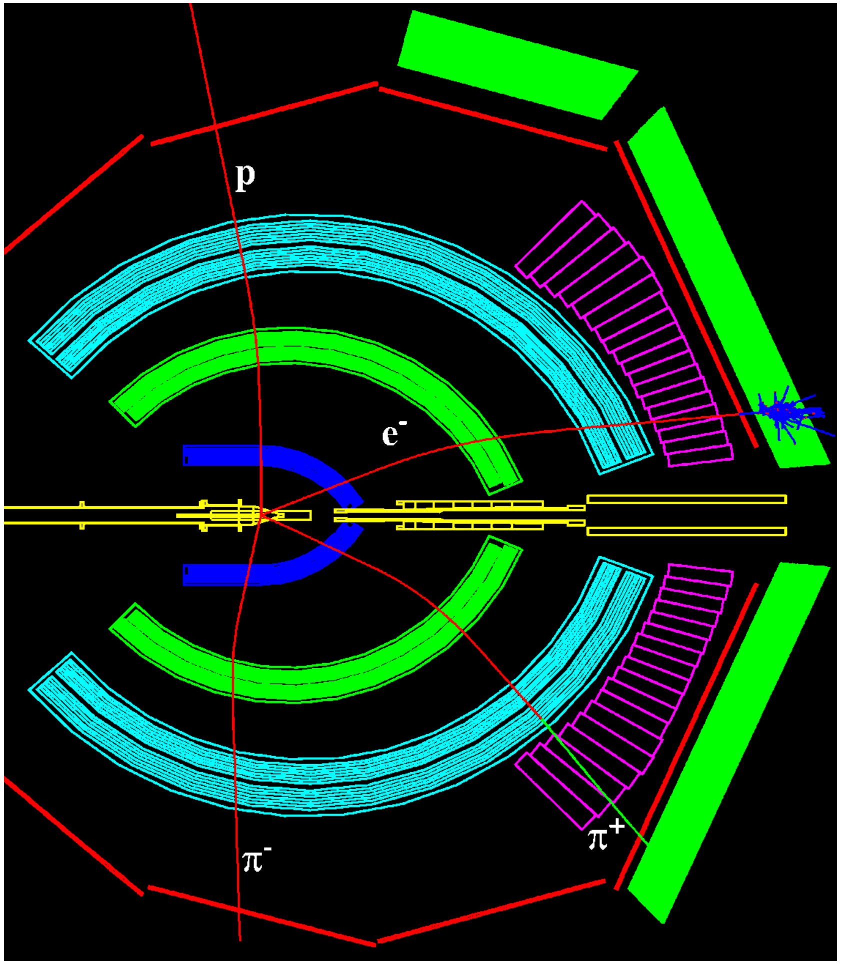
# eA pion production at CLAS aimed at neutrinos

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University of Rochester

Department of Physics and Astronomy

INT Workshop

Seattle, December 2013

*Representing the CLAS (EG-2) collaboration*

# Motivation – why eA?

➢ High statistics.

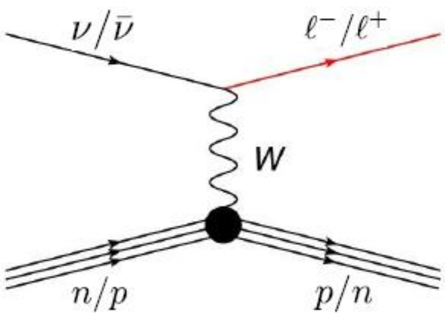
➢ Control over initial energy and interaction point – gives kinematic constraints and ability to optimize detector.

*Summary slide from talk by Costas Andreopolos at NUINT 2009*
*"Electron scattering data and its use in constraining neutrino models"*

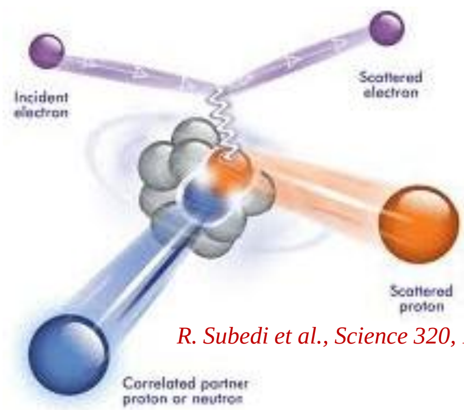
- Electron (and muon) scattering data provide a wealth of information about the **nucleon and nuclear structure** and **in-medium modifications**
  - *Nucleon Elastic Form Factors*
  - *PDFs, R, d/u, …*
  - *Resonances & QE → DIS transition, Non-Resonance Backgrounds*
  - *Nucleon momentum distributions and binding energies*
  - *Nuclear charge distributions, energy levels, ...*
  - *N-N correlations*
  - *Medium modifications*
    - *EMC effect, ...*
    - *Effects on hadronization: Landau-Pomeranchuck-Migdal and Cronin effects*
  - *...*

**This information has been central in building comprehensive picture of neutrino interactions in the ~few GeV energy range**

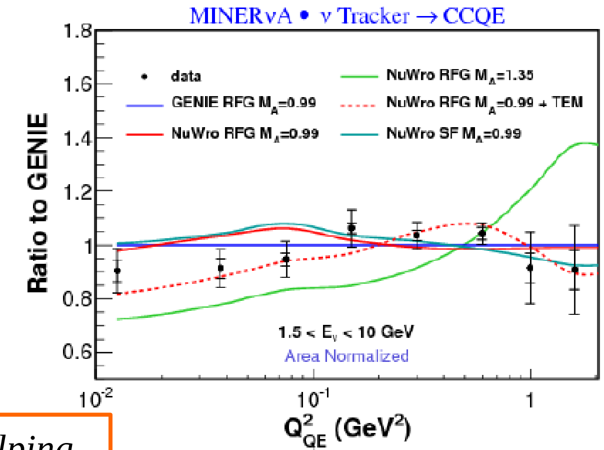
# Why eA? – Well … this group at INT has shown quite a few slides I could put here …




*Interactions are on nuclei rather than nucleons*

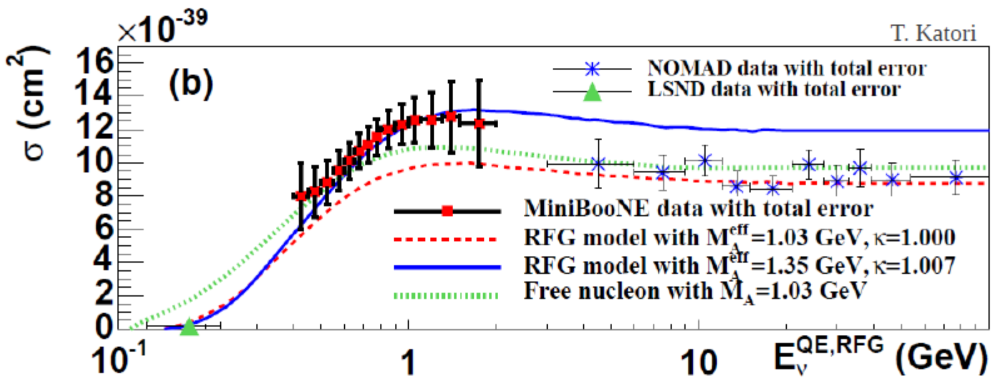


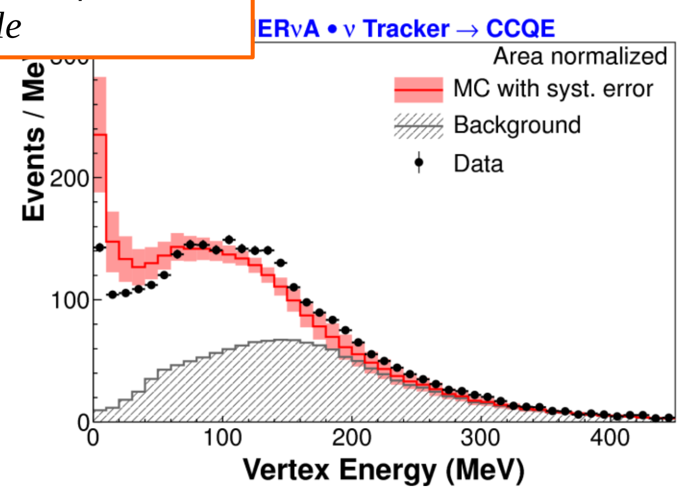

*R. Subedi et al., Science 320, 1476 (2008)*




*Input from eA has been important in helping us understand the potential effects of SRC and MEC, for example*

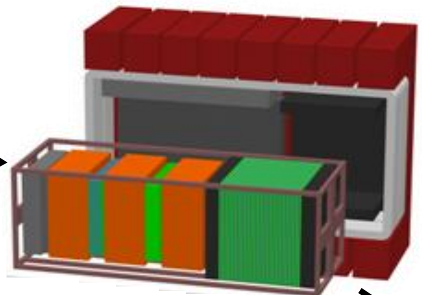
*G.A. Fiorentini et al., PRL 111, 022502 (2013)*



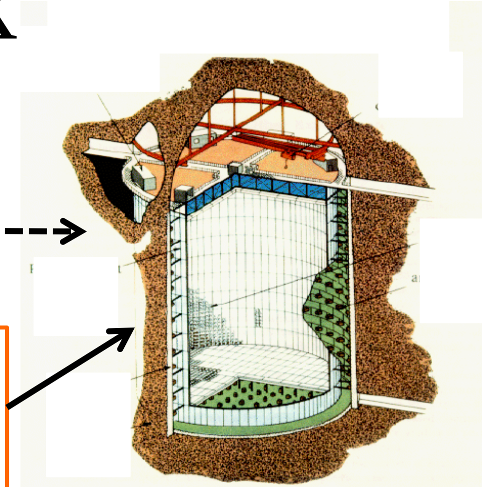



# Why eA? – This work

Neutrino beam



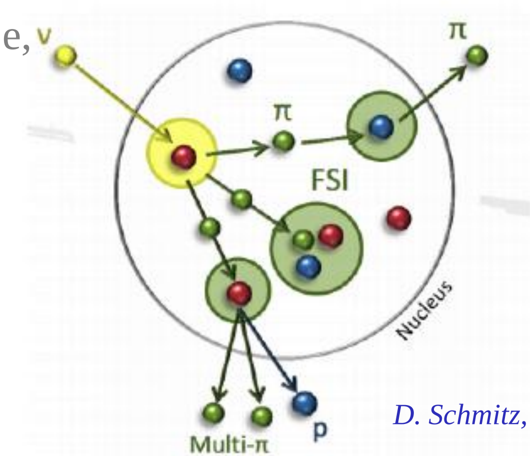
Long baseline



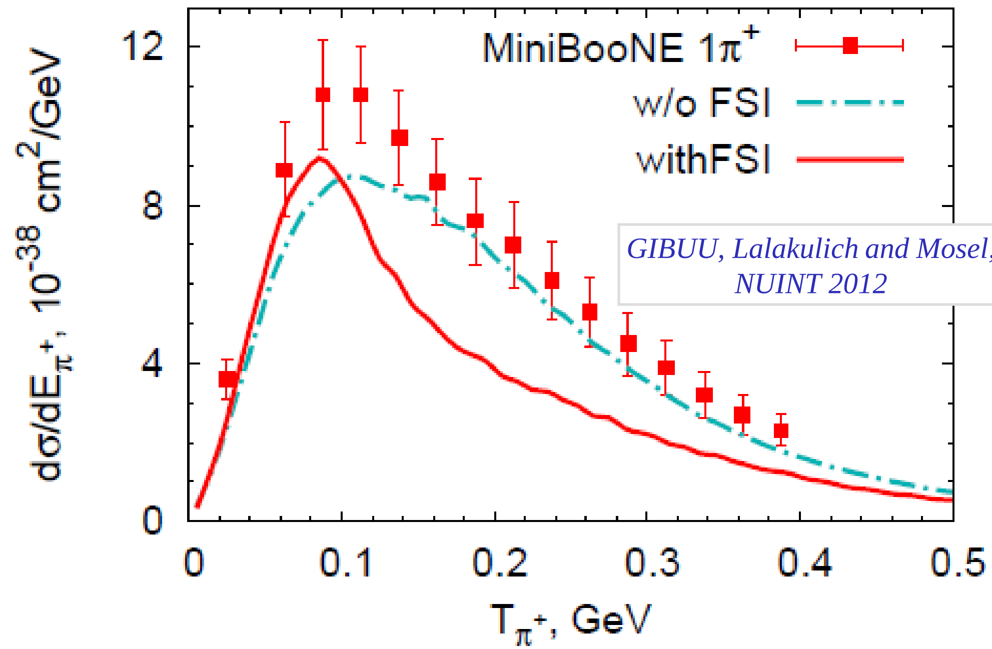
*Measure flux and backgrounds in near detector and propagate to far detector and the uncertainties "cancel out"*

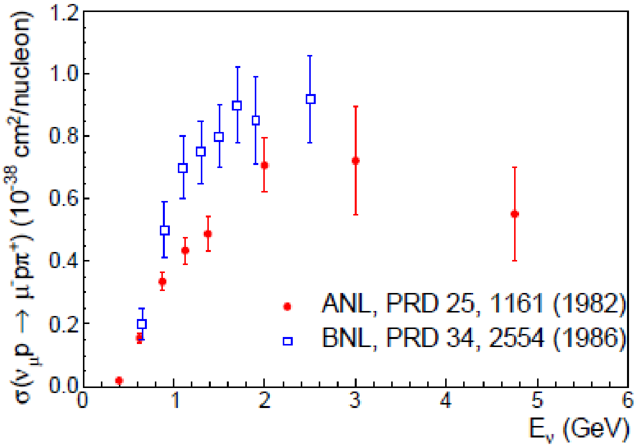
*Cross-sections, nuclear effects and backgrounds don't cancel simply/completely, even in the limit of identical detectors.*

*Model*
*Even more important if near and far detectors are not the same material*



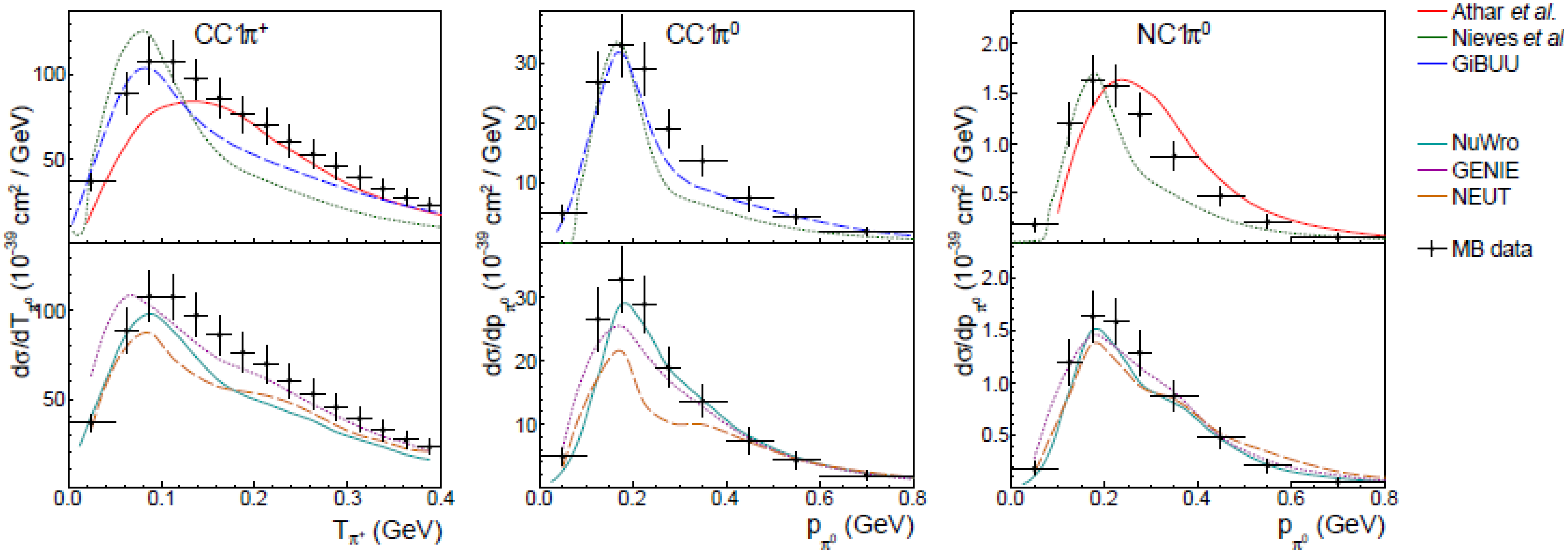

*D. Schmitz,*






Old deuterium data on single pion production: large errors

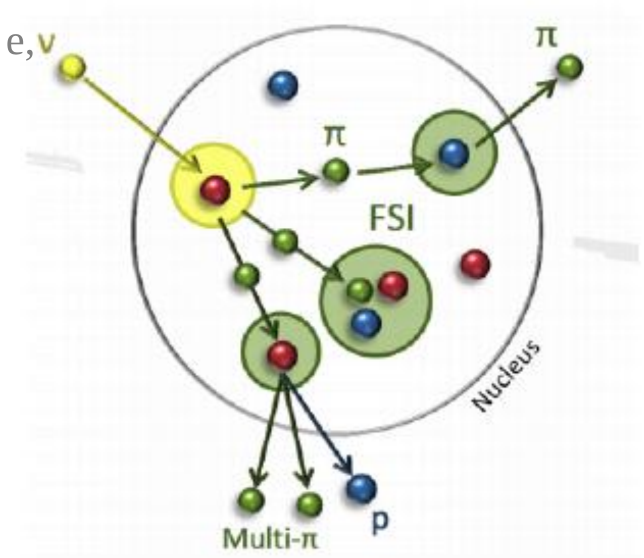
Comparisons with MiniBooNE differential distributions suggest our understanding of FSI is problematic or measurement is problematic …
Lacking a perfect model, experiment must turn knobs to adjust model to agree with data as well as possible and estimate error induced by this process/model *AND* seek other data to help constrain model



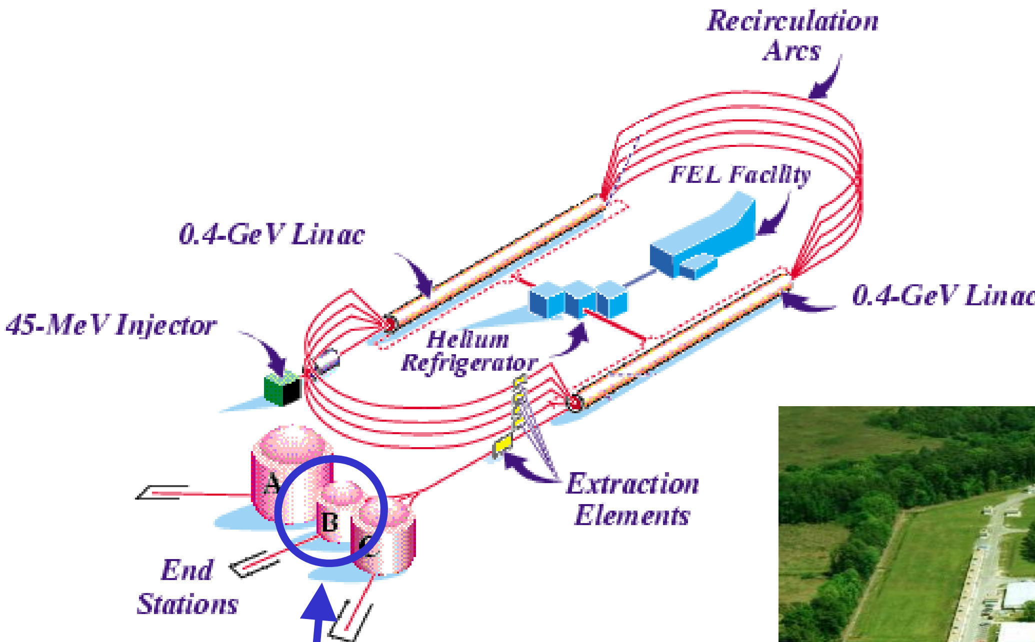

*P. Rodrigues, NUINT 2012*

# Why eA? – This work

This work aims to produce high statistics, multidimensional, differential, charged pion production measurements on different nuclei. The hope is that this will be useful for learning about and tuning models for FSI.



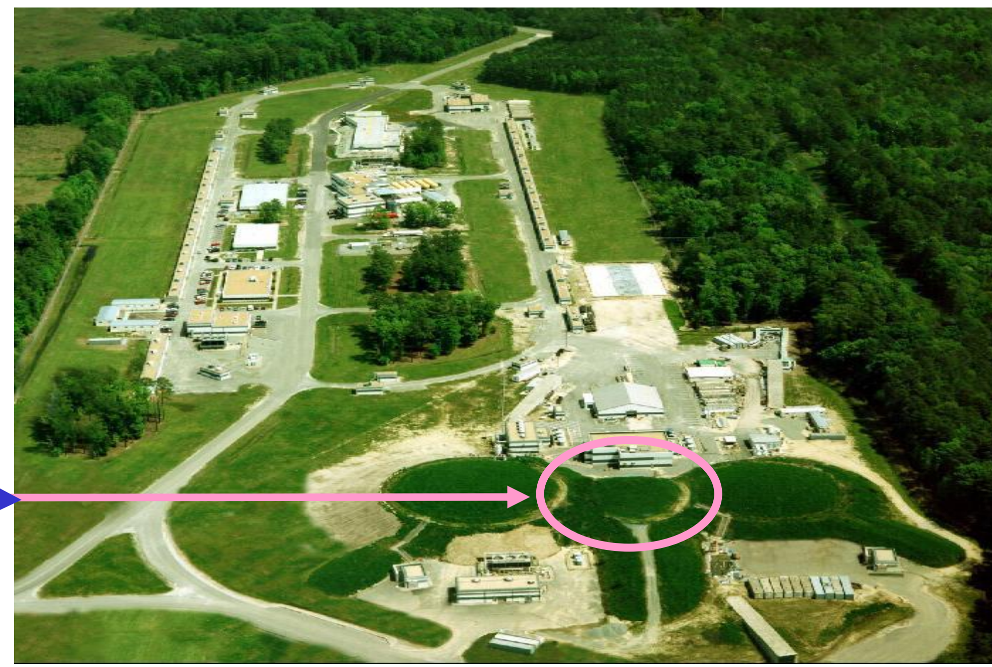
# Jefferson Lab (Newport News, Virginia)



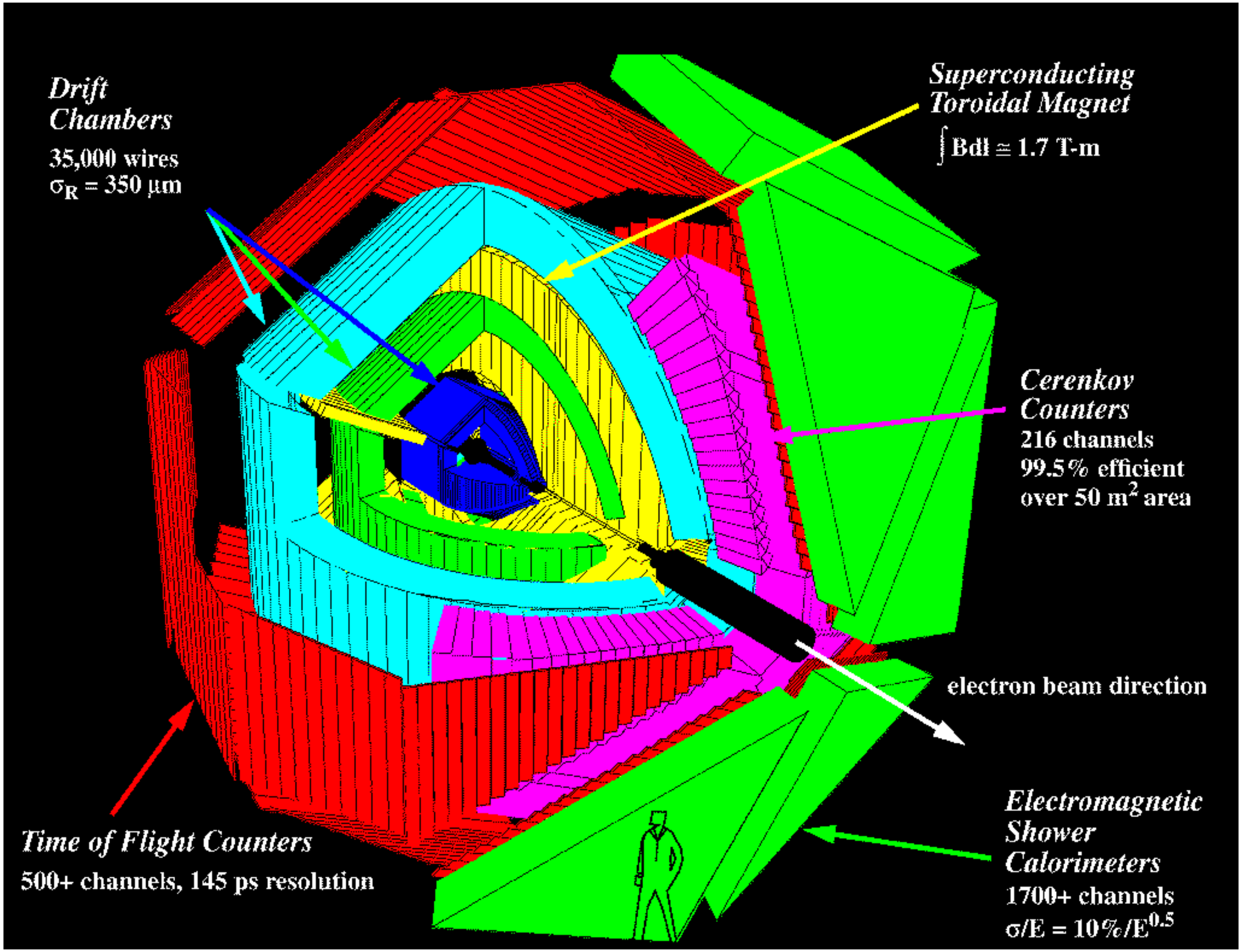

| | |
|---|---|
| $E_{max}$ | ~ 6 GeV |
| $I_{max}$ | ~ 200 μA |
| Duty Factor | ~ 100% |
| $\sigma_E/E$ | ~ 2.5 $10^{-5}$ |
| Beam P | ~ 80% |

12 GeV upgrade underway

CLAS

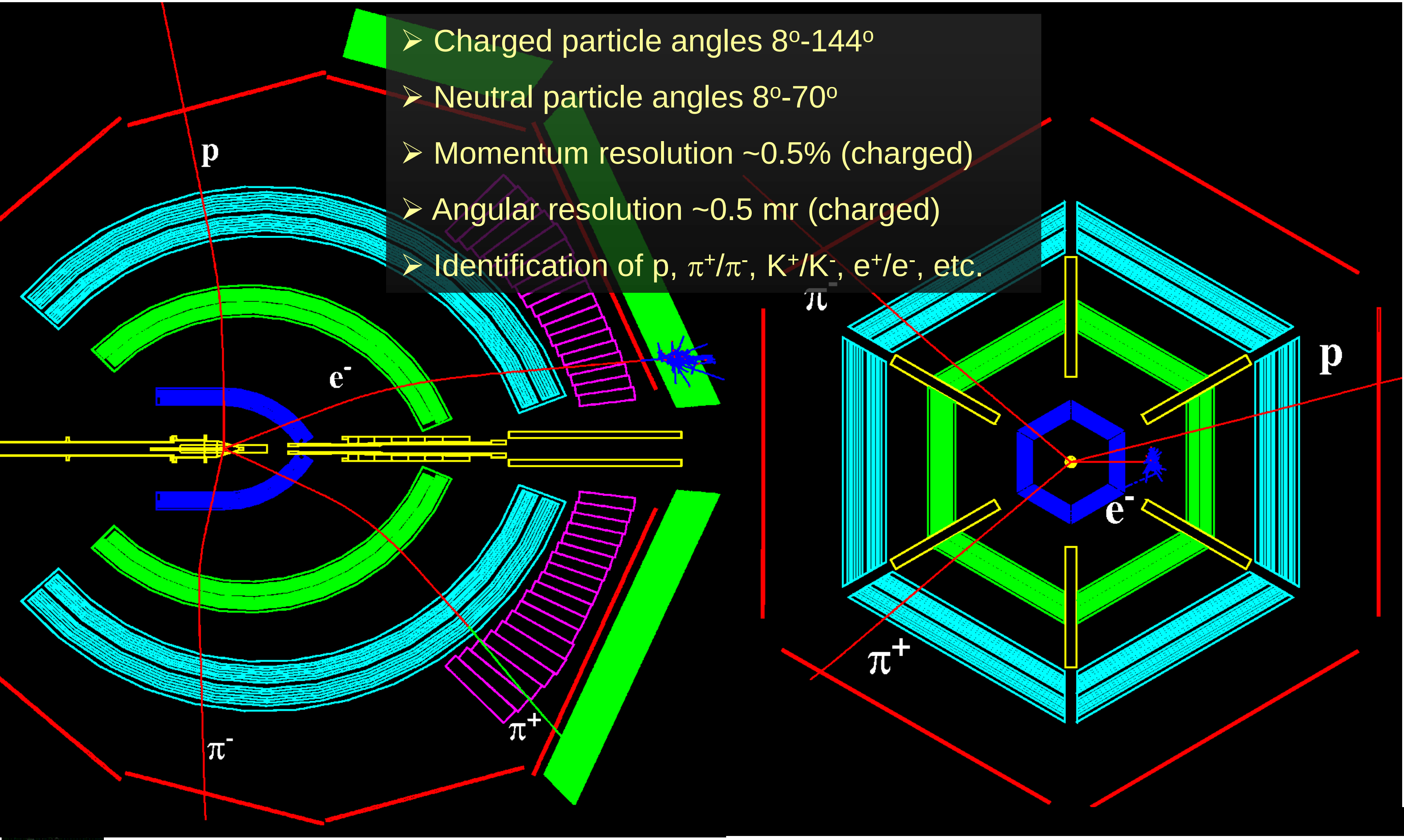


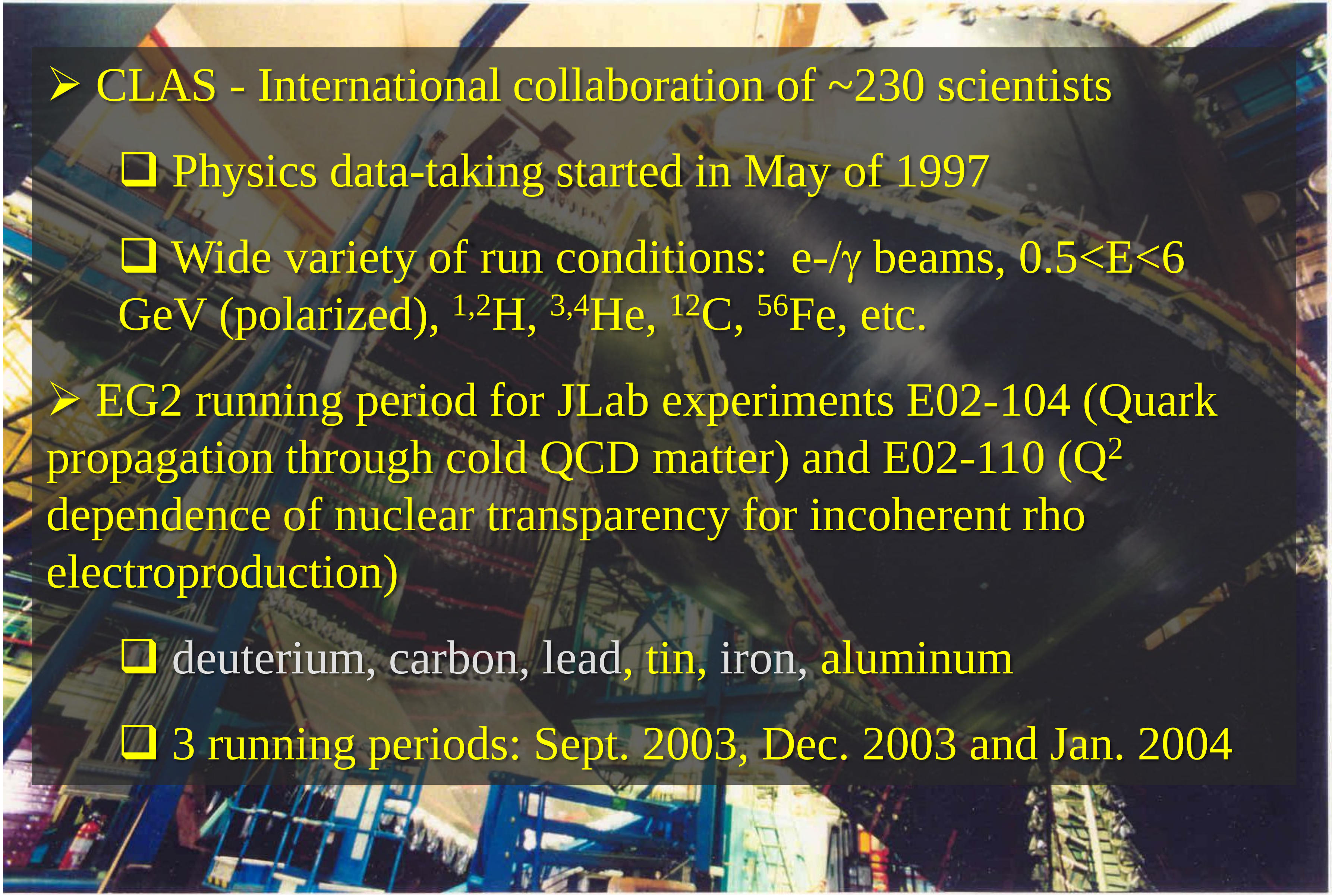
# CLAS: CEBAF Large Acceptance Spectrometer (Hall B)



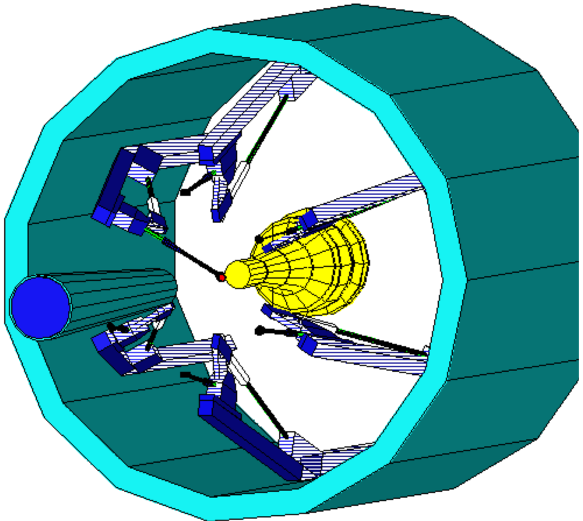
# CLAS Single Event Display

- Charged particle angles 8º-144º
- Neutral particle angles 8º-70º
- Momentum resolution ~0.5% (charged)
- Angular resolution ~0.5 mr (charged)
- Identification of p, $\pi^+/\pi^-$, $K^+/K^-$, $e^+/e^-$, etc.

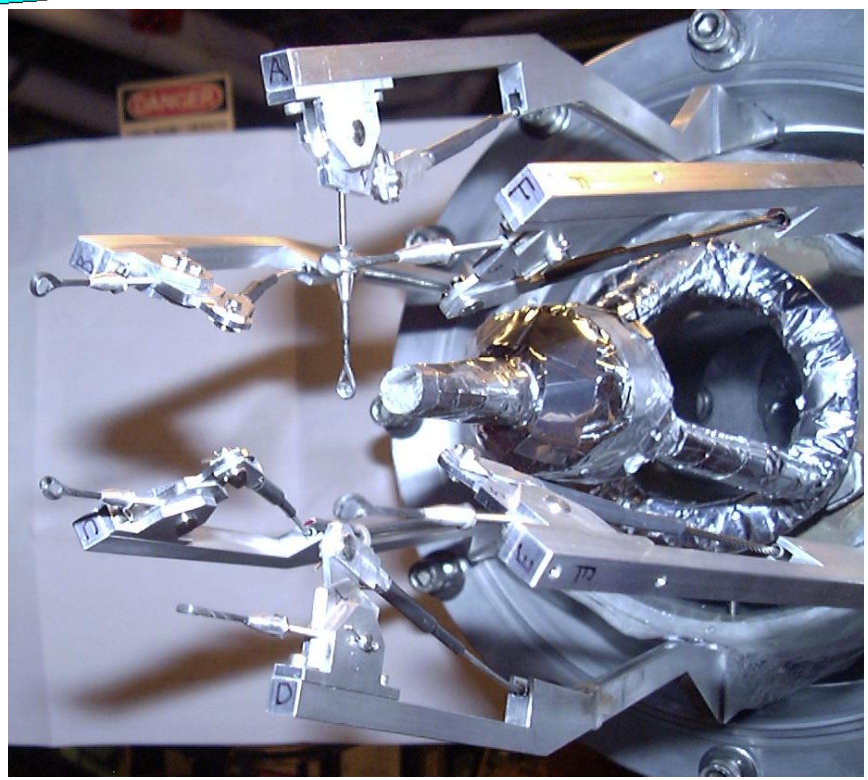




- CLAS - International collaboration of ~230 scientists
  - Physics data-taking started in May of 1997
  - Wide variety of run conditions: e-/$\gamma$ beams, $0.5<E<6$ GeV (polarized), $^{1,2}$H, $^{3,4}$He, $^{12}$C, $^{56}$Fe, etc.
- EG2 running period for JLab experiments E02-104 (Quark propagation through cold QCD matter) and E02-110 ($Q^2$ dependence of nuclear transparency for incoherent rho electroproduction)
  - deuterium, carbon, lead, tin, iron, aluminum
  - 3 running periods: Sept. 2003, Dec. 2003 and Jan. 2004



# CLAS EG2
## Targets



- *Two* targets in the beam simultaneously
- 2 cm LD2, upstream
- Solid target downstream
- Six solid targets:

 -Carbon

 -Aluminum (2 thicknesses)

 -Iron

 -Tin

 -Lead

# GENIE eA

Using GENIE version 2.6.8 in eA mode with $Q^2>0.5$
for acceptance calculations and comparison


C. Andreopoulos: GENIE eA mode is a “straightforward adaptation of the neutrino generator”

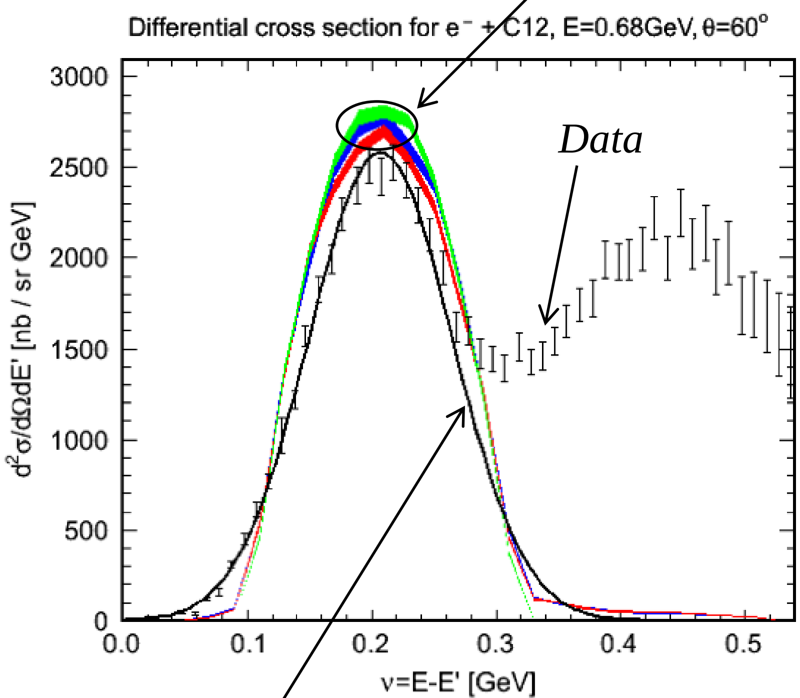
- Use charged lepton predictions of cross-section models: Rein-Sehgal, Bodek-Yang, etc.
- Transition region handled as in neutrino mode.
- Nuclear model (Bodek-Ritchie, Fermi-Gas) same as in neutrino mode.
- Intranuclear cascade (INTRANUKE/hA) same as in neutrino mode.
- Small modifications to take into account probe charge for hadronization model and resonance event generation.
- In-medium effects to hadronization same as in neutrino mode.

# GENIE eA validation

Using GENIE version 2.5.1

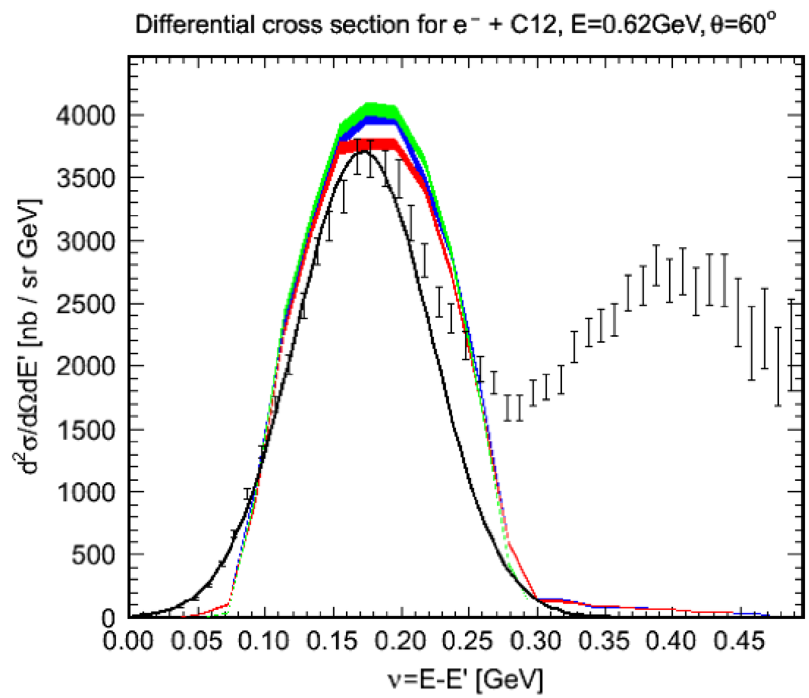
*GENIE eA with different Fermi gas models (red is default)*

Data from Donal Day's online quasielastic electron nucleus scattering archive http://faculty.virginia.edu/qes-archive/index.html




*Data*

*Gaussian fit to data*



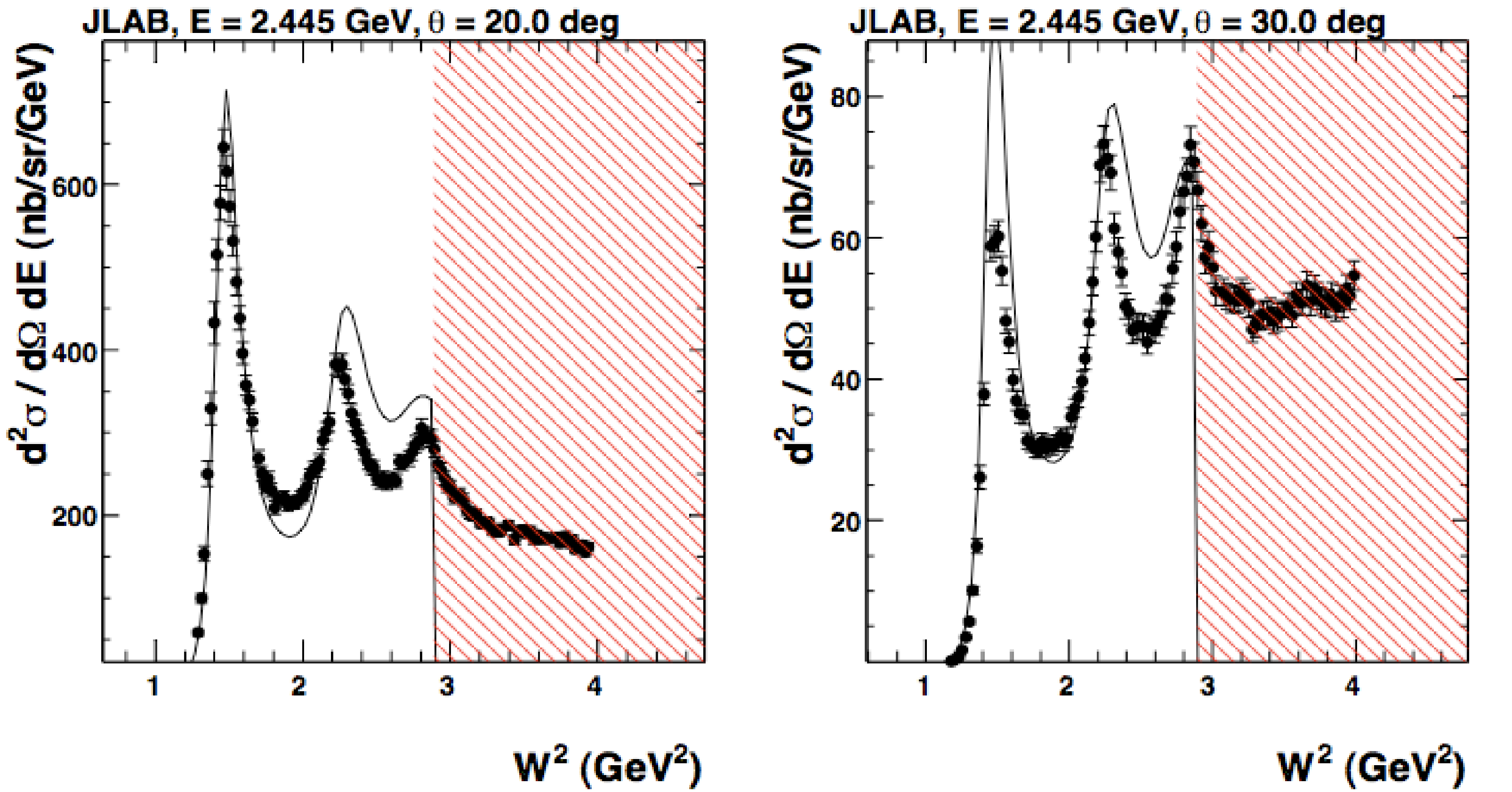

*-From C. Andreopoulos*

## Comparison with electron quasi-elastic scattering data

# GENIE eA validation

Using GENIE version 2.5.1

Data from Hampton University and JLab Hall C resonance data archive
http://hallcweb.jlab.org/resdata/




*-From C. Andreopoulos*

Comparison with electron scattering resonance data

# Samples

EG-2 data sample size ($E_{beam}$=5.015 GeV):

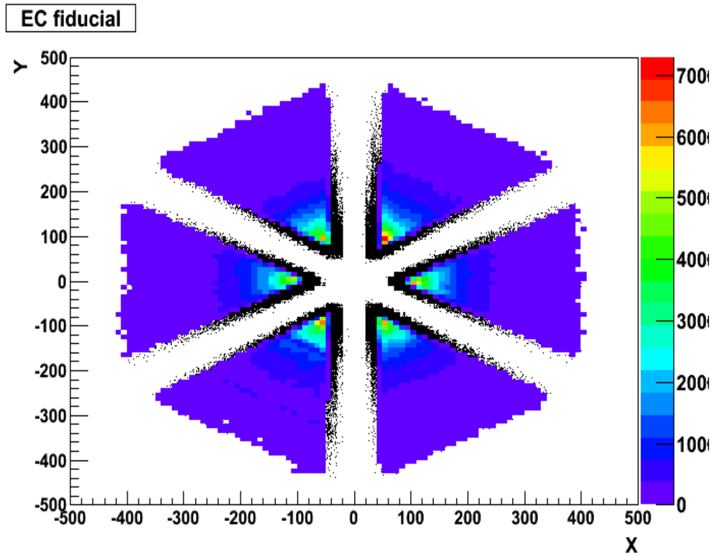
| | |
|---|---|
| Deuterium + C/Fe/Pb raw events | 1.1/2.2/1.5 ($\times 10^9$) |
| D2/C/Fe/Pb events passing all cuts | 28.1/5.0/7.6/2.5 ($\times 10^6$) |

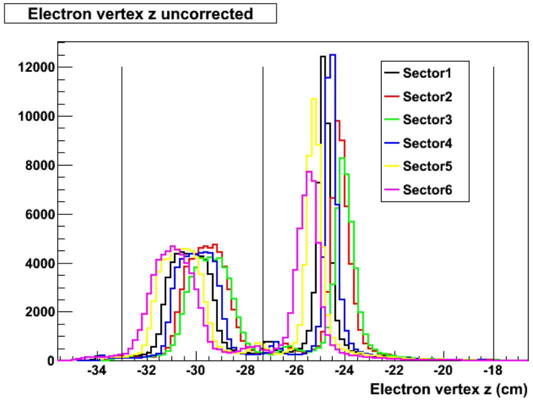
Simulated sample size (Genie MC + detector simulation):

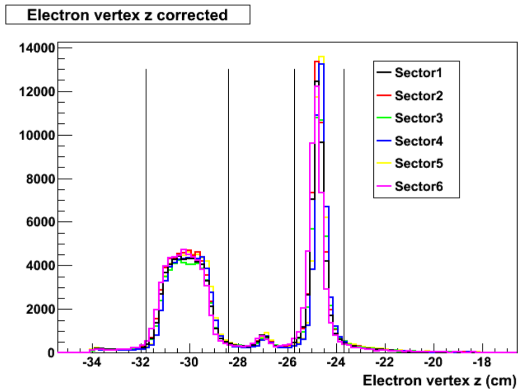
| | |
|---|---|
| D2/C/Fe/Pb generated events | (4)$\times 1.0\times 10^8$ |
| D2/C/Fe/Pb events passing all cuts | 7.9/6.4/5.5/4.8 ($\times 10^6$) |

# Analysis cuts

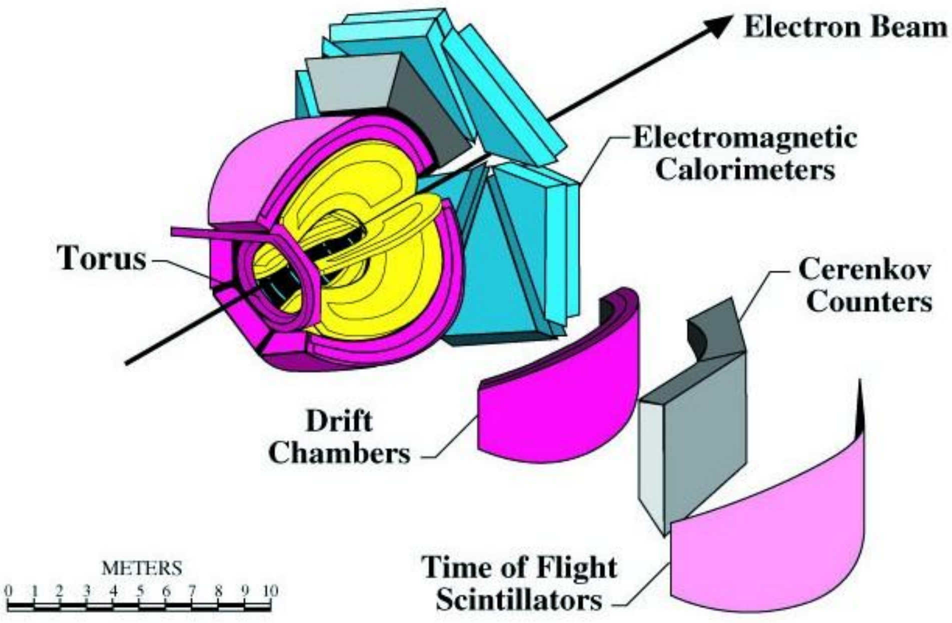
- Demand electron enter calorimeter safely away from edges
- Demand energy deposit as function of depth in ECAL be uneven
- Adjust vertex Z position for sector-by-sector beam offset
- Demand momentum of outgoing e-: p>0.64 GeV (or y<0.872) (removes bias due to electromagnetic energy threshold in trigger)
- Implement "relatively" easy to model cuts in W, $Q^2$, $\theta$ for the electron and $p_\pi$, $\theta_\pi$ for the pion



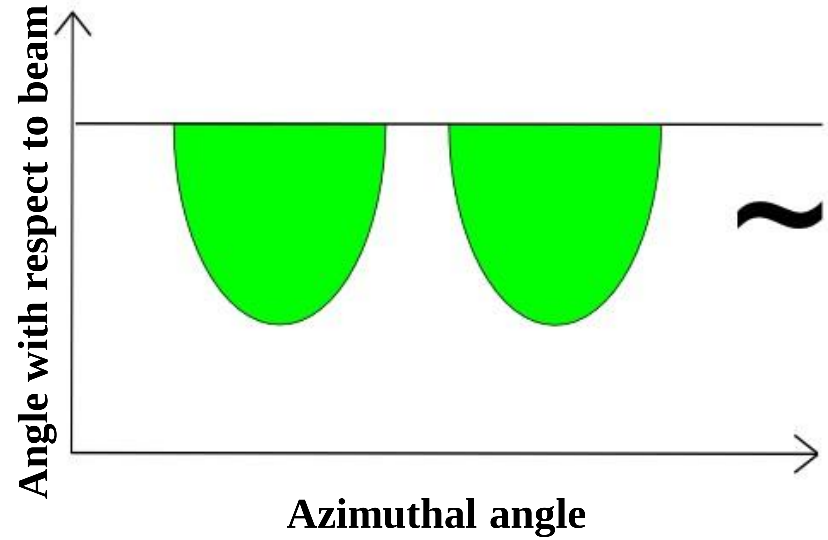



# Fiducial volume complications

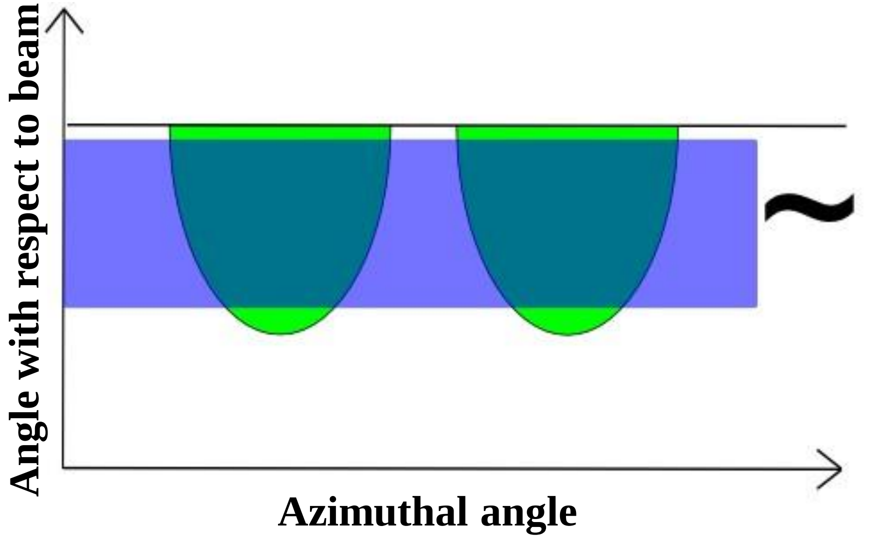



*Six azimuthal regions of angular acceptance that are a function of $\theta$, p, charge*

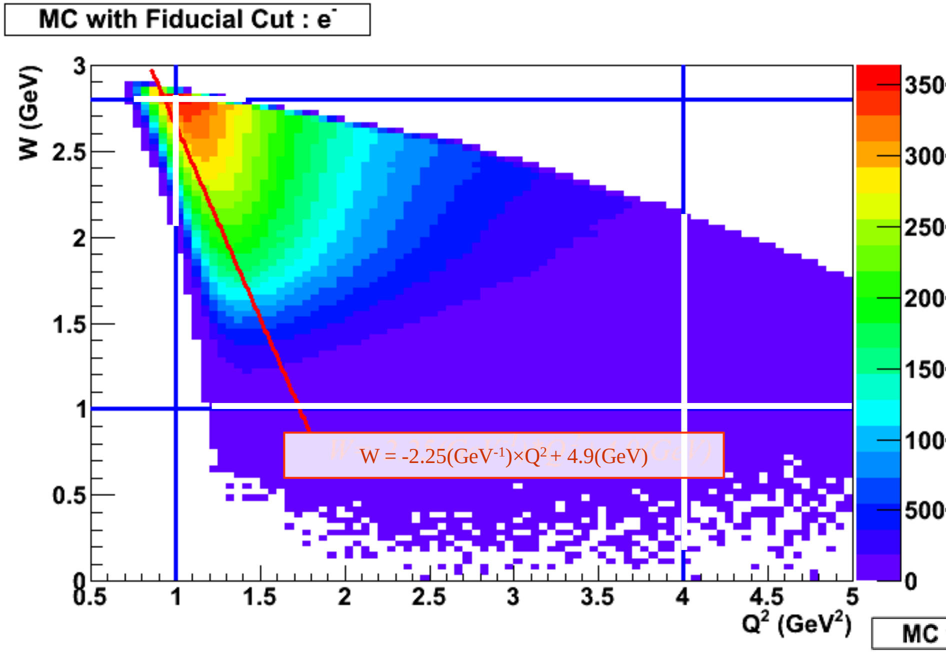



- The optimal fiducial regions for the detector are not conveniently modeled for comparison to calculations

# Fiducial volume complications

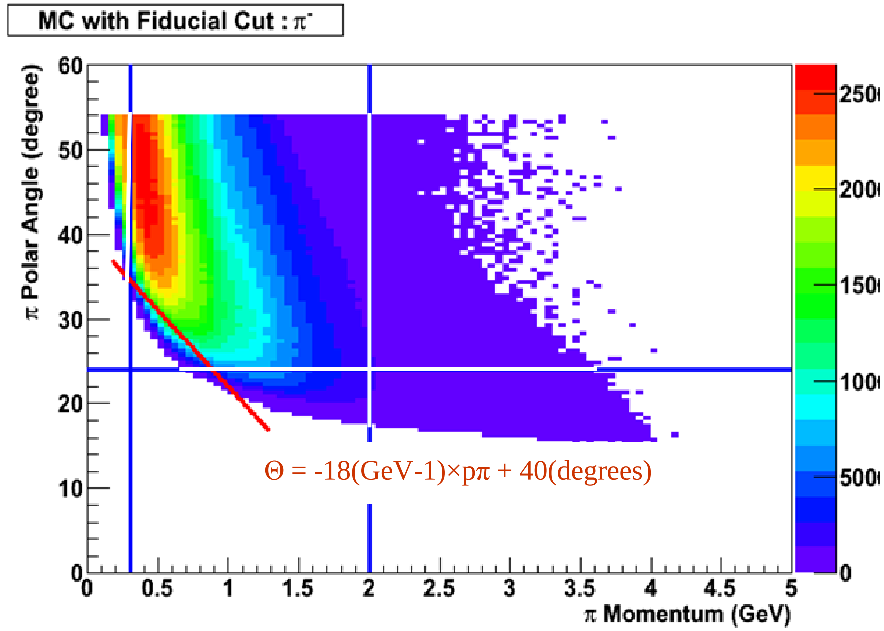



➢ Report results with geometric correction to be azimuthally symmetric
➢ Implement "relatively" easy to model cuts in W, $Q^2$, $\theta$ for the electron and $p_\pi$, $\theta_\pi$ for the pion




For $e^-$

- ➢ $y>0.872$
- ➢ $1\,GeV^2<Q^2<4\,GeV^2$
- ➢ $1\,GeV<W<2.8\,GeV$
- ➢ red line shown

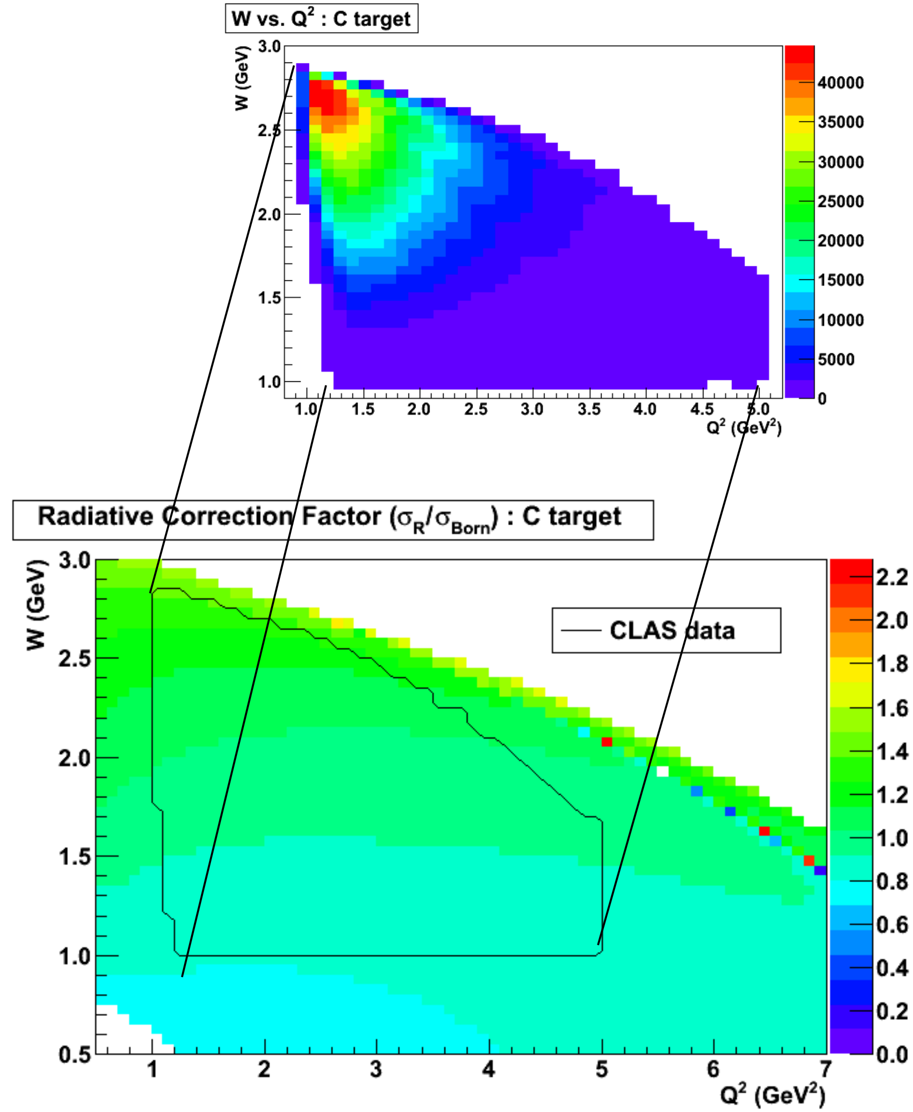



For $\pi^-$ ($\pi^+$ has distinct but similar cuts)

- ➢ $0.3<p_\pi<2$
- ➢ $24^o<\theta_\pi<54^o$
- ➢ red line shown

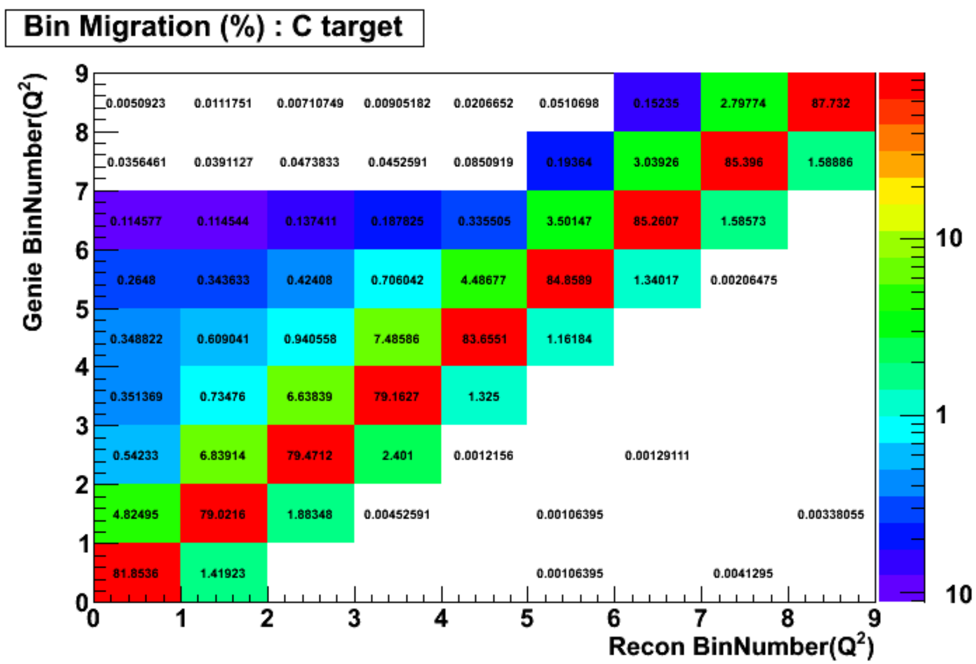
# Radiative corrections

- ➢ Use "externals_all" routine designed for EG1-DVCS experiment (P. Bosted, EG1-DVCS technical note 5, 2010)
- ➢ Calculate differential cross sections (W, $Q^2$) with and without QED radiative effects in the process.
- ➢ Remove (quasi-)elastic contribution (since we demand a pion be present)
- ➢ Only consider leptonic side (in neutrinos we don't typically worry about the radiative corrections on the hadronic side)



# Acceptance and bin migration

- ➢ Work in 4-dimensional space (W, $Q^2$, $p_\pi$, $\theta_\pi$)
- ➢ Multi-dimensional acceptance correction and bin migration correction from MC (<10%, typically smaller)
- ➢ Non-acceptance corrected GENIE distributions look very similar to the data distributions – reasonable to use the GENIE samples for the acceptance corrections.
- ➢Require at least one $\pi^\pm$ reconstructed, take leading pion as the analysis pion
- ➢ MC indicates single $\pi^\pm$ sample to originate from ~40% percent single $\pi^\pm$ with most of the rest from multiple $\pi$ events.
- ➢ Missing mass analysis improves single-$\pi$ purity with a big loss in statistics.  Not using for current results.



# Caveats

- All results shown here are preliminary
- The errors shown are statistical only
- Systematic errors are under investigation
- Expectation/goal is to hold the systematic errors to <10%
- Vast amount of differential data.  Only sampling shown here.
- Ask if you want to see preliminary result on something I do not have time to show here.

# Systematics (under study)

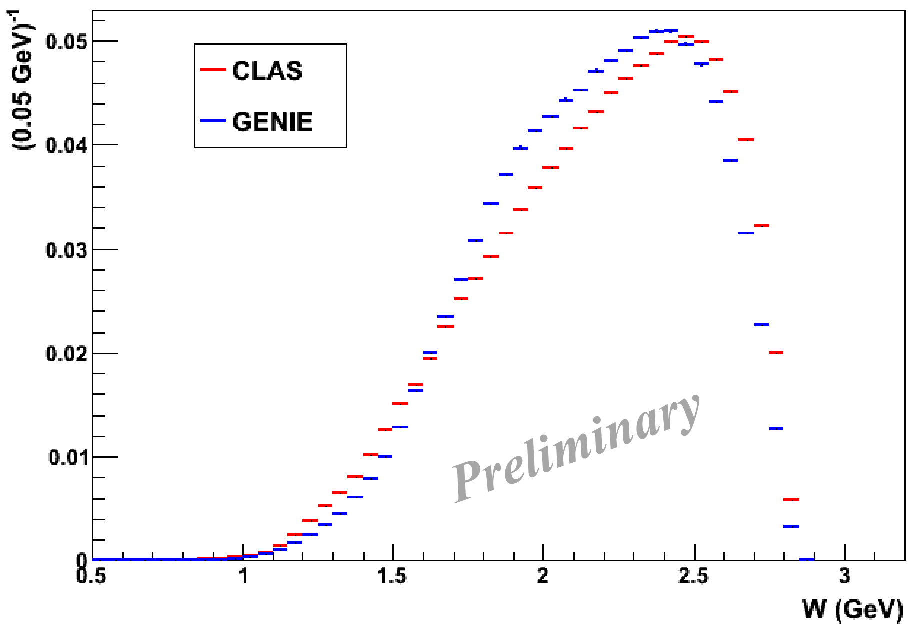
- observed pion/beam current stability
- target thickness
- acceptance stability with different generator
- also have haprad implemented for radiative corrections
- Integrated total x-secs agree roughly with GENIE
- Looking to compare with published delta xsec measurements
- May release ratios

# Data-MC comparison

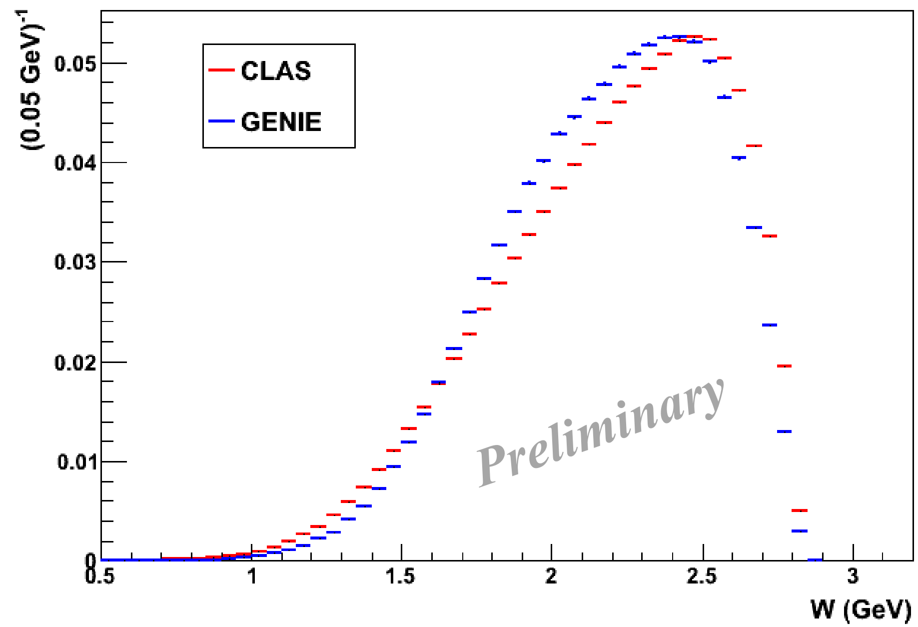
(no acceptance corrections, detector optimized fiducial definition)

- GENIE events run through CLAS detector simulation (GSIM) with EG2 target geometry and same analysis chain as data
- Require single $\pi^{\pm}$ reconstructed

Deuterium




Carbon



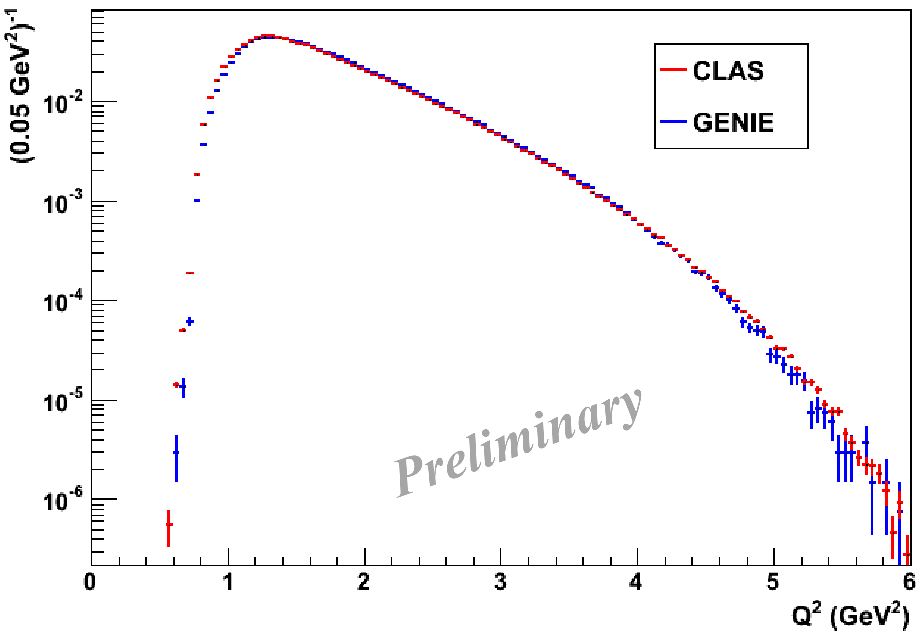

W distribution (other variables integrated over)

# Data-MC comparison

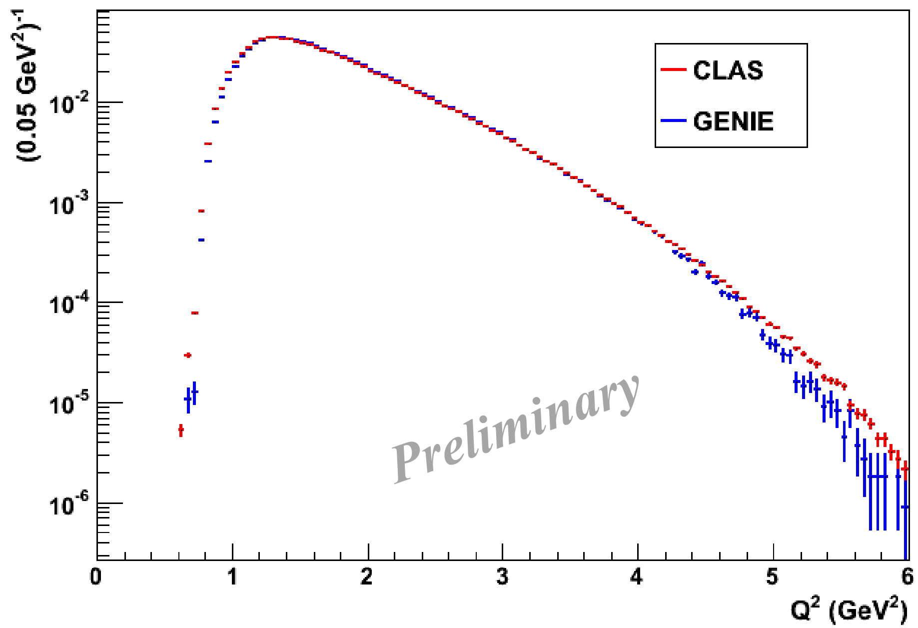
Using GENIE version 2.5.1

(no acceptance corrections, detector optimized fiducial definition)

Deuterium




Carbon



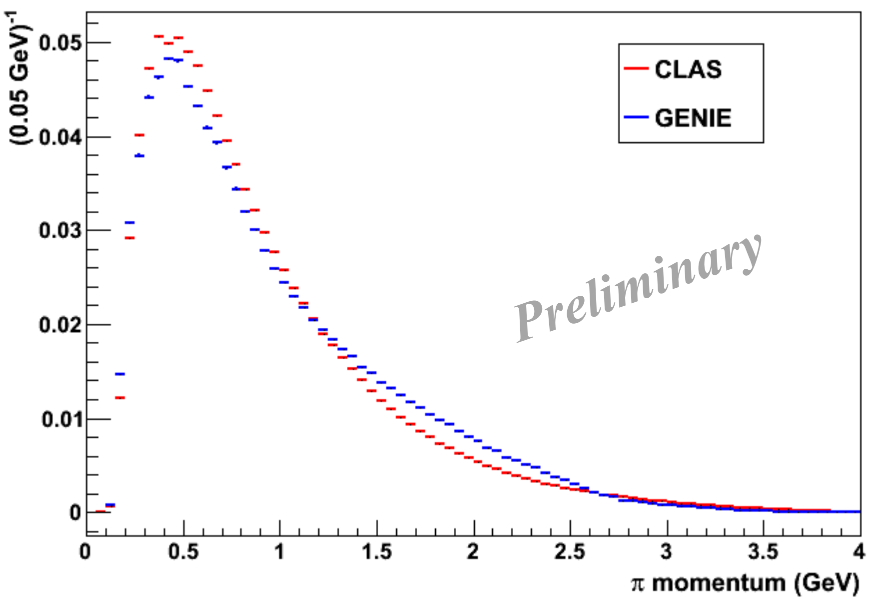

$Q^2$ distribution (other variables integrated over)

# Data-MC comparison

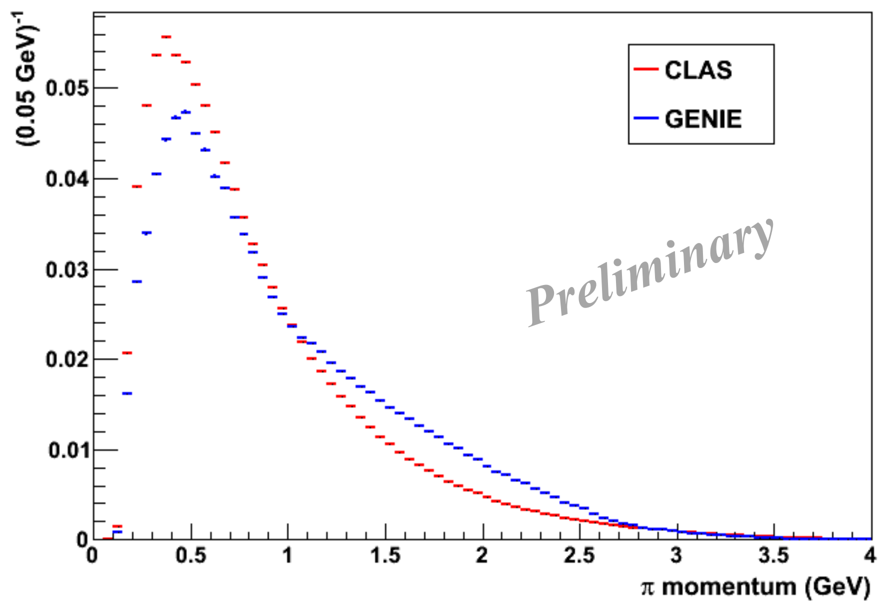
(no acceptance corrections, detector optimized fiducial definition)

Using GENIE version 2.5.1

Deuterium




Carbon




Momentum of $\pi$ in the lab frame

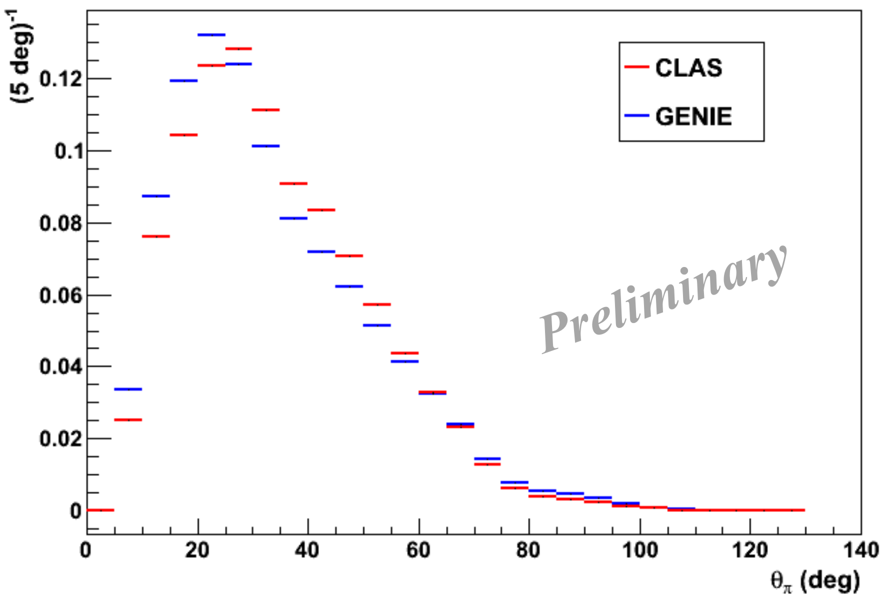
(other variables integrated over)

Using GENIE version 2.5.1

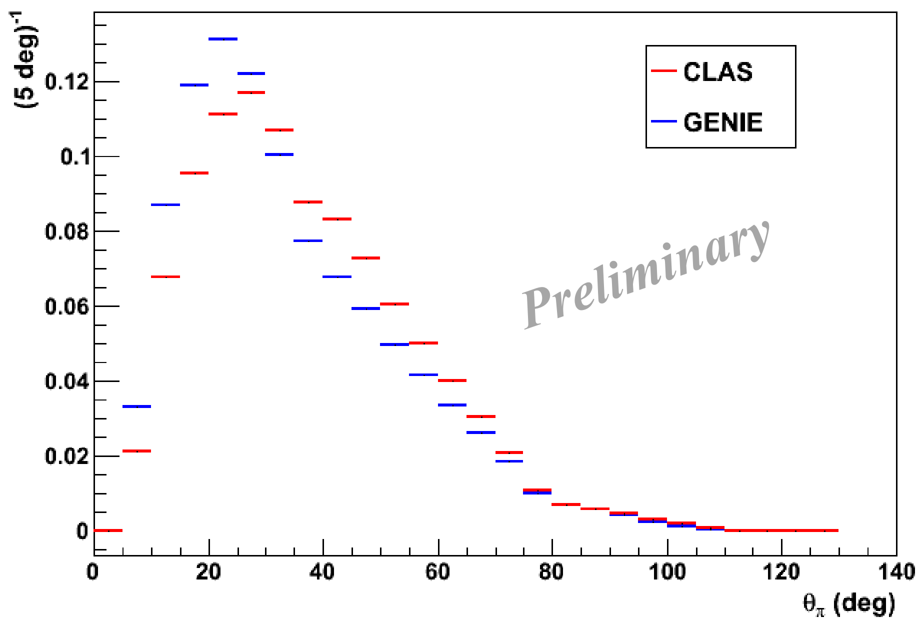
# Data-MC comparison

(no acceptance corrections, detector optimized fiducial definition)

Deuterium



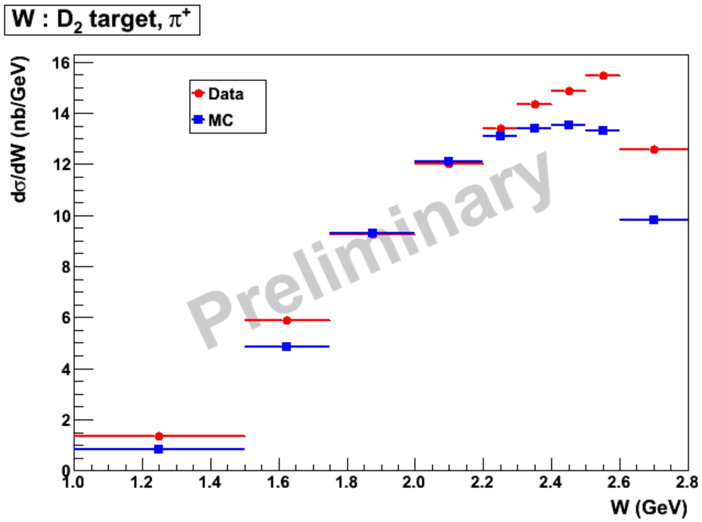

Carbon

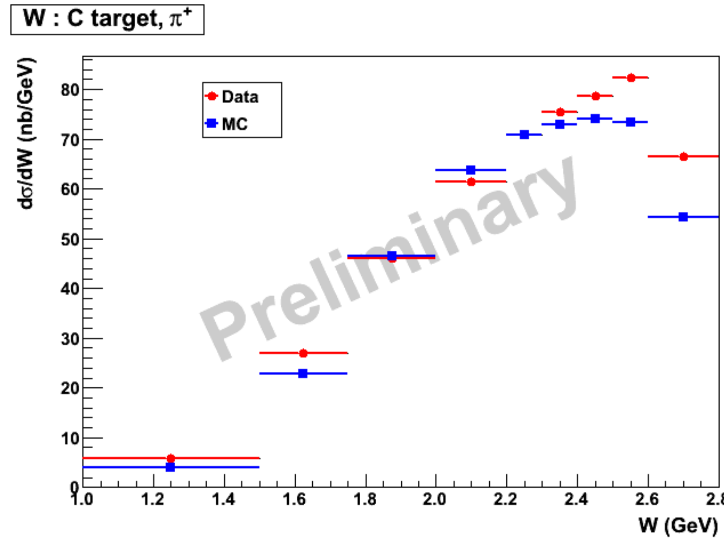



Angle of π with respect to the beam direction
(other variables integrated over)

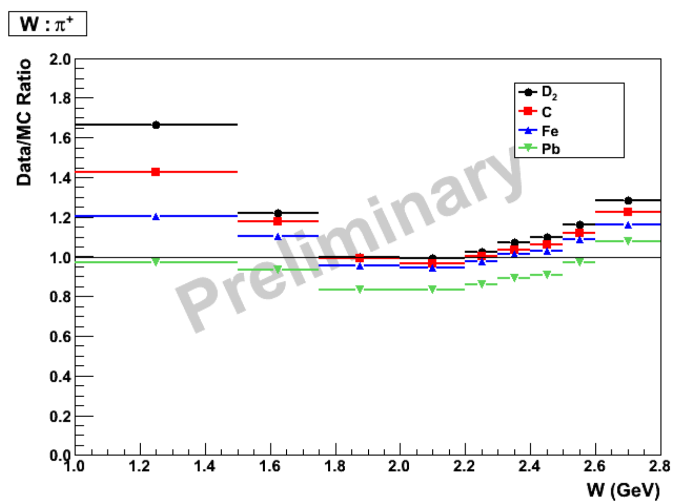
# Data-MC comparison

(Comparison friendly fiducial region, corrected for acceptance and radiative effects, only statistical errors shown , three variables integrated over)



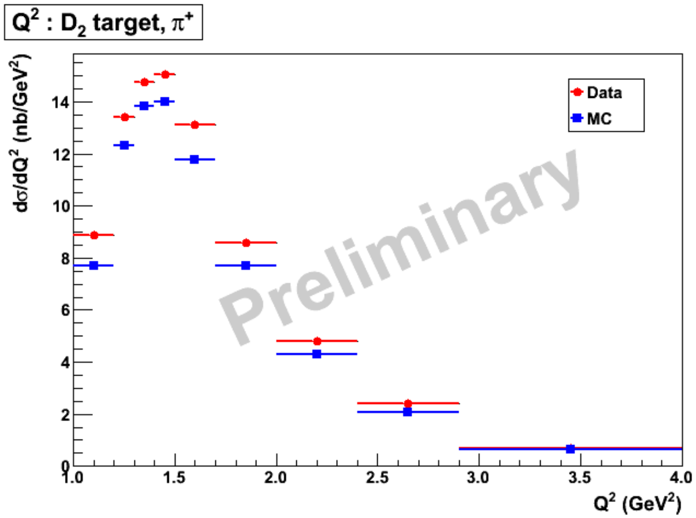

W, $\pi^+$

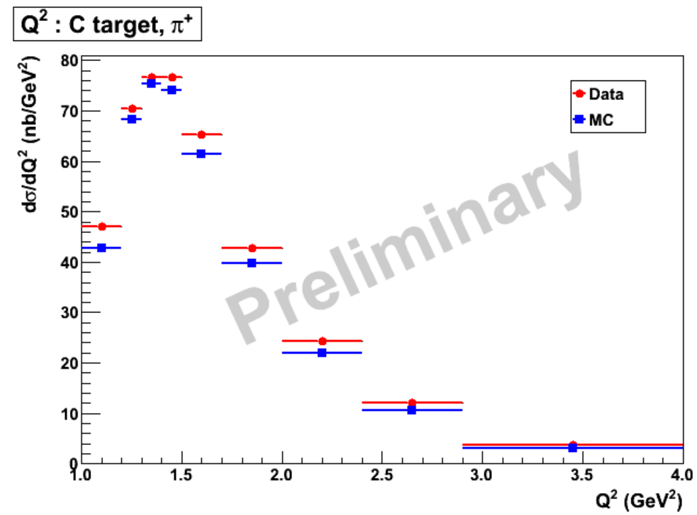



Data/MC ratio, all targets

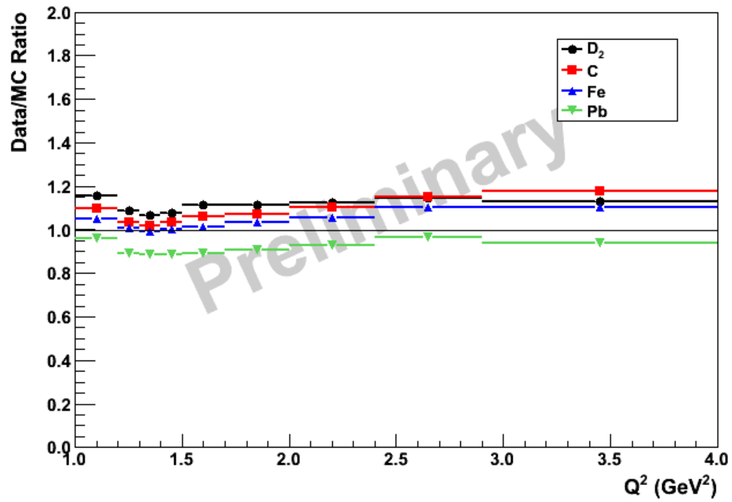
# Data-MC comparison

(Comparison friendly fiducial region, corrected for acceptance and radiative effects, only statistical errors shown , three variables integrated over)



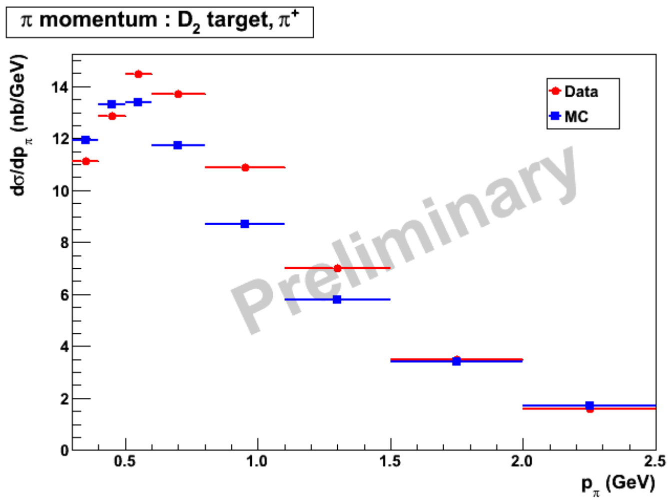

$Q^2$, $\pi^+$

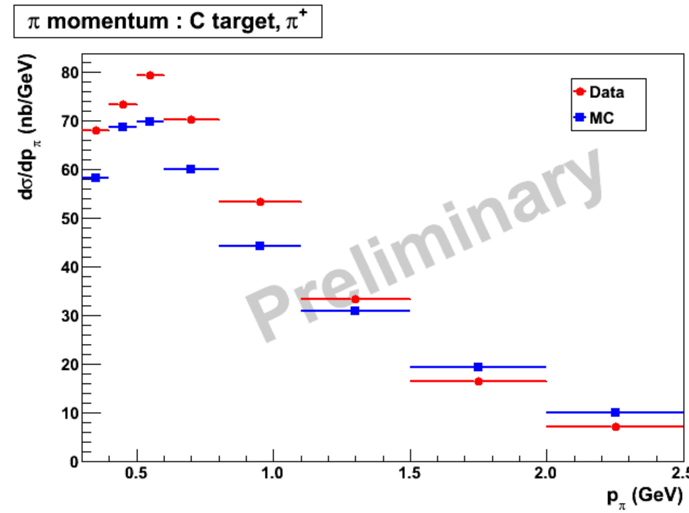



Data/MC ratio, all targets

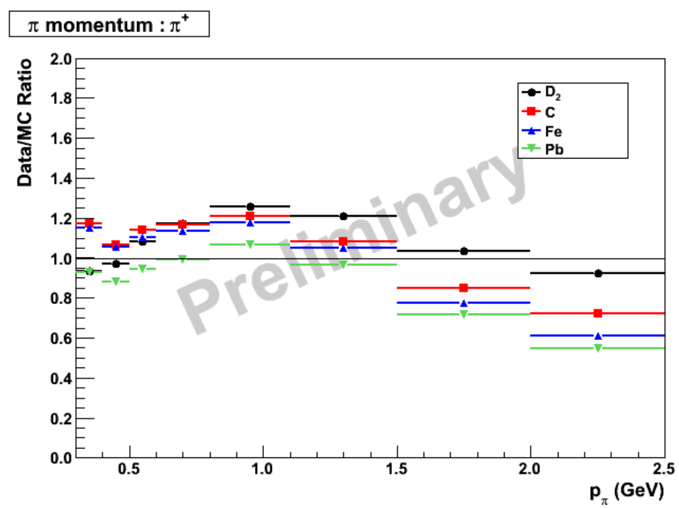
# Data-MC comparison

(Comparison friendly fiducial region, corrected for acceptance and radiative effects, only statistical errors shown , three variables integrated over)



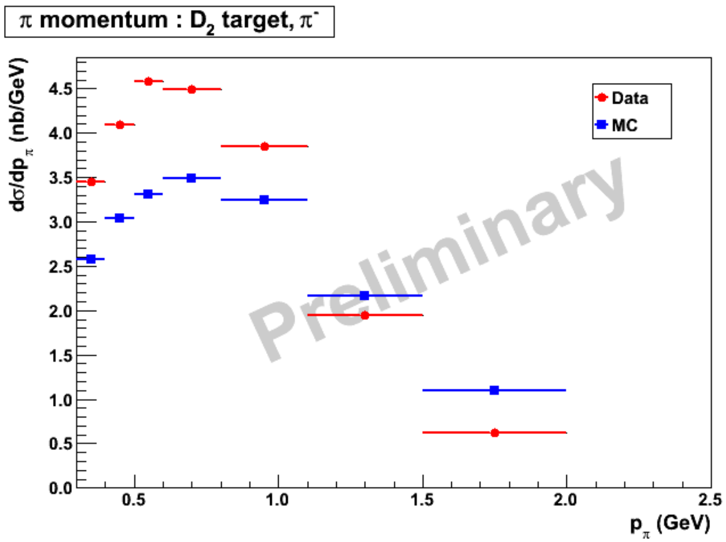

$p_\pi$, $\pi^+$

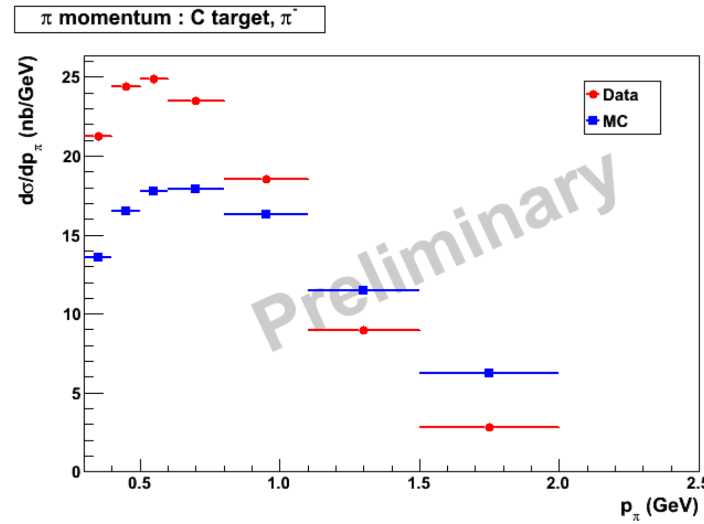



Data/MC ratio, all targets

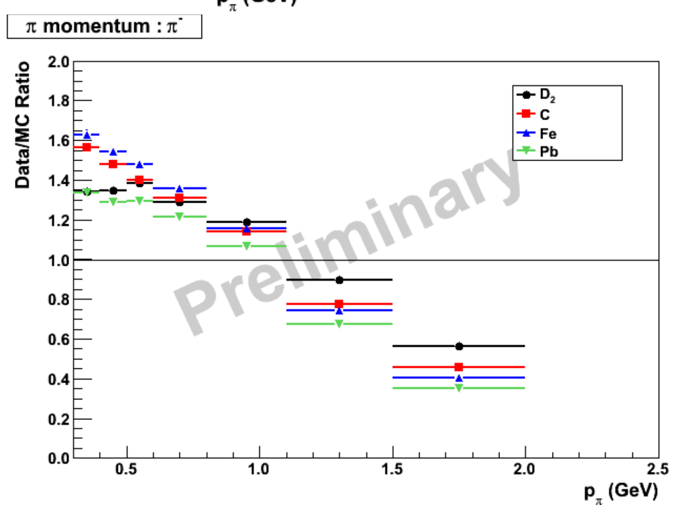
# Data-MC comparison

(Comparison friendly fiducial region, corrected for acceptance and radiative effects, only statistical errors shown , three variables integrated over)




$p_{\pi}$, $\pi^{-}$




Data/MC ratio, all targets

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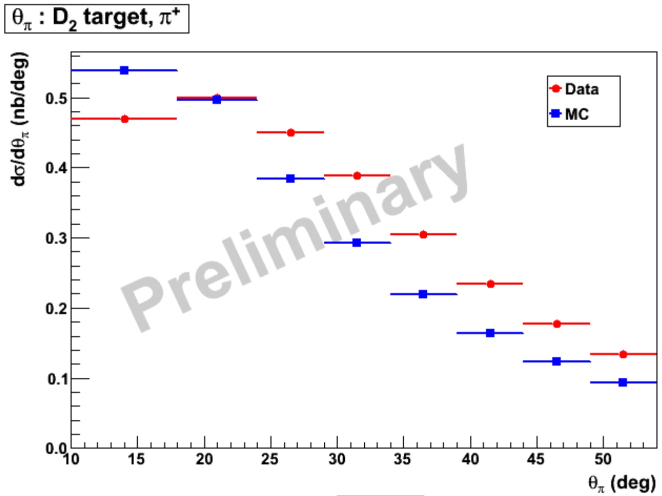
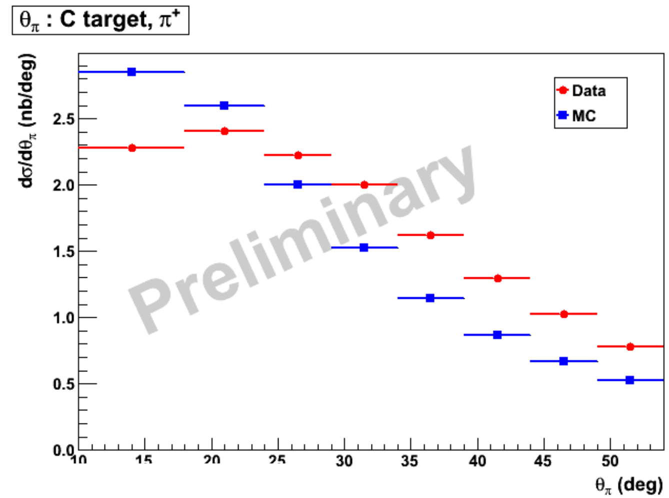
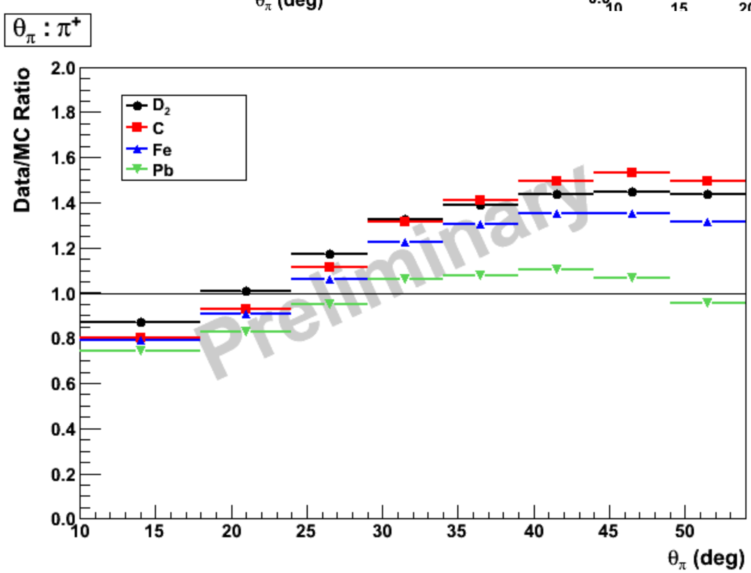
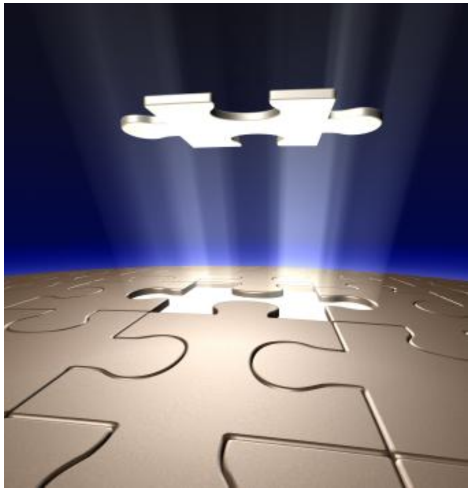



$\theta_\pi$, $\pi^+$



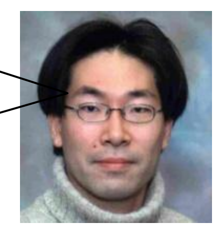

Data/MC ratio, all targets



High precision neutrino results are a product of many pieces carefully fit together

- CLAS/EG2 is making significant progress toward releasing multi-dimensional precision $\pi^{\pm}$ production cross-sections on different nuclei in a region of phase space relevant for the current precision neutrino physics program.  We hope for final results to be released in the spring/early summer.

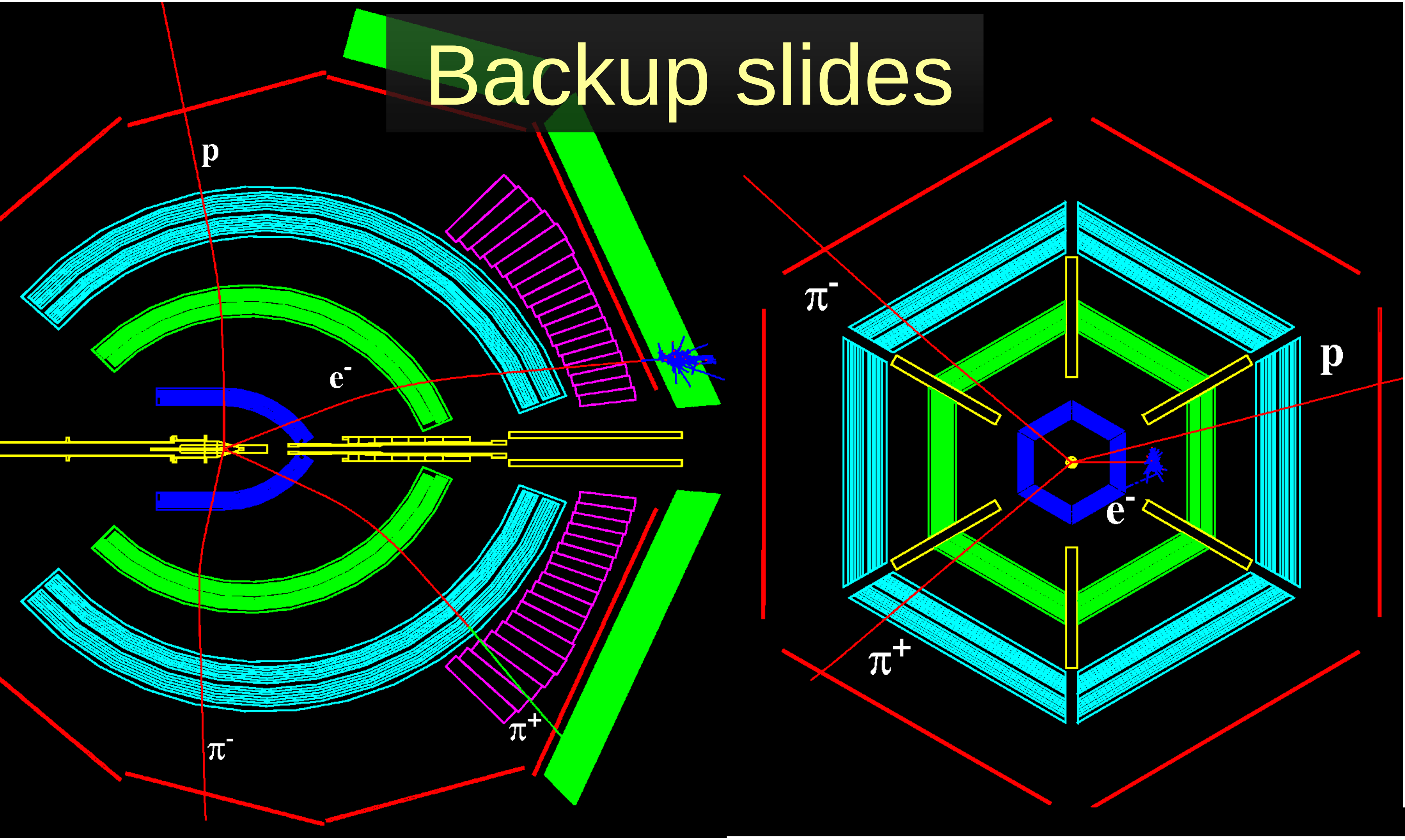
Let's finish this up.  I need to graduate!



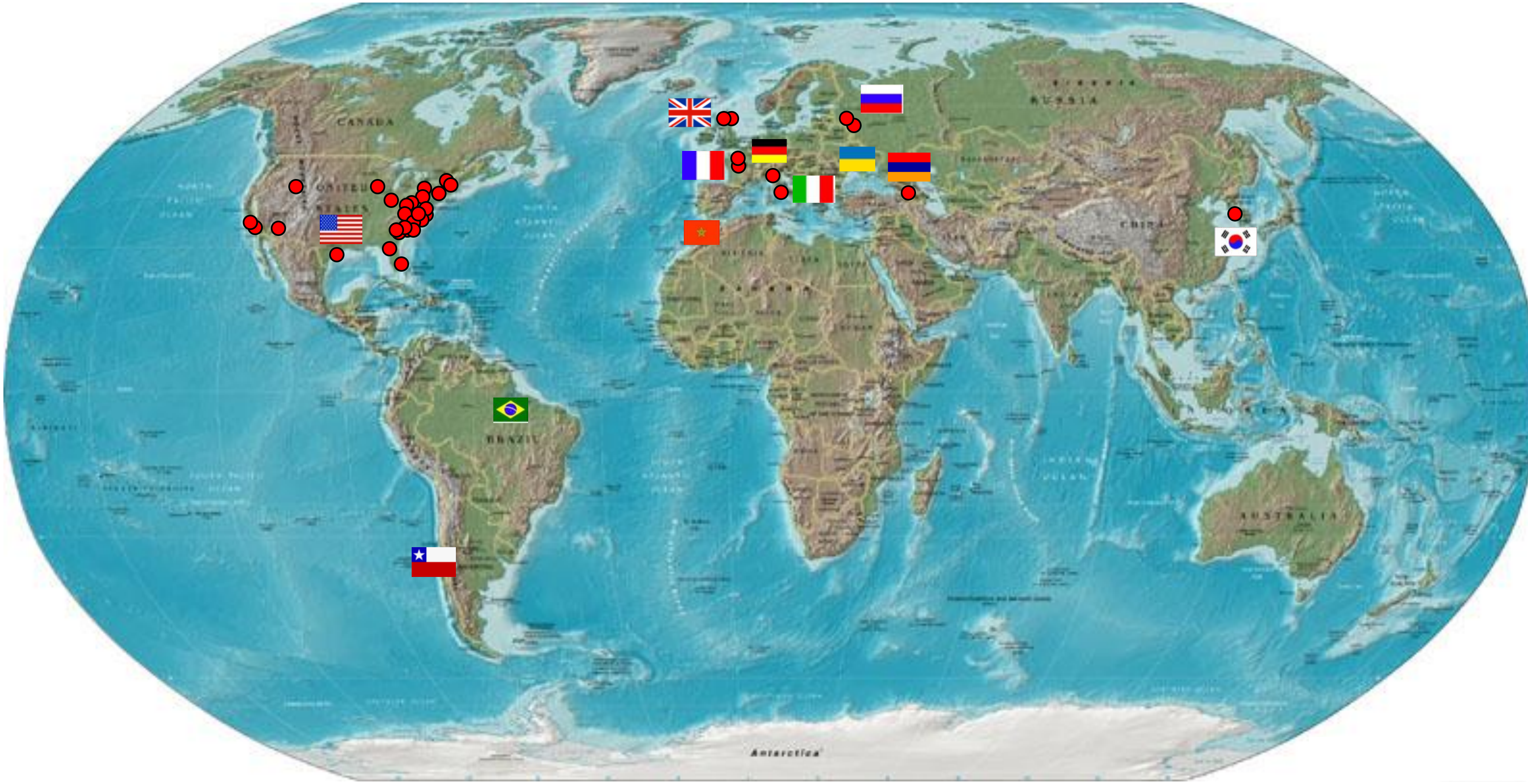
# Wish list?

- Limited capacity to do much beyond this, but …
- If your favorite generator (or new and improved release) has eA mode that produces output we can digest, we can include, *in principle*, comparisons with data in paper (data will be generally available for comparison after paper published). Probably need the MC in ~February (takes a month to generate the events for comparison).
- Conversation with Jan Sobczyk over breakfast: look at W over single pion threshold and use missing mass to measure events with zero pions. Will have low stats, but only two dimensions.

# Backup slides



# The CLAS Collaboration



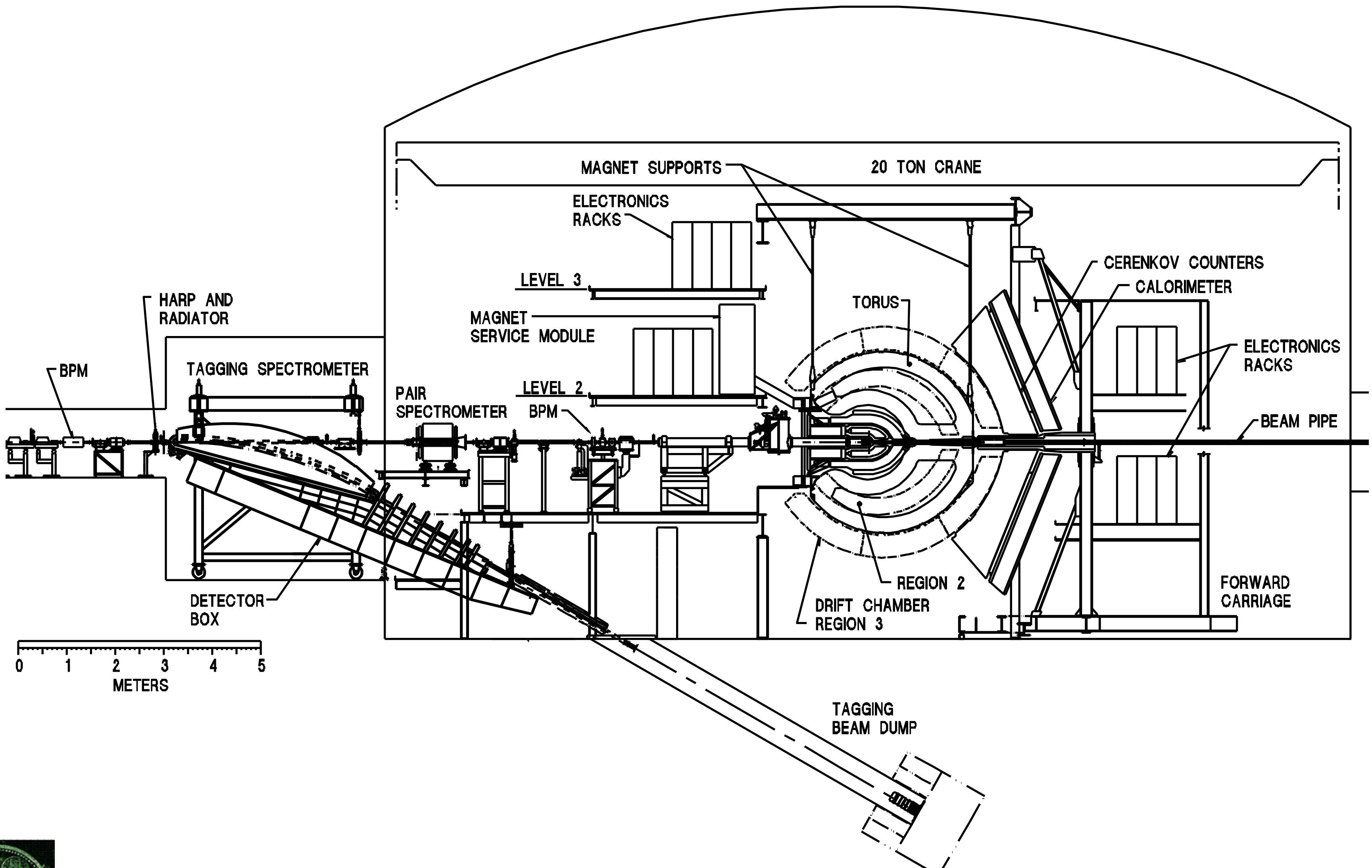
Arizona State University, Tempe, AZ
University of California, Los Angeles, CA
California State University, Dominguez Hills, CA
Carnegie Mellon University, Pittsburgh, PA
Catholic University of America
CEA-Saclay, Gif-sur-Yvette, France
Christopher Newport University, Newport News, VA
University of Connecticut, Storrs, CT
Edinburgh University, Edinburgh, UK
Florida International University, Miami, FL
Florida State University, Tallahassee, FL
George Washington University, Washington, DC
University of Glasgow, Glasgow, UK

Idaho State University, Pocatello, Idaho
INFN, Laboratori Nazionali di Frascati, Frascati, Italy
INFN, Sezione di Genova, Genova, Italy
Institut de Physique Nucléaire, Orsay, France
ITEP, Moscow, Russia
James Madison University, Harrisonburg, VA
Kyungpook University, Daegu, South Korea
University of Massachusetts, Amherst, MA
Moscow State University, Moscow, Russia
University of New Hampshire, Durham, NH
Norfolk State University, Norfolk, VA
Ohio University, Athens, OH
Old Dominion University, Norfolk, VA

Rensselaer Polytechnic Institute, Troy, NY
Rice University, Houston, TX
University of Richmond, Richmond, VA
University of South Carolina, Columbia, SC
Thomas Jefferson National Accelerator Facility, Newport News, VA
Union College, Schenectady, NY
Virginia Polytechnic Institute, Blacksburg, VA
University of Virginia, Charlottesville, VA
College of William and Mary, Williamsburg, VA
Yerevan Institute of Physics, Yerevan, Armenia

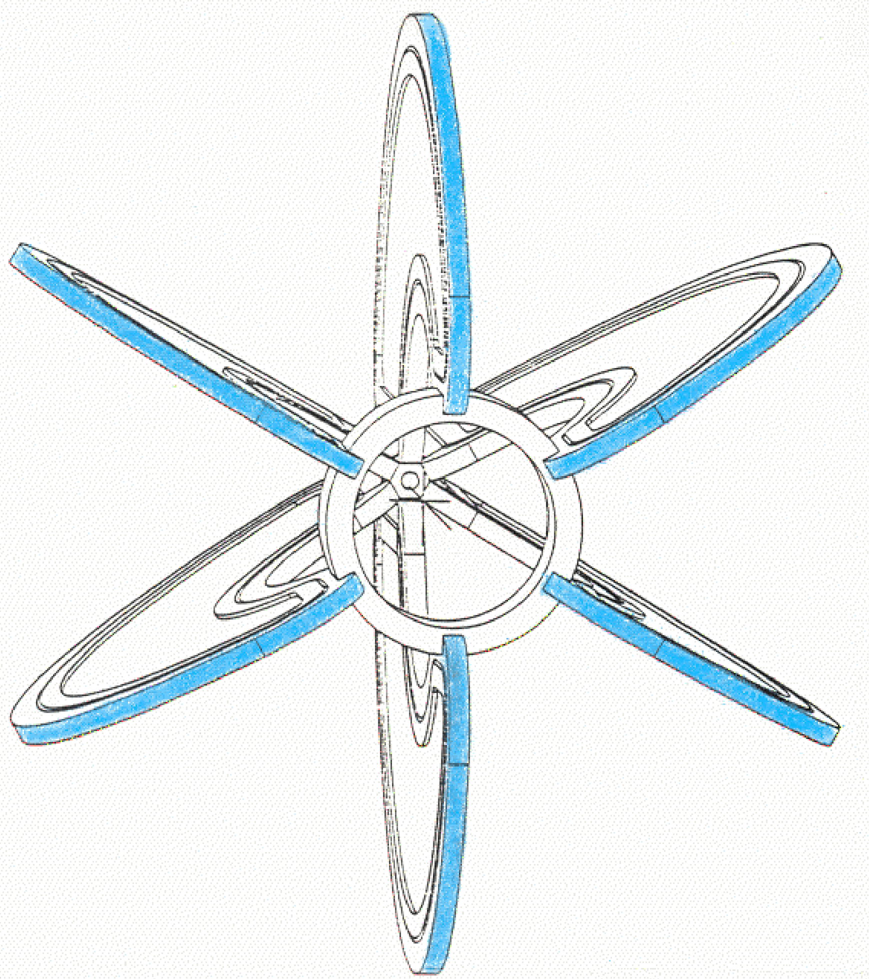
Brazil, Germany, Morocco and Ukraine,
as well as other institutions in France and in the USA,
have individuals or groups involved with CLAS,
but with no formal collaboration at this stage.

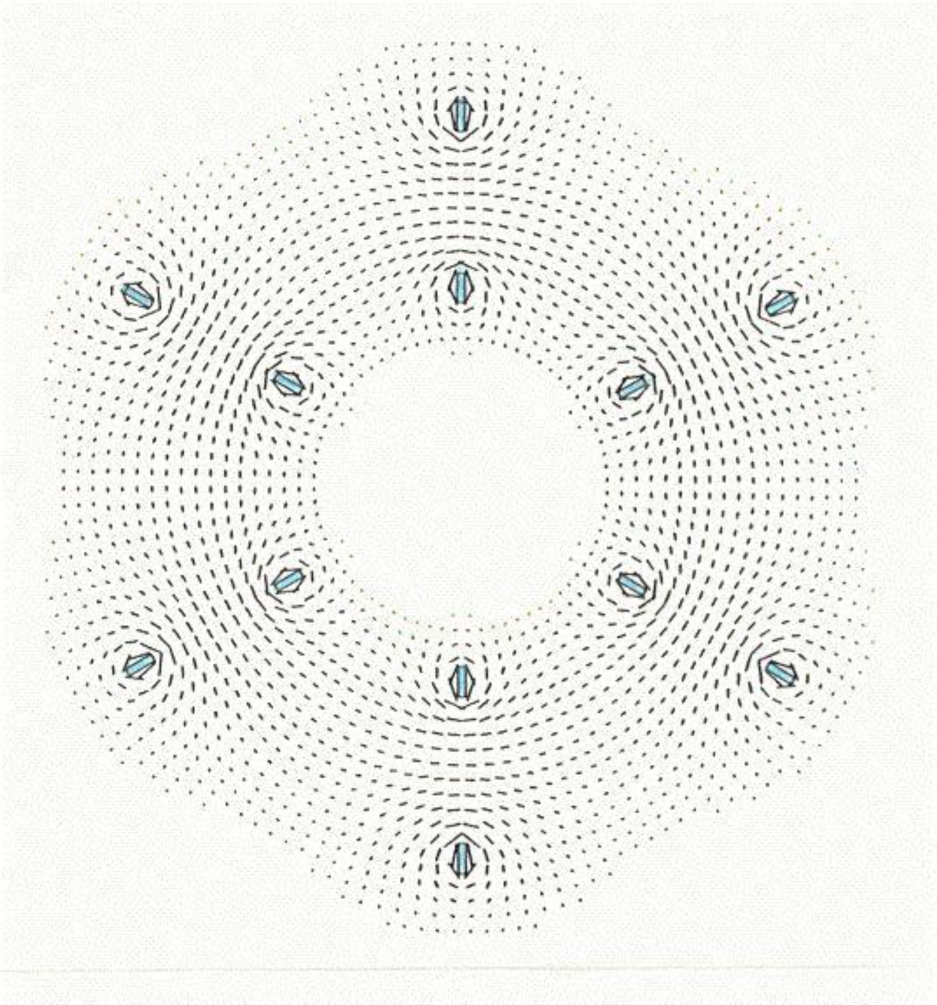
# Hall B Side View

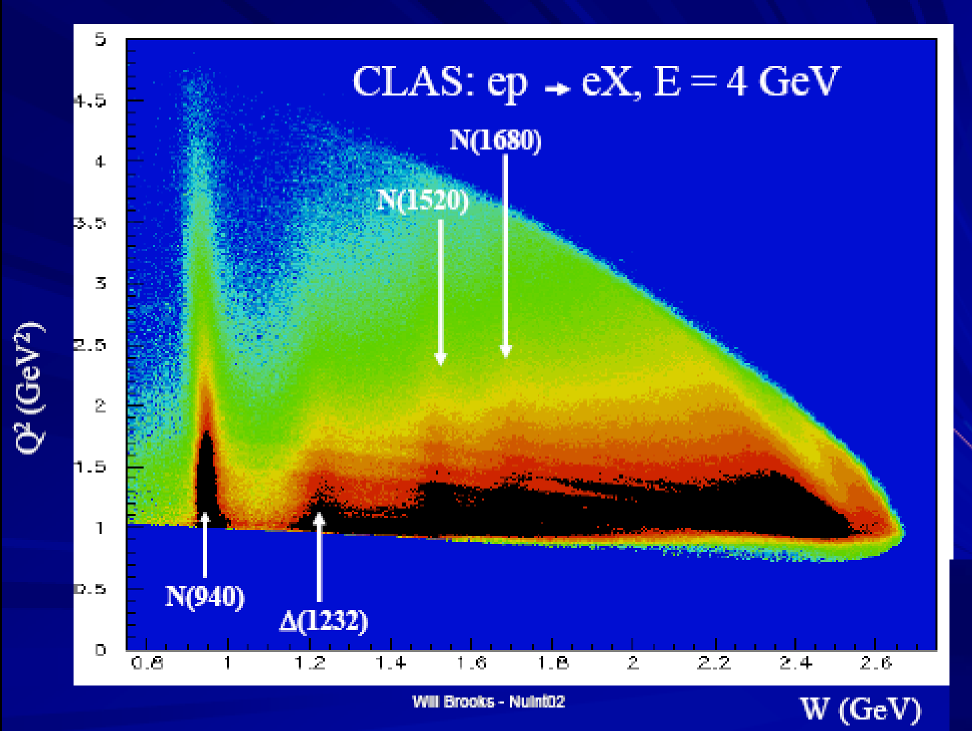


# Super-conducting toroidal magnet with six kidney-shaped coils

5 m diameter, 5 m long, 5 M-Amp-turns, max. field 2 Tesla

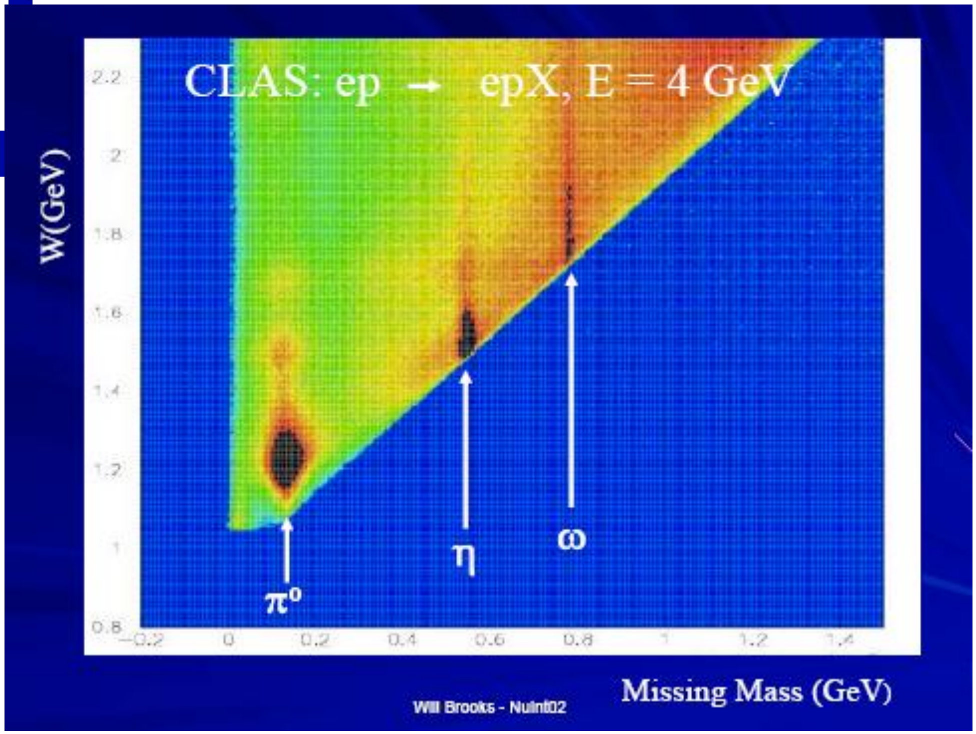






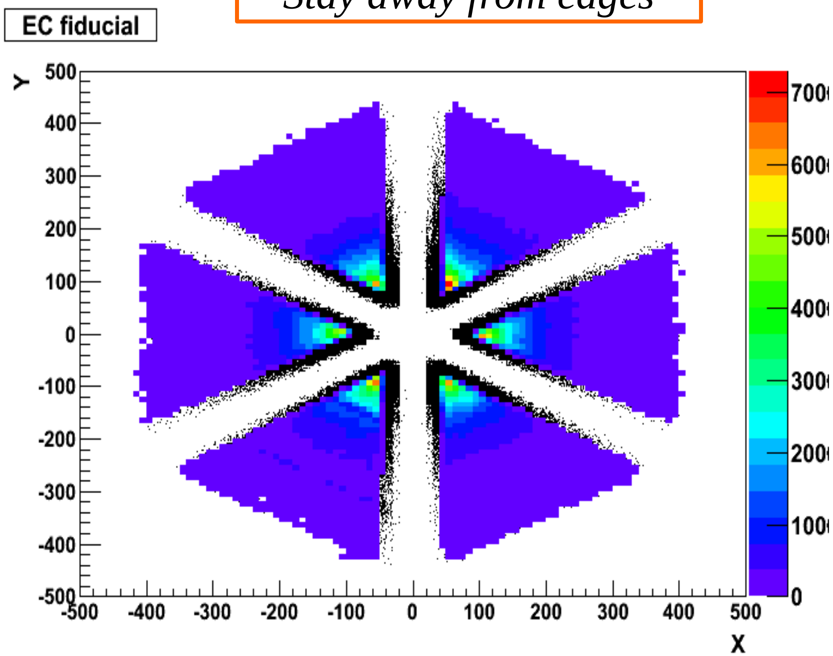

# From Will Brooks at NUINT02

*H target with $E_{beam}$ = 4 GeV illustrates the power of CLAS*

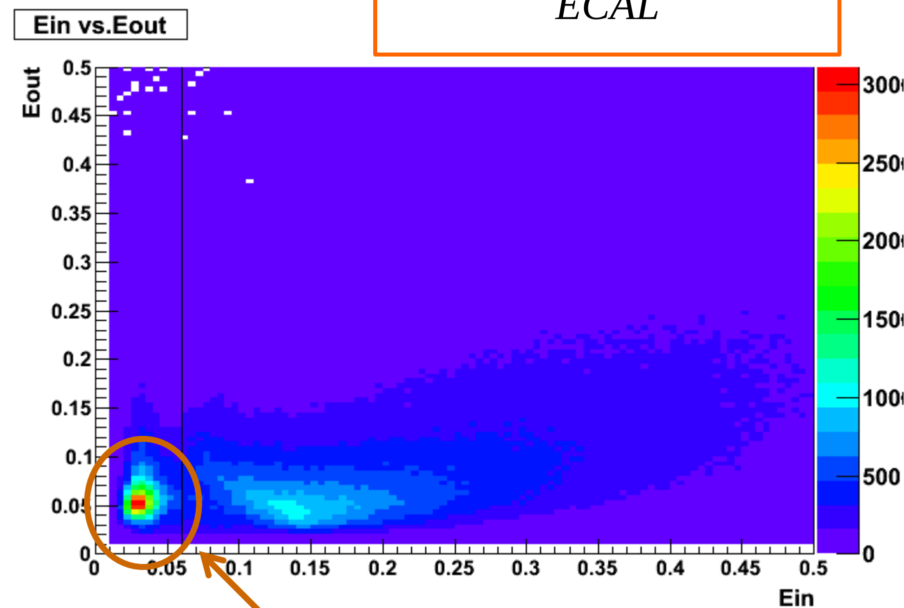


# Analysis cuts

*Stay away from edges*



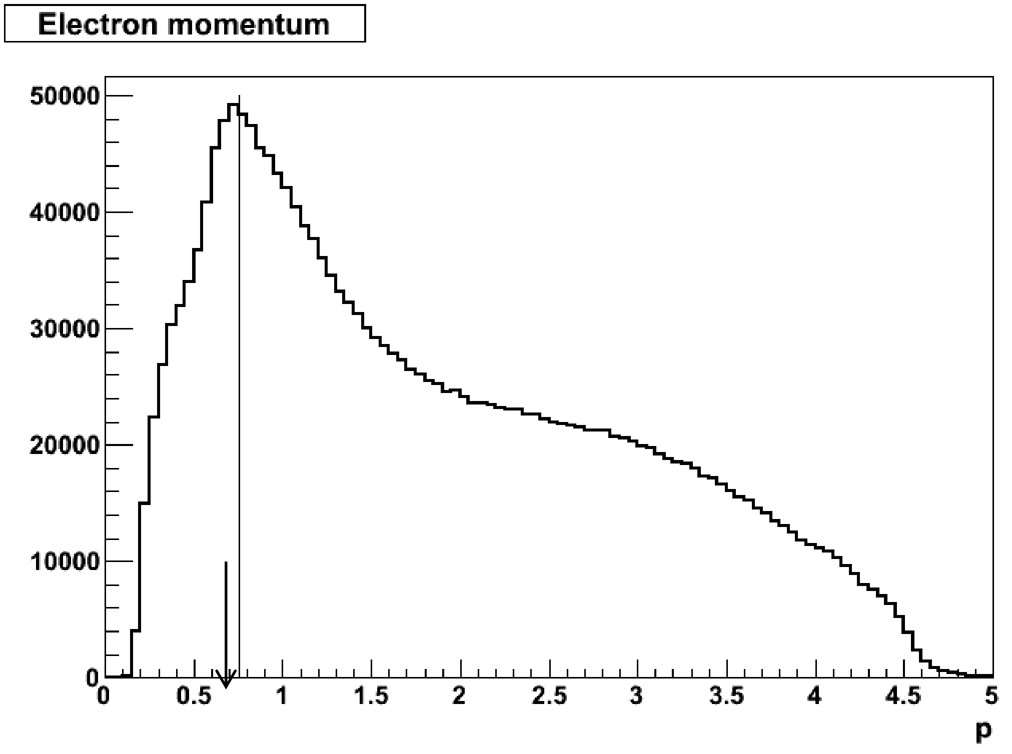

*Remove events with even energy depostion in the two layers of the ECAL*




*Mostly pions and muons*

Calorimetric fiducial and ID cuts on outgoing $e^-$

# Analysis cuts




- Momentum of outgoing e-:  p>0.64 GeV (or y<0.872)
- Removes bias due to electromagnetic energy threshold in trigger.
- Also reduces sensitivity to radiative effects.