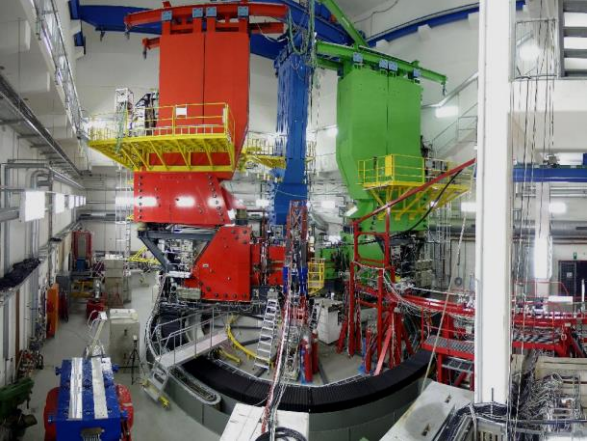
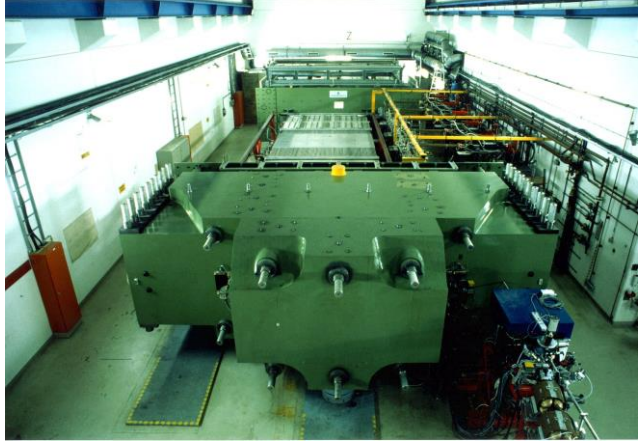
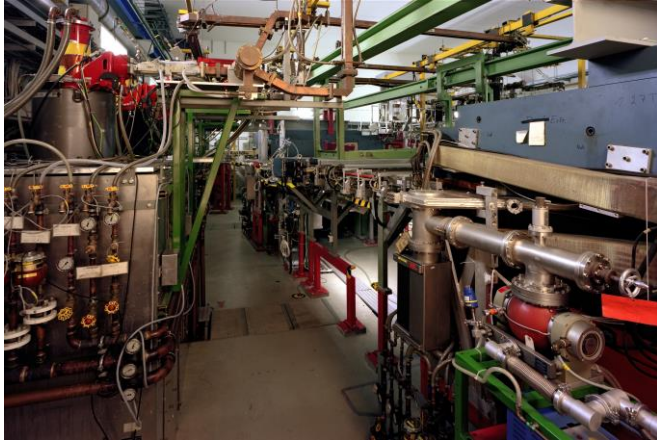




Quasielastic experiments with ^{12}C and ^{16}O

Miha Mihovilovič and Luca Doria
for A1-Collaboration

PAC 2020

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

JG|U

SLOVENIAN RESEARCH AGENCY

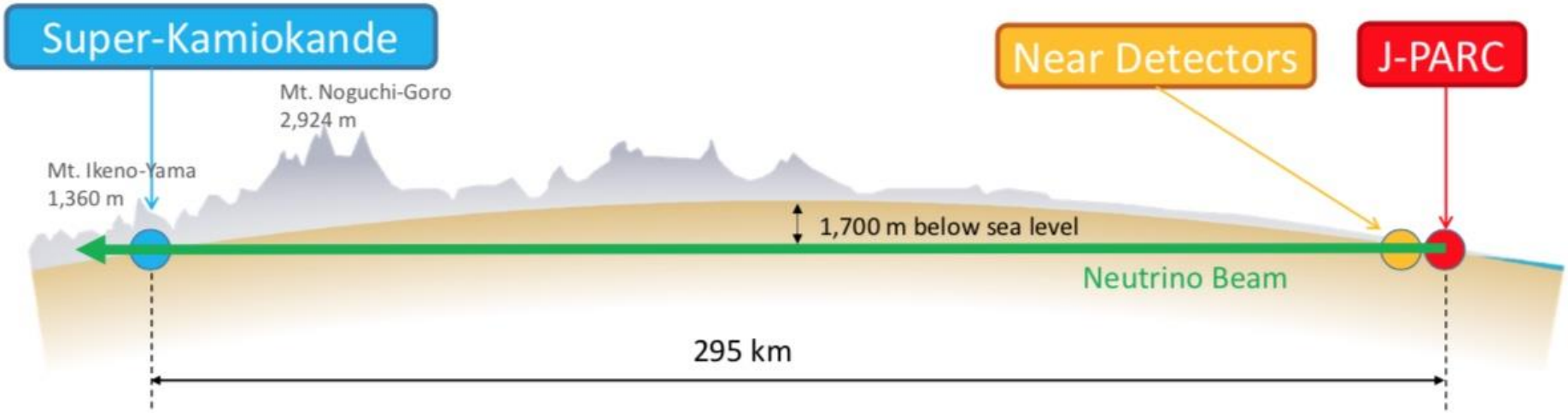
We are proposing ...

- Precision electron-induced scattering experiment on oxygen and carbon.
- Measurement of inclusive cross-sections in quasi-elastic and delta resonance.

- Study the nuclear structure and validate existing theories.
- **Quenching of the Coulomb sum rule**.
- **Provide new input to deficient existing models employed to interpret signals detected in accelerator-based neutrino experiments.**

Motivation –T2K

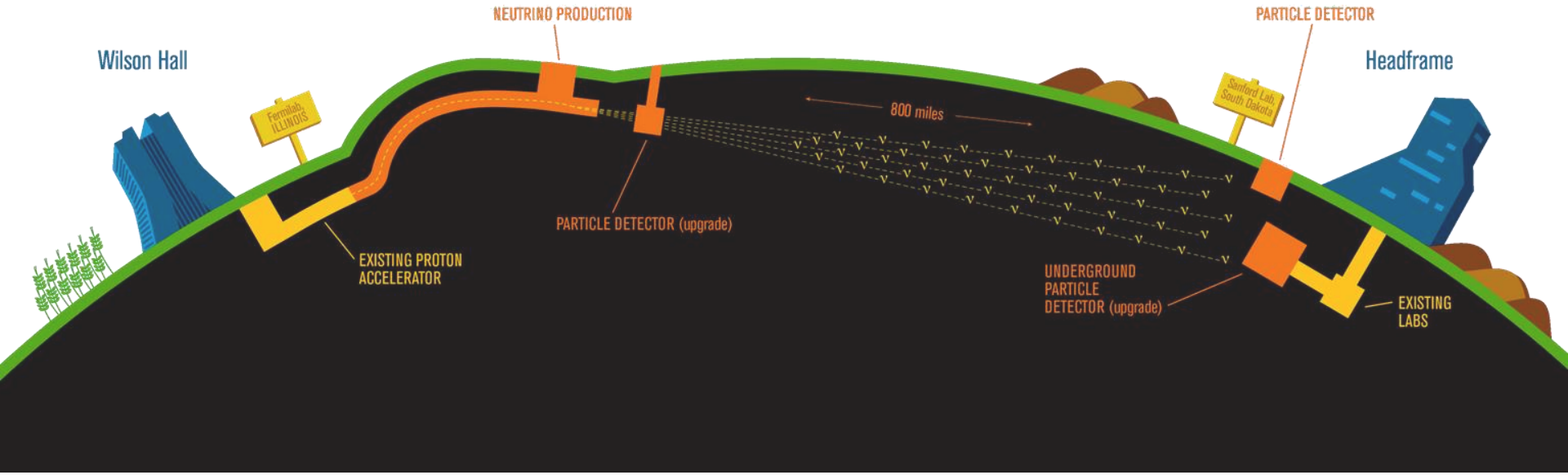
- T2K provided most precise measurement of θ_{23} and constraints on δ_{CP} .



	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}

Motivation - DUNE

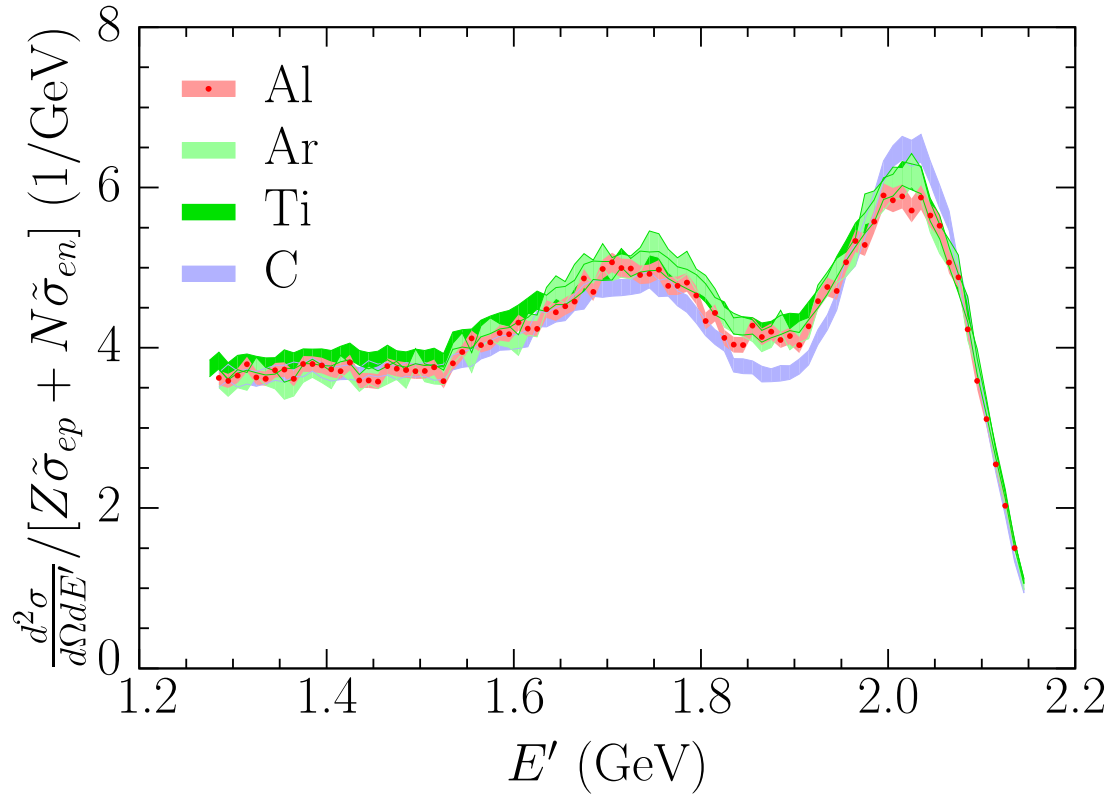
- DUNE for even more precise measurement of θ_{23} and δ_{CP} .



	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}

Motivation – E12-14-012

- Successful experiment performed at Jefferson Lab.
- Inclusive (and exclusive) data collected for C, Al, Ar, Ti targets at 2.2 GeV and 15.5º.



- Experiment confirmed approximate scaling.

Neutrino oscillations

- The properties of neutrinos determined through the measurement of probability of flavor oscillation:

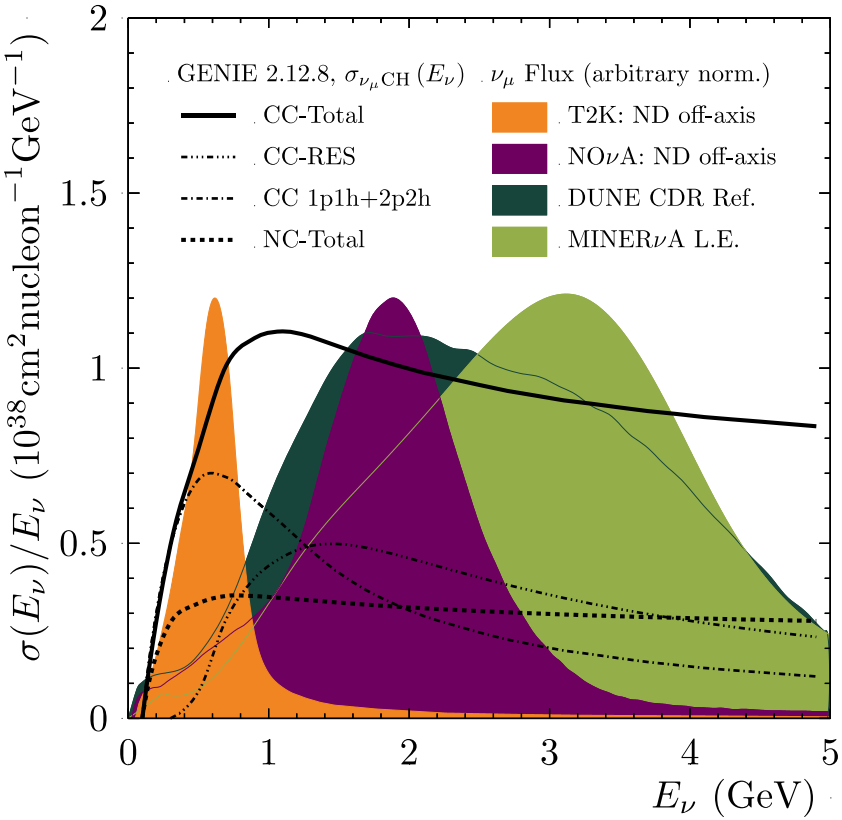
$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- The probability is maximized, when:

$$E \approx \frac{\Delta m^2 L}{(4n+2)p}$$

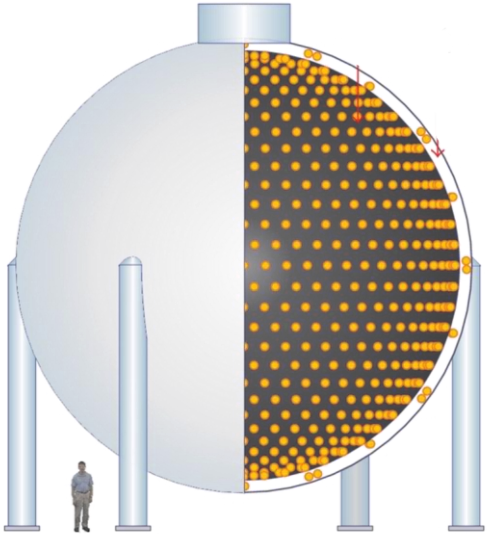
- The amplitude of the oscillation:

$$P_{\max} \mu \sin^2 2q$$

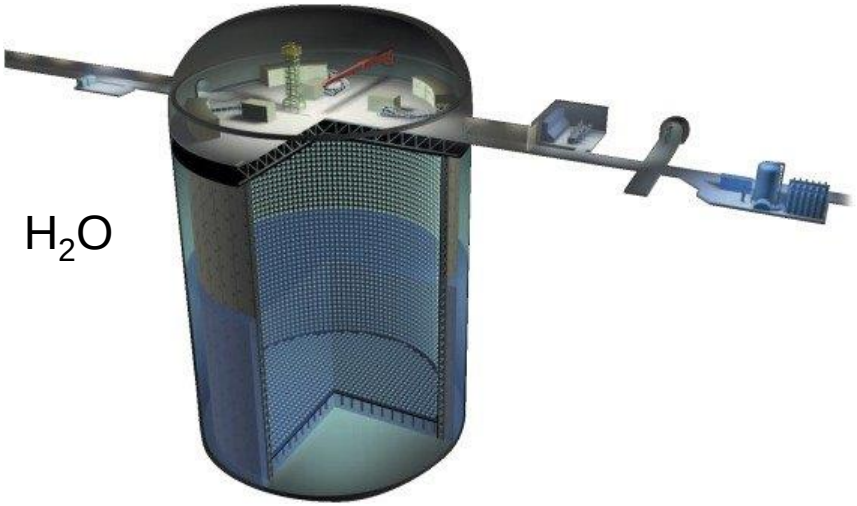


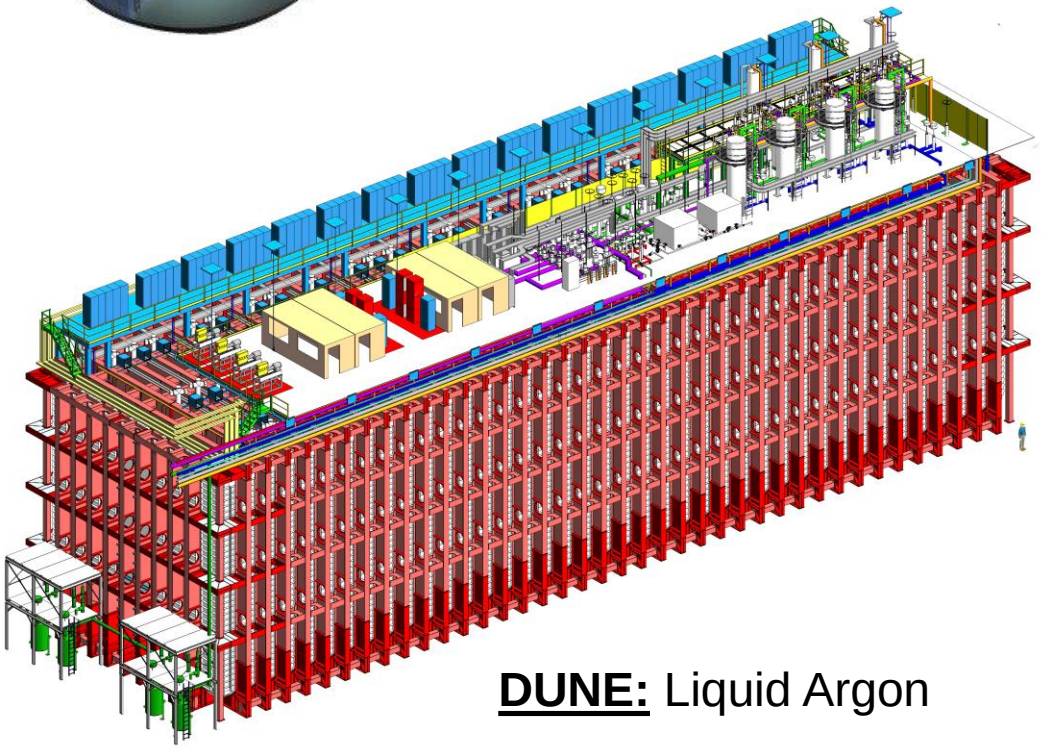
Detectors and detector medium

MiniBooNE: Mineral oil



T2K: H_2O

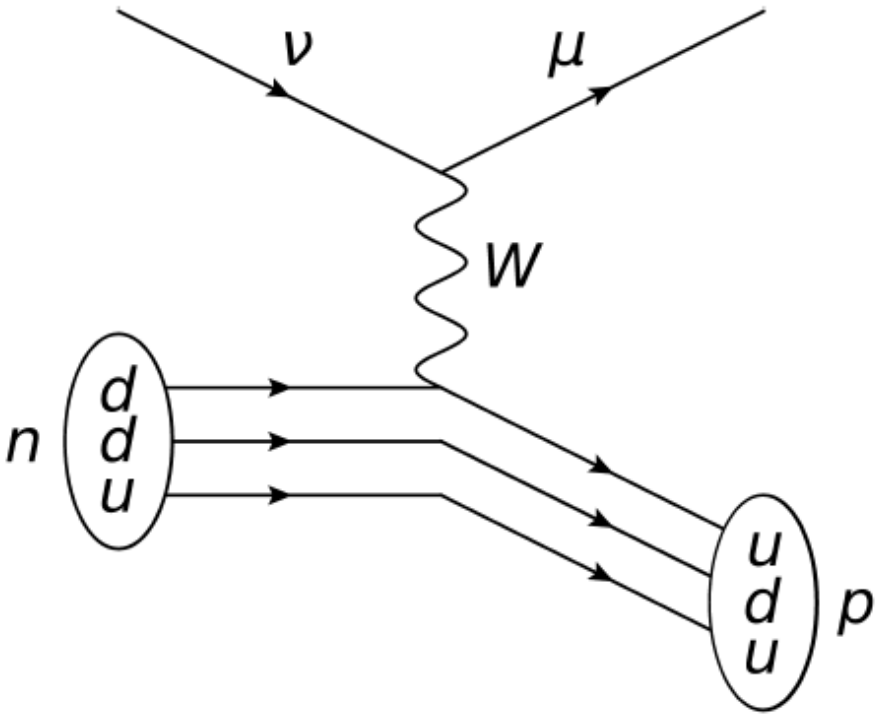


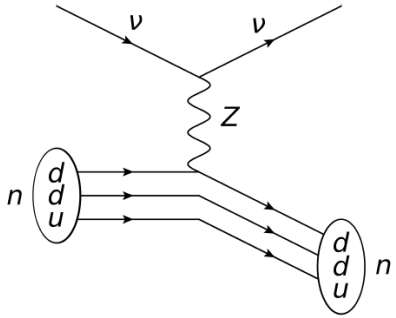


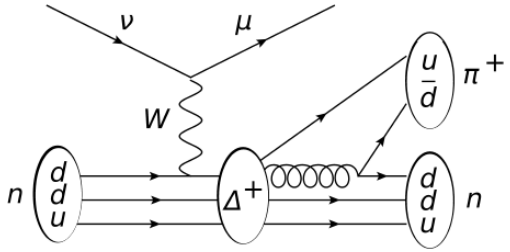
DUNE: Liquid Argon

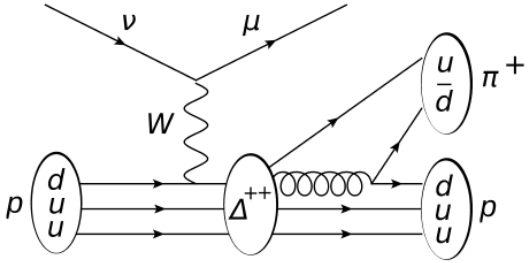
Interactions with neutrinos

- In detector neutrino interacts with nuclear medium predominantly through **CCQE**.
- Only final lepton is detected.
- Contributions of other processes are also present: NCQE, CCRES, …
- **Accompanying effects: FSI, SRC.**









Analysis of detected events

- Detected rates in the near and far detector:

$$N^{\alpha\to\beta}(\vec{p}_n) = \sum_i \Phi_\alpha(E_{True}) \cdot P_{\alpha\beta}(E_{True}) \cdot \sigma^i_\beta(\vec{p}_{True}) \cdot \varepsilon_\beta(\vec{p}_{True})$$

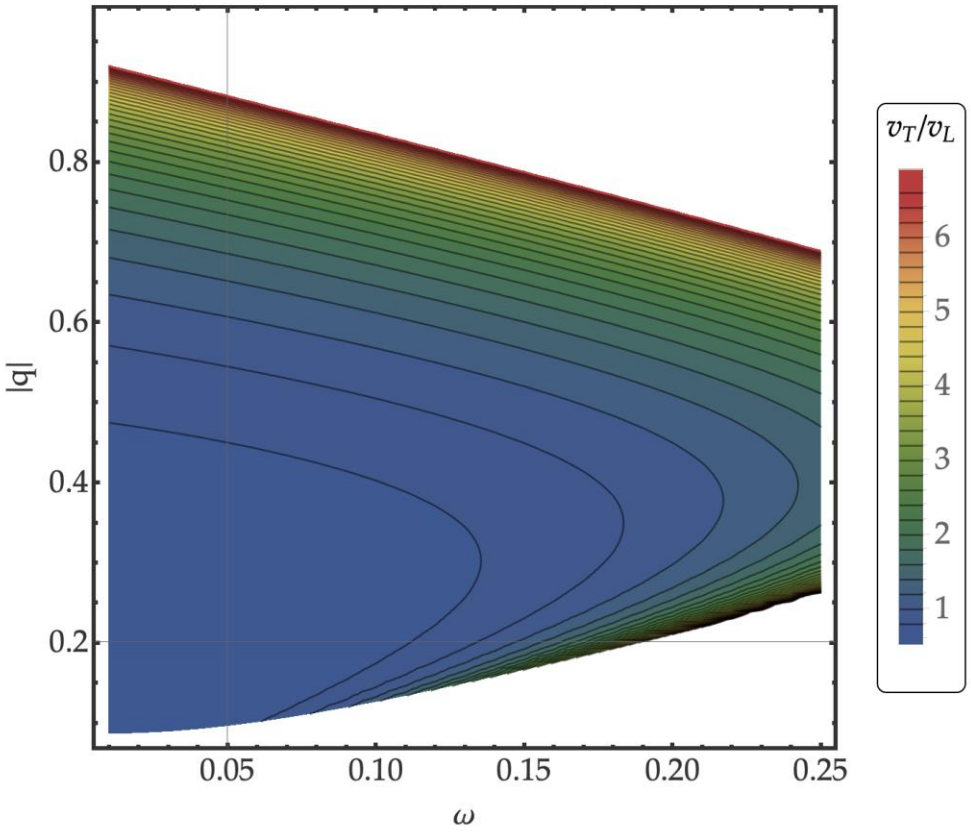
Important role of QE scattering of electrons from nuclei!

- **Energy reconstructed assuming specific process. Hit nucleon in nuclear medium not at rest!**
- **Precise input from theory is needed!**

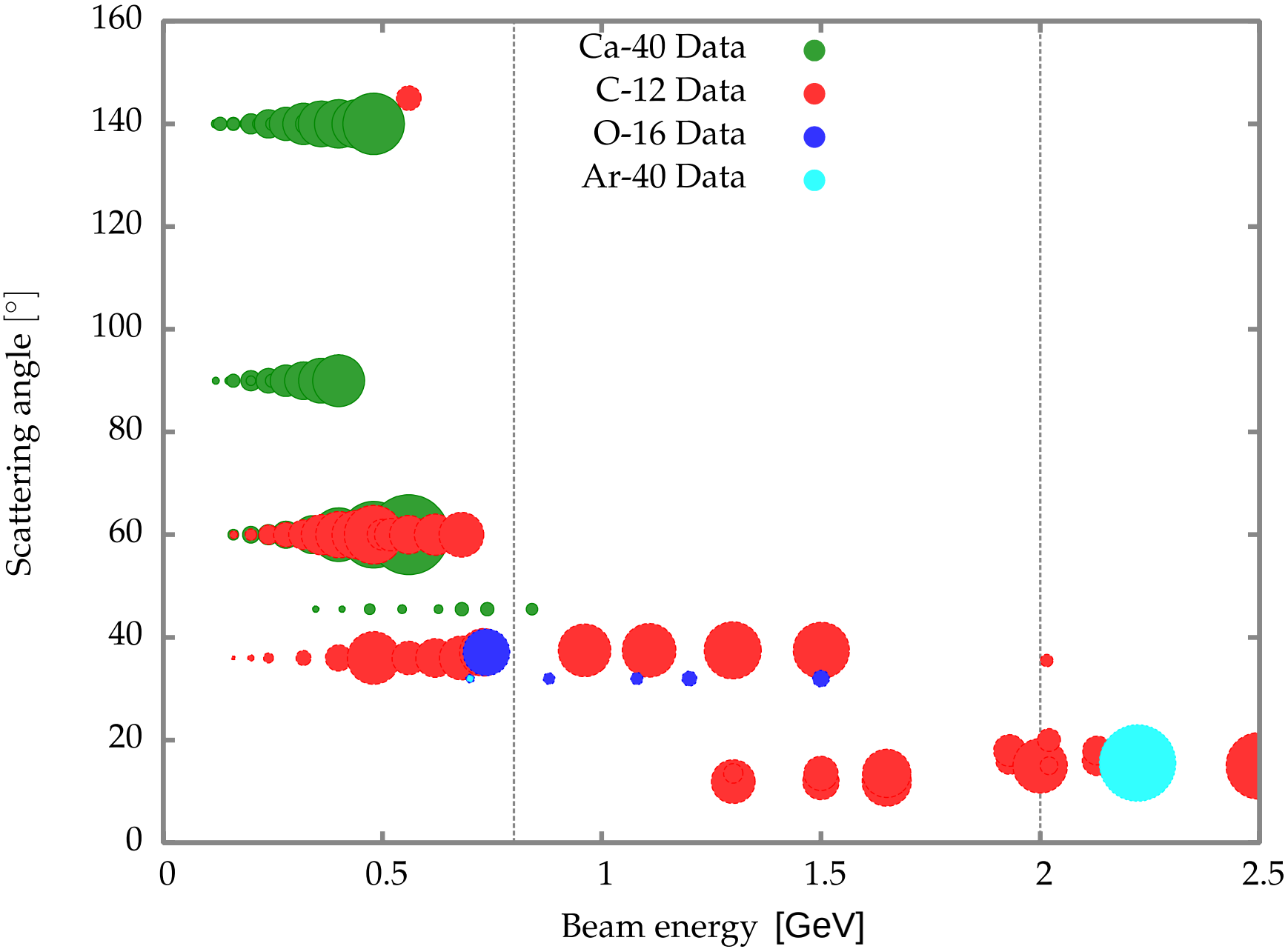
Inclusive quasi-elastic scattering

$$ds = ds_0 \cdot \left[v_L R_L + v_T R_T \right]$$

- Response $\mathbf{R_L}$ depends on transition charge density; sensitive to nucleon-nucleon correlations.
- Response $\mathbf{R_T}$ depends on magnetic currents; descripes dynamics on nucleons in nucleus.
- $\mathbf{R_L}$ dominates cross-sections at small scattering angles. $\mathbf{R_T}$ dominates large angle scattering.



Existing inclusive data



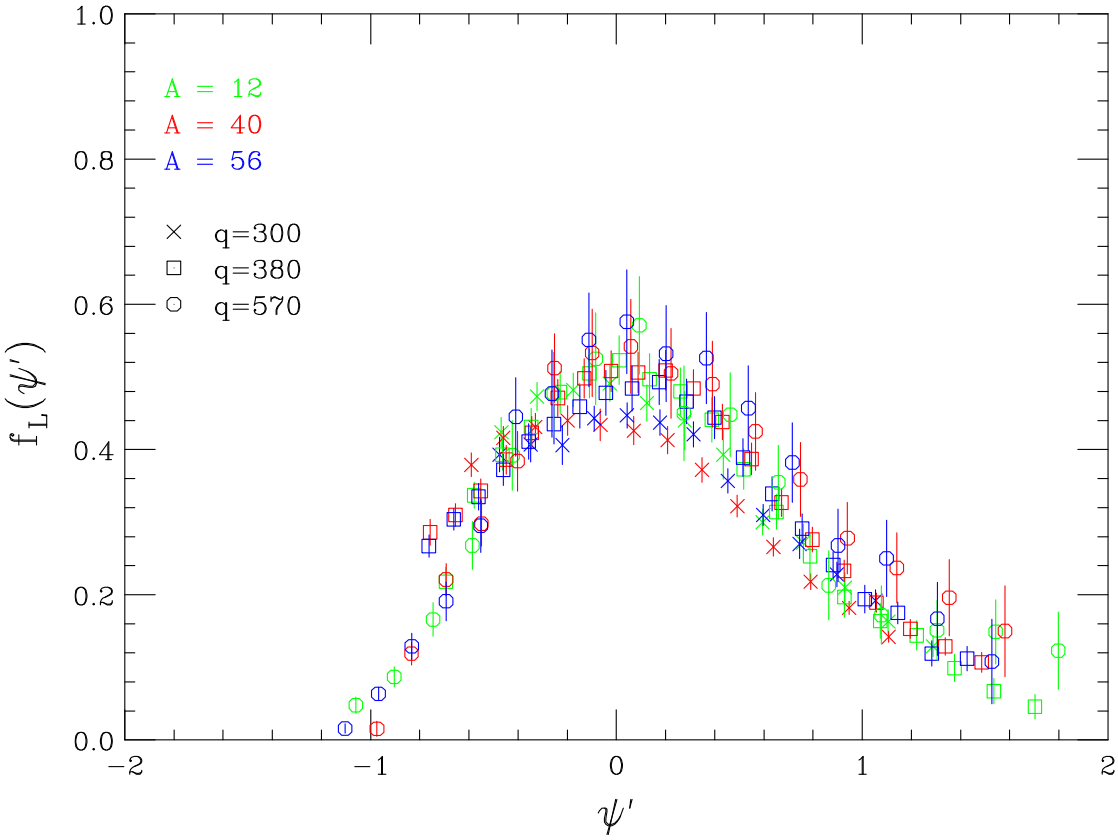
Scaling

- Scaling is a powerful concept. Important for predictions of nuclear response, when no experimental data exist.

- In QE scattering both responses expected to scale to universal curve.

- Integral of the superscaled result should satisfy the Coulomb sum rule.

- **Longitudinal response scales with the momentum transfer and atomic mass.**

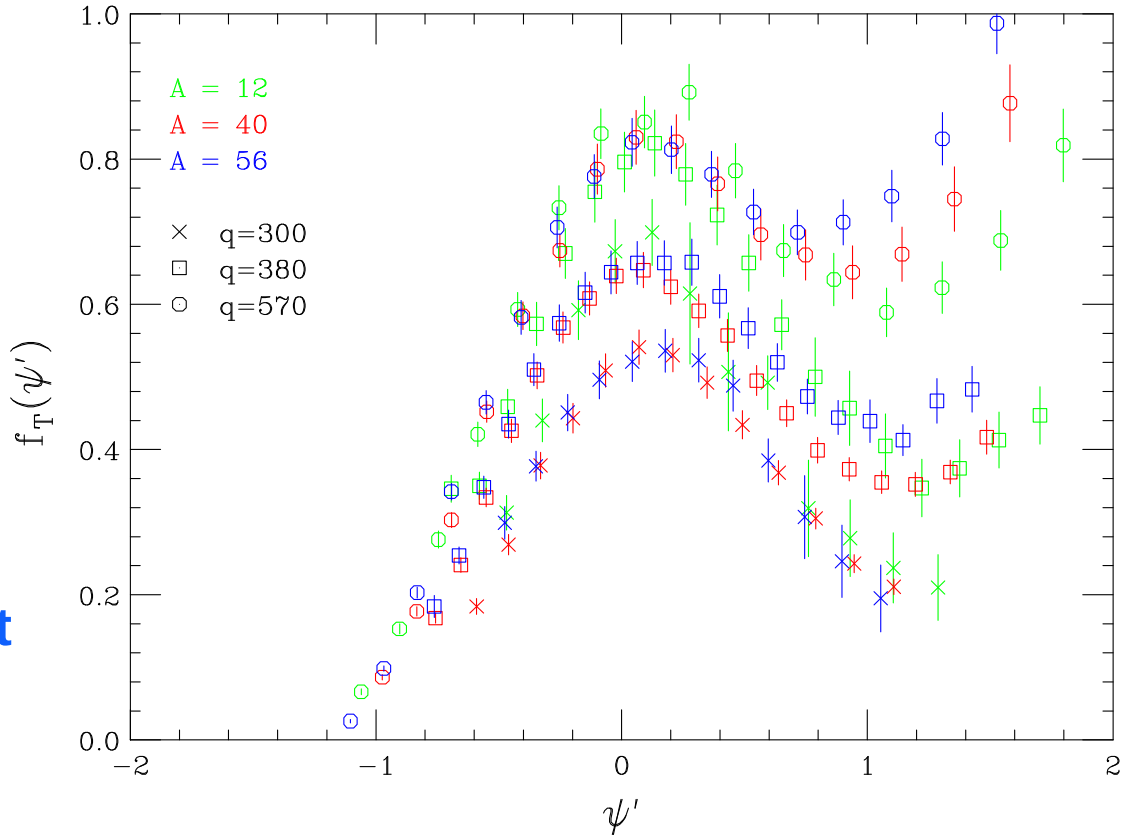


Scaling breaking

- **Transverse response breaks the superscaling.**

- In the absence of real data the description of scattering under large angles is not under control. Generators are unreliable.

- **Need for experimental data to determine the behavior at large scattering angles.**



New experiment

Considerations:

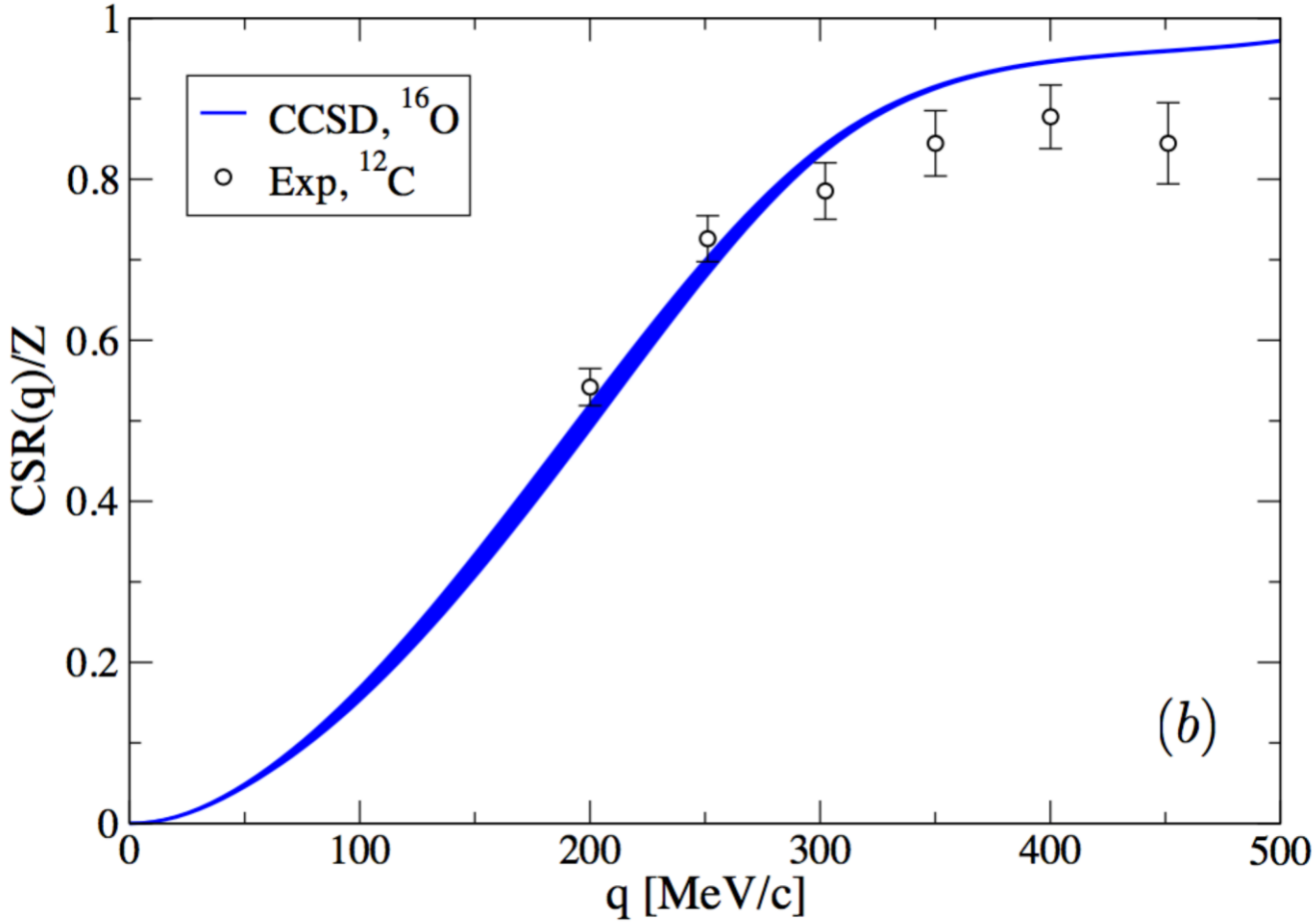
- Running experiment T2K uses oxygen and carbon as a detection medium.
- Only sparse data available for oxygen.
- New theoretical group at KPH led by Sonia Bacca, who performs ab initio calculations of processes on oxygen.

Decision:

- **Provide comprehensive data for ^{16}O(e,e') and ^{12}C(e,e').**
- **Data not only input for neutrino physics but relevant for fundamental nuclear physics.**

Coulomb Sum Rule – ^{16}O

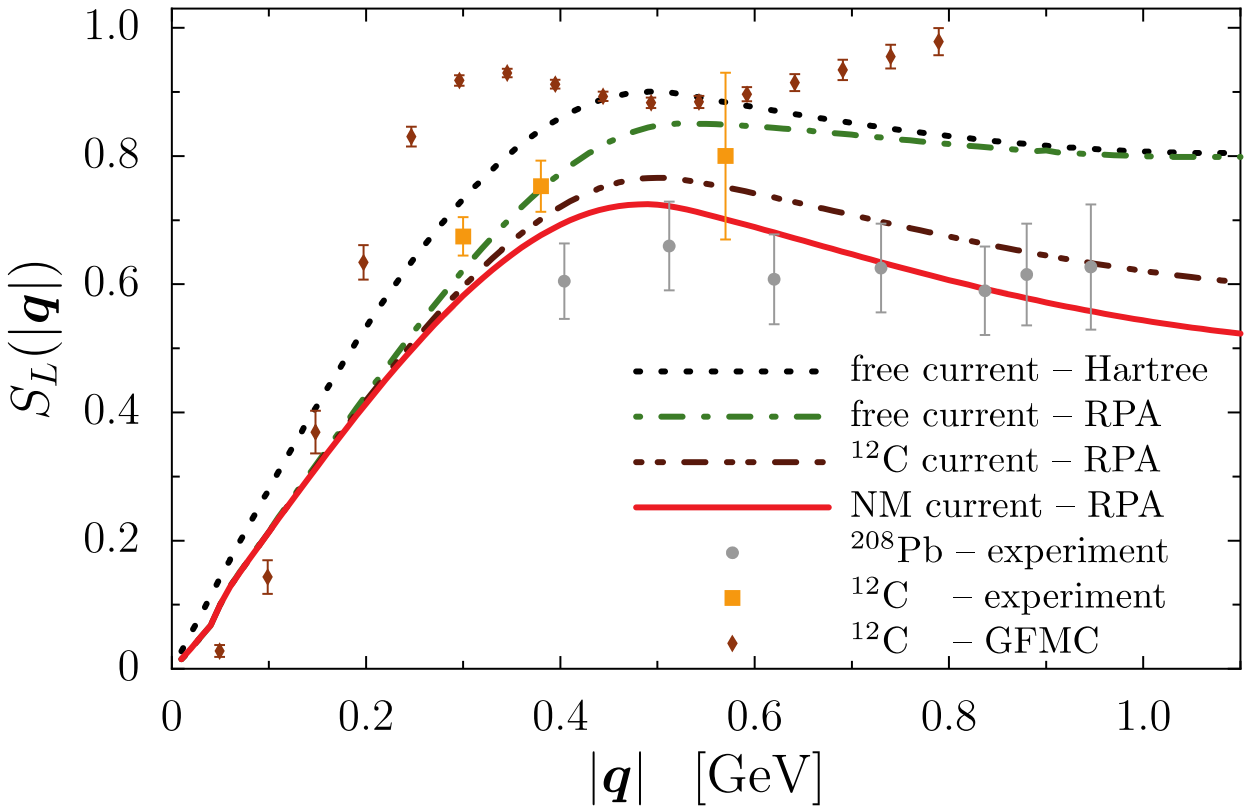
- Coulomb sum rule for Oxygen using coupled cluster theory (S. Bacca) .



- Theory extendable to ab-initio studies of neutrino-nucleus cross-sections.
- **No data exist!**

Coulomb Sum Rule – ^{12}C

- Carbon data for checking systematics.
- Determination of Coulomb sum for Carbon
- Complement experiment E05-110 at Jefferson Lab.



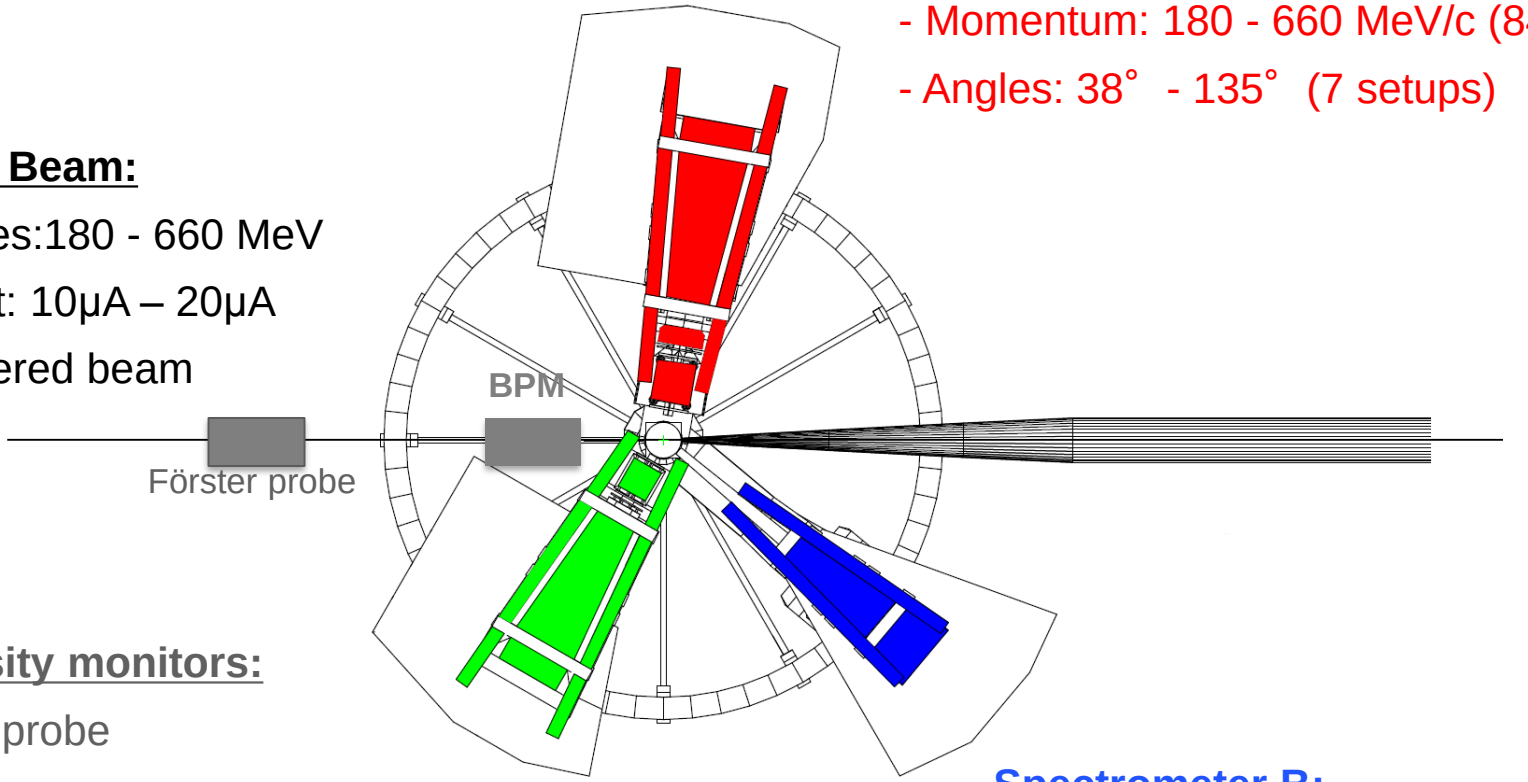
Experimental setup

Spectrometer A:

- Data taking
- Momentum: 180 - 660 MeV/c (84 setups)
- Angles: 38° - 135° (7 setups)

Electron Beam:

- Energies:180 - 660 MeV
- Current: 10μA – 20μA
- Unrastered beam



Luminosity monitors:

- Förster probe

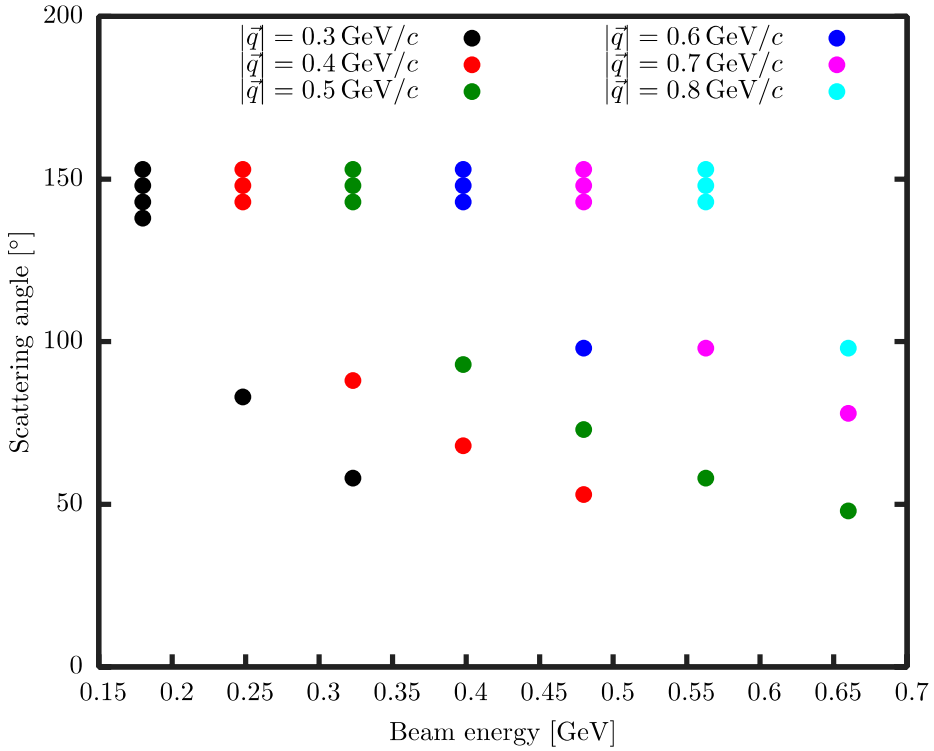
Spectrometer C:

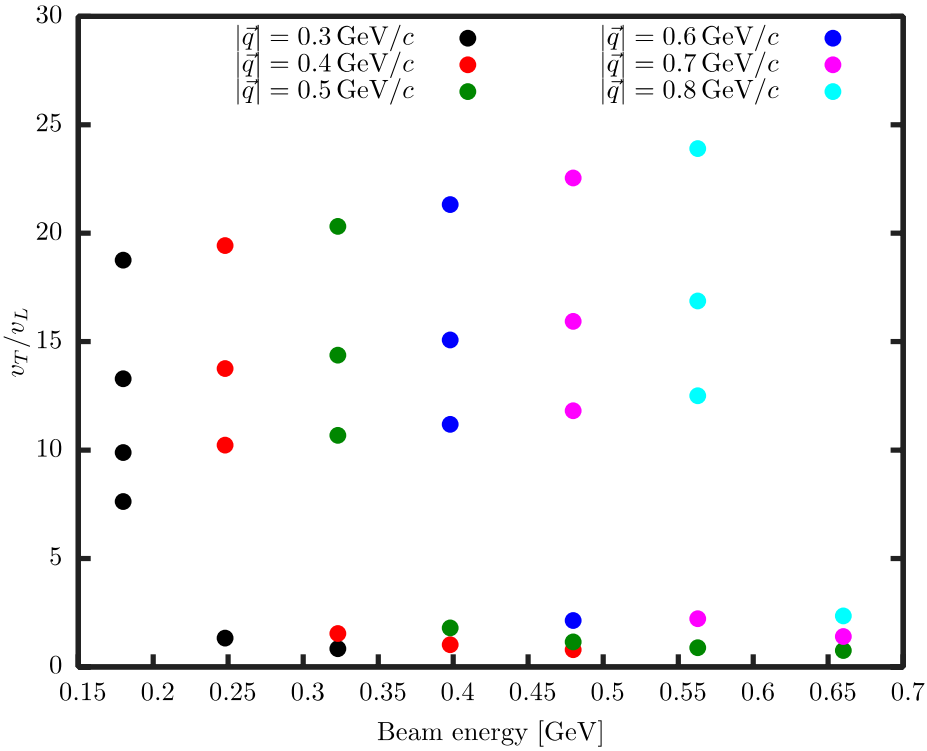
- Not used

Spectrometer B:

- Luminosity monitor (const. setting)
- Angle: 30°
- Momentum: 660 MeV/c

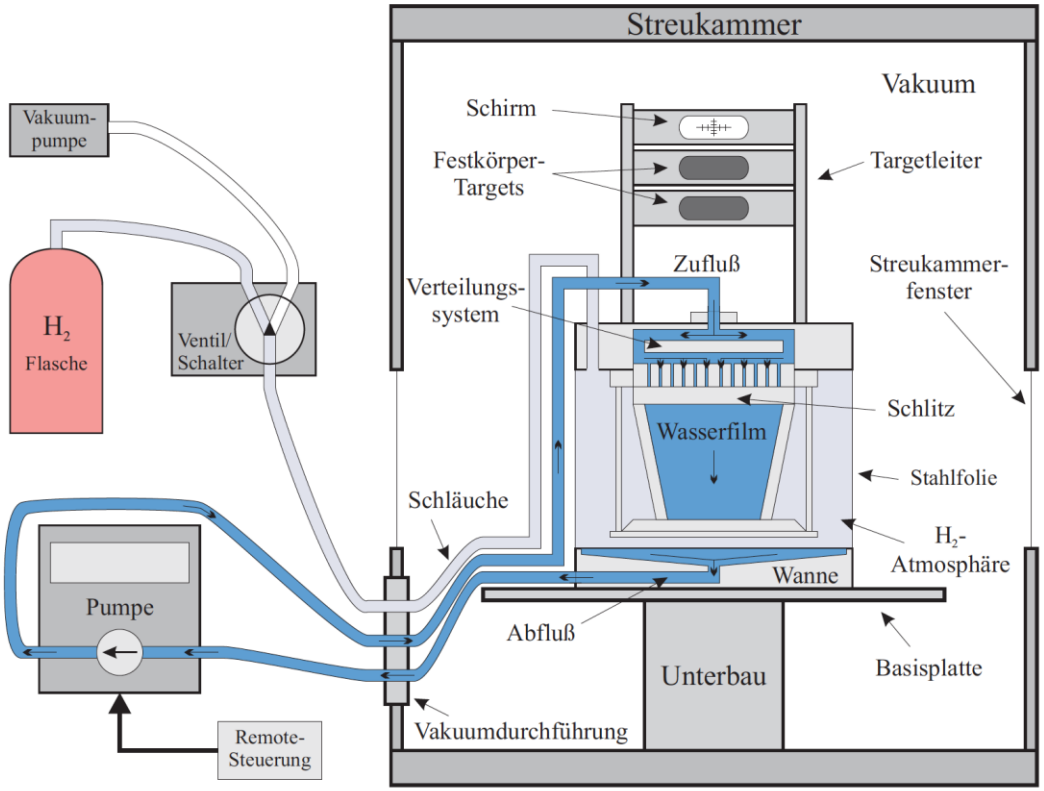
Kinematics





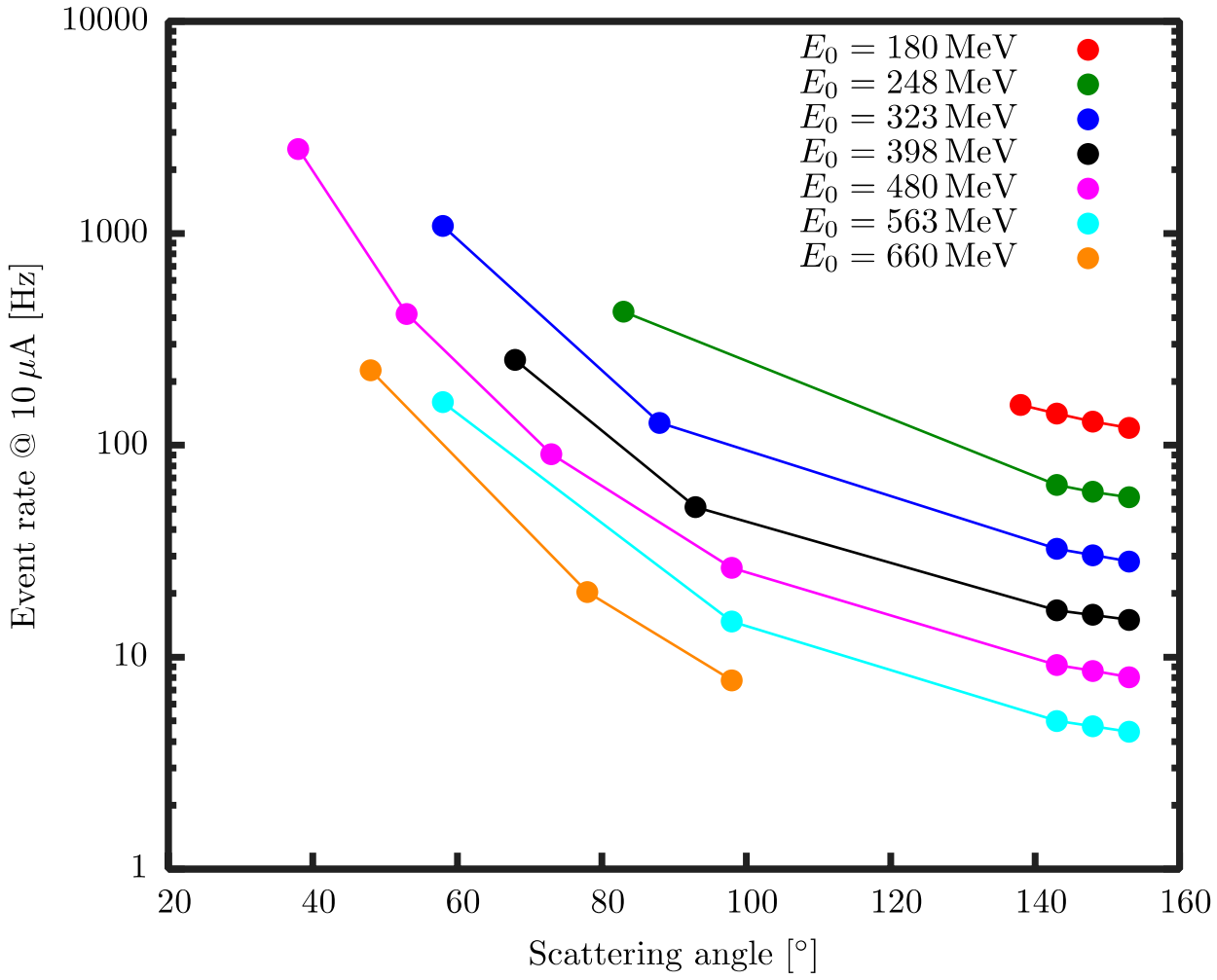
- Data will cover both QE and DR regime.
- R_L and R_T could be separated and individually studied.
- Coulomb sum for 0.3 GeV ≤ |q| ≤ 0.8 GeV could be determined.
- **Hypothesis: Deviations between theory and data at large scattering angles are expected.**

Target



- Waterfall target is established equipment of A1.
- Measurement without background from target walls.
- Hydrogen background subtracted using sophisticated simulations.
- **Luminosity of $4 \cdot 10^{35}/cm^2/s$ at 20µA.**

Experimental Rates



- With beam current of ~20μA rates between 20Hz and 500Hz are expected.

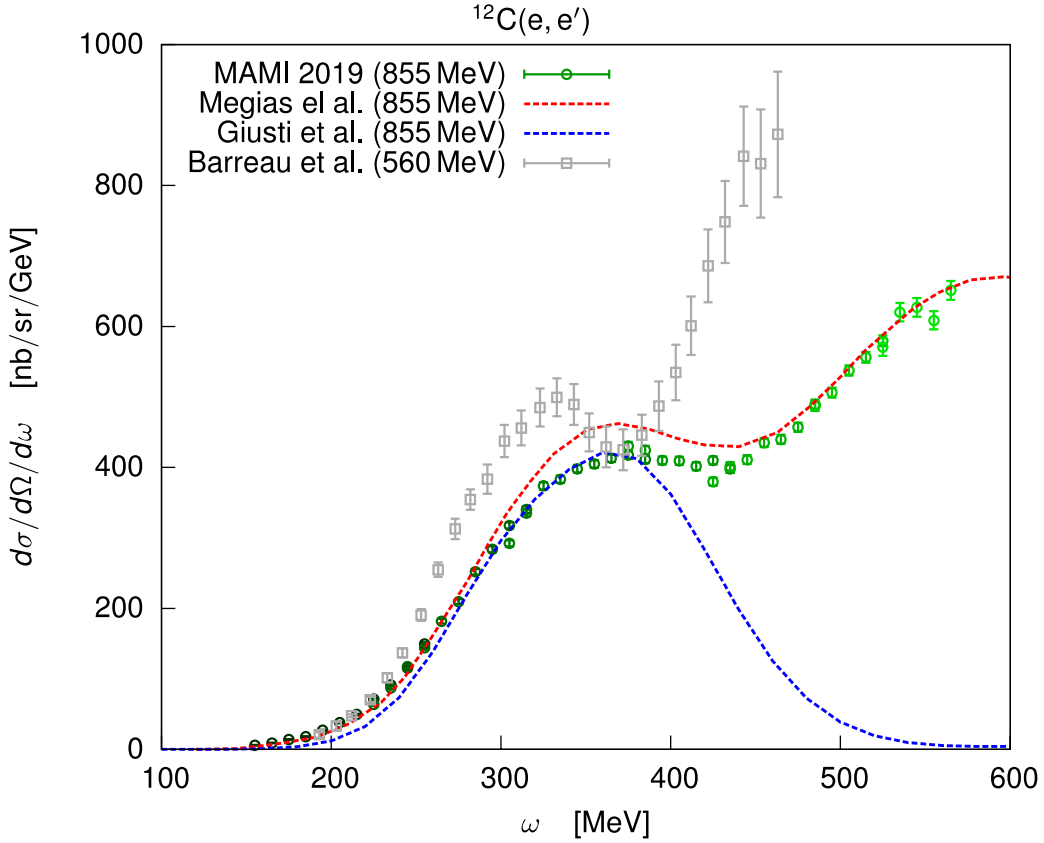
Beam-time requests

- Asking for polarized MAMI-B beam with currents above 20μA.
- To complete the inclusive experiment with both targets, **41 days** of beam-time are needed (including setup changes and accelerator maintenance).
- **7 days** for the detector calibration and optics studies (optional).

All together asking for 48 days of beam-time.

Feasibility Study

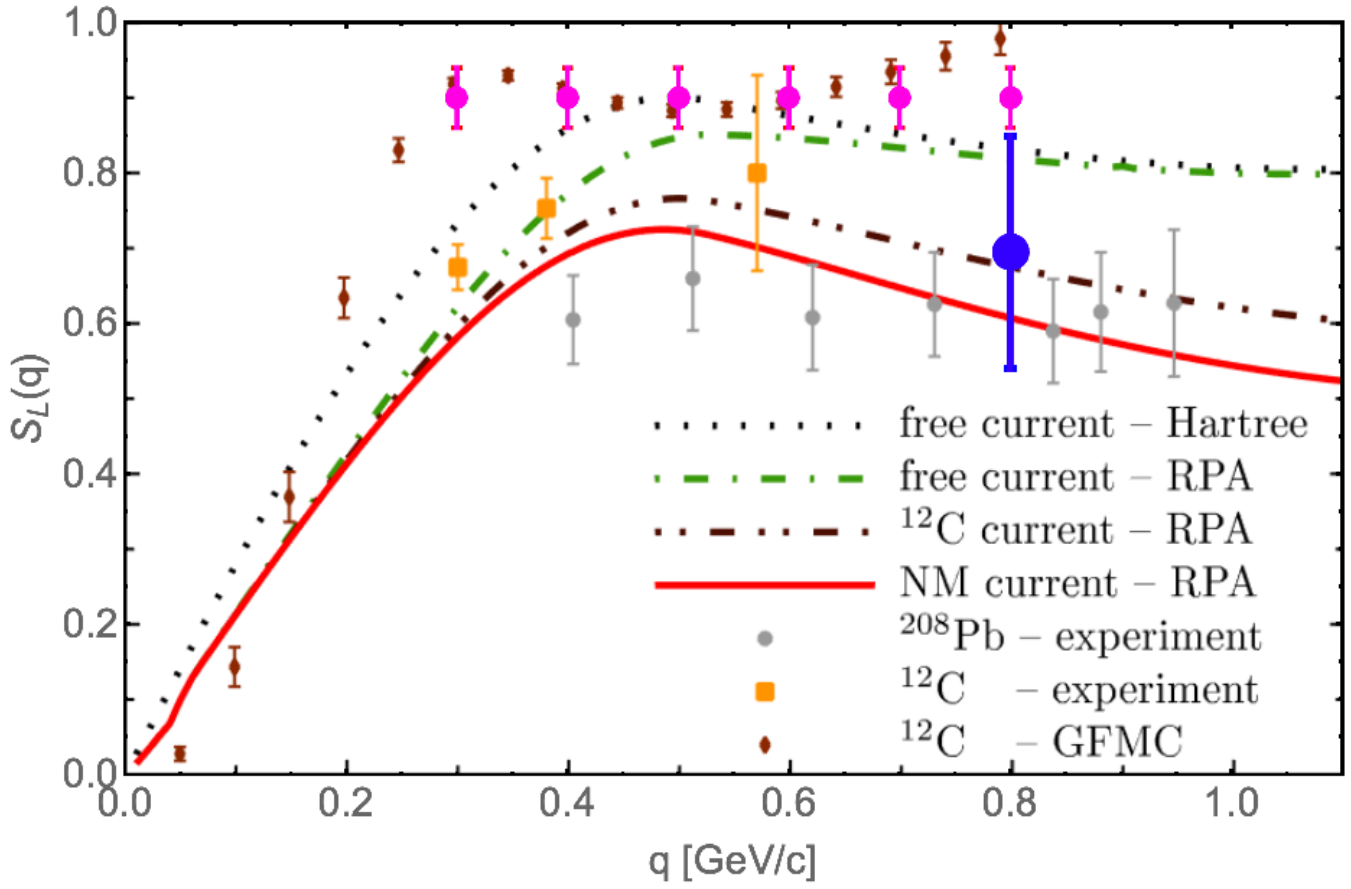
- Short test experiment performed in 2019.
- Beam energy of 855 MeV and scattering angle of 70°.
- 7 different momentum settings, 1h each.



- Results consistent with calculations of Giusti et al. and Megias et al.

Feasibility Study #2

- Combining the results with the previous measurements from 1983, Coulomb sum could be determined.
- Uncertainty dominated by the large angle data.



Summary

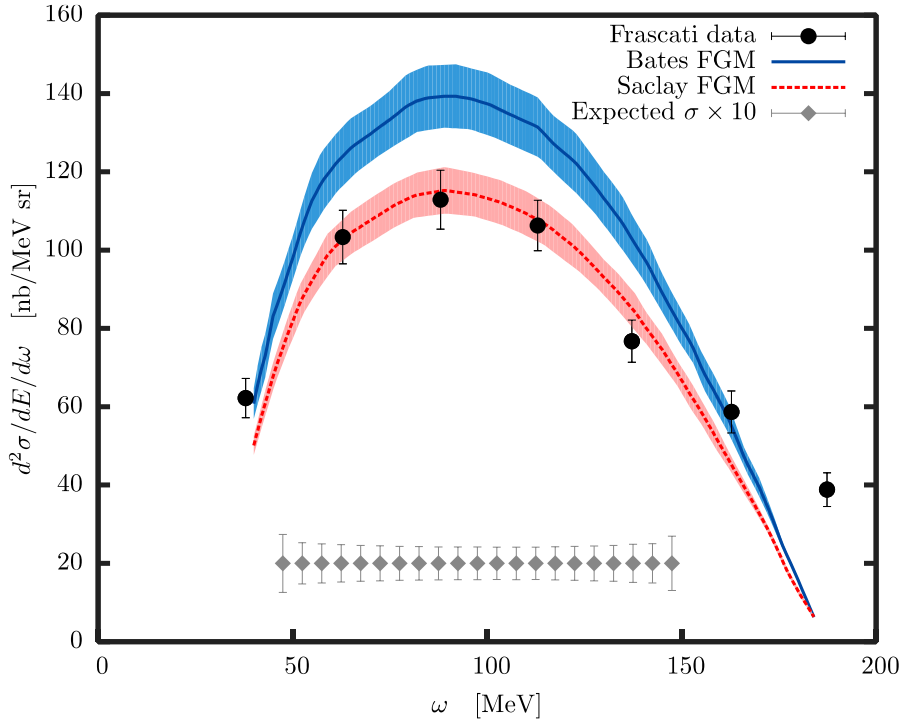
- Most important questions of today's physics related to neutrinos.
- Neutrino experiments relay on Monte-Carlo simulations, which depend on nuclear structure models.
- Present theoretical models are still deficient.
- **The proposed new experiment at A1 has potential to provide valuable input to the theory.**
- **Quasi-elastic experiments on ^{12}C and ^{16}O are important also in the context of fundamental nuclear physics.**
- **Asking for 48 days of beam-time.**

Thank you!

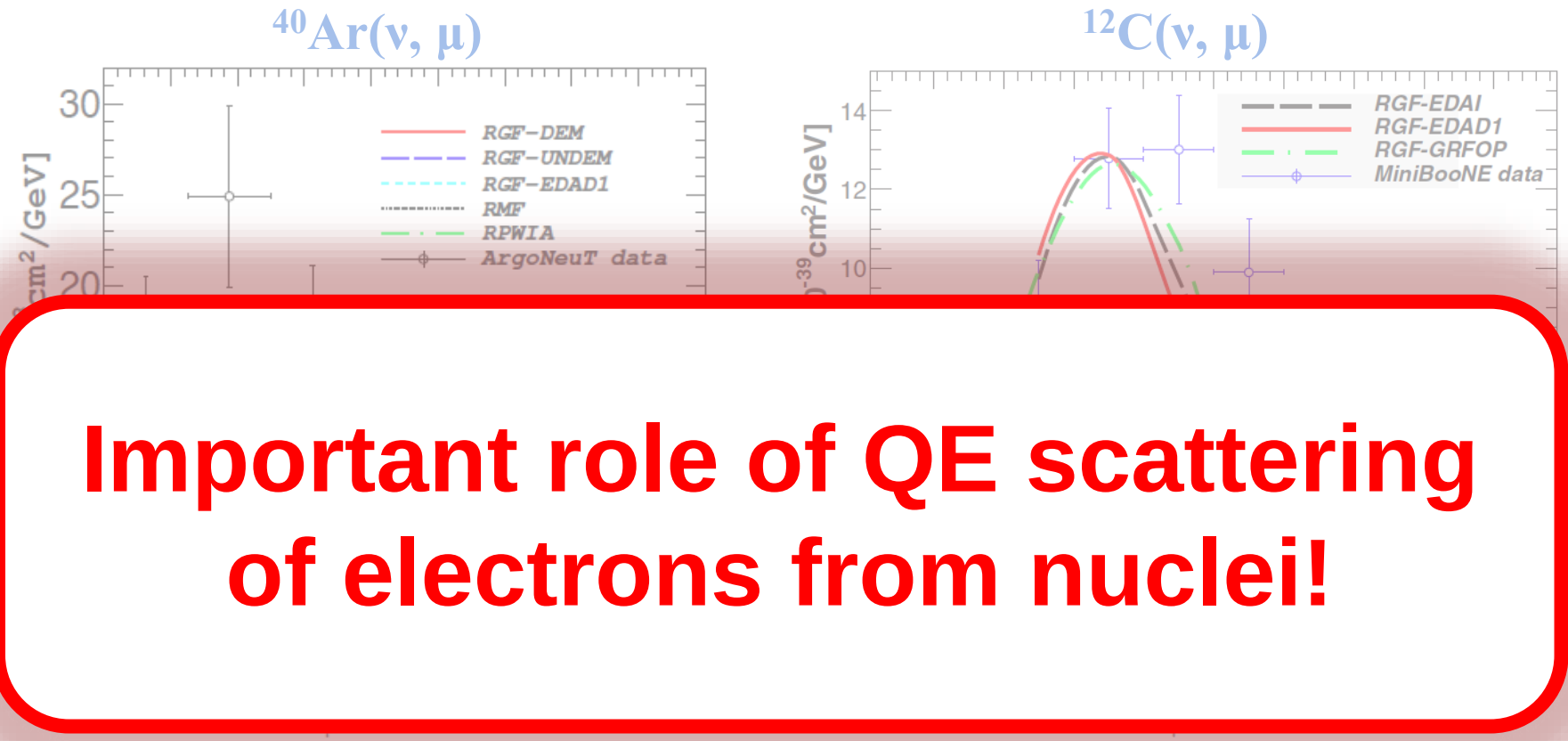
Backups…

The LOI 2017

- The proposal is an evolution of LOI 2017.
- Presented before the results of the JLab experiment published.
- **LOI focused on experiment on Ar.**
- Mostly forward kinematics.
- **Inclusive channel to verify Frascatti data.**
- Exclusive channel to investigate spectral function and complement JLab experiment.
- Double polarized data to study FSI.
- Relevant for DUNE and μBooNE.



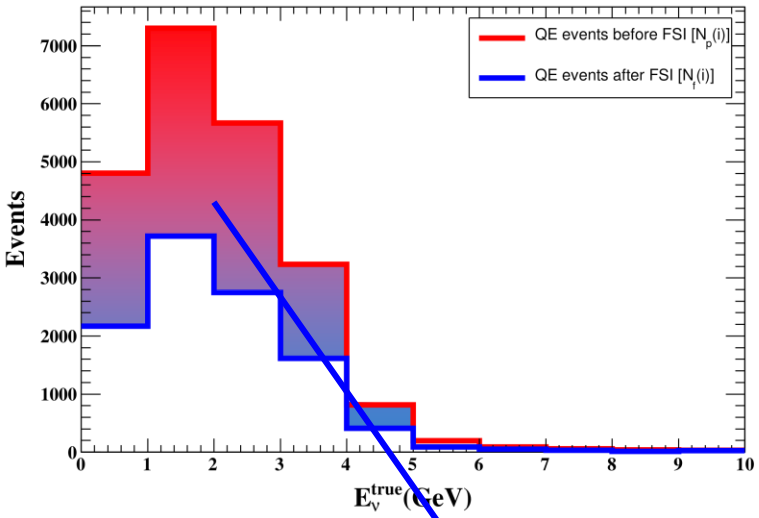
Deficient theoretical description

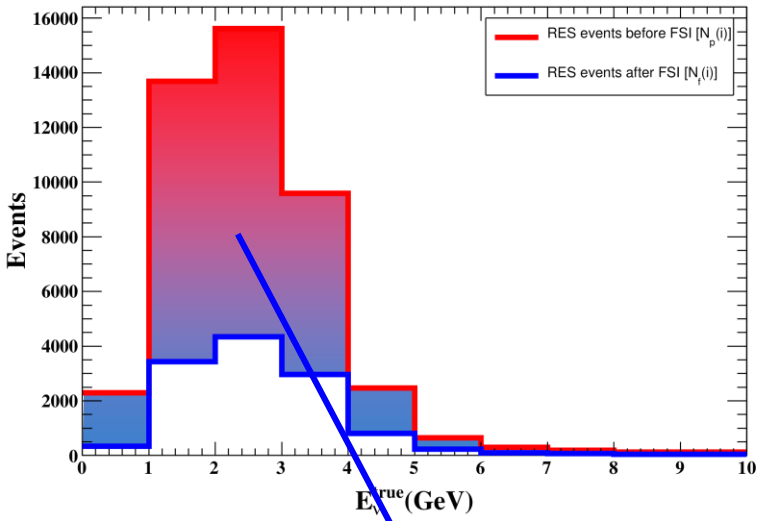


Important role of QE scattering of electrons from nuclei!

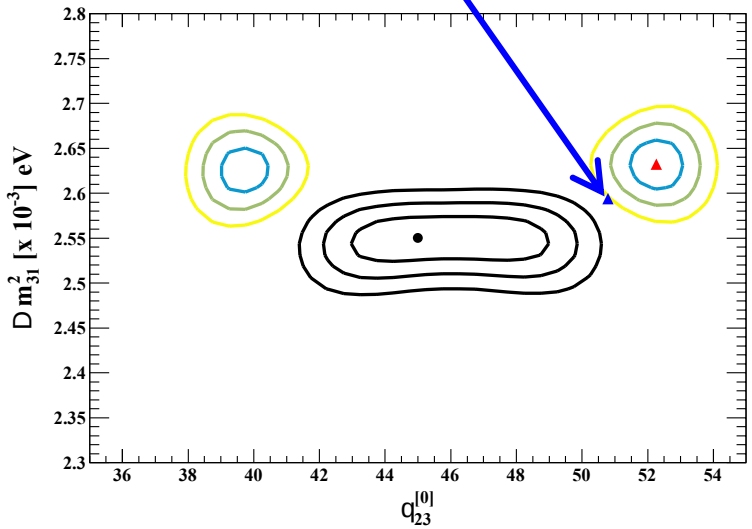
- Available theoretical models incapable of reproducing the measured data.
- **New precision studies can not be done without improvements to the theoretical description of the processes.**

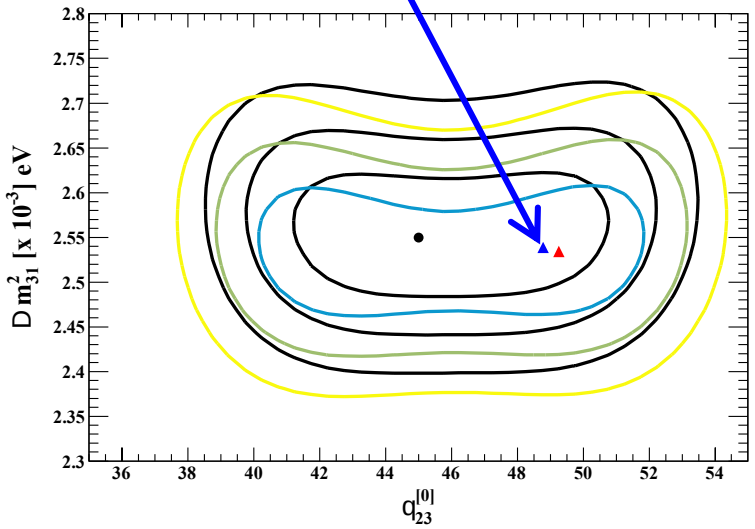
Fake vs. true neutrino events





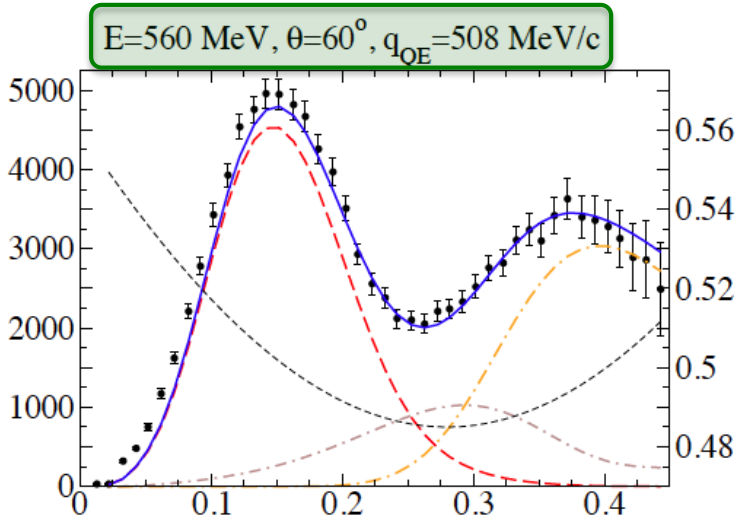
S. Naaz et al., NPB 933 (2018) 44

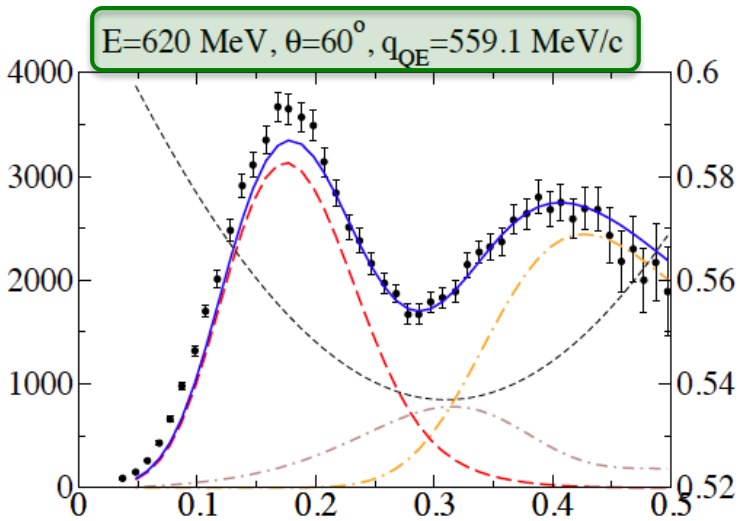


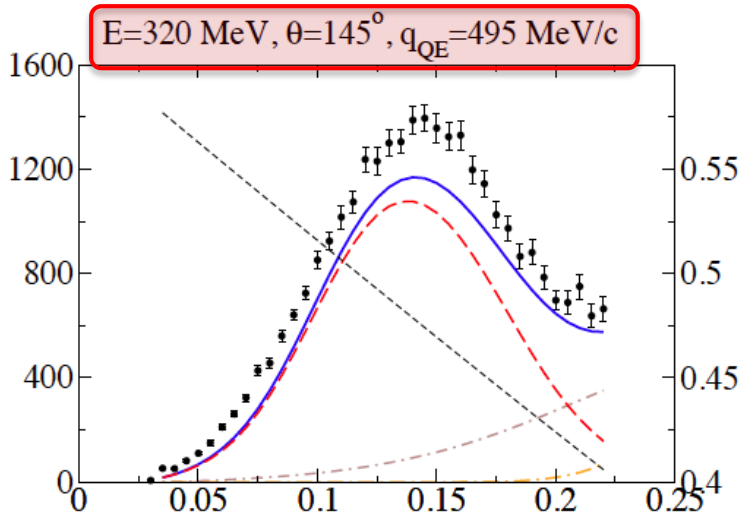


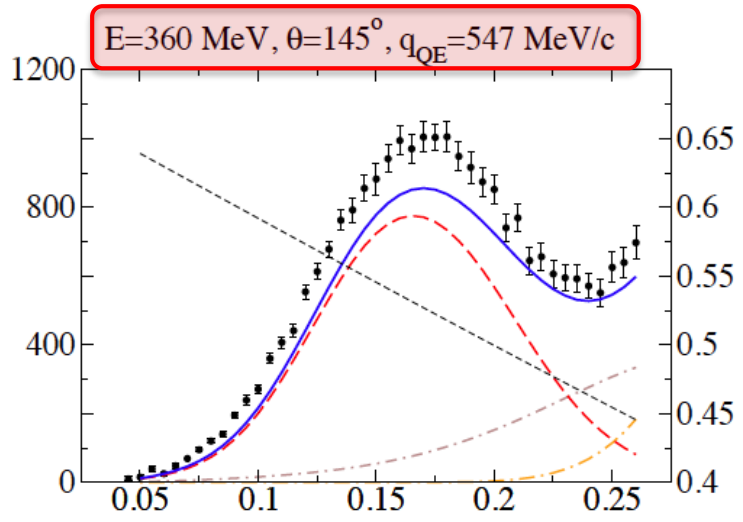
- Nuclear effects cause migration of 50-70 % of neutrino events, causing **deviation of oscillation parameters on the order of 1σ-3σ**.

Incomplete theoretical description (e,e')









G. D. Megias et al., Phys. Rev. D 94, 013012

- Theoretical description remains deficient in the transverse kinematics!

The generators

- Dominant process is QE scattering, but other processes need to be considered as well (Delta, FSI, MEC).

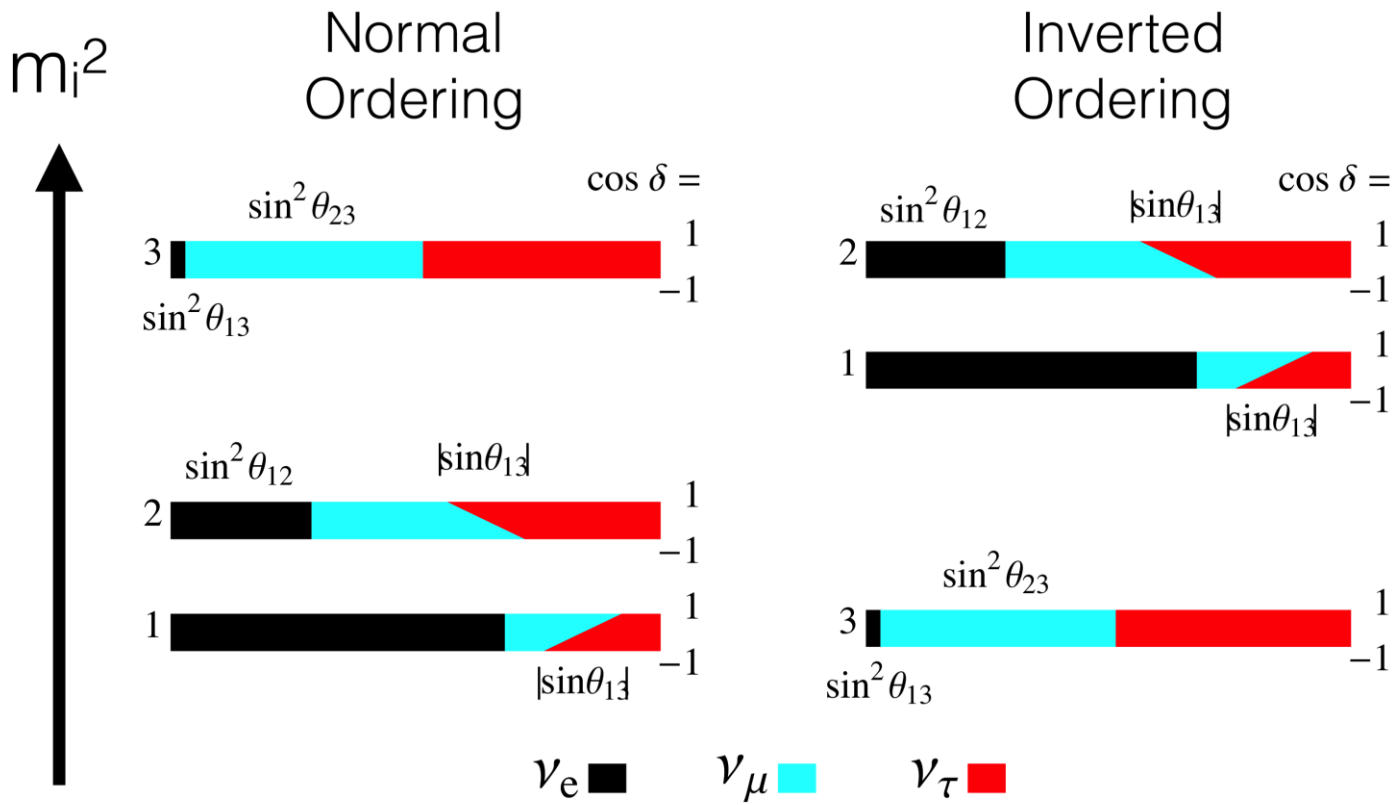
- **The complete theoretical descriptions (eg. Giusti) too complex to be included into the event generators.**

- Consider large momentum and angular coverage.

- **Employ phenomenological parameterizations of nuclear cross-section, relaying on scaling.**

Current knowledge

	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}



Goals of upcoming experiments

	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}

- More accurate determination of $\Theta_{23.}$
- Establish whenever there is a CP violation in lepton sector.
- Determine the correct mass order (normal, inverted)?
- Determine the absolute mass of the neutrinos.

Future experiments

- New accelerator based experiment underway.
- Combines neutrino source at Fermilab and 40t liquid Ar detector at SURF.

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Due to three stage production process the energy of initial neutrinos not defined. **Energy ranges from 100MeV to 3GeV**.