Some insights on the ^{4}He mysteries from α – scattering measurements

Vasilis Soukeras

Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud (INFN – LNS)

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"Cutting-edge developments in nuclear structure physics"

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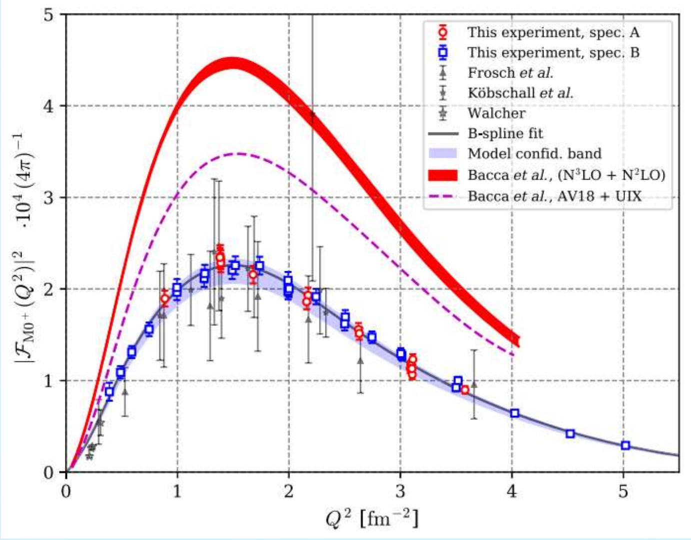
The physics case

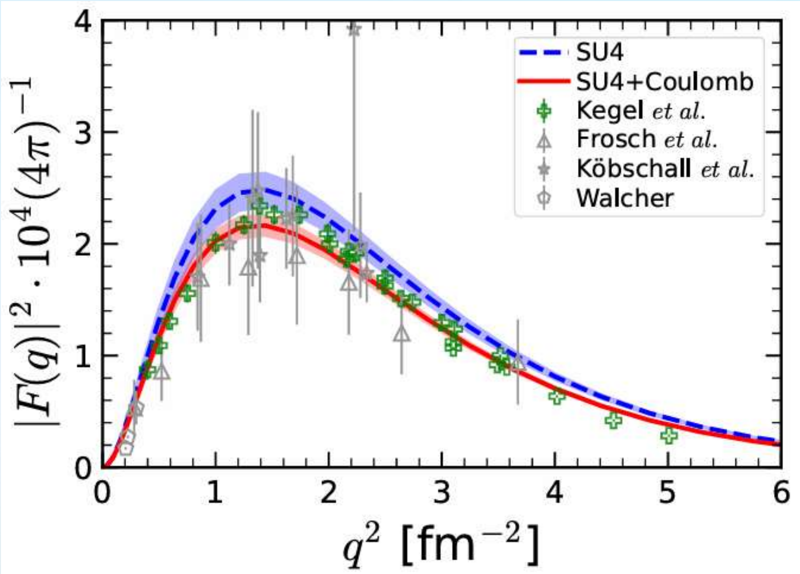
- Significant disagreements between recent **ab-initio calculations** of the monopole transition form factor of ^{4}He

See for example:
E. Hiyama et al., Phys. Rev. C 70, 031001 (2004)
S. Bacca et al., Phys. Rev. Lett. 110, 042503 (2013)
S. Kegel et al., Phys. Rev. Lett. 130, 152502 (2023)
E. Epelbaum, Physics (Viewpoint) 16, 58 (2023)
M. Kamimura, Prog. Theor. Exp. Phys. 071D01 (2023)
U.-G. Meißner et al., Phys. Rev. Lett. 132, 062501 (2024)
M. Viviani et al., Few Body Systems 65, 74 (2024)
N. Michel et al., Phys. Rev. Lett. 131, 242502; 133, 239901(E) (2024)

➢ **The calculation of the isoscalar monopole form factor remains an open subject**

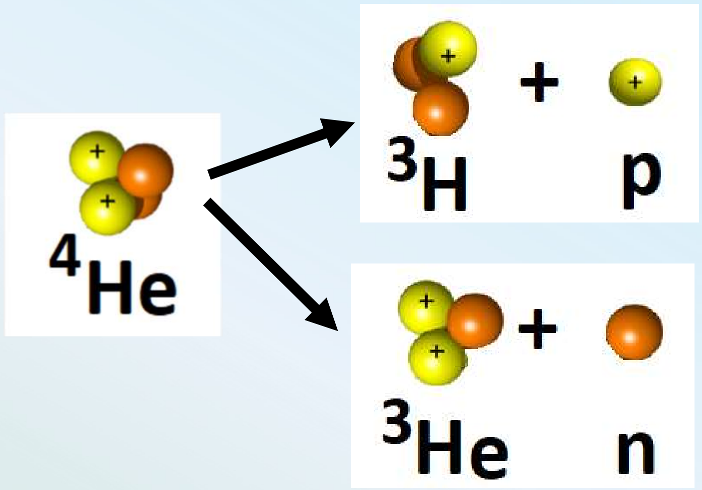


S. Kegel et al., Phys. Rev. Lett. 130, 152502 (2023)



U.-G. Meißner et al., Phys. Rev. Lett. 132, 062501 (2024)

The physics case



S_p = 19.813 MeV

S_n = 20.578 MeV

Open questions:

- Line shape of the 0^+_2 resonance
- Dependence on the different probes
- Interference phenomena

- **Resonance energy and width were obtained as an average of different values**
- **No real attempt to obtain the real line shape**

It is important to extract in a modern measurement the position and width of the first 0^+ resonance with a good accuracy and to establish the line shape

E_r (MeV)	Γ_r (MeV)	Probe	Reference
20.28±0.05	0.41±0.05	(α,α)	Gross 1969
20.29±0.02	0.89±0.04	(α,α)	Baumgartner 1981
20.46±0.14	0.34±0.04	(p,p)	Williams 1966
20.26±0.16	0.39±0.10	(e,e)	Frosch 1968
20.10±0.05	0.27±0.05	(e,e)	Walcher 1970
20.12±0.16	0.24±0.07	(e,e)	Kobschall 1983
20.21	0.26±0.05	(e,e)	Kegel 2023
20.21	0.29±0.03	(e,e)	Kegel 2023

- **It is important to investigate the properties of the 0^+_2 resonance wavefunction**

- ❖ **In (e,e´) studies the calculations select only isoscalar monopole form factors while, we may have also isovector components and higher multipolarities in the experimental spectra**

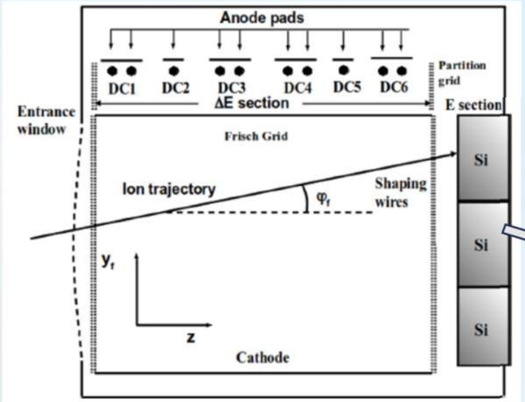
We proposed

- ✓ **to study in an exclusive measurement the $^{4}He(^{4}He,^{4}He)^{4}He^{*}$ inelastic scattering**
- ✓ **to revisit existing data sets in a consistent way**

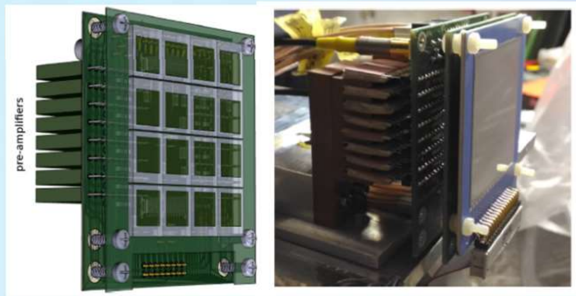
Low background

Offers an interesting complementarity with electron scattering data

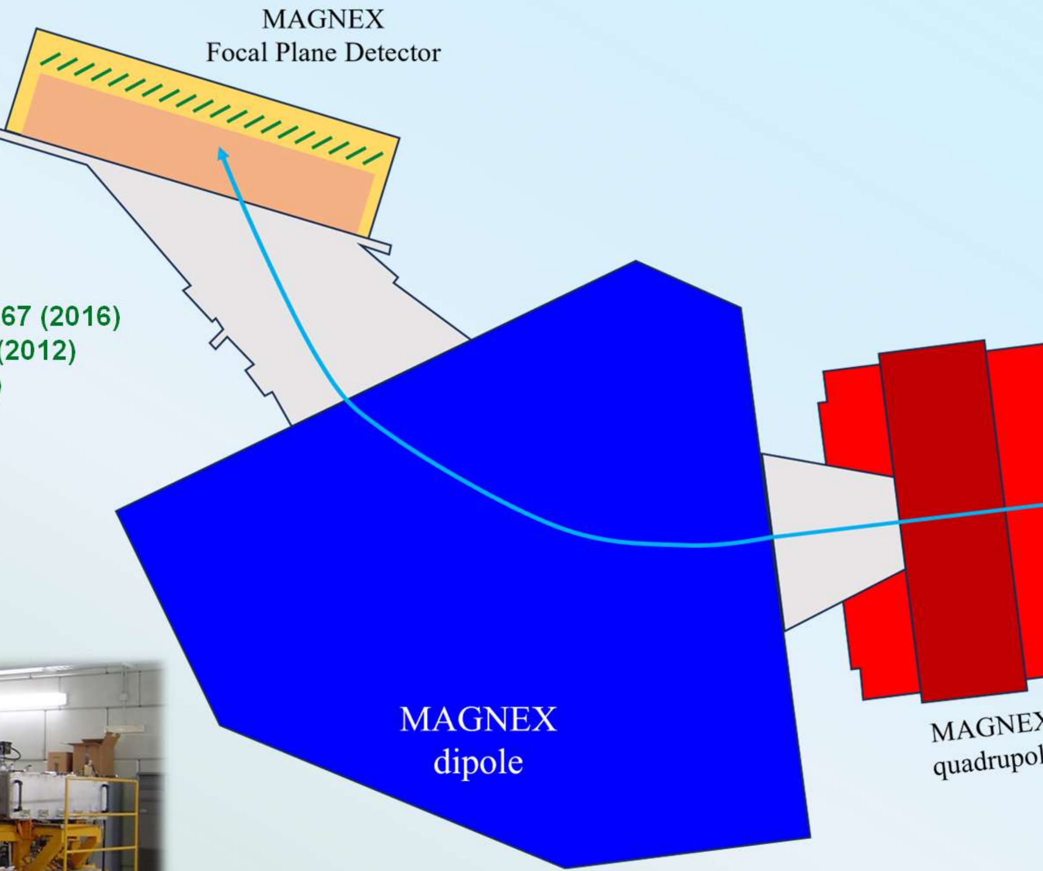
Experimental setup

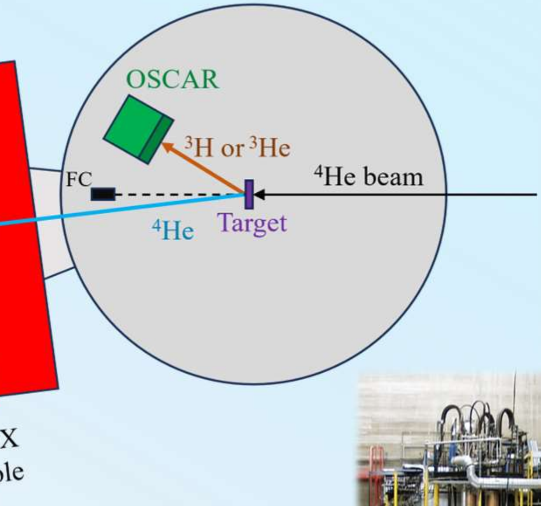


F. Cappuzzello et al., Eur. Phys. J. A 52, 167 (2016)
M. Cavallaro et al., Eur. Phys. J. A 48, 59 (2012)
D. Torresi et al., NIM A 989, 164918 (2021)



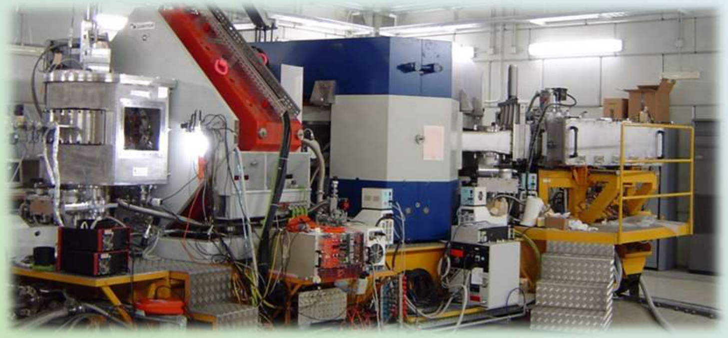
D. Dell'Aquila et al., NIM A 877, 227 (2018)





NUMEN

See also talk by
Alessandro Spatafora



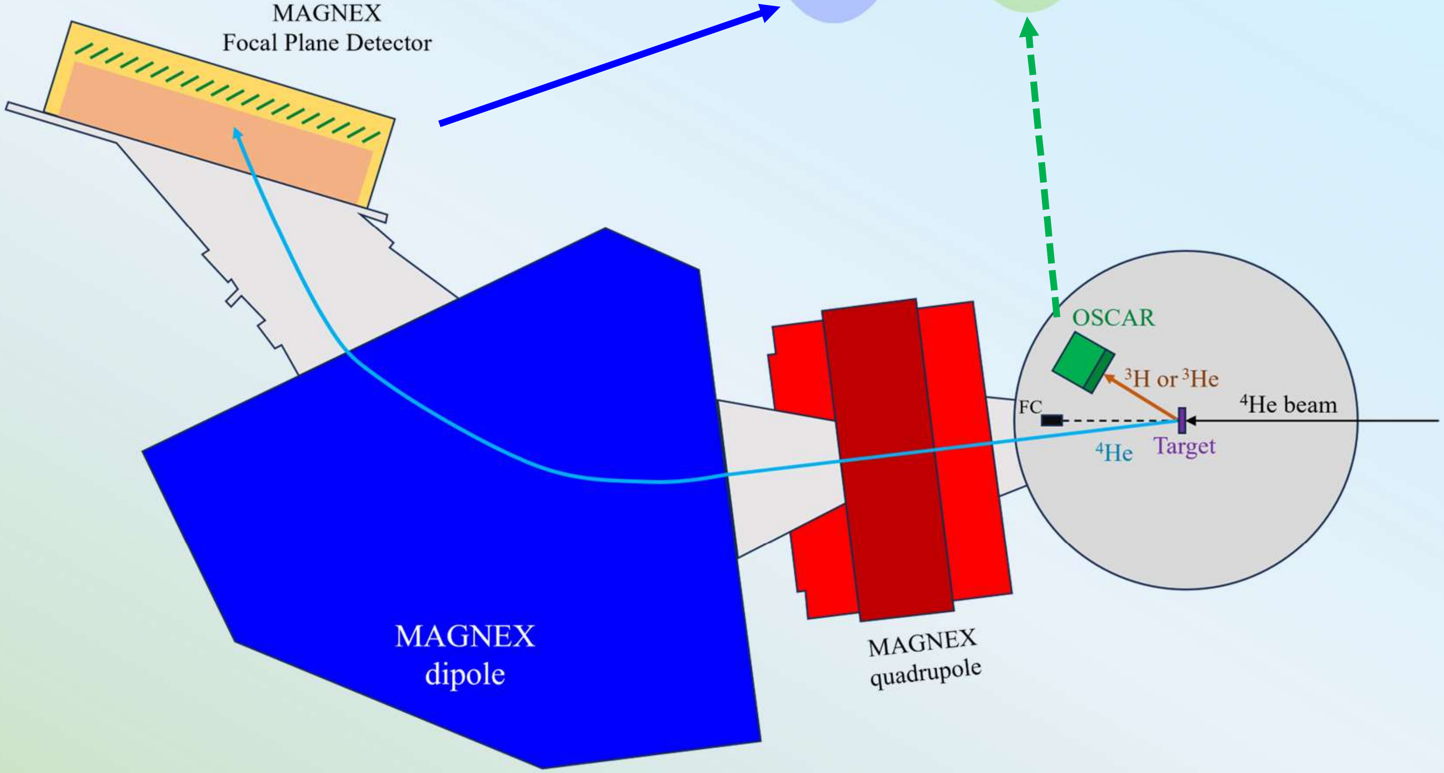
Experimental setup

- $^4He + ^4He \rightarrow$ **^4He** + ^4He
- $^4He + ^4He \rightarrow ^4He + ^4He^* \rightarrow$ **^4He** + **^3H** + ^1H
- $^4He + ^4He \rightarrow ^4He + ^4He^* \rightarrow$ **^4He** + **^3He** + n

Exclusive measurement for the first time

Almost background free !

(signal to background ratio: 15 – 40)



V. S. et al., EPJ-WoC 304, 01006 (2024)

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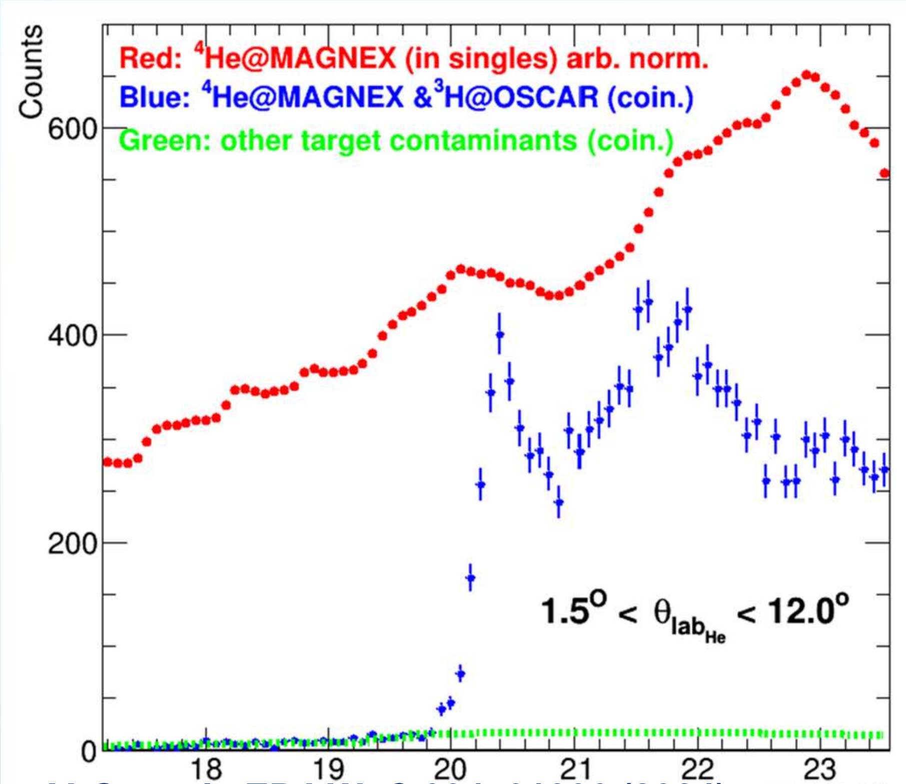
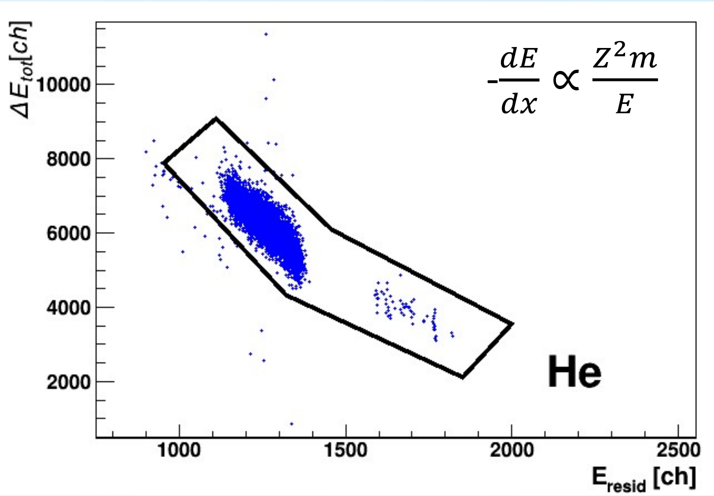
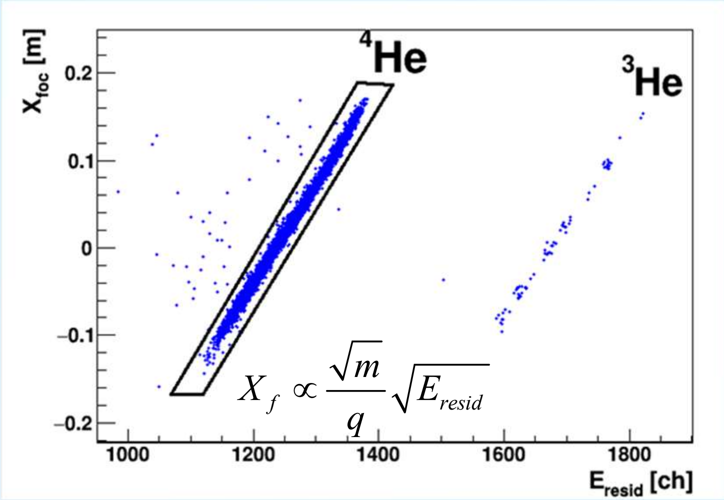


V. S. et al., EPJ-WoC 304, 01006 (2024)

Particle Identification

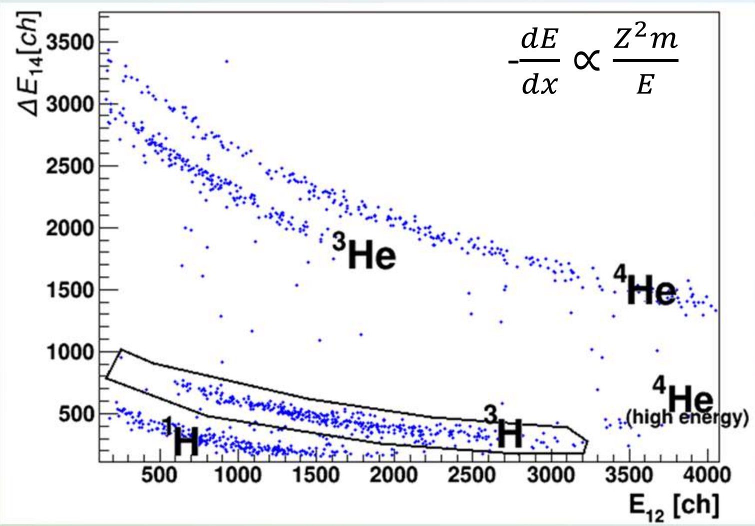
MAGNEX





- Unambiguous Particle identification !

OSCAR



For more details on the **experimental setup** and **data reduction**:

V. S. et al., EPJ-WoC 252, 04007 (2021)

V. S. et al., Jour. Phys.: Conf. Ser. 2586, 012033 (2023)

V. S. et al., EPJ-WoC 304, 01006 (2024)

→Goals of the present study:

- ❑ **Clarify** the previous inconsistencies between (^{4}He,^{4}He) and (e,e') data
- ❑ Extract the **characteristics of the first excited state (0^+_2)** of ^{4}He in a modern measurement with good accuracy
- ❑ Investigate the **role of the accessible partial waves**
- ❑ **Investigate possible interference between the 0^+_2 resonance with underlying non-resonant L=0 continuum**

Line shape analysis

+

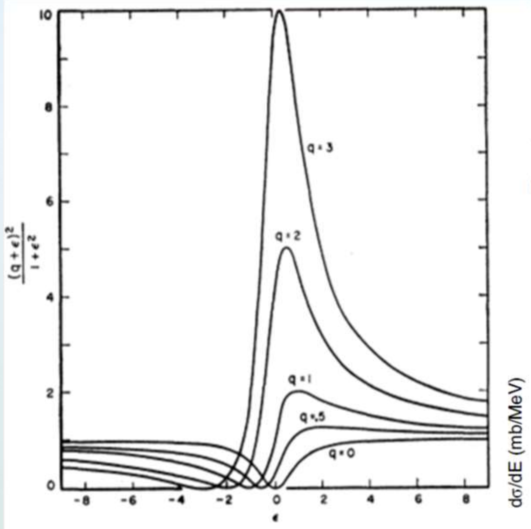
Fano theory

- ❑ **Probe ab-initio theories** adopted for the electron scattering data interpretation with a complementary set of ^{4}He + ^{4}He data

Coupled channel calculations

Aim to put strong constraints towards the solution of the puzzle !

Line shape analysis adopting the Fano function



Natural line shapes for different values of q. (Reve
scale of abscissas for negative q.)

$$\sigma = \sigma_{\text{cont}} \frac{|q+\epsilon|^2}{1+\epsilon^2}$$

$$\epsilon = 2(E - E_r)/\Gamma_r$$

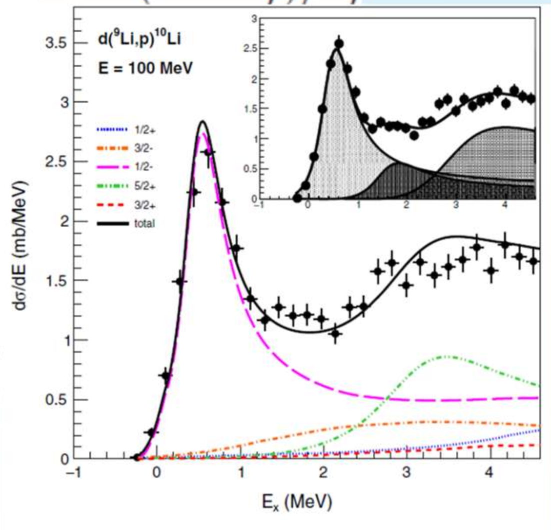
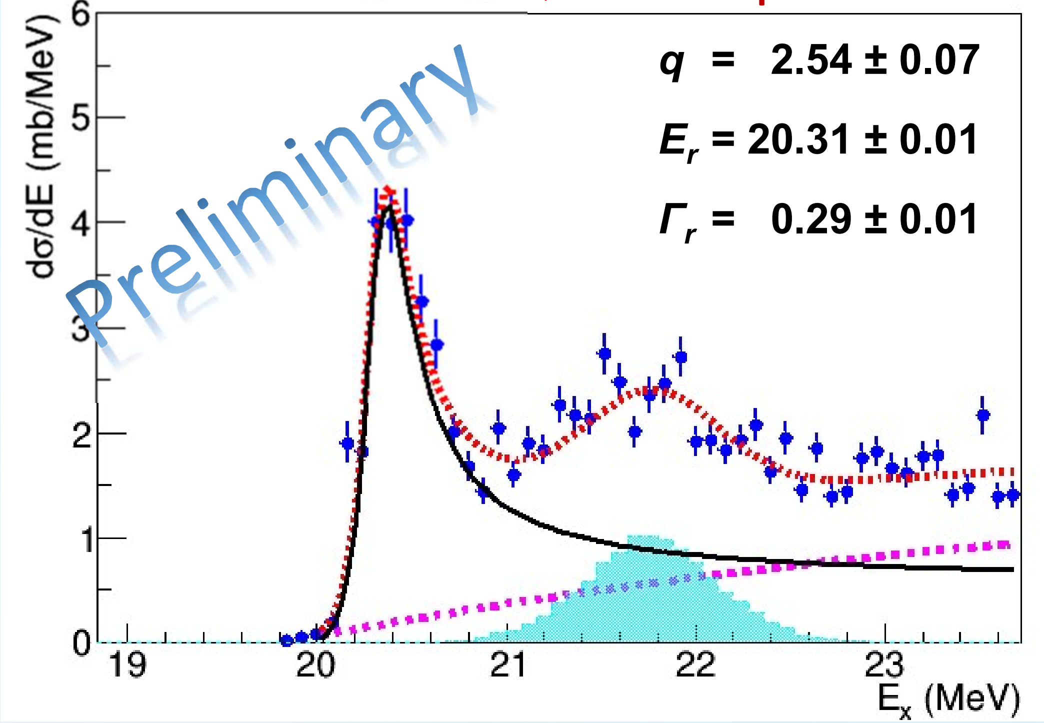


FIG. 1. ^{10}Li energy spectrum for the $d(^9\text{Li}, p)^{10}\text{Li}$ reaction at 100 MeV incident energy and $\theta_{CM} = [5.5°, 16.5°]$. The curves

- U. Fano, Phys. Rev. 124, 1866 (1961)
- C. Ott et al., Science 340, 716 (2013)
- M.F. Limonov et al., Nature Photonics 11, 543 (2017)
- M. Cavallaro et al., Phys. Rev. Lett. 118, 012701 (2017)

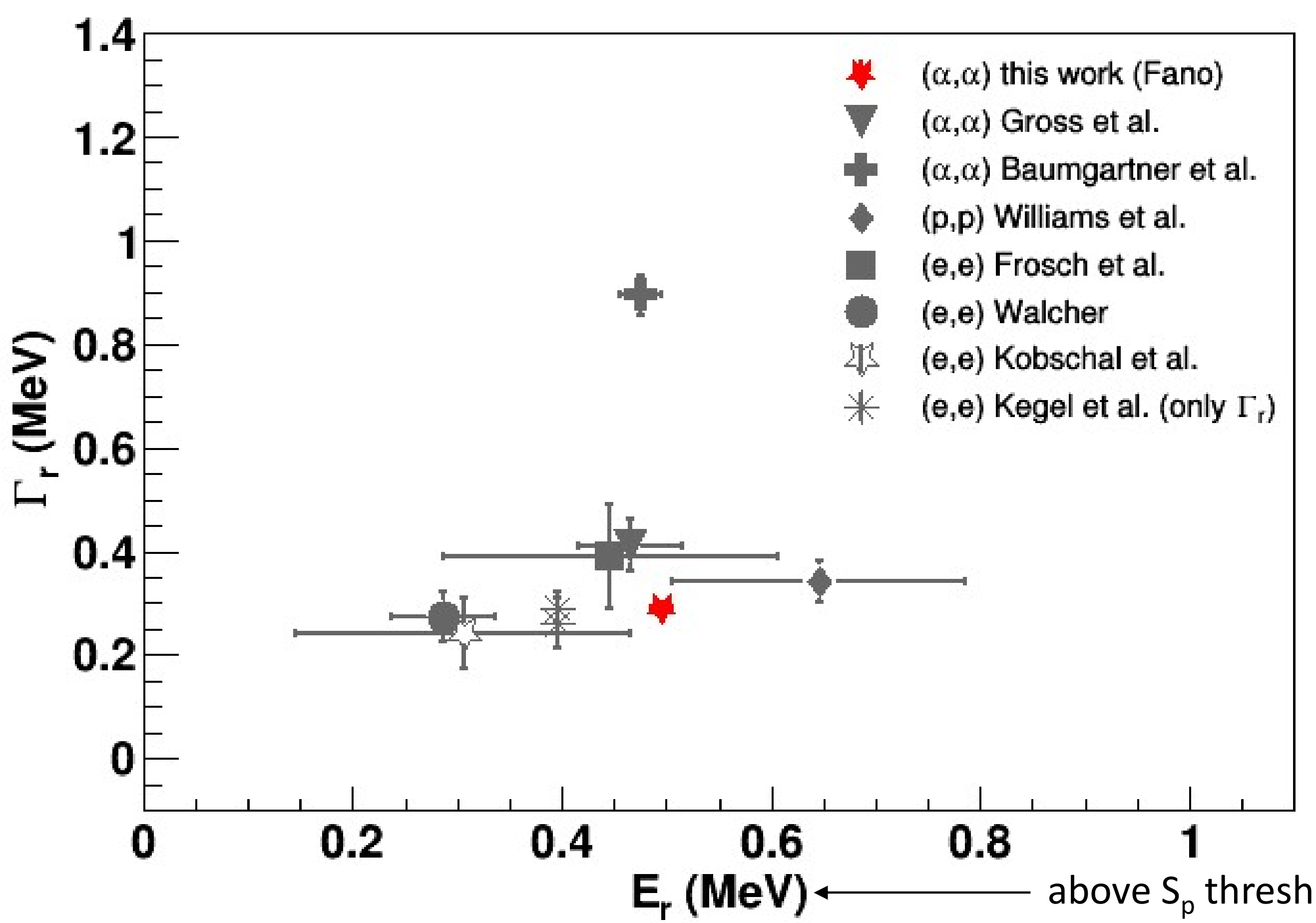
^{4}He + ^{4}He* → ^{4}He + ^{3}H + p



Fano (0^+_2 & non – resonant) &
1^- – resonant state (24.25 MeV) &
transfer (^{4}He+^{4}He → ^{3}H+^{5}Li → ^{4}He+^{3}H+^{1}H)

- 1^- resonance: following the prescription of K.W. McVoy and P. Van Isacker, NPA 576, 157 (1994) by using MULTIP (O. Sgouros et al., EPJ A 53, 165 (2017))

Resume of the results reported so far



above S_p threshold

E. E. Gross et al., Phys. Rev. 178, 1584 (1969)

M. Baumgartner et al., Nucl. Phys. A 368, 189 (1981)

L.E. Williams et al., Phys. Rev. 144, 815 (1966)

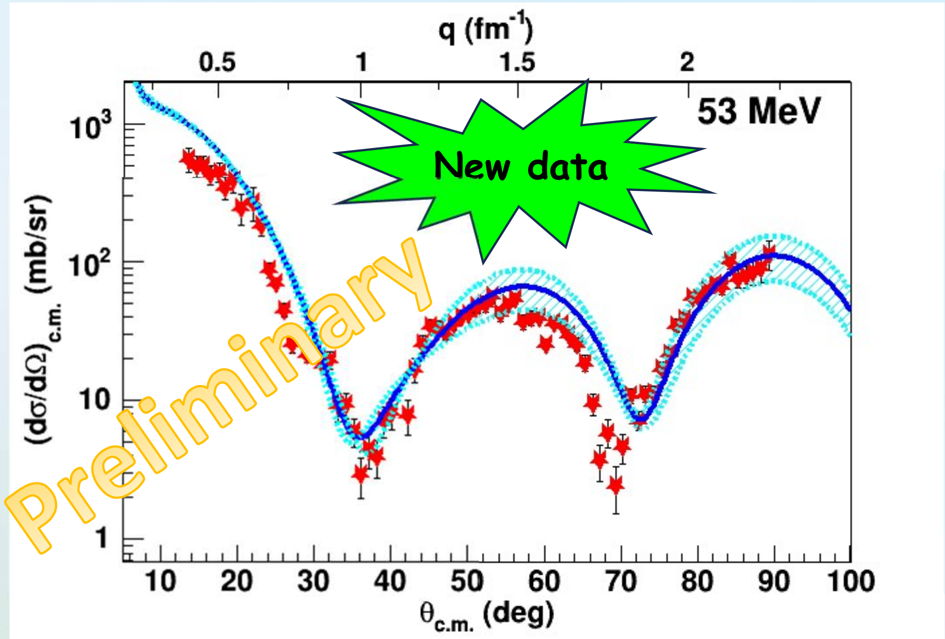
R. F. Frosch et al., Nucl. Phys. A 110, 657 (1968)

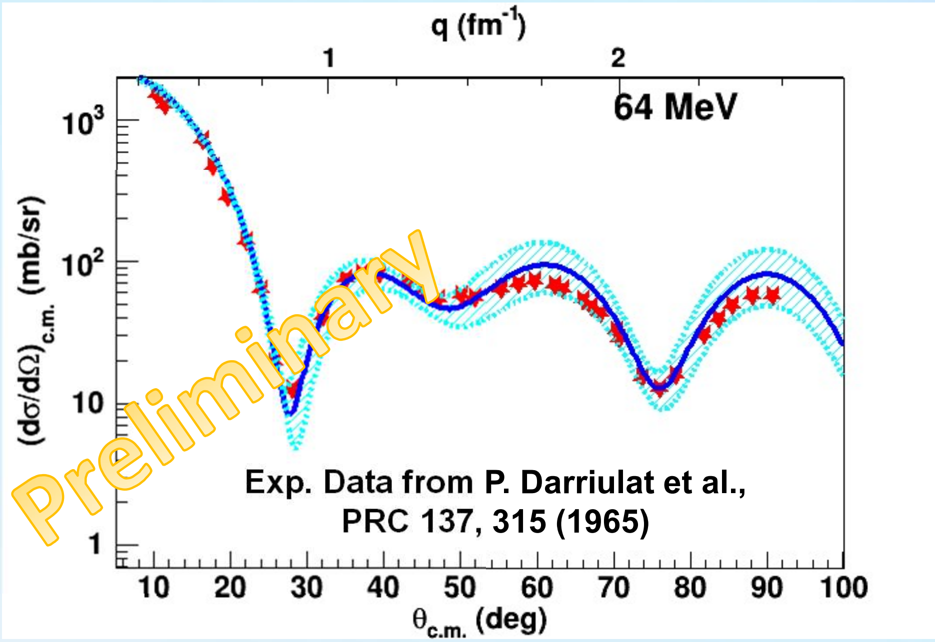
Th. Walcher, Phys. Lett. B31, 442 (1970)

G. Kobshall et al., Nucl. Phys. A 405, 648 (1983)

S. Kegel et al., PRL 130, 152502 (2023)

Elastic scattering @ 53 & 64 MeV





$U_j(R) = V_j^{(C)}(R) + N_{Rj}V_j^{(N)}(R) + iN_{Ij}V_j^{(N)}(R)$, *j=0,1 for ISI and FSI*

$U_{coup}(R) = V_{coup}(R) + i\,\beta_I\,V_{coup}(R)$

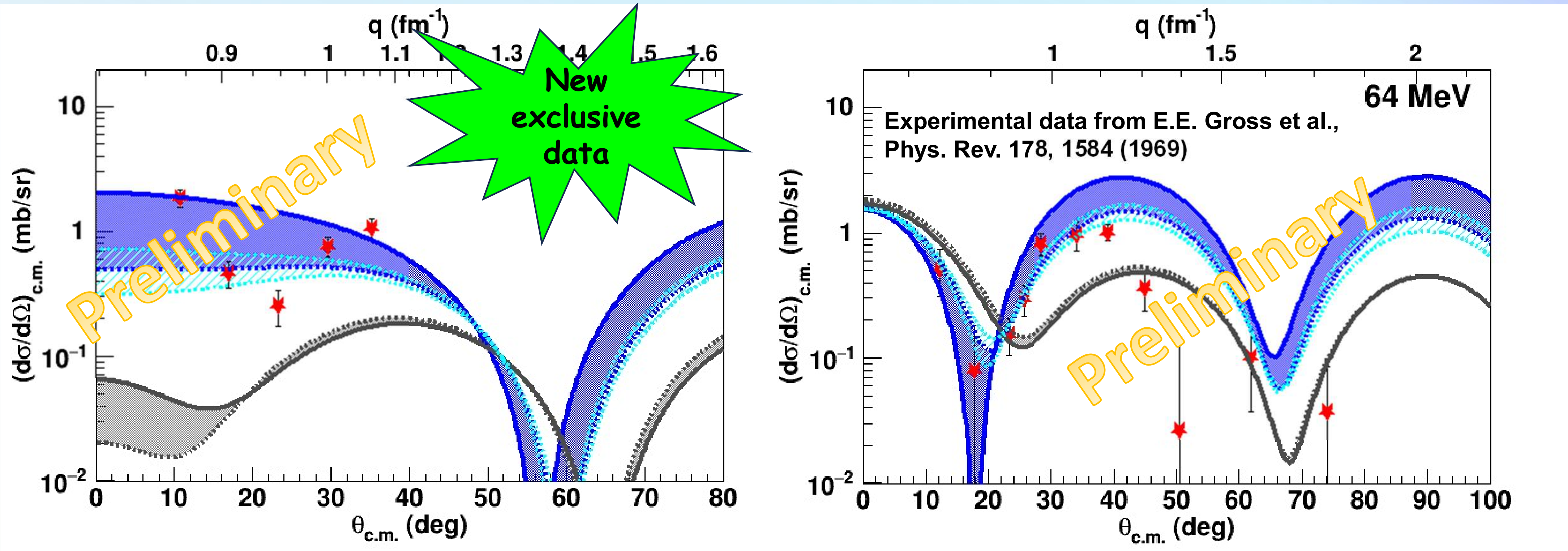
N_{R0} & N_{I0} from fit of the experimental S matrix at elastic scattering data at similar energies

Ab-initio models used:

S. Bacca et al., Phys. Rev. Lett. 110, 042503 (2013) *[chiral EFT]*
M. Viviani et al., Few Body Systems 65, 74 (2024) *[chiral EFT]*
U.-G. Meißner et al., Phys. Rev. Lett. 132, 062501 (2024)
E. Hiyama et al. PRC 70, 031001(R) (2004)

Blue curves: no visible difference between different ab-initio models
The cyan blue band accounts for the uncertainties in the reaction modelling

Inelastic scattering @ 53 & 64 MeV



Ab-initio models used:

S. Bacca et al., Phys. Rev. Lett. 110, 042503 (2013) *[chiral EFT]* ———

M. Viviani et al., Few Body Systems 65, 74 (2024) *[chiral EFT]* - - - - - -

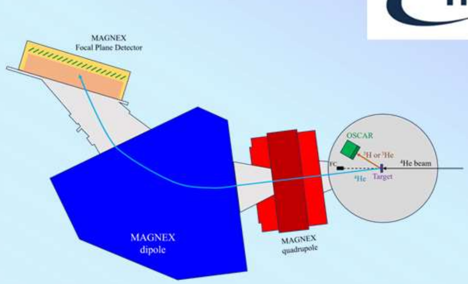
U.-G. Meißner et al., Phys. Rev. Lett. 132, 062501 (2024) ———

E. Hiyama et al. PRC 70, 031001(R) (2004) - - - - - -

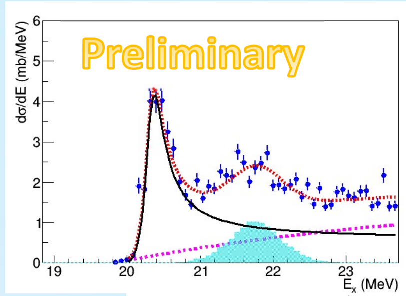
The cyan blue band accounts for the uncertainties in the reaction modelling

Summary

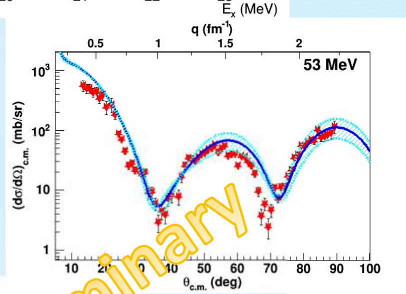
✓ **Elastic** and **inelastic scattering exclusive measurements** were performed for the first time at the beam energy of 53 MeV ($E_{c.m.}$=26.5 MeV) at the MAGNEX facility



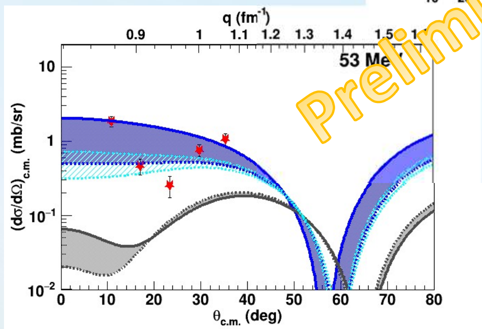
✓ The **line shape analysis with the Fano function** indicates sizeable interference between resonant (0^+_2) and non-resonant continuum



✓ The experimental cross sections were interpreted in the **coupled channels** framework adopting physics models from **ab-initio theories**



→ chiral effective field theory model seems to be in better agreement with ^{4}He(^{4}He,^{4}He)^{4}He* experimental data



Collaboration

F. Cappuzzello, V. Soukeras*, S. Bacca, D. Carbone, M. Cavallaro, L. C. Chamon, M. Fisichella, I. Lombardo, M. Viviani, C. Agodi, H.-W. Becker, G. A. Brischetto, S. Calabrese, C. Ciampi, M. Cicerchia, M. Cinausero, I. Ciraldo, D. Dell' Aquila, C. Frosin, A. Hacisalihoglu, M. Hilcker, A. Kievsky, Y. Kucuk, T. Marchi, G. Orlandini, O. Sgouros, A. Spatafora, D. Torresi, M. Vigilante, A. Yildirim

- INFN – Laboratori Nazionali del Sud, Catania, Italy
- Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Catania, Italy
- Institut fur Kernphysik, Johannes Gutemberg – Universität Mainz, Mainz, Germany
- Helmholtz – Institut Mainz, Johannes Gutemberg – Universität Mainz, Mainz, Germany
- Departamento de Fisica Nuclear, Instituto de Fisica da Universidade de Sao Paulo, Sao Paulo, Brasil
- INFN – Sezione di Pisa, Pisa, Italy
- Ruhr – Universitat Bochum, Bochum, Germany
- INFN – Sezione di Firenze, Firenze, Italy
- INFN – Laboratori Nazionali di Legnaro, Legnaro, Italy
- Dipartimento di Fisica "Ettore Pancini", Università degli Studi di Napoli "Federico II", Napoli, Italy
- INFN – Sezione di Napoli, Napoli, Italy
- Institute of Natural Science, Karadeniz Teknik Universitesi, Trabzon, Turkey
- Akdeniz University, Antalya, Turkey
- Dipartimento di Fisica, Università di Trento, Trento, Italy
- Istituto Nazionale di Fisica Nucleare, TIFPA, Trento, Italy

* e-mail: vasileios.soukeras@lns.infn.it


Thank you very much
for your attention