State-of-the-art input for simulation of nuclear processes at high energy: where heavy-ion and nuclear structure meets

Benjamin Bally

QCD challenges from pp to AA collisions

Münster - 04/09/2024

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Motivations

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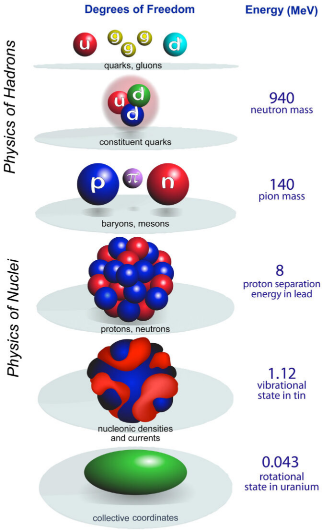
- Potential new method to probe low-energy observables

Nuclear theory: hierarchy of scales

- Nuclear matter made of quarks and gluons



Courtesy of ORNL

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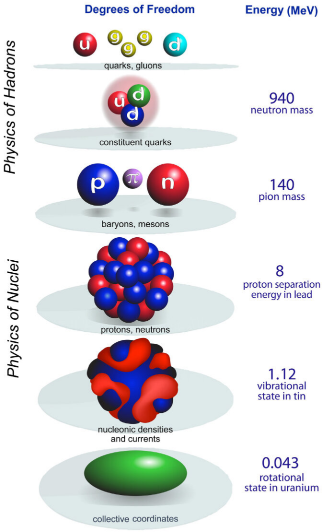

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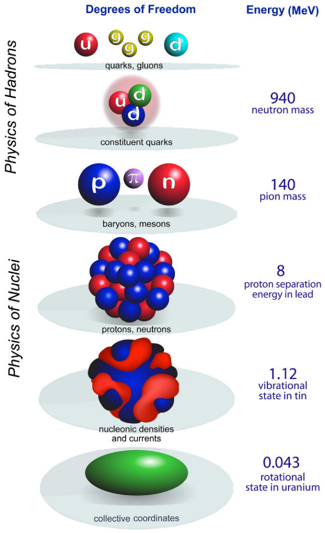
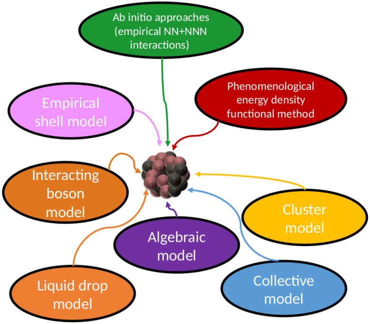
  - What would we learn?
- Define appropriate degrees of freedom for the scale
- Connect different scales

→ **Tower of Effective Field Theories**

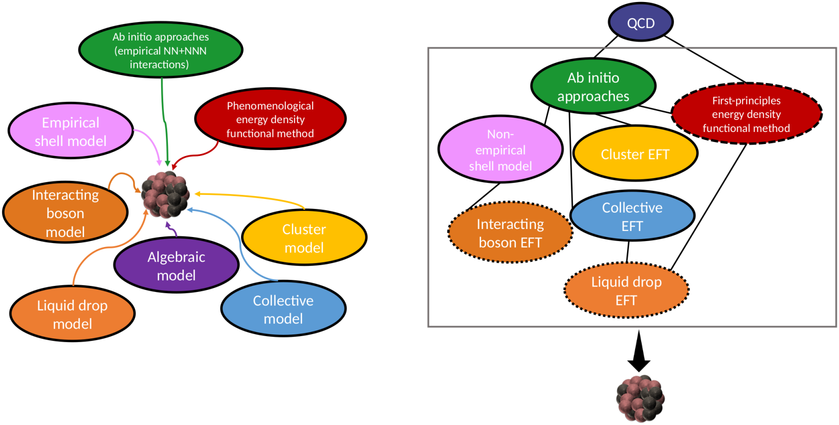


Courtesy of ORNL

NS: from models to effective theories



Courtesy of J.-P. Ebran



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Ab initio nuclear theory

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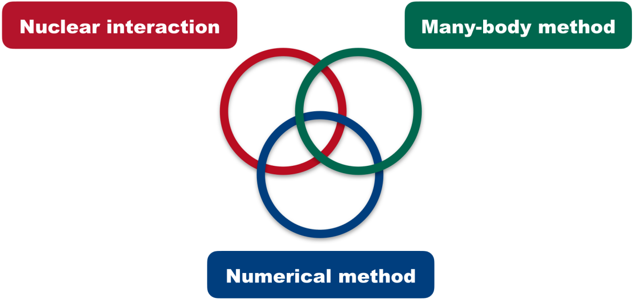

Courtesy of P. Arthuis

Effective field theory of the nuclear Hamiltonian

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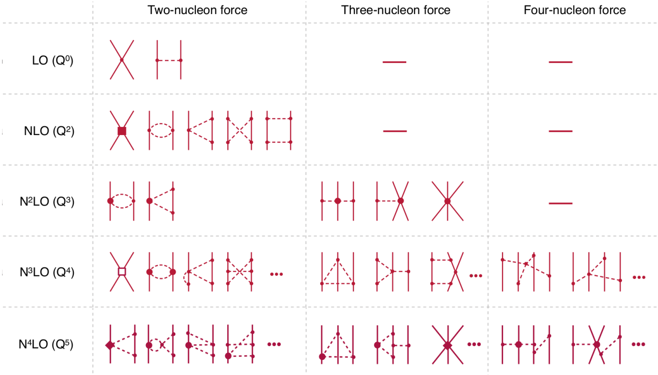
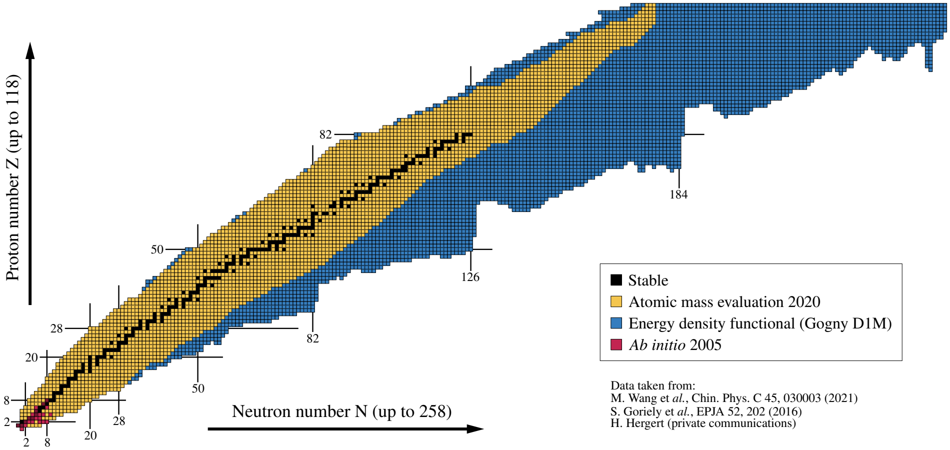


Epelbaum *et al.*, Front. Phys. 8, 98 (2020)


Proton number Z (up to 118)
Neutron number N (up to 258)
2
8
20
28
50
82
126
184
Stable
Atomic mass evaluation 2020
Energy density functional (Gogny D1M)
Ab initio 2005
Data taken from:
M. Wang et *al.*, Chin. Phys. C 45, 030003 (2021)
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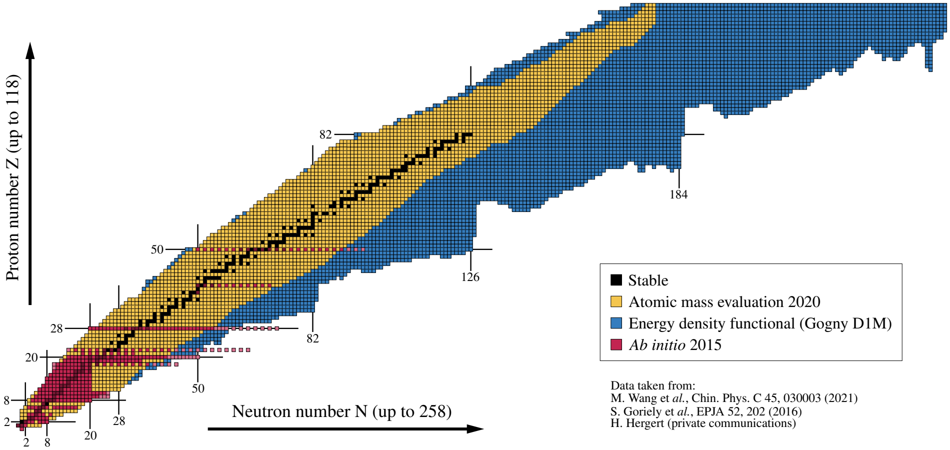

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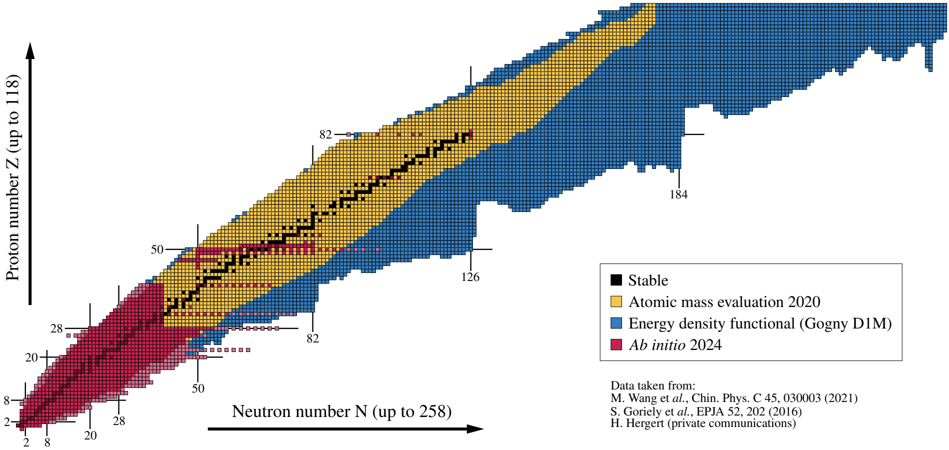
Status of *ab initio* theory: 2024



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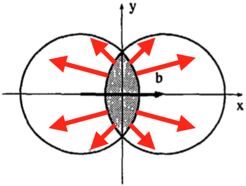
Nuclear deformation impacts overlap region



Ollitrault, PRD 46, 229 (1992)

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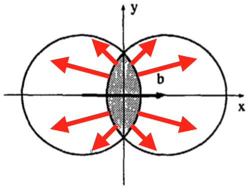

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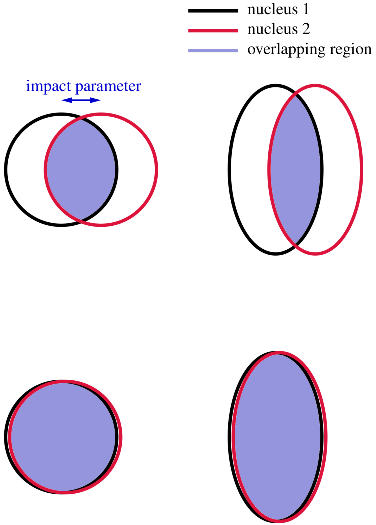
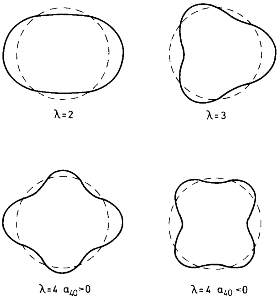


Intrinsic deformations

- Nuclear phenomenology often relies on the picture of intrinsic shapes
- Multipole expansion where small values of λ are the most important



Ring and Schuck, The Nuclear Many-Body Problem (1980)

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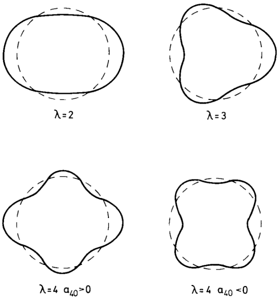

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- Warning: these shapes are not observables!
  $\rightarrow$ Convenient way to include many-body correlations in a one-body framework

Simplest input: microscopically-based WS parameters

- Woods-Saxon (WS) density profile

$$\rho_{\text{ws}}(r,\theta,\phi) = \frac{\rho_0}{1 + \exp\left[\frac{1}{a}\left(r - R(\theta,\phi)\right)\right]}$$

with nuclear radius (**surface** deformation)

$$R(\theta,\phi) = R_0 \left\{ 1 + \sum_{\lambda} \sum_{\mu=-\lambda}^{\lambda} a_{\lambda\mu} Y_{\lambda\mu}(\theta,\phi) \right\}$$

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  - ◇ take the WS parameters from NS calculations based on different definitions
    → in general NS use **volume** deformations related to $\langle \Phi | r^{\lambda} Y_{\lambda\mu} | \Phi \rangle$

    Ryssens *et al.*, PRL 130, 212302 (2023)

Simplest input: microscopically-based WS parameters

- A better, and still very simple, approach would be
  - perform NS calculations to determine $\rho_{\text{mic,n}}(r, \theta, \phi)$ and $\rho_{\text{mic,p}}(r, \theta, \phi)$
  - fit ρ_{ws} to ρ_{mic} for protons and neutrons separately
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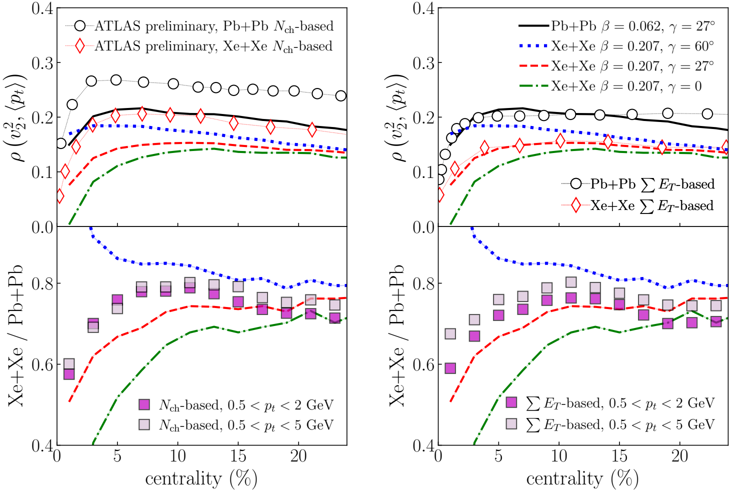
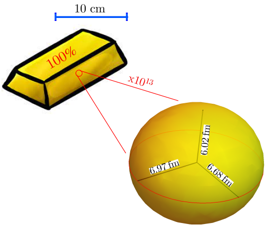
- Parameters from *phenomenological* calculations available for
  - ^{129}Xe → Bally *et al.*, PRL 128, 082301 (2022)
  - ^{197}Au → Bally *et al.*, EPJA 59, 58 (2023); Ryssens *et al.*, PRL 130, 212302 (2023)
  - ^{208}Pb → Bally *et al.*, PRL 128, 082301 (2022)
  - ^{238}U → Ryssens *et al.*, PRL 130, 212302 (2023)

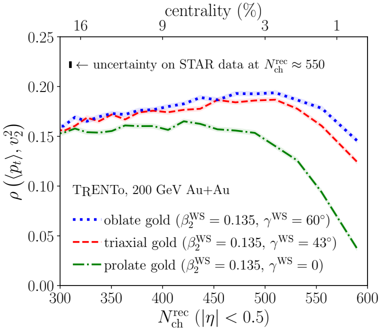
Example: ^{129}Xe+^{129}Xe and ^{208}Pb+^{208}Pb at LHC



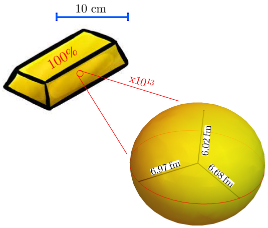
- Only triaxiality explains LHC results

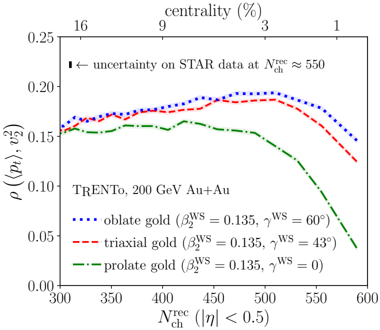
Example: ^{197}Au+^{197}Au at RHIC





Bally *et al.*, EPJA 59, 58 (2023)





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- Remark: excellent agreement for neutron skin (although WS not perfect)

  $\Delta r_{np}[\text{STAR}] = 0.17 \pm 0.03\ (\text{stat.}) \pm 0.08\ (\text{syst.})$ fm   STAR, Science Adv. 9, eabq390 (2023)

  $\Delta r_{np}[\text{MREDF}] = 0.17$ fm

  $\Delta r_{np}[\text{WS fit}] = 0.19$ fm

Ab initio inputs for ^{16}O and ^{20}Ne

- Collisions scheduled or already performed at LHC/RHIC
  - $^{16}\text{O} + {}^{16}\text{O}$
  - $^{208}\text{Pb} + \text{Ne}$

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- New ideas related to
  - collectivity in small systems
  - physics program/opportunities at LHCb/SMOG2

EFT → **Nuclear structure** → **Relativistic hydrodynamic** → **Hadron transport** → **Nucl-th**

χEFT N3LO

```
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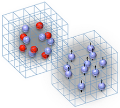
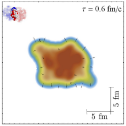
TAURUS

PGCM

$\not\pi$EFT LO



NLEFT



Trajectum

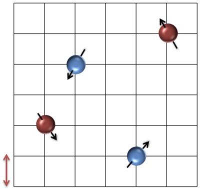
smash

arXiv:2402.05995

- TAURUS: `https://github.com/project-taurus`
- *Trajectum*: `https://sites.google.com/view/govertnijs/trajectum`
- SMASH: `https://github.com/smash-transport/smash`

NLEFT calculations

- Nuclear Lattice Effective field Theory (NLEFT)
  Lee, Front. in Phys. 8, 174 (2020)
  Lähde and Meißner, Lectures Notes in Phys., Springer (2019)



- Mesh with 8 sites and spacing $a = 1.315$ fm

- Minimal pionless EFT Hamiltonian with SU(4) symmetry

- Pin-hole algorithm → sample nucleon positions from A-body density (include all correlations)
  Elhatisari *et al.*, PRL 119, 222505 (2017)

PGCM calculations

- Projected Generator Coordinate Method (PGCM)

  Hill and Wheeler, Phys. Rev. 89, 1102 (1953); Griffin and Wheeler, Phys. Rev. 108, 311 (1957)

  Bally *et al.*, EPJA 60, 62 (2024)

- Approximate wave function of the form: $|\Psi\rangle = \sum_q f(q)|\Phi(q)\rangle$
  $q \equiv$ collective degrees of freedom

- Variational principle: $\delta \frac{\langle\Phi|H|\Phi\rangle}{\langle\Phi|\Phi\rangle} = 0 \Leftrightarrow \text{diag}\left[\text{span}(\{|\Phi(q)\rangle\})\right]$

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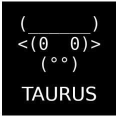
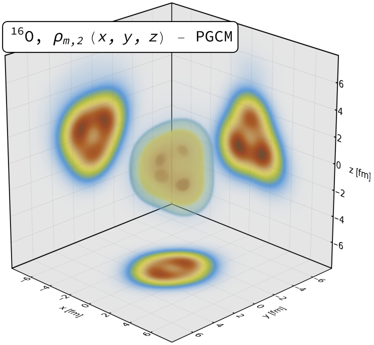
- Large-scale computations using numerical suite TAURUS on Topaze supercomputer (CEA/CCRT)

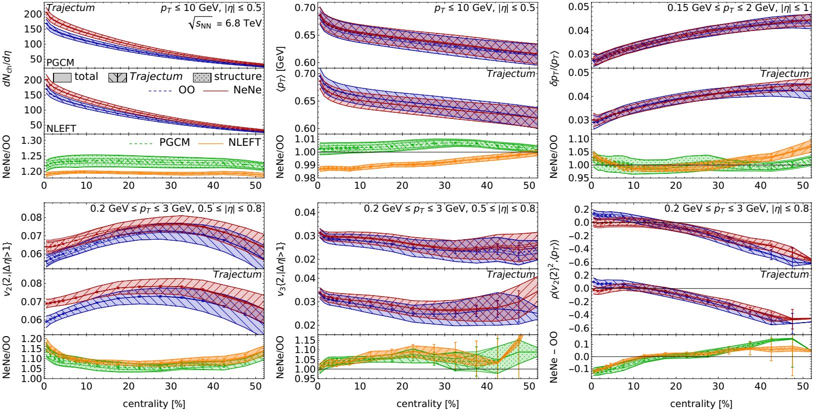


PGCM-based one-body densities



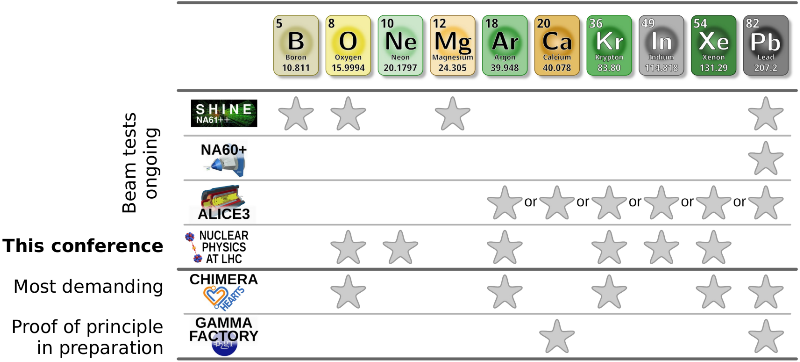
- Determine average deformation of PGCM ground state: $\bar{q}$
- One-body density: $\rho_m(x,y,z) = \sum_{st} \frac{\langle \Phi(\bar{q}) | a^{+}_{xyzst} a_{xyzst} P^Z P^N | \Phi(\bar{q}) \rangle}{\langle \Phi(\bar{q}) | P^Z P^N | \Phi(\bar{q}) \rangle}$
- Sample ρ_m

Results: general comments



- Impact of ^{20}Ne and ^{16}O structure
- NLEFT and PGCM in good agreement

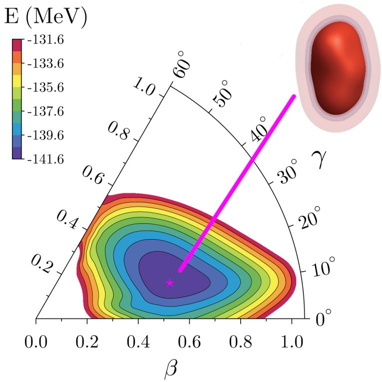
Experimental landscape at CERN

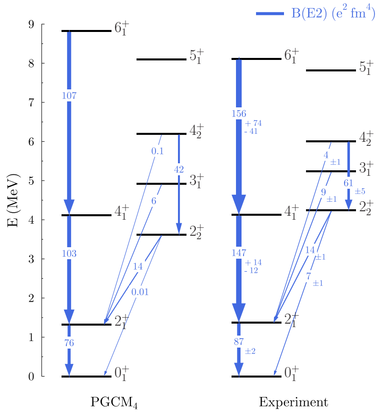


Presentation by Maciej Slupecki (CERN), Beijing, 2024

⇒ **All these nuclei are within the reach of ab initio nuclear structure**

Example: ^{24}Mg





Bally *et al.*, EPJA 60, 62 (2024)

- Ground state exhibits large intrinsic triaxial deformation
- Excellent description using χEFT Hamiltonian

Conclusion

- *Ab initio* nuclear structure can provide microscopic inputs for the initial stage

  ⇒ From low-energy approximation of QCD to hot dense QCD matter

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  $\Rightarrow$ From low-energy approximation of QCD to hot dense QCD matter

- Collaboration between low- and high-energy communities has a lot of potential
  - Better analyze and interpret high-energy data collected at LHC or EIC
  - Exploit structure of colliding species in high-energy experiment
  - Access to properties of atomic nuclei difficult to observe at low energy

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- Collaboration between low- and high-energy communities has a lot of potential
  - Better analyze and interpret high-energy data collected at LHC or EIC
  - Exploit structure of colliding species in high-energy experiment
  - Access to properties of atomic nuclei difficult to observe at low energy

- Fully exploit the versatility of LHCb/SMOG2