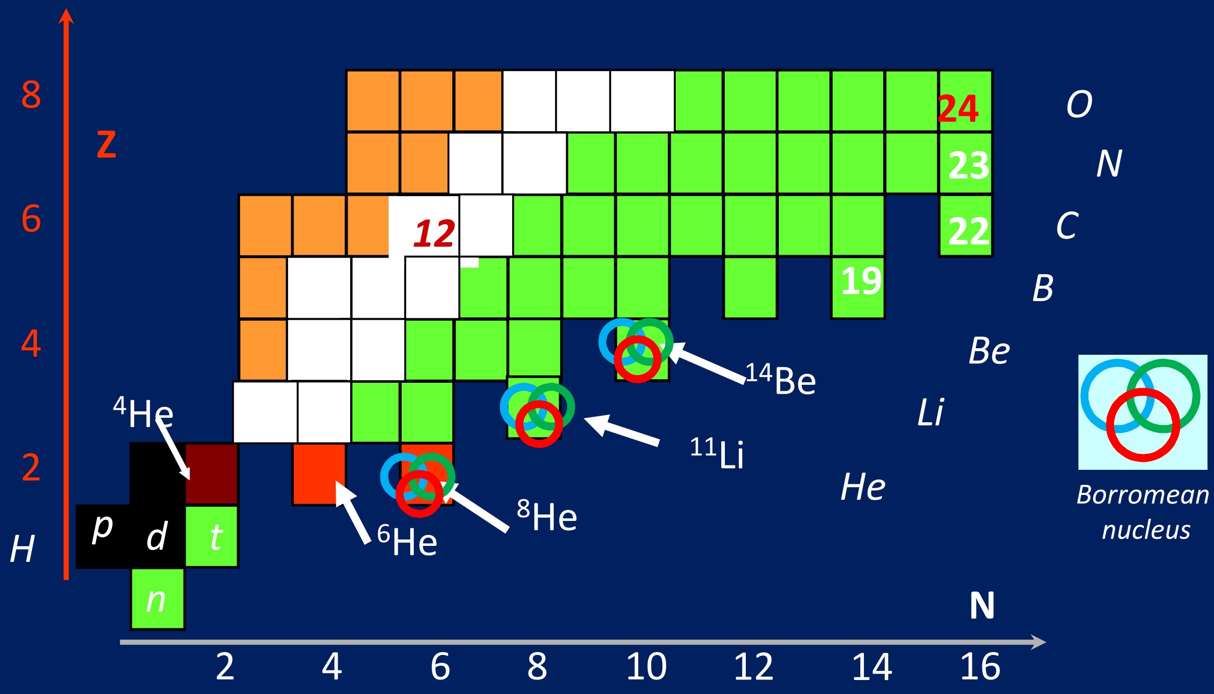
Benchmark observables for nuclear models from direct reactions of the exotic ^{6,8}He on proton

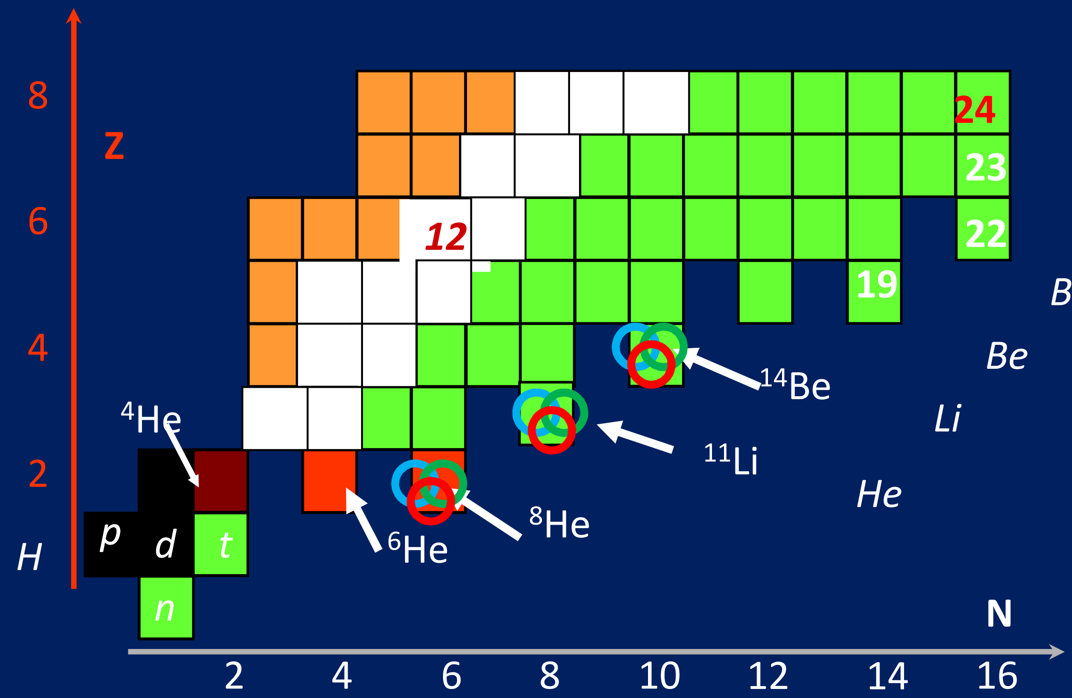


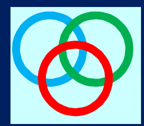
Eur. Phys. J. A (2015) ***51****: 91*
doi:10.1140/epja/i2015-15091-2
Weakly-bound Borromean structures of the exotic ^{6,8}He nuclei through direct reactions on proton

How can we improve our knowledge on nuclear interactions ?

Valérie Lapoux, CEA-Saclay

Exotic nuclei: questions & probes




borromean nucleus

Motivations
Benchmark of nuclear interactions
How to improve our description?
Observables & Relevant probes?

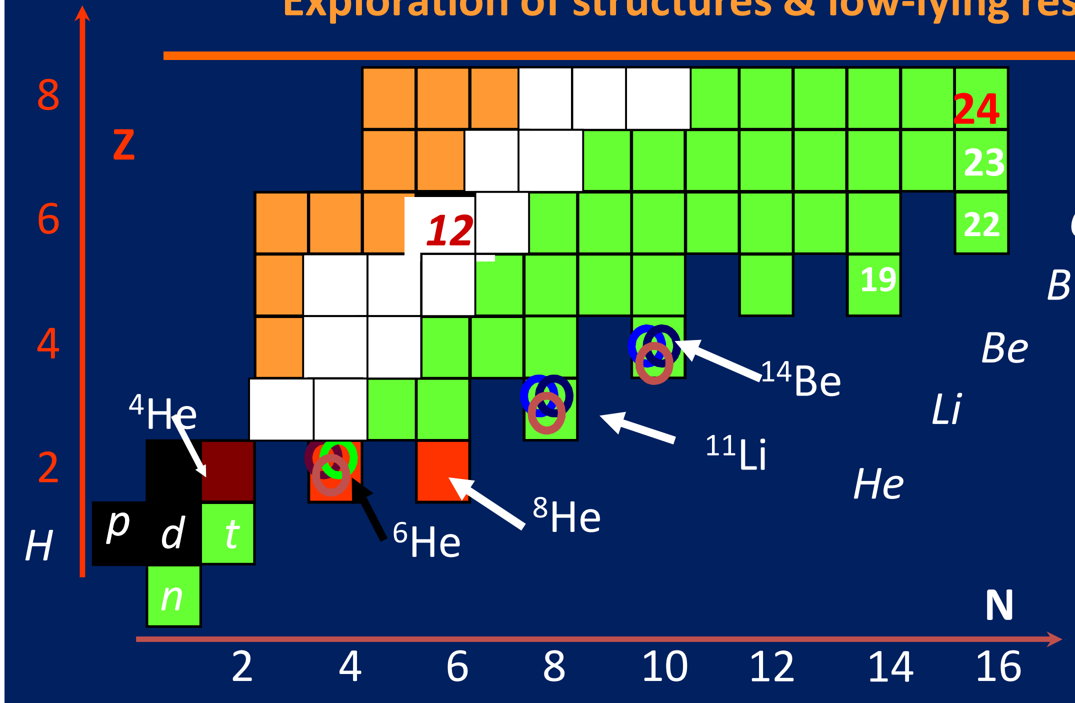
Exotic nuclei
+ Exploration of new phenomena
→ Constraints on nuclear models
+ Evolution of properties with isospin
→ Constraints on interactions

+ Properties in neutron-rich nuclei towards the dripline,
Three-body forces & continuum:
binding energy, radii, low-lying (2^+) states in even-even

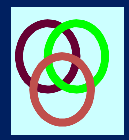
Weakly-bound, large asymmetry
→ Test cases: ^{6,8}**He**

Spectroscopy & Nuclear matter radii
via elastic scattering on proton target

Exploration of structures & low-lying resonances of weakly-bound nuclei



Beyond dripline: nuclei as resonances ~10⁻²¹s → n decay

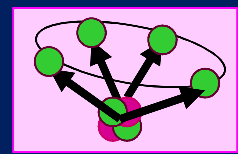


Evolution of structure spectroscopy at large isospin?
→ unbound excited states

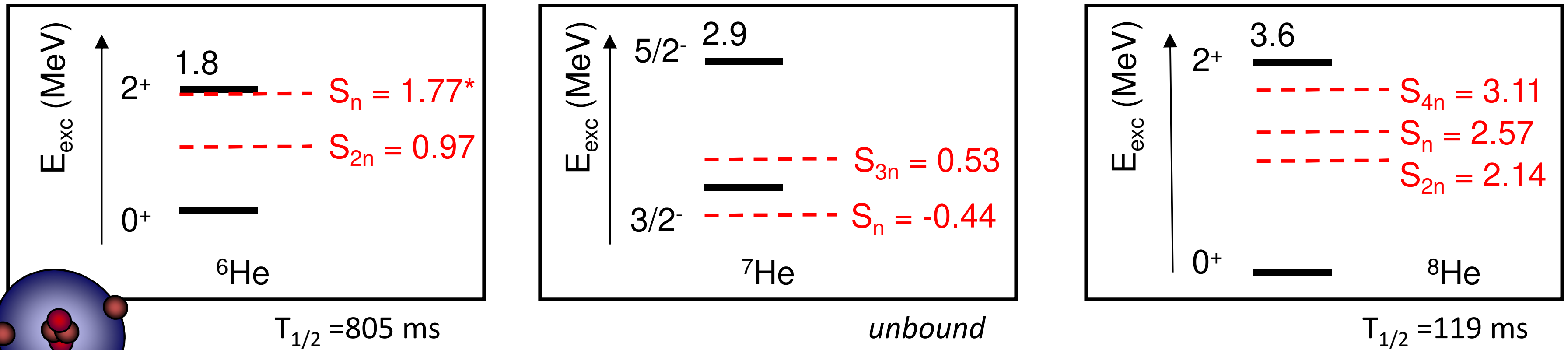
VIA DIRECT REACTIONS
→ simple mechanism & models

BUT …check interplay between coupled (reaction) channel effects

^{8}He N/Z =3
drip-line nucleus



***AME03, 1.8 : AME12**

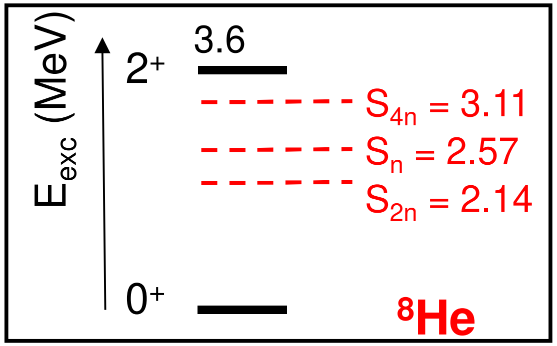


GOALS

Study of weakly-bound nuclei at large asymmetry (N-Z)/A
→ constraints on the nuclear structure models

TEST reaction models, extract new resonant states, Ex, J^{π}, overlap of wf (Spectro.Factors)

^{8}He drip-line N/Z =3

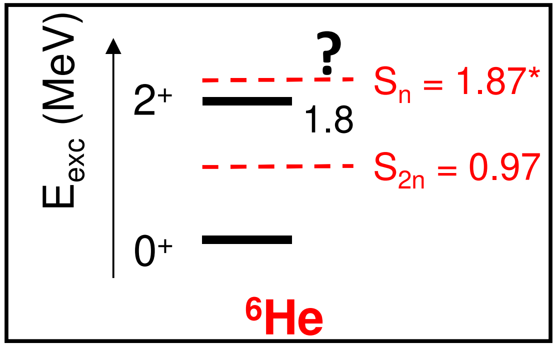


2 neutron-transfer

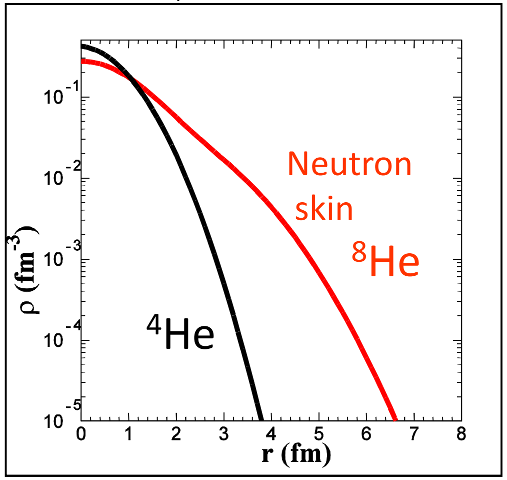
^{8}He+p→ ^{6}He+triton

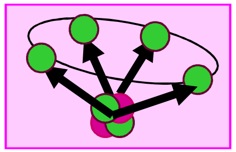
^{8}He+p→ ^{6}He*+triton
→^{4}He+2n+t

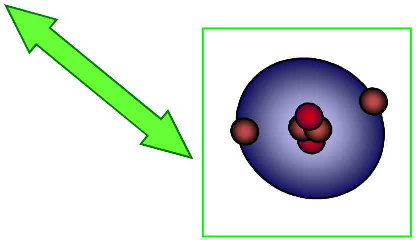
***AME12**



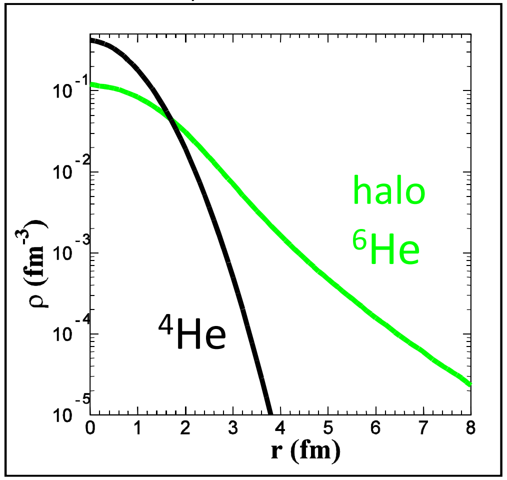
$T_{1/2}$ =119 ms



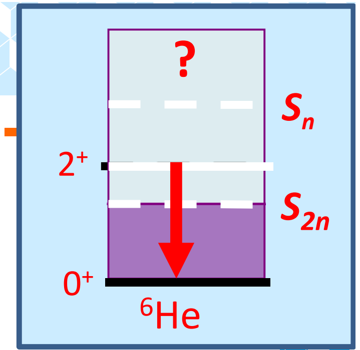




$T_{1/2}$ =805 ms

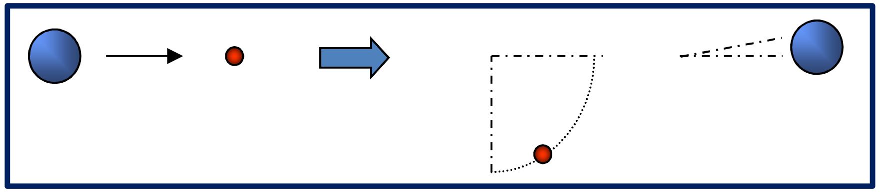


Direct reactions with exotic beams: principle and technique



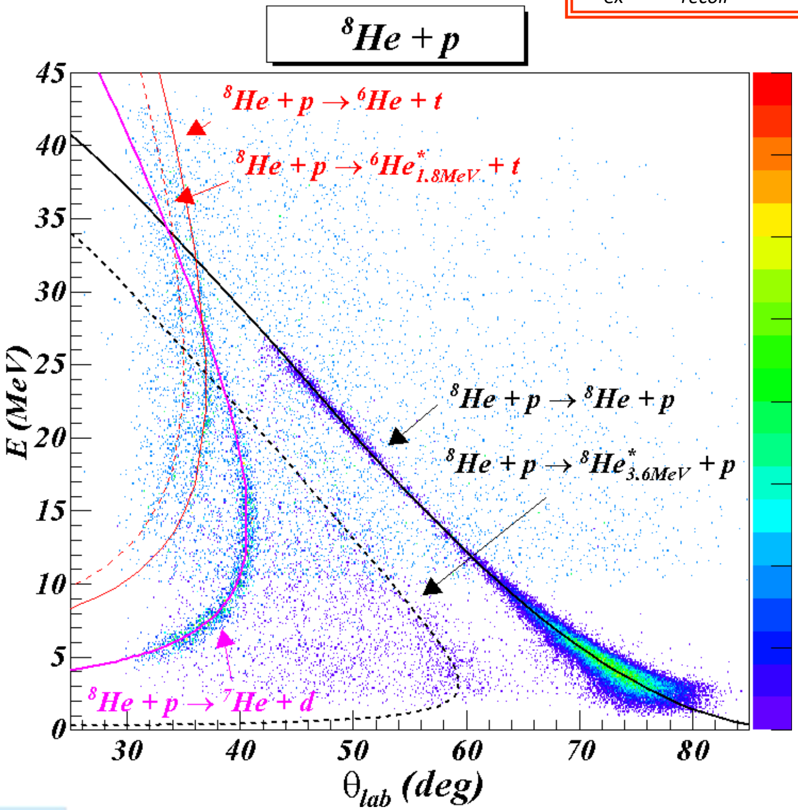
^{8}He + p → ^{6}He + t

^{8}He + p → ^{6}He* + t
→ ^{4}He +n+n + t



Kinematics

Reaction energy conservation ; Ex from (Ep, ***p***)
$M_{recoil}\,c^2 = E_0 + 2(p_{inc}\,c^2)(p_p\,c^2)(\cos\Theta_p) - 2T_p(E_{inc}+m_p c^2)$
$E_{ex} = M_{recoil}\,c^2 - E_0$



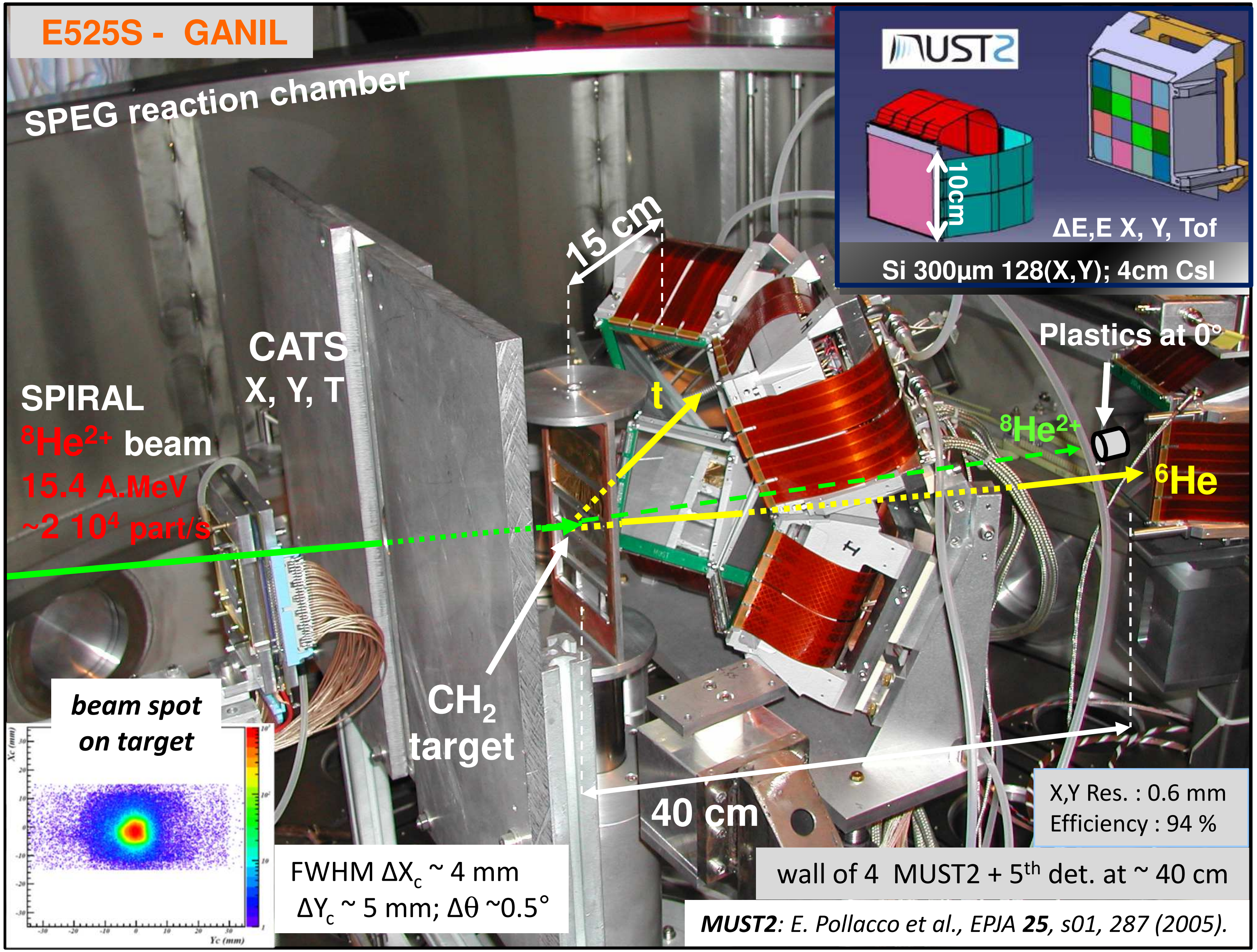
Kinematical reconstruction ^{8}He(p,t)^{6}He*

Spectra E_x +dσ/dΩ

Missing mass method
Coincidence (ejectile +p) >> Signature of reaction
Ex (^{6}He) from (***p***, E) of proton

MUST2
X,Y, E,TOF
identification
E_{tot}, θ

Beam tracking **CATS**
impact on target; θ_{inc}

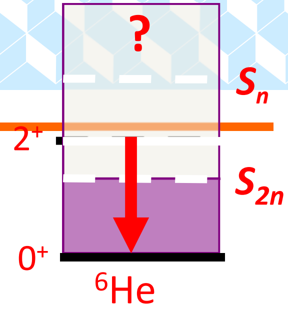


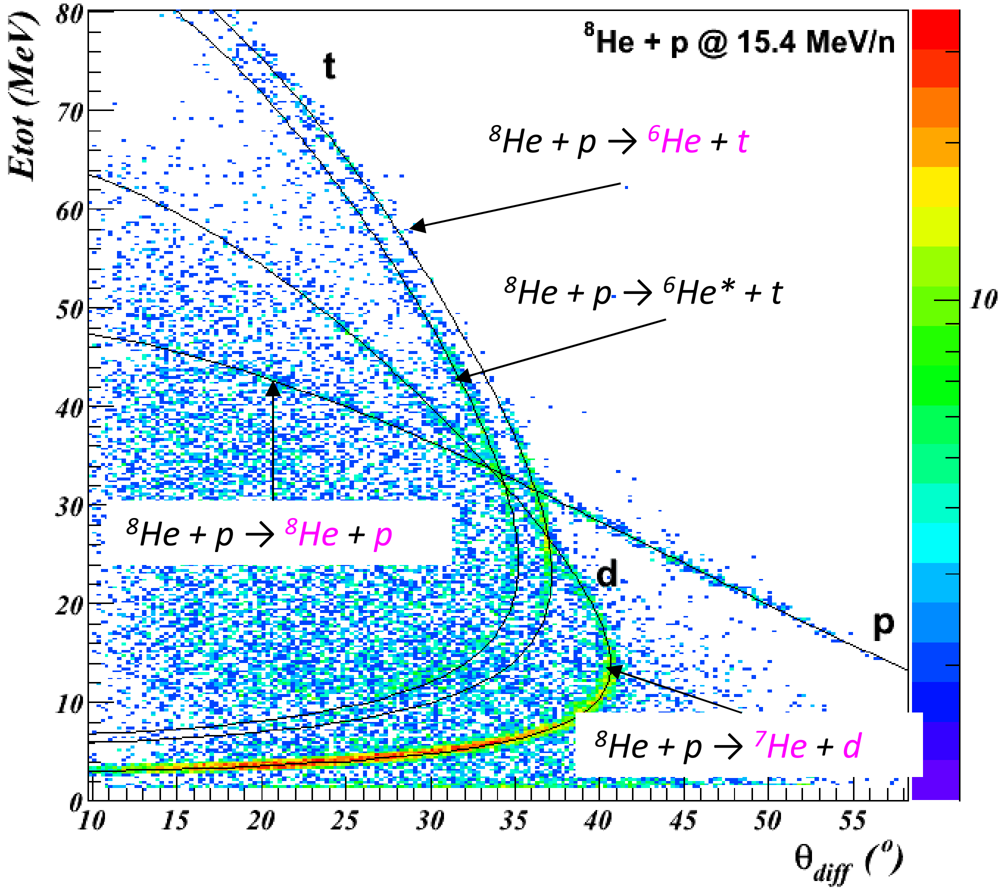
*MUST2: E. Pollacco et al., EPJA **25**, s01, 287 (2005).*

Observables from kinematical reconstruction of direct reactions on proton

Reactions, Ex Kinematics

^{8}He(p,t)^{6}He*





^{8}He + p → ^{6}He + t

^{8}He + p → ^{6}He* + t
→ ^{4}He +n+n + t

6He

^{8}He + p → ^{7}He + d

^{8}He + p → ^{6}He+ n + d
→ ^{4}He +3n+ d

7He

Missing mass method
Signature of reaction
Coincidence (ejectile +p)
Eexc (^{6}He) from (***p***, E) of proton

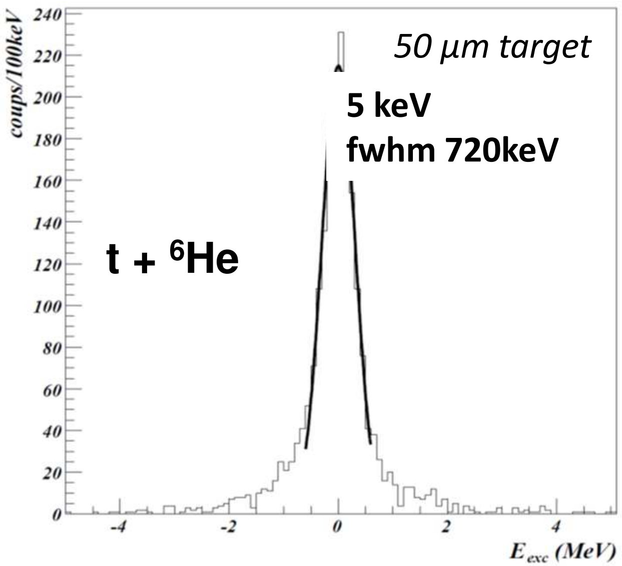
Spectra E_x +$d\sigma/d\Omega$

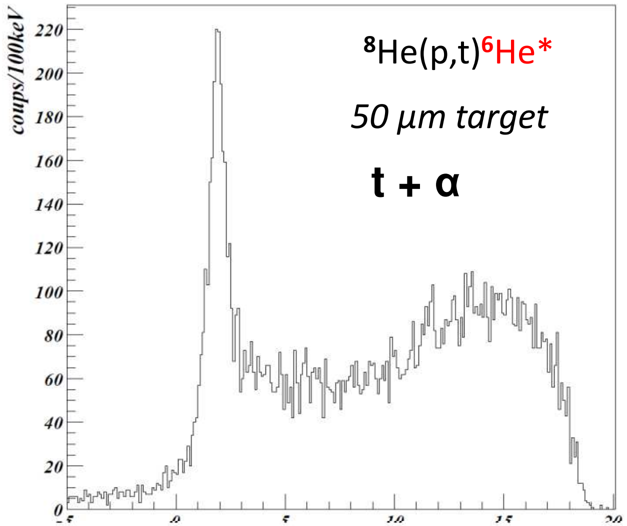
ΔE* ~ 400-750 keV

Precision on the ^{6}He gs position: 5-10 keV
Energy resolution: 720 keV with a 50 μm (4.48mg/cm^2) CH_2 target

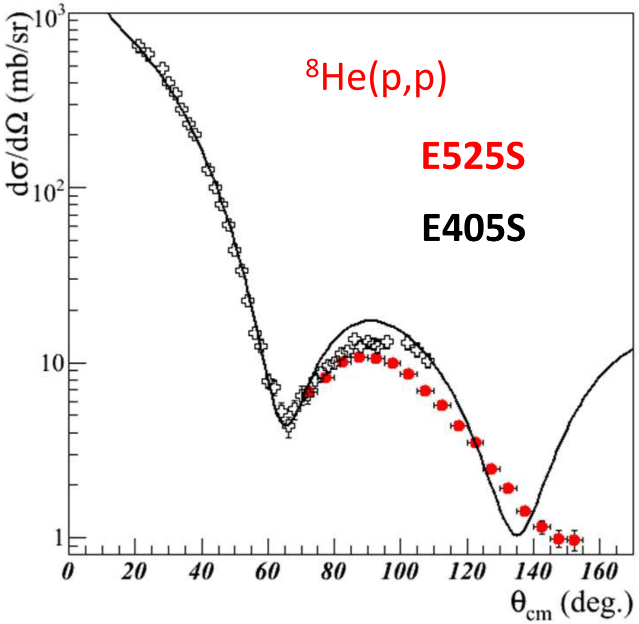
Observables from direct reactions on proton

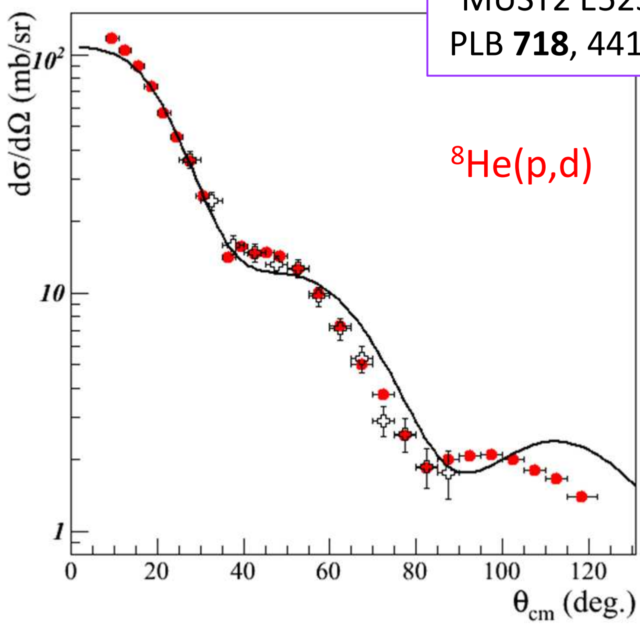
Excitation energy spectra with particle coincidences

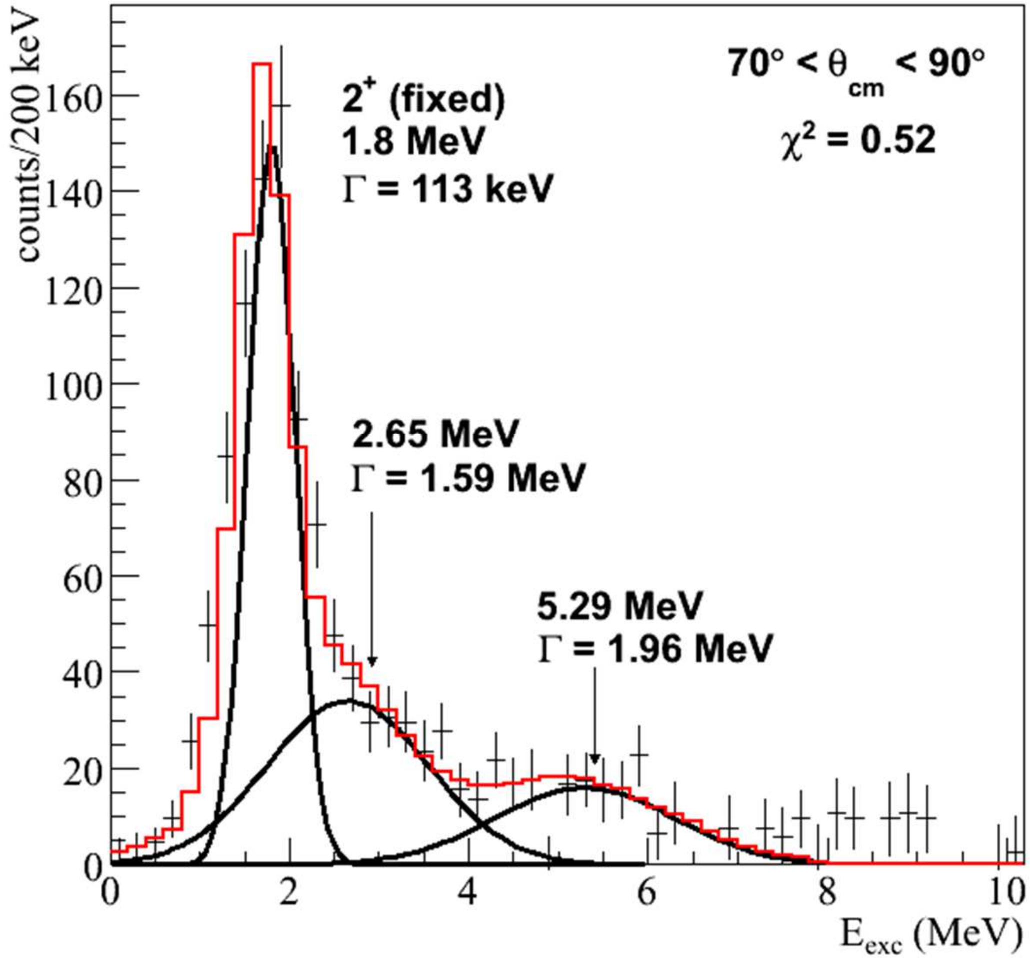




MUST2 E525S data
PLB **718**, 441 (2012).



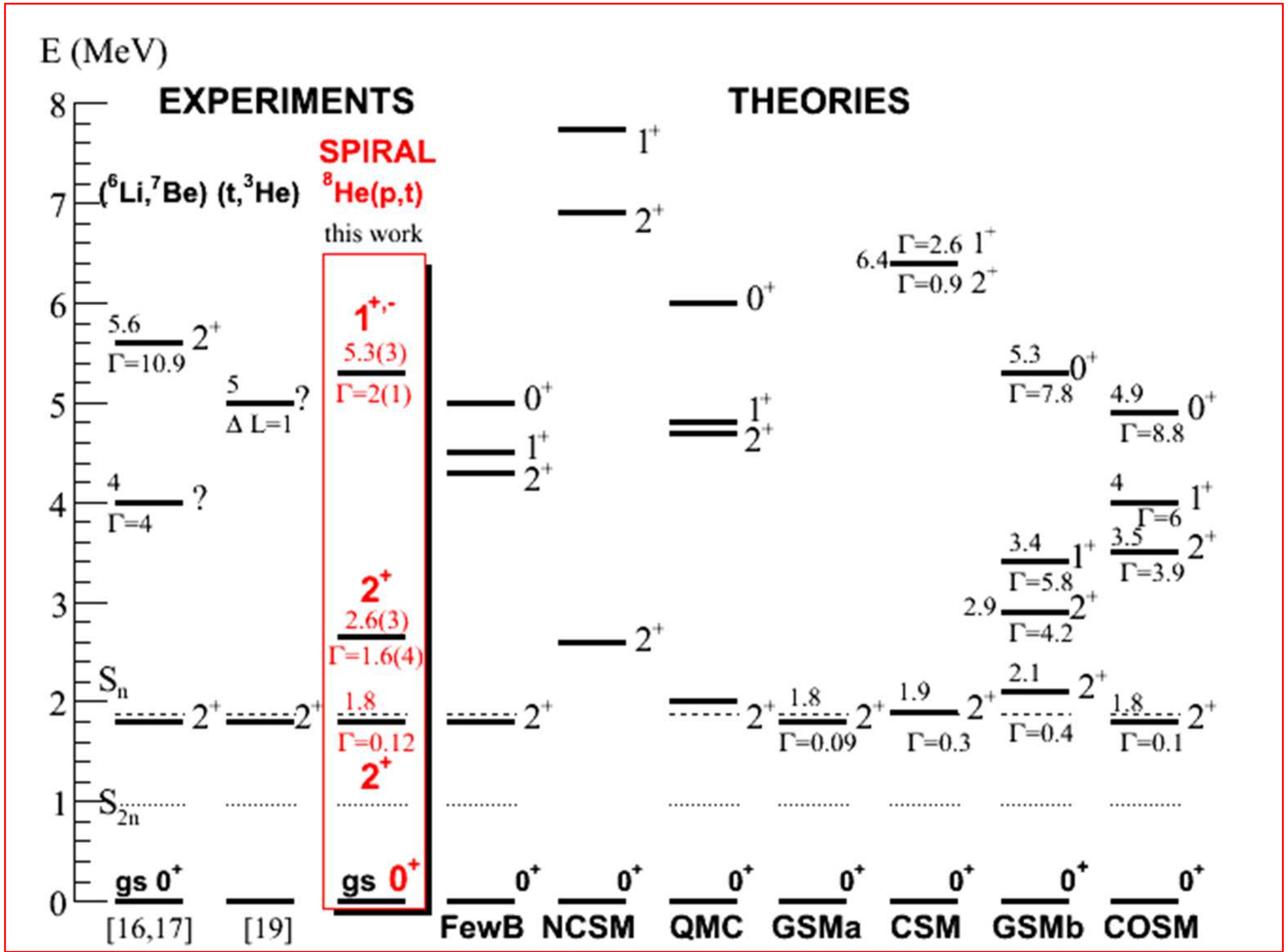




MUST2 E525S data at GANIL

X. Mougeot , V.L. *et al.,* PLB **718**, 441 (2012). PhD work: X. Mougeot (CEA)

Observables - , spectroscopy of ^{6}He from ^{8}He(p,t)



QMC
Pieper *et al.*
PRC **70**,054325 ('04)

NCSM
No Core Shell Model
Navratil, Barrett *et al.*

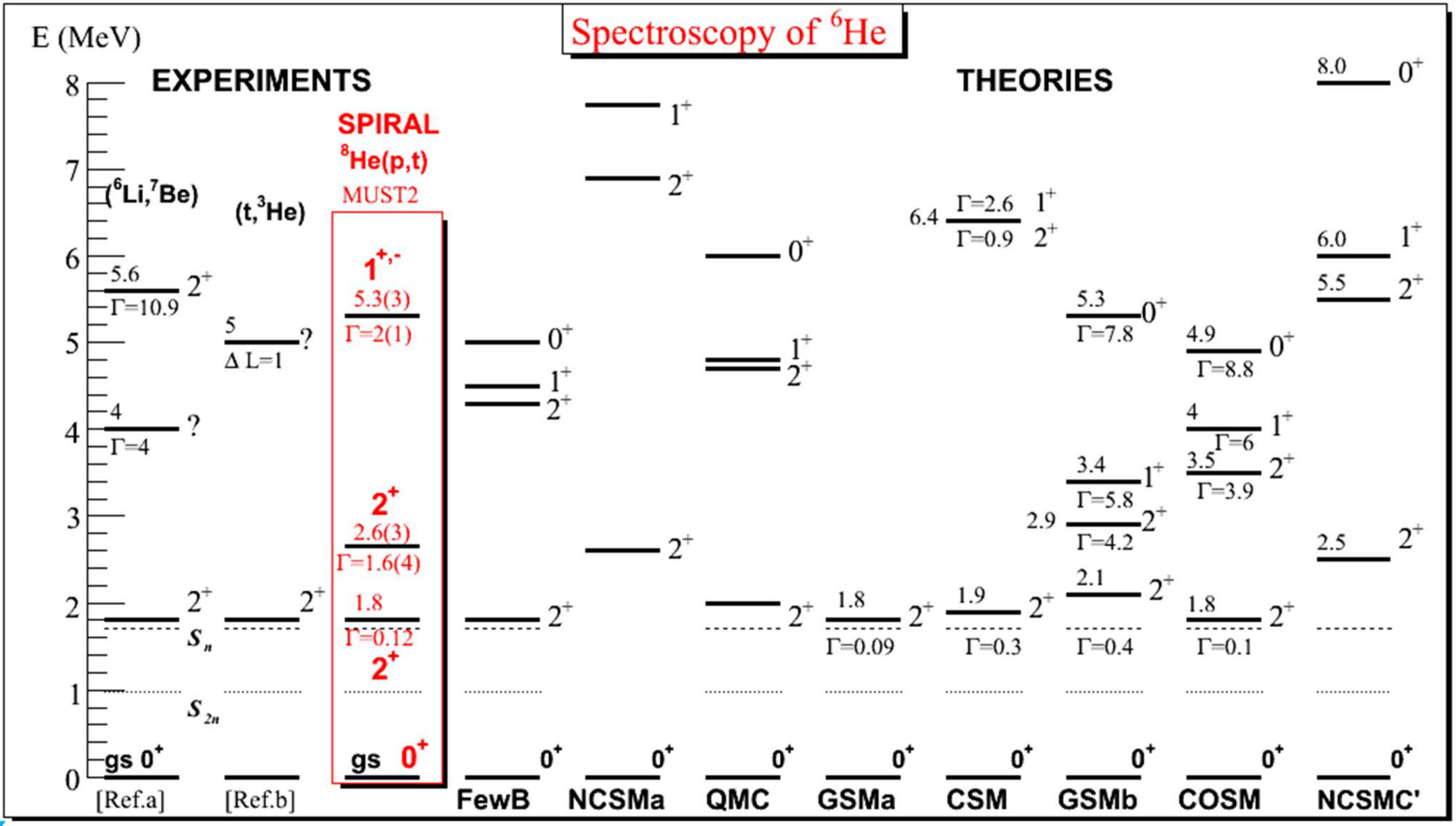
FewB Danilin *et al.*
PRC **55**, 577 ('97).

CSM
Volya, Zelevinsky,
PRL**94,** 052501 ('05).
GSMa Ploszajczak
GSMb Hagen, Hjorth-Jensen, Vaagen,
PRC**71**, 044314 ('05).

[16] J. Jànecke *et al.*, PRC **54**, 1070 (1996).
[17] S. Nakayama *et al.*, PRL **85**, 262 (2000).
[19] T. Nakamura *et al.*, PLB **493**, 209 (2000); EPJA**13**, 33 (2002).

Fig - E525S results
PLB **718**, 441 (2012).
N.B. AME2003 Sn =1.86 MeV
2015: AME2012 1.71 MeV

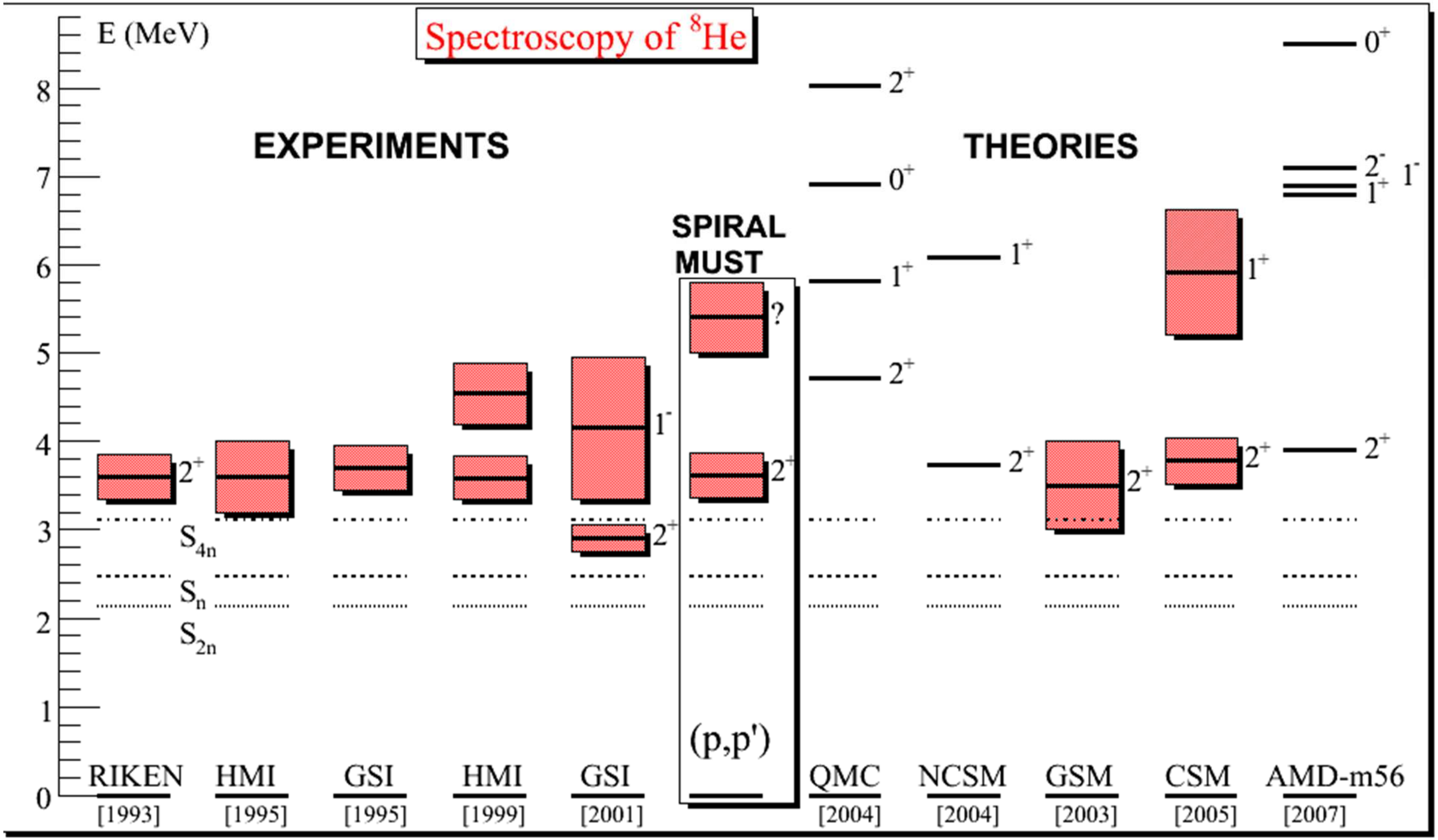
Observables



EPJA *51:91 (2015)*

NCSMC': +RGM CC effects
P Navratil et al, PRL ('13)

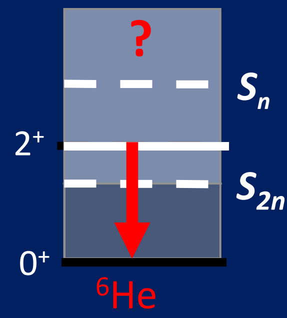
Comparison experiment-theory for Ex energies



(Comparison experiment-theory for gs energies → few MeV)

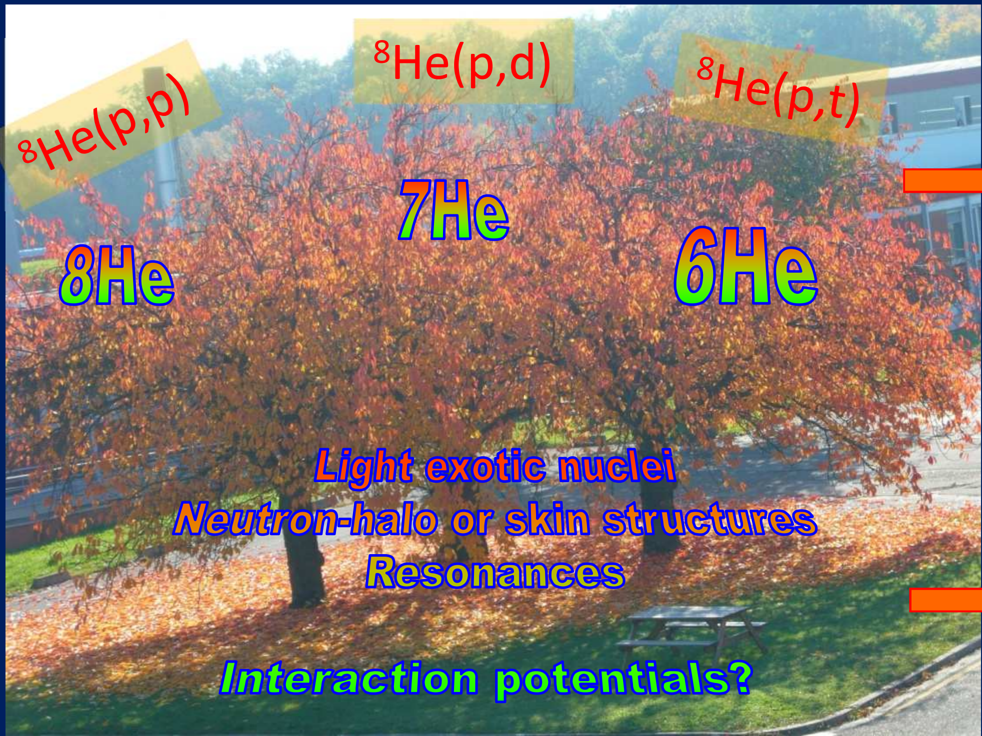
Review art. EPJA2015 51:91

Structure and spectroscopy of ^{6,7,8}He isotopes via direct reactions



Comparison experiment-theory for gs & Ex observables

Questions on structure-reaction mechanisms



Optical Model Potential (OMP) frameworks

Microscopic potential

→ **Matter radii, densities, multipoles moments**

Motivations

Low-lying spectroscopy, shell evolution

→ **Program of direct reactions**

SPIRAL beams + MUST2 array

Experimental conditions

To measure unbound states

Via (p,p) scattering

→ **Analysis**

Coupled Reaction Channel Model

QUESTIONS:

Structure–reaction framework?

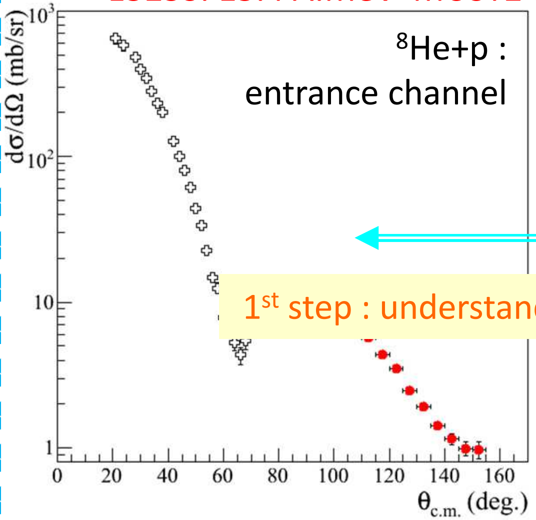
Unified consistent theory?

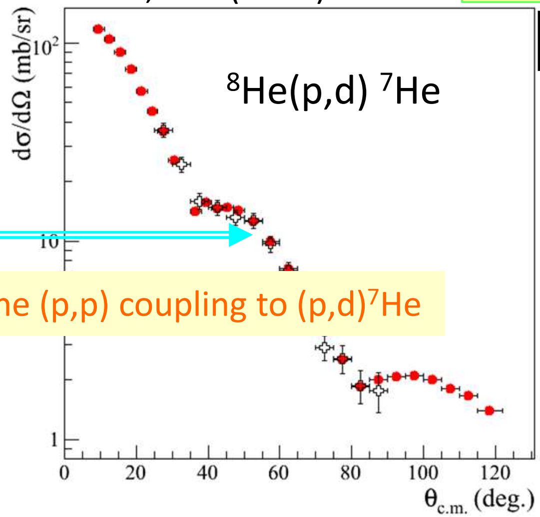
Observables: Elastic &transfer data of ^{8}He +p

E405S: 15.7 A.MeV; MUST data,
E525S: 15.4 A.MeV MUST2 data PLB **718**, 441 (2012).

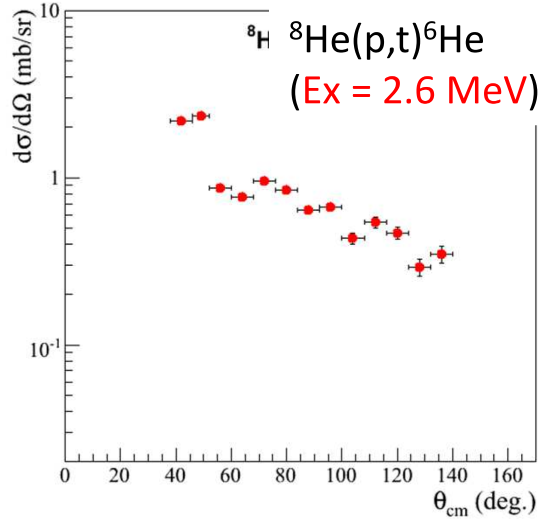
→ extract structure information (densities, SF)
→ check the consistency of the calculations
on the data set for the various reaction channels

all direct reactions at the same incident energy

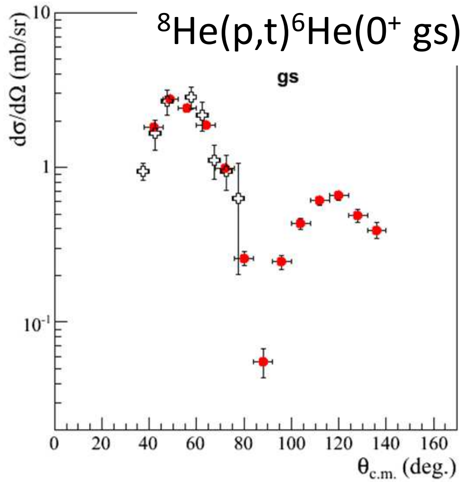


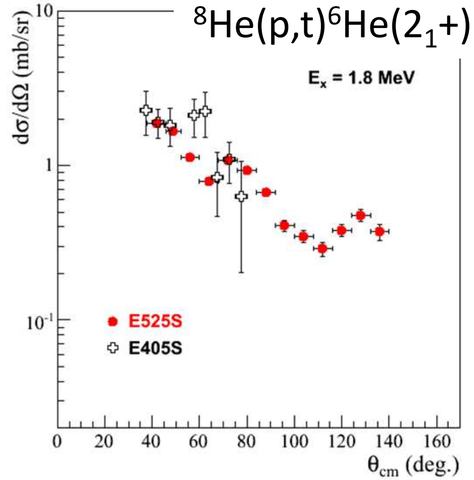


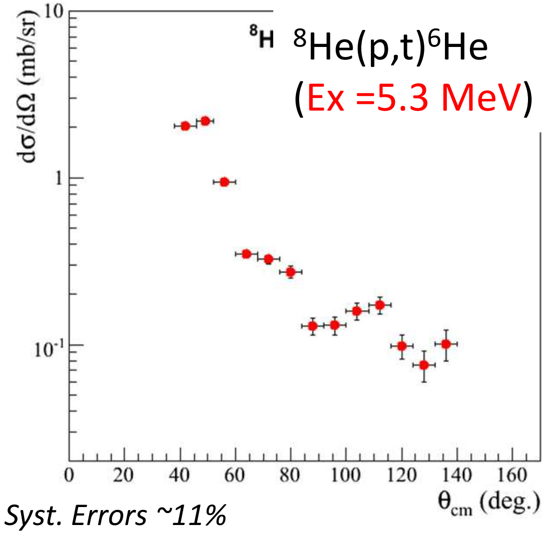
1st step : understand the (p,p) coupling to (p,d)^{7}He



* Large (p,d), (p,t) cross sections compared to (p,p) → DWBA not valid
GENERAL framework : Coupled Reactions Channel model







NB: Total Syst. Errors ~11%

The JLM microscopic nucleon-nucleus optical potential

J.P. **J**eukenne, A. **L**ejeune and C. **M**ahaux,
PRC **16**, 80 (‘77)

Brueckner-Hartree-Fock approximation
and Reid hard core *NN* interaction

$$V(\rho, E) = \sum \alpha_{ij} \rho^i E^{(j-1)}$$

Improved Local Density Approx
(by smearing the potential)

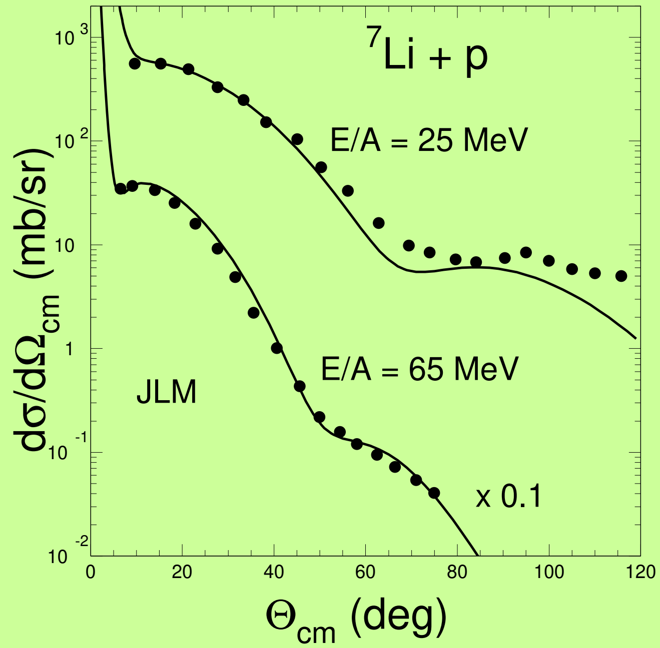
$$U(r,E) = \int V(\rho,E) f(r - \vec{r}\,')\, d\vec{r}\,'$$

Microscopic complex optical potential
energy and density-dependent
domain of validity : E_p < 160 MeV

$$U(\rho, E_p) = \lambda_v V(\rho, E_p) + i \lambda_w W(\rho, E_p)$$

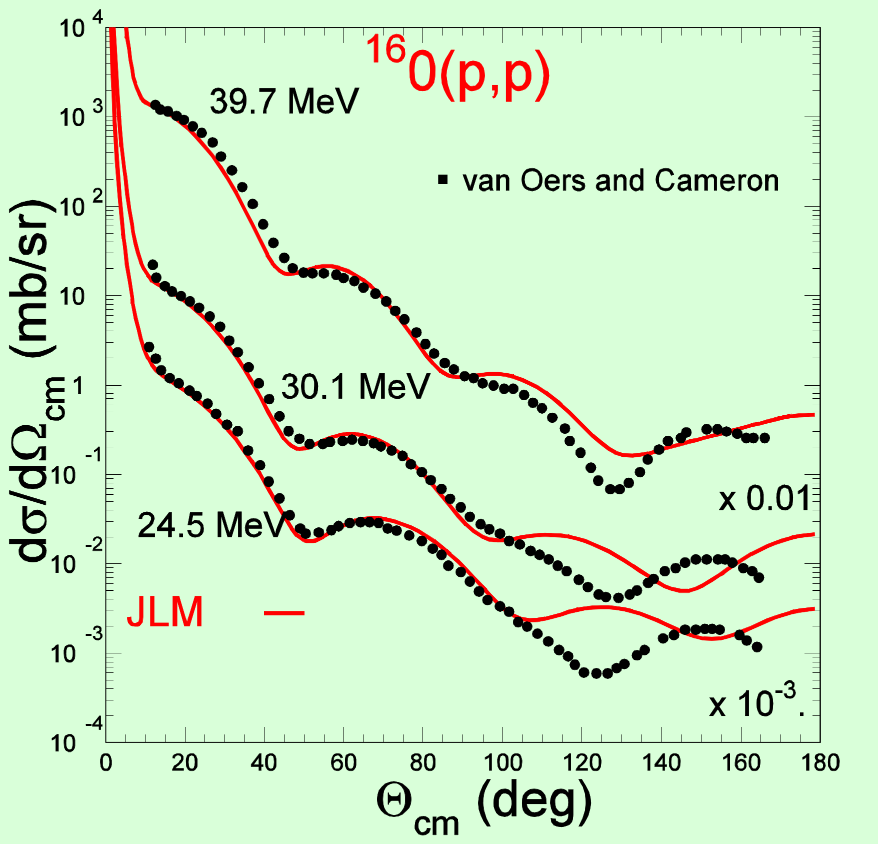
$$\rho : \rho_n , \rho_p$$

Light nuclei:
λ_w= **0.8**

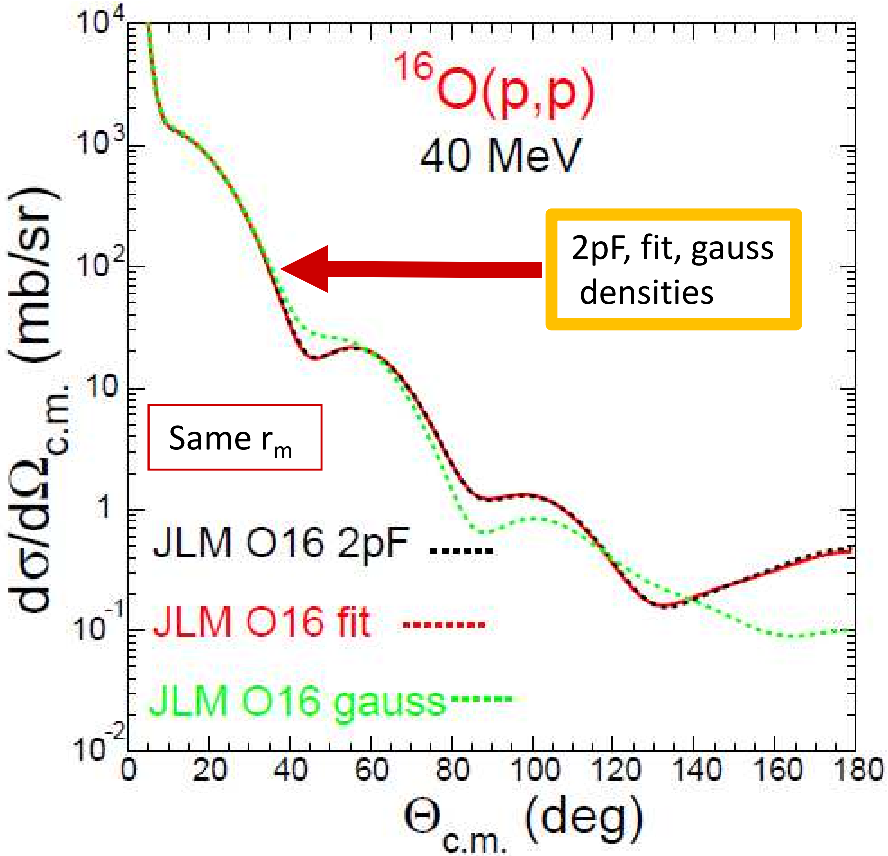


JLM calc. for ^{7}Li+p in ref . V. L et al., PLB **517**, 18 (‘01)

Proton Elastic Scattering: microscopic OMP analysis to extract rms radii



JLM calc. $^{16}O+p$: V. Lx, HDR report



Other examples of JLM analysis
$^{10,11,12}C$ (p,p') PRC **72**, 014308 ('05)
JLM lighter nuclei: λ_w= **0.8**

^{16}O experimental density (e,e); *Sick 1970*
At. Nucl. data tables, De Vries et al. (1987)
r_{ch}= 2.730 (25) fm → r_p exp 2.59 (7) fm
r_m = 2.57 fm (p,p) analysis

The sensitivity of (p,p) to r_m is ~±0.1 fm

Previous analysis: coupling effects observed for ^{6,8}He(p,p)

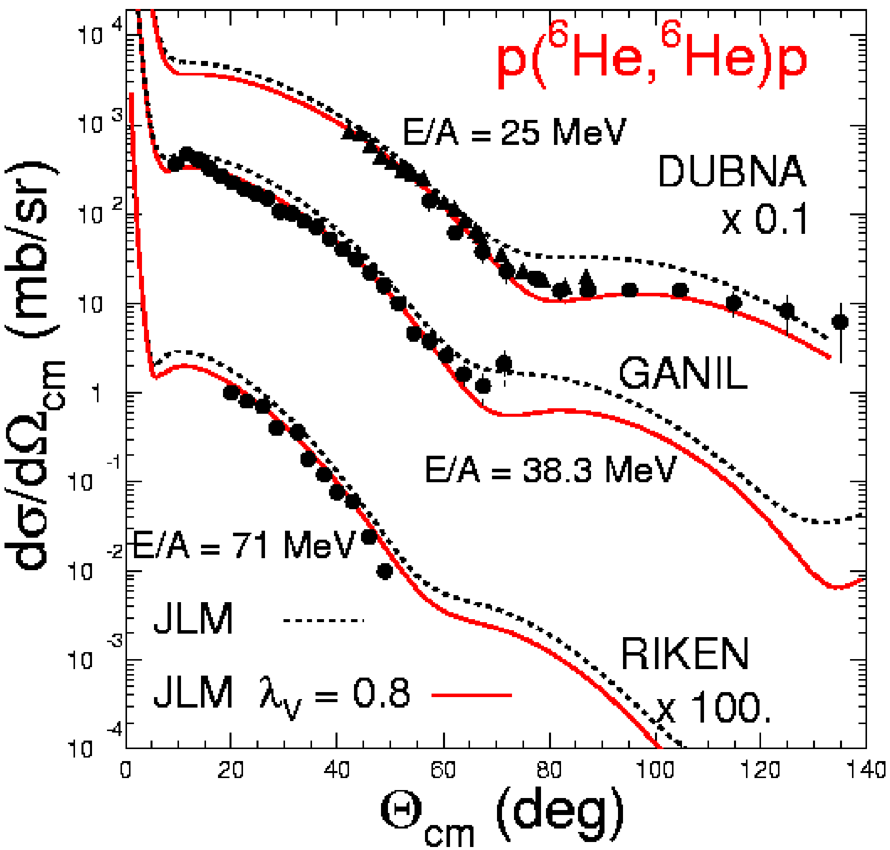
The JLM microscopic nucleon-nucleus optical potential
J.P. Jeukenne, A. Lejeune and C. Mahaux, PRC **16**, 80 (‘77)

$U_{JLM}(^8He+p) = \lambda_V V + i\, \lambda_W W$

$\lambda_V = 0.8$; $\lambda_W = 0.8$

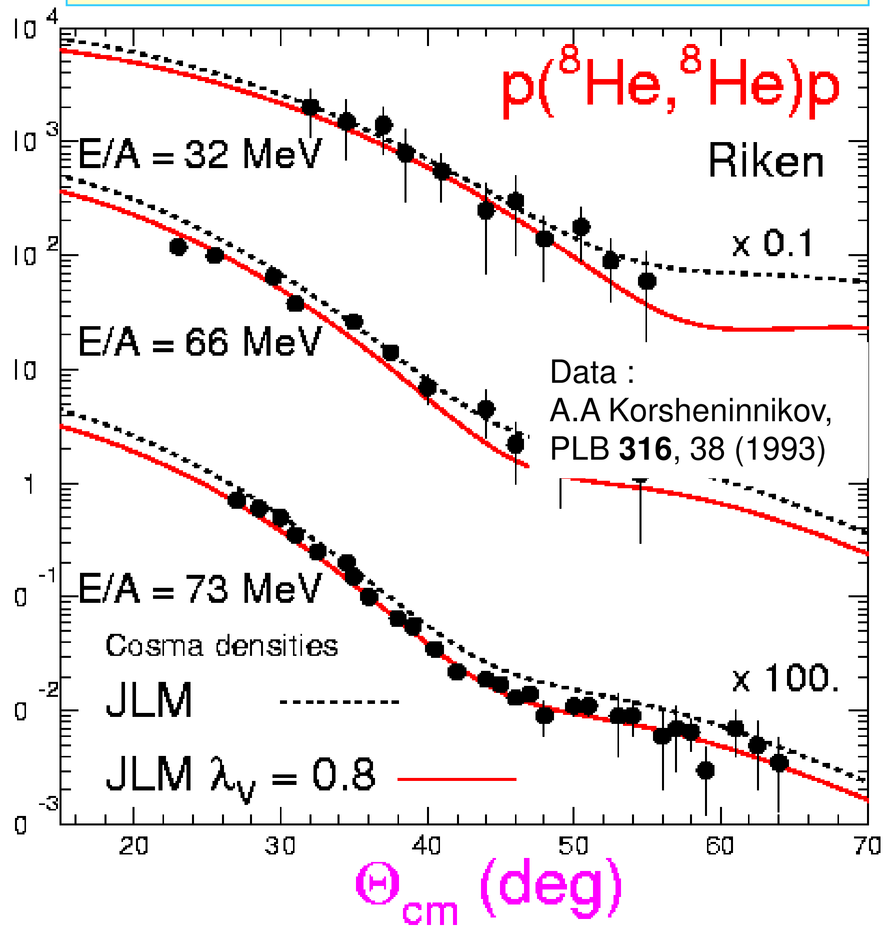
GANIL data + JLM analysis:
VLx et al., PLB **517**,18 (‘01)

Reduction of the real part: repulsive surface term
(from VCP virtual coupling potential)



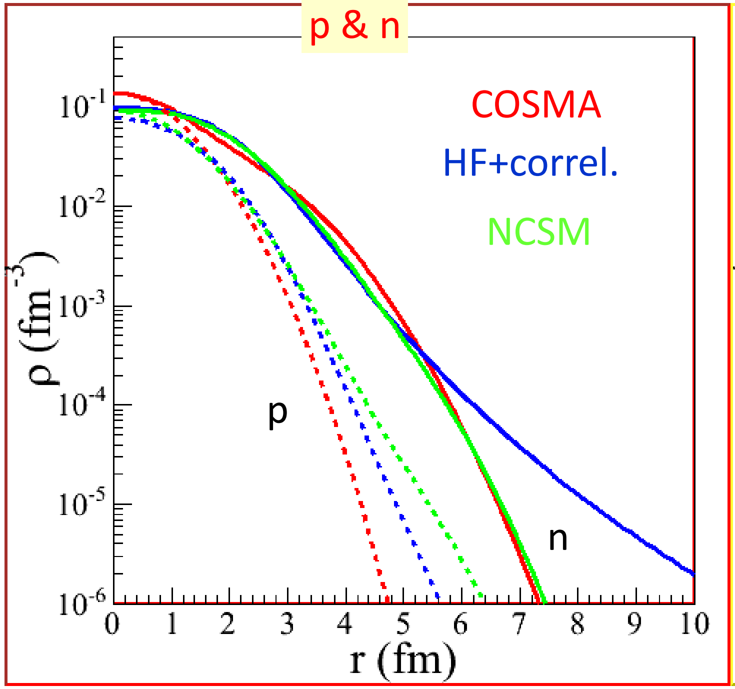
Dubna data :
R. Wolski et al.,
PLB **467**, 8 (1999)

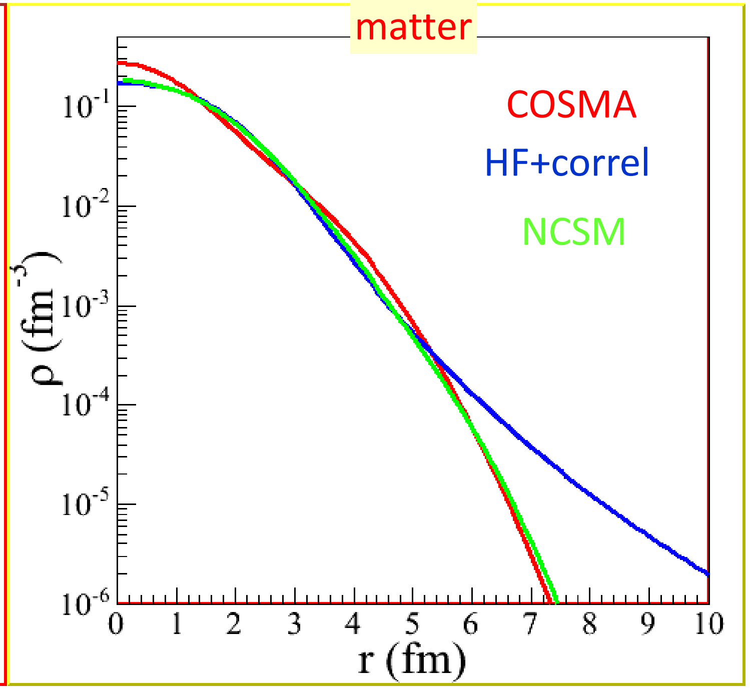
Riken Data : A.A
Korsheninnikov,
NPA**617**, 45 (1997)

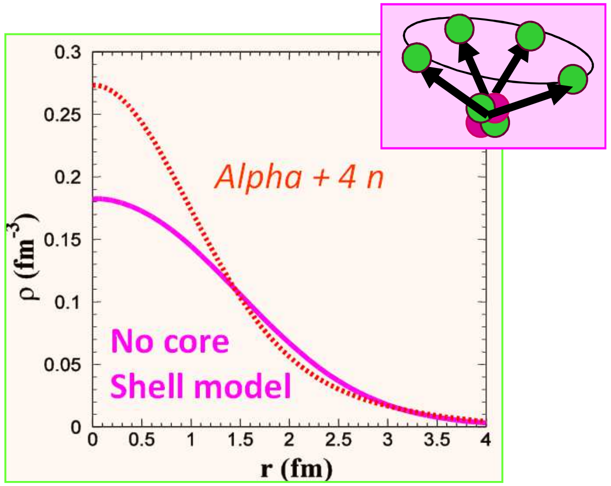


Halo/skin Densities: matter rms 2.5 ± 0.1 fm

Densities of ^{8}He:to be tested via (p,p) scattering







COSMA: M.V. Zhukov, A.A Korsheninnikov and M.H Smedberg, PRC 50 (1994) R1
HF+Correlations: H. Sagawa, PLB 286 (1992) 7
NCSM P. Navratil, priv. Co.+ PRC (98)

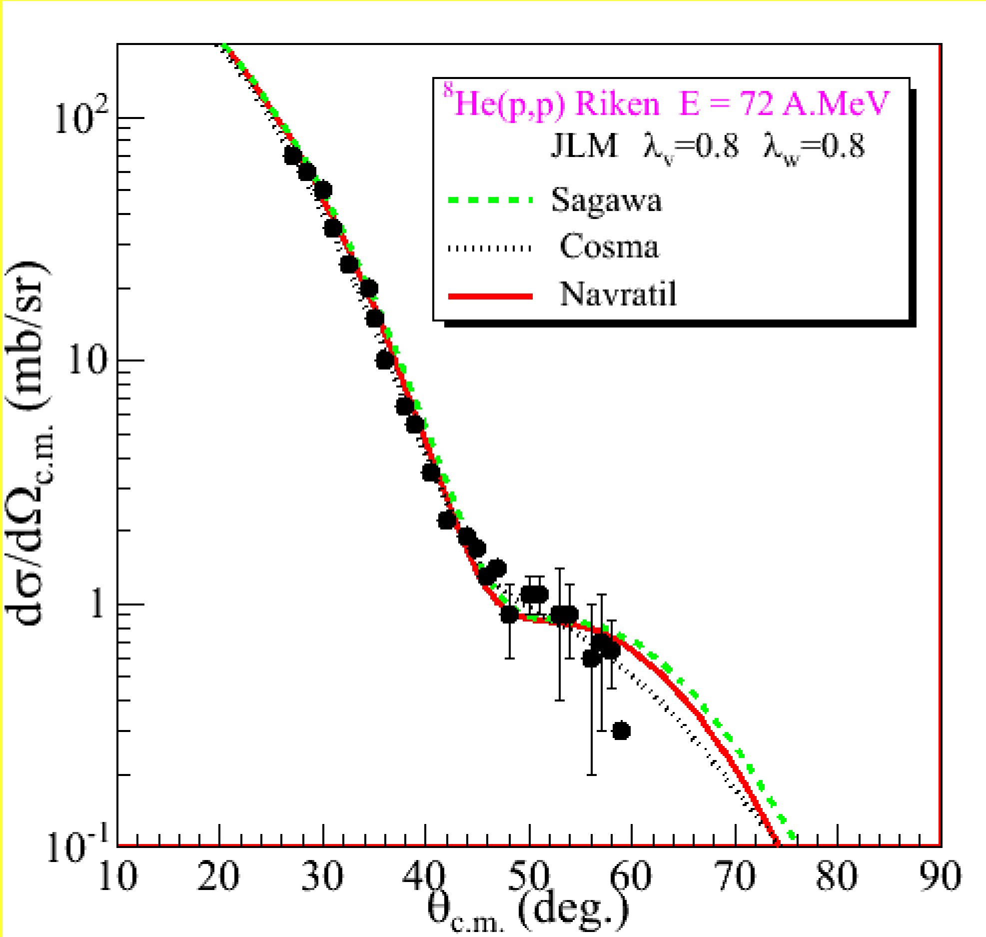
^{8}He	Rms (fm)		
	Proton	Neutron	Matter
COSMA 5-body	1.69	2.74	2.52
HF+corr Sagawa	1.95	2.67	2.51
NCSM, Navrátil	2.00	2.59	2.46

Analysis of elastic ^{8}He(p,p) within optical model framework

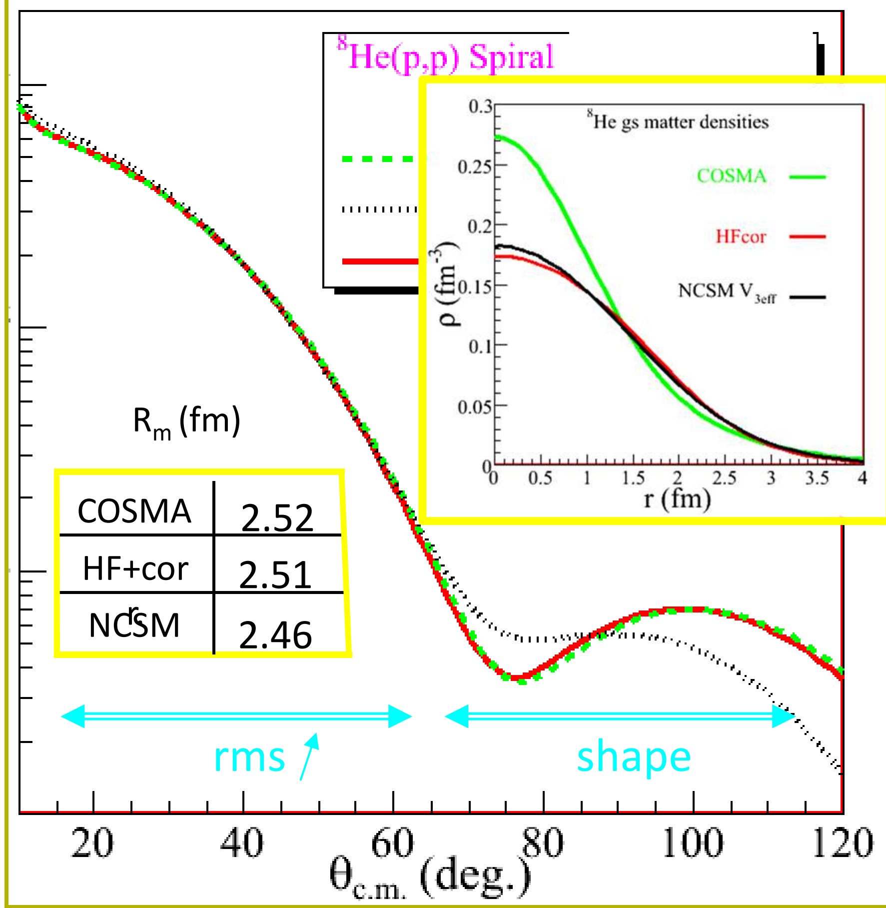
$U_{JLM}(^8He+p) = \lambda_V V + i\, \lambda_W W$

Reduction of the real part :
Repulsive surface term
generated by couplings

$\lambda_V = 0.8$; $\lambda_w = 0.8$



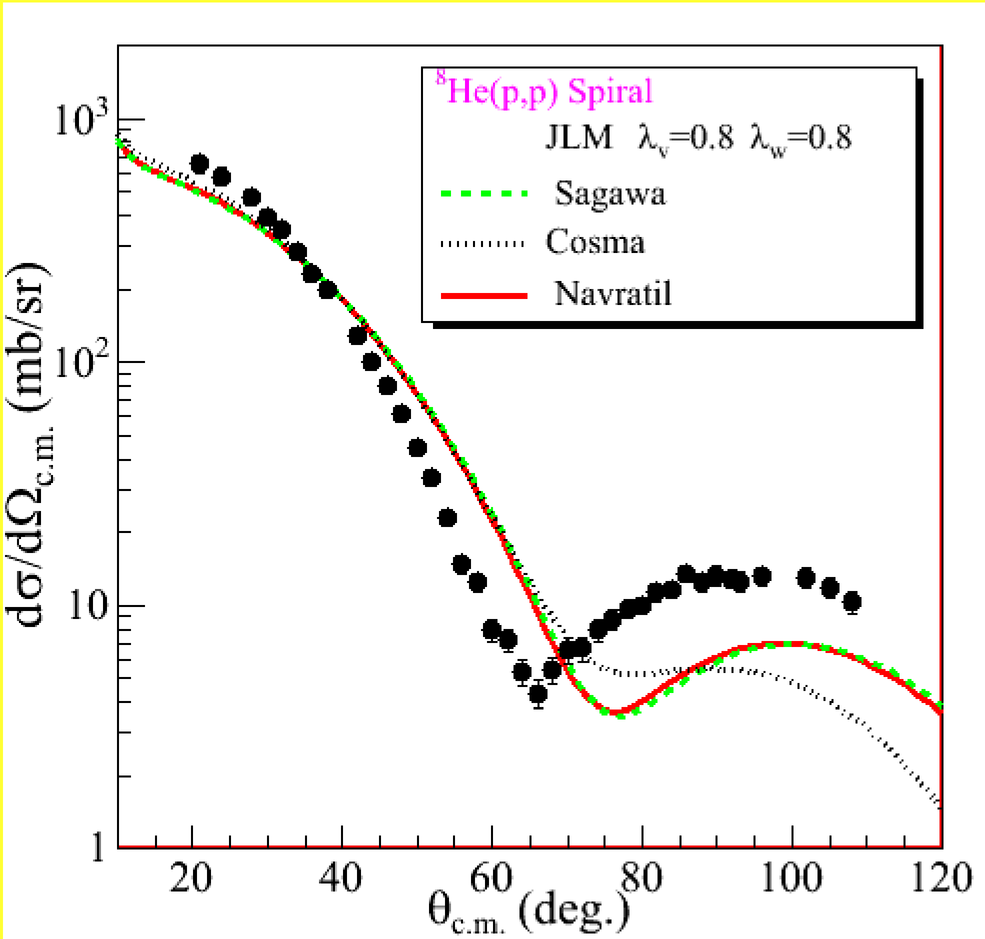
Eur.Phys. J A **51: 91** (2015)

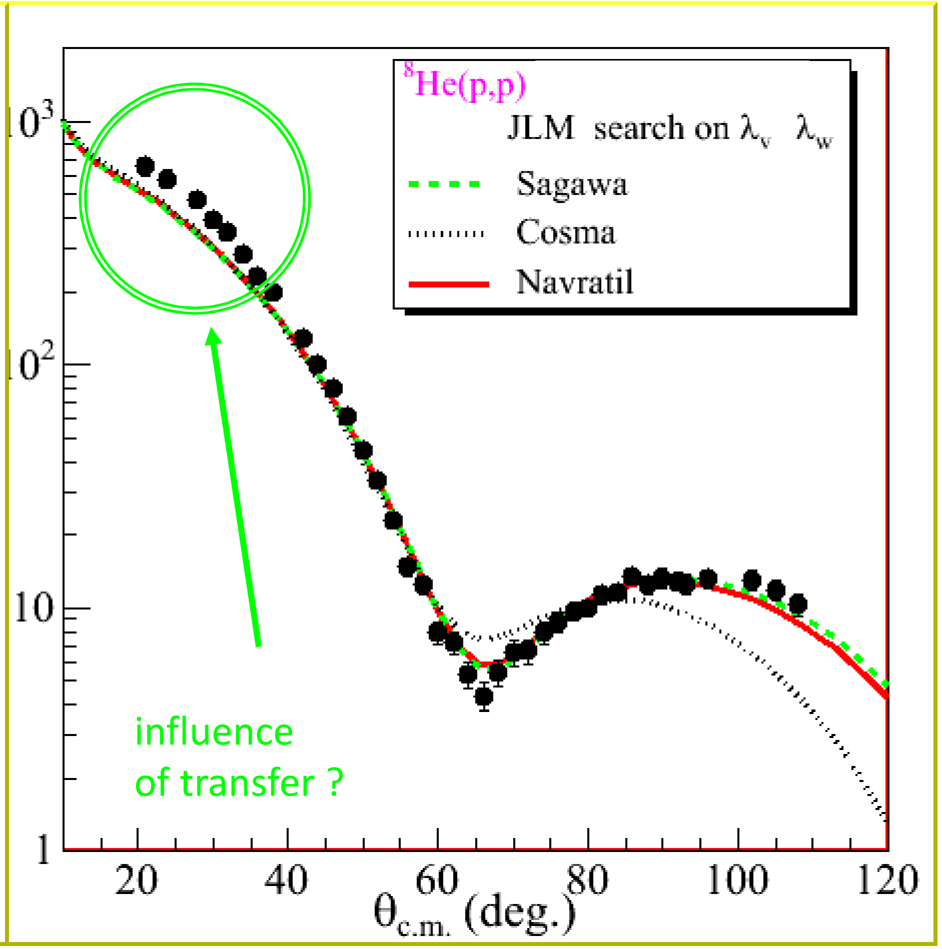


COSMA	2.52
HF+cor	2.51
NCSM	2.46

Neutron-skin densities: matter rms 2.5 ± 0.1 fm

Analysis of elastic ^{8}He(p,p) within optical model framework





$U_{JLM}(^8He+p) = \lambda_v V + i\,\lambda_w W$

EPJA **51: 91** (2015)

At low energy, V reduction not enough
→change of the potential due to the (p,d) coupling generating a complex Virtual Coupling Potential VCP

	λ_v	λ_w
COSMA	1.04	1.16
SAGAWA	1.13	1.07
Navrátil	1.11	1.06

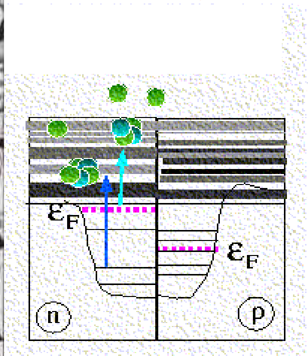
Optical model : $U_E = N_r\, V_{00} + i\, W$

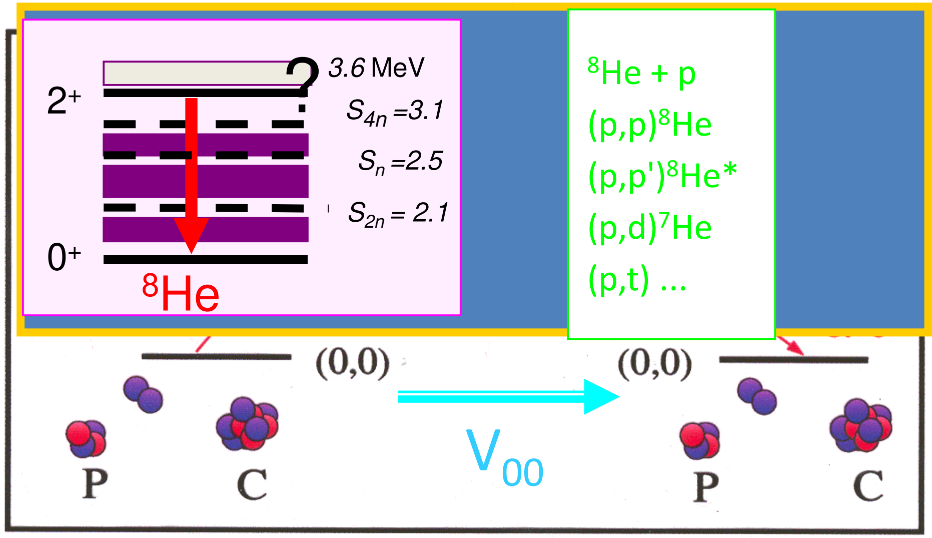
Reproduction of the data with $N_r \sim 1 \Rightarrow$ validity of the model

$N_r < 1 \Rightarrow$ coupling effects

◇ General framework of the nuclear reaction theory by FESHBACH

$$U_E = V_{00} + \lim_{\varepsilon \to 0} \sum_{\substack{(\alpha,\alpha') \\ \neq (0,0)}} V_{0\alpha} \left(\frac{1}{E - H + i\varepsilon} \right)_{\alpha\alpha'} V_{\alpha'0}$$

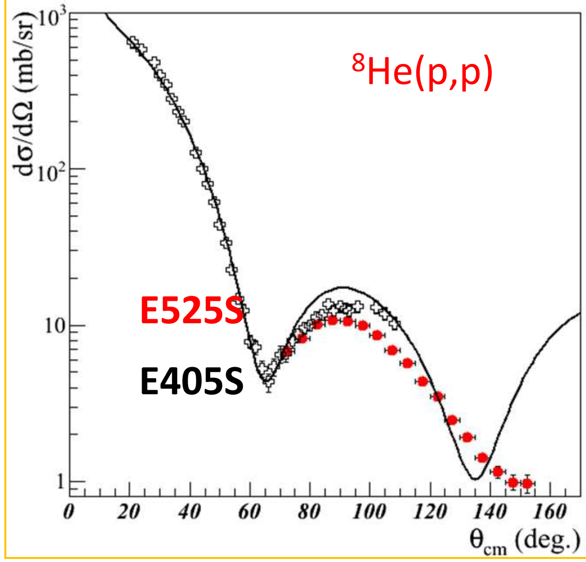




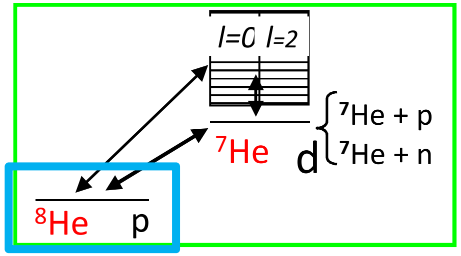
$\Rightarrow$ $U_E = V_{00}$ + VCP

References +examples:
R. Satchler, *Direct reactions* textbook
+ Y. Sakuragi , PRC 98 ('89)
$^{6}Li+^{12}C$, ^{28}Si,...

Comparisons EXP-theory for all the data sets of ^{8}He+p



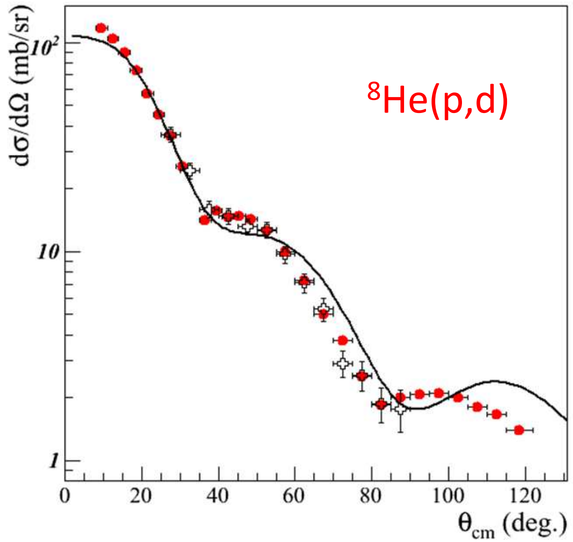
Pick-up effects on the
^{8}He(p,p) .Data +CRC:
PLB **619**, 82 (2005)

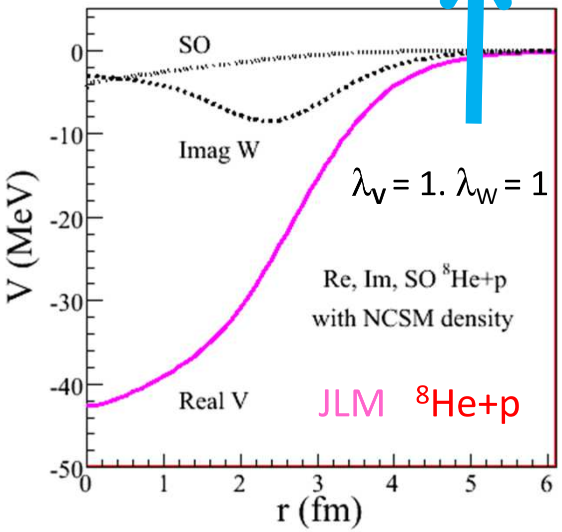


Effective coupling potential obtained from CRC with JLM

$U_E = V_{00}$ + VCP

[λ_v V+ i λ_WW]+PotCRC





λ_V = 1.05
λ_W = **0.2**

"Remaining" W:
CC, CRC, CN effects

EPJA **51: 91** (2015)

E525S data (MUST2) and CRC calculations (N. Keeley, Wasaw) + OMP JLM (V.L.): PLB **718,** 441 ('12)

Structure of ^{8}He extracted from CRC interpretation of direct reactions: ^{8}He+p @ 15.6 MeV/n

E405s at GANIL-MUST

$d\sigma/d\Omega$ > 10 mb/sr

1-n transfer elastic

Q ^{8}He(p,d) = -0.35

Q ^{8}He(p,t) = 6.34 MeV

CRC calculations *N. Keeley (Warsaw) + JLM calc. V. Lx*

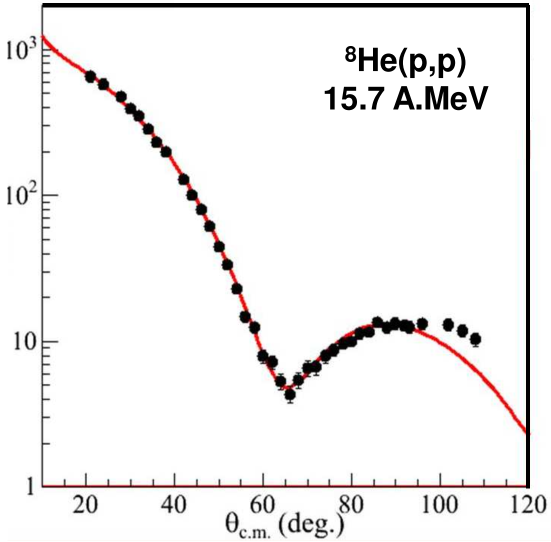
Data (p,p) PLB **619**, 82('05) ; (p,d) PRC **73**, 044301('06); (p,t) PLB **646**, 222('07)

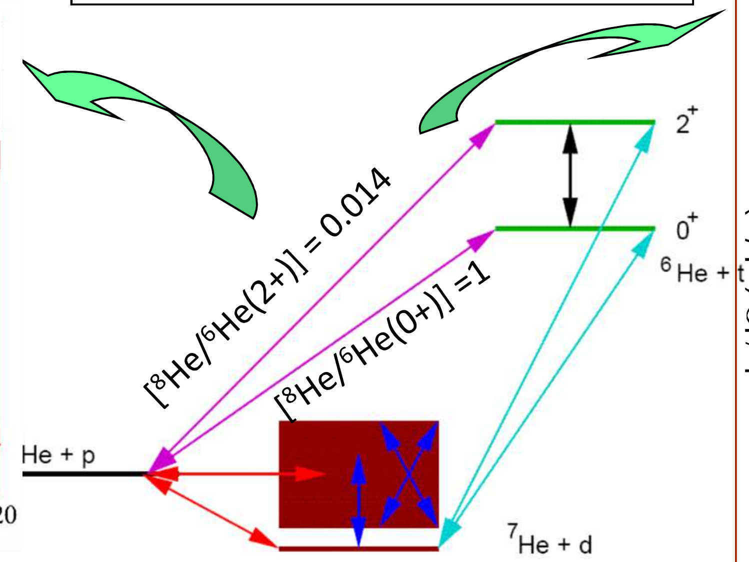
Spectroscopic factor

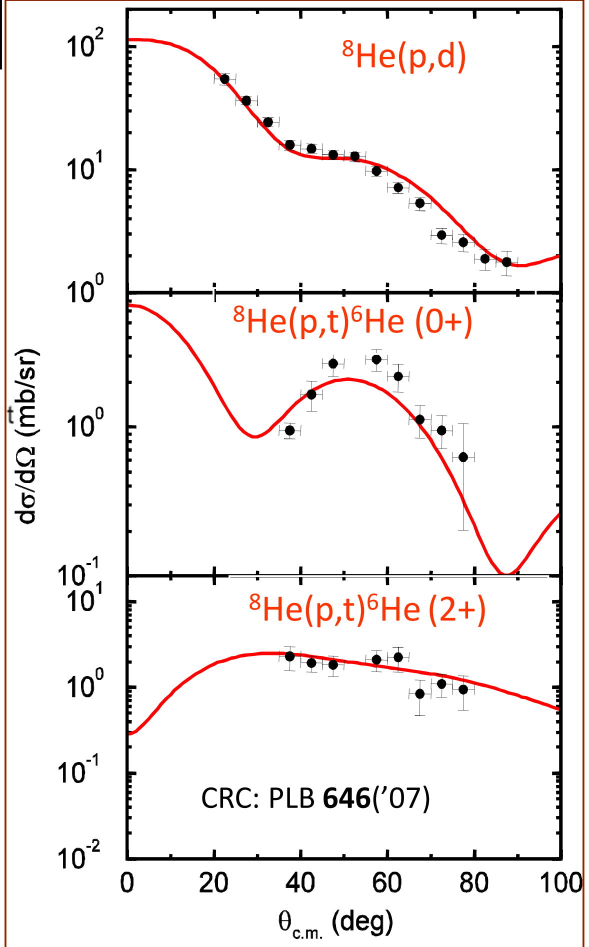
With **DWBA:** $C^2S\,(d\sigma/d\Omega)_{theo} = (d\sigma/d\Omega)_{exp}$

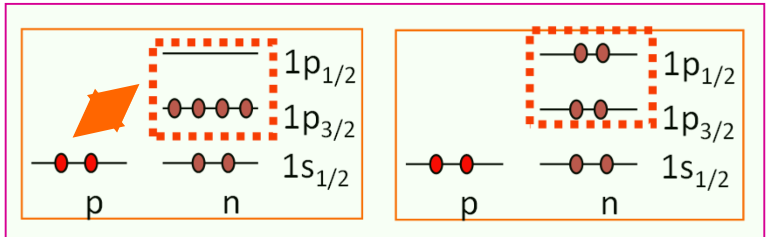
With **CRC** C^2S set for the CC %set of data

Transferred ang. momentum $L_t \rightarrow J^\pi$



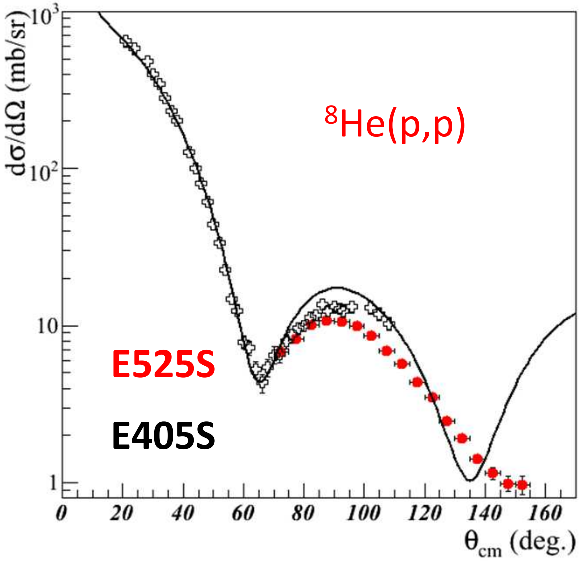


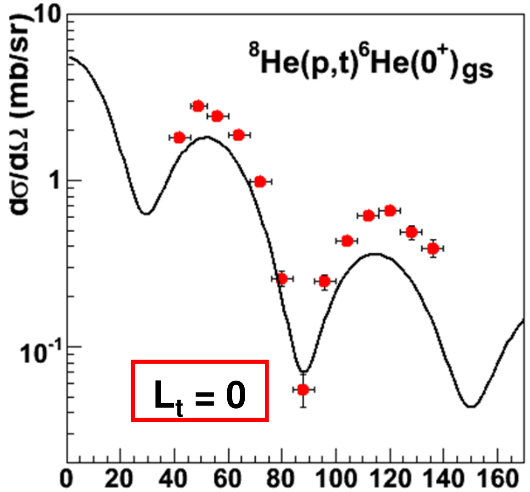


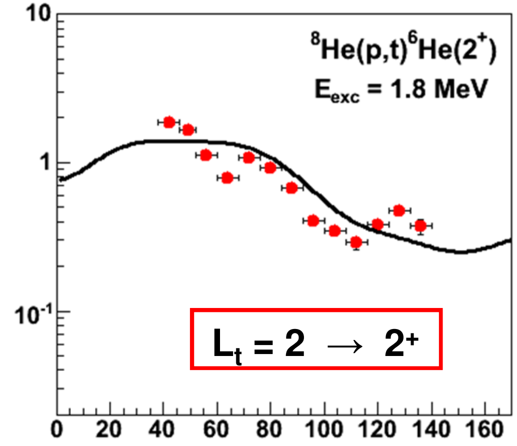


E525S data PLB **718,** 441 ('12)
CRC calc. N Keeley (Warsaw)

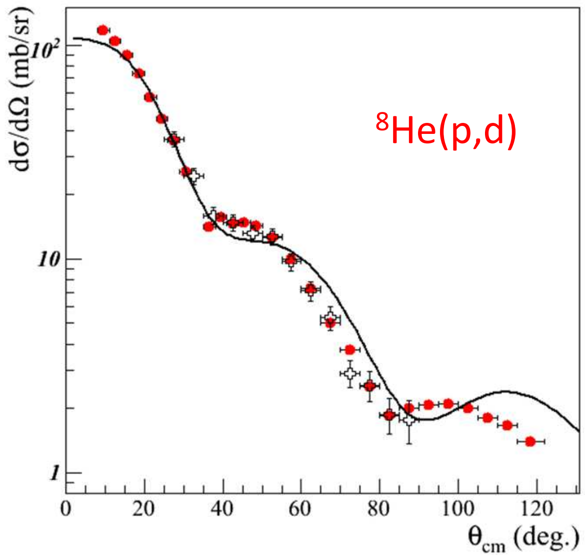
Comparisons EXP-theory for all the data sets of ^{8}He+p



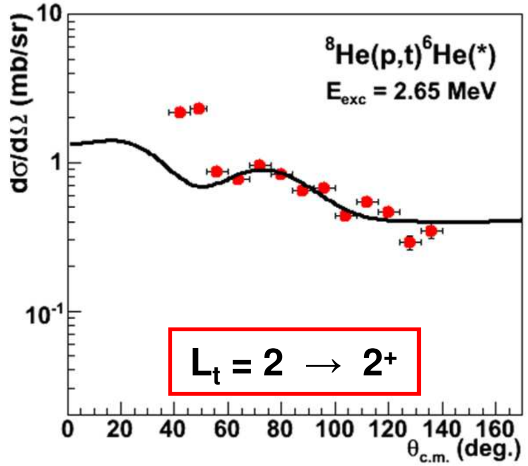




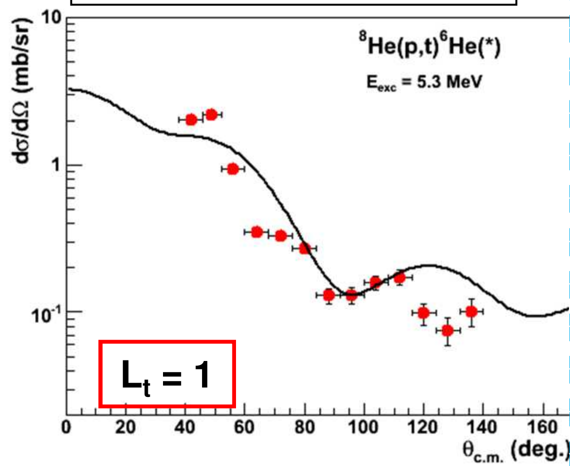
Shape of dσ/dΩ (θ_{cm}) gives L_t



E_{exc} = 2.6 MeV Γ = 1.6 MeV



E_{exc} = 5.3 MeV Γ = 2 MeV

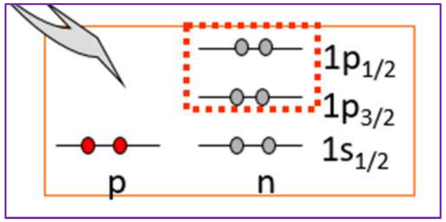


SPIRAL data obtained with MUST2 at the same energy -interpreted within various reaction model analysis

^{8}He(p,d)^{7}He SPIRAL *(MUST-1)* → ^{8}He % ^{7}He_gs SF
From CCBA → *$C^2S = 4.4 \pm 1.3$ (consistent with a full p3/2 subshell for 8He).*
Phys. Rev. C **73**, 044301 (2006). → *NOT THE END!*

SPIRAL data obtained with MUST2, at the same energy and interpreted in CRC analysis
PLB **646**, 222('07) + PLB **718,** 441 ('12)
(p,d) → ^{8}He % ^{7}He_gs SF
^{8}He(p,d)^{7}He SPIRAL → $C^2S = 2.9 \pm 0.9$

(p,t) → wave function ^{8}He % ^{6}He
[^{8}He/^{6}He(0+)] =1 ; [^{8}He/^{6}He(2+)] =0.014
Mixing: $(p3/2)^4$ and $(p3/2)^2$ $(p1/2)^2$



→ Consistent with the results from quasi-elastic scattering of ^{8}He at GSI,
L.V. Chulkov et al, NP***A759***, 43(2005) [^{8}He/^{6}He(0+)] : 1.3 ± 0.1 [^{8}He/^{7}He(gs)] =3.3 ± 0.3
→ Consistent with recent theoretical calculations:
K. Hagino, N. Takahashi, H. Sagawa PRC **77**, 054317 (2008)
Neutron configurations % ^{8}He (gs.) : $(1p_{3/2})^4$: 34.9 % ; $[(1p_{3/2})^2(p_{1/2})^2]$: 23.7 %
$(1p_{3/2})^2$ $(1d_{5/2})^2$: 10.7 % ; $[(2s_{1/2})^2(1p_{3/2})^2]$: 7.8 %

→ *Cf AMD calculations and the discussion of the dineutron configurations in the 8He wf.*
Dineutron structure in 8He Y. Kanada-En'yo, PRC 76, 044323 (2007)
N.B. The AMD densities and NCSM (in the V3eff version) present similar proton and neutron rms radii.

Conclusions

Perspectives

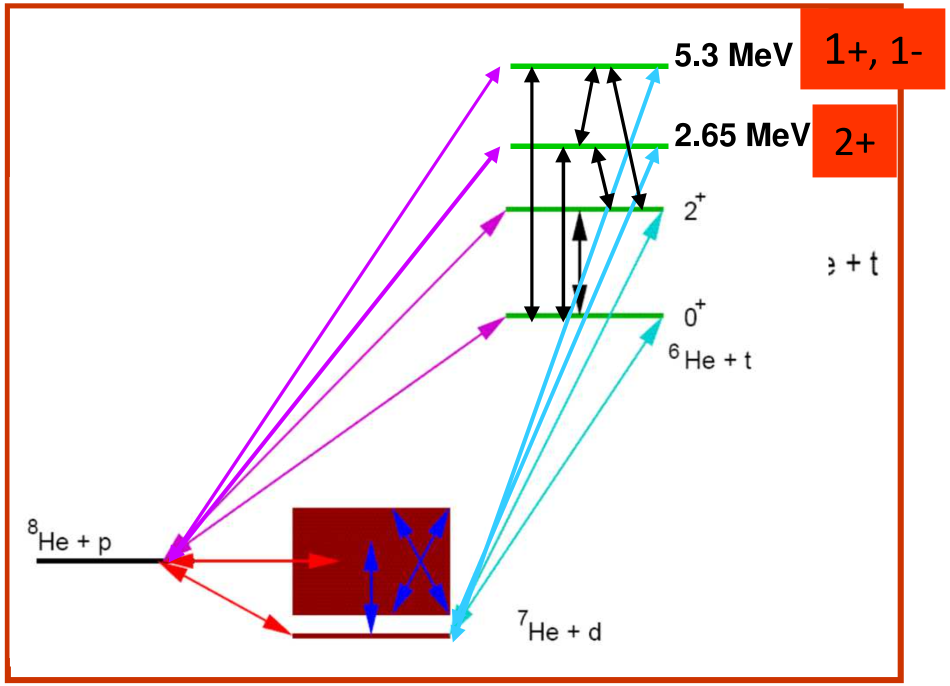
Reaction **frameworks**
State of the art: Coupled Reaction Channel analysis
Explicit channel coupling+microscopic potentials JLM

Next — REQUEST TO THEORISTS: use/check ^{8}He+p system !

^{8}He

CRC and mixing:
$(p3/2)^4$; $(p3/2)^2$ $(p1/2)^2$

Results
Spectroscopy of ^{6}He via ^{8}He(p,t) –Ex, Xs
MUST2 E525S data at GANIL
PhD work: X. Mougeot (CEA)
Collaborator for CRC calculations :
N. Keeley *(NCBJ, Nuclear Centre for Nuclear Research)*
New excited states in the halo nucleus ^{6}He,
PLB **718**, 441 (2012).

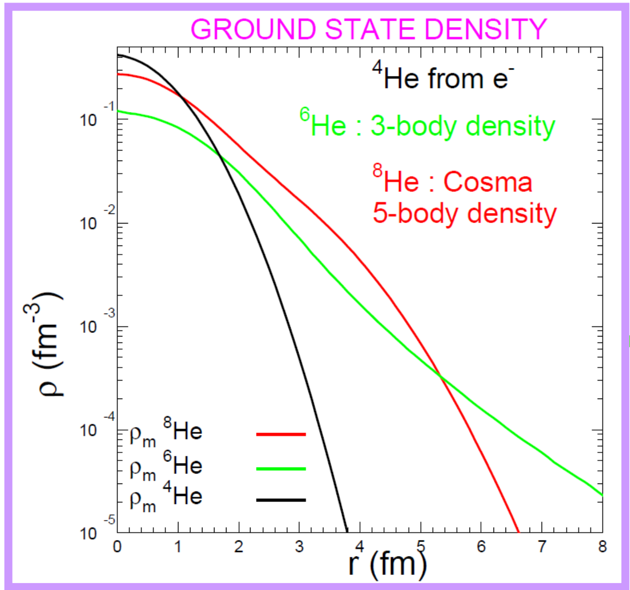


- **Test the assumptions on the structure and the validity of the framework**
- **This requires to make “coupled-channel” type measurements**

Accurate data / large angular domain
Transfer data including **elastic (p,p):**
entrance OM potential under control
→ Checking the CRC calc. **consistency**

Observables

Next question: evaluation of the exp. data for rms radii



Long-term goals for experimental nuclear densities:
charge &matter profiles for RI as done for stable nuclei

Limitations due to achievable luminosity;
physics cases limited to radii, for nuclei close to the valley of stability

Ab-initio results can be compared to exp. charge & matter radii
Binding energies: ok see O isotopes but problems with rm
There are some troubles in the force…or in the concept
Look also at EDF results
which are encoding the nuclear properties in an effective way

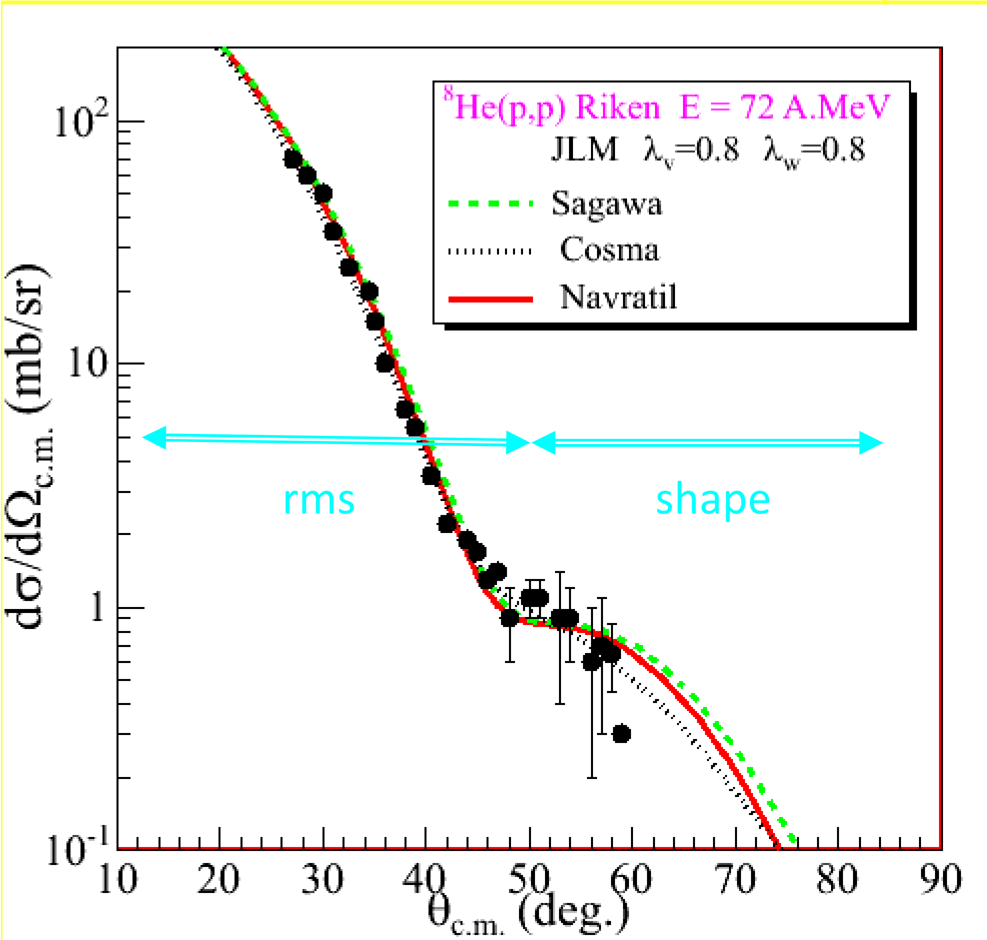
Perspectives for combined e-& (p,p) scattering?
→We need to look back at the (e,e)& (p,p) data using modern structure &reaction model calculations to extract the nuclear densities

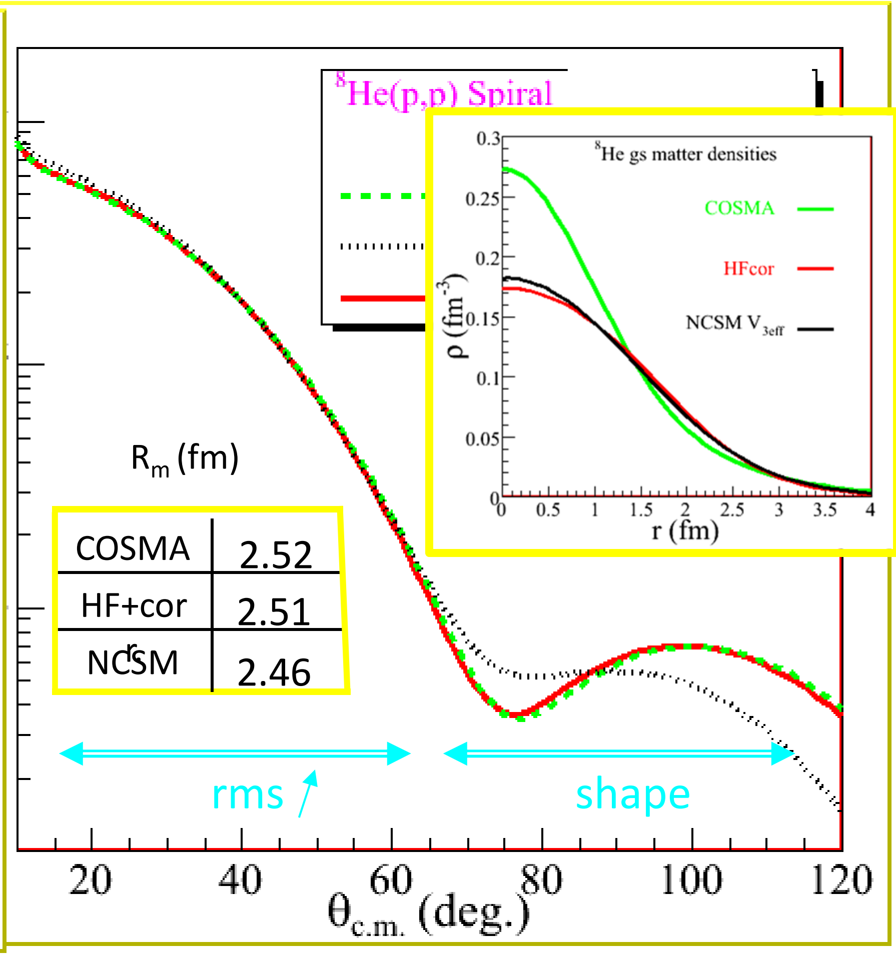
Questions: evaluation of the exp. data for rms radii + uncertainties related to the microscopic interaction used for the (p,p) reaction models, whatever the nucleon energy? In the case of the radioactive exotic nuclei, how to deal with the weak-binding effects?

Nuclear matter radii via (p,p) scattering

$U_{JLM}(^{8}He+p) = \lambda_V V + i\,\lambda_W W$

Reduction of the real part due to a repulsive surface term generated by couplings $\lambda_V = 0.8$; $\lambda_W = 0.8$

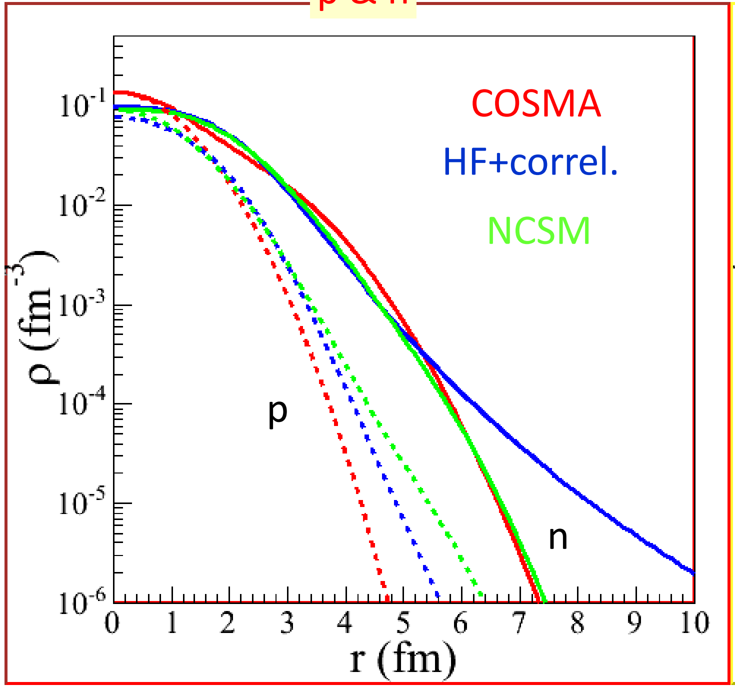


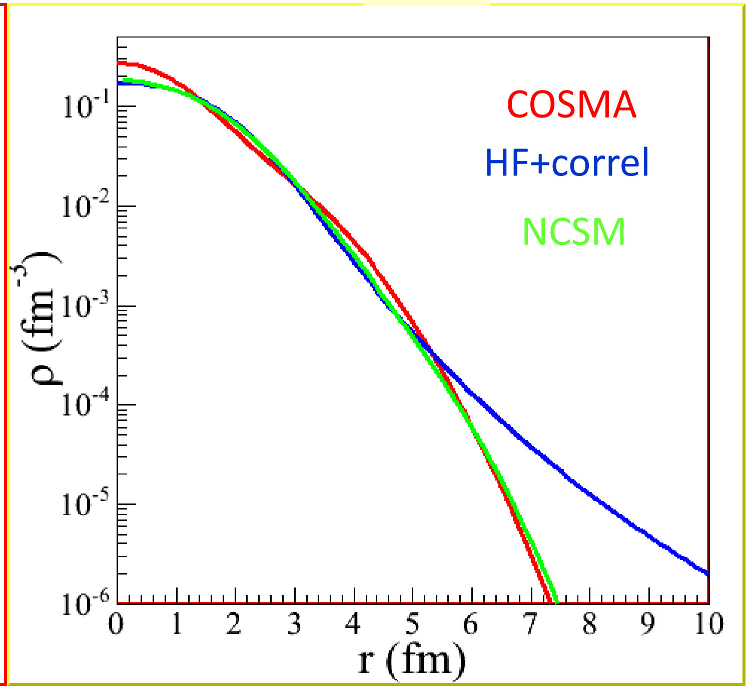


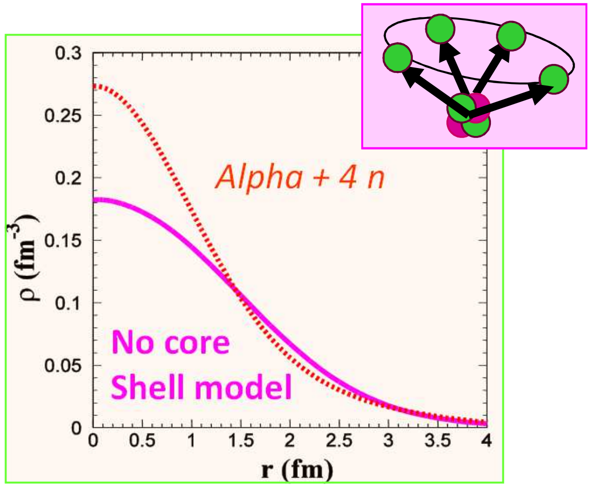
COSMA	2.52
HF+cor	2.51
NCSM	2.46

V. Lapoux and N. Alamanos, EPJA **51** 91 (2015).

Densities of ^{8}He: to be tested via (p,p) scattering







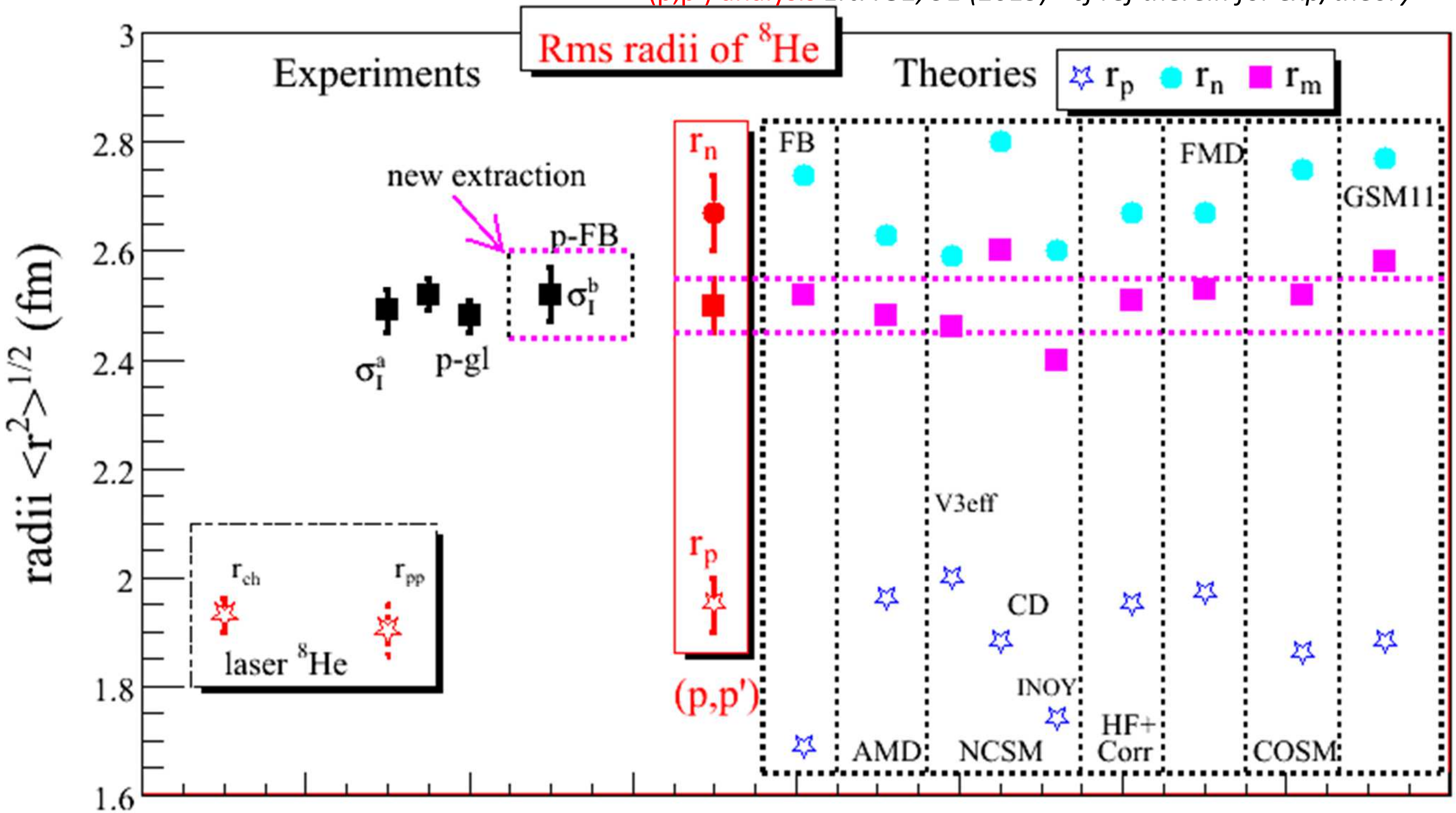
COSMA: M.V. Zhukov, A.A Korsheninnikov and M.H Smedberg, PRC 50 (1994) R1
HF+Correlations: H. Sagawa, PLB 286 (1992) 7
NCSM P. Navratil, priv. Co.+ PRC (98)

^{8}He	Rms (fm)		
	Proton	Neutron	Matter
COSMA 5-body	1.69	2.74	2.52
HF+corr Sagawa	1.95	2.67	2.51
NCSM, Navrátil	2.00	2.59	2.46

8He

Experiment versus theories for proton and matter radii

(p,p') analysis *EPJA **51**, 91 (2015) - cf ref therein for exp/theory*



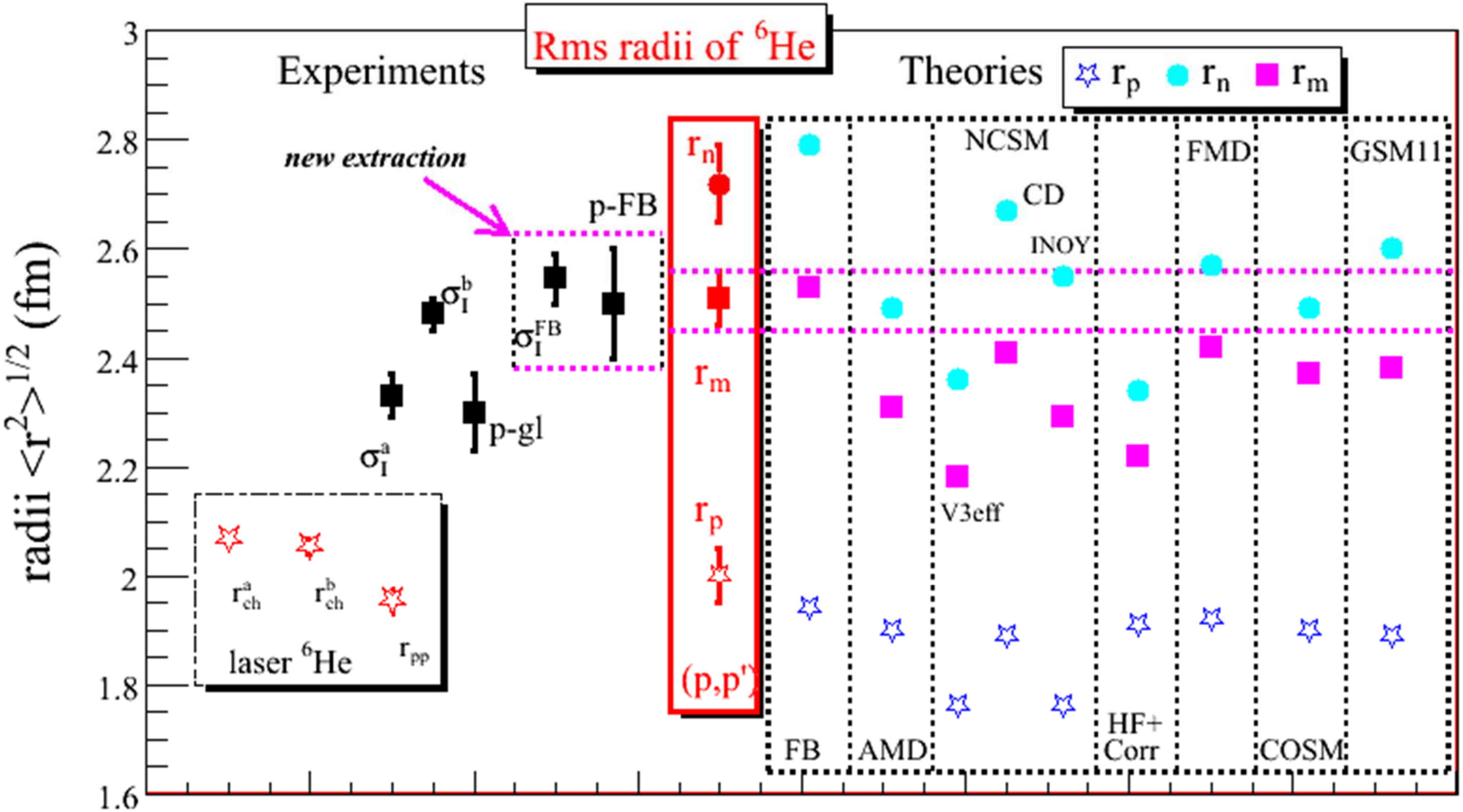
Laser L.B. Wang et al., PRL 93, 142501 (2004). P. Mueller et al., PRL 99, 252501 (2007). M. Brodeur et al., PRL. 108, 052504 (2012).

p-gl G.D. Alkhazov et al., PRL 78, 2313 (1997).
p-FB J. Tostevin, J. Al-Khalili, NPA 616, 418c ('97). PRC 57, 1846 ('98)
σ A. Ozawa, T Suzuki, I. Tanihata NPA **693**, 32 (2001)

AMD-m56 K. En'yo PRC **76** ('07)
FMD T. Neff, H. Feldmeier, NPA **738,** 357 (2004)
HF+corr H.Sagawa et al PLB **286** (1992)
COSM T. Myo et al, PRC **76** ('07); PRC **80** (09)
GSM11 G. Papadimitriou PRC **84** ('11)

6He

Experiment versus theories for proton and matter Rms radii



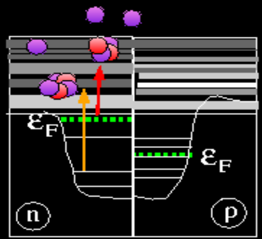
Laser L.B. Wang et al., PRL 93, 142501 (2004).
P. Mueller et al., PRL 99, 252501 (2007).
M. Brodeur et al., PRL. 108, 052504 (2012).

(p,p') analysis:VLx, N. Alamanos, ***EPJA 51**, 91 (2015)*
Weakly-bound structures of the exotic ^{6,8}He Cf ref therein

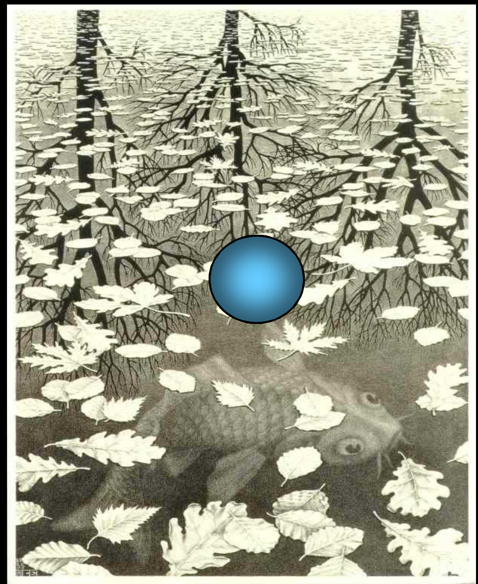
AMD-m56 K. En'yo PRC **76** ('07)
FMD T. Neff, H. Feldmeier, NPA **738,** 357 (2004)
HF+corr H.Sagawa et al PLB **286** (1992)
COSM T. Myo et al, PRC **76** ('07); PRC **80** (09)
GSM11 G. Papadimitriou PRC **84** ('11)

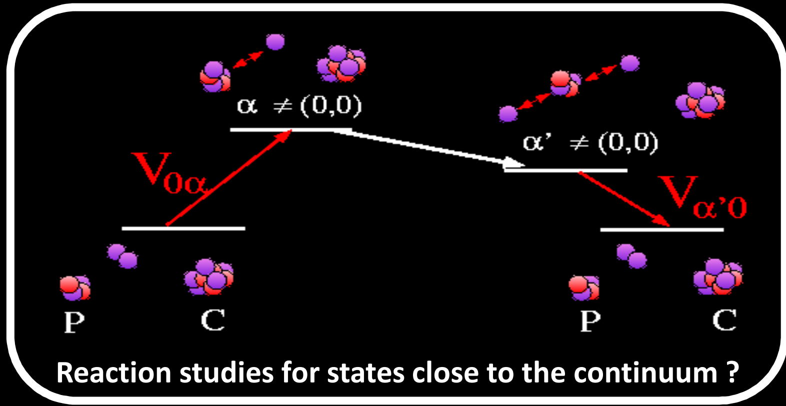
Goals for structure-reaction theories: from fish to bird

Scattering states



Bound states





We need theories with:

- structure and reactions on the same footing
- Treatment of states embedded in the continuum
- Treatment of reaction coupling between nucleon transfer & elastic entrance channels
- possibly taking into account realistic ab-initio nuclear forces

ψ ***Observables***

Theories for E_{gs}, E_x , r_{ch}, r_m … ρ_{ch}, ρ_m
+ direct access to (p,p), (e,e) reactions

→ **Crucial role played by the r_m observable**

→ benchmarks for theories
Evolution of interactions

→ **necessary step to build an unified model for structure & reactions**