The physics goals of the CBM experiment at FAIR

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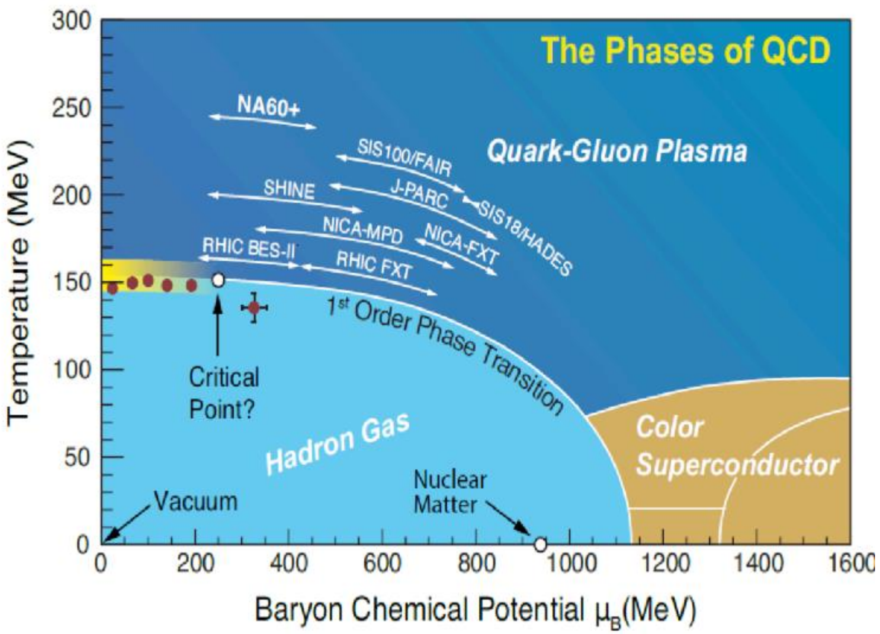
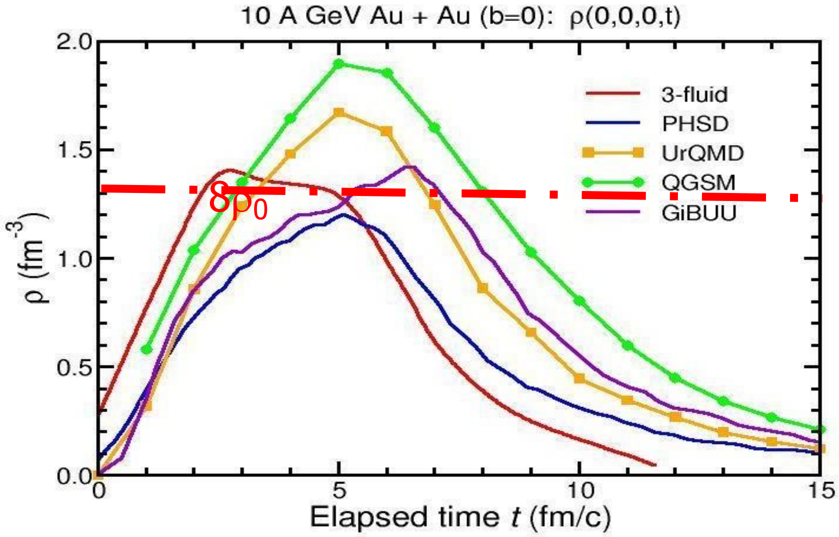
for the CBM Collaboration

ICPAQGP 2023, February 7 – 10, 2023

QCD phase diagram at high net-baryon densities



I. Arsene et al. PRC75 034902 (2007)

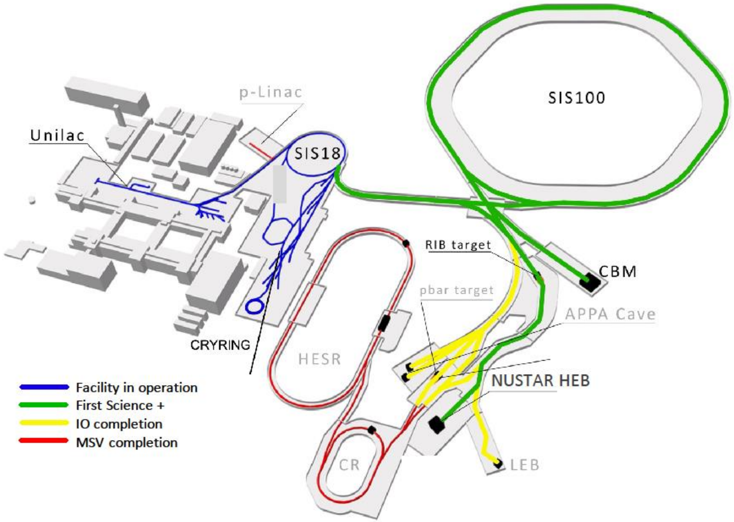


- QCD matter at high net baryon densities (high μ_B):

  Theoretical models predict 1st order phase transition ending at 2nd order CEP, exotic phases
- Collision of heavy-ions at relativistic energies produce dense baryonic matter in laboratory

  CBM experiment at FAIR SIS100: A+A collisions in $E_{kin} = 2.5A - 11A$ GeV

FAIR: Facility for Anti-proton and Ion Research



SIS100: synchrotron ring of magnetic rigidity 100 Tm
CBM: heavy-ion experiment at the beam line

Beam	maximum intensity	$E^{k}_{lab, max}$	$\sqrt{s_{NN, max}}$
Nuclei (Au,Ca,C)	10^9/s	11A GeV	4.9 GeV
Protons	10^{11}/s	29 GeV	7.5 GeV

Time line:

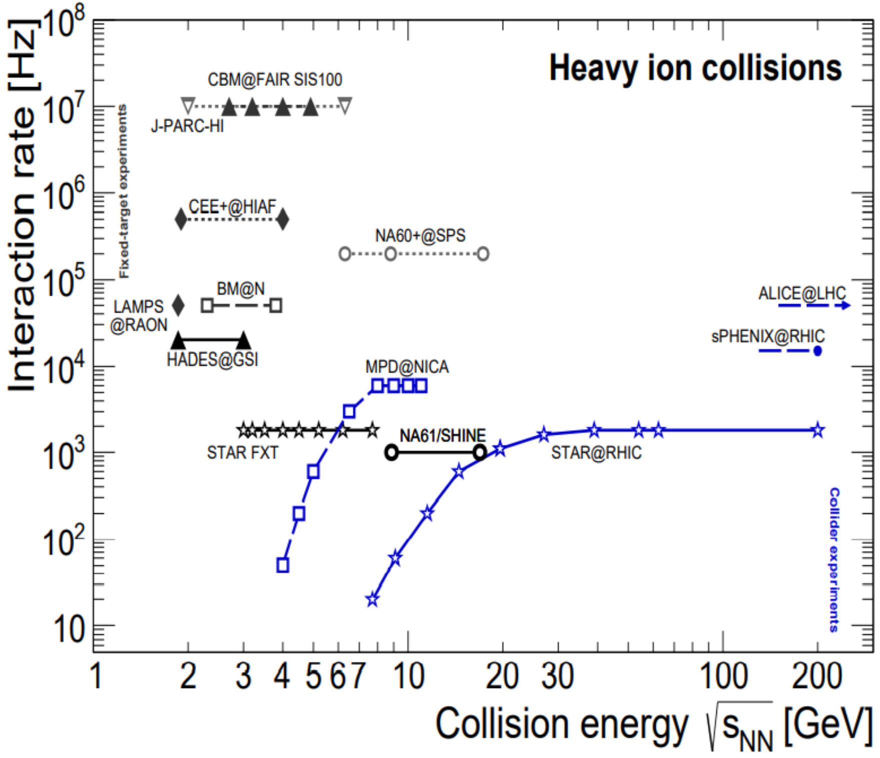
- CBM cave shell in 2023
- Technical building infrastructure in 2024
- CBM installation activities (platform) start from 2023
- CBM ready for beam in 2027
- SIS100 beam in CBM cave 2028

CBM physics and observables

CBM Mission Statement :
Systematically explore QCD matter at large baryon densities with high accuracy and rare probes.

- QCD matter equation-of-state at large baryon densities, coexistence of hadronic & partonic phases:
  - Hadron yields, collective flow, correlations, fluctuations
  - (Multi-)strange hyperons (K, Λ, Σ, Ξ, Ω)
  - Dileptons
- Emissivity of matter at large baryon densities
  - In-medium modifications of light vector mesons
  - $\rho, \omega, \varphi \rightarrow e^{+}+e^{-}$ $(\mu^{+}+\mu^{-})$ via dilepton measurements
- Hypernuclei
- Charm production and propagation in baryon rich matter
  - Excitation function in p+A collisions (J/ψ, D^0 , D^{+-}
  - Charmonium suppression in cold nuclear matter

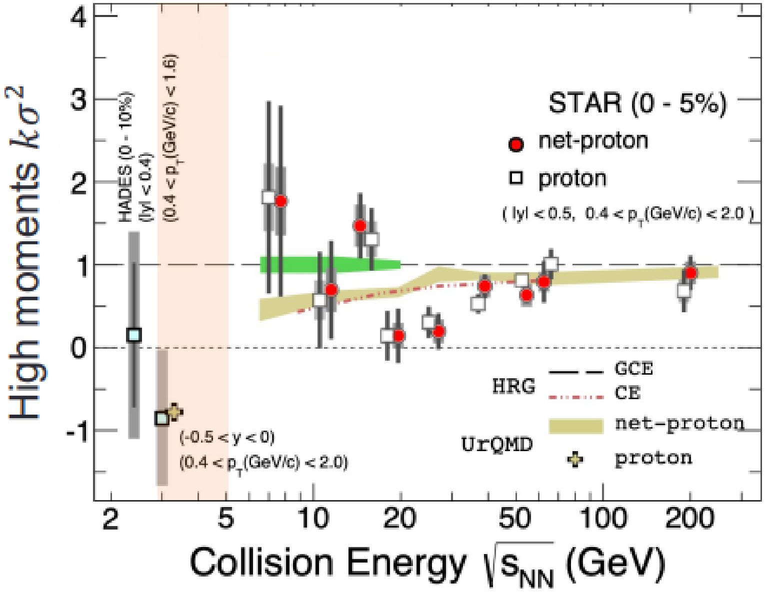
T. Galatyuk, https://github.com/tgalatyuk/interaction_rate_facilities, 2022



Precision and rare probes need high statistics: achieved with high rates 10^5 - 10^7 Au-Au collisions/sec!

Search for Critical End Point (CEP)

STAR, PRL 128 (2022) 20, 202303
HADES, PRC 102 (2020) 2, 024914



Higher order cumulants sensitive to critical fluctuation

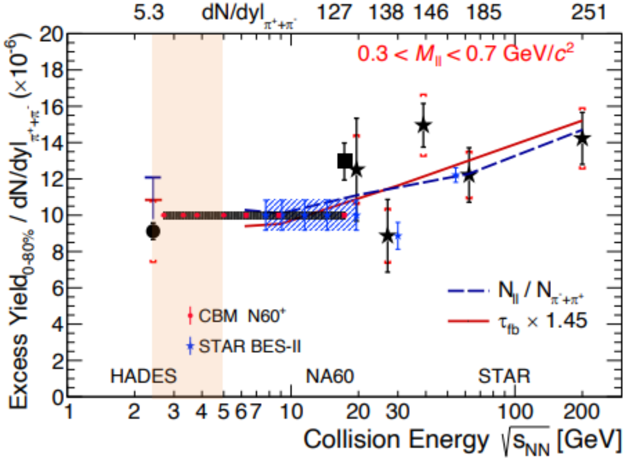
Non-monotonic behaviour observed ?

STAR BES-II: Hadronic interactions dominant @ 3 GeV (negative C_4/C_2)

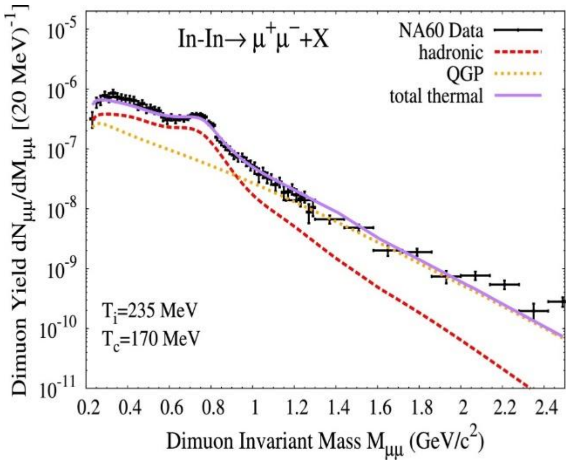
Fill the gap between 2-7.7 GeV

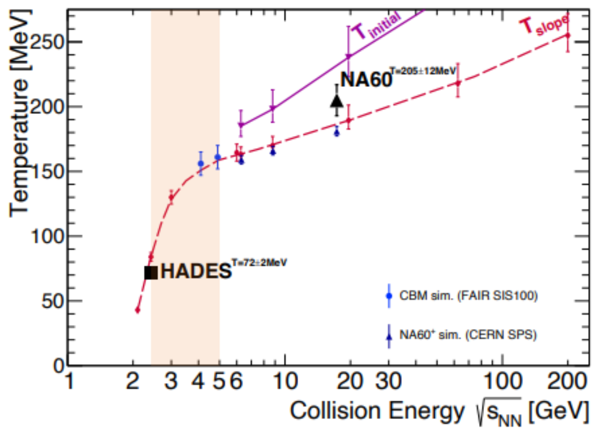
Future experiments need larger acceptance at mid-rapidity

Dileptons as fireball chronometer and thermometer



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



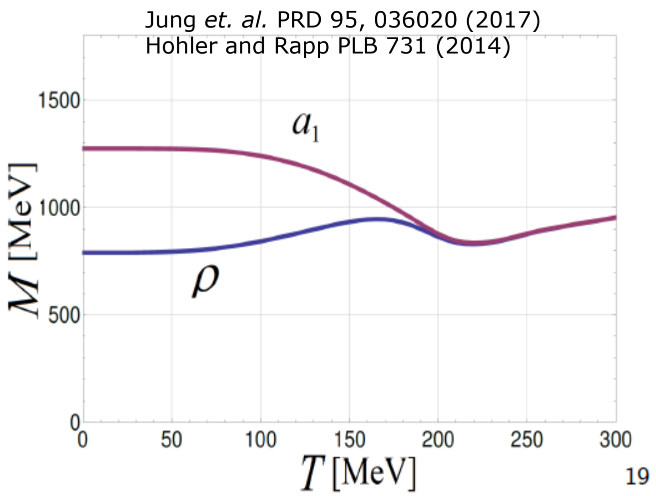


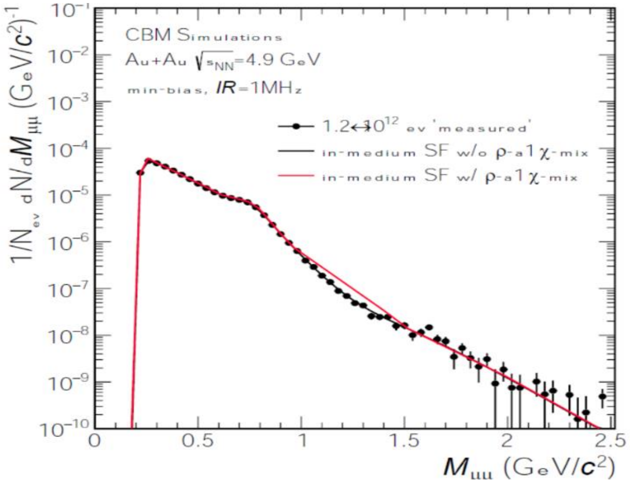
Ref: GitHub - tgalatyuk/QCD_caloric_curve

- Low mass excess integrated dilepton yield ($0.3 < M < 0.7$ GeV/c^2) tracks the fireball lifetime remarkably well
- Promising tool to determine source lifetime: “anomalous enhancement” may be triggered by 1st order transition
- Dimuon excess in the intermediate mass region ($1.5 < M < 2.5$ GeV/c^2) is dominated by radiation from the partonic phase: exponentially falling shape of the spectra
- Extracted inverse slope parameter gives true temperature (no blue shift): stable thermometer of the fireball
- Extract temperature in small bins of energy between $\sqrt{s_{NN}}$ ~ 3-20 GeV: measurement of ***caloric curve*** possible
- Flattening would indicate 1st order transition

CBM dilepton projections after first 3 years of running

IMR: ρ-a_1 chiral mixing and restoration of chiral symmetry





- Broadening of ρ-meson spectral function is qualitatively consistent with chiral symmetry restoration → need to investigate the chiral partner a_1
- No direct coupling of axial states to dilepton channel → in vacuum the (l^+l^- → hadrons) x-section has a dip in the a_1 mass range

- Chiral Symmetry Restoration → mixing of vector (V) and axial vector (A) correlators via multiple pion (4π and higher) states → enhanced dilepton production for $M_{\mu\mu}$ ~ 1- 1.4 GeV/c^2 (10-20% enhancement for full mixing)

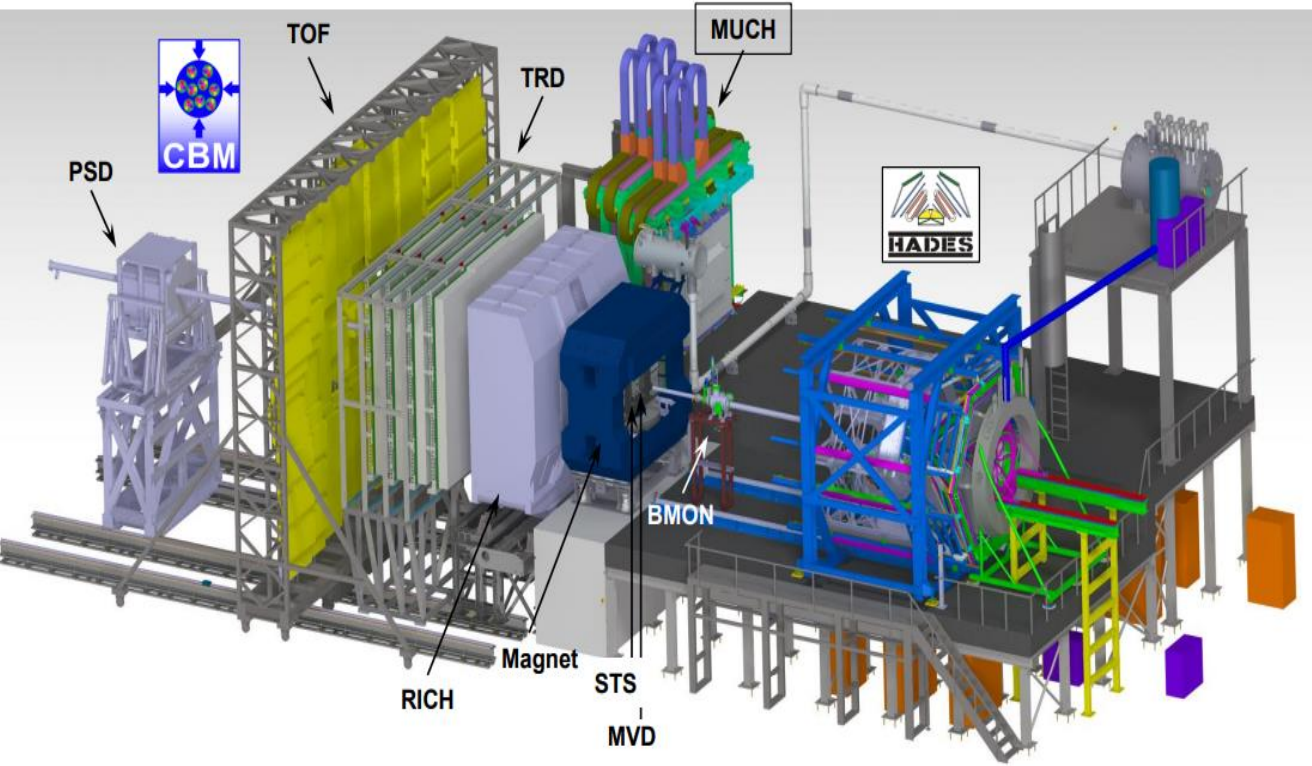
Low energy measurements expected to be more sensitive to chiral transition effects

- Negligible contribution from open charm

Precise estimation and subtraction of the combinatorial to detect the foreseen enhancement

CBM detector subsystem

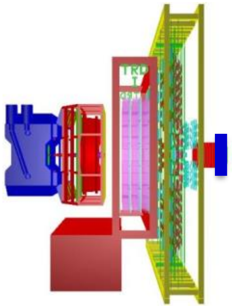
A multiple purpose detector system for simultaneous measurement of hadrons and leptons



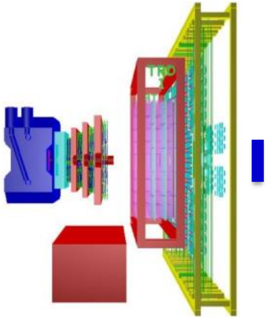
- Fast radiation hard detectors
- Tracking acceptance:
  - $2^o < \theta_{lab} < 25^o$
- PID alternatives
  - electron/hadron: RICH, TRD, TOF
  - muon: MUCH, TRD, TOF
- Free streaming DAQ
- Online event selection
- 4-D tracking (space, time)
- Peak R_{int} = 10 MHz (Au+Au).
- (with MVD R_{int} = 0.1 MHz (Au+Au))
- Day-1 physics with moderate rate
- Data rate 1 TB/sec
- High Performance Computing farm for data processing

Expected start of operation 2028

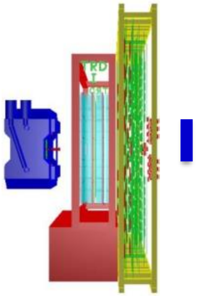
Different CBM setups



ELEHAD



MUON



HADR

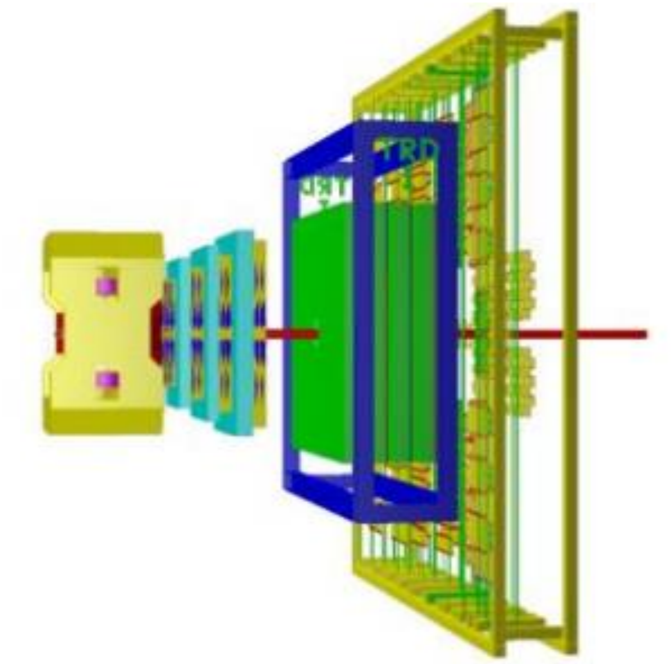
Different CBM setup depending on goal

- *ELEHAD: tracking, vertexing, e/p separation*
- *MUON: Identification of muons*
- *HADR: Highest rate for rare hadrons*

More on detectors: mini-review talk by Maksym Teklishyn

Setup	Included subsystems	Average day-1 interaction rate	Average MSV - interaction rate	Average event size in Au+Au collisions
ELEHAD	MVD,STS,RICH,TRD,TOF,FPW	0.1 MHz	0.1 MHz	75 kB
MUON	STS,MUCH,TRD,TOF,FPW	1 MHz	5 MHz	30 kB
HADR	STS,TRD,TOF,FPW	0.5 MHz	5 MHz	50 kB

MuCh @ FAIR SIS100: Reconstruction of di-muons (μ+μ-)



Major Indian contribution

- Comprises of several detectors & segmented hadron absorbers made of graphite concrete and iron
- Total absorber is segmented & detectors are placed inside absorbers to facilitate tracking
- Momentum dependent muon identification
- High areal particle density in the first station
- GEM detectors in the first two stations and RPC in the next two stations
- Angular acceptance:

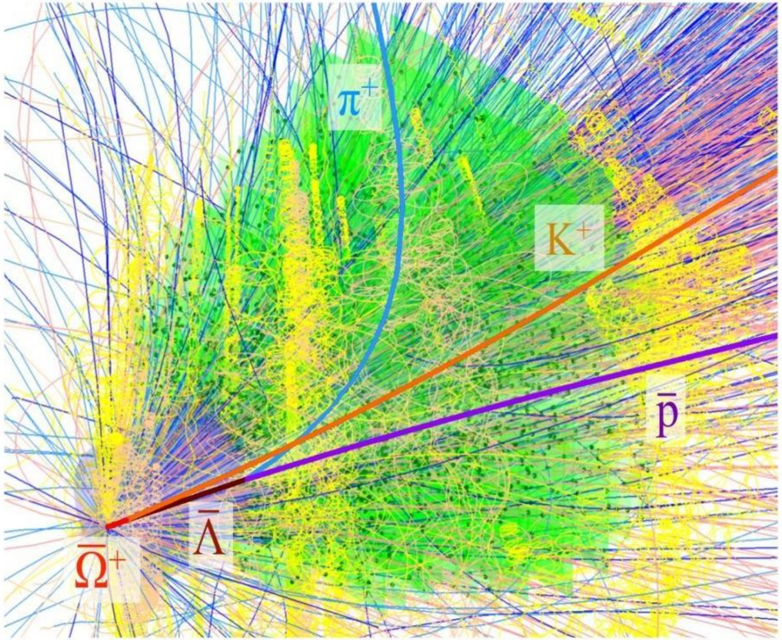
$\theta_{min}=5.7^o$: $\eta_{max}= 3$

$\theta_{max}=25^o$ degree: $\eta_{min}=1.44$

Muon reconstruction strategy:
primary tracks passing through STS, MuCh and TRD, and mass determination via TOF

CBM Physics Performance studies

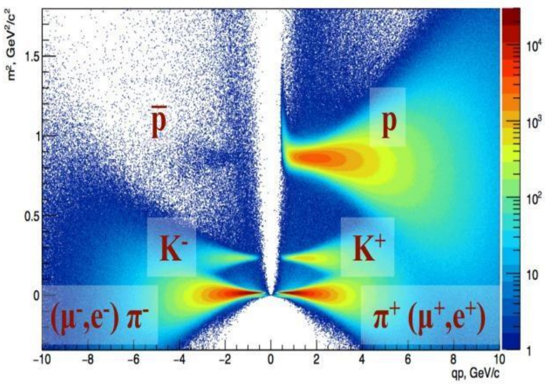
central Au+Au collision @ 10*A* GeV/*c*



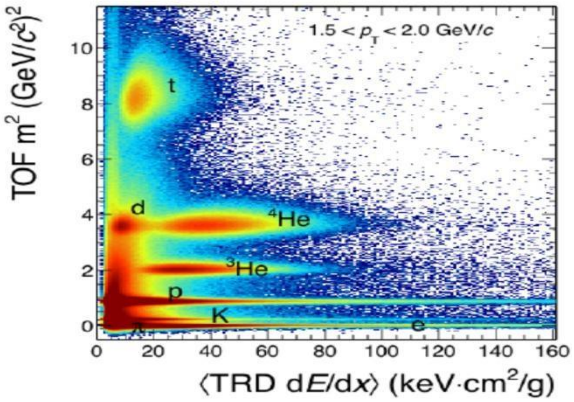
- Event generators as input:
  UrQMD, (P)HSD, DCM-QGSM-SMM, Pluto
- Heavy-ion (Au+Au) collisions
- Detector geometry with realistic
  material budget, segmentation and response
- Good efficiency and S/B:
  feasible detection of rare probes at SIS100
- Multi-differential analysis with high statistics
- In progress: free streaming data taking performance

Particle identification at CBM

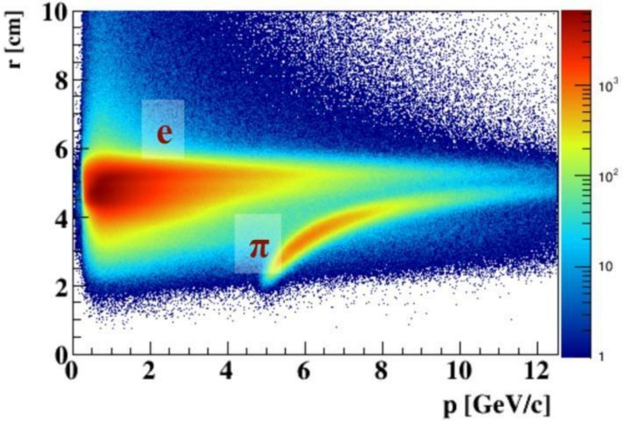
TOF



TRD+TOF



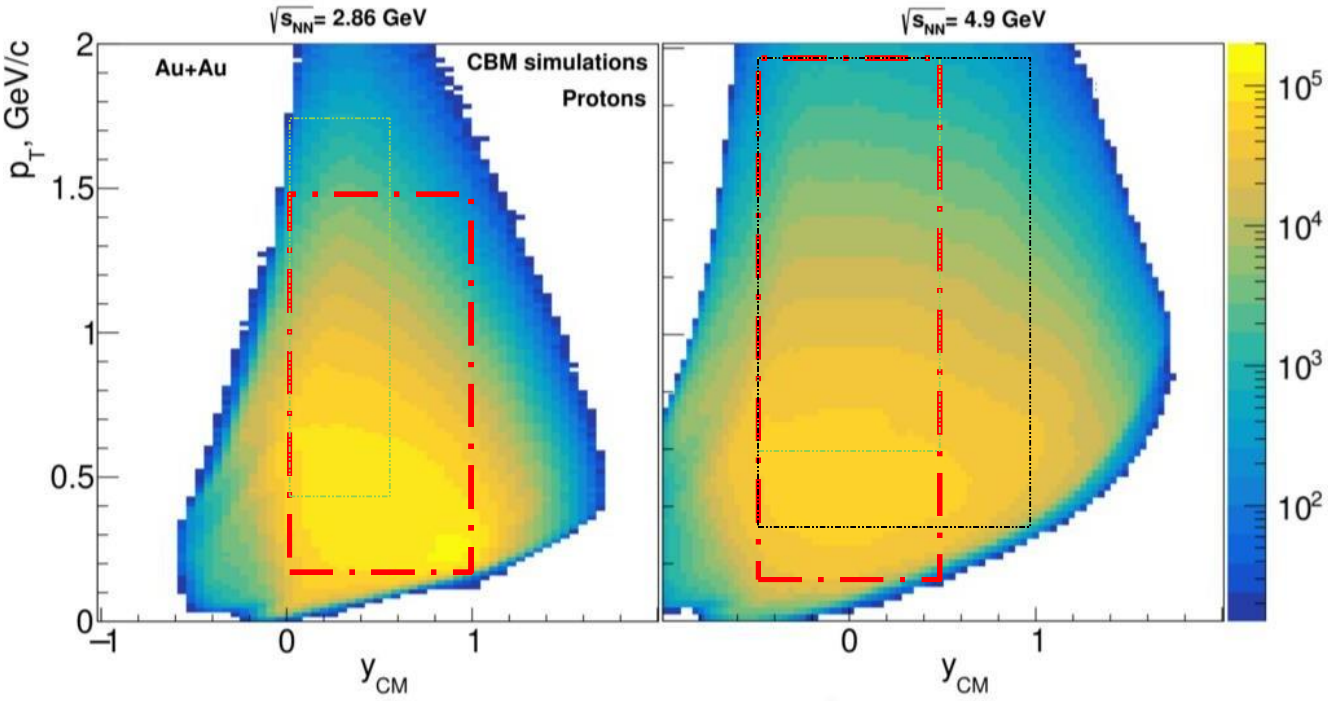
RICH



CBM simulation central Au+Au collisions @ 10*A* GeV/*c*

- Charged hadrons, nuclei: TOF + TRD
- Electrons: RICH + TRD
- Muons: MUCH + TOF + TRD

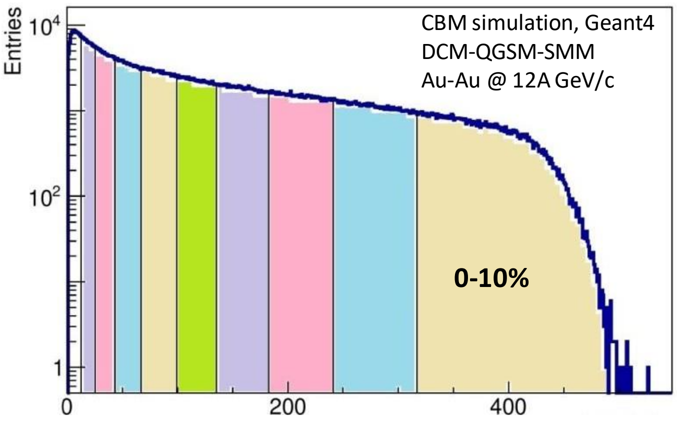
CBM Proton Acceptance



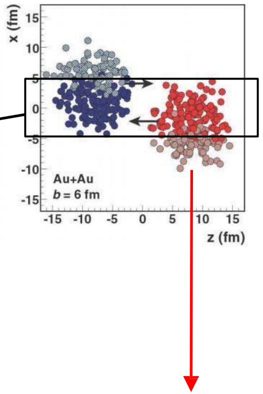
1) Wide rapidity and low p_T proton coverages in 2.9 – 4.9 GeV AuAu collisions
2) Rapidity and p_T scan of proton high moments are possible with CBM

Centrality determination in CBM

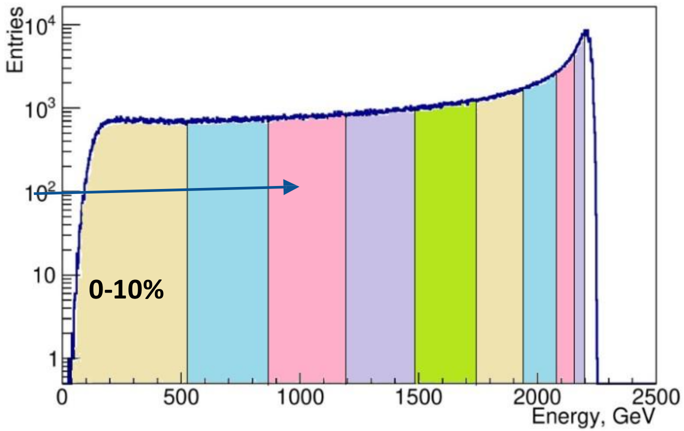
Charged hadrons multiplicity



STS track multiplicity



Projectile spectators energy

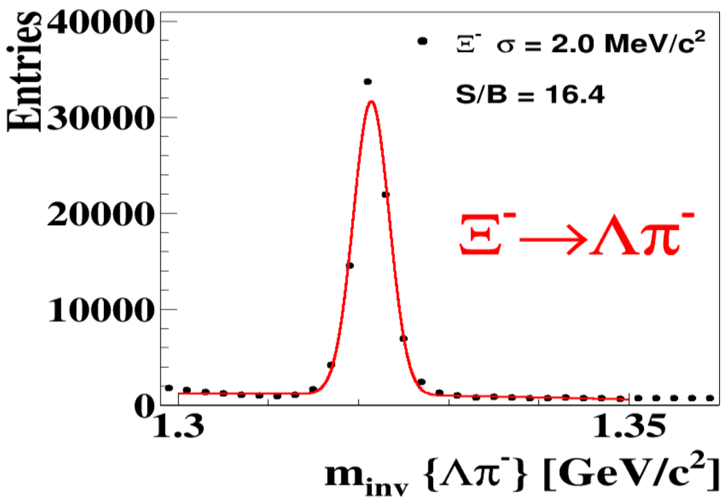


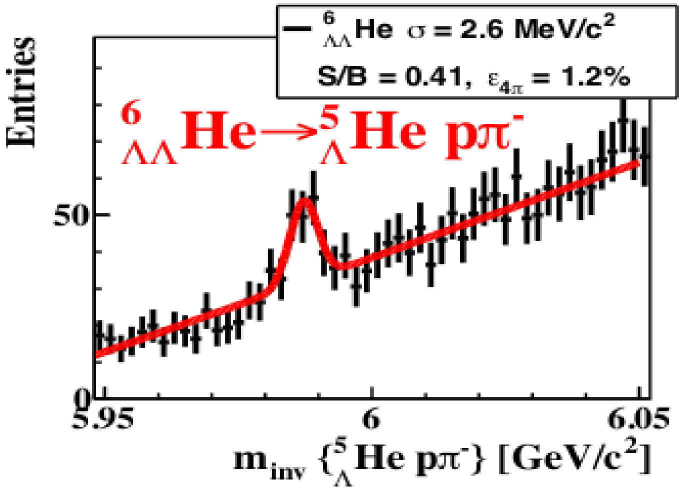
PSD energy, GeV

Target spectators (not measured)

Strangeness and hypernuclei at CBM

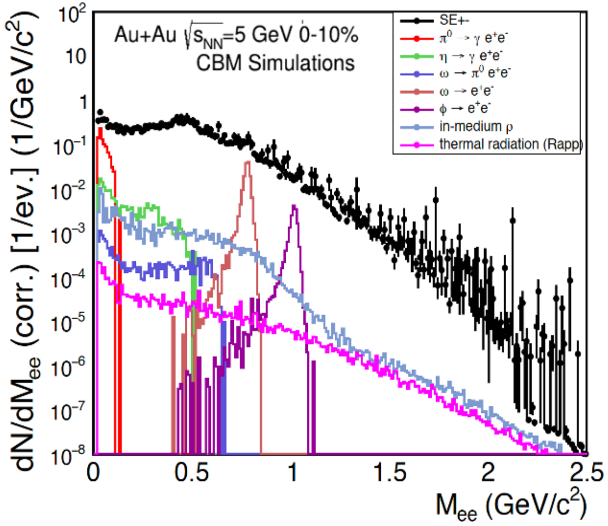
Simulation of 10 A GeV/c Au+Au collisions

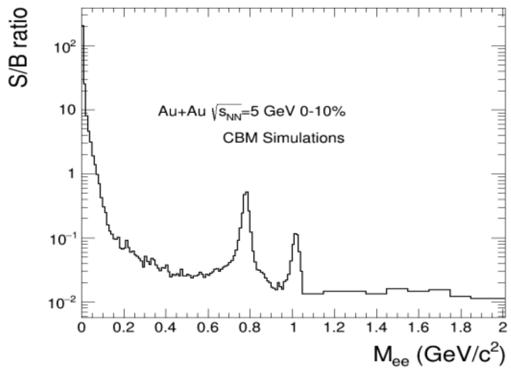




- Multi-strange hyperons and hypernuclei accessible at SIS100 energies
- Reconstruction of decay topology via dedicated KFParticleFinder package
- 4×10^8 Ξ^- in 1 week (R_{int}=0.1 MHz) and 146 $_{\Lambda\Lambda}{}^6He$ in 10 weeks (R_{int}=10 MHz)
- Analysis tools successfully applied to STAR BES data

Dielectron measurements at CBM





Electron setup: R_{int} = O(0.1MHz)

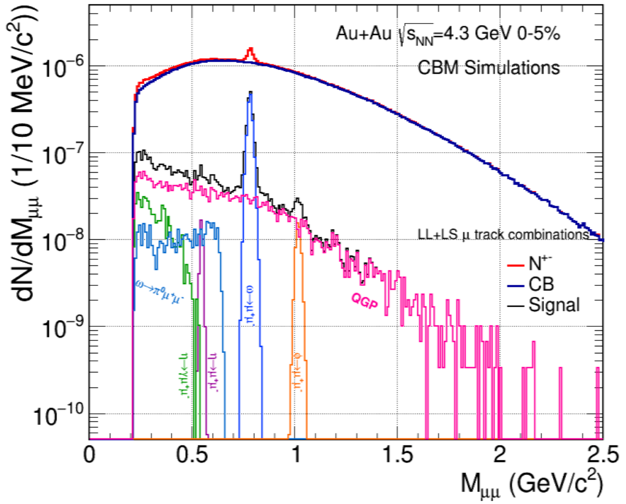
Challenge:

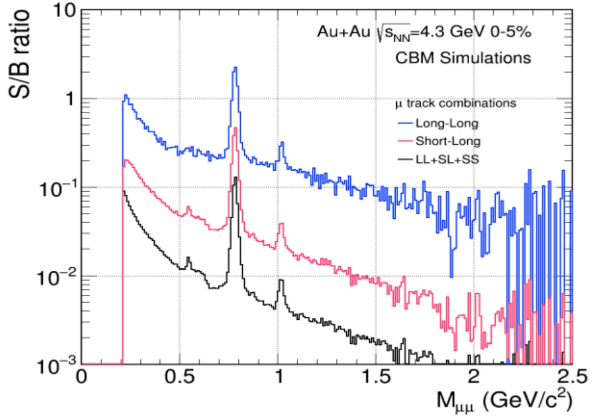
- No electron identification before tracking
- Background due to γ-conversion in target, material budget of tracker

Strategy:

- Sufficient pion suppression (>10^4)
- Reconstruction of pairs from g-conversion π^0 Dalitz decays
- Topological cuts used to reject CB

Dimuon measurements at CBM





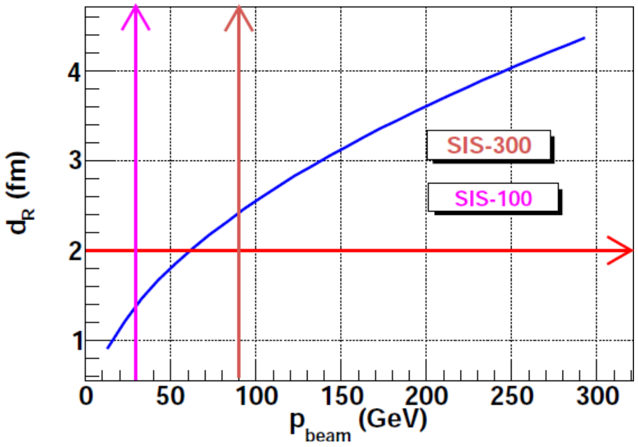
Muon setup (R_{int} = O(1 MHz))

- Challenge:
  - μ at low energies
  - High areal particle rates in first detector
- Strategy:
  - Identification after hadron absorber with intermediate tracking layers
  - Triple GEM detectors with pad read-out
  - Remove last two absorbers for beam energies < 4*A* GeV

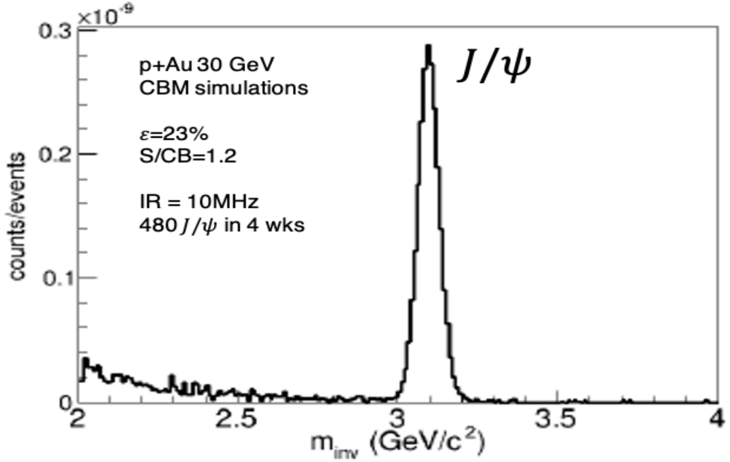
- Clear peaks for the low mass vector mesons after background subtraction with 5M Au+Au collisions
- Comparable S/B in both channles
- Access to thermal signal is very feasible with good background description

Charmonium at SIS100 in p+A collisions

PPB, M. Deveaux, A. Toia, JPG 45 (2018) 055103



J/ψ in p+Au @ 30 GeV/*c*



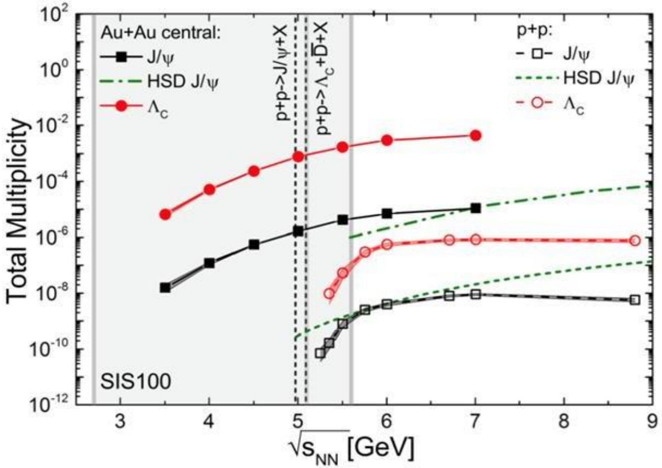
J/ψ propagation in cold nuclear matter

- Probe resonance-nucleon interaction
- Constraint on theoretical models

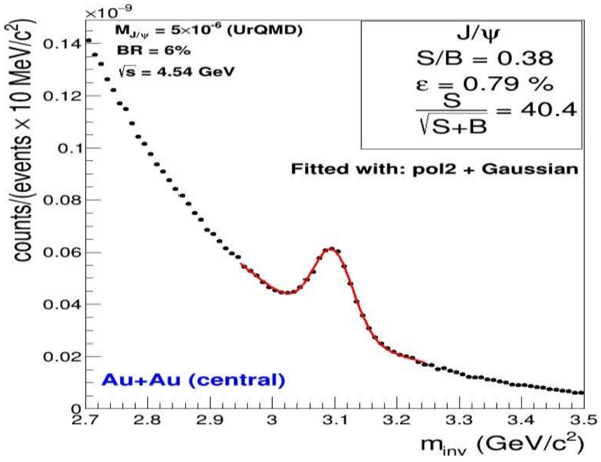
- J/ψ reconstred via $\mu^+\mu^-$ decay channel using STS+MuCh+TRD detectors
- ~500 J/ψ in 4 weeks with 10 MHz peak rate

Charmonium at SIS100 in Au +Au collisions

J. Steinheimer et al., PRC 95 (2017) 1, 014911



10 A GeV/c central Au+Au collisions



J/ψ production is rare but measurement is feasible

- Production below kinematic threshold
- Production via multiple collision process
- No data below collision energy 158*A* GeV

Reconstruction via $\mu^+\mu^-$ decay channel

- Clear signal peak -> feasible detection
- Detectors: STS+MuCh+TRD
- Expected yield:
  ~30K J/ψ in 4 weeks @R_{int} = 10 MHz

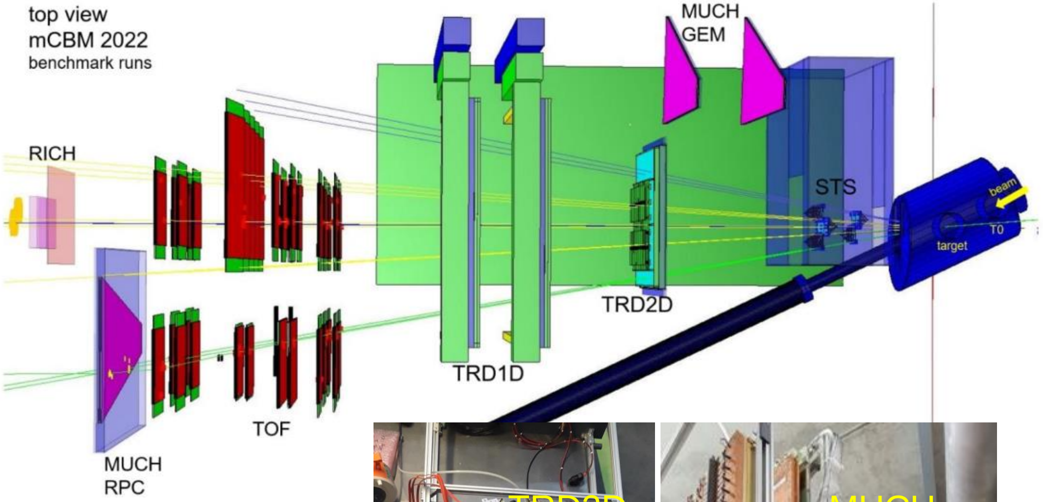
Year 1 – 3 scenario as of May 2022

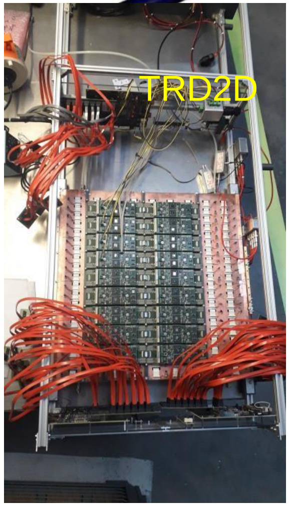
Year	Setup	Reaction	Beam Energies T_{lab} [AGeV]	Days on Target	Number of events	Remarks
0	ELEHAD	C+C, Ag+Ag, Au+Au	2,4,6,8,10,max	60		Commissioning
1	ELEHAD	Au+Au	2,4,6,8,10,max	30 (5 each)	$2 \cdot 10^{10}$ each	EB minBias
1	ELEHAD	C+C	2,4,6,8,10,max	18 (3 each)	$4 \cdot 10^{10}$ each	minBias
1	ELEHAD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

Focus on beam energy scan: early measurement of excitation function to locate anomalies
60 days/year beam on target
Full 2nd year muon beamtime for first IMR slope measurement for dimuon channel

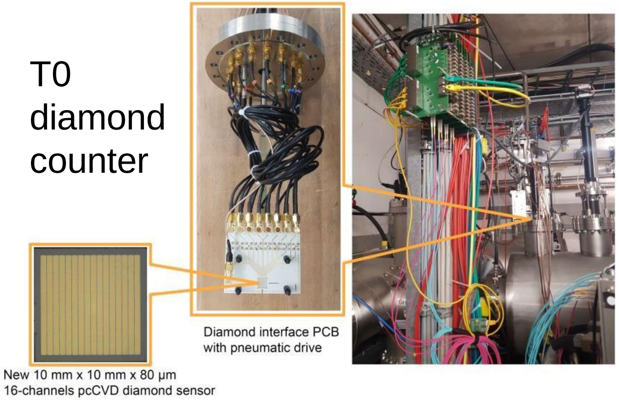
mCBM status

Talk by Chandrasekhar Ghosh





T0
diamond
counter



benchmark runs 2022

Ni + Ni, T = 1.93 AGeV
May 26, 2022, total run duration: 5h 55m
av. collision rate: 400kHz
av. data rate 1.5 GB/s to disc, 32 TB tsa files

Au + Au, T = 1.23 AGeV
June 17 - 18, 2022, total run duration: 34h 33m
av. collision rate: 200 - 300kHz
av. data rate 1.4 - 2.2 GB/s to disc,
180 TB tsa files

Summary

Physics mission

- Precision study of QCD phase diagram and EOS in the region of high net-baryon densities

Unique measure of rare diagnostic probes

- High precision multi-differential measurements (yield, flow, fluctuations) of hadrons including the multi-strange hyperons and di-leptons

  for different beam energies and collision systems
- Energy scan of hyperon, hyper-nuclei, di-lepton already possible with day-1 physics program (R_{int} ~ 100 KHz)

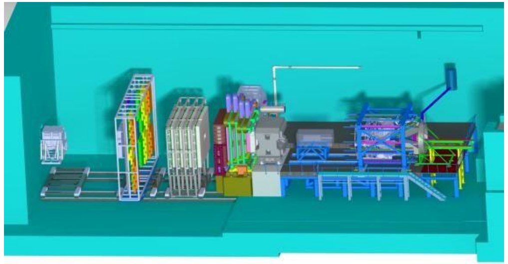
Major experimental challenges

- Detectors with high rate capability and DAQ
- Online event reconstruction and selection

Preparedness:

- Extensive physics performance studies
- Detector production has been started
- FAIR phase-0 program: use and understanding detector components, reconstruction software …

2023: CBM is moving in



Exciting time for CBM, ready for beam in 2027

The CBM Collaboration

47 institutions, 11 countries, ~400 members

Competitiveness statements

3 year

Competitiveness with respect to STAR FXT and BM@N after 3 years of running

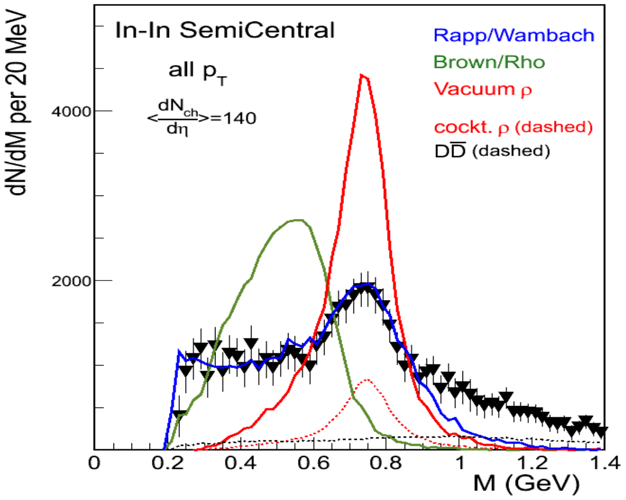
- The CBM data will improve the statistical errors of the STAR measurements in the SIS100 energy range by at least a factor of 10.
- BM@N will have hadron data available comparable to CBMs HADR setup in the beam energy range below 4.5 AGeV with an event sample size of max. $1\cdot10^{11}$.

8 year

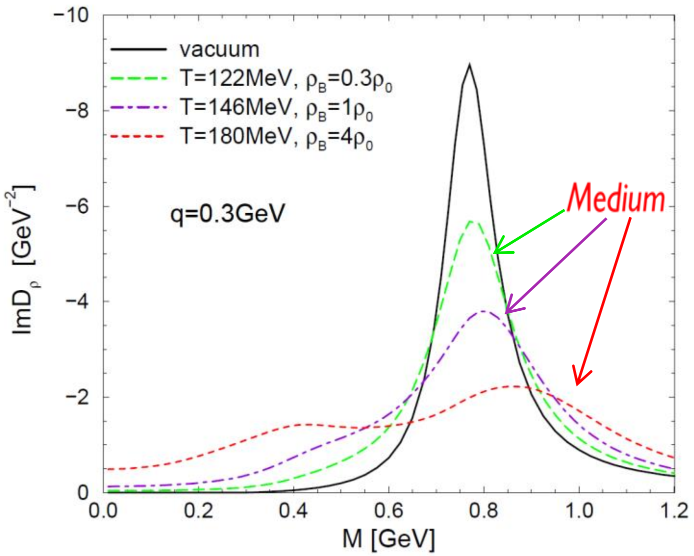
In the years 4 - 8, high-statistics measurements are foreseen, aiming for more precise IMR studies of di-lepton spectra and ultra-rare probes such as multi-strange hypernuclei and charmed hadron production.

Around that time an upgrade of the silicon trackers (MVD and STS) will be plausible with novel pixel detector technology with high-rate readout capabilities. Increased rate capabilities of the electron setup and extended beamtime periods will allow to increase the collected statistics by another factor of 10 allowing us to reach data samples of 10^{12} events for heavy collision systems necessary for significant studies of the IMR of the di-lepton spectra. Studies of charmed hadron interaction with cold nuclear matter in pA and intermediate mass collision systems like Ni+Ni become feasible.
This part of the CBM program has currently no competitors and is world-wide unique.

LMR: ρ meson spectral function



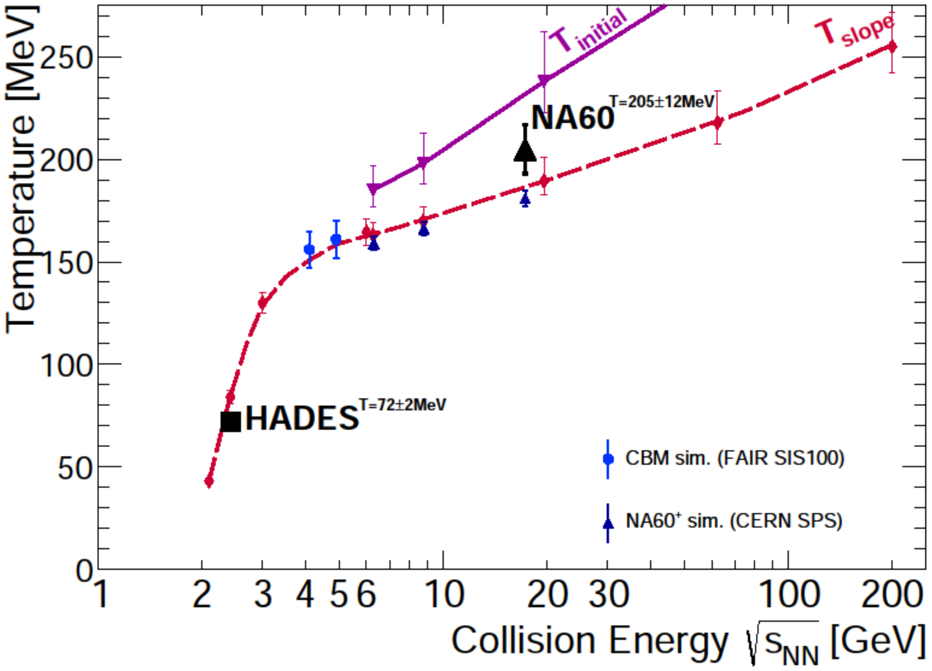
R. Rapp and J. Wambach, Eur. Phys. J A 6(1999)



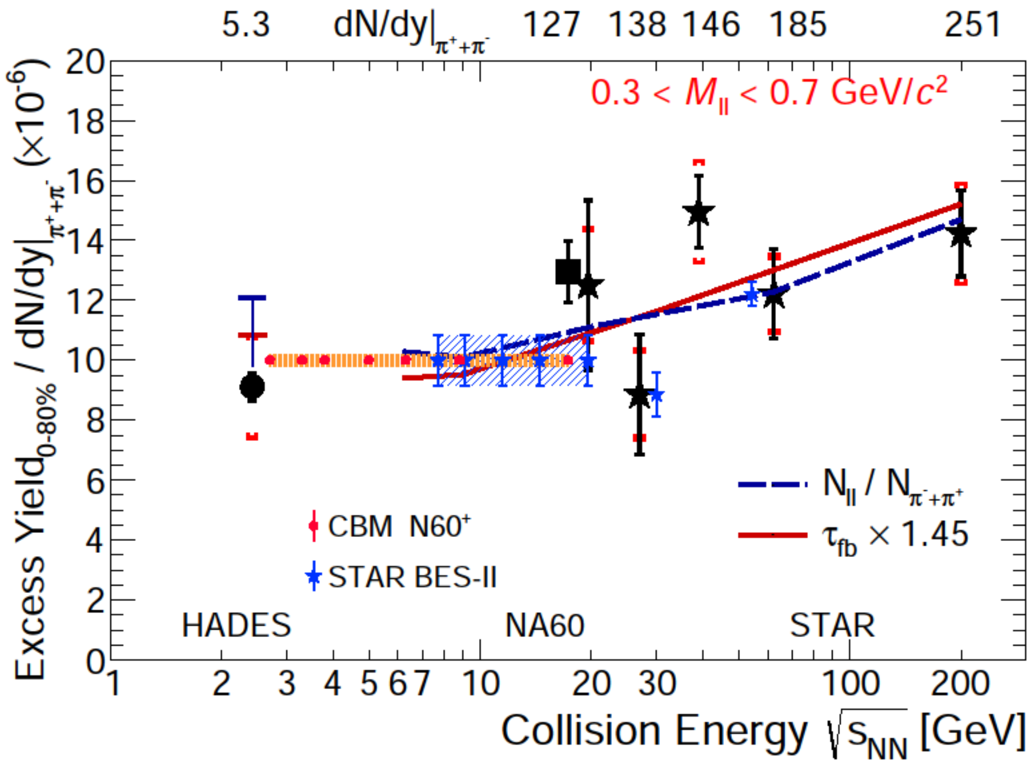
In In+In collisions @ NA60:

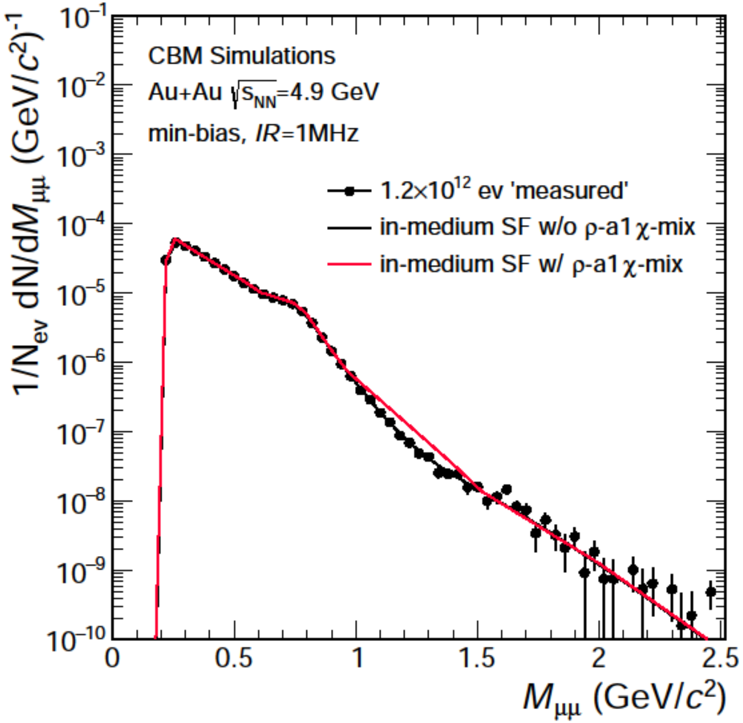
- *No observable shift of the pole mass; strong in-medium broadening*
- *Disfavors dropping mass scenario*
- *Can be connected to chsr in a model dependent way*

Strong broadening of the in-medium spectral function due to coupling with baryons:can be accessed through high precision di-muon data to be collected @ CBM SIS100



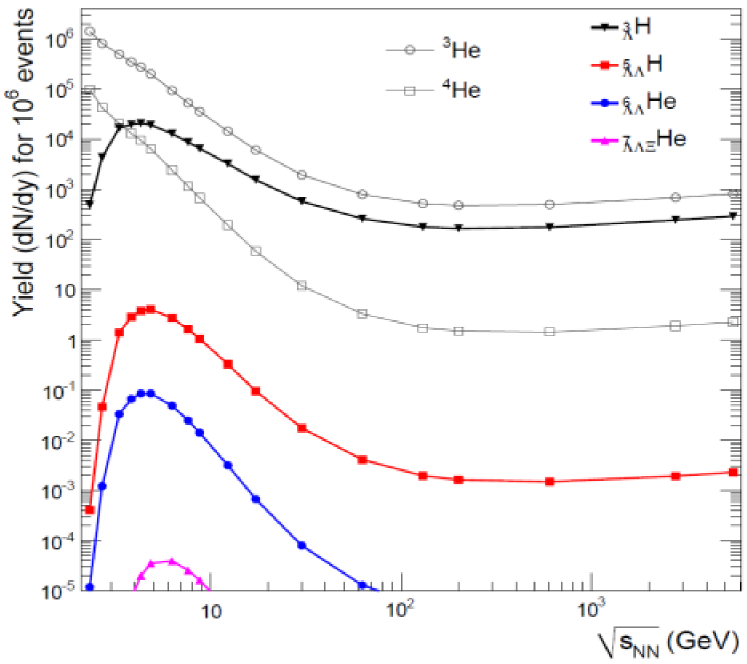
Temperature [MeV]
Collision Energy $\sqrt{s_{NN}}$ [GeV]
T initial
T slope
NA60 T=205±12MeV
HADES T=72±2MeV
CBM sim. (FAIR SIS100)
NA60+ sim. (CERN SPS)
0
50
100
150
200
250
1
2
3
4
5
6
10
20
30
100
200


5.3
dN/dy|π⁺+π⁻
127 138 146 185 251
0.3 < M_ll < 0.7 GeV/c²
Excess Yield0-80% / dN/dy|π⁺+π⁻ (×10⁻⁶)
CBM N60⁺
STAR BES-II
N_ll / N_π⁻+π⁺
τ_fb × 1.45
HADES
NA60
STAR
Collision Energy √s_NN [GeV]


CBM Simulations
Au+Au $\sqrt{s_{NN}}$=4.9 GeV
min-bias, IR=1MHz
1.2×10^{12} ev 'measured'
in-medium SF w/o ρ-a1 χ-mix
in-medium SF w/ ρ-a1 χ-mix
$1/N_{ev}\, dN/dM_{\mu\mu}$ $(GeV/c^2)^{-1}$
$M_{\mu\mu}$ (GeV/c^2)

Hypernuclei as a probe of dense baryonic matter

Thermal model prediction for Au+Au



A. Andronic, et al., Phys. Lett. B697 (2011) 203