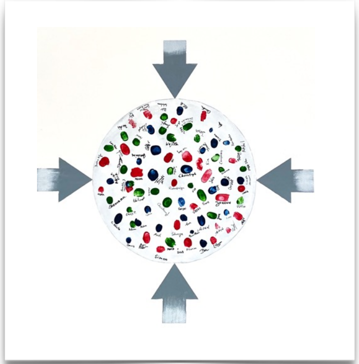
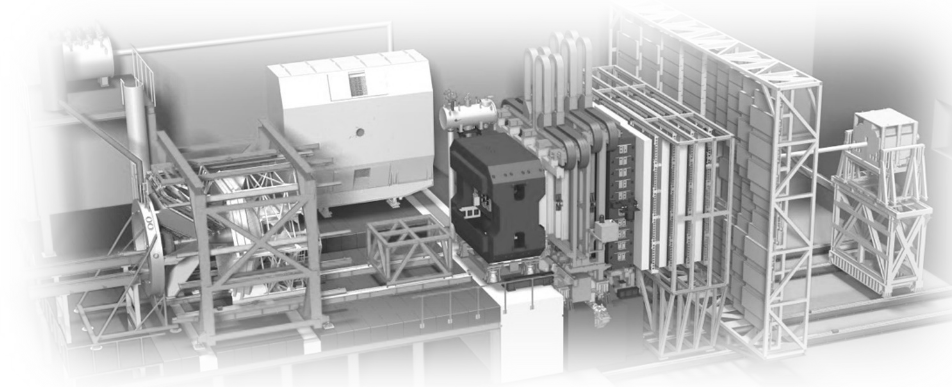


Physics Program in CBM Experiment at FAIR

Tetyana Galatyuk,
GSI / Technische Universität Darmstadt



Physics of High net-baryon Densities (PHD2025)

GSI, Apr 13 – 15, 2025

45. CBM Collaboration Meeting

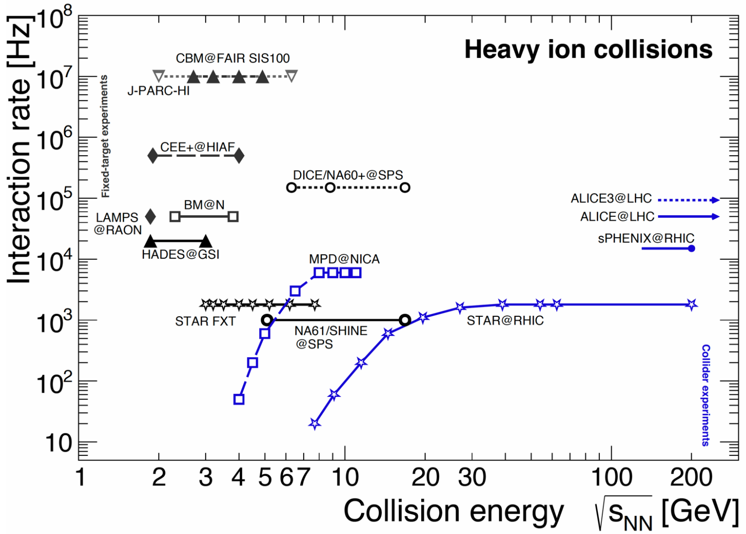
GSI, Darmstadt 16-21 February 2025

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

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

CBM mission

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

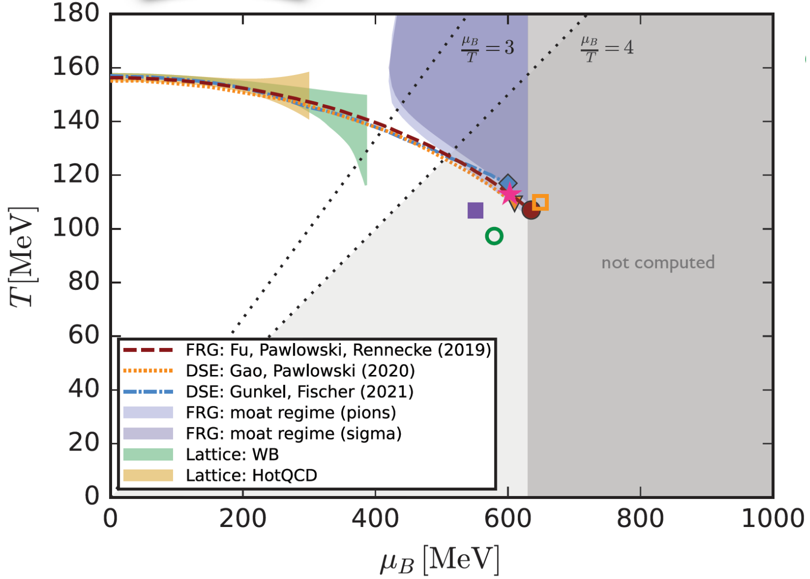
→ **heavy-ion beams**

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

→ **p, d beams**

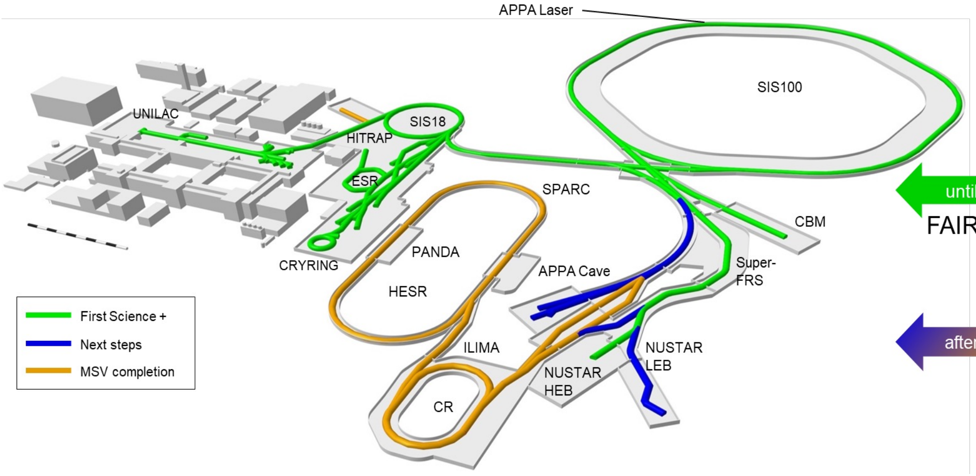
F. Rennecke QM25



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

$$\sqrt{s_{NN}} \approx 3.6 - 4.1\ \mathrm{GeV}$$

Facility for Antiproton and Ion Research



until 2028
FAIR 2028

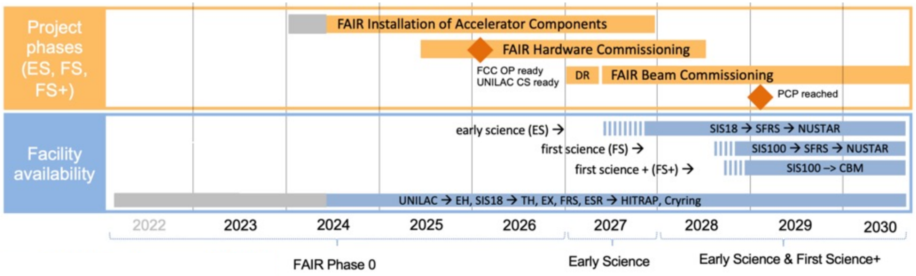
after 2028

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

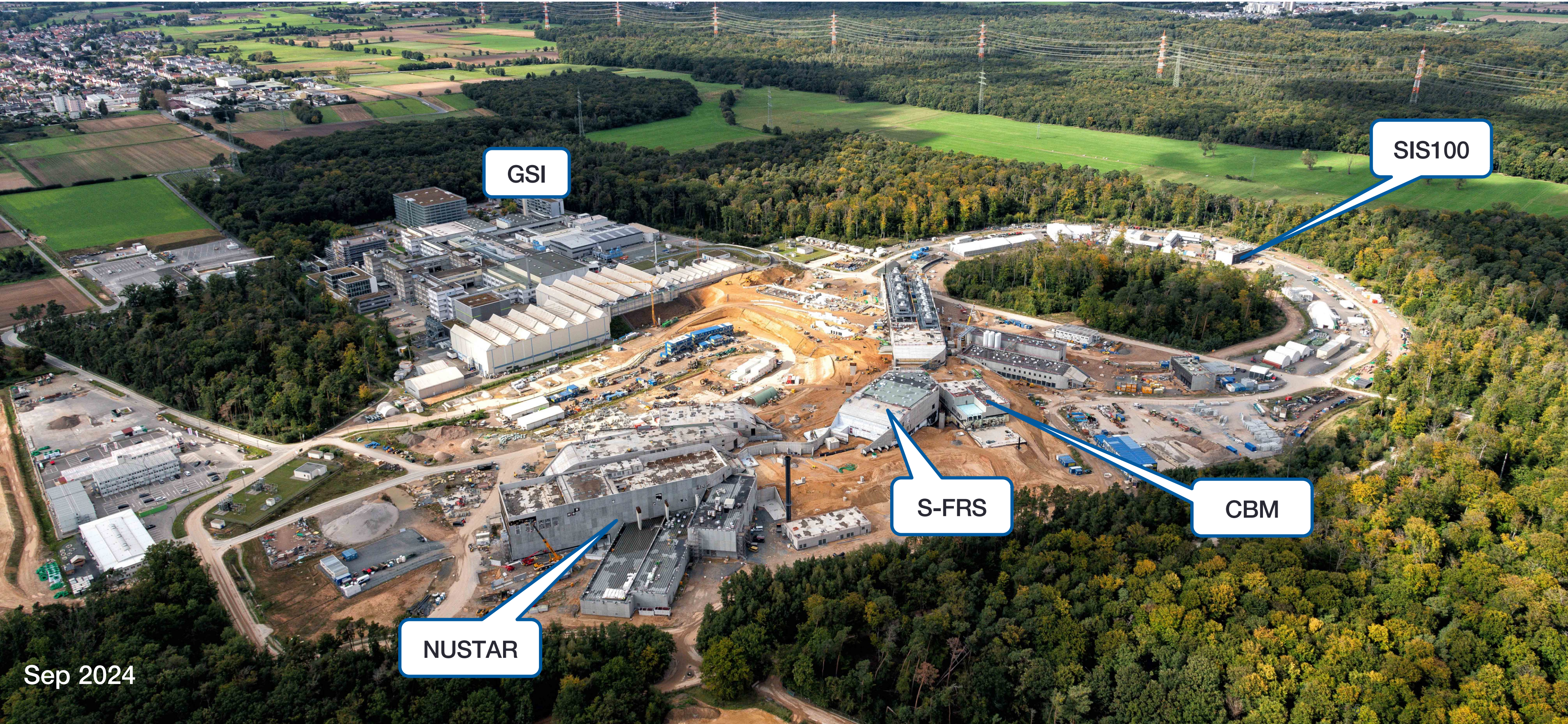
Intensity: $\sim 10^{13}$/s for p; $\sim 10^{11}$/s for U

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**

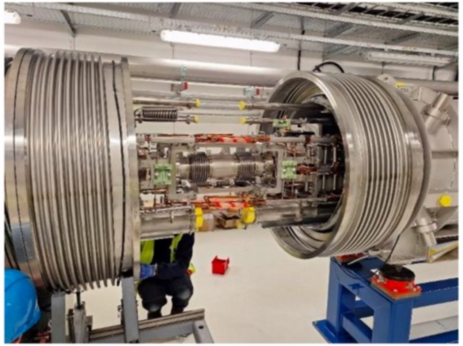


FAIR status



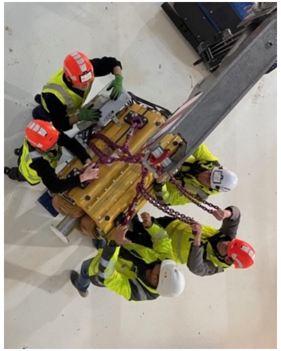
TBI and ACC installation well advanced

Aug'24: first interconnection of a pair of dipole modules in the accelerator tunnel



Oct' 24: Sector 3 Arc dipole installation complete

First quadrupole magnet in tunnel, Mar'24



Apr'24: 6 x 100 m^3 He tanks of the cryo facility were installed

Technical installation on the roof of main supply building completed

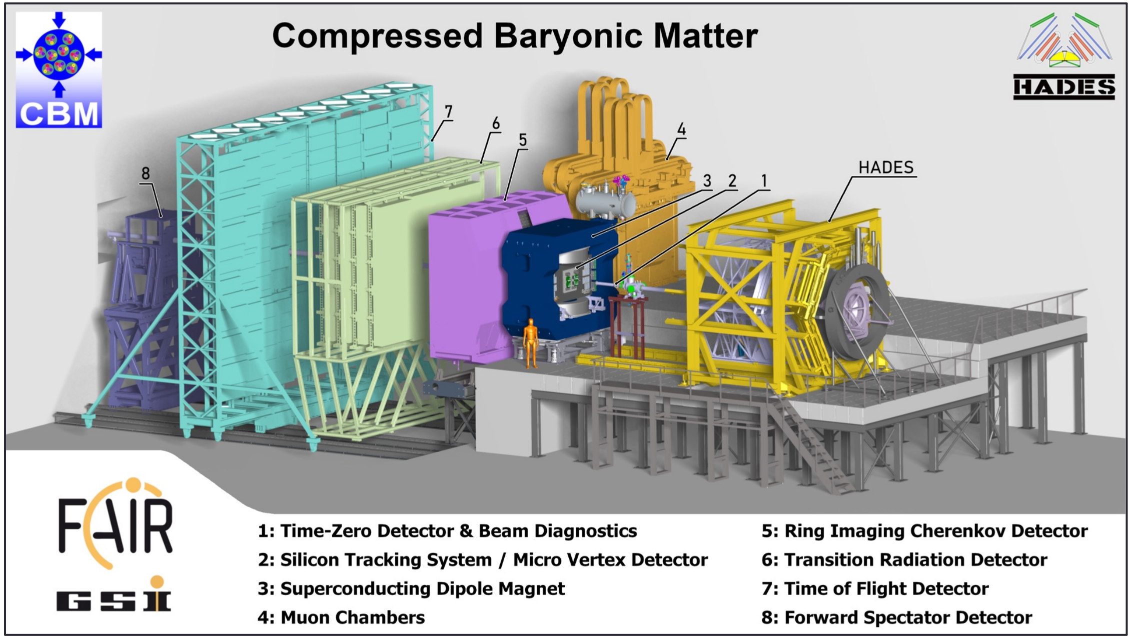
CBM building, Q1 2025

CBM target hall with magnet foundation,

23 Dec 2024

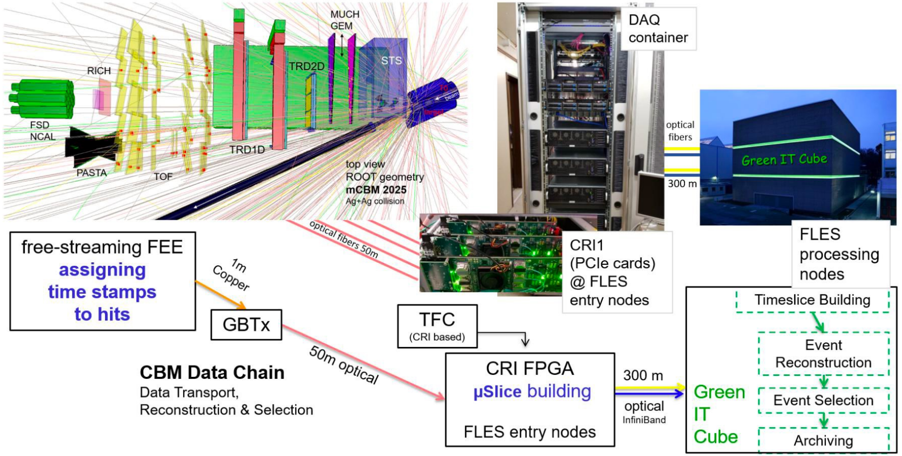
Compressed Baryonic Matter experiment

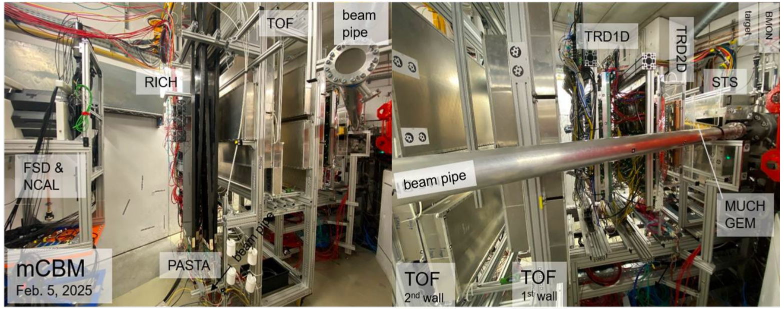
- Fixed target experiment
  → obtain highest luminosities
- Versatile detector systems
  → lepton and hadron identification
  → optimal setup for given observable
- Tracking based entirely on silicon
  → fast and precise track reconstruction
- Free-streaming FEE
  → nearly dead-time free data taking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



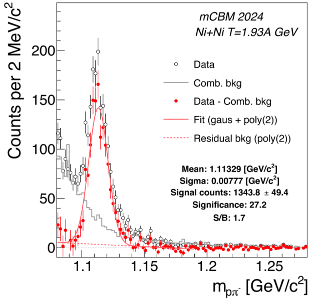
Prototype of CBM online data processing with mini-CBM

- Full system test, verification of the triggerless-streaming read-out and data transport of CBM
- High-rate detector tests with up to 10 MHz collision rates





Full system test with SIS18 beam
- Detector pre-series modules
- Free-streaming readout implemented and commissioned
- Connection scheme and hardware close to the final CBM DAQ



- Gained experience in operations, calibration and alignment
  → speed up of commissioning of CBM
- Λ reconstruction with CA track reconstruction and KFParticle package

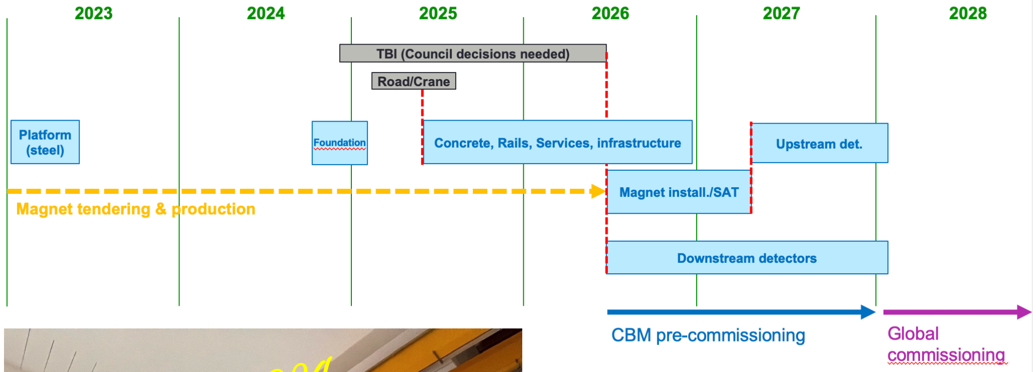
CBM installation / commissioning

CBM Cave

- a dedicated cave with a massive beam dump for high-intensity, high-energy beams
- CBM cave/building shell completed
- Technical Building Infrastructure in 2025/2026

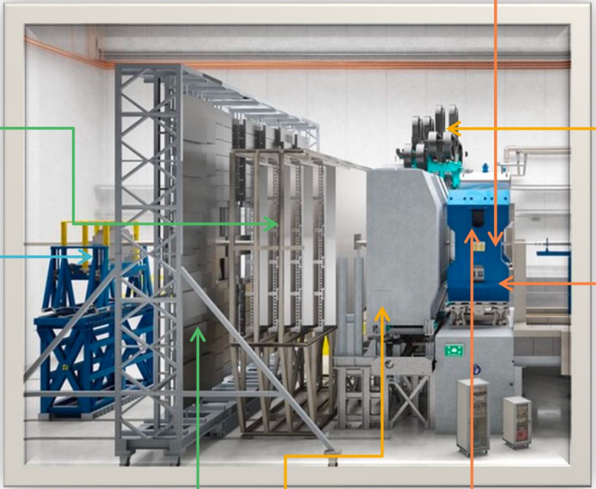
CBM Installation

- CBM installation activities (platform)
- started in June 2023
- CBM ready for beam by 2028, ~12 months contingency for CBM global commissioning



Subsystem production status

P. Chaloupka
QM25

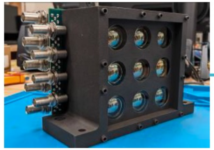


Transition Radiation Detector

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

#1094: Production of the CBM Transition Radiation Detector

Forward Spectator Detector

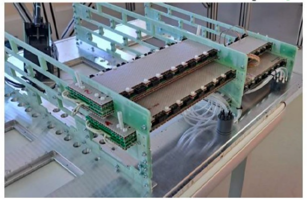


Test modules

#742: Forward Spectator Detector for CBM

Time of flight detector

TOF@STAR



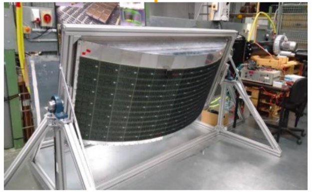
20% MRPC counters produced

Ring Imaging Cherenkov detector

1 of 2 photo cameras ready

50% FEE produced

RICH@HADES

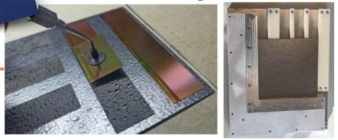


#828.:Status of the CBM RICH detector project at FAIR

#927: The mirror system of the CBM RICH detector

Micro Vertex Detector

sensor/module integration



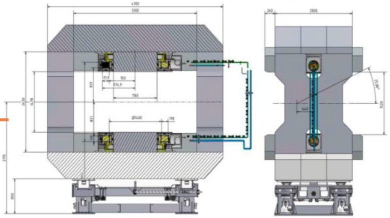
#36: The Micro Vertex Detector for the CBM Experiment at FAIR

MUon CHamber system

Series production of Station 1 GEM chambers starts soon

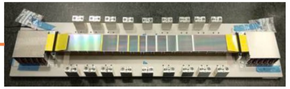
Superconducting dipole magnet

Production Readiness Review ongoing



Beam monitoring system

Silicon Tracking System



first STS series ladder

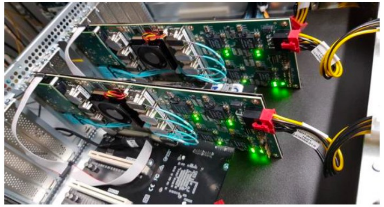
50% modules assembled

STS@J-PARC E16

#693: From Concept to Implementation: The Silicon Tracking System of the CBM Experiment

#694: Module and ladder characterization of the Silicon Tracking System for the CBM experiment

CRI for FLES entry nodes



FELIX cards (BNL), tested with mCBM

#695: The Silicon Tracking System of the E16 experiment at J-PARC: commissioning and results from the test beam

CBM observables

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)

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

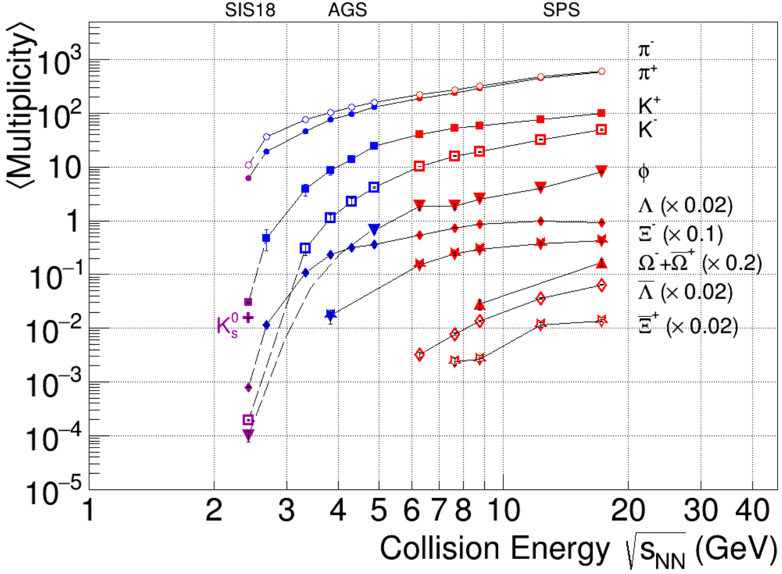
Anticipated CBM physics performance (selected cases)

Hadron yields, flow and polarization

Chemical f.o., Equation of State

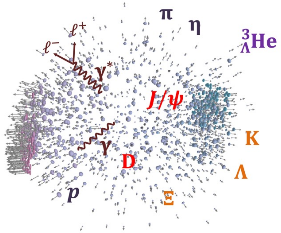
Hadron production

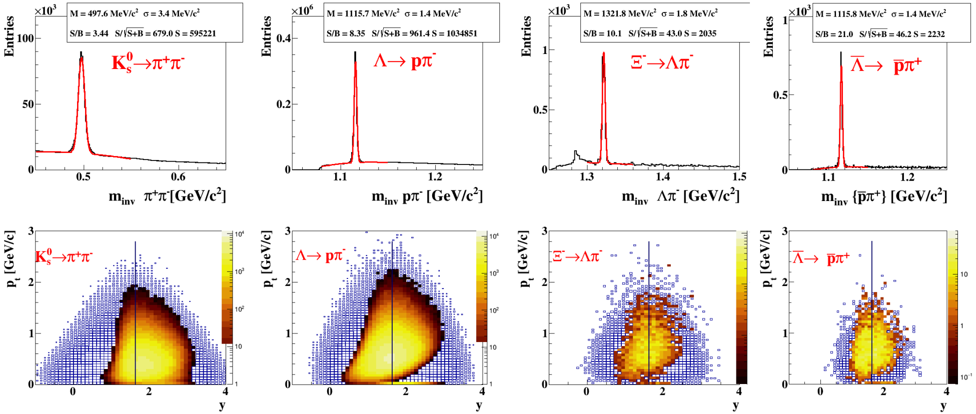
An impressive set of data, however data below AGS energies are missing for less abundant particles (Ξ, Ω)



Blume, Markert, PPNP 66 (2011)

I. Vassiliev
Y. Zhou
QM25

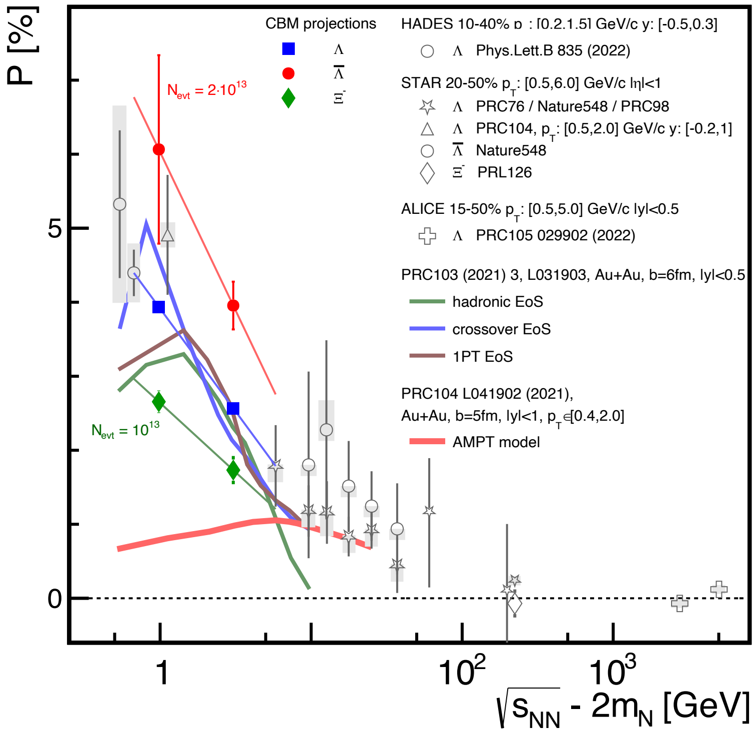




Mapping the chemical freeze-out

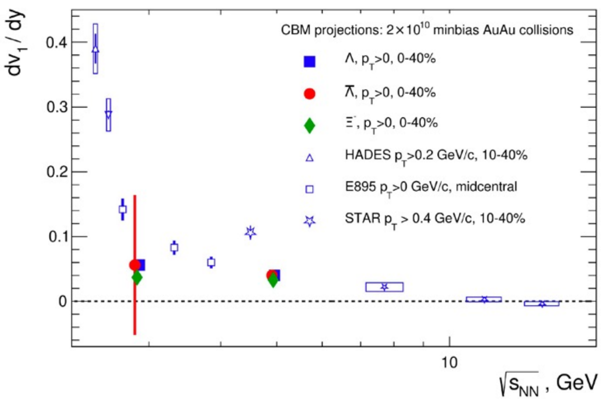
- Analysis of hadron yields within the statistical (thermal) model
- Test hypothesis of hadron abundancies in equilibrium $\rightsquigarrow T_{CF}, \mu_B, V$

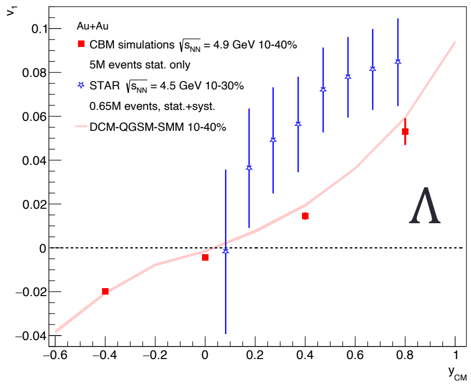
Collective flow and polarization of $\Lambda, \bar{\Lambda}$ and Ξ^- in CBM



- Strong increase of polarization signal towards few GeV energies
- Origin of the polarization mechanism? Sensitivity to EoS?
- **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





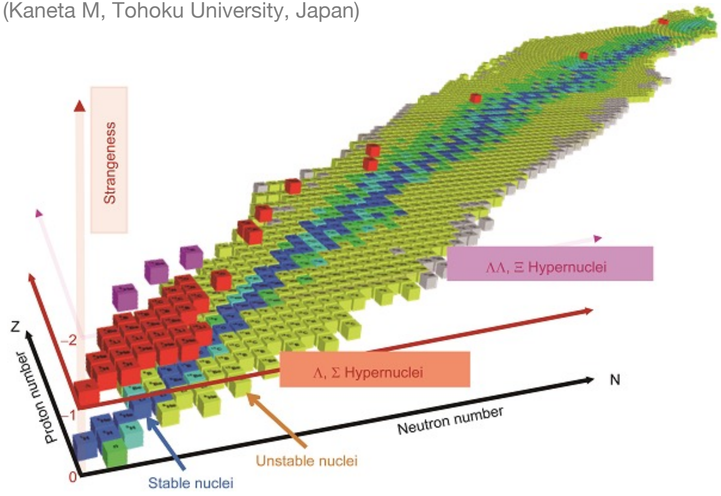
Hypernuclei

INTERACTION

Nuclei and hyper-nuclei production

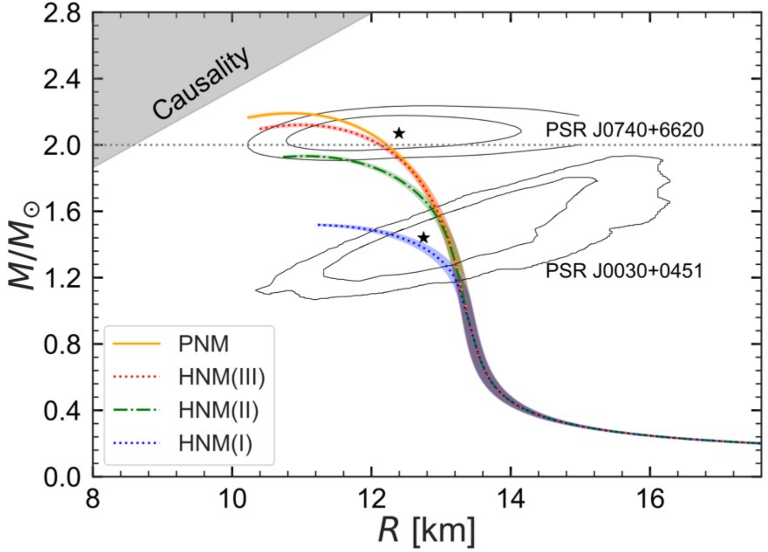
Three-dimensional nuclear chart

(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

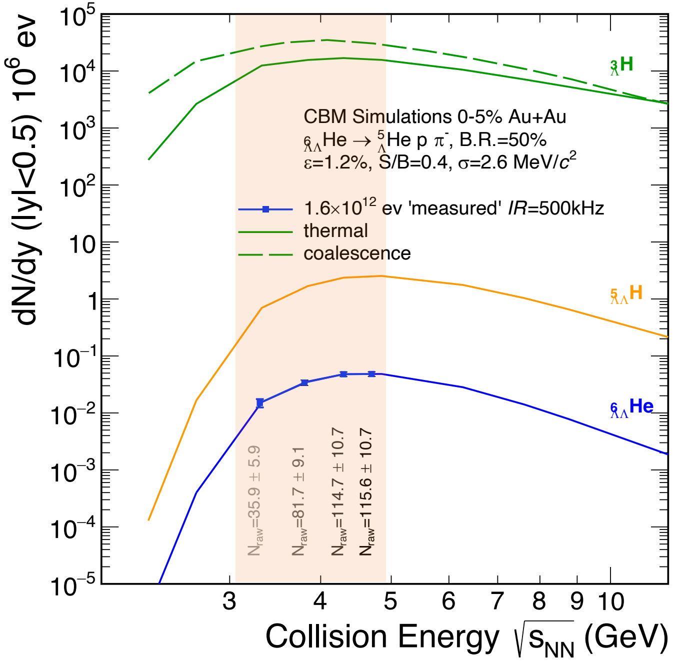
three-body hyperon-nucleon interaction plays a fundamental role in the softening of the EoS

I. Vassiliev
Y. Zhou
and
S. Glaessel
QM25

CBM performance

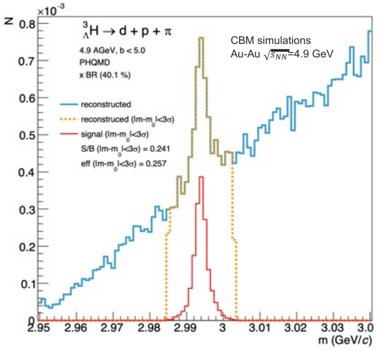
CBM collision energies optimal for hypernuclei production

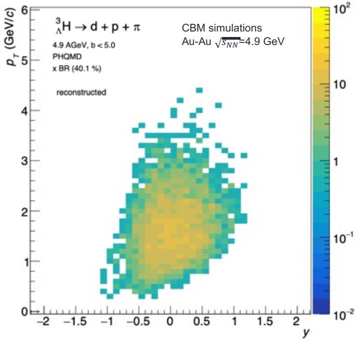
Thermal: Andronic *et al.*, PLB 697 (2011)
Coalescence: Steinheimer *et al.*, PLB 714 (2012)

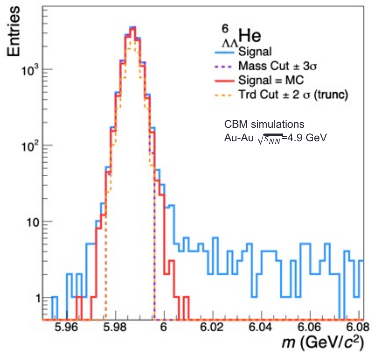


- CBM high interaction rates and clean identification allow precision measurements of single- and double Λ-hypernuclei
  - spectra and flow pattern
  - complex structure via Dalitz plot
  - life-time (particularly sensitive to YN and YY interaction)
- Search for the new hyper-nucleus or charmed nucleus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

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







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

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

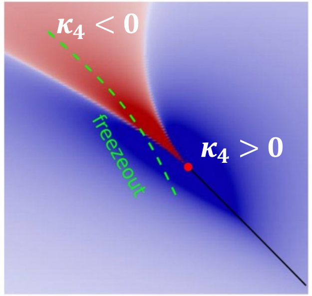
κ_n - cumulants (measurable in experiment)
$\hat{\chi}_n^q$ - susceptibilities (e.g. from lQCD)

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

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

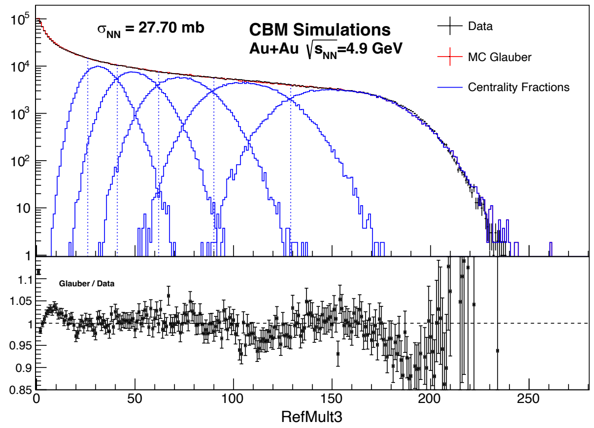
$\xi \to \infty$ **diverges at critical point**

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

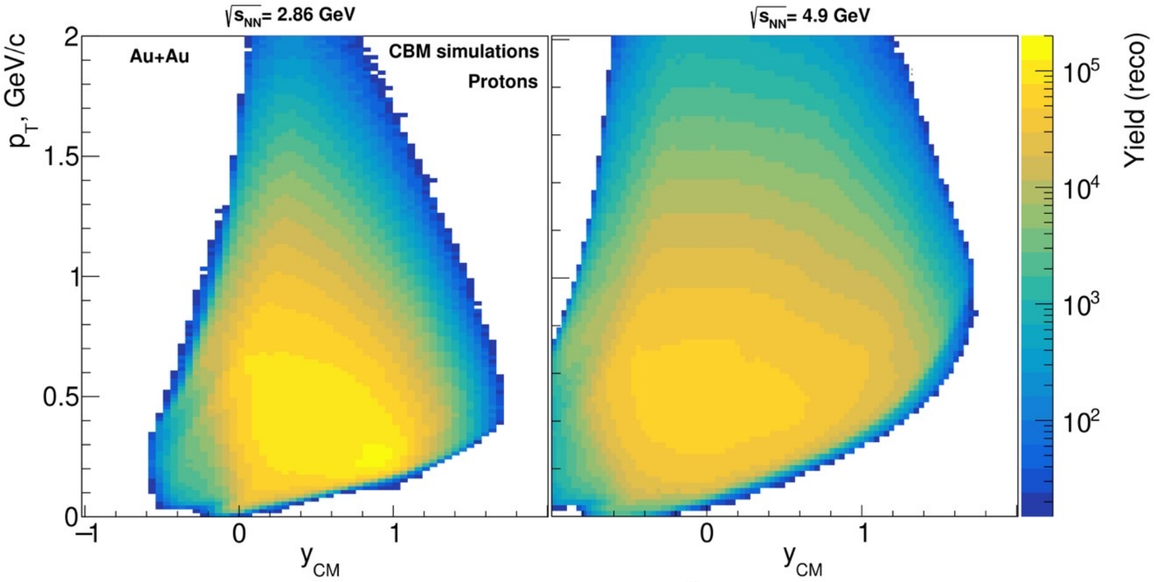
Performance studies in CBM

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

impact of the effects is being scrutinized



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



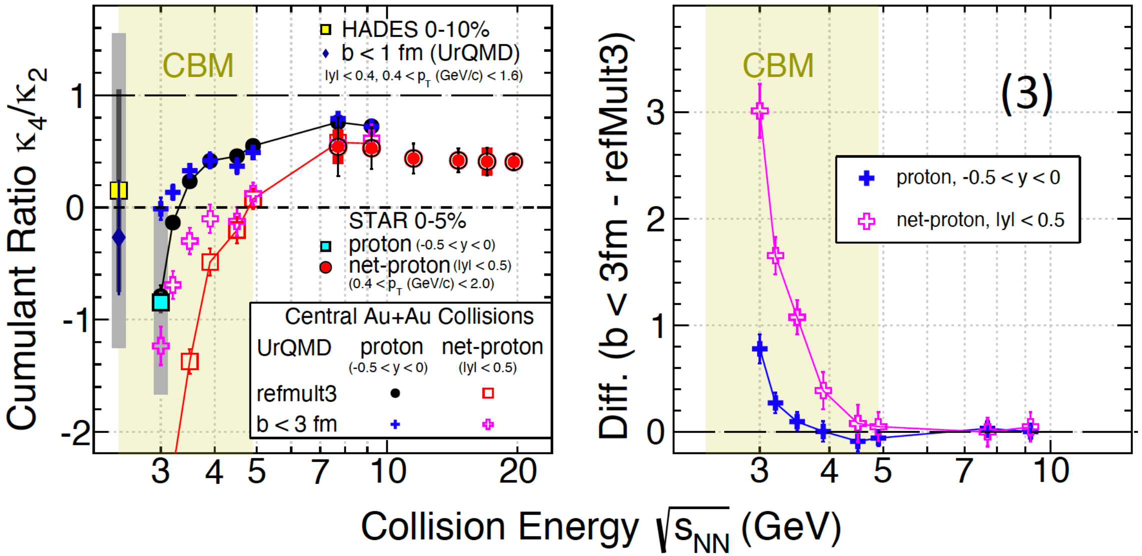
Low p_T and midrapidity coverage for all energies

Reconstruction efficiency allows for precision measurement of cumulants

Centrality dependence of (net-)proton κ_4/κ_2

- Au+Au collisions at $\sqrt{s_{NN}}$ = 3 – 5 GeV in the UrQMD transport model

Xin Zhang
QM25



After 3 years of running:

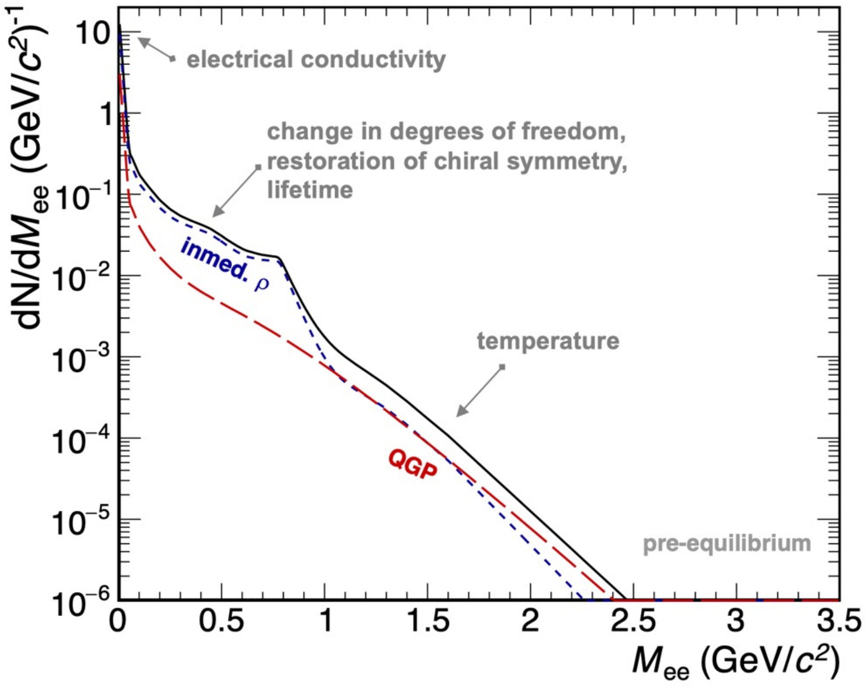
- completion of the excitation function for $\kappa_4(\mathrm{p})$
- first results on $\kappa_6(\mathrm{p})$
- extension into strangeness sector $\kappa_4(\Lambda)$

C. Feier-Riesen
A. Meyer-Ahrens
P. Subramani
A. Kumar Sharma
QM25

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?

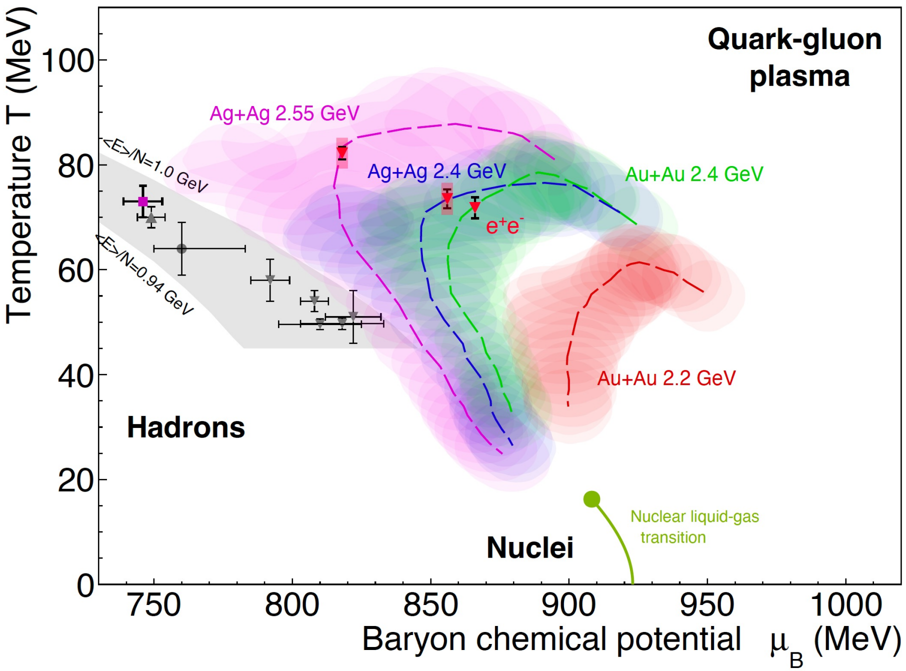
Transport coefficient: electrical conductivity
(as fundamental as $4\pi\ \eta/s$ and $2\pi\ T\ D_s^{HF}$)

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

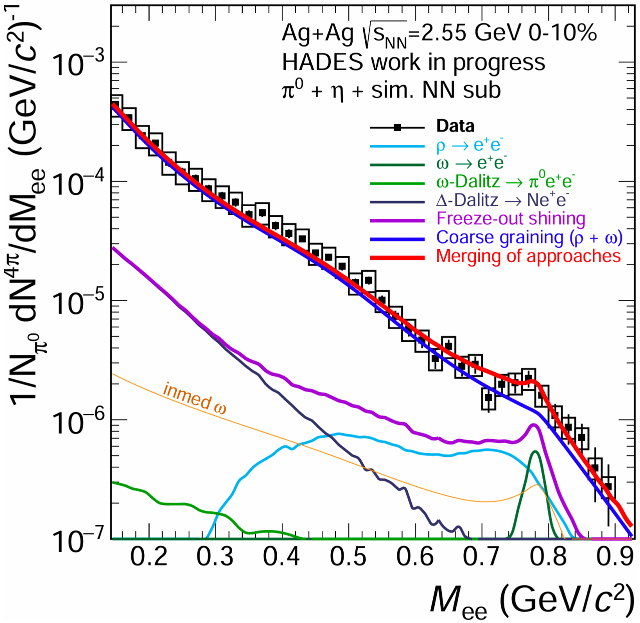
Fireball diagnostics:

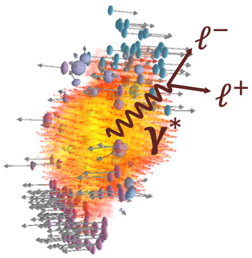
- early temperatures (M_{ee} spectra; no blue-shift distortion)
- lifetime of radiating phase (inclusive low-mass yield)
- production mechanism (spin polarization)
- pressure anisotropies (dilepton flow)
  ⇝ detect presence of 1st order transition (critical point?)

Thermal dileptons at HADES



Acceptance corrected excess yields vs coarse-graining approach



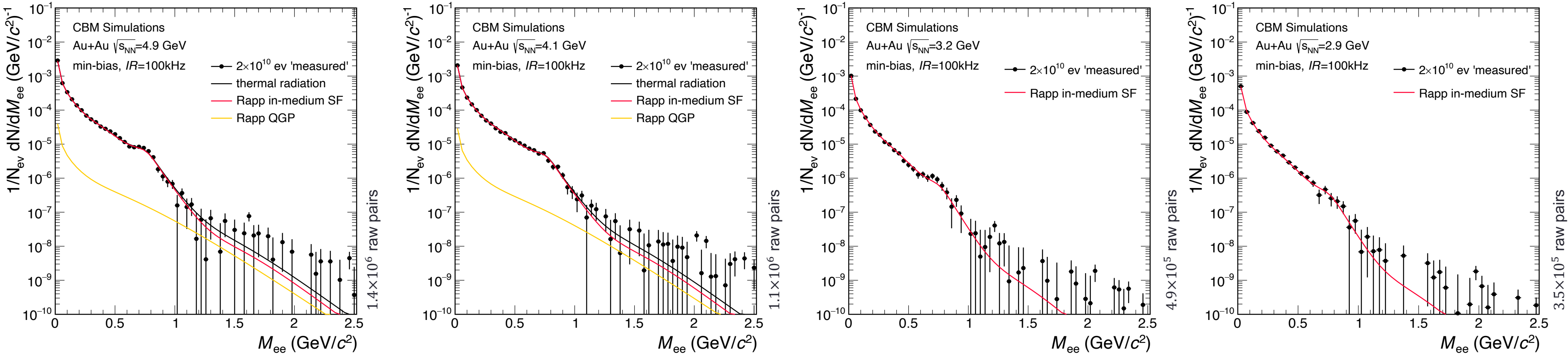


Freeze-out curve:J. Cleymans, K. Redlich, Nucl. Phys. A 661 (1999) 379
Au+Au 2.4 GeV: HADES, Nature Phys. 15 (2019) 1040
Ag+Ag 2.4 GeV, 2.55 GeV: HADES in preparation

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

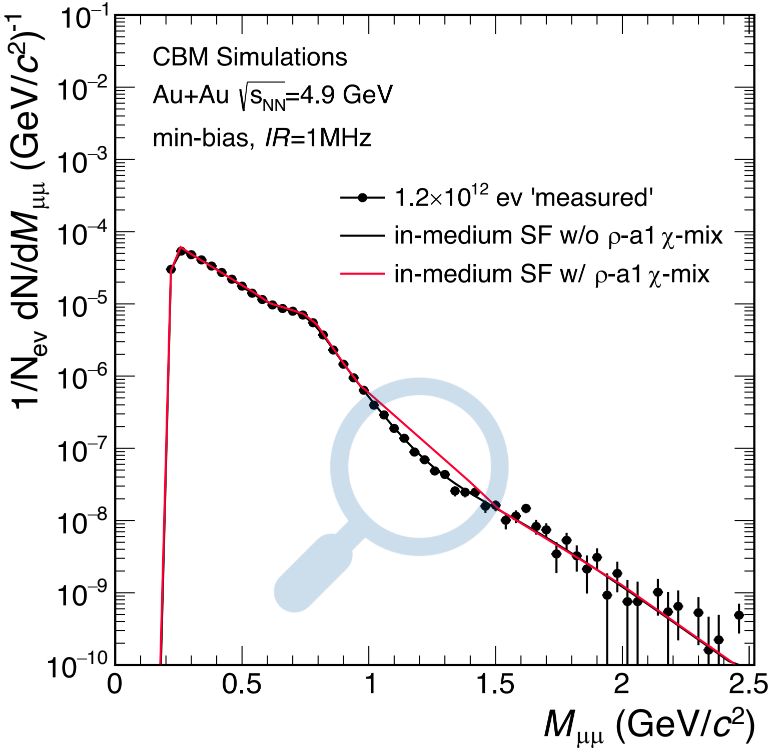
Isolated dielectron thermal radiation yield, corrected for acceptance × efficiency:

- 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

(additional) Signature for chiral symmetry restoration



- Changes in yield and shape at $M_{\ell\ell} > 1.1$ GeV/c^2 due to **$\rho - a_1$ chiral mixing**
- $\pi a_1 \rightarrow \gamma^* \rightarrow \ell^+\ell^-$ (chiral mixing) is a dominant hadronic source in IMR
- **20-30% enhancement** w.r.t. no chiral mixing is **predicted**

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

Experimental challenge: physics background ($M_{\ell\ell}$ > 1 GeV/c^2)

- correlated charm: excellent vertex resolution → topological separation of prompt and non-prompt source employing DCA cut
- QGP: decrease towards lower energy
- $\mathcal{D}$rell-Υan: pp, pA measurements

- **CBM sensitivity** to detect a signal is **demonstrated**

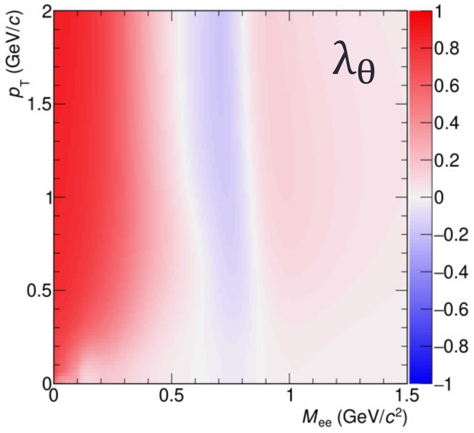
Virtual photon polarization

- Decompose spectral function using projectors for a spin-1 particle $\rho^{\mu\nu}_{EM} = \rho_L\, P^{\mu\nu}_L + \rho_T\, P^{\mu\nu}_T$ with $g_{\mu\nu}\, \rho^{\mu\nu}_{EM} = \rho_L + 2\rho_T$
- Angular distribution of single lepton in γ^* rest frame depends on polarization of γ^*

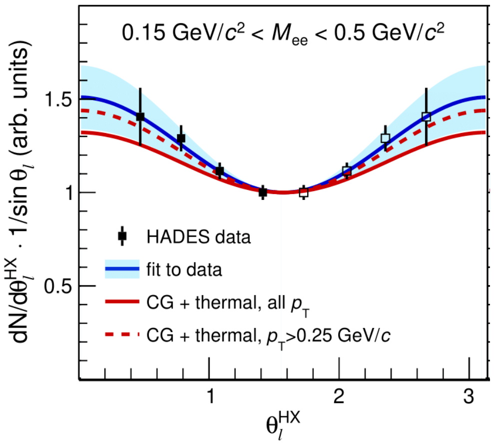
$$\frac{dN}{d^4x d^4q d\Omega} = \mathcal{N}(1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda^\perp_\varphi \sin^2\theta \sin 2\varphi + \lambda^\perp_{\theta\varphi} \sin 2\theta \sin\varphi)$$

- Different virtual photon **production mechanisms** imprint different anisotropy parameters λ
- λ coefficients related to **difference** between **longitudinal and transverse** spectral function components $\lambda_\theta = \frac{\varrho_T - \varrho_L}{\varrho_T + \varrho_L}$

Seck *et al.*, arXiv: 2309.03189

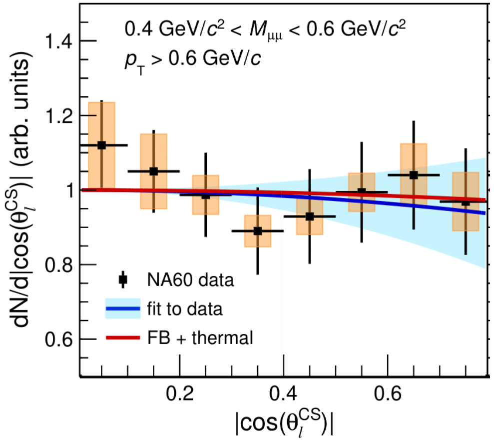


HADES, Ar+KCl



data points: HADES, PRC 84 (2011) 014902

NA60, In+In

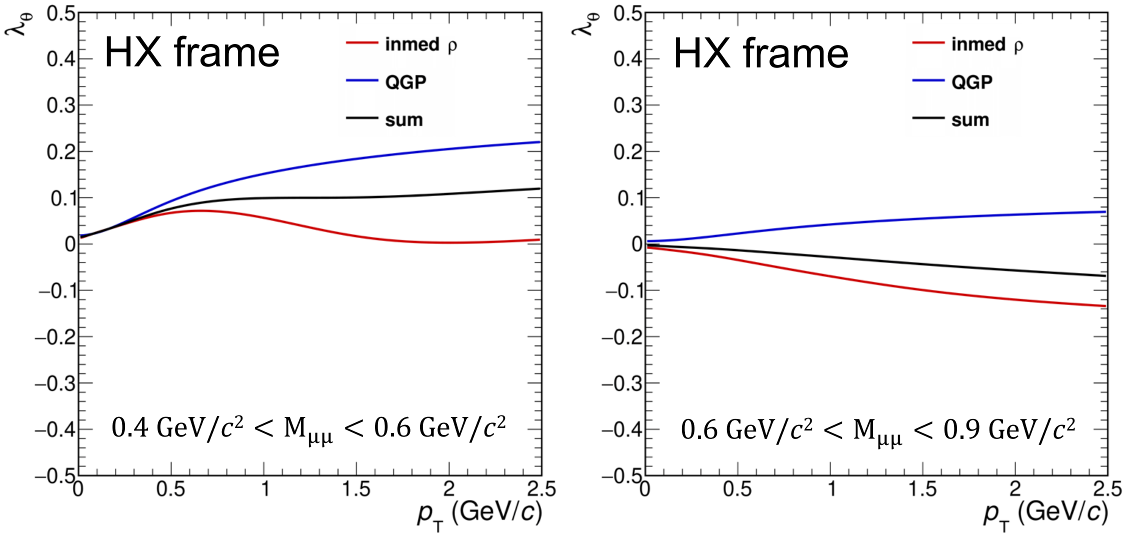


data points: NA60, PRL 102 (2009) 222301

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

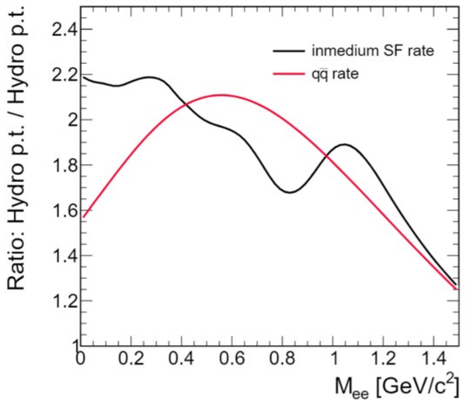
- search for onset of QGP
- important in disentangling $\rho - a_1$ chiral mixing from QGP around M_{ll} ~ 1.2 GeV/c^2

Thermal dileptons excitation functions

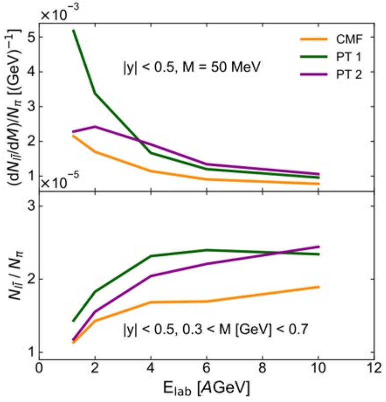
Excess yield in LMR tracks fireball lifetime

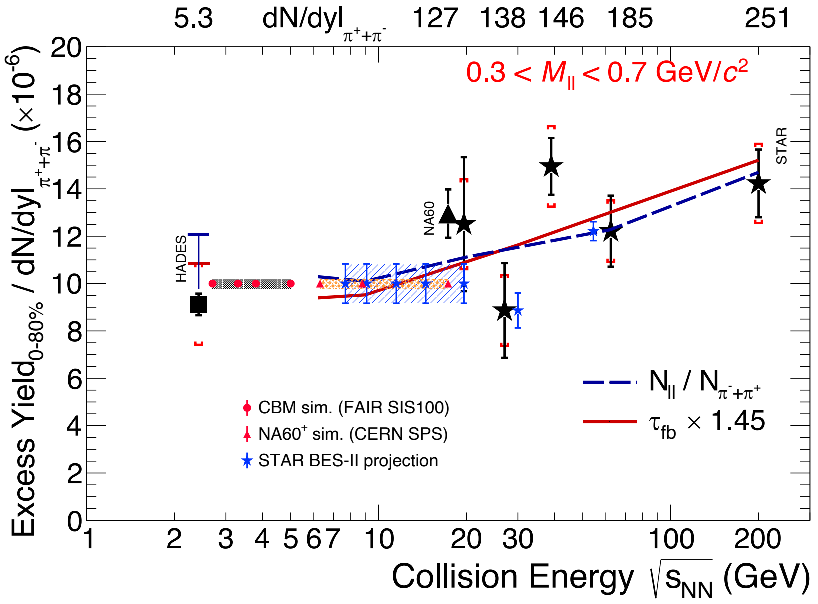
- search for "**extra radiation**" due to latent heat around **phase transition** (& critical point?)
- 1st order phase transition could result in factor 2 larger yield due to extended "cooking"
- CBM precision for LMR yield 1.5 – 4.5%

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



Savchuk, *et al.*, J.PG 50 (2023) 12, 125104





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

See also
Tripolt *et al.*, NPA 982 (2019) 775
Li and Ko, PRC 95 (2017) no.5, 055203

Excitation function of the $\langle T \rangle$ of the fireball

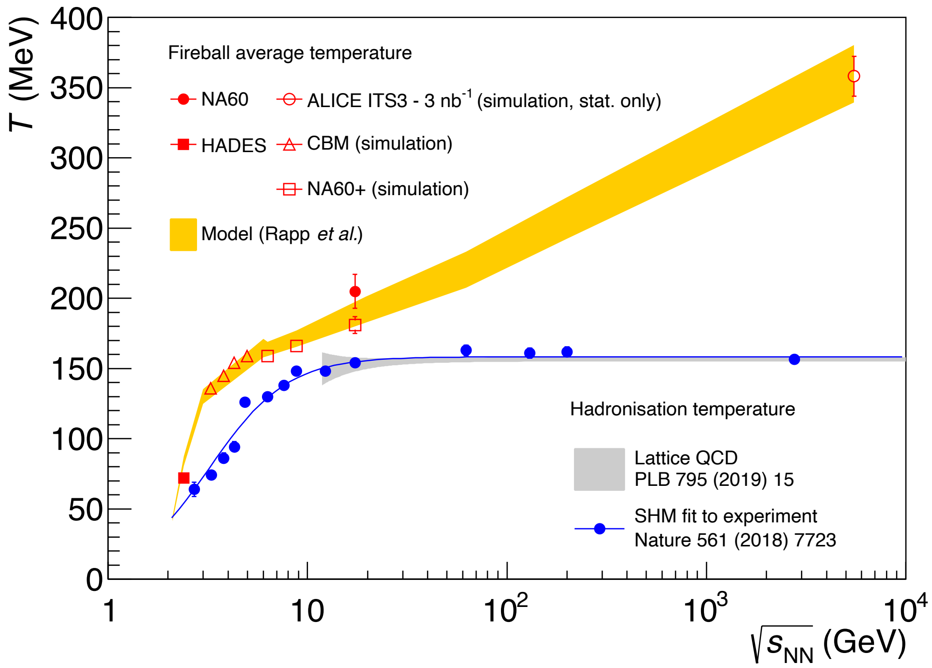
- Invariant mass slope measures radiating source $\langle T \rangle$ (free from blue-shift effects)

$$\frac{dR_{ll}}{dM} \propto (MT)^{\frac{3}{2}} \exp\left(-\frac{M}{T}\right)$$

Rapp, van Hees, PLB753 (2016)

- Assumption: $\frac{Im\Pi_{EM}}{M^2} \sim const.$

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



https://github.com/tgalatyuk/QCD_caloric_curve

Hadron physics

INCLUSIVE & EXCLUSIVE

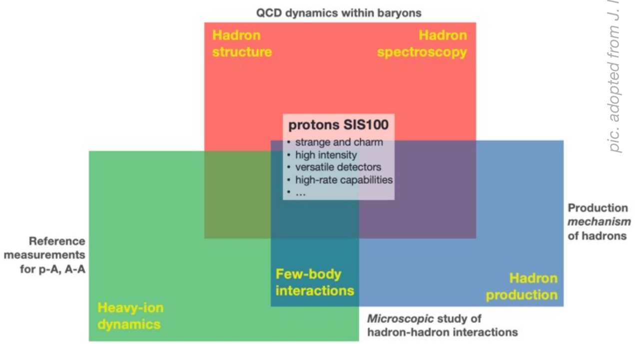
A comprehensive QCD program with SIS100 proton beam

- **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

- **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**



pic. adopted from J. Messchendorp

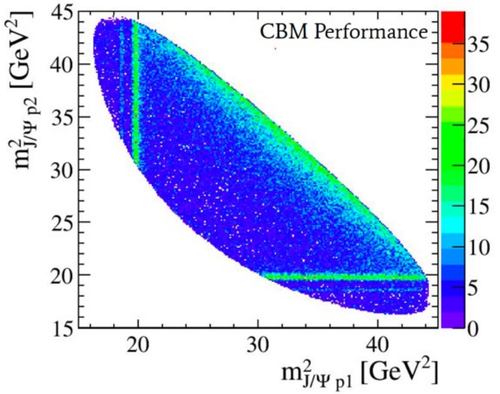
Physics opportunities with proton beams at SIS100 Workshop Wuppertal, Feb 2024
https://indico.gsi.de/event/18475/overview

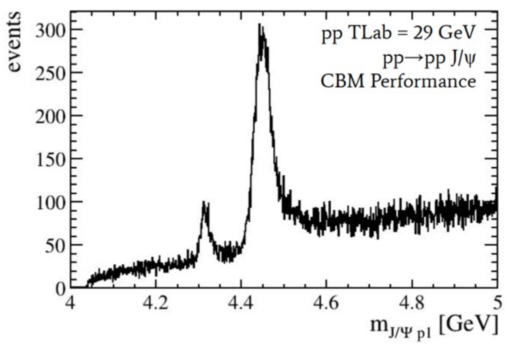
QCD at FAIR workshop, Nov 11-14, 2024,
https://indico.gsi.de/event/20301/

White-paper preparation

Charm of CBM (pp / pA / AA)

Reconstructed Dalitz plot with pentaquarks

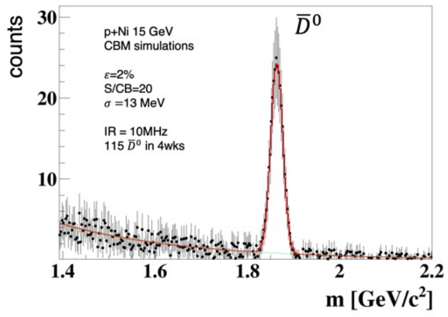


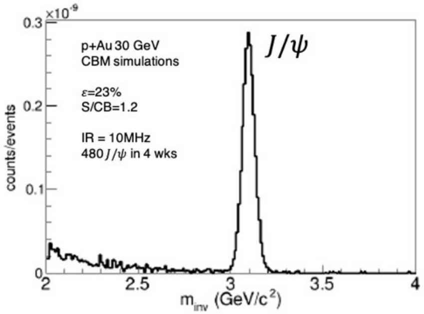


- **CBM is well adapted to the pp exclusive channels program**
  - high-rate capabilities and free-streaming DAQ's
  - excellent mass resolution (~2%)
  - excellent coverage for exclusive channels

- **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





Summary: The future is bright!

- High μ_B region is driven by experiment
- Large discovery potential

- **Timely completion of SIS100**: unique physics program with CBM
- Long-term prospects: highly competitive due to high interaction-rate capability (detector upgrades, well understood running experiment)

- CBM is progressing well towards the science program with SIS100 beams
- High-rate capabilities achieved in the extensive R&D phase
- All subsystems are on the verge of the series production
- Ultimate goal: **CBM ready for beam in 2028!**


Grafik: GSI/FAIR, Zeitrausch