Electron-induced single-pion production to extract the neutron spectral function of ^{40}Ar.

A proof of concepts.

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Protons in ^{40}Ar

- **Liquid argon** is the detector material in some present and future neutrino experiments: MicroBoone, SBND, ICARUS and DUNE.

- Precise information about the structure of the target nucleus (**binding energies** and **momentum distributions**) is important for **ν energy reconstruction**.

- Recently, the E12-14-012 experiment studied the spectral function of ^{40}Ar. Results for the **proton spectral function** were obtained from the analysis of $^{40}\mathrm{Ar}(e, e'p)$. PRD 105, 112002 (2022).

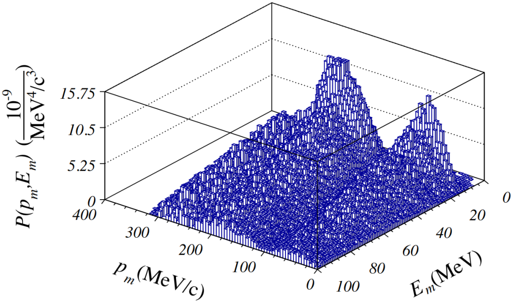
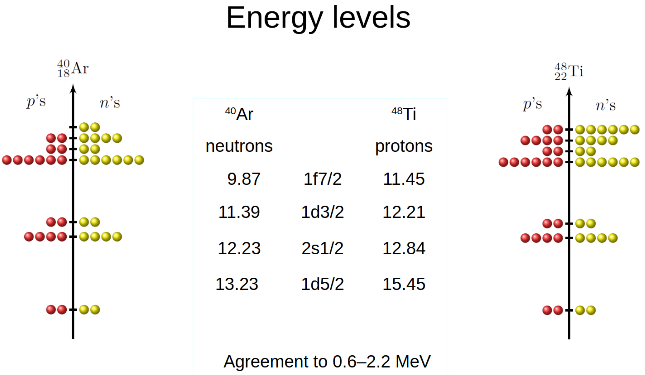


FIG. 10. Reduced cross section as function of missing energy and missing momentum.

Neutrons in ^{40}Ar (protons in ^{48}Ti)

- That was for protons. What about **neutrons**? Because neutrino and antineutrino couple both proton and neutron, **both spectral functions are needed**.

- Determination of proton spectral function of titanium from ^{48}Ti$(e, e'p)$. PRD 107, 012005 (2023).



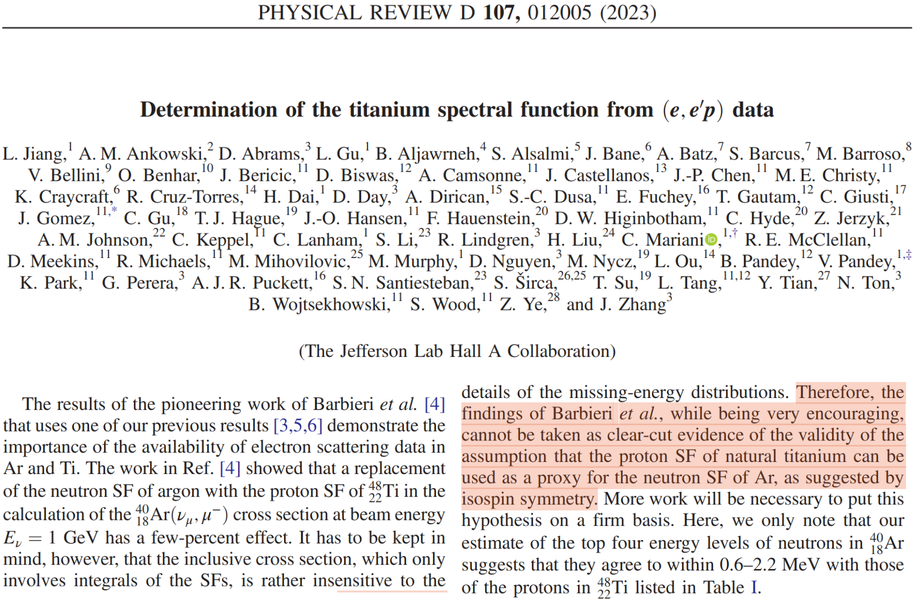
Energy levels

^{40}Ar neutrons		^{48}Ti protons
9.87	1f7/2	11.45
11.39	1d3/2	12.21
12.23	2s1/2	12.84
13.23	1d5/2	15.45

Agreement to 0.6–2.2 MeV

Fig. from Ankowski, talk@ECT* 2024

Neutrons in ^{40}Ar (protons in ^{48}Ti)



PHYSICAL REVIEW D **107,** 012005 (2023)

Determination of the titanium spectral function from $(e, e'p)$ data

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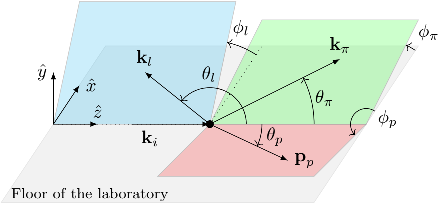
(The Jefferson Lab Hall A Collaboration)

The results of the pioneering work of Barbieri *et al.* [4] that uses one of our previous results [3,5,6] demonstrate the importance of the availability of electron scattering data in Ar and Ti. The work in Ref. [4] showed that a replacement of the neutron SF of argon with the proton SF of $^{48}_{22}$Ti in the calculation of the $^{40}_{18}\mathrm{Ar}(\nu_\mu, \mu^-)$ cross section at beam energy $E_\nu = 1$ GeV has a few-percent effect. It has to be kept in mind, however, that the inclusive cross section, which only involves integrals of the SFs, is rather insensitive to the details of the missing-energy distributions. Therefore, the findings of Barbieri *et al.*, while being very encouraging, cannot be taken as clear-cut evidence of the validity of the assumption that the proton SF of natural titanium can be used as a proxy for the neutron SF of Ar, as suggested by isospin symmetry. More work will be necessary to put this hypothesis on a firm basis. Here, we only note that our estimate of the top four energy levels of neutrons in $^{40}_{18}$Ar suggests that they agree to within 0.6–2.2 MeV with those of the protons in $^{48}_{22}$Ti listed in Table I.

Single pion production as an alternative

- We investigate the potential use of the **triple coincidence experiment** $^{40}\mathrm{Ar}(e, e'p\pi^-)$ as a way to constrain the neutron spectral function of ^{40}Ar.



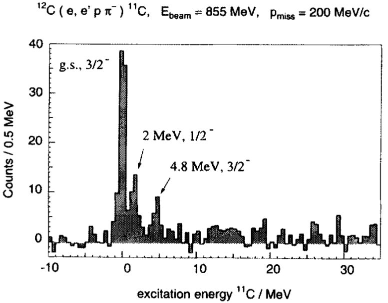


Fig. 32. Spectrum of the triple coincidence reaction $^{12}\mathrm{C}(e, e'p\pi^-)$ in the Δ resonance region as a function of the excitation energy of the residual nucleus ^{11}C.

Missing energy: $E_m = \omega - T_p - E_\pi - T_R$

Missing momentum: $\mathbf{p}_m = \mathbf{p}_p + \mathbf{k}_\pi - \mathbf{q}$

Nuclear Instrument and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 403, 263 (1998).

Theoretical models

- **Elementary vertex for single-pion production:** Ghent-Hybrid model. PRD 95, 113007 (2017)

- **Nuclear model:** relativistic plane-wave impulse approximation (RPWIA). PRC 100, 045501 (2019), PRC 109, 024608 (2024)
  - **Initial state:** independent-particle shell model (IPSM), the relativistic mean-field model (RMF).
  - **Final state:** relativistic plane-waves for both proton and pion.

- **Nuclear energy levels:**
  - Eigenvalues from the IPSM smeared into Gaussians ($\sigma = 0.5$ MeV). Occupancies of 80%.
  - The missing 20% of nucleons are modeled as a high-E_m, high-p_m background starting at the $2N$-knockout threshold.

- **Final state interactions (FSI):** we propagate the events through NuWro intranuclear cascade (INC). PRCC 86, 015505 (2012), PRC 100, 015505 (2019)

In this work...

MAMI@Mainz

MAMI website

Nuclear Instrument and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 403, 263 (1998).

CLAS@JLab

CLAS website

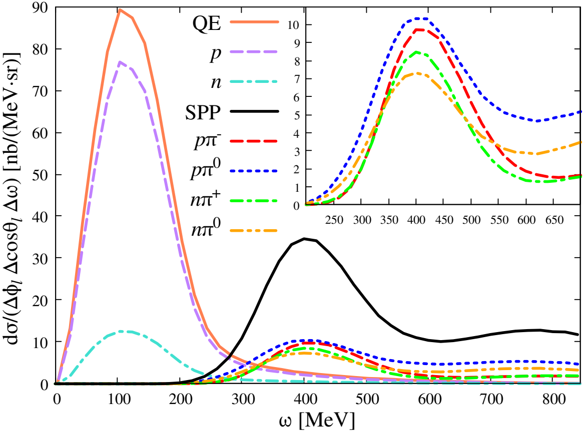
Nature volume 599, pages 565–570 (2021).

MAMI simulation: a quick overview

- MAMI is a **three-spectrometer facility** for electron beams at University of Mainz.
- The spectrometers have **small acceptances** and **extremely good momentum resolution**.
- The **energy beam** for the MAMI accelerator is $E_i = 855$ MeV.
- We want **balance** between large cross sections and QE-dominated process. We choose $\theta_l = 30$ deg.

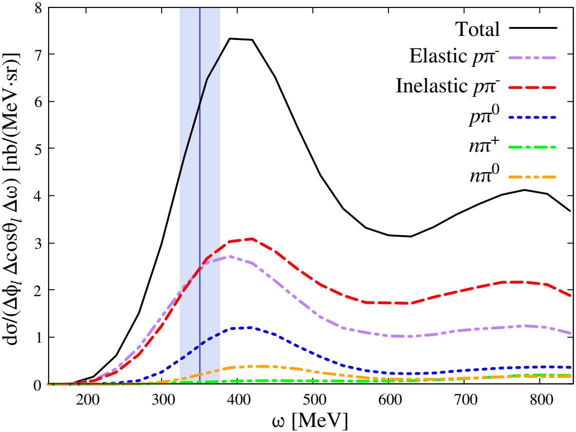
Spec.	Particle	p [MeV]	Δp [MeV]	θ [deg]	$\Delta\theta$ [deg]	ϕ [deg]	$\Delta\phi$ [deg]
A	Proton	470	10%	25.00	7.73	198	4
B	Lepton	505	7.5%	30.00	1.15	0	4
C	Pion	145	12.5%	95.00	7.73	90	4

MAMI simulation: channels taken into account



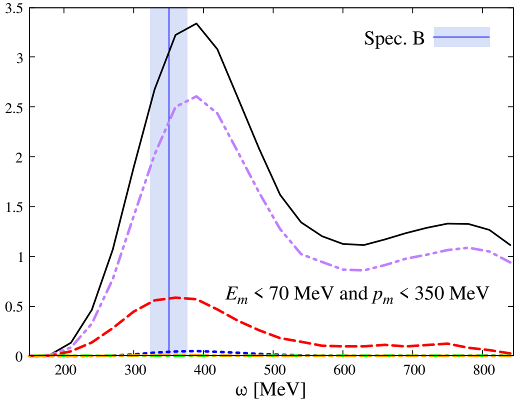
- **Inclusive cross section** for $E_i = 855$ MeV, $\theta_l = 30 \pm 1.15$ deg and $\phi_l = 0 \pm 4$ deg.
- We show all the **channels taken into account** in this study.
- **No FSI.**

MAMI simulation: estimation of the backgrounds



- E_l (ω) **close to the Δ-resonance peak** but **below it** so the contribution from 2π production and higher-mass resonances is negligible.
- **FSI**: events that end up in the *at least* $1p1\pi^-$ channel.
- **Backgrounds** coming from QE are completely **negligible** (less than 1%).

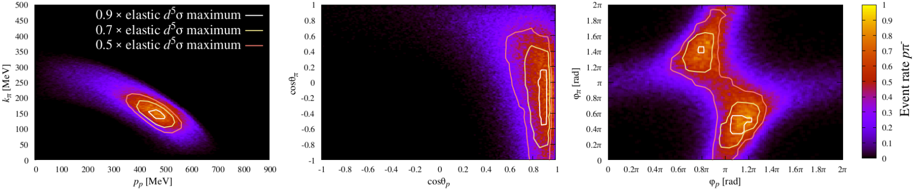
MAMI simulation: estimation of the backgrounds



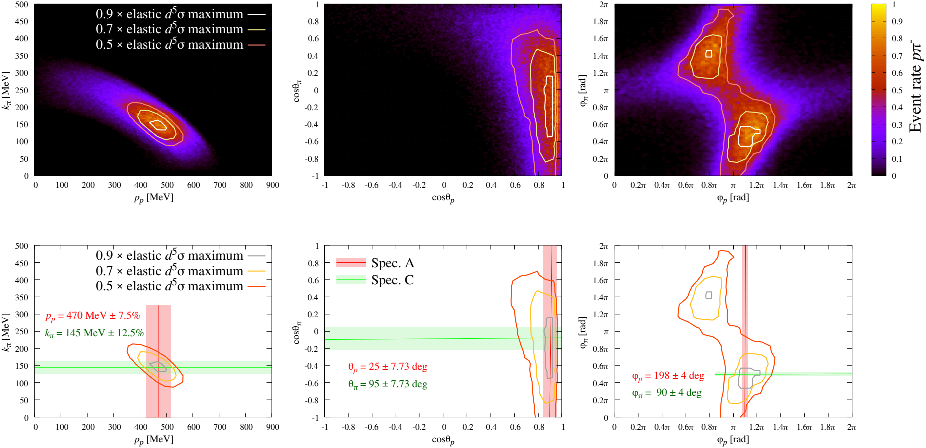
- E_l (ω) **close to the Δ-resonance peak** but **below it** so the contribution from 2π production and higher-mass resonances is negligible.
- **FSI**: events that end up in the *at least* $1p1\pi^-$ channel.
- Making **cuts** in missing energy (E_m) and missing momentum (p_m) helps **eliminate backgrounds**.

Where do we place the detectors for the hadrons?

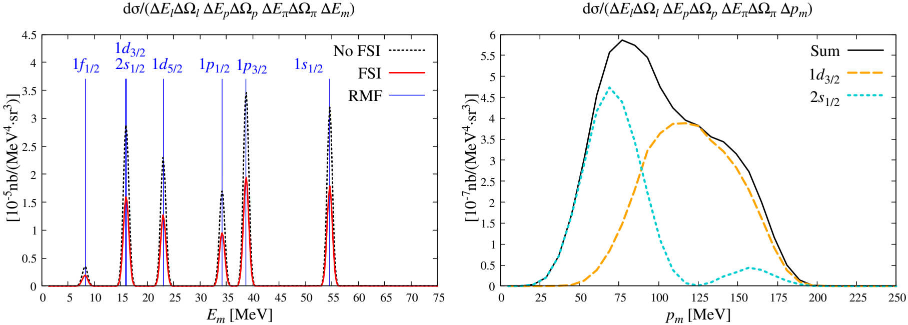
We want **large cross-sections** and **as less FSI as possible (small backgrounds)**



Where do we place the detectors for the hadrons?



MAMI simulation: results

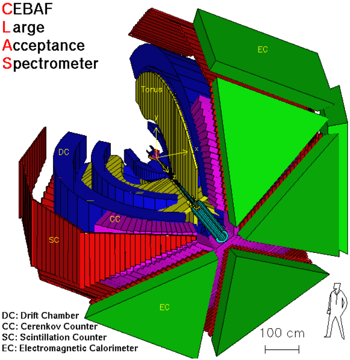


- **Cuts** in E_m and p_m are implemented.
- We see our **input model** for the E_m-profile. Each peak corresponds to a **different energy level**.
- The levels $1d_{3/2}$ and $2s_{1/2}$ **overlap**.
- The p_m-distributions of these two $\ell = 0$ and $\ell = 2$ states are different.
- One could **disentangle** them by looking at the cross section in terms of p_m (in the corresponding E_m window).

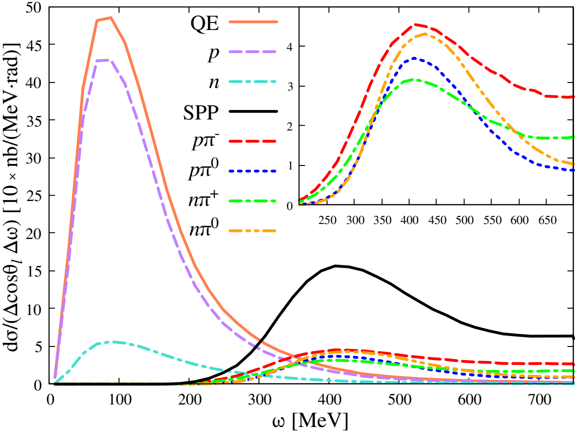
CLAS simulation: a quick overview

- CLAS is a **large solid angle** spectrometer at JLab.
- We use a **energy beam** of $E_i = 1159$ MeV.
- We use the following **acceptances** and **momentum resolutions**:

Particle	p [MeV]	θ [deg]	Resolution
Proton	> 300	> 10	3.0%
Lepton	> 400	30 ± 15	1.5%
Pion	> 150	> 22	2.1%

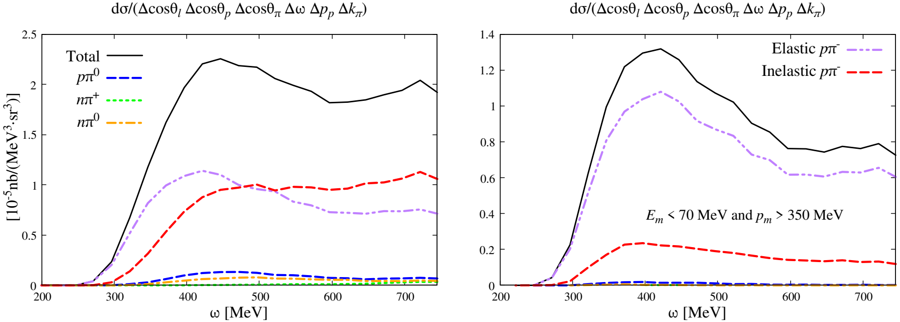


CLAS simulation: channels taken into account



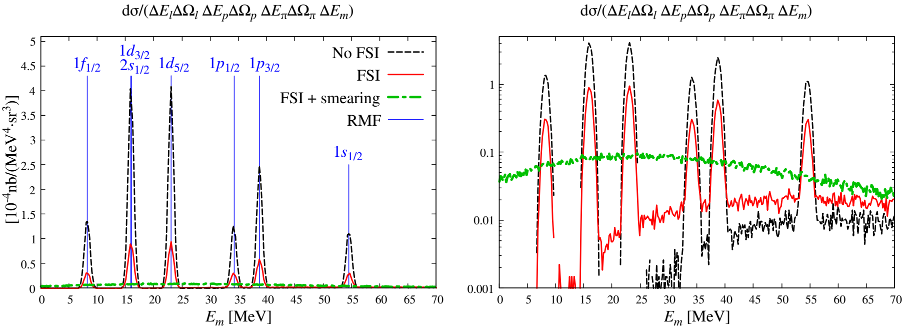
- **Inclusive cross section** for $E_i = 1159$ MeV and $\theta_l = 30 \pm 15$ deg
- We show all the **channels taken into account** in this study.
- **No FSI.**

CLAS simulation: estimation of the backgrounds



- **After FSI:** contributions that end up in *at least* $1p1\pi^-$ and could **contaminate** the measurements.
- **Backgrounds** coming from QE are completely **negligible** (less than 1%).
- Making cuts in missing energy (E_m) and missing momentum (p_m) helps **eliminate backgrounds**.

CLAS simulation: results



- **Cuts** in E_m and p_m are implemented.

- The final particles' momenta are **smeared using Gaussian distributions** with $\sigma = 1.5\%$ (lepton), $\sigma = 3.0\%$ (proton) and $\sigma = 2.1\%$ (pion).

- Using the momentum resolution of CLAS **we cannot solve** the shell structure.

Final remarks

- We propose the **triple coincidence experiment** $^{40}\mathrm{Ar}(e, e'p\pi^-)$ as a way to **constrain the neutron structure** in $^{40}\mathrm{Ar}$.

- We have performed **theoretical predictions** for the cross sections and estimated the main background using constraints compatible with the **MAMI** and **CLAS facilicites**.

- We account for FSI using **NuWro INC**. Most of the **background could be eliminated** just performing **cuts** in E_m and p_m.

- In the case of **MAMI** we have studied the **optimal position** for the three spectrometers. We solve the shell structure. For **CLAS**, due to the momentum resolution, the shell structure is **unsolved**.

This is a *proof of concepts.*

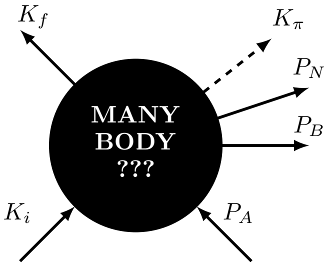
Next steps would include the **distortion of the hadrons** (with different nuclear potentials), state-of-the-art **SPP models**, the use of **different INCs**.

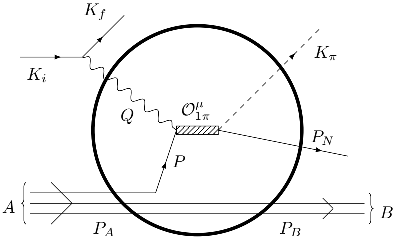
Thank you so much
for your attention!

Just-in-case slides

How do we model SPP on nuclei?

All the nuclear information is enclosed in the nuclear current J^μ





The lepton only interacts with one nucleon inside the nucleus

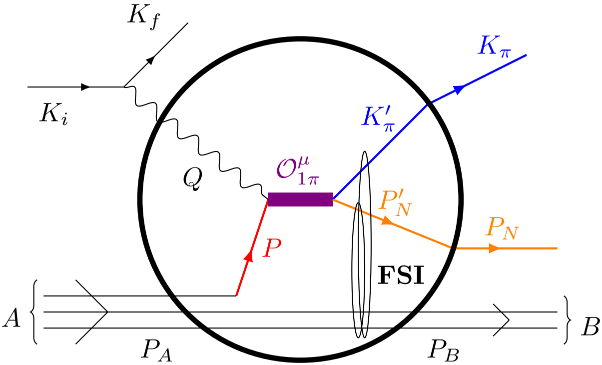
$$J^\mu = \langle N, A-1 | \mathcal{O}^\mu_{many-body} | A \rangle \xrightarrow{\textbf{IA}} J^\mu \propto \int \bar{\Psi}_F \, \phi^*_\pi \, \mathcal{O}^\mu_{one-body} \, \Psi_B$$

- $\mathcal{O}^\mu_{1\pi}$ from lepton-(free) nucleon interaction
- $\bar{\Psi}_F$, ϕ^*_π, and Ψ_B are single-particle wave functions
- Exchanged boson: $Q = (\omega, \mathbf{q})$

Impulse approximation and nuclear model

Most general: **both** pion and nucleon are **distorted waves**
They account for the **interaction with the residual nucleus**

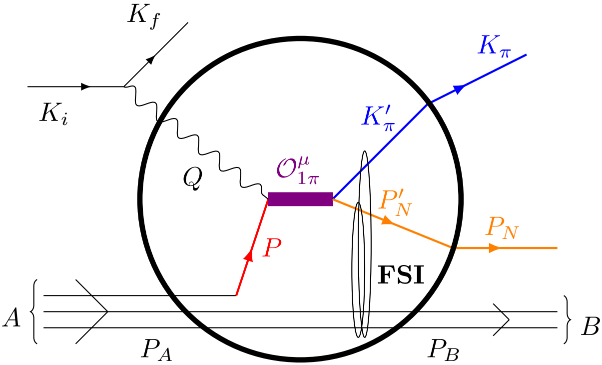
$$J^{\mu} \propto \int d\mathbf{p} \int d\mathbf{p}'_N \; \bar{\Psi}_F(\mathbf{p}'_N, \mathbf{p}_N) \, \phi^*_{\pi}(\mathbf{p} + \mathbf{q} - \mathbf{p}'_N, \mathbf{k}_{\pi}) \, \mathcal{O}^{\mu}_{1\pi}(Q, P'_N, P) \, \Psi_B(\mathbf{p})$$



Impulse approximation and nuclear model

Asymptotic (or local) approximation: $O^\mu_{1\pi}$ is evaluated **only once**

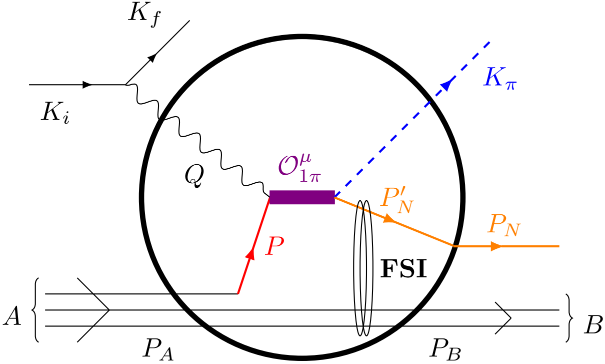
$$J^\mu \propto \int d\mathbf{p} \int d\mathbf{p}'_N \; \bar{\Psi}_F(\mathbf{p}'_N, \mathbf{p}_N)\, \phi^*_\pi(\mathbf{p}+\mathbf{q}-\mathbf{p}'_N, \mathbf{k}_\pi)\, \boxed{\mathcal{O}^\mu_{1\pi}(Q, P_N, P)}\, \Psi_B(\mathbf{p})$$



Impulse approximation and nuclear model

The **pion** is a **plane wave**, the nucleon is still a distorted wave

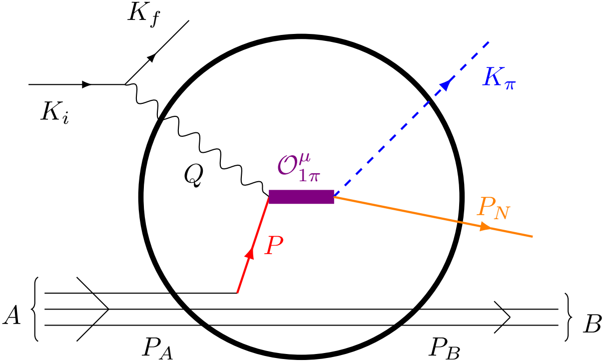
$$J^\mu \propto \frac{1}{\sqrt{2E_\pi}} \int d\mathbf{p}\ \bar{\Psi}_F(\mathbf{q}+\mathbf{p}-\mathbf{k}_\pi, \mathbf{p}_N)\ \mathcal{O}^\mu_{1\pi}(Q, P_N, P)\ \Psi_B(\mathbf{p})$$



Impulse approximation and nuclear model

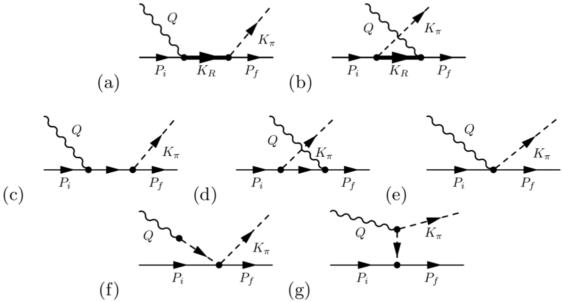
Both **pion** and **nucleon** are **plane waves**

$$J^\mu \propto \sqrt{\frac{M_N}{2E_\pi E_N}} \bar{u}_F(\mathbf{p}_N, s_N)\, \mathcal{O}^\mu_{1\pi}(Q, P_N, P)\, \Psi_B(\mathbf{p}_N + \mathbf{k}_\pi - \mathbf{q})$$



Ghent-Hybrid π-model

Resonances + ChPT $N\pi$-Lagrangian



Resonances: $P_{33}(1232)$ (Δ-baryon), $D_{13}(1520)$, $S_{11}(1535)$, $P_{11}(1440)$
Works up to $\sqrt{s} = W < 1.4$ GeV $\rightarrow$ Extended via Regge Theory

PRD **76**, 033005 (2007)
PRD **95**, 113007 (2017)

Matthias Hooft (UGent) is working on the **unitarization**

Relativistic Mean Field

$$\begin{aligned}\mathcal{L} = {} & \bar{\Psi}\left(i\gamma_\mu\partial^\mu - M\right)\Psi + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - U(\sigma)\\ & - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\mathbf{R}_{\mu\nu}\mathbf{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\rho^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\\ & - g_\sigma\bar{\Psi}\sigma\Psi - g_\omega\bar{\Psi}\gamma_\mu\omega^\mu\Psi - g_\rho\bar{\Psi}\gamma_\mu\boldsymbol{\tau}\rho^\mu\Psi - g_e\frac{1+\tau_3}{2}\bar{\Psi}\gamma_\mu A^\mu\Psi.\end{aligned}$$

$$\Big[-i\boldsymbol{\alpha}\cdot\boldsymbol{\nabla} + V(r) + \beta(M + S(r))\Big]\Psi_i(\boldsymbol{r}) = E_i\Psi_i(\boldsymbol{r})$$

Regge Theory

- For increasing energies → higher order contributions
- RTh: Infinite summation over all partial waves in the $t-$channel amplitude (→ contour integral in complex angular momentum space)
- A Regge pole corresponds to a pole in that complex space
- Regge pole ≡ whole family of $t-$channel contributions
- Regge propagator (with Regge trajectory) replaces the previous one

$$P_\pi(t,s) = -\alpha'_\pi \varphi_\pi(t)\Gamma[-\alpha_\pi(t)](\alpha'_\pi s)^{\alpha_\pi(t)}$$

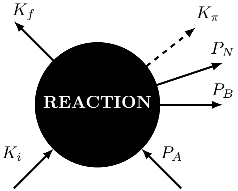
$$\alpha_\pi(t) = \alpha'_\pi(t - m_\pi^2) \quad , \quad \Gamma[-\alpha_\pi(t)] = \frac{-\pi}{\sin[\pi\alpha_\pi(t)]\Gamma[-\alpha_\pi(t)+1]}$$

Nucl. Phys. A **627**, 645 (1997)

Independent variables and cross section

Lepton-induced SPP on nuclei: $l + A \longrightarrow l' + B + N + \pi$

Counting independent variables	
4×6 particles	+24
four-mom. conservation	−4
5×on-shell ($E^2 = p^2 + m^2$)	−5
Target at rest	−3
Fixed projectile direction	−2
Fixed incoming energy	−1



$$\frac{d^9\sigma}{dE_f d\Omega_f \; dE_N d\Omega_N \; dE_\pi d\Omega_\pi} \propto L_{\mu\nu} H^{\mu\nu}$$

Four-momenta of every actor

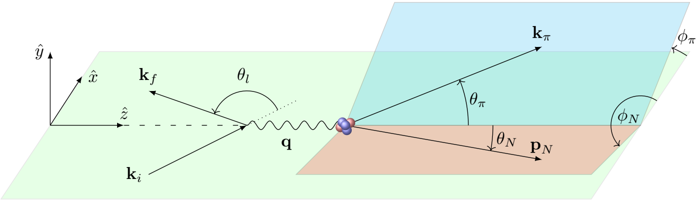
$l \to K_i$	$A \to P_A$	$l' \to K_f$	$B \to P_B$	$N \to P_N$	$\pi \to K_\pi$
$(E_i, \mathbf{k}_i)$	$(m_A, \mathbf{0})$	$(E_f, \mathbf{k}_f)$	$(E_B, \mathbf{p}_B)$	$(E_N, \mathbf{p}_N)$	$(E_\pi, \mathbf{k}_\pi)$

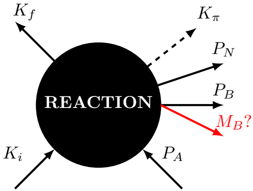
PoS(NuFACT2018)086

Kinematics of SPP on nuclei

Nothing depends on ϕ_l

Is the residual system **excited**?





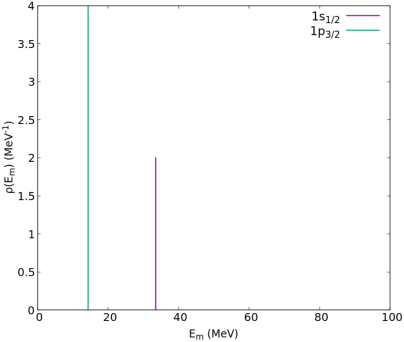
$$\frac{d^9\sigma}{dE_f \, d\cos\theta_f \; dE_N d\Omega_N \; dE_\pi d\Omega_\pi \; dE_m} \propto \rho(E_m) L_{\mu\nu} H^{\mu\nu}$$

- Energy conservation: $\omega + m_A = E_B + E_N + E_\pi$
- Mom. conservation: $\mathbf{q} = \mathbf{p}_B + \mathbf{p}_N + \mathbf{k}_\pi$
- Mass of the residual system: $m_B = E_m + m_A - M$
- Nucleon binding energy: $E_\kappa = E_m$

Independent particle shell model: ^{12}C

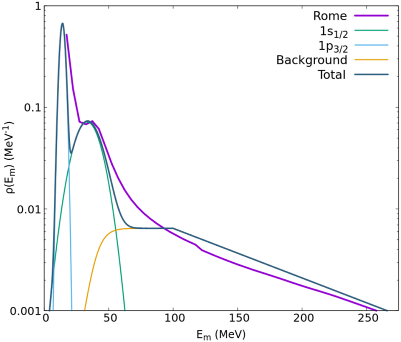
Let's take ^{12}C:

- In a pure shell model $\rho(E_m) = \delta(E_m - E_\kappa)$



$N_s = \mathbf{2}$ and $N_p = \mathbf{4}$

- More realistic approach: spectral function $S(E_m, p_m)$



$N_s = \mathbf{1.8}$ and $N_p = \mathbf{3.3}$
$N_{BG} = \mathbf{0.9}$ (SRC)

FIGS. Tania Franco-Munoz