### Historical Review and Future Program for Neutrino Cross-Section Measurements and Calculations

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**\*** Why cross sections are relevant for neutrino oscillation

**\*** Past and present measurements of neutrino cross sections

**\*** Theoretical models of neutrino cross sections

**\*** Future program for neutrino cross section measurements and calculations

## Addressing Neutrino-Oscillation Physics

$$
P_{\nu_{\mu}\to\nu_{e}}(E,L) \sim \sin^{2} 2\theta \sin^{2}\left(\frac{\Delta m^{2}L}{4E}\right) \to \Phi_{e}(E,L)/\Phi_{\mu}(E,0)
$$





Detectors measure the neutrino interaction rate:



A quantitative knowledge of  $\sigma(E)$  and  $f_{\sigma}(E)$  is crucial to precisely extract v oscillation parameters

## To study neutrinos we need nuclei



Utilize heavy target in neutrino detectors to maximize interactions→ understand nuclear structure calculated from Eq. (7) using the M~ values in Table I. The Utilize heavy target in neutrino part by the U. S. Department of Energy and the National maximize inte



### Lepton-nucleus cross section

Different reaction mechanisms contributing to lepton-nucleus cross section —fixed value of the beam energy (monochromatic)



### *CONTENTS* 12 Neutrino fluxes for different experiments

Energy distribution of neutrino fluxes

**Present to Future:** T2K, MicroBooNE, Nova, MINERvA, Hyper-Kamiokande, DUNE



## **MiniBooNE**



FIGUOR IL HOU LO DO UNHUIGO GHU UGDHOUCU. minimers background promated.<br>
PHYSICAL REVIEW D  $81,092005$  (2010) Intrinsic background: pion absorption in nuclei. It has to be simulated and subtracted. RPS = unsmearing transformation to true variables



 $\overline{C}$ plons are detected in a In MiniBooNE data analysis, an event is labeled as CCQE if **no final state pions** are detected in **addition to the outgoing muon.** 

suich licht of the **uduble unierential cross section**  $\frac{1}{2}$  $S$ . Seation ing on  $\sim$ First measurement of the **double differential cross section**  for CCQE scattering on 12C

s the dete sereful eveluation of nueleer effects interaction events that interest the contains that is a primary muoto predominant contains the contain a primar<br>International muoto predoma predominant contains the contains of the contains of the contains of the contact o ing as a contribution of the seen in the seed in the second in the To explain the data careful evaluation of nuclear effects was required: **multi-nucleon emission** first identified



## T2K

The T2K experiment data-taking started in January 12 2010 and continues in 2020 and beyond. The **dominant process** at the peak energy of ~0.6 GeV is **CCQE scattering**. 8 i r<br>2C<br>~C  $\overline{r}$   $\overline{r}$   $\overline{r}$ -39 <u>าวุ</u>  $\mathsf{a}$  $\overline{a}$ <sup>µ</sup> C, 0 < cosθ





## MINERvA

MINERvA is the first neutrino experiment in the world to use a **high-intensity beam** to study neutrino reactions with a **variety of nuclei**: He,C,O,Pb and Fe. Strongly constraints neutrino interactions **y of nuclei**: He,C,O,Pb and Fe. Strongly constraints neutrino interactions The Q2 efficiency is shown in the compact of the reduction at the reduction of the red eutrino experiment in the world to use a **high-intens**i The Evidence is shown in Fig. 23. The lower is shown in Fig. **eam** to study neutrino



**Eine-grained scintillator tracker** allows to identify and<br>a marginal measure autosing nuclear and u. Dusha musham **EREADERENT PRECISELY MEASURE OUTGOING protons and µ. Probe nuclear effects** using **the transverse imbalance of p and µ External reflects** using the transverse imbalance of p and  $\mu$ 

 $e$ ) no 2.022504  $\frac{1}{2}$  in  $\frac{1}{2}$ ,  $\frac{1}{2}$  is  $\frac{1}{2}$  $\bullet$  PID, X.G. et al, Phys Rev Lett. 121 (2018) no 2, 022504  $\mathscr D$  Lu, X.G.

 $\mathfrak{b}$ ● T2K, Phys. Rev. D 98 (2018), 032003

Full double differential cross section projected using the kinematics of the  $\mu$ : 4 /GeV < 2.0 || 1.5 < p /GeV < 2.5 || 2.0 < p  $\mathbf{C}$ ial<br> rojecte n Oj

 $\mathbb{R}^3$ ✐ Phys. Rev. D 99 , 012004 (2019)



### NOvA<sup>N</sup> • Intranuclear rescattering

The neutrino flux in the NOvA ND is a narrow band beam peaked at 1.9 GeV, between 1.1 and 2.8 GeV setien medeling is one of the leading overemetic une  $\overline{V}$  and is a narrow band beam peaked at 1.9 GeV, between 1.1 and 2.8 GeV. Cross section modeling is one of the leading systematic uncertainties for NOvA's measurements.



 $NC$  coherent  $\pi 0$  production on a carbon:







### ✐ Taken from: S.K.Lin's talk @ SUSY <sup>2019</sup>

NC coherent **π0 production** on a carbon:  $v_\mu$  CC π<sup>0</sup> seminclusive results: both RES and DIS



## MicroBooNE

oscillation: resolve the source MiniBooNE low energy excess ferent<br>:h for fferent baselines along the  $\overline{\phantom{0}}$ m<sup>2</sup> neutrino and <del>the D</del> 0.4 -38 [10 -38 [10 Booster Neutrino Beam will search for **high Δm2 neutrino**   $\begin{array}{c} \text{Multi-1} \\ \text{Multi-1} \end{array} \begin{array}{c} \text{Matrix} \\ \text{Matrix} \end{array}$ oscillation: resolve the source MiniBooNE low energy excess Multiple LAr-TPC detectors at different baselines along the



 MicroBooNE precision measurements **ν**-**Ar** cross sections in the hundreds-of-MeV to few-GeV energy range  $of-M$ ents v-Ar cross sections in the hundreds  $\mathbf{I}$ s sections in the MicroBooNE precision measurements v-Ar cro

### **Multiple proton emission**  $\mathsf{m}$  emiss



Figure 3: Event display showing an on-beam data event in  $2$ is the longest track shown is accompanied with its labeled with its labeled with its labeled with its labeled w<br>Its labeled with its labe model for multi-nucleon emission and multiplicity and kinematics and purely statistical uncertainties shown in the purely statistical uncertainties 1 CS<br>n  $\overline{O}$ |
|
|-Important test for: nuclear physics model for multi-nucleon emission and moder for multi-nucleon emission and<br>event generator predictions for proton

First measurement of  $v_\mu$  CC double-differential inclusive cross sections on Ar at  $\langle E_v \rangle = 0.8$  GeV GeV ONS ON A



 $\mu$ 

0 0.5 1 1.5 2 2.5

### Theory of lepton-nucleus scattering

The cross section of the process in which a lepton scatters off a nucleus is given by



The initial and final wave functions describe many-body states:

$$
|0\rangle = |\Psi_0^A\rangle, |f\rangle = |\Psi_f^A\rangle, |\psi_p^N, \Psi_f^{A-1}\rangle, |\psi_k^{\pi}, \psi_p^N, \Psi_f^{A-1}\rangle \dots
$$

One and two-body current operators



### Global Fermi gas: independent particles **rectangular: it is constant inside the nucleus and stops sharply at its edge — Neutrons and protons are distinguishable fermions and are therefore situated in**

 $m$  **extedaba** *moving* freely within the nuclear volume Protons and neutrons are considered as

**Simple picture of the nucleus: only Statistical correlations** are retained **the pairs of nucleons** ! **no free states , no** (Pauli exclusion principle)

The energy of the highest occupied **Example 1 State 1 State 1 State is the referred state in the reference state.** state is the **Fermi energy:** E<sub>F</sub>, B'





 $\overline{\mathbf{Q}}$  16  $\overline{\mathbf{C}}$  16  $\overline{\mathbf{C}}$   $\overline{\mathbf{C}}$  and  $\overline{\mathbf{C}}$  and  $\mathbf{C}$  are  $\mathbf{C}$  and  $\mathbf$ in comparisons of neutrino scattering data.

> MiniBooNE data analysis to reproduce the data: MA~1.35 GeV is incompatible with former measurements in bubble chamber:  $M_A \sim 1.03$  GeV



Nuclear effects can explain the axial mass puzzle

### Valencia - Lyon models Advances in High Energy Physics 9 *W* or *Z W* or *Z d*2 *σ/d* cos 0





Long-range NN correlations are included in the RPA Long-range NN correlations are included in the RPA



, INTEVES, SODC  $\overline{\phantom{0}}$ −38 cm

This approach allows for a unified treatment of different reaction mechanisms .<br>.<br>. l treatr

QE, two-nucleon emission, π-production are obtained performing different cuts on the *internal lines of the W-boson self energy:*  $\overline{a}$ internal lines of the W-boson s<br>**Optical theorem** *E*<br>2) Diamed performing different cuts on the */dq / σ*

### **Optical theorem**

### Valencia - Lyon models

**Multi-nucleon emission** first proposed as a solution of the **MiniBooNE axial-mass puzzle** in Martini et al, PRC 80, 065501 (2009)<br> *Martini et al, PRC 80, 065501 (2009)* 





 $2n$ MBooNE data (×0*.*9) Morfin, Nieves, Sobczyk Adv.High Energy Phys. 2012 934597

 $CCQE-like, CCOT and CC inclusive data for different$  $\begin{array}{ccc} \hline \end{array}$  experiments The Valencia and I von model have been tested in the  $\mathcal{A}$ But, it is seen that the data of the data of the data of the data of the summer of  $\sigma$  the self-equation diagrams depicted in  $\sigma$ The Valencia and Lyon model have been tested in the CCQE-like, CC0π and CC inclusive data for different

> They are currently implemented in different EG two mechanisims contribute to the CCLC-like cross section  $\mathcal{C}$  for simplicity, we will define the CCLCCCCC

of an a<sub>nd</sub> the motivation of the nucleus. Indeed, one should consider a function in the nucleus. In the nucleus we are the n  $i$  interaction medium baryon-ba RPA effects more relevant at low-q $^2$ *d* appedistortion in the QE cross section The inclusion of RPA effects more relevant at low-q<sup>2</sup> yielding shape distortion in the QE cross section  $T$  inclusion of the 2p2 h contributions enables  $37, 384$  the double differential cross  $37, 384$ 

 $b = 0.025501(2014)$ ✐ M. Martini et al, Phys.Rev.C90,025501(2014)



### SuSav2 model and the comparison of the companion E=961 MeV, θ=37.5o  $\mathcal{L}^{\mathcal{L}}(\mathcal{L}^{\mathcal{L}})$  parametrization of the microscopic model  $ESI$ these also affect the 2p2h case, the largest difference here sus avz model  $mod \, \sim$ using the SuSAv2 parametrization of the microscopic model

 $\oslash$  G.D. Megias et al, Phys Rev D 94. 013012 (2016)  $\mathscr O$  G.D. Megias et al, Phys Rev D 94. 013012 (2016)  $\mathscr{O}$  G.

**Extensive** comparison with electron scattering data  $12C(e,e')$  double differential cross section  $0 \longrightarrow \frac{1}{0.2}$  0.4 0.6 0.8 500 1000 1500 5000 2000 1200  $E=1299$  MeV, θ=37.5°, q<sub>QE</sub>=792 MeV/c E=620 MeV, θ=60°, α<br>2000  $\frac{E=1299 \text{ MeV}}{12.5}$  $0\frac{0.2}{0.1}$  0.3 0.4 0.5 100 1000 200 300  $\overline{a}$ 500 4000 E=620 MeV,  $\theta$ =60<sup>o</sup>, q<sub>QE</sub>=559.1 MeV/c  $0 \longrightarrow 0.2$  0.4 0.6 0.  $\frac{1}{2}$  $0 \begin{array}{cccc} 0 & 0.1 & 0.2 & 0.3 & 0.4 & 0.5 \end{array}$ 2000 0.65 3000  $0.5$  $0 \longrightarrow 0.2$  0.4 0.6 0.8  $\overline{1}$  $\overline{\phantom{0}}$  $\omega$  (GeV)  $\overline{0.1}$   $\overline{0.2}$   $\overline{0.3}$   $\overline{0.4}$   $\overline{0.5}$  $\vdash$  $\vdash$  $\begin{array}{ccc} \begin{array}{ccc} \end{array} & \end{array}$  $0\frac{0}{0}$   $0.1$   $0.2$   $0.3$   $0.4$  $\vert$  $\mathbb{R}^n$  $\mathbf{1}$  $\parallel$  $\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$  $\mathbb{R}^n$ ω (GeV) **Compariso** electron<br>Cood and the full subset of the f<br>SuSAVID SUSANDING TELECTION SUSANDING SUSANDING SUSANDING SUSANDING SUSANDING SUSANDING SUSANDING SUSAN section  $\sqrt{\frac{1}{2}}$  $\frac{1500}{\frac{1}{2}}$  and  $\frac{1500}{\frac{1}{2}}$  absorption  $\frac{1}{2}$  absorption  $\frac{1}{2}$  and  $\frac{1}{2}$  absorption  $\frac{1}{2}$  and  $\frac{1}{2}$ prediction for  $\mathcal{P}$  inclusive and semi-semi-inclusive and semi-inclusive and semi-inclusive  $\mathcal{P}$  $\begin{bmatrix} 1000 \end{bmatrix}$  results. The implemented in the implementary shows that the implementary shows that the implementary shows that in the implementary shows that in the implementary shows that in the implementary shows t  $S \qquad \qquad 500$ the SuSA model able to describe the very form for  $\mathcal{A}$  $0\frac{1}{0.2}$   $\frac{1}{0.4}$   $\frac{1}{0.6}$   $\frac{1}{0.8}$   $\frac{1}{0.1}$   $\frac{1}{0.2}$  $\omega$  (GeV)  $\omega$  (GeV)  $\overline{p}$  $\frac{50}{100}$  $\sqrt{1}$  $\frac{1}{2}$ -39 (10 **−** 0  $1^1$  $\frac{1}{1}$   $\frac{q_{QE} = 192 \text{ NIEV/C}}{1}$  $\mathbf{L}^{\prime}$  $\int_1^R$ .<br>.<br>. σd $\ddot{\phantom{0}}$ ʻ -1 Nucleon Change  $\frac{1}{\sqrt{2}}$  $\frac{1}{2}$ µ $\overline{0}$ . σ5  $-359.1 \text{ MeV/c}$ 4 6  $\frac{1}{2}$   $\sum_{i=1}^n$  $\mathbf{N}_{1}$ d p dmore detailed conclusions regarding the  $\sqrt{H^2 \xi_{H_1}^2}$ as the 1500  $\frac{1}{4}$  remains dominant do Importantly is called the seen that the  $\begin{array}{ccc} \begin{array}{ccc} \text{1000} \end{array} & \begin{$  $2s$  called the implementations in General in  $\int$  remaining differences in the  $\int$   $\frac{1}{2}$  from  $\int$   $\frac{1000}{\sqrt{2}}$  $\begin{array}{|c|c|c|c|c|}\hline \multicolumn{1}{|c|}{0} & \multicolumn{$ these also affect the 2p2h case, the largest difference here  $T<sup>o</sup>$ , q<sub>OE</sub>=559.1 MeV/c Figures 10 and 11 show a comparison of the SuSAv2 and  $\begin{bmatrix} \frac{1}{2} & \frac{1}{2$  $M_{\rm H}$  in General in  $M_{\rm H}$  $\mathbb{E}[X]$  $\sum_{i=1}^N\frac{1}{i!}\sum_{j=1}^N\frac{1}{j!}\sum_{j=1}^N\frac{1}{j!}\sum_{j=1}^N\frac{1}{j!}\sum_{j=1}^N\frac{1}{j!}\sum_{j=1}^N\frac{1}{j!}\sum_{j=1}^N\frac{1}{j!}\sum_{j=1}^N\frac{1}{j!}\sum_{j=1}^N\frac{1}{j!}\sum_{j=1}^N\frac{1}{j!}\sum_{j=1}^N\frac{1}{j!}\sum_{j=1}^N\frac{1}{j!}\sum_{j=1}^N\frac{1}{j!}\sum_{j=1}^N\frac{$  $\sqrt{\frac{1}{2}}$ the SuSA model able to describe the very forward data and  $t = 0.3$  u.e  $t = 0.3$ <br>(GeV)

FIG. 10. Comparison of the T2K CC0 $\tilde{H}$ 

 $\frac{1}{2}$ et al, Phys  $\mathscr O$  S. Dolan et al, Phys Rev D 101 no.3, 033003 (2020)



absorption contribu<br>as implemented in<br>aπαντεί with an additional pionand Valencia models each  $\mathsf{D}\mathsf{T}$  $\mathbf{k}$ π<br>Γενιέ⊏ absorption contribution Comparison of the T2K t<br>Va IE. vµ-C with the SuSAv2 CC0π measurement of mparison of the T2K<br>
Dπ measurement of<br>
C with the SuSAv2<br>
Valencia models each<br>
an additional pion-<br>
orption contribution<br>
mplemented in<br>
WIE. d GENIE. 0.5 1 1.5 2

, and  $\mu$ 

 $\mu$ 

500

better. The discrepancies between the model and data are

10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10<br>10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (10 0.94 (1

 $\overline{a}$ 

)

 $-1$ 

### Nuclear many-body theory

Neutrino experiment are becoming more and more sensitive to the complexity of nuclear dynamics.

Same starting point for different many-body methods: Effective Field Theory interactions and currents



**Argoneut**



 $H = \sum$ *i*  $\mathbf{p}_i^2$ 2*m*  $+\sum$ *i<j*  $v_{ij} + \sum$ *i<j<k*  $V_{ijk} + \ldots$ 

**Green's Function Monte Carlo**

**Spectral Function (SF) Short-time Approximation (STA)**









## Short Time Approximation

The STA method utilizes QMC techniques to predict the response function of nuclei in the quasielastic region. the r

Assumption: for short times (moderate **q**) only the active pair of nucleons propagate  $\epsilon$  $\alpha$  inclusive scattering. Longitudinal response at  $\alpha$ 



Interaction effects at the two-nucleon level are fully retained, and the **interference between one-**R and two-body terms are consistently accounted for, access to exclusive channels  $I$ nteraction effects at the two-pucleon level.

Electromagnetic responses of 4He:



### Factorization Scheme and Spectral Function

For sufficiently large values of |**q**|, the **factorization scheme** can be applied



 The intrinsic properties of the nucleus are described by the **Spectral Function→** effective field theory and nuclear manybody methods

$$
d\sigma_A = \int dE d^3k \ d\sigma_N P(\mathbf{k}, E)
$$

 $\mathcal O$  O. Benhar, A. Fabrocini, and S. Fantoni, Nucl. Phys. A505, 267 (1989).



 $\frac{1}{2}$   $\frac{1}{2}$ 

 $\frac{1}{2}$   $\frac{1}{2}$ 

nucleon is free  $\frac{1}{2}$  corrections  $\frac{1}{2}$  corrections  $\frac{1}{2}$  corrections sections secti  $0.00000 - 0.1200 - 0.200 - 0.200 - 0.200 - 0.000 - 0.1$  $\omega$  [GeV] [GeV]

 $\frac{1}{2}$   $\frac{1}{2}$ 

### $\Gamma$ s obeyi obtained  $\Omega$ skec $s$  special  $\Omega$  spectral  $\Gamma$ .  $\mathbb{R}$ **Factonzation Scrieme and Spectral Function** to the CBF and SCGF sections, respectively. The dashed lines correspond to the IA calculation in which the outgoing  $\mathcal{L}_\text{max}$ at 2.2 GeV and 15.5 scattering angle. The solid (dashed) line shows the quasielastic cross section without (with) the inclusion of FSI obtained utilizing the SCGF spectral function calculations. Experimental data are taken from Ref. [94, 95] and show both the quasielastic peak and the contribution from meson production at larger missing energies. actorization Scheme and Spectral Function to the CBF and SCGF SF calculations, respectively. The dashed lines correspond to the IA calculation in which the outgoing Factorization Scheme and Spectral Function

to the Carculations, respectively. The corresponding to the IA calculation in the IA calculation in which the IA calculation in which the IA calculation in which the outgoing the outgoing the IA calculation in which the o



 $p^{\text{max}}_{\text{max}}$  and dashed blue line corresponding to the total cross section obtained blue corresponds to the total cross section obtained by  $\mathbb{R}^n$ 

 $\frac{3}{\sqrt{2}}$  up the di⊄erent contributions associated with the di⊄erent reaction mechanisms. The dashed blue lines associated with the dashed blue lines associated blue lines associated blue lines associated blue lines as

 $\begin{array}{ccc} 0 & 0.2 & 0.4 & 0.0 & 0.0 & 1 & 1.2 & 1.4 \ & & & & \end{array}$ 

summing up the di↵erent contributions associated with the di↵erent reaction mechanisms. The dashed blue line

 $\frac{1}{\sqrt{2}}$ 

 $\cup$ 

 $\frac{25}{25}$  0.05<br>  $\frac{5}{25}$  0<br>  $\frac{1}{25}$  0<br>  $\frac{1}{25}$  0.05<br>  $\frac{1}{25}$  0.05<br>  $\frac{1}{25}$  0.05<br>  $\frac{1}{25}$  0.02<br>
0.4<br>
0.6<br>
0.8<br>
1 1.2<br>
1.4

 $p_{\perp}$  [GeV]

 $0.05$ 

 $0.1$ 

 $\frac{1}{2}$  0  $\frac{1}{2}$  0 0.2 0.4 0.6 0.8 1 1.2 1.4

theoretical results have been obtained using the CBF spectral function and correcting for FSI e↵ects the quasielastic Right panel: same as left panel but for CC ⌫*<sup>µ</sup>* scattering on <sup>12</sup>C. The energy of the ⌫*<sup>µ</sup>* is 1 GeV and the scattering angle is 30. theoretical results have been obtained using the CBF spectral function and correcting for FSI e↵ects the quasielastic part corresponding to the dashed blue line. The solid black line corresponds to the total cross section obtained current operator has been included. Next steps: **inclusion of MEC and π production and absorption**

## Future experiments and theory efforts

DUNE and Hyper-K high-precision measurement of neutrino oscillation parameter  $\rightarrow$  accurate cross section predictions supplemented by theoretical uncertainty



**Electron for Neutrinos**: constrain interaction models used in v energy reconstruction

**Jlab E12-14-012 experiment**: study the properties of Ar nucleus by electron scattering. The data cover different reaction mechanisms

QE-RES: rich set of new cross section measurements T2K, MINERvA, NOvA, MicroBooNE

DIS: data and new analyses from MINERvA on different nuclei

### *Gandolfi et al.* **Nuclei: QMC and EFT Interactions** *Gandolfi et al.* **Nuclei: QMC and EFT Interactions** Future experiments and theory efforts

✐ S.Gandolfi, D.Lonardoni, et al, *Front.Phys.* 8 (2020) 117

 $0\frac{1}{1}$  bady problem are needed to include by 20 40 60 80 100  $120$  the chiral expansion and statistical uncertainty  $\frac{1}{2}$  40  $\frac{1}{2}$  $---$  SF IA SF IA+FSI **with ab-initio results effects. Benchmark** with ab-initio results Ar*(e,eʹ)* 0 20 40 60 80 100 120 140 160  $E_e = 2.2 \text{ GeV}, \ \theta_e = 15.5^\circ$ Ti*(e,eʹ)*  $0\frac{1}{50}$  100 150 200 250 300 350 400 450 5 10 15 20 25 30 35 40 45 50 *ω* [MeV] *d/d*Ω*ℓʹdEℓʹ* [10-8 nb/sr MeV]  ${}^{12}C(\nu_{\mu},\mu^{-})$  ${}^{40}\text{Ar}(\nu_{\mu},\mu^{-})$  $\frac{4}{3}$  $\theta_{\mu}$  = 30° 4 0 6 8 20 12 40  $60^\theta$  $60\sqrt{v^2} = 30\sqrt{2p^2}$  $\sqrt{\frac{1}{2}}C(v_\mu, v_\mu)$  $\int_0^{\infty} Ar(v_\mu, v_\mu)$  $^{40}$ Ar[p]<sup>+48</sup>Ti[p]( $v_\mu, v_\mu$ )  $\overline{a}$   $\overline{a}$ -0.1  $\sum_{i=1}^n$  $\frac{m}{\sqrt{2}}$  $\mathbf{v}'$  $\frac{1}{2}$  $\begin{array}{cccccccccc} \bullet\hspace{-.4cm} & \bullet$ E'(GeV)  $\frac{1}{2}$  $\frac{1}{\Gamma}$  $\sqrt{2}$  $\frac{1}{2}$  $-60$   $-60$  $-40$   $\leftarrow$  $\begin{bmatrix} 20 \\ 1 \end{bmatrix}$ 160<br>160  $\rm{^{3}H}$   $\rm{^{3}He}$ 1.2  $1.4$  1.6  $1.8$  2.2  $\mathbb{E}^{\text{CEV}}$ 80 100 120 140  $^{40}$ Ar (c) ) double differential cross section of carbon, titanium and argon from [19, 20], compared with the SuSAv2- FIG. 43. The (e, e shown in green at the center. GFMC (AFDMC) results for the NV2+3-Ia [11] (GT+E⌧ -1.0 [89]) potential  $100 - \frac{1}{2}$  for the scale-init  $\frac{15}{10}$  calculations of lepton-Ar oross sections  $\frac{15}{10}$  $\frac{1}{\sqrt{100}}$  and  $\frac{1}{\sqrt{100}}$  be previous and the previous analysis of the SuSAV-MEC model and the scaling of the scaling of the scaling of the scaling  $\omega$   $\left[\text{MeV}\right]$ **rules applied when the extrapolation of the analysis of the analysis of the recent values of the recent Julie data for inclusive**  $\alpha$ data SuSAv2-MEC Inelastic **OE**  $\overline{100}$  $\overline{2}$ . $\overline{2}$  $\checkmark$  $\overline{\phantom{0}}$  $\mathbf{1}$  $\mathbb{A}$  $\sqrt{2}$  $\mathbf{1}$ ′  $0^\circ$  double differential compared  $\frac{12}{2}C(\nu_\mu, \mu^-)$  ----- $\text{N}_{\text{L}}$  and  $\text{N}_{\text{L}}$  and intelastic contributions are also shown. The beam energy is a shown. The be  $\frac{2}{3}$   $\frac{35}{1}$  deg. D. Comparison with recent JLab data ativistic  $0\frac{1}{50}$   $\frac{100}{100}$   $\frac{150}{200}$   $\frac{200}{250}$   $\frac{300}{300}$   $\frac{350}{300}$   $\frac{400}{450}$  $r$ ults applied when  $\omega$  [MeV] and  $\omega$  and  $\omega$  inclusive  $\omega$ -140  $-\frac{1}{2}20$  $-100$ -80 -20 0  ${}^{4}$ He  ${}^{6}$ He  ${}^{6}$ Li  ${}^{7}$ Li  $^{\rm 5}$ He 8Be  $\overline{\phantom{a}}$  $\mathbf{H}$ <sup>1111</sup> E (MeV) NV2#P#B Exp  $\mathbf{G}$ T+Eτ-1.0 Figure 2. Ground-state energies in *A* 16 nuclei. For each nucleus, experimental results [122] are are shown in red and the left (right) of the experimental values. For the experimental values of  $\sim 45+^{6}\mu^{-30}$  $\mathbb{E}_{\mathbb{E}} \left[ \begin{array}{ccc} \mathbb{E}_{\mathbb{E}} & \mathbb$  $\mathbb{R}$   $\mathbb{R}$  in  $\mathbb{R}$  interferential uncertainties of the order of few percent. For the  $\frac{20}{20}$ **the theoretical errors community compared the chiral expansion of the star-of the star-of the star-of the star-** $\mathcal{A}$  $\frac{1}{6}$  body problem and inequal to include relativistic  $\frac{0}{50}$   $\frac{100}{100}$   $\frac{150}{150}$  $.1 \times 0.2$ <sup>r</sup>  $.3 \times 0.4 \times 0.5 \times 0.6 \times 0.7 \times 0.8 \times 0.9$  8Li 8Be  $\overline{1}$  $\frac{1}{\sqrt{1-\frac{1}{2}}}$  $^{12}\mathrm{C}$ 16<sub>O</sub> Figure 2. Ground-state energies in *A* 16 nuclei. For each nucleus, experimental results [122] are  $s \sim 1$  . GeV (AFDMC) results for the NV2+3-Ia (GT+E  $\sim$  1.0  $\sim$  1  $\alpha$ <sup>0</sup>  $\rightarrow$  Theoretical uncertainty estimate: truncation of  $p_0$  is the full uncertainty evaluation in  $\mathbb{N}^{\mathbb{N}}$  is the full uncertainty errors.  $\mathbb{R}^d$  methods in the order of the order of  $\mathbb{R}^d$  the order of  $\mathbb{R}^d$ , final,  $\begin{bmatrix} 60 \\ 1 \end{bmatrix}$  Using more approximate methods, first  $t_{10}$   $\Box$   $\Box$  calculations of lepton-Ar orgs sections  $\overline{\phantom{a}}$  is currently being done in developing such potentials.  $F_0 \sim 4$  shows the charge radial of  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$ 0 0.1  $\frac{0.1}{0.2}$   $\frac{0.3}{0.5}$   $\frac{0.4}{0.4}$   $\frac{0.5}{0.5}$   $\frac{0.6}{0.7}$   $\frac{0.7}{0.8}$   $\frac{0.8}{0.9}$ point-proton radius *r*pt using the relation ab-initio method calculations of lepton-Ar oross sections Controlled approximation of the nuclear-many body problem are needed to include relativistic

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# Thank you for your attention!