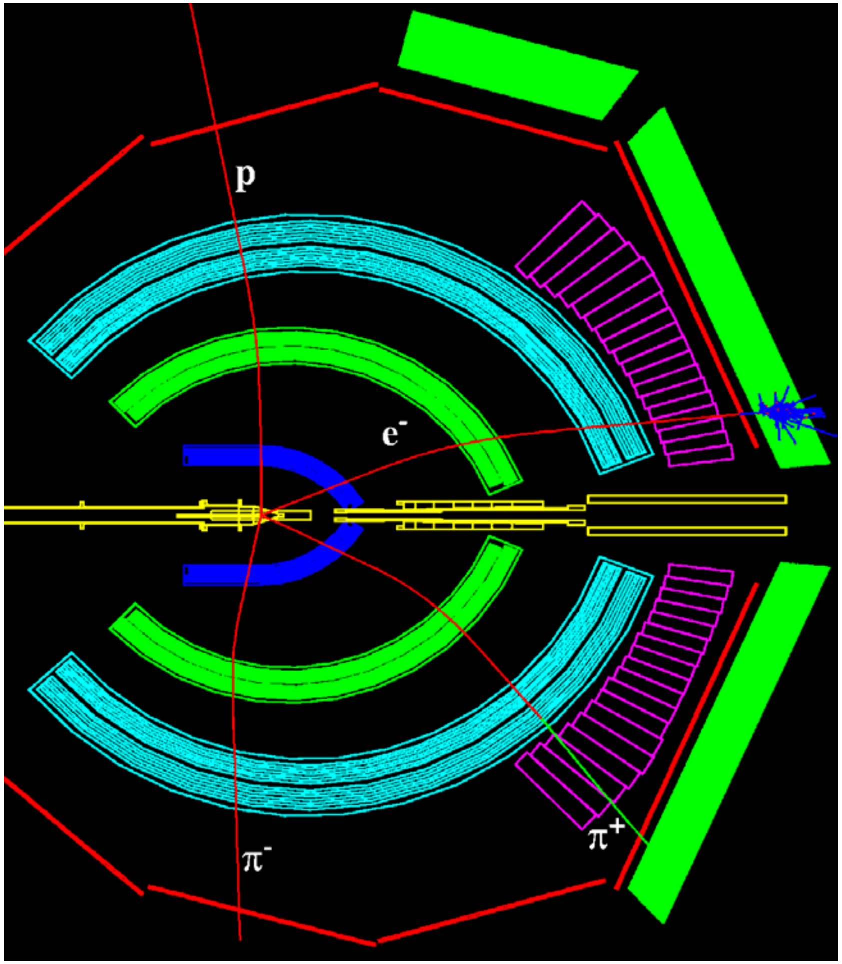
eA pion production at CLAS aimed at neutrinos



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University of Rochester

Department of Physics and Astronomy

NUINT 2014

London, May 2014

Representing the CLAS (EG-2) collaboration

Motivation – why eA?

- High statistics.

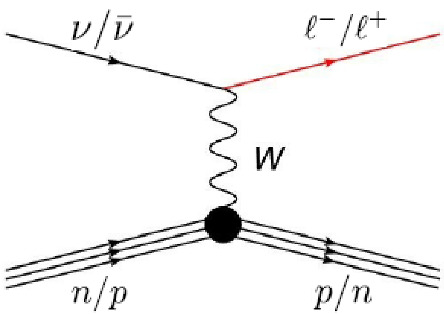
- Control over initial energy and interaction point – gives kinematic constraints and ability to optimize detector and use thin target.

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

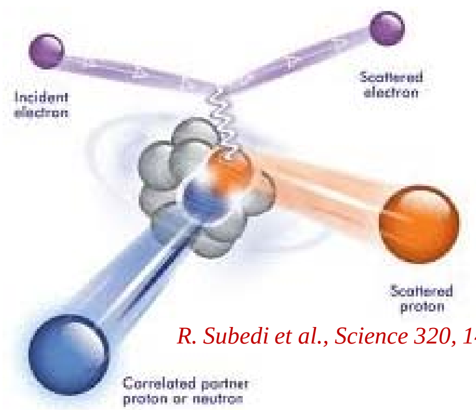
- Electron (and muon) scattering data provide a wealth of information about the **nucleon and nuclear structure** and **in-medium modifications**
  - *Nucleon Elastic Form Factors*
  - *PDFs, R, d/u, …*
  - *Resonances & QE → DIS transition, Non-Resonance Backgrounds*
  - *Nucleon momentum distributions 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

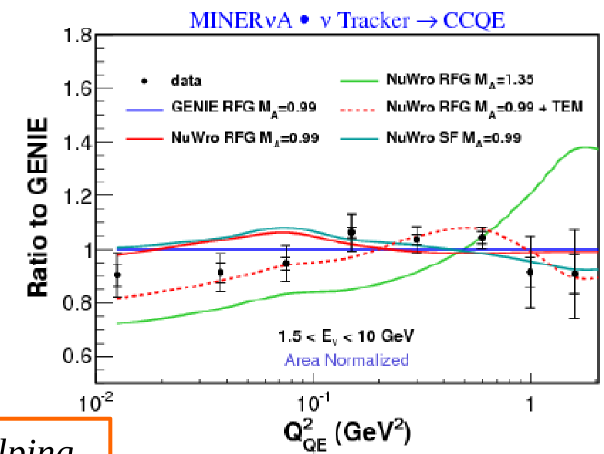
Why eA? – Hardly a need to say much to this group …



Interactions are on nuclei rather than nucleons

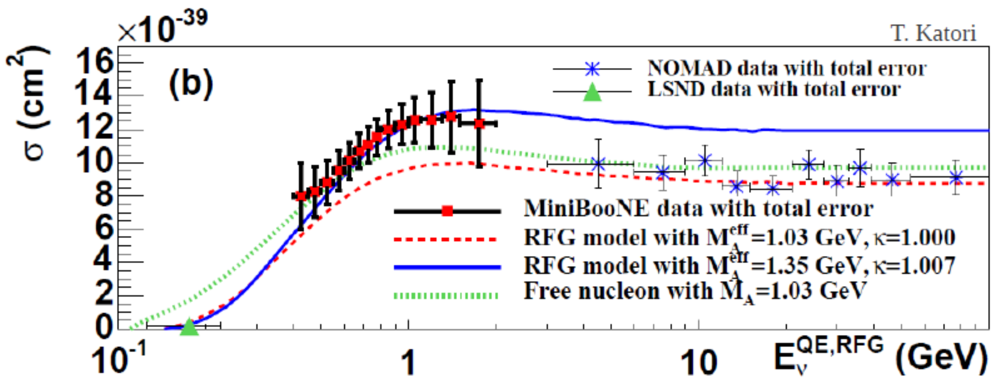


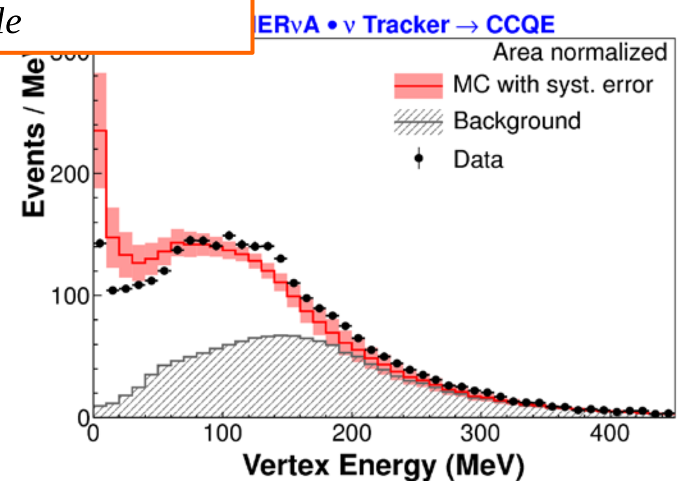
R. Subedi et al., Science 320, 1476 (2008)



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

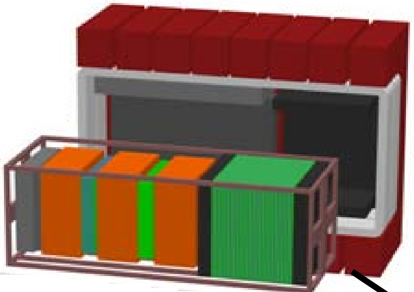
Input from eA has been important in helping us understand the potential effects of SRC and MEC, for example



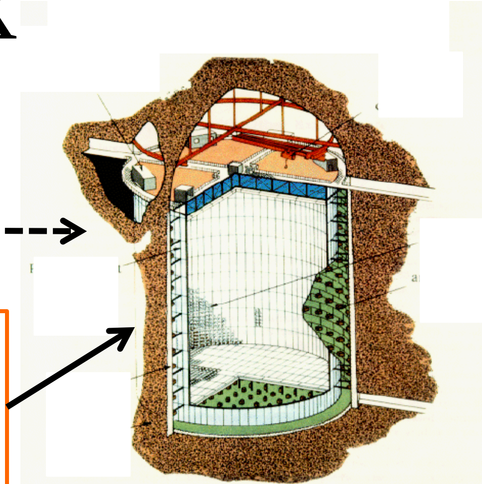


Why eA? – This work

Neutrino beam



Long baseline

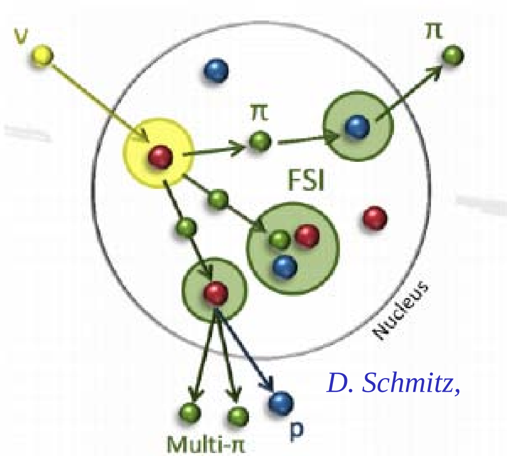


Measure flux and backgrounds in near detector and propagate to far detector and the uncertainties "cancel out"

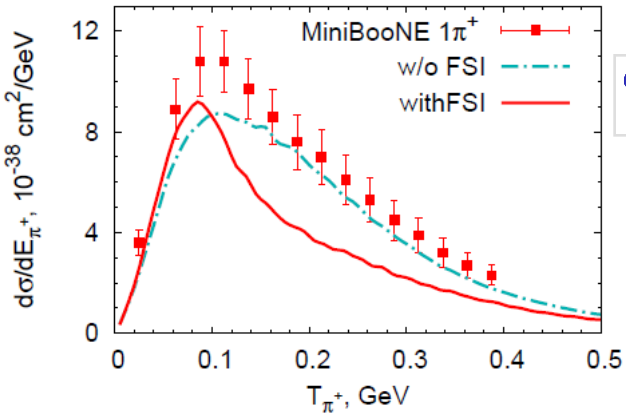
Cross-sections, nuclear effects and backgrounds don't cancel simply/completely, even in the limit of identical detectors.

<u>*Model*</u>

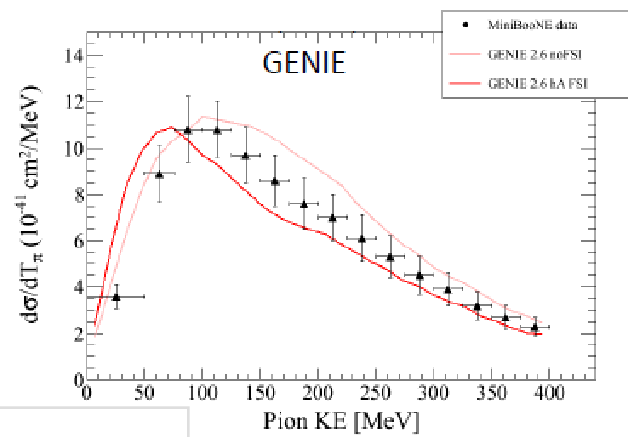
Even more important if near and far detectors are not the same material



D. Schmitz,

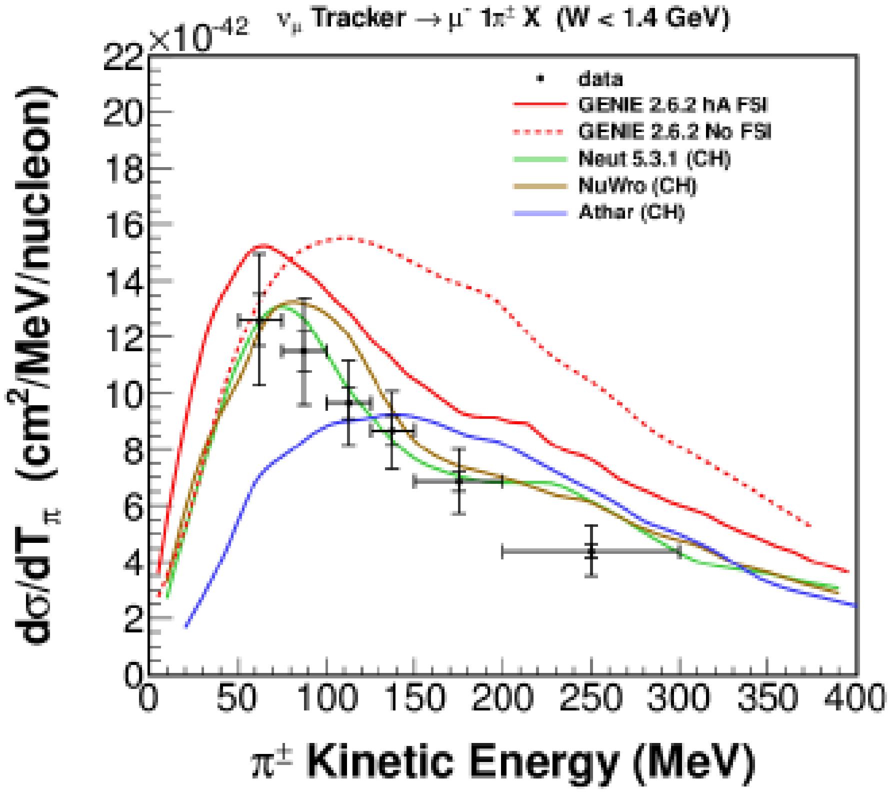


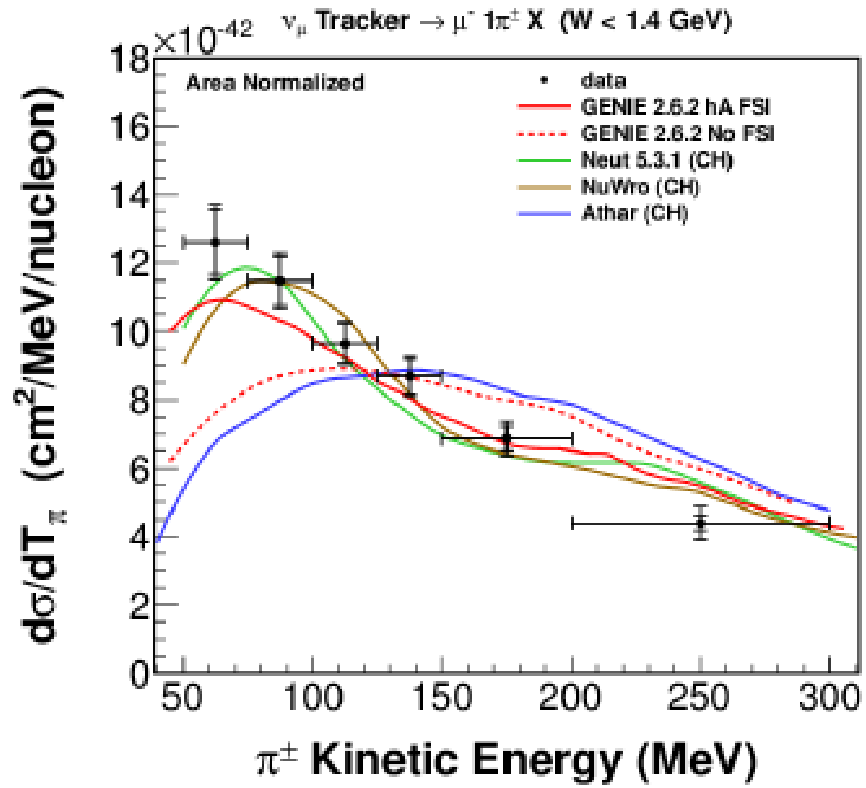
GIBUU, Lalakulich and Mosel, NUINT 2012



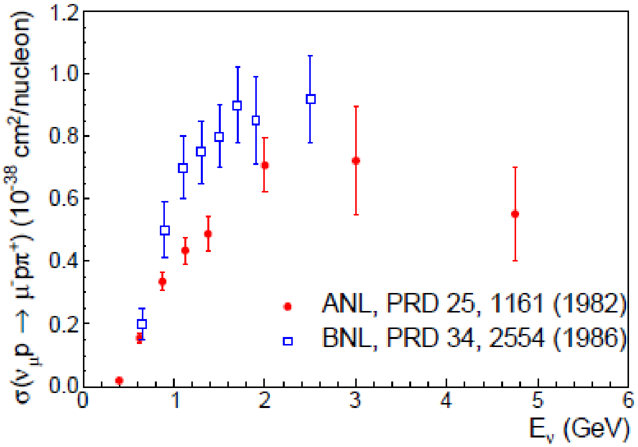
From S. Dytman via B. Eberly

MINERvA has shown preliminary results.
Expect to see final results/paper on this work soon.





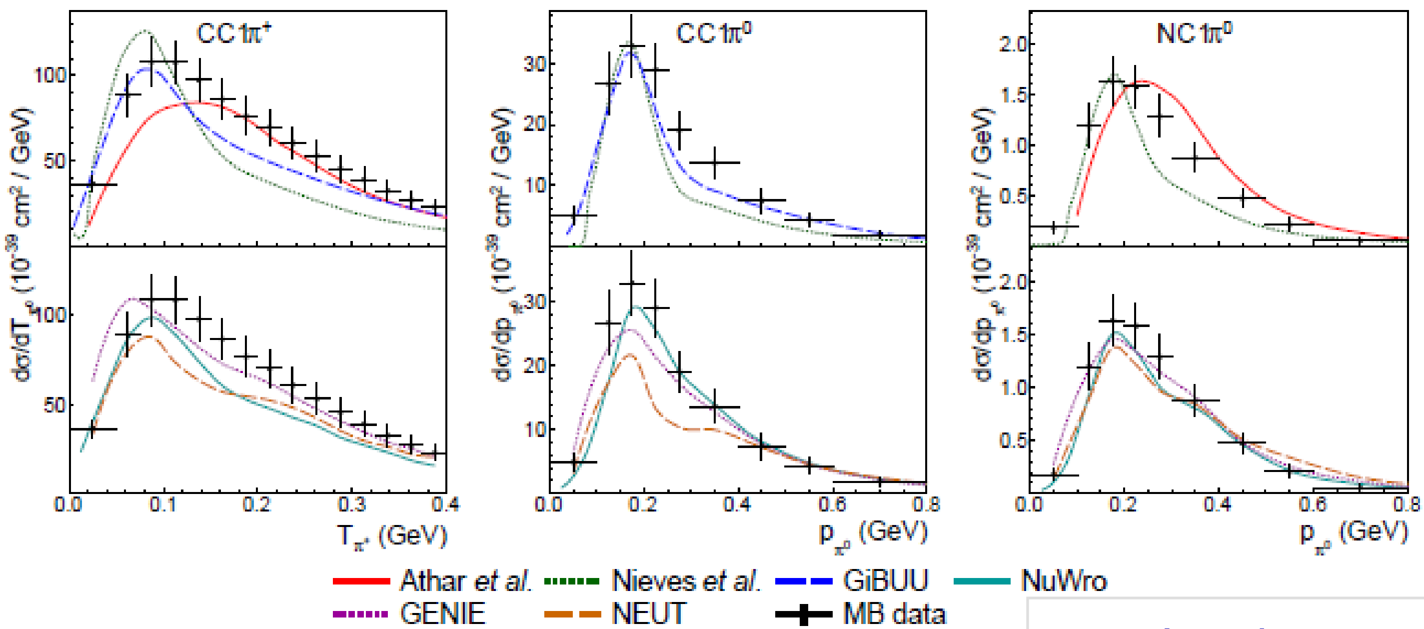
B. Eberly (MINERvA), prliminary results shown at FNAL Joint Experimental-Theoretical Seminar, Feb. 17, 2014



Old deuterium data on single pion production: large errors, inconsistent

Difficult to tune current models to describe consistently MiniBooNE differential distributions. Suggests something is problematic in our expertimental or theoretical understanding of FSI

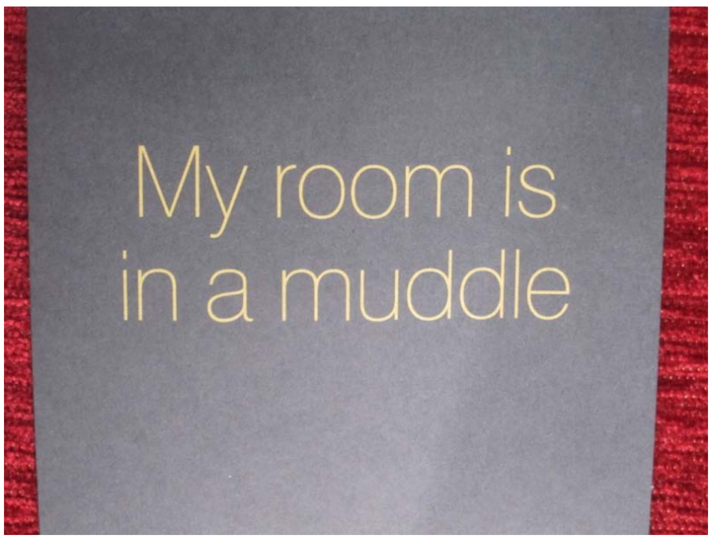
Lacking a perfect model, experiment must turn knobs to adjust model to agree with data as well as possible and estimate error induced by this process/model *AND* seek other data to help constrain model



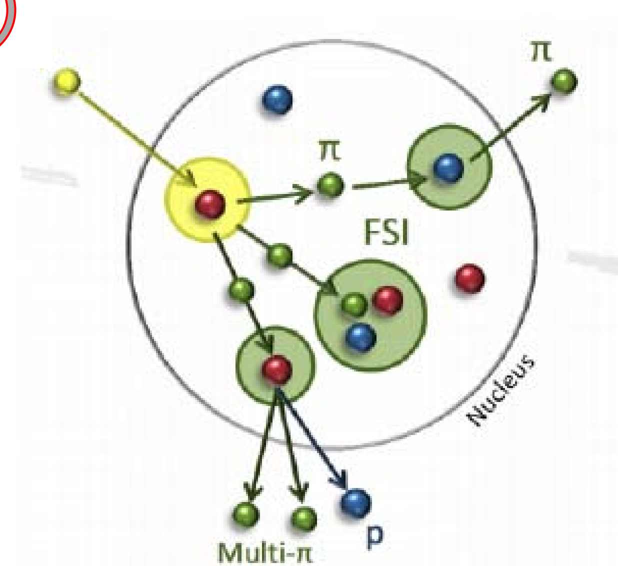
P. Rodrigues, hep-ex: 1402.4709

Goal of this work

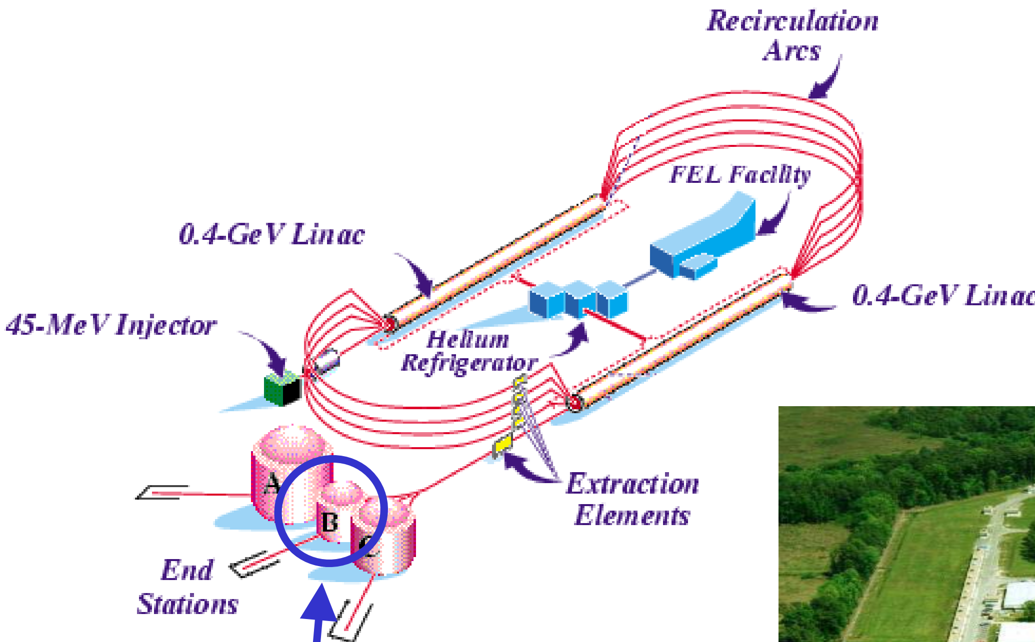
This work aims to produce high statistics, differential, charged pion production measurements on different nuclei that will be useful for learning about and tuning models for FSI.



e^- ν



Jefferson Lab (Newport News, Virginia)



E_{max} ~ 6 GeV

I_{max} ~ 200 μA

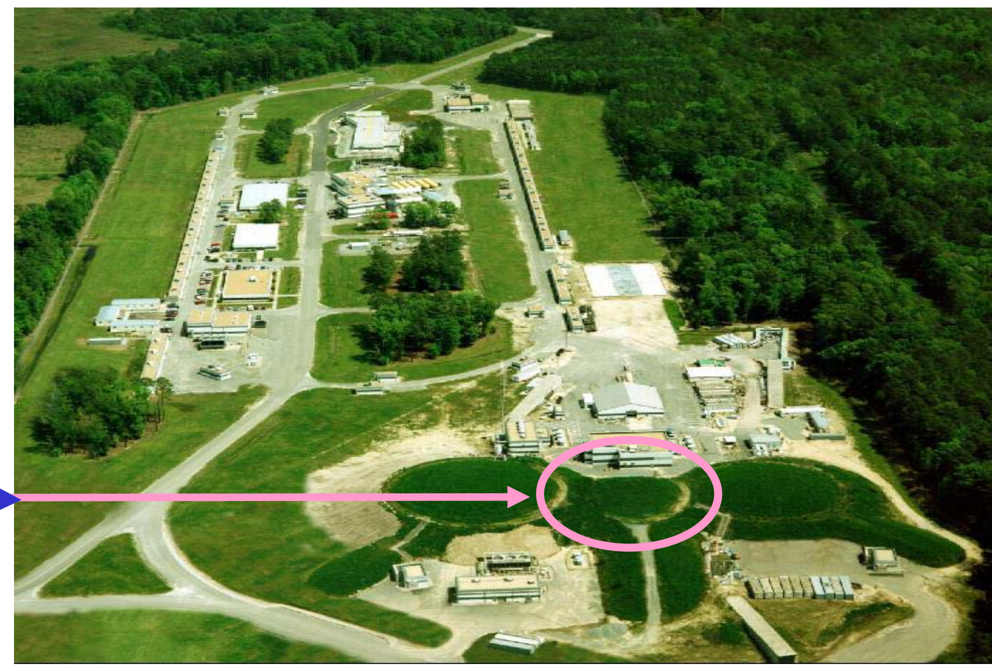
Duty Factor ~ 100%

σ_E/E ~ 2.5 10^{-5}

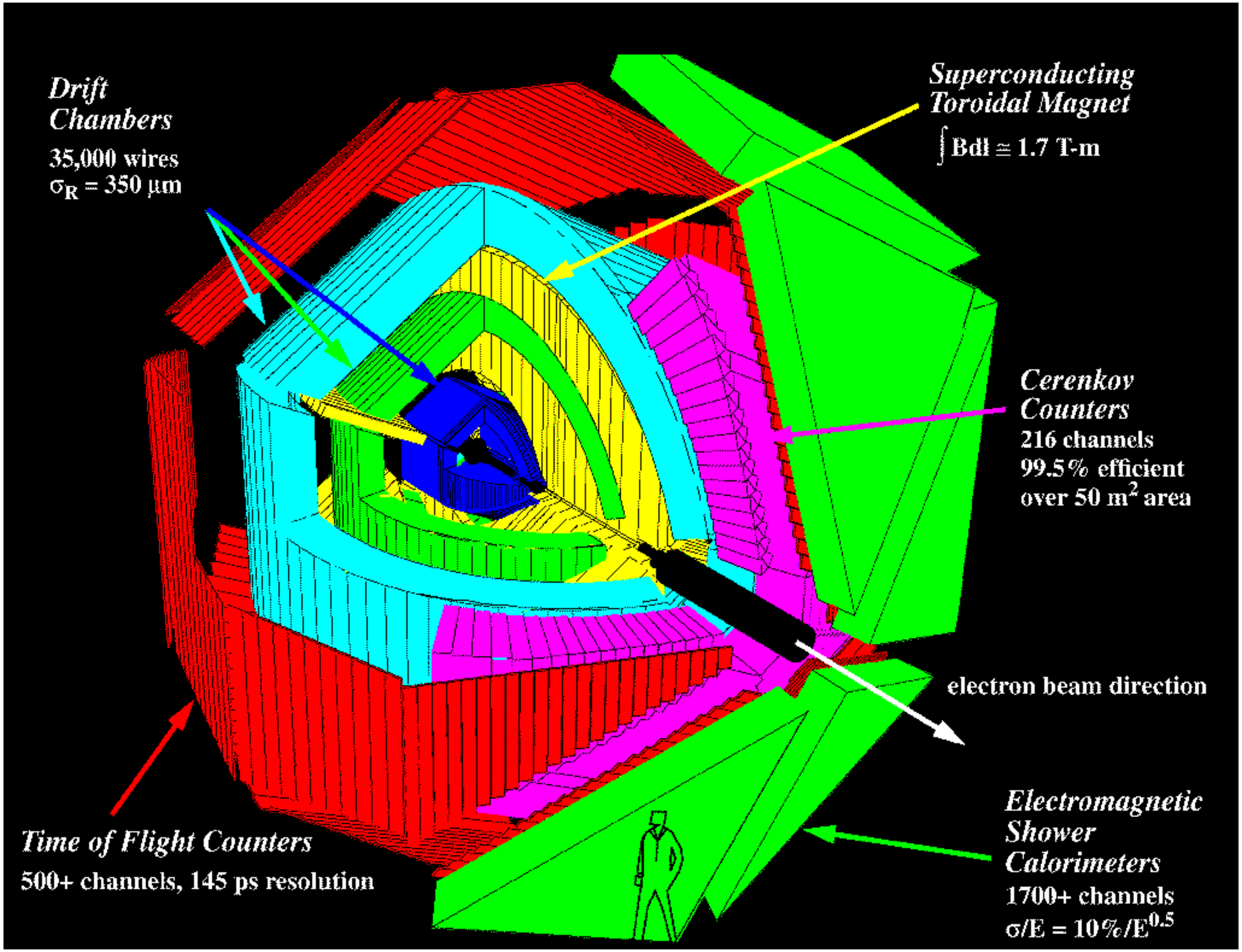
Beam P ~ 80%

12 GeV upgrade underway

CLAS

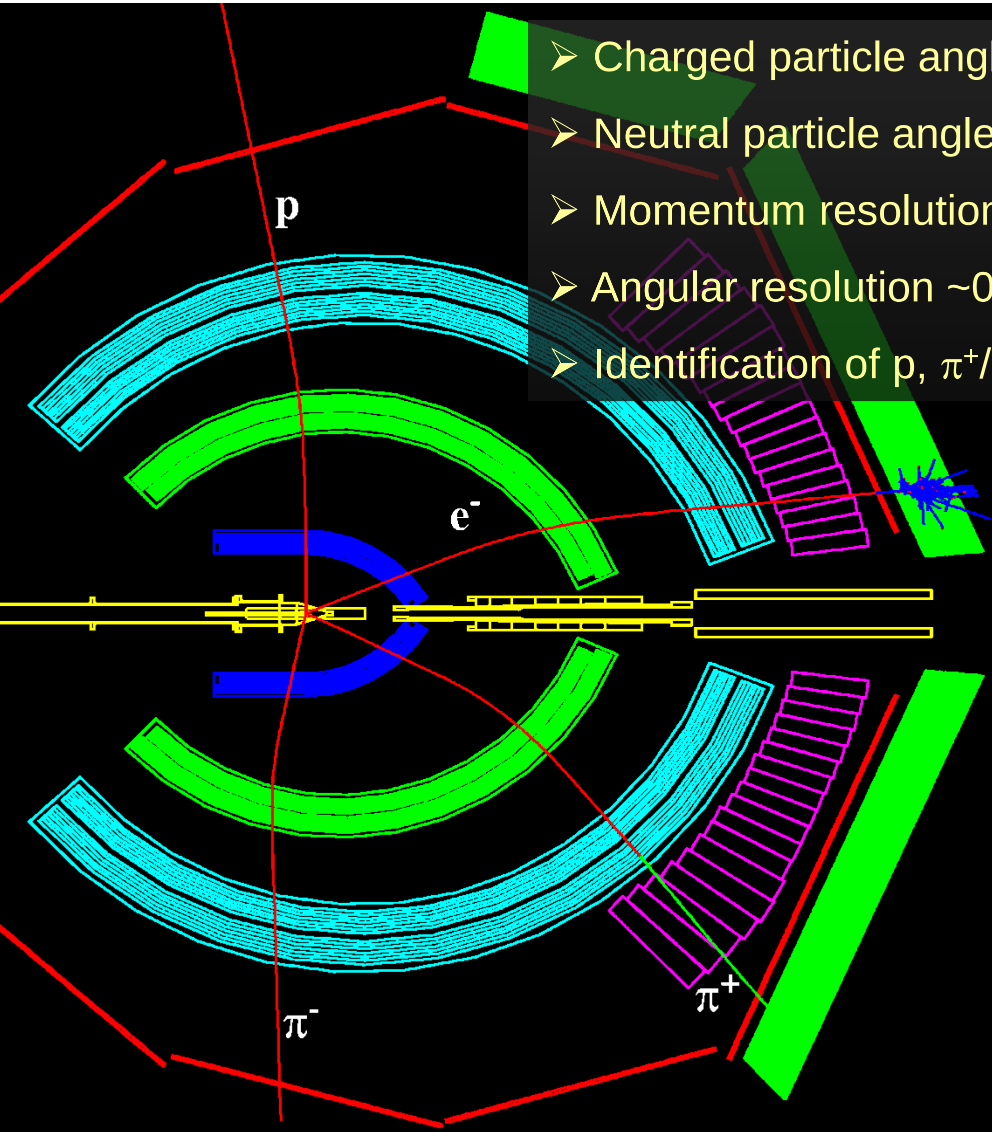


CLAS: CEBAF Large Acceptance Spectrometer (Hall B)



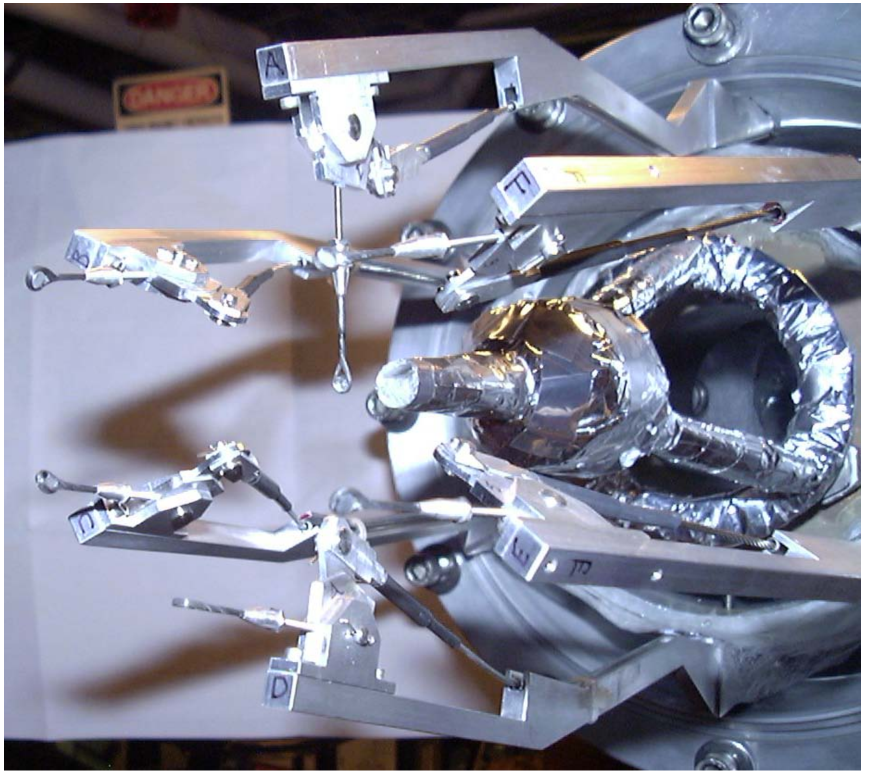
CLAS Single Event Display

- Charged particle angles 8^o-144^o
- Neutral particle angles 8^o-70^o
- Momentum resolution ~0.5% (charged)
- Angular resolution ~0.5 mr (charged)
- Identification of p, π^+/π^-, 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-/γ 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)

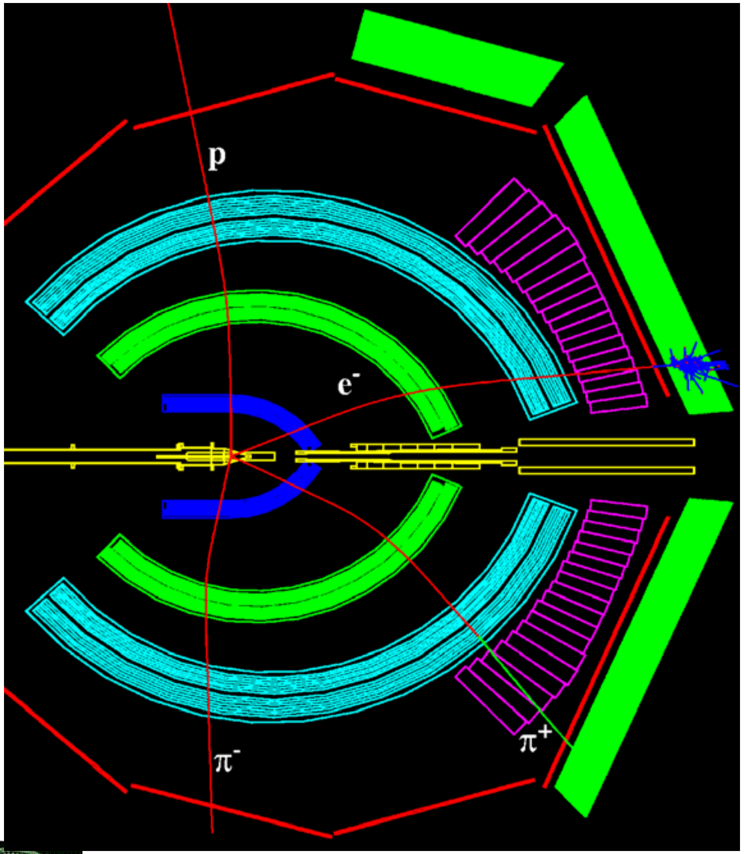
  -Iron

  -Tin

  -Lead

Evolving analysis

At NUINT 2012, we "showed" preliminary, full 5-dimensional distributions in W, Q^2, p_π, θ_π, $\pm$, using "at least one pion" and using the leading pion as the one for which we extract the pion variables.



The bad news:

- The 2012 result used fiducial cuts optimal for the analysis and very difficult for others to reproduce for comparison.
- Needed to update to newer GENIE with better treatment of the pion nuclear interactions.
- Realized that for D_2, default GENIE 2.6.8 uses Fermi gas model with k_F for Li. Fails to reproduce delta peak in D_2 data.
- Full 5-dimensional analysis requires very high statistics and necessarily involves multiple pions. Perhaps more useful and, in principle, cleaner and easier to interpret if we require single pion production and reduce granularity/dimensionality.

Evolving analysis

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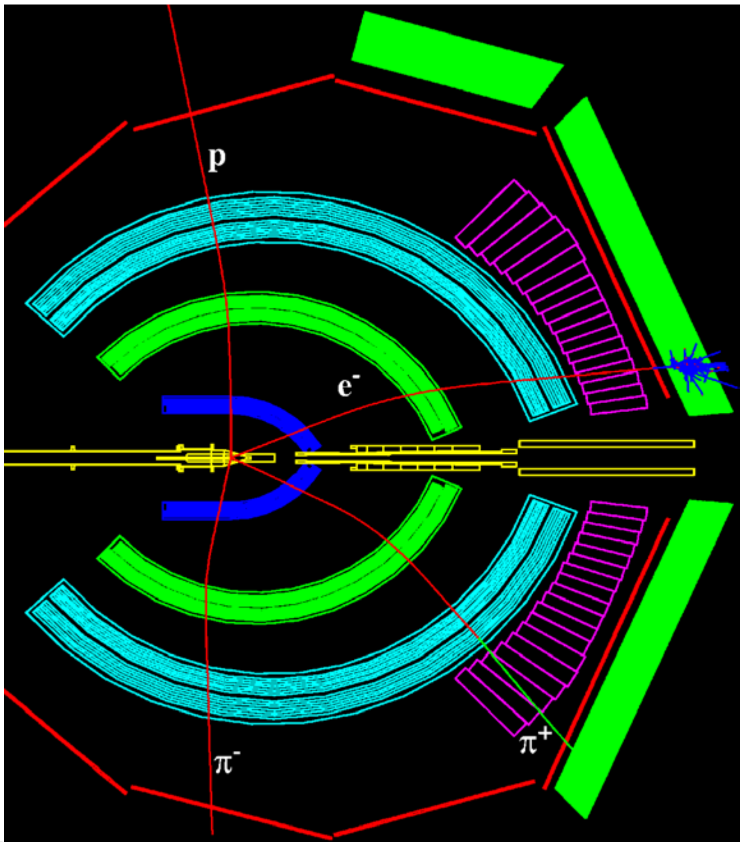

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The good news:

- Hyupwoo has not yet graduated

GENIE eA

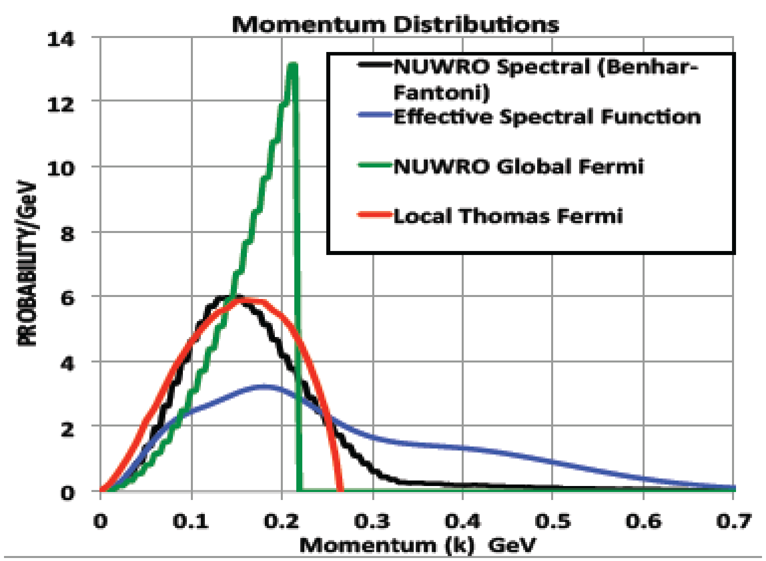
Start with GENIE version 2.8.1 in eA mode with Q^2>0.5 for acceptance calculations and comparison

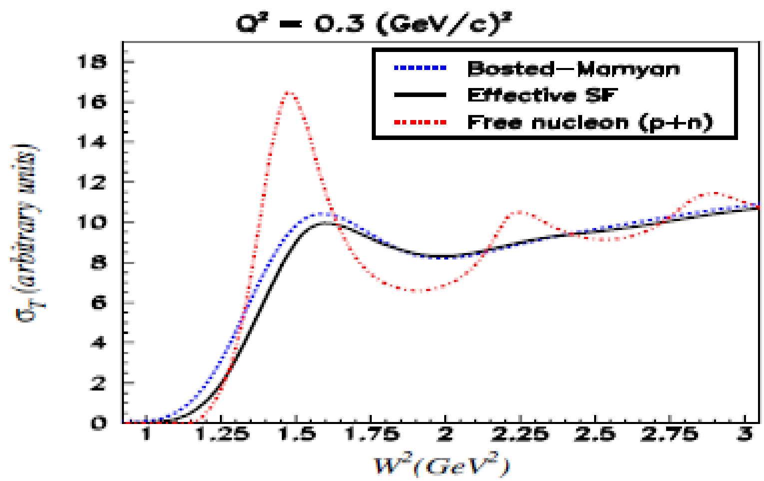
C. Andreopoulos: GENIE eA mode is a “straightforward adaptation of the neutrino generator”

- 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.

Using "effective spectral functions" and new deuterium model in GENIE eA

- Bodek, Christy, Coopersmith, hep/ph: 1405.0583
- Create "effective spectral functions" - give good fits to quasielastic e scattering data $(1/\sigma)(d\sigma/d\nu)$ for the 2014 ψ' superscaling function at Q^2 values of 0.1, 0.3, 0.5, 0.7.
- Modify with correction at low Q^2 to reduce nucleon removal energy.
- Effective spectral function includes more than the initial state.
- Fermi motion effects in resonance and deep inelastic regimes done in fashion similar to Bosted and Mamyan (arXiv: 1203.2262), with probability function taken from the effective spectral function.



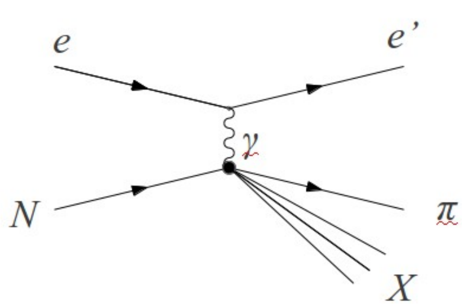


Figs. From Bodek, Christy, Coopersmith, hep/ph: 1405.0583

Using new deuterium model in GENIE eA

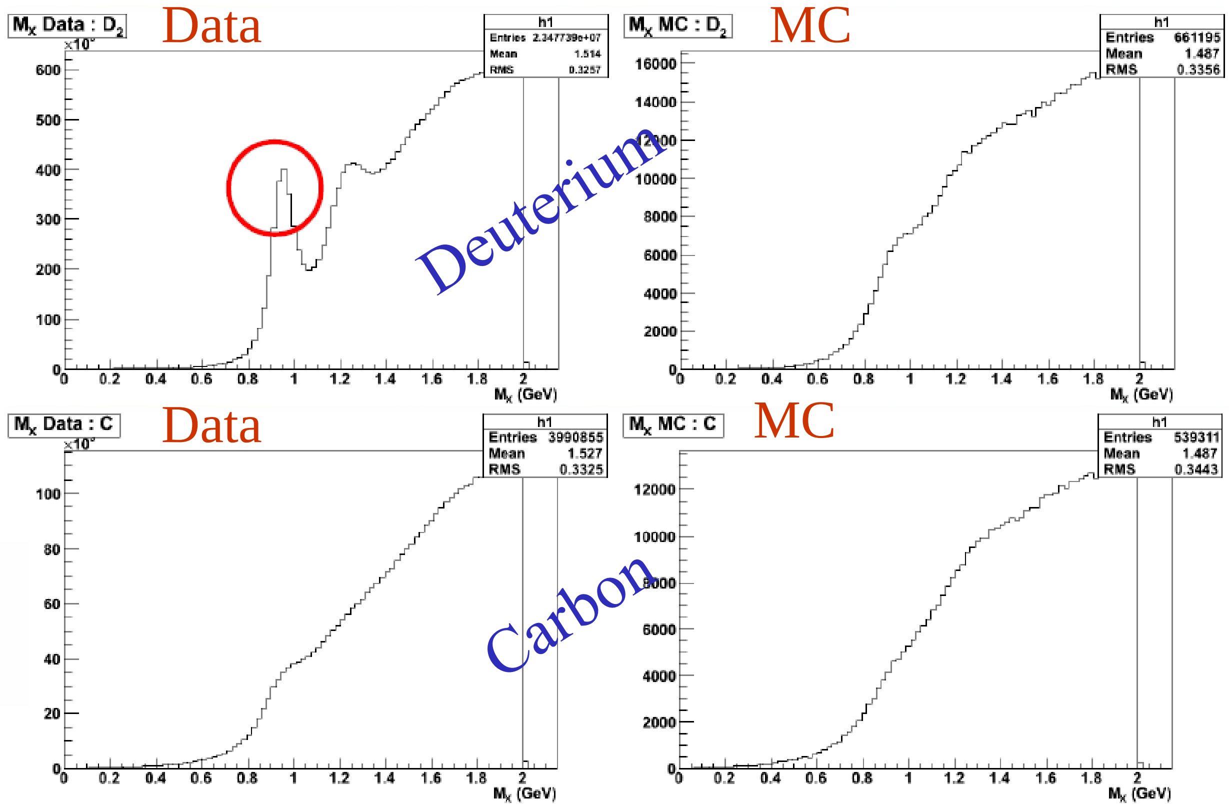
- Significant data-MC disagreement in missing-mass plots for D_2 traced to use of Li Fermi gas constant in GENIE 2.8.1 D_2 nuclear model.
- Put patch in GENIE 2.8.1 using new D_2 model (incorporated with the effective spectral functions from Bodek, Christy, Coopersmith). New D_2 model comes from fit to theoretical calculations from paper in preparation by Christy, Kalantarians, Ethier, and Melnitchouk.

Before patch



Missing mass

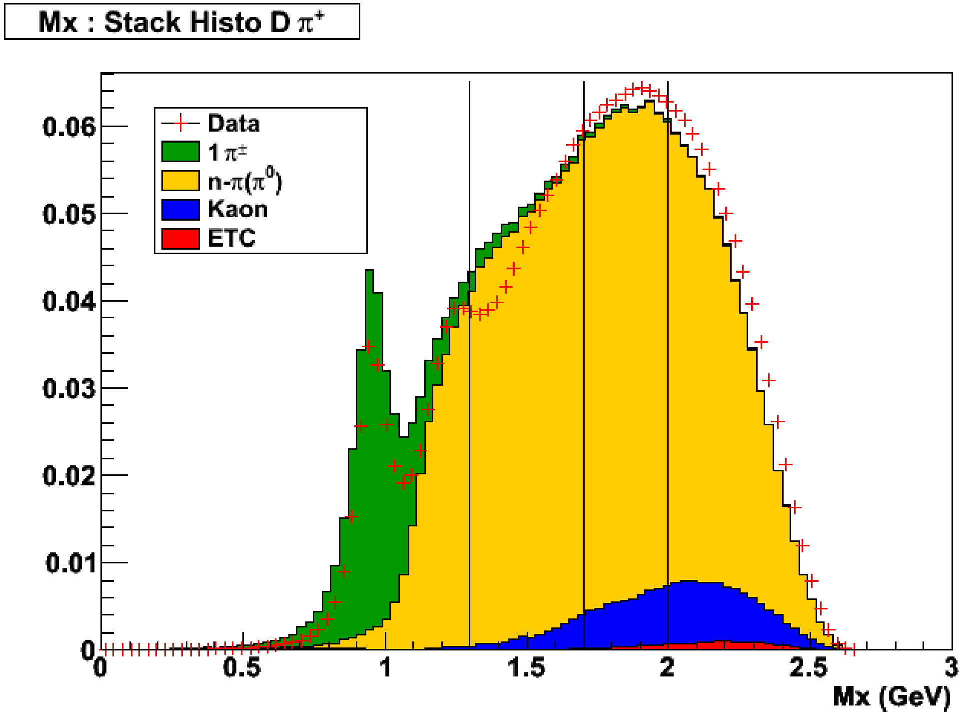
$$M_X^2 = (p_\gamma + p_N - p_\pi)^2$$



Using new deuterium model in GENIE eA

- Significant improvement in the data-MC agreement in missing-mass plots for D_2 with implementation of effective spectral functions, including the fit to calculations from Christy et al.
- Note that this is important for background subtraction in the analysis.
- Will come back to this after introduction to analysis

After patch



Samples

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

Deuterium + C/Fe/Pb raw events 1.1/2.2/1.5 ($\times 10^9$)

D_2/C events passing all cuts 4.7/0.7 ($\times 10^6$)

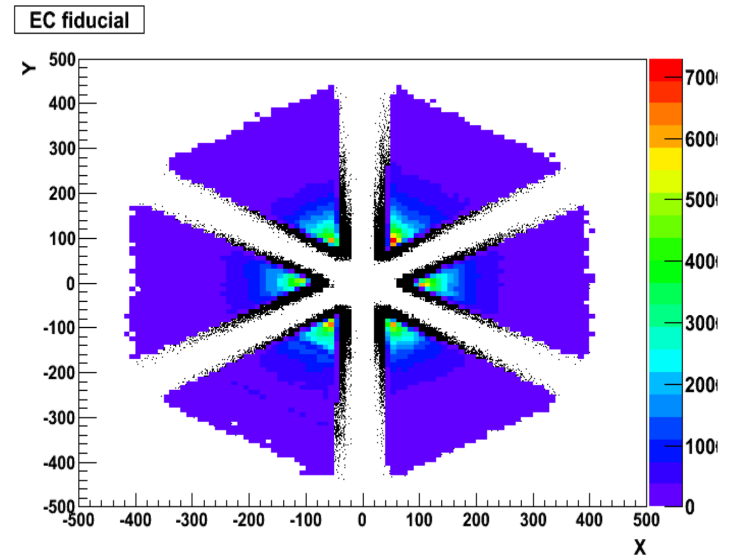
Simulated sample size (Genie MC + detector simulation):

D_2/C generated events (2)$\times$1.0$\times 10^8$

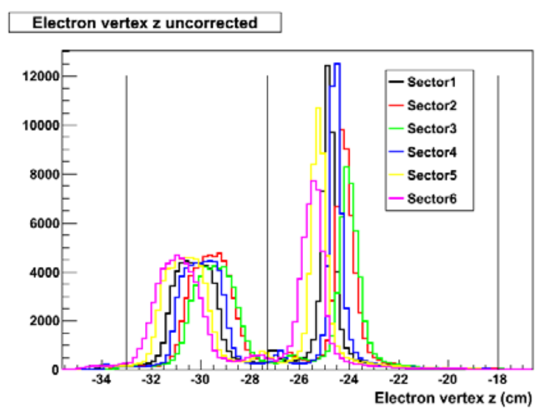
D_2/C events passing all cuts 1.6/1.1 ($\times 10^5$)

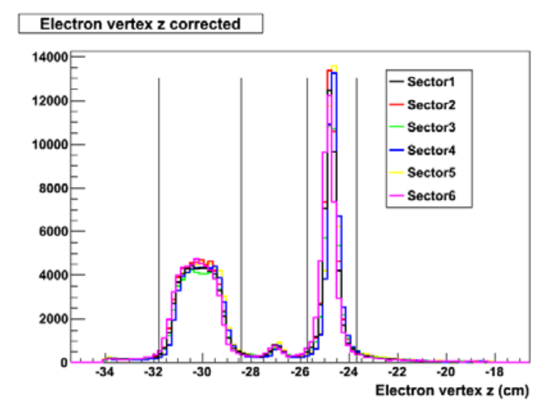
Recently began using the effective spectral function and new D_2 nuclear model modifications. Only had time to generate D_2 and C simulations to date. Plan to do same for Pb and Fe. Target dependent MC important for acceptance/radiative corrections/unfolding. So will not show Pb or Fe data here.

Analysis cuts

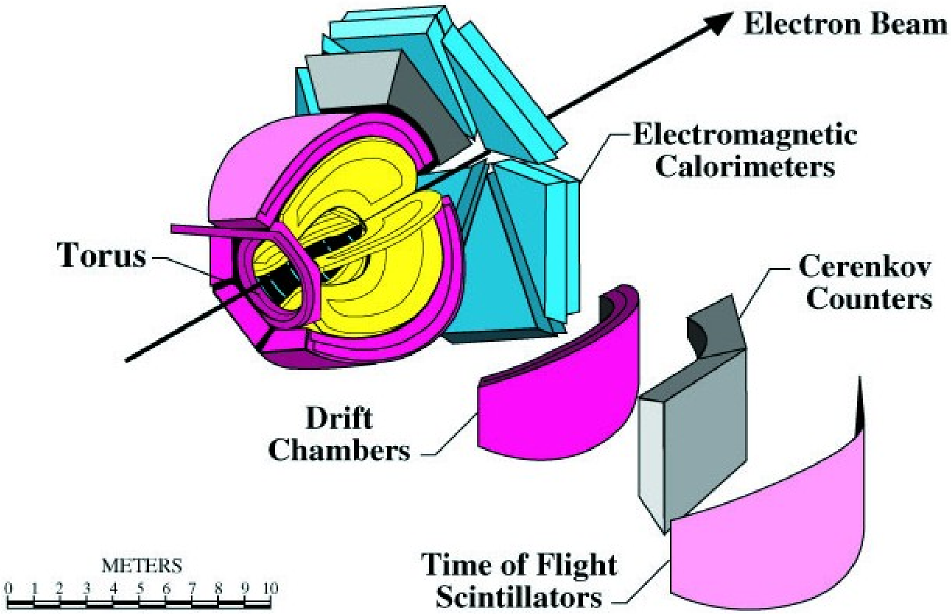


- Demand electron enter calorimeter safely away from edges
- Demand energy deposit as function of depth in ECAL be uneven
- Adjust vertex Z position for sector-by-sector beam offset
- Demand momentum of outgoing e-: p>0.64 GeV (or y<0.872) (removes bias due to electromagnetic energy threshold in trigger)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

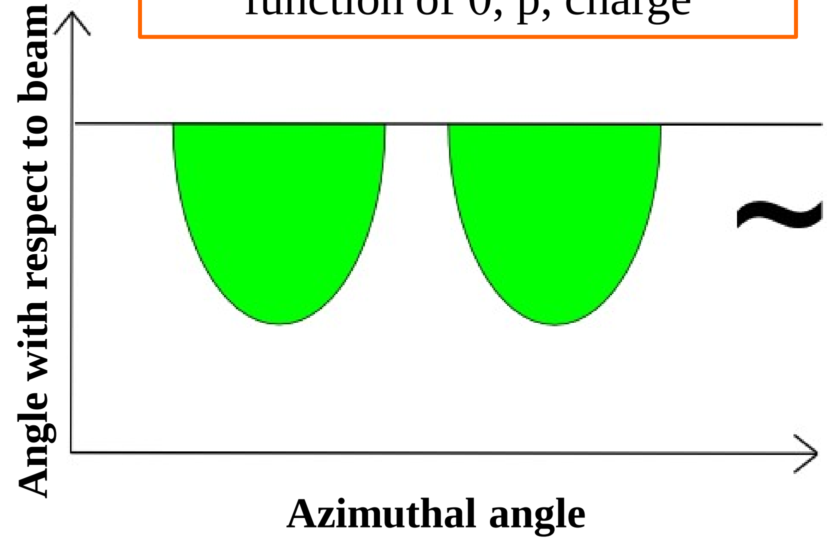




Fiducial volume complications

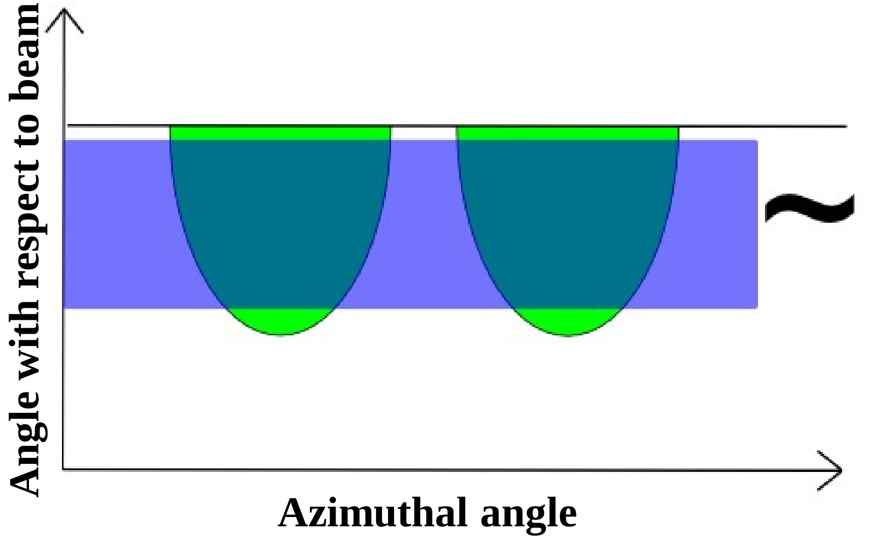


Six azimuthal regions of angular acceptance that are a function of θ, p, charge



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

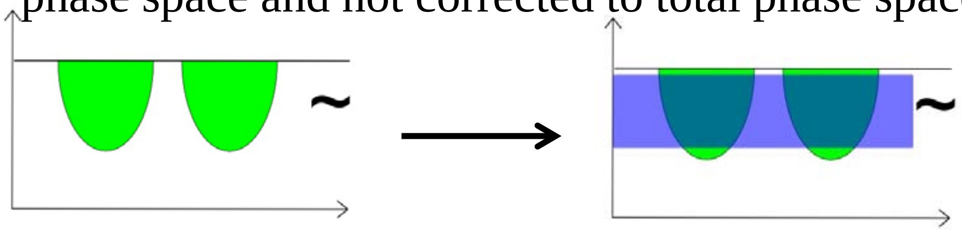
Fiducial volume complications

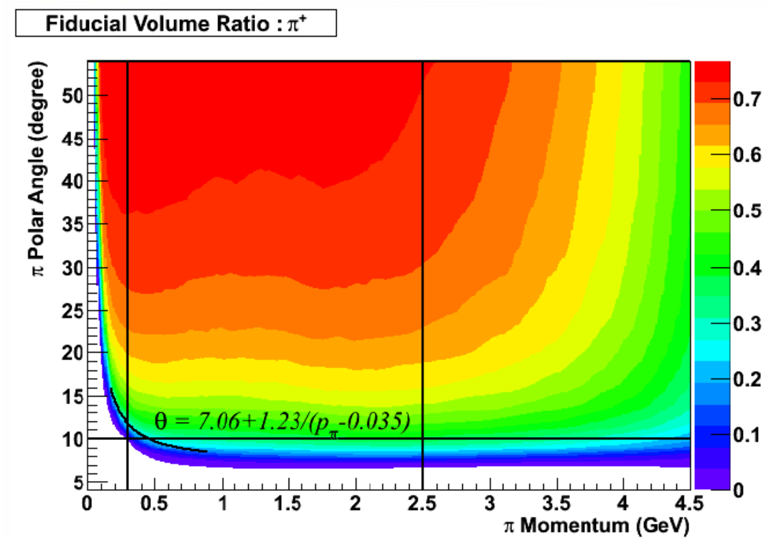


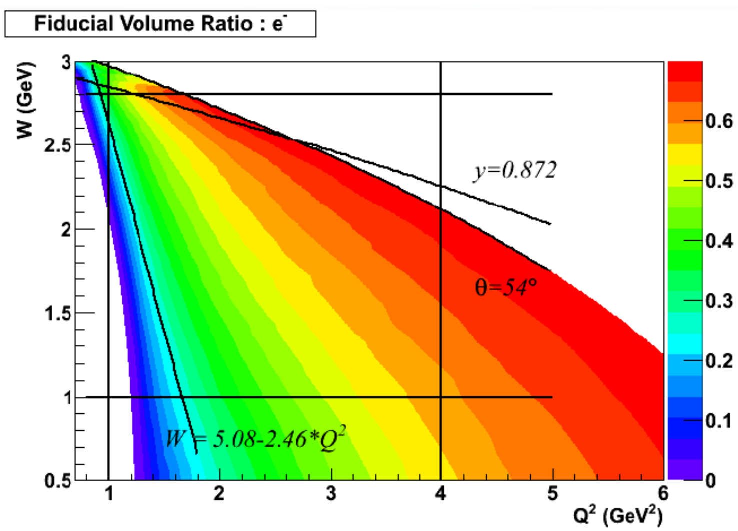
- Report results with geometric correction to be azimuthally symmetric
- Implement “relatively” easy to model cuts in W, Q^2, θ for the electron and p_π, θ_π for the pion

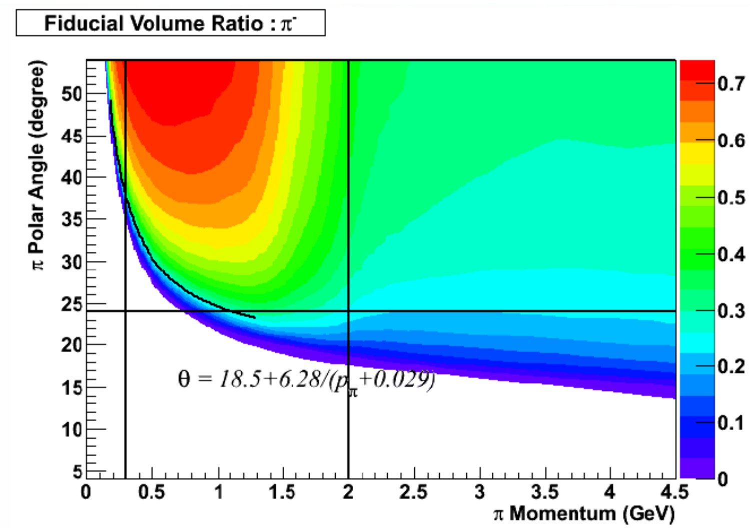
Geometric acceptance

- Geometric scaling for electron and pion independently
- Use region in W and Q^2 for electron
- Use region in θ_π and p_π for pion
- Cross sections reported for these regions of phase space and not corrected to total phase space.









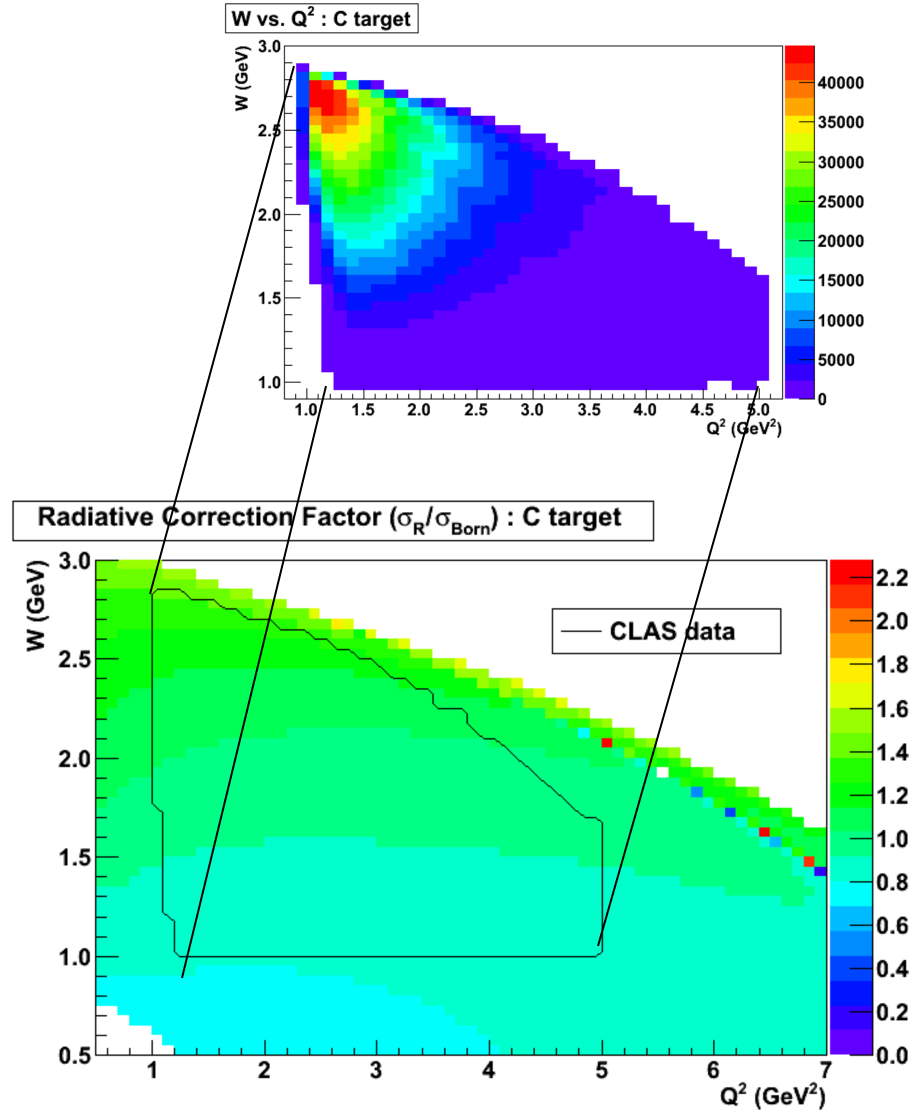
Radiative corrections

➢ 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)

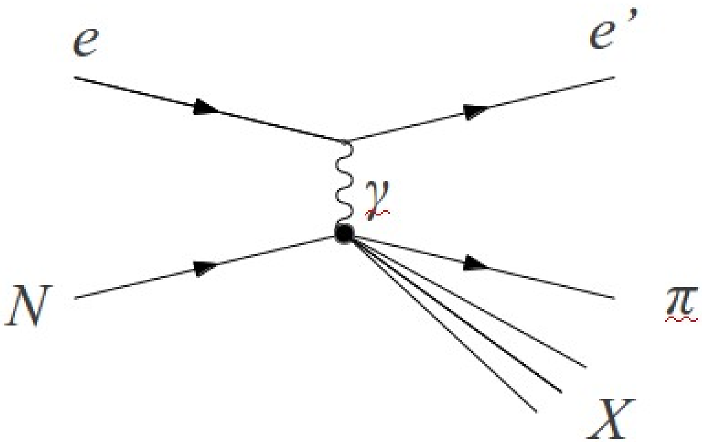
➢ Only consider leptonic side (in neutrinos we don't typically worry about the radiative corrections on the hadronic side)



Unfolding

- ➢ Using Bayesian unfolding implemented with RooUnfold with GENIE MC response matrix as prior and default 4 iterations
- ➢ Included here, but needs further study, one of reasons results are "preliminary"

Background removal

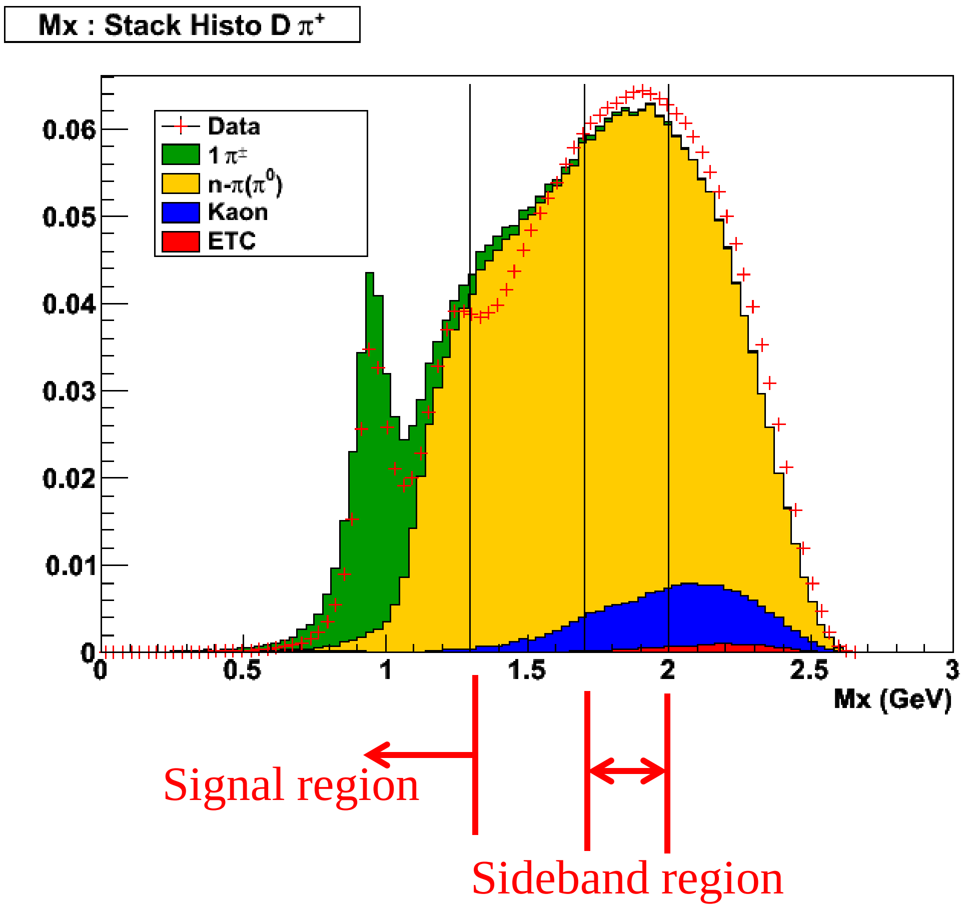


Use cut in missing mass

$$M_X^2 = (p_\gamma + p_N - p_\pi)^2$$

- ➢ Assume target nucleon is at rest
- ➢ For single charged pion production, expect the "missing mass" distribution to peak around the target nucleon mass

Background removal – sideband subtraction



- Use signal region Mx<1.3 GeV
- Select sideband region 1.7<Mx<2 GeV
- Scale MC Nπ background to match data in bins of Q^2. Scale factors ~1±0.05.
- Loose cut on signal region leads to purity of ~50%.
- Can get much higher purity with tighter Mx cut about peak, but MC structure does not match well the data (might be physics).
- This aspect of analysis not yet optimized.

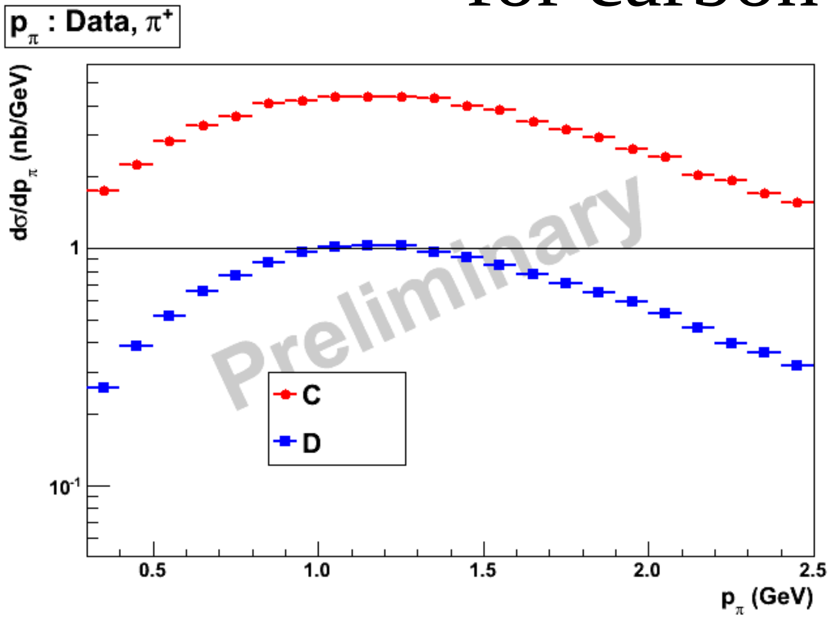
More caveats

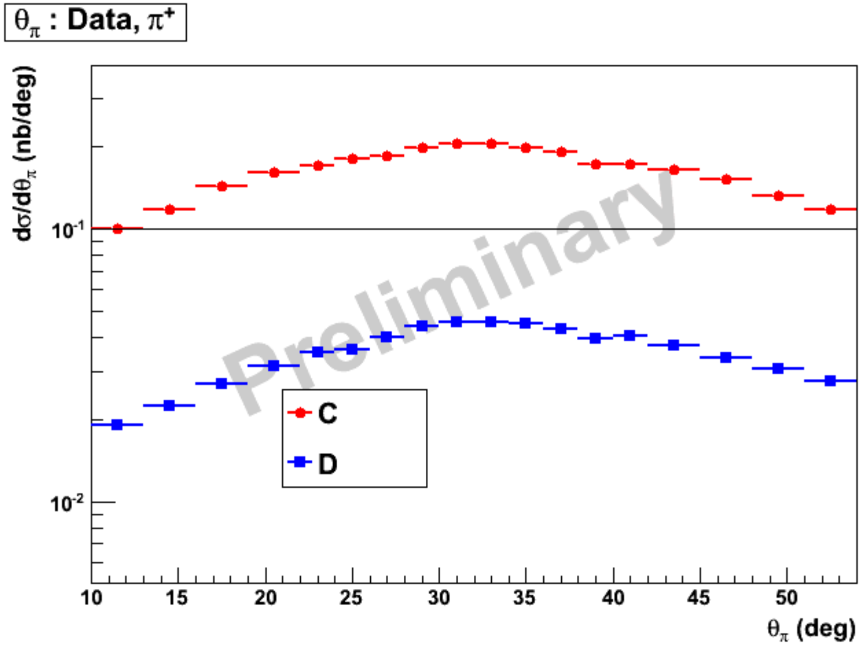
- All results shown here are preliminary
- Significant modifications in the analysis are recent and might not be optimal – unfolding and background subtraction, in particular
- The errors shown are statistical only
- Systematic errors are under investigation
- Expectation/goal is to hold the systematic errors to <10%

Systematics (under study)

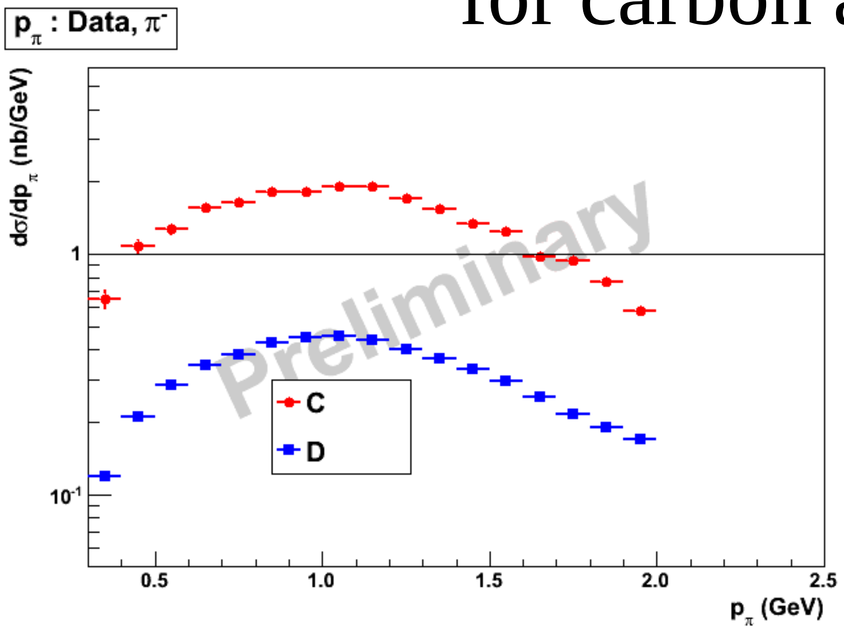
- Observed pion/beam current stability
- Target thickness
- Acceptance stability with different generator
- Stability with respect to missing mass cut and sideband regions
- Also have haprad implemented for radiative corrections
- May release data in form of nuclear target ratios as well as absolute single target measurements

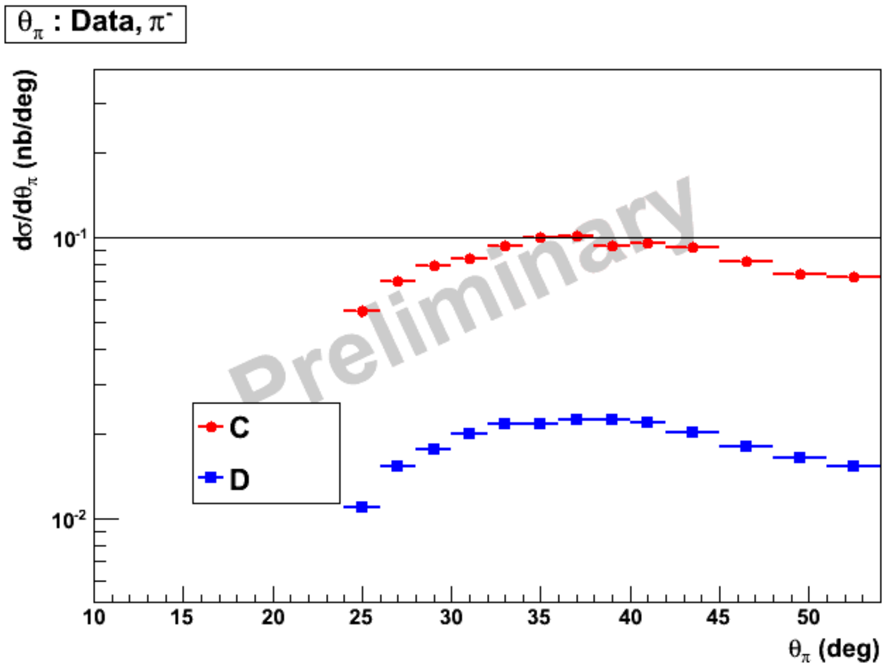
π^+ momentum and angle distributions for carbon and deuterium



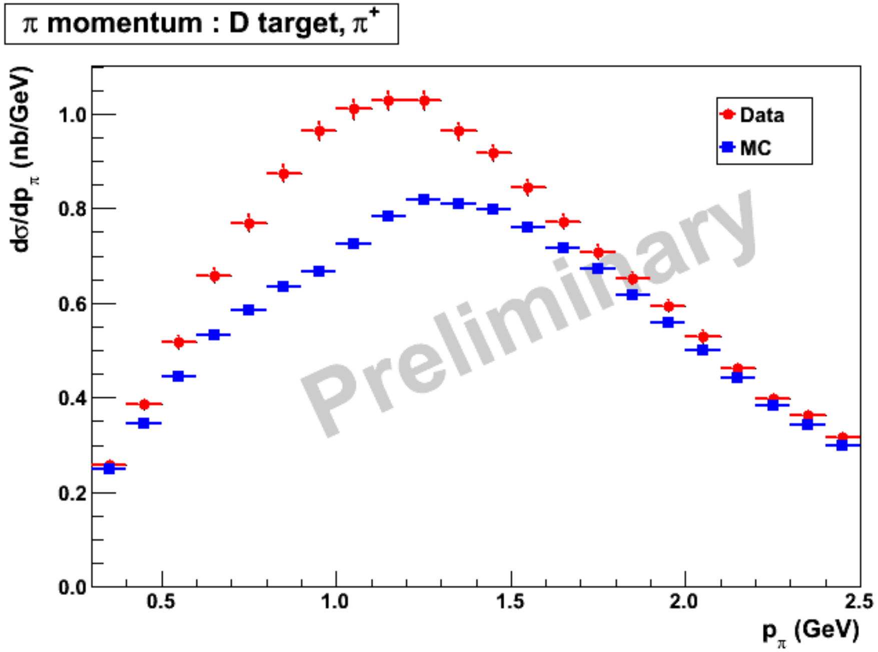


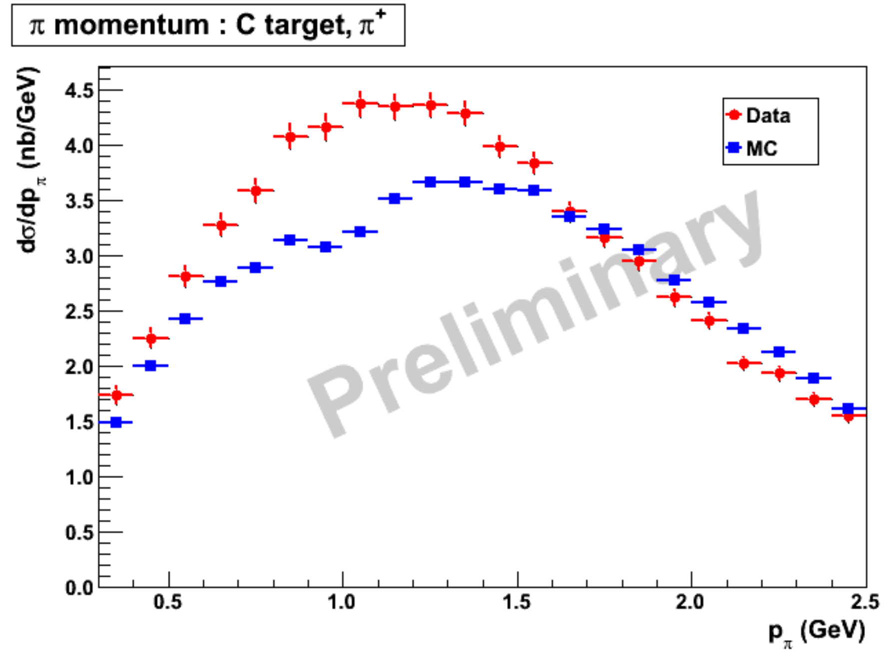
π^- momentum and angle distributions for carbon and deuterium



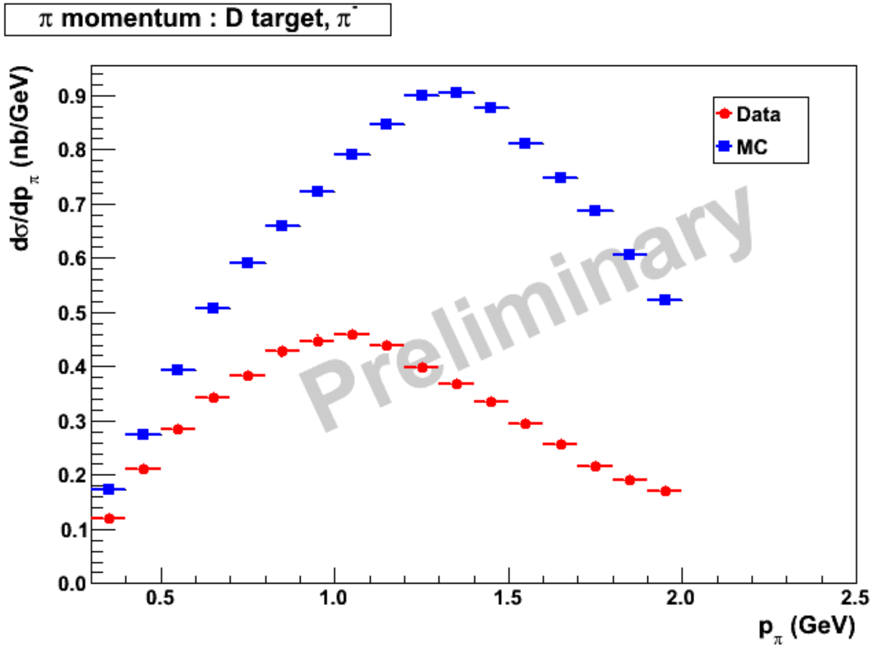


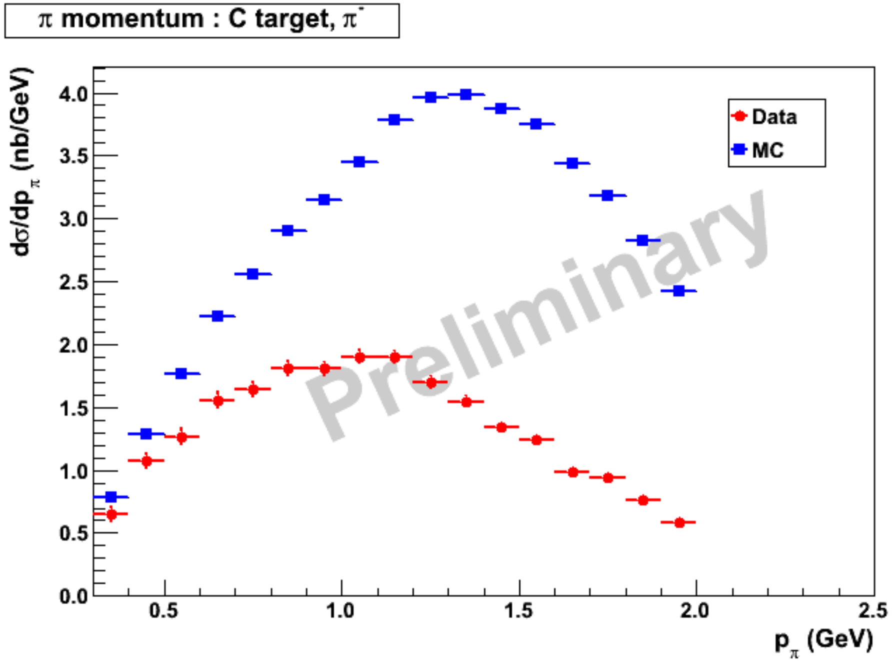
π^+ momentum data-MC comparison for carbon and deuterium



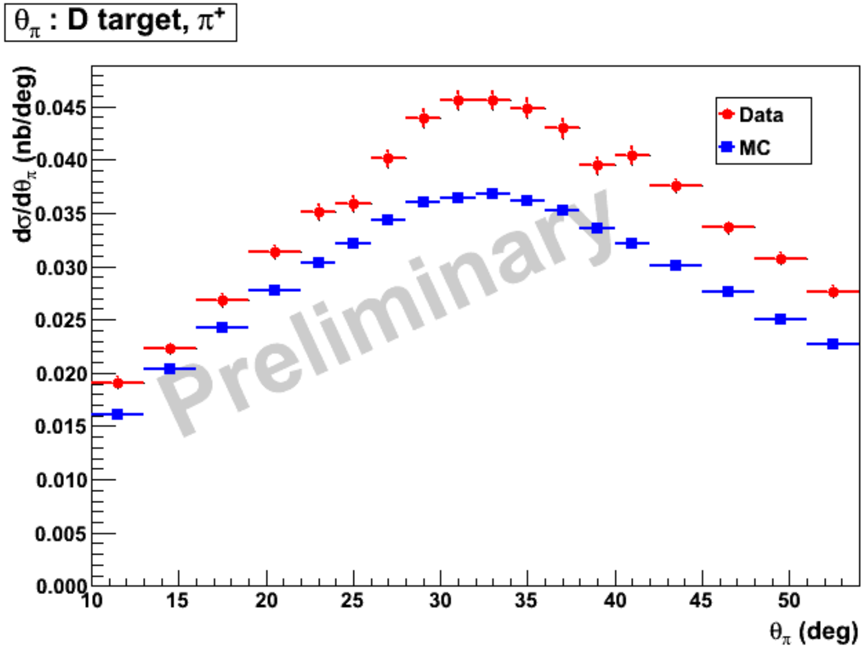


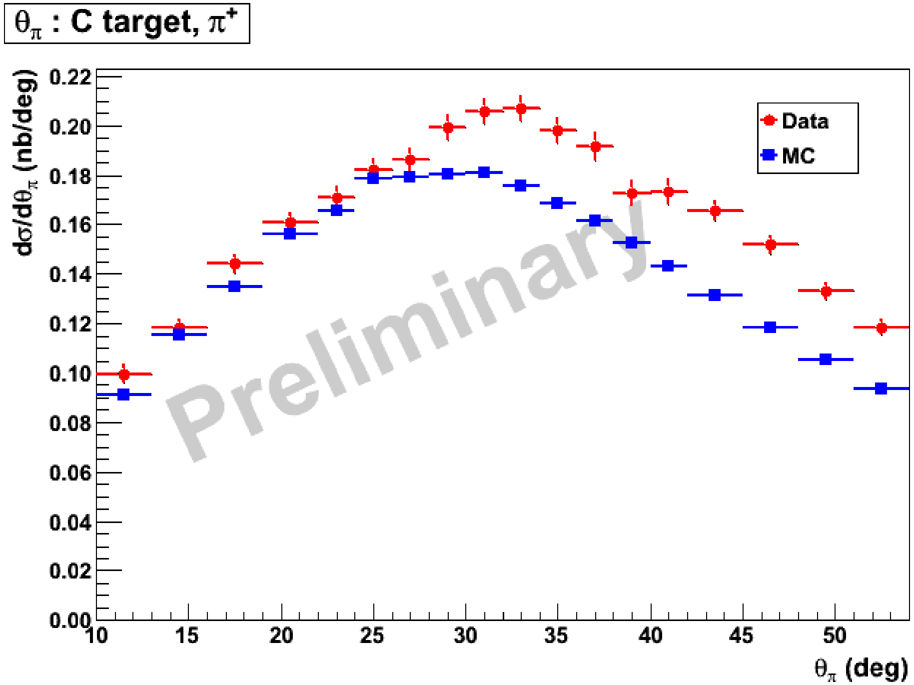
π^- momentum data-MC comparison for carbon and deuterium



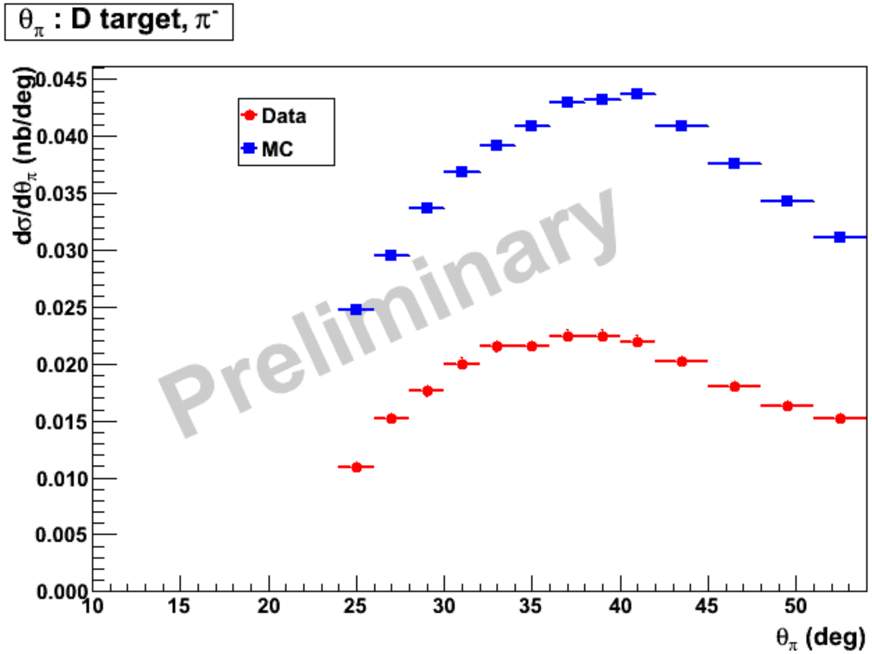


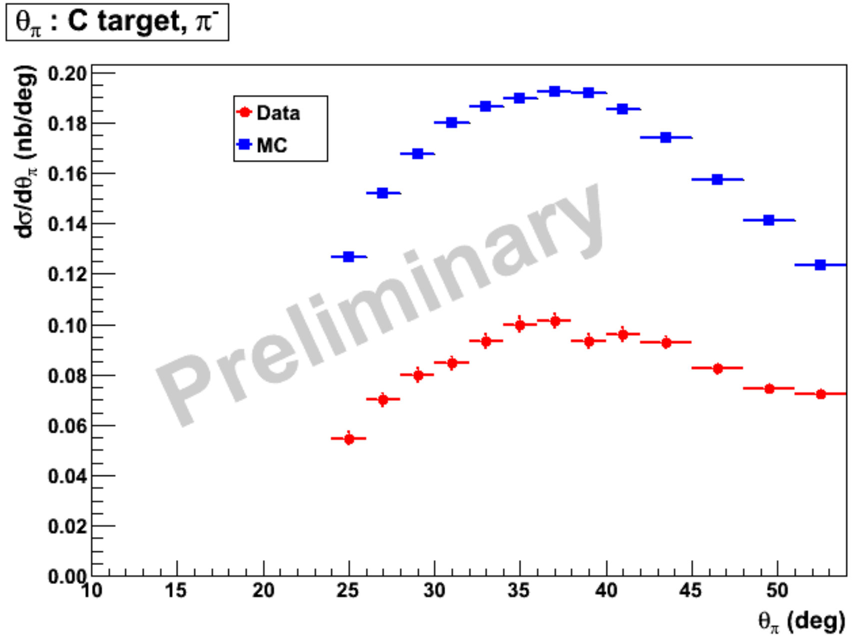
π^+ angle data-MC comparison for carbon and deuterium

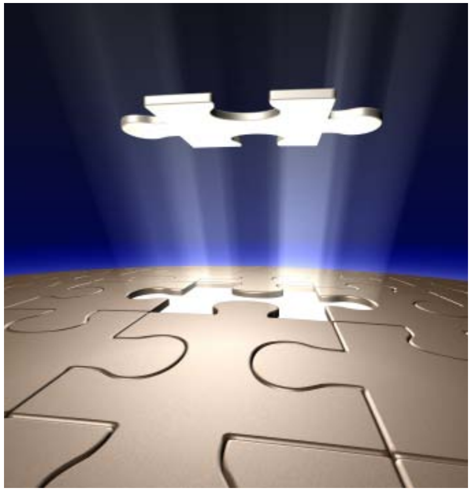




π^- angle data-MC comparison for carbon and deuterium



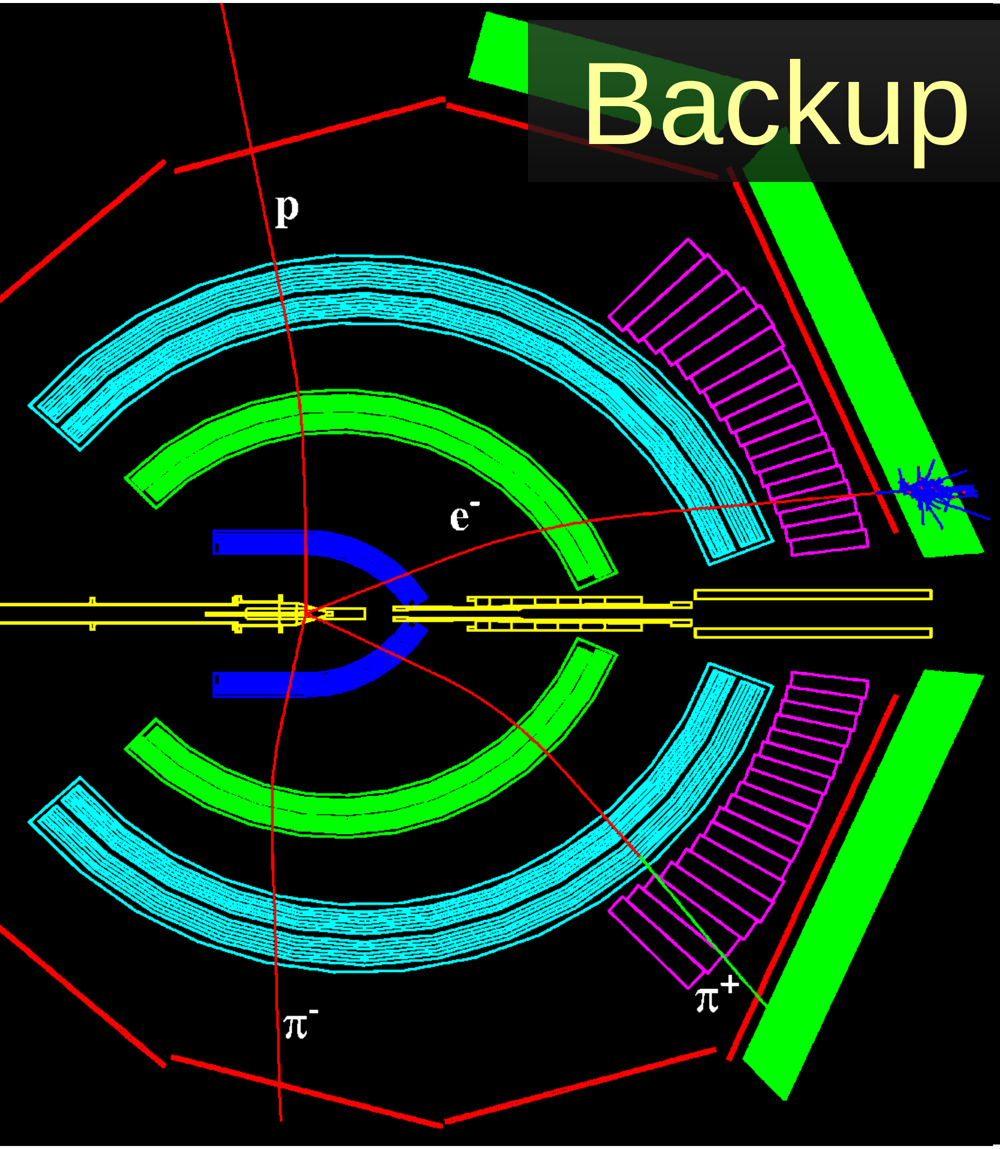




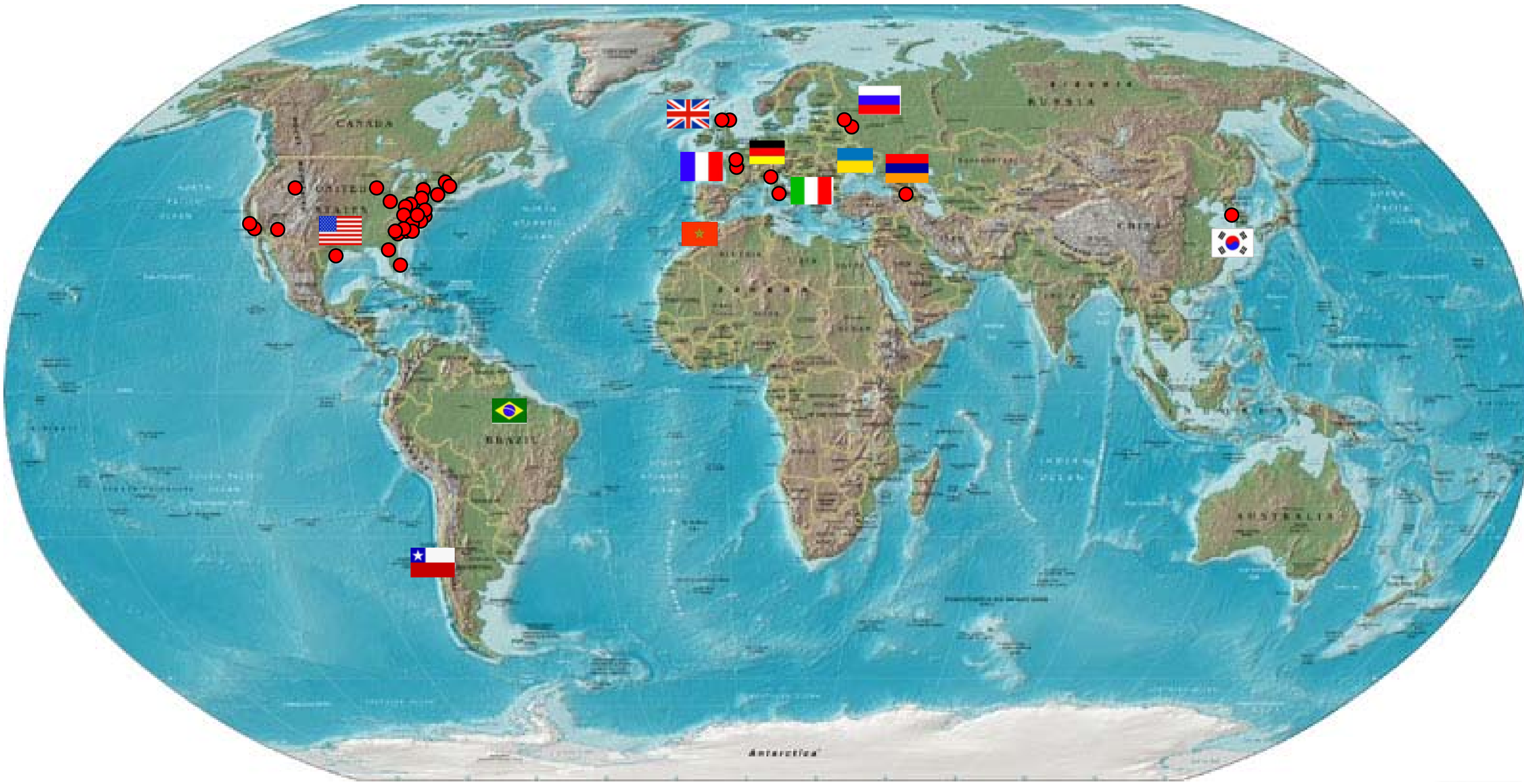
High precision neutrino results are a product of many pieces carefully fit together

- 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.
- Significant recent changes in analysis that we hope will simplify end-game and interpretation (and lead to HL graduating!)
- Hope to finalize results later this year.

Backup slides



The CLAS Collaboration



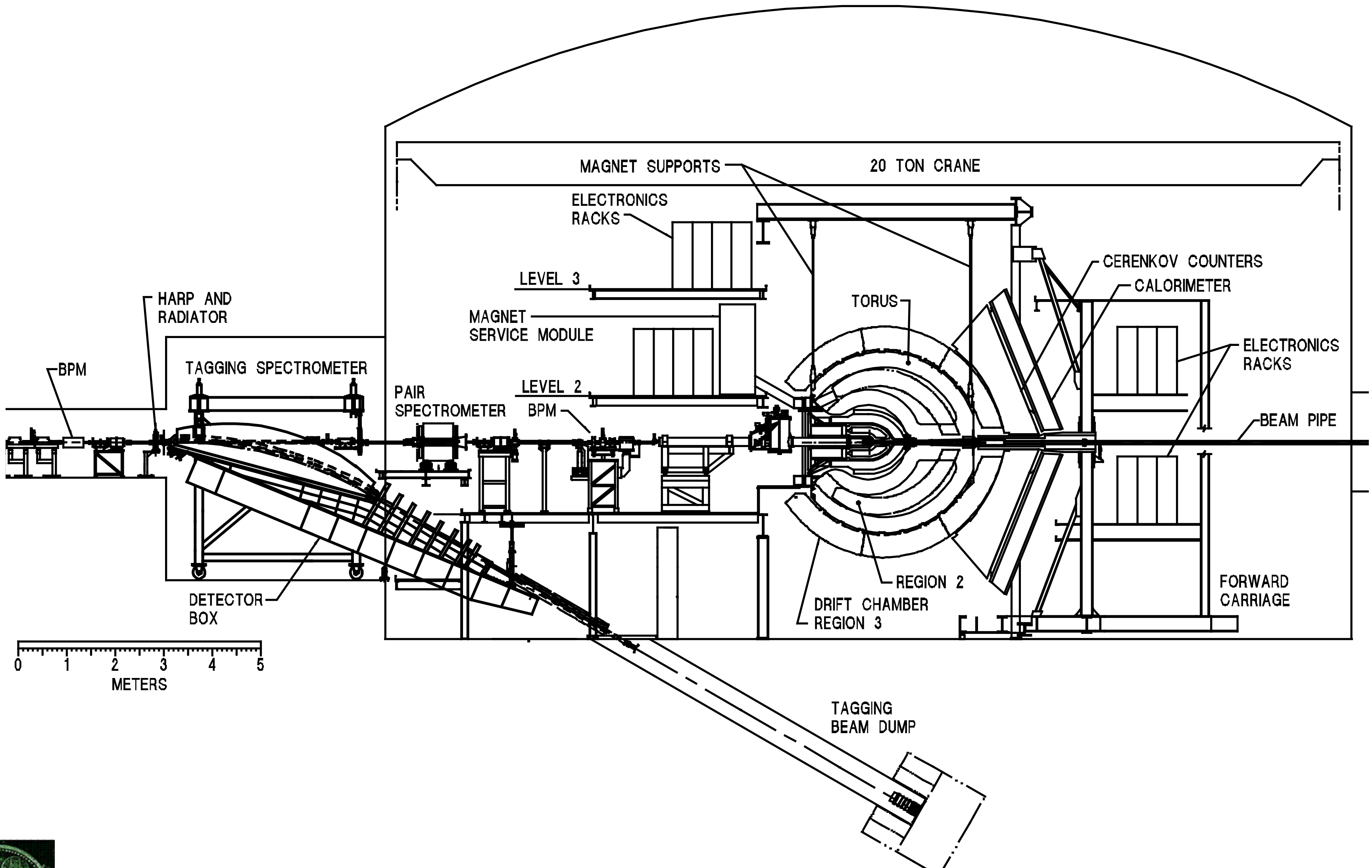
Arizona State University, Tempe, AZ
University of California, Los Angeles, CA
California State University, Dominguez Hills, CA
Carnegie Mellon University, Pittsburgh, PA
Catholic University of America
CEA-Saclay, Gif-sur-Yvette, France
Christopher Newport University, Newport News, VA
University of Connecticut, 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

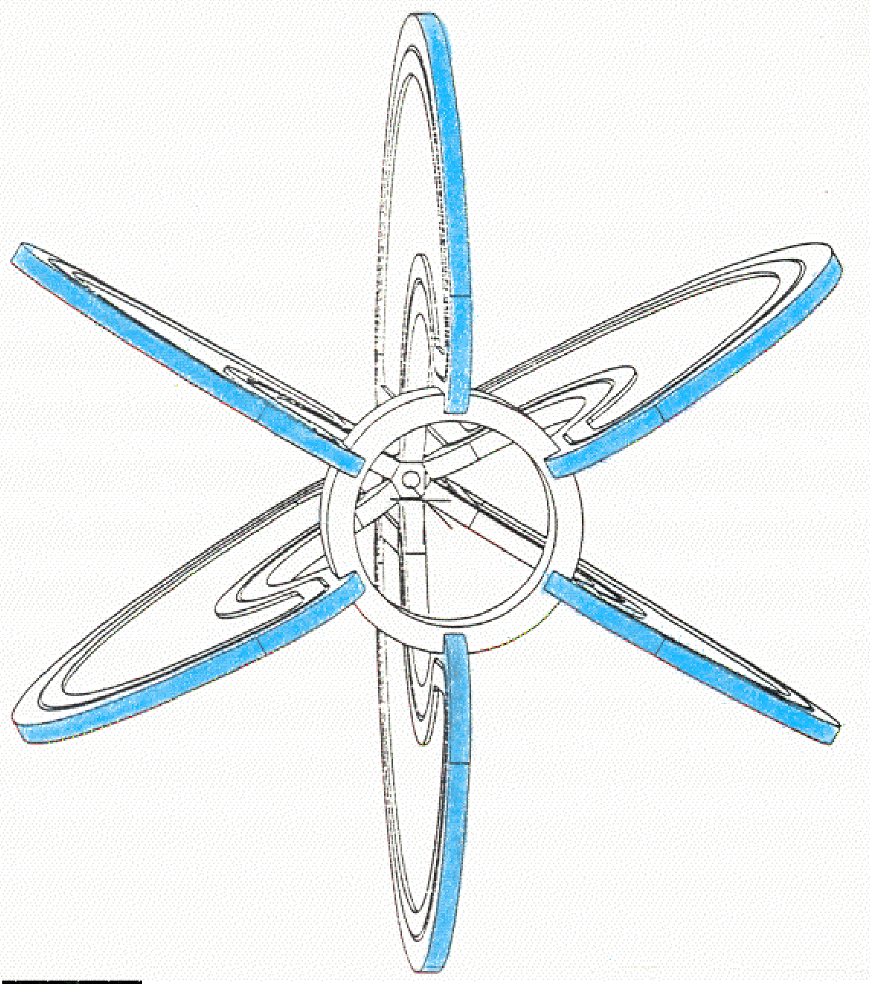
Brazil, Germany, Morocco and Ukraine,
as well as other institutions in France and in the USA,
have individuals or groups involved with CLAS,
but with no formal collaboration at this stage.

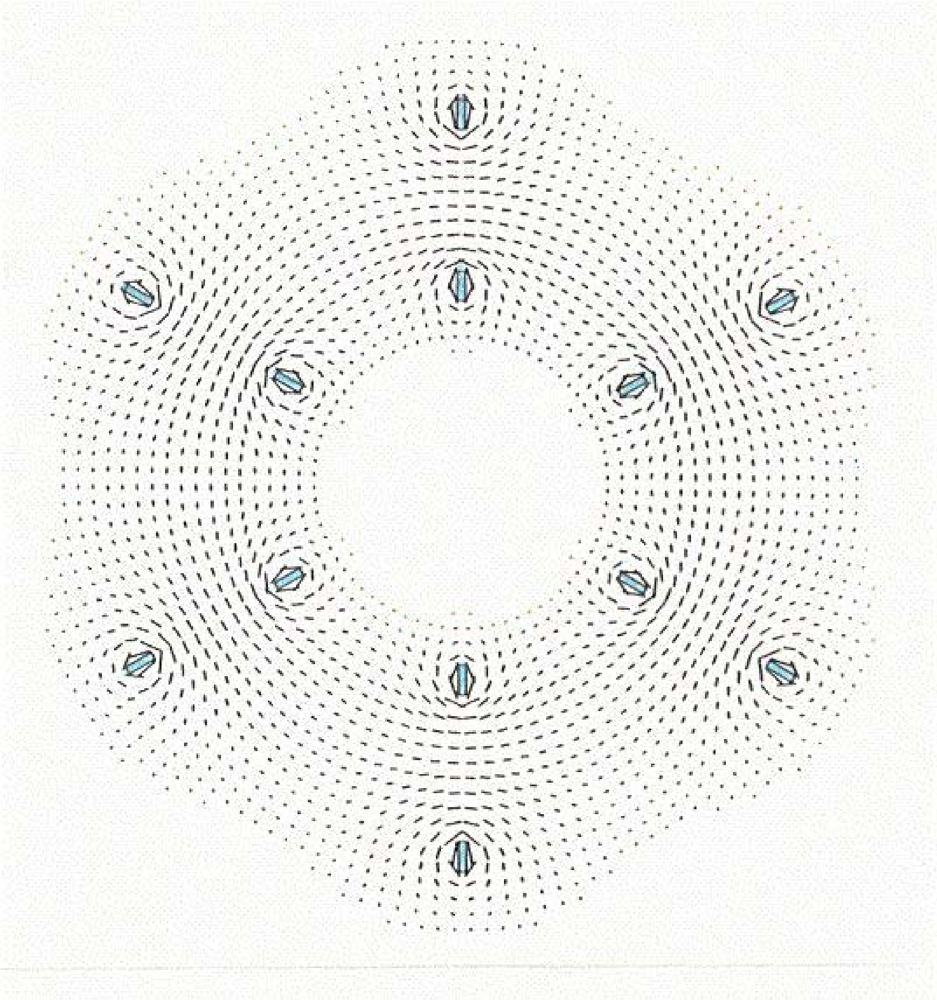
Hall B Side View

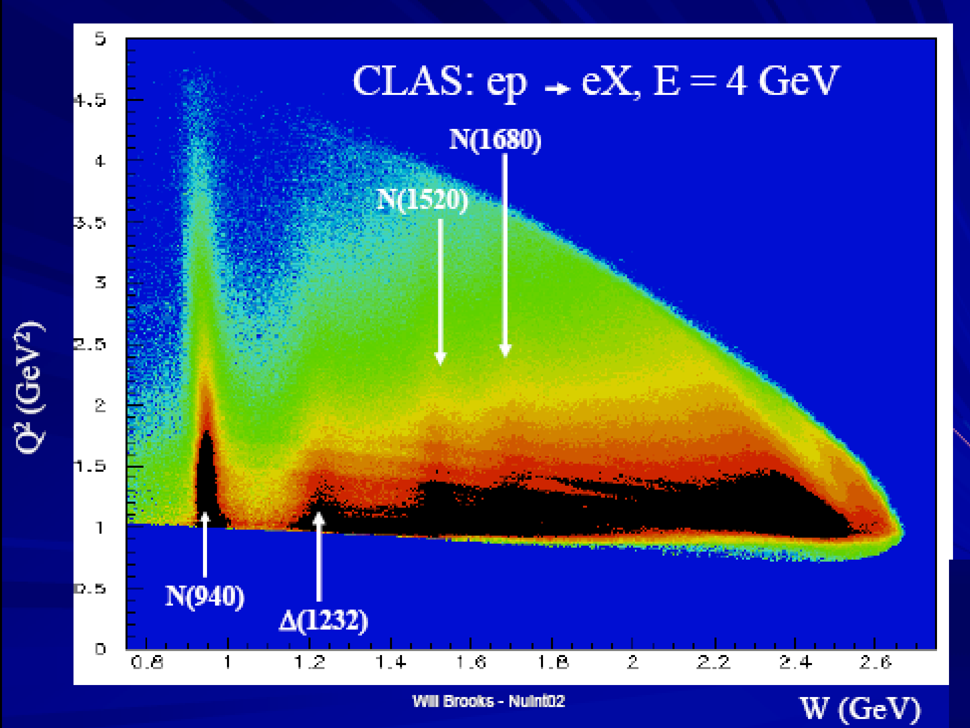


Super-conducting toroidal magnet with six kidney-shaped coils

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

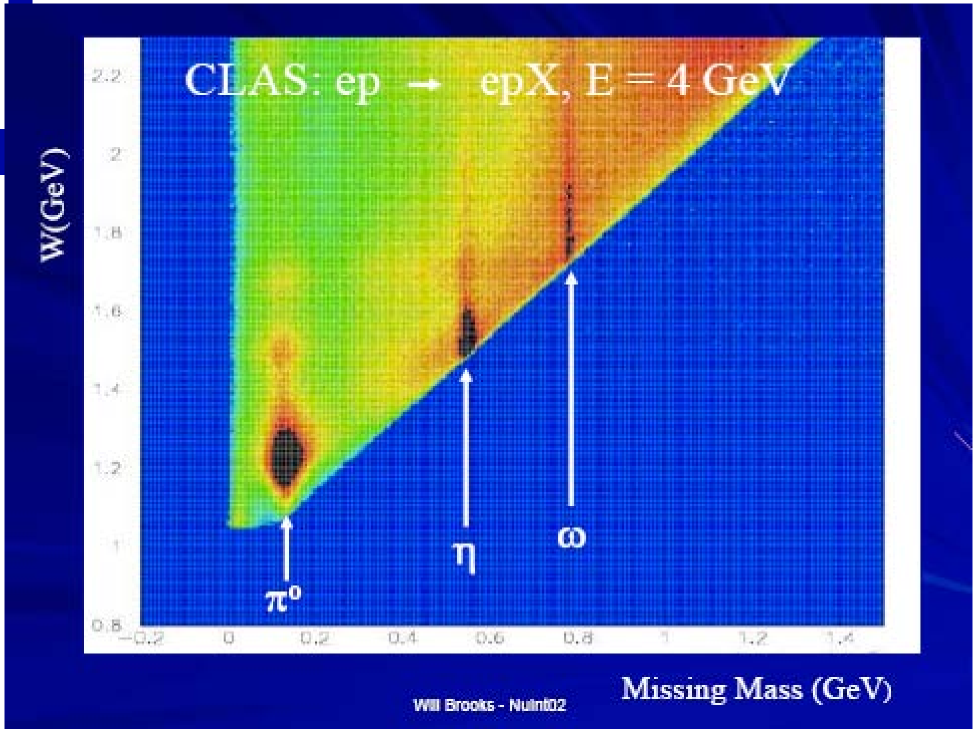






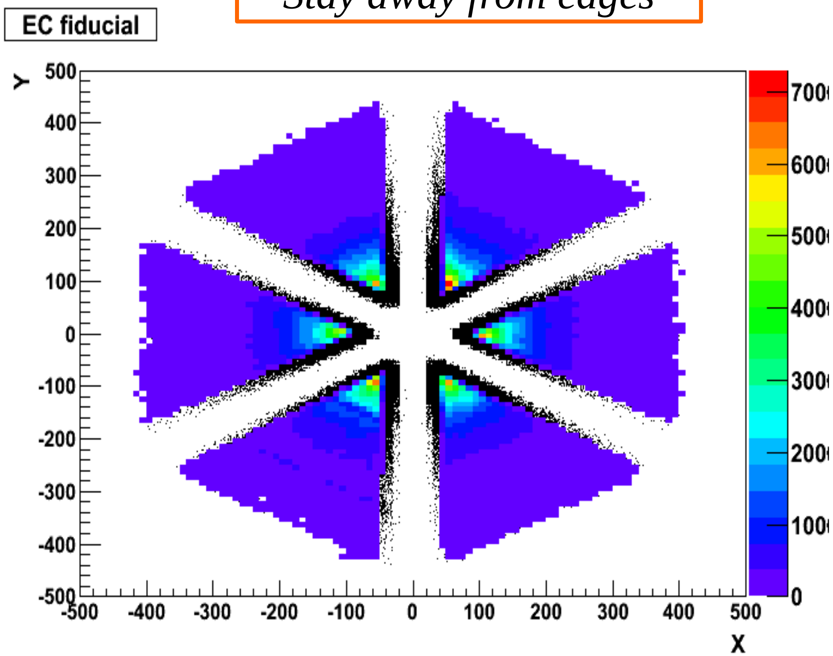
From Will Brooks at NUINT02

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

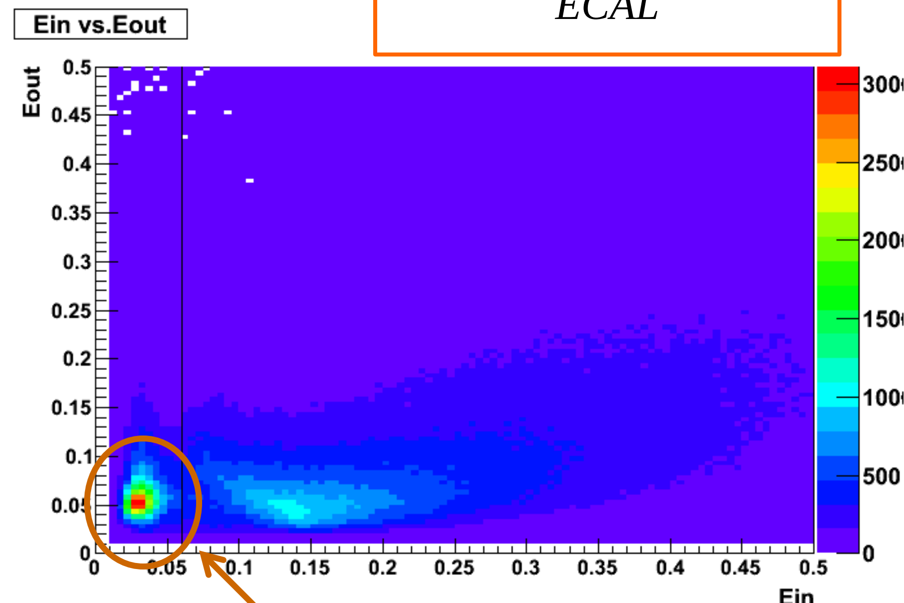


Analysis cuts

Stay away from edges



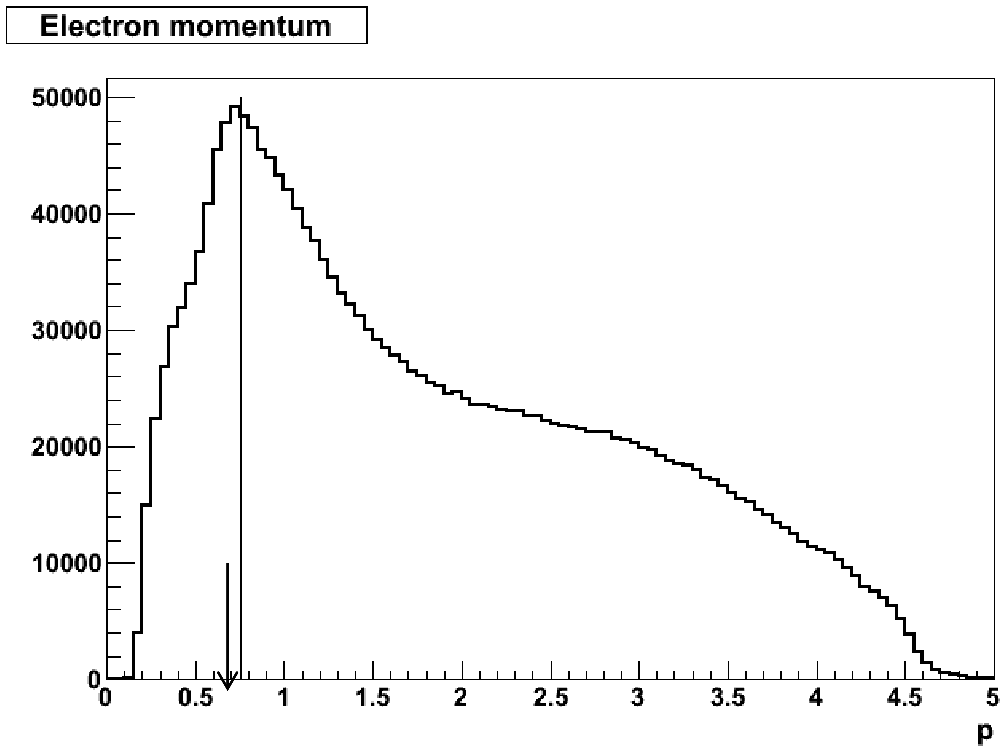
Remove events with even energy depostion in the two layers of the ECAL



Mostly pions and muons

Calorimetric fiducial and ID cuts on outgoing e^-

Analysis cuts



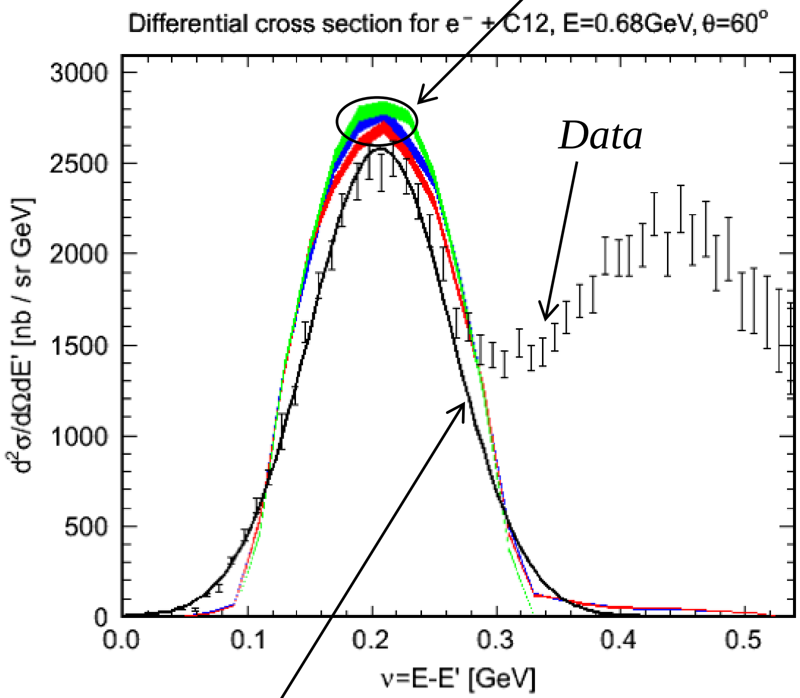
- Momentum of outgoing e-: p>0.64 GeV (or y<0.872)
- Removes bias due to electromagnetic energy threshold in trigger.
- Also reduces sensitivity to radiative effects.

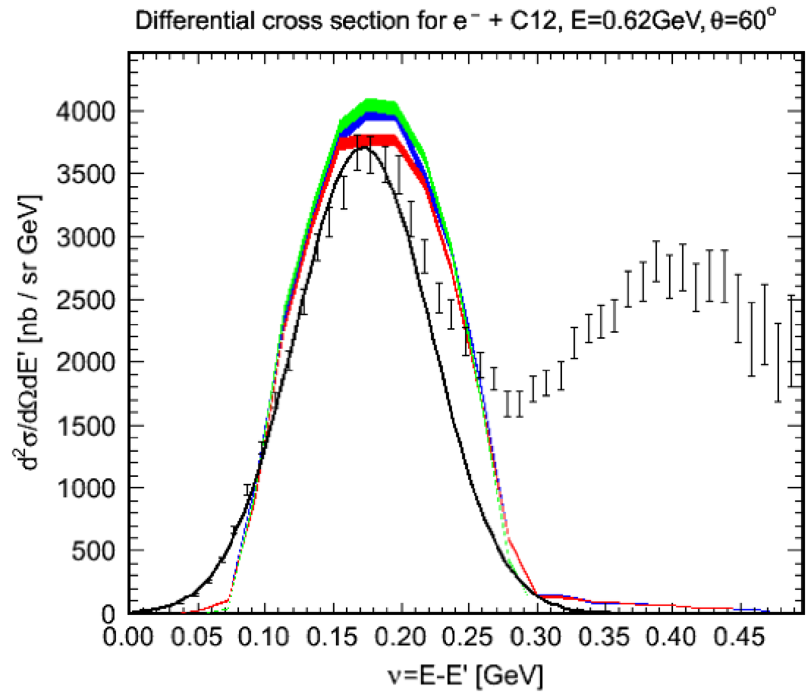
GENIE eA validation

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





Gaussian fit to data

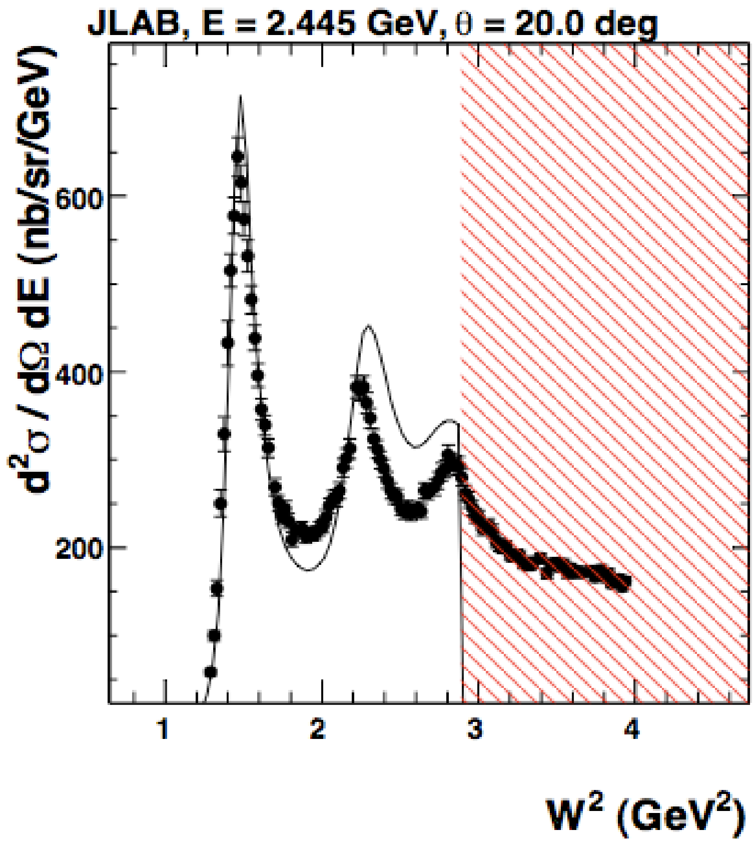
-From C. Andreopoulos

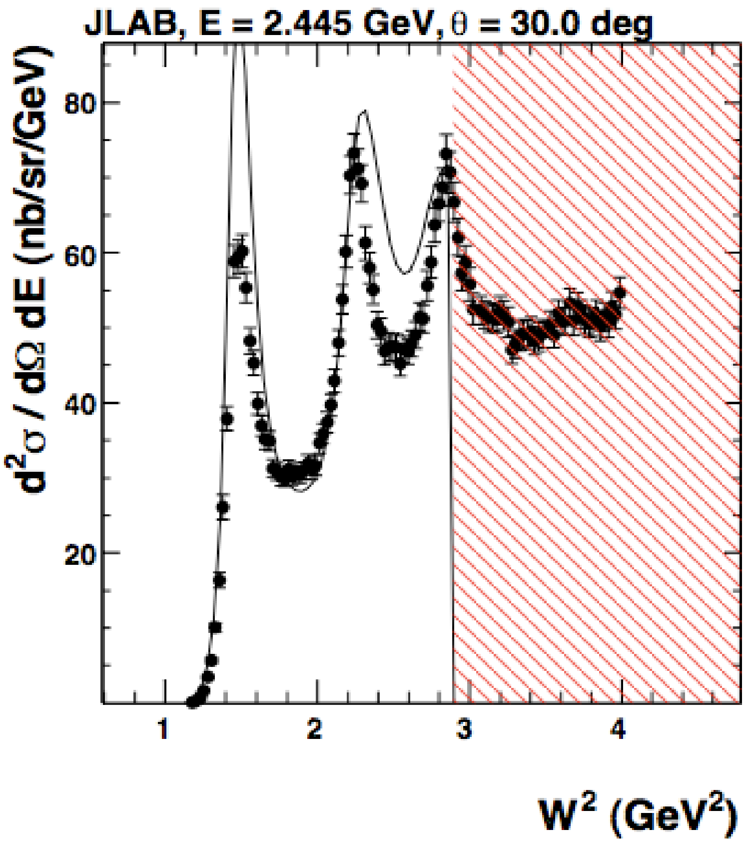
Comparison with electron quasi-elastic scattering data

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