Electron Scattering from an almost Free Neutron

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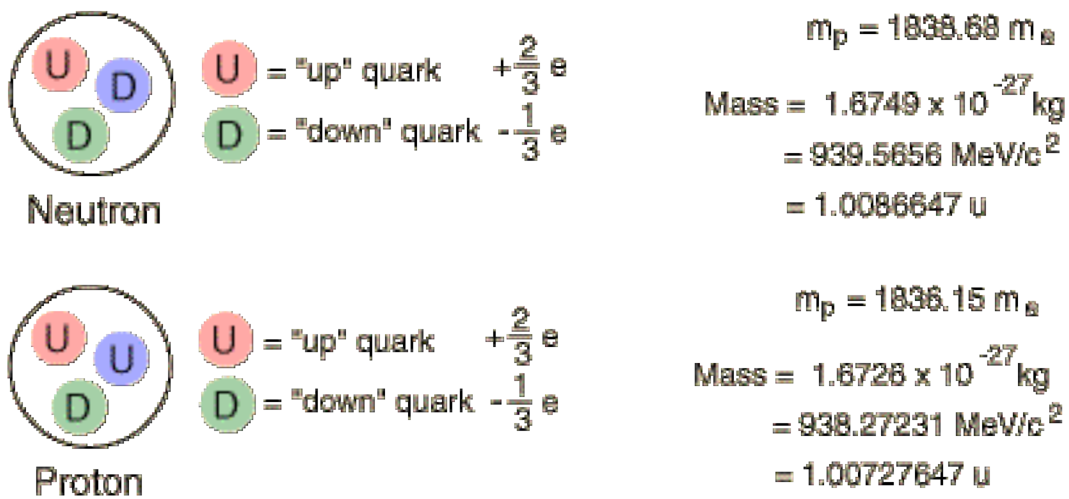
Undergrad Seminar Phys309

28 February 2006

The Nucleon

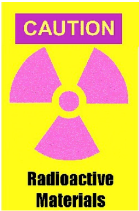
- The neutron and proton are two charge states of the 'same' particle: the nucleon.
- The nucleon also contains gluons, the messenger particles for the strong force, and quark-antiquark pairs, u, ubar, d, dbar, s, sbar.



Structure Functions

- Jefferson Lab is a large electron microscope
- Proton radius is about 1 fm
- Resolution is about 0.1 fm
- We scatter from quarks inside the nucleon
- $F_2(x) = \sum_i e_i^2 \, x f_i(x)$ is the scattering probability
- Here x is the fraction of the proton momentum carried by the struck quark, e is the quark charge, and f is the probability distribution for observing a quark with momentum fraction x.

Neutron Data Are Important…
…but hard to get

- Free neutrons decay in 15 minutes.
- Radioactivity! 

- Zero charge makes it difficult to create a dense target
  Magnetic bottle: 10^3 - 10^4 n/cm^2 [TU München]
  Typical proton target: $4{\cdot}10^{23}$ p/cm^2 [10 cm LH]

  => Alternative Solution: Deuterons and Helium-3.
  BUT: potentially large (and not completely known) nuclear corrections: Kinematic smearing, Binding and off-shell effects, "EMC-effect", final state interactions, coherent processes, non-nucleonic components of the wave function…

What can we do?

To learn more about the structure of the neutron, we can try two approaches:

- Study modifications of the neutron structure for bound neutrons in detail, to single out the best theoretical description of binding effects.
- Use the best possible approximation for a free neutron target: a neutron that is "barely" off-shell.

In both cases: Lepton scattering off the deuteron with simultaneous detection of a "backwards going" proton:

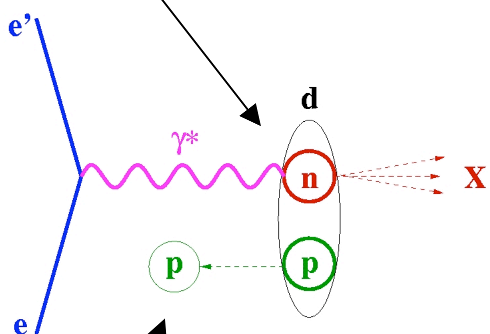
$D(e,e'p_s)X$

Relativity

- $E^2 = p^2 + m^2$ (speed of light c=1)
- E is the total energy, p is the momentum, and m is the mass (energy in rest frame) of a particle.
- $Q^2 = p^2 - E^2$ for virtual photon exchanged
- $W^2 = E^2 - p^2$ for the struck nucleon (after absorbing the virtual photon.

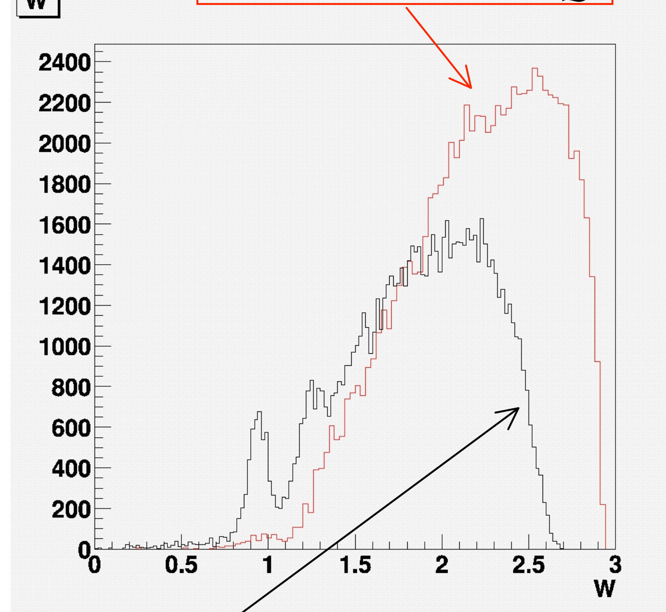
"Spectator Tagging"

$$p_n = (M_D - E_S, -\vec{p}_S); \quad \alpha_n = 2 - \alpha_S$$



$$p_S = (E_S, \vec{p}_S); \quad \alpha_S = \frac{E_S - \vec{p}_S \cdot \hat{q}}{M_D / 2}$$

$$W^2 = M^2 + 2M\nu - Q^2$$



$$W^2 = (p_n + q)^2 = p_n^{\mu} p_{n\mu} + 2((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}) - Q^2$$

$$\approx M^{*2} + 2M\nu(2 - \alpha_S) - Q^2$$

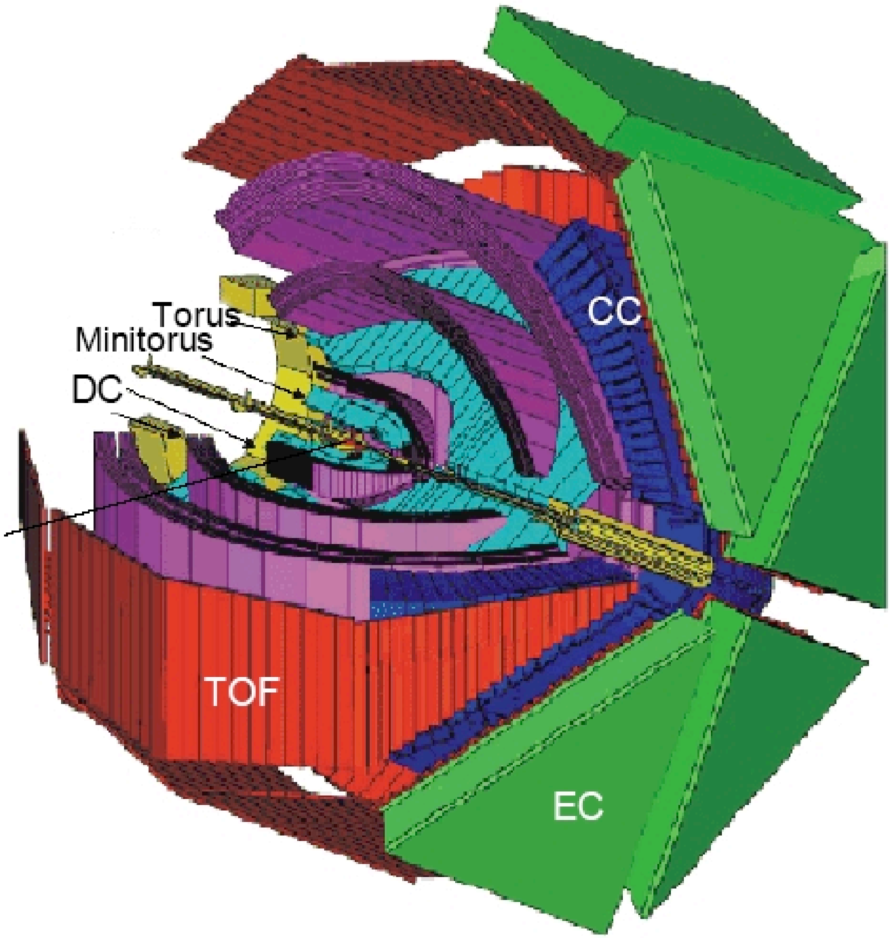
$$x^* = \frac{Q^2}{2 p_n^{\mu} q_{\mu}} \approx \frac{Q^2}{2M\nu(2 - \alpha_S)}$$

Modification of Bound Neutrons - the D(e,e'p_s) Experiment

- Experiment 94-102 at Jefferson Lab
- Run period "E6" in Hall B (CLAS)
- 5.75 GeV / 7 nA Electrons on a 5 cm long LD_2 target => L=10^{34}/cm^2s
- 8 calendar weeks in spring of 2002; 4.5 billion triggers
- CLAS-Collaboration and 2 Ph.D. students:
  Dr. Alexei Klimenko and Dr. Cornel Butuceanu

CEBAF Large Acceptance Spectrometer

Schematic Diagram



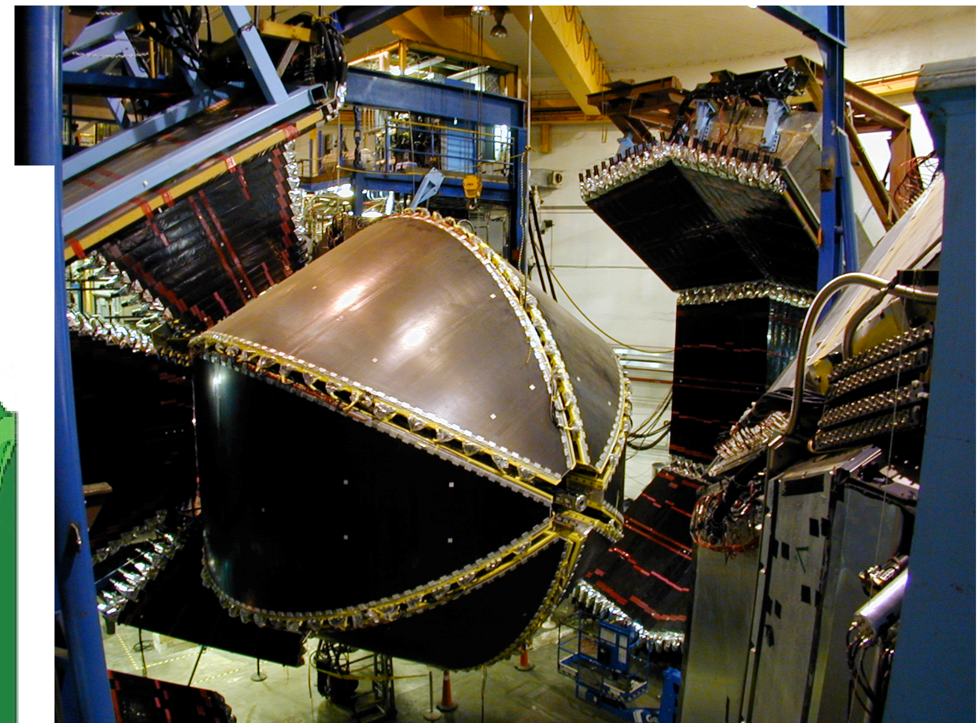
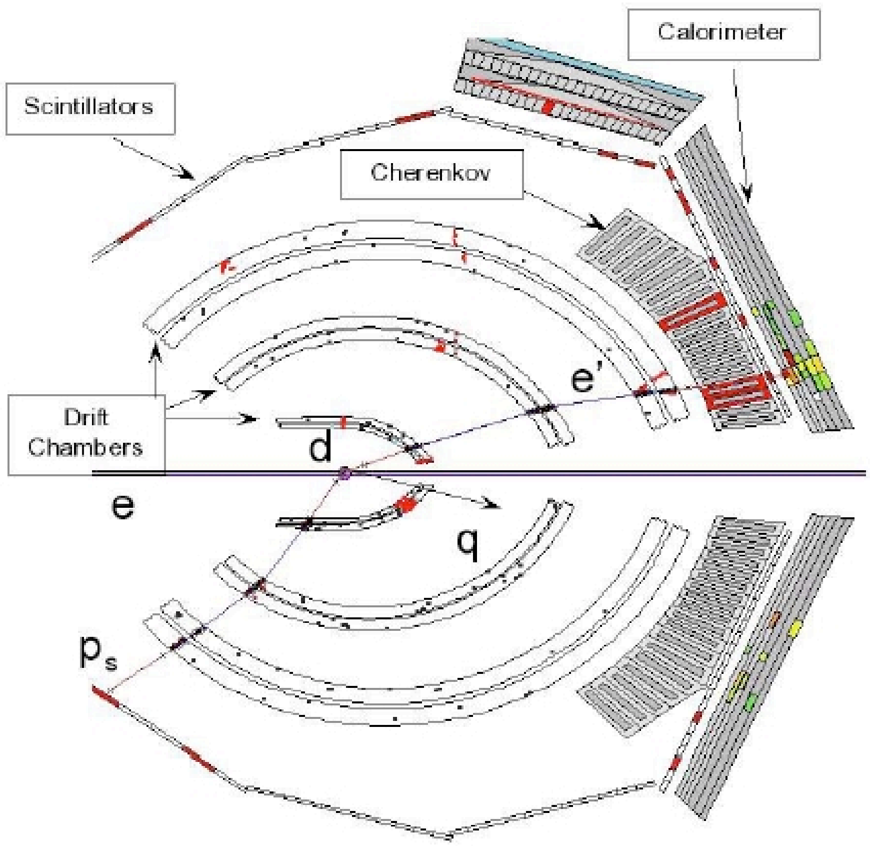
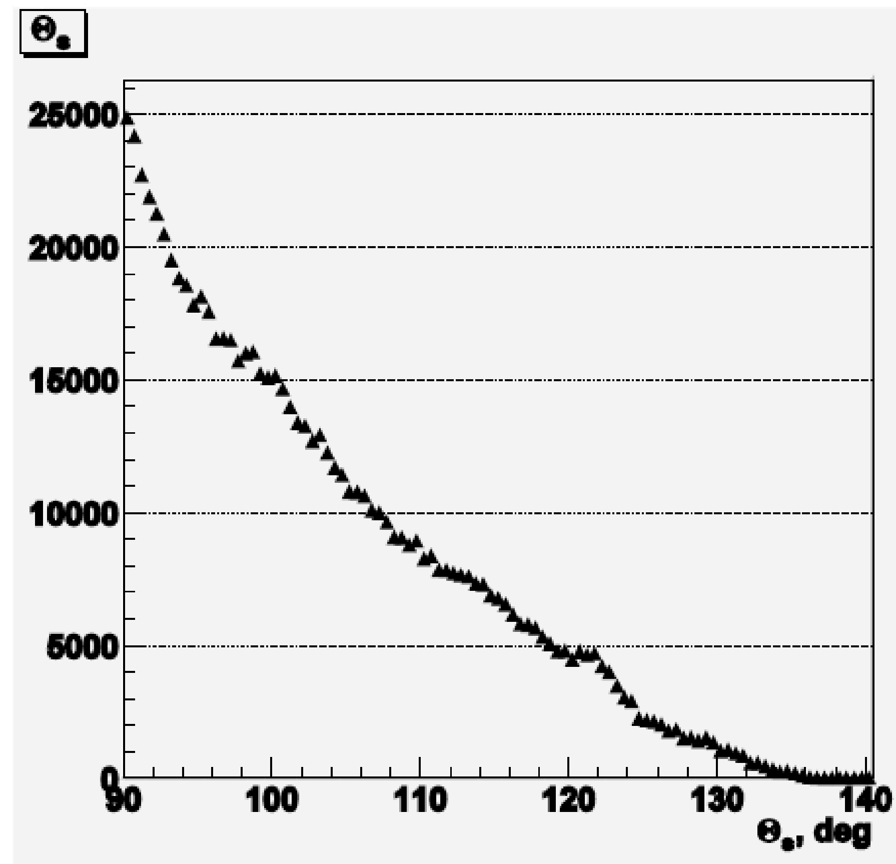


Photo of Hall B - CLAS has been opened up for service work

Experimental Details

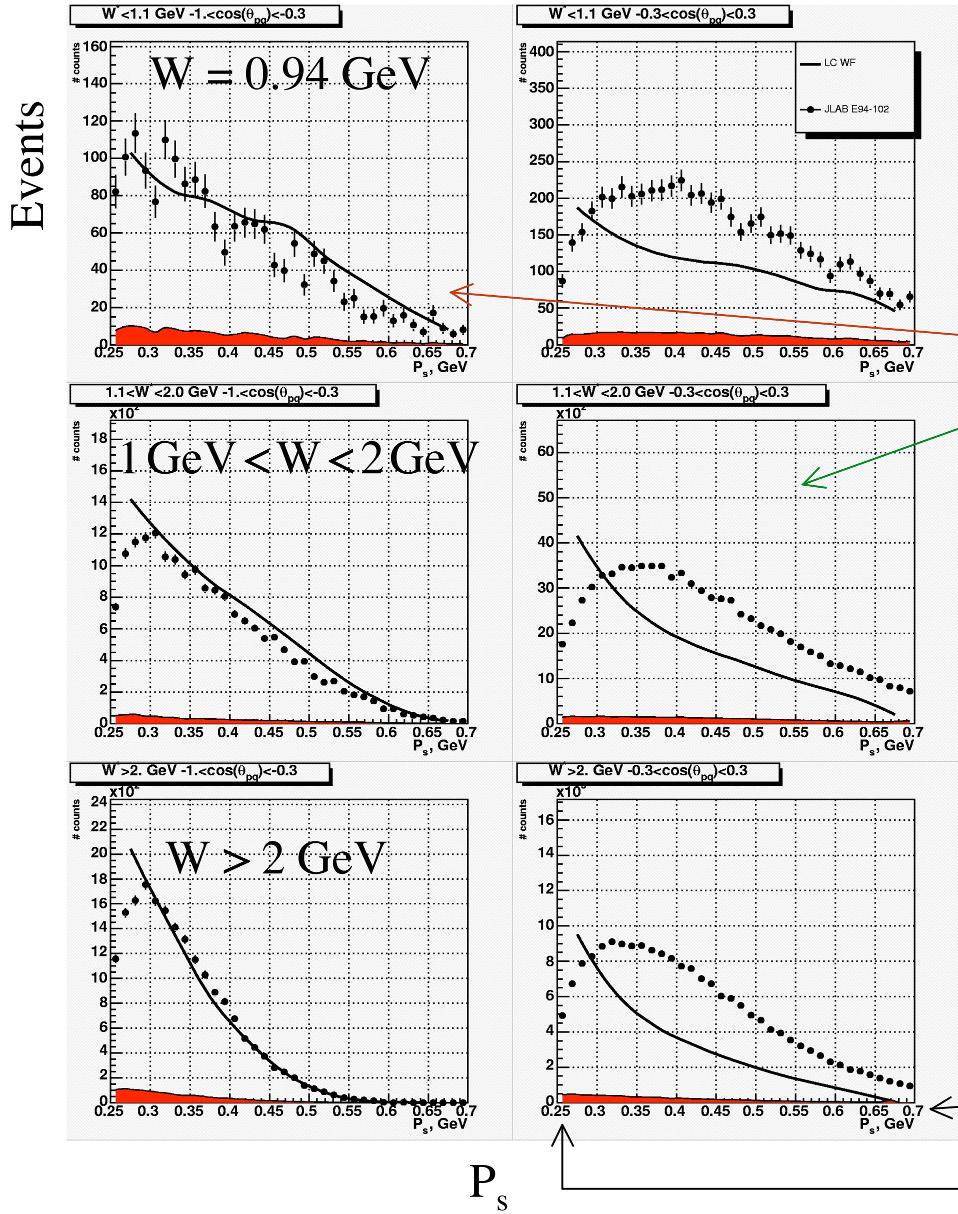


A typical event



Acceptance for protons in the backward hemisphere

Results: Momentum Distribution



Vertical axis: Number of events

Horizontal axis: Proton momenta from 250 to 700 MeV/c

Left: Angular range > 107.5^{O}

Right: Angular range 72.5^{O} - 107.5^{O}

3 different ranges in the final state mass W of the unobserved struck neutrons

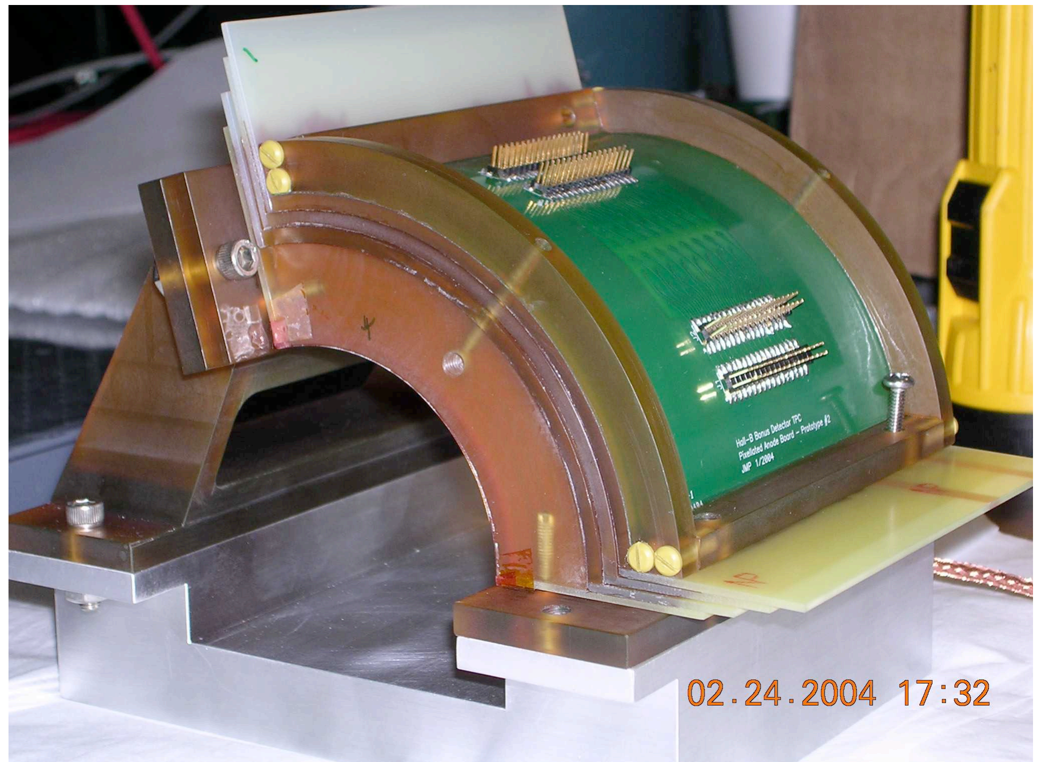
PWIA model with "light cone"-wave function for deuterium

700 MeV/c

250 MeV/c

Inclusive Scattering off a “free” Neutron - the BoNuS* Experiment

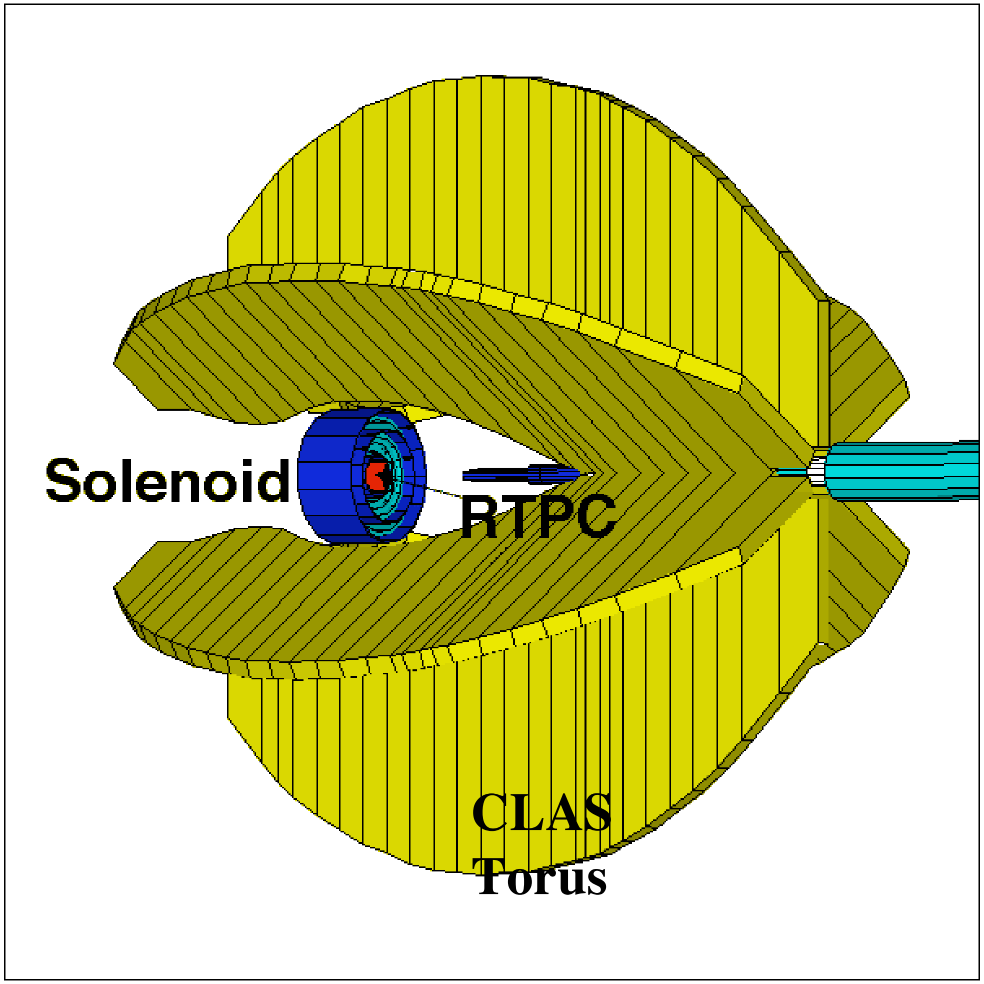
- Experiment 03-012 at Jefferson Lab in Hall B (CLAS)
- 4 and 6 GeV / 200 nA electrons impinging on a 10 cm long D_2 gas target (7 atm) => $L = 0.4 \cdot 10^{34}/\mathrm{cm}^2\mathrm{s}$
- PAC-approved for 2 calendar months of running (2005/6)
- Old Domininon Univ., Jefferson Lab, Hampton Univ., William & Mary, James Madison Univ., and the CLAS collaboration

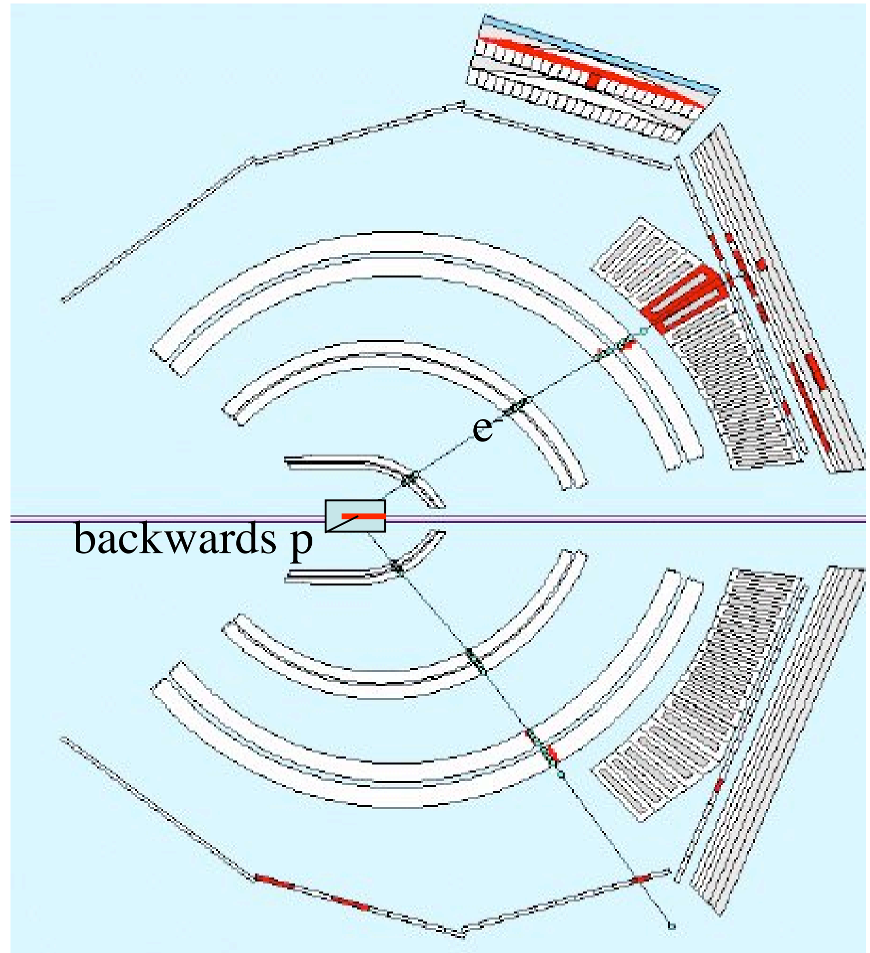


Radial TPC Prototype

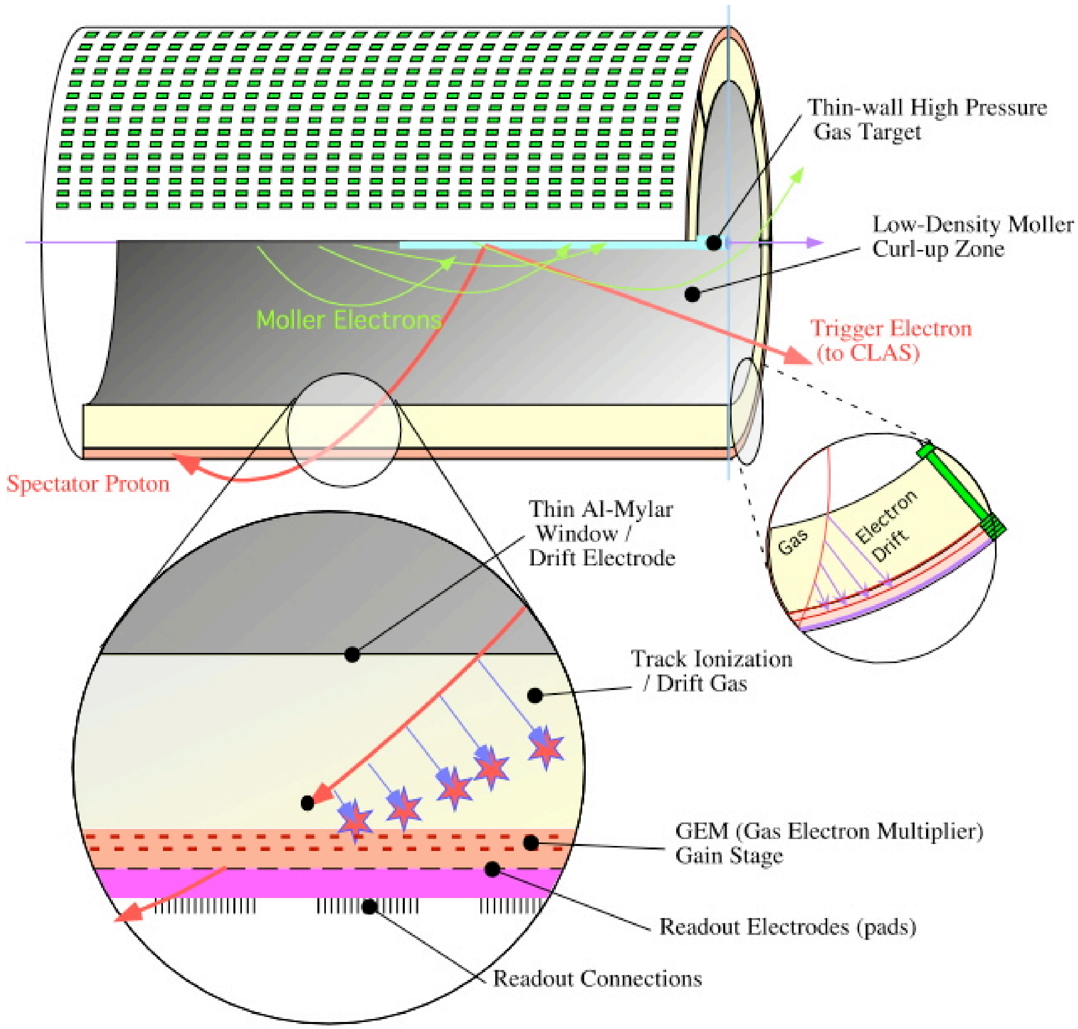
* BoNuS = **B**arely **o**ff-shell **Nu**cleon **S**cattering

BoNuS - Experimental Setup





Target-detector system for slow protons

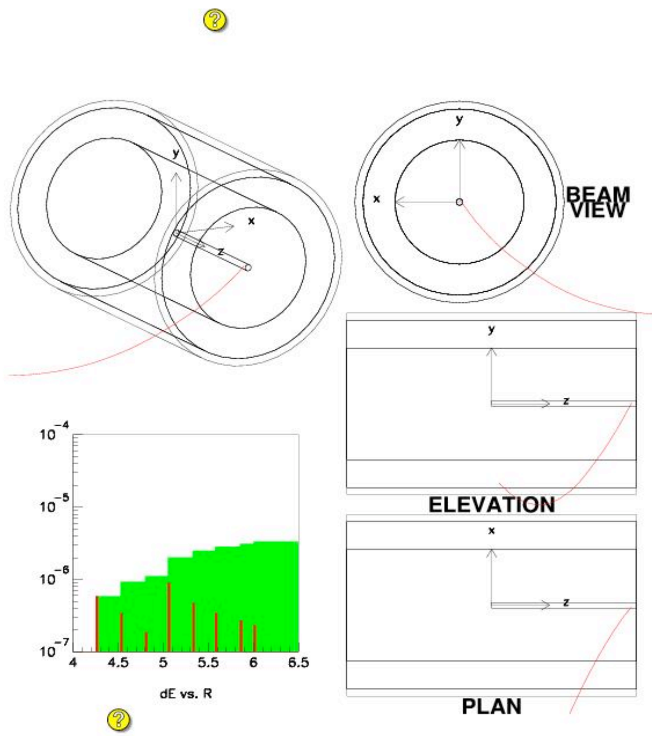


- Thin-walled gas target (7 atm., room temperature)
- **R**adial **T**ime **P**rojection **C**hamber (RTPC) with **G**aseous **E**lectron **M**ultipliers (GEMs)
- 2 Tesla longitudinal magnetic field (to suppress Möller electrons and to measure momentum)
- 3-dimensional readout of position and energy loss (“pads”)

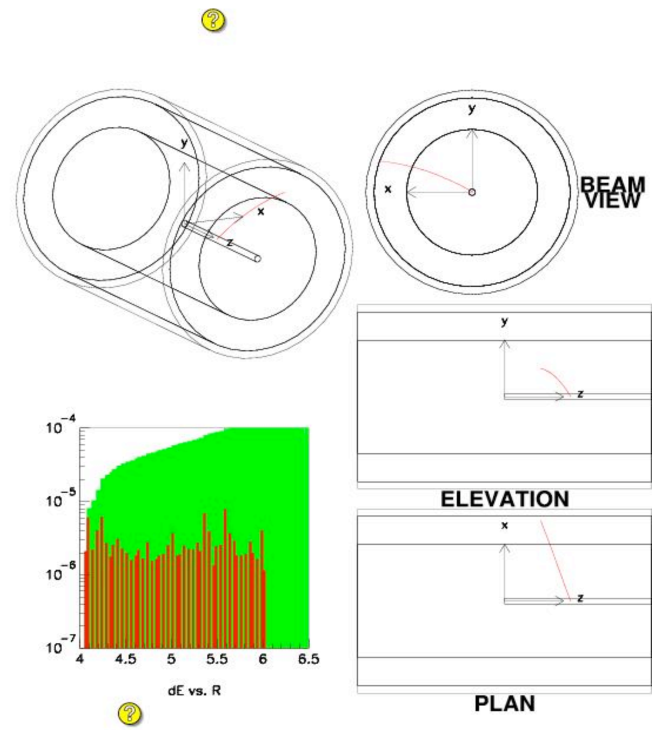
Detector Parameters

- Geometric Acceptance
  - Sensitive over 148 deg. In phi, 20cm in Z.
- Momentum Acceptance
  - Protons from ~70 MeV/c
- Proton Identification *(next slide)*
- Vertex Z resolution <~ 10mm
- Track Momentum Resolution
- Track E information from dE/dx - *studying*
- Rate & Timing Issues

Proton ID by dE/dx & Curvature

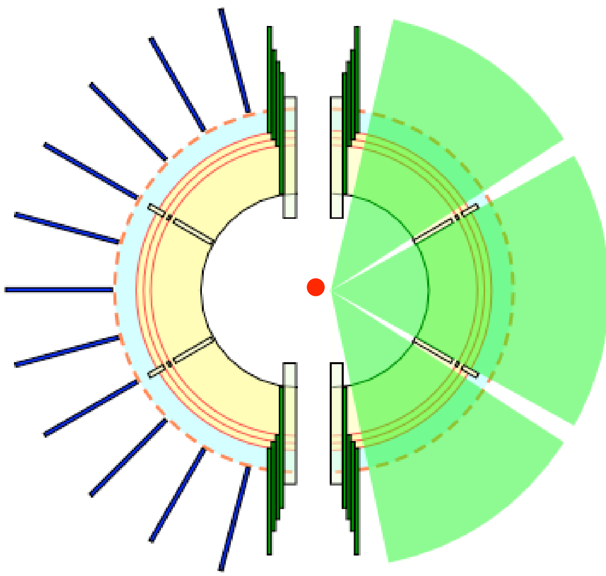


100 MeV/c pion

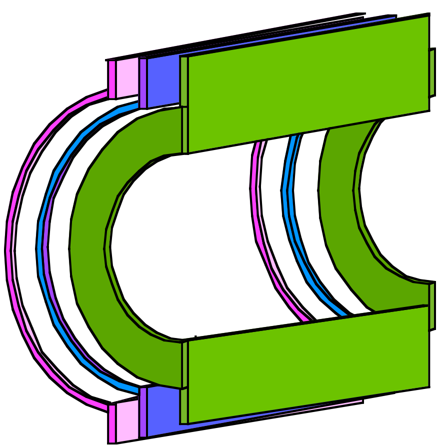


100 MeV/c proton

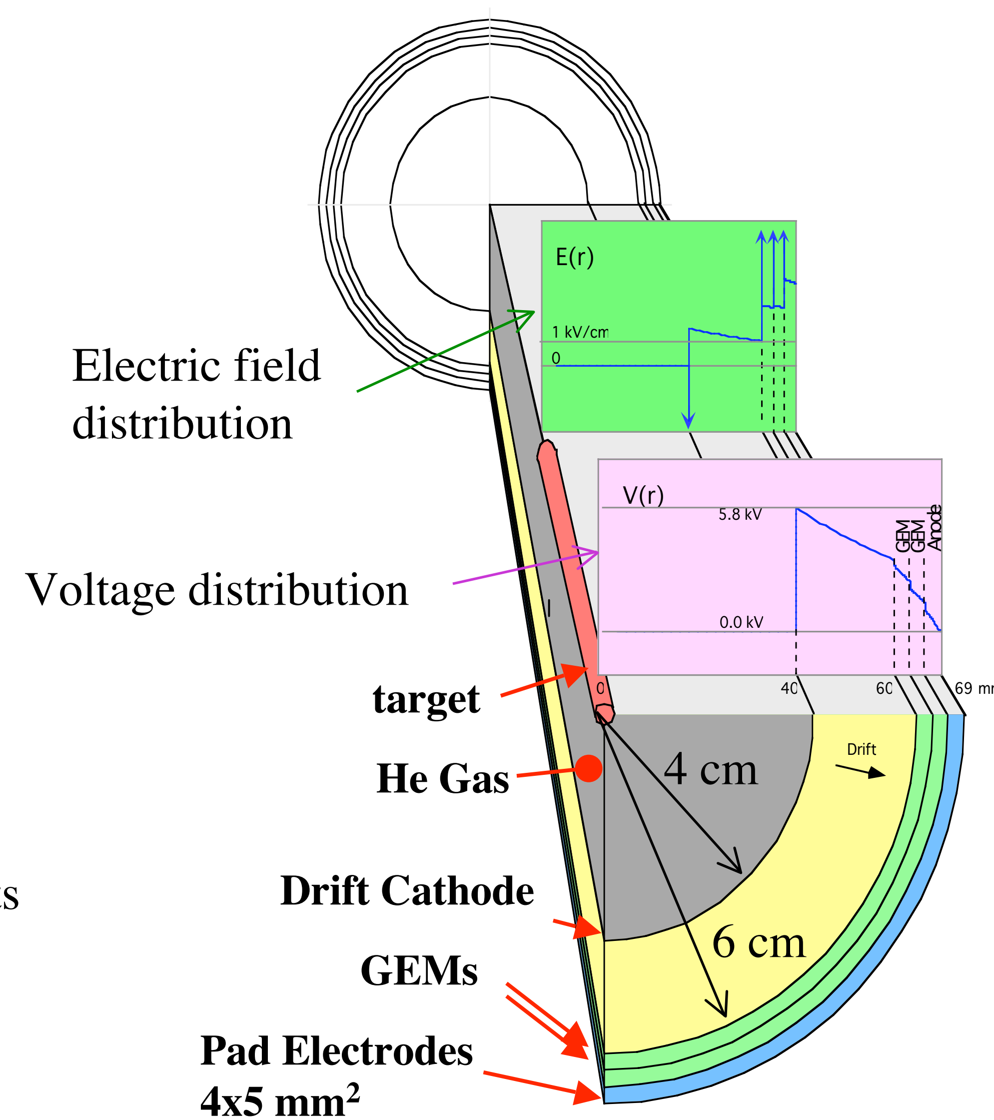
RTPC - Concept



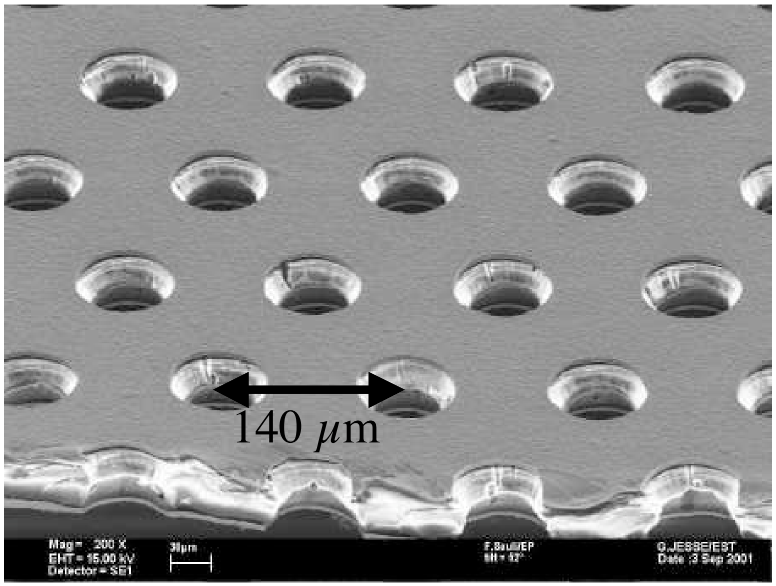
Cross sectional view

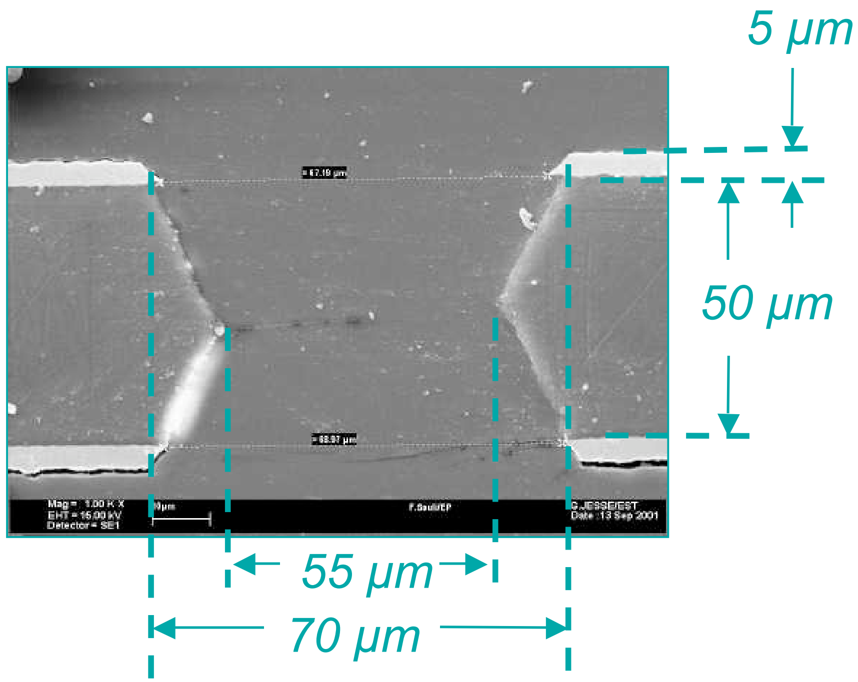


Foil supports

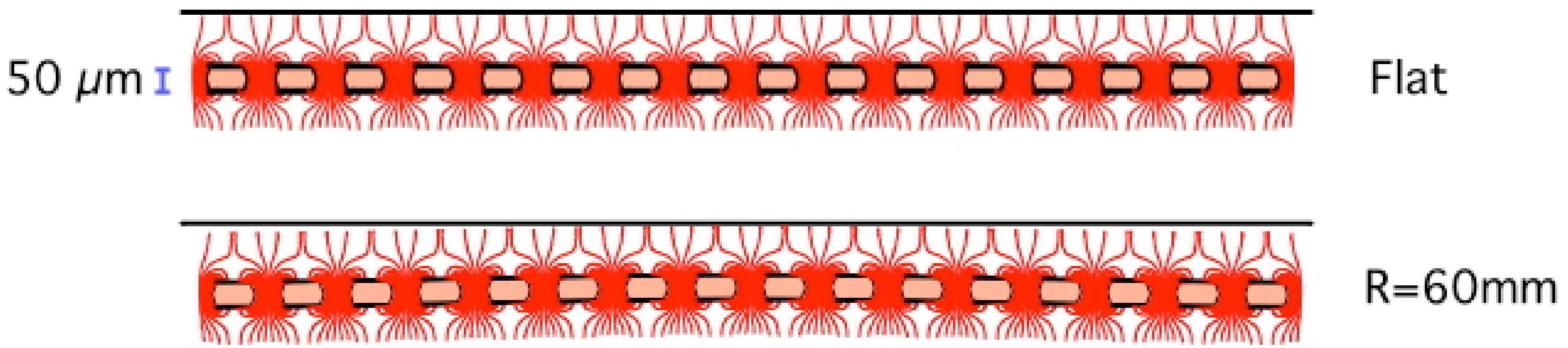


RTPC - GEMs



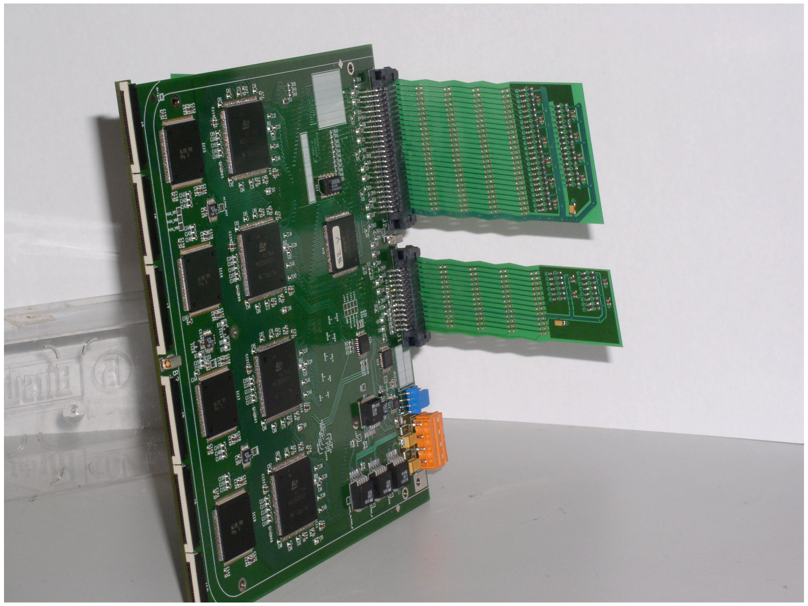


300-500 V, Gain 100-200



RTPC - Data Acquisition

- Alice TPC electronics (CERN) with Altro Chip
- 16 channels, 10 bit ADC with up to 25 MHz data rate
- 3-dimensional track reconstruction (using drift time information and 2 -dimensional location of readout pads)



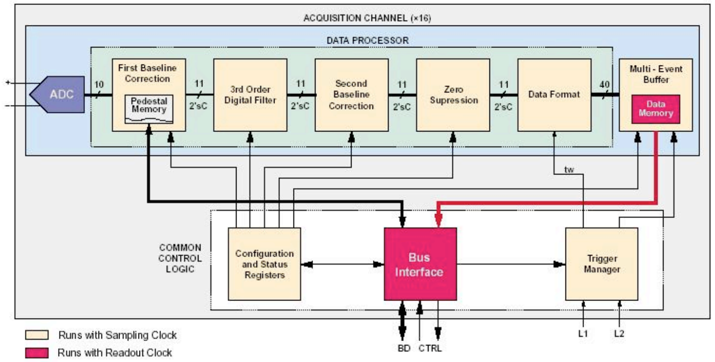
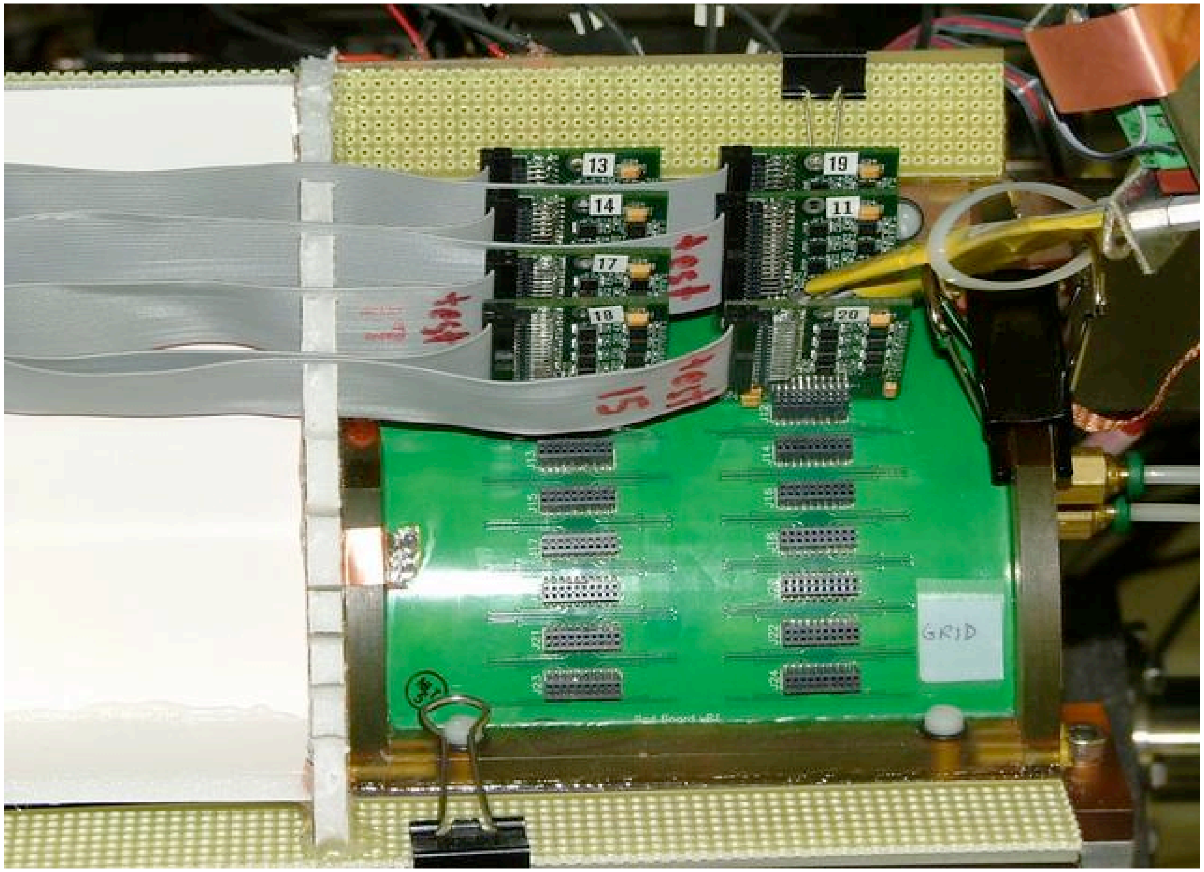


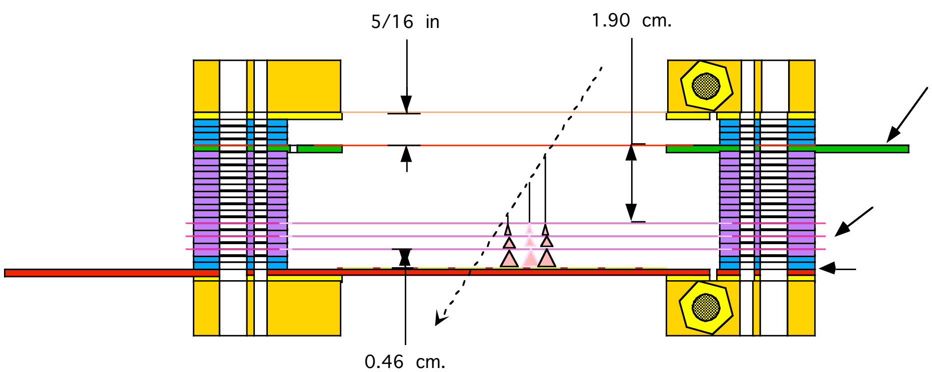
Figure 1.1. ALTRO Processing Chain

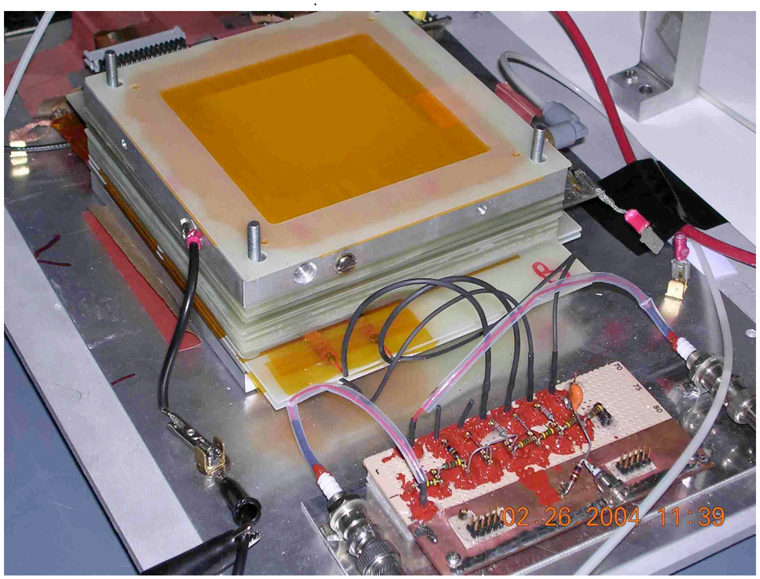
pRTPC w/ Inverter/Driver Cards

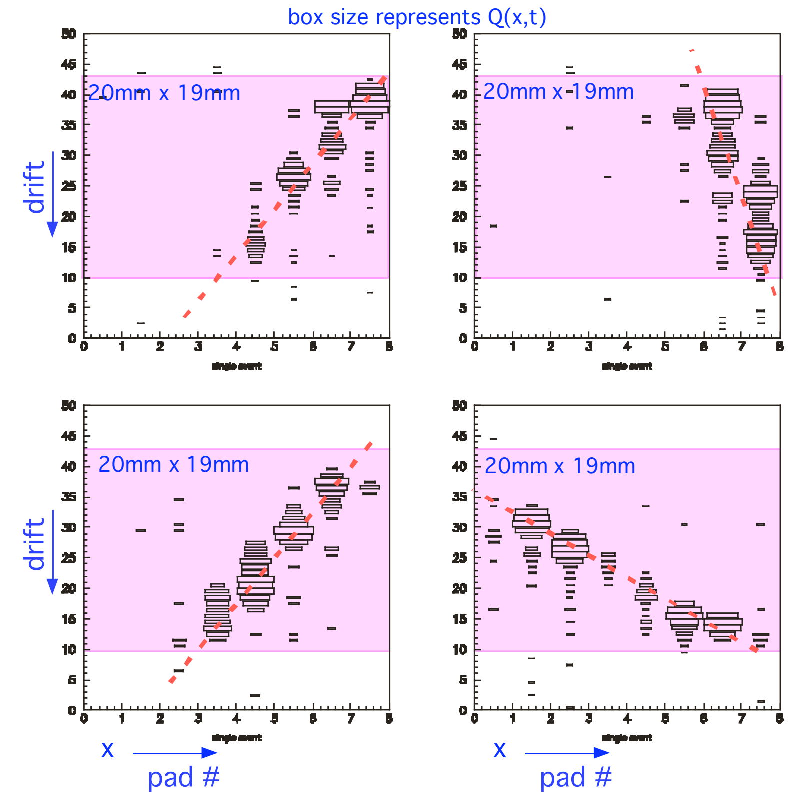
Ribbons To Readout System



RTPC - 1st Prototype

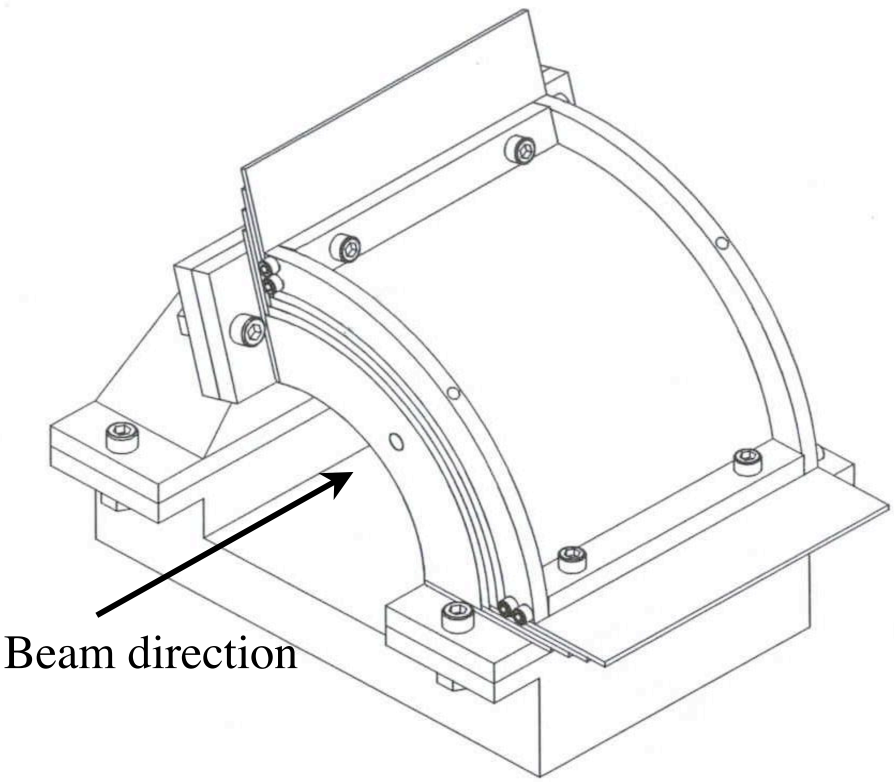


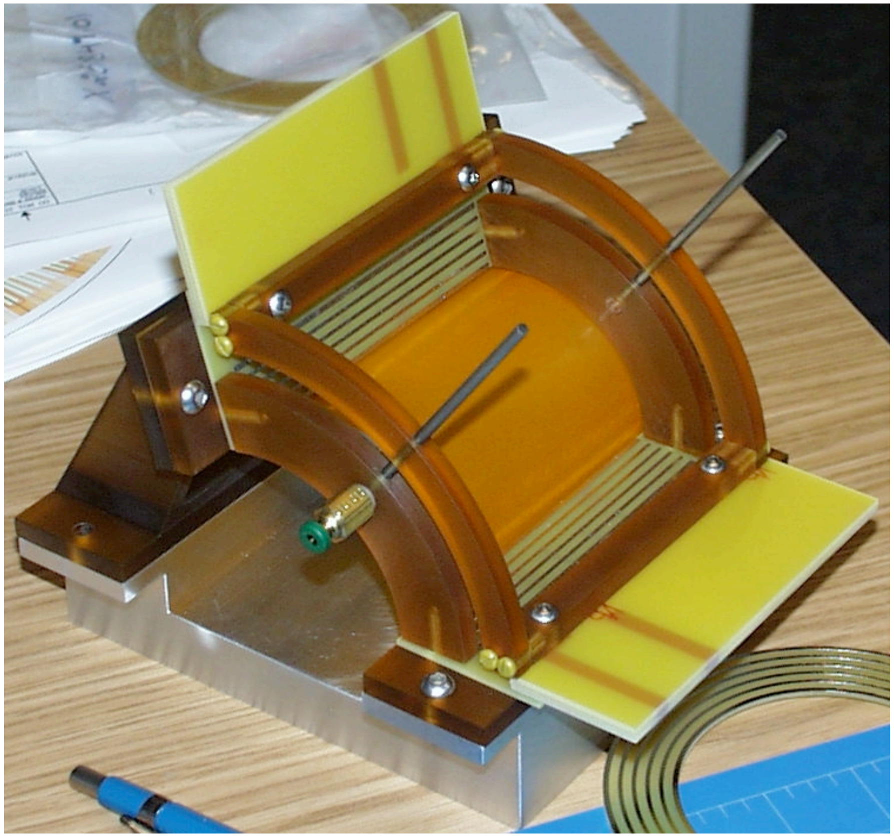




Tracks from a test run at Triangle Universities Nuclear Lab (TUNL) with 100 MeV/c protons

RTPC - 2nd Prototype

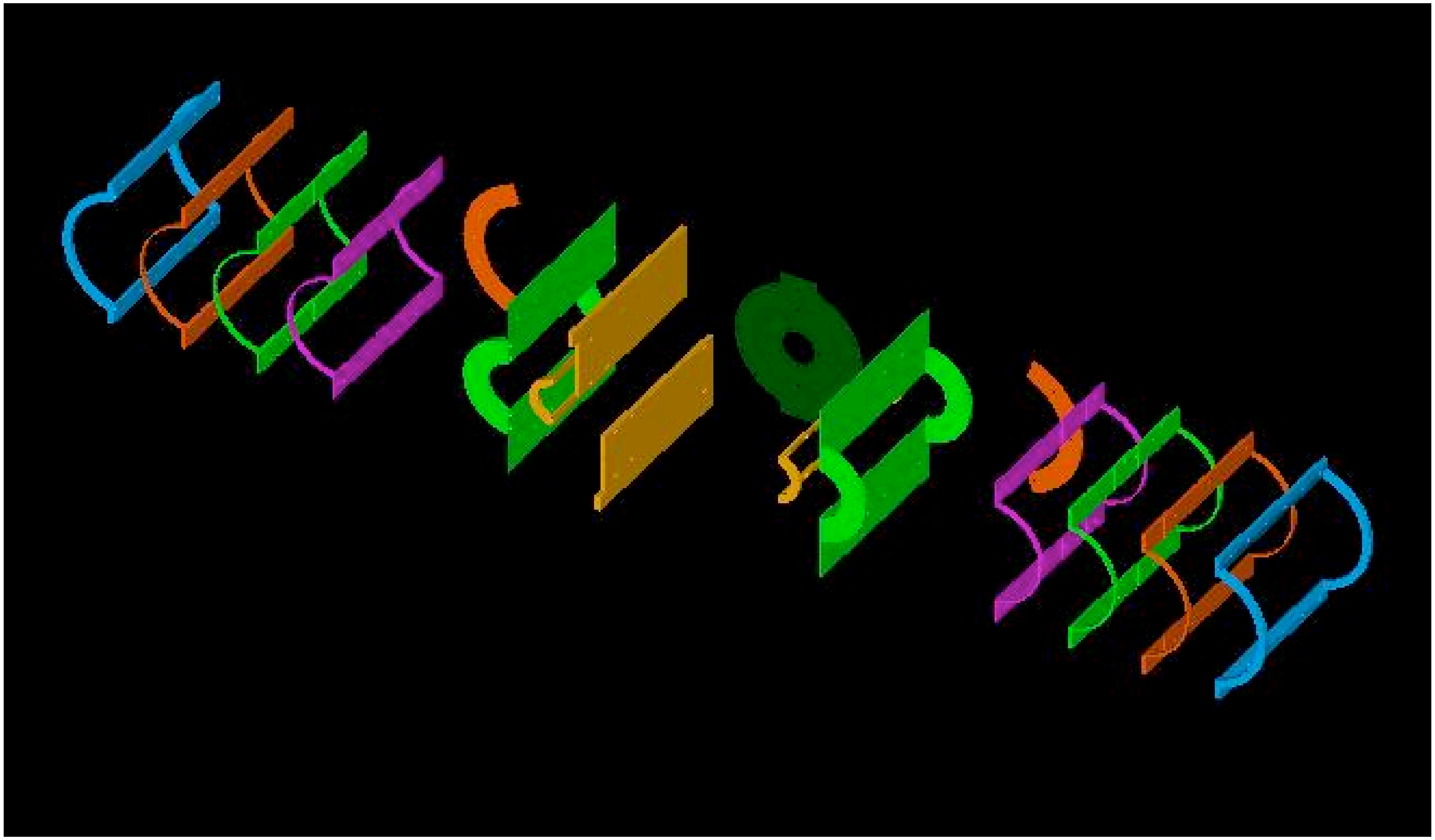




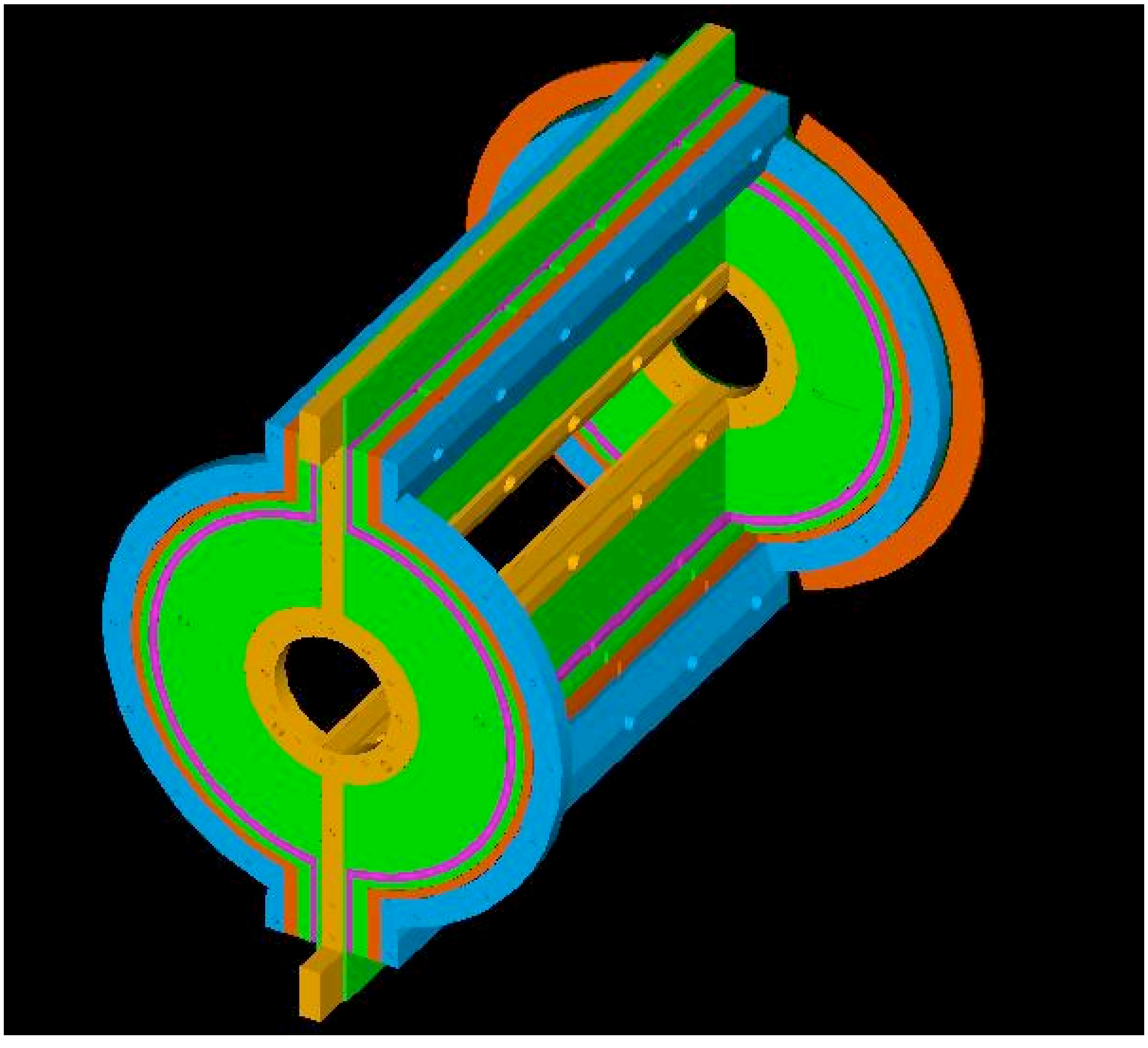
Scale 1:1, 1/8 of the final RTPC (1/2 length, 1/4 of 360°)

Tested at TUNL, planned engineering run with CLAS

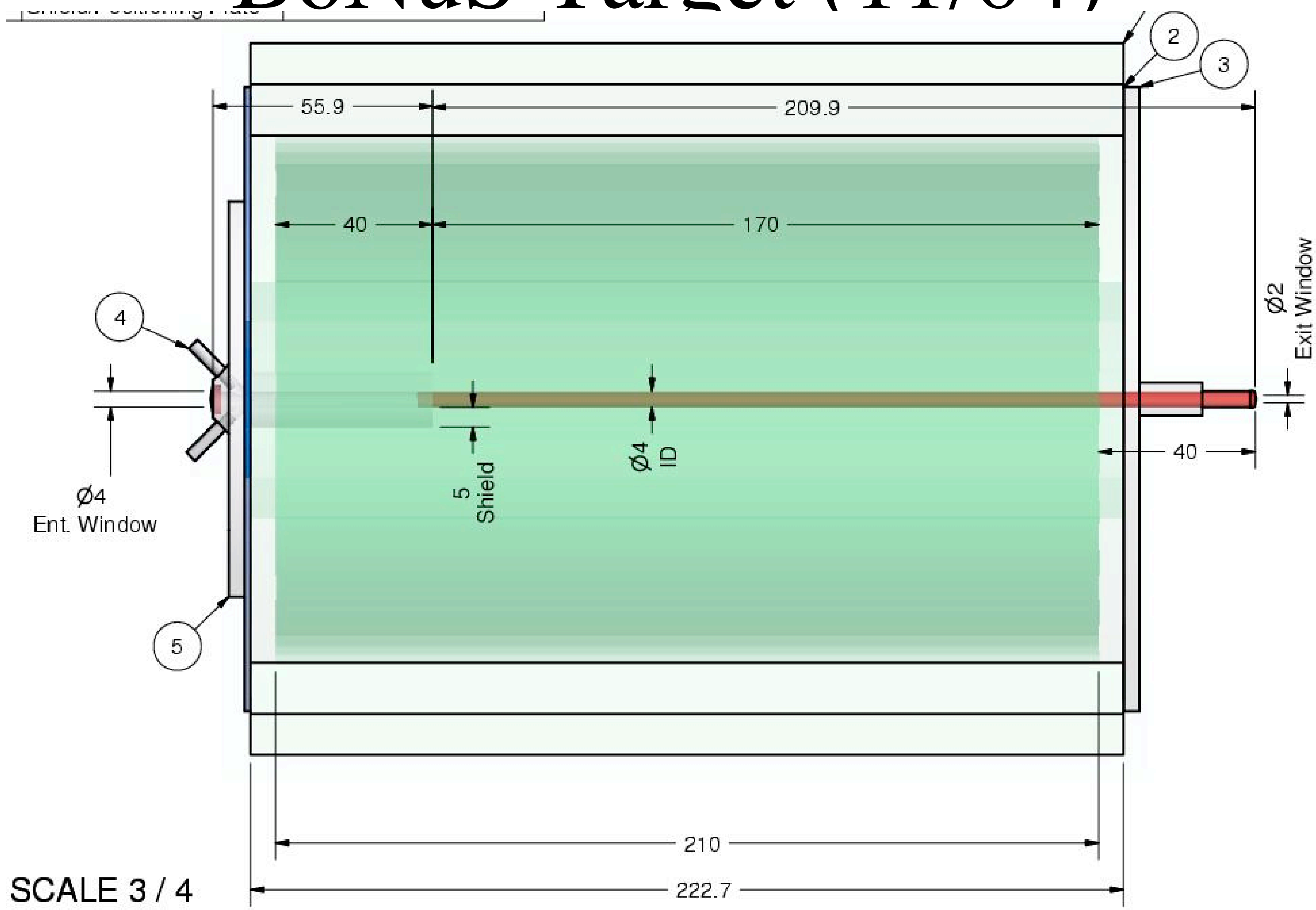
Production Model: Exploded View



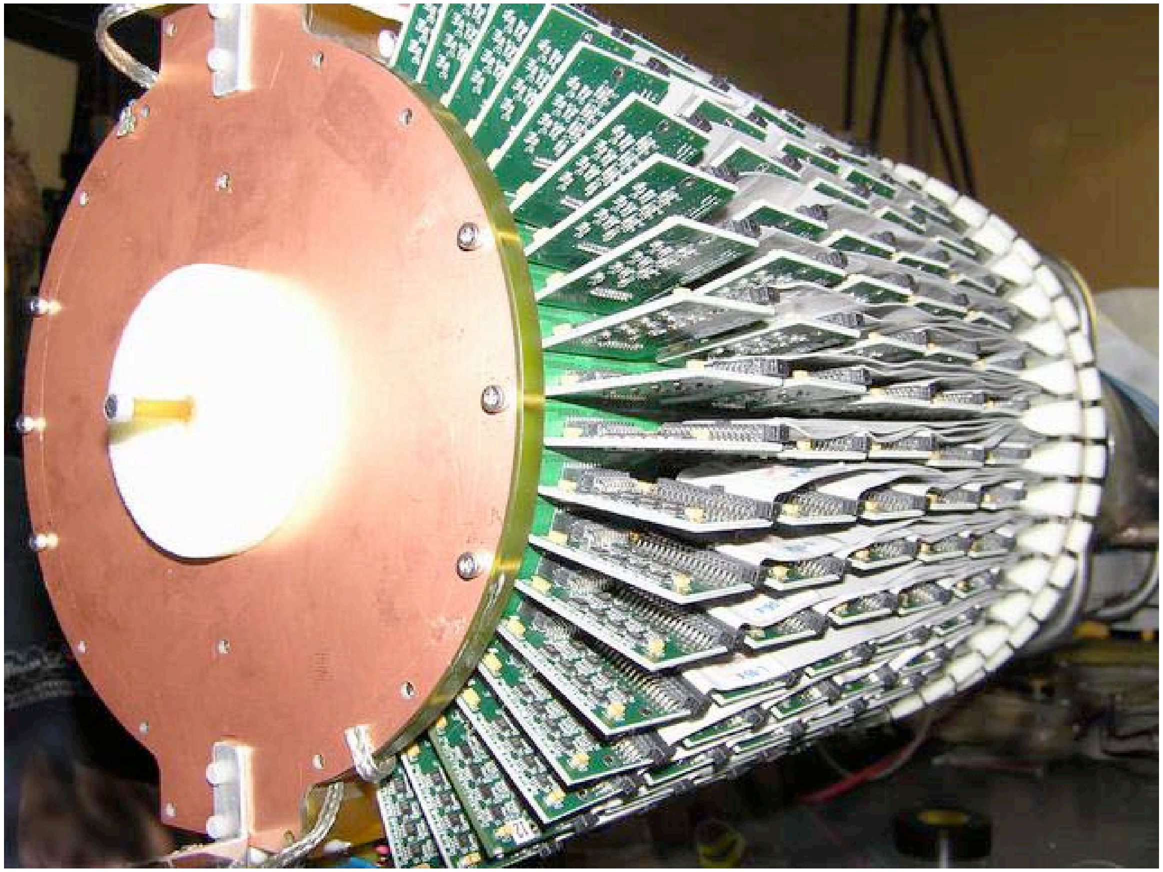
Production Model



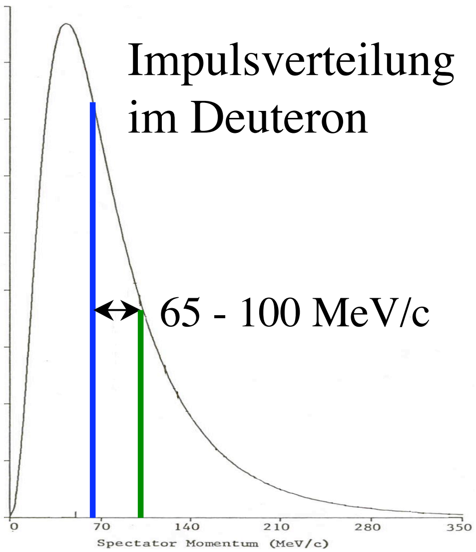
BoNuS Target (11/04)

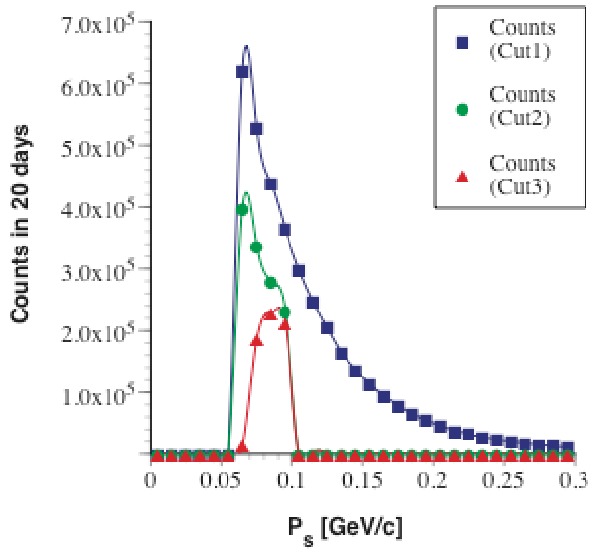


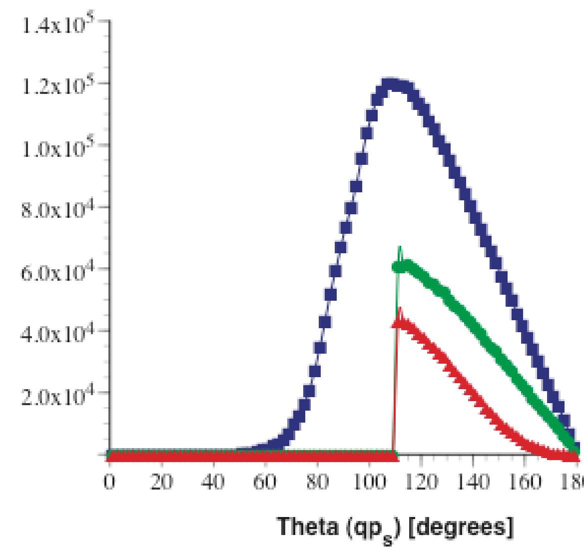
The Finished Detector



Acceptance for Protons







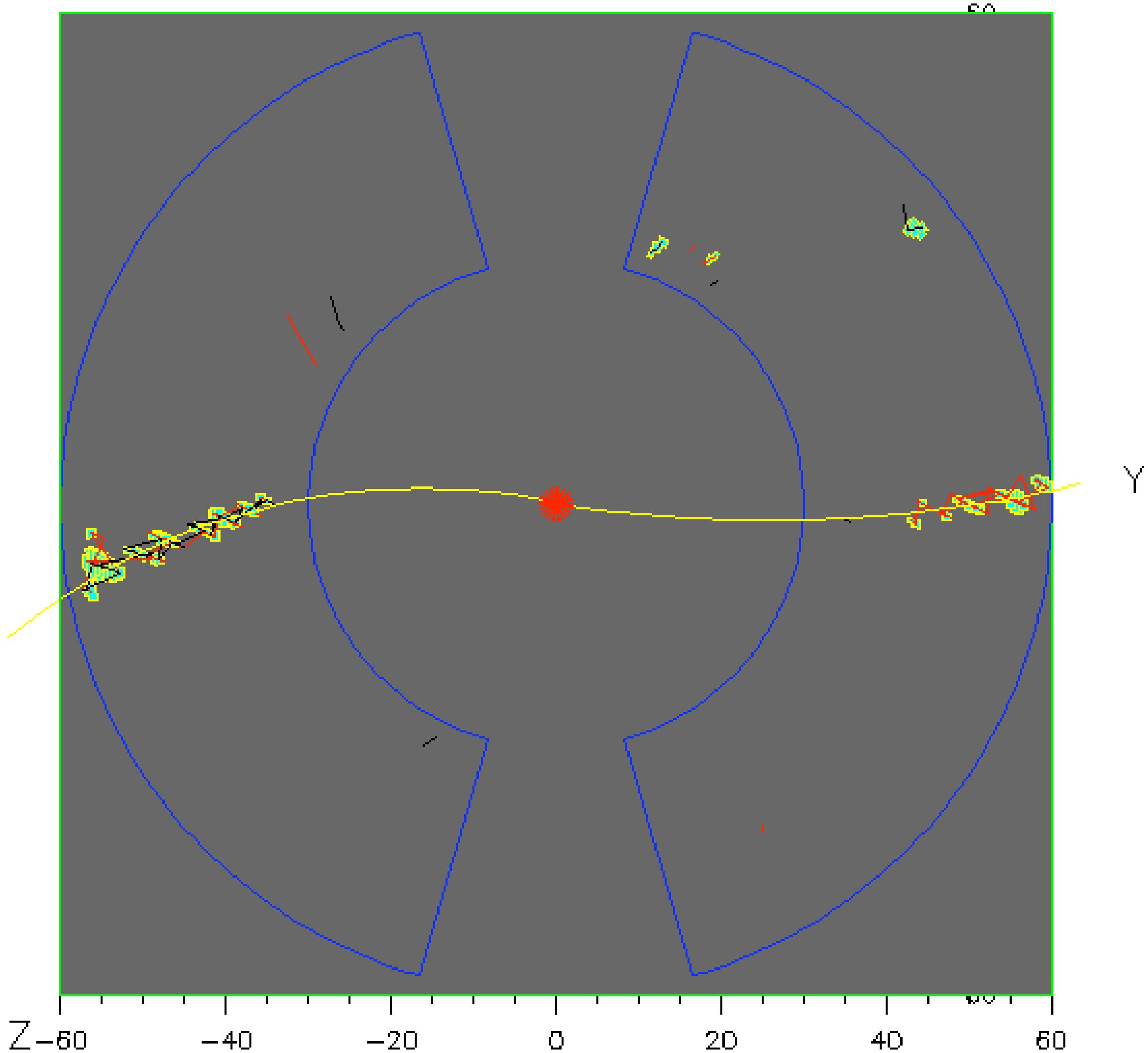
6 GeV electron beam, 20 "ideal" days -> registered "events"

Scattered electron within CLAS fiducial cuts, proton above 60 MeV/c und 90°

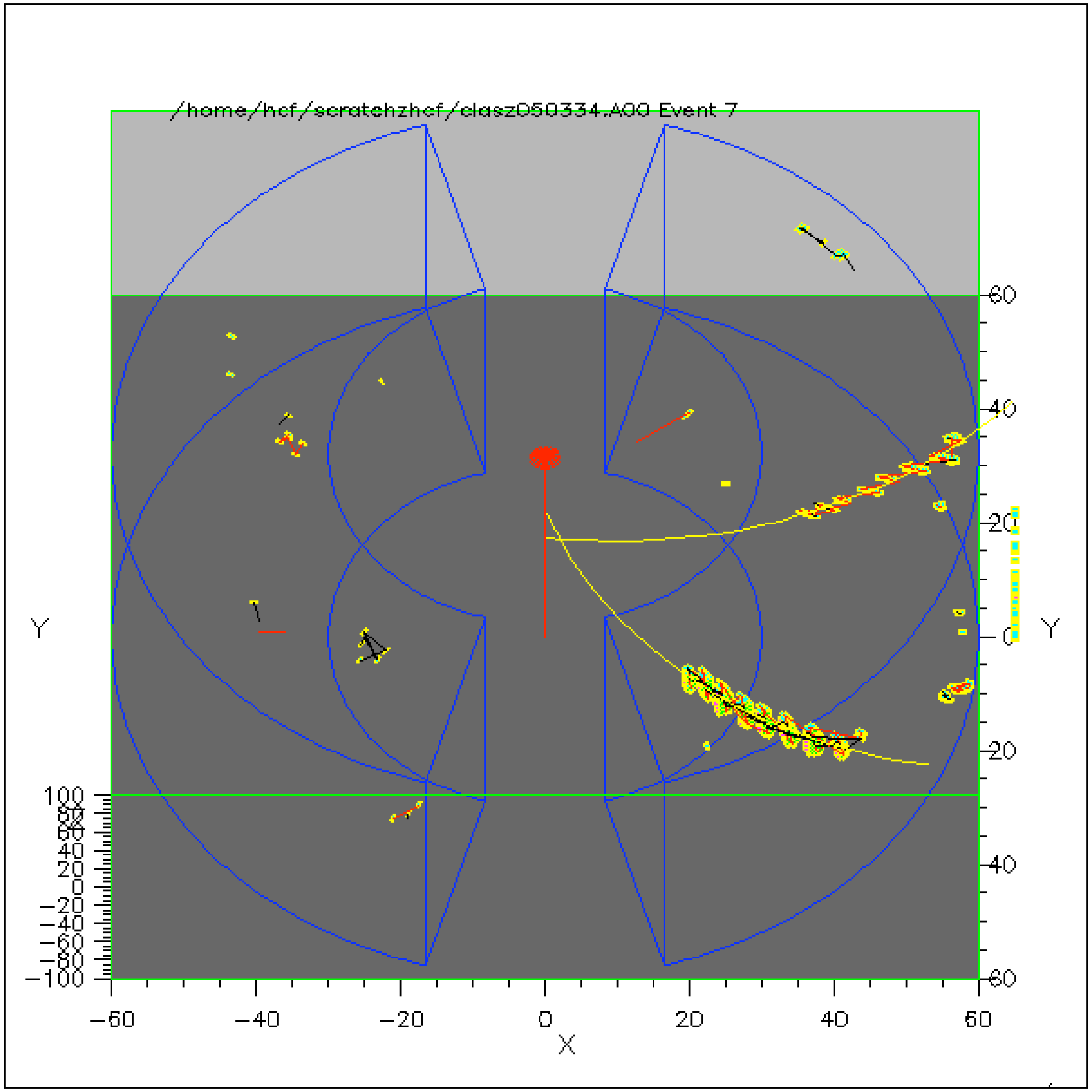
"VIPs": p(proton) < 100 MeV/c, $\theta_{pq} > 110^o$

Proton reconstructed by the RTPC

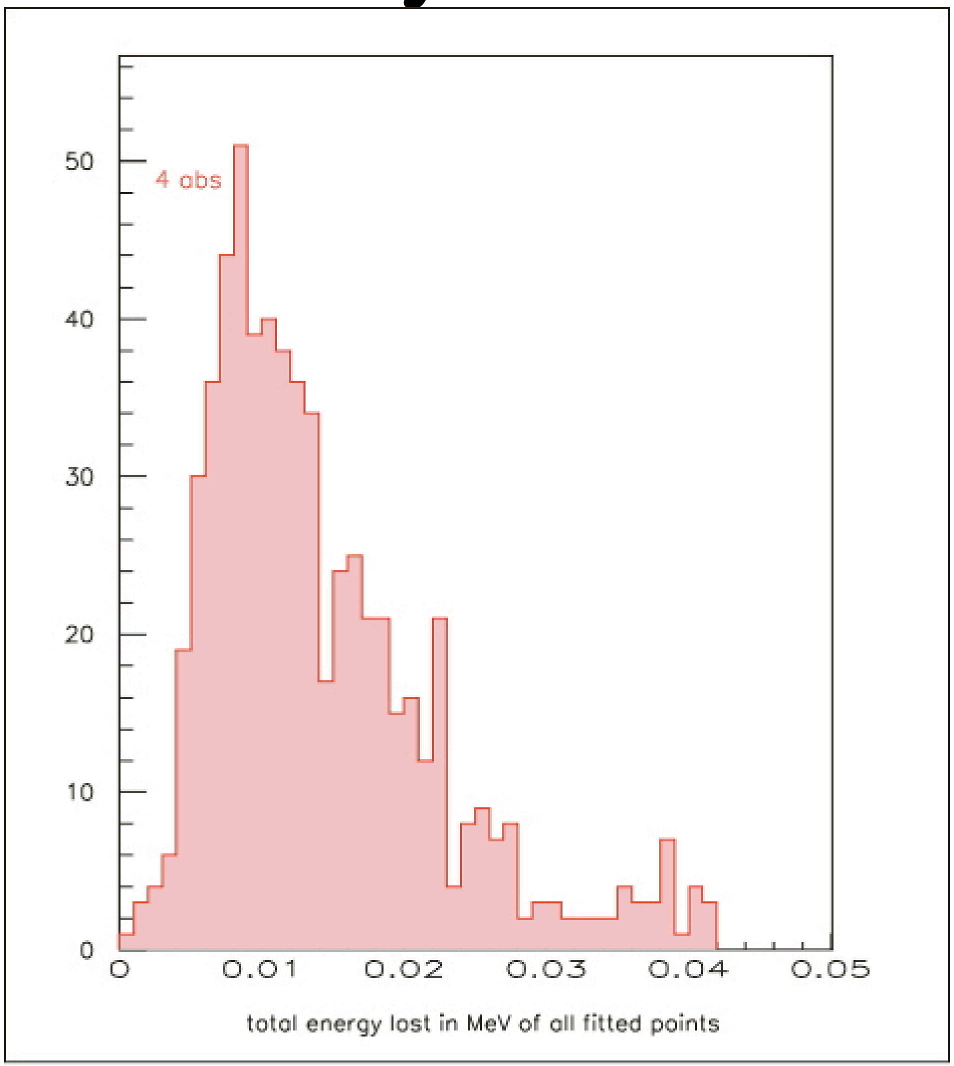
Proton and Electron Tracks



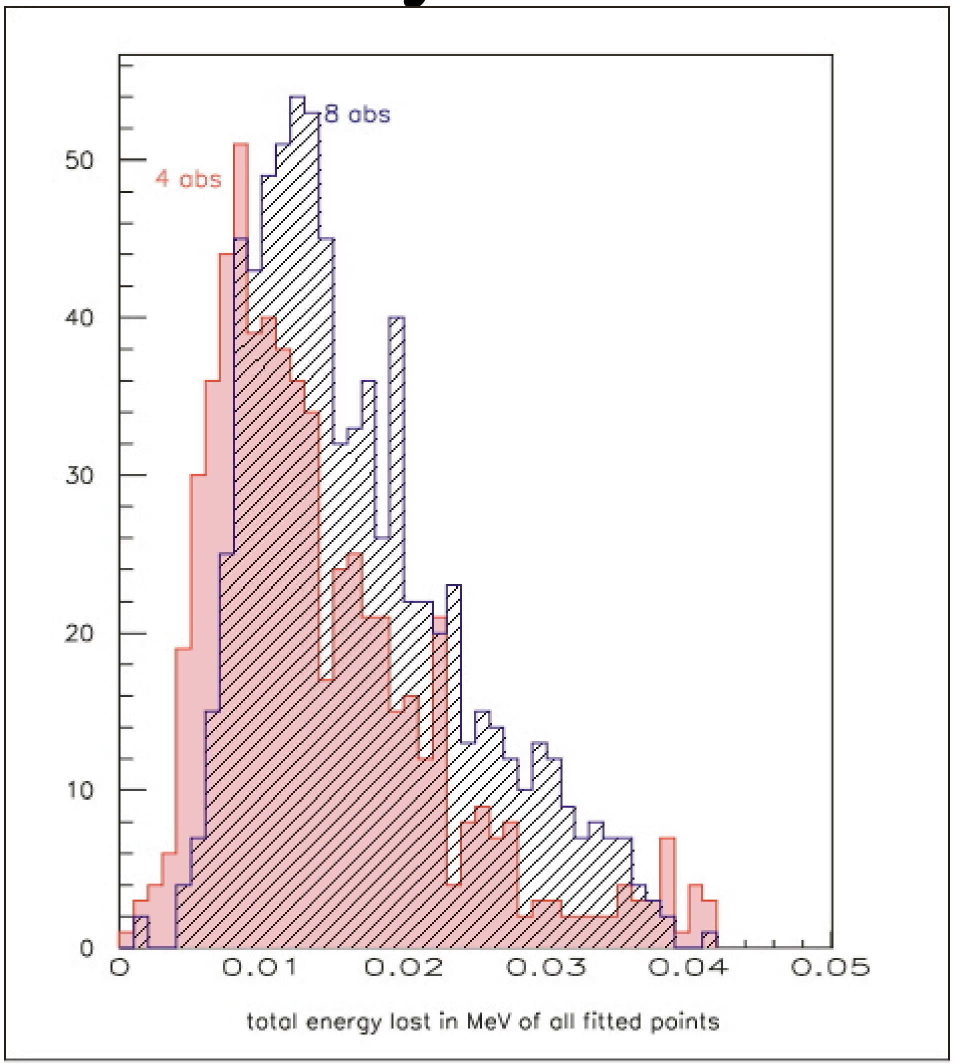
An Event with Perspective



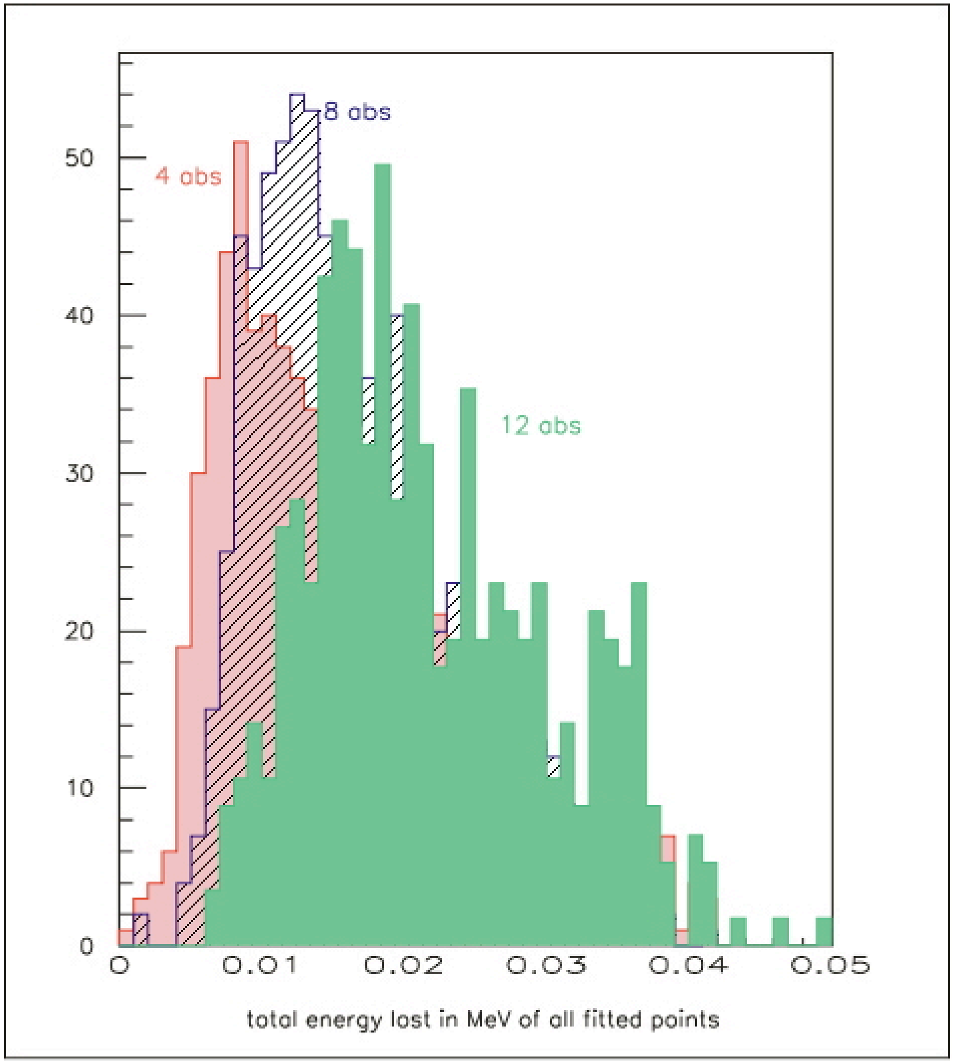
dE/dx Analysis from TUNL



dE/dx Analysis from TUNL

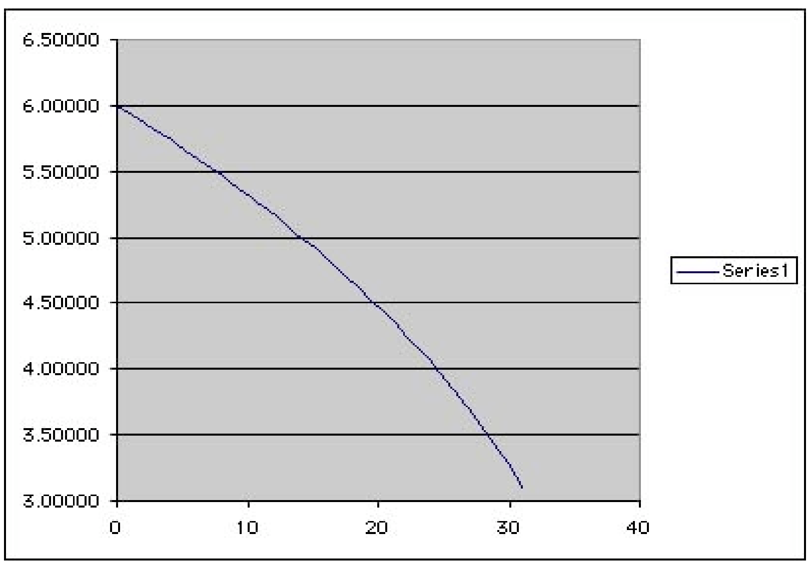


dE/dx Analysis from TUNL

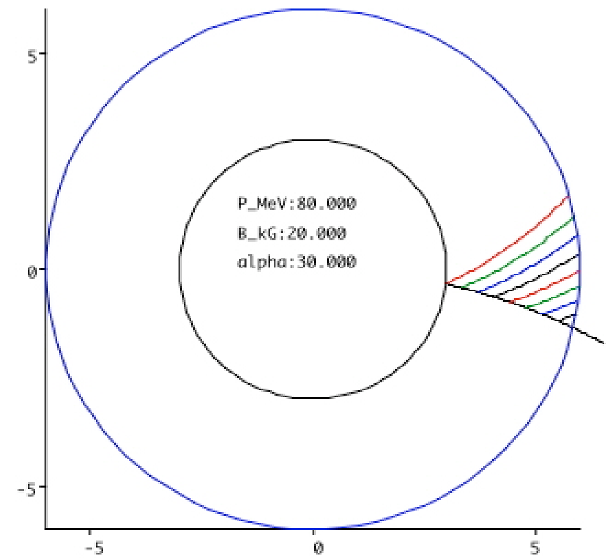


Reconstructing a Track

- Need to incorporate
  - Vdrift(R)
  - Field
  - Lorentz angle
- Need Simulation and Simulated Data

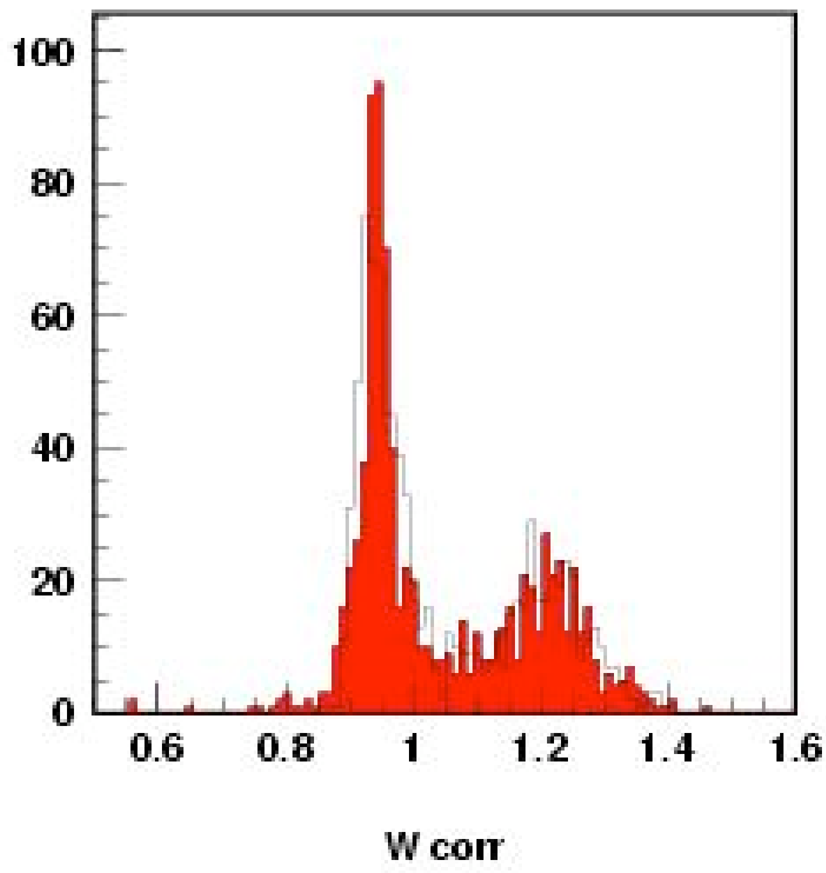


R_{HIT} vs. Time Bin
(V_{drift} varies with R)

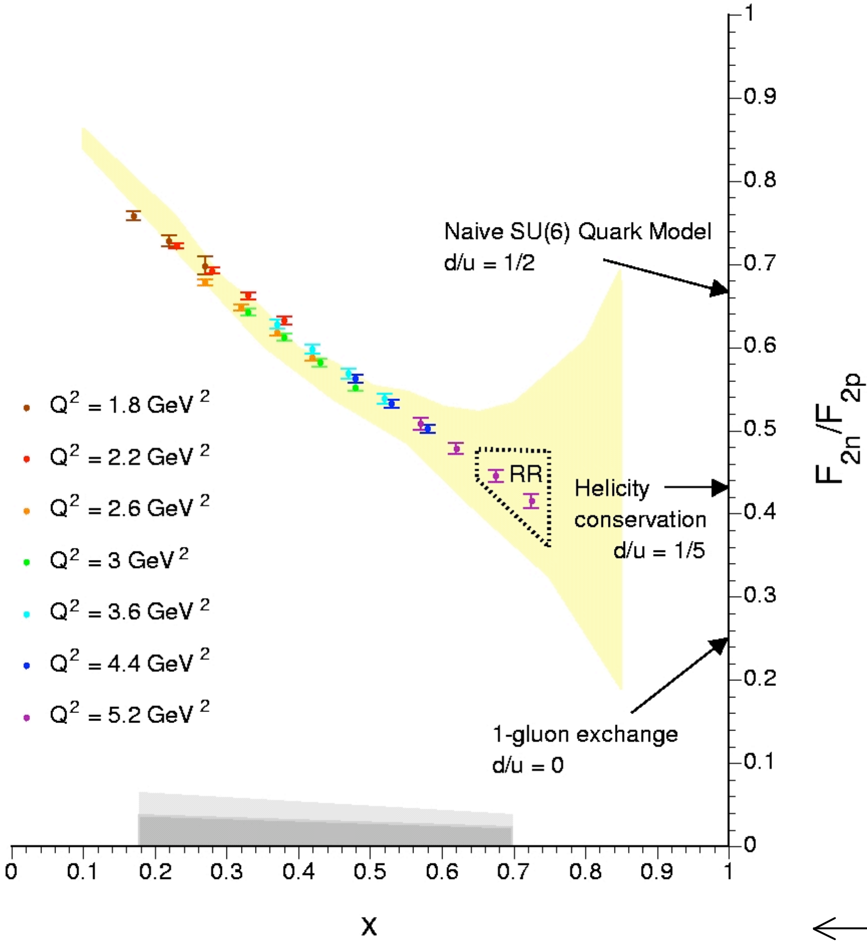


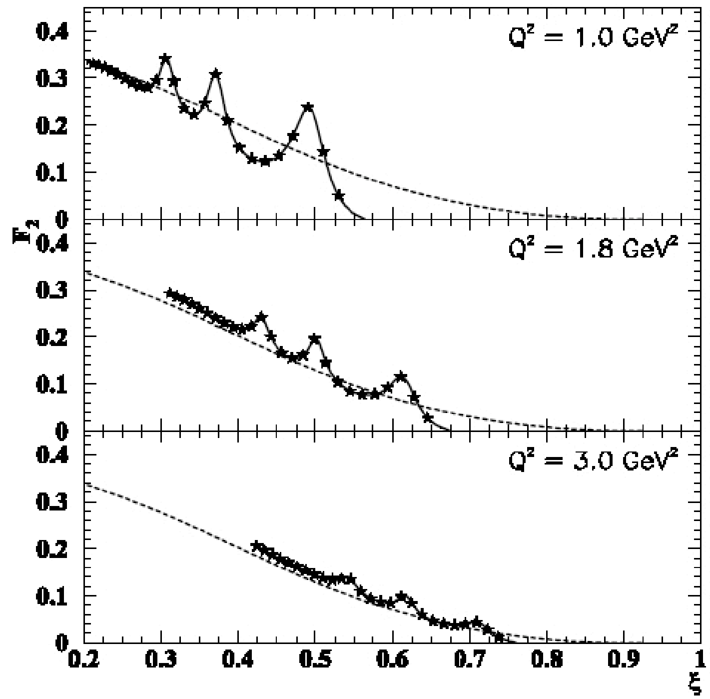
Curved e^- Drift
N.B.: nonuniform B

Corrections for Moving Nucleon in d(e,e'p_s)n



Expected Data





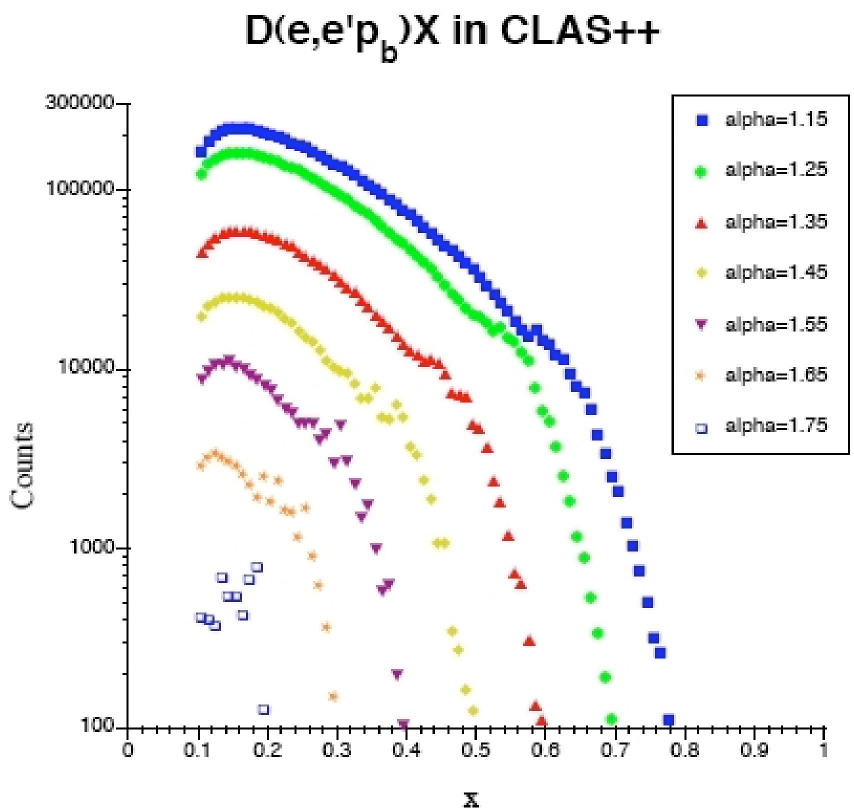
Systematics ~5%

← d/u

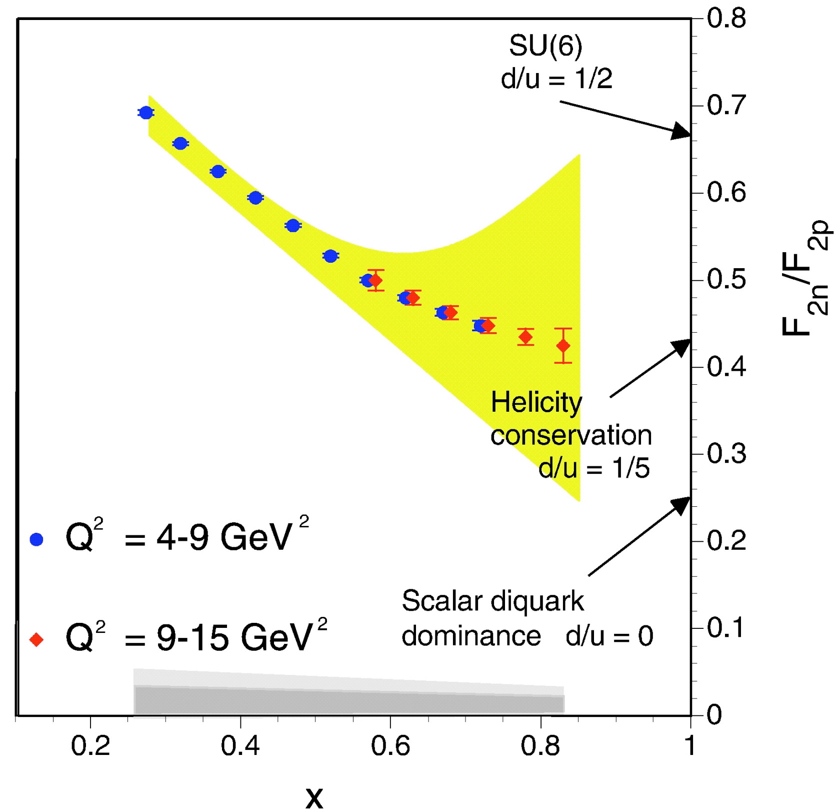
↑ Duality

The Future - 11 GeV

D(e,e'p_s)



BoNuS



Conclusions

- Proton tagging with deuterium targets is a fantastic technique for understanding properties of the nucleon
- BONUS is the first almost free nucleon target, which will allow measurements free of uncertainties due to nuclear physics.
- New technical developments have made this possible.
- Data taking occurred in Fall 2005 at Jlab!
- Data analysis is in progress.