# CBM EXPERIMENT AT FAIR: BECOMING REALITY

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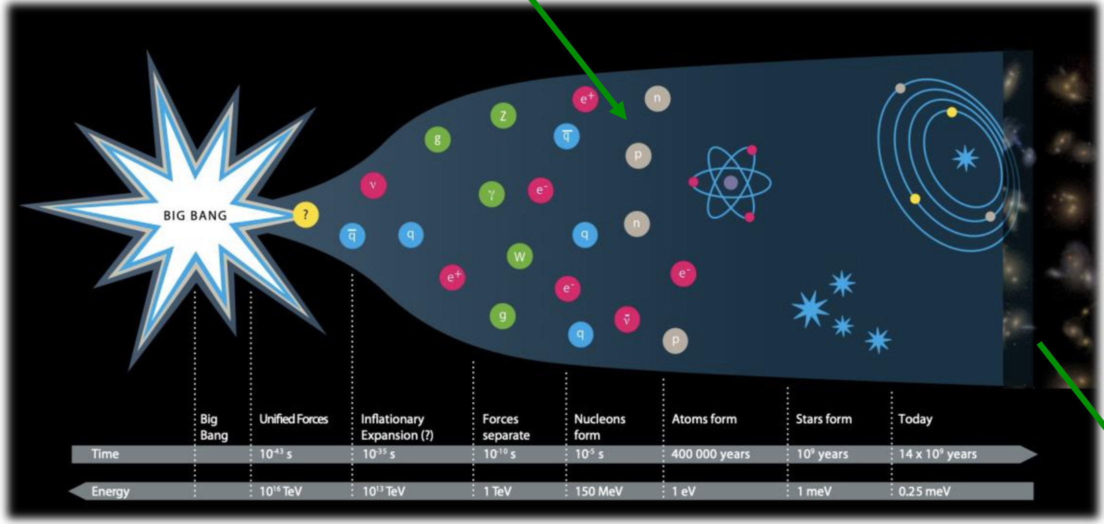
# MOTIVATION

# Objective

- Decode the phases of hot/compressed nuclear matter...
- Unravel the role of the strong interaction in the evolution of our universe

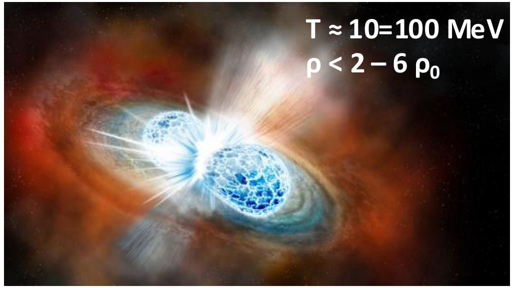
**Nature of phase transition in strong-interaction matter?**




**Neutron star**

$M \sim 1.4 - 2.0\, M_\odot$
$R \sim 12$ km
$T \sim$ keV
$n \lesssim 10\, n_{sat}$

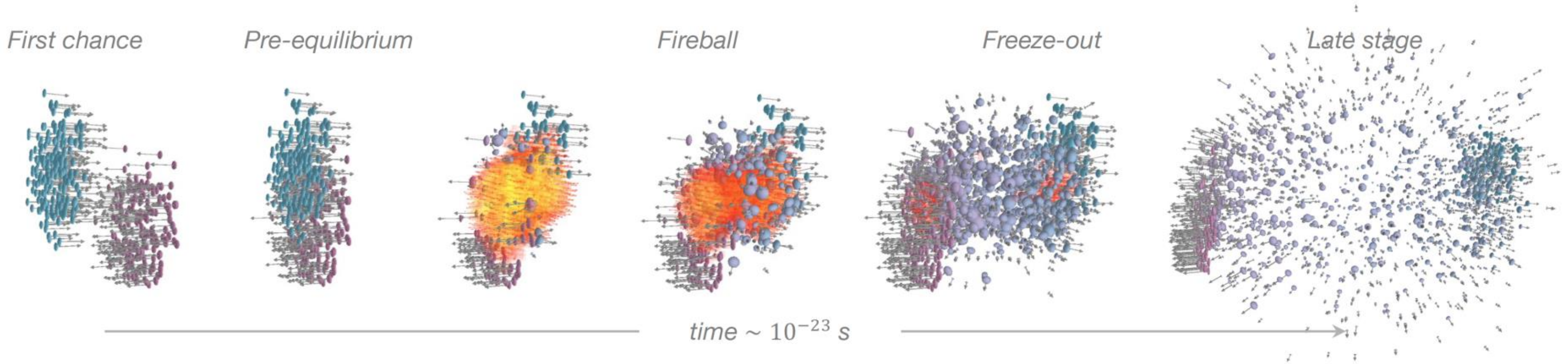
**Neutron star mergers**




**Matter properties in compact stellar objects?**

# Method

- Recreate various forms of cosmic matter in laboratory ⟶ high-energy heavy-ion collisions
- Investigate transient states of QCD matter under extreme conditions



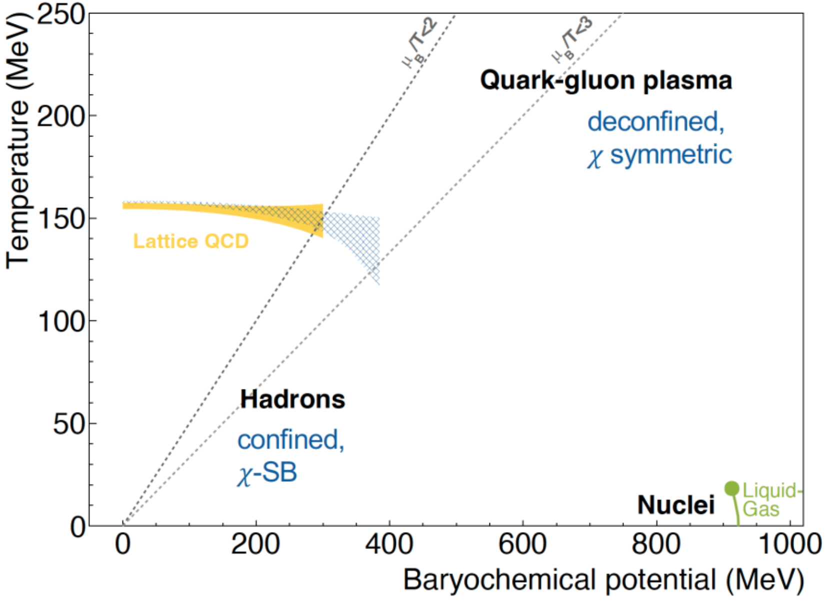

pic: Seck,Galatyuk

# Exploring the QCD phase diagram at high net baryon densities

## Vanishing $\mu_B$, high $T$ (lattice QCD)

- Smooth crossover from hadronic to partonic medium
  - $T_{pc} = 156.5 \pm 1.5$ MeV (physical quark masses)
  - $T_{pc} = 158.0 \pm 0.6$ MeV (physical quark masses)
  - $T_c = 132^{+3}_{-6}$ MeV (chiral limit)
- No critical point indicated by lattice QCD at $\mu_B/T_c < 3$

*Bazavov et al. (HotQCD), Phys. Lett. B 795 (2019) 15*
*Borsanyi et al. [Wuppertal-Budapest], PRL 125 (2020)*
*Borsanyi et al. [Wuppertal-Budapest], JHEP 1009 (2010) 073*



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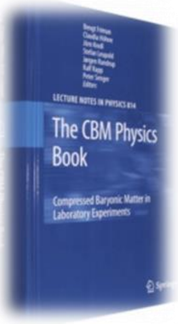
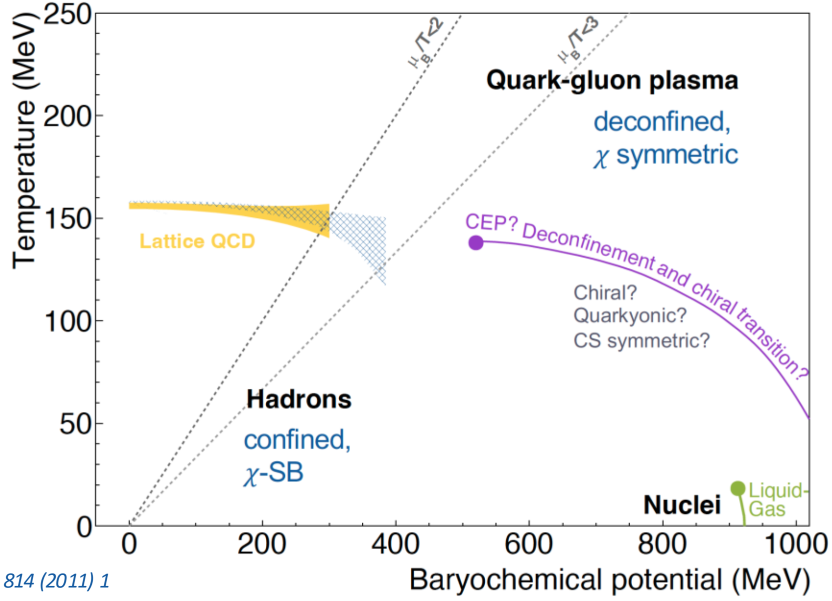
## Large $\mu_B$, moderate $T$

- Limits of hadronic existence?
- 1st order phase transition?
- QCD Critical point?
- Equation-of-state of dense matter?



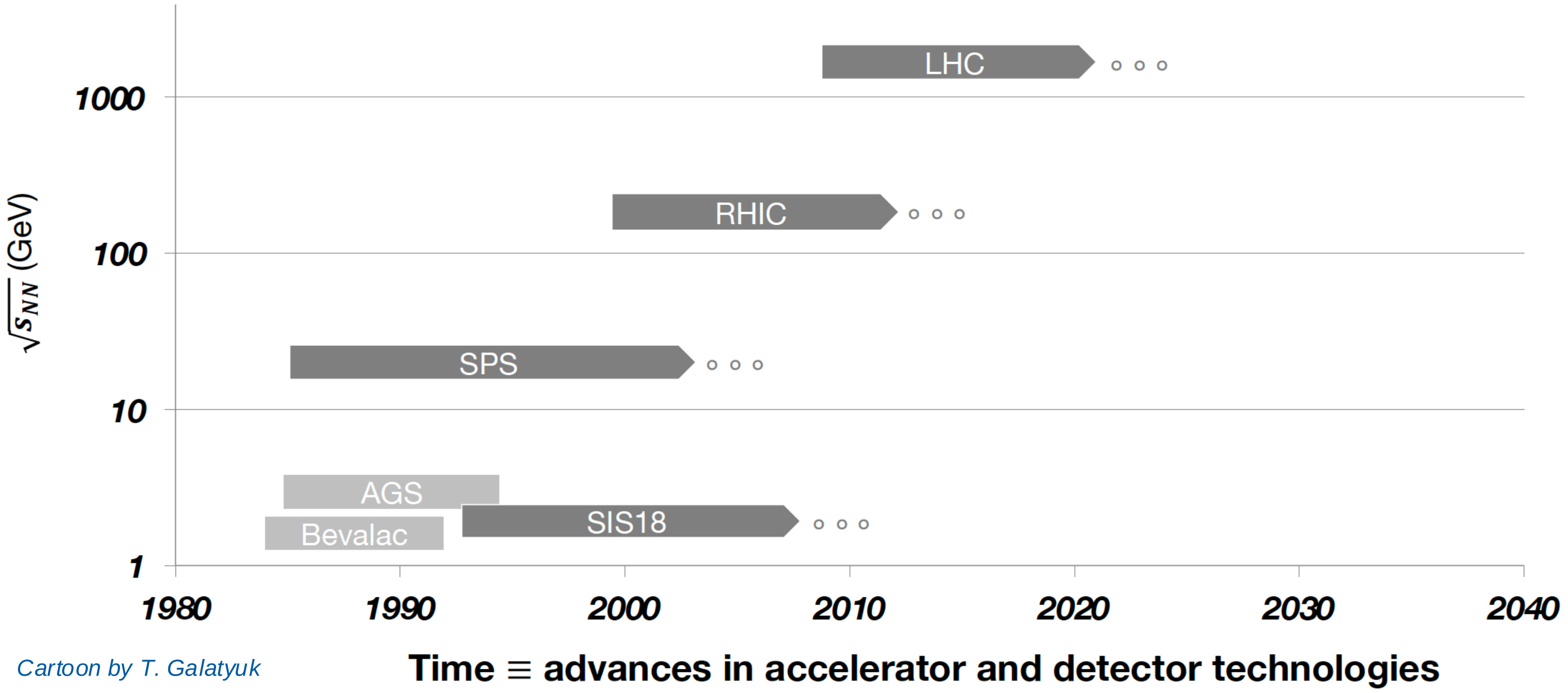

*Friman et al., Lect. Notes Phys. 814 (2011) 1*

*Gao, Pawlowski, PLB 820 (2021) 136584*
*Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141*
*McLerran, Pisarski, NPA 796 (2007) 83*
*Glozman, Philipsen, Pisarski, EPJA 58 (2022) 12, 247*




**Worldwide experimental and theory efforts!**

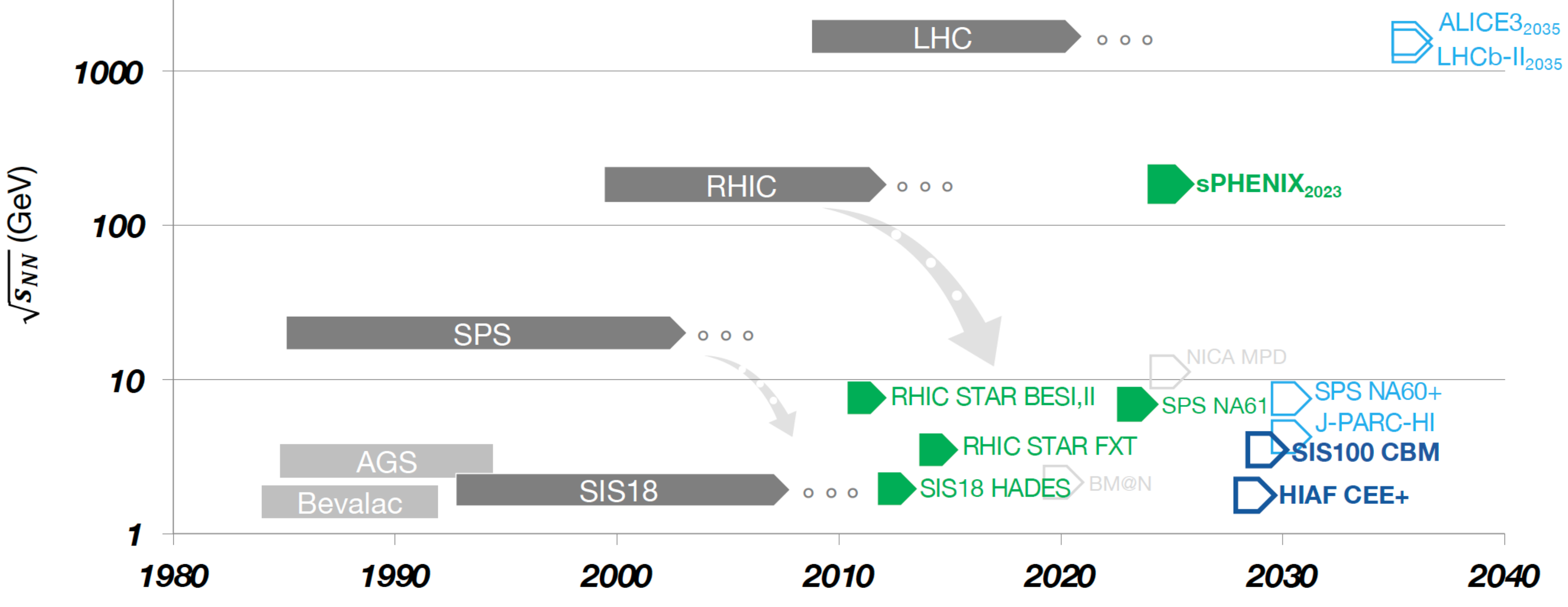
# The quest for the highest energy




*Cartoon by T. Galatyuk*

# The quest for the utmost precision and rare probes

~25 years progress
in technology since AGS
(begin of high $\mu_B$ explorations)




*Cartoon by T. Galatyuk*

**Time ≡ advances in accelerator and detector technologies**

# Compressed Baryonic Matter experiment mission

**Systematically explore QCD matter at large baryon densities with high accuracy and rare probes at the highest interaction rates**

## Experimental challenge:

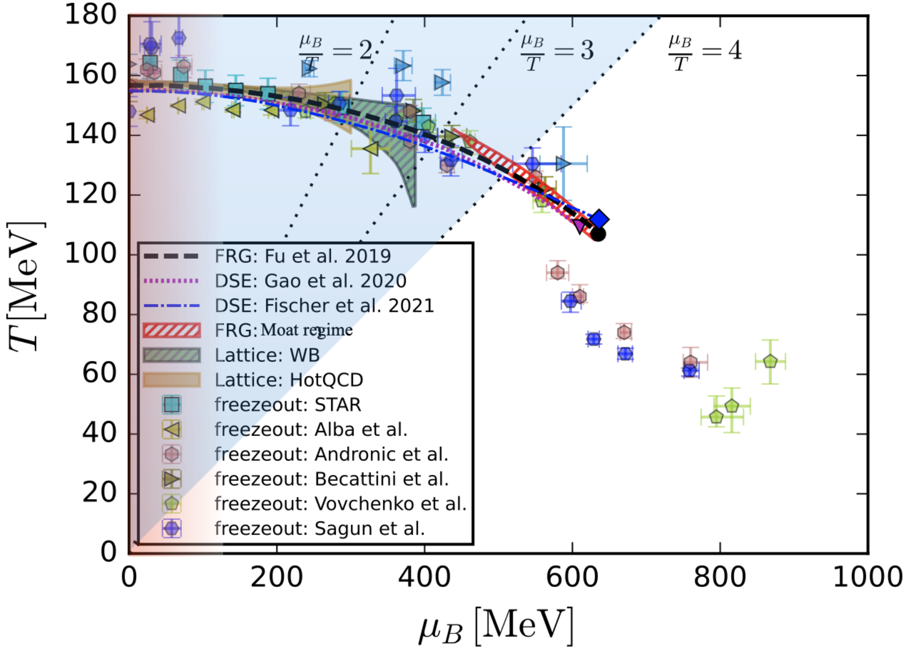
- Isolate unambiguous signals of new phases of QCD matter, order of phase transitions, conjectured QCD critical point
- Probe the microscopic matter properties

## Measure with utmost precision:

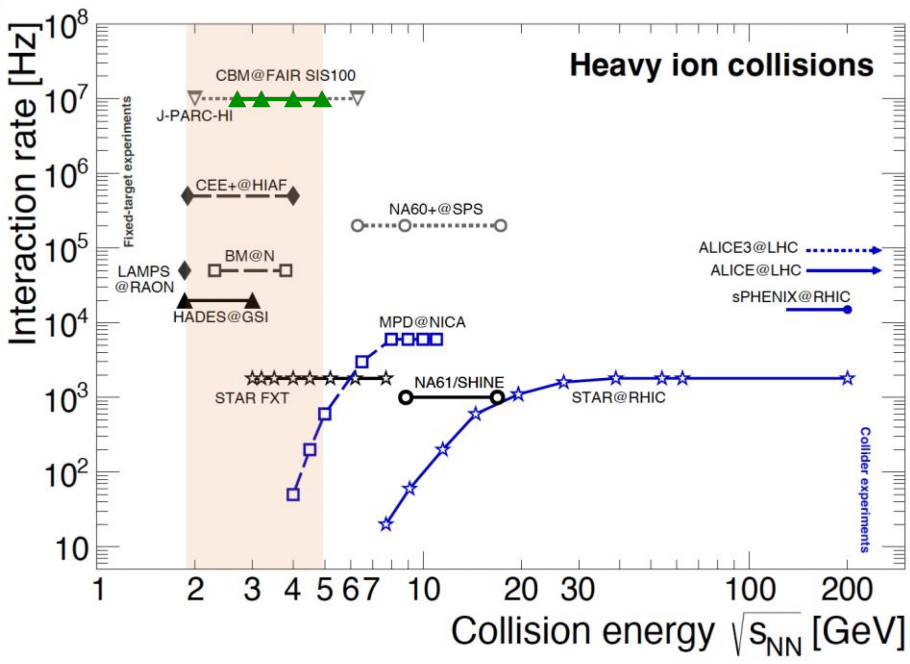
- Event-by-event fluctuations (criticality)
- Dileptons (emissivity)
- Strangeness (vorticity)
- Hypernuclei (equation-of-state)
- Charm (transport properties)

**Almost unexplored (not accessible) so far in the high-$\mu_B$ region**

Gao, Pawlowski, PLB 820 (2021) 136584



# The quest for the highest rates




T. Galatyuk, NPA 982 (2019), update 2023
https://github.com/tgalatyuk/interaction_rate_facilities,
CBM, EPJA 53 3 (2017) 60

**The program needs ever more precise data and sensitivity for rarest signals**

- **CBM** will play a unique role in the exploration of the QCD phase diagram in the region of high $\mu_B$ with rare and electromagnetic probes: high-rate capability
- HADES: established thermal radiation at high $\mu_B$, limited to 20kHz and $\sqrt{s_{NN}}$ = 2.4 GeV
- STAR FXT@RHIC: BES program completed; limited capabilities for rare probes
- CEE+@HIAF under construction: multipurpose detector based on TPC, anticipated rate capability 500 kHz
- J-PARC-HI proposal: highest proton beam intensities, addition of heavy-ion option (HI booster), state-of-the-art detectors ($e$, $\mu$, hadrons)

# FAIR

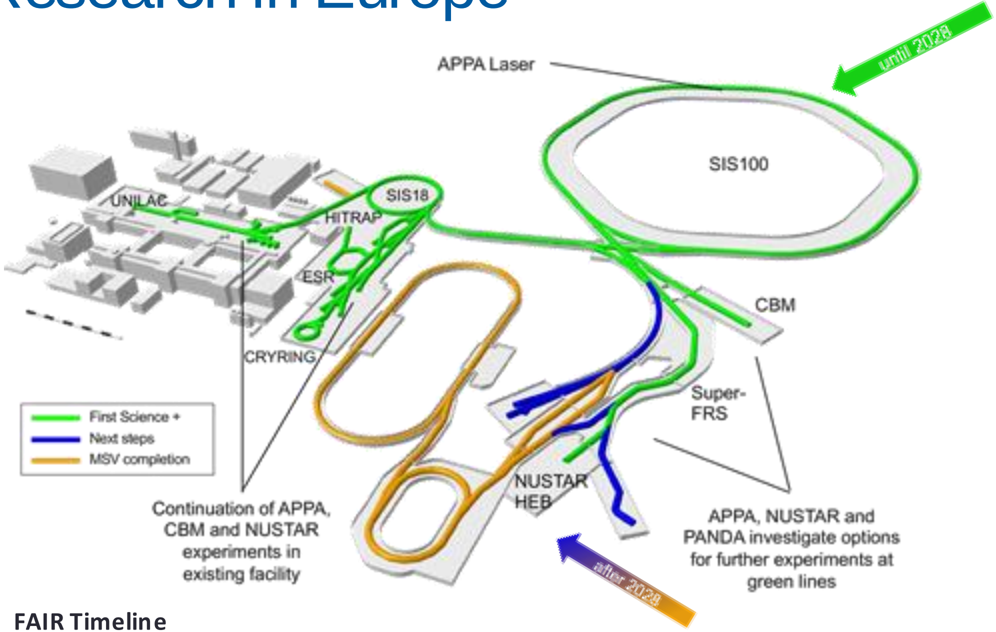
# Facility for Antiproton and Ion Research in Europe

## FAIR pillars:

- **APPA** - Atomic, Plasma Physics and Applications
- **CBM** - Compressed Baryonic Matter
- **NUSTAR** - Nuclear Structure, Astrophysics and Reactions
- **PANDA** - Physics with High Energy Antiprotons

| 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: ~$10^{13}$/s for p; ~$10^{11}$/s for U
- Antimatter: antiproton beams
- Precision: System of storage and cooler rings




**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)
- 2024: Start of installation
- 2025: Start of commissioning
- **2028: FAIR 2028 Operation**

# FAIR facility: becoming reality

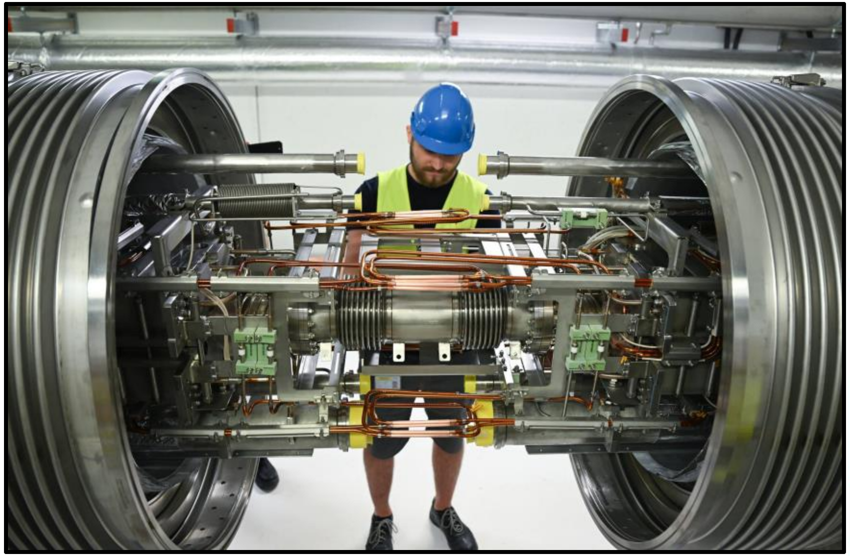

FAIR Construction site, Q4.2024

Movies from the facility: https://www.youtube.com/@FAIRGSI

# Installation

- Cryogenic plant installed in 2023, commissioning in July 2025
- Technical Building Infrastructure, cables pulling – 60% complete
- Accelerator installation since January 2024 (50% dipoles installed)

100%



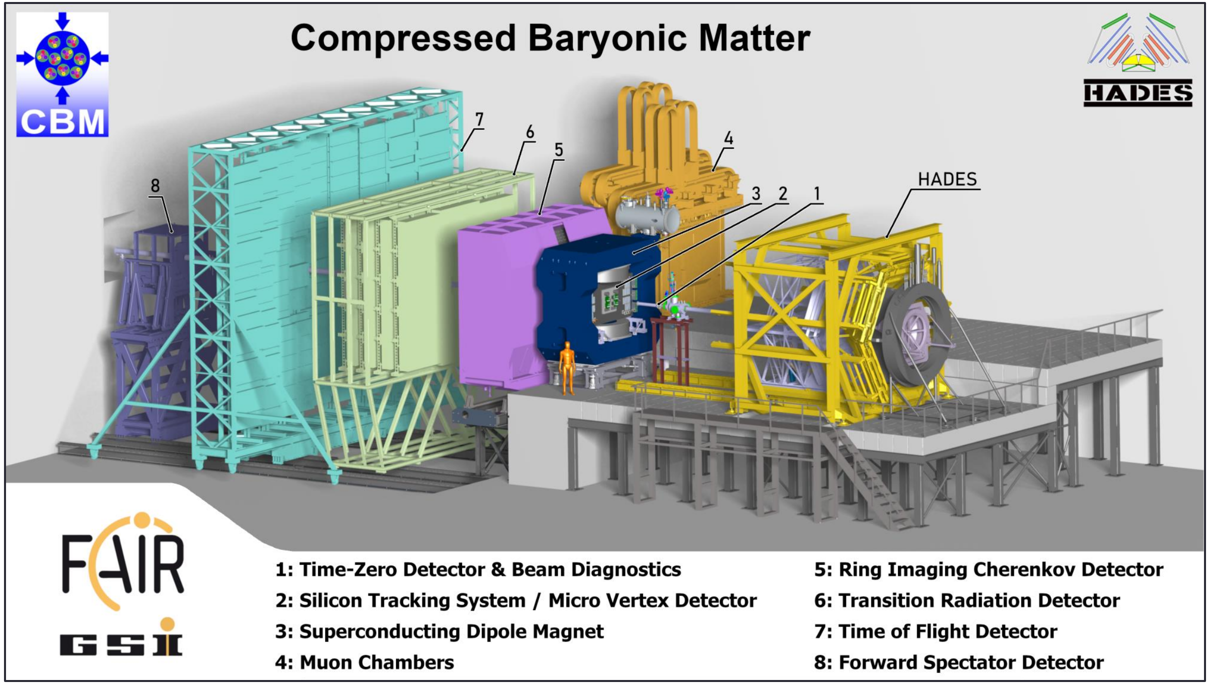
50%

60%

# COMPRESSED BARYONIC MATTER EXPERIMENT @ FAIR

# CBM

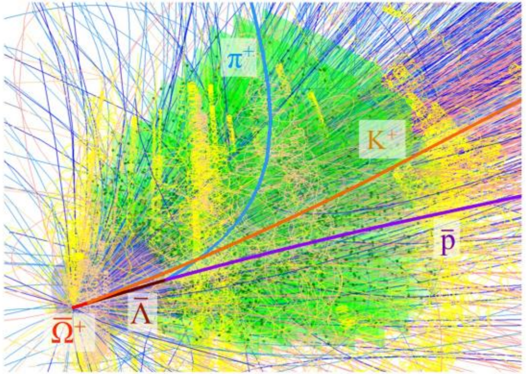
- Fixed target experiment
  - obtain highest luminosities
- Versatile detector systems
  - optimal setup for a given observable
- Tracking based entirely on silicon
  - fast and precise track reconstruction
- Particle identification:
  - hadrons and leptons, displaced (~50 µm) vertex reconstruction, decay topology




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

# CBM Experiment: rate challenge

- High event rates, up to $10^7$ Hz Au+Au collisions
- High multiplicity collisions, O(750) particles/collision
- Data rates: O(TB/s)
- Data volume: 10-20 PB/year



CBM simulation, central Au+Au @ 10 AGeV/*c*

- Fast, radiation hard detectors & front-end electronics
- Free-streaming front-end connectivity up to 10 MHz
- High-speed DAQ and high-performance computing farm for online event selection ⟶ highly selective data reduction


GSI Green IT Cube

# CBM Target Hall

**CBM Cave**

- A dedicated cave with a massive beam dump for high-intensity, high-energy beams
- CBM Cave/Building shell completed
- **T**echnical **B**uilding **I**nfrastructure in 2025

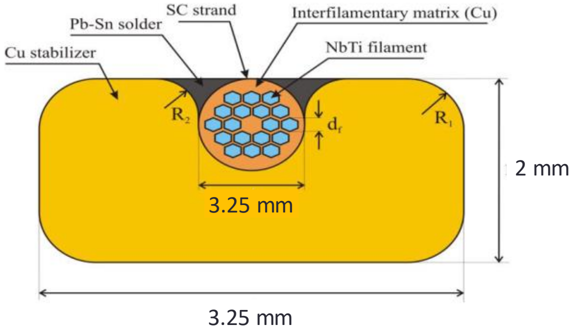
**CBM Installation**

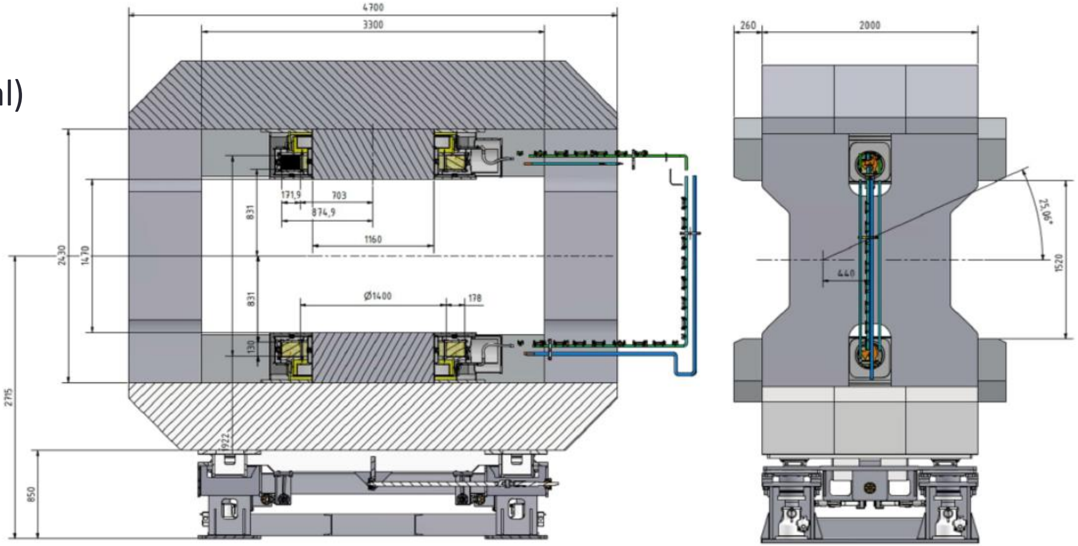
- CBM installation activities (platform) started in June 2023!
- CBM ready for beam by 2028, ~12 months contingency for CBM global commissioning
- SIS100 ready for beam to CBM in ~Q4.2028

# CBM: BECOMING REALITY

# The CBM superconducting dipole

- Magnetic field: 1 T ($\Delta p/p < 2\%$)
- Aperture: 1.47 × 3.3 $m^2$
- Acceptance: ±25° (vertical), ±30° (horizontal)
- Total weight of the yoke: ~150 t
- Conductor: NbTi in copper; Cu/SC ≥ 5
- Operating temperature: 4.5 K



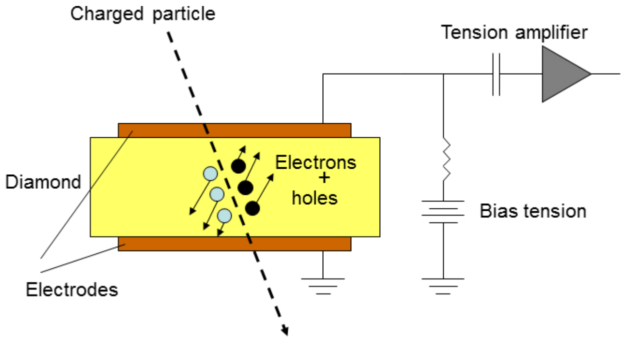

Status March 2025: **Production Readiness Review**

# Beam Monitoring: T0 and HALO

TU Darmstadt, GSI

**Day-1 concept based on pcCVD high-purity diamond sensors**

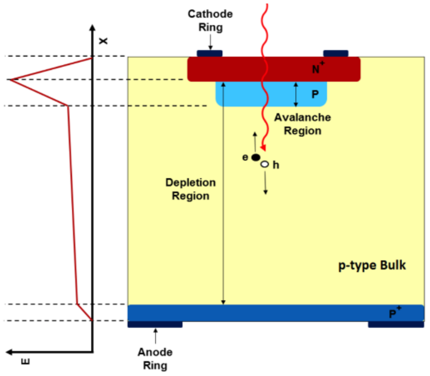
- High purity pcCVD diamond material: 1 cm × 1 cm, 80 µm thickness, striped metallization 16ch/side
- Required time resolution: 50 ps

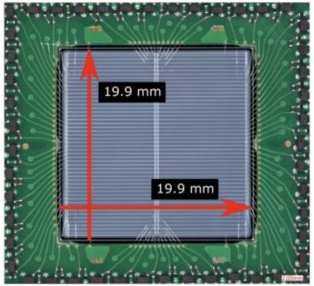



16CH pcCVD prototype

**R&D on novel sensor technologies → LGAD**

- Currently employed by HADES START detector
- Sensor development: Bruno Kessler Foundation;
- Performance with high-intensity heavy ion beams to be shown
- Further R&D activities (NIM 1039 (2022) 167046): HADES T0, Medical applications, Beam diagnostics for S-DALINAC



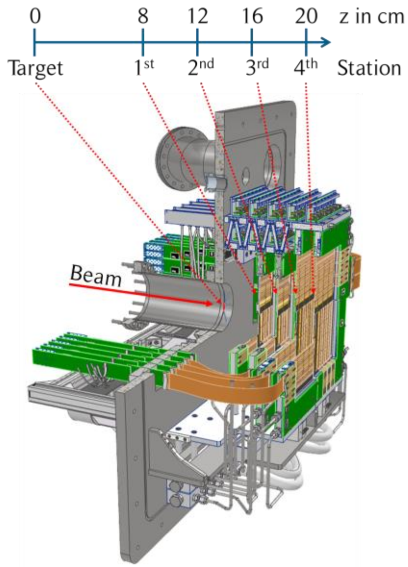




HADES LGAD-T0

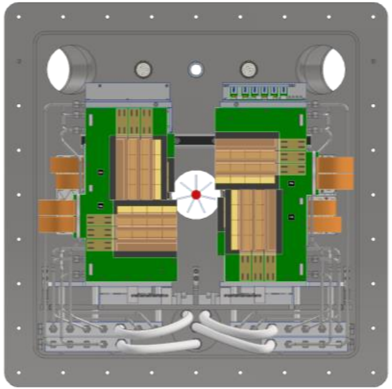
# Micro Vertex Detector

Goethe University Frankfurt, GSI, IPHC Strasbourg, CTU Prague, IMP-CAS

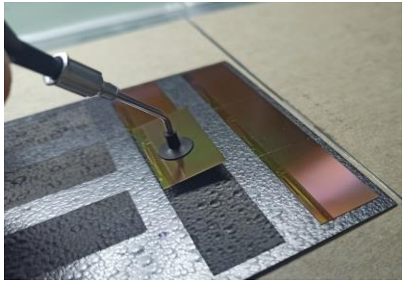
- 4 detector stations, based on **MAPS** technology (~1200 $cm^2$)
  - 100 kHz Au+Au @ 11 AGeV and 10 GHz p+Au @ 30 AGeV
  - Non-uniform hit density in time and space
  - High radiation environment, operating in a vacuum
  - Material budget of $\mathcal{O}(0.5\% X_0)$ with TPG (pCVD diamond) carriers
- Pointing precision at the target region
- Reconstruction of low-momentum tracks



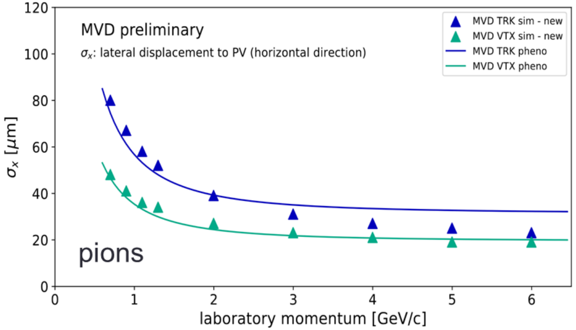

MVD in TRacKing configuration

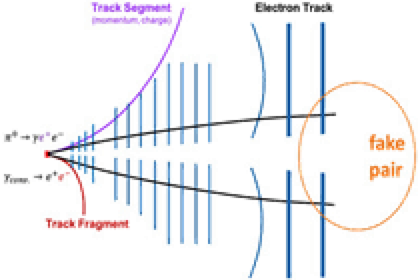


MVD open/close for beam tuning



Placing MAPS sensors on TPG carriers



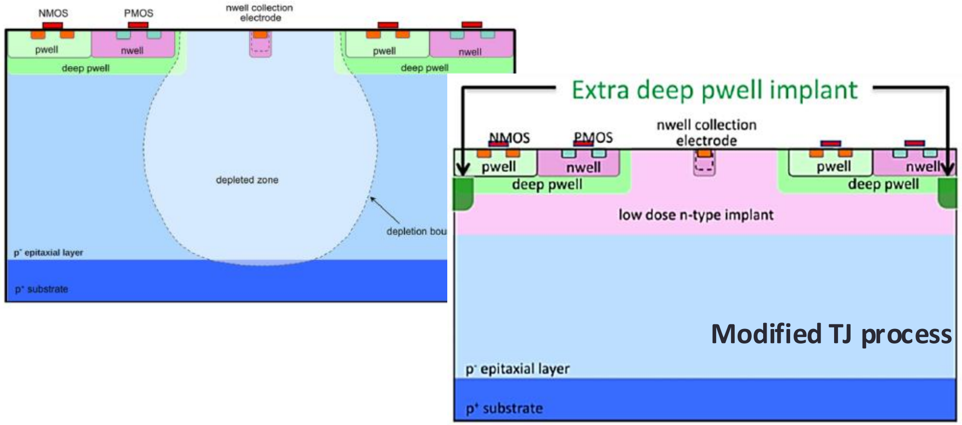



# MIMOSIS chip

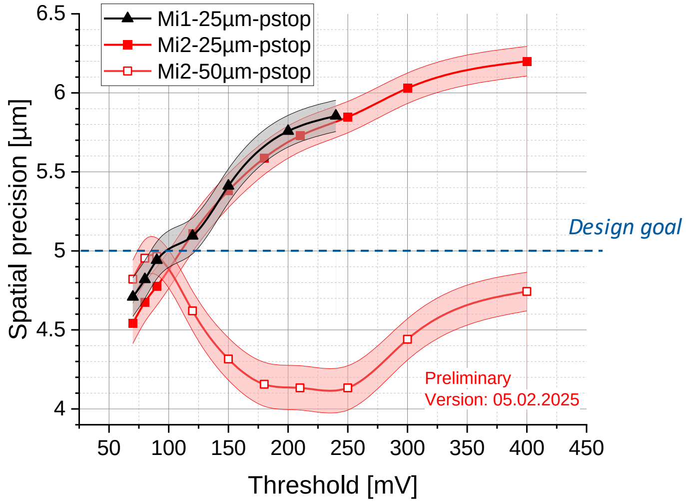
- MIMOSIS based on the ALPIDE (ALICE ITS2 chip) architecture
- Full-size prototypes: MIMOSIS-1, MIMOSIS-2, MIMOSIS-2.1
- 504 × 1024 pixels (27 µm × 30 µm pitch)
- Final chip MIMOSIS-3 ⟶ **submission in 2025**
- CBM pioneering work on MAPS in heavy-ion physics
  - Heavy Flavour Tracker (STAR@RHIC) based on MIMOSA sensor – MIMOSIS predecessor

| Chip requirements | |
|---|---|
| Spatial / time resolution | ~5 µm / 5 µs |
| Material budget | ~0.05% $X_0$ |
| Rad. tolerance (non-ionizing) | ~ 7 x $10^{13}$ $n_{eq}/cm^2$ |
| Rad. tolerance (ionizing) | ~ 5 MRad |
| Rate capability (mean/peak) | (20/80) MHz/cm² |
| Data rate | > 2 Gbit/s |
| Readout mode | Continuous |

- *Established by ALPIDE* (Spatial / time resolution, Material budget)
- *~10 × ALPIDE (mod. TJ process)* (Rad. tolerance, non-ionizing and ionizing)
- *High internal bandwidth needed* (Rate capability, Data rate)

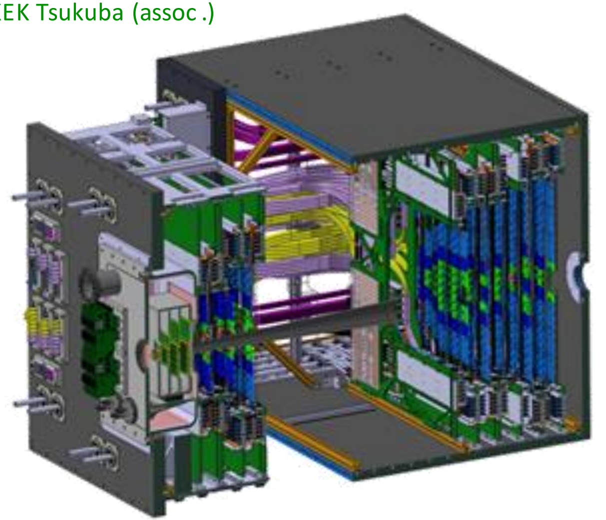



W. Snoeys, "FASTPIX: sub-nanosecond radiation tolerant CMOS pixel sensors", ATTRACT

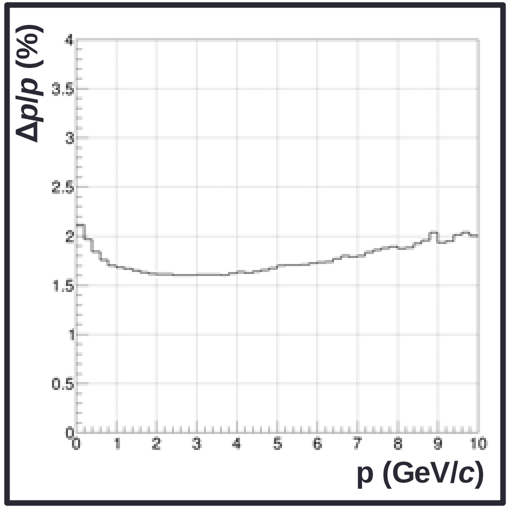


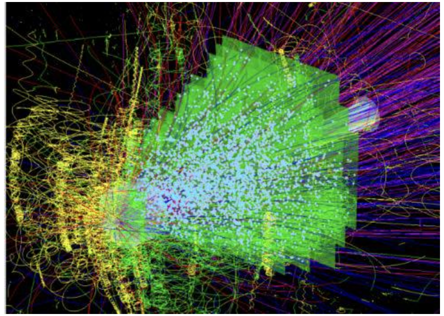
# Silicon Tracking System

GSI Darmstadt, KIT Karlsruhe, JU Cracow, AGH Cracow, KINR Kiev, Univ. Tübingen, Warsaw UT, Uni. Frankfurt, KEK Tsukuba (assoc.)



- **Main CBM detector for charged particle tracking and momentum determination**
  at $10^5$ – $10^7$/s (A+A), up to $10^9$/s (p+A) collision rates
- 8 tracking stations
  - double-sided silicon microstrip sensors
  - hit spatial resolution ≈ 15 μm (*x*), 110 μm (*y*)
- Low-power, self-triggering front-end electronics
  - SMX v2.2 ASIC NIM A 908 (2018) 225)
  - 128 channels: 5 bit ADC, time resolution ≲ 5 ns
- Material budget: 0.3% – 1.5% $X_0$ per station
  - Δp/p < 2% (p > 1 GeV/c, 1 Tm field)
- Rad. tolerance: ~$10^{14}$ 1 MeV $n_{eq}$ over lifetime

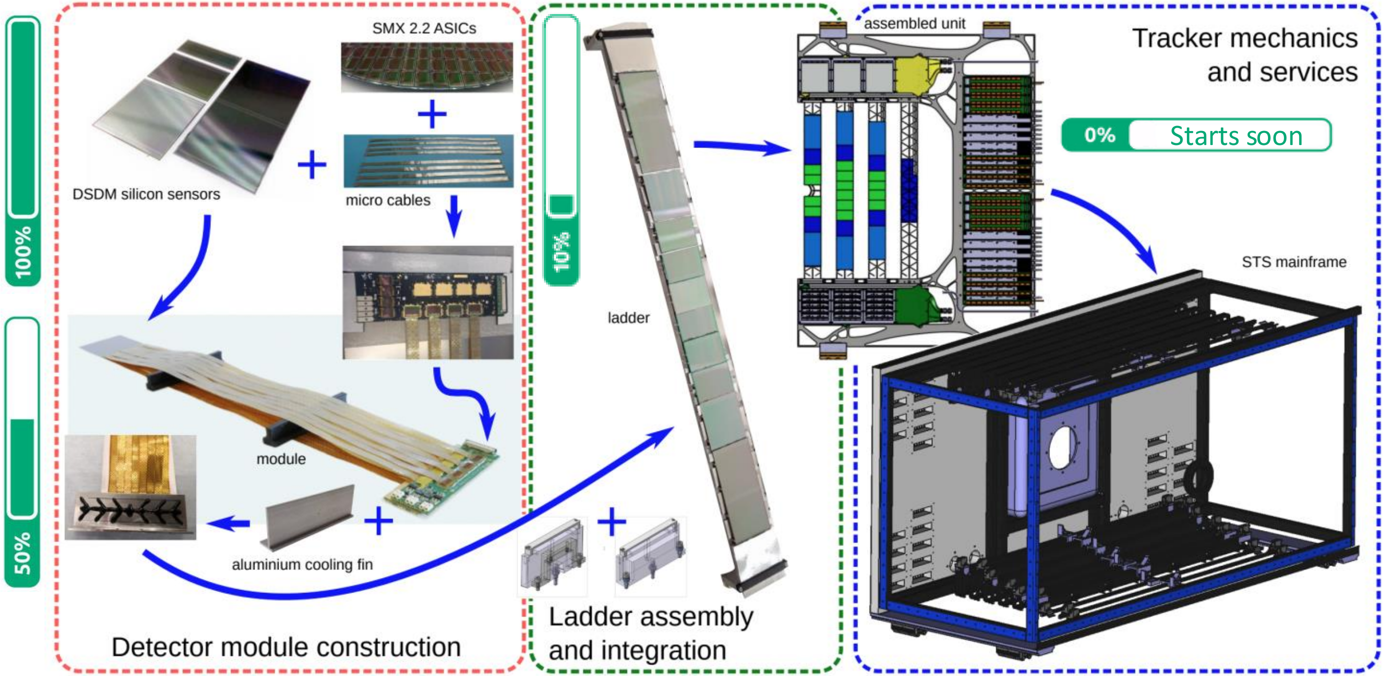


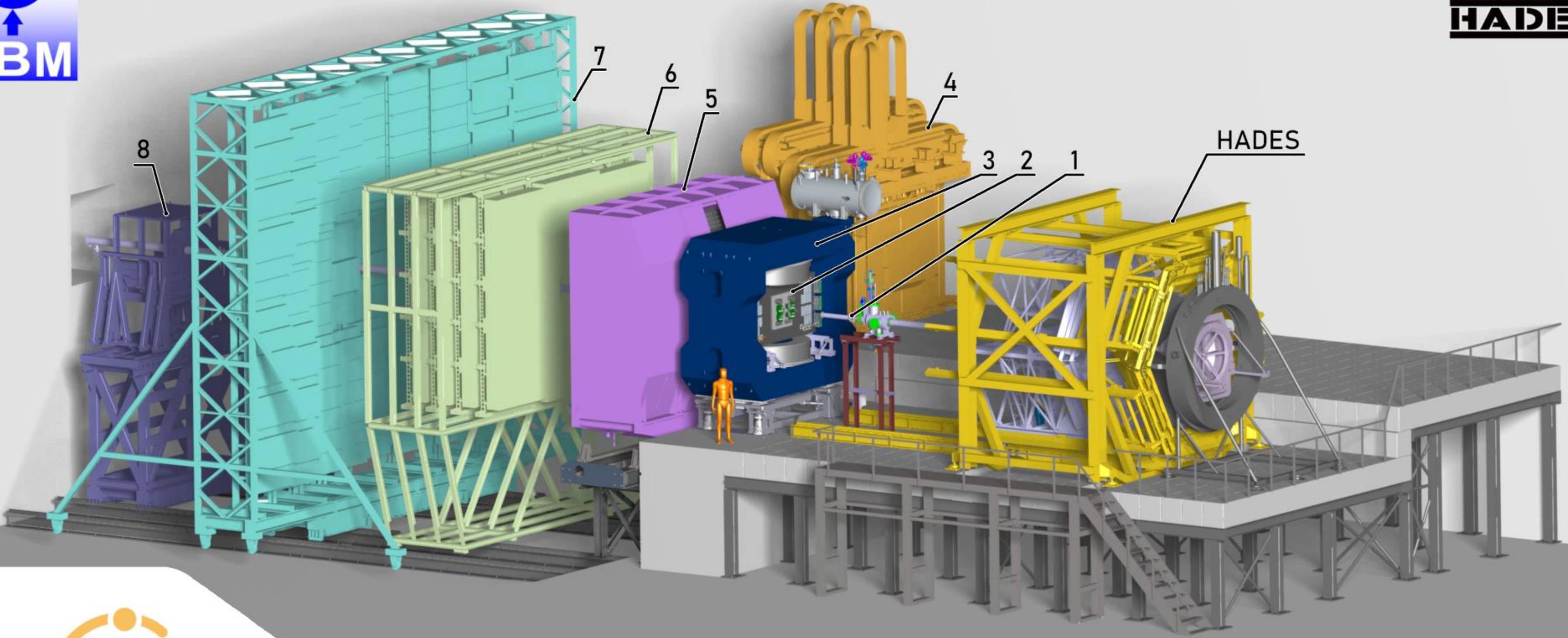
CBM simulation: Au-Au 12 AGeV/*c*

# Silicon Tracking System

- Very complex lightweight system, integration effort
- Series production ongoing: 876 modules, 106 ladders, 8 tracking layers



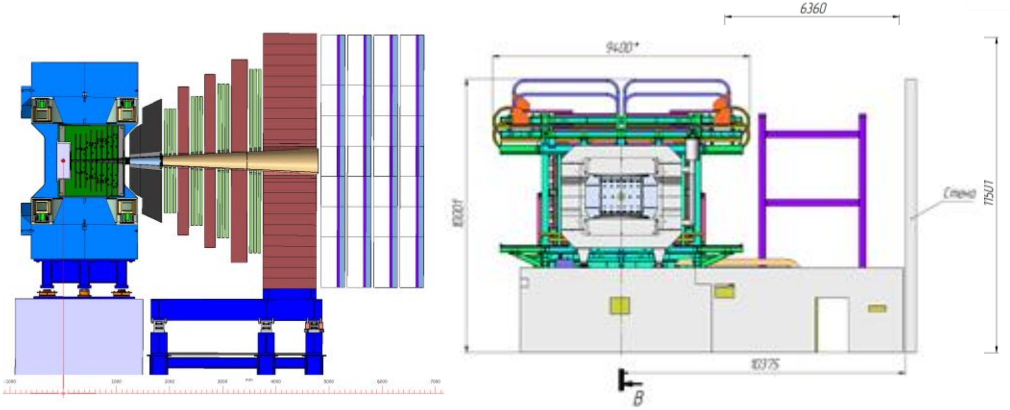
# Compressed Baryonic Matter



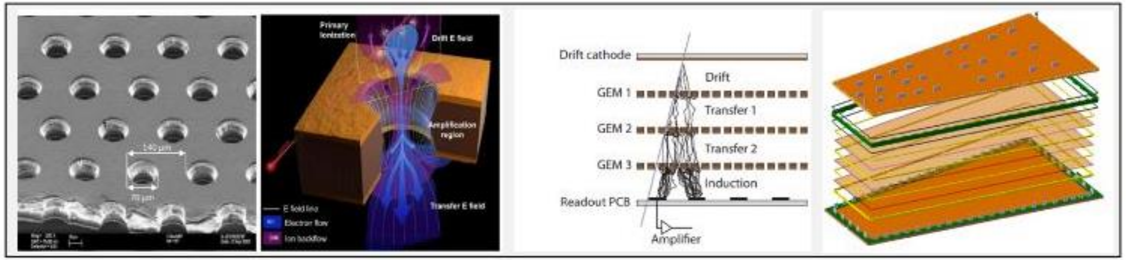

DOWNSTREAM DETECTORS

# Muon Chambers

Aligarh Muslim U., Bose Inst. Kolkata, Panjab U., U. of Jammu. , U. of Kashmir, U. of Calcutta, B.H. U. Varanasi, VECC Kolkata, IOP Bhubaneswar, NISER Bhubaneswar, IIT Kharagpur, IIT Indore, Guwahati U.




- 5 absorbers (Graphite, Fe, Fe, Fe, Fe)
- 4 detector stations, 3 detector layers each,
  - Station 1 and 2: GEM chambers
  - Station 3 and 4: RPCs
- Movable (110 t) between data taking in di-muon mode and parking during the di-electron mode runs
- Different configurations for different collision energies and physics
- 10 MHz interaction rate capability
- Di-muon trigger!



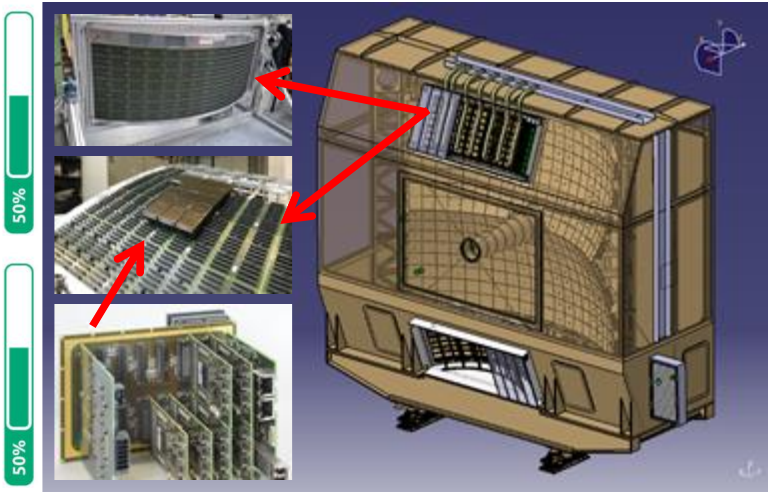

© CERN. CMS GEMs

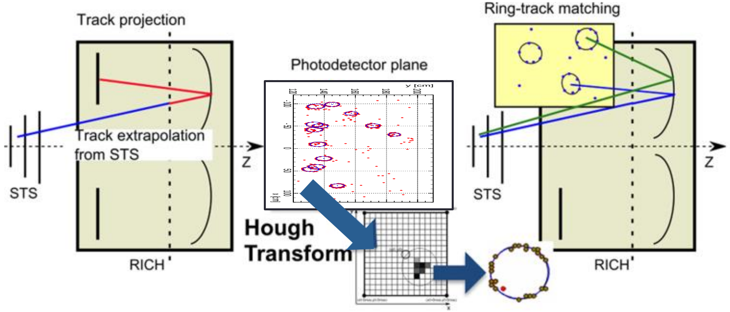
- Series production of Station 1 GEM chambers **starts soon**!

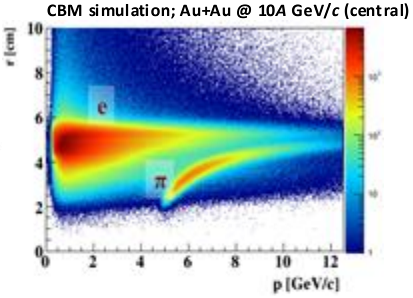
# Ring Imaging Cherenkov Detector

Univ. Giessen, Univ. Wuppertal, GSI Darmstadt

- Gaseous RICH detector for electron identification ($p$ < 8 GeV/c)
- Radiator: $CO_2$ as radiator gas ($p_{\pi,th}$ = 4.65 GeV/$c$), ~80 $m^3$ volume
- Photodetector: 2 photodetector planes (MAPMTs, Hamamatsu H12700) with approx. 55 000 channels
- Mirror: 2 large spherical mirrors ($R$ = 3 m) as focussing optics, Al+$MgF_2$ reflective coating
- **Production** of cameras and FEE ongoing
- Next: Mirror Wall **Production Readiness**

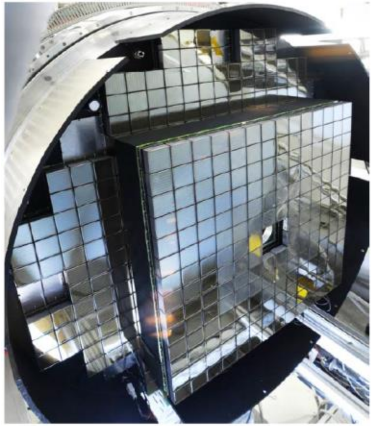


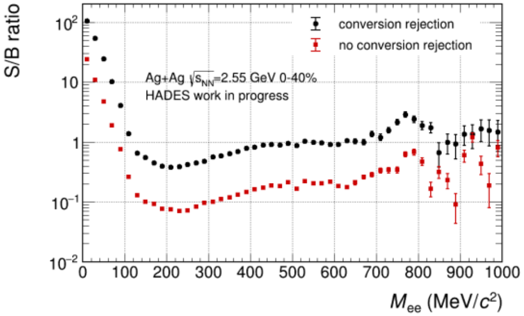



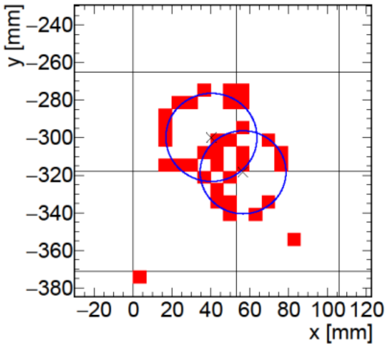



# HADES RICH upgrade with CBM technology

- HADES photon detector replaced by 428 H12700 MAPMTs (~40% of CBM MAPMTs)
- New readout electronics developed based on the „DiRICH“ family,
  - average timing precision ~225 ps, same development for CBM!
- Great performance figures of the upgraded HADES RICH
  - very low noise and clear rings
  - ring finder integrated efficiency > 99.5%
  - electrons integrated purity > 99.5%
  - 15-19 measured photoelectrons per ring
  - pion suppression factor $>10^4$
  - excellent double ring detection (factor of 8 better signal-to-background ratio)





# Transition Radiation Detector

NIPNE Bucharest, Univ. Frankfurt, Univ. Heidelberg, Univ. Münster, IRI Frankfurt, GSI and FFN (U. Bochum)

- Electron-ID at high momenta

⇒ π-suppression 10–20 (90% e-eff.)

- ID of light nuclei (e.g. d – $^4$He)

⇒ *dE*/*dx*-resolution ~25 %

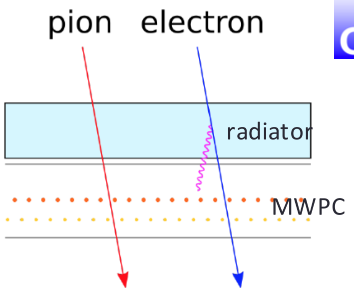
- Tracking between STS and TOF

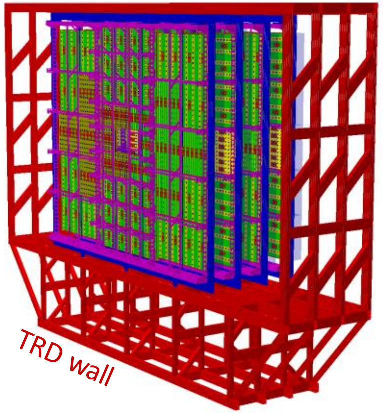
⇒ space-point resolution ~300 µm (across the pads)

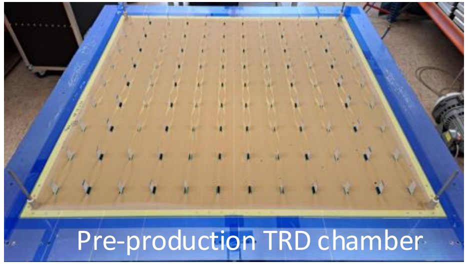
- High rates ⇒ fast detector (max. signal coll. 0.3 µs)

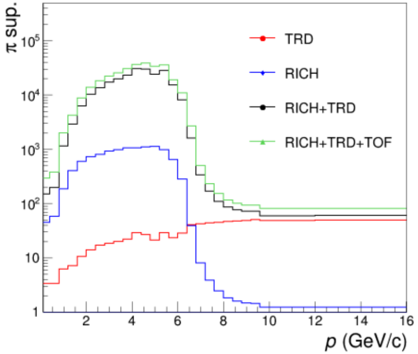
**Preproduction ongoing, next production readiness!**

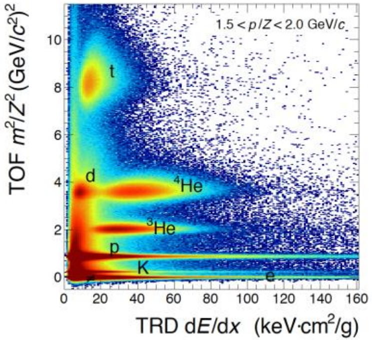
- Four detector layers (SIS100): radiator with PE foam foils + MWPC
- ~250 000 channels, SPADIC ASIC FEE
- Inner Wall (TRD2D) for the highest rates with enhanced spatial res.



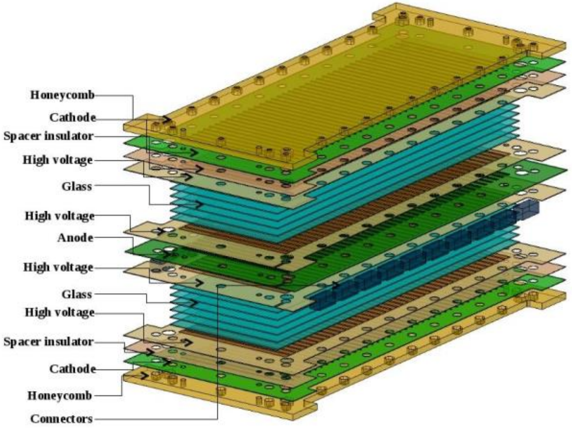



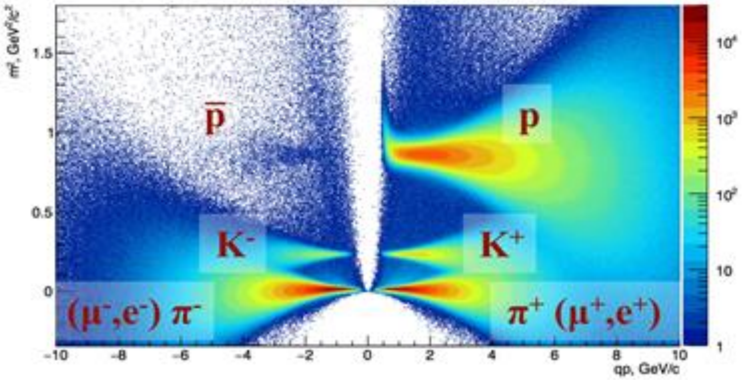

CBM simulation; Au+Au @ 10*A* GeV/*c* (central)

# Time of Flight

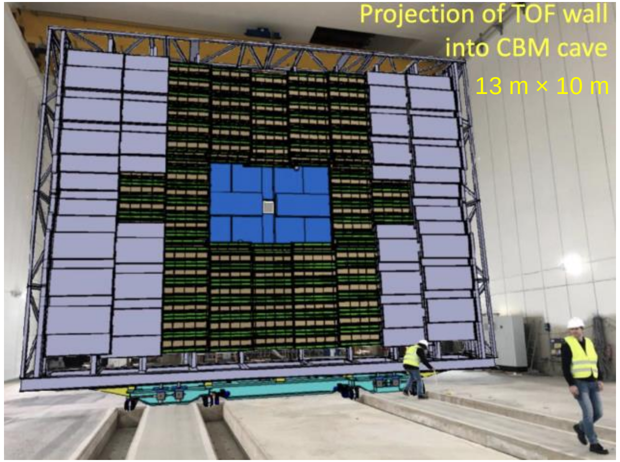
U. Heidelberg, THU Beijing, NIPNE Bucharest, GSI, TU Darmstadt, USTC Hefei, HZDRRossendorf, CCNU Wuhan

- Double-stack multi-gap resistive plate chambers for ultra-high rates
- All CBM TOF wall requirements met!
  - system time resolution: $\sigma_{sys} \approx 80$ ps
  - efficiency: $\varepsilon \gtrsim 95$ %
  - rate capability up to 50 kHz/cm$^2$ (depending on the region) achieved with a float ($\rho \approx 10^{12}$ Ω cm) and low resistivity ($\rho \approx 10^{10}$ Ω cm) glass
  - Low power FEE (100 000 ch) ⟶ PADI XI + GET4 ASICs (GSI development)



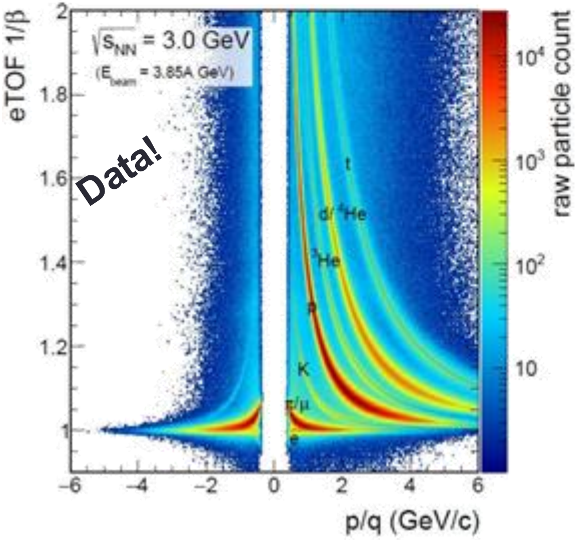

CBM simulation; Au+Au @ 10*A* GeV/*c* (central)



# Endcap TOF at STAR with CBM MRPCs

- As a part of the FAIR Phase-0 program, the CBM TOF detectors have been installed and successfully operated in the STAR BES II
  - 36 modules, 108 MRPCs, ~7000 FEE channels
  - **system time resolution 66 ps (108 counters)**
  - PID capability demonstrated
  - physics analysis started: $4\times10^9$ events collected in FXT and COLL modes
  - operation will continue at $\sqrt{s_{NN}}$ = 200 GeV in the coming years

- **CBM MRPC series production ongoing!**
  - ~230 modules, 1400 MRPCs, 90’000 FEE channels
  - Counter production in China, modules assembly in Bucharest and Heidelberg

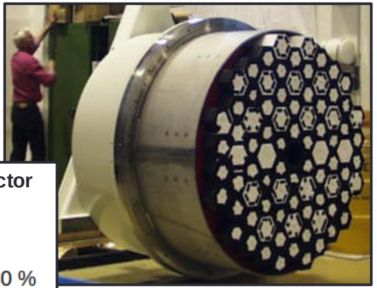



MRPC assembly in Tsinghua University

# Forward Spectator Detector

CTU Prague, GSI and FFN (U. Bochum)

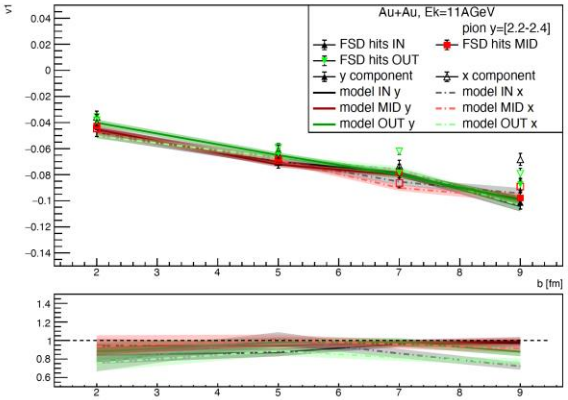
- **Important subsystem for centrality determination**
- Original concept based on hadronic calorimeter (Pb/Scintillator) – contract cancelled
- Replacement **based on plastic scintillator** (see e.g. HADES forward hodoscope)
- Background and performance studies ongoing
- 5×5 cm$^2$ scintillator module prototypes with PMTs; TRB+DiRICH readout
- Possibility of adding COSY-TOF neutron detector



COSY-TOF neutron detector
Ø 126 cm
84 modules, l = 45 cm
plastic scintillator
n-detection efficiency ≈ 30 %

- Aim for the **TDR in the mid. 2025**

**$v_1$ of pions: reconstruction vs. model**




FSD support structure at FAIR

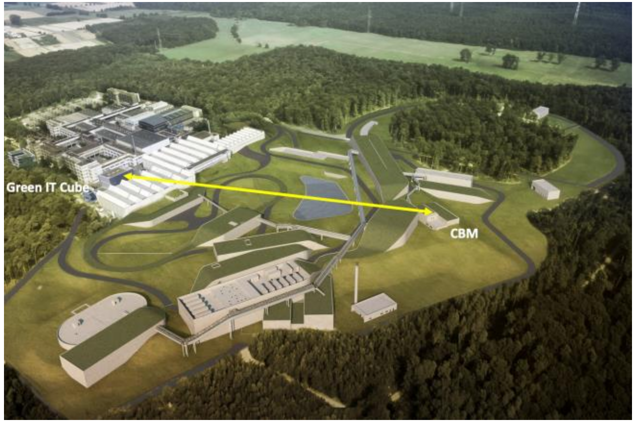
# CBM data acquisition

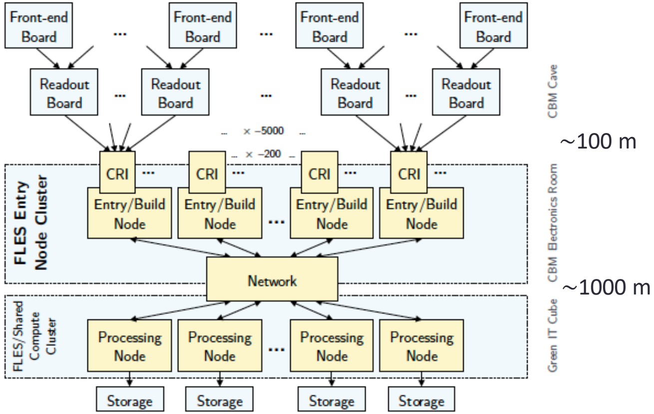
FIAS, GSI, KIT, ZIB

- **Free-streaming readout up to 10 MHz interaction rates (peak)**
- **Raw data rate about 0.5-1.0 TB/s**
- **Online reduction of the raw data by ~2 orders of magnitude**

- FEE of all CBM detectors autonomous and self-triggered, delivers time-stamped hit messages
- FEE synchronized by a central timing system (TFC)
- Online systems: collect, aggregate and deliver data to the online compute farm
- First Level Event Selector: event reconstruction and inspection online, up to the software trigger decision

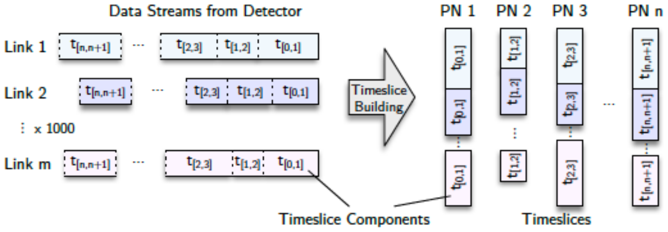
- **DAQ/FLES TDR was accepted in June 2023!**



# Online systems

FIAS, GSI, KIT, ZIB

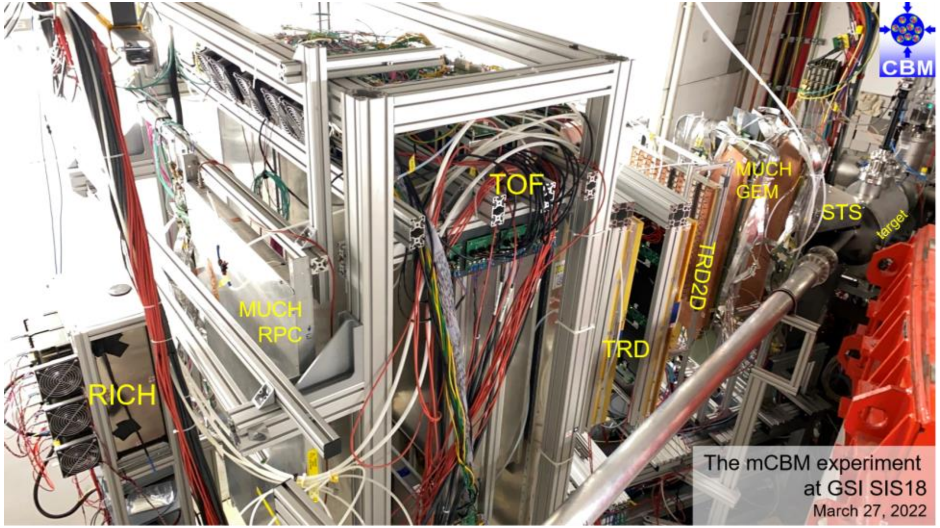


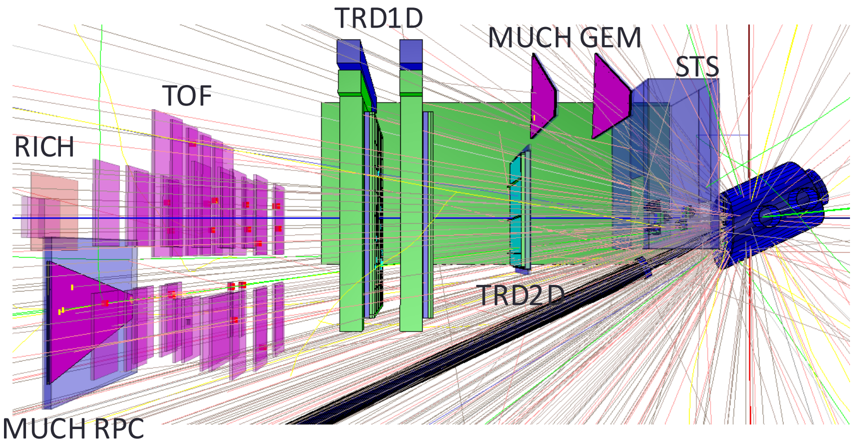

- Readout boards (mostly GBTx-based) send time-stamped data stream (time-slice components) via optical links to CRIs
- The **First-level Event Selector (FLES)** is the central data handling and event selection entity of the CBM experiment
- FPGA-based **Common Readout Interface** PCIe cards:
  - Reformats data received from FEE into micro-slices, suitable for processing in the FLES
  - Forwards clock and time information to FEE
- Timeslice components assembled by the entry nodes are transferred over an InfiniBand network to the processing nodes at GSI Green-IT Cube (CPU/GPU farm)
- Required online computing capacity: ~1000 kHEPSPEC06

CRI1.0 board (BNL-712 v2)


GSI Green-IT Cube

# FAIR Phase-0: mCBM at SIS18

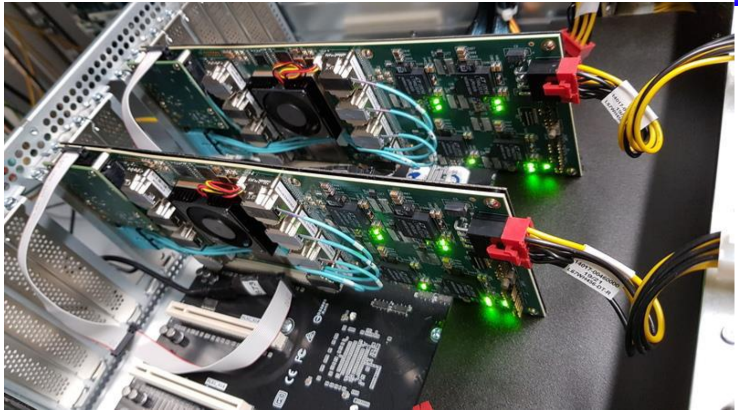



- Full system test, verification of the triggerless-streaming read-out and data transport of CBM
- High-rate detector tests with up to 10 MHz collision rates
- Physics program: Λ excitation function in the SIS18 energy range

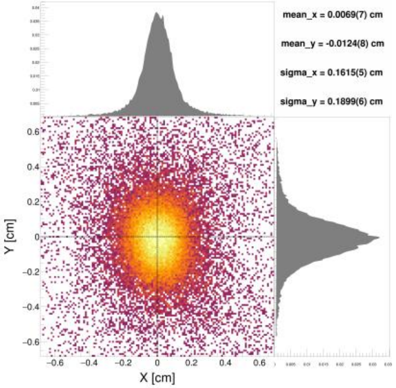
# mCBM data acquisition

- Free-streaming readout implemented and commissioned in mCBM
- Connection scheme, hardware, achieved occupancies close to the final CBM DAQ → can be scaled towards full CBM
- High-rate capabilities demonstrated up to 10 MHz

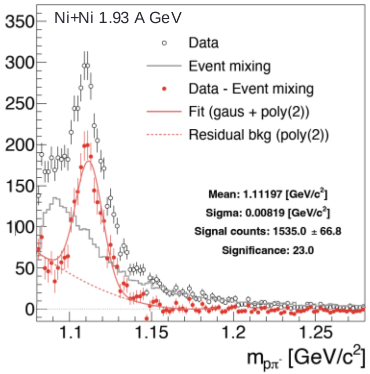


**mCBM DAQ with CRIs (prototype for CBM) in an entry node**

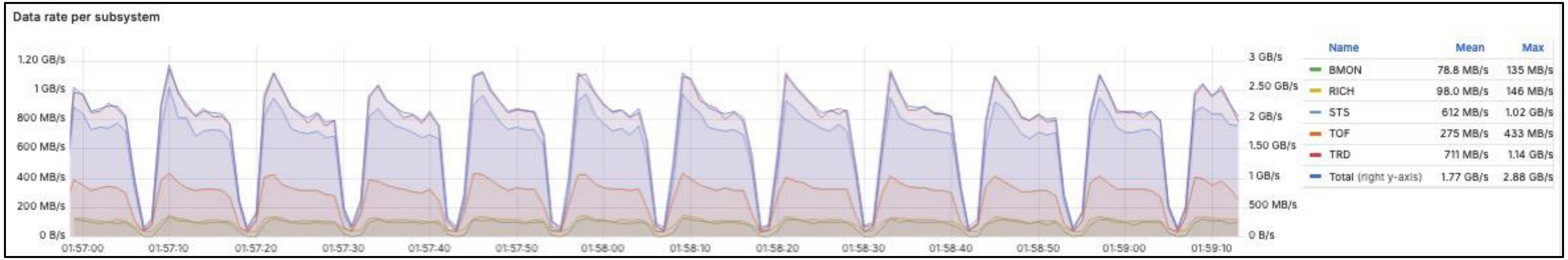
- CBM readout concept demonstrated and verified!
- High-rate tests of detector prototypes
- First results: Λ signal identified with topological + timing cuts only (calibration and alignment studies ongoing)

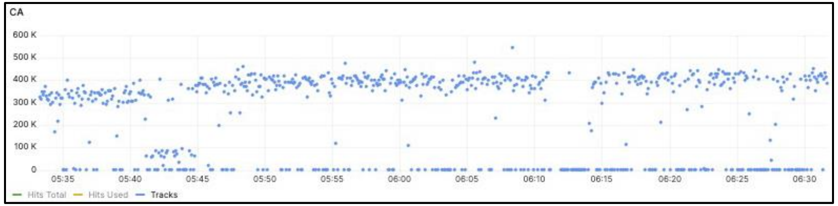


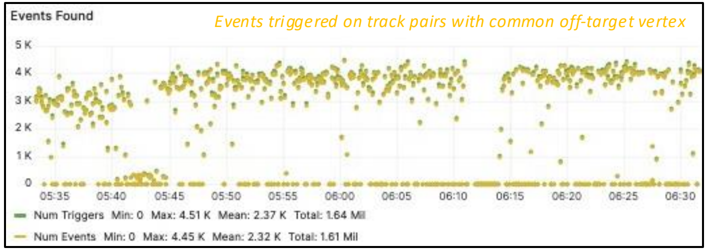

*mCBM vertex reconstruction (multi-track PCA)*



# mCBM @ SIS18 – CBM full system setup



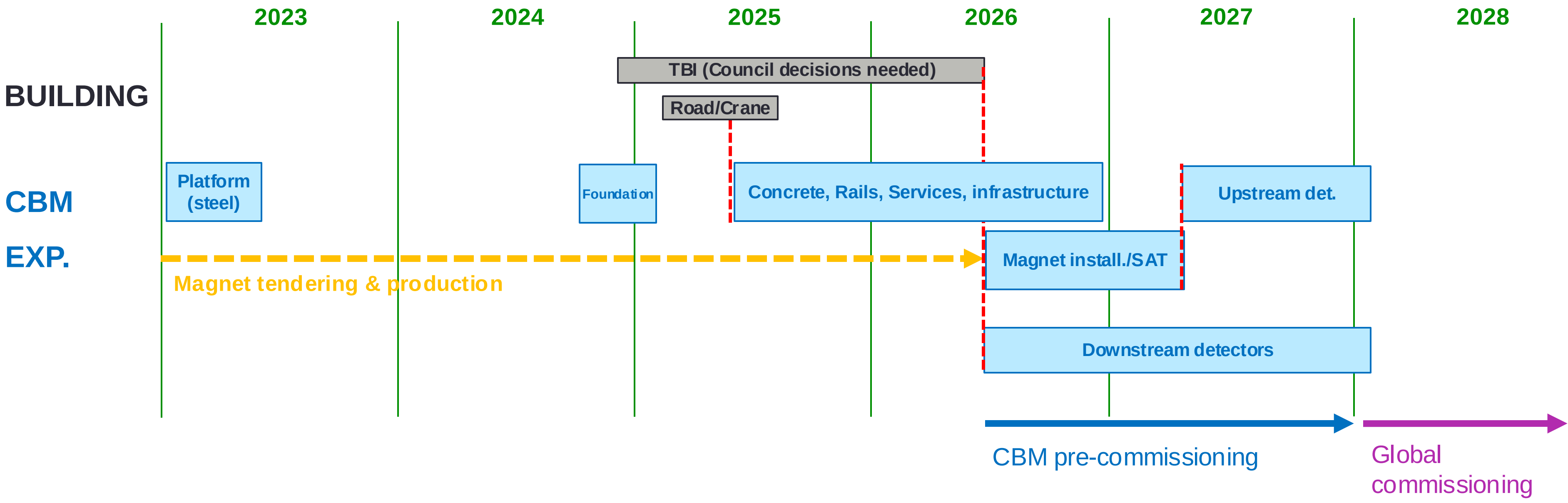




**mCBM campaign in 2024-2025**

- Runs in 2024-2025 approved by GSI-PAC
- Further development of the readout chain and **online** analysis tools
- High-rate detector tests: Production Readiness Reviews, QA/QC

# Installation/commissioning




- **Ultimate goal: CBM ready for beam in 2028**
- ~1y contingency until SIS100 “ready for physics” (used for CBM global commissioning)
- CBM Technical Building Infrastructure and Magnet production on the critical path

# HIGHLIGHTED FUTURE DIRECTIONS

# CBM physics topics

### QCD matter properties at large $\mu_B$

- Critical point, deconfinement phase transition, Equation-of-State
- Hadron yields, collective flow, dileptons, correlations, fluctuations
- (Multi-)strange hyperons (Λ, Σ, Ξ, Ω)

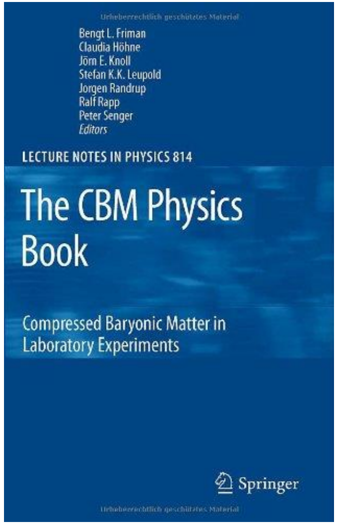
### Chiral symmetry at large $\mu_B$

- In-medium modifications of light vector mesons
- Chiral $\rho$-$a_1$ mixing via intermediate mass dileptons

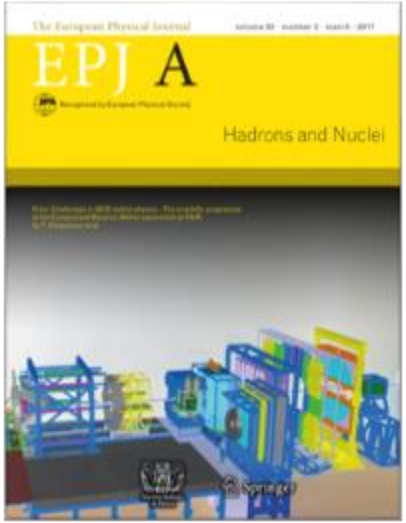
### Hypernuclei

### Charm production and propagation at threshold energies

- Excitation function in p+A collisions (J/ψ, $D^0$ , $D^{+/-}$)
- Charmonium suppression in cold nuclear matter




Lect. Notes Phys. 814 (2011) pp.1-980
DOI: 10.1007/978-3-642-13293-3

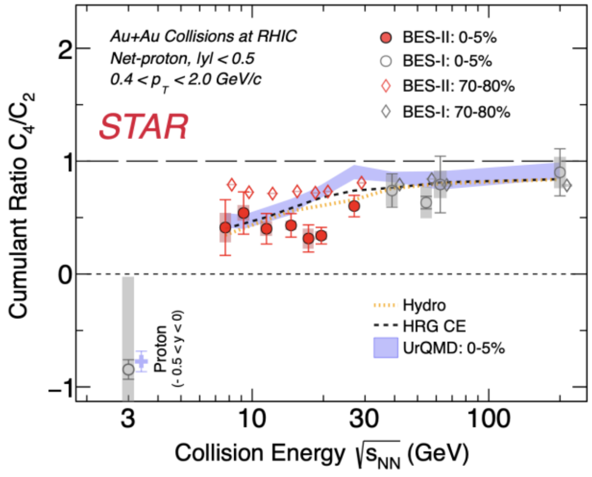


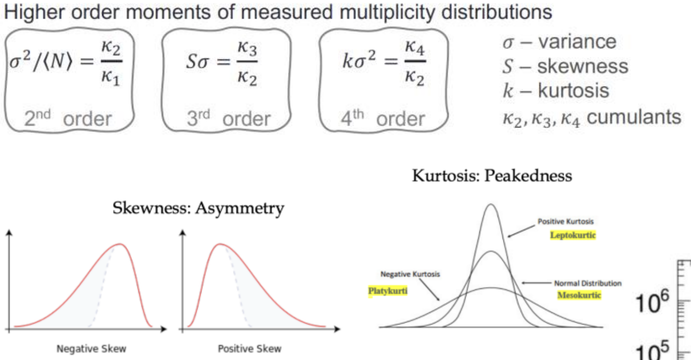

Eur.Phys.J.A 53 (2017) 3, 60
DOI: 10.1140/epja/i2017-12248-y

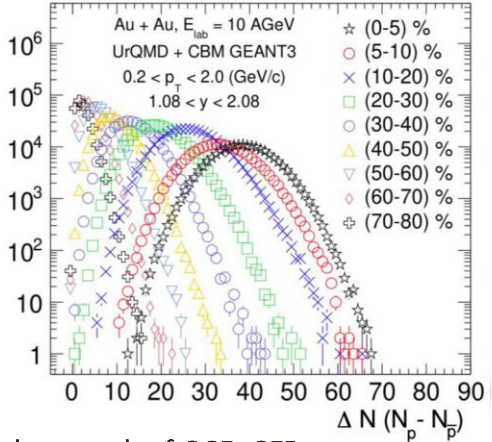
# Critical fluctuations

- Discontinuities of the higher moments of particle number distributions, and ratios of conserved quantities (B, Q, S) are sensitive to QCD CEP → beam energy scan

© A. Pandav for STAR, CPOD 2024 (link)



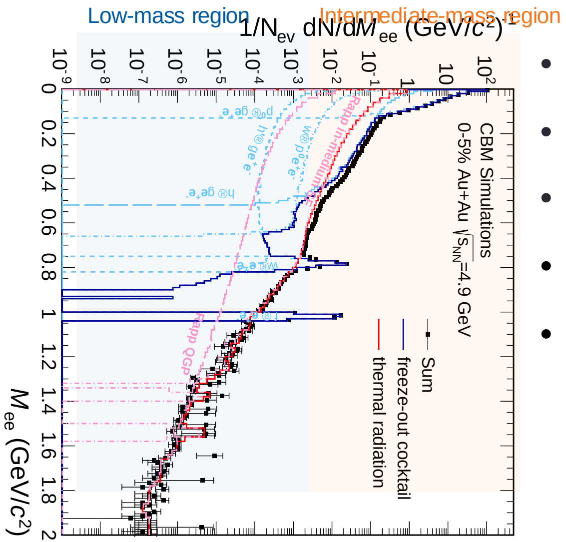




- Higher-order moments probe the tails - statistics!

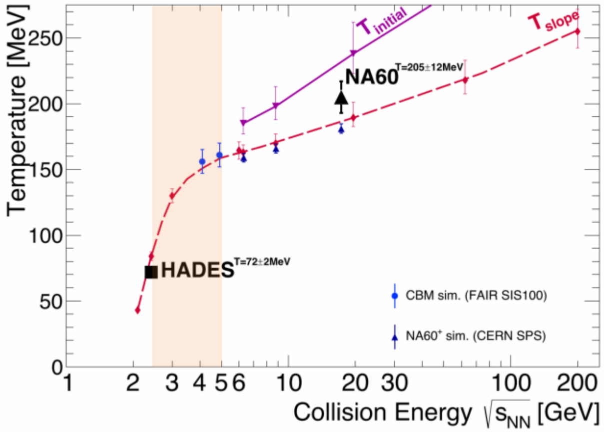
  (6th order derivatives particularly sensitive to features of the QCD phase diagram)

- CBM can systematically study the higher-order cumulants and ratios to contribute significantly to the search of QCD-CEP

# Dilepton measurements




- Electromagnetic Probes: produced in all stages of heavy ion collision
- Low mass range: total yield ~ fireball lifetime
- Intermediate mass range: slope ~ emitting source temperature
- Access to thermal signal is very feasible with good background description
- Crucial for high-quality data: interaction rates and S/B ratio



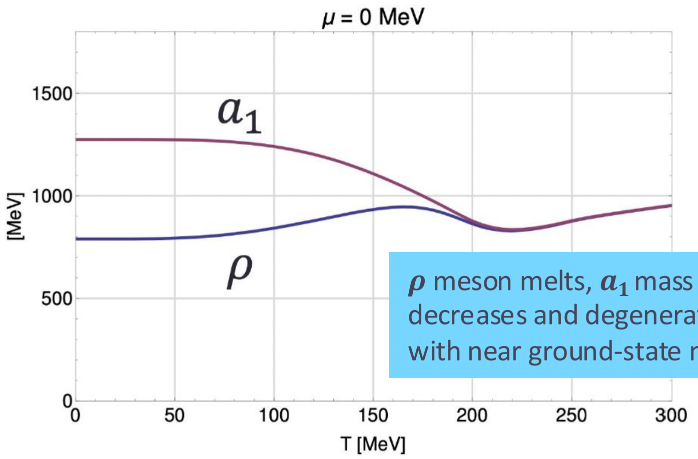

- Non-monotonous behaviour of the caloric curve (flattening) would give evidence for a phase transition.
- CBM will be the first experiment to use di-leptons for systematic measurements in both production channels (e+e- and μ+μ-) in the same

# Dileptons and chiral symmetry of QCD

**Spontaneously broken** in the vacuum

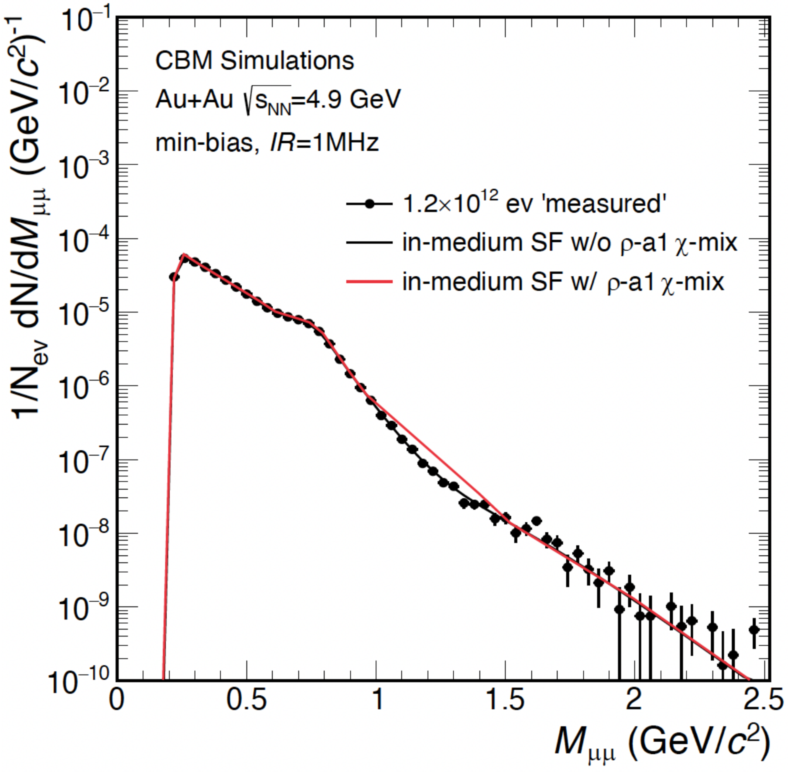
$\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \neq 0$

**Restoration** at finite $T$ and $\mu_B$ manifests itself through mixing of vector and axial-vector correlators



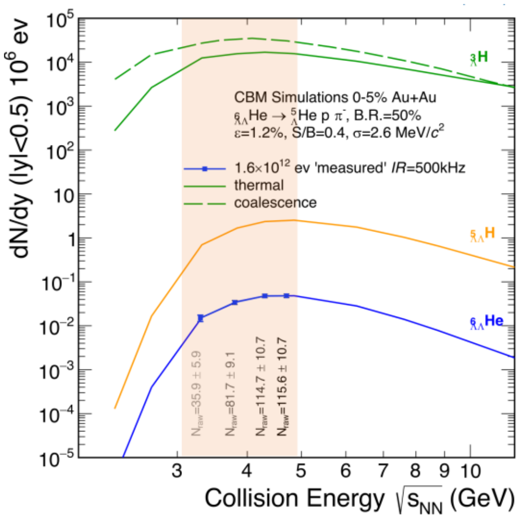

$\rho$ meson melts, $a_1$ mass decreases and degenerates with near ground-state mass

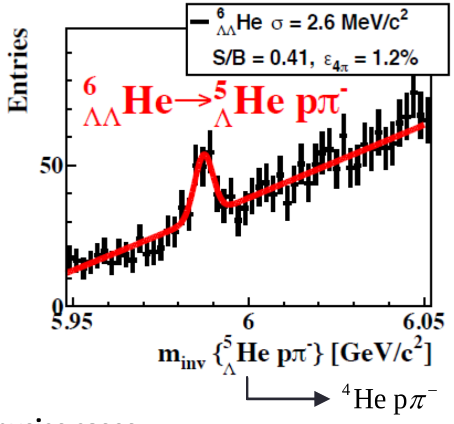
Jung *et al.*, PRD 95, 036020 (2017)
Hohler and Rapp, PLB 731 (2014)

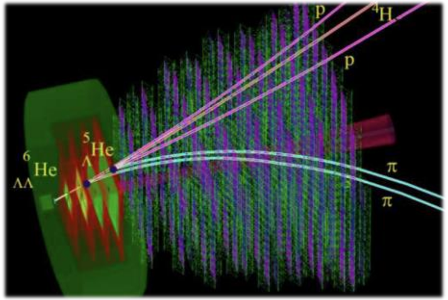


# Hypernuclei

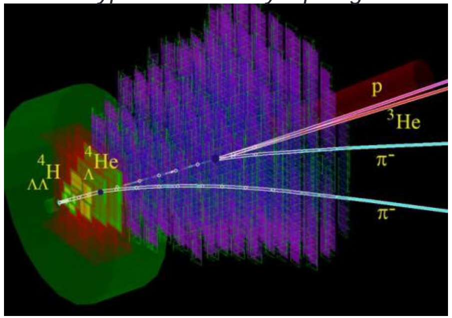
- Precise and comprehensive study of hypernuclei possible at SIS100
- High rate capabilities + online analysis (clean identification) → increased yield




*Hypernuclei decay topologies*




**CBM physics cases:**

- How (hyper)nuclei form in heavy ion collisions?
- Lifetime and binding energy measurement → YN, YY, YNN interactions
- Do YY bound states exist?

# Astrophysical relevance of high $\mu_B$

- Equation of state at neutron star density
- What is the inner core of a neutron star composed of
  - Strange matter, hyperons, quark matter, …
- Upper limits for mass-radius of neutron stars

- Remarkable similarity between

  **binary neutron star merger** and **heavy ion collisions**

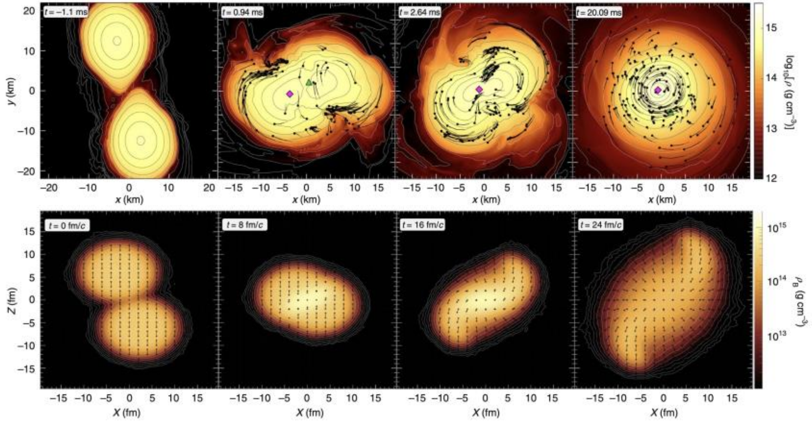
| | |
|---|---|
| **NS merger:** | $T \approx 10 - 100$ MeV |
| | $\rho < 2 - 6\ \rho_0$ |
| **Heavy-ion collision:** | $T < 120$ MeV |
| | $\rho < 5 - 10\ \rho_0$ |


nature physics

ARTICLES

Probing dense baryon-rich matter with virtual photons

The HADES Collaboration*




Different stages of the collision of 2 neutron stars (top) / 2 Au ions (bottom)

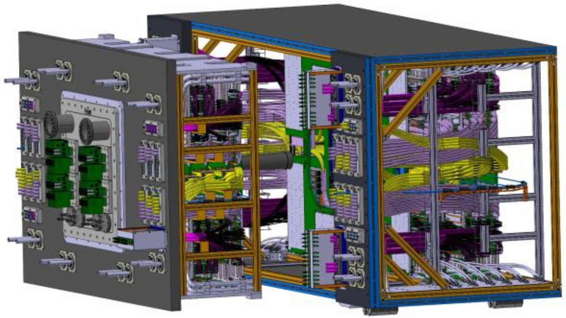
**18 orders of magnitude in scale, still similar conditions!**

# Summary

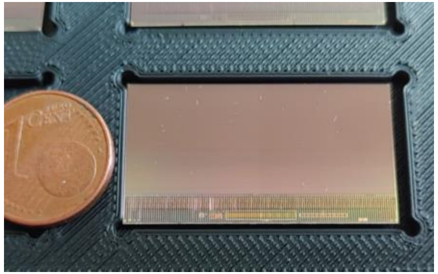
- **Timely completion of SIS100**: unique physics program with CBM
- Long-term prospects: highly competitive due to high interaction rate capability

- 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!**

# Outlook: strategy for detector upgrades



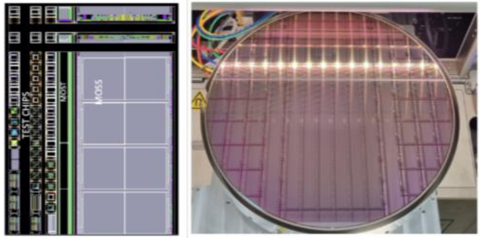
- **After the first years of operation major upgrades are considered**
  - upgrade upstream STS stations with radiation hard pixel sensors (e.g. next generation MAPS (IPHC, CERN developments))
  - possible addition of timing silicon layers (LGADs, SPADs)
  - forward silicon tracker (fragments ID inside the beampipe)



State-of-art MAPS for MVD

- **Timeline fits well the upgrade/production plans of the HL-LHC, eIC, ...**
  - aim for state-of-art rate capability, improved time measurement, reduced material budget and improved radiation hardness
  - improved cooling → readout rates

- **Long-term upgrades (see e.g. ECFA detector R&D roadmap)**
  - tracking, muon systems, PID detectors, timing, calorimetry, ...



Pushing the boundaries: MAPS developments for ALICE ITS3, ALICE3, …

Thank you!

# MIMOSIS-1 performance

- >99% efficiency after $10^{14}$neq/cm² + 5 Mrad
- < 6 µm spatial resolution
  (depending on radiation, threshold, etc.)
- < $10^{-6}$/pixel dark rate at end of lifetime dose.
- No latch-up seen up to LET = 20

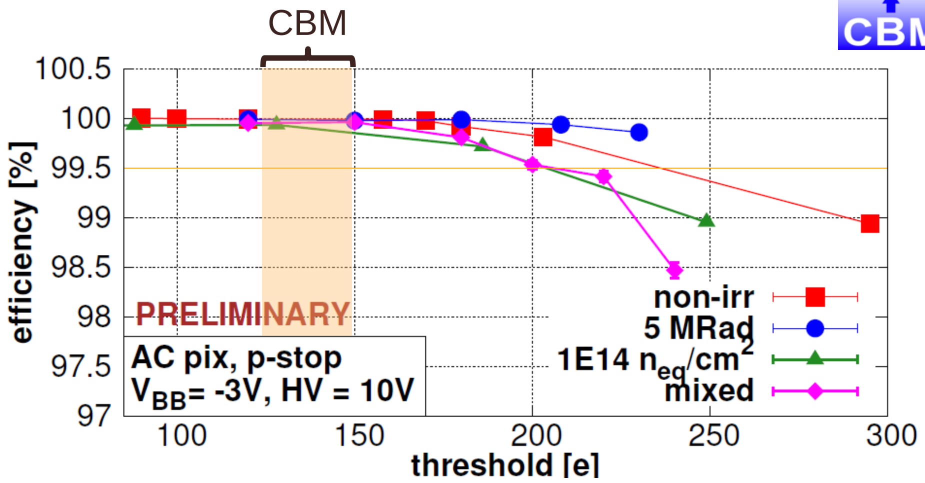
**Conclusion on sensor performance:**

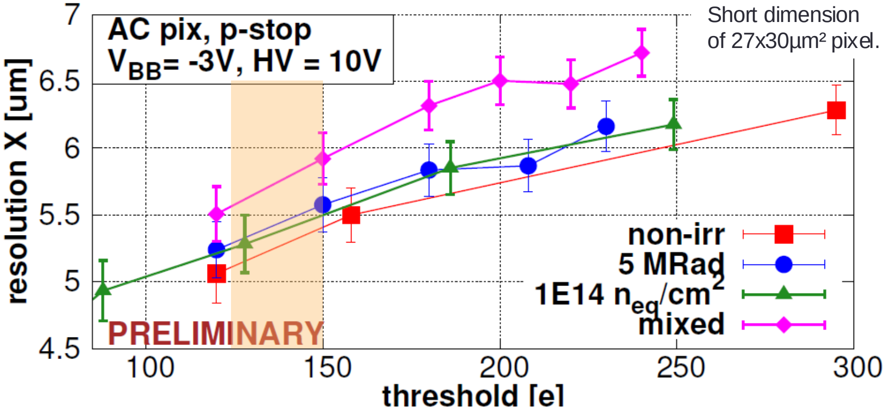
✓ All pixels work excellent before irradiation.

✓ Standard pixels show best spatial resolution.

✓ P-stop AC pixel most radiation hard, matches requirements of CBM

- MIMOSIS-2 prototype development ongoing
- Final chip (MIMOSIS-3) by 2026



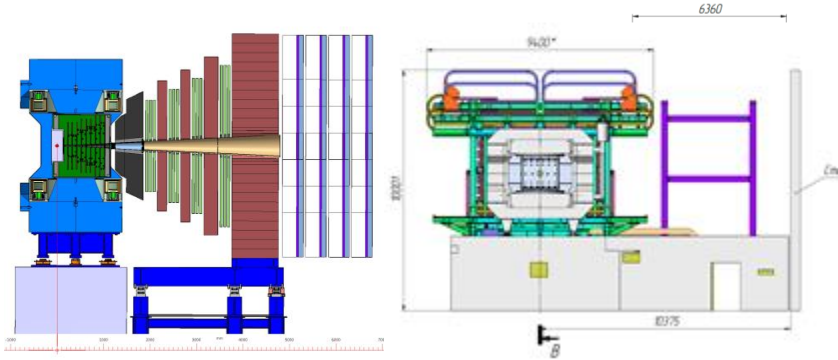




Short dimension of 27x30µm² pixel.

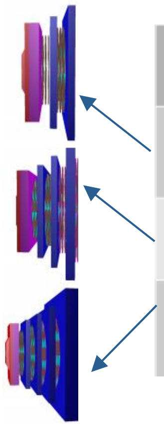
# Muon Chambers

Aligarh Muslim U., Bose Inst. Kolkata, Panjab U., U. of Jammu. , U. of Kashmir, U. of Calcutta, B.H. U. Varanasi, VECC Kolkata, IOP Bhubaneswar, NISER Bhubaneswar, IIT Kharagpur, IIT Indore, Guwahati U.

- 5 absorbers (Graphite, Fe, Fe, Fe, Fe)
- 4 detector stations, 3 detector layers each, sandwiched between two absorbers
  - Station 1 and 2: GEM chambers
  - Station 3 and 4: RPCs
- Movable (110 t) between data taking in CBM di-muon mode and parking in during CBM di-electron mode runs
- Different configurations for different collision energies and physics
- Capable of taking data at up to 10 MHz interaction rate
- Di-muon trigger!




## MUCH geometry variants

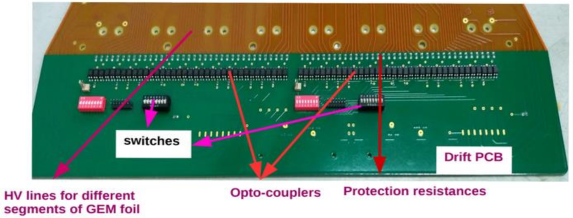


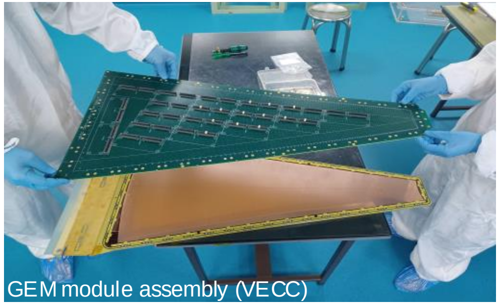
| MuCh Geometry variant | No of absorbers | Configuration of the absorbers | No of detector stations | Purpose |
|---|---|---|---|---|
| LE version | 3 | 1st : 58 cm (28 C + 30 cm concrete) 2nd & 3rd : 20 cm Iron | 2 (GEM stations) | LMVM detection $E_b$ < 4 A GeV (Au beam) |
| LVMV version | 4 | 1st : 58 cm (28 C + 30 cm concrete) 2nd & 3rd : 20 cm Iron 4th : 30 cm Iron | 2 (GEM stations) 2 (RPC stations) | LMVM detection $E_b$ > 4 A GeV (Au beam) |
| J/Ψ version | 5 | 1st : 58 cm (28 C + 30 cm concrete) 2nd & 3rd : 20 cm Iron 4th : 30 cm Iron 5th : 100 cm Iron | 2 (GEM stations) 2 (RPC stations) | J/ψ detection |

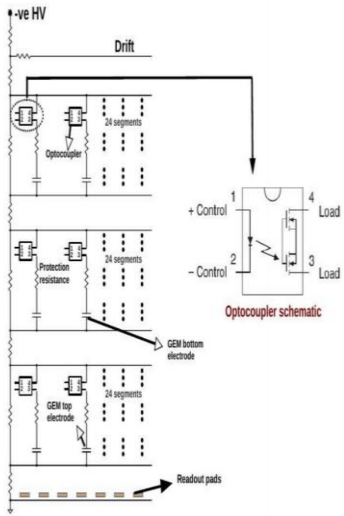
# MUCH

## GEM chambers, Station 1/2

- Triple GEM, 3/2/2/2 mm gap configuration, Ar/$CO_2$ (70/30)
- 48/60 modules, 0.2 $m^2$/0.25 $m^2$ area each, ∼220 000 SMX2.2 channels
- Up to 400 kHz/$cm^2$ in the innermost regions of station 1
- Innovative optocoupler-based HV system for segment isolation
- Stable operation at GIF++, and high-rate tests with hadron beams

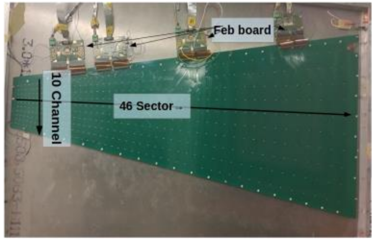


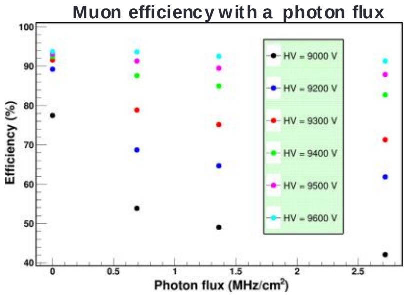


GEM module assembly (VECC)




## RPC chambers, Station 3/4

- Single-gap (2 mm) RPC with 1.2 mm Bakelite electrodes ($\rho \approx 10^{10}\ \Omega$ cm) R134a/iC4H10/SF6 (95.2/4.5/0.3)
- 54/54 modules, 0.35 $m^2$ / 0.51 $m^2$ area each, 50 000 SMX2.2 channels
- Up to 34 kHz/$cm^2$ in the innermost region of Station 3
- Tested up to 2.5 MHz/$cm^2$ photon flux (24kHz/$cm^2$ digi rate) with 90% muon efficiency at GIF++,

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# TRD-2D

- High-rate MWPCs with 2D readout for ultra-low $p_t$ tracking for the inner-most TRD region;
- Can act as an intermediate tracker for particles: 4 layers with *xy* information
- The pad plane is split into triangular pads (200k channels in total):
  - The read-out is organized based on overlapping R-pairs/T-pairs; pairing by the FASP ASIC
  - Identification of the anode wire where the charge is amplified
- Spatial resolution of < 100 μm (along the pads) obtained in high-rate hadron environment
- Rate capabilities up to 100 kHz/cm$^2$ demonstrated!