Report on LNS theory group (GR4) activity

Danilo Gambacurta
Laboratori Nazionali del Sud (Catania)

Presentazione Attività e Preventivi 2025
10 e 11 Luglio 2025

Iniziative Specifiche di CSN4@LNS:

- MONSTRE
- SIM

MONSTRE

Unità: ***LNS****, Bologna, CT,Milano, Padova, Trento*
FTE totale: ≈30, **FTE (LNS)** *≈3.6*

Responsabile Nazionale: Danilo Gambacurta (LNS)

Responsabile Locale: Stefano Burrello

Collaborazioni: LNS+CT (Chimera, Medea, NUMEN, ASFIN), Firenze, Napoli, Genova,IPN-Orsay, GANIL, GSI, Monaco, Bucharest, Giessen, Darmstadt, Siviglia, MSU, Pechino, Lanzhou, Rio de Janeiro, RIKEN, ...

Obiettivi generali:

Modeling nuclear structure and reaction properties

Four WorkPackages (WPs)

- WP1: ***Ab initio* many body methods for nuclei and nuclear matter**: increasing the accuracy and predictive power
- WP2: **Advanced theoretical studies of nuclear phenomena:** addressing the experimental challenges
- WP3: **Nuclear matter under extreme conditions:** from nuclear dynamics to compact objects
- WP4: **Emerging computational technologies:** quantum information and machine learning techniques

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LNS Activities: Nuclear Structure and Reaction Studies

Theoretical Models and Techniques

- ***Energy Density Functional for Ground state (*** *HF, HF+BCS, HFB* ***) and Excited states: (****RPA, QRPA, SRPA, TDHF)*
- ***Transport theories based on EDF (****including clusters d.o.f. , short range correlations, many-body correlations , …)*
- ***DWBA and/or coupled channel*** *calculations*
- ***Formulation of scattering theories and methods*** *(Double-Charge reactions)*

Main Physical Cases of Interest

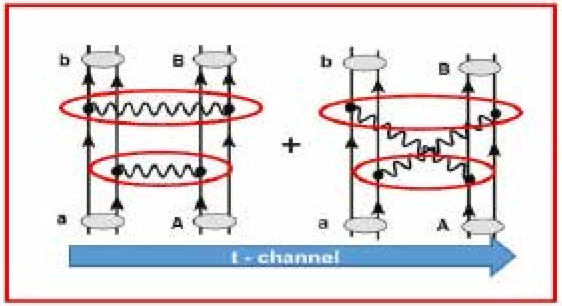
- ***Collective nuclear excitations,*** *especially in neutron-rich and exotic nuclei*
- ***EoS of asymmetric matter*** *(from nuclear structure and reaction studies)*
- ***Charge exchange excitations*** *(Gamow-Teller, Fermi, etc,) and* ***Beta Decay*** *(single and double)*
- ***Nuclear reactions*** *at Fermi/intermediate energies and* ***Direct reaction*** *(transfer, charge exchange, probing spin-isospin channels)*
- ***Reactions for astrophysical studies*** *(light systems, cluster structure)*

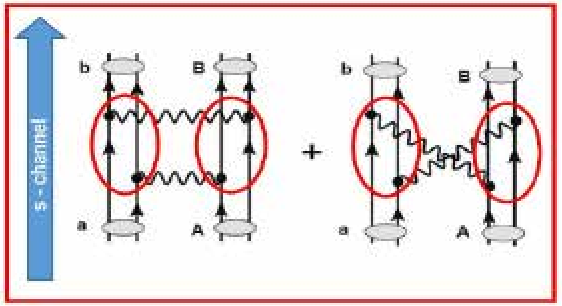
PHYSICAL REVIEW C **111**, L061602 (2025)

Letter

Heavy-ion double-charge-exchange reactions as probes for two-body transition densities

Jessica I. Bellone,[1,2,*] Maria Colonna,[1,†] Danilo Gambacurta,[1,‡] and Horst Lenske[3,§]





➢Double Charge Exchange (**DCE**) as a sequential two-step process (DSCE) → *Second order* DWBA [→ J.Bellone, M.Colonna, D.Gambacurta, H.Lenske]

arXiv:2505.24753, Phys. Rev. C 111, L061602 (2025)

TME

$$M^{(2)}_{\beta\alpha}(\mathbf{k}_\beta,\mathbf{k}_\alpha) \simeq L^{(+)}_\gamma(\omega_\alpha) \sum_{S_1,S_2}\sum_{S,M}(-1)^{S_1+S_2+S-M} \sum_{c,C}\int d^3q\, F^{(BCA)}_{SM}(\mathbf{q}) F^{(bca)}_{S-M}(\mathbf{q}) \tilde{V}^{DSCE}_{S_1S_2T}(q) D_{\alpha\beta}(\mathbf{q})$$

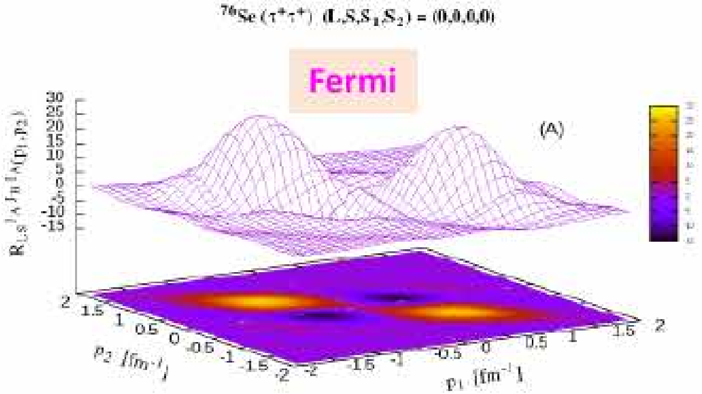
DCE form factors (2BTDs)

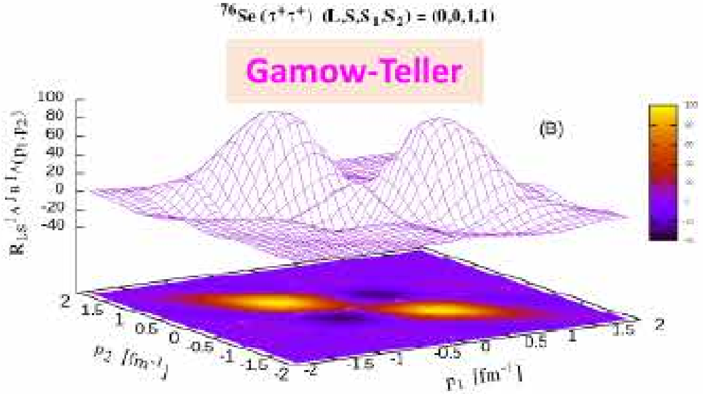
rank-2 NN interactions

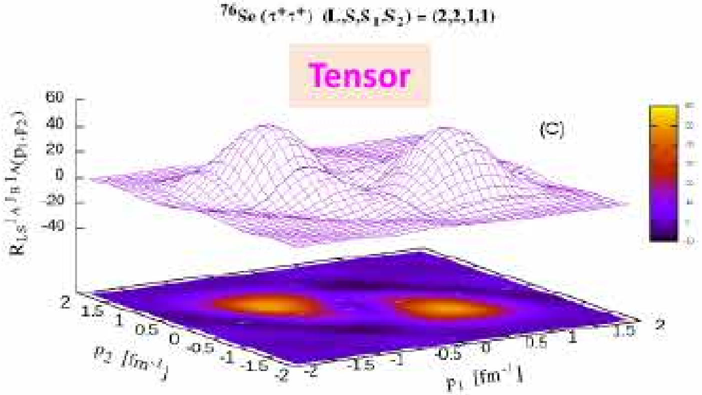
S-channel:
separation and factorization of the 2-step process in target and projectile => Selective information on target and projectile

➤ $^{76}Se(^{18}O,^{18}Ne_{g.s.})^{76}Ge_{g.s.}$ – DCE NMEs (2BTD)

Two-body transition densities

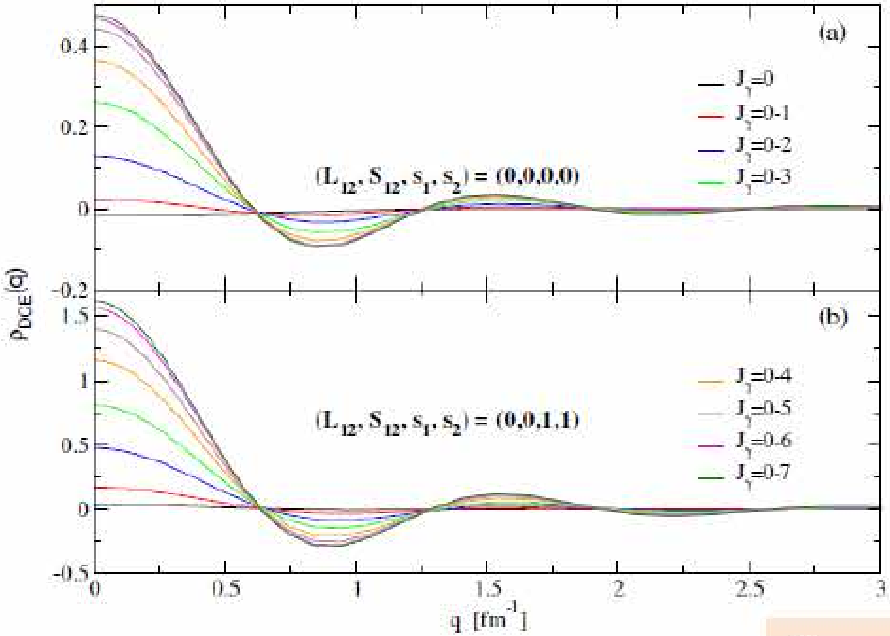




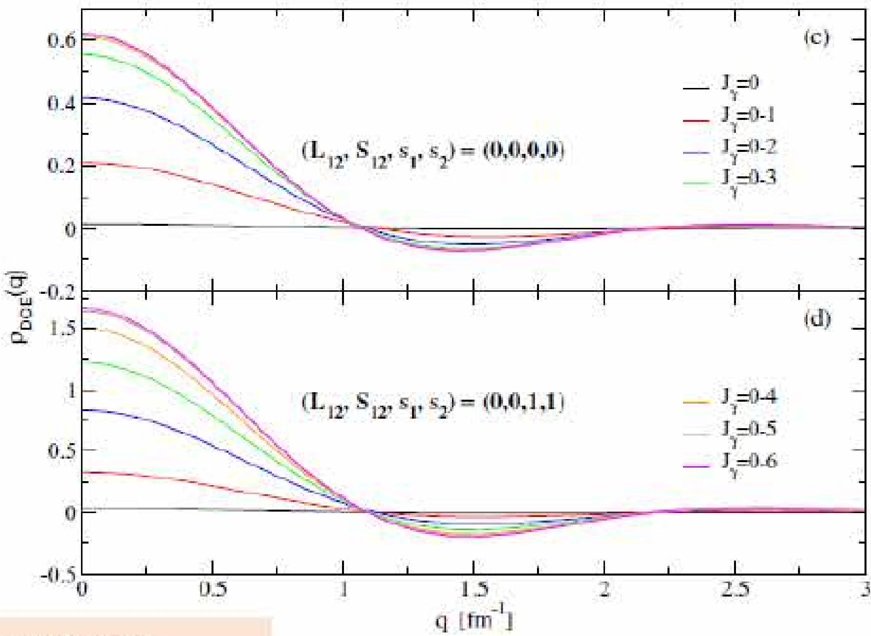


approximation

2BTDs $^{76}Se_{gs} \rightarrow {}^{76}Ge_{gs}$



2BTD $^{18}O \rightarrow {}^{18}Ne_{g.s.}$



E_{max} = 50 MeV

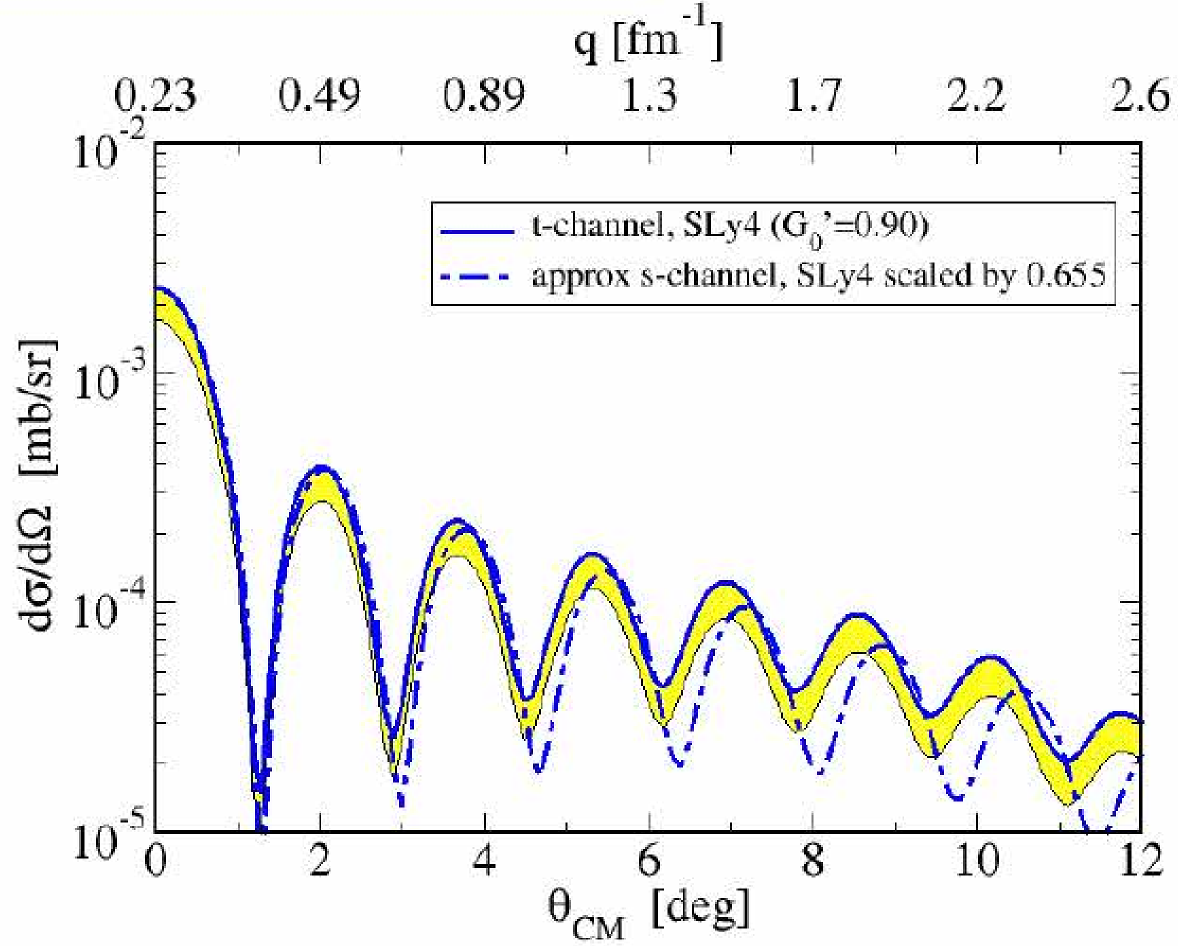
Two-body transition densities in approx. s-channel representation

QRPA calculations
Sly4 Skyrme interaction

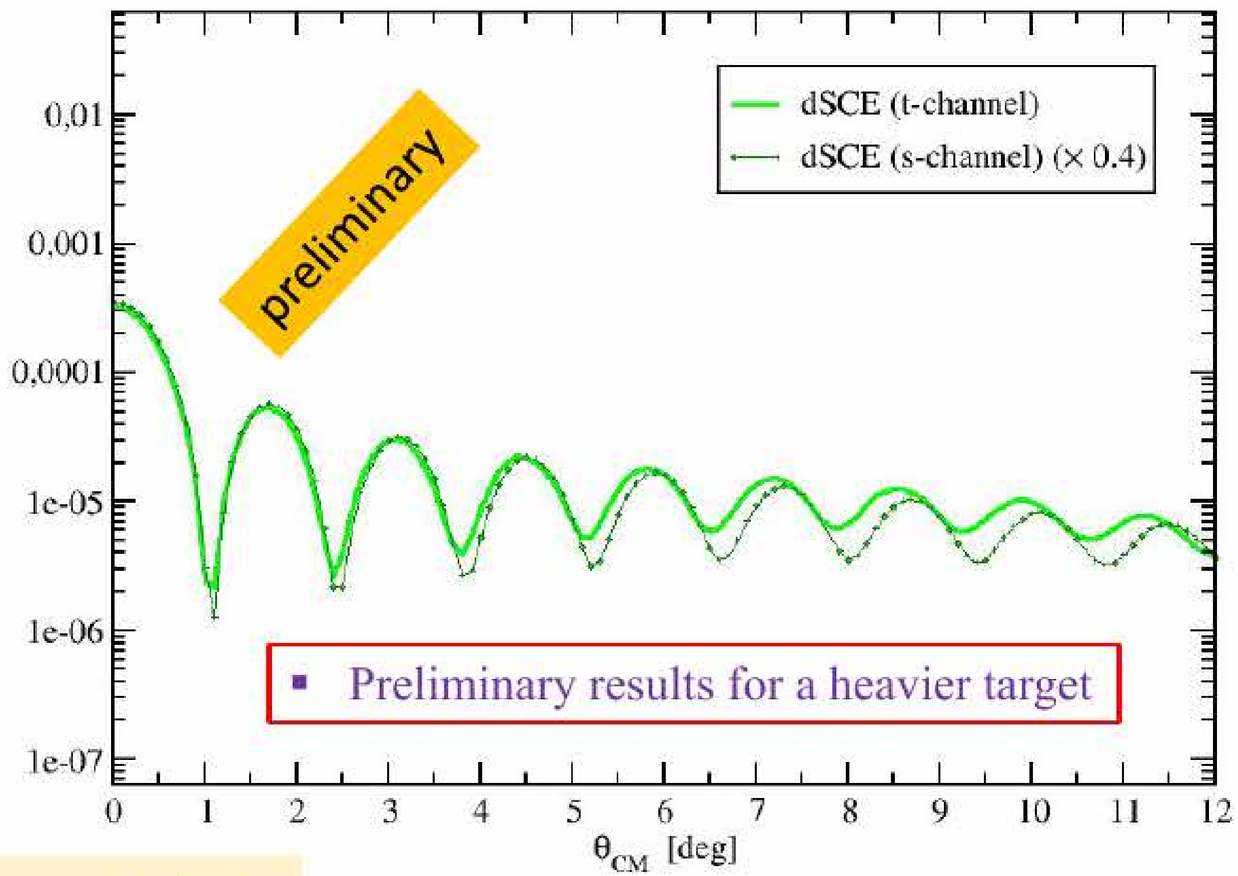
Bellone, Colonna, Gambacurta, Lenske
Phys. Rev. C 111, L061602 (2025)

➢ s-channel results for cross sections

$^{76}Se(^{18}O,^{18}Ne_{g.s.})^{76}Ge_{g.s.}$



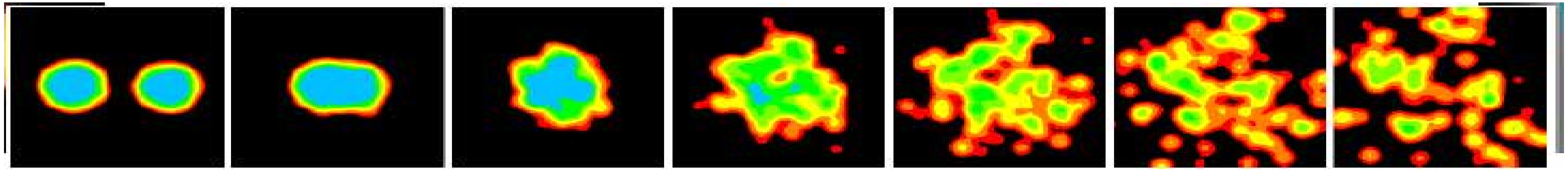
$^{116}Cd\ (^{20}Ne,\ ^{20}O)\ ^{116}Sn$ @ 15.3 AMeV



DSCE cross section

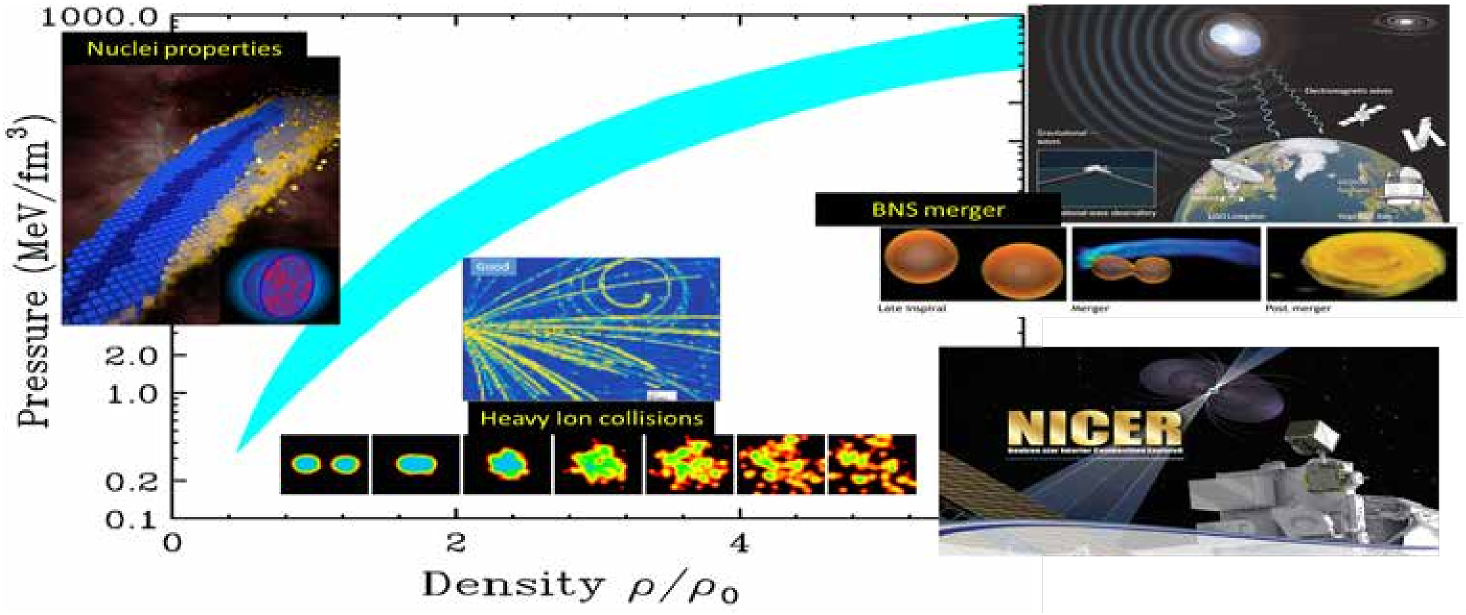
Dissipative reactions provide a unique opportunity to create nuclear matter in several conditions of density and temperature in laboratory

Femto-nova explosion created by heavy ion collisions !



from A. Ono

- Explore the nuclear matter **phase diagram** and access the nuclear **Equation of State (EOS)**



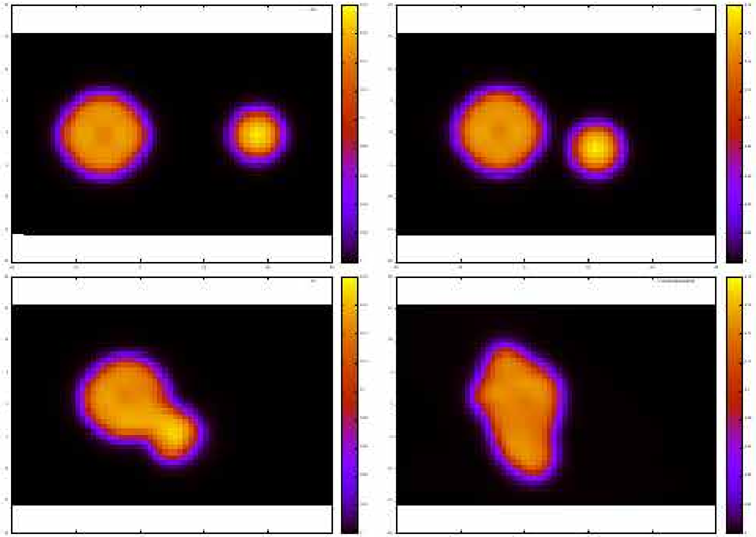
The EOS of asymmetric nuclear matter

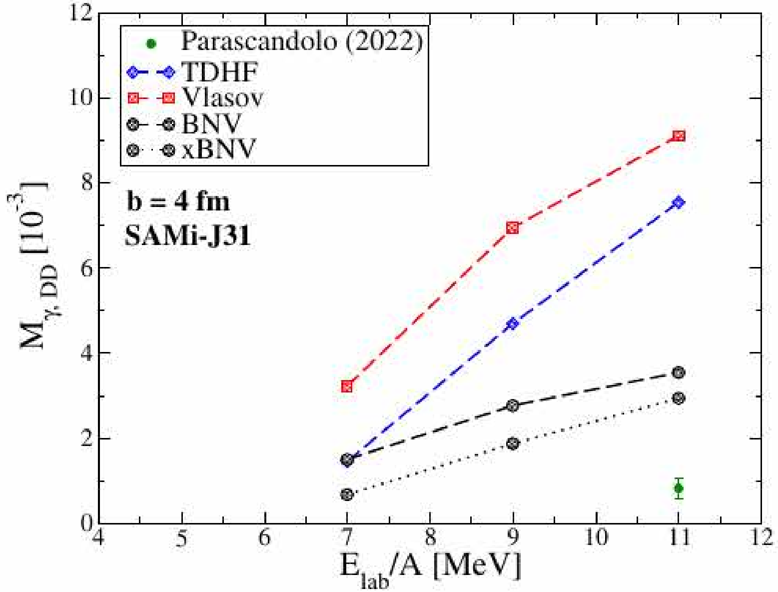
Dynamics of low-energy heavy-ion collisions (HIC)

- **Mean-field** models based on (Skyrme-like) energy density functionals (**EDFs**)
  - Time-Dependent Hartree-Fock (TDHF) theory (or semi-classical counterpart)

$$i\hbar\dot{\hat{\rho}}(t) + \left[\hat{\rho}, \hat{H}_{eff}[\rho]\right] = 0$$

- Equilibration mechanisms in **charge-asymmetric** reactions around Coulomb barrier
  - **Pre-equilibrium** emission in ^{40}Ca+^{152}Sm at $E_{\rm beam}$=11 AMeV ⇒ **Dynamical dipole**





PHYSICAL REVIEW C **111**, 014609 (2025)

Probing nuclear structure and the equation of state through pre-equilibrium dipole emission in charge-asymmetric reactions

L. Shvedov,[1,*] S. Burrello,[1,†] M. Colonna,[1,‡] and H. Zheng[2,§]
[1]Laboratori Nazionali del Sud, INFN, I-95123 Catania, Italy
[2]School of Physics and Information Technology, Shaanxi Normal University, Xi'an 710119, China

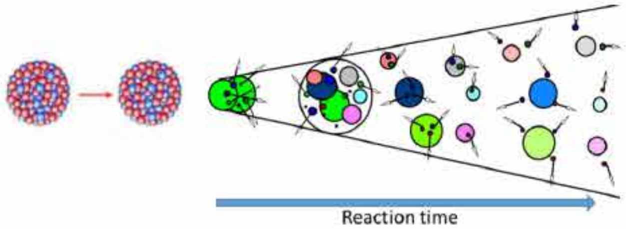
		TDHF	BNV	xBNV
$M_{\gamma,\rm DD}$ [10^{-3}]	b = 4 fm	7.59	3.63	3.02
	b = 6 fm	3.15	1.99	1.25
	$\langle b\rangle_{\rm expt} \simeq 5$ fm	0.82 ± 0.24 (Ref. [43])		

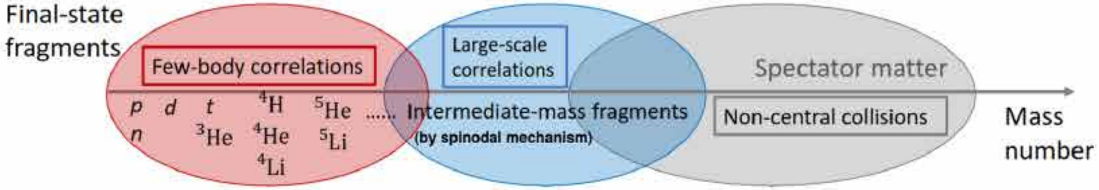
Improving models for HIC at intermediate energies

- Kinetic approach for **HIC** at $E_{\mathrm{beam}} \approx (30-300)$ AMeV$\Rightarrow$ (beyond) Boltzmann eqs.

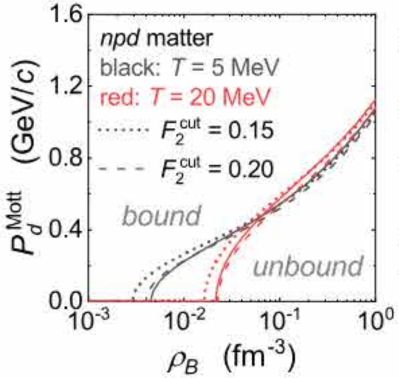
$$(\partial_t + \nabla_{\mathbf{p}}\varepsilon_\tau \cdot \nabla_{\mathbf{r}} - \nabla_{\mathbf{r}}\varepsilon_\tau \cdot \nabla_{\mathbf{p}})\, f_\tau = I_\tau^{\mathrm{coll}}[f_n, f_p, \ldots], \qquad \tau = n, p, d, t, h, \alpha$$

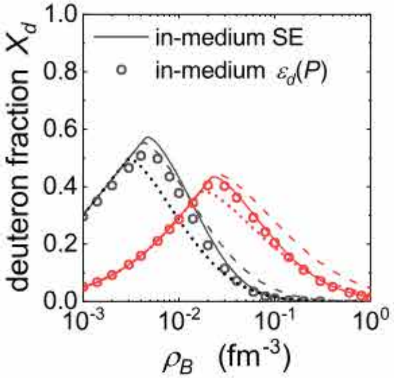
  - **Consistent** description of **light** clusters (+ in-medium effects) and **fragments**





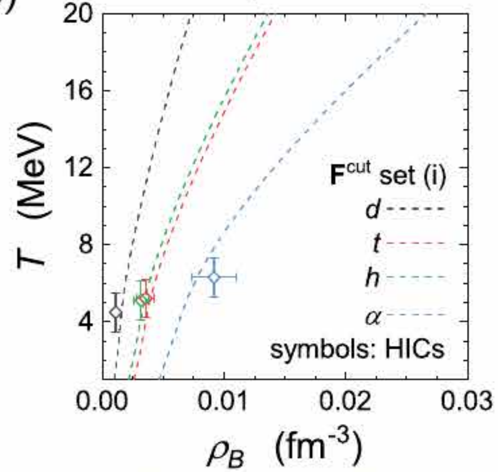
- Embedding **Mott** (Pauli-blocking) effect from **in-medium** Schrödinger equation (**SE**)

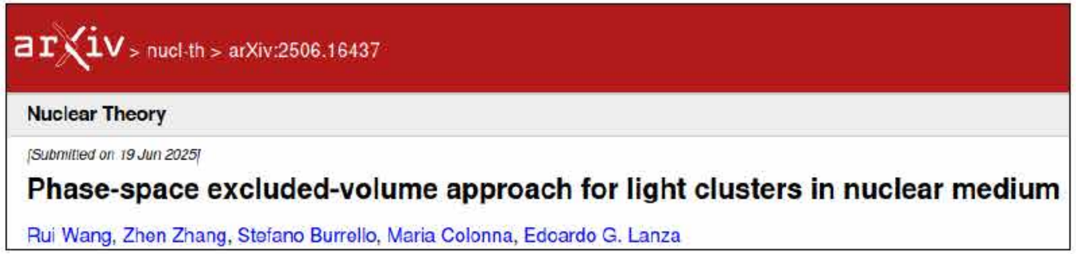




- **Phase-space excluded-volume** approach

$$\langle f_\tau \rangle_\nu(\vec{P}) \equiv \int \frac{\mathrm{d}\vec{p}}{(2\pi\hbar)^3} f_\tau^{\mathrm{tot}}(\vec{p}) |\tilde{\phi}_{\nu,\vec{P}}(\vec{p})|^2 < F_A^{\mathrm{cut}}$$




arXiv > nucl-th > arXiv:2506.16437

Nuclear Theory

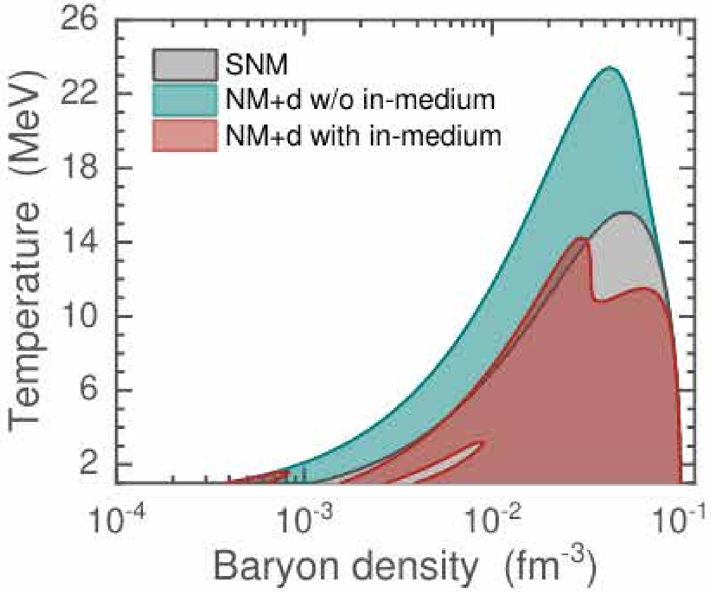
[Submitted on 19 Jun 2025]

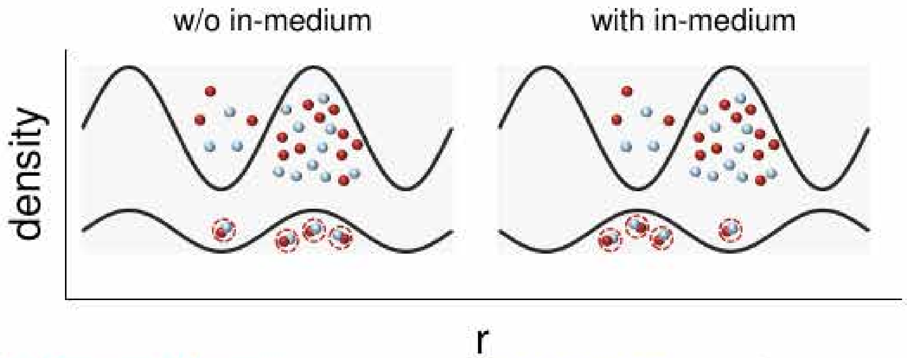
Phase-space excluded-volume approach for light clusters in nuclear medium

Rui Wang, Zhen Zhang, Stefano Burrello, Maria Colonna, Edoardo G. Lanza

Dynamics of dilute nuclear matter with clusters

- **Linear** response to collision-less Boltzmann ⇒ linearized **Vlasov** eqs. $(\omega = \omega(k))$
- $\omega = \mathrm{Im}(\omega) \Leftrightarrow$ **spinodal region**





- w/o in-medium: clusters **cooperate** to fragments
- with in-medium: clusters separately emitted

Editors' Suggestion | Letter

Dynamics of dilute nuclear matter with light clusters and in-medium effects

Rui Wang, Stefano Burrello, Maria Colonna, and Francesco Matera
Phys. Rev. C **110**, L031601 – Published 16 September 2024

- Further **developments** (stay tuned!):
  - Interplay among cluster species $(d + \alpha)$ & connection with **hydrodynamics**

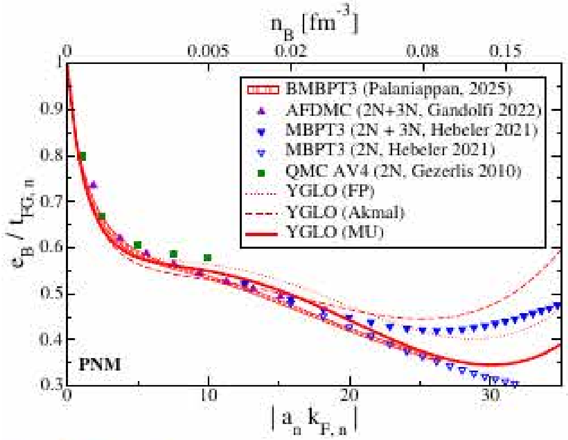
    [Carmelo Piazza's Master's Thesis work]
  - **Microscopic** description of in-medium effects from in-medium SE

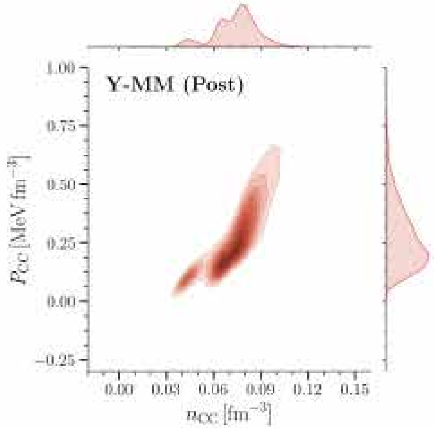
    [Pablo Nieto Gallego's Master's Thesis work]
  - **Implementation** within transport models [Rui Wang's postdoctoral project]

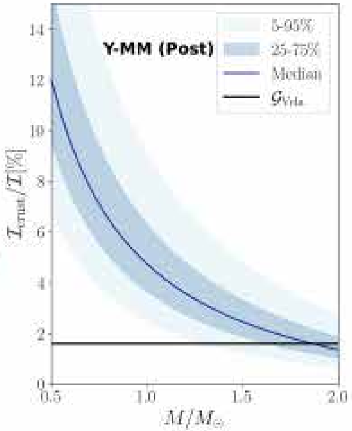
  ⇒ Development of **emulators** to constrain equation of state (EOS) from **HI**

EOS and modelization of compact stellar objects

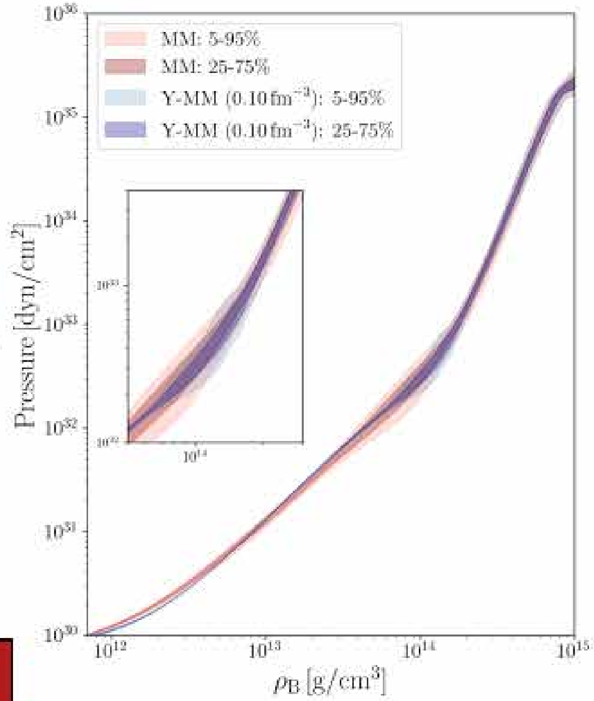
- **Unified** neutron star (**NS**) EDF-based **modeling** (Ligo-Virgo-Kagra (**LVK**) coll.)
  - $\Rightarrow$ meta-model (**MM**) [J. Margueron, R. H. Casali & F. Gulminelli, Phys. Rev. C 97, 025805 (2018)]
- **Refined** meta-model (**Y-MM**) approach at **low-density**
  - **Consistency** with **ab-initio neutron matter** calculations







- NS (**crust**) **EOS**
  - $\ll$ **uncertainties**
  - Different **outer**



- **Crust-core** (CC) transition & **moment of inertia** $\mathcal{I}_{crust}$
  - CC transition density n_{CC} & pressure P_{CC} **estimation**
  - **Compatibility** with **Vela pulsar glitches** $\left(\frac{\mathcal{I}_{crust}}{\mathcal{I}} > \mathcal{G}_{Vela}\right)$

arXiv > nucl-th > arXiv:2506.05603

Nuclear Theory

[Submitted on 5 Jun 2025]

Bayesian inference of neutron star crust properties using an ab initio-benchmarked meta-model

S. Burrello, F. Gulminelli, M. Antonelli, M. Colonna, A. Fantina

- **Theoretical** support for interpreting **gravitational wave** signals (**Einstein Telescope**)

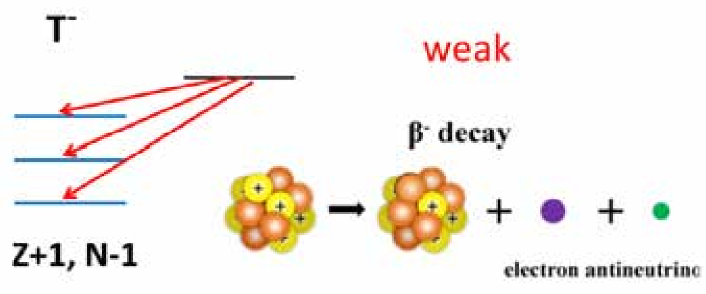
Improving beta decay half-lives description

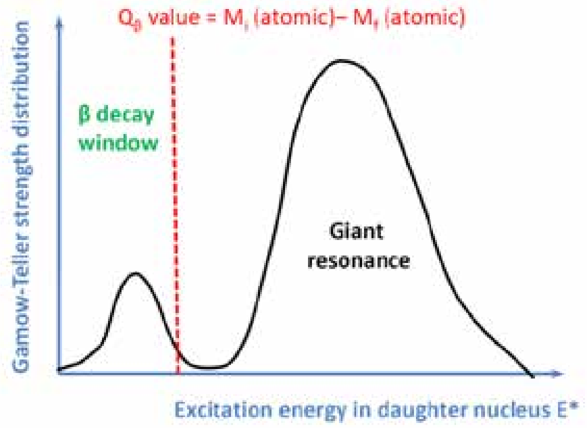
Eur. Phys. J. A (2025) 61:146
https://doi.org/10.1140/epja/s10050-025-01611-8
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article - Theoretical Physics

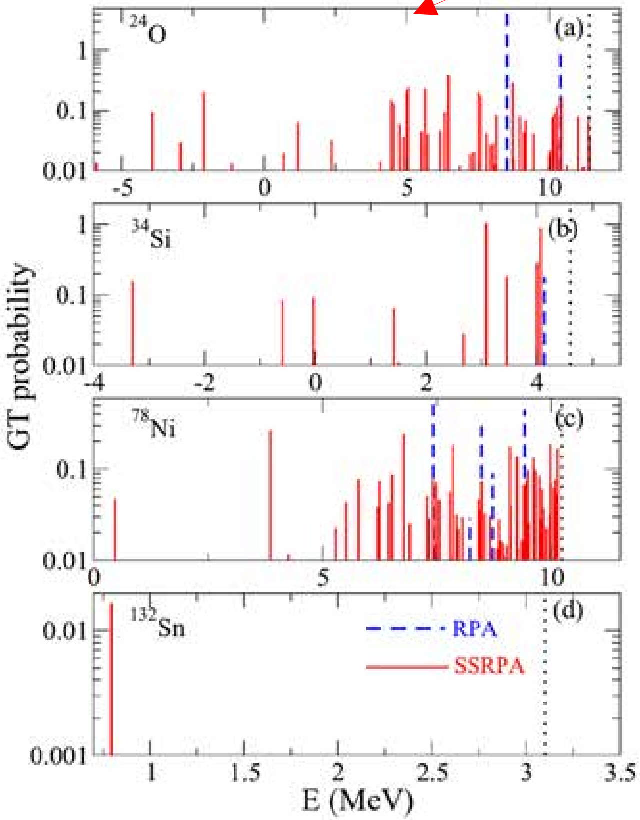
Nuclear β-decay half-lives within the subtracted second random-phase approximation

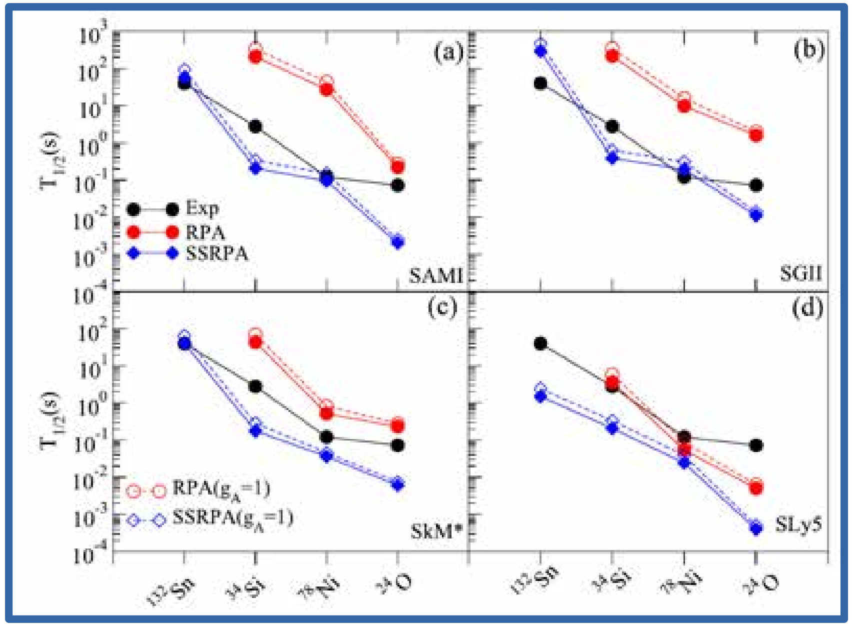
D. Gambacurta[1,a], M. Grasso[2]

$$Q_\nu^\dagger = \sum_{ph} X_{ph}^\nu a_p^\dagger a_h - \sum_{ph} Y_{ph}^\nu a_h^\dagger a_p + \sum_{p<p',h<h'} \left(X_{php'h'}^\nu a_{p'}^\dagger a_p^\dagger a_{h'} a_h - Y_{php'h'}^\nu a_h^\dagger a_{h'}^\dagger a_p a_{p'} \right).$$









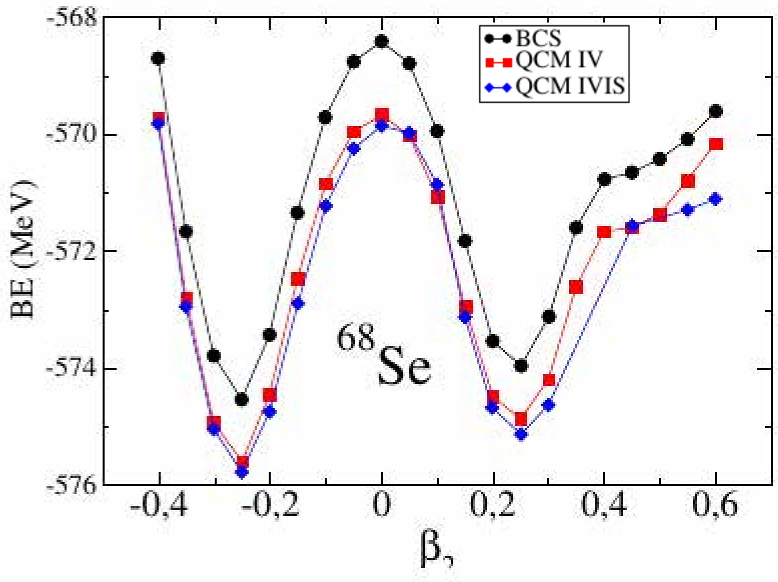
Implications for NME in **neutrino-less double-β decay, PANDORA** and **NUMEN project**

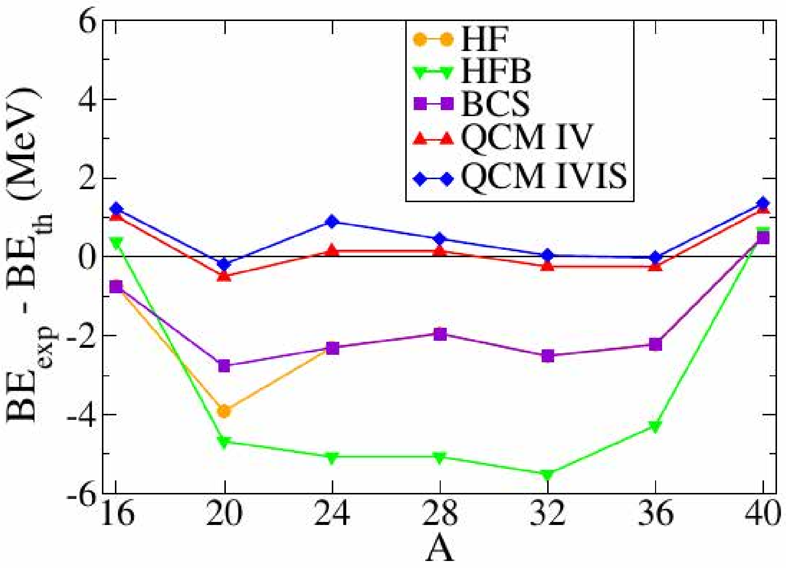
Quark Meson Coupling calculations with proton-neutron pairing: $N = Z$ nuclei

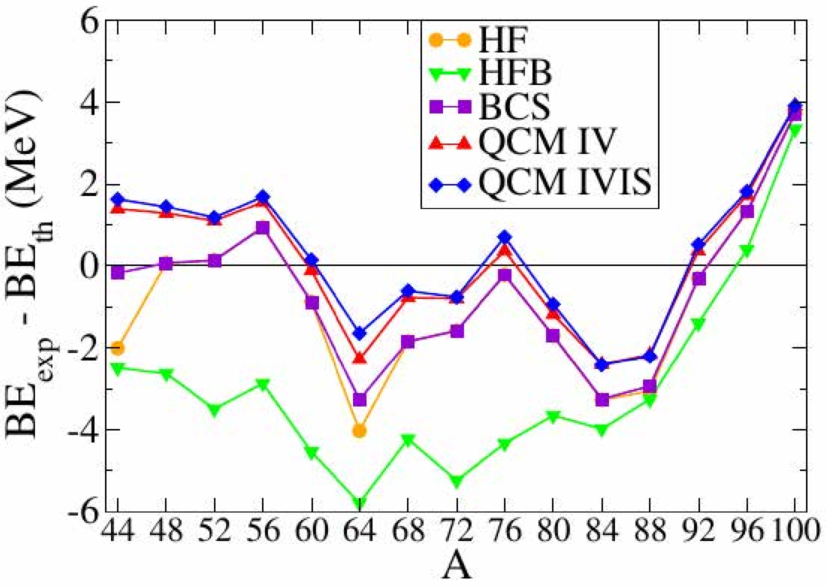
Proton-neutron pairing in even-even N = Z nuclei 20 ≤ A ≤ 120 mass region using a energy density functional based on the Quark Meson Coupling model. Pairing described qithin the **Quartet Condensation Model** beyond BCS

- Isoscalar (IS) and isovector (IV) pairing described simultaneously (and consistently)
- Isospin and particle number symmetries are preserved
- Pairing and deformation interplay

Better description of binding energies







T. Popa, N. Sandulescu and D. Gambacurta, to be submitted to Physical Review C

Attività 2026: MONSTRE

- Single and double beta decay studies (RPA, QRPA and Second RPA)
- Proton-neutron pairing studies
- Transport theories**:** formation of light clusters, treated as explict degrees of freedom
- Equation of State including light clusters, short range correlations, ... (Einstein Telescope physics)
- Emulators (based on Machine Learning) for transport codes
  (combining heavy-ions and astrophysical constraints for EoS)
- Charge Exchange: Systematic studies and use of different structure model inputs (shell model vs. QRPA)
- Consistent description of competing channels (multi-nucleon transfer) and, more in general, of all open reaction channels (multi-channel approach)

FTE: MONSTRE (3.55) *4.4 in 2024*

cognome	nome	contratto	profilo	perc	sezione
Bonaccorso	**Angela**	Associato	Associazione Senior	0%	Pisa
Bonasera	**Aldo**	Associato	Associazione Senior	45%	LNS
Burrello	**Stefano**	Dipendente	Ricercatore	70%	LNS
Colonna	**Maria**	Dipendente	Dirigente di Ricerca	60%	LNS
Gambacurta	**Danilo**	Dipendente	Primo Ricercatore	80%	LNS
Gargano	**Angelina**	Dipendente	Primo Ricercatore	0%	Napoli
Rui	**Wang**	Dipendente	Assegno di Ricerca	100%	LNS

SIM: Strongly Interacting Matter at high density and temperature

*Units: Catania, Firenze, **LNS**, Torino,*
FTE totale: ≈20
FTE (LNS) *≈5.1*

Responsabile Nazionale: Andrea Beraudo (TO)

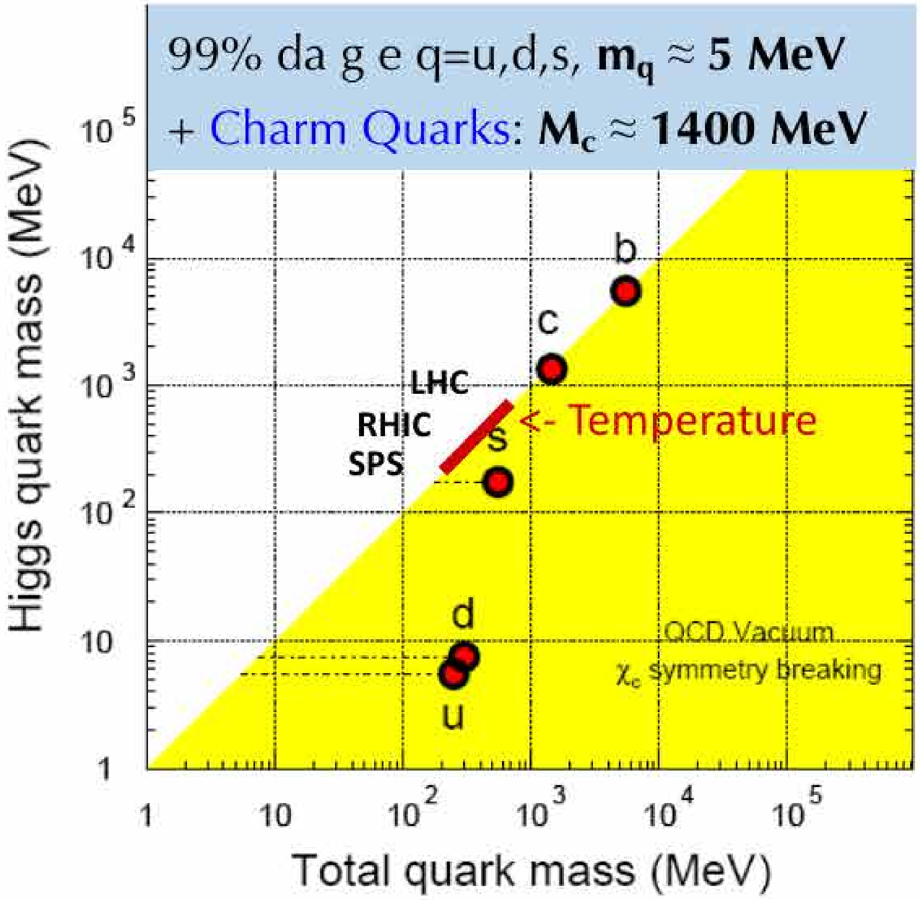
Responsabile Locale: Vincenzo Greco/Salvatore Plumari

Collaborazioni: CT, TO, Francoforte, Nantes, CERN, Berkeley LBL, Texas A&M, Duke U., Lanzhou University, University of Barcellona, IIT Ghoa,Jyväskylä , ...

Obiettivi generali: Study of strongly interacting matter at high density and temperature

- Fenomenologia del Quark Gluon Plasma (QGP)
- Dinamica dei quarks e meccanismi di adronizzazione
- Equazioni del trasporto per i partoni (beyond hydrodynamics):
- Dinamica dei quark pesanti: charm e bottom
- Early stage, dinamica di non-equilibrio AA, pA e pp

An elephant in the liquid: Heavy Charm Quark



Heavy because:

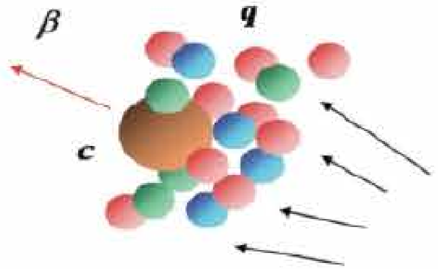
✧ **$M \gg \Lambda_{QCD}$ (particle physics)**

✧ **$M \gg T$ (plasma physics)**

Fokker-Planck Equation – Brownian motion

$$\frac{\partial f_{c,b}}{\partial t} = \gamma \frac{\partial (p f_{c,b})}{\partial p} + D \frac{\partial^2 f_{c,b}}{\partial p^2}$$

<p> Drag   <Δp²> Diffusion



→ Poorly dragged & long thermalization time (!?)

$\tau_{C,therm} \approx O(10^2) \gg \tau_{QGP} \gg \tau_{q,therm} \approx O(1)$ fm/c

Goal : determine strength of QCD interaction and thermalization time of Heavy quarks

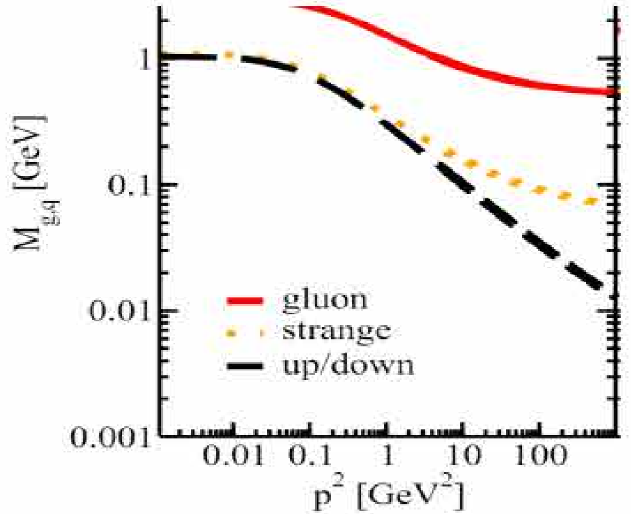
Long stand problem → reproduce both p_T spectra (R_{AA}) and elliptic flow (v_2)

Momentum dependent masses : p >> Λ_{QCD} $m_{u,d,s}$ → current masses

$$M_g(T,\mu_q,p) = \left(\frac{3}{2}\right)\left(\frac{g^2(T^\star/T_c(\mu_q))}{6}\left[\left(N_c+\frac{1}{2}N_f\right)T^2+\frac{N_c}{2}\sum_q\frac{\mu_q^2}{\pi^2}\right]\left[\frac{1}{1+\Lambda_g(T_c(\mu_q)/T^\star)p^2}\right]\right)^{1/2}+m_{\chi g}$$

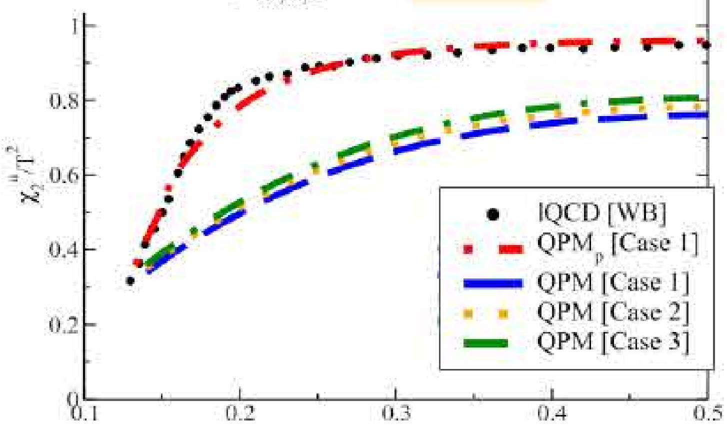
$$M_{q,\bar{q}}(T,\mu_q,p) = \left(\frac{N_c^2-1}{8N_c}g^2(T^\star/T_c(\mu_q))\left[T^2+\frac{\mu_q^2}{\pi^2}\right]\left[\frac{1}{1+\Lambda_q(T_c(\mu_q)/T^\star)p^2}\right]\right)^{1/2}+m_{\chi q}$$

$m_{u,d,s}(p)$ expected on theoretical ground → susceptibilities…



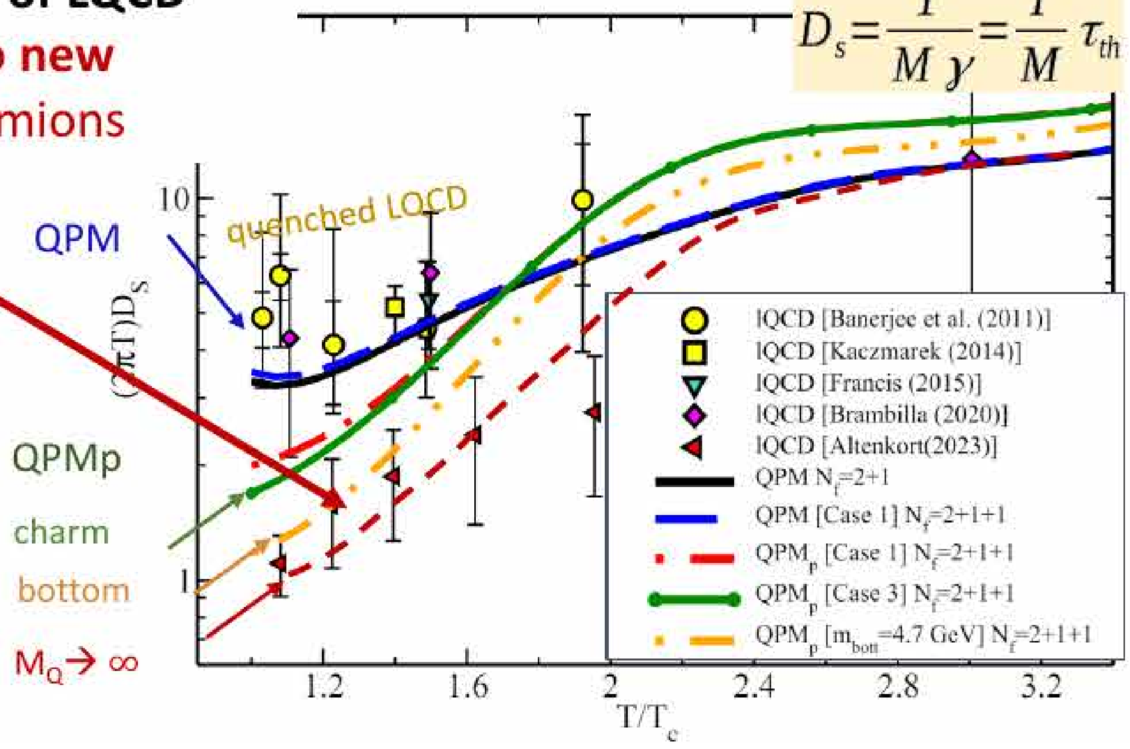
$$\chi_{u,s,c} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial \mu^2_{u,s,c}}$$

LIGHT



- **QPMp** describes **ε,P, χ_q, χ_s of LQCD**
  + closer than QPM to D_S to **new LQCD** with dynamical fermions

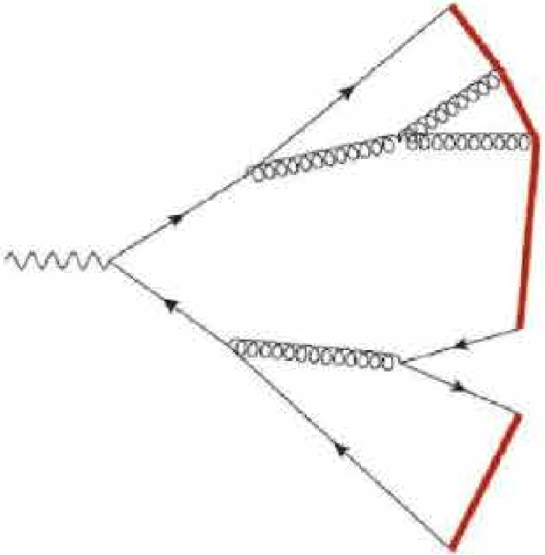
$$D_s = \frac{T}{M\gamma} = \frac{T}{M}\tau_{th}$$

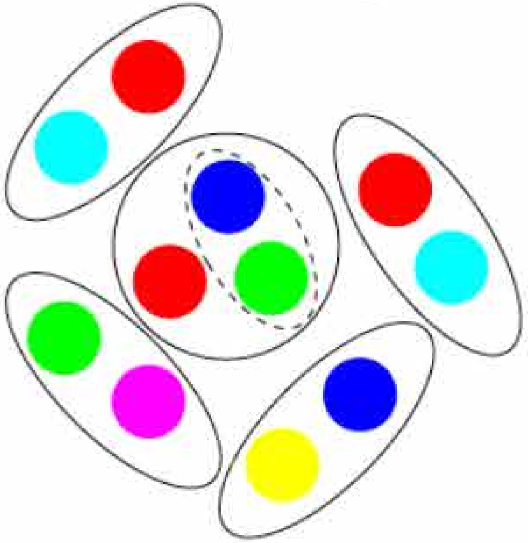


- **Can this new $D_s(T)$ generate predictions for R_{AA}, v_2, v_3 in agreement with experimental data?**

M. L. Sambataro et al., EPJC 84 (2024) no.9, 881

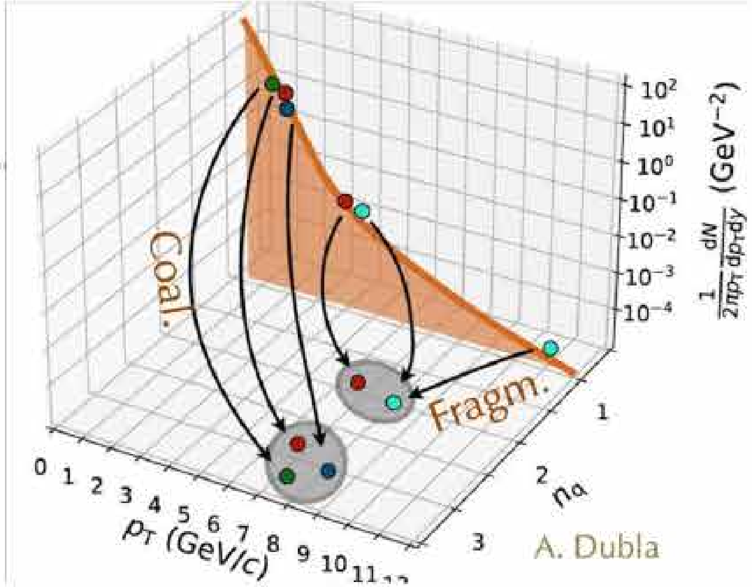
Hadronization from e^+e^- to pp and AA





π, K, D, ...

p, Λ, Λ_c , ..



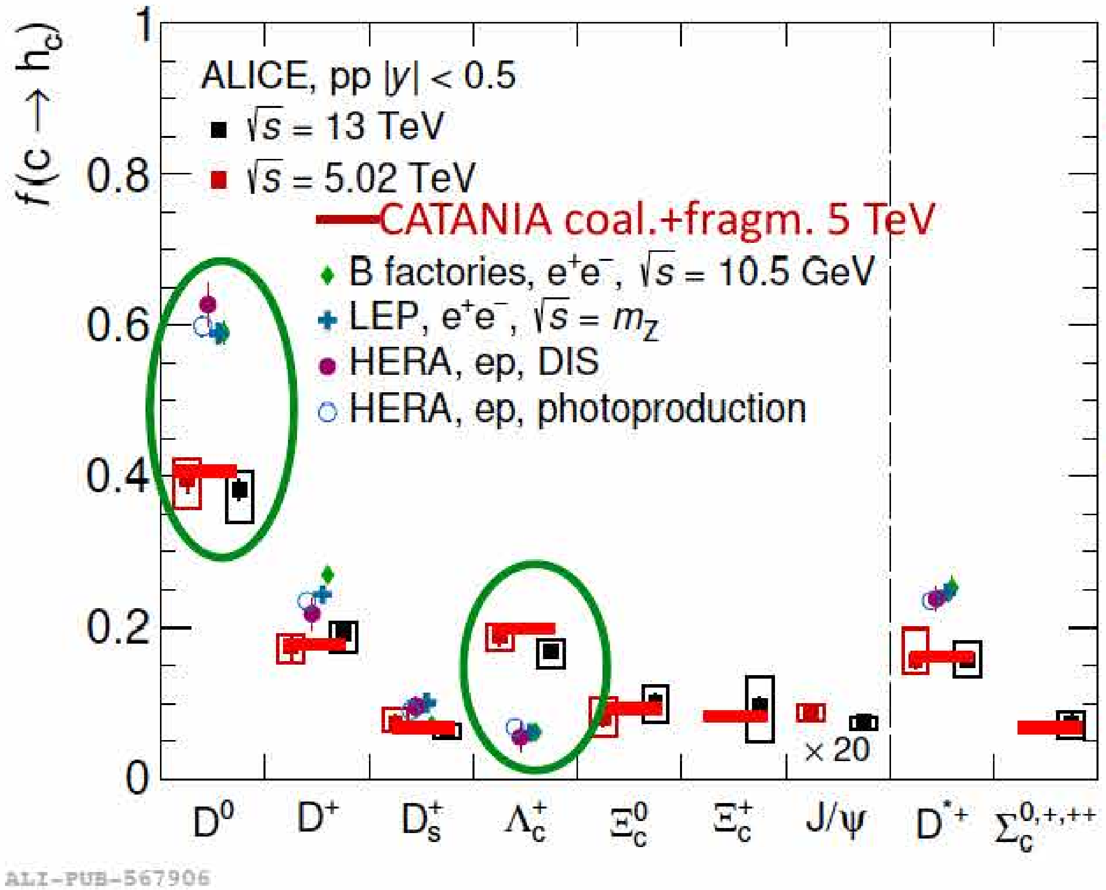
Fragmentation

$$f_H(P_H = zp_T) = f_{q,g}(p_T) \otimes D_{q,g\to H}(z) \quad , z < 1$$

Coalescence

$$f_M \approx f_q \otimes f_{\bar{q}} \otimes \Phi_M \cdot \delta(\vec{p}_M - \vec{p}_q - \vec{p}_{\bar{q}})$$

"Fragmentation" Fractions in pp Catania Coalescence

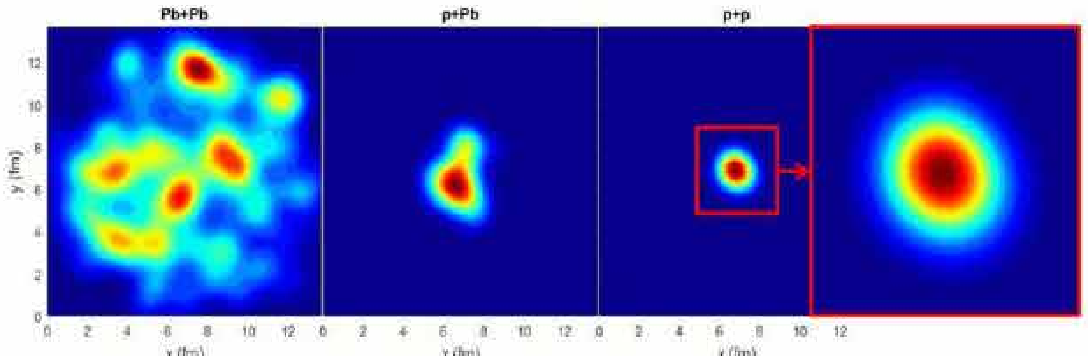


Altmann, Dubla, Greco, Rossi & Skands, arXiv:2405.19137

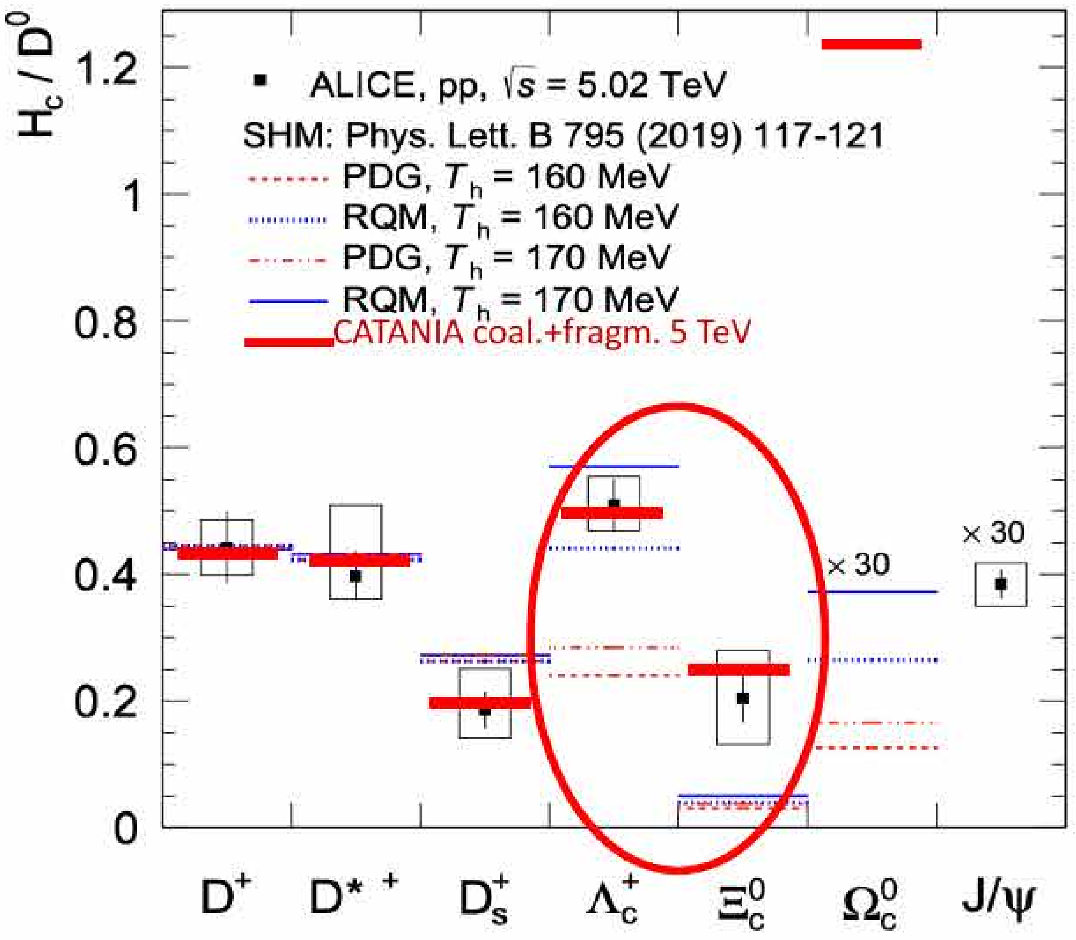
- Evidence of different "Fragmentation" Fractions in pp at LHC wrt $e^+e^-(e^-p)$ collisions while very similar to AA collisions
- Catania Coal+Fragm. : same approach to pp and AA: pp@TeV like a little drop of AA

Coalescence $f_M \approx f_q \otimes f_{\bar{q}} \otimes \Phi_M \cdot \delta(\vec{p}_M - \vec{p}_q - \vec{p}_{\bar{q}})$

Daring to assume a small fireball according **viscous hydro** applied to pp as in AA, but **size,time, flow given by hydro for pp**



“Fragmentation” Fractions in pp Catania Coalescence



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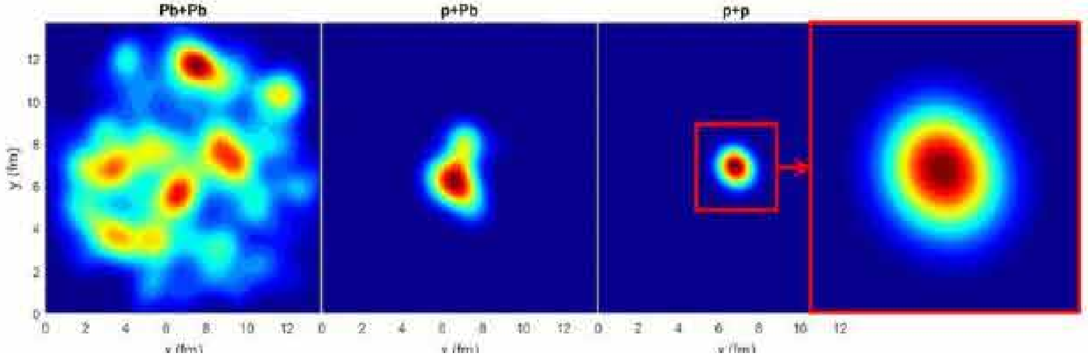
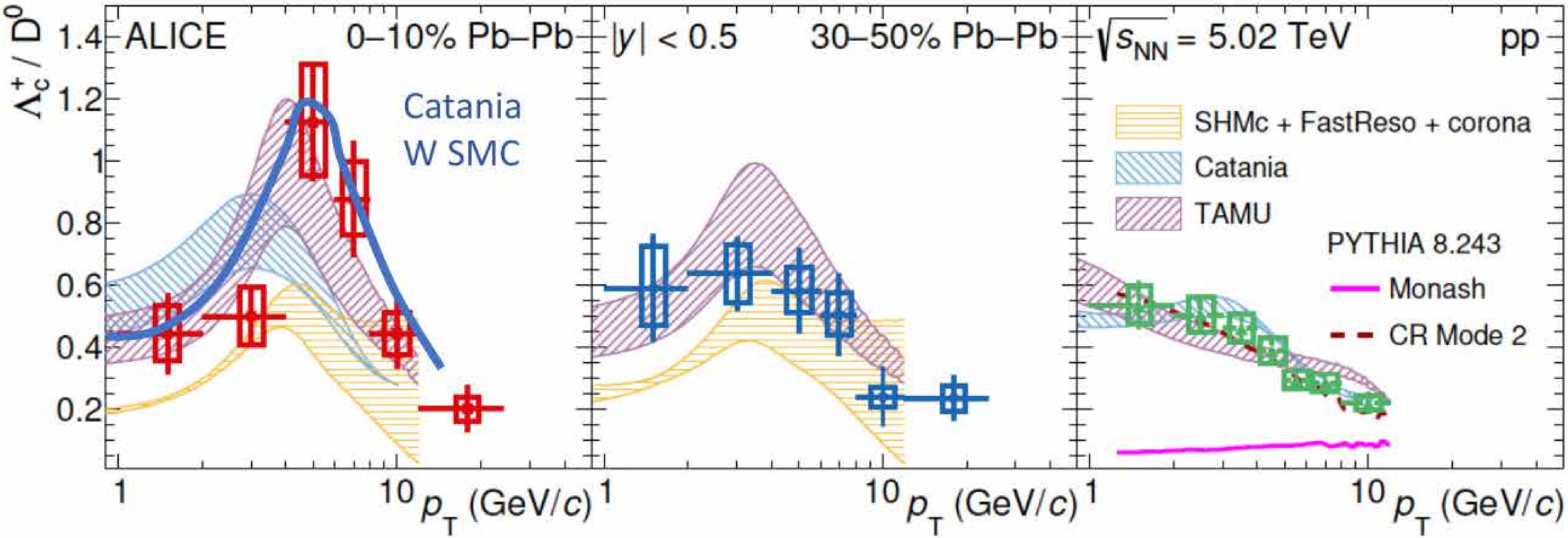
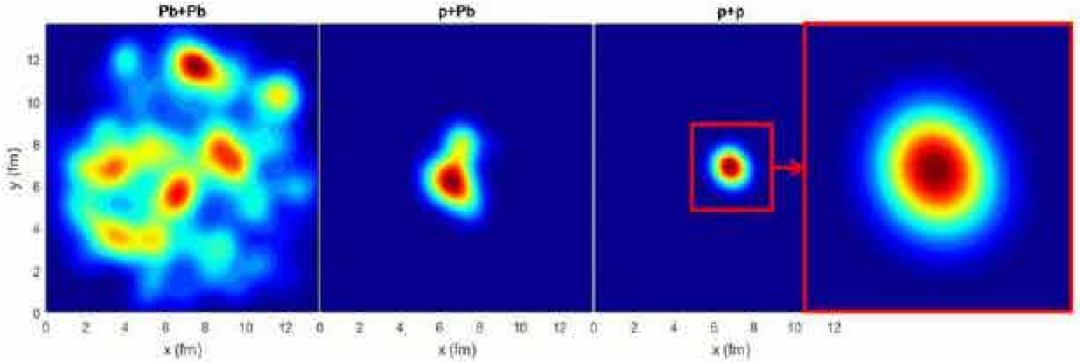


From AA to pp baryon/meson vs p_T



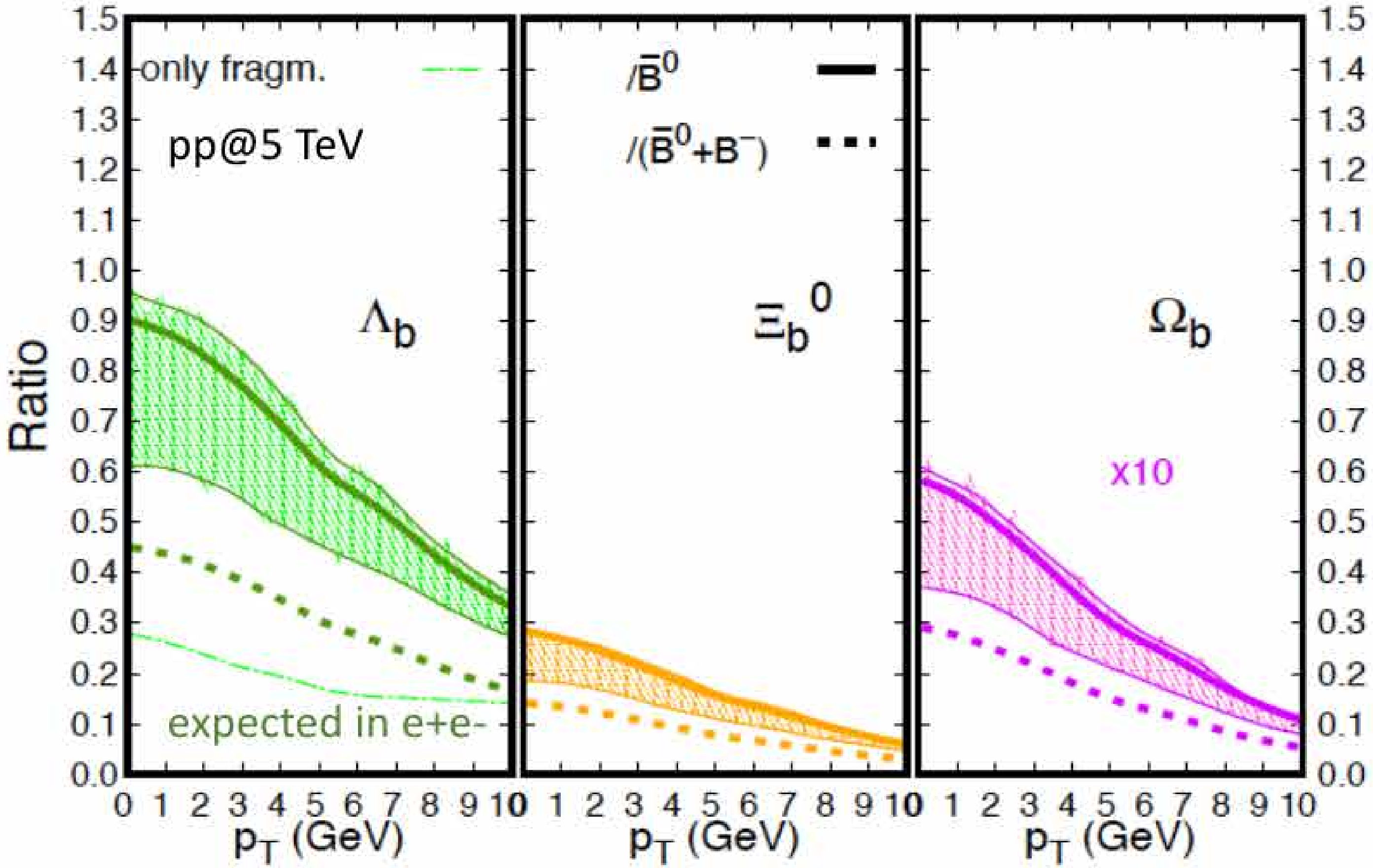
Same hadronization approach in pp and AA:
pp@TeV like a drop of AA with smaller size & radial flow



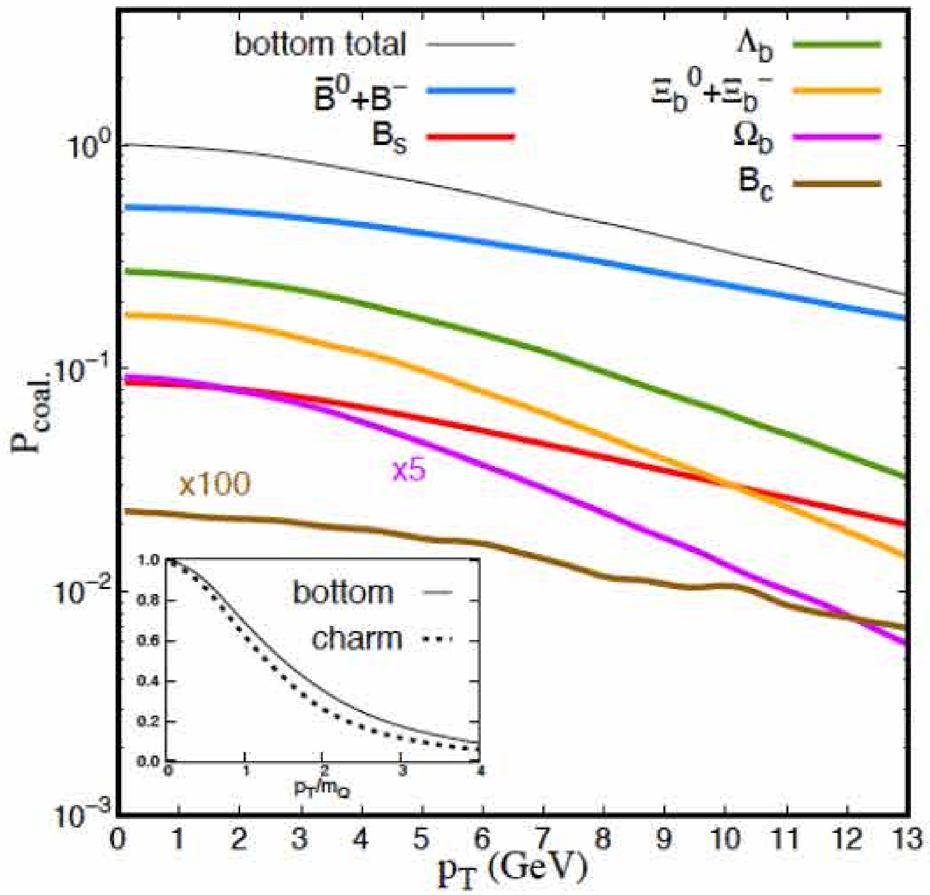
SMC: Space-Momentum correlation

"Extension to bottom baryons

V. Minissale et al., PLB 860 (2025), 139190

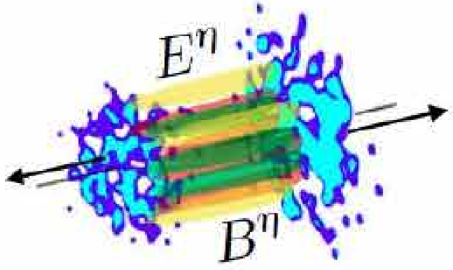


Coalescence probability



- Similar but even larger Λ_b/B than Λ_c/D
- Extension of coalescence probability in p_T about proportional to the heqvy quark mass

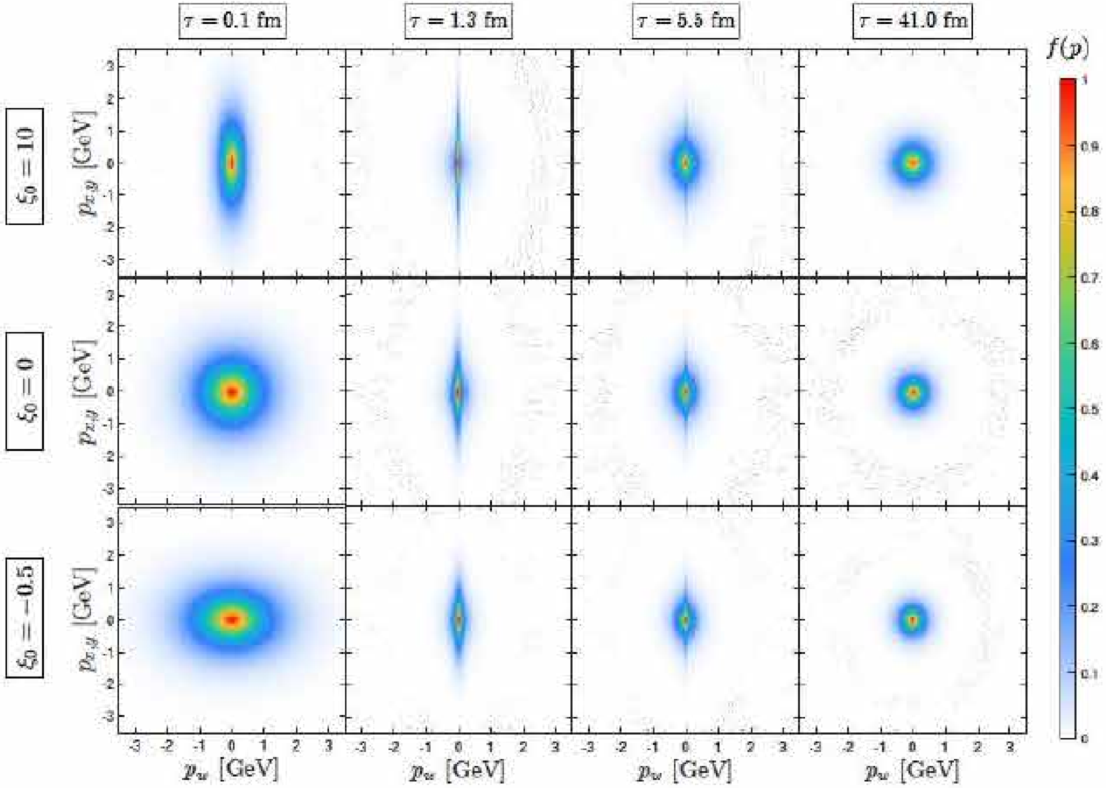
Very early stage dynamics



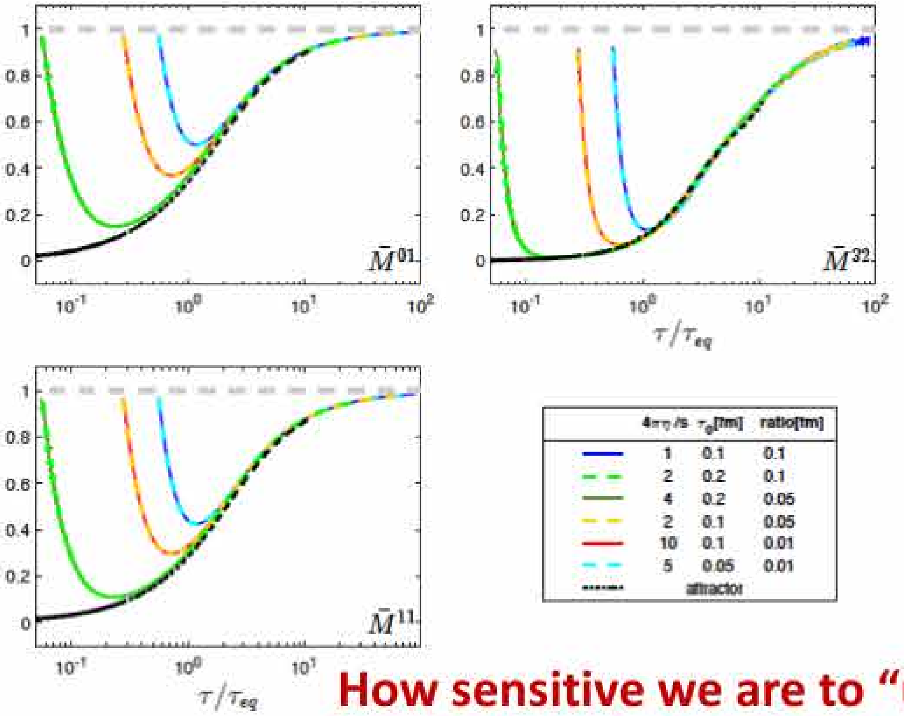
$$p^\mu \partial_\mu f_q(x,p) + m(x)\,\partial^x_\mu m(x)\,\partial^\mu_p f_q(x,p) = C[f_q, f_g]$$

$$\mathcal{M}^{mn}(\tau) = \int dP\,(p\cdot u)^n\,(p\cdot z)^{2m}\,f(\tau,p).$$

transverse to flow* longitudinal



Evolution of the moments of the distribution function



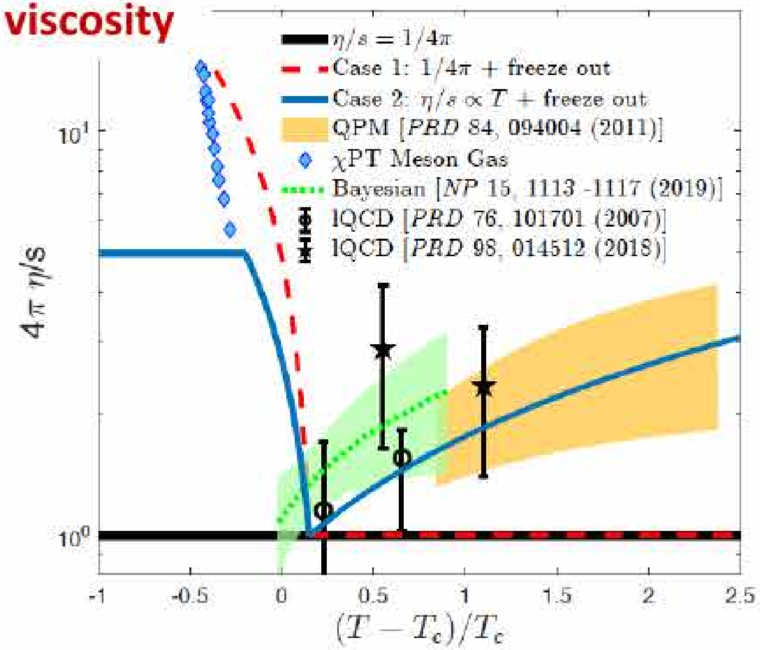
Simulation in 1+1D

How sensitive we are to "unknown" initial conditions and early stage attractions?

V. Nugara et al., EPJC 84 (2024) 8, 861;

Impact of transition to hadronic matter

Shear viscosity



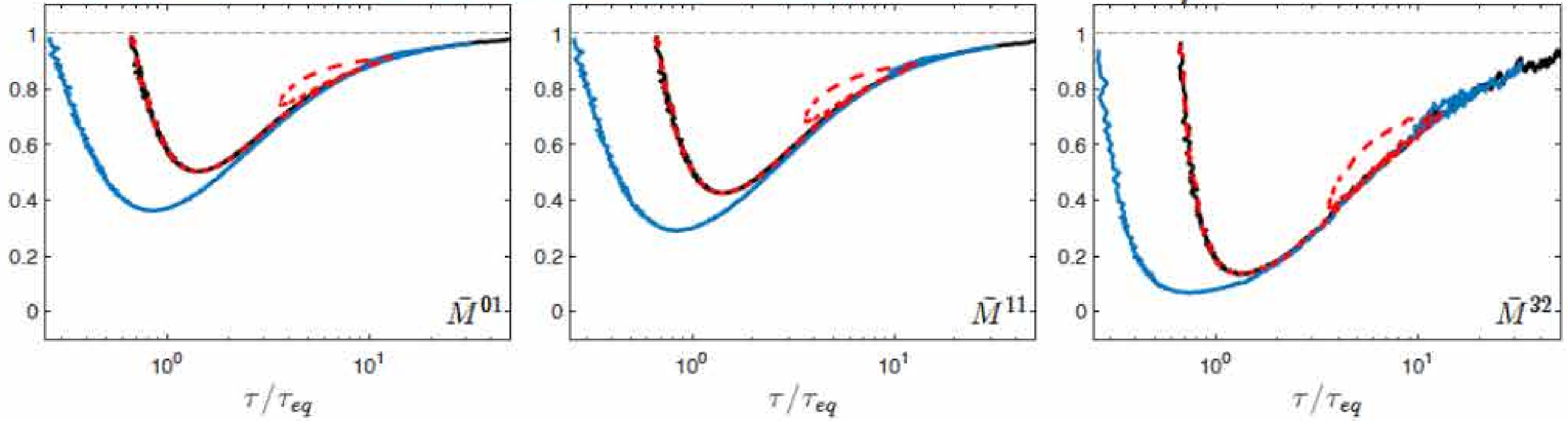
Even the strong rise of the shear viscosity at the transition to hadronic matter (→ increase of equil. time) does not breaking the evolution toward equilibration

$$\tau_{eq} = 5(\eta/s)/T(\tau)$$

V. Nugara et al., EPJC 84 (2024) 8, 861;

Moments M^{mn} normalized to equilibrium values

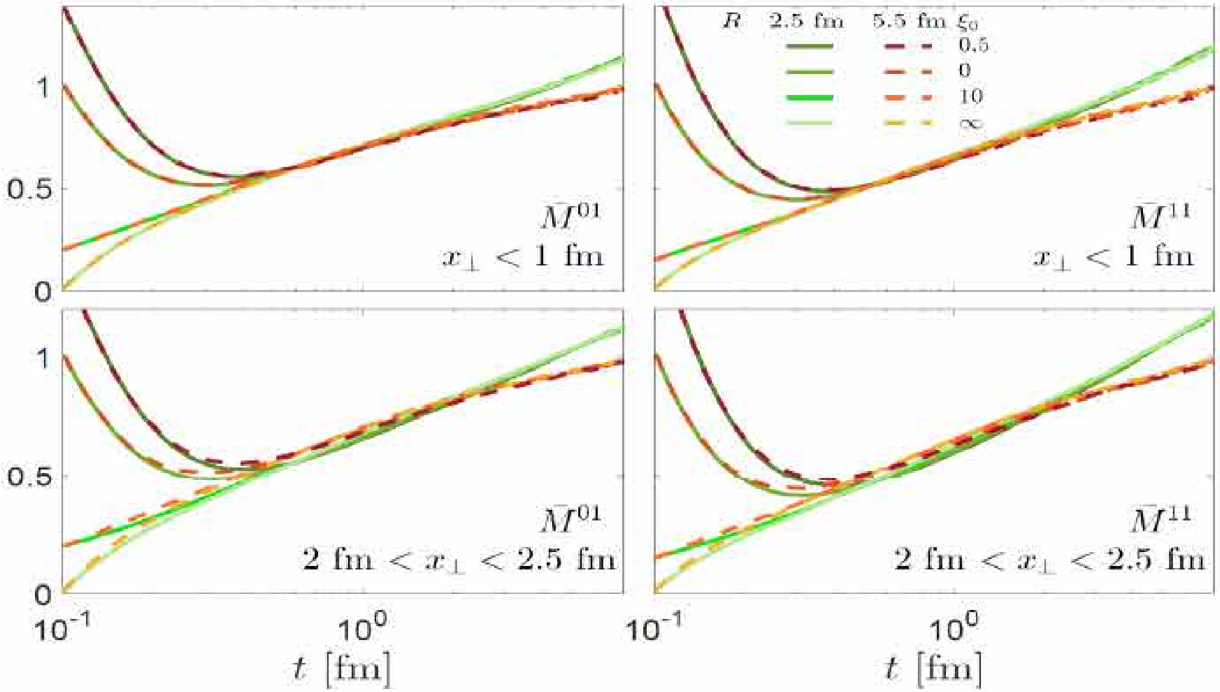
$$\mathcal{M}^{mn}(\tau) = \int dP\,(p\cdot u)^n\,(p\cdot z)^{2m}\,f(\tau,p).$$



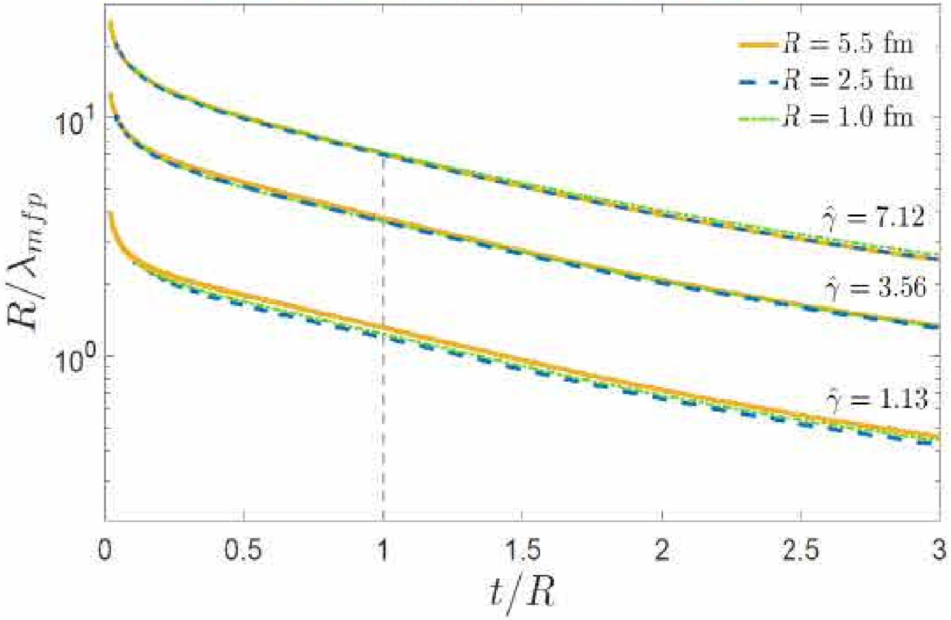
Extension to 3+1D

V. Nugara et al., EPJC 85 (2025) 3, 311

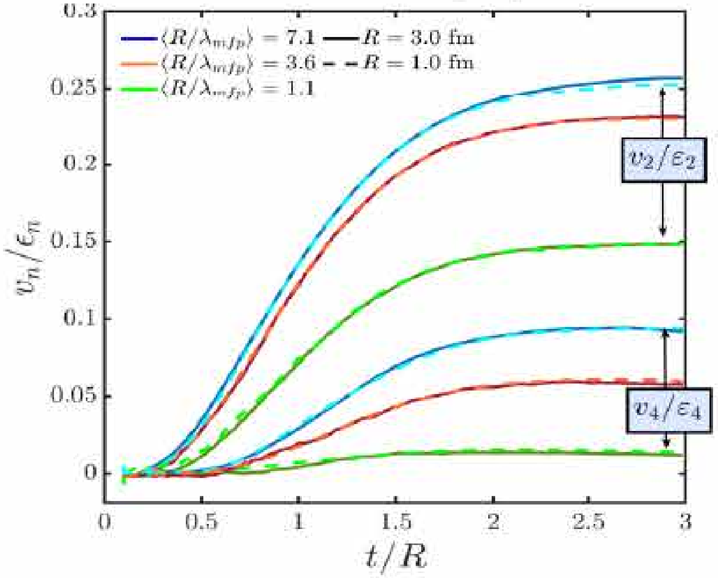
- **Same trend of 1D: attractor due to initial longitudinal expansion (identical in 1D and 3D)**
- **Reached at same t for different R (transverse size doesn't matter)**
- **Differentiate when transverse expansion starts to play a role**



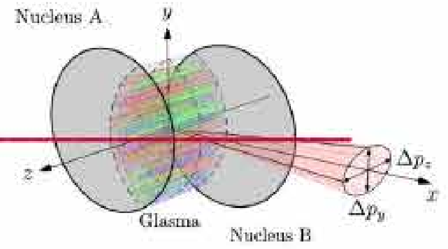
Universality classes in R/λ_{mfp}



Universality of collective flows w.r.t Knudsen number!



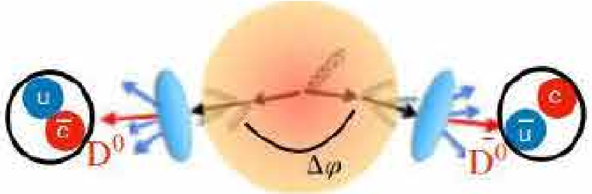
Glasma impact on angular $Q\bar{Q}$

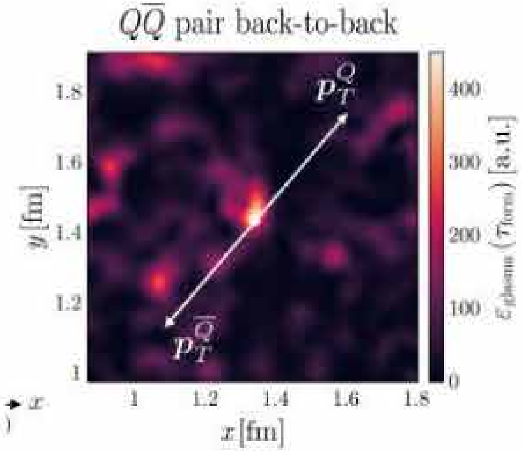


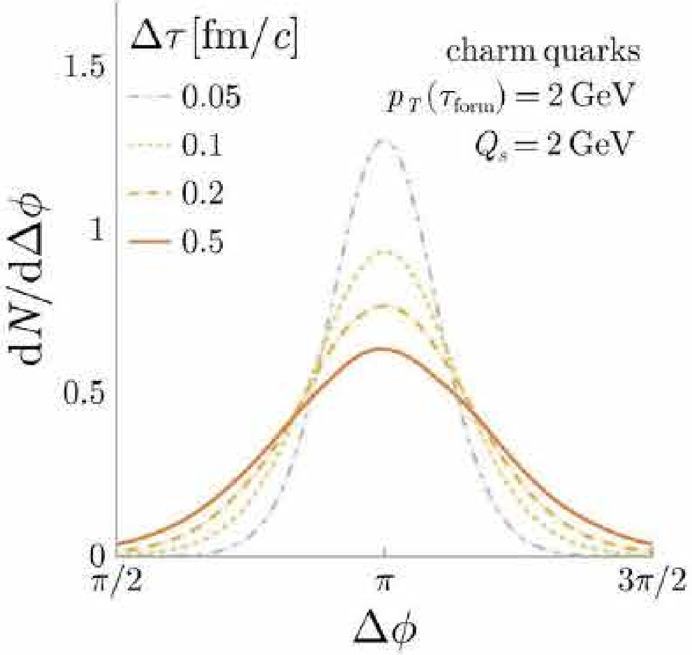
First study of azimuthal $Q\bar{Q}$ correlation: large decorellation **in only 0.2 fm/c**

Calculation in **SU(3) +longitudinal expansion**

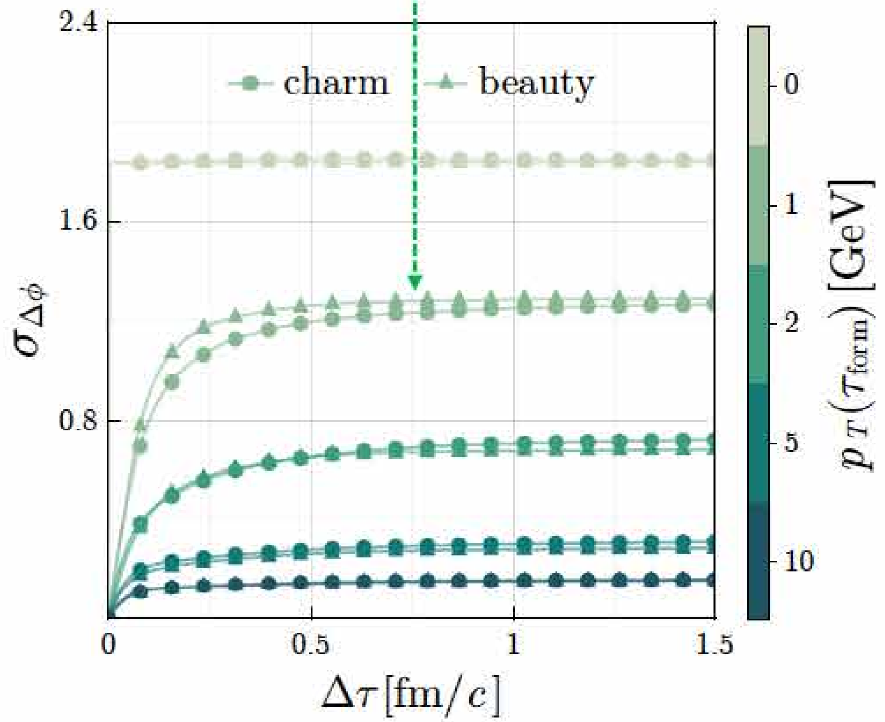
D. Avramescu et al., PRL 134 (2025)







Nearly **identical for bottom,** despite larger mass thanks to smaller τ_{form} and v_T



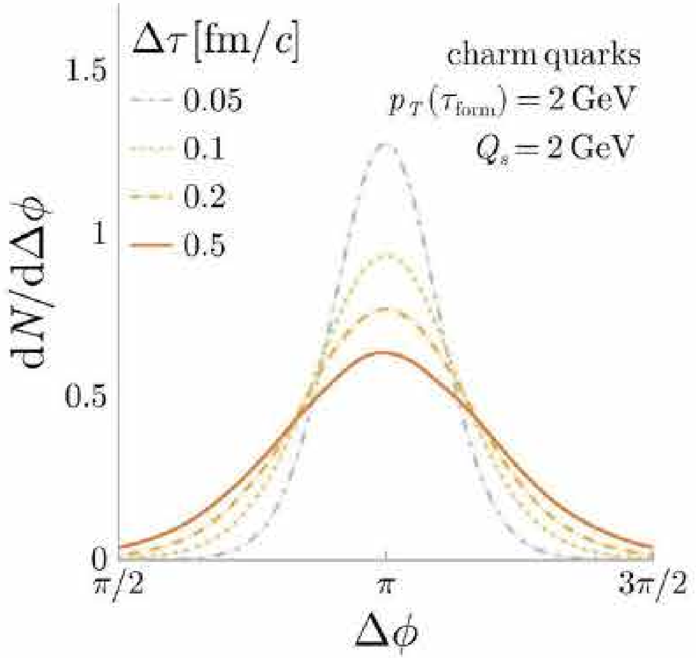
Significant effect of glasma on HQ! Quite Stronger than on R_{AA}

Width at t~0.2 fm/c comparable that induced by QGP in AA

M. Nahrgang et al, PRC90 (2014)

Glasma impact on angular $Q\bar{Q}$

D. Avramescu et al., PRL 134 (2025)



In pA smaller width wrt AA may allow to:

- solve the puzzle od R_{pA} ~1 and v_2 large ?
- disentagle shadowing from glasma ?

<u>To be done toward a full realistic calculation</u>:

- beyond back-to-back : flavor excitation, gluon splitting
- Matching with QGP kinetic transport
- Inclusion of hadronization [mainly p_T reshaping]

Is τ_{th} of charm (bottom) sufficiently large to keep memory of early stage dynamics?

New estimate of τ_{th}(charm)~ 1 fm/c from $2\pi T D_s$ from LQCD, to answer is not trivial

It is likely necessary to go to:

- Small systems like OO and pA
- Bottom less affected by flavor excitation and gluon splitting

Attività SIM 2025-26

- Develop a relativistic event-by-event transport theory suitable to perform realistic simulations of relativistic HIC's from AA to pA collisions.

  → Study the existence of dynamical attractors in 3+1 D: **impact on observables**

  → Heavy Quark dynamics in a unified frameworks in pA and AA (extension to b quarks)

  → Early stage Heavy Quark in the Glasma (collaboration with INFN-CT):
  solve the puzzle of R_{pA} ~1[no change in dN/dp_T] but a large elliptic flow v_2

- Explore impact of open quantum system tecniques in high energy physics on quantum computing (NQSTI – PNRR)

FTE: SIM (5.1) *6.0 in 2024*

cognome	nome	contratto	profilo	perc	sezione
Coci	**Gabriele**	Associato	RTDA-PNRR	10%	LNS
Greco	**Vincenzo**	Associato	Prof. Ordinario	100%	LNS
Nugara	**Vincenzo**	Associato	Dottorando III	100%	LNS
Parisi	**Gabriele**	Associato	Dottorando III	100%	LNS
Plumari	**Salvatore**	Associato	Prof. Associato	100%	LNS
Sambataro	**Maria Lucia**	Associato	Assegnista	100%	LNS

Budget (in k€)

	Missioni	Inviti	Seminari	Consumi	Inventariabile	Totale
Dotazioni	9	5	4	4	7	29
MONSTRE	7	-	-	-	-	7
SIM	12	-	-	-	-	12
Totale	28	5	4	4	7	48