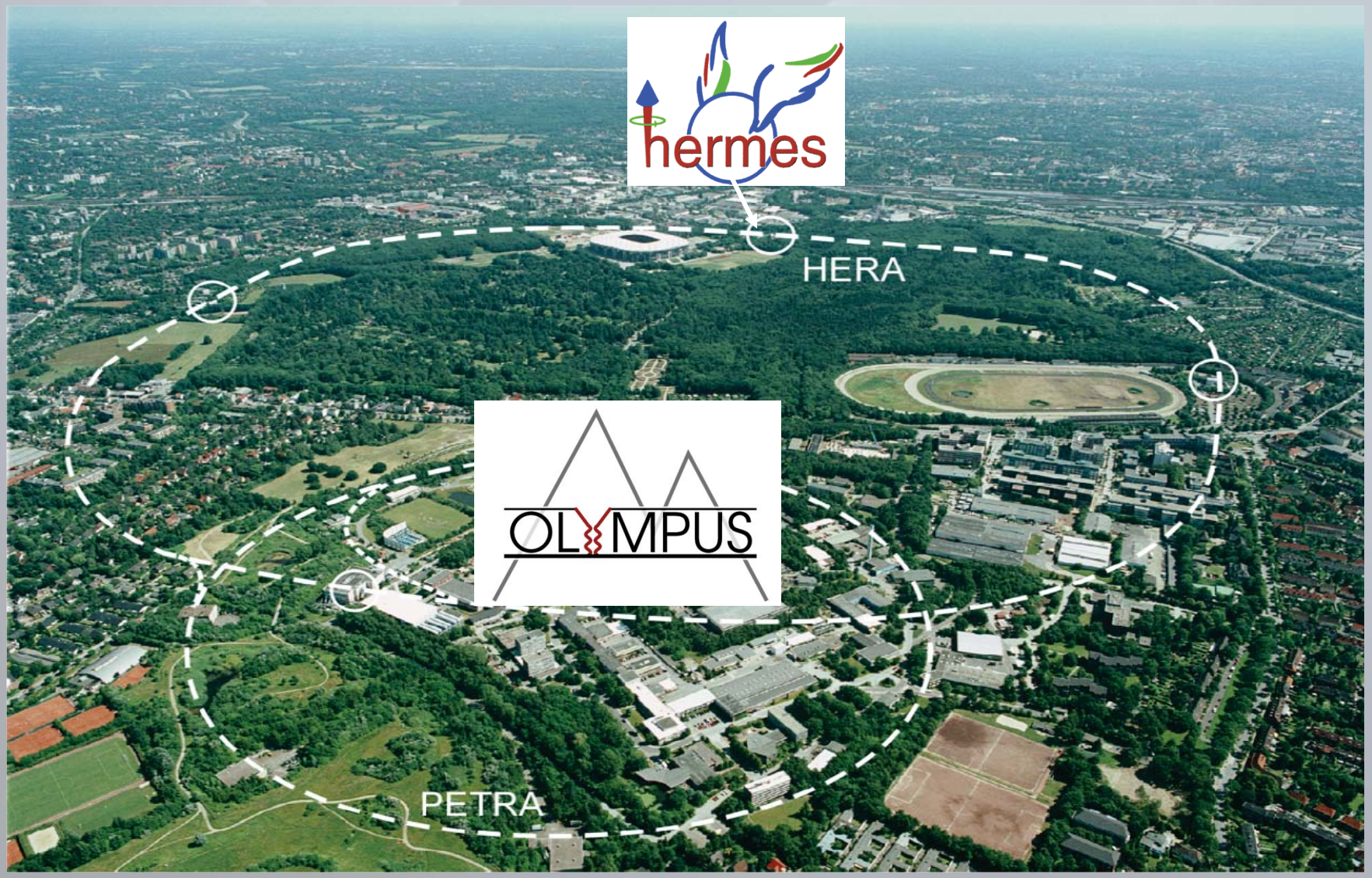



- BLAST Detector Set-Up
  - Fulfils most criteria
- MIT-Bates South Hall Ring
  - Too low $Q^2$ to study the observed effect

C.B. Crawford et al., PRL 98 (2007) 052301



# DESY Site

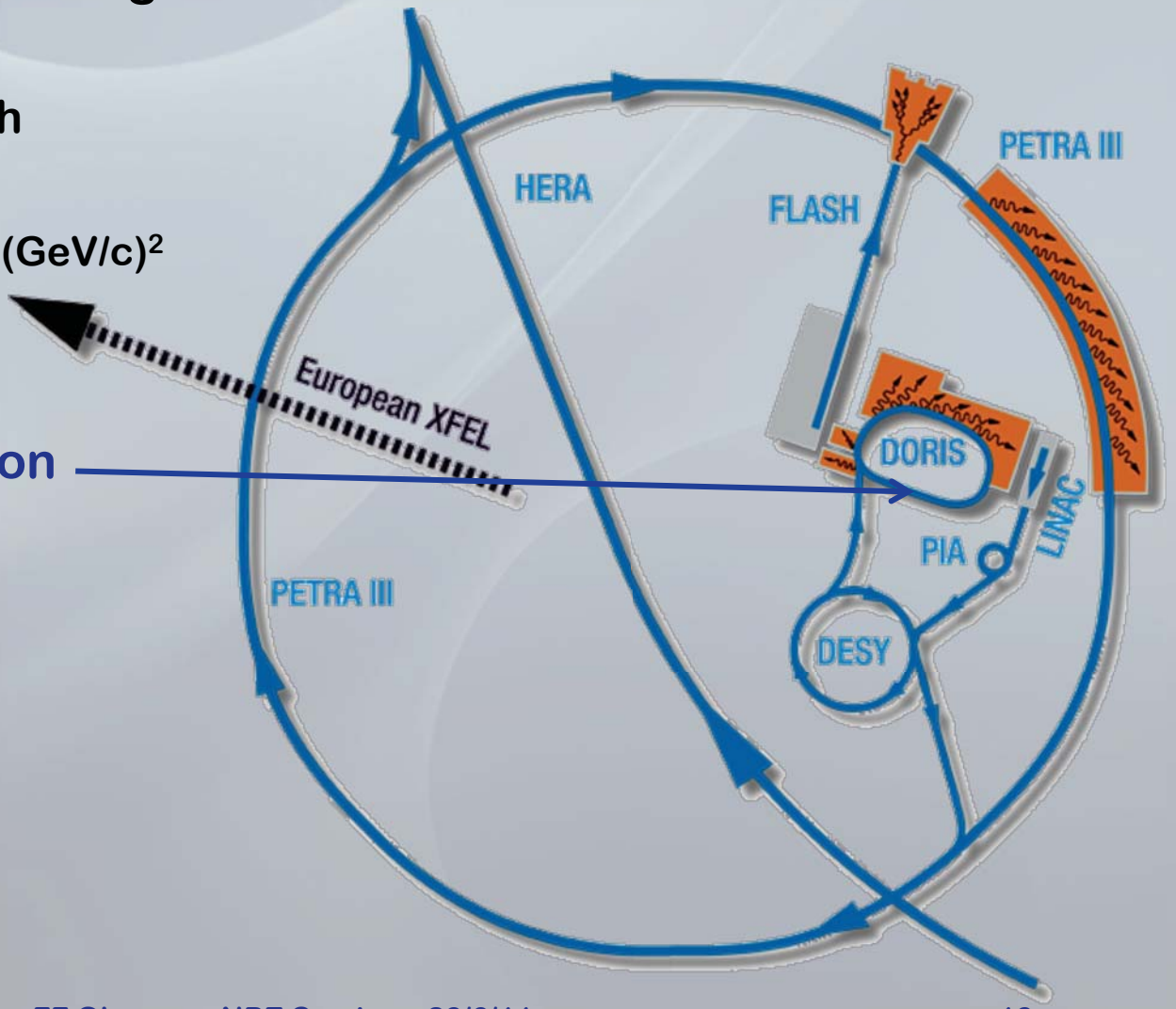


# DORIS Ring

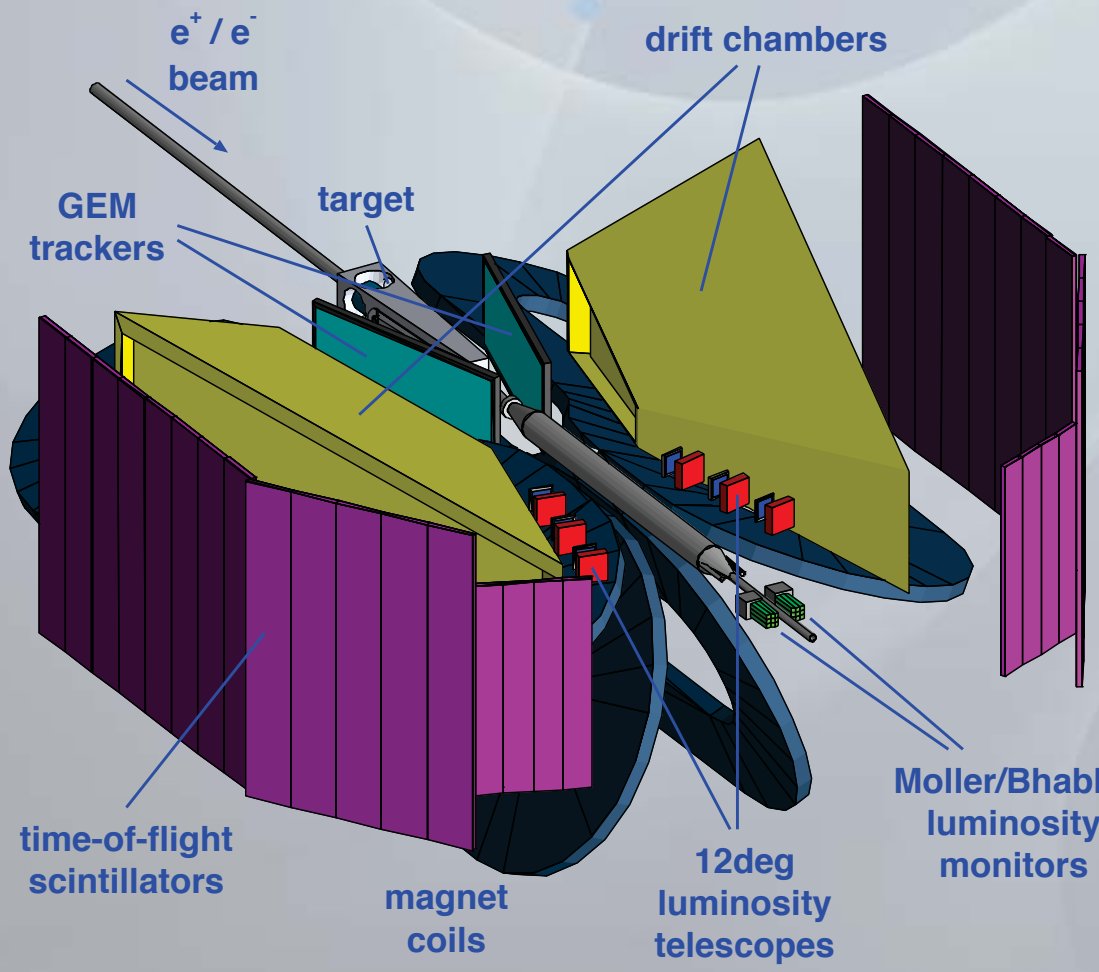
**DORIS at DESY, Hamburg**

- $e^+$ and $e^-$ beams
  - frequent switch
- E = 2.0 (4.5)GeV
  - $Q^2$ = 0.6-2.4(4.1) $(GeV/c)^2$

- **OLYMPUS location**



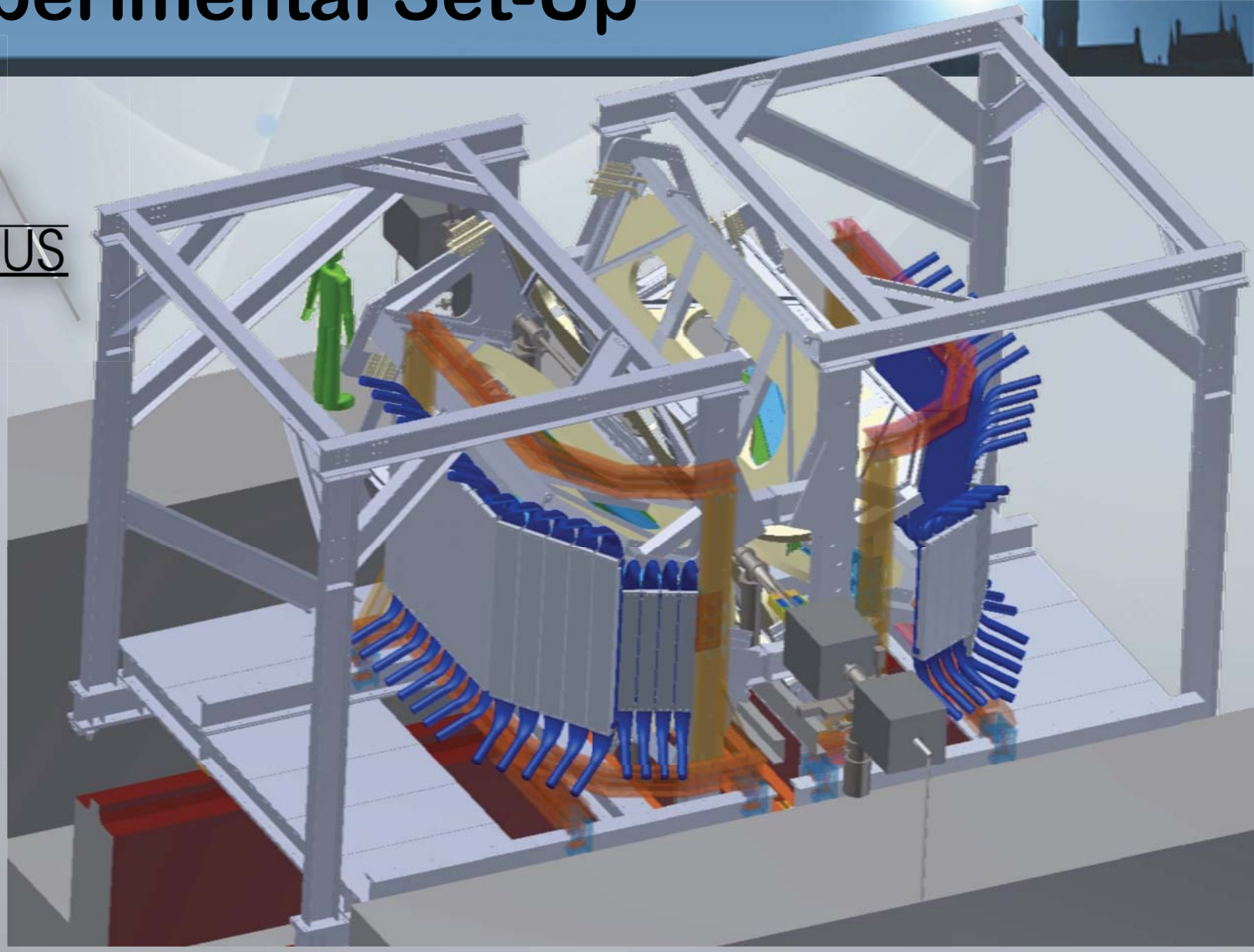
# Experimental Set-Up

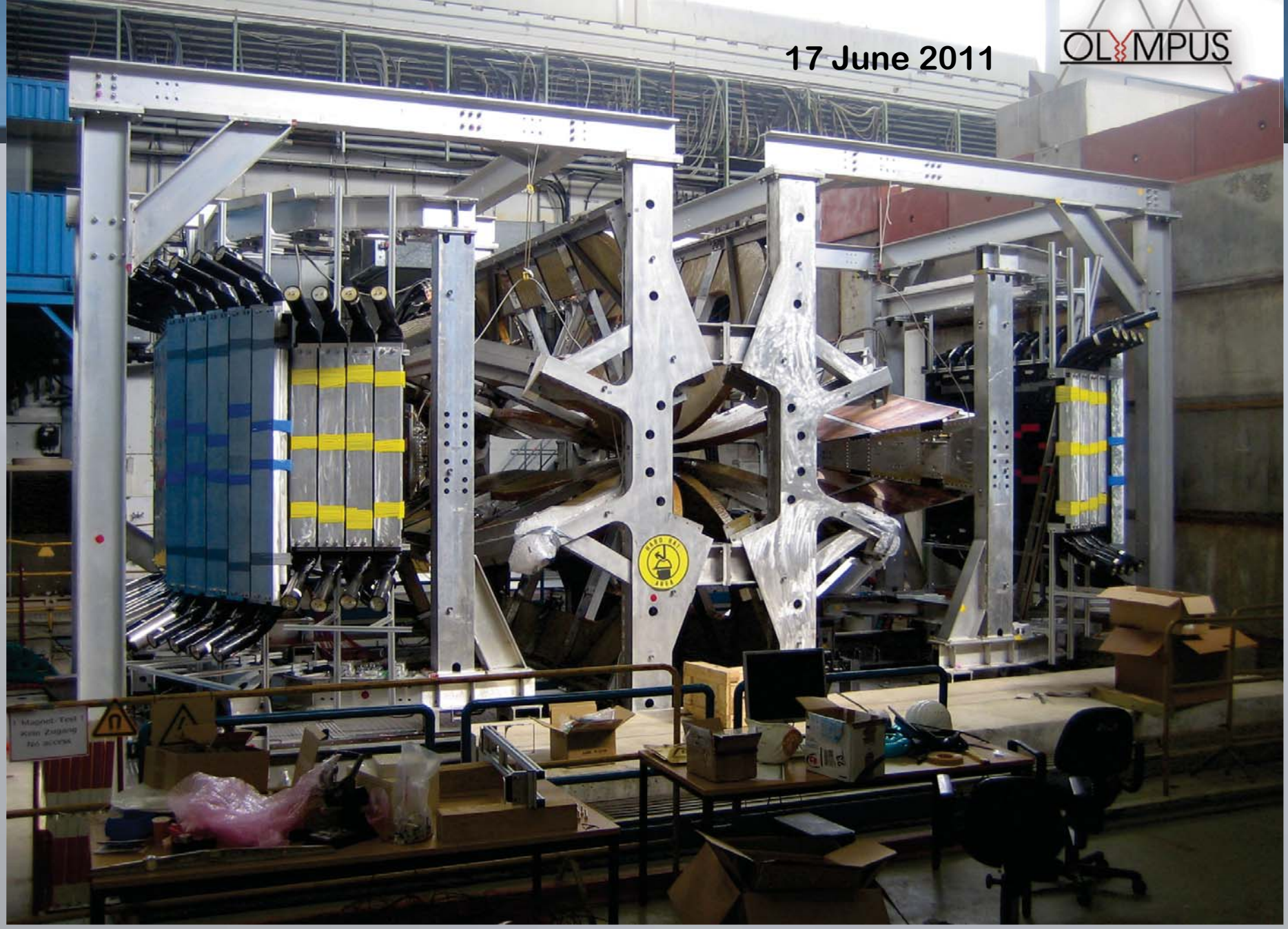



- Use BLAST detector from MIT-Bates
  - refurbished
  - add-ons
- Symmetric spectrometer
- Luminosity monitors
  - precise + redundant
- Toroidal field
  - frequent reversal

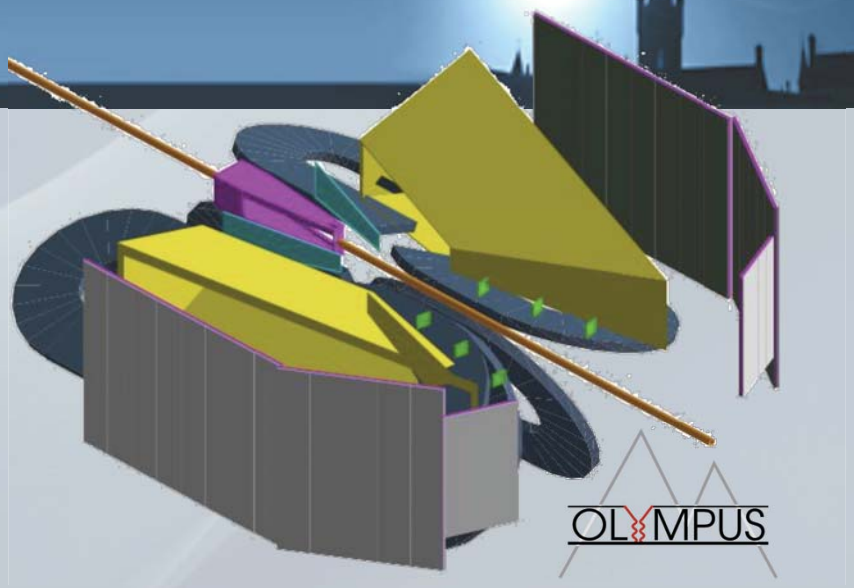
OLYMPUS

# Experimental Set-Up



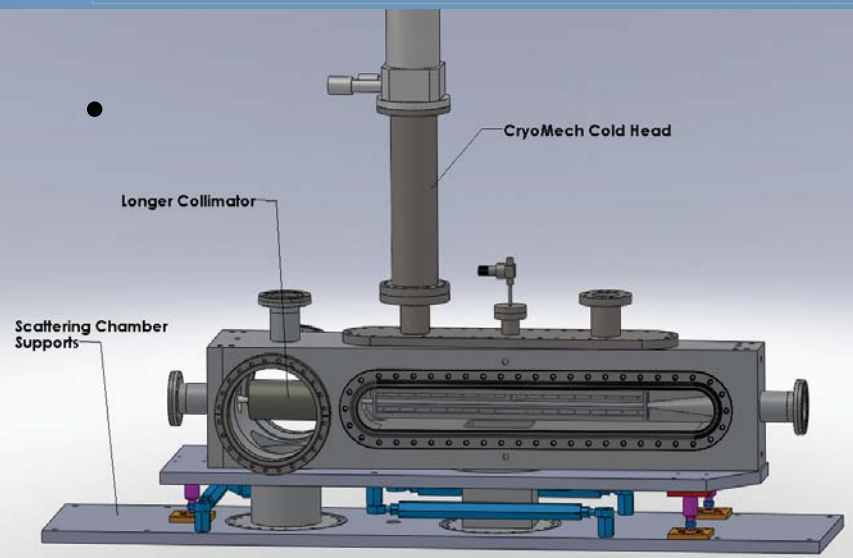

17 June 2011
OLYMPUS

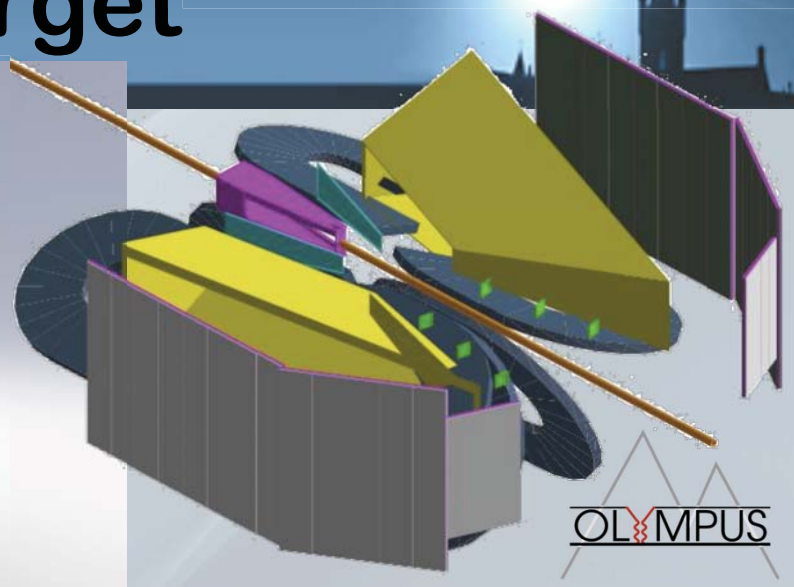
# Toroidal Magnet

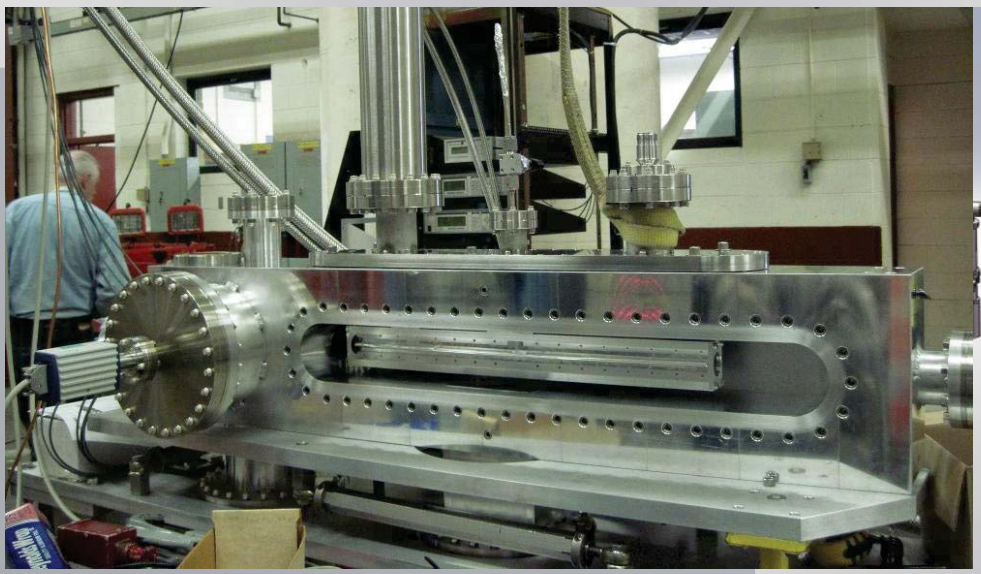


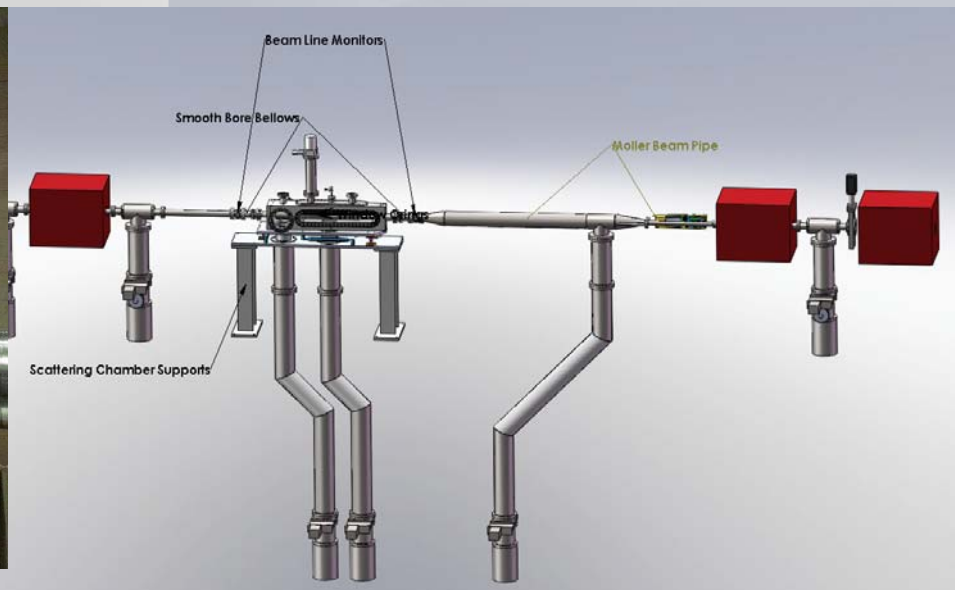

- Assembled, aligned and tested
- Field mapped

# Beam Line and Target



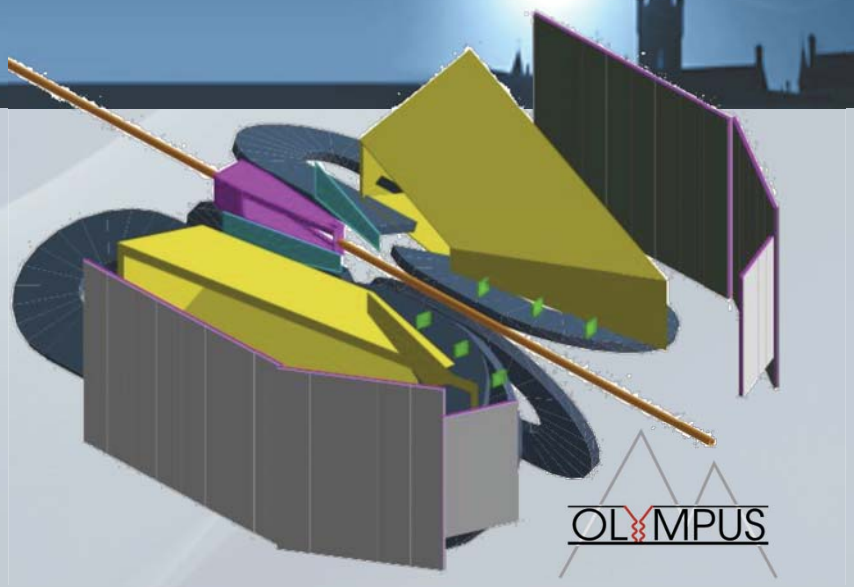



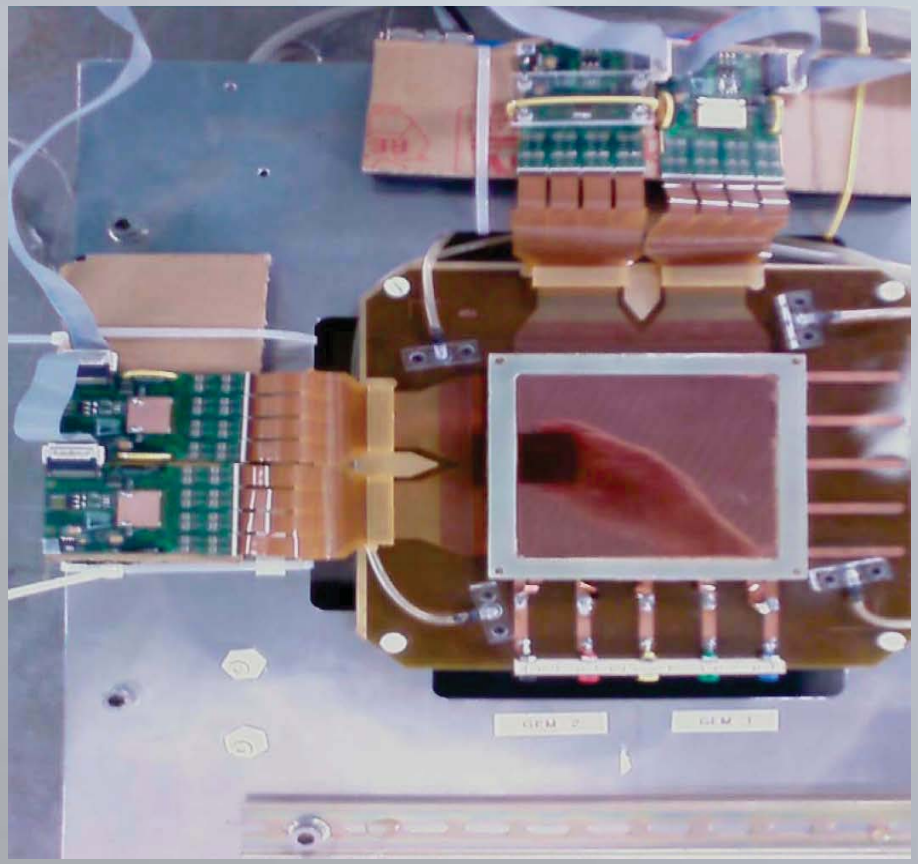



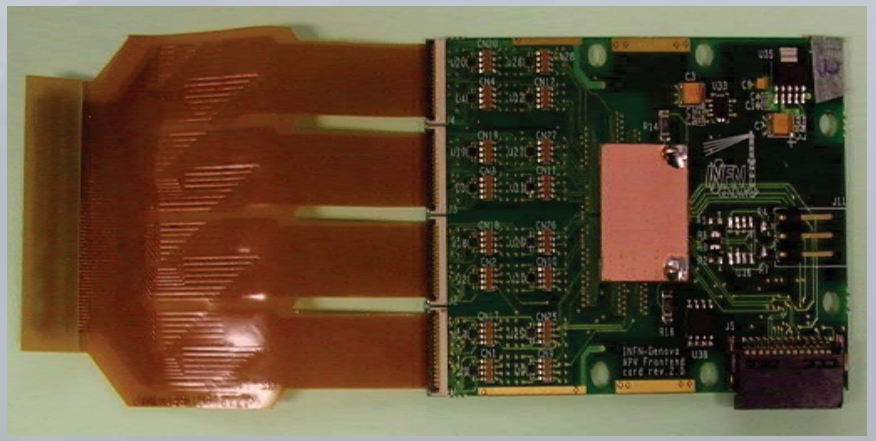


# GEM Trackers

- Large area triple GEM
- Production starting

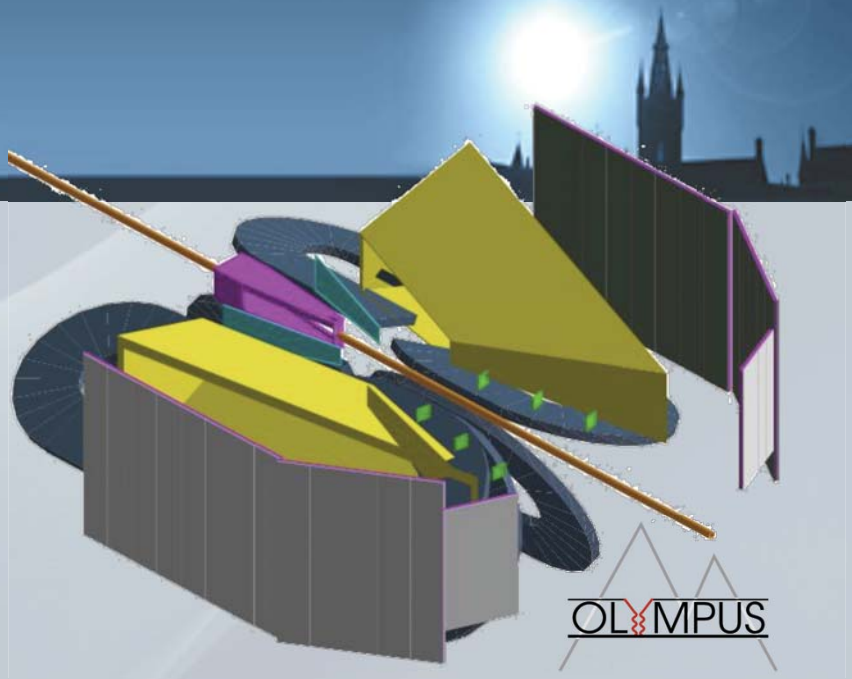


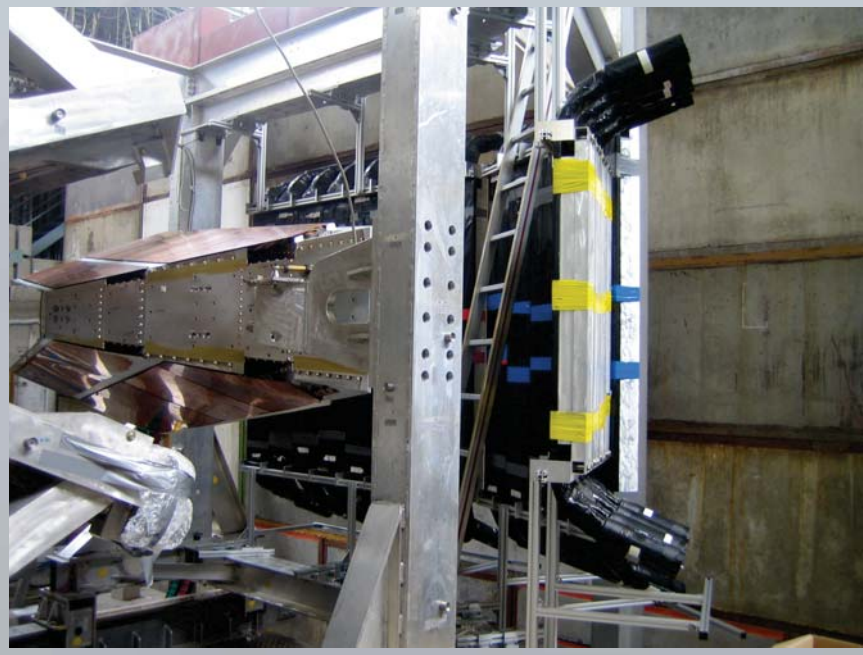





# Wire Chambers

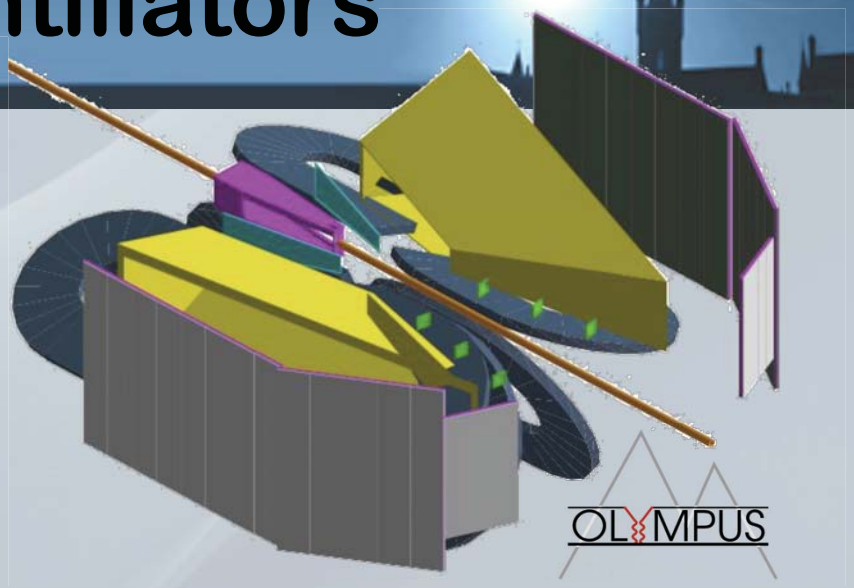
- Shipped without wires
- Completely re-wired
- Assembled and under tests

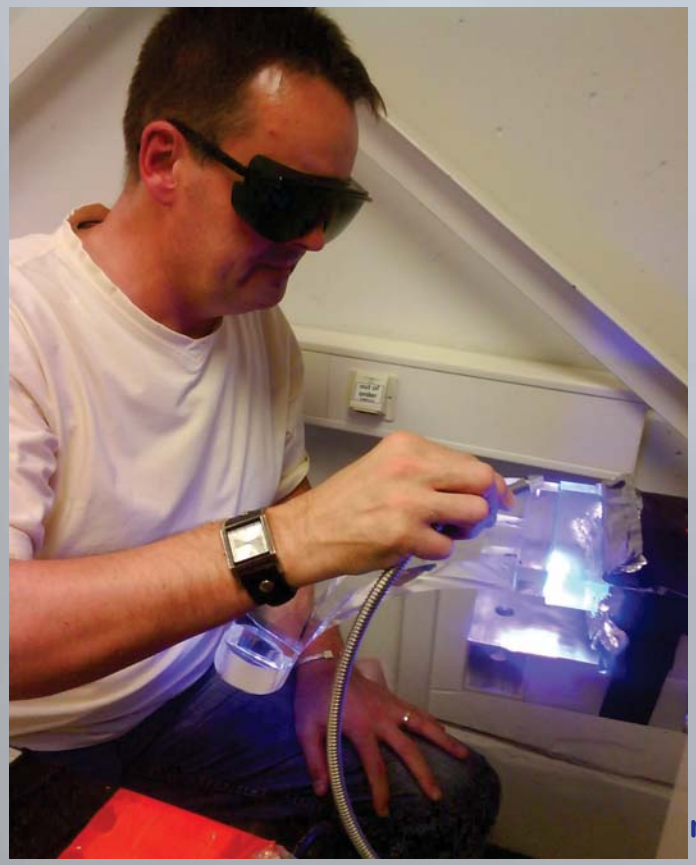


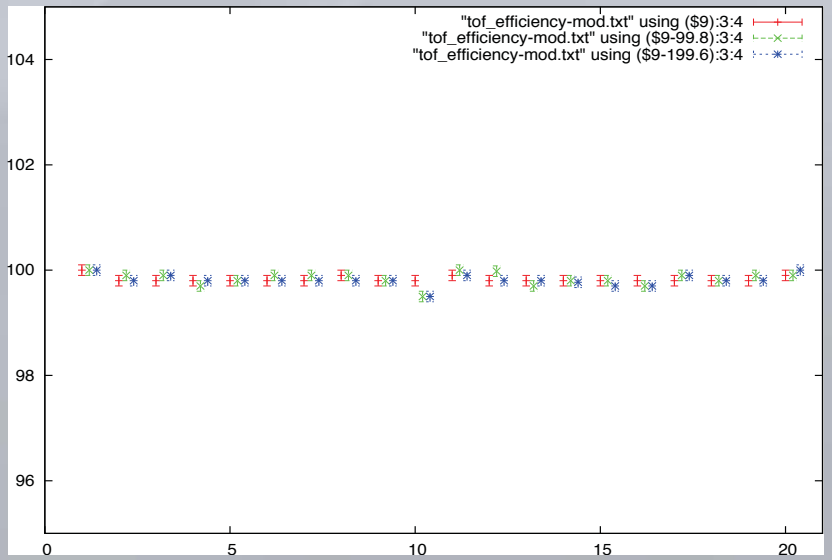
# Time-of-Flight Scintillators

- Glasgow's responsibility
- Scintillators
  - 9 joints re-glued
  - calibrated



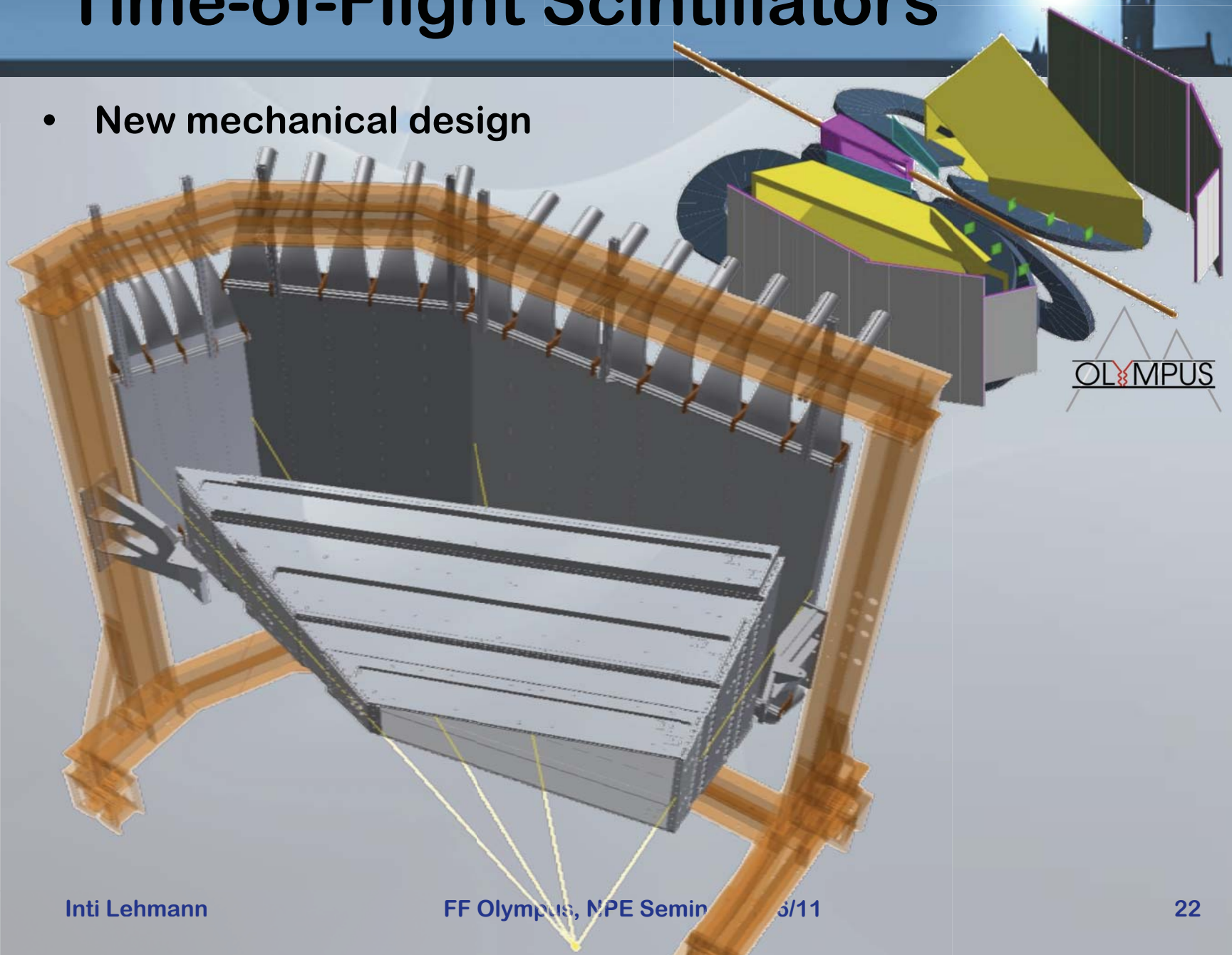



Efficiencies, $\langle\varepsilon\rangle = (99.82+/-0.09)\%$, $\varepsilon_{min} = 99.6\%$



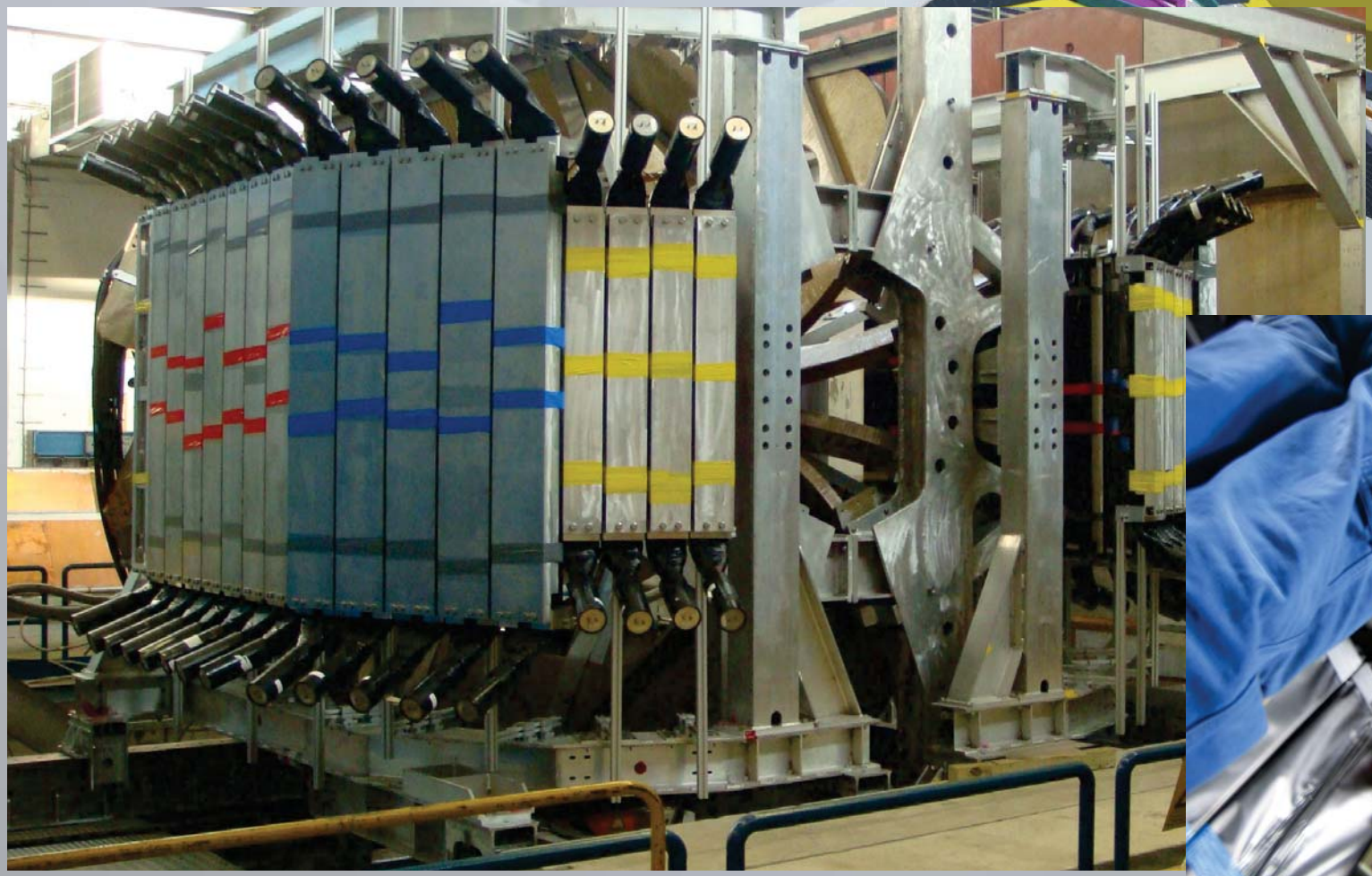
# Time-of-Flight Scintillators

- New mechanical design



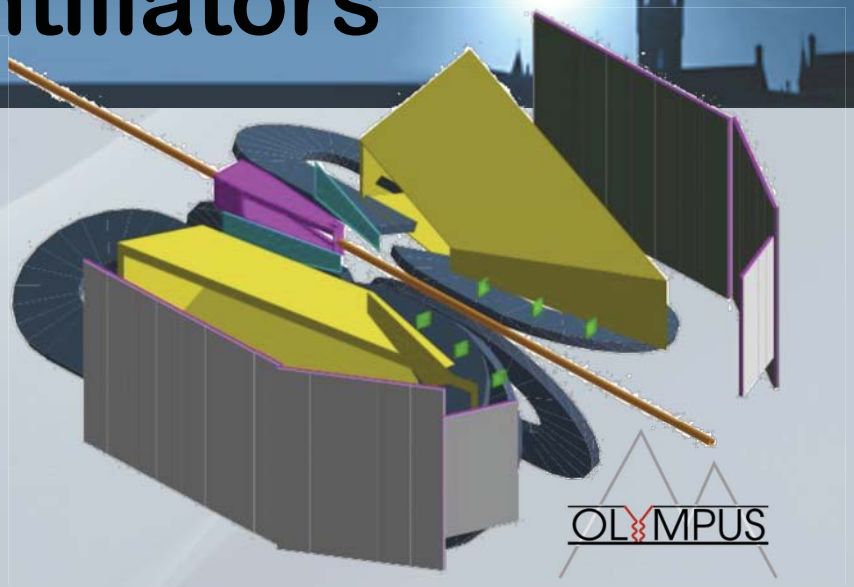
# Time-of-Flight Scintillators

- Assembled



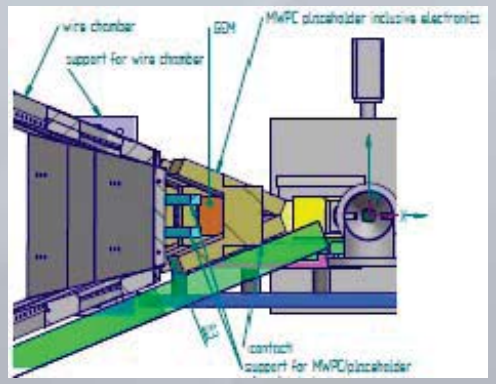
# Time-of-Flight Scintillators

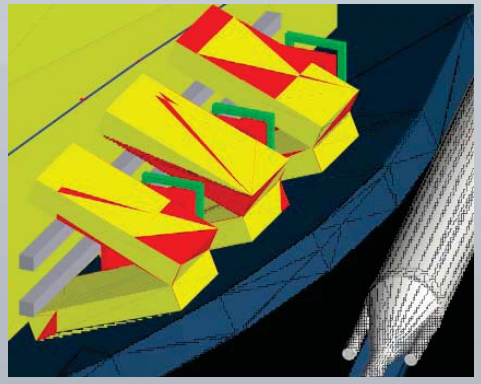
- Light flasher in preparation

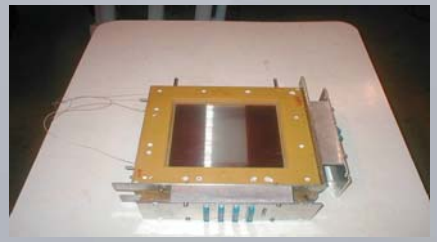




# 12deg Lumi Telescopes

- 3 GEMs + 3 MWPCs
- In test beam at DESY

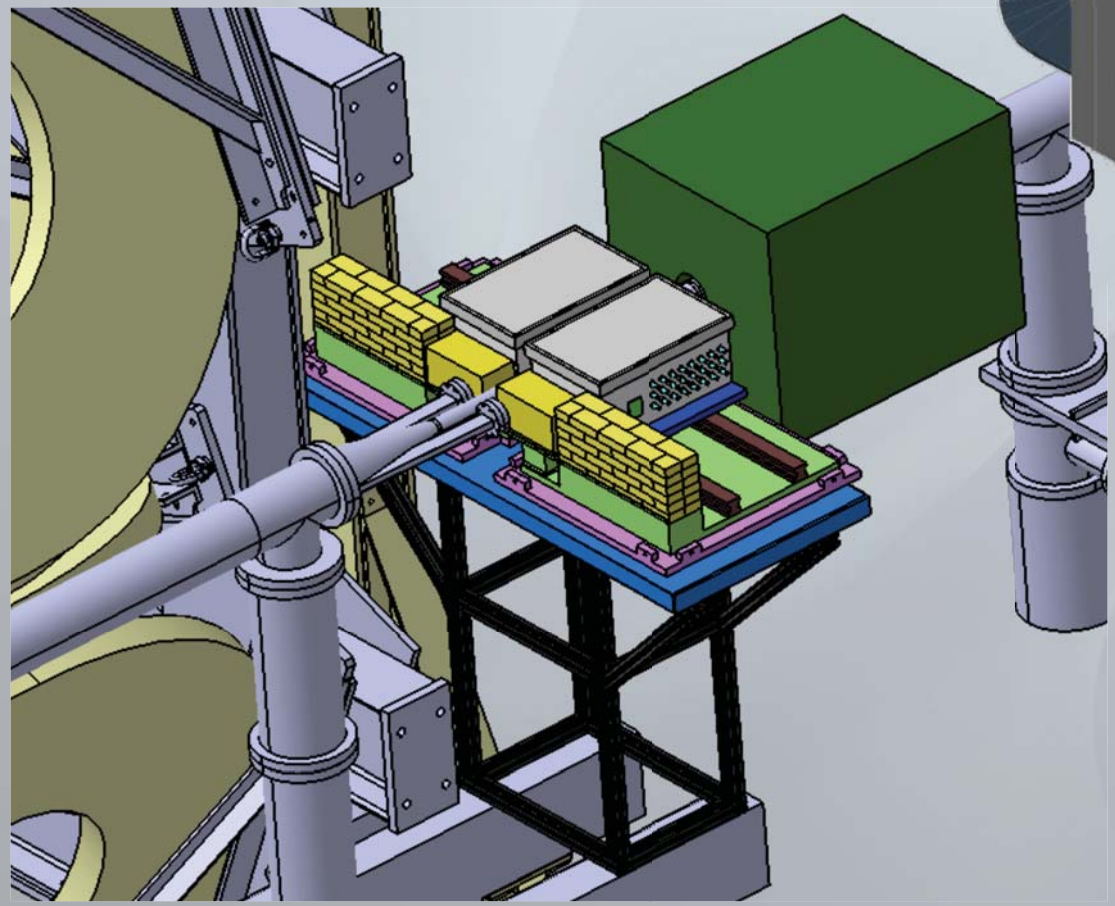



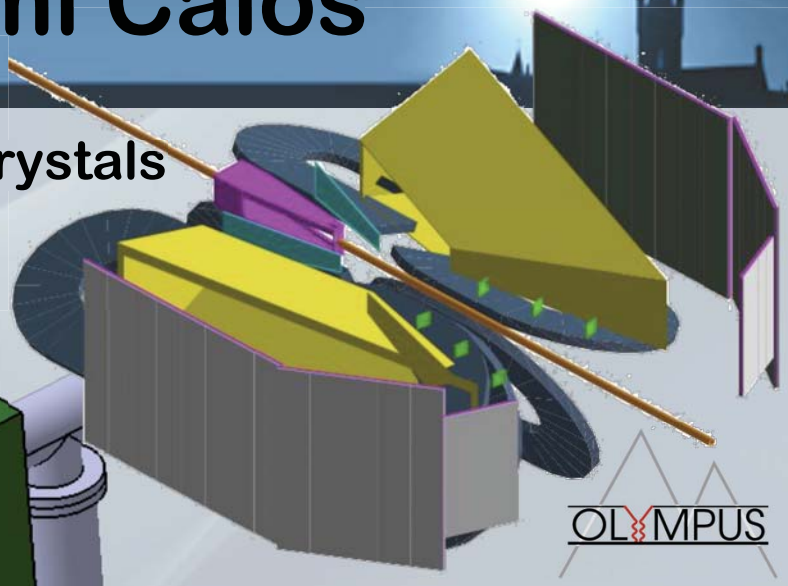



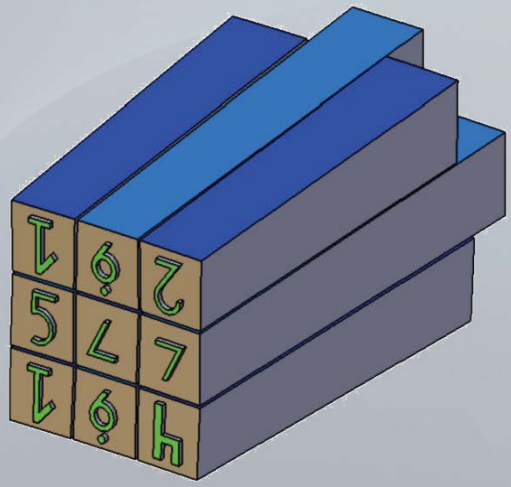


# Moller/Bhabha Lumi Calos

- Existing radiation hard $PbF_2$ crystals
- Assembly and testing

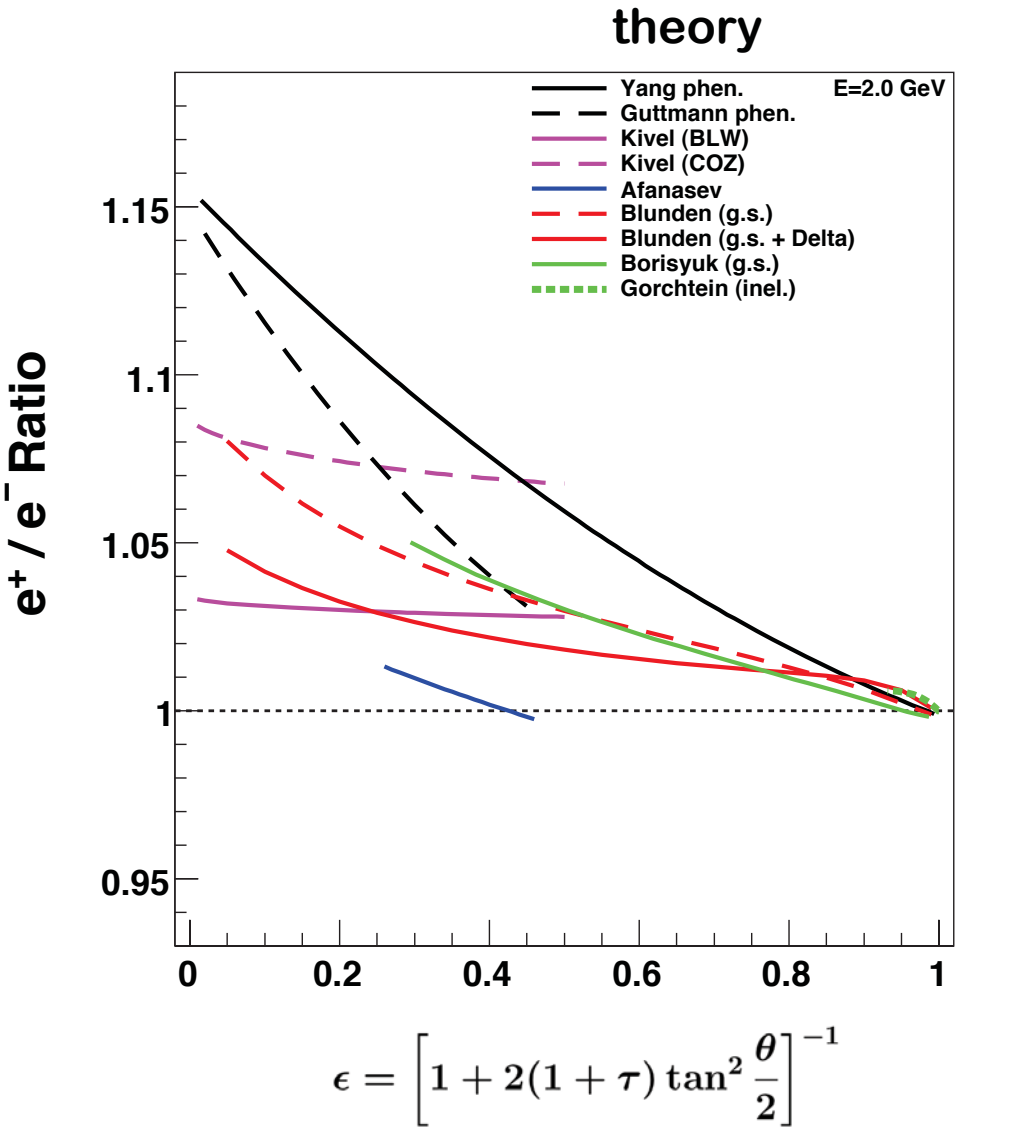




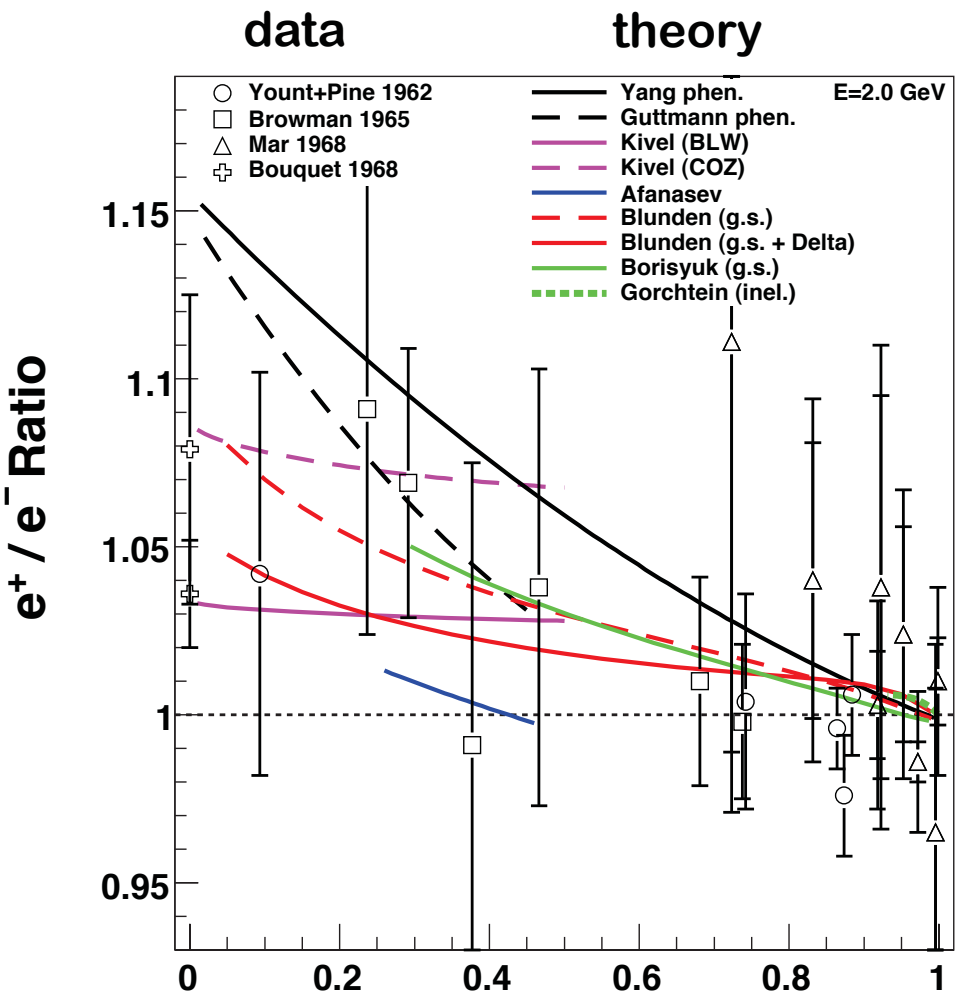
# Expected Performance

- Theoretical predictions
  - large variations



# Expected Performance

- Theoretical predictions
  - large variations
- Existing data
  - not conclusive



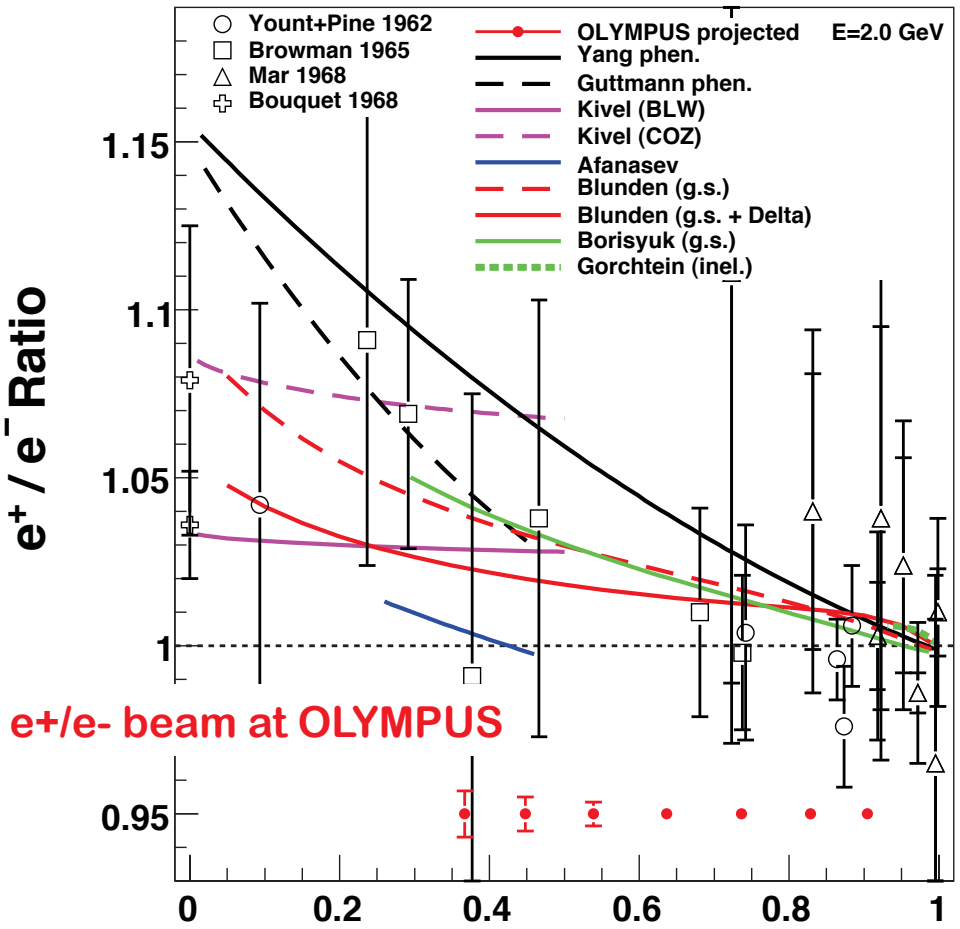

$$\epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

# Expected Performance

- Beam E = 2 GeV
  - $Q^2 = 0.6 – 2.2\ (GeV/c)^2$
  - $\varepsilon = 0.37 – 0.9$
  - sys. uncert. 1%

OLYMPUS

**OLYMPUS projected**

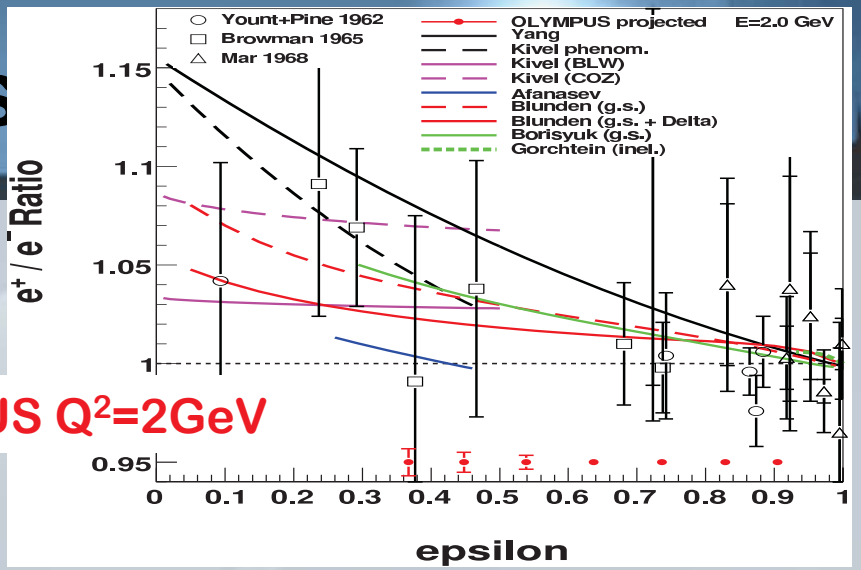



500+500h e+/e- beam at OLYMPUS

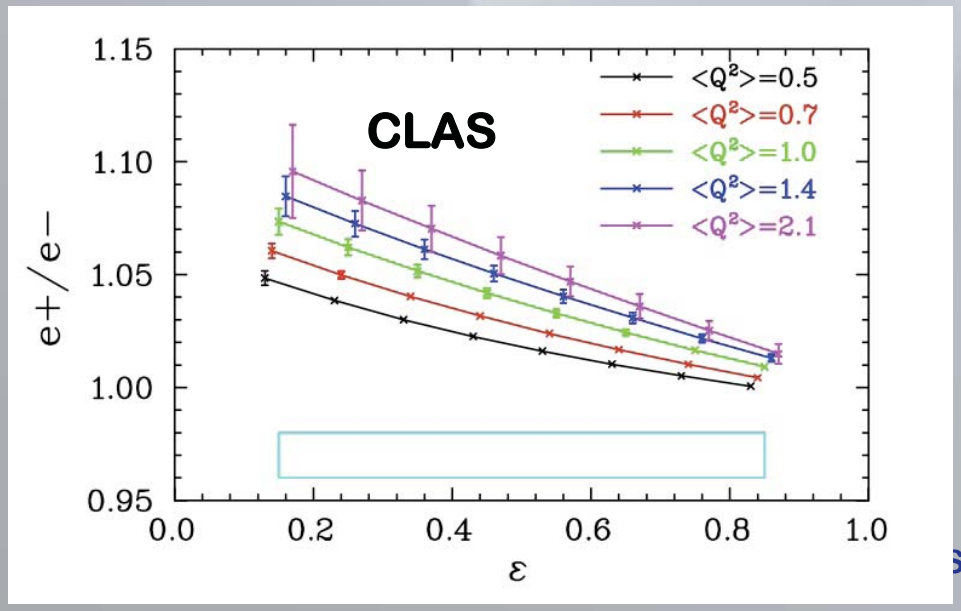
$$\epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

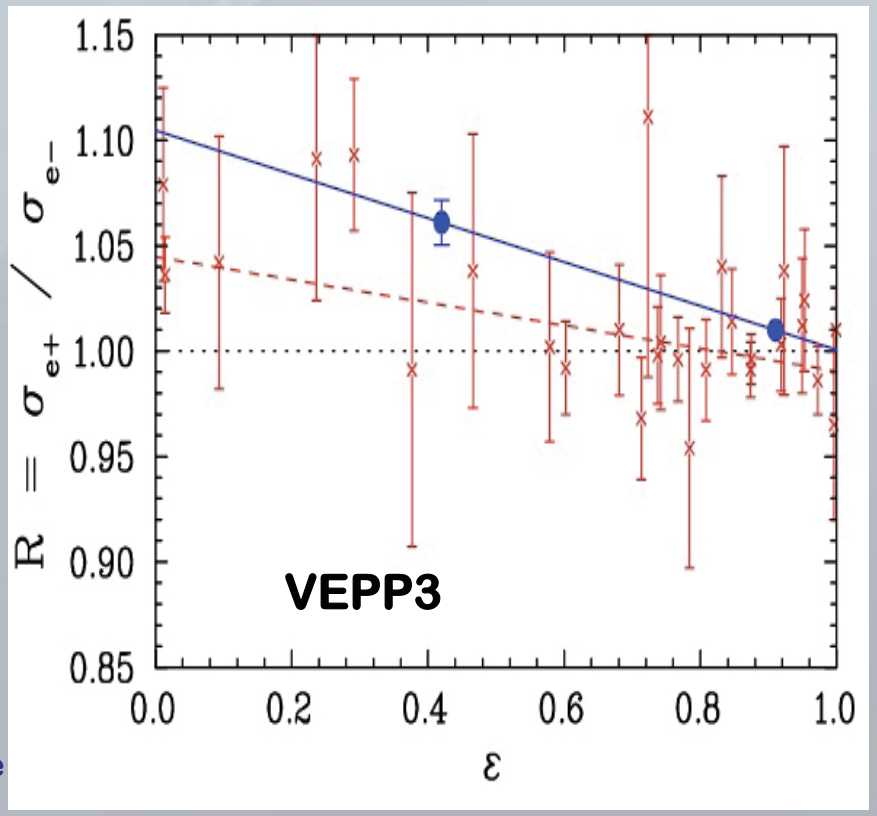
# Other Experiments

- Projected resolutions
  - scaled to fit scales
- CLAS/PR04-116
  - secondary $e^+/e^-$ beam
  - syst. challenging
- Novosibirsk/VEPP-3
  - storage ring/intern. target
  - low statistics



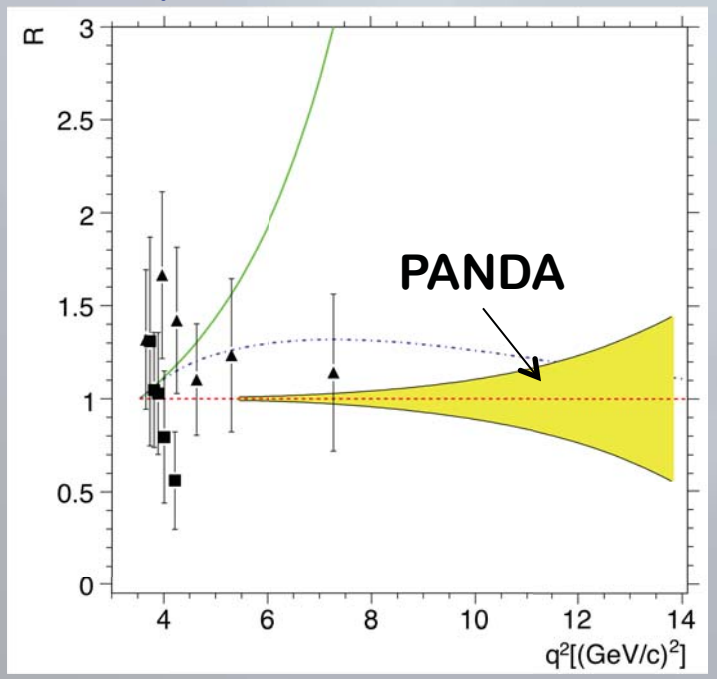

OLYMPUS $Q^2$=2GeV



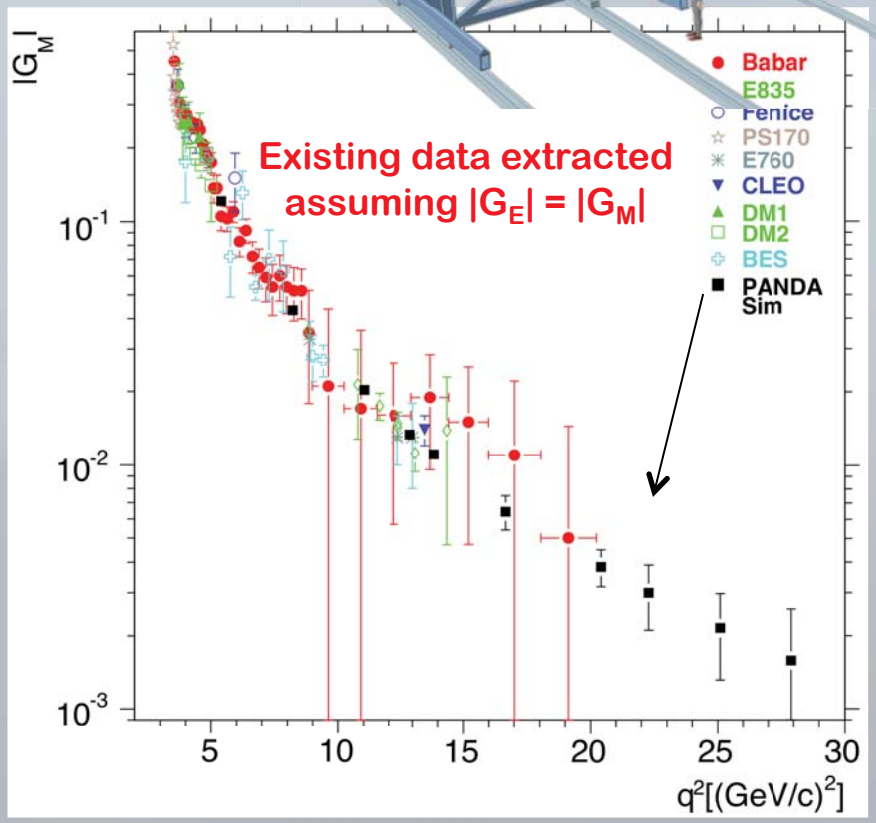



# Aside: Time Like Form Factors

- PANDA (FAIR)
  - R = $\mu_p G_E/G_M$ with unprecedented precision



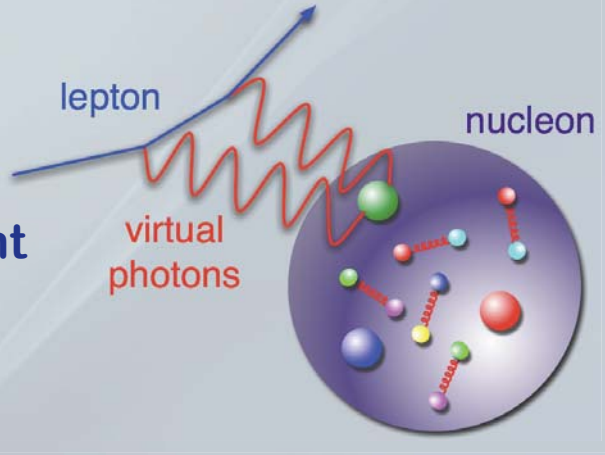

  - absolute value of $|G_M|$ up to 30(GeV/c)$^2$




PANDA Physics Performance Report: arXiv:0903.3905

# Conclusions

- Form factors
  - old but still hold surprises
- Discrepancy in $G_E/G_M$
  - unpredicted, 2-photon exch. not sufficient
  - no experimentally verified explanation
- Experimental approach
  - measure $e^+/e^-$ ratio over large $\varepsilon$ range
  - systematic uncertainties ~1%
- The OLYMPUS experiment
  - symmetric toroidal spectrometer at DESY
  - preparation progressing well
  - measurements in 2012
- Decisive information
  - nature of discrepancy
  - sensitivity to nucleon EM structure
- Further future: time-like form factors (PANDA)




OLYMPUS

# Olympus Collaboration

- Arizona State University
- DESY Hamburg
- Hampton University
- INFN Bari
- INFN Ferrara
- INFN Rome
- Massachusetts Institute of Technology
- Petersburg Nuclear Physics Institute
- Universität Bonn
- University of Colorado
- University of Glasgow
- University of Kentucky
- Universität Mainz
- University of New Hampshire
- Yerevan Physics Institute