Measuring Two Photon Exchange with OLYMPUS

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July 9, 2012
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Proton form factors

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

Rosenbluth Formula

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

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

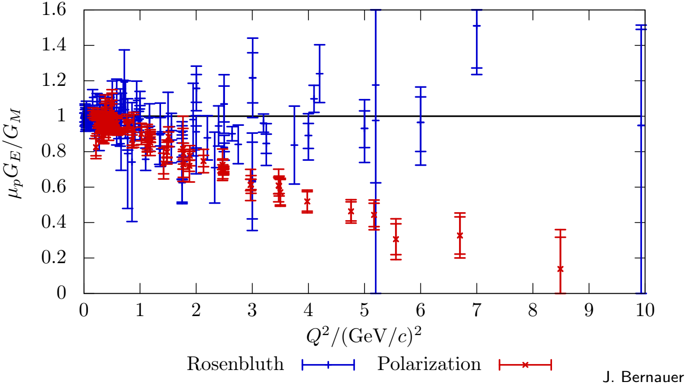
- New techniques with polarized beams and targets

Form factor ratio from polarization transfer

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

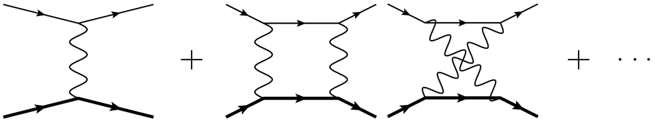
Form factor ratio discrepancy

The two methods do not agree!



Large two-photon exchange correction to Rosenbluth data?

Measuring the two-photon effect



- Odd lepton-sign power in interference term

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

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

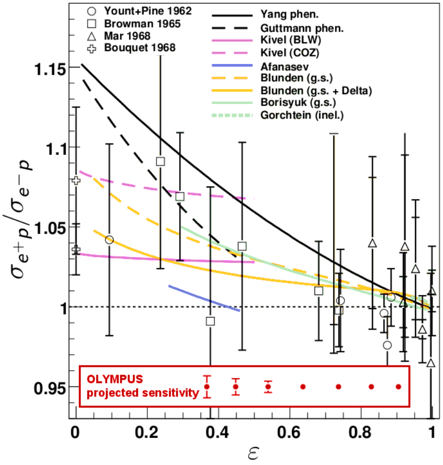
$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx 1 + 4\frac{\Re\{\mathcal{M}_{1\gamma}^\dagger \mathcal{M}_{2\gamma}\}}{|\mathcal{M}_{1\gamma}|^2}$$

Status of measurements

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

The OLYMPUS experiment

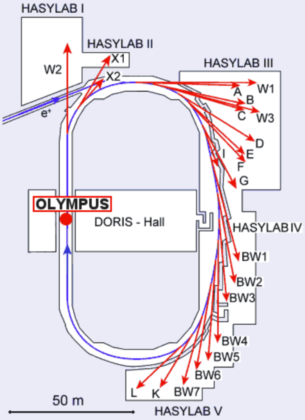
$$E = 2 \text{ GeV}$$
$$0.6 \text{ GeV}^2 \leq Q^2 \leq 2.2 \text{ GeV}^2$$
$$0.3 \leq \varepsilon \leq 0.9$$
Measure ratio to $< 1\%$



- Two other ongoing experiments: at JLab and Novosibirsk

Conception of the experiment

OLYMPUS in DORIS



- Large acceptance spectrometer

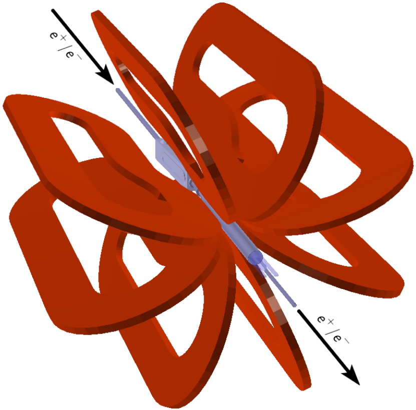
  BLAST at MIT-Bates

- 2 GeV electrons and positrons at up to 100 mA

  DORIS at DESY

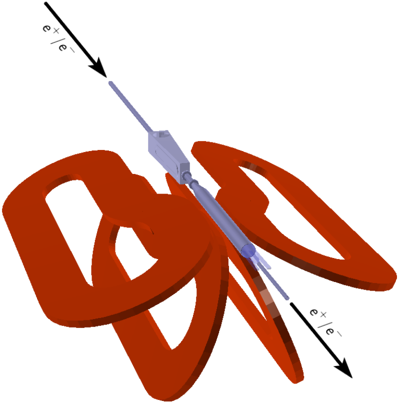
- BLAST moved to Hamburg, Germany
- Upgrades and new sub-detectors

Toroidal magnet



- 8 copper coils
- 75% field
- ±5,000 A current → maximum 2.8 kG B-field

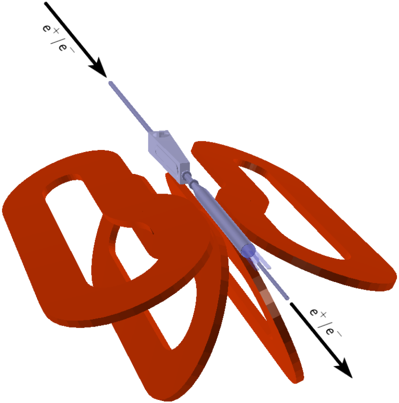
Internal hydrogen target



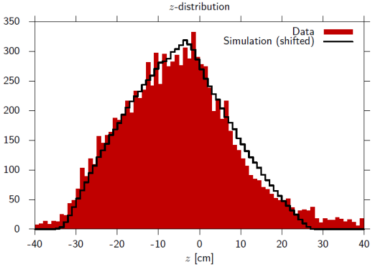
Open-ended target cell

- 9 mm×27 mm cross section, 60 cm long
- 10^{15} atoms/cm^2 thickness
- 99.99998% pure H_2

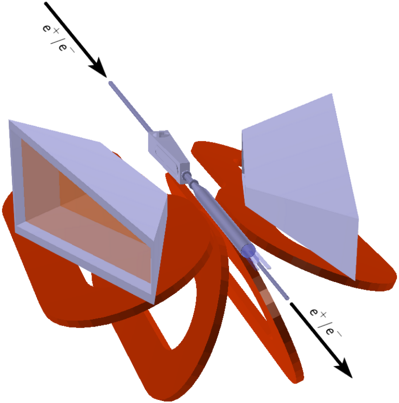
Internal hydrogen target



Hydrogen distribution:



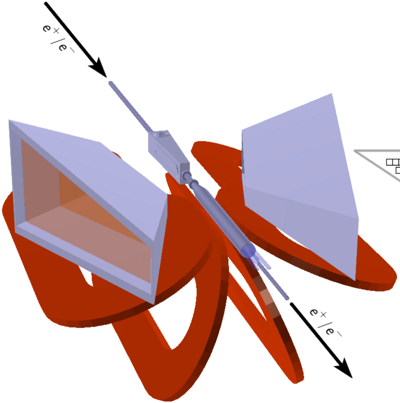
Drift chambers



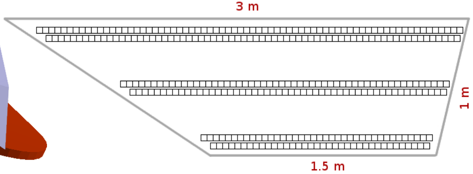
Acceptance:

- $20^\circ < \theta < 80^\circ$
- $-15^\circ < \phi < 15^\circ$

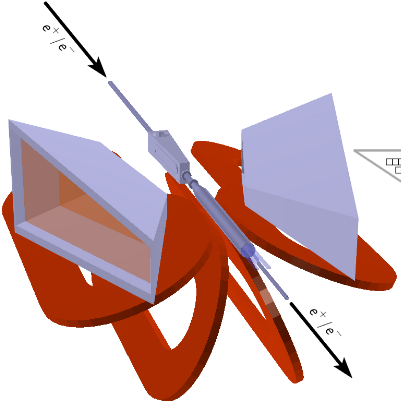
Drift chambers



Horizontal cross section of sector:



Drift chambers



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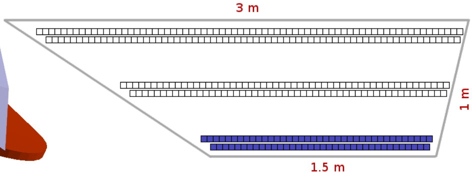
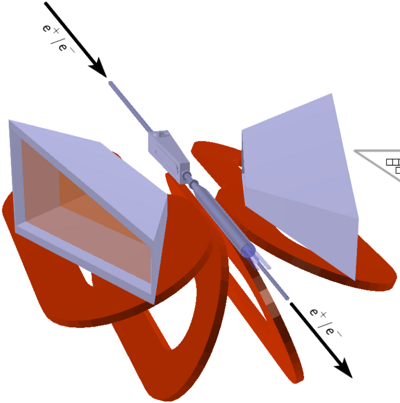


Drift chambers



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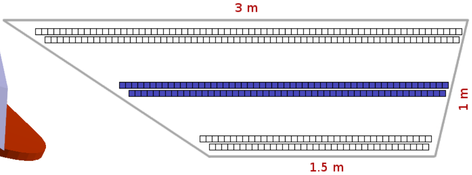
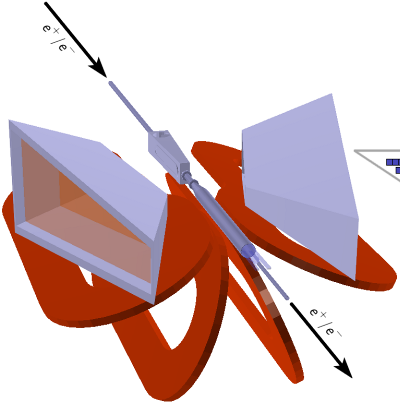


Drift chambers



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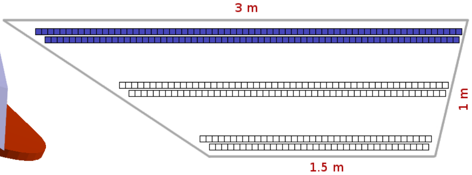
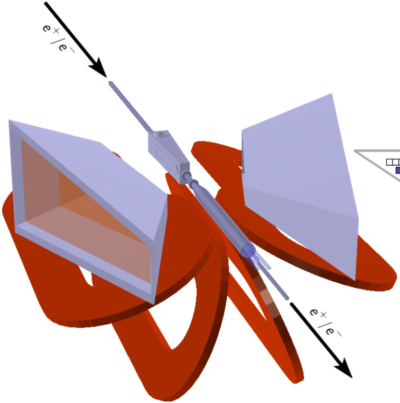


Drift chambers



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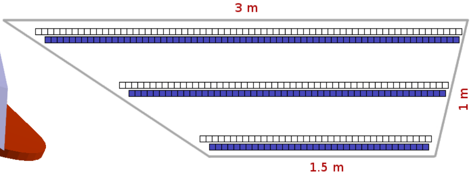
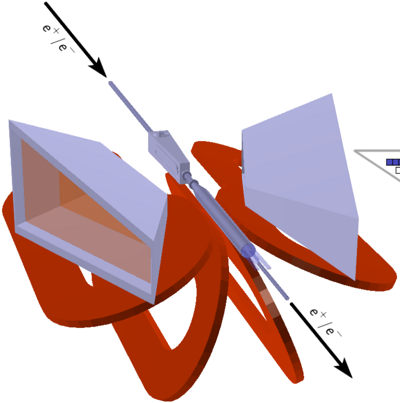
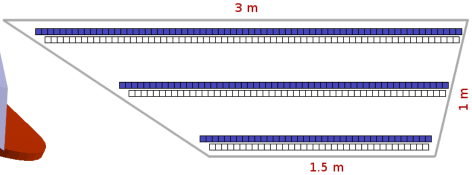


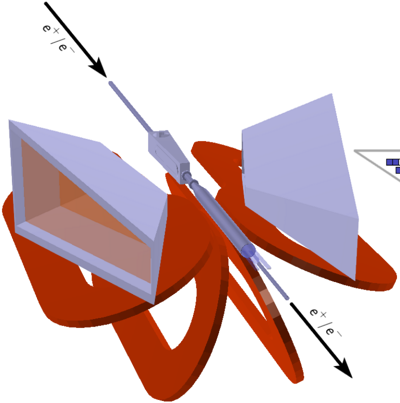
Drift chambers



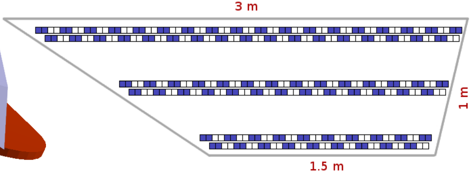
Horizontal cross section of sector:



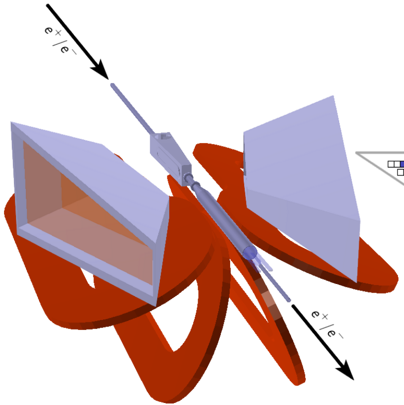
Drift chambers



Horizontal cross section of sector:



Drift chambers



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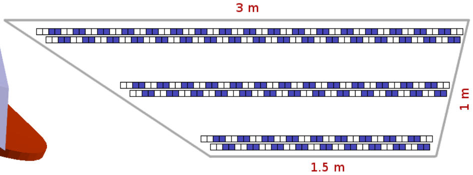
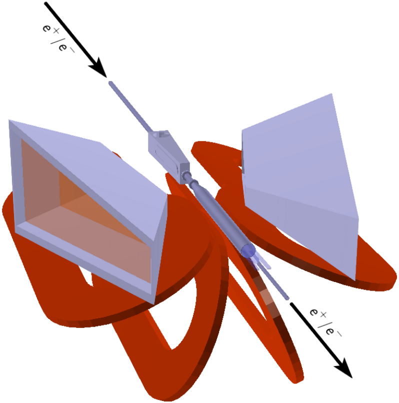
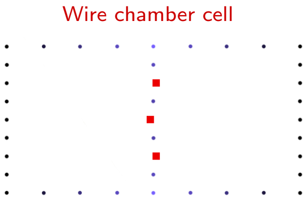
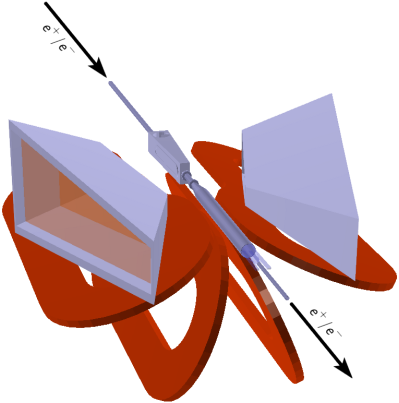


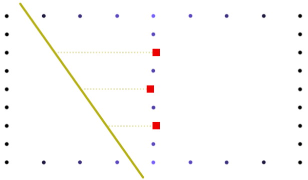
Drift chambers



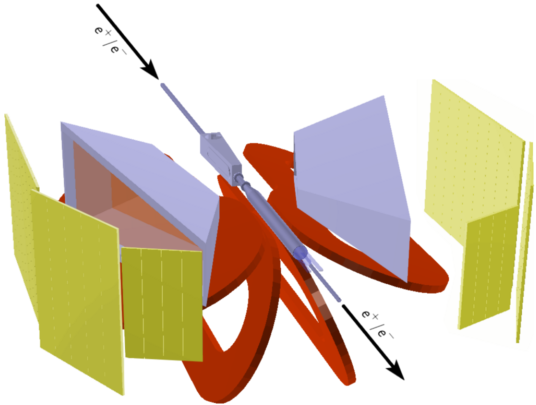


Drift chambers



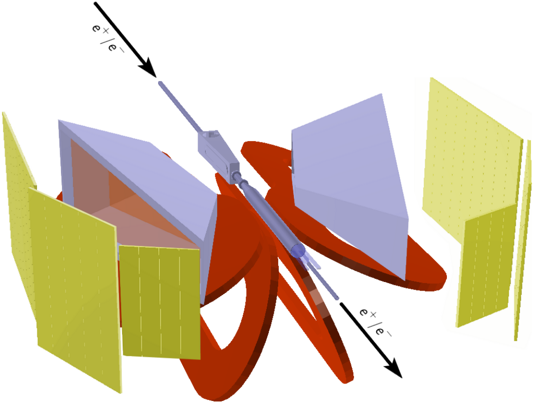


Time of flight detectors



- Full acceptance of drift chambers
- 36 vertical scintillator bars
- Kinematic trigger

Time of flight detectors



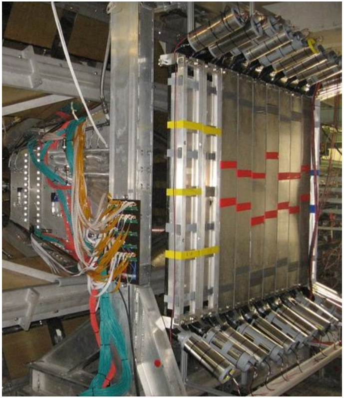


Photo: A. Schmidt

Measuring the cross section ratio

Small asymmetries in detector setup?

Measure the superratio

$$\frac{\sigma_{e^+}}{\sigma_{e^-}} = \sqrt{\frac{n_{(e^+,\uparrow)} n_{(e^+,\downarrow)}}{n_{(e^-,\uparrow)} n_{(e^-,\downarrow)}} \cdot \frac{n^{\text{lumi}}_{(e^-,\uparrow)} n^{\text{lumi}}_{(e^-,\downarrow)}}{n^{\text{lumi}}_{(e^+,\uparrow)} n^{\text{lumi}}_{(e^+,\downarrow)}}}$$

- Switch beam species regularly
- Switch magnet polarity regularly

Measuring the cross section ratio

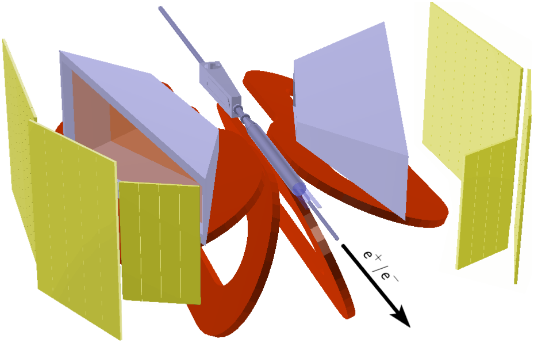
Variance in beam current and target density?

Measure the luminosity

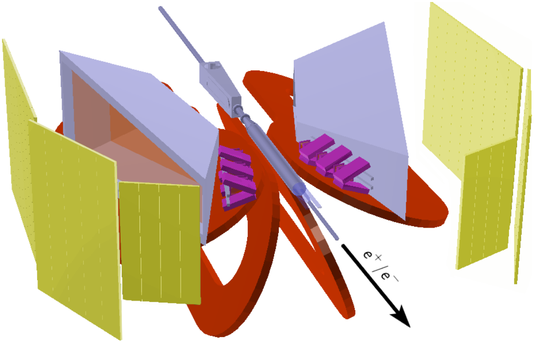
$$\frac{\sigma_{e^+}}{\sigma_{e^-}} = \sqrt{\frac{n_{(e^+,\uparrow)}\, n_{(e^+,\downarrow)}}{n_{(e^-,\uparrow)}\, n_{(e^-,\downarrow)}} \cdot \frac{n^{\mathrm{lumi}}_{(e^-,\uparrow)}\, n^{\mathrm{lumi}}_{(e^-,\downarrow)}}{n^{\mathrm{lumi}}_{(e^+,\uparrow)}\, n^{\mathrm{lumi}}_{(e^+,\downarrow)}}}$$

- Beam and target measurements
- Luminosity monitors

12° luminosity monitors



12° luminosity monitors



- Pair of tracking telescopes

  Two systems:
  - 3 GEMs (100 mm x 100 mm)
  - 3 MWPCs (105 mm x 105 mm)

12° luminosity monitors

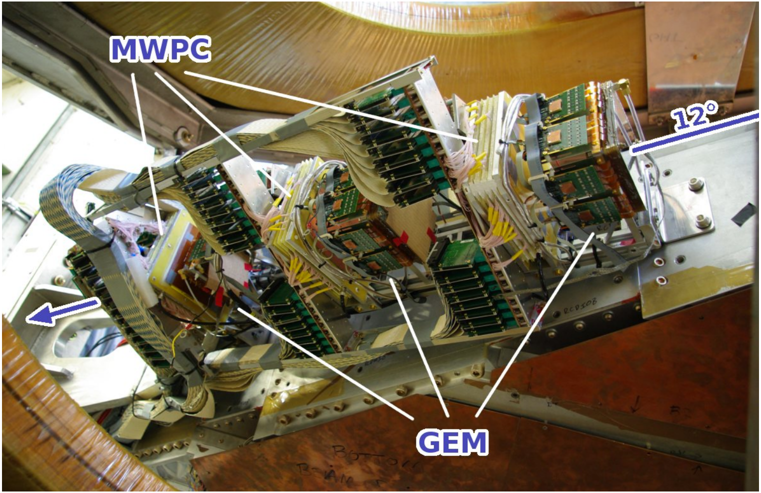
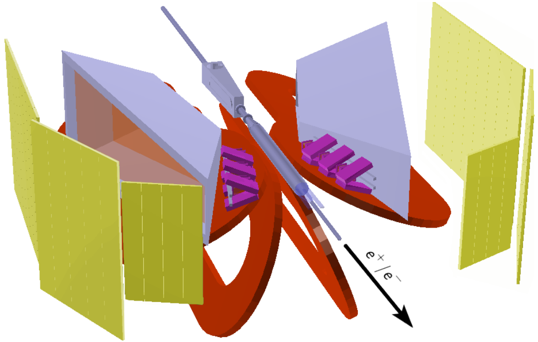
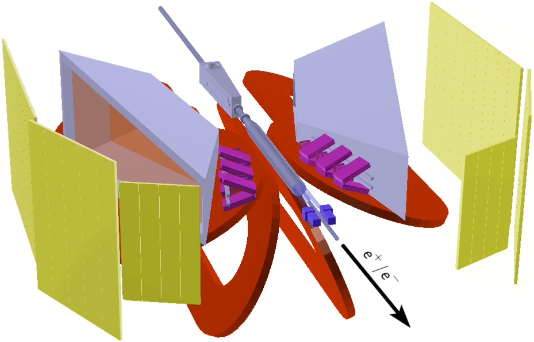


Photo: O. Ates

Symmetric Møller/Bhabha detectors

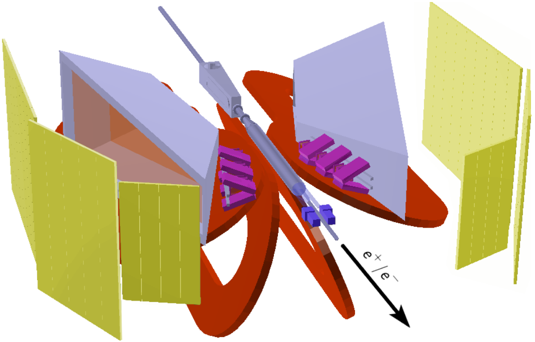


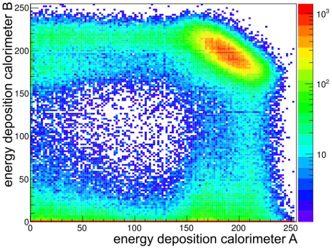
Symmetric Møller/Bhabha detectors



- Elastic ee scattering
- 1.3° from beam line
  → symmetric
- Pure QED calculable
- Coincidence
  → low background

Symmetric Møller/Bhabha detectors





Symmetric Møller/Bhabha detectors

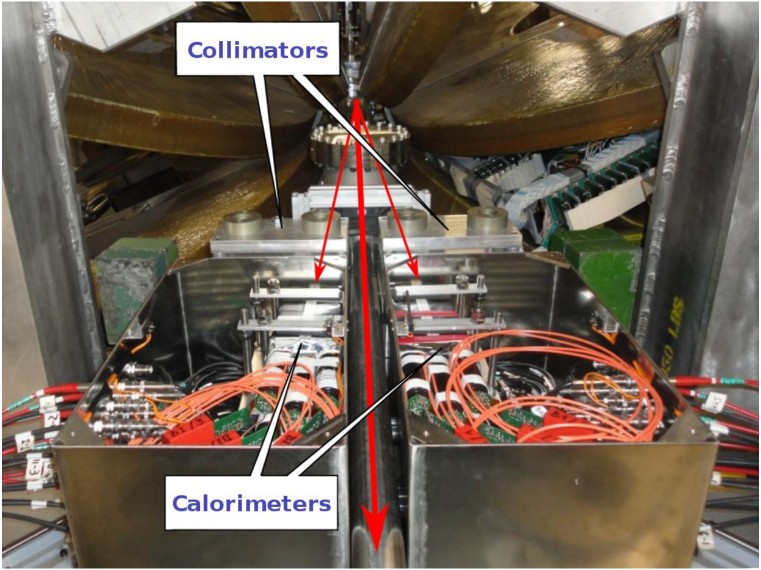
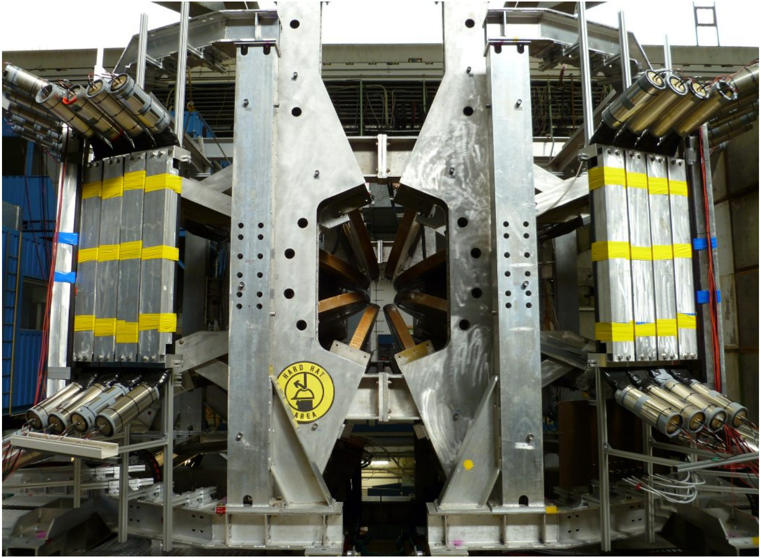


Photo: R. Perez-Benito

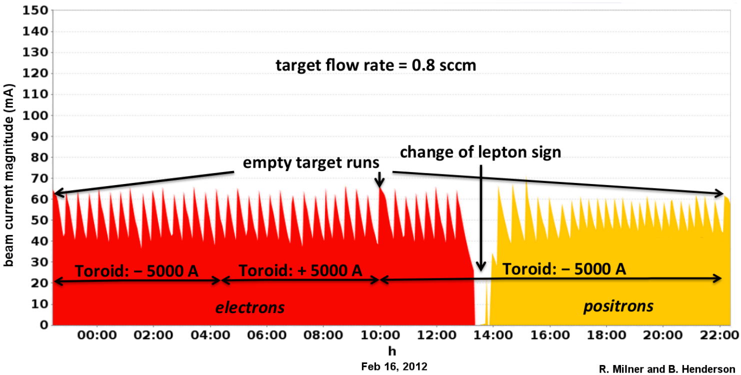
OLYMPUS with sub-detector frame out

OLYMPUS with sub-detector frame in



OLYMPUS first run

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



- Analysis underway

OLYMPUS timeline

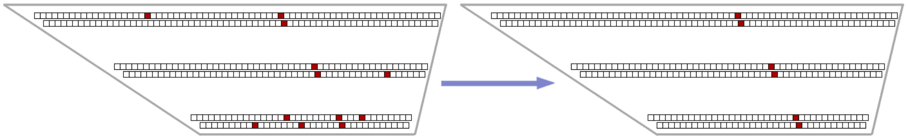
OLYMPUS full proposal	**September 2008**
Experiment funded by DOE	**January 2010**
BLAST moved to Germany	**Spring 2010**
Target test experiment	**February 2011**
Drift chambers installed	**Spring 2011**
12° luminosity monitors installed	**Summer 2011**
OLYMPUS rolled in to DORIS beam line	**July 2011**
First full OLYMPUS test experiment	**August 2011**
Symmetric Møller/Bhabha installed	**Fall 2011**
First data run	**February 2012**
Tracking detector upgrade	**Summer 2012**
Second data run	**October-December 2012**
DORIS retires	**2013**

Track selection

Tree search algorithm

M. Dell'orso and L. Ristori, "A Highly Parallel Algorithm for Track Finding", *Nucl. Inst. Meth.* **A287**, (1990) 436-338

- Removes noise
- Reduces combinatorics
- Fast
- Estimate of starting parameters



Tracking

- Combine DC+ToF tracks with 12° detectors
- All OLYMPUS detectors in Monte Carlo

  → Use to reconstruct track parameters
- Two error-estimation methods:
  - Global fit
  - Kalman filter
- Iterative process to find time-to-distance for drift chambers
- Simulation of field and electron drift in gas (Garfield/Magboltz)

Radiative Corrections

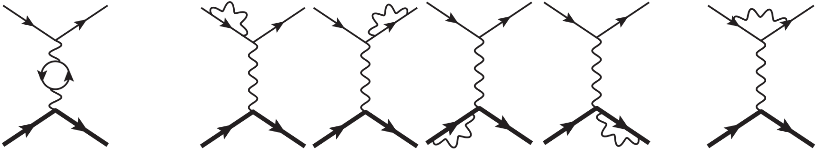
What are we trying to measure?

Hard part of two photon exchange correction to elastic ep

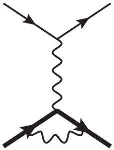
- Lots of other radiative corrections that contribute
- Generally taken into account with:
  - L. W. Mo and Y. S. Tsai, "Radiative Corrections to Elastic and Inelastic ep and νp Scattering" *Rev. Mod. Phys.* **41**, 205 (1969)
  - L.C. Maximon and J. A. Tjon "Radiative corrections to electron-proton scattering" *Phys. Rev. C* **62**, 054320 (2000)
- Note: Papers have different separation of hard and soft TPE
- Want to use well-established physics only in primary result

Corrections with a second virtual photon (elastic)

- Soft parts contain IR divergences
- All even in lepton sign except TPE



vacuum polarization   self-energy diagrams   electron vertex

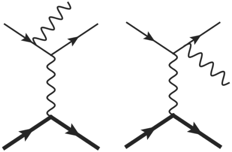


- Maximon and Tjon calculate structure-dependent part of the proton vertex
- Negligible in ratio at OLYMPUS energies

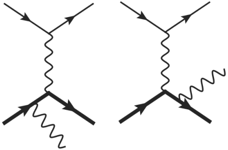
Corrections with a real photon (bremsstrahlung)

- Most important correction

Charge-odd terms come from



interfering with



- IR divergences cancel exactly with those from virtual photon
- Depends fundamentally on details of the experimental setup
- Use generator with Monte Carlo $\rightarrow$ analyze just like data

Radiative Corrections

- Maximon and Tjon estimate:

  Ratio just from radiative corrections is 1.08 at large angles

- Larger correction with higher resolution

Two important things to take away:

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

The OLYMPUS Collaboration

Members from. . .

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