CBM and future high-μ_B facilities

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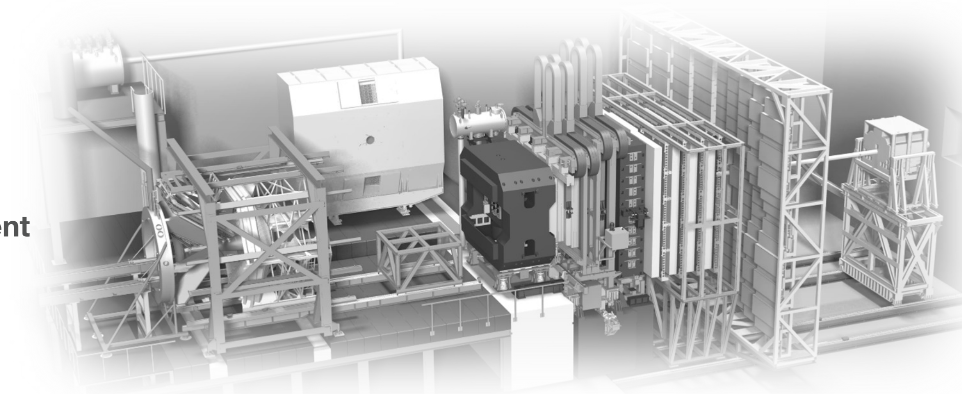
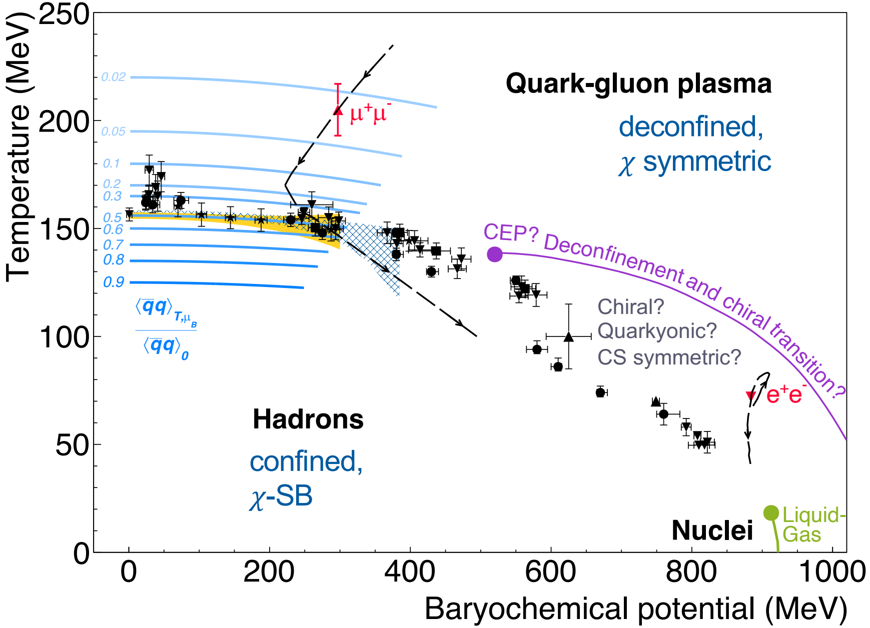
GSI / Technische Universität Darmstadt



15th workshop on critical point and onset of deconfinement
May 21-25, 2024
Berkeley

Searching for landmarks of the QCD matter phase diagram



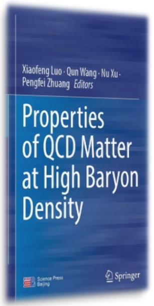
Experimental challenges:

- 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



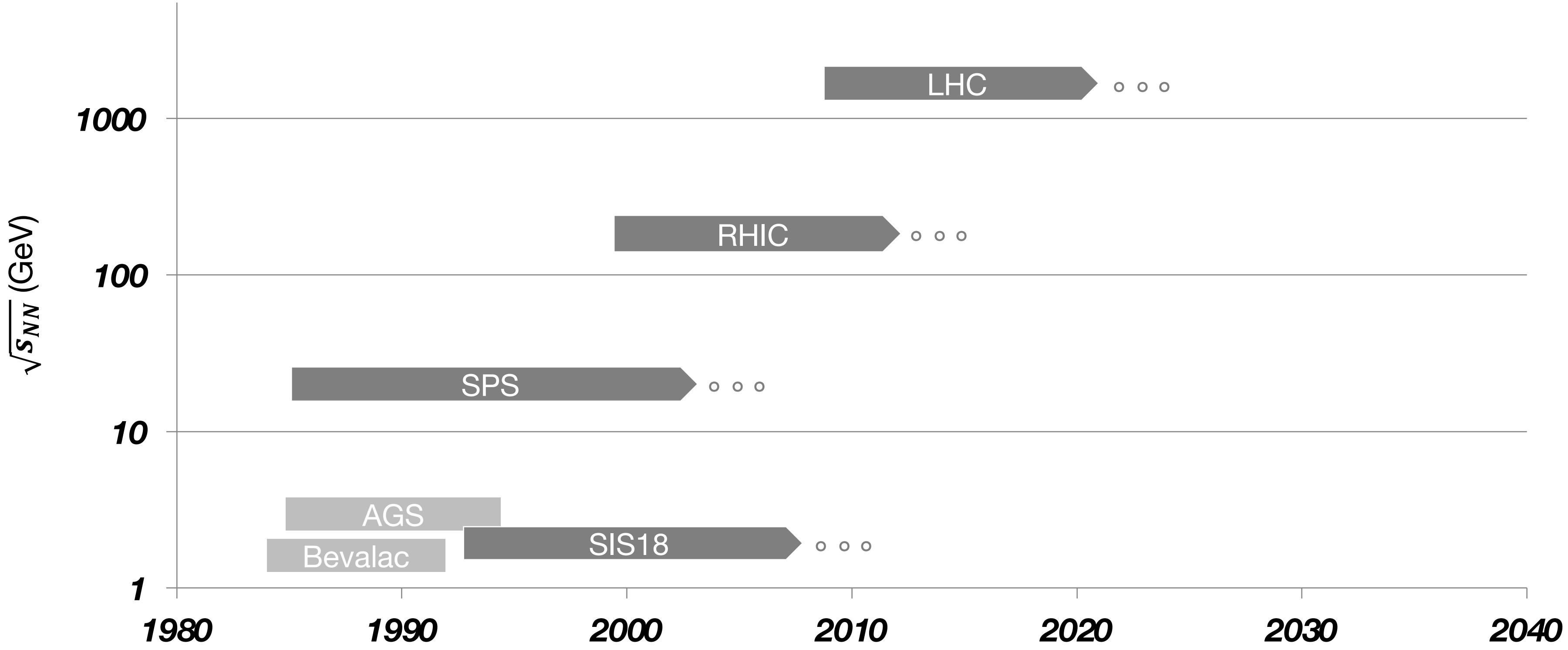
Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
Borsanyi *et al.* [Wuppertal-Budapest], PRL 125 (2020)

McLerran, Pisarski, NPA 796 (2007) 83
Glozman, Philipsen, Pisarski, EPJA 58 (2022) 12, 247

HADES, Nature Phys. 15 (2019) 10, 1040-1045
NA60, Specht *et al.*, AIP Conf.Proc. (2010) 1322
Andronic *et al.*, Nature 561 (2018) no.7723

Chen, Dong, Fukushima, Galatyuk, *et al.*, doi:10.1007/978-981-19-4441-3_4 (2022)

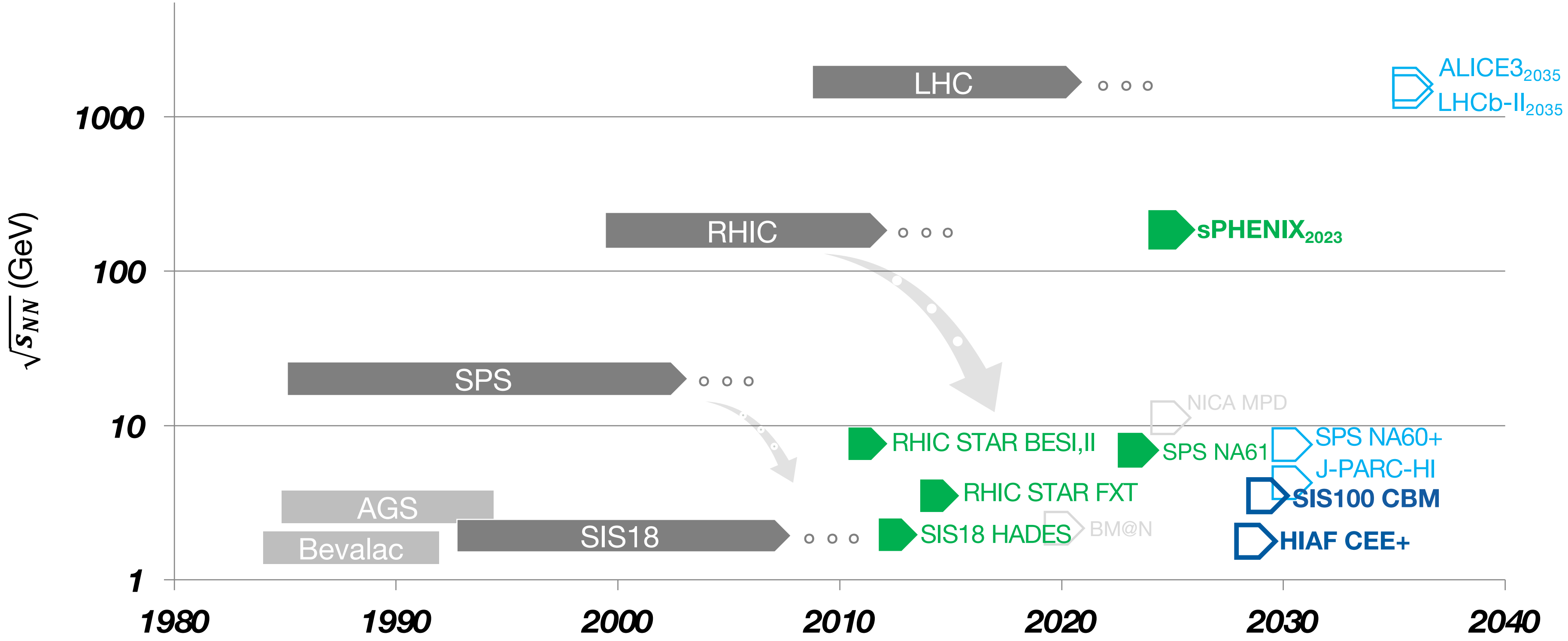
The quest for highest energy



Time ≡ advances in accelerator and detector technologies

The quest for utmost precision and sensitivity for rare signals

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



Time ≡ advances in accelerator and detector technologies

Facility for Antiproton and Ion Research

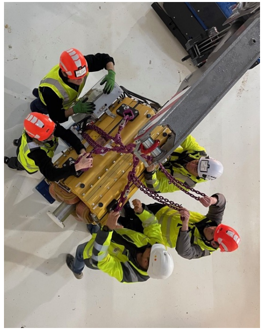
multi-purpose (strong interaction) facility

FAIR project status

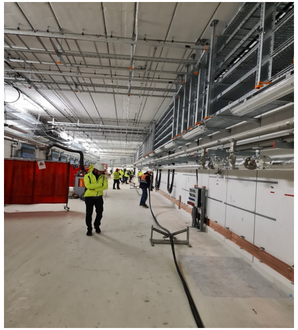
installation of SIS100 dipoles Apr’24

cryogenic bypass lines SIS100 placed in SIS100 tunnel, Apr‘24

transport of the first quadrupole magnet in tunnel, Mar‘24



start of cable pulling work, Q3/23



6 He tanks of the cryo facility were installed, Apr’24

construction side May‘24

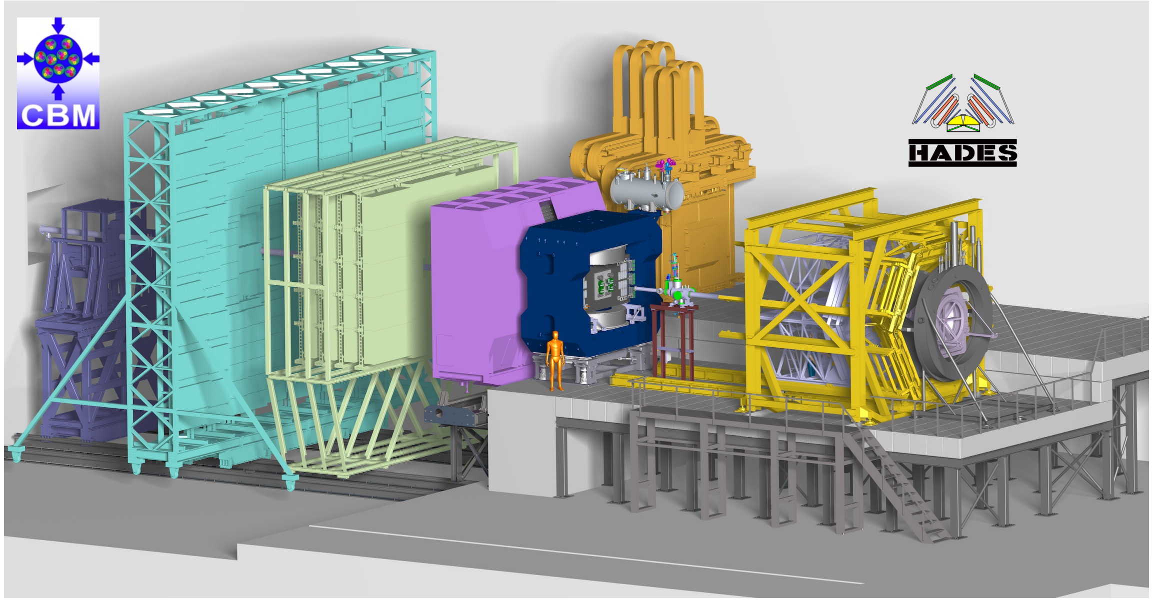
construction area south

CBM cave, Feb‘24

Compressed Baryonic Matter experiment

315 full members from 10 countries
47 full member institutions
10 associated member institutions

- Fixed target experiment
  → obtain highest luminosities
- Versatile detector systems
  → optimal setup for given observable
- Tracking based entirely on silicon
  → fast and precise track reconstruction
- Free-streaming FEE
  → nearly dead-time free data taking
- On-line event selection
  → highly selective data reduction

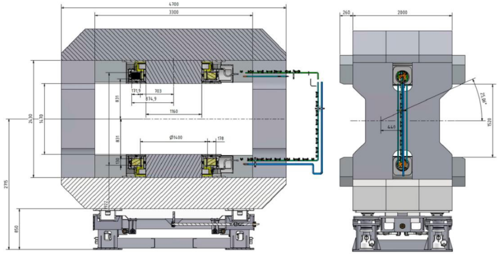


Q4 2027 – installation and commissioning w/o beam
Q4 2028 – commissioning with SIS100 beam

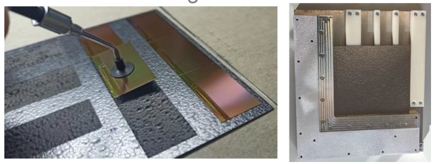
CBM subsystems are on the verge of series production

➥ pre-production is ongoing in all systems

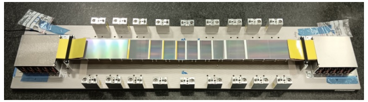
Superconducting dipole magnet
award of contract to Bilfinger Noell GmbH 20.12.2023



Micro Vertex Detector
sensor/module integration



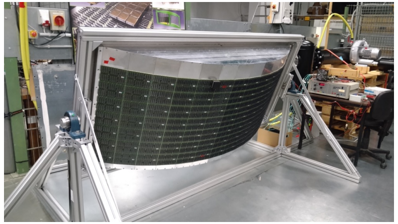
Silicon Tracking System



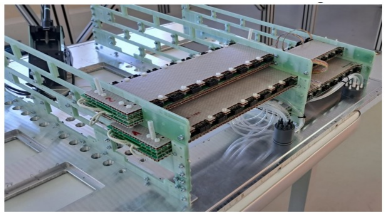
first STS series ladder

> 100 modules assembled

Ring Imaging Cherenkov detector
1 of 2 photo cameras ready
50% FEE produced



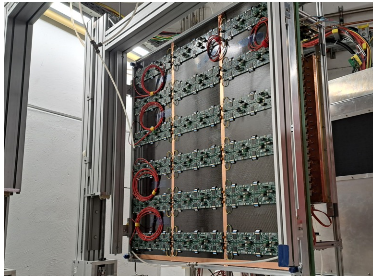
Time of flight detector



module pre-production concluded

Beam monitoring system

Transition Radiation Detector

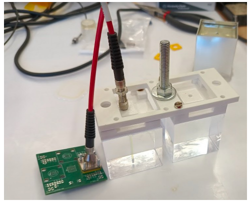


pre-production modules of 1D and 2D options ready

MUon CHamber system

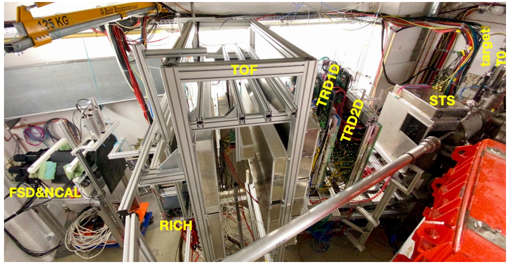
test of full-size GEM and RPC prototypes

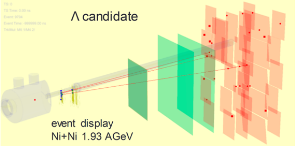
Forward Spectator Detector

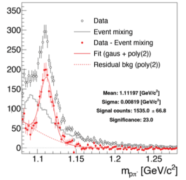


ZnS scintillators and LYSO crystals read-out via SiPM or/and PMT

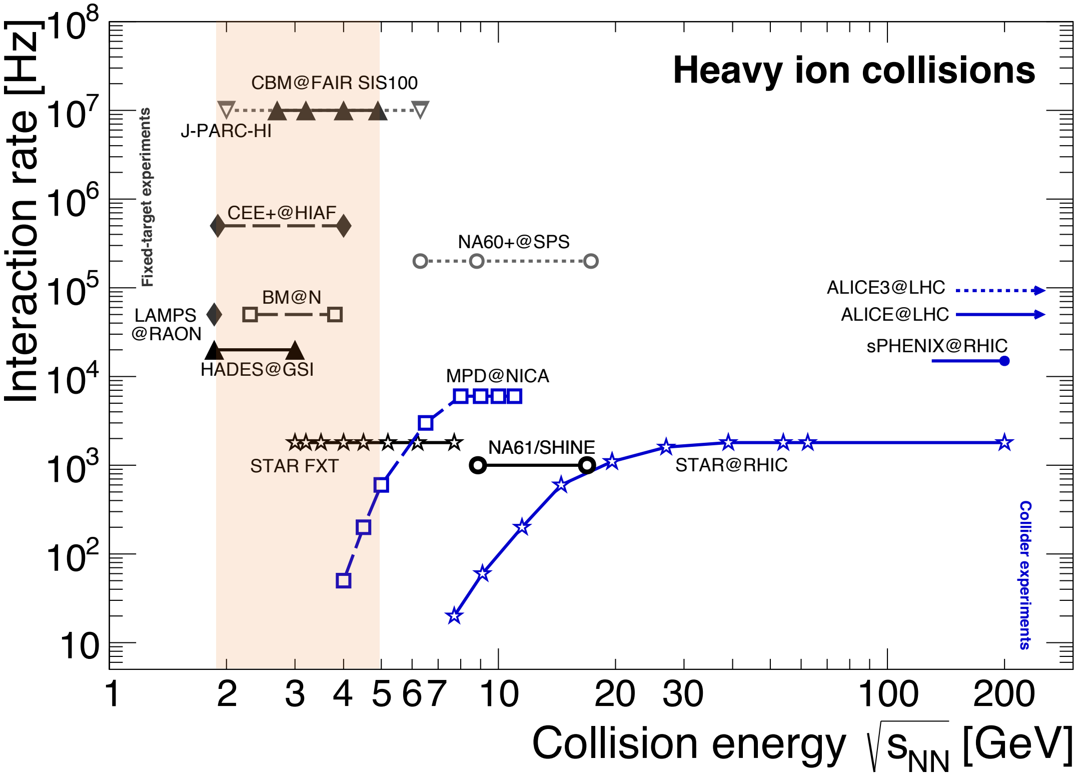
Prototype of CBM online data processing tests with mCBM







Some basic facts on high μ_B facilities

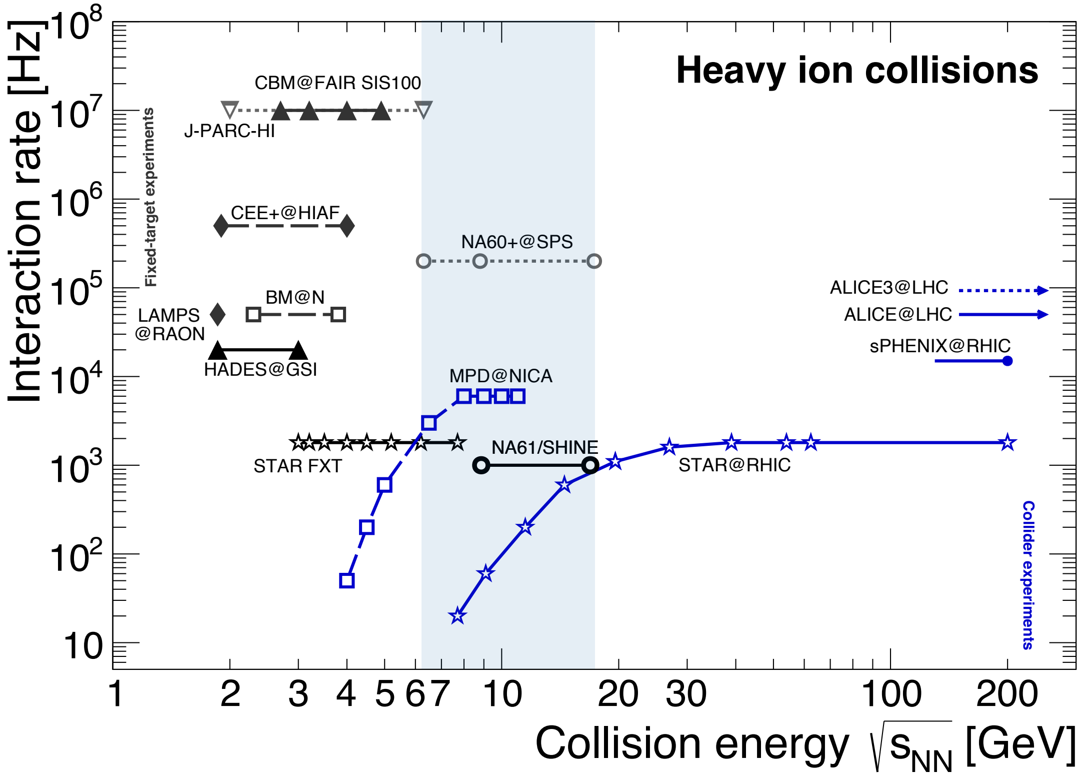


- **CBM** will play a unique role in the exploration of the QCD phase diagram in the region of high μ_B with rare and electromagnetic probes: high rate capability, energy range 3< $\sqrt{s_{NN}}$ <5 GeV
- **HADES**: established thermal radiation at high μ_B, limited to 20 kHz and $\sqrt{s_{NN}}$=2.4 GeV
- **STAR FXT@RHIC**: BES program completed; limited capabilities for rare probes
- **CEE+@HIAF construction**: multipurpose detector based on TPC, anticipated rate capability 500 kHz, anticipated start 2025
- **J-PARC-HI proposal:** addition of heavy-ion booster, state of the art detectors (e, μ, hadrons)

...

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

Some basic facts on high μ_B facilities



SPS: wide energy range $6 < \sqrt{s_{NN}} < 17$ GeV, high luminosity beams 10^6 –10^7 ions/s, existing facility

- **NA61/SHINE:** multi-purpose experiment investigating hadron production since 2009
- **NA60++ proposal:** dimuon spectrometer employing hadron absorber, >10^5 Hz rate capability ⇝ high statistics for rare and penetrating probes
- **ALICE 3 proposal:** exploit the forefront detector technologies and high luminosity potential of the LHC for ions

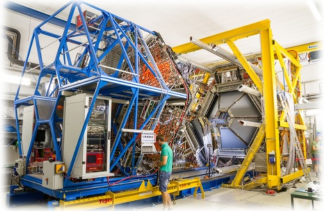
LHC ⟶ RHIC ⟶ SPS ⟶ SIS program needs ever more precise data and sensitivity for rare signals

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

High μ_B instruments

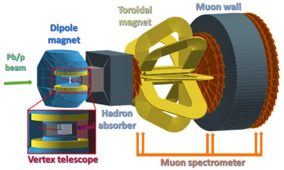
CBM/HADES at SIS100 (2028)

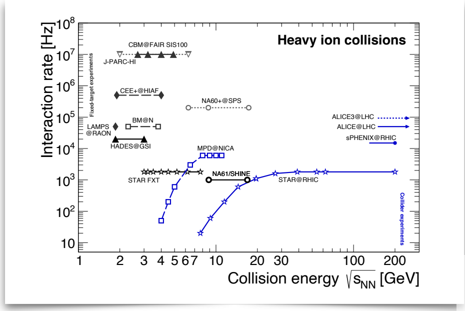
HADES at SIS18 (running)



NA61/SHINE at SPS (running)

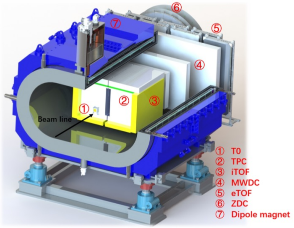
NA60+ at SPS (>2030, after LHC LS3)



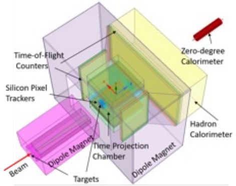


STAR at RHIC (completed)

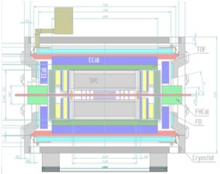
CEE+ at HIAF (2027)



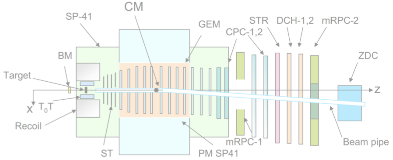
J-PARC-HI



MPD at NICA



BM@N



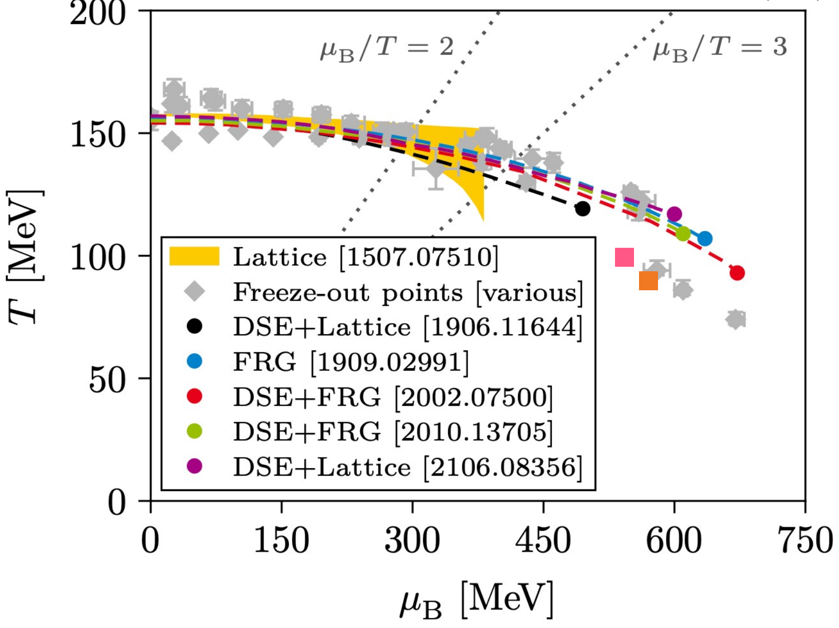
*Performance studies with realistic detector geometries, material budget, and response

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

CRITICALITY

Critical point predictions from theory

[1]DSE: Bernhardt, Fischer and Isserstedt, PLB 841 (2023)



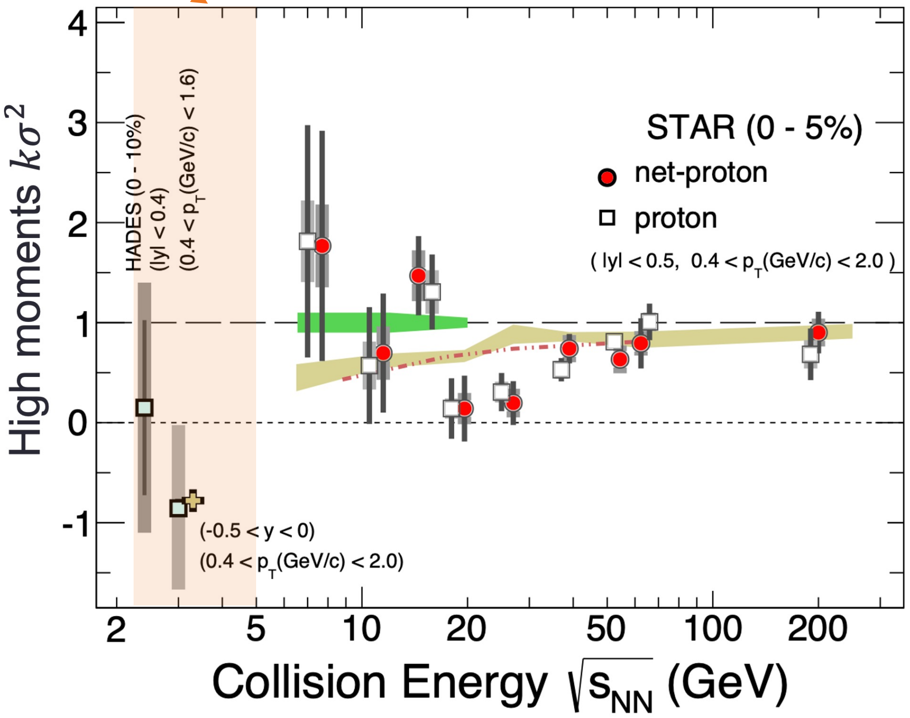
Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
Borsanyi *et al*. [Wuppertal-Budapest], PRL 125 (2020)

- Lattice QCD disfavours QCD critical point at $\mu_B/T < 3$
- Effective QCD theories[1-3] and lattice-Pade[5,6] predict QCD critical point in a similar ballpark $T\sim 90-120$ MeV, $\mu_B \sim 500-650$ MeV
- If true, reachable in heavy-ion collisions at $\sqrt{s_{NN}} \sim 3-5$ GeV
- Including possibility that the QCD critical point does not exist

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

[2]FRG: Fu, Pawlowski, Rennecke, PRD 101, 053032 (2020)
[3]BHE: Hippert et al., arXiv:2309.00579
[4]lQCD-Pade: Basar, arXiv:2312.06952
[5]lQCD-Pade: Clarke *et al.*, PoS LATTICE2023 (2024), 168

Critical point search



encodes the EoS

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

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

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

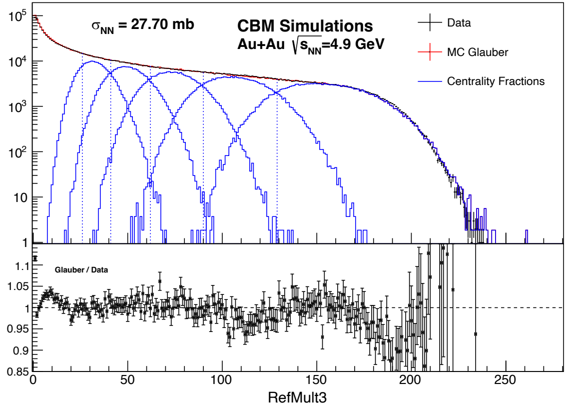
- Current data consistent with non-critical physics?
  → reduced errors to come from STAR BES-II
- Sensitivity to features of the QCD phase diagram grows with the order of the moment
- **Higher order moments probe the tails – statistics/artefacts!**
- Detailed **systematic** studies of experimental effects **is curtail**

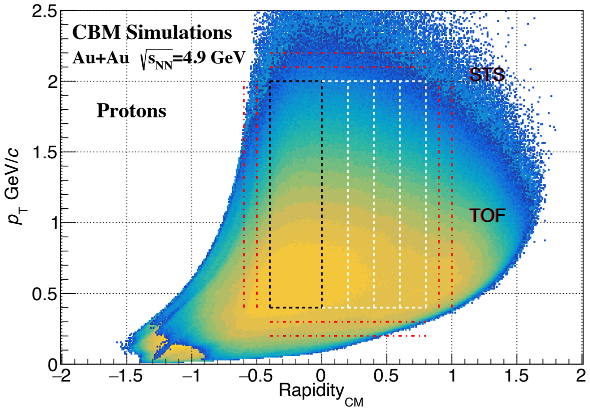
Holzmann, Koch, Rustamov, Stroth, arXiv:2403.03598 [nucl-th]
Kitazawa'2012, Skokov'2013, Bzdak '2016, Kitazawa'2016, Braun-Munzinger'2017

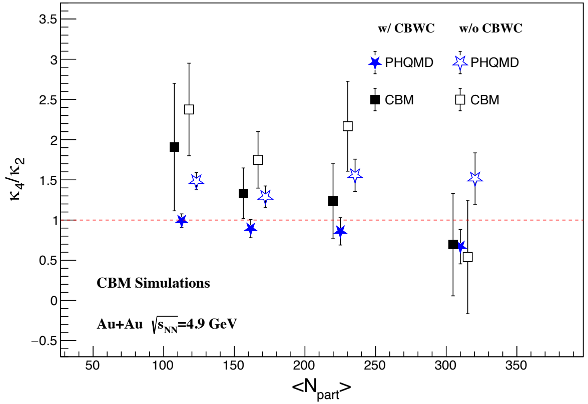
Performance studies in CBM

- Corrections for volume fluctuations and conservation laws
- Event-by-event changes of efficiency
- Proper selection of $p_T - y$ bite
- (Net-)baryons vs. protons, neutrons, nuclei

} impact of the effects is being scrutinized







Crucial: centrality determination with independent detector → avoids bias on e-b-e fluctuation observables

Studies employing FSD centrality detector ongoing

Low p_T and midrapidity coverage for all energies

Reconstruction efficiency allows for precision measurement of cumulants

Statistics sufficient to study derivatives of order $> \mathcal{O}(4)$

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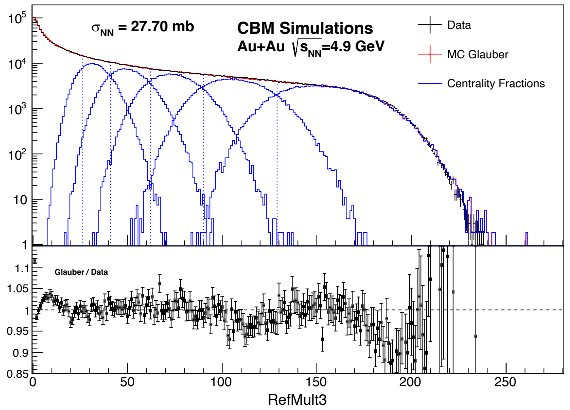
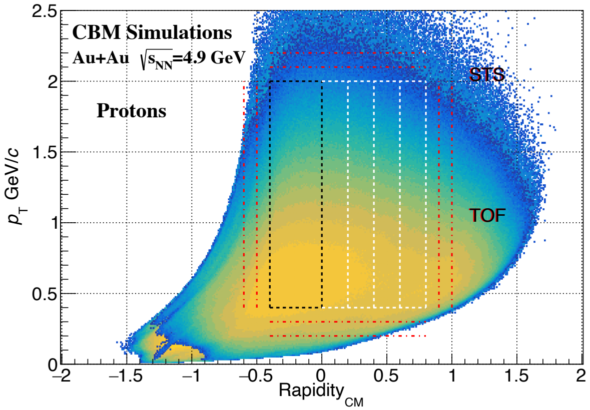
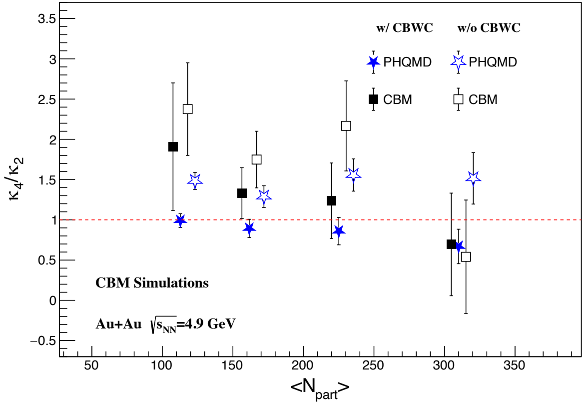
CBM after 3 years of running:
- **completion of the excitation function for $\kappa_4(\mathrm{p})$**
- **first results on $\kappa_6(\mathrm{p})$**
- **extension into strangeness sector $\kappa_4(\Lambda)$**

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







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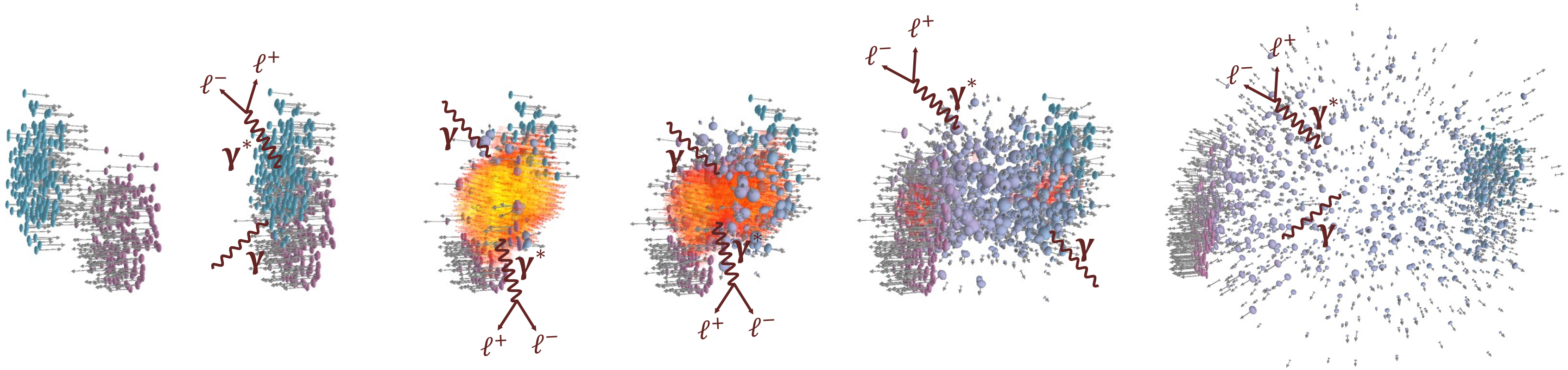
Electromagnetic radiation

EMISSIVITY

Electromagnetic radiation as multi-messenger of fireball



Electromagnetic radiation (γ, γ^*)

Reflect the whole history of a collision

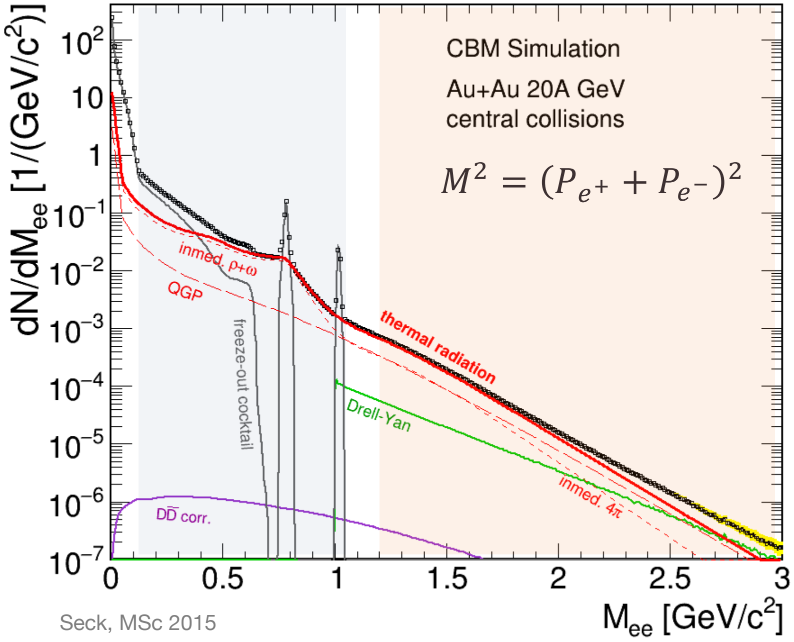
No strong final state interaction
↝ leave reaction volume undisturbed

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

Low-mass regime Intermediate-mass regime

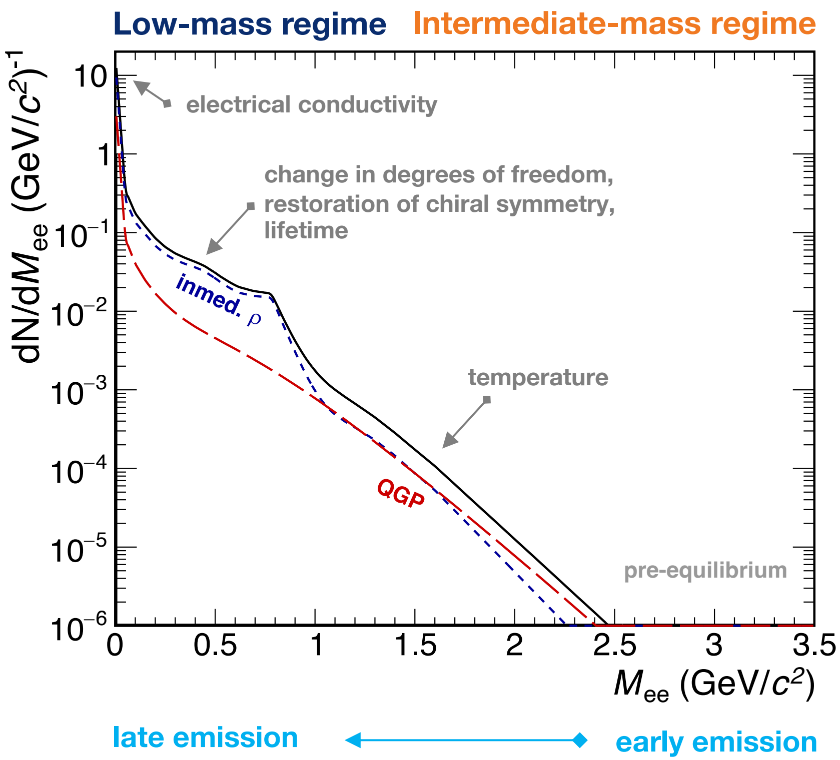


Seck, MSc 2015

- 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 dilepton measurements



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

- Emission rate of thermal dileptons
  → unique direct access to in-medium spectral function

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

'Planck-like'

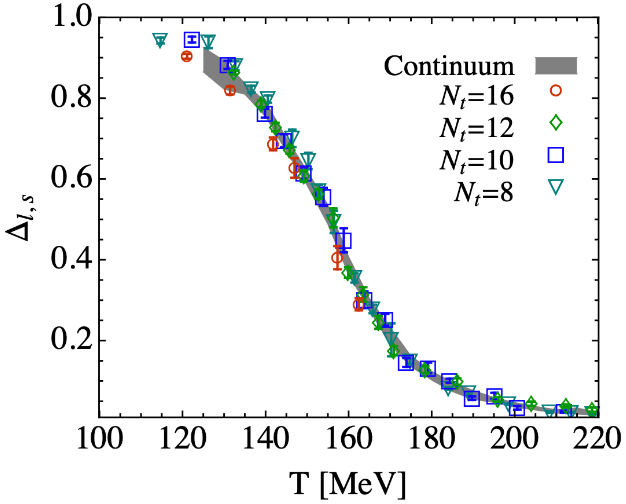
In-medium spectral function

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

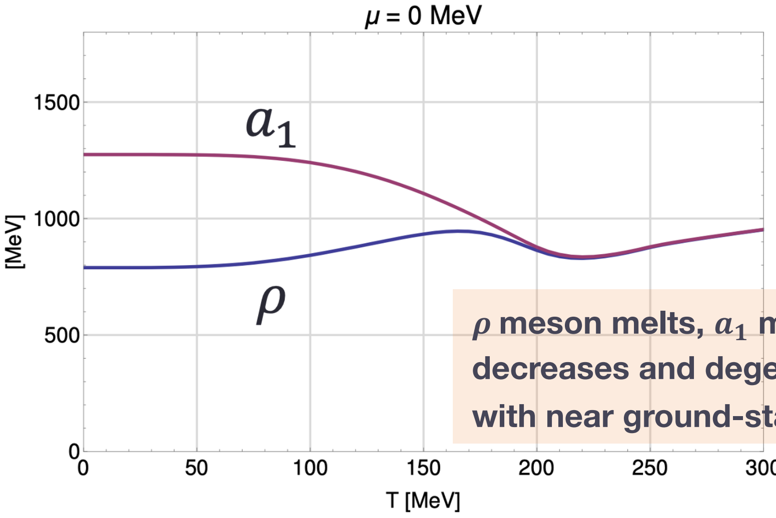


Bazavov *et al.* [Hot QCD Coll.], PRD90 (2014) 094503

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



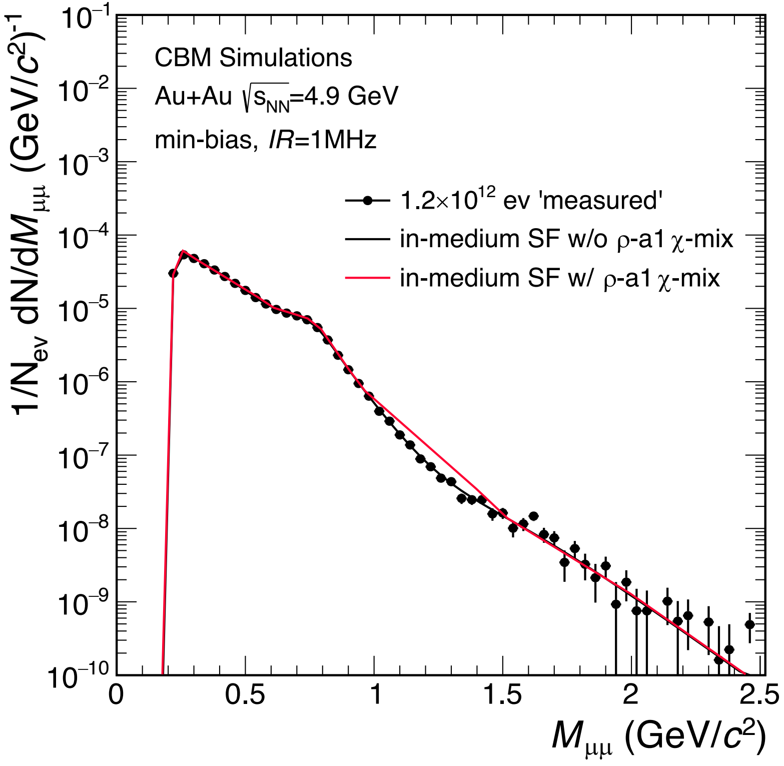
ρ meson melts, a_1 mass decreases and degenerates with near ground-state mass

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

Additional 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

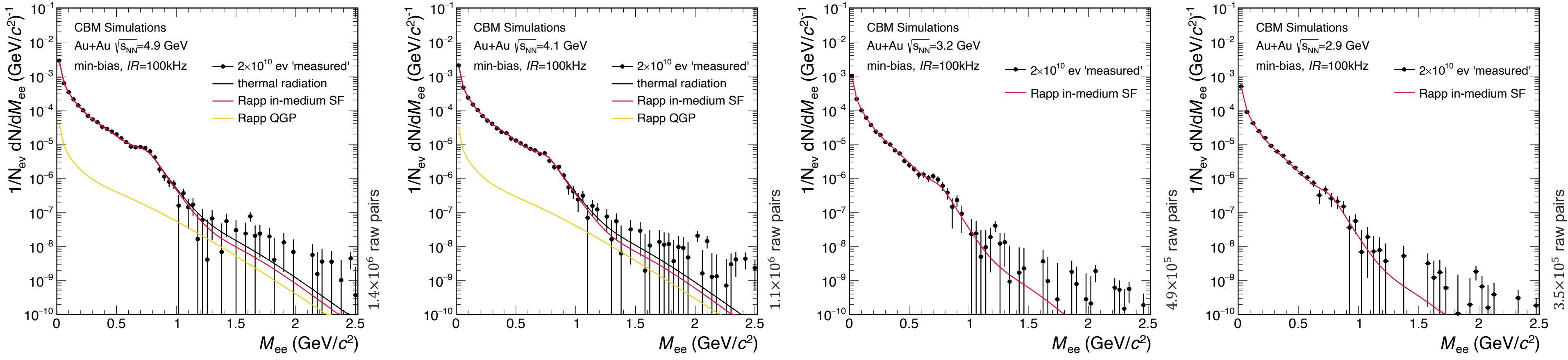
Dey, Eletsky, Ioffe, PLB252 (1990)
Rapp, Wambach, ANP 25 (2000)
Sakai *et al.*, arXiv:2308.03305 [nucl-th]

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

CBM dielectron performance (first year, 5 days / energy)

Isolated dielectron thermal radiation yield, corrected for acceptance x efficiency:

- Dominated by ρ contribution at low mass ($M_{\ell\ell}$ <1GeV/c^2); can be reconstructed with precision of 1.5 – 4.5%
  - allows fireball lifetime measurement
  - transport properties – electrical conductivity? $\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} Im\Pi_{em}(q_0, q = 0; T)$
- Intermediate mass range ($M_{\ell\ell}$>1GeV/c^2) accessible, statistics will not (yet) be sufficient to extract physics

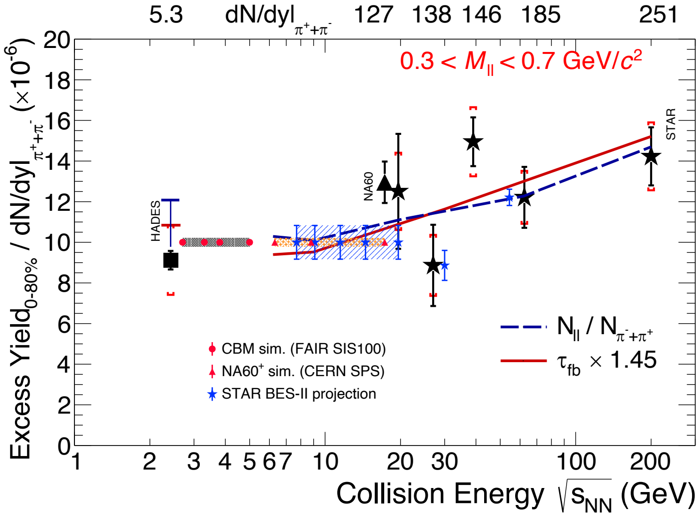


T vs. baryon density effects
from partonic to hadronic fireballs

Thermal dileptons excitation functions CBM & NA60+

Excess yield in LMR tracks fireball lifetime

- Search for "**extra radiation**" due to latent heat around **phase transition** (& critical point?)

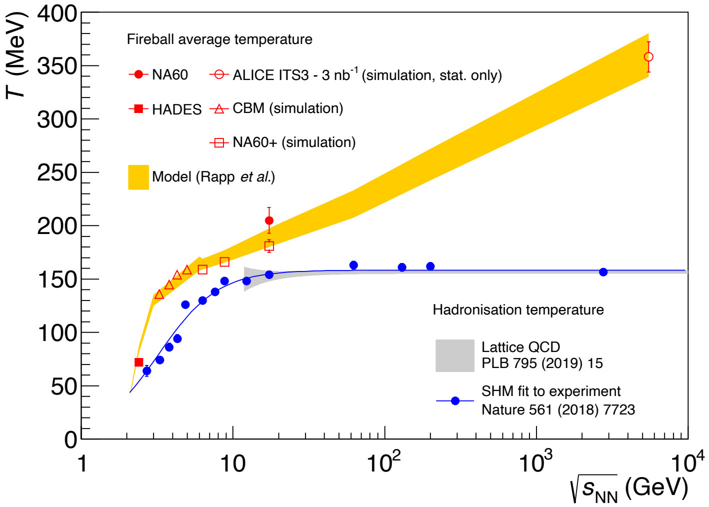


TG, JPS Conf.Proc. 32 (2020) 010079

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*

Seck, Friman, TG, van Hees, Speranza, Rapp, Wambach, [arXiv:2309.03189 [nucl-th]]

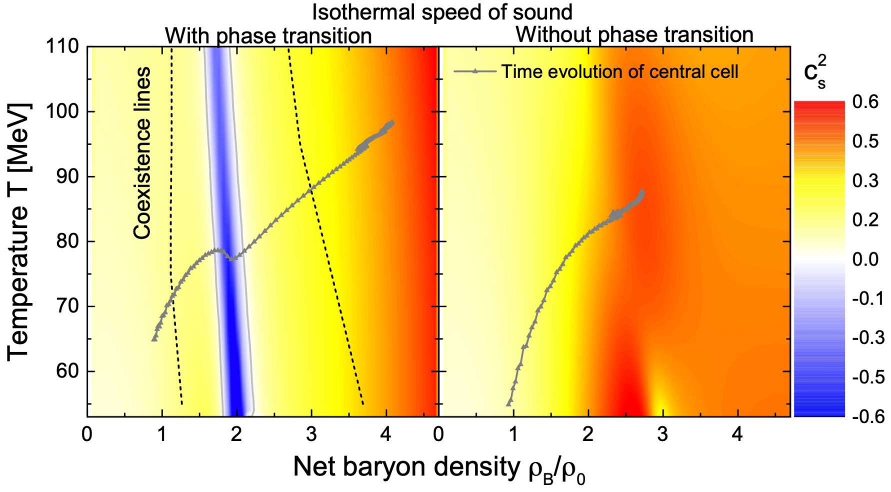


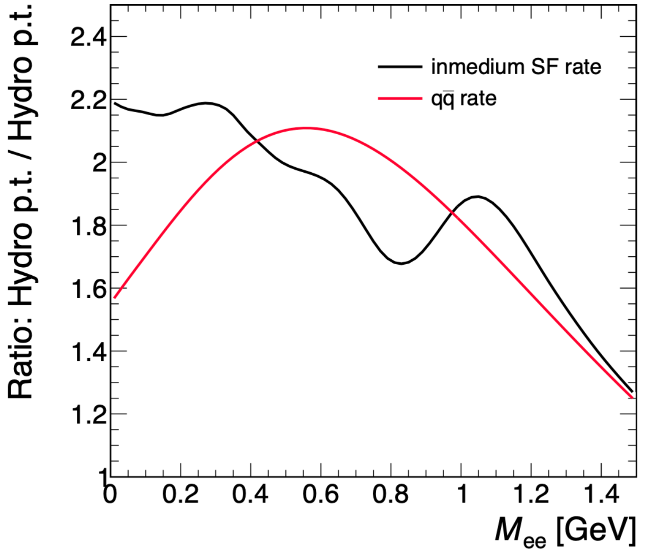
https://github.com/tgalatyuk/QCD_caloric_curve

Dilepton signature of a 1st order phase transition

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

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





- 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"

Chemistry, vorticity, flow

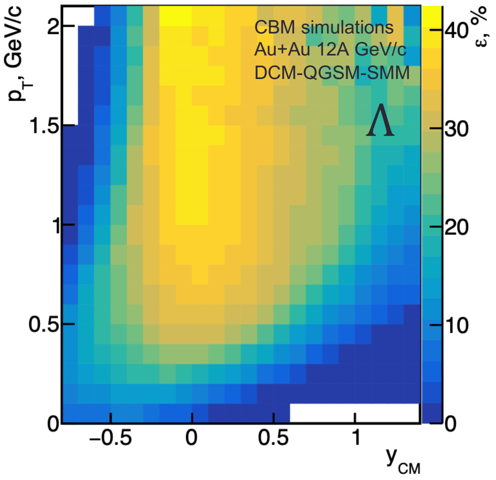
EQUATION OF STATE

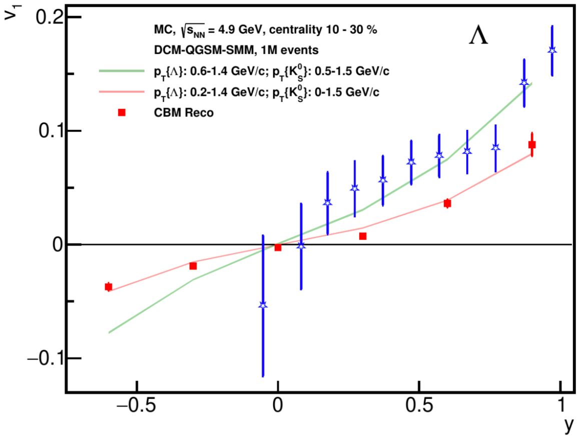
Collective flow and polarization of $\Lambda, \bar{\Lambda}$ and Ξ^- in CBM

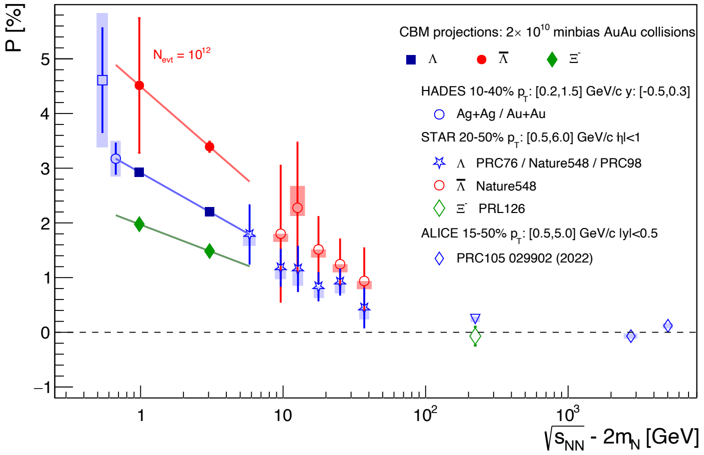
- Excellent phase space coverage (y_{CM} coverage for all $\sqrt{s_{NN}}$)
- Reconstruction efficiency ~30%
- Event plane resolution $\Re 1 \cong 0.8$, $\Re 2 \cong 0.5$

- Precision measurement of spectra and flow pattern (no data for Ξ, Ω available below AGS energies)
- Superior CBM performance to the STAR-FXT flow measurements

- Measurement of polarization of Λ and Ξ^- with precision of 5%
- Mapping of the excitation function for $\bar{\Lambda}$ requires $\geq 10^{13}$

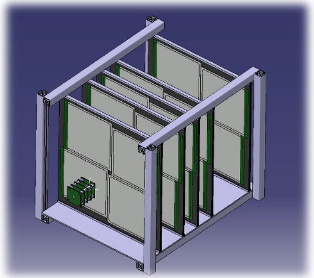






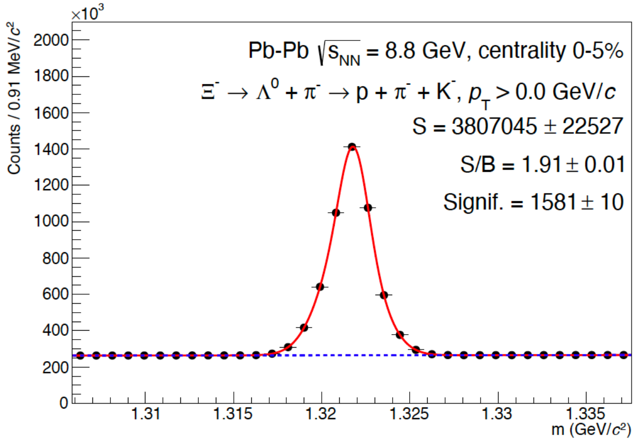
Anticipated physics performance

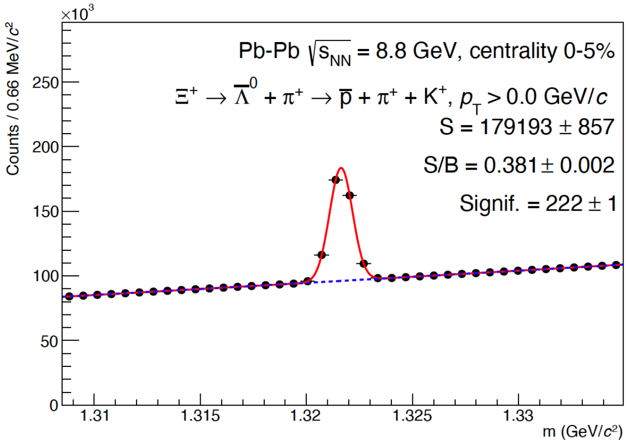
5-10 planes of MAPS detectors



NA60++

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





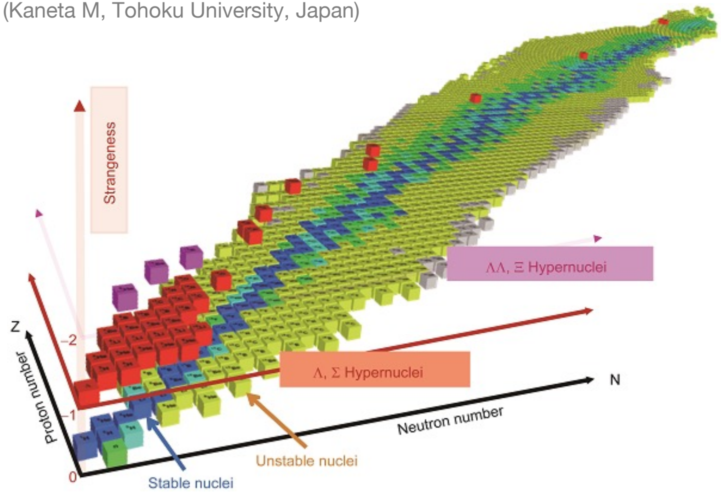
Alocco *et al.*, NA60+, PoS FAIRness2022 (2023) 002

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

Nuclei and hyper-nuclei production

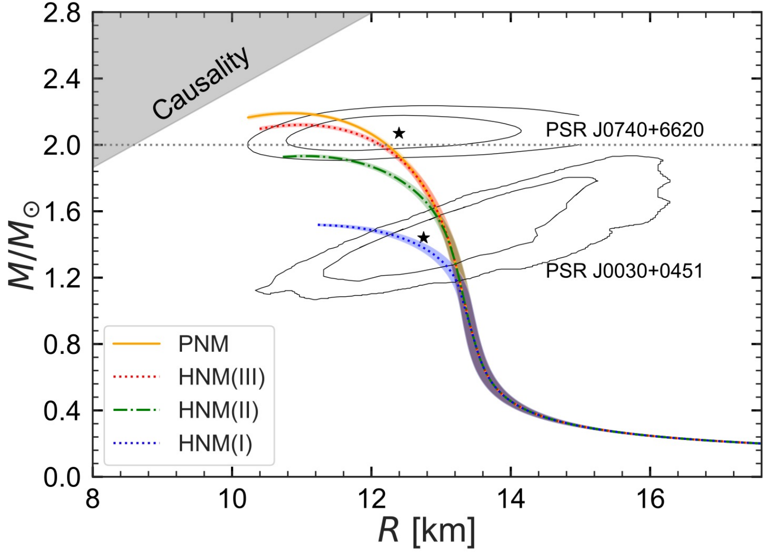
Three-dimensional nuclear chart

(Kaneta M, Tohoku University, Japan)



Ab initio calculation of hyper-neutron matter

Tong, Elhatisari, Meißner, [arXiv:2405.01887 [nucl-th]]



- How do nuclei and hyper-nuclei form?
- What are their properties?
- How do YN and YY interact?

Crucial for neutron star physics

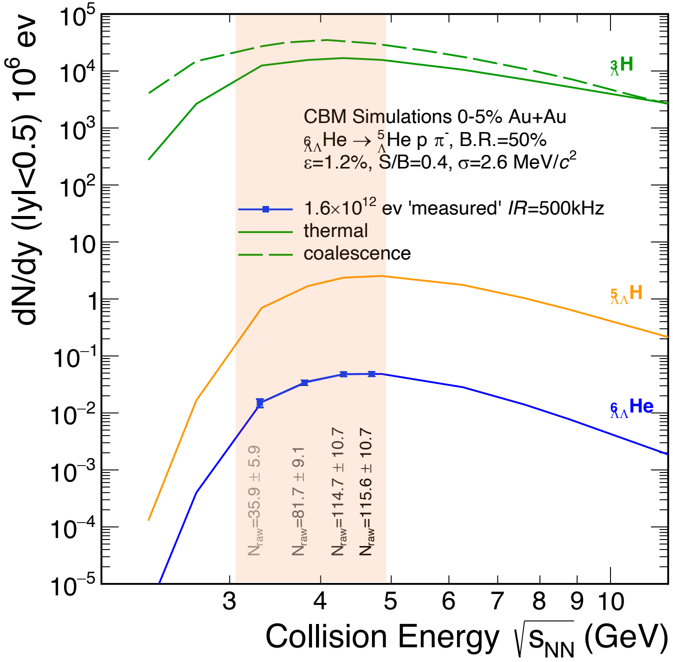
EoS of high density matter

three-body hyperon-nucleon interaction plays a fundamental role in the softening of the EoS

CBM performance

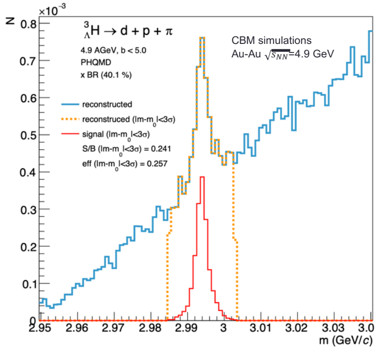
CBM collision energies optimal for hypernuclei production

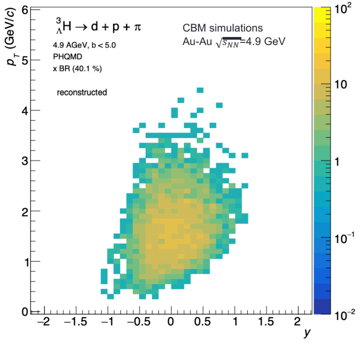
Thermal: Andronic *et al.*, PLB 697 (2011)
Coalescence: Steinheimer *et al.*, PLB 714 (2012)

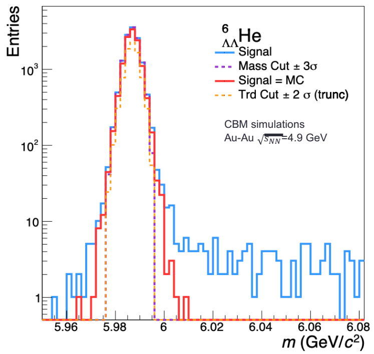


- CBM high interaction rates and clean identification allow precision measurements of single- and double Λ-hypernuclei
  - spectra and flow pattern
  - complex structure via Dalitz plot
  - life-time (particularly sensitive to YN and YY interaction)
- Search for the new hyper-nucleus or charmed nucleus $^{4}_{D}He$

Dover, Kahana, PRL 39, 1506, 1977
Xu, Lin, Yang in preparation



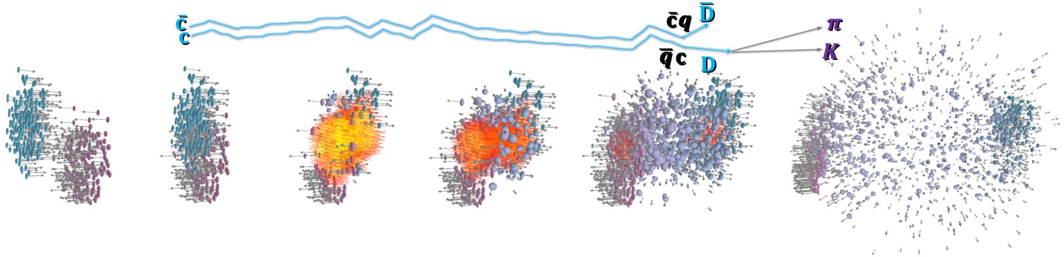




Charm $(c, \bar{c})$ of the baryon-rich matter

IN-MEDIUM QCD FORCE

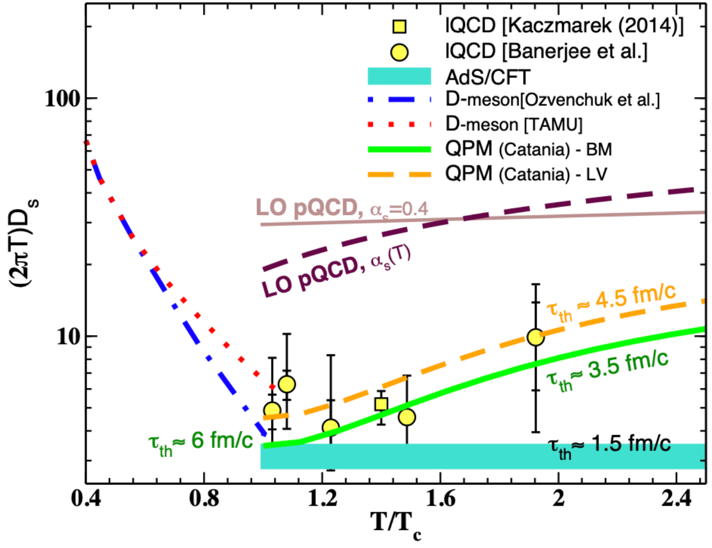
What is so “charming” about charm?



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, PRL 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

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

Charm performance studies

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

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

NA60++ / CBM (cross-sections unknown!)

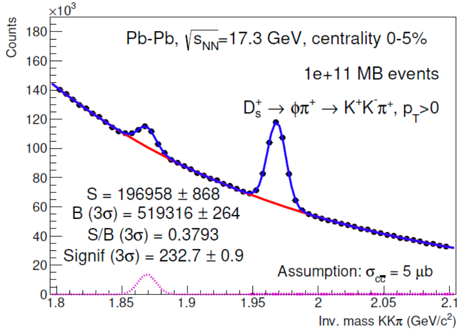
Open charm

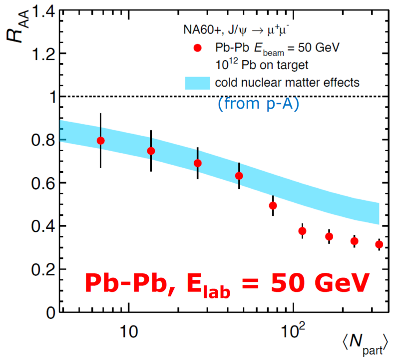
- accessible down at lowest $\sqrt{s_{NN}}$ with 1% statistical precision
  ⤳ R_{AA} and v_2 vs p_T, y and centrality
  → charm diffusion coefficient and thermalization
- **D_s** and **Λ_c** yield feasible with statistical precision of few percent
  → insight on hadronization mechanism

J/ψ

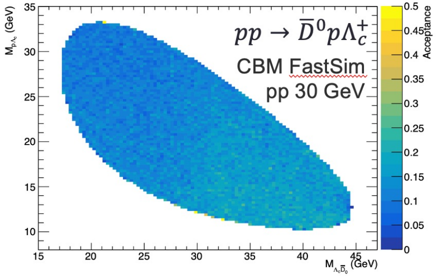
- detection of **onset of anomalous suppression** effects down to low SPS energy ($\psi(2S)$ also within reach for E~100 *A*GeV)
- pp/pA collisions to establish cold nuclear matter effects
- study intrinsic charm component of the hadron wave function

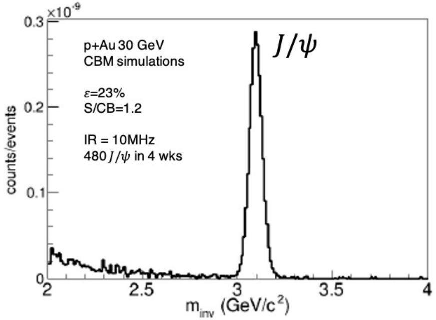
Vogt, PRC 106 (2022) 2, 025201
NNPDF, Nature 608 (2022) 7923, 483-487





Charm-N interaction





Tremendous physics potential with proton beam from SIS100

Workshop "physics opportunities with proton beams at SIS100" in Wuppertal, February 2024
https://indico.gsi.de/event/18475/overview

Summary: The future is bright!

Encouraging prospects for studying high μ_B region

- **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, 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!**

Summary: The future is bright!

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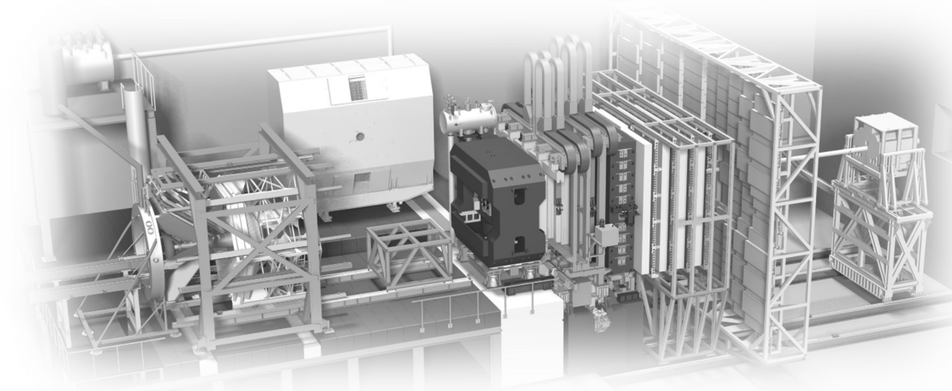
Bonus slides

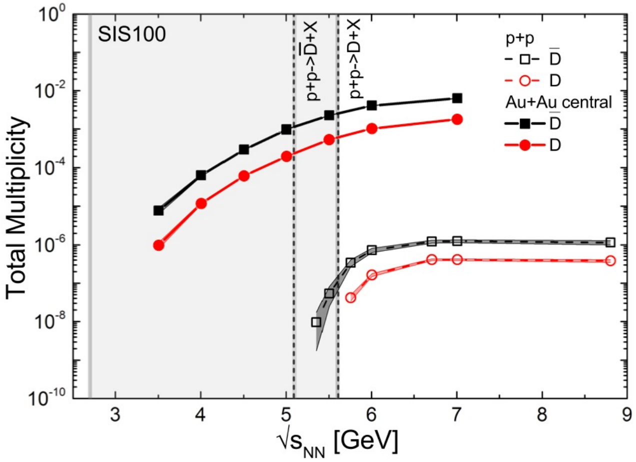


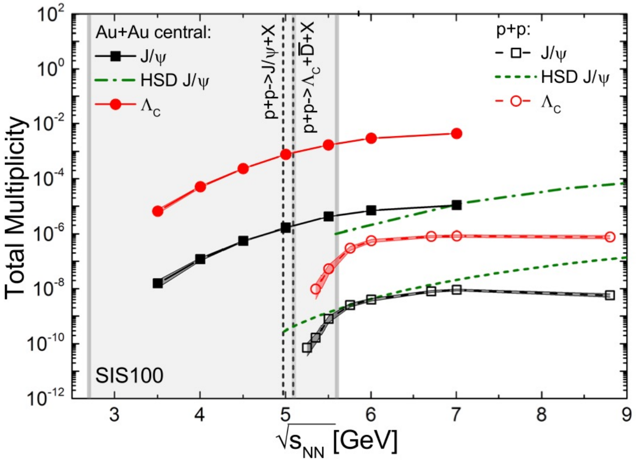
Charm $(c, \bar{c})$ of the baryon-rich matter

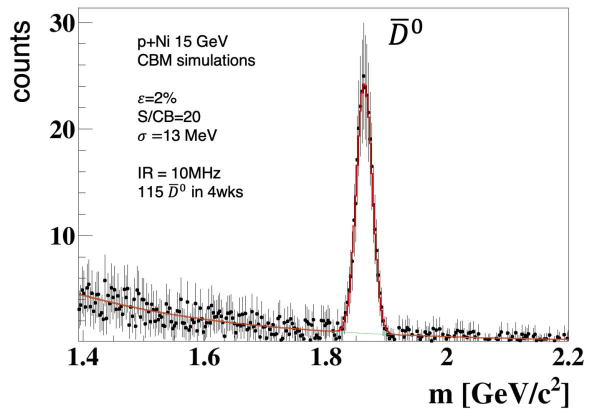
IN-MEDIUM QCD FORCE

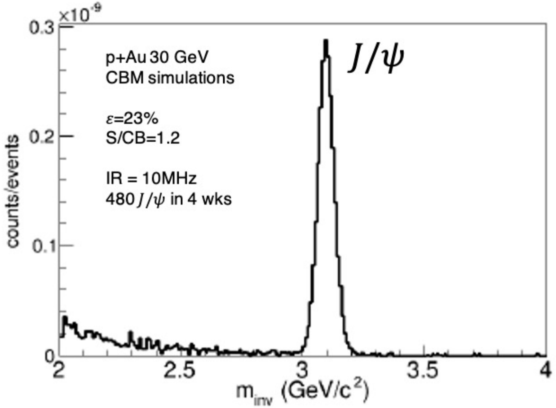
Open charm and charmonium at SIS100

J. Steinheimer *et al.*, PRC 95 (2017) 1, 01491







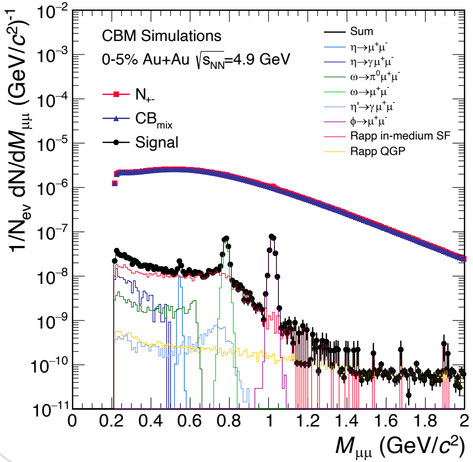


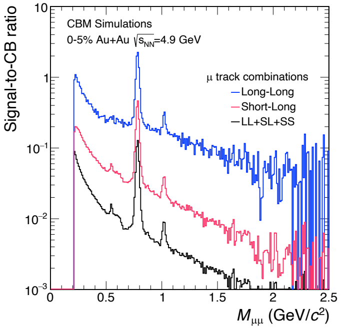
CBM dilepton detection performance

- **Electron-setup R_{int} = O (0.1 MHz):** identification with RICH-TRD-ToF (π suppr. ≥ 10^4); major CB γ-conversions in target, π^0 Dalitz decays; topological cuts used to reject CB
- **Muon-setup R_{int} = O (1 MHz):** instrumented hadron absorber, low- and high energy configuration
- Performance studies with realistic detector geometries, material budget, and response

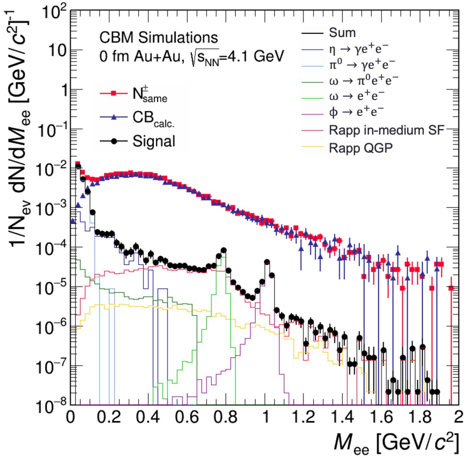
Rapp, Wambach Adv. Nucl.Phys. 25, 1 (2000)
TG *et al.*: EPJA 52 (2016) 131

- Input to the simulations:
  - thermal radiation; in-medium hadronic rates (ρ, ω) and QGP rates folded with coarse-grained medium evolution from transport
  - hadronic “cocktail” generator Pluto ($\pi^0, \eta, \omega, \varphi$)
  - hadron and photon BG – Au+Au transport model calculations
- $\langle S/CB \rangle$ allows precise measurement
- Mass resolution: $\sigma_{M_{\ell\ell}}(\omega)$= 14 MeV/$c^2$

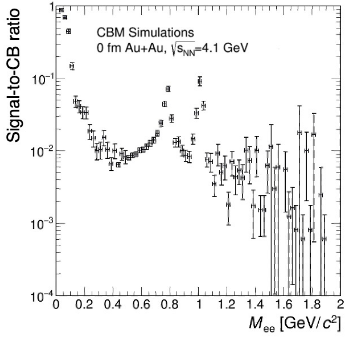




$\mu^+\mu^-$



e^+e^-



First 3 years scenario (as of May 2022)

Year	Setup	Reaction	Beam Energies T_{lab} [AGeV]	Days on Target	Number of events	Remarks
0	ELEHAD	C+C, Ag+Ag, Au+Au	2,4,6,8,10,max	60		Commissioning
1	ELEHAD	Au+Au	2,4,6,8,10,max	30 (5 each)	$2\cdot10^{10}$ each	EB minBias
1	ELEHAD	C+C	2,4,6,8,10,max	18 (3 each)	$4\cdot10^{10}$ each	minBias
1	ELEHAD	p+Be	3,4,8,29	12 (3 each)	$2\cdot10^{11}$ each	minBias
2	MUON	Au+Au	2,4,6,8,10,max	30 (5 each)	$2\cdot10^{11}$ each	minBias
2	MUON	C+C	2,4,6,8,10,max	18 (3 each)	$4\cdot10^{11}$ each	minBias
2	MUON	p+Be	3,4,8,29	12 (3 each)	$2\cdot10^{12}$ each	minBias
3	HADR	Au+Au	2,4,6,8,10,max	12 (2 each)	$4\cdot10^{11}$ each	EB + Selector(s)
3	HADR	C+C	2,4,6,8,10,max	6 (1 each)	$8\cdot10^{11}$ each	
3	HADES	Ag+Ag	2,4	28 (14 each)	10^{10} each	
3	ELEHAD	Ag+Ag	2,4	8 (4 each)	$2\cdot10^{10}$ each	minBias

Setup	Included subsystems	Average day-1 interaction rate
ELEHAD	MVD,STS,RICH,TRD,TOF,FPW	0.1 MHz
MUON	STS,MUCH,TRD,TOF,FPW	1 MHz
HADR	STS,TRD,TOF,FPW	0.5 MHz

- **Focus on beam energy scan**
- 60 days / year beam on target → factor 100 more statistics w.r.t. STAR FXT

- Different detector configurations (Piotr's talk)
- Subject to a reshaping depending on findings (*e.g.* long run at maximum $\sqrt{s_{NN}}$ with MUON setup)