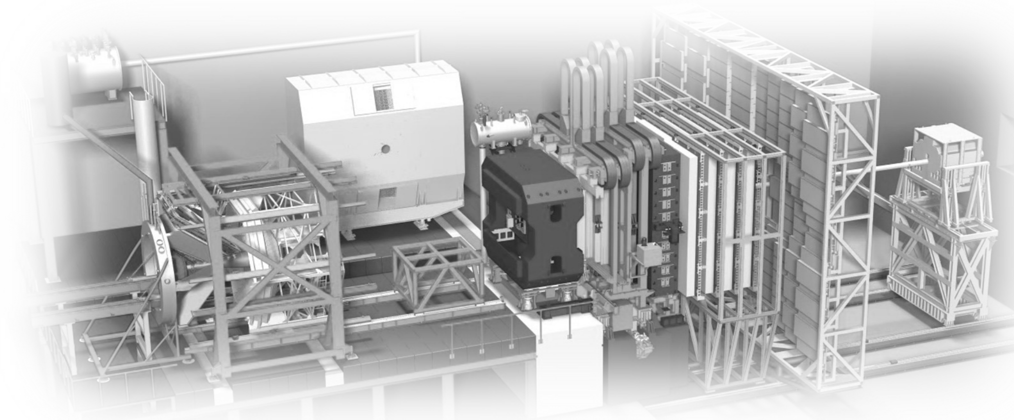
TOWARDS THE CBM EXPERIMENT AT FAIR

Piotr Gasik (GSI/FAIR)

Physics opportunities with proton beams at SIS100

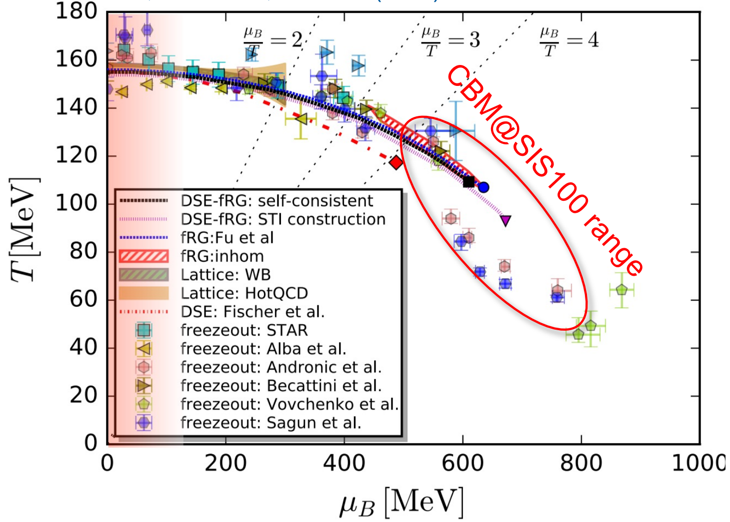
Wuppertal University
9 February 2024



09 February, 2024

CBM experiment

Gao, Pawlowski, PLB 820 (2021) 136584

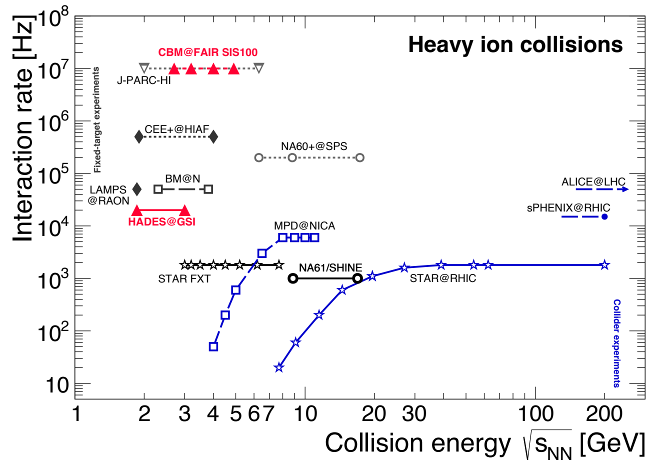


CBM Mission Statement:

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

Experimental challenge:

- Locate the 1st order chiral phase transition
- Detect the conjectured QCD critical point
- Probe microscopic matter properties



T. Galatyuk, NPA 982 (2019), update 2022 (GitHub link)
CBM, EPJA 53 3 (2017) 60

CBM physics topics

QCD matter properties at large μ_B

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

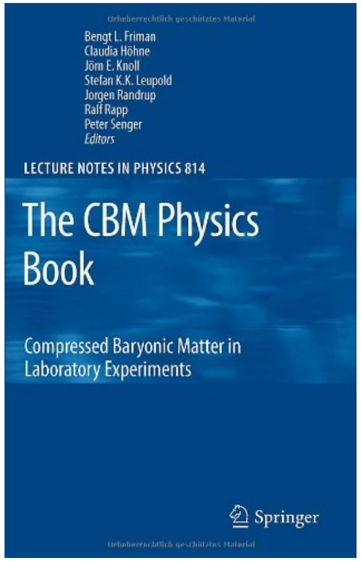
Chiral symmetry at large μ_B

- In-medium modifications of light vector mesons
- Chiral ρ-a_1 mixing via intermediate mass dileptons

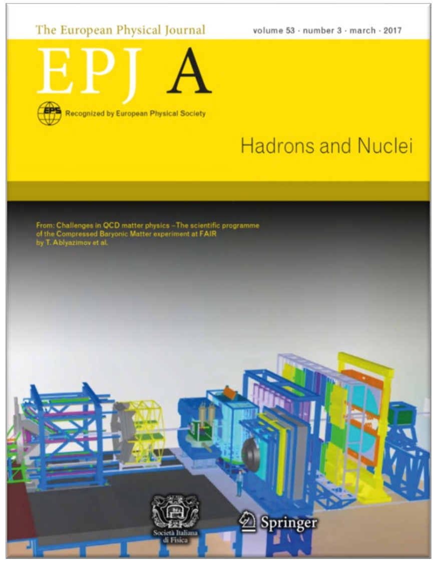
Hypernuclei

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

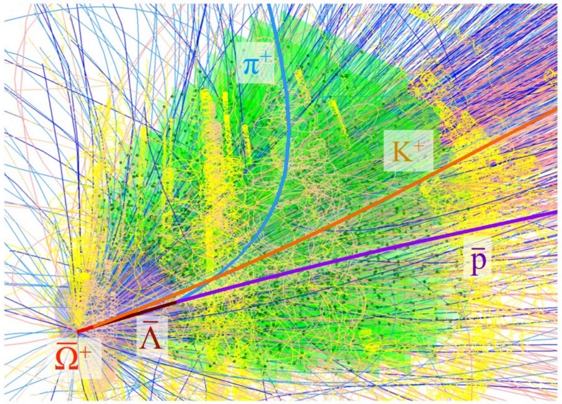


Eur.Phys.J.A 53 (2017) 3, 60
DOI: 10.1140/epja/i2017-12248-y

Physics goals realization (rate challenge)

- High event rates, up to 10^7 Hz Au+Au collisions
- High multiplicity collisions, $\mathcal{O}(1000)$ particles/collision
- Data rates: ~0.5 TB/s
- Data volume: 10-20 PB/year

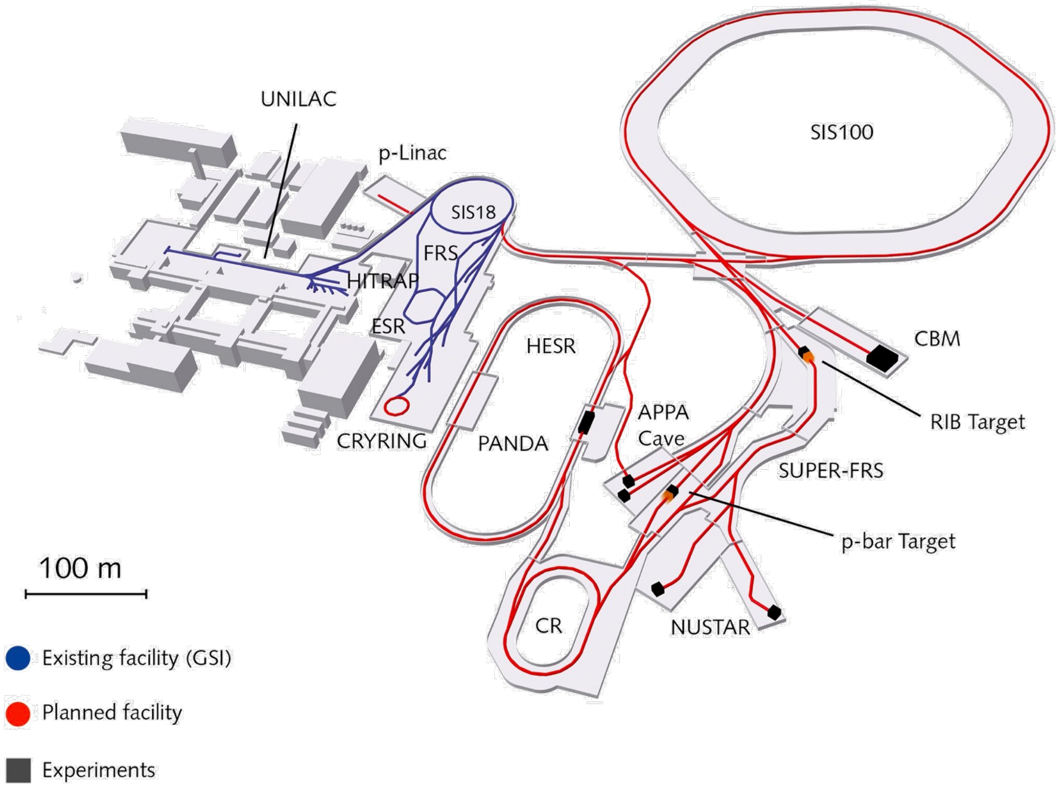
- Fast, radiation hard detectors & front-end electronics
- Free-streaming readout and online event reconstruction
- PID: hadrons and leptons, displaced (~50 µm) vertex reconstruction for charm measurements, decay topology
- High-speed DAQ and high-performance computing farm for online event selection



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

GSI Green IT Cube

Facility for Antiproton and Ion Research in Europe



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 gain: × 100–1000 (~10^{13}/s for p; ~10^{11}/s for U)
- 10× energy (compared to SIS-18@GSI)
- Spill length: 1–100 s
- Antimatter: antiproton beams
- Precision: System of storage and cooler rings

FAIR construction site

Installation

- Cryogenic plant installed in 2023
- Technical Building Infrastructure, cables pulling - ongoing
- Accelerator installation started in January 2024
- Commissioning: 2025 onwards

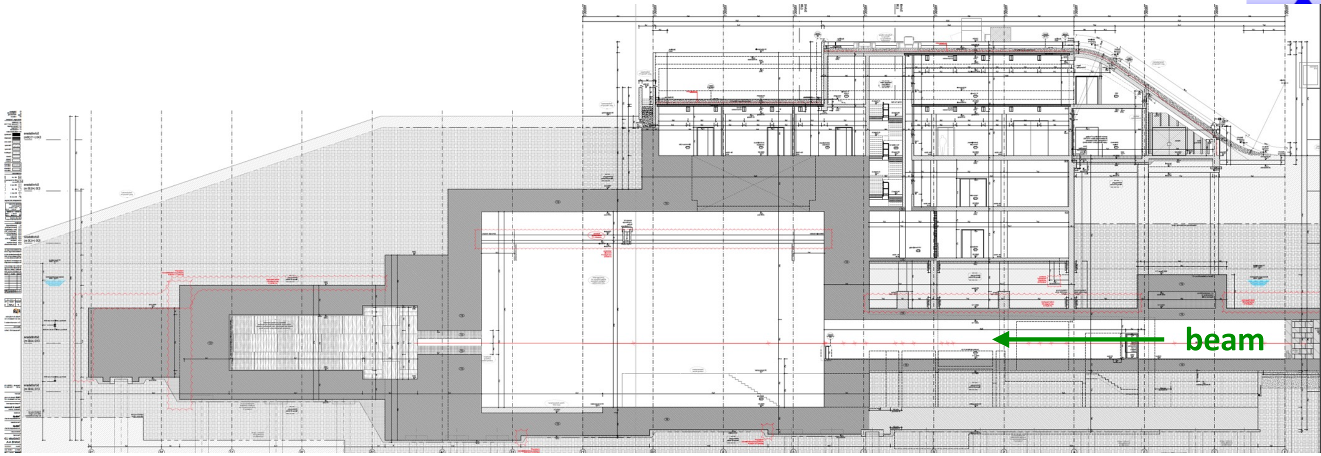
SIS100 tunnel


SIS100 dipoles ready for installation


SFRS multiplets tested at CERN


Cryo2 compressors

CBM Building



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

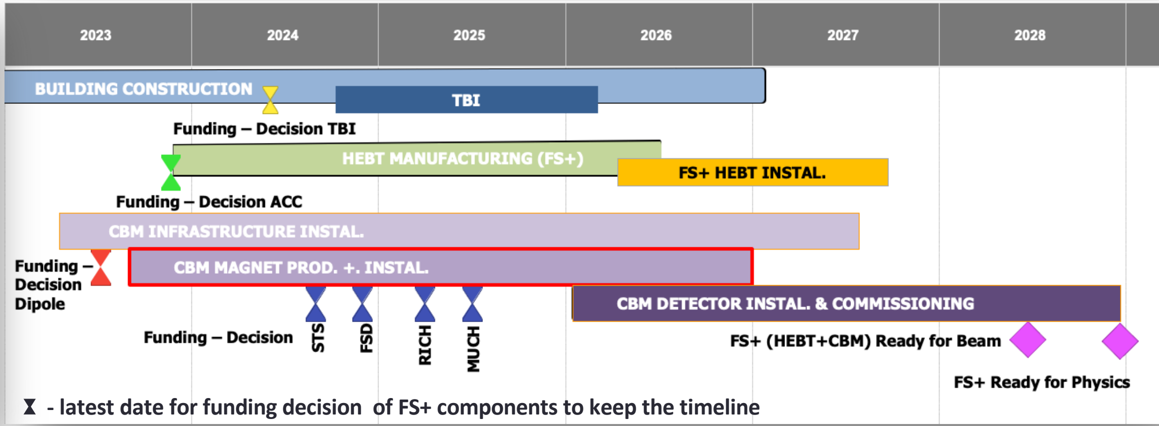
CBM Installation

- 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

Upstream Platform (NPI CAS Rež, CTU Prague)

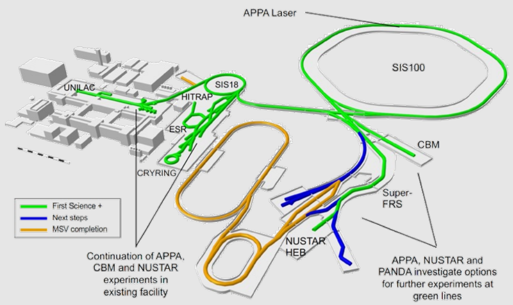
CBM in FS+

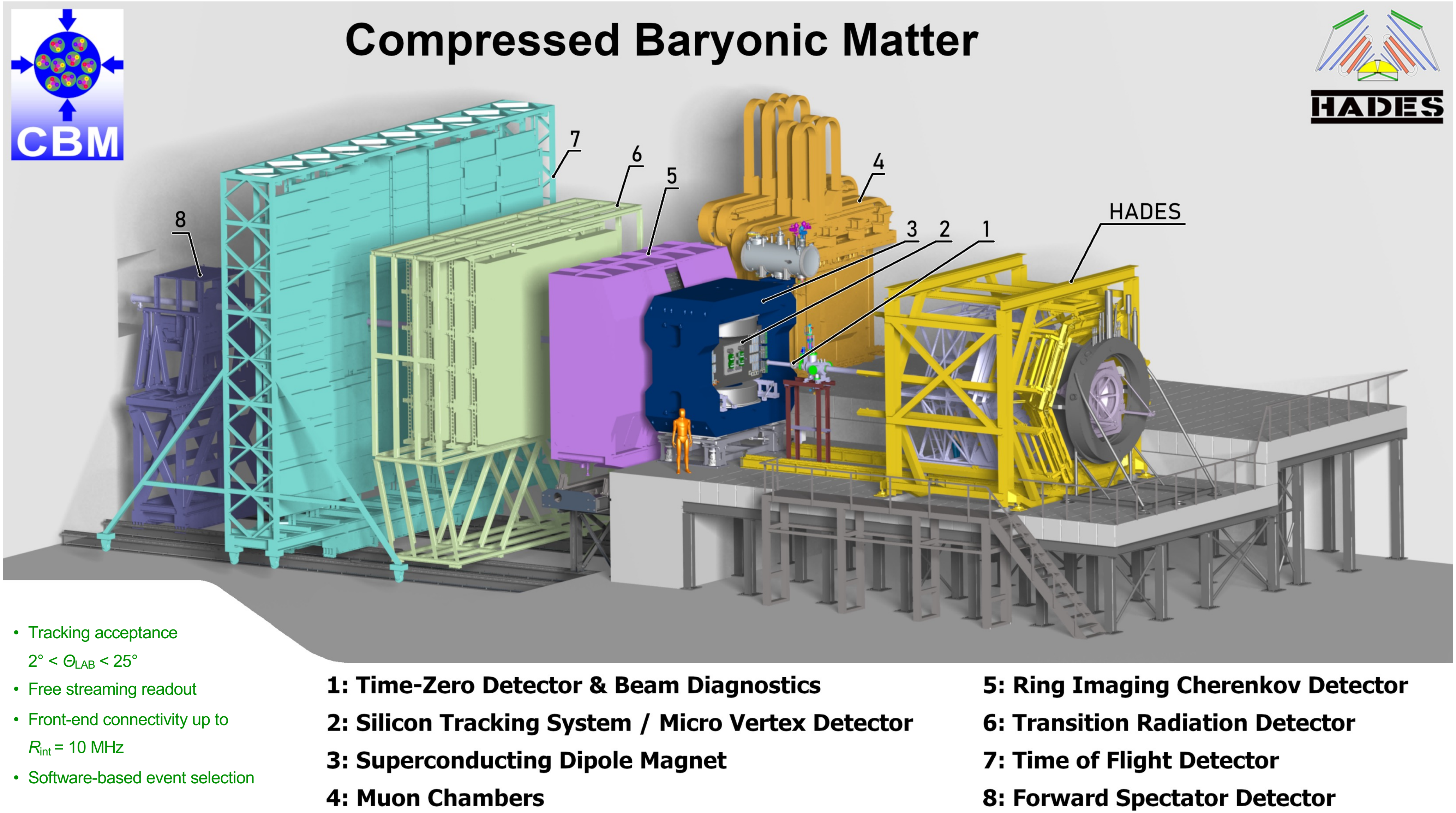
✓ **Action 2: Release for procurement CBM Magnets (done)**



FAIR project time schedule 2023 re-baselining report | 10.10.2023

- **FS+ is currently not fully funded → support of national Funding Agencies is absolutely crucial for the completion of CBM!**
- **Current strategy: get subprojects approved step by step: magnet re-procurement accomplished, next step: HEBT magnets**
- **Critical for CBM: commissioning of buildings and detector installation requires timely completion of TBI (⧗)**

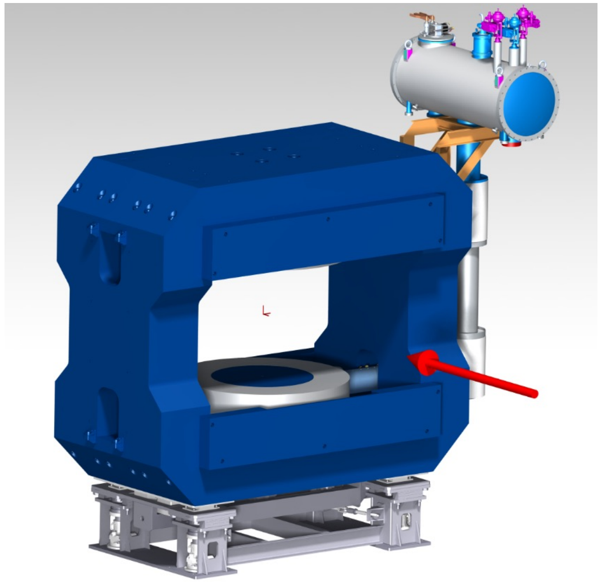


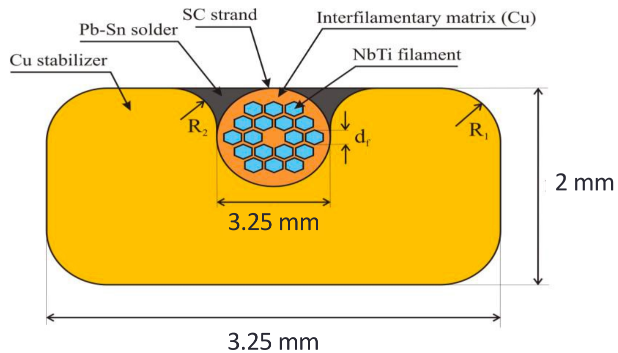

Compressed Baryonic Matter
CBM
HADES
8
7
6
5
4
3
2
1
HADES
Tracking acceptance
2° < Θ_{LAB} < 25°
Free streaming readout
Front-end connectivity up to
R_{int} = 10 MHz
Software-based event selection
1: Time-Zero Detector & Beam Diagnostics
2: Silicon Tracking System / Micro Vertex Detector
3: Superconducting Dipole Magnet
4: Muon Chambers
5: Ring Imaging Cherenkov Detector
6: Transition Radiation Detector
7: Time of Flight Detector
8: Forward Spectator Detector

The CBM superconducting dipole

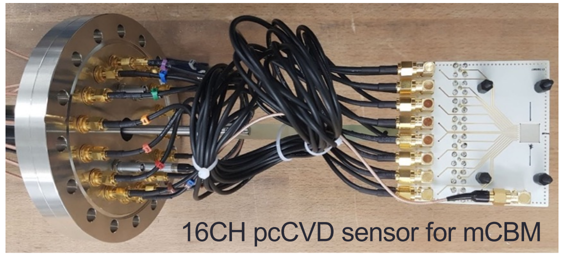
- Magnetic field integral of 1 Tm along 1 m (Δp/p < 2%)
- Conductor: NbTi (filament < 60 μm), Cu/SC ≥ 5
- Aperture: 1.47 × 3.3 m^2
- Acceptance: ±25° (vertical), ±30° (horizontal)
- Total weight of the yoke: ~150 t
- Operating temperature: 4.5 K

- Tendering: January – October 2023
- Contract awarded in December to BNG!
- Expected delivery: **Q4.2026/Q1.2027**



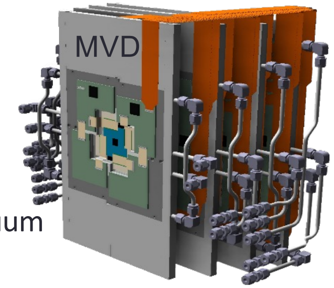


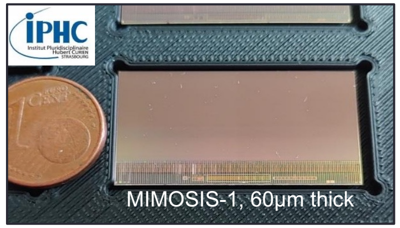
Detector projects


16CH pcCVD sensor for mCBM

BMON (TU Darmstadt, GSI)

- High purity pcCVD diamond material: 1 cm × 1 cm, 80 µm thickness, striped metallization 16ch/side
- Required time resolution: 50 ps
- Readout: PADI-XI Discriminator + Get4 TDC (see CBM-TOF)

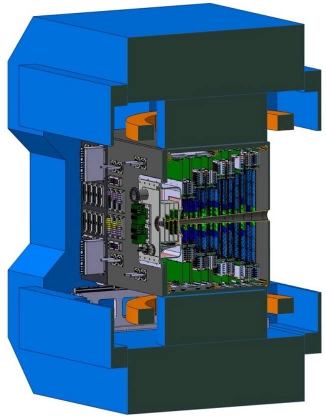




MIMOSIS-1, 60µm thick

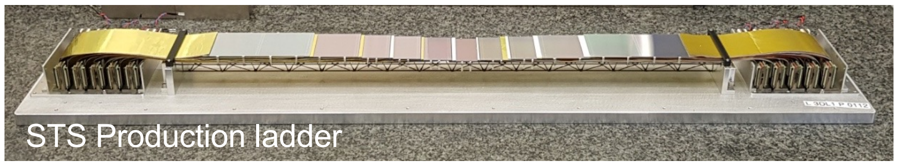
MVD (IKF Frankfurt, GSI, IPHC Strasbourg, CTU Prague, Pusan Nat'l Univ., IMP-CAS, CTU Prague)

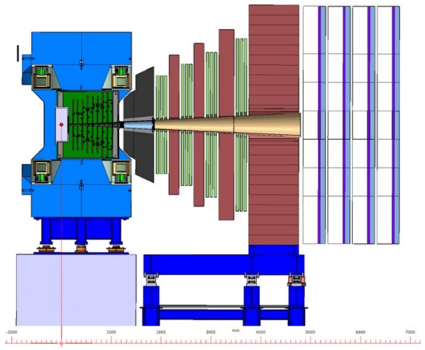
- 4 detector stations, based on MAPS technology (MIMOSIS chip)
- Non-uniform hit density in time and space, high radiation environment, operating in a vacuum
- Material budget of O(0.5% X_0) with TPG (pCVD diamond) carriers
- MIMOSIS-1 performance fulfils requirements (>99% efficiency after 10^{14}neq/cm² + 5 Mrad ,< 6 µm spatial resolution)
- MIMOSIS-2 development ongoing



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

- 8 stations of double-sided silicon microstrip sensors (spatial res. 15 µm (*x*), 110 µm (*y*))
- Track point measurement in a high-rate collision environment: 10^5 – 10^7/s (A+A), up to 10^9/s (p+A),
- Self-triggering front-end electronics, time-stamp resolution ≲ 5 ns
- Material budget: 0.3% – 1.5% X_0 per station, Δp/p < 2% (p > 1 GeV/c, 1 Tm field)
- Production of the STS modules is ongoing.
- PRR in Spring 2024!

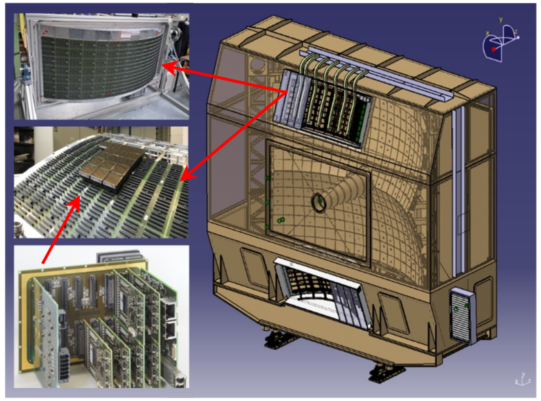

STS Production ladder



Detector projects

MUCH (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.)

- 4 detector stations, 3 detector layers each (GEMs + RPCs), sandwiched between two absorbers
- 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 reach
- Capable of taking data at up to 10 MHz interaction rate; Di-muon trigger!

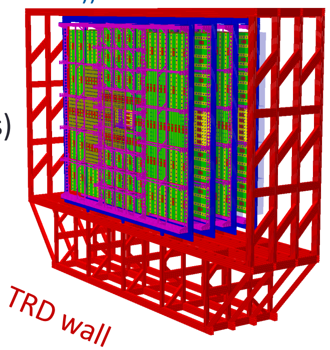


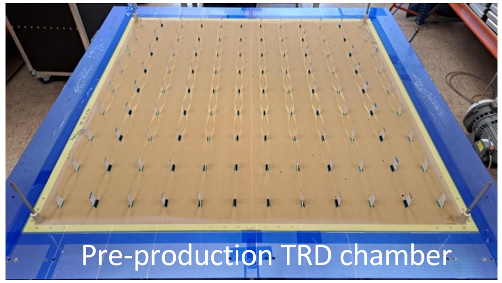
RICH (U Giessen, U Wuppertal, GSI Darmstadt)

- 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

TRD (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)

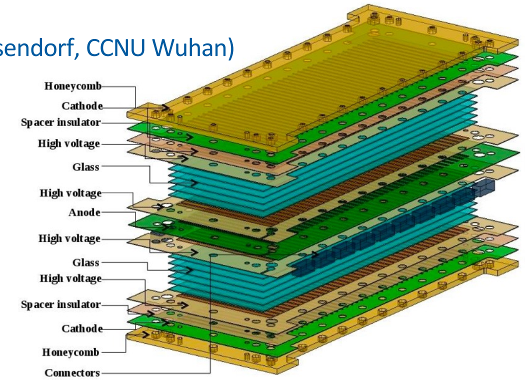


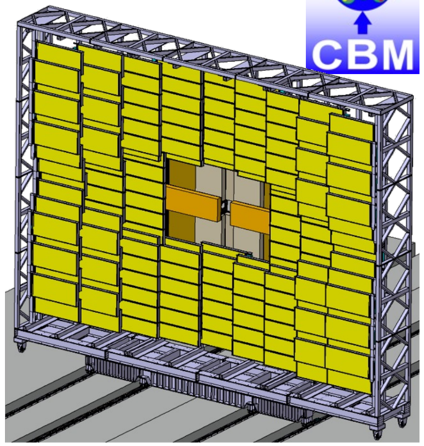


Detector projects

TOF (U. Heidelberg, THU Beijing, NIPNE Bucharest, GSI, TU Darmstadt, USTC Hefei, HZDR Rossendorf, CCNU Wuhan)

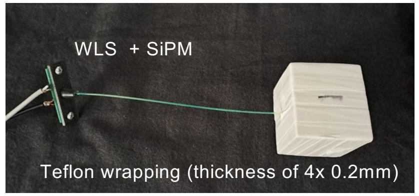
- Double-stack multi-gap resistive plate chambers for ultra-high rates
- System time resolution: $\sigma_{sys} \approx 80$ ps, efficiency: $\varepsilon \gtrsim 95$ %
- Rate capability up to 50 kHz/cm2 (depending on the region) achieved
- Low power FEE (100 000 ch), continuous RO

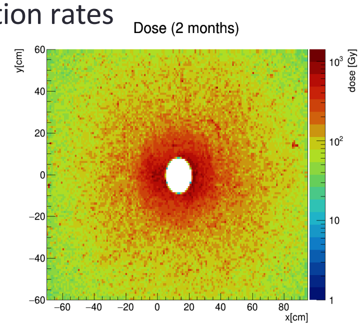




FSD (CTU Prague, GSI and FFN (U. Bochum))

- **Important subsystem for centrality determination**
- Original concept based on hadronic calorimeter (Pb/Scintillator) – in-kind contract cancelled
- Replacement **based on plastic scintillator**, similar to HADES forward hodoscope wall or STAR Event Plane Detector
- Provides an **opportunity to improve performance** at low energies and high interaction rates
- Background and performance studies have been launched
- 5×5 cm^2 scintillator module prototypes with WLS+SiPM or PMT readout





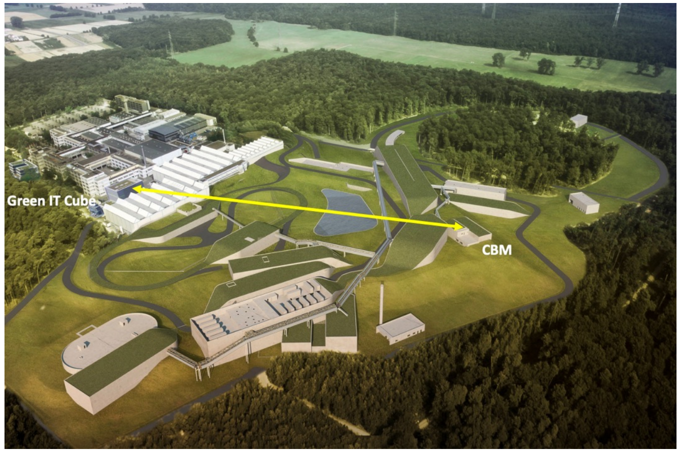
CBM data acquisition

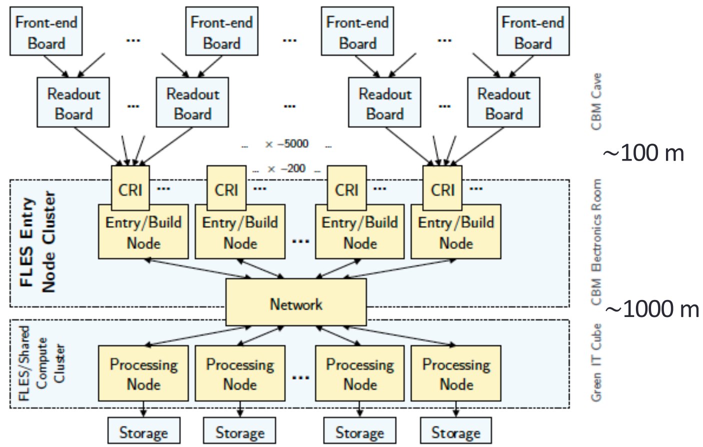
FIAS, GSI, KIT, ZIB

- **Free-streaming readout up to 10 MHz interaction rates (peak)**
- **Raw data rate about 500 GB/s**
- **Online reduction of the raw data by ~2 orders of magnitude**

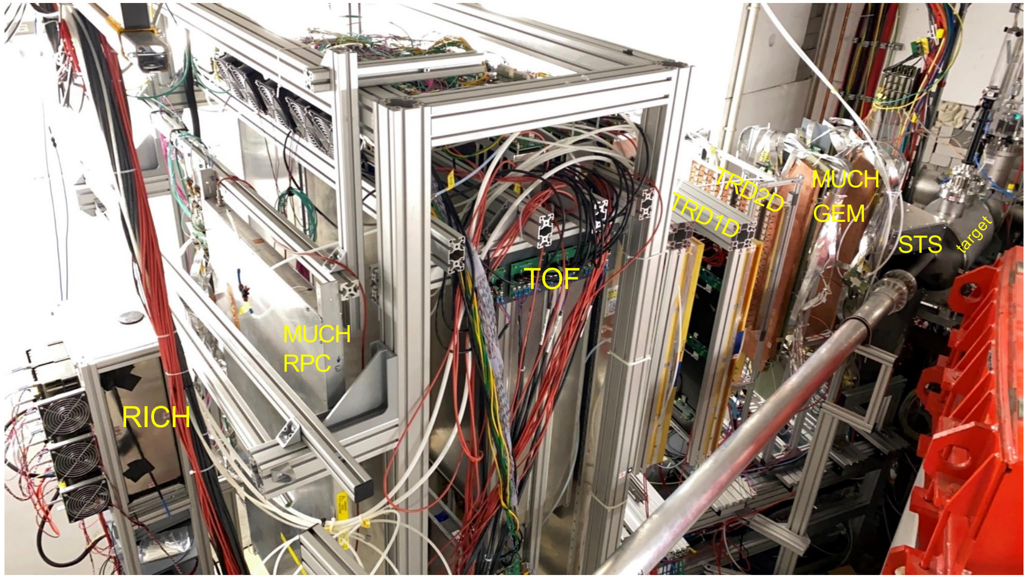
- FEE of all CBM detectors autonomous and self-triggered, delivers time-stamped hit messages
- FEE synchronized by a central timing system (TFC)
- Online systems: collect, aggregate and deliver data to the online compute farm
- First Level Event Selector: event reconstruction and inspection online, up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

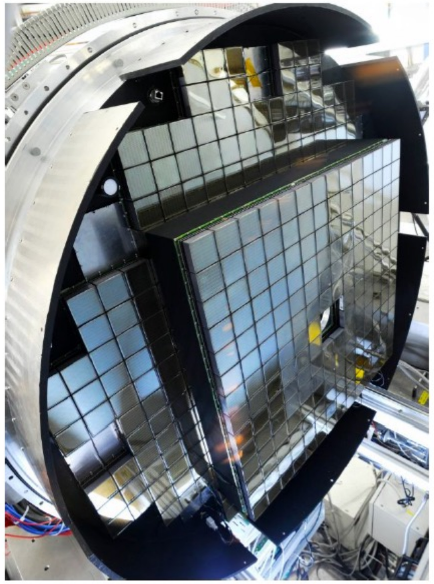
- **DAQ/FLES TDR was accepted in June 2023!**



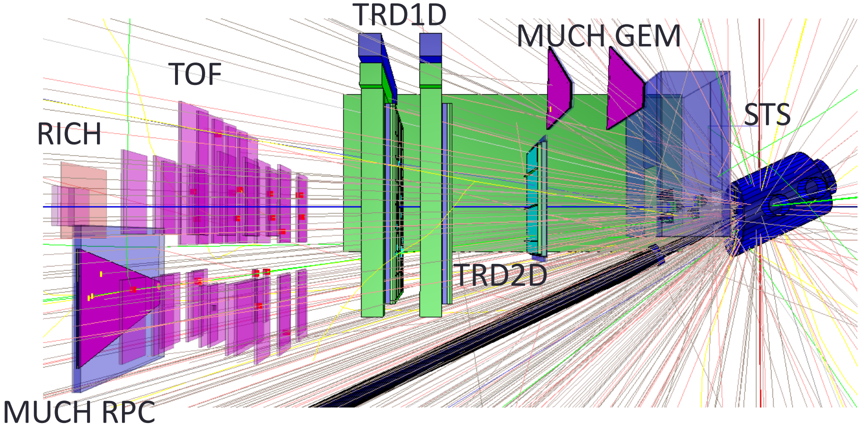


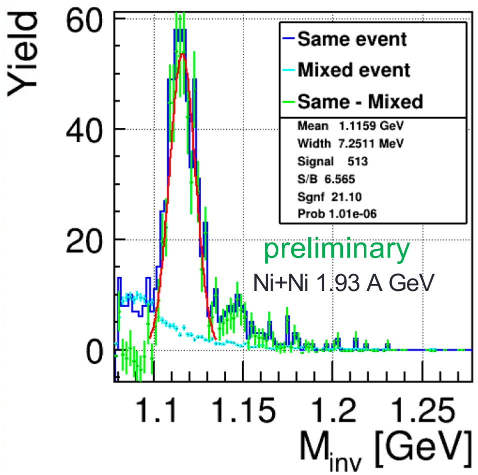
FAIR Phase-0 research program





mCBM @ SIS18 – CBM full system setup





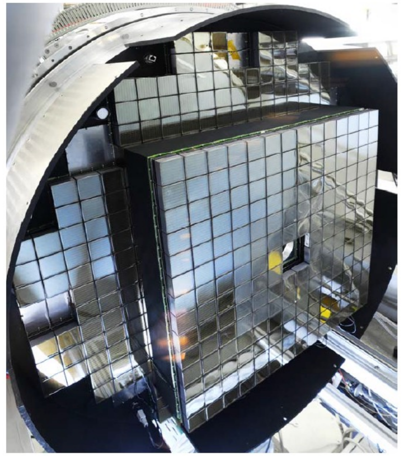
- **Verification of CBM triggerless-streaming read-out and data transport**
- **High-rate detector tests with up to 10 MHz collision rates**

- 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
- **Λ** benchmark runs (2022): Λ signal identified with topological + timing cuts (calibration and alignment studies ongoing)

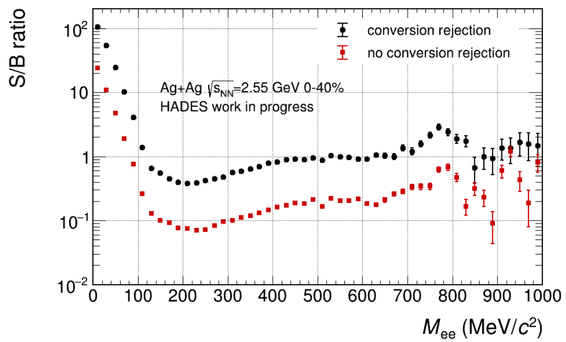
mCBM campaign in 2024-2025

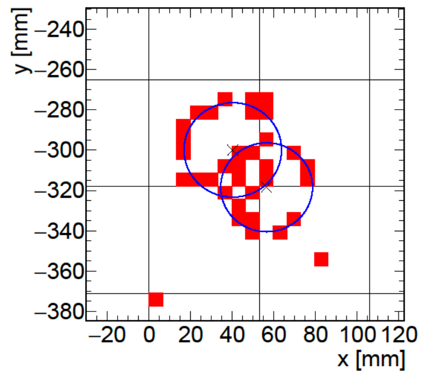
- Upgraded detectors (production modules/electronics)
- Λ excitation function at SIS-18 energies (Au+Au, Ni+Ni)
- Further development of the readout chain and **online** analysis tools
- High-rate detector tests: Production Readiness Reviews, QA/QC
- Testing of the next generation of CRI cards

HADES RICH upgrade with CBM technology



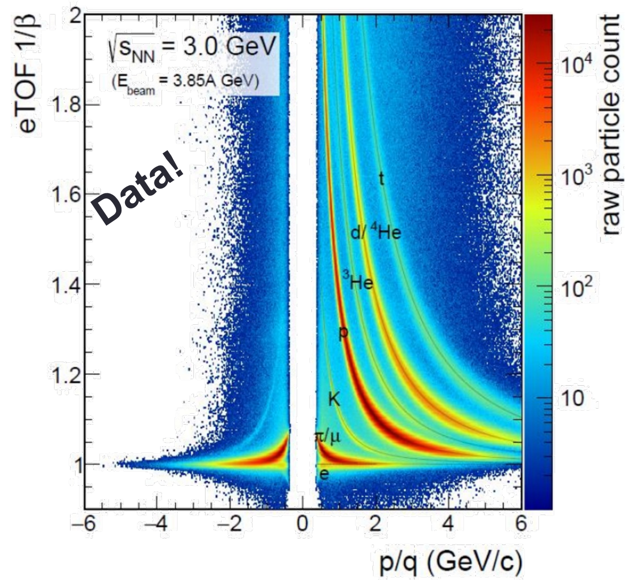
- HADES photon detector replaced by 428 H12700 MAPMTs (~40% of CBM MAPMTs)
- New readout electronics developed based on the „DiRICH“ family,
  - average timing precision ~225 ps, same development for CBM!
- Great performance figures of the upgraded HADES RICH
  - very low noise and clear rings
  - ring 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)



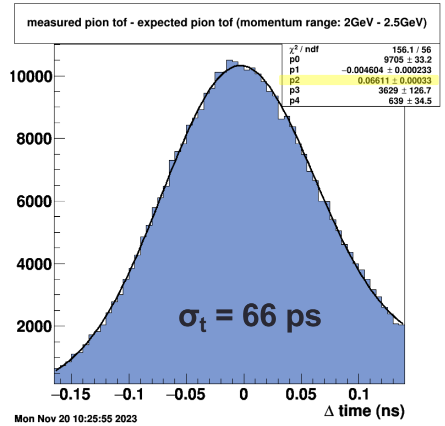


Endcap TOF at STAR with CBM MRPCs

- 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: 4×10^9 events collected in FXT and COLL modes
  - operation will continue at $\sqrt{s_{NN}}$ = 200 GeV in the coming years

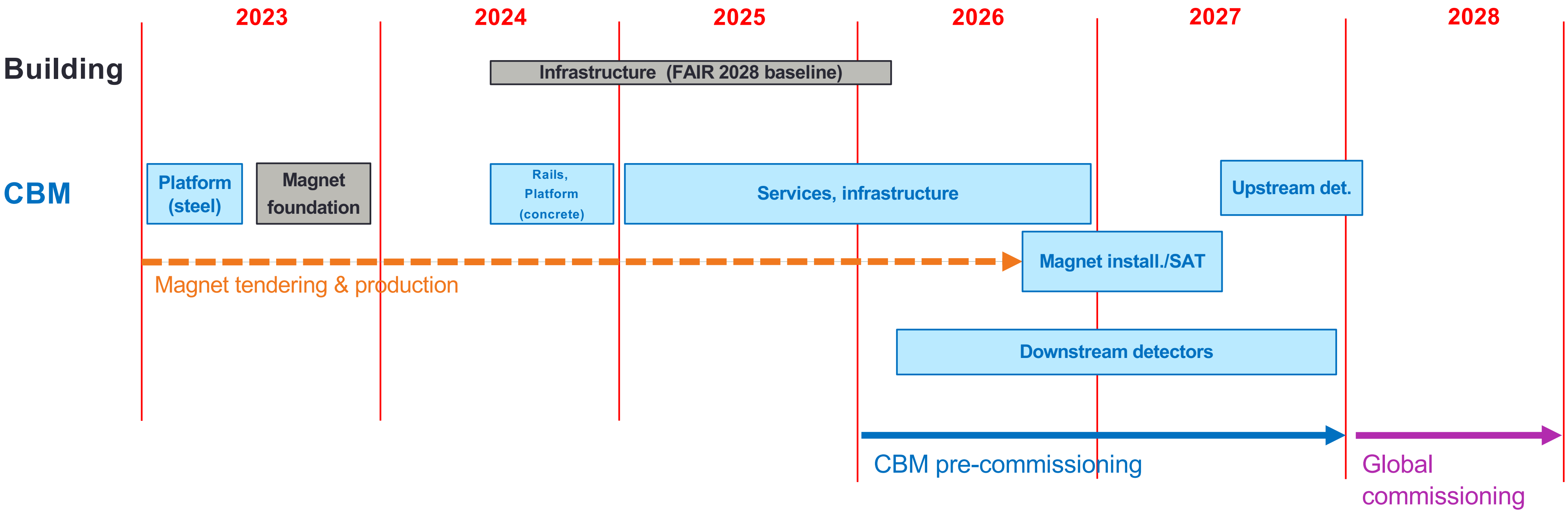


- CBM MRPC counter production starts this year, followed by modules assembly
  - ~230 modules, 1400 MRPCs, 90'000 FEE channels
  - counter production in China, modules assembly in Bucharest (RO) and Heidelberg (DE)



Phase 0
Research Program

CBM installation/commissioning timeline

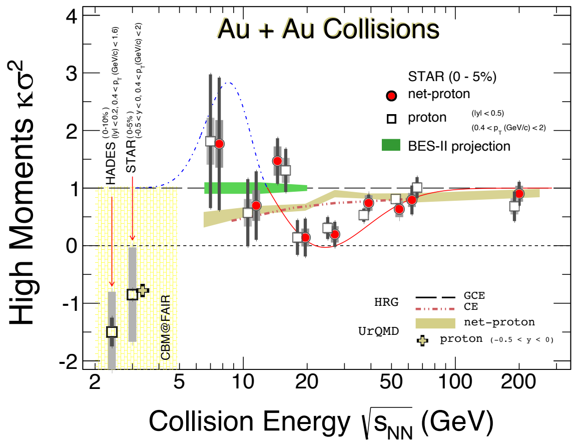


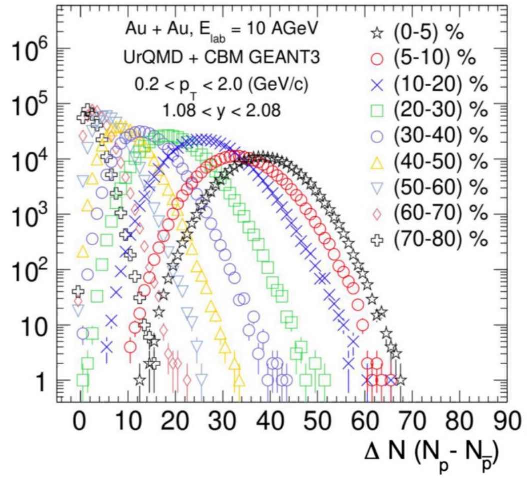
- **We plan CBM to be ready for beam beginning of 2028**
- ~1y contingency until SIS100 “ready for physics” (used for CBM global commissioning)

Highlighted future directions

- Critical point search: 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

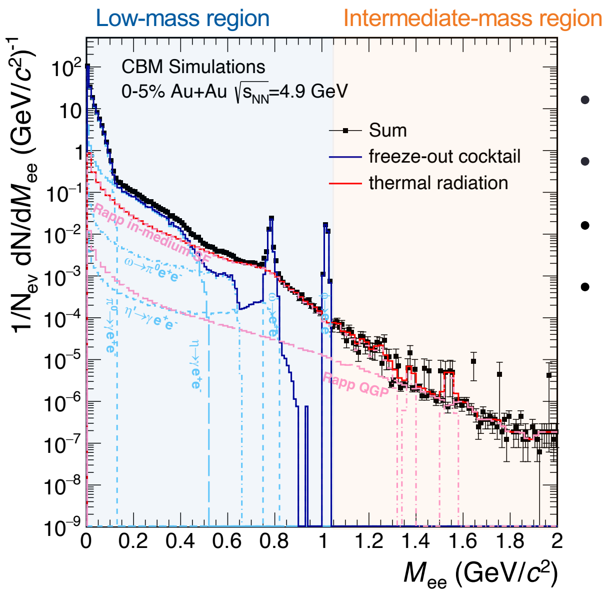
STAR, PRL 128 (2022) 20, 202303
HADES, PRC 102 (2020) 2, 024914





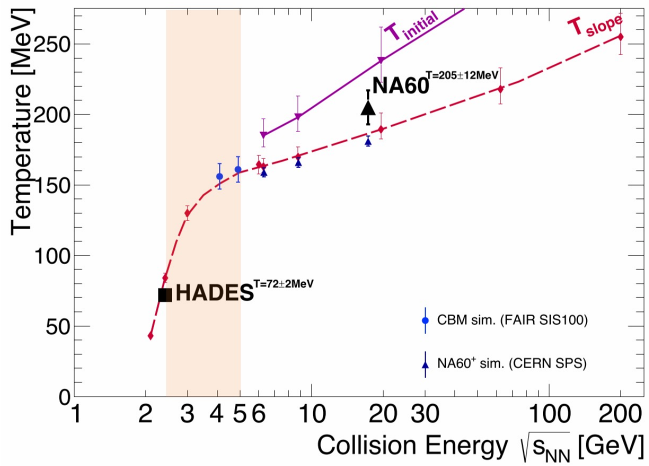
- CBM can systematically study the higher-order cumulants and ratios to contribute significantly to the search of QCD-CEP

Dilepton measurements



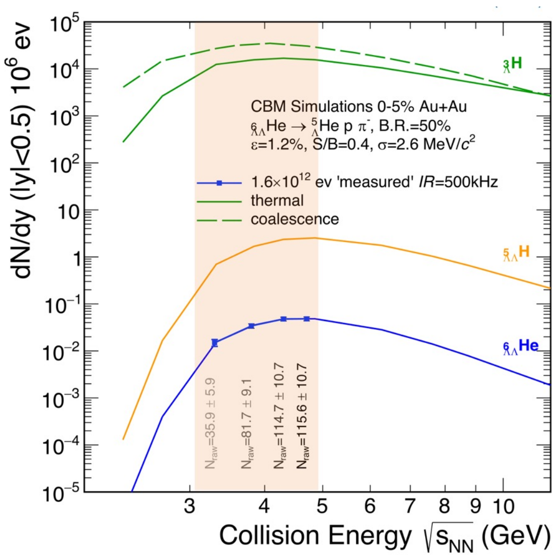
- Low mass range: total yield ~ fireball lifetime
- Intermediate mass range: slope ~ emitting source temperature
- Access to thermal signal is very feasible with good background description
- Crucial for high-quality data: interaction rates and S/B ratio

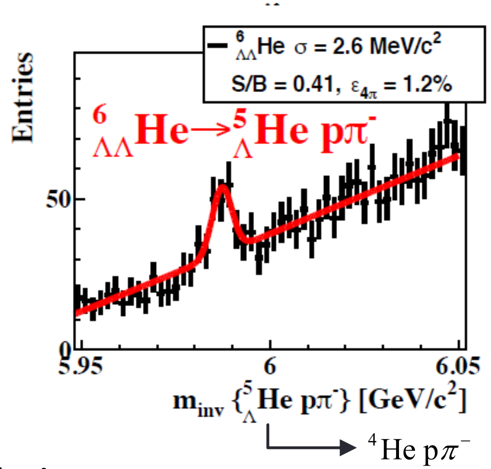
- Non-monotonous behaviour of the caloric curve (flattening) would give evidence for a phase transition.
- CBM will be the first experiment to use di-leptons for systematic measurements in both production channels (e+e- and μ+μ-) in the same coverage.



Hypernuclei

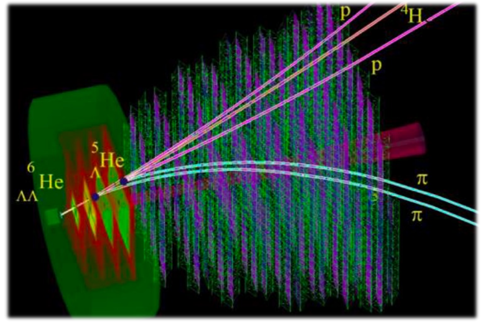
- Precise and comprehensive study of hypernuclei possible at SIS100
- High rate capabilities + online analysis (clean identification) → increased yield



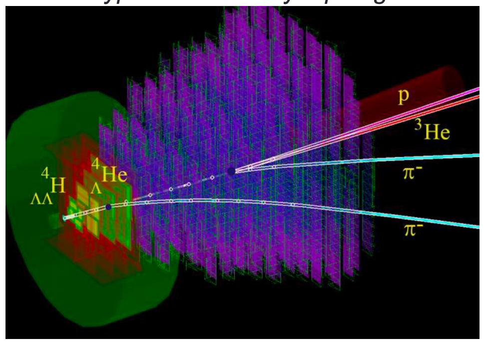


CBM physics cases:

- How (hyper)nuclei form in heavy ion collisions?
- Hypernuclei lifetime --> YN, YY interactions
- Do YY bound states exist?

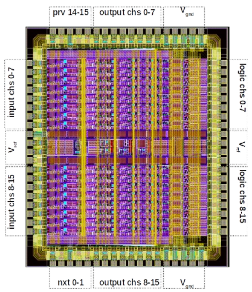


Hypernuclei decay topologies

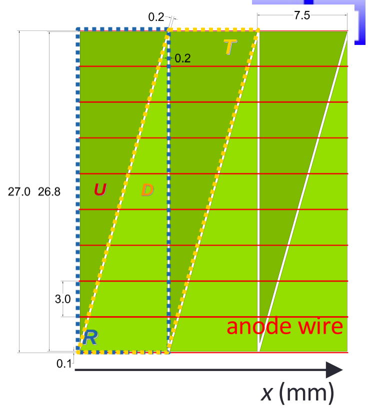


Ongoing improvements for Day-1

- **High-rate MWPCs with 2D readout for ultra-low p_t tracking for the inner-most TRD region**
  - Triangular pads ➞ dentification 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!

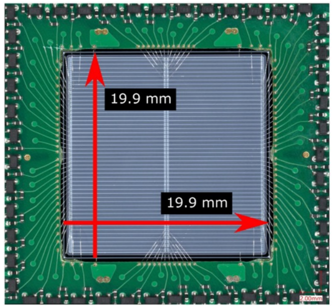


FASP readout

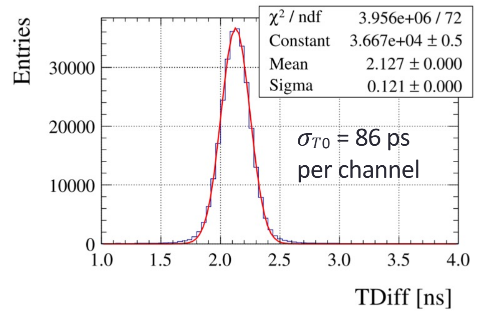


- **Start and HALO detectors based on LGAD sensors**
  - Currently employed by HADES START detector;
  - Sensor development: Bruno Kessler Foundation;
  - Readout: DiRICH5 discriminator + TDC ([trb.gsi.de](trb.gsi.de))
  - Performance with high-intensity heavy ion beams to be shown
  - Further R&D activities (NIM 1039 (2022) 167046):

    HADES T0, Medical applications, Beam diagnostics for S-DALINAC

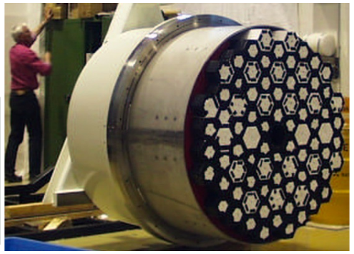


HADES T0

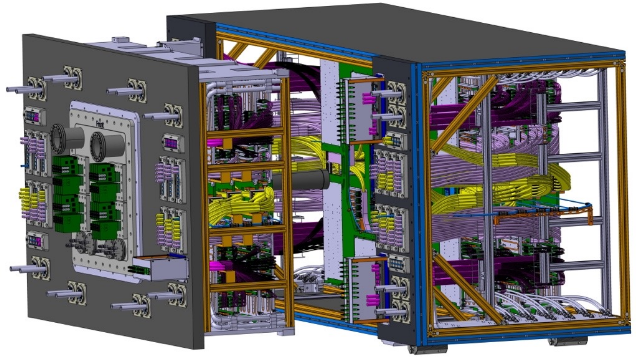


- **Upgrade to forward spectrometer (an option)**
  - Neutron detection with COSY-TOF neutron detector
  - PANDA outer straw tube tracker?

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



Strategy for detector upgrades

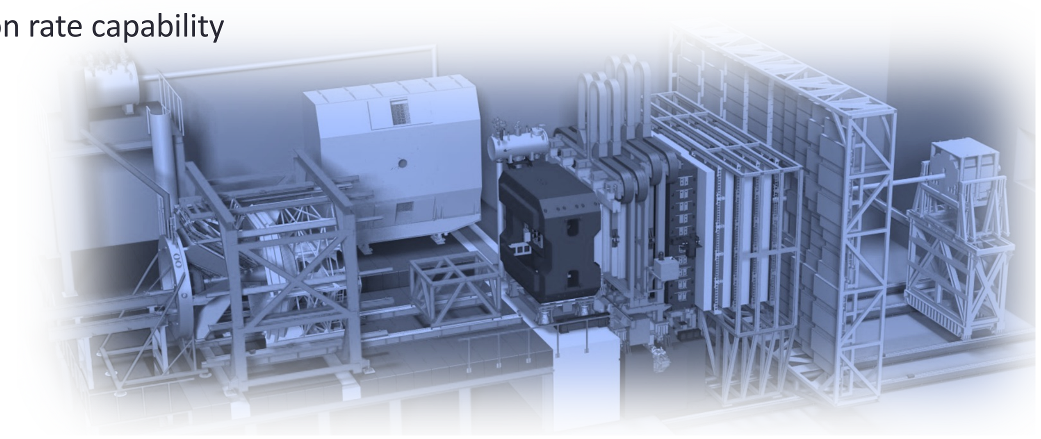


- **After the first few years of operation, major tracker upgrades are considered**
  - E.g. upgrade upstream STS stations with radiation hard pixel sensors
  - Physics projections: target position, material budget, strip-to-pixel transition
  - Possible addition of timing silicon layers (LGADs, SPADs)
  - Forward silicon tracker (fragments ID inside the beampipe)
- **The timeline fits well the upgrade/production plans of the HL-LHC, eIC, ...**
  - aim for state-of-the-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)**
  - muon systems, PID detectors, timing, calorimetry, ...

Summary

- CBM is progressing well towards science program with SIS100 beams
- High-rate capabilities achieved in the extensive R&D phase
- All subsystems on the verge of the series production
- **CBM aims for taking data in 2028!**

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



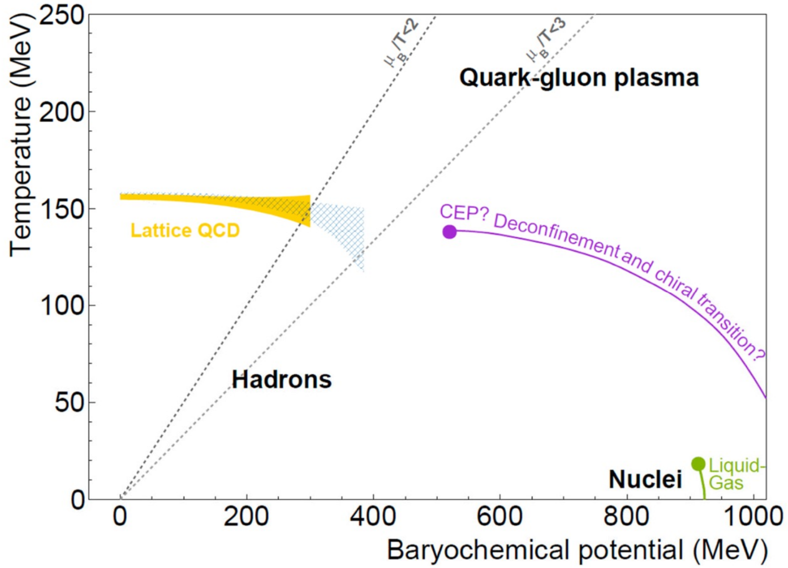
BACKUP

Exploring the QCD phase diagram at high net baryon densities

Vanishing μ_B, high T (lattice QCD)

- Smooth crossover from hadronic to partonic medium
  - $T_{pc} = 156.5 \pm 1.5$ 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., PLB 795 (2019) 15-21
Ding et al., PRL 123 (2019) 6, 062002
Dini et al., Phys. Rev. D 105 (2022) 3, 034510



Large μ_B, moderate T

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

Worldwide experimental and theory efforts, relevance for astrophysics

Astrophysical relevance of high μ_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 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
	$\rho < 5 - 10\ \rho_0$

18 orders of magnitude in scale, still similar conditions!

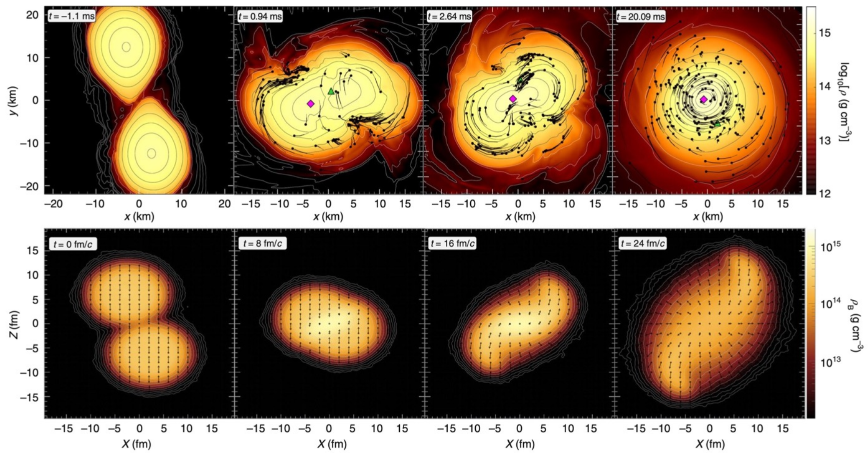

nature physics

ARTICLES

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

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)

Compressed Baryonic Matter experiment mission

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

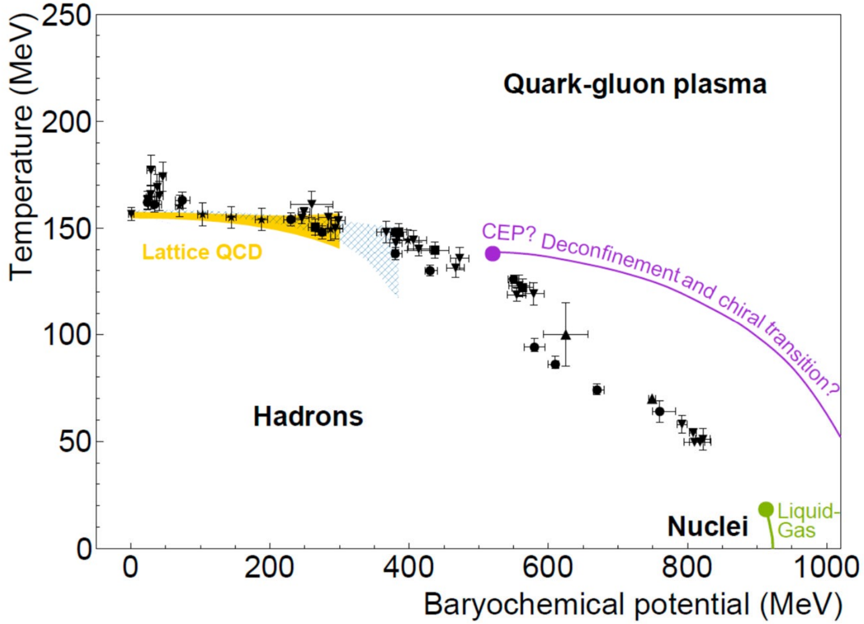
Experimental challenge:

- Locate the onset of new phases of QCD
- Detect the conjectured QCD critical point
- Probe microscopic matter properties

Measure with upmost precision:

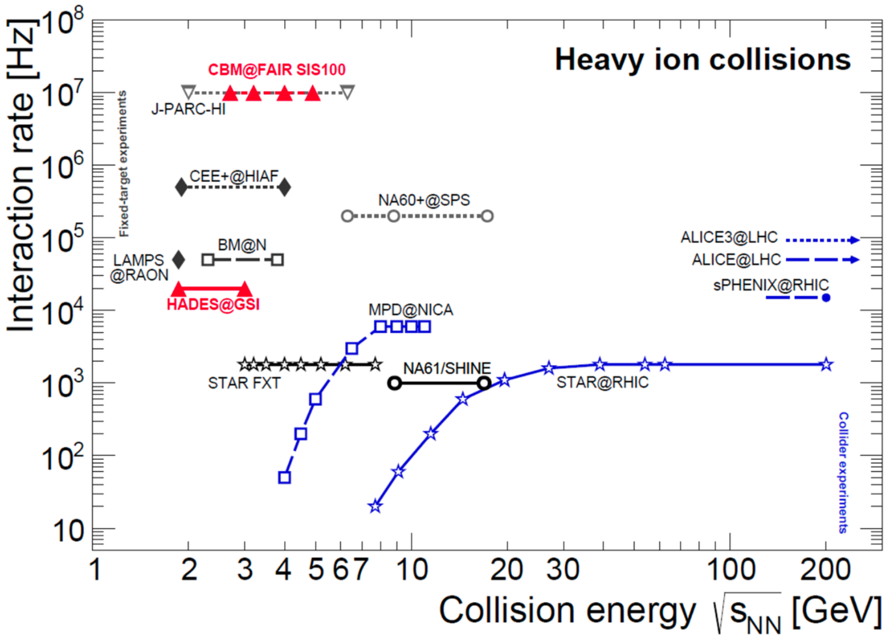
- Event-by-event fluctuations (criticality)
- Dileptons (emissivity)
- Strangeness (vorticity)
- Hypernuclei (equation-of-state)
- Charm (transport properties)

Almost unexplored (not accessible) so far in the high-μ_B region



HADES, Nature Phys. 15 (2019) 10, 1040-1045
NA60, Specht et al., AIP Conf.Proc. (2010) 1322
Andronic et al., Nature 561 (2018) no.7723

Rate challenge



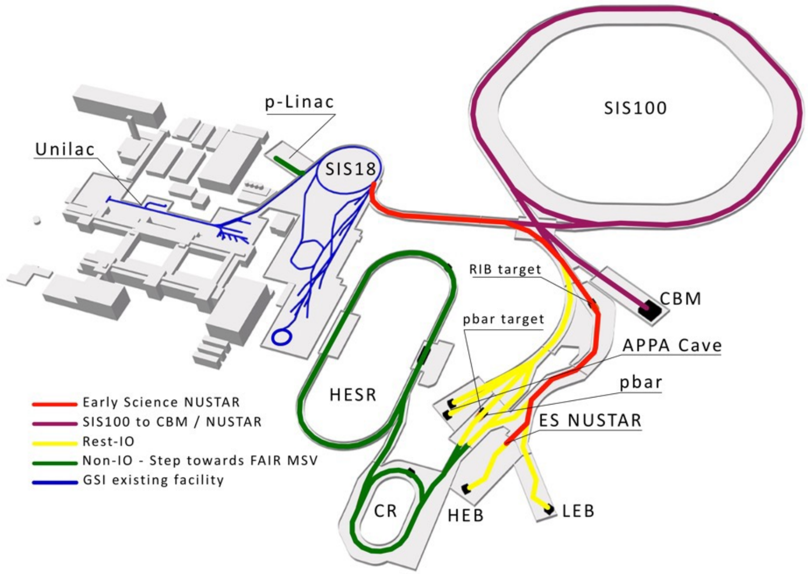
T. Galatyuk, NPA 982 (2019), update 2023
https://github.com/tgalatyuk/interaction_rate_facilities,
CBM, EPJA 53 3 (2017) 60

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 μ_B with rare and electromagnetic probes: high-rate capability
- HADES: established thermal radiation at high μ_B, limited to 20kHz and $\sqrt{s_{NN}}$ = 2.4 GeV
- STAR FXT@RHIC: BES program completed; limited capabilities for rare probes
- BM@N: running (light systems), limited capabilities for rare probes
- CEE+@HIAF proposal: 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, μ, hadrons)

CBM @ SIS100

- **C.B.M. at FAIR: dedicated high-rate heavy ion experimental program**
- Accelerator chain: injector (UNILAC+SIS18), SIS100, high-energy beam transfer lines
- Proton and heavy-ion beams parameters well defined
  - no special requirements (see FAIR Operation Modes – review Q4)
  - up to 10^{10} ions per spill (10 s), at full SIS100 energy range



- Beam intensity requirements demonstrated by the injector chain
- Ultimate parameters can be reached within a few months of commissioning.
- Current estimate: SIS100 commissioning with beams starts in Q2.2028

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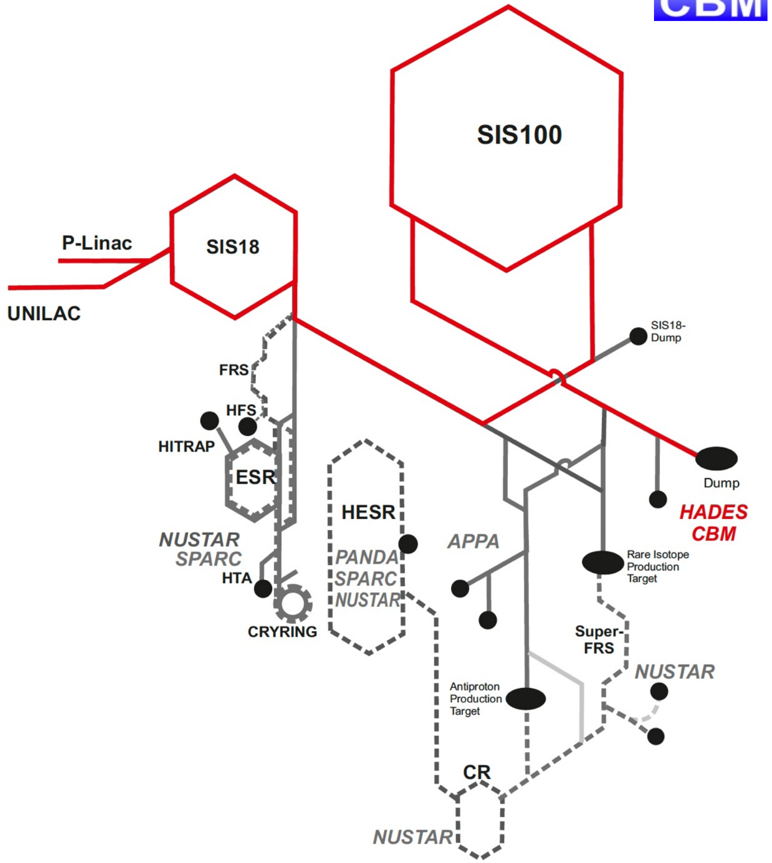
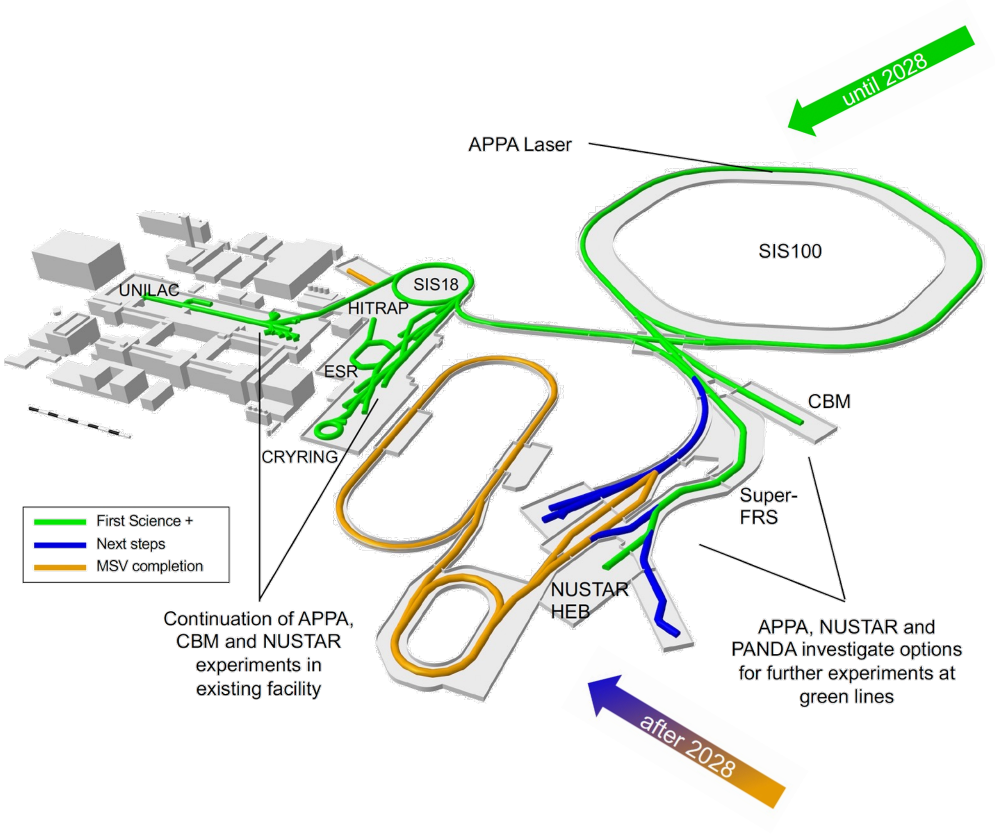


FAIR status



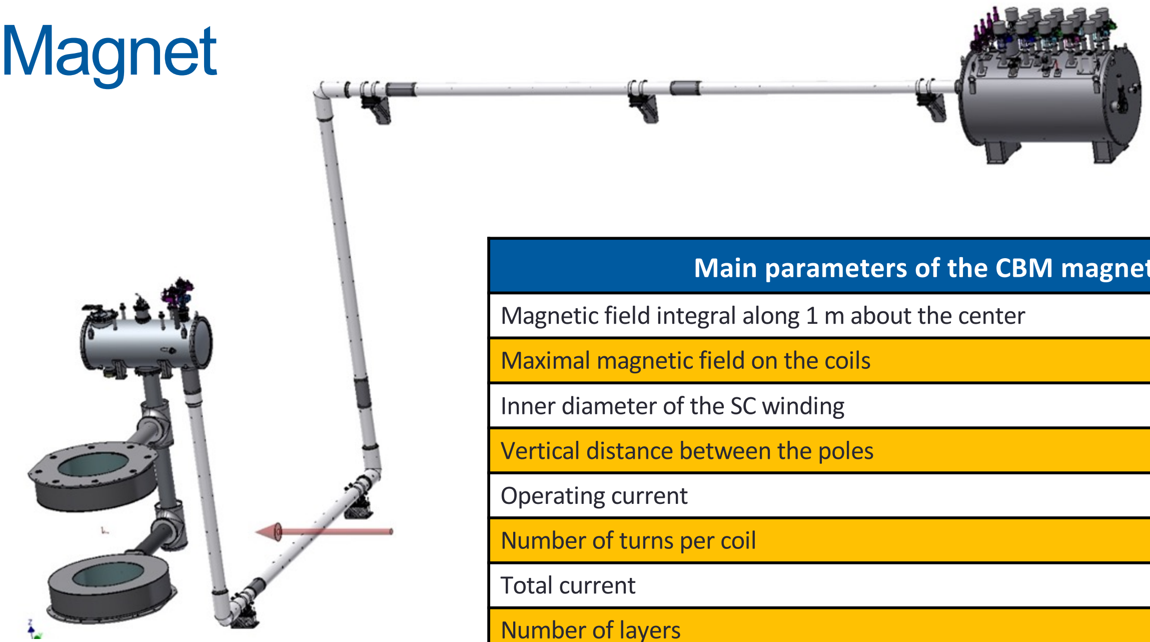
Four FAIR pillars:

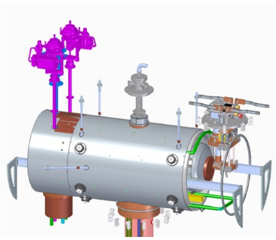
- **APPA** - Atomic, Plasma Physics and Applications
- **CBM** - Compressed Baryonic Matter
- **NUSTAR** - Nuclear Structure, Astrophysics and Reactions
- **PANDA** - Physics with High Energy Antiprotons

FAIR Timeline

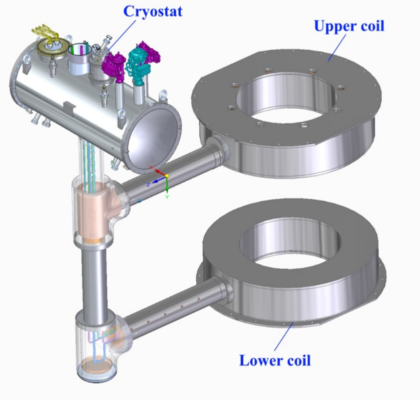
- July 2017: Start of excavation and trench sheeting
- July 2018: Start of shell construction
- June 2022: staging review
- 2023: Buildings completed (First Science+ and Next steps)
- 2024: Start of installation
- **2028: FAIR 2028 Operation**

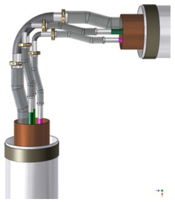
Magnet





Main parameters of the CBM magnet	
Magnetic field integral along 1 m about the center	1.02 Tm
Maximal magnetic field on the coils	3.6 T
Inner diameter of the SC winding	1.396 m
Vertical distance between the poles	1.47 m
Operating current	666 A
Number of turns per coil	1716
Total current	1.143 MA
Number of layers	52
Stored energy at test current	5.0 MJ
Coils cold mass	3600 kg
Operating temperature	4.5 K
Inductance at operating current	21 H
Vertical force acting on the coils toward the iron yoke	3.0 MN
Total weight of the yoke	150 t

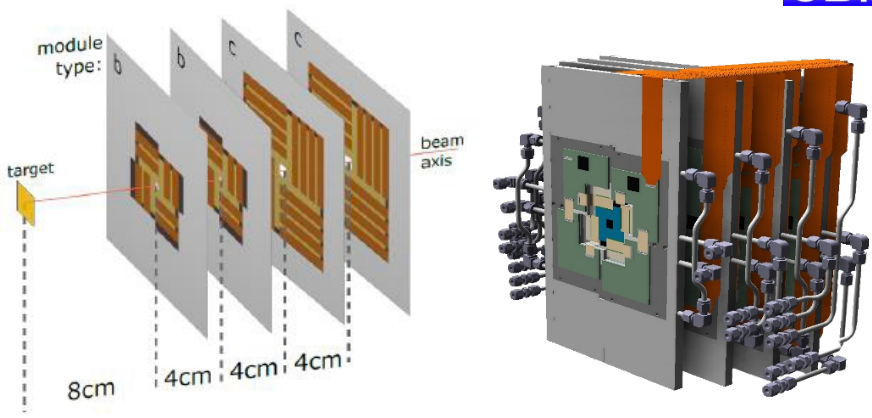




Micro Vertex Detector

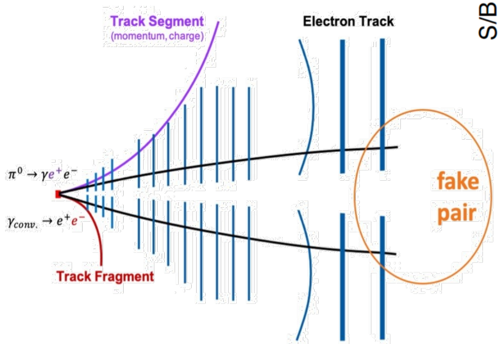
IKF Frankfurt, GSI, IPHC Strasbourg, CTU Prague, Pusan Nat‘l Univ., IMP-CAS, CTU Prague

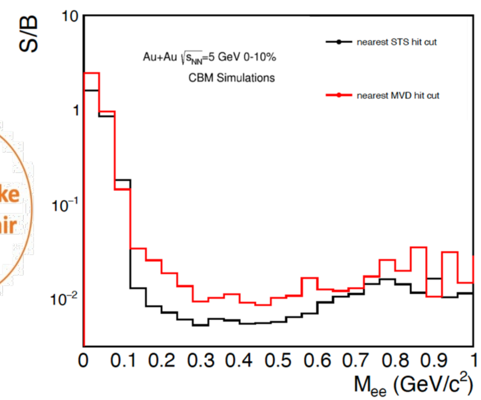
- 4 detector stations, based on MAPS technology
- 100 kHz Au+Au @ 11 AGeV and 10 GHz p+Au @ 30 AGeV
- Non-uniform hit density in time and space
- High radiation environment, operating in a vacuum
- Material budget of $\mathcal{O}(0.5\%\ X_0)$ with TPG (pCVD diamond) carriers



MVD @ CBM

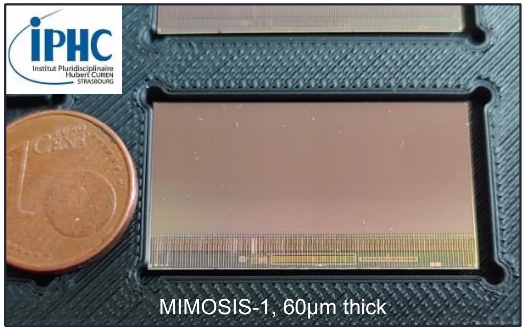
- Pointing precision at the target region
- Reconstruction of low-momentum tracks
- Among others, substantial di-electron background rejection
  - incompletely reconstructed conversion and Dalitz decays
  - way out with MVD: reconstruction of track fragments and segments





MIMOSIS chip

- Based on ALPIDE architecture
- First full-size prototype: MIMOSIS-1
- 504 × 1024 pixels (27 µm × 30 µm pitch)
- Optionally: fully depleted



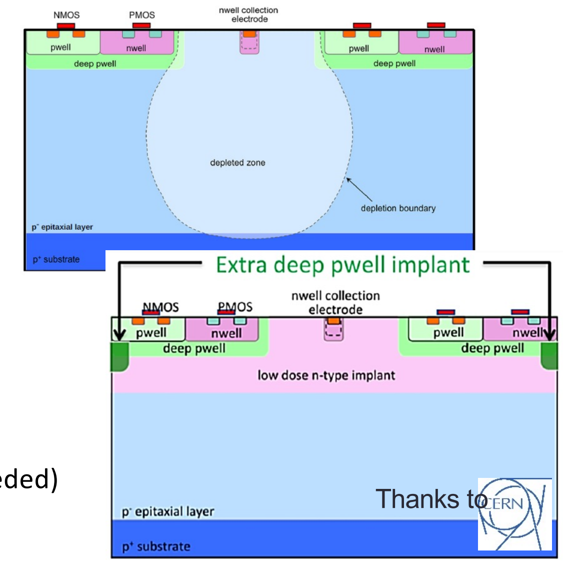
Parameter	Value
Technology	TowerJazz 180 nm
Epi layer	∼25 µm
Epi layer resistivity	$> 1k\Omega cm$
Sensor thickness	60 µm
Pixel size	26.88 µm × 30.24 µm
Matrix size	1024 × 504 (516096 pix)
Matrix area	≈4.2 cm^2
Matrix readout time	5 µs (event driven)
Power consumption	40-70 mW/cm^2

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/cm^2
Data rate	> 2 Gbit/s
Readout mode	Continuous

Spatial / time resolution and material budget: Mostly established by ALPIDE

Radiation tolerance (non-ionizing and ionizing): ~10 x ALPIDE (see modified TJazz process)

Rate capability and data rate: Incompatible with ALPIDE (higher internal bandwidth needed)



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

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

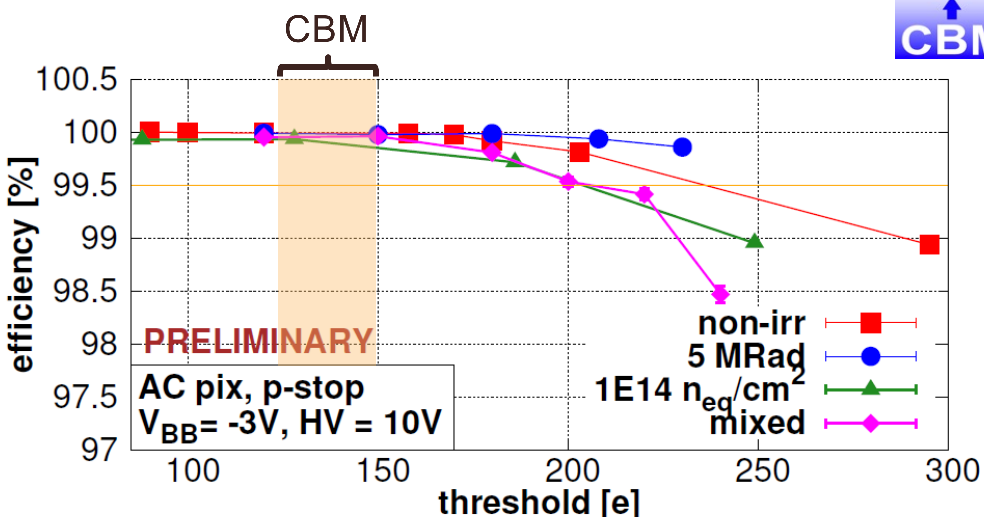
Conclusion on sensor performance:

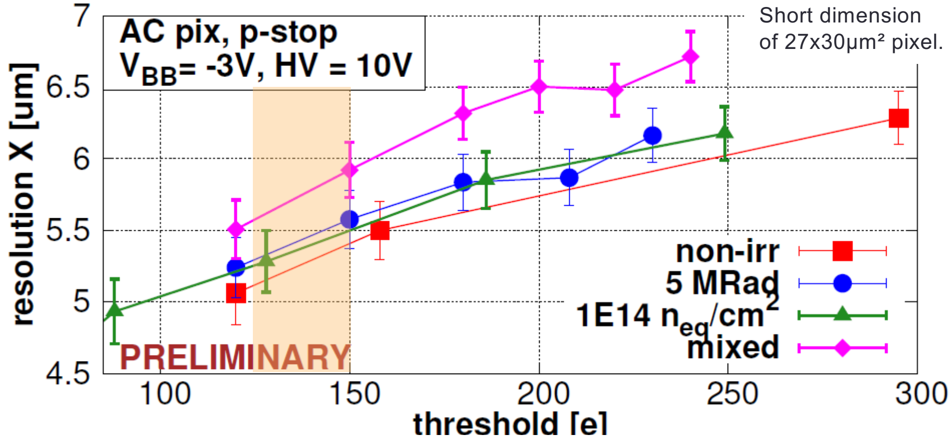
✓ All pixels work excellent before irradiation.

✓ 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.

Test of MIMOSIS-2

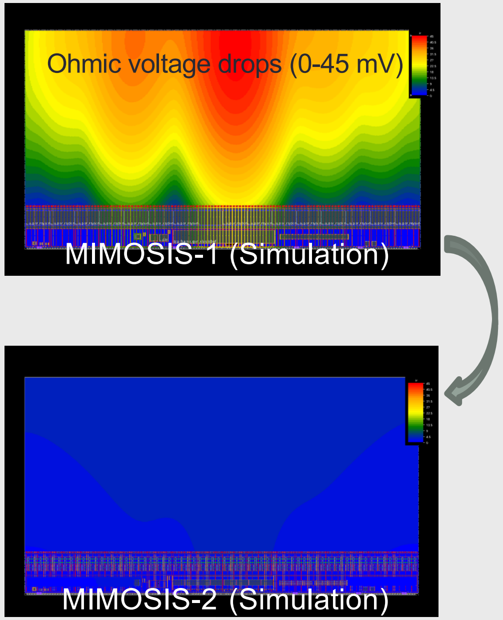
MIMOSIS-0 (2018)
- Demonstrate pixel concept.
- Demonstrate zero suppression.
- Demonstrate readout concept.

MIMOSIS-1 (2020)
- Full dimension sensor
- Add buffer structure.
- SEE hardening 1/2

MIMOSIS-2 (2024)
- On-chip pixel grouping
- Final pixels
- SEE hardening 2/2

MIMOSIS-3
- Final sensor for mass production

MIMOSIS-2 vs. MIMOSIS-1 design changes (example)



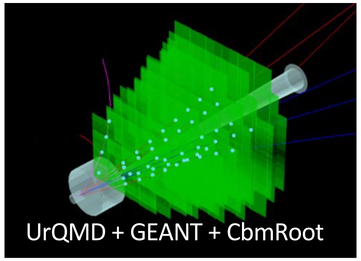
Power grid reworked.
x10 improvement.

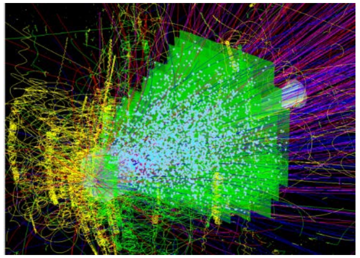
Expect lower FP-Noise

Silicon Tracking System

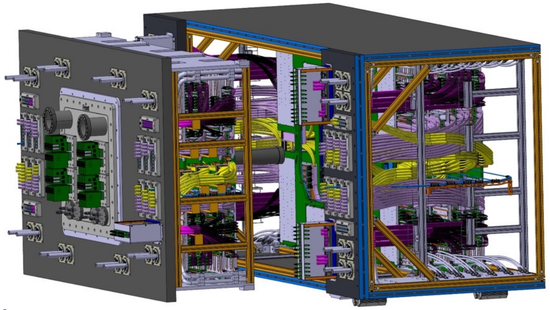
GSI Darmstadt, KIT Karlsruhe, JU Cracow, AGH Cracow, KINR Kiev, Univ. Tübingen, Warsaw UT, Uni. Frankfurt, KEK Tsukuba (assoc.)

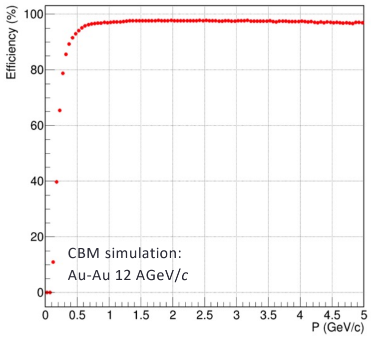
Main CBM detector for charged particle measurement incl. momentum determination.

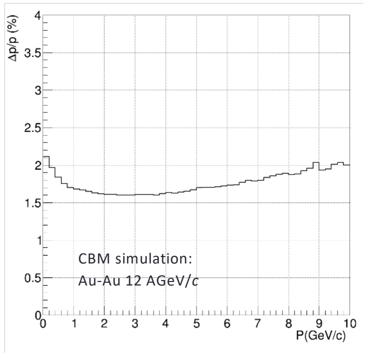




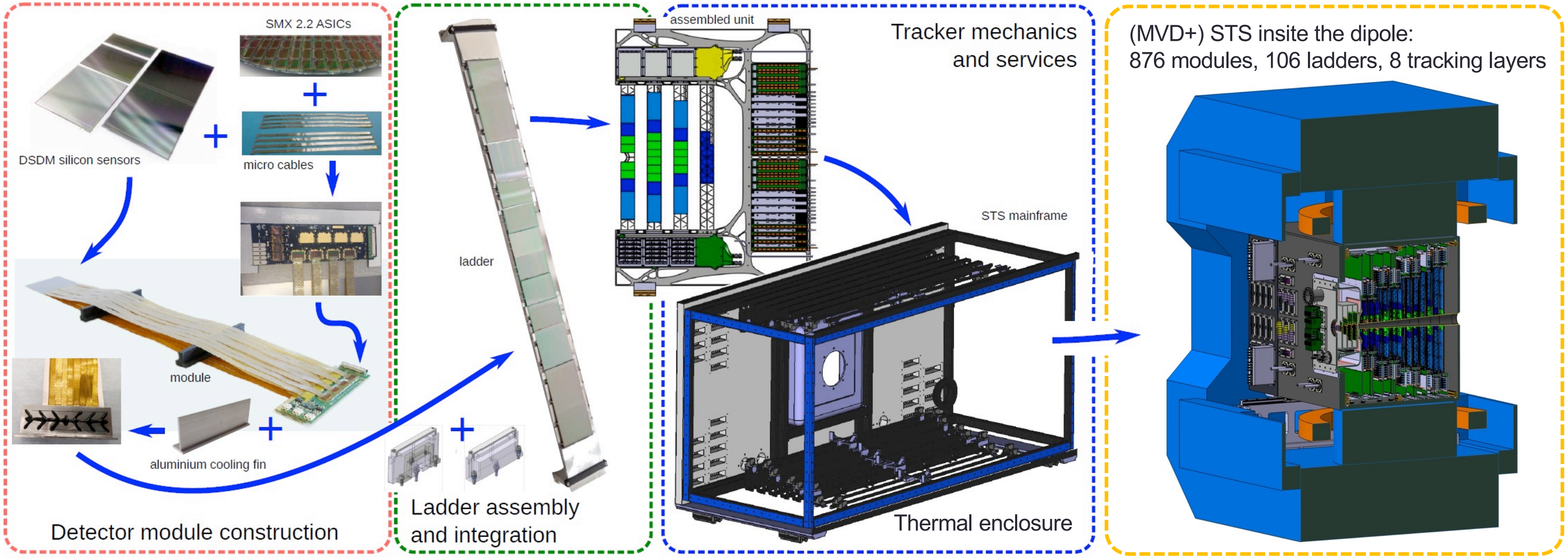
- track point measurement in a high-rate collision environment:
  $10^5 - 10^7$/s (A+A), up to 10^9/s (p+A),
- physics aperture, distance from the target: $2.5° \leq \Theta \leq 25°$, $0.2\ \mathrm{m} \leq \Delta z \leq 1.0\ \mathrm{m}$
- 8 tracking stations
  - double-sided silicon microstrip sensors
  - hit spatial resolution ≈ 15 µm (x), 110 µm (y)
- self-triggering front-end electronics
  - time-stamp resolution $\lesssim$ 5 ns
- Material budget: 0.3% – 1.5% X_0 per station
  - $\Delta p/p < 2\%$ (p > 1 GeV/c, 1 Tm field)
- Rad. tolerance: $\sim 10^{14}$ 1 MeV n_{eq} over lifetime







Silicon Tracking System



- Very complex lightweight system, integration effort

Silicon Tracking System

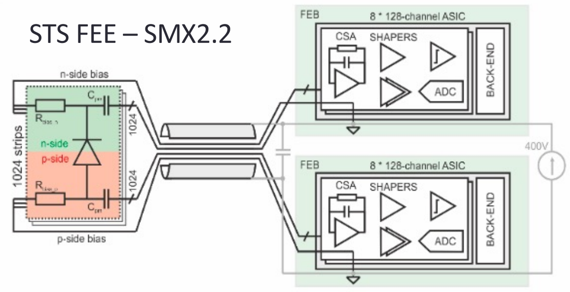
STS-MUCH-XYTER v2.2

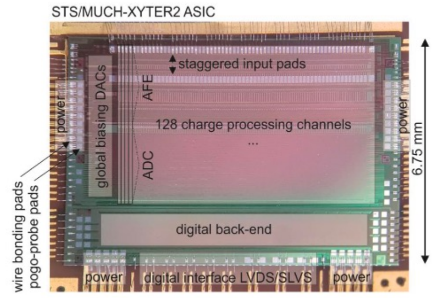
K. Kasinski et al., NIM A 908 (2018) 225

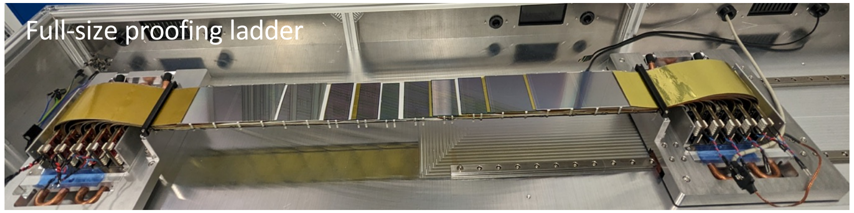
- Low-power, self-triggering ASIC
- 128 channels: 5 bit ADC, 14 bit timestamp
- Time resolution ≲ 5 ns, linearity range up to 15 fC
- Radiation hard layout

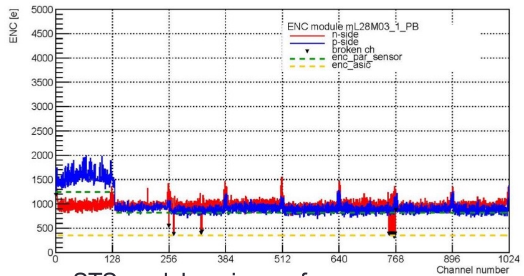
All final components available, pre-production ongoing

- > 60 modules assembled (see experience NIM A 1058 (2024) 168813)
- Ladder assembly ongoing
- PRR in Spring 2024

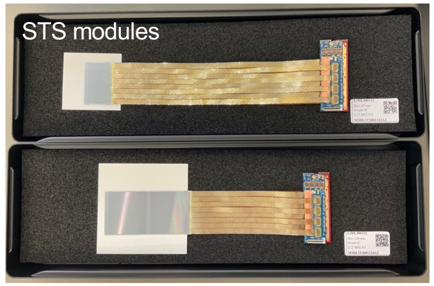








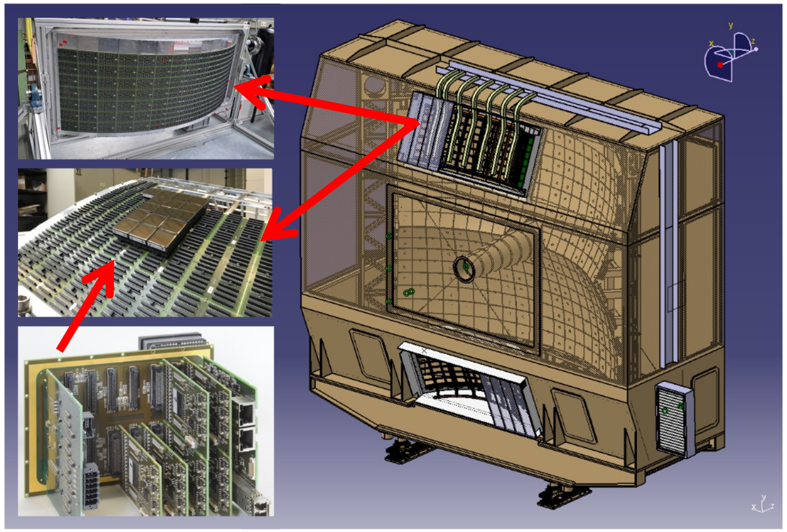
STS module noise performance

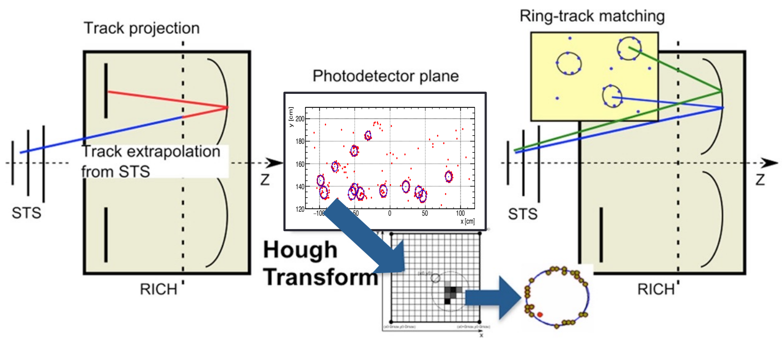


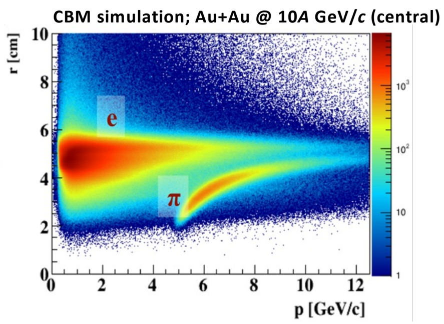
Ring Imaging Cherenkov Detector

Univ. Giessen, Univ. Wuppertal, GSI Darmstadt

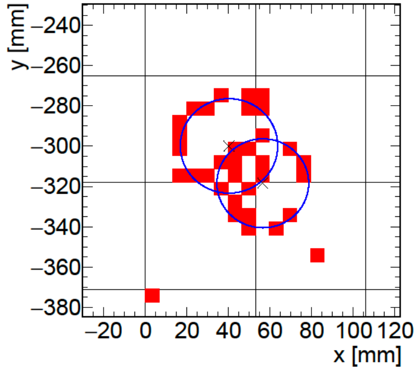
- Gaseous RICH detector for electron identification (p < 8 GeV/c)
- Radiator: CO_2 as radiator gas ($p_{\pi,th}$ = 4.65 GeV/c), ~80 m^3 volume
- Photodetector: 2 photodetector planes (MAPMTs, Hamamatsu H12700) with approx. 55 000 channels
- Mirror: 2 large spherical mirrors (R = 3 m) as focussing optics, Al+MgF_2 reflective coating
- Vertical splitting of RICH geometry because CBM dipole magnet is located in front of the RICH



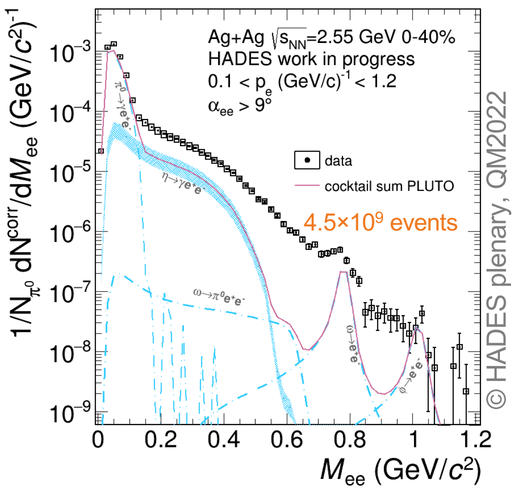


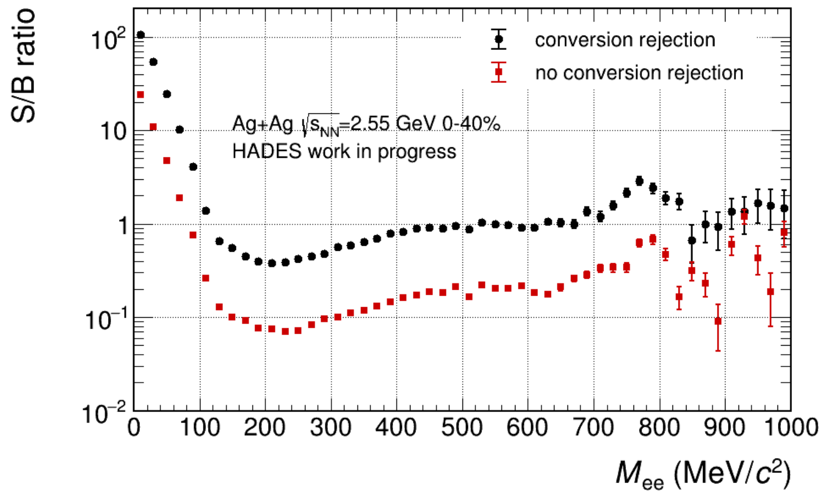


HADES RICH performance



- Superb performance of MAPMT-based RICH photo detector
  - dilepton measurement successfully extended
  - pion suppression factor $>10^4$
  - excellent double ring detection (factor of 8 better signal-to-background ratio)
  - excess radiation observed in Ag+Ag collisions

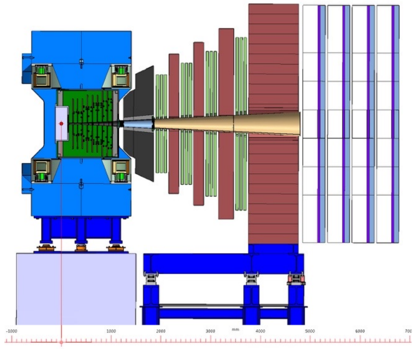


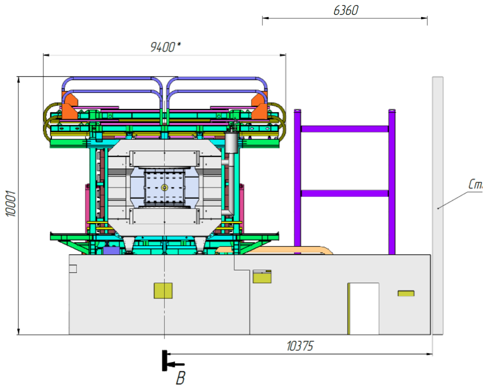


Muon Chambers

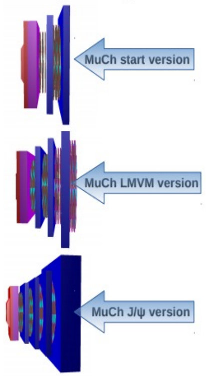
Aligarh Muslim U., Bose Inst. Kolkata, Panjab U., U. of Jammu. , U. of Kashmir, U. of Calcutta, B.H. U. Varanasi, VECC Kolkata, IOP Bhubaneswar, NISER Bhubaneswar, IIT Kharagpur, IIT Indore, Guwahati U.

- 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 reach (see table)
- Capable of taking data at up to 10 MHz interaction rate
- Di-muon trigger!





MuCh geometry variants

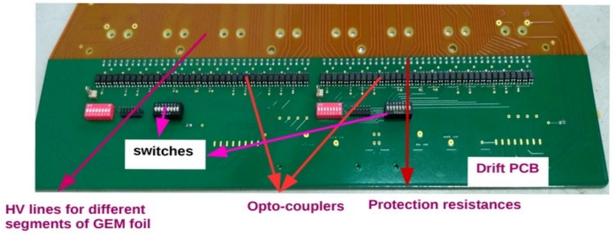


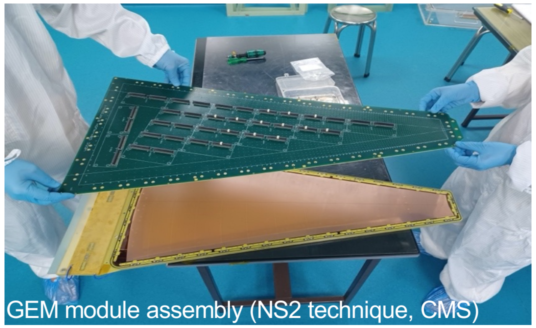
MuCh Geometry variant	No of absorbers	Configuration of the absorbers	No of detector stations	Purpose
LE version	3	1st : 58 cm (28 C + 30 cm concrete) 2nd & 3rd : 20 cm Iron	2 (GEM stations)	LMVM detection $E_b < 4$ A GeV (Au beam)
LVMV version	4	1st : 58 cm (28 C + 30 cm concrete) 2nd & 3rd : 20 cm Iron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

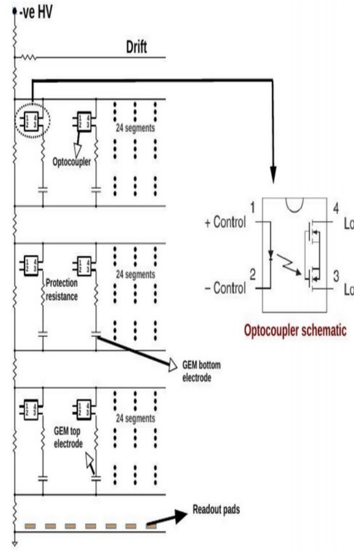
MUCH

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

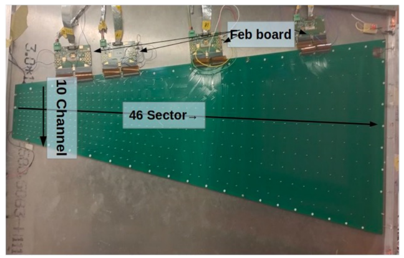


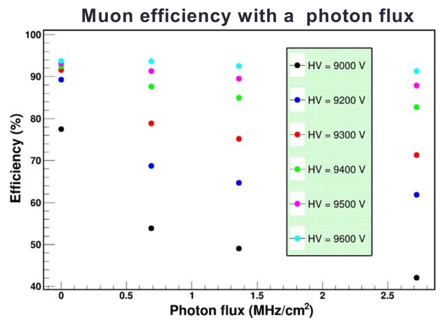

GEM module assembly (NS2 technique, CMS)



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++,





NIMA 1054 (2023) 168384

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 %

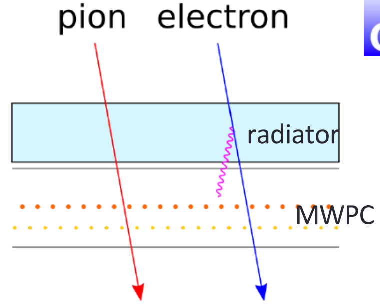
- Tracking between STS and TOF

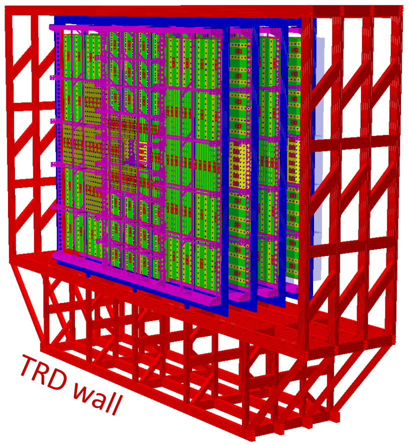
⇒ space-point resolution ~300 μm (across the pads)

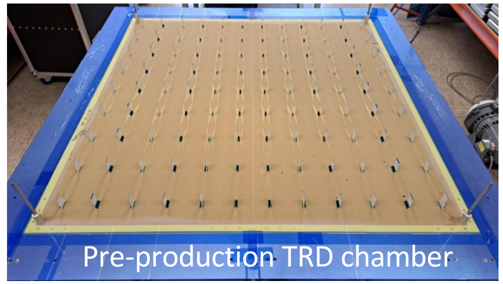
- High rates ⇒ fast detector (max. signal coll. 0.3 μs)

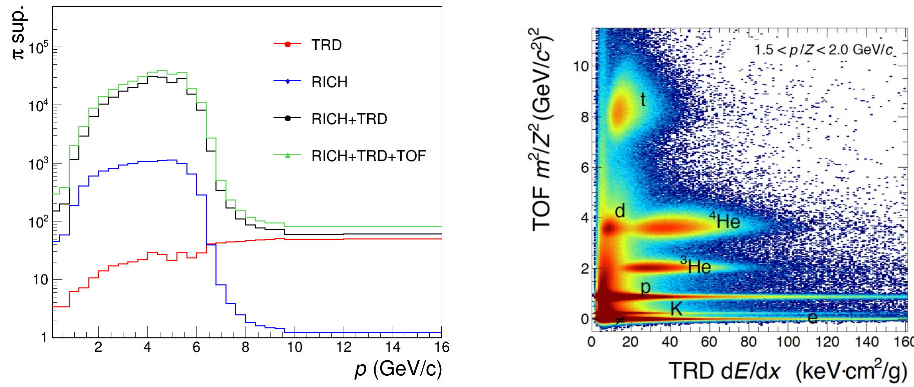
Components

- Four detector layers (SIS100): radiator with PE foam foils + MWPC
- ~250 000 channels, SPADIC ASIC FEE
- Gas mixture: Xe/CO_2 (85/15)





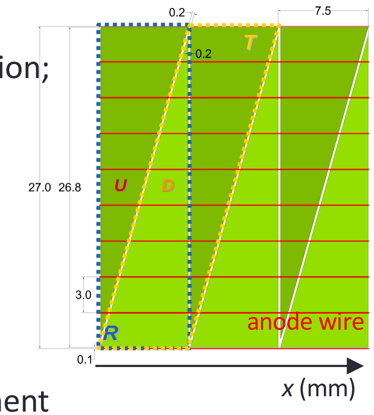


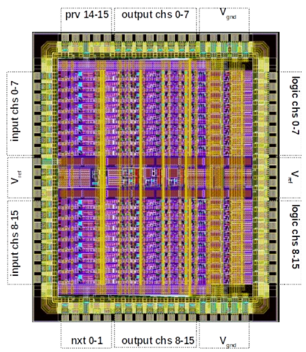


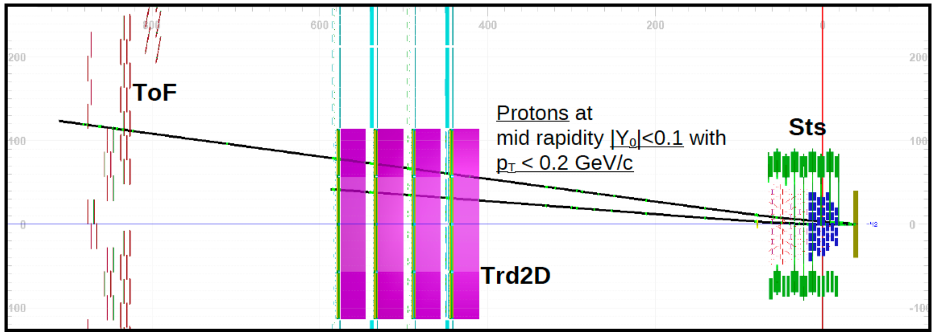
CBM simulation; Au+Au @ 10*A* GeV/*c* (central)

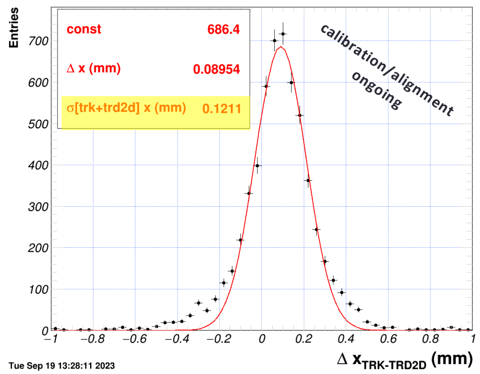
TRD-2D

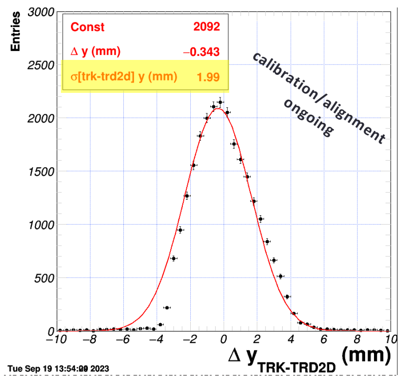
- High-rate MWPCs with 2D readout for ultra-low p_t tracking for the inner-most TRD region;
- Can act as an intermediate tracker for particles: 4 layers with *xy* information
- The pad plane is split into triangular pads (200k channels in total):
  - The read-out is organized based on overlapping R-pairs/T-pairs; 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!





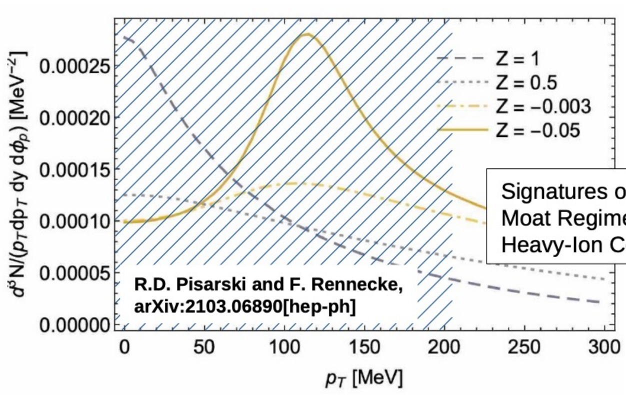




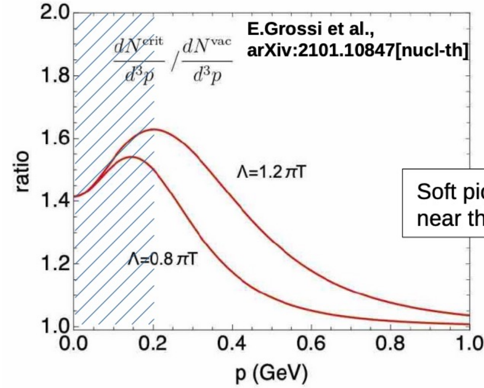


TRD2D

- **Dense QCD matter can exhibit spatially modulated regimes**. They can be characterized by particles with a **moat spectrum, where the minimum of the energy is over a sphere at nonzero momentum**. Such a moat regime can either be a **precursor for the formation inhomogeneous condensates, or signal a quantum pion liquid.**

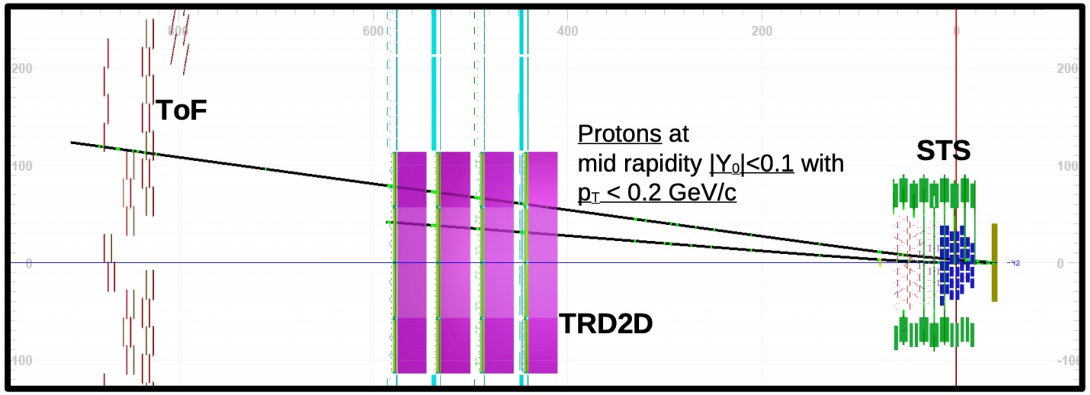


Signatures of Moat Regimes in Heavy-Ion Collisions



Soft pions and transport near the chiral critical point

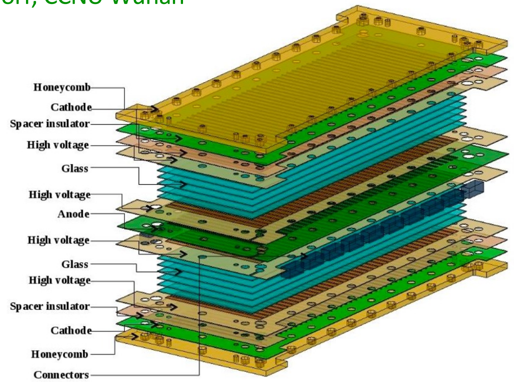
A graphical example showing how **low p_T protons** can get unidentified by **STS** but still identified by an **intermediate tracker (TRD2D)**

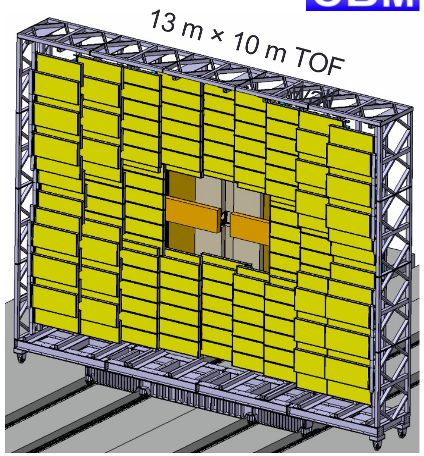


Time of Flight

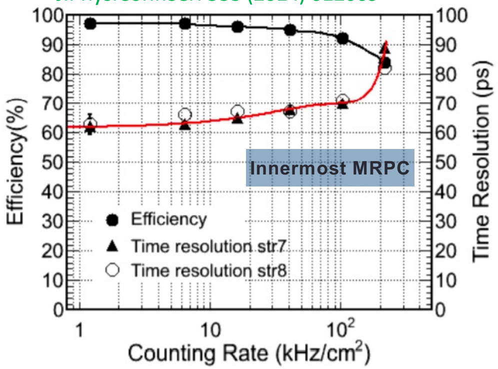
U. Heidelberg, THU Beijing, NIPNE Bucharest, GSI, TU Darmstadt, USTC Hefei, HZDR Rossendorf, CCNU Wuhan

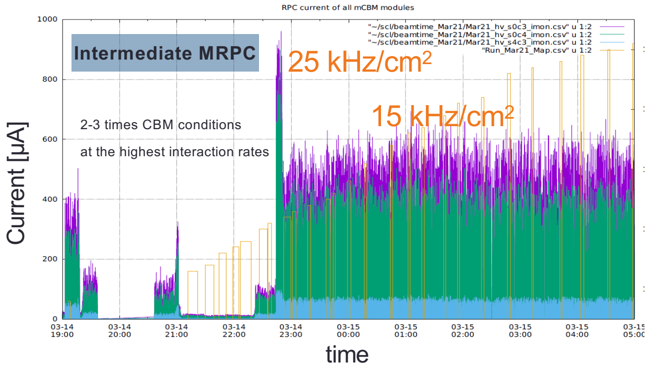
- Double-stack multi-gap resistive plate chambers for ultra-high rates
- All CBM TOF wall requirements met!
  - system time resolution: $\sigma_{sys} \approx 80$ ps
  - efficiency: $\varepsilon \gtrsim 95$ %
  - rate capability up to 50 kHz/cm^2 (depending on the region) achieved with a float ($\rho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



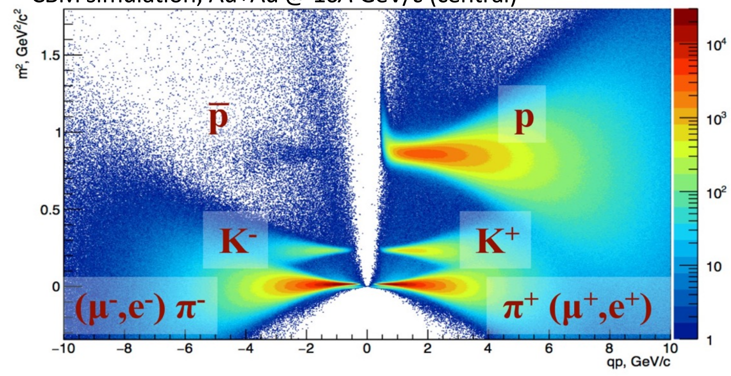


J.Phys.Conf.Ser. 533 (2014) 012009





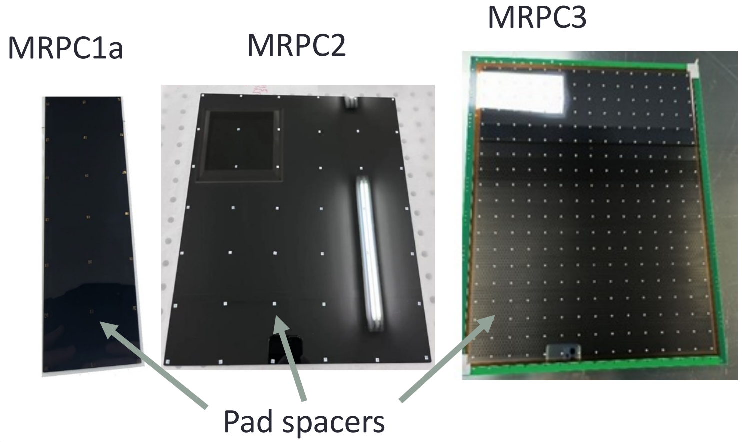
CBM simulation; Au+Au @ 10*A* GeV/*c* (central)

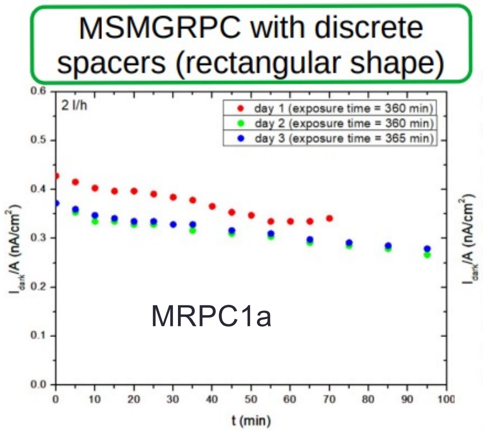


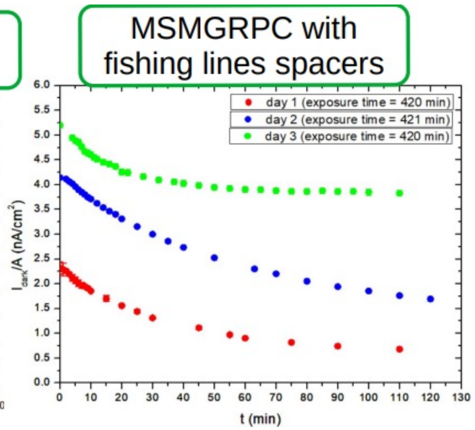
TOF

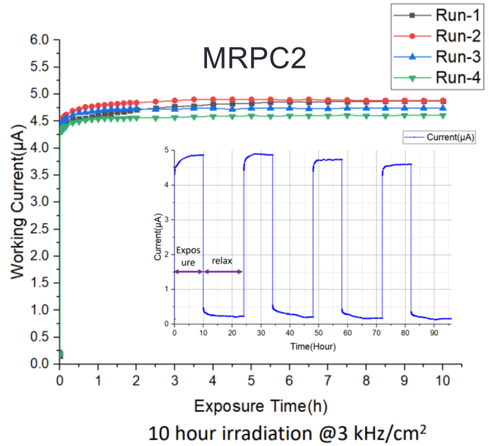
Main achievements in last ~6 months

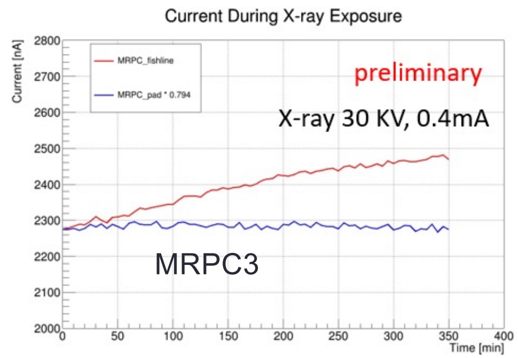
- **Counter pre-production finished** -> all counters arrived in Heidelberg
- Design and production of **several pad spacer counters** from type MRPC1a , 2 and 3
- **Aging tests of all produced pad spacer counters with X-rays**
- **Engineering design on the main frame in full swing**
- 12 module chambers build – to be integrated in the mockup frame
- First MRPC1b and c assembled in Bucharest and tested with cosmic rays
- FEE ASIC PRR successfully finished on 30 May 2023 -> new batch of FEE chips to be produced soon











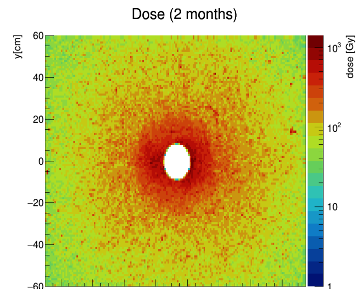
Forward Spectator Detector

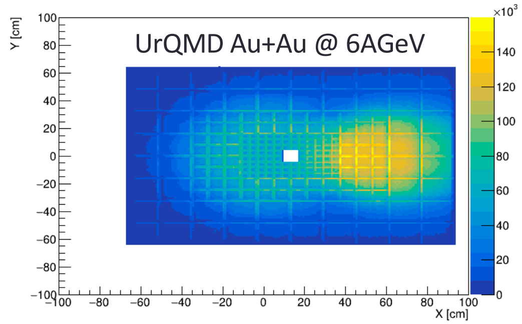
CTU Prague, GSI and FFN (U. Bochum)

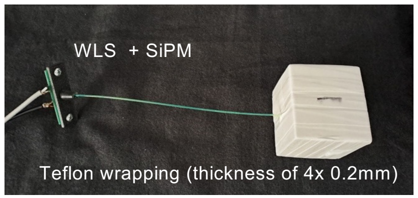
- **Important subsystem for centrality determination**
- Original concept based on hadronic calorimeter (Pb/Scintillator) – in-kind contract cancelled

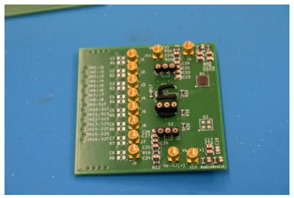
FSD support structure at FAIR

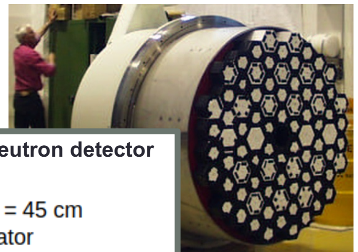
- Replacement **based on plastic scintillator**, similar to HADES forward hodoscope wall or STAR Event Plane Detector
- Provides an **opportunity to improve performance** at low energies and high interaction rates
- Background and performance studies have been launched
- 5×5 cm^2 scintillator module prototypes with WLS+SiPM or PMT readout
- Readout based on TRB+DiRICH – proven GSI in-house technology
- Possibility of adding COSY-TOF neutron detector









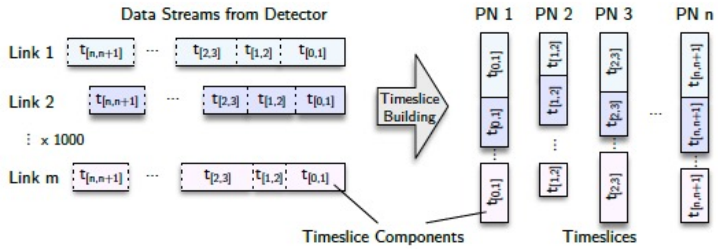


COSY-TOF neutron detector
Ø 126 cm
84 modules, l = 45 cm
plastic scintillator
n-detection efficiency ≈ 30 %

Online systems

FIAS, GSI, KIT, ZIB

- The First-level Event Selector (FLES) is the central data handling and event selection entity of the CBM experiment
- Readout boards (mostly GBTx-based) send time-stamped data stream (time-slice components) via optical links to CRIs
- 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

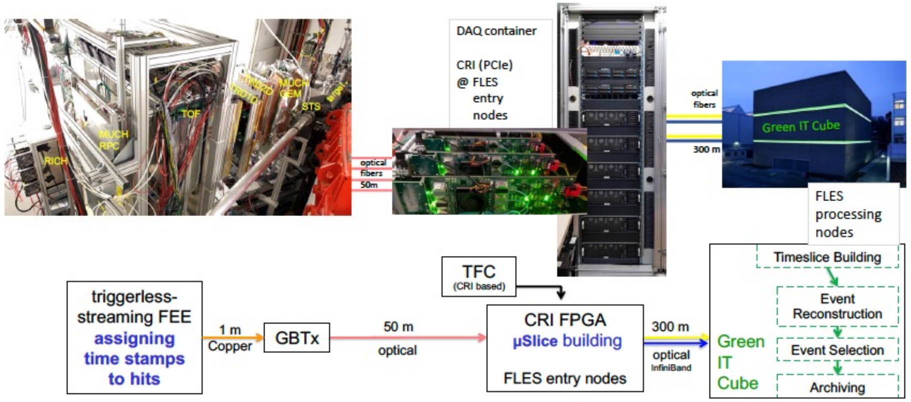


CRI1.0 board (BNL-712 v2)

GSI Green-IT Cube

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

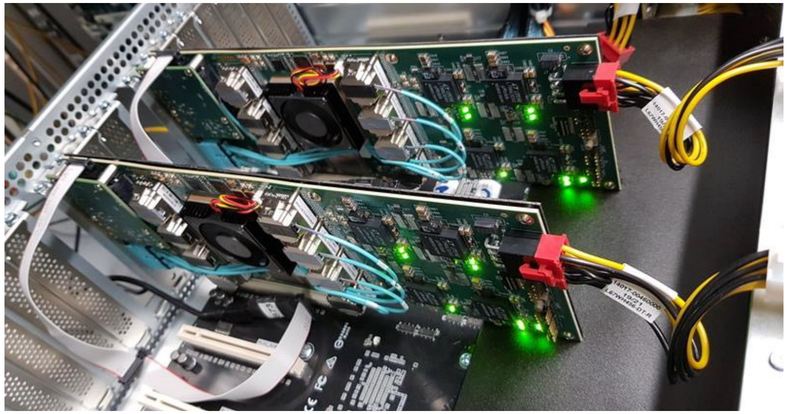


Ni + Ni, T = 1.93 AGeV, run duration: 6 h

- av. collision rate: 400 kHz
- av. data rate 1.5 GB/s to disc, 32 TB data collected

Au + Au, T = 1.23 AGeV, run duration: 35h

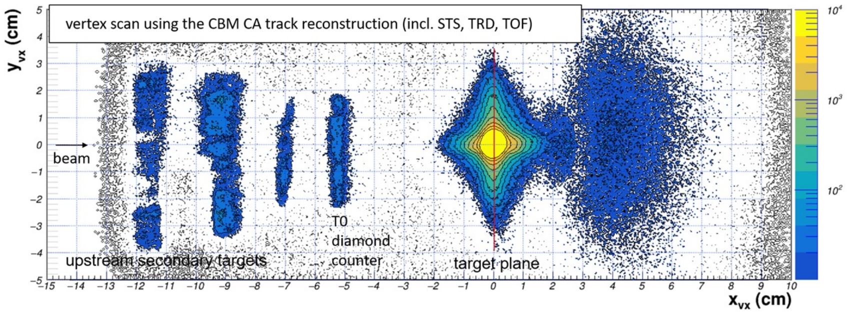
- av. collision rate: 200 – 300 kHz
- av. data rate 1.4 – 2.2 GB/s to disc, 180 TB data collected



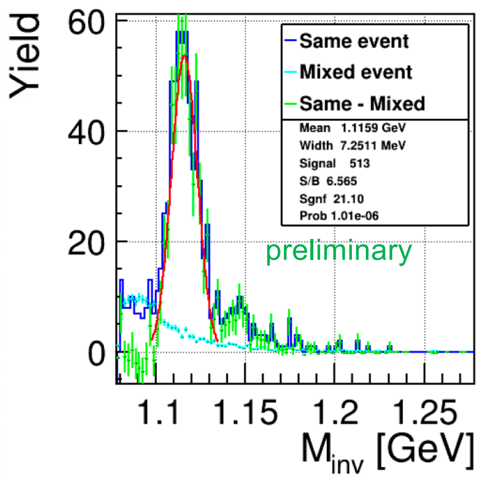
mCBM DAQ with CRIs (prototype for CBM) in an entry node

mCBM @ SIS18 – CBM full system setup

Ni+Ni 1.93 AGeV



Ni+Ni 1.93 A GeV



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

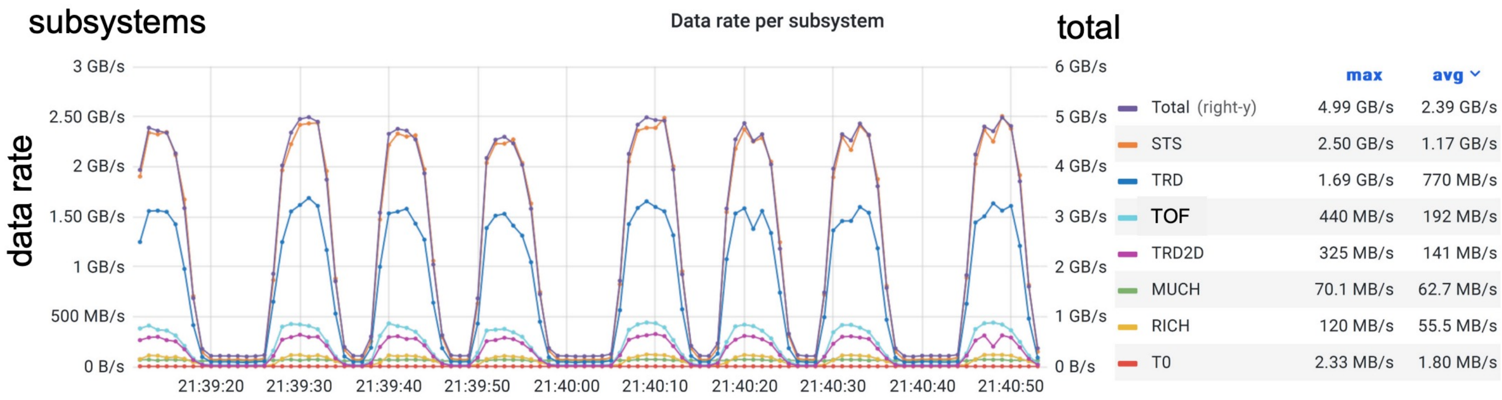
  (calibration and alignment studies ongoing)

mCBM campaign in 2024-2025

- Runs in 2024-2025 with upgraded detectors (production modules/electronics)
- Λ excitation function at SIS-18 energies (Au+Au, Ni+Ni)
- Further development of the readout chain and **online** analysis tools
- High-rate detector tests: Production Readiness Reviews, QA/QC
- Testing of the next generation of CRI cards

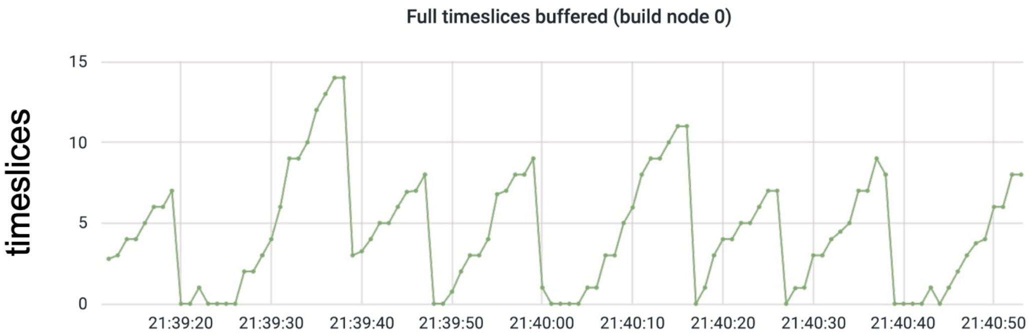
Data path performance - FLES input and output data rates

FLES input



Note: SIS18 micro-spill structure!

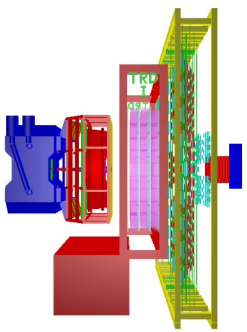
FLES output

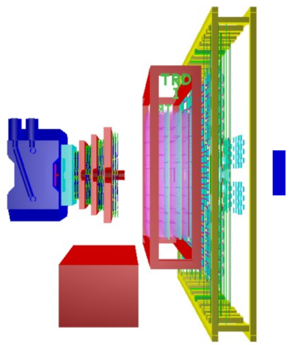


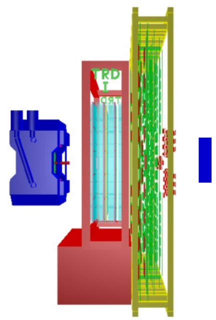
run 2448
June 16, 2022
Au + Au, T = 1.23 AGeV
av. collision rate: 300 - 400kHz
av. data rate 2.4 GB/s to disc

CBM setups

Setup	Included detectors	Average "Day-1" interaction rate	Average MSV - interaction rate
ELEHAD	MVD,STS,RICH,TRD,TOF,FSD	0.1 MHz	0.1 MHz
MUON	STS,MUCH,TRD,TOF,FSD	1 MHz	5 MHz
HADR	STS,TRD,TOF,FSD	0.5 MHz	5 MHz


ELEHAD


MUON

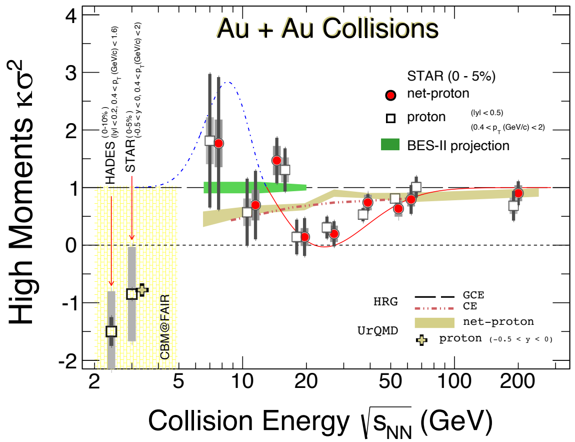

HADR

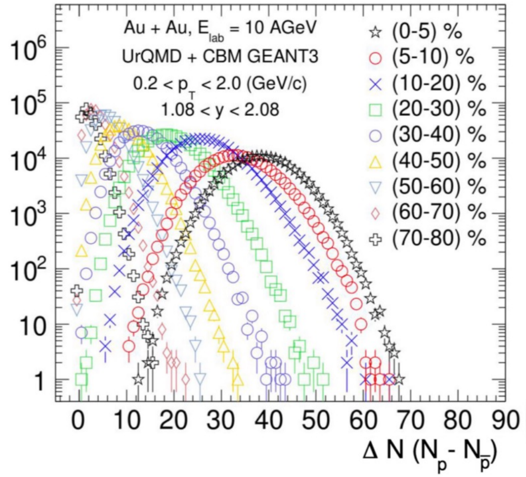
- CBM commissioning with beam (earliest on the floor):
  - preferred configuration: ELEHAD setup
  - minimum configuration: HADR setup

Highlighted future directions

- Critical point search: discontinuities of the higher moments of particle number distributions, visible in a beam energy scan

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

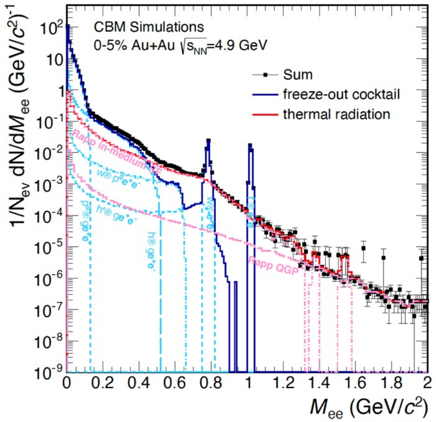


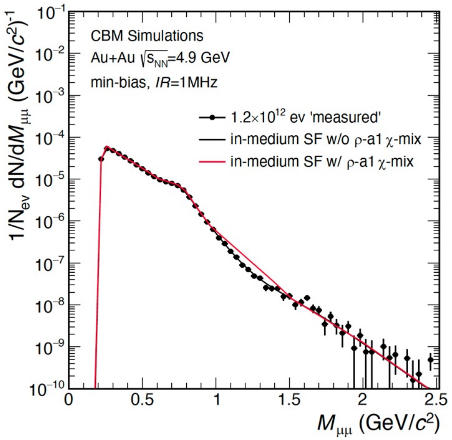


After 3 years of running:

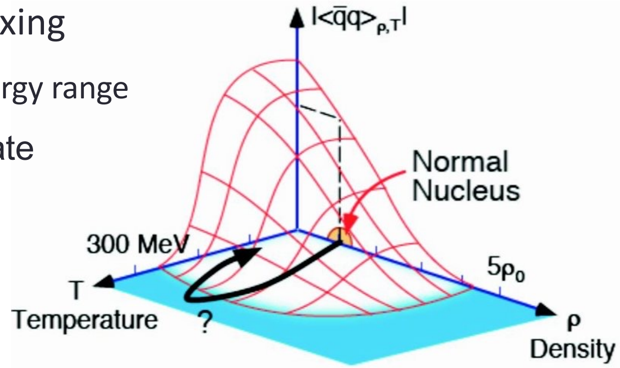
- Completion of the excitation function for $\kappa_4(\mathrm{p})$
- First results on $\kappa_6(\mathrm{p})$ - particularly sensitive to features of the QCD phase diagram
- Extension into strangeness sector $\kappa_4(\Lambda)$

Dilepton measurements



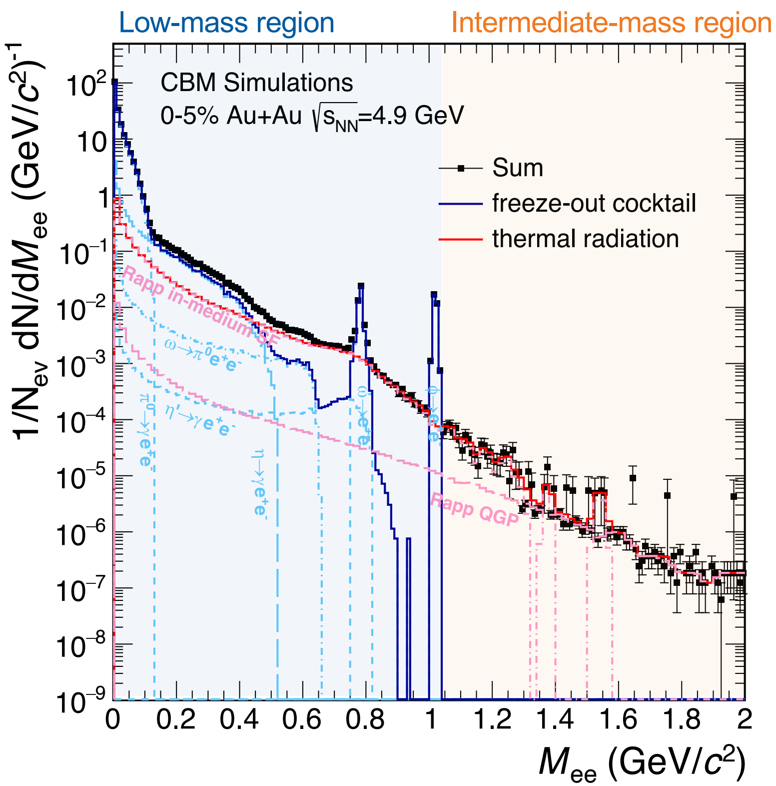


- Low mass range: total yield ~ fireball lifetime
- Intermediate mass range: slope ~ emitting source temperature
- Access to thermal signal is very feasible with good background description
- Chiral symmetry resotration → ρ and a_1 mixing
  - Mapping phase boundary over full incident energy range
  - *T* and *ρ* dependence of the quark condensate
  - Complementary to the LHC measurements



- Crucial for high quality data:
  - Interaciton rate
  - S/B ratio

Emissivity



Electron-setup $R_{int} = \mathcal{O}(0.1\ \text{MHz})$:

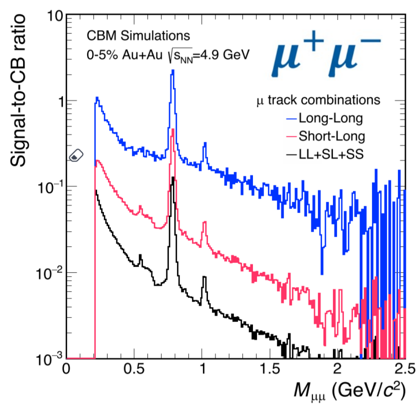
- identification with RICH-TRD-ToF (π suppr. ≥ 10^4);

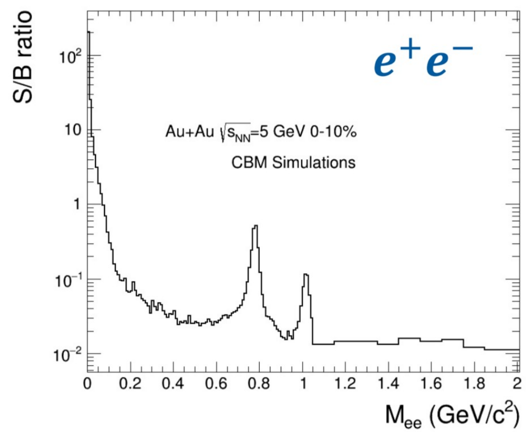
- major CB γ-conversions in target, π^0 Dalitz decays;

- topological cuts used to reject CB

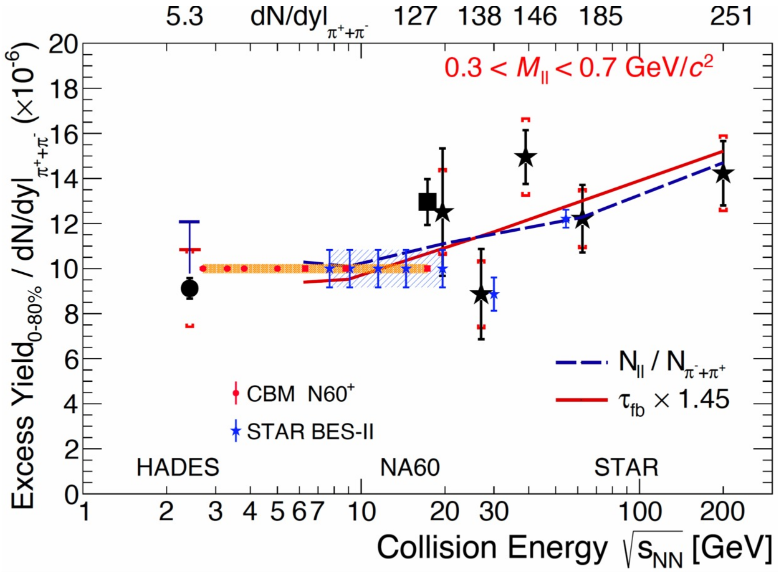
Muon-setup $R_{int} = \mathcal{O}(1\ \text{MHz})$:

- instrumented hadron absorber, low- and high energy configuration



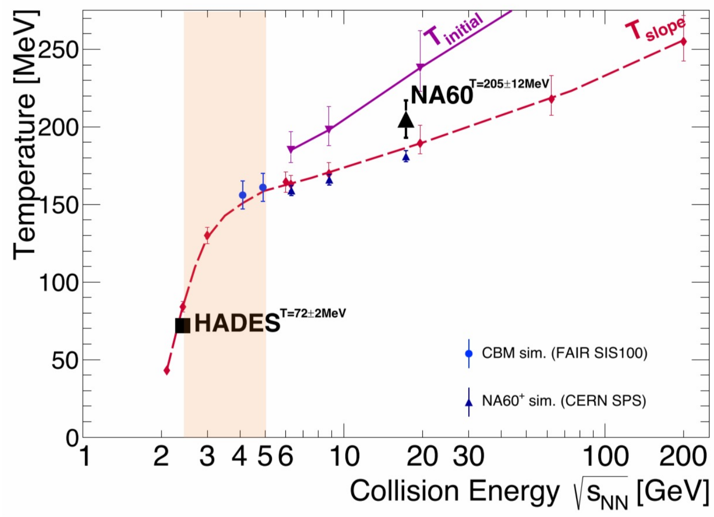


Emissivity with $e^{+}e^{-}$ after 3 years



Excess yield in Low Mass Region tracks fireball lifetime

- Search for "**extra radiation**" due to latent heat at **phase transition.**
- Precision sufficient to observe 1st order phase transition,

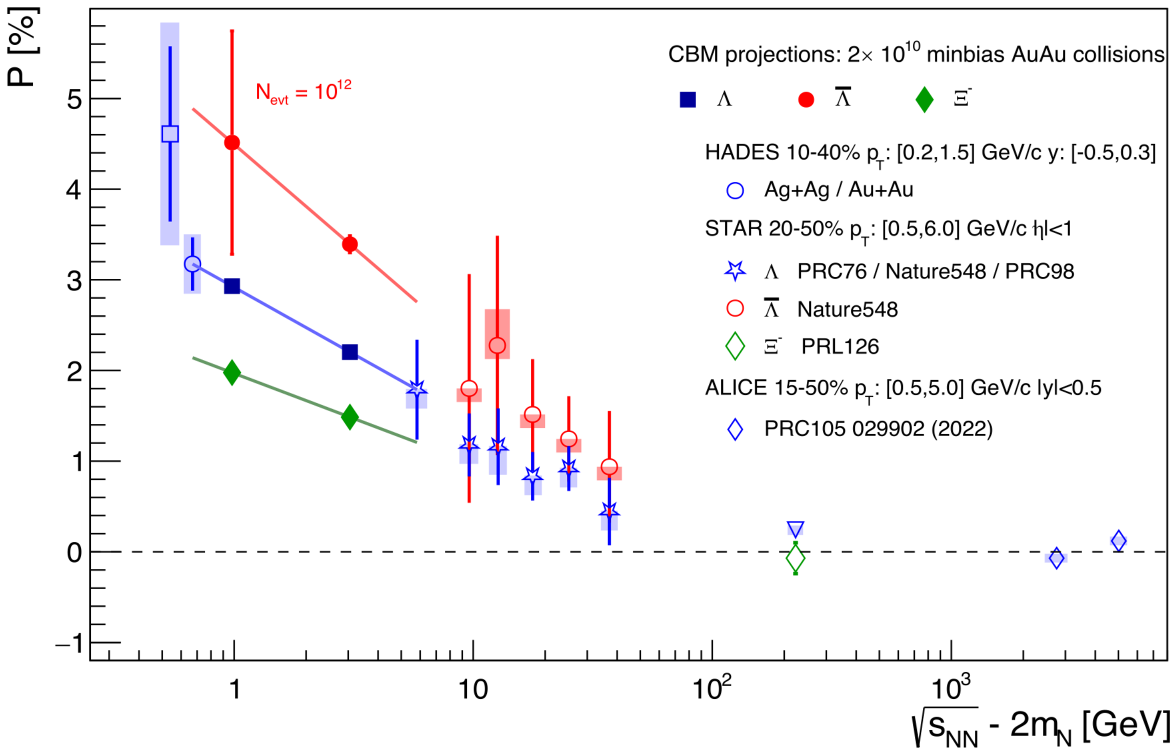


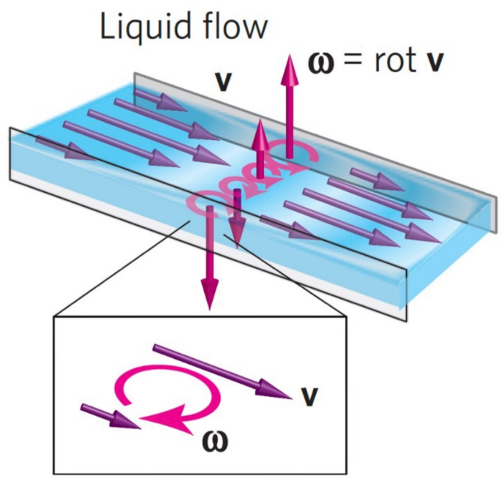
Slope of invariant mass spectra in Intermediate Mass Region measures source temperature

- **Flattening** of caloric curve (T vs ε) would give evidence for a **phase transition.**
- Statistics after 3 years not sufficient for conclusive results .

Vorticity

Global spin polarization of hyperons as a probe of fluid behaviour

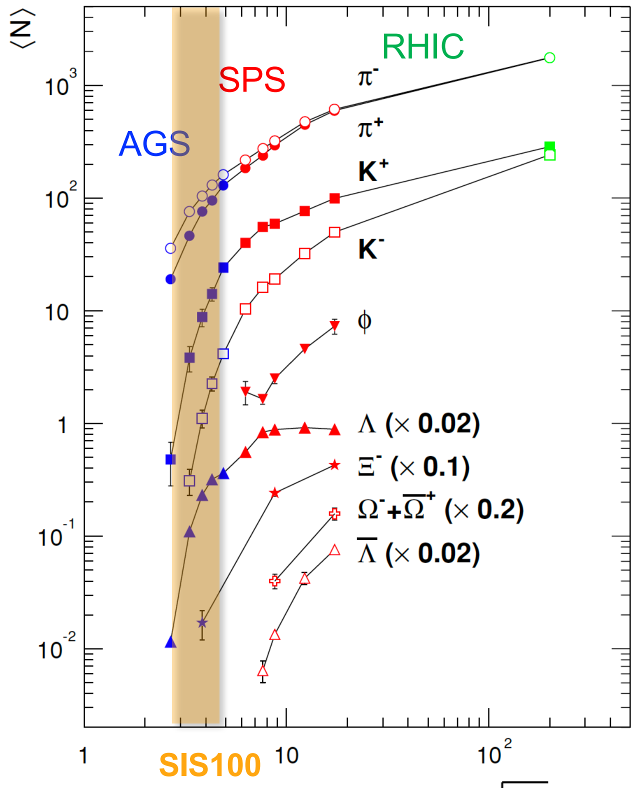




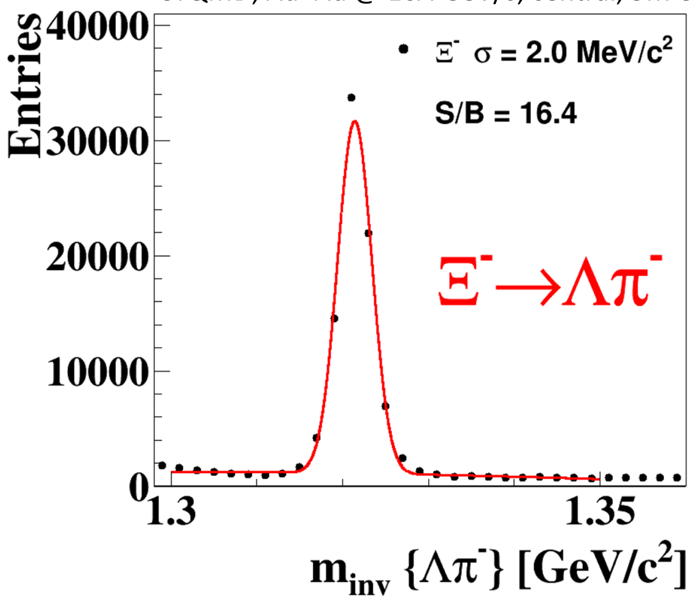
Takahashi, et al. Nat. Phys. (2016)

- Driving mechanism for coupling orbital momentum to spin not understood yet.
- Measurement of polarization of Λ and Ξ^{-} with precision of 5% possible.
- Mapping of the excitation function for $\overline{\Lambda}$ requires $\geq 10^{13}$ events.

Multi-strange hadrons



J. Phys. G 31, S57 (2005)



- High-precision measurements of excitation functions of multi-strange hyperons in A+A collision at SIS100 energies!