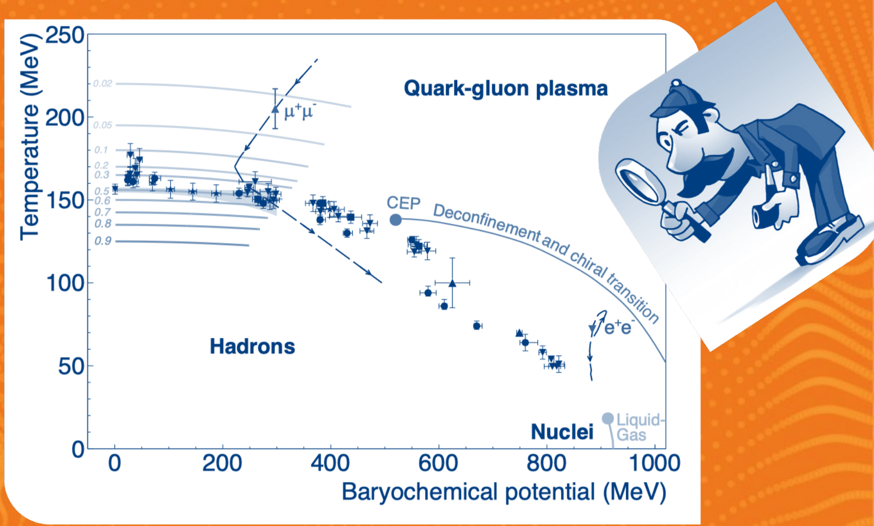
HELMHOLTZ

RESEARCH FOR GRAND CHALLENGES

EMERGING FACILITIES TO STUDY QCD MATTER AT HIGH μ_B WITH RARE PROBES



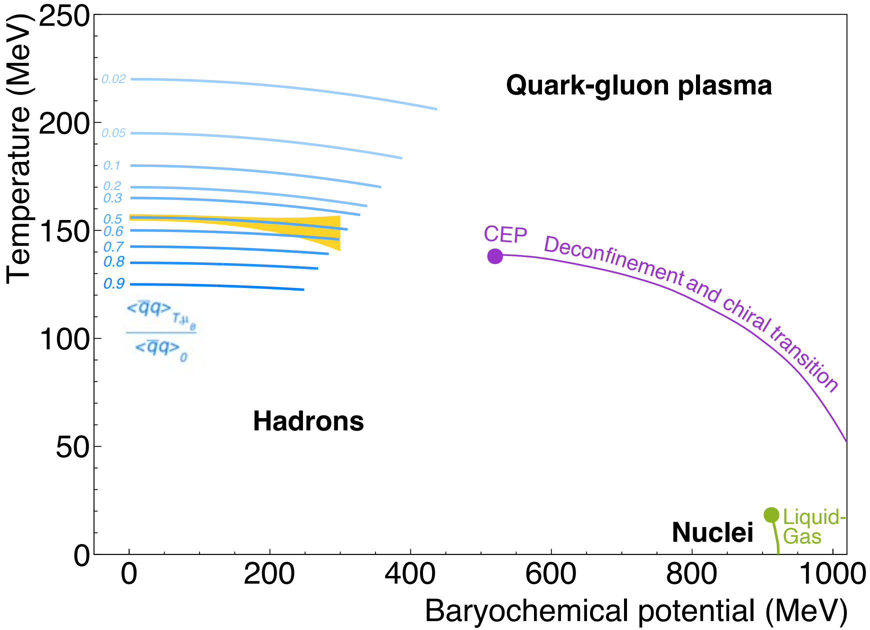
Tetyana Galatyuk

GSI/ TU Darmstadt

Terzo inconto di fisica con ioni pesanti alle alte energie 2021 | 25-26 Nov 2021

GSI TECHNISCHE UNIVERSITÄT DARMSTADT HFHF Helmholtz Forschungsakademie Hessen für FAIR Bundesministerium für Bildung und Forschung EL EM EN TS CRC-TR 211

SEARCHING FOR LANDMARKS OF THE QCD MATTER PHASE DIAGRAM



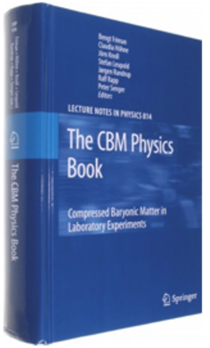
Borsanyi et al. [Wuppertal-Budapest Collab.], JHEP 1009 (2010) 073
Isserstedt, Buballa, Fischer, Gunkel, PRD 100 (2019) 074011
Fu, Pawlowski, Rennecke, PRD 101, (2020) 054032
Gao, Pawlowski, PLB 820 (2021) 136584

- **Vanishing μ_B, high T (lattice QCD)**
  - crossover
    - $T_{pc} \cong 156$ MeV (physical quark masses)
    - $T_c \cong 132$ MeV (chiral limit)
  - no critical point indicated by lattice QCD at $\mu_B^{CEP}/T_c \leq 3$

Bazavov et al. [HotQCD], PLB 795 (2019) 15-21
Ding et al. [HotQCD], PRL 123 (2019) 6, 062002

- **Large μ_B moderate T (lQCD inspired models)**
  - limits of hadronic existence?
  - 1st order transition?
  - QCD critical point?
  - equation-of-state of dense matter?

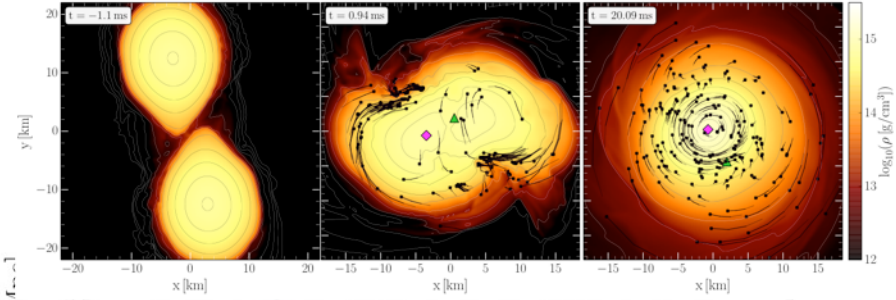
High μ_B region – large discovery potential!

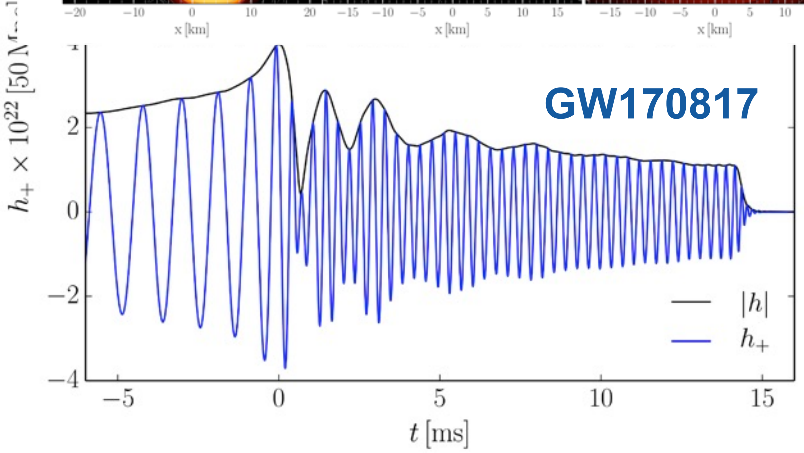


B. Friman *et al.*, Lect. Notes Phys. 814 (2011) 1

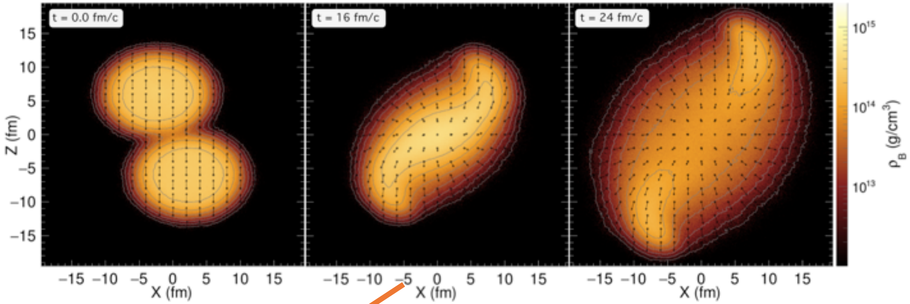
LABORATORY STUDIES OF THE MATTER PROPERTIES (EoS) IN COMPACT STELLAR OBJECTS

Neutron Star merger (model calculations)





Au+Au $\sqrt{s_{NN}} = 2.4\ GeV$ (UrQMD)



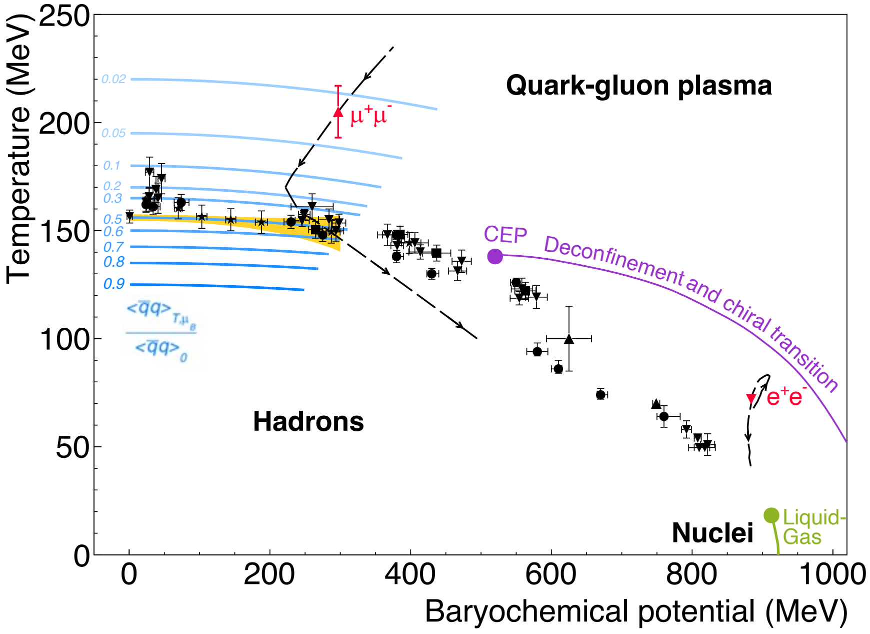
- T < 70 MeV, $\rho < 3\rho_0$ for both (note the different isospin)
- Role of YN, YY phase shifts in EOS!

  HADES Collab. Phys.Rev. C94 (2016) 025201
  ALICE Collab. Nature 588 (2020) 232-238

Hanauske, Journal of Phys.: Conf. Series 878 (2017) 012031
Rezzolla *et al.*, Phys. Rev. Lett. 122, no. 6, 061101 (2019)

Strong connections between the fields

SEARCHING FOR LANDMARKS OF THE QCD MATTER PHASE DIAGRAM



HADES Collab., Nature Phys. 15 (2019) 10, 1040-1045
Andronic *et al.*, Nature 561 (2018) no.7723

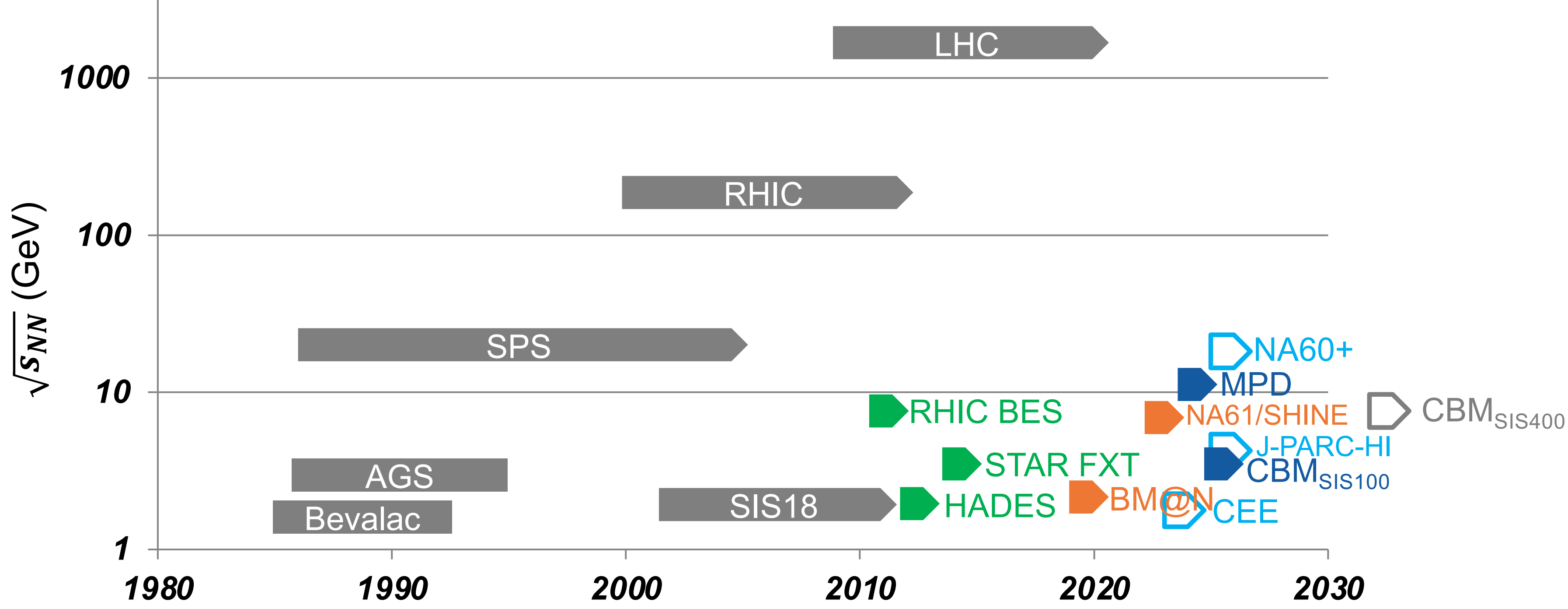
- **Experimental challenge:**
  - locate the onset of QGP
  - detect the conjectured QCD critical point
  - probe microscopic matter properties

- **Measure with utmost precision:**
  - strangeness (chemistry)
  - charm (transport properties)
  - e-b-e correlations and fluctuations (criticality)
  - dileptons (emissivity of matter)

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

QUEST FOR HIGHEST PRECISION AND SENSITIVITY FOR RARE SIGNALS

~20 years progress
in technology since AGS
(begin of high μ_B explorations)



Time ≡ advances in accelerator and detector technologies

RUNNING AND PLANNED HIGH μ_B FACILITIES

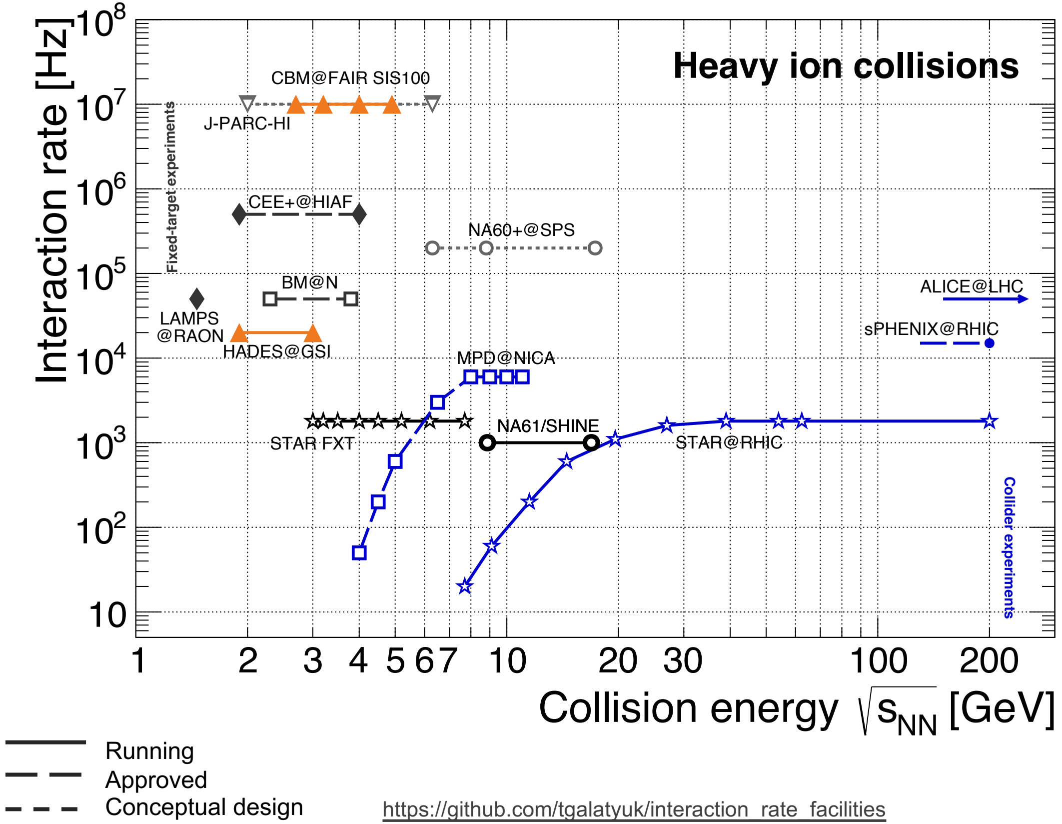
Facility	SIS18	HIAF	Nuclotron	J-PARC-HI	SIS100	NICA	RHIC	SPS	SPS
Experiment	HADES /mCBM	CEE	BM@N	DHS, D2S	CBM / HADES	MPD	STAR	NA61/SHINE	NA60+
Start	2012, 2018	2023	2022 (Au)	>2025(?)	2025	2022	2010, 2019	2009 - 2022	>2025(?)
$\sqrt{s_{NN}}$, GeV	2.4 – 2.6	2 – 2.7	2 – 3.5	2 – 6.2	2.7 – 5	4 – 11	3 – 19.6	4.9 – 17.3	4.9 – 17.3
μ_B, MeV	800 – 770	880 – 760	880 – 670	880 – 430	760 – 500	580 – 300	720 – 210	520 – 230	520 – 230
Hadrons	+	+	+	+	+	+	+	+	(+)
Dileptons	+			+	+	+	+		+
Charm				(+)	(+)	+	+	+	+

Compilation TG, Nucl.Phys. A982 (2019)

Allows overlap and independent confirmation of results

SOME BASIC FACTS ON HIGH μ_B FACILITIES

TG, Nucl.Phys. A982 (2019), update 2021
CBM, EPJA 53 3 (2017) 60



https://github.com/tgalatyuk/interaction_rate_facilities

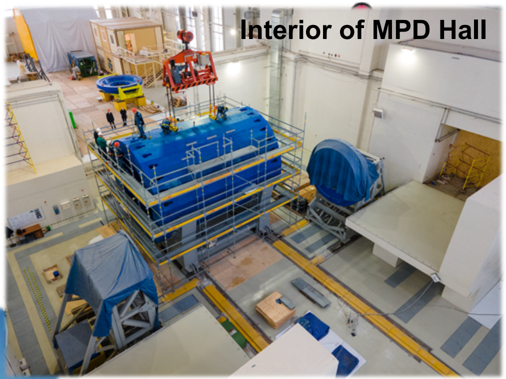
Program needs high precision data

- High intensity beams
- Multipurpose detectors:
  - Large acceptance, high efficiency
  - Trigger-less, free streaming read-out electronics with high bandwidth online event selection
- Substantial progress in detector technologies (mainly driven by ALICE upgrade, CBM and sPHENIX)
- High-performance / scientific computing

FACILITIES

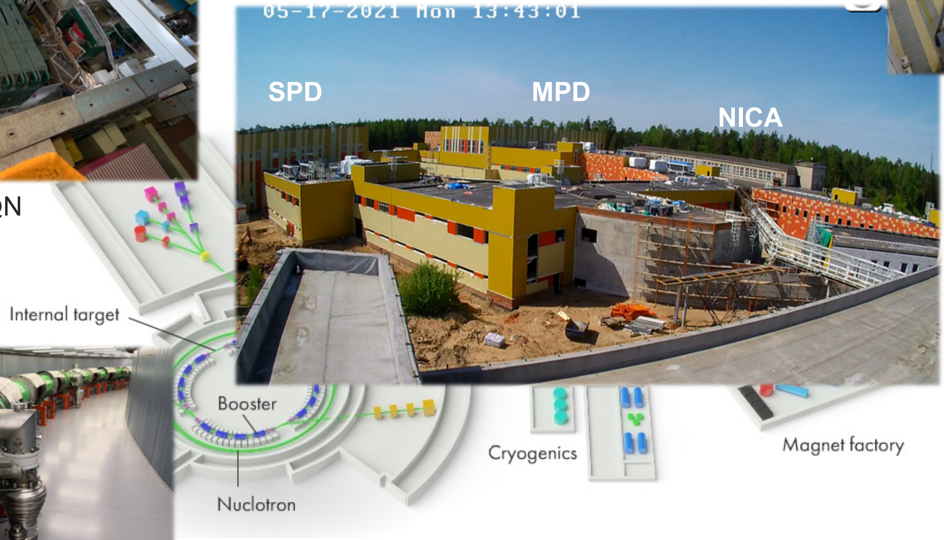
NICA ACCELERATOR COMPLEX IN DUBNA

Nuclotron-based Ion Collider Facility at JINR (NICA Complex)



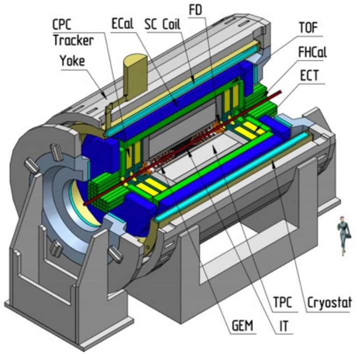
BM@N
in operation
since 2018

Baryonic Matter at Nuclotron BM@N
10 countries, 20 institutions,
246 members



Booster commissioning Dec 30th, 2020:
Injected He^{1+}, 3.2 MeV/u,
Accelerated up to 100 MeV/u
(design value 600 MeV/u)

All components of the MPD Stage I configuration advanced in production



Multi-Purpose Detector (MPD)
12 countries, >500 members,
42 institutes and JINR

NICA RUNNING PLAN

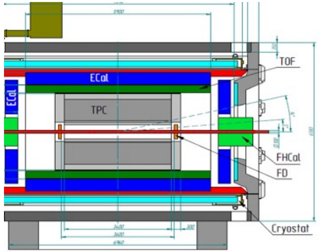
2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028

Extensive commissioning of Booster

Heavy-ion (Fe/Kr/Xe) run of Booster + Nuclotron setup

Completion of Collider and transfer lines

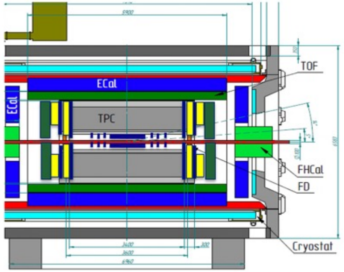
Run of NICA Bi+Bi 9.2*A* GeV



MPD Stage I
(barrel detectors)
10^8 good min. bias events

Run of NICA Au+Au 11*A* GeV

Maximizing luminosity, possibility of collision energy and system size scan

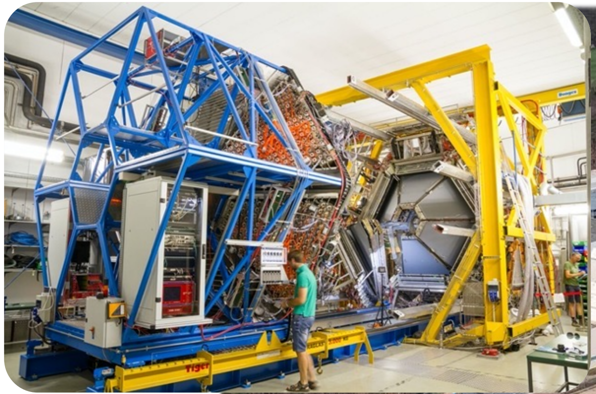


MPD Stage II
inner tracker, endcaps (dileptons)

FACILITY FOR ANTIPROTON AND ION RESEARCH

... is a multi-purpose (strong interaction) facility!

watch FAIR construction site 2021



High Acceptance Di-Electron Spectrometer (HADES), 9 countries, 26 institutions, 175 members

In operation since 2002
Beams from SIS18

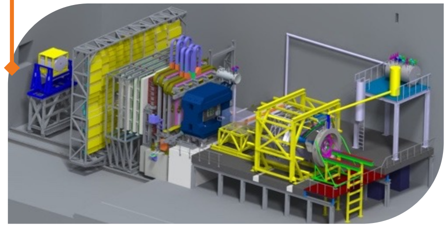
All components advanced in production

COMPRESSED BARYONIC MATTER

FAIR Phase 0 | FAIR Early science | FAIR Day 1

2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028

- HADES run pp 4.5 GeV
- CBM cave ready (heavy infra.)
- mCBM online Λ reco. at 10MHz demonstrated
- HADES Au+Au 0.2 – 0.8 GeV/u
- CBM magnet supports services
- CBM detectors
- physics with CBM



Hadrons, dielectrons and dimuons, charm

FAIR Phase 0 Research Program

- **Demonstrator** for full **CBM data taking** and analysis chain under load Au+Au, 10^7 interactions/s at SIS18
- Important tests of newly developed CBM detector components and data analysis tools in running experiments

HADES STAR ALICE BM@N SHINE

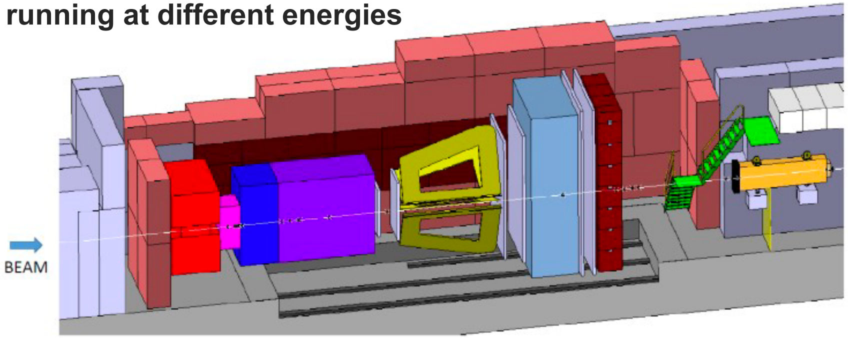
HADES

- new since 2019 RICH photo camera, ECAL (5 sectors)
- in 2021 forward detector system Sraw Tracker, RPC, LGAD
- for 2022 new MDC FEE and 100 kHz DAQ upgrade

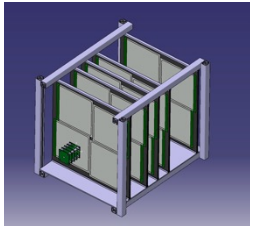
NA60+ at SPS

AA, pA, pp program (beam energy scan) with focus on dileptons and charm

Longitudinally scalable setup for running at different energies



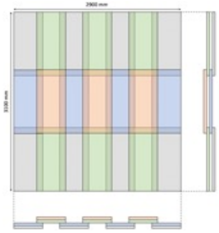
MAPS with stitching technology 5μm spatial resolution



Dipole magnet

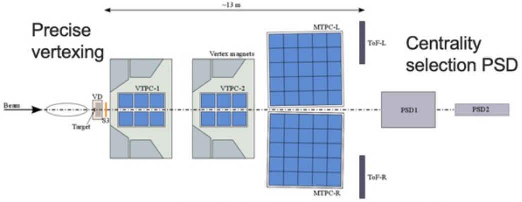
Toroid magnet

GEM μ tracking stations



- Muon measurement with tracking in front of and behind hadron absorber
  - Vertex spectrometer: 5 layers of MAPS (synergy with ALICE, R&D funded by Italian Research ministry)
  - m spectrometer: large area tracker based on GEMs (expertise within ALICE GEM TPC)
  - Toroid magnet ($BR = 0.2 - 0.5\ Tm$)
- Beam intensities of 10^7 Pb ions/ 20 s spill
- Installation foreseen at the SPS, EHN1 hall, H8 beam line
- EOI submitted to SPSC May’19
- LoI under preparation
- Start data taking with LHC run 4, in 2027

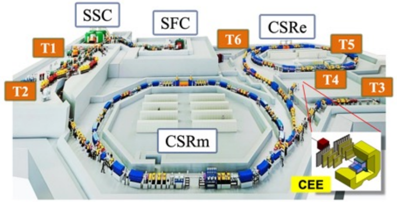
FURTHER FACILITIES



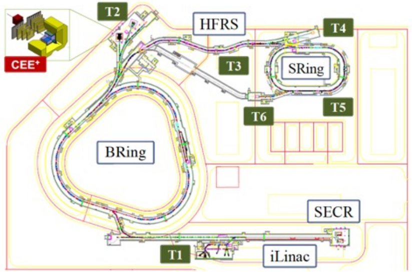
PID via dE/dx in 5 TPCs and ToF

NA61/SHINE at SPS
HI program with focus on charm during LHC Run 3
$\geq 7.6 \cdot 10^4\ D^0 + \overline{D}^0$ 84 days 150*A* GeV 2022+2023
$\geq 3.6 \cdot 10^3\ D^0 + \overline{D}^0$ 42 days 40*A* GeV 2024

HI Research Facility at Lanzhou (HIRFL)

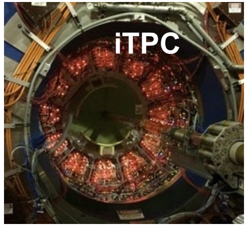


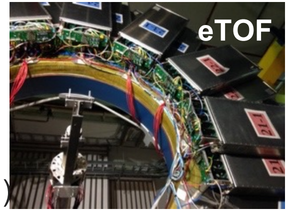
High Intensity heavy-ion Accelerator Facility (HIAF) at Huizhou



CSR External-target Experiment
CEE at HIRFL (start 2024)
CEE+ at HIAF (start 2027)

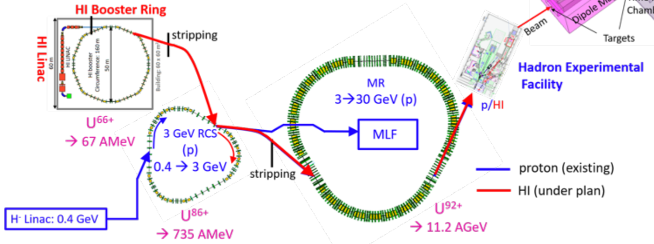
⇝ Focus event-by-event fluctuations and correlations
⇝ Hadron production and flow

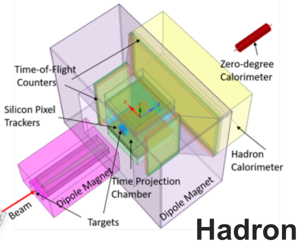




STAR at BNL
Beam Energy Scan I/II completed
$2{\times}10^9$ Au+Au $\sqrt{s_{NN}}$=3 GeV
(low-mass dielectron analysis ongoing)

J-PARC-HI

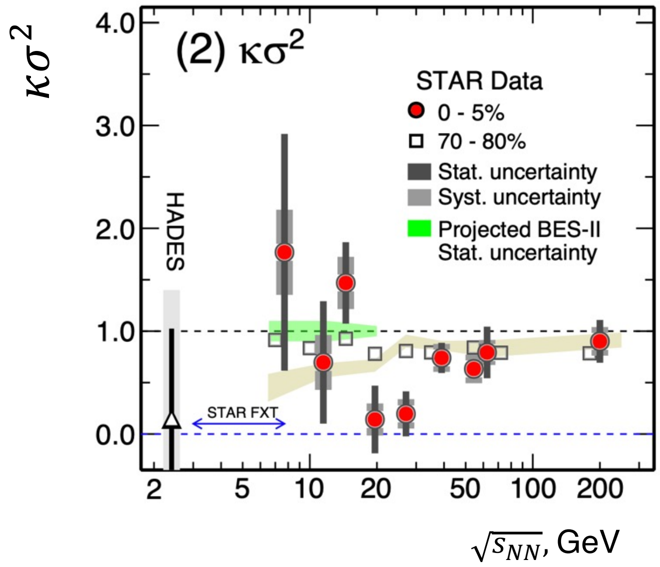




Hadron and dielectron setup

CRITICAL FLUCTUATIONS

STAR Collab., PRL 126 (2021) 092301
HADES Collab., PRC 102 (2020) 2, 024914



Crossing features of the QCD phase-diagram (**phase boundaries, CEP**) is expected to result in:

- ☐ Diverging susceptibilities and correlation length
- ☐ „Extra“ **fluctuations of conserved quantities** (e.g. baryon number, charge, strangeness)
- ☐ Observable **discontinuities of the higher moments** of particle number distributions, visible e.g. in a beam energy scan

Higher moments probe the tails of the (number) distributions. Needs statistics! No measurements 2.4 < $\sqrt{s_{NN}}$ < 7.7 GeV!

Direct link to EoS $\frac{1}{VT^3} k_n = \frac{\partial^n \hat{p}}{\partial \hat{\mu}^n}$

$\hat{p} = \frac{p}{T^4}$ reduced pressure

$\hat{\mu} = \frac{\mu}{T}$ reduced chemical potential

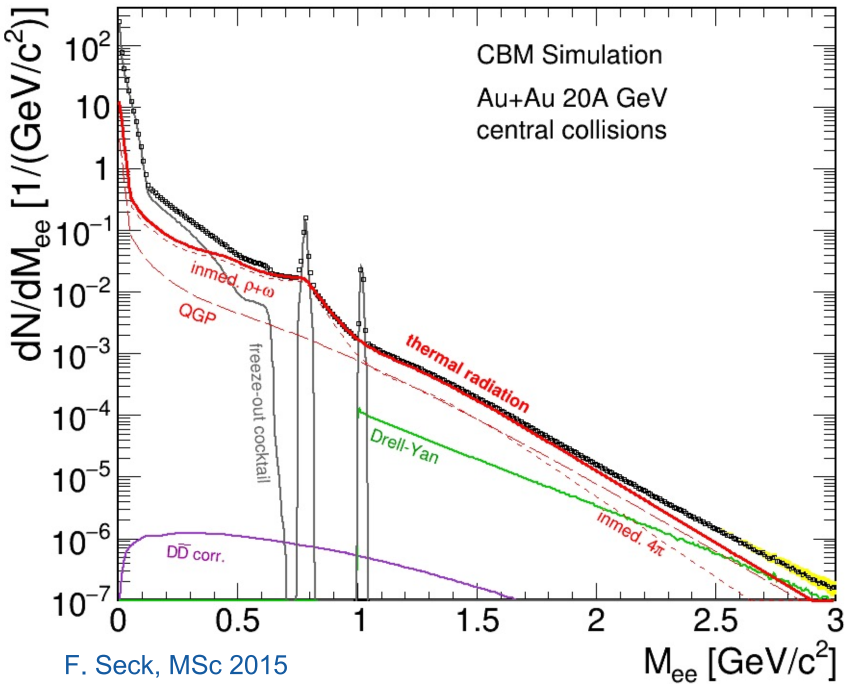
V. Skokov *et al.*, PRC 88 (2013) 034911
Bzdak *et al.*, Phys.Rev. C94 (2016) 064907
PBM *et al.*, NPA 960 (2017) 114
M. Kitasawa, PRC 93 (2016)

cf. B. Friman *et al.*, EPJC 71 (2011) 1694
M. Stephanov, PRL107, 052301(2011)

ELECTROMAGNETIC PROBES

DILEPTON INVARIANT MASS SPECTRA

Characteristic features



F. Seck, MSc 2015

i. 'Primodial' $q\bar{q}$ annihilation (Drell-Yan):
- $NN \rightarrow e^+e^-X$
- short-lived states

ii. Thermal radiation from QGP and hadronic matter:
- $q\bar{q} \rightarrow e^+e^-$, $\pi^+\pi^- \rightarrow e^+e^-$
- short-lived states Δ, N^*, …
- multi-meson reactions ('4π'): $\pi\rho, \pi\omega, \pi a_1$, …

iii. Decays of long-lived mesons:
- $\pi^0, \eta, \omega, \varphi$, correlated $D\bar{D}$ pairs, …

Excess yield = dilepton yield after subtraction of (measured) decay cocktail (i. and iii.)

ELECTROMAGNETIC PRODUCTION RATE

em current-current correlation function

$$\Pi_{em}^{\mu\nu}(q_0, q) = -i \int d^4x\, e^{iq\cdot x}\theta(x^0)\langle\langle[j^\mu(x), j^\nu(0)]\rangle\rangle$$

determines both photon and dilepton rates

- photons characterized by “transverse” momentum:

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

- dileptons carry extra information: invariant mass
  → unique direct access to in-medium spectral function

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

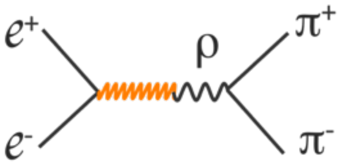
McLerran, Toimela, Phys.Rev. D31, 545 (1985)
Weldon, Phys.Rev. D42, 2384-2387 (1990)
Gale, Kapusta, Phys.Rev. C35, 2107 (1987) & Nucl.Phys. B357, 65-89 (1991)

EM CORRELATOR IN THE VACUUM

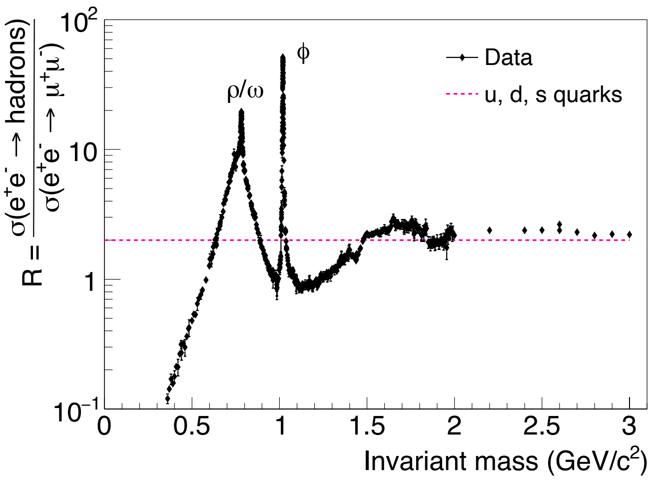
accurately known from e^+e^-annihilation $R \propto \frac{Im\Pi_{em}^{vac}}{M^2}$

low-mass regime

em spectral function is saturated by light vector mesons (VMD $J^P = 1^-$ for both γ^* and VM, ρ playing a dominant role)

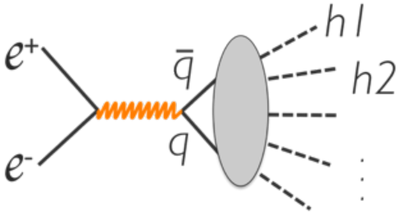


Beringer *et al.* (PDG), Phys. Rev. D (2012) 010001



intermediate-mass regime

perturbative QCD continuum (quark degrees of freedom)



$$Im\Pi_{em}^{vac} = \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 ImD_v^{vac}(M)$$

Sakurai, Ann.Phys. 11 (1960)

$$Im\Pi_{em}^{vac} = -\frac{M^2}{12\pi}\left(1 + \frac{\alpha_s(M)}{\pi} + \cdots\right) N_c \sum_{q=u,d,s} (e_q)^2$$

IN-MEDIUM SPECTRAL FUNCTIONS FROM HADRONIC MANY BODY THEORY

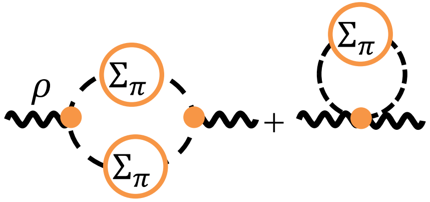
ρ meson in medium interacts with hadrons from heat bath

additional contributions to the ρ-meson self-energy

$$D_\rho(M, q, T, \mu_B) = \frac{1}{[M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}]}$$

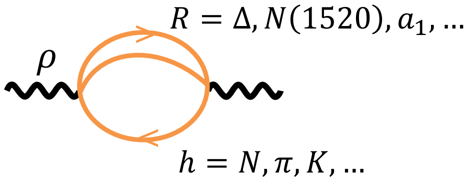
in-medium pion cloud

$\Sigma_{\rho\pi\pi} =$

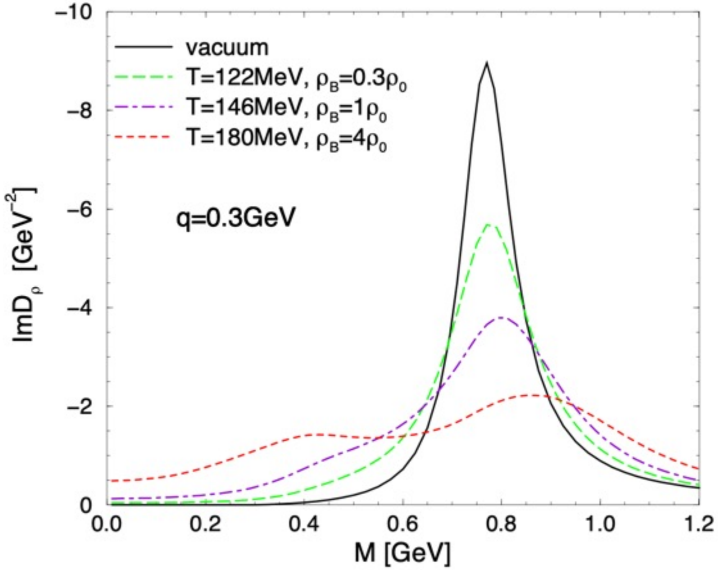


direct ρ-hadron scattering

$\Sigma_{\rho B,M} =$



Rapp and Wambach, Eur.Phys.J. A6 (1999)



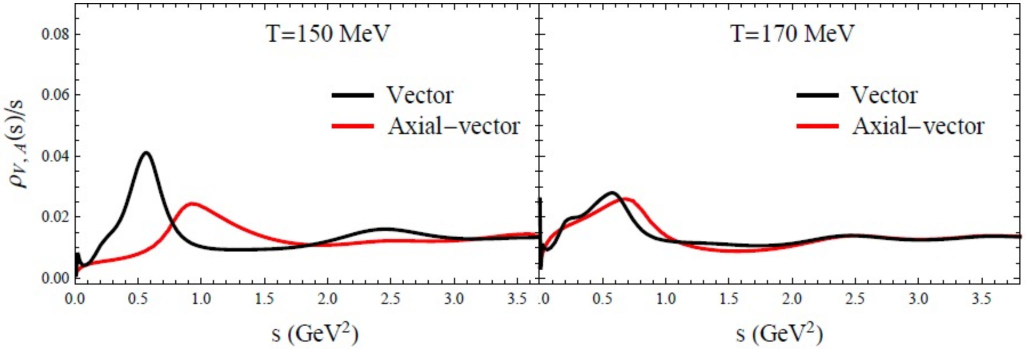
↝ **ρ-peak undergoes a strong broadening**
↝ **baryonic effects are crucial**

Alam *et al.*, Annals Phys.286 (2001) 159 (2001)
Leupold, Metag, Mosel, Int.J.Mod.Phys. E19 (2010) 147
Rapp, Acta Phys.Polon. B42 (2011) 2823-2852

IN-MEDIUM EM SPECTRAL FUNCTIONS

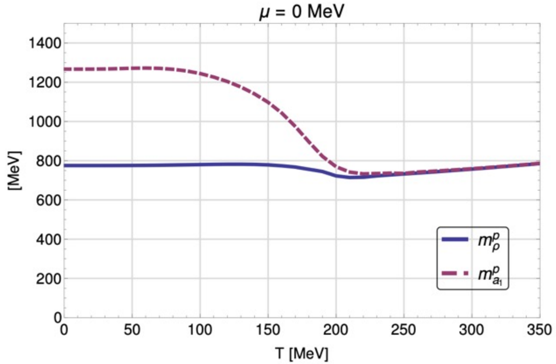
Connection to chiral symmetry χ_c

- Spontaneously broken in the vacuum
- Restoration of χ_c at finite T and μ_B manifests itself through mixing of vector and axialvector correlators
- ρ meson melts in hot/dense matter, $a_1$mass decreases and degenerates with near ground-state mass



Hohler, Rapp, Annals Phys. 368, 70-109 (2016)
Holt, Hohler, Rapp, Phys.Rev. D87, 076010 (2013)

Degeneracy of hadronic chiral partners

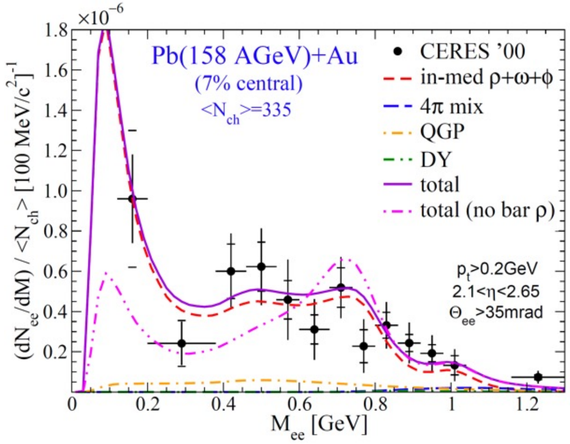


Jung, Rennecke, Tripolt, von Smekal, Wambach, Phys.Rev. D95, 036020 (2017)

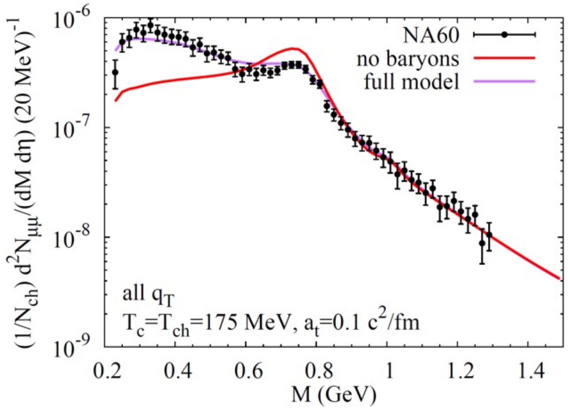
MEASURED EXCESS DILEPTON INVARIANT-MASS SPECTRA

Strongly supports melting of ρ, in particular due to baryon-induced effects

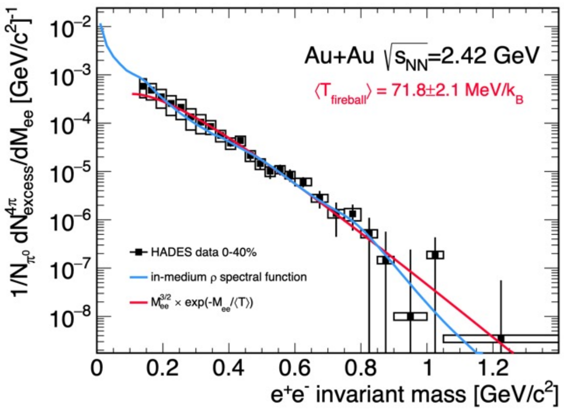
[CERES/NA45], Phys.Lett.B 666 (2008) 425



[NA60], EPJC 61(2009) 711



[HADES], Nature Phys. 15(2019) 1040



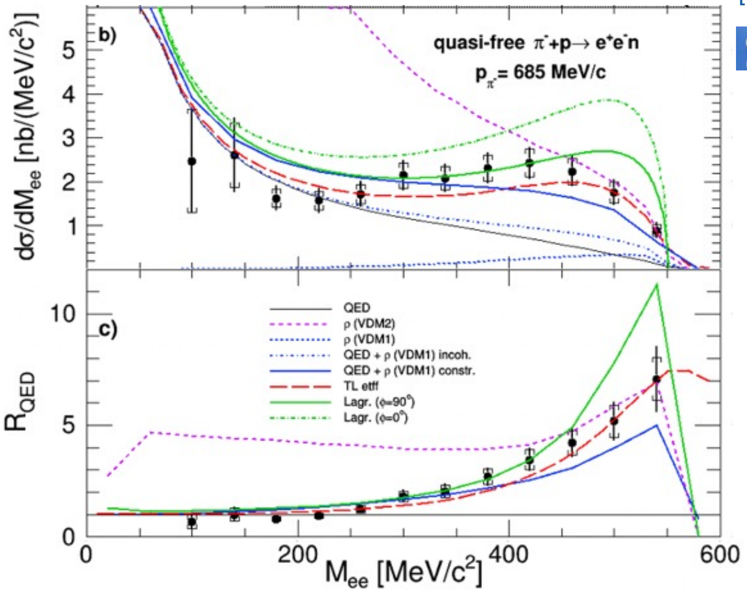
- RW in-medium spectral function consistently describes the low-mass dilepton excess for SIS – SPS – RHIC BES – RHIC – LHC energies
- Baryon effects important even at net-baryon density $\rho_B = 0$
- Sensitive to $\boldsymbol{\rho_{B_{tot}}} = \boldsymbol{\rho_B} + \boldsymbol{\rho_{\bar{B}}}$ (ρN and $\rho\bar{N}$ interactions identical)

Rapp, Wambach, Eur.Phys.J. A6 (1999) 415-420 (1999)
Rapp, Wambach, van Hees, Landolt-Bornstein 23 (2010) 134
CG GSI-Texas A&M TG et al.: Eur.Phys.J. A52 (2016) no.5, 131

MESON CLOUD

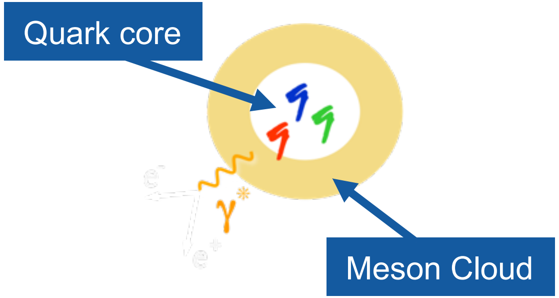
exclusive analysis $\pi^- p \rightarrow e^+ e^- n$

HADES, in preparation



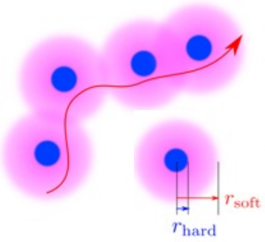
Ramalho, Pena, Phys. Rev. D95 (2017) 014003
Zetenyi, Nitt, Buballa, Galatyuk, Phys. Rev. C arXiv:2012.07546
Speranza *et al.*, Phys.Lett. B764 (2017) 282

[HADES] Phys.Rev.C 102 (2020) 2, 024001
[HADES] Phys.Rev.C 95 (2017) 065205



4 first entries ($N\rho$)
4 additional entries
first entry BR $\Delta \rightarrow pe^+e^-$

- Study the structure of the nucleon as an extended object (quark core and meson cloud)
- Dominance of the $N^*(1520)$ resonance
  - contribution fixed by analysis of $\pi^+\pi^-$ channel with PWA



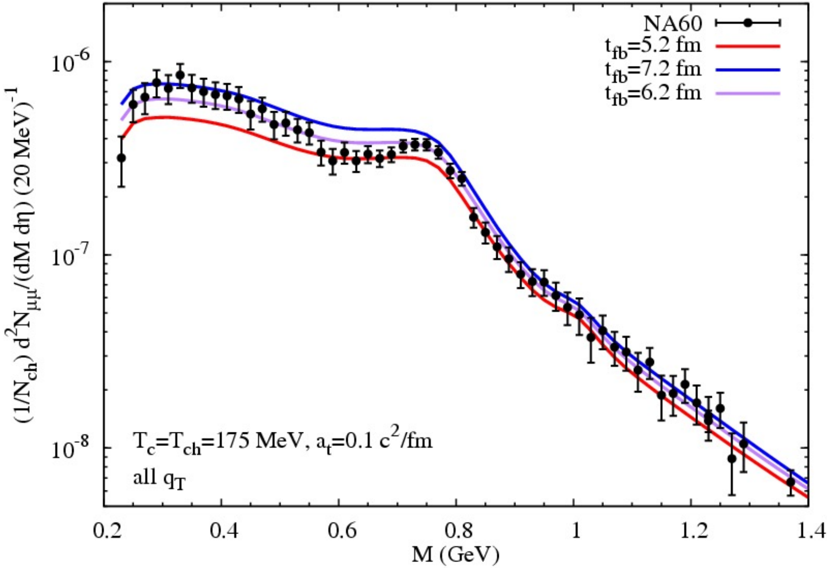
connection to "soft deconfinement"?

Fukushima, Kojo, Weise, PRD 102 (2020) 9, 096017

quantum percolation of the interaction meson clouds

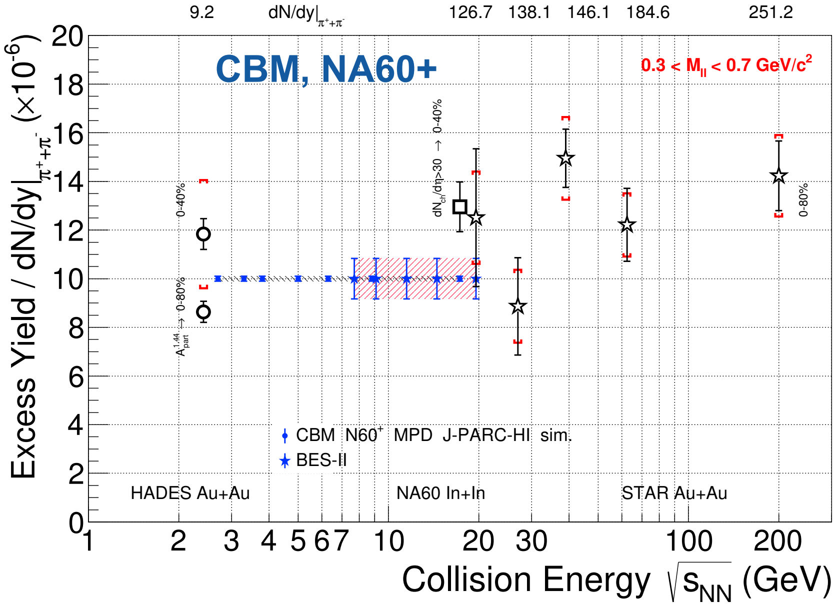
THE FIREBALL LIFETIME

Rapp, Acta Phys.Polon.B 42 (2011) 2823-2852



“explicit” measurement of interacting-fireball lifetime: $\tau_{FB} \approx (7 \pm 1)\ fm/c$

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



- Integrated low-mass radiation $0.3 < M < 0.7$ GeV/c^2 tracks the fireball lifetime

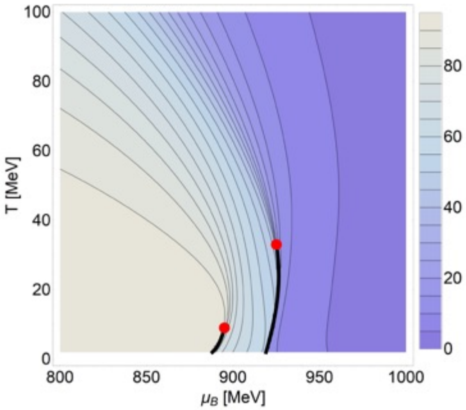
  Heinz and Lee, PLB 259, 162 (1991)
  Barz, Friman, Knoll and Schulz, PLB 254, 315 (1991)
  Rapp, van Hees, PLB 753 (2016) 586

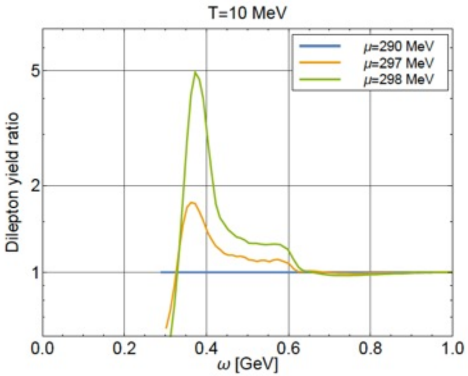
- Signature for phase transition (and critical point)?
  ⇝ latent heat ⇝ longer life time ⇝ extra radiation

DILEPTON SIGNATURE OF A 1ST ORDER PHASE TRANSITION

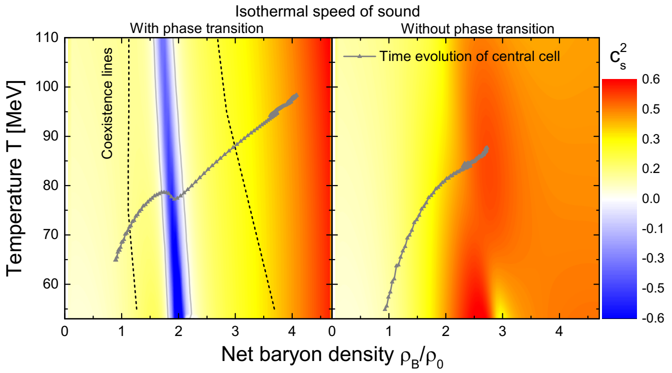
- em spectral function from FRG flow equations
- Dilepton rates at CEP $\boldsymbol{T}$=**10 MeV**, $\boldsymbol{\mu}$=**292 MeV**

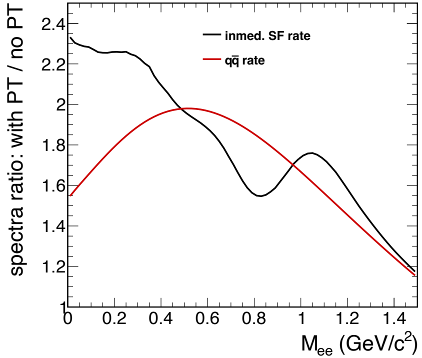
Tripolt *et al.*, Nucl. Phys. A982 (2019) 775
Jung *et al.*, Phys. Rev. D 95 (2017) 036020





- Dilepton radiation in hydrodynamics with and w/o "strong" 1st-order transition
- Factor of ~2 extra radiation in case of hydro with phase transition

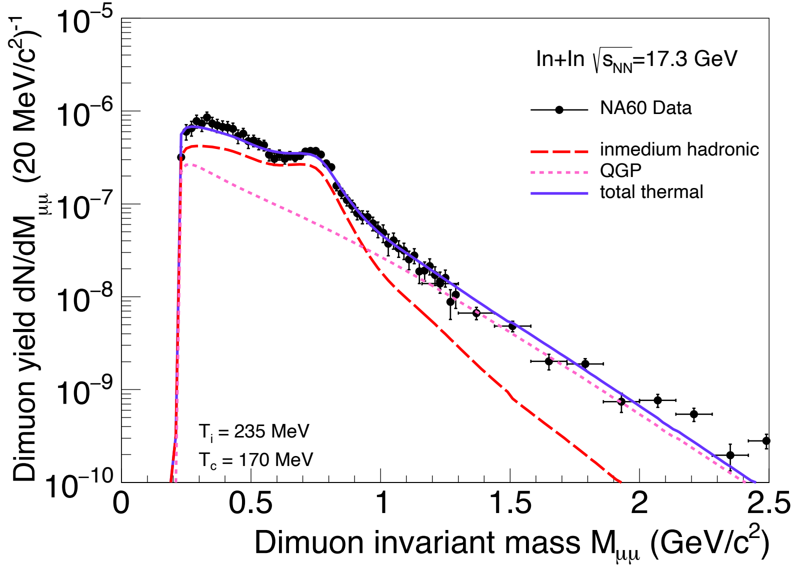




Seck, TG, et al., arXiv:2010.04614 [nucl-th]
Li and Ko, Phys. Rev. C 95 (2017) no.5, 055203

DILEPTONS AS THERMOMETER

Acceptance corrected $\mu^+\mu^-$excess yield



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

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

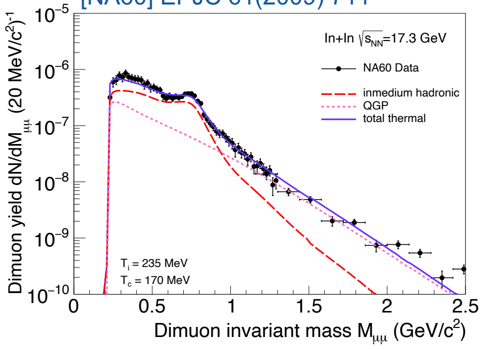
- ☐ **IMR** spectrum falls exponentially
- ☐ in the **IMR** the dilepton rate $\frac{dR_{ll}}{dM} \propto (MT)^{\frac{3}{2}}\exp(-\frac{M}{T})$
- ☐ independent of flow: no blue shift!

$\langle T\rangle = 205\ \pm 12\ MeV$

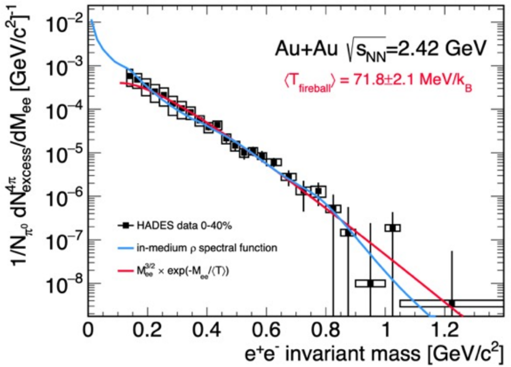
↝ **the only explicit temperature measurement above T_{pc} in heavy-ion collisions**

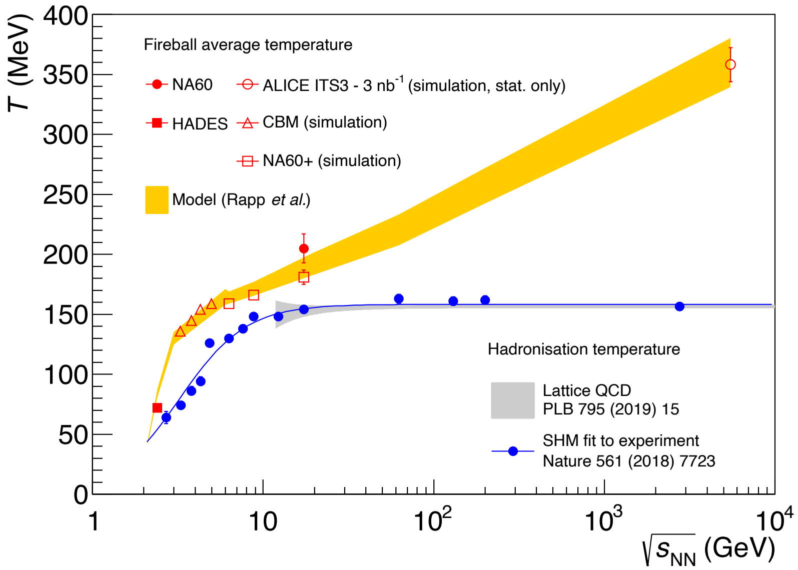
MAPPING QCD "CALORIC CURVE" (T vs ε)

[NA60] EPJC 61(2009) 711



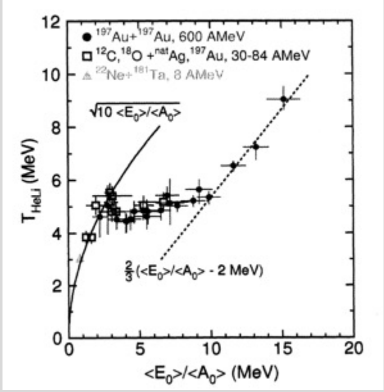
[HADES] Nature Phys. 15(2019) 1040





Rapp and v. Hess, PLB 753 (2016) 586
TG *et al.*, EPJA 52 (2016) 131
https://github.com/tgalatyuk/QCD_caloric_curve

Nuclear liquid-gas phase transition



Pochodzalla *et al.*, PRL 75 (1995) 1040

signature for phase transition?

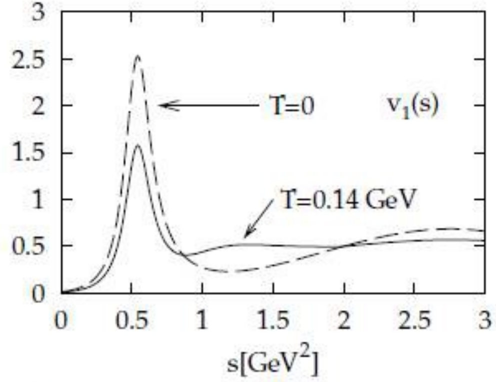
↝ **phase transition may show up as a plateau!**

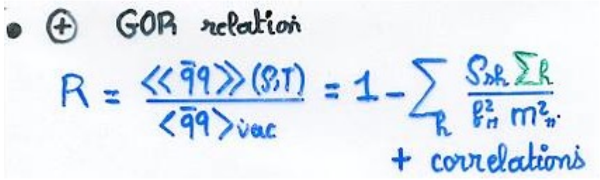
↝ **future high statistics experiments**

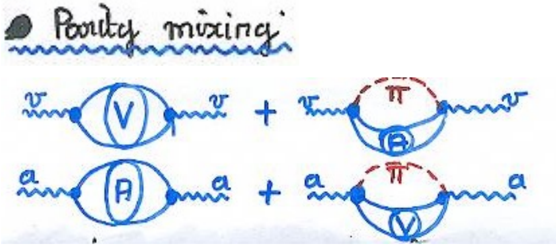
ADDITIONAL SIGNATURE FOR CHIRAL SYMMETRY RESTORATION

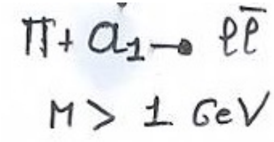
- Changes in yield and shape at $M_{ee} > 1.1$ GeV/c^2 due to **$\rho - a_1$ chiral mixing**
- $\pi a_1 \rightarrow \gamma^* \rightarrow l^+ l^-$ (chiral mixing) is a dominant hadronic source in IMR

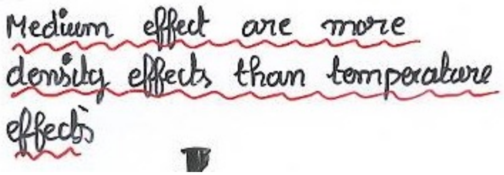
Dey, Eletsky and Ioffe, Phys.Lett. B252 (1990)





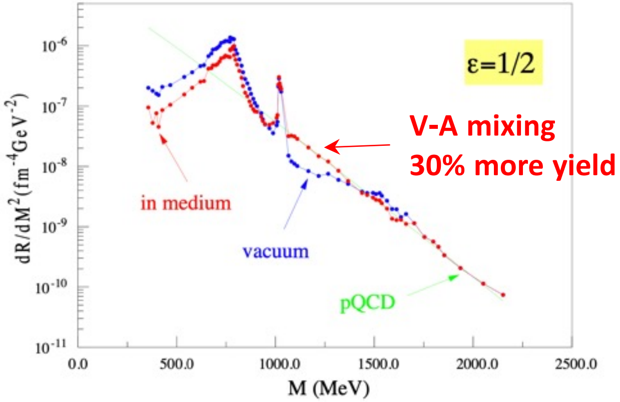






Guy Chanfray, 1999 Lecture Notes

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

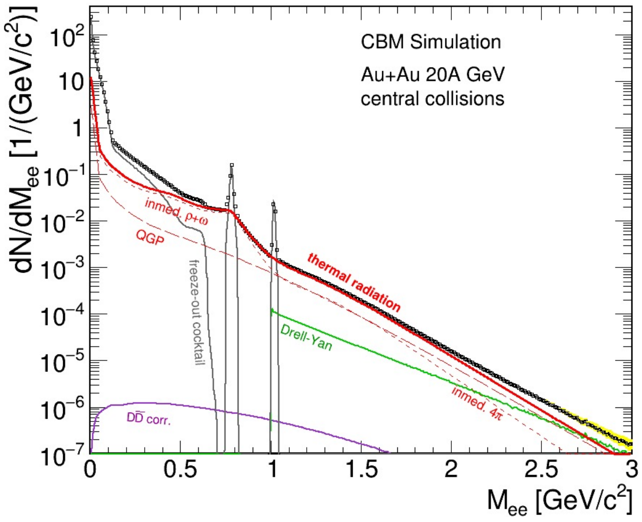


EXPERIMENTAL CHALLENGE

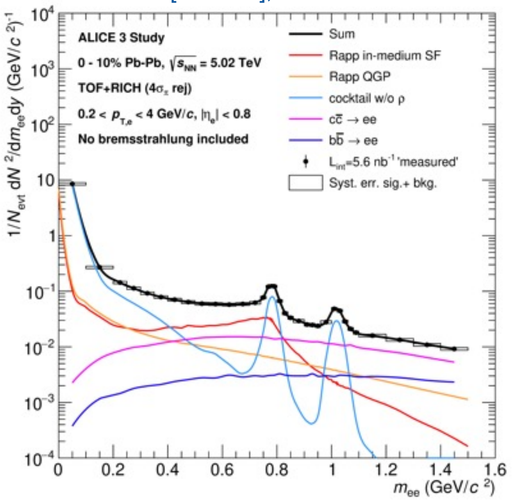
There is no such thing as a free lunch

Physics background (M_{ll} > 1 GeV/c^2)

Seck [CBM], 2015



Eisenhut [ALICE3], DPG 2021



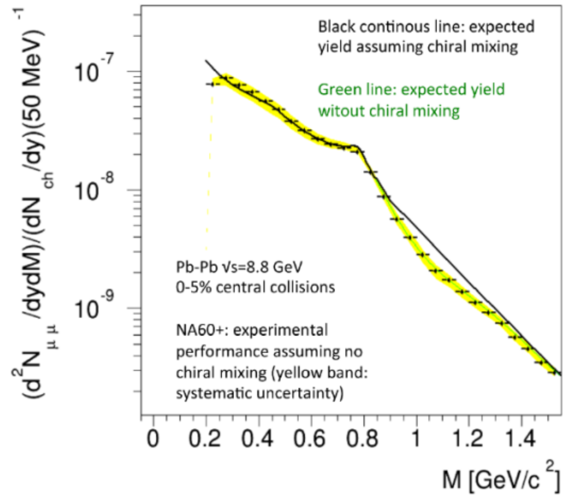
- Towards lower energy
  - negligible correlated charm contribution
  - decrease of QGP
  - Drell-Yan contribution
- LHC energies
  - large contribution from $c\bar{c}, b\bar{b}$ and QGP
  - negligible Drell-Yan

EXPERIMENTAL CHALLENGE

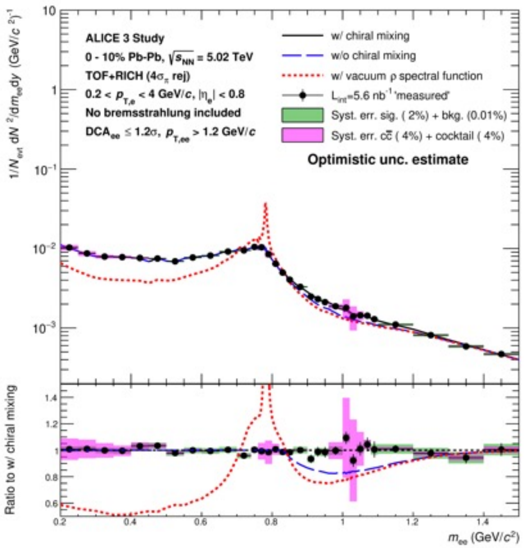
There is no mission impossible

Physics background ($M_{ll} > 1$ GeV/c^2)

Usai [NA60+], 2020



Eisenhut [ALICE3], DPG 2021



- Towards lower energy
  - Drell-Yan contribution → pp, pA measurements!
- LHC energies
  - excellent vertex resolution → topological separation of prompt and non-prompt source employing DCA cut
  - choice of the p_T cut

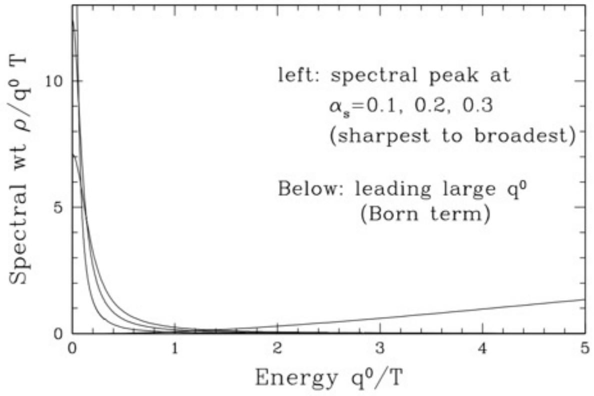
TRANSPORT PROPERTIES OF THE MEDIUM

Electrical conductivity

EM spectral function connected to electrical conductivity:

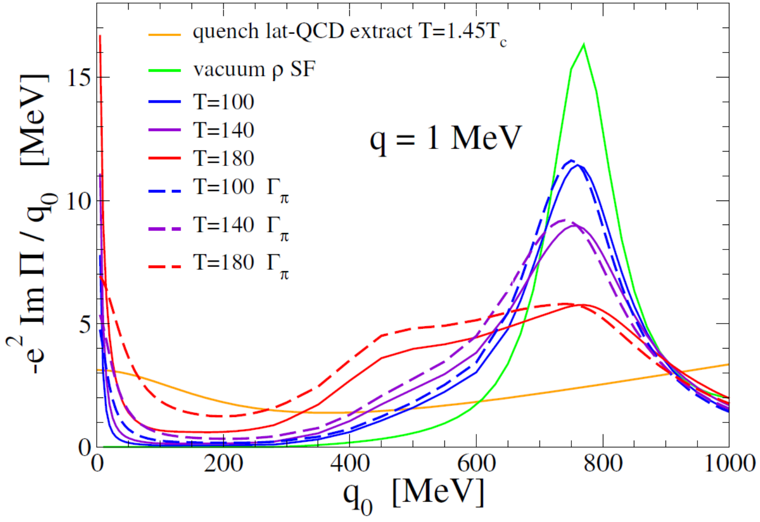
$$\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} Im\Pi_{em}(q_0, q = 0; T)$$

Transport peak in the limit of very low mass and p_T



Moore and Robert, arXiv:hep-ph/0607172

Rapp, EMMI RRTF 2021

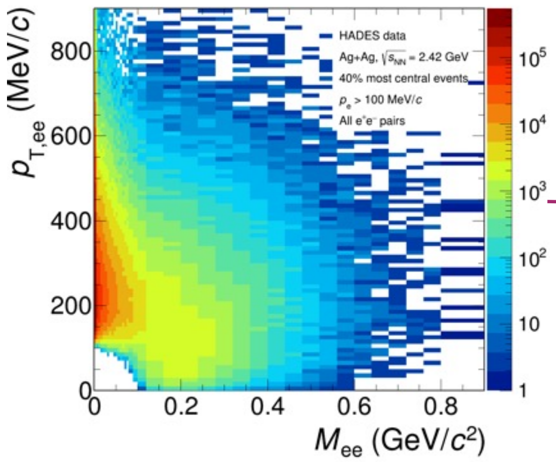


- Conductivity is reduced when thermal-pion interactions included
- Transport peak broadens

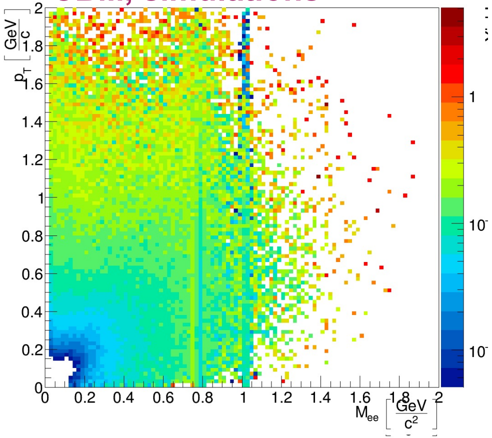
EXPERIMENTAL CHALLENGE

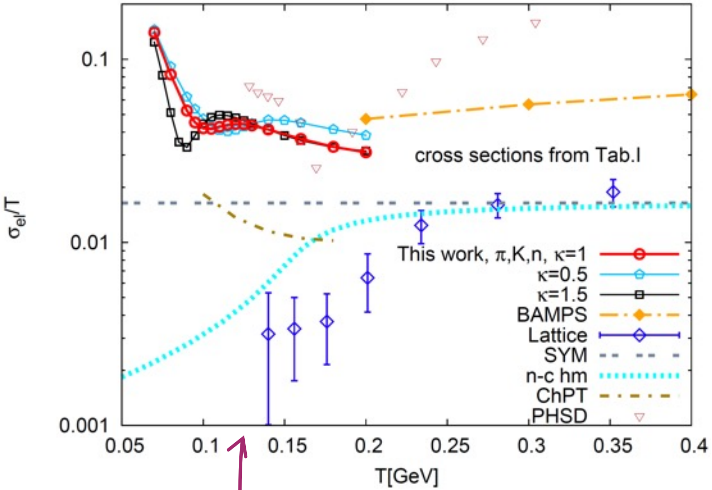
Measure accurately low mass – low p_T thermal excess yiled

HADES, data

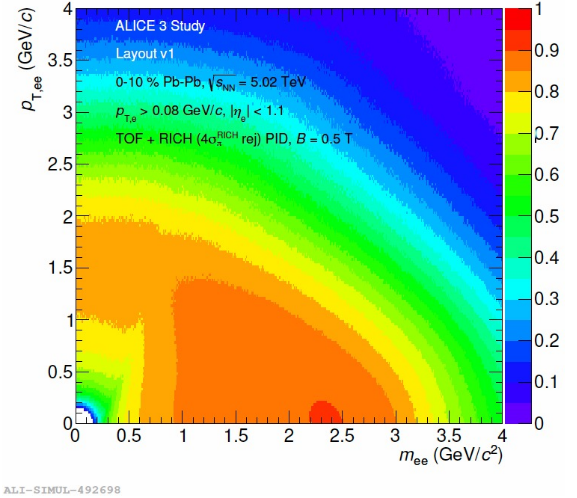


CBM, simulations





ALICE 3, simulations

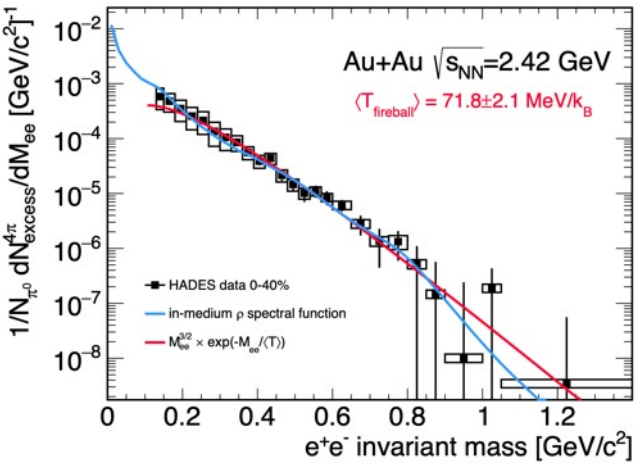


large spread in literature

Greif, Greiner, Denicol, Phys.Rev. D93 (2016) 096012
Atchison, Rapp, Phys. Conf.Ser. 832 (2017) 012057 (2017)

DILEPTONS CARRY INVALUABLE INFORMATION IN TERMS OF THEIR FOUR-MOMENTUM

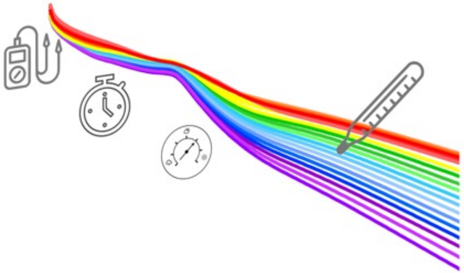
Invariant mass



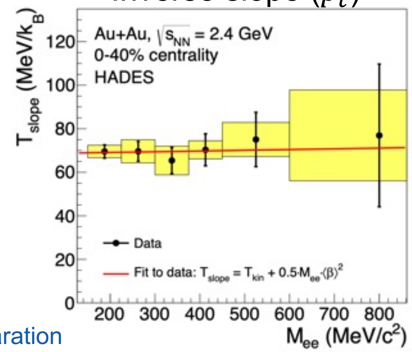
[HADES] Nature Phys. 15(2019) 1040

Uniquely encode information on matter properties

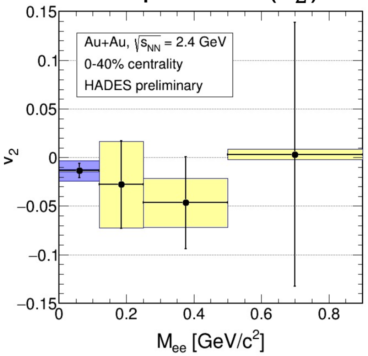
- Spectrometer
- Chronometer
- Barometer
- Thermometer
- Polarimeter
- Amperemeter



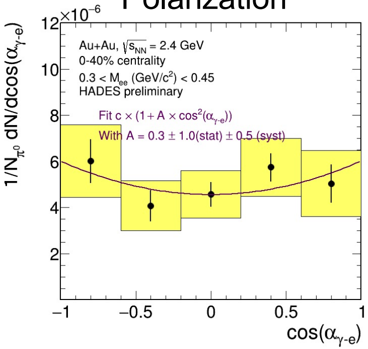
Inverse slope (p_t)



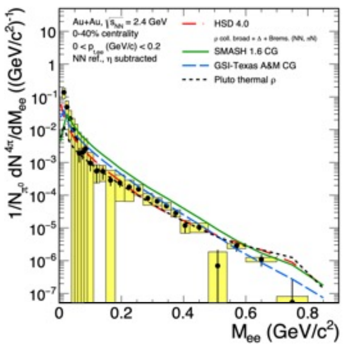
Elliptic flow (v_2)



Polarization



Electric conductivity?



[HADES] in preparation

SUMMARY – HIGH μ_B

- **Open questions:**
  - Quest for deconfinement / chiral symmetry restoration conditions at high μ_B
  - Quest for the conjectured QCD critical point
- **Challenges:**
  - Rare and statistics „hungry“ observables
  - Many aspects – nature of transitions between the various phases, relevant EoS, origin of hadron mass and 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
- **Objectives:**
  - Systematic energy scan with full exploration of all relevant observables
    → CBM – NA60+ – MPD offer important complementarities

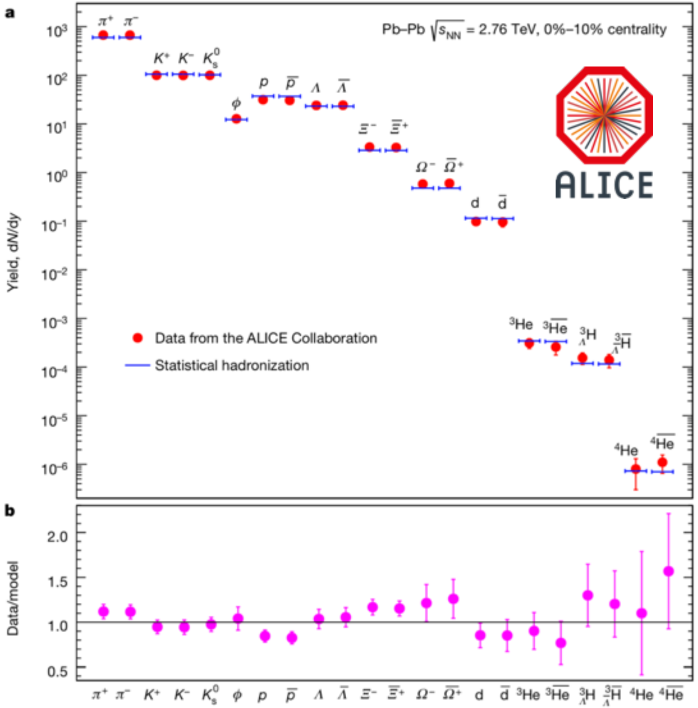
Thank you for your attention!

BONUS SLIDES

HADRON YIELDS AND STATISTICAL HADRONIZATION MODEL

Are we creating a thermal medium in experiments?

$\sqrt{s_{NN}} = 2.76\ TeV$

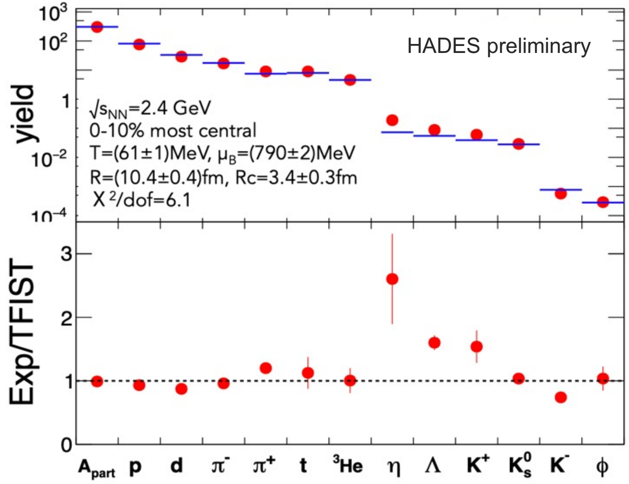


A. Andronic *et al.*, Nature 561 (2018) no.7723

1 ppm

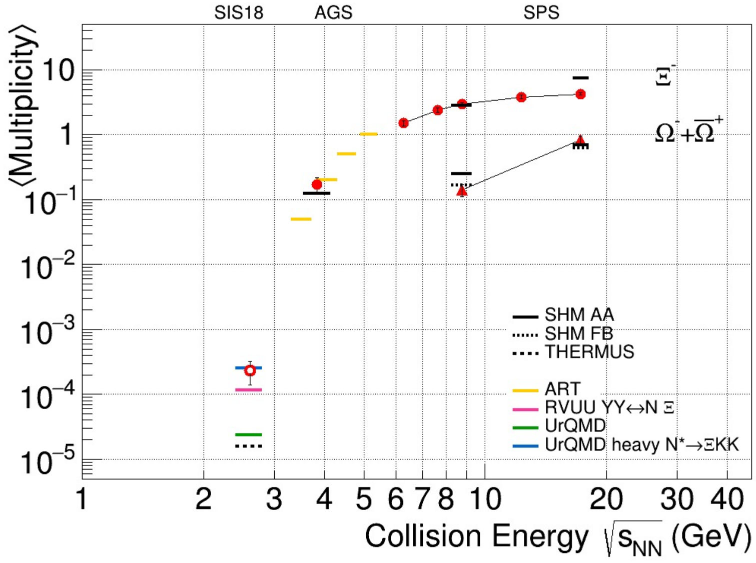
- Factor 1000 in beam energy / factor ~2 in temperature
- Hadron abundances described in framework of SHM
  - Strangeness canonical treatment at low beam energies
  - Include feed-down from $^{4}He,\ ^{4}H,\ ^{4}Li$

D. Hahn, H. Stöcker, Nucl.Phys.A 476 (1988) 718-772
E. Shuryak, J. M. Torres-Rincon Phys.Rev.C 101 (2020) 3, 034914



1 ppm

MULTI-STRANGE BARYONS



- $\sqrt{s_{NN}}$ < 6 GeV – baryon rich matter, data are missing for less abundant particles (Ξ, Ω)!
- Unexpectedly large Ξ^- yield at sub-threshold energies (HADES ArKCl, pNb)
  - Not in equilibrium?
  - Role of YY interaction, high mass baryonic resonances?

Precision measurement of spectra and flow pattern

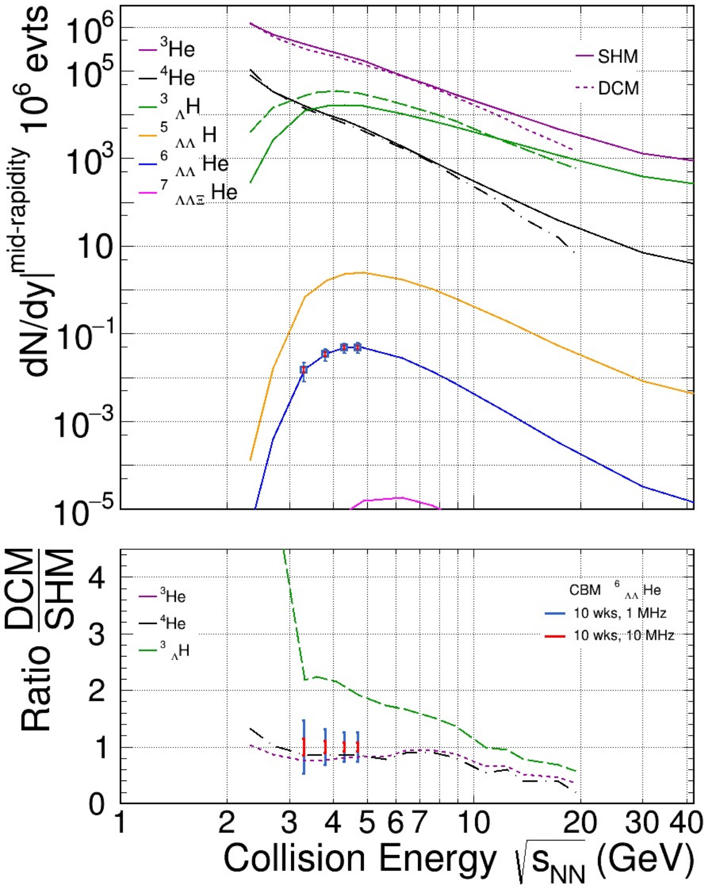
C. Blume, C. Markert, PPNP (2011) 66
HADES Coll., PRL 103 (2009) 132301

RVUU: F. Li et al., PRC 85 (2012) 064902
UrQMD: J. Steinheimer et al., J.Phys. G43 (2016) 015104
ART: C.M. Ko et al., PLB595 (2004) 158-164

A. Andronic et al., NPA 772 (2006)
F. Becattini et al., PRC69 (2004) 024905

E. Seifert et al., PRC97 (2018)

	$\sqrt{s_{NN}}$	Run time	R_{int}, kHz	Ξ^-	Ξ^+	Ω^+
HADES (Ag)	2.6 GeV	4 wks	10	2.5×10^3		
MPD Stage'1	11 GeV	10 wks	5	1.5×10^6	8×10^4	1.5×10^4
CBM	3.8 GeV	1 wk	1000	4×10^9	5×10^6	3.3×10^5



SHM: A. Andronic et al., Phys.Lett. B697 (2011)
DCM: J. Steinheimer et al., Phys.Lett. B714 (2012)

NUCLEI AND HYPER-NUCLEI PRODUCTION

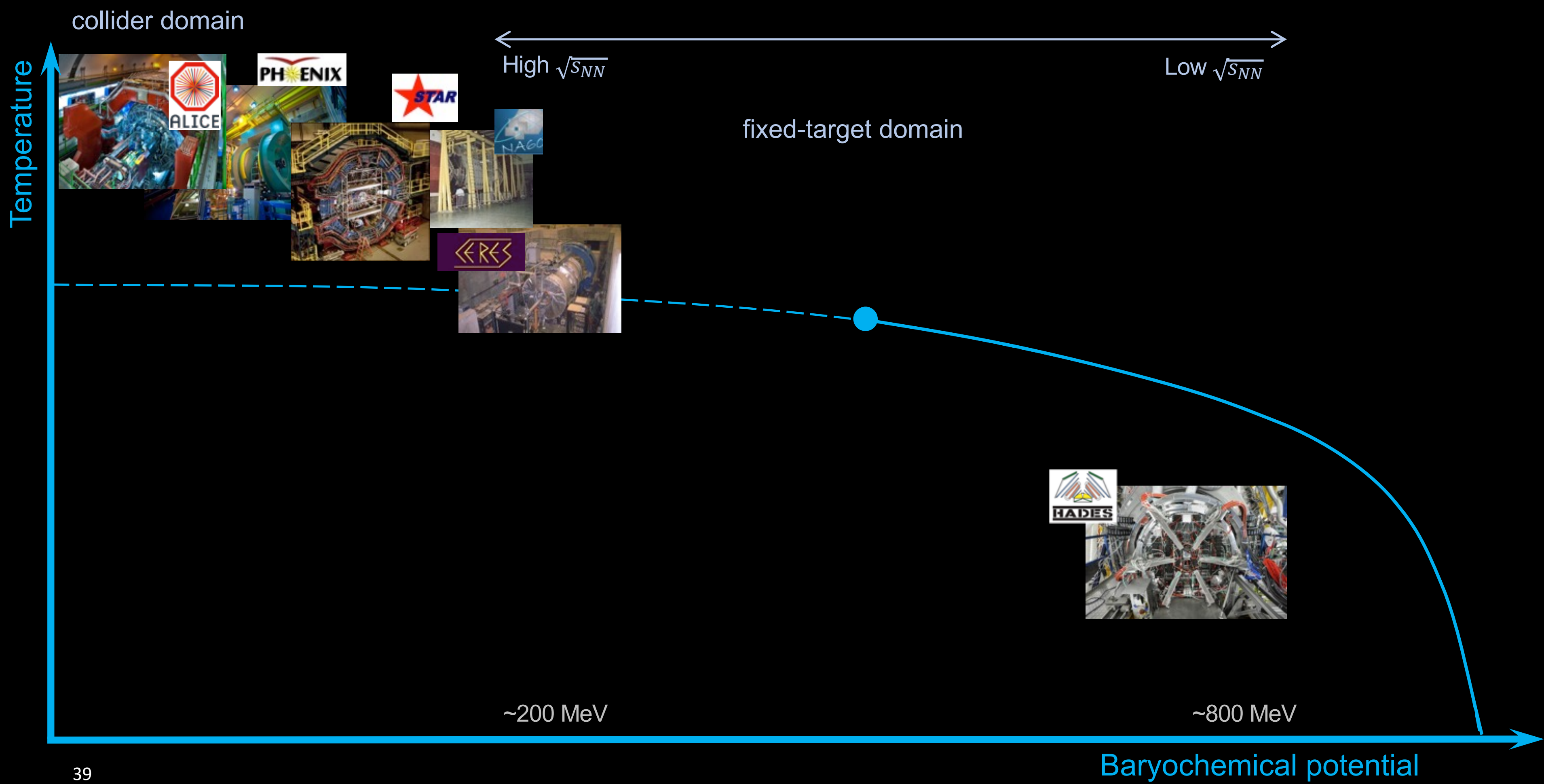
- How do nuclei and hyper-nuclei form?
  - Compact multi-quark states at the phase boundary?
  - Coalescence?
- What are their properties?
- Do YY bound states exist?
- How do YN, YY interact?

ALICE Collab., Phys. Lett. B 754 (2016) 360
STAR Collab., arXiv:1710.00436 [nucl-ex]
HAL CD Coll., arXiv:1709.00654 [hep-lat]

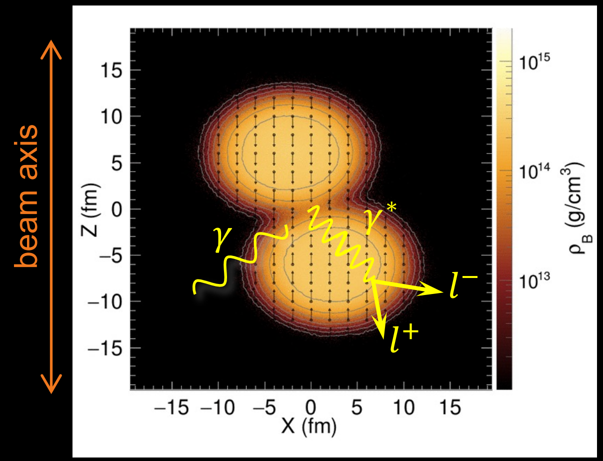
Multi-differential analysis (spectra, flow) needed to increase the discrimination power with respect to models

	$\sqrt{s_{NN}}$	Run time	R_{int}, kHz	ε %	$^4_\Lambda He$	$^6_{\Lambda\Lambda}He$
CBM	4.7 GeV	1 wk	1000	15	$7x10^7$	
CBM	4.7 GeV	10 wks	10.000	1.3		600
MPD Stage'2	5 GeV	10 wks	5	0.4	$1x10^4$	

THE EXPERIMENTAL LANDSCAPE FOR RARE PROBES

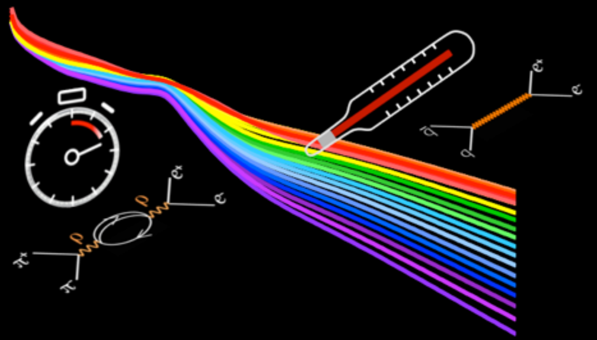


EXTREME AND SHINY



- Electromagnetic radiation (γ, γ^*)
  - Penetrating probe
  - Reflect the whole history of a collision
  - No strong final state interaction
    ⇝ leave reaction volume undisturbed

- Encodes information on matter properties
  - Change in degrees of freedom
  - Restoration of chiral symmetry
  - Transport properties
  - Temperature, lifetime, acceleration, polarization

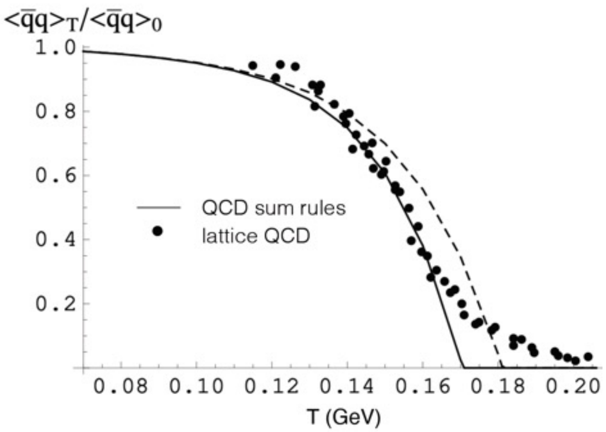


IN-MEDIUM EM SPECTRAL FUNCTIONS

S. Weinberg, Phys. Rev. Lett. 18 (1967) 507

connection to chiral symmetry χ_c

- χ_c is broken spontaneously by dynamical formation of a quark condensate $\langle\bar{q}q\rangle$
- condensates $\langle\bar{q}q\rangle$ constrained by lattice QCD

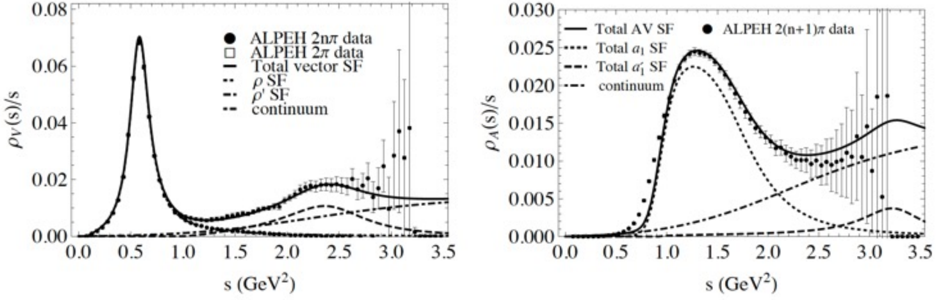


Hohler and Rapp, Annals Phys. 368 (2016) 70-109
Holt, Hohler, Rapp, Phys.Rev. D87 (2013) 076010

QCD and chiral sum rules…

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

… accurately satisfied in vacuum



… remain valid in medium

Kapusta and Shuryak, Phys.Rev. D49 (1994) 4694

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