Track Reconstruction for OLYMPUS

Rebecca Russell
Massachusetts Institute of Technology

Frontiers and Careers in Photonuclear Physics
October 31, 2015

Proton form factors

- Study G_E and G_M with elastic electron-proton scattering
- The Rosenbluth separation method at constant Q^2

Rosenbluth Formula

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

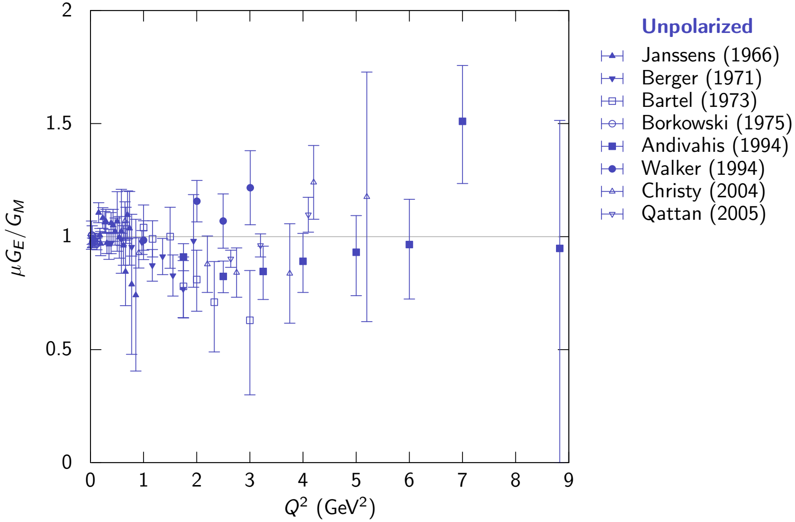
where $\tau = Q^2/4M^2$ and $\varepsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}$

- New techniques with polarized beams and targets

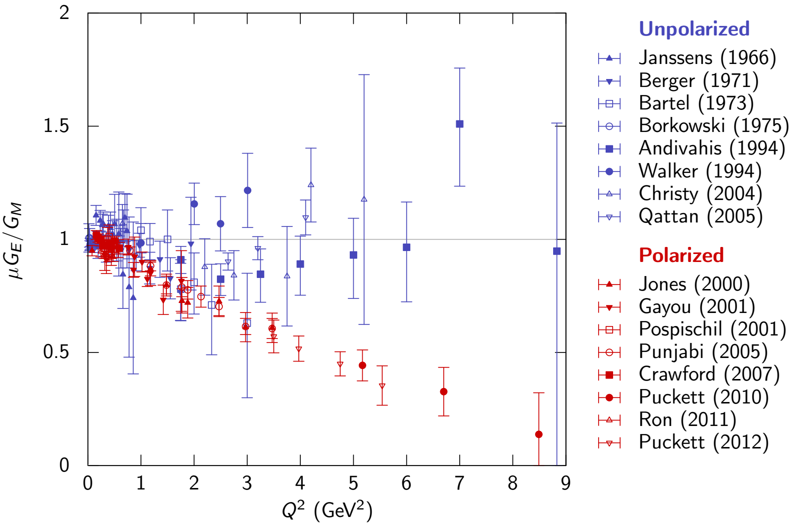
Form factor ratio from polarization transfer

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

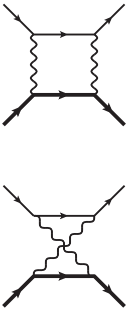
Form factor ratio discrepancy



Form factor ratio discrepancy

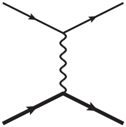


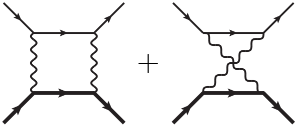
Two photon exchange



- Most popular explanation of discrepancy
- Only partially accounted for in standard radiative corrections
- Could affect Rosenbluth separation greatly, but not polarization measurements
- Highly model-dependent: need to measure experimentally to resolve

Measuring the two-photon exchange

$\mathcal{M}_{1\gamma} =$ 

$\mathcal{M}_{2\gamma} =$ 

- Odd lepton-sign power in interference term

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

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

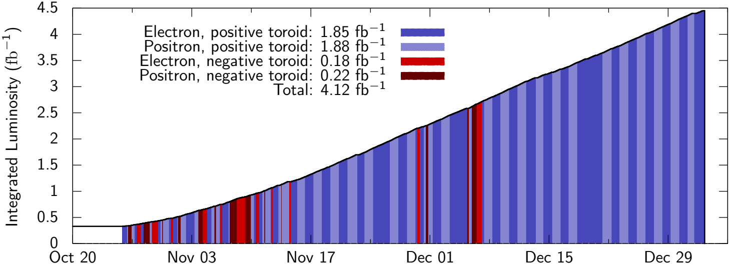
$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx 1 + 2\frac{2\,\mathrm{Re}[\mathcal{M}_{1\gamma}^\dagger \mathcal{M}_{2\gamma}]}{|\mathcal{M}_{1\gamma}|^2}$$

The OLYMPUS experiment

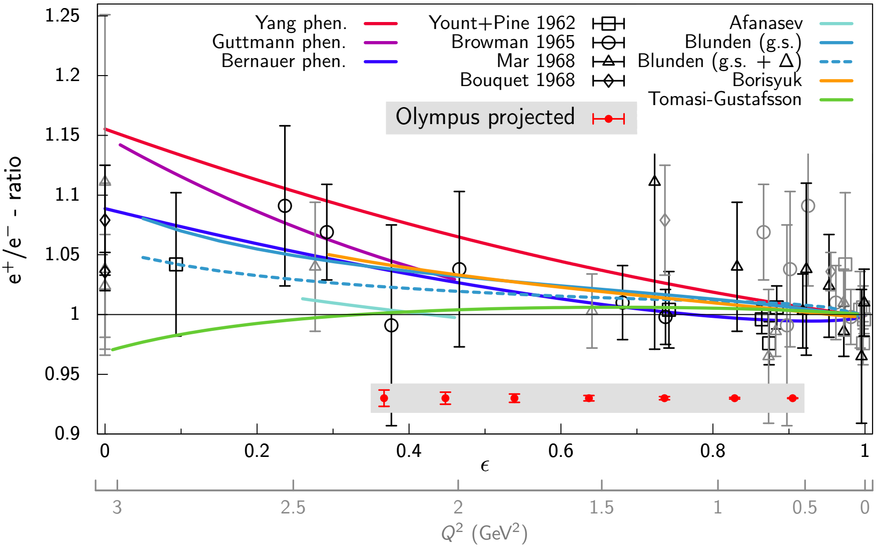
Single physics goal:

Precise measurement of hard two photon exchange

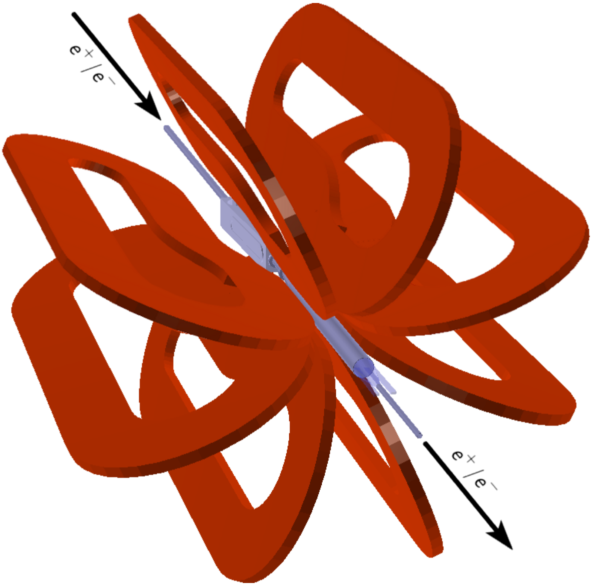
- Collaboration of 13 institutions from 6 countries
- Based on BLAST spectrometer (MIT/Bates), located at DESY
- Fixed 2 GeV beam measurement of cross section ratio
- Data collected in 2012



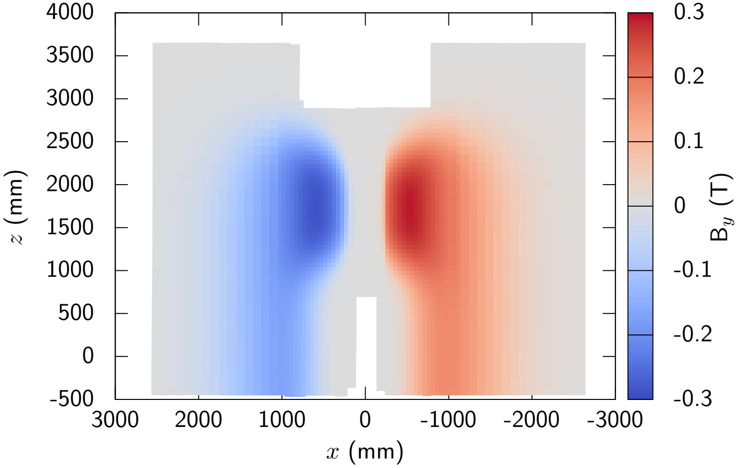
The view at E = 2 GeV



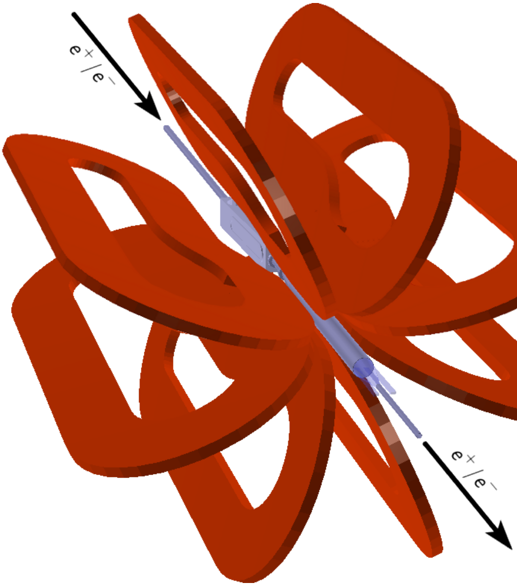
Toroidal magnet



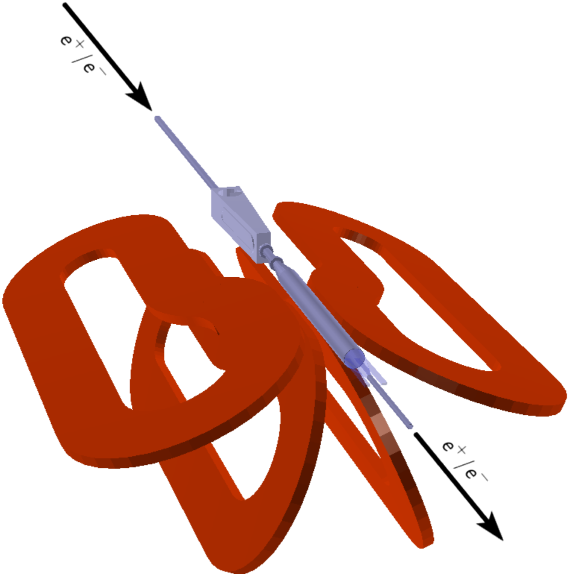
Toroidal magnet



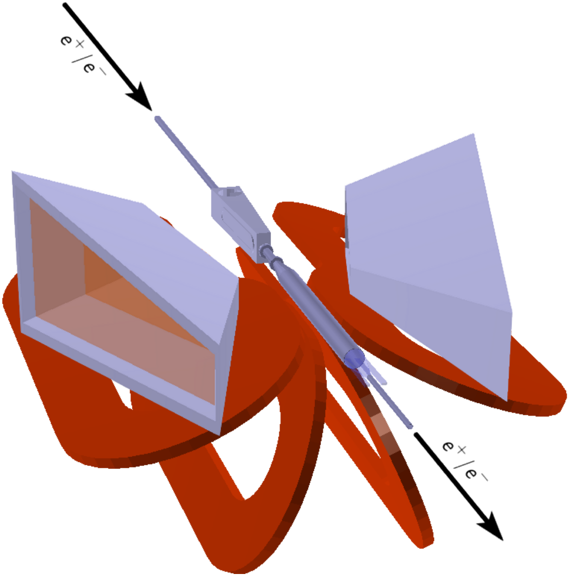
Toroidal magnet



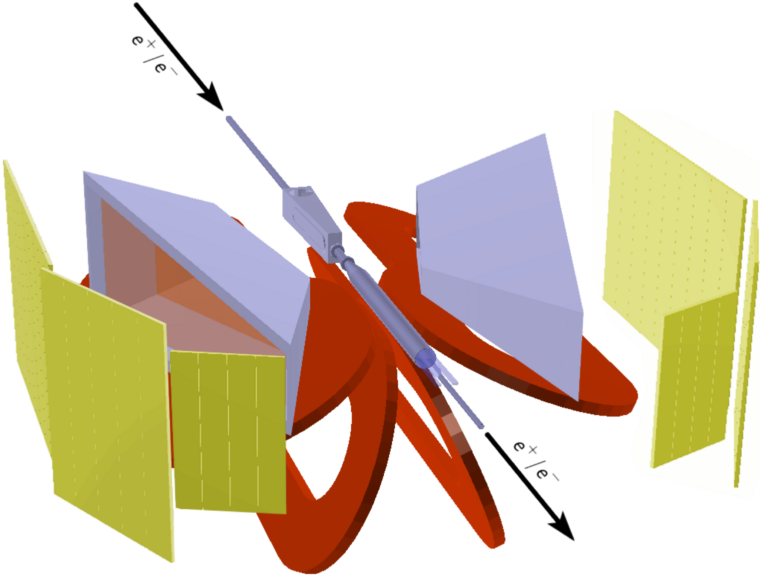
Internal hydrogen target



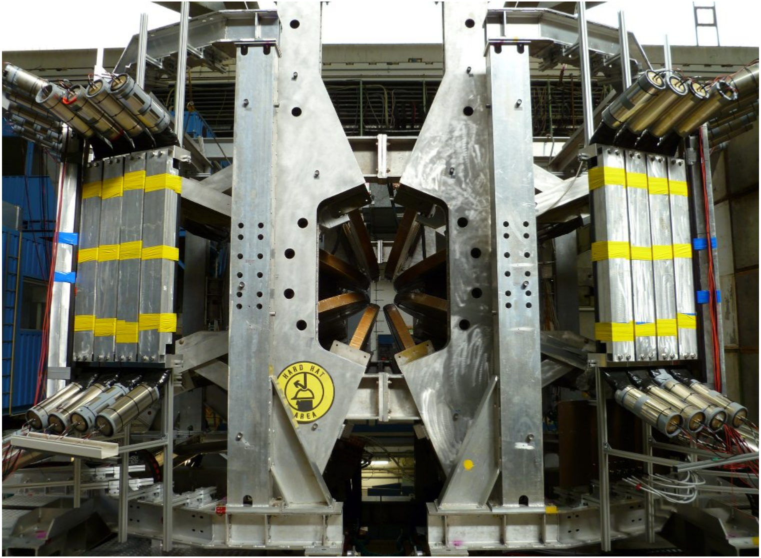
Drift chambers



Time of flight detectors



OLYMPUS spectrometer in DORIS hall



Tracking in OLYMPUS

Reconstruct scattered lepton and outgoing proton

- θ angle from beam
- ϕ angle from horizontal plane through beam
- z vertex from target
- Momentum

Tracking needs to be

- as similar for electrons and positrons as possible
- fast enough to be able to retrack our data set many times

Tracking in OLYMPUS

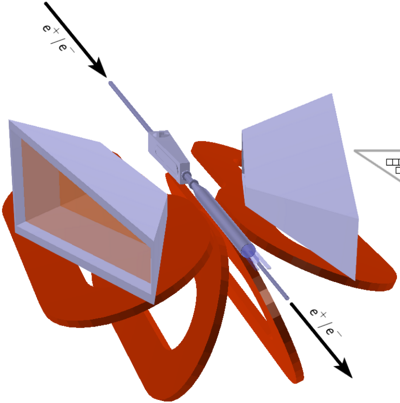
Drift chambers

- Acceptance: $20^\circ < \theta < 80^\circ$, $|\phi| < 15^\circ$
- Drift gas: Ar-CO_2-ethanol (87.4:9.7:2.9)
- 18 wire planes

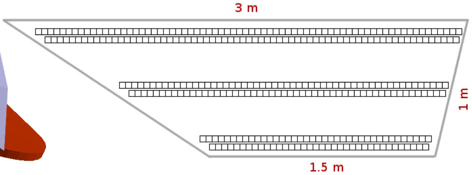
Time of Flight (ToF)

- Larger acceptance than drift chambers
- Each scintillator bar has a top and bottom PMT
- Position in bar (difference between PMT times)
- Time of track flight (mean of PMT times)

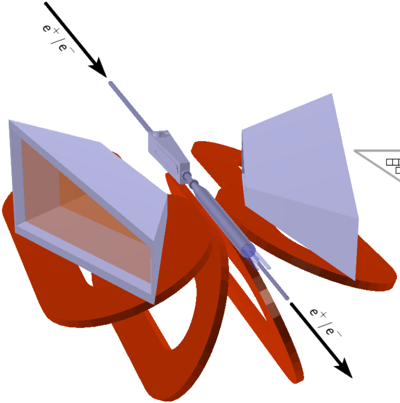
Anatomy of a drift chamber



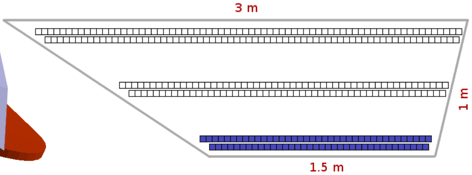
Horizontal cross section of sector:



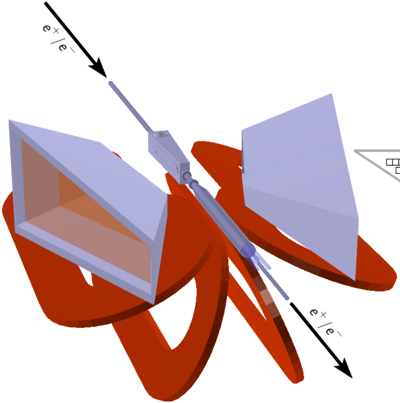
Anatomy of a drift chamber



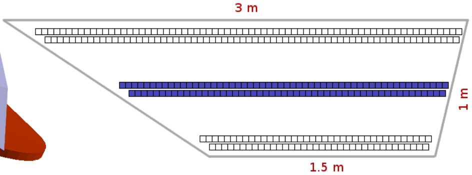
Chambers in a sector:



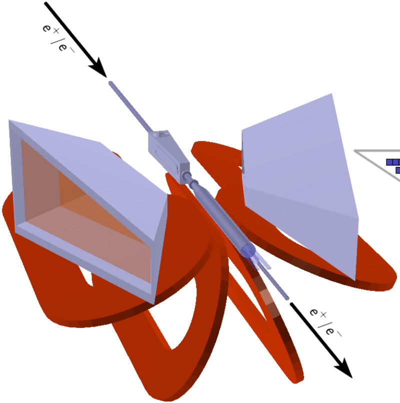
Anatomy of a drift chamber



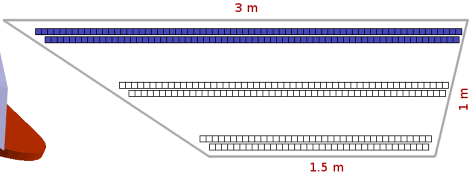
Chambers in a sector:



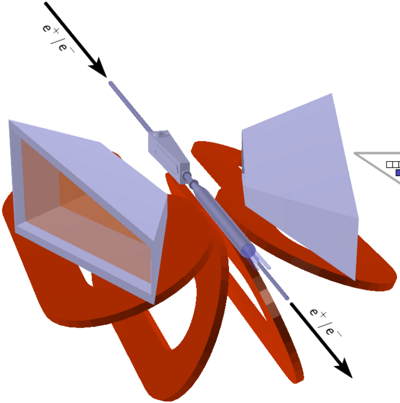
Anatomy of a drift chamber



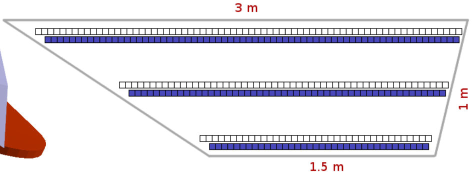
Chambers in a sector:



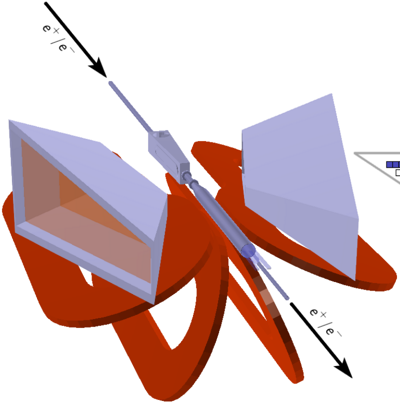
Anatomy of a drift chamber



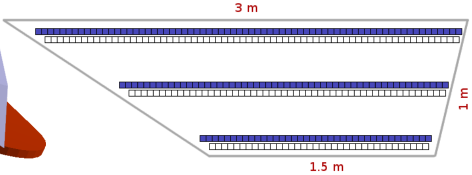
Superlayers in chambers:



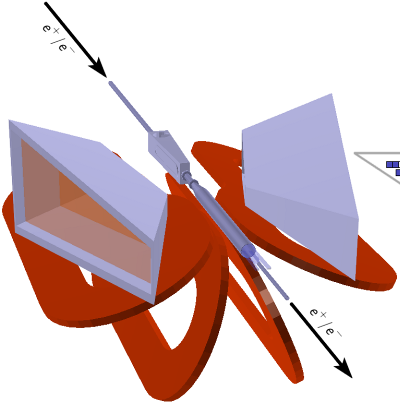
Anatomy of a drift chamber



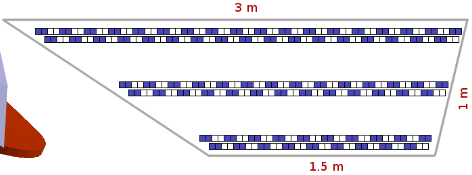
Superlayers in chambers:



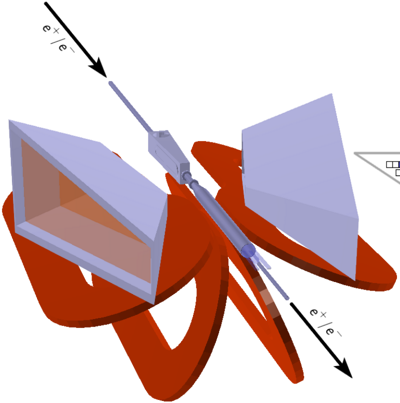
Anatomy of a drift chamber



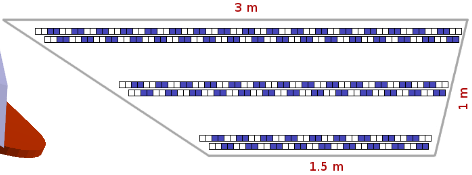
Cells in superlayers:



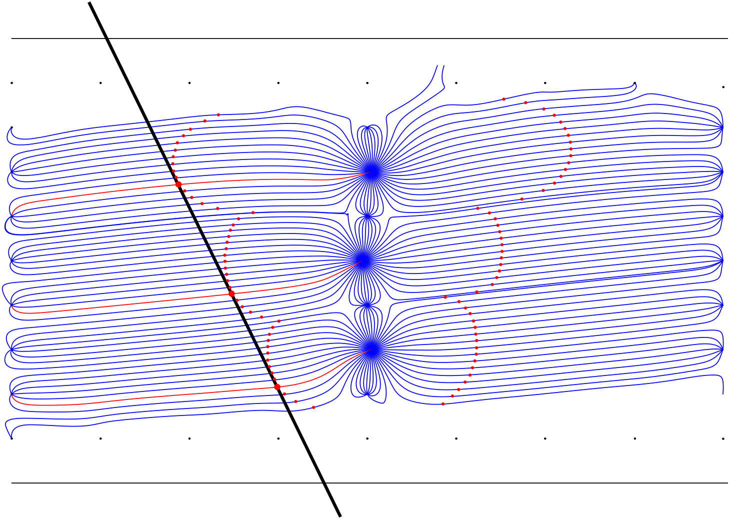
Anatomy of a drift chamber



Cells in superlayers:

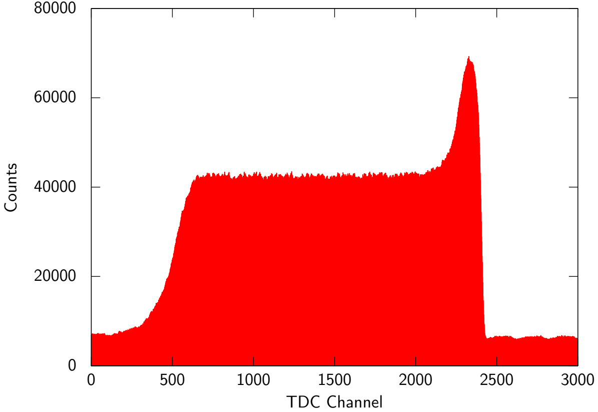


Drift chamber cell



Raw TDC for a sense wire

Characteristic shape from geometry and time-to-distance:



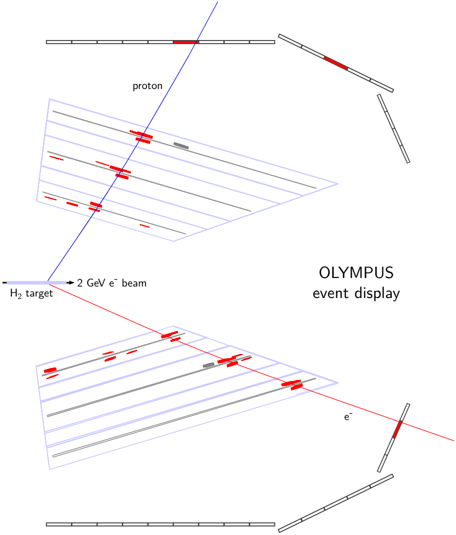
Time-to-distance (TTD) functions

- Needs to be fit from data
- Varies significantly with magnetic field
  - Different for each wire and position on each wire
- Varies with track angle α from perpendicular to wire plane
- TTD varies with alcohol level – which varied over time!
  - Break up data into blocks where TDC shape was stable

Fitting procedure for the 954 sense wires:

- Get initial wire guess for shape from TDC shape inversion
- Add freedom in α and ϕ for each wire side
- Use distances from best fit tracks to modify, and iterate until convergence

Example event from data

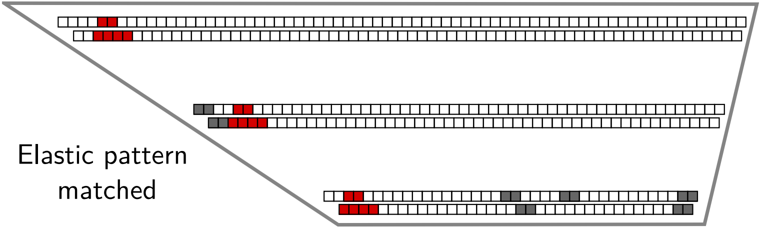


Track selection

Tree search algorithm for cell-level hit pattern

M. Dell'Orso and L. Ristori (1990)

- Reduces noise/combinatorics
- Fast



Library of patterns built from large Geant4 data set

Track propagation

- Geant4 track propagation to slow to use in tracker
- What we want from Geant4:
  - position $x_\ell(\boldsymbol{\pi})$ in each wire layer for given track starting parameters
  - angle $\alpha_\ell(\boldsymbol{\pi})$ perpendicular to wire plane for TTD
  - ToF parameters: $y(\boldsymbol{\pi})$ (vertical position at ToF), $b(\boldsymbol{\pi})$ (approximate ToF bar index), $d(\boldsymbol{\pi})$ (distance to bar)
- Precompute Geant4e set, fit cubic splines in four dimensions (θ, ϕ, z, $1/p$) for each value
- Also useful are the first and second derivatives: $\partial x_\ell / \partial \pi_i$, $\partial^2 x_\ell / \partial \pi_i \partial \pi_j$
- Computed for both protons and leptons ($p < 0$ is electron, $p > 0$ is positron)

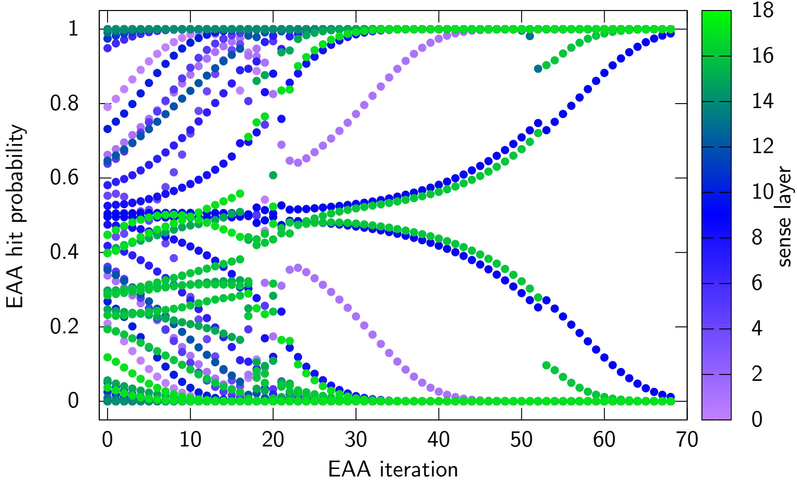
Tracking algorithm

- "Elastic arms" with deterministic simulated annealing (Ohlsson 1992)
- Temperature T determines the length scale
- Noise penalty λ determines how strongly to reject noise
- Find the track $\boldsymbol{\pi}$ that minimize, as T and λ are reduced,

$$E_{eff}(\boldsymbol{\pi}) = -T \sum_{w} \ln \left(N_w e^{\lambda/T} + \sum_{h=1}^{N_w} e^{-(d_w(t_h, \alpha_w(\boldsymbol{\pi}), \phi) - x_w(\boldsymbol{\pi}))^2/T} \right)$$

  where N_w is the number of hits in wire w, d_w is our time-to-distance function for wire w, and α_w and x_w are our angle and position Geant4e fits
- Probability that a hit is "included" in the track can be calculated, goes to 0 or 1 as cooled

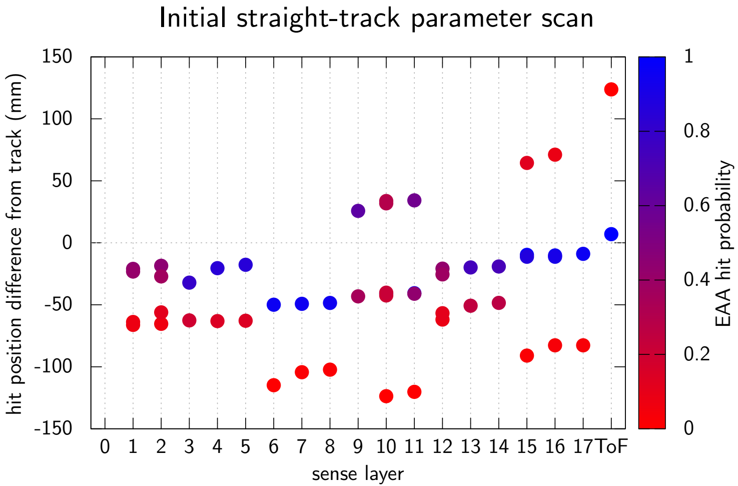
Elastic Arms Algorithm probability evolution



Tracking algorithm

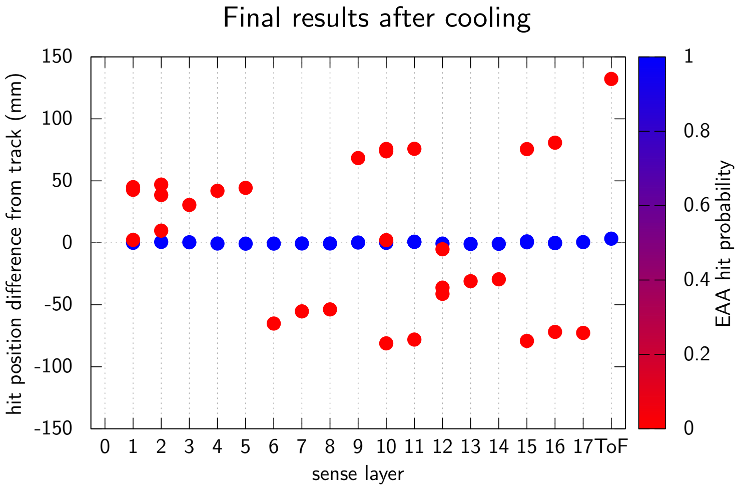
- E_{eff} gets more minima as temperature is cooled – easier to find global minimum at high temperatures
- Cool slowly while minimizing to stay in the global minimum
  - Left-right ambiguities can complicate this
- Initial angle estimations come from ToF
- E_{eff} minimization done using a mixture of
  - Parameter scans
  - Newton's method (using first and second derivatives)
  - Gradient descent (using first derivatives)

Elastic Arms Algorithm in action



proton $\theta = 55.1°$ $\phi = -5.6°$ $z = 0$ mm $p = \infty$ MeV

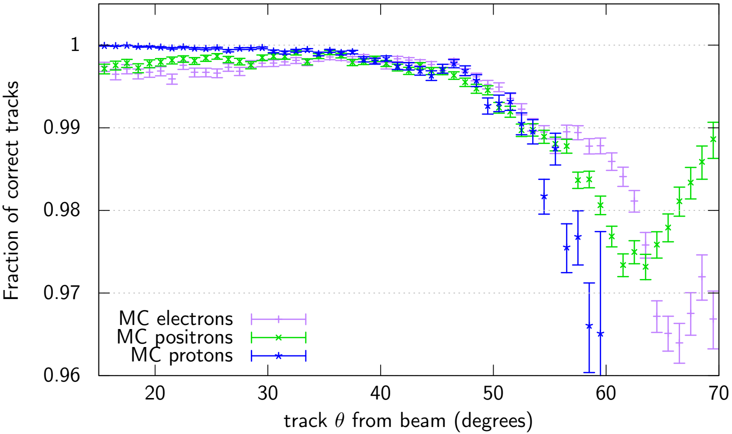
Elastic Arms Algorithm in action



proton $\theta = 55.9^\circ$ $\phi = -6.4^\circ$ $z = 94$ mm $p = 860$ MeV

Monte Carlo studies of tracking

Still getting some left-right ambiguities wrong, especially at back angles:



Closing notes

- Tracking for OLYMPUS has been complicated by
  - Left-right ambiguities within cells
  - Noise and background, inefficiencies
  - Inhomogeneous magnetic field
  - Unknown time-to-distance functions
- These issues have been mostly overcome using pattern matching and an elastic arms algorithm tracker
- Still working on final improvements
  - Time-to-distance parameterizations and fits
  - Tracking algorithm at back angles