Cross sections, electron scattering, and new results from electron-Argon experiment at Jefferson Lab

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VIRGINIA TECH

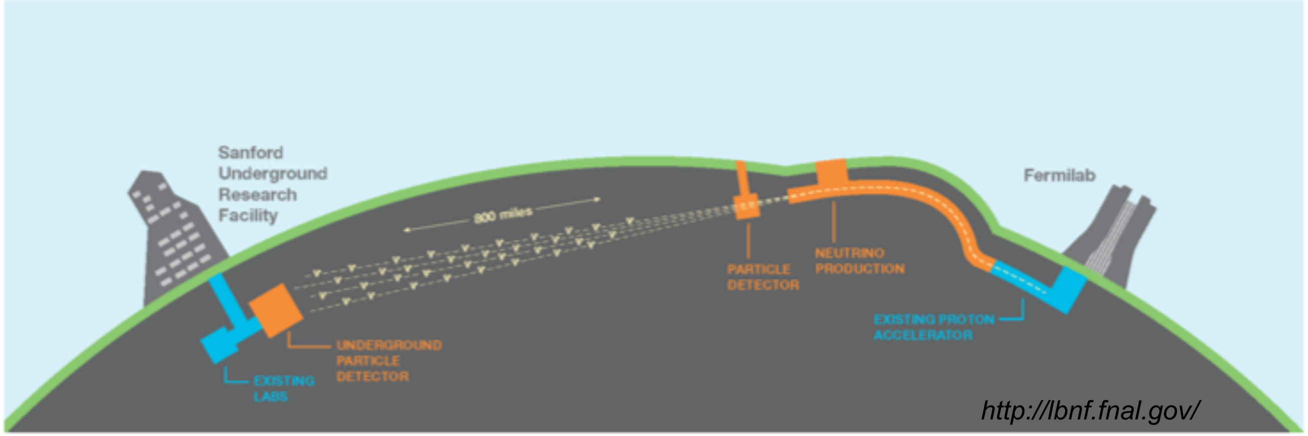
NSF

NuFACT 2018, The 20th International Workshop on Neutrinos from Accelerators, August 12-18, 2018

Prologue

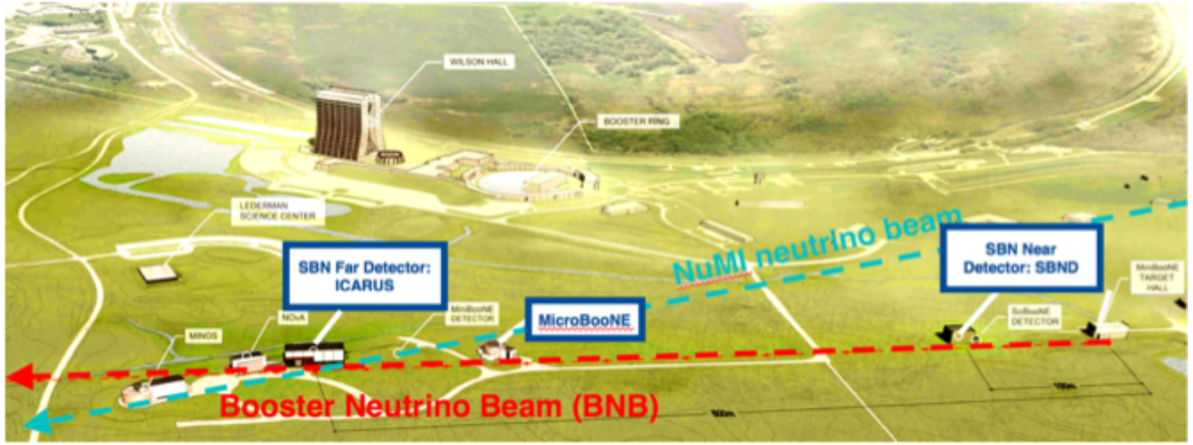
- The success of liquid argon time projection chamber (LArTPC) based - *long-baseline*, ***DUNE***, *and short-baseline*, ***SBND***, ***MicroBooNE***, ***ICARUS*** - neutrino programs in achieving an unprecedented percent-level precision will rely greatly on the level of precision with which we understand the complexity of *isospin-asymmetric* ***Argon*** nucleus and it's electroweak response.

- **DUNE**



http://lbnf.fnal.gov/

- **SBN Program at FNAL**



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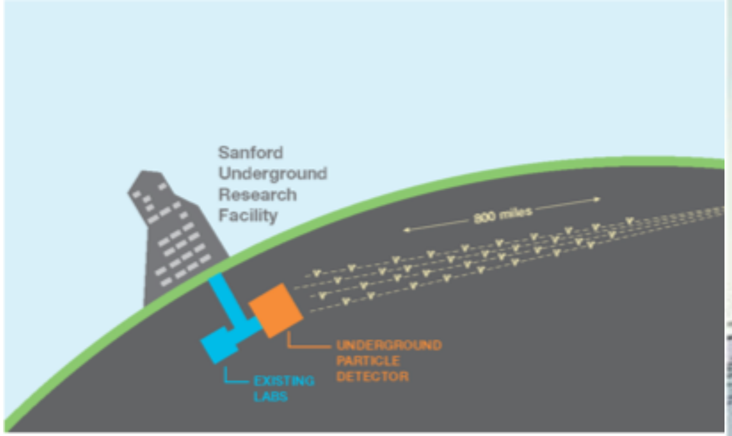

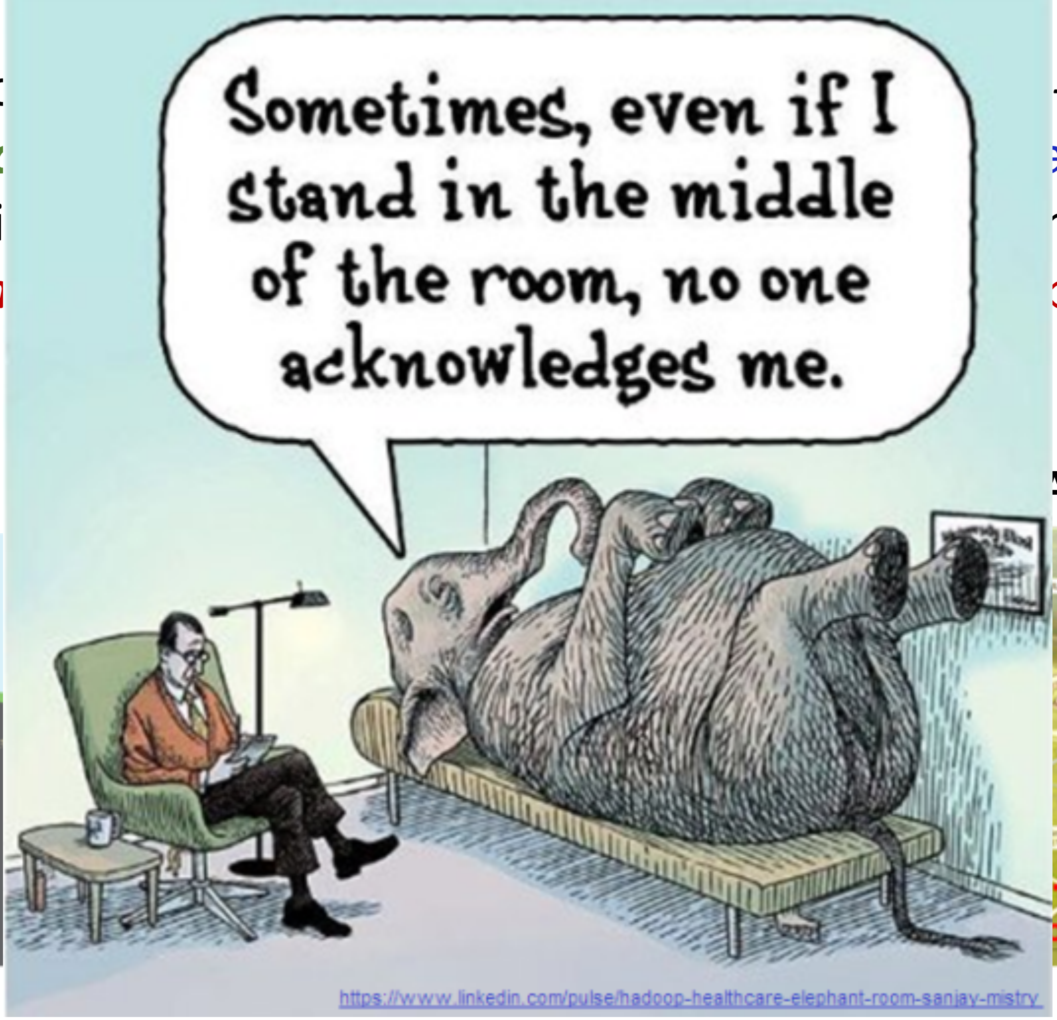

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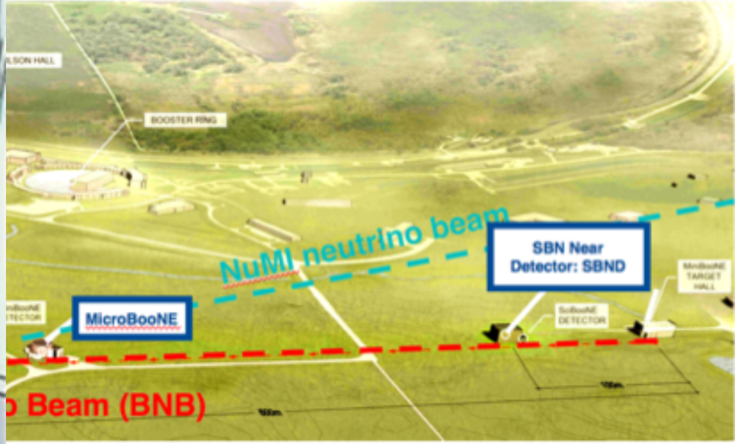
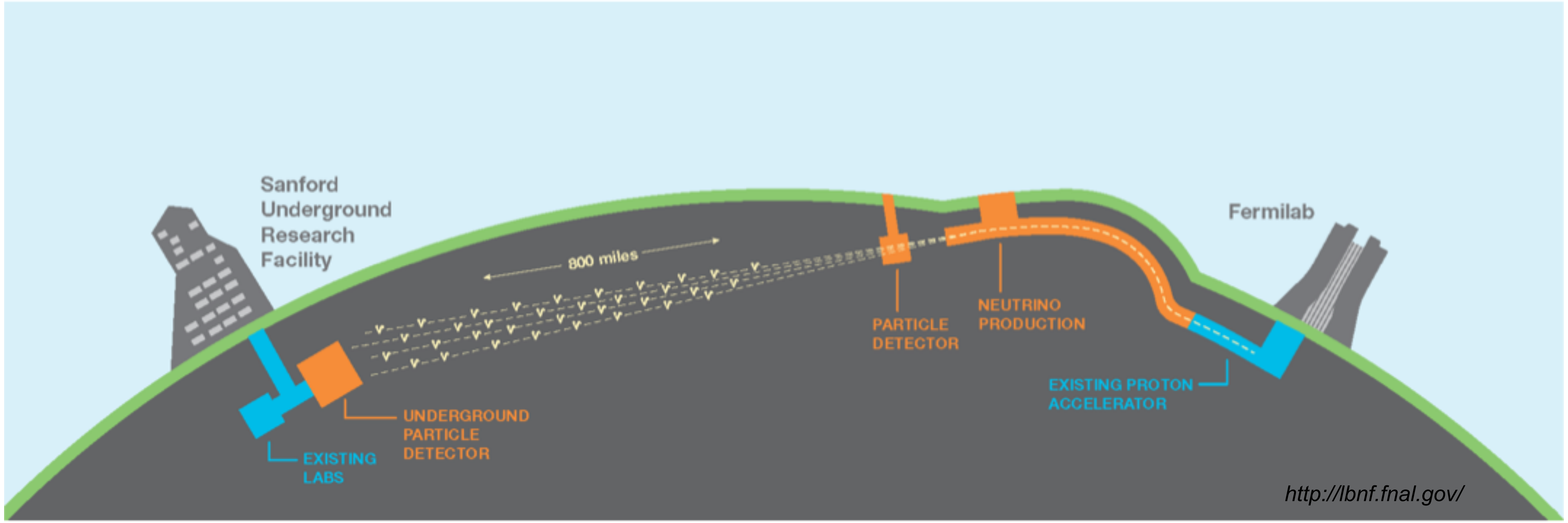


Reminder: Some challenges of accelerator-based neutrino program

"Now about this fixation about reminding yourself of everything."


Sanford
Underground
Research
Facility
800 miles
Fermilab
PARTICLE
DETECTOR
NEUTRINO
PRODUCTION
EXISTING PROTON
ACCELERATOR
UNDERGROUND
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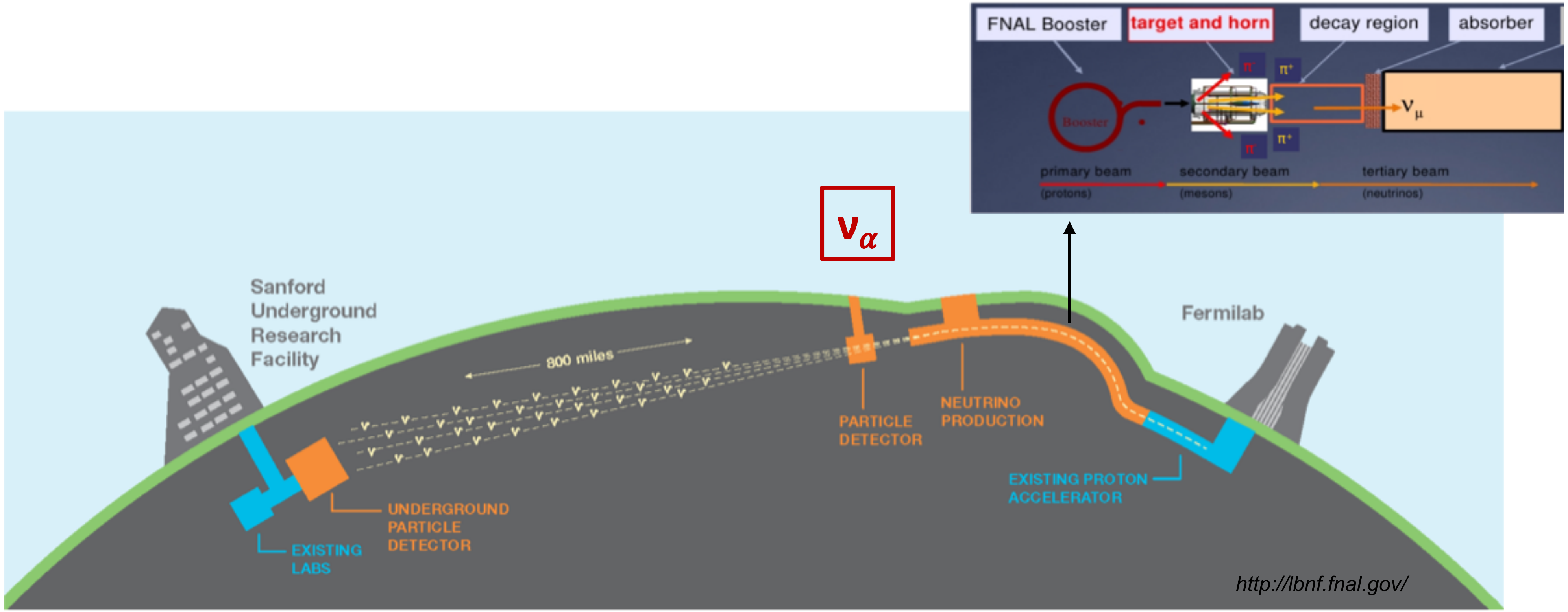
FNAL Booster
target and horn
decay region
absorber
Booster
π^+
ν_μ
primary beam
(protons)
secondary beam
(mesons)
tertiary beam
(neutrinos)
ν_α
Sanford
Underground
Research
Facility
800 miles
Fermilab
PARTICLE
DETECTOR
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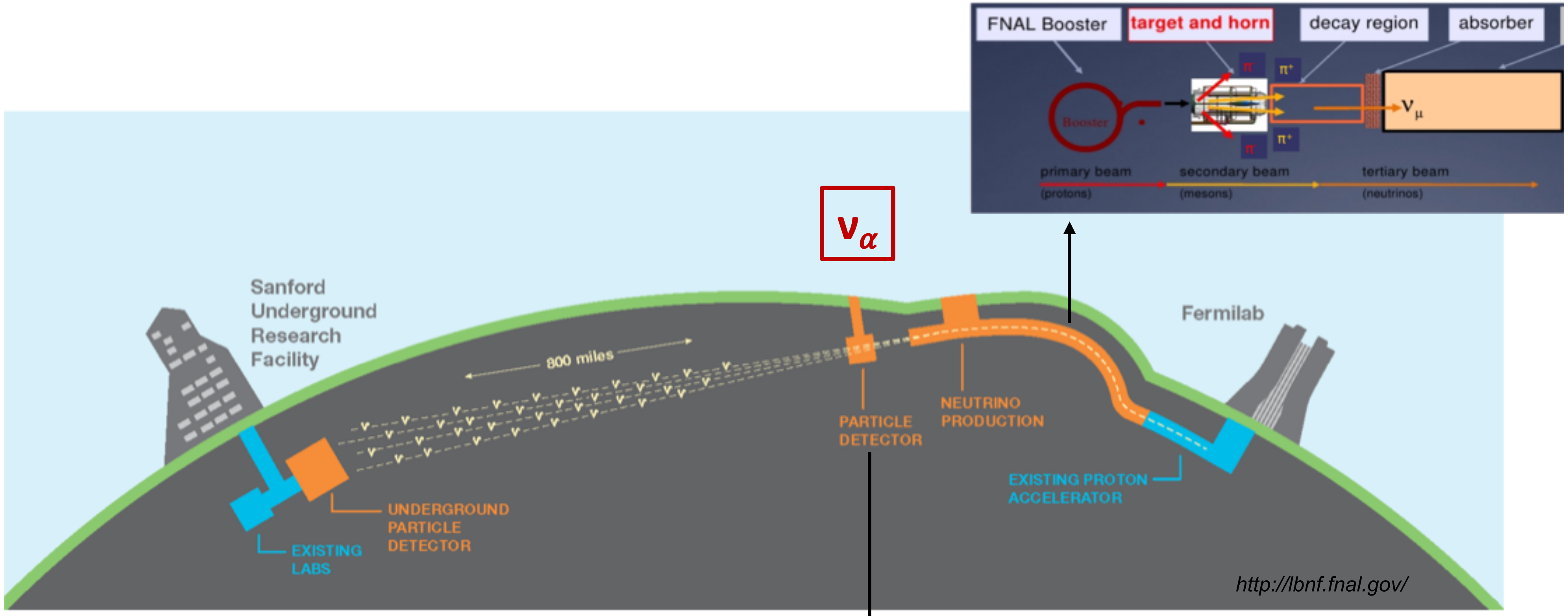
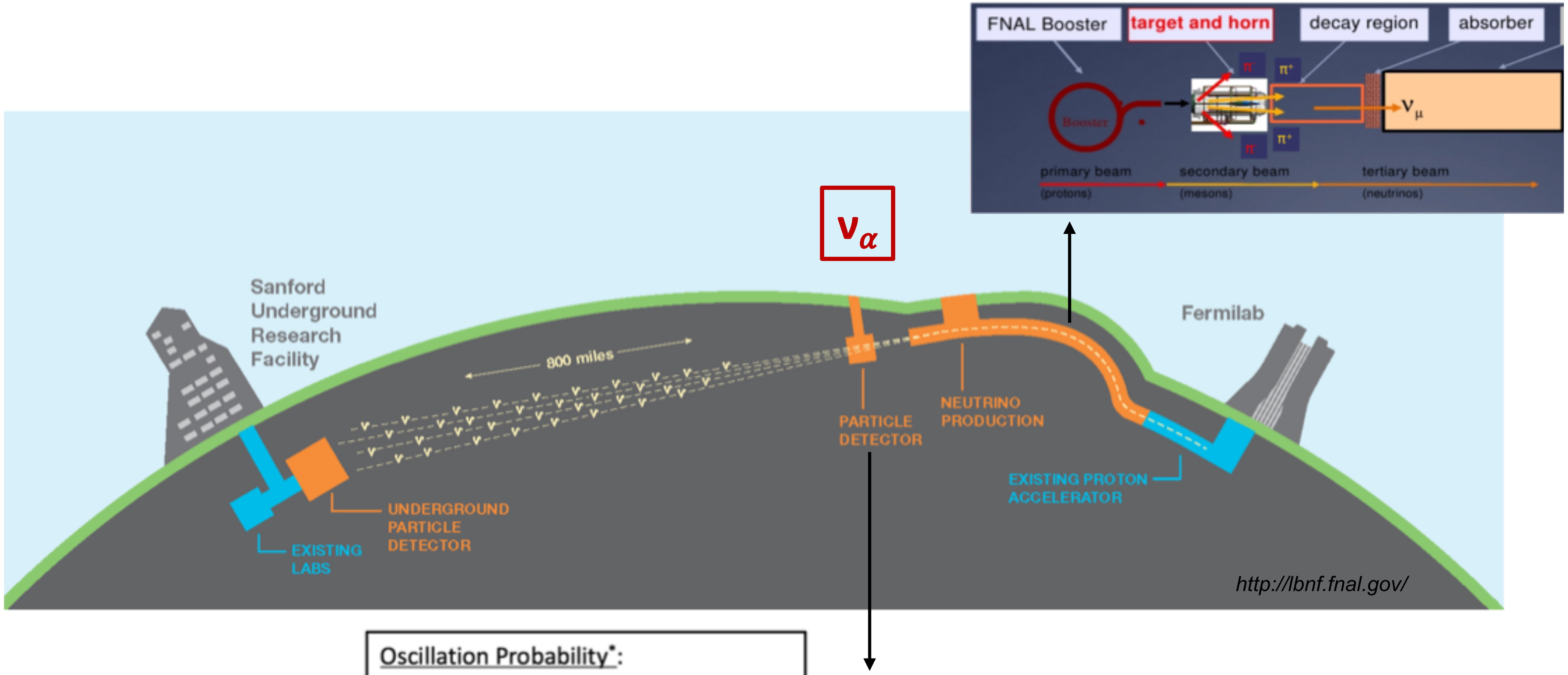


<u>Event Rate at near detector:</u>

$$N_{\mathrm{ND}}^{\alpha}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times \sigma_\alpha^i(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\alpha(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}}; \boldsymbol{p}_{\mathrm{reco}})$$



Oscillation Probability*:

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

two neutrino flavors, for simplicity

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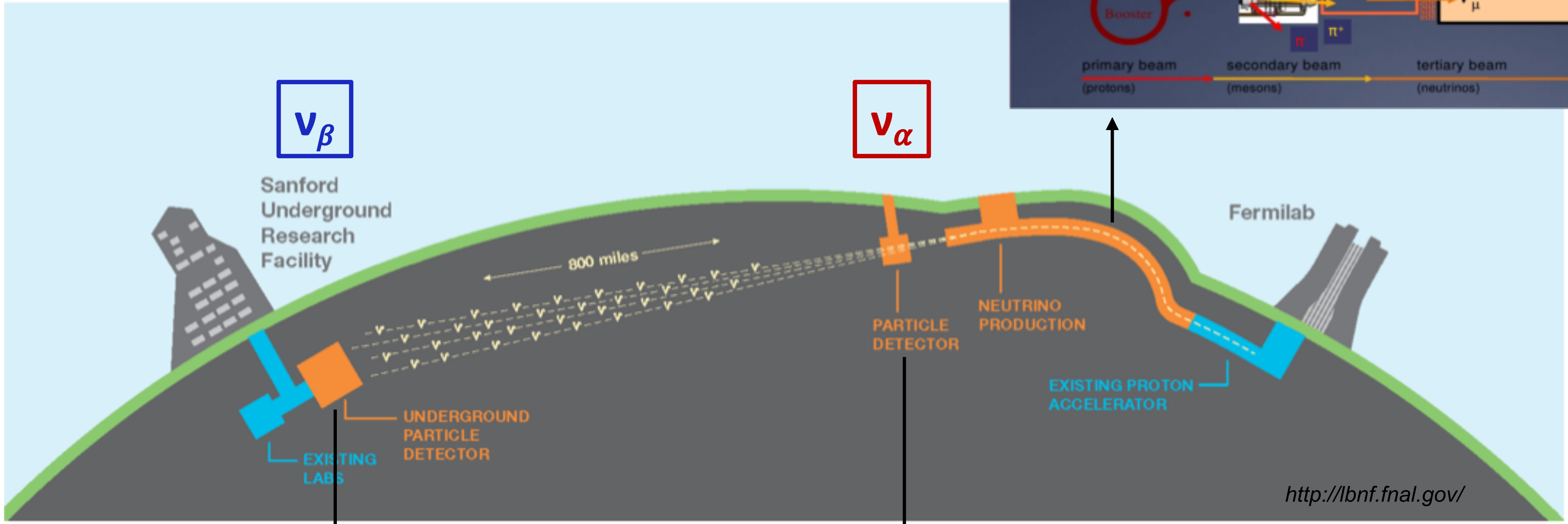

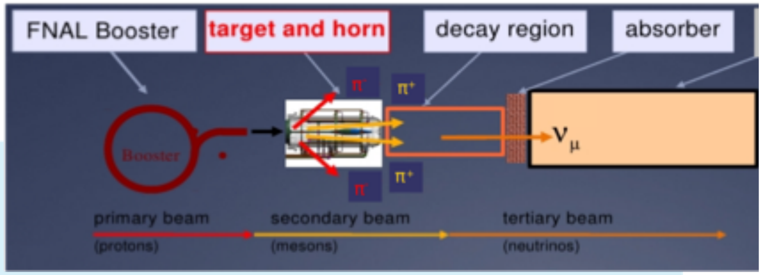

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Prog. Part. Nucl. Phys. 100, 1 (2018)

- Ideally, we would expect that we can extract the oscillation probability by taking the ratio of far to near detectors.

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    - The neutrino flavor at near and far detector are different (appearance experiment).
    - The neutrino flux and neutrino-nucleus cross sections are convoluted.

- In fact, it is not clear, how to interpret the ratio - what can be constrained with the ratio?

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- Remember that even a modest improvement in systematics will notably decrease the running time required for significant sigma-level coverage of DUNE objectives.

A. Scattering and cross sections

Event Rate at far detector:

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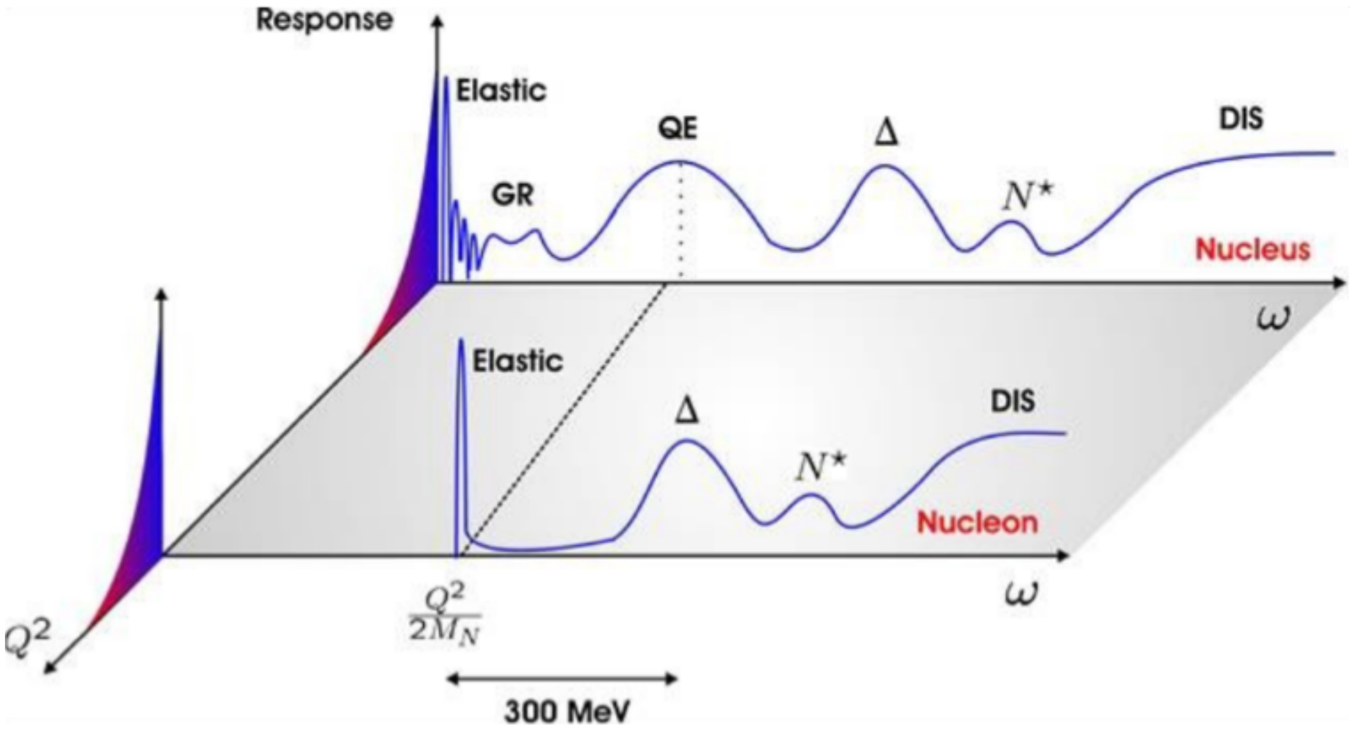

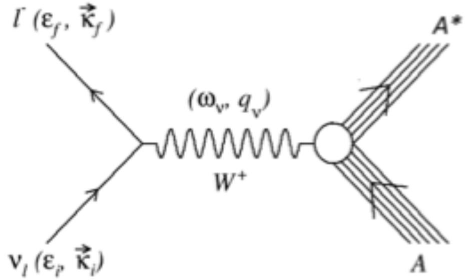

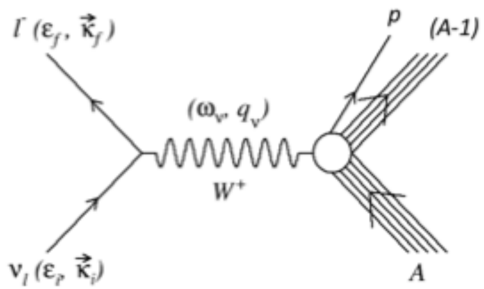

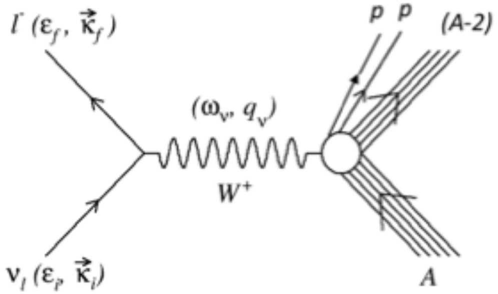

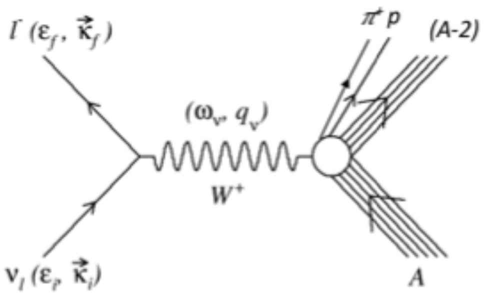

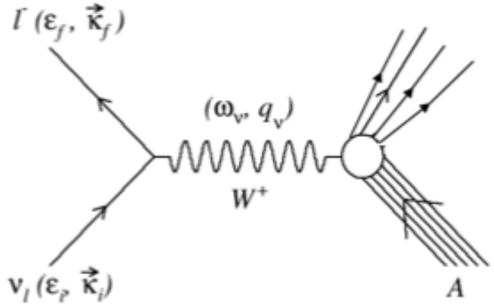

B: Energy Reconstruction

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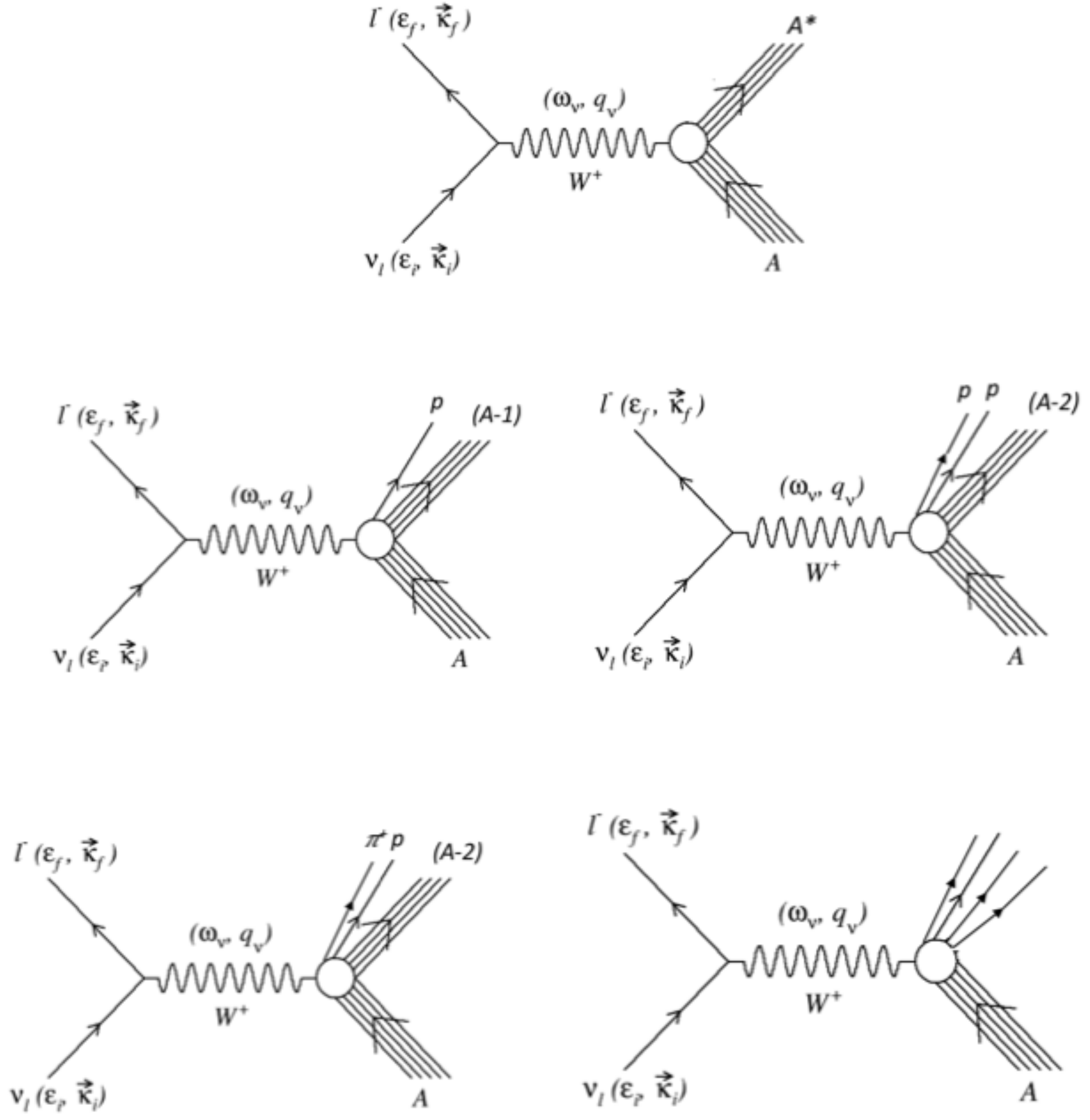

- Reconstruct the observed event topology and energy.
- Take the reconstructed event topology and energy back through the nucleus (using a nuclear model) to identify the neutrino energy at interaction vertex.
- Note: Not all the final state particle are observed (detector threshold, etc) and for any observed topology, many interactions processes could contribute and both the initial and final state nuclear effects play a role.

Generators

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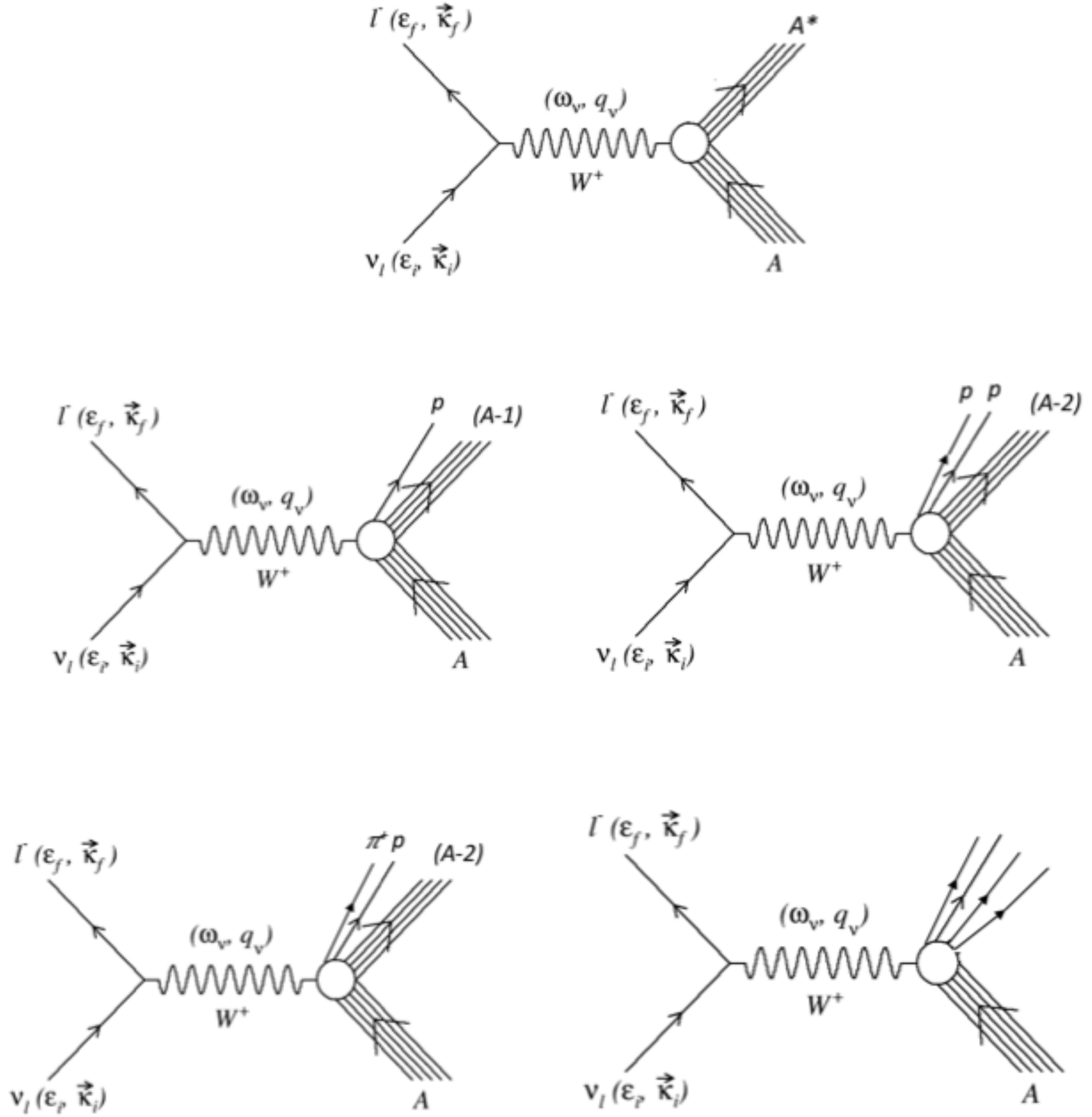
- Experiments rely on generators to connect observations in the detector to true interaction processes and kinematics.
- For experiments, generates paint the initial picture of the target nuclear system, weight different scattering process, calculates efficiencies, acceptance, backgrounds, etc..
- Needless to say, the best known (and well tested) theoretical models should be at the core of generator ingredients.



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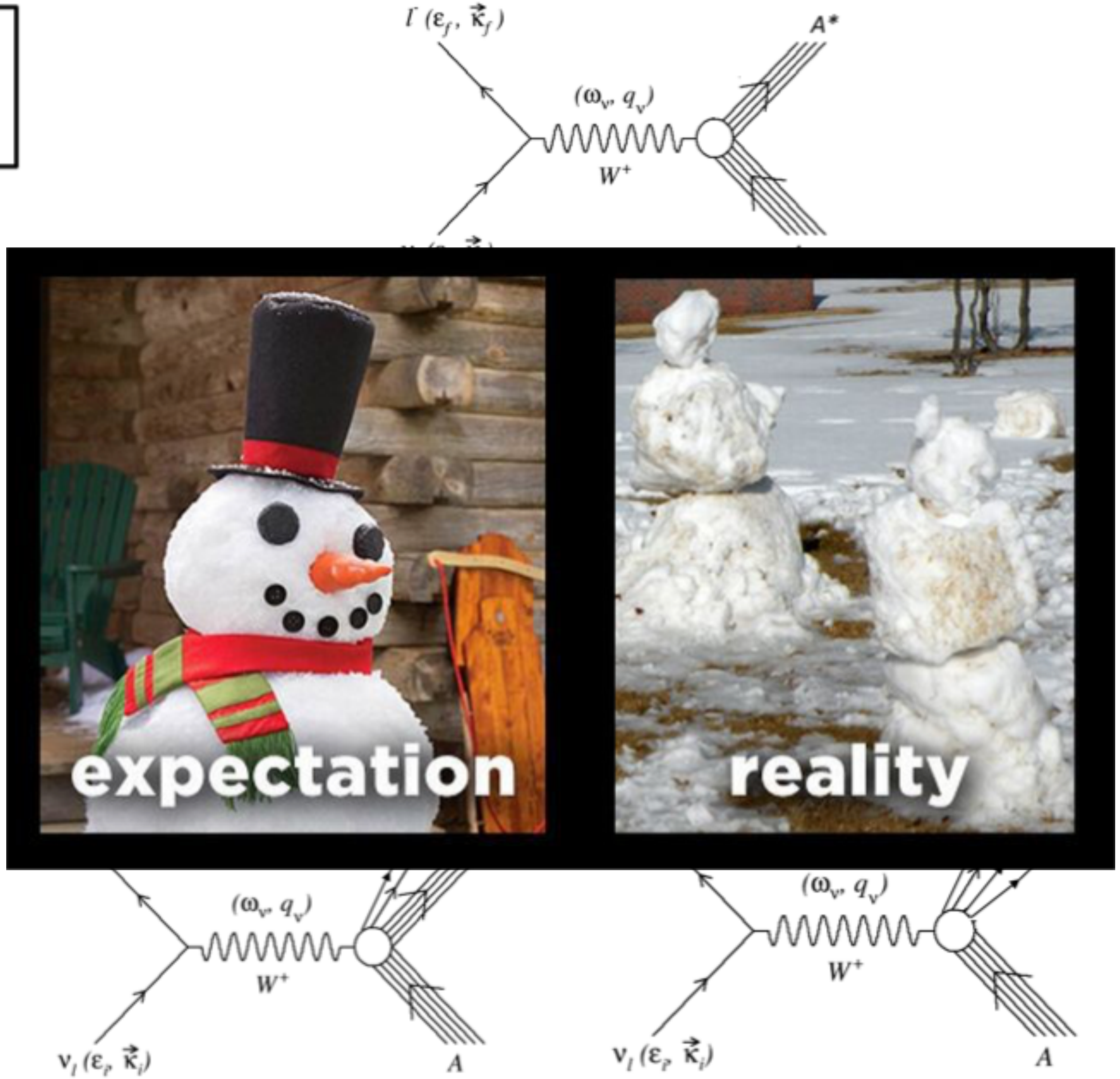
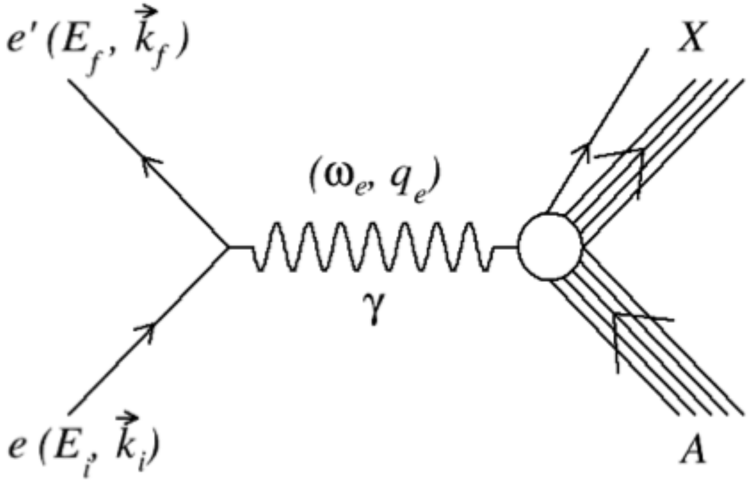


Electron to neutrino scattering

QE e-A scattering

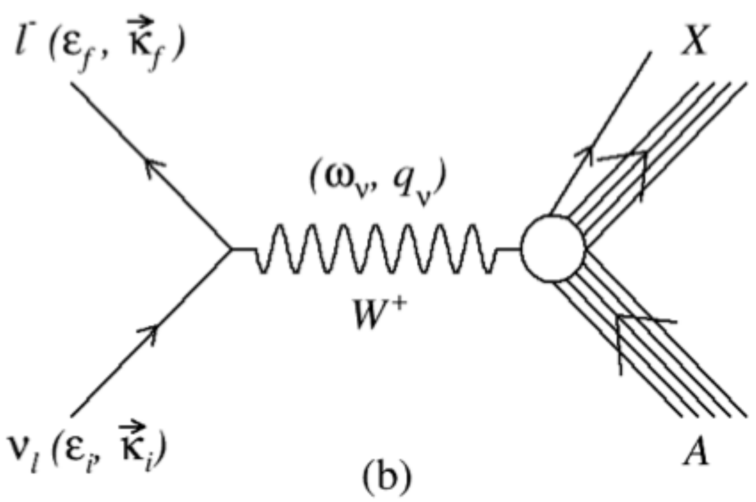


$$\left(\frac{d^2\sigma}{d\omega_e d\Omega}\right)_e = \frac{\alpha^2}{Q^4}\left(\frac{2}{2J_i+1}\right)\frac{1}{k_f E_i} \times \zeta^2(Z', E_f, q_e)\left[\sum_{J=0}^{\infty}\sigma^J_{L,e} + \sum_{J=1}^{\infty}\sigma^J_{T,e}\right]$$

$$\sigma_{L,e} = v_e^L R_e^L$$

$$\sigma_{T,e} = v_e^T R_e^T$$

QE v-A scattering



$$\left(\frac{d^2\sigma}{d\omega_\nu d\Omega}\right)_\nu = \frac{G_F^2 \cos^2\theta_c}{(4\pi)^2}\left(\frac{2}{2J_i+1}\right)\varepsilon_f\kappa_f \times \zeta^2(Z', \varepsilon_f, q_\nu)\left[\sum_{J=0}^{\infty}\sigma^J_{CL,\nu} + \sum_{J=1}^{\infty}\sigma^J_{T,\nu}\right]$$

$$\sigma^J_{CL,\nu} = \left[v_\nu^{\mathcal{M}} R_\nu^{\mathcal{M}} + v_\nu^{\mathcal{L}} R_\nu^{\mathcal{L}} + 2\, v_\nu^{\mathcal{ML}} R_\nu^{\mathcal{ML}}\right]$$

$$\sigma^J_{T,\nu} = \left[v_\nu^T R_\nu^T \pm 2\, v_\nu^{TT} R_\nu^{TT}\right]$$

sign is the only difference between v and anti-v

v's → Leptonic coefficients → Purely kinematical → Easy to calculate

R's → Response functions → Nuclear dynamics → **Need nuclear models to calculate!**

Electron to neutrino scattering

QE e-A scattering | **QE ν-A scattering**

Quasielastic Electron Nucleus Scattering Archive

- Home page
- Data
- Table & Notes
- Utilities
- Bibliography
- Acknowledgements

Announcement - April 2015: Fomin:2010 (e02019) data now available

Welcome to Quasielastic Electron Nucleus Scattering Archive

In connection with a review article (Quasielastic Electron-Nucleus Scattering, by O. Benhar, D. Day and I. Sick) published in the Reviews of Modern Physics [Rev. Mod. Phys. 80, 189-224, 2008], we have collected here an extensive set of quasielastic electron scattering data in order to preserve and make available these data to the nuclear physics community.

We have chosen to provide the cross section only and not the separated response functions. Unless explicitly indicated the data do not include Coulomb corrections.

Our criteria for inclusion into the data base is the following:

1. Data published in tabular form in journal, thesis or preprint.
2. Radiative corrections applied to data.
3. No known or acknowledged pathologies

At present there are about 600 different combinations of targets, energies and angles consisting of some 19,000 data points.

In the infrequent event that corrections were made to the data after the original publications, we included the latest data set, adding an additional reference, usually a private communication.

As additional data become known to us, we will add to the data sets.

If you wish to be alerted to changes in the archive or to the inclusion of new data, send an email to me (Donal Day) [dbd at virginia.edu]. Send any comments or corrections you might have as well.

Finally, we would appreciate an reference (e-Print Archive: nucl-ex/0603032) if you make use of the data in this archive in your work.

Visit the Nuclear Charge Density Archive

Donal Day
April 14, 2015

http://faculty.virginia.edu/qes-archive/

nti-ν

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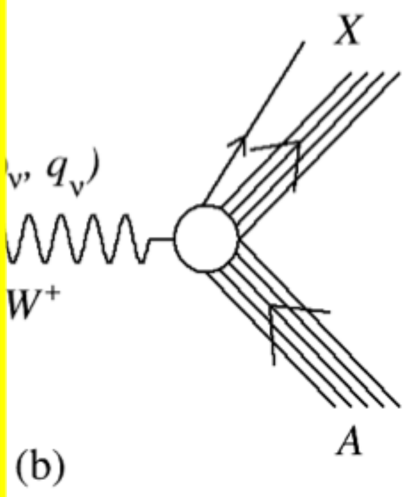
... scattering



Year	Laboratory	Energies (GeV)	Angles	Targets	Mode	PID	DeltaP/P (%)	In Archive	Citation
1980	Bates	0.1--0.37	90--160	Fe	S	Ckov	<0.1	N	Altemus:1980wt, Altemus:1980
1984	Bates	.15--.3	180	Fe	S	Ckov	<0.1	Y	Hotta:1984
1986	Bates	0.1-0.69	60--160	238U	S	Ckov	<0.1	Y	Blatchley:1986qd, Blatchley:1984
1986	Bates	0.22-0.32	180	2H	S	Ckov	<0.1	Y	Parker:1986
1987	Bates	.537 and .730	37.1	4He, Be, C and O	S	Ckov	<0.1	Y	O'Connell:1987ag
1988	Bates	0.07--0.79	54--134.5	3H, 3He	E	Ckov	<0.1	Y	Dow:1988rk, Dow:1987
1988	Bates	.3--.6	60, 134.5	2H, 3He, 4He	E	Ckov	<0.1	N	Dytman:1988fi
1988	Bates	.29--.44	60, 134.5	2H	E	Ckov	<0.1	N	Quinn:1988ua
1990	Bates	0.28--0.73	60 and 134.5	4He	E	Ckov	<0.1	Y	vonReden:1990a
1997	Bates	0.130--.84	45.5, 90, 140	Ca40	S/E	Ckov	<0.1	Y	Williamson:1997, Yates:1993jg
1971	CEA	1--4	8.5--18	C	E	SC,Ckov		N	Stanfield:1971eg
1974	DESY	2.7	12--15	Li	E	SC,Ckov	1.2	N	Heimlich:1974rk, Heimlich:1973
1974	DESY	2--2.7	15	C	E	SC,Ckov	1.2	Y	Zeller:1973ge
1996	Frascati	.7--1.5	32, 37.1 and 83	16O		SC,Ckov	few %	Y	Anghinolfi:1996vm
1971	HEPL	0.5	60	Li,C,Mg,Ca,Ni,Y,Sn,Ta,Pb	S	Ckov	0.1	Y	Moniz:1971mt, Whitney:1974hr
1976	HEPL	0.5	60	3He, 4He	S	Ckov	0.1	Y	McCarthy:1976re
1998	JLAB	4.045	15-55	2H,C,Fe,Au	E	SC,Ckov	0.1	Y	Arrington:1998ps, Arrington:1998hz
2011	JLAB	5.766	18.00-55.00	2H, 3He, 4He, 9Be, 12C, 64Cu, 197Au	E	SC,Ckov	0.1	Y	Fomin:2010ei
1969	Kharkov	0.6--1.	16--60	C		Ckov		N	Dementii:1969
1969	Kharkov	1.1	25	C		SC,Ckov		N	Titov:1969
1971	Kharkov	1.1--1.2	20--60	C,Al,Ni,Mo,W		SC,Ckov		N	Titov:1971
1972	Kharkov	1.18	16--55	6Li		SC,Ckov		N	Titov:1972
1974	Kharkov	1.2	20--35	Be,Cu, Ag		SC,Ckov		N	Titov:1974
1976	Kharkov			4He				N	Dementii:1976
1983	Saclay	0.120--0.60	36,60,90,and 145	C	S	Ckov	0.1	Y	Barreau:1983ht
1984	Saclay	0.120--0.695	60,90, and 140	40Ca, 48Ca, Fe	S	Ckov	0.1	Y	Meziani:1984is
1985	Saclay	0.12--0.67	36--145	3He	S	Ckov	0.1	Y	Marchand:1985us
1993	Saclay	0.14--0.65	34--145	4He and Pb	E	Ckov	0.1	Y	Zghiche:1993xg
1976	SLAC	6.5--18.4	8	2H	E	SC,Ckov	0.5	Y	Schutz:1976he
1979	SLAC	2.8--14.7	8	3He	E	SC,Ckov	0.2	Y	Day:1979bx
1981	SLAC	6.5--11.3	8	4He	E	SC,Ckov	0.1	Y	Rock:1981aa
1987	SLAC	up to 4 GeV	15-39	4He, C, Al, Fe, Au	E	SC,Ckov	0.1	Y	Day:1987az, Day:1993md, Potterveld:1989wn
1988	SLAC	0.65--1.65	11--55	C and Fe	E	SC,Ckov	0.1	Y	Baran:1988tw, Baran:1989
1988	SLAC	0.8 --1.3	180	2H	E	SC,Ckov	0.1	Y	Arnold:1988us
1989	SLAC	1--1.5	37.5	4He,C, Fe, W	E	SC,Ckov	0.1	Y	Sealock:1989nx
1991	SLAC	9.7-21	10	2H	E	SC,Ckov	0.1	Y	Rock:1991jy
1992	SLAC	1.1--4.3	15 and 85	3He, 4He, Fe	E	SC,Ckov	0.1	Y	Chen:1991vb, Chen:1990kq, Meziani:1992xr
1992	SLAC	1.5--5.5	15--90	2H	E	SC,Ckov	0.1	Y	Lung-thesis:1992
1992	SLAC	2--9.8	15--61	Al	E	SC,Ckov	0.1	Y	Bosted:1992fy
1992	SLAC	2.8--14.7	8	Al	E	SC,Ckov	0.1	Y	Rock-pc
1995	SLAC	2.--5.	15--57	2H, C, Fe, Au	E	SC,Ckov	0.1	Y	Arrington:1995hs
1988	Yerevan	1.9-2.1	16-18	C	S	SC	0.5	Y	Bagdasaryan:1988hp

$\left(\frac{d^2\sigma}{d\omega_e d\Omega}\right)_e$ ... $\cos^2\theta_c$ ... $\pi)^2$ $\left(\frac{2}{2J_i+1}\right)\varepsilon_f\kappa_f$

$\times\ \zeta$ ... $\left[\sum_{J=0}^{\infty}\sigma^J_{CL,\nu}+\sum_{J=1}^{\infty}\sigma^J_{T,\nu}\right]$

$\sigma_{L,e} = v$ ... $+\ v^{\mathcal{L}}_\nu R^{\mathcal{L}}_\nu +\ 2\ v^{\mathcal{ML}}_\nu R^{\mathcal{ML}}_\nu]$

$\sigma_{T,e} = v$ ... $\pm\ 2\ v^{TT}_\nu R^{TT}_\nu]$

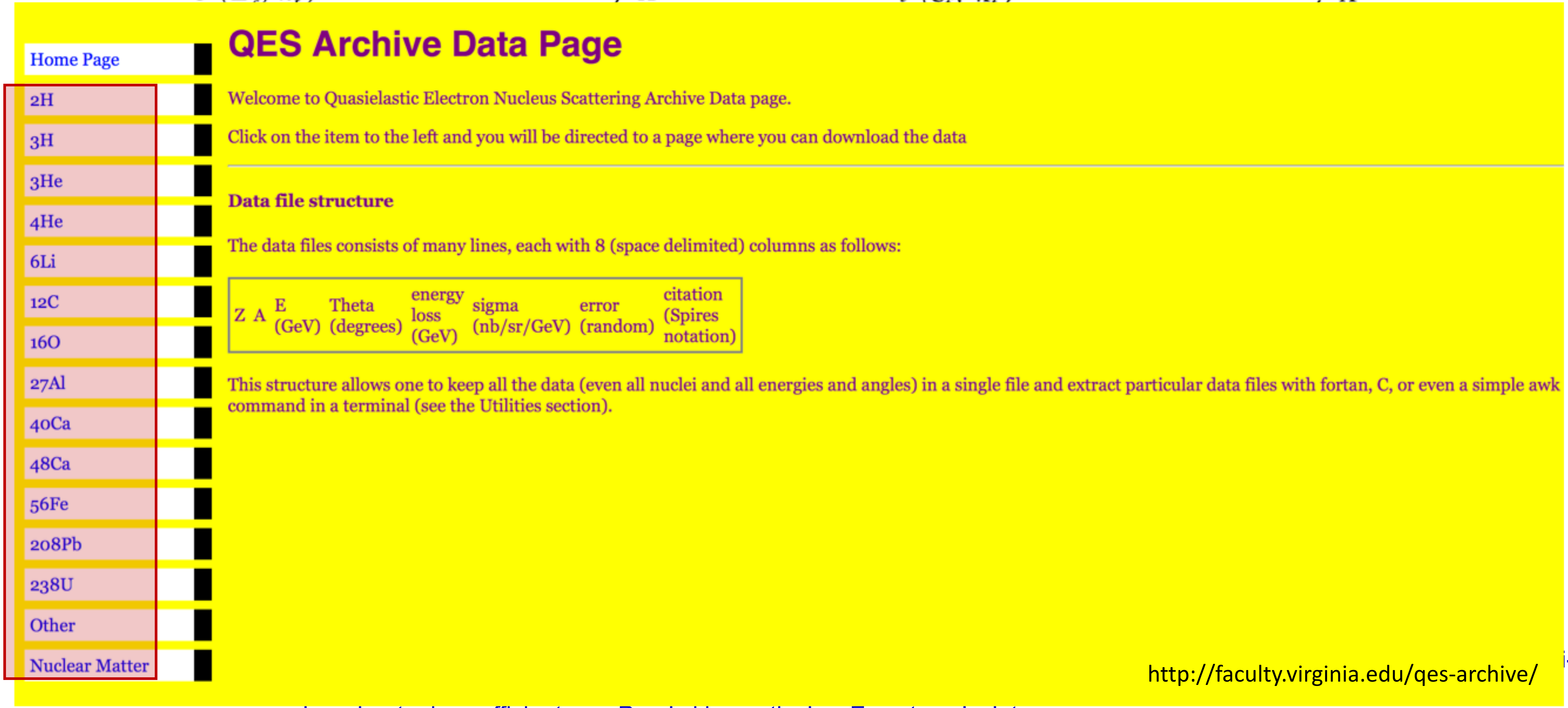
... n is the only difference between v and anti-v

... s to calculate!

Electron to neutrino scattering

QE e-A scattering **QE ν-A scattering**

$e'(E_f, \vec{k}_f)$ X $l^-(\varepsilon_f, \vec{\kappa}_f)$ X



Home Page

2H
3H
3He
4He
6Li
12C
16O
27Al
40Ca
48Ca
56Fe
208Pb
238U
Other
Nuclear Matter

QES Archive Data Page

Welcome to Quasielastic Electron Nucleus Scattering Archive Data page.

Click on the item to the left and you will be directed to a page where you can download the data

Data file structure

The data files consists of many lines, each with 8 (space delimited) columns as follows:

Z	A	E (GeV)	Theta (degrees)	energy loss (GeV)	sigma (nb/sr/GeV)	error (random)	citation (Spires notation)

This structure allows one to keep all the data (even all nuclei and all energies and angles) in a single file and extract particular data files with fortan, C, or even a simple awk command in a terminal (see the Utilities section).

http://faculty.virginia.edu/qes-archive/

i-v

v's → Leptonic coefficients → Purely kinematical → Easy to calculate

R's → Response functions → Nuclear dynamics → **Need nuclear models to calculate!**

Electron to neutrino scattering

QE e-A scattering | **QE ν-A scattering**

$e'(E_f, \vec{k}_f)$ X $l^-(\varepsilon_f, \vec{\kappa}_f)$ X

QES Archive Data Page

Home Page

- 2H
- 3H
- 3He
- 4He
- 6Li
- 12C
- 16O
- 27Al
- 40Ca
- 48Ca
- 56Fe
- 208Pb
- 238U
- Other
- Nuclear Matter

Ar?

Welcome to Quasielastic Electron Nucleus Scattering Archive Data page.

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- The current systematics related to neutrino-nucleus interactions are of the order of 5 to 10% even with relatively well-known isospin symmetric nuclei – carbon and oxygen - of which a range of electron scattering data is available.

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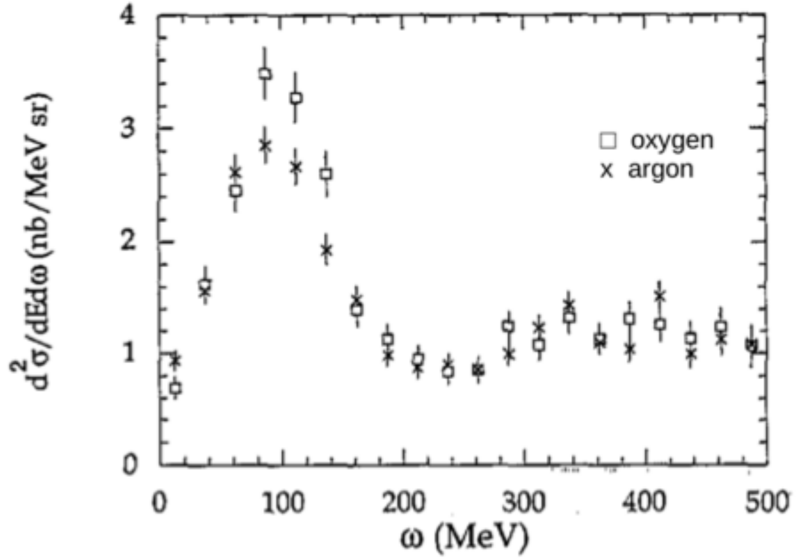
- The only available e-Ar data is (e,e') cross section measured at Frascati National Laboratory using the electron-positron collider ADONE and a jet target.

E = 700 MeV, θ = 32 deg



M. Anghinolfi et al., J. Phys. G21, L9 (1995)

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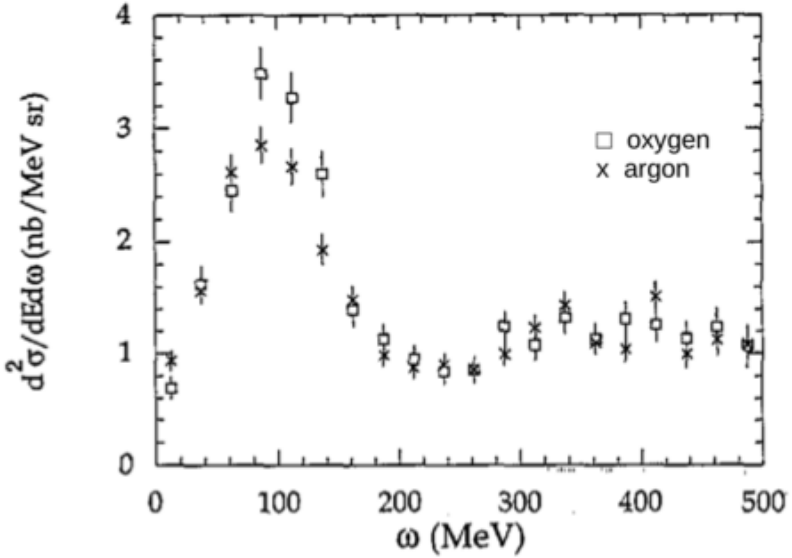


M. Anghinolfi et al., J. Phys. G21, L9 (1995)

- The only available e-Ar data is (e,e') cross section measured at Frascati National Laboratory using the electron-positron collider ADONE and a jet target.

- ^{40}Ar, isospin asymmetric nuclei, neutron excess (N>Z).

- If neutrinos and antineutrinos behold different nuclear effects (different number of protons and neutrons in ^{40}Ar), this will directly impact our ability to test for the presence of CP-violating effects in the data.

- 2p-2h isospin dependence?

- …..

electron-Argon experiment at Jefferson Lab [E12-14-012]

Goals:

- Measuring spectral functions of Ar nucleus.
- Measuring (e,e’) and (e,e’p) cross sections on Ar, Ti (and C, Al) nuclei.

PR12-14-012

Scientific Rating: A-

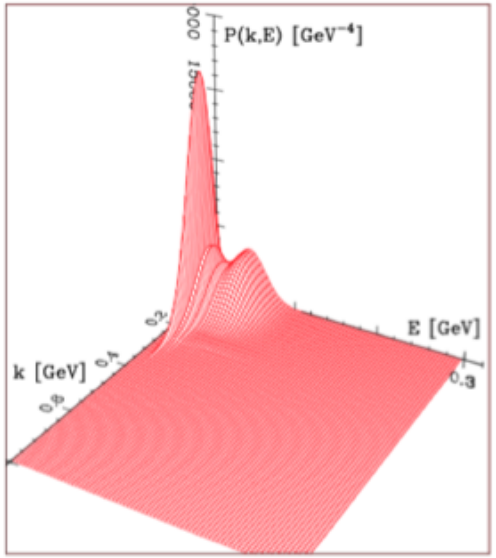
Recommendation: Approve

Title: **Measurement of the Spectral Function of ^{40}Ar through the (e,e′p) reaction**

Spokespersons: O. Benhar, C. Mariani, C.-M. Jen, D.B. Day, D. Higinbotham

Motivation: This experiment is motivated by the need to model the response of liquid Argon detectors to neutrino beams. This information is important for the LBNF program (and other oscillation experiments) that use liquid Ar. The critical issue is that reconstruction of the neutrino energy depends on the spectral functions of neutrons and protons in ^{40}Ar. The neutrino beam has an energy spread and hence the neutrino flux as a function of energy has to be extracted by simulations that include the correct nuclear physics. A challenge is that the next generation of neutrino oscillation experiments aim at a precision of 1% and hence ensuring that the nuclear corrections are properly addressed is critical. This data will provide experimental input to construct the argon spectral function, thus allowing the most reliable estimate of the neutrino cross sections. In addition, the analysis of the (e,e′p) data will help a number of theoretical developments, such as the description of final-state interactions needed to isolate the initial-state contributions to the observed single-particle peaks, that is also needed for the interpretation of the signal detected in neutrino experiments.

electron-Argon experiment at Jefferson Lab [E12-14-012]



Goals:

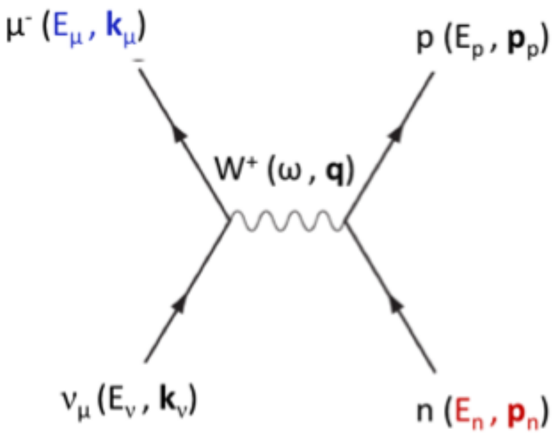
- Measuring spectral functions of Ar nucleus.
- Measuring (e,e') and (e,e'p) cross sections on Ar, Ti (and C, Al) nuclei.

Why Spectral Functions?

I. Energy Reconstruction: Measuring spectral functions of argon nucleus will provide the energy and momentum distribution of protons and neutrons bound in argon nucleus that will allows more accurate reconstruction of the incoming neutrino and antineutrino energies.

Kinematic Energy Reconstruction for CCQE process:

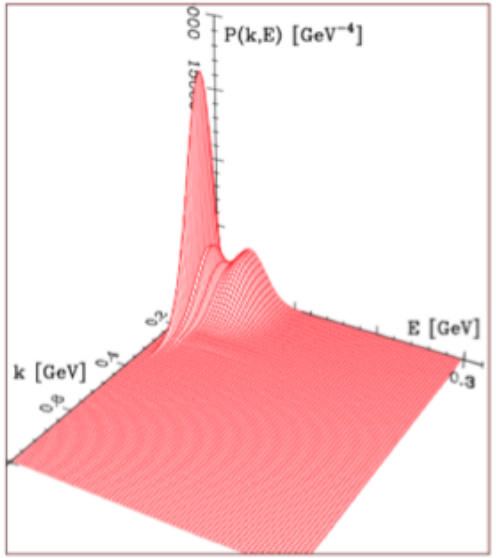
$$E_\nu = \frac{m_p^2 - m_\mu^2 - E_n{}^2 + 2E_\mu E_n - 2\mathbf{k}_\mu \cdot \mathbf{p}_n + |\mathbf{p}_n{}^2|}{2(E_n - E_\mu + |\mathbf{k}_\mu|\cos\theta_\mu - |\mathbf{p}_n|\cos\theta_n)}$$



where $|k_\mu|$ and θ_μ are measured, while p_n and E_n are the unknown momentum and energy of the interacting neutron.

Existing simulation codes routinely use $|p_n| = 0$, $E_n = m_n - \varepsilon$, with $\varepsilon \sim 20$ MeV for carbon and oxygen, or the Fermi gas (FG) model.

electron-Argon experiment at Jefferson Lab [E12-14-012]



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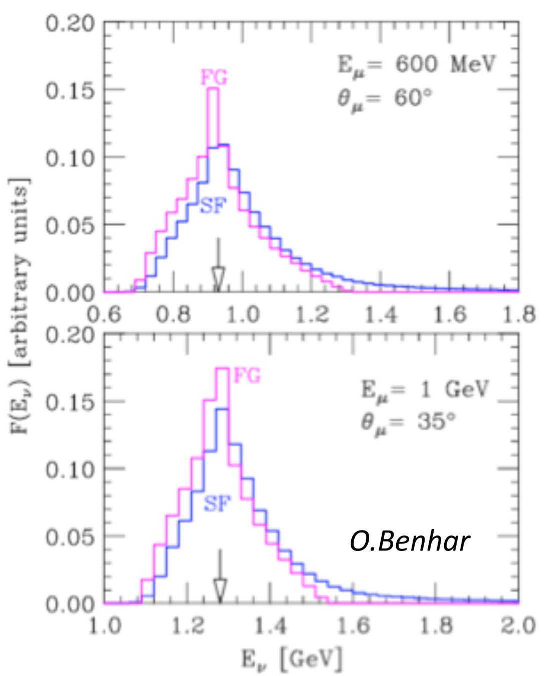
- Neutrino energy reconstructed using 2 ×10^4 pairs of (|p|, E) values sampled from realistic (SF) and FG oxygen spectral functions.
- The average value ⟨E_ν⟩ obtained from the realistic spectral function turns out to be shifted towards larger energy by ∼ 70 MeV.



electron-Argon experiment at Jefferson Lab [E12-14-012]

Goals:

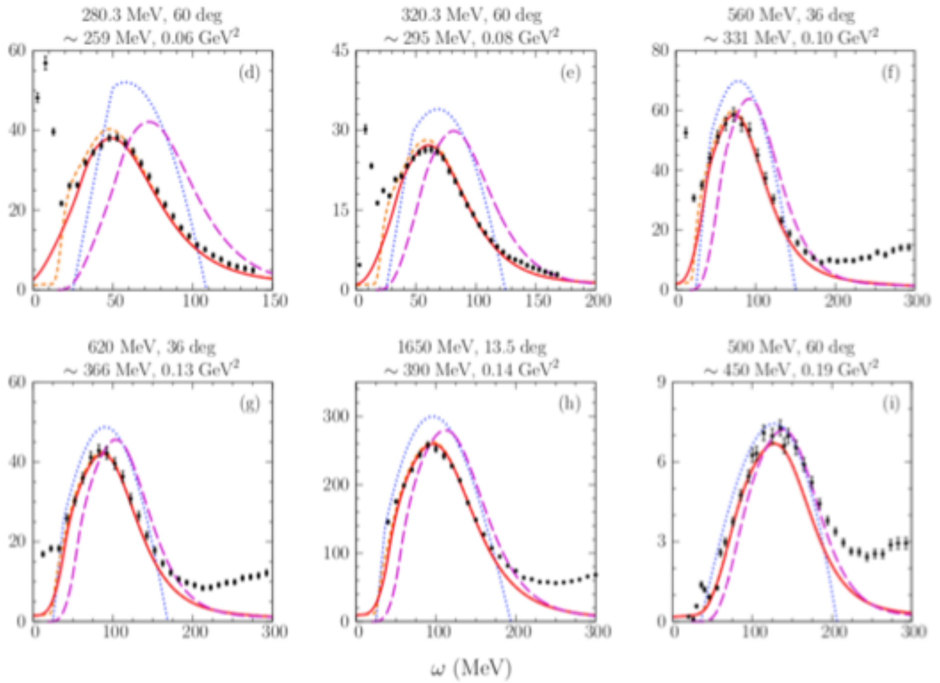
- Measuring spectral functions of Ar nucleus.
- Measuring (e,e’) and (e,e’p) cross sections on Ar, Ti (and C, Al) nuclei.

Why Spectral Functions?

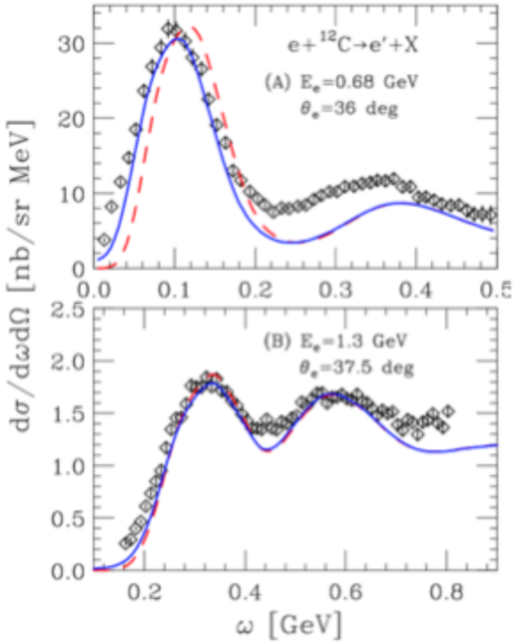
II. Nuclear Model: The measured argon spectral functions will provide vital input to the theoretical model based on the factorization *ansatz* dictated by the impulse approximation and spectral function formalism [*Benhar et al*.].

The approach which has been successful in describing inclusive electron-scattering data in a variety of kinematical regimes.

And has been extended to the analysis of neutrino scattering.



A. M. Ankowski, O. Benhar, M. Sakuda, Phys. Rev. D 91, 054616 (2015).



N. Rocco, A. Lovato, O. Benhar, Phys. Rev. Lett. 116, 192501 (2016).

electron-Argon experiment at Jefferson Lab [E12-14-012]

Goals:

- Measuring spectral functions of Ar nucleus.
- Measuring (e,e’) and (e,e’p) cross sections on Ar, Ti (and C, Al) nuclei.

➢ Nevertheless, a new high precision e-Ar data will provide vital information about argon nucleus and it’s electroweak response to the community that can be used as a testbed for the development of theoretical models. It will be a significant step ahead in improving the accuracy with which DUNE and SBN program can perform measurements.

Extracting Spectral Functions from Data

- We plan to study the **coincidence (e,e'p) processes** in the **kinematical region** in which single nucleon knock out of a nucleon occupying a shell model orbit is the dominant reaction mechanism.

Coincidence *(e,e'p)* process:

- Both the outgoing electron and the proton are detected in coincidence, and the recoiling nucleus can be left in any bound state.

- Within the Plane Wave Impulse Approximation (PWIA) scheme:

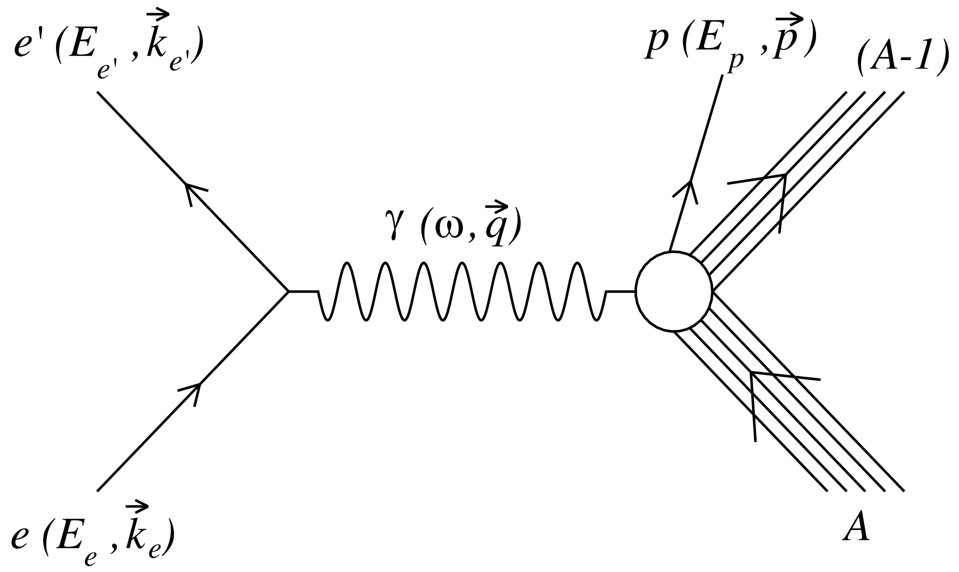
$$\frac{d\sigma_A}{dE_{e'}d\Omega_{e'}dE_p d\Omega_p} \propto \sigma_{ep} P(p_m, E_m)$$

- The initial energy and momentum of the knocked out nucleon can be identified with the measured missing momentum and energy, respectively as

$$\mathbf{p}_m = \mathbf{p} - \mathbf{q}$$

$$E_m = \omega - T_p - T_{A\text{-}1} \sim \omega - T_p$$

Where $T_p = E_p - m$, is the kinetic energy of the outgoing proton.



Extracting Spectral Functions from Data

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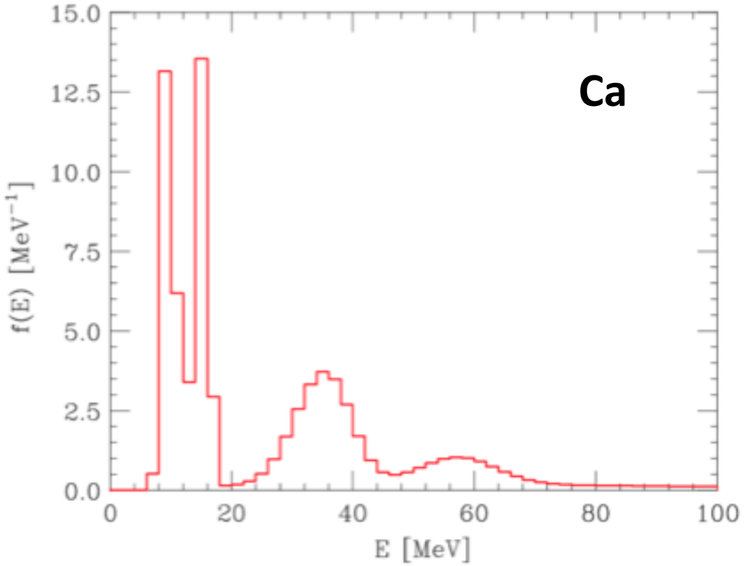
Kinematic region:

- Separation energies of the proton and neutron shell model states for Ca and Ar ground states

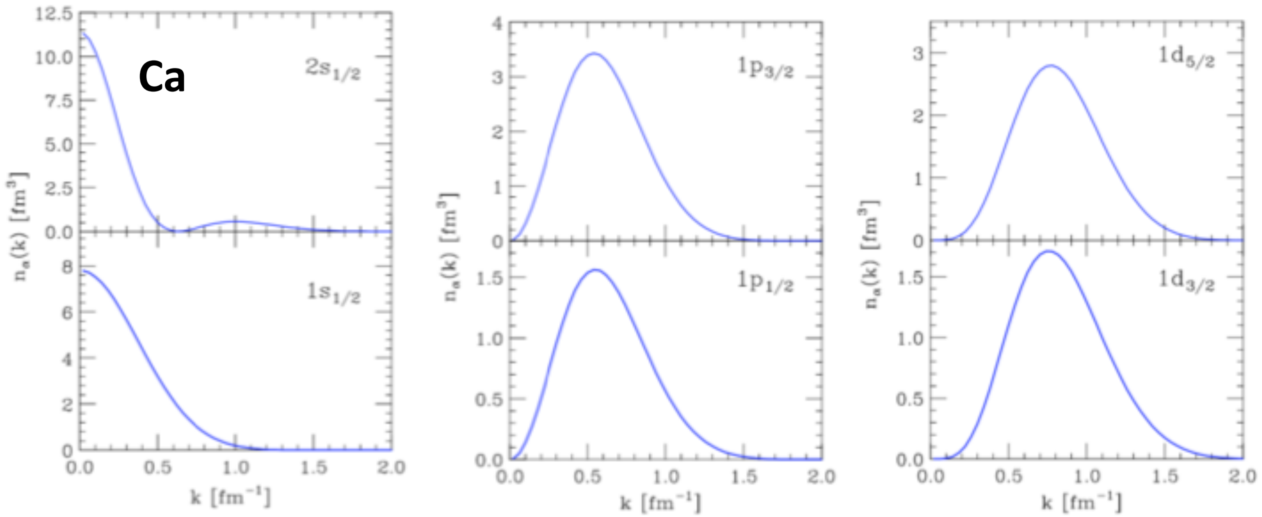
	protons		neutrons	
	$^{40}_{20}$Ca	$^{40}_{18}$Ar	$^{40}_{20}$Ca	$^{40}_{18}$Ar
$1s_{1/2}$	57.38	52	66.12	62
$1p_{3/2}$	36.52	32	43.80	40
$1p_{1/2}$	31.62	28	39.12	35
$1d_{5/2}$	14.95	11	22.48	18
$2s_{1/2}$	10.67	8	17.53	13.15
$1d_{3/2}$	8.88	6	15.79	11.45
$1f_{7/2}$				5.56

- The energy distribution

$$f(E) = 4\pi \int dk\; k^2 P(k, E)$$



- The momentum distribution



> ➢ Kinematic region for argon
> 6 MeV ≲ E_m ≲ 60 MeV
> $\mathbf{p}_m$ ≲ 350 MeV

A. M. Ankowski and J. T. Sobczyk, Phys. Rev. C77, 044311 (2008)

Extracting Spectral Functions from Data

- We plan to study the **coincidence (e,e'p) processes** in the **kinematical region** in which single nucleon knock out of a nucleon occupying a shell model orbit is the dominant reaction mechanism.

- Cross section within the Plane Wave Impulse Approximation (PWIA) scheme:

$$\frac{d\sigma_A}{dE_{e'} d\Omega_{e'} dE_p d\Omega_p} \propto \sigma_{ep} P(p_m, E_m)$$

- The spectral function extracted from the data will be

$$P_{MF}(p_m, E_m) = \sum_\alpha Z_\alpha \, |\xi_\alpha(p_m)|^2 F_\alpha(E_m - E_\alpha)$$

In the absence of correlations, $Z_\alpha \to 1$, and $F_\alpha(E_m - E_\alpha) \to \delta(E_m - E_\alpha)$.

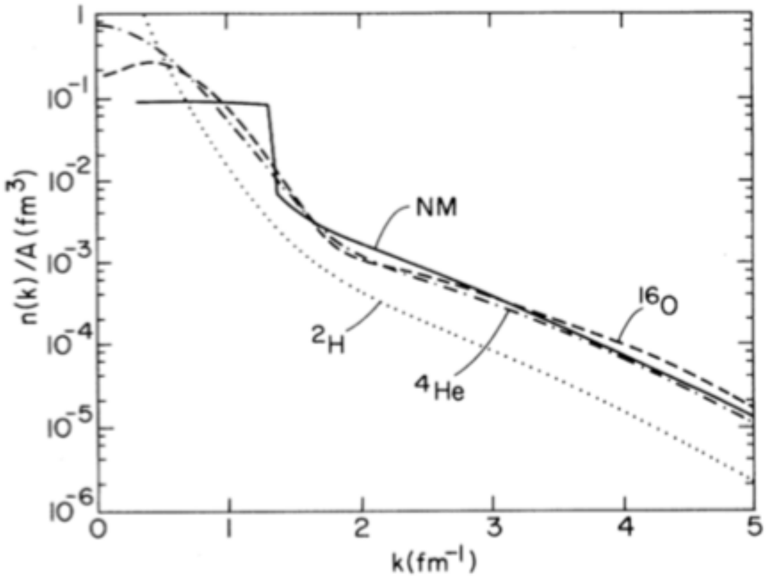
- The correlation contribution to the spectral function of a finite nucleus of mass number A can be calculated within the Local Density Approximation (LDA):

$$P_{\rm corr}(p_m, E_m) = \int d^3r \; \rho_A(\mathbf{r}) P^{NM}_{\rm corr}(p_m, E_m; \rho = \rho_A(\mathbf{r}))$$

- In Kahlen-Lehman representation: the full LDA spectral function is given by the sum

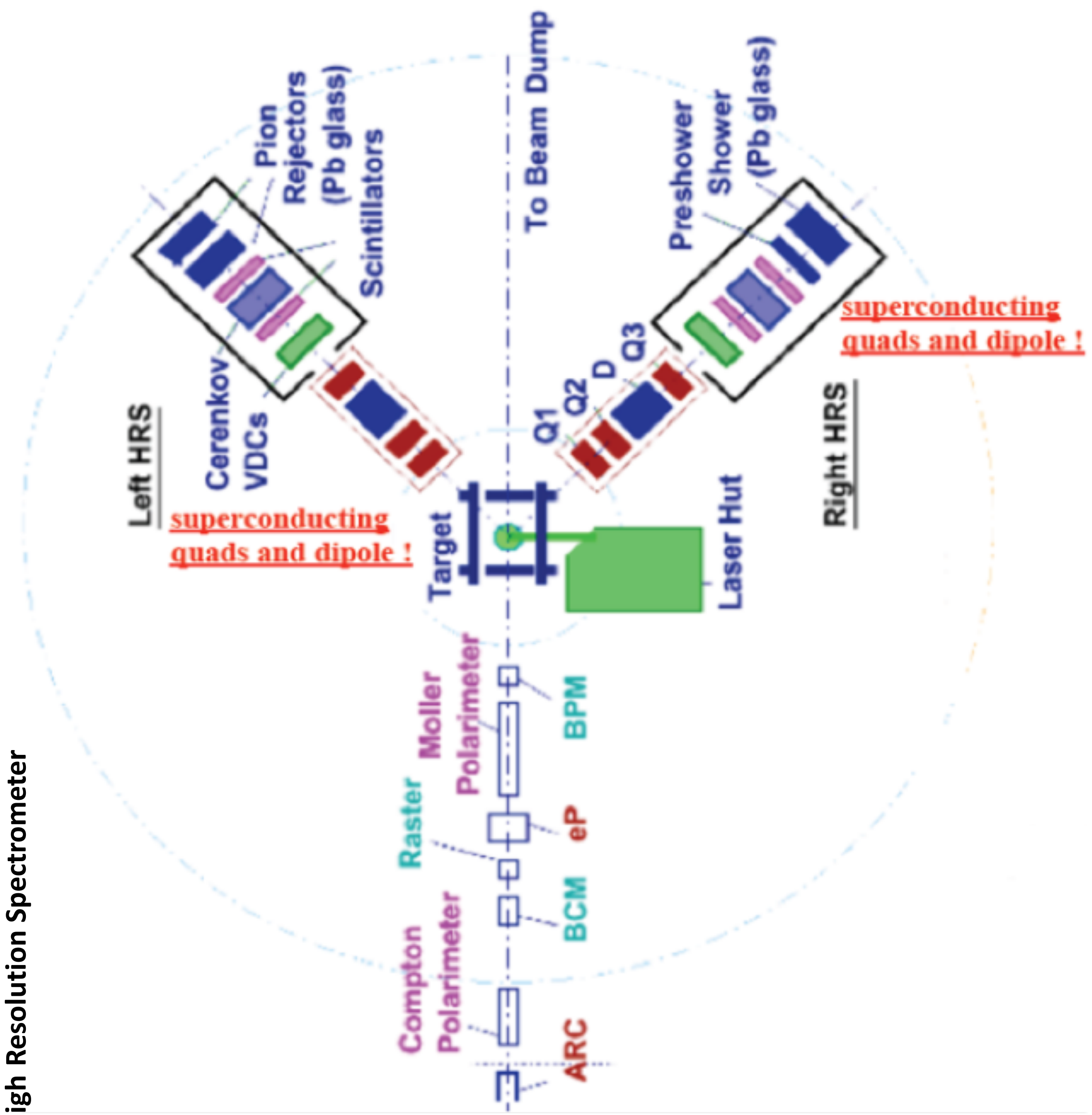
$$P(p_m, E_m) = P_{MF}(p_m, E_m) + P_{\rm corr}(p_m, E_m)$$

$$n(p_m) = \int dE \; P(p_m, E_m)$$



O. Benhar, S. C. Pieper, V. R. Pandharipande, Rev. Mod. Phys. 65, 817 (1993).

HALL A Schematics



Beam

HRS: High Resolution Spectrometer

High Resolution Spectrometer

Superconducting magnets:

- large acceptance in both angle and momentum
- good resolution in position and angle

Detector Package:

Vertical Drift Chambers:

- collecting tracking information (position and direction)

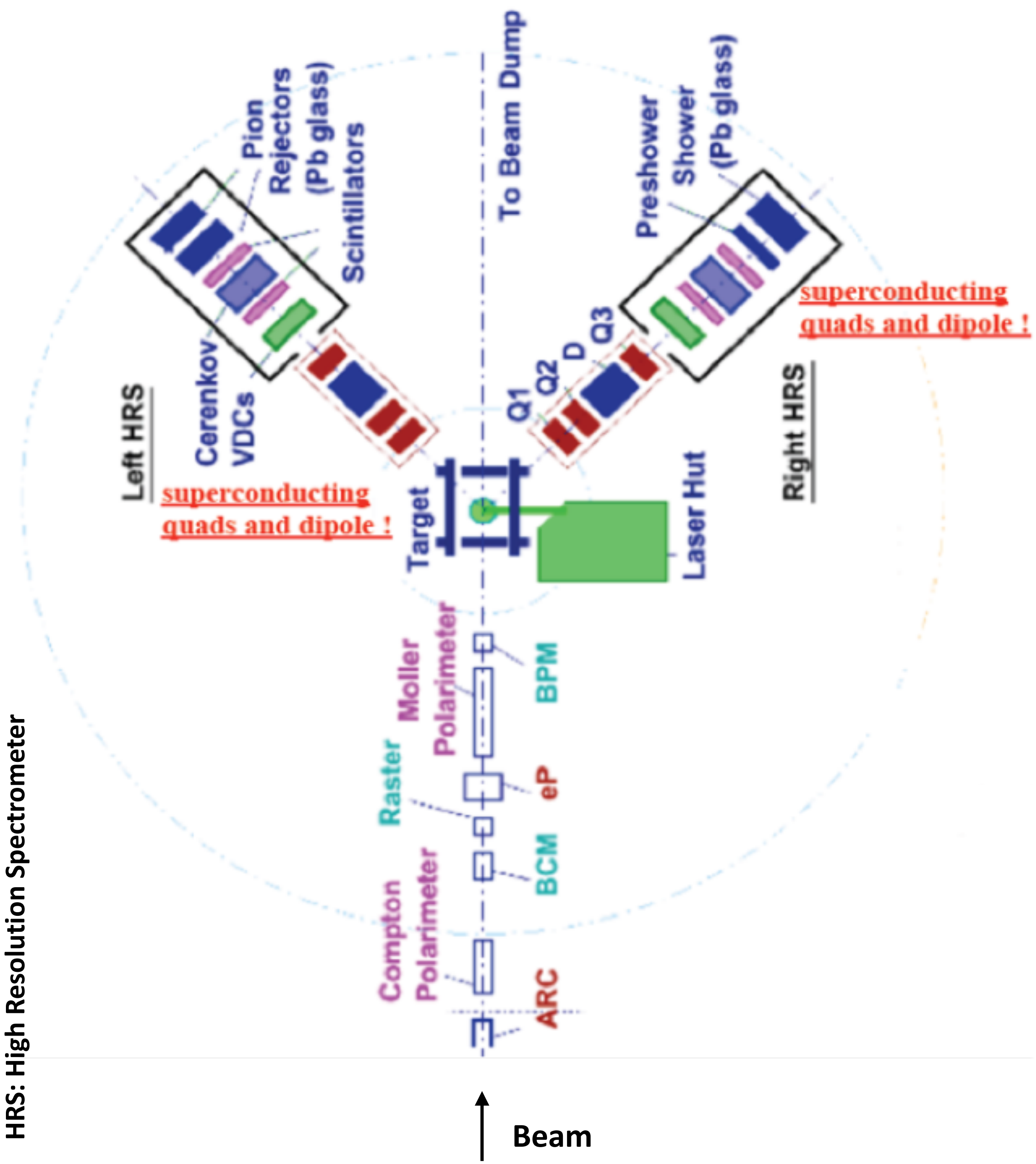
Scintillators:

- trigger to activate the data-acquisition electronics
- precise timing information for time-of-flight measurements and coincidence determination

Cherenkov:

- The particle identification, obtained from a variety of Cherenkov type detectors (aerogel and gas) and lead-glass shower counters

HALL A Schematics



HRS: High Resolution Spectrometer

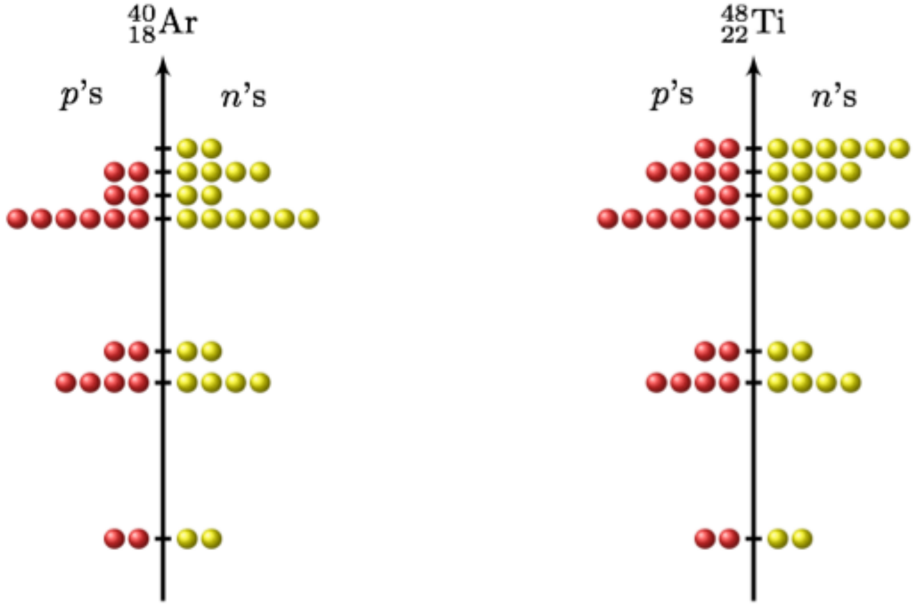
HALL A Characteristics

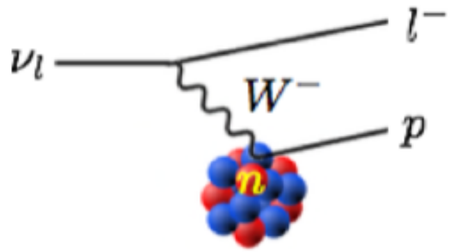
Beam energy resolution	5 x10^{-4}
Momentum range	0.3 – 4.0 GeV/c
Momentum acceptance	-4.5% < δp/p < +4.5%
Momentum resolution	2 x10^{-4}
Angular range	
HRS-L	12.5^0 – 150^0
HRS-R	12.5^0 – 130^0
Angular acceptance	
Horizontal	± 30 mrad
Vertical	± 60 mrad
Angular resolution	
Horizontal	0.5 mrad
Vertical	1.0 mrad

Why Titanium?

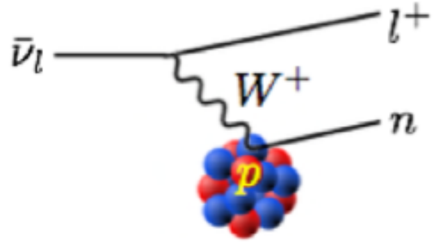
- The reconstruction of neutrino and antineutrino energy in liquid argon detectors will require the understanding of the spectral functions describing both neutrons and protons.

- Exploiting the correspondence of the level structures, the neutron spectral function of argon can be obtained from the proton spectral function of titanium.



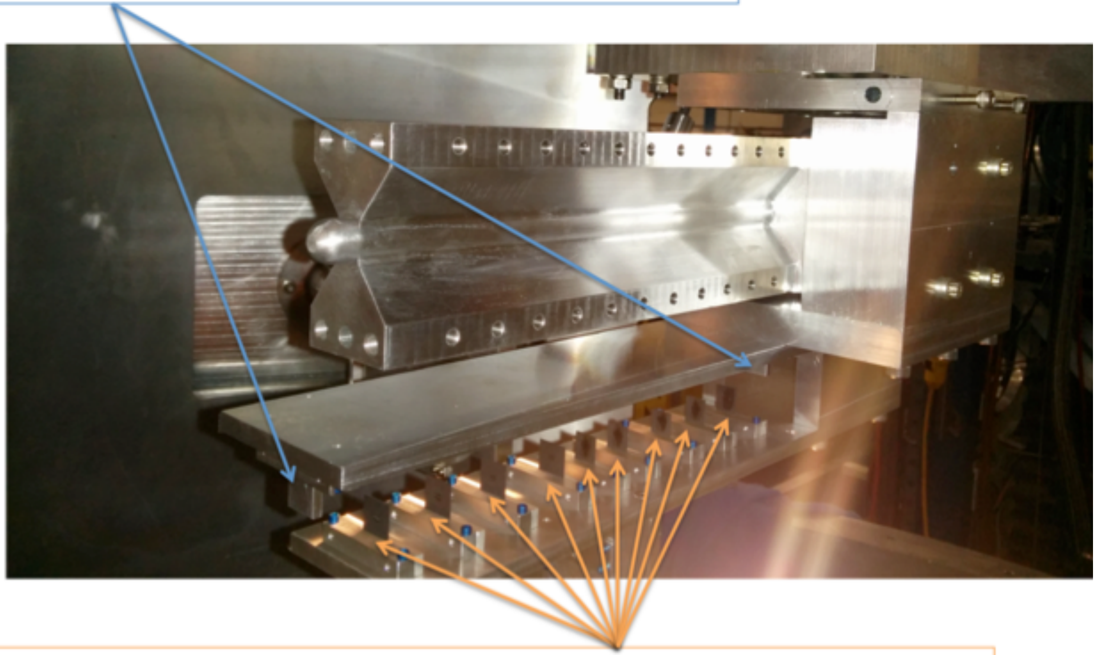


$$\nu_l + n \rightarrow l^- + p$$



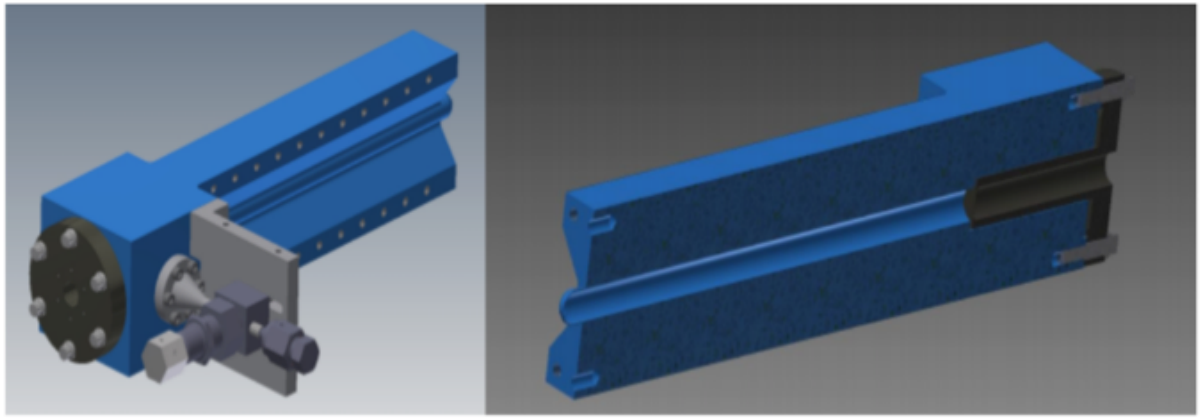
$$\bar{\nu}_l + p \rightarrow l^+ + n$$

Target setups



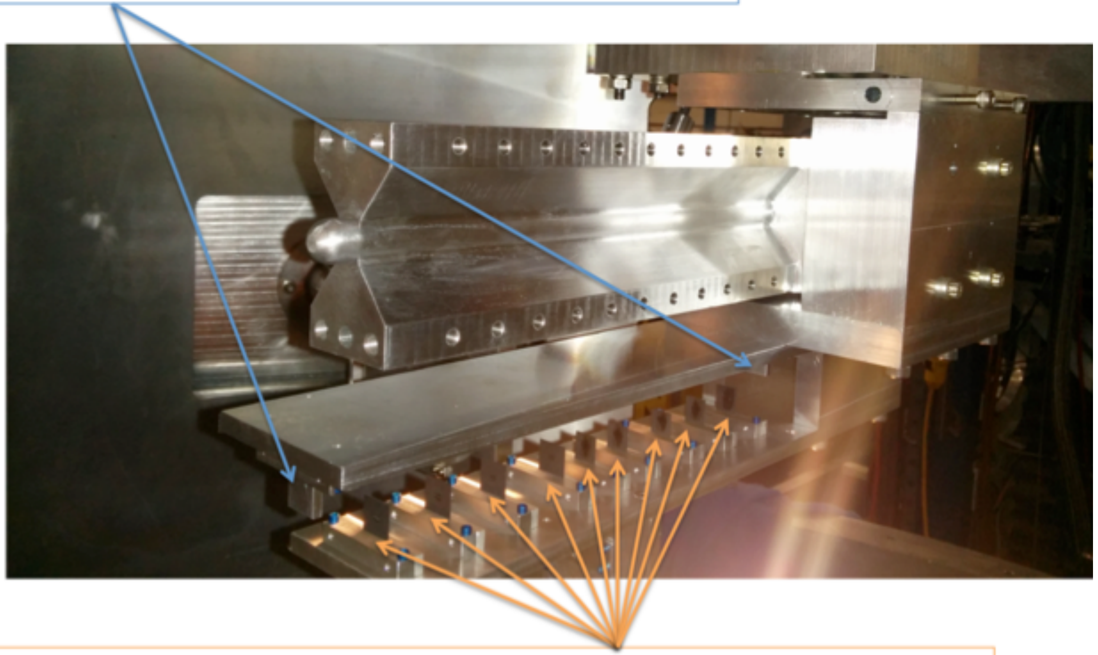
<u>Ar Target</u>

- Gas Cell
- Length = 25 cm
- Pressure = 500 PSI
- Temperature = 300 K.
- Target thickness = 1.381 g cm^{-2}
- Luminosity = 4.33×10^{37} atoms cm^{-2} sec^{-1}.



Target setups

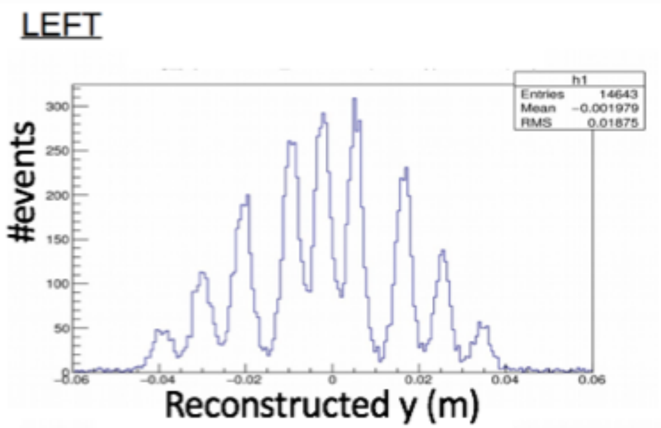
Dummy target: same as the entry and exit window as the gas target

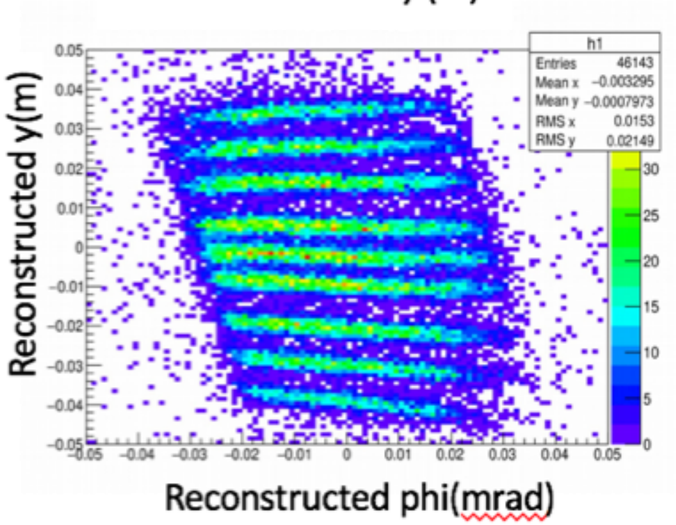


Optical target: a series of foils of carbon (9) to check the alignment of target and spectrometers (optics)

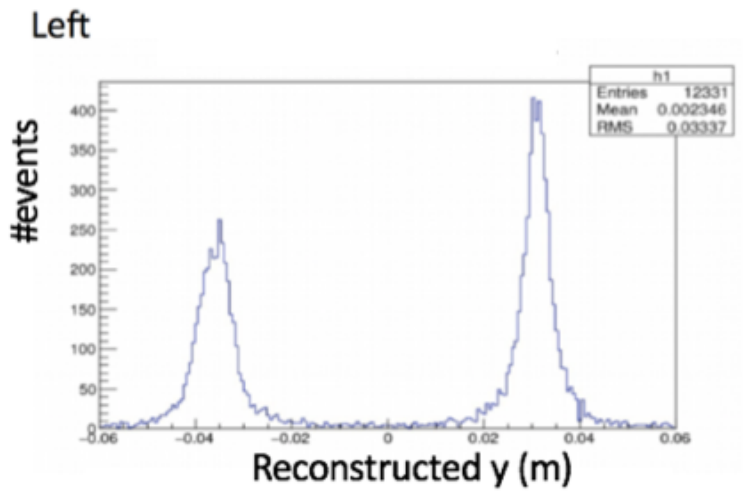
12

Multiple foil:



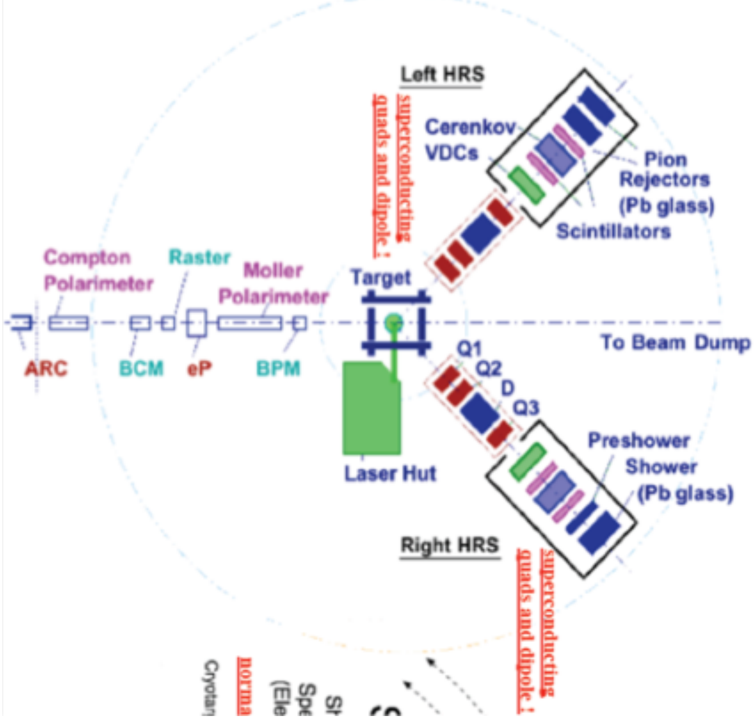


Dummy:



Kinematic setups

	E_e	$E_{e'}$	θ_e	P_p	θ_p	$\lvert \mathbf{q} \rvert$	p_m
	MeV	MeV	deg	MeV/c	deg	MeV/c	MeV/c
kin1	2222	1799	21.5	915	−50.0	857.5	57.7
kin3	2222	1799	17.5	915	−47.0	740.9	174.1
kin4	2222	1799	15.5	915	−44.5	658.5	229.7
kin5	2222	1716	15.5	1030	−39.0	730.3	299.7
kin2	2222	1716	20.0	1030	−44.0	846.1	183.9
Inc-kin5	2222	-	15.5	-	-	730.3	299.7



Run Period: Feb-March 2017

kin1

Collected Data	Hours	Events(k)
Ar	29.6	43955
Ti	12.5	12755
Dummy	0.75	955

kin3

Collected Data	Hours	Events(k)
Ar	13.5	73176
Ti	8.6	28423
Dummy	0.6	2948

kin2

Collected Data	Hours	Events(k)
Ar	32.1	62981
Ti	18.7	21486
Dummy	4.3	5075
Optics	1.15	1245
C	2.0	2318

kin4

Collected Data	Hours	Events(k)
Ar	30.9	158682
Ti	23.8	113130
Dummy	7.1	38591
Optics	0.9	4883
C	3.6	21922

kin5

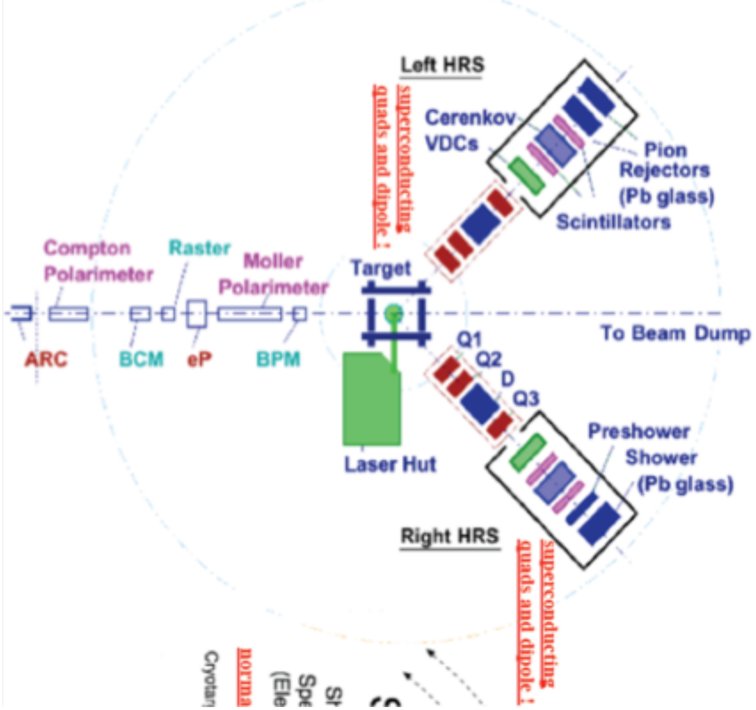
Collected Data	Hours	Events(k)
Ar	12.6	45338
Ti	1.5	61
Dummy	5.9	16286
Optics	2.9	160

kin5 - Inclusive

Collected Data	Minutes	Events(k)
Ar	57	2928
Ti	50	2993
Dummy	56	3235
C	115	3957

Kinematic setups

	E_e	$E_{e'}$	θ_e	P_p	θ_p	$\lvert\mathbf{q}\rvert$	p_m
	MeV	MeV	deg	MeV/c	deg	MeV/c	MeV/c
kin1	2222	1799	21.5	915	−50.0	857.5	57.7
kin3	2222	1799	17.5	915	−47.0	740.9	174.1
kin4	2222	1799	15.5	915	−44.5	658.5	229.7
kin5	2222	1716	15.5	1030	−39.0	730.3	299.7
kin2	2222	1716	20.0	1030	−44.0	846.1	183.9
Inc-kin5	2222	-	15.5	-	-	730.3	299.7



Run Period: Feb-March 2017

kin1

Collected Data	Hours	Events(k)
Ar	29.6	43955
Ti	12.5	12755
Dummy	0.75	955

kin3

Collected Data	Hours	Events(k)
Ar	13.5	73176
Ti	8.6	28423
Dummy	0.6	2948

kin2

Collected Data	Hours	Events(k)
Ar	32.1	62981
Ti	18.7	21486
Dummy	4.3	5075
Optics	1.15	1245
C	2.0	2318

kin4

Collected Data	Hours	Events(k)
Ar	30.9	158682
Ti	23.8	113130
Dummy	7.1	38591
Optics	0.9	4883
C	3.6	21922

kin5

Collected Data	Hours	Events(k)
Ar	12.6	45338
Ti	1.5	61
Dummy	5.9	16286
Optics	2.9	160

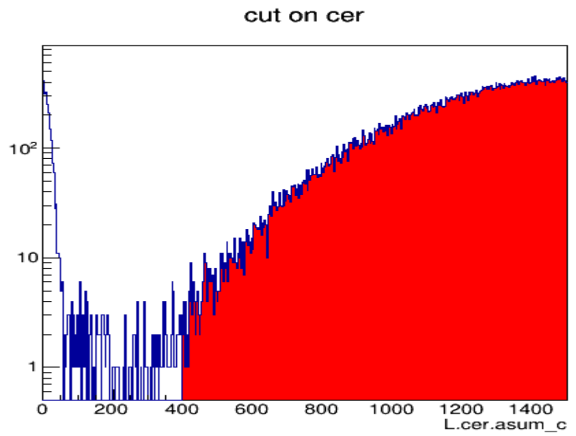
kin5 - Inclusive

Collected Data	Minutes	Events(k)
Ar	57	2928
Ti	50	2993
Dummy	56	3235
C	115	3957

Inclusive Data Analysis

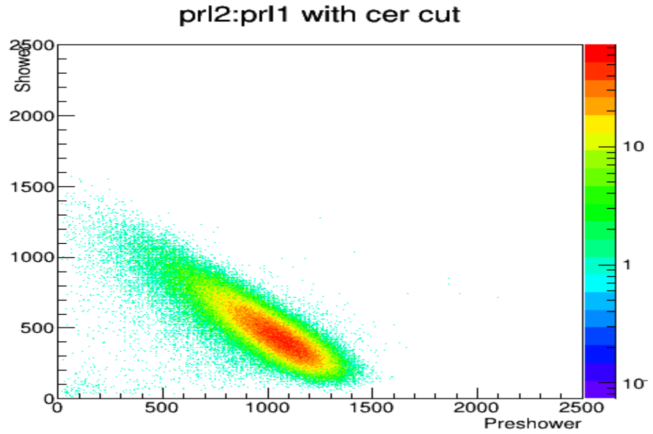
- Analysis is mainly performed by hardworking graduate students - Hongxia Dai (VTech), Matt Murphy (VTech), and Daniel Abrams (UVA).

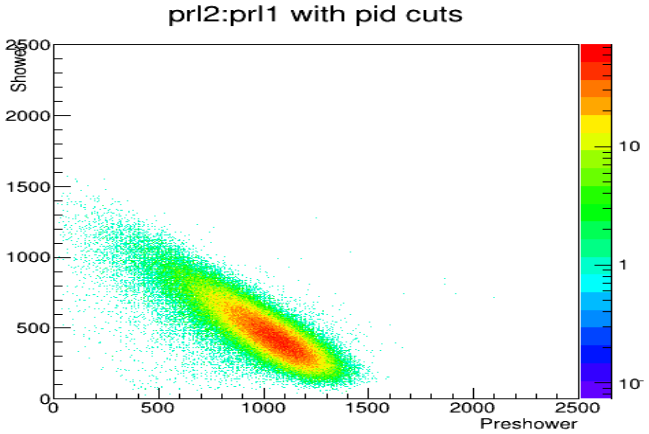
- **Particle Identification and Electron Selection**



Cerenkov cut: cer > 400

Calorimeter cut: E/p > 0.3





Inclusive Data Analysis

VDC efficiency

- Non-zero track ratio: R1
  - Cut1: Trigger, PID cut
  - $R1 = \frac{N_{track>0}}{N_{sample1}}$
- One track ratio: R2
  - Cut2: Trigger, PID cut, acceptance cut
  - $R2 = \frac{N_{track==1\&\&\,y\ \text{within}\ 5\sigma}}{N_{sample2}}$
- Efficiency=R1*R2 ~ 95 %

Trigger Efficiency

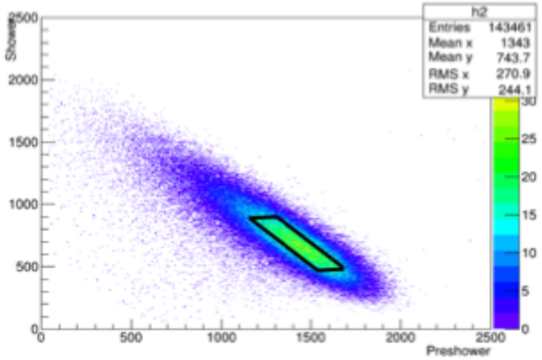
- Production trigger: T3: (S0&&S2) && (GC||PR) [LEFT]
- Efficiency trigger: T5: (S0||S2) && (GC||PR) [LEFT]
- Selected Sample
  - T5
  - Single track cut
  - Acceptance Cuts
  - PID Cuts
- $Eff = \frac{\#events\ with\ signal\ on\ both\ S0\ and\ S2}{\#sample\ events}$ ~ 99.9 %

Calorimeter cut efficiency

- Set cut as E/p0 > 0.3
- Select Sample events
  - T3 (S0&&S2)&&(GC||PR)
  - Single track
  - Acceptance cuts
  - Cerenkov cut
- $\epsilon = \frac{\#events\ with\ E/p0>0.3}{\#sample\ events}$
- Efficiency ~ 99.9 %

Cerenkov cut efficiency

- Negligible pion contamination, cer cut at 400
- Select Sample events
  - T3 (S0&&S2)&&(GC||PR)
  - Single track
  - Acceptance cuts
  - Calorimeter cut
- $\epsilon = \frac{\#events\ with\ cer>400}{\#sample\ events}$ ~ 99.9%



Extracting Inclusive Cross Section

- **Yield Ratio Method:**

For ith bin:

$$\sigma^{i}{}_{data} = \sigma^{i}{}_{model} \frac{Y^{i}{}_{data}(E',\theta)}{Y^{i}{}_{MC}(E',\theta)}$$

Where, $$Y^{i}{}_{data} = \frac{N_s^i * prescale}{N_e * (live\ time) * \epsilon_{eff}}$$

N_s^i : Number of scattered electrons
N_e : Total number of electrons in the beam
ϵ_{eff} : Total efficiency

- **Acceptance Correction Method:**

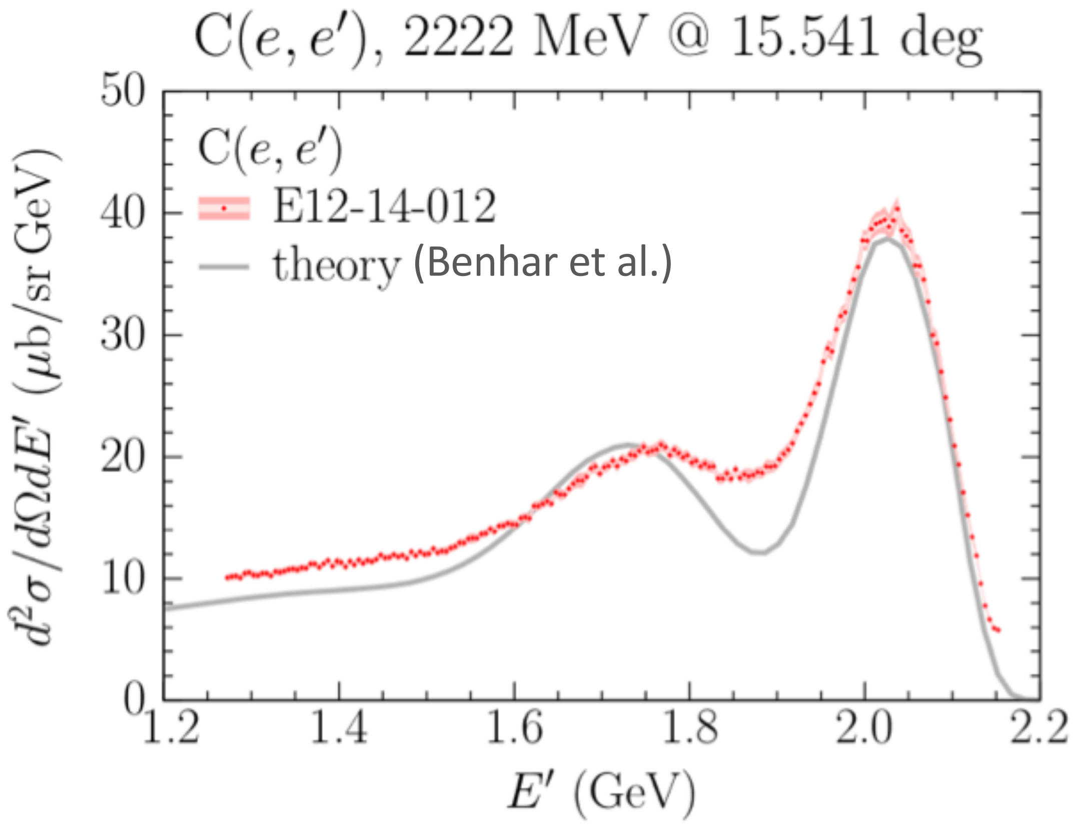
For each bin in $\Delta E \Delta\Omega$:

$$\sigma^{i}{}_{data} = \frac{Y^{i}{}_{data}(E',\theta)}{[\Delta E \Delta\Omega\ * A(E',\theta) * L]}$$

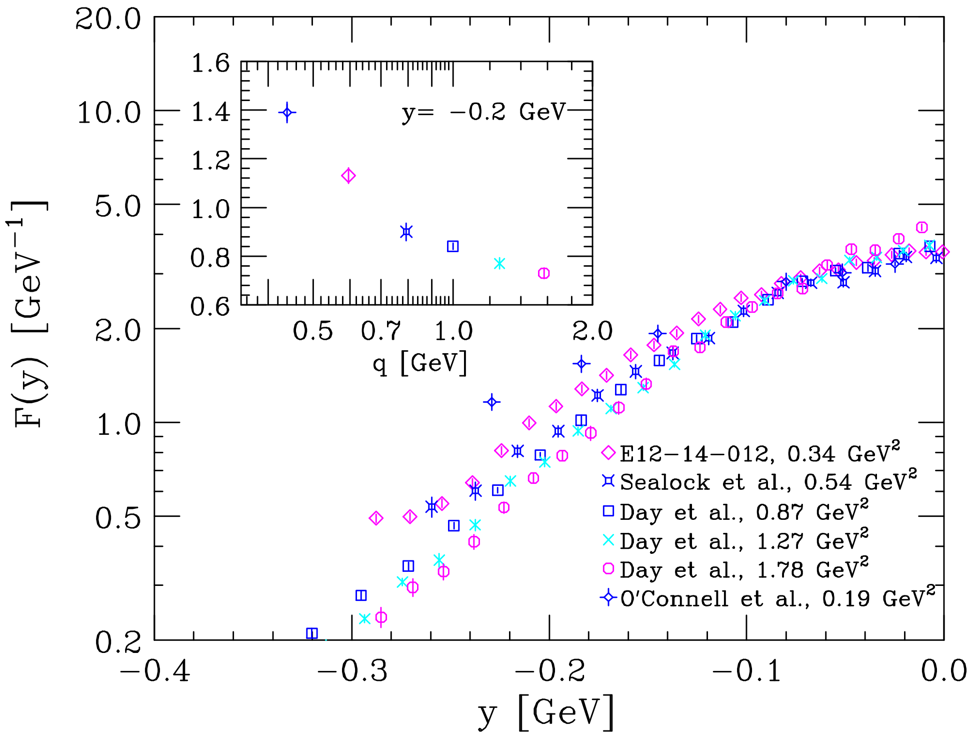
Where, L is Integrated Luminosity *(Number of beam electrons*targets/area)*
$A(E',\theta)$ is the Acceptance for a bin.

Inclusive Cross Section Results

Phys. Rev. C98, 014617 (2018)



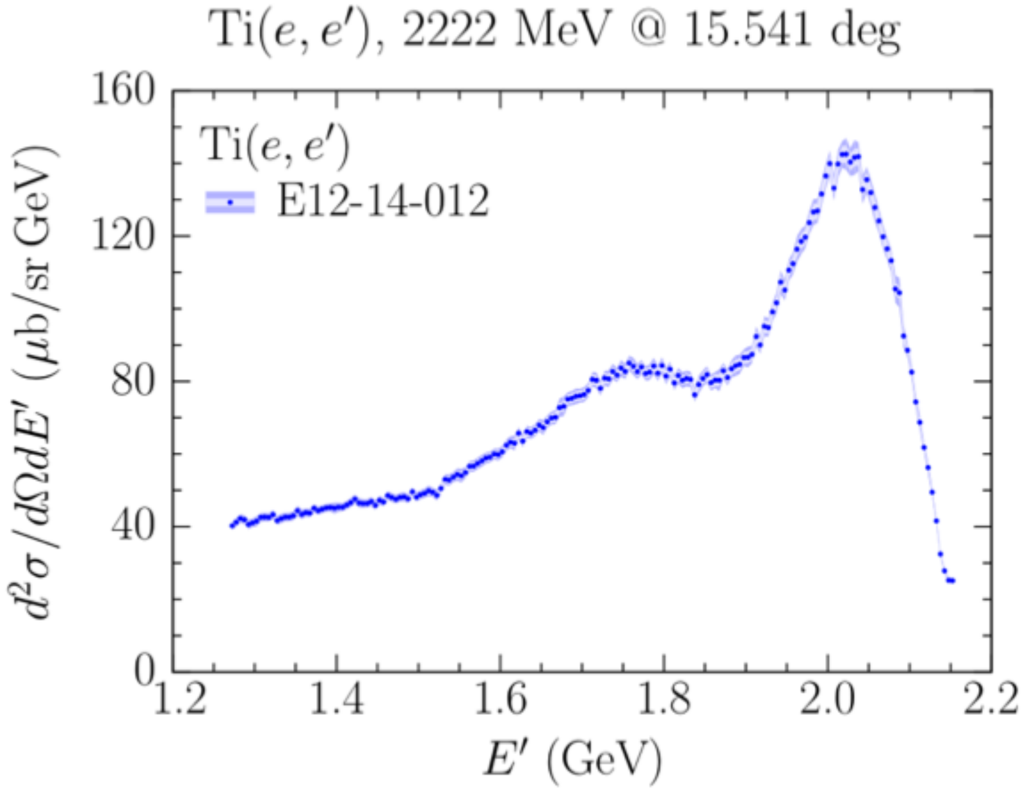
The y-scaling function: F(y)



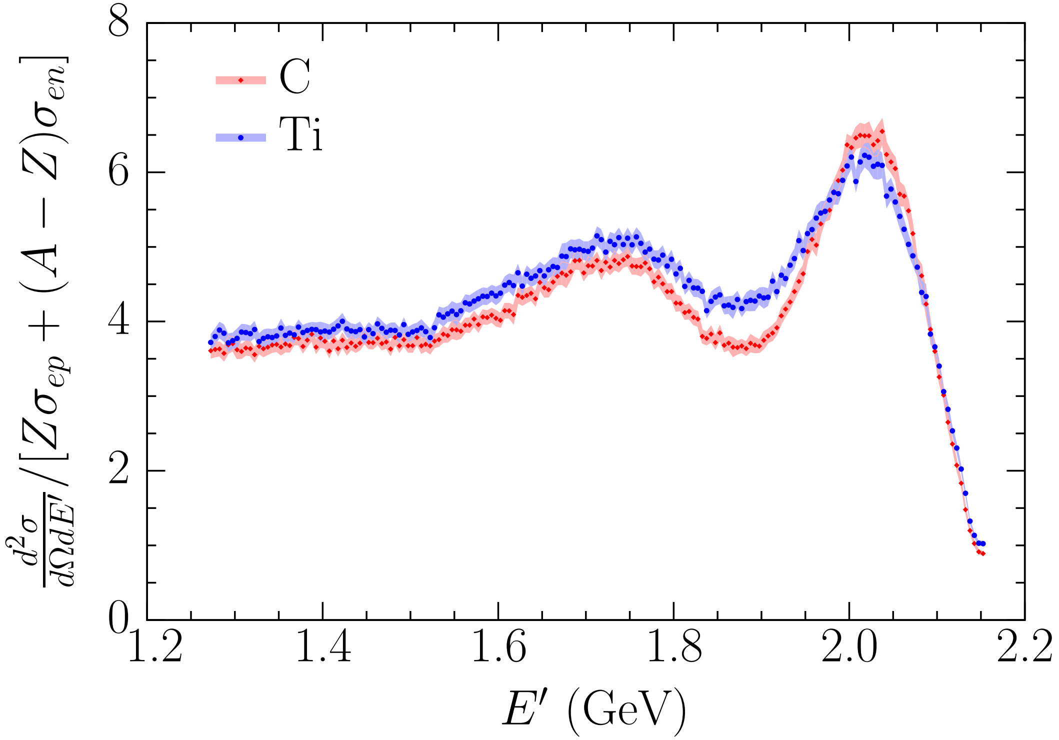
R. M. Sealock et al, Phys. Rev. Lett. 62, 1350 (1989).
D. B. Day et al, Phys. Rev. C 48, 1849 (1993).
J. S. O'Connell et al., Phys. Rev. C 35, 1063 (1987).

Inclusive Cross Section Results

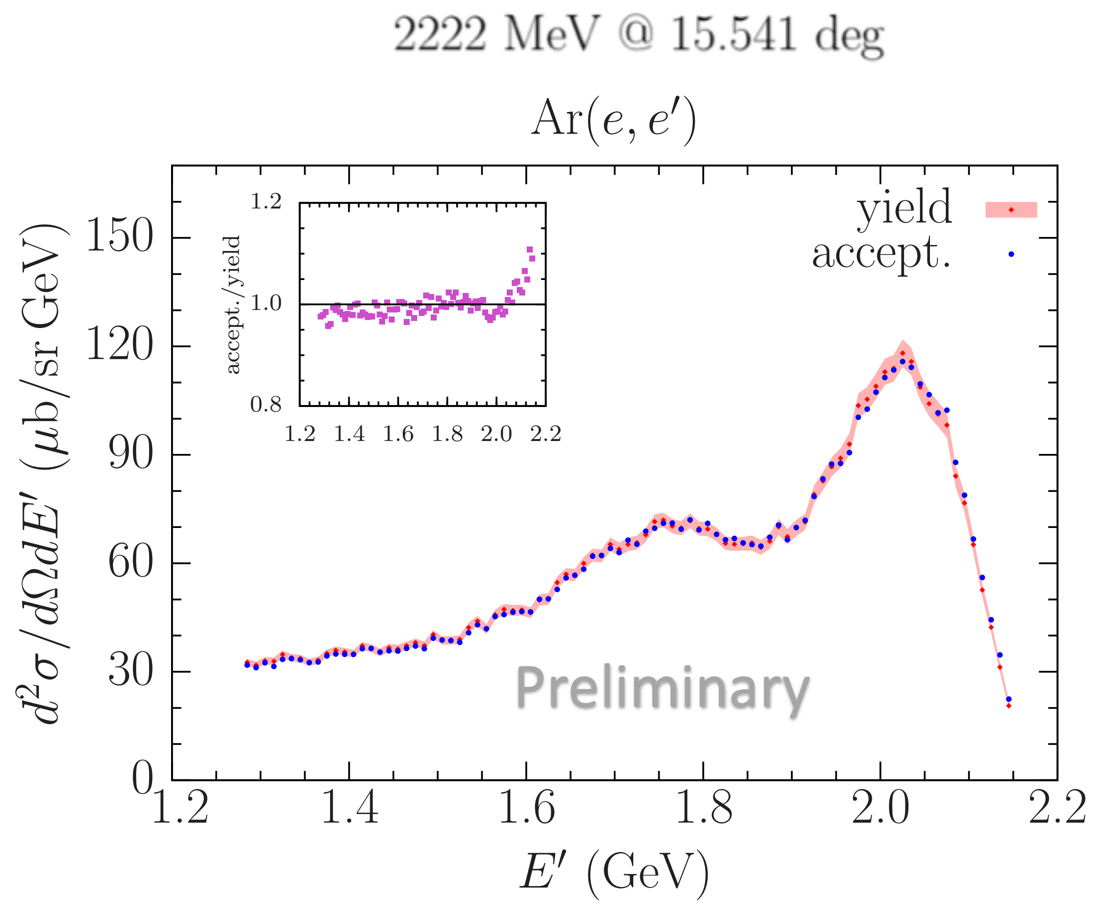
Phys. Rev. C98, 014617 (2018)



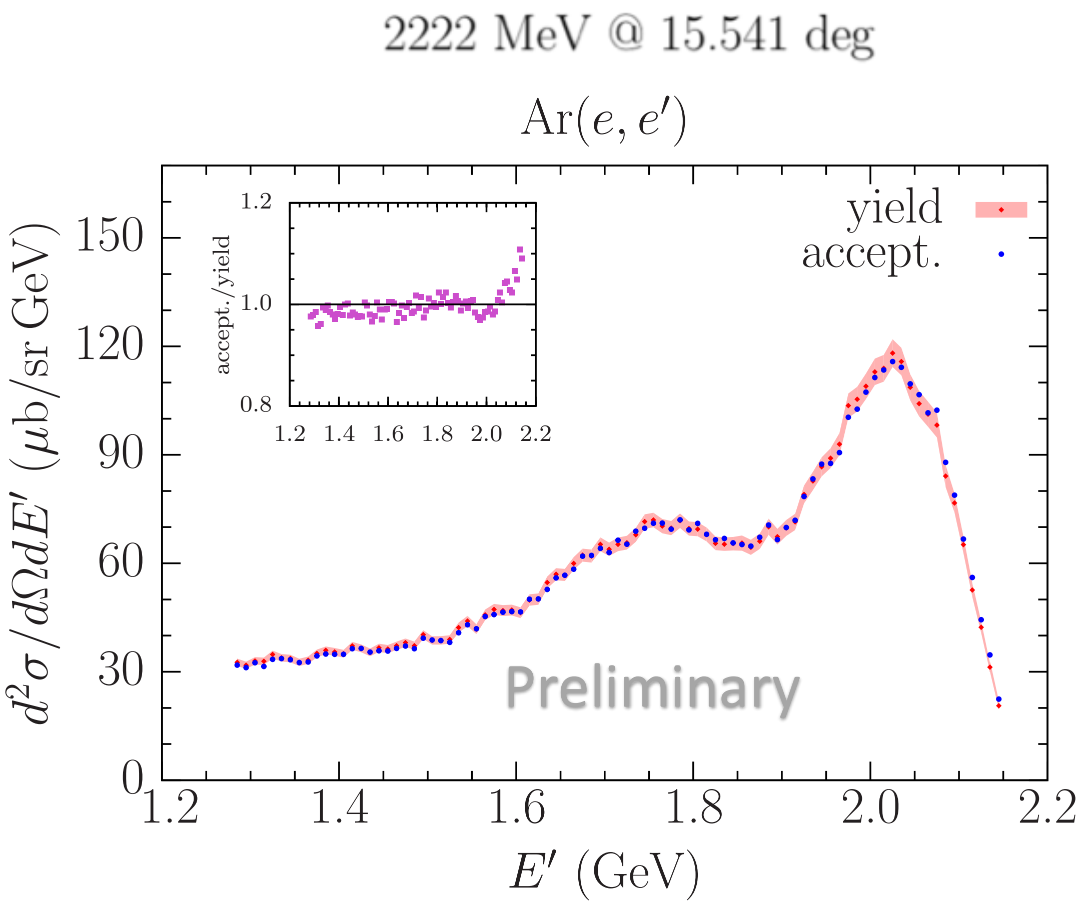
$$\frac{d^2\sigma}{d\Omega dE'}/[Z\sigma_{ep} + (A-Z)\sigma_{en}]$$



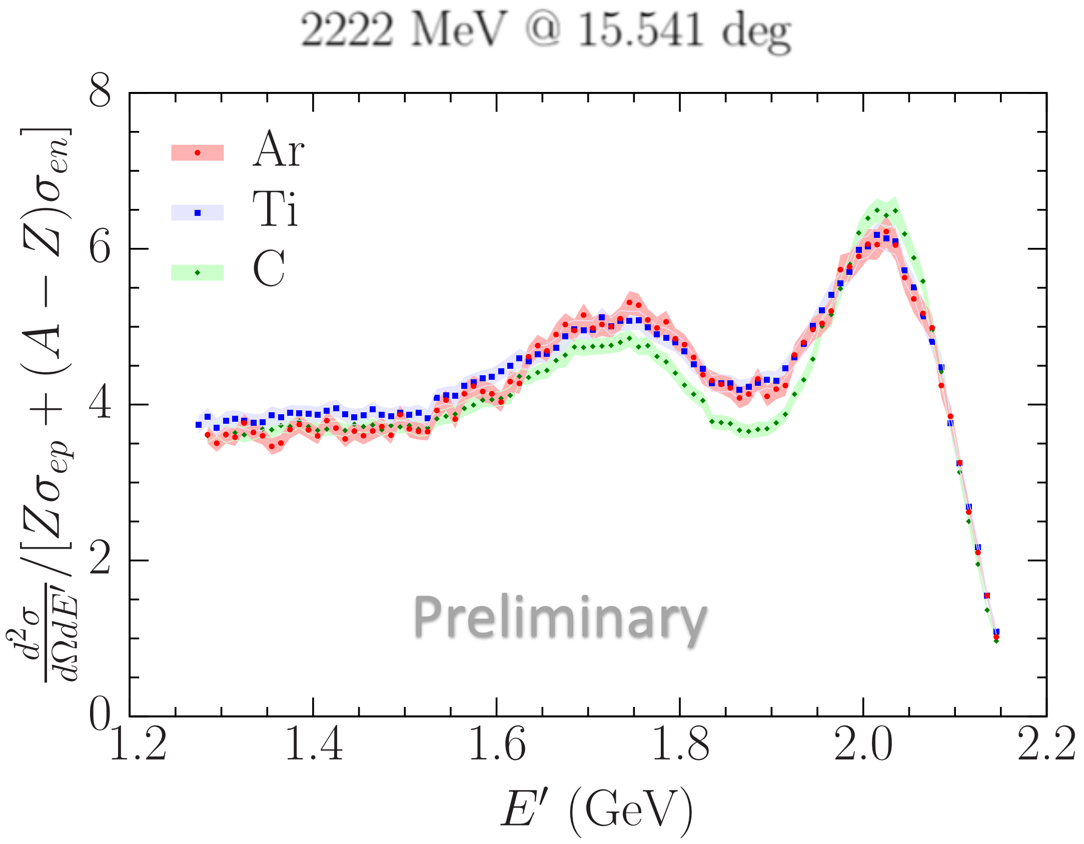
New Results


2222 MeV @ 15.541 deg
Ar(e, e′)
yield
accept.
Preliminary
d²σ/dΩdE′ (μb/sr GeV)
E′ (GeV)
0
30
60
90
120
150
1.2
1.4
1.6
1.8
2.0
2.2
accept./yield
0.8
1.0
1.2

New Results



2222 MeV @ 15.541 deg
Ar(e, e′)
yield
accept.
accept./yield
Preliminary
$d^2\sigma/d\Omega dE'$ (μb/sr GeV)
E' (GeV)



2222 MeV @ 15.541 deg
Ar
Ti
C
Preliminary
$\frac{d^2\sigma}{d\Omega dE'}/[Z\sigma_{ep} + (A - Z)\sigma_{en}]$
E' (GeV)

Summary

- The success of liquid argon time projection chamber (LArTPC) based - long-baseline, DUNE, and short-baseline, SBND, MicroBooNE, ICARUS - neutrino programs in achieving an unprecedented percent-level precision will rely greatly on the level of precision with which we understand the complexity of argon nucleus and it's electroweak response.

- In E12-14-012 experiment (e-Ar/Ti) at Jefferson Lab Hall A, we study the properties of argon and titanium nucleus by the scattering of precise (continuous) electron beams on nuclei.

- The first results, consisting of the Ti(e,e′) and C(e,e′) cross sections at beam energy E = 2.222 GeV and scattering angle θ =15.541 deg with uncertainties < 2.75%, have recently been reported [Phys. Rev. C98, 014617 (2018). The measured cross section covers a broad range of energy transfer where quasielastic scattering and delta production are the dominant reaction mechanisms.

- We also presented our first Ar(e,e′) cross section results at E = 2.222 GeV and scattering angle θ =15.541 deg and it's comparison with Ti(e,e′) and C(e,e′) data.

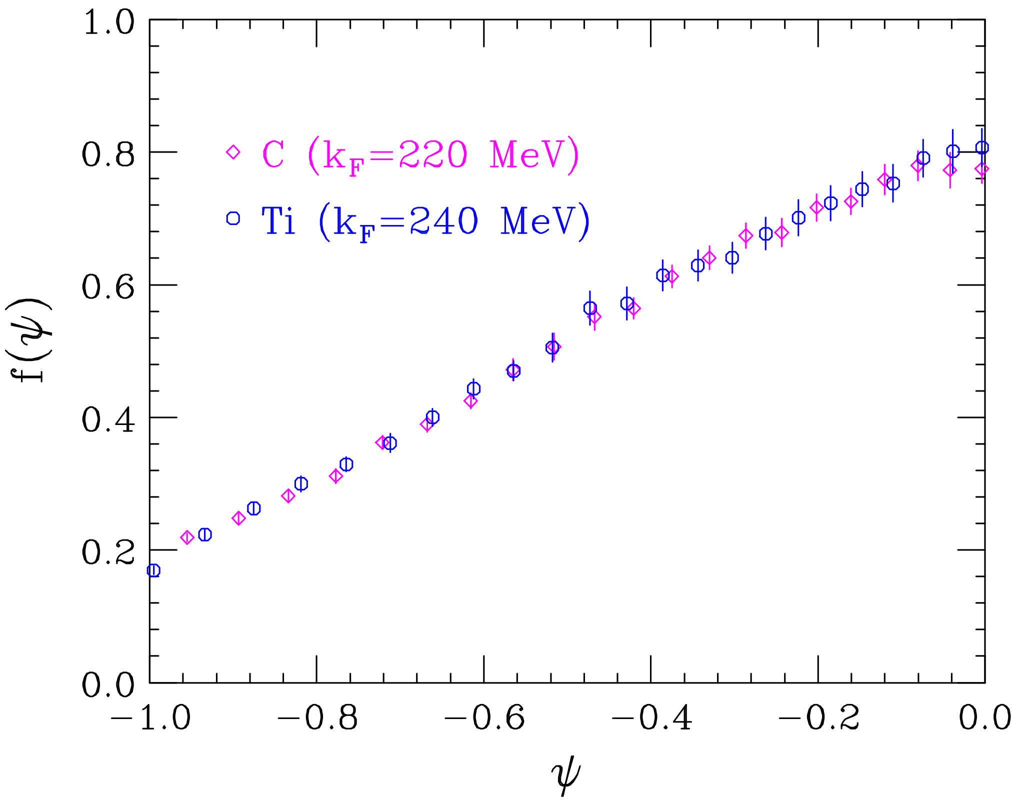
- More results including (e,e'p) cross sections will follow soon - stay tuned!

Back-up

Uncertainity table

1. Total statistical uncertainty	1.2%
2. Total systematic uncertainty	2.0–2.9%
a. Beam charge & Beam Energy	0.3%
b. Beam offset $x\&y$	0.1%–0.4%
c. Target thickness	0.1%–0.4%
d. HRS offset $x\&y$+ Optics	1.3%–2.0%
e. Acceptance cut(θ,ϕ,dp/p)	1.0%–1.4%
f. Calorimeter & Čerenkov cuts	0.01%–0.02%
g. Cross Section Model	0.1%–0.2%
h. Radiative +Coulomb Corr.	1.0–1.3%

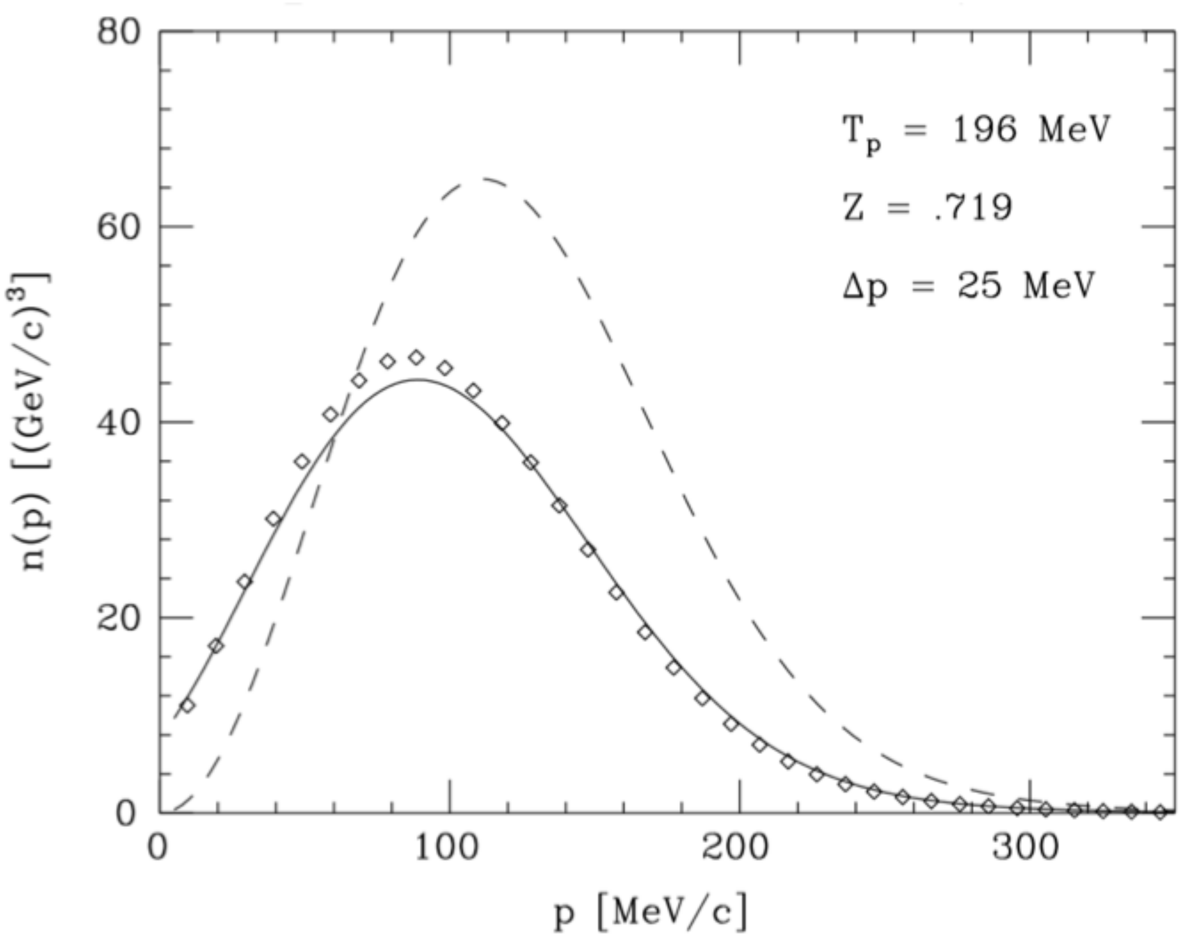
Superscaling function



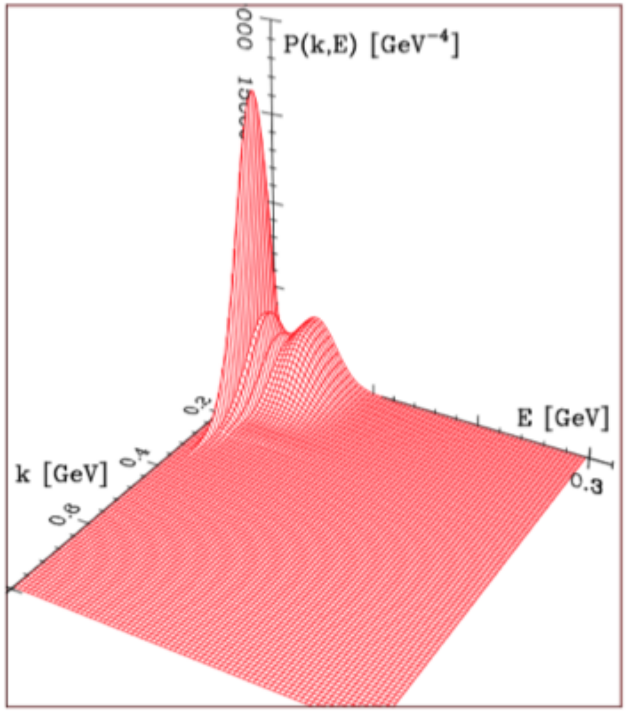
Inclusion of Final State Interations

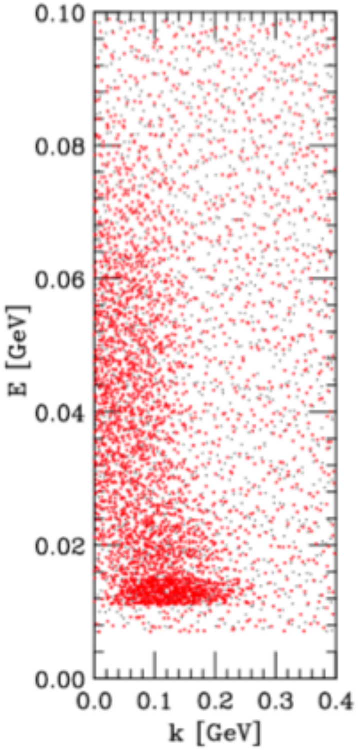
- The Distorted Wave Impulse Approximation (DWIA), obtained from a complex potential fitted to proton-nucleus scattering data.

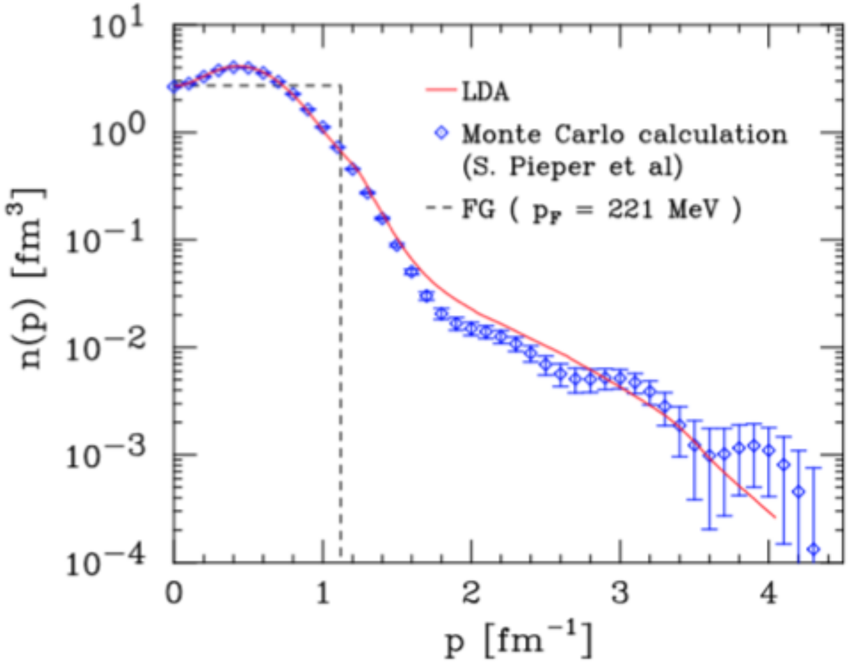
- The real part of the optical potential shifts the momentum distribution of the shell model states by an amount Δp, while inclusion of the the imaginary part leads to a significant reduction of the PWIA result, typically by a factor Z ∼ 0.7.



Oxygen Spectral Function







- FG model: $P(\mathbf{p}, E) \propto \theta(p_F - |\mathbf{p}|)\, \delta(E - \sqrt{|\mathbf{p}|^2 + m^2} + \epsilon)$
- shell model states account for $\sim 80\%$ of the strenght
- the remaining $\sim 20\%$, arising from NN correlations, is located at high momentum *and* large removal energy ($|\mathbf{p}| \gg p_F \sim 220$ MeV, $E \gg \epsilon$)

Kinematic setups