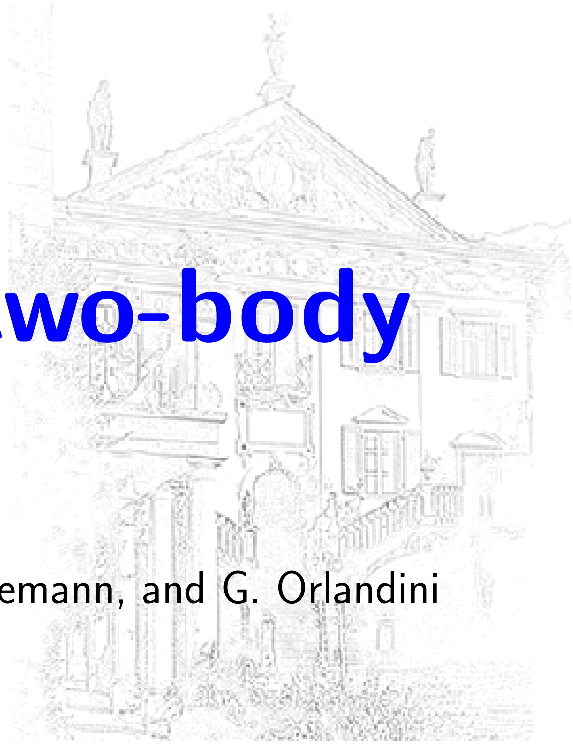
UNIVERSITÀ DEGLI STUDI
DI TRENTO
Dipartimento di Fisica



Electromagnetic two-body breakup of ^{4}He

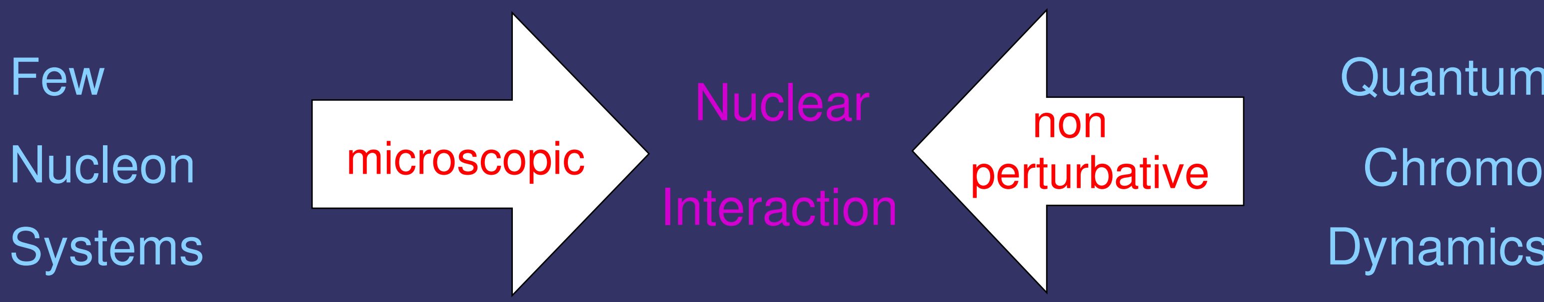
S. Quaglioni, D. Andreasi, V. D. Efros, W. Leidemann, and G. Orlandini

Outline of the Talk

- Quest for a fundamental NN interaction
- Two–fragment reactions through LIT
- Photodisintegration
- Electrodisntegration
- Conclusions and Outlook

Quest for a fundamental NN interaction

Nucleons are composite bound states of quarks and gluons



"Theoretical laboratory" to test nuclear force models

- ○ structure of light nuclei
- ○ few–nucleon scattering and reactions

A consistent treatment of both ISI and FSI is mandatory!

What have we learned?

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A=2 almost perfect description of 2N data

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A=3 binding energies $\Rightarrow$ local V_{NN} not sufficient!

- $\rightsquigarrow$ off–shell effects!
- $\rightsquigarrow$ 3NF forces? Non local terms?

What have we learned?

A=2 almost perfect description of 2N data

A=3 binding energies $\Rightarrow$ local V_{NN} not sufficient!

- $\leadsto$ off–shell effects!
- $\leadsto$ 3NF forces? Non local terms?

scattering observables $\Rightarrow$ fundamental!

- $\leadsto$ open problems: A_y–puzzle, . . .
- $\leadsto$ find reaction observables sensitive to 3NF: inclusive or exclusive?

Total electrodisintegration of ^{3}He: Role of 3NF

Longitudinal Response

low energy

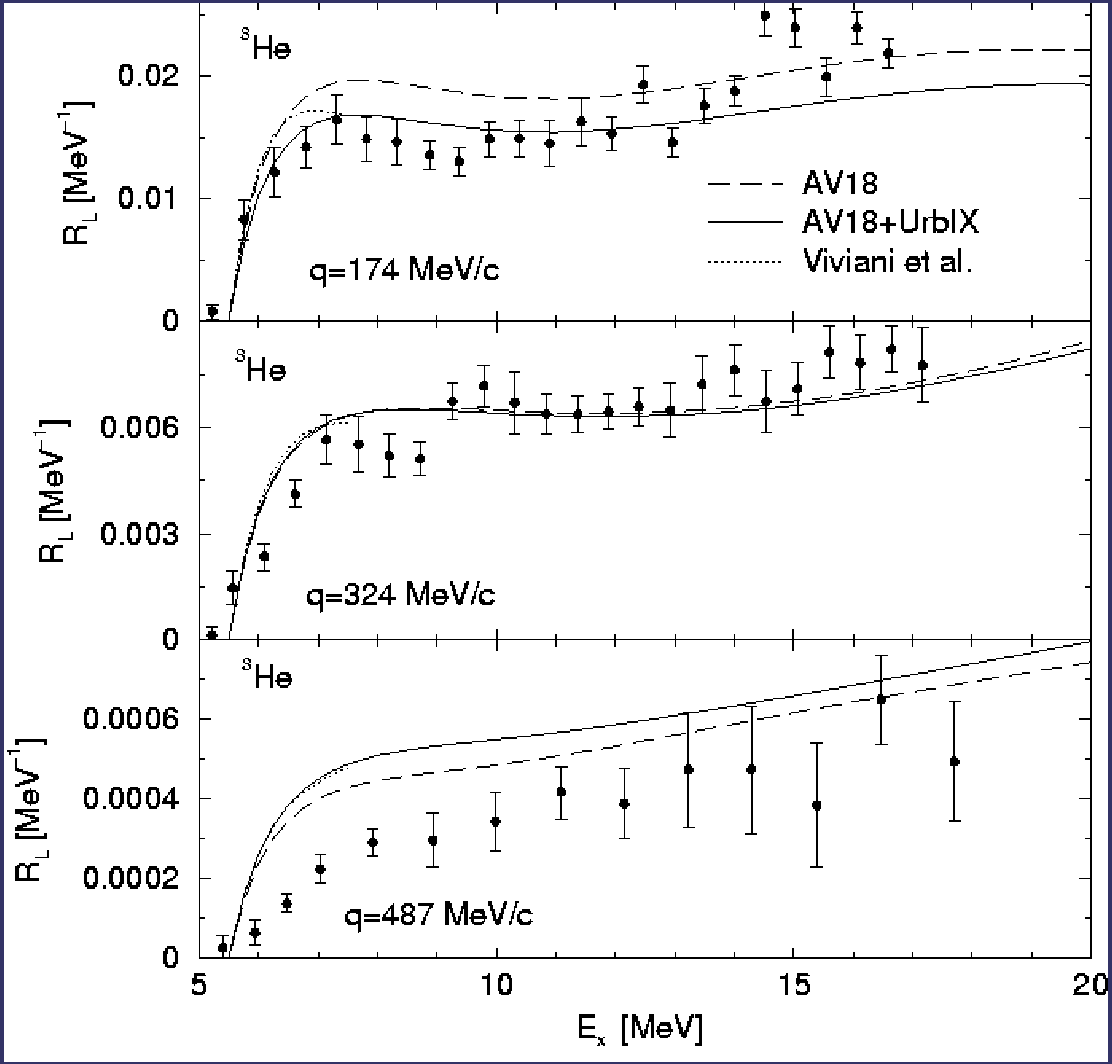
- - - AV18

—— AV18+UIX

CHH

Efros, Leidemann, Orlandini, Tomusiak PRC69(2004)044001

—●— Retzlaff *et al.*, PRC49(1994)1263



Exclusive $^3\mathrm{He}(\gamma, pp)n$ reaction

3NF effects

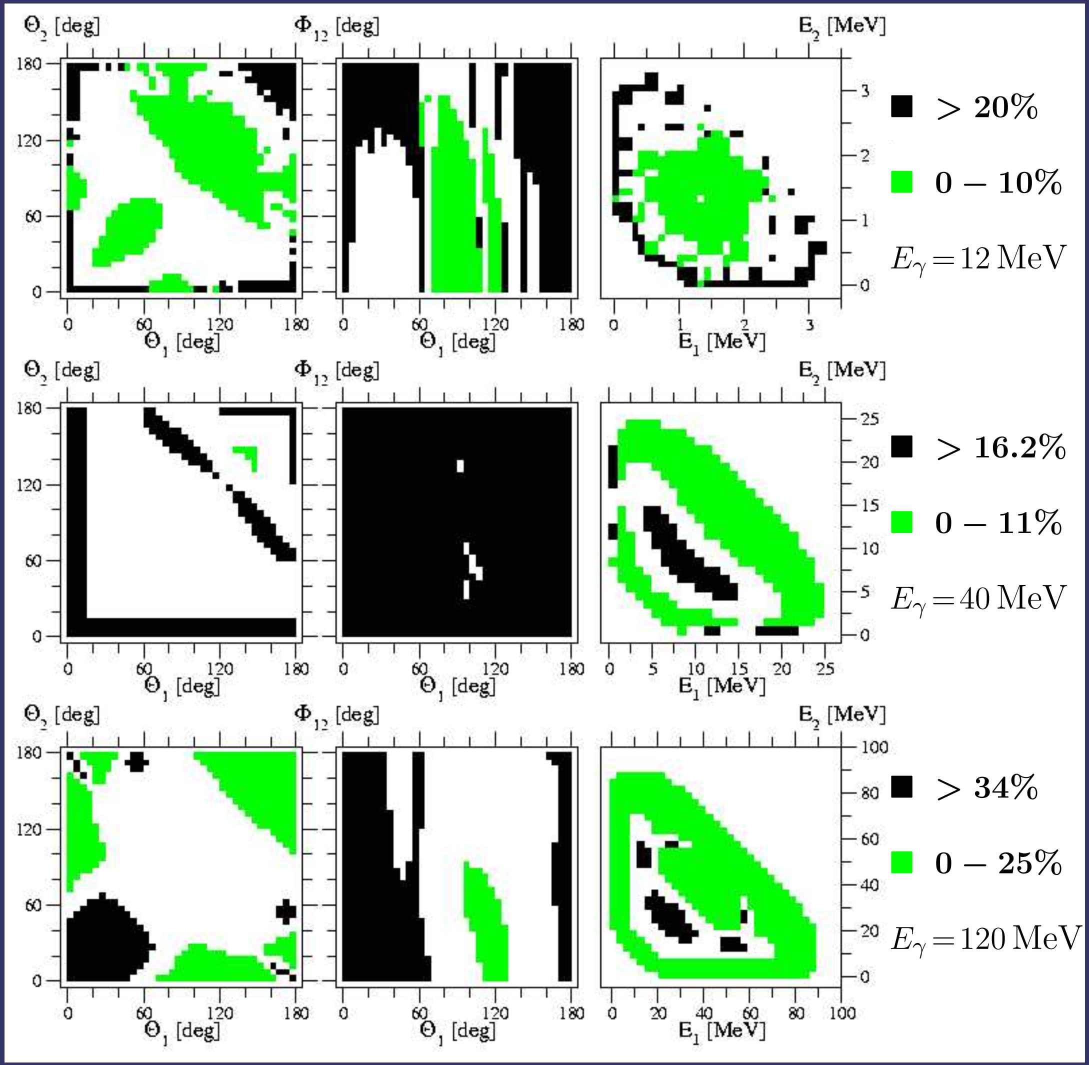
3N breakup phase–space

AV18+UIX+MEC

versus

AV18+MEC

Golak *et al.*, nucl-th/0505072



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scattering observables $\Rightarrow$ fundamental!

- $\rightsquigarrow$ open problems: A_y–puzzle, ...
- $\rightsquigarrow$ find reaction observables sensitive to 3NF: inclusive or exclusive?

A=4 a novel testground for nuclear interactions

Low–energy n–^{3}H scattering: A novel testground for nuclear interactions

Lazauskas, Carbonell, Fonseca, Viviani, Kievsky, Rosati,

PRC71(2005)034004

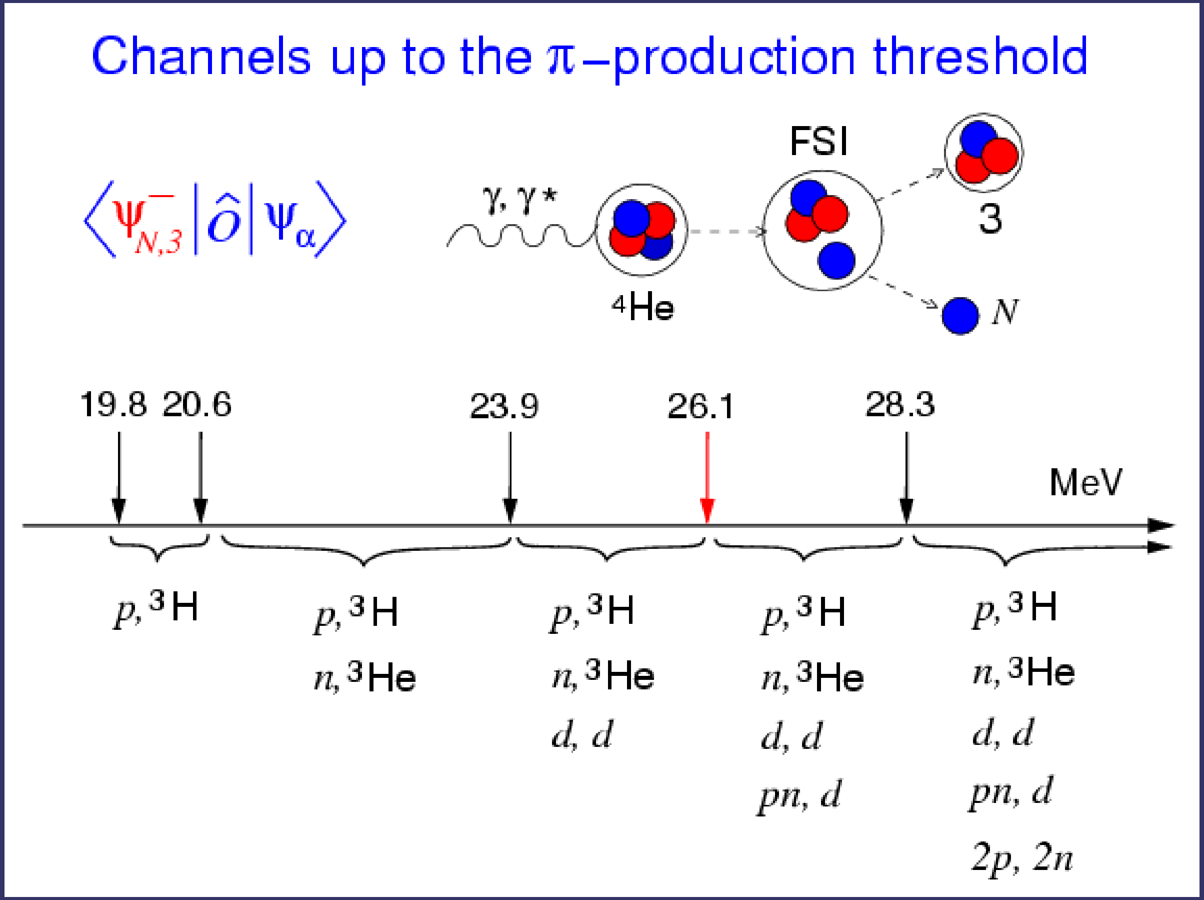
"The four–nucleon system represents a qualitative jump in complexity relative to the $A = 3$ case ..."

"... Unlike the $A = 3$ systems, $A = 4$ shows a delicate and rich structure of excited states in the continuum, whose position and width depends critically on the underlying NN interaction ..."

"... Therefore is of the utmost importance to have reliable few–body techniques powerful enough to deal with this system ..."

Where is the challenge?

Push *ab initio* calculation of exclusive reactions of a 4–particle system, also beyond the 3–body breakup threshold



- ▲ full FSI also beyond 3bbu
- ▼ V_{NN} model: MTI-III

Two–Fragment Reactions through LIT

Which theoretical technique?

The Lorentz integral transform method:

- ▷ the only feasible beyond the 3–body breakup threshold
- ▷ already applied for inclusive reactions: $A \leq 7$
- ▷ less known in its exclusive version: first application to the 4–nucleon system

Exclusive perturbation-induced processes

$$T_f(E_f) = \langle \Psi_f^-(E_f) | \widehat{O} | \Psi_0 \rangle$$

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$$= \int \frac{F_f(E)}{E_f + i\varepsilon - E}\, dE$$

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$$= \int \frac{F_f(E)}{E_f + i\varepsilon - E} \, dE$$

$$F_f(E) = \sum\!\!\!\!\!\!\int_\nu \left\langle \Phi_f \left| \widehat{V} \right| \Psi_\nu \right\rangle \left\langle \Psi_\nu \left| \widehat{O} \right| \Psi_0 \right\rangle \delta(E - E_\nu)$$

Integral Transform Approach

$$\Phi[F](\sigma) = \int F(E)K(\sigma, E)dE$$

Aim: determining $F(E)$ via the integral transform.
It means to calculate $\Phi[F](\sigma)$ without knowledge of $F(E)$.

$$\Phi[F](\sigma) \Rightarrow \text{inversion} \Rightarrow F(E)$$

- Laplace Transform:

  $K(\sigma, E) = e^{-E\sigma}$

- Stiltjes Transform:

  $K(\sigma, E) = \frac{1}{E+\sigma}$

- Lorentz Transform:

  $K(\sigma, E) = \frac{1}{(E-\sigma_R)^2+\sigma_I^2}$

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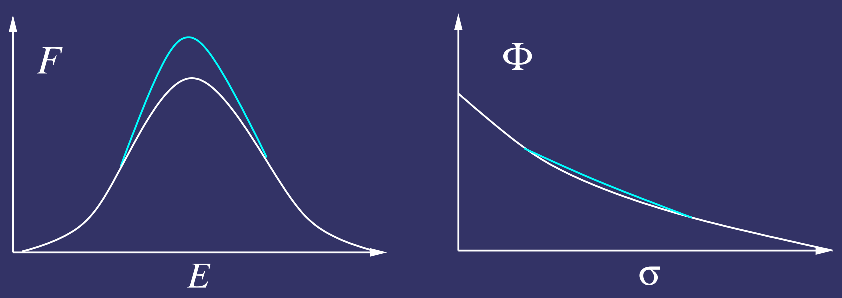

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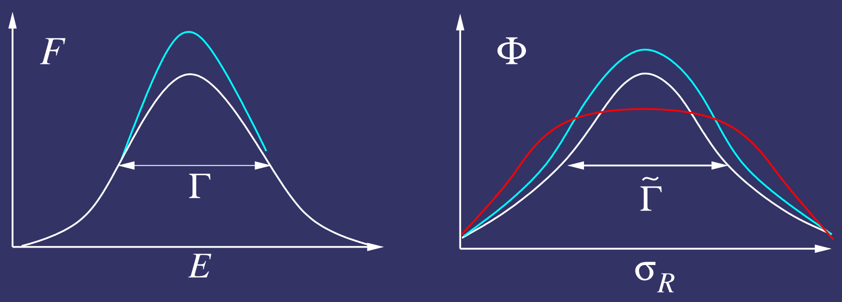


The Lorentz Transform

$$L[F_f](\sigma) = \int F_f(E)\,\frac{1}{(E-\sigma_R)^2+\sigma_I^2}\,dE$$

$$= \int \sum_\nu \frac{\left\langle \Phi_f \middle| \widehat{V} \middle| \Psi_\nu \right\rangle \left\langle \Psi_\nu \middle| \widehat{O} \middle| \Psi_0 \right\rangle \delta(E - E_\nu)}{(E-\sigma_R+i\sigma_I)\,(E-\sigma_R-i\sigma_I)}\,dE$$

$$= \sum_\nu \left\langle \Phi_f \middle| \widehat{V}\frac{1}{E_\nu-\sigma^*} \middle| \Psi_\nu \right\rangle \left\langle \Psi_\nu \middle| \frac{1}{E_\nu-\sigma}\widehat{O} \middle| \Psi_0 \right\rangle$$

$$= \sum_\nu \left\langle \Phi_f \middle| \widehat{V}\frac{1}{H-\sigma^*} \middle| \Psi_\nu \right\rangle \left\langle \Psi_\nu \middle| \frac{1}{H-\sigma}\widehat{O} \middle| \Psi_0 \right\rangle$$

$$= \left\langle \Phi_f \middle| \widehat{V}\frac{1}{H-\sigma^*}\,\frac{1}{H-\sigma}\widehat{O} \middle| \Psi_0 \right\rangle = \left\langle \widetilde{\psi}_2 \,\middle|\, \widetilde{\psi}_1 \right\rangle$$

The Lorentz Transform

$$L[F_f](\sigma) = \int F_f(E) \, \frac{1}{(E-\sigma_R)^2 + \sigma_I^2} \, dE$$

$$= \left\langle \Phi_f \left| \widehat{V} \frac{1}{H-\sigma^*} \, \frac{1}{H-\sigma} \widehat{O} \right| \Psi_0 \right\rangle = \left\langle \widetilde{\psi}_2 \,\middle|\, \widetilde{\psi}_1 \right\rangle$$

To calculate $L[F_f](\sigma)$ one doesn't need to know $F_f(E)$.
Solve for many σ_R and fixed σ_I:

$$(H - \sigma_R - i\sigma_I) \left| \widetilde{\psi}_1 \right\rangle = \widehat{O} \, |\Psi_0\rangle$$

$$(H - \sigma_R - i\sigma_I) \left| \widetilde{\psi}_2 \right\rangle = \widehat{V} \, |\Phi_f\rangle$$

$F_f(E)$ from inversion of $L[F_f](\sigma)$: FSI included

Procedure:

1. choose an NN-interaction
2. find the excitation operator relevant to the reaction (consistent with NN-interaction)
3. choose a good bound-state technique
   - to solve A-body Schrödinger equation

     $$(H - E_0)|\Psi_0\rangle = 0$$

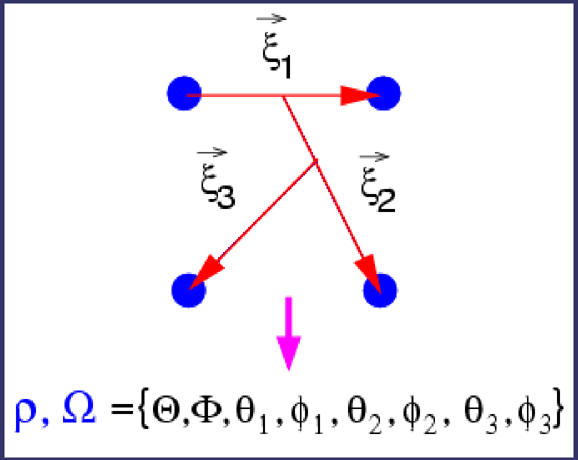
   - to solve A-body LIT equation

     $$(H - \sigma_R - i\sigma_I)|\widetilde{\psi}\rangle = |Q\rangle$$

4. calculate the overlap $L[F_f](\sigma) = \langle\widetilde{\psi}_2|\widetilde{\psi}_1\rangle$
5. invert transform $L[F_f](\sigma) \longrightarrow F_f(E)$
6. calculate matrix element $T_f^{\mathrm{FSI}}(E_f) = \int \frac{F_f(E)}{E_f + i\varepsilon - E} dE$

Remove CM Degrees of Freedom

$$\Phi\left(\vec{r}_1,\vec{r}_2,\vec{r}_3,\vec{r}_4\right)=\phi\left(\vec{R}_{\rm cm}\right)\Psi\left(\vec{\xi}_1,\vec{\xi}_2,\vec{\xi}_3\right)$$



$$H=-\frac{1}{2m}\left(\triangle_\rho-\frac{\hat{K}^2}{\rho^2}\right)+\sum_{i<j}^{4}v_{ij}$$

$$\hat{K}^2\mathcal{Y}^{\mu}_{[K]}(\Omega)=K(K+7)\mathcal{Y}^{\mu}_{[K]}(\Omega)$$

Which dynamical model?

Spin dependent S-wave interaction MTI-III

$$v_{ij}=V_{31}(r)\mathcal{P}^{+}_{\sigma}\mathcal{P}^{-}_{\tau}+V_{13}(r)\mathcal{P}^{-}_{\sigma}\mathcal{P}^{+}_{\tau}$$

Total photodisintegration of ^3H:

MTI-III vs AV14

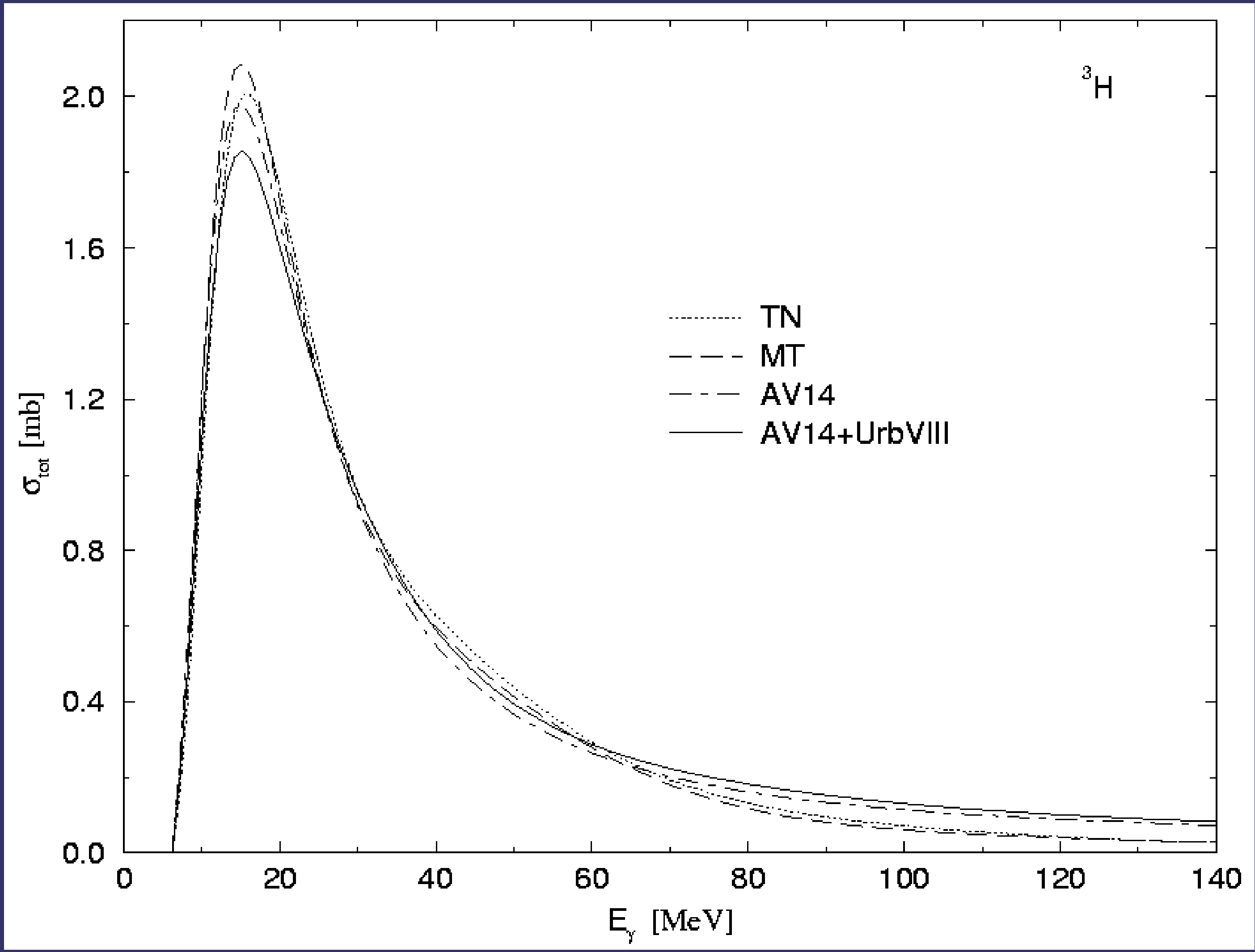
Total cross section

– – – MTI-III

— · — AV14

CHH

Efros, Leidemann, Orlandini, Tomusiak PLB484(2000)223



CHH Expansion Method

We seek the solutions of Schrödinger and LIT equations in the following form:

$$\Psi = \sum_{n,[K]}^{n_{max},[K_{max}]} C_n^{[K]} \mathcal{J} R_n(\rho) \left[\mathcal{Y}_{[K]}^{\mu}(\Omega) \Theta_{ST}^{\bar{\mu}} \right]_{JT}^{a}$$

$$\mathcal{J} = \prod_{i<j} f(r_{ij}) \longrightarrow \text{Jastrow factor}$$

$$R_n(\rho) \sim L_n^{\nu}(\rho/\rho_0) \exp\left[-\rho/2\rho_0\right]$$

$\hookrightarrow$ hyperradial functions

$$\mathcal{Y}_{[K]}^{\mu}(\Omega) \longrightarrow \text{hyperspherical harmonics}$$

$$\Theta_{ST}^{\bar{\mu}} \longrightarrow \text{spin} - \text{isospin functions}$$

Photodisintegration:

$$\gamma + {}^4\text{He} \rightarrow N + 3$$

Total cross section

$$\sigma_{N,3} \propto \int |\langle \Psi^{-}_{N,3} | \mathbf{D} | \Psi_{\alpha} \rangle|^2 d\Omega$$

The $n,{}^3$He channel ▶

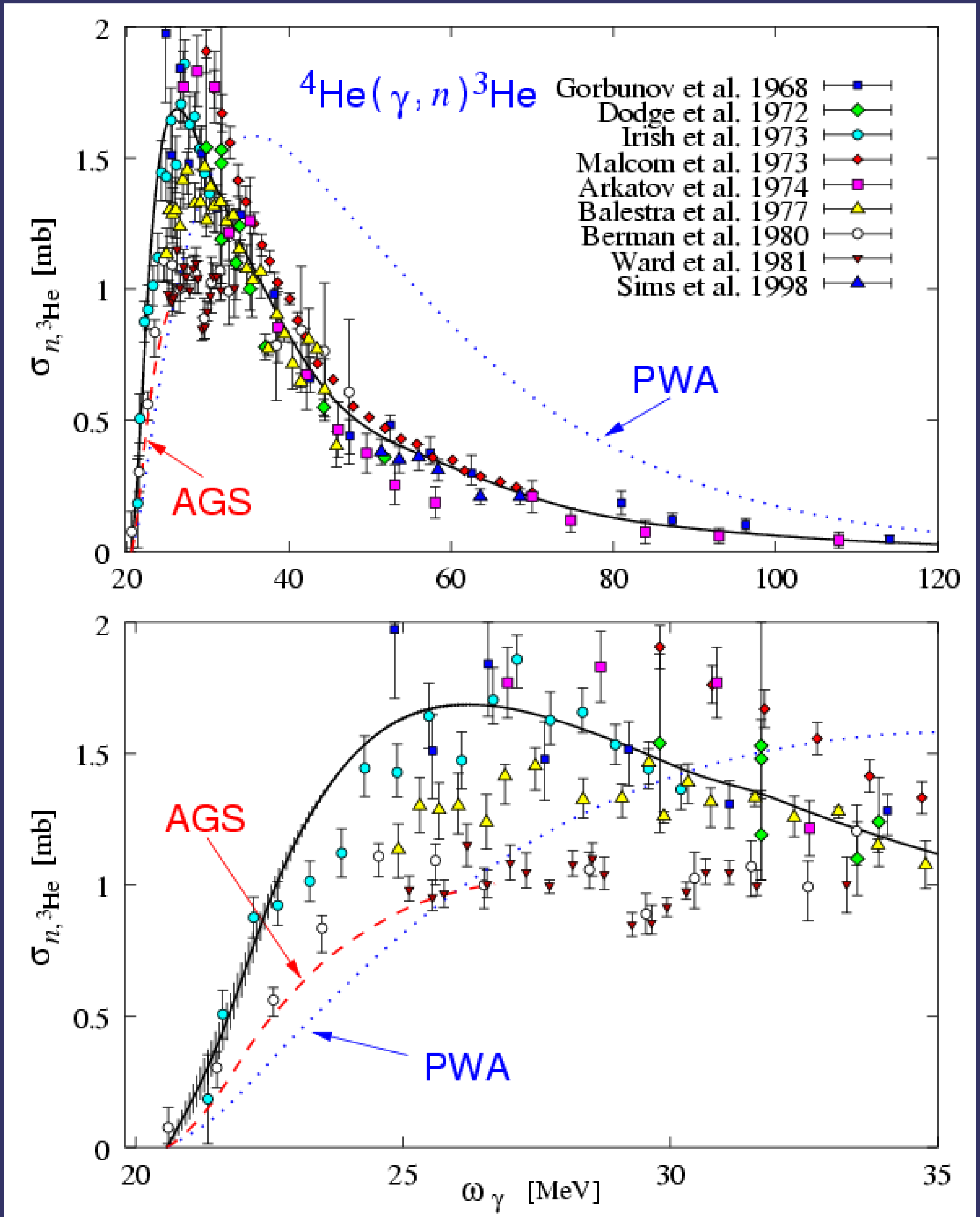
⋯⋯ PWA

—— FULL

MTI-III

CHH

Quaglioni, Barnea, Efros, Leidemann, Orlandini,
PRC69(2004)044002



Test the PWA Approximation

A simple model: Gaussian Wave Functions

$$\Psi_{\mathsf{A}}^{\mathsf{GWF}} = \left(\frac{2b_{\mathsf{A}}}{\pi}\right)^{\frac{3(\mathsf{A}-1)}{4}} \prod_{i=1}^{A} e^{-b_{\mathsf{A}}\left|\mathbf{r}_i - \mathbf{R}_{cm}^{(\mathsf{A})}\right|^2} \Theta_{T_{\mathsf{A}} S_{\mathsf{A}}}^{a}$$

Analytical result:

$$\sigma_{n,{}^3\mathsf{He}}^{\mathsf{GPWA}} = 4\pi^2 \alpha \omega_\gamma k \mu \left(\frac{4}{3}\right)^{\frac{9}{2}} \frac{4\, b_3^3\, k^2\, e^{-\frac{2k^2}{3b_4}}}{\sqrt{2\pi b_4}(b_3 + b_4)^6}$$

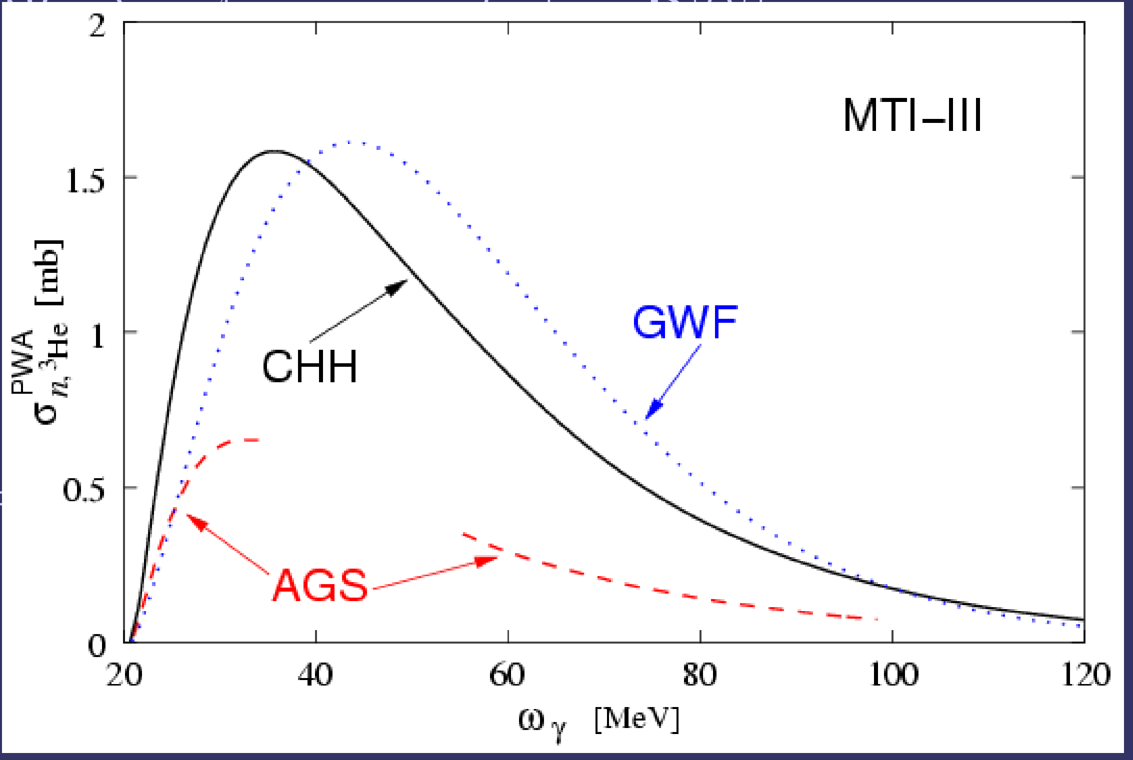
Test the PWA Approximation

A simple model: Gaussian Wave Functions

$$\Psi_{\mathsf{A}}^{\mathsf{GWF}} = \left(\ldots \right)^{\frac{3(\mathsf{A}-1)}{\ldots}} \ldots A \ldots \Big| \ldots \mathsf{R}^{(\mathsf{A})} \Big|^2$$

Analytical result:

$$\sigma_{n,{}^3\mathsf{He}}^{\mathsf{GPWA}} = \ldots$$



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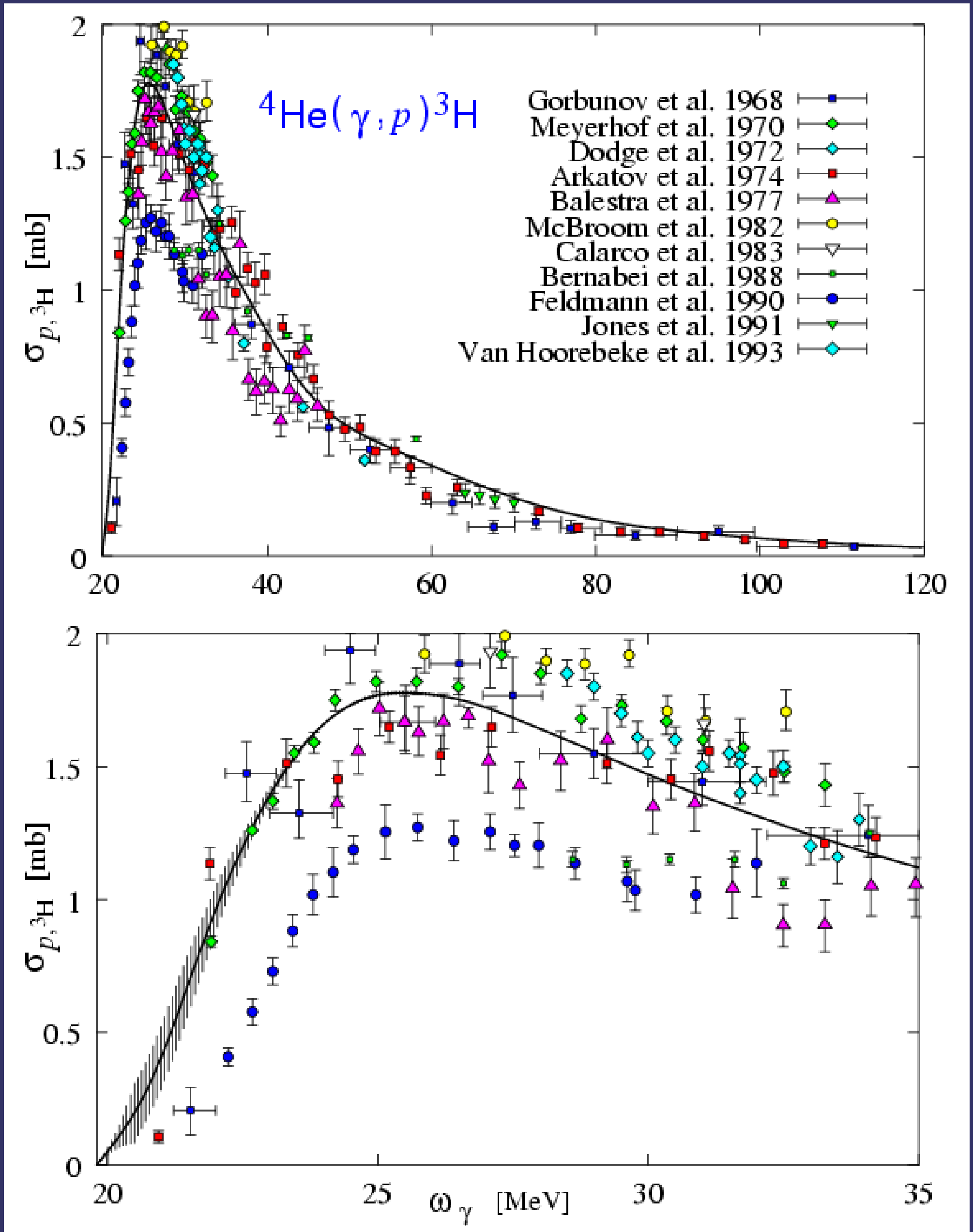
The $p,{}^3$H channel ▶

—— MTI-III

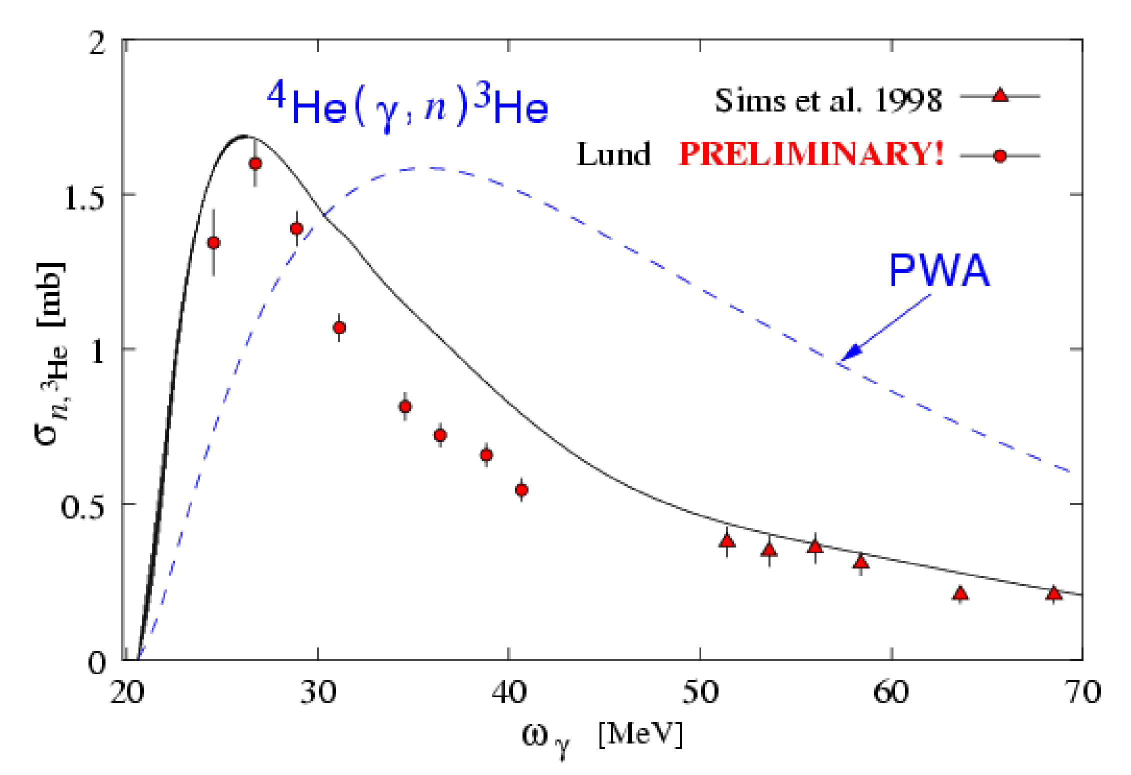
CHH

Quaglioni, Barnea, Efros, Leidemann, Orlandini,
PRC69(2004)044002



New Experimental Data

The availability of 4-body *ab initio* calculations also beyond the 3-body breakup threshold has given birth to a new experimental interest



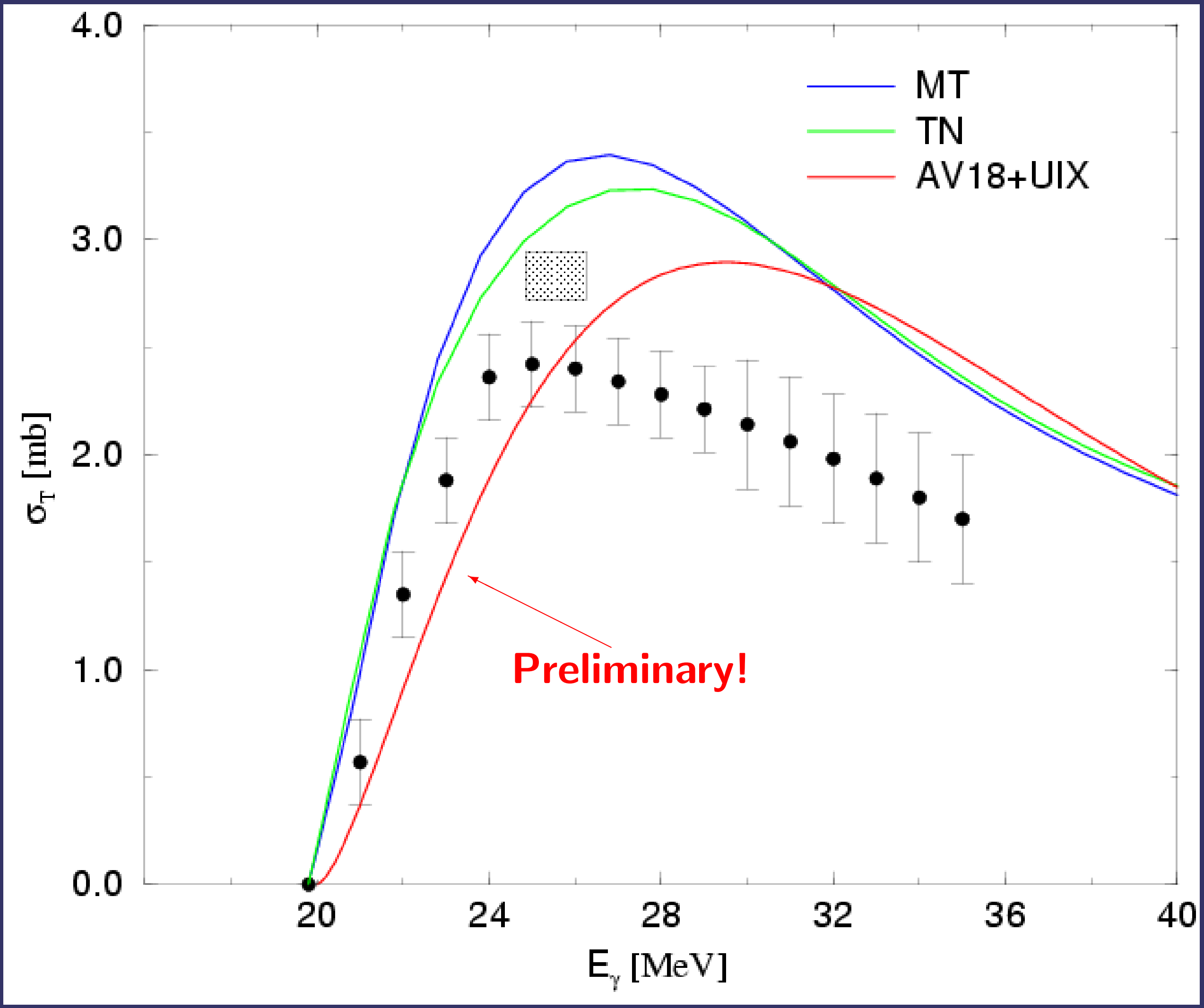
Tagged Photons

Total photodisintegration of ^{4}He:

Total cross section

EIHH

Barnea, *et al.*



—●—

(γ, n) Berman *et al.* (1980)
+
(γ, p) Feldman *et al.* (1990)

Electrodisintegration: $e + {}^4\mathbf{He} \rightarrow e' + x + Y$

$$\frac{d^5\sigma}{dE' d\Omega_{e'} d\Omega_x} \propto [V_L F_L + V_T F_T + V_{LT} F_{LT} \cos\phi + F_{TT} F_{TT} \cos 2\phi]$$

^{4}He$(e, e'x)Y$ Longitudinal Response

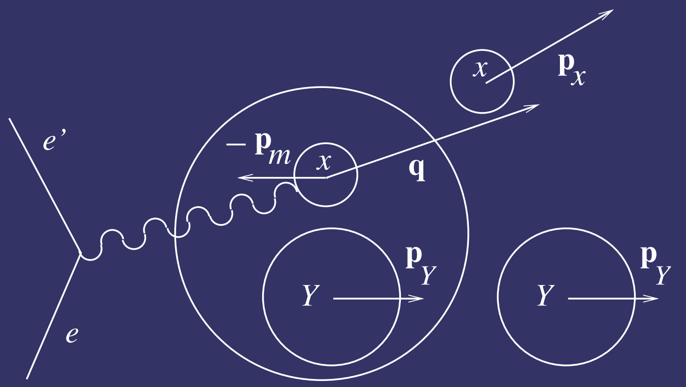
$$F_L(\mathbf{q}, \omega, \theta_x) \propto |\langle \Psi^-_{x,Y} | \hat{\rho}(\mathbf{q}) | \Psi_\alpha \rangle|^2$$

Investigate validity of PWIA:

- direct knock-out of x
- Y is a spectator

⇓

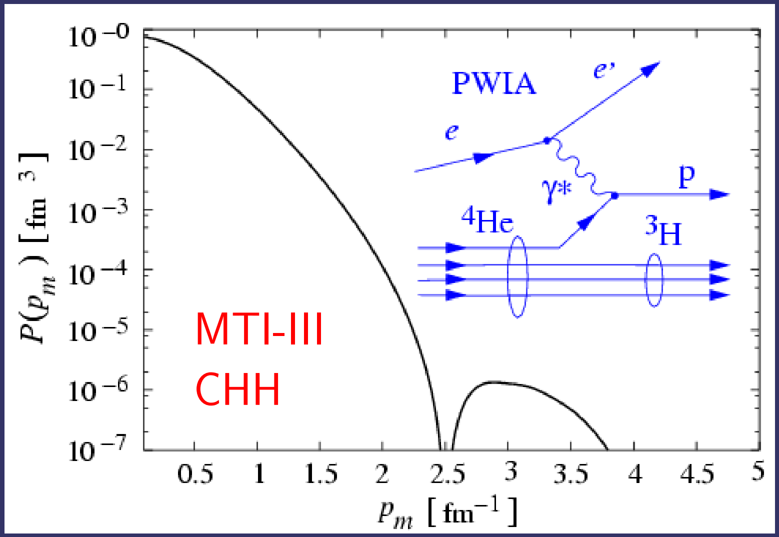
NO Antisymmetrization
NO Final State Interaction



The $p, {}^3$H channel

The PWIA longitudinal response turns out to be proportional to the proton-triton momentum distribution

$$F_L = Z_\alpha (G_E^p)^2 P(p_m)$$

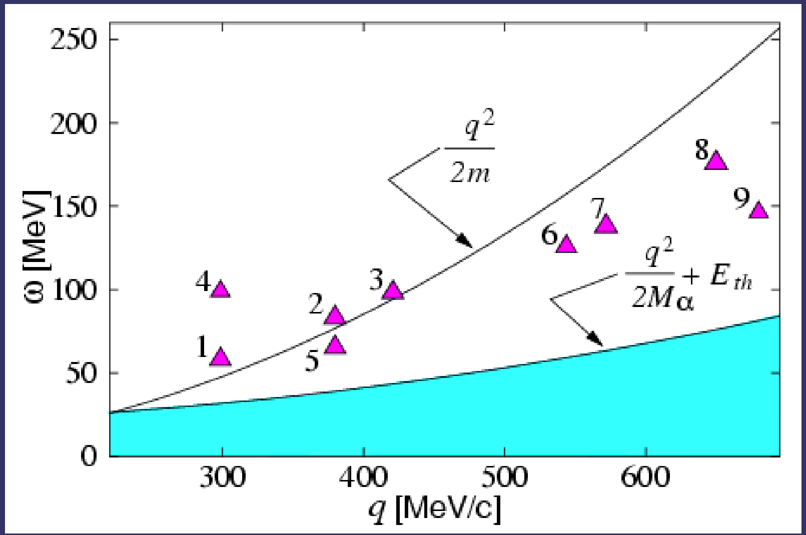


- ▷ access to g.s. quantities
- ▷ get informations on short range correlations from the high p_m region

check!

Longitudinal Response

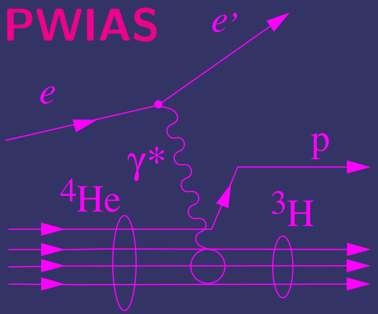
parallel kinematics → p_p → q



Deviations from PWIA

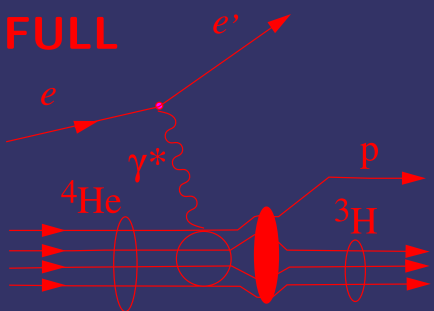
+ antisymmetrization

PWIAS



+ FSI

FULL

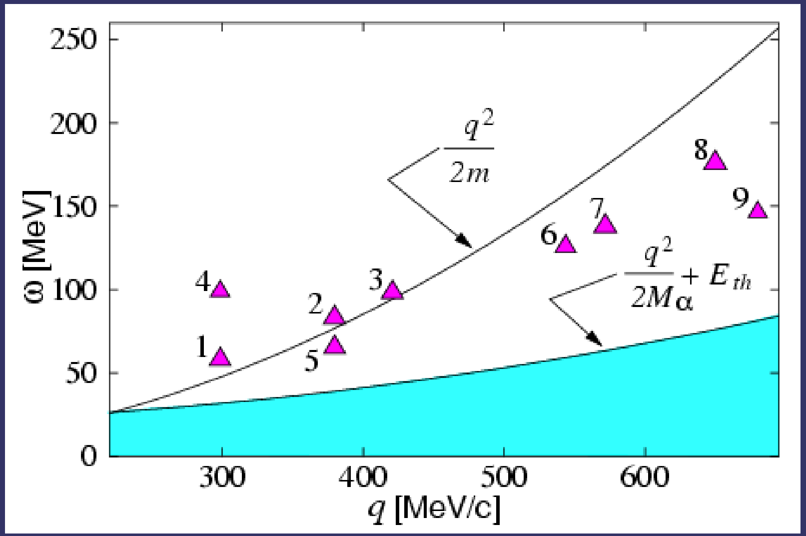


Kin. No.	PWIA $F_L/(\widetilde{G}_E^p)^2$ $[(\mathrm{GeV}/c)^{-3}\ \mathrm{sr}^{-1}]$	Δ_{PWIAS} (%)	Δ_{FULL} (%)
1	185.2	+ 9.3	− 39.6
2	185.2	+ 1.2	− 20.1
3	185.2	+ 0.0	− 12.8
4	100.0	+ 4.5	− 43.4
5	100.0	+ 3.9	− 16.6
6	100.0	− 1.1	+ 11.4
7	100.0	− 1.9	+ 11.5
8	100.0	− 1.7	+ 10.8
9	14.63	− 4.4	+ 52.1

Longitudinal Response

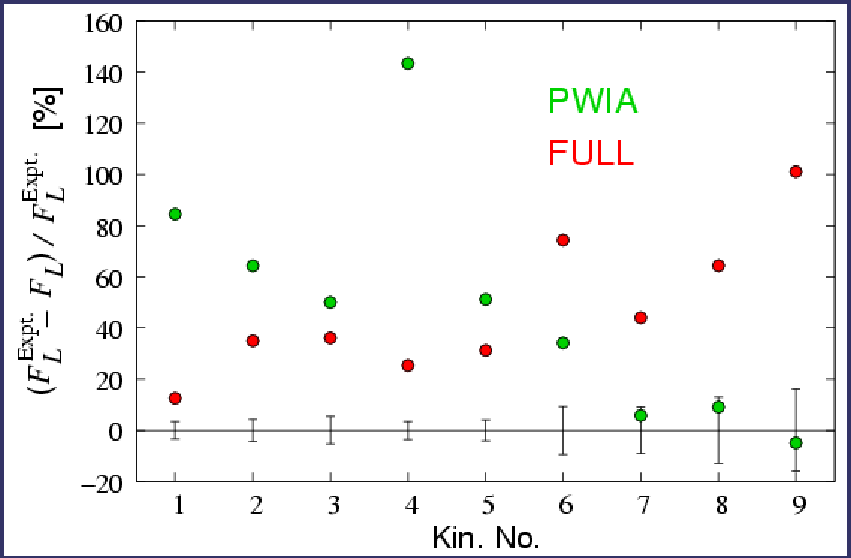
parallel kinematics $\mathbf{p}_p$ $\mathbf{q}$

$$\frac{d^5\sigma}{dE' d\Omega_{e'} d\Omega_p} \propto [V_L F_L + V_T F_T]$$



Comparison with experiment

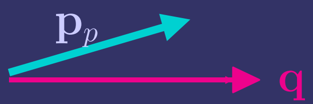
J.E. Ducret et al. NPA556(1993)373

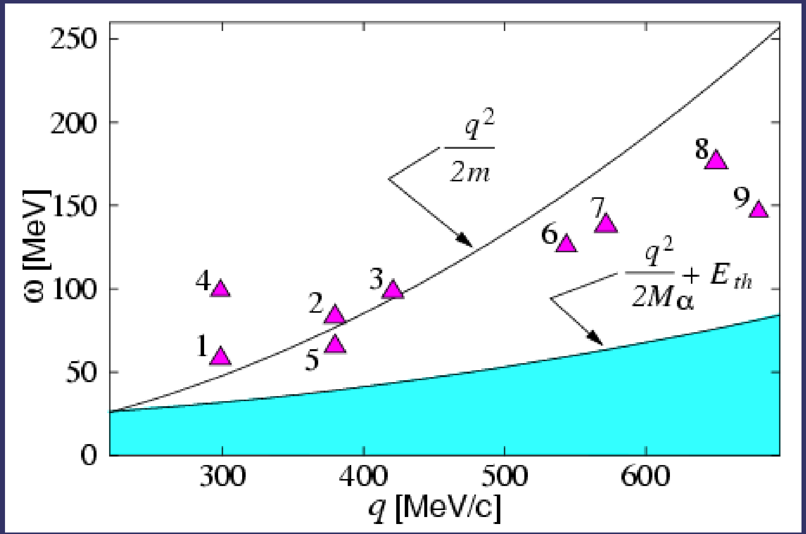


Kin. No.	F_L [(GeV/c)$^{-3}$ sr^{-1}] Expt.			FULL
1	59.0	±2.0	±2.2	66.4
2	49.6	±2.1	±2.1	66.9
3	46.2	±2.5	±2.2	62.7
4	27.8	±1.0	±1.2	34.9
5	28.4	±1.2	±1.3	37.2
6	14.8	±1.4	±1.2	25.9
7	16.0	±1.5	±1.3	23.0
8	9.96	±1.29	±1.15	16.3
9	1.35	±0.22	±0.22	2.73

Longitudinal Response

nonparallel kinematics

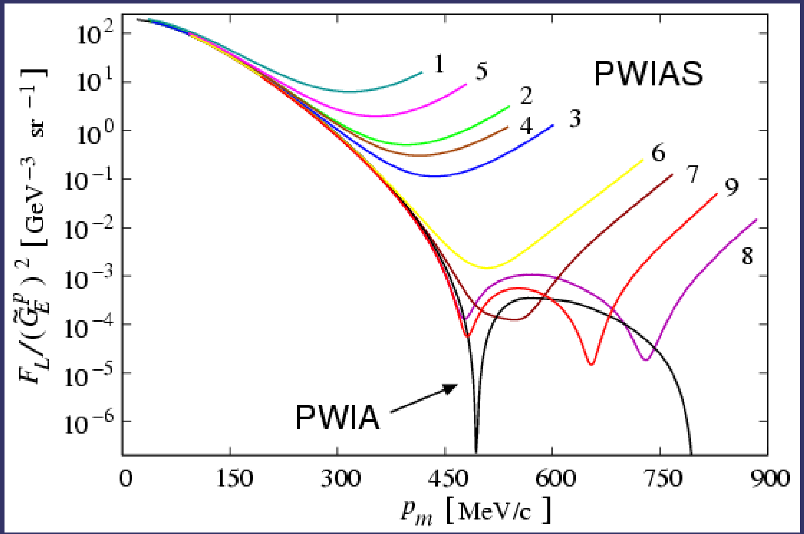


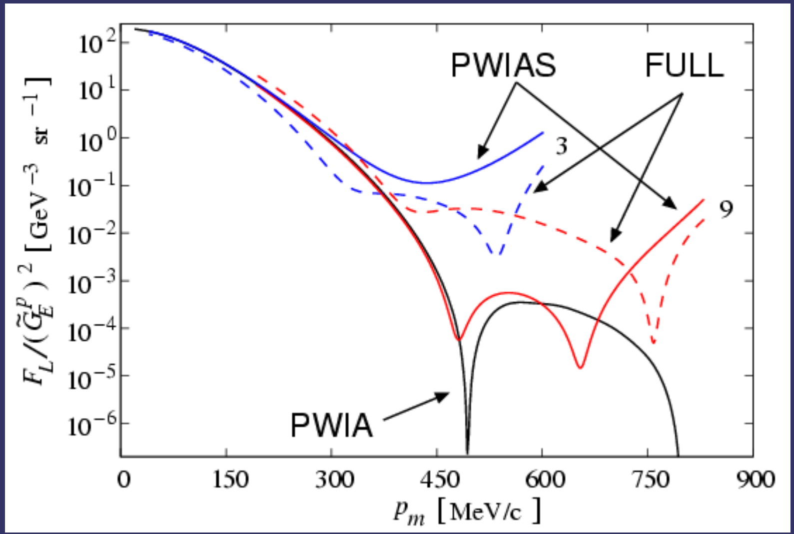


Deviations from PWIA

+ antisymmetrization ⇒ **PWIAS**

+ FSI ⇒ **FULL**





The d, d channel: Longitudinal Response

Deviations from PWIA

+ **antisymmetrization** $\Rightarrow$ **PWIAS**

+ **FSI** $\Rightarrow$ **FULL**

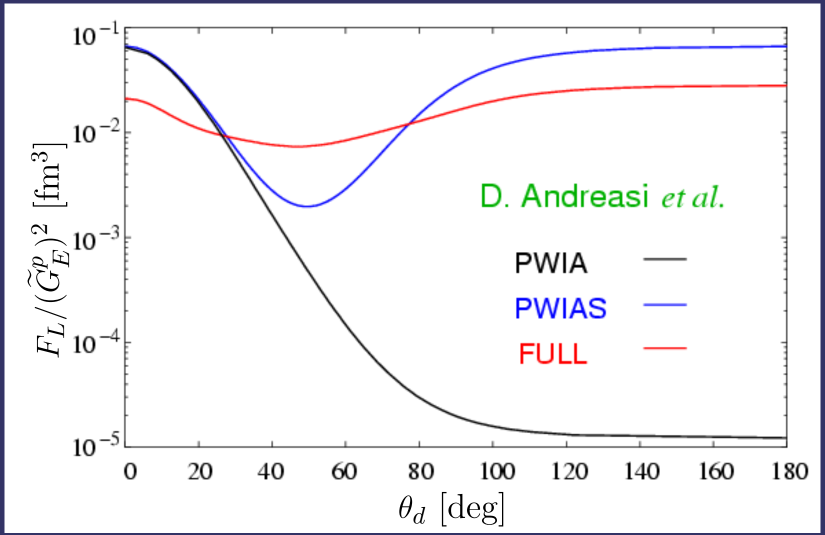
$Q^2 = 4.93\ \mathrm{fm}^{-2}, \quad E_{cm} = 35\ \mathrm{MeV}$

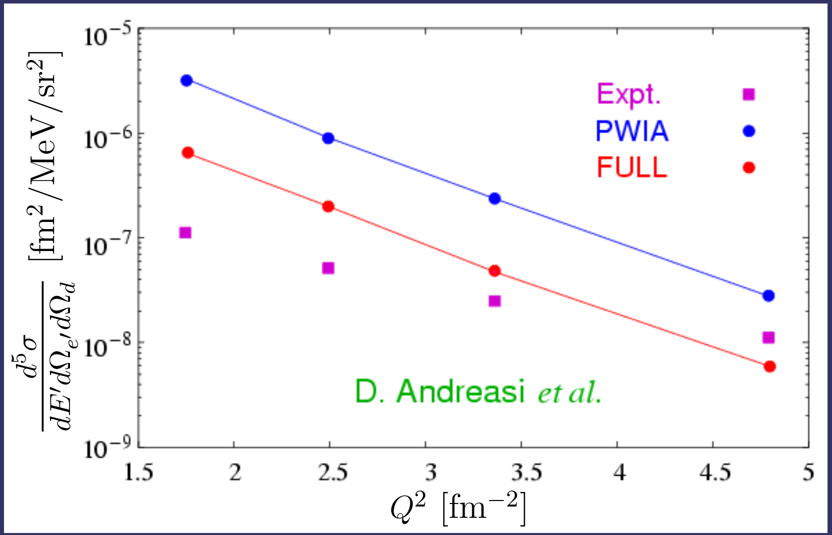
Comparison with experiment

R. Ent et al. PRL**67**(1991)18

$Q^2 = 1.75, 2.49, 3.36, 4.93\ \mathrm{fm}^{-2}$

$E_{cm} = 35\ \mathrm{MeV}, \quad p_m = 125\ \mathrm{MeV/c}$





Hadronic Processes

Two fragments both in the initial and in the final state

on–shell T–matrix

$$T_{fi}(E) = \langle \Psi_f^-(E)|V_i|\Phi_i(E)\rangle = \langle \Phi_f(E)|V_f|\Psi_i^+(E)\rangle$$

$$= \langle \Phi_f(E)|V_f|\Phi_i(E)\rangle + \int \frac{F_{fi}(E')}{E+i\varepsilon-E'}\, dE'$$

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$$F_{fi}(E') = \sum\!\!\!\!\!\!\!\int_{\nu} \langle \Phi_f \, | V_f | \, \Psi_\nu \rangle \, \langle \Psi_\nu \, | V_i | \, \Phi_i \rangle \, \delta(E' - E_\nu)$$

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$$L[F_{fi}](\sigma) = \langle \Phi_f | V_f \frac{1}{H - \sigma^*} \frac{1}{H - \sigma} V_i | \Phi_i \rangle = \langle \widetilde{\psi}_f | \widetilde{\psi}_i \rangle$$

$$(H - \sigma_R - i\sigma_I) | \widetilde{\psi}_{i/f} \rangle = V_{i/f} | \Phi_{i/f} \rangle \;\longrightarrow\; \text{full FSI!}$$

Hadronic Processes

Two fragments both in the initial and in the final state

on–shell T–matrix

$$T_{fi}(E) = \langle \Psi^-_f(E)|V_i|\Phi_i(E)\rangle = \langle \Phi_f(E)|V_f|\Psi^+_i(E)\rangle$$

$$= \langle \Phi_f(E)|V_f|\Phi_i(E)\rangle + \int \frac{F_{fi}(E')}{E+i\varepsilon-E'}\, dE'$$

$$L[F_{fi}](\sigma) = \langle \Phi_f|V_f \frac{1}{H-\sigma^*}\,\frac{1}{H-\sigma} V_i|\Phi_i\rangle = \langle \widetilde{\psi}_f|\widetilde{\psi}_i\rangle$$

$$(H - \sigma_R - i\sigma_I)|\widetilde{\psi}_{i/f}\rangle = V_{i/f}|\Phi_{i/f}\rangle \;\longrightarrow\; \text{full FSI!}$$

to be investigated!

Conclusions

Summary

- First *ab initio* calculation of exclusive reactions in the continuum of a 4–particle system also beyond the 3–body breakup threshold
- FSI has been rigorously taken into account via the LIT method: first application to exclusive processes with $A > 2$
- The 2–fragment breakup of ^{4}He induced by real or virtual photons has been studied

Photodisintegration

- The ^{4}He$(\gamma, p)^3$H and ^{4}He$(\gamma, n)^3$He total cross sections show a pronounced dipole peak at 27 MeV, which favours the high–peaked experimental data
- The FSI plays a fundamental role in the cross section evaluation

Electrodisintegration

- We have investigated the reliability of direct knock–out hypothesis and the role of FSI for both ^{4}He$(e, e'p)^3$H and ^{4}He$(e, e'd)d$ reactions

Outlook

- More quantitative predictions with realistic two–body interactions and three–body forces
- Application of the method to the study of other exclusive reactions: ^{6}Li$(\gamma,^3\mathrm{He})^3$H
- Application of the method to hadronic processes: four–body phase shifts