Effect of collective and non-collective pairing excitations in transfer reactions

Denis Lacroix

GANIL-Caen

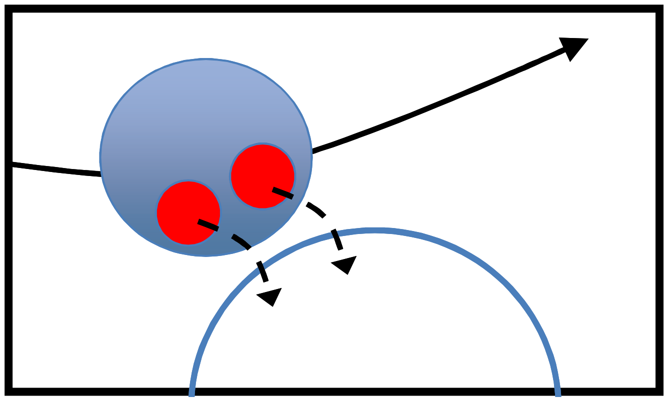
Outline:

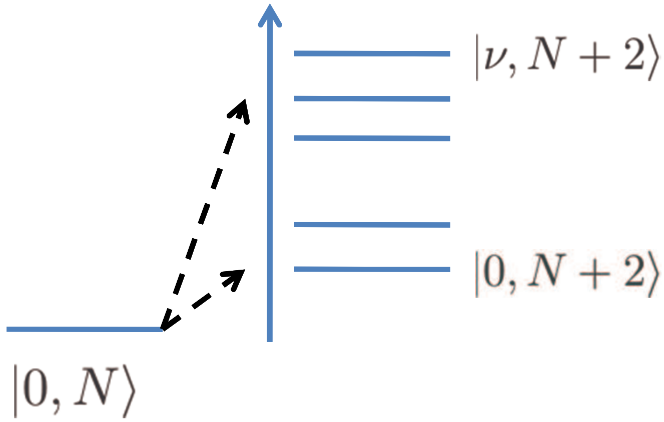
- Pair transfer (the nuclear structure point of view)
- Pair transfer (the nuclear reaction point of view)
- Treatment of continuum

Coll: **M. Grasso, A. Vitturi**
D. Gambacurta
G. Scamps

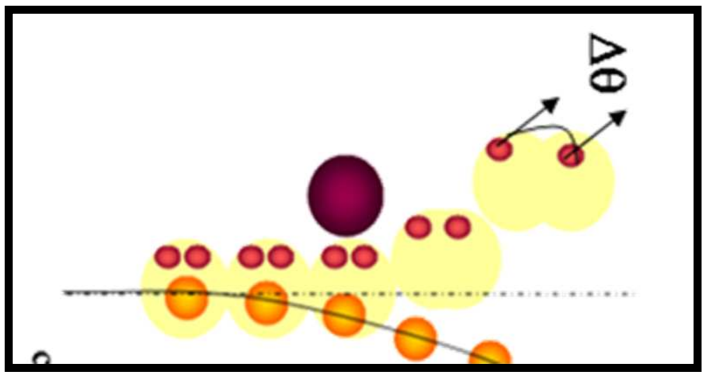
transfer and break-up reactions

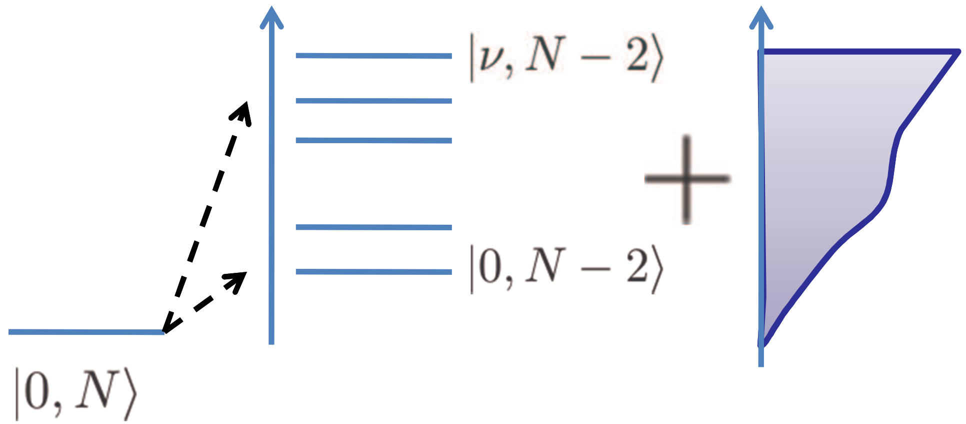
2n-transfer reactions





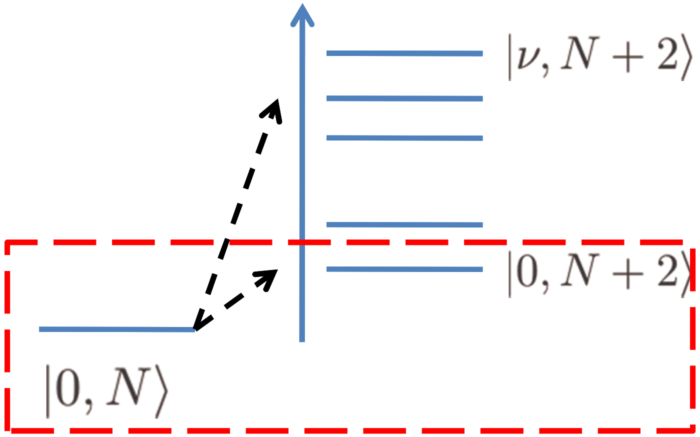
2n-break-up reactions





Description

$$
\begin{aligned}
|\Psi(t)\rangle \;=\; & e^{-itE_0^N/\hbar}\Big\{\sum_\nu c_\nu^N e^{-it(E_\nu^N-E_0^N)/\hbar}|\nu,N\rangle \\
& + \sum_\nu c_\nu^{N-2} e^{-it(E_\nu^{N-2}-E_0^N)/\hbar}|\nu,N-2\rangle \\
& + \sum_\nu c_\nu^{N+2} e^{-it(E_\nu^{N+2}-E_0^N)/\hbar}|\nu,N+2\rangle\Big\}
\end{aligned}
$$



Assuming a pair transfer excitation operator:

Bes and Broglia, NPA 80 (1966), Ripka and R. Padjen, NPA132 (1969).

$$\hat{T} = \sum_i (T_{i\bar{i}} a_i^\dagger a_{\bar{i}}^\dagger + T_{i\bar{i}}^* a_{\bar{i}} a_i)$$

$$|\Psi(t)\rangle \Rightarrow S(E) = \sum_\nu |\langle N+2,\nu|\hat{T}|N,0\rangle|^2 \delta\left(E - \Delta E_\nu^{N+2}\right) + \sum_\nu |\langle N-2,\nu|\hat{T}|N,0\rangle|^2 \delta\left(E - \Delta E_\nu^{N-2}\right)$$

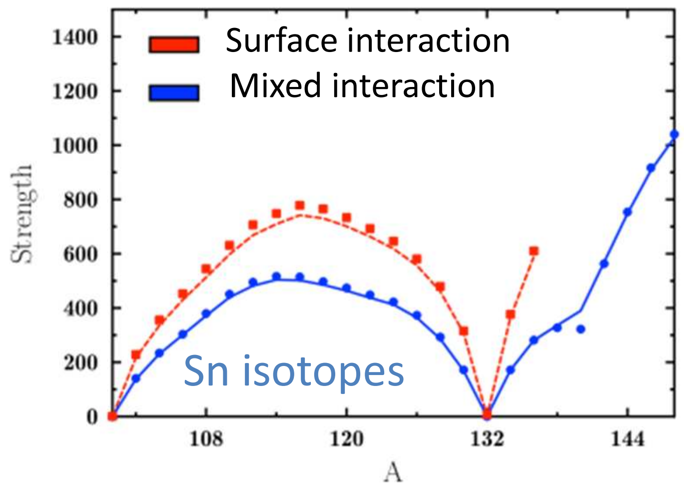
Nuclear structure input

Transfer from Ground state (GS) to GS : the mean-field strategy based on quasi-particles

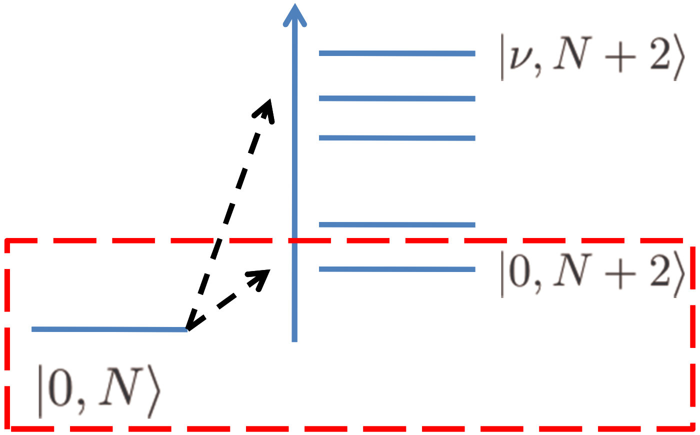
$$|0,N\rangle \simeq |QP\rangle = \prod_{i>0} \left(U_i + V_i a_i^\dagger a_{\bar{i}}^\dagger\right)|0\rangle$$

$$\left.\begin{array}{l} |\langle N+2,0|\hat{T}|N,0\rangle|^2 \\ |\langle N-2,0|\hat{T}|N,0\rangle|^2 \end{array}\right| \simeq |\langle QP|\hat{T}|QP\rangle|^2$$

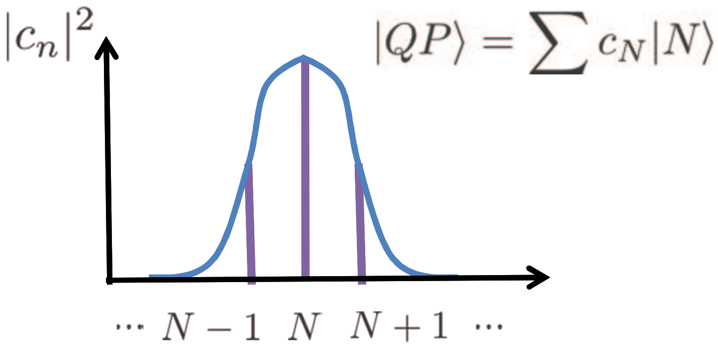
Illustration



Grasso, Lacroix, Vitturi, PRC85 (2012)
(see also Marcella talk)

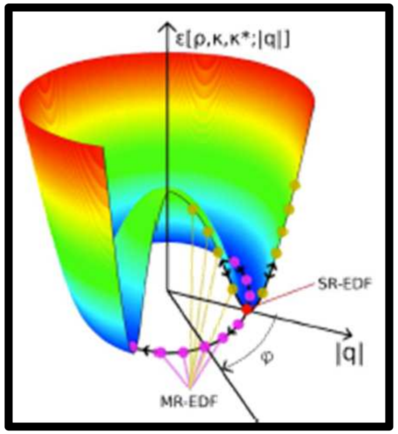


Particle number non-conservation

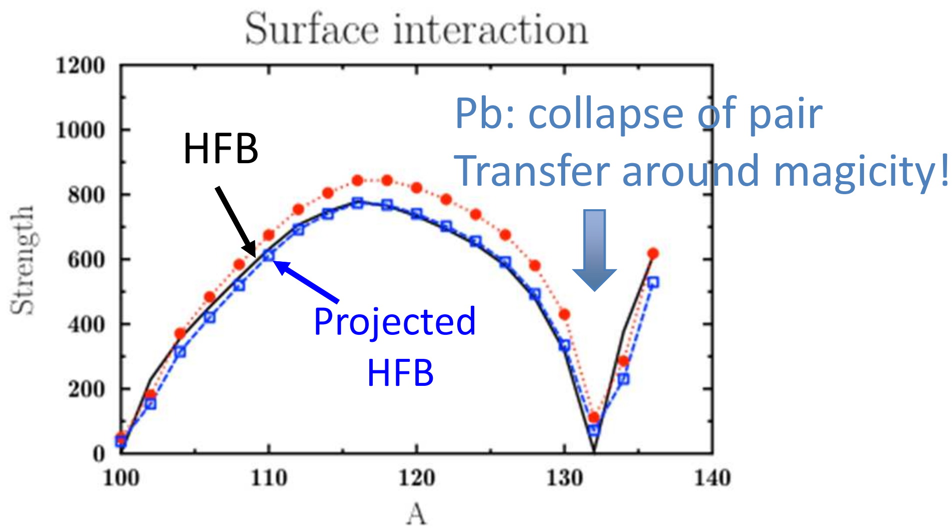


$$|N\rangle = P_N |QP\rangle$$

$$P^N = \frac{1}{2\pi}\int_0^{2\pi} d\varphi \; e^{i\varphi(\hat{N}-N)}$$

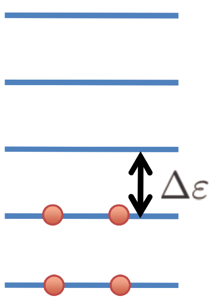


Projection After Variation applied to pair transfer



Grasso, Lacroix, Vitturi, PRC85 (2012)

Testing ideas with the pairing model



$$H = \sum_{i=1}^{\Omega} \varepsilon_i a_i^\dagger a_i + \sum_{i \neq j}^{\Omega} v_{ij} a_i^\dagger a_{\bar{i}}^\dagger a_{\bar{j}} a_j$$

Mean-Field

$$\delta \langle QP | H | QP \rangle = 0$$

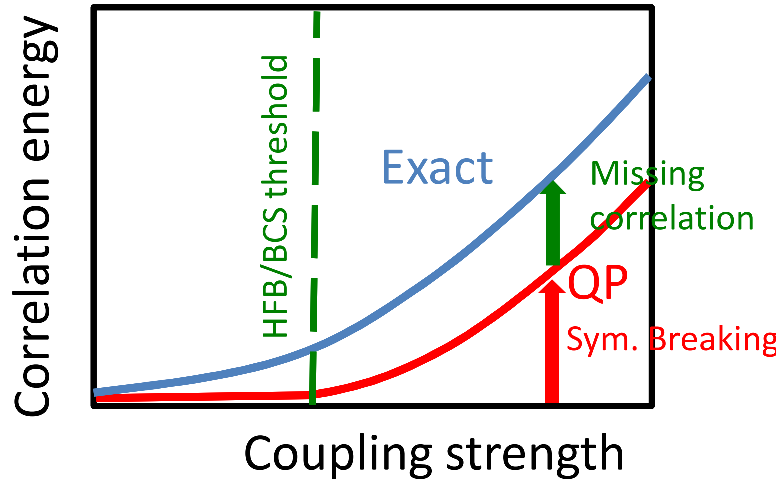
Projection After Variation

Does not solve the threshold problem

Variation After Projection

$$\delta \langle QP | P_N H P_N | QP \rangle = 0$$

Solve the problem but is rather involved. (Hupin, Lacroix, PRC86 (2012).)



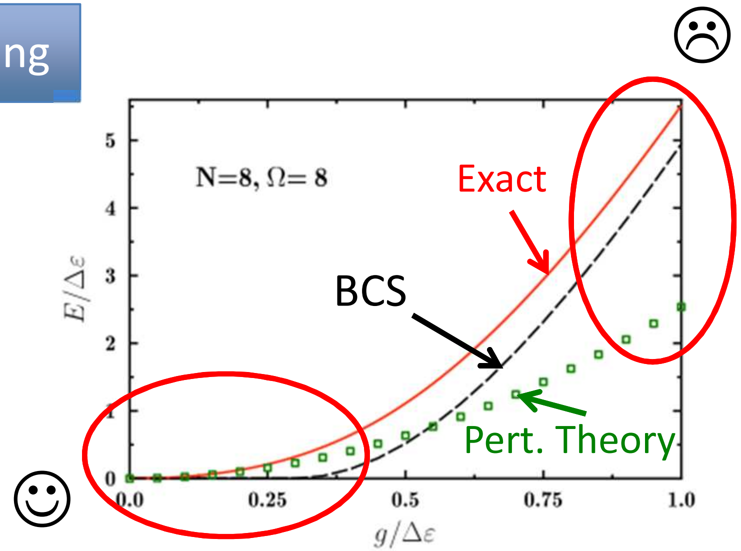
Simple perturbative approach to pairing at weak coupling

Normal phase: standard perturbation theory

$$H = \sum_{i=1}^{\Omega} \varepsilon_i a_i^\dagger a_i + g \sum_{i \neq j}^{\Omega} a_i^\dagger a_{\bar{i}}^\dagger a_{\bar{j}} a_j$$

H_0 $V_{\rm res}$ Treated as a perturbation

$$|\Phi_0'\rangle = |\Phi_0\rangle + \sum c_{\rm 2p2h} |\Phi_{\rm 2p2h}\rangle$$



From particles to quasi-particles

$$|0,N\rangle \;\Rightarrow\; |QP\rangle$$

$$a_i^\dagger \;\Rightarrow\; \beta_i^\dagger$$

$$H \;\Rightarrow\; H_0 = E_0 + \sum E_i \beta_i^\dagger \beta_i$$

$$H|QP\rangle = \left(H_0 - \sum_{i\neq j} v_{ij} U_i^2 V_j^2 \beta_i^\dagger \beta_i^\dagger \beta_j^\dagger \beta_j^\dagger \right) |QP\rangle$$

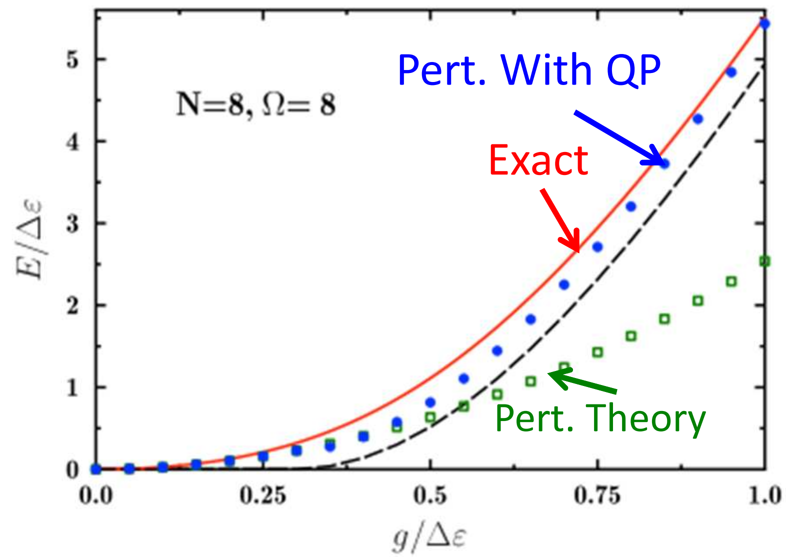
$\Downarrow V_{\rm res}$

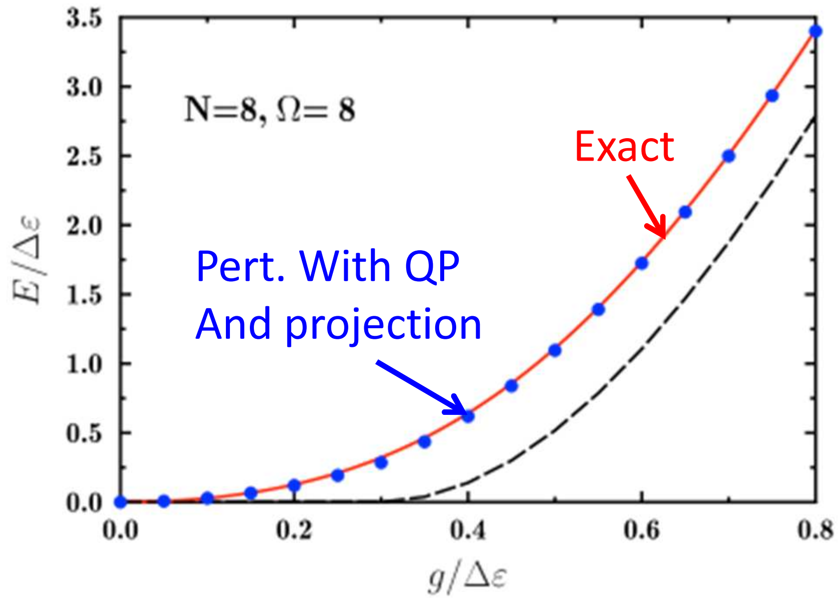
Step 1: Perturbation theory

$$|\Phi_0'\rangle = |QP\rangle + \sum c_{4QP} |\Phi_{4QP}\rangle$$

Step 2: Projection on particle number

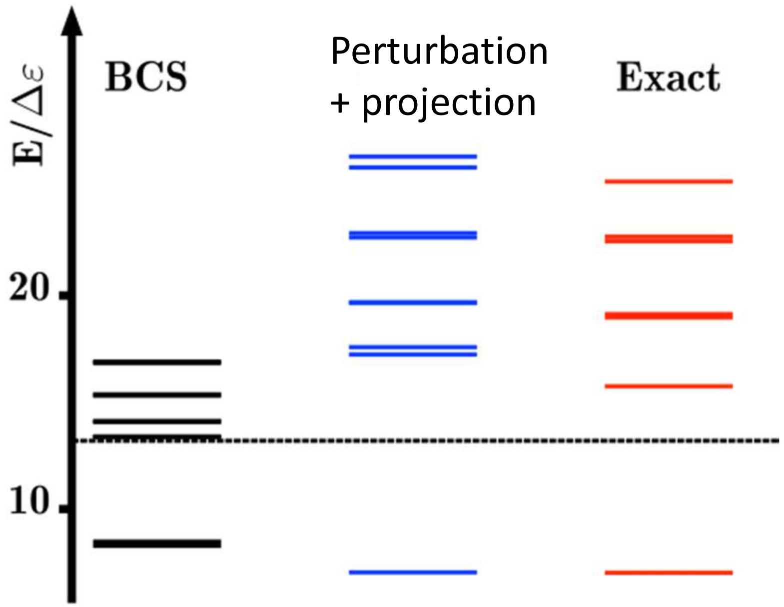
$$E_0 = \frac{\langle \Phi_0' | P_N H P_N | \Phi_0' \rangle}{\langle \Phi_0' | P_N | \Phi_0' \rangle}$$ (PAV like method)





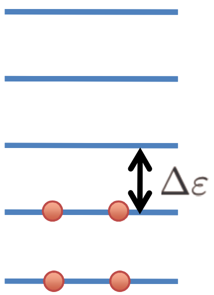
Lacroix and Gambacurta PRC86, (2012).

Result of perturbation + projection technique



Lacroix and Gambacurta, PRC86, (2012).

- Very good for the ground state.
- Still not satisfactory for excited state.
- Alternative: use QRPA



$$H = \sum_{i=1}^{\Omega} \varepsilon_i a_i^\dagger a_i + g \sum_{i \neq j}^{\Omega} a_i^\dagger a_{\bar{i}}^\dagger a_{\bar{j}} a_j$$

QRPA applied to pair transfer

$$|\nu\rangle = Q_\nu^\dagger |0\rangle$$

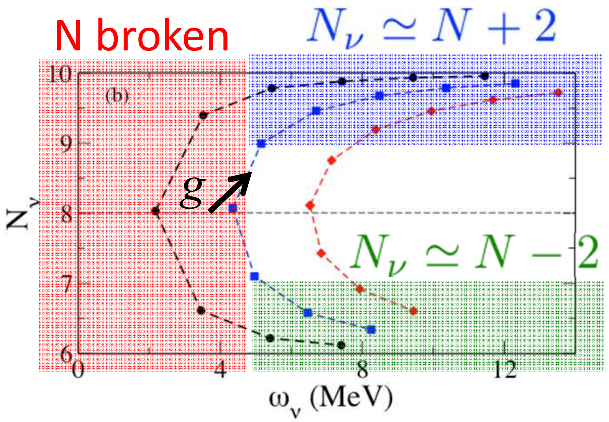
Normal phase: $Q_\nu^\dagger = \sum_p X_p^\nu a_p^\dagger a_{\bar{p}}^\dagger + \sum_h Y_h^\nu a_h^\dagger a_{\bar{h}}^\dagger,$

Superfluid phase: $Q_\nu^\dagger = \sum_i (X_j^\nu \alpha_i^\dagger \alpha_{\bar{i}}^\dagger - Y_j^\nu \alpha_{\bar{i}} \alpha_i)$

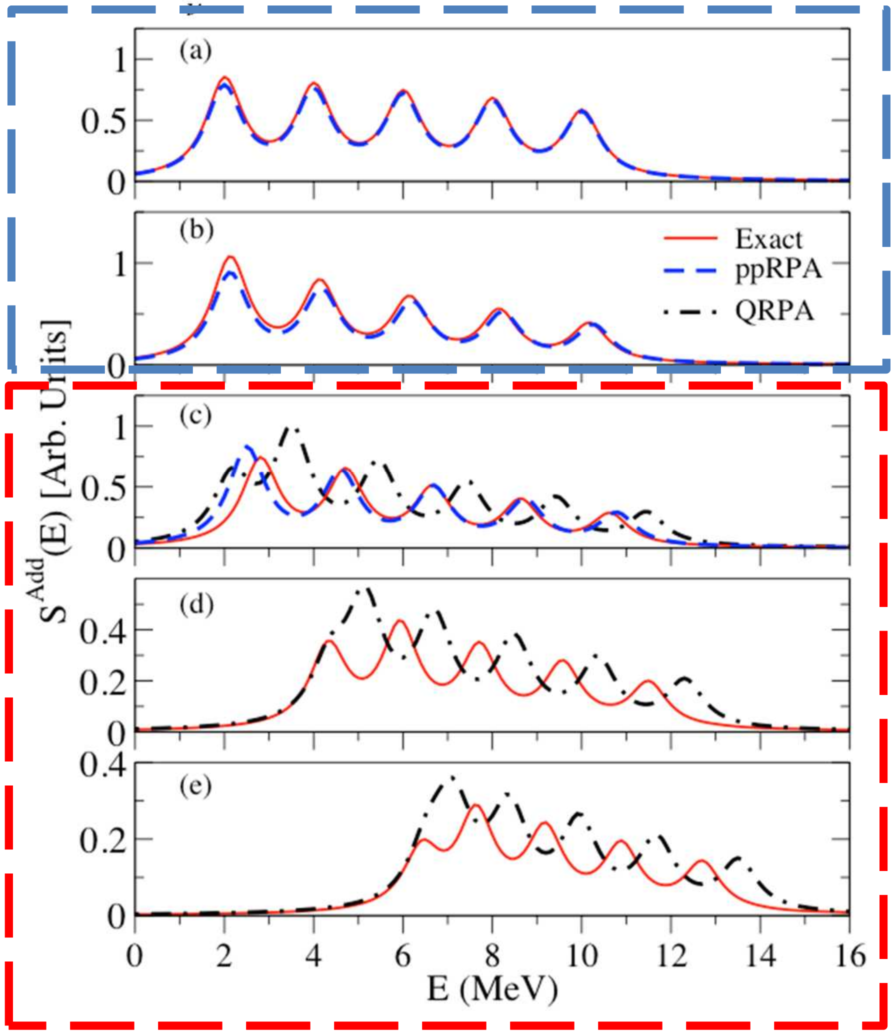
- ppRPA very good
- QRPA is *globally* good

Role of particle number non-conservation?

$$N_\nu = \langle \nu | \hat{N} | \nu \rangle$$



$$\sum_\nu |\langle N+2, \nu | \hat{T} | N, 0 \rangle|^2 \delta\left(E - \Delta E_\nu^{N+2}\right)$$



Gambacurta and Lacroix, PRC86 (2012).

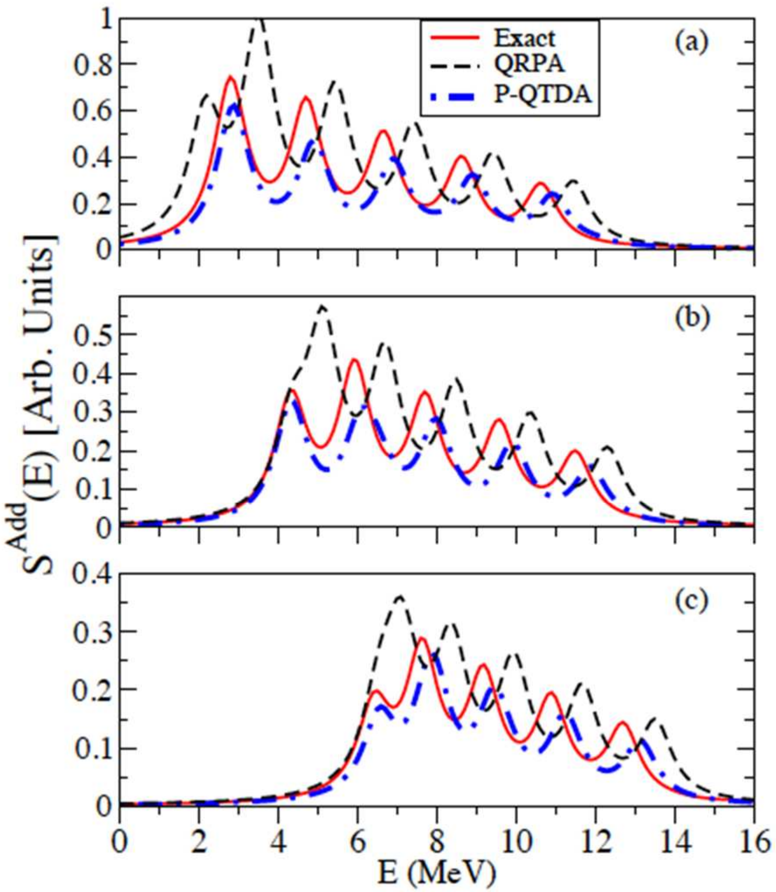
Recipe:

Take all 2QP states + GS

$$|\Phi_k\rangle = \hat{P}_{N+2}\alpha^\dagger_k\alpha^\dagger_{\bar{k}}|0,QP\rangle$$

orthonormalization

Diagonalize H in the reduced space

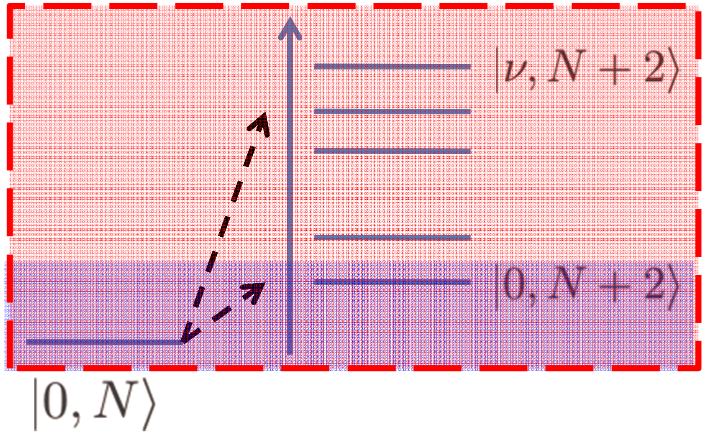


(a) $G/\Delta\varepsilon = 0.5$, (b) 0.7, (c) 0.9

- Confirms the role of U(1) sym. breaking
- Improve the QRPA
- Directly applicable in existing HFB codes

Gambacurta and Lacroix, PRC86 (2012).

The nuclear structure point of view



Improved description pair transfer to excited states.
(Projected QRPA like)

Improved description of ground state
(QP perturbation theory)

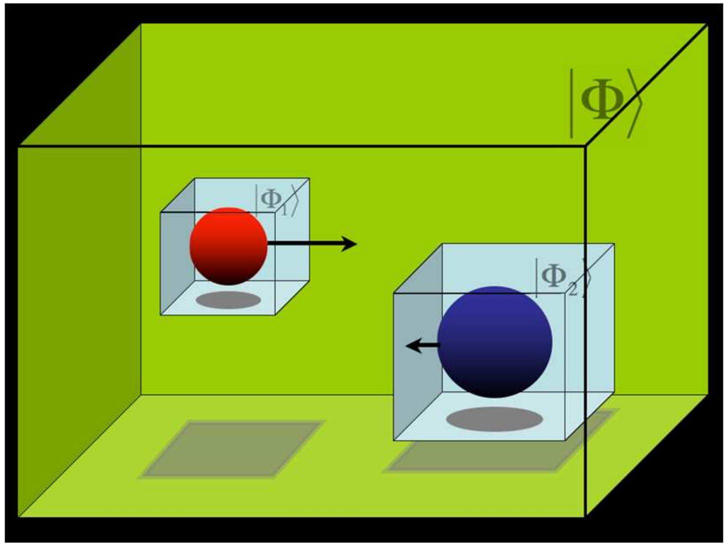
Present status:

- Directly applicable on existing HFB codes
- Application to nuclei
- Need to couple to reactions codes

Other strategy:

- Perform nuclear structure and reaction in a unique framework

Nuclear reaction on a mesh



TDHF is a standard tool $|\Phi_i\rangle$: Slater

$$i\hbar\frac{d\rho}{dt} = [h(\rho),\rho]$$ ➡ Single-particle evolution

Simenel, Lacroix, Avez, arXiv:0806.2714v2

Introduction of pairing: TDHFB

$$i\hbar\frac{d}{dt}\mathcal{R} = [\mathcal{H}(\mathcal{R}),\mathcal{R}] \qquad \mathcal{R} = \begin{pmatrix} \rho & \kappa \\ -\kappa^* & 1-\rho \end{pmatrix}$$

➡ Quasi-particle evolution

(Active Groups: France, US, Japan…)

BCS limit of TDHFB (also called Canonical basis TDHFB)

TDHFB = 1000 * (TDHF)

Neglect Δ_{ij}

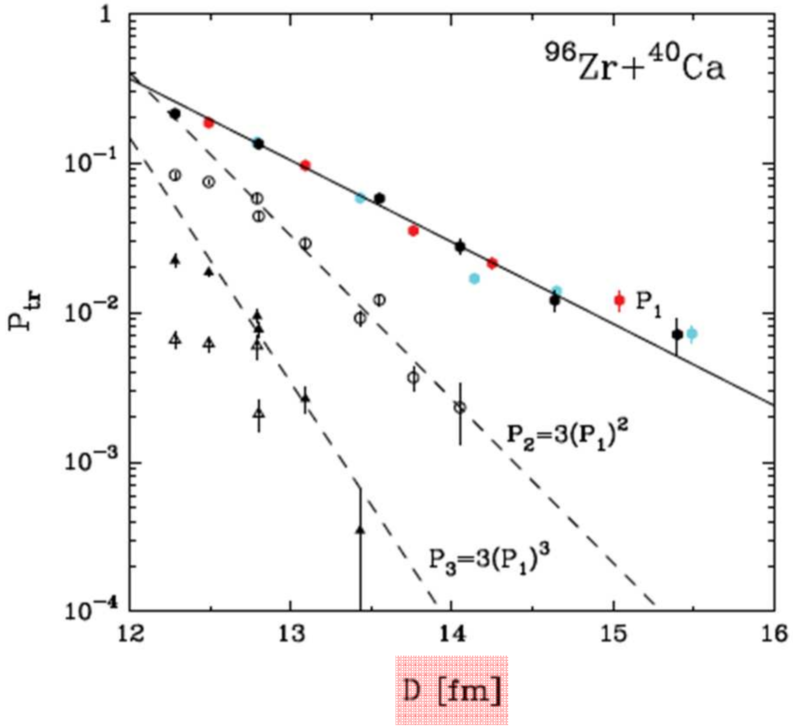
$$|\Phi(t)\rangle = \prod_{k>0}\left(u_k(t) + v_k(t)a^\dagger_k(t)a^\dagger_{\bar{k}}(t)\right)|-\rangle.$$

➡ Less demanding than TDHFB

➡ Reasonable results for collective motion — Ebata, Nakatsukasa et al, PRC82 (2010)

➡ Sometimes more predictive than TDHFB — Scamps, Lacroix, Bertsch, Washiyama, PRC85 (2012)

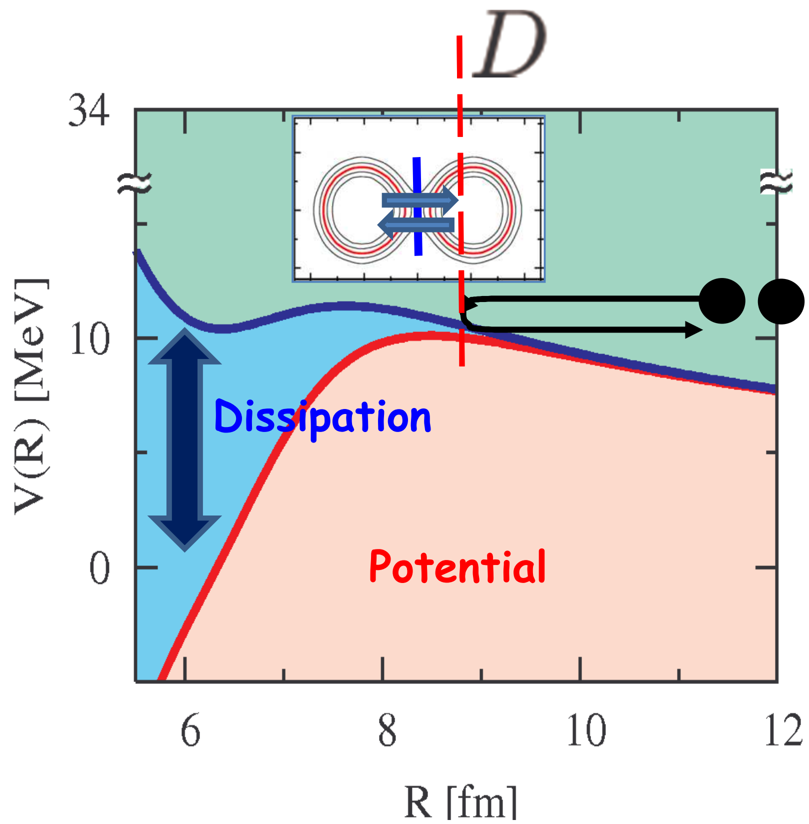
Illustration of useful data (for us)



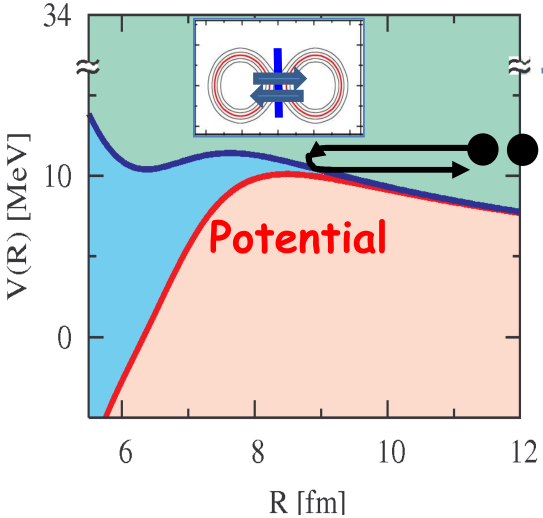
Corradi et al, Phys. Rev. C 84 (2011)

Our goal:

- Consider system with pairing in the GS
- Perform time-dependent simulation
  Close to be compared with experiments

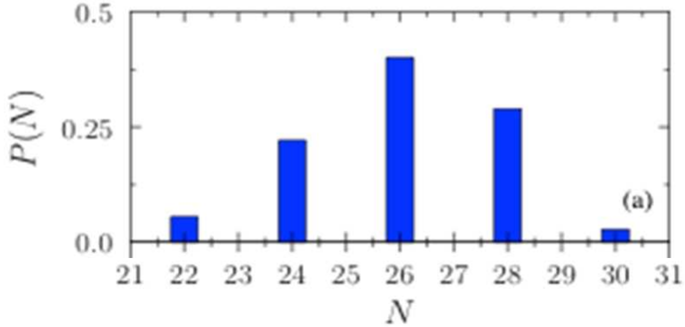


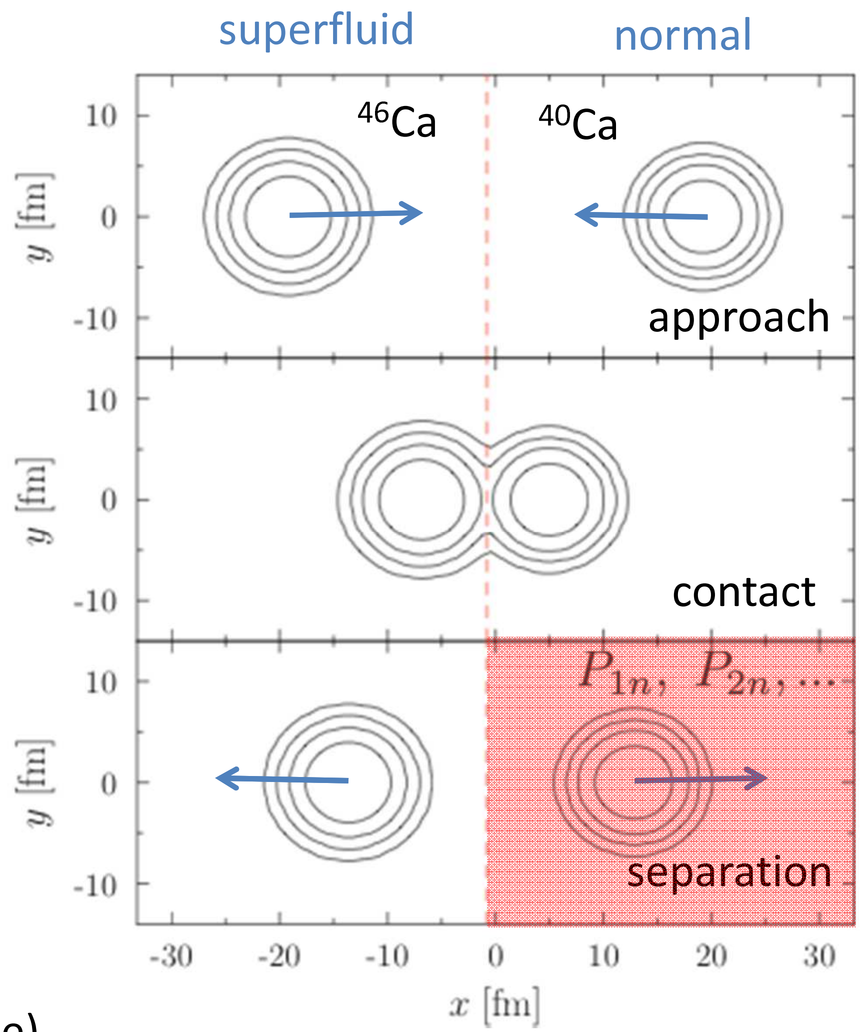
Dynamics with pairing



Besides the numerical difficulty, interpreting results is not so easy…

➡ ^{46}Ca or not ^{46}Ca ?





Scamps, Lacroix, PRC 87 (2013)

➡ Requires 2 projection (total and left side)

The no pairing limit ?

➡ HFB : spherical HF: deformed

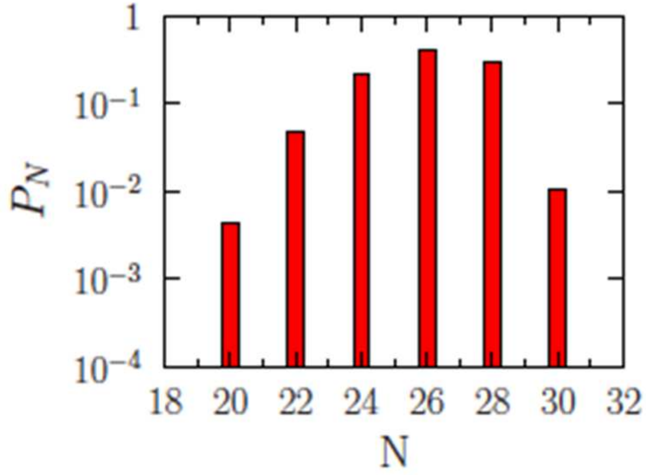
We used a generalization of TDHF to statistical Density matrix (filling approximation)

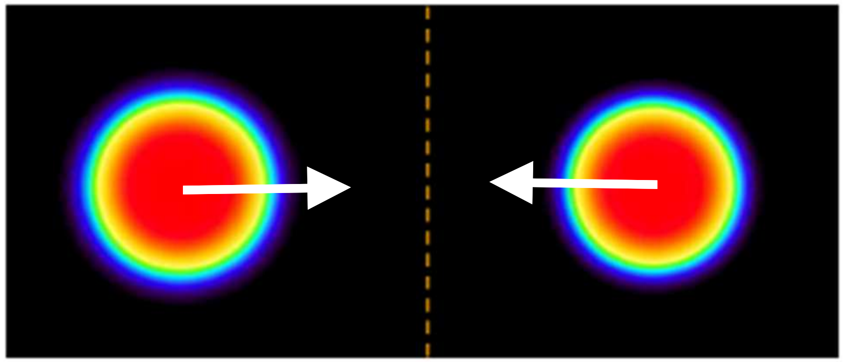
Dynamics with pairing:
Illustration

Initial time

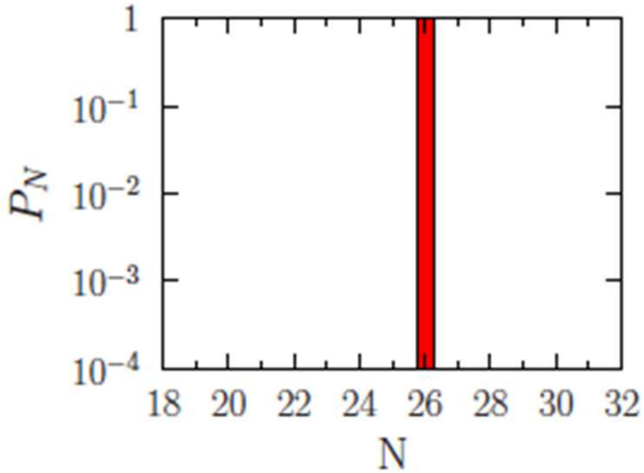
Single projection scheme (only on the left side)

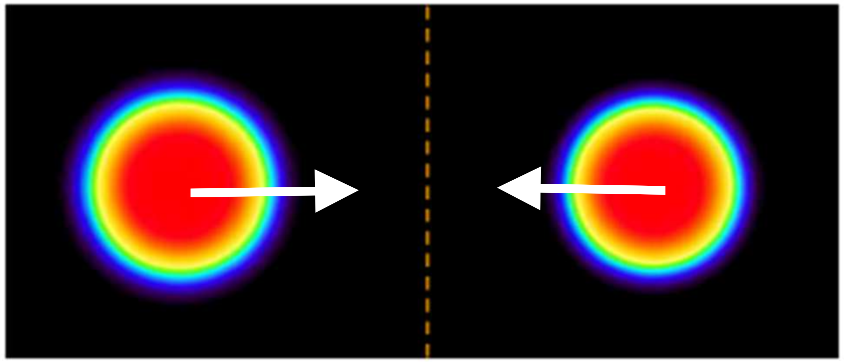
$^{46}Ca + ^{40}Ca$





Double projection scheme (total and left side)



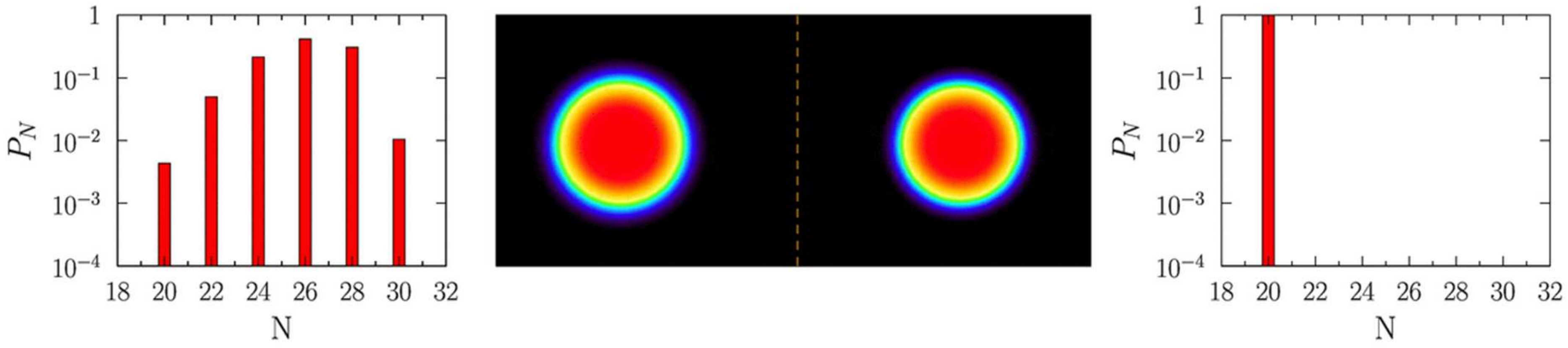


(Courtesy G. Scamps)

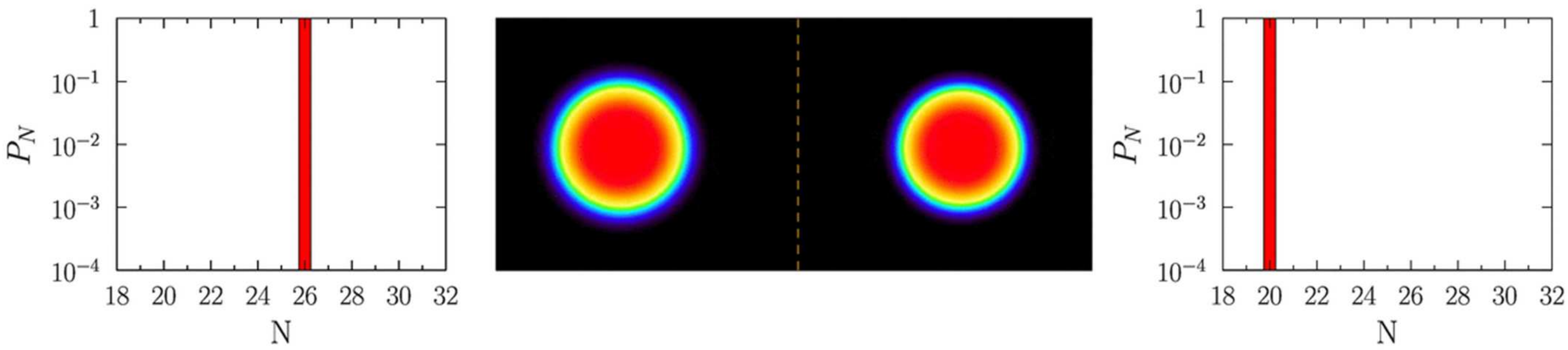
Initial time

Single projection scheme (only on the left side)

$^{46}Ca + ^{40}Ca$



Double projection scheme (total and left side)

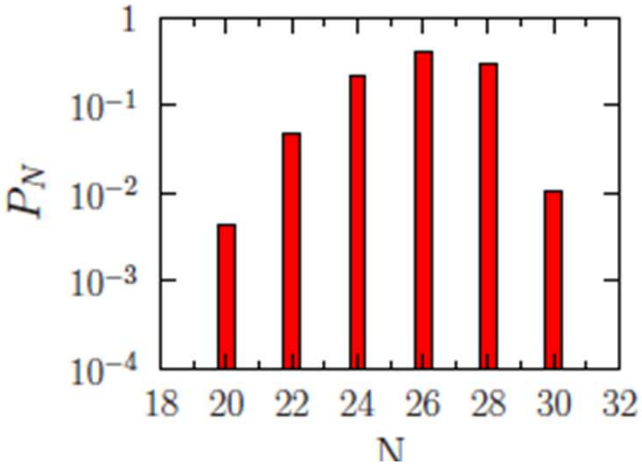


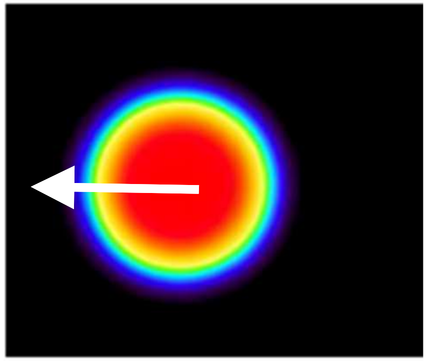
(Courtesy G. Scamps)

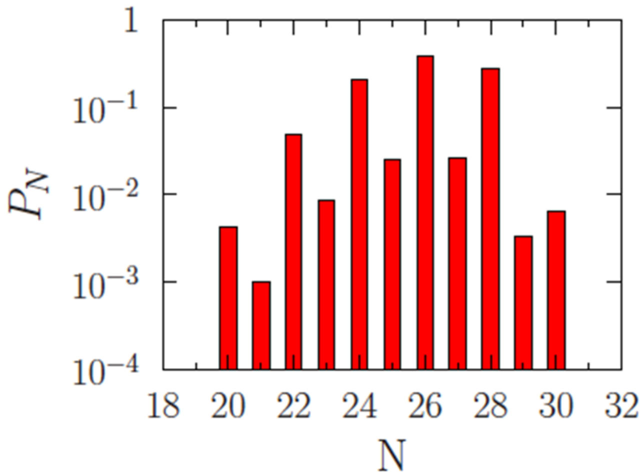
Initial time

Final time

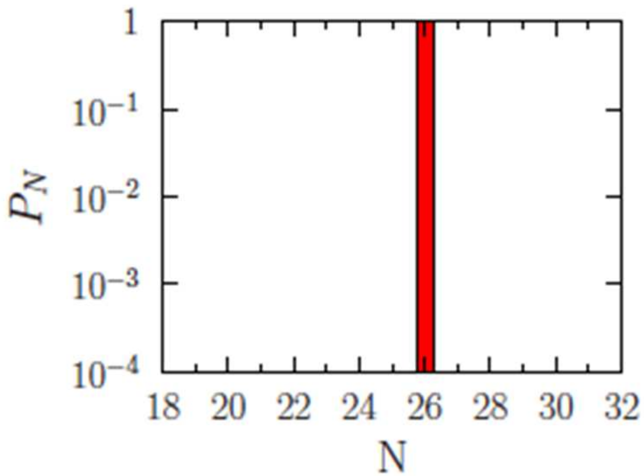
Single projection scheme (only on the left side)

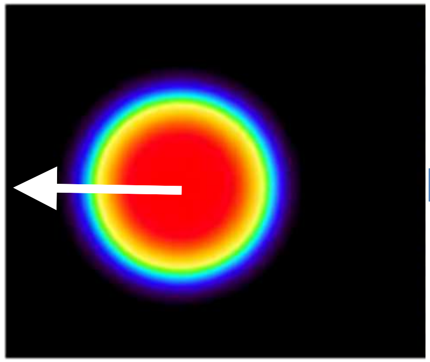


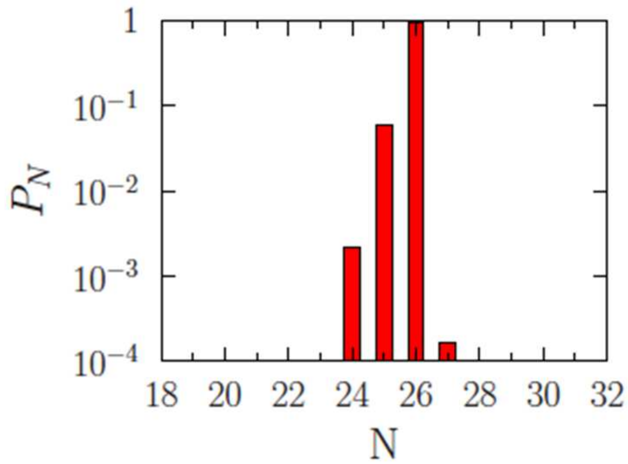




Double projection scheme (total and left side)

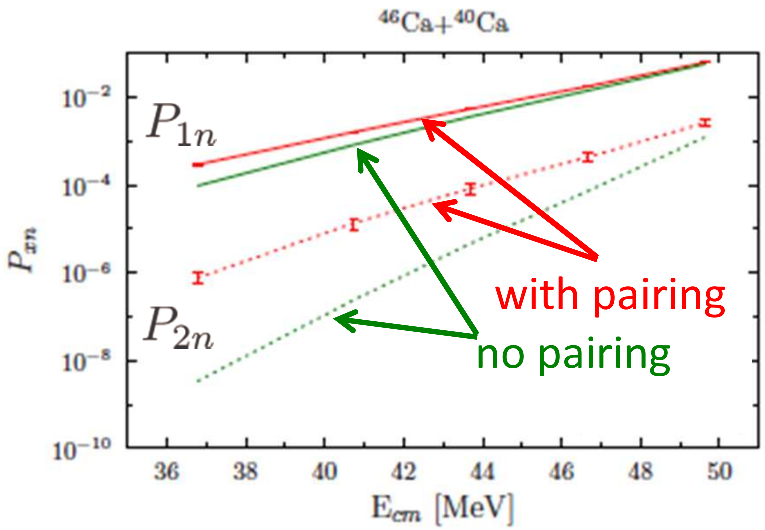






(Courtesy G. Scamps)

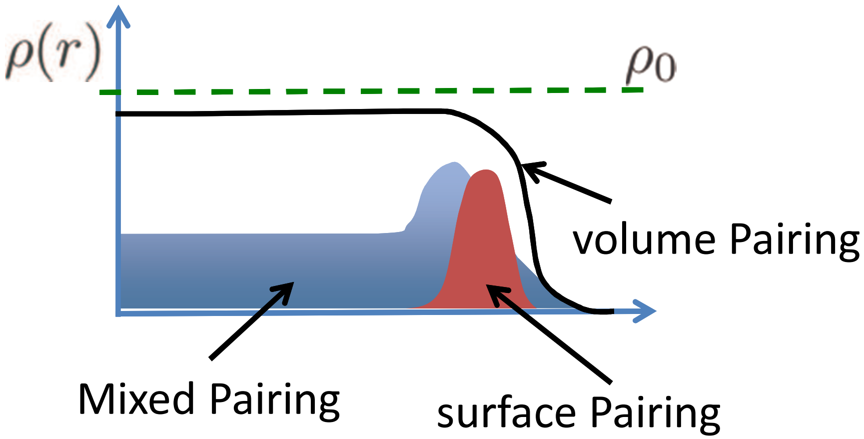
Enhancement of the pair transfer probability

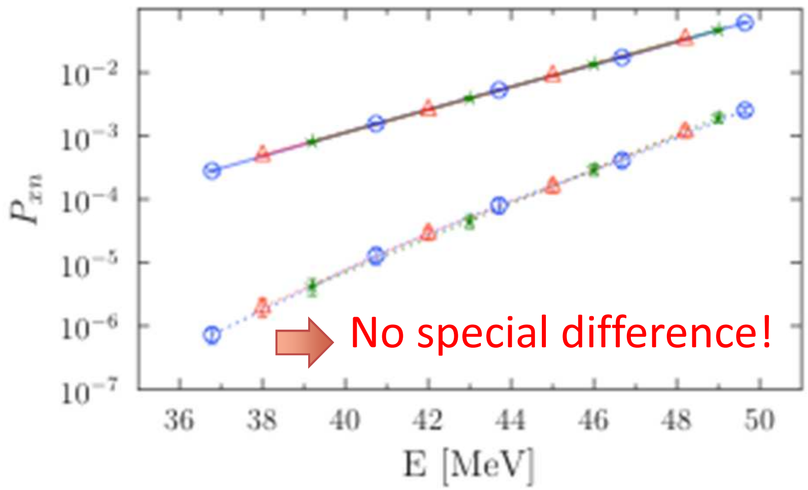


First conclusion

$\nearrow$ $P_{1n},\ P_{2n}, \ldots$

Can the pair transfer really probe the nature of the pairing force?

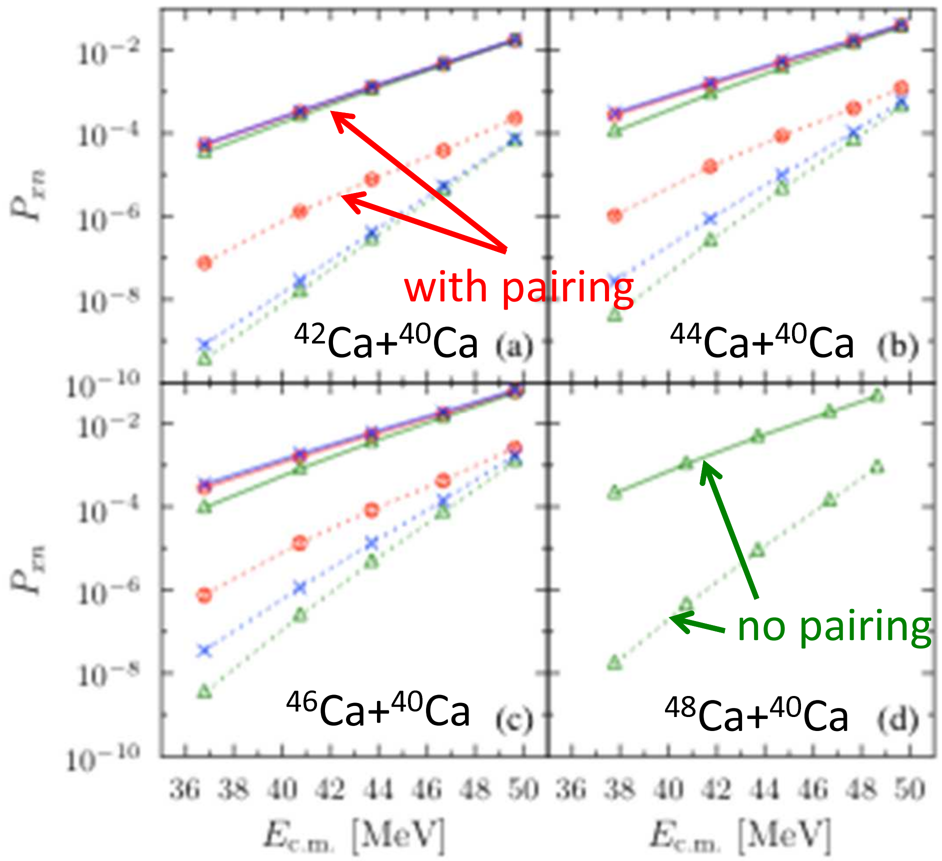




Scamps, Lacroix, PRC 87 (2013)

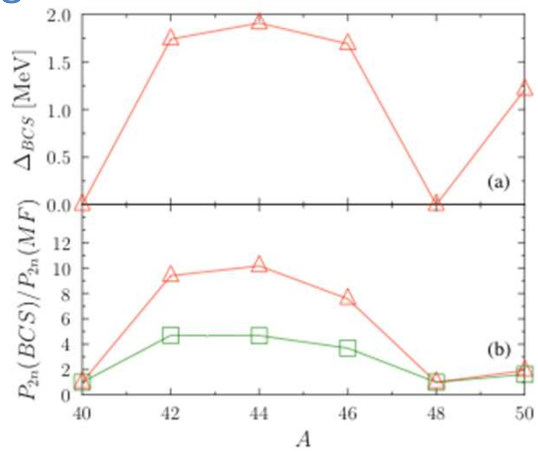
➡ The three contact forces have been adjusted to reproduce the experimental pairing gap

Systematic study

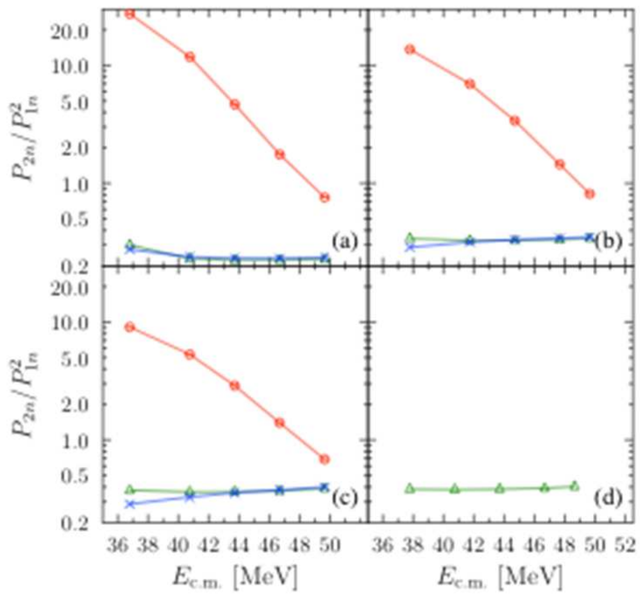


Scamps, Lacroix, PRC 87 (2013)

Link between pairing strength and pairing gap:

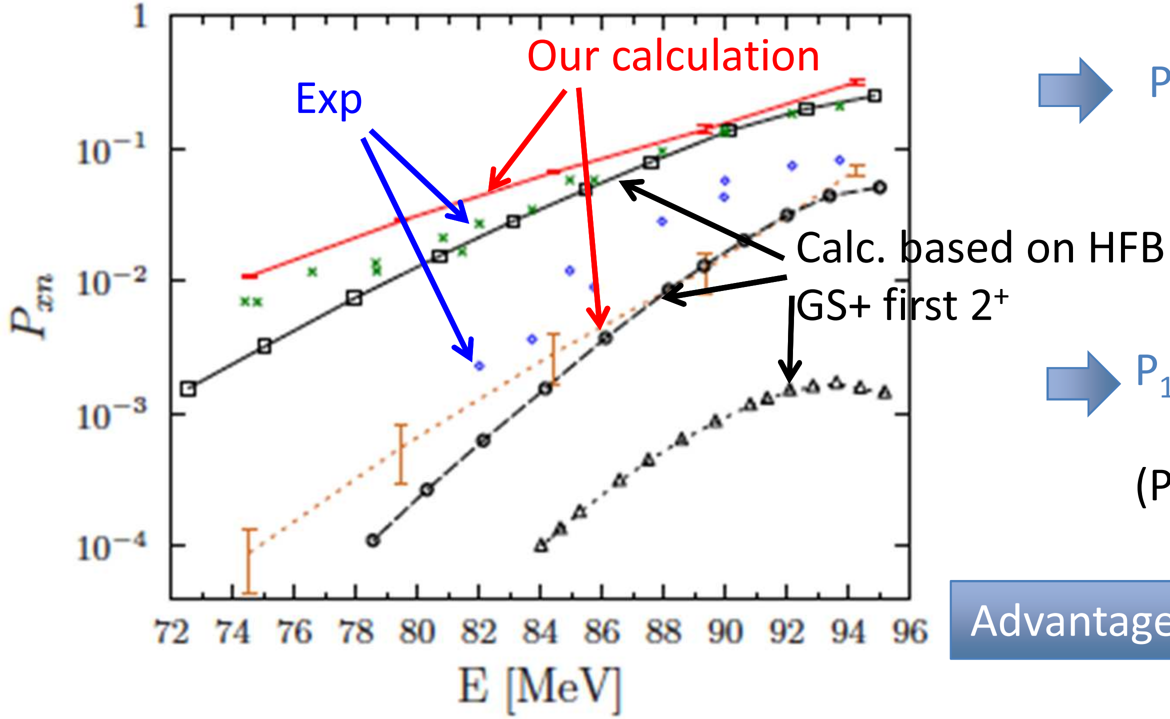


The enhancement depends strongly
On the beam energy



Comparison with experiment

Corradi et al, Phys. Rev. C 84 (2011)



- The dynamical approach is competitive Compared to other approaches
- P_{2n} is underestimated

  (Other effects are important!)

- P_{1n} is not so well reproduces:

  (Problem with the single-particle field)

Advantages and drawback of the BCS method

- Valid for not too exotic nuclei (gas problem)

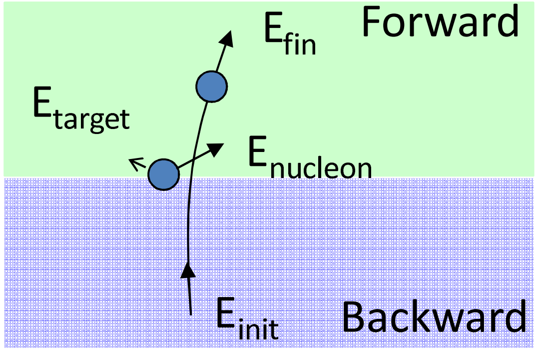
  TDHFB? (has also some problems)

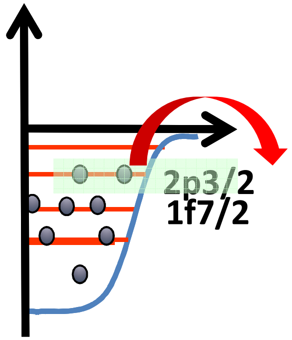
- Easy to perform
- Continuum for free! (r-space solution)

Success of the time-dependent independent particle picture

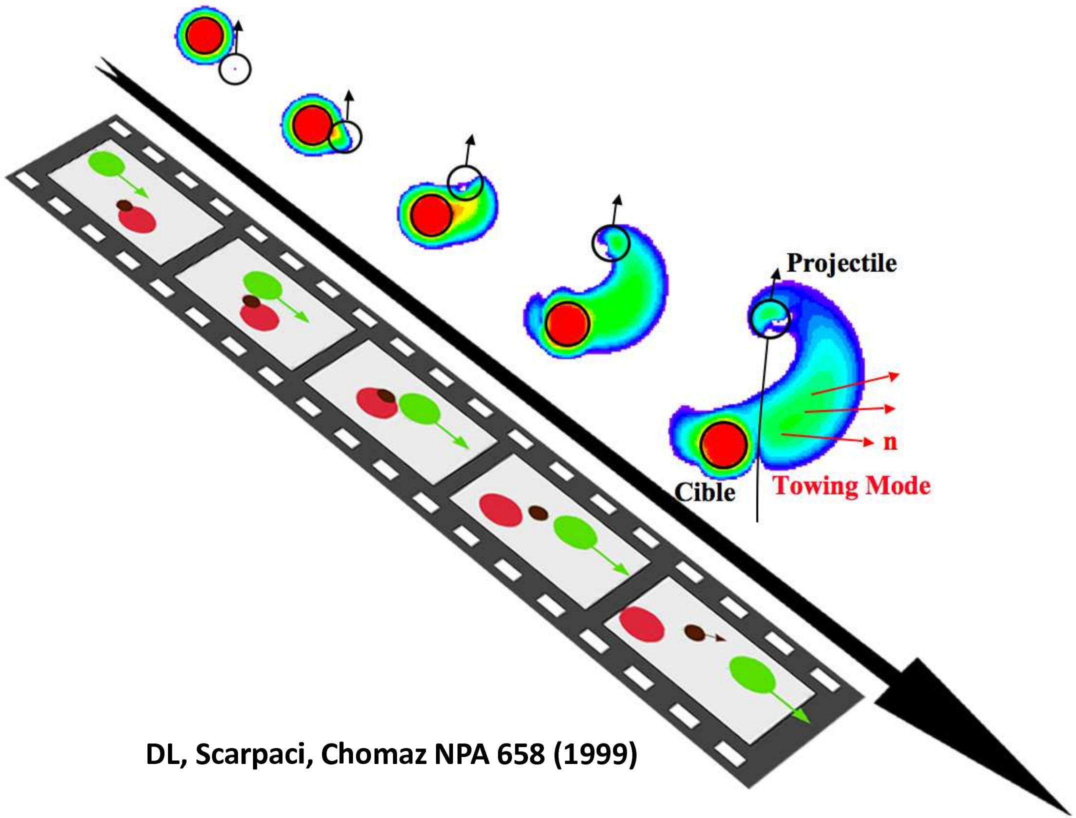
Break-up and continuum emission of one particle

Experimental motivation: ^{58}Ni break-up @44 MeV/A





Scarpaci et al., Phys. Lett. B428 (1998)

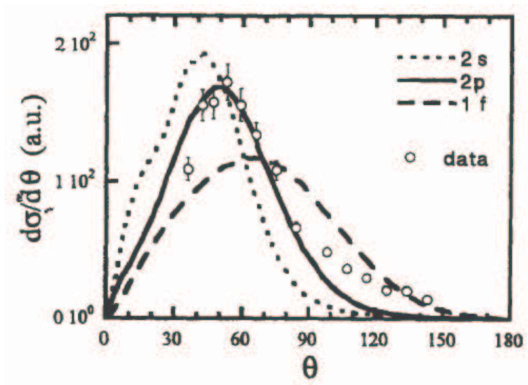


DL, Scarpaci, Chomaz NPA 658 (1999)

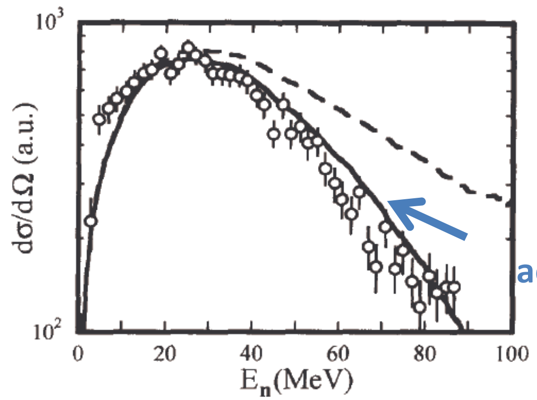
Time-dependent description

$$i\hbar\partial_t|\Phi_\alpha(t)\rangle = \left\{\frac{\mathbf{p}^2}{2m} + V_P(\vec{\mathbf{r}},t) + V_T(\vec{\mathbf{r}},t)\right\}|\Phi_\alpha(t)\rangle$$

Angular distribution:

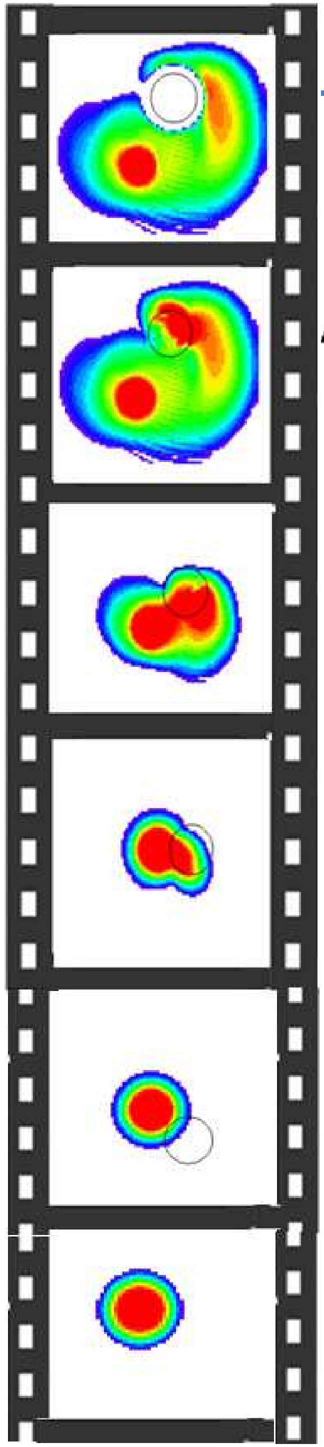


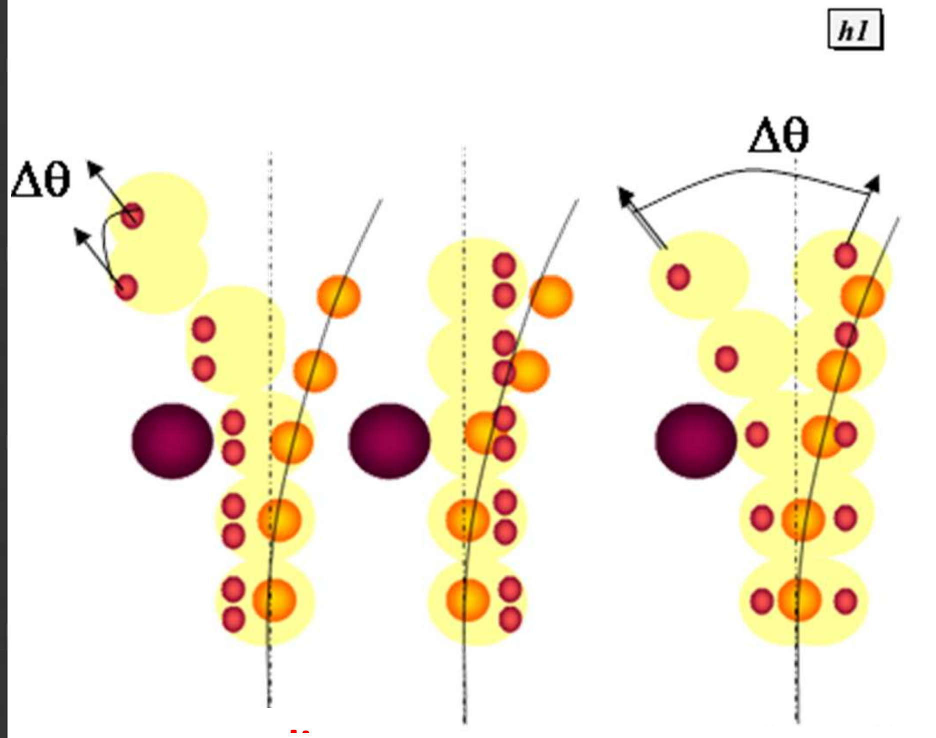
Kinetic Energy distribution:



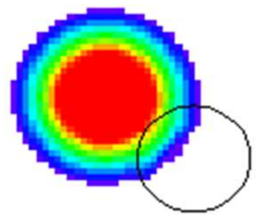
With detector acceptance

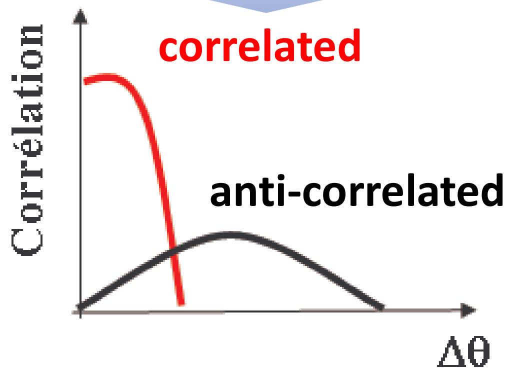
Theoretical description





correlated anti-correlated

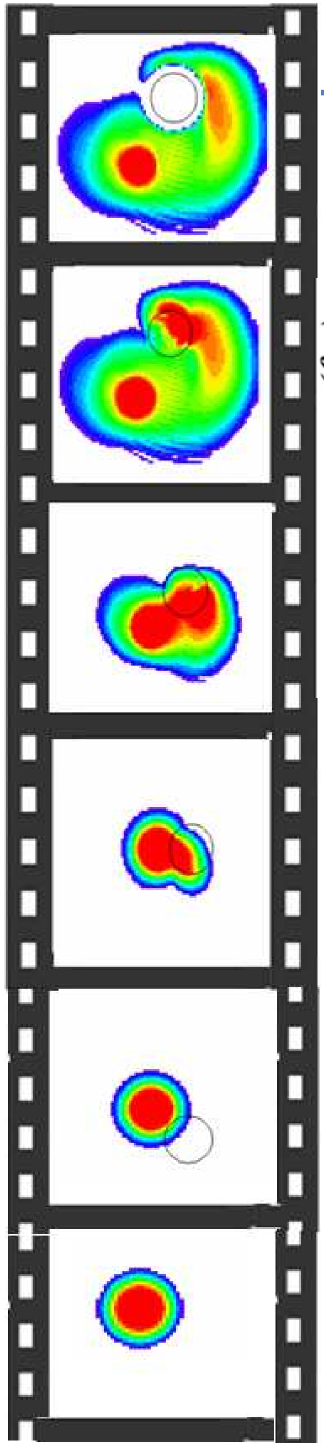




(Assié and Lacroix, PRL102 (2009))

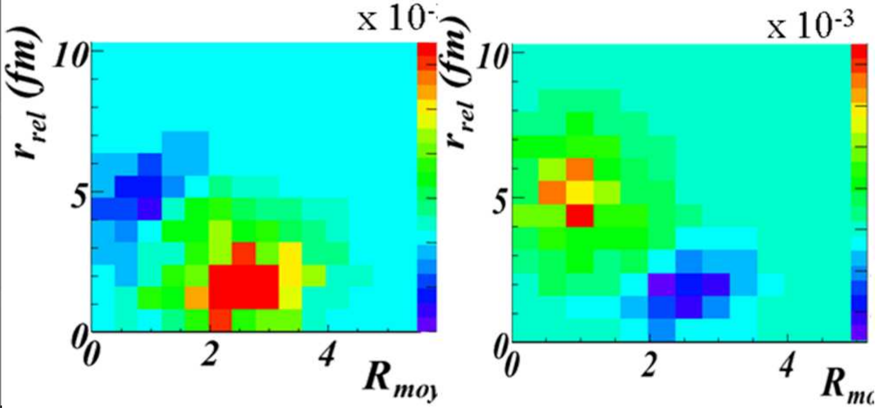
Can we probe nn correlations with nuclear break-up?

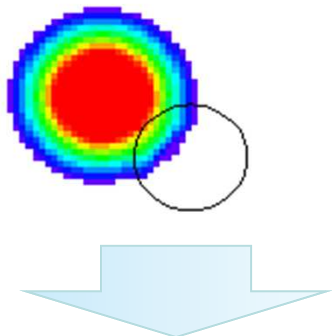
Theoretical description



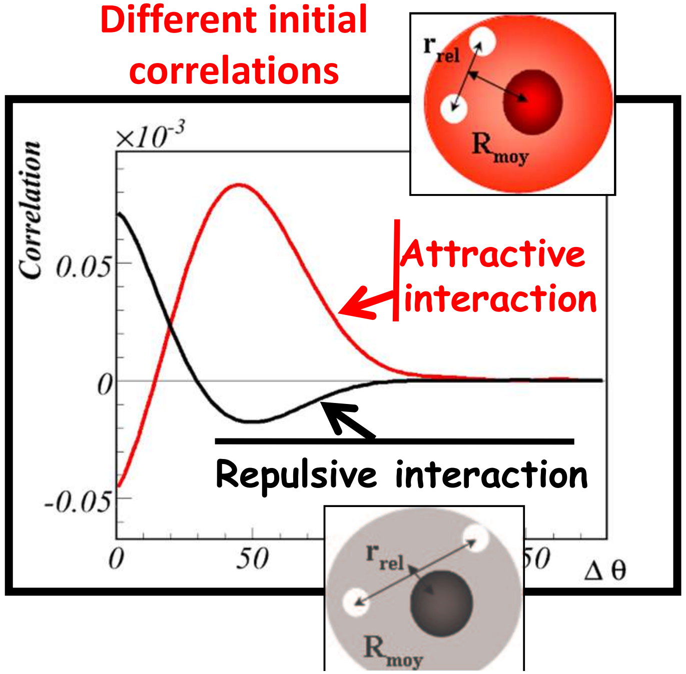
attractive int.

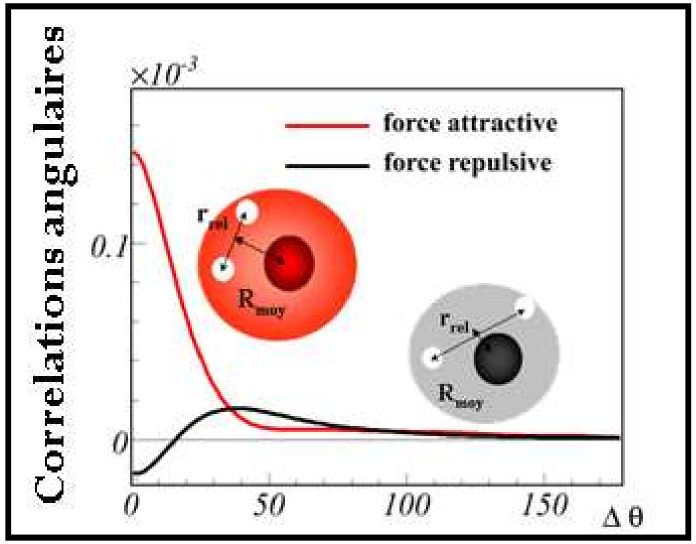
répulsive int.





Different initial correlations





(Assié and Lacroix, PRL102 (2009))

Summary/Discussion:

- Dynamical theory are finally not so difficult to perform with
Or without correlation

- It contains naturally continuum effects

My feeling

- Going to higher energies requires to treat relativity,
to include other degrees of freedoms (pions,…)

- Pairing correlations can have important effects

- But this is certainly not the end of the story…

- Need to incorporate other important quantal effect:
-Fluctuations in collective space (see our recent work on stochastic mean-field)
-configuration mixing effects
-quantum interferences