CBM Overview

ECT*-Workshop on
"Exploring High μ_B Matter with Rare Probes"

Trento, Italy
11. — 15. Oct. 2021

Christoph Blume
University of Frankfurt

FONDAZIONE BRUNO KESSLER
ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Outline

- High μ_B matter
- CBM experiment + physics program
- CBM detector components: MVD, RICH, TRD, MUCH
- Physics performance examples:
  - LMR and IMR di-leptons
  - Charmonia (A+A and p+A)
  - Open charm (A+A and p+A)

High μ_B Matter

- Fundamental questions:
  - Equation-of-state at neutron star densities
  - Phase structure of QCD matter
  - Bound states with strangeness
  - Chiral symmetry restoration at large densities
  - Charm in dense baryonic matter

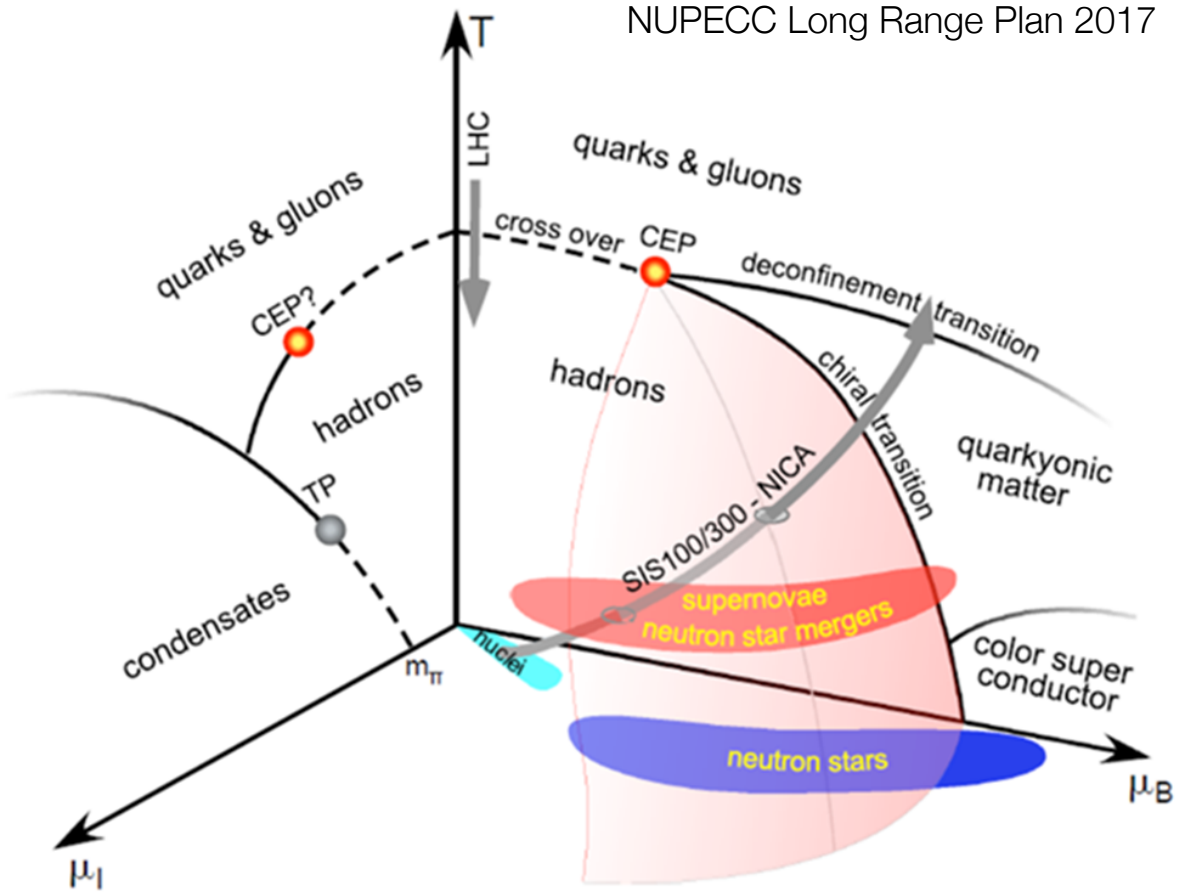
Neutron star merger

$T \approx 10 - 100$ MeV
$\rho < 2 - 6\ \rho_0$

Heavy-ion collisions

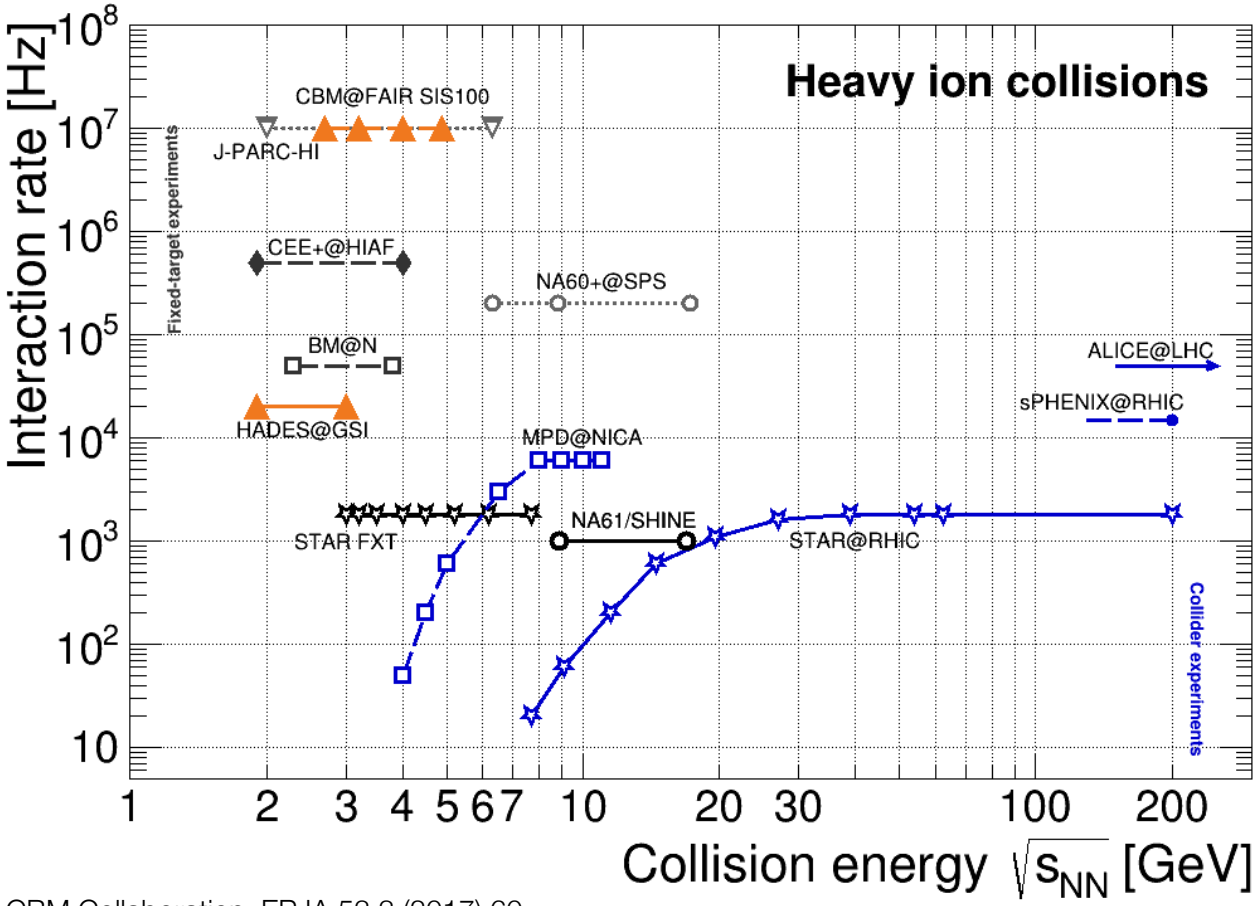
$T < 120$ MeV
$\rho < 5 - 15\ \rho_0$

NUPECC Long Range Plan 2017



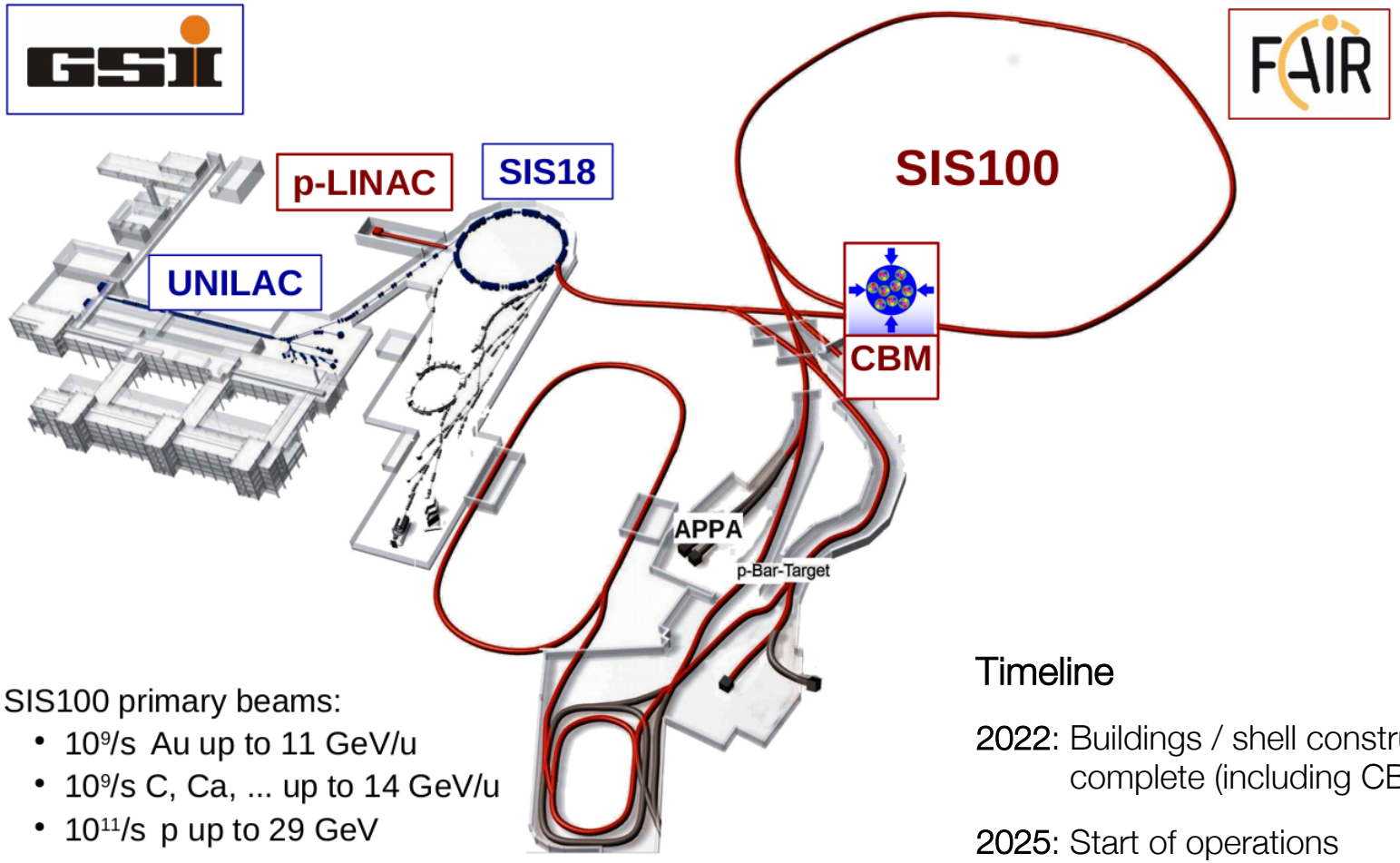
High μ_B Matter

- Systematic exploration of QCD phase diagram
- High accuracy + rare probes
  - High statistics required ⟹ High interaction rates
  - CBM: up to 10^7 interaction/s



CBM Collaboration, EPJA 53 3 (2017) 60
T. Galatyuk, NPA982 (2019), update (2021)

Facility for Antiproton and Ion Research



SIS100 primary beams:

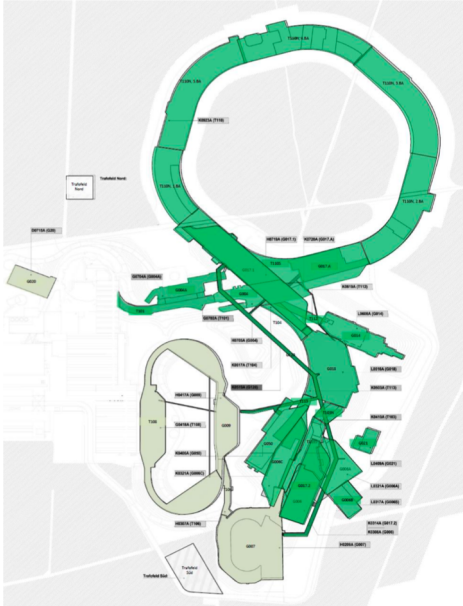
- 10^9/s Au up to 11 GeV/u
- 10^9/s C, Ca, ... up to 14 GeV/u
- 10^{11}/s p up to 29 GeV

Timeline

2022: Buildings / shell construction complete (including CBM cave)

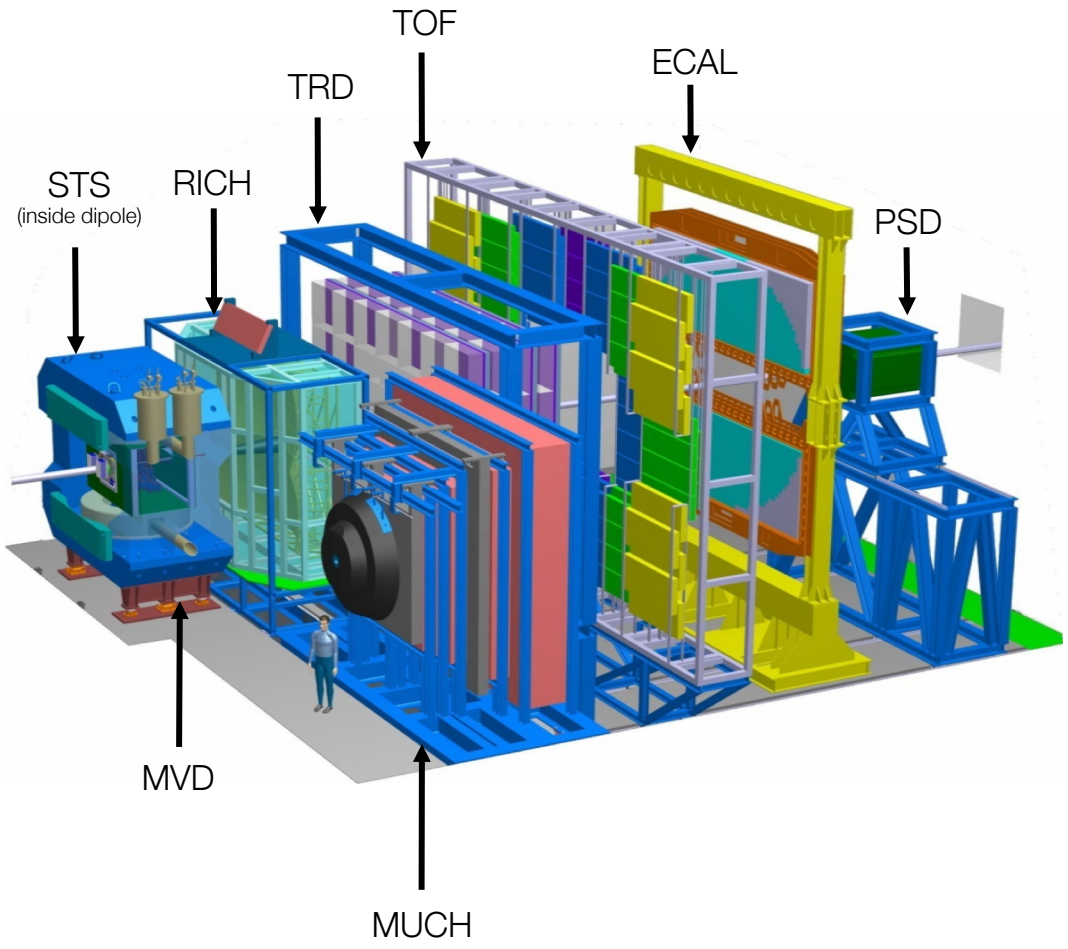
2025: Start of operations

FAIR intermediate objective



CBM Experiment

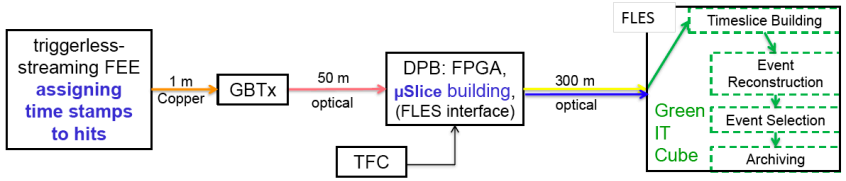
- Tracking acceptance: $2.5^{o} < \theta_{Lab} < 25^{o}$
- Peak interaction rate: 10 MHz (Au+Au)
  (300 kHz for MVD)
- Fast and radiation hard detectors
- Free-streaming DAQ
- 4D-tracking (space + time)
- Online event reconstruction and selection
- Data rate: 1 TB/sec



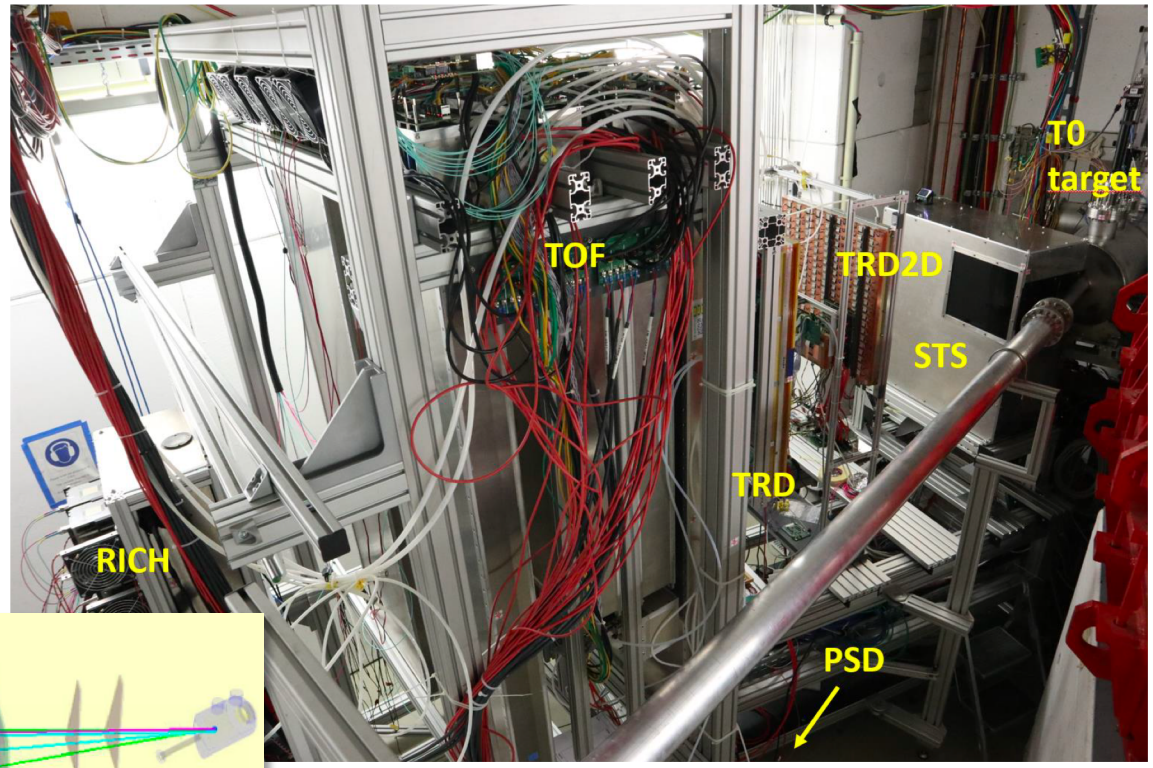
CBM Experiment

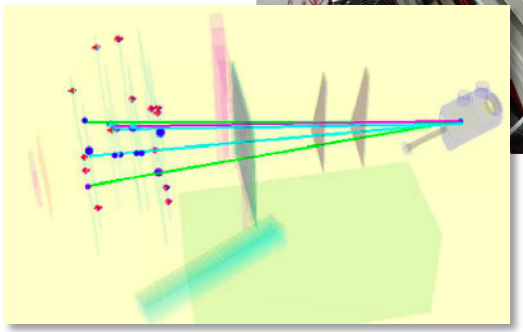
CBM Experiment

- mCBM@SIS18
  - Full system test with high rate AA collisions (up to 10 MHz collision rate for Ag+Ag)
  - Data transport of all subsystems in a common, synchronized data stream



  - Verification of free-streaming DAQ (time and spatial correlations between detector subsystems observed)
  - Physics goal: Λ reconstruction

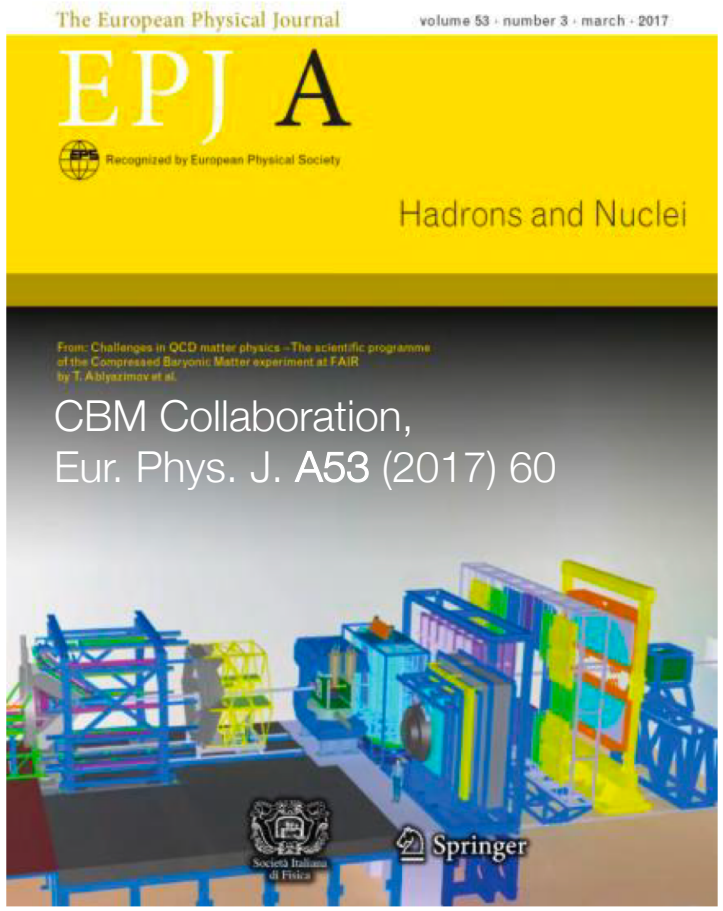




Pb+Au at 1.2 AGeV

CBM Physics Program

- QCD equation-of-state
  - Collective flow of identified particles
  - Particle production at threshold energies
- Phase transition
  - Excitation function of hyperons
  - Excitation function of intermediate mass di-leptons
- Critical point
  - Event-by-event fluctuations of conserved quantities
- Chiral symmetry restoration at large μ_B
  - Di-leptons at low invariant masses
- Strange matter
  - Hyper-nuclei
  - Meta-stable objects (e.g. strange di-baryons)
- Heavy flavour in cold and dense matter
  - Excitation function of open and hidden charm production

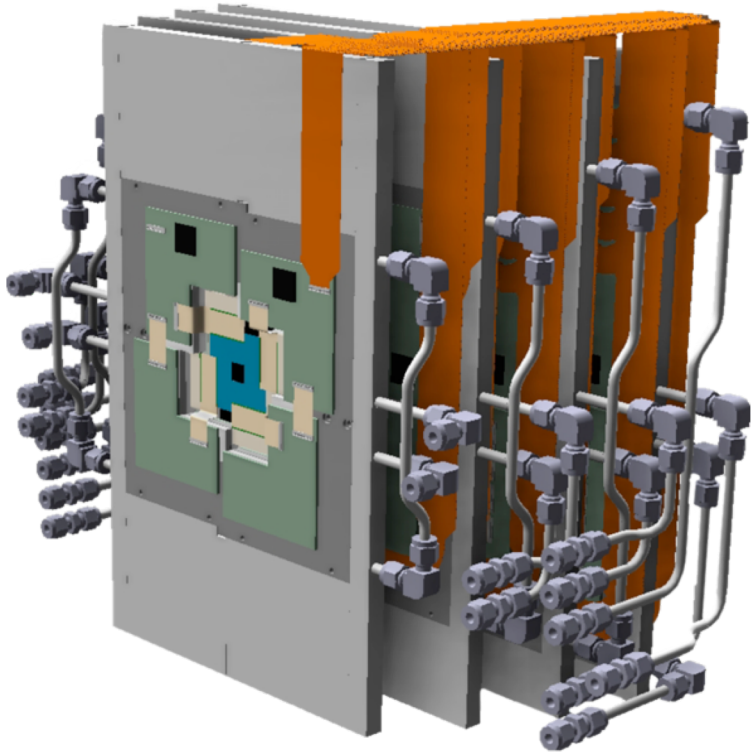


CBM Physics Program

- Phase-0 (2018 — 2025): mCBM@SIS18
  - Sub-threshold Λ and light hyper-nuclei production
- Day-1 (2026 — 2027): Excitation functions with up to 10^5 interactions/s
  - Di-leptons
  - Multi-strange (anti-)baryons
  - Light hyper-nuclei
  - Flow, fluctuations and correlations of charged particles
- MSV (> 2027): Measurements with up to 10^7 interactions/s
  - Double-Λ hyper-nuclei
  - (Sub-)threshold J/ψ production
  - Charmed particle interaction in cold nuclear matter
  - Search for exotica

CBM Detector Components: MVD

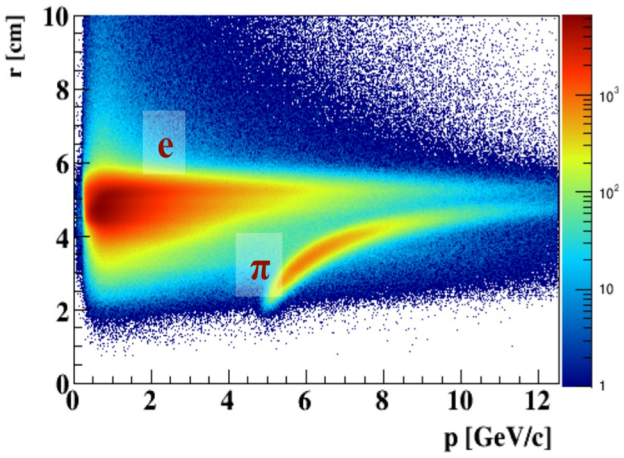
- Micro Vertex Detector (MVD)
- Secondary vertex reconstruction (~ 10 μm res.)
- Operation in vacuum + magnetic field
- 4 stations of CMOS pixel sensors
  ~ 300 MIMOSIS chips, 50 μm thin,
  power dissipation: 150 mW/cm^2,
  ~10 μs readout time
- Radiation tolerance: > 10^{13} n_{eq}/cm^2 and > 1 Mrad

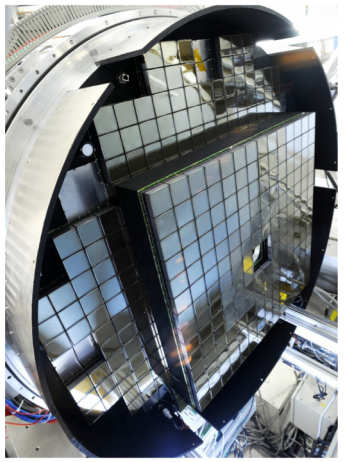


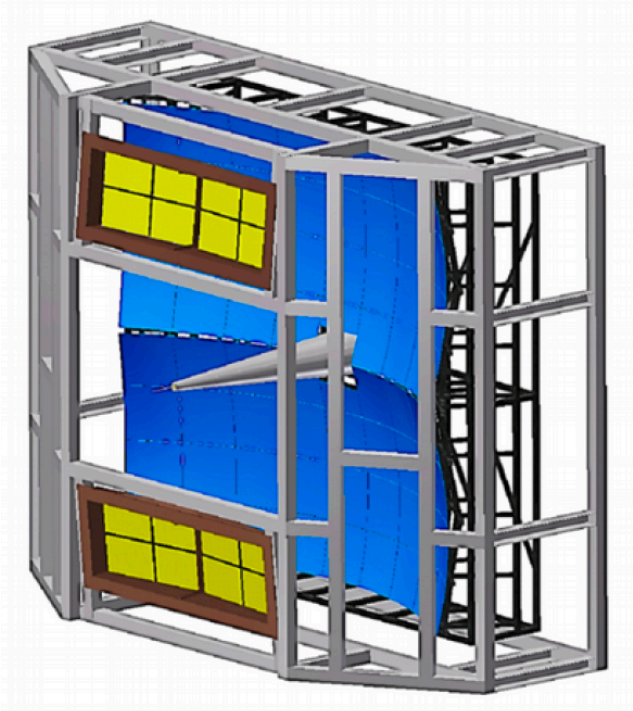
CBM Detector Components: RICH

- Ring Imaging Cherenkov Detector
- Electron identification at low momenta
  ($p < 6 - 8$ GeV/c)
- Radiator: CO_2
- UV-photon detector:
  1100 Multi-Anode Photomultipliers (MAPTs)

  430 MAPTs already installed
  in HADES-RICH (FAIR phase-0)

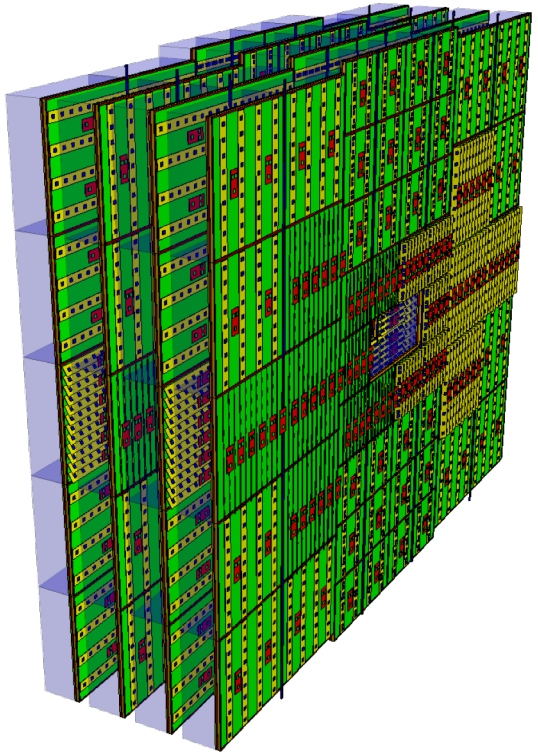


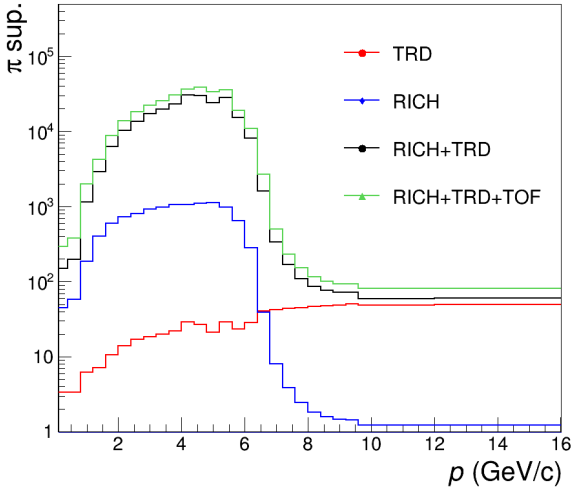




CBM Detector Components: TRD

- Transition Radiation Detector (TRD)
- Electron identification at high momenta
  (p > 5 – 6 GeV/c)
- Pion suppression factor > 20
  (at 90 % electron efficiency)
- Four detector layer, 55 modules each
  (# readout channels: ~330,000,
  active area: 113.4 m^2, material budget < 5 %)
- Fast MWPC as readout chambers
  (12 mm gas gap thickness)
- PE foam foil stacks as radiator



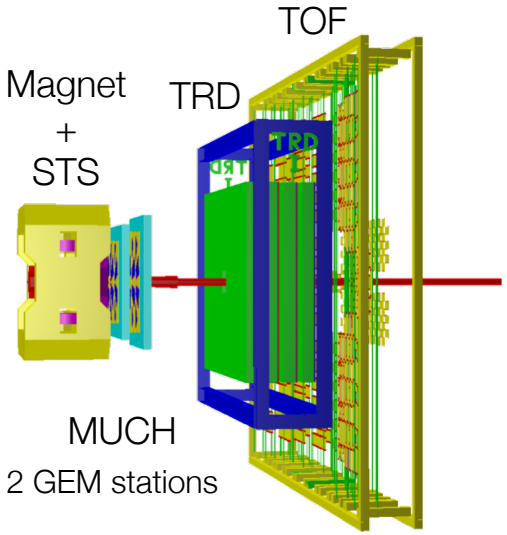


CBM Detector Components: MUCH

- Different configurations
- Absorbers:
  C, Fe, concrete
- Tracking stations:
  GEMs + RPCs
  TRD as last station
- Replaces RICH

High beam energies
(above 4 *A*GeV for Au beam)

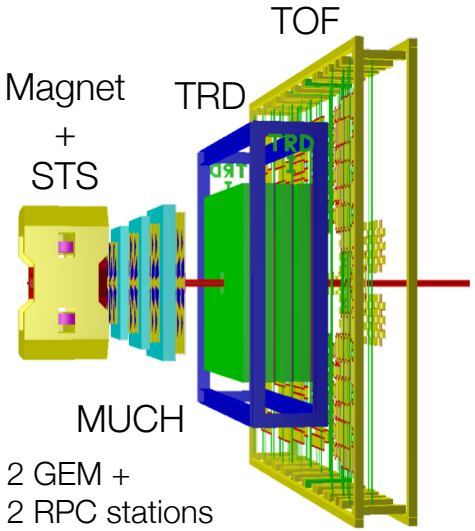
Low beam energies
(up to 4 *A*GeV for Au beam)



2 GEM stations

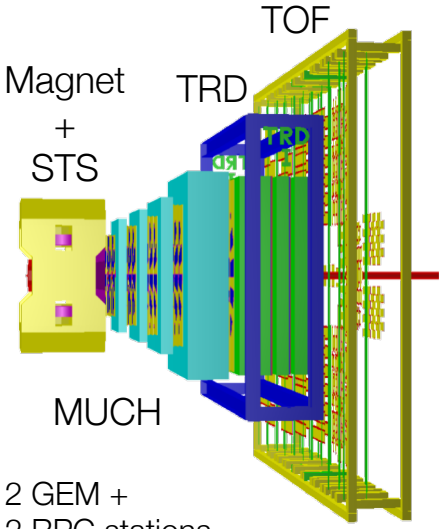
Absorbers:
58 cm C + concrete
(20+20) cm Fe

Low invariant mass region



2 GEM +
2 RPC stations
Absorbers:
58 cm C + concrete
(20+20+30) cm Fe

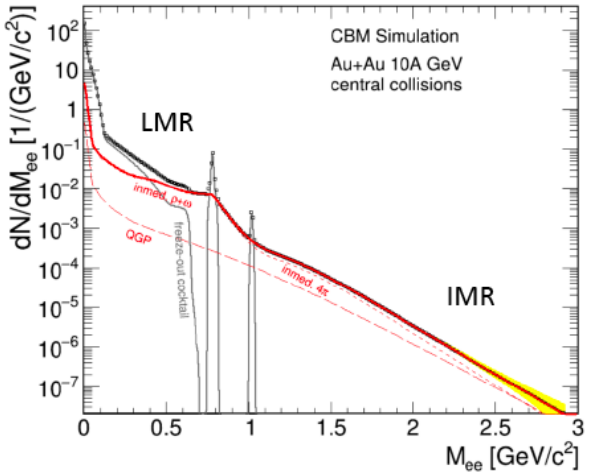
Intermediate and high invariant mass region

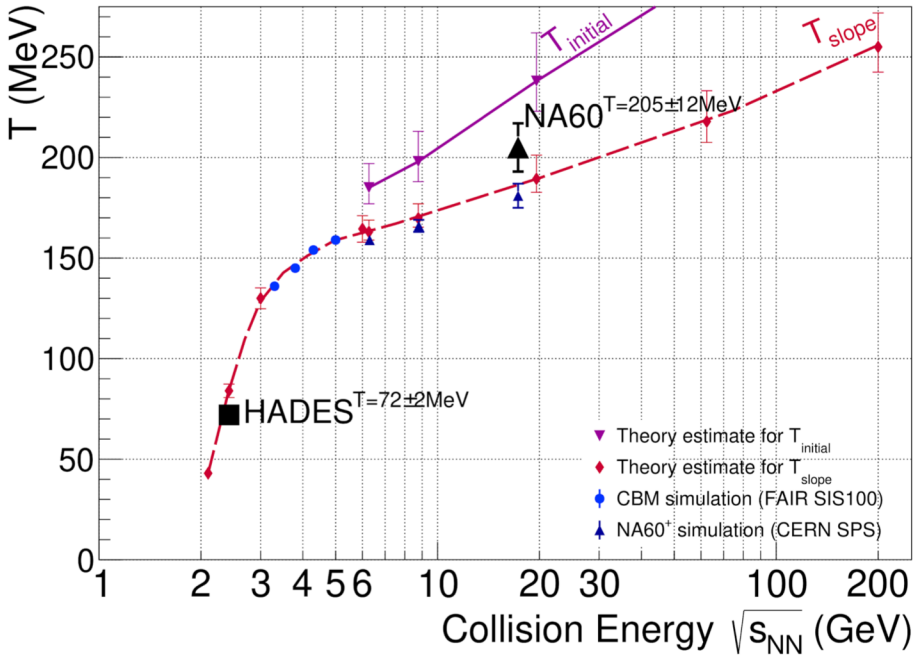


2 GEM +
2 RPC stations
Absorbers:
58 cm C + concrete
(20+20+30+100) cm Fe

Di-Leptons

- LMR di-leptons
  - Chiral symmetry restoration
  - Energy dependence of excess radiation
- IMR di-leptons
  - Fireball temperature and ρ–a_1-mixing
  - Energy dependence of slope parameter *T* ⟹ caloric curve
  - Sensitivity to 1st order phase transition ⟹ non-monotonic behavior of *T*
  - CBM: ~10^{11} evts. (~ 20 days) for 10% stat. uncertainty on *T*



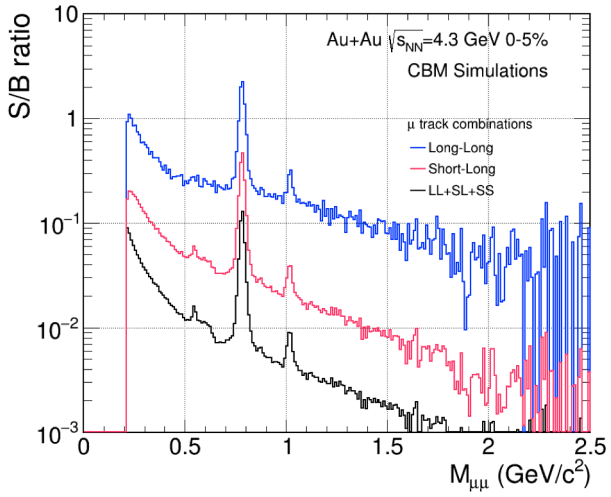


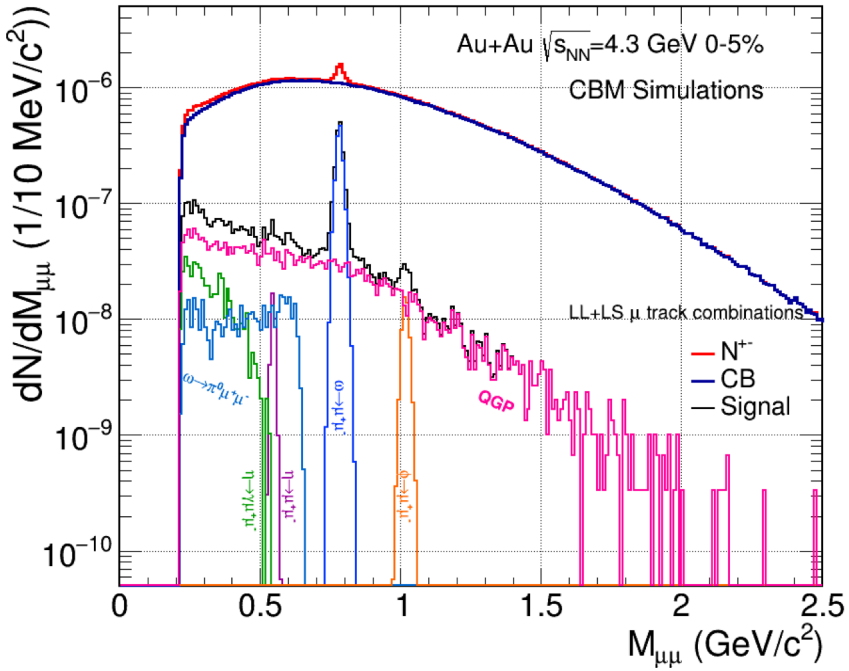
T. Galatyuk, Quark Matter 2018
R.-A. Tripolt, Nucl. Phys. **A1005** (2021) 121755
NA60, Eur. Phys. J. **C61** (2009) 711
HADES, Nature Phys. **15** (2019) 1040

$\sqrt{s_{NN}}$ > 6 GeV: R. Rapp and H. v. Hess, Phys. Lett. **B753** (2016) 586
$\sqrt{s_{NN}}$ < 6 GeV: T. Galatyuk et al.: Eur. Phys. J. **A52** (2016) 131

Di-Leptons: $\mu^+\mu^-$

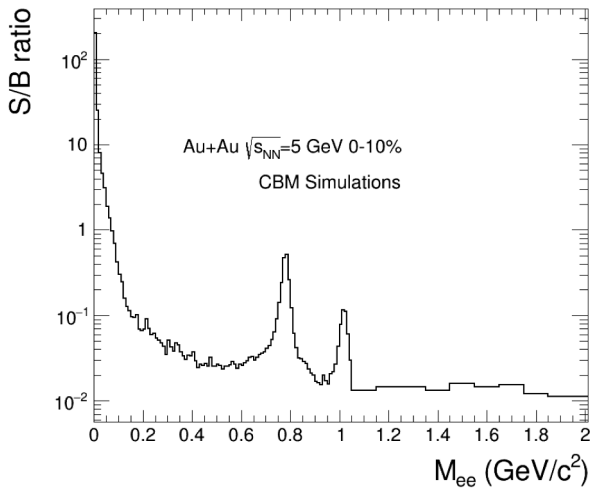
- Challenge:
  - Muons at low energies
  - High areal particle rates in first detector
- Strategy:
  - Identification after hadron absorber with intermediate tracking layers
  - Triple GEM detectors with pad read-out
  - Remove last two absorbers for beam energies < 4*A* GeV

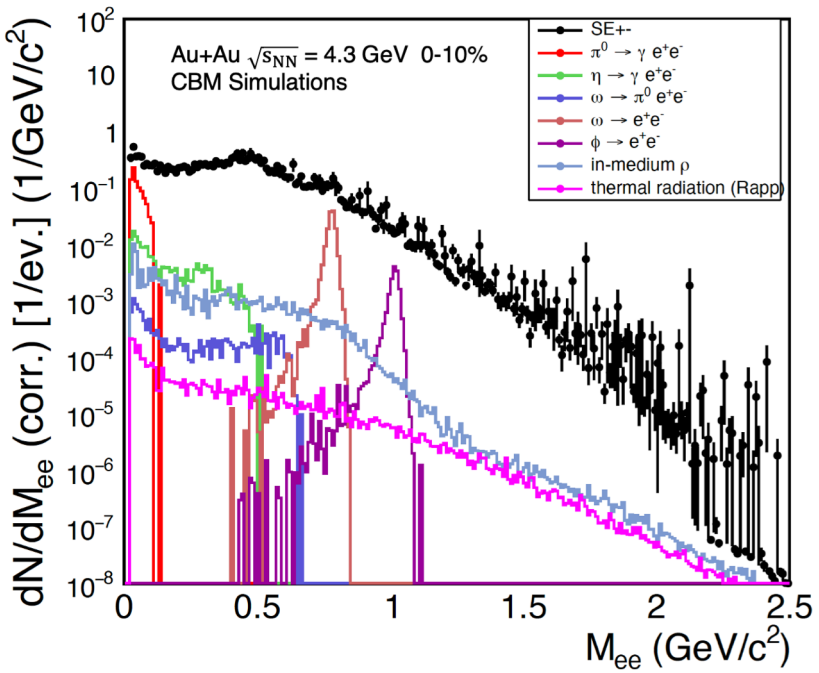




Di-Leptons: e^+e^-

- Challenge:
  - No electron identification before tracking
  - Background due to material budget of the tracking system
- Strategy:
  - Sufficient pion discrimination RICH + TRD (+ TOF)
  - Reduction of background by reconstructing pairs from γ-conversion and π^0-Dalitz decay (employing topology cuts)

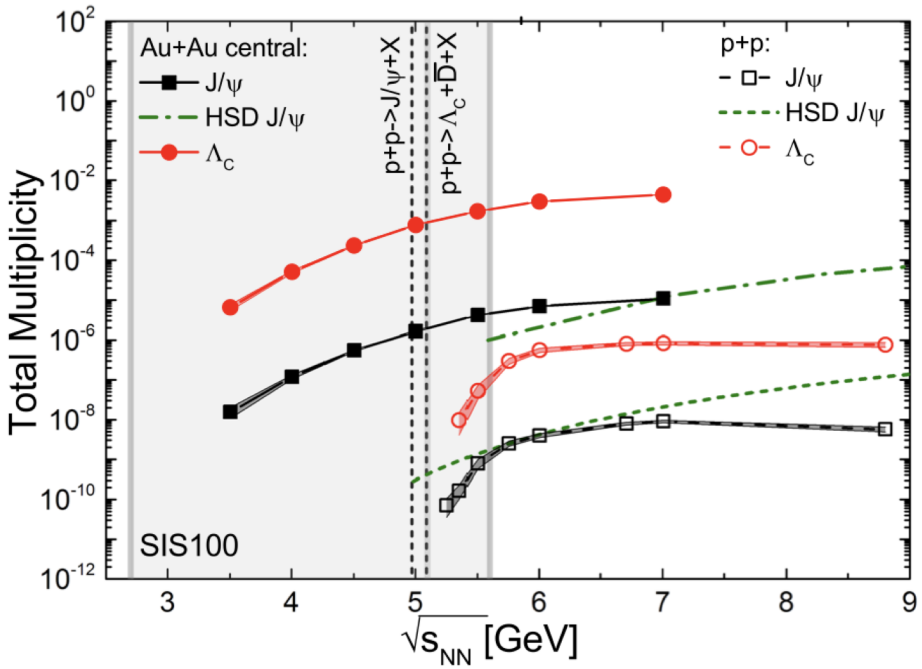




5×10^6 0-10% most central Au+Au collisions at 12*A* GeV
⟹ 3 min beam on target at interaction rate of 0.3 MHz
Realistic background and detector response (Geant3)

Charmonia at SIS100

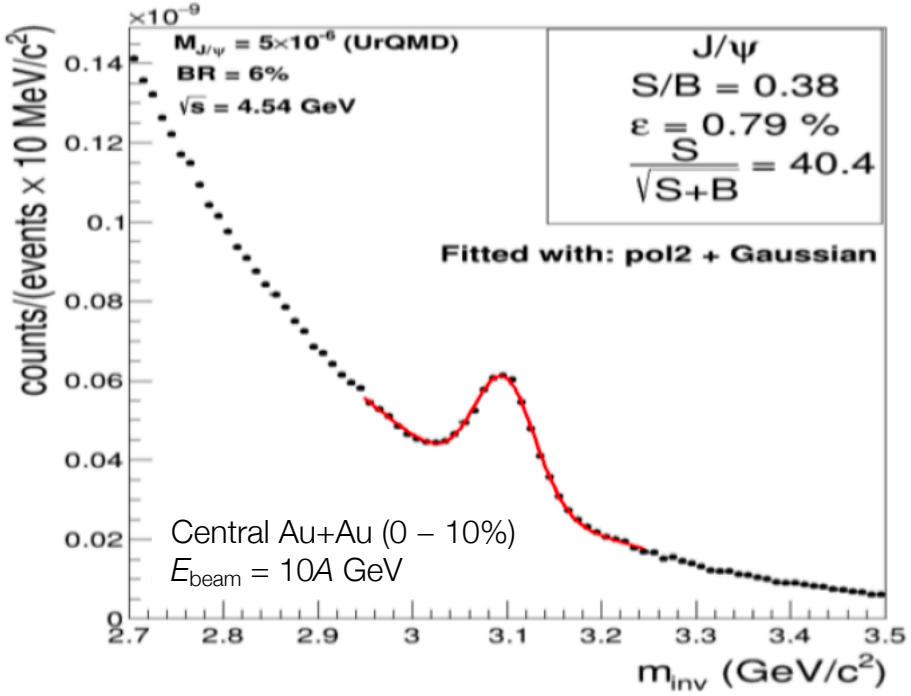
- J/ψ in heavy-ion collisions
  - Sub-threshold
  - Production is rare but measurement is still feasible
  - Multiple collision processes
  - No existing data below 158*A* GeV
- Measurements with CBM
  - $\mu^+\mu^-$ and e^+e^- decay channel accessible
  - Production threshold can be exceeded with SIS100 beam of $N = Z$ nuclei



J. Steinheimer et al., Phys. Rev. C95 (2017) 014911

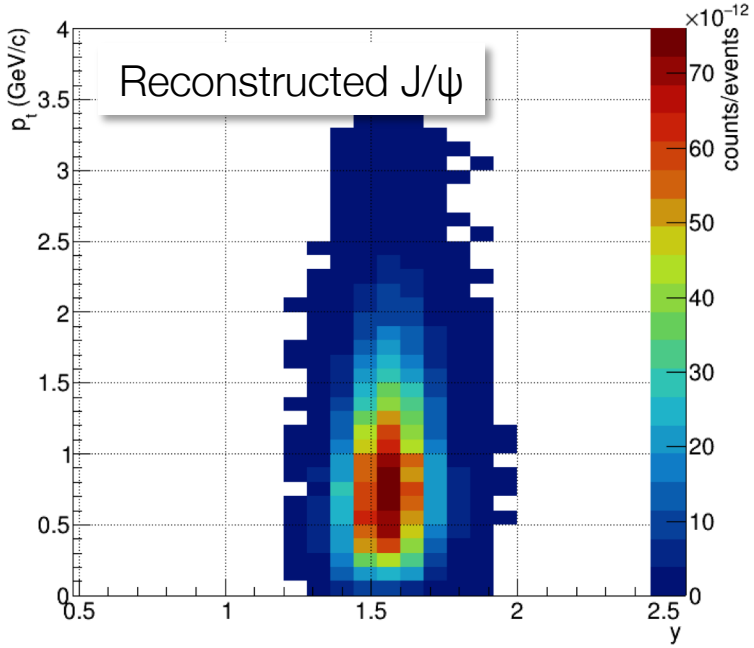
Charmonia at SIS100

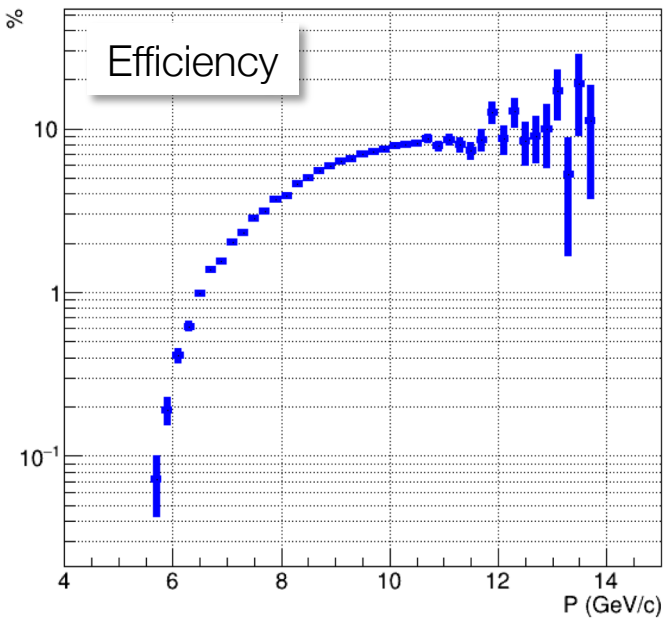
- $J/\psi \longrightarrow \mu^+\mu^-$ in Au+Au
  - Clear signal peak
    $\Longrightarrow$ measurement feasible
  - Detectors:
    STS + MUCH + TRD
  - Expected yield:
    ~30k J/ψ in 4 weeks at 10 MHz interaction rate



Charmonia at SIS100

- $J/\psi \longrightarrow \mu^+\mu^-$ in Au+Au
  - Detectors:
    STS + MUCH + TRD
  - Particle ID with ANN
  - Large acceptance
    mid- ⟶ forward rapidities



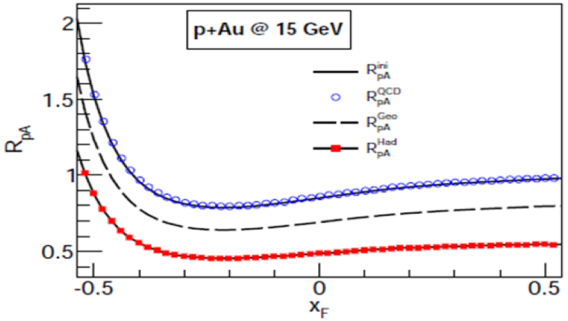


Central Au+Au (0 – 10%)
E_{beam} = 8*A* GeV

A. Senger, ICNFP 2021

Charmonia at SIS100

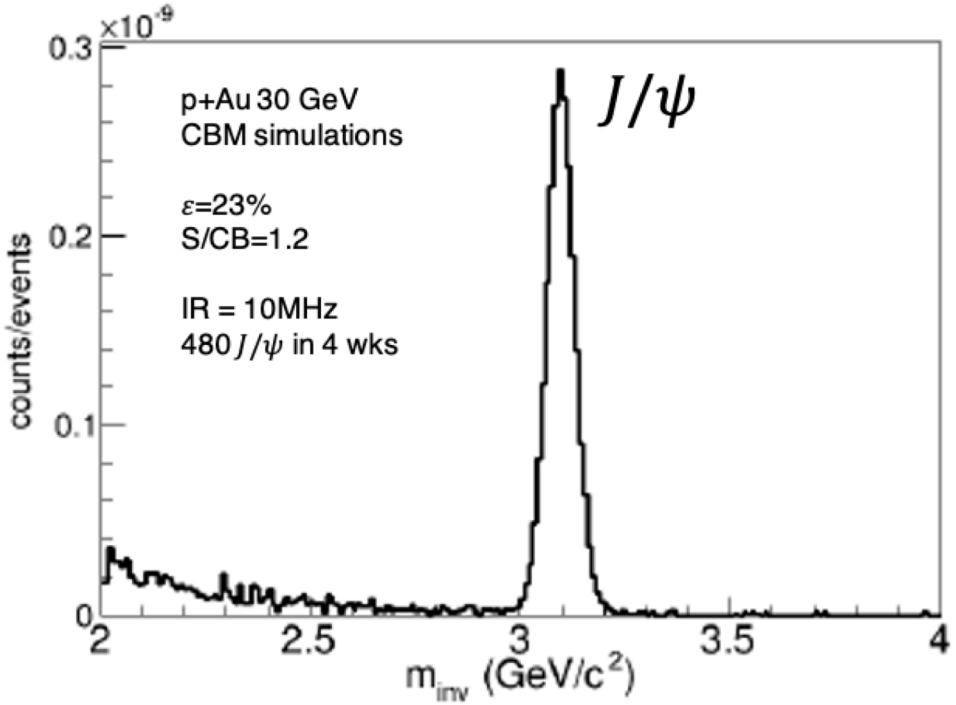
- J/ψ propagation in cold nuclear matter
  - Probe resonance-nucleon interaction
  - Constraint on theoretical models



Transparency ratio (R_{pA}) vs Feynman-x (x_F)

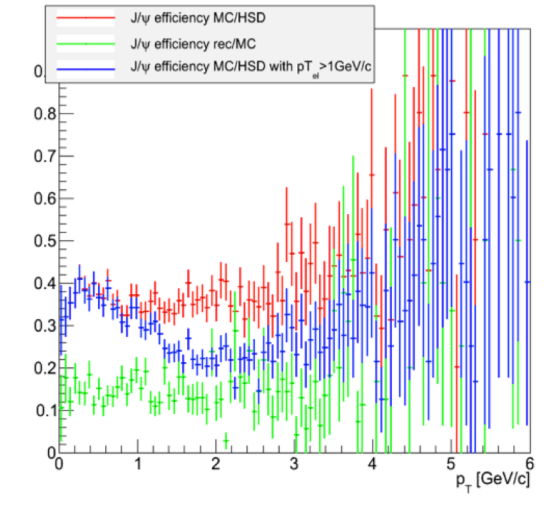
M. Deveaux, A. Toia
J. Phys. **G45** (2018) 055103

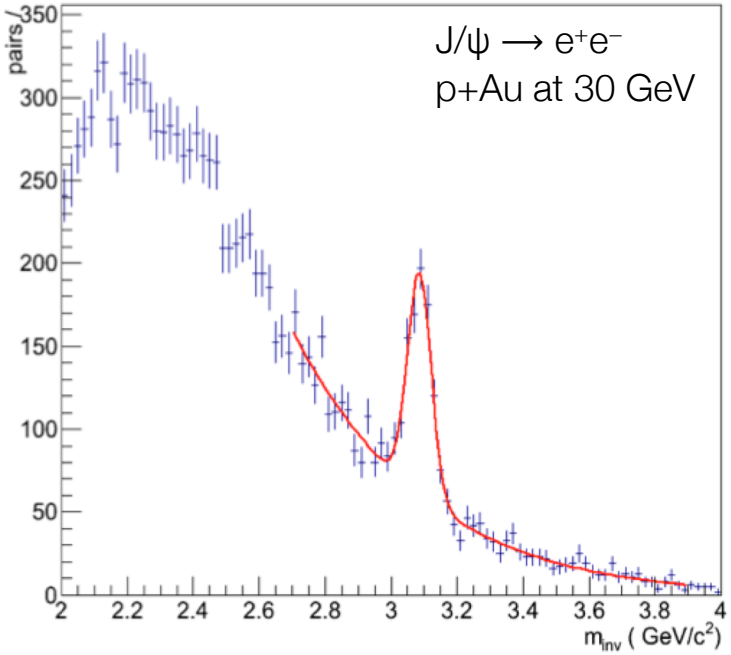
- J/ψ ⟶ $\mu^+\mu^-$ in p+Au
  - Detectors:
    STS + MUCH + TRD
  - Expected yield:
    ~500 J/ψ in 4 weeks at 10 MHz peak interaction rate



Charmonia at SIS100

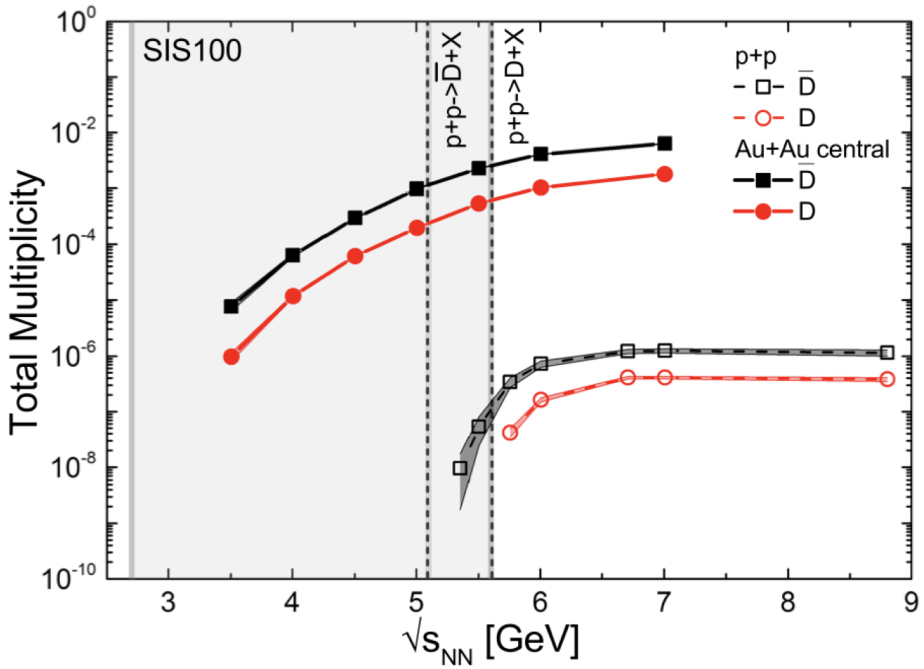
- $J/\psi \longrightarrow e^+e^-$ in p+Au
  - Detectors:
    STS + RICH + TRD
  - Clean signal expected
  - Expected yield:
    ~600 J/ψ in 40 days
    at 10 MHz peak interaction rate
    (Input yield: HSD prediction)
  - Efficiency: ~ 5%
    (e-track p_t > 1 GeV/*c*)





Open Charm at SIS100

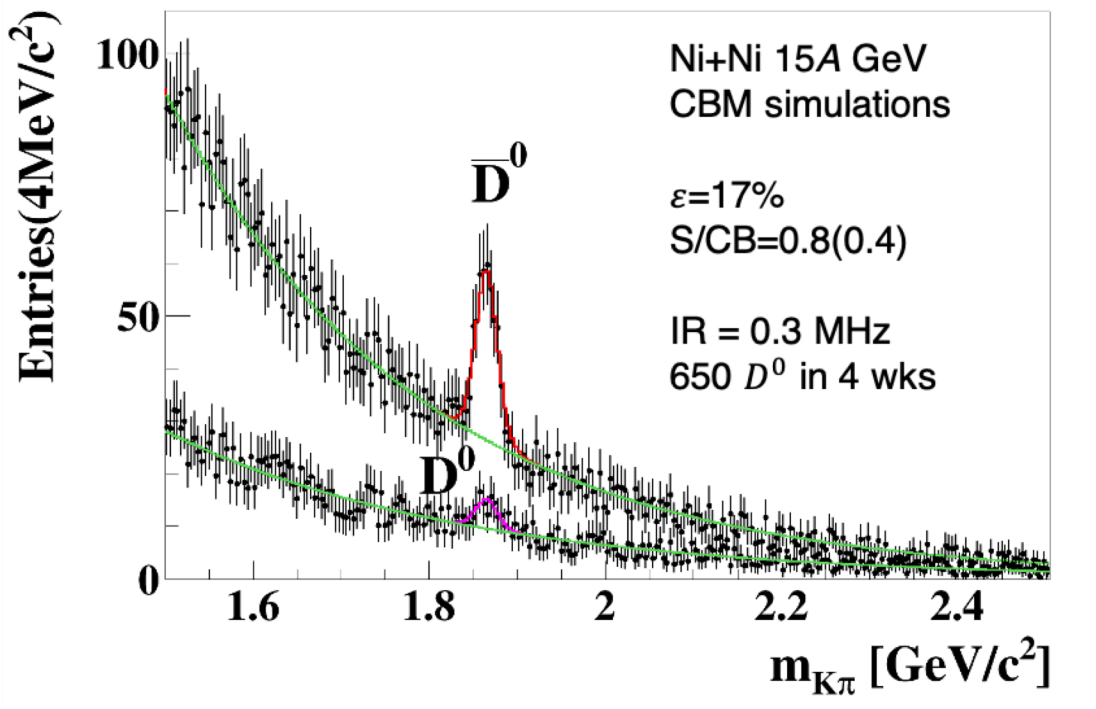
- Heavy-ion collisions
  - Sub-threshold for large systems (Au+Au) Production threshold can be exceeded with SIS100 beam of $N = Z$ nuclei
  - What are the production mechanisms relevant at these energies?
  - Propagation of charm quarks in dense matter?
  - Indicators for collectivity?
- Proton-nucleus collisions
  - Charm production at threshold
  - Cold nuclear matter effects



J. Steinheimer et al., Phys. Rev. C95 (2017) 014911

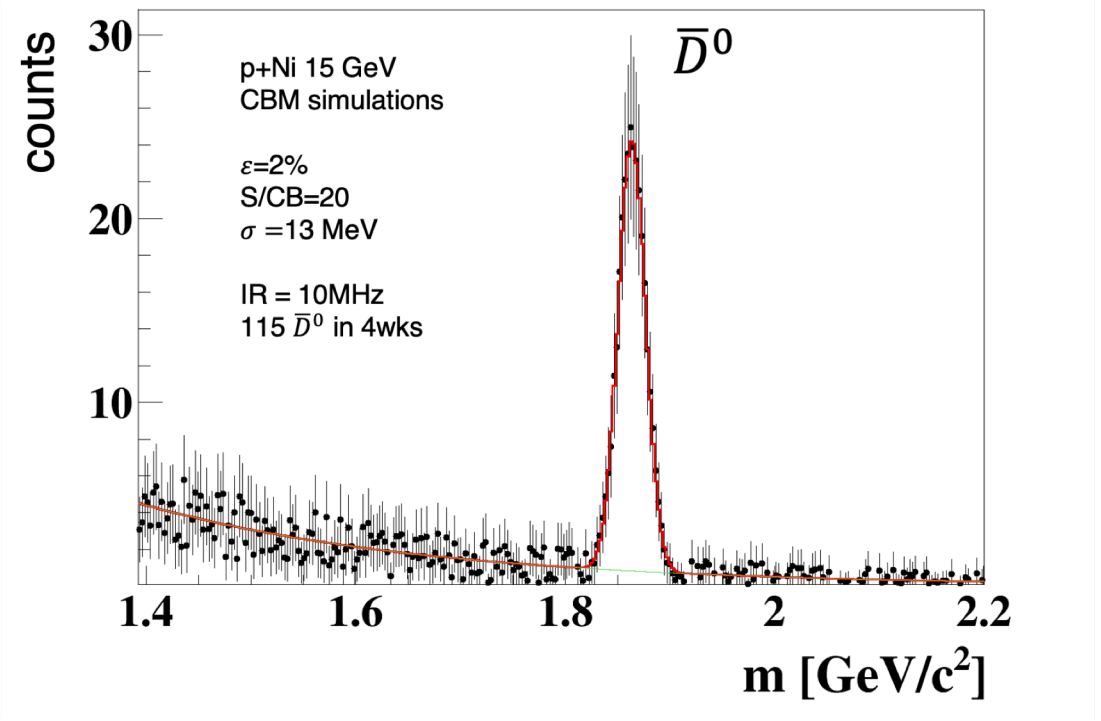
Open Charm at SIS100

- Open charm in heavy-ion collisions
  - $D^0 \longrightarrow K + \pi$
    in Ni+Ni collisions at 15*A* GeV
  - Detectors:
    MVD + STS + TOF
    4 planes of Monolithic Active Pixel Sensors
    8 planes of Silicon Tracking Stations
  - Secondary vertex resolution
  - Expected yield (Ni+Ni at 15*A* GeV):
    ~650 D^0 in 4 weeks at 0.3 MHz interaction rate



Open Charm at SIS100

- Open charm in p+A collisions
  - $D^0 \longrightarrow K + \pi$
    in p+Ni collisions at 15 GeV
  - Detectors:
    MVD + STS + TOF
    4 planes of Monolithic Active Pixel Sensors
    8 planes of Silicon Tracking Stations
  - Secondary vertex resolution
  - Expected yield (Ni+Ni at15*A* GeV):
    ~115 D^0 in 4 weeks at 10 MHz interaction rate



Conclusions

- Rare probes are essential part of CBM physics program
- Di-leptons
  - LMR and IMR via di-muon and di-electron channel
  - Energy dependence of fireball temperature ($\Longrightarrow$ phase transition)
- Quarkonia
  - Di-muon and di-electron channel
  - Sub-threshold in A+A (higher energy accessible with $N = Z$ nuclei)
  - Cold nuclear matter effects with p+A
- Open charm
  - Accessibly due to good vertex resolution

CBM Collaboration

56 Institutions, 12 countries, ~450 members

China
CCNU Wuhan
Tsinghua Univ.
USTC Hefei
CTGU Yichang
IMP Lanzhou

Czech Republic
CAS, Rez
Techn. Univ.Prague

France
IPHC Strasbourg

Hungary
KFKI Budapest
Budapest Univ.

Germany
Darmstadt TU
FAIR
Frankfurt Univ. IKF
Frankfurt Univ. FIAS
Frankfurt Univ. ICS
GSI Darmstadt
Giessen Univ.
Heidelberg Univ. P.I.
Heidelberg Univ. ZITI
HZ Dresden-Rossendorf
KIT Karlsruhe
Münster Univ.
Tübingen Univ.
Wuppertal Univ.
ZIB Berlin

India
Aligarh Muslim Univ.
Bose Inst. Kolkata
Panjab Univ.
Univ. of Jammu
Univ. of Kashmir
Univ. of Calcutta
B.H. Univ. Varanasi
VECC Kolkata
IOP Bhubaneswar
IIT Kharagpur
IIT Indore
Gauhati Univ.

Korea
Pusan Nat. Univ.

Romania
NIPNE Bucharest
Univ. Bucharest

Poland
AGH Krakow
Jag. Univ. Krakow
Warsaw Univ.
Warsaw TU

Russia
IHEP Protvino
INR Troitzk
ITEP Moscow
Kurchatov Inst., Moscow
MEPHI Moscow
PNPI Gatchina
SINP MSU, Moscow

Ukraine
T. Shevchenko Univ. Kiev
Kiev Inst. Nucl. Research

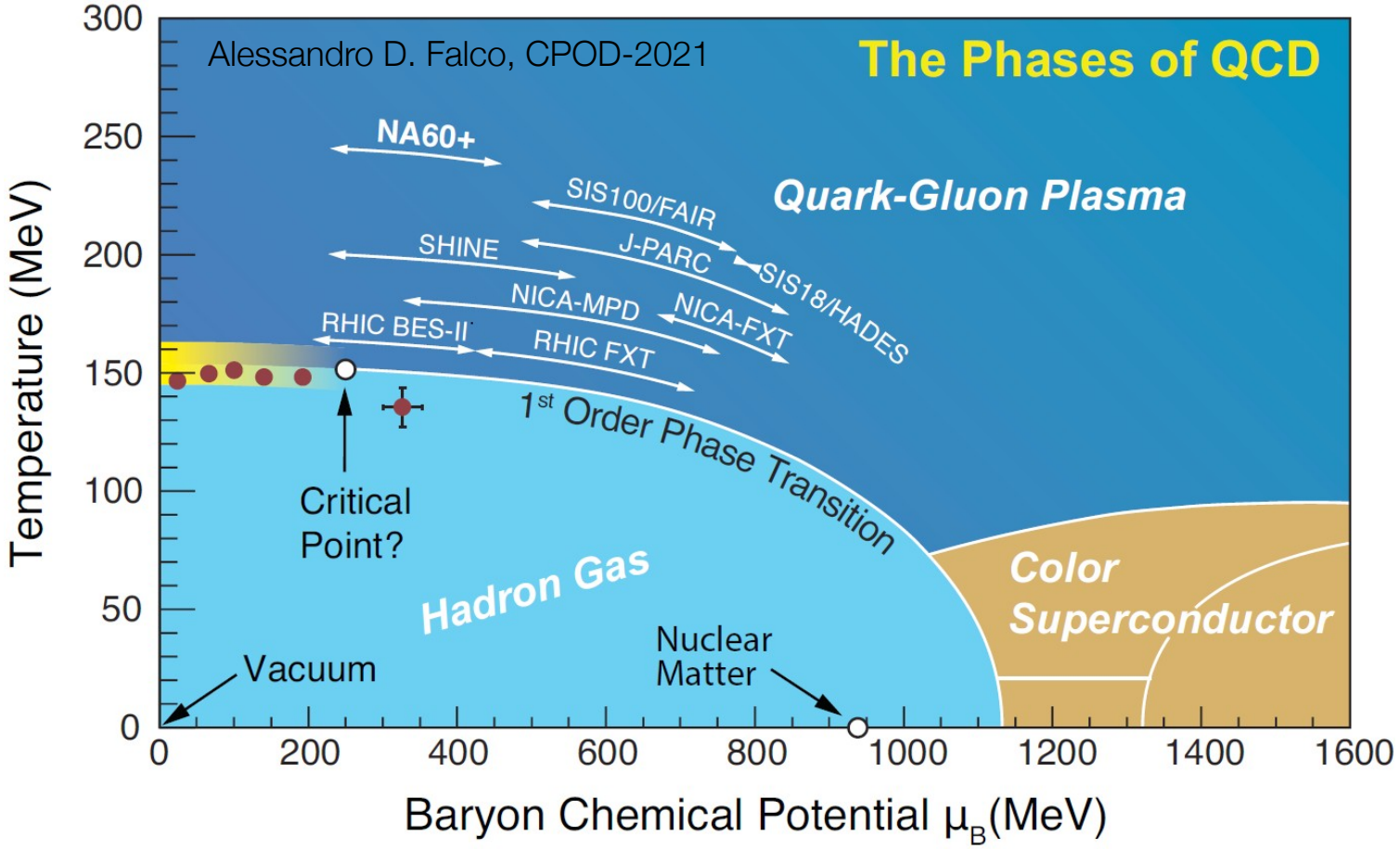
JINR
VBLHEP, Dubna
LIT, Dubna

CBM Collaboration

CBM Collaboration

34th CBM Collaboration Meeting, September 2019, Kolkata, India

High μ_B Matter



Muon Setup

- Muon Chambers:
  2 GEM + 2 RPC stations

- Absorbers:
  Concrete + C: 58 cm
  Fe: 20+20+30+100 cm