ECT* Workshop

"Critical stability of few-body quantum systems"

October 23-27, 2023, Trento (Italy)

Large scattering lengths & Four-neutron correlations

F. Miguel Marqués

Outline

- Scattering lengths :
  - neutron off exotic 'containers'
  - ^{17}B+n : a schocking case !
- Experimental program @ RIKEN :
  - stat. & acceptance : effective range
  - multi-channel : determine (a_s, r_e) !
  - Universality ($|a_s|/r_e \sim 100$)

- Tetraneutron "signal" !
  - resonance / spatial correlations ?
  - link to momentum correlations ?
- Experimental program @ RIKEN :
  - first 4n invariant masses
  - some low-energy structures
  - explore full kinematics ...

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Emeline Oliveira, PhD

Audrey Anne, PhD

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- Low-energy scattering :

$$\varphi_k(r) \approx \frac{\sin(kr + \delta_0)}{kr}, \; k = \sqrt{2\mu E} \quad (1)$$

$$\sigma(k) = 4\pi \frac{\sin^2(\delta_0)}{k^2} \quad (2)$$

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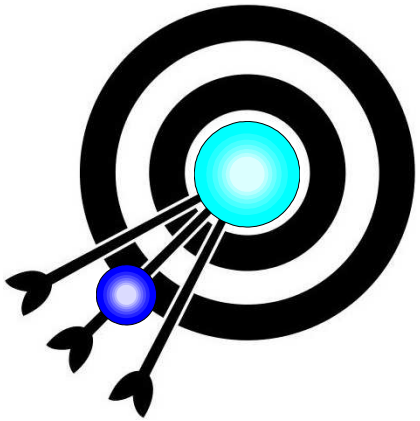
$\Rightarrow$ $a_s \sim$ R of hard sphere !



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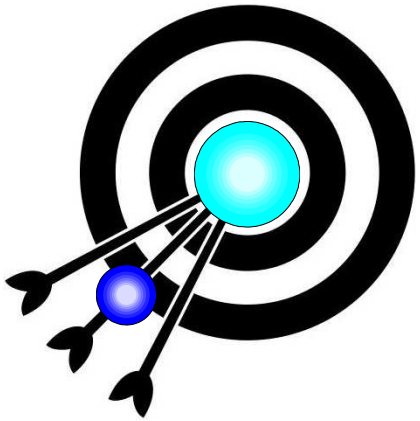
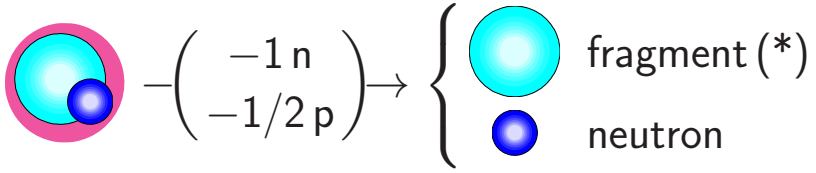


- Neutron scattering :
  - ✔ neutrons are neutral
  - ✘ neutrons are neutral
  - ✘ exotic nuclei (& neutrons) are unstable

- knockout reactions :



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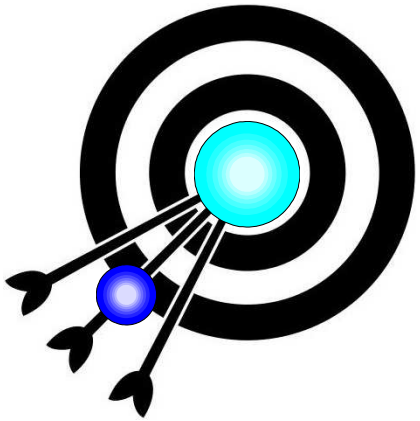

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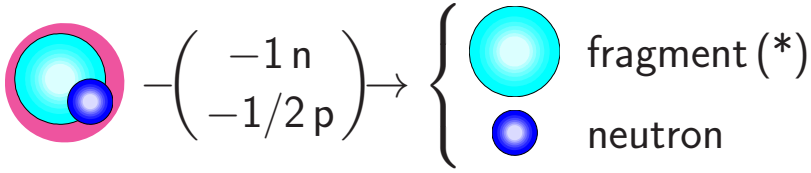

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- halo nuclei : Bertsch, PRC 57 (1998) 1366

$$\psi_i(r) \approx e^{-\alpha r}/r\,, \; \alpha = \sqrt{2\mu_i S_n} \quad (5)$$

$$\sigma(k) \approx \left(\cos\delta_0 + \frac{\alpha}{k}\sin\delta_0\right)^2 \frac{k}{(\alpha^2+k^2)^2} \quad (6)$$

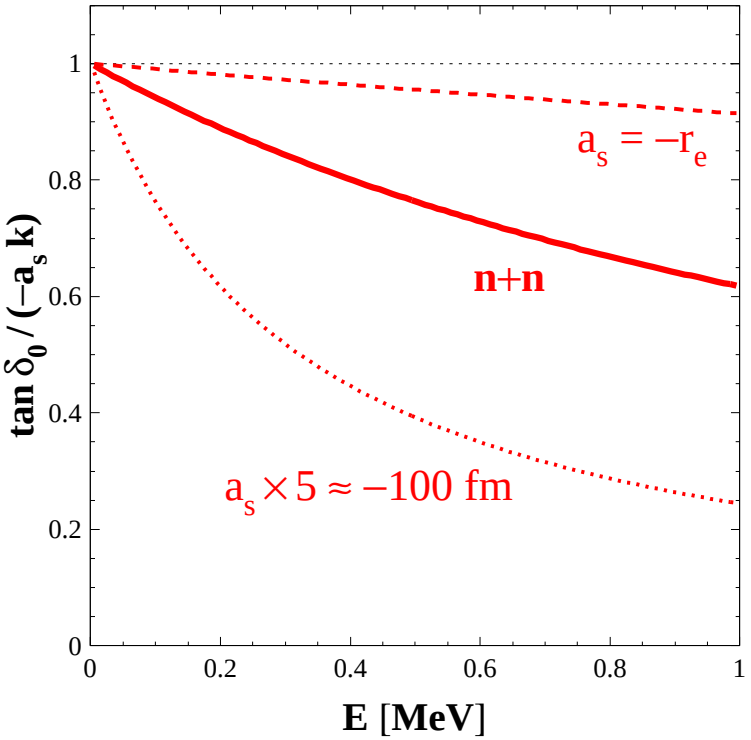
⇨ $\sigma(k) = (2/4/6)$ & $\delta_0 = (3)$

Example : neutron off neutron

- Effective-range (k^2) term ?

$$\frac{-a_s\,k}{\tan\delta_0} \;=\; 1 \;-\; \frac{a_s\,r_e}{2}\,k^2 \;+\; \mathcal{O}(k^4)$$

n+n $\begin{cases} a_s &= -18.5 \text{ fm} \\ r_e &= 2.8 \text{ fm} \end{cases}$



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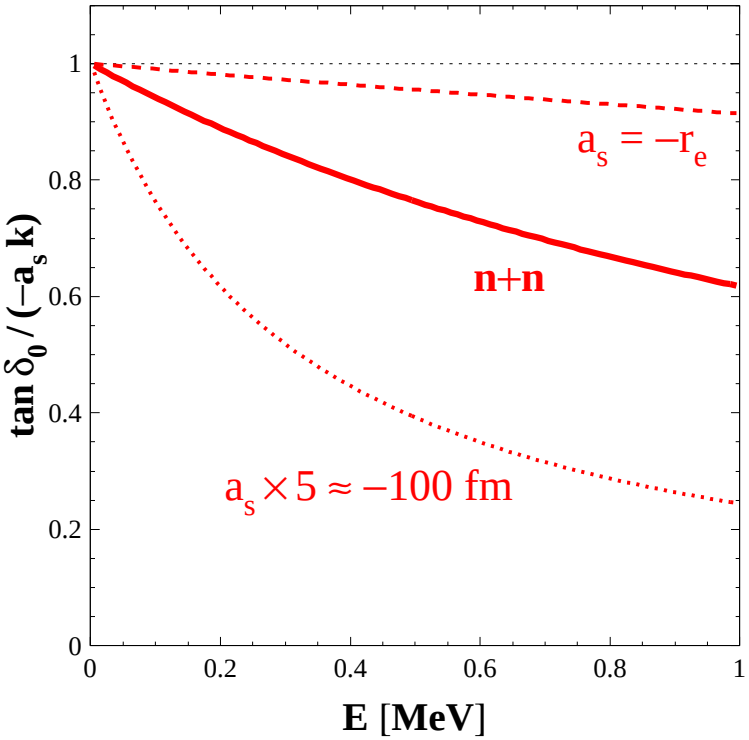

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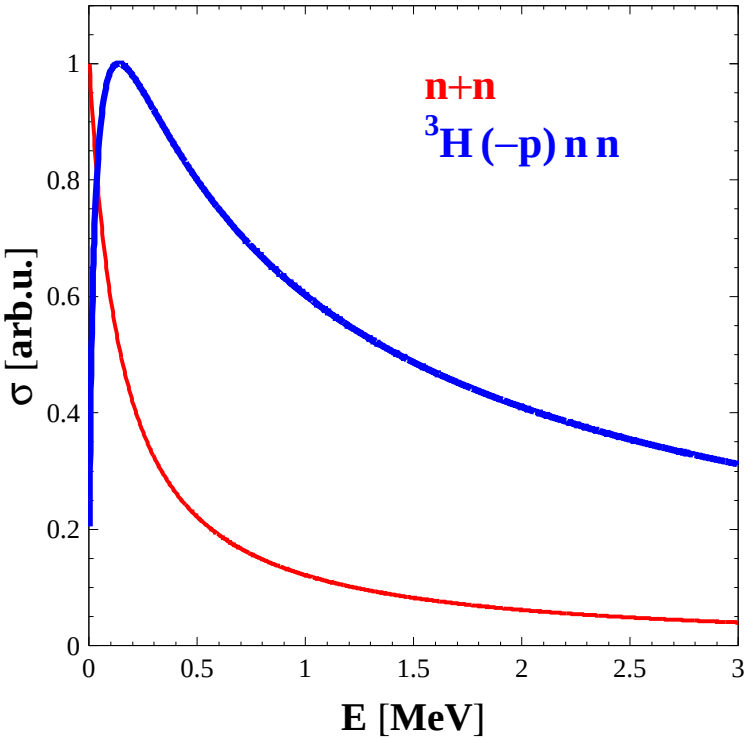

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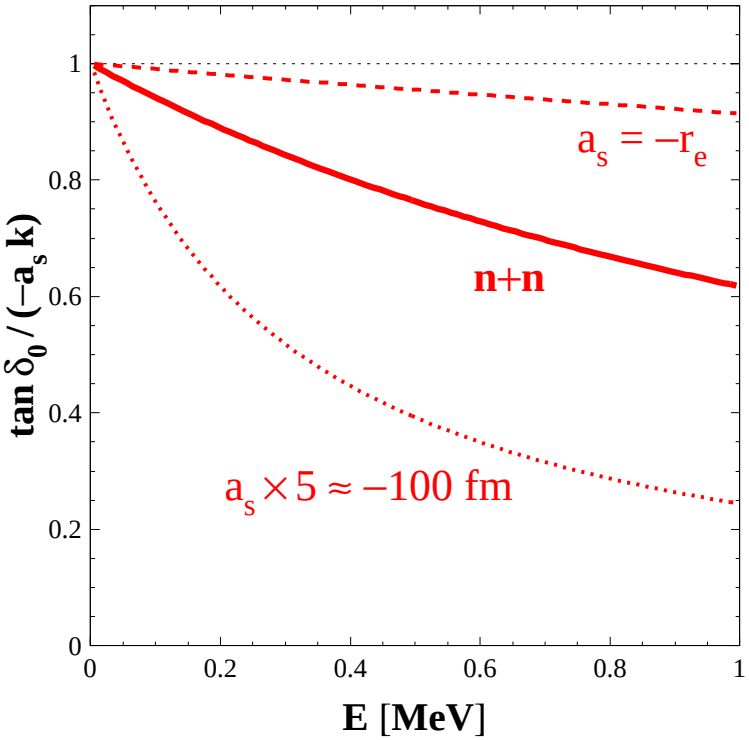

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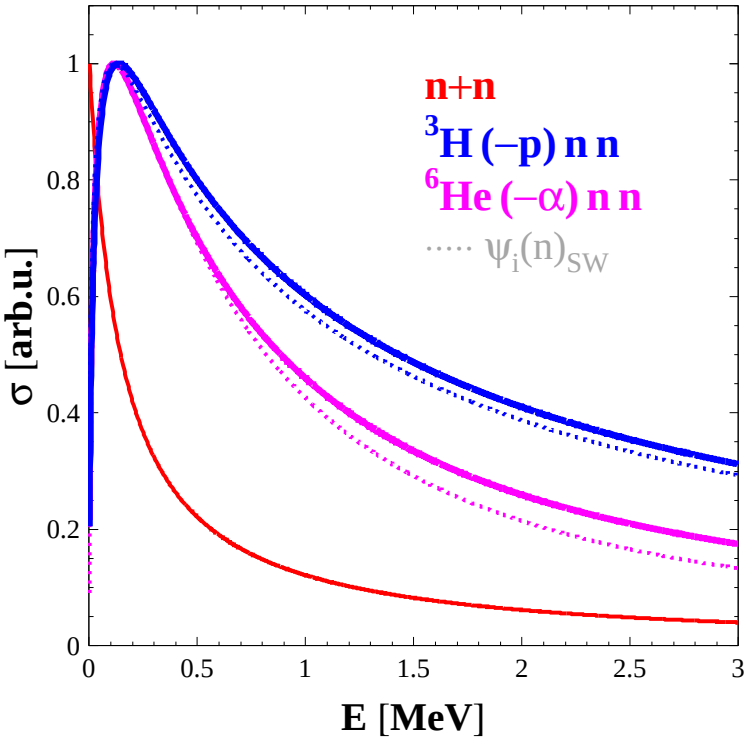

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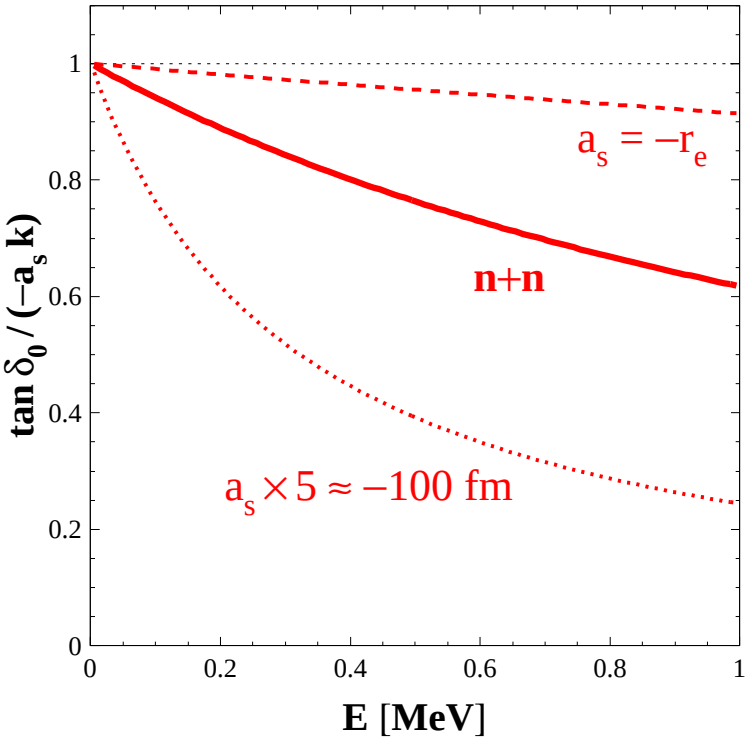

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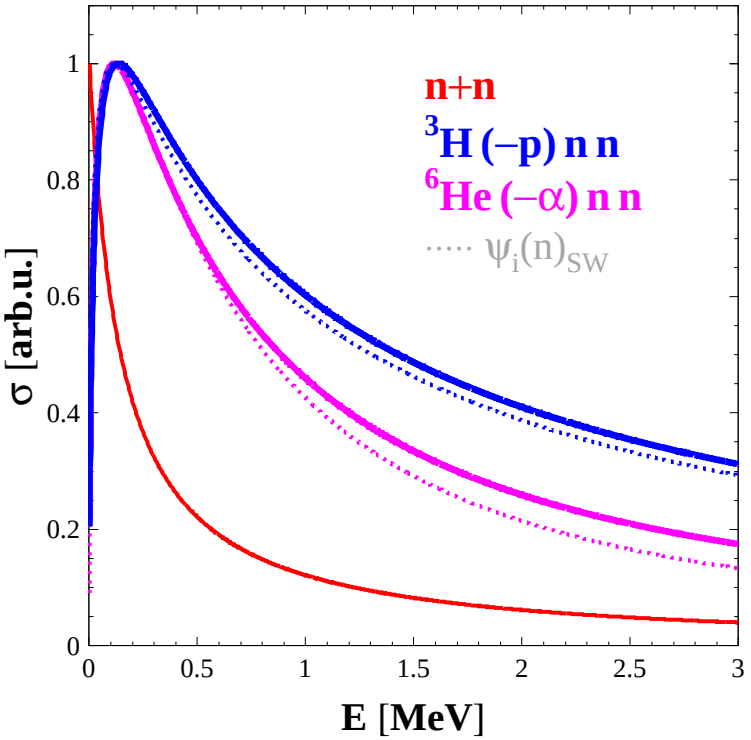
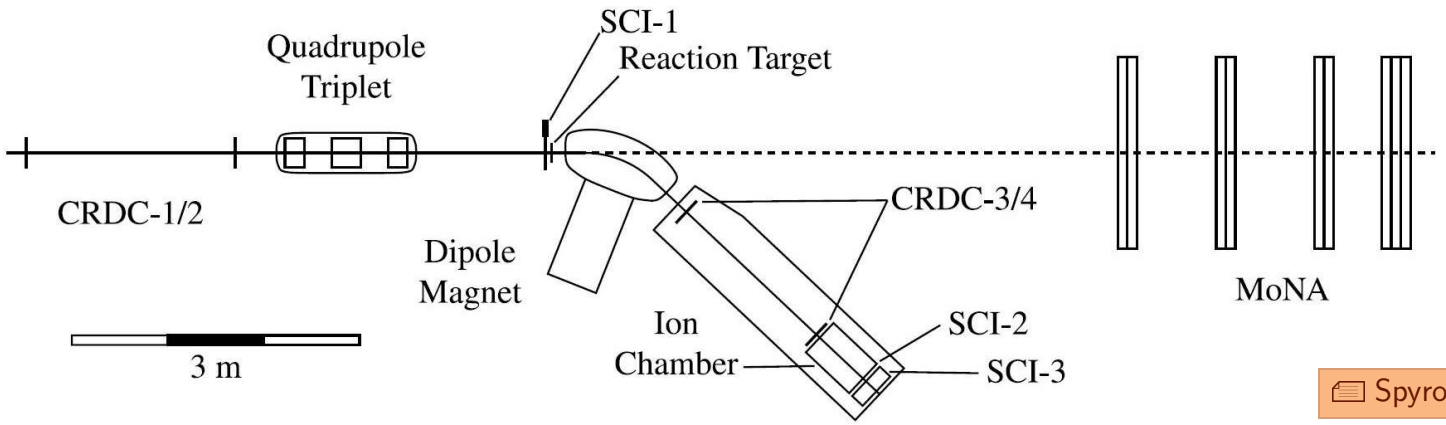


- n+(A>1) : Carbonell, SciPost Phys Proc 3 (2020) 008
  - attractive n-N / n-A Pauli repulsion
  - $|a_s| \sim r_e$ progressively from + to − ...

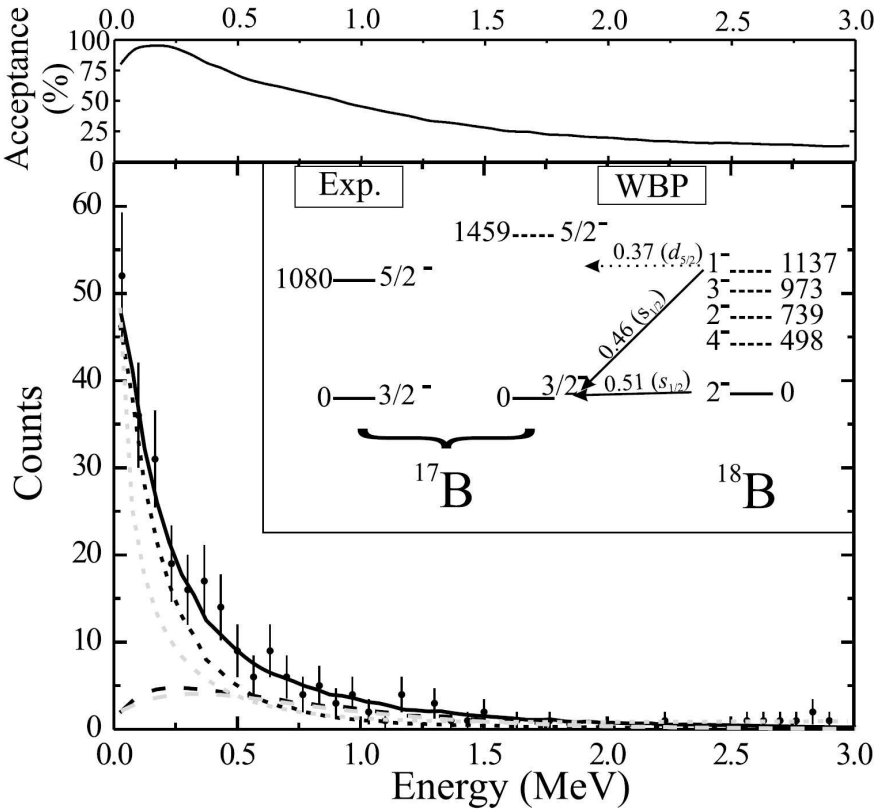
  ⇨ until Z=5 : $^{18}_{5}$B !!!

Boron 18 : only a limit is known



- ^{19}C (Be, −1p) $^{18}_{5}$**B** @ 62 MeV/N :
  - ✔ first evidence of ^{17}B+n virtual state

Spyrou, PLB 683 (2010) 129



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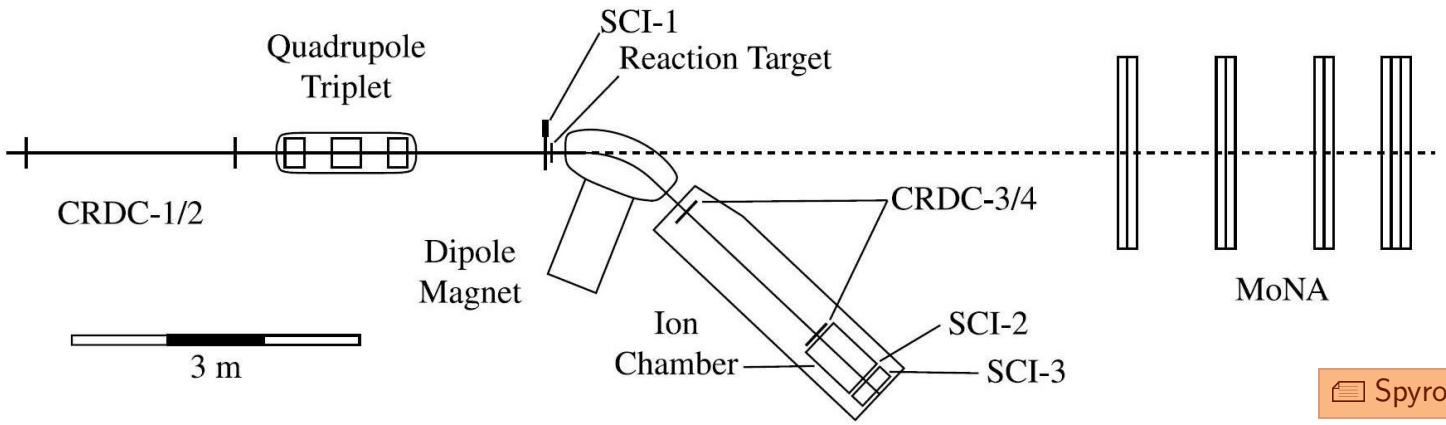
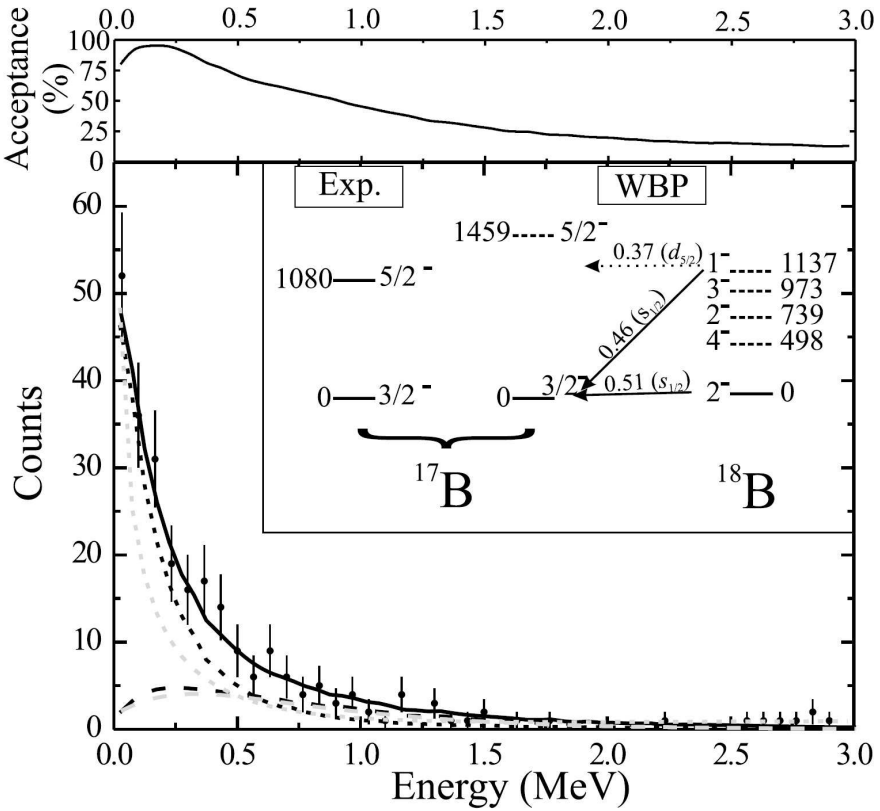


- ^{19}C (Be, −1p) $^{18}_{5}$**B** @ 62 MeV/N :
  - ✔ first evidence of ^{17}B+n virtual state
  - ✘ E(^{17}B+n) only below ∼1 MeV
  - ✘ insensitive to r_e
  - ✘ insensitive to lower bound on a_s
  - ✘ ad-hoc "non-resonant" Maxwellian ...

  ⇨ $a_s(^{17}\text{B+n}) < -50$ fm

Spyrou, PLB 683 (2010) 129



17B+n+n : Efimov trimers ?

- Efimov effect :

  "*a scale-invariant 3-body attraction*"

  Naidon, Rep Prog Phys 80 (2017) 056001

  → induced long-range interaction

  → discrete scale invariance

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  - Efimov physics :

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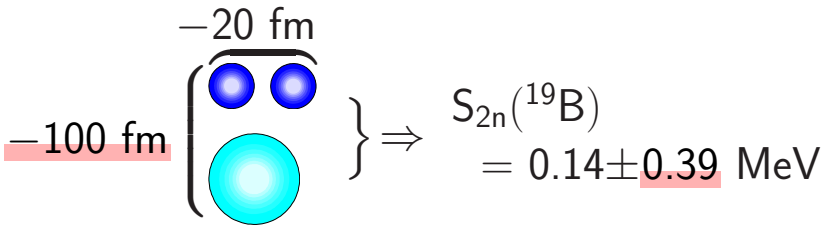

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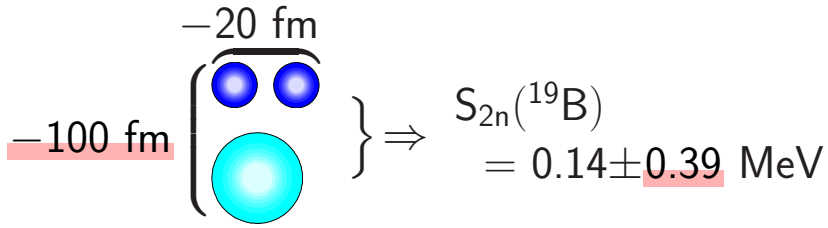

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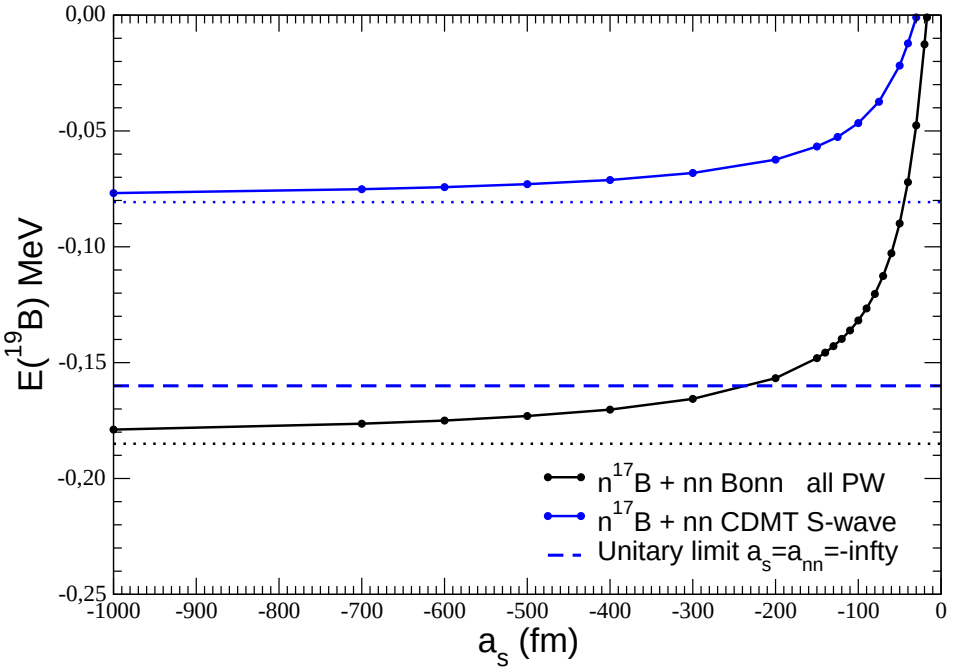
Hiyama, PRC 100 (2019) 011603R



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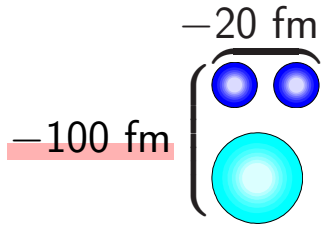

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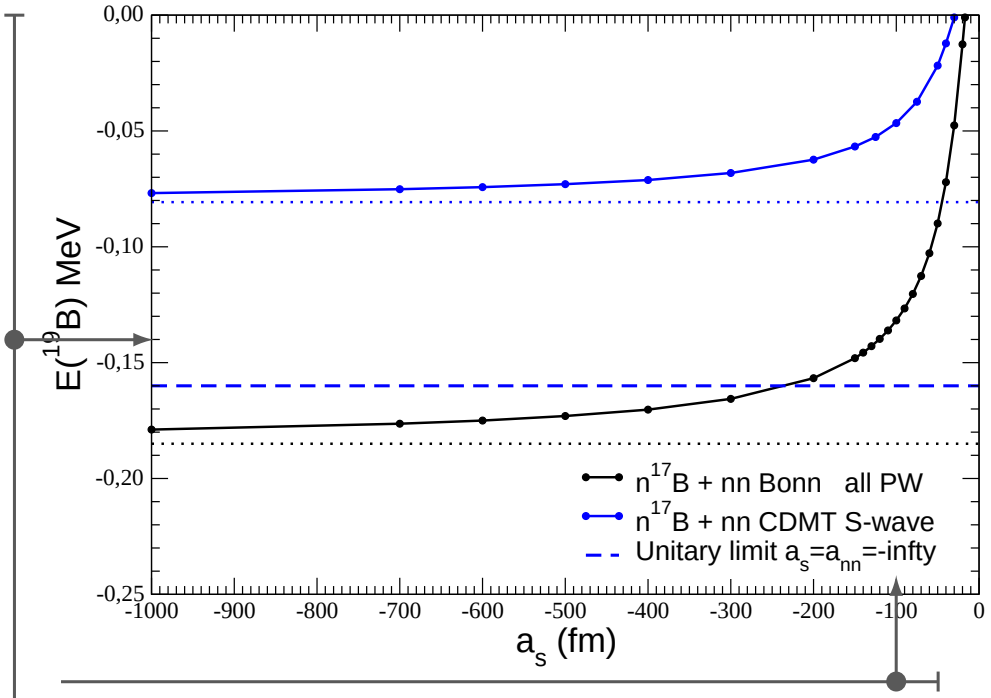

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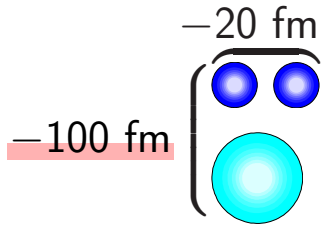

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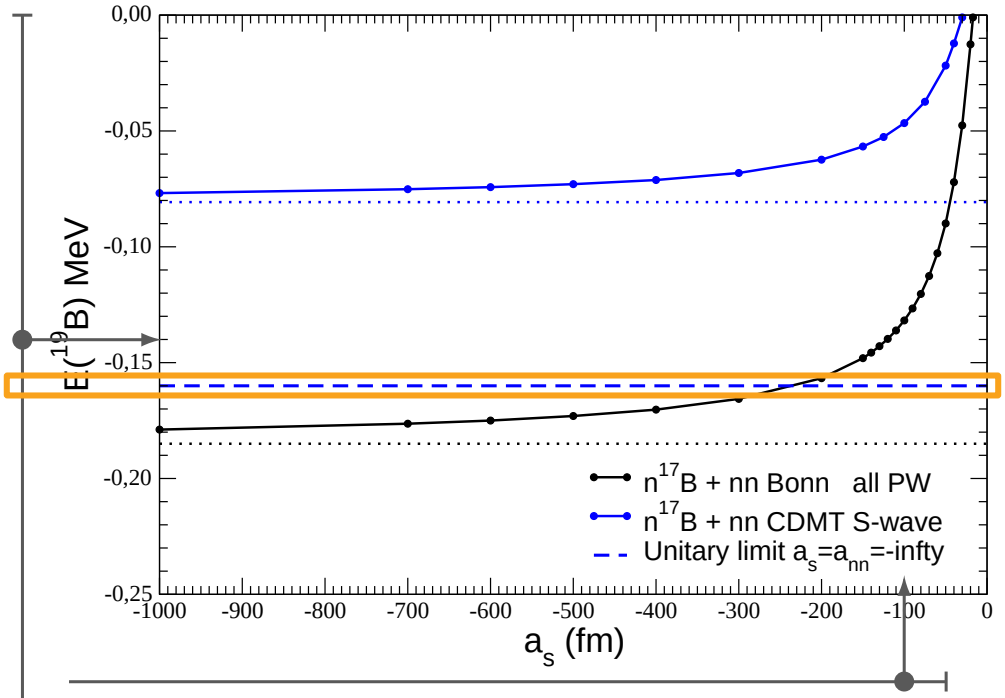

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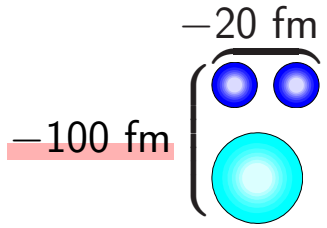

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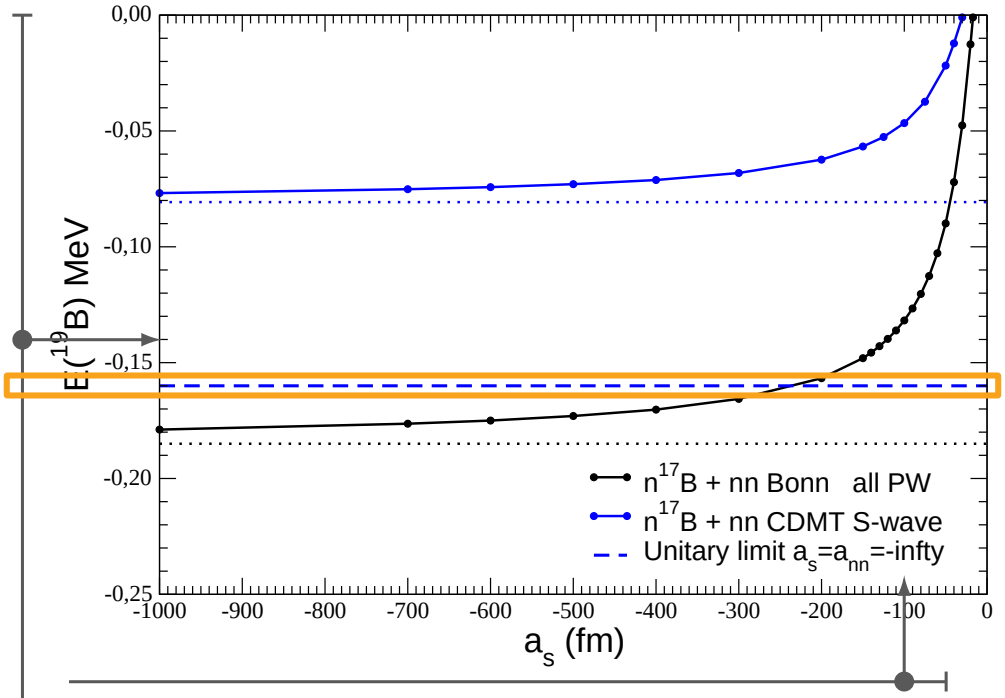
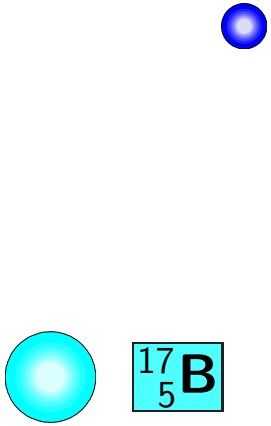


- ✔ ^{19}B bound state & unbound states !
- ✔ good description @ Unitary Limit !
- ✘ other trimers unlikely ($a_s \sim$ kfm)
- ✔ $|\Psi(r,R)|^2$: molecule-like !
- ✔ only binary inputs (no 3NF) !!!

Boron 18 @ RIKEN



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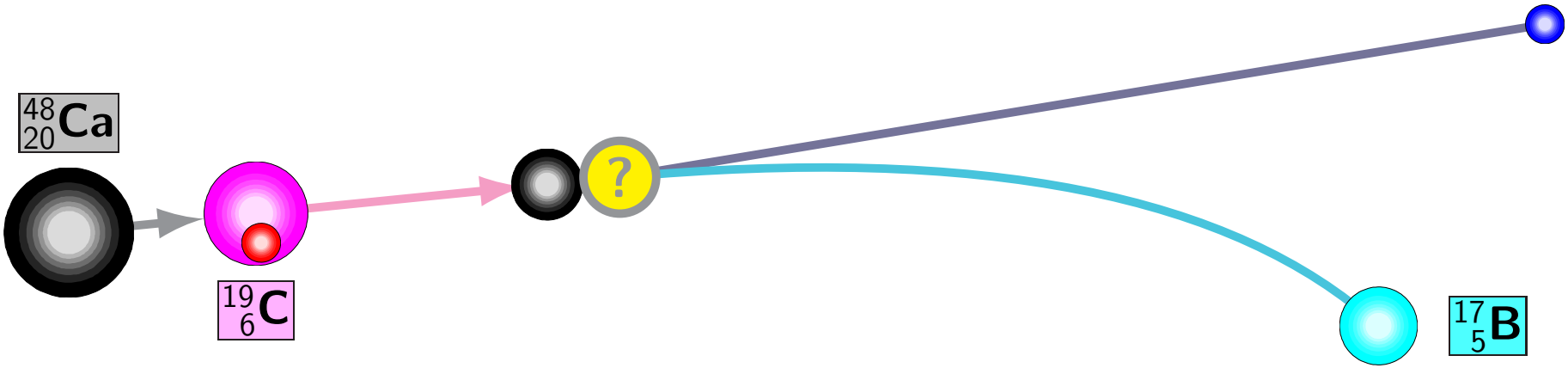

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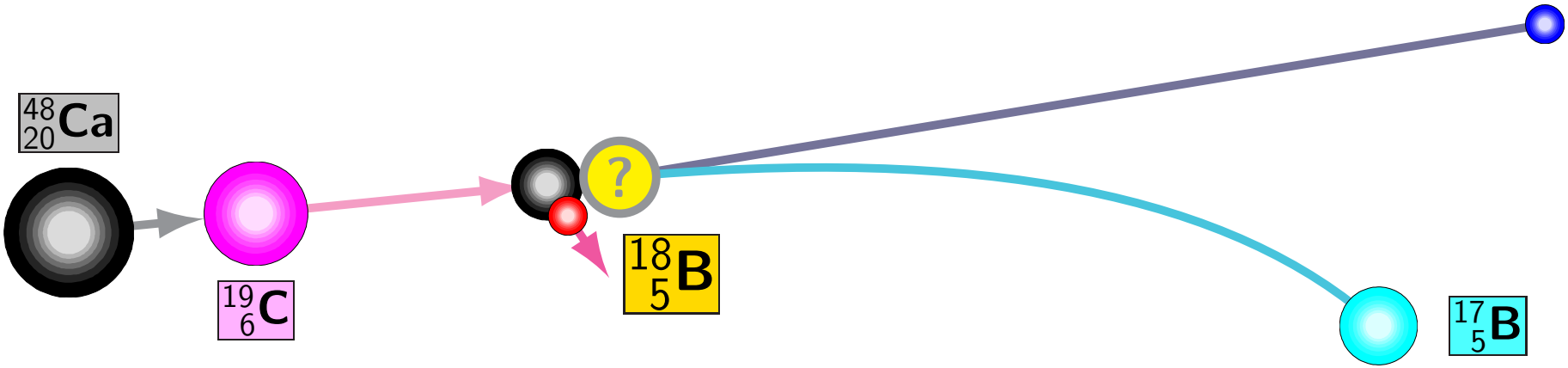

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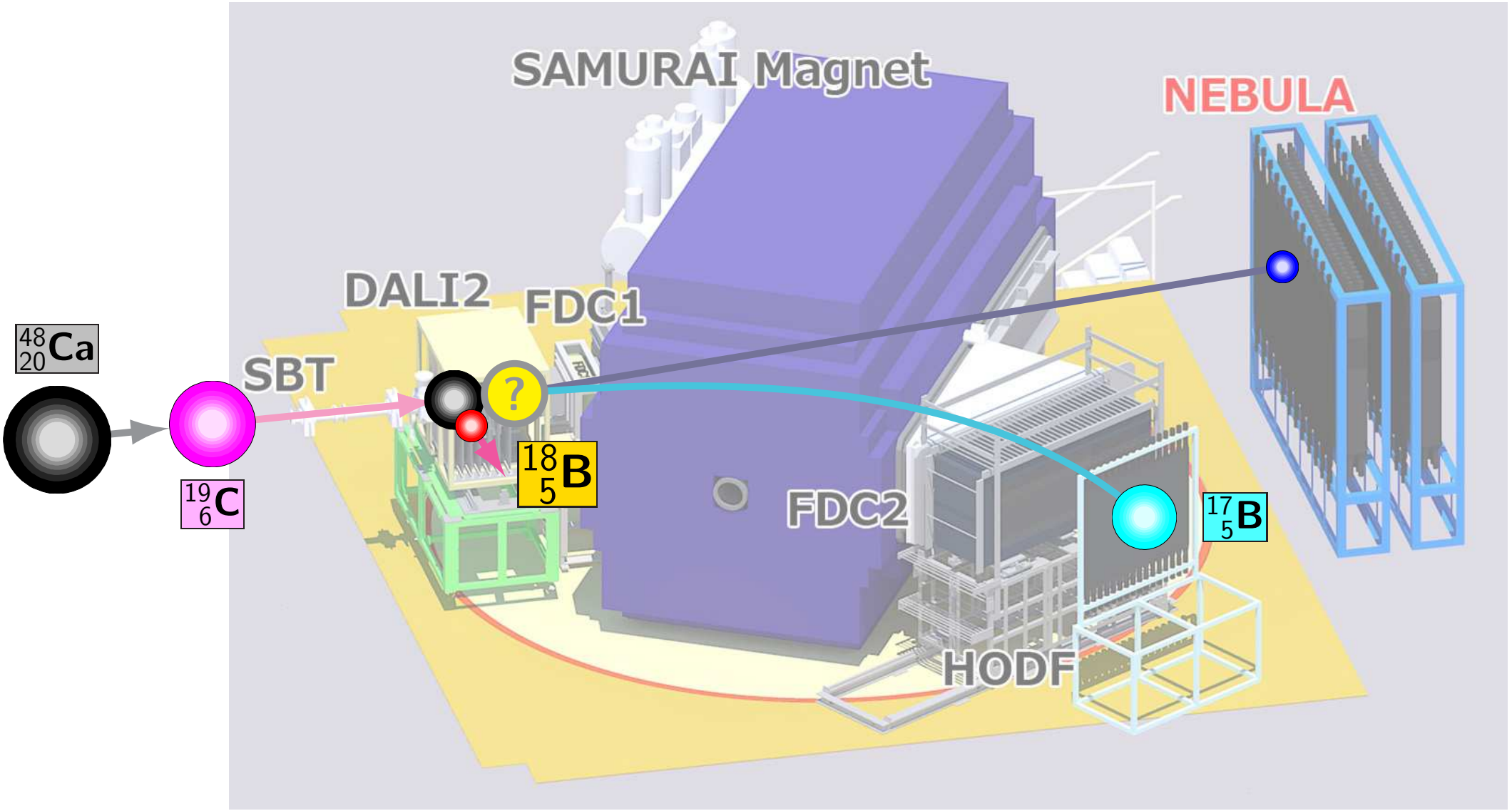

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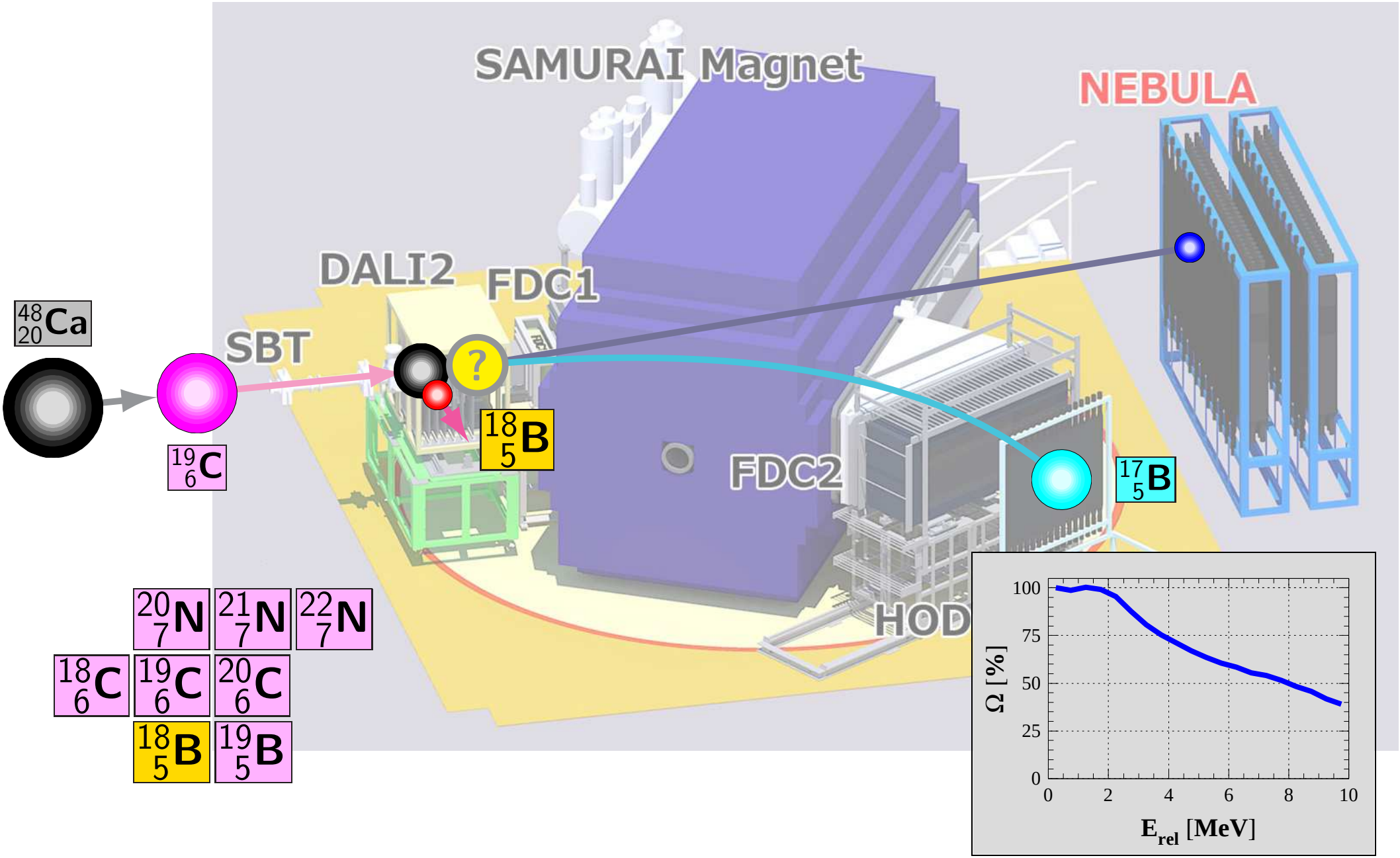
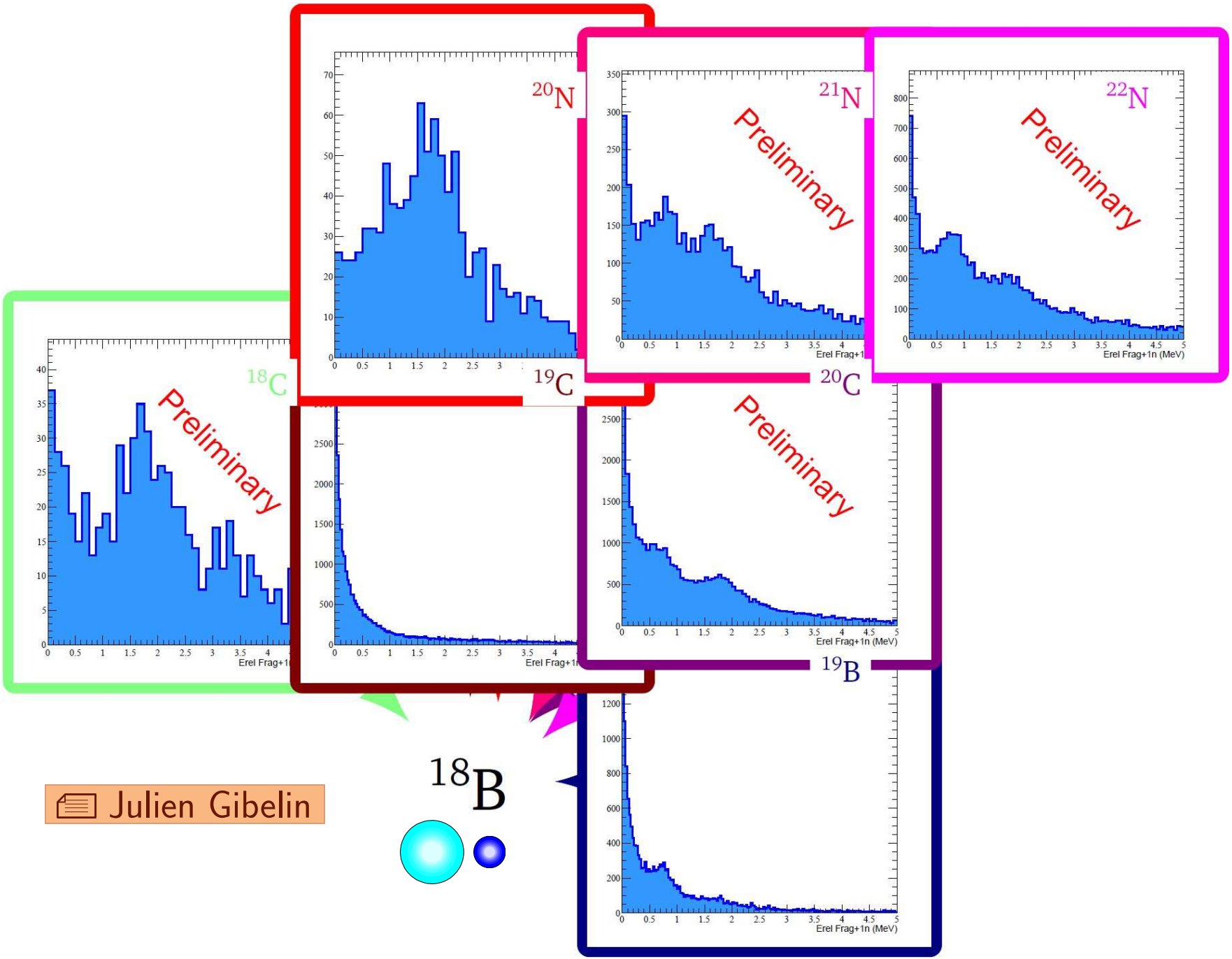


Boron 18 : virtual state from 6 channels !



^{18}B

Julien Gibelin

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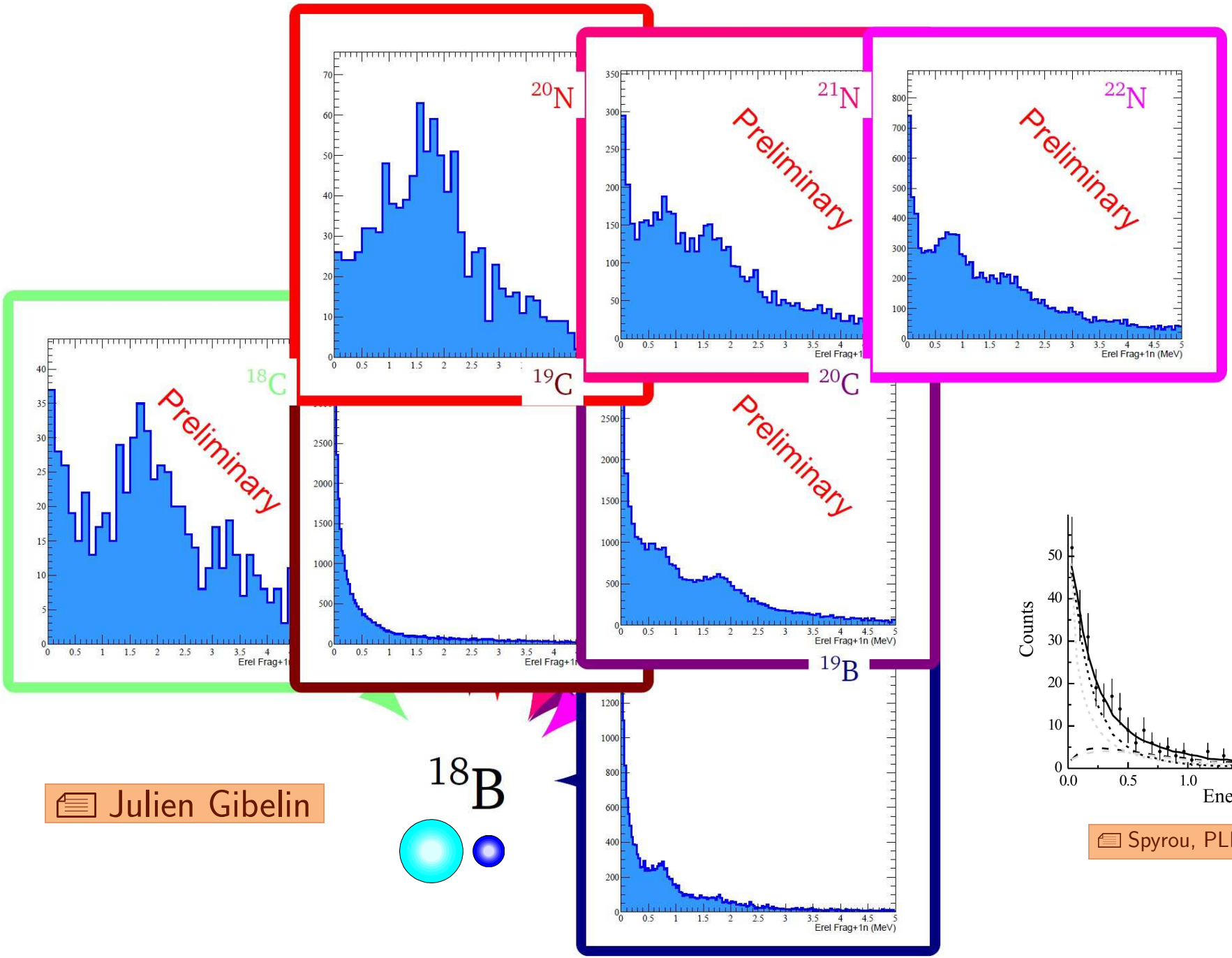

^{18}B

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Spyrou, PLB 683 (2010) 129

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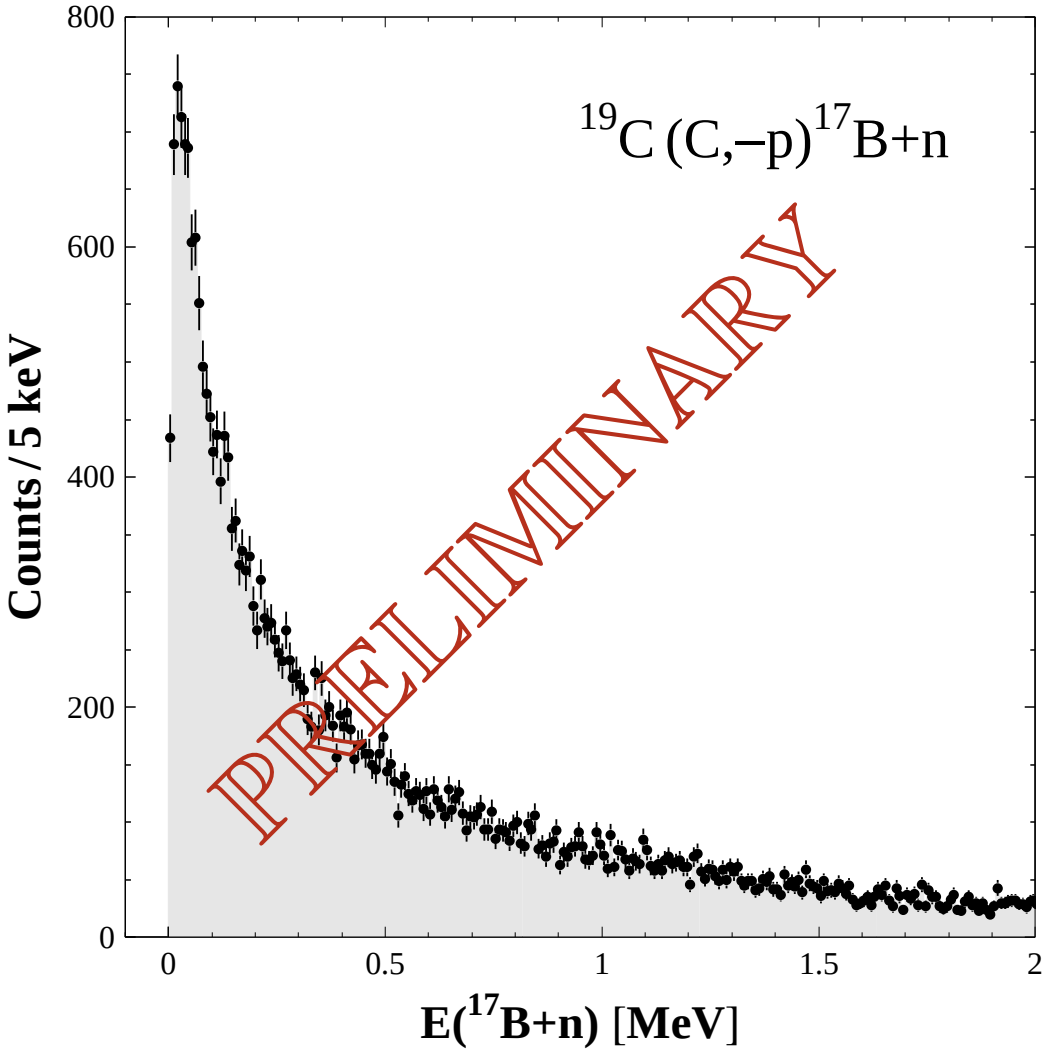

- ✔ unprecedented statistics
- ✔ large acceptance & resolution
- ✔ uncorrelated component : event mixing
- ✔ 'pure' population from s-wave halo
- ✔ $S_n(^{19}\mathrm{C}) \sim 0.5$ MeV : asymptotic ψ_i(n)

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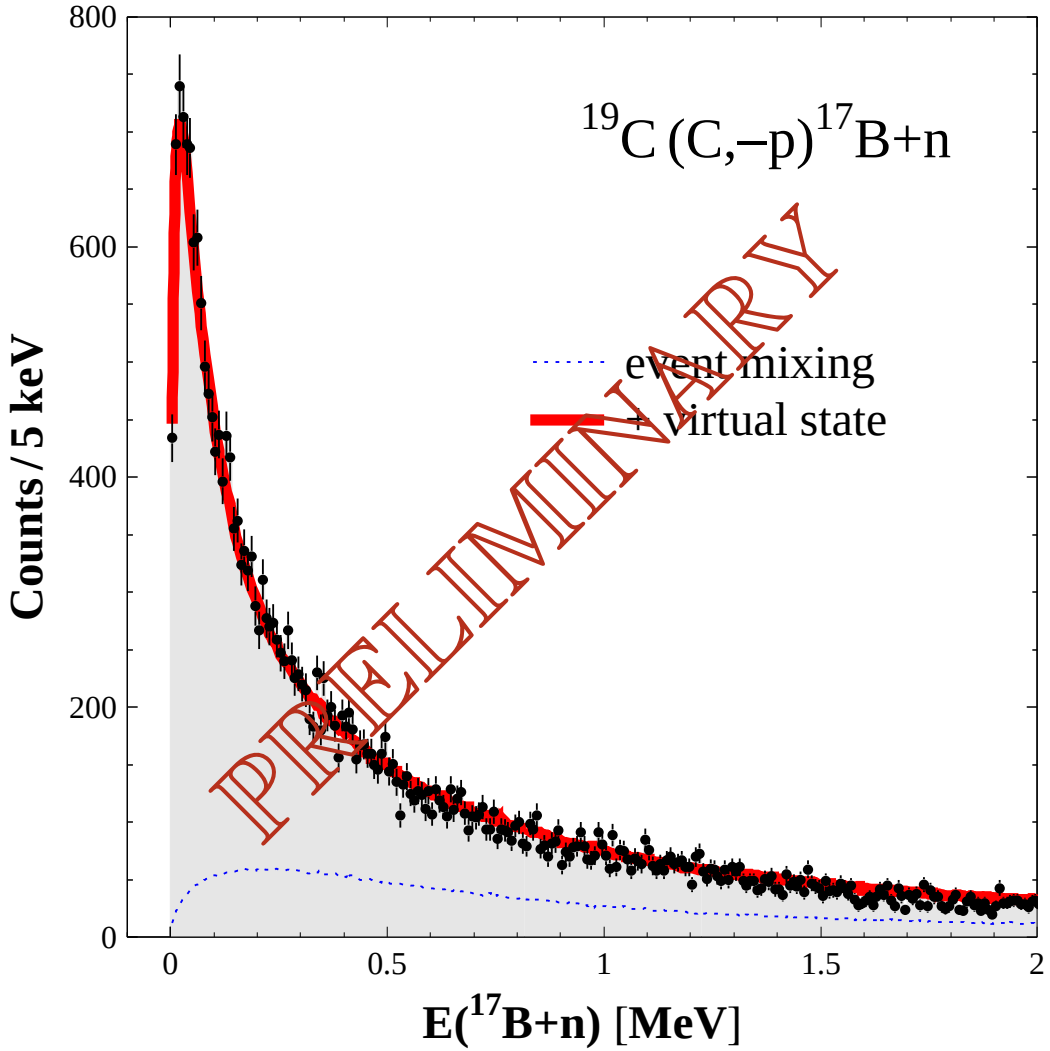

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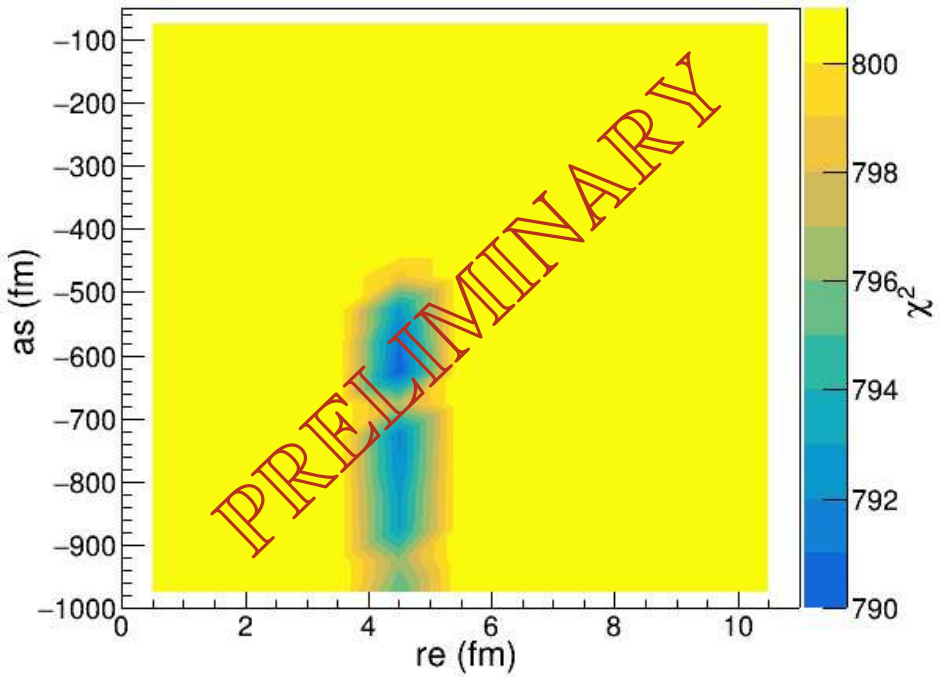
⇨ very accurate fit for :

$a_s = -600$ fm & $r_e = 4$ fm

$\frac{|a_s|}{r_e} = 150$!!!

Sensitivity to both scattering parameters

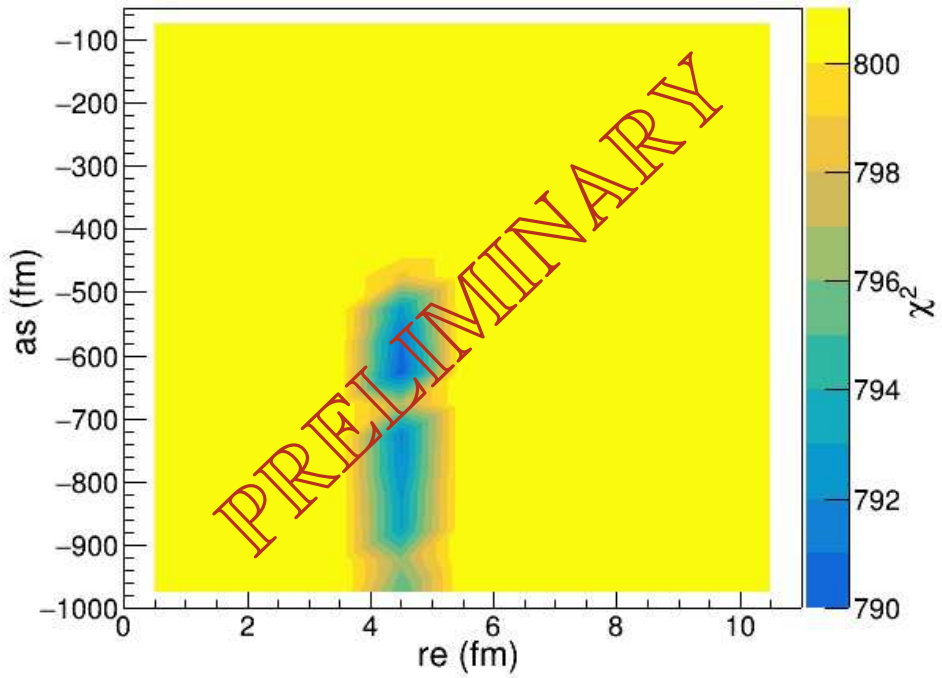
- $\chi^2(a_s, r_e)$ surface :
  - ^{19}C (C,–p) ^{17}B+n
  - asymptotic ψ_i(n) in ^{19}C
  - fit data for E=0–3 MeV



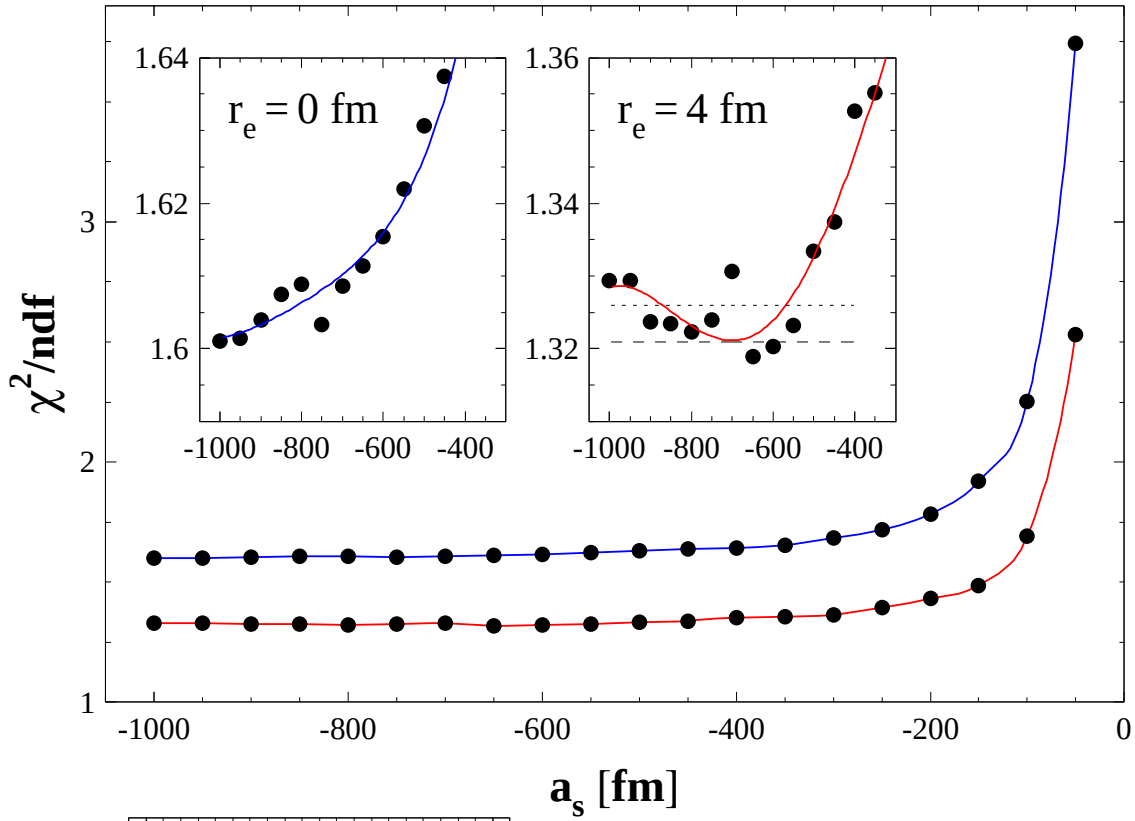
Emeline Oliveira, PhD

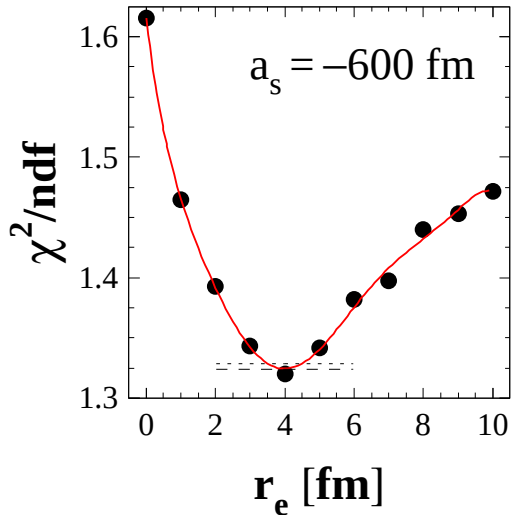
Sensitivity to both scattering parameters

- $\chi^2(a_s, r_e)$ surface :
  - ^{19}C (C,–p) ^{17}B+n
  - asymptotic ψ_i(n) in ^{19}C
  - fit data for E=0–3 MeV



Emeline Oliveira, PhD

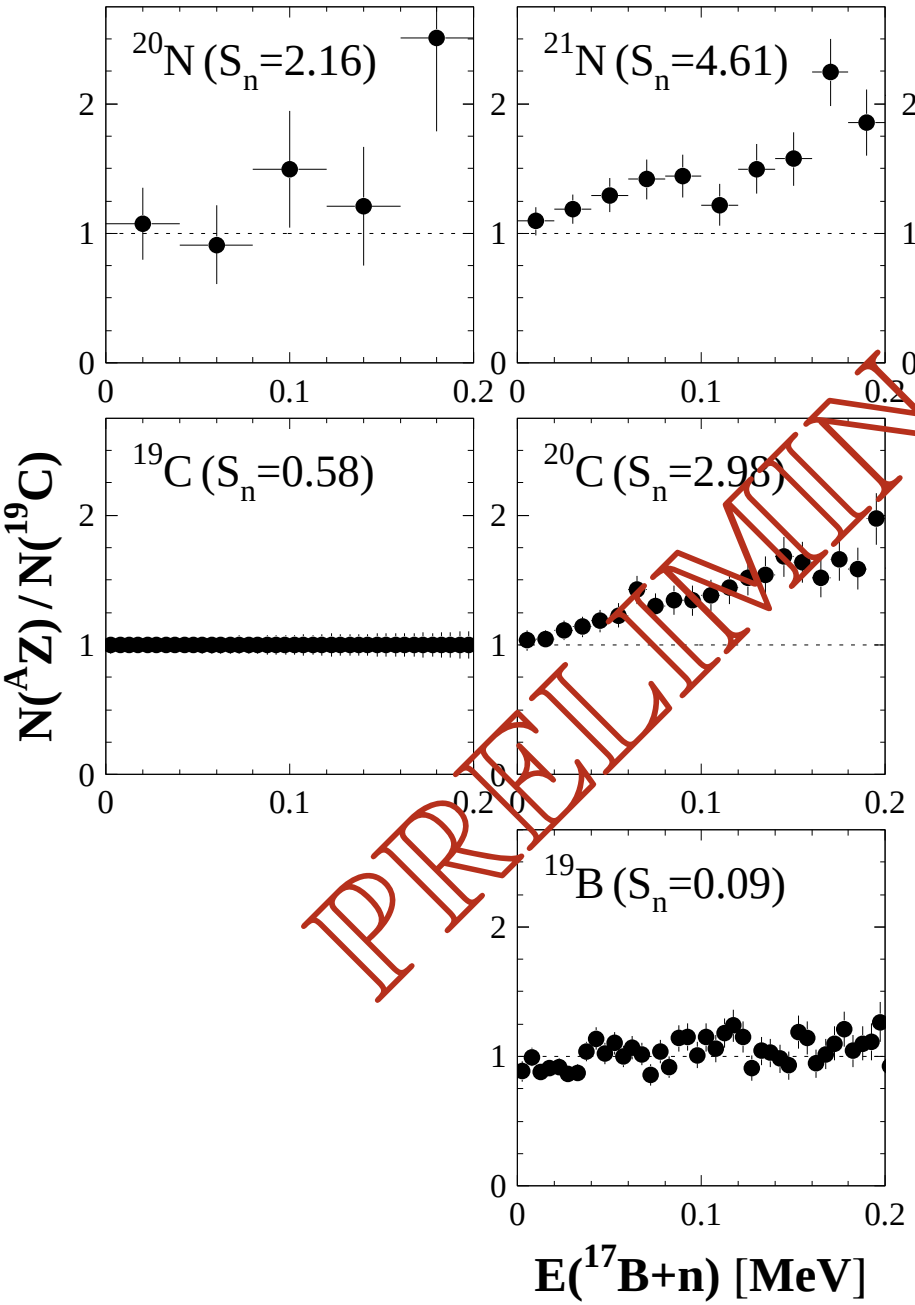




⇨ r_e at tenths of fm !

⇨ a_s at hundreds of fm !

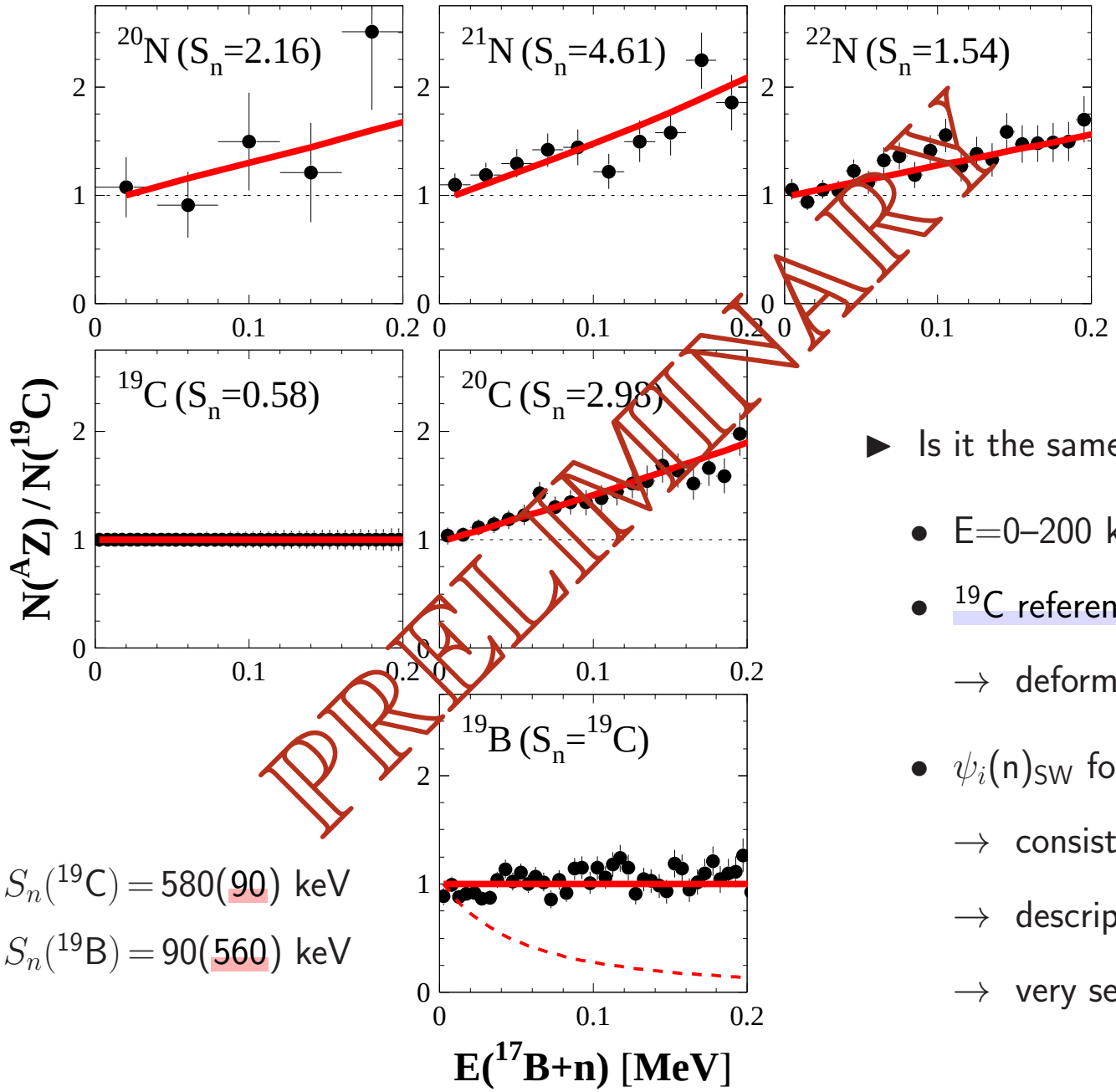
Effect of the nuclear 'container'



- Is it the same virtual state ?
  - E=0–200 keV (no other resonances)
  - ^{19}C reference ('pure' state)

    $\rightarrow$ deformation increases with S_n

Effect of the nuclear 'container'



$S_n(^{19}\mathrm{C}) = 580(90)$ keV

$S_n(^{19}\mathrm{B}) = 90(560)$ keV

- Is it the same virtual state ?
  - E=0–200 keV (no other resonances)
  - ^{19}C reference ('pure' state)

    → deformation increases with S_n
  - $\psi_i(\mathrm{n})_{\mathrm{SW}}$ for $(a_s, r_e) = (-600, 4)$ fm

    → consistent with same state !

    → description of container effects

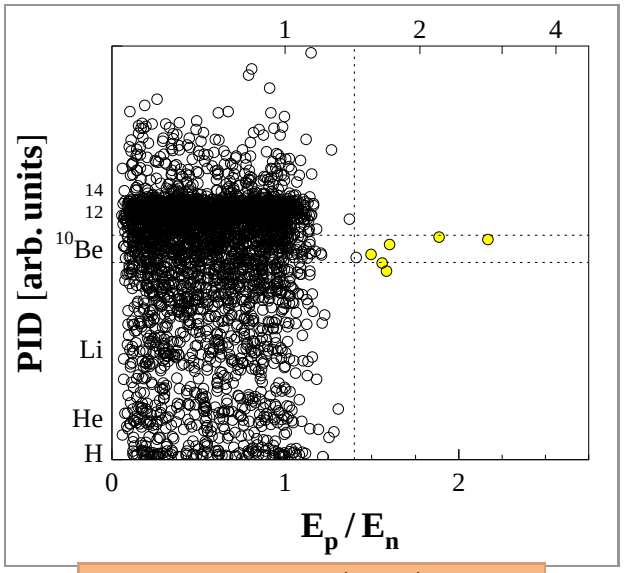
    → very sensitive to $S_n(^{19}\mathrm{B})$!!!

Outline

- Scattering lengths :
  - neutron off exotic 'containers'
  - ^{17}B+n : a schocking case !
- Experimental program @ RIKEN :
  - stat. & acceptance : effective range
  - multi-channel : determine (a_s, r_e) !
  - Universality ($|a_s|/r_e \sim 100$)

- Tetraneutron "signal" !
  - resonance / spatial correlations ?
  - link to momentum correlations ?
- Experimental program @ RIKEN :
  - first 4n invariant masses
  - some low-energy structures
  - explore full kinematics ...

Confirmation of a 4n "signal"



FMM, PRC 65 (2002) 044006

FMM, arXiv:nucl-ex/0504009

E(4n) ∼ [–1,+2] MeV (2.5σ)

?

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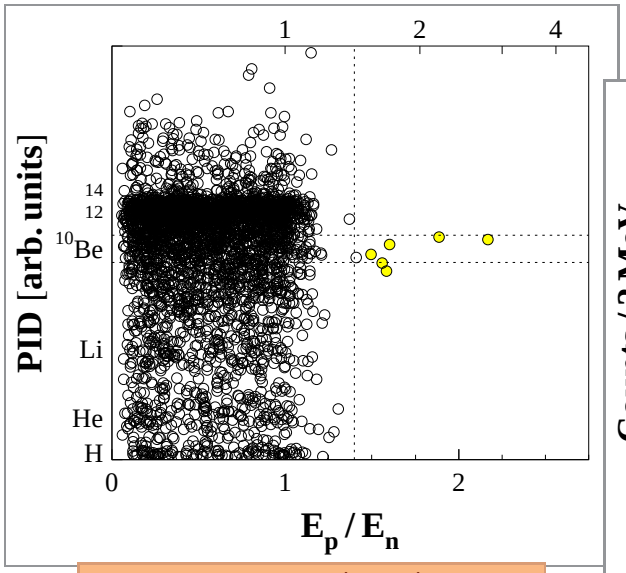

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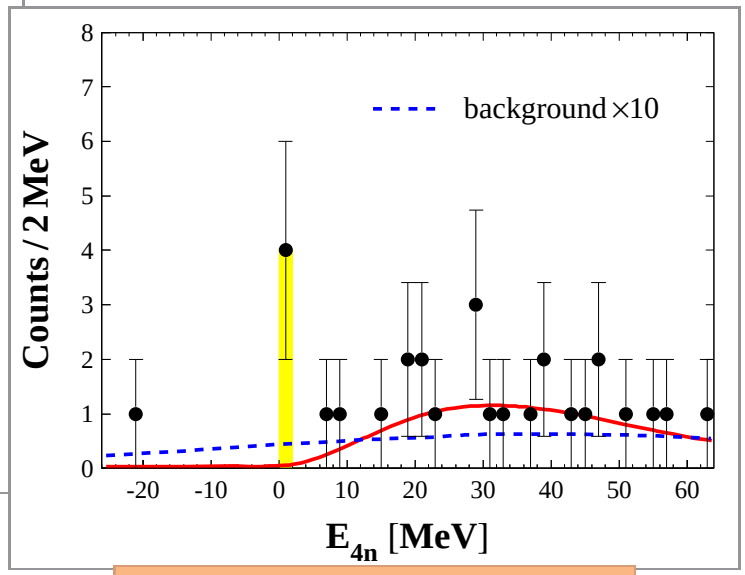
FMM & Carbonell, EPJA 57 (2021) 105

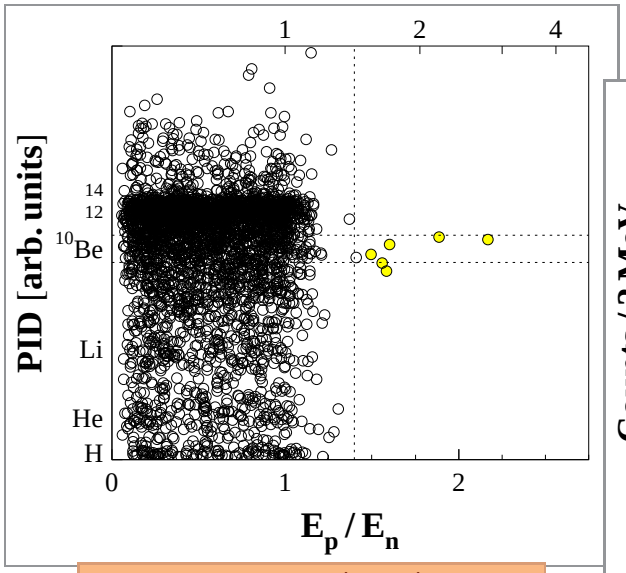


Kisamori, PRL 116 (2016) 052501

$E(4n) = 0.8 \pm 1.3$ MeV (4.9σ)

?

Confirmation of a 4n "signal"



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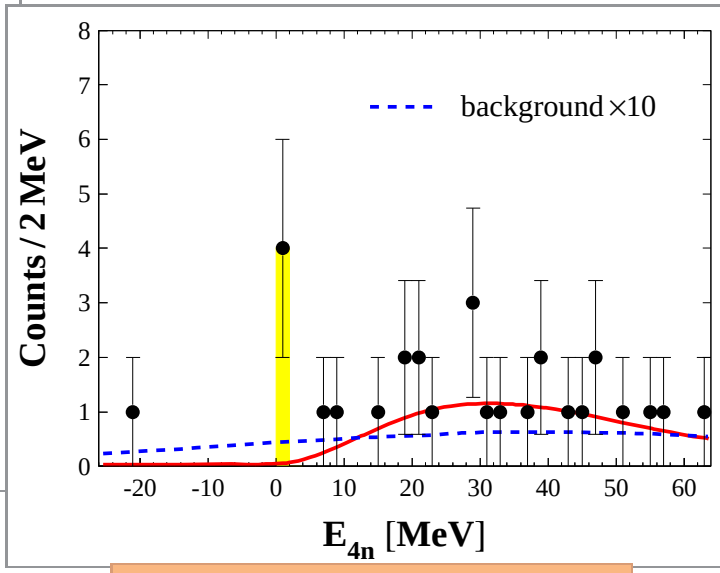

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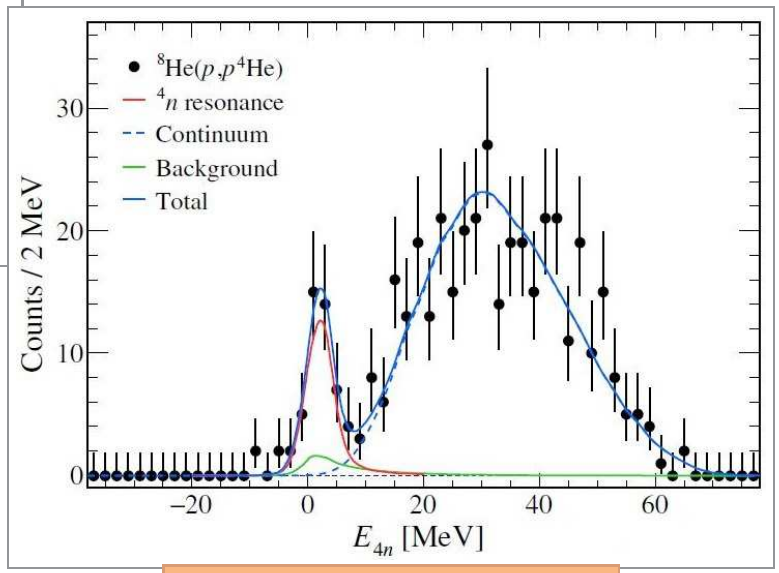
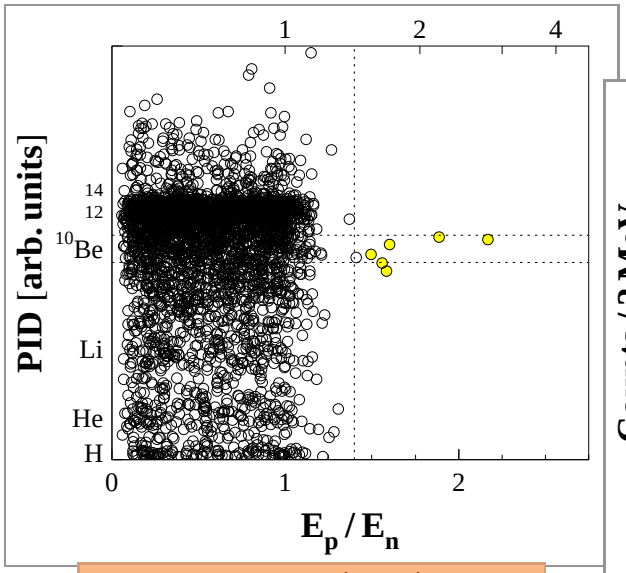


Duer, Nature 606 (2022) 678

E(4n) = 2.4±0.6 MeV ($\gg 5\sigma$)

Confirmation of a 4n "signal"



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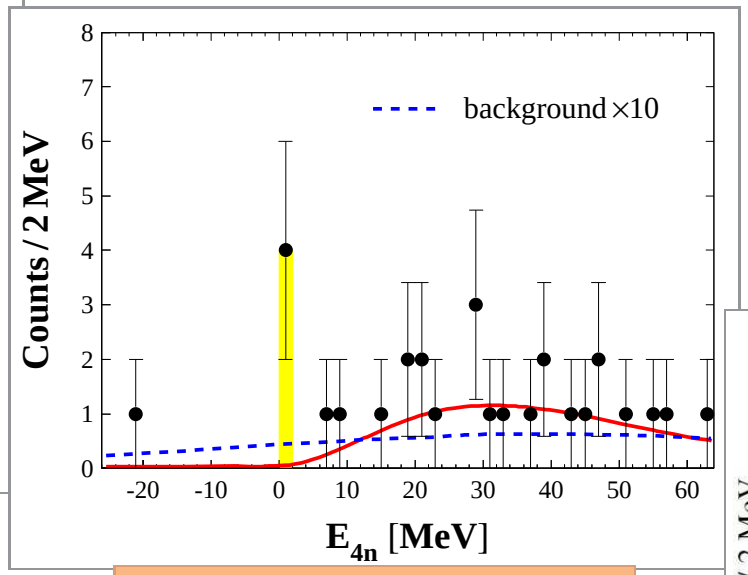

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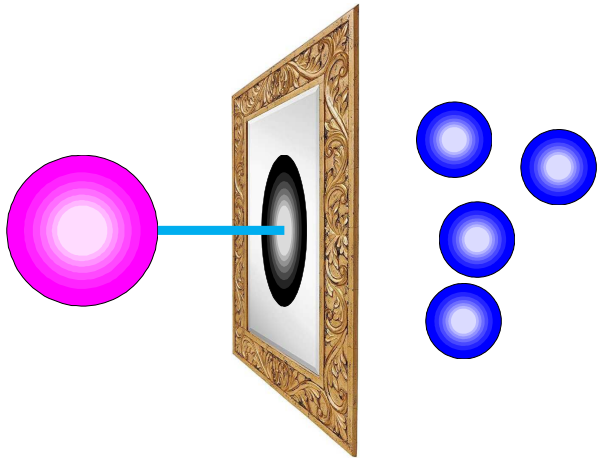

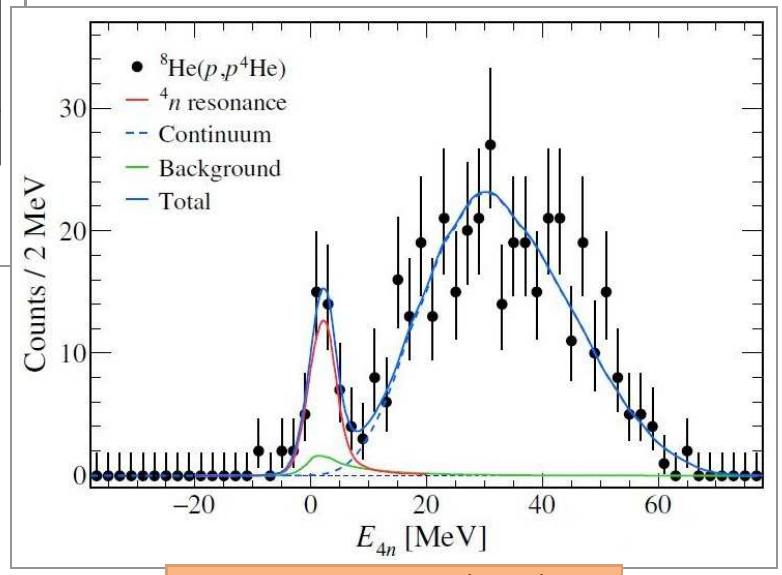

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Lazauskas, PRL 130 (2023) 102501

(nn)-(nn) correlations in ^{8}He ?

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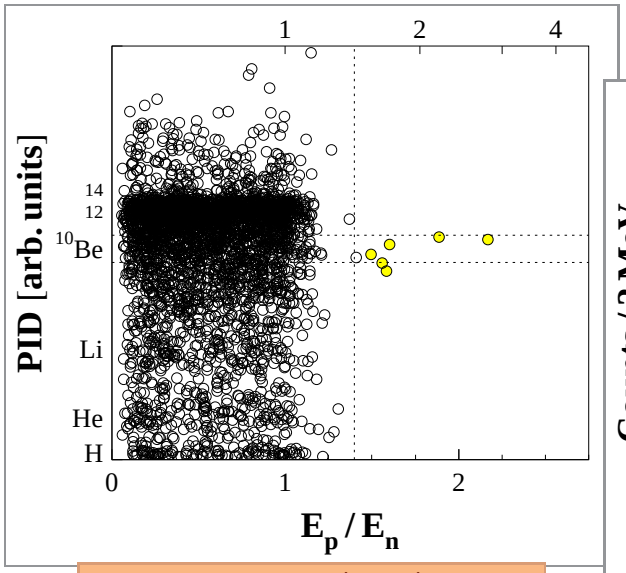

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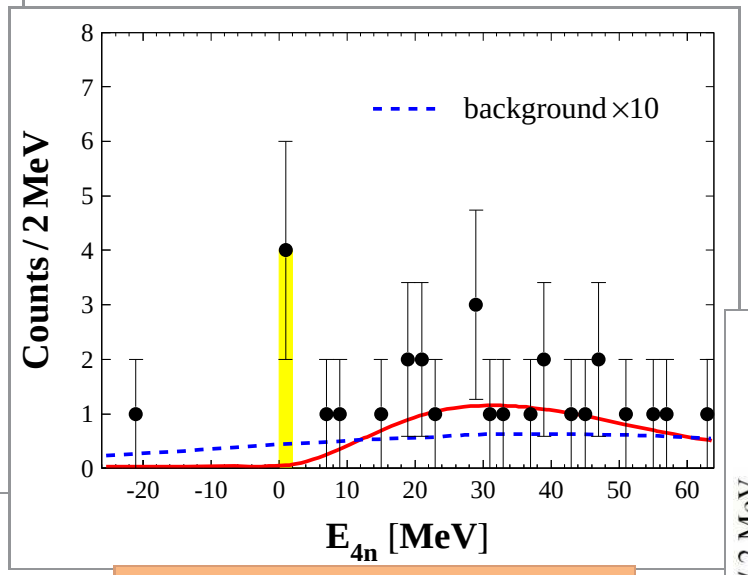
FMM & Carbonell, EPJA 57 (2021) 105



Kisamori, PRL 116 (2016) 052501

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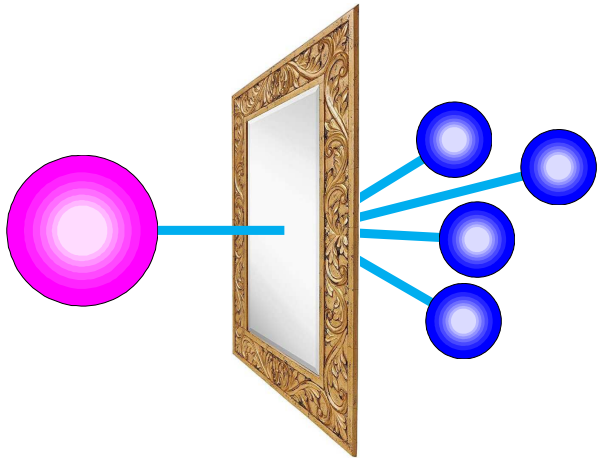

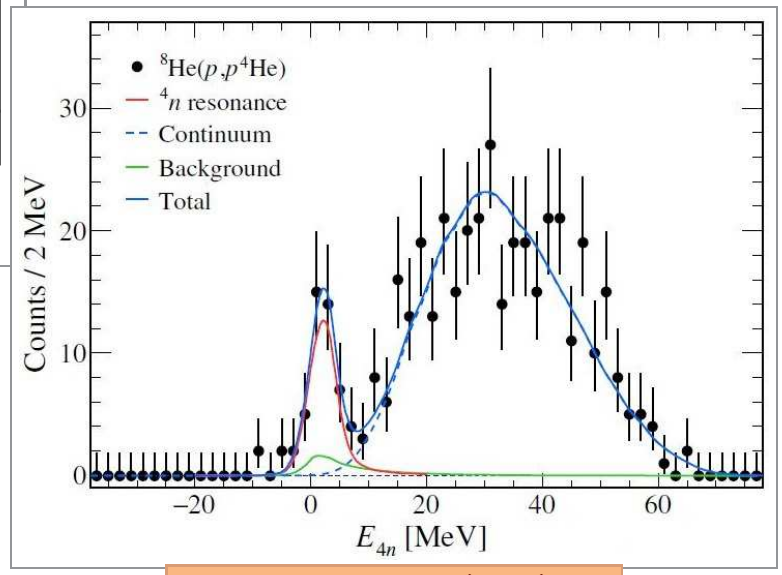

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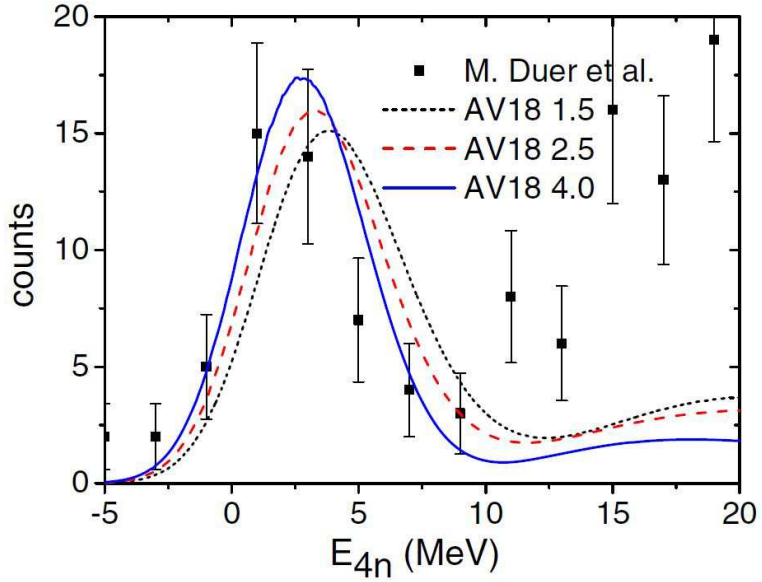
Lazauskas, PRL 130 (2023) 102501

(nn)-(nn) correlations in ^{8}He ?

Low-energy structures in nuclear reactions with 4n in the final state

^{8}He (p,pα) 4n



→ ^{8}He (nn)-(nn) correlations

→ core+4n : fast core removal

→ general phenomenon in 4n haloes ?

⇨ no need of ^{4}n resonance

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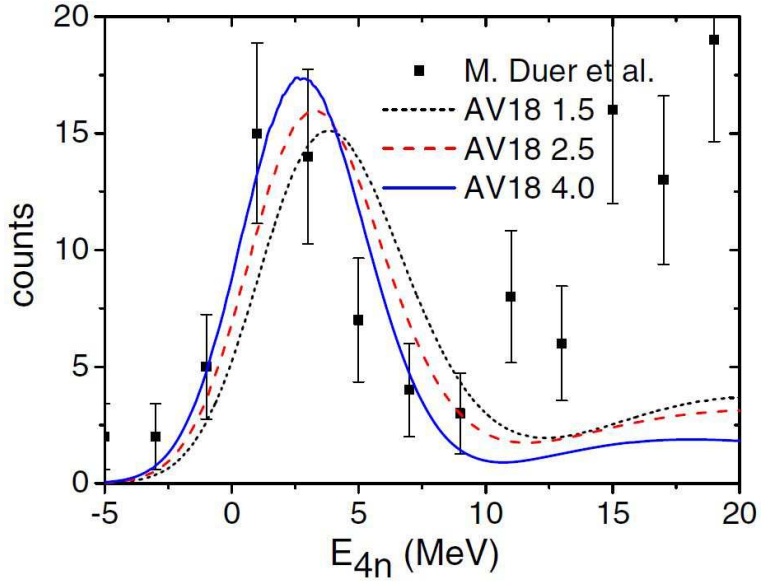

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- How to disentangle both hypothesis ?

$$\text{core} \begin{pmatrix} nn \\ nn \end{pmatrix} \Rightarrow \boxed{E(4n) \sim 0} \Leftarrow \{ \; ^{4}n\text{-core}$$

⇨ new observables (invariant mass)

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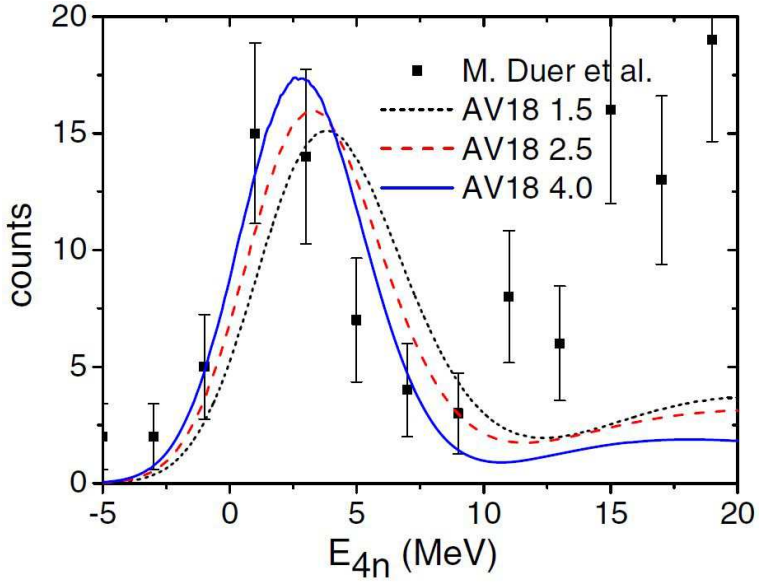

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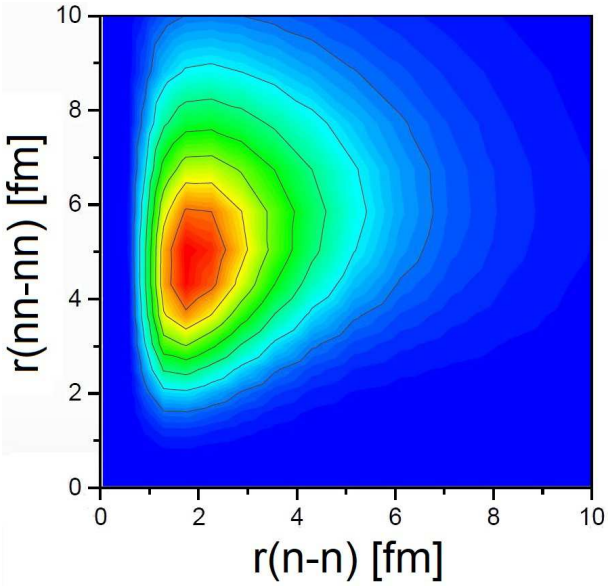
⇨ new observables (invariant mass)

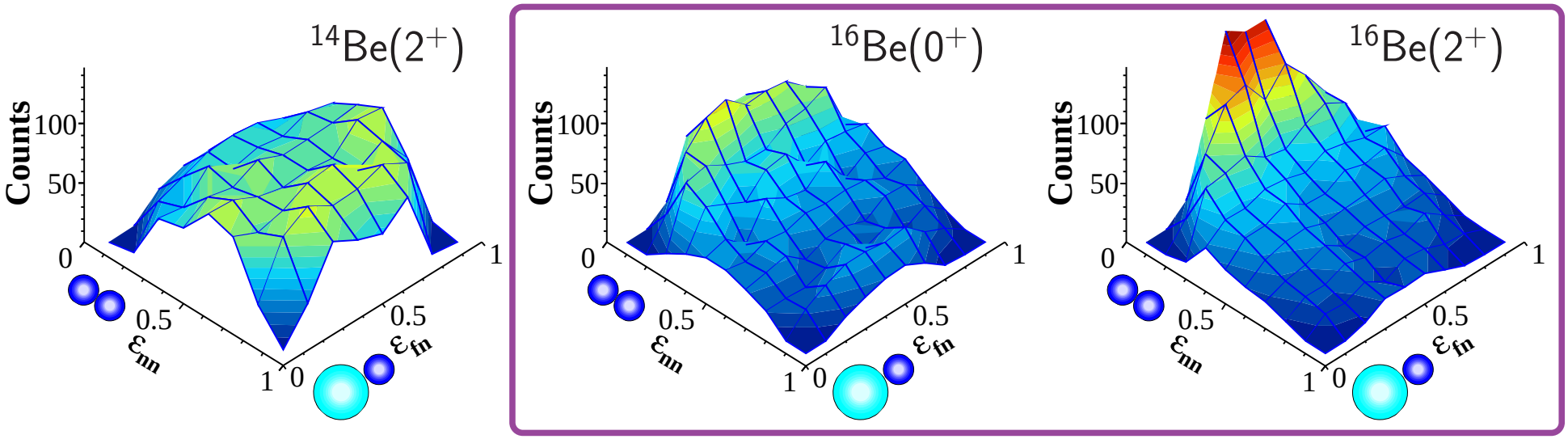
- Spatial (nn)-(nn) correlations :



⇨ link to (exp) momentum space ?

Beryllium 16 : ψ(2n) in momentum space

- Dalitz plot of 2n decay :



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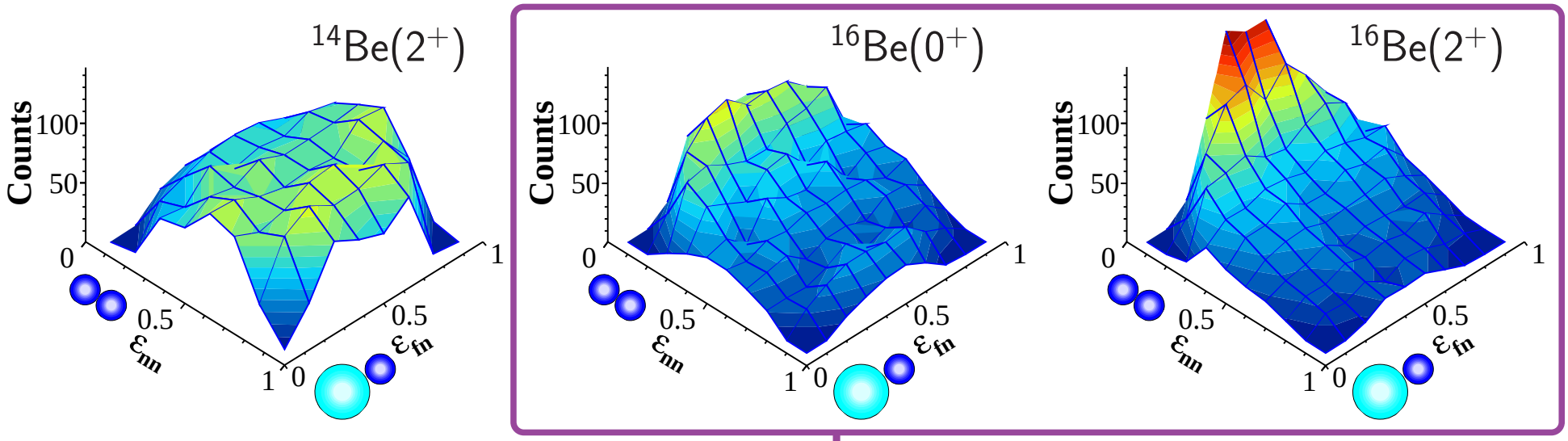
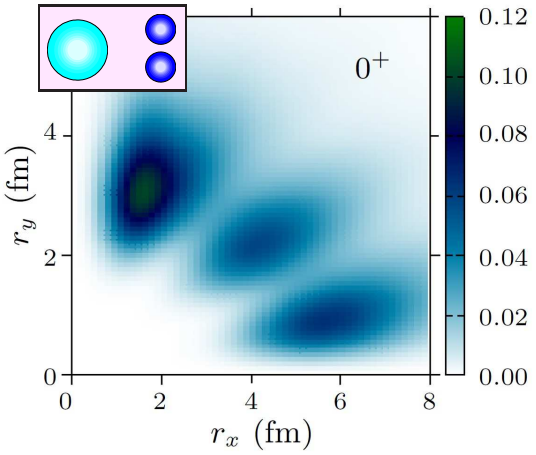
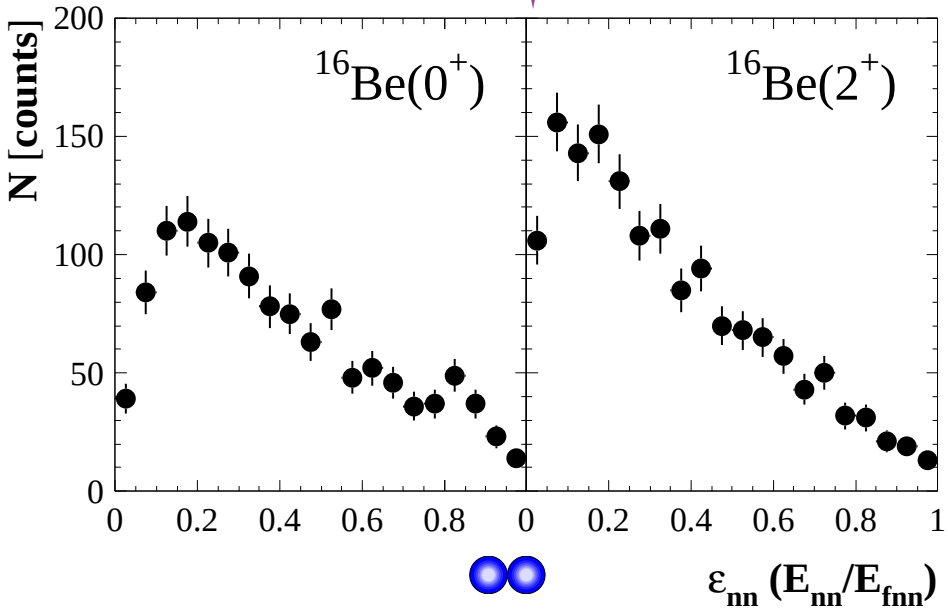
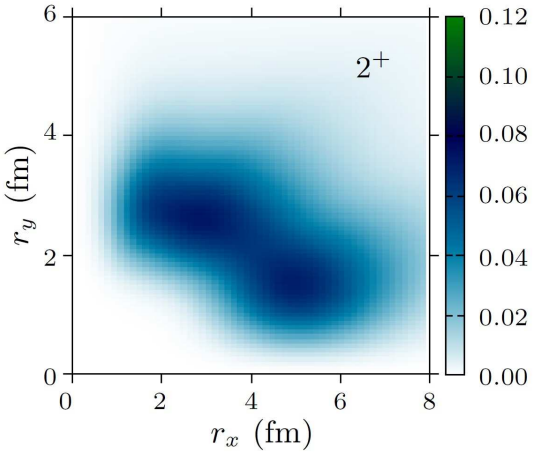


Casal, PRC 99 (2019) 014604







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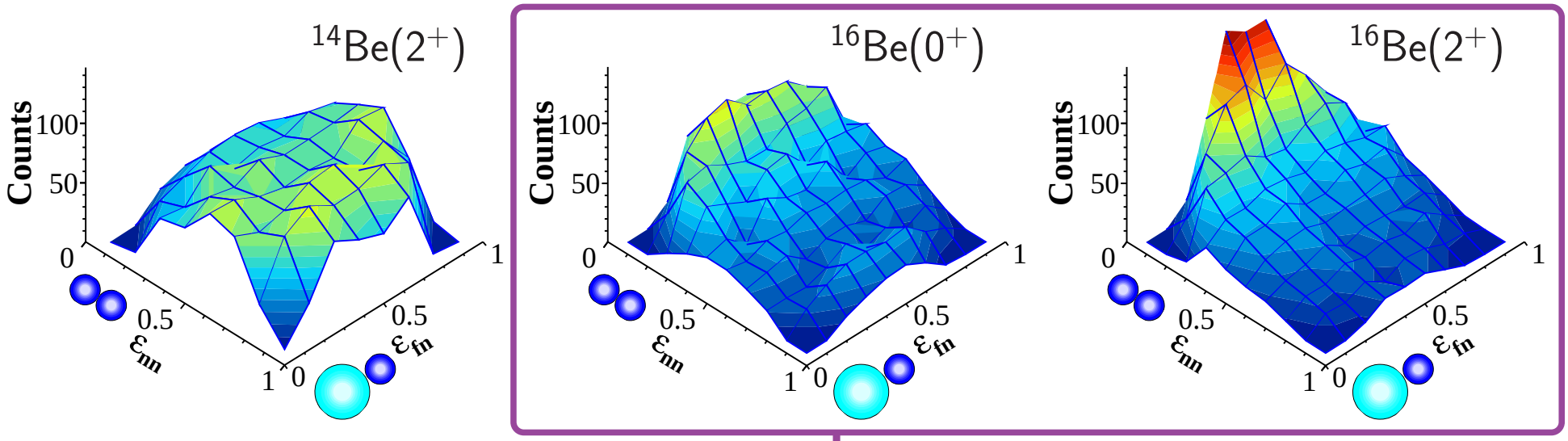
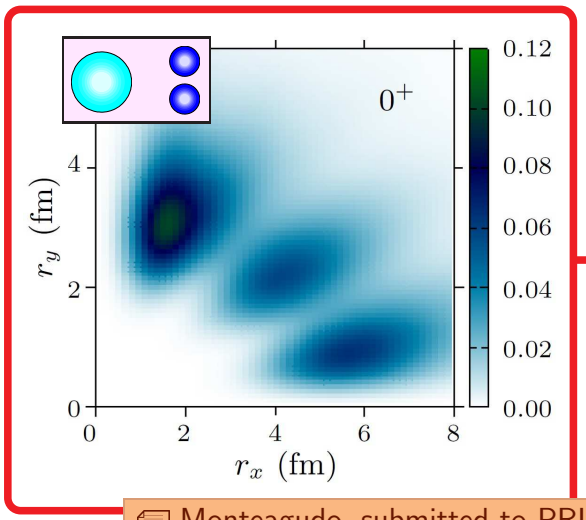
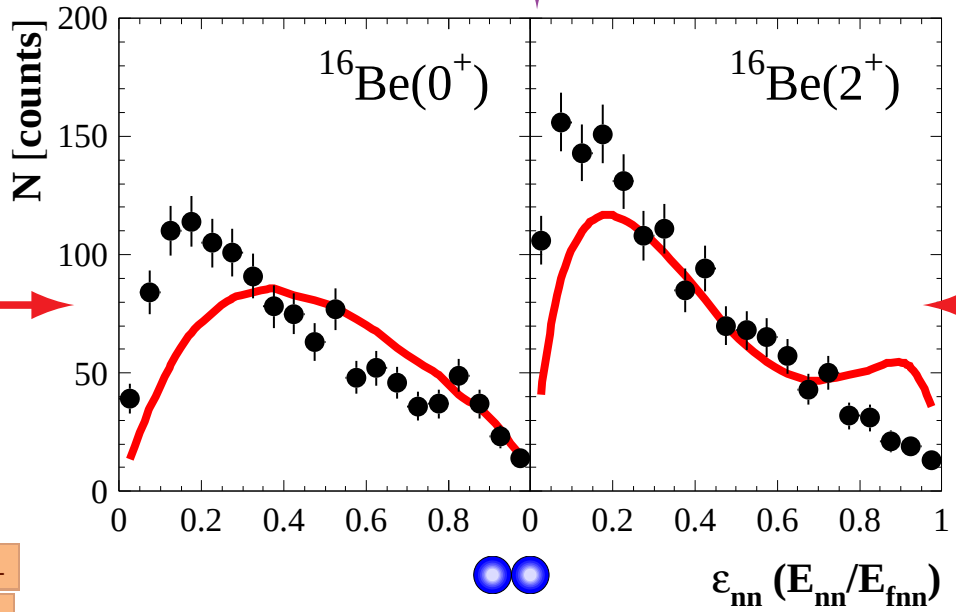


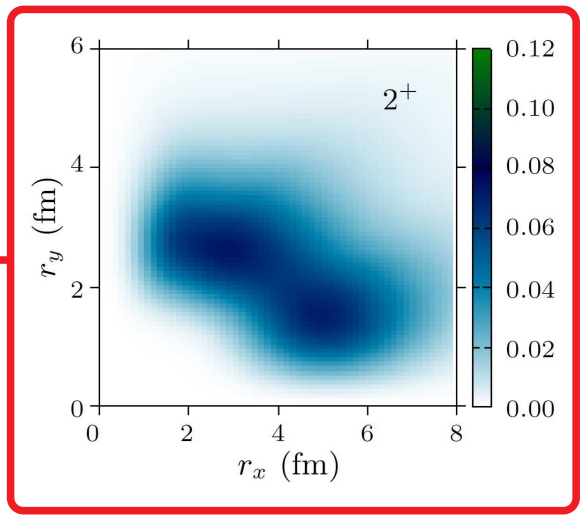
Casal, PRC 99 (2019) 014604



Monteagudo, submitted to PRL

Wang, PRL 126 (2021) 142501





Pauli-principle driven correlations in four-neutron nuclear decays

"The valence neutrons are pushed to the symmetry-allowed configurations in the 4n-precursor structure ... It should be noted that much more correlation information characterizing core+4n decay in principle exist. However ... at the moment we find too premature to discuss such complicated things"

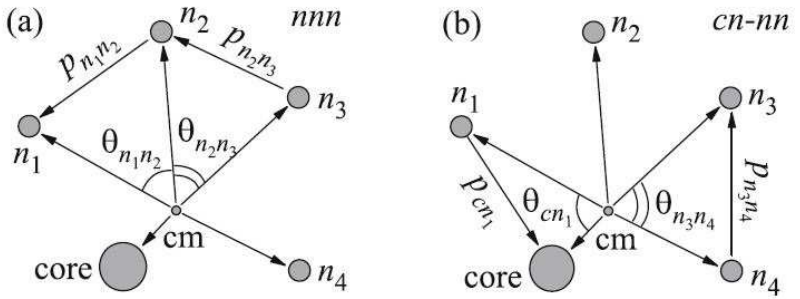


Fig. 3. Schemes of kinematical variables describing 5-body decays, which are used in constructing correlated two-dimensional energy $\{\varepsilon_{ik}, \varepsilon_{nm}\}$ and angular $\{\theta_{ik}, \theta_{nm}\}$ distributions of fragments. Examples (a) of "connected" nnn and (b) of "disconnected" cn-nn topologies. The related energy distribution parameters are defined as $\varepsilon_{ik} = p_{ik}^2/(2\mu_{ik}E_T)$

$$^{7}\mathrm{H} : [p_{3/2}^4]_0 \to C_{2323}[p_{3/2}^4]_0 + C_{0123}[s_{1/2}^2 p_{3/2}^2]_0, \quad (12)$$

$$^{28}\mathrm{O} : [d_{3/2}^4]_0 \to C_{4343}[d_{3/2}^4]_0 + C_{0143}[s_{1/2}^2 d_{3/2}^2]_0 + C_{0123}[s_{1/2}^2 p_{3/2}^2]_0. \quad (13)$$

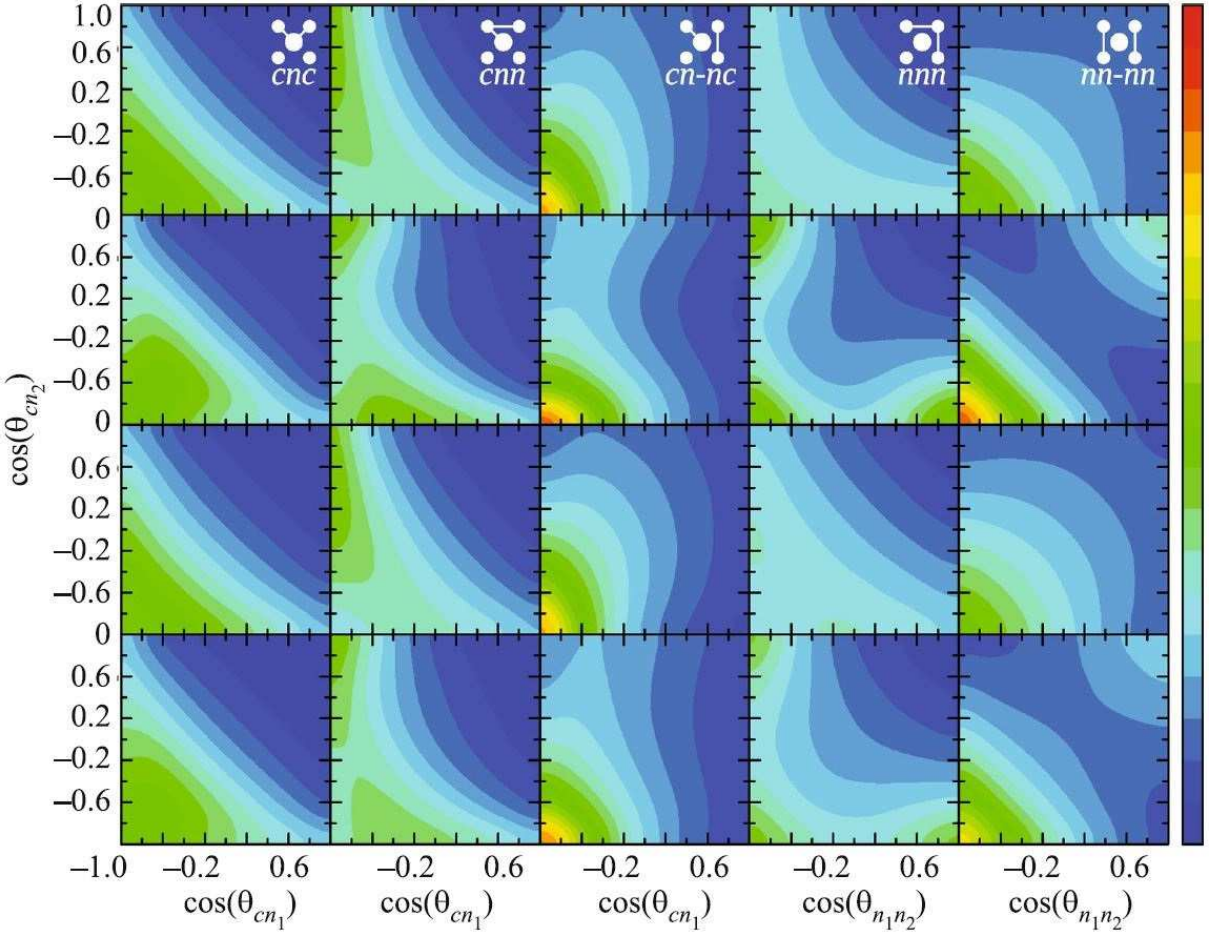
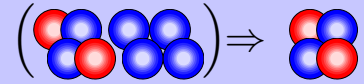
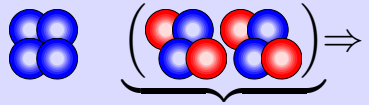
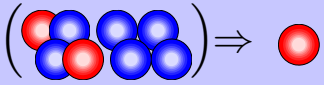
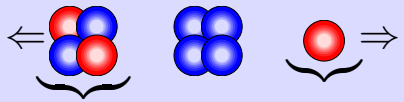
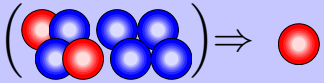
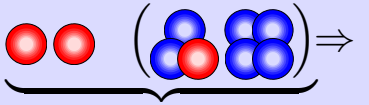


Fig. 9. Correlated distributions for core+4n decays in $C_{0123}[s_{1/2}^2 p_{3/2}^2]_0 + C_{0121}[s_{1/2}^2 p_{1/2}^2]_0$ configuration mixing. The following cases are illustrated: $C_{0121} = 1, 0.48, -0.48$, and 0.

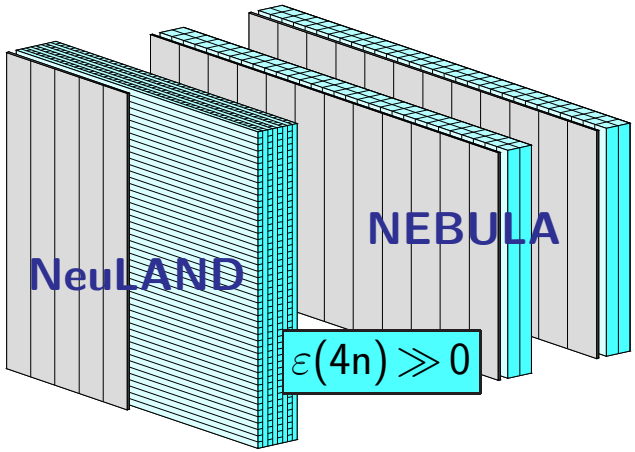
Experimental acces to 4n correlations

- 2016/17 "tetraneutron campaign" @ RIKEN :

  → first invariant-mass measurement of 4n decay !

reaction	initial state	final state	σ	results
('16) ^{4}He $(^{8}$He, $\alpha\alpha)$ ^{4}**n** Shimoura, NP1512-SHARAQ10			nb	$N_{evt} \sim 10$ s ^{4}n : E, Γ
('17) ^{8}He (p,pα) ^{4}**n** Paschalis, NP1406-SAMURAI19			μb	$N_{evt} \sim 1000$ s ^{4}n : E, Γ
('17) ^{8}He (p,2p) $\{^{3}$**H**$+^{4}$**n**$\}$ FMM/Yang, NP1512-SAMURAI34			**mb**	$N_{evt} \sim$ **10,000** s ^{4}n & ^{7}H : E, Γ, Ω

^{8}He (p,2p) ^{7}H $\longrightarrow$ ^{3}H $+$ ^{4}n ?



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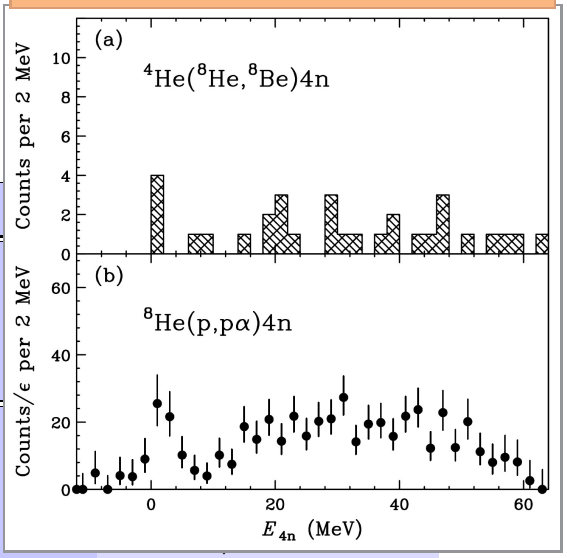
Shimoura, NP News 33/3 (2023) 15



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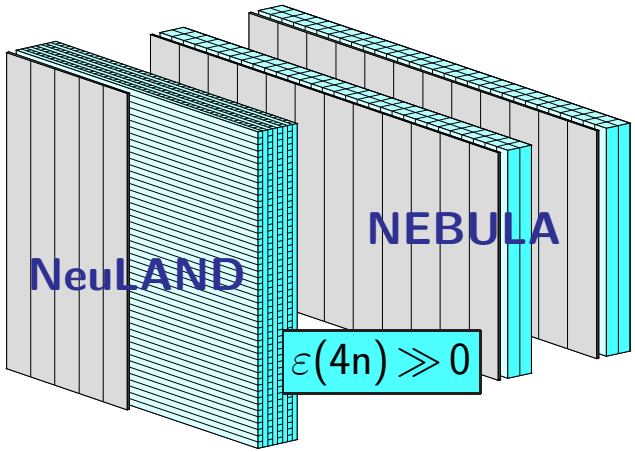
('16) ^{4}He (^{8}He, $\alpha\alpha$) ^{4}**n** Shimoura, NP1512-SHARAQ10				
('17) ^{8}He (p,pα) ^{4}**n** Paschalis, NP1406-SAMURAI19				
('17) ^{8}He (p,2p) {^{3}**H**+^{4}**n**} FMM/Yang, NP1512-SAMURAI34			**mb**	$N_{evt} \sim$ **10,000** s ^{4}n & ^{7}H : E, Γ, Ω

^{8}He (p,2p) ^{7}H $\longrightarrow$ ^{3}H + ^{4}n ?

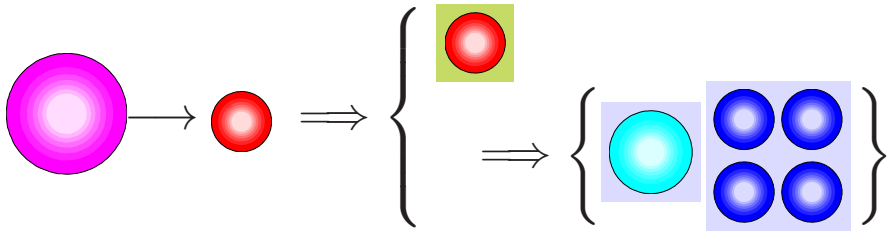
^{8}He (p,pn) ^{7}He* $\longrightarrow$ ^{4}He + ^{3}n ??

^{8}He (p, p') ^{8}He* $\longrightarrow$ ^{4}He + ^{4}n ???



VERY PRELIMINARY results !

^{8}He (p,p') ^{4}He+ 4n @ 150 MeV/N :



Audrey Anne, PhD

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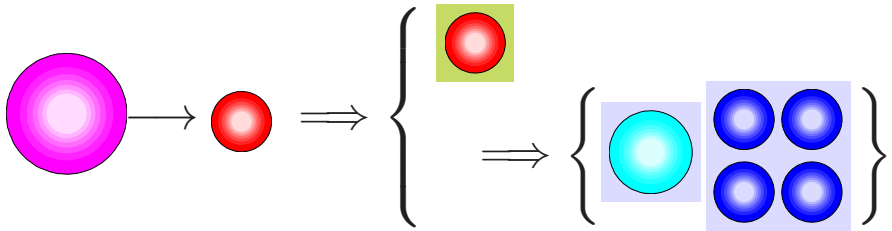

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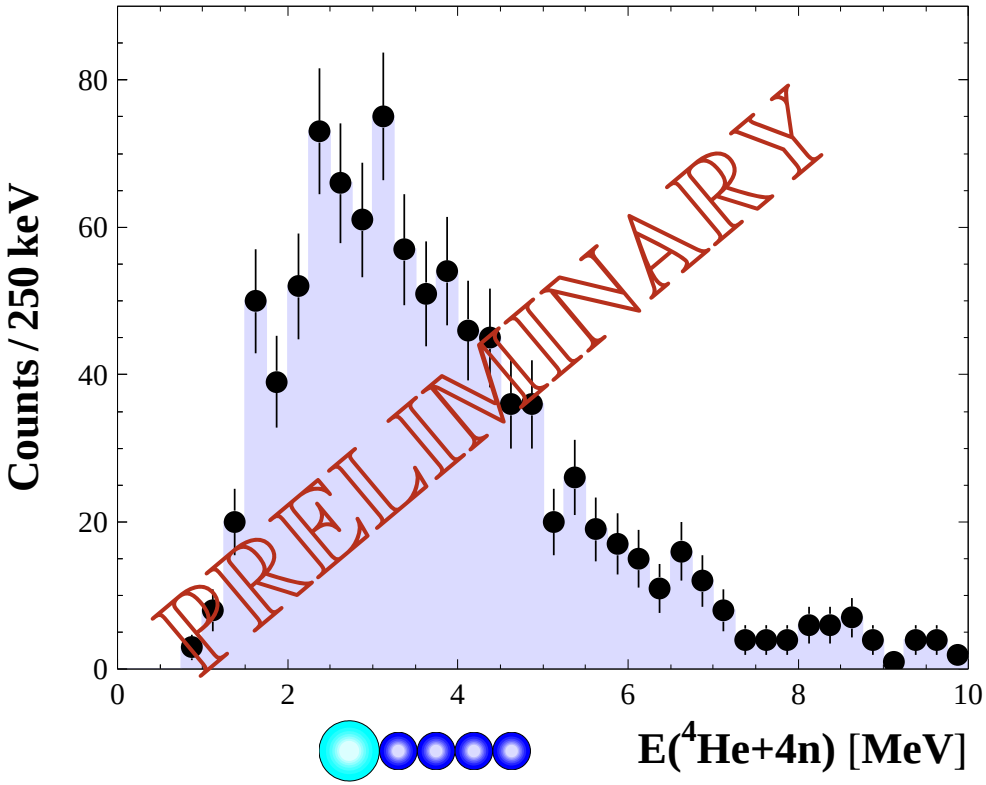

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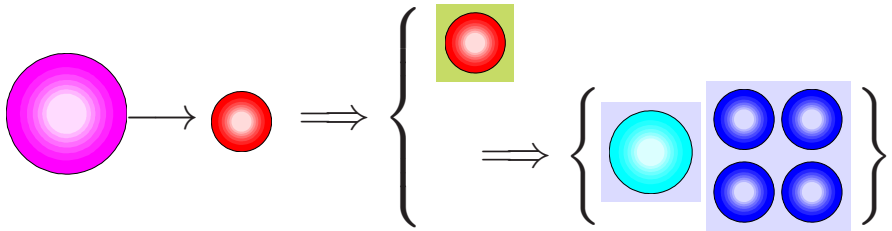

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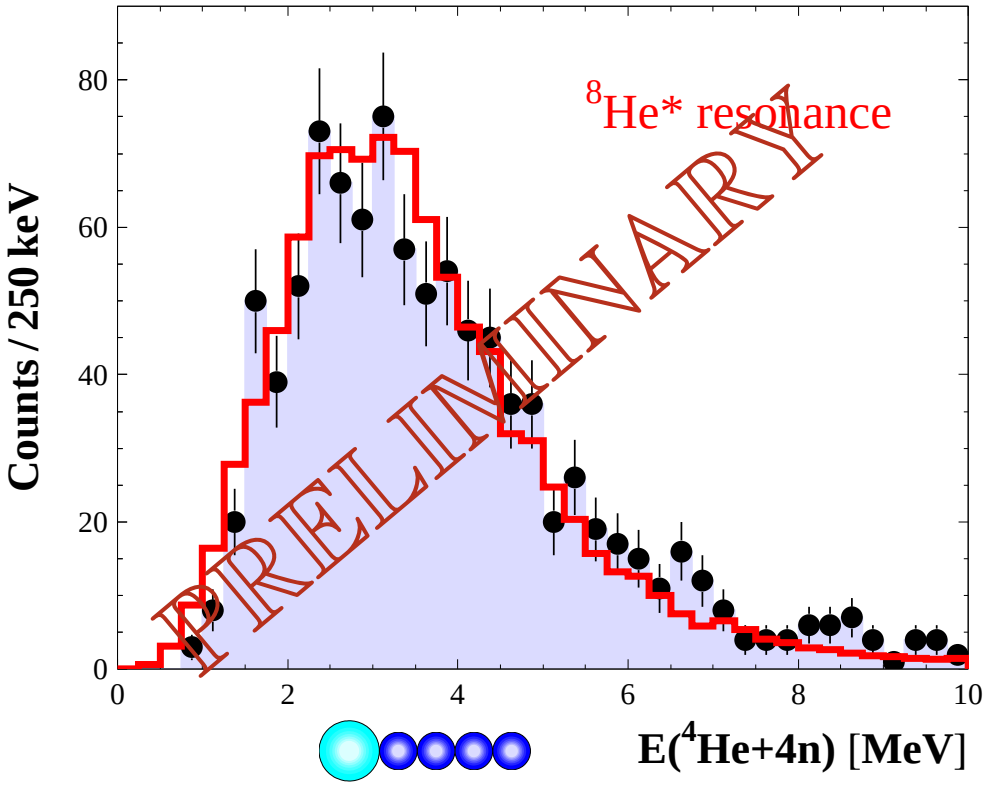

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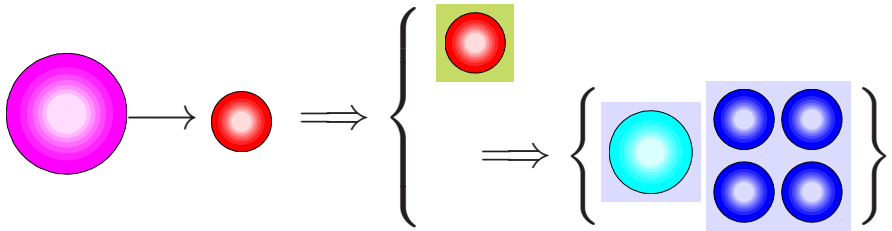

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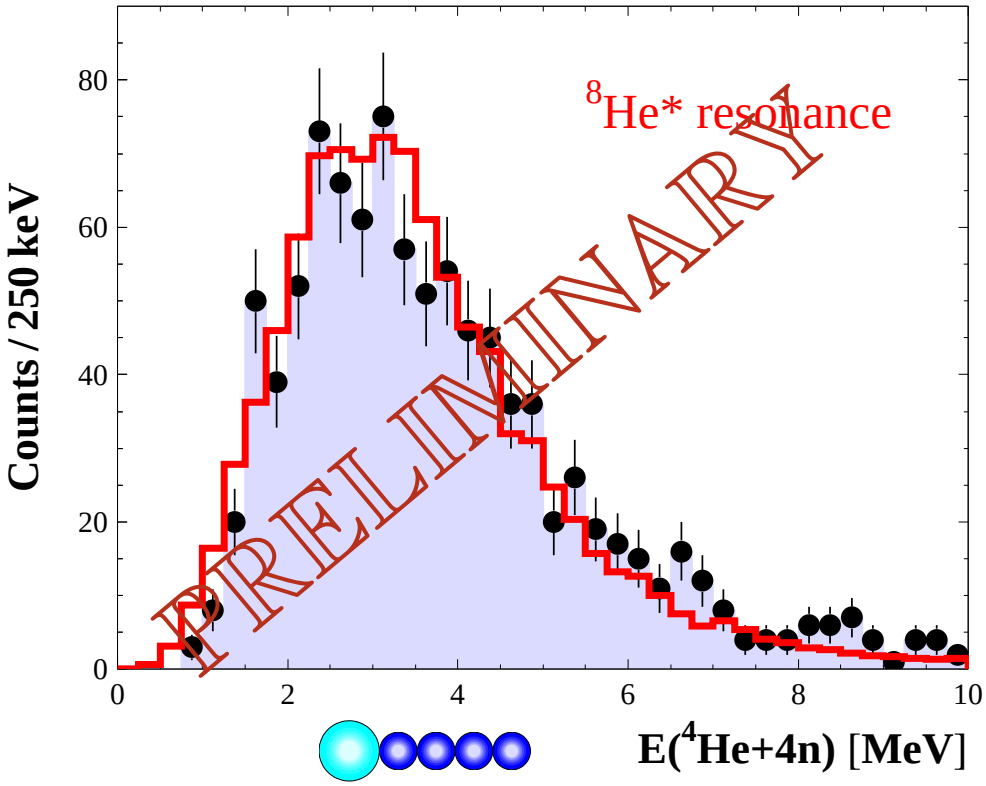

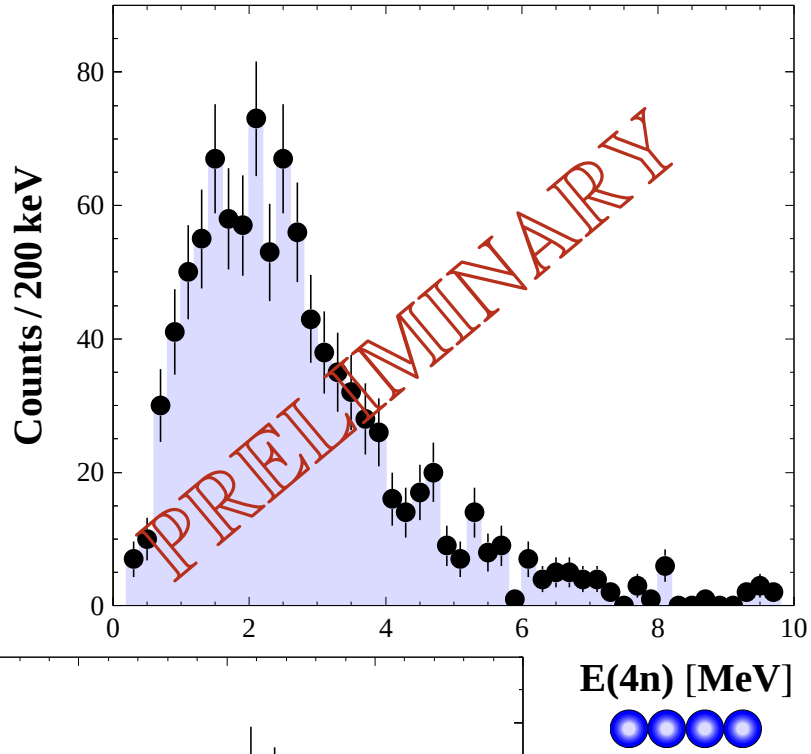

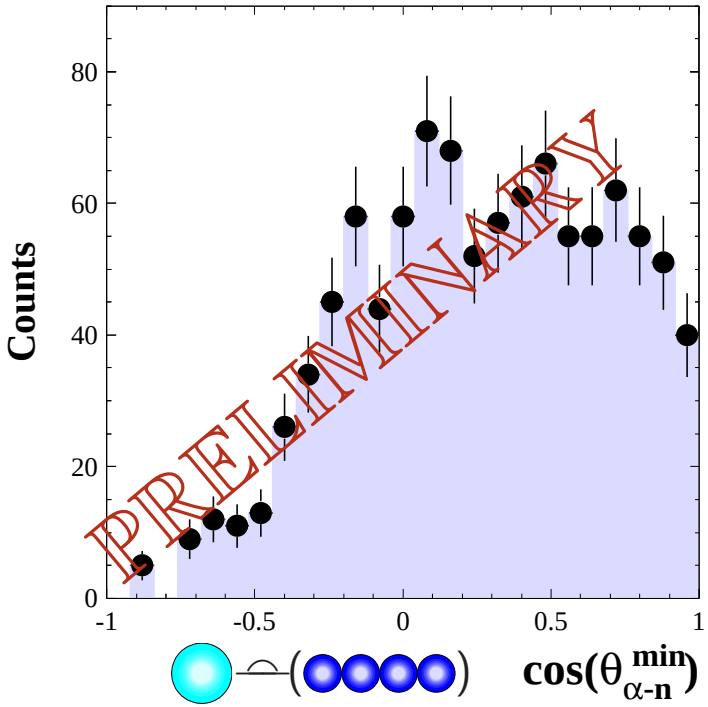

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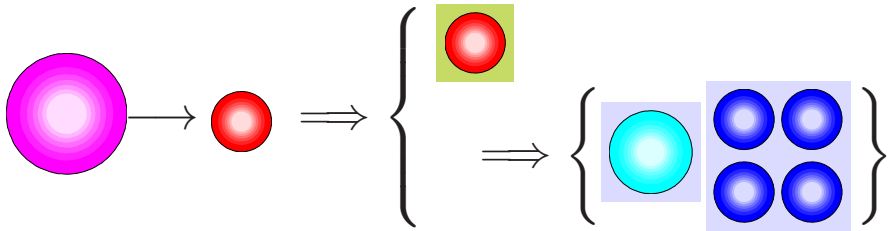

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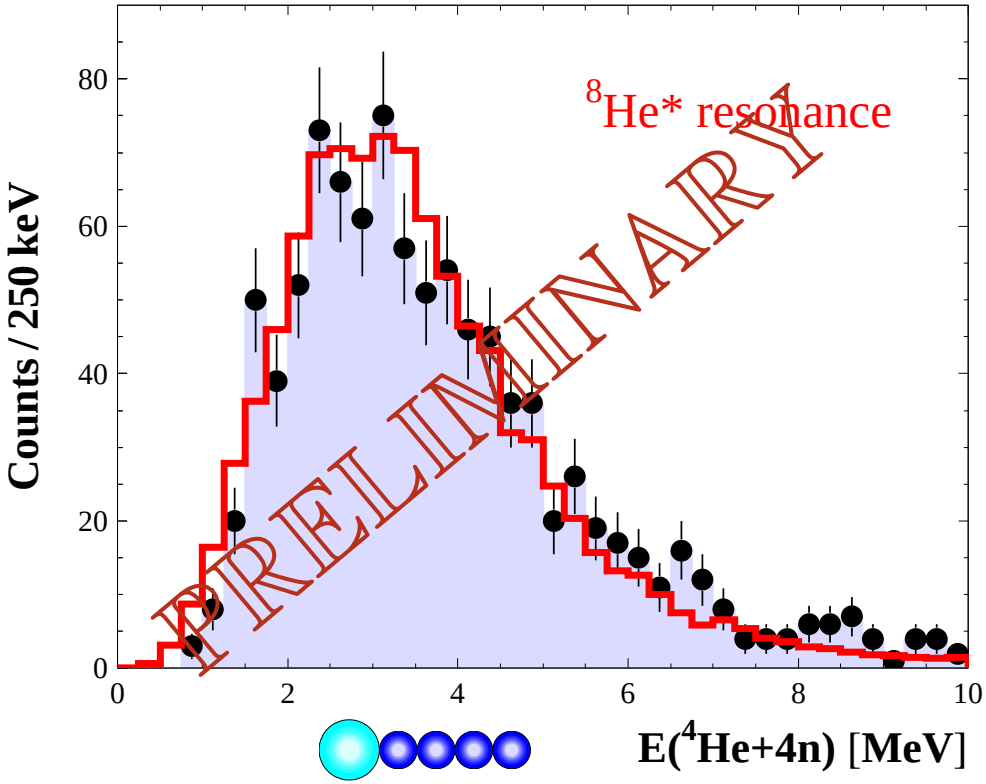
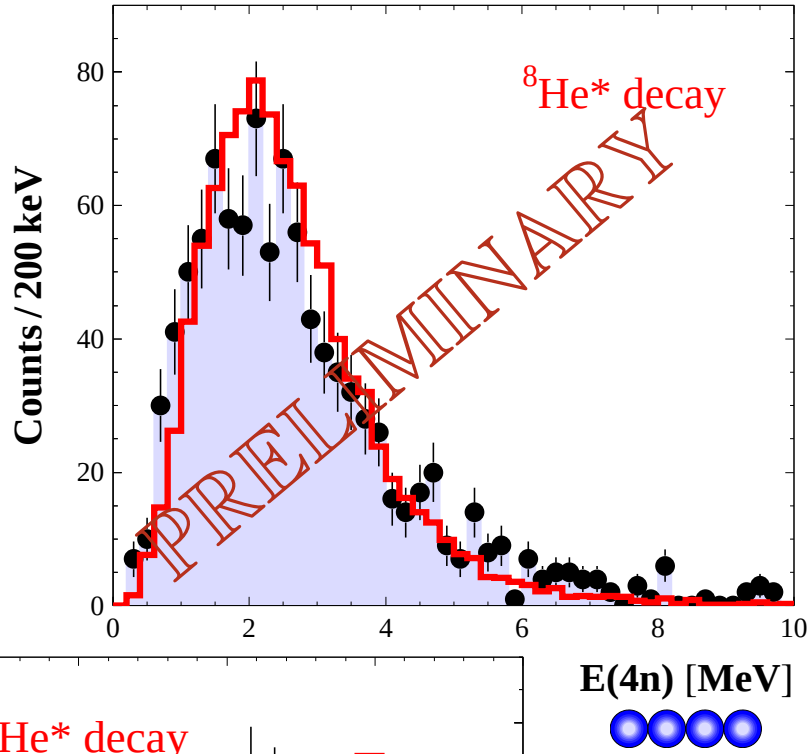
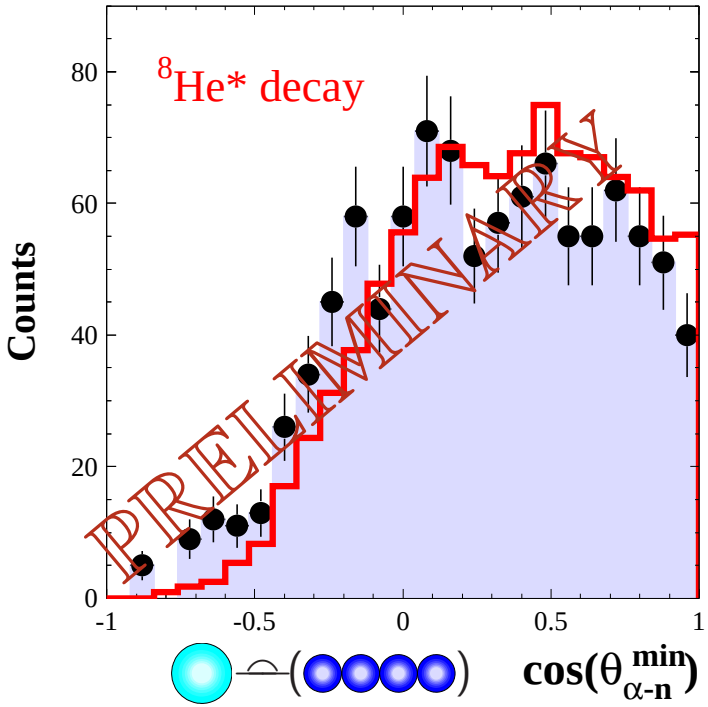
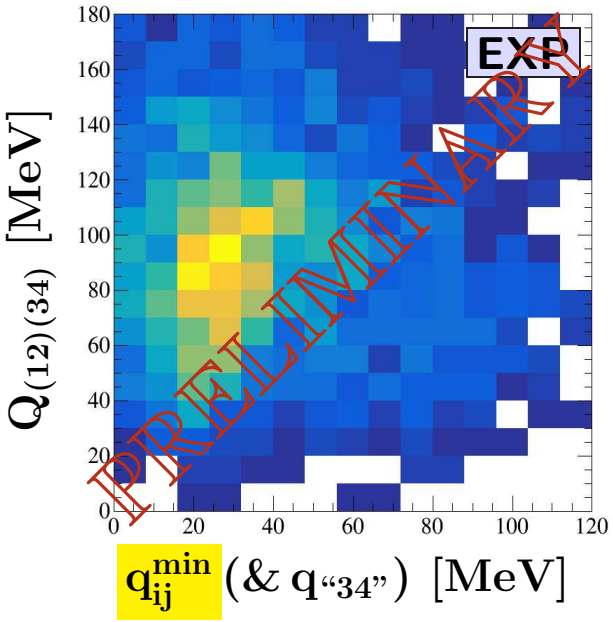
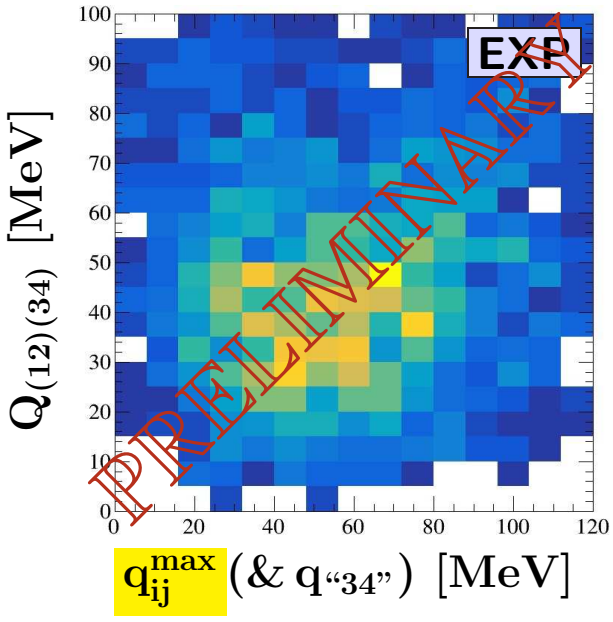


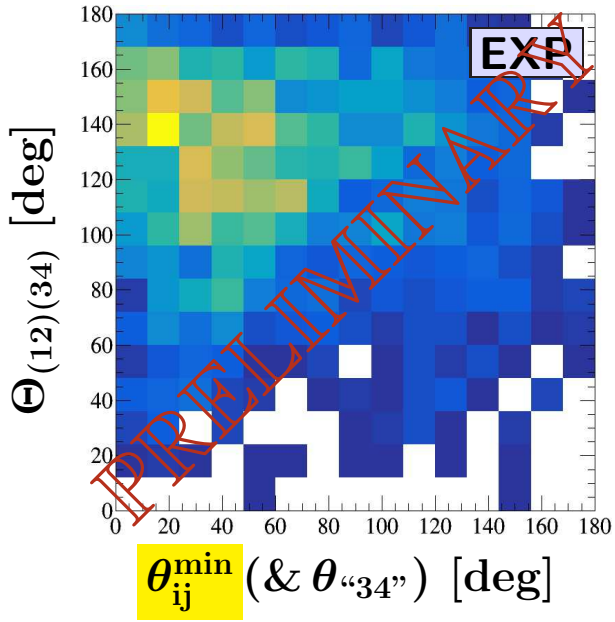




Preliminary 4n correlation observables







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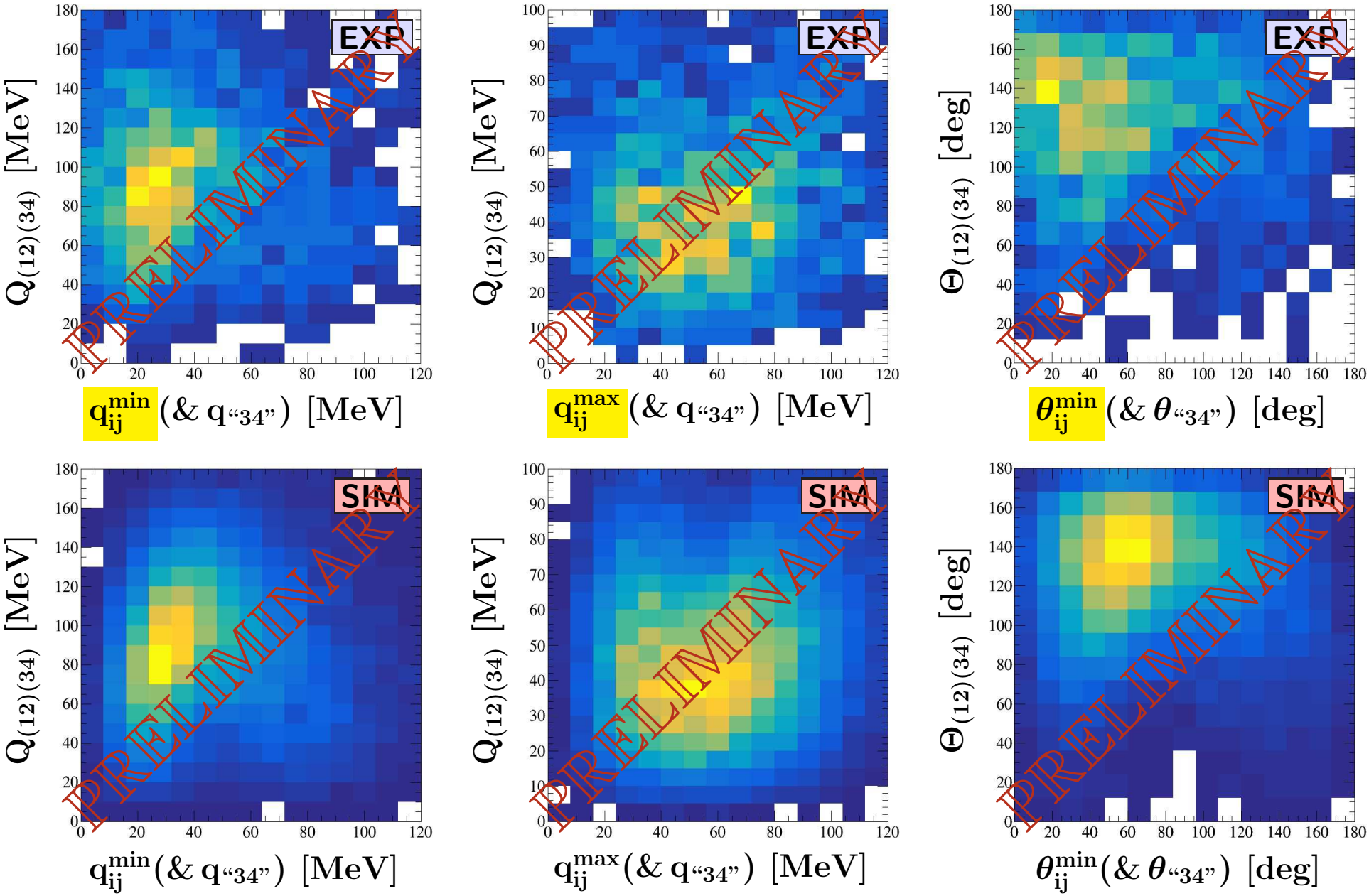

Summary

Emeline Oliveira, PhD

Audrey Anne, PhD

- Scattering lengths :
  - neutron off exotic 'containers'
  - ^{17}B+n : a schocking case !
- Experimental program @ RIKEN :
  - stat. & acceptance : effective range
  - multi-channel : determine (a_s, r_e) !
  - Universality ($|a_s|/r_e \sim 100$)

- Tetraneutron "signal" !
  - resonance / spatial correlations ?
  - link to momentum correlations ?
- Experimental program @ RIKEN :
  - first 4n invariant masses
  - some low-energy structures
  - explore full kinematics ...