Stochastic mean-field approach to fission observables

Yusuke Tanimura and Denis Lacroix

IPN Orsay

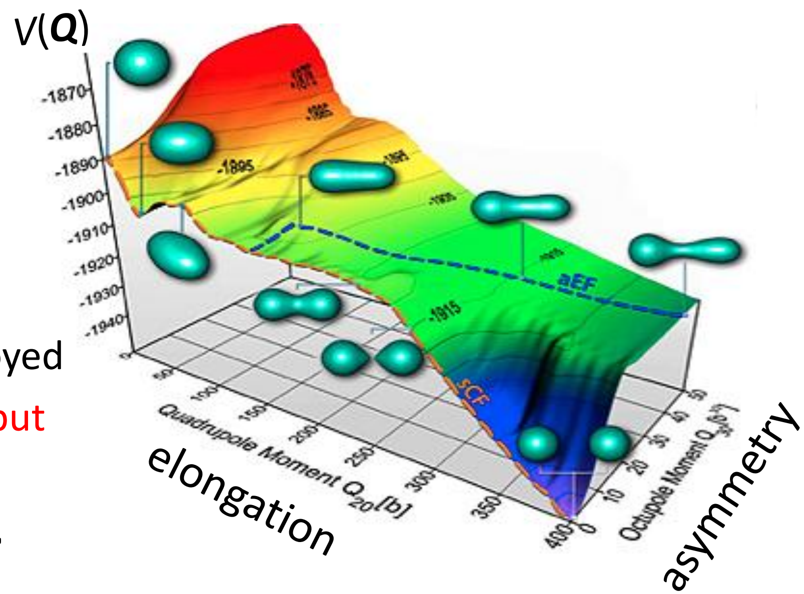
"Assemblee Generale" at IPNO, 23 June 2016

Theories for nuclear fission

- **Conventional strategy**

1.	select a set of relevant collective degrees of freedom ***Q*** *ex. elongation, mass asymmetry, etc.*
2.	construct potential energy *V*(***Q***) and inertial parameters
3.	solve the equations of motion of ***Q*** to get fission observables *lifetime, fragment mass/charge distribution, etc.*

- **Macroscopic** approaches based on the liquid-drop model have been successful
- Fully **microscopic** theories for fission are still under development
- With microscopic approaches ...
  - energy density functional (EDF) theory is employed
  - only EDF and initial conditions are needed as input



We aim to establish a microscopic theory for description of the fission process

Microscopic approaches to fission

Time-Dependent Hartree Fock (TDHF)

Negele et al, PRC**17**, 1098 (1978),
Umar and Simenel, PRC**89**, 031601 (2014).
YT, Lacroix, and Scamps, PRC**92**, 034601 (2015).

Compared to TDGCM,

Goutte et al PRC**71**, 024316 (2005),
Regnier, Dubray, Schunk, and Verrière, PRC**93**, 054611 (2016).

- No need to select collective coordinates
- No adiabaticity is assumed
- Collective motion is nearly classical
- No spontaneous symmetry breaking

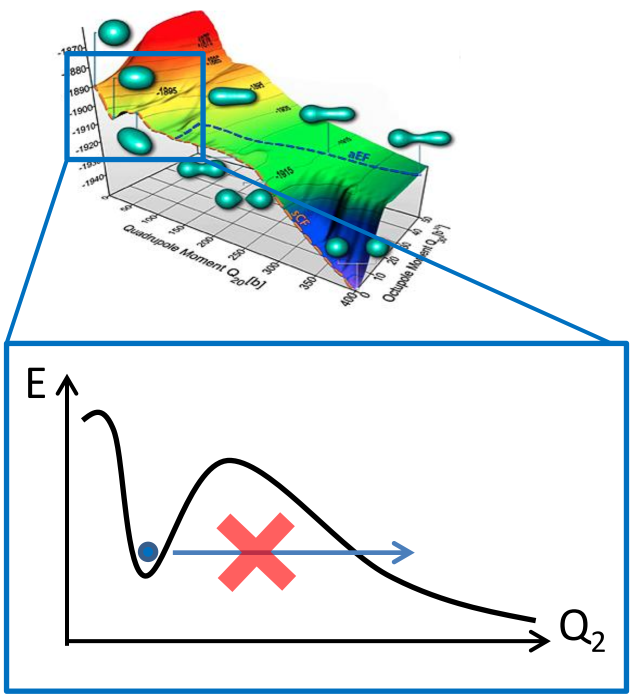
Microscopic approaches to fission

Time-Dependent Hartree Fock (TDHF)

Negele et al, PRC**17**, 1098 (1978),
Umar and Simenel, PRC**89**, 031601 (2014).
YT, Lacroix, and Scamps, PRC**92**, 034601 (2015).

Compared to TDGCM, Goutte et al PRC**71**, 024316 (2005),
Regnier, Dubray, Schunk, and Verrière, PRC**93**, 054611 (2016).

- No need to select collective coordinates
- No adiabaticity is assumed
- Collective motion is nearly classical
- No spontaneous symmetry breaking



Time-Dependent Hartree Fock (TDHF)

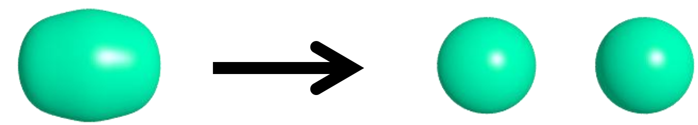
Compared to TDGCM,

- No need to select collective coordinates
- No adiabaticity is assumed
- Collective motion is nearly classical
- No spontaneous symmetry breaking

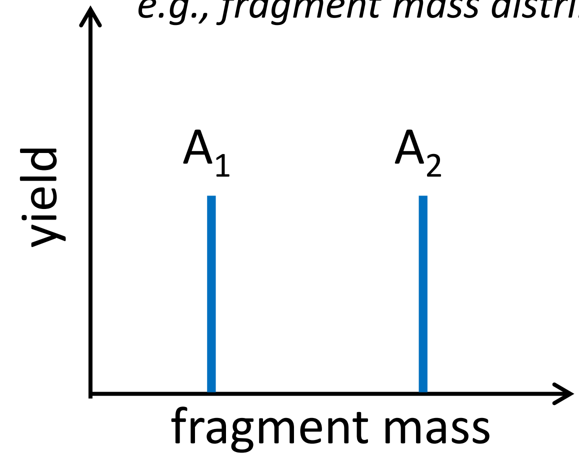
Beyond-mean-field effect must be taken into account

TDHF equation (deterministic)

$$i\hbar\frac{\partial}{\partial t}\rho(t) = [h[\rho(t)], \rho(t)]$$



e.g., fragment mass distribution



Our method:

Stochastic mean field (SMF) theory

Ayik, PLB**658**, 174 (2008)
Lacroix and Ayik, EPJA**50**, 95 (2014)
Lacroix, YT, Ayik, and Yilmaz EPJA**52**, 94 (2016)

- **Evolution of a quantum wavepacket is simulated by an ensemble of TDHF trajectories**

- Quantum fluctuation at $t = 0$ is taken into account by random sampling of one-body density matrix $\{\rho^{(n)}\}$

$$\rho^{(n)}(t=0) = \overline{\rho^{(n)}(t=0)} + \delta\rho^{(n)}$$

- Gaussian distribution is assumed for $\delta\rho^{(n)}$:

$$\begin{aligned} \overline{\delta\rho^{(n)}_{ij}} &= 0 \\ \overline{\delta\rho^{(n)}_{ij}\delta\rho^{(n)*}_{i'j'}} &= \frac{1}{2}\delta_{ii'}\delta_{jj'}[n_i(1-n_j)+n_j(1-n_i)] \end{aligned}$$

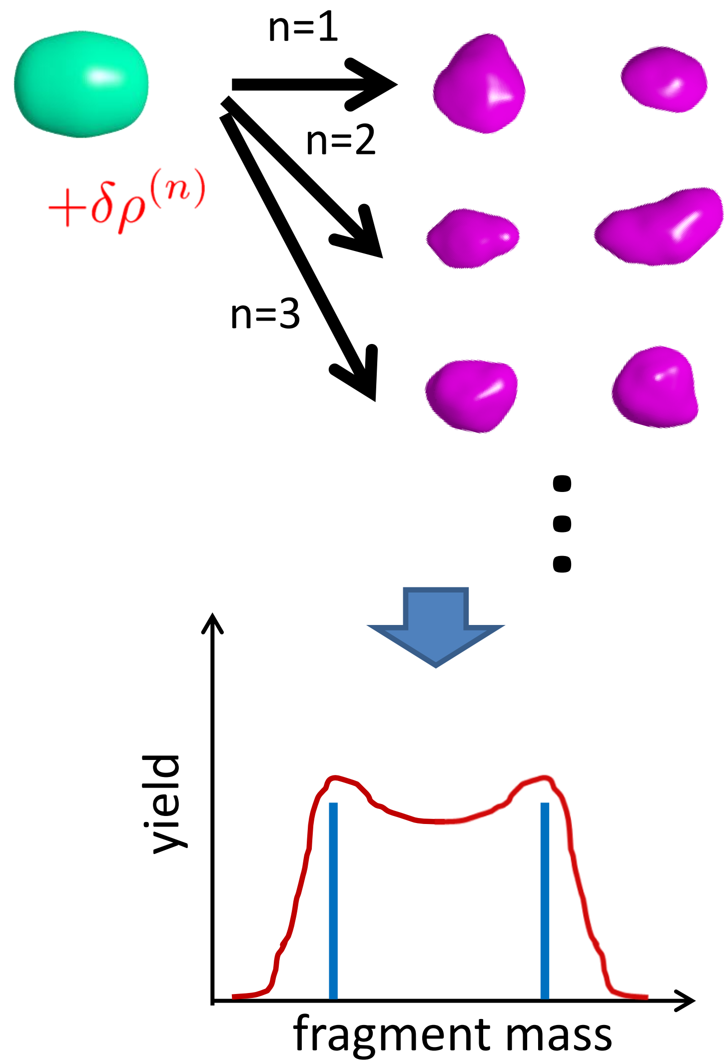
n_i: occupation number

- Evolution of a quantum wave packet is simulated by an ensemble of classical (TDHF) trajectories

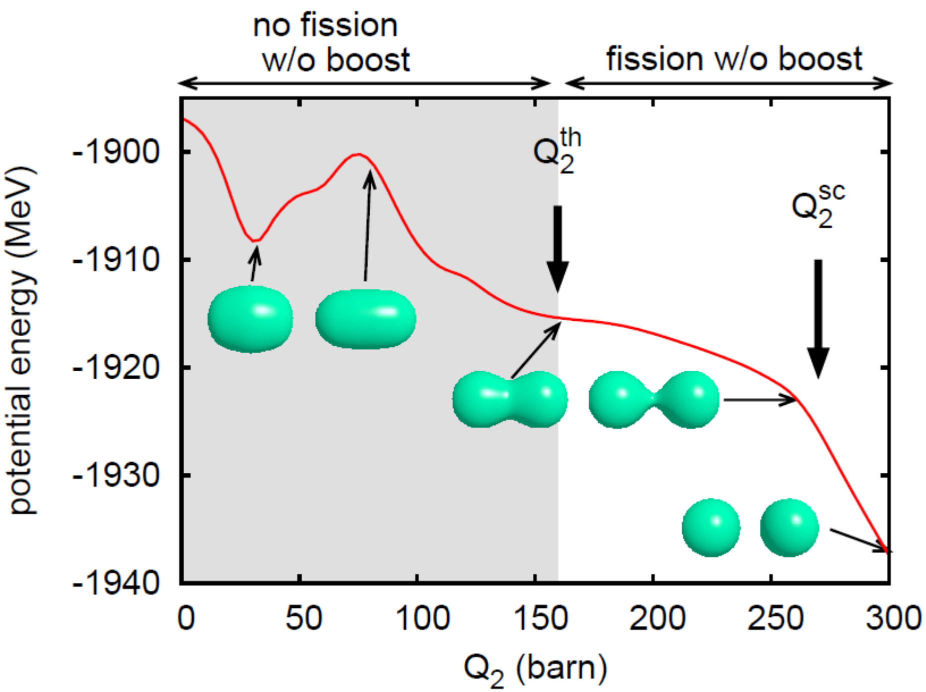
$$i\hbar\frac{\partial}{\partial t}\rho^{(n)} = [h[\rho^{(n)}], \rho^{(n)}]$$

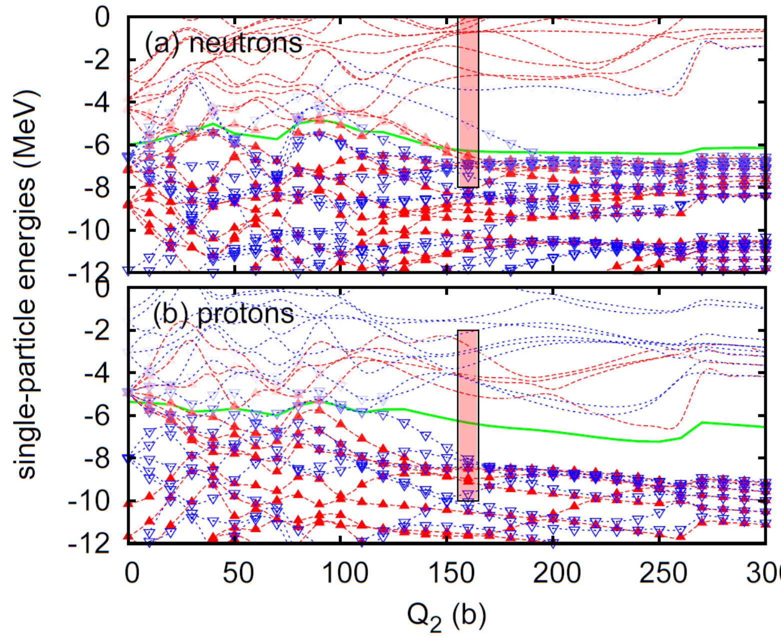
TDHFs with stochastic sampling

$$i\hbar\frac{\partial}{\partial t}\rho^{(n)} = [h[\rho^{(n)}], \rho^{(n)}]$$



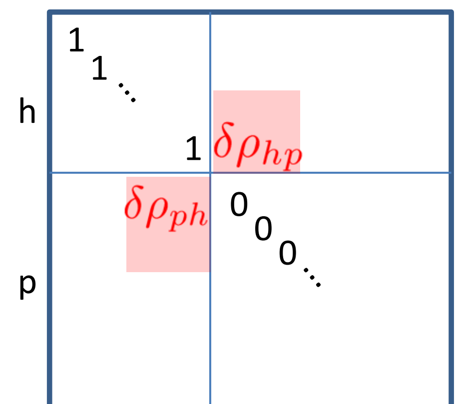
Application to spontaneous fission of ^{258}Fm

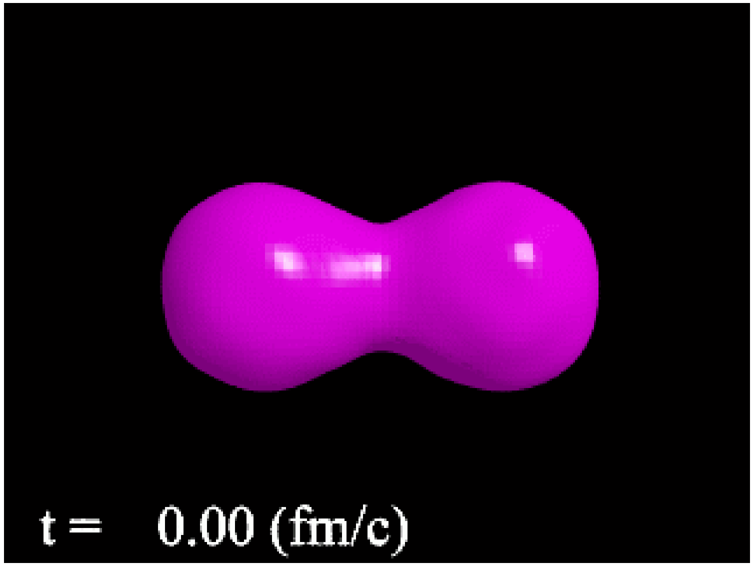


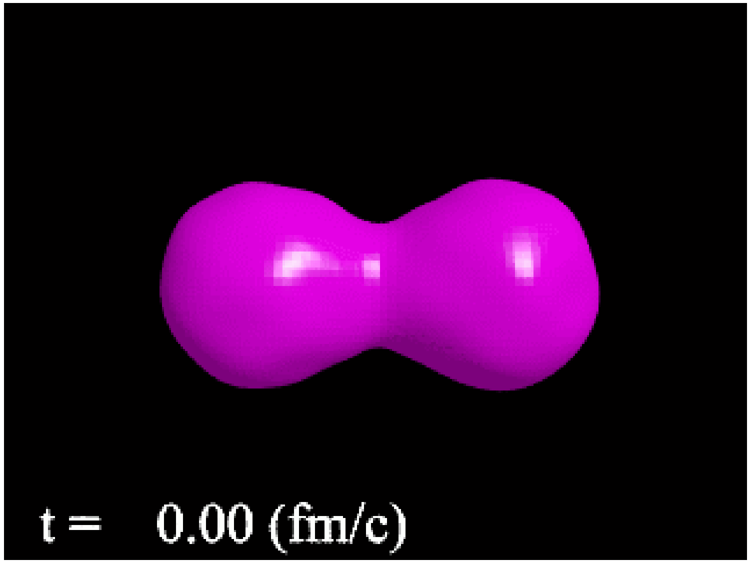


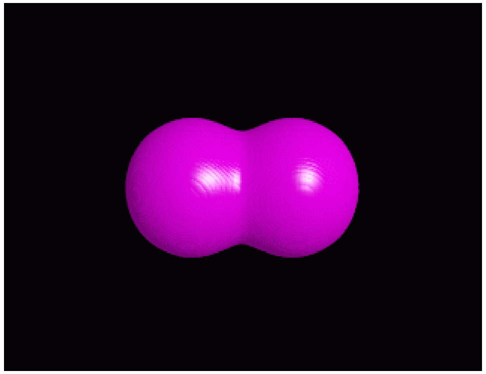
- interaction: SLy4d (+ pure pairing force)
- 338 events are generated

$$\rho_{ij}^{(n)}(t=0) = \delta_{ij} n_i + \color{red}{\delta\rho_{ij}^{(n)}} =$$



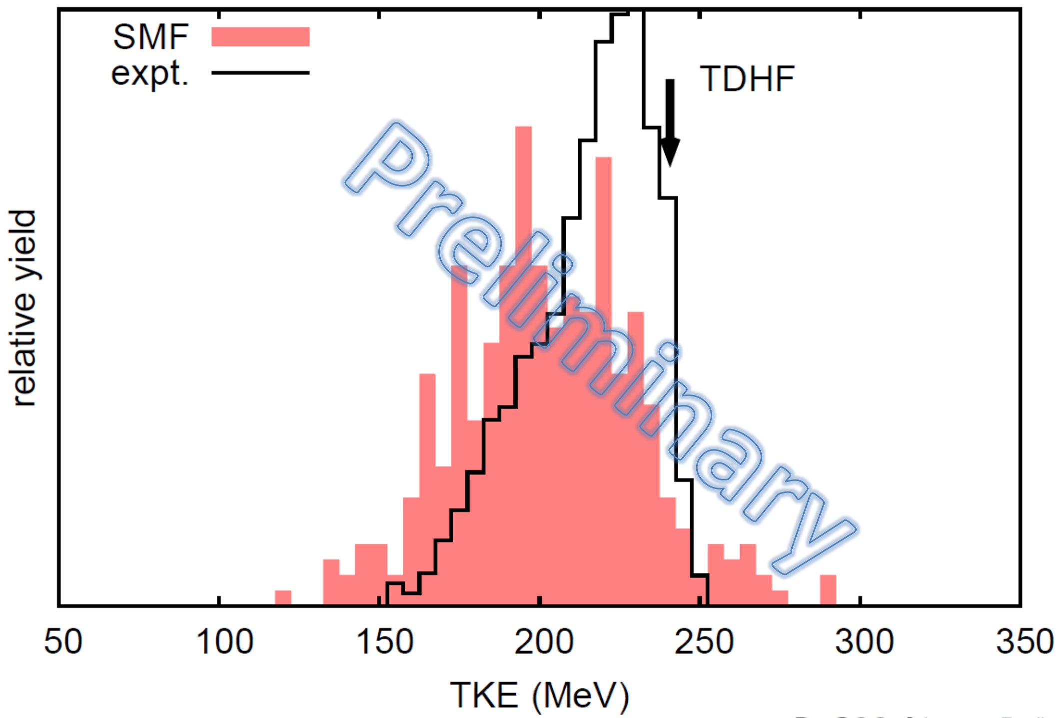






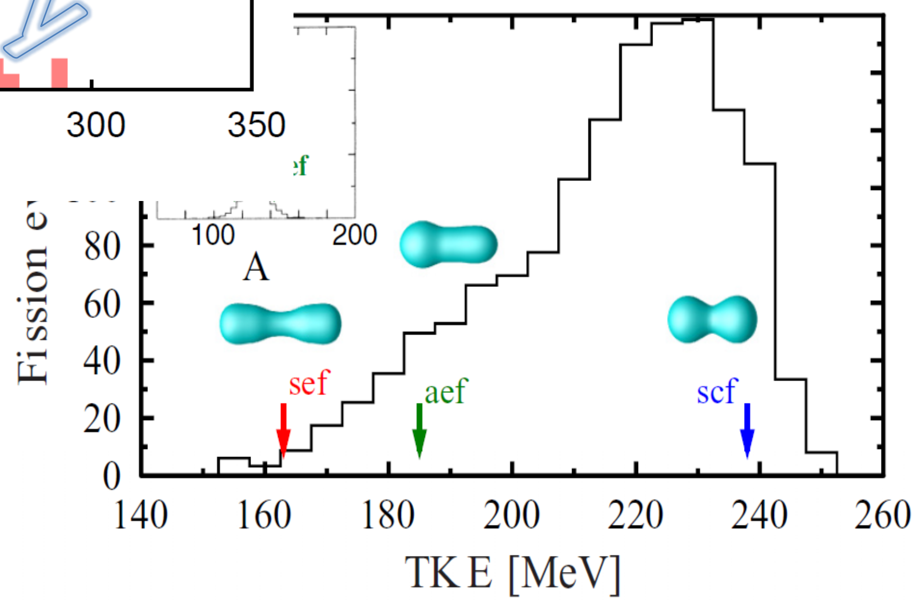
← TDHF starting from Q = 160 b

Total kinetic energy of fragments



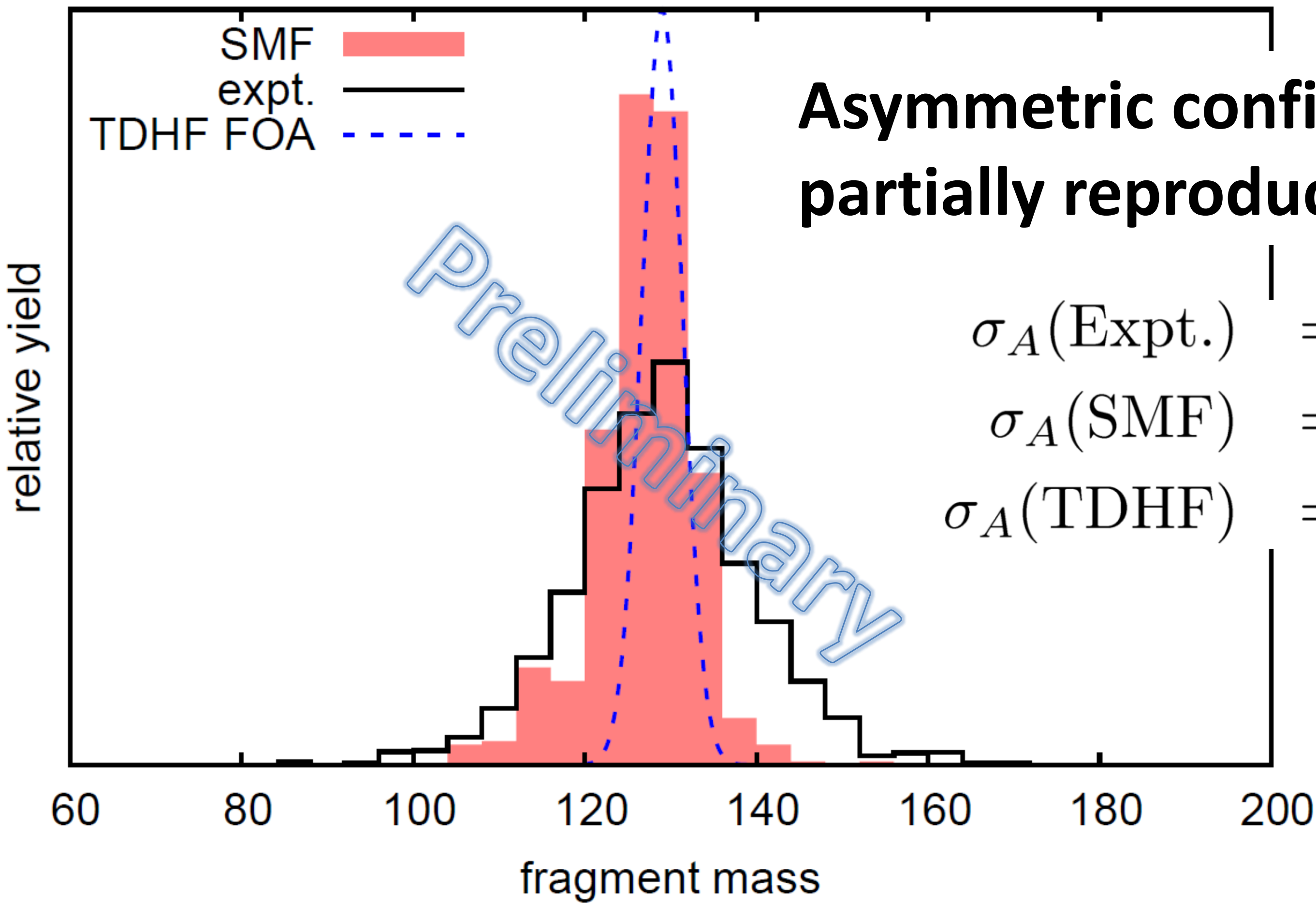
$$\overline{\mathrm{TKE}}(\mathrm{Expt.}) = 215.5\ (\mathrm{MeV})$$
$$\overline{\mathrm{TKE}}(\mathrm{SMF}) = 202.4\ (\mathrm{MeV})$$
$$\overline{\mathrm{TKE}}(\mathrm{TDHF}) = 240.7\ (\mathrm{MeV})$$
$$\sigma_{\mathrm{TKE}}(\mathrm{Expt.}) = 19.3\ (\mathrm{MeV})$$
$$\sigma_{\mathrm{TKE}}(\mathrm{SMF}) = 28.4\ (\mathrm{MeV})$$

- **Width of distribution is reasonably reproduced**
- **Peak position is shifted from TDHF value**
- **Does not reproduce the asymmetric shape of TKE distribution**



Scamps, Simenel, and Lacroix, PRC**92**, 011602(R) (2015)
Hulet et al., PRL**56**, 313 (1986)

Fragment-mass distribution



Asymmetric configurations partially reproduced by SMF

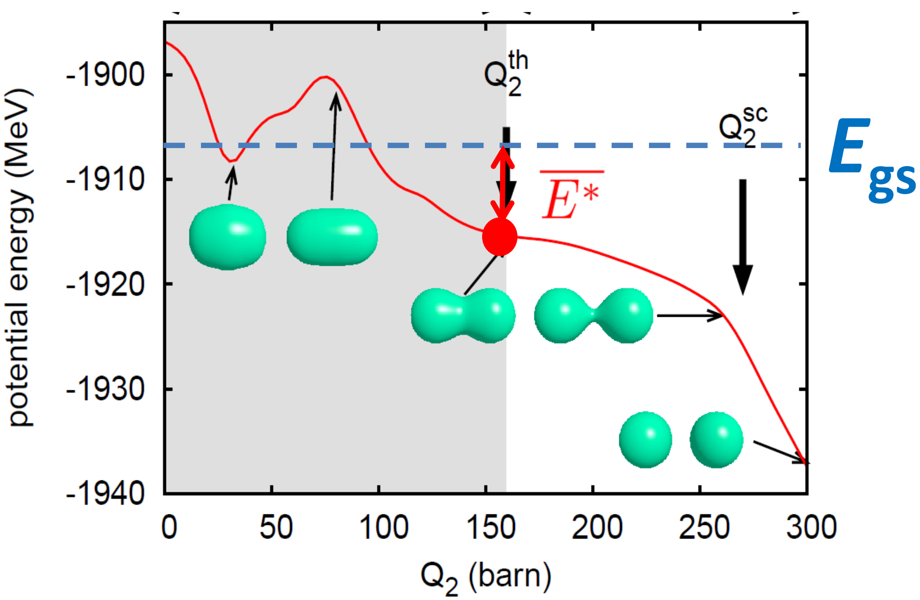
$$\sigma_A(\mathrm{Expt.}) = 10.6$$
$$\sigma_A(\mathrm{SMF}) = 6.1$$
$$\sigma_A(\mathrm{TDHF}) = 2.4$$

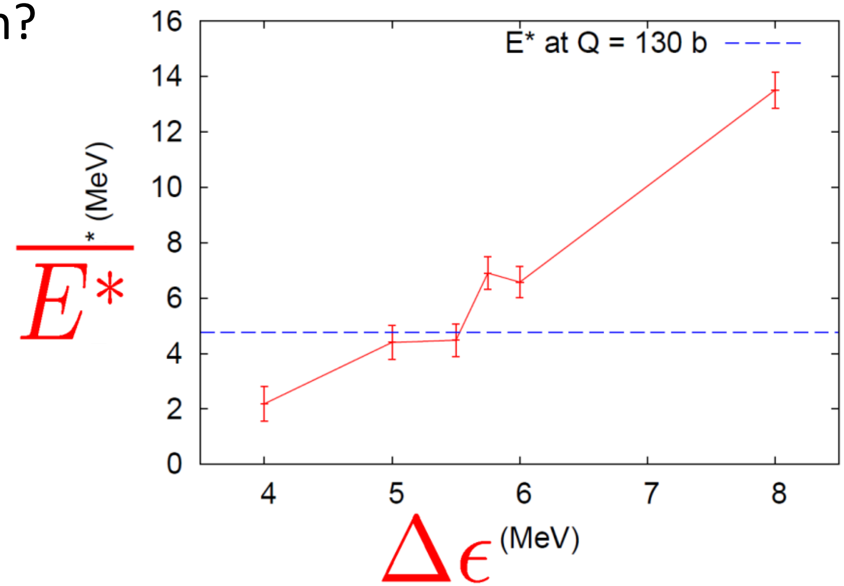
Works ongoing:

Sensitivity of results to initial condition?

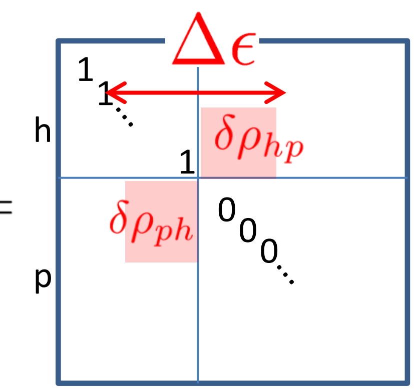
1. **Truncation in s.p. space**
2. Starting point

$$\overline{E^*} = \overline{E[\rho^{(n)}]} - E[\overline{\rho^{(n)}(t=0)}]$$



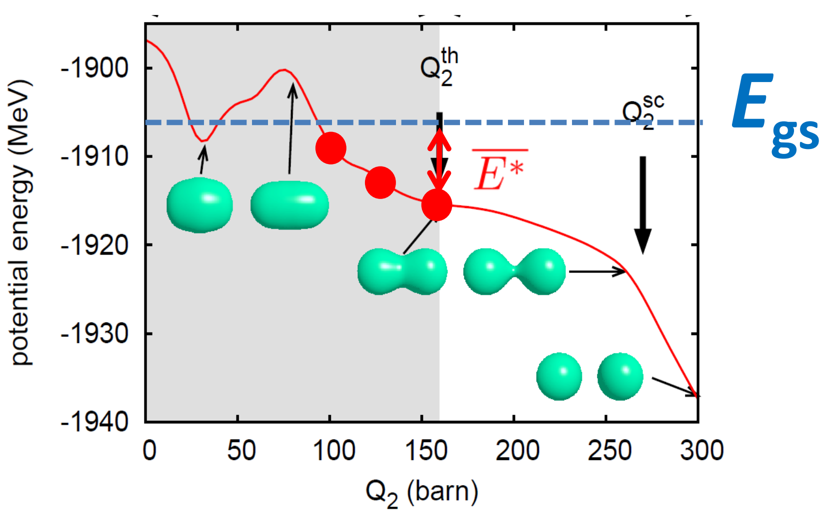


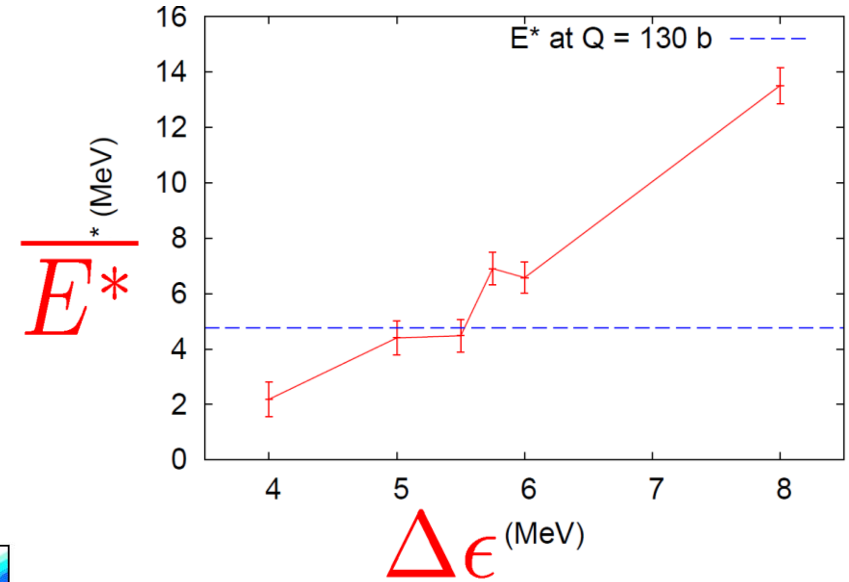
$$\rho_{ij}^{(n)}(t=0) =$$

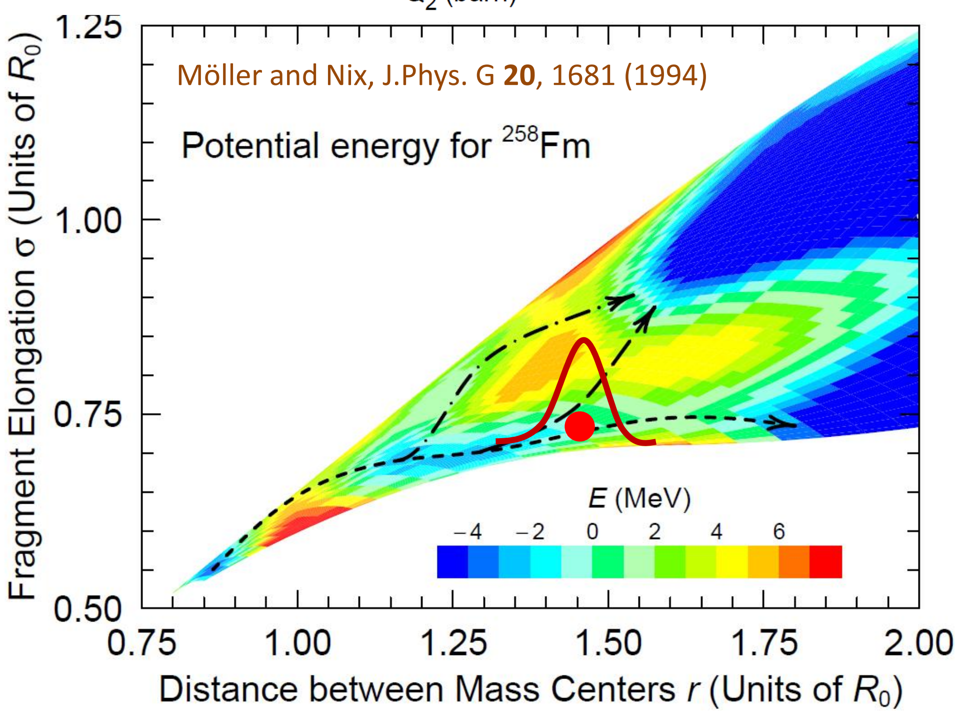


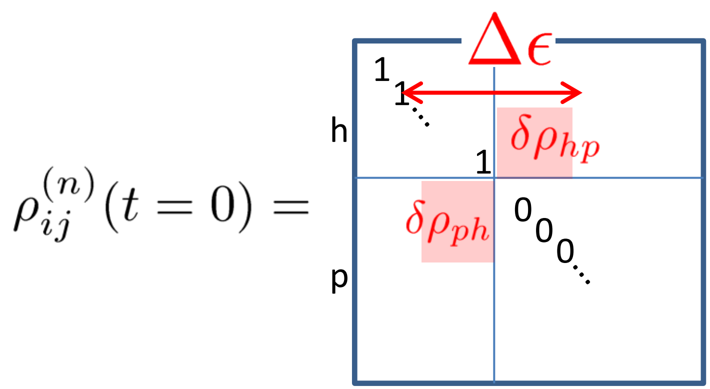
Works ongoing:

$$\overline{E^*} = \overline{E[\rho^{(n)}]} - E[\overline{\rho^{(n)}(t=0)}]$$





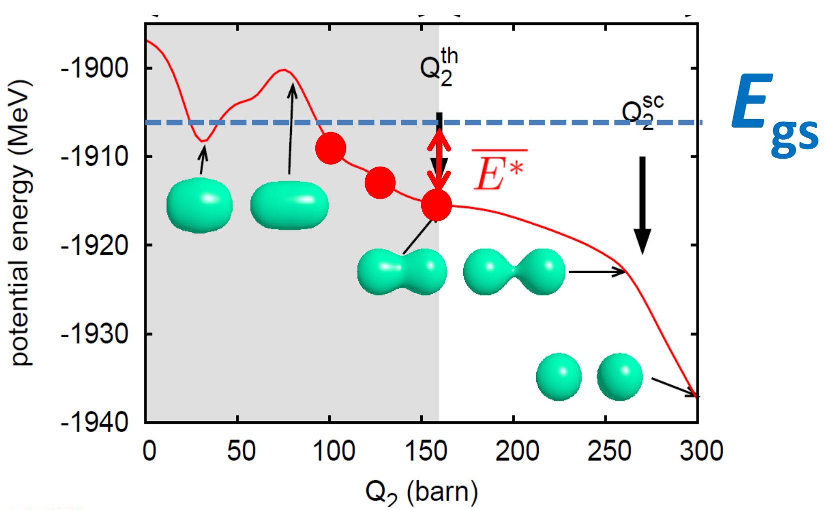


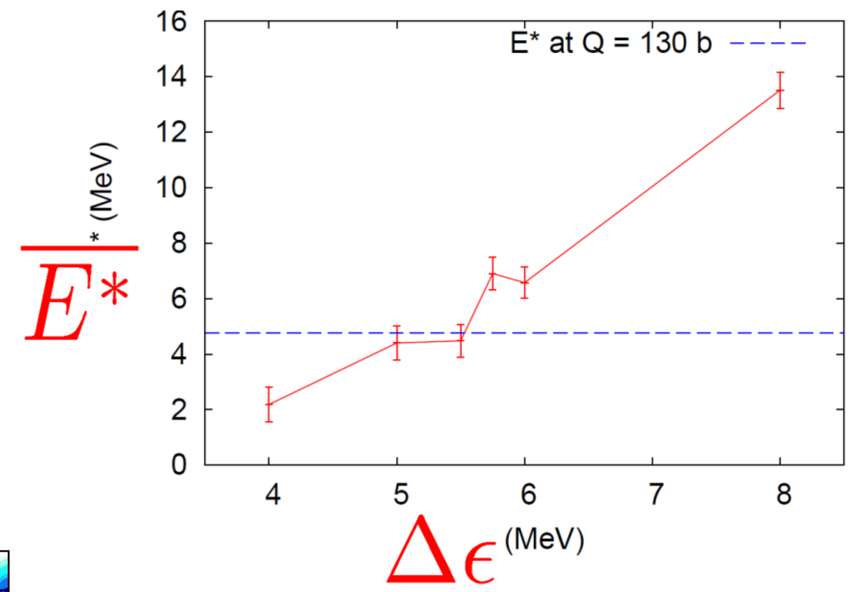


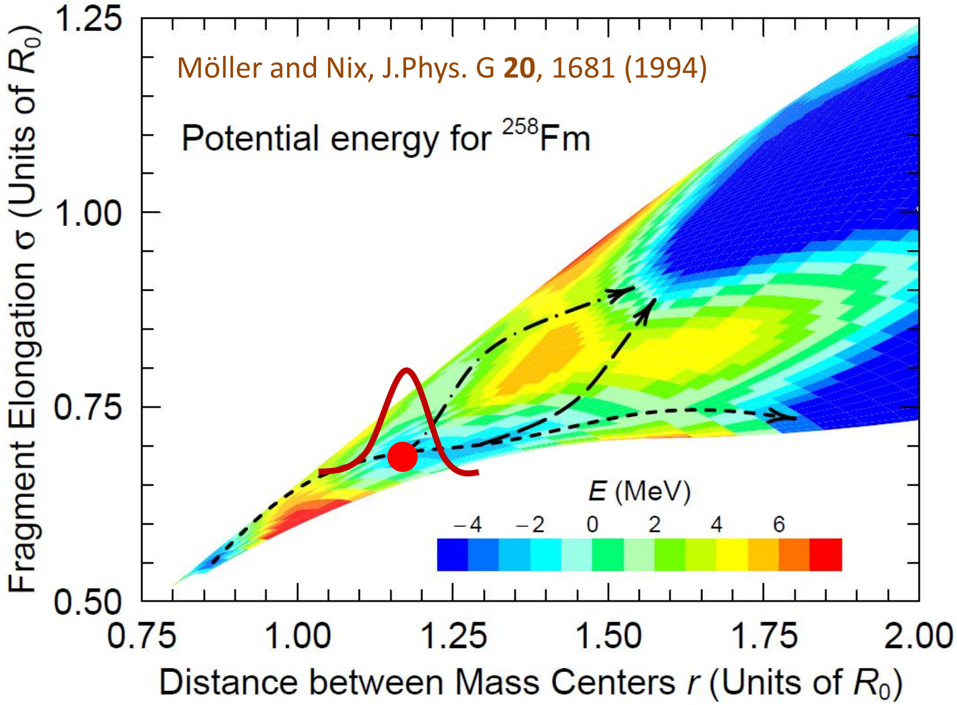
1. Fit Δε to reproduce E* at given Q_2
2. **Start from $Q_2 < Q_2^{th}$**

Works ongoing:

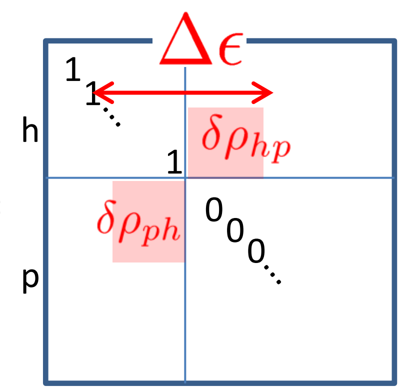
$$\overline{E^*} = \overline{E[\rho^{(n)}]} - E[\overline{\rho^{(n)}(t=0)}]$$







$$\rho_{ij}^{(n)}(t=0) =$$

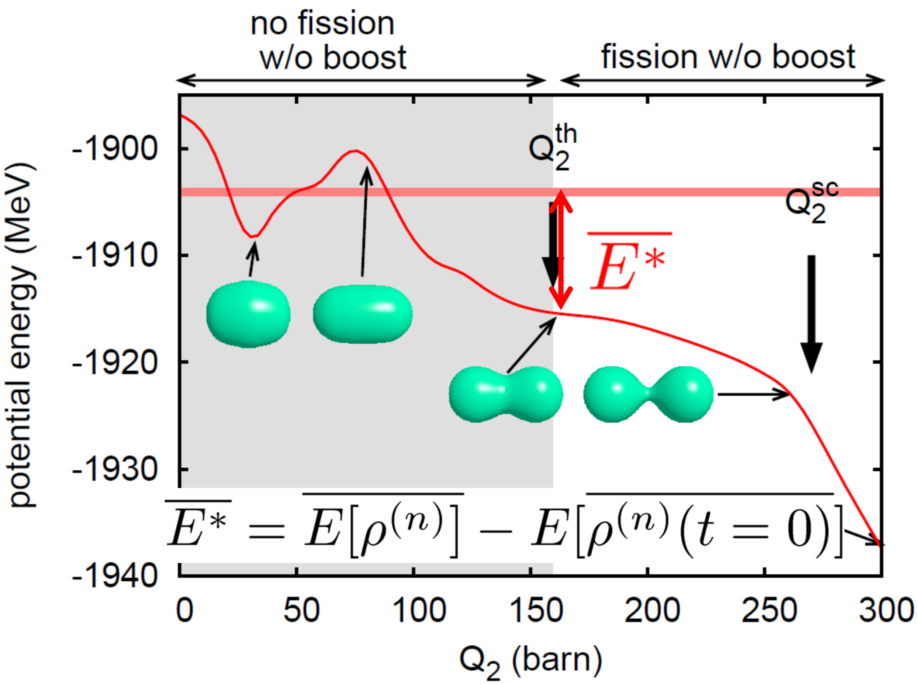


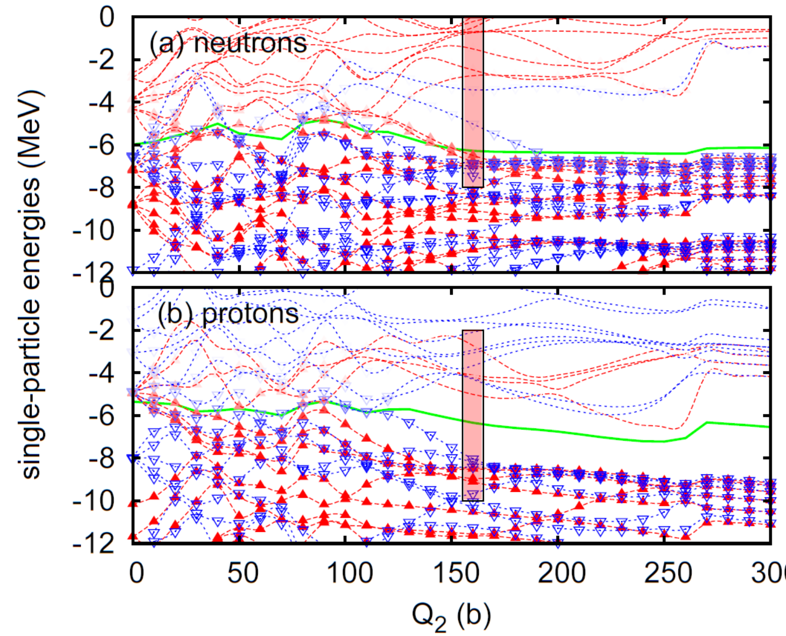
1. Fit $\Delta\varepsilon$ to reproduce E^* at given Q_2
2. **Start from $Q_2 < Q_2^{th}$**

Summary

- **Aim: Fully microscopic and dynamical description for fission**
- **We tested the SMF theory to take into account the quantum fluctuations missing in TDHF**
  - fluctuation of ρ_{ij} is introduced at $t = 0$ by random sampling
  - **possible to obtain realistic TKE and fragment-mass distributions**
- Spontaneous fission of ^{258}Fm
  - Fluctuations in observables are improved compared to TDHF
- **Sensitivity to Initial condition will be further studied**

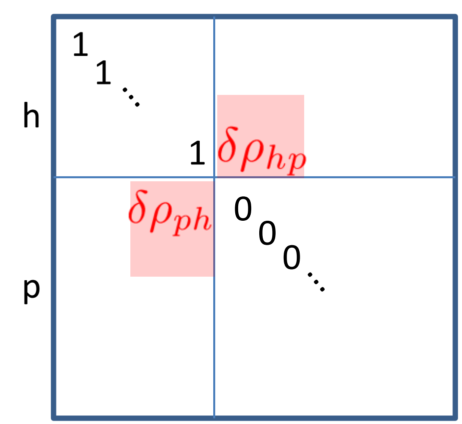
Application to spontaneous fission of ^{258}Fm





- interaction: SLy4d (+ pure pairing force)
- 338 events are generated

$$\rho_{ij}^{(n)}(t=0) = \delta_{ij} n_i + \delta\rho_{ij}^{(n)} =$$

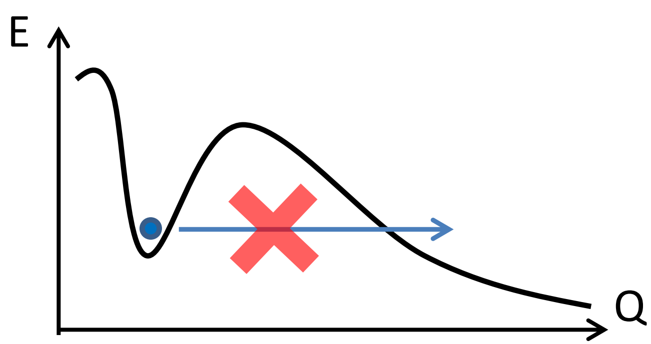


Microscopic dynamical approaches

Time-Dependent Hartree Fock (TDHF)

Negele et al, PRC**17**, 1098 (1978).
Umar and Simenel, PRC**89**, 031601 (2014).
YT, Lacroix, and Scamps, PRC**92**, 034601 (2015).

- No need to select collective coordinates
- No adiabaticity is assumed
- Collective motion is nearly classical
- No spontaneous symmetry breaking



Time-dependent generator-coordinate method (TDGCM)

Goutte et al PRC**71**, 024316 (2005).
Regnier, Dubray, Schunk, and Verrière, PRC**93**, 054611 (2016).

- Quantum treatment of collective degrees of freec
- Nont … of colle … es
- Numerical cost rises rapidly with number of coordinates