EoS studies with CBM and HADES

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EMMI Workshop: Collective phenomena and the Equation-of-State of dense baryonic matter

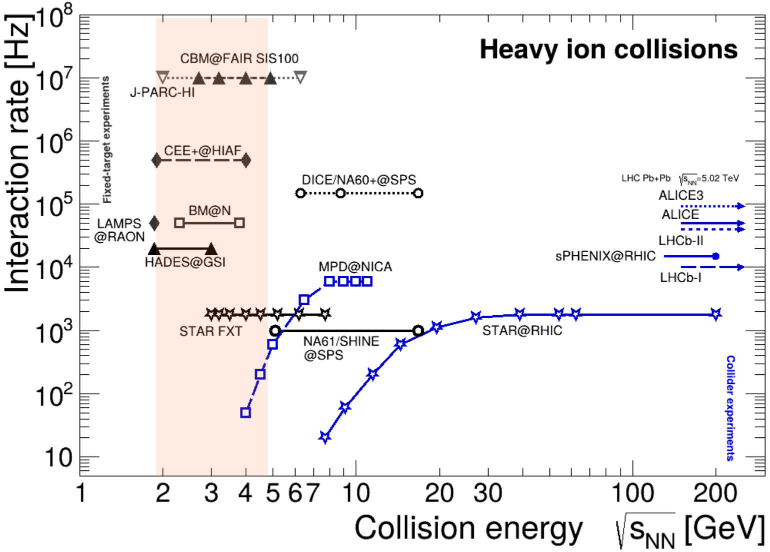
Nov 10 – 13, 2025, GSI

HADES/CBM Objective

"Explore the phase properties and microscopic structure of strong-interaction matter at high(est) net-baryon densities"

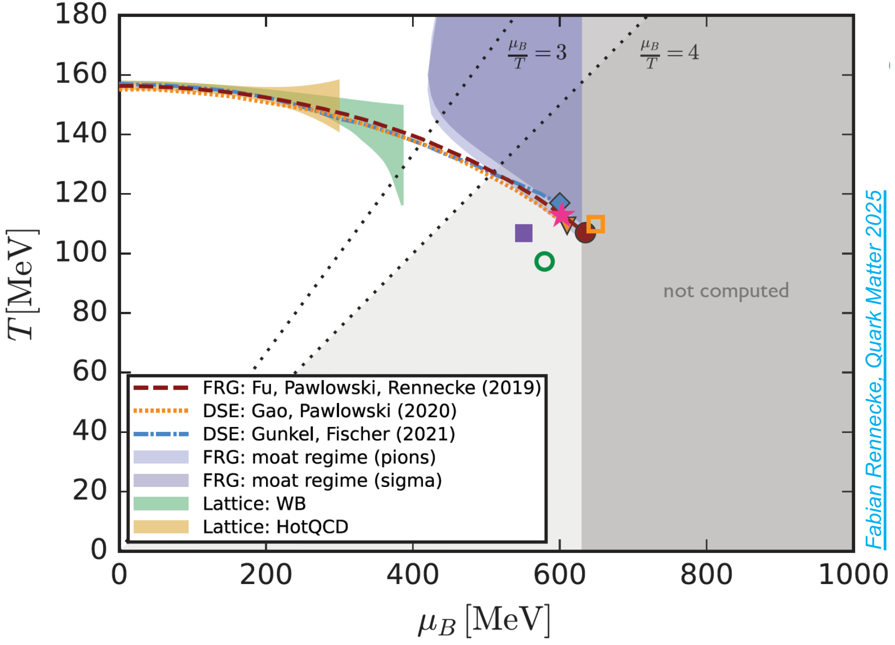
Focus on rare/penetrating probes and precission measurements

Requires high statistics/rates and excellent understanding of detector response



TG, NPA 982 (2019), update 2025
https://github.com/tgalatyuk/interaction_rate_facilities

HADES/CBM mission



CEP location well constrained by now. And it's in FAIR range!

$\sqrt{s_{NN}} = 3.6 - 4.1$ GeV

Search for landmarks of the QCD matter phase diagram:

- isolate unambiguous signals of new phases of QCD matter, order of phase transitions, conjectured QCD critical point
- establish high net-baryon density EoS
- probe microscopic matter properties

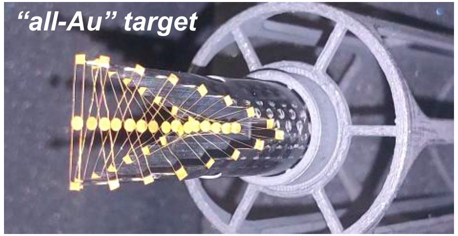
→ **heavy-ion beams**

Study various aspects of meson/baryon physics:

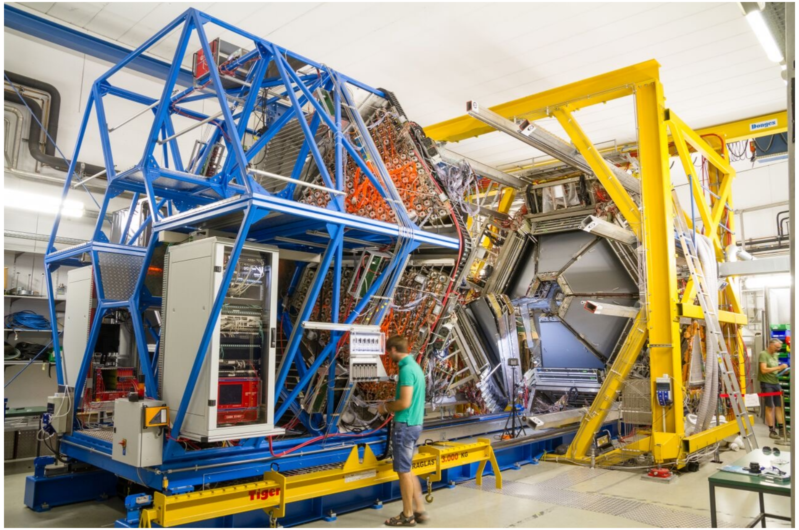
- (*u, d, s, c*) hadron production mechanism, spectroscopy (|*s*|=*2,3*, |*c*|=*1*), interactions, hadron structure
- electromagnetic transition form-factors

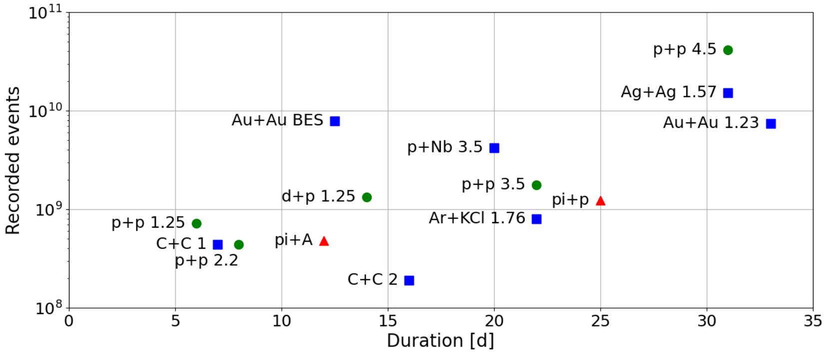
→ **secondary π, p, d beams**

High Aceptance DiElectron Spectrometer at GSI



- **Fixed target** setup, designed with a minimal material budget to reduce conversion
- **High acceptance**
  - Full azimuthal coverage, 18°-85° polar angle
  - Pair acceptance ≈ 0.35
- **Efficient** track reconstruction particle identification
  - 6-coils super conducting toroid
  - MDC – 4 planes of mini-drift chamber (~30.000 cells)
  - START, RICH, RPC, ToF, ECAL, FW
- **Precise:** mass resolution few %
- Heavy-ion, p and secondary π SIS18 beams
- **Fast:** accepted trigger rates
  - up to 20 kHz for heavy-ions
  - up to 50 kHz for hadron beams





Particle identification

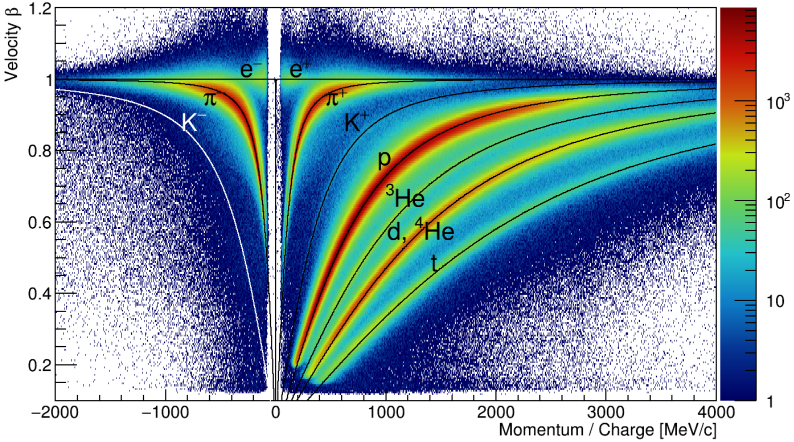
By means of: momentum, velocity, specific energy loss, Cherenkov radiation

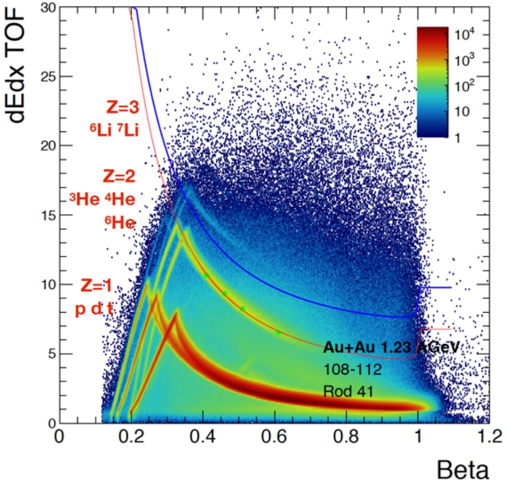
All combined in a multivariate analysis (neural network)

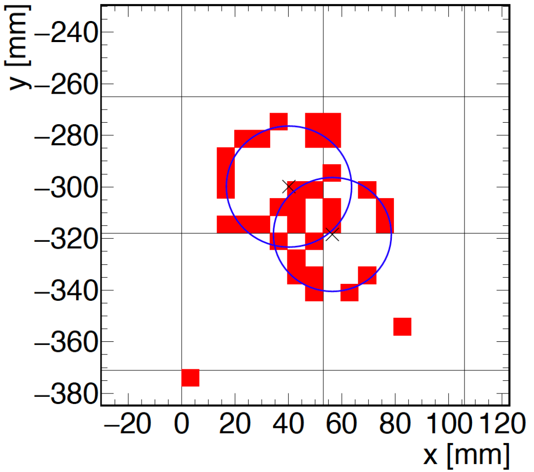
⇝ Best purity and efficiency

FAIR Phase 0 Research Program

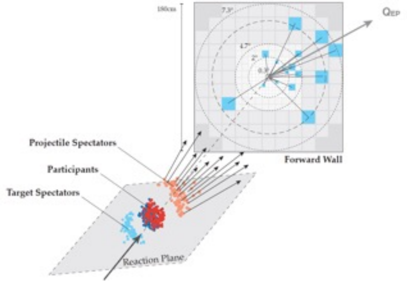
Upgrade of HADES RICH employing CBM technology - MAPMT based photo camera







Event characterization centrality estimator



Centrality estimator

Off-line centrality selection based on hit or track multiplicity and/or Forward Wall (FW) integral charge

Centrality determination based on FW avoids bias on e-b-e fluctuation observables

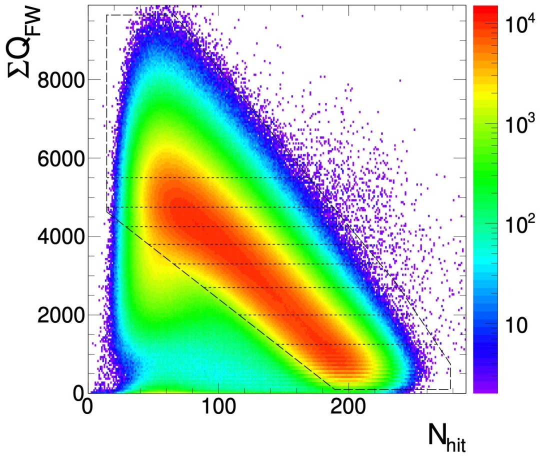
Using Glauber MC - distributions agree with transport model calculations

Event plane reconstruction

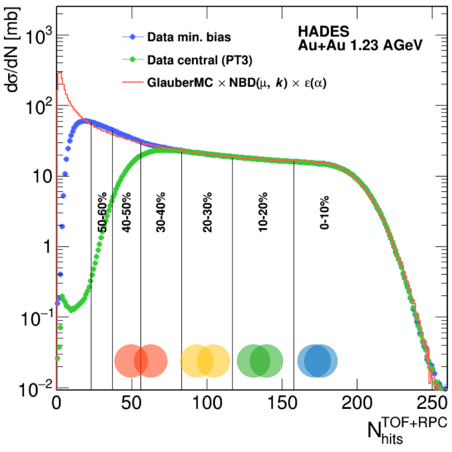
Hits of charged projectile spectators in the FW

Resolution determined from sub-event resolution based on method by J.-Y. Ollitrault, arXiv:nucl-ex/9711003

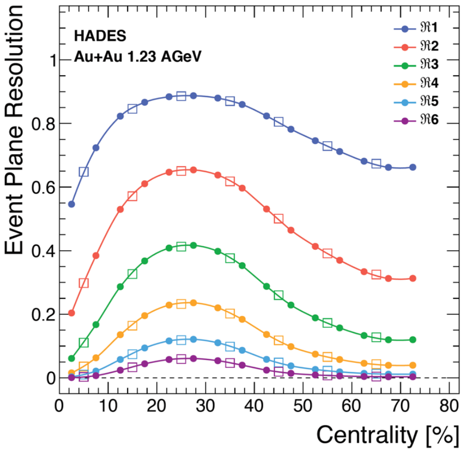
$$v_n = v_n^{obs}/\Re_n \qquad \Re_n = \langle cos[n(\Psi_n - \Psi_{RP})]\rangle$$



HADES, PRC 102 (2020) 2, 024914

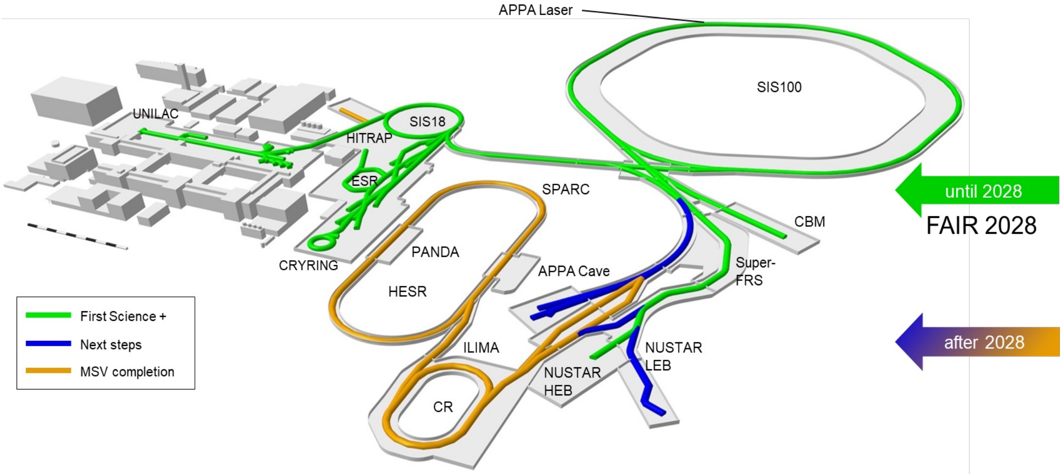


HADES, EPJA 54 (2018) 5, 85



HADES, PRL 125 (2020) 262301

Facility for Antiproton and Ion Research

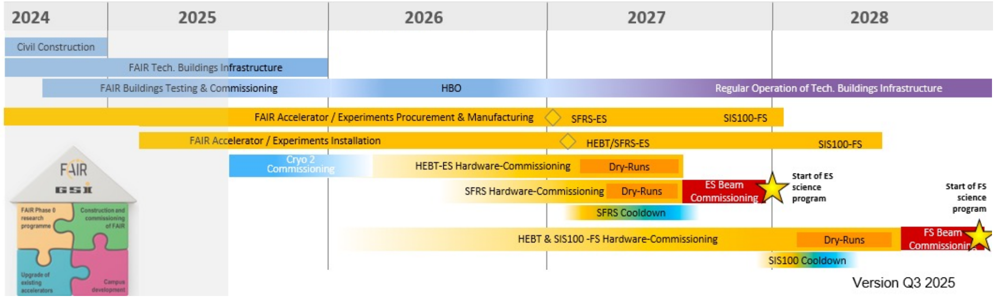


SIS-100 Capabilities			
Beam	Z	A	E_{max} [AGeV]
p	1	1	29
d	1	2	14
Ca	20	40	14
...			
Au	79	197	11
U	92	238	10

Intensity: $\sim 10^{13}$/s for p; $\sim 10^{11}$/s for U

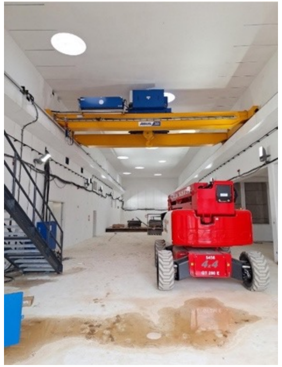
FAIR Timeline

- July 2017: Start of excavation and trench sheeting
- July 2018: Start of shell construction
- **June 2022: staging review**
- 2023: Buildings completed (First Science+ and Next steps)
- **2028: FAIR 2028 Operation**
- Beam time beyond 2028: 200 days annually



FAIR Project Progress
SIS100 installation

CBM building is accessible by road

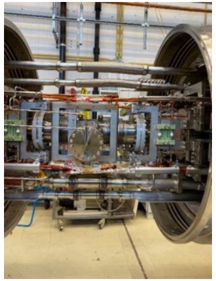


30-ton crane installed and commissioned

Installation of the main dipole- and quadrupole power converters in SIS100 tunnel started

Start of commissioning of Cryo plant and Cooling water system

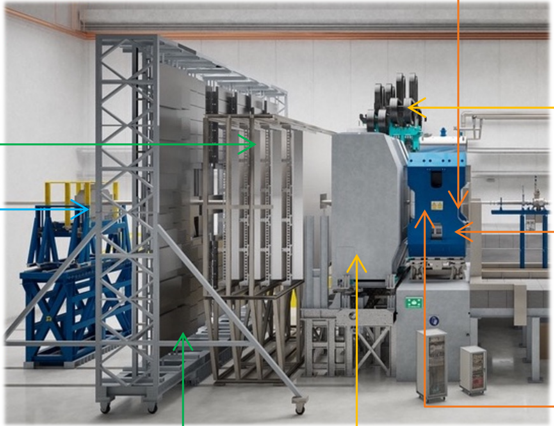
Process line welding successfully developed



Start of installation of the SIS100 laser cooling system


CBM
HADES
~2032 at SIS18
© GSI/FAIR, Zeitrausch

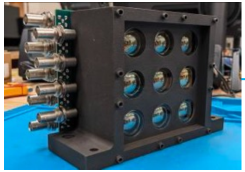
CBM systems mass production



Transition Radiation Detector

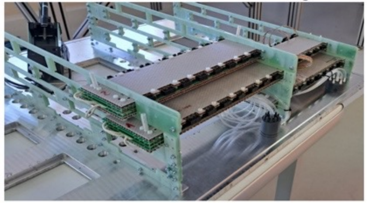
pre-production modules of 1D and 2D options ready

Forward Spectator Detector



3x3 FSD test module

Time of flight detector



20% counters assembled, module pre-production ongoing successful operation of mToF in 2025

Ring Imaging Cherenkov detector

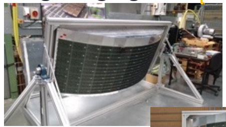
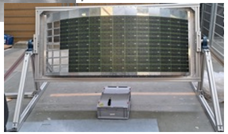


photo camera 1

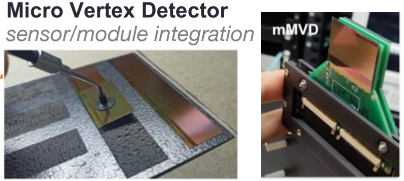
photo camera 2

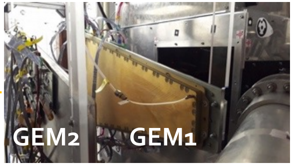


preparations for final batch of 1500 DIRICH FEBs

Micro Vertex Detector

sensor/module integration

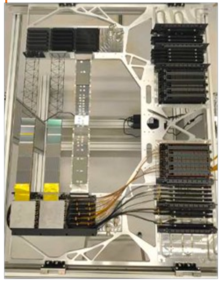




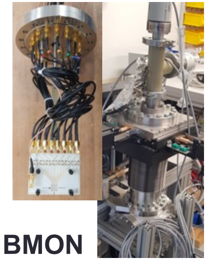
Superconducting dipole magnet

Magnet support factory acceptance test

Silicon Tracking System



STS half-unit assembly and Integration



BMON

T0 manipulator X/Y/Z Vacuum test – done

CBM installation / commissioning / Day-1

CBM Cave

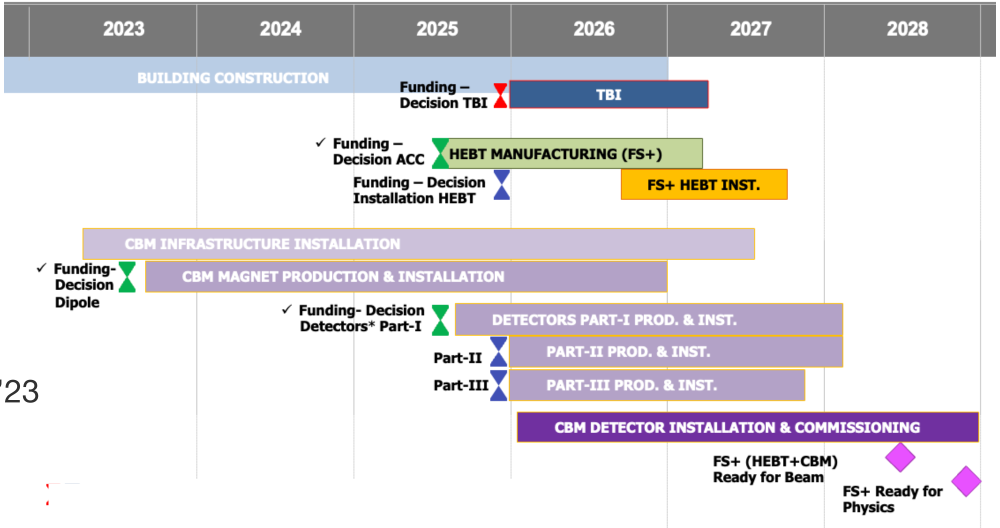
- a dedicated cave with a massive beam dump for high-intensity, high-energy beams
- CBM cave/building shell completed, road, crane
- Technical Building Infrastructure in 2026/2027

CBM Installation

- CBM installation activities (platform), started in Jun'23
- CBM ready for beam by 2028

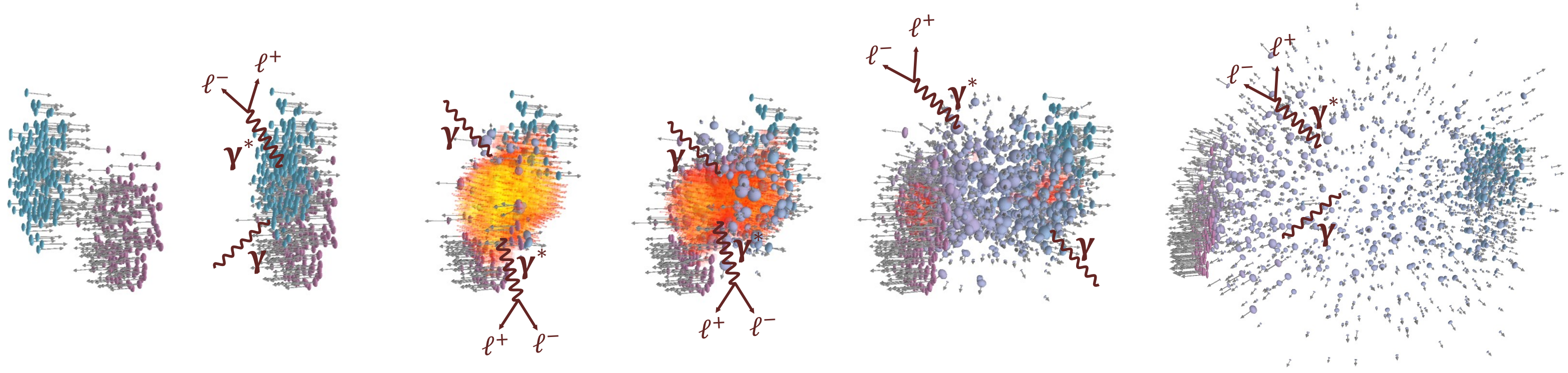
First 3 years scenario: focus on beam energy scan

- 60 days / year beam on target
- different detector configurations
- subject to a reshaping depending on findings (e.g. long run at maximum $\sqrt{s_{NN}}$ with MUON setup)



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

HADES/CBM strategy

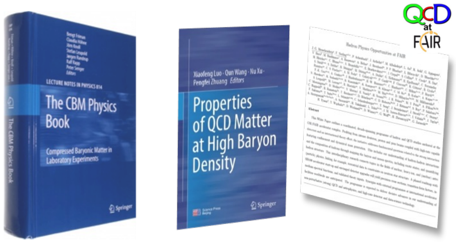


Measure with utmost precision (abundant / rare):

- light flavour hadrons, incl. (multi-)strangeness
  ↦ chemical freeze-out T, μ_B
  flow, vorticity ↦ equation-of-state

- event-by-event fluctuations (criticality)
- dileptons (emissivity)
- charm (transport properties)
- hypernuclei (interaction, production mechanism ↦ EoS)

Worldwide experimental and theoretical efforts



Friman *et al.*, Lect. Notes Phys. 814 (2011) 1
Chen, Dong, Fukushima, Galatyuk, *et al.*, doi:10.1007/978-981-19-4441-3_4 (2022)
Messchendorp, Nerling, *et al.,* White Paper "Hadron Physics Opportunities at FAIR"

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

CRITICALITY

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

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

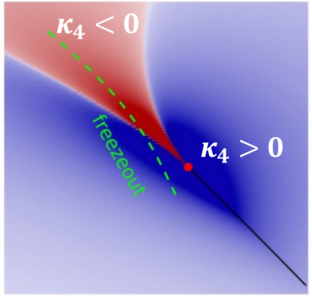
κ_n - cumulants (measurable in experiment)
$\hat{\chi}_n^q$ - susceptibilities (e.g. from lQCD)

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

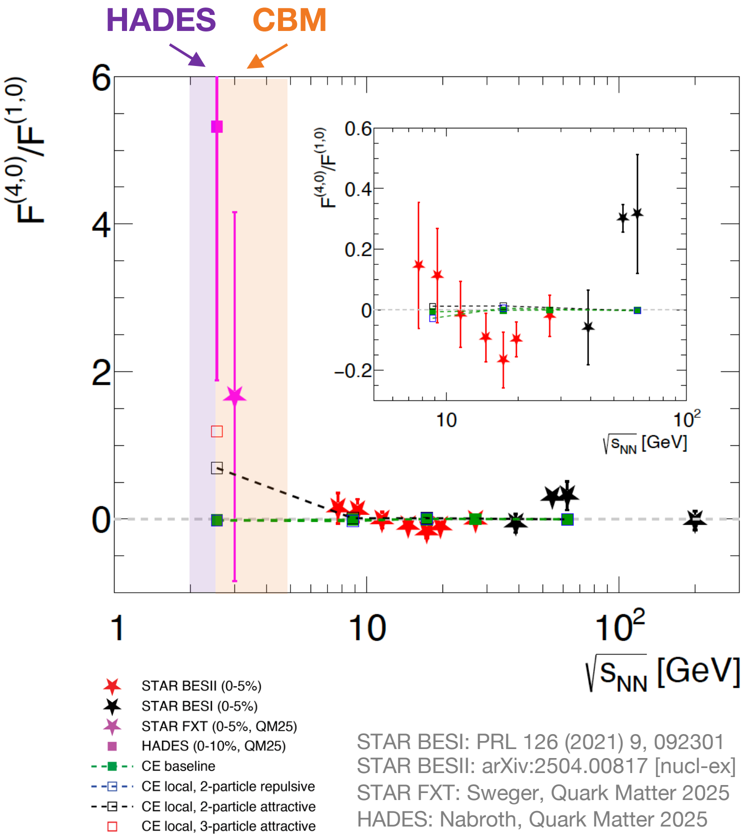
QCD critical point: large correlation length and fluctuations

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

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

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

Critical point search



STAR BESI: PRL 126 (2021) 9, 092301
STAR BESII: arXiv:2504.00817 [nucl-ex]
STAR FXT: Sweger, Quark Matter 2025
HADES: Nabroth, Quark Matter 2025

- Interplay between repulsive (high-) and attractive (low-energies) forces

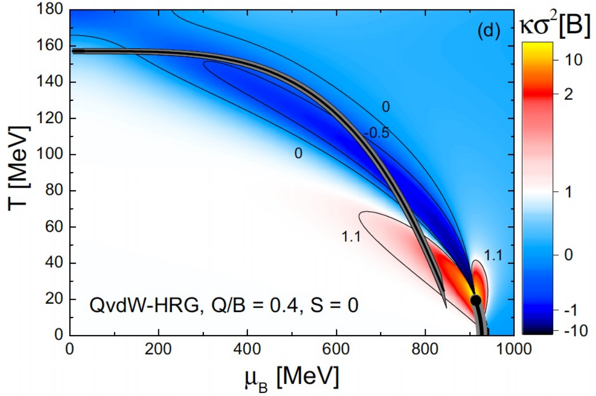
Friman, Rustamov, Redlich, e-Print: 2508.18879 [nucl-th]
DeMartini and Shuryak, PRC 104 (2021) 024908

- 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**

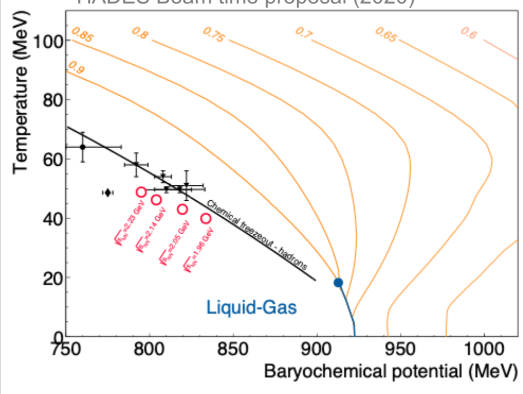
Holzmann, Koch, Rustamov, Stroth, arXiv:2403.03598 [nucl-th]
Kitazawa'2012, Skokov'2013, Bzdak '2016, Kitazawa'2016, Braun-Munzinger'2017
Braun-Munzinger, Friman, Redlich, Rustamov, Stachel, NPA 1008 (2021) 122141

HADES BES, Runs Feb24 and Mar25

Poberezhnyuk *et al.*, PRC100 (2019) no.5, 054904



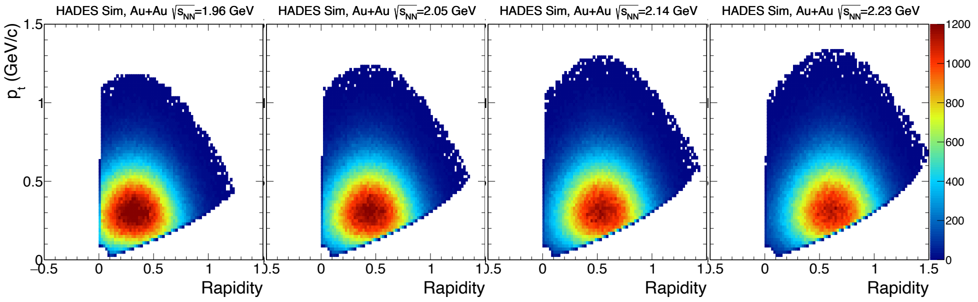
HADES Beam time proposal (2020)



What are the measurable consequences of phase transition and critical point in the QCD phase diagram?

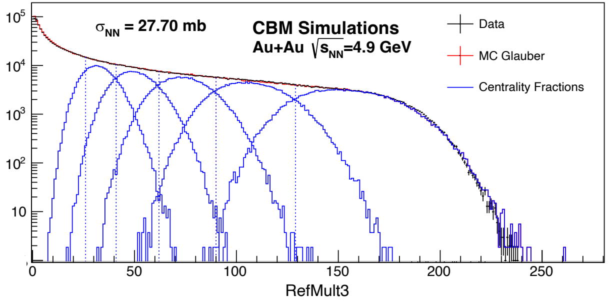
- Probe matter in the vicinity of the nuclear liquid-gas phase transition
- Study the onset of fluctuations moving from small to heavy system
  - C+C collisions ($N_p = N_n$) are an essential reference!
- Studying contributions of stopped protons to multi-particle correlations

0.7×10^9 $1.\times10^9$ 1.7×10^9 $3.3\times10^9 + 0.7\times10^9$ (low-field)

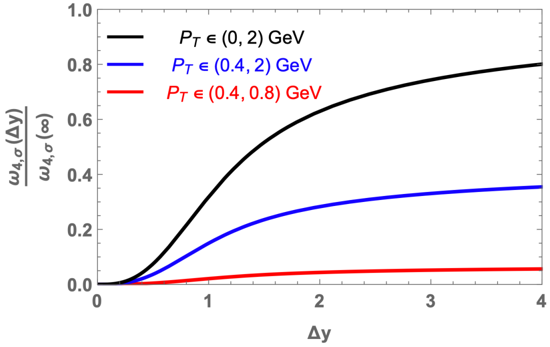


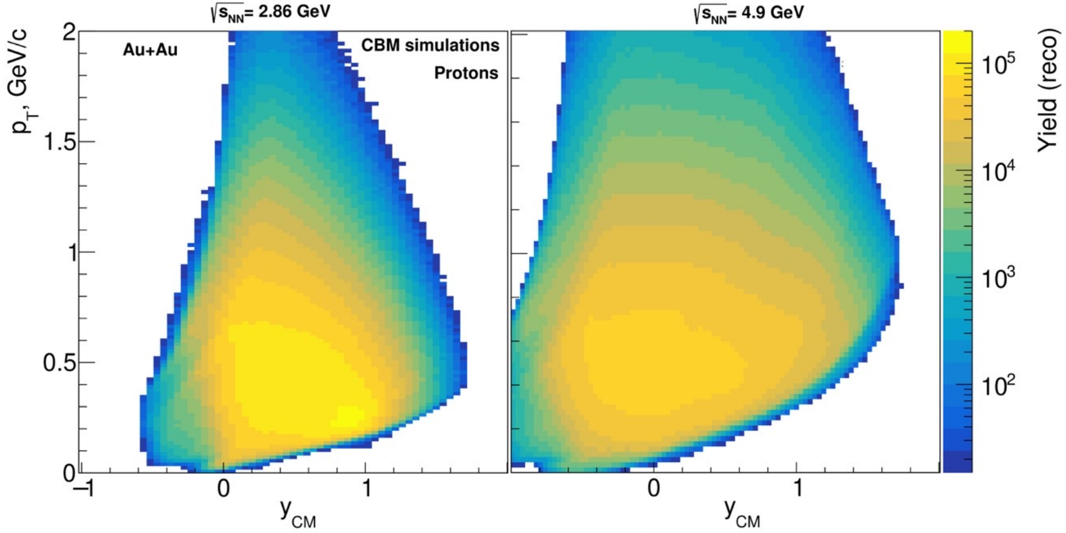
Performance studies in CBM

Crucial: centrality determination with independent detector (FSD) → reduces **auto-correlations** with mid-rapidity protons



Phase space coverage: larger acceptance in Δy and p_T leads to significantly larger critical point signal Ling and Stephanov, PRC 93 (2016) 034915

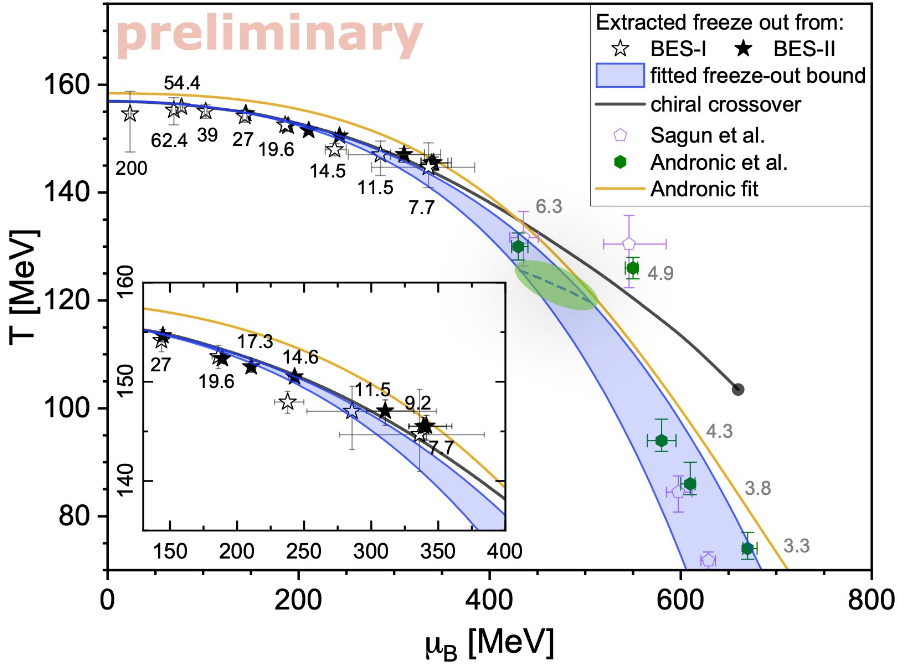




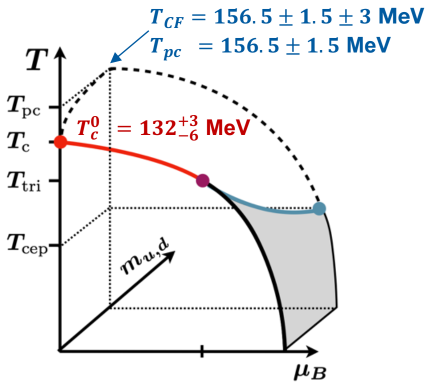
Low p_T and midrapidity coverage for all energies

Reconstruction efficiency allows for precision measurement of cumulants

Fingerprints of criticality



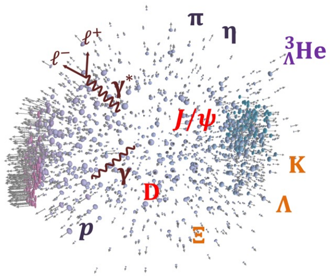
Pawlowski, this WP



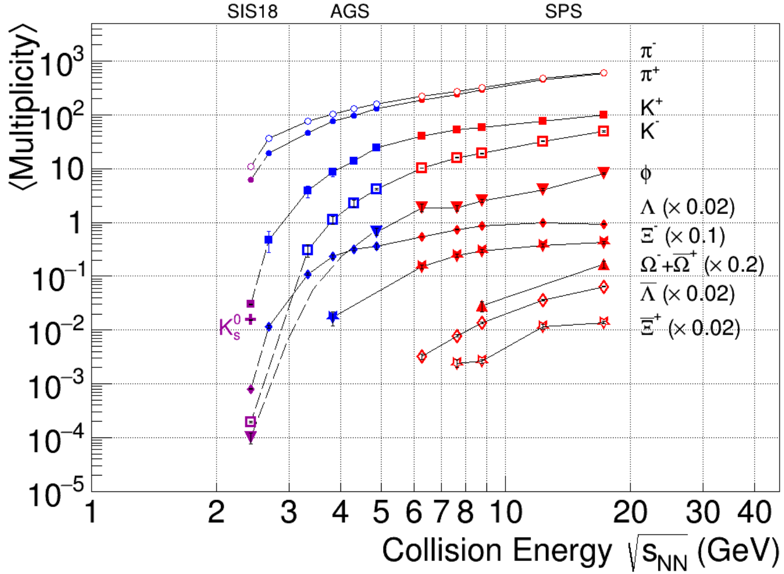
Kaczmarek *et al.*, PoS LATTICE2021 (2022) 429

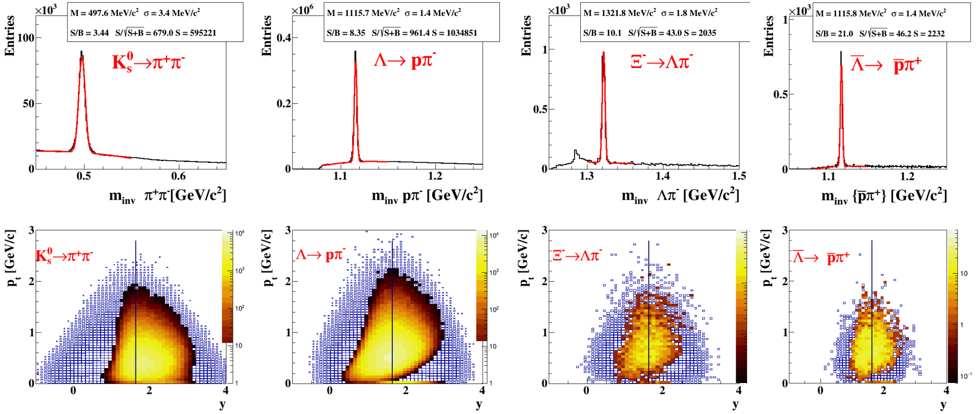
- High order cumulants probe remnants of chiral transition
- At $\mu_B = 0$ chemical freeze-out seems to occur at or near the QCD transition region for physical m_q
- k_6^B/k_2^B offer the possibility to probe the proximity of the chemical freeze-out to the crossover line
- At $\mu_B \neq 0$ accurate mapping the chemical freeze-out required
  - test hypothesis of hadron abundancies in equilibrium $\rightsquigarrow T_{CF}, \mu_B, V$
  - demand for build in dynamics

Hadron production



An impressive set of data, however data below AGS energies are missing for less abundant particles (Ξ, Ω)



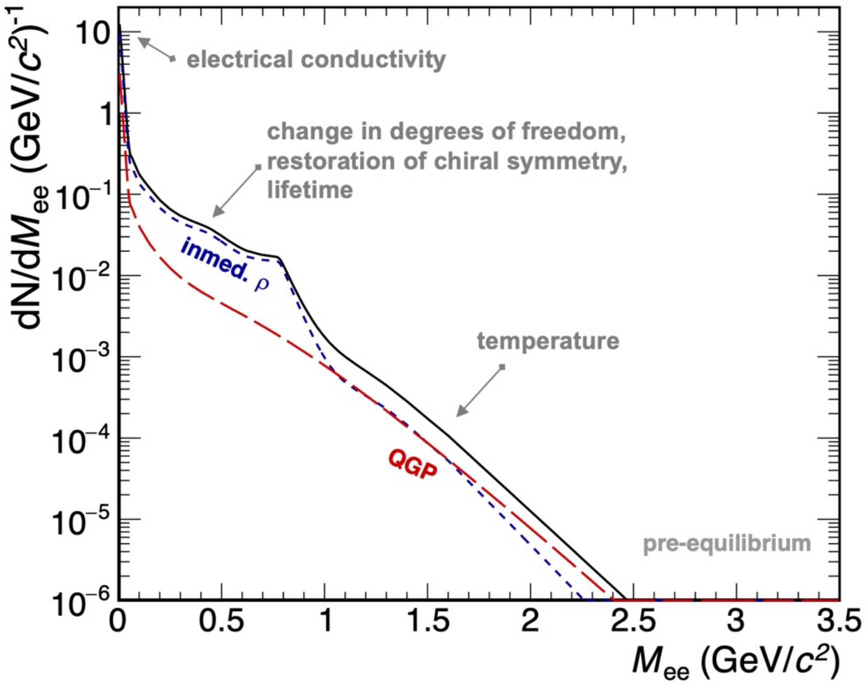


Blume, Markert, PPNP 66 (2011)
see also yield ratios for Si+Au Braun-Munzinger, Stachel, Wessels, Xu, PLB 344 (1995)

Electromagnetic radiation

EMISSIVITY

Thermal dileptons from baryon rich matter



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

Spectral information: precision measurement of ρ line shape

- change in degrees of freedom: ρ melts into partonic continuum
- chiral symmetry restoration: $\rho - a_1$ degeneracy
- baryons are main catalyst of medium effects?
  ⇝ stringent test at high μ_B, deconfinement vs. chiral transition?

Transport coefficient: electrical conductivity
(as fundamental as $4\pi\,\eta/s$ and $2\pi\,T\,D_s^{HF}$)

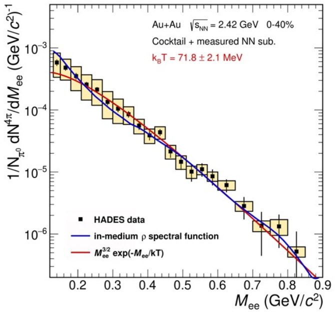
$$\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} Im\Pi_{em}(q_0, q = 0; T)$$

Fireball diagnostics:

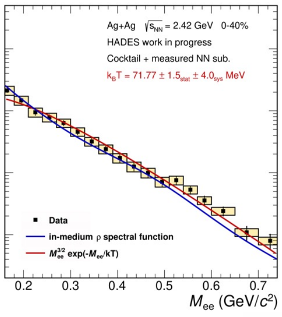
- early temperatures (M_{ee} spectra; no blue-shift distortion)
- lifetime of radiating phase (inclusive low-mass yield)
- production mechanism (spin polarization)
- pressure anisotropies (dilepton flow)
  ⇝ detect presence of 1st order transition (critical point?)

Mapping QCD phase diagram with dileptons

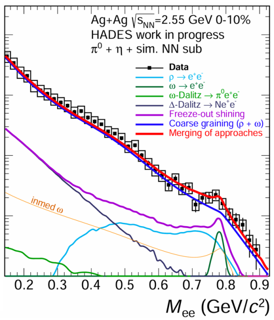
Au+Au $\sqrt{s_{NN}} = 2.42$ GeV



Ag+Ag $\sqrt{s_{NN}} = 2.42$ GeV



Ag+Ag $\sqrt{s_{NN}} = 2.55$ GeV

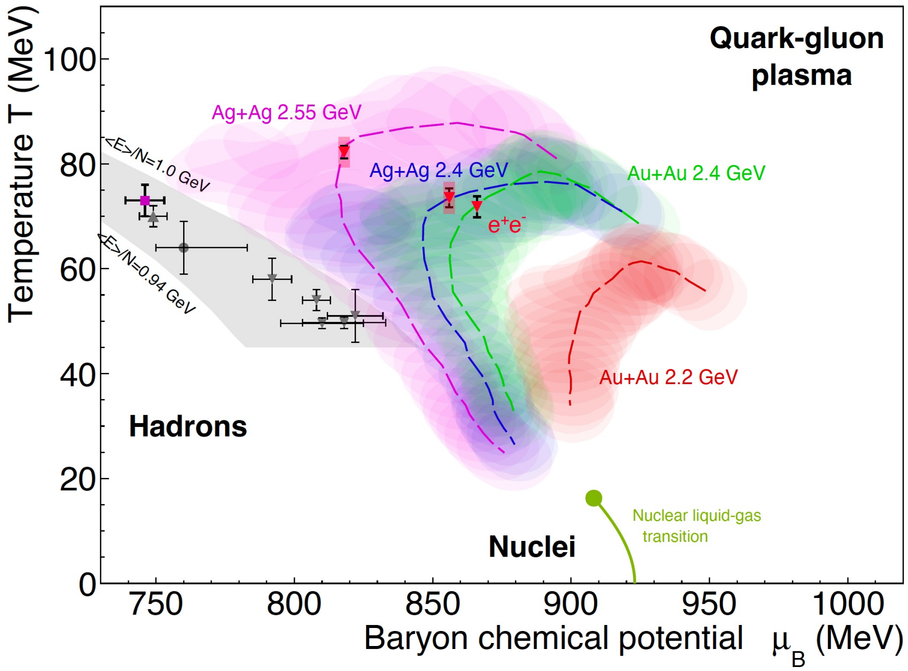


HADES, in preparation

- Dileptons sensitive to hot and dense phase
- Sensitive to phase transition (and critical point)?
  ⤳ latent heat ⤳ longer life time ⤳ extra radiation
- Probe time dependence of fireball $\langle T \rangle$: $M_{\ell\ell}$ versus v_2

→ No measurements $\sqrt{s_{NN}} = 2.55 - 7.7$ GeV

→ CBM at FAIR

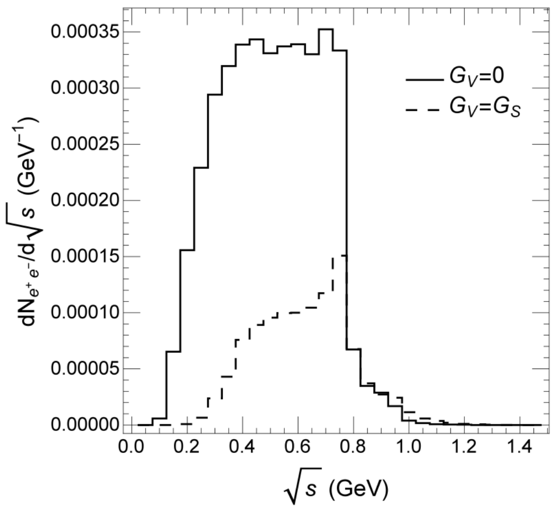


Freeze-out curve:J. Cleymans, K. Redlich, NPA 661 (1999) 379
Au+Au 2.4 GeV: HADES, Nature Phys. 15 (2019) 1040
Ag+Ag 2.4 GeV, 2.55 GeV: HADES in preparation

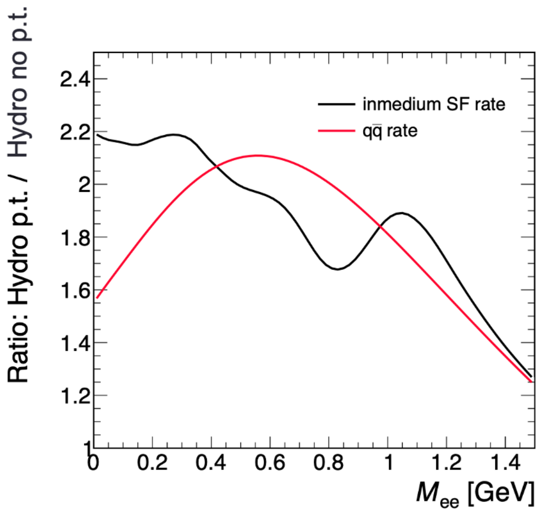
Dilepton signature of a 1st order phase transition

- Modification of the expansion trajectory in the phase diagram
- Significant effect: factor 2 enhancement of dilepton emission due to extended "cooking"

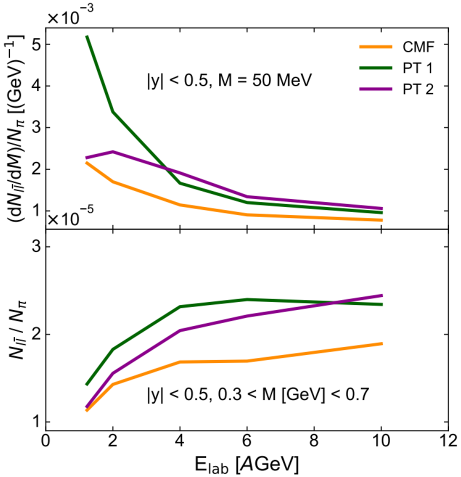
- **Integrated excess yield radiation $0.3 < M < 0.7\ GeV/c^2$ tracks the fireball lifetime**
  ↝ search for "**extra radiation**" due to latent heat around **phase transition** (& critical point?)



F. Li and C.M. Ko PRC 95 (2017) 5, 055203



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



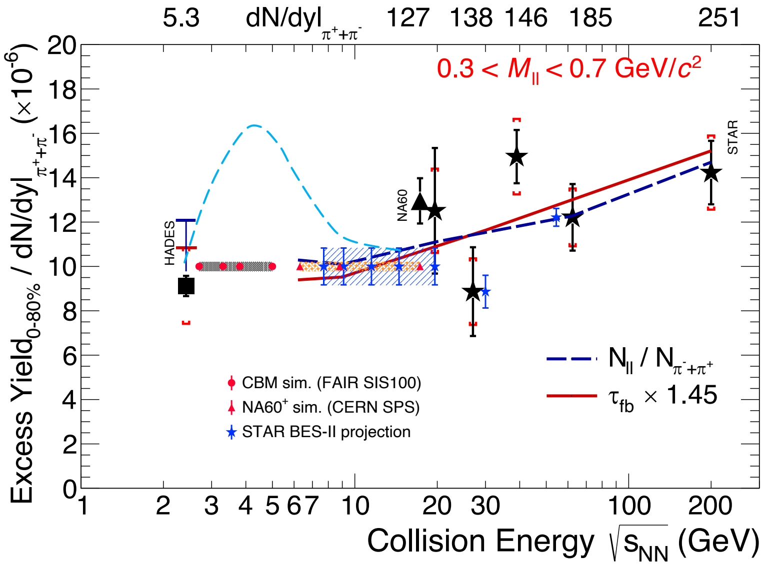
Savchuk, Steinheimer, TG *et al.*, JPG 50 (2023) 12, 125104

"Ripples of the critical point"

Fu, Luo, Pawlowski, Rennecke, Yin, PRD 111 (2025) 3, L031502

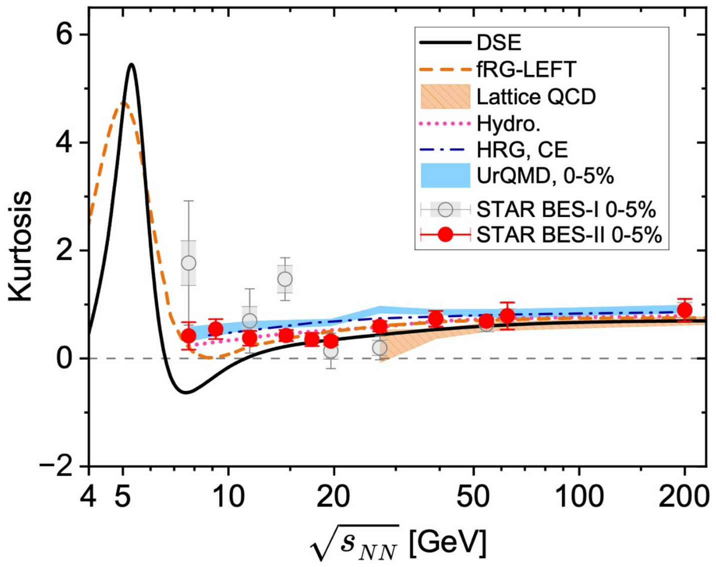
Thermal dilepton excitation function of excess yield (also $\langle T \rangle$, v_2)

Event-by-event net-baryon number fluctuations



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

Azure dashed blue – sketch



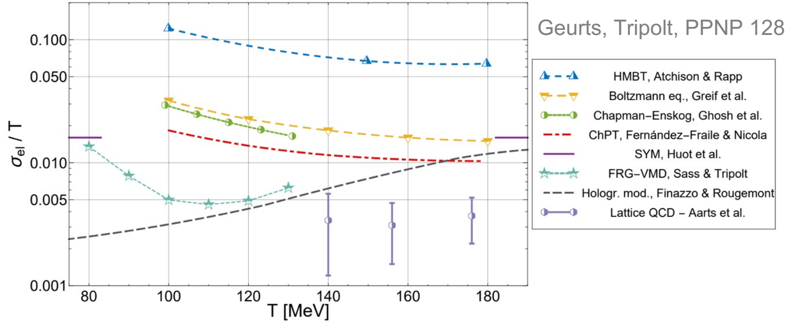
Lu, Gao, Liu, JMP, arXiv: 2504.05099

Transport properties of the medium

Electrical conductivity, σ_{el} - can be directly obtained from the low-energy limit of the EM spectral function (σ_{el} as fundamental as $4\pi\ \eta/s$ and $2\pi\ T\ D_s^{HF}$)

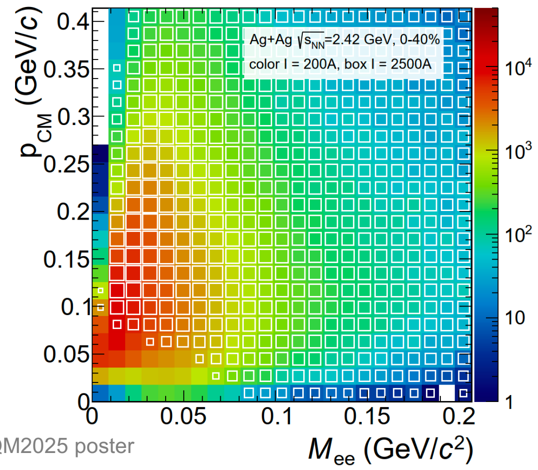
Non-monotonic trend* of σ_{el} as the phase transition occurs? visible in a beam energy scan?

** also for photon polarisation observable*



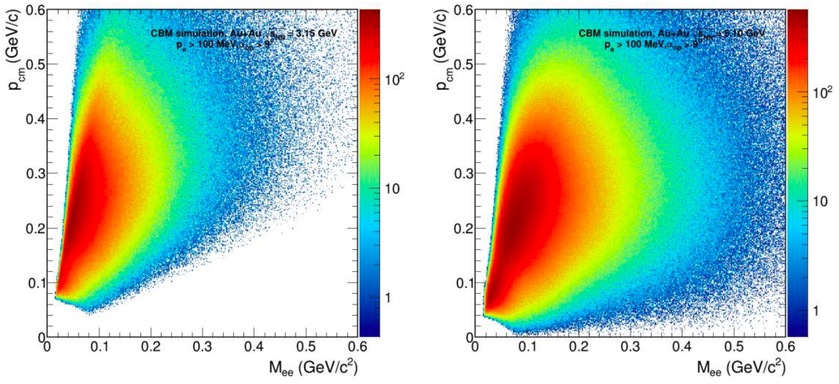
Geurts, Tripolt, PPNP 128 (2023)

Ag+Ag $\sqrt{s_{NN}} = 2.42$ GeV, HADES data



Udrea, QM2025 poster

CBM simulations, Au+Au $\sqrt{s_{NN}} = 3.15$ GeV ; $\sqrt{s_{NN}} = 4.9$ GeV



Udrea, 42nd CBM CM

Flow and polarization

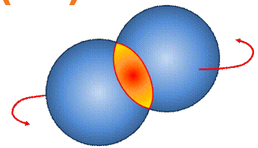
Collectivity and Vorticity

Azimuthal anisotropy

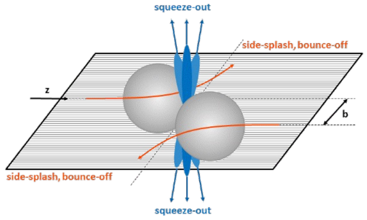
with respect to reaction plane (RP)

Fourier coefficients of the distribution

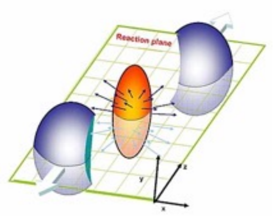
$$\frac{dN}{d(\phi - \Psi_{EP})} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_{EP}))$$



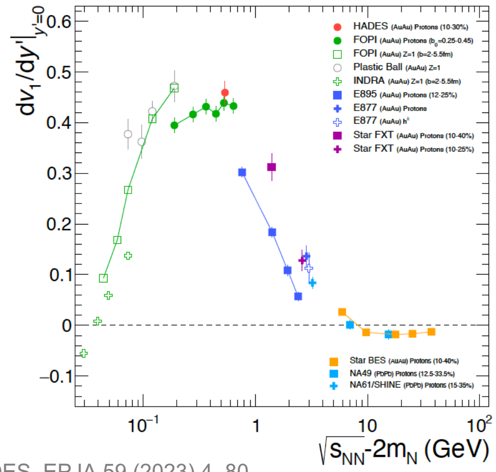
v_1 deflection of matter in the RP (signal of the phase transition?)
Paech *et al.*, NPA 681 (2001)

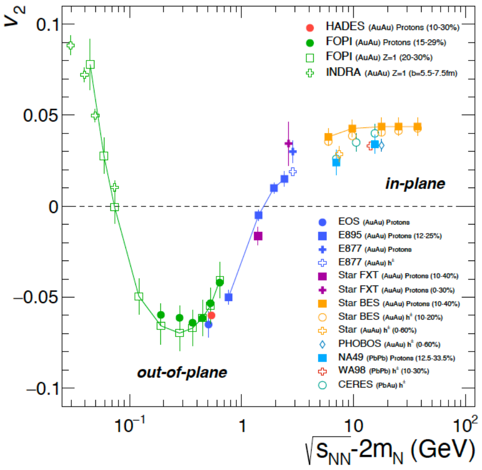


$v_2 < 0$ long spectator passing time $\tau_{passing} \approx \tau_{expansion} \Rightarrow$ "squeeze-out"



$v_2 > 0$ when spectators pass faster than fireball expands



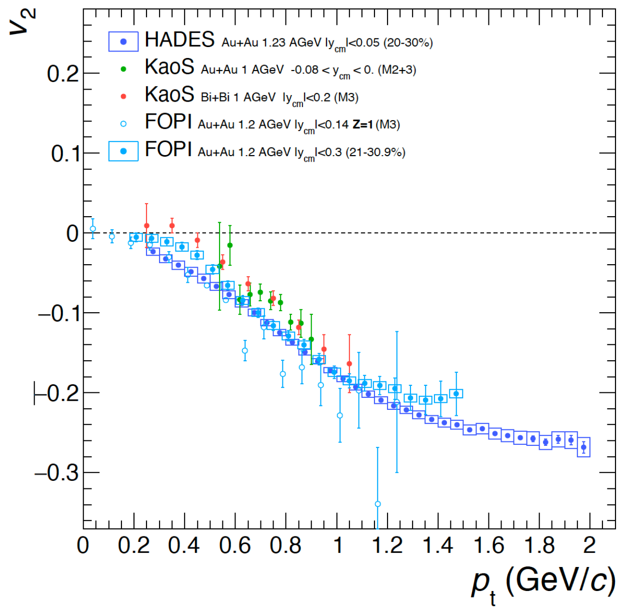


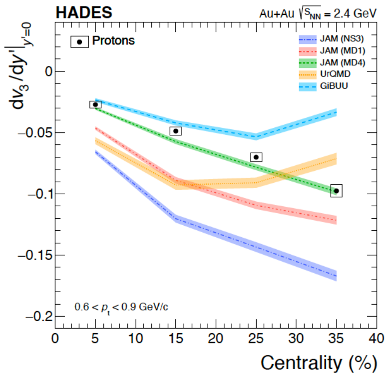
HADES, EPJA 59 (2023) 4, 80

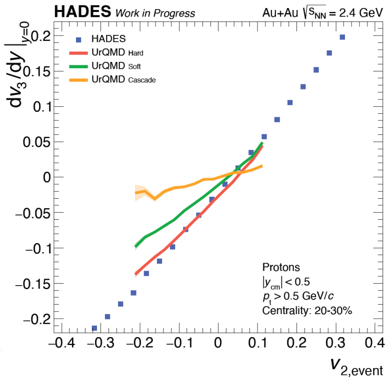
constrain equation-of-state by means of microscopic transport model

Sensitivity to EoS and transport properties η/s

- High precision multi-differential data for protons and light nuclei $v_n, n = 1-6$
- Data compared to QMD and BUU models
  - ➥ higher moments provide more discriminating power
  - ➥ consistent description of all flow harmonics over the whole phase space and at all centralities

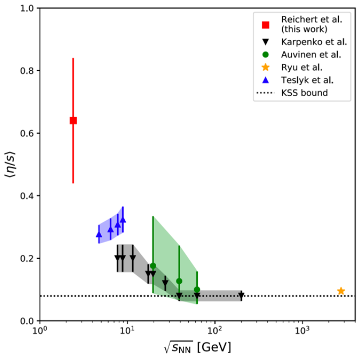






JAM (NS3)	hard momentum independent NS3
JAM (MD1)	hard momentum dependent
JAM (MD4)	soft momentum dependent MD4
UrQMD	"hard EoS" (UrQMD 3.4)
GiBUU	"soft EoS" (GiBUU 2019, Skyrme 12)

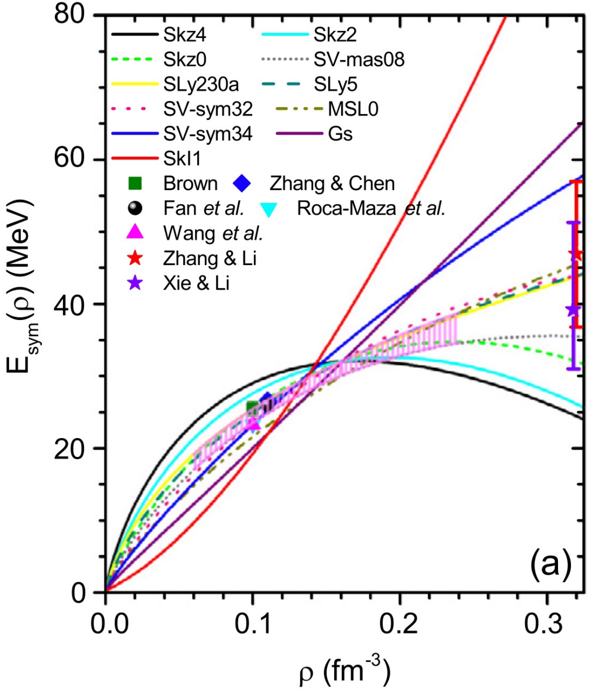
Reichert *et al.*, PLB 817 (2021) 136285



coarse graining analysis of the UrQMD transport simulations

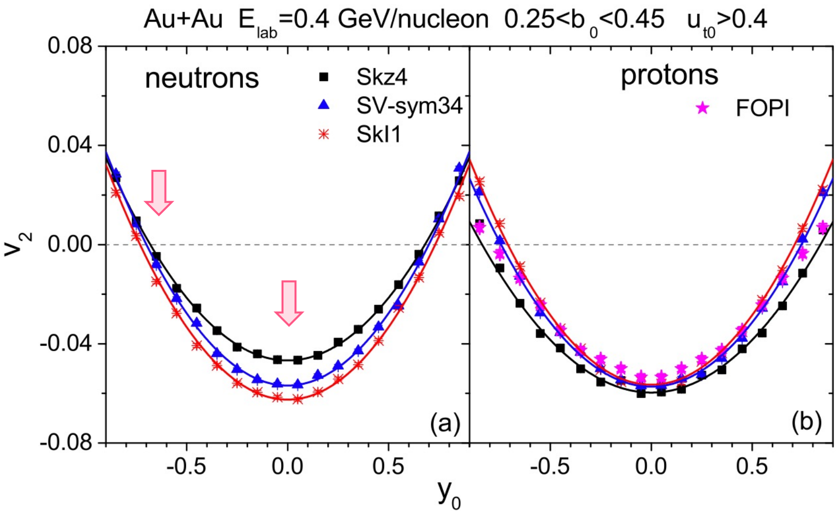
Constraining the nuclear symmetry energy

Wang *et al.*, PLB 802 (2020) 135249



$$E(\rho,\delta) = E(\rho) + E_{sym}(\rho)\,\delta^2$$

$$L_0 = 3\rho_0 \left(\frac{\partial E_{\mathrm{sym}}(\rho)}{\partial \rho}\right)|_{\rho=\rho_0}$$



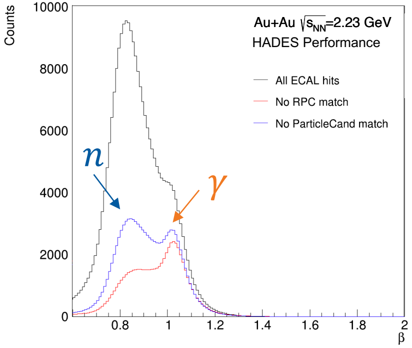
- Density dependence of E_{sym} , L_0 is of a great importance and becomes a part of multi-messenger
- Important, but very uncertain at high-density!

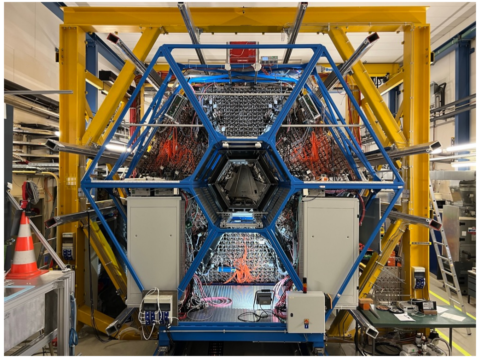
⇝ **neutron flow measurements crucial to address E_{sym} at $\rho > \rho_0$**

Prospects for neutron flow measurements

HADES Electromagnetic calorimeter

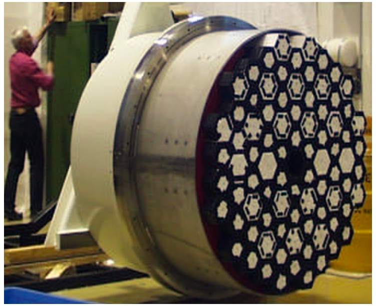
- proven technology: lead glass modules read out with Hamamatsu PMTs
- $\Delta E/E = 5.5\%$ at 1 GeV (photons)
- all six sectors setup, Dec'23
- measurement of neutron flow is feasible (large statistical data sample vs. neutron detection efficiency)





Neutron detection capability in CBM

- COSY-TOF neutron detector
  - ∅ 126 cm, 84 modules, l = 45 cm
  - plastic scintillator
  - n-detection efficiency ≈ 30%
- Neutrons detection with MRPC (Tsukuba U, Japan)

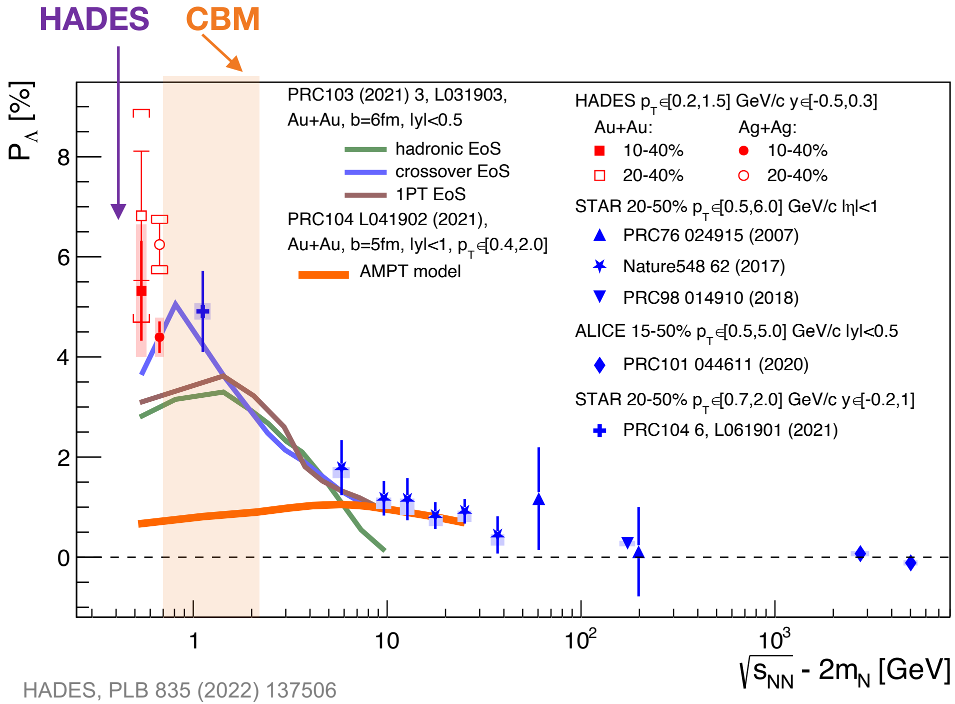


Neutron detector test mCBM run'25

Hyperon polarization

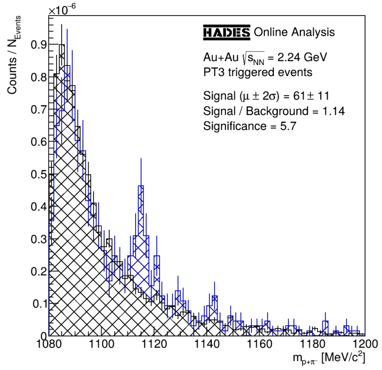
- Non-central heavy-ion collisions ⇝ large orbital angular momenta ($\sim 1000\hbar$) ⇝ vortical structure of the system?
  - probed via parity-violating decay of Λ hyperons
  - estimation of angular momentum direction via spectator deflection

STAR, Nature 548 (2017) 62-65



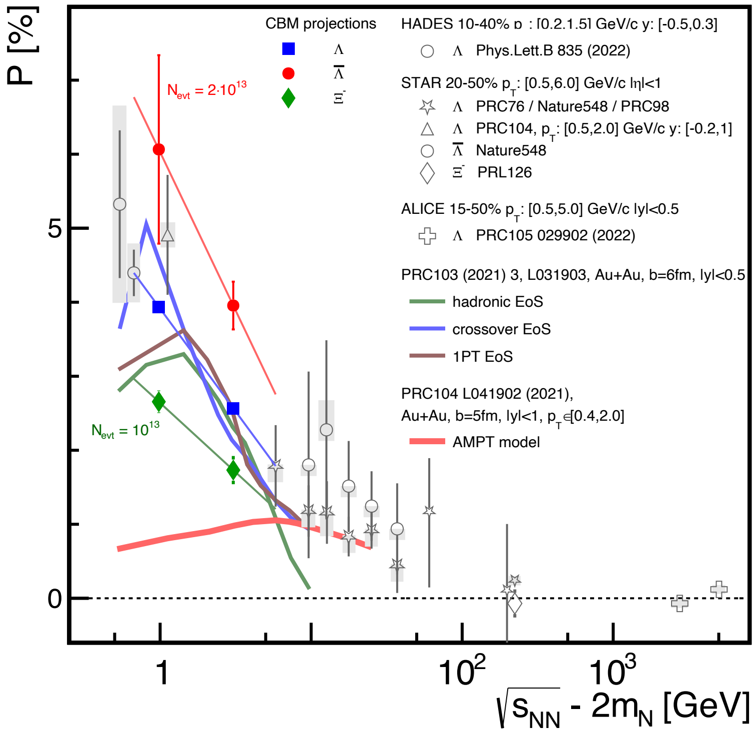
HADES, PLB 835 (2022) 137506

- Strong increase of polarization signal towards few GeV energies
- Highest polarization measured by HADES, SIS18
- Origin of the polarization mechanism? Sensitivity to EoS?



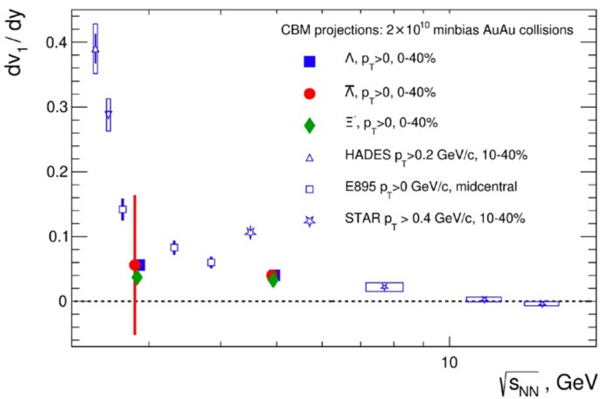
https://web-docs.gsi.de/~webhades/onlineMon/apr25/hades-online.html

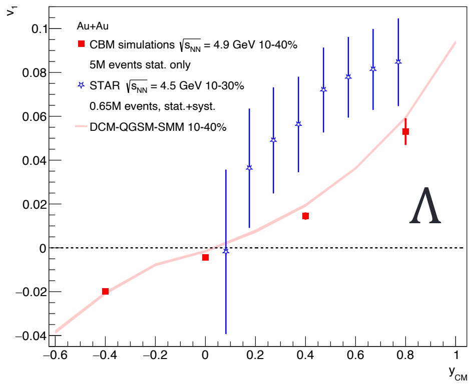
Collective flow and polarization of $\Lambda, \bar{\Lambda}$ and Ξ^- in CBM



- **Polarization, spectra and flow of Λ and Ξ^-** (also Ω) with precision of 5% with CBM (mapping of the excitation function for $\bar{\Lambda}$ requires $\geq 10^{13}$)

Superior CBM performance to the STAR-FXT flow measurements





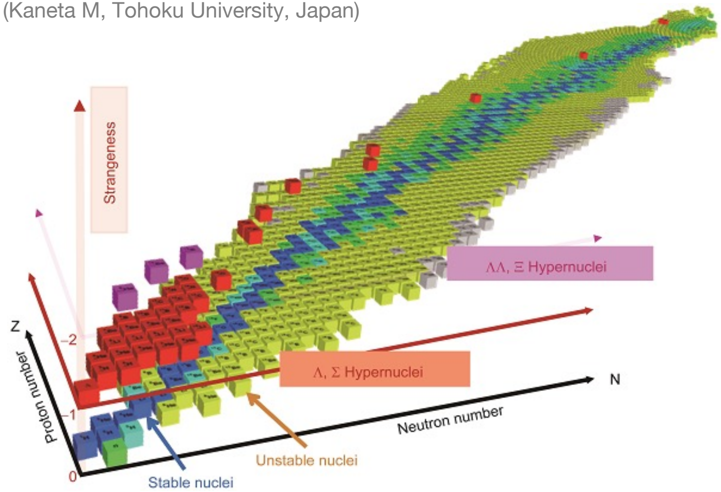
Hypernuclei

INTERACTION

Nuclei and hyper-nuclei production

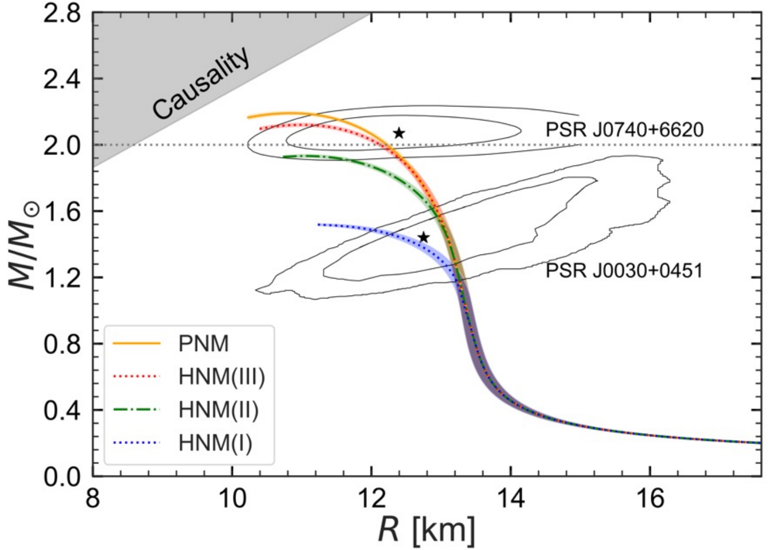
Three-dimensional nuclear chart

(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

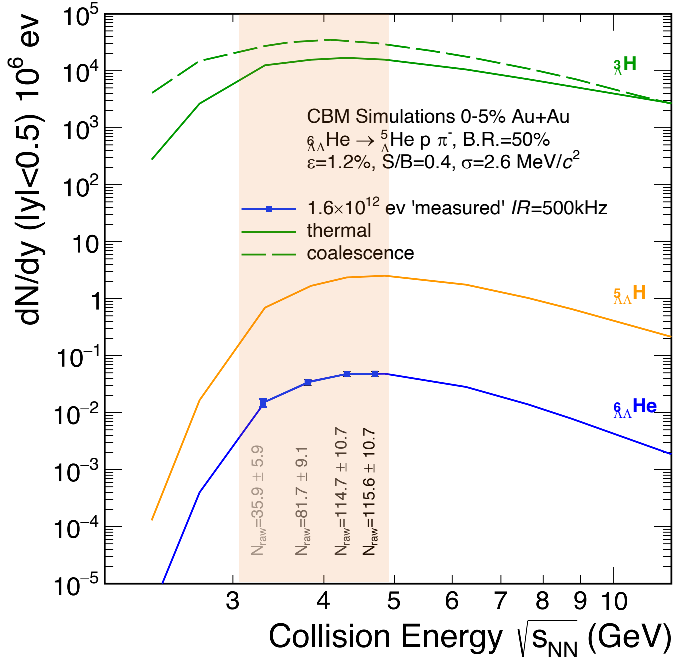
EoS of high density matter

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

CBM performance

CBM collision energies optimal
for hypernuclei production

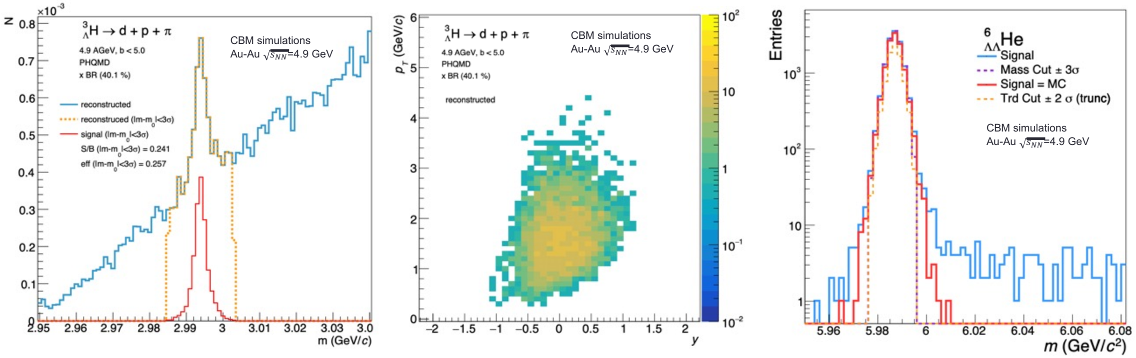
Thermal: Andronic *et al.*, PLB 697 (2011)
Coalescence: Steinheimer *et al.*, PLB 714 (2012)



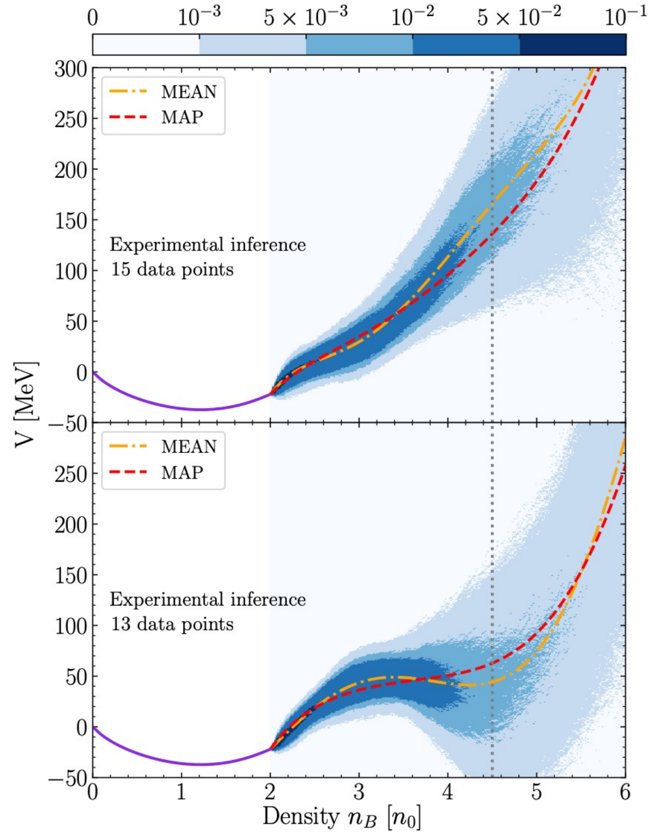
- CBM high interaction rates and clean identification allow precision measurements of single- and double Λ-hypernuclei
  - spectra and flow pattern
  - complex structure via Dalitz plot
  - life-time (particularly sensitive to YN and YY interaction)

- Search for the new hyper-nucleus or charmed nucleus $^{4}_{D}He$

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



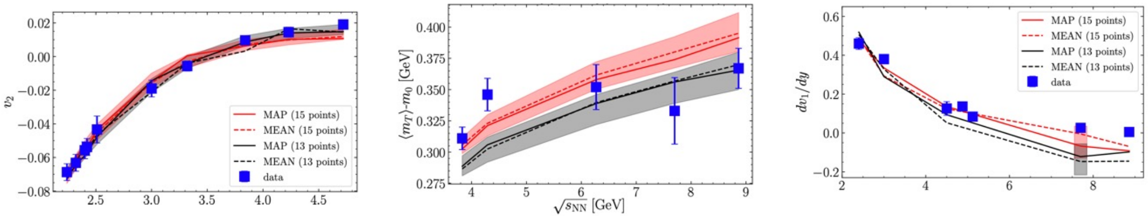
Bayesian inference for the dense QCD EoS



Novel high-density EoS: Bridging the gap between the high density EoS of heavy-ion collisions and neutron stars while incorporating findings from lattice QCD

Steinheimer *et al.*, JPG 52 (2025) 035103

Omana Kuttan, Steinheimer, Zhou and Stoecker, Phys. Rev. Lett. 131 (2023) 202303



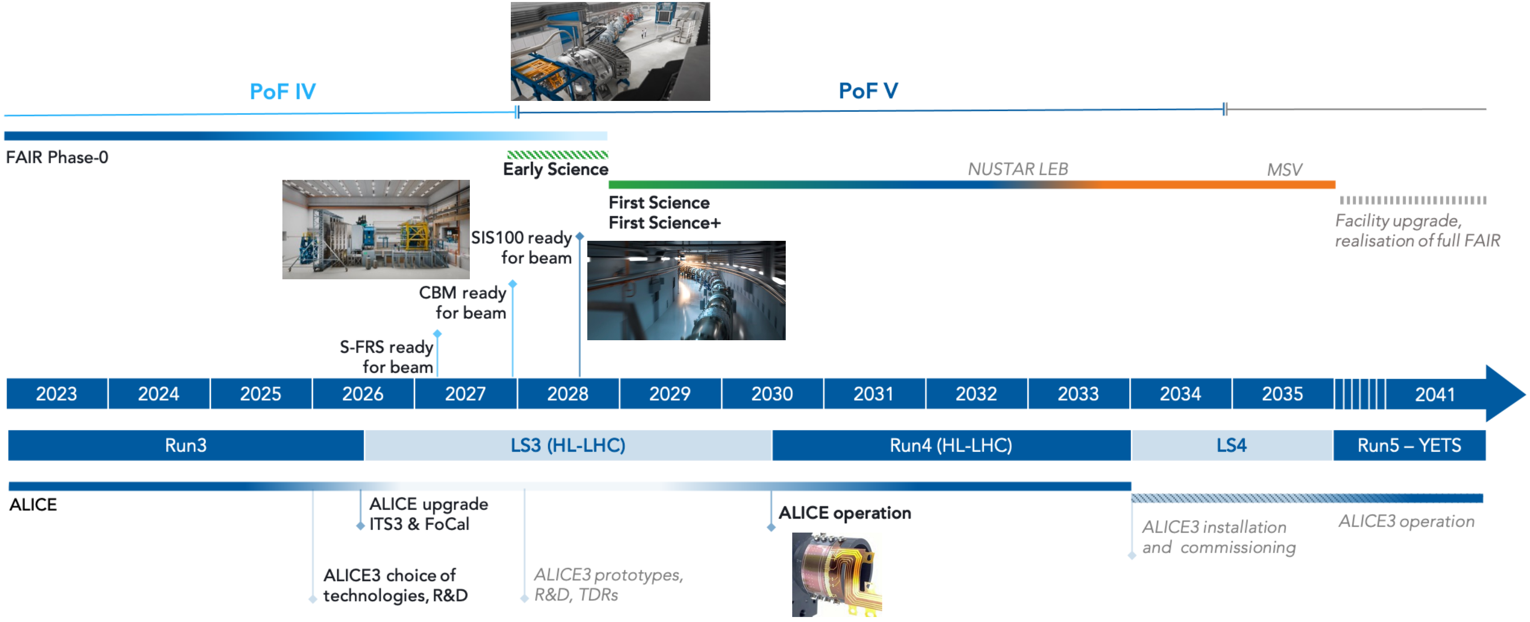
A strong dependence on data used is observed

Need for high quality, high precission and high statistics data in the SIS100 energy range

Long term vision

Installation of second (stretcher) ring for higher energies and efficient parallel operation with storage ring experiments

- beyond Modularize Start Version → strong community support needed to exploit full potential
- SIS400(450) has relevance for future heavy-ion program and would enable high level of parallel operation in case of vivid storage ring experiments



Summary: The future is bright!

Encouraging prospects for studying extreme matter in the laboratory

- **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

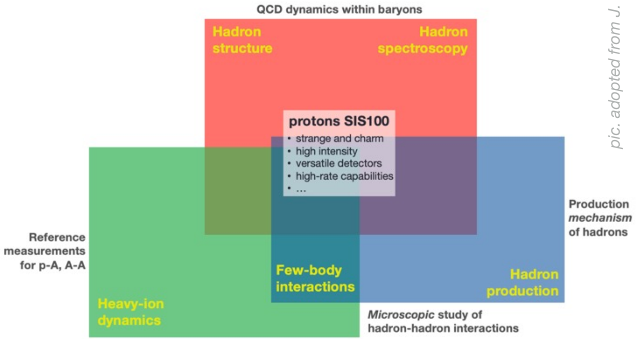
- **Timely completion of SIS100**: unique physics program with CBM
- Ultimate goal: **CBM ready for beam in 2028!**

Hadron physics

INCLUSIVE & EXCLUSIVE

A comprehensive QCD program with SIS100 proton beam

- **Opening new realm: proton energy range 4.7 GeV (SIS18) – 29 GeV (SIS100)**
  - production, spectroscopy and interactions of double and triple strangeness
  - charm production and interactions close to production threshold
  - significant increase in production yield of hyperons



pic. adopted from J. Messchendorp

- **Theory enrichment:**
  - theoretically complicated region to describe, transition from resonance to string production
  - important new insight into hadron structure (hyperon spectrum, study intrinsic charm component of the hadron wave function)

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

- **Competitive and complementary program to other facilities world-wide**

Physics opportunities with proton beams at SIS100 Workshop Wuppertal, Feb 2024
https://indico.gsi.de/event/18475/overview

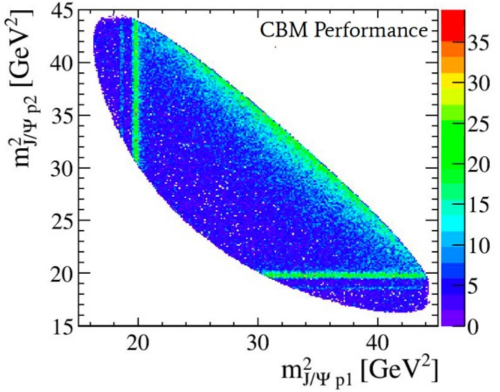
QCD at FAIR workshop, Nov 11-14, 2024,
https://indico.gsi.de/event/20301/

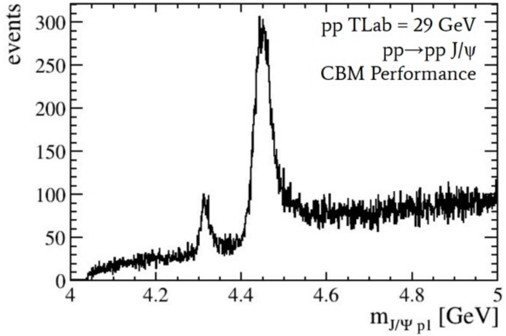
White-paper preparation

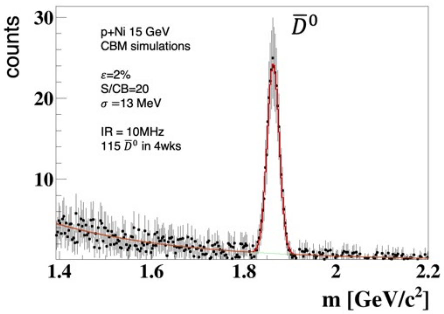
Charm of CBM (pp / pA / AA)

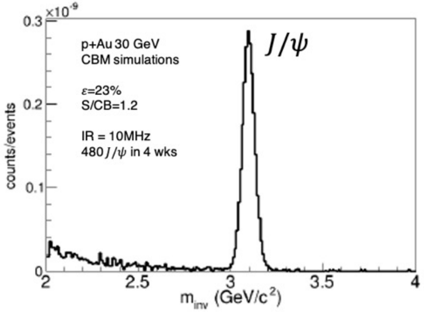
Reconstructed Dalitz plot with pentaquarks

- **CBM is well adapted to the pp exclusive channels program**
  - high-rate capabilities and free-streaming DAQ's
  - excellent mass resolution (~2%)
  - excellent coverage for exclusive channels
- **pp/pA collisions to establish baseline and to study cold nuclear matter effects**
- **AA (light ions) probe in-medium QCD force**
  - how is the fundamental QCD force screened at $\mu_B > 0$?
  - consequences for heavy-quark transport





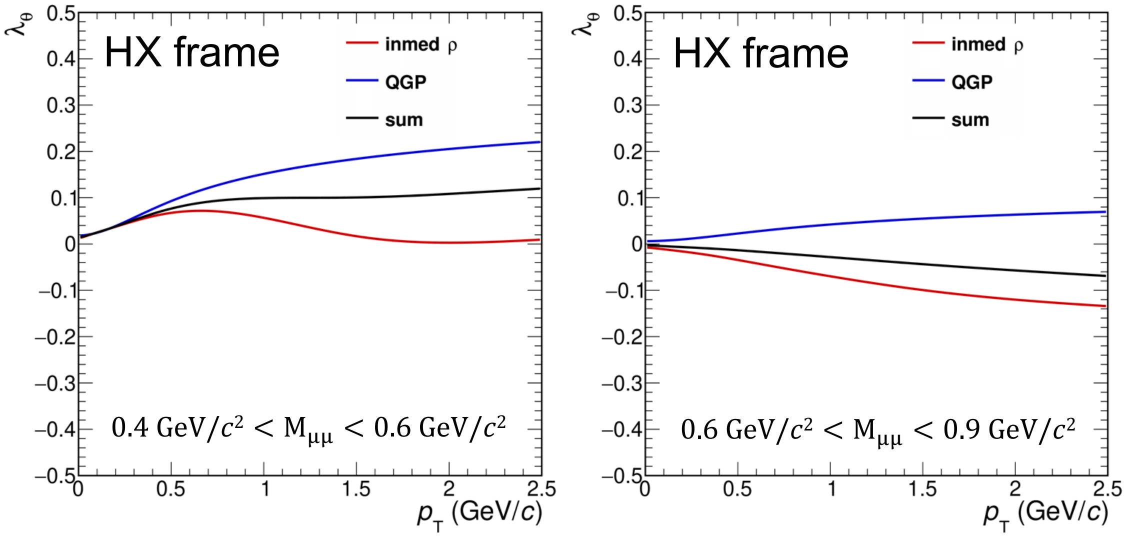




Prospect of disentangling hadronic and partonic sources

Polarization plays important role in exploring the mechanisms underlying EM emission

Seck *et al.*, arXiv: 2309.03189
Coquet, Winn, Du, Ollitrault, Schlichting, PRL132 (2024) no.23, 232301
Speranza *et al.*, PLB 782, 395 (2018)
Baym *et al.*, PRC95, 044907(2017)
Bratkovskaya *et al.*, PLB 376, 12 (1996)



Multi-differential measurements of the γ^* polarization

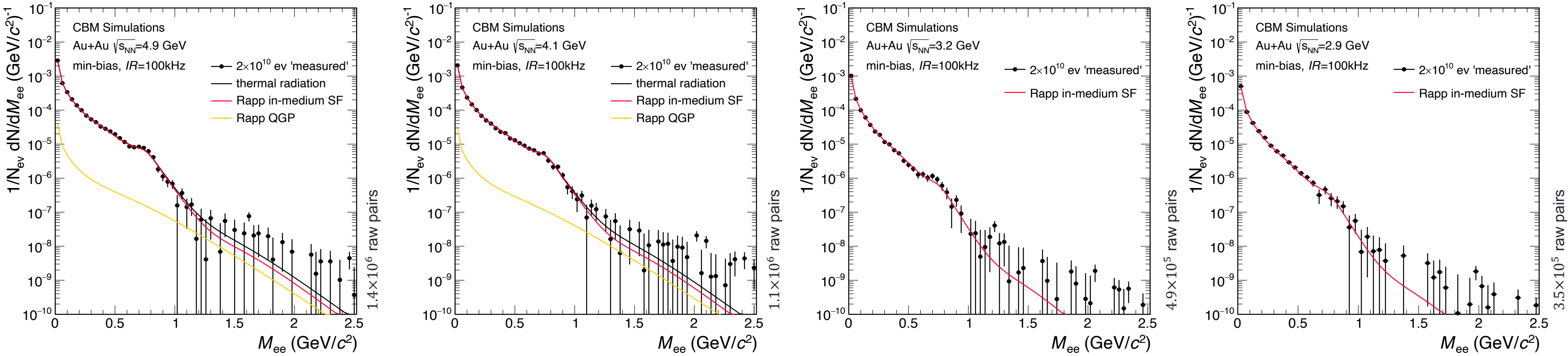
- resolve mass, p_T, rapidity, lepton emission angles $\theta_l, \varphi_l \rightarrow$ large datasets needed
- future high-rate experiments CBM, NA60+ and ALICE3

- search for onset of QGP
- important in disentangling $\rho - a_1$ chiral mixing from QGP around M_{ll} ~ 1.2 GeV/c^2

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

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

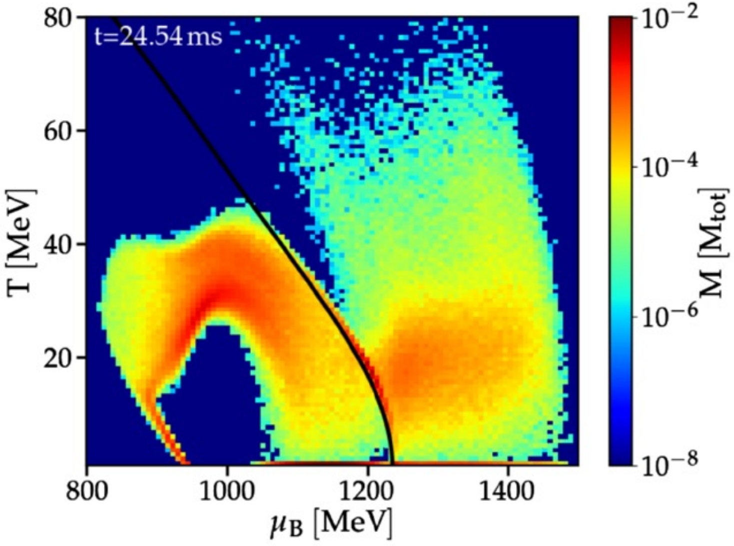
- Dominated by ρ contribution at low mass ($M_{\ell\ell}$ <1GeV/c^2); can be reconstructed with precision of ~5%
- Intermediate mass range ($M_{\ell\ell}$>1GeV/c^2) accessible, considering trigger



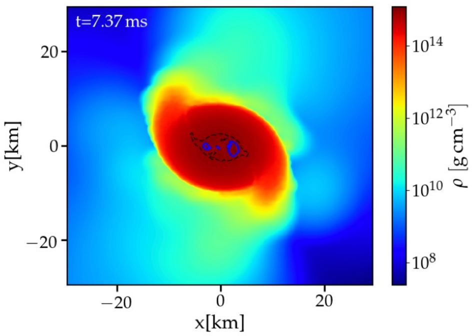
T vs. baryon density effects
from partonic to hadronic fireballs

Connection to astrophysics

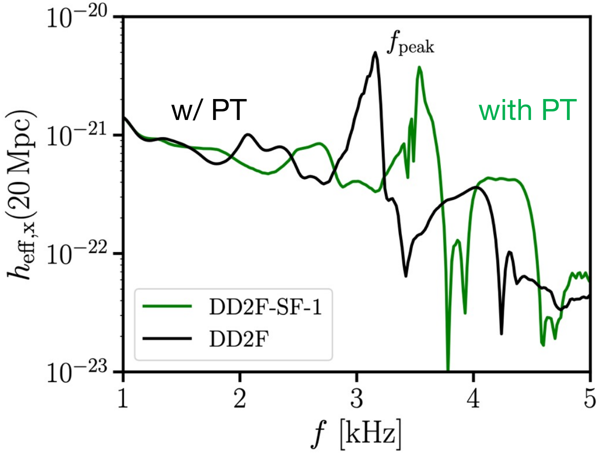
18 orders of magnitude in scales
still similar T < 70 MeV, $\rho < 3\rho_0$ for both



Blacker *et al.*, PRD 102 (2020) 123023



Bauswein *et al.*, PRL 122 (2019) 061102



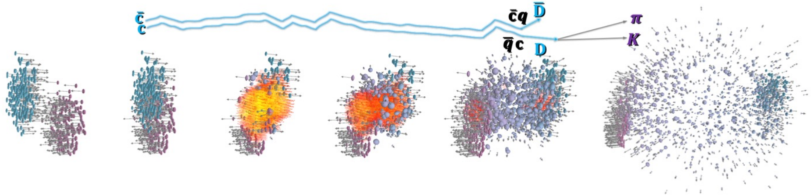
- NS mergers probe bulk properties of EoS – microphysics only accessible through combined effort

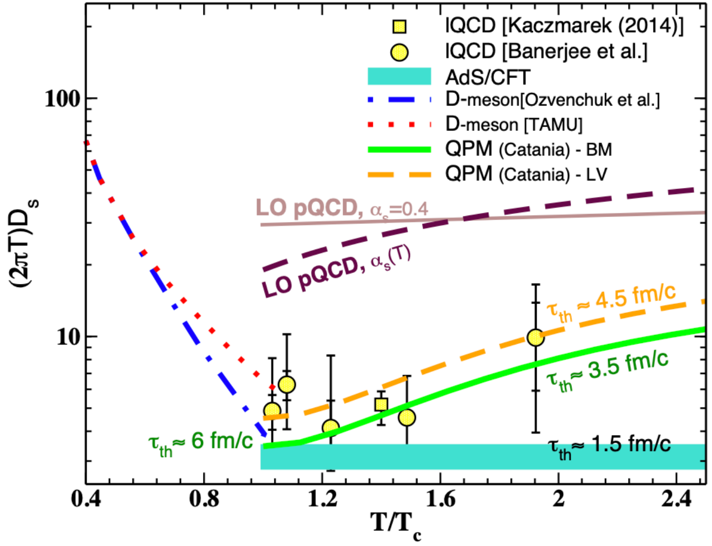
Blacker *et al.*, PRD 109 (2024) 043015
Vijayan *et al.*, PRD 108 (2023) 023020

- Study the possible occurrence of the hadron-quark phase transition and its signature in Gravitational Waves
- **"MultiGav"** Helmholtz Innovation pool KIT-GSI-DESY ongoing

w/ GSI theory

What is so “charming” about charm?





Scardina *et al.*, PRC96, 044905 (2017)
HotQCD, PRL 132 (2024) 5, 051902
Altenkort *et al.*, PRL132 (2024)

- 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 → **measure charm probe in-medium QCD force!**

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

Consequences for heavy-quark transport
Discontinuity? Associated to 1st order phase transition?

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

w/ GSI ALICE