CRC 1660 Kick-Off Meeting

Dec 9 – 10, 2024
Helmholtz Institute,
Johannes Gutenberg University,
Mainz

Hadrons CRC 1660 Nuclei

N03 Few-body systems

Experimental studies of few-nucleon systems with hadronic and electromagnetic probes

MAGIX

Elżbieta Stephan
UNIVERSITY OF SILESIA
IN KATOWICE

How to look into nuclei...

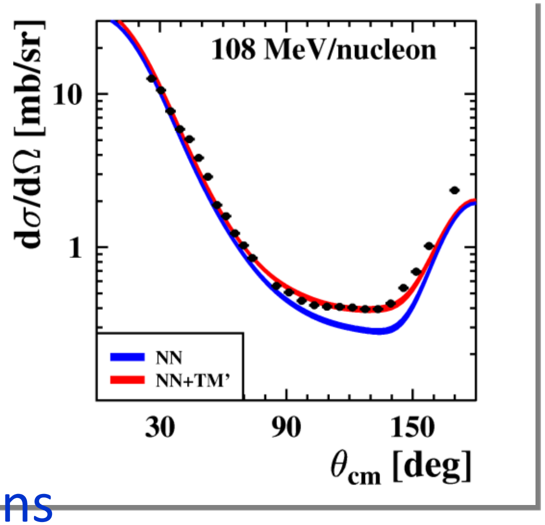
- The response to **electromagnetic and hadronic probes** provides direct information on **dynamics of the nucleus**.
- **The rich structure of nuclear interactions and currents**, combined with availability of different probes, offers the opportunity to study many intriguing aspects of nuclear dynamics
- A comprehensive study of nuclear response requires an **understanding of the nuclear groundstate wave function**, couplings of the various probes to the nucleus, and final-state interactions.

Few-Nucleon Systems

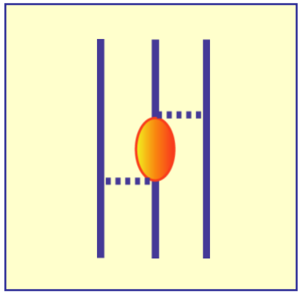
Predictions of NN potentials alone:

- **fail** to reproduce binding energies of 3N, 4N and heavier systems
- **fail** to reproduce minimum of the d(N,N)d elastic scattering cross section

Binding energy [MeV]	^3H	^3He	^4He
Experimental value	8.48	7.72	28.3
CD Bonn	8.01	7.29	26.3
CD Bonn + TM99	8.48	7.73	29.2



- Introducing concept of **three-nucleon forces**: genuine (irreducible) interaction of three nucleons
  - as a consequence of internal nucleon structure
- Systematic approach within ChEFT



Three-Body Force

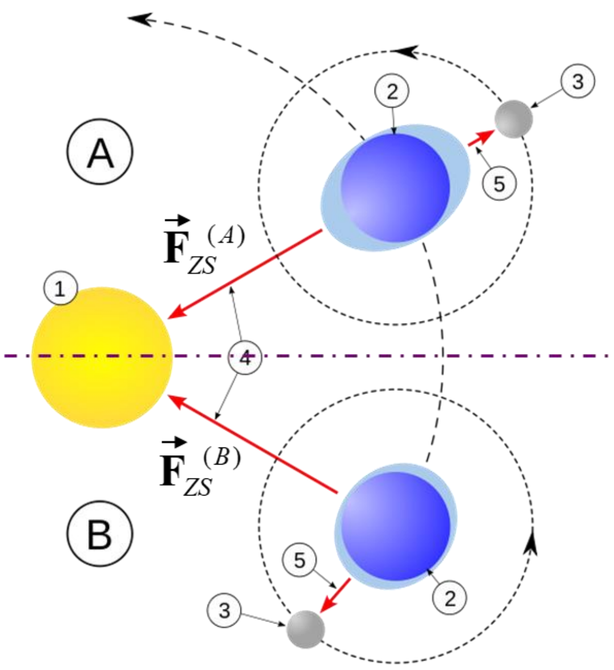
Conditions:

- to be described: interactions of at least 3 non-point (non-elementary) bodies;
- pairwise interactions are known, but their description neglects the internal structure (treat the bodies as point-like /elementary objects);

➢ thus 3-Body Force has to be added to pairwise interactions!

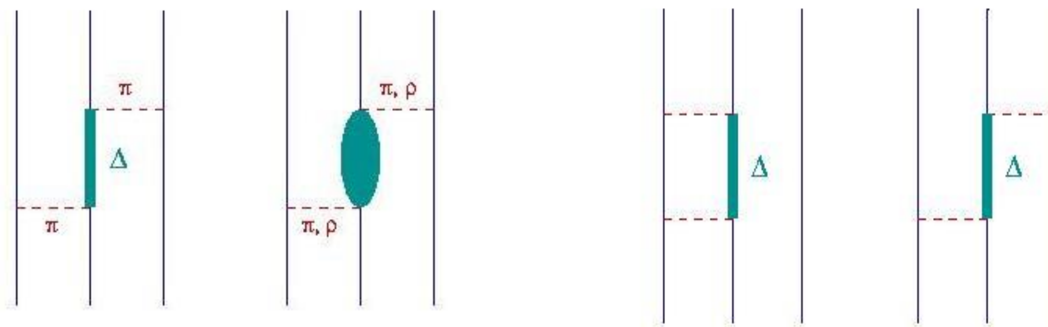
Gravity: Sun & Earth & Moon

$$\vec{\mathbf{F}}_{ZS}{}^{(A)} \neq \vec{\mathbf{F}}_{ZS}{}^{(B)}$$

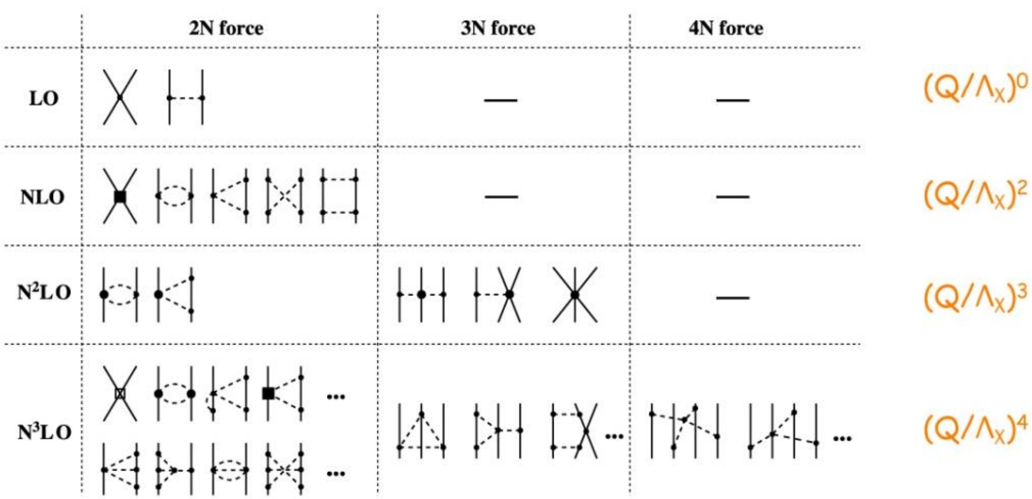


Three-Nucleon Force

- ❑Models of 3NF:



- ❑Naturally appearing in Chiral Effective Field Theory at N2LO:



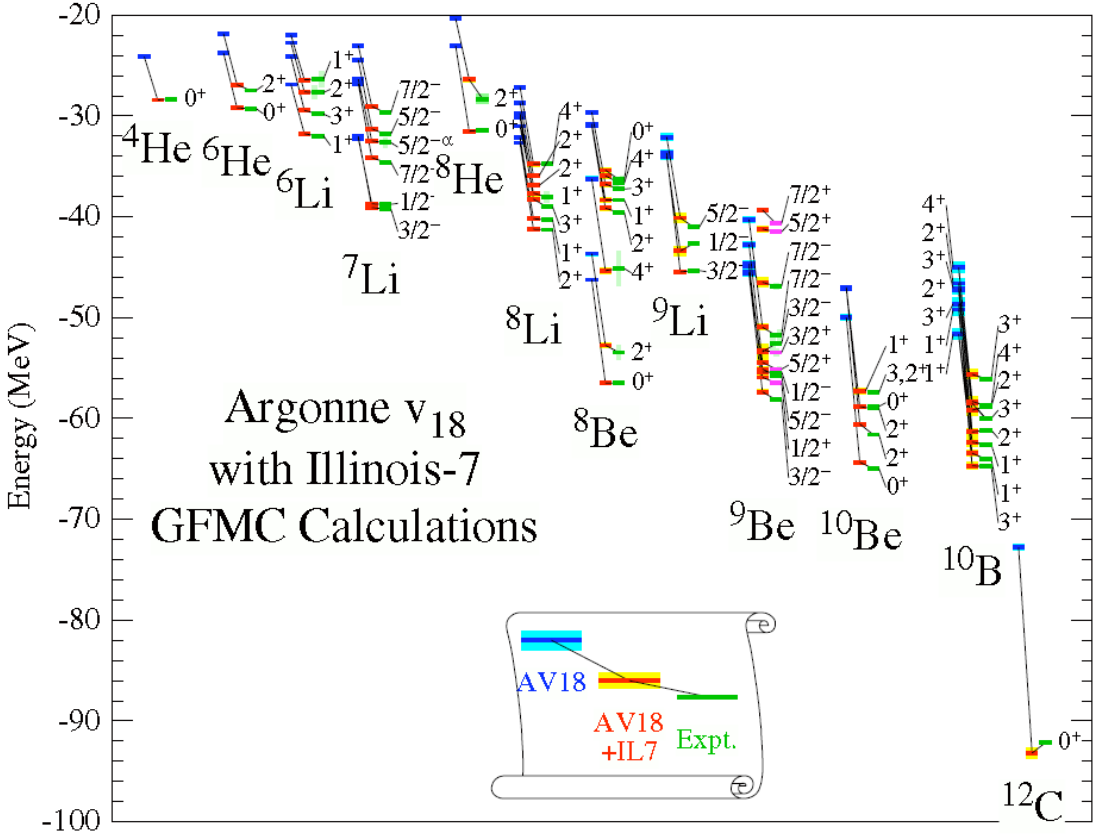
- Starts from Lagrangian consistent with QCD symmetries.
- Perturbative: power counting scheme, systematic improvement of results.
- Uncertainties of observables calculated at given order can be derived.
- Consistent treatment of electromagnetic currents!

Three-Nucleon Force Effects

Binding Energies

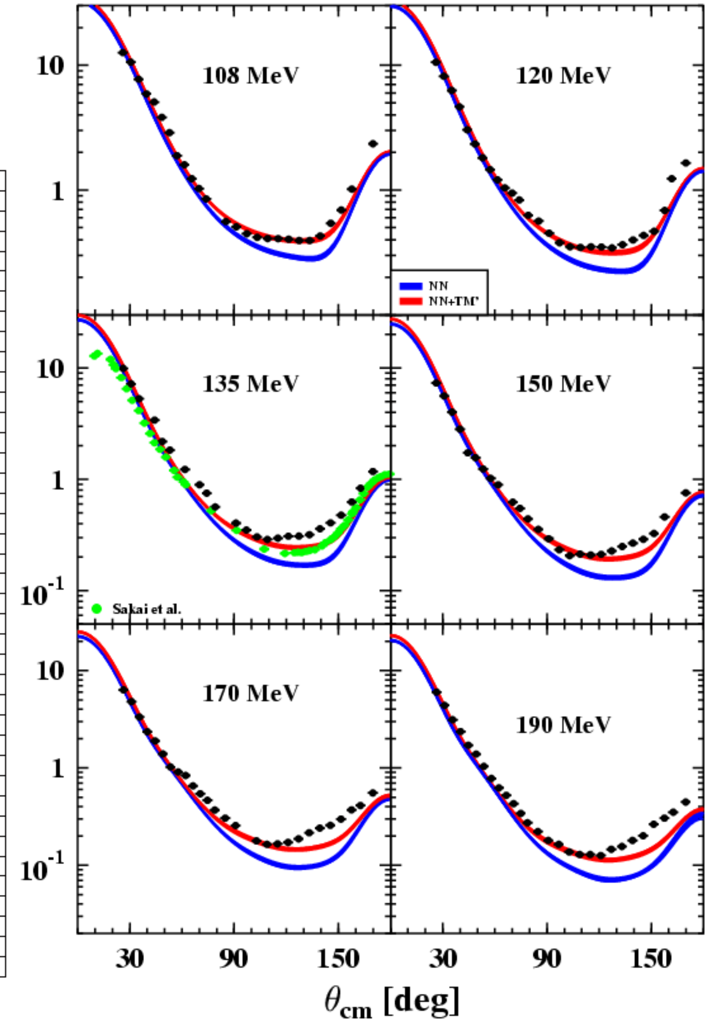
Light Nuclei

- Effects of 3NF clearly visible



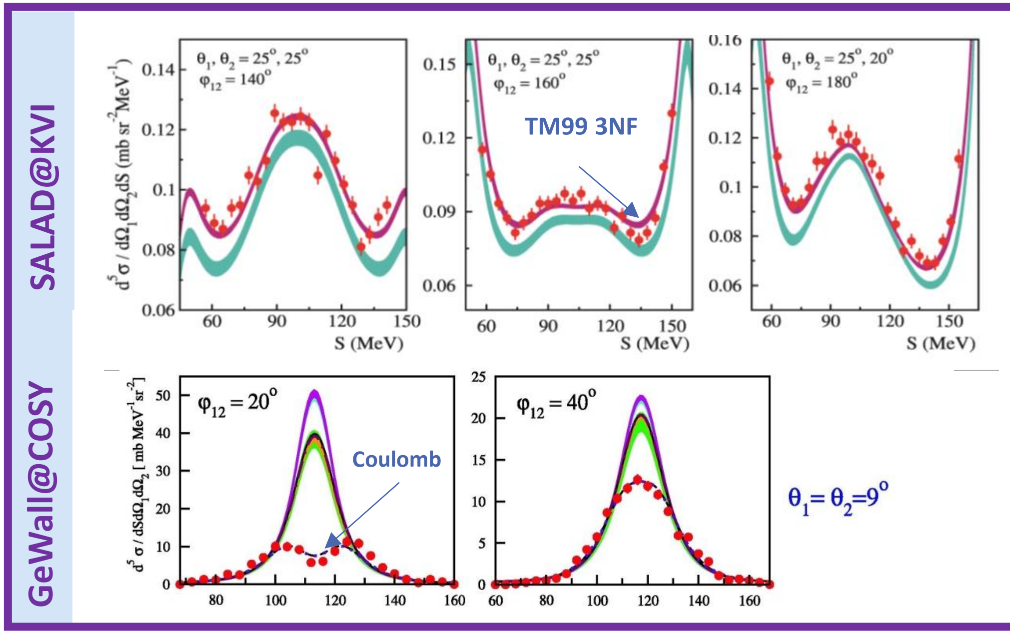
p-d Elastic Scattering

Differential Cross Section



Deuteron Breakup in Collision with Proton

Differential Cross Section



$^1H(d,pp)n$ 65 MeV/nucleon

St.Kistryn et al., Phys. Rev C 72 , 044006 (2005)

I.Ciepał et al., Few-Body Syst. 56, 665 (2015)

calculations: Witała et al. (CD-Bonn+TM99), Deltuva et al. (CD-Bonn+Δ+Coulomb)

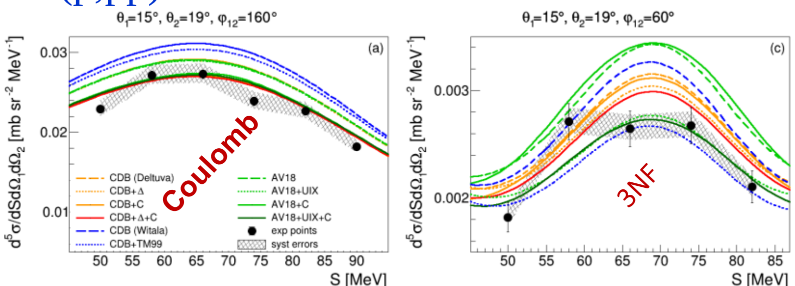
- Continuum of final states studied with large acceptance detectors.
- With applied binning: 500-1000 data points per experiment.
- **3NF – when predicted, then confirmed**.
- Surprise: large Coulomb repulsion effects, in particular in pp FSI configuration.
- Bulk of data is well described by NN+Coulomb.

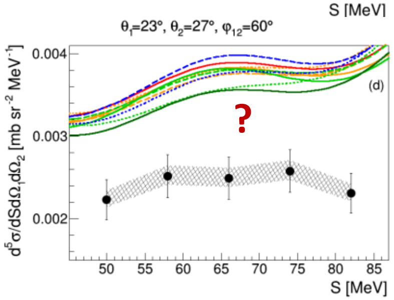
Deuteron Breakup in Collision with Proton

Differential Cross Section at lower and higher energies

BINA@CCB

^{2}H(p,pp)n 108 MeV



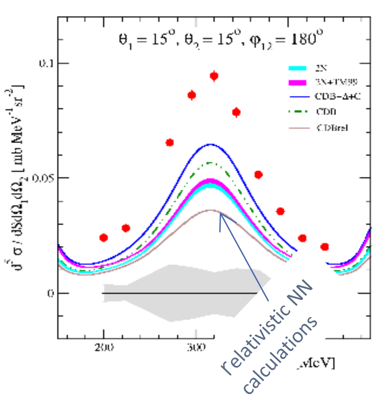


84 configurations studied.
Generally, 3NF effects play an important role.
In a few configurations significant discrepancies observed.

A.Łobejko et al., ***arXiv:2407.01582*** (2024)

WASA@COSY

^{1}H(d,pp)n 170 MeV/nucleon



Kinematical region of low 3NF effects studied. Locally large discrepancy observed, not removed by relativistic NN calculations (without 3NF). Problem confirmed at 190 MeV/nucleon.
Large relativistic effects in 3NF?

WASA@COSY ***Phys. Rev. C 101**, 044001* (2020)
B.Kłos for WASA@COSY ***Few-Body Syst 65*** (2024)

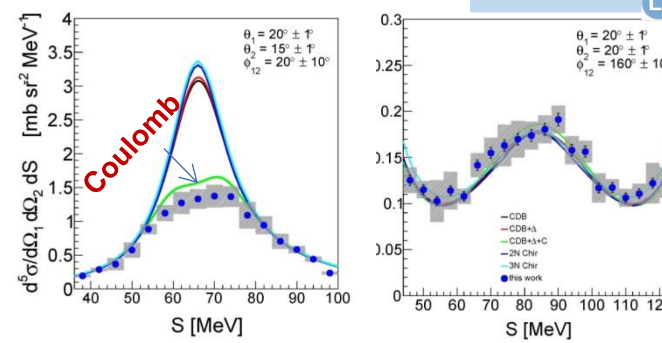
BINA@KVI

^{1}H(d,pp)n 50 MeV/nucleon

tests of Chiral Effective Field Theory

N^{4}LO 2NF and N^{2}LO 3NF

LENPIC



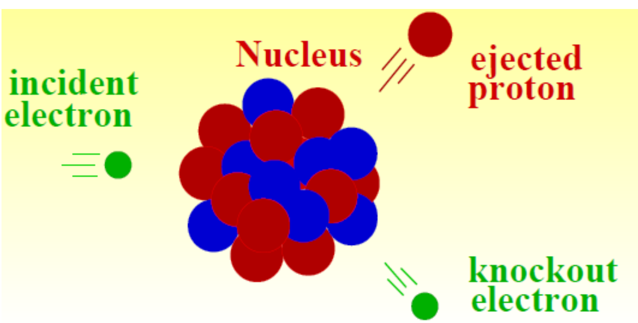
I.Skwira et al., ***Few-Body Syst 65*** (2024)

- **3NF & Coulomb effects confirmed**, general success of theoretical description
- At low energies, first calculations of the breakup reactions with **ChEFT potentials** are tested, quality of description similar to the one of realistic potentials. Coulomb has to be included!
- Local **discrepancies** between data and all theories are observed, in particular at higher energies. They are not solved by relativistic NN calculations.

UNIWERSYTET ŚLĄSKI W KATOWICACH
UNIWERSYTET JAGIELLOŃSKI W KRAKOWIE
UNIWERSYTET WARSZAWSKI
KVI-CART
WASA@COSY

3N Systems
what can be studied experimentally?

- Purely hadronic processes:
  - Elastic scattering: N + d → N + d
  - Breakup: N + d → N + N + N
- Electromagnetic processes:
  - Bremsstrahlung, radiative capture
  - Reactions with scattering of real photons
  - **Electron scattering**



Impulse Approximation (IA) :
the nuclear electromagnetic- and weak-current operators are expressed in terms of those associated with the individual protons and neutrons.
It cannot be sufficient:

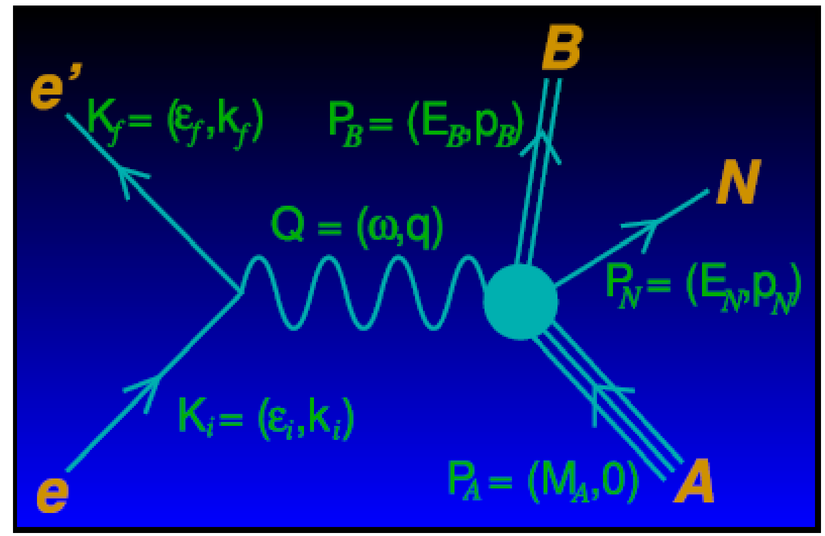
- The NN interaction is mediated at large & medium distances by **meson-exchange** mechanisms.
- This leads to effective many-body current operators.

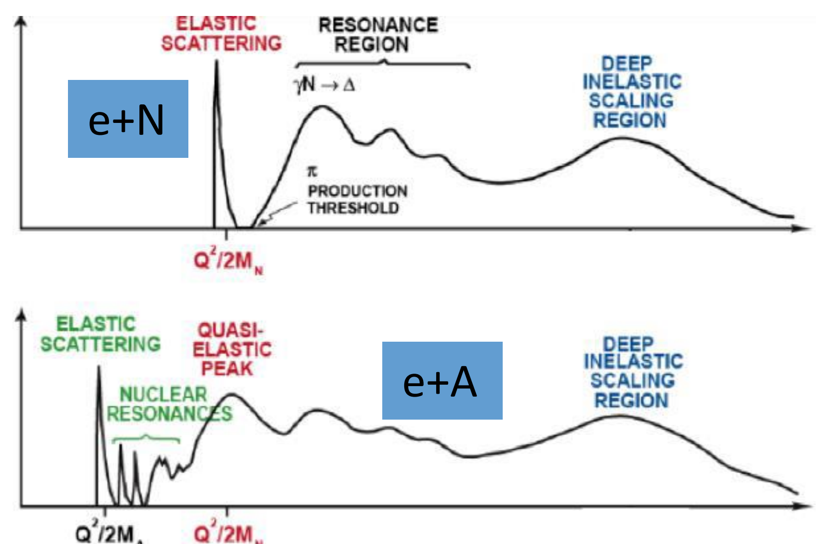
Two-body currents are included in the state-of-the –art calculations!

Electron-Nucleus Scattering

Varying the momentum q transferred to the nucleus, we can focus on particular dynamical regimes. At low q, the collective behaviour of nucleons is studied.

- **Elastic scattering**: photon interacts with entire nucleus, which recoils after the interaction.
- **Inelastic scattering**: photon interaction results in the break-up of the nucleus.
- **Quasi-elastic scattering** (high q): photon interacts with one proton or neutron in a nucleus of A nucleons. Nucleus breaks up in a nucleon and an A-1 nucleus.

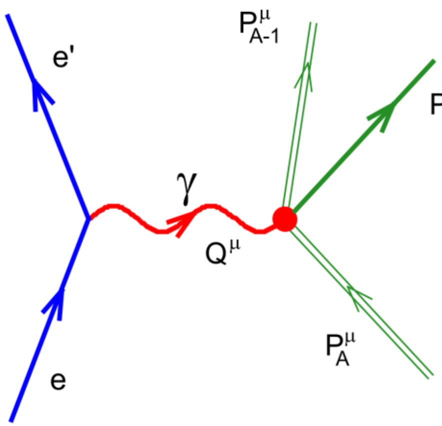


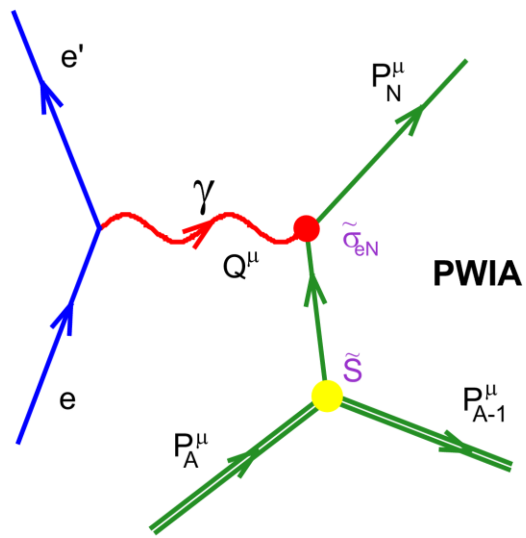


Quasielastic Scattering:

Impulse Approximation vs FSI

Scattering off a nucleus ⇒ incoherent sum of single-nucleon scattering processes



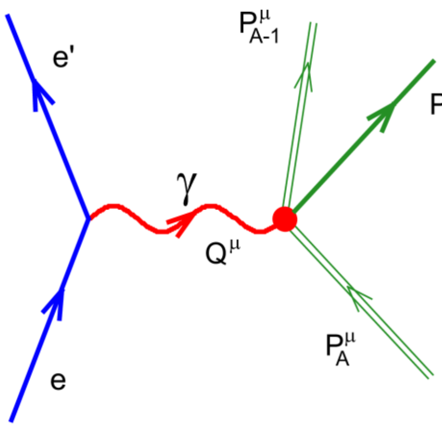


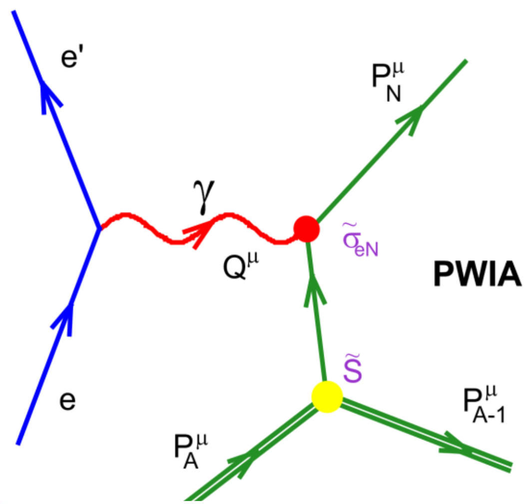
approx. true for large q combined with the quasi elastic regime $\omega = {}^{q^2}/_{2m}$

otherwise more ingredients to be included...

Quasielastic Scattering:
Impulse Approximation vs FSI

Scattering off a nucleus ⇒ incoherent sum of single-nucleon scattering processes





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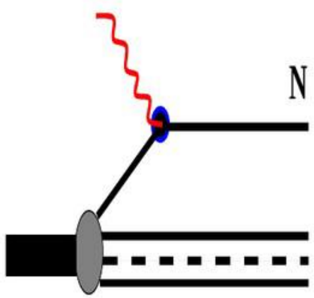
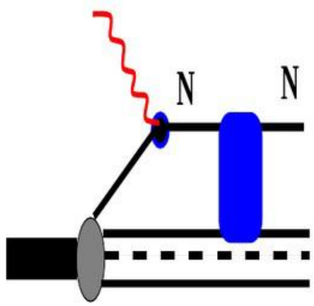
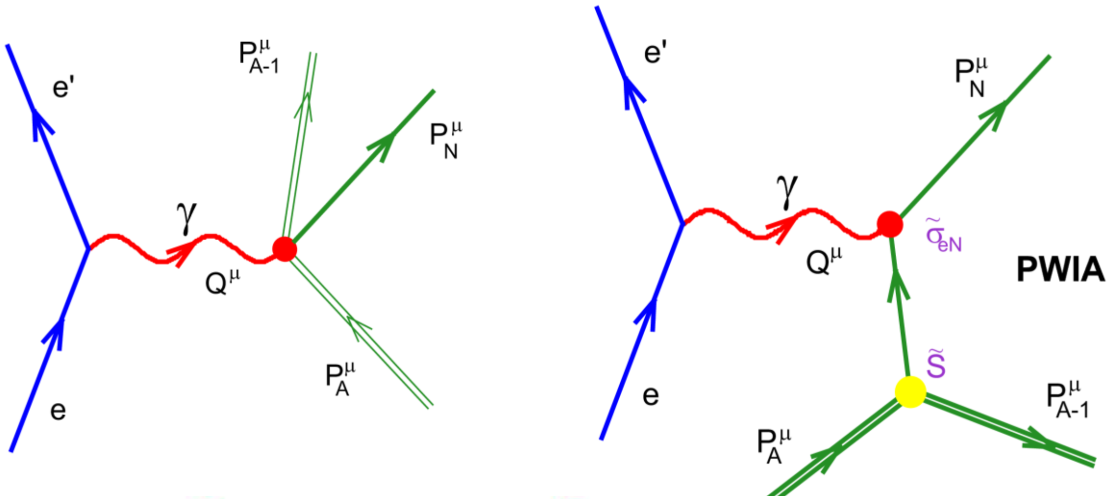




FSI

Quasielastic Scattering:
Impulse Approximation vs FSI

Scattering off a nucleus ⇒ incoherent sum of single-nucleon scattering processes



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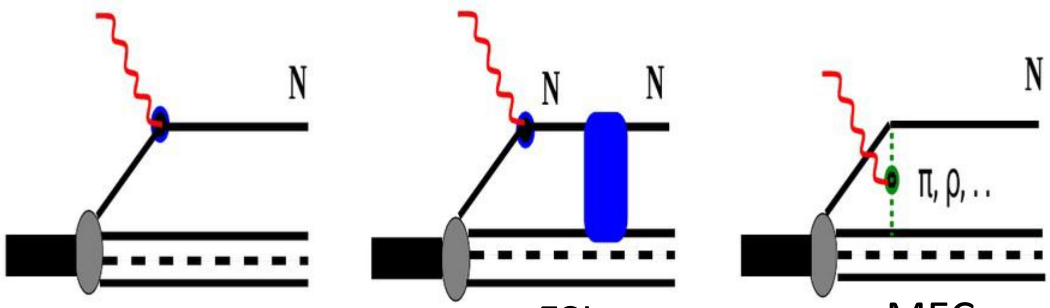

Quasielastic Scattering:
Impulse Approximation vs FSI

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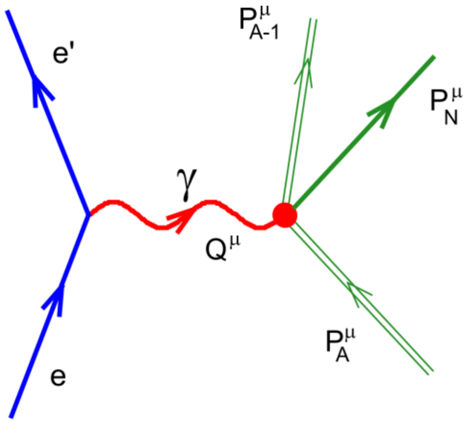

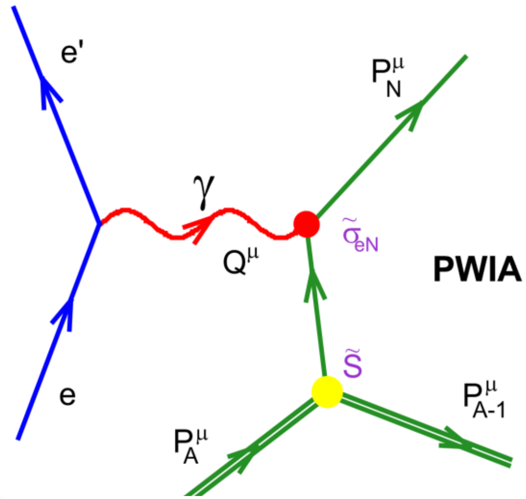

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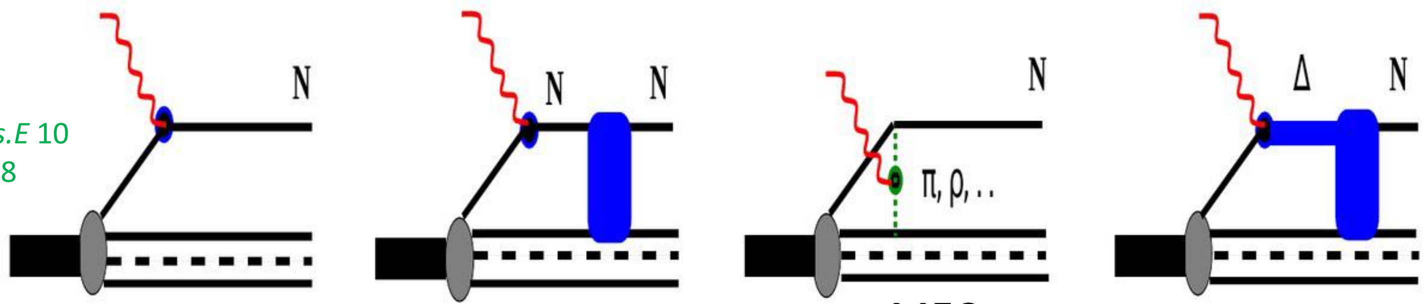
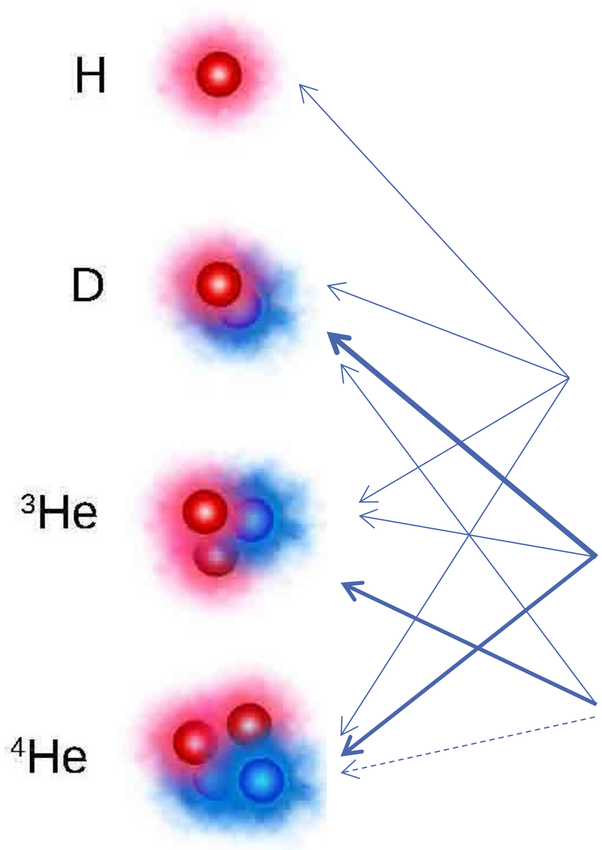
M.M.Sargsian
Int.J.Mod.Phys.E 10 (2001) 405-458



FSI MEC non-nucleonic d.f.

Electron scattering in Few-Nucleon Systems at low energy



elastic scattering Form Factors

inclusive
Response Func.

inelastic scattering / break-up

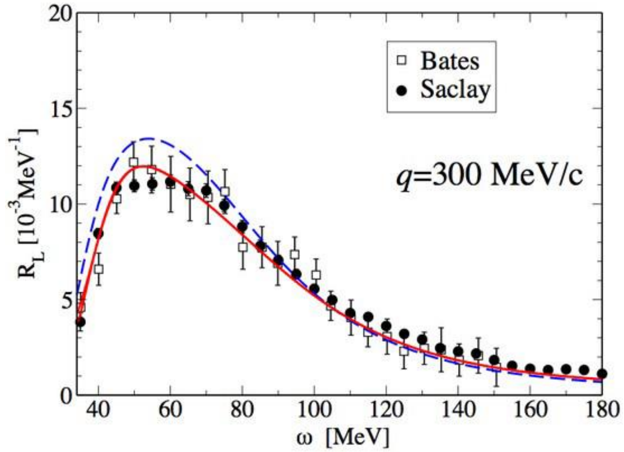
(semi)exclusive
few-fold cross section distributions

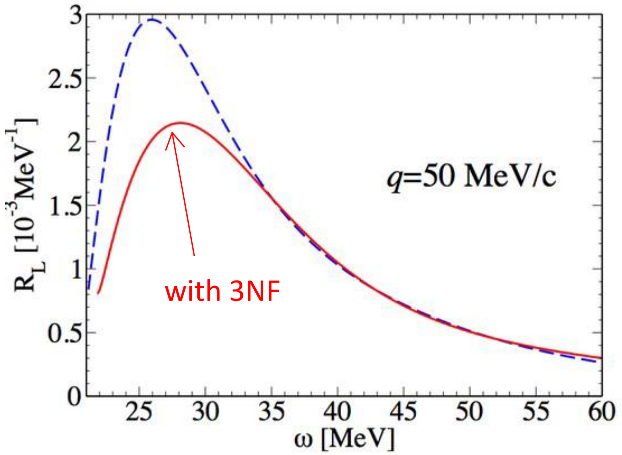
Can any observables measured with EM probes tell us something about nuclear interactions, in particular 3NF? and/or about MEC's?

e+^{4}He, inelastic, inclusive

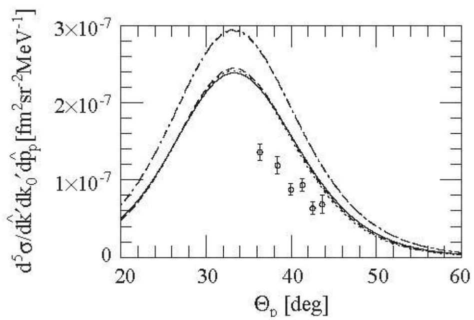
S.Bacca et al., Phys. Rev. Lett. 102 (2009) 162501

- ^{4}He has relatively large average density and binding energy ⇒ ”similarity” to heavier nuclei.
- From naive counting of pairs and triples: 3NF should play a more important role than for ^{3}He
- *Ab-initio* calculations of inclusive process (⇒ response function R_L) are available:
  - full 4-body continuum considered;
  - NN realistic potential (AV18);
  - 3NF included (UIX);
  - rigorous inclusion of FSI.
- Importance of FSI was shown.
- **Strong sensitivity to 3NF** at low momentum transfer!
- **Electromagnetic observable is complementary to purely hadronic observables in studies of 3NF**

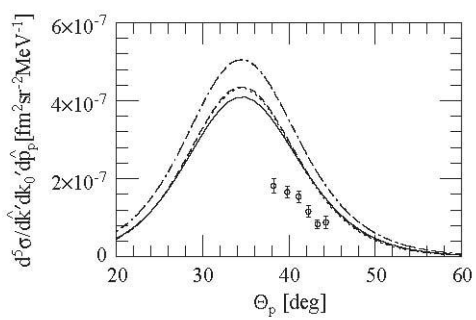




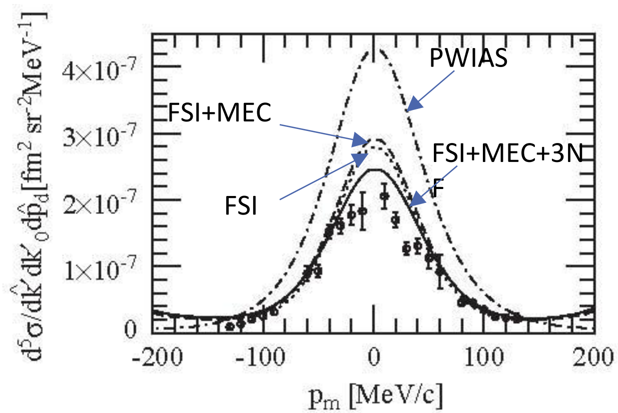
Ab-initio calculations for exclusive observables
Cross section for $^{3}He(e,e'p)d$ at 370 MeV



data: Keizer, PhD Thesis
calc: J.Golak et al, Phys. Rep. 415 (2005) 89



data: C.M.Spaltro et al., Nucl. Phys. A 706 (2002) 403
calc: J.Golak et al, Phys. Rep. 415 (2005) 89



- sensitivity to FSI and 3NF
- small MEC effects
- systematic overestimation of the data

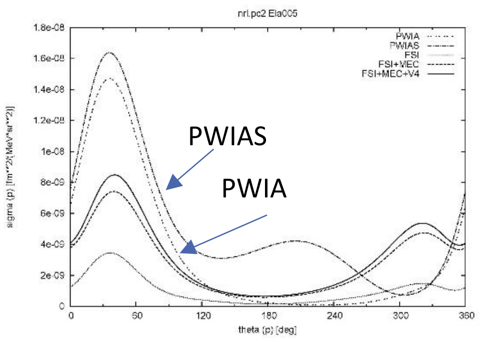
other data near proton knock-out measured at MAMI: 540, 675, 855 MeV; R. E. J. Florizone et al., Phys. Rev. Lett. 83 (1999) 2308

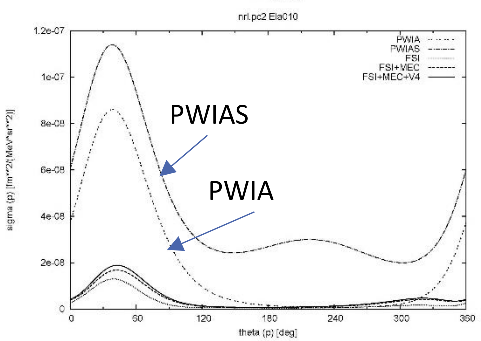
Cross section for exclusive ^{3}He 2-body breakup at 105 MeV

PWIA and **PWIAS** (Impulse Approximation) are insufficient to describe any of the studied configurations, FSI very important.

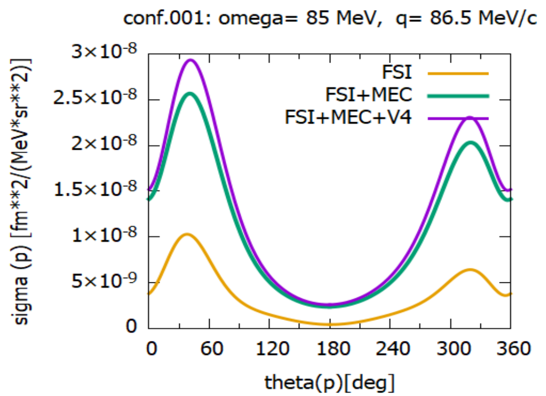
- at **large ω** or **low q**, **MEC** effects are very large;
- **3NF** effects are also significant, increasing c.s.

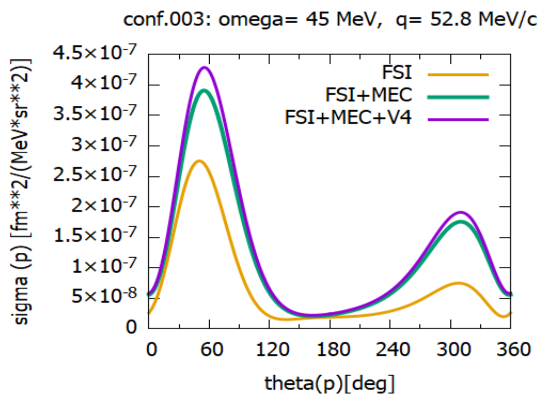
- in region of **large q and low ω**, **MEC** effects are generally small
- for the lowest studied ω, **3NF** is decreasing c.s. by about 20%

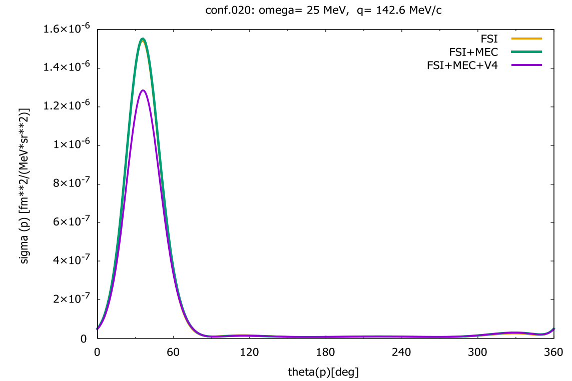


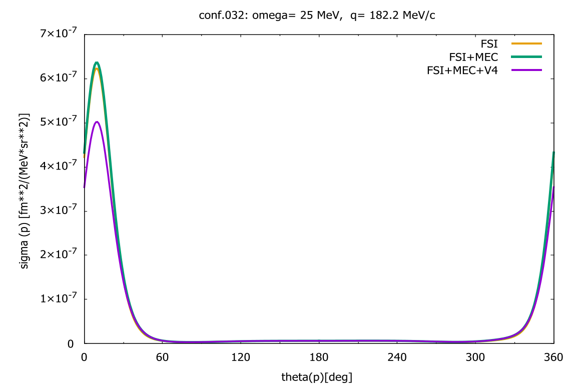


calculations: J.Golak

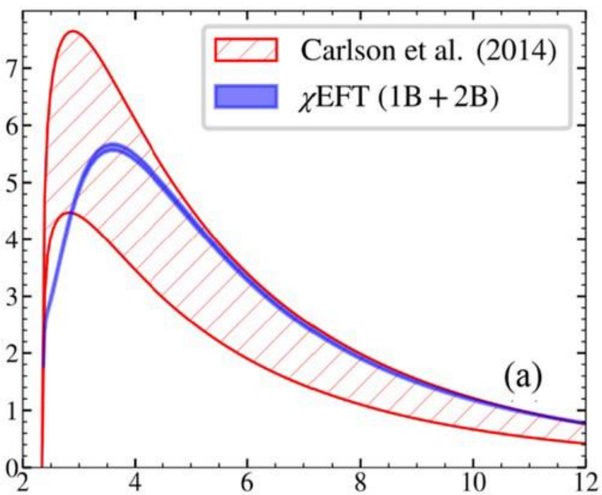


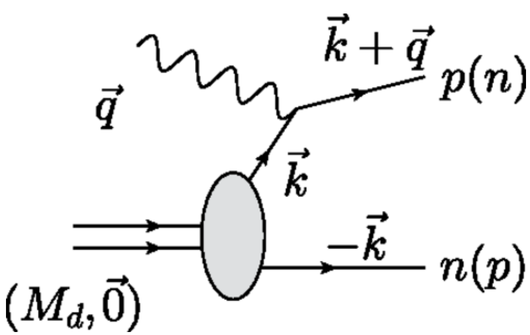






Deuteron Electro-disintegration





- Motivated by proton radius puzzle:
  - *e data vs muonic atom Lamb shift*
- Determination of deuteron radius from muonic atom Lamb shift:
  - two photon exchange (TPE) correction has to be determined;
  - main source of the TPE uncertainty: nuclear structure corrections;
  - to solve this problem, low momentum transfer deuteron electro-disintegration data needed for fit (in the data-driven approach).

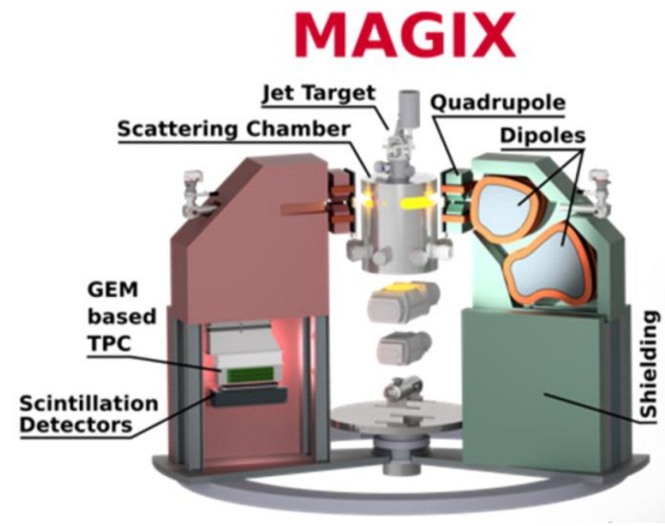
C.Carlson, M.Gorchtein, M. Vanderhaeghen,
PRC A **89** (2014) 022504

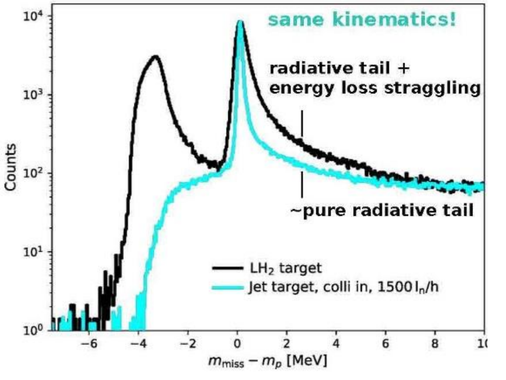
Experimental aspects

Mainz Gas Injection Target Experiment

Precise determination of the outgoing electron momentum is crucial, while difficult at low energies.

- **Spectrometers**:
  - high momentum resolution ($^{\Delta p}/_{p} < 10^{-4}$) ,
  - large acceptance ($^{\delta p}/_{p_{centr}} \approx \pm 15\%$)
- **Jet Target** (10^{18} cm^{-2}):
  - no target cell;
  - pointlike reaction region – no integration over target volume needed;
  - no electron rescattering in the target.
  - Low target density (as compared to „traditional" ones) compensated with high current of 105 MeV ERL MESA beam.
  - Challenge: very effective ^{3}He recovery.





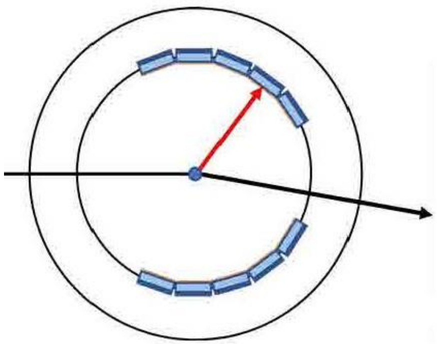
B.S. Schlimme *et al.*, NIMA **1013** (2021) 165668
Y. Wang *et al.*, PRC **106** (2022) 044610

Experimental aspects

Mainz Gas Injection Target Experiment

- **Recoil** (ion) **detectors** for exclusive measurements:
  - Silicon strip (transmission) detector
  - Plastic scintillator with SiPM readout (as stopping Detector)

  To be optimized/solved:
  - optimal Si thickness for experiments with p vs d identification ($\Delta E - E$) and α recoils;
  - Si detector „lifetime” at high radiation environment;
  - SiPM read-out of scintillators: effective light collection (low threshold for recoils) and position-sensitive (background suppression).



Conclusions

- Progress in theory allows for combining important aspects of dynamics of inelastic electron scattering on few-nucleon systems. Therefore MEC and 3NF can be studied.
- ChEFT is constantly developed, providing consistent picture for NN+3NF interactions and currents. Low energies require not-so-many orders of expansion, thus they are the place to start comparisons.
- LEC are calibrated against pion-nucleon scattering, but also NN and, recently, few-nucleon data. Thus **new observables**, outside purely hadronic systems, might become **crucial for testing the ChEFT** predictions.
- **Observables in electron inelastic scattering at low energy appear to be sensitive to many important aspects of dynamics**, as predicted by recent theoretical calculations. This is the case both for inclusive and exclusive measurements.
- Cross section for ^{3}He(e,e'd)p reaction at 105 MeV reveals sensitivity to MEC and 3NF effects, strongly variating with the kinematic configuration.
- **MAGIX@MESA offers unique conditions** (precision of momentum determination, low background, point-like reaction region, large acceptance) for the next generation of **electron scattering experiments in few-nucleon systems at low energies**.