Nucleon knockout reactions on ^{3,4}He induced by virtual photons

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- **introduction**
- **exclusive ^{3,4}He(e,e'p)**
- **semi-exclusive ^{4}He(e,e'p)pnn**
- **exclusive ^{3}He(e,e'pp) and ^{3}He(e,e'pn)**
- **conclusions**

Introduction

To describe properties of few-body systems in terms of baryon-meson d.o.f. a microscopic model is needed.

Hamiltonian: $H = -\frac{\hbar^2}{2m}\sum_i \nabla_i^2 + \sum_{i<j} v_{ij} \; (+\sum_{i<j<k} V_{ijk})$

Need a realistic NN-interaction:

$$v_{ij} = \sum_{p=1,N} v^p(r_{ij})\, O_{ij}^p$$

$$O_{ij}^p = 1, \sigma_i.\sigma_j, \tau_i.\tau_j, (\sigma_i.\sigma_j)(\tau_i.\tau_j), S_{ij}, S_{ij}(\tau_i.\tau_j), (\mathbf{L.S})_{ij}, \ldots\ldots$$

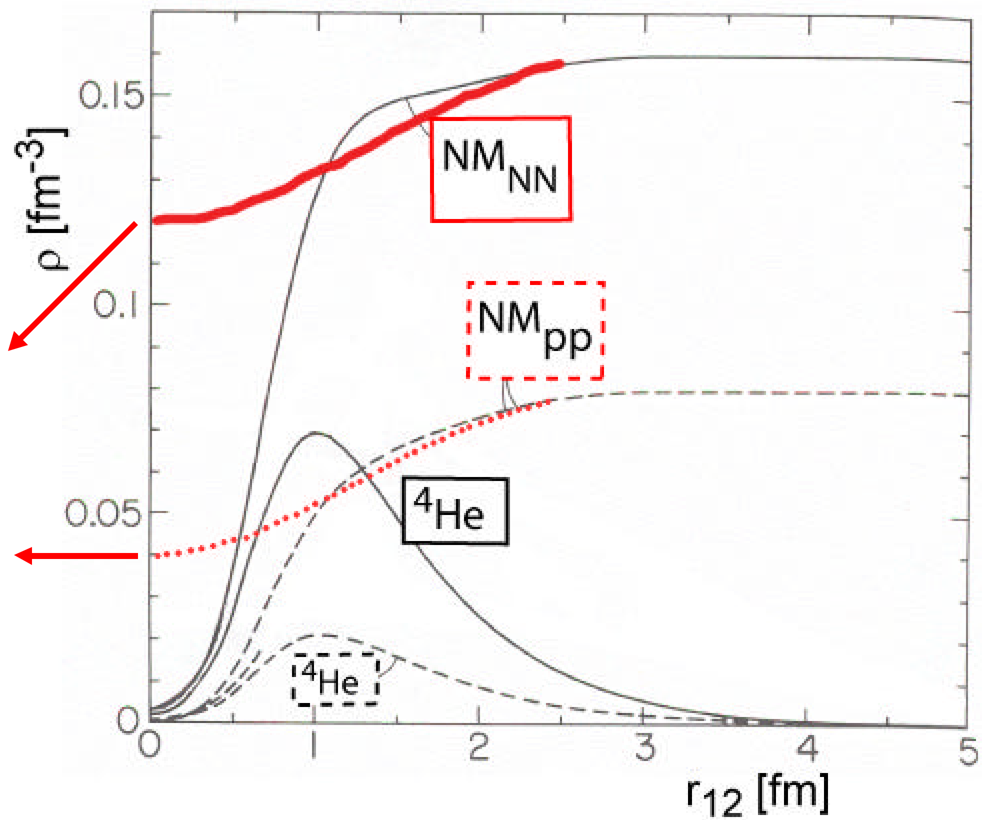
Realistic nuclear forces induce spatial, tensor and spin-(iso)spin correlations, some of which are only known phenomenologically.

two-nucleon density $\rho(\mathbf{r}_1,\mathbf{r}_2)$

——— ρ_{NN}

- - - - - - ρ_{pp}

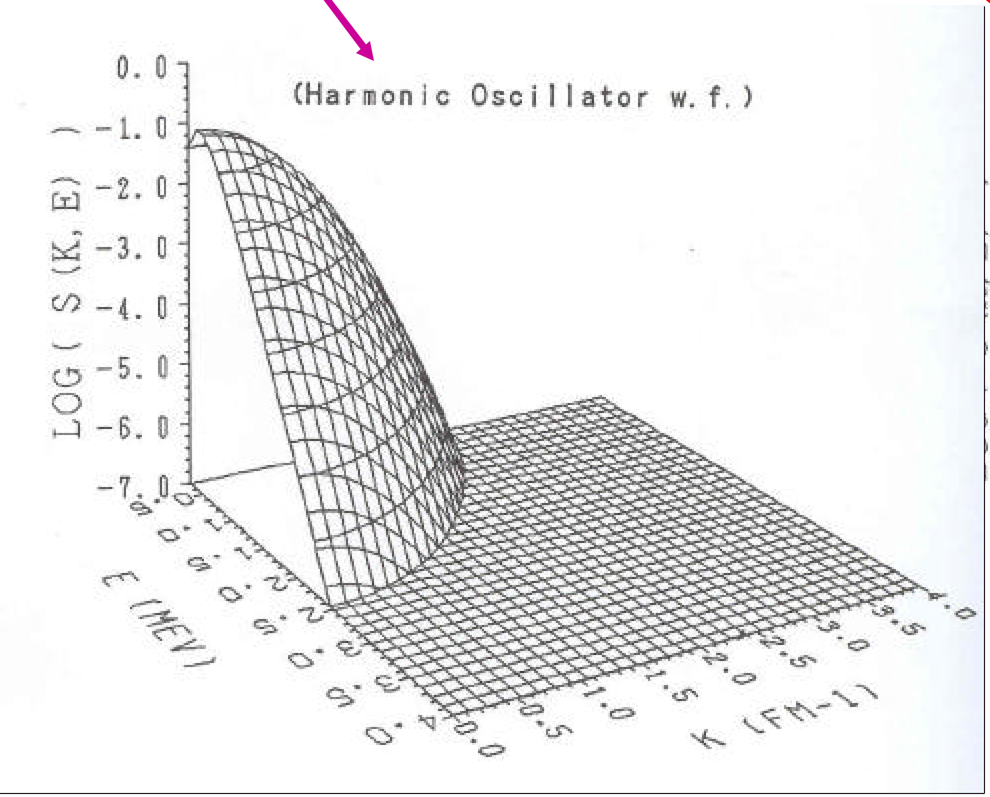
Slater determinant wave functions

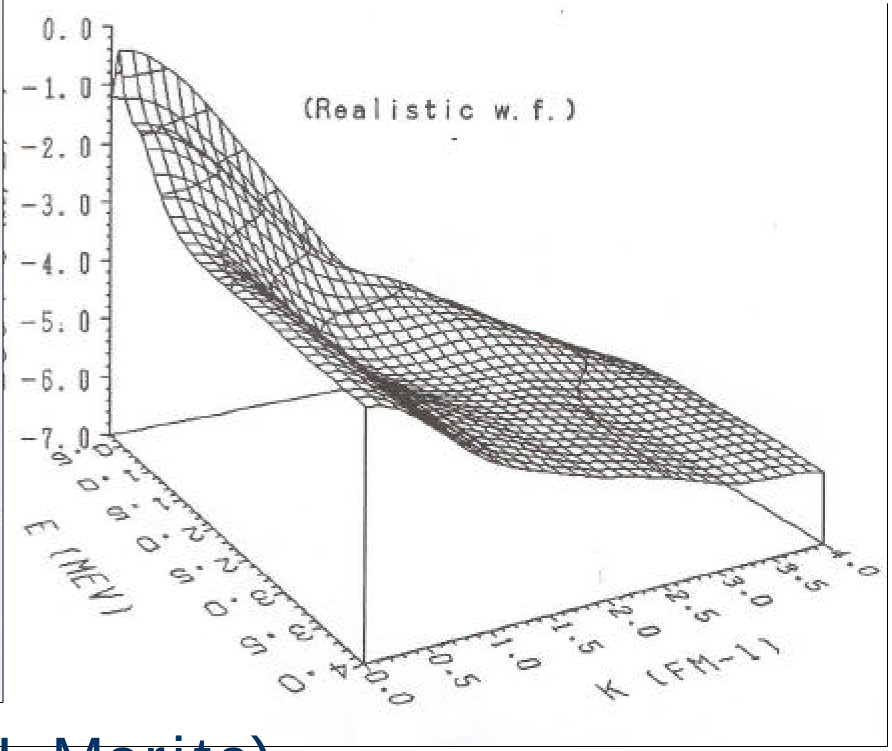


Solve Schrödinger equation for 3N-system with Faddeev, VMC or GFMC.

Spectral function S(k,E)

non-correlated and correlated proton spectral function ^{4}He





ATMS method (H. Morita)

Investigate high-momentum components with electro-induced single-nucleon knockout reaction

- clean probe, i.e. (**q**,ω) of the virtual photon
- well-defined final state
- light target nucleus:
  * initial and final state can be calculated precisely
  * disturbing processes can be calculated reliably

exclusive ^{3,4}He(e,e'p)^{2,3}H reaction

Investigate strength at high missing momentum and high removal energies: **semi-exclusive ^{4}He(e,e'p)**

Electron-induced two-nucleon knockout reactions to study initial and final-state correlations:

^{3}He(e,e'pp) and ^{3}He(e,e'pn)

(e,e'p) reaction

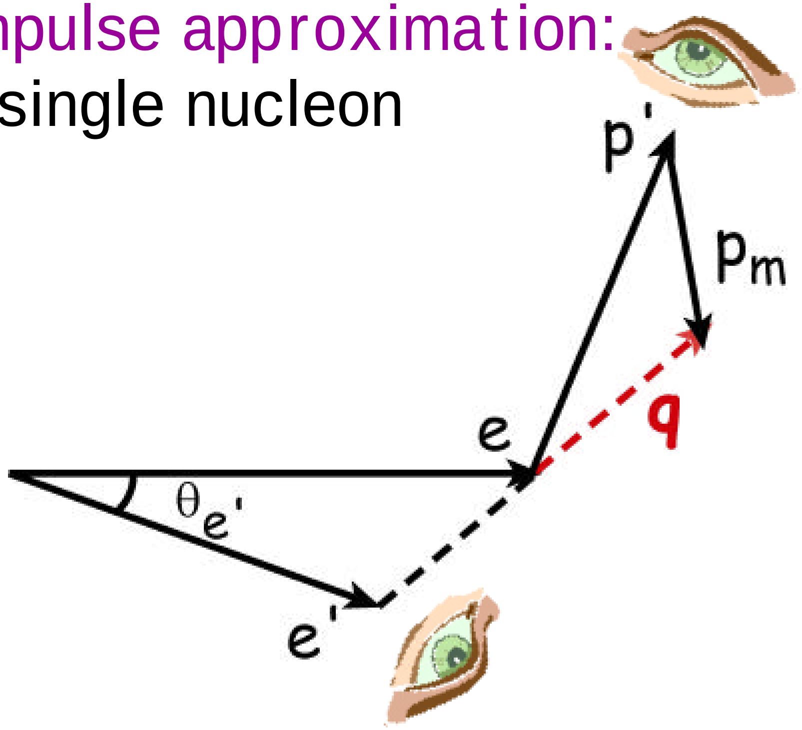
concept of (e,e'p) reaction in impulse approximation:
virtual photon interacts with a single nucleon that subsequently is ejected

? =e-e'

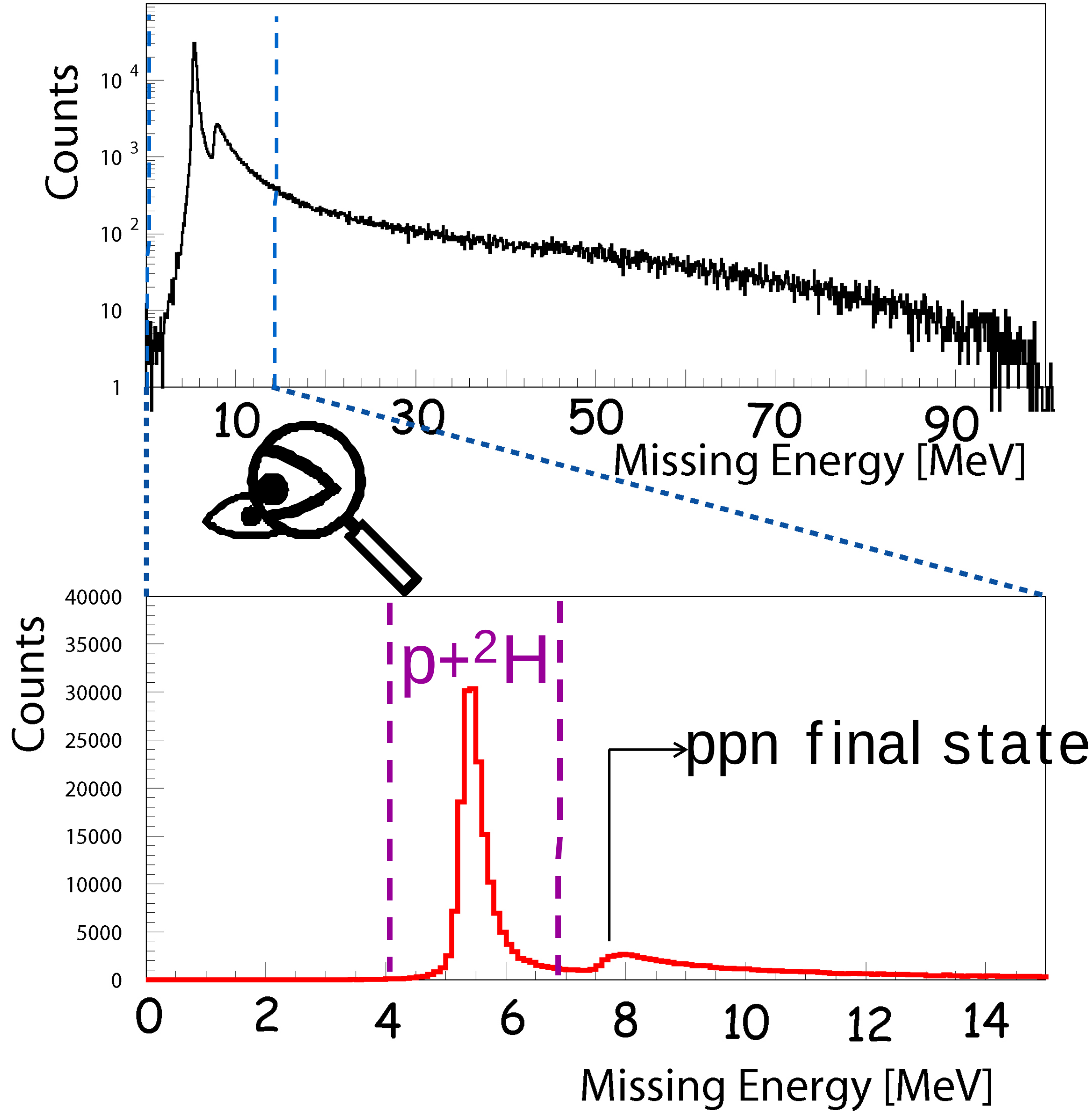
$\vec{q}=\vec{e}-\vec{e}'$

$\vec{p}_m=\vec{q}-\vec{p}'$

$E_m=e-e'-T_p-T_{A-1}$



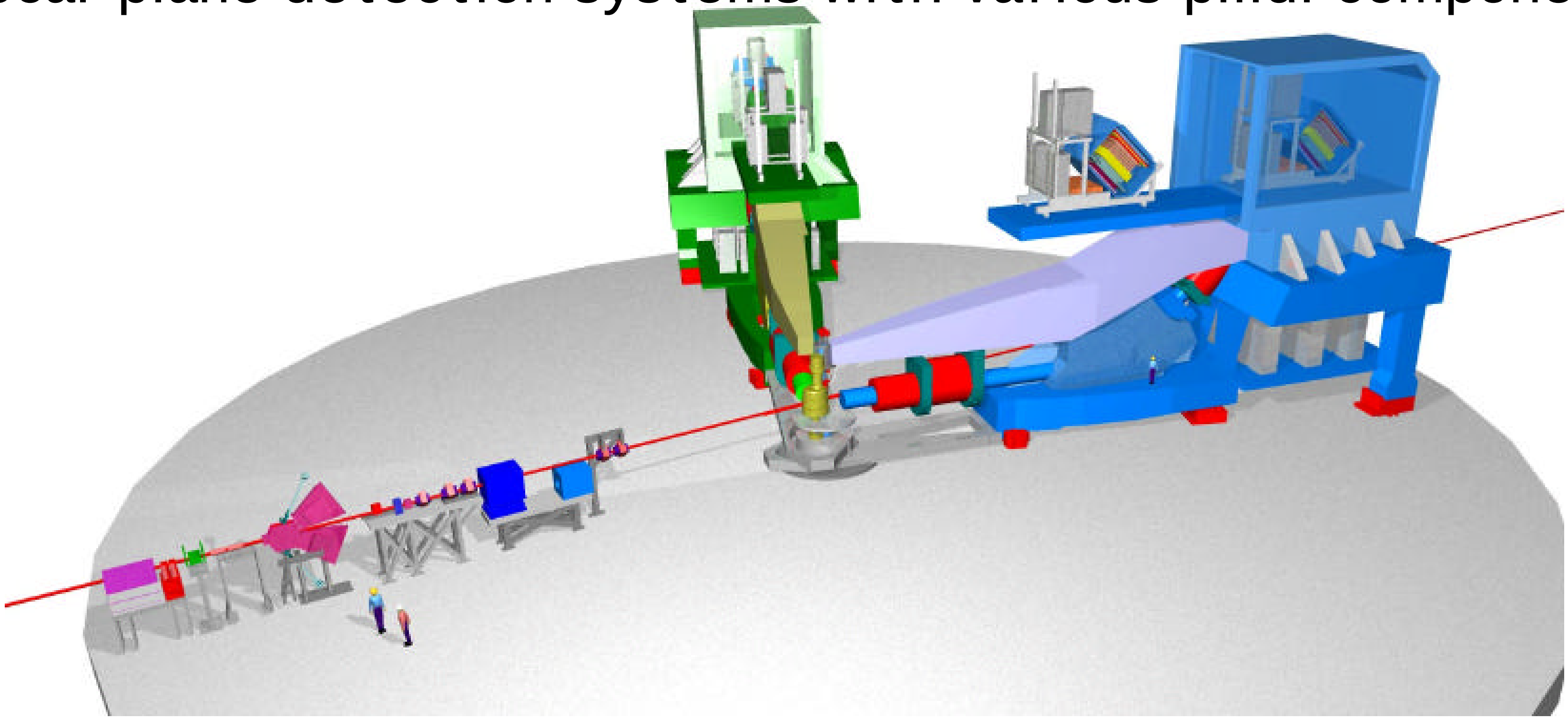
example E_m-spectrum of ^{3}He(e,e'p) reaction



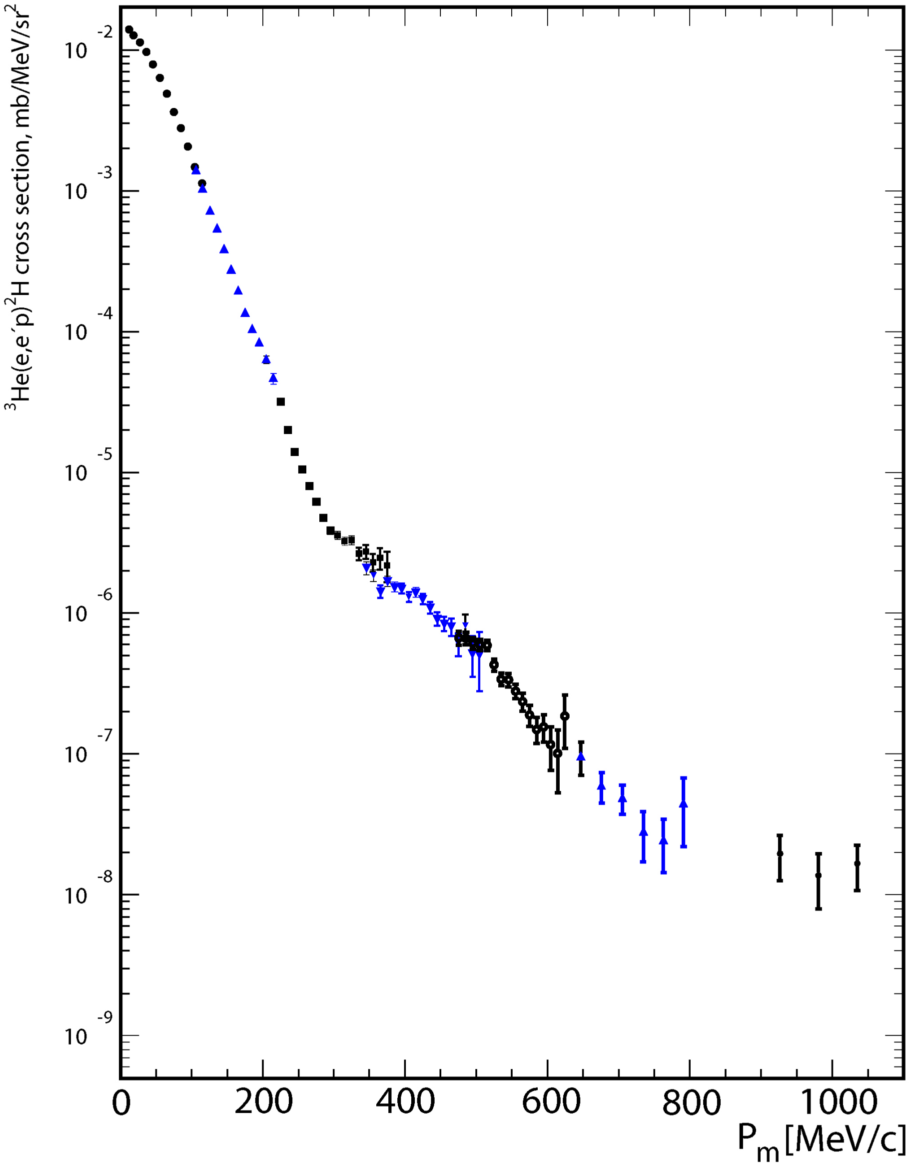
$^3He(e,e'p)^2H$ reaction

Hall-A of Jefferson Lab:

6 GeV 100% duty factor electron beam
high-power cryogenic targets
two high-resolution magnetic spectrometers
focal-plane detection systems with various p.i.d. components



p_m-distribution of $^3He(e,e'p)^2H$



experiment E89-044
(MIT-thesis of
Marat Rvachev (2003))

ω=837 MeV
q=1500 MeV/c
Q^2=1.5 (GeV/c)^2

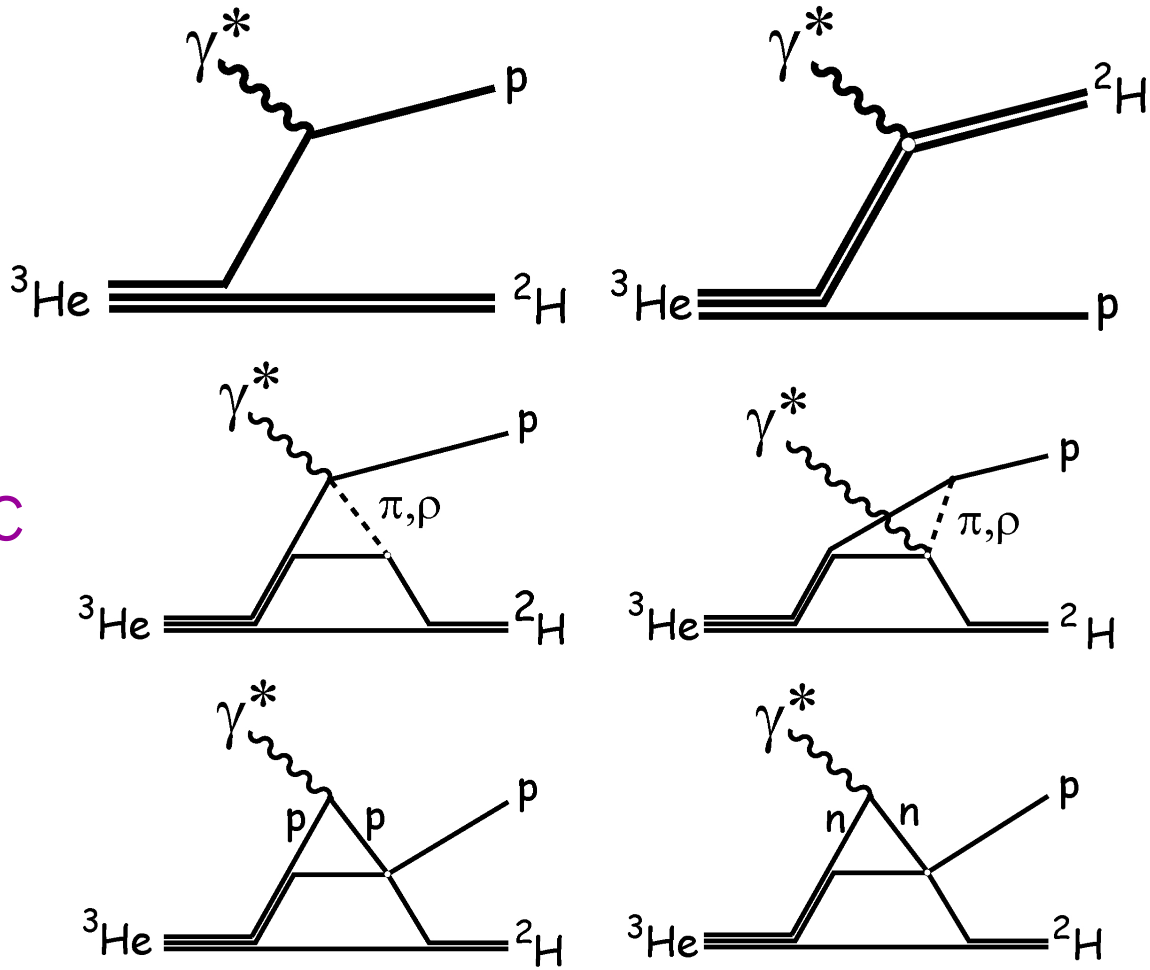
data up to p_m=1000 MeV/c

diagrammatic approach of Laget

PWIA

MEC

FSI

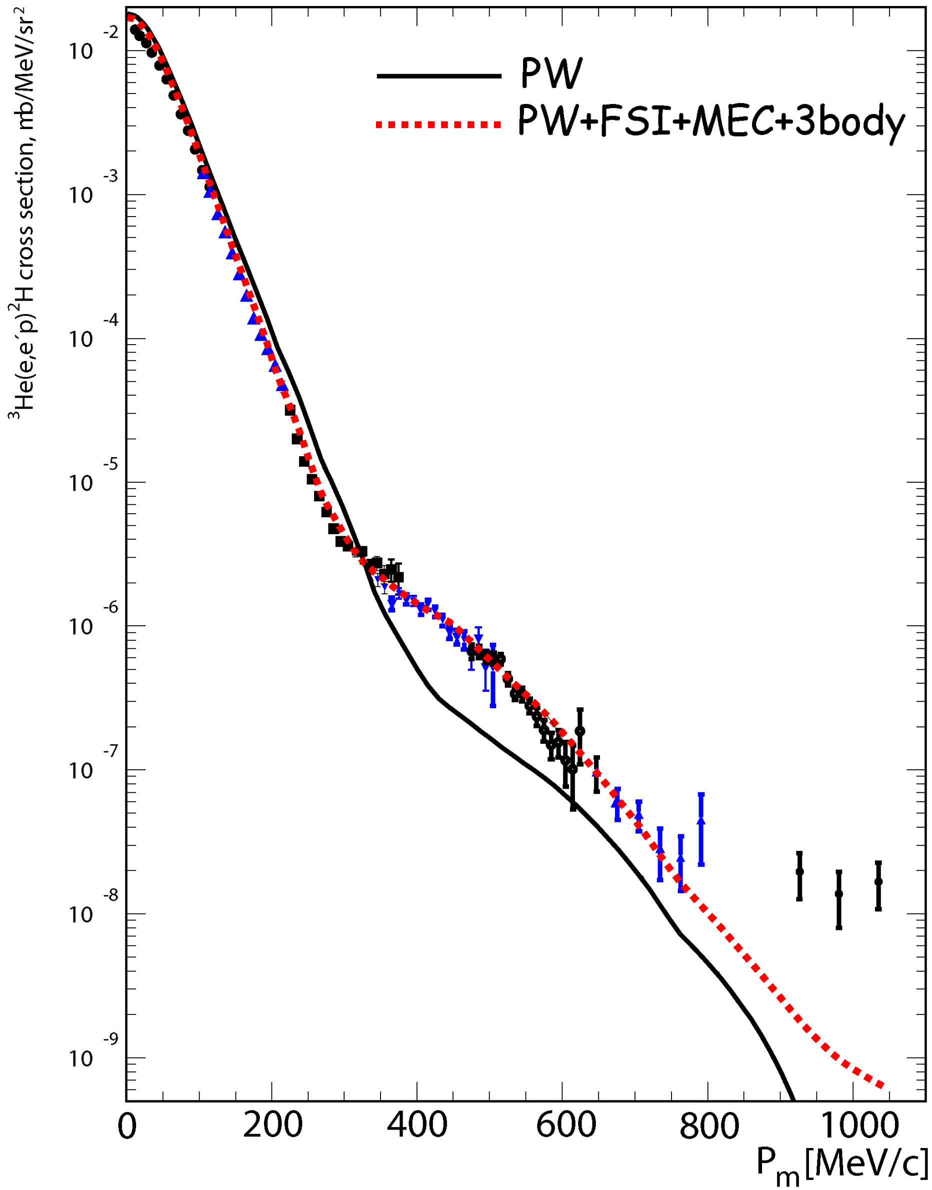


MEC

charge-exchange

+ three-body mechanisms

p_m-distribution of $^3He(e,e'p)^2H$



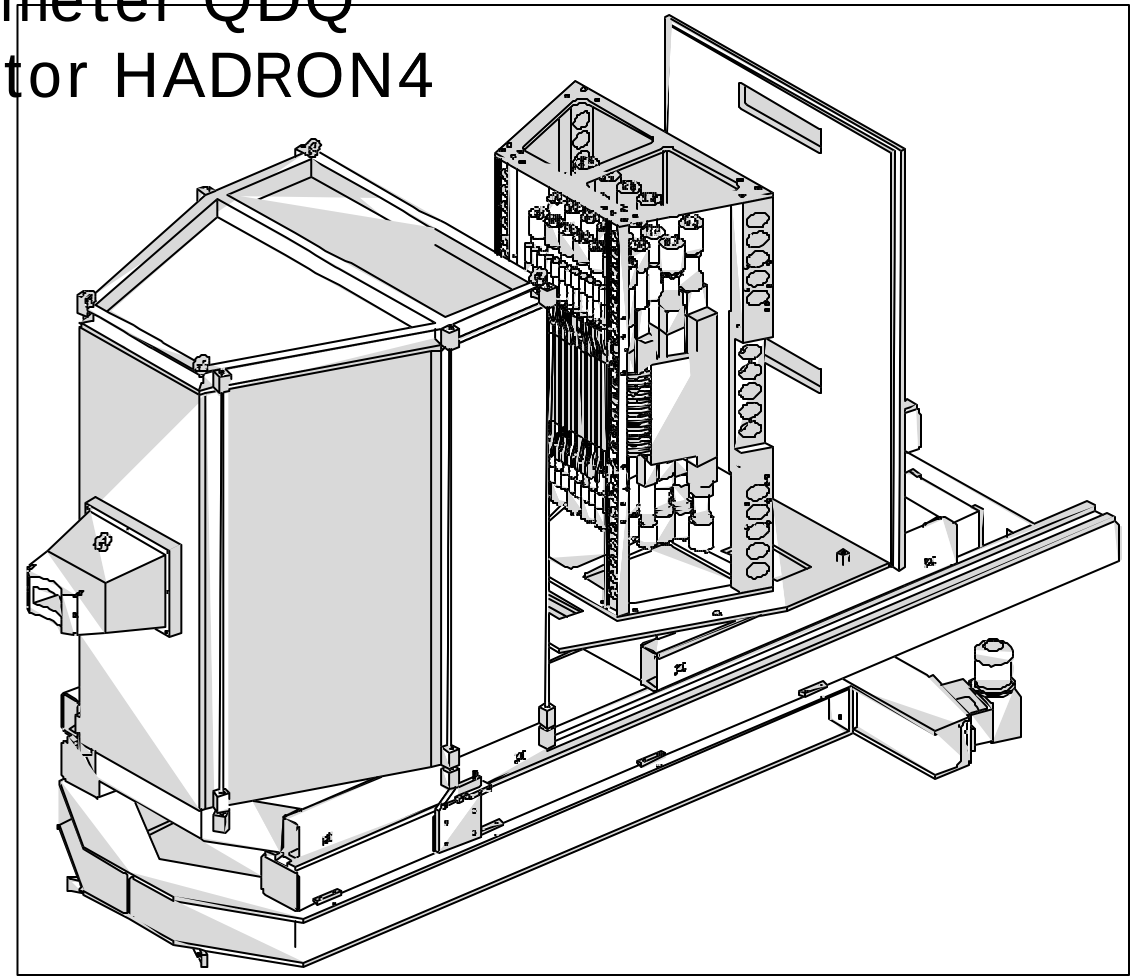
- large contributions from FSI and non-nucleonic currents at p_m > 400 MeV/c
- excess strength at p_m>800

- relativistic effects ??
- breakdown of meson-baryon description ??

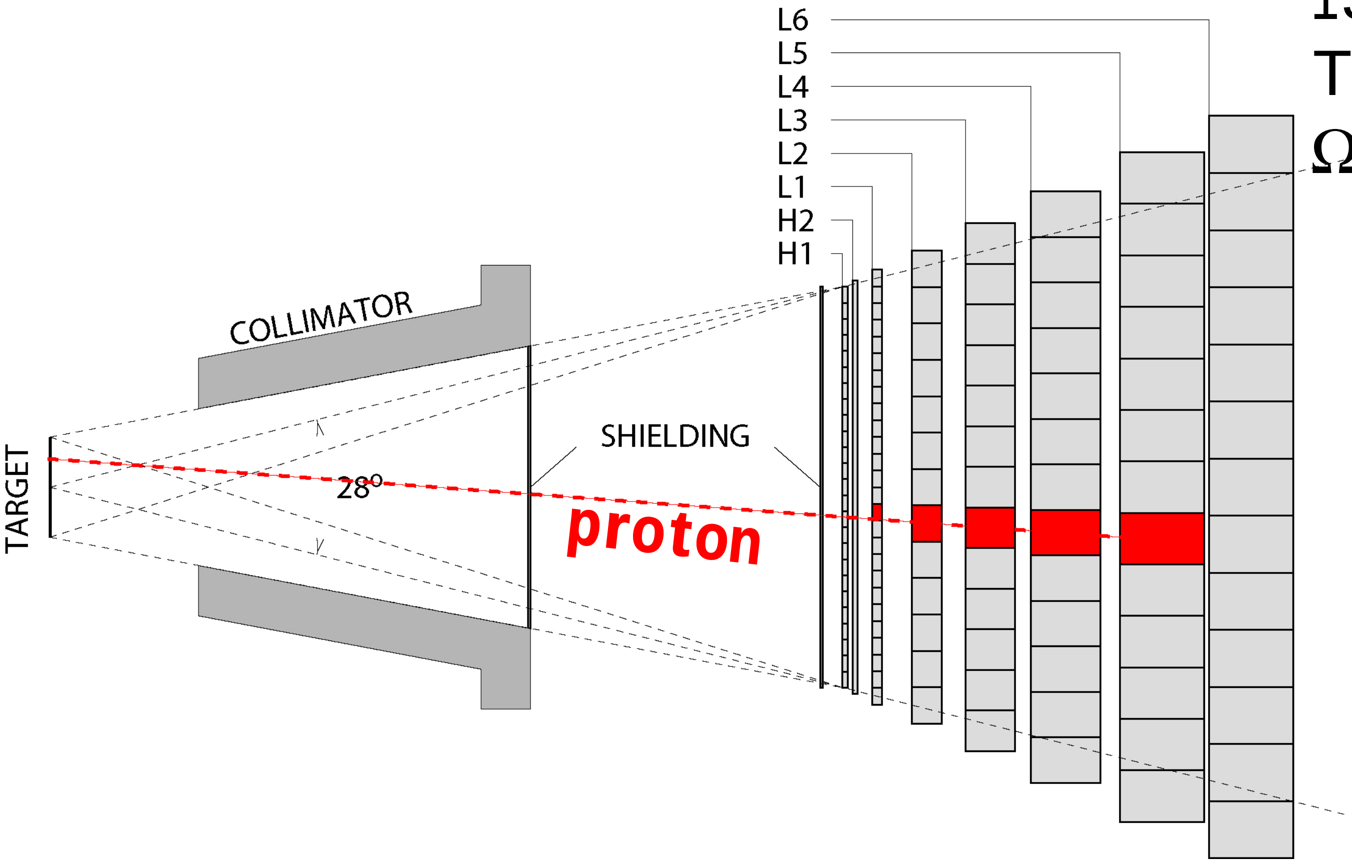
^{4}He(e,e'p) reaction @ NIKHEF

e': magnetic spectrometer QDQ

p': segmented detector HADRON4



HADRON4 for proton detection



94 scintillators
134 PMs
T_p= [67,195] MeV
Ω=550 msr

determine:
T_p and p.i.d.
from generated light,
angles with hodoscope

$^4He(e,e'p)$ experiment @ NIKHEF

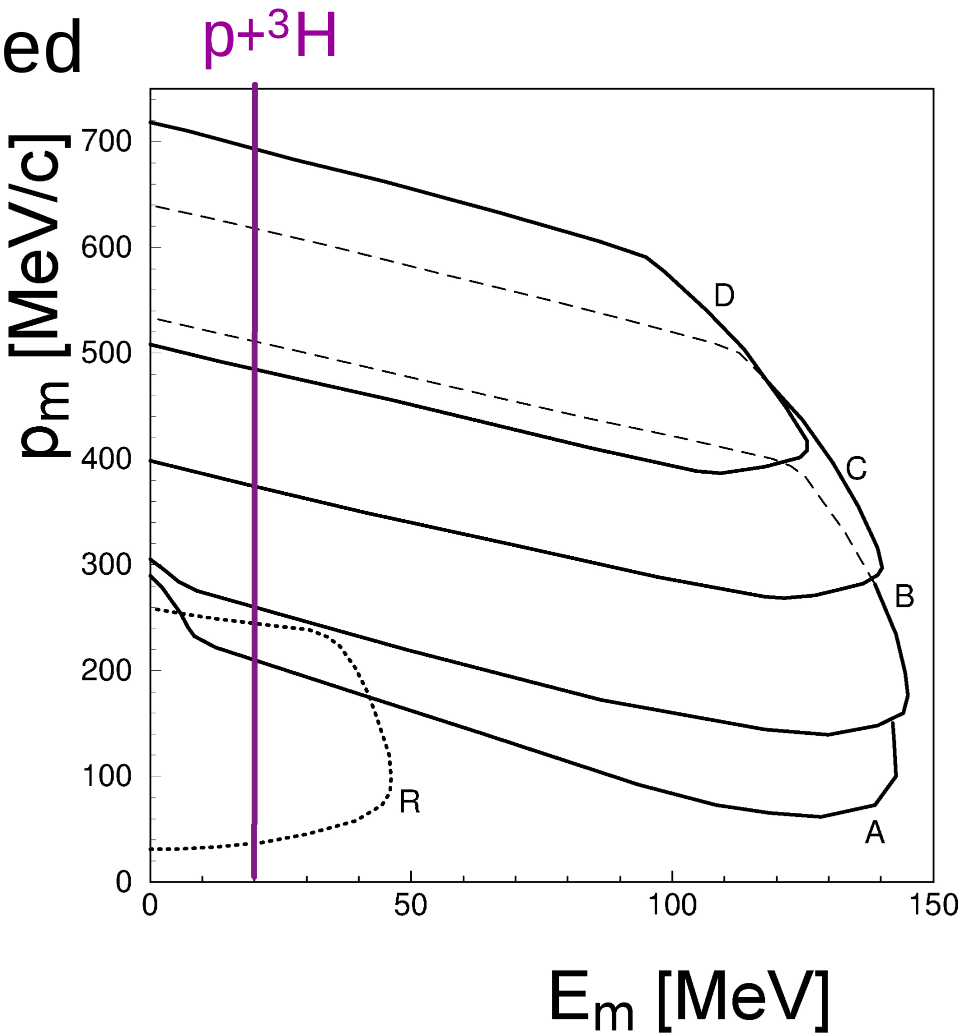
(E_m, p_m) phase space covered

ω=215 MeV

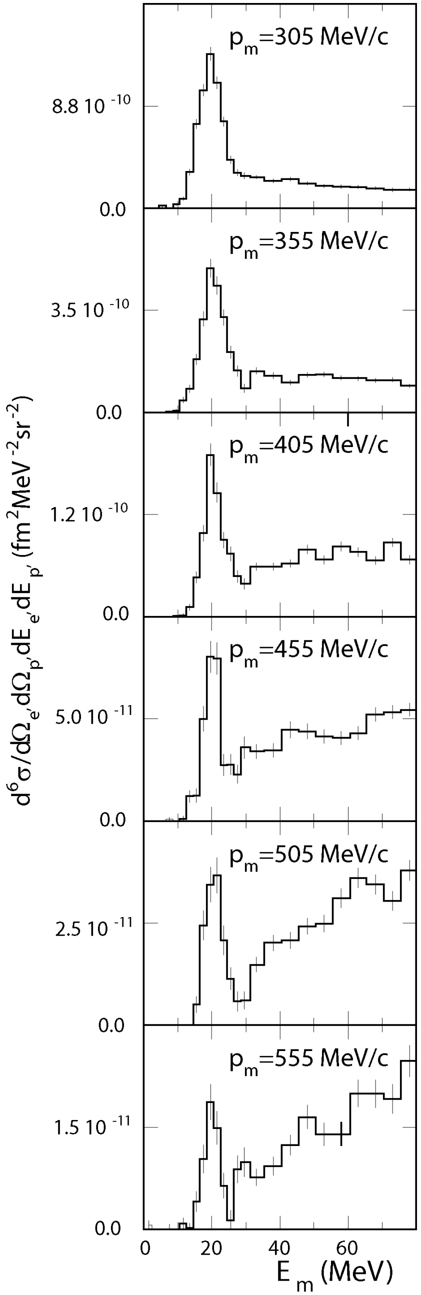
q=400 MeV/c

Q^2=0.11 $(GeV/c)^2$

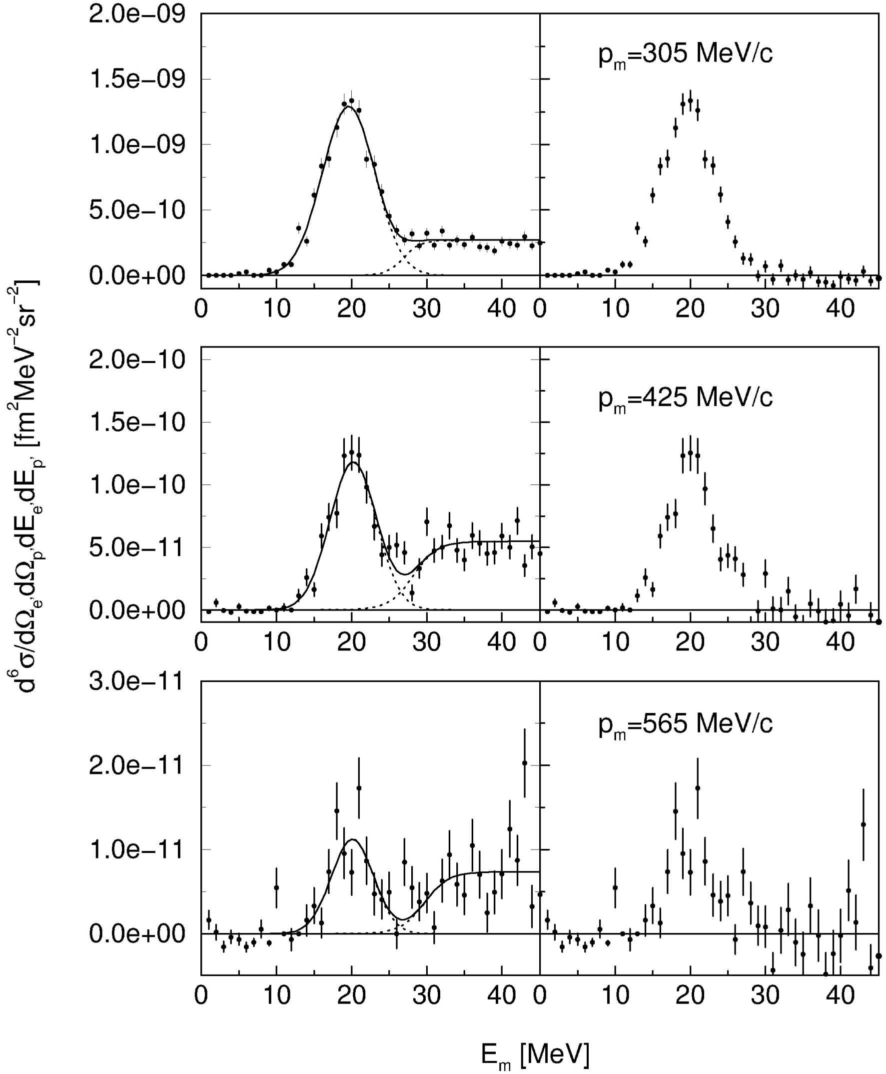
zero predicted in
pT-momentum distribution
around p_m 400-500 MeV/c



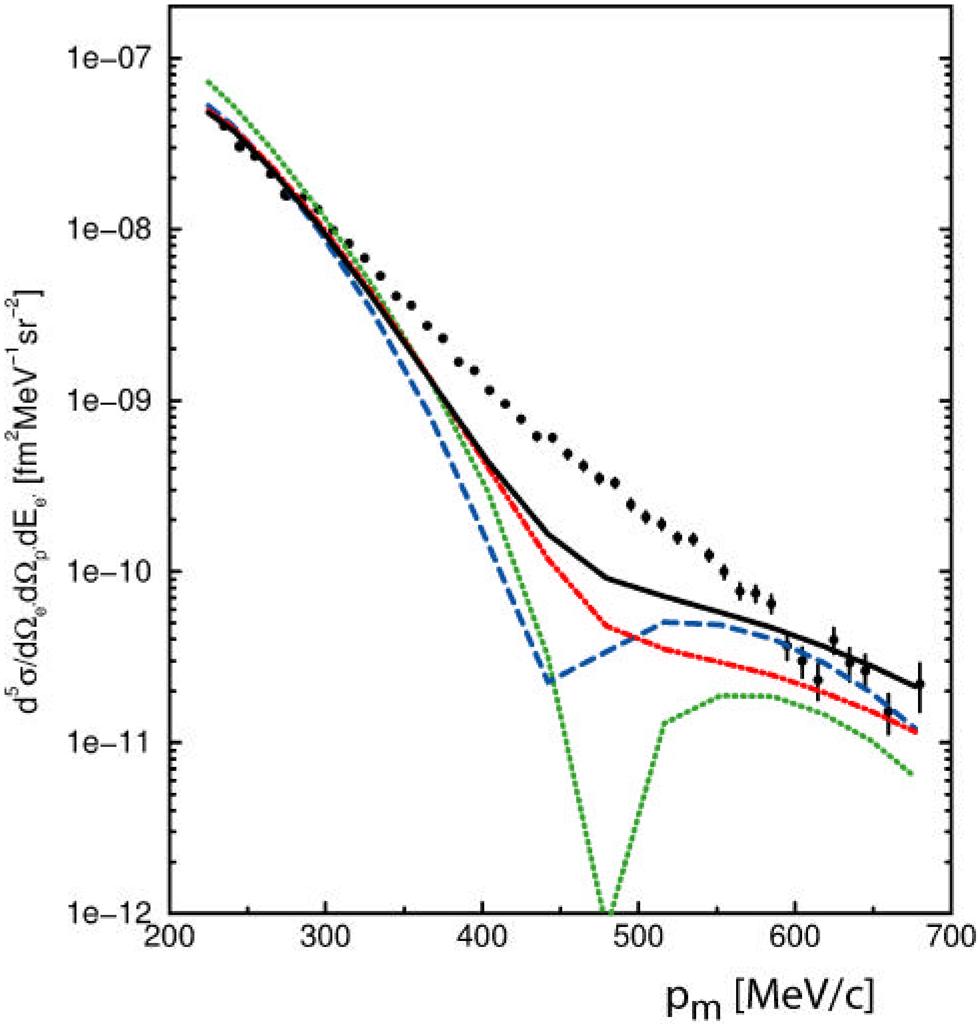
E_m-spectra of $^4He(e,e'p)$



selection of pT-breakup



p_m - dependence of $^4He(e,e'p)^3H$



no zero/minimum observed in these data.

...... PWIA (v14+Urbana-VII)

----- +FSI

-·-·-·-· +FSI+MEC

——— full

More complete dataset of E97-111 of JLab

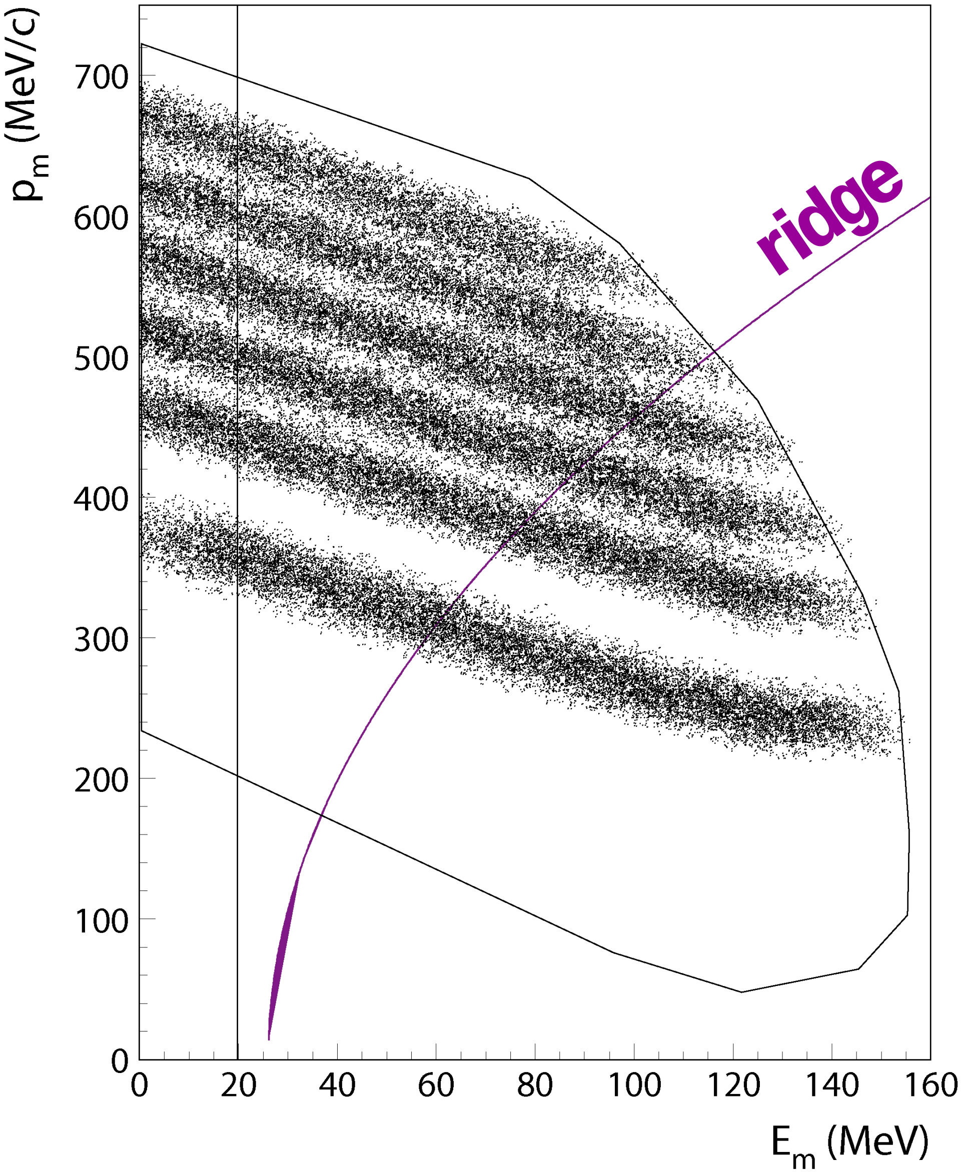
K. van Leeuwe et al. PRL **80** (1998) 2543

semi-exclusive $^{4}He(e,e'p)$

scattering from a
correlated pp/pn pair:

$$E_{m,ridge}(p_m) = E_{thr} + \frac{A-2}{A-1}\frac{p_m^2}{2M}$$

5^o wide slices centered at
γ_{pq}=35^o, 50^o, 60^o, 70^o, 80^o, 89

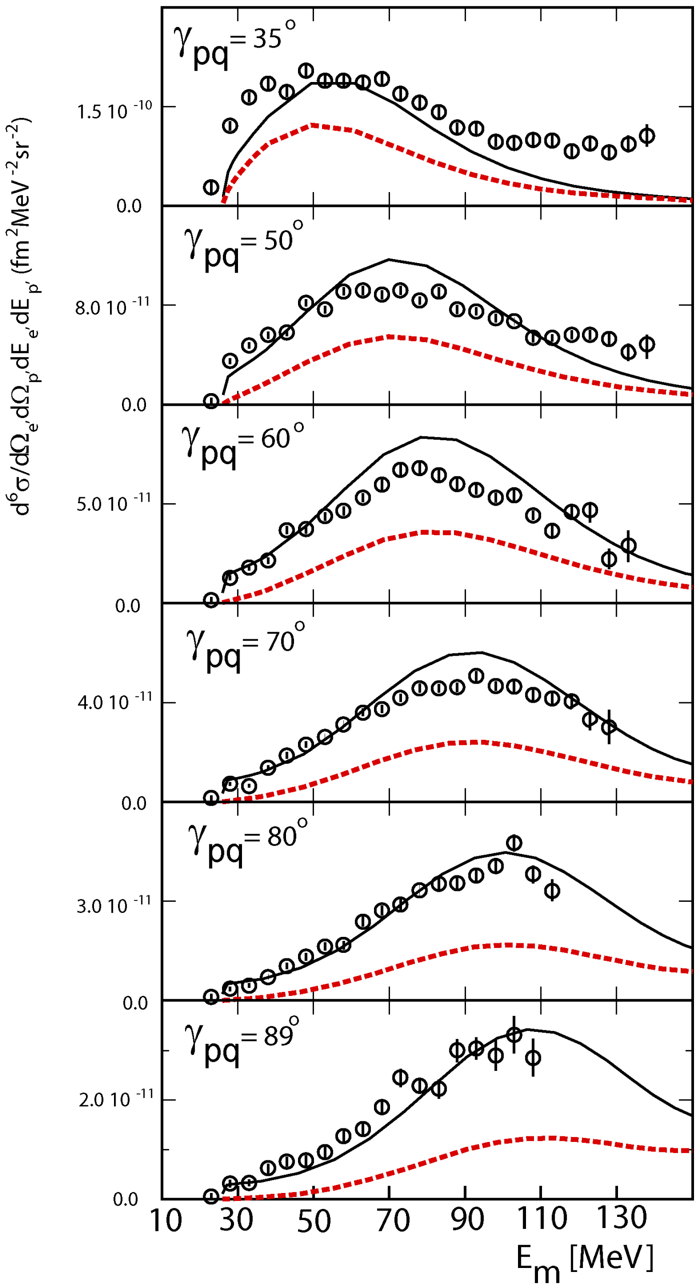


E_m-dependence(γ_{pq})

Laget

---- one-body +FSI

——————— +MEC + IC



K. van Leeuwe et al.
Phys. Lett. B523 (2001) 6

summary of (e,e'p) on $^{3,4}He$

- benchmark datasets for exclusive $^{3,4}He(e,e'p)$ up to very high p_m.
- signatures of scattering from a correlated nucleon-pair in semi-exclusive $^{4}He(e,e'p)$.

- advanced structure calculations of few-body systems.
- calculation of reaction dynamics needs to be improved.
- relativity needs to be included.

$^3He(e,e'pp)$ and $^3He(e,e'pn)$

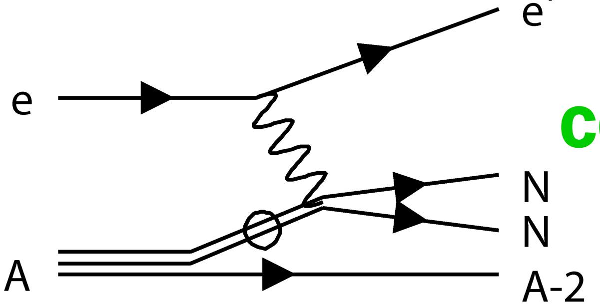
uncorrelated wave function $\Rightarrow$ in PWIA $\sigma(e,e'NN)=0$

If one nucleon of a correlated pair gets hits by the virtual photon, both will presumably be emitted.

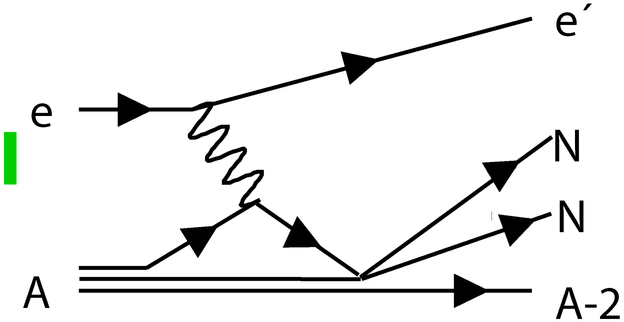
Two kind of processes in two-nucleon knockout:

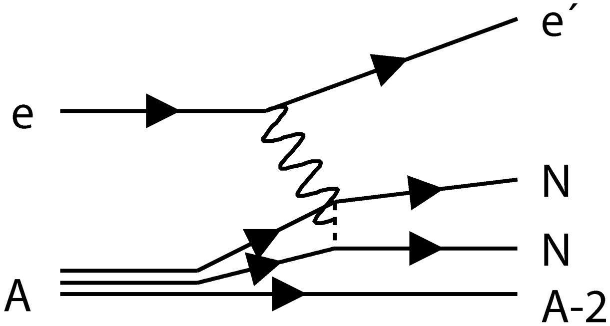
- via one-body current j_1: pp and pn initial-state correlations
- via two-body current j_2: MECs and ICs

Feynman diagrams of two-nucleon knockout



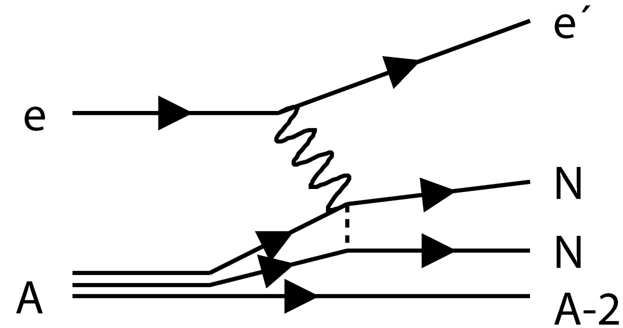
correlations j_1 **FSI**

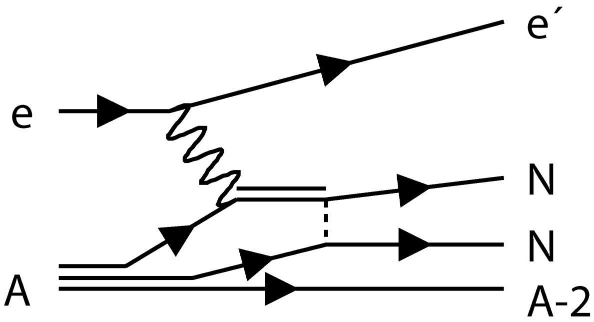




j_2

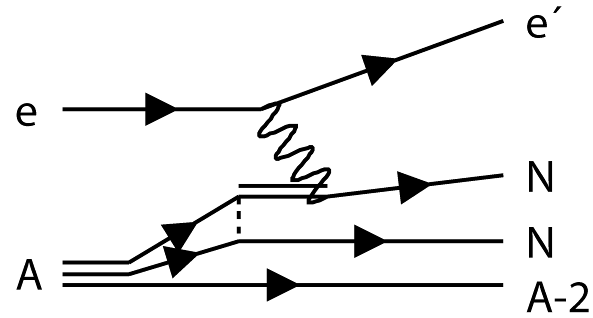
MEC





j_2

IC



Every process has its specific sensitivity to T, q, ω and ε.

Unpolarized (e,e'NN) cross section is a function of 6 nuclear structure functions.

Disentangle the contributions via comparison of pp and pn-knockout under various kinematical conditions.

^{3}He is chosen because continuum Faddeev calculations are available for various realistic NN-potentials.

reconstruct p_m and E_m from measured e', p_1' and p_2'

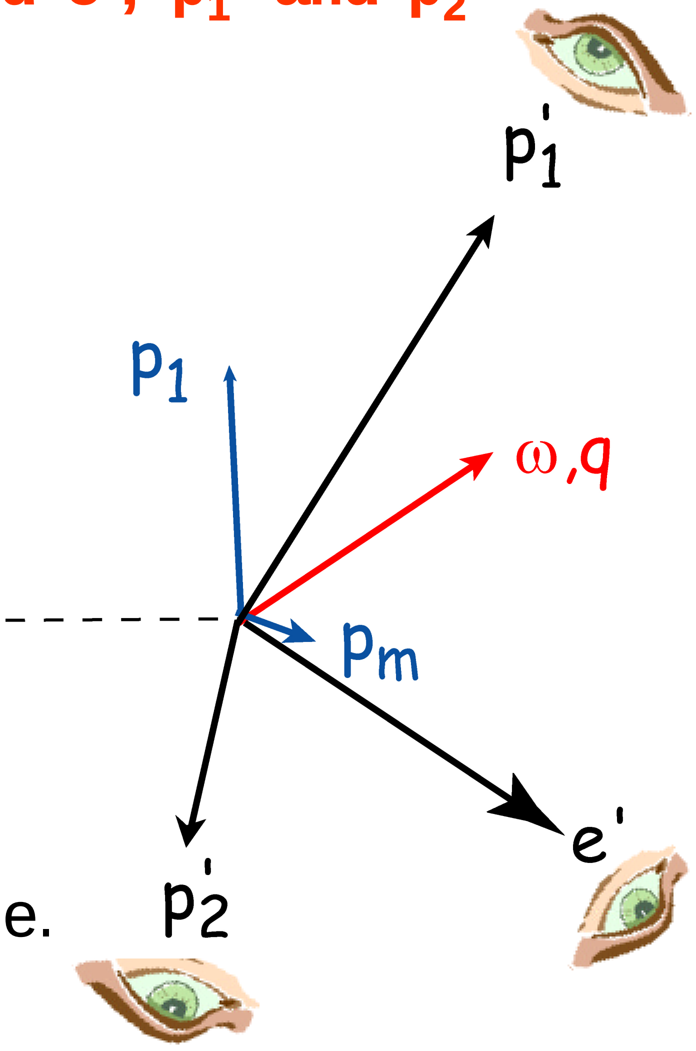
$E_m = \omega - T_1 - T_2 - T_{(A-2)}$

$E_m \sim E_{exc}$ of (A-2) system

$\vec{p}_m = \vec{q} - \vec{p}_1^{\,'} - \vec{p}_2^{\,'}$

^{3}He: (A-2)=nucleon, so p_m is momentum of the (unobserved) nucleon in the final state.

in PWIA: $-\mathbf{p}_m$ = CoM momentum of the pair in the initial state.



^{3}He(e,e'pp) experiment performed at AmPS (NIKHEF, Amsterdam)

D. Groep et al., PRL **83** (1999) 5443

D. Groep et al., PR C**63** (2000) 014005

^{3}He(e,e'pn) experiment performed at A1 (MAMI, Mainz)

NIKHEF, Amsterdam, The Netherlands

Institut für Kernphysik, Mainz, Germany

Physikalisches Institut, Tübingen, Germany

University of Glasgow, Glasgow, Scotland

measurements at the same central values of (ω,q)

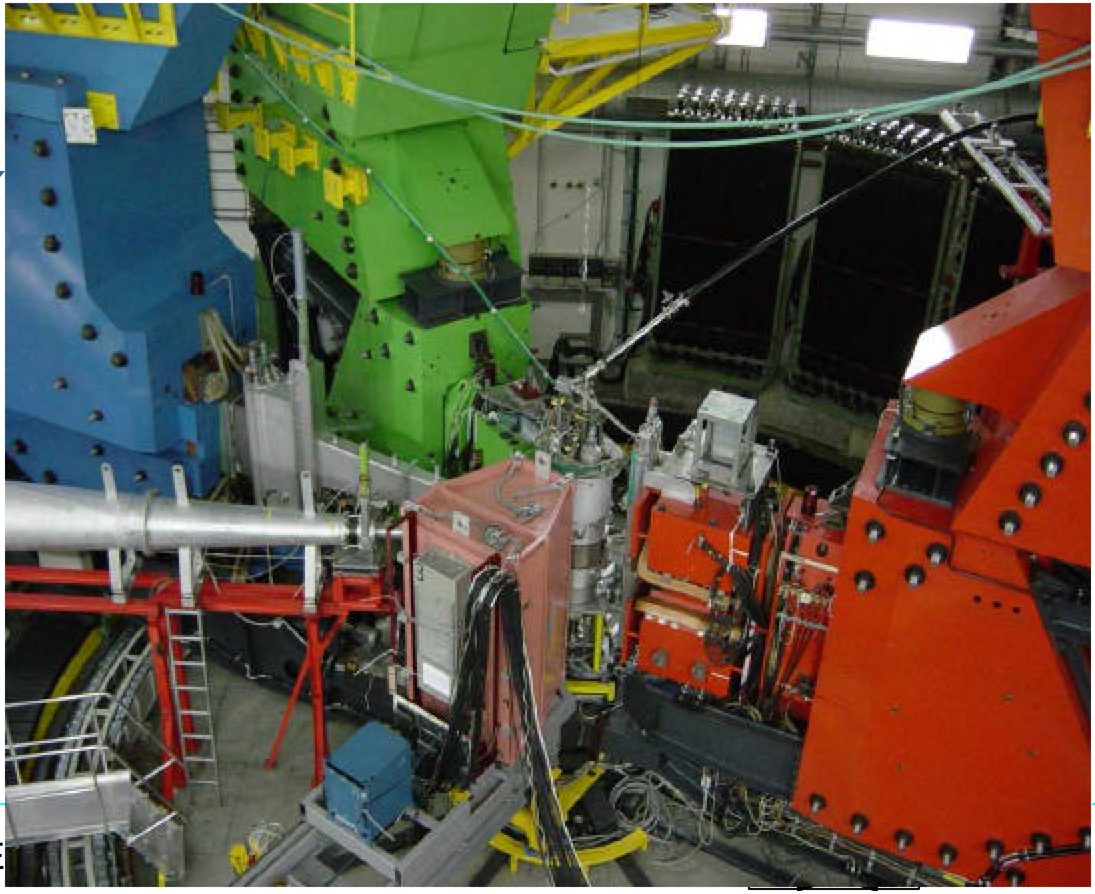
experimental tools

- high duty-factor electron beam
- cryogenic target
- magnetic spectrometers for electron detection
- large solid angle scintillator detectors, with a high degree of segmentation, for proton & neutron detection

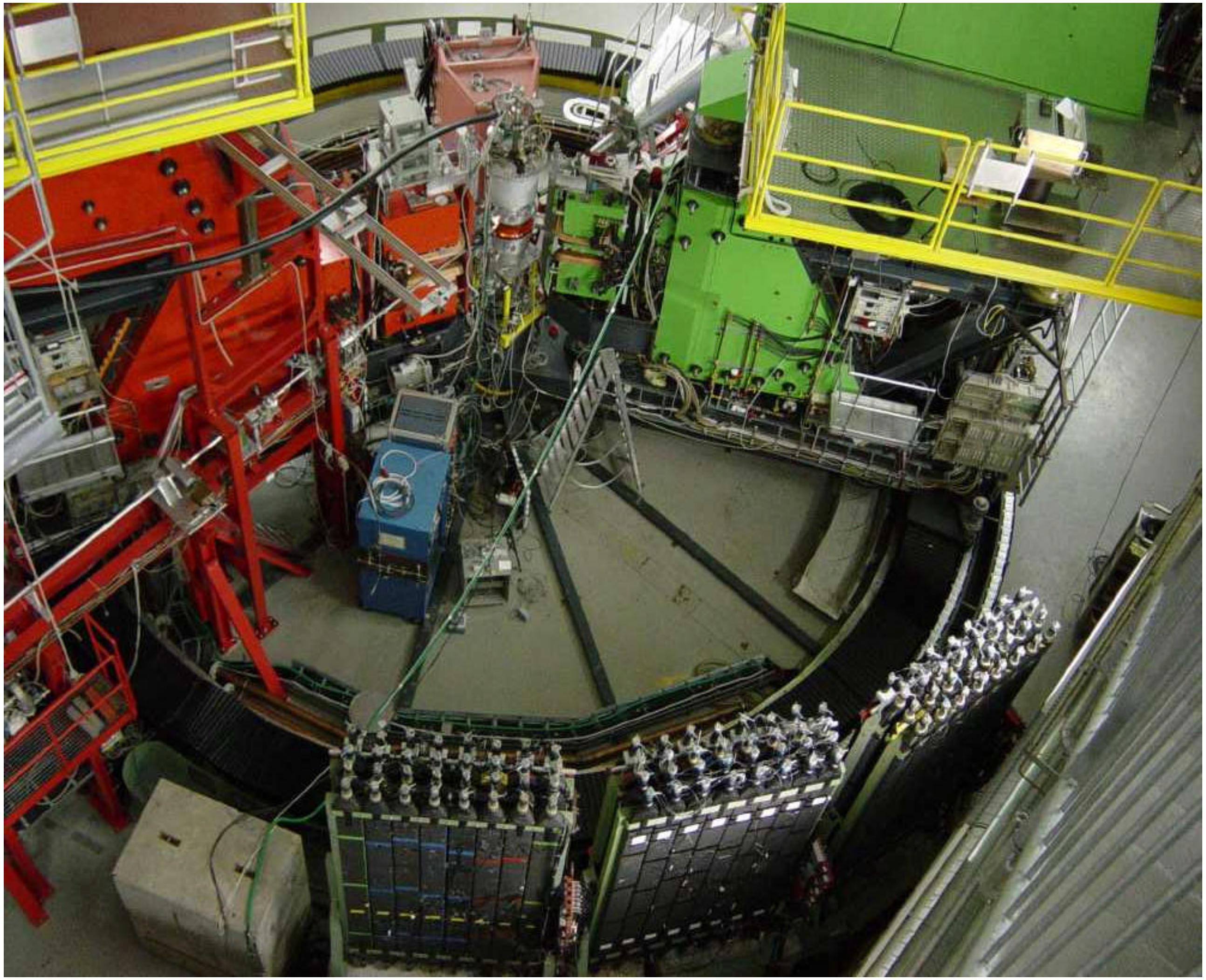
A1-hall of MAMI

spekB: Ω=5.6 msr
$\Delta p/p$=15%

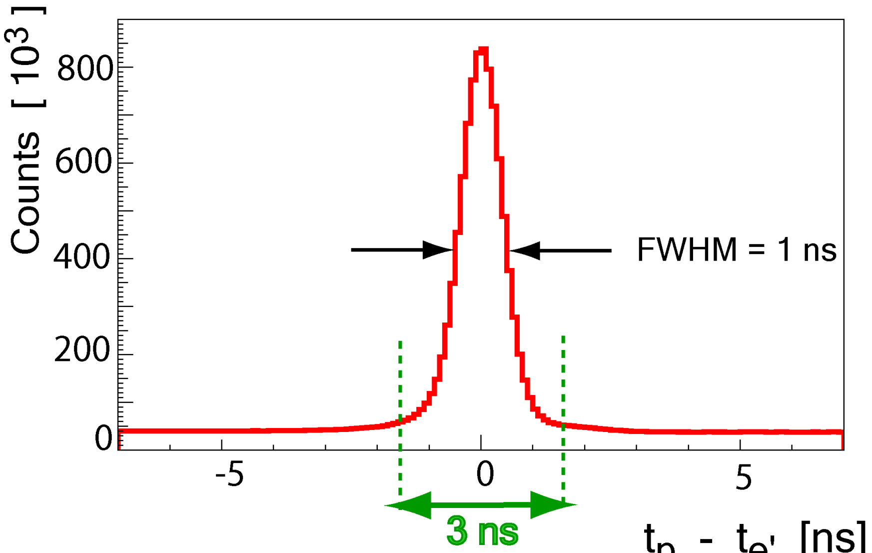
Luminosity:
10^{36} cm^{-2}.s^{-1}



A1-hall at MAMI

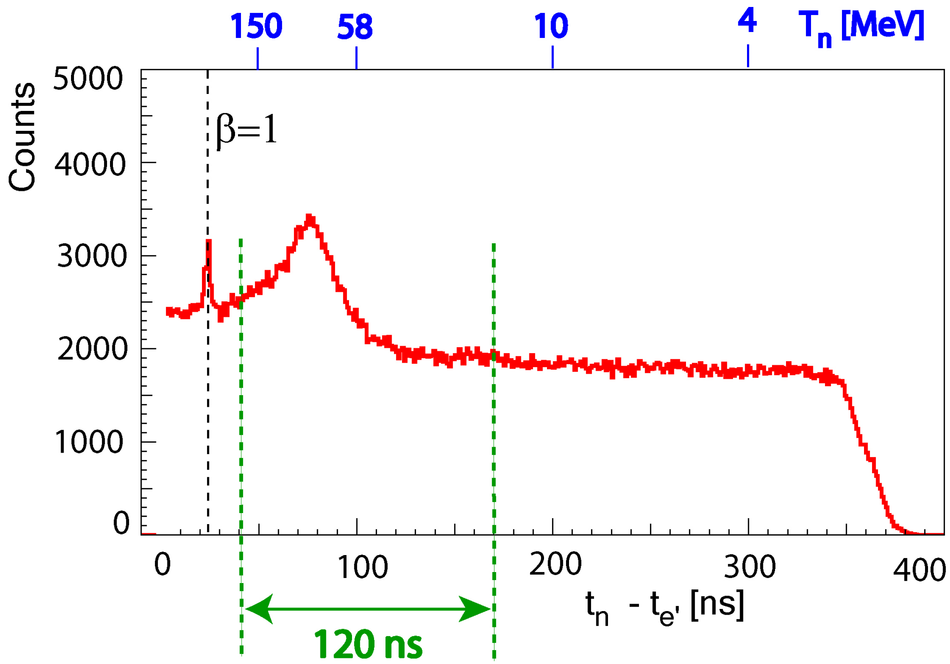


electron-proton time difference spectrum



time and energy of proton are uncorrelated

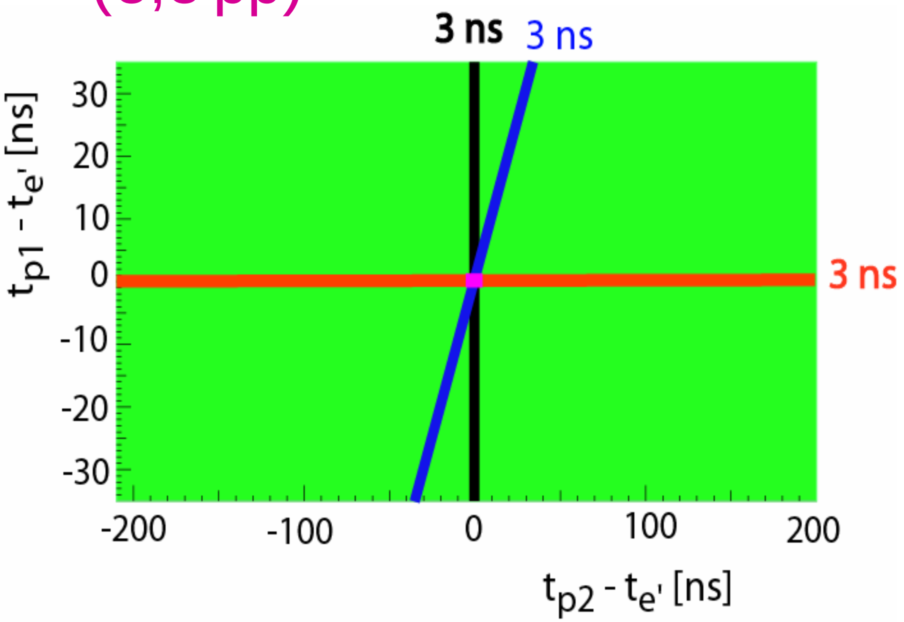
electron-neutron time difference spectrum



time and energy of neutron are correlated

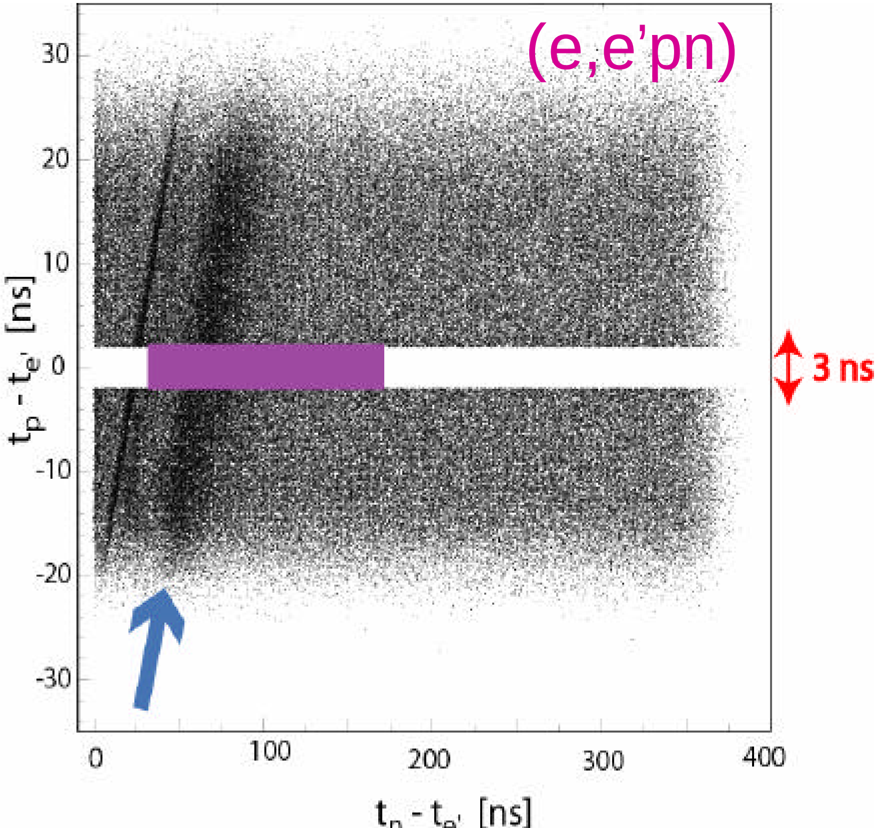
coincidence times and accidental subtraction procedures

(e,e'pp)



- three-fold uncorrelated singles
- real-(e'p_1) + accidental n (3 ns)
- real-(e'p_2) + accidental p_1 (3 ns)
- real-(p_1p_2) + accidental e' (3 ns)

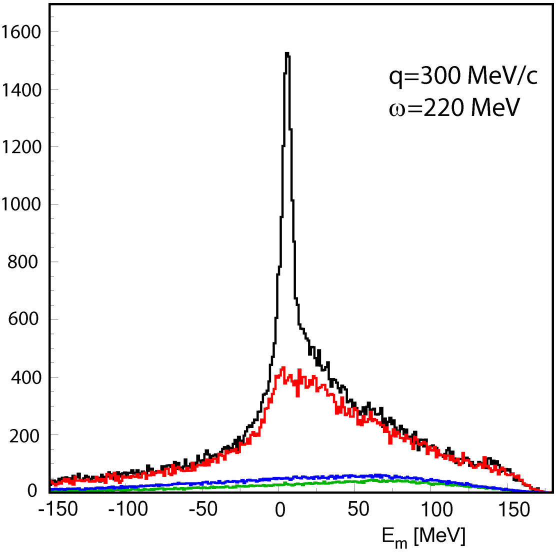
real (e,e'pp) in 3x3 ns^2

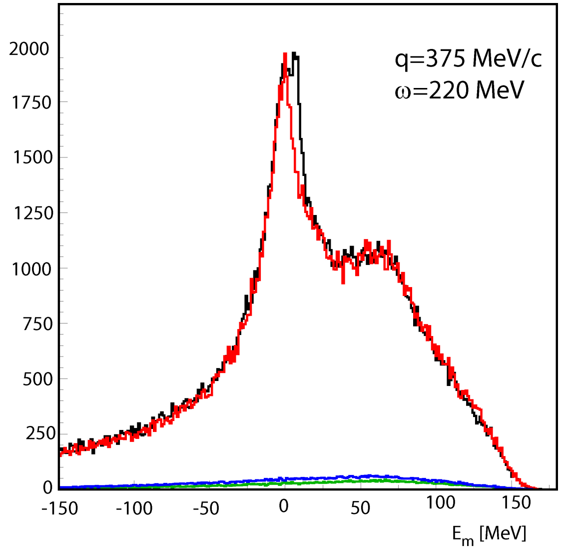


- three-fold uncorrelated singles
- real-(e'p) + accidental n (3 ns)
- real-(e'n) + accidental p (120 ns)
- real-(pn) + accidental e' (120 ns)

real (e,e'pn) in 3x120 ns^2

E_m spectra of $^3He(e,e'pn)$ @ MAMI

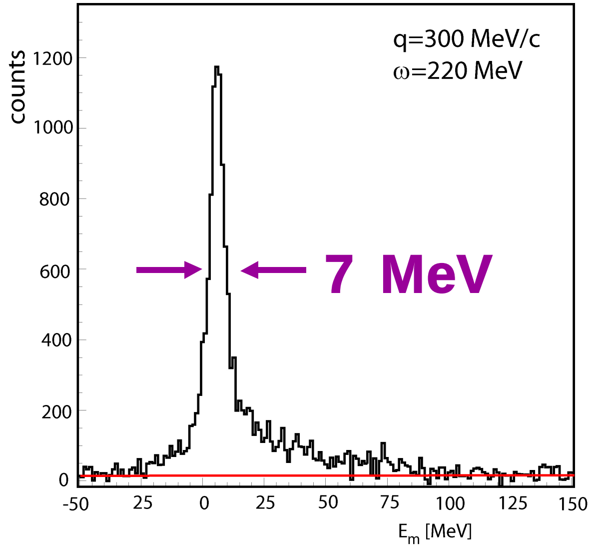


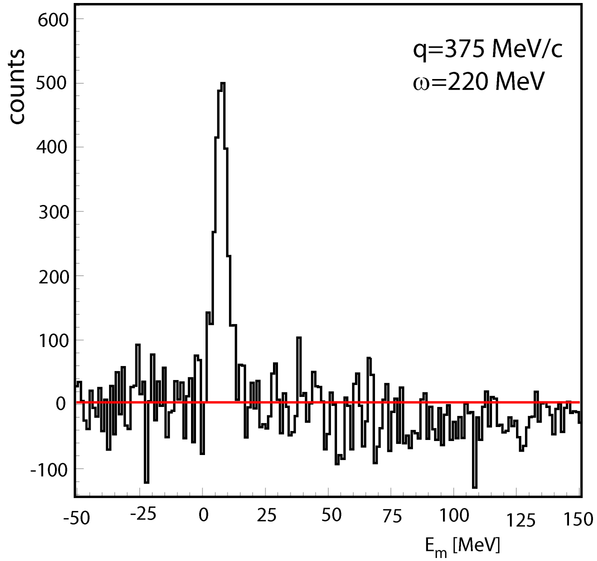


in 3x120 ns²

- total (e'pn)
- 3x uncorrelated singles
- real-(e'n) + acc. p
- real-(pn) + acc. e'
- real-(e'p) + acc. n

after accidental subtraction



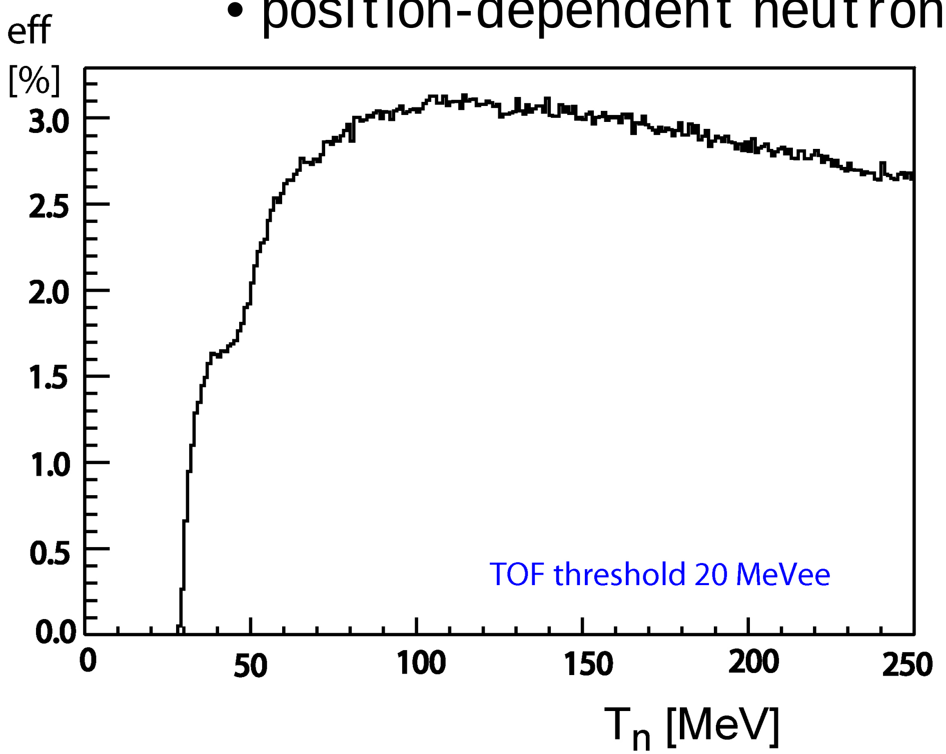


integrate strength in $-2<E_m<18$ MeV and plot versus other variables

determination of experimental differential cross section

- luminosity
- dead-time effects

  by means of (MC) simulations:
  - detection volume in phase space
  - hadronic interactions of proton
  - position-dependent neutron detection efficiency



effect of
neutron threshold
10→20 MeVee:
Signal: factor 2 ⇓
Noise: factor 4 ⇓

calculations of ^{3}He(e,e'NN) cross section

continuum Faddeev calculations of the Bochum group
(J. Golak et al., Phys. Rev. **C51** (1995) 1638)

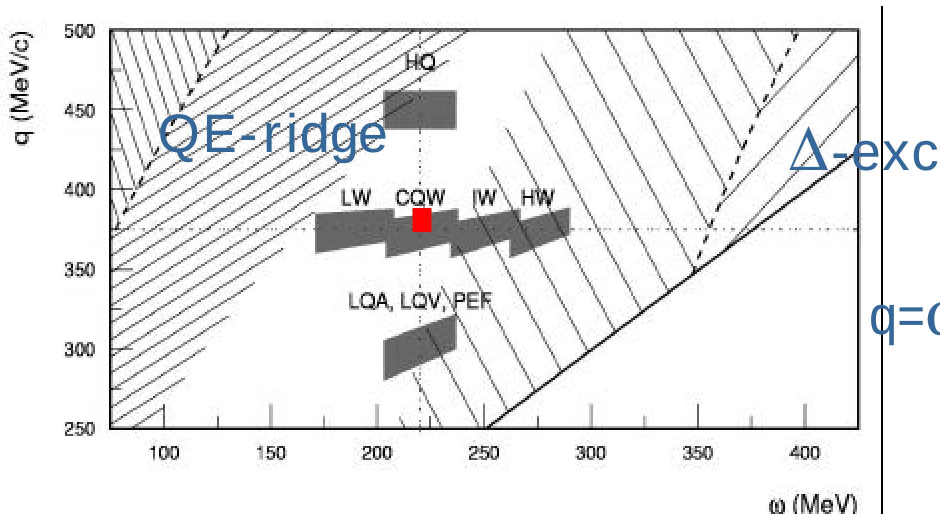
Employ realistic NN-interactions like Bonn-B, CD-Bonn, V18, Nijmegen93,.
- parameter-free model
- calculate wave functions of ^{2}H and ^{3}He.
- include NN-rescattering up to all orders
- one-body current operator
- MECs included via a π and ρ exchange current operator (Schiavilla&Riska)
- Δ-current in, static, low-energy approximation $$j_{p\Delta} \cong \frac{f_p^2}{(m_\Delta - m_N)} G_M^V(q)[....] \times q$$

Here: Bonn-B potential, j≤3, J≤15/2

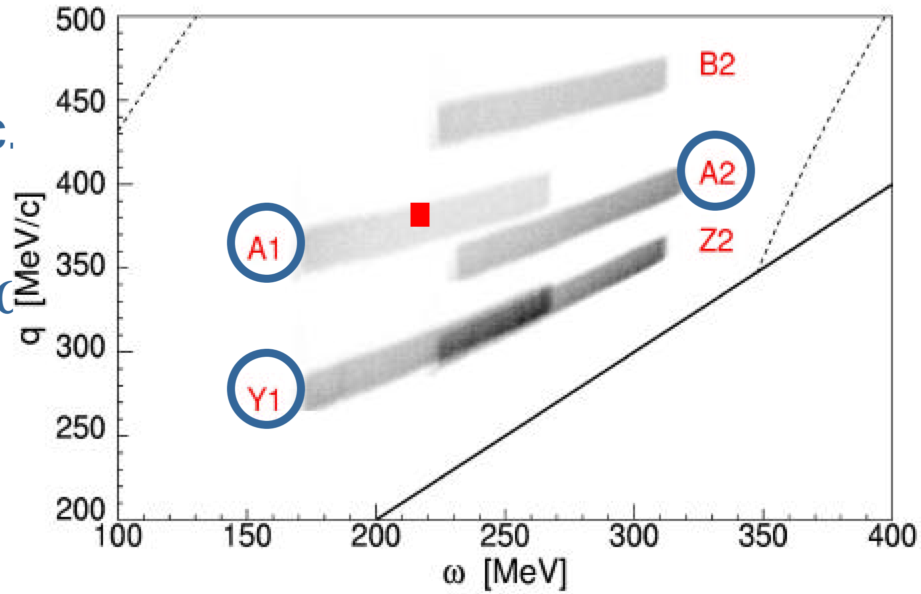
σ_{theo} evaluated over 2.5 x 10^6 grid points /kinematics in 5-D space of detected hadrons at the central value of (q,ω)

Kinematic coverage

$^3He(e,e'pp)$ @ AmPS



$^3He(e,e'pn)$ @ MAMI



- p_m-dependence
- q-dependence
- ω-dependence

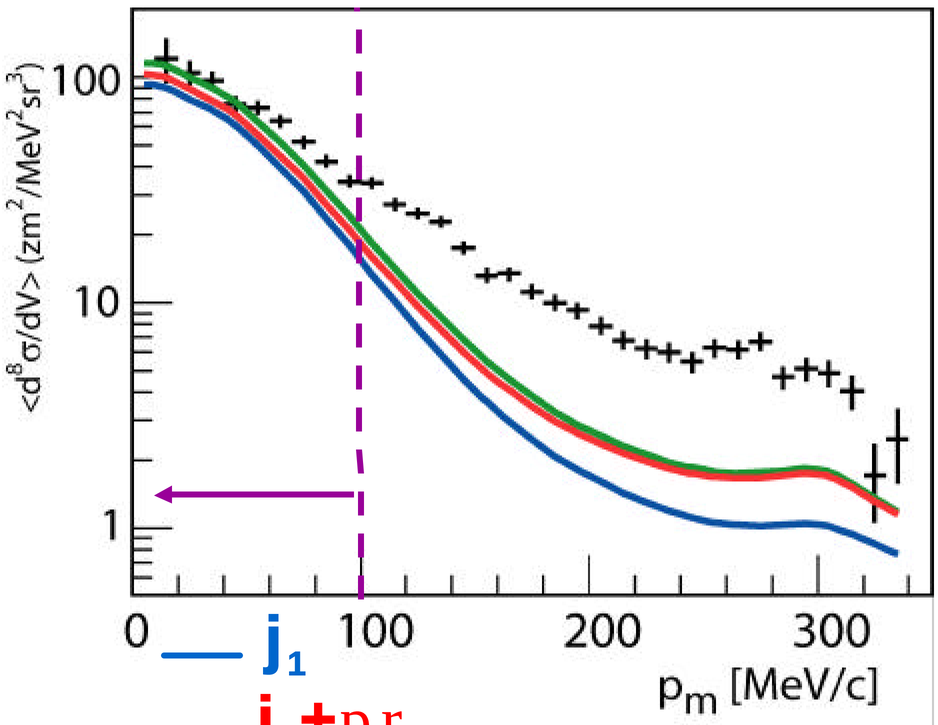
$d^8\sigma$ in $zm^2/MeV^2/sr^3$

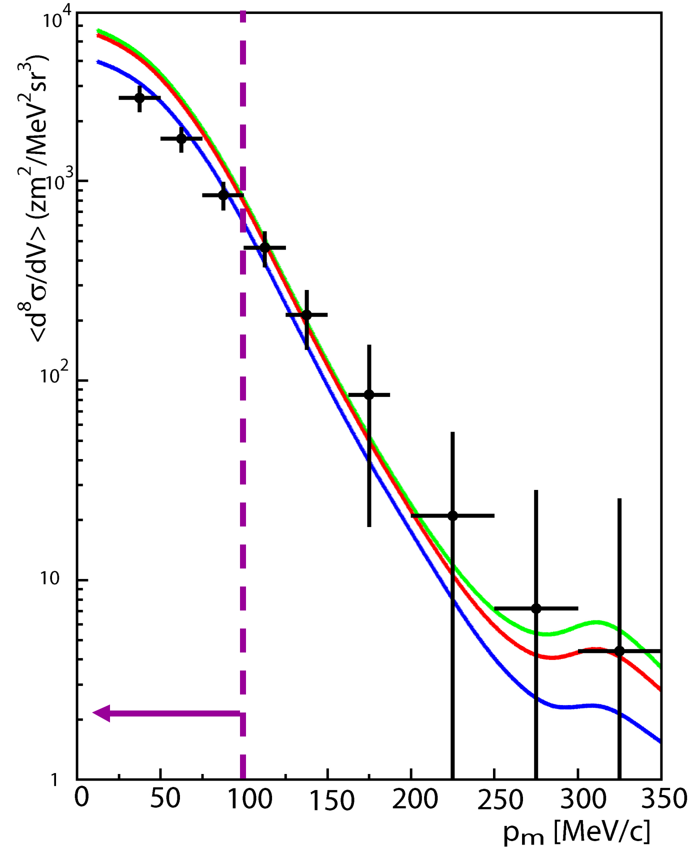
($1\ zm^2 = 10^{-14}$ barn)

PRELIMINARY

p_m dependence

$^3He(e,e'pp)$ q=300 MeV/c ω=220 MeV $^3He(e,e'pn)$





— j_1

— j_1+pr

— j_1+pr + static-D

$\frac{\text{data}}{\text{theory}} \approx$ 1.3 for $0<p_m<80$ MeV/c

3 for $p_m>200$ MeV/c

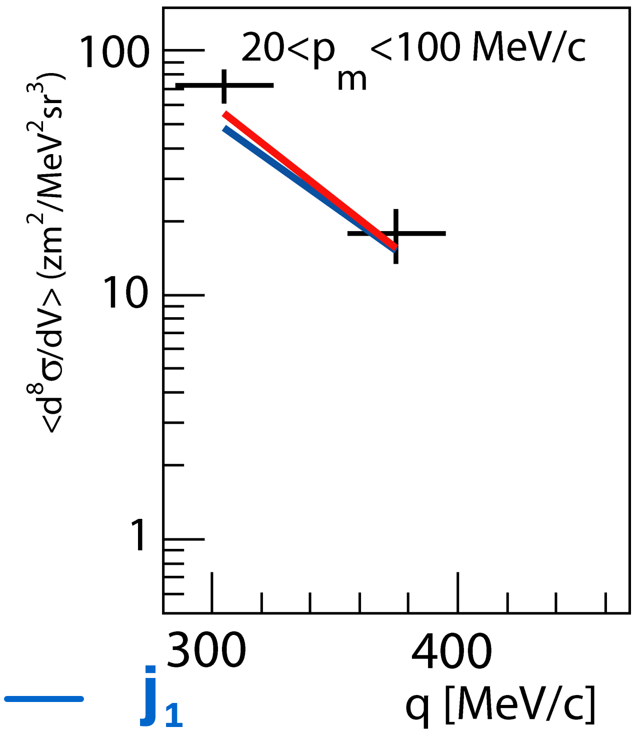
$\frac{\text{data}}{\text{theory}} \approx$ 0.6 for $p_m<80$ MeV/c

q-dependence

PRELIMINARY

^{3}He(e,e'pp)

ω=220 MeV

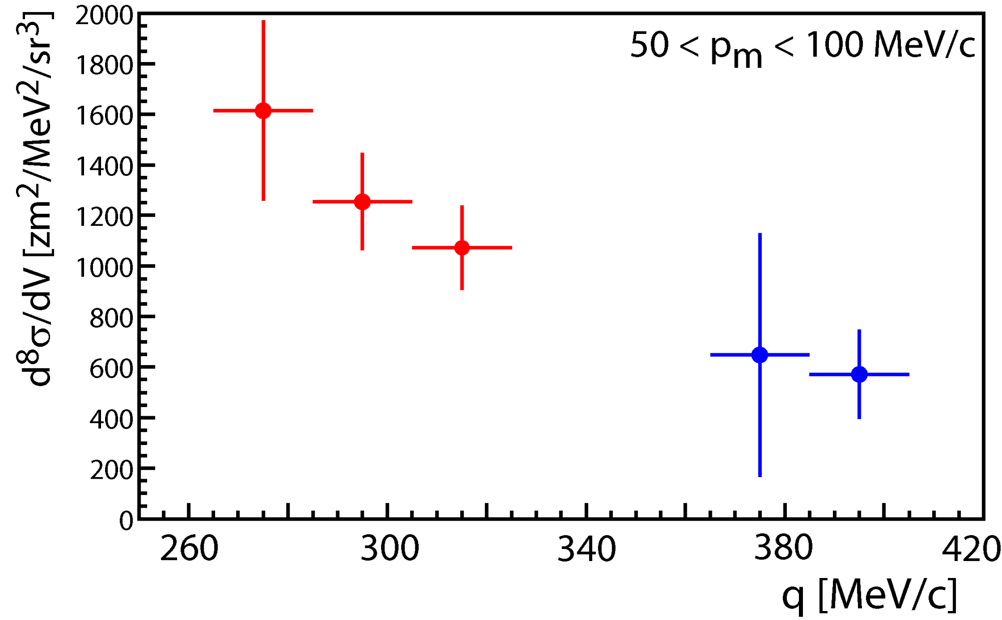


— j_1

— j_1+pr

$$\frac{s@(q=300)}{s@(q=375)} » 6$$

^{3}He(e,e'pn)



$$\frac{s@(q=300)}{s@(q=375)} » 2$$

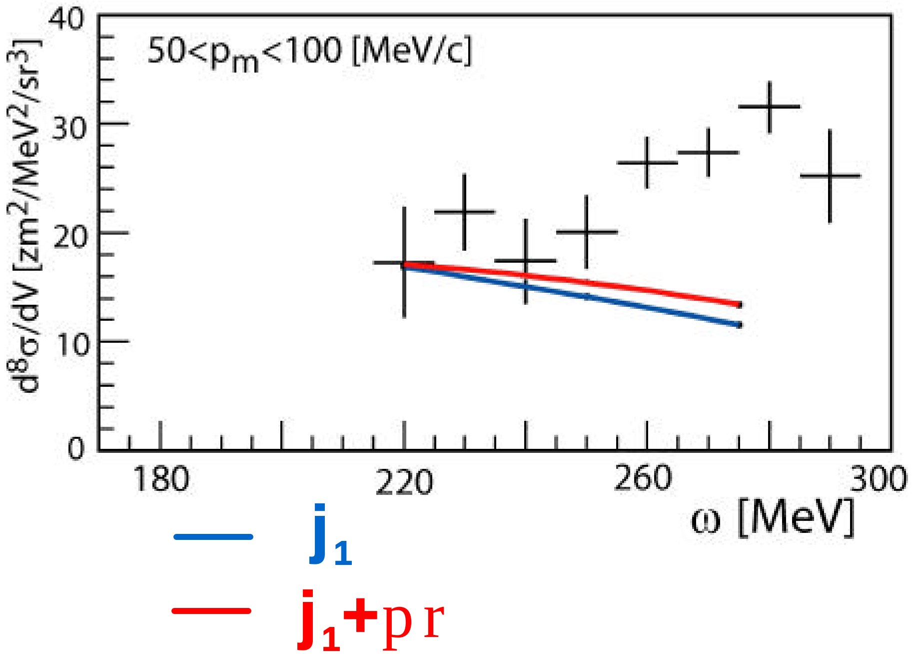
at low p_m the ^{3}He(e,e'pp) reaction is dominated by direct two-proton emission induced by a one-body hadronic current.

ω dependence

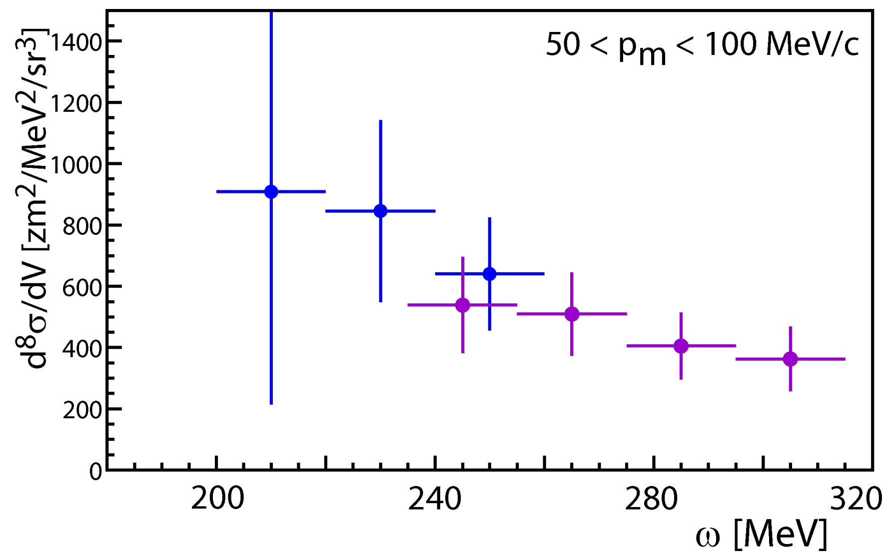
PRELIMINARY

q=375 MeV/c

^{3}He(e,e'pp)



^{3}He(e,e'pn)



$$\frac{\textbf{data}}{\textbf{theory}} = \begin{matrix} 1.0 \text{ for } \omega \sim 220 \text{ MeV} \\ 2.3 \text{ for } \omega \sim 280 \text{ MeV} \end{matrix}$$

$$\frac{\textbf{data @ } (\omega = 220)}{\textbf{data @ } (\omega = 300)} \approx 2\,(\pm 1)$$

Conclusions of ^{3}He(e,e'pp) and ^{3}He(e,e'pn)

- at low p_m the ^{3}He(e,e'pp) reaction seems well suited to study initial-state correlations.
- at $200<p_m<350$ MeV/c continuum Faddeev calculations underestimate the ^{3}He(e,e'pp) data by up to a factor 3.
- this discrepancy increases for increasing ω ($170\rightarrow290$ MeV).

- ^{3}He(e,e'pn) is harder but feasible: at low p_m the measured cross sections are about a factor 2 smaller than predicted.
- q-dependence of ^{3}He(e,e'pn) differs from that of pp-knockout.
- measured ^{3}He(e,e'pn) cross section is decreasing between ω=210 and 320 MeV.

- finalize the ^{3}He(e,e'pn) analysis.
- the role of the Δ-resonance seriously needs theoretical attention. (i.e. Hannover and Bochum group).
- (e,e'pN) data need to be measured with good statistics over a wide kinematic range and then sorted in narrow bins in many variables (q, ω, p_m, γ_1, p_{ij},...)