Proton spectral function from the Ti(*e*,*e'p*) cross sections

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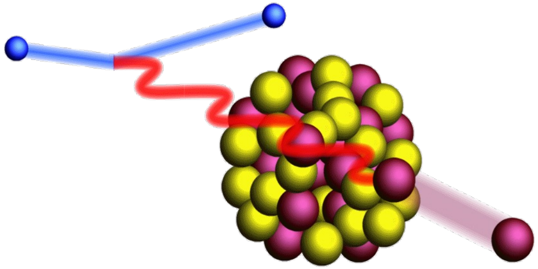
E12-14-012: (*e*,*e'*) and (*e*,*e'p*) on Ar and Ti

Aim: Obtaining the experimental input indispensable to construct the argon spectral function, thus paving the way for a reliable estimate of the neutrino cross sections in DUNE. In addition, stimulating a number of theoretical developments, such as the description of final-state interactions.
[Benhar *et al.*, arXiv:1406.4080]



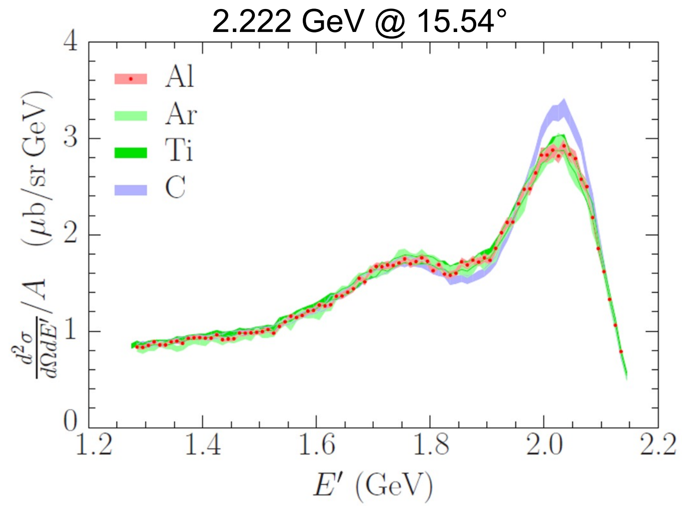
$E_e = 2.222$ GeV

	E'_e (GeV)	θ_e (deg)	$\lvert\mathbf{p}'\rvert$ (MeV)	$\theta_{p'}$ (deg)	$\lvert\mathbf{q}\rvert$ (MeV)	p_m (MeV)	E_m (MeV)
kin1	1.777	21.5	915	−50.0	865	50	73
kin2	1.716	20.0	1030	−44.0	846	184	50
kin3	1.799	17.5	915	−47.0	741	174	50
kin4	1.799	15.5	915	−44.5	685	230	50
kin5	1.716	15.5	1030	−39.0	730	300	50

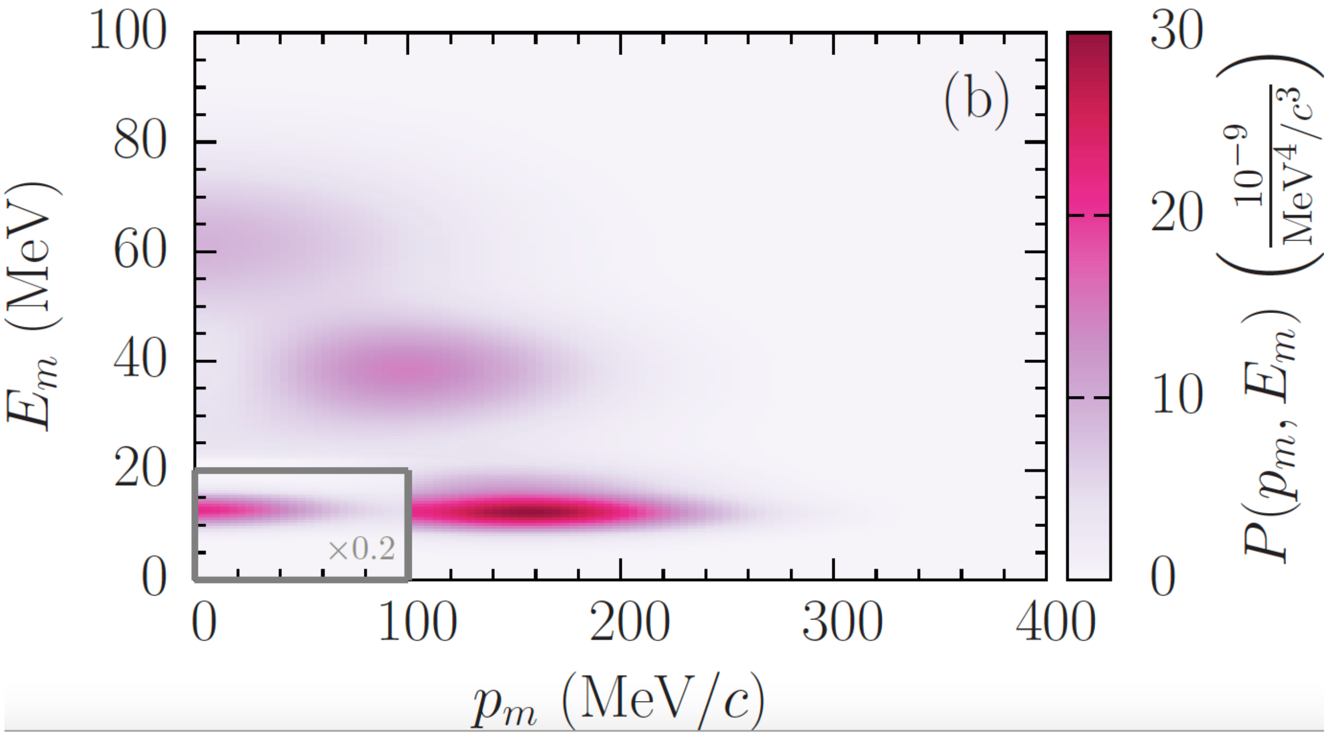
Exploratory analysis of the full dataset

Publications

- Inclusive cross sections for C and Ti,
  [Dai *et al.*, PRC 98, 014617 (2018)]
- Inclusive cross section for Ar,
  [Dai *et al.*, PRC 99, 054608 (2019)]
- Inclusive cross section for Al-7075, Ar, C and Ti of all (*e,e'*) data
  [Murphy *et al.*, PRC 100, 054606 (2019)]
- Exclusive Ar & Ti cross sections for a single kinematics, p_m ~ 50–60 MeV, E_m ~ 50–70 MeV
  [Gu *et al.*, PRC 103, 034604 (2021)]
- Exclusive Ar cross sections for all kinematics, p_m ~ 50–350 MeV/c, E_m ~ 10–70 MeV
  [Jiang *et al.*, PRD 105, 112002 (2022)]

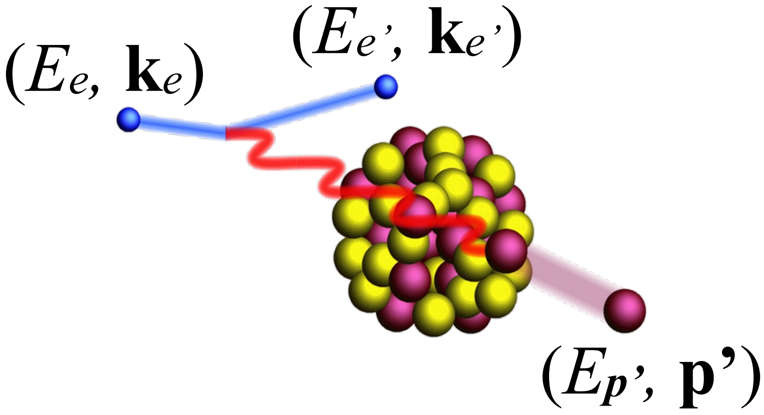


This analysis: extraction of the spectral function



Universal property of the nucleus, independent of the interaction.

Missing momentum $\mathbf{p}_m$ and missing energy E_m



Without final-state interactions,

$$E_e + M - \underline{E_m} = E_{e'} + E_{p'}$$

known

$$\mathbf{k}_e + \underline{\mathbf{p}_m} = \mathbf{k}_{e'} + \mathbf{p}'$$

$E_m - E_{\mathrm{thr}}$ is the excitation energy

$p_m \equiv |\mathbf{p}_m|$ is the initial proton momentum

(*e,e'p*) cross section

elementary cross section

nuclear transparency

$$\frac{d^6\sigma_{\mathrm{IA}}}{d\Omega_{e'}dE_{e'}d\Omega_{p'}dE_{p'}} \propto \sigma_{ep}\, S(p_m, E_m)T(E_{p'})$$

spectral function

Analysis procedure

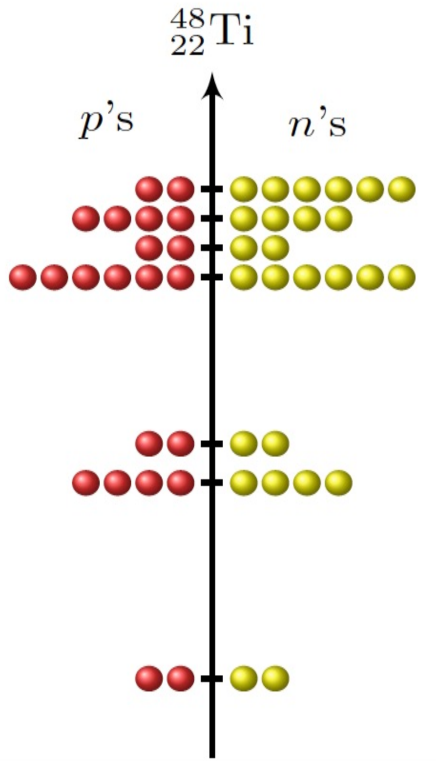
1) Extract of the (*e,e'p*) cross section

2) Using σ_{cc1} of de Forest and nuclear transparency, obtain the reduced cross sections as a function of (a) p_m and (b) E_m.

3) Find the parameters of the spectral function (*i.e.*, spectroscopic factors) from the fits to the reduced cross sections as a function of p_m.

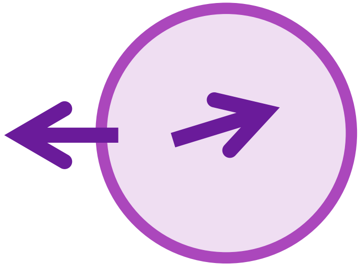
4) Using the priors from Step 3), find the parameters of the spectral function (*i.e.*, spectroscopic factors, peak positions, distribution widths) from the fits to the reduced cross sections as a function of E_m. Correct for transparency.

Test spectral function:
80% mean-field + 20% *NN* correlations



Independent-particle shell model

+



Convolution model of the correlated spectral function

Mean-field part of the spectral function

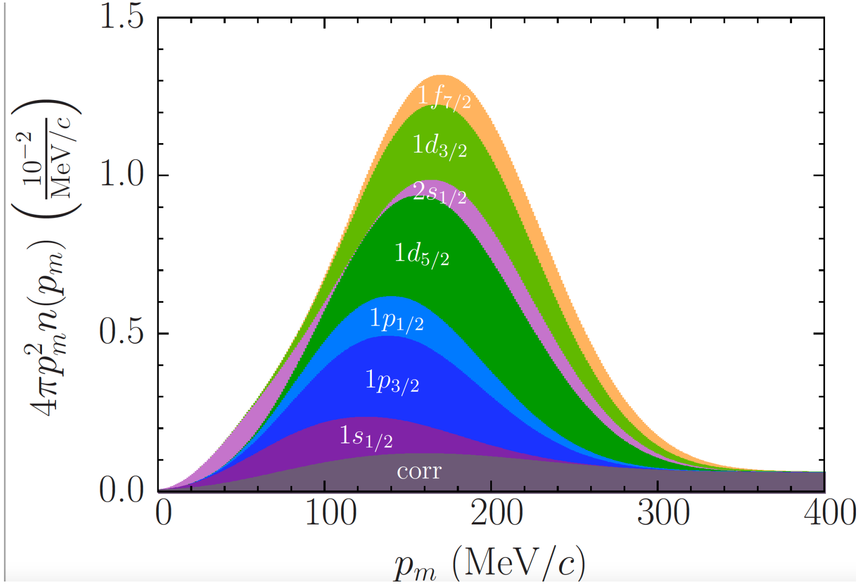
spectroscopic factor

energy distribution

$$P_{\mathrm{MF}}(p_m, E_m) = \sum_{\alpha} S_{\alpha} |\phi_{\alpha}(p_m)|^2 f_{\alpha}(E_m)$$

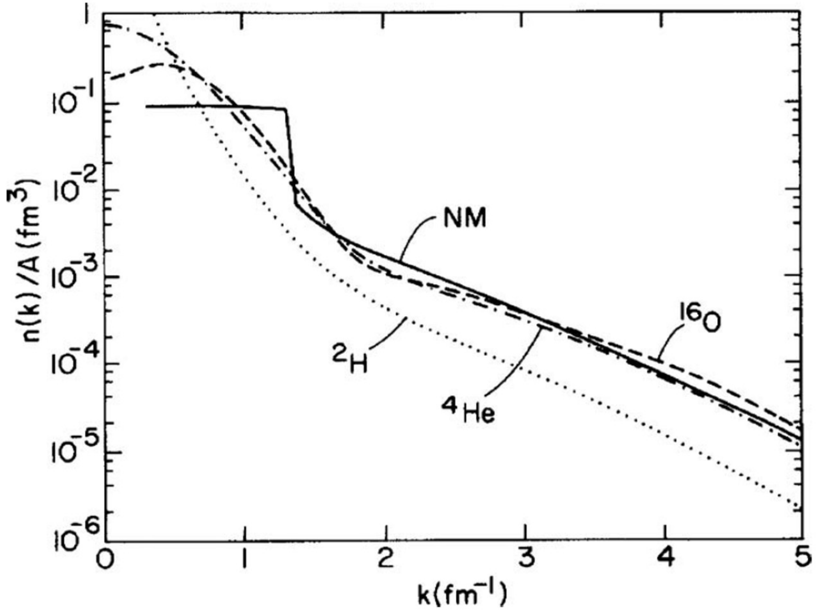
wave function in momentum space

Relativistic MF calculations by C. Giusti



Correlated part of the spectral function

Benhar *et al.,* RMP **80**, 189 (2008)



Ciofi degli Atti and Simula, PRC **53**, 1689 (1996)

- Correlated nucleons form quasi-deuteron pairs, with the relative momentum distributed as in deuteron.
- *NN* pairs undergo CM motion (Gaussian distrib.)
- Excitation energy of the (A − 1)-nucleons is their kinetic energy plus the *pn* knockout threshold

p_m fit results

```
Spectroscopic factor normalized by 2j+1, no transparency correction

1f72 - Spectroscopic factor(2) = 0.78 +/- 0.28
1d32 - Spectroscopic factor(4) = 2.60 +/- 0.22
2s12 - Spectroscopic factor(2) = 1.94 +/- 0.09
1d52 - Spectroscopic factor(6) = 2.34 +/- 1.15
1p12 - Spectroscopic factor(2) = 2.73 +/- 0.05
1p32 - Spectroscopic factor(4) = 5.46 +/- 0.01
1s12 - Spectroscopic factor(2) = 2.10 +/- 0.1-
Correlated part - Spectroscopic factor = 1.64 +/- 0.17

Chi2/ndof = 1.42
Ndof = 683
```

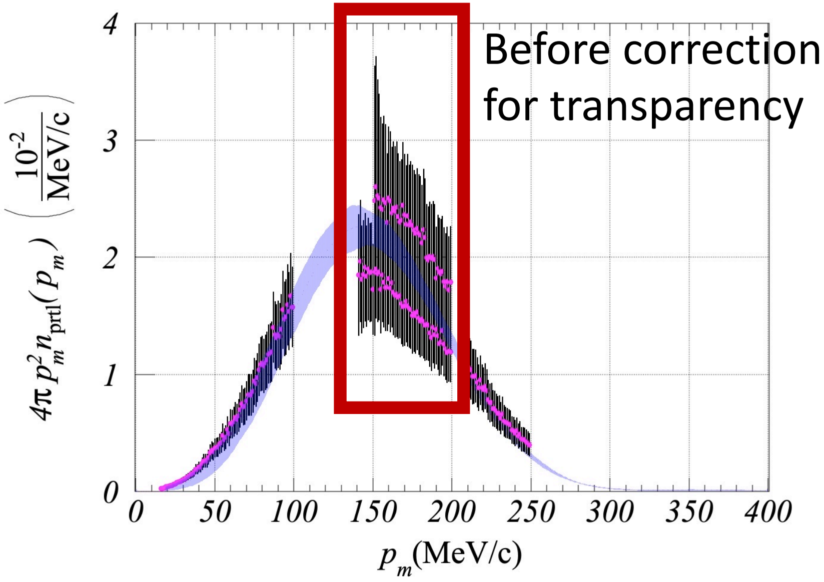
In the p_m fit, only deeply bound states are sensitive to the correlated spectral function.

p_m fit results

```
Spectroscopic factor normalized by 2j+1, with transparency correction

1f72 - Spectroscopic factor(2) = 0.78 +/- 1.25
1d32 - Spectroscopic factor(4) = 1.15 +/- 0.09
2s12 - Spectroscopic factor(2) = 1.96 +/- 0.09
1d52 - Spectroscopic factor(6) = 2.34 +/- 0.96
1p12 - Spectroscopic factor(2) = 2.73 +/- 0.23
1p32 - Spectroscopic factor(4) = 5.24 +/- 0.06
1s12 - Spectroscopic factor(2) = 2.08 +/- 0.10
Corr - Spectroscopic factor    = 0.66 +/- 0.17

Transparency corr. for kin2    = 0.75 +/- 0.02

Chi2/ndof = 1.42, Ndof = 683
```

Sum = 19.18 +/- 1.60

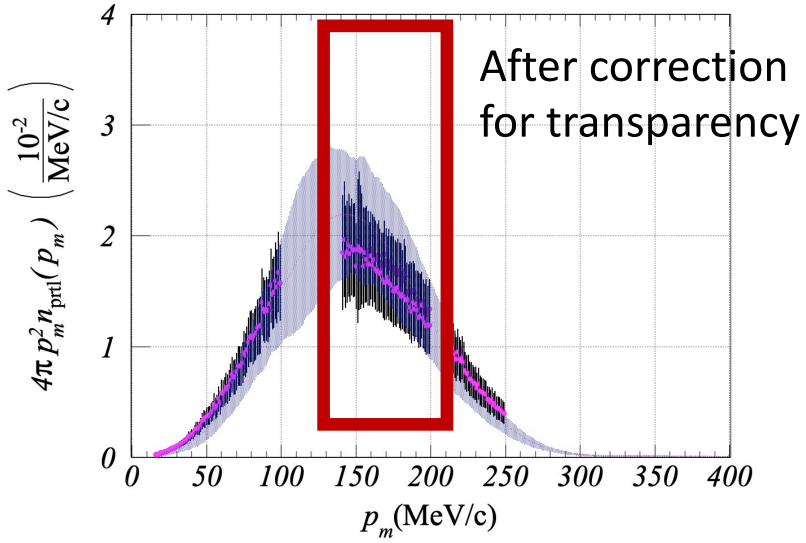
In the p_m fit, only deeply bound states are sensitive to the correlated spectral function.



Kinematic 2 has a proton momentum of 1030 MeV/C

Kinematic 3 has a proton momentum of 915 MeV/c

Kin2 data should be corrected for the change in nuclear transparency



E_m fit results

Orbital Strength and Errors

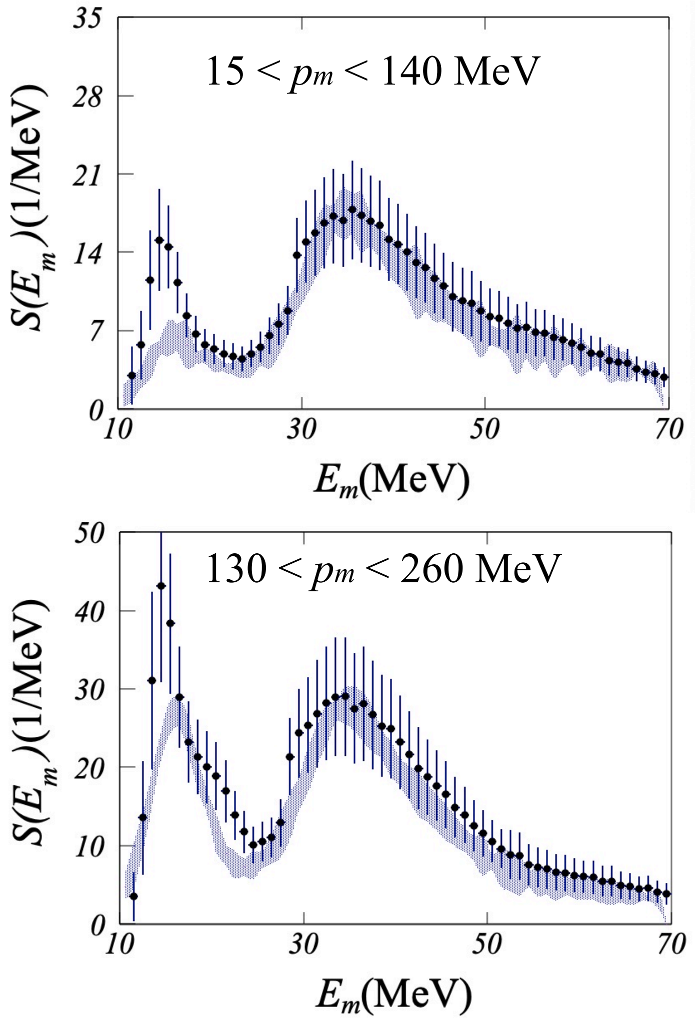
```
1f72 (2)      1.43 +/- 0.28
1d32 (4)      2.94 +/- 0.50
2s12 (2)      1.89 +/- 0.11
1d52 (6)      2.60 +/- 0.18
1p12 (2)      2.68 +/- 0.06
1p32 (4)      3.53 +/- 0.16
1s12 (2)      2.20 +/- 0.13
```

Sum=21.10 +/- 0.81

Corr 0.87+-0.08

Chi2/ndof = 1.25
Ndof = 125

Valence level – 9.11 MeV



E_m fit results

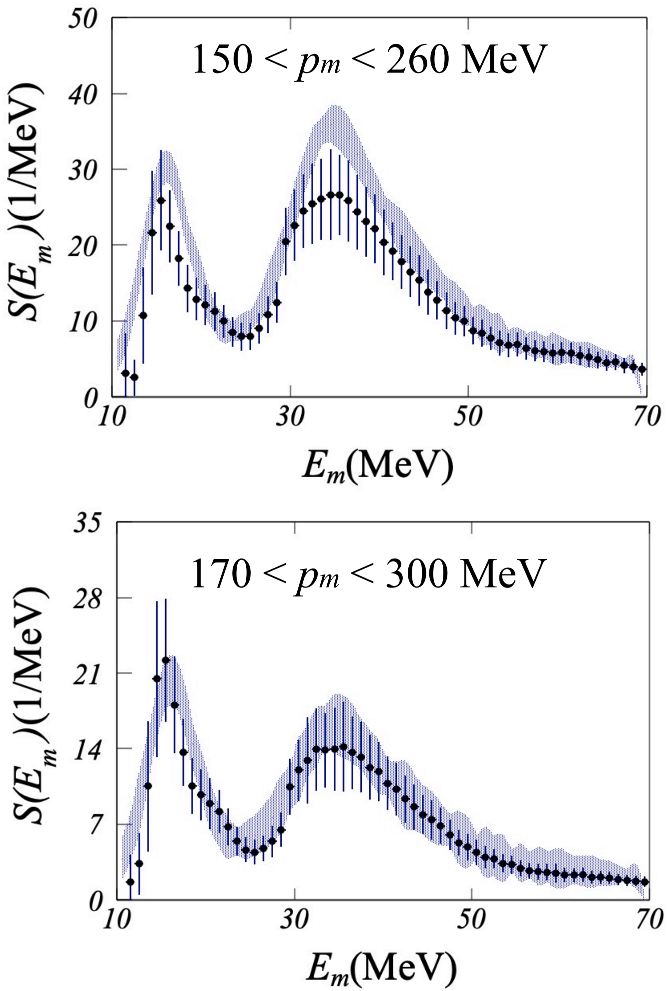
Orbital Mean and Errors (all in MeV)

1f72	11.32 +/- 1.65	g.s.
1d32	12.39 +/- 0.40	1.07 MeV
2s12	12.80 +/- 0.95	1.48 MeV
1d52	16.12 +/- 0.29	4.80 MeV
1p12	33.68 +/- 0.37	22.36 MeV
1p32	39.85 +/- 0.86	28.53 MeV
1s12	56.07 +/- 2.69	44.75 MeV

Corr 24.2 MeV

Chi2/ndof = 1.25
Ndof = 125

Valence level – 9.11 MeV,



E_m fit results - priors

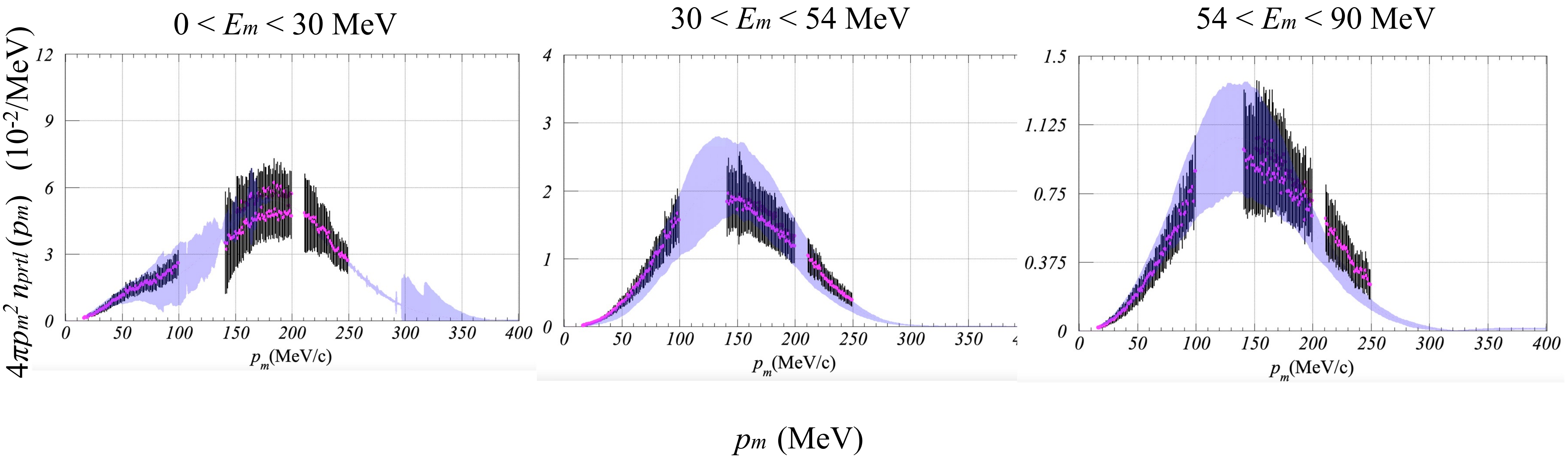
Priors included in the E_m fit as penalty terms to the Chi^2

1f72 11.31 +/- 0.2 MeV
1d32 12.10 +/- 0.5 MeV
2s12 12.70 +/- 0.5 MeV
1d52 15.36 +/- 0.9 MeV

SO 1d32–1d52 3.7 +/- 2.0 MeV

SO 1p12–1p32 6.1 +/- 1.0 MeV

P_m fit results



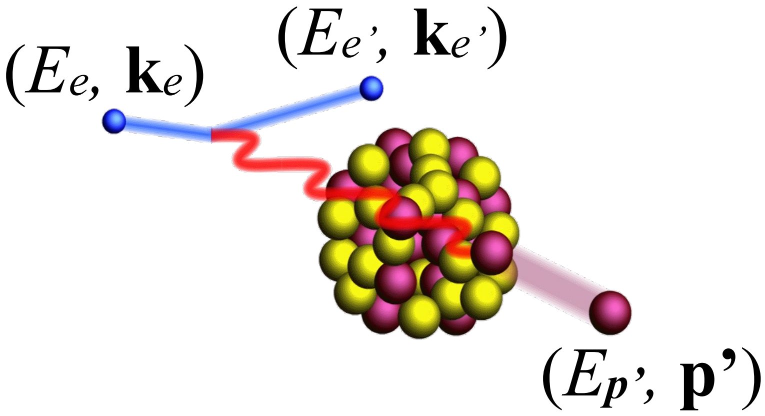
Data from different kinematics are consistent within uncertainties.

Summary

- The first, exploratory analysis of the full dataset for Ti, results still preliminary.
- Reasonable parametrization of the spectral function of ^{48}Ti is found.
- Comparison with past results is underway.
- Separation of individual contributions requires improved analysis. Numerous theoretical developments are necessary.
- Need to work on using this measurement for computing the Ar-n spectral function
- Paper is in preparation
- Investigate the transparency measurement and correction

Backup

Missing momentum $\mathbf{p}_m$ and missing energy E_m



$$E_e + M_A = E_{e'} + E_{p'} + E^*_{A-1}$$

known determined

$$\mathbf{k}_e + 0 = \mathbf{k}_{e'} + \mathbf{p}' + \mathbf{p}_{A-1}$$

In the absence of final state interactions

$-\mathbf{p}_{A-1} = \mathbf{p}_m$ initial proton momentum; $p_m \equiv |\mathbf{p}_m|$

$E^*_{A-1} = \sqrt{(M_A - M + E_m)^2 + \mathbf{p}_m^2}$, with excitation energy $E_m - E_{\text{thr}}$