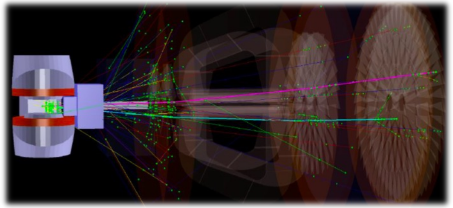
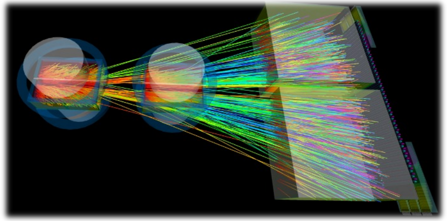
NA60++



NA61++

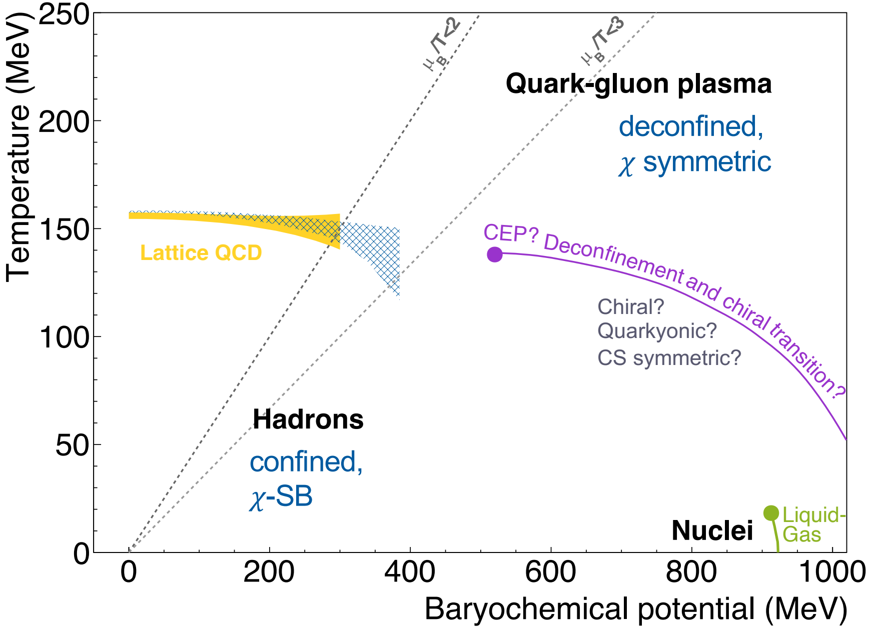


Physics potential of the NA ion programme

Tetyana Galatyuk, GSI / Technische Universität Darmstadt

Physics Beyond Colliders Annual Workshop, March 25-27, 2024, CERN

Searching for landmarks of the QCD matter phase diagram



Objective:

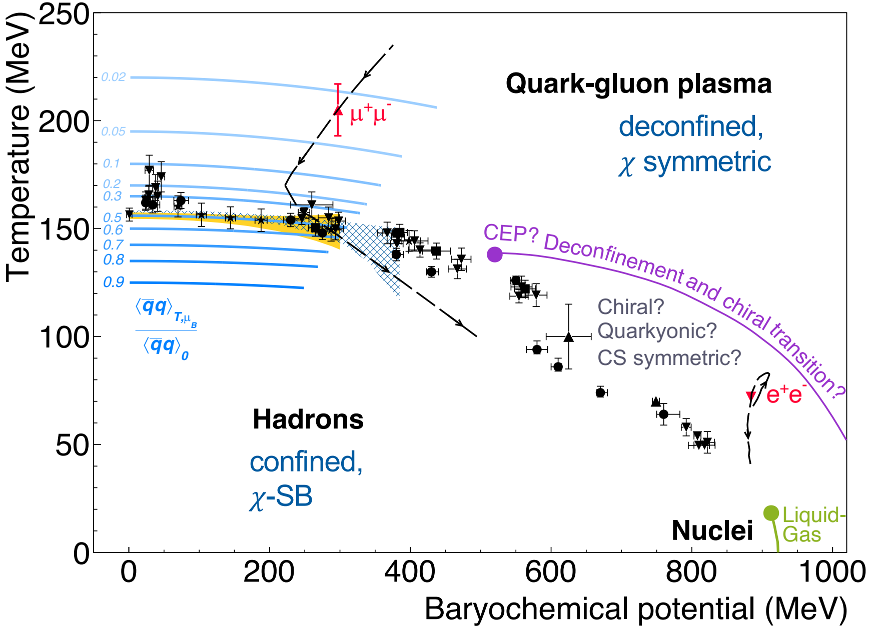
- decode the phases of nuclear matter in the non-perturbative regime of QCD
- unravel the role of the strong interaction in the evolution of our universe

Method:

- high-energy heavy-ion collisions
  - ⇝ recreate various forms of cosmic matter in laboratory
  - ⇝ investigate transient states of QCD matter under extreme conditions

Worldwide experimental and theoretical efforts

Searching for landmarks of the QCD matter phase diagram



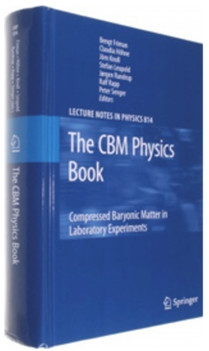
Experimental challenges:

- isolate unambiguous signals of new phases of QCD matter, order of phase transitions, conjectured QCD critical point
- probe microscopic matter properties

Measure with utmost precision:

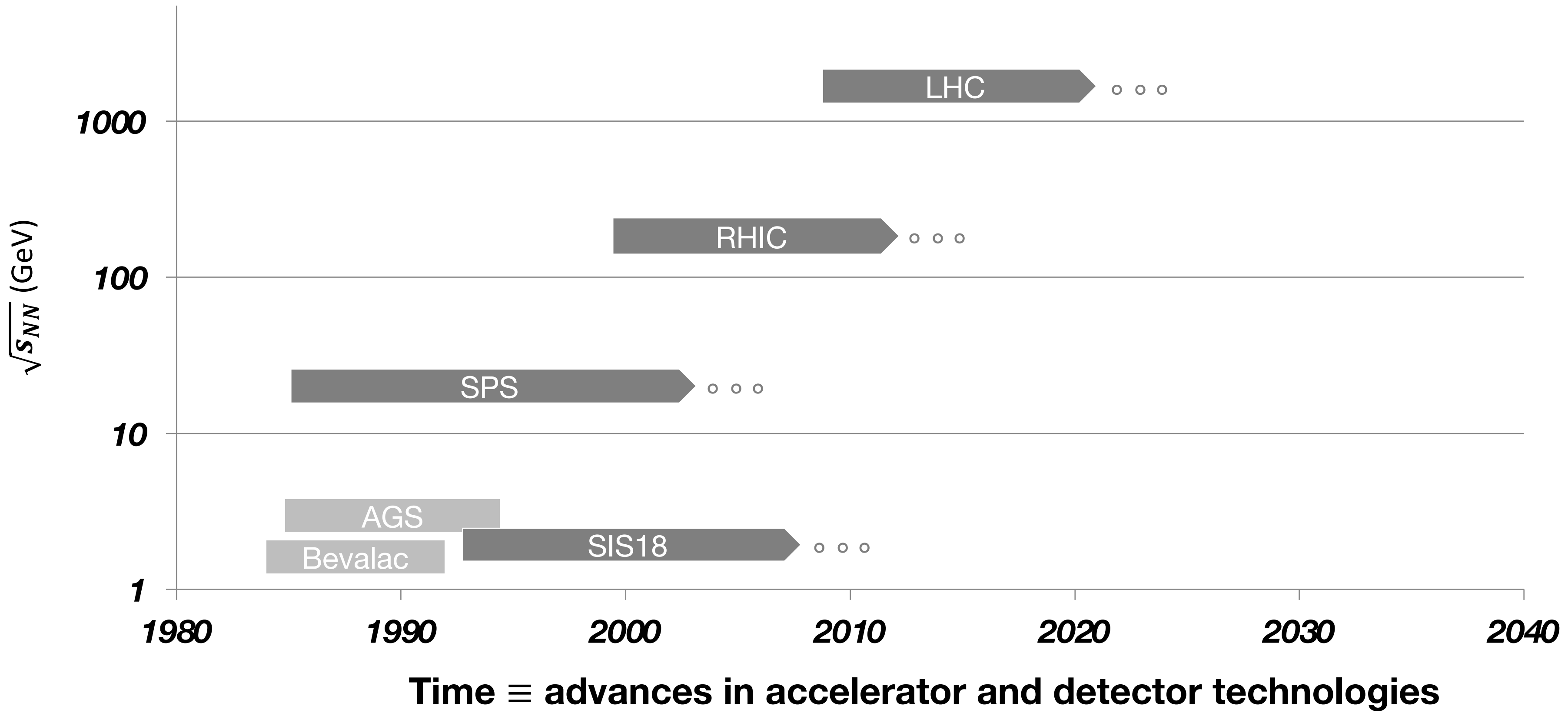
- light flavour (chemistry, vorticity, flow)
- event-by-event fluctuations (criticality)
- dileptons (emissivity)
- charm (transport properties)
- hypernuclei (interaction)

Almost unexplored (not accessible) so far in the high μ_B region



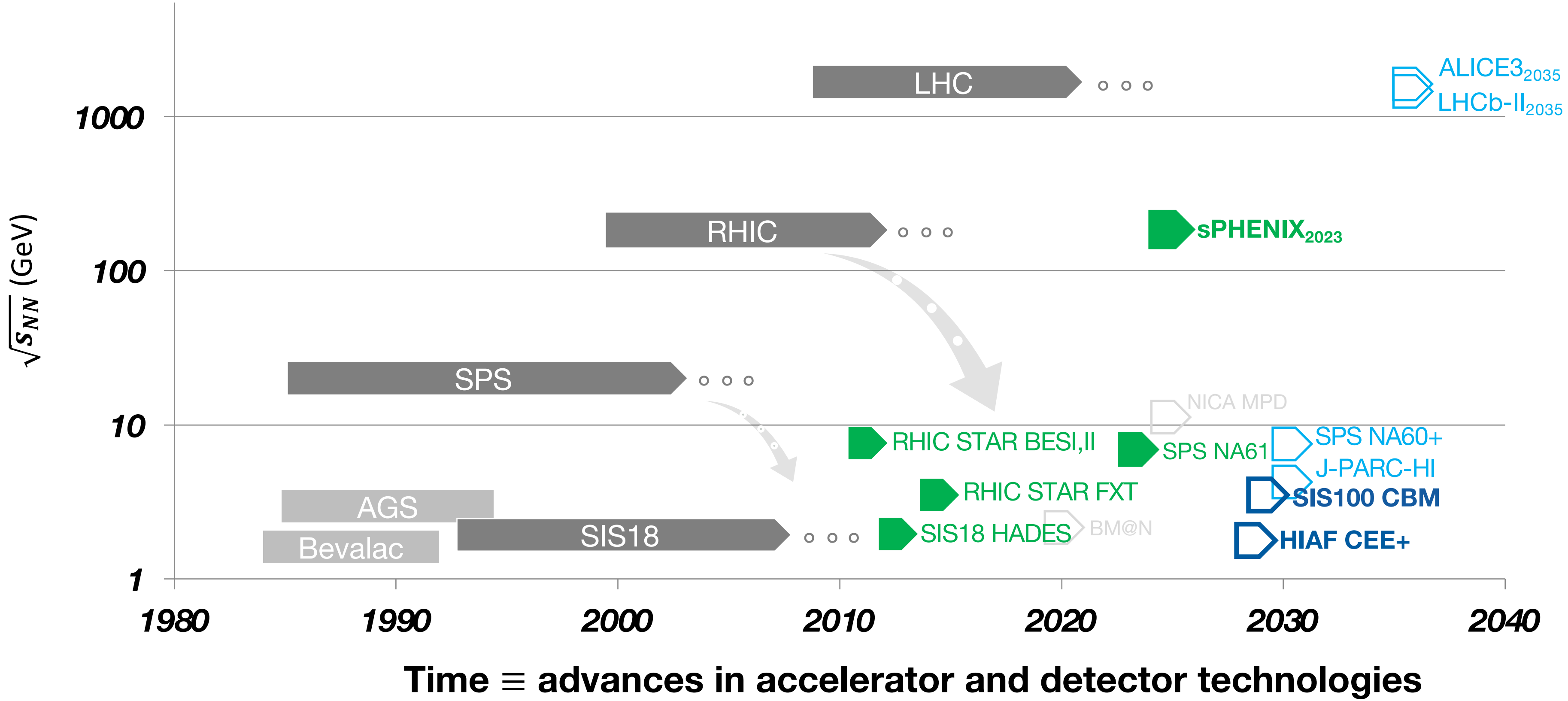
Friman *et al.*, Lect. Notes Phys. 814 (2011) 1

The quest for highest energy



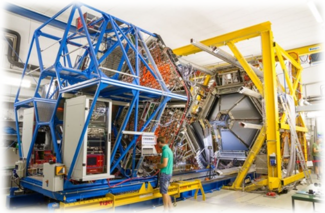
The quest for utmost precision and sensitivity for rare signals

~25 years progress in technology since AGS (begin of high μ_B explorations)



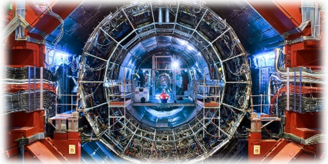
Extreme matter instruments

HADES

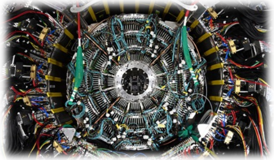


NA61/SHINE

ALICE

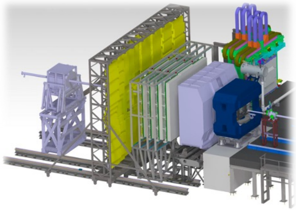


sPHENIX

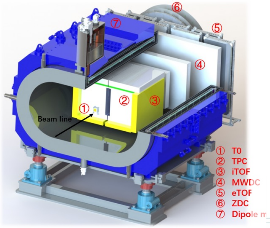


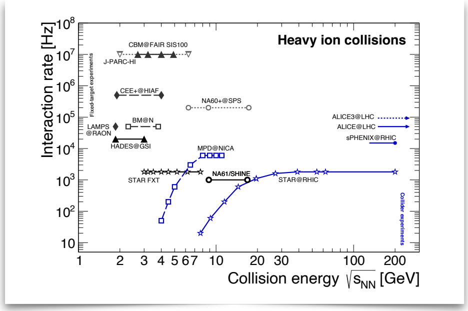
STAR

CBM

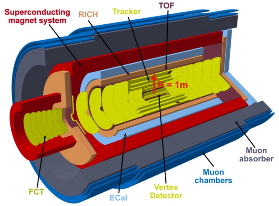


CEE+

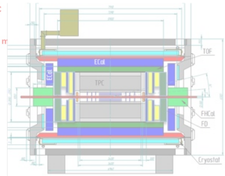




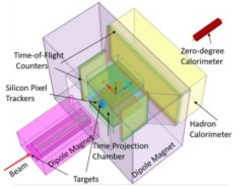
ALICE3



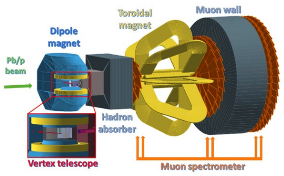
MPD



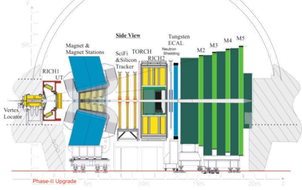
J-PARC-HI



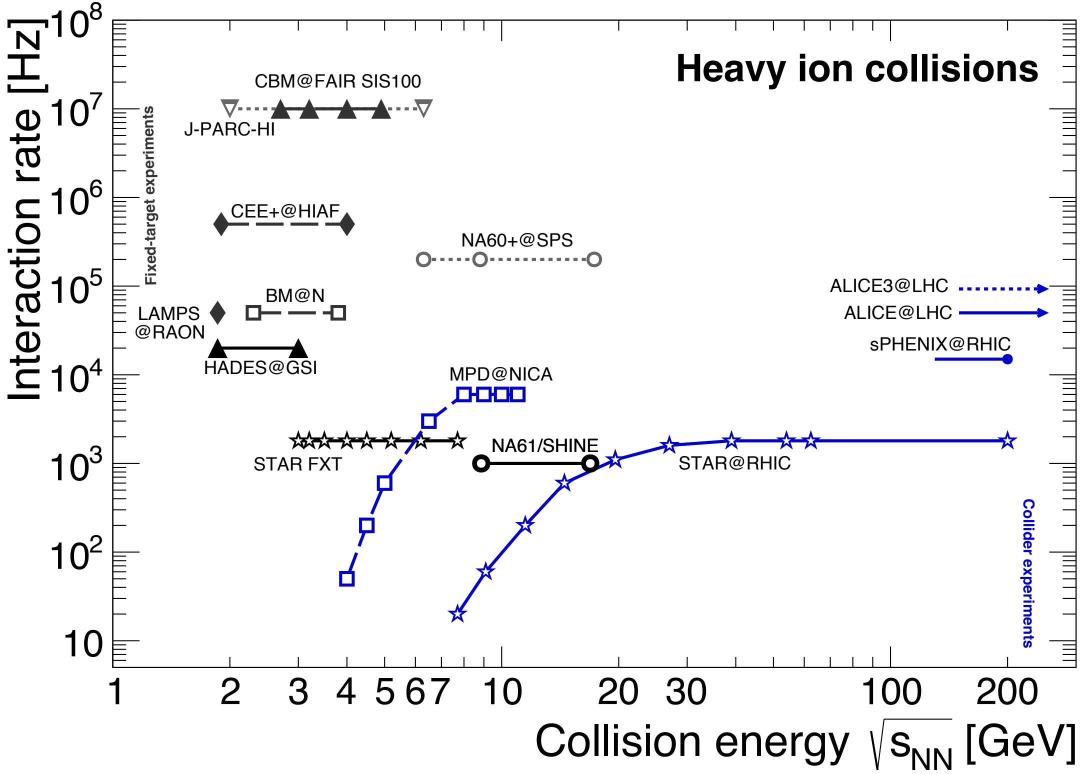
NA60+ at SPS



LHCb-II



Some basic facts on extreme matter facilities

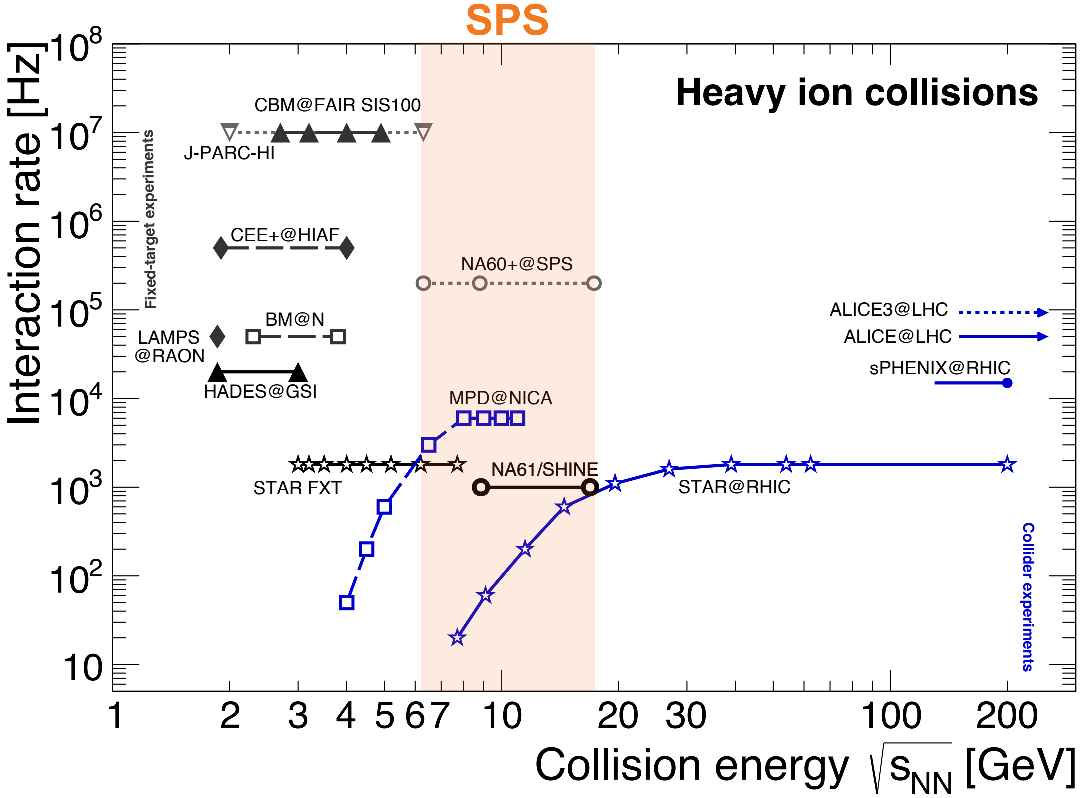


- **CBM** will play a unique role in the exploration of the QCD phase diagram in the region of high μ_B with rare and electromagnetic probes: high rate capability
- **HADES**: established thermal radiation at high μ_B, limited to 20 kHz and $\sqrt{s_{NN}}$=2.4 GeV
- **STAR FXT@RHIC**: BES program completed; limited capabilities for rare probes
- Proposals: **CEE+@HIAF, J-PARC-HI**
- **ALICE / ALICE 3:** exploit the forefront detector technologies and high luminosity potential of the LHC for ions

…

TG, NPA 982 (2019), update 2024 https://github.com/tgalatyuk/interaction_rate_facilities
CBM, EPJA 53 3 (2017) 60

Some basic facts on extreme matter facilities



SPS: wide energy range $6 < \sqrt{s_{NN}} < 17$ GeV, high luminosity beams 10^6 –10^7 ions/s, existing facility with renowned past and present results at top SPS …
… **and exciting future below top SPS**

- **NA61/SHINE:** multi-purpose experiment investigating hadron production since 2009
- **NA60++:** unique in energy coverage combined with $>10^5$ Hz rate capability ⇝ high statistics for rare and penetrating probes (thermal dileptons, open/hidden charm, strangeness)

LHC ⟶ RHIC ⟶ SPS ⟶ SIS program needs ever more precise data and sensitivity for rare signals

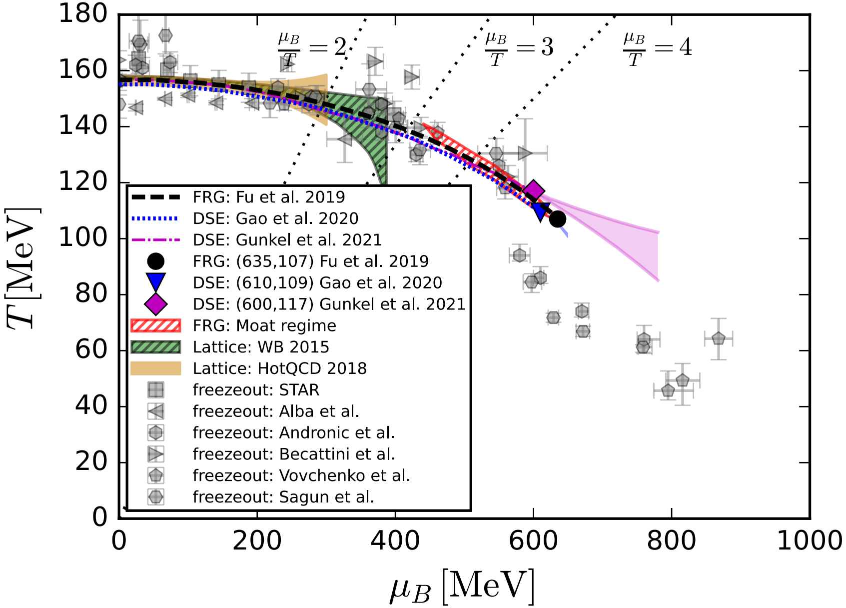
TG, NPA 982 (2019), update 2024 https://github.com/tgalatyuk/interaction_rate_facilities
CBM, EPJA 53 3 (2017) 60

Quest for critical phenomenon connected to the 1st order phase transition

CRITICALITY

Critical point predictions from theory

Pawlowski *et al.*, in preparation (2024)



Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
Borsanyi *et al*. [Wuppertal-Budapest], PRL 125 (2020)

- Lattice QCD disfavours QCD critical point at $\mu_B/T < 3$
- Functional QCD approaches predict QCD critical point in a similar ballpark: $\boldsymbol{T \sim 90 - 120}$ **MeV**, $\boldsymbol{\mu_B \sim 600 - 650}$ **MeV**
- If true, reachable in heavy-ion collisions at $\sqrt{s_{NN}} \sim \mathbf{3-5}$ **GeV** (FAIR)
- Including possibility that the QCD critical point does not exist

Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141
Vovchenko *et al.*, PRD 97, 114030 (2018)

Event-by-event fluctuations and statistical mechanics

- In strong interactions, baryons, electrical charges and strangeness are conserved ($q \in \{B, Q, S\}$)
- Event-by-event fluctuations of q predicted within grand canonical ensemble

cf. Friman *et al.*, EPJC 71 (2011) 1694
Stephanov, RPL 107 (2011) 052301

encodes the EoS

$$\frac{\kappa_n(N_q)}{VT^3} = \frac{1}{VT^3}\frac{\partial^n \ln Z(V,T,\vec{\mu})}{\partial(\mu_q/T)^n} = \frac{\partial^n \hat{P}}{\partial \hat{\mu}_q^n} \equiv \hat{\chi}_n^q$$

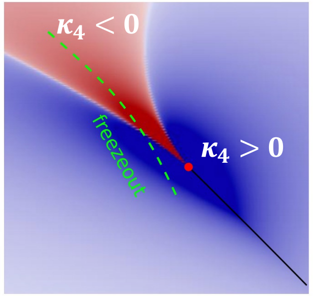
κ_n - cumulants (measurable in experiment)
$\hat{\chi}_n^q$ - susceptibilities (e.g. from lQCD)

Higher order cumulants describe the shape of measured distributions and quantify fluctuations

Variance $\kappa_2 = \langle(\delta N)^2\rangle = \sigma^2$

Skewness $\kappa_3 = \langle(\delta N)^3\rangle$

Kurtosis $\kappa_4 = \langle(\delta N)^4\rangle - 3\langle(\delta N^2)\rangle^2$



Stephanov, RPL 107 (2011) 052301

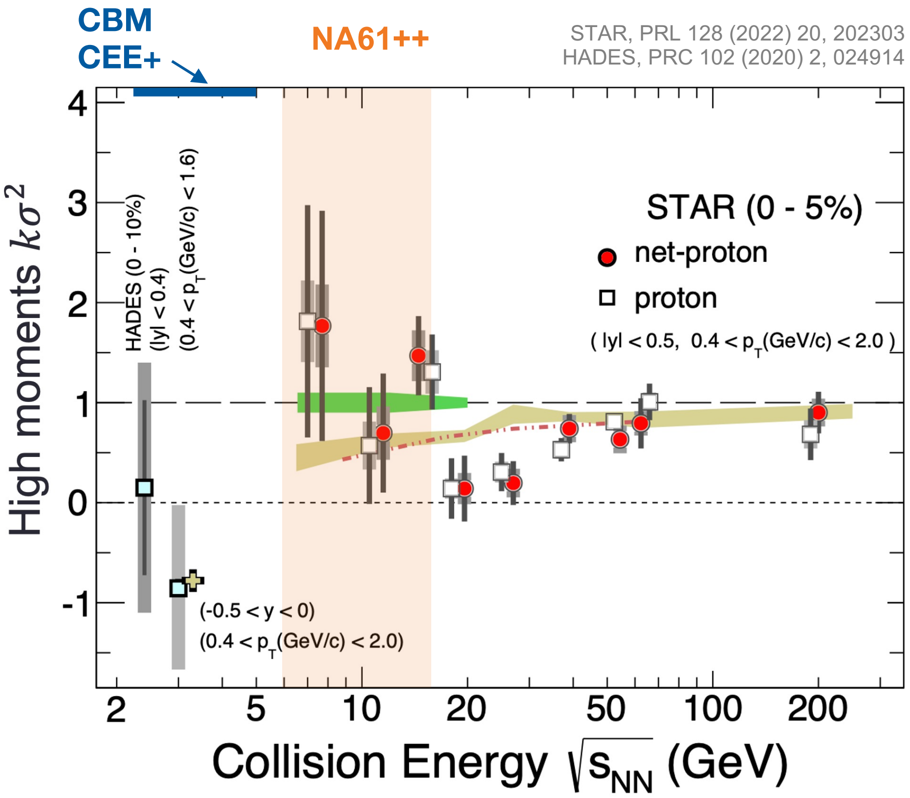
QCD critical point: large correlation length and fluctuations

$\kappa_2 \sim \xi^2,\ \kappa_3 \sim \xi^{4.5},\ \kappa_4 \sim \xi^7$

$\xi \rightarrow \infty$ **diverges at critical point**

➡ Look for **enhanced fluctuations** and **non-monotonicity**

Critical point search



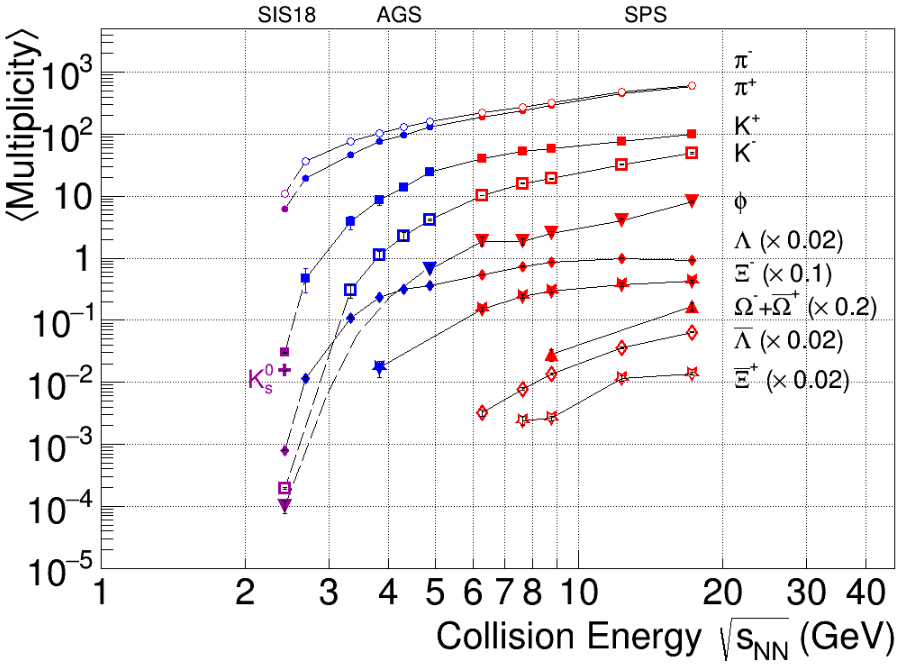
Non-monotonic trend of the higher moments κ_4/κ_2 of net-proton number distributions, visible in a beam energy scan?

- Current data consistent with non-critical physics?
  → reduced errors to come from STAR BES-II

Braun-Munzinger, Friman, Redlich, Rustamov, Stachel, NPA 1008 (2021) 122141

- NA61++
  - κ_4/κ_2 is universally negative when the critical point is approached on the crossover side ⇝ Pb-Pb data crucial to establish/verify the non-monotonic trend
  - energy scan with light and medium-mass ions (^{10}B, ^{16}O, ^{24}Mg, ^{40}Ar) to study onset of deconfinement

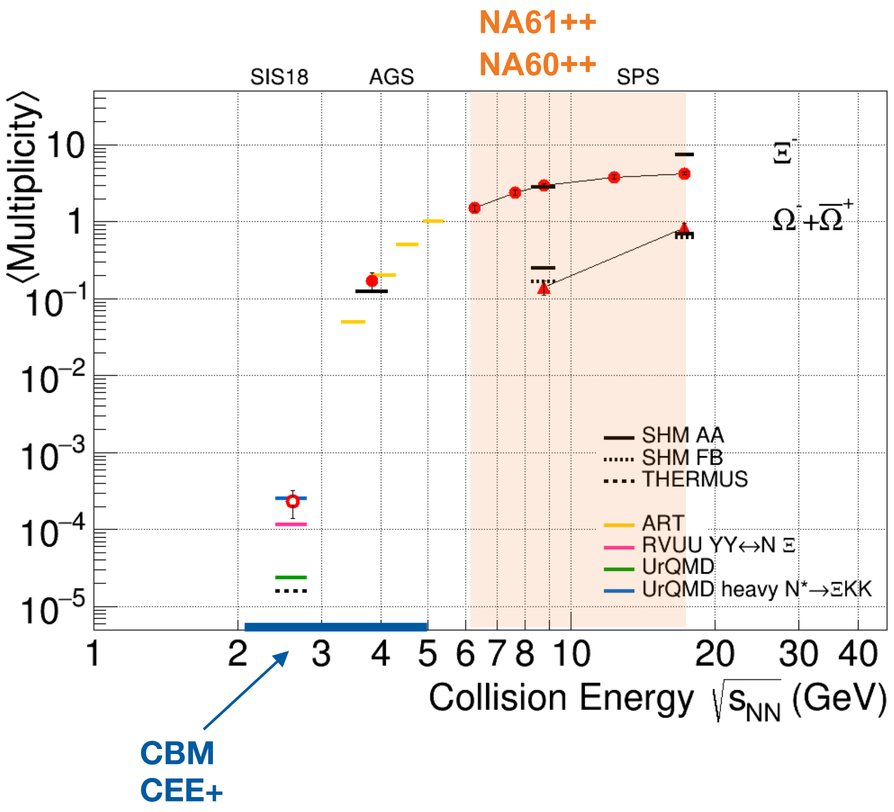
Multi-strange baryons



Blume, Markert, PPNP 66 (2011)
HADES, PLB 778 (2018)

- An impressive set of data, **however**

Multi-strange baryons



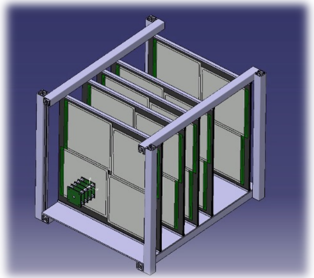
- An impressive set of data, **however** high-statistics, multi-differential data are missing for less abundant particles (Ξ, Ω)!

- Historically a signature for QGP
- High sensitivity to equation-of-state

- Precission measurements of spectra, flow pattern and polarization with NA61++ and NA60++

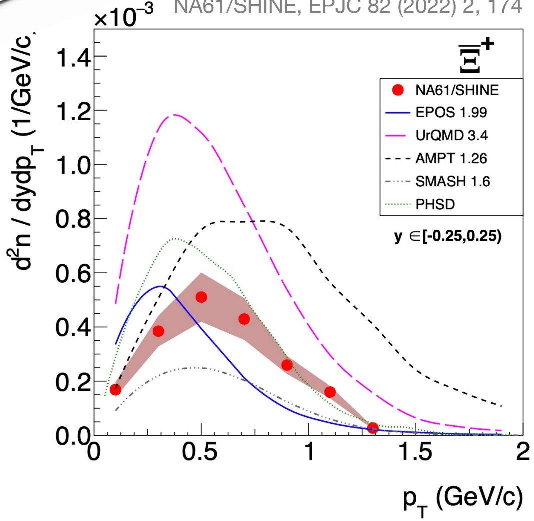
Anticipated physics performance

5-10 planes of MAPS detectors



NA61++

NA61/SHINE, EPJC 82 (2022) 2, 174

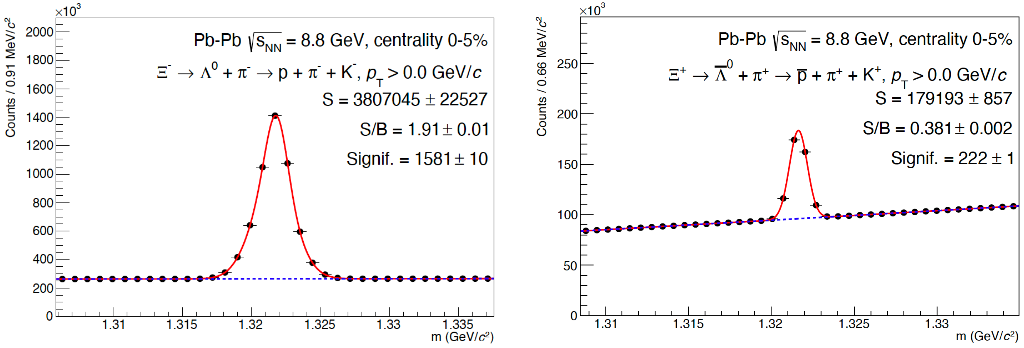


- $\Xi^-, \bar{\Xi}^+$ production in pp at $\sqrt{s_{NN}} = 17.3$ GeV
- important constraint for model calculations

⇝ Pb-Pb data

NA60++

- no hadron identification
- employ decay-vertex topology in the vertex spectrometer



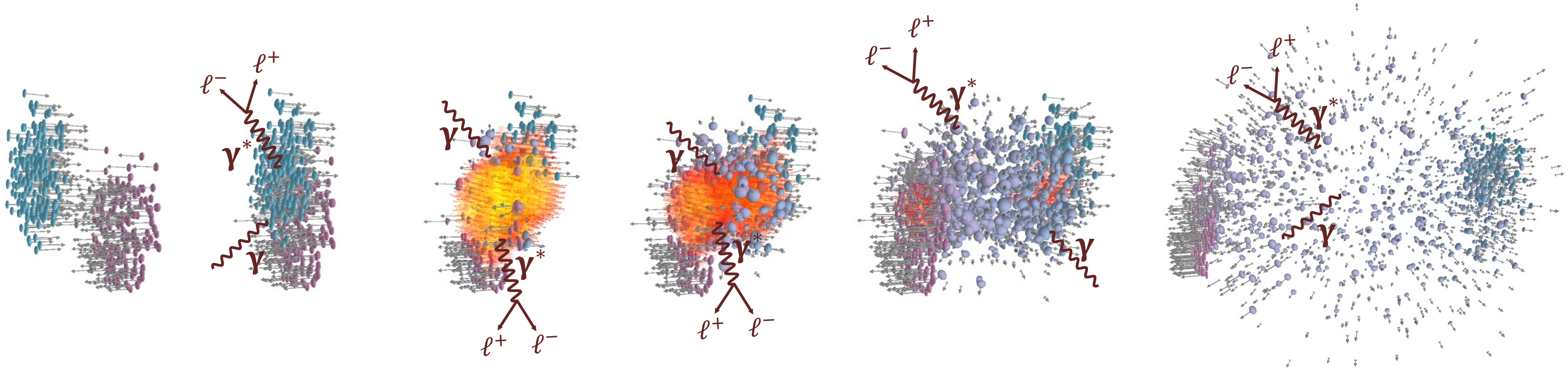
Alocco *et al.*, NA60+, PoS FAIRness2022 (2023) 002

- large statistical significance for $K_S^0, \Lambda, \Xi, \Omega$ as well as $\phi \rightarrow K^+K^-$
- allows multi-differential analysis of yield, flow, polarization
- similar technique to measure hypernuclei

Electromagnetic radiation

EMISSIVITY

Electromagnetic radiation as multi-messenger of fireball



Electromagnetic radiation (γ, γ^*)

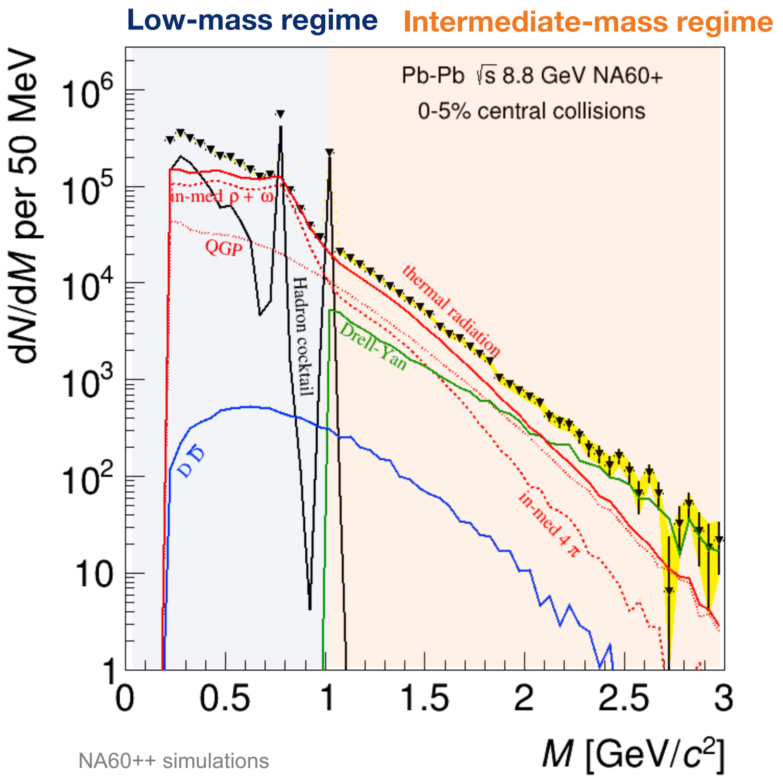
Reflect the whole history of a collision

No strong final state interaction
⇝ leave reaction volume undisturbed

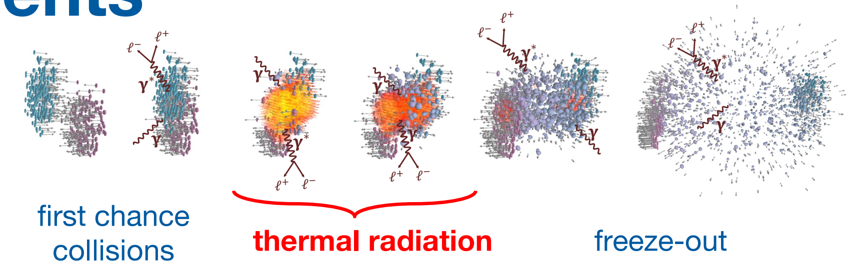
Encodes information on matter properties enabling unique measurements

- degrees of freedom of the medium
- fireball lifetime, temperature, acceleration, polarization
- transport properties
- restoration of chiral symmetry

Thermal dilepton measurements

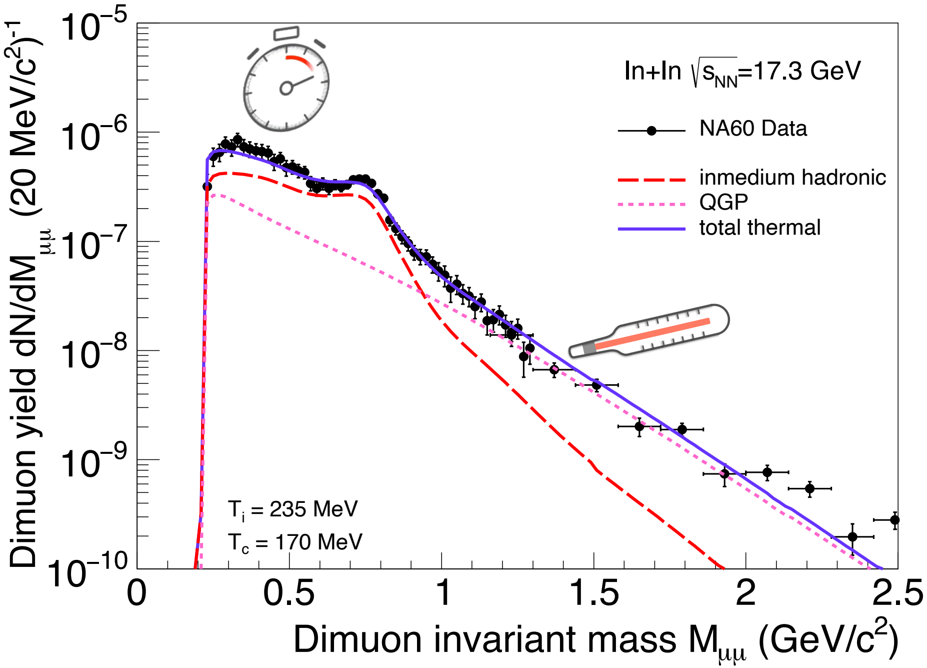


NA60++ simulations



- Dileptons are rare probes!
- Decisive parameters for data quality:
  interaction rates (IR) and signal-to-combinatorial background ratio (S/CB): effective signal size: $S_{eff} \sim IR \times S/CB$
- Needs coverage of mid-rapidity, low-$M_{\ell\ell}$, and low-p
- Isolation of thermal radiation by subtraction of measured decay cocktail $(\pi^0, \eta, \omega, \varphi)$, Drell-Yan, $c\bar{c}$ $(b\bar{b})$

Thermal dileptons from NA60



NA60, EPJC 61(2009) 711
NA60, Chiral 2010, AIP Conf.Proc. 1322 (2010)
Rapp, v. Hess, PLB 753 (2016) 586

'Planck-like' **In-medium spectral function**

$$\frac{dN_{ll}}{d^4q\,d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^B(q_0, T)\, Im\Pi_{em}(M, q, T, \mu_B)$$

McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

- ρ-meson peak undergoes a strong broadening in medium, baryonic effects are crucial
- in-medium spectral function from many-body theory consistently describes SIS18, SPS, RHIC, LHC energies

Rapp and Wambach, Adv.Nucl.Phys. (2000) 25

Thermal dileptons excitation functions

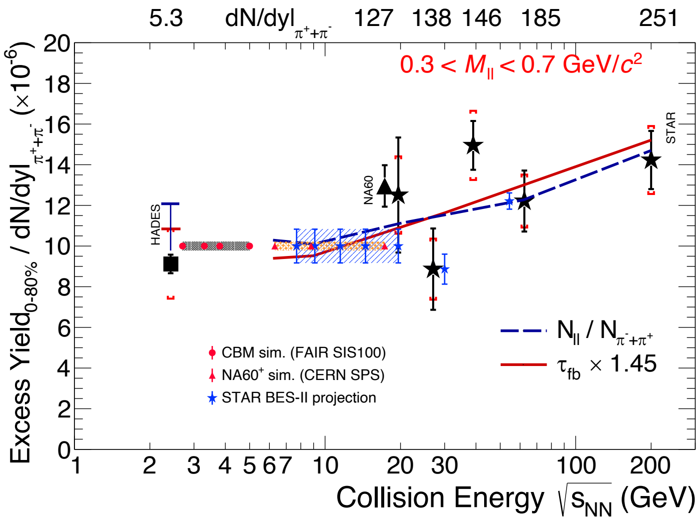
Excess yield in LMR tracks fireball lifetime

- Search for "**extra radiation**" due to latent heat around **phase transition** (& critical point?)
- Precision sufficient to observe 1st order phase transition, predicted to be of the order 2 – 3

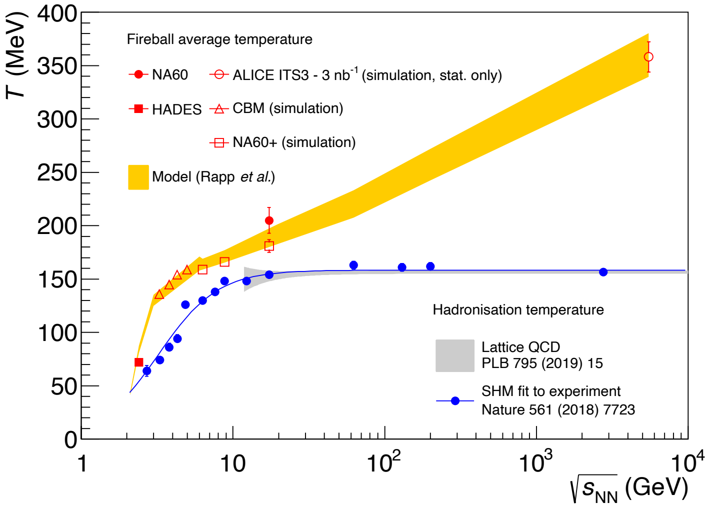
Savchuk, TG, *et al.*, J.Phys.G 50 (2023) 12, 125104

Invariant mass slope measures radiating source T

- **Flattening** of caloric curve (T vs ε) → evidence for a **phase transition**
- Probe time dependence of fireball temperature: *$M_{\ell\ell}$ versus v_2, photon polarization*



TG, JPS Conf.Proc. 32 (2020) 010079



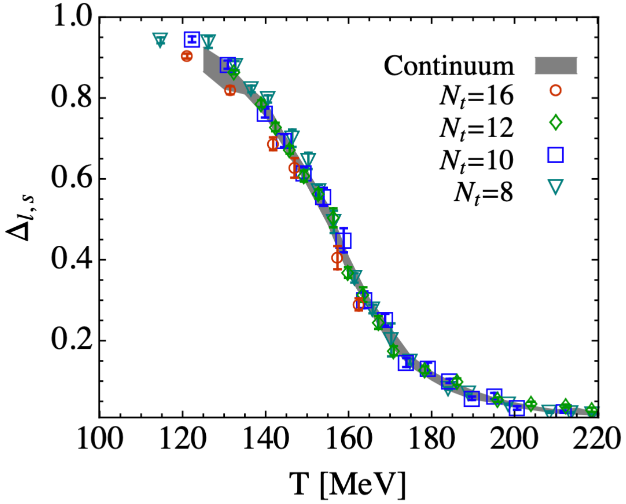
https://github.com/tgalatyuk/QCD_caloric_curve

Dileptons and chiral symmetry of QCD

Spontaneously broken in the vacuum

$\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \neq 0$

Condensates $\langle\bar{q}q\rangle$ calculated by lattice QCD

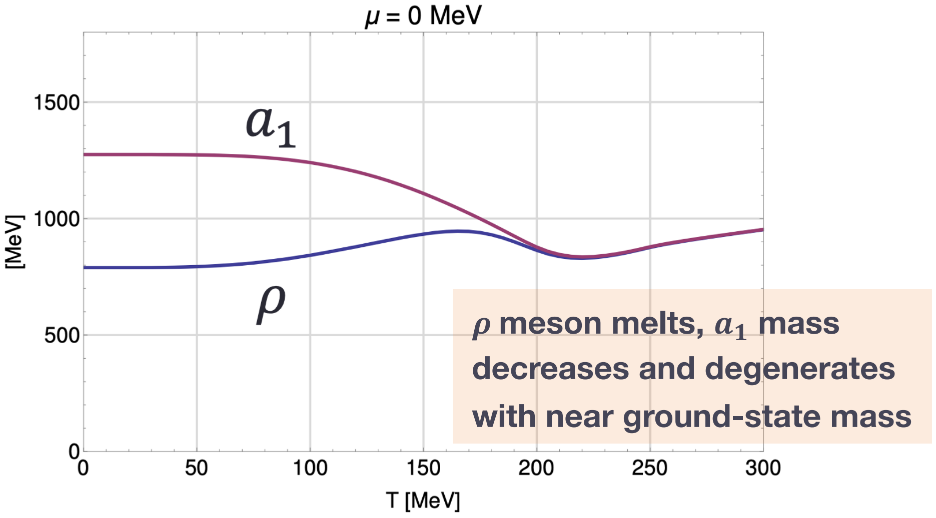


Bazavov *et al.* [Hot QCD Coll.], PRD90 (2014) 094503

S. Weinberg, PRL 18 (1967) 507

$$\int_0^\infty \frac{ds}{\pi}[\Pi_V(s) - \Pi_{AV}(s)] = m_\pi^2 f_\pi^2 = -2m_q\langle\bar{q}q\rangle$$

Restoration at finite T and μ_B manifests itself through mixing of vector and axial-vector correlators



Hadronic many-body theory Hohler and Rapp, PLB 731 (2014)
FRG Jung, Rennecke, Tripolt, v. Smekal, Wambach, PRD95 (2017) 036020
Light mesons and baryons from lattice QCD, Aartz, QM2022, April 2022

Signature for chiral symmetry restoration: chiral $\rho - a_1$ mixing

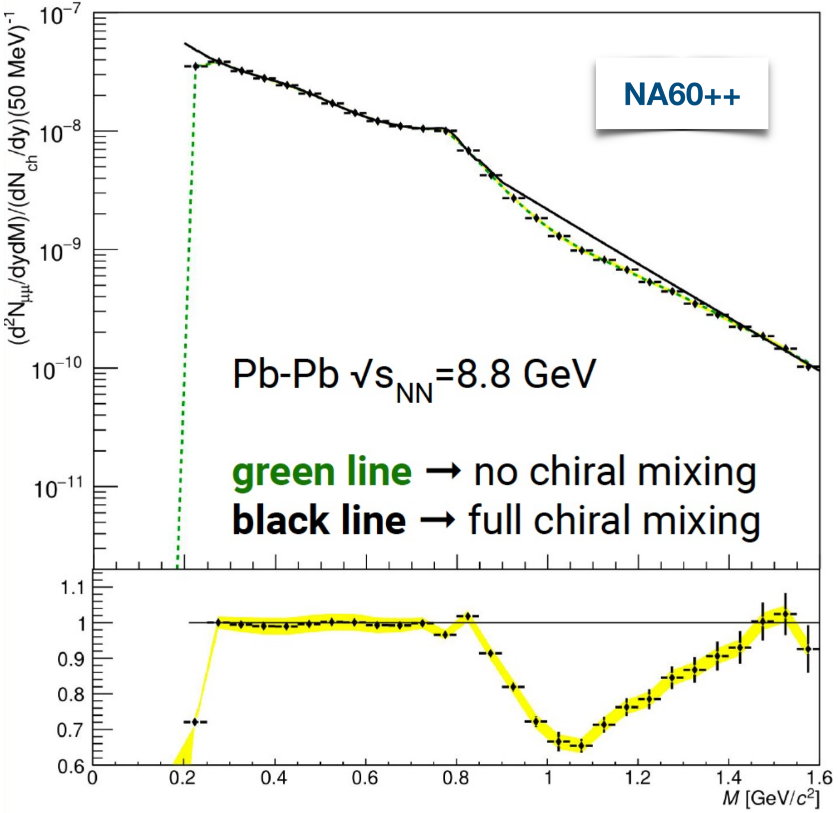
Experimental challenge: physics background ($M_{\ell\ell}$ > 1 GeV)

- correlated charm: excellent vertex resolution → topological separation of prompt and non-prompt source employing DCA cut
- QGP: decrease towards lower energy
- 𝒟rell-𝒴an: pp, pA measurements

- **20-30% enhancement** w.r.t. no chiral mixing is **predicted** in the region 0.8<M<1.5 MeV/c^2

Dey, Eletsky, Ioffe, PLB252 (1990)
Rapp, Wambach, ANP 25 (2000)
Sakai *et al.*, arXiv:2308.03305 [nucl-th]

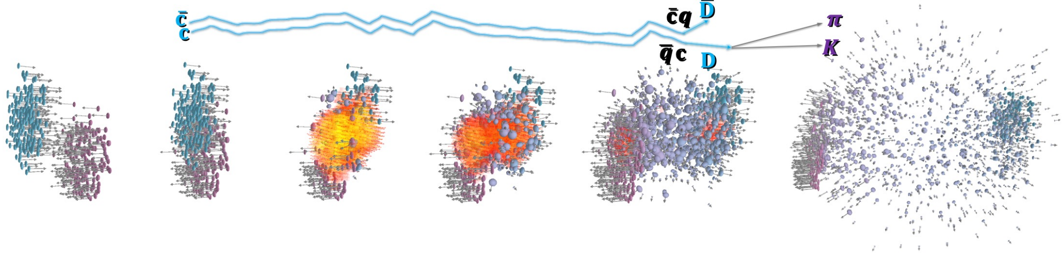
- **NA60++ sensitivity** (statictical and systematic) to detect a signal is **demonstrated**



Charm $(c, \bar{c})$ of the baryon-rich matter

IN-MEDIUM QCD FORCE

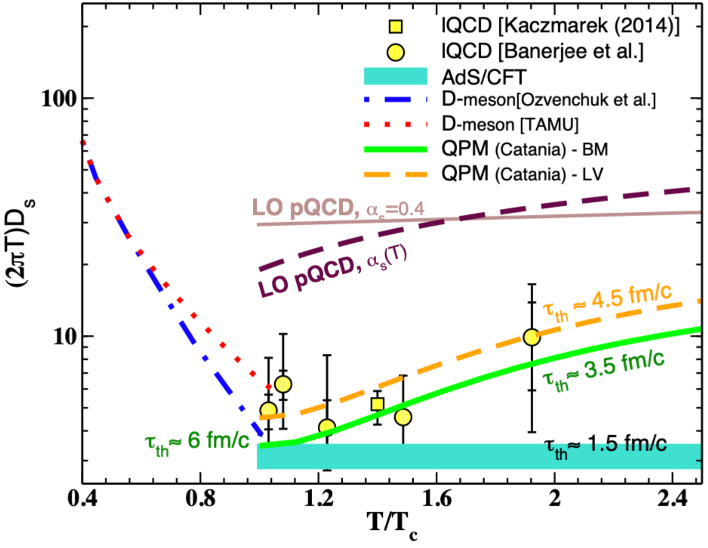
What is so “charming” about charm?



Heavy quarks

- produced in initial hard scattering processes
- experience the full evolution of the QCD medium

→ **probe in-medium QCD force!**



Scardina *et al.*, PRC96, 044905 (2017)
HotQCD, PRLett. 132 (2024) 5, 051902

- heavy-quark potential accurately known in the vacuum (Ψ , Υ spectroscopy)
- $\mu_B = 0$, finite T – heavy-quark potential is modified (screened), guidance from LQCD

How is the fundamental QCD force screened at $\mu_B > 0$?

Consequences for heavy-quark transport

$\sqrt{s_{NN}}\sim 6$ GeV (and below) increased sensitivity to hadronic medium effects – important input for precision measurements at LHC

First step: charm measurement with NA61/SHINE

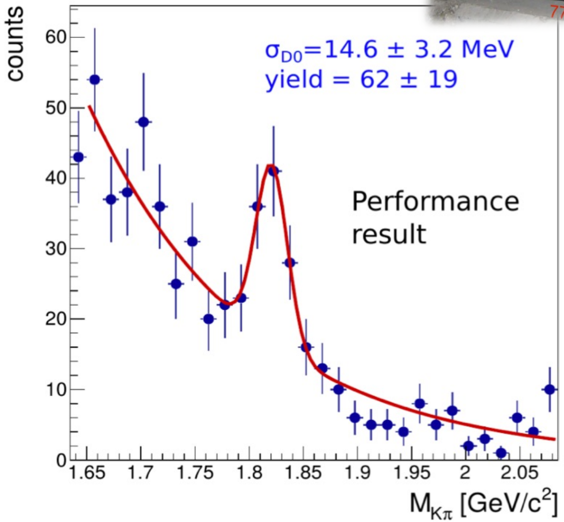
- NA61/SHINE (upgrade of vertex detector)
  - Measurement of open charm cross section at 150 and 40 *A*GeV Pb-Pb collisions feasible
  - Study of $c\bar{c}$ correlations could be attempted, might be statistically limited

Estimate for $5{\times}10^8$ min.bias events at 150 *A*GeV

	0–10%	10–20%	20–30%	30–60%	60–90%
$\#(D^0+\overline{D^0})$	31k	20k	11k	13k	1.3k
$\#(D^+ + D^-)$	19k	12k	7k	8k	0.8k
$\langle W \rangle$	327	226	156	70	11

Small Acceptance Vertex Detector

Pilot Run 2018, 150 *A*GeV



detector technology - synergy with ALICE and CBM

Larsen *et al.*, NA61/SHINE, EPJ Web Conf. 191 (2018) 05003

Charm of NA60++

Open charm

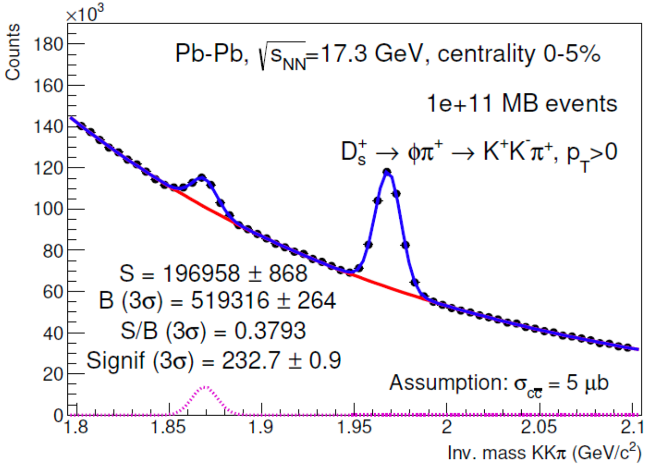
- 3×10^6 **D^0**, 0-5% Pb-Pb, $\sqrt{s_{NN}} = 17.3$ GeV
- accessible also at lower $\sqrt{s_{NN}}$ with 1% statistical precision
  ↝ R_{AA} and v_2 vs p_T, y and centrality
  → charm diffusion coefficient and thermalization

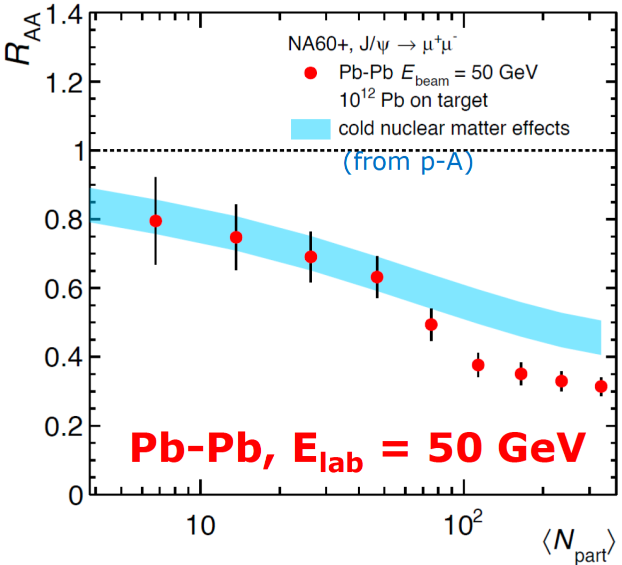
- **D_s** and **Λ_c** yield feasible with statistical precision of few percent
  → insight on hadronization mechanism

J/ψ

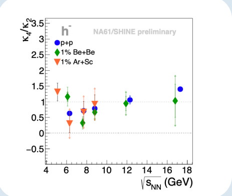
- detection of **onset of anomalous suppression** effects down to low SPS energy ($\psi(2S)$ also within reach for E~100 AGeV)
- pA collisions to establish cold nuclear matter effects
- study intrinsic charm component of the hadron wave function

Vogt, PRC 106 (2022) 2, 025201
NNPDF, Nature 608 (2022) 7923, 483-487

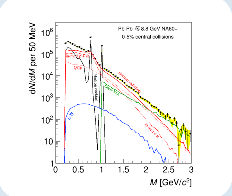




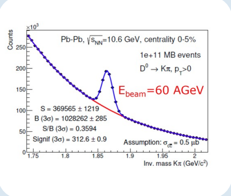
NA experiments complementarity



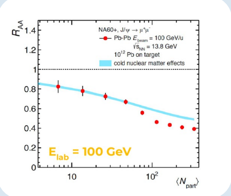
Fluctuations



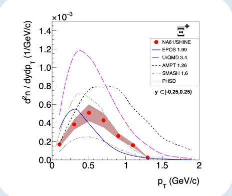
Dileptons



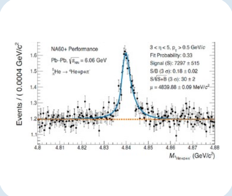
Open charm



Charmonium



Hadrons



Hypernuclei

	Fluctuations	Dileptons	Open charm	Charmonium	Hadrons	Hypernuclei
NA60++		●	●	●	● $(K_S^0, \Lambda, \Xi, \Omega, \phi)$	●
NA61++	●		● (stat. lim.)		●	●

NA61++: neutrino and cosmic ray physics:

- measurements for neutrino programs at J-PARC and Fermilab
- measurements of nuclear fragmentation cross section for cosmic ray physics

Résumé and prospects

Encouraging prospects for studying high μ_B region

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  - quest for deconfinement / chiral symmetry restoration conditions at high μ_B
  - quest for the conjectured QCD critical point
- **Challenges**
  - rare and statistics „hungry“ observables, systematic effects
  - many aspects – nature of transitions between the various phases, relevant EoS, spectral properties of hadrons in the medium, collective and transport properties of the medium, ... – await a better understanding
- **Opportunities**
  - discoveries, EoS of dense matter and connection to violent stellar processes
  - development of forefront detector technologies

➥ **Systematic energy scan with full exploration of all relevant observables from LHC ⟶ RHIC ⟶ SPS ⟶ SIS offer important complementarities!**

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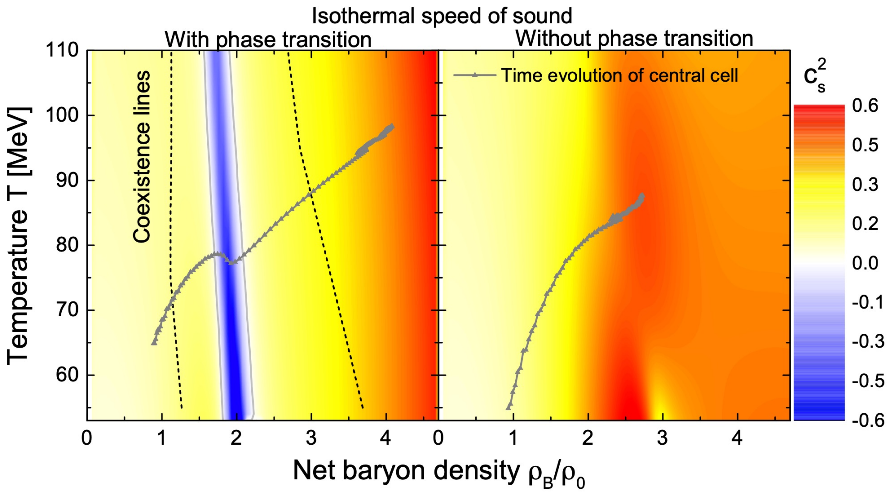
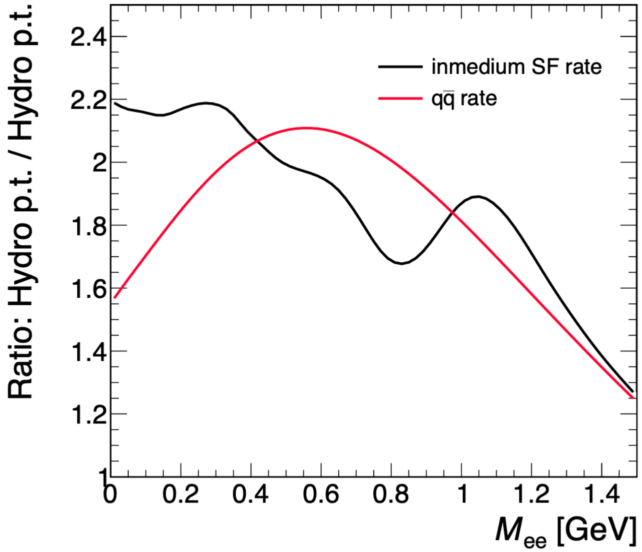
Bonus slides

Dilepton signature of a 1st order phase transition

Seck, TG, *et al.*, PRC 106 (2022) 1, 014904

See also:
Savchuk, TG, *et al.*, J.Phys.G 50 (2023) 12, 125104
Tripolt *et al.*, NPA 982 (2019) 775
Li and Ko, PRC 95 (2017) no.5, 055203





- Ideal hydro simulations with and w/o first order nuclear matter – quark matter phase transition
- Chiral Mean Field model that matches lattice QCD at low μ_B and neutron-star constraints at high density

Most et al., PRD 107 (2023) 4, 043034

Dilepton emission shows a significant effect: factor 2 enhancement of dilepton emission due to extended "cooking"