An Experiment to Definitively Determine the Contributions of Multiple Photon Exchange in Elastic Lepton-Nucleon Scattering

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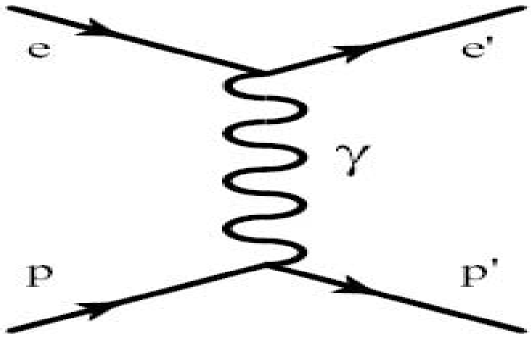
- Introduction
- Motivation for the Experiment
- Description of the Experiment
- Summary

Elastic Electron Scattering from Proton



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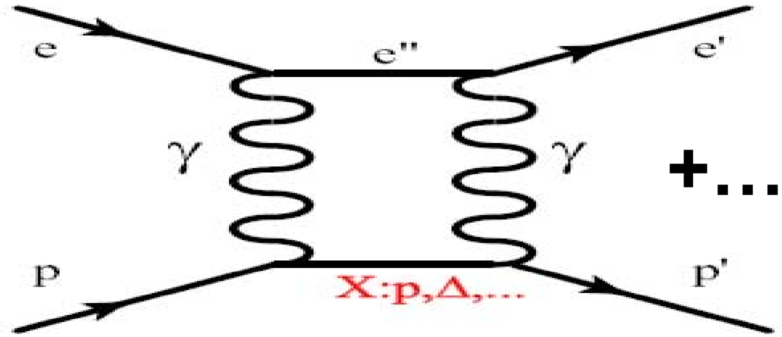

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Dirac, Pauli FF

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

Sachs FF

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

Nucleon elastic form factors

- Defined in the context of single photon exchange
- Fundamental observables describing the distribution of charge and magnetism in the proton and neutron
- Experimentally, data well described (to first order) by an exponential spatial fall off of nucleon's charge and magnetism ~ $e^{-\mu r}$

  => dipole form factor

  $G_D(Q^2) \sim (1 + Q^2/0.71)^{-2}$
- At $Q^2 \gg 1$, $\sigma \sim \sigma_{Mott} G^2{}_D \sim Q^{-12}$
- FF determined by quark structure of proton
- Will be calculable in lattice QCD

Unpolarized Elastic e-N Scattering

$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = \frac{\sigma}{\sigma_0} = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}$$

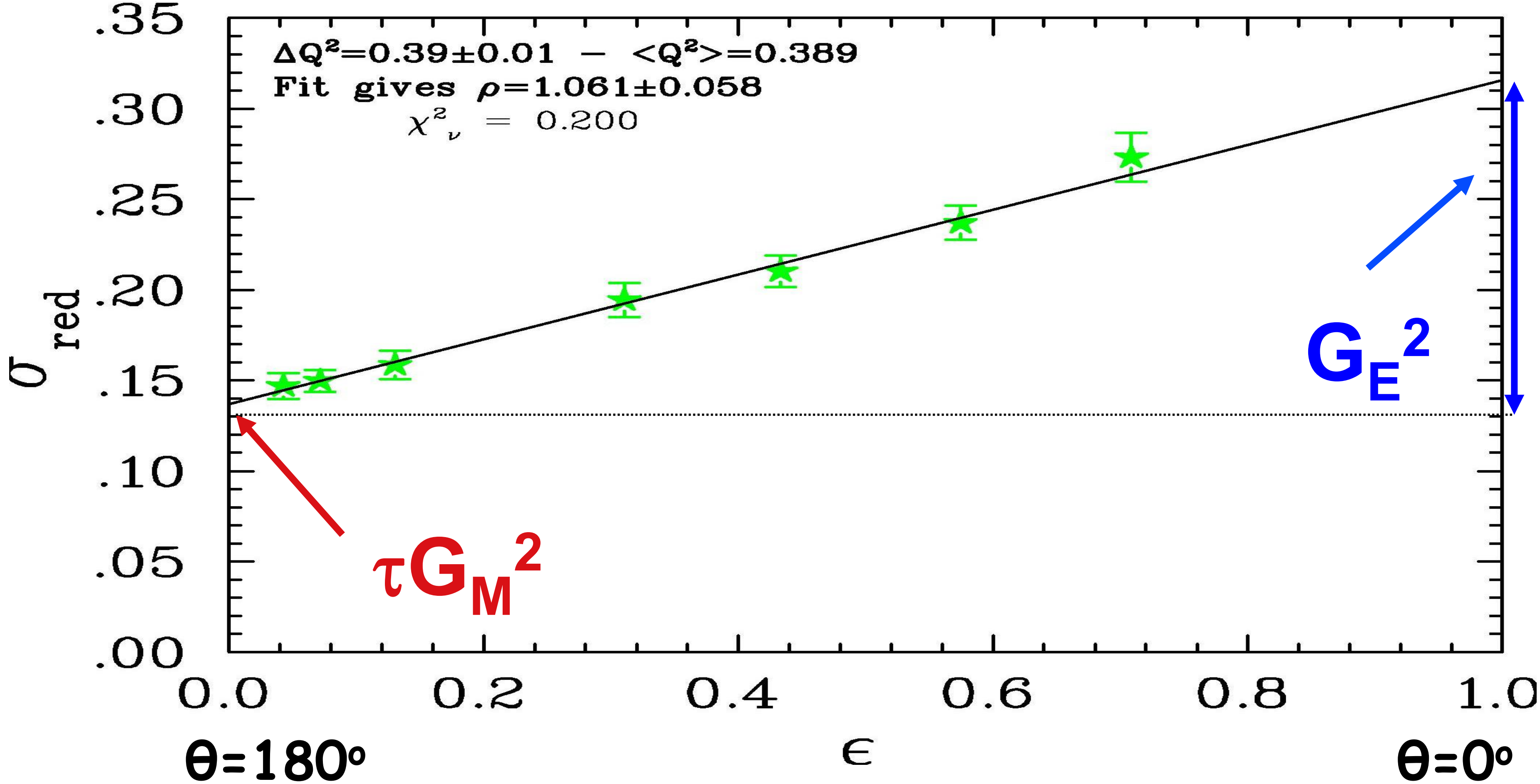
$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$

For ~ 50 years unpolarized cross section measurements have determined the elastic FF G^p_E and G^p_M using the Rosenbluth separation

$\sigma_{red} = d\sigma/d\Omega\ [\varepsilon(1+\tau)/\sigma_{Mott}] = \tau G_M^{\ 2} + \varepsilon G_E^{\ 2}$

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

Rosenbluth Separation



Polarization Measurements of Elastic FF

- Double polarization in elastic ep scattering:
  Recoil polarization or polarized target
  $^1H(\vec{e},e'\vec{p})$, $^1\vec{H}(\vec{e},e'p)$

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

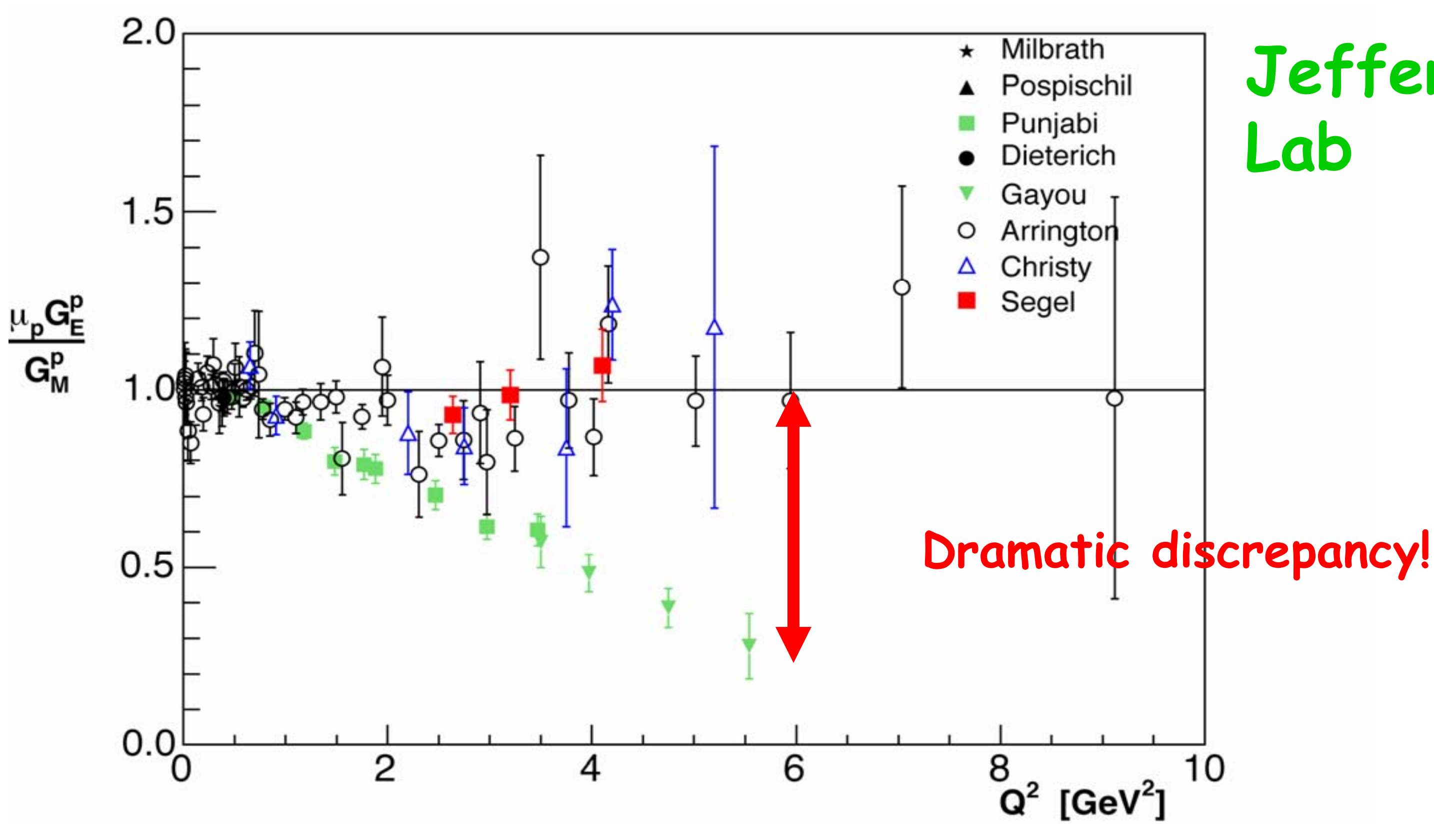
- Double spin asymmetry

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

- 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

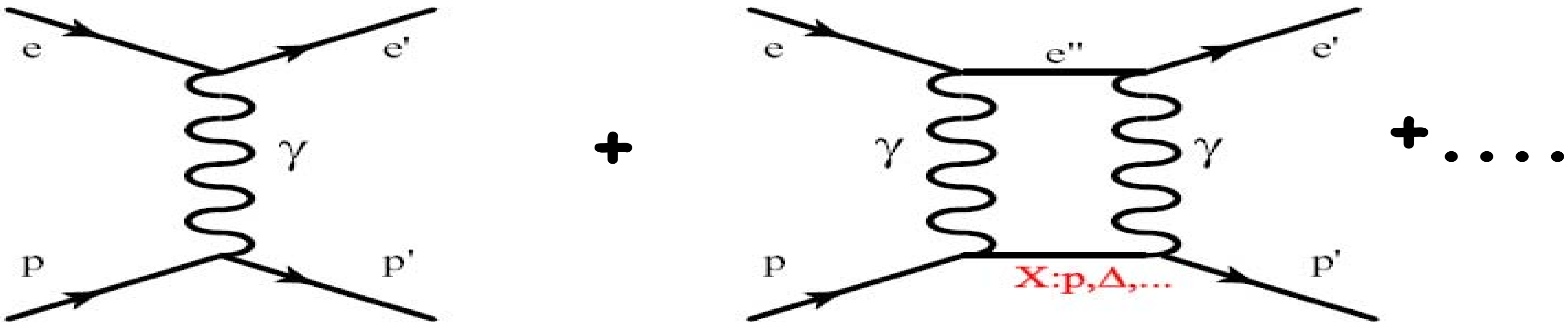
Proton Form Factor Ratio



Jefferson Lab

- All Rosenbluth data from SLAC and Jlab in agreement.
- Dramatic discrepancy between Rosenbluth and recoil polarization technique

Calculation of Two Photon Exchange Effects



- P.A.M. Guichon and M. Vanderhaeghen, PRL91, 142303 (2003)
- P.G. Blunden, W. Melnitchouk, and J.A. Tjon, PRC72, 034612 (2005), PRL91, 142304 (2003)
- M.P. Rekalo and E. Tomasi-Gustafsson, EPJA22, 331 (2004)
- Y.C. Chen et al.,PRL93, 122301 (2004)
- A.V. Afanasev and N.P. Merenkov, PRD70, 073002 (2004)

Estimation of TPE Contribution

P.G. Blunden et al.,
Phys. Rev. C 72, 034612
(2005)

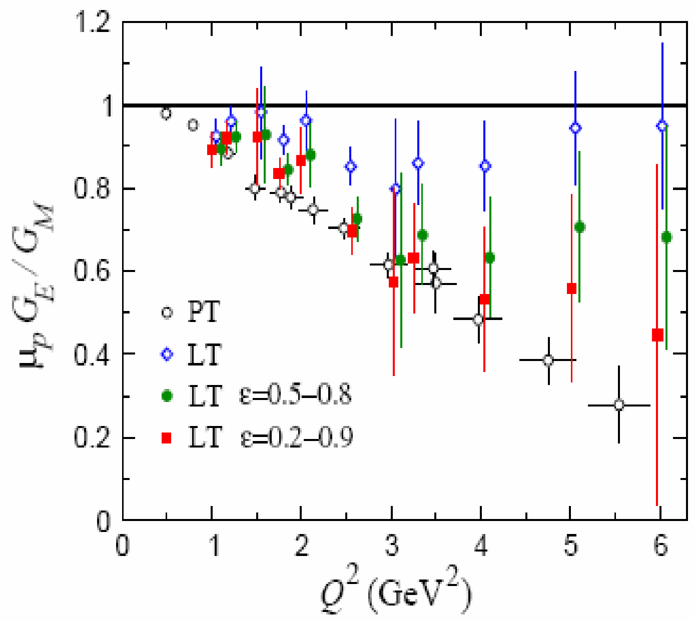


FIG. 5: The ratio of proton form factors $\mu_p G_E/G_M$ measured using LT separation (open diamonds) [2] and polarization transfer (PT) (open circles) [5]. The LT points corrected for 2γ exchange are shown assuming a linear slope for $\varepsilon = 0.2 - 0.9$ (filled squares) and $\varepsilon = 0.5 - 0.8$ (filled circles) (offset for clarity).

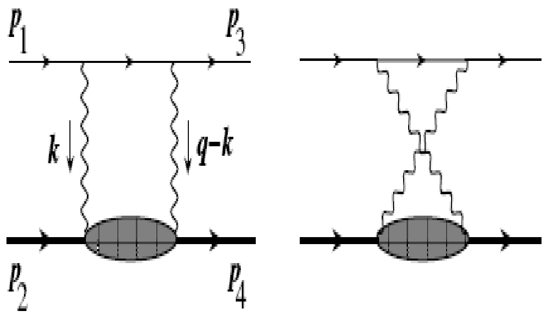
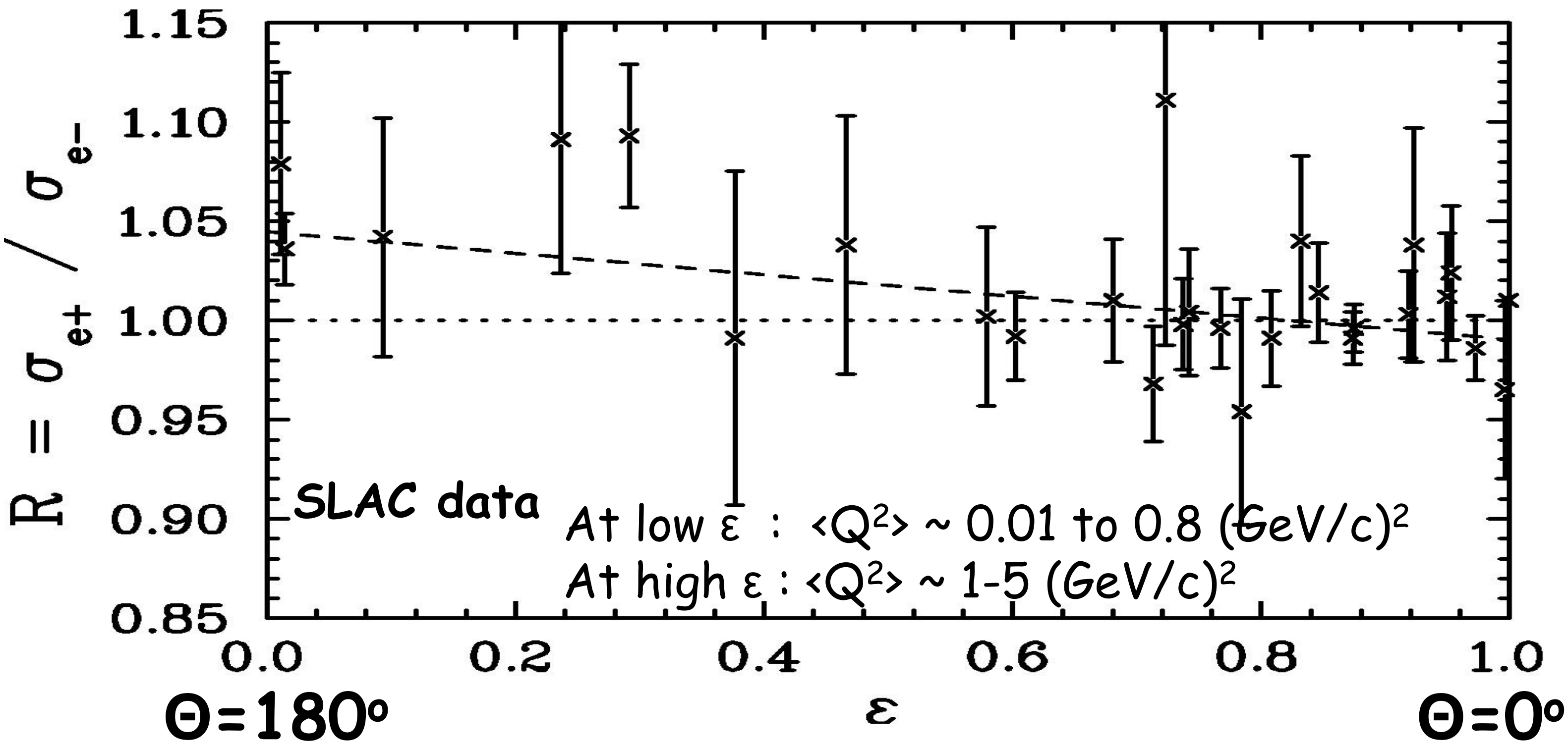


FIG. 1. Two-photon exchange box and crossed box diagrams for elastic electron-proton scattering.

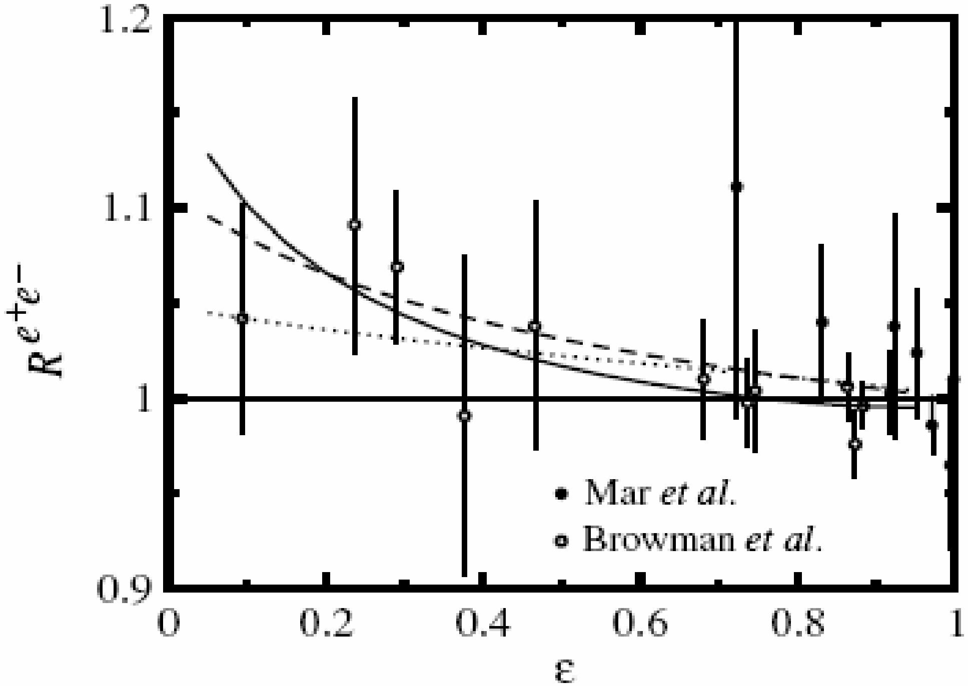
How do we verify that the TPE contribution interpretation is correct?

Precision comparison of positron-proton and electron-proton elastic scattering over a sizable ε range at $Q^2 \sim$ 2-3 $(GeV/c)^2$

J. Arrington PRC 69, 032201(R) (2004)



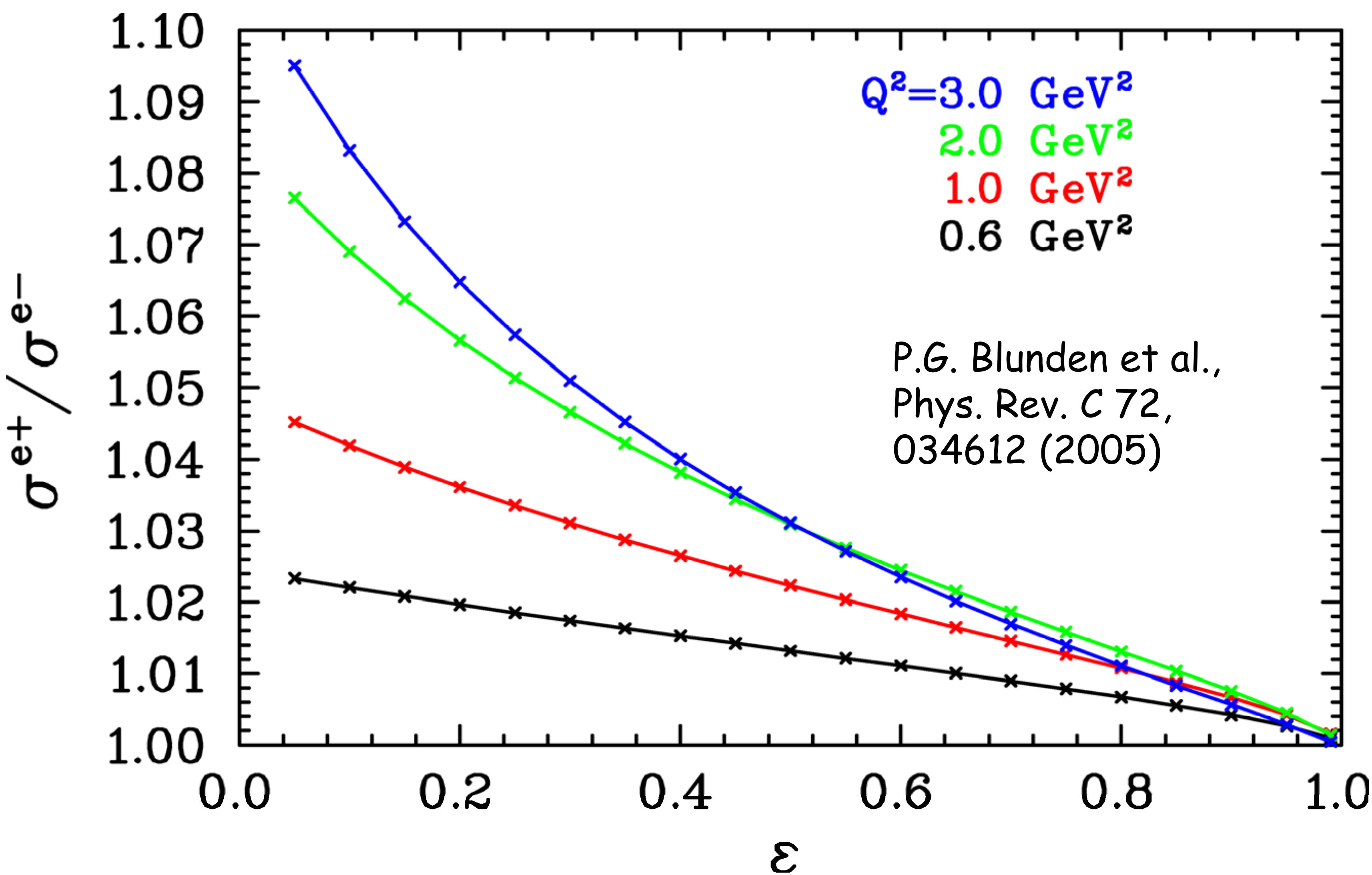
TPE Calculation comparison with e^+p/e^-p scattering data



P.G. Blunden et al., Phys. Rev. C 72, 034612 (2005)

FIG. 7. Ratio of elastic e^+p to e^-p cross sections. The data are from SLAC [31,32], with Q^2 ranging from 0.01 to 5 GeV^2. The results of the 2γ exchange calculations are shown by the curves for $Q^2 = 1$ (dotted), 3 (dashed), and 6 GeV^2 (solid).

e^+p/e^-p Cross Section Ratio



e^+p/e^-p Cross Section Ratio

P.G. Blunden et al., Phys. Rev. C 72, 034612 (2005)

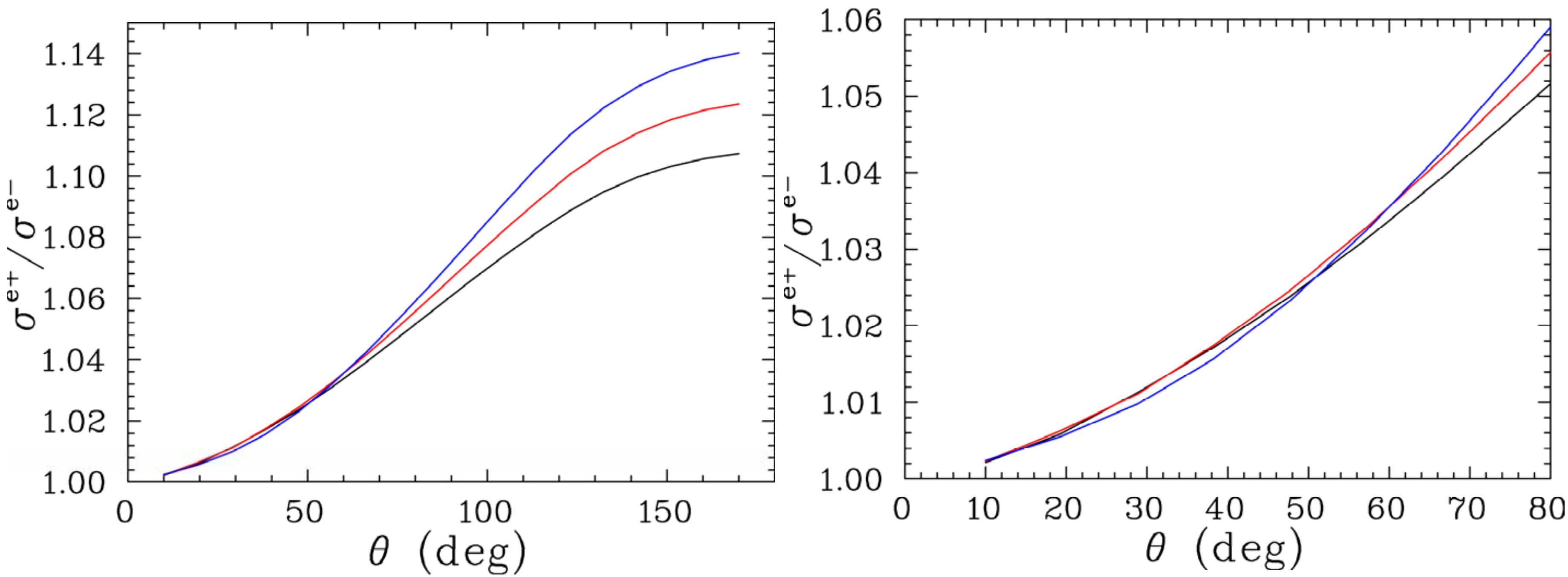
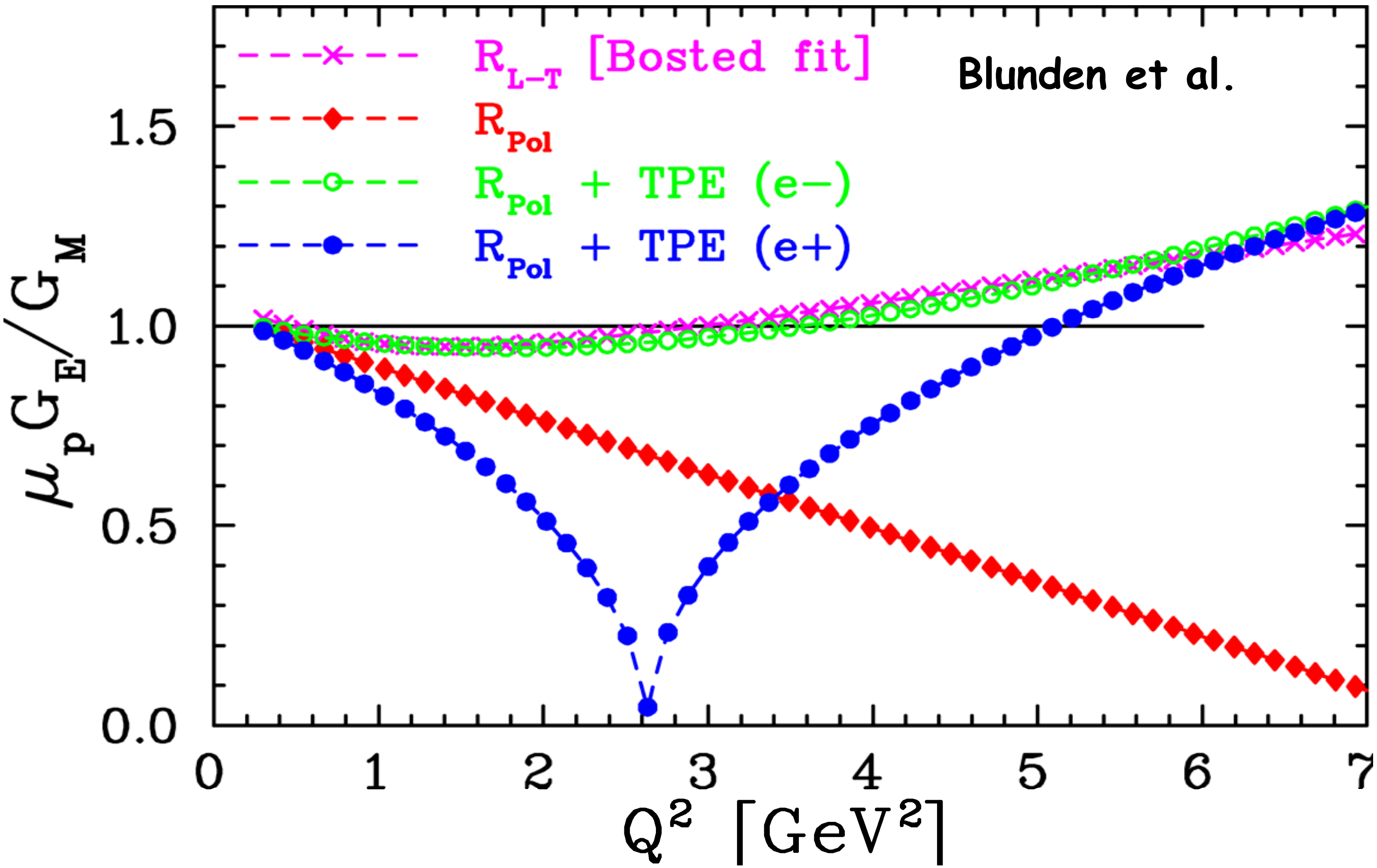


Figure 3: e^+p/e^-p cross section ratio as a function of scattering angle, for three different beam energies (black=2.0 GeV, red=2.5 GeV, blue=3.0 GeV) [16, 17]. The figure on the right zooms into the region up to 80°, where only little energy dependence of the two-photon effect is evident.

Proton form factor ratio



Proposed DESY Experiment

- Electrons/positrons (100mA) in multi-GeV storage ring DORIS at DESY, Hamburg, Germany
- Unpolarized internal hydrogen target (like HERMES) 4×10^{15} at/cm^2 @ 100 mA $\rightarrow L = 2\times10^{33}$ / (cm^{2}s)
- Measure elastic e^+/e^- proton scattering at 2.3 to 4.5 GeV energies with ε range from 0.4 to 1 at high $Q^2 \sim 2\text{-}3$ (GeV/c)^2
- Experiment requires switching from e^+ beam to e^- beam on timescale of $\leq$ 1 day.
- Redundant monitoring of luminosity, pressure, temperature, flow, current measurements - small-angle elastic scattering at high ε and low Q^2
- Measure ratio of positron-proton to electron-proton unpolarized elastic scattering to 1% stat.+sys.

BLAST: an experiment to study nucleon structure at low Q^2

- Pion is essential to understanding both nucleon and nuclear structure
- In low energy elastic electron-nucleon scattering one would expect effects of mesons to occur at

$$r \sim 2 \text{ fermi} \Rightarrow Q^2 \sim 0.1\ (\text{GeV}/c)^2$$

- Search for effects of meson cloud on long distance structure of nucleon
- Seek precise determination of neutron electric form factor with low systematic uncertainties
- Spin structure of deuterium is a stringent test of our understanding of the nucleon-nucleon interaction in nuclei
- **New experimental technique**: precision experiments possible using polarized gas target internal to electron storage ring

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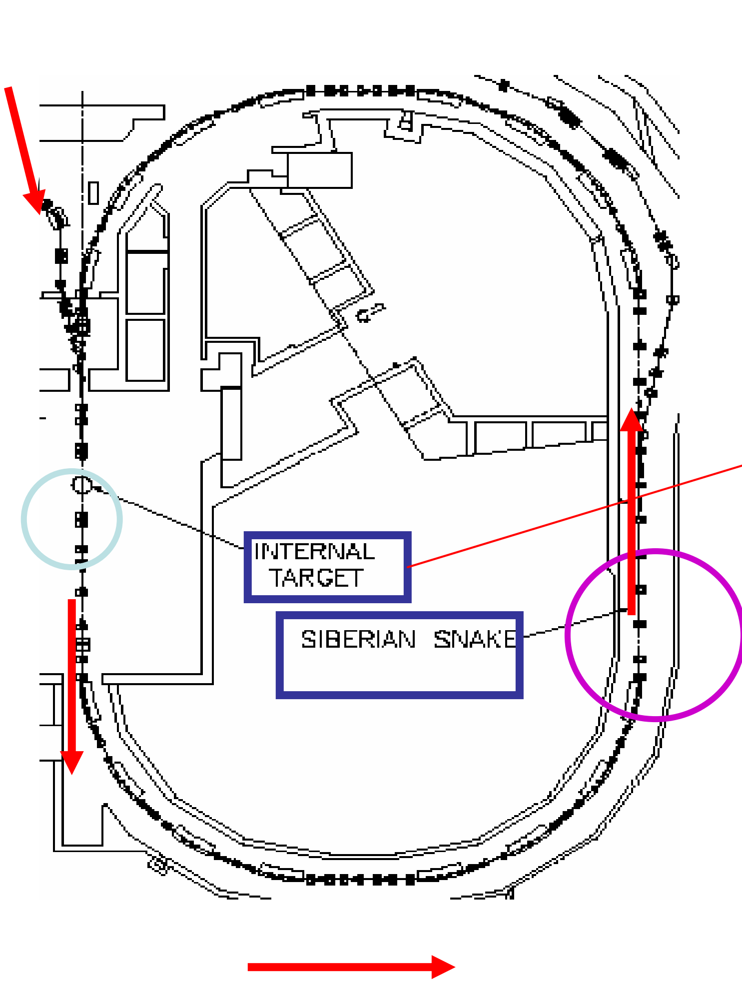
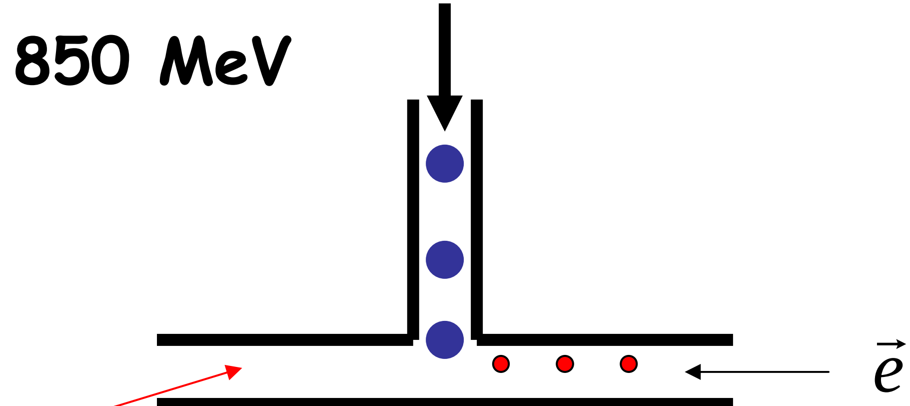
BLAST Experimental Configuration



South Hall Ring

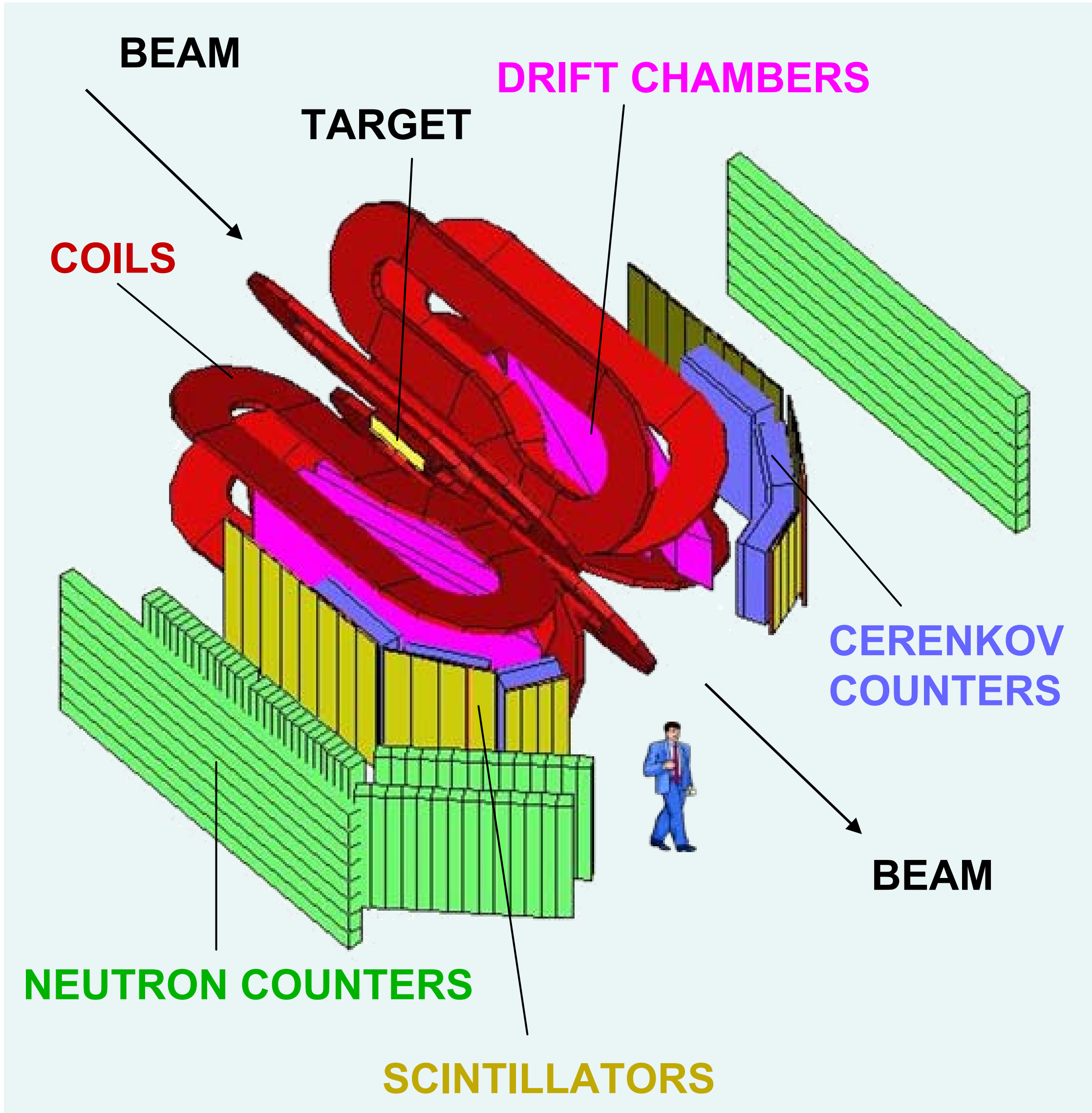


- high polarization
- pure target
- thin cell walls
- low holding field
- low systematics

$L \approx 10^{32}$ atoms cm^{2}s^{-1}

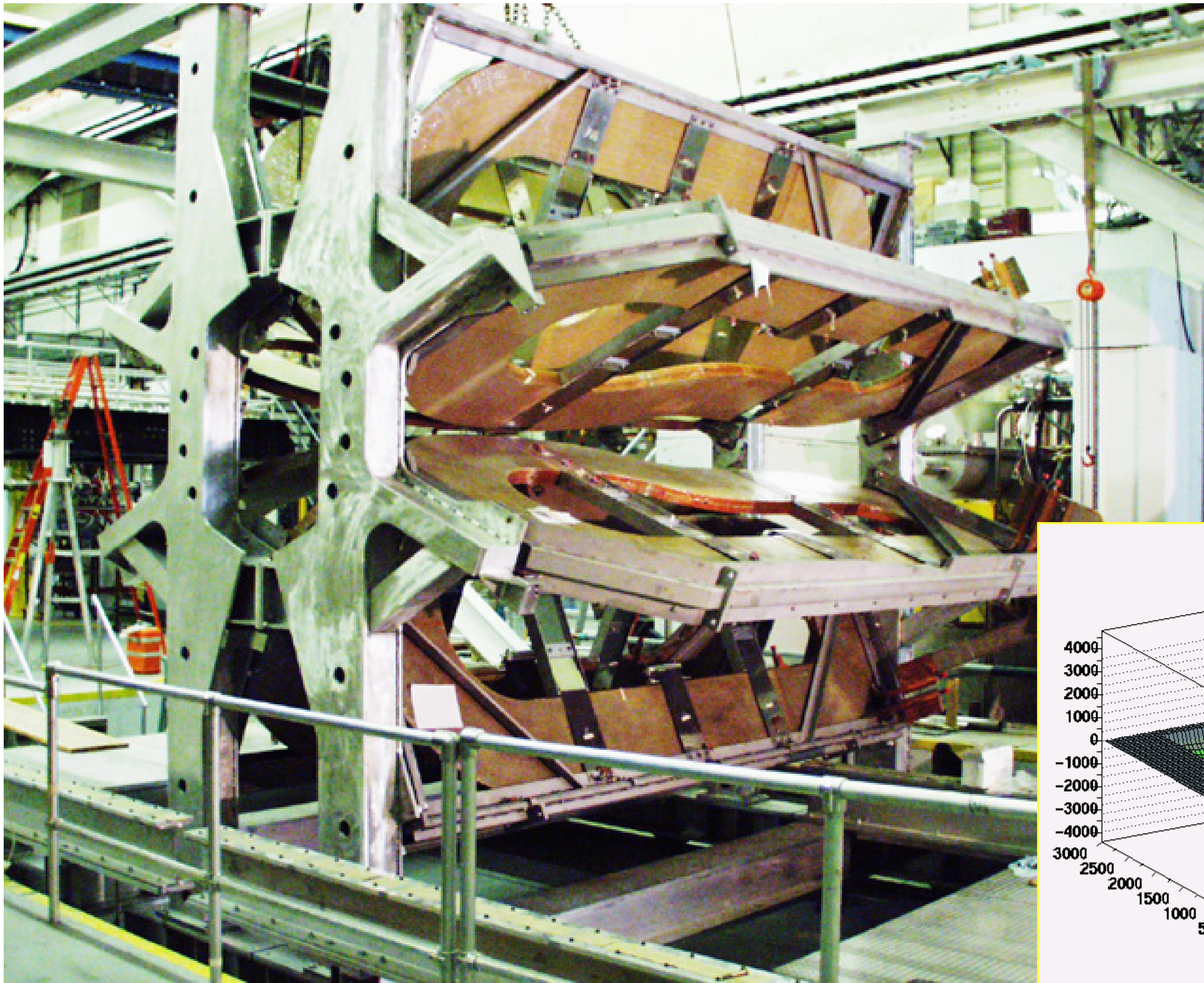
The BLAST Detectors

- **Left-right symmetric**
- **Large acceptance:**
  $0.1 < Q^2/(GeV/c)^2 < 0.8$
  $20^o < q < 80^o$, $-15^o < \phi < 15^o$
- COILS $B_{max} = 3.8$ kG
- DRIFT CHAMBERS
  Tracking, PID (charge)
  $dp/p=3\%$, $dq = 0.5^o$
- CERENKOV COUNTERS
  e/p separation
- SCINTILLATORS
  Trigger, ToF, PID (p/p)
- NEUTRON COUNTERS
  Neutron tracking (ToF)

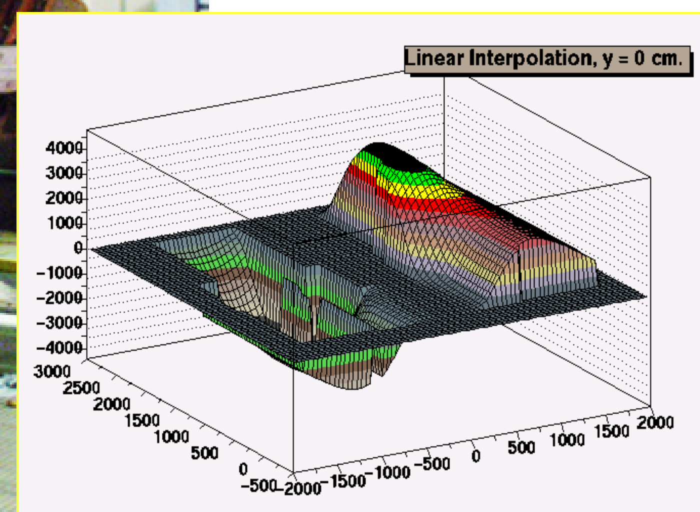


Richard Milner

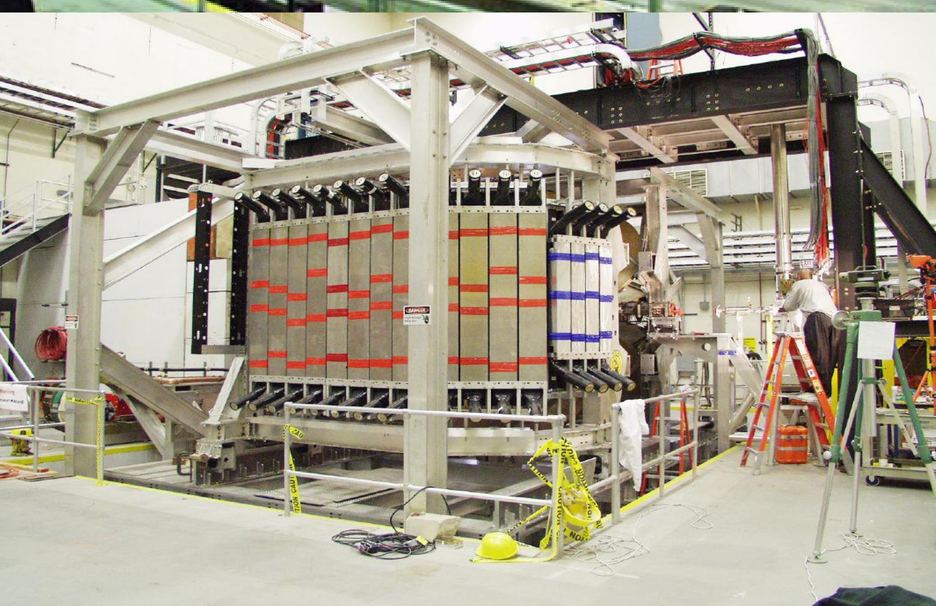
Bates Large Acceptance Spectrometer Toroid



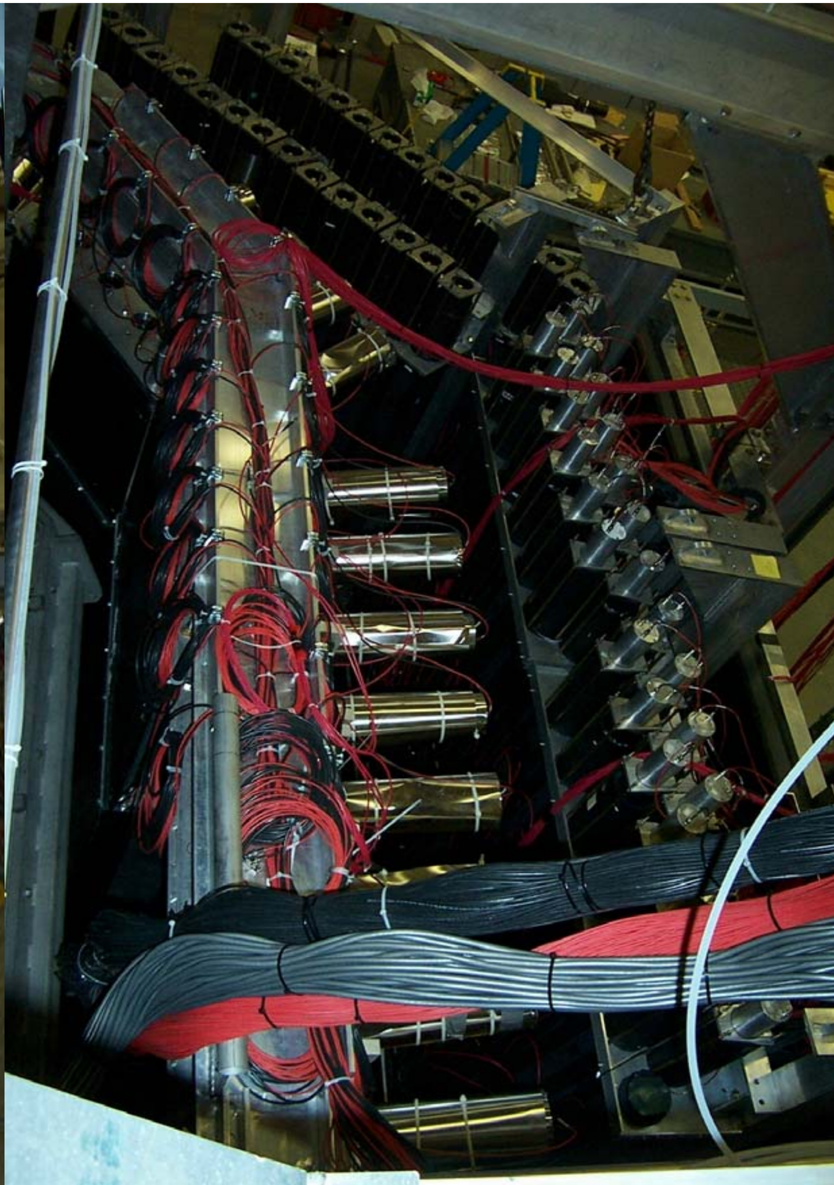
- 8 copper coils
  - 6730 A
  - 3700 G
- field mapped (3D)
  - coil position adjusted
  - ±1% of calculated
  - minimize target field
  - tracking



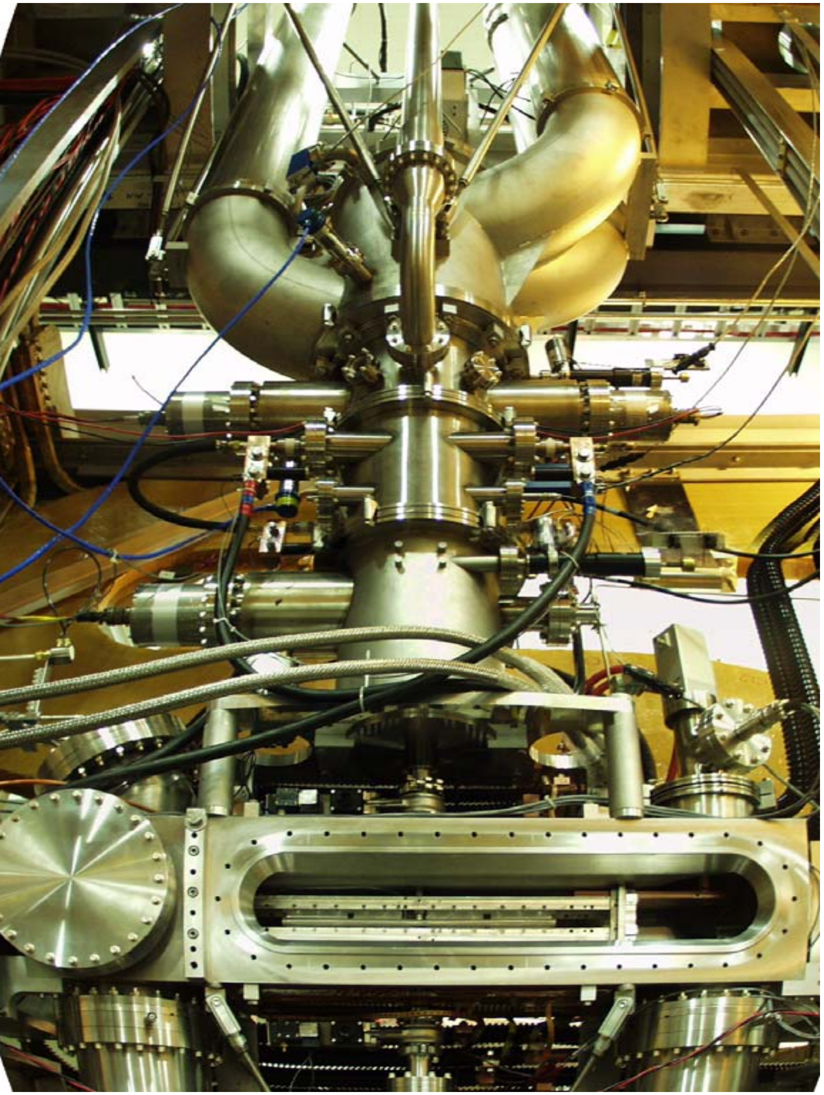
The BLAST Detector components

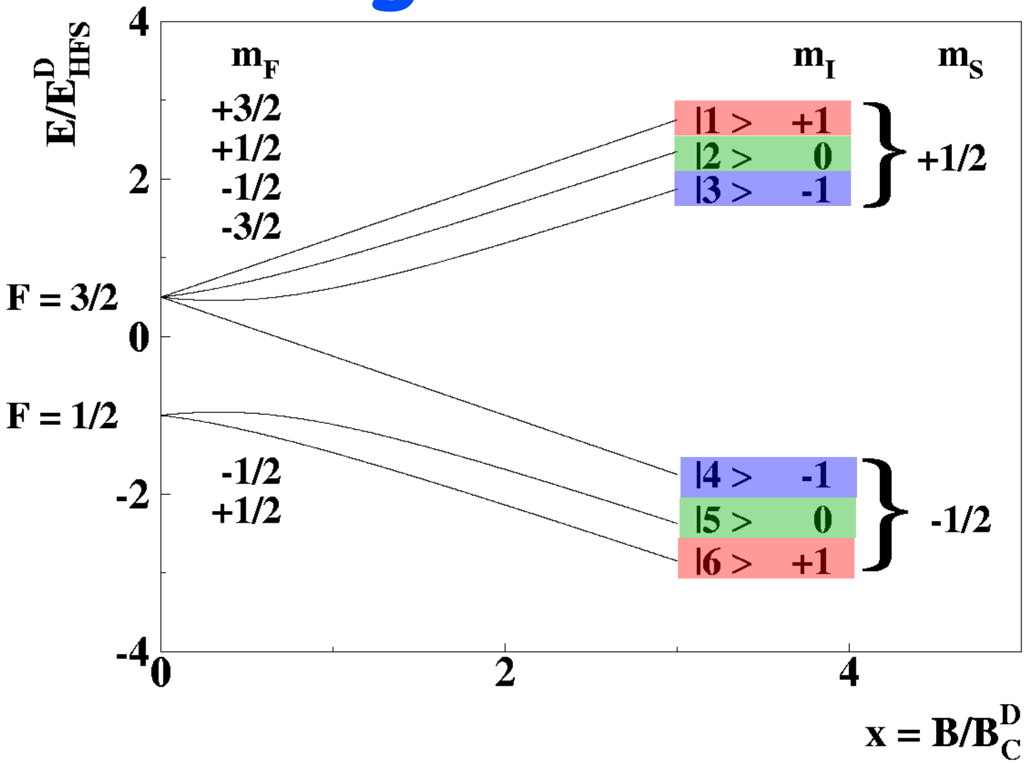


The BLAST Neutron Detectors

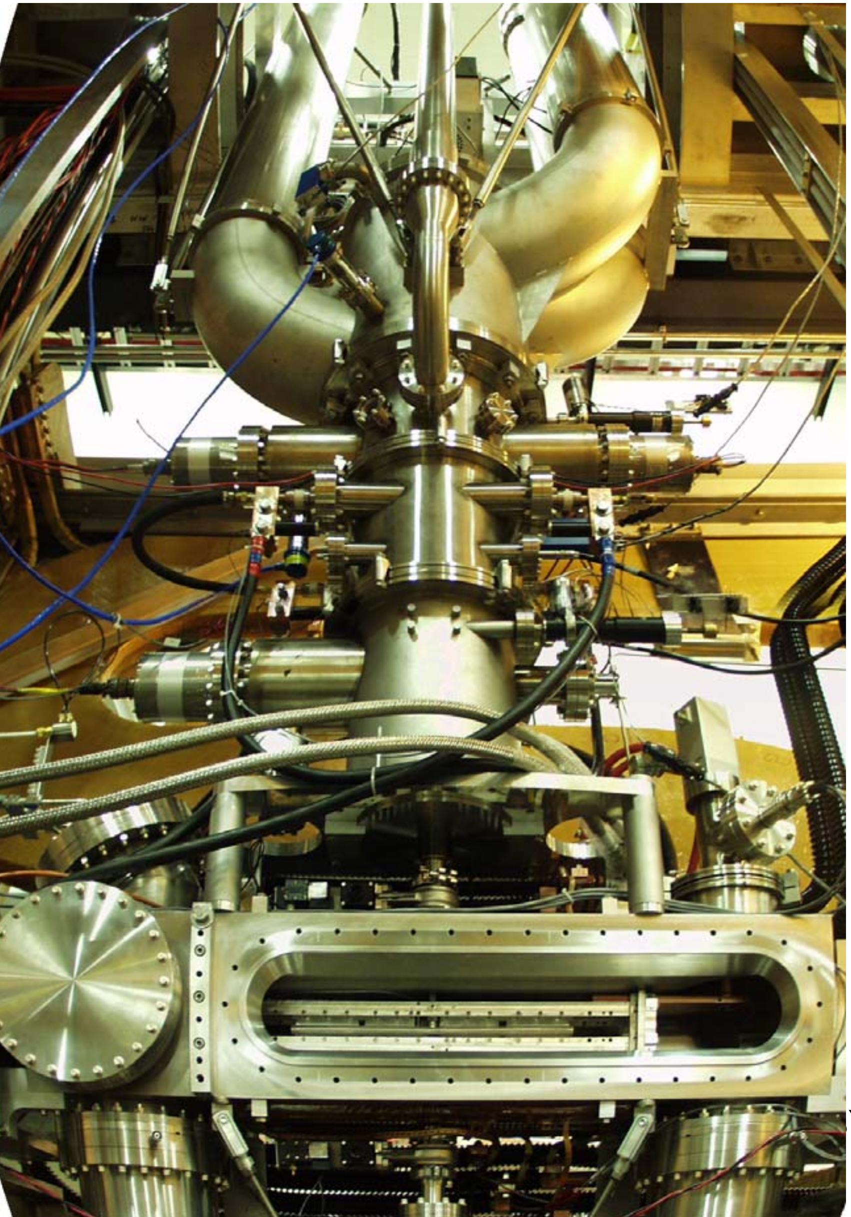
The BLAST Polarized Hydrogen/ Deuterium target



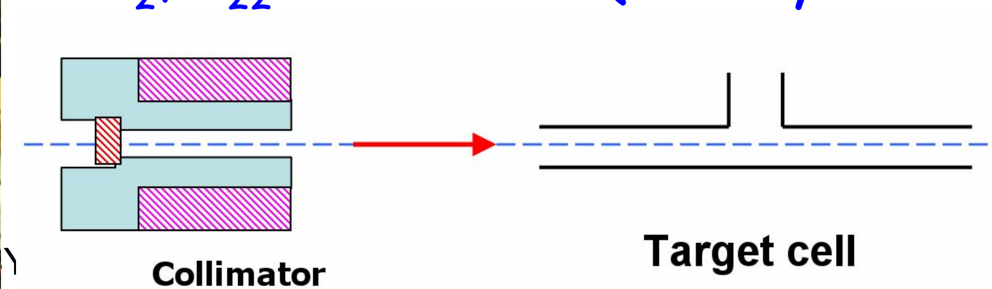


- Separately prepare m_I = +1, 0, -1 with sextupoles and RF transitions
- Switch between states every 5 minutes

BLAST Target Performance

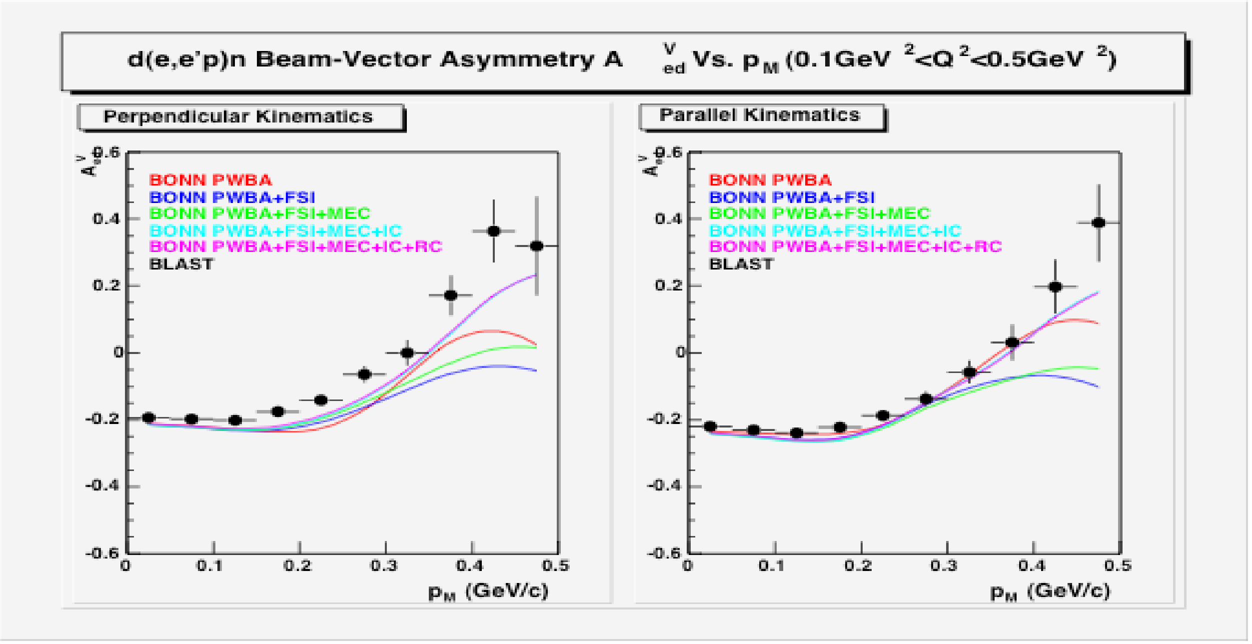


- Isotopically pure H or D atoms
  (Vector-) polarized H
  Vector- and tensor-polarized D
- Target thickness / luminosity
  $r=6x10^{13}$ at/cm^2,
  $L=6x10^{31}/(cm^2 s)$
- Operated within BLAST B-field
  $B_{max} = 3.8$ kG
- Target polarization 70-80%
  P_z, P_{zz} from low Q^2 analysis

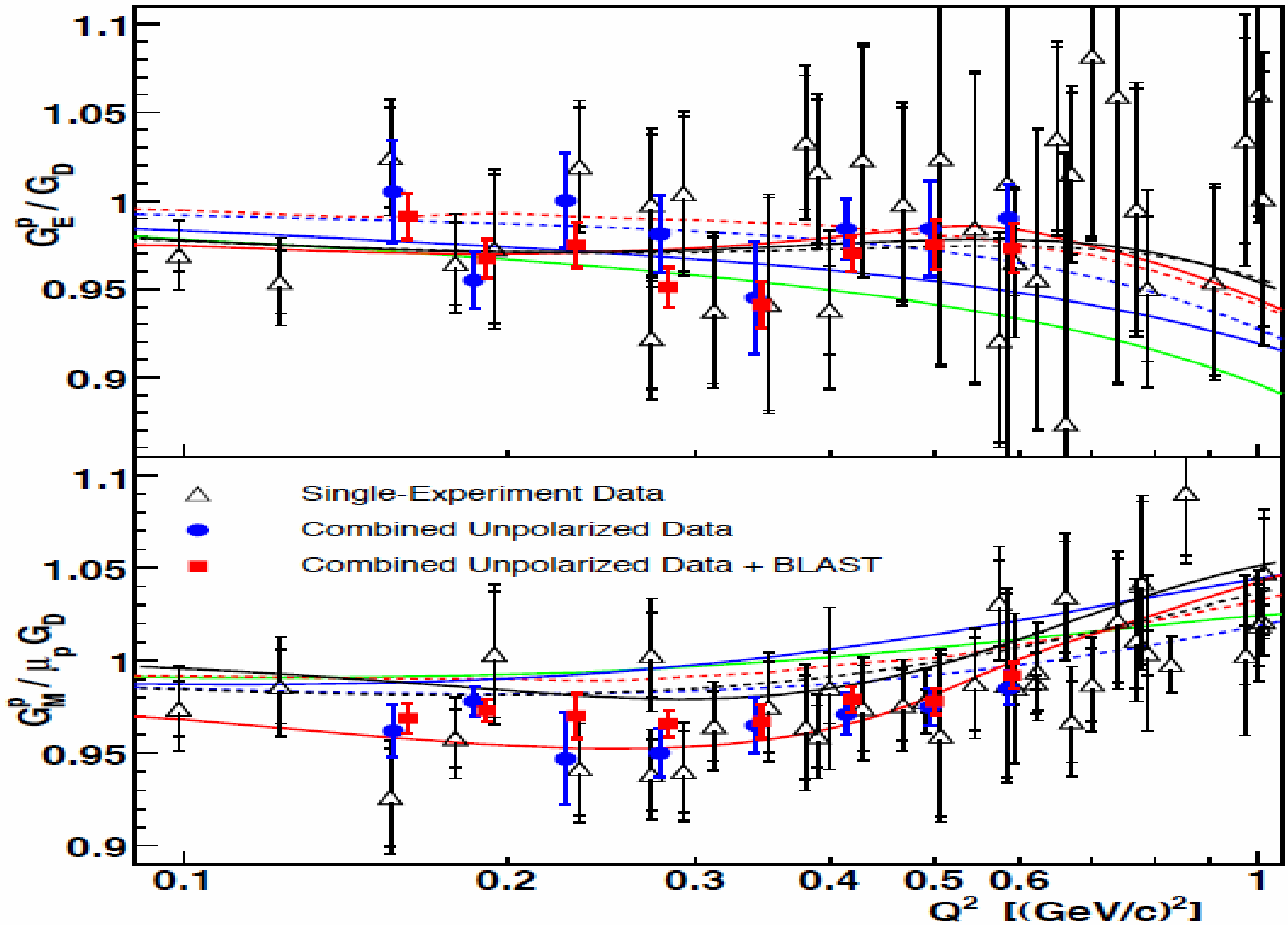


BLAST science highlights

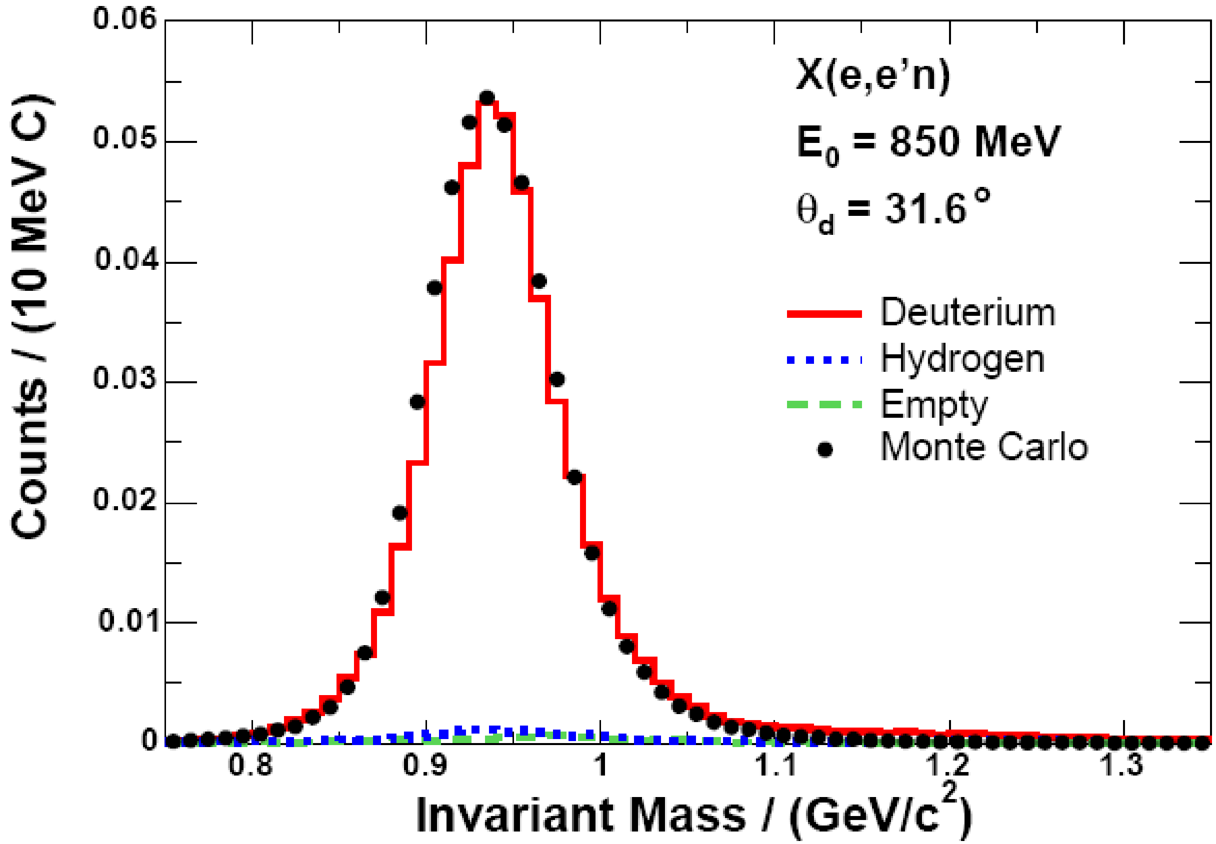
- BLAST constructed in 1999-2002
- BLAST commissioned in 2003
- BLAST took data in 2003-2005 on spin-dependent electron scattering from polarized hydrogen and deuterium at 850 MeV



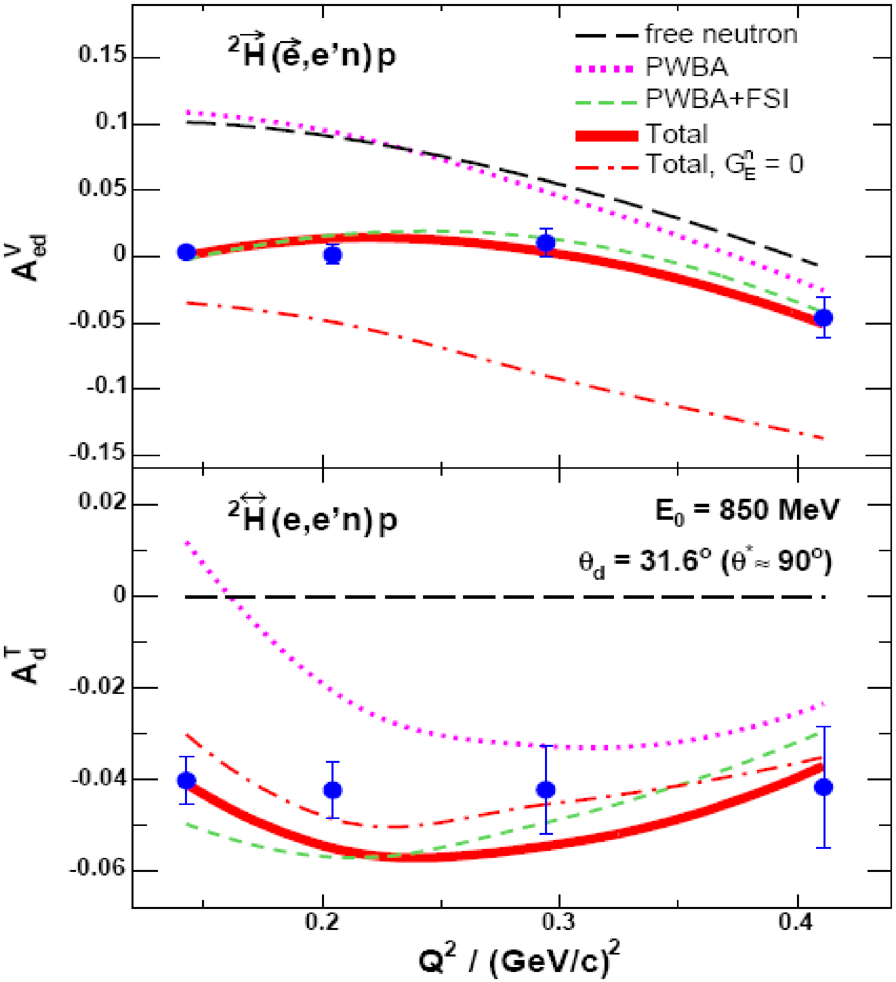
Extraction of G_E^p and G_M^p



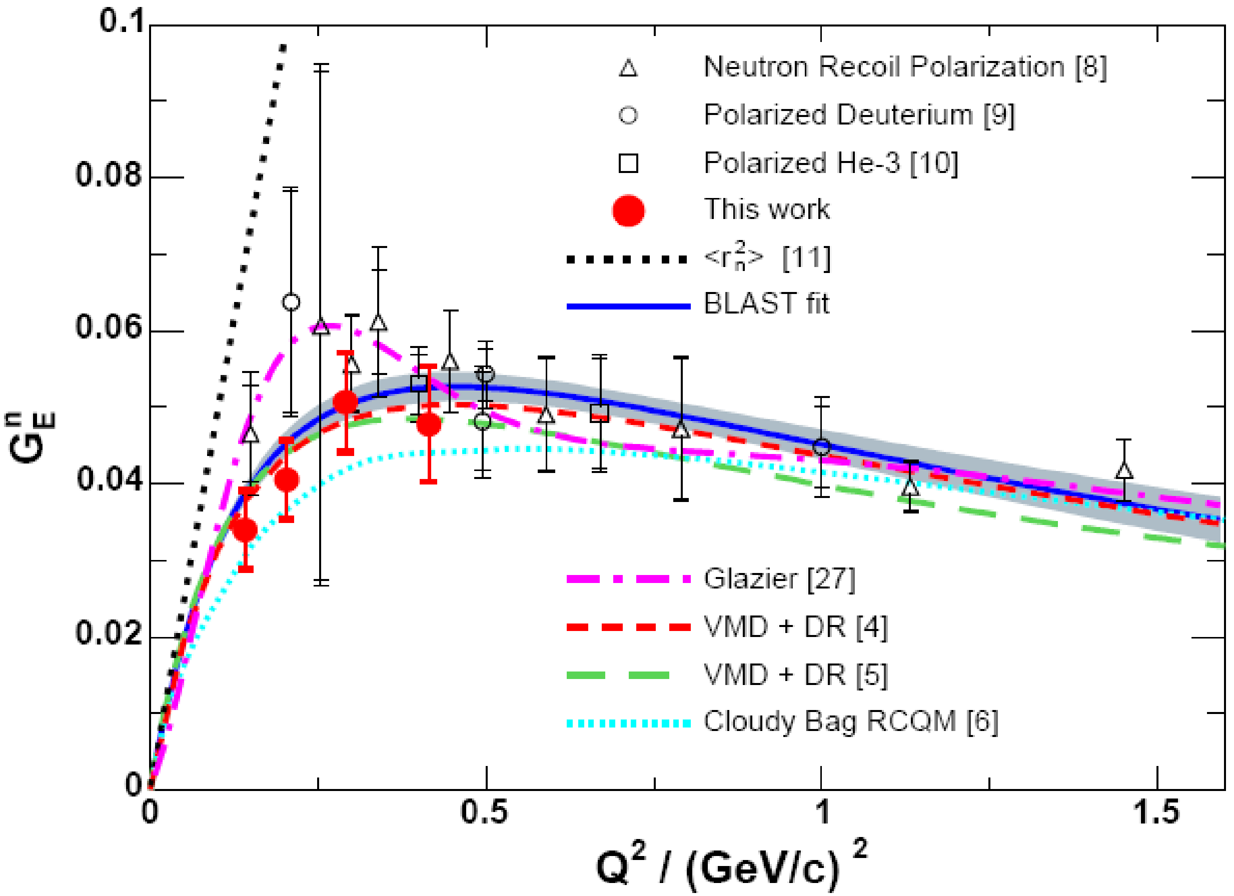
Yield of $^2H(e,e'n)$ events



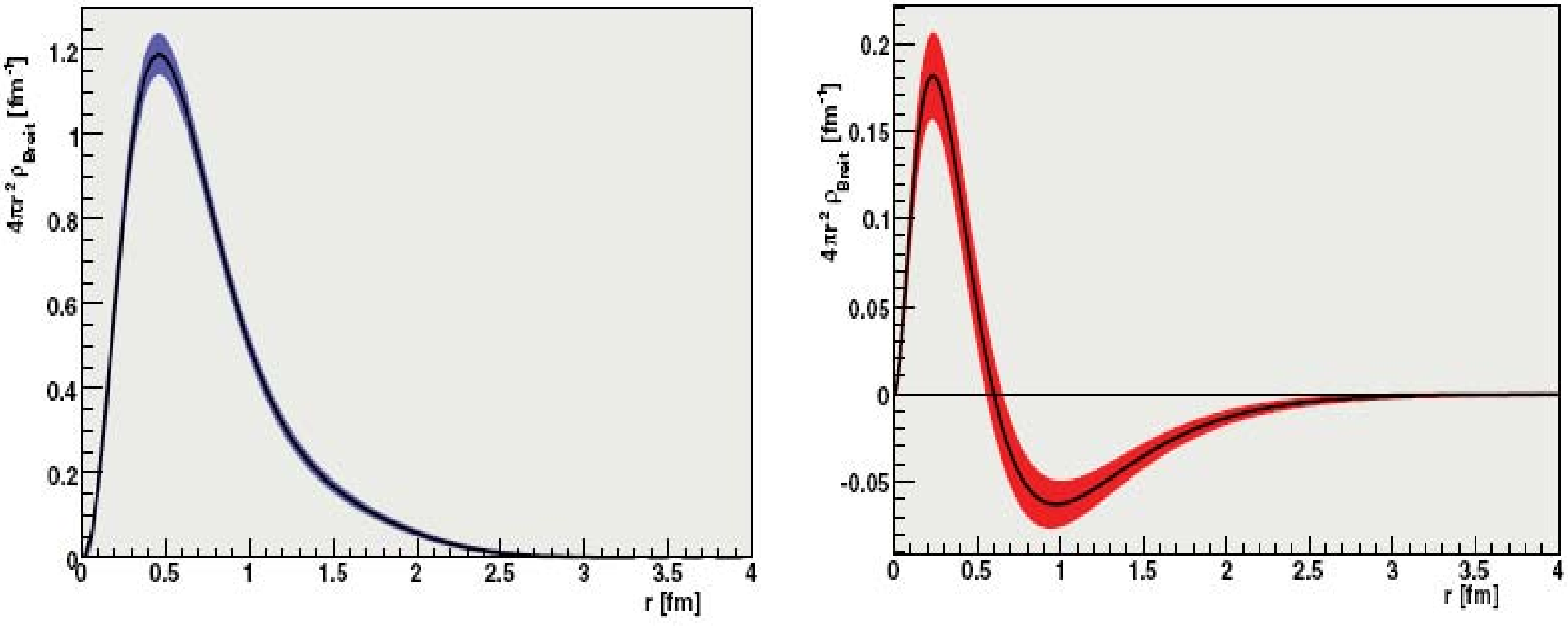
Low Q^2 Test of Arenhövel Model



World's G^n_E data from spin measurements



Spatial Distribution



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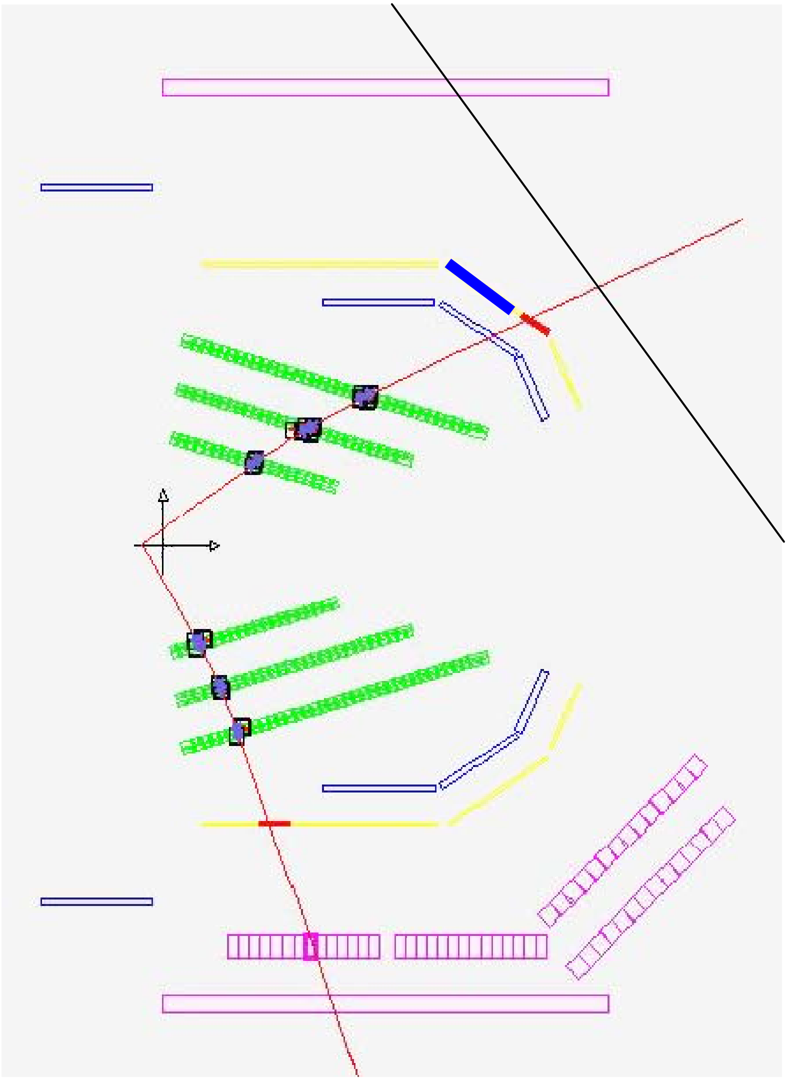
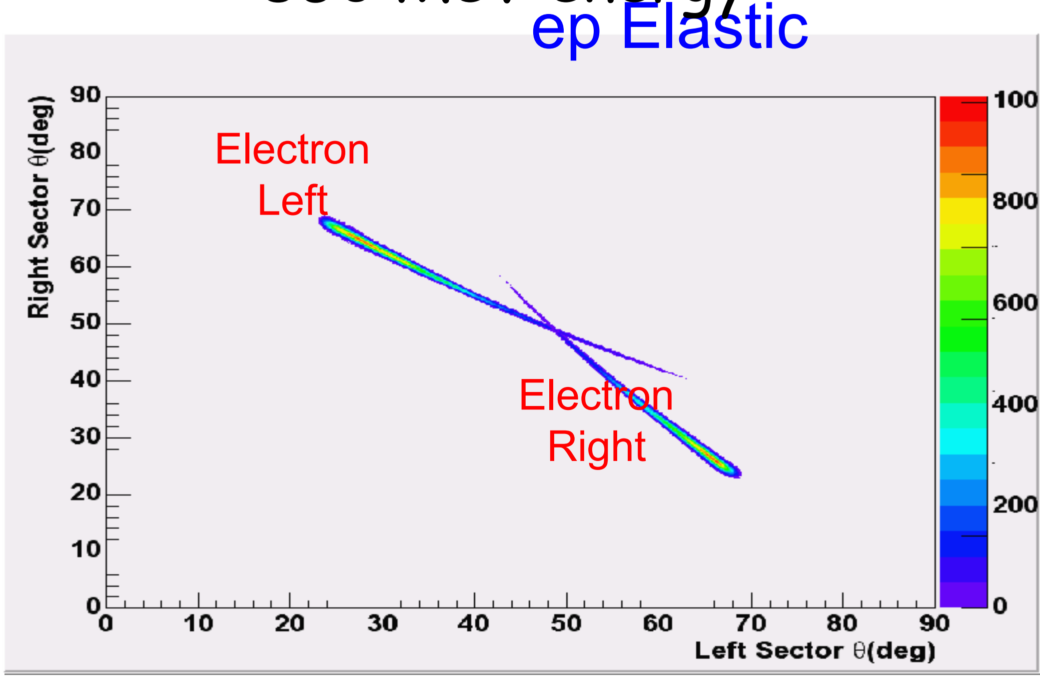
a long range plan for U.S. nuclear science

BLAST event reconstruction

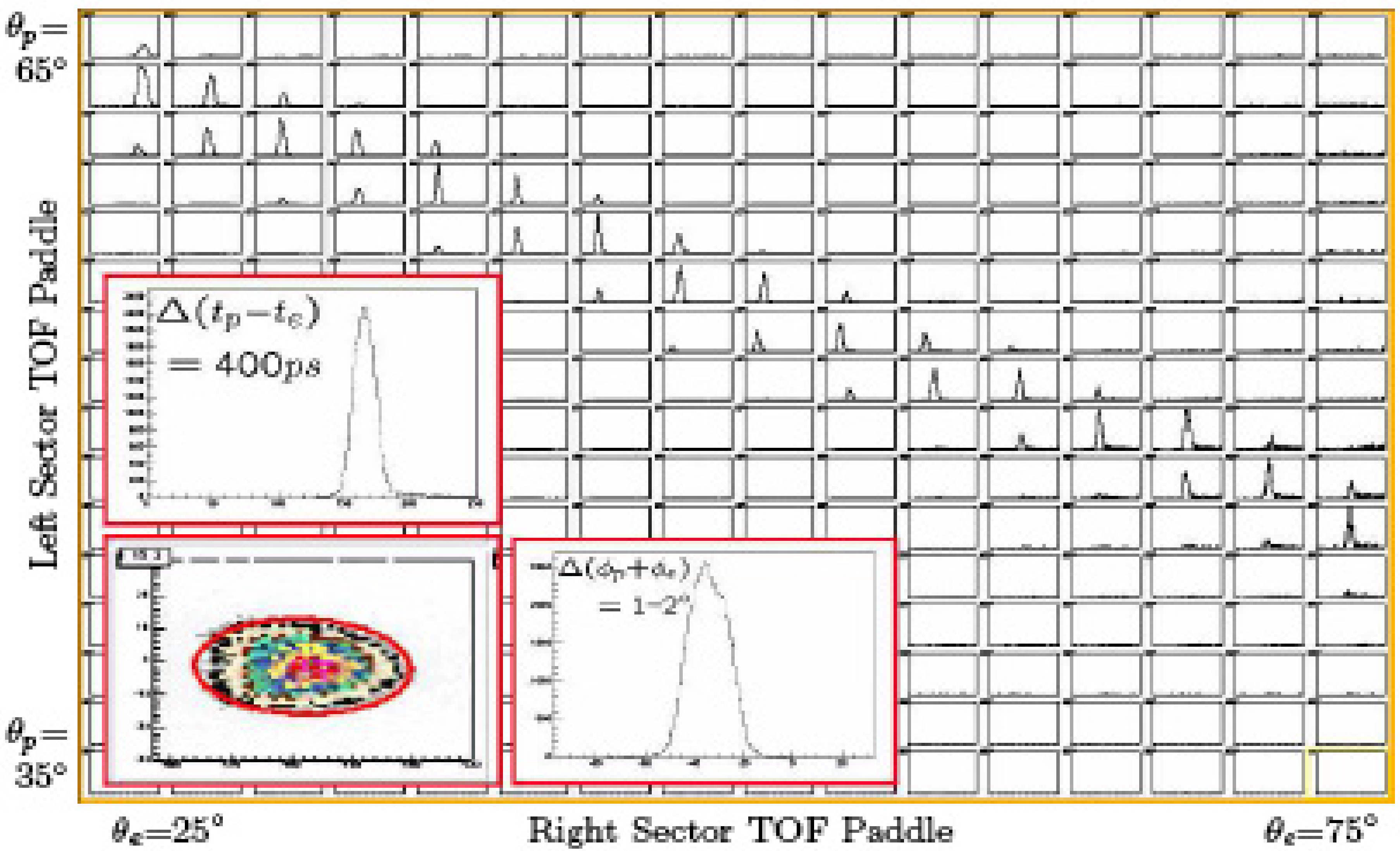


850 MeV energy

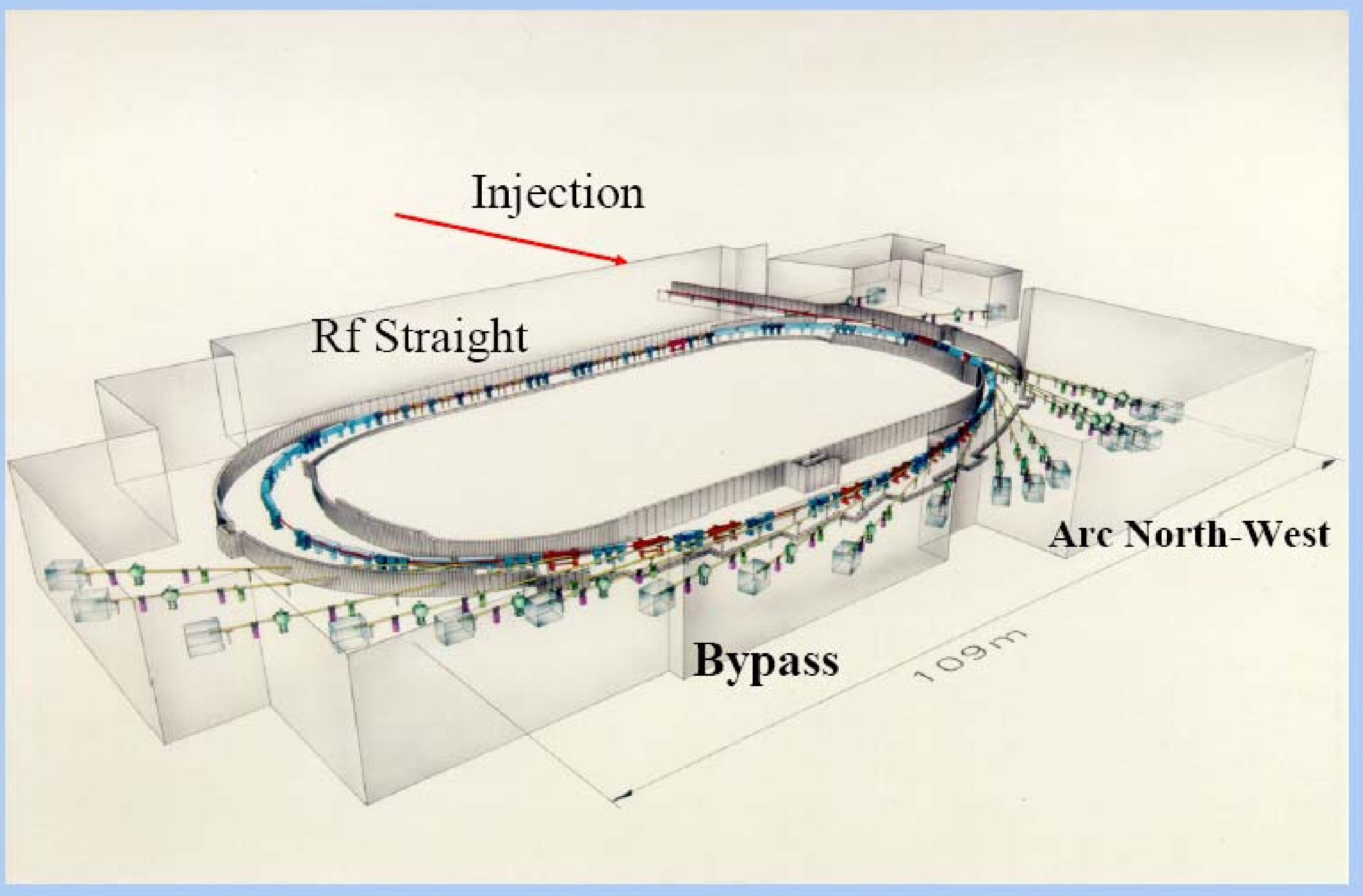


- Advantages of magnetic field:
  - suppression of background
  - 2-3% momentum resolution
- $\sigma_\theta = 0.5^o$ and $\sigma_\varphi = 0.5^o$

Elastic ep timing with BLAST



DORIS

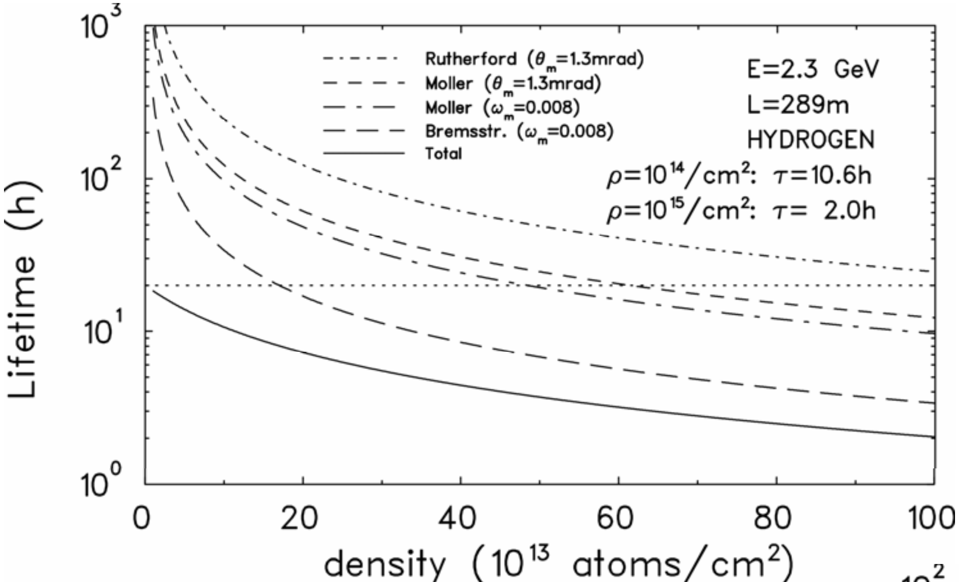


DORIS parameters

Positron energy:	4.45 GeV
RF frequency	500 MHz
Initial positron beam current (5 bunches):	120 mA
Circumference:	289.2 m
Number of buckets:	482
Number of bunches:	1 (for tests), 2 and 5
Bunch separation (minimum):	964 nsec (for tests), 480 nsec and 192 nsec
Horizontal positron beam emittance:	404 π nmrad
Coupling factor:	3%
Vertical positron beam emittance:	12 π nmrad
Positron beam energy spread (rms):	0.11%
Curvature radius of bending magnets:	12.1849 m
Magnetic field of bending magnets:	1.2182 T
Critical photon energy from bending magnets:	16.04 keV

Lifetime in DORIS vs. target thickness

C. Tschalär MIT

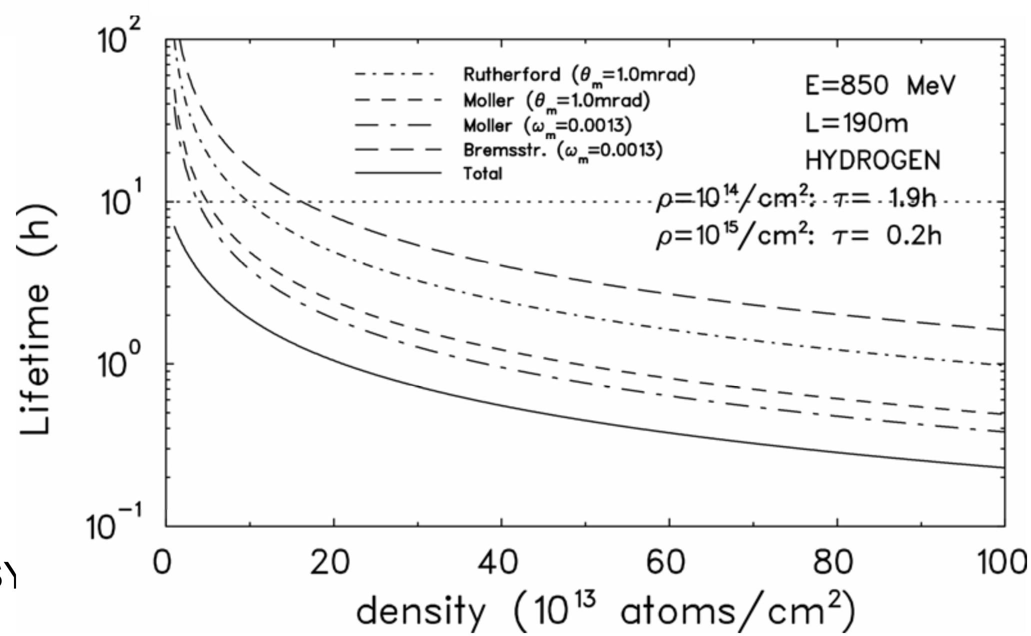


DORIS

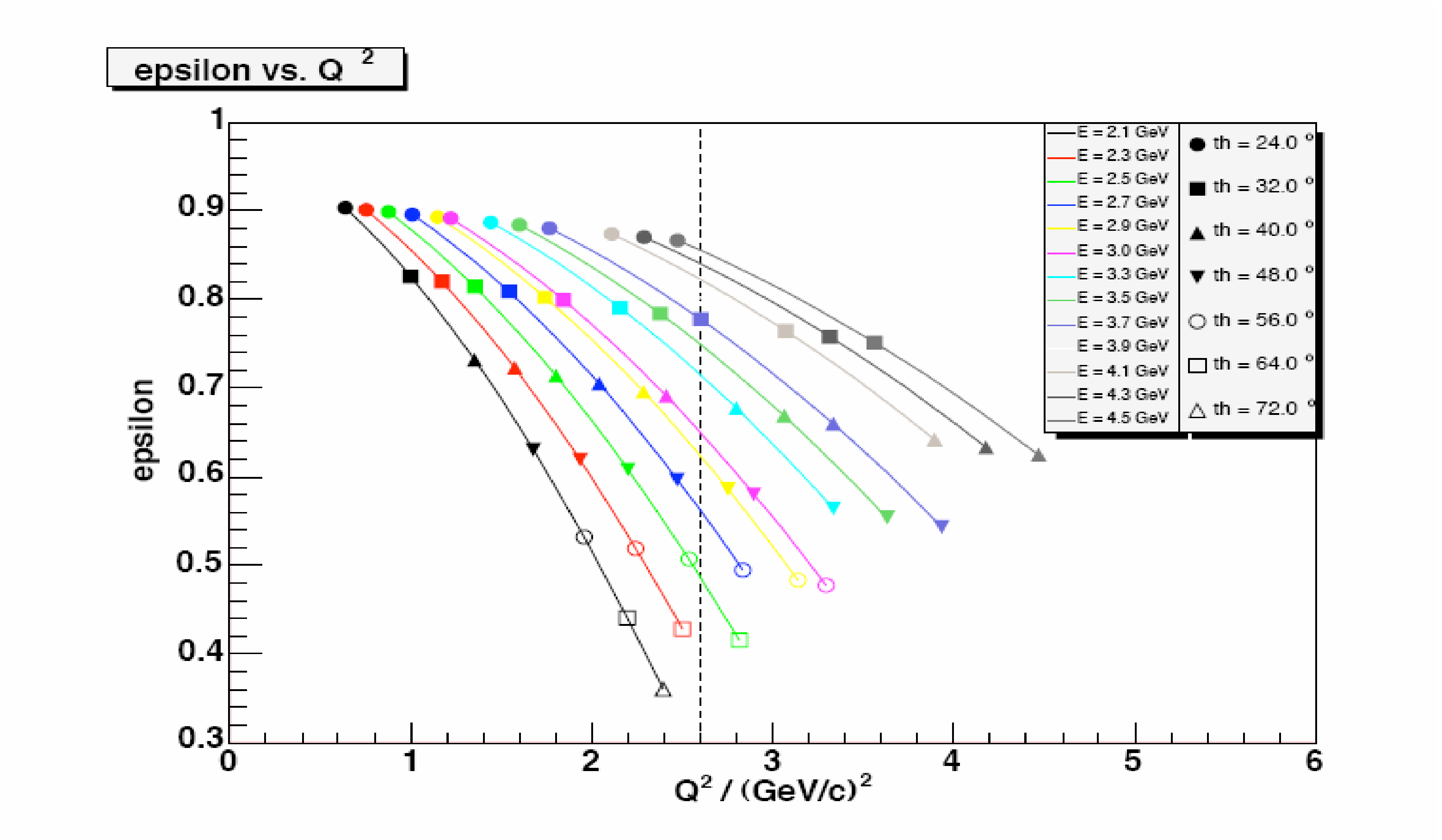
θ_m = 1.3 mrad
ω_m = 0.8%

MIT SHR

θ_m = 1.0 mrad
ω_m = 0.13%



Acceptance with BLAST

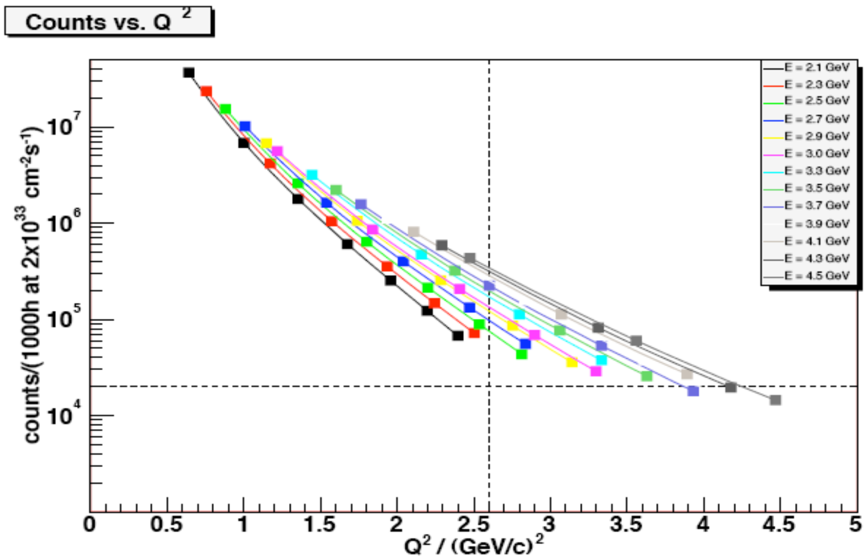


- **Lowest epsilon ~0.4 only for E < 2.3 GeV**
- **At epsilon = 0.4, require E>2 GeV to maintain Q^2 > 2 $(GeV/c)^2$**

Count rate estimate

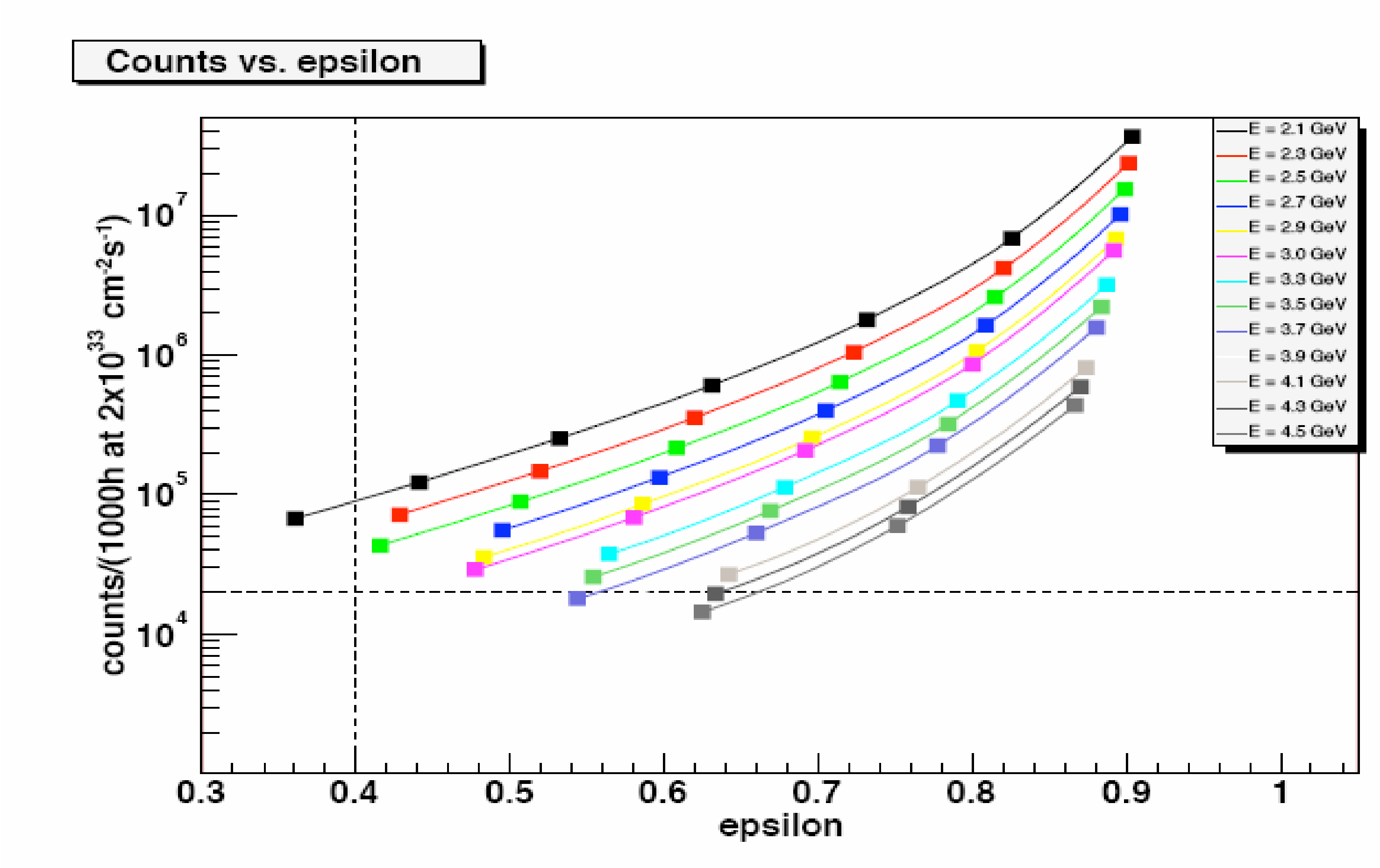
E_0 [GeV]	Q^2 [(GeV/c)^2]	θ_e	$p_{e'}$ [GeV/c]	ϵ	θ_p	p_p [GeV/c]
4.5	2.6	24.9°	3.114	0.86	38.0°	2.125
3.0	2.6	43.0°	1.614	0.65	31.2°	2.125
2.3	2.6	67.6°	0.914	0.39	23.4°	2.125

Table 2: Kinematics for three beam energies and $Q^2 = 2.6$ (GeV/c)^2.



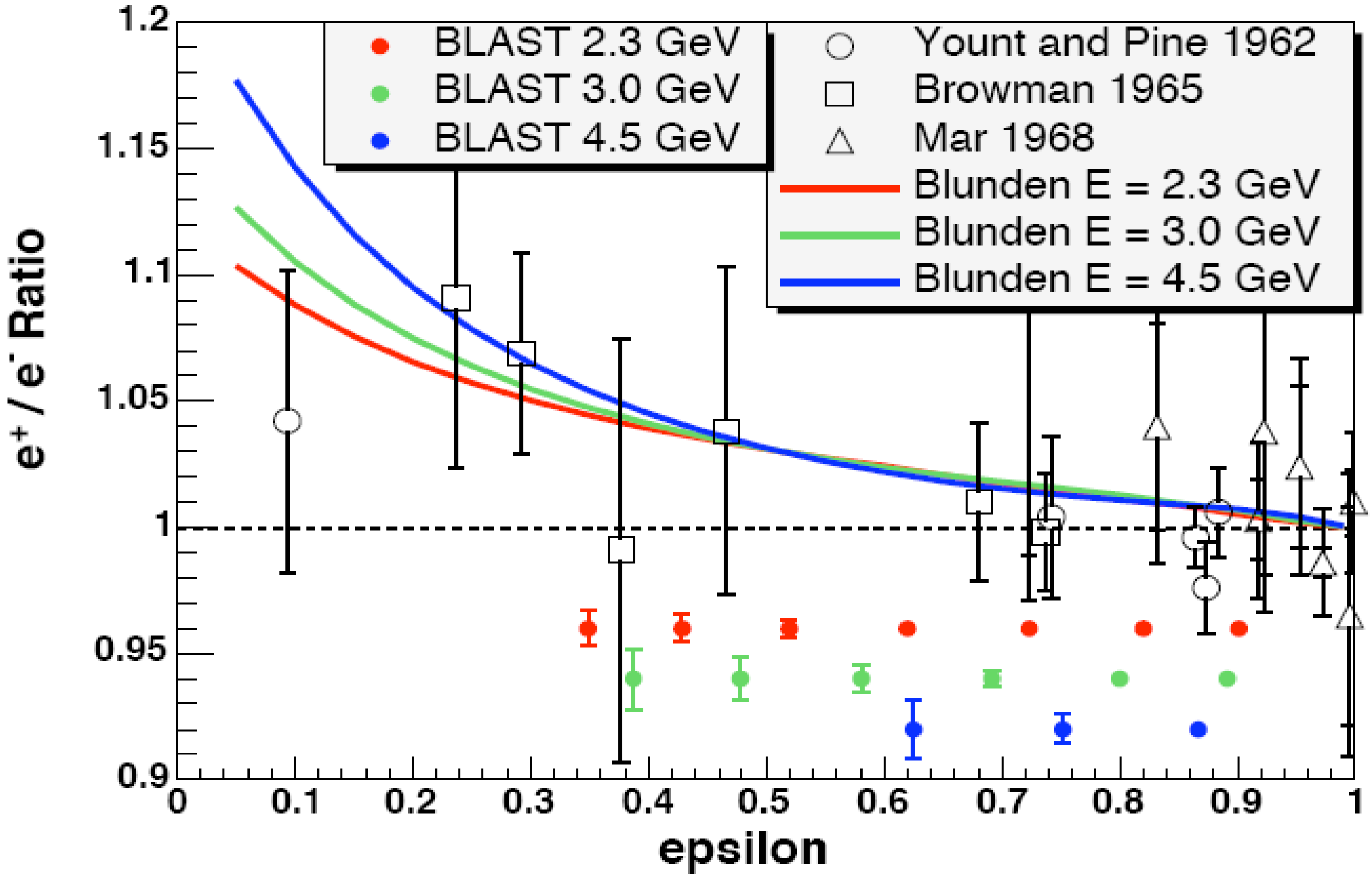
- **Sufficient counts at all angles only for E<2.3 GeV**
- **At Q^2 = 2.6 (GeV/c)^2 beam energies 2.3-4.5 GeV for Rosenbluth sepn.**

Count rate estimate



- ***Sufficient counts at all angles only for E<2.3 GeV***
- **Epsilon = 0.4 achievable**

Projected results for DORIS experiment

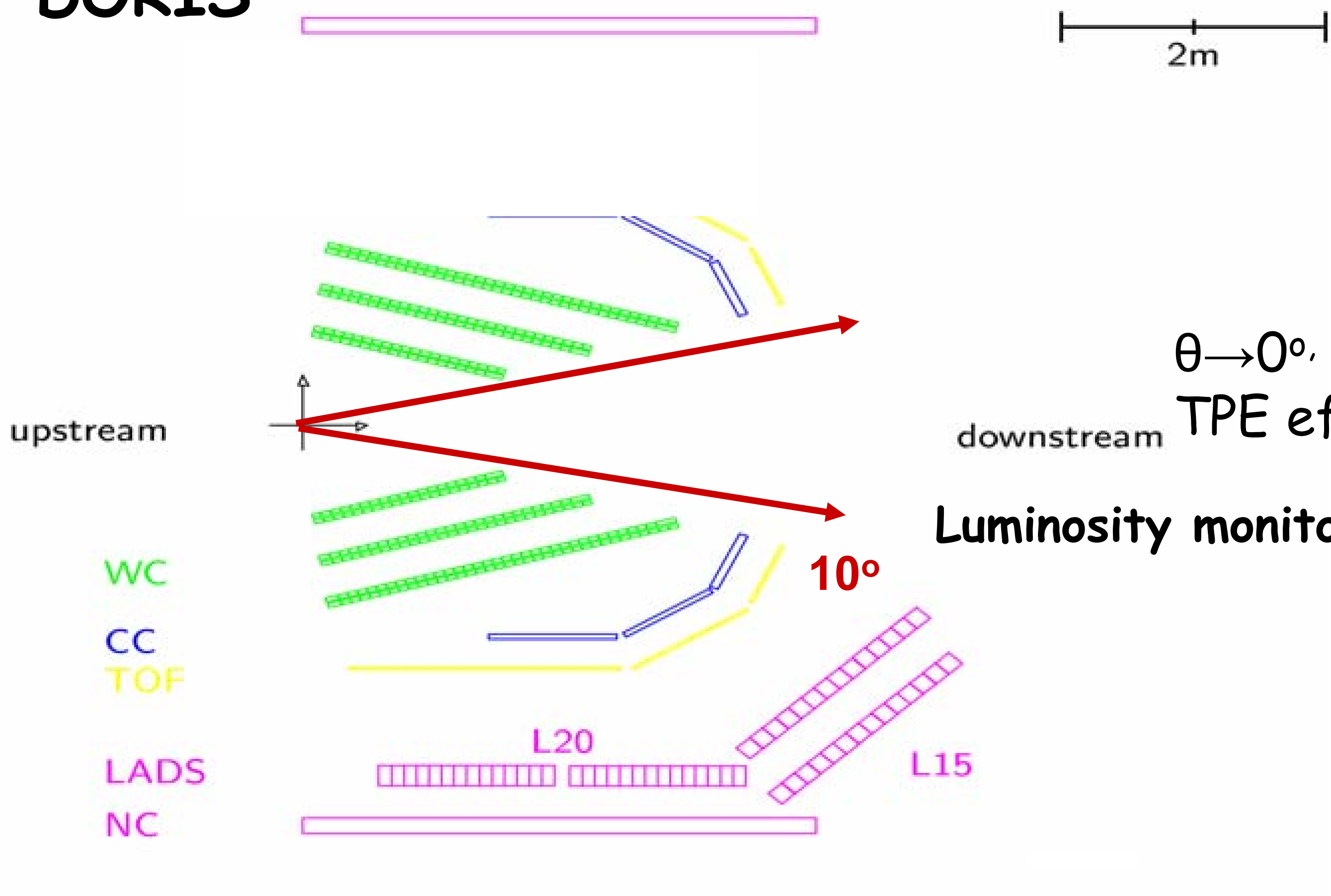


1000 hours each for e+ and e-

Lumi = 6 x 10^{32} cm^{-2} s^{-1}

Control of systematics

BLAST @ DORIS



$\theta \rightarrow 0^{o}, \varepsilon \rightarrow 1$

TPE effects → 0

Luminosity monitors

- Change BLAST polarity once a day
- Change between electrons and positrons regularly
- Left-right symmetry

Control of systematics

$$N_{ij} = L_{ij}\sigma_i \kappa^p_{ij}\kappa^l_{ij}$$

i = e+ or e-
j= pos/neg polarity of BLAST field

Geometric proton **efficiency:** $\kappa^p_{\mathrm{e}+j} = \kappa^p_{\mathrm{e}-j}$

$$\frac{N_{\mathrm{e}+j}/L_{\mathrm{e}+j}}{N_{\mathrm{e}-j}/L_{\mathrm{e}-j}} = \frac{\sigma_{\mathrm{e}+}}{\sigma_{\mathrm{e}-}} \cdot \frac{\kappa^l_{\mathrm{e}+j}}{\kappa^l_{\mathrm{e}-j}}$$

Ratio in single polarity j

Geometric lepton **efficiency:** $\kappa^l_{\mathrm{e}++} = \kappa^l_{\mathrm{e}--}$ and $\kappa^l_{\mathrm{e}+-} = \kappa^l_{\mathrm{e}-+}$

Control of systematics

Super ratio:

$$\left[\frac{N_{e^+ +}/L_{e^+ +}}{N_{e^- +}/L_{e^- +}} \cdot \frac{N_{e^+ -}/L_{e^+ -}}{N_{e^- -}/L_{e^- -}}\right]^{\frac{1}{2}} = \frac{\sigma_{e^+}}{\sigma_{e^-}}$$

Cycle of four states ij
Repeat cycle many times

- Change between electrons and positrons regularly
- Change BLAST polarity every day
- Left-right symmetry provides additional redundancy – two identical experiments simultaneously taking data

PRC64 (Nov. 2007) Report

- **Internal Target Experiment at DORIS**

  The PRC formed an external referee group to review the proposal of a possible new experiment at DORIS using the available MIT-BLAST detector and an unpolarized hydrogen gas target. The goal of the experiment is to determine the contribution of multiple photon exchange processes and to resolve the existing discrepancy in lepton-nucleon scattering data. Dedicated data taking for one month per year for several years would be sufficient to carry out the experiment. The external referees strongly support the physics case. The PRC thus recommends that the DESY management discuss this new experimental opportunity with the accelerator group.

Other experiments

- **JLab**

Approved experiment to compare e^+p to e^-p elastic scattering using secondary beams and the CEBAF Large Acceptance Spectrometer. Challenging systematics.

- **Novosibirsk**

Similar experiment to DESY experiment has been considered. Positron currents are about an order of magnitude lower. No momentum measurement.

- **Parity violating electron scattering**

Experiments at JLab and Mainz which measure transverse spin asymmetries are sensitive to two photon effects but not directly to the contribution which enters in G_E^p/G_M^p.

Summary

- The measurement of the elastic form-factors of the proton is in question. The determination of the contribution of multiple photon exchange processes is essential to resolving the discrepancy, which may have relevance for other areas of hadron structure.
- A precision comparison (~ 1%) of elastic electron-proton and positron-proton elastic scattering at 2.3 to 4.5 GeV at large angles (~ 60^0) will be definitive to resolving this discrepancy. This definitive experiment can be carried out at DESY/DORIS using the available MIT-BLAST detector and an unpolarized hydrogen gas target.
- The physics case for the proposed experiment has been favorably reviewed by the DESY PRC. The next step is to submit a full proposal.