An overview of neutrino cross sections and challenges

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Neutrino Experiments

Current Knowledge:
(3-neutrino paradigm)

	θ_{12}	θ_{13}	θ_{23}	$\Delta m^2_{21}/10^{-5}$	$\Delta m^2_{3j}/10^{-3}$	δ_{CP}
Normal Ordering	$33.56^{+0.77}_{-0.75}$	$8.46^{+0.15}_{-0.15}$	$41.6^{+1.5}_{-1.2}$	$7.50^{+0.19}_{-0.17}$	$2.524^{+0.039}_{-0.040}$	261^{+51}_{-59}
Inverted Ordering	$33.56^{+0.77}_{-0.75}$	$8.49^{+0.15}_{-0.15}$	$50.0^{+1.1}_{-1.4}$	$7.50^{+0.19}_{-0.17}$	$-2.514^{+0.038}_{-0.041}$	277^{+40}_{-46}

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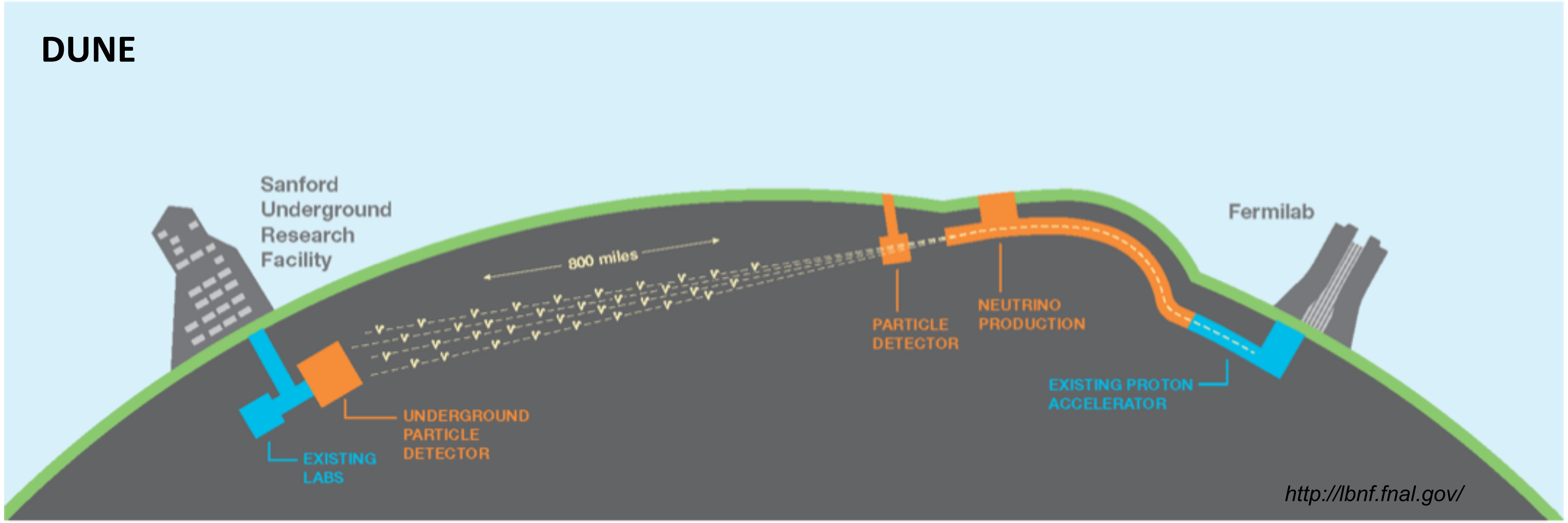
Current and Future Goals:

- Establish whether there is CP violation in the lepton sector and, if so, measure δ_{CP}
- Improve the accuracy on θ_{23}
- Determine the neutrino mass ordering: $m_1 < m_2 < m_3$ or $m_3 < m_1 < m_2$
- Sterile neutrino search at short baselines
- Dark matter searches?

Current and Future Accelerator-based Experiments:

- **Short baseline experiments: MicroBooNE** (running), **ICARUS** (under construction), **SBND** (under construction), and **MiniBooNE** (running)
- **Long baseline experiments: DUNE** (under construction), **NOvA** (running), **T2K** (running), **T2HK** (under construction)

Long-baseline neutrino-oscillation experiments



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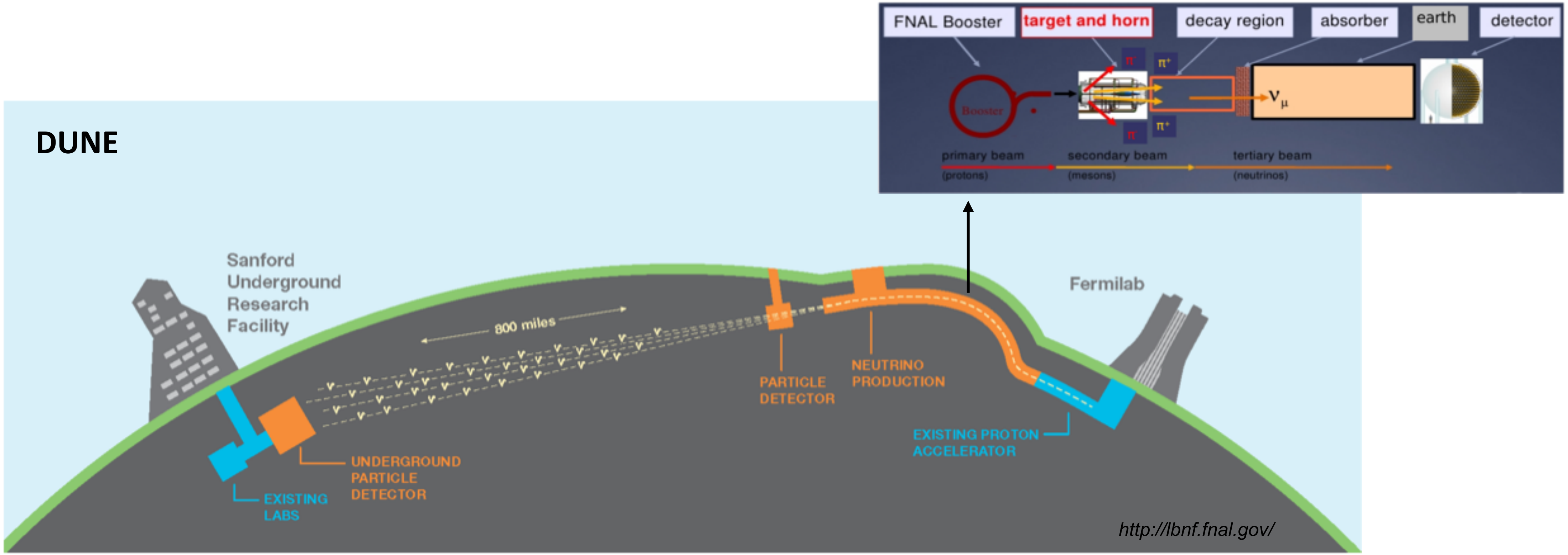

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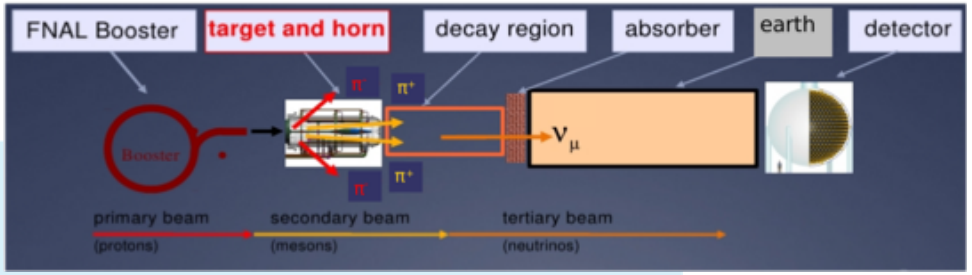

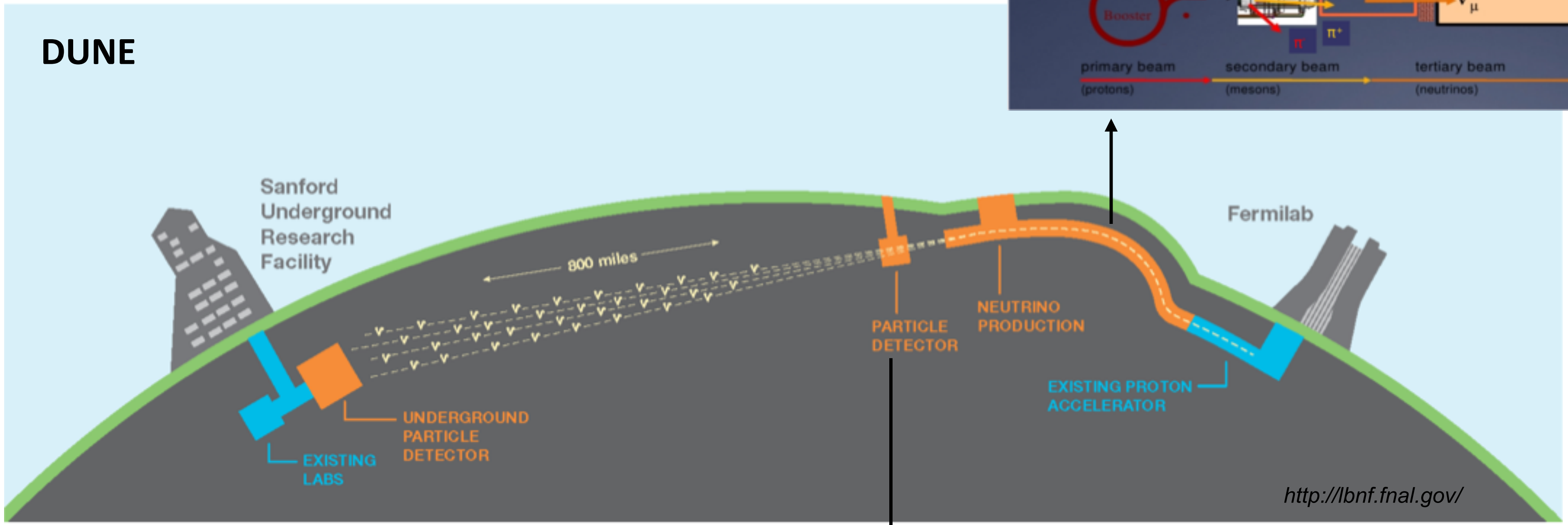

Event Rate at near detector:

$$N^{\alpha}_{\rm ND}(\boldsymbol{p}_{\rm reco}) = \sum_i \phi_\alpha(E_{\rm true}) \times \sigma^i_\alpha(\boldsymbol{p}_{\rm true}) \times \epsilon_\alpha(\boldsymbol{p}_{\rm true}) \times R_i(\boldsymbol{p}_{\rm true};\boldsymbol{p}_{\rm reco})$$

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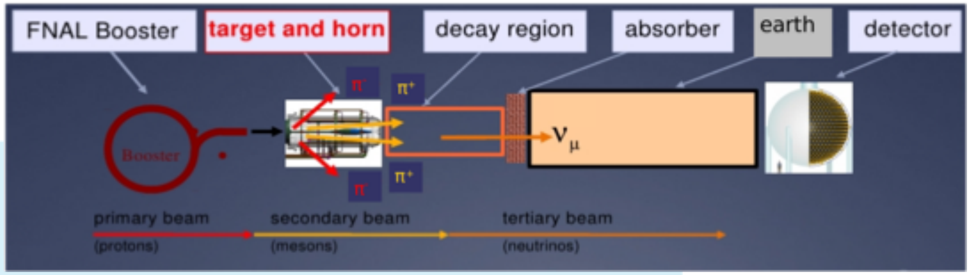

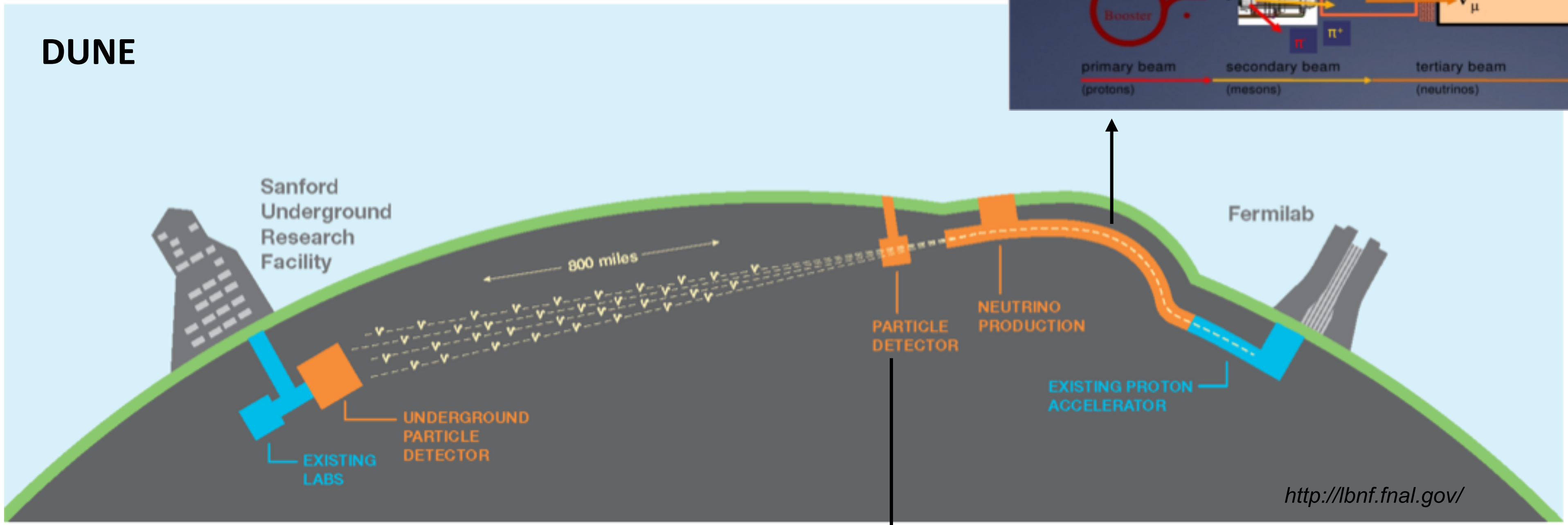

Oscillation Probability*:

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

two neutrino flavors, for simplicity

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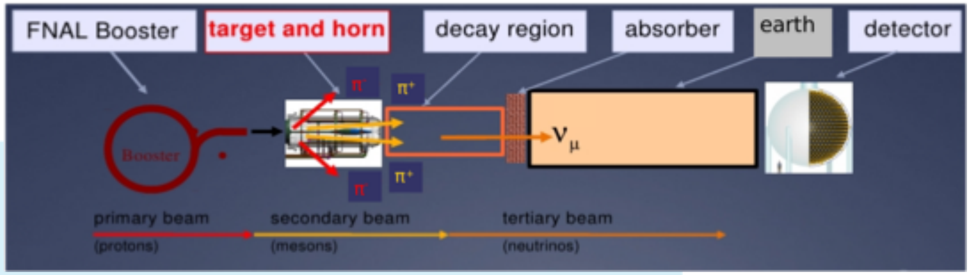

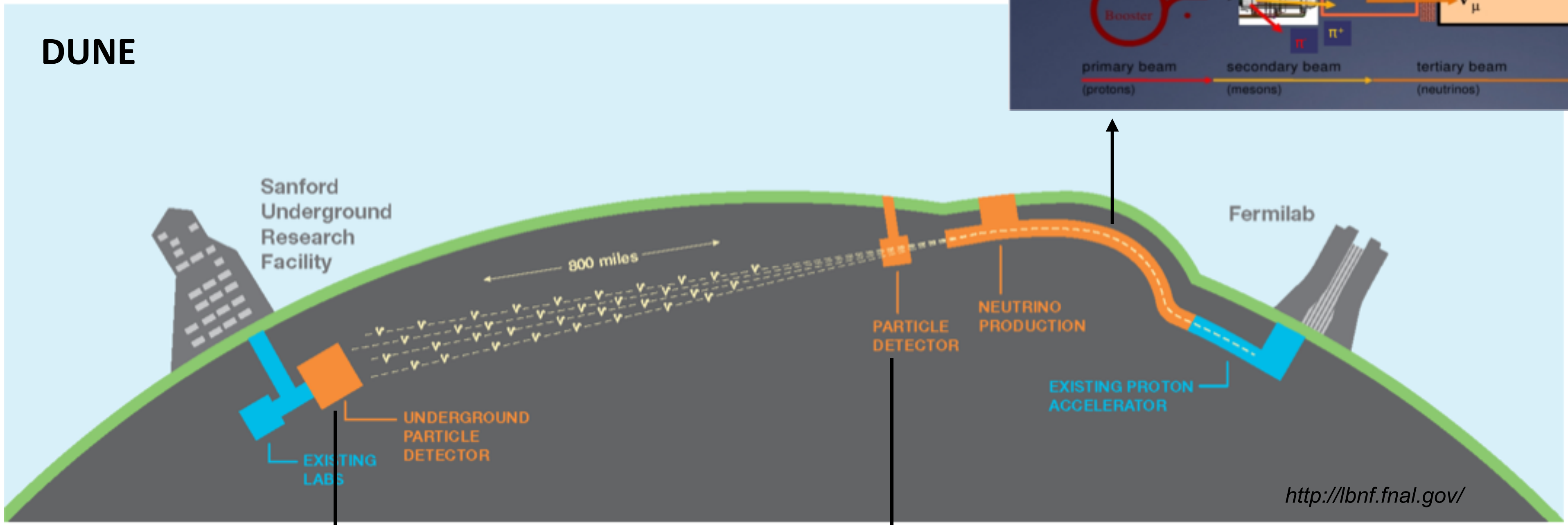

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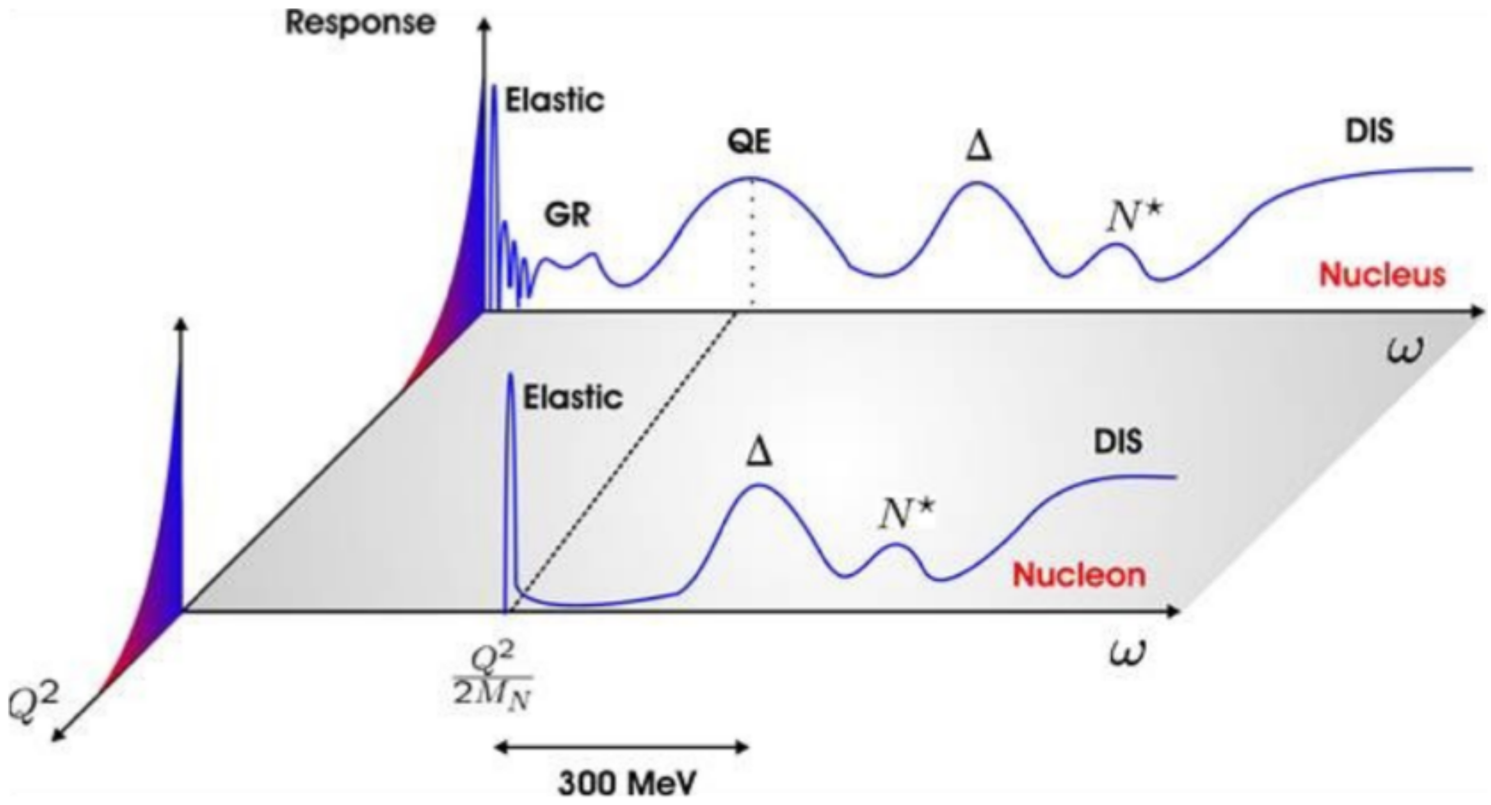

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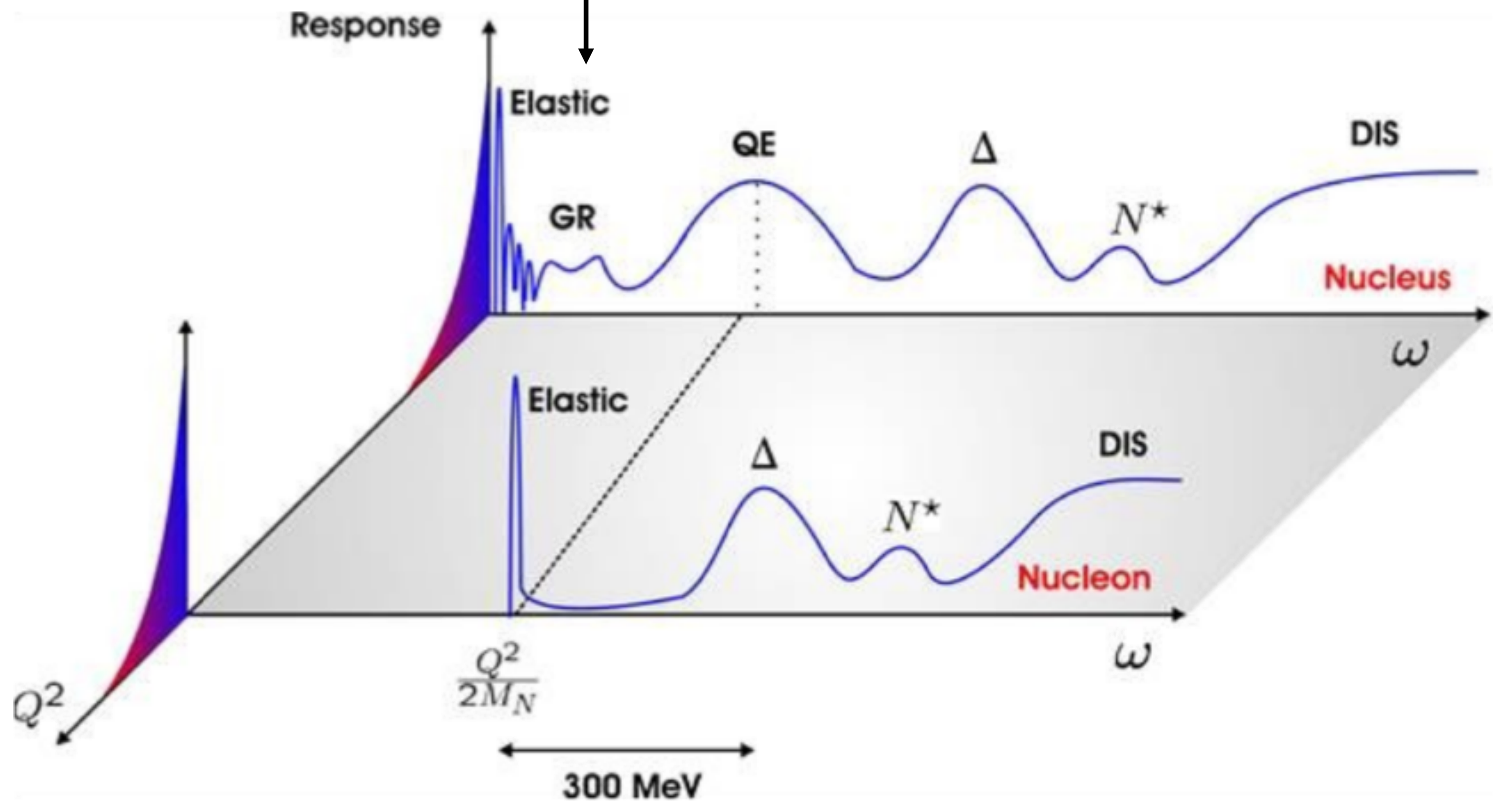
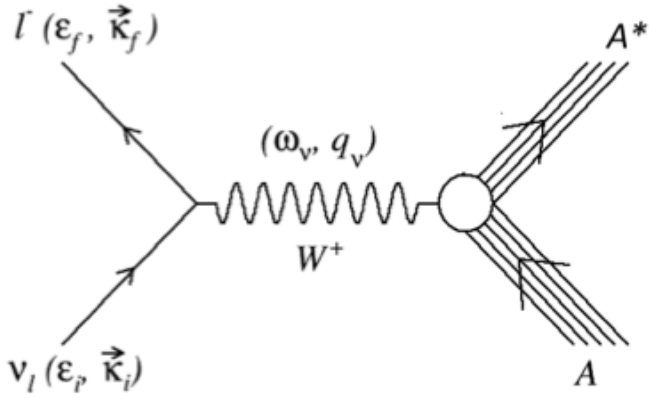


- **Elastic and Giant Resonances**



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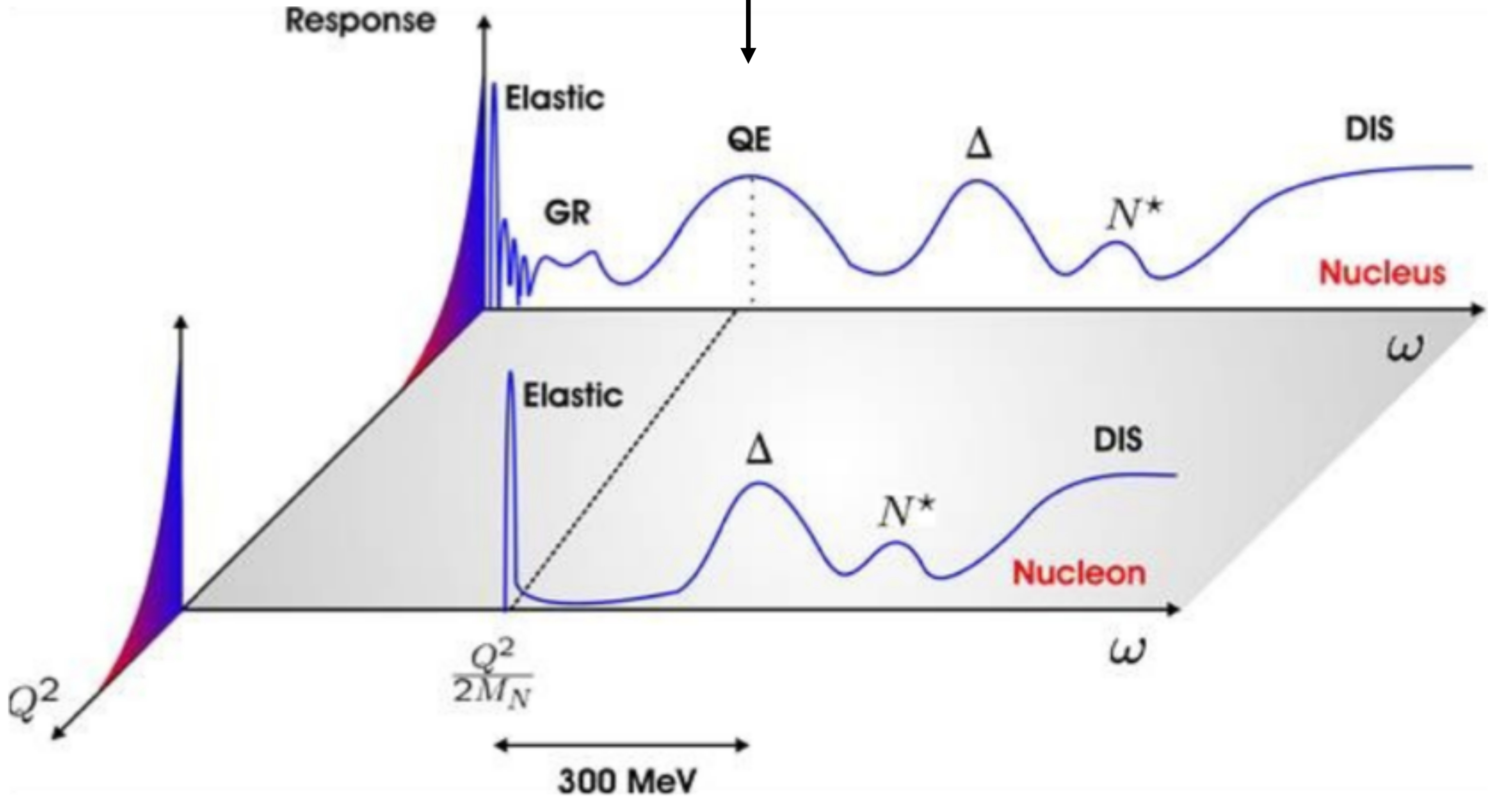
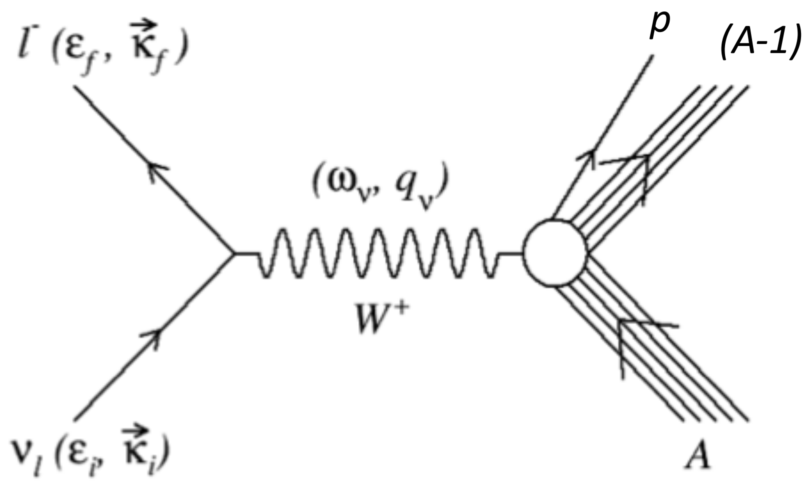


- **Quasielastic**



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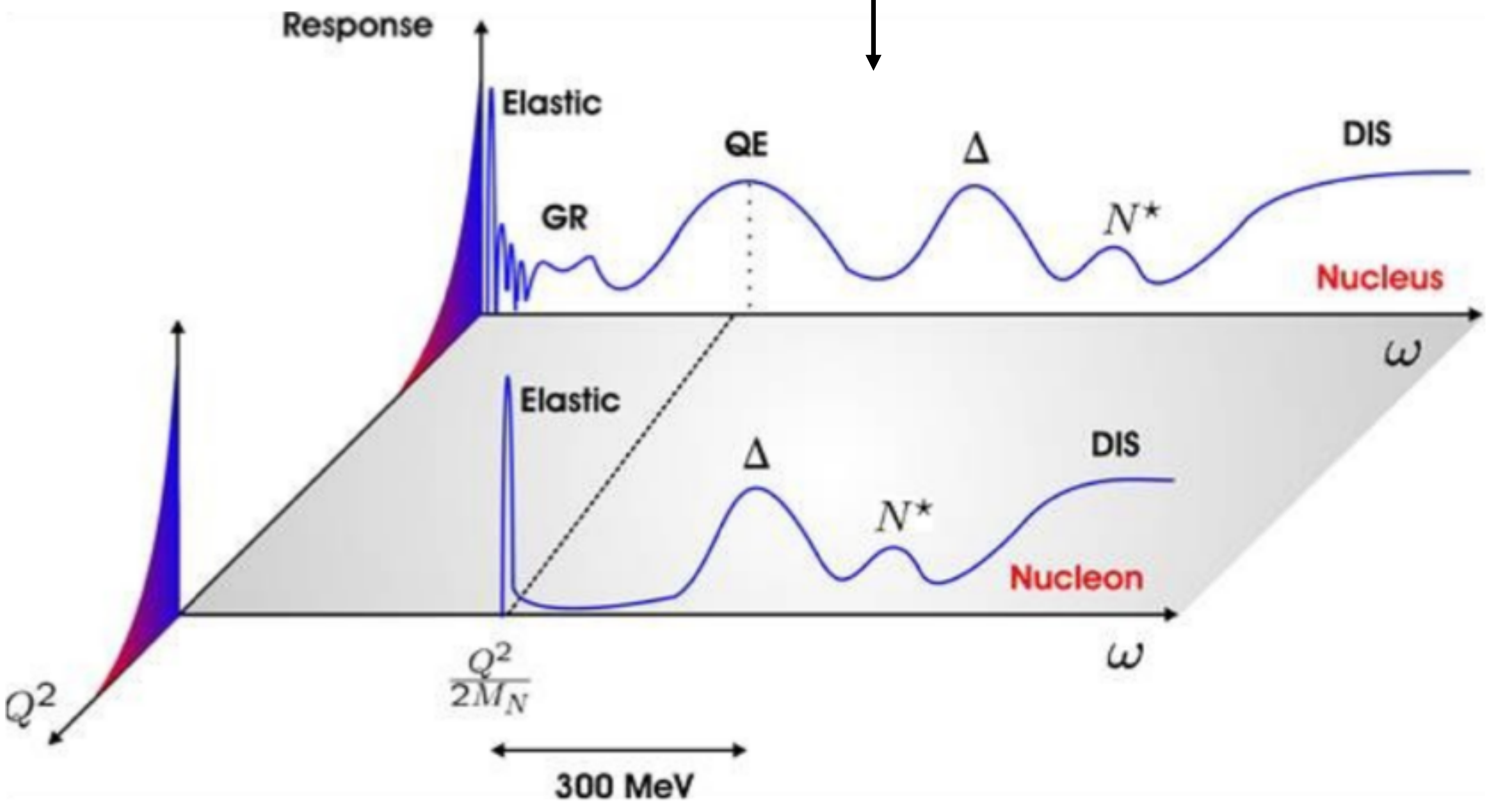
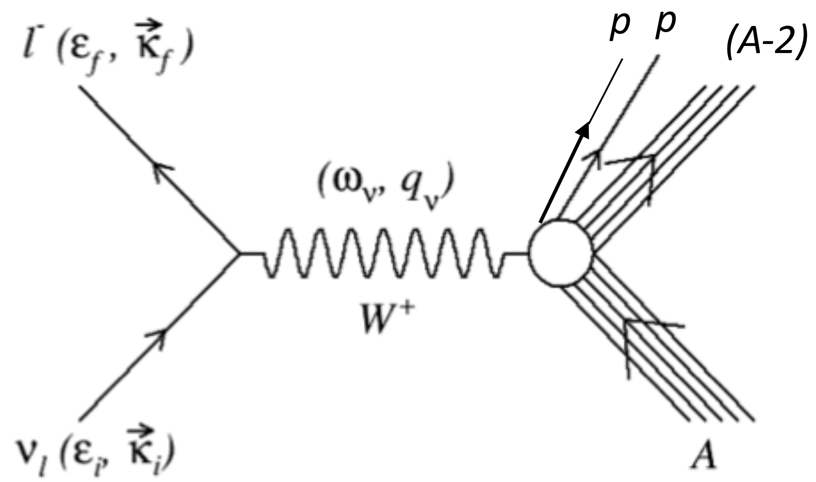


- **Dip-region**



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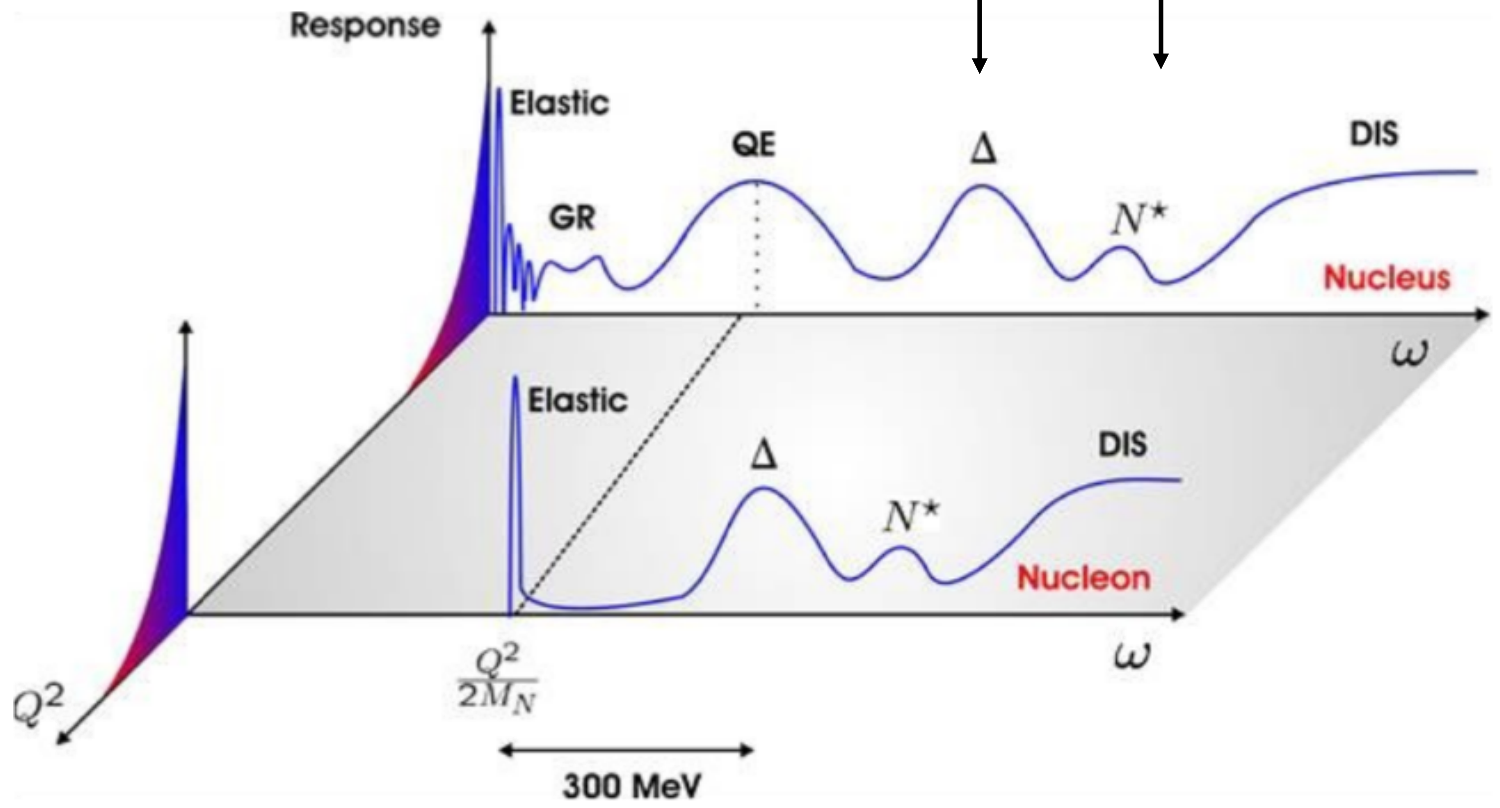
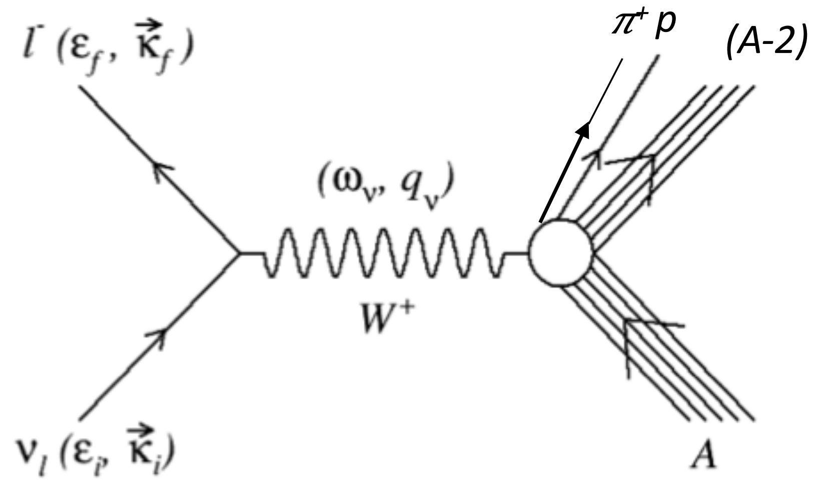


- **Resonance**



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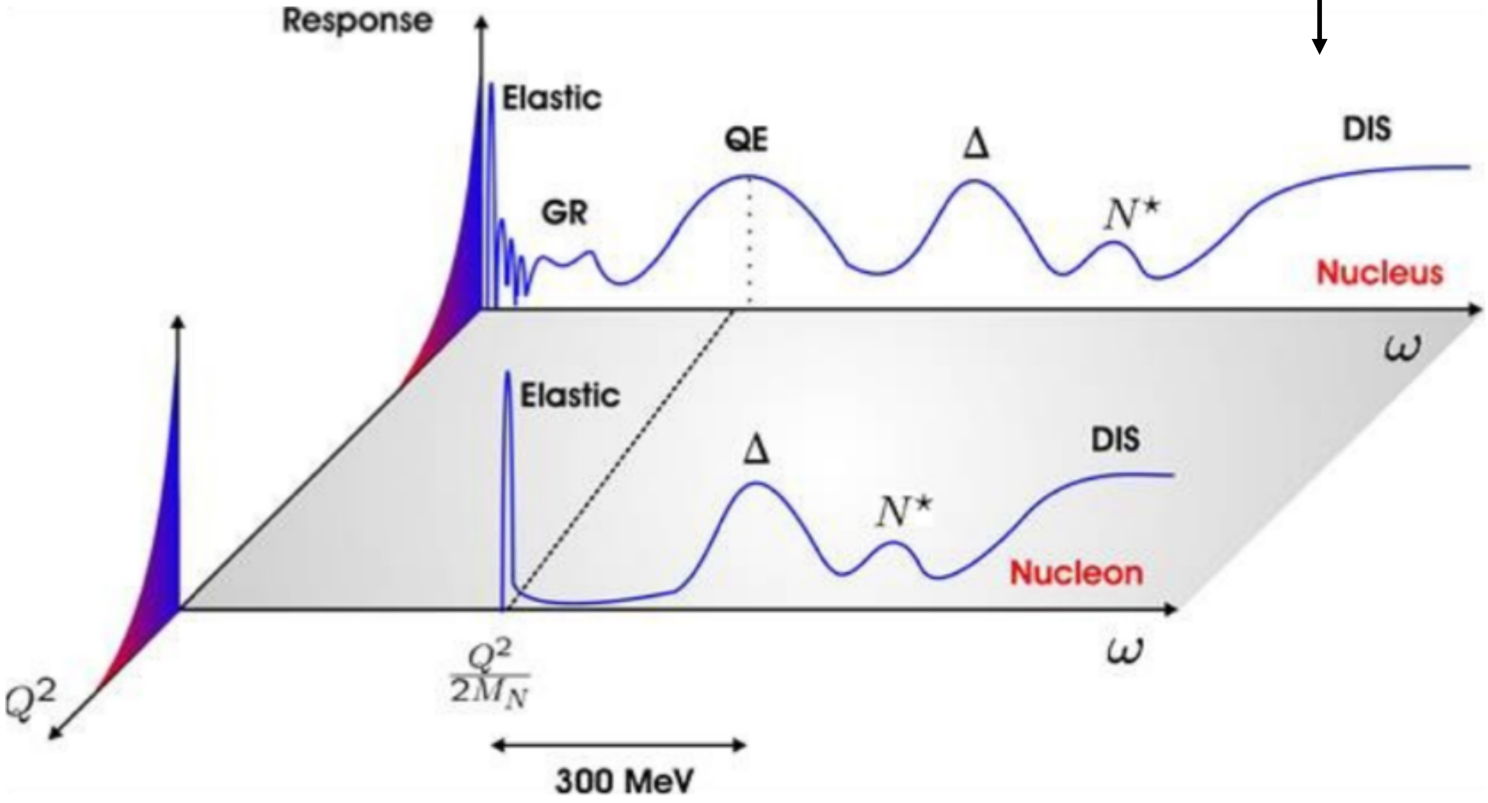
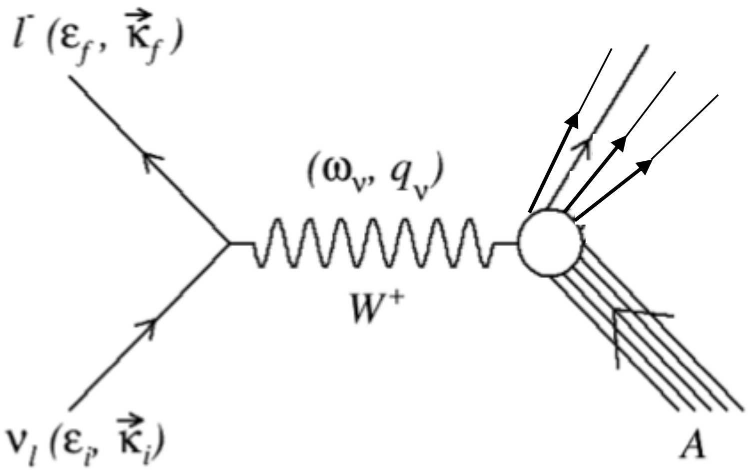


- **Deep inelastic**



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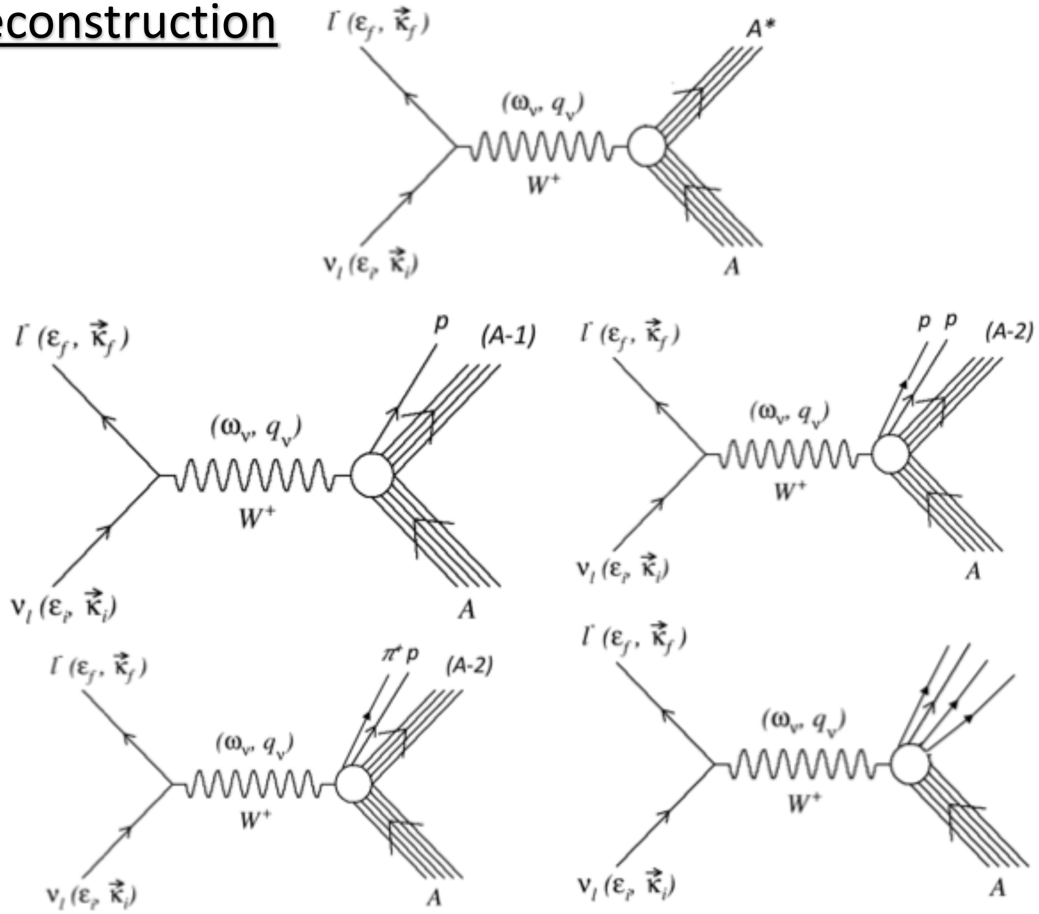

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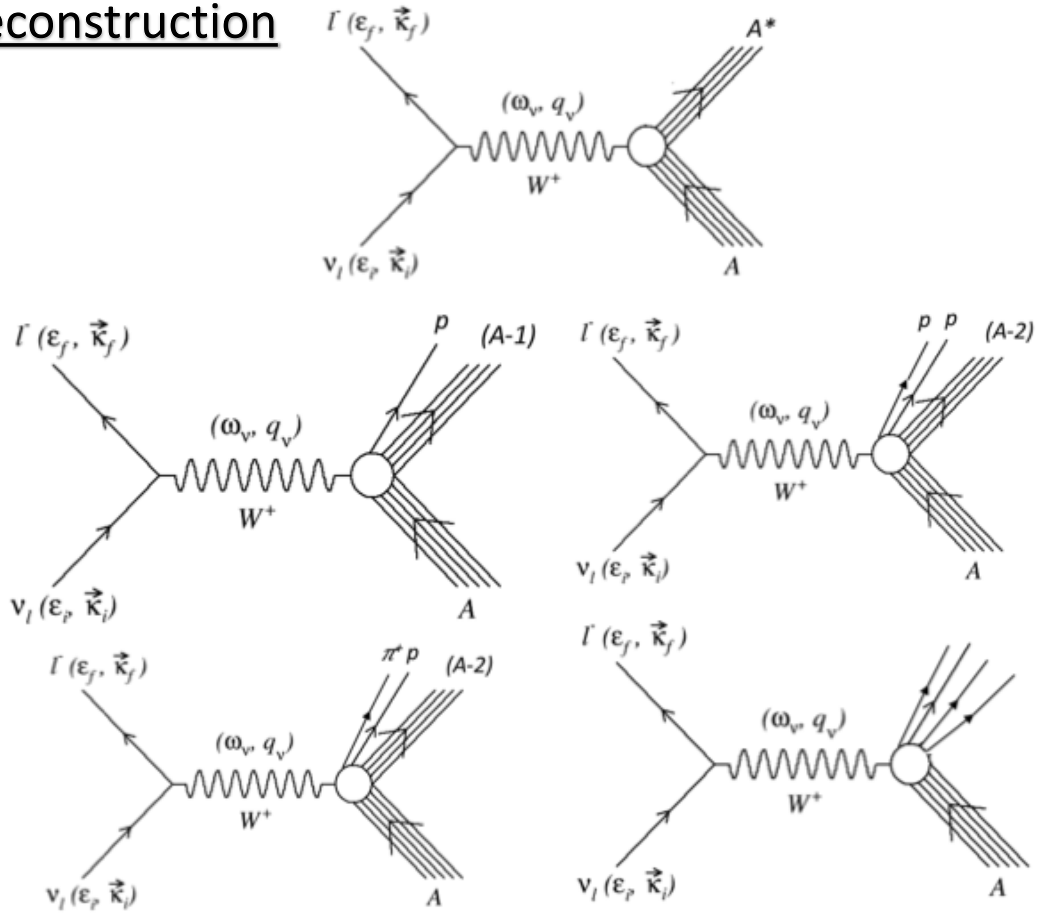

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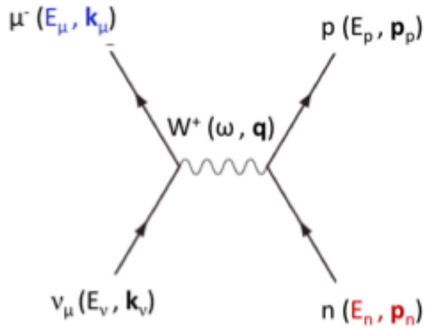
➢ Example: For CCQE process, the reconstructed neutrino energy is

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

- 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.



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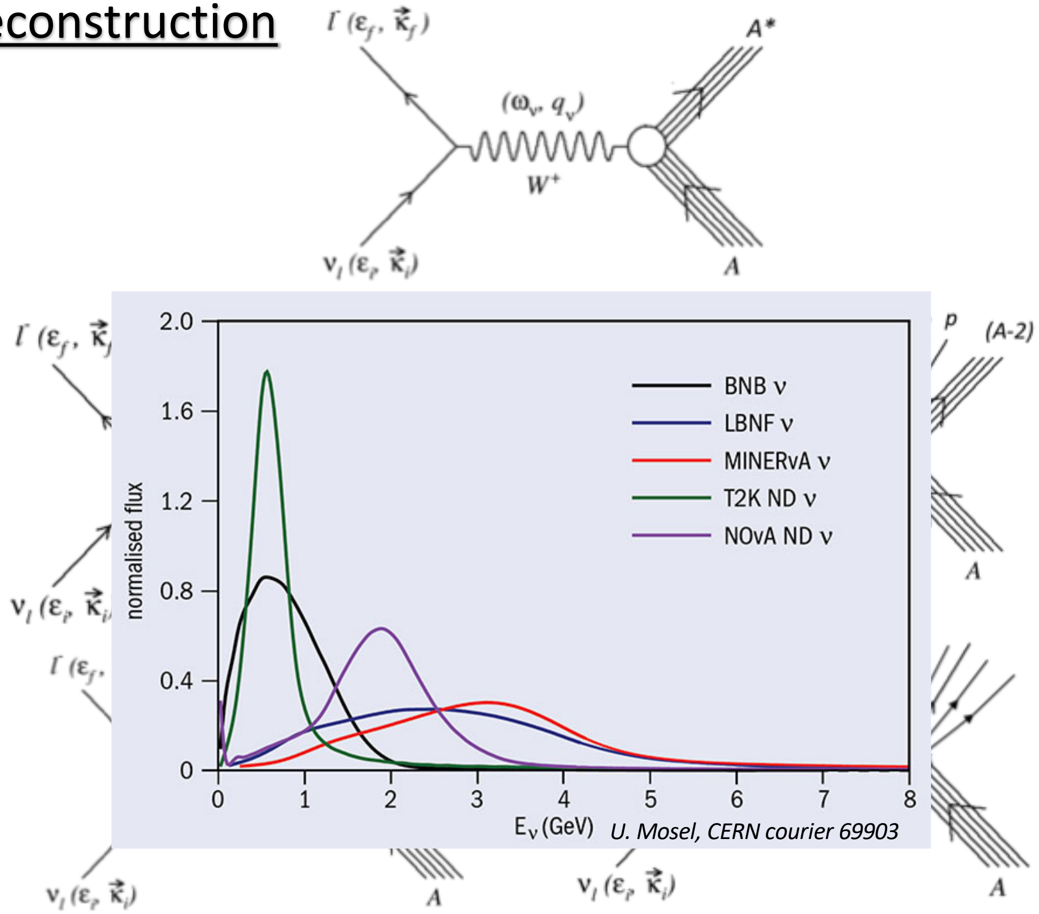

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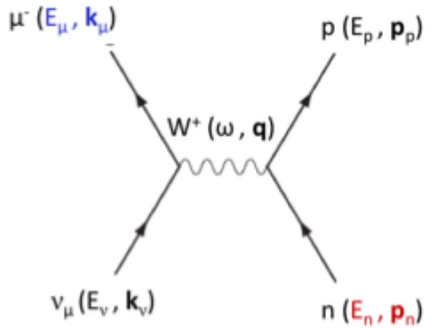

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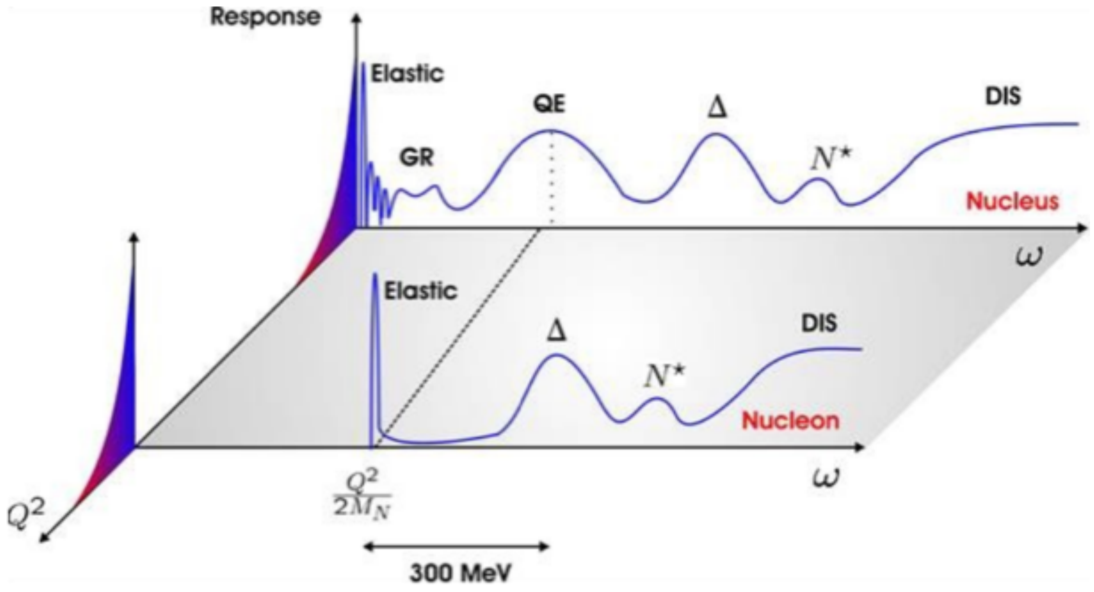

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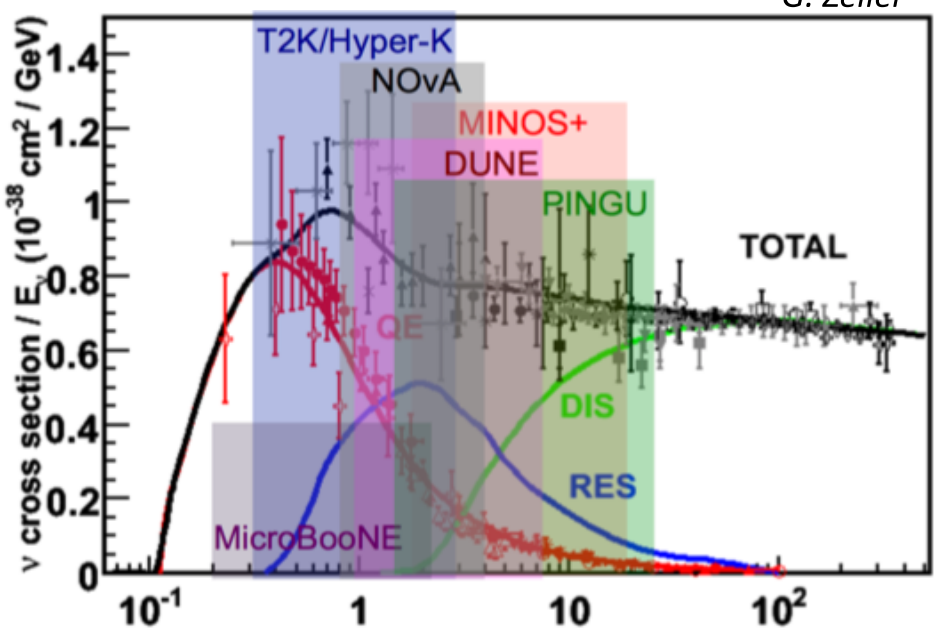
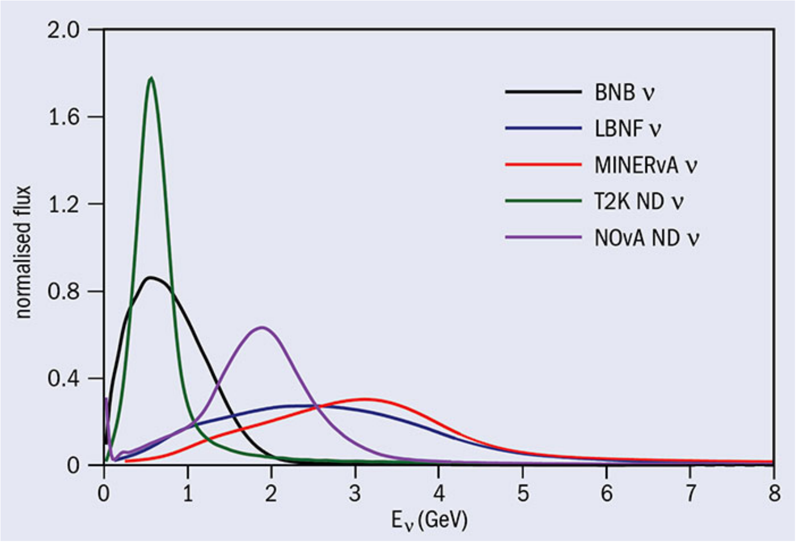
G. Zeller





U. Mosel, CERN courier 69903

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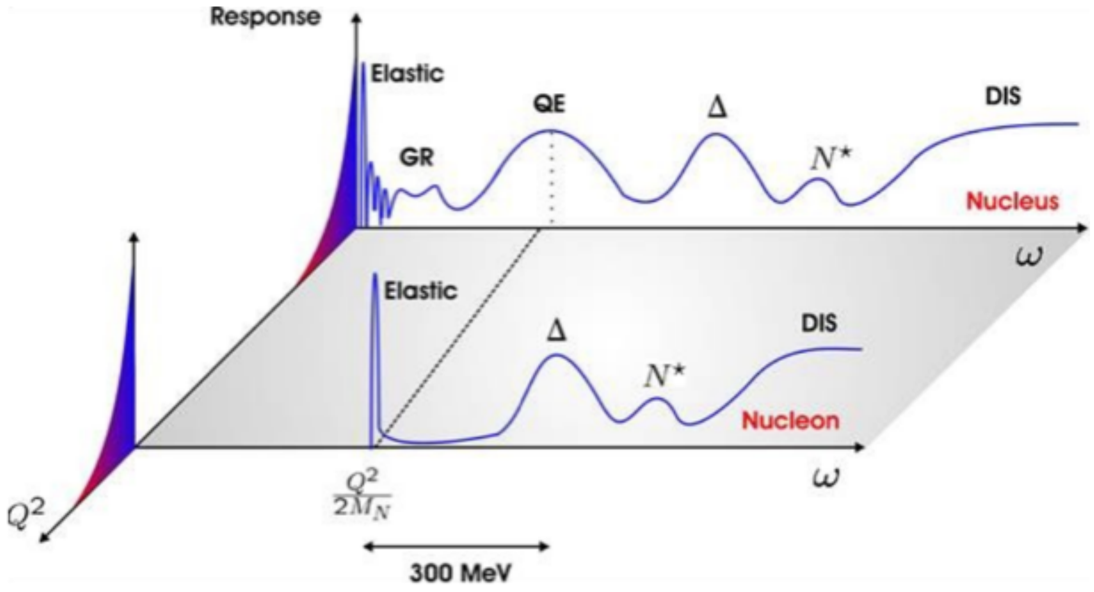

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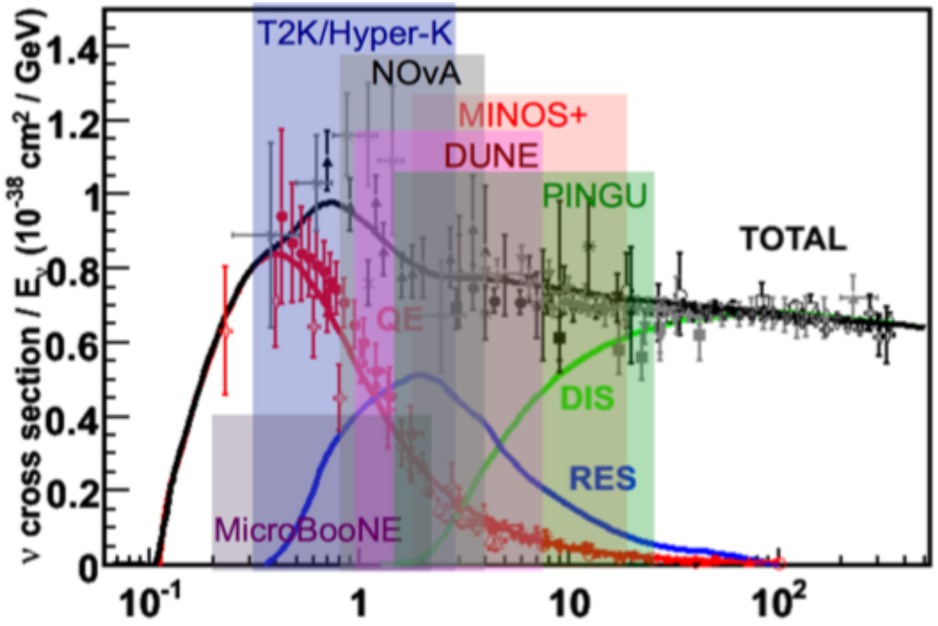

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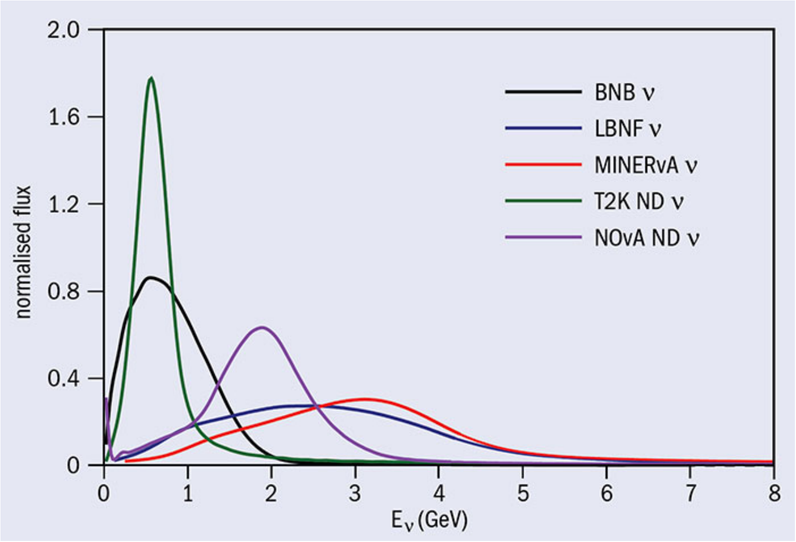
- To achieve discovery level precision - a realistic nuclear model (in Monte-Carlo simulations) is needed at every step of the analysis!



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Nuclear Modeling

- Probing systems at different energies:

QCD
- d.o.f. : quarks and gluons
- Asymptotic freedom
- Confinement

Atomic Systems ←

1 MeV — **1 GeV** — **100 GeV**

← **Few MeV to Few GeV** →

- Nucleus as a whole: Nuclear Matter
- Nucleus as a many-body system with (effective) d.o.f. as hadrons: *Baryons (n, p) and*
  Mesons (pions, kaons, etc.)

Messy world of Nuclear Physics!

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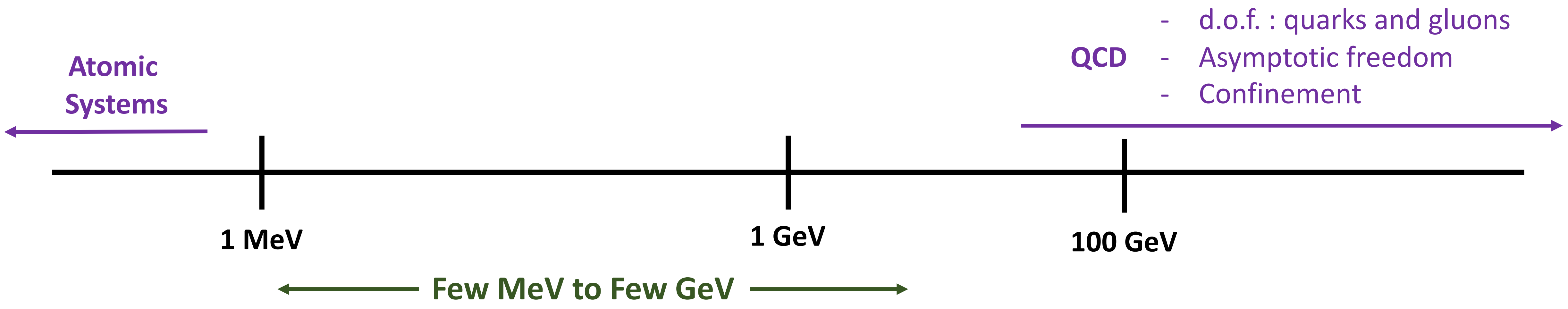
Nightmare of nuclear theorists!

- A typical nuclear potential is – *attractive, short-range, spin-dependent, non-central, charge independent, exchange character, hard-core, spin-orbit dependent …..*

Nuclear Modeling



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- Some nuclear properties, though difficult but, can be obtained from first principle (e.g. through time-dependent Hartree-Fock treatment) but can only be solved for few-body systems (light nuclei).

- The complexity of nuclear many-body systems leads to replacement of such a description by – *specific models using specific assumptions and approximations.*

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Nuclear theory is far from being complete and free from assumptions!

Overview of the neutrino-nucleus business

- **Neutrino Experiments**

• DUNE

• MicroBooNE
• ICARUS
• SBND

• MiniBooNE

• T2HK
• T2K

• NOvA

- **Neutrino Generators**

• GENIE
• NEUT

• NuWro
• NUANCE
• GiBUU

- **Nuclear Theory Models (QE examples)**

- Fermi Gas + RPA (Martini, Ericson, *et al*)
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- Hartree-Fock+continuum RPA (Pandey, Jachowicz *et al*)

- Super-Scaling approach (Amaro, Barbaro, Caballero, Donnelly, Megias, *et al.*)

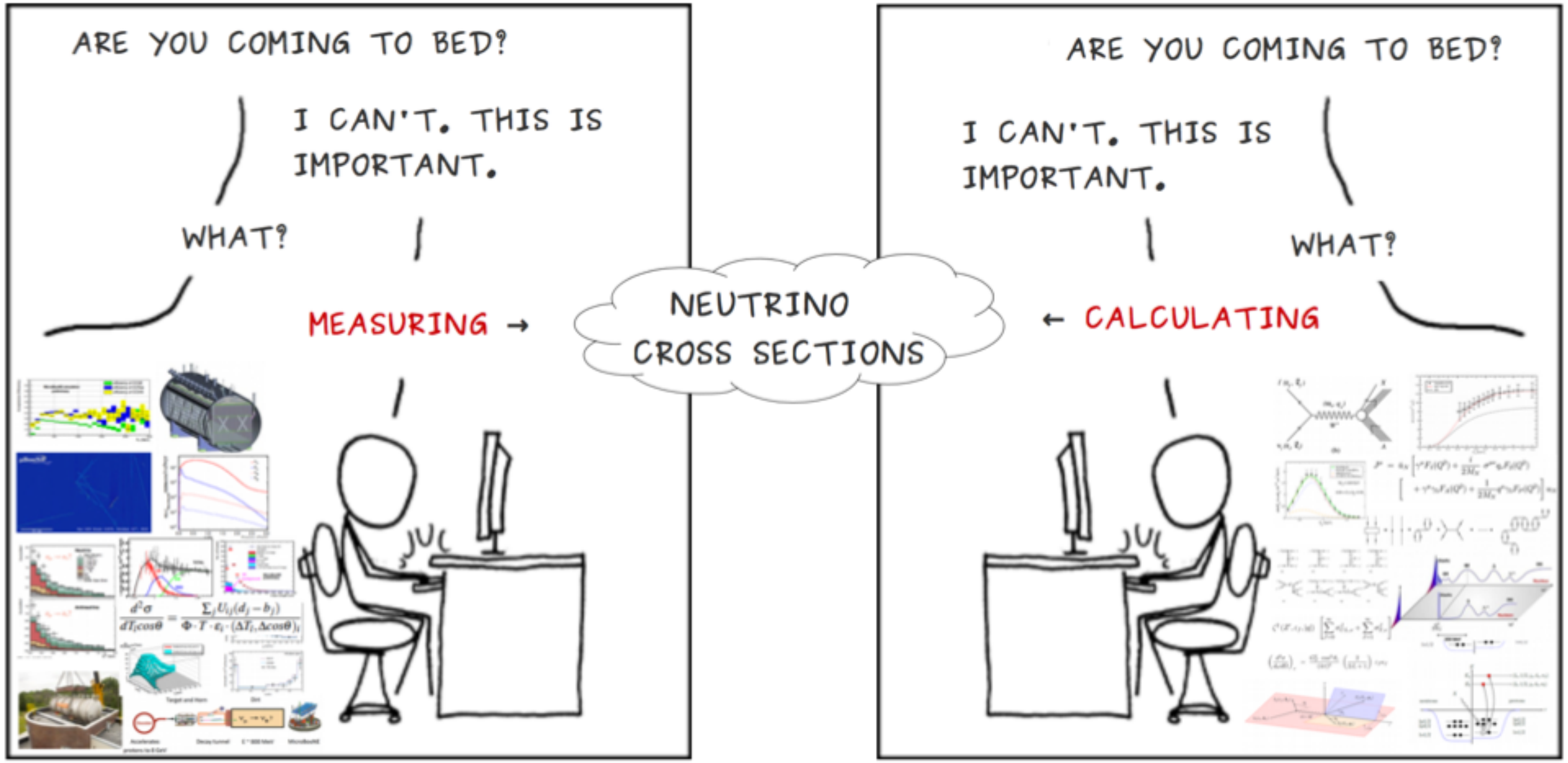
- Spectral Function Formalism (Benhar, *et al.*)

- Green's Function Monte Carlo Approach (Lovato, Gandolfi, Carlson, *et al.)*

- …, *etc.*

Neutrino Experimentalist's Desk

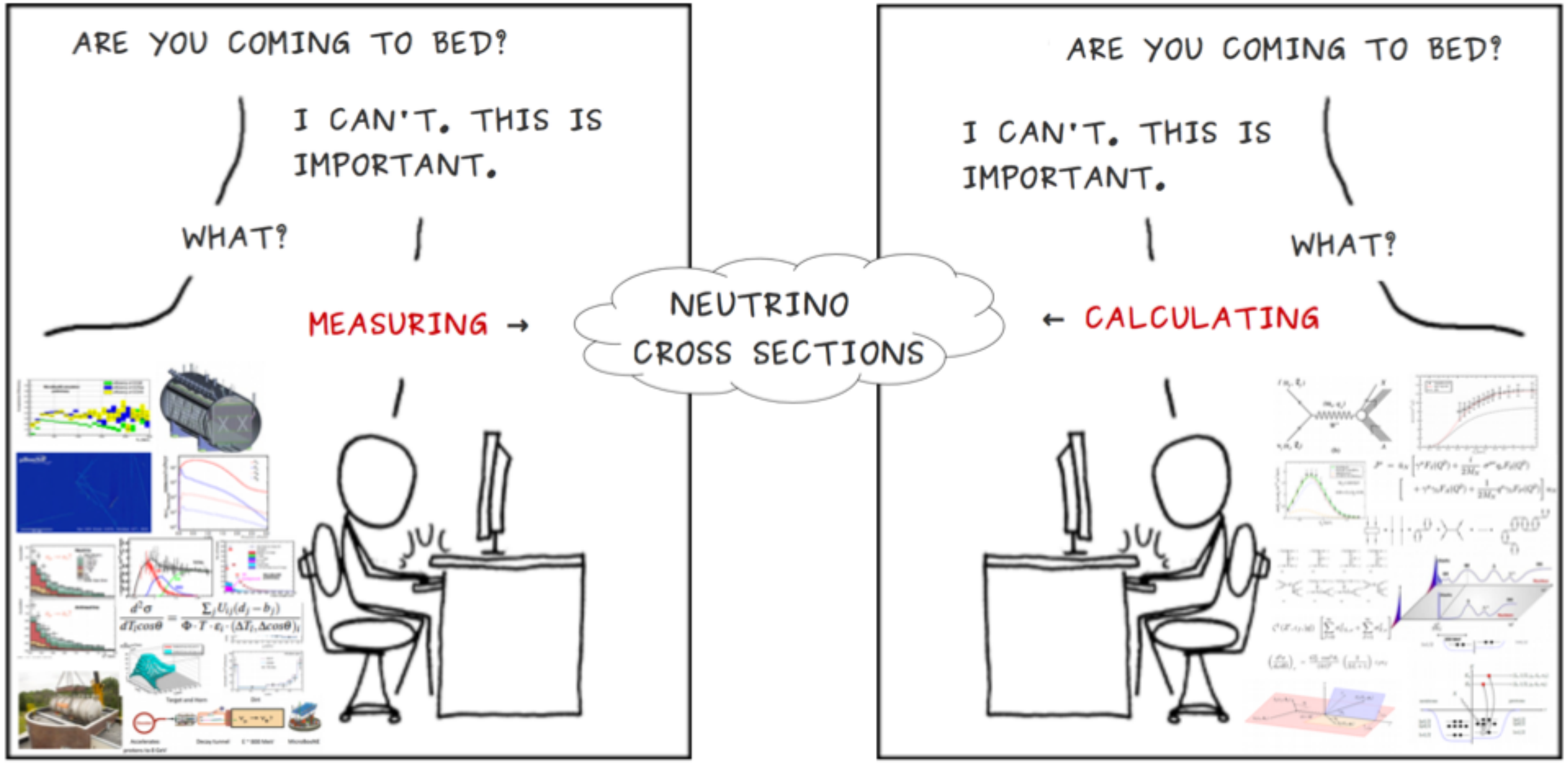
Nuclear Theorist's Desk



- Need better models to reduce systematic uncertainties to eventually make precise measurements
- Need precise data to test and validate the assumptions and approximations to eventually improve the model

- **In an ideal world:** with strong collaboration between neutrino experimentalists and nuclear theorists - we all understand neutrino-nucleus interactions with high accuracy and make precise oscillations measurements.

Neutrino Experimentalist's Desk **Nuclear Theorist's Desk**

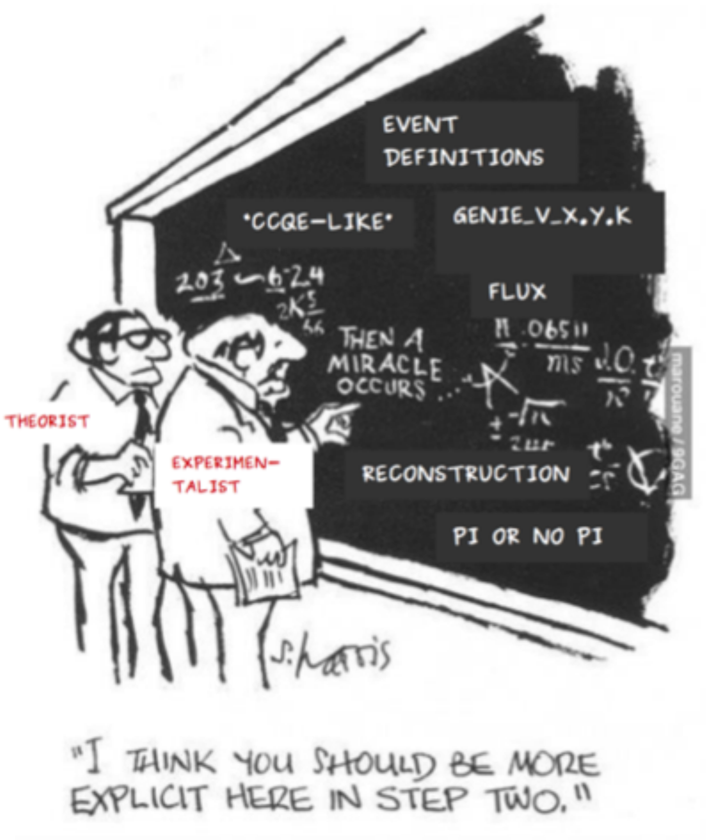


And they lived happily ever after…

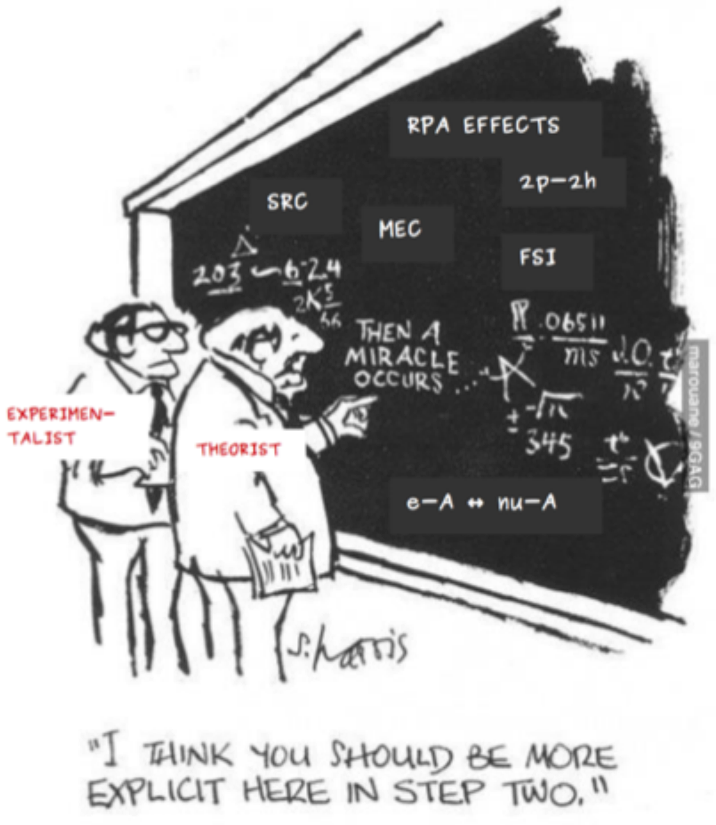
- **In real world:** things are a bit messy!

''Has physics changed from being a unified science to a series of subfields that ignore each other?'' *[Paraphrasing from a book that I don't remember the name]*

When nuclear theorists talk to neutrino experimentalists



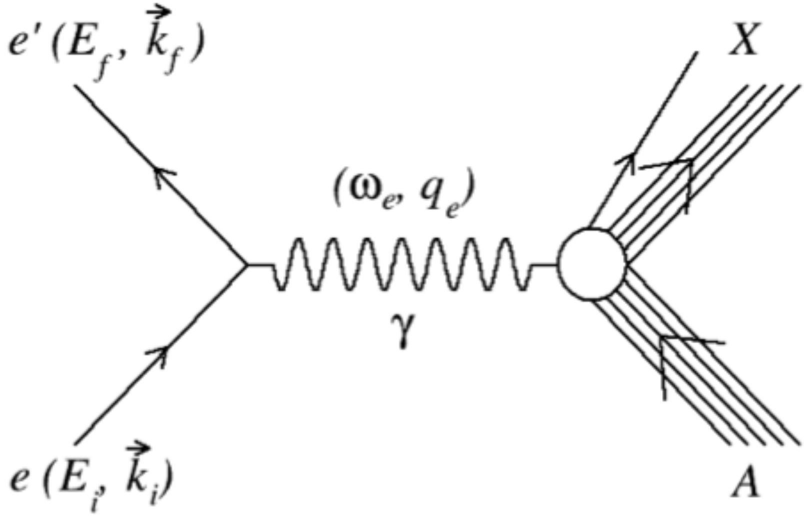
When neutrino experimentalists talk to nuclear theorists



State of the art!

General cross section formalism

QE e-A scattering

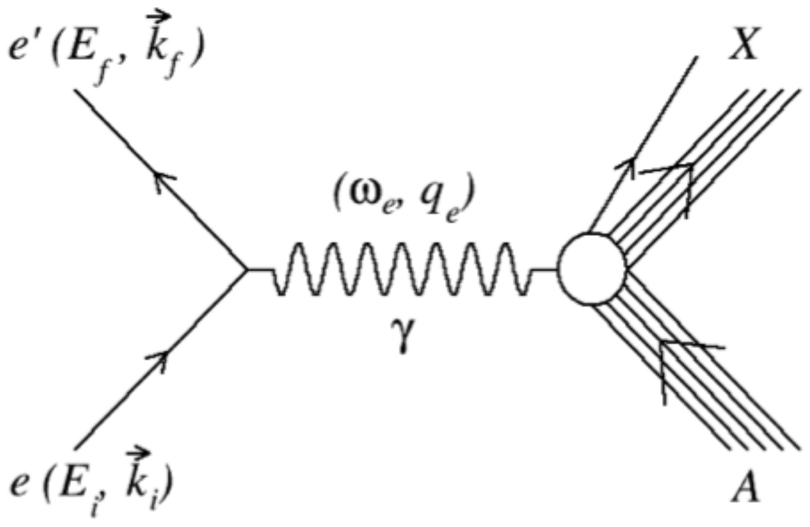


Kinematics: $\omega = \varepsilon_i - \varepsilon_f$, $q = |\mathbf{k}_i - \mathbf{k}_f|$

$$Q^2 = q^2 - \omega^2$$

General cross section formalism

QE e-A scattering



Kinematics: $\omega = \varepsilon_i - \varepsilon_f$, $q = |\mathbf{k}_i - \mathbf{k}_f|$

$$Q^2 = q^2 - \omega^2$$

Cross section: $d\sigma \sim |M_{fi}|^2 \sim \frac{1}{Q^4} |j_\mu \; J^\mu{}_{fi}|^2$

$$d\sigma \sim \frac{1}{Q^4} L_{\mu\nu} W^{\mu\nu}$$

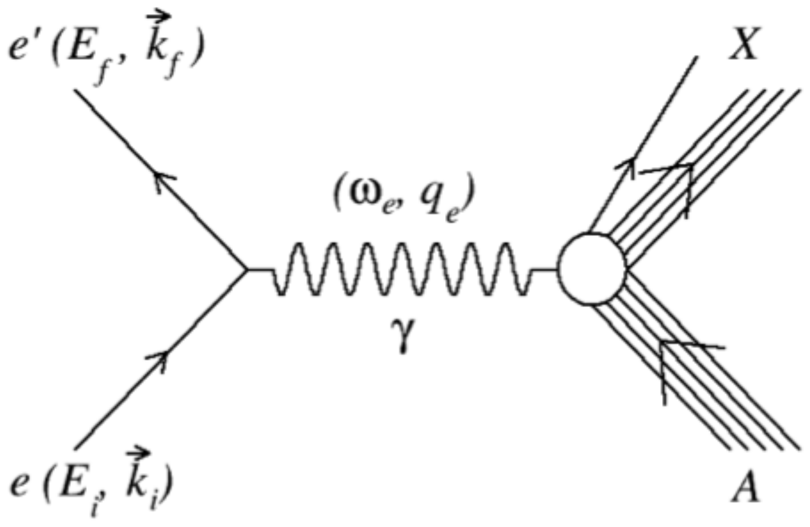
$$\boxed{\left(\frac{d^2\sigma}{d\omega_e d\Omega}\right)_e = \frac{\alpha^2}{Q^4} \left(\frac{2}{2J_i+1}\right) \frac{1}{k_f E_i} \; \zeta^2(Z', E_f, q_e) \left[\sum_{J=0}^{\infty} \sigma^J_{L,e} + \sum_{J=1}^{\infty} \sigma^J_{T,e}\right]}$$

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

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

General cross section formalism

QE e-A scattering



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

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

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

General cross section formalism

QE e-A scattering

Kinematics: $\omega = \varepsilon_i - \varepsilon_f$, $q = |\mathbf{k}_i - \mathbf{k}_f|$

$e'(E_f$

$e(E_i$

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/

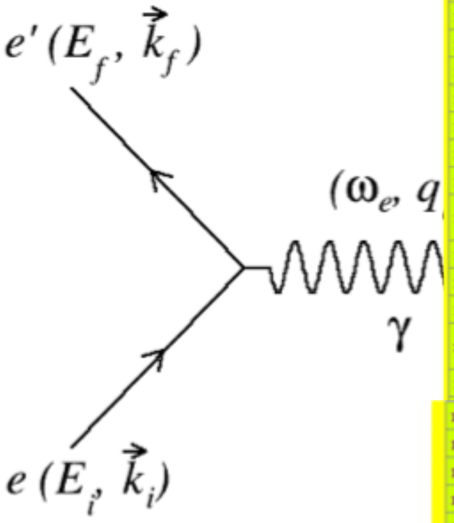
$$\sigma_{T,e} = v_e^T R_e^T$$

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

QE e-A scat

$= |\mathbf{k}_i - \mathbf{k}_f|$

ω^2



$^2 \sim \frac{1}{Q^4} |j_\mu \, J^\mu{}_{fi}|^2$

$W^{\mu\nu}$

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

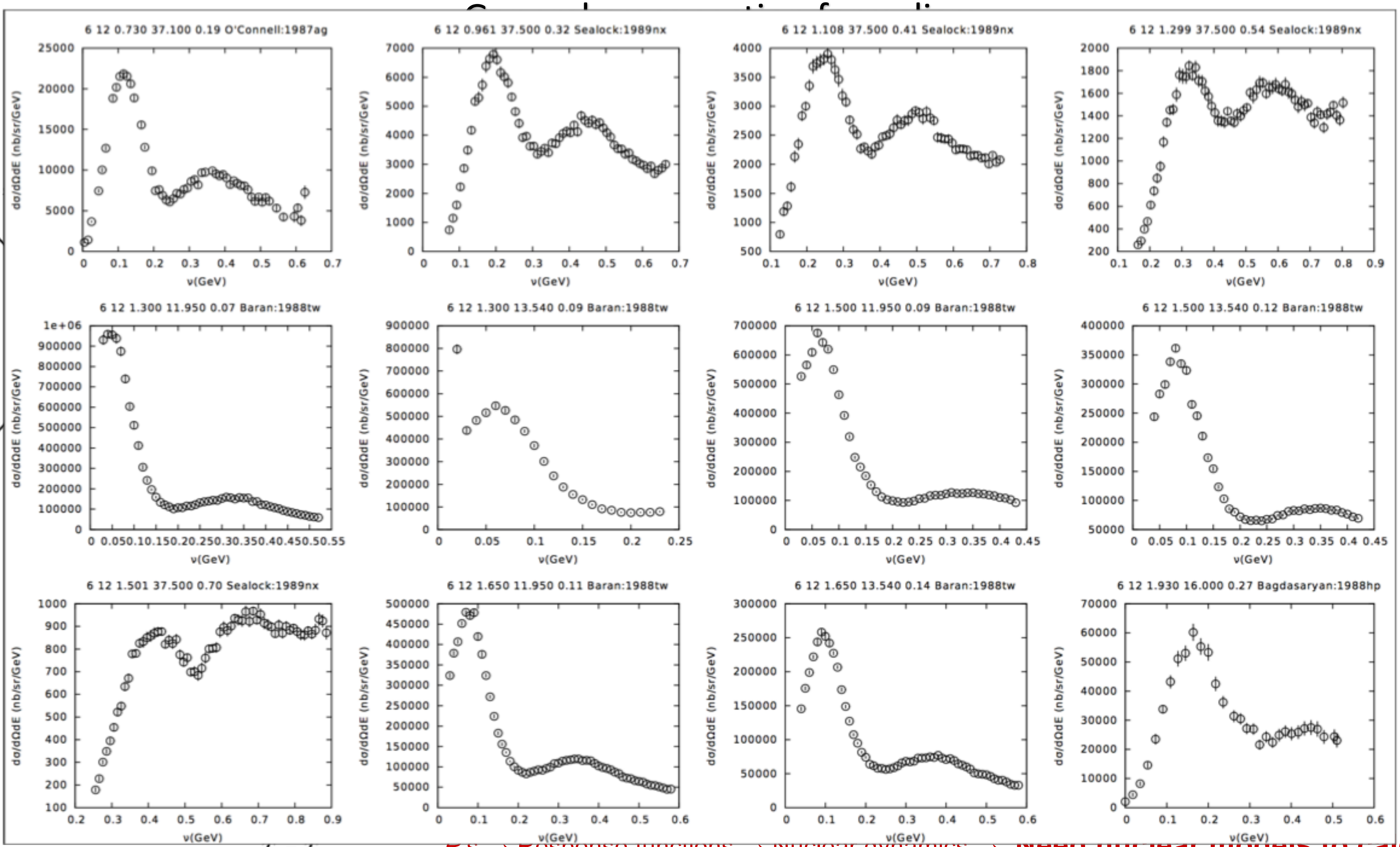
$\left(\frac{d^2\sigma}{d\omega_e d\Omega}\right)_e$ … $\sigma^J_{T,e}\Big]$

$\sigma_{L,e} =$ … asy to calculate

$\sigma_{T,e} =$ … eed nuclear models to calculate!

$e'(E_f$

$e(E_i$



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

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

General cross section formalism

QE e-A scattering

Kinematics: $\omega = \varepsilon_i - \varepsilon_f$, $q = |\mathbf{k}_i - \mathbf{k}_f|$

- 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).

- No studies on Argon nucleus? What About liquid-argon based detectors in SBN and DUNE?

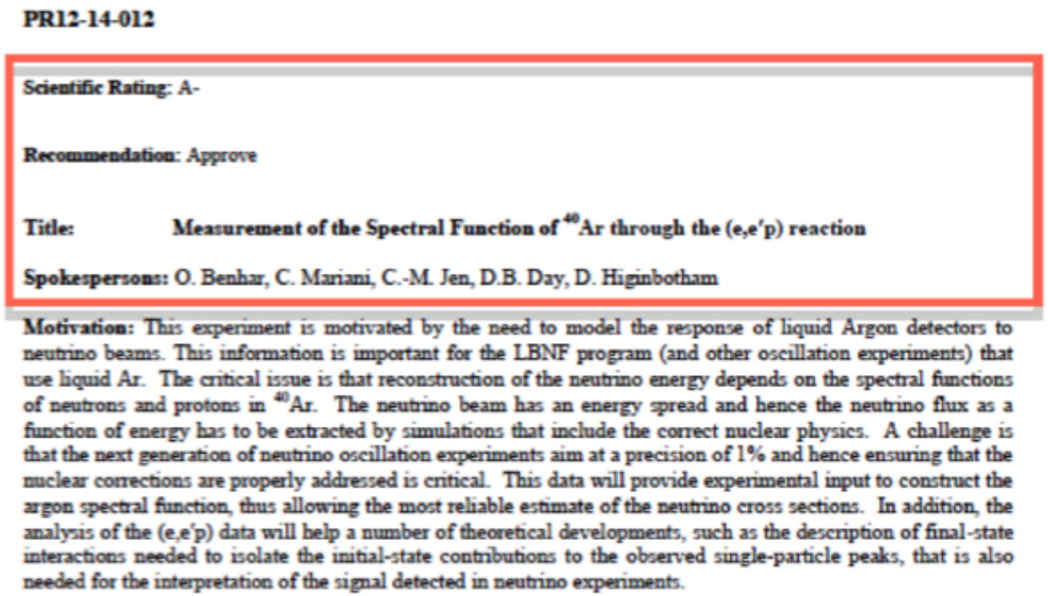
http://faculty.virginia.edu/qes-archive/

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

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

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

- ^{40}Ar is a not a isospin symmetric 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?
- .....



PR12-14-012

Scientific Rating: A-

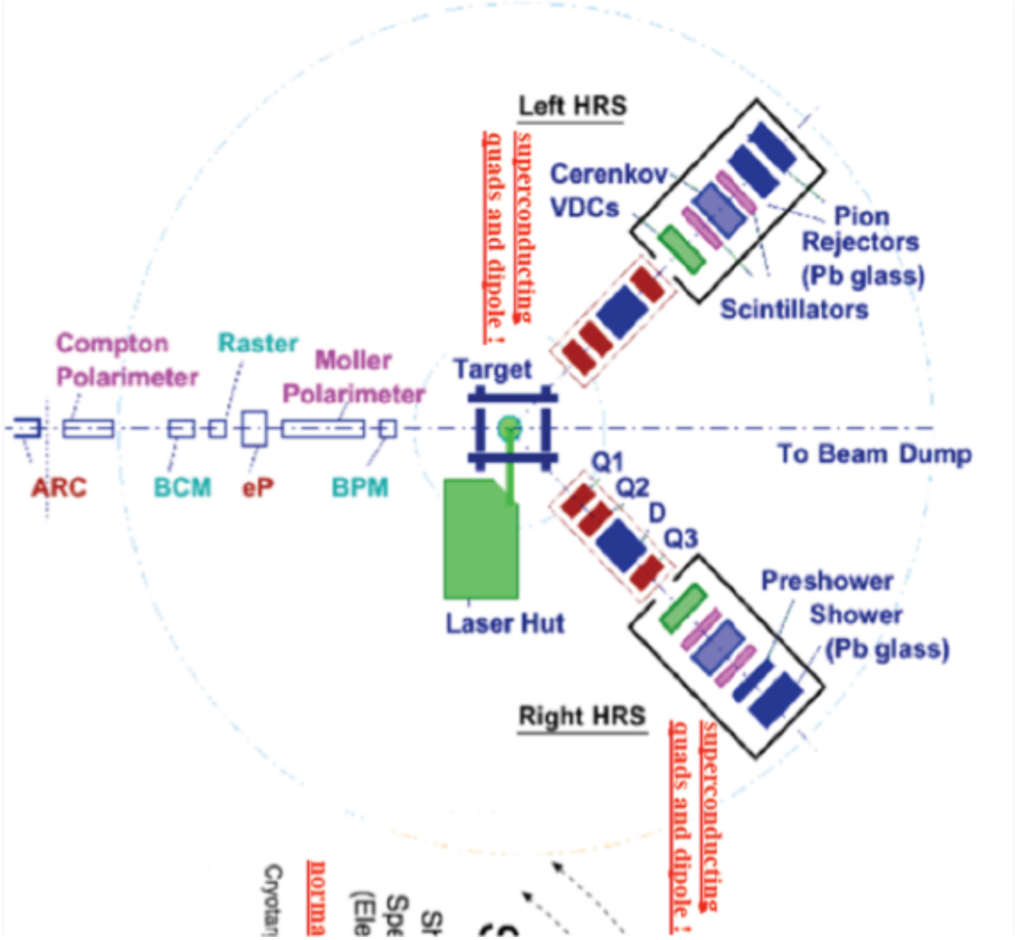
Recommendation: Approve

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

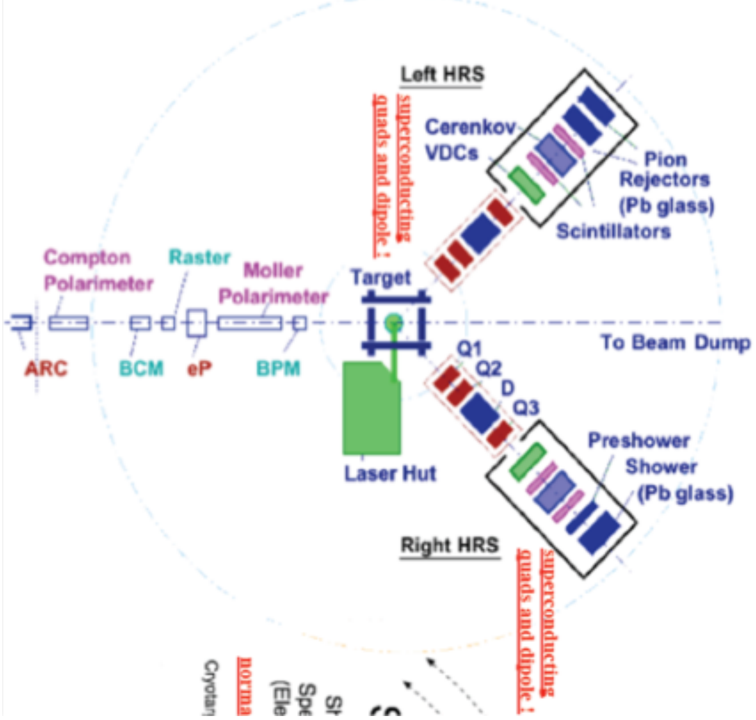
Motivation: This experiment is motivated by the need to model the response of liquid Argon detectors to neutrino beams. This information is important for the LBNF program (and other oscillation experiments) that use liquid Ar. The critical issue is that reconstruction of the neutrino energy depends on 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.

- Completed data taking last year: Feb-March 2017
- **First results out** [arXiv:1803.01910]



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

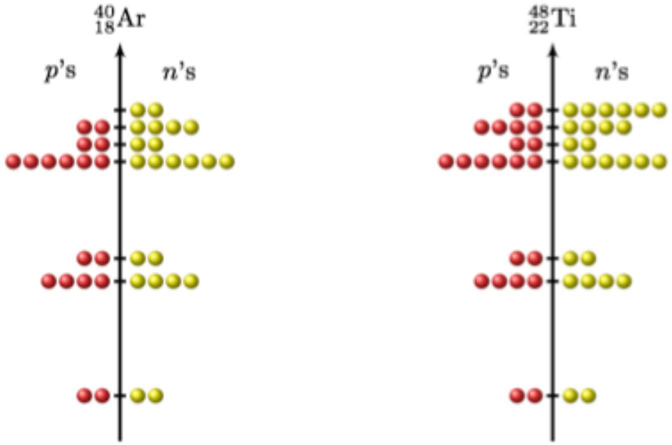
Collected Data	Minutes	Events(k)
Ar	57	2928
Ti	50	2993
Dummy	56	3235
C	115	3957

Kinematic setups

Run Period: Feb-March 2017

Nuclear Targets – Ar and Ti

- 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.



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kin5 - Inclusive

Collected Data	Minutes	Events (k)
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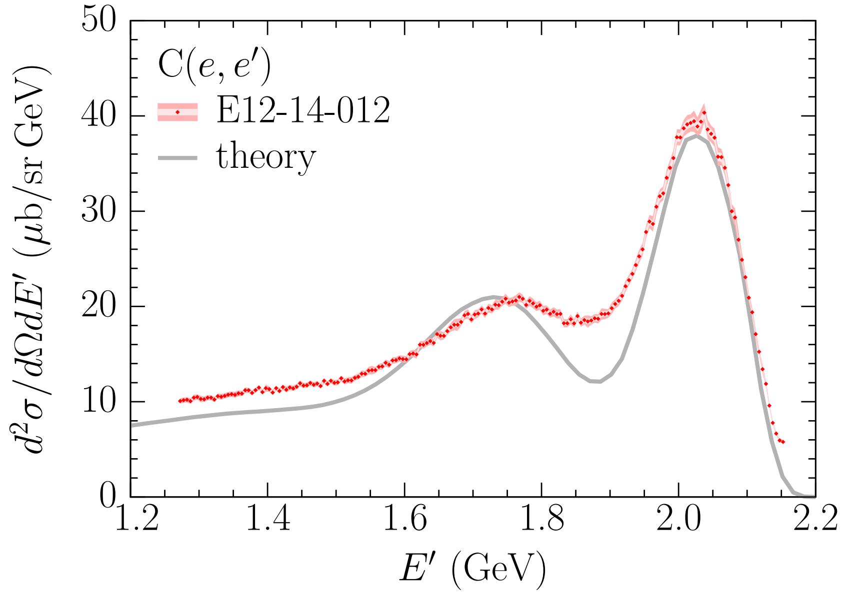
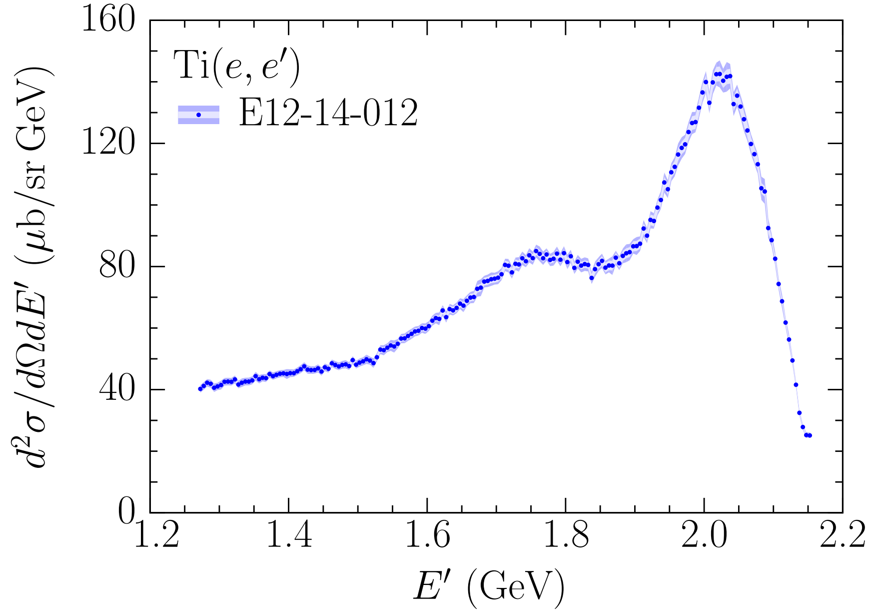
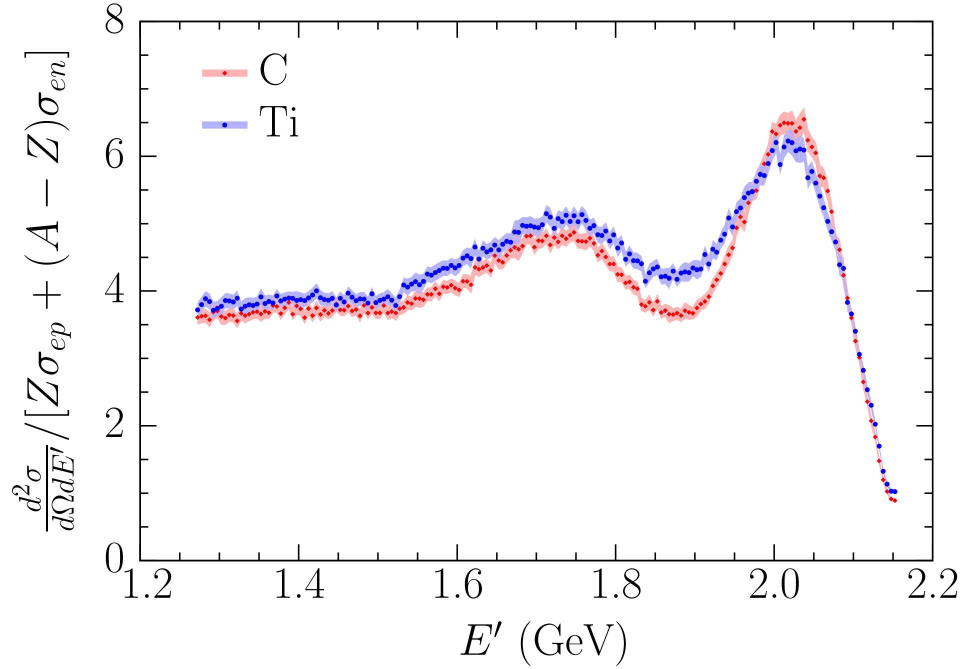
Dummy	56	3235
C	115	3957

(e,e') cross section results at E = 2.222 GeV, θ = 15.541 deg





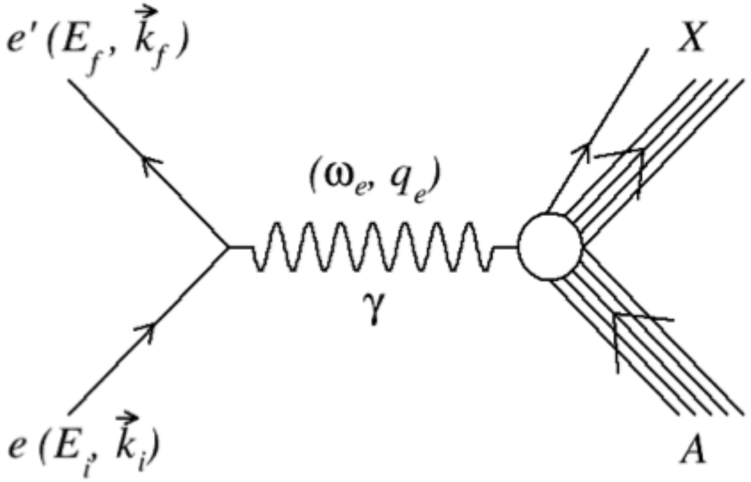
arXiv:1803.01910



- **(e,e')Ar** cross section results will be out this summer!

Electron to neutrino scattering

QE e-A scattering



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

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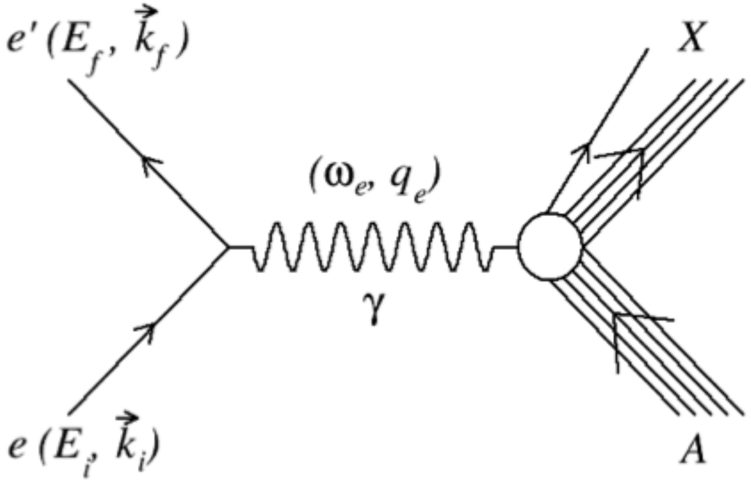
R's → Response functions → Nuclear dynamics → **Need nuclear models to calculate!**

Electron to neutrino scattering

QE e-A scattering



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

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

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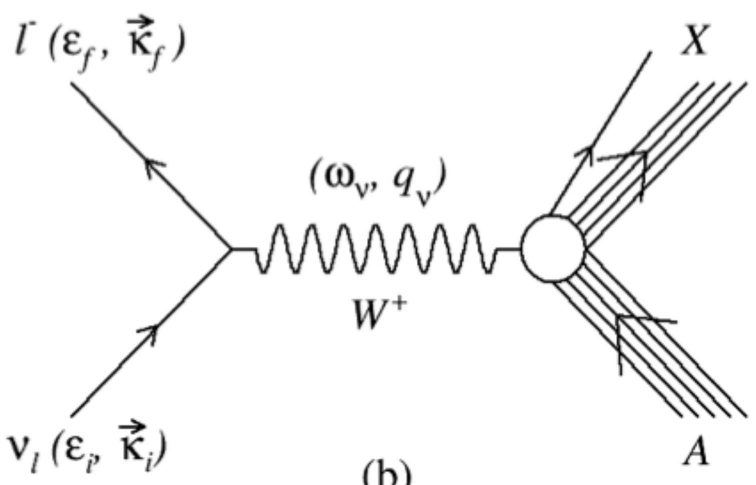
QE ν-A scattering



(b)

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

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

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

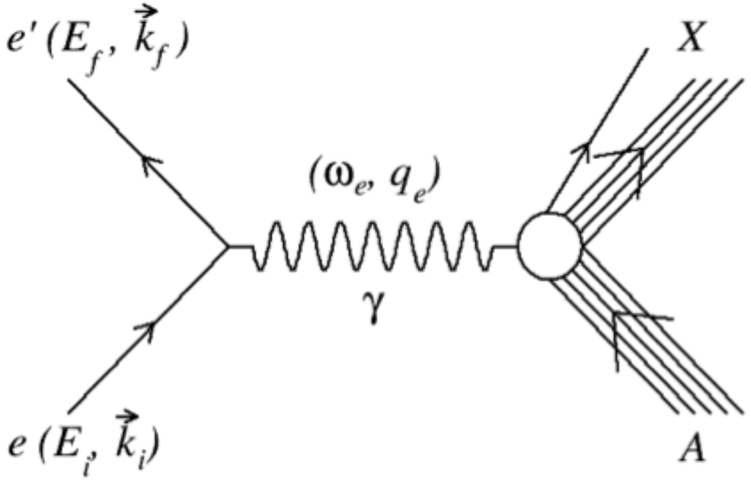
sign is the only difference between ν and anti-ν

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

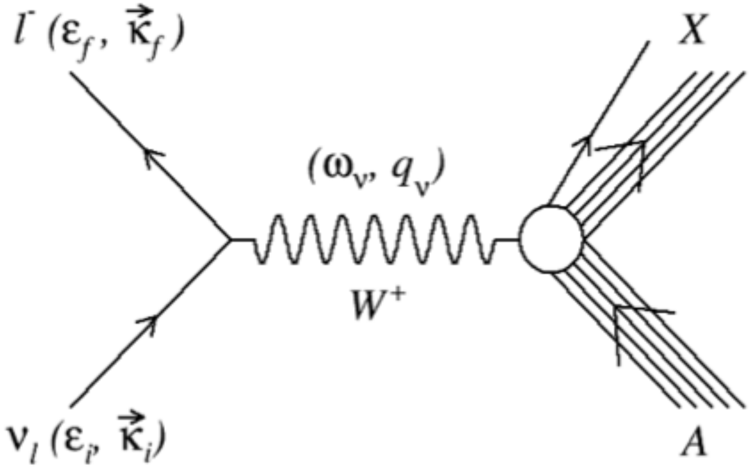
R's → Response functions → Nuclear dynamics → **Need nuclear models to calculate!**

Electron to neutrino scattering

QE e-A scattering



QE ν-A scattering



CAUTION: CHALLENGES AHEAD

- Monoenergetic beams (E_e known precisely; ω, q can be calculated)
- Hence, different reaction channels can be separated

- E_ν has to be reconstructed → wide flux
- Hence, difficult to distinguish different reactions channels.
- What experimentalist's measure:

$$\frac{d^2\sigma}{dT_l cos\theta} = \frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \varepsilon_i \cdot (\Delta T_l, \Delta cos\theta)_i}$$

- What theorist's calculate:

$$\frac{d^2\sigma}{dT_l\, d\cos\theta} = \frac{1}{\int \Phi(E_\nu)\, dE_\nu} \int dE_\nu \left[\frac{d^2\sigma}{d\omega\, d\cos\theta}\right]_{\omega = E_\nu - E_l} \Phi(E_\nu)$$

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- T2K

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- …, *etc.*

- How the nucleus is described?
- What assumptions/approximations go into different model?
- The effect of those in the cross sections.

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- …, *etc.*

'A model is like an Austrian timetable. Austrian trains are always late. A Prussian visitor asks the Austrian conductor why they bother to print timetable. The conductor replies: If we didn't , how would we know how late the trains are?' - V. F. Weisskopf

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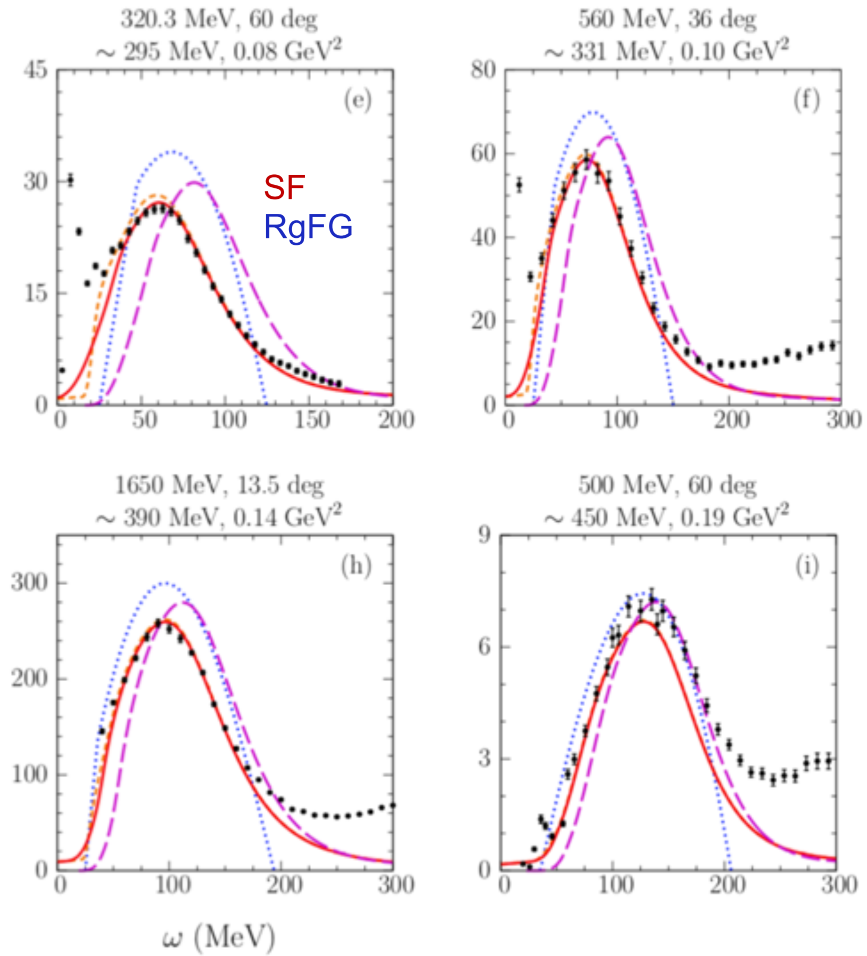
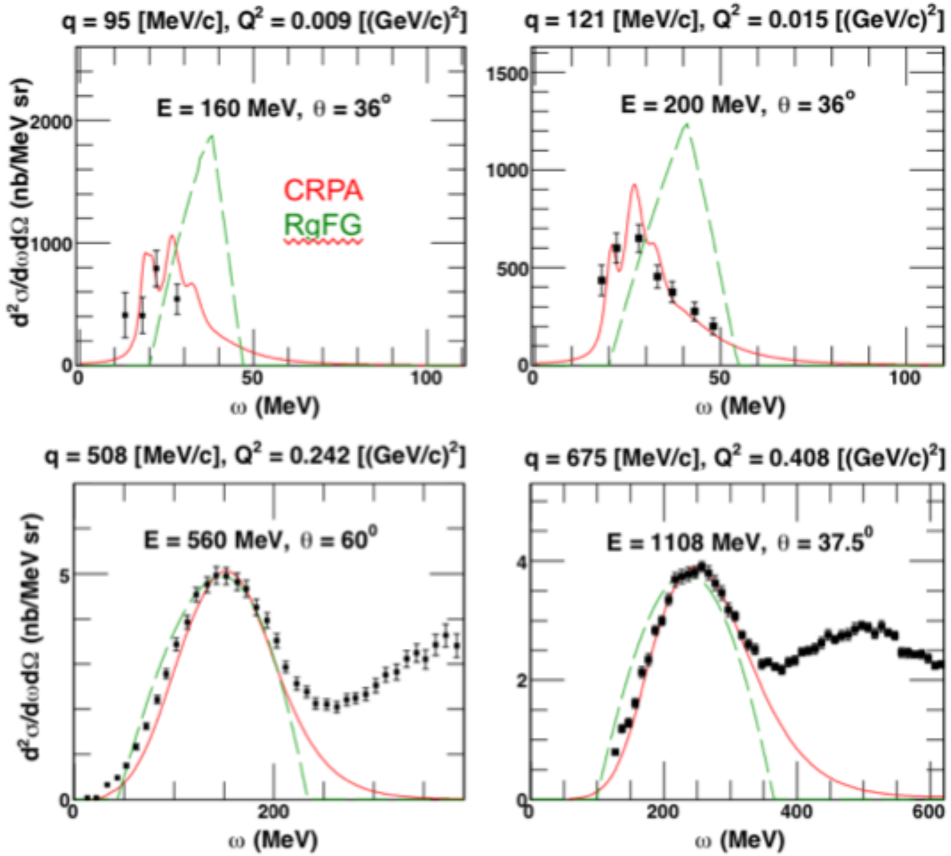
- …, *etc.*

- **Fermi-gas based models**
  - **Global Fermi-gas** [GENIE, NEUT, …]
    - Considering nuclear matter.
    - The nuclear ground state is a Fermi gas of non-interacting nucleons characterized by a fixed Fermi momentum.



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

(e,e') data on ^{12}C

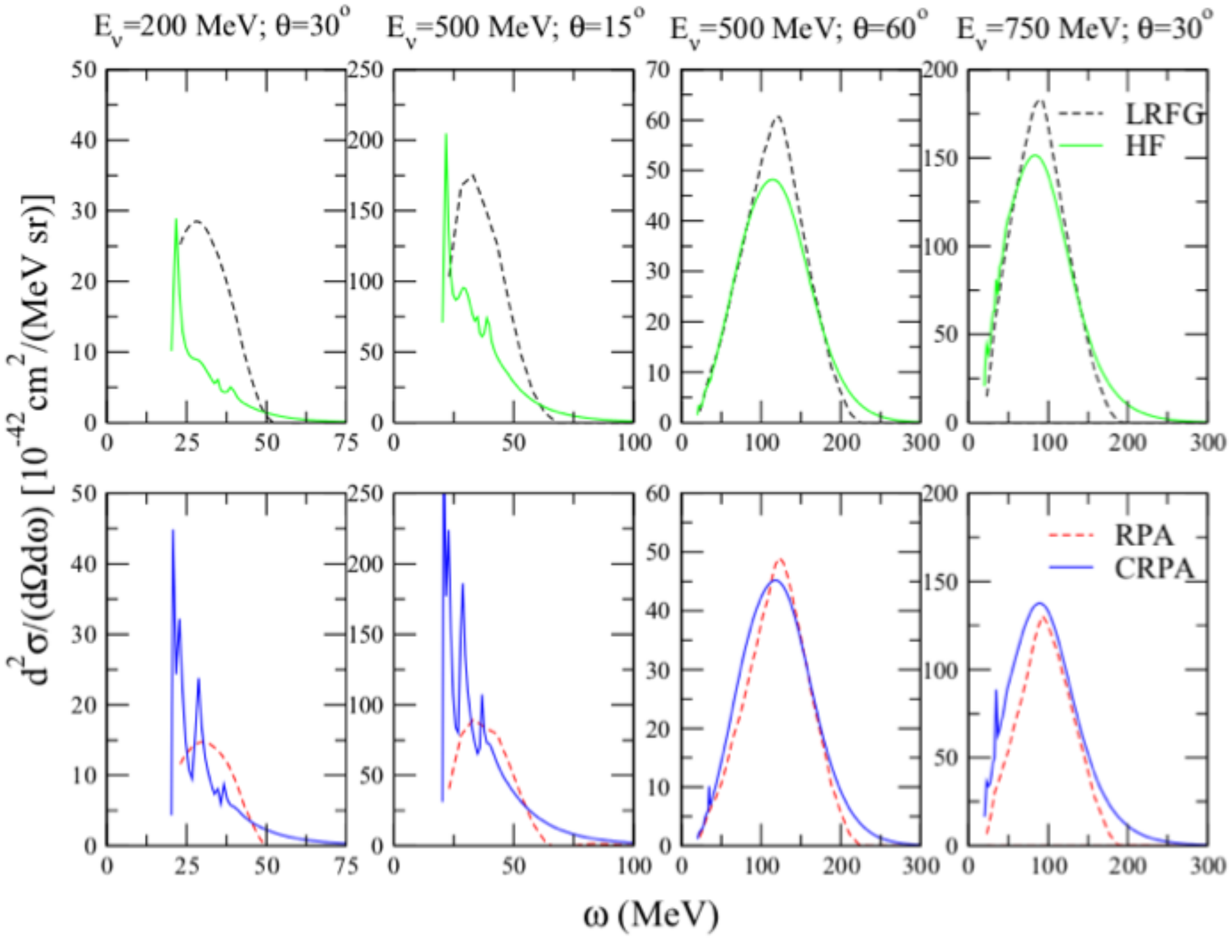


VP, PhD thesis (2016)

- <u>**Fermi-gas based models**</u>
  - **Local Fermi-gas** [Martini, Ericson, *et al,* and Nieves*, et al.]*
    - The nuclear ground state is a Fermi gas of non-interacting nucleons characterized by a Fermi momentum fixed according to the local density of protons and neutrons.
    - The **RPA** correlations are introduced through pion exchange, rho exchange, and contact Landau-Migdal parameters.

➢ LRFG, RPA: Martini, Ericson *et al.*

➢ HF, CRPA: Pandey, Jachowicz *et al.*



M. Martini, N. Jachowicz, M. Ericson, and VP *et al., PRC 94, 015501 (2016).*

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- …, *etc.*

- **HF-CRPA Approach** [Pandey, Jachowicz, *et al*.] – Ghent Model

  - We start by describing the nucleus with a Hartree-Fock (HF) approximation. The mean-field (MF) potential is obtained by solving the HF equations and using a Skyrme (SkE2) two-body interaction.

  - Once we have bound and continuum single-nucleon wave functions, we introduce long-range correlations between the nucleons through a continuum Random Phase Approximation (CRPA).

  - The propagation of particle-hole pairs in the nuclear medium is described by the polarization propagator. In the Lehmann representation, this particle-hole Green's function is given by

$$\Pi(x_1, x_2, x_3, x_4; E_x) = \hbar \sum_n \left[\frac{\langle \Psi_0 | \hat{\psi}^\dagger(x_2) \hat{\psi}(x_1) | \Psi_n \rangle \langle \Psi_n | \hat{\psi}^\dagger(x_3) \hat{\psi}(x_4) | \Psi_0 \rangle}{E_x - (E_n - E_o) + i\eta} - \frac{\langle \Psi_0 | \hat{\psi}^\dagger(x_3) \hat{\psi}(x_4) | \Psi_n \rangle \langle \Psi_n | \hat{\psi}^\dagger(x_2) \hat{\psi}(x_1) | \Psi_0 \rangle}{E_x + (E_n - E_o) - i\eta} \right]$$

  - RPA equations are solved using a Green's function approach.

- **HF-CRPA Approach** [Pandey, Jachowicz, *et al*.] – Ghent Model

- We start by describing the nucleus with ... s obtained by solving the HF equations and using a

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- The propagation of particle-hole pairs i ... he Lehmann representation, this particle-

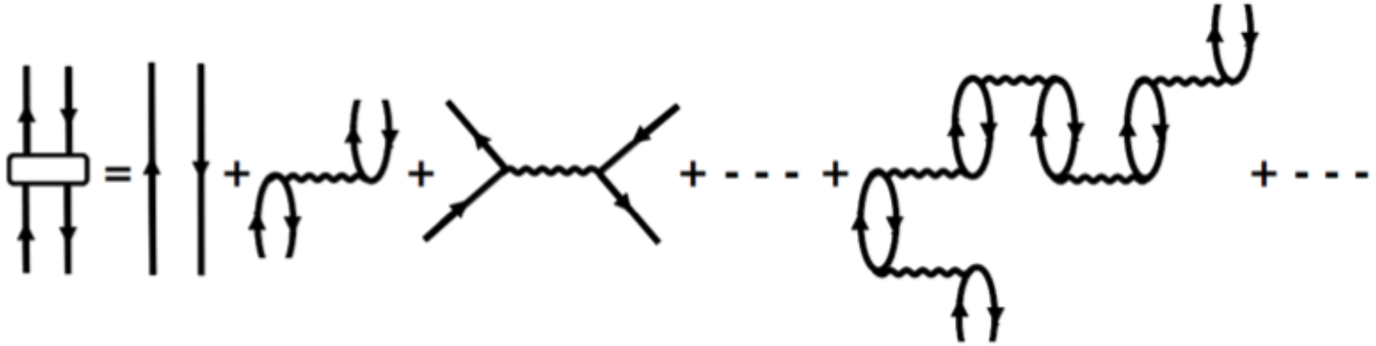
$$\Pi(x_1, x_2, x_3, x_4; E_x) \quad =$$

$$
\begin{aligned}
V(\vec{r_1}, \vec{r_2}) \quad = \quad & t_0\ (1 + x_0 \hat{P}_\sigma)\ \delta(\vec{r_1} - \vec{r_2}) \\
& - \frac{1}{8} t_1 \left[(\overleftarrow{\nabla}_1 - \overleftarrow{\nabla}_2)^2\ \delta(\vec{r_1} - \vec{r_2}) + \delta(\vec{r_1} - \vec{r_2})\ (\overrightarrow{\nabla}_1 - \overrightarrow{\nabla}_2)^2 \right] \\
& + \frac{1}{4} t_2 (\overleftarrow{\nabla}_1 - \overleftarrow{\nabla}_2)\ \delta(\vec{r_1} - \vec{r_2})\ (\overrightarrow{\nabla}_1 - \overrightarrow{\nabla}_2) \\
& + i W_0\ (\overrightarrow{\sigma}_1 + \overrightarrow{\sigma}_2) \cdot (\overleftarrow{\nabla}_1 - \overleftarrow{\nabla}_2) \times \delta(\vec{r_1} - \vec{r_2})\ (\overrightarrow{\nabla}_1 - \overrightarrow{\nabla}_2) \\
& + \frac{1}{6} t_3\ (1 - x_3)\ (1 + \hat{P}_\sigma)\ \rho\ \frac{(\vec{r_1} + \vec{r_2})}{2}\ \delta(\vec{r_1} - \vec{r_2}) \\
& + \frac{e^2}{|\vec{r_1} - \vec{r_2}|}\ +\ x_3 t_3\ \delta(\vec{r_1} - \vec{r_2})\ \delta(\vec{r_1} - \vec{r_3}) \\
& - \frac{1}{24} t_4 \left\{ \left[(\overleftarrow{\nabla}_1 - \overleftarrow{\nabla}_2)^2 + (\overleftarrow{\nabla}_2 - \overleftarrow{\nabla}_3)^2 + (\overleftarrow{\nabla}_3 - \overleftarrow{\nabla}_1)^2 \right] \right\} \\
& \qquad \delta(\vec{r_1} - \vec{r_2})\ \delta(\vec{r_1} - \vec{r_3}) +\ \delta(\vec{r_1} - \vec{r_2})\ \delta(\vec{r_1} - \vec{r_3}) \\
& \qquad \left\{ \left[(\overrightarrow{\nabla}_1 - \overrightarrow{\nabla}_2)^2 + (\overrightarrow{\nabla}_2 - \overrightarrow{\nabla}_3)^2 + (\overrightarrow{\nabla}_3 - \overleftarrow{\nabla}_1)^2 \right] \right\}.
\end{aligned}
$$

- RPA equations are solved using a Green's function approach.

- The RPA-polarization propagator

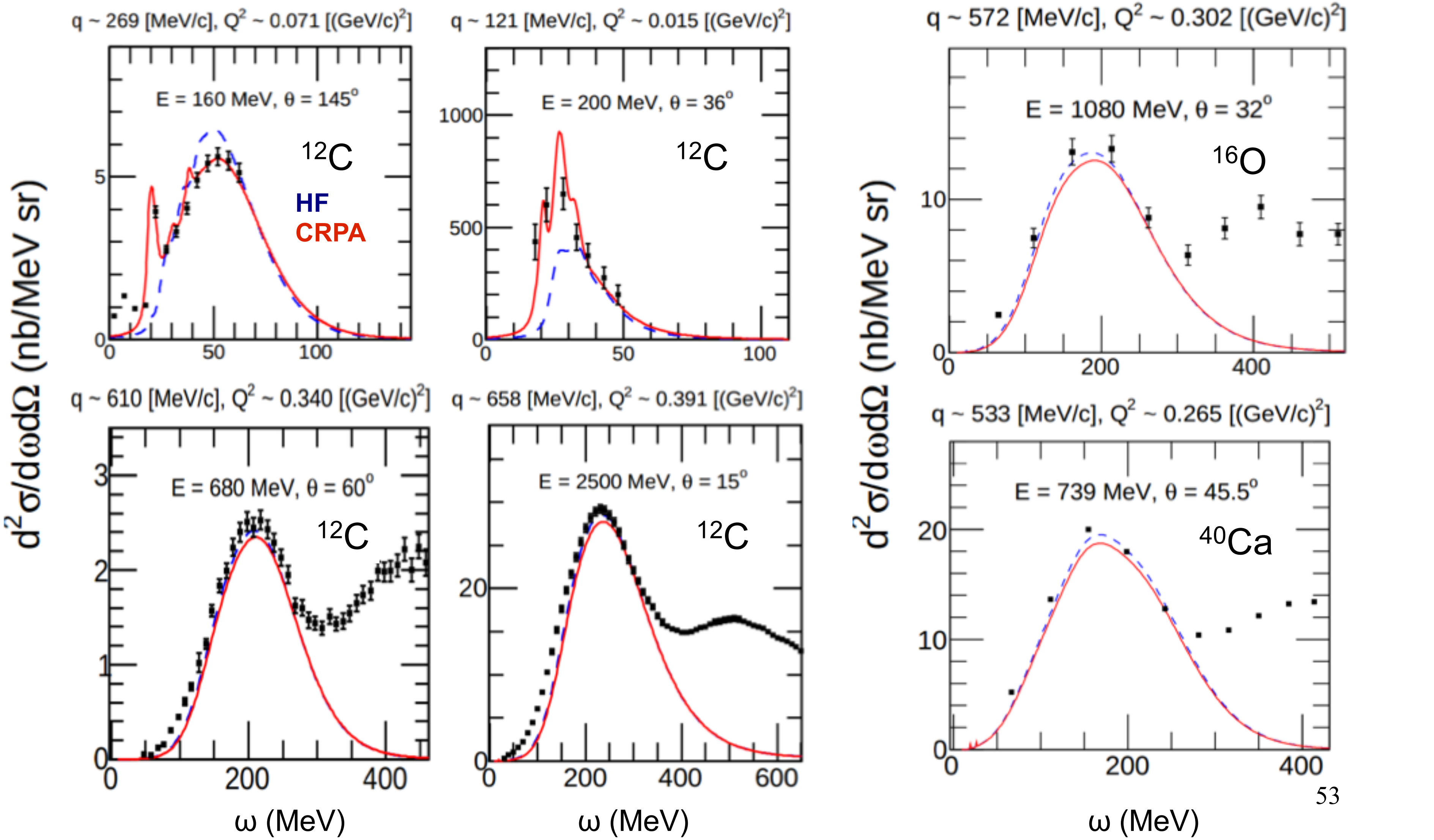
$$\Pi^{(RPA)}(x_1, x_2; E_x) = \Pi^{(0)}(x_1, x_2; E_x) + \frac{1}{\hbar}\int dx dx'\, \Pi^{0}(x_1, x; E_x) \times \tilde{V}(x, x')\, \Pi^{(RPA)}(x', x_2; E_x)$$



- The Skyrme (SkE2) nucleon-nucleon interaction, which was used in the HF calculations, is also used to perform CRPA calculations. That makes this approach self-consistent.

Comparison with (e,e') data for ^{12}C, ^{16}O, ^{40}Ca

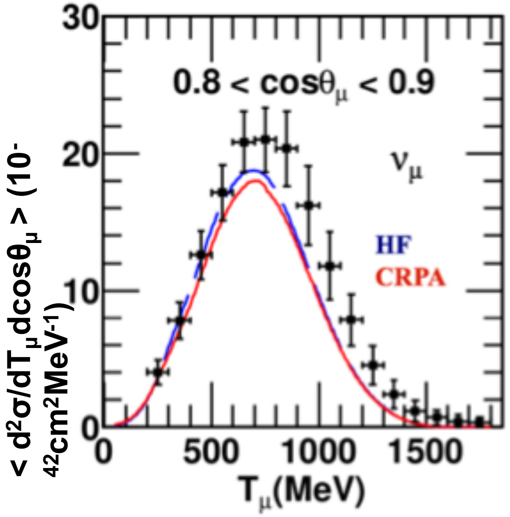
VP, N. Jachowicz, PRC 92, 024606 (2015)



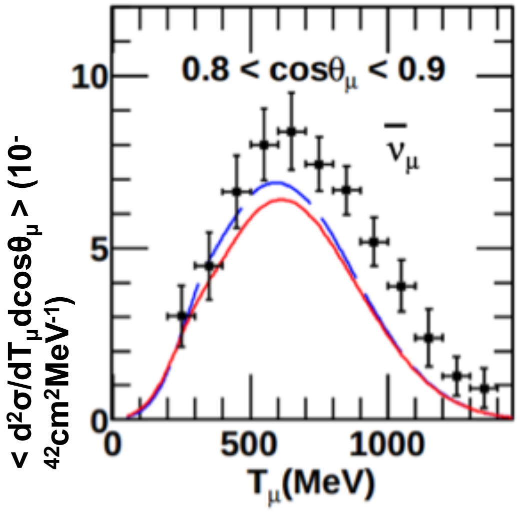
Comparison with neutrino data

VP, N. Jachowicz, PRC 94, 054609 (2016)

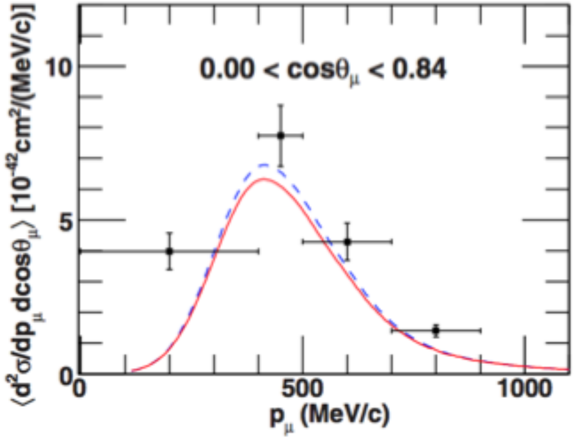
MiniBooNE DATA



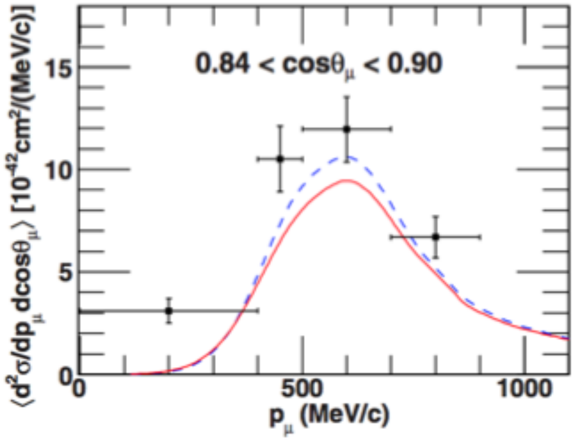
MiniBooNE DATA

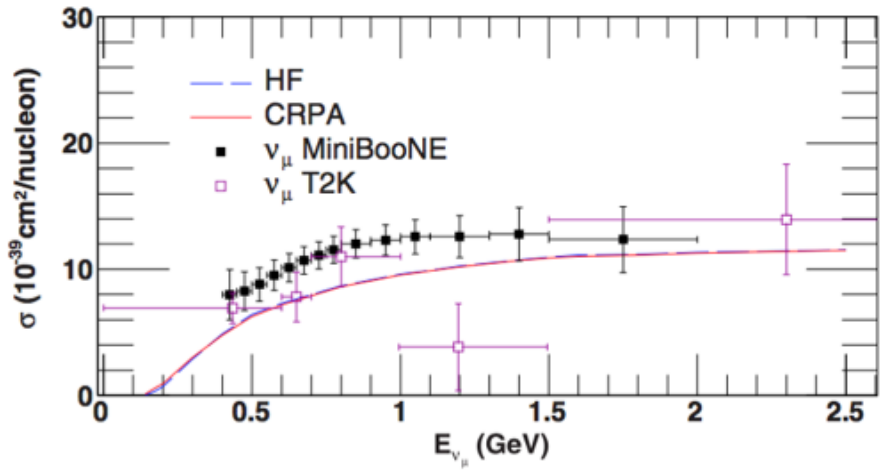


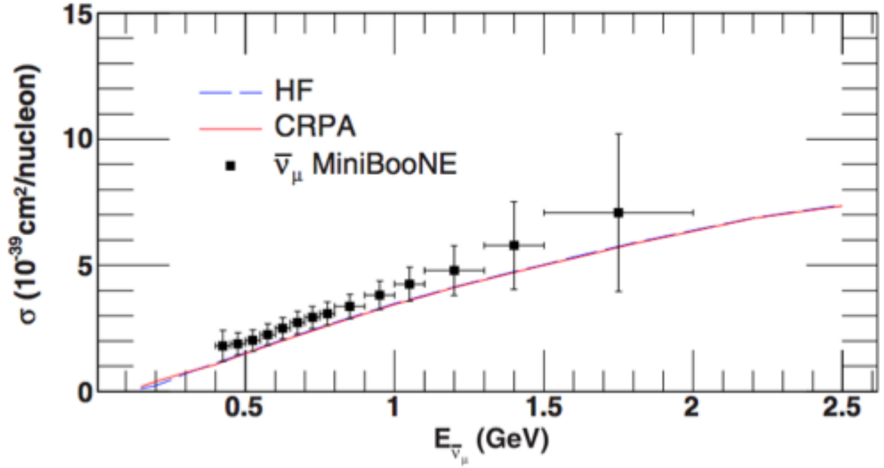
T2K ND280 DATA



T2K ND280 DATA







Comparing RPA-based models

RPA polarization propagator: $$\Pi = \Pi^0 + \Pi^0\, V\, \Pi$$

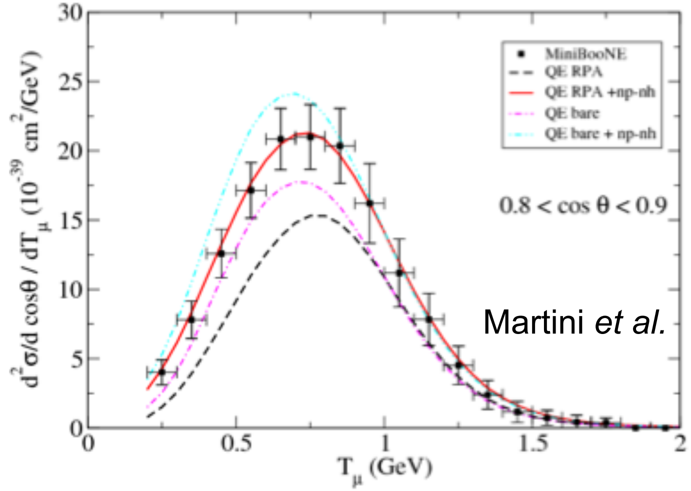
Comparing RPA-based models

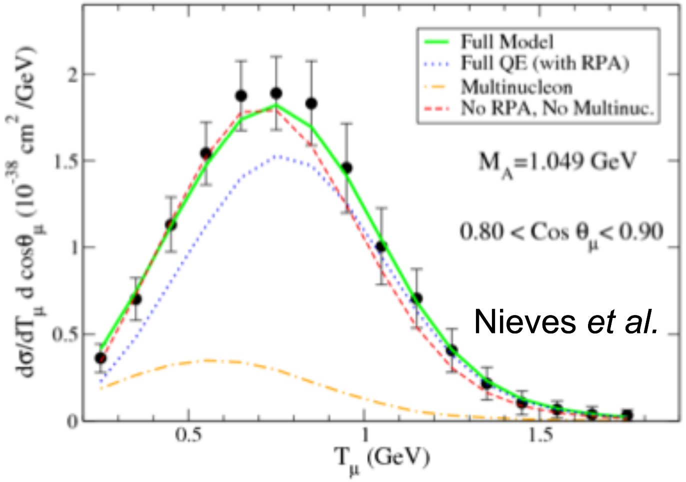
RPA polarization propagator: $$\Pi = \Pi^0 + \Pi^0 \, V \Pi$$

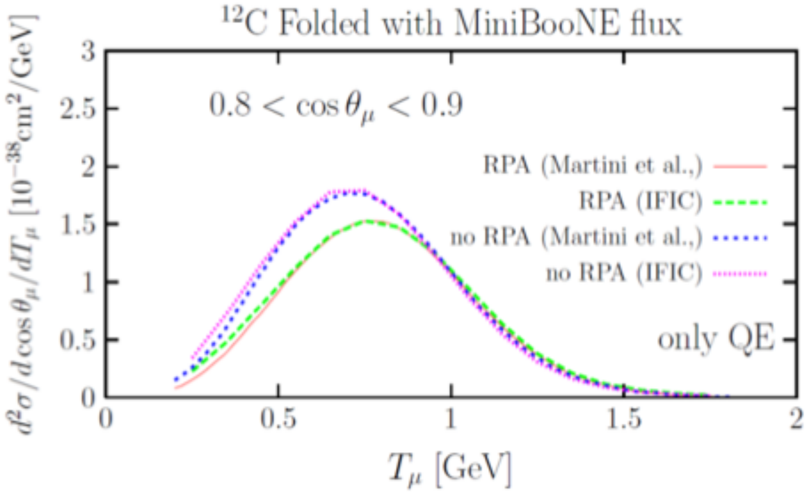
[Martini *et al.* and Nieves *et al.*]

Bare Propagatoor (RIFG)

π exchnage, ρ exchnage, contact Landau-Migdal parametrs







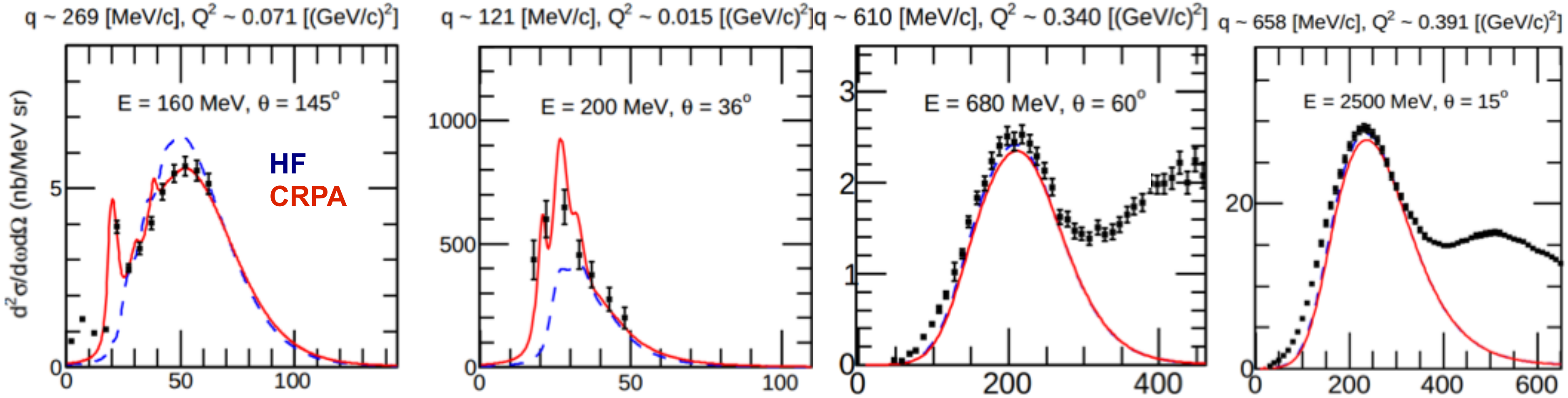
- Significant RPA quenching in both approaches.
- Genuine QE bare (RIFG) and RPA very similar in both approaches.

RPA polarization propagator: $\Pi = \Pi^0 + \Pi^0 V \Pi$

HF

Skyrme (SkE2)

[Pandey, Jachowicz *et al.*]



VP, N. Jachowicz, PRC 92, 024606 (2015)

- At low ω, RPA (long-range correlations) describes the collective behavior of the nucleus (low-energy excitations)
- At high ω, RPA effects are smaller.
- Approach compares well with the (e,e') cross section.

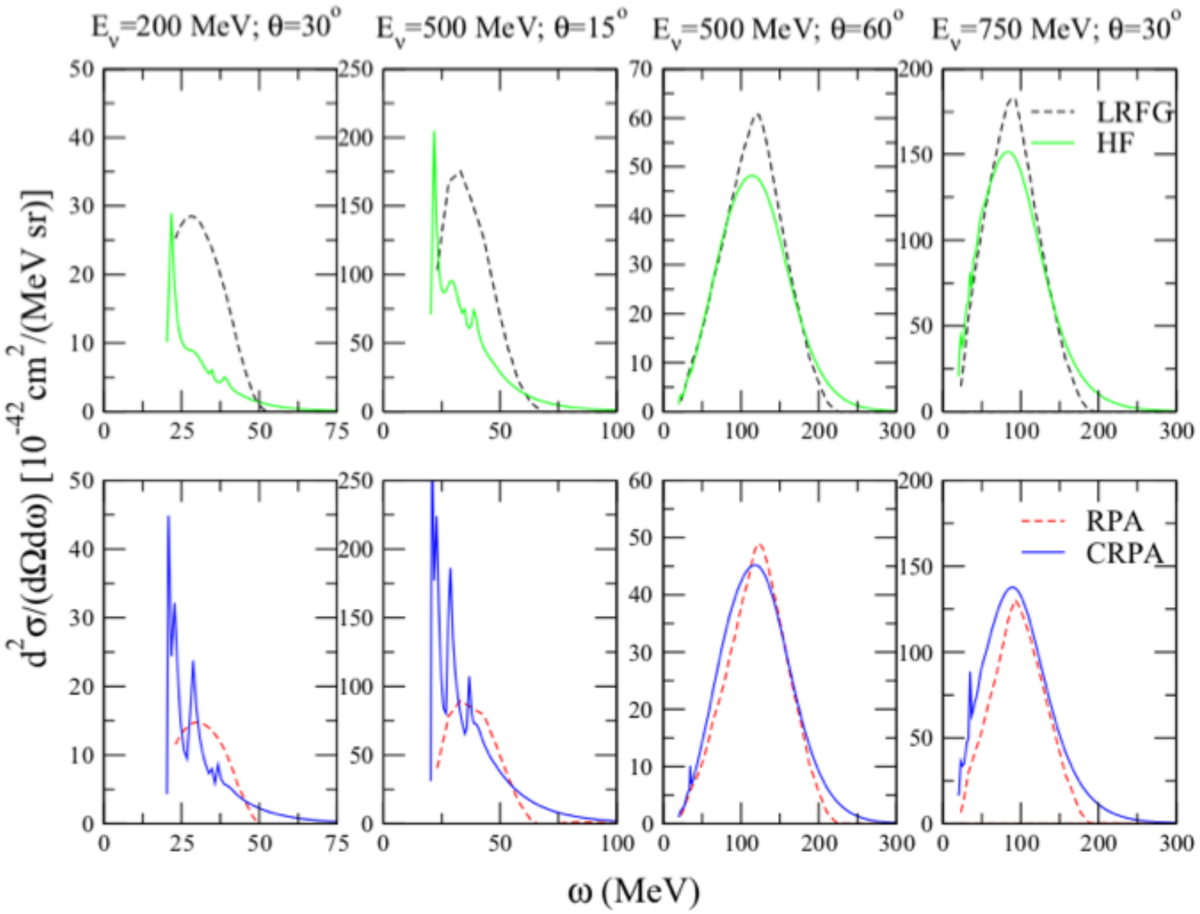
Comparing RPA-based models

For more details: M. Martini, N. Jachowicz, M. Ericson, and VP *et al., PRC 94, 015501 (2016)*

LRFG, RPA: Martini, Ericson *et al.*
HF, CRPA: Pandey, Jachowicz *et al.*

- Important differences at both ends of the spectrum

→ Low-energy excitations at low ω
→ High ω tail



Comparing RPA-based models

Model	Starting point	N-N interaction	Shell effects	Low-energy excitations & Giant resonances	RPA effect
Martini, Ericson *et al.*	Local Fermi Gas	Meson -exhange (π,ρ,g')	No	No	Significant suppression (LLEE effect*)
Nieves *et al.*	Local Fermi Gas	Meson -exhange (π,ρ,g')	No	No	Significant suppression (LLEE effect*)
Pandey, Jachowicz *et al.*	Hartree-Fock	Skyrme	Yes	Yes	Describes low ω physics, not much effects at higher ω

- Significant differences between RPA and CRPA approach, at both ends of the (one-body) ω spectrum.

*Lorentz-Lorentz-Ericson-Ericson effect: accounts for the possibility of a Δ-hole excitation in the RPA chain

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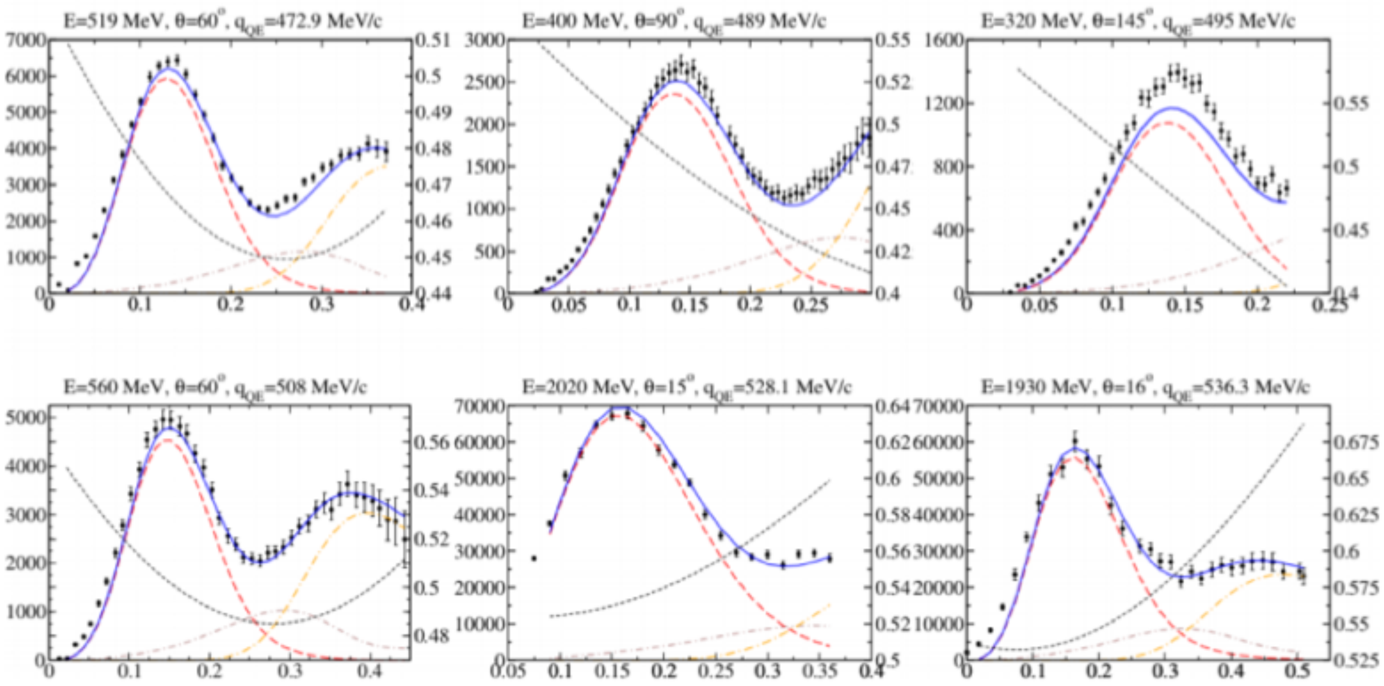
- …, *etc.*

- **Super-Scaling Approach [SuSA]** [Amaro, Barbaro, Caballero, Donnelly, Megias, *et al.]*

  - The basic procedure consists of dividing the experimental (e,e’) data by an appropriate single-nucleon cross section to obtain scaling function.
  - Nuclear effects are analyzed through the scaling function.
  - Scaling of 1st kind – independent of q.
  - Scaling of 2nd kind – independent of A.
  - The Super-scaling behavior of (e, e’) scattering is extended to neutrino scatterings.

$\Rightarrow$ SuperScaling



(e,e') data on ^{12}C

Megias *et al*, PRD 94, 013012 (2016)

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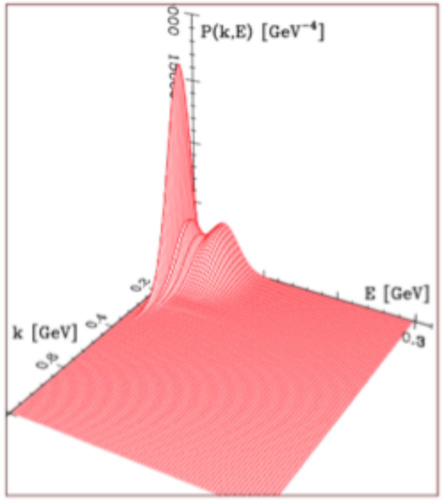
- …, *etc.*

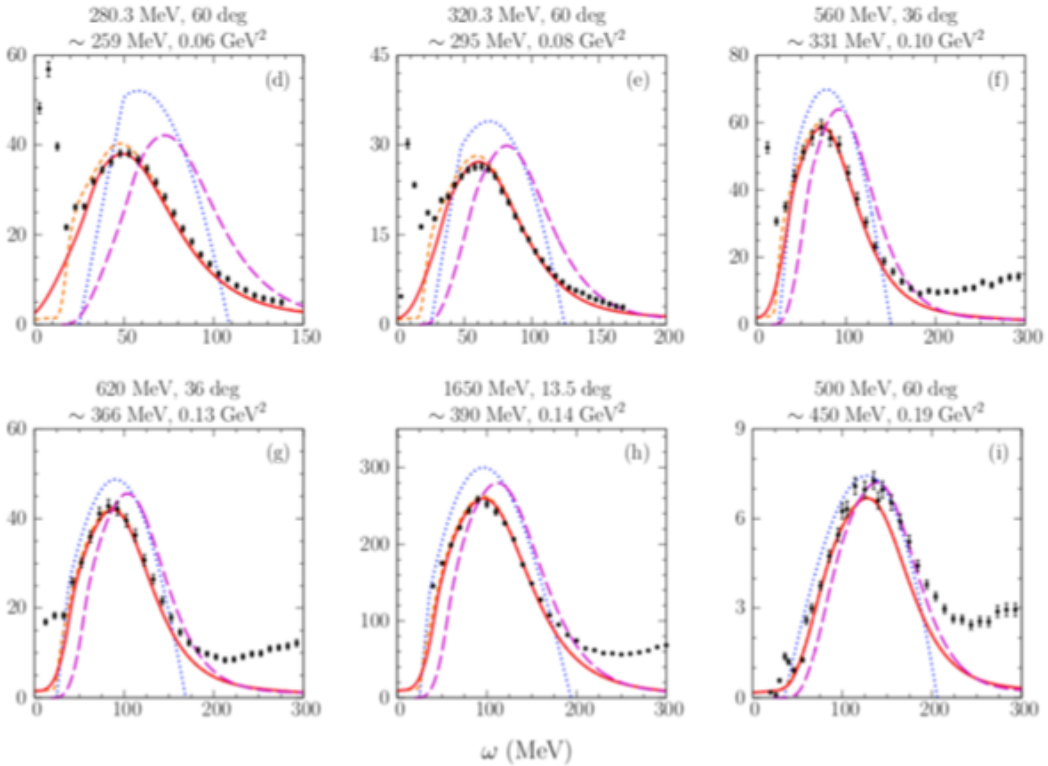
- **Spectral Function** [Benhar, *et al.]*

- Within the impulse approximation and factorization ansatz, the nuclear current can be written as a sum of one-body currents

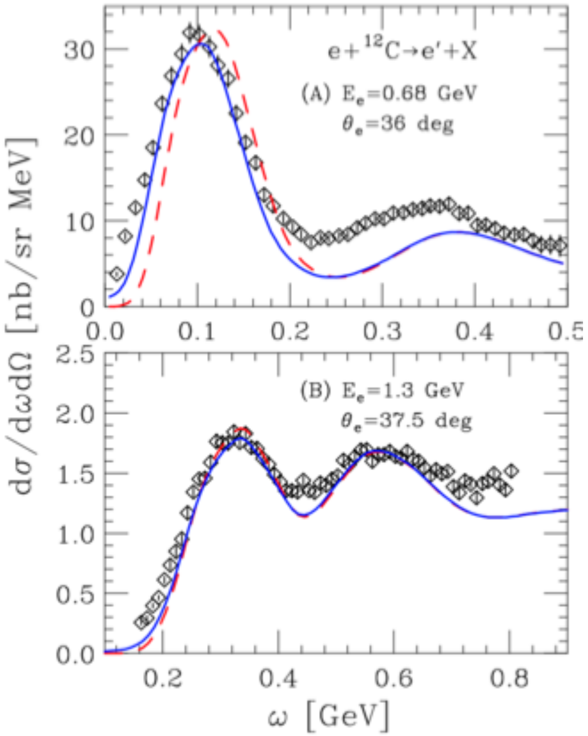
$$J^\mu \to \sum_i j_i^\mu,$$

$$\frac{d^2\sigma_{IA}}{d\Omega_\mu dE_\mu} = \int d^3k\, dE\, P(\mathbf{k}, E)\, \frac{d^2\sigma_{\nu N}}{d\Omega_\mu dE_\mu}$$





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

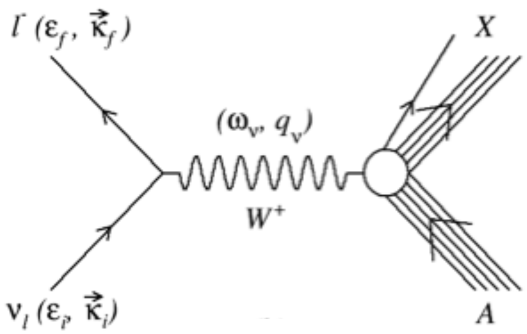


(e,e') data on ^{12}C

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

Impact of low energy excitations

Inclusive ν-A scattering



- **Excitation energy (ω):**

  Energy transferred from the incoming neutrino to the nucleus

  $\omega = \varepsilon_i - \varepsilon_f = E_\nu - E_l$

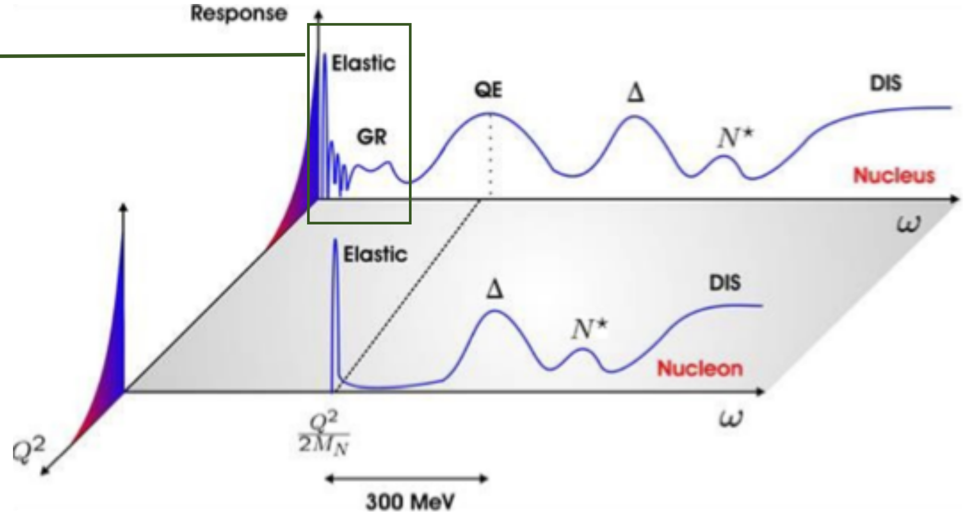
- **Typical cross section as a function of ω:**

- **Low (excitation)-energy neutrino cross sections**

Physics before QE process (typically for ω < 50 MeV) i.e. when the energy transferred to the nucleus is not enough to knock-out a nucleon

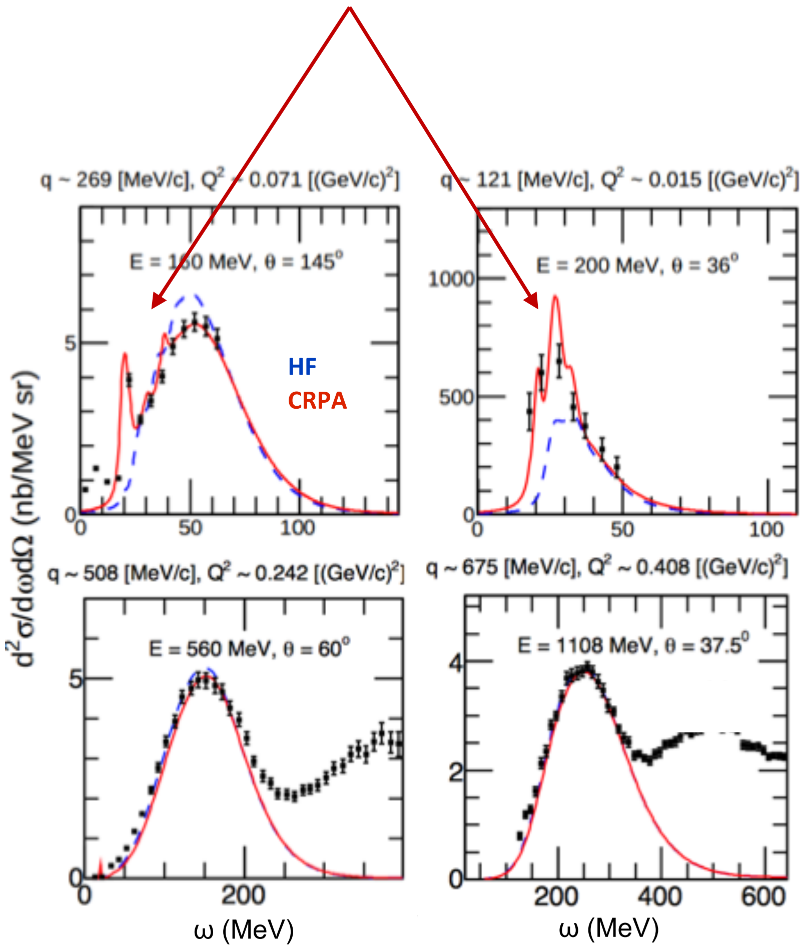
Low-energy excitation and Giant Resonances

Details of nuclear structure physics



Impact of low energy excitations

- **<u>Physics well known from electron scattering</u>:** Example from ^{12}C (e,e') reactions



VP, N. Jachowicz, Phys. Rev. C92, 024606 (2015)

Impact of low energy excitations

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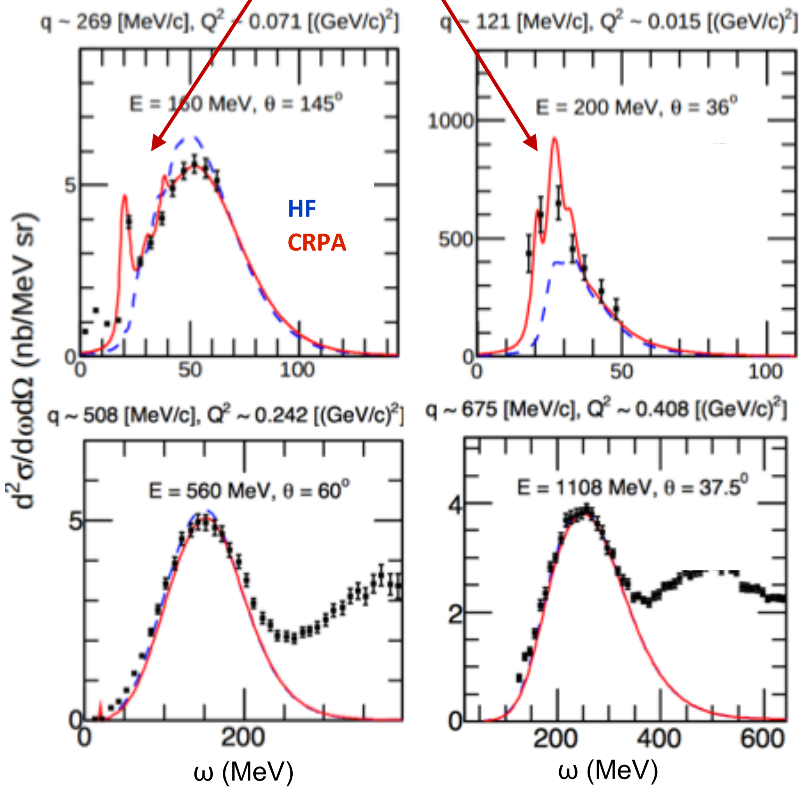
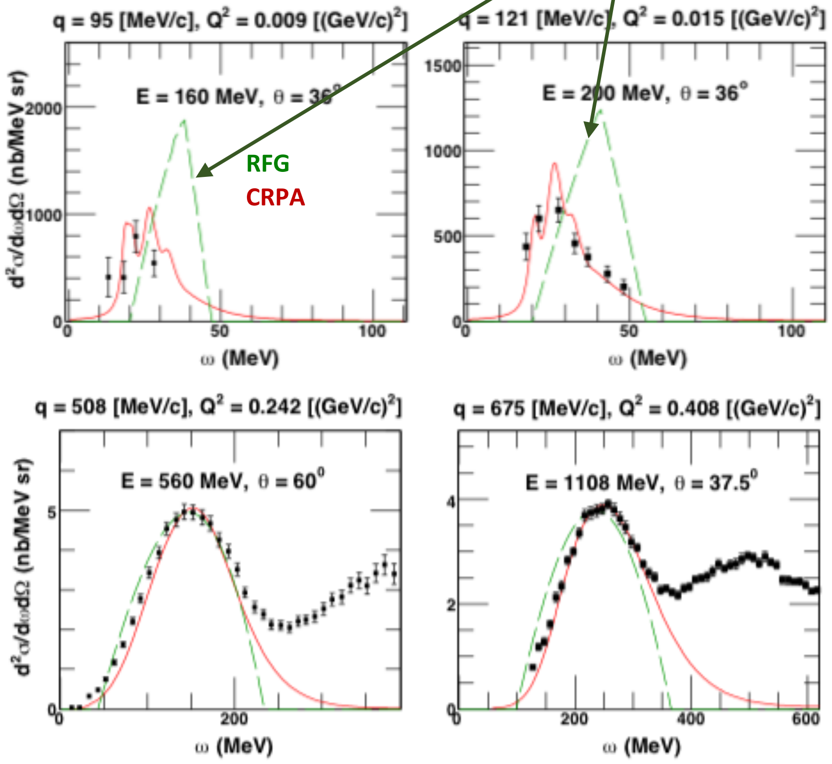


VP, N. Jachowicz, Phys. Rev. C92, 024606 (2015)

- Searching these effects with **Relativistic global Fermi Gas** glasses
  (Parabolic structure abruptly cut by Pauli-blocking)



- In neutrino experiments, we don't know ω, so let's look at things through outgoing lepton kinematics.
  For a given neutrino energy E_ν , cross sections as a function of muon energy T_μ , and scattering angle θ_μ . ($T_\mu = E_\nu - \omega$)

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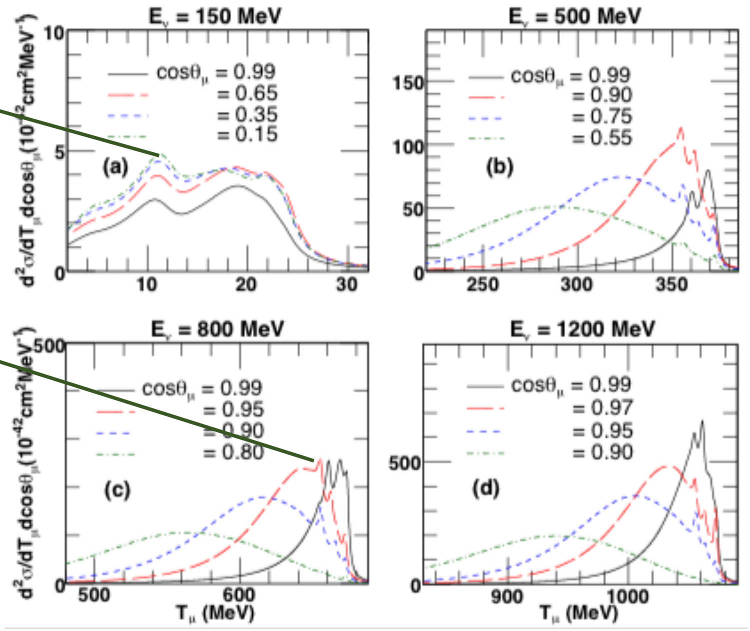
  - Low E_ν : cross section is dominated by low-energy excitations.

  - E_ν = 800 MeV: energy close to the peak of MicroBooNE flux, forward scattering receive contribution from low-energy excitations.



VP, N. Jachowicz et al, Phys. Rev. C92, 024606 (2015)

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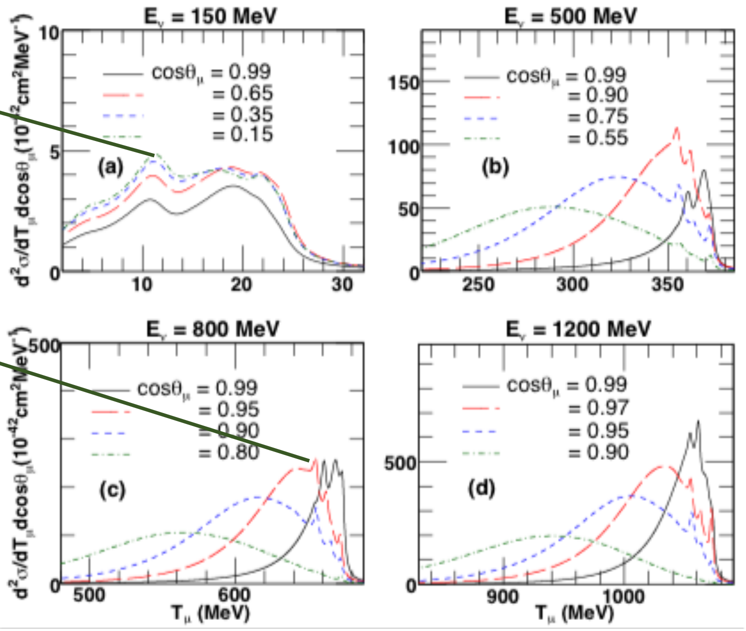

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- E_ν = 800 MeV: energy close to the peak of MicroBooNE flux, forward scattering receive contribution from low-energy excitations.

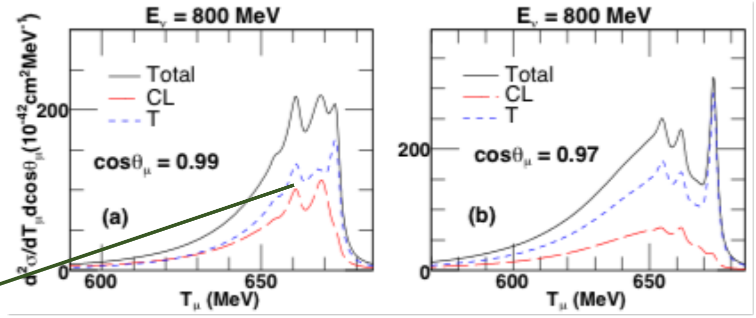
- **A bit more detail:**

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

Coulomb-longitudinal (CL)

Transverse (T)

$$\sigma^J_{CL,\nu} = \left[v^{\mathcal{M}}_\nu R^{\mathcal{M}}_\nu + v^{\mathcal{L}}_\nu R^{\mathcal{L}}_\nu + 2\,v^{\mathcal{ML}}_\nu R^{\mathcal{ML}}_\nu\right] \qquad \sigma^J_{T,\nu} = \left[v^T_\nu R^T_\nu \pm 2\,v^{TT}_\nu R^{TT}_\nu\right]$$



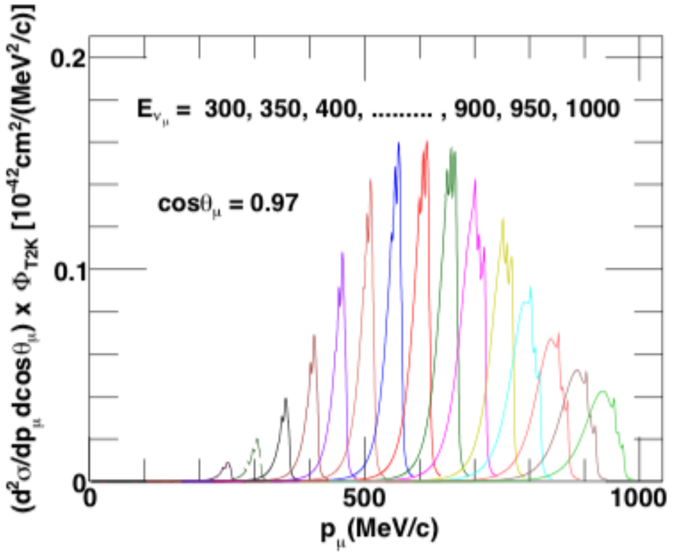
- We know that in general neutrino cross sections are dominated by Transverse contribution.
- The forward we go in scattering angle, for instance at energies ~ 800 MeV, the longitudinal contribution starts competing with the transverse one.

VP, N. Jachowicz et al, Phys. Rev. C92, 024606 (2015)

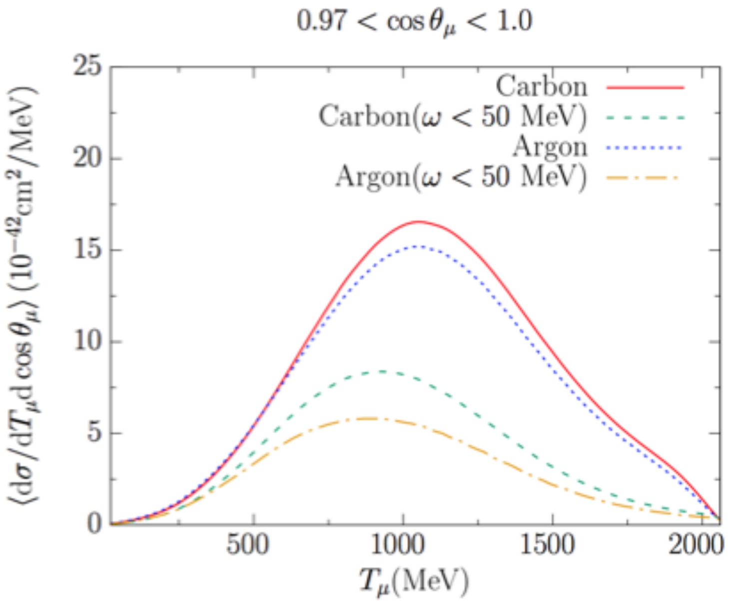
What about flux folded cross sections?

- Cross sections (on ^{12}C) for a fixed $\cos\theta_\mu = 0.97$ and for fixed neutrino energies from 300 MeV to 1000 MeV, weighted with the T2K ν_μ flux and plotted as a function of p_μ.

- After integrating over energies (with a fine mesh), the peaks disappear but the significant contributions of low-energy excitations ($\omega < 50$ MeV) stays.



VP, N. Jachowicz et al., Phys.Rev. C94, 054609 (2016).

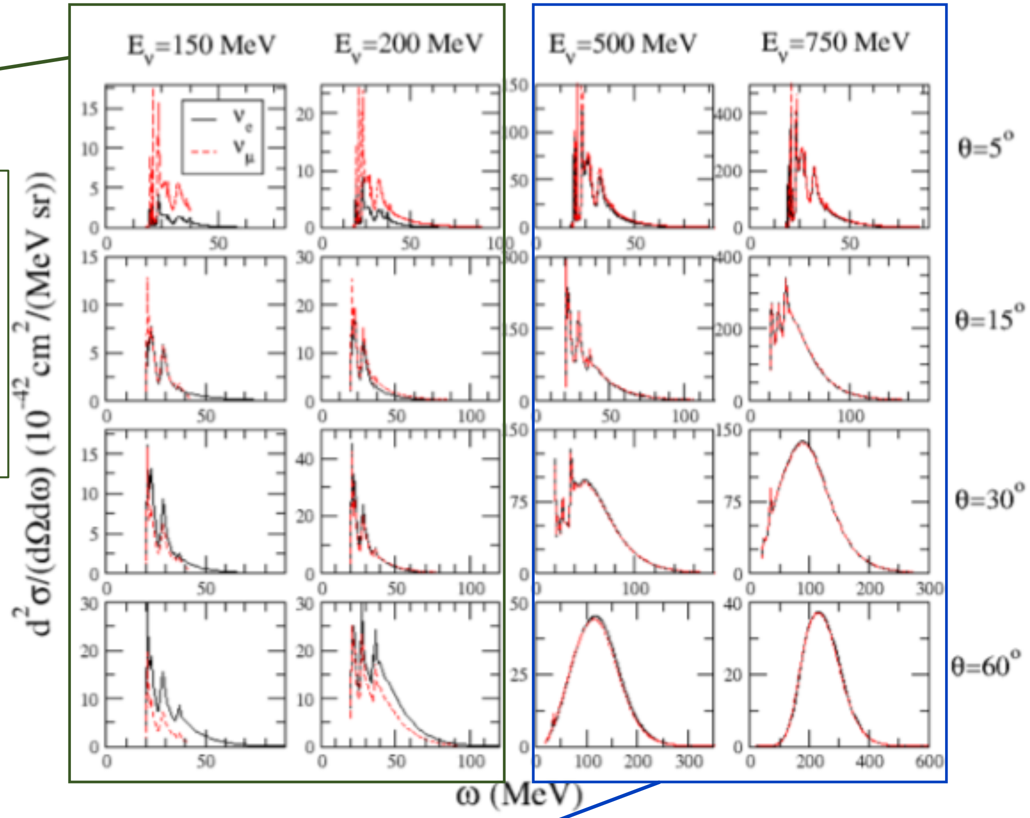


- BNB flux-folded cross section on ^{12}C and ^{40}Ar. A significant amount of contribution comes from $\omega < 50$ MeV effects.

N. Van Dessel, N. Jachowicz, R. González-Jiménez, VP et al, Phys.Rev. C97, 044616 (2018).

What about ν_e *vs* ν_μ?

- The only difference between $\boldsymbol{\nu_\mu}$ and $\boldsymbol{\nu_e}$ cross sections is the mass of the outgoing lepton. But the mass affects the three momentum transfer (q) which eventually enters into the kinematics as well as the dynamics of the nuclear model (nuclear response functions are the functions of q and ω).



- At low energies:
  - For small scattering angles, such as 5^0, ν_μ cross sections are higher than the ν_e ones.
  - For larger scattering angles, such as 60^0, this behavior is opposite.
  - At intermediate angles, the two cross sections are closer to each other.

M. Martini, N. Jachowicz, M. Ericson, VP et al. , Phys. Rev. C94, 015501 (2016)

- At E_ν = 500 MeV:
  - This above angular behavior weakly survives.
- At E_ν = 750 MeV:
  - both cross sections practically coincide for all the scattering angles.

What about ν_e *vs* ν_μ?

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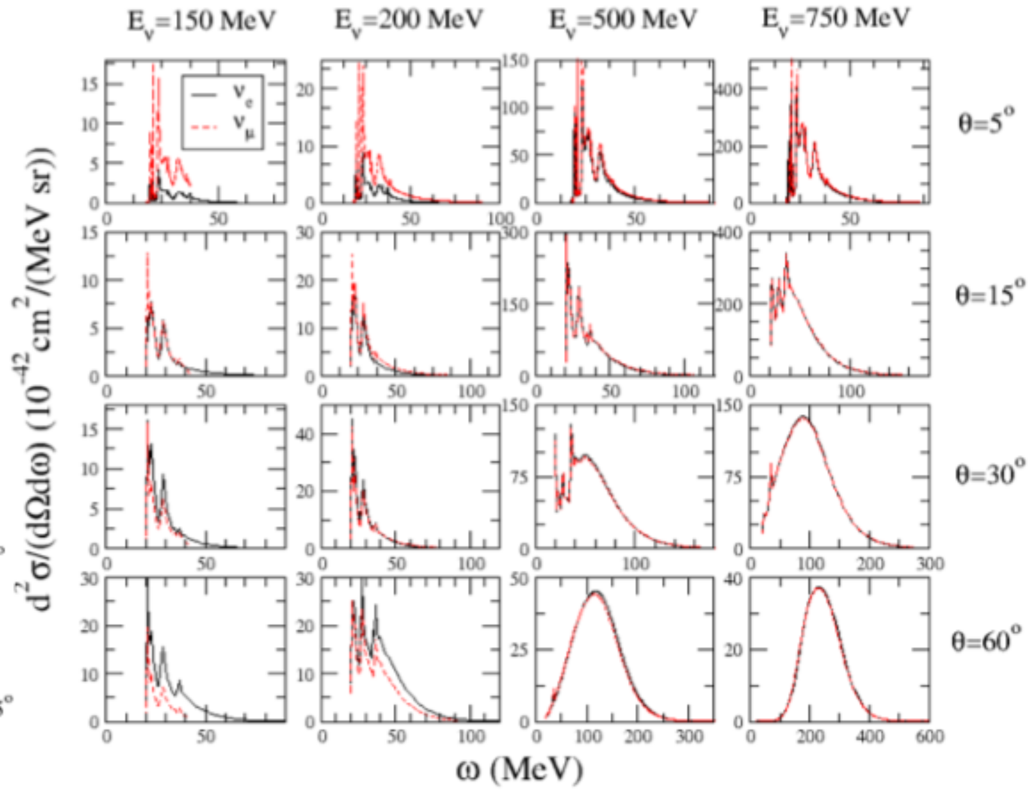
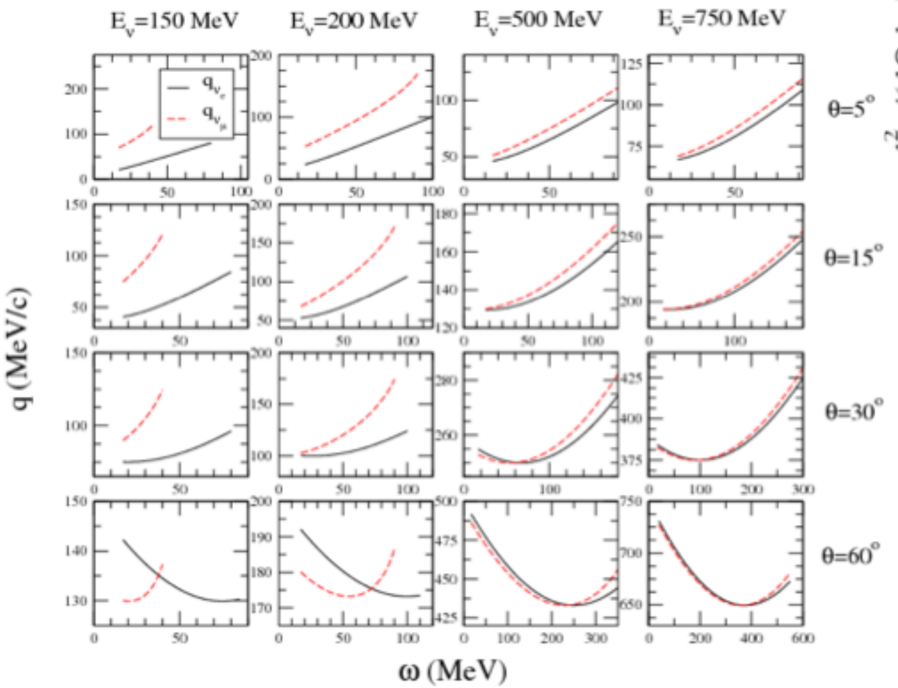


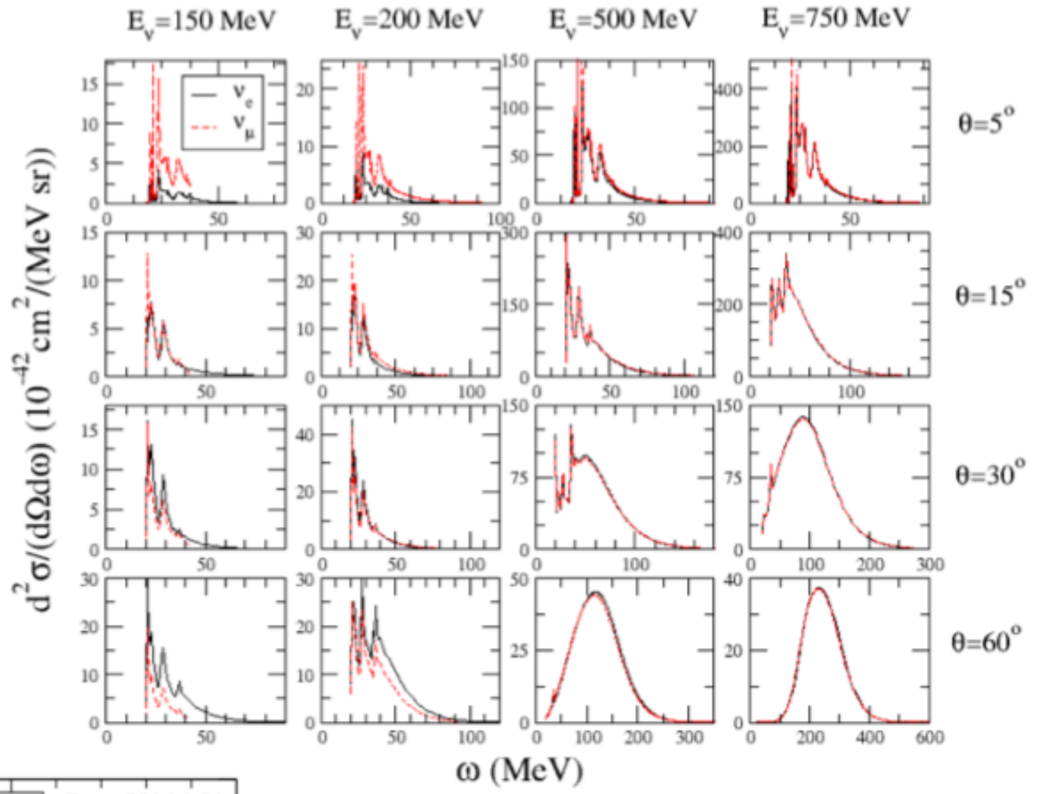
- Looking at q vs ω for all 16 panels
  - As expected, the major differences between ν_μ and ν_e appear at small neutrino energies.



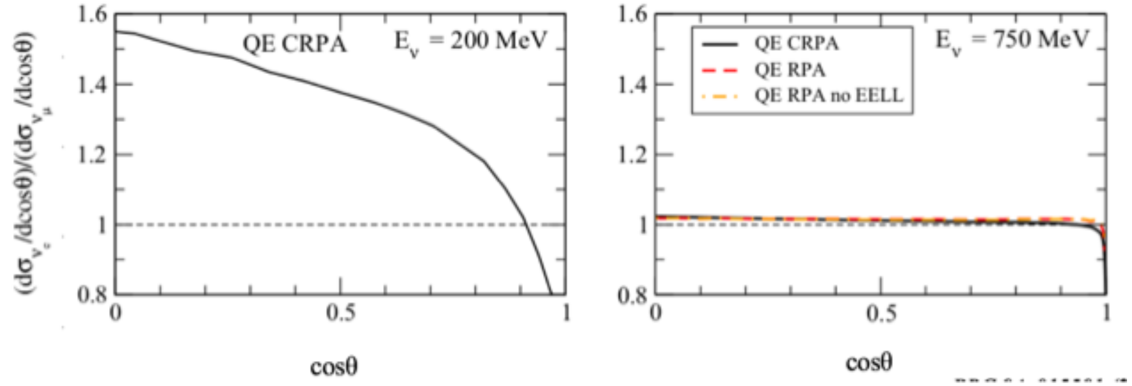
M. Martini, N. Jachowicz, M. Ericson, VP et al. , Phys. Rev. C94, 015501 (2016)

- **What about ν_e *vs* ν_μ?**
  - The only difference between ν_μ and ν_e cross sections is the mass of the outgoing lepton. But the mass affects the three momentum transfer (q) which eventually enters into the kinematics as well as the dynamics of the nuclear model (nuclear response functions are the function of q and ω).

- Integrating 2nd and 4th column over ω and plotting ratio of ν_e *vs* ν_μ cross section as a function of cosθ
  - At 200 MeV, the ratio varies significantly from 1.
  - At 750 MeV, the ratio is almost 1 (black line, ignore the other two curves).



M. Martini, N. Jachowicz, M. Ericson, VP et al. , Phys. Rev. C94, 015501 (2016)



Summary

- Precision level measurements at neutrino experiments rely greatly on an accurate description of the target nucleus and its electroweak response.

- The problem is multifold – understanding and identifying different neutrino-nucleus interactions type, reconstructing neutrino energy and calculating cross sections accordingly.

- Modeling many-body nuclear systems and their electroweak response, for the broad range of energies covered in neutrino experiments, is difficult but there are many approximate methods.

- The tested and validated models should enter into Monte-Carlo codes and should be used in the description of the experimental data.

- Let’s hope for the best!