The means to test nuclear interaction in few-nucleon systems

R. Lazauskas, IPN, Orsay

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- ✓ **Properties of heavy and medium nuclei vary smoothly**

  Individuality of single nucleons is lost

  Constant density
  Constant binding per nucleon

- ✓ **Diverse properties of light nuclei**

  Nucleons still behave as individuals

  Diverse nuclear densities, bindings
  Neutron richest structures
  One can still trace NN interaction effects!!!
  Can handle exactly…

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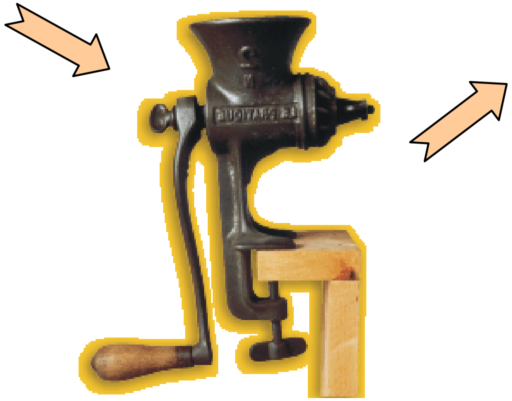
First principles:
NN interaction

No-adjustments!!



Complete description:
Bound states, scattering, EM reactions

Machinery:

Bound states A≤12 : Green function Monte-Carlo[1], No-core shell model[2],…

[1] S.C. Pieper, V.R. Pandharipande, R.B. Wiringa and J. Carlson: Phys. Rev. **C 64** (2001) 014001.
[2] P. Navratil, J P. Vary, B. R. Barrett: Phys. Rev. Lett. **84** (2000) 5728.

Scattering A≤4 !!! Faddeev-Yakubovski eq., Hyperspherical Harmonics.

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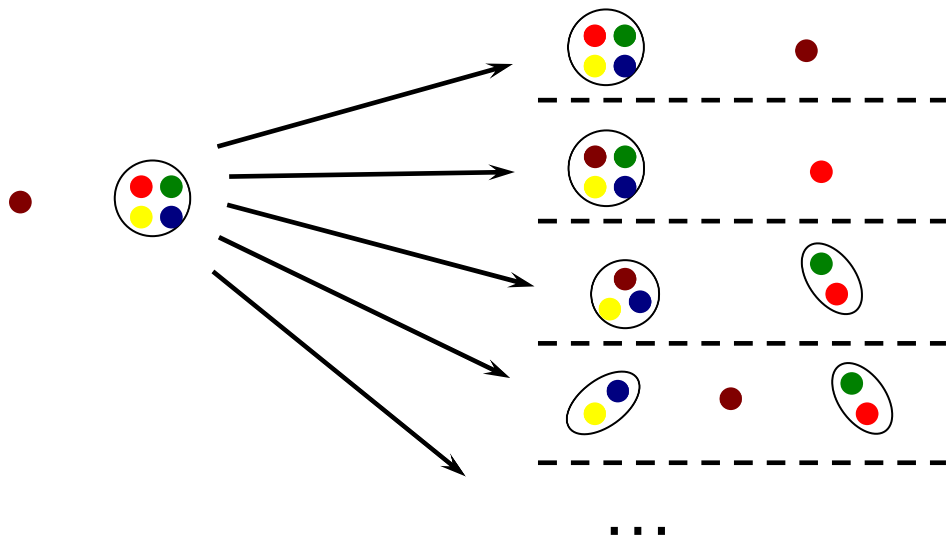
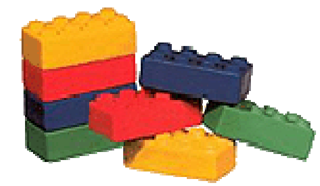
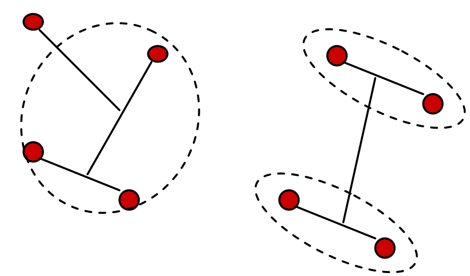


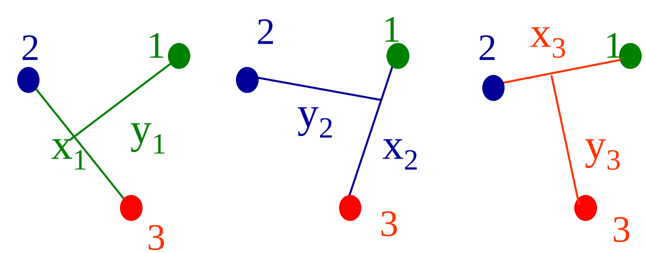


$$\Psi = \sum_{\alpha} \psi_{\alpha}$$



- *Schrödinger eq. is not enough (provided solutions are not unique)*
    - *Faddeev-Yakubovski equations*

$$\begin{cases} \left(\hat{H}_0 + V_{23} - E\right)\psi_1 = -V_{23}(\psi_2 + \psi_3) \\ \left(\hat{H}_0 + V_{13} - E\right)\psi_2 = -V_{13}(\psi_1 + \psi_3) \\ \left(\hat{H}_0 + V_{12} - E\right)\psi_3 = -V_{12}(\psi_1 + \psi_2) \end{cases}$$



+ *correct boundary conditions for components ψ_α!!! Special care to make for break-up!*

Problems with Coulomb break-up: recently resolved for 3N system

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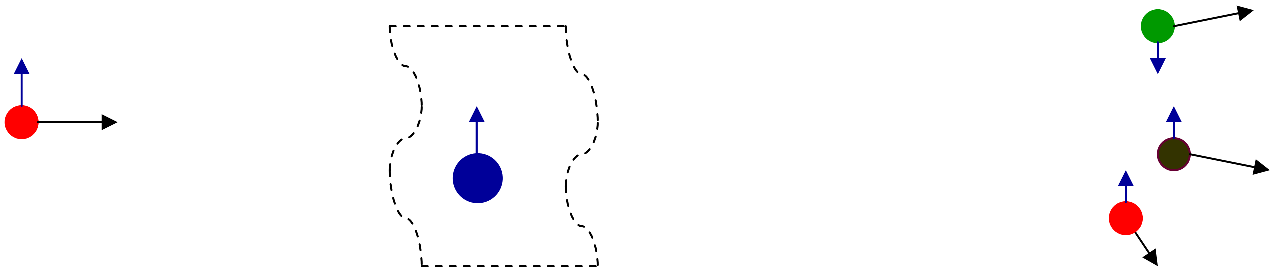
o Why scattering?

The scattering experiment is the richest source of information about NN interaction



In theory:

Faddeev-Yakubovski eq. → Full systems wave function

Full systems wave function → elastic asymptotes

Full systems wave function → Break-up asymptotes

↓

Any experimental observable!!!

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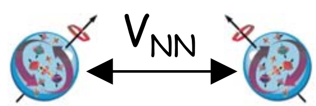
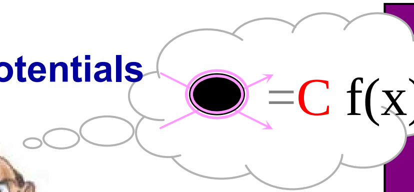
Freestyle: **phenomenological models**

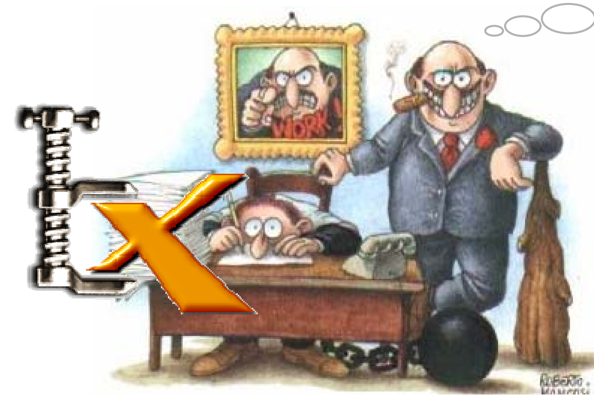
MT I-III (Malfliet-Tjon)

INOY (Doleschall)…



Extreme sports: **realistic potentials**





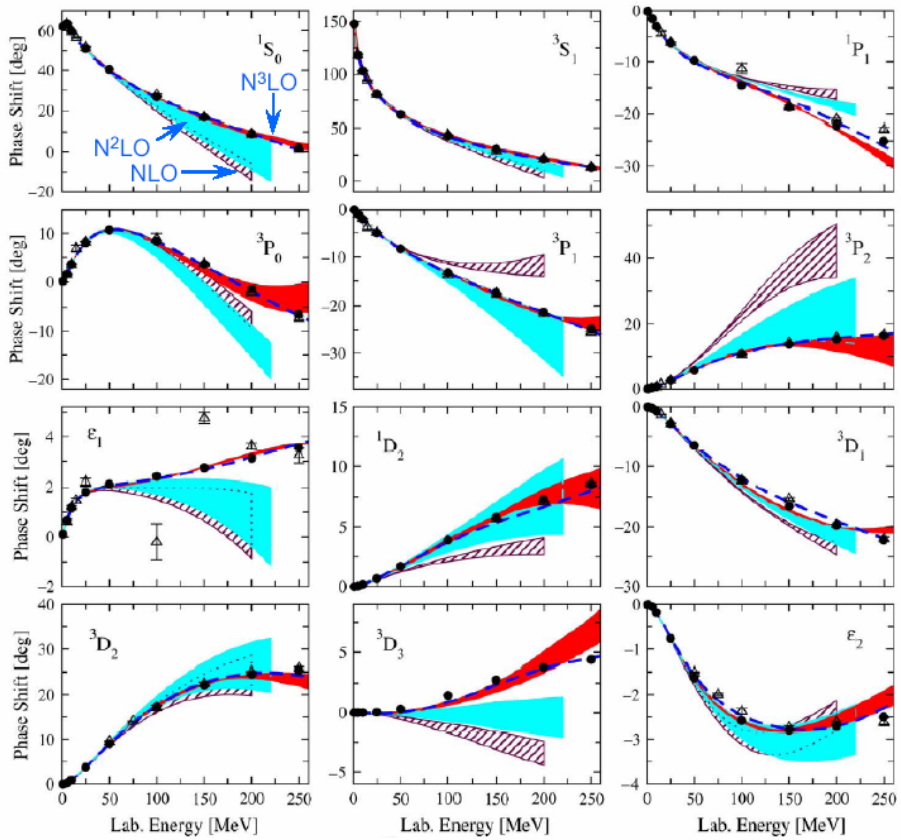
Paris
Nijmegen: Nijm I, Nijm II, Reid
Urbana/Argonne: Av.14, Av18
Bonn: Bonn B, CD Bonn, …

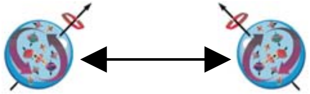
Effective field theory (EFT) and
Chiral perturbation theory (χPT)

Manufacture of parameters: to fit *NN* data (n-p and p-p). Description with $\chi^2_{data} \approx 1.01$ (*n~40 free parameters...*).

✓ NN data: realistic potentials adjusted to describe it with $\chi^2 \approx 1.01$

Neutron-proton phase shifts up to N^{3}LO





(Entem & Machleidt '03; E.E., Meißner & Glöckle '05)

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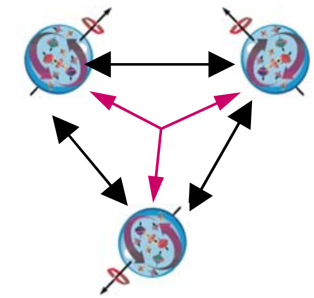
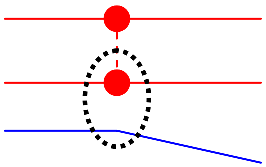
✓ NN data: realistic potentials adjusted to describe it with $\chi^2 \approx 1.01$

✓ 3N bound state (problems starts)

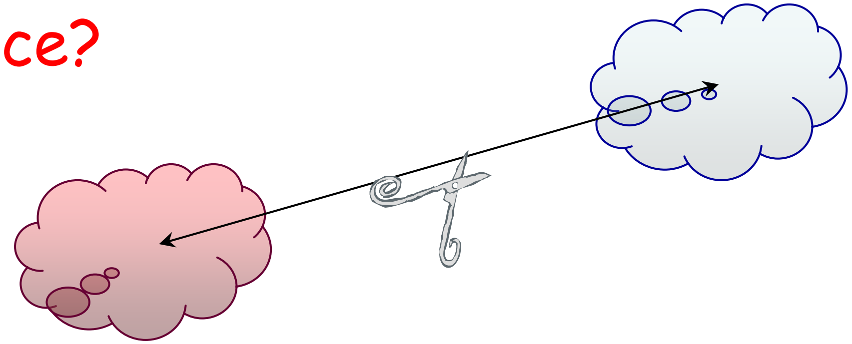


	$B(^3H)$; MeV	$B(^3He)$; MeV
N3LO	7.84	
Nijm II	7.741	7.011
Av.18	7.616	6.914
AV.18+UIX	8.473	7.739
Doleschall	8.476	7.711
Exp.	8.482	7.718

Off-shell effects:



How strong is three-body force?



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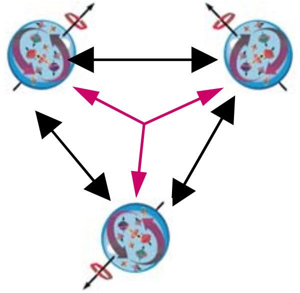

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Off-shell effects:

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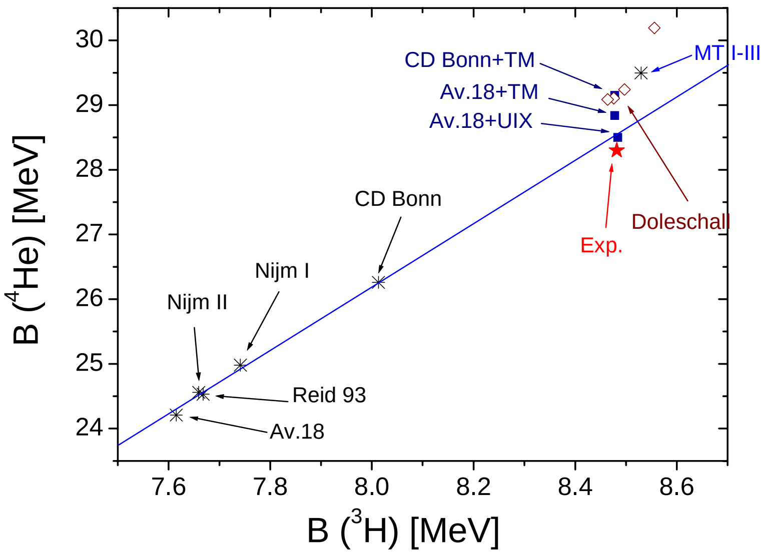
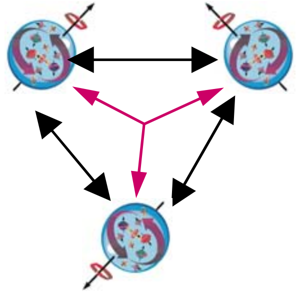


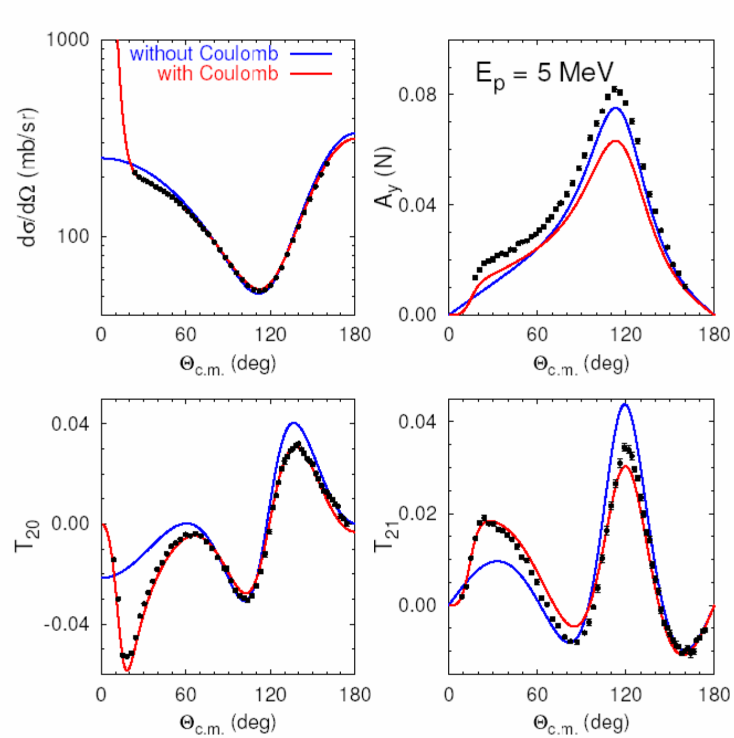
eans to test nuclear interaction in few-nucleon s

✓ NN data: realistic potentials adjusted to describe it with $\chi^2\approx 1.01$

✓ 3N bound state (problems starts)

✓ 3N scattering: many observables well described, except $A_{y\ldots}$, $\chi^2>1$

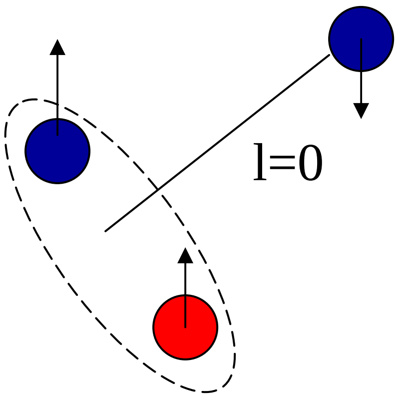




3NF effects are very small…

✓ deutron is large

✓ Nd singlet scattering cross sections are very low



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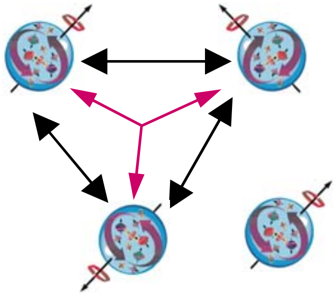
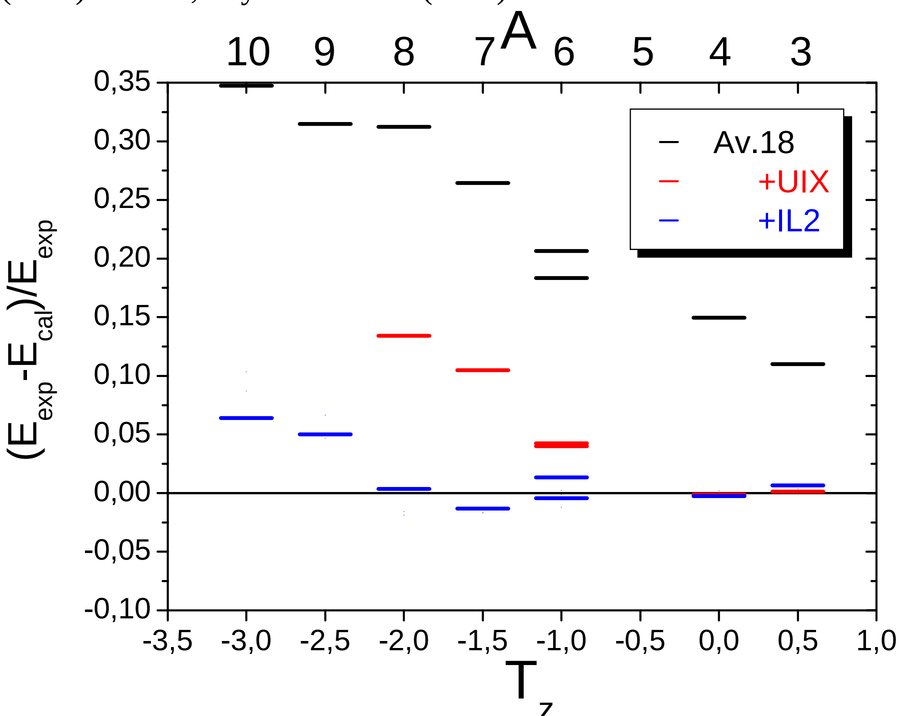


Bound states of heavier systems

C. Pieper et al.: Phys. Rev. C 64 (2001) 014001; Phys. Rev. Lett. 89 (2002) 182501; Phys. Rev. C 66 (2002) 044310



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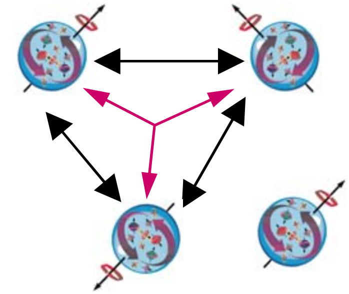
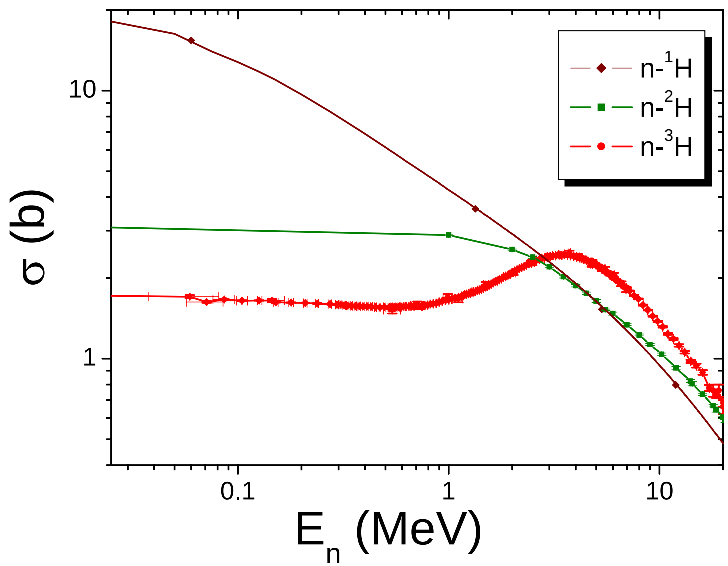
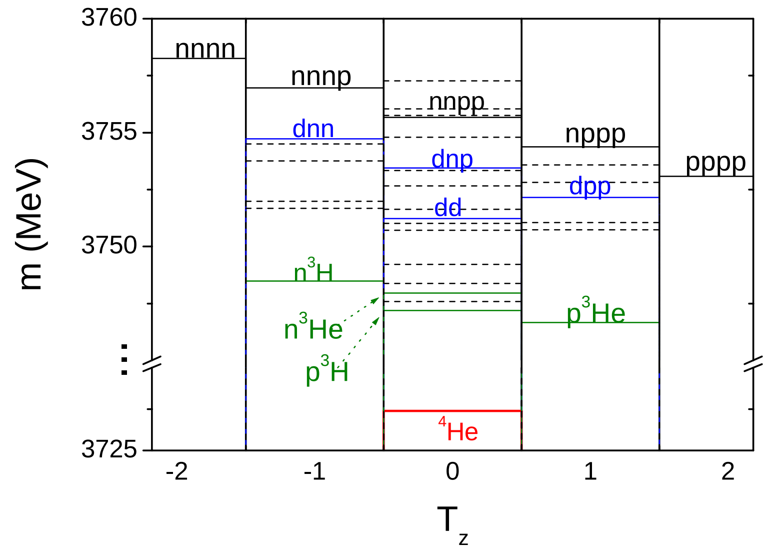


✓ 4N scattering: considerably more technically as well as structurewise





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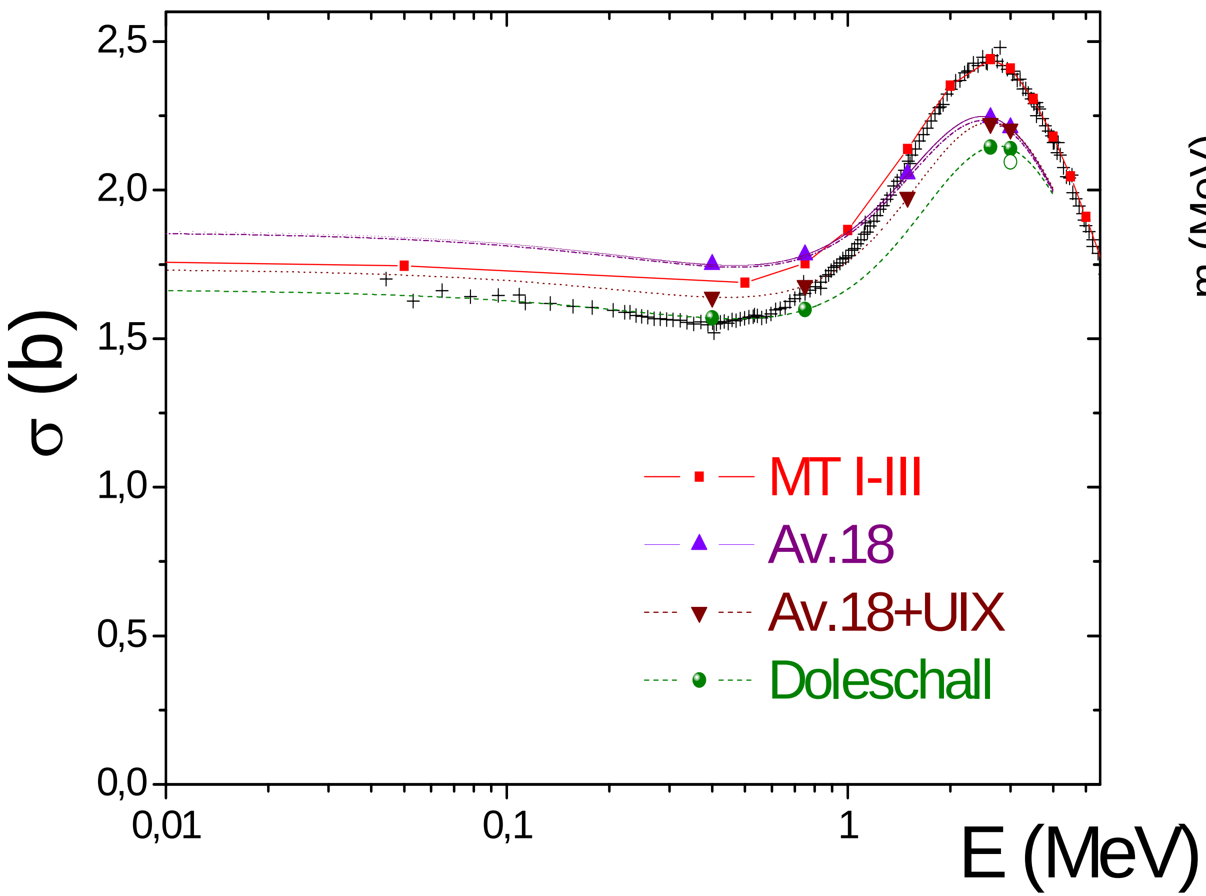
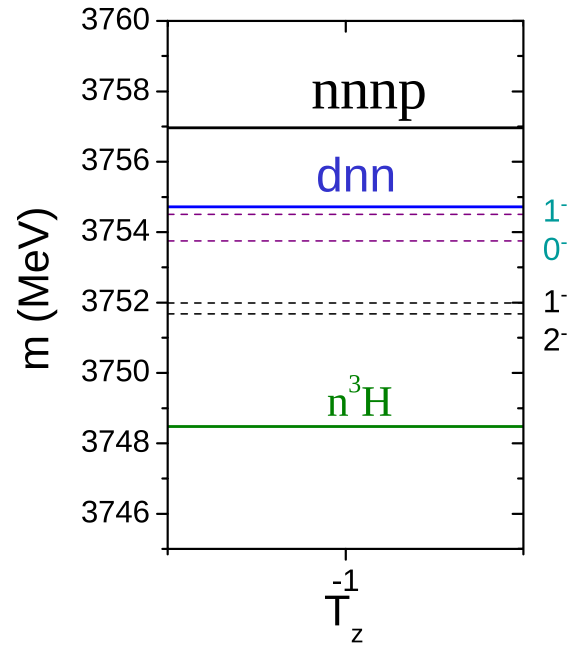
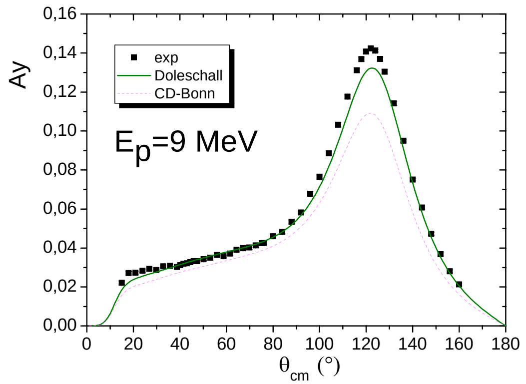
n+^{3}H elastic scattering: the simplest case







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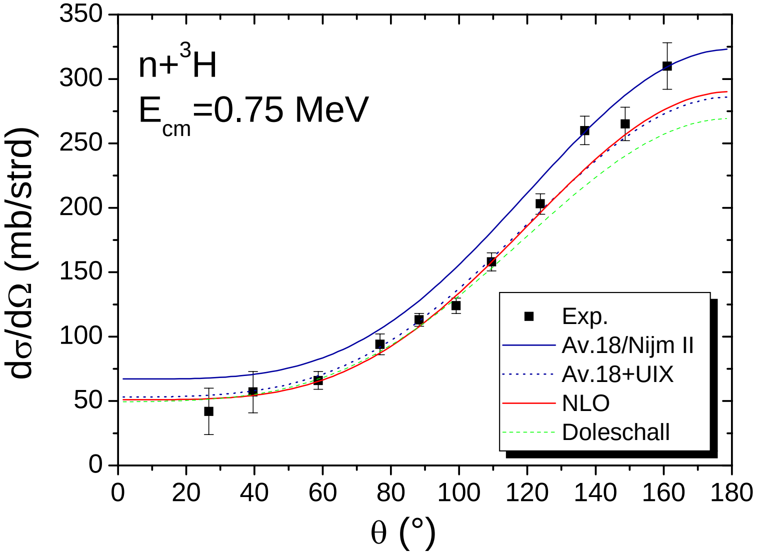
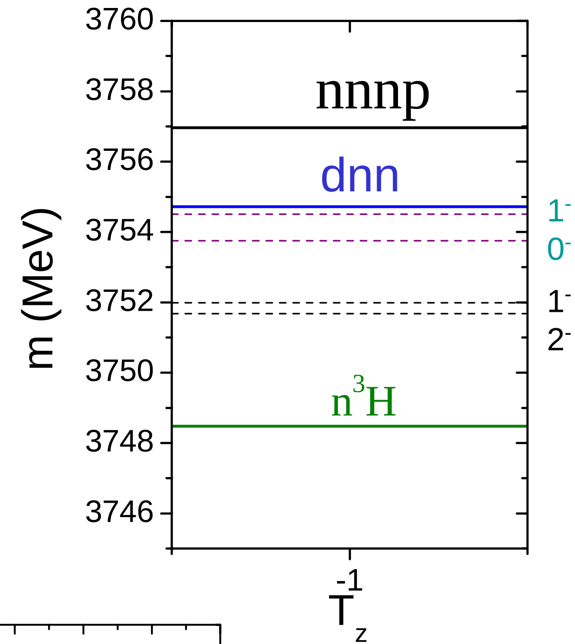
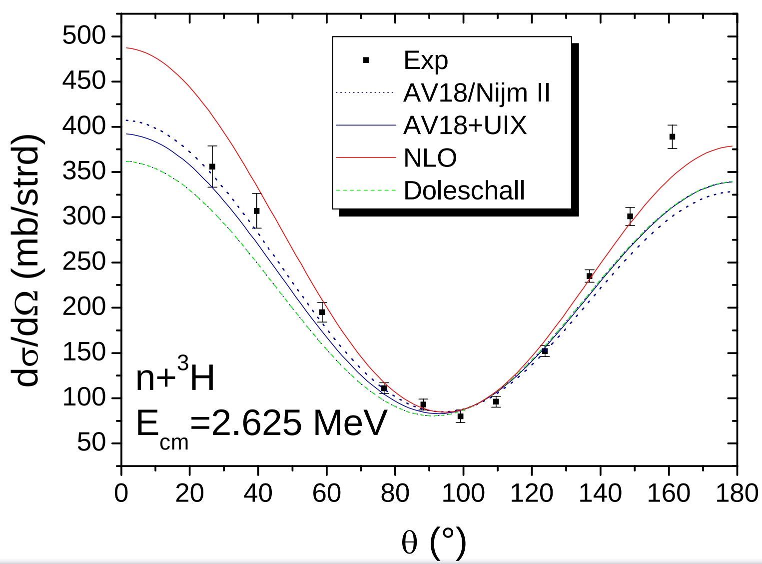
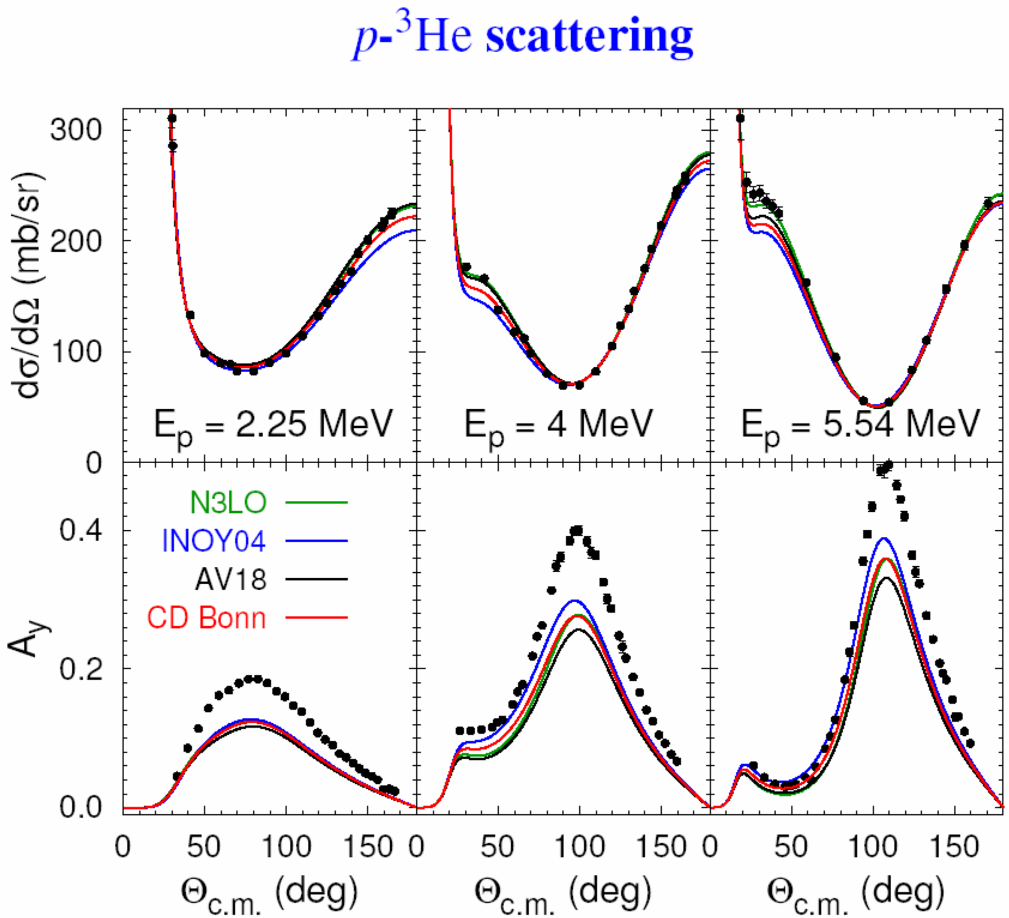
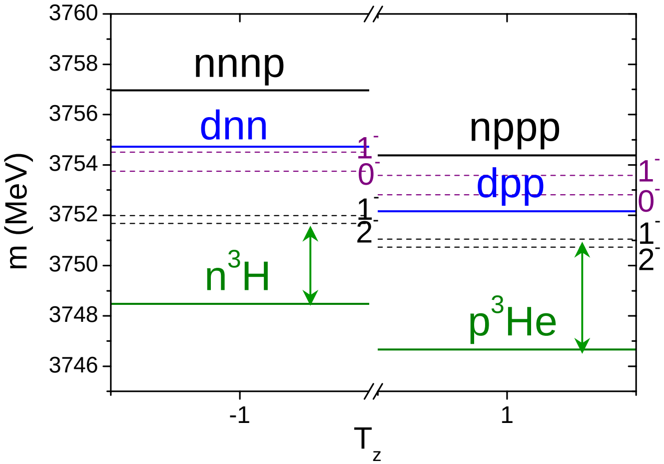








A. Deltuva, A. Fonseca: to appear in PRC



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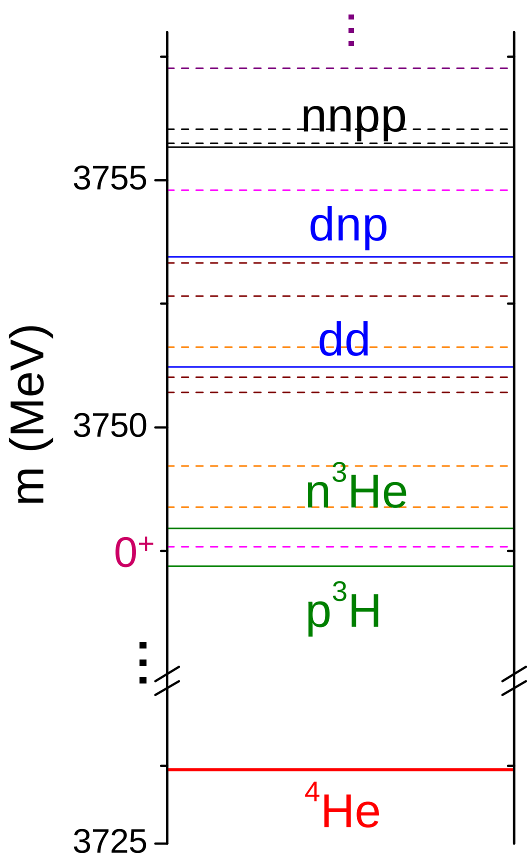

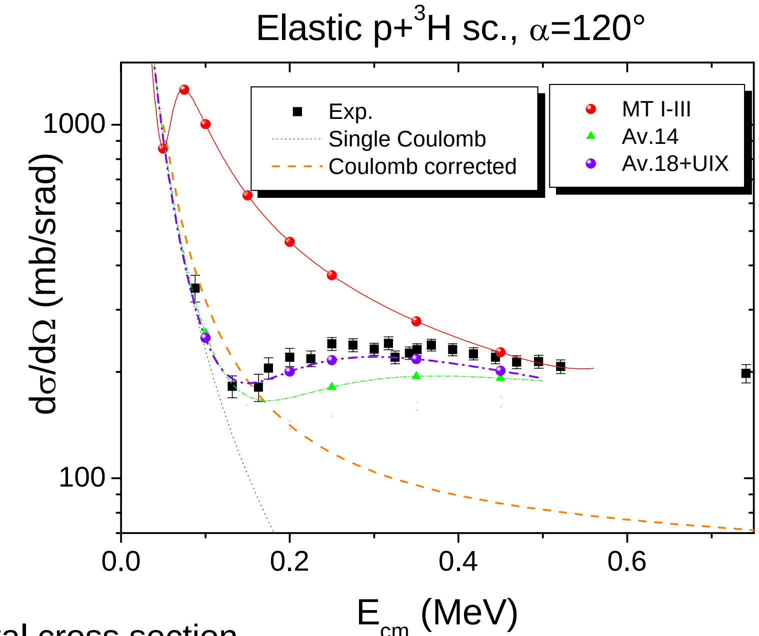

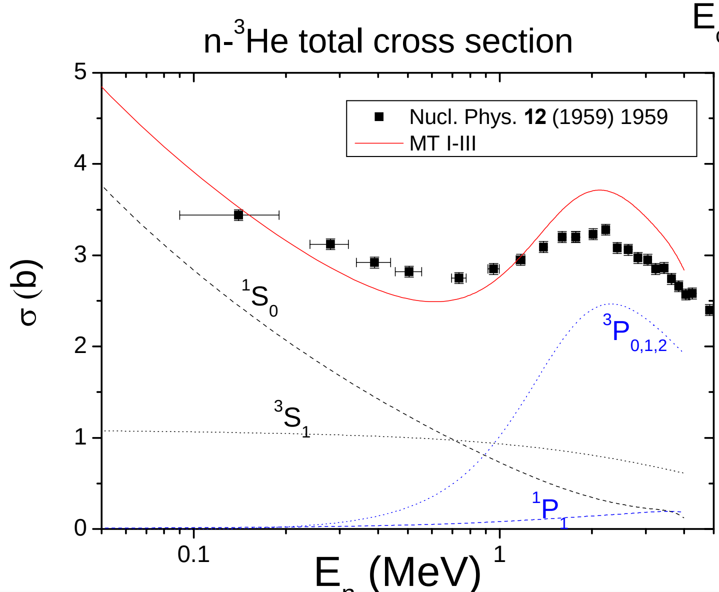

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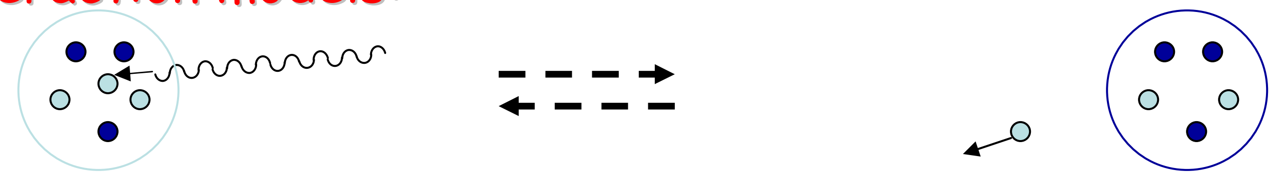
Weak and EM probes are very useful to test nuclear structure and interaction models:

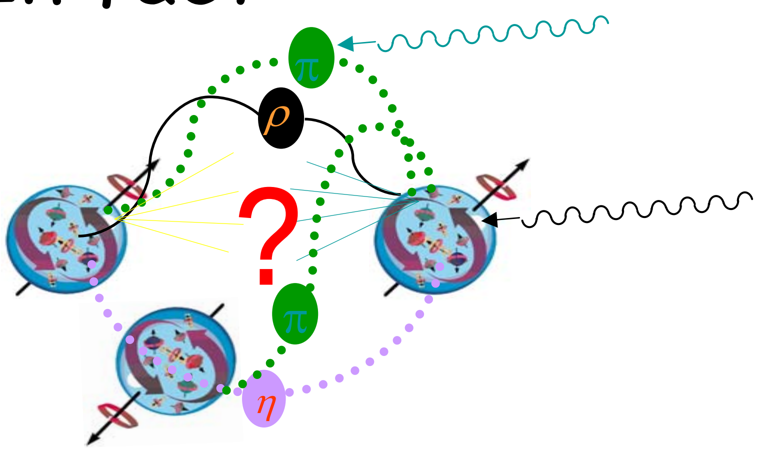


$\langle \Psi_f |$ $\qquad \vec{J}_\nu(\vec{q})$ $\qquad | \Psi_i \rangle$

$$\mathcal{M} = \langle \Psi_f | \hat{H}_\nu | \Psi_i \rangle \approx \langle \Psi_f | \vec{J}_\nu(\vec{q}) | \Psi_i \rangle$$

$$\vec{\mu}_f = e \frac{i}{2} \langle \Psi_f | \lim_{|q| \to 0} \vec{\nabla}_{\vec{q}} \times \vec{J}(\vec{q}) | \Psi_f \rangle$$

In fact:



$$\vec{J}_\nu(\vec{q}) = \vec{j}_{1B}(\vec{q}) + \vec{j}_{2B}(\vec{q}) + \vec{j}_{3B}(\vec{q}) + \ldots$$

$$\vec{j}_{2B}(\vec{q}) = f(V_{NN})$$

$$\vec{j}_{3B}(\vec{q}) = f(V_{NNN})$$

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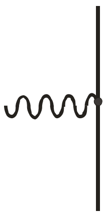
Derivation of EM current consistent with NN interaction using χPT:



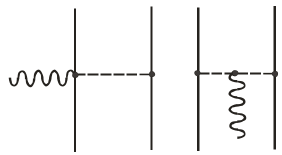
+ Counting N^{n}LO: $n = 1 - \frac{E_N}{2} + 2L + \sum_i \nu_i$

Number of external externes

Number of loops

Chiral order of vertex $(\Lambda_\chi \sim 4\pi f_\pi \sim m_N \sim 1\,GeV)$

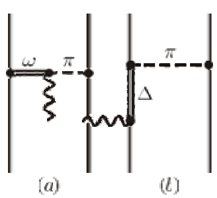
NLO: 1-pion exchange



+ ....

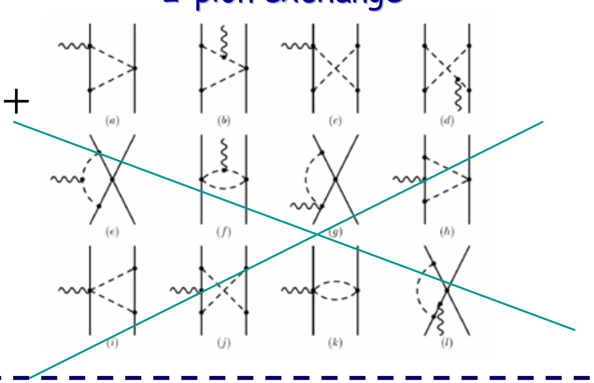
N^{3}LO:

Vertex correction



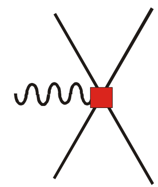
+

2-pion exchange



+

Contact terms (2 parameters)



$$\vec{j}(\vec{q}) = e^{-i\vec{q}\cdot\vec{R}} \frac{i}{2m} \vec{q} \times \left[g_{4S} (\sigma_1 + \sigma_2) + g_{4V} (\tau_1 - \tau_2)(\sigma_1 - \sigma_2) \right] \delta_\Lambda^{(3)}(r)$$

Tae-Sun Park & Young-Ho Song (KIAS, Seoul National University,Korea)

T.S. Park et al.: Phys. Rev. C 67, 055206 (2003)

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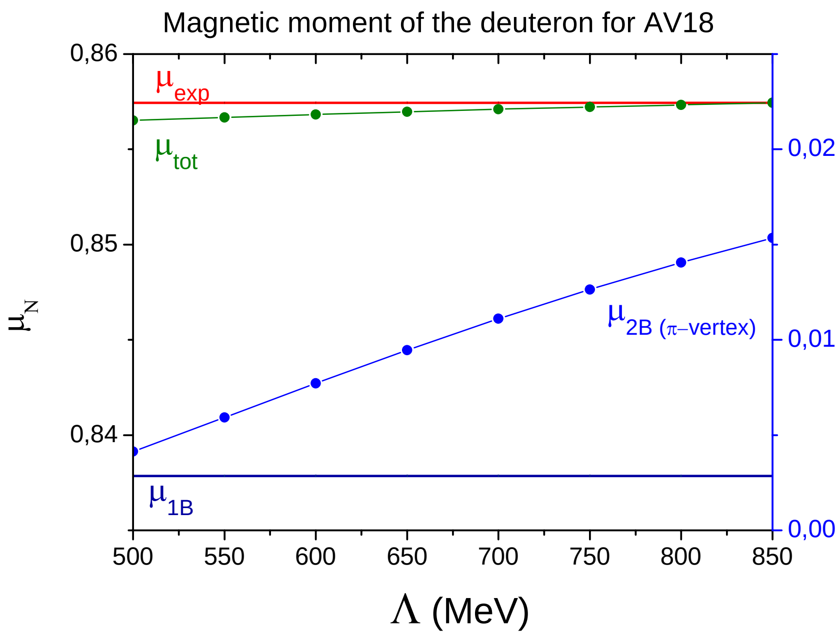
- Regularisation of the momenta:

$$S_\Lambda(k^2) = e^{-\frac{k^2}{2\Lambda^2}}$$

$$J_{12\ldots n}(\vec{q}) = J_{12\ldots n}(\vec{q}; r_i's, p_i's, \sigma_i's, \tau_i's)$$
$$= \int d\vec{x} e^{-i\vec{q}\cdot\vec{x}} \prod_{i=1}^{n} [\int \frac{d\vec{k}_i}{(2\pi)^3} e^{i\vec{k}_i\cdot(\boldsymbol{r}_i-\vec{x})} S_\Lambda(k_i^2)] J_{12\ldots n}(\vec{k}_1, \vec{k}_2, \cdots, \vec{k}_n)$$

- Λ values: $\Lambda \sim m_\pi$, $\Lambda < (m_{\rho,\omega}, \sim \Lambda_\chi)$

- Λ dependence



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	$\mu(^2H)$		$M(np \to d\gamma)$	
	1-corp	Total	1-corp	Total
NLO	0.851-0.857	0.857-0.858	391-395	407.1-409.
Nijm II	0.8406	0.8581(3)	393.58	409.8(1)
Av.18	0.8402	0.8569(4)	393.2	409.4(1)
AV.18+UIX	0.8402	0.8601(3)	393.2	408.7(1)
Doleschall	0.8537	0.8561(1)	395.36	408.7(1)
Exp.		**0.85744**		**409.9±0.5**

For thermal neutron radiative capture on ^3He meson exchange currents account 90% of transition amplitude!!!

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- **Small nuclear systems are crucial to understand nuclear interaction:** progress in ab-initio treatment of nuclear reactions is slow but steady
- **Resolution of 3N system is possible in all its complexity:** small discrepancies with data suggest reveals lack of understanding in spin dependence of nuclear force
- **4N is in oven:** stronger discrepancies with data, rich field for studying nuclear forces