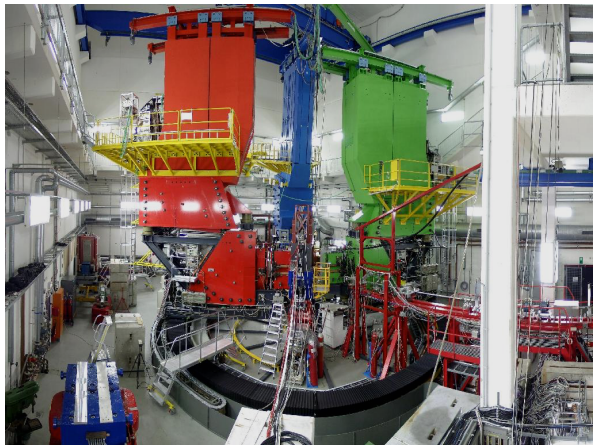
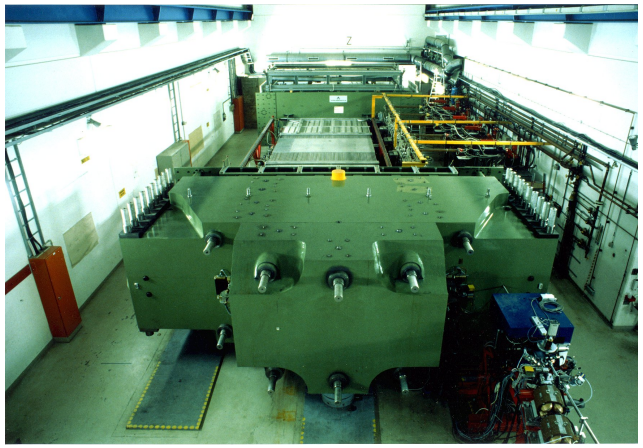




Accessing neutrino physics with electron scattering on nuclei

Miha Mihovilovič A1 Collaboration

U Ljubljana, JGU Mainz and JSI

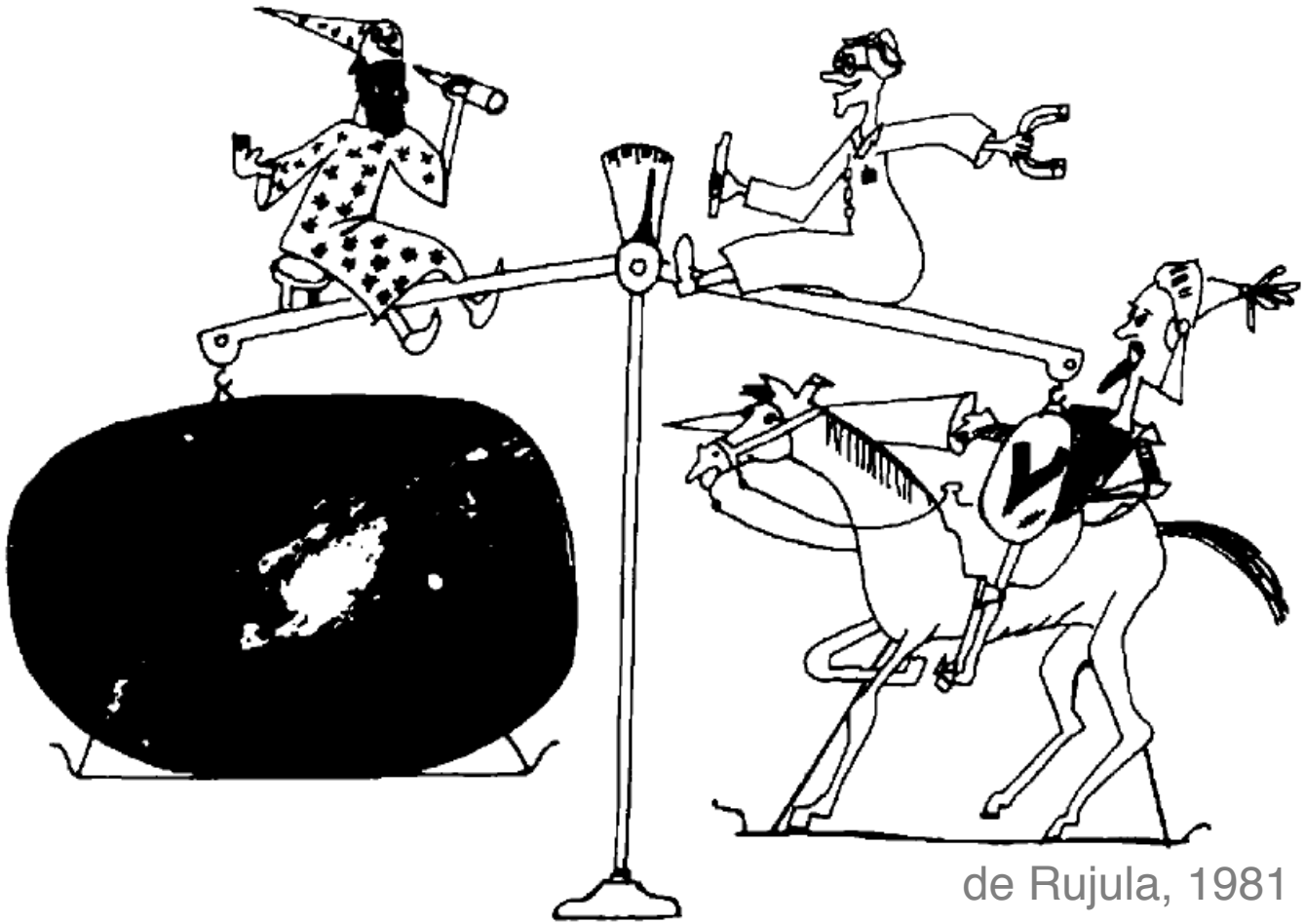
Mainz 2018

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

JG|U

SLOVENIAN RESEARCH AGENCY

Motivation

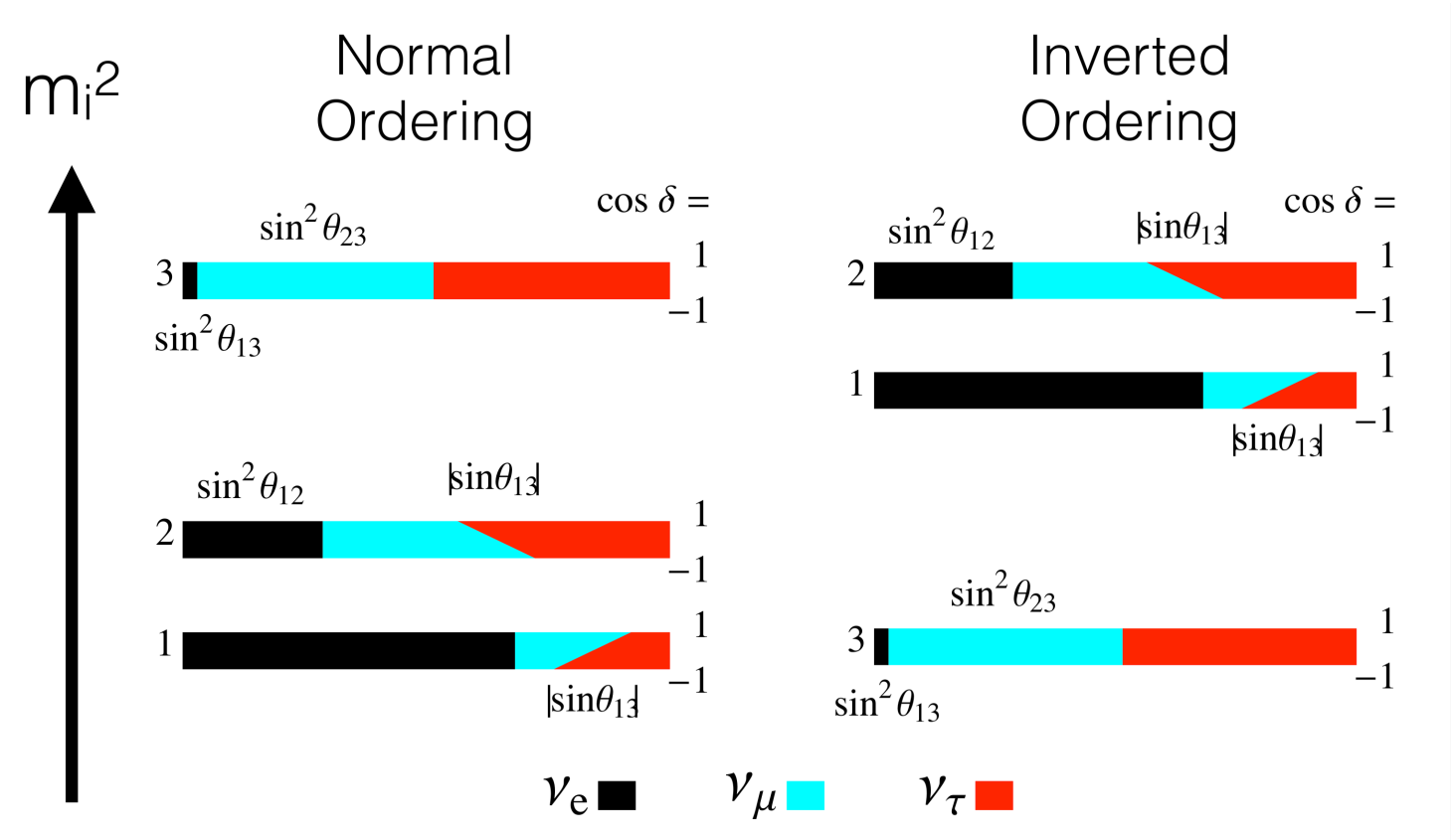


de Rujula, 1981

Precise determination of neutrino properties is a priority and motivates experiments also in nuclear physics.

Current knowledge

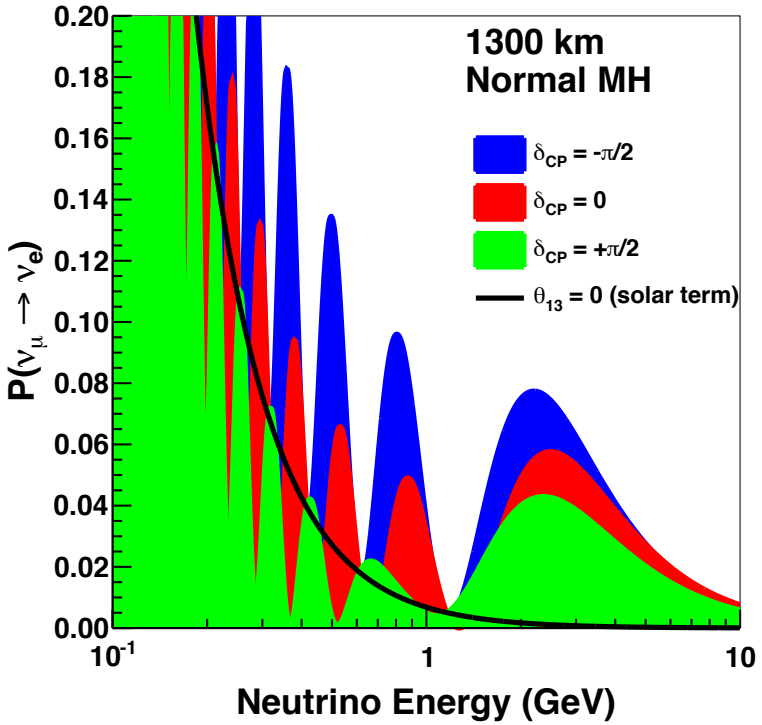
	θ_{12}	θ_{13}	θ_{23}	$\Delta m^2_{21}/10^{-5}$	$\Delta m^2_{3j}/10^{-3}$	δ_{CP}
Normal Ordering	$33.56^{+0.77}_{-0.75}$	$8.46^{+0.15}_{-0.15}$	$41.6^{+1.5}_{-1.2}$	$7.50^{+0.19}_{-0.17}$	$2.524^{+0.039}_{-0.040}$	261^{+51}_{-59}
Inverted Ordering	$33.56^{+0.77}_{-0.75}$	$8.49^{+0.15}_{-0.15}$	$50.0^{+1.1}_{-1.4}$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



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:

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

- The amplitude of the oscillation:

$$P_{\max} \propto \sin^2 2\theta$$

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 ordering (normal, inverted)?
- Determine the absolute mass of the neutrinos.

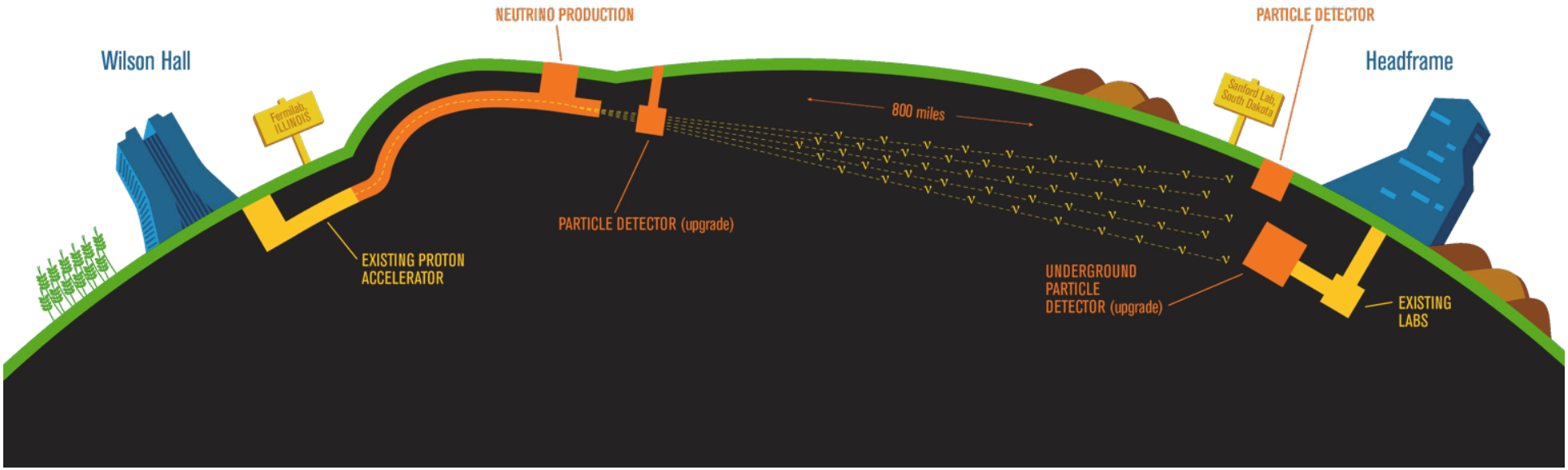
Future experiments

- New accelerator based experiment underway.

- Combines neutrino source at Fermilab and 40t liquid Ar detector at SURF.

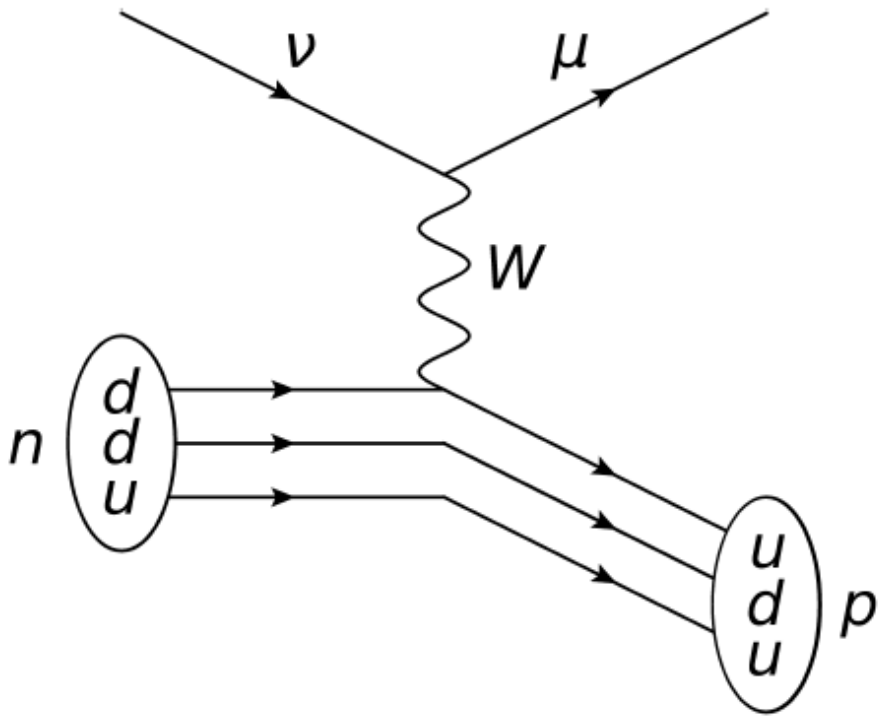
DEEP UNDERGROUND NEUTRINO EXPERIMENT

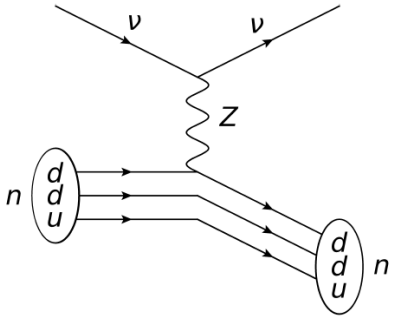
- Due to three stage production process the energy of initial neutrinos not defined. **Energy ranges from 100MeV to 3GeV**.

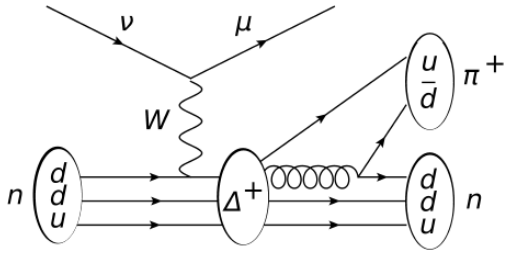


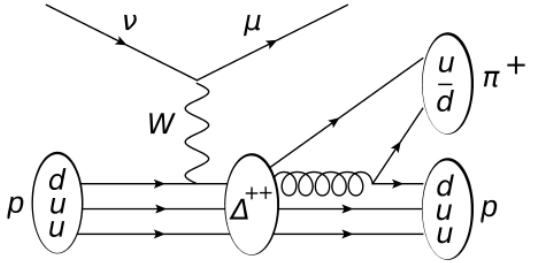
Interactions with neutrinos

- 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

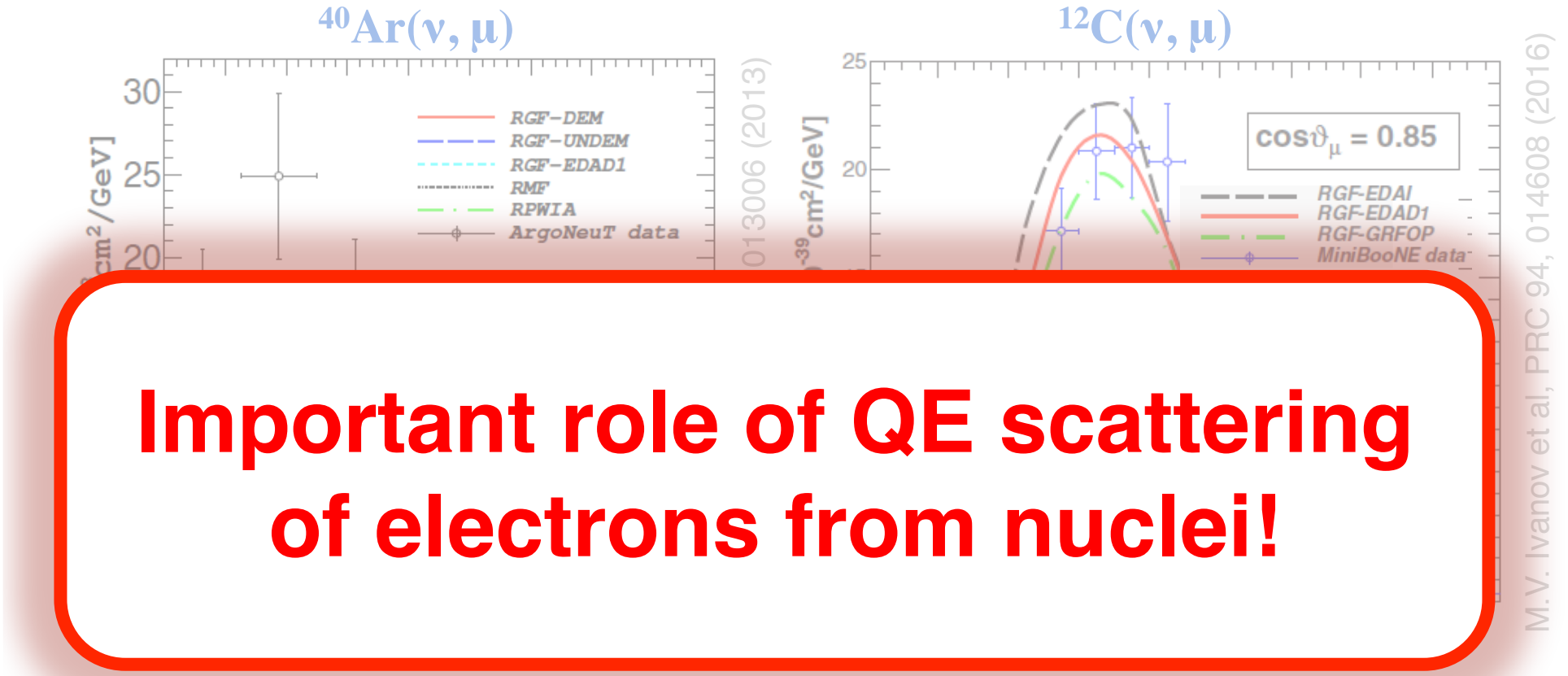
- Detected rates in the near and far detector:

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

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

- **Energy reconstructed assuming specific process. The target nucleon embedded in nucleus is not at rest.**
- **Precise input from theory is needed!**

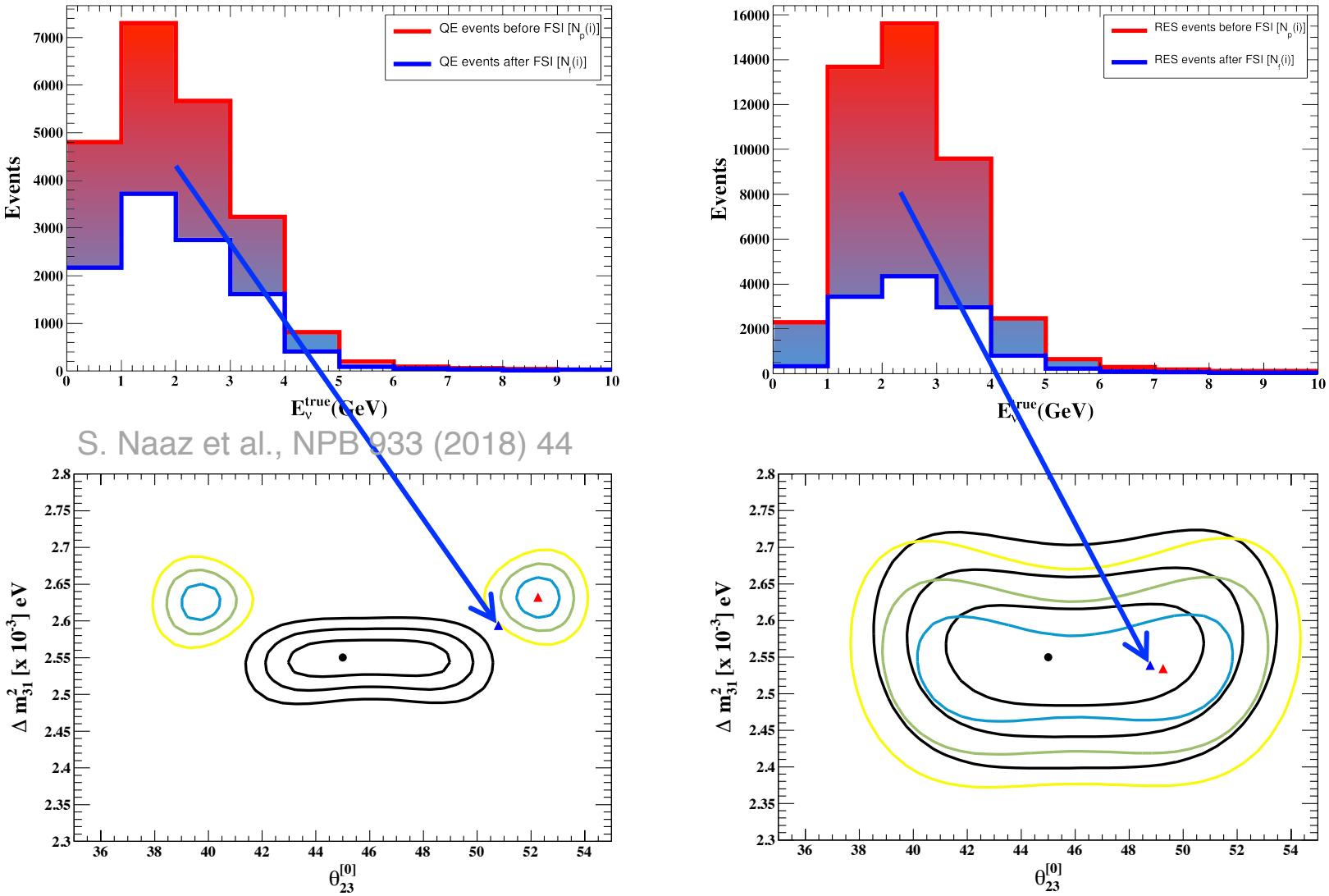
Incomplete theoretical description



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.**

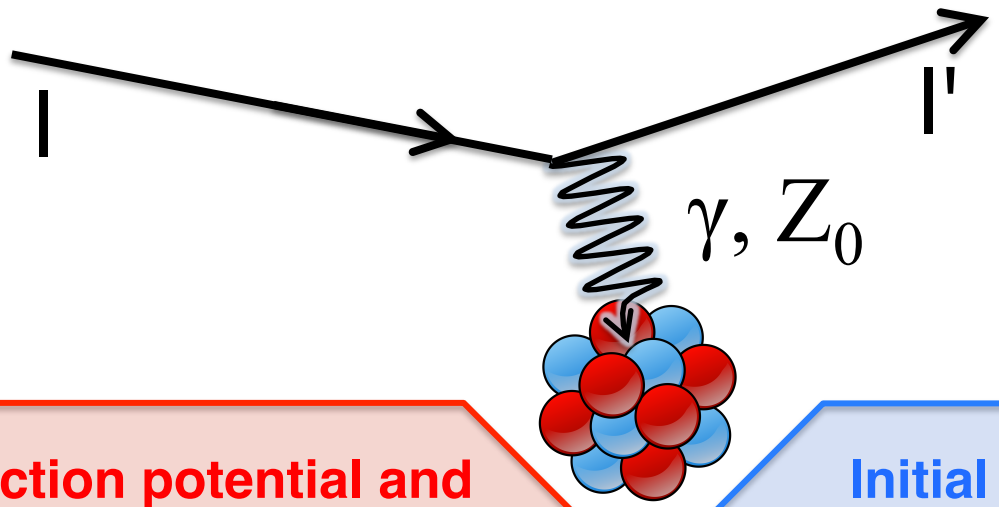
Fake vs. true neutrino events



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**.

Key ingredients



Interaction potential and nuclear current

$$J^{\mu}(\mathbf{q}) = \int \langle \Psi_f | \hat{J}^{\mu}(\mathbf{r}) | \Psi_i \rangle e^{i\mathbf{q}\cdot\mathbf{r}} d\mathbf{r}$$

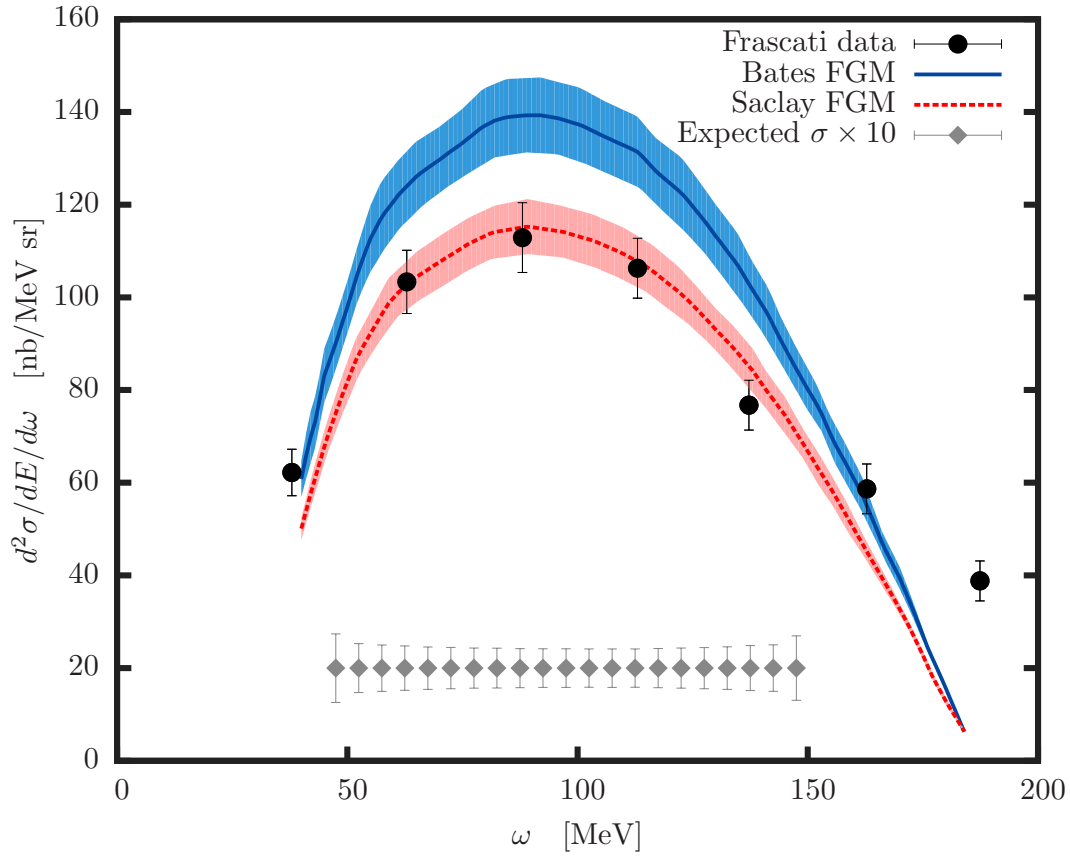
Initial wave function

$$\psi_{GS} = \psi' + \psi'' + \psi''' + \cdots$$

- The exclusive processes (l,l'p) sensitive to details of the initial nucleon ground-state wave-function.
- **Inclusive reactions (l,l') sensitive to properties of interaction potential.**
- **Best (first) tests of nuclear models are electron scattering experiments.**

Existing ^{40}Ar(e,e') data

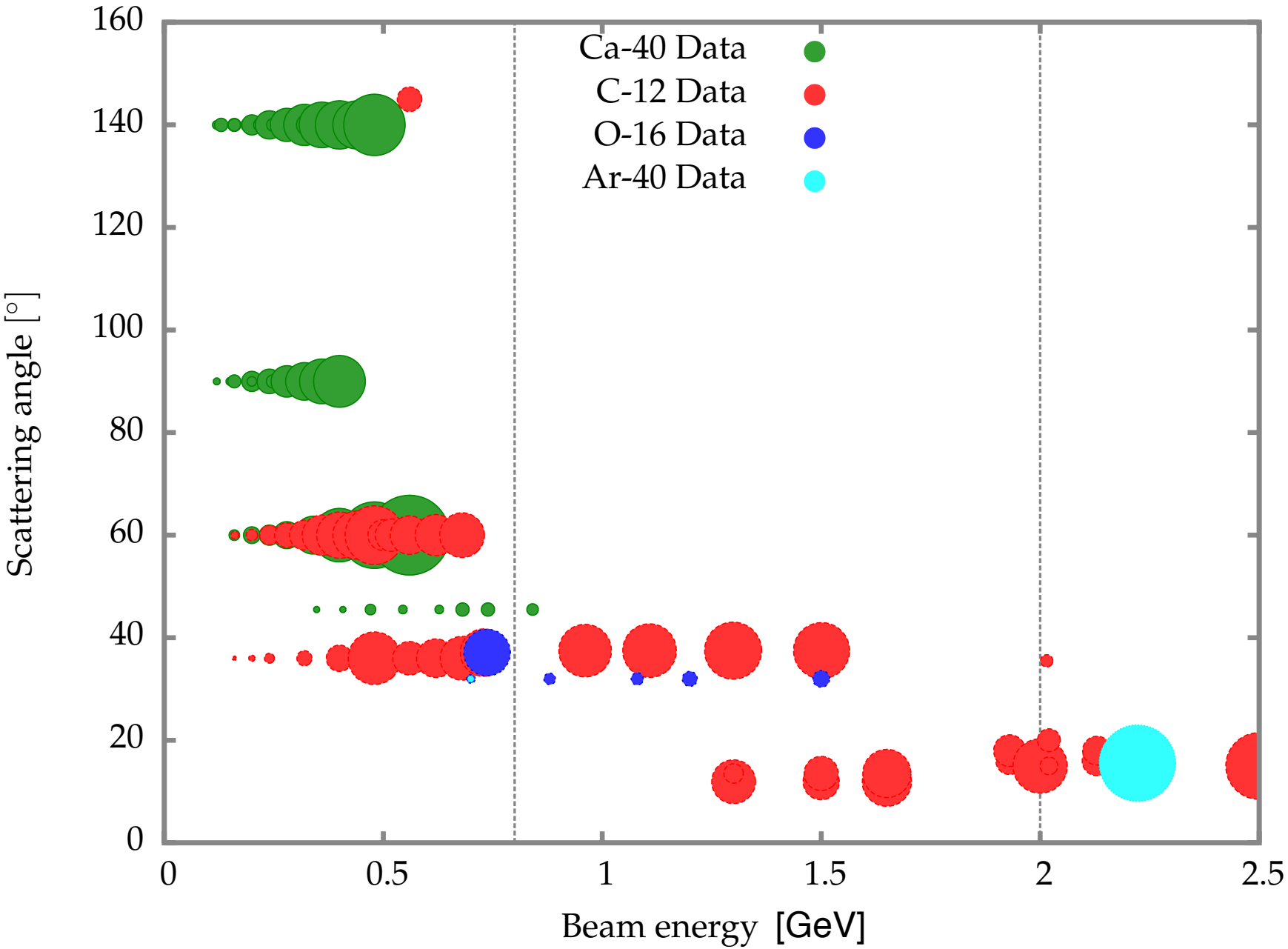
- Situation with ^{40}Ar critical. Only one inclusive data-set from Frascati available:



- Presently, theoretical models tested on the neighboring nuclei, predominantly ^{40}Ca.

- **New data are needed!**

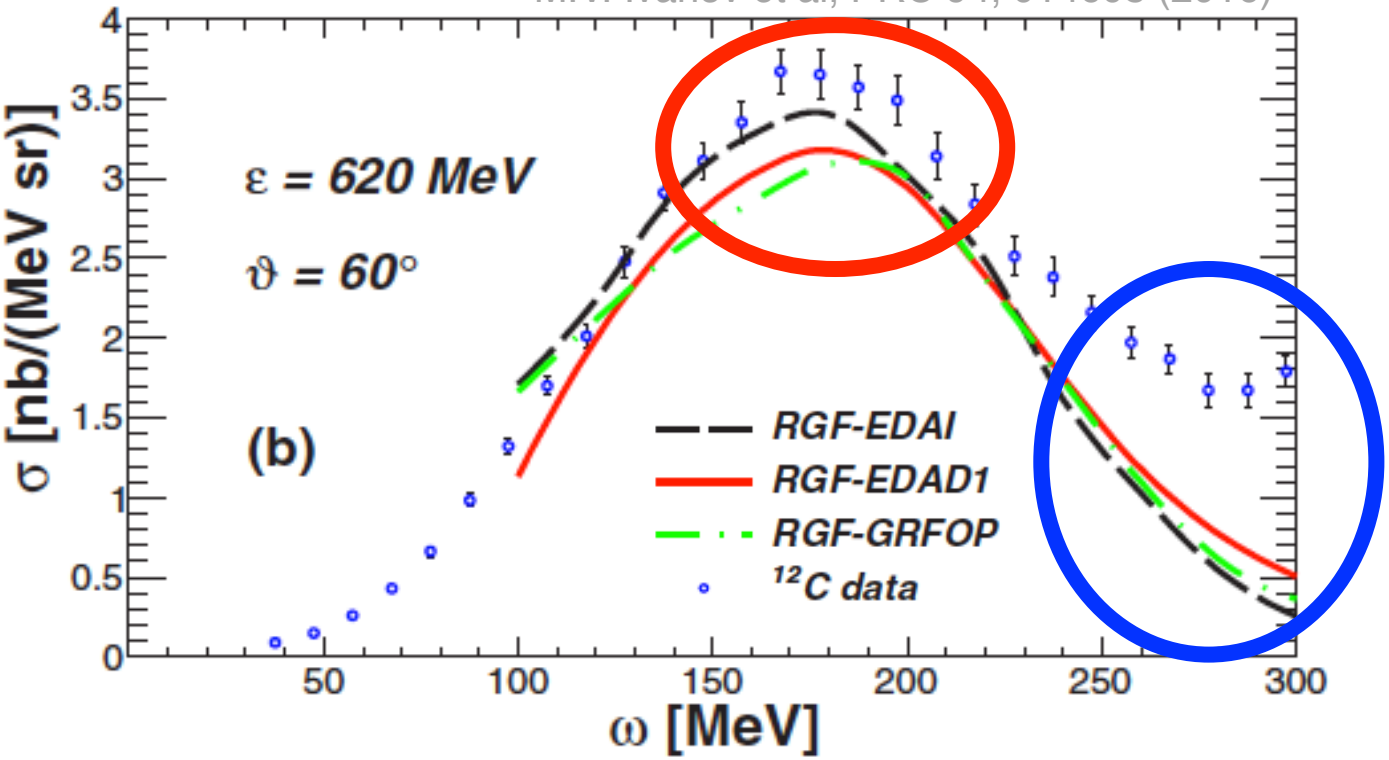
Existing Inclusive data



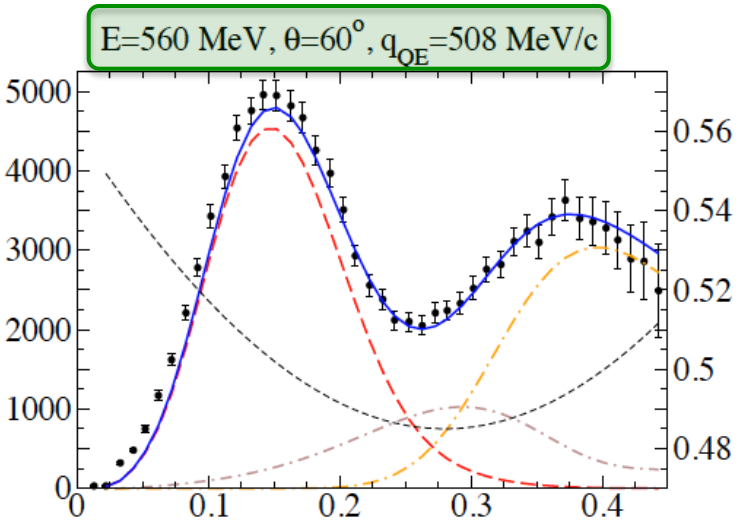
Incomplete theoretical description of (e,e’)

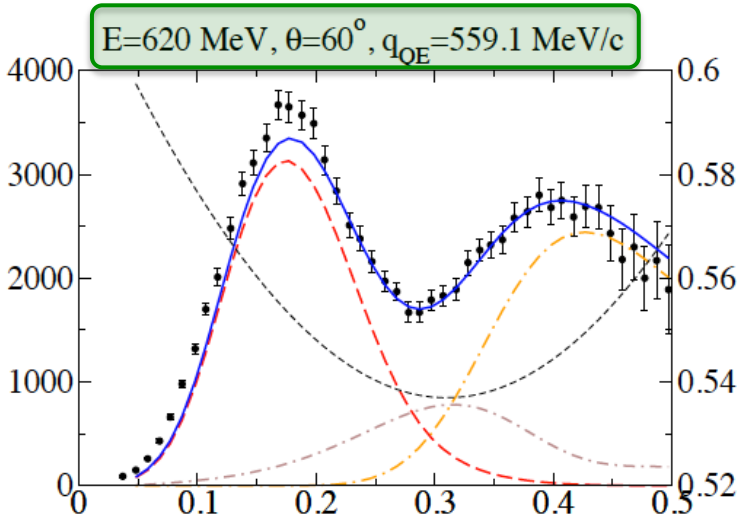
- Plethora of electron-scattering data exist for ^{12}C nucleus.
  Detailed studies possible.
- Interesting for MiniBooNE.
- Presently available models still incomplete!

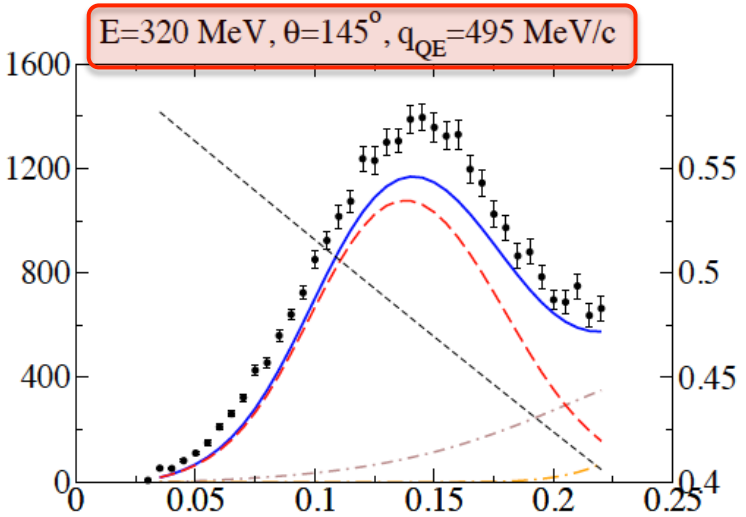
M.V. Ivanov et al, PRC 94, 014608 (2016)

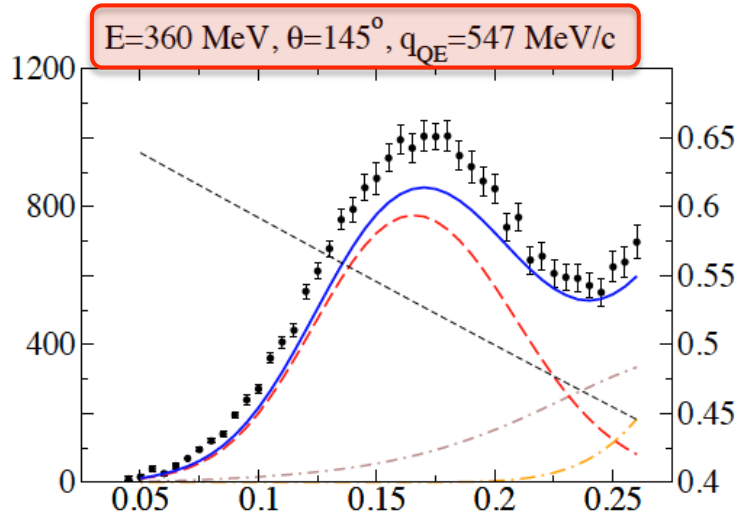


Incomplete theoretical description (e,e')









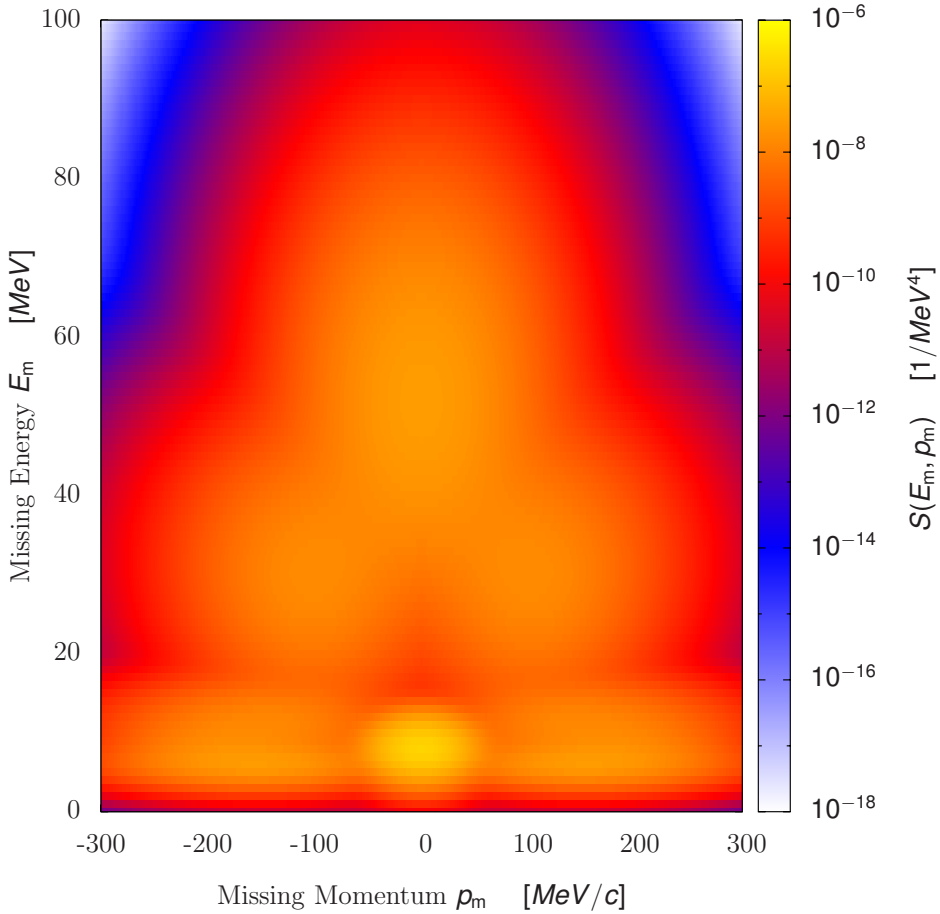
G. D. Megias et al., Phys. Rev. D 94, 013012

- Theoretical description remains deficient in the transverse kinematics!

New ^{40}Ar(e,e'p) experiment @ JLab

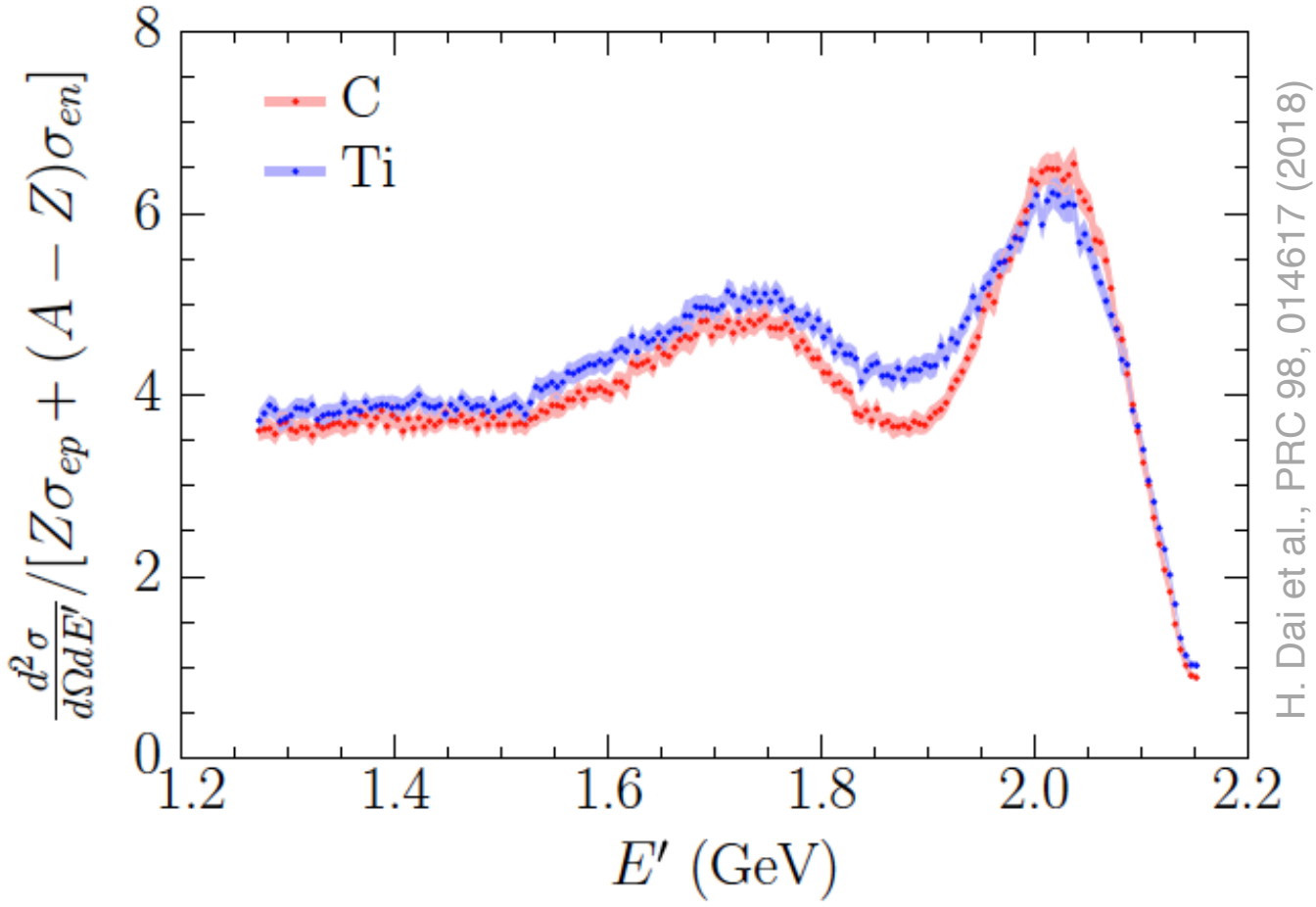
$$\frac{d\sigma}{dE_{e'}d\Omega_{e'}dE_p d\Omega_p} = K\sigma_{ep}S(E_m, p_m)$$

- The spectral function embodies the **complete response** of a nucleus.
- Experimental data validate the predictions of the many-body theories.
- First measurements done at Jefferson Lab @ 2.2 GeV.



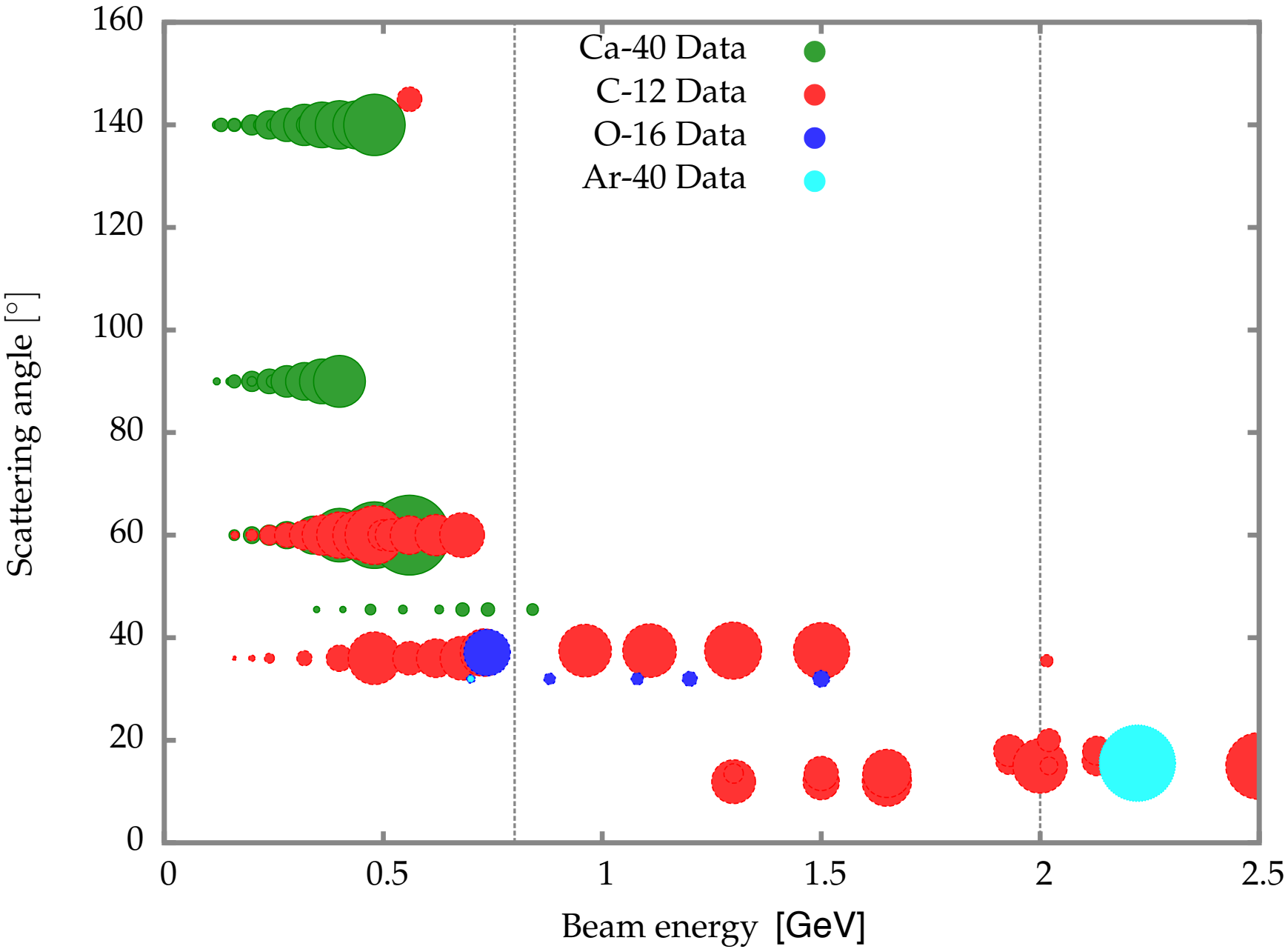
New ^{40}Ar(e,e') data from JLab

- JLab experiment collected data at fixed angle and wide range of ω.
- Analysis almost done!



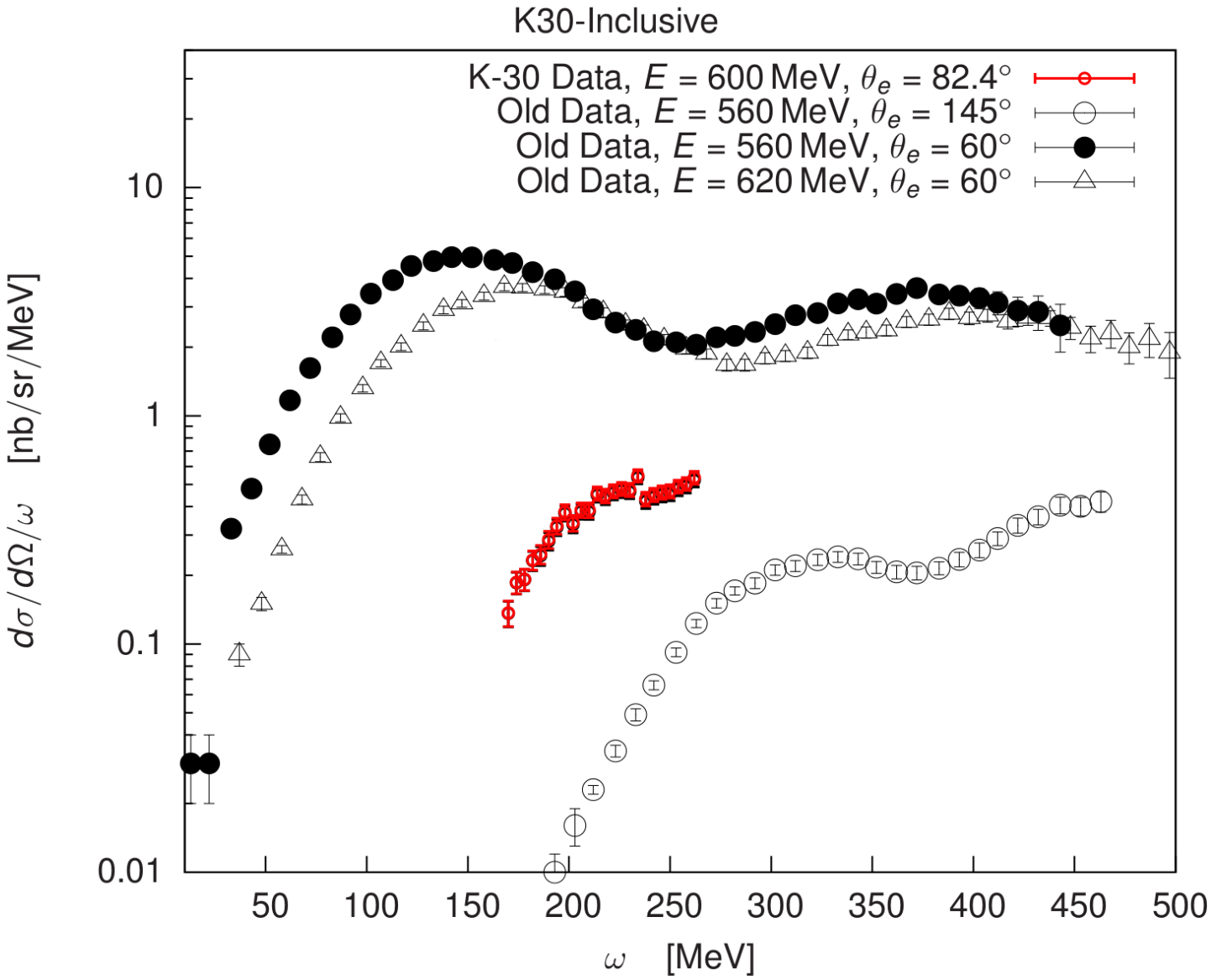
- **The endeavor could be extended with experiments at MAMI**.

No data from Mainz?



Yes, we can!

- With outstanding resolution and luminosity old data can be matched within minutes.



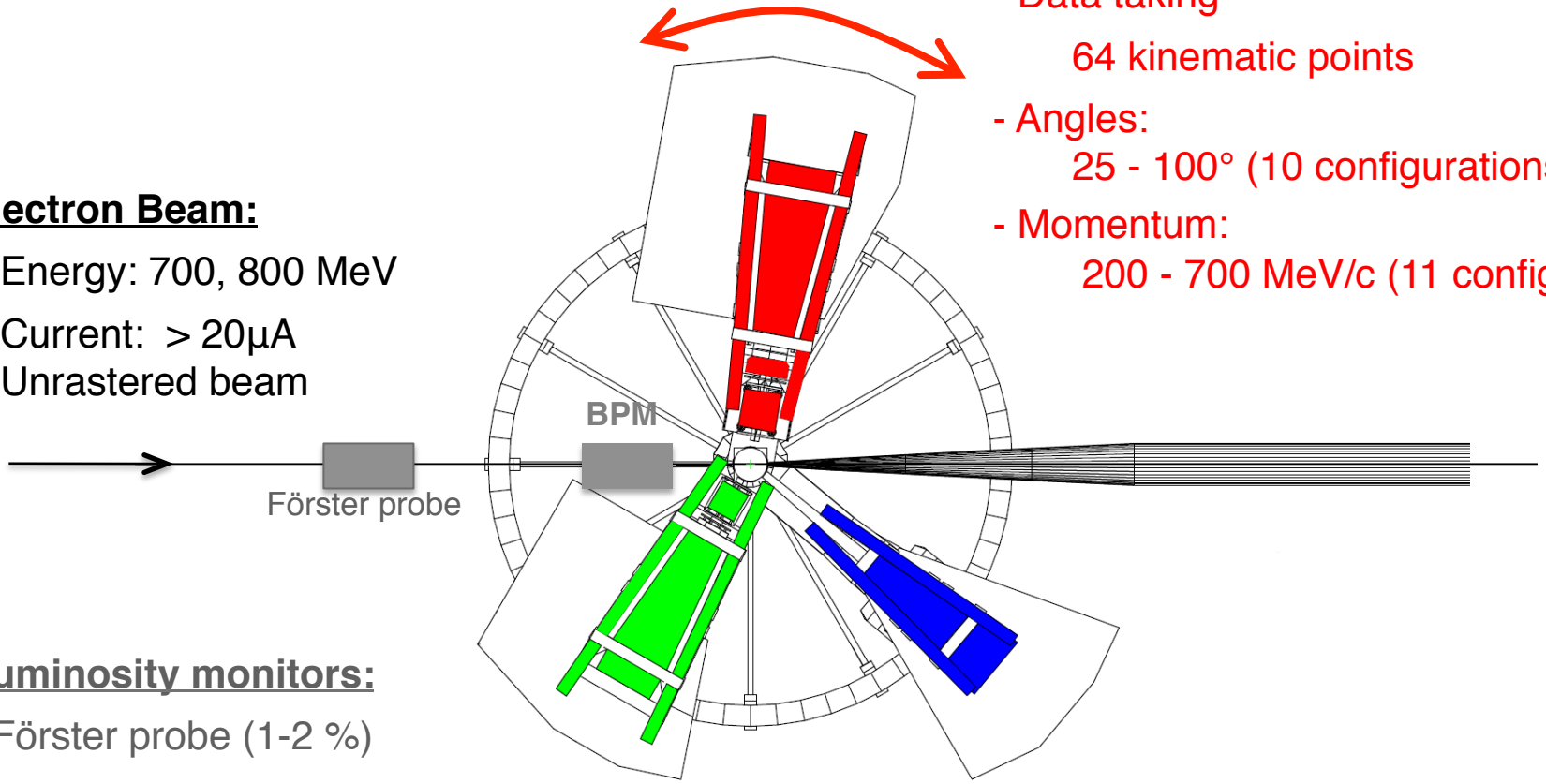
The MAMI experiment

Spectrometer A:

- Data taking
  64 kinematic points
- Angles:
  25 - 100° (10 configurations)
- Momentum:
  200 - 700 MeV/c (11 configurations)

Electron Beam:

- Energy: 700, 800 MeV
- Current: > 20μA
- Unrastered beam



Luminosity monitors:

- Förster probe (1-2 %)

Spectrometer C:

- Not used

Spectrometer B:

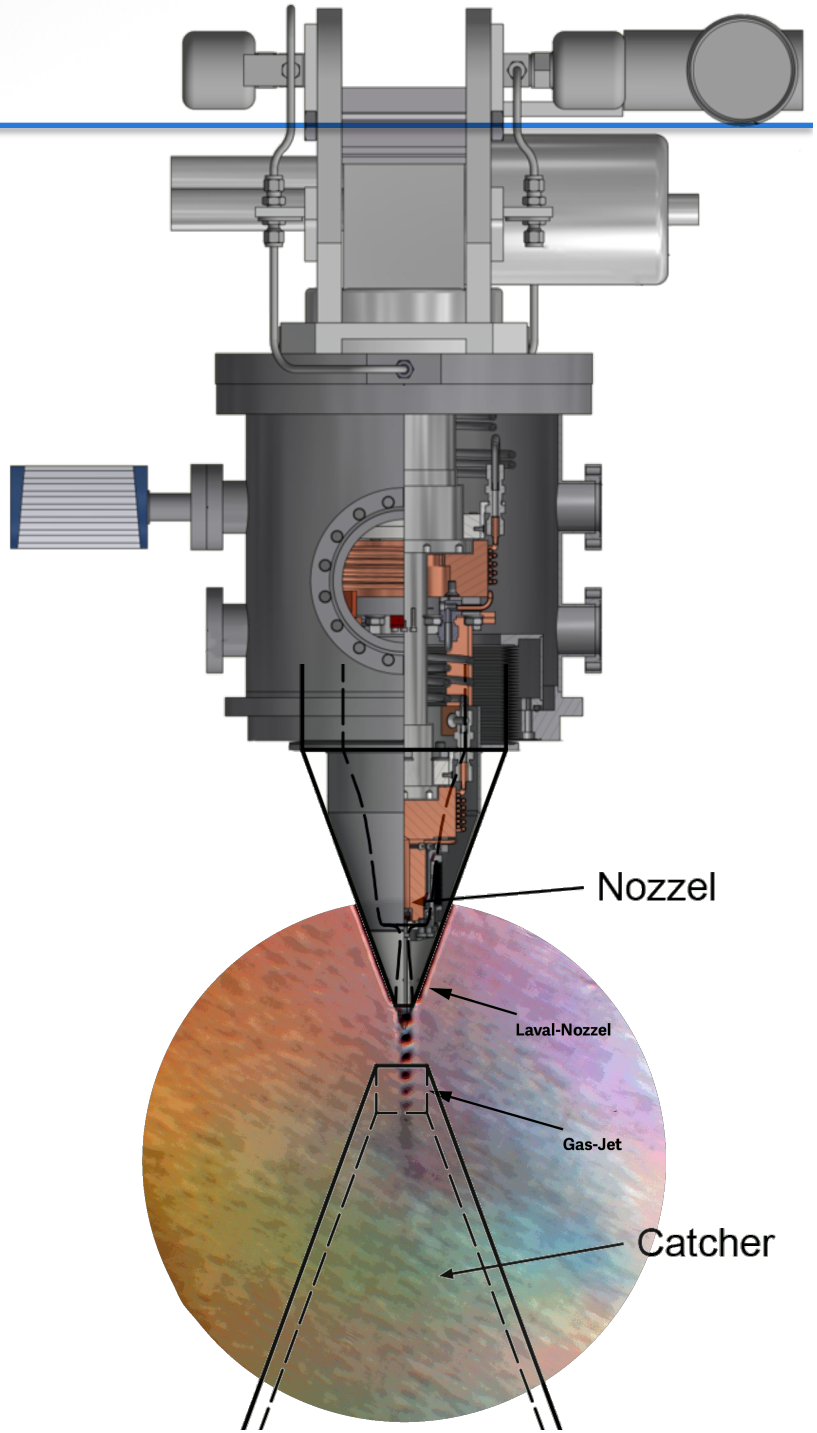
- Luminosity monitor (const. setting)
- Momentum: 700, 800 MeV/c
- Angles: 50°

Hypersonic jet target

- Target developed for MAGIX, but could be used also in A1.

- No metal frame near the vertex.
- No target walls.
- Width of the jet 2mm (point-like target)
- Originally designed for ^{1}H, but applicable also for ^{40}Ar (and ^{16}O).

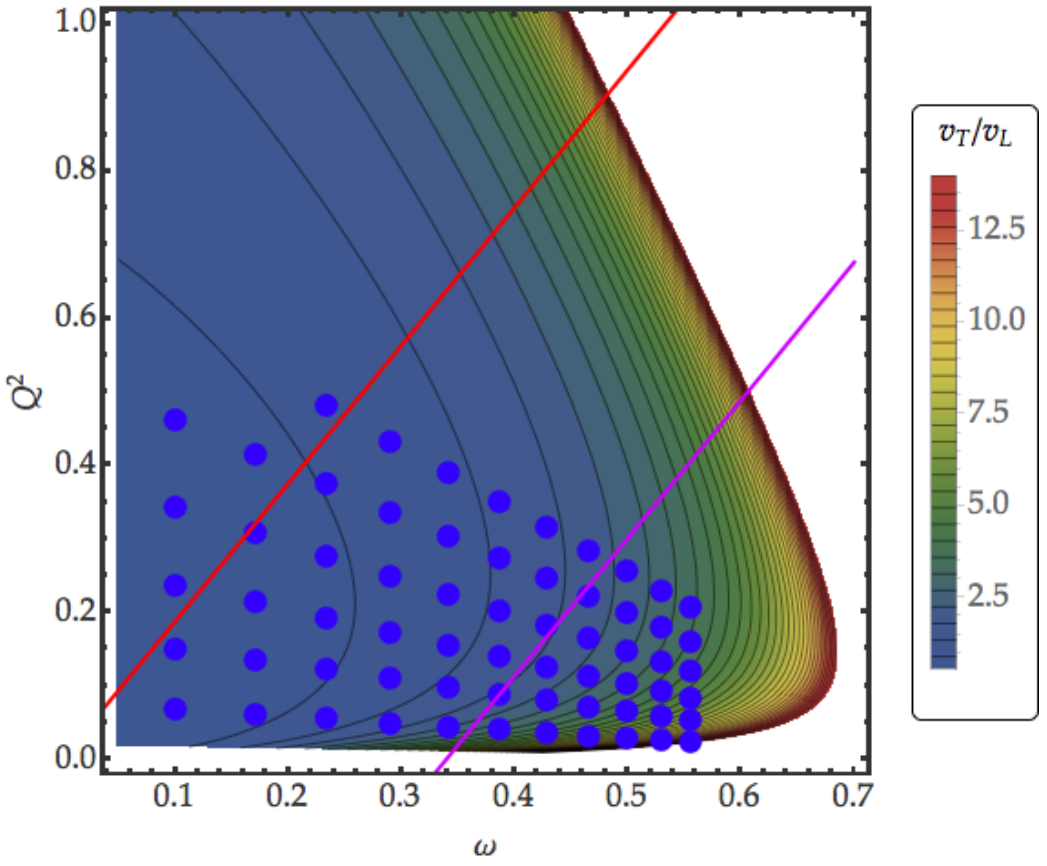
- Density of **2.7×10^{-3} g/cm^3** at 15 bar.
- Luminosity of **1.7×10^{34}/cm^{2}s** can be achieved at MAMI.



New ^{40}Ar(e,e') experiment

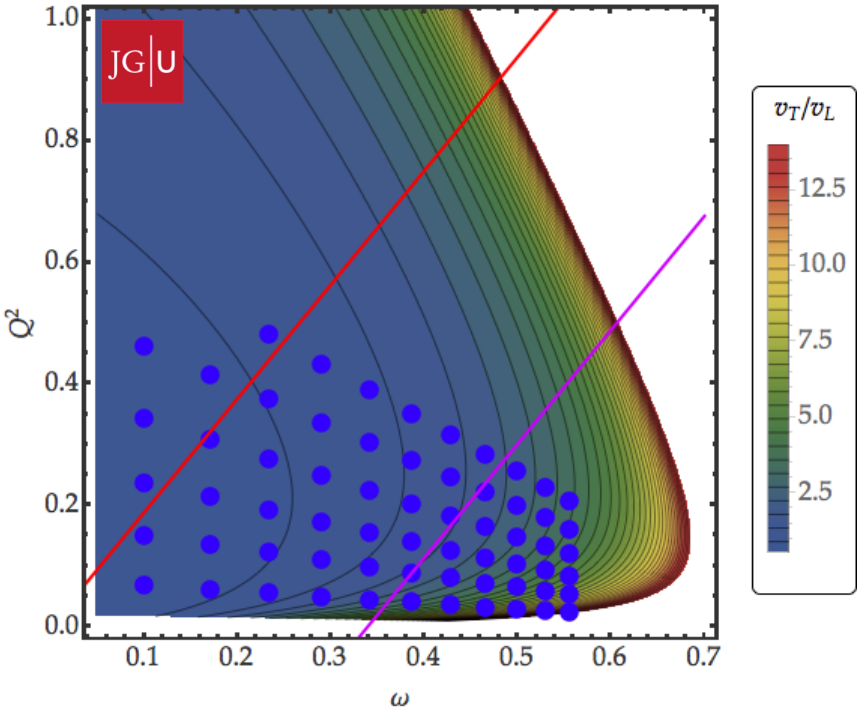
$$d\sigma = d\sigma_0 \times \left[v_L R_L + v_T R_T \right]$$

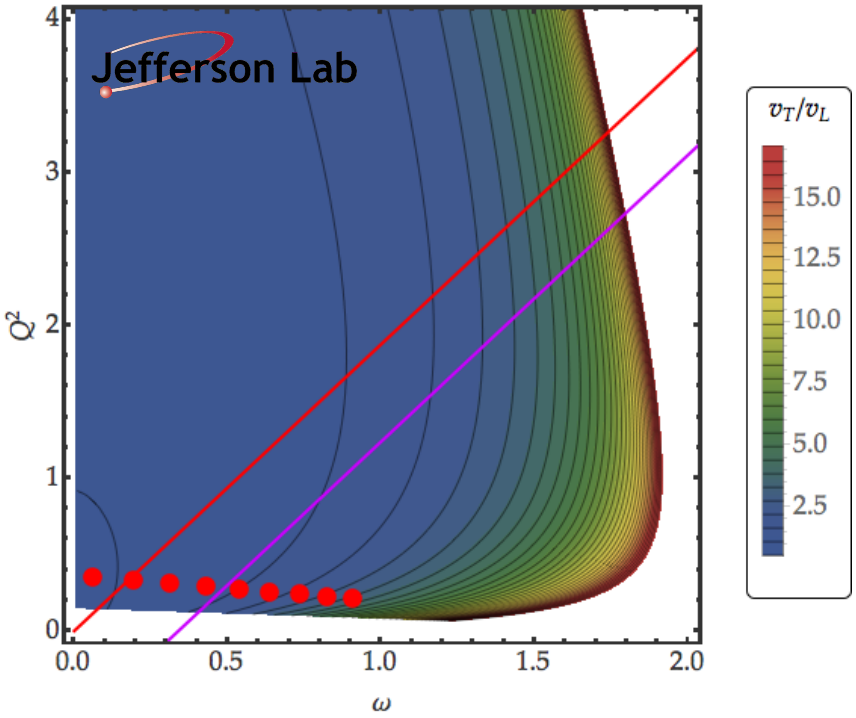
- Dominating terms **R_L** and **R_T** sensitive to magnetic density and currents!
- Measurements at kinematics sensitive to R_T are proposed.
- Detection rates 20-2000Hz.
- **For each setting 20-times better precision than Frascati.**



Why another measurement

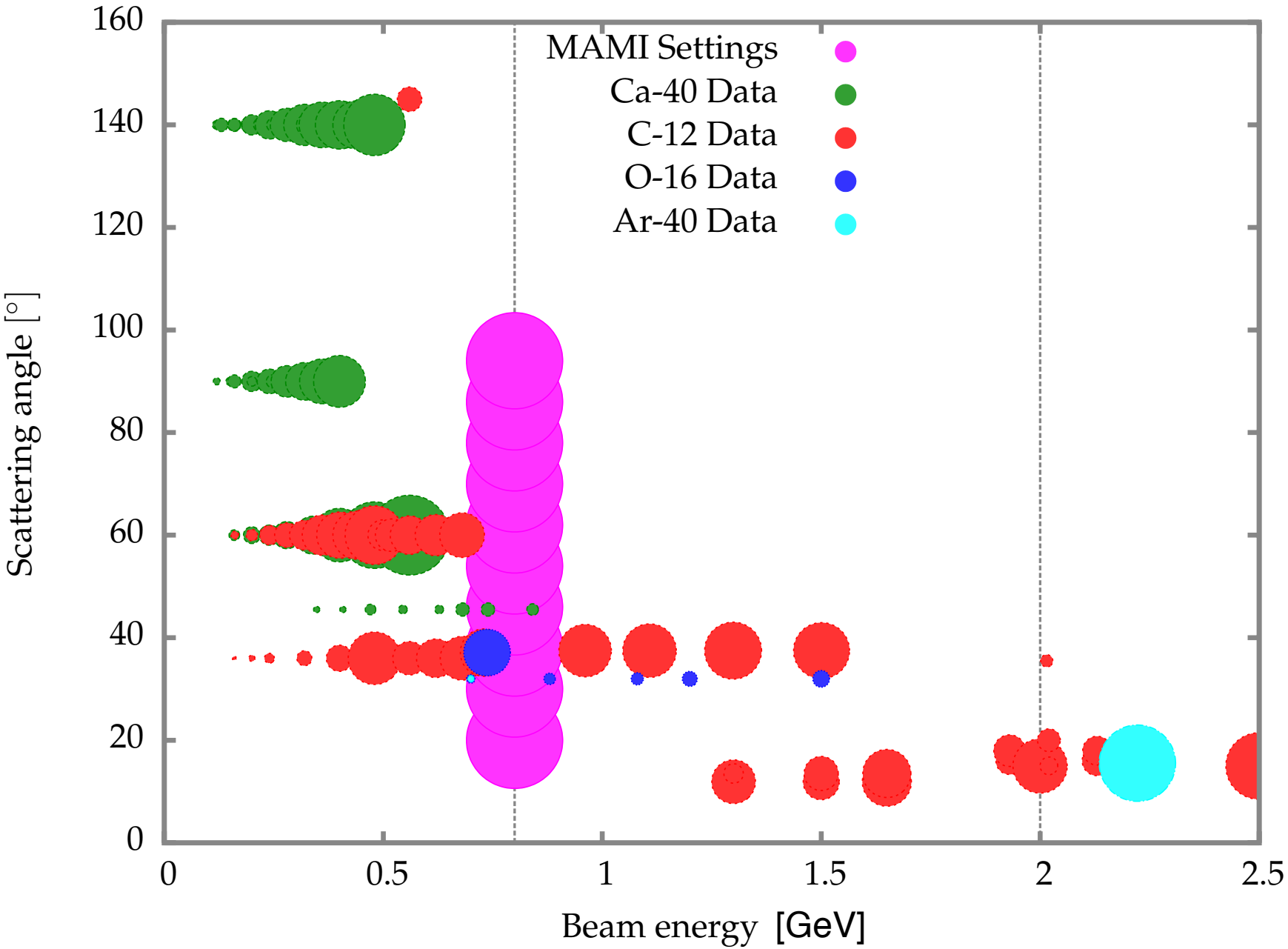
- JLab performed ω scan of (e,e') at 2.2GeV relevant for the interpretation of data at the first diffraction maximum.



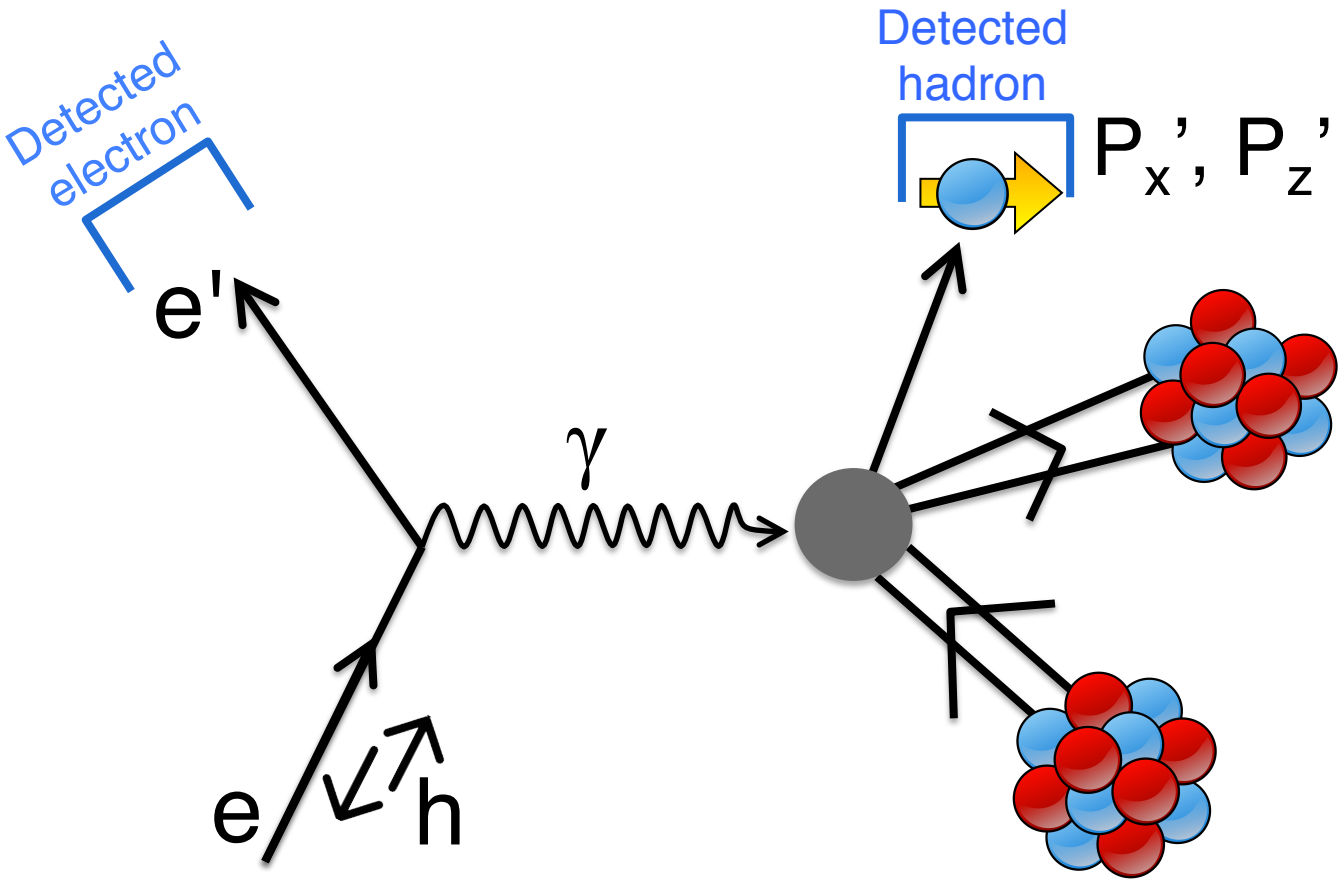


- Complement JLab with data at 800MeV for the analysis of the neutrino data around second diffraction minimum.
- **Provide also data at large θ_e, sensitive to both L,T parts of CS.**

New data from Mainz!



Double polarized electron scattering



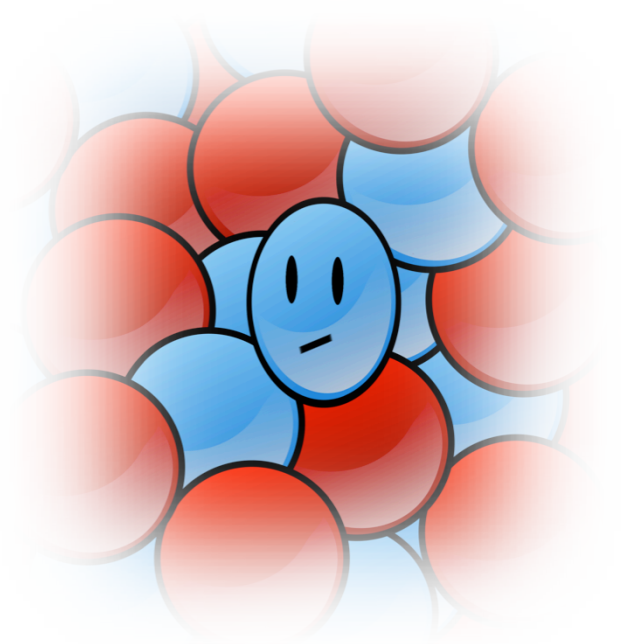
$$P_x', P_z' = \frac{\Delta\sigma(h_{\pm}, \vec{S})}{\sigma_0}$$

In-medium modifications

- In free proton polarization transfer ratio gives insight into form-factor ratio:

$$\frac{P_x'}{P_z'} = -\frac{G_E^p(Q^2)}{G_M^p(Q^2)} \frac{2M}{E+E'} \frac{1}{\tan(\theta_e/2)}$$

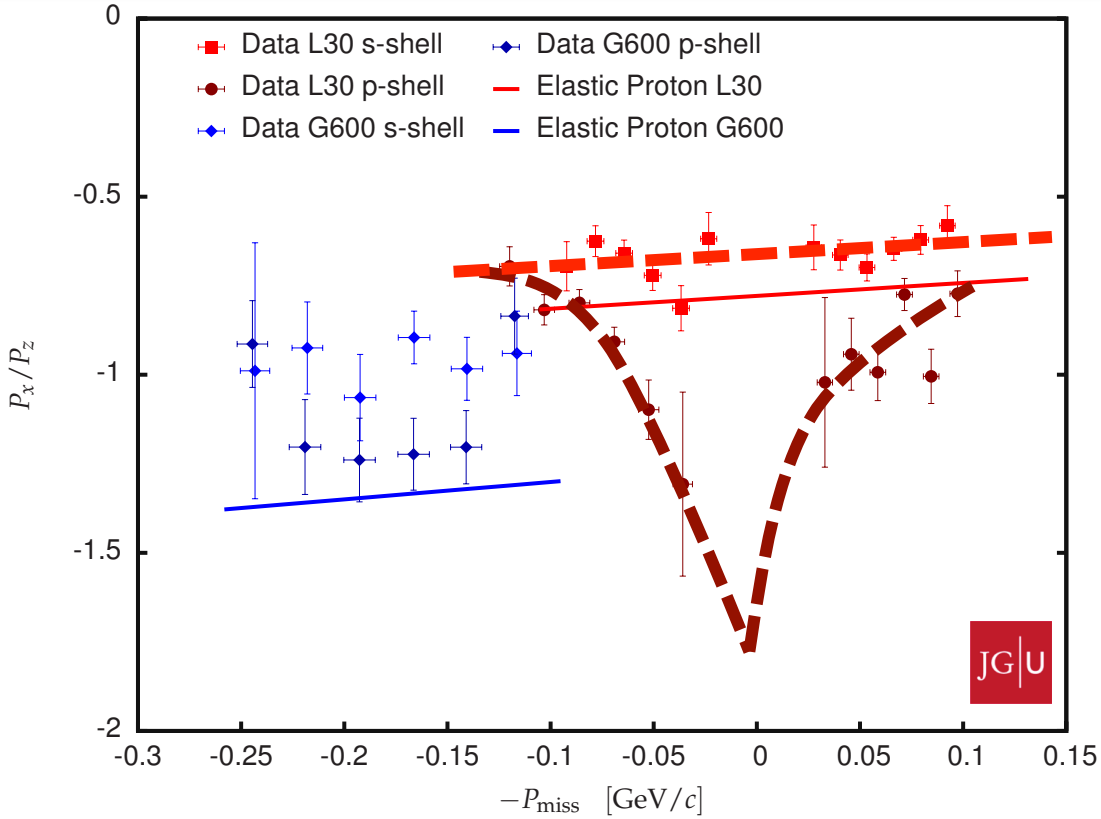
Nuclear medium



- Sensitivity to medium modifications via polarization transfer in QE nucleon knockout:

$$\left(\frac{P_x'}{P_z'}\right)_A \propto -\frac{\tilde{G}_E^p(Q^2)}{\tilde{G}_M^p(Q^2)} \neq -\frac{G_E^p(Q^2)}{G_M^p(Q^2)}$$

Recoil polarization measurement in ^{12}C

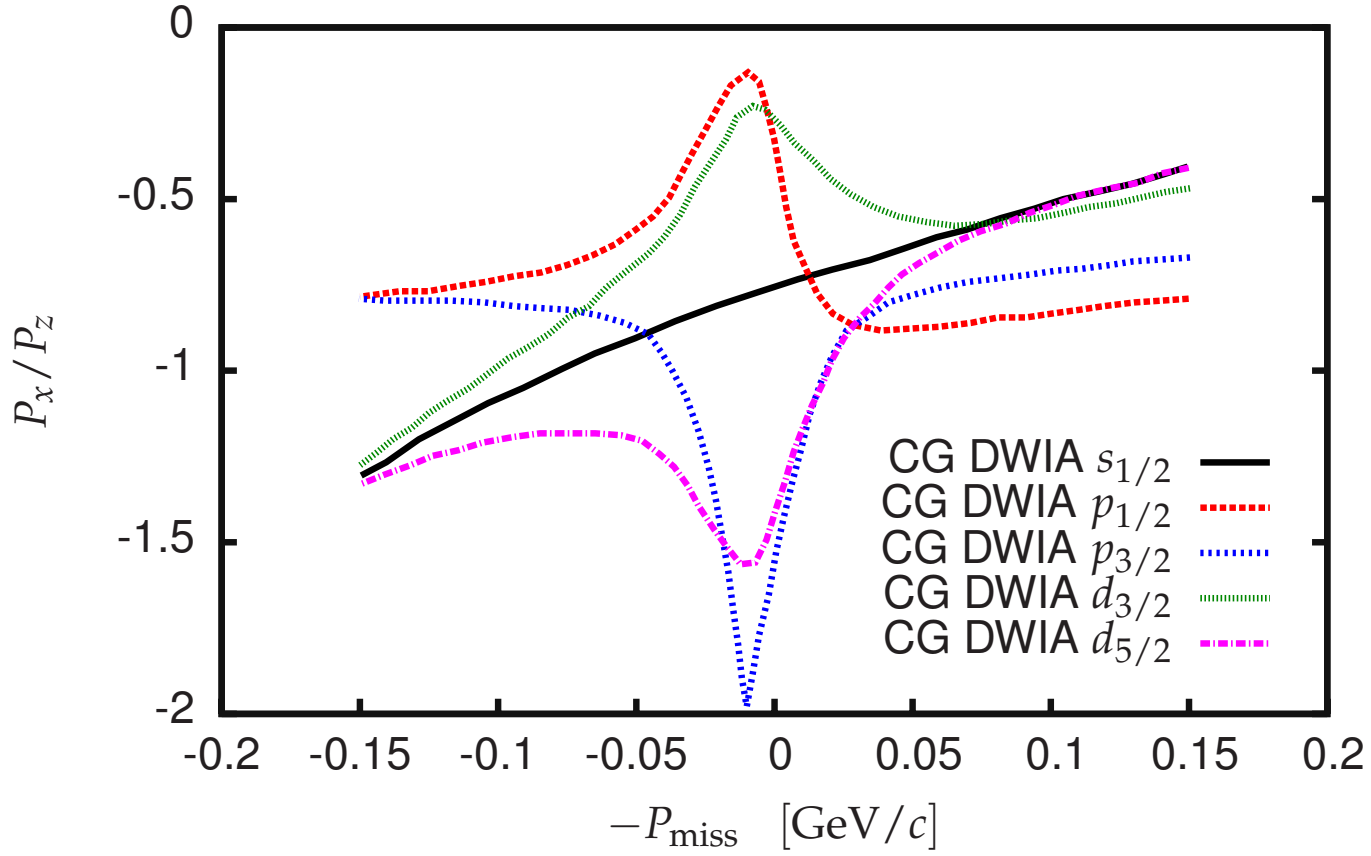


- Deviation from free proton depend on properties of initial proton wave-function, optical potential and FSI). In-medium modification?!

- **Strong dependence on protons angular momentum** ➔ Insight into the nuclear structure and dynamics.

- **Detailed analysis underway** (collaboration with group from Pavia).

^{40}Ar($\vec{e}$,e'$\vec{p}$) experiment @ MAMI

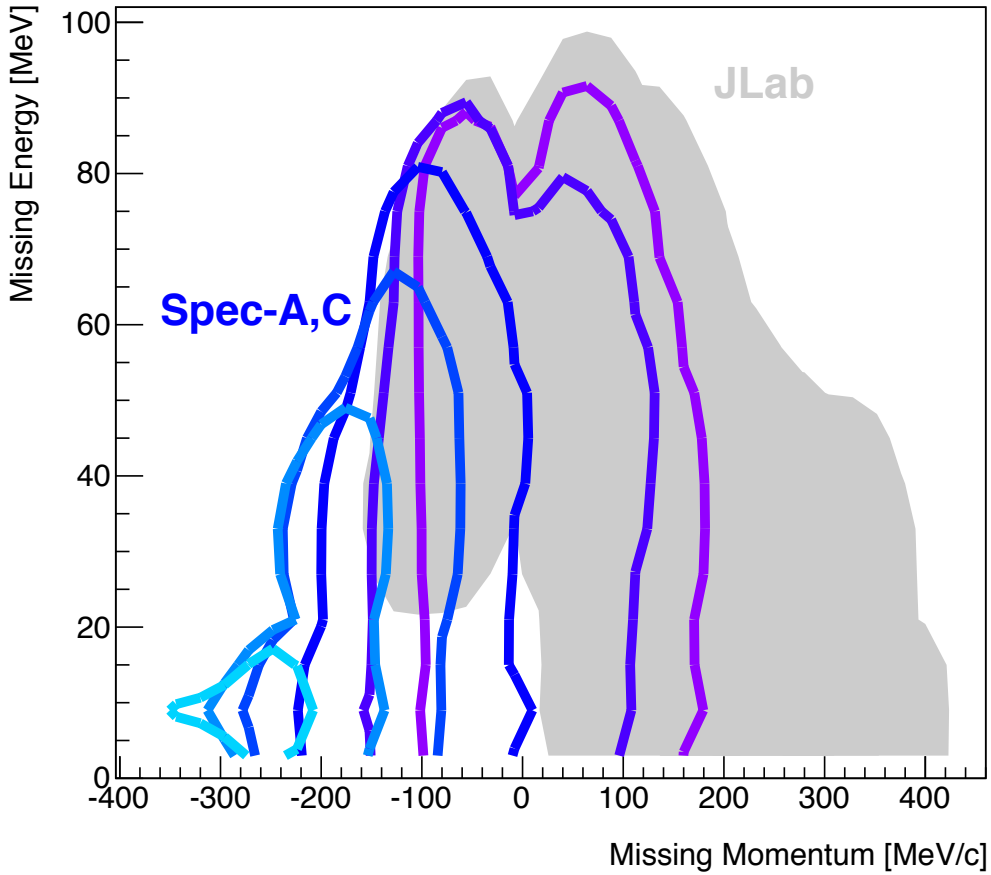


- Theoretical description provided by C. Giusti and A. Deltuva.
- Double polarization experiment offers a unique opportunity to study details of the nucleon wave function, not accessible in CS measurement:
  Angular momentum dependence, effects of LS Coupling !!!

(Free) ^{40}Ar(e,e'p) data

- JLab's E12-14-012 provided data only for $p_m > 0$.

- Experiment at A1 could complement JLab experiment with measurements at $p_m < 0$ for complete picture of nuclear response.



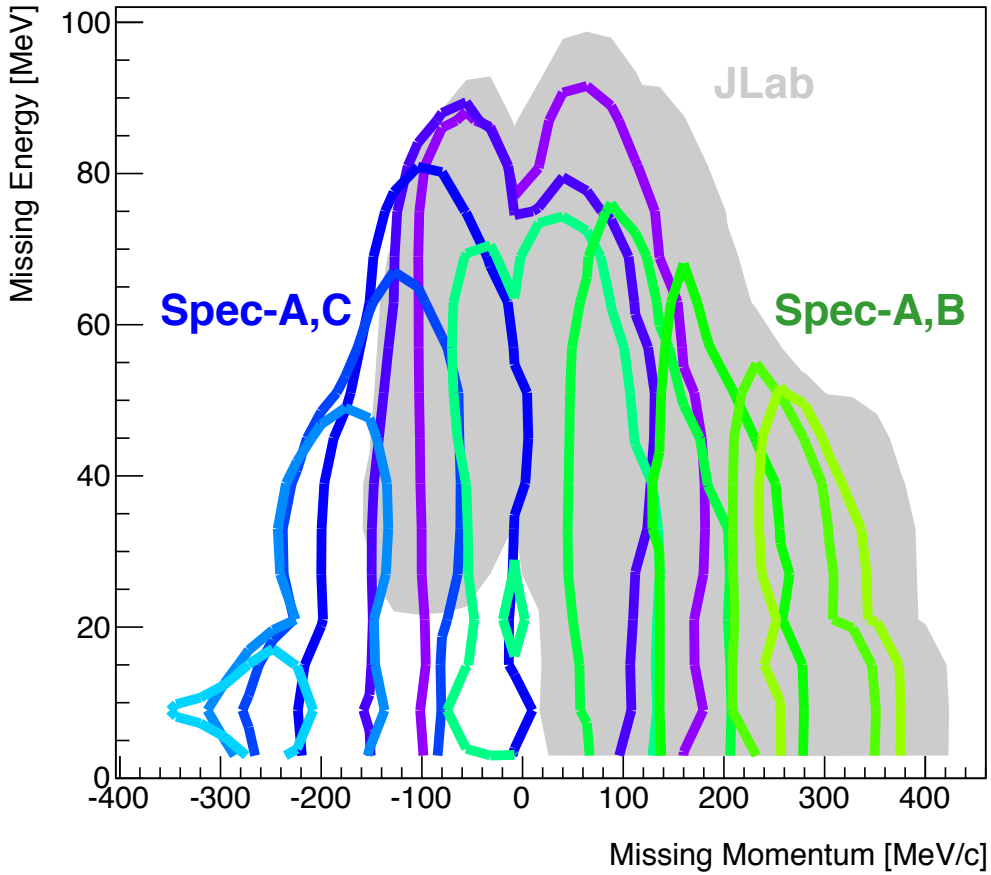
Kinematics:

E_{beam}:	600 MeV
E':	450 MeV
$\theta_{e:}$:	50^o – 100^o
p_p:	512 MeV/c
$\theta_{p:}$:	33^o – 49^o
Target:	4cm gas cell
L:	$4 \cdot 10^{35}$ cm^{-2} s^{-1}

^{40}Ar(e,e'p) experiment at MAMI

- Exclusive coincidence experiment required two spectrometers (A & C).

- Including third spectrometer to the measurement, the $p_m > 0$ data can be obtained for free (with A & B) to double check the JLab data.



Kinematics:

E_{beam}:	600 MeV
E':	450 MeV
$\theta_{e:}$:	$15^o - 50^o$
p_p:	512 MeV/c
$\theta_{p:}$:	$38^o - 50^o$
Target:	4cm gas cell
L:	$4 \cdot 10^{35}$ cm^{-2} s^{-1}

Proposed timeline of the experiments

- One day parasitic run on ^{12}C that could be used to set up the analysis.
- **One week test run with ^{40}Ar target at 700MeV and 32^{o} to validate the apparatus and reproduce the Frascati results.**
- **Full the fully inclusive experiment, 21 days of beam time needed.**
- For the exclusive (polarized) experiment **14 days** are required.

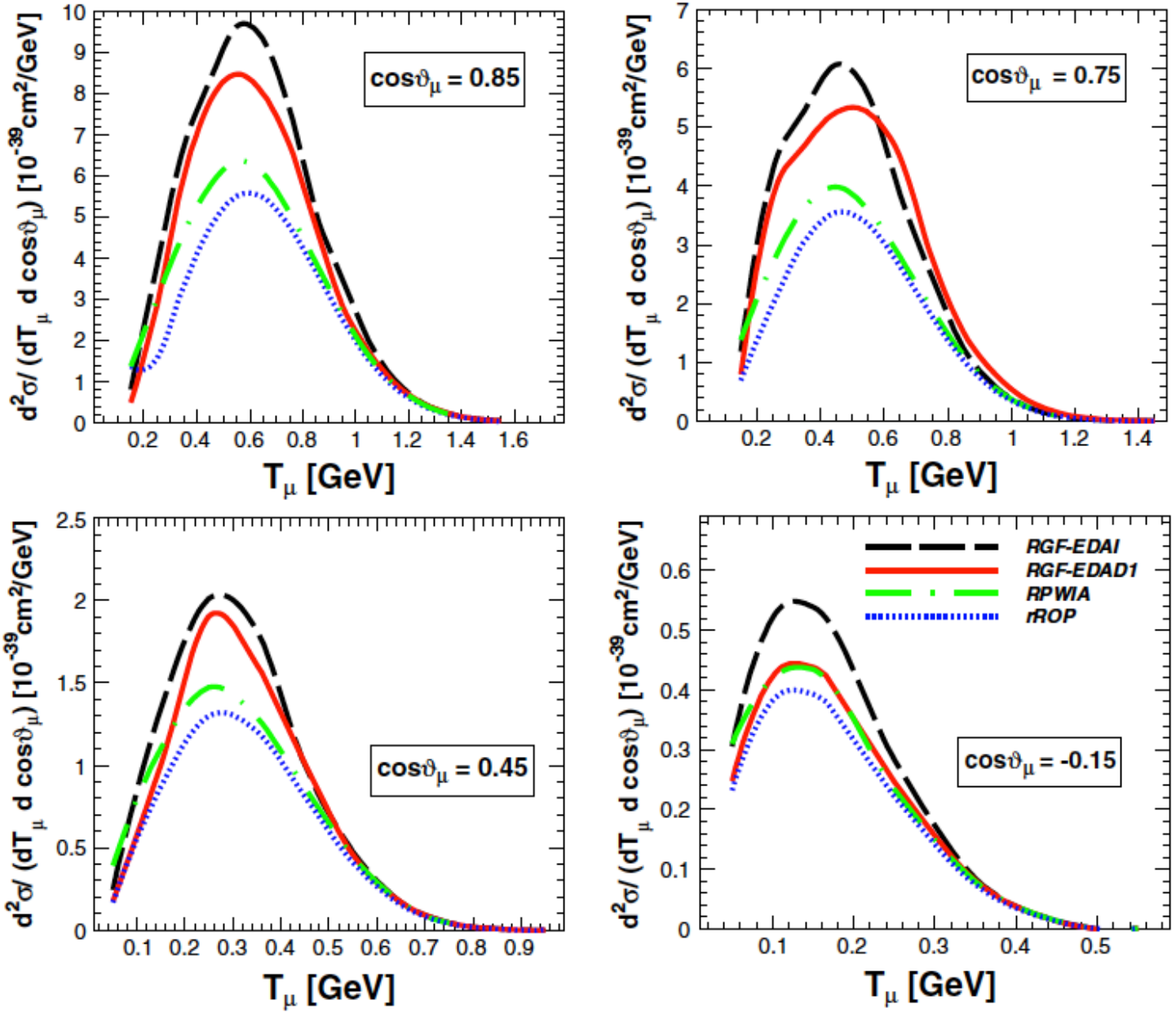
Summary

- Most important questions of today's physics related to neutrinos.
- All future neutrino experiments rely on Monte-Carlo simulations, which depend on nuclear structure models.
- Present theoretical models are still deficient.
- **The proposed new experiments at A1 have the potential to provide valuable input to the theory.**
- **Experiments could be done in together with measurements for other nuclei, e.g. ^{16}O.**
- **Quasi-elastic experiments on ^{16}O, ^{40}Ar interesting also in the context of fundamental nuclear physics.**

Thank you!

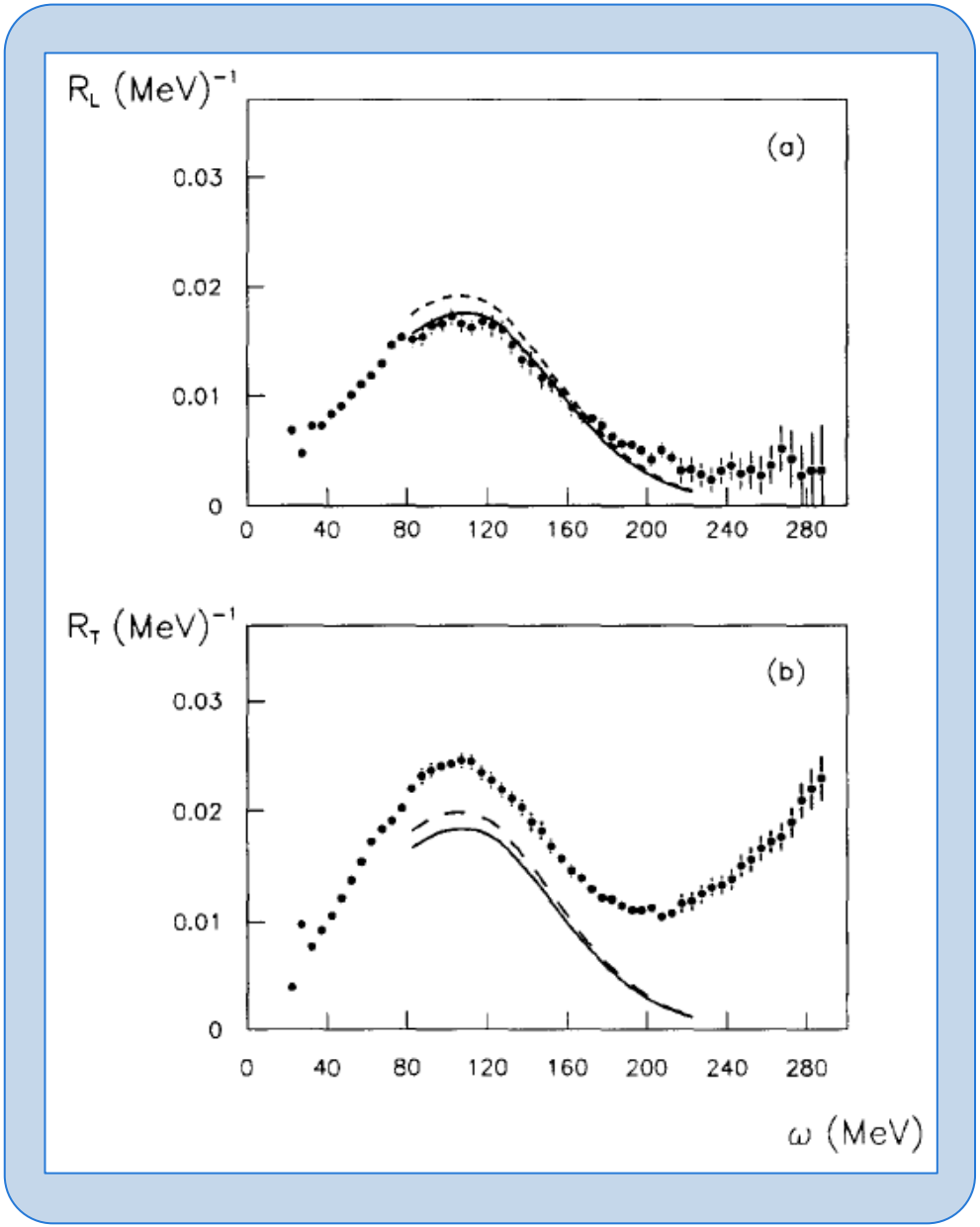
Backups…

Incomplete theoretical description



Existing ^{12}C(e,e'p) data

- Plethora of electron-scattering data exist for various nuclei!
- Detailed studies made for ^{12}C.
- Interesting for MiniBooNE.
- **Transverse response still not understood!**



$^{40}Ar(\vec{e},e'\vec{p})$ experiment @ MAMI

- FSI are important contribution to the ν-N cross-section.
- **Double polarization experiment offers a unique opportunity to validate theoretical description of the FSI, not accessible in CS measurement.**
- Theoretical description provided by C. Giusti (and A. Deltuva).
- Theory predicts < 20% decrease in Px/Pz ratio, which is accessible with the experiment.
- No extra beam time is needed.