Future facilities: the CBM experiment

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for the CBM collaboration

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CBM : Exploring the QCD phase diagram in regions of high net baryon density

CBM

Bazavov et al., PLB 795 (2019) 15-21
Ding et al., PRL 123 (2019) 6, 062002
Dini et al., Phys. Rev. D 105 (2022) 3, 034510

Vanishing μ_B, high T (lattice QCD):

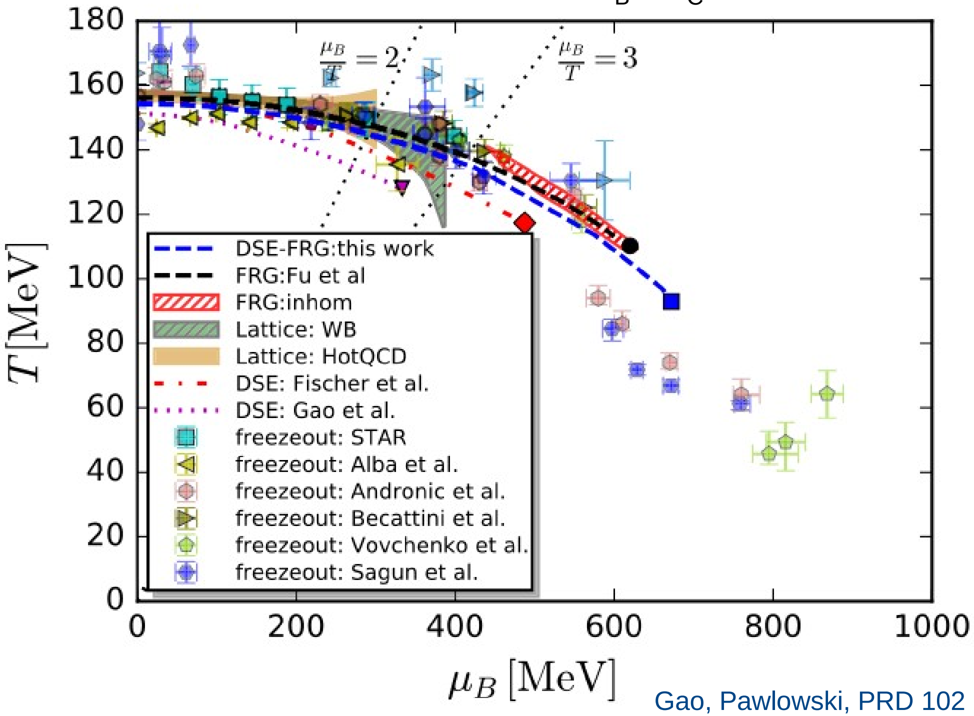
→ Smooth cross over from hadronic to partonic medium
→ $T_C = 132^{+3}_{-6}\,\mathrm{MeV}$ at chiral limit, no critical point indicated by lattice QCD at μ_B / T_C < 3

Large μ_B, moderate T ???

- 1st order phase transition ?
- QCD Critical Point ?
- Chiral restoration at high μ_B ?
- EoS of dense nuclear matter ?
- Quarkyonic matter ?

→ Worldwide experimental efforts to answer these questions

→ **CBM : dedicated experiment to explore this regime**



Gao, Pawlowski, PRD 102 (2020) 3, 034027

Astrophysical relevance of high μ_B:

Baryonic matter at high μ_b also of astrophysical relevance:

- Equation of state at neutron star density ?
- How is the inner core of a neutron star composed ?
  Strange matter ? Hyperons ? Quark matter
- Upper mass limit for neutron stars ?


nature physics

ARTICLES
https://doi.org/10.1038/s41567-019-0583-8

Probing dense baryon-rich matter with virtual photons

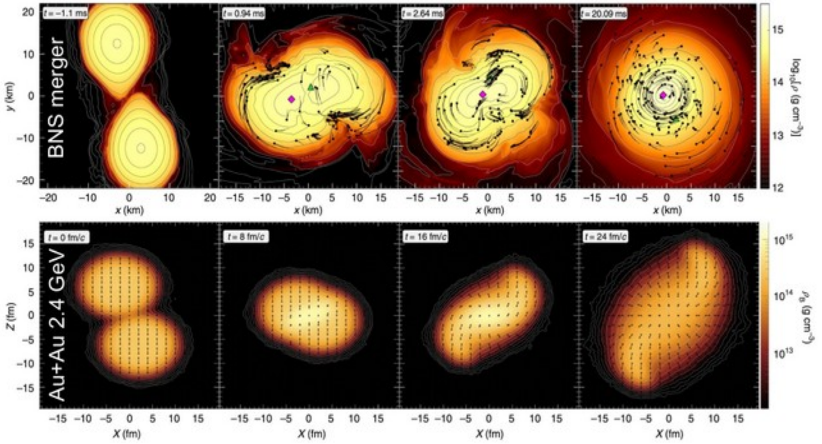
The HADES Collaboration*

HADES collaboration,
Nature Phys. Vol 15 (2019), 1040

Remarkable similarity between
Binary neutron star merger and **Heavy ion collision:**

Neutron star merger : T ~ 10 – 100 MeV
$\rho < 2 – 5 \rho_0$

Heavy-ion collision: T < 80 MeV
$\rho < 3 \rho_0$



different states of the collision of
2 neutron stars (top) vs
Au-Au HI collision 2.4 AGeV (bottom)

18 orders of magnitude difference in scale,
20 orders in time duration
→ still similar conditions !

CBM Physics Program

Phase diagram and phase transition

- Excitation function of intermediate mass di-leptons
- Excitation function of hyperons

Chiral Symmetry restoration at large μ_B

- **Di-leptons at low invariant masses**

Critical point

- Event-by-event fluctuations of conserved quantities

QCD equation-of-state

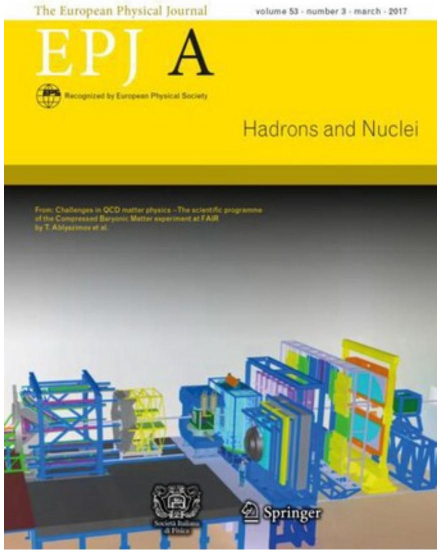
- Collective flow of identified particles
- Particle production at threshold energies

Strange matter

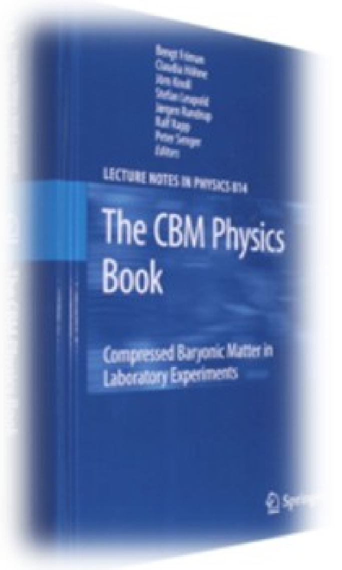
- Hyper-nuclei
- Meta stable objects (e.g. strange dibaryons)

Heavy flavour in cold and dense matter

- Excitation function of open and hidden charm production



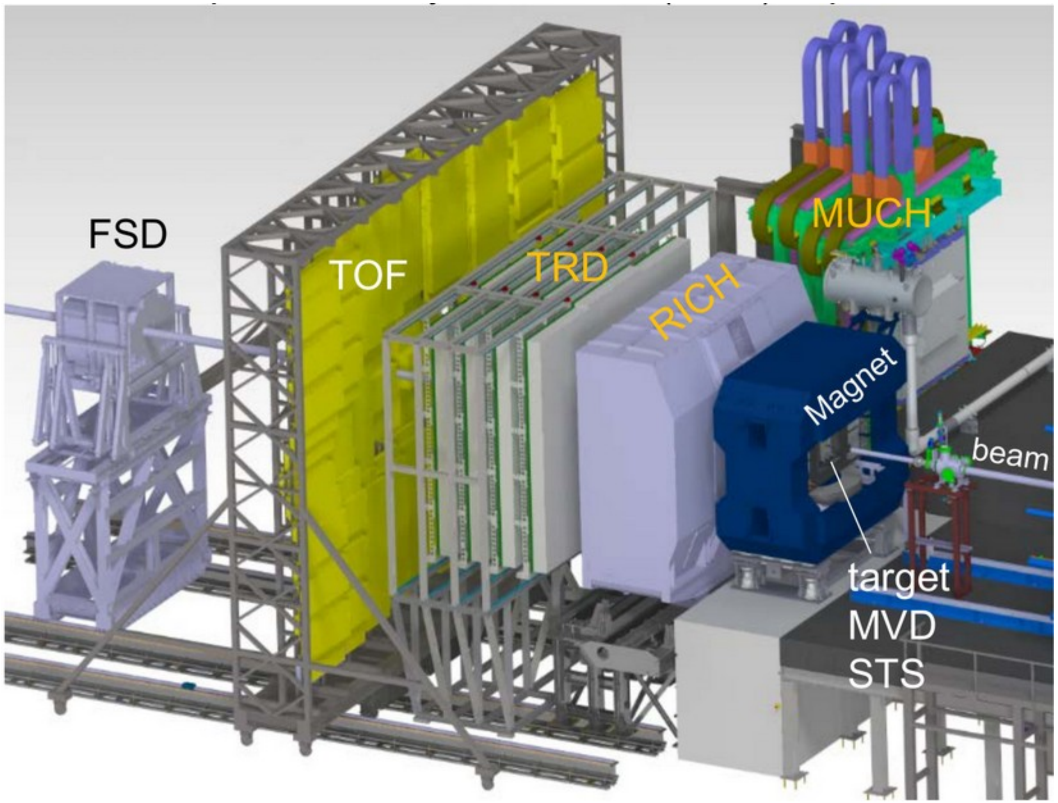
"Challenges in QCD matter physics"
CBM Collaboration,
Eur. Phys. J. A53 (2017) 60



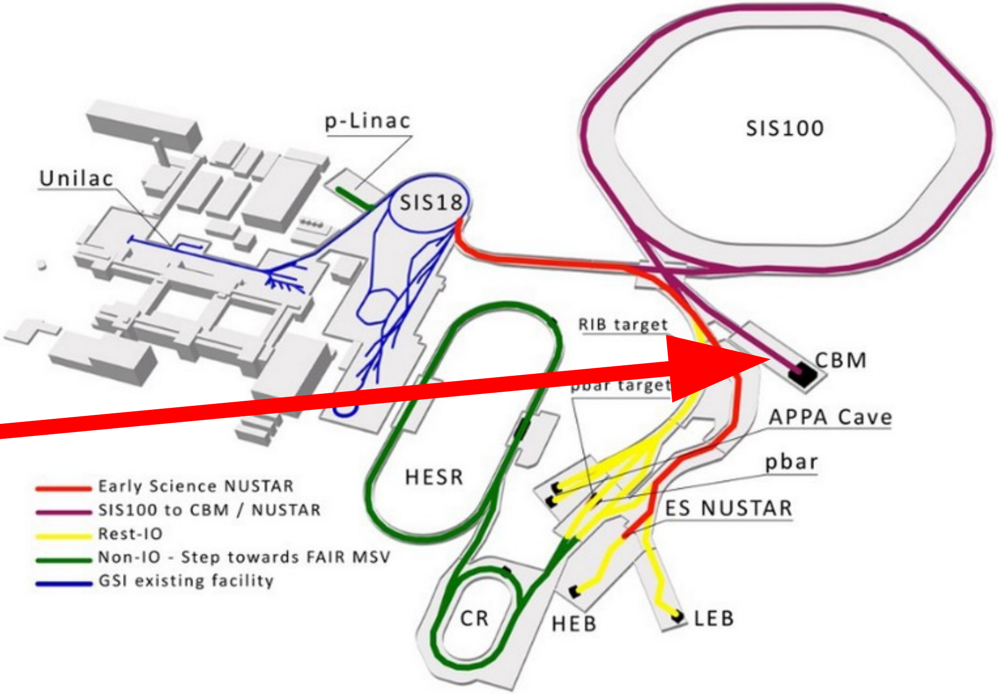
Friman et al.,
Lect. Notes Phys.
814 (2011) 1

The CBM Experiment

- Fixed target experiment
  tracking acceptance : 1.5° < Θ_{lab} < 25°
- 2 interchangeable detector setups:
  - Electron setup : RICH detector for e / π separation
  - Muon setup : MUCH, instrumented iron absorber
- Peak interaction rate : 10 MHz (Au+Au)
  (300 kHz with MVD)
- Free-streaming, self-triggered DAQ system
- Online event reconstruction and selection
- Fast and radiation hard detectors
- 4d tracking (space + time)
- Data rate : up to 1 TB/sec online data
  ~ 10^5 ev/s to disk



FAIR facility and CBM cave



CBM cave ready !

SIS 100 primary beams:

- 10^9 Au up to 11 GeV/u
- 10^9 C, Ca, … up to 14 GeV/u
- 11^{11} p up to 29 GeV

CBM compared to other high μ_B facilities

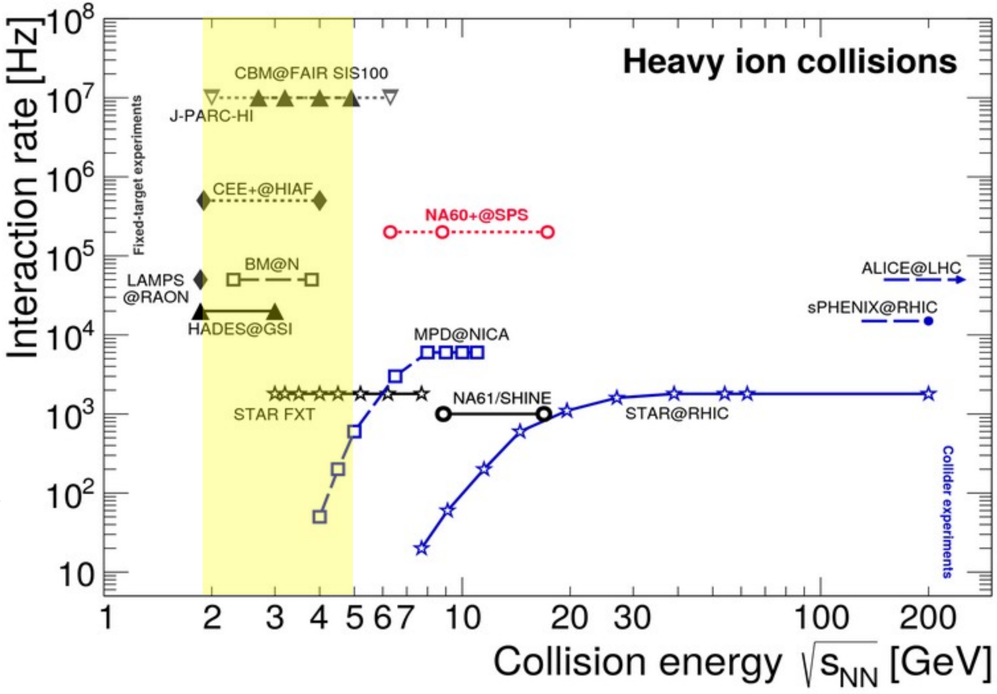
- **CBM** will play a crucial role in exploration of the QCD phase diagram in region of high μ_B
  → dedicated to highest interaction rates (up to 10 MHz)
  → rare probes, high accuracy
  → multi-purpose detector, electron + muon + hadron setup

- **HADES @ SIS100:**
  overlap with CBM at lowest energy → systematics
  limited to 20 kHz and $\sqrt{S_{NN}}$=2.4 GeV
  excellent di-electron capabilities

- **STAR FXT@RHIC:**
  BES program completed; limited capabilities for rare probes

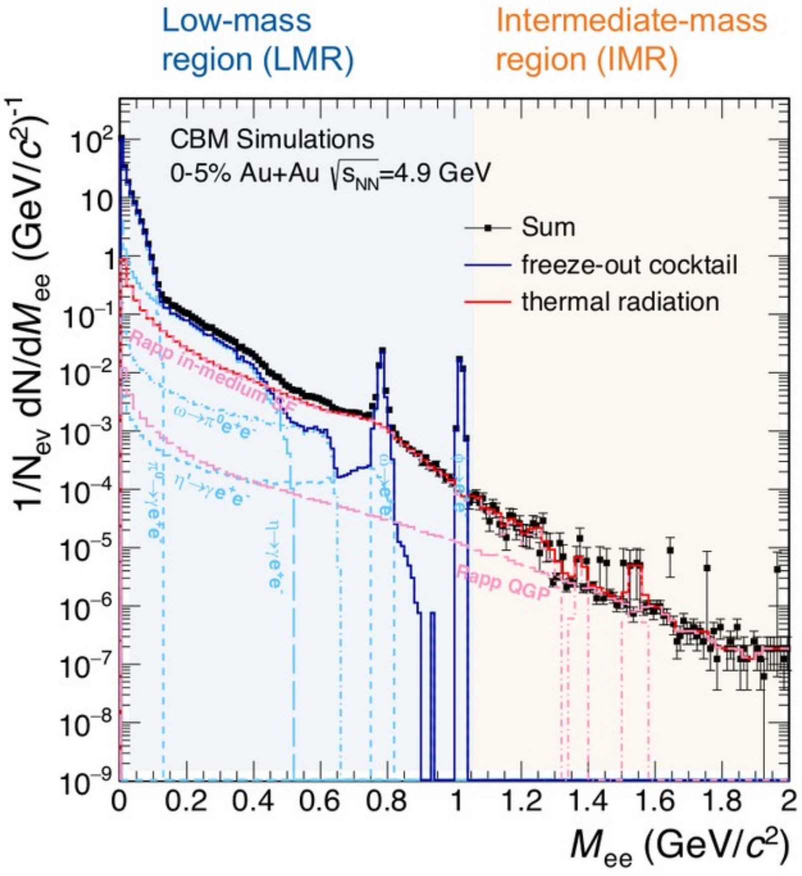
- **J-PARC-HI proposal:**
  addition of heavy ion option (HI booster)

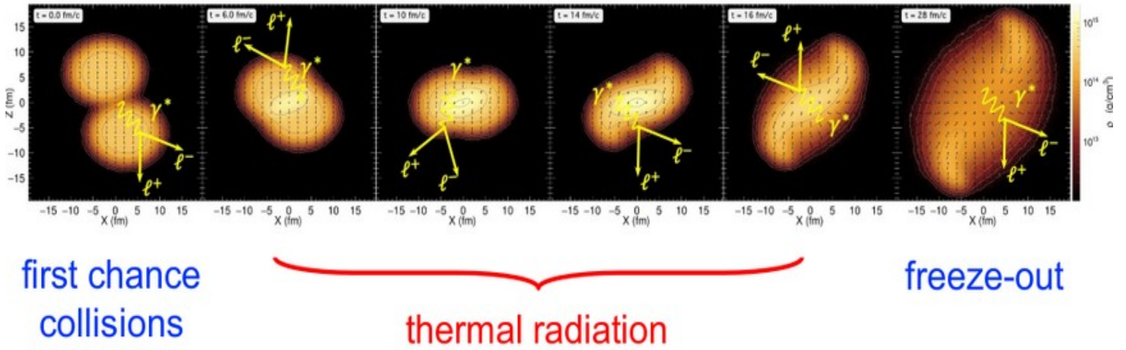
- **CEE+@HIAF proposal:**
  multipurpose detector based on TPC,
  anticipated rate capability 500 kHz
  hadronic probes only



T. Galatyuk, NPA982 (2019), update (2022)
CBM, EPJA 53 3 (2017) 60

Dileptons – one of CBM's key observables





Electromagnetic radiation as multi-messenger of fireball

- No strong final state interaction
  → leave interaction volume undisturbed
  → reflect the whole history of HI collision

- Encodes information of matter properties
  – degrees of freedom of the medium
  – fireball lifetime, temperature, acceleration, polarization
  – restoration of chiral symmetry

LMR → "Chronometer" : total yield ~ fireball lifetime
IMR → "Thermometer" : slope ~ emitting source temperature

CBM di-lepton performance

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- Performance studies with realistic detector geometries, material budget, detector response
- input : thermal radiation, in-medium hadronic rates (ρ, ω), and QGP rates → Rapp, Wambach Adv. Nucl.Phys. 25, 1 (2000); Galatyuk et al.: EPJA 52 (2016) 131
- **Inv. mass resolution : $\sigma(M_{\omega\rightarrow l+l-}) \sim 14$ MeV/c²**
- **<S / CB > allows for precise measurements**

Di-electron performance

R_{in} = O (100 kHz, limited by MVD, DAQ rate).

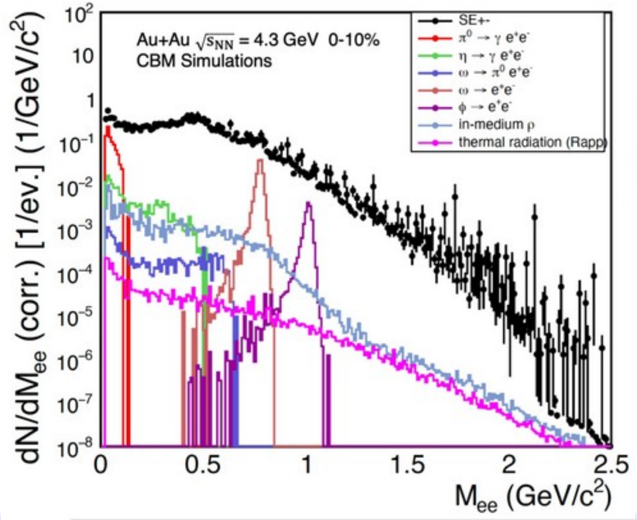
e^+ / e^- ID : RICH + TRD + TOF

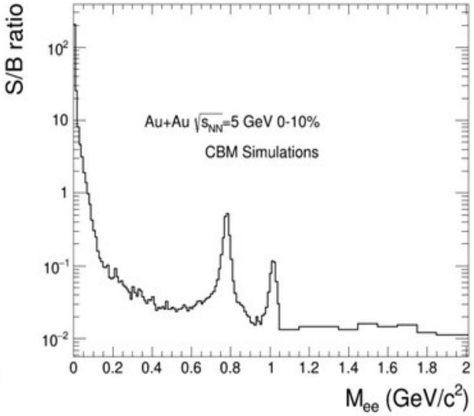
pion suppresson >= 10^4

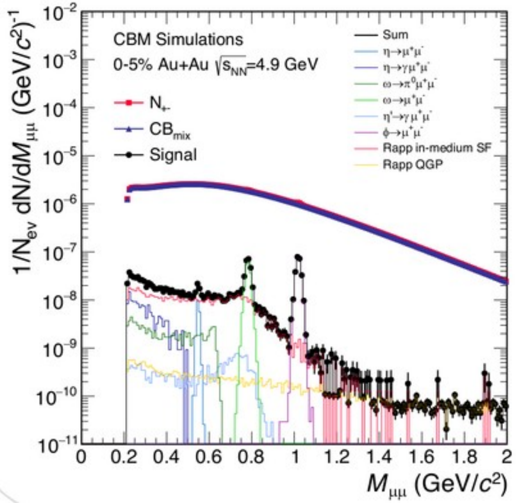
Di-muon performance

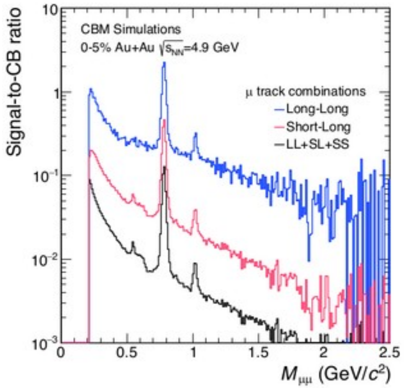
R_{int} = O (1 MHz)

μ ID: instrumented hadron absorber









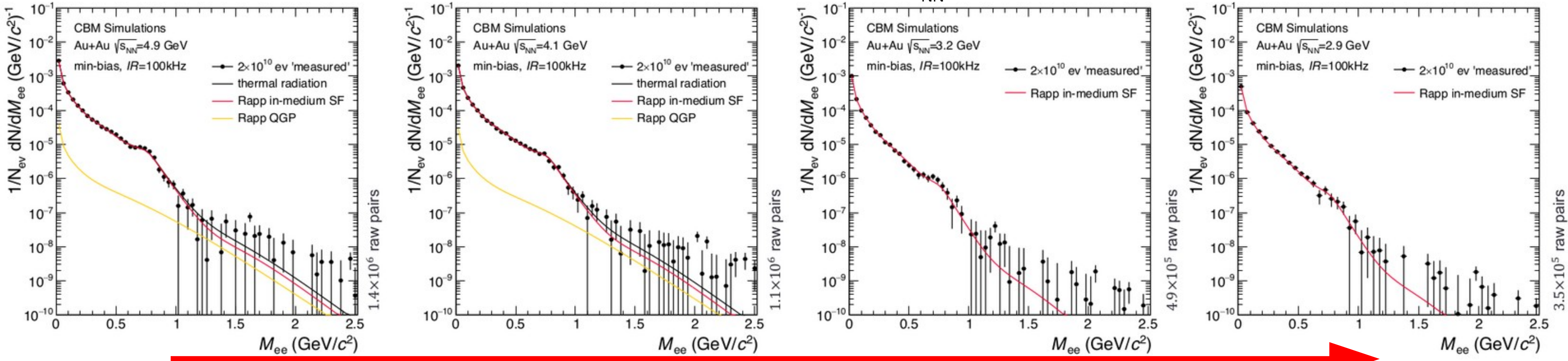
CBM dielectron performance: first 3 years, 5 days/energy

isolated dielectron thermal radiation yield after first energy scan (corrected for Acceptance x Efficiency):

- 5 days per energy, 100 kHz IR
- **Low mass (M_{e+e-} < 1 GeV/c²)**, dominated by ρ, yield can be reconstructed with **precision of 1.5 – 4.5 %**
  → allows for fireball lifetime measurement

- **Intermediate mass (M_{e+e-} > 1 GeV/c²)** : accessible, statistics not yet sufficient to extract physics

$\sqrt{S_{NN}}$ = 4.9 GeV $\sqrt{S_{NN}}$ = 4.1 GeV $\sqrt{S_{NN}}$ = 3.2 GeV $\sqrt{S_{NN}}$ = 2.9 GeV



from partonic to hadronic fireballs

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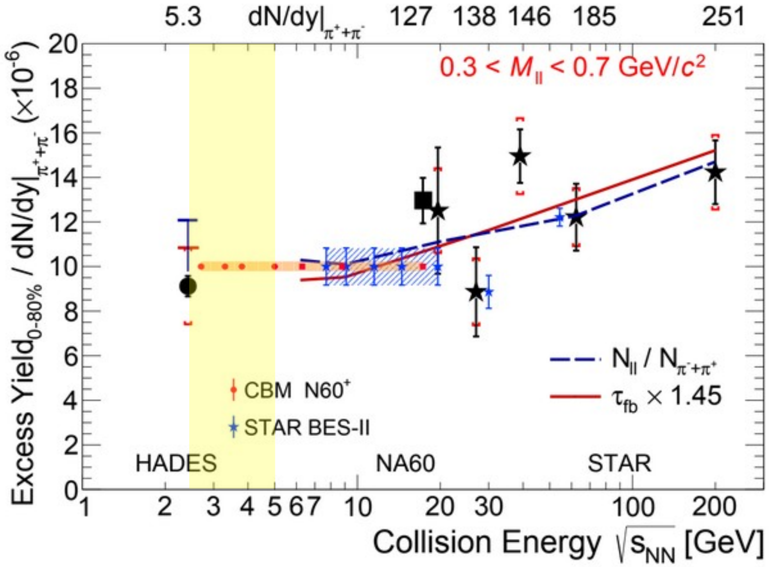
first results after 3 years

Thermal excess radiation in Low mass range (lMR):
(all resonance contibutions subtracted)

- Sensitive to fireball lifetime (“chronometer”)
- Search for “extra radiation” due to latent heat:
  → hints to phase transition ? critical point ?
- **2-3 years: precision sufficient for 1st ord. phase trans.**
  (expected enhancement: min. factor 2-3)

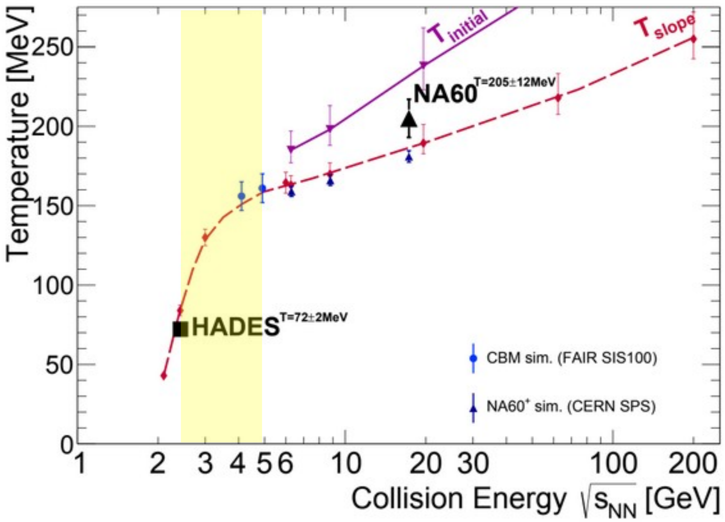


T. Galatyuk, JPS Conf. Proc. **32** 010079 (2020)

CBM@SIS100

Caloric curve: Temperature vs collision energy

- Invariant mass slope in IMR as measure of T (”thermometer”)
- Flattening of caloric curve
  → possible indication for phase transition
- **9% uncertainty in $T_{fireball}$ for 2 energies in $\mu^+\mu^-$**

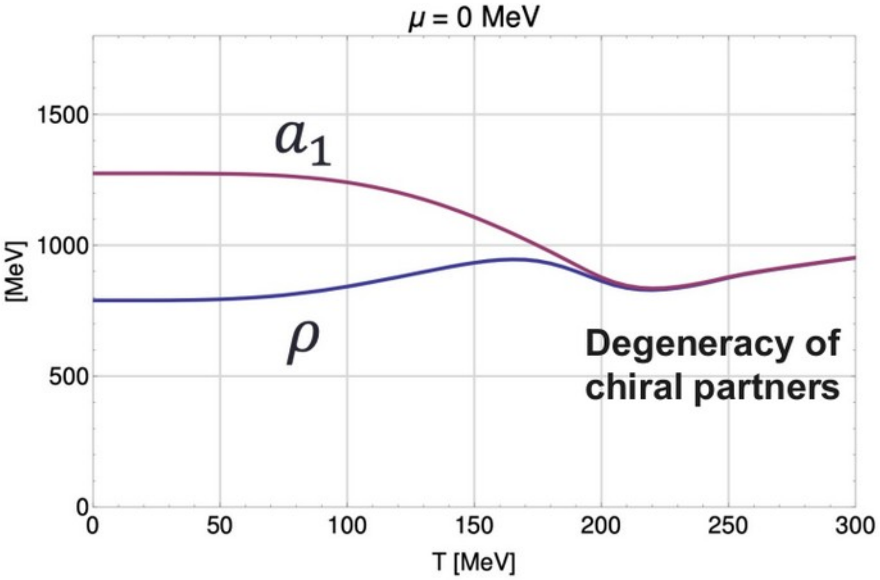


Rapp and v. Hess, PLB **753** 586 (2016)
Galatyuk et al., EPJA **52** 131 (2016)

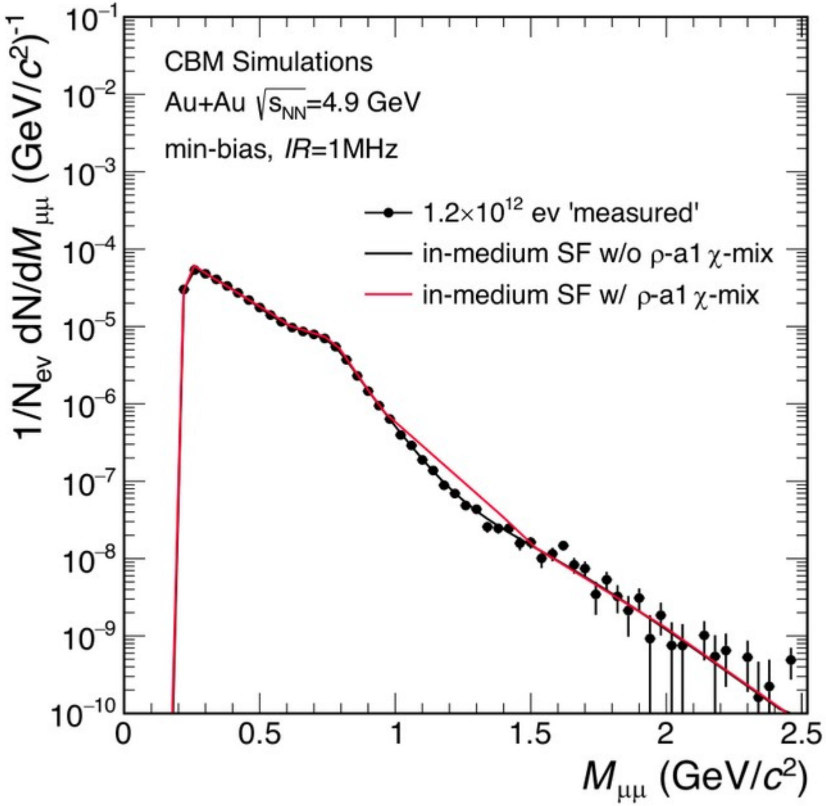
Dileptons and chiral symmetry of QCD

- The ρ- and a_1 meson are chiral partners (vector / axial vector)
- Spectral function degenerates if chiral symmetry is restored

→ Precise measurement of IMR spectral function as probe for chiral symmetry restoration

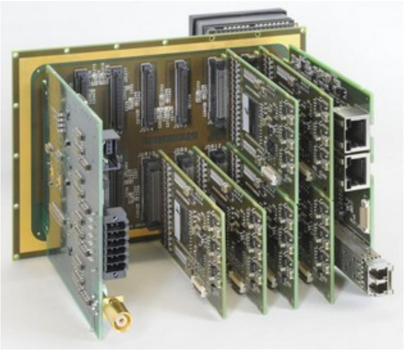


Jung *et al.*, PRD 95, 036020 (2017)
Hohler and Rapp, PLB 731 (2014)

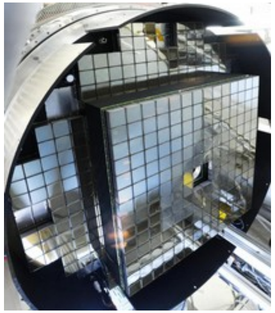


CBM/FAIR Phase 0 : HADES RICH upgrade

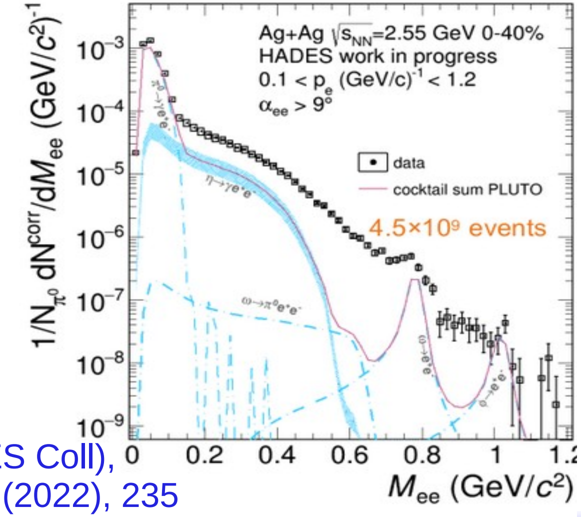
- Extensive CBM/FAIR Phase 0 program ongoing now...
- One example : N**ew HADES RICH photon detector (2019) using ~50% of CBM RICH MAPMTs**
- **Same DIRICH based readout electronics**
- Common software developments CBM - HADES
- **Fantastic performance after RICH upgrade:**
  - excellent timing precison : ~ 250 ps (sigma gauss)
  - 15 – 19 detected photoelectrons per ring (!), low noise

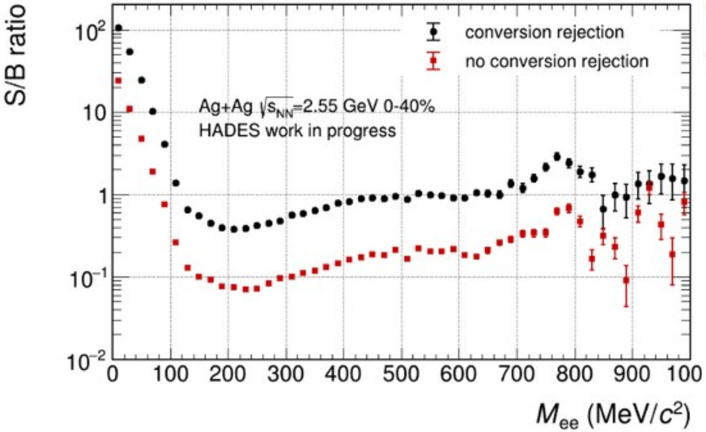


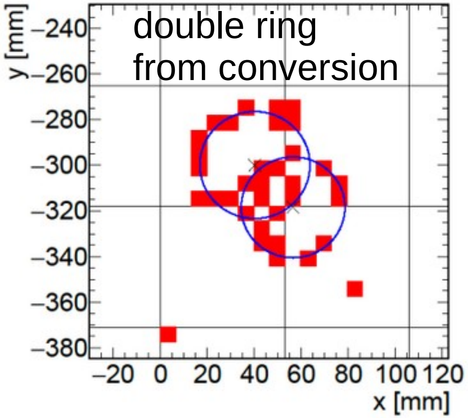
MAPMT readout module CBM / HADES



HADES RICH photon detector







J.-H. Otto (HADES Coll), PoS PANIC2021 (2022), 235

Summary and outlook

- **CBM + SIS100 @ FAIR is dedicated experiment to study high μ_B region of QCD phase diagram**

- **Unprecedented interaction rates up to 10 MHz in HI collisions** provide access to many, also rare probes
  - Di-leptons (Low mass / Intermediate mass range, <1 GeV /c^2 / >1 GeV/c^2)
  - Hadron flow dynamics
  - Strangeness production
  - Fluctuations of conserved quantities
  - Hyperons and Hypernuclei
  - Charmonium / open charm

- **Multi purpose detector** in different configurations for eletron / muon and hadron focussed measurements
  → good control of systematics
  → overlap in energy with existing HADES experiment

- **Extensive FAIR Phase0 activities** to assure quick success for day-1 operation
  - mini-CBM with prototypes of DAQ and all sub detectors
  - HADES RICH using CBM RICH technology already now

- **CBM first beam (according to present FAIR time plan) : expected for 2028**

spares

CBM/FAIR Phase 0 – The path to success for day 1

CBM first beam expected 2028
Measurement program for first 3 years of operation:

- focus on beam energy scan program
- 60 days/year beam on target
- different detector configurations: e / μ / hadron setup
- slowly approaching full rate capability

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

Rich CBM/FAIR phase 0 program already now ongoing:

- **mCBM at GSI - SIS18 :** CBM full system test setup
  - pre-series prototypes of all CBM sub-detectors
  - verification of trigger-less data transport
  - high-rate detector-tests with up to 10 MHz collision rates
- - online Λ reconstruction, online tracking
  - physics program : Λ excitation function in SIS 18 energy range
- **Useage of CBM detectors in other experiments**
  - eTOF @ STAR installed, commissioned and running
  - Use of PSD modules at NA61 / Shine (and BM@N)
  - HADES RICH upgrade ...