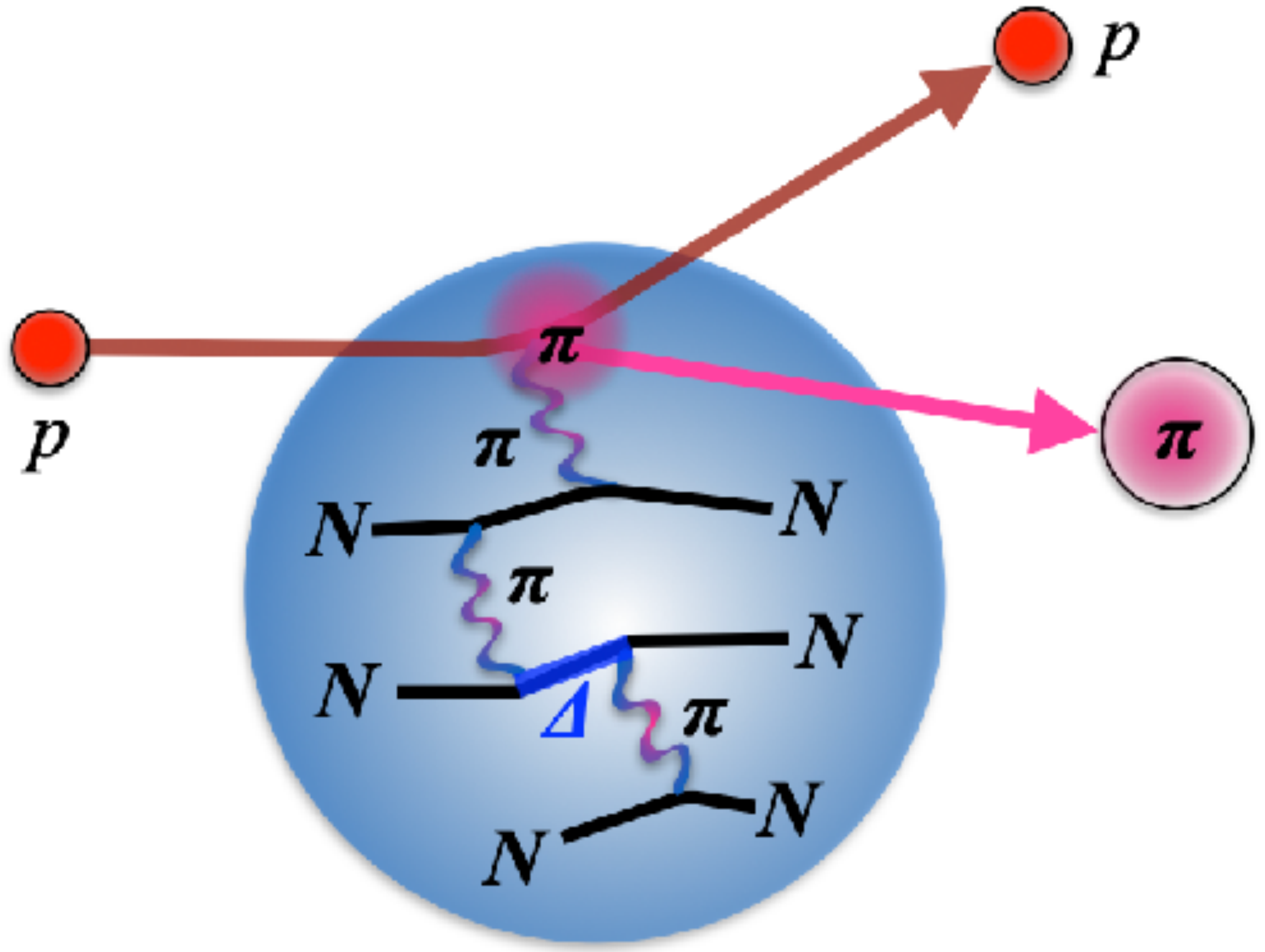
$(p, p\pi)$ project for pion nuclear physics

Hiroshi Toki (RCNP/Osaka)
Junki Tanaka (RCNP/Osaka)



Collaborators from RIKEN and RCNP

RAON collaboration is welcome

Strong interaction is very interesting and difficult

Nambu

The fundamental dynamics is QCD

$$L_{QCD} = \bar{\psi}(i\gamma_\mu(\partial^\mu - eA^\mu) - m)\psi + \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a}$$

Quarks and Gluons

Confinement (Dual Meissner effect)

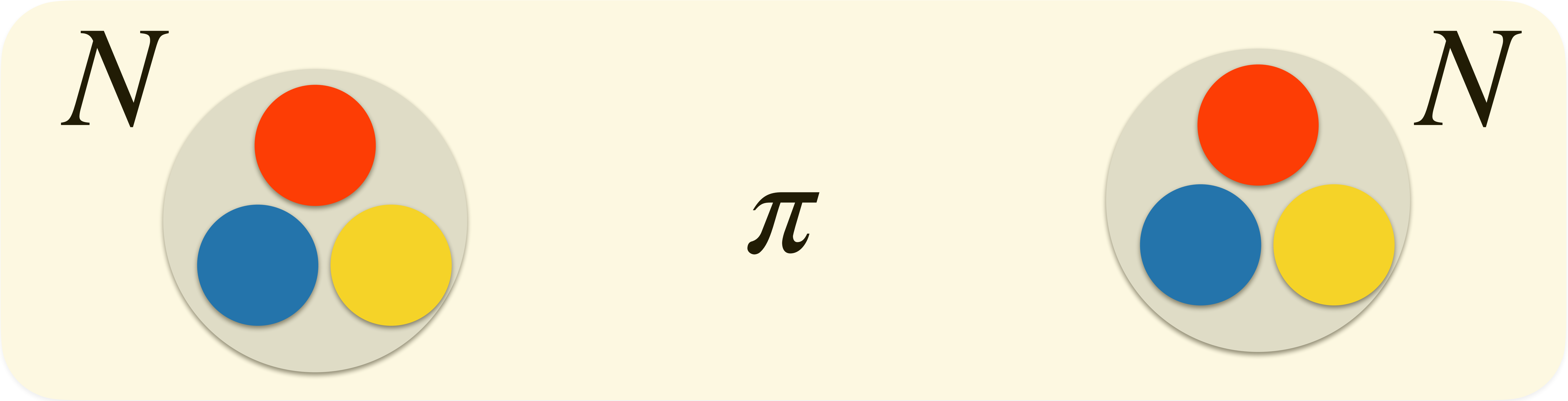
Chiral Symmetry Breaking

$m \to M = M_N/3$

π nearly zero mass pion 0^-

nucleon

Nucleon-nucleon interaction

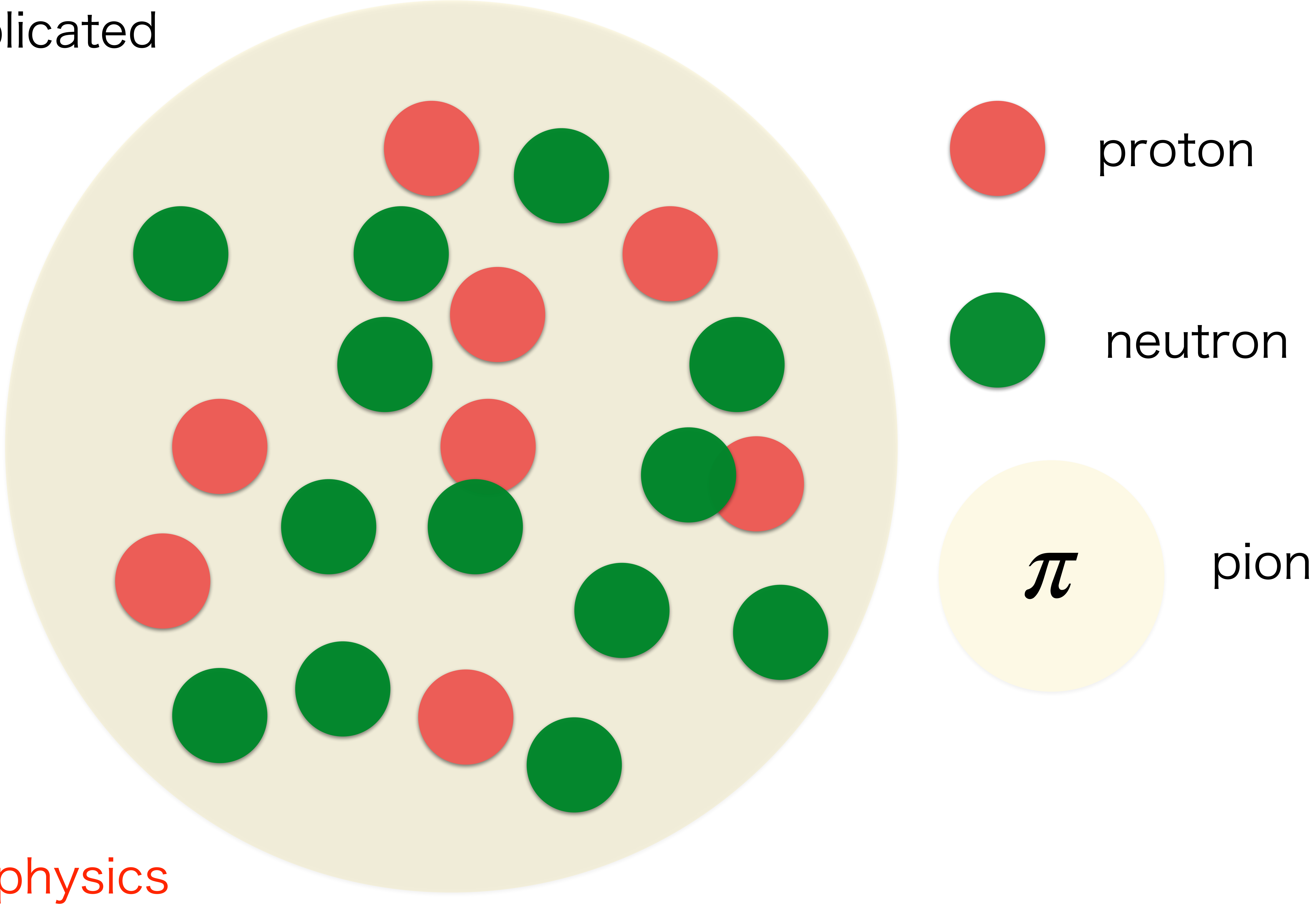


$$V_\pi = -\frac{f_\pi^2}{m_\pi^2}\frac{(\sigma_1 \cdot q)(\sigma_2 \cdot q)}{m_\pi^2 + q^2}\tau_1\tau_2$$

Pion exchange interaction:

Very strong: Long range: High momentum: Tensor interaction

Nucleus is complicated



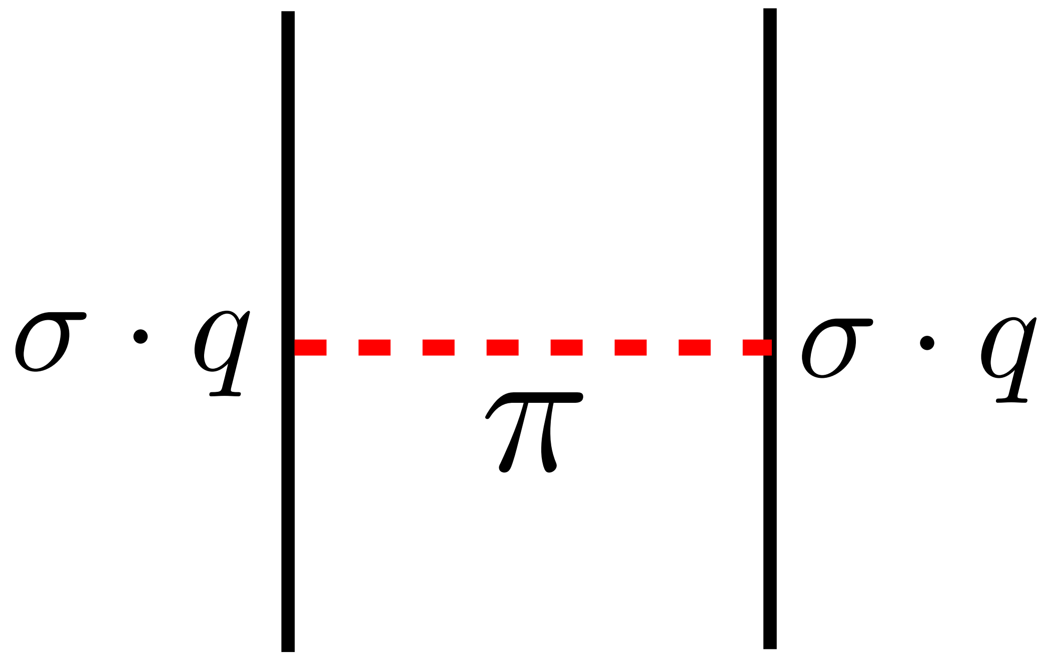
Pion nuclear physics

Why tensor interaction is strong?

Pion is a pseudoscalar meson $J^\pi = 0^-$

Pion interaction = Tensor interaction

$$V_\pi = -\frac{f_\pi^2}{m_\pi^2}\frac{(\sigma_1\cdot q)(\sigma_2\cdot q)}{m_\pi^2+q^2}\tau_1\tau_2$$

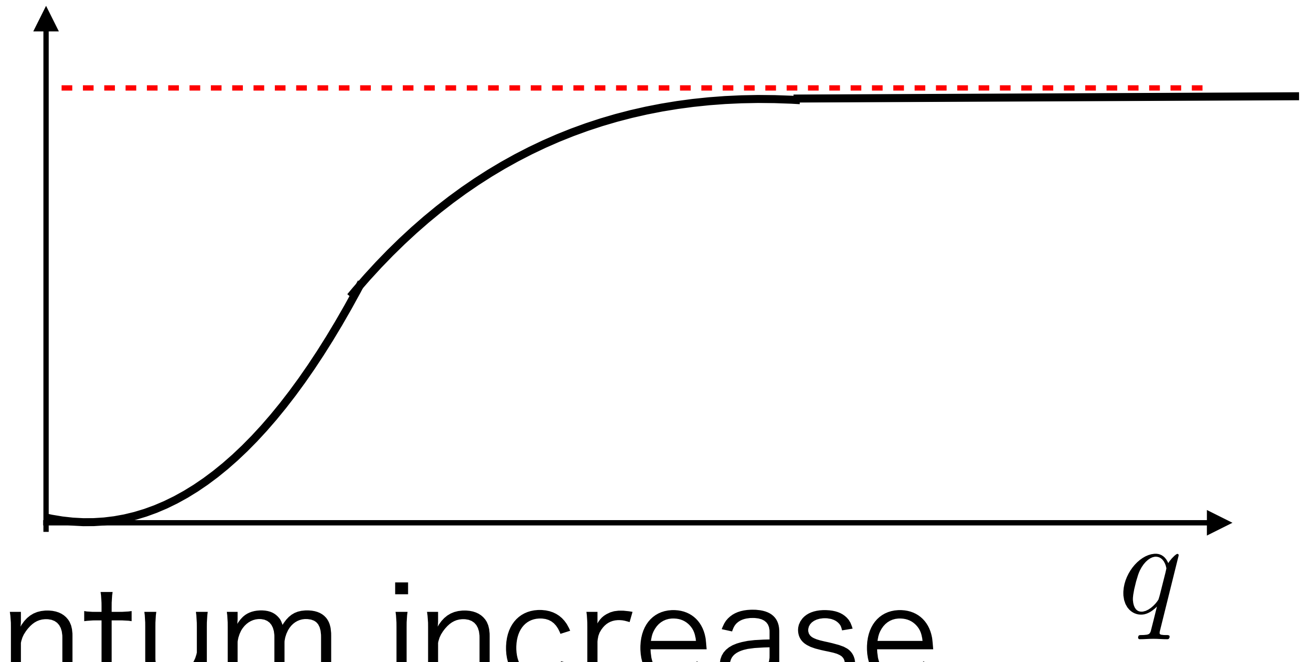


Pion Yukawa Tensor

$$\frac{(\sigma_1\cdot q)(\sigma_2\cdot q)}{m_\pi^2+q^2} = \frac{1}{3}\sigma_1\sigma_2\left[\cancel{\frac{m_\pi^2+q^2}{m_\pi^2+q^2}} - \frac{m_\pi^2}{m_\pi^2+q^2}\right] + \frac{1}{3}S_{12}(q)\frac{q^2}{m_\pi^2+q^2}$$

δ関数

$$S_{12}(q) = [[\sigma_1\sigma_2]_2 \times Y_2(q)]_0$$

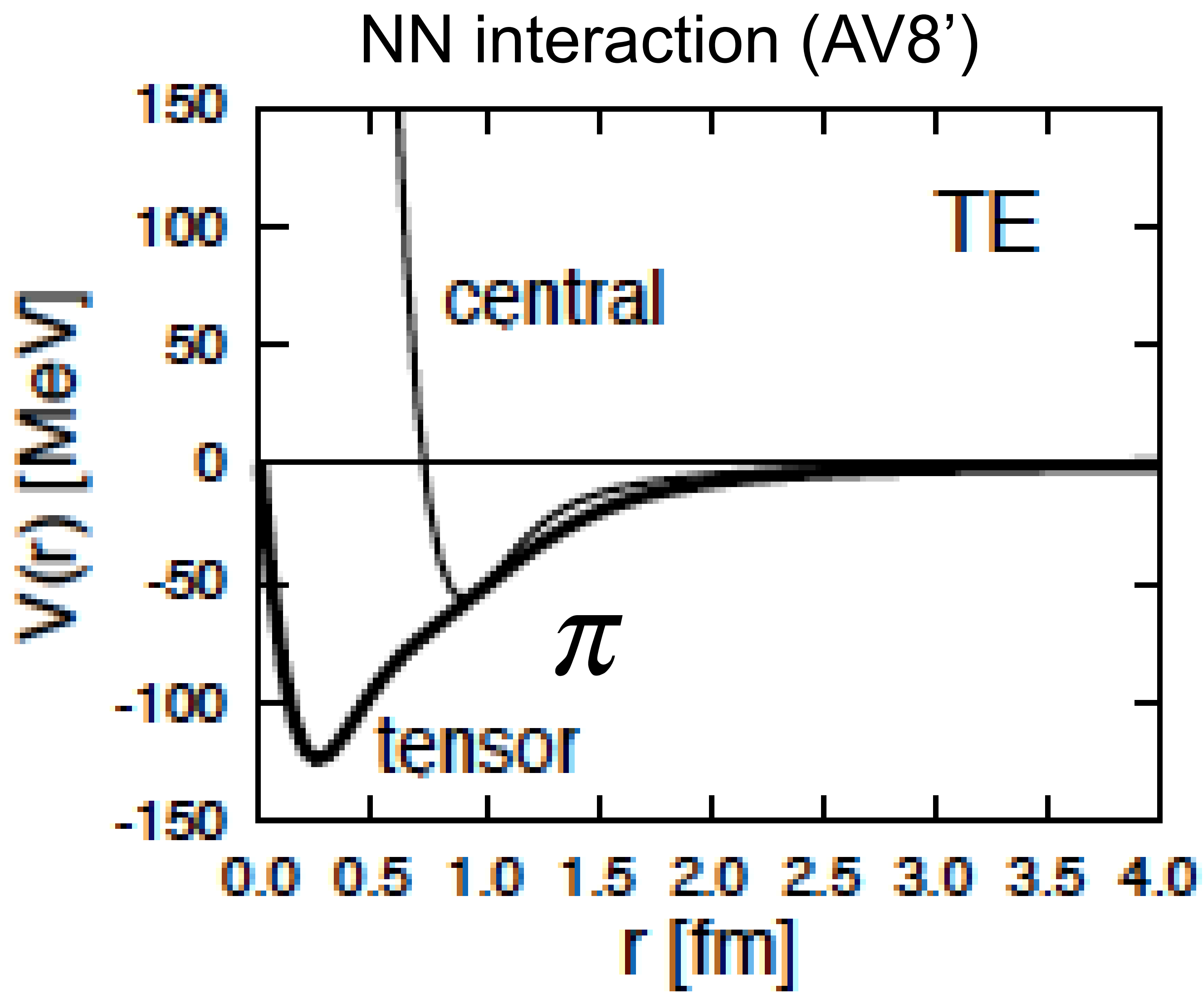


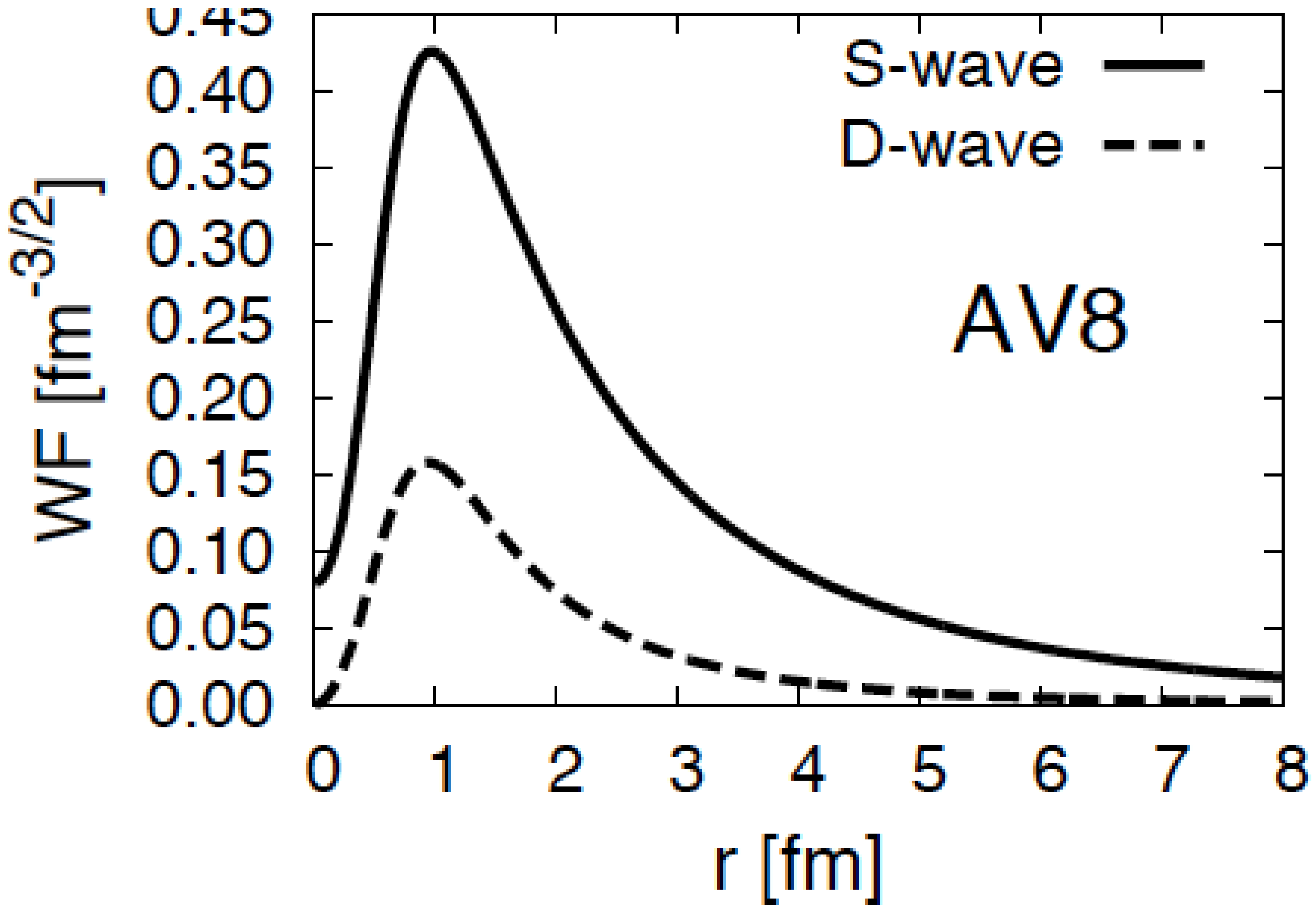
Tensor interaction is stronger with momentum increase

Deuteron (1^+)

S=1 and L=0 or 2 T=0

$$\Psi = \Phi_S + \Phi_D = (1 + F_D)\Phi_S$$





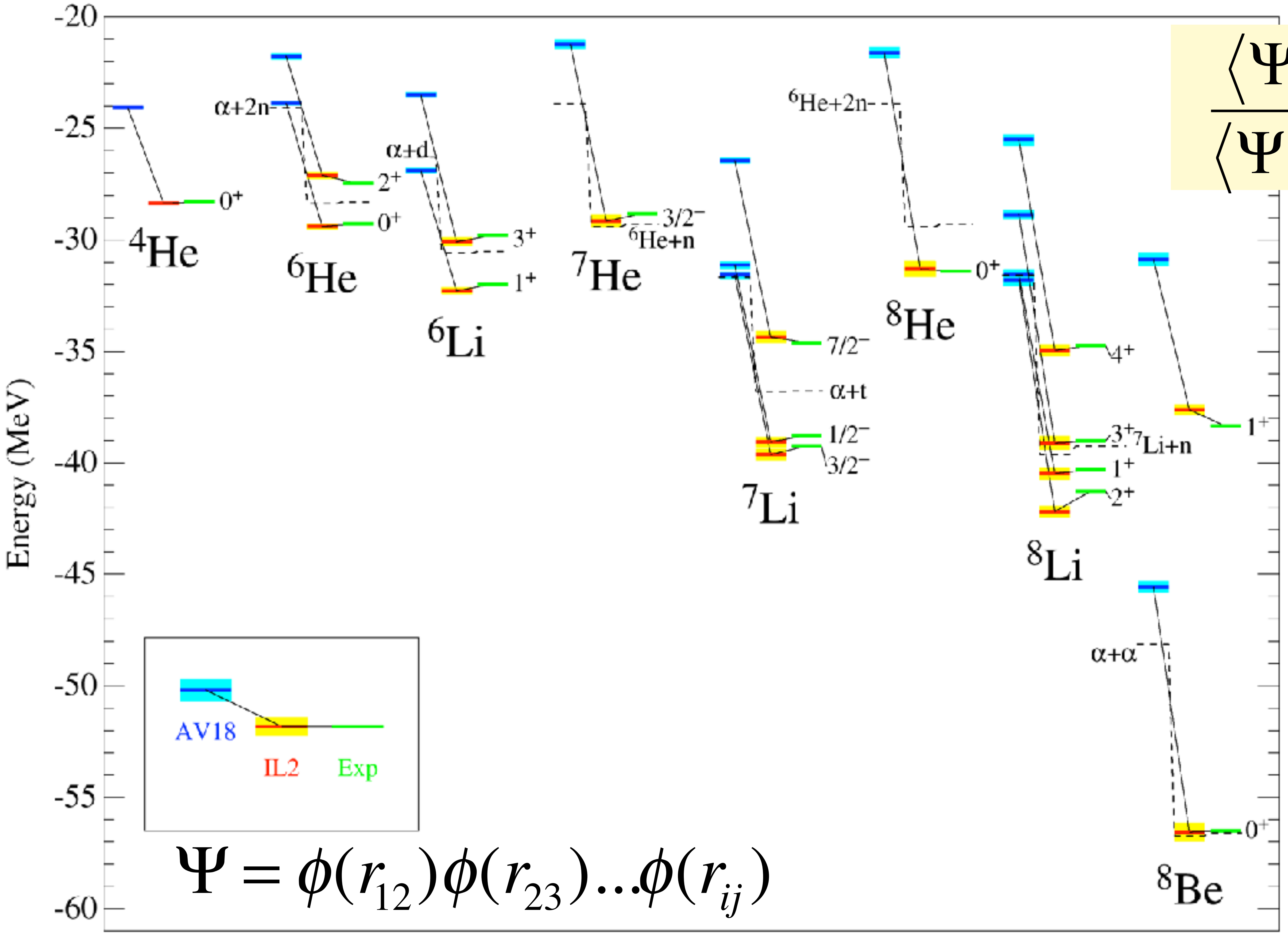
Tensor interaction is strong!!

Energy	−2.24 [MeV]
Kinetic	19.88
(SS)	11.31
(DD)	8.57
Central	−4.46
(SS)	−3.96
(DD)	−0.50
Tensor	−16.64
(SD)	−18.93
(DD)	2.29
LS	−1.02
P(*D*)	5.78 [%]
Radius	1.96 [fm]
(SS)	2.00 [fm]
(DD)	1.22 [fm]

Variational calculation of light nuclei with NN interaction (Argonne calculation)

VMC+GFMC

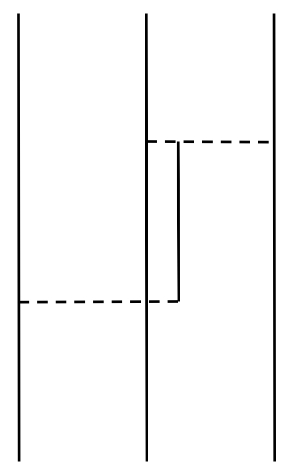
$$\frac{\langle\Psi|V_\pi|\Psi\rangle}{\langle\Psi|V_{NN}|\Psi\rangle} \sim 80\%$$



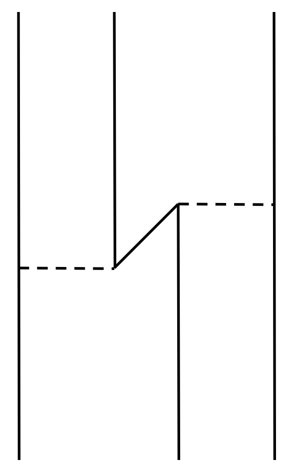
$$\Psi = \phi(r_{12})\phi(r_{23})\ldots\phi(r_{ij})$$

C. Pieper and R. B. Wiringa, Annu. Rev. Nucl. Part. Sci.51(2001)

V_{NNN}



Fujita-Miyazawa



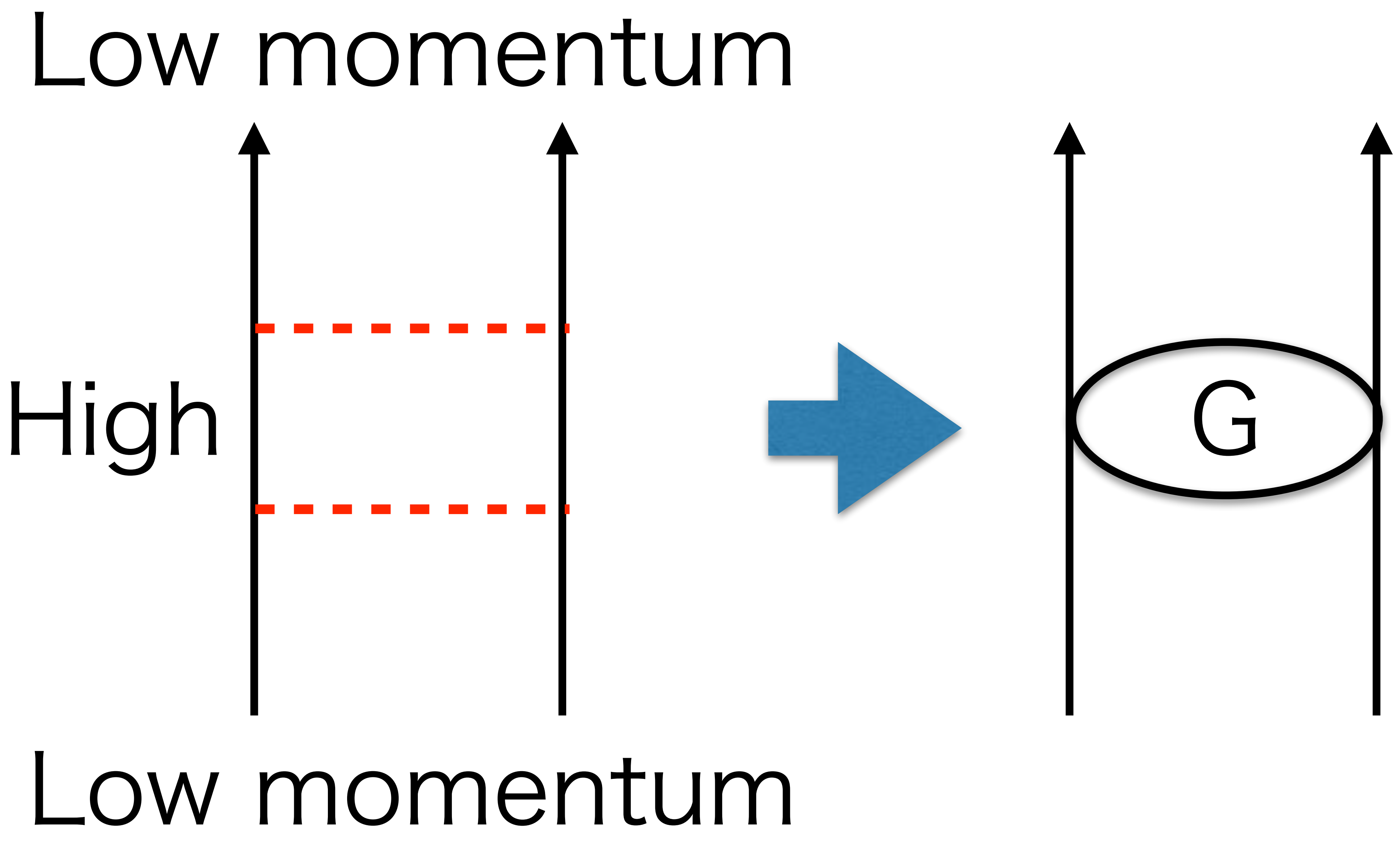
Relativistic

Heavy nuclei (Super model)

Pion is key

What the Argonne calculation tells us?

Shell model



Low momentum

High

Low momentum

G

Pion nuclear physics

$$\Psi = |low> + |high>$$

short range correlation

$< high|V_\pi|low >$ is the source of binding

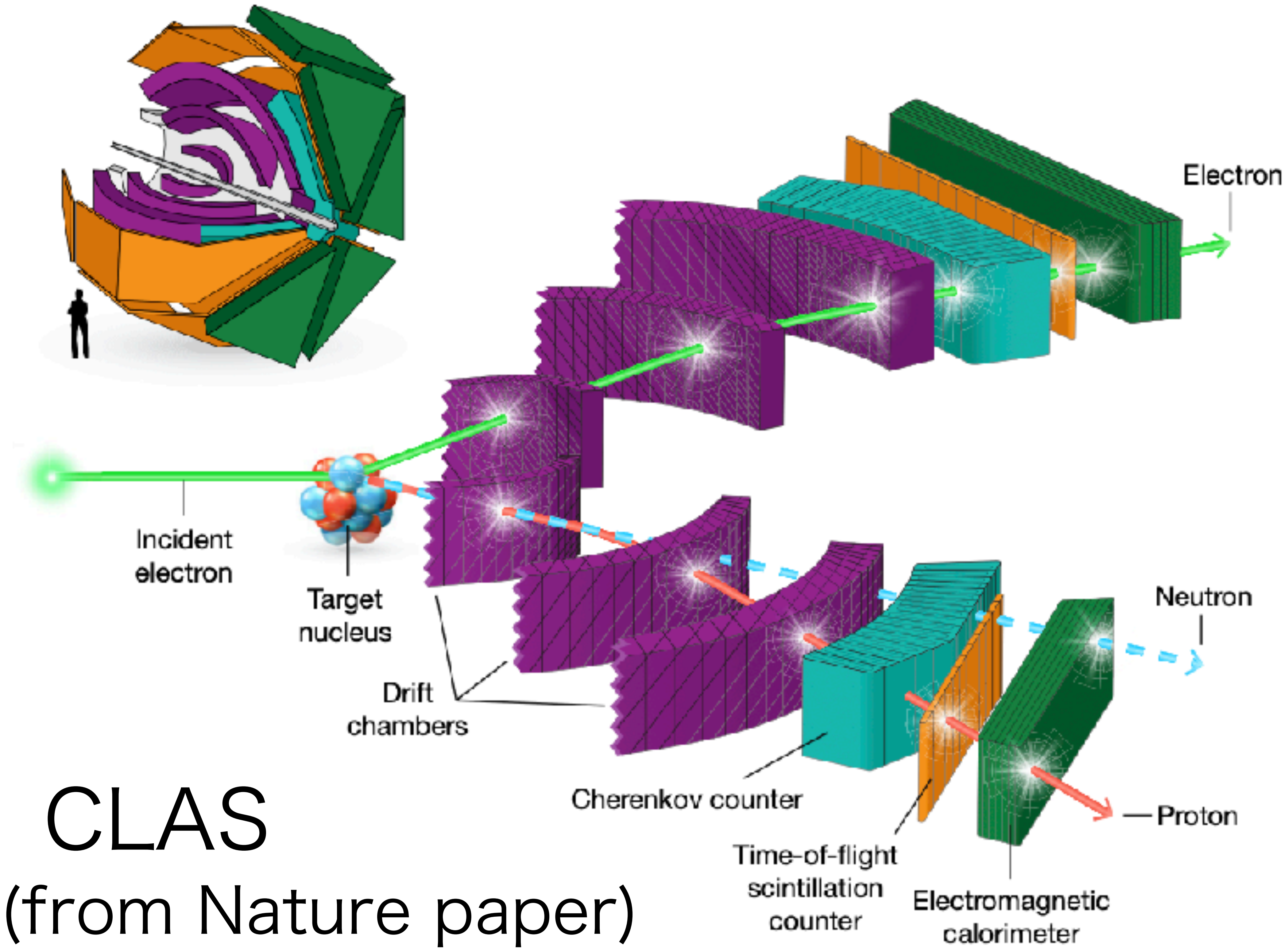
Shell model: Describe nucleus with low momentum components only

Pion nuclear physics: Describe nucleus with both low and high momentum components.

J-Lab experiments

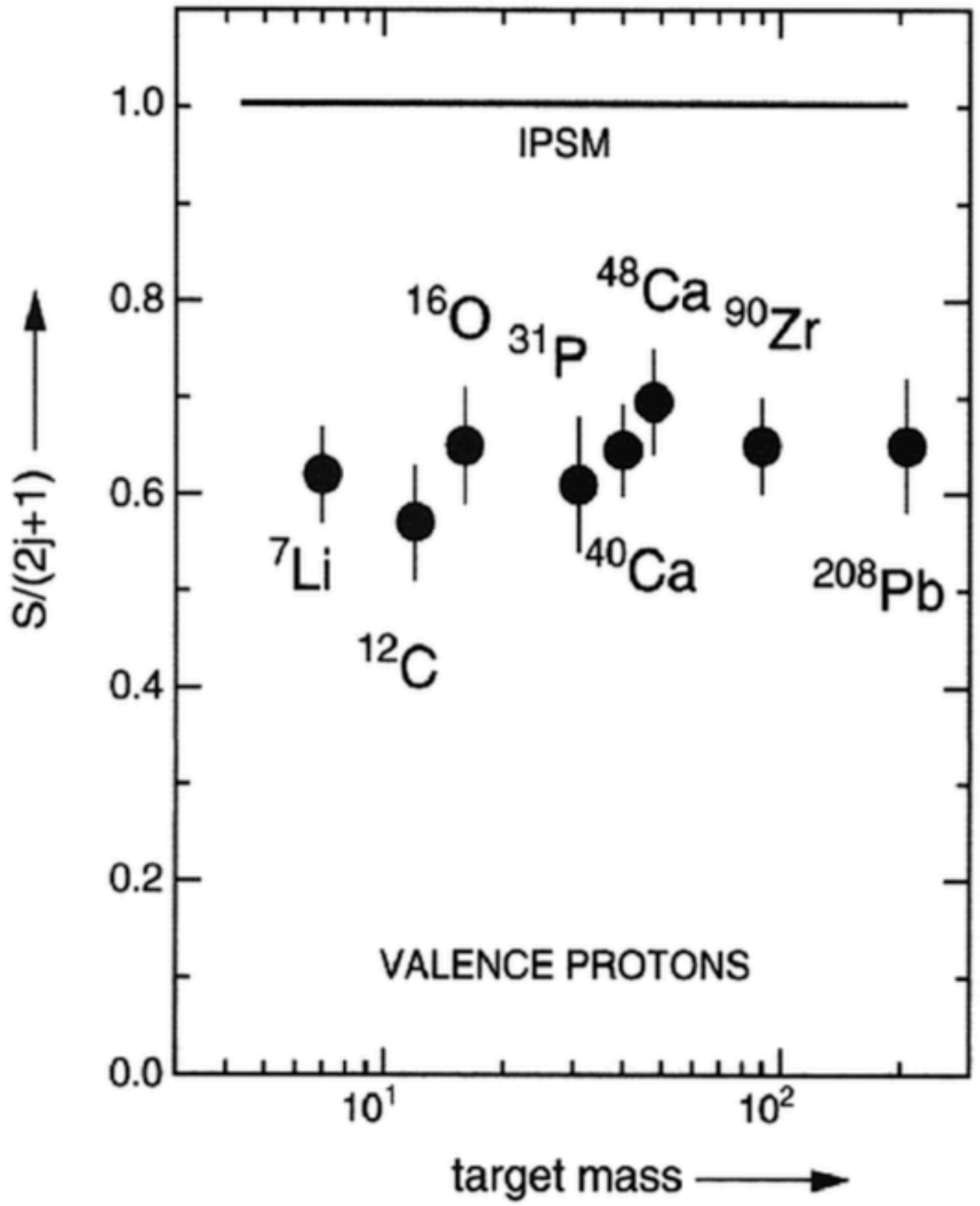
REVIEWS OF MODERN PHYSICS, VOLUME 89, OCTOBER–DECEMBER 2017

Or Hen Gerald A. Miller Eli Piasetzky Lawrence B. Weinstein



CLAS
(from Nature paper)

$(e, e'p)$



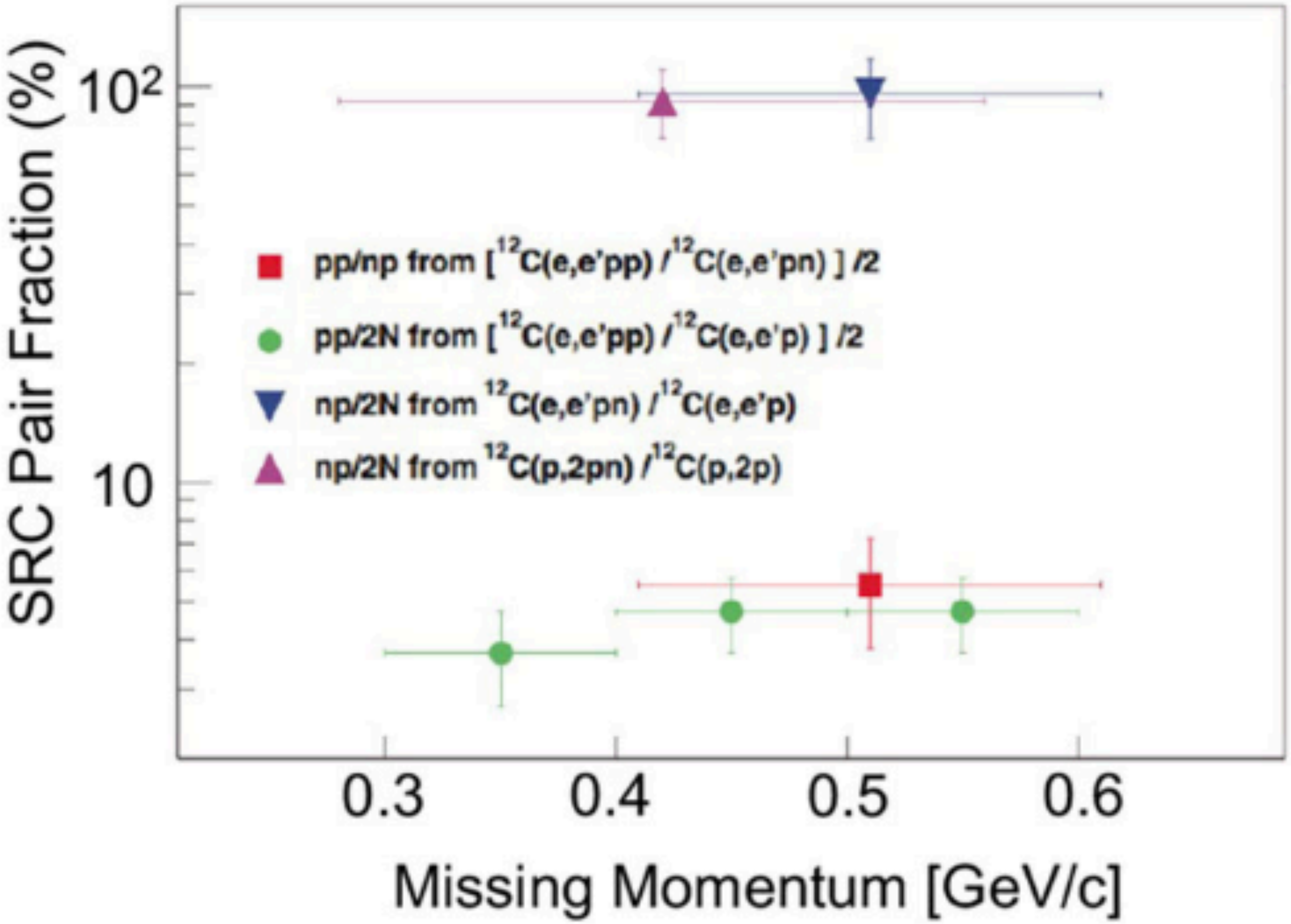
Low momentum components are missing by 40%

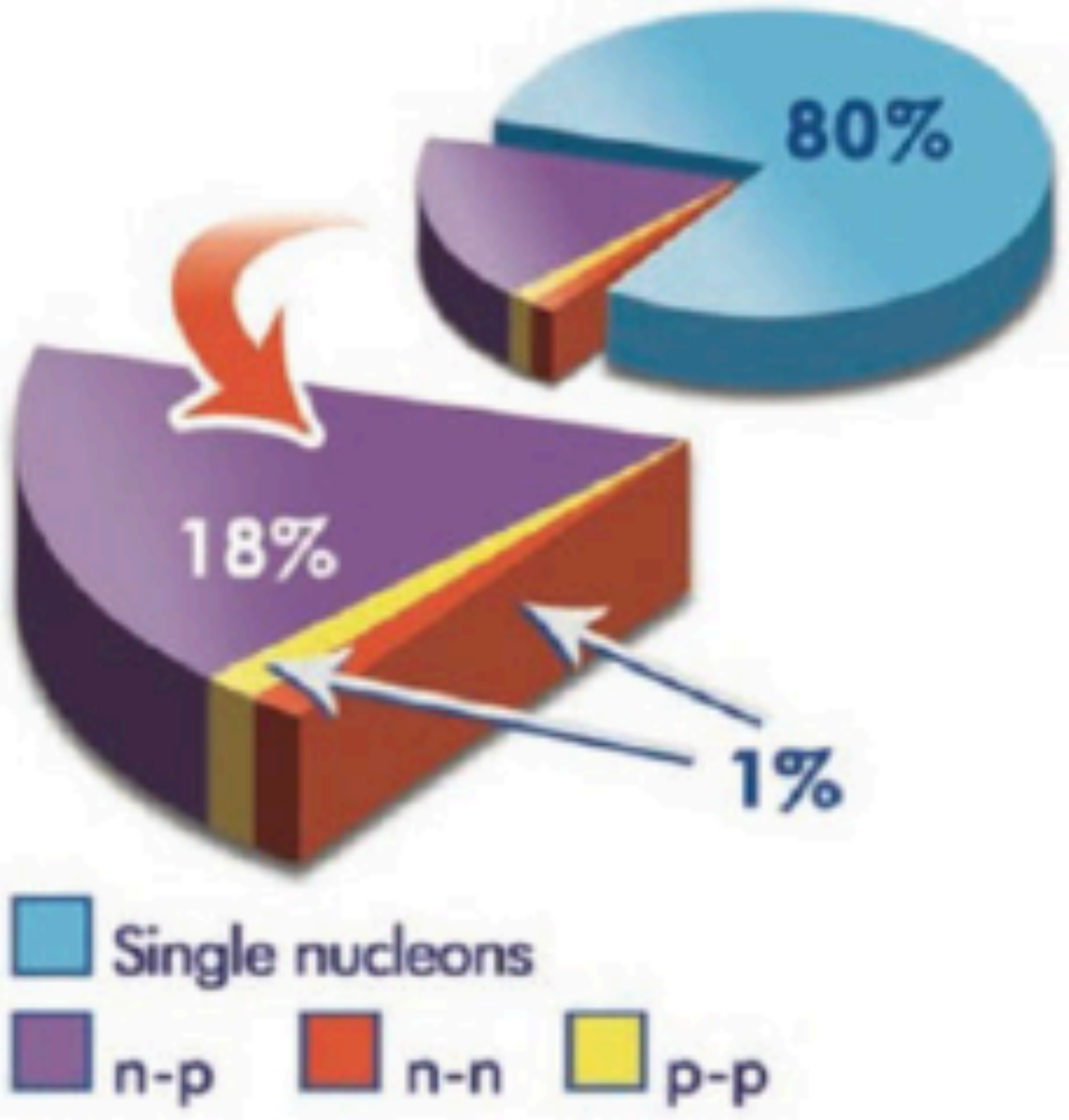
→ High momentum components?

$(e, e'NN)$

Two Science papers

Two Nature papers





Two nucleon components

20% missing

more complicated?

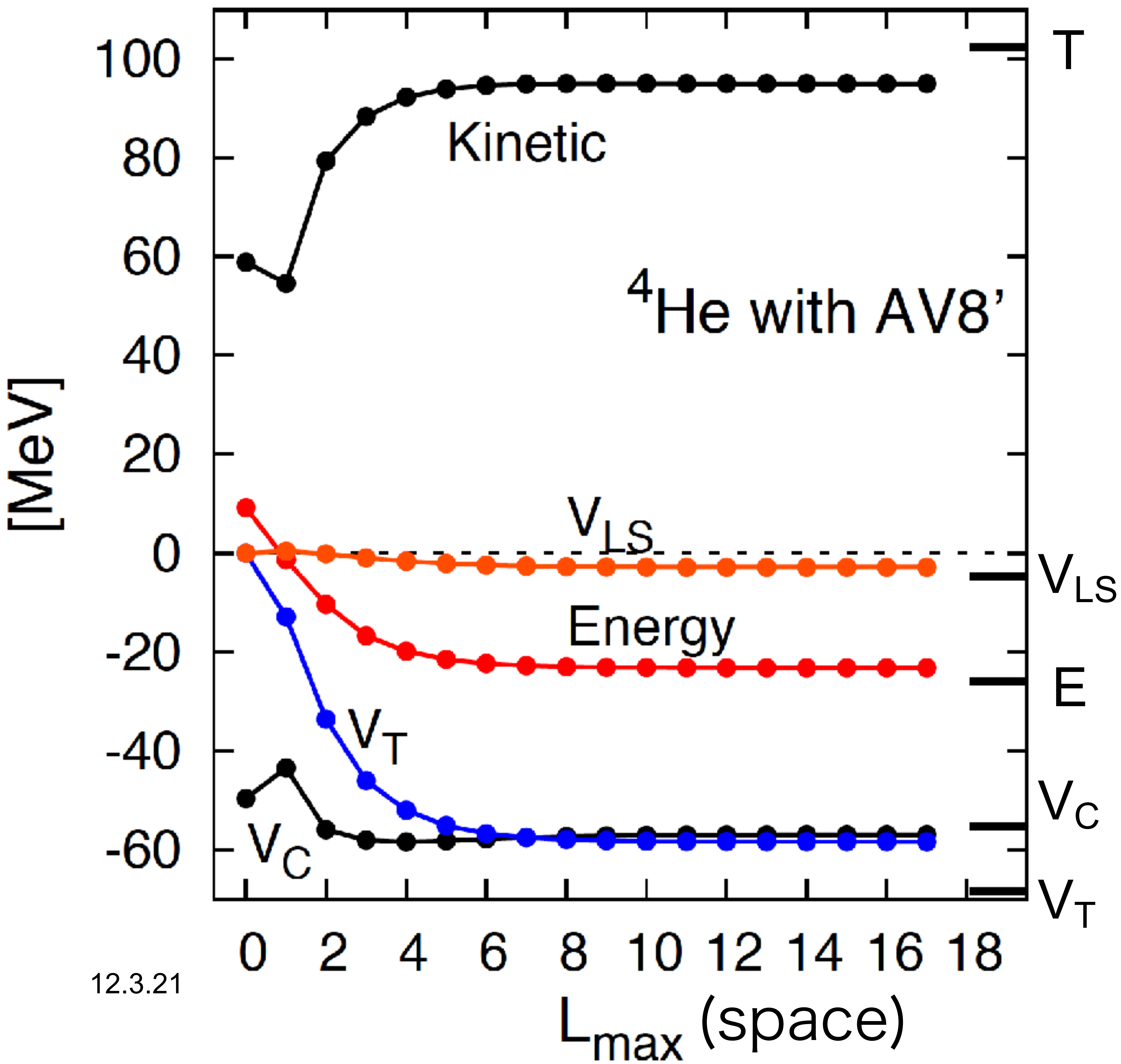
Two nucleon pairs are made of proton and neutron.

Pion is the source for proton-neutron pairs

TOSM+UCOM with AV8’

$$\Psi = C_0|0\rangle + \sum_{\alpha} C_\alpha |2p2h:\alpha\rangle$$

T.Myo H.Toki K.Ikeda
PTP121(2009)511

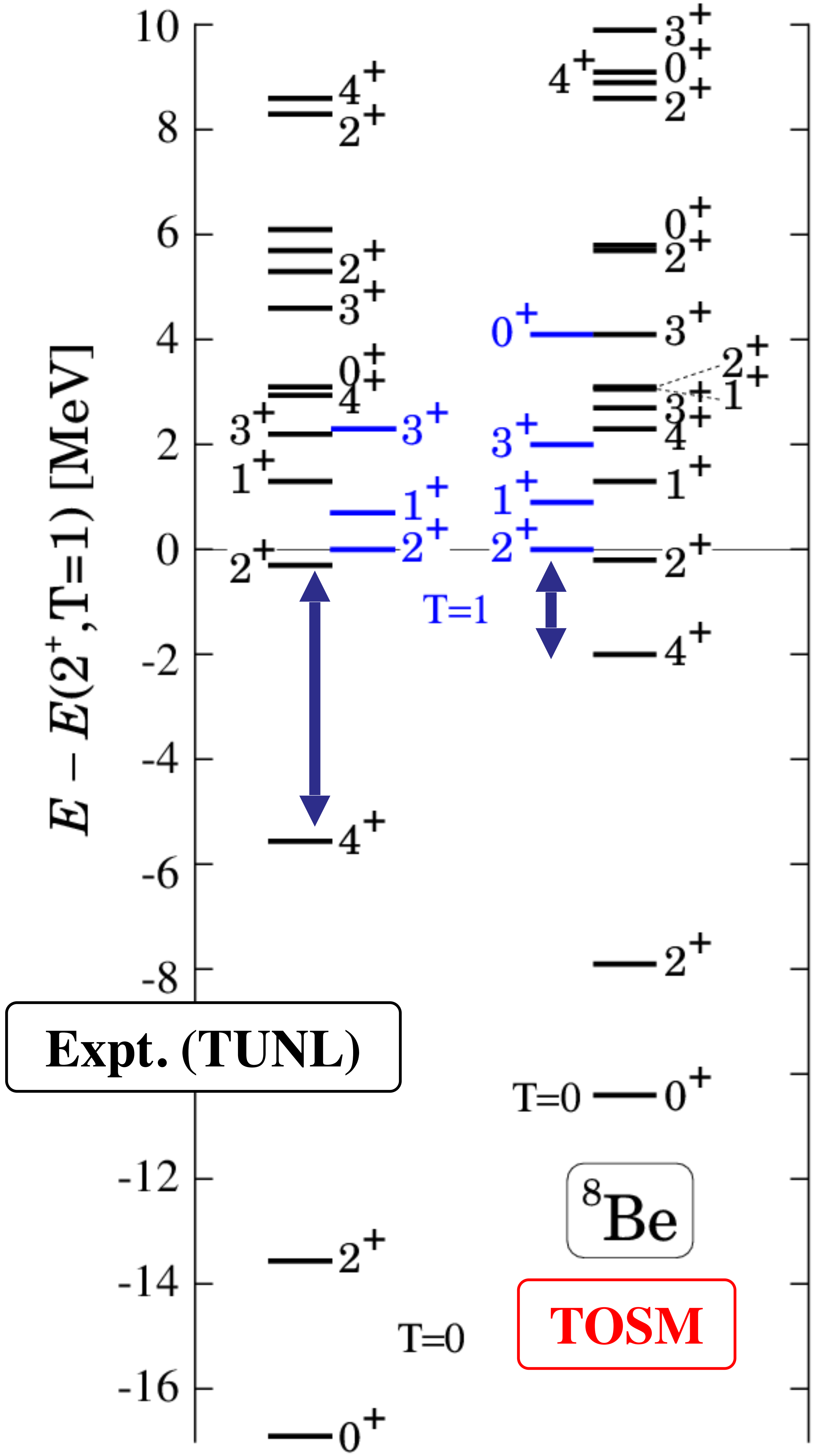


TOSM

Tensor optimized
Shell model

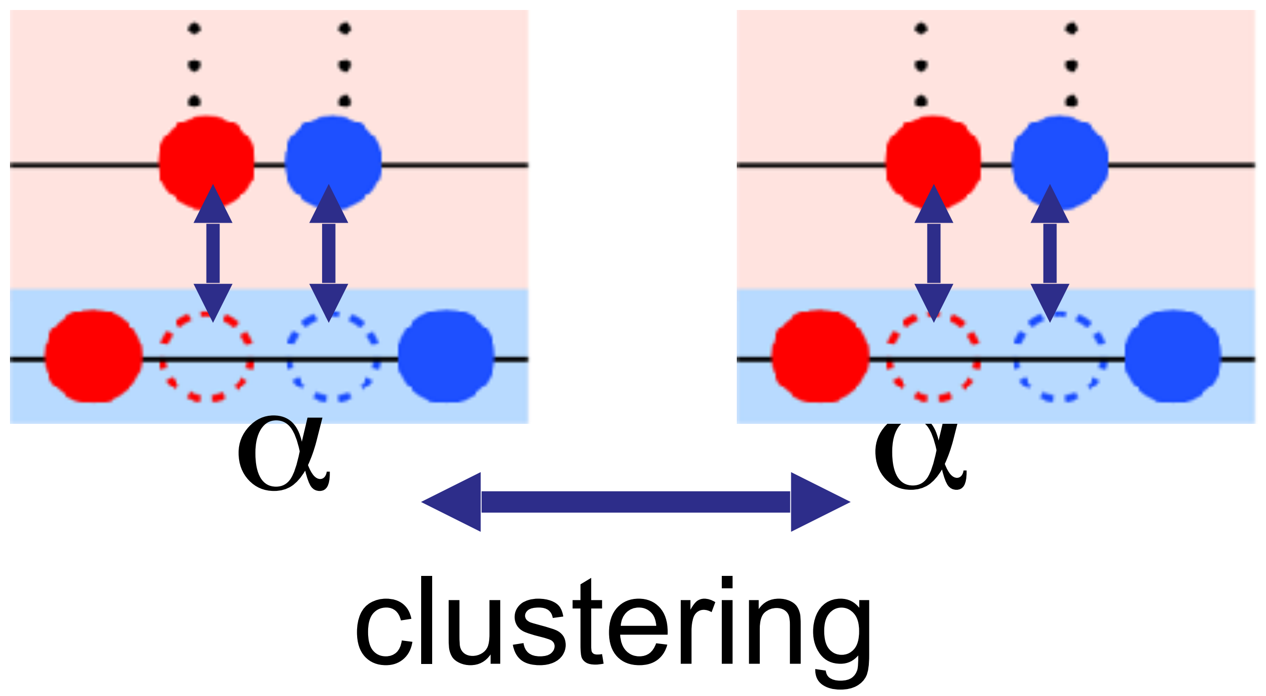
2 particle correlation
is not enough

Few body
Calculation
(Kamda et al)



^{8}Be in TOSM
– AV8' –

- correct level order (T=0,1)
- tensor contribution : T=0 > T=1
- α : 0p0h+2p2h with high-k
  - 2α needs 4p4h.
  - spatial asymptotic form of 2α



⇒ TOAMD

3p3h+4p4h+..

Tensor Optimized Antisymmetrized Molecular Dynamics (TOAMD)

Myo Toki Ikeda

Tensor optimized shell model (TOSM)

1. We include tensor interaction most effectively to shell model
2. Difficult to treat cluster structure

+

Horiuchi Enyo Kimura..

Antisymmetrized molecular dynamics (AMD)

1. Cluster+shell structure is handled on the same footing using effective inte
2. Difficult to treat bare nucleon-nucleon interaction

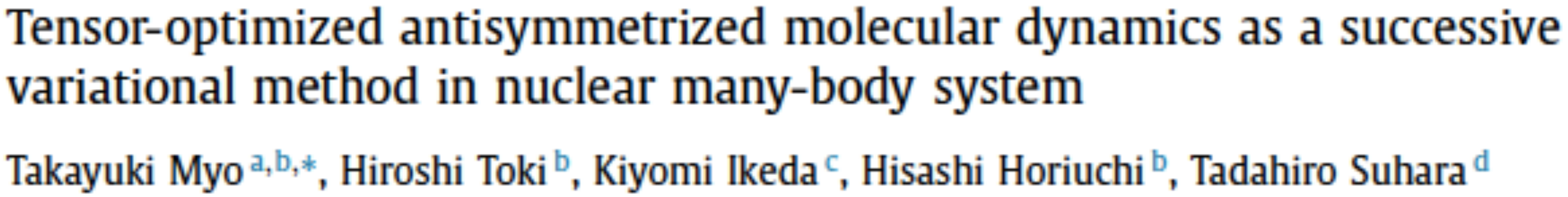
↓

Study nuclear structure based on bare NN interaction

Prog. Theor. Exp. Phys. **2015**, 073D02 (38 pages)
DOI: 10.1093/ptep/ptv087

Tensor-optimized antisymmetrized molecular dynamics in nuclear physics

Takayuki Myo[1,2,*], Hiroshi Toki[2], Kiyomi Ikeda[3], Hisashi Horiuchi[2],
and Tadahiro Suhara[4]



Tensor-optimized antisymmetrized molecular dynamics as a successive variational method in nuclear many-body system

Takayuki Myo[a,b,*], Hiroshi Toki[b], Kiyomi Ikeda[c], Hisashi Horiuchi[b], Tadahiro Suhara[d]

Phys. Lett. B769 (2017) 213

PHYSICAL REVIEW C **95**, 044314 (2017)

Successive variational method of the tensor-optimized antisymmetrized molecular dynamics for central interaction in finite nuclei

Takayuki Myo,[1,2,*] Hiroshi Toki,[2,†] Kiyomi Ikeda,[3,‡] Hisashi Horiuchi,[2,§] and Tadahiro Suhara[4,∥]

Hybridization of tensor-optimized and high-momentum antisymmetrized molecular dynamics for light nuclei with bare interaction

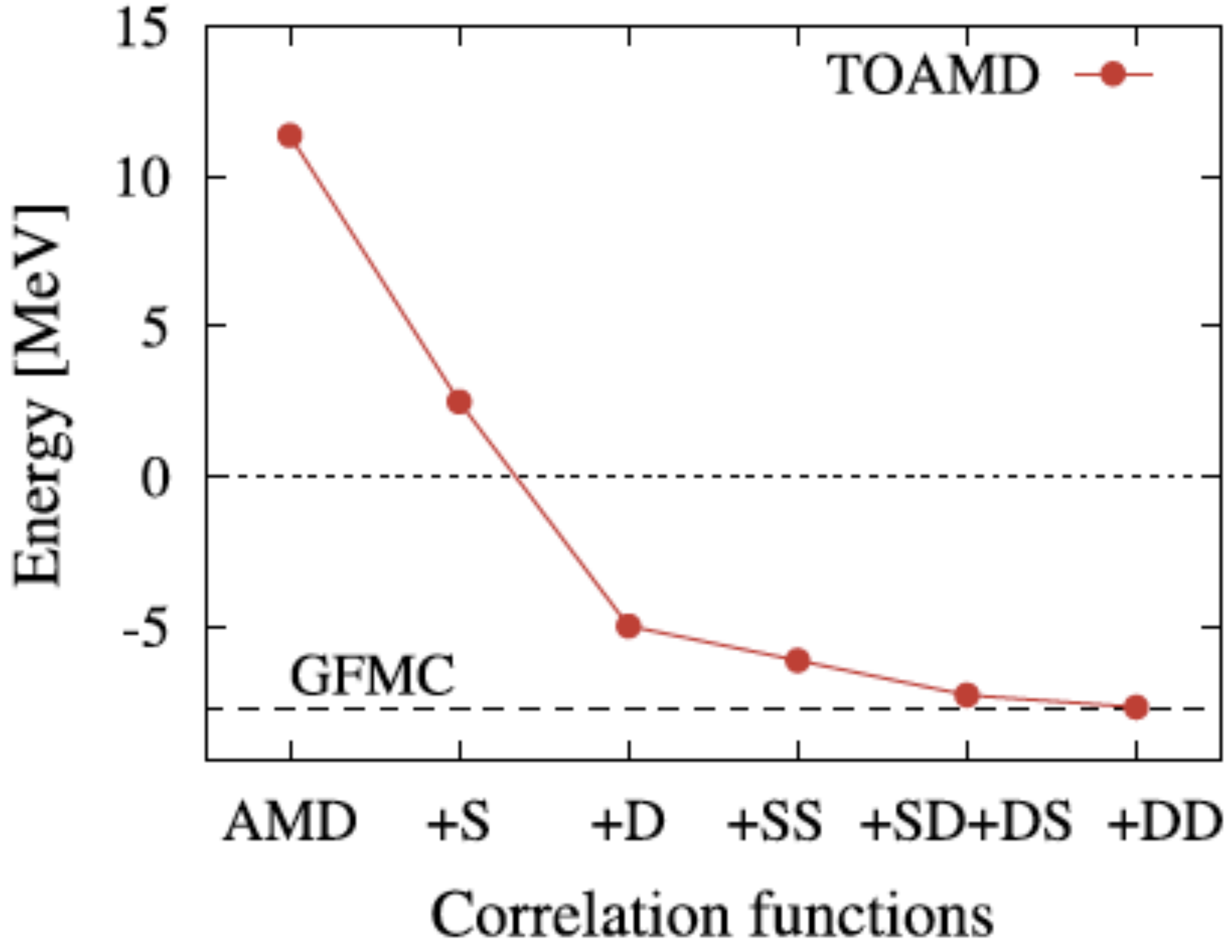
Prog. Theor. Exp. Phys. **2018**, 011D01 (9 pages)

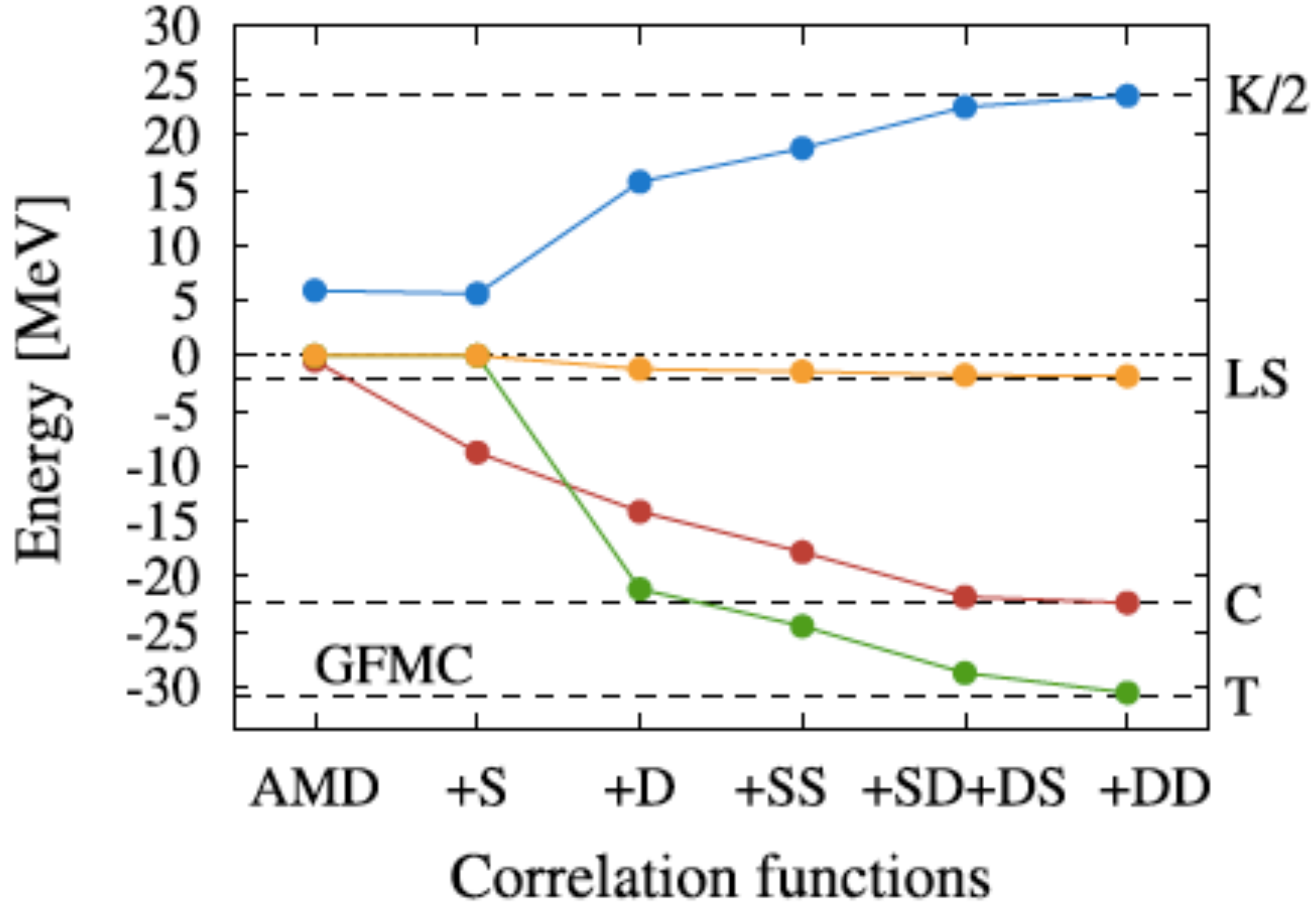
Mengjiao Lyu[1,*], Masahiro Isaka[1], Takayuki Myo[1,2,*], Hiroshi Toki[1], Kiyomi Ikeda[3],
Hisashi Horiuchi[1], Tadahiro Suhara[4], and Taiichi Yamada[5]

He(A=3)

Interaction is AV8'

TOAMD group: Phys. Lett. B769 (2017) 213





$$\Phi_{TOAMD} = (1 + F_S + F_D + F_S F_S + F_S F_D + F_D F_D)\Phi_{AMD}$$

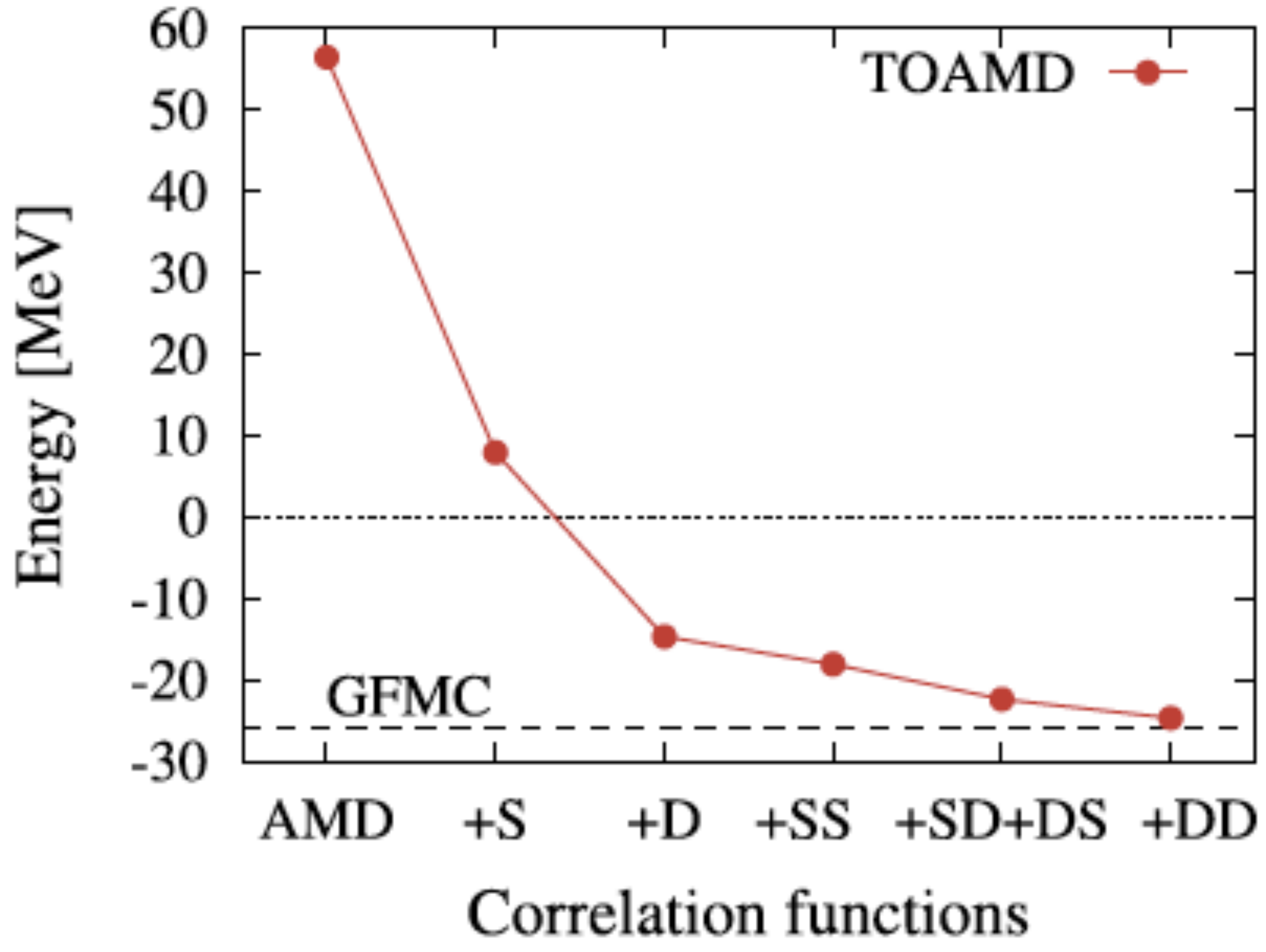
We achieve convergence successively.

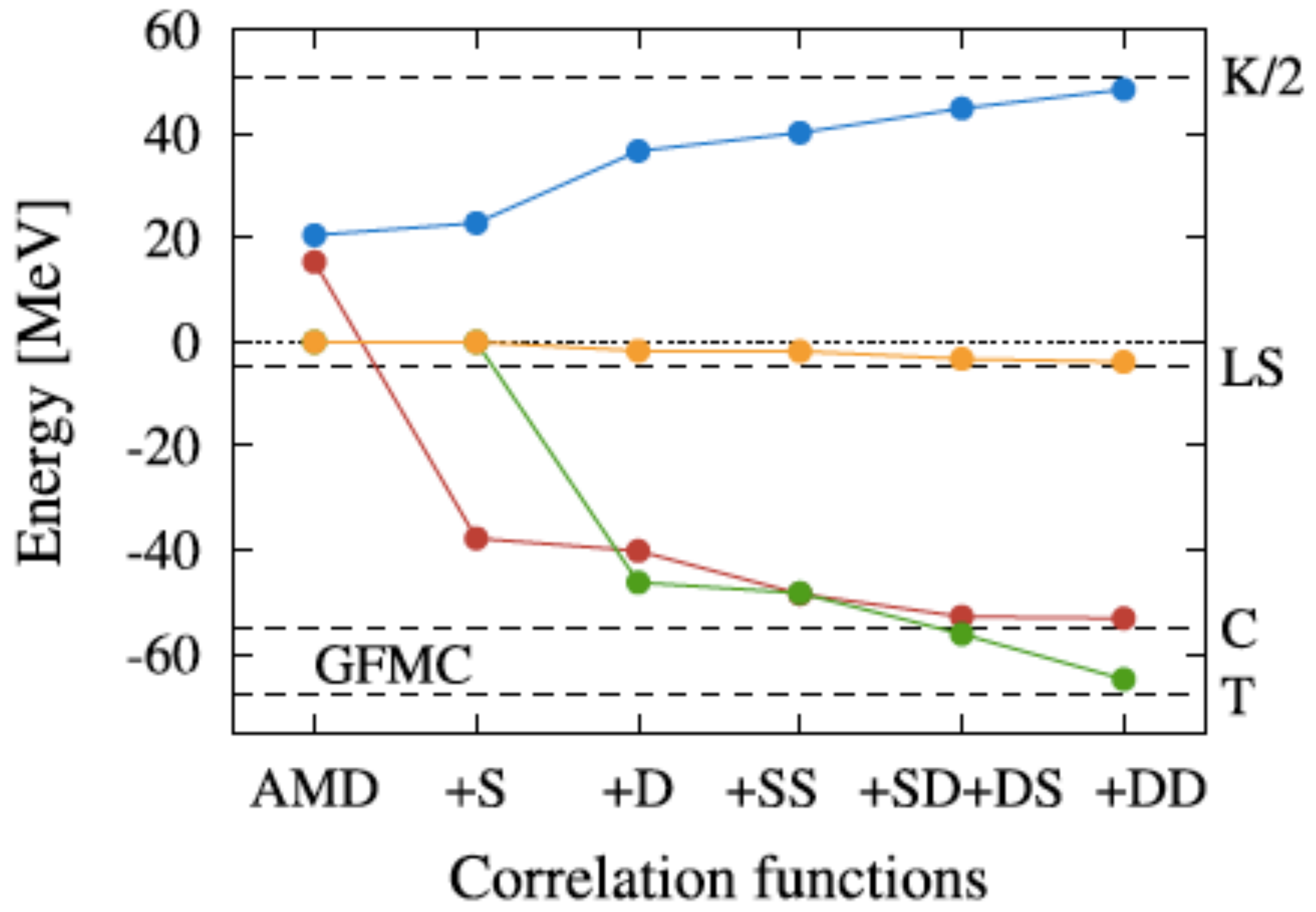
(Successive variational method)

He(A=4)

Interaction is AV8'

TOAMD group: Phys. Lett. B769 (2017) 213





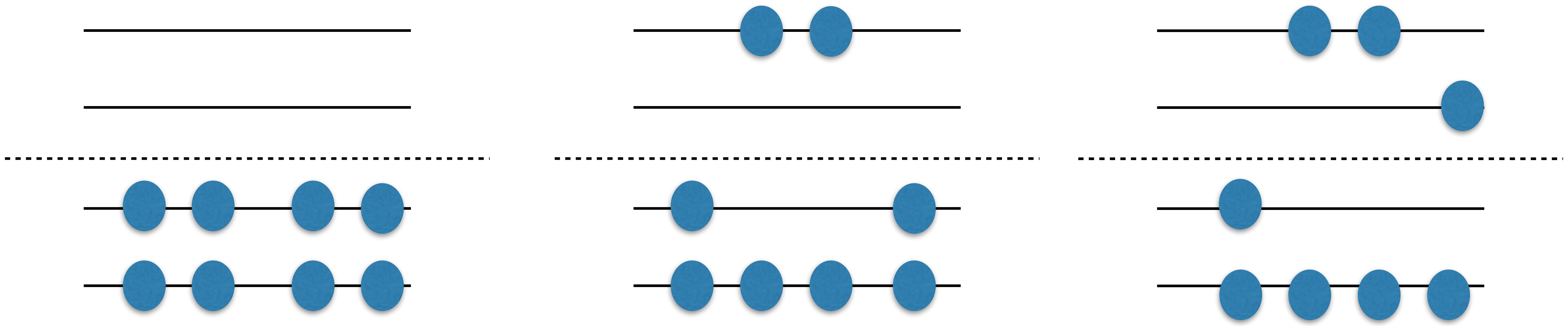
$$\Phi_{TOAMD} = (1 + F_S + F_D + F_S F_S + F_S F_D + F_D F_D)\Phi_{AMD}$$

2p2h 3p3h

Even high momentum components have complicated dynamics!!

Experiments

$\Psi = | low > + | high >$ Wave function of ground state



high momentum

low momentum

CLAS 60% 20%

One body operator $< \Psi | O | \Psi > = < low | O | low > + < high | O | high >$

O

60% 40%

μ	Magnetic moment
σ	Spin operators
e^{ikr}	Form factor

Effective parameters

quenching factor	0.5
effective charge.	2.0

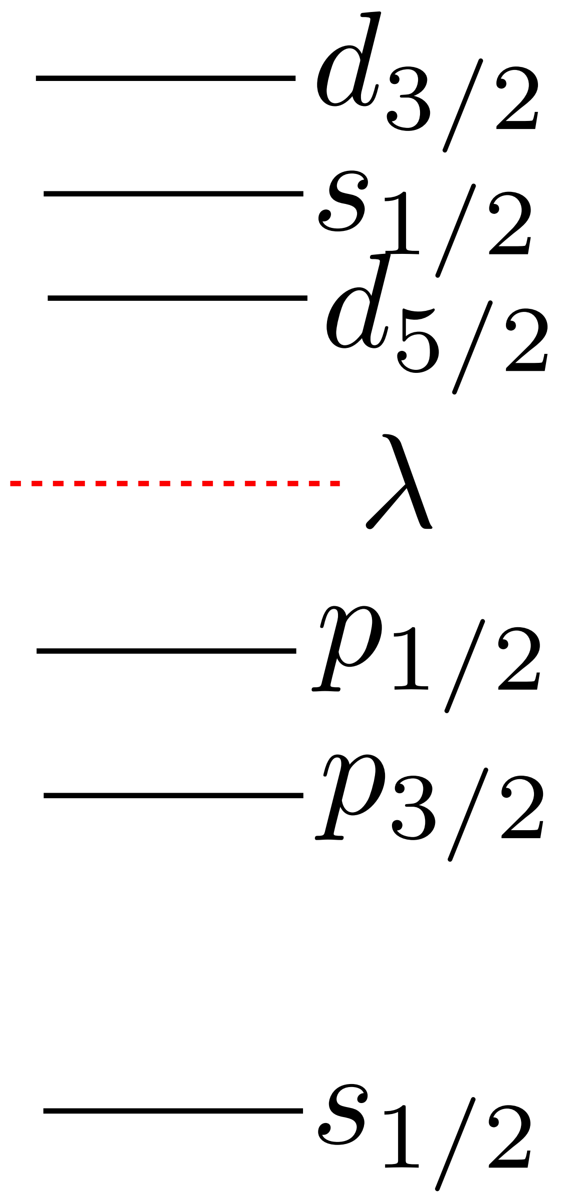
RCNP

Ong, Tanihata et al

^{15}O

Level scheme

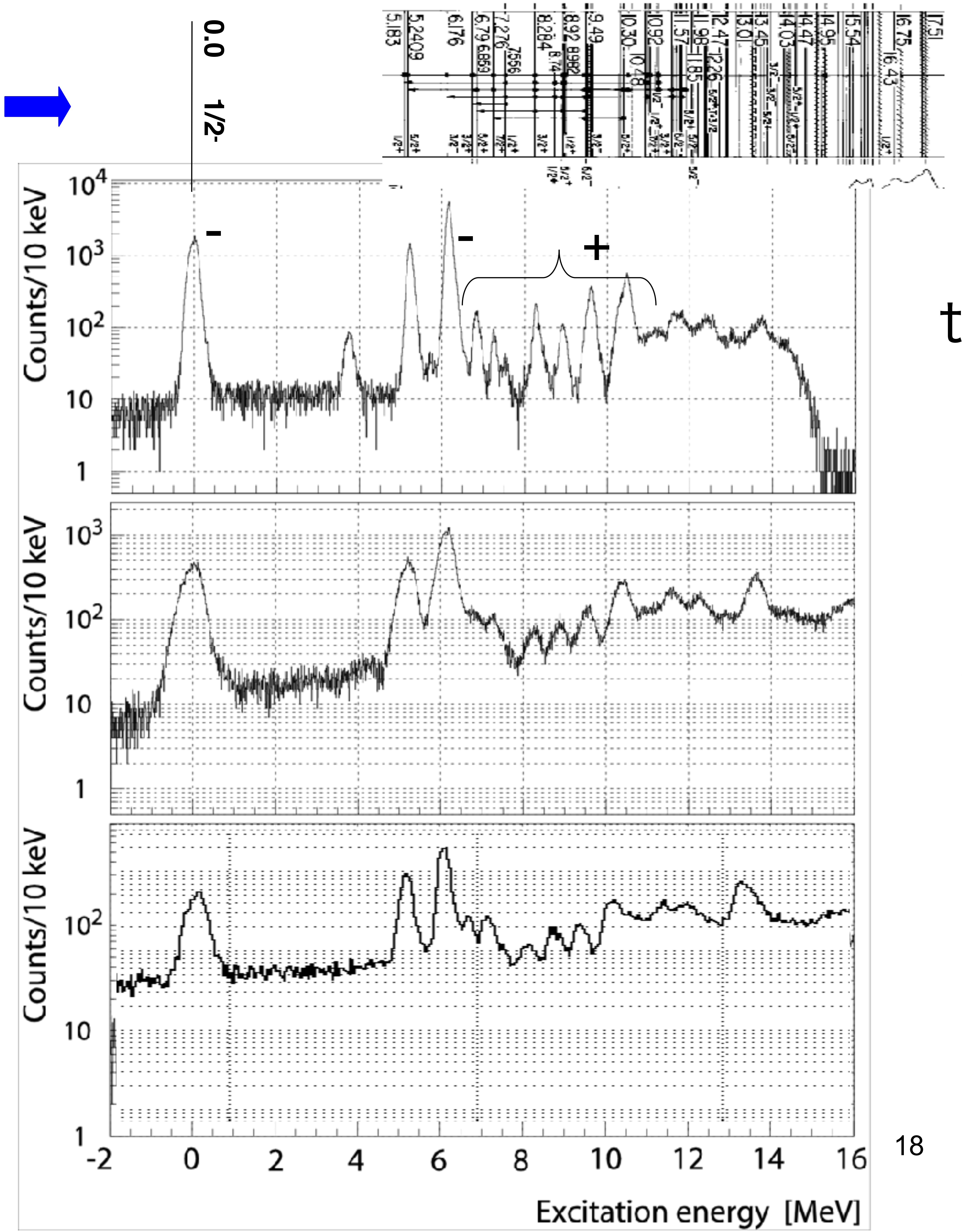
High momentum (HM) states pioneering!!



^{16}O (*p,d*)
$E_p = 198$ MeV
$\Theta_d = 10°$

^{16}O (*p,d*)
$E_p = 295$ MeV
$\Theta_d = 10°$

^{16}O (*p,d*)
$E_p = 392$ MeV
$\Theta_d = 10°$



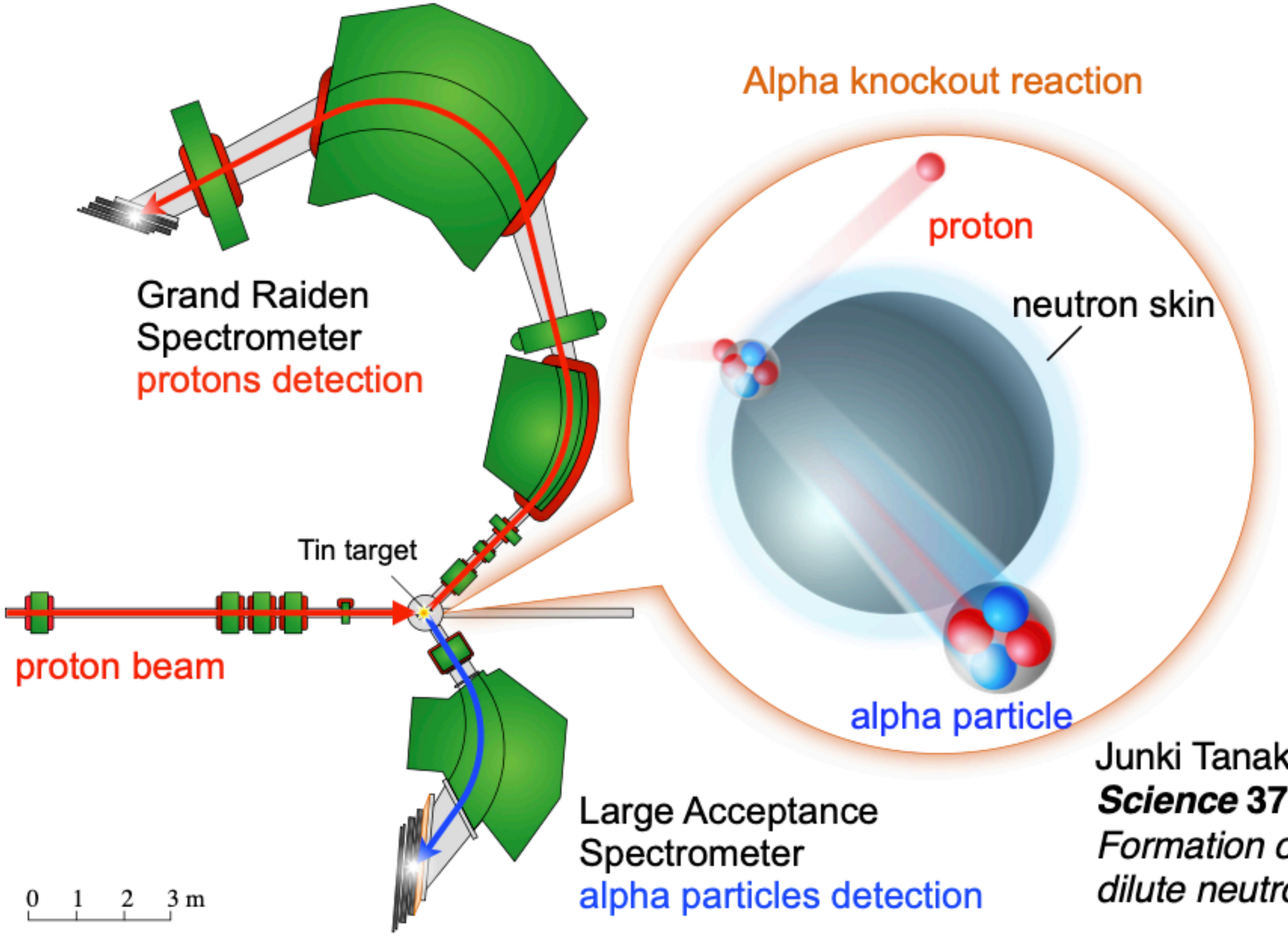
CLAS: HM components in GS

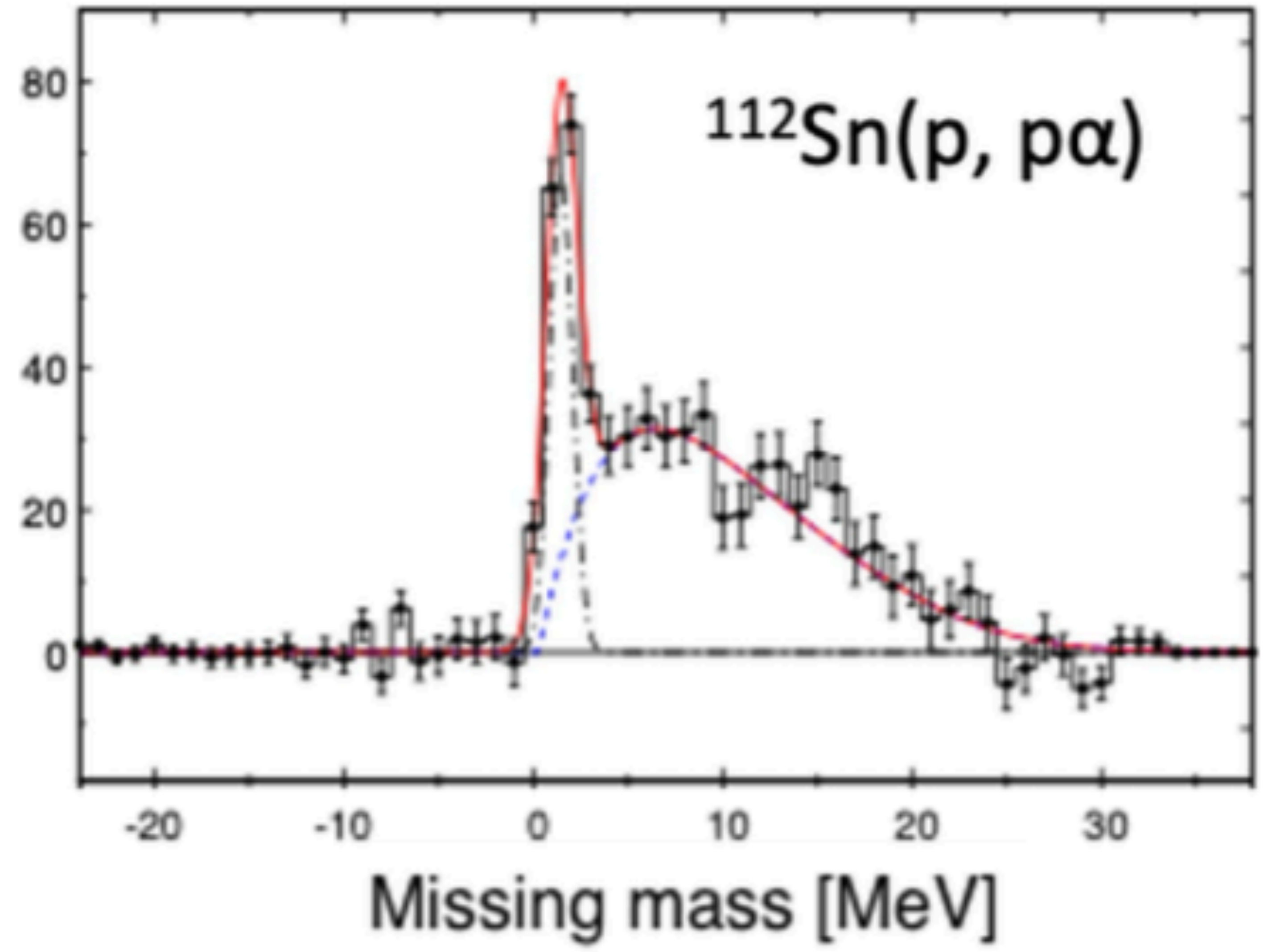
What are those states

?

No theory

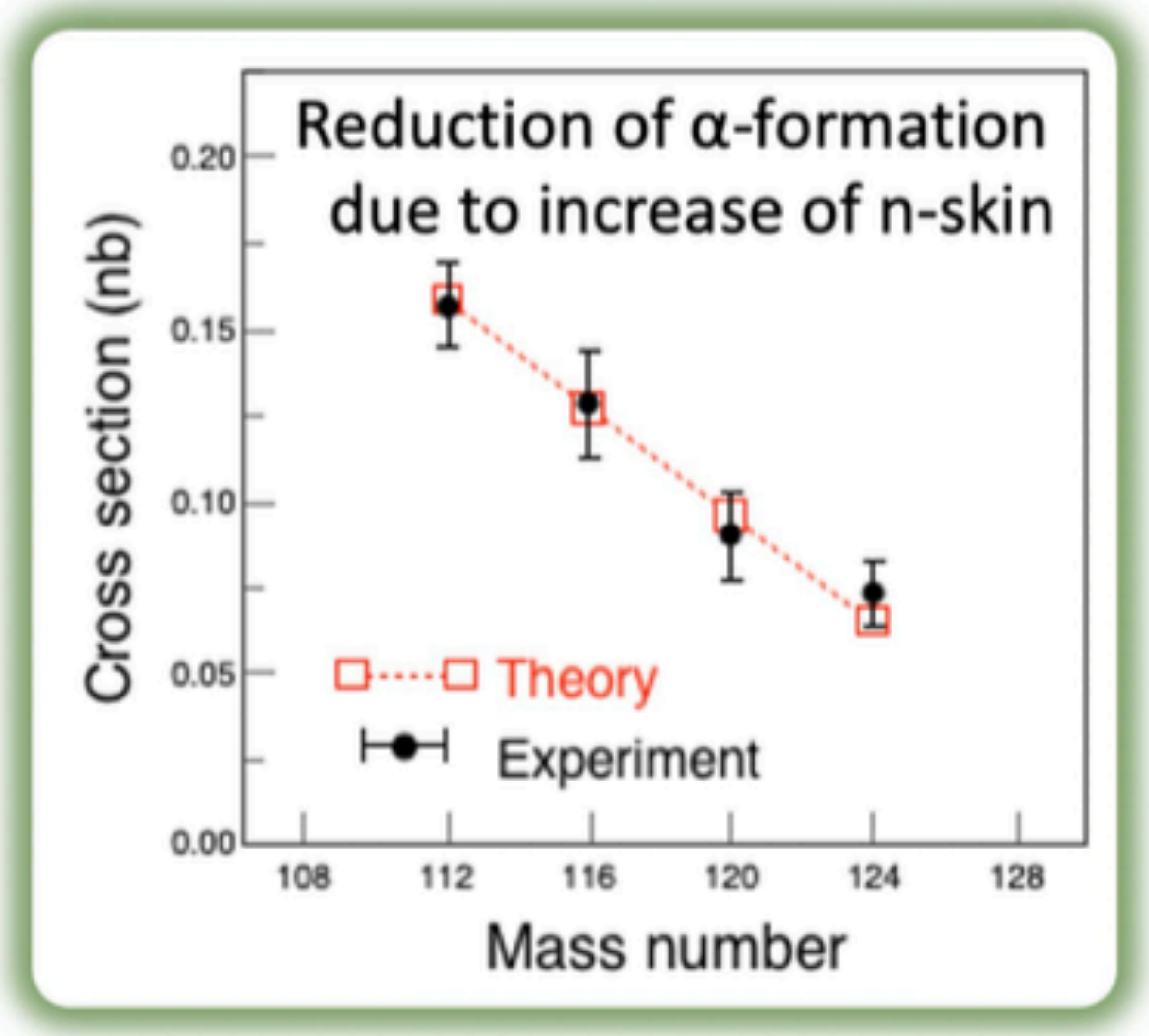
Cluster Knockout Experiment





Junki Tanaka et. al.,
***Science* 371**, 260-264
Formation of α clusters in dilute neutron-rich matter

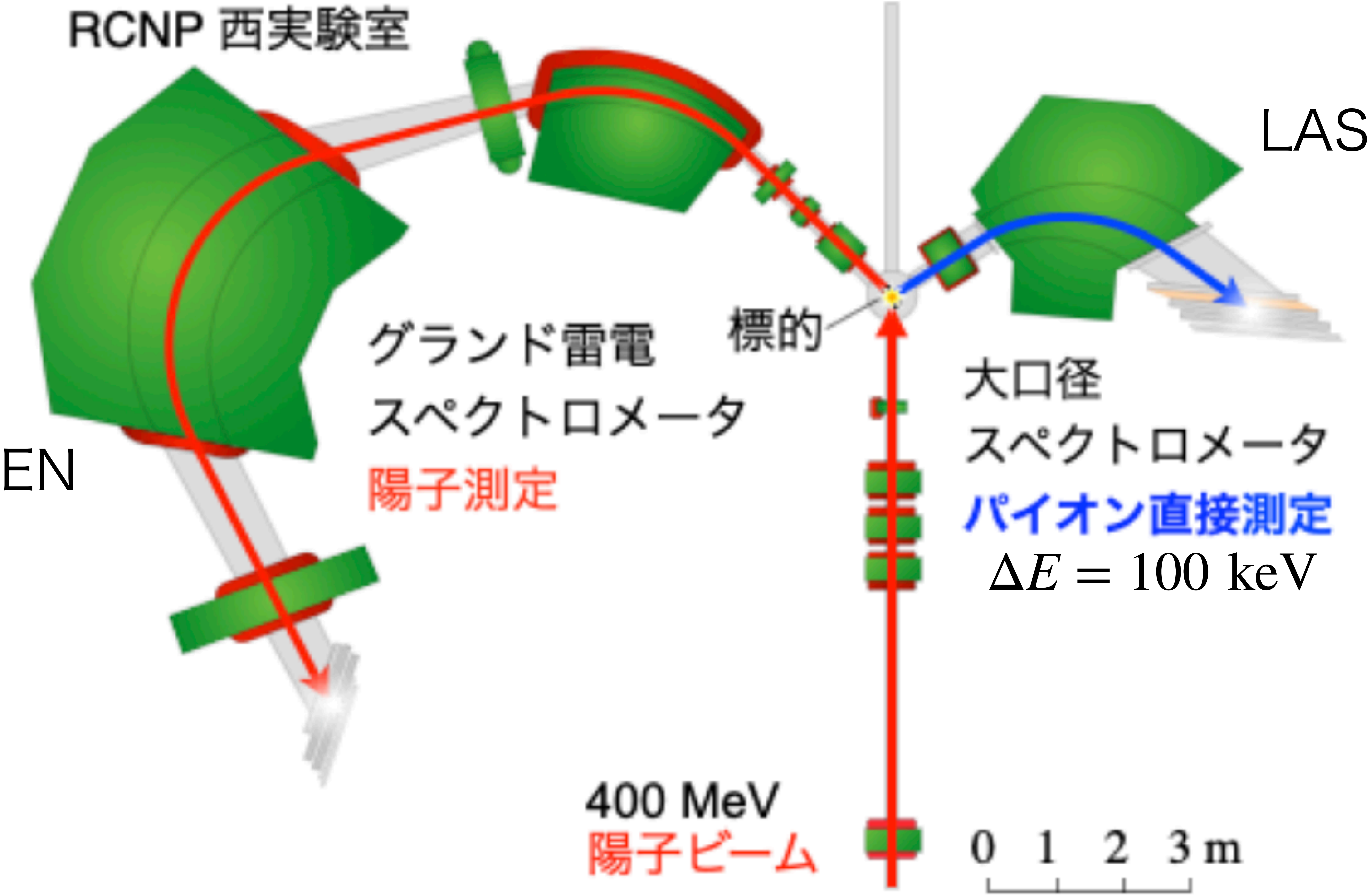
ONOKORO Collaboration



Proton induced pion knock-out reaction

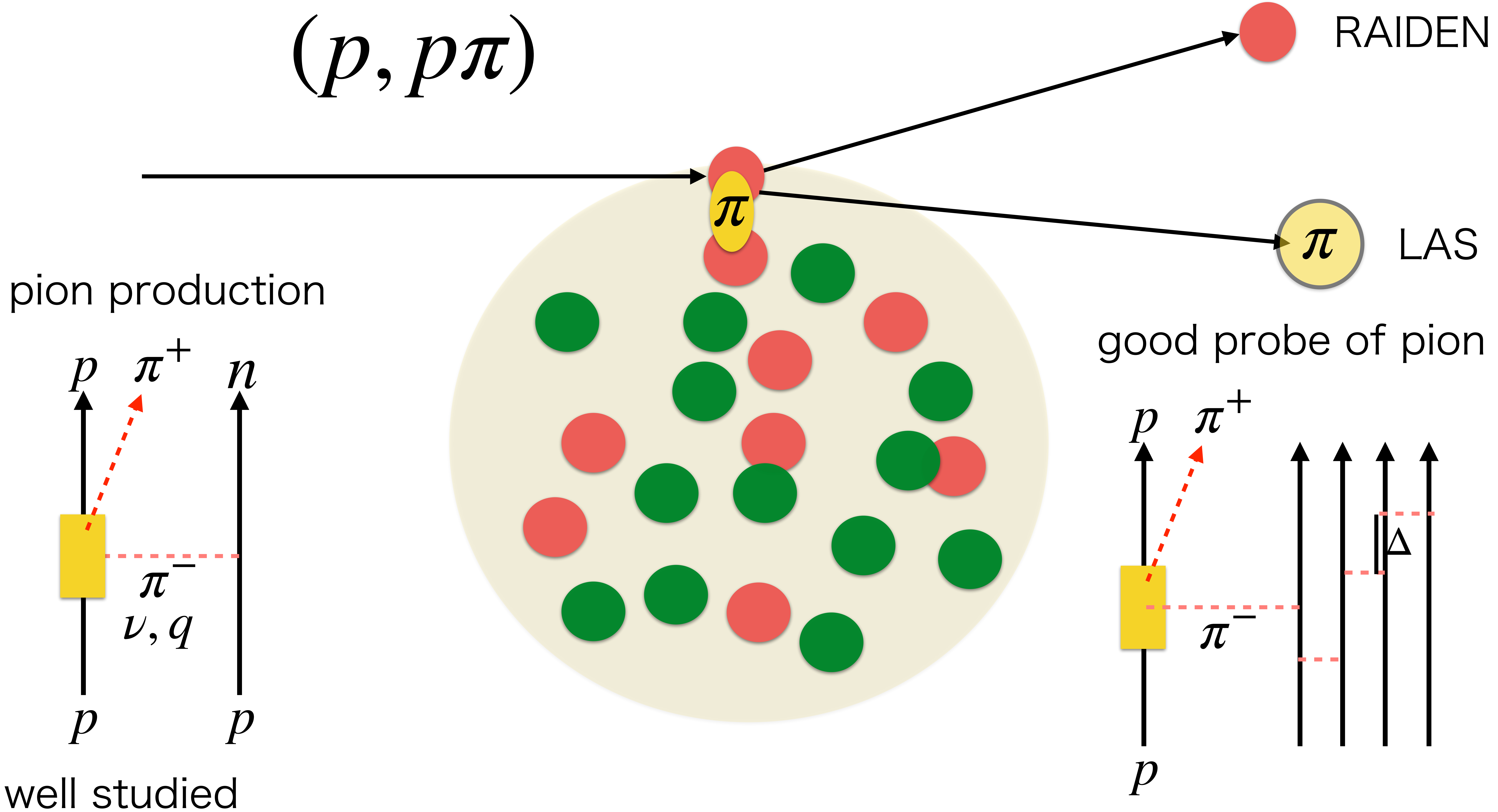
RCNP detector system

$(p, p\pi)$ project



$\Delta E = 100$ keV

$(p, p\pi)$



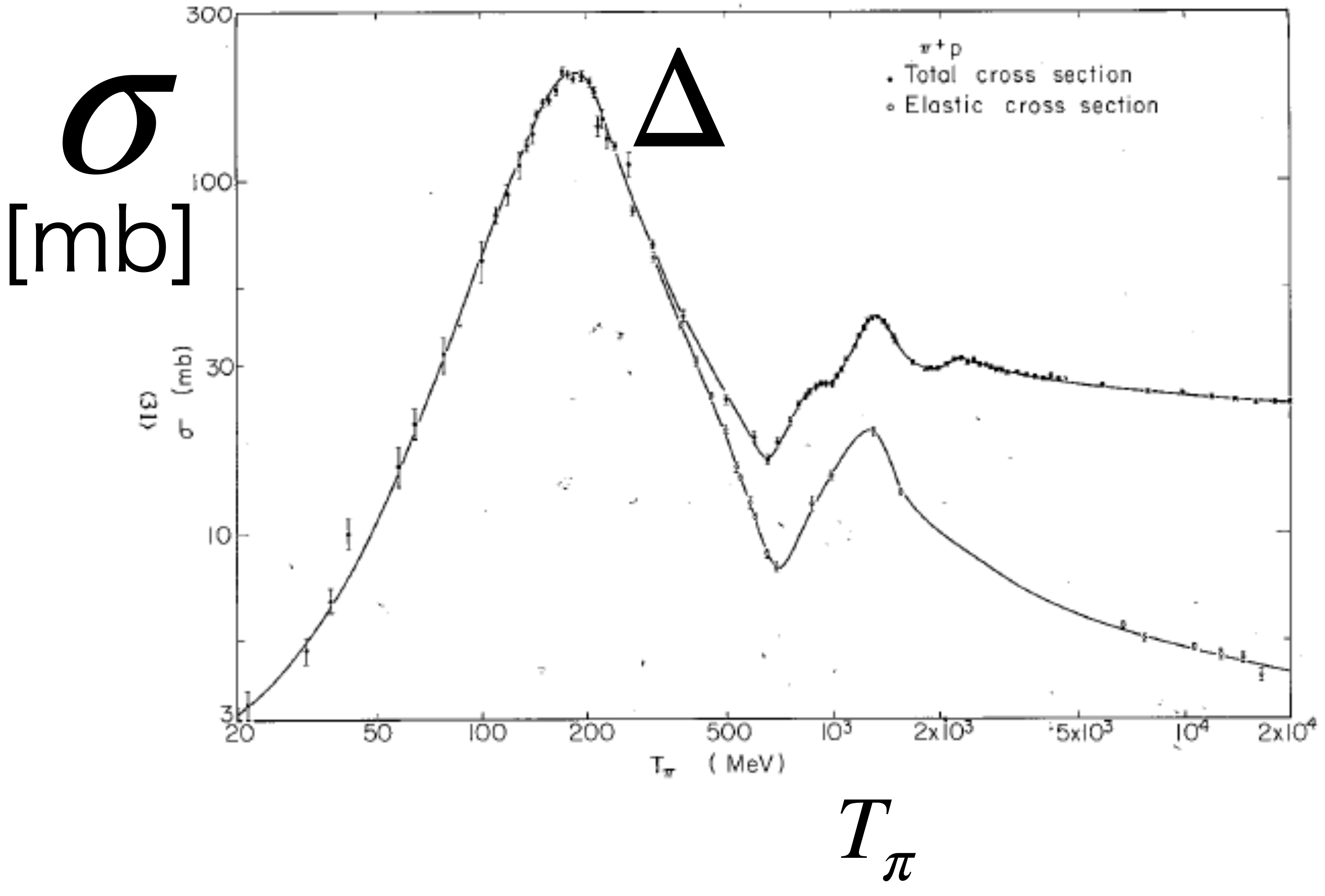
pion production

well studied

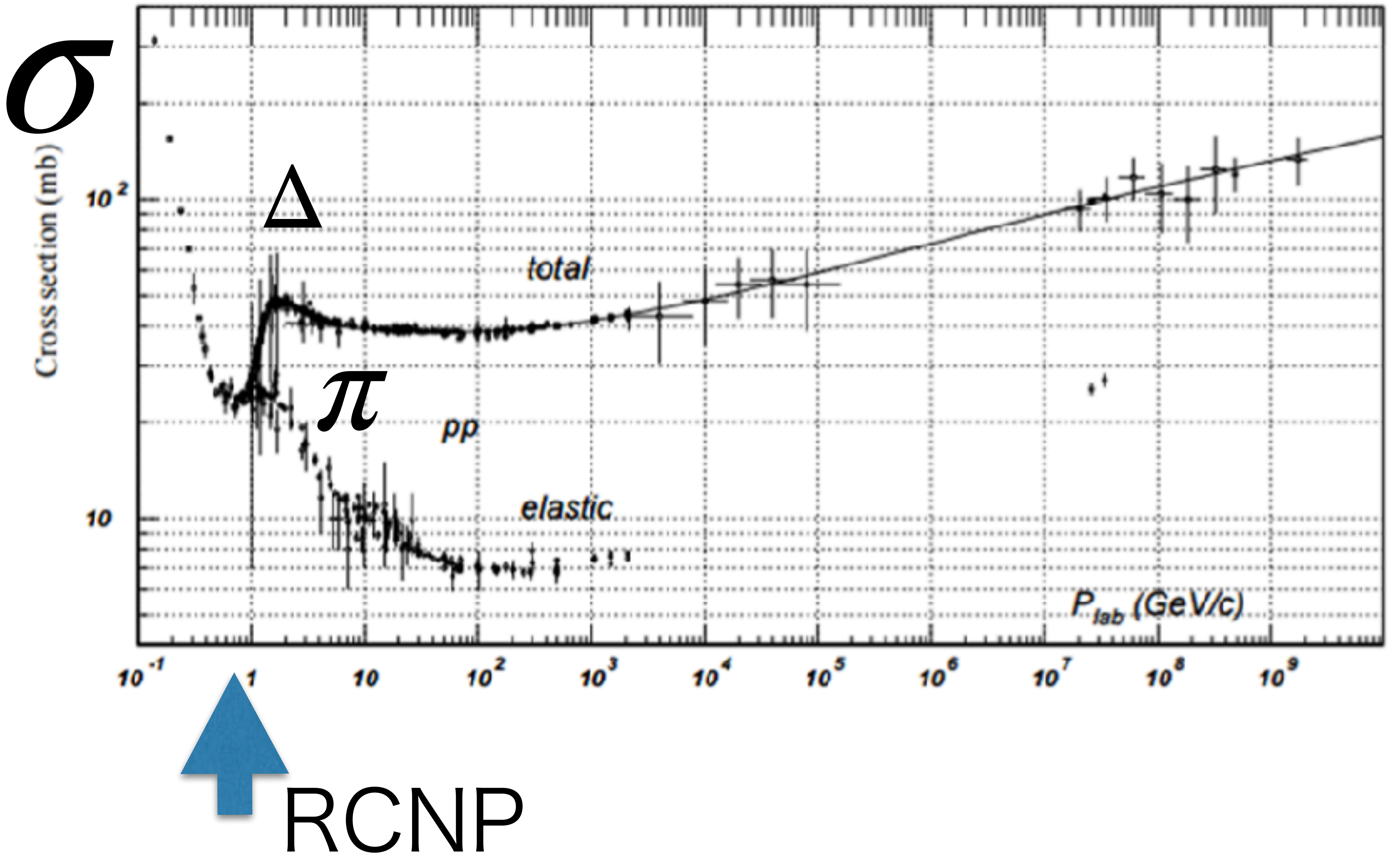
good probe of pion

How large is the cross sections?

$\pi + p$ reaction



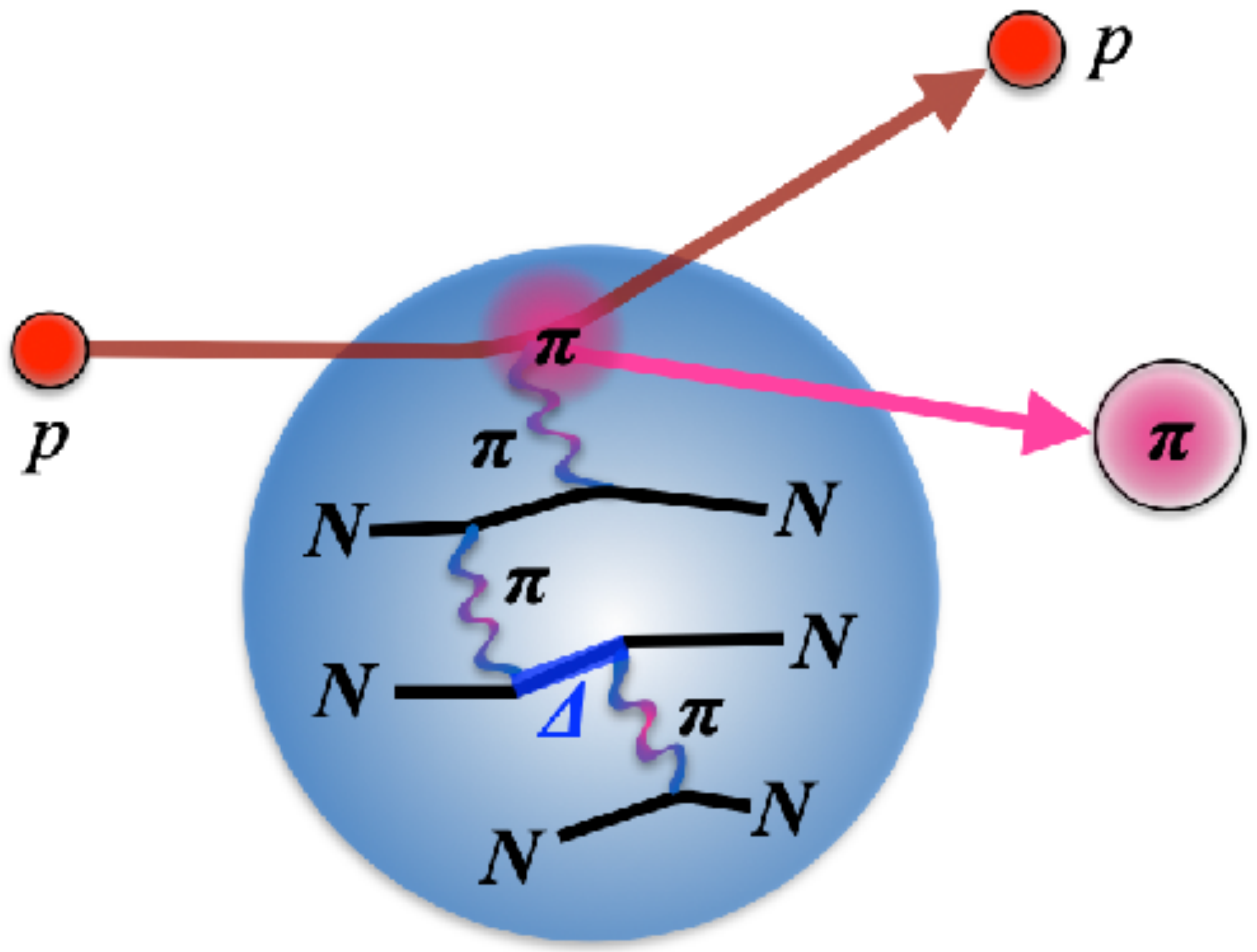
$p + p$ reaction

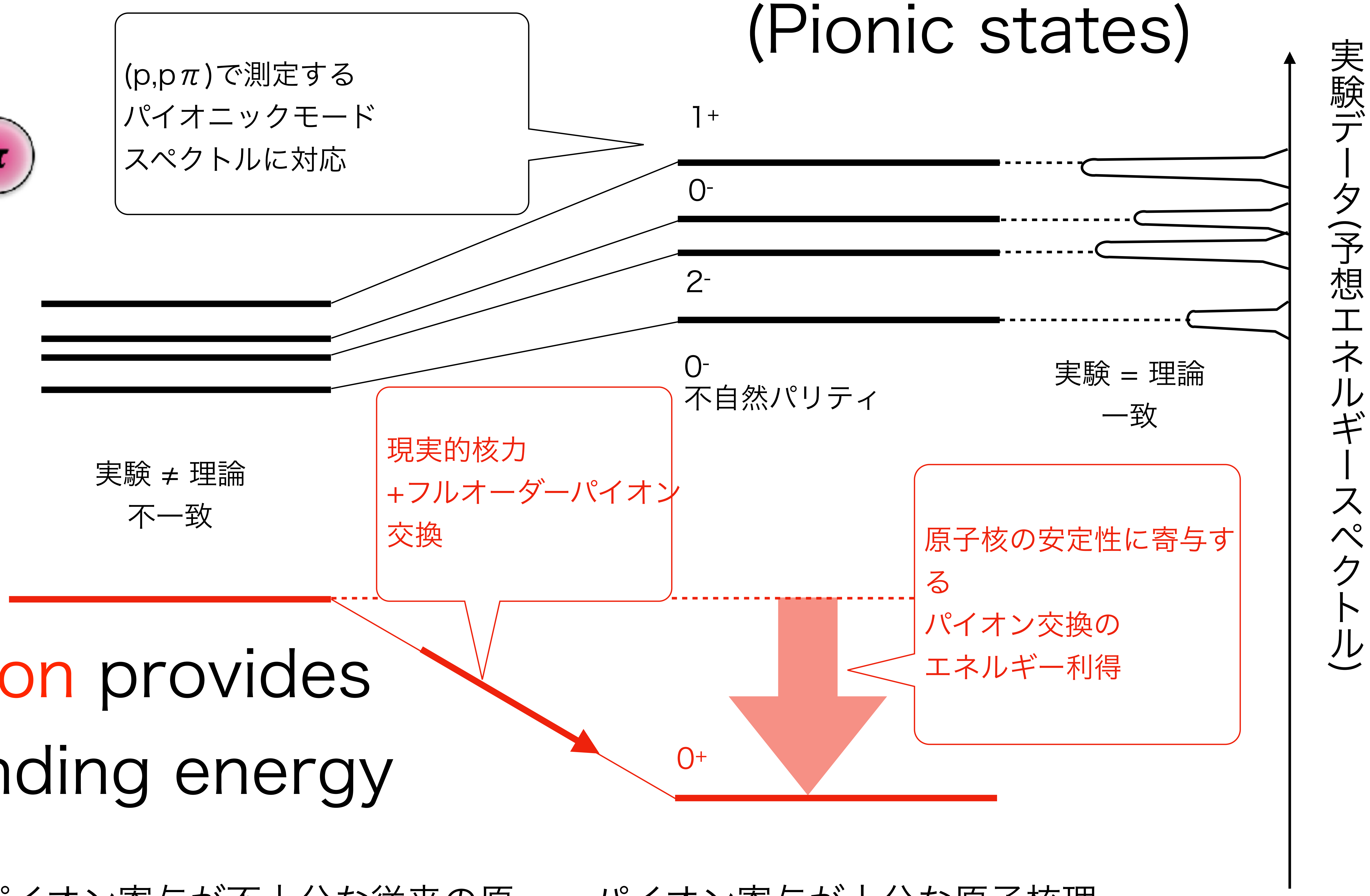


Delta states are important

Comfortably large cross section

Unnatural parity states
(Pionic states)




(p,pπ)で測定する
パイオニックモード
スペクトルに対応

1^+

0^-

2^-

0^-
不自然パリティ

実験 = 理論
一致

実験 ≠ 理論
不一致

現実的核力
+フルオーダーパイオン交換

原子核の安定性に寄与する
パイオン交換の
エネルギー利得

0^+

実験データ(予想エネルギースペクトル)

pion provides binding energy

パイオン寄与が不十分な従来の原子核理論

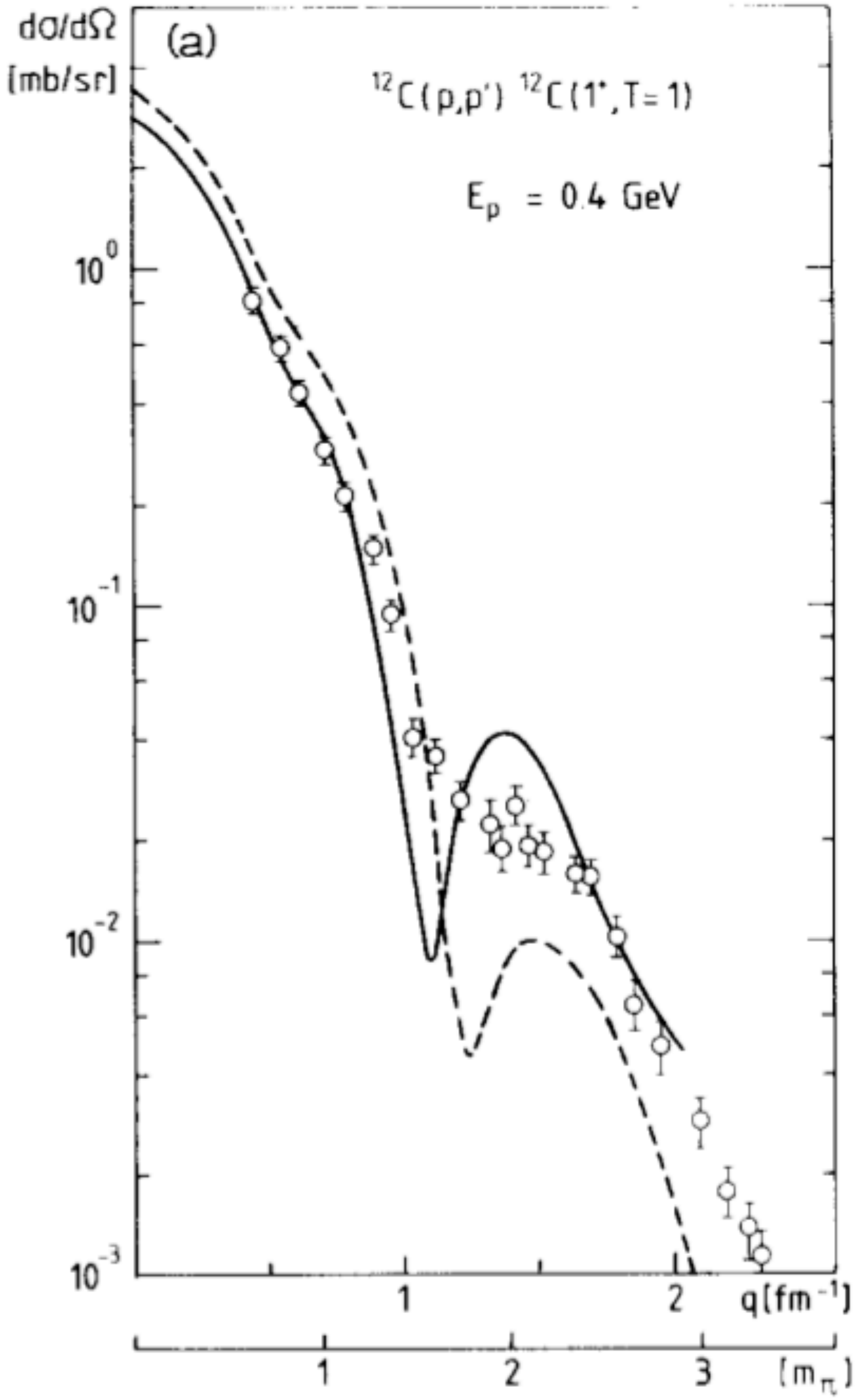
パイオン寄与が十分な原子核理論(本研究)

$(p, p\pi)$ project

unexplored states

Oset Toki Weise
Phys. Rep. 83 (1982)

$^{12}C(1^+)$



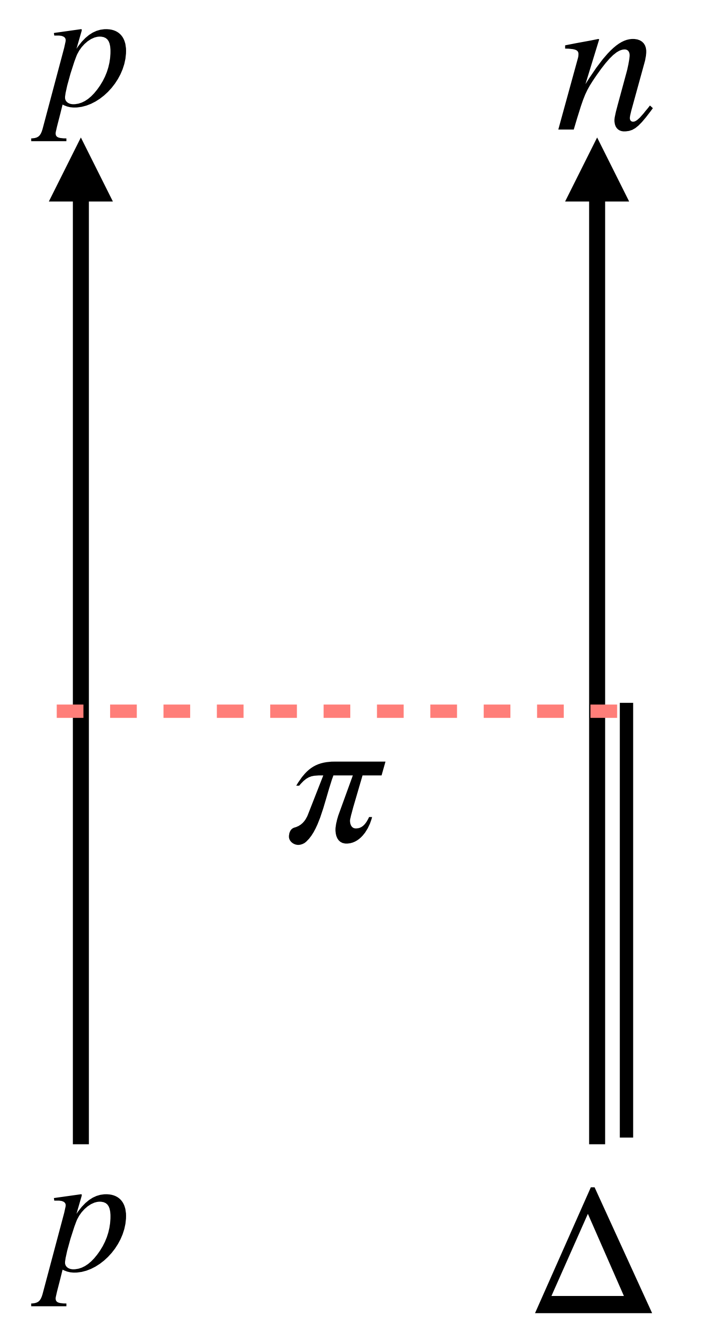
$(\sigma \cdot q)$ $(\sigma \times q)$ mixed

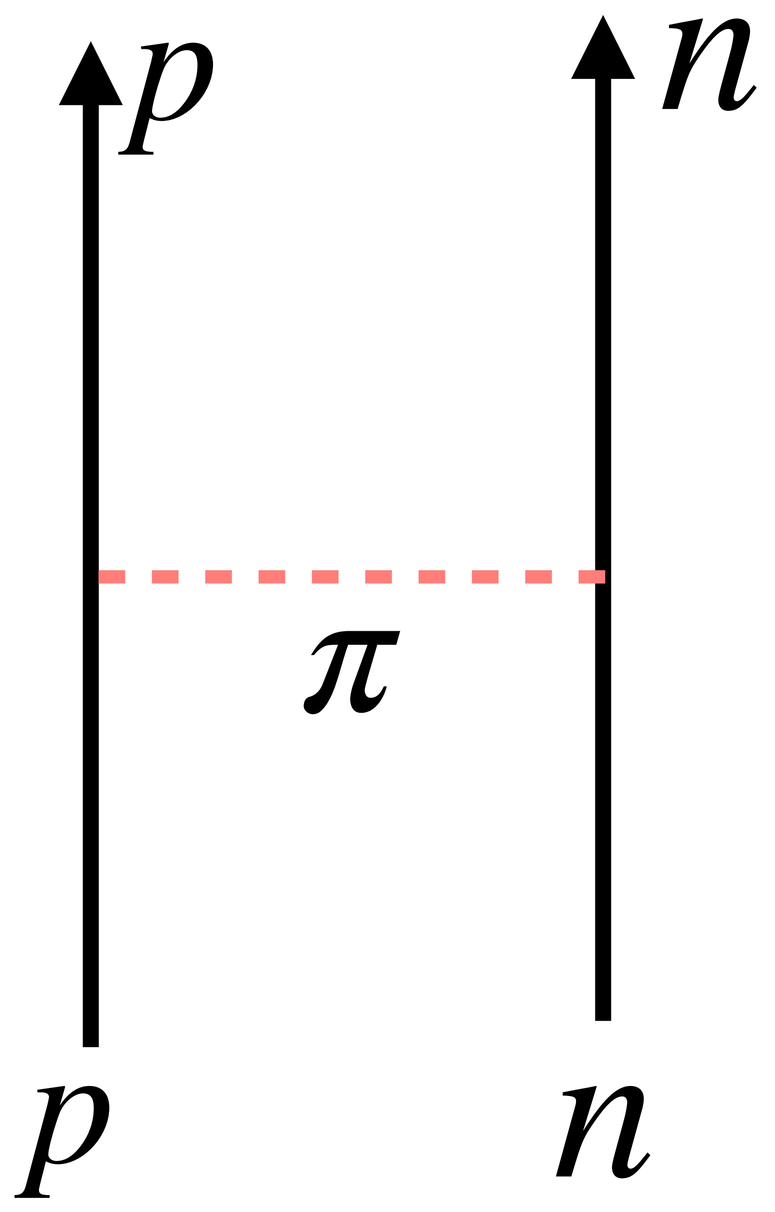
Unexplored!!

New findings

1. Giant resonance states
2. Unnatural parity spectra
3. Pionic atoms
4. Delta states

Real source of magic numbers
(biggest mystery of NP)



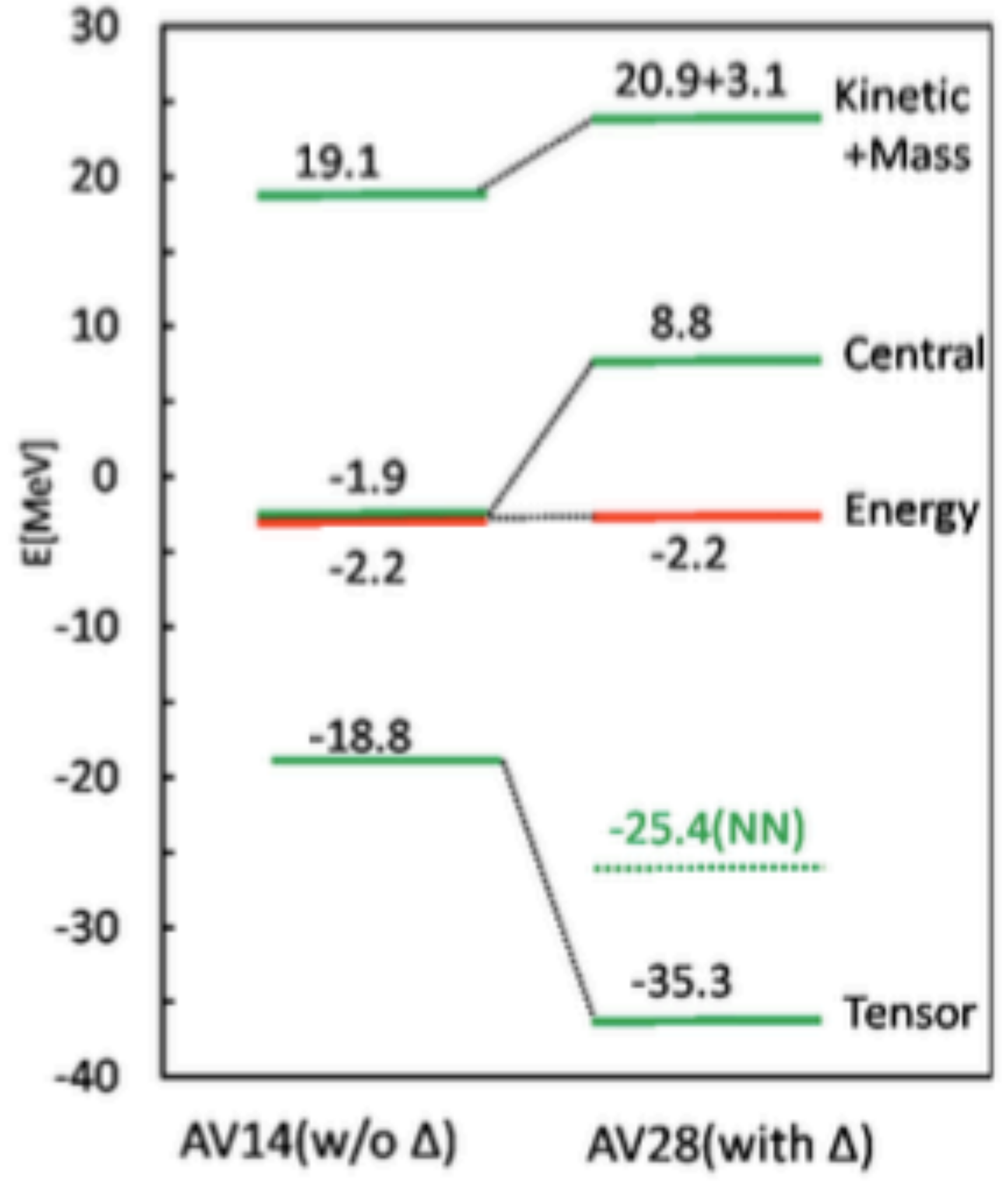


Tensor force and delta excitation for the structure of light nuclei

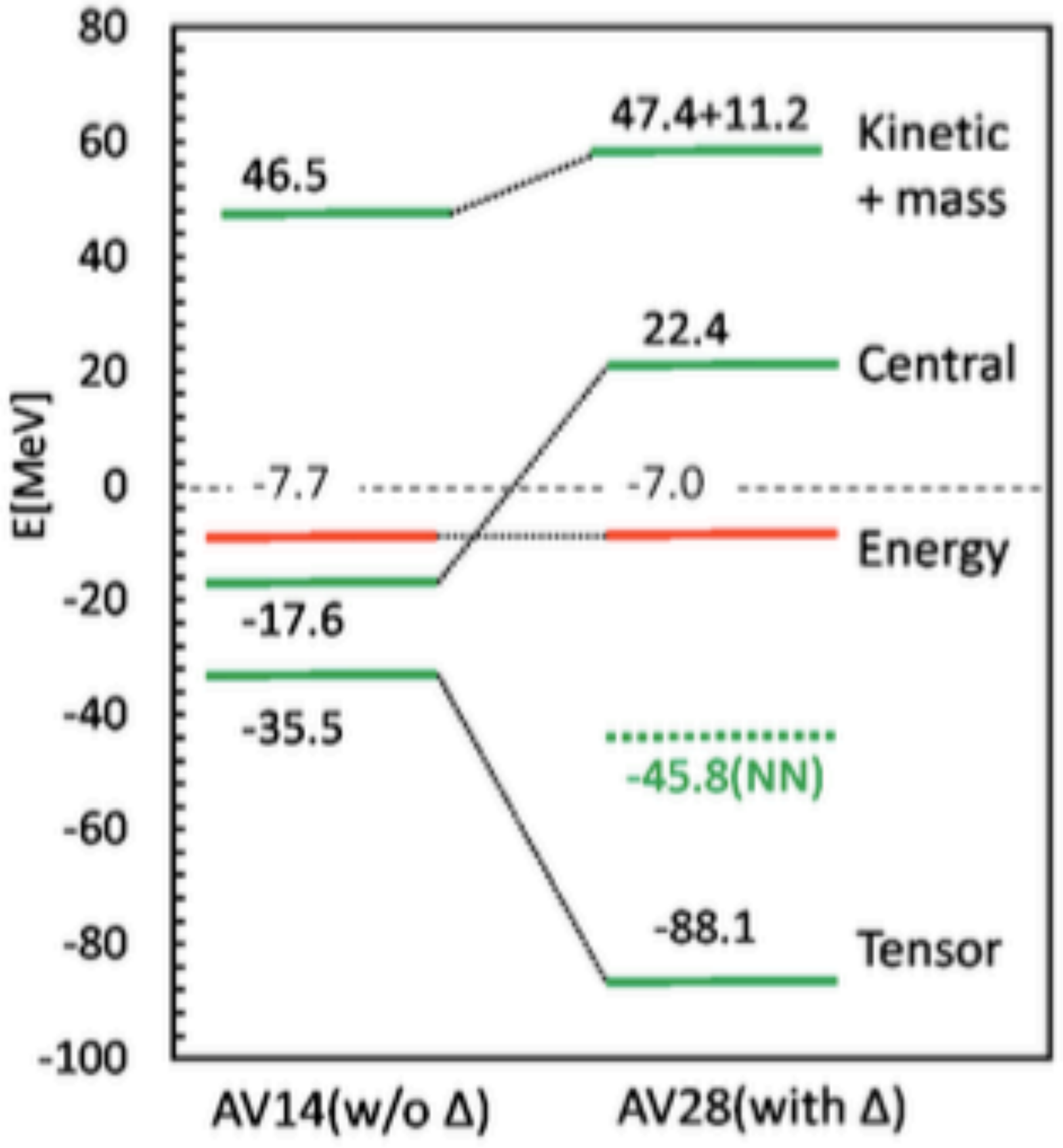
Journal of Physics: Conference Series **569** (2014) 012076

K. Horii[1], T. Myo[2,3], and H. Toki[3]

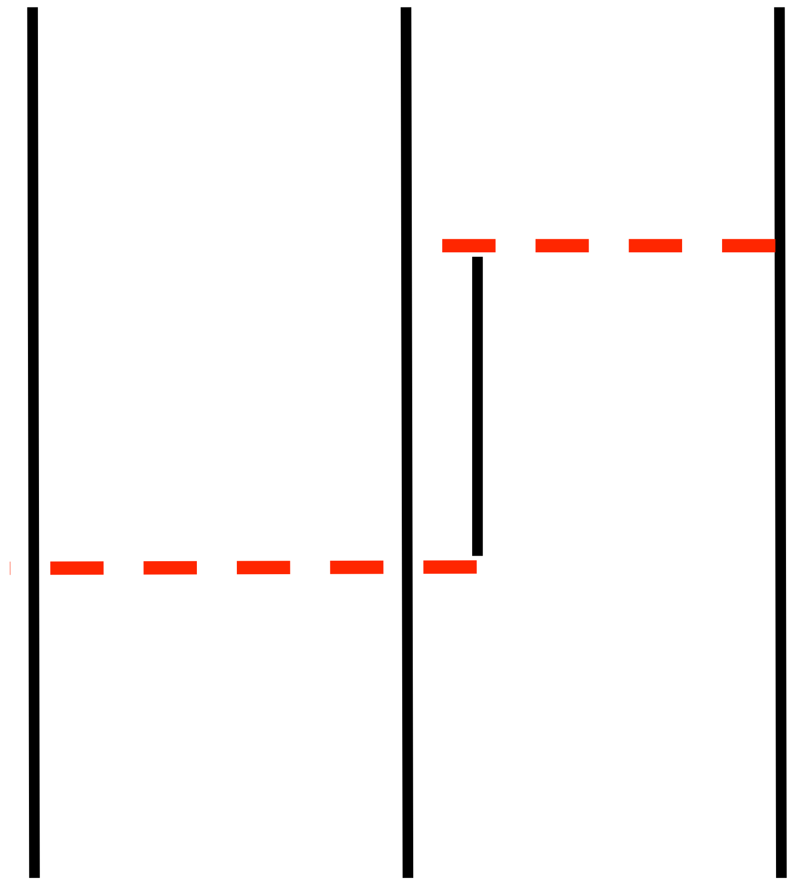
Neutron



Triton



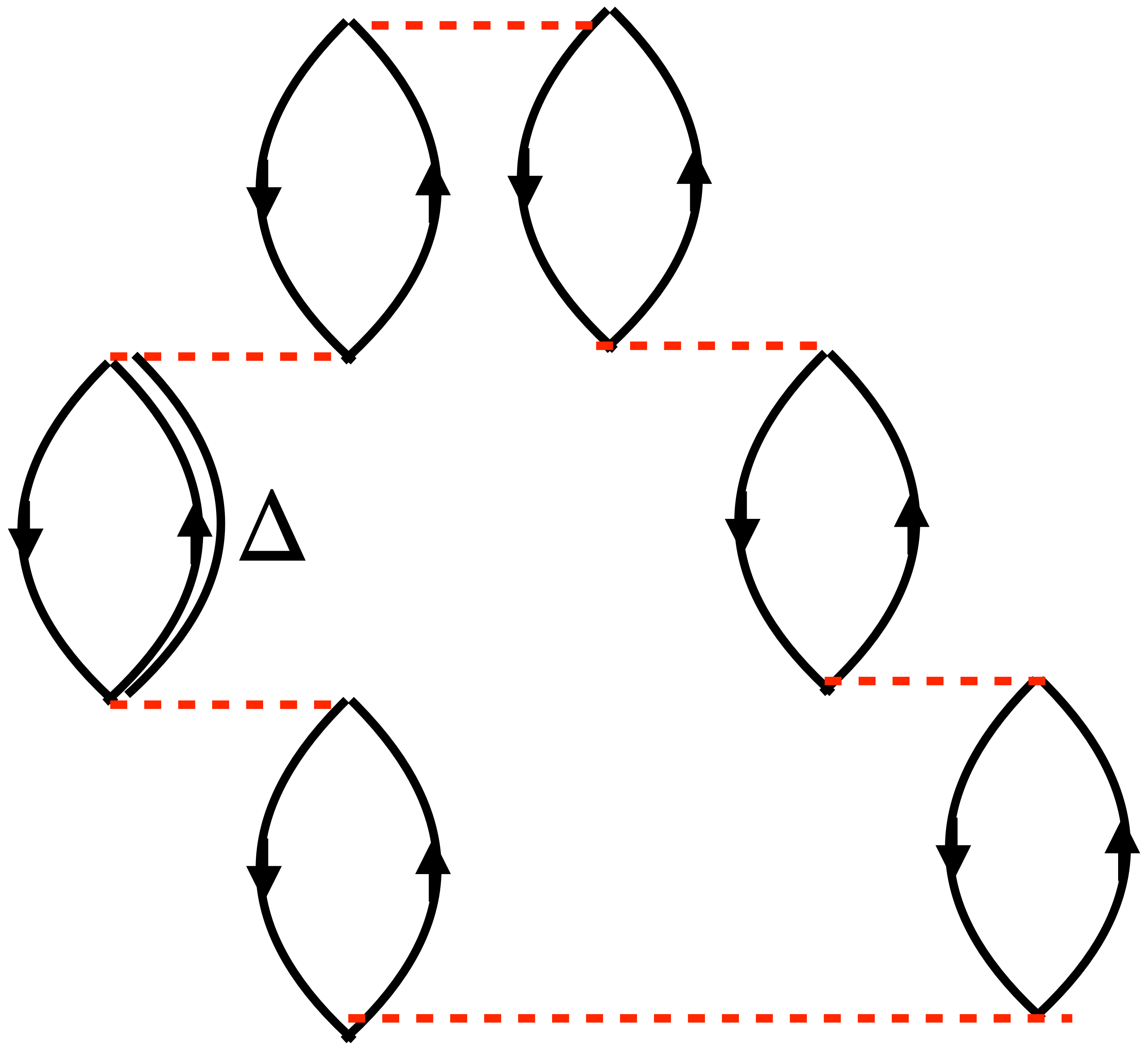
Three body interaction



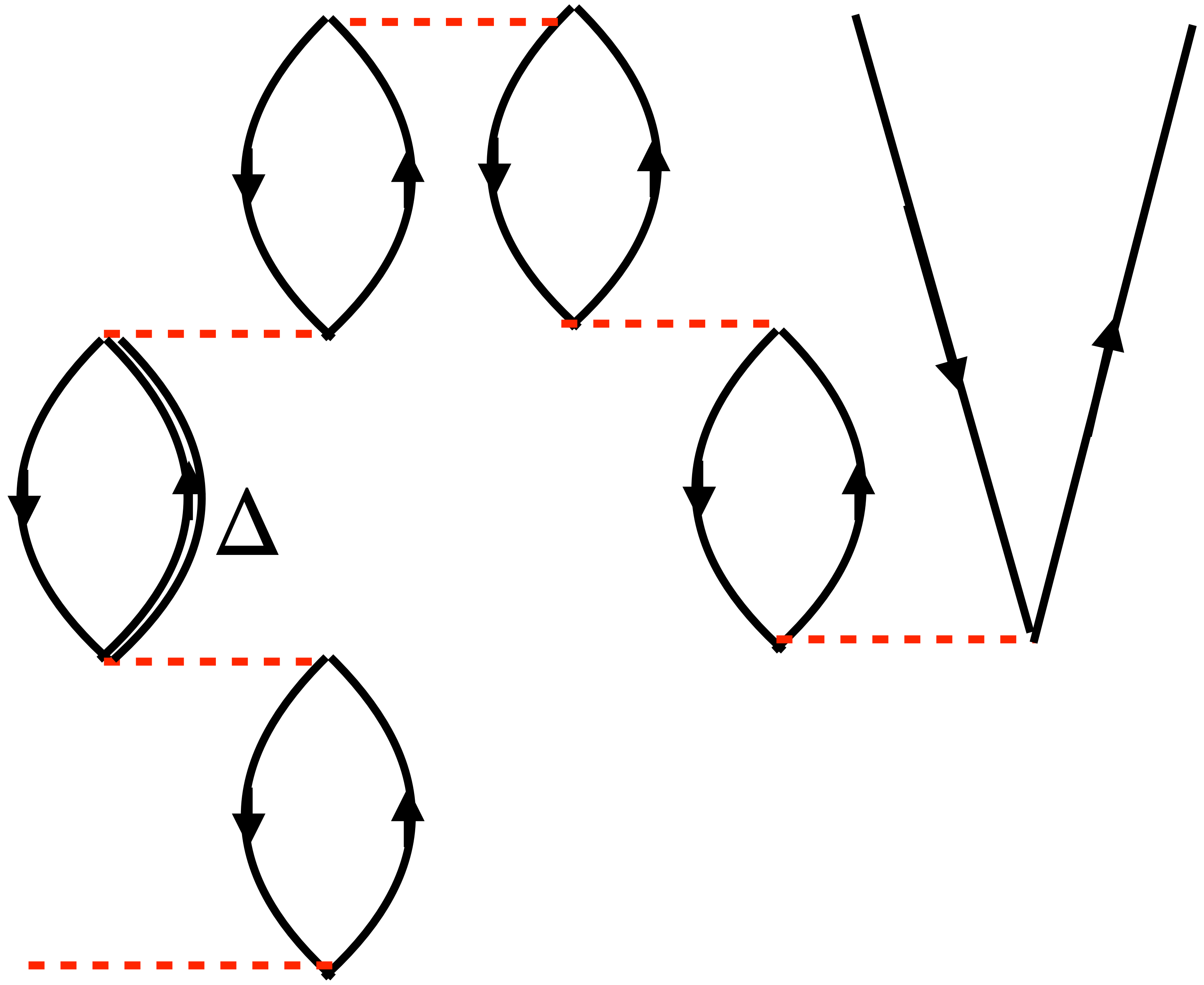
All the attraction comes from the tensor interaction by adding the delta excitations explicitly

Theory has to be developed!

Fetter-Walecka many body theory
Ring diagram formulation



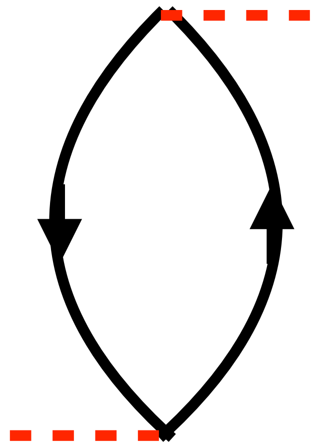
Ground state



Excited state

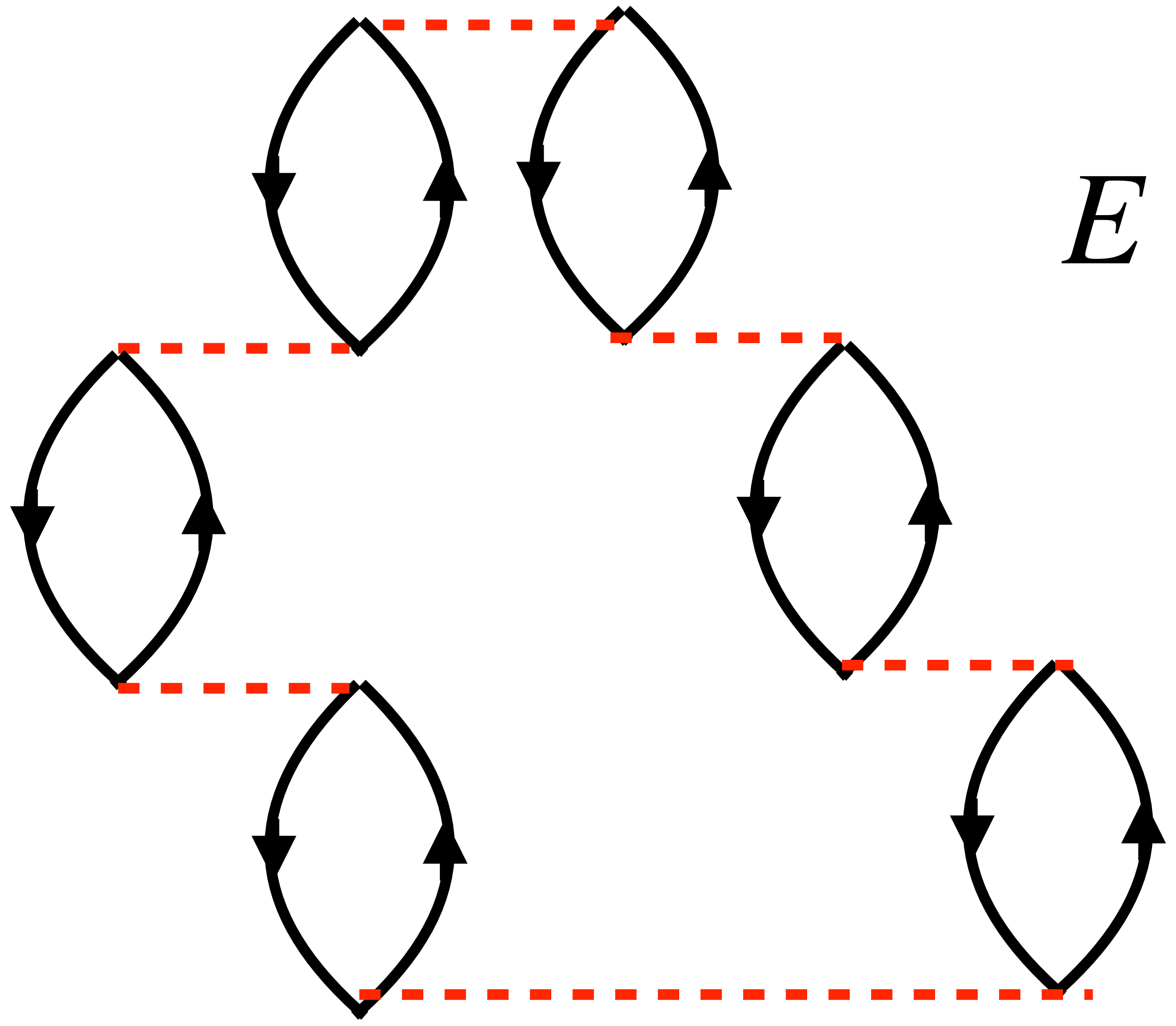
Pion condensation formalism

Pion ring diagram formulation (flavor)



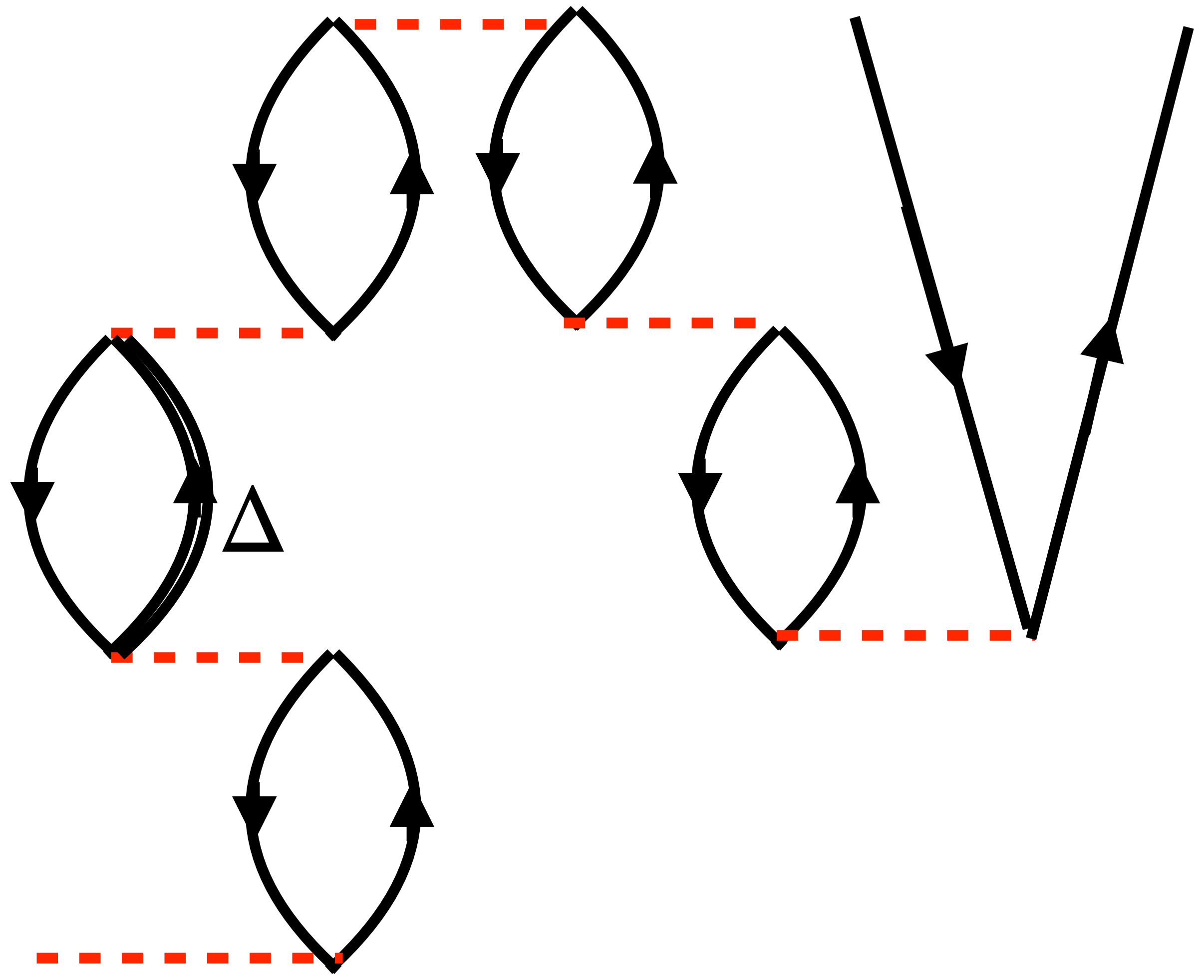
$$\Pi(\omega, q) = -\frac{f_\pi^2(q^2)}{m_\pi^2} \sum_{ph} < q|\sigma q|ph > [\frac{1}{E_p - E_h - \omega + i\eta} + \frac{1}{E_p - E_h + \omega + i\eta}] < ph|\sigma q|q >$$

$$R(\omega, q) = \Pi + \Pi D \Pi + \ldots = \Pi + \Pi D R \qquad R(\omega, q) = \Pi(\omega, q)/(1 - \Pi(\omega, q) D(\omega, q))$$



$$E = -i \frac{1}{2(2\pi)^4} \int d^4 q \{\log[1 - D\Pi] - D\Pi\}$$

$$\sigma \sim Im[\Pi(\omega, q)/(1 - D\Pi)]$$



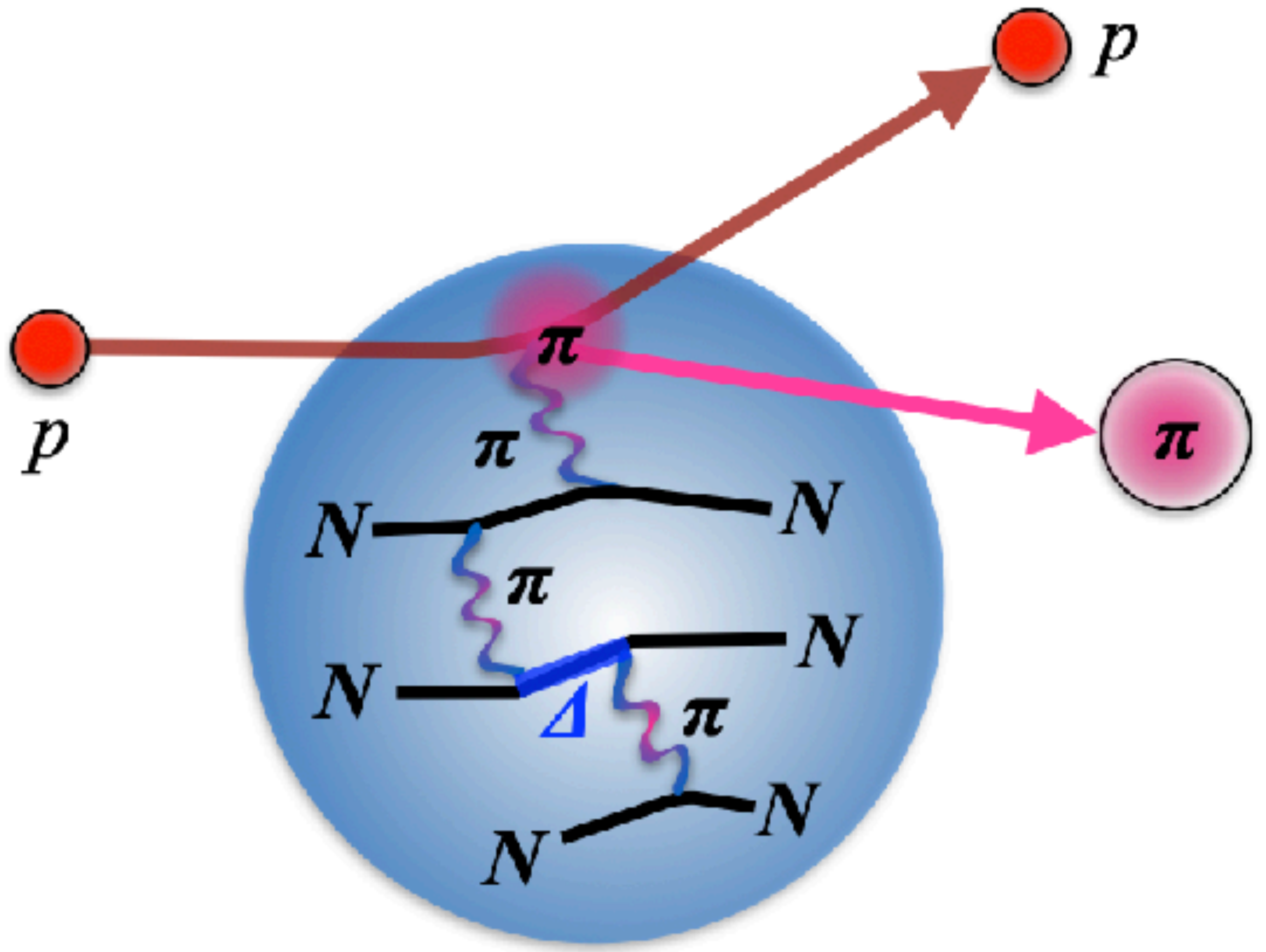
Conclusion:

Pion nuclear physics

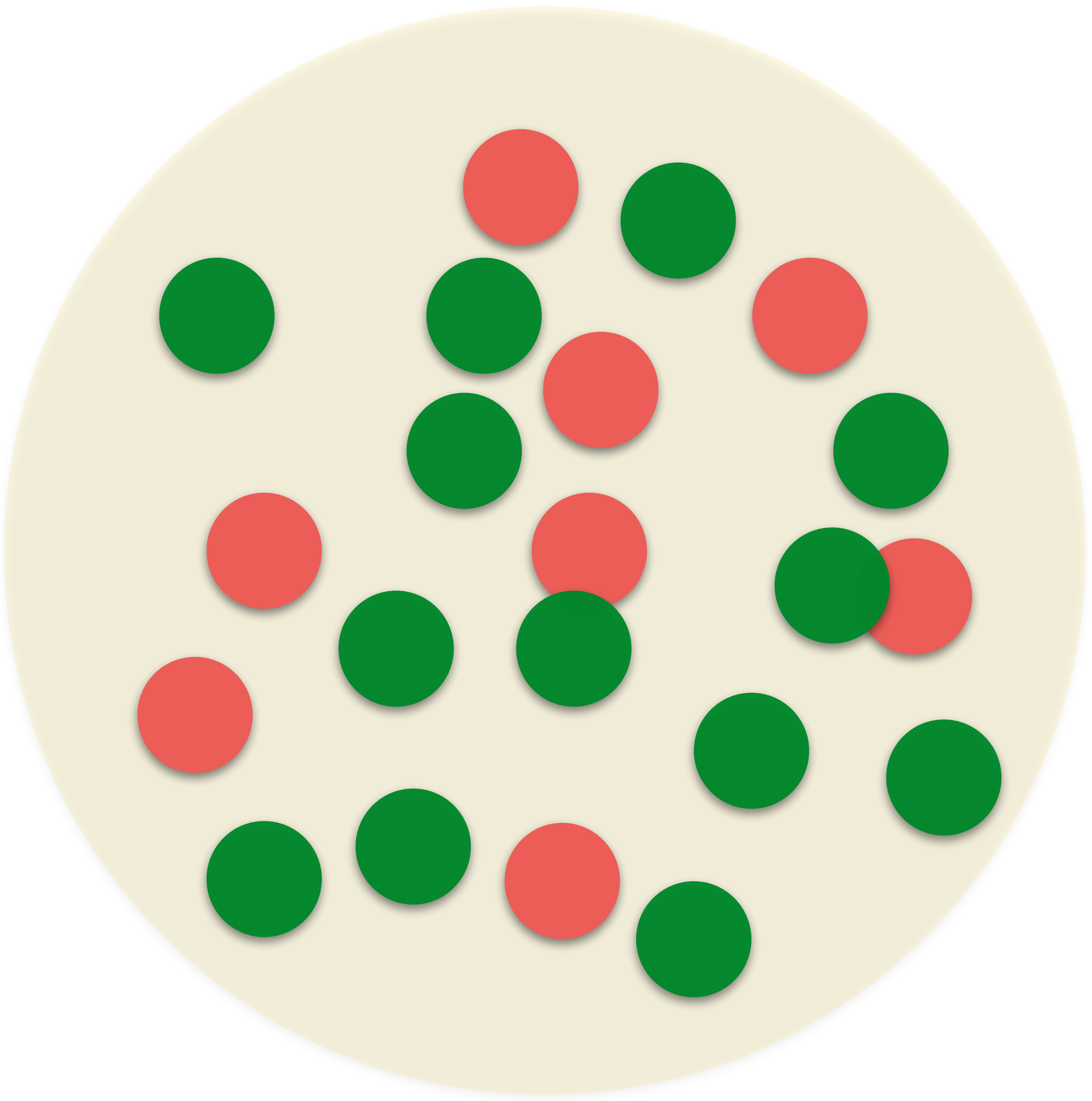
$(p, p\pi)$ project (Experiment)

Unnatural parity states with high momentum pion prove

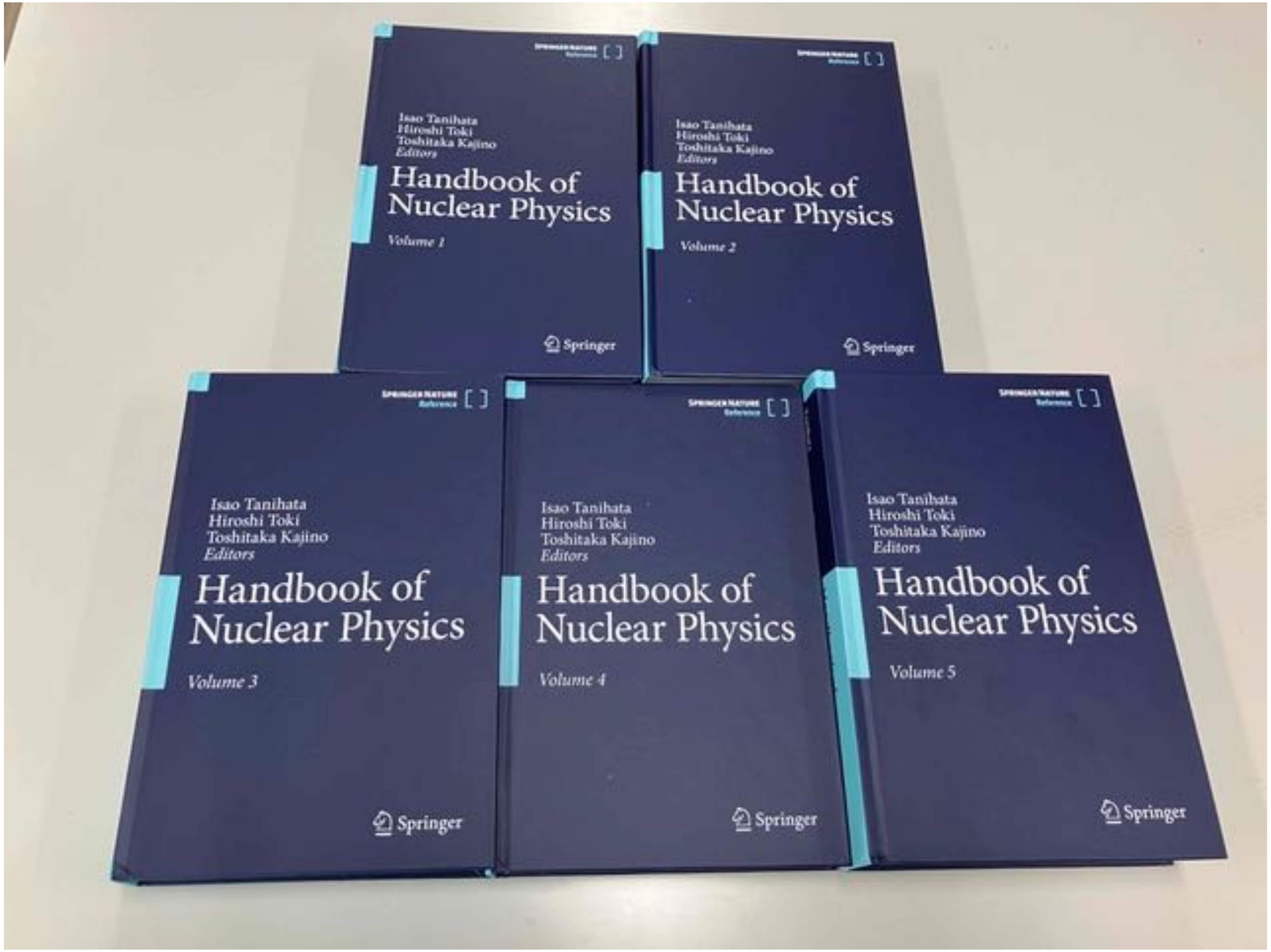
Ring diagram formulation (Theory)



$$\Psi = \underbrace{|\,low > + \,|\,high >}_{\pi}$$



Handbook of Nuclear Physics (2023)



Super Editors
I. Tanihata
H. Toki
T. Kajino

Section editors
13

Chapters
113

5 volumes
4000 pages