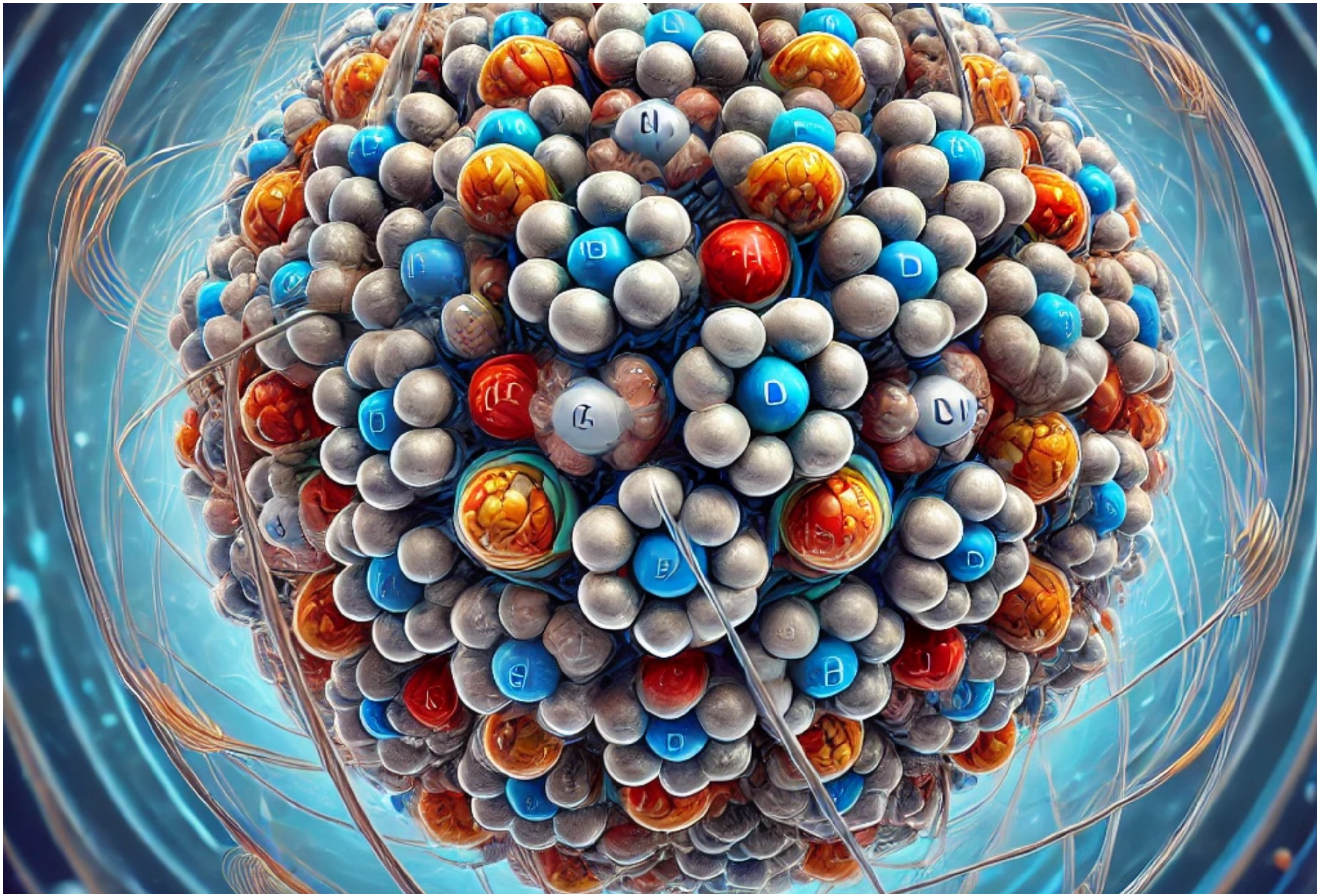
From nucleons to nuclei and beyond

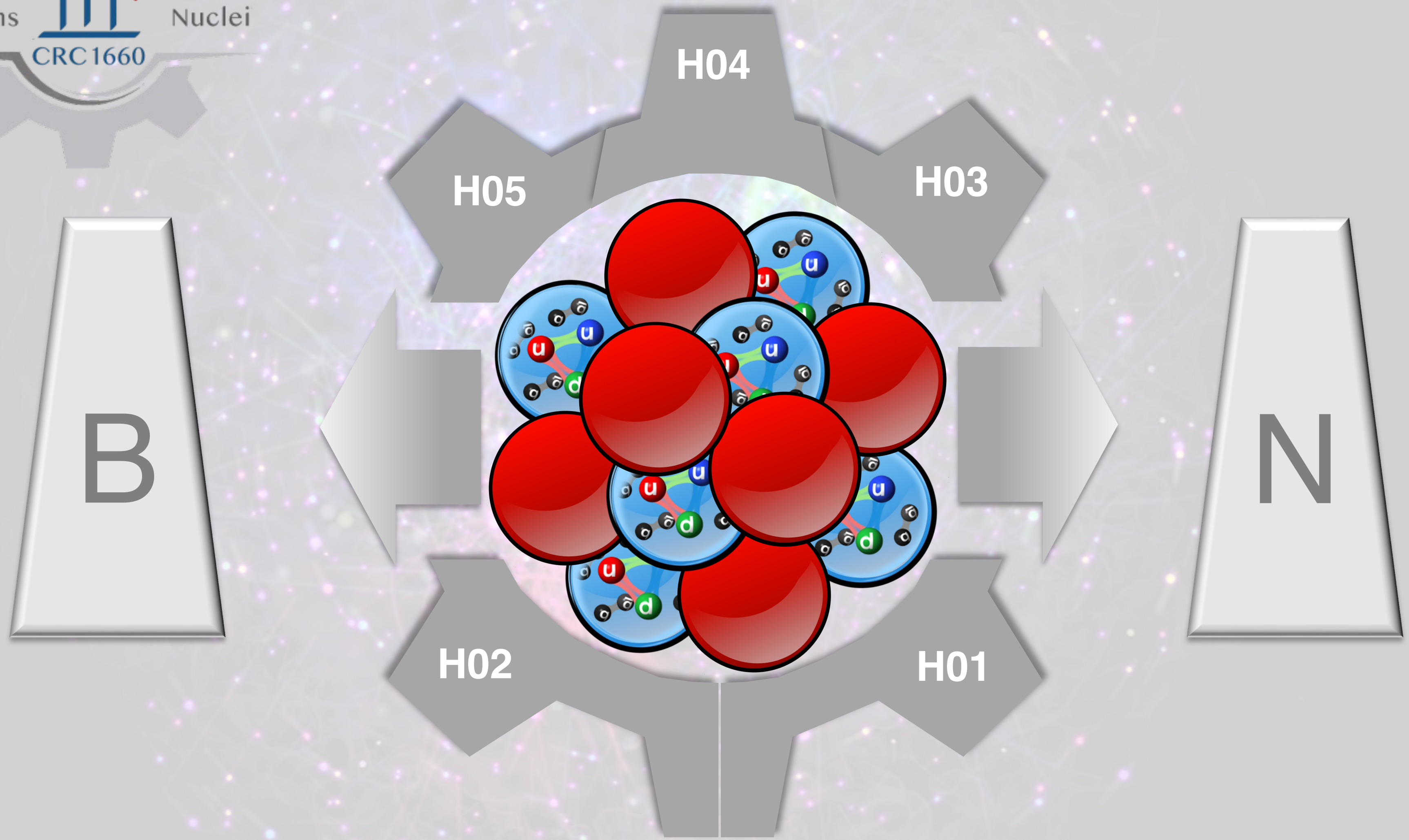
M. Mihovilovič

AI impression of nucleus



H: Interface between Hadron and Nuclear Physics

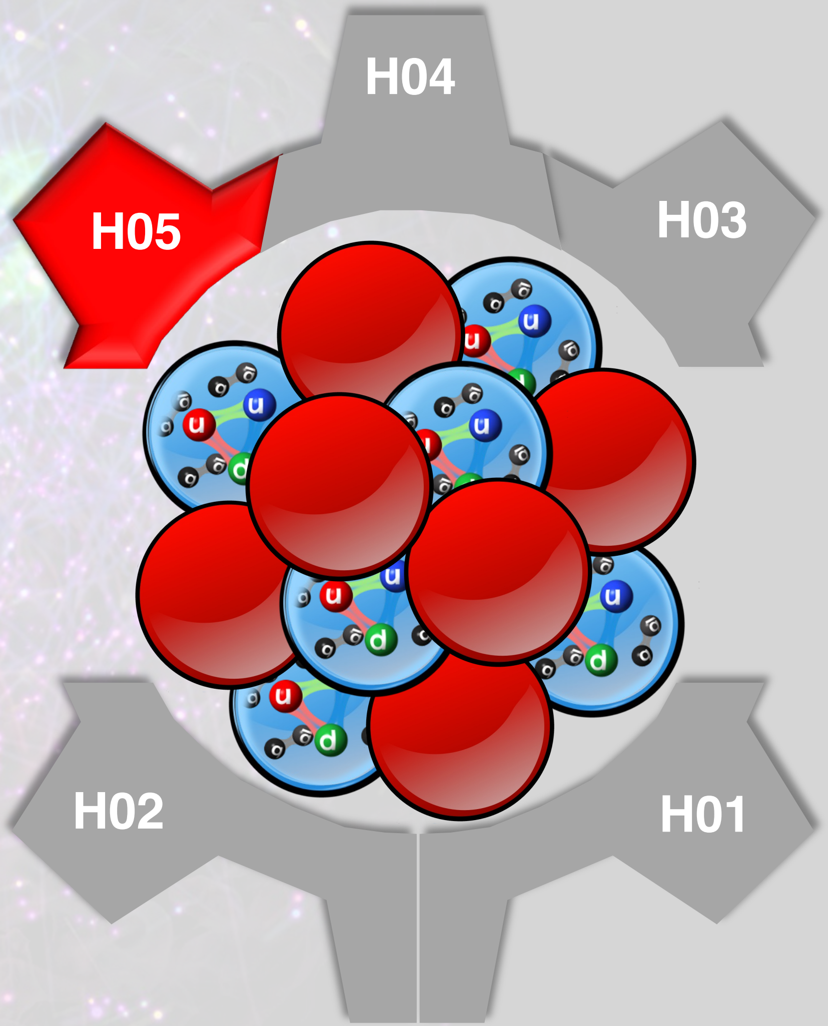
Hadrons Nuclei
CRC 1660



Electron and photon scattering

Project goals:

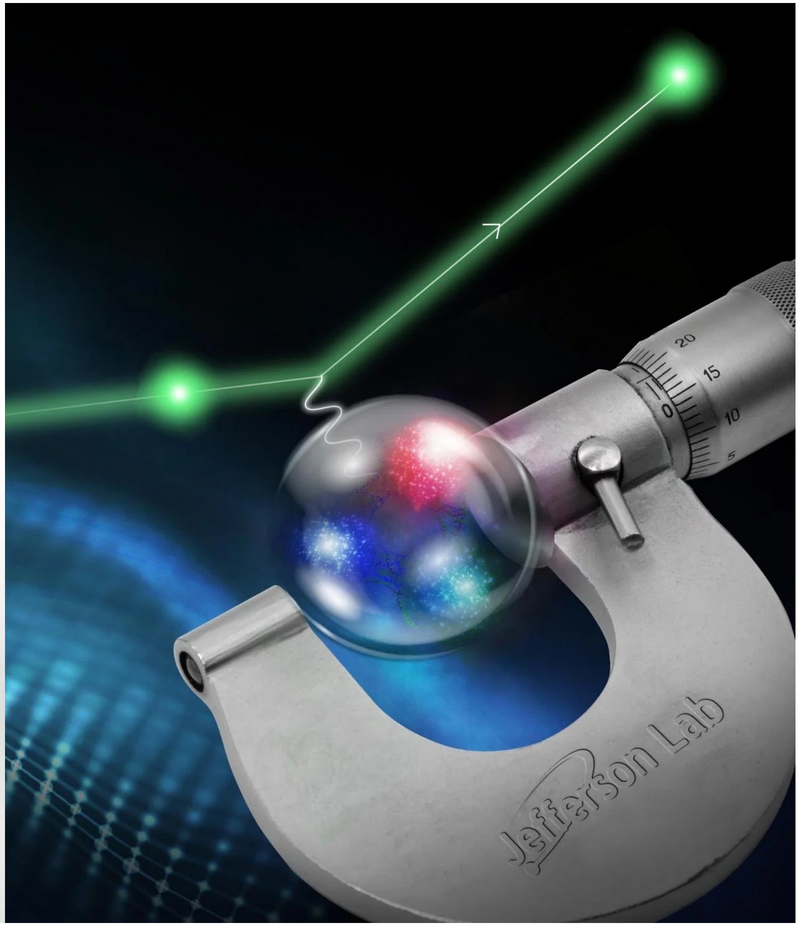
- New precise measurements of electromagnetic form factors
- More robust determination of charge and magnetic radius of nucleon.
- Refine the experimental determinations of the nucleon polarizabilities



PLs: A. Khoukaz, H. Merkel, M. Ostrick

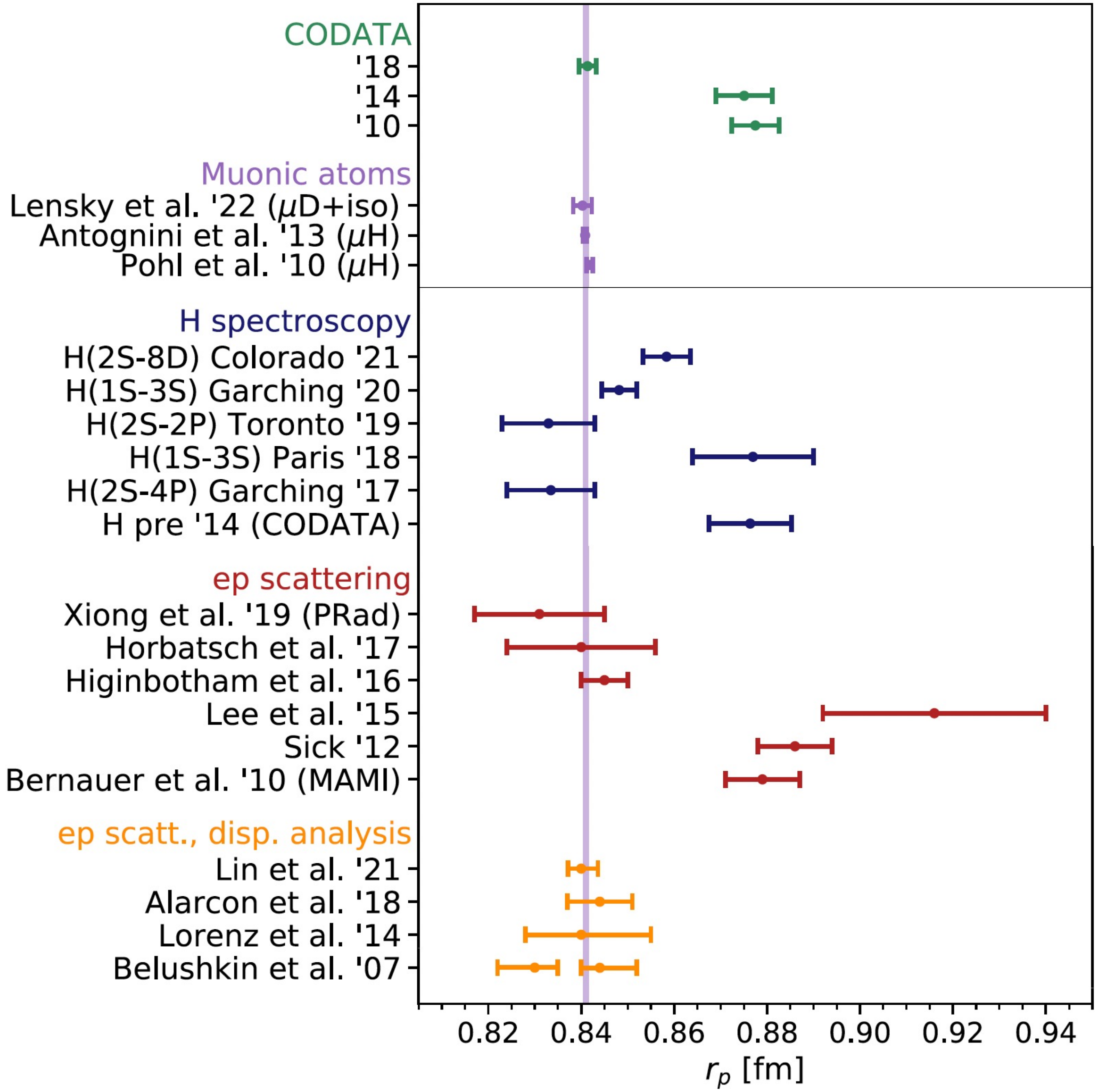
Motivation - The proton radius problem

- The "Proton radius puzzle" - a 6σ discrepancy between different measurements of proton charge radius.



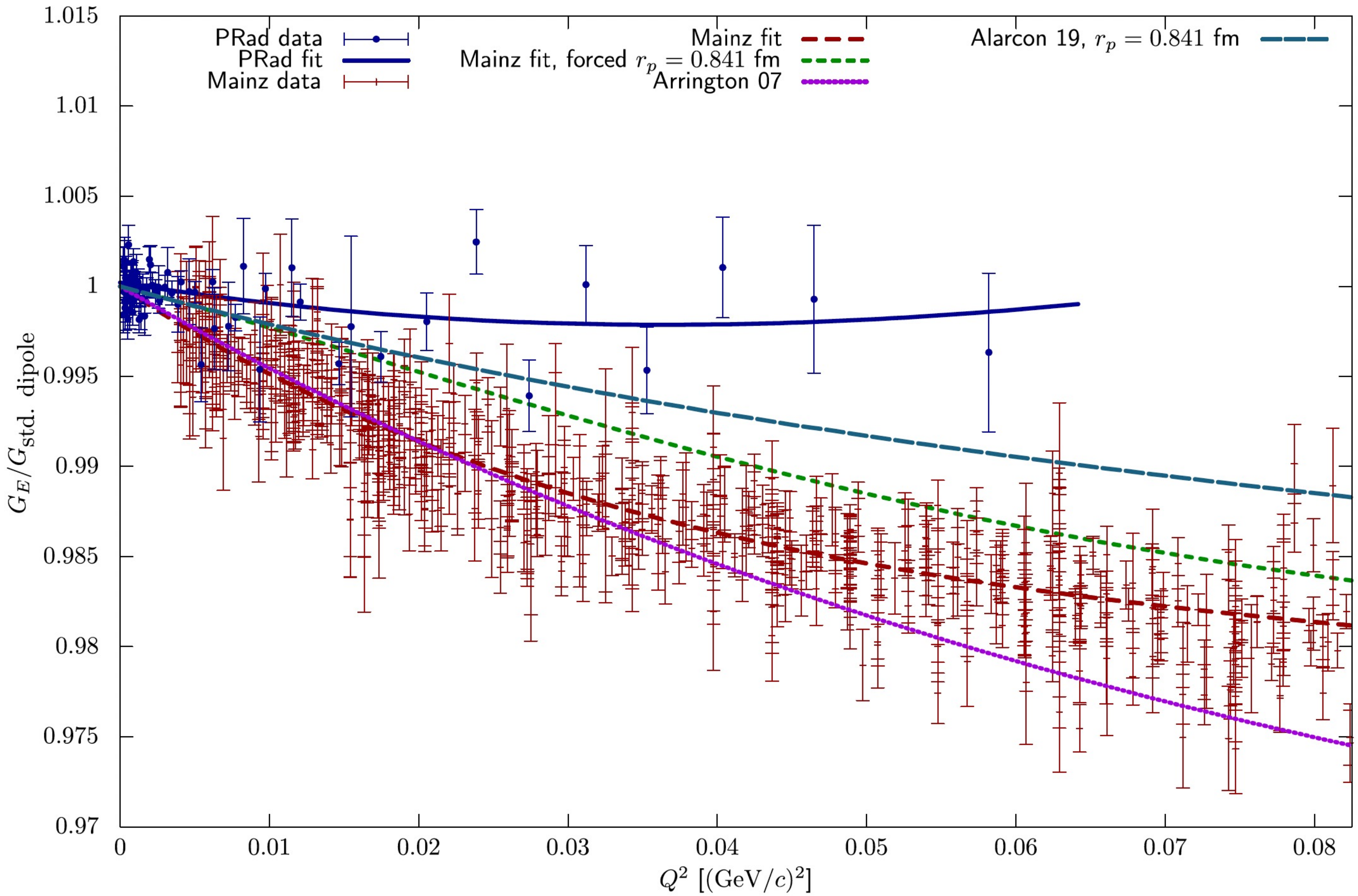
The proton radius measurements

- Differences in scattering results due to different experimental results or inconsistent interpretations of the data



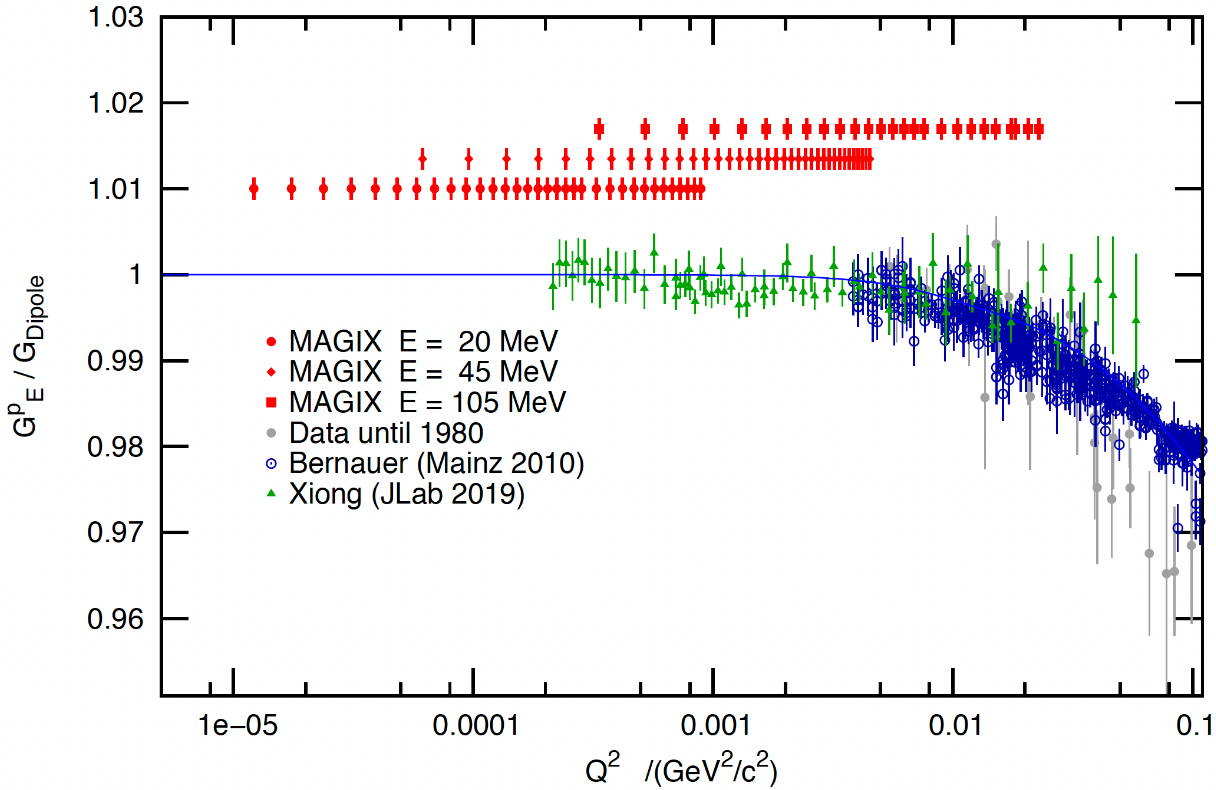
Inconsistencies in G_E^p measurements

- Significant disagreement between PRad results and all previous measurements at $Q^2 \geq 0.02$ GeV^2 motives new experiments.



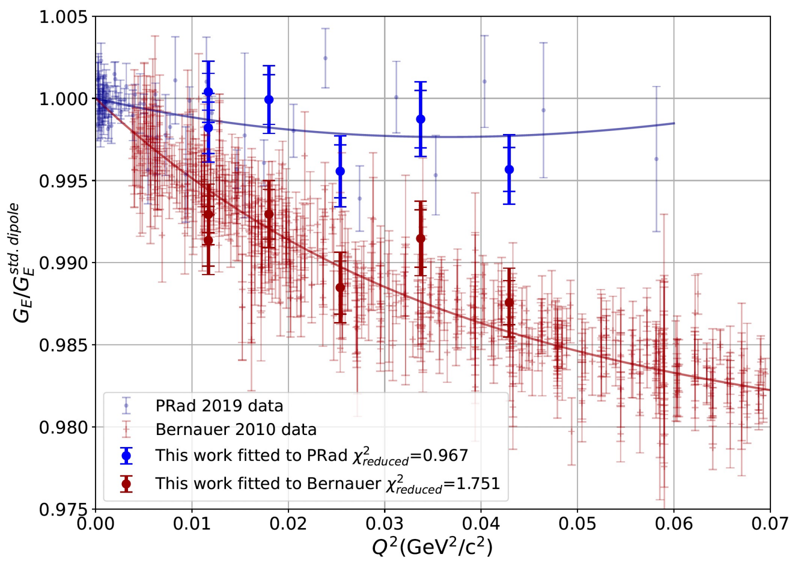
Form factor measurements @ MAGIX

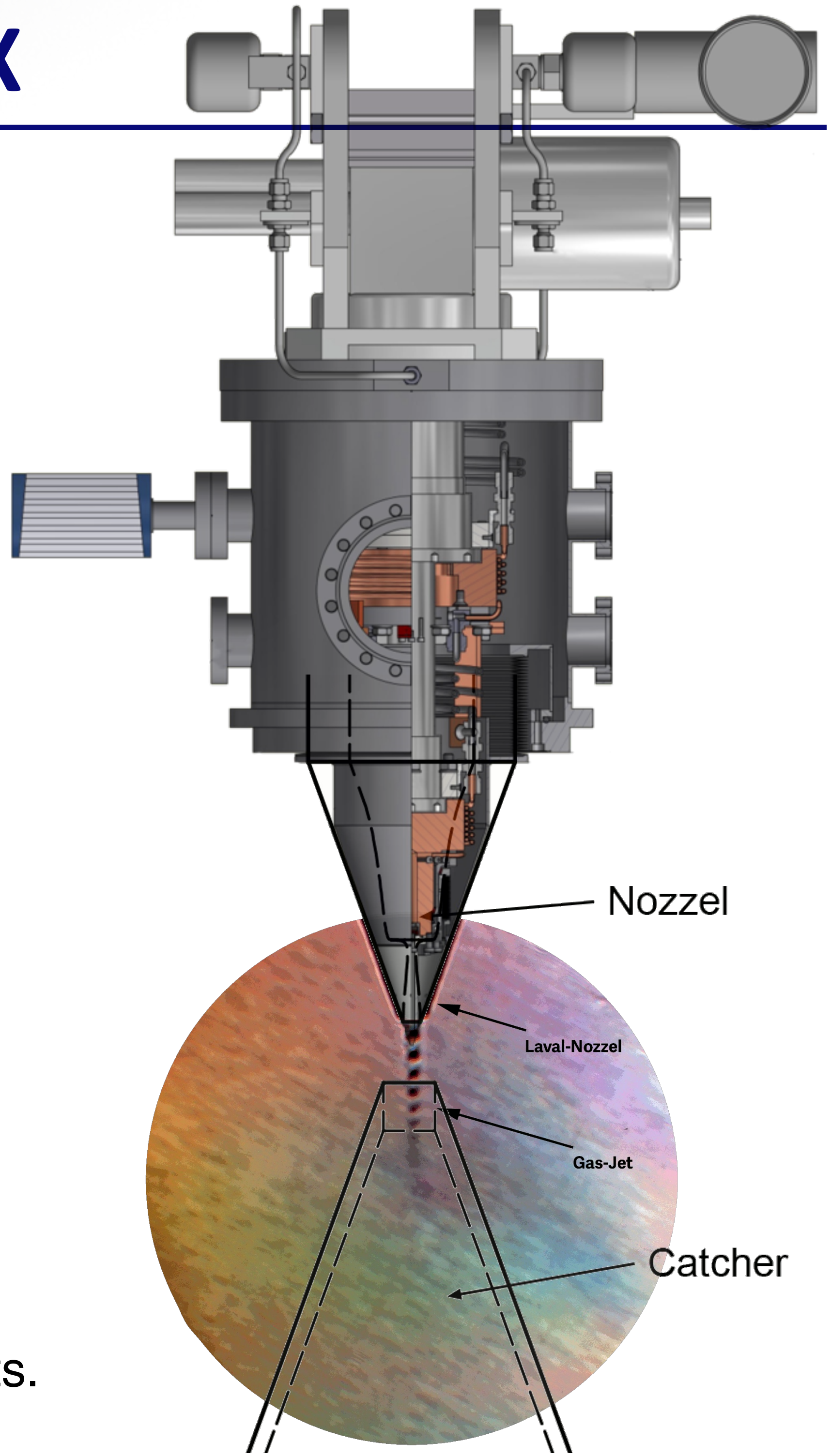
- Persistent discrepancy between different determinations of the proton radius demands further measurements.
- New measurement planned also at Magix @ MESA
- Measurement of G_E^p at Q^2 between $1 \cdot 10^{-5}$ and 0.03 GeV^2
- Expected statistical uncertainty ~ 0.1 %.
- Expected systematical uncertainty < 0.5 %.
- G_M^p also accessible with large angular coverage and high statistics.



Cluster-jet target @ MAGIX

- **No target walls.**
- Width of the jet 2mm (point-like target)
- Target thickness of **10^{18} atoms/cm.**
- Successfully tested at A1.



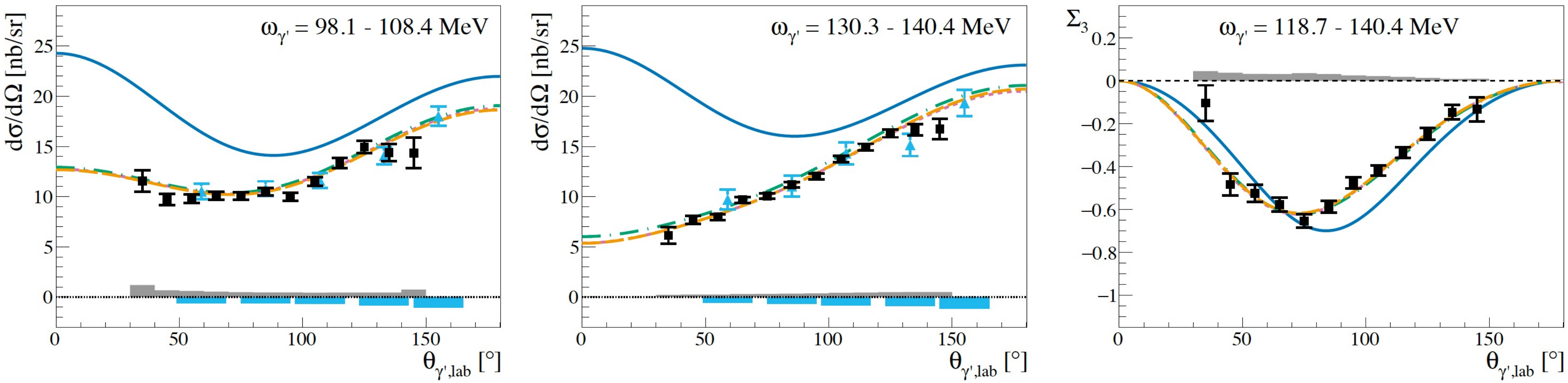


- Together with MAGIX spectrometers forms a unique experimental setup for FF measurements.

Polarizabilities of the nucleon (neutron)

- Polarizabilities are fundamental properties of the nucleon and provide a test bed of ab initio calculations.

- Proton polarizabilities extensively studied in Compton scattering experiments at A2.

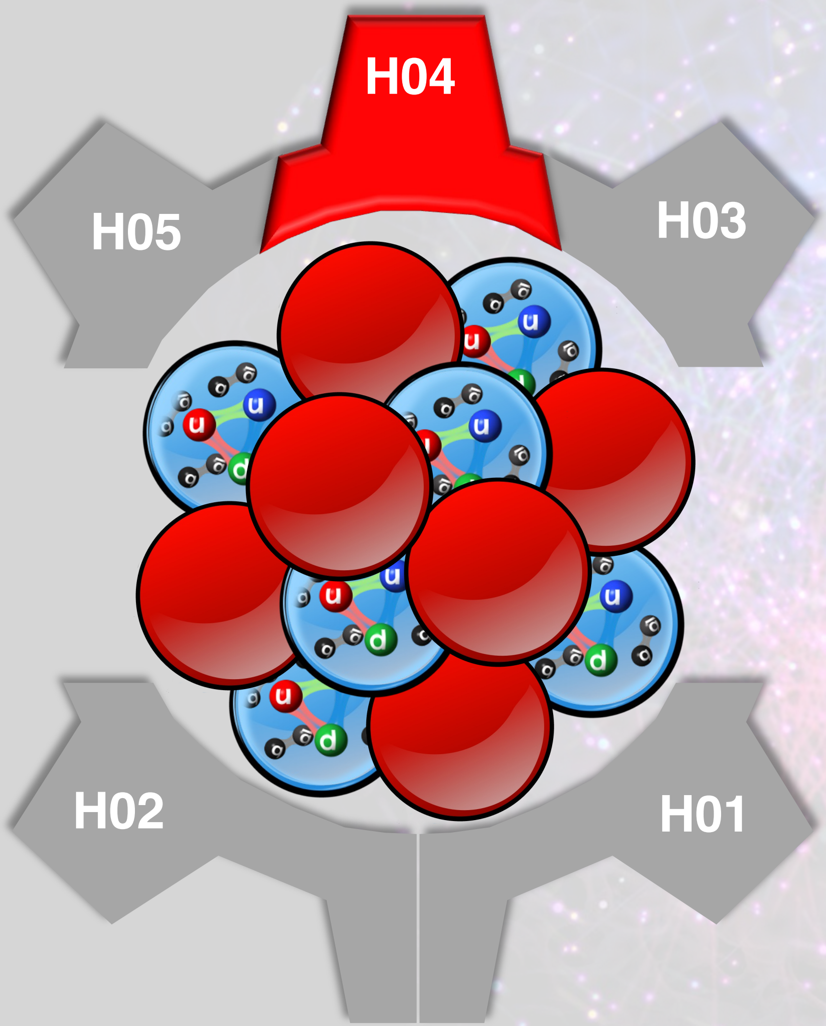


- **Polarizabilities of the neutron an exciting open question.**

- Accessible via Compton scattering experiments off light nuclear targets (^{2}H, ^{3}He, ^{4}He).

- Measurements combined with modern χEFT calculations for robust extraction of polarizabilities.

Precision nucleon structure in μH vs. electron scattering

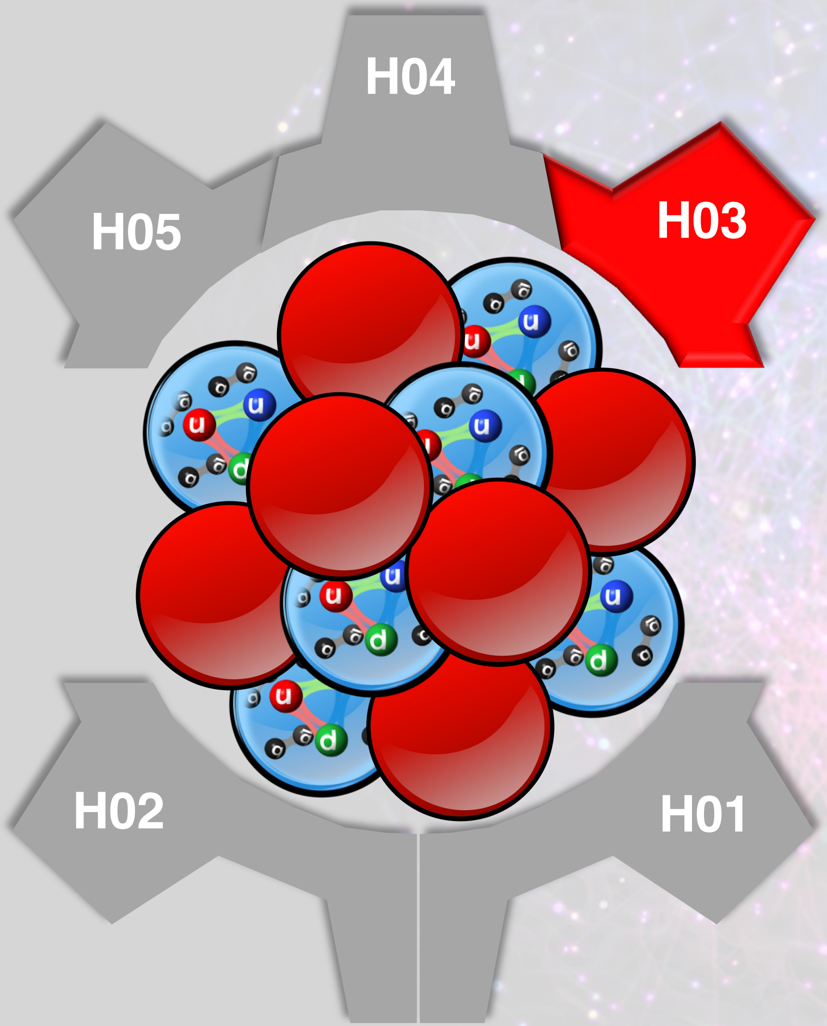


Project goals:

- Theoretical studies of low-energy nucleon structure at the precision frontier.
- Improve hadronic corrections to muonic atom spectroscopy using EFTs and dispersive techniques.
- Implementation of the state-of-the-art 2PE radiative corrections for McMule.
- Framework for interpretation of e-N and γ-N Compton scattering experiments.

PLs: F. Hagelstein, V. Pascalutsa, M. Vanderhaeghen

Muonic atom spectroscopy

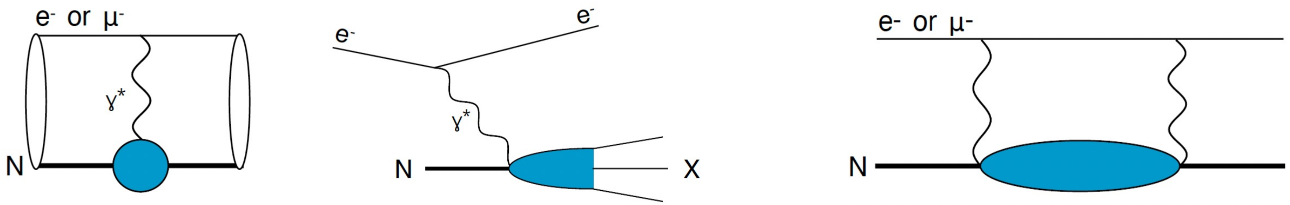


Project goals:

- Precision spectroscopic experiments with µ-atoms to test QED and the Standard Model.
- Measurement of hyperfine splitting in µH muonic hydrogen for more precise extraction of Zemach radius.
- Valuable input for nucleon and few-body nuclear theory.
- X-ray spectroscopy of Z > 2 light nuclei and determination of their charge radii.

PLs: R. Pohl, F. Wauters

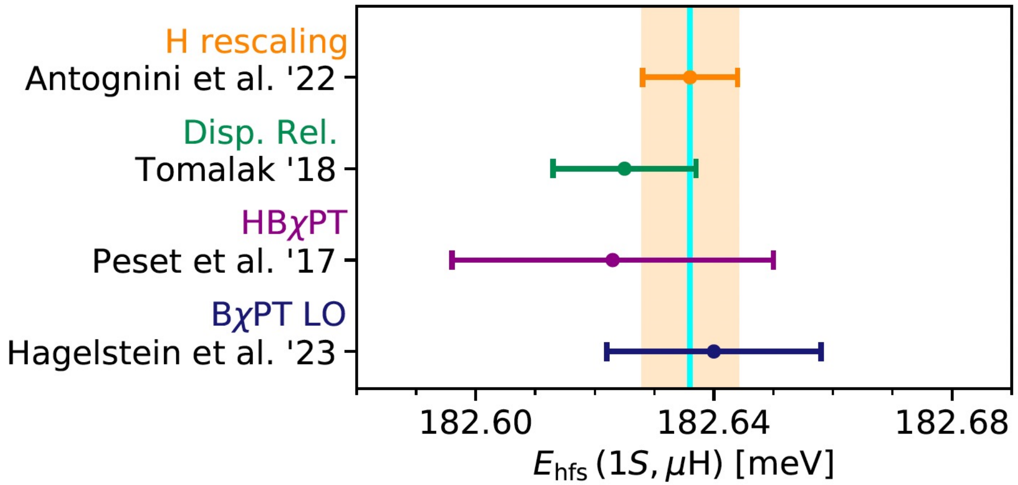
Higher-order corrections and HFS in μH



- One-photon exchange is insufficient to describe high-precision experiments. **Nucleon/nuclear structure contributions and higher-order radiative corrections need to be considered:**

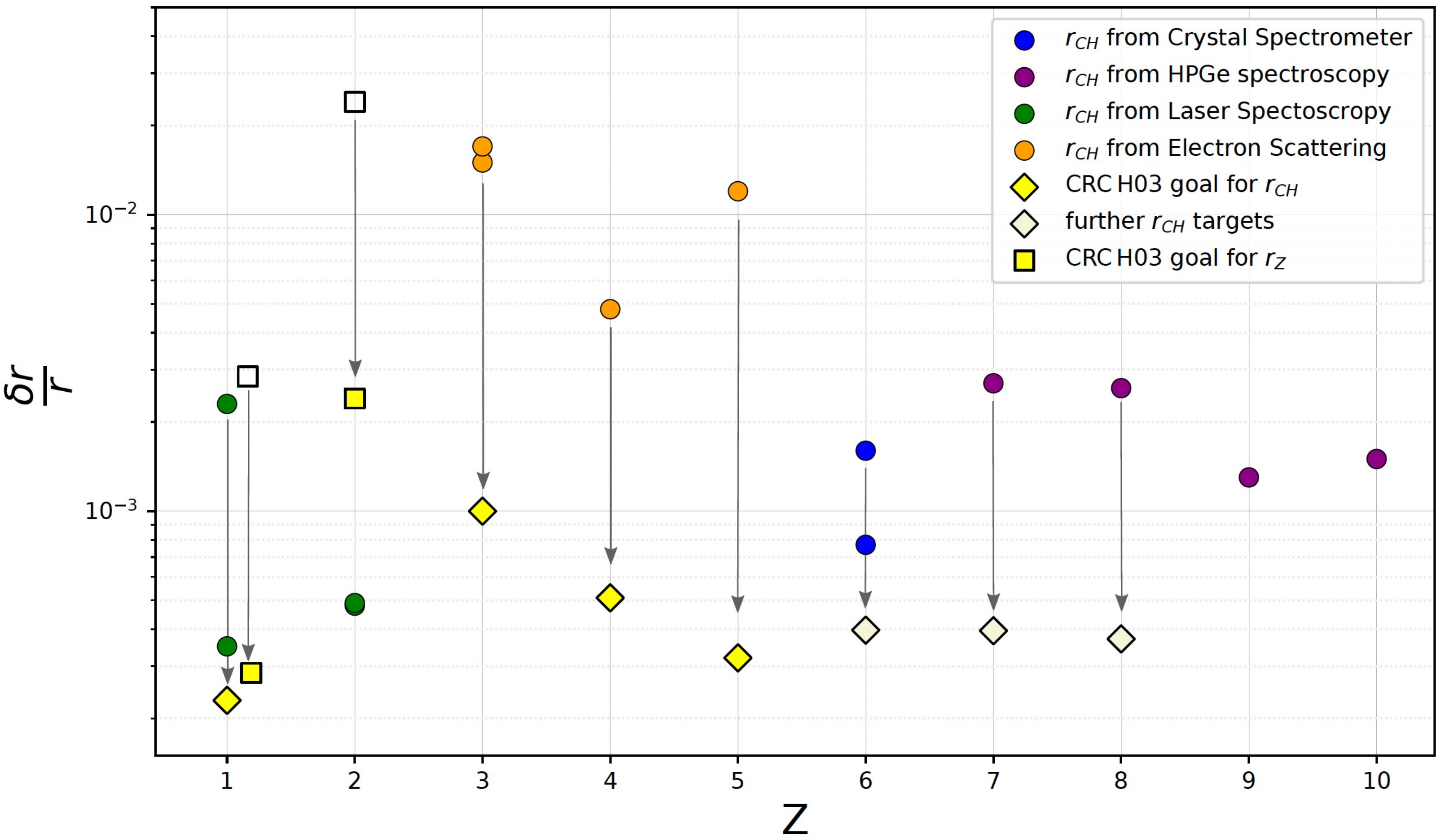
$$E(1\mathrm{S}-\mathrm{HFS}) = 183.797(7) \times (1 + 1.01656(4)\Delta_{recoil} + 1.00402\Delta_{pol}) - 1.30653(17)(\frac{r_Z}{fm})\ \mathrm{meV}$$

- High precision measurement of 1S HFS together with the improved calculations of Δ_{pol} and Δ_{recoil} will lead to 10x more precise determination of Zemach radius.



New determinations of Zemach and charge radii

- New technologies and advances in measurement techniques will provide an order of magnitude more precise values of radii.

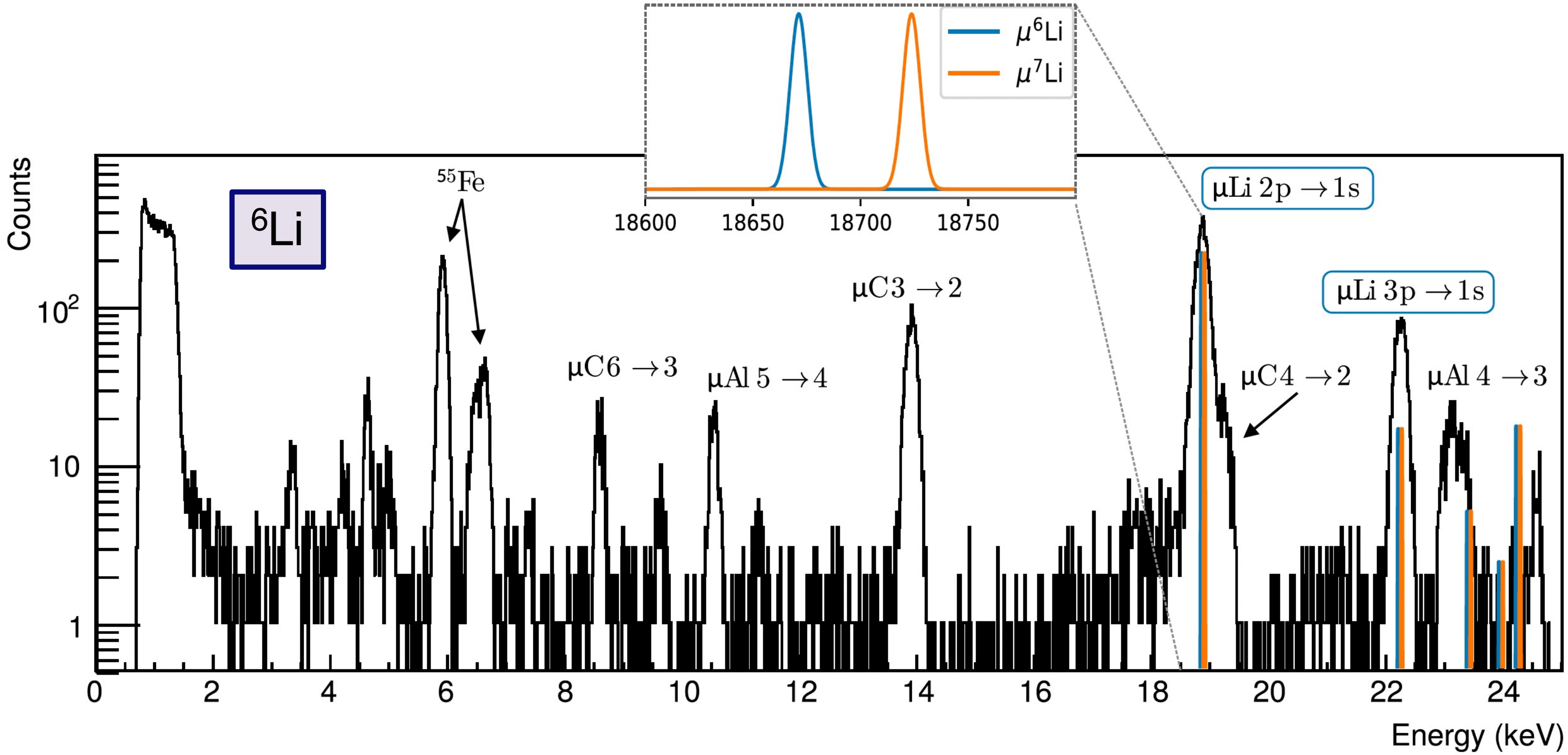


- Results of spectroscopic measurements as benchmark for EFT calculations and results of Lattice QCD.

QUARTET Collaboration and MMC Detectors

- Core new components are cryogenic Magnetic Metallic Microcalorimeters (MMCs) with superior energy resolution compared to existing detectors.

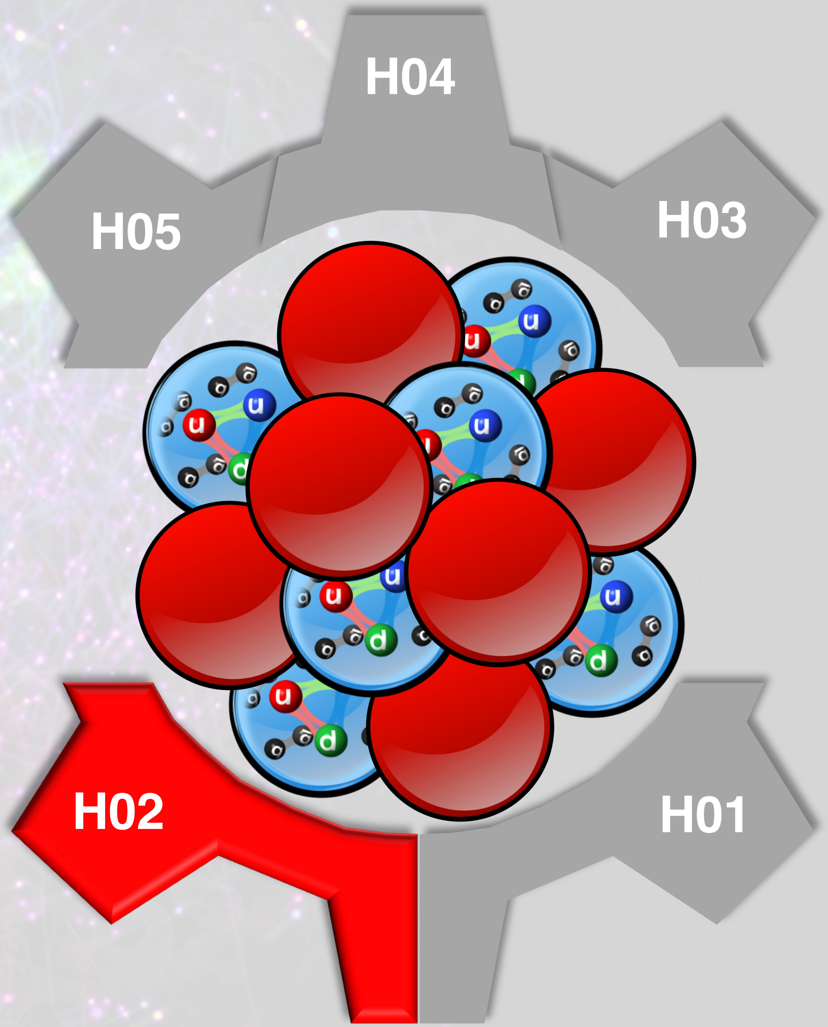
- At least ten-fold improved precision on the X-ray transition energies of light muonic atoms.



Electrons for neutrinos: nuclei

Project goals:

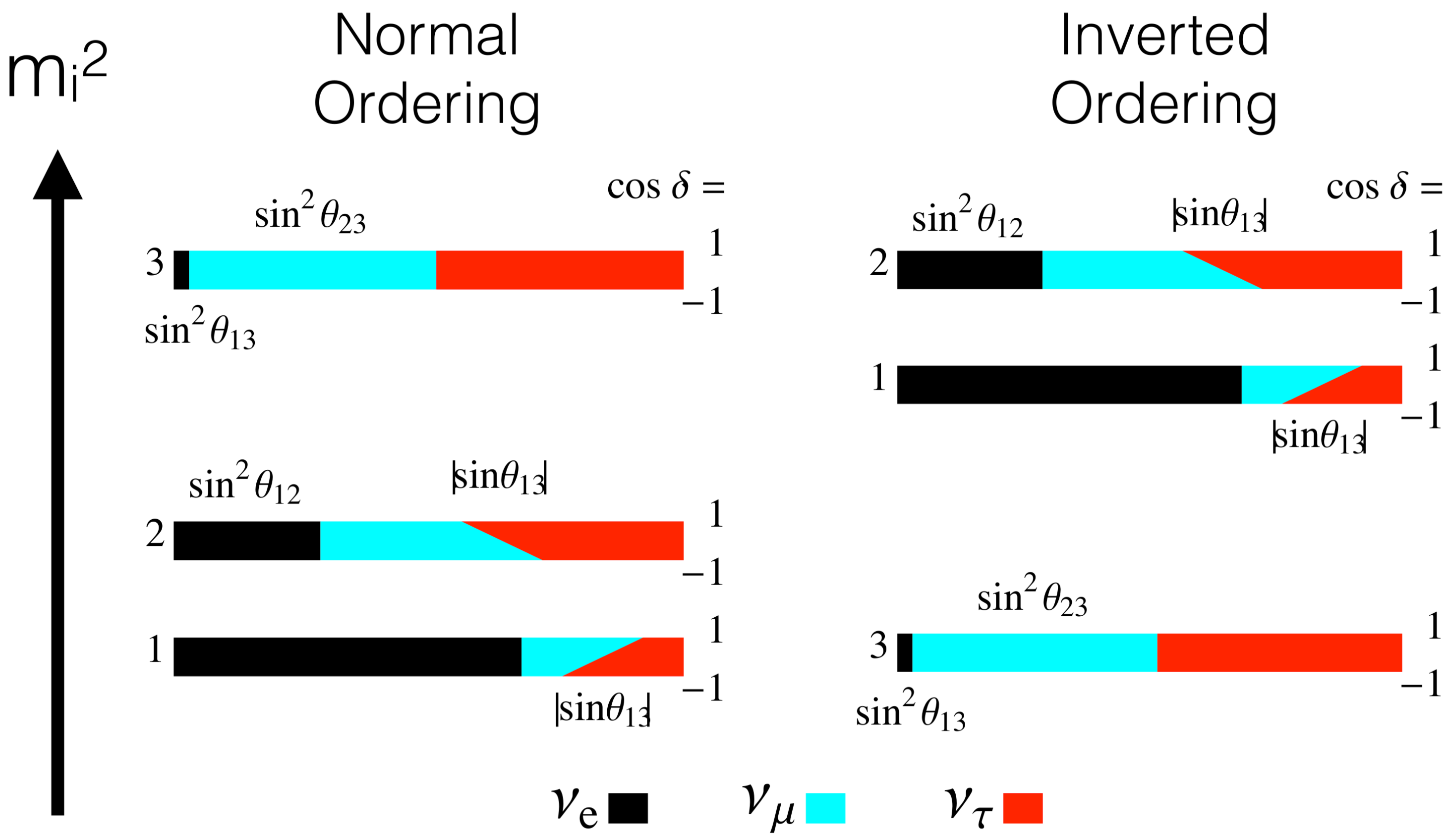
- Theoretical and experimental studies of electron scattering off medium-mass nuclei
- Better understanding of the nuclear structure and dynamics governing lepton-nucleus cross sections.
- Reduced systematic uncertainties emerging from nuclear structure that affect the precision of neutrino oscillation experiments.



PLs: S. Bacca, L. Doria, J. Sobczyk

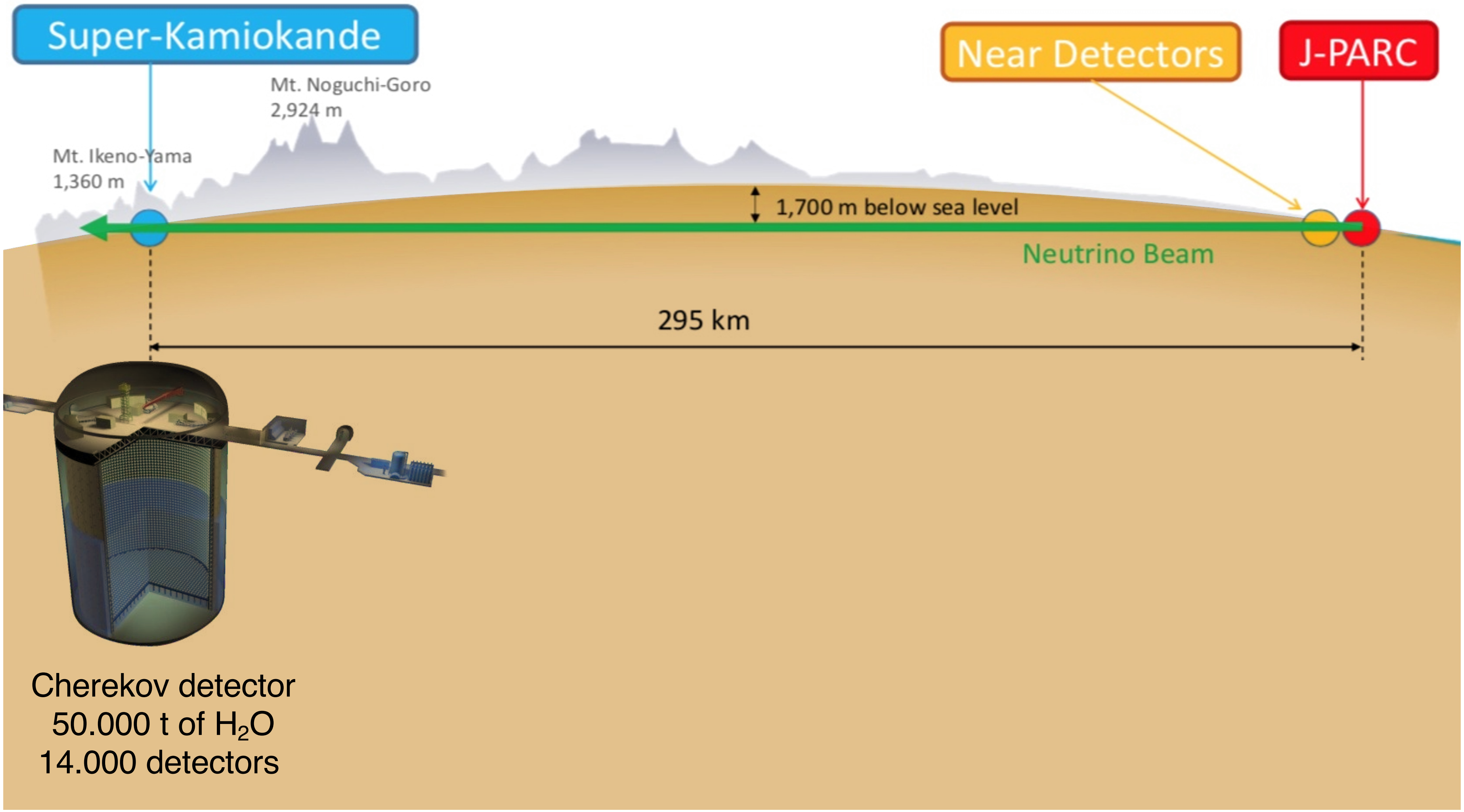
Neutrinos

- Standard Model considers neutrinos of three leptonic flavors.
- Neutrinos have extremely small masses.
- Neutrinos change flavor.



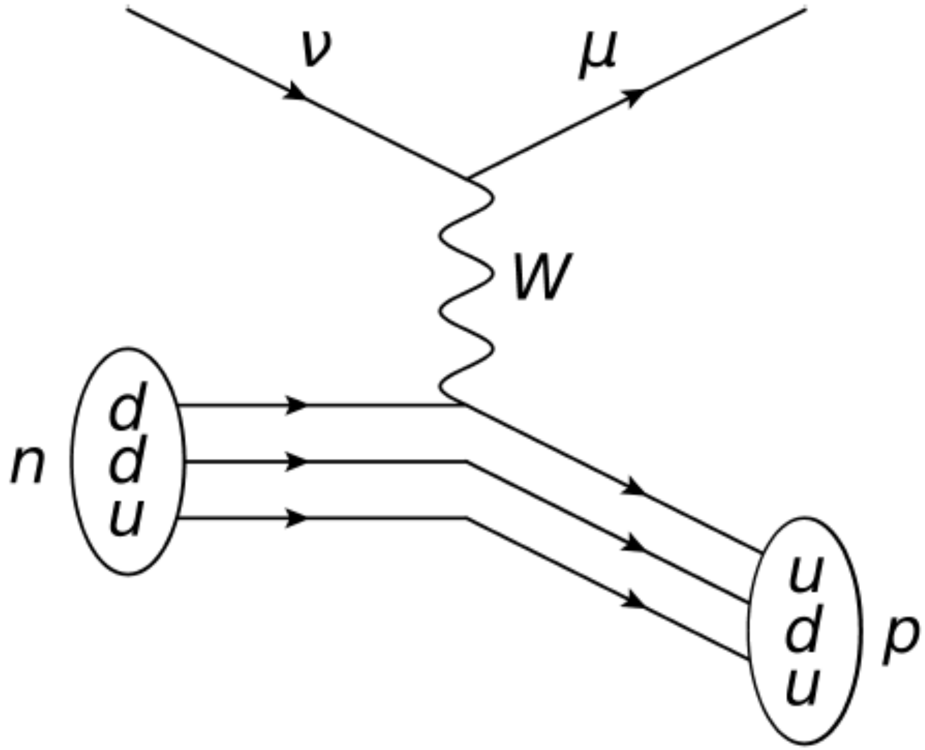
e. g. T2K

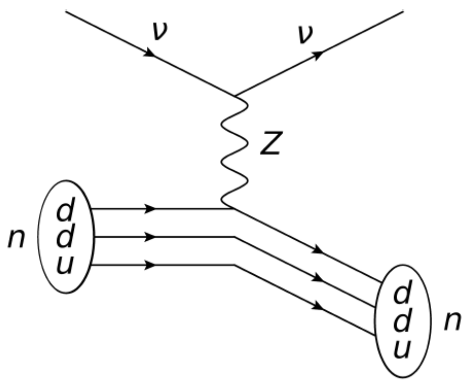
- T2K provided most precise measurement of θ_{23} and constraints on δ_{CP} .

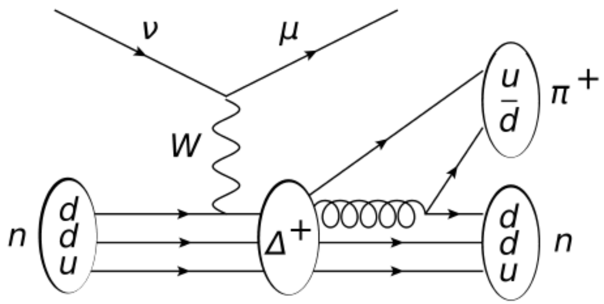


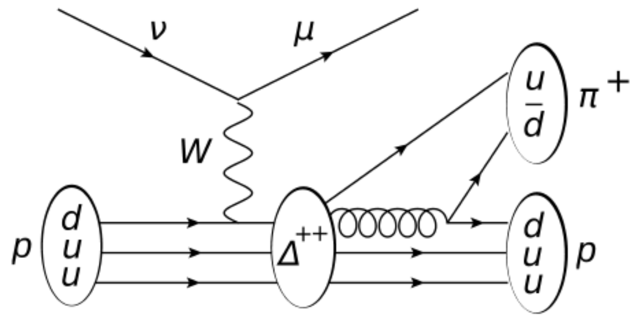
Interactions with neutrinos

- In detector neutrino interacts with nuclear medium predominantly through **CCQE**.
- Contributions of other processes are also present: NCQE, CCRES, …
- **<u>Accompanying effects: FSI, SRC.</u>**



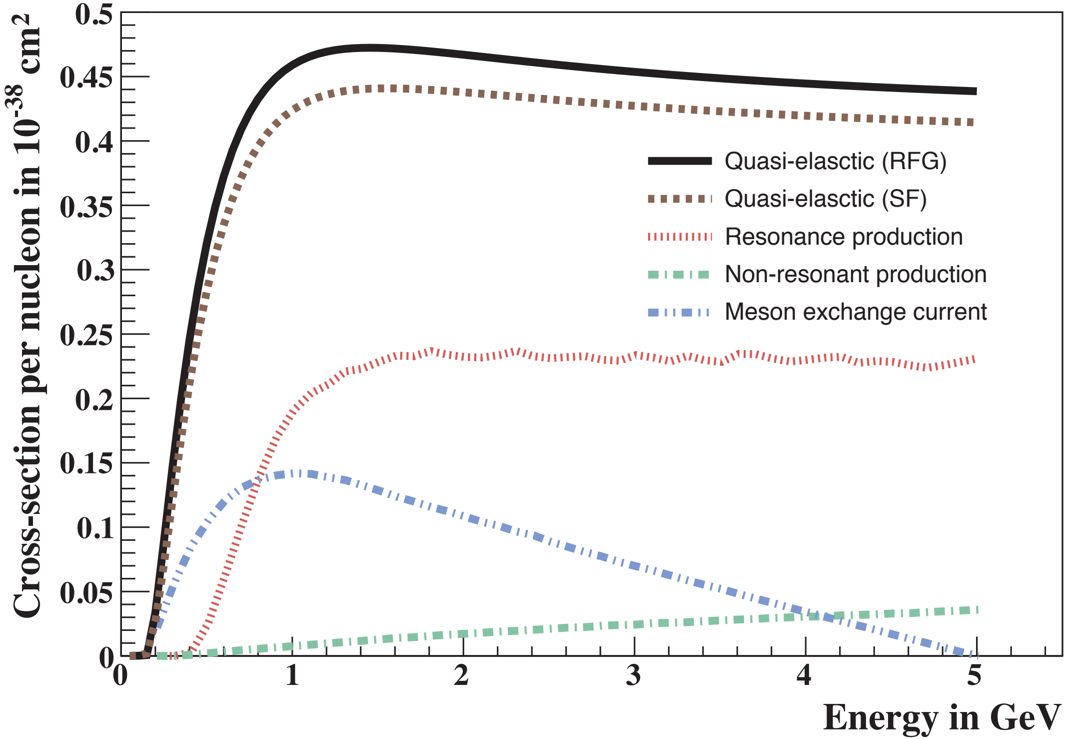


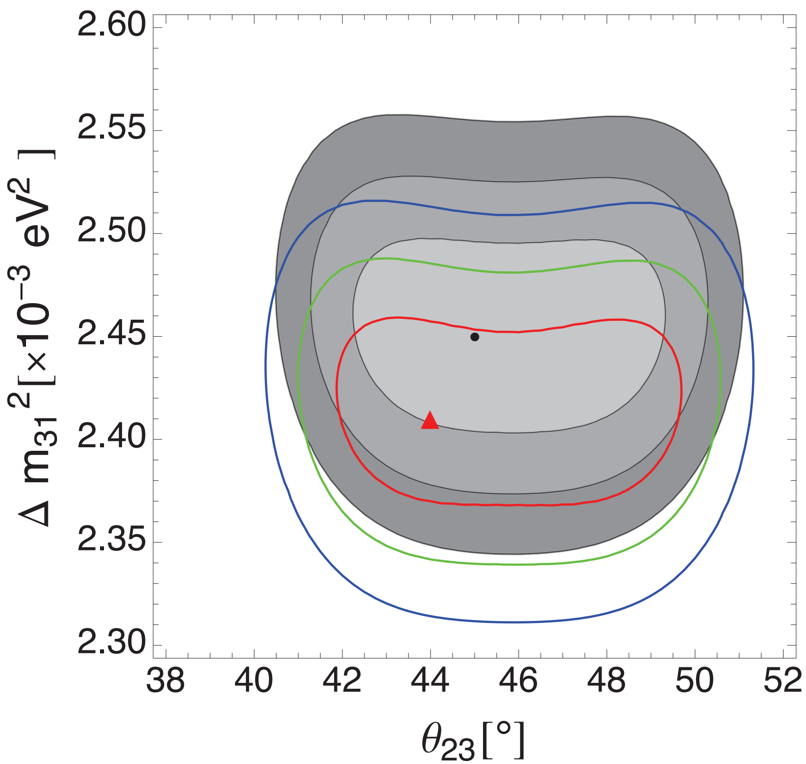




Interpretation of neutrino experiments

- Interpretation of signals detected in accelerator-based neutrino experiments depends strongly on the nuclear models/theories built-in the event generators.
- Reliable description of nuclear interaction is crucial.





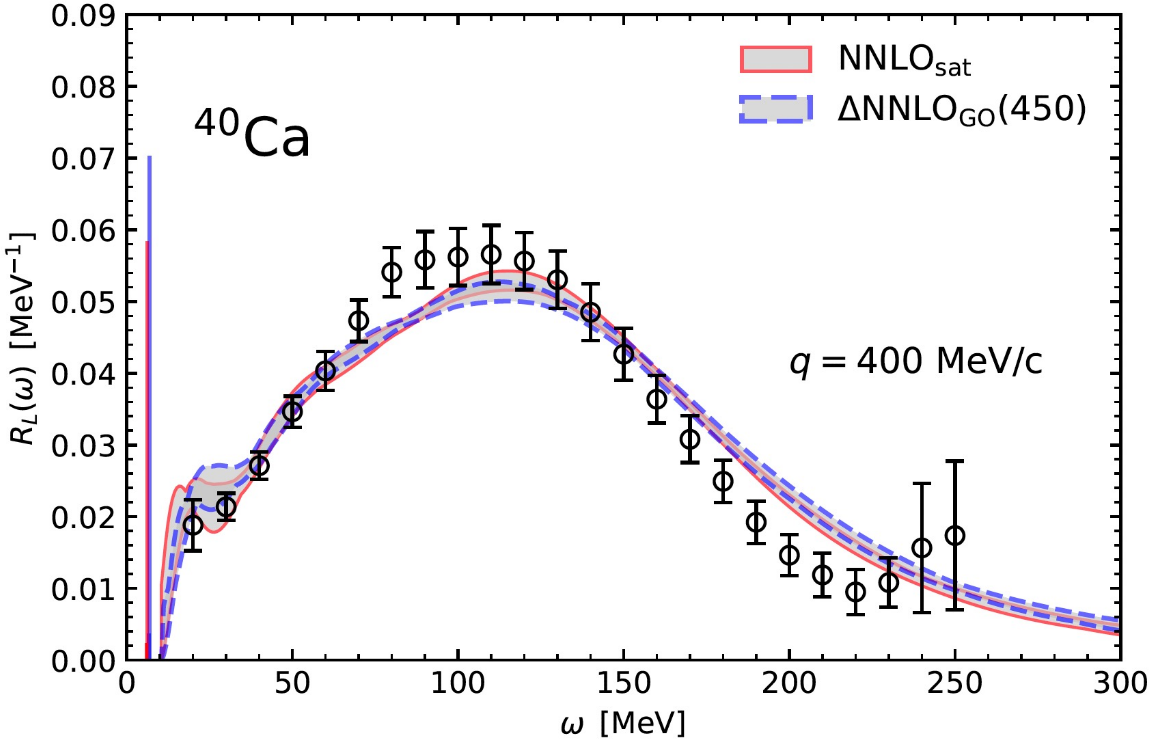
A.M. Ankowski, C. Mariani (arXiv:1609.00258)

Ab initio calculations of relevant processes

- Nuclei of interest: ^{12}C, ^{16}O, ^{40}Ca.

- **Calculations of inclusive and semi-exclusive reactions based on spectral function formalism and ab-initio calculations based on LIT-CC approach.**

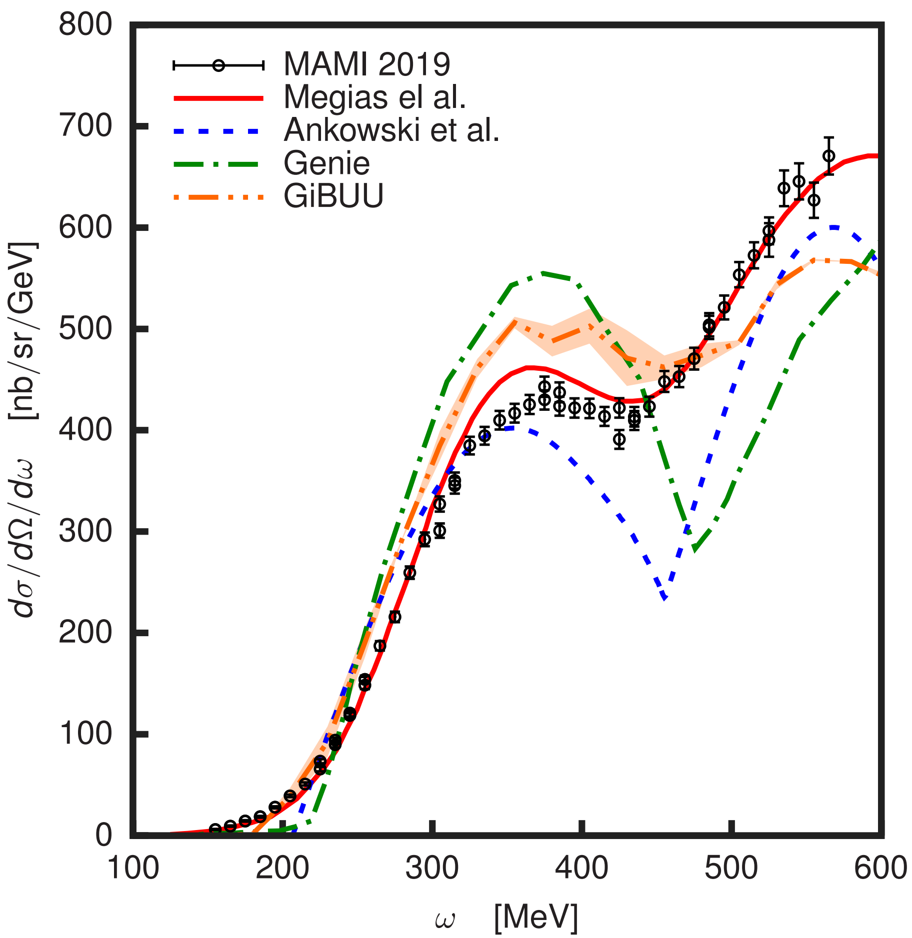
- LIT-CC method already successfully described available ^{40}Ca data at $q \leq 400 MeV/c$.

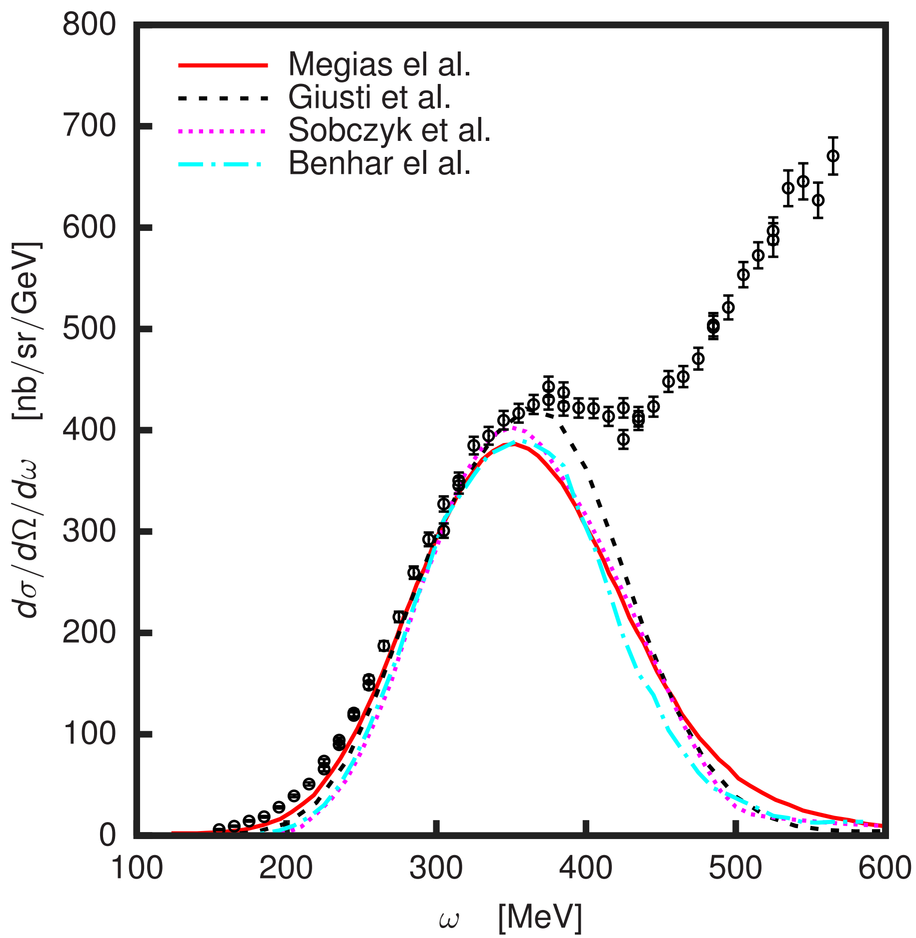


- Calculations will be challenged by the dedicated measurements at MAMI.

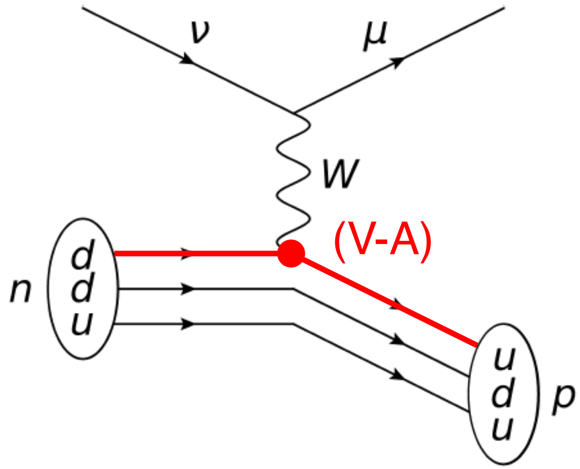
Results of Pilot Carbon Experiment

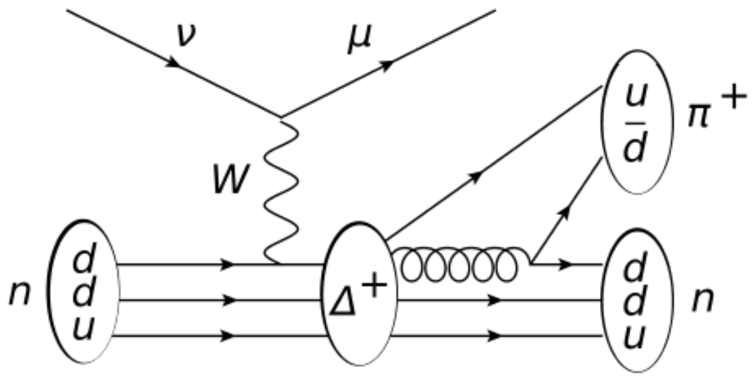
- Proof-of-principle measurement at **855 MeV** (70°)
- Comparison with the full calculations (QE+Δ+MEC)
- Comparison with QE calculations.





N-ν interraction





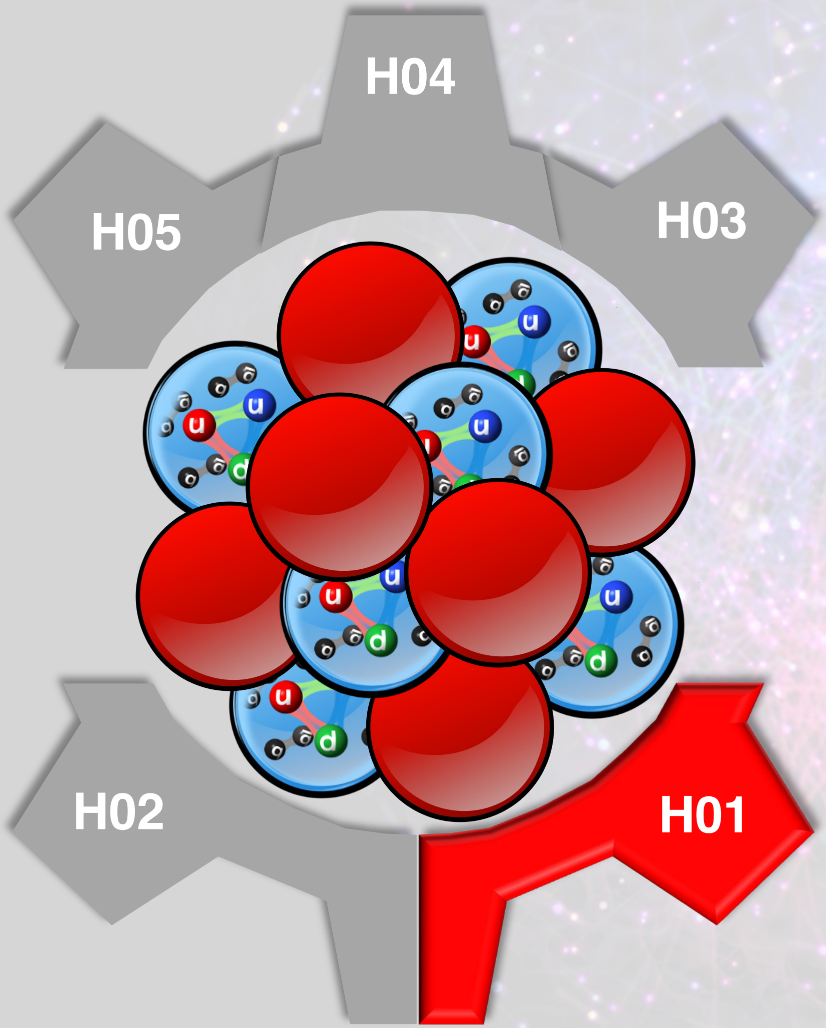
- Two parts of weak current in neutrino-nucleon interaction:

$$\langle N, \vec{p}', s' | V^\mu(y) | N, \vec{p}, s \rangle = e^{iq\cdot y}\, \bar{u}^{s'}(\vec{p}') \left(\gamma^\mu F_1(q^2) + i\sigma^{\mu\nu} \frac{q_\nu}{2m} F_2(q^2) \right) u^s(\vec{p})$$

$$\langle N, \vec{p}', s' | A^\mu(y) | N, \vec{p}, s \rangle = e^{iq\cdot y}\, \bar{u}^{s'}(\vec{p}') \left(\gamma^\mu \gamma^5 G_A(q^2) + \gamma^5 \frac{q^\mu}{2m} G_P(q^2) \right) u^s(\vec{p})$$

- Vector part and G_E and G_M well determined via electron-scattering experiments.
- **Axial part and form factors G_A and G_P investigated with lattice QCD.**
- Lattice QCD also paves the way to understanding of inelastic N-ν processes.

Nucleon form factors for ν detection

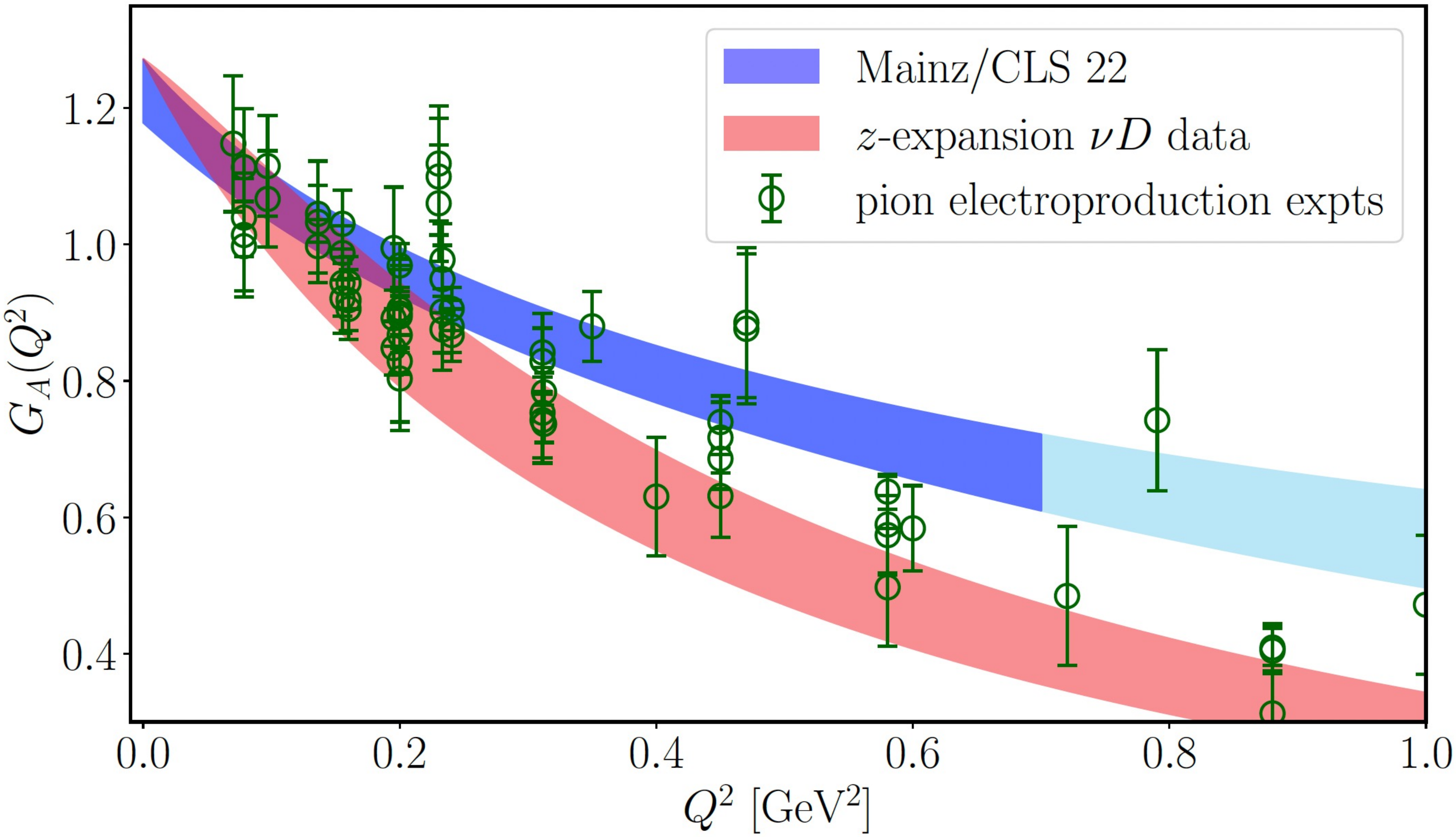


Project goals:

- High-quality lattice-QCD based calculations of the axial FFs.
- Calculated axial FFs will be essential hadronic input for nuclear-theory predictions of neutrino-nucleus cross sections crucial for long-baseline neutrino oscillation experiments

PLs: G. von Hippel, H. Meyer

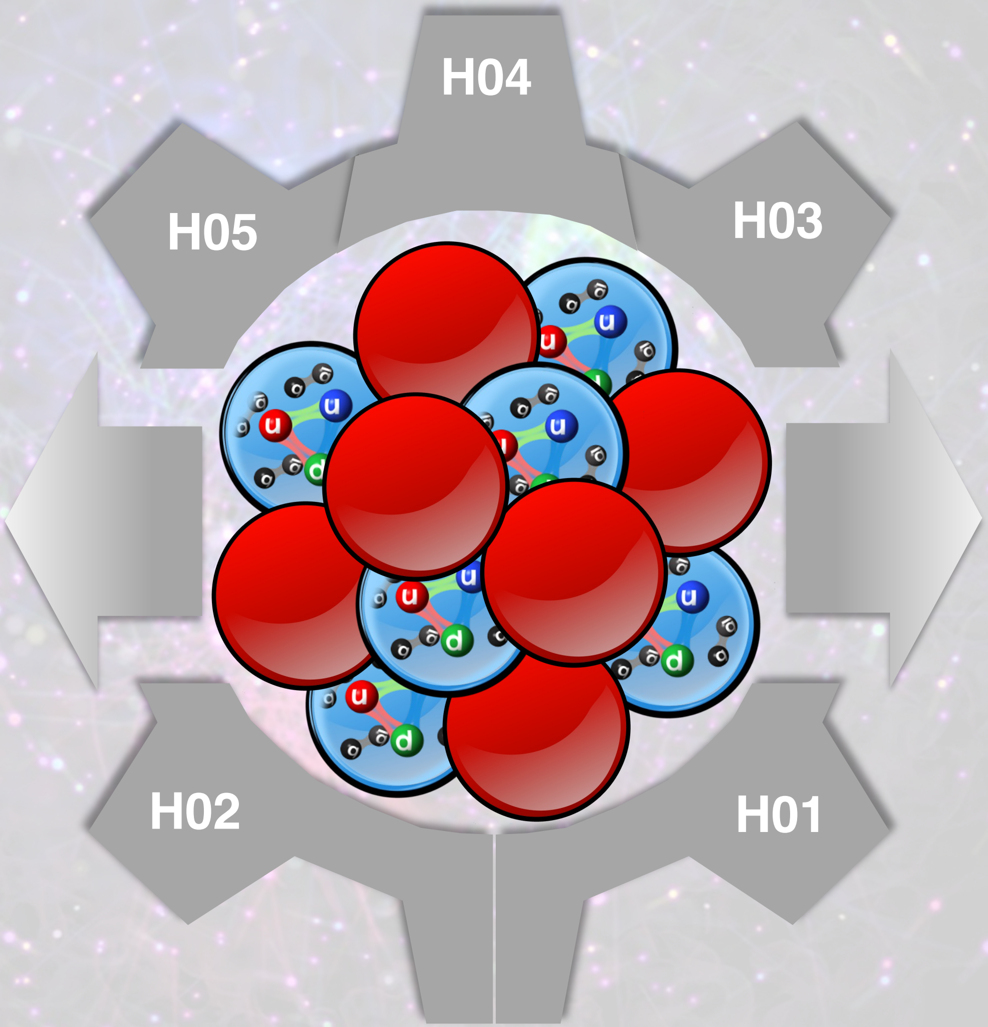
Isovector axial form factor



- The major goal of this project is to determine the isovector axial FF of the nucleon up to a virtuality Q^2 of 1 GeV^2

Summary

Insight into structure and dynamics of nucleons and nuclei and underlying forces that bind basic constituents together.



Advancement of further scientific discoveries precise tests of existing theories and models.

Happy Holidays!

Thank you!