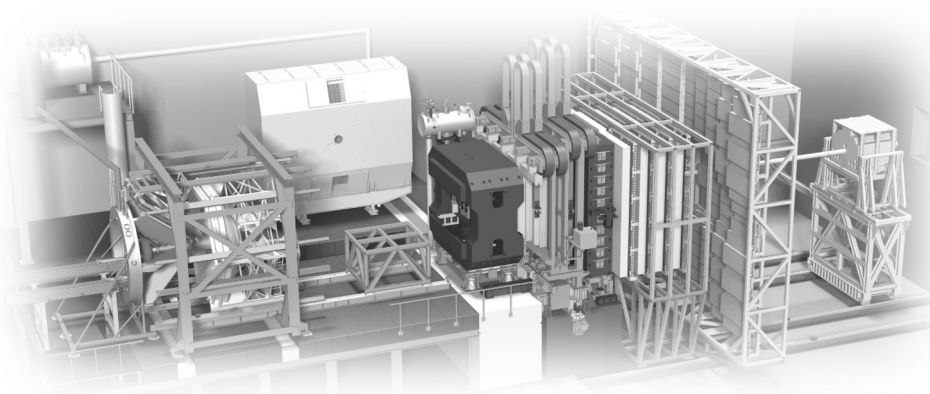
# Insight into fixed target proton beam at CBM/HADES: physics and instrumentation

**Tetyana Galatyuk, GSI / TU Darmstadt**
**for the HADES and CBM Collaborations**

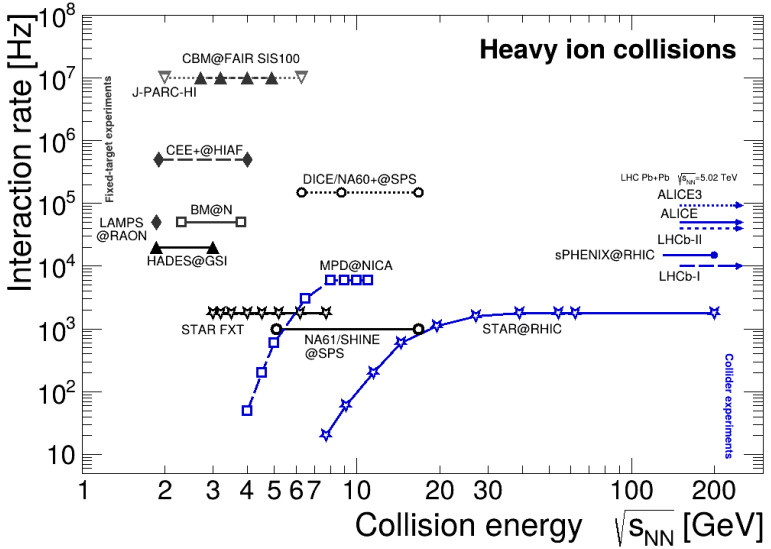
Advancing Nuclear Physics: New Horizons with Fixed-Target Proton-Nucleus Experiments at Intermediate Energies
July 10-11, 2025, Stony Brook University/Online



# HADES/CBM objective

***"Explore the phase properties and microscopic structure of strong-interaction matter at high(est) net-baryon densities"***

- Focus on rare/penetrating probes and precission measurements
- Requires high statistics/rates and excellent understanding of detector response




https://github.com/tgalatyuk/interaction_rate_facilities, update May 2025

# HADES/CBM mission

**Search for landmarks of the QCD matter phase diagram:**

- isolate unambiguous signals of new phases of QCD matter, order of phase transitions, conjectured QCD critical point
- establish high net-baryon density EoS
- probe microscopic matter properties

→ **heavy-ion beams**

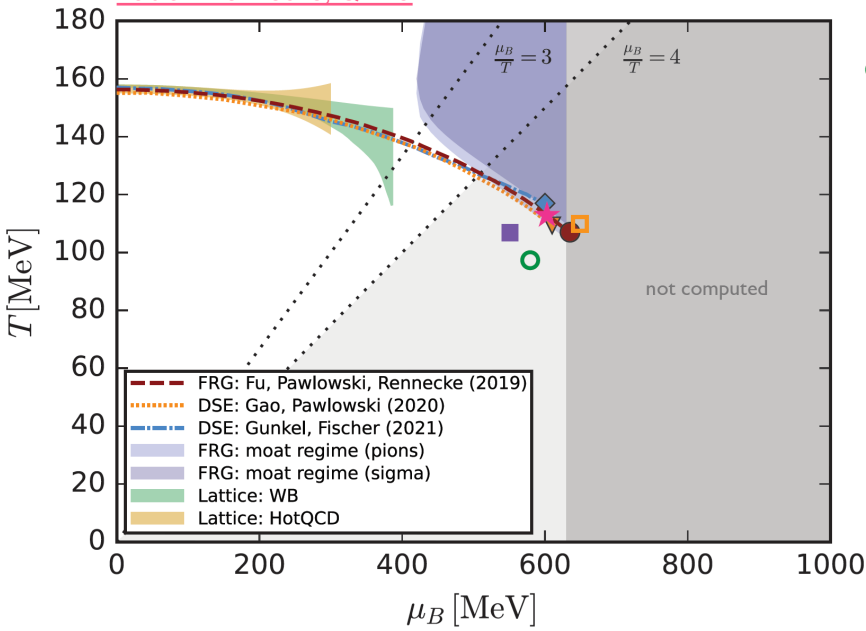
**Study various aspects of meson/baryon physics:**

- (*u, d, s, c*) hadron production mechanism, spectroscopy (|*s*|=*2,3,* |*c*|=*1*), interactions, hadron structure
- electromagnetic transition form-factors

→ **secondary π, p, d beams**

**Worldwide experimental and theoretical efforts**
**Relevance for astrophysics**

Fabian Rennecke, QM25




CEP location well constrained by now. And it's **in FAIR range!**

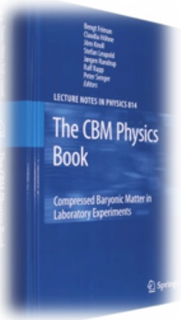
$\sqrt{s_{NN}} \approx 3.6 - 4.1$ GeV

# HADES/CBM strategy

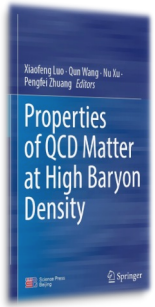
**Measure with utmost precision (abundant / rare):**

- light flavour hadrons, incl. (multi-)strangeness
  ↦ chemical freeze-out $T, \mu_B$
  flow, vorticity ↦ equation-of-state

- event-by-event fluctuations (criticality)
- dileptons (emissivity)
- charm (transport properties)
- hypernuclei (interaction, production mechanism ↦ EoS )

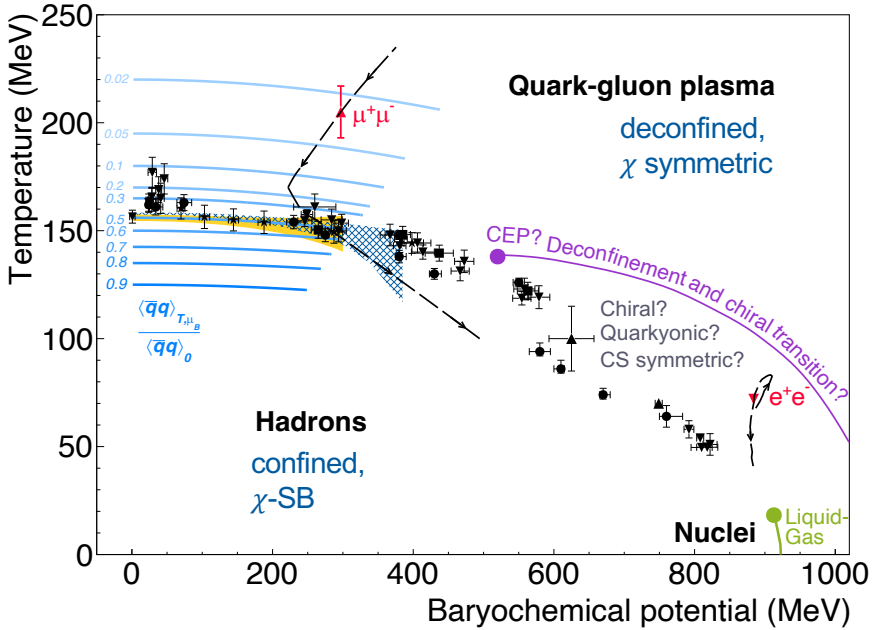



Friman *et al.*,
Lect. Notes Phys. 814 (2011) 1



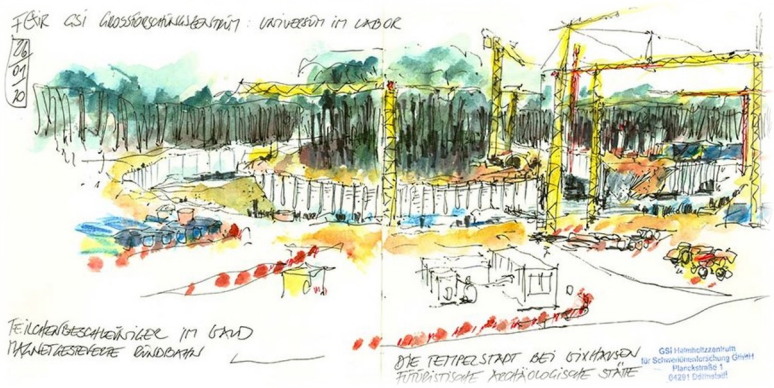

Chen, Dong, Fukushima, Galatyuk, *et al.*,
doi:10.1007/978-981-19-4441-3_4 (2022)

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

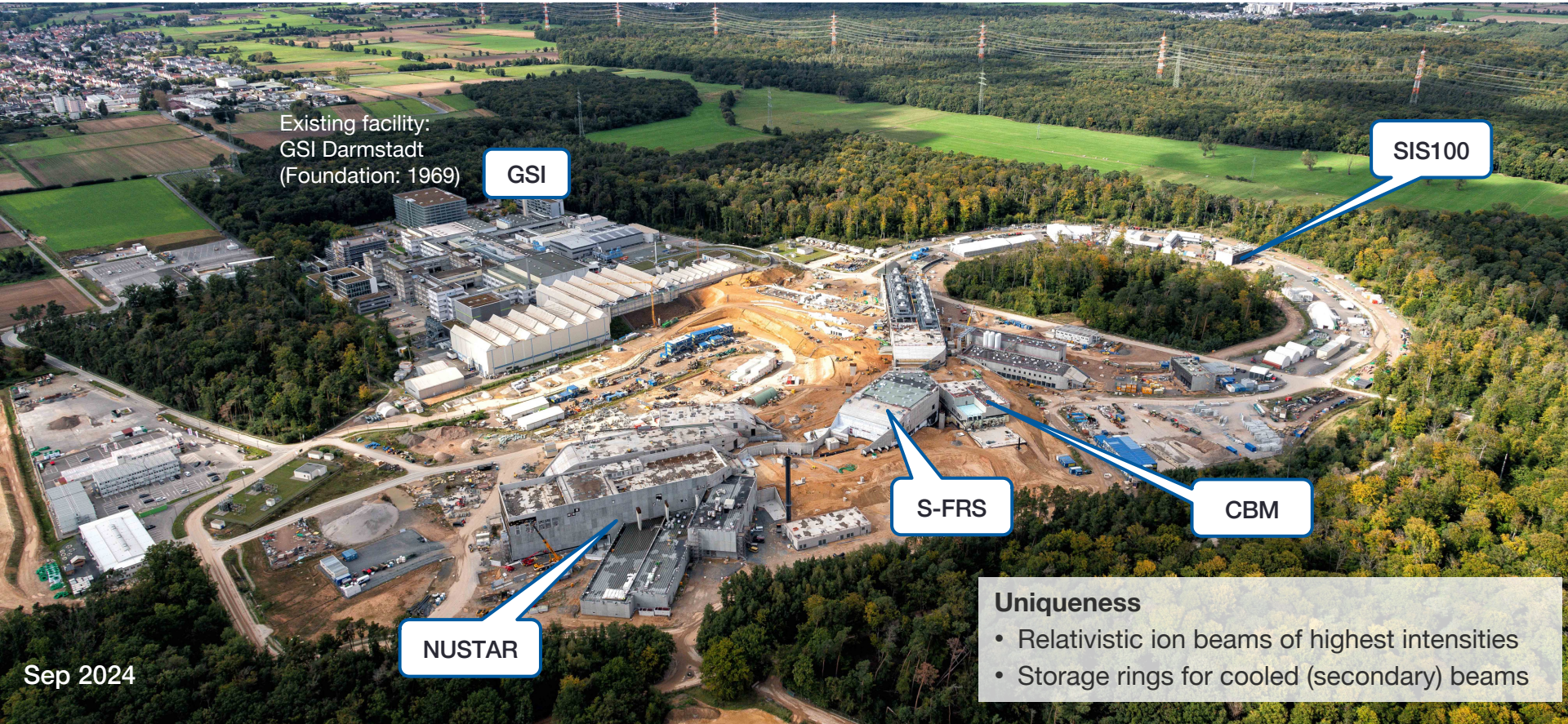


Accelerator

# GSI/FAIR



# FAIR status

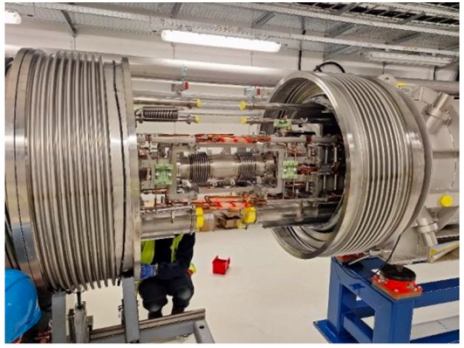



**Uniqueness**

- Relativistic ion beams of highest intensities
- Storage rings for cooled (secondary) beams

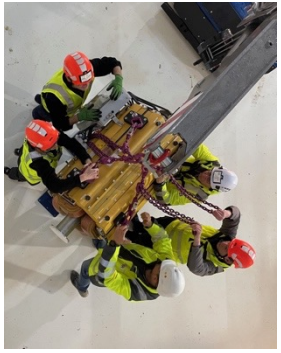
# TBI and ACC installation in full swing

Aug'24: first interconnection of a pair of dipole modules in the accelerator tunnel



Oct' 24: Sector 3 Arc dipole installation complete

First quadrupole magnet in tunnel, Mar'24



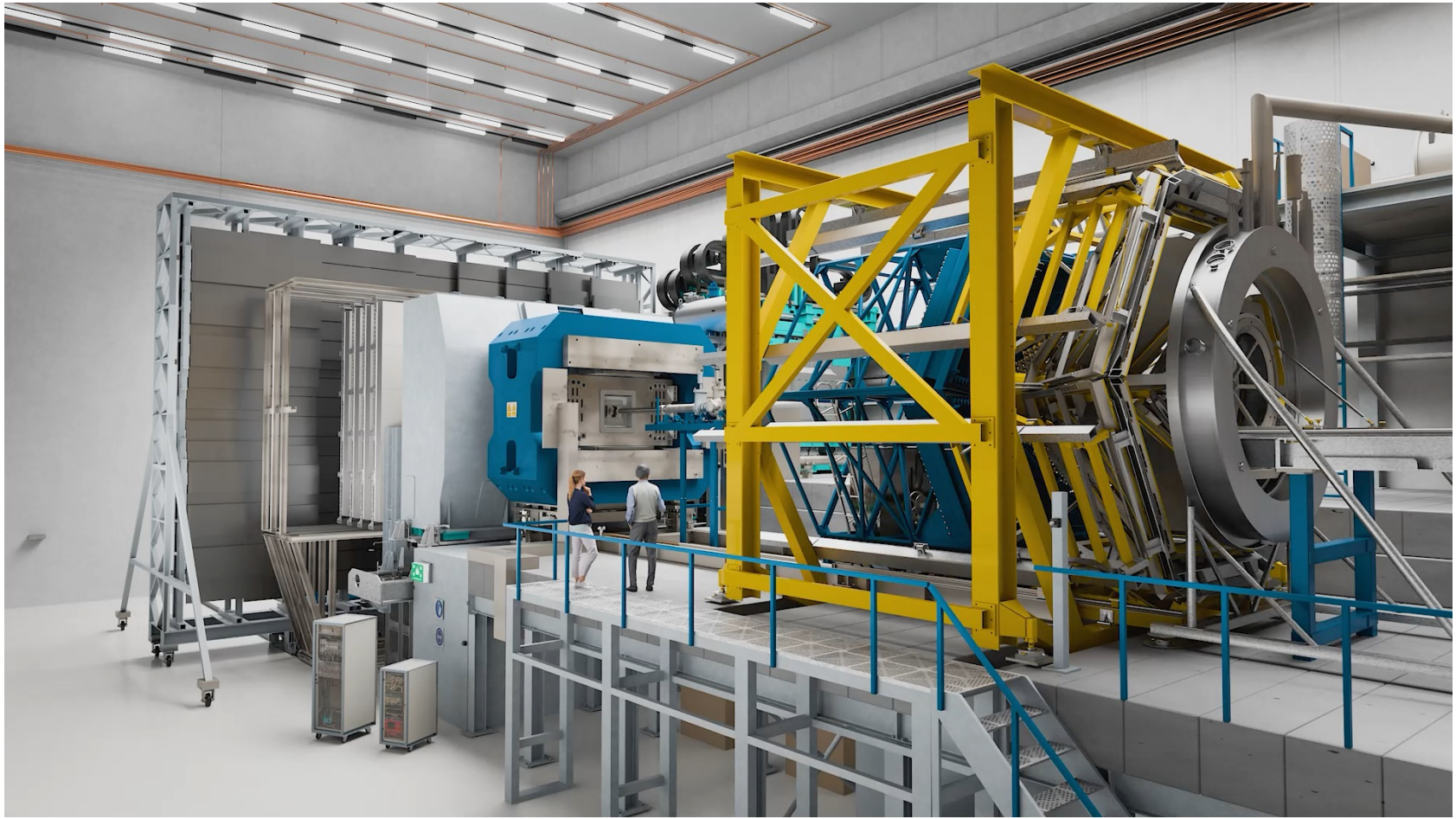
Apr'24: 6 x 100 $m^3$ He tanks of the cryo facility were installed

Technical installation on the roof of main supply building completed

**CBM building entrance, Q3 2025**

**CBM target hall with magnet foundation,**

**23 Dec 2024**




144 members
19 institutions from 7 European countries

**24 PhDs ongoing**

High Acceptance DiElectron Spectrometer

# HADES

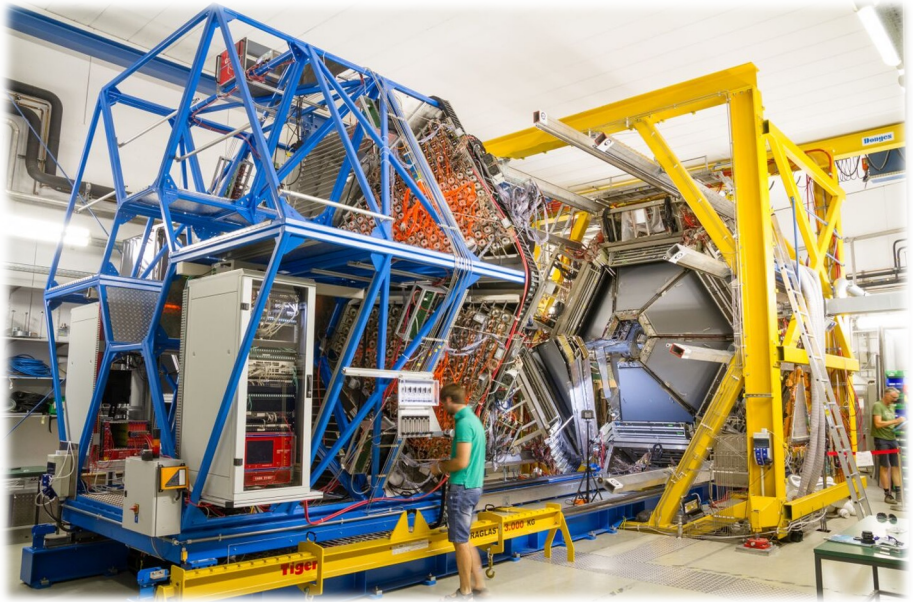
# The HADES spectrometer at GSI SIS-18

### Geometry
- Fixed target experiment
- Full azimuthal coverage with 6 identical sectors
- 18°-85° polar angle (≈35% pair acceptance)

### Particle identification
- RICH – MAPMT based photo detection plane
- TOF – scintillator rods
- RPC – 2 layers of shielded cells ($\sigma_t \approx 70$ ps)
- ECAL – lead glas ($\sigma_t \approx 150$ ps)
- START – segmented LGAD or CVD ($\sigma_t < 50$ ps)

### Low-mass tracking
- Superconducting toroid
- MDC – 4 planes of low-mass drift chambers
- Mass resolution few %

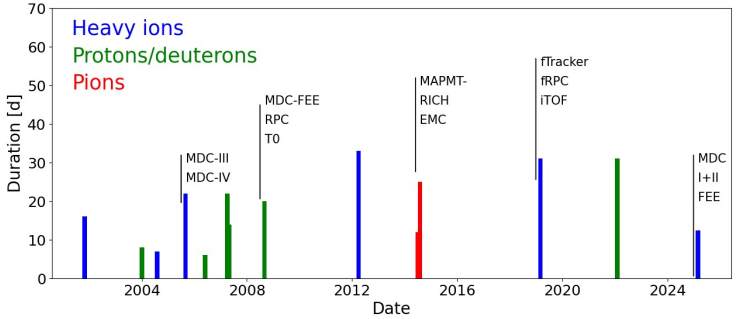
### High interaction rate
- Up to 50kHz accepted trigger rates (HIC)



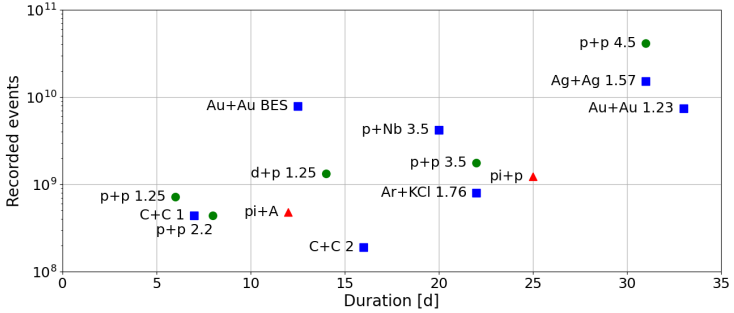
- since 2019 RICH photo camera (with CBM)
- since 2021 forward detector system RPC + Sraw Tracker (with PANDA)
- since 2015 ECAL (6 sectors)
- since 2025 new MDC FEE and 100 kHz DAQ upgrade

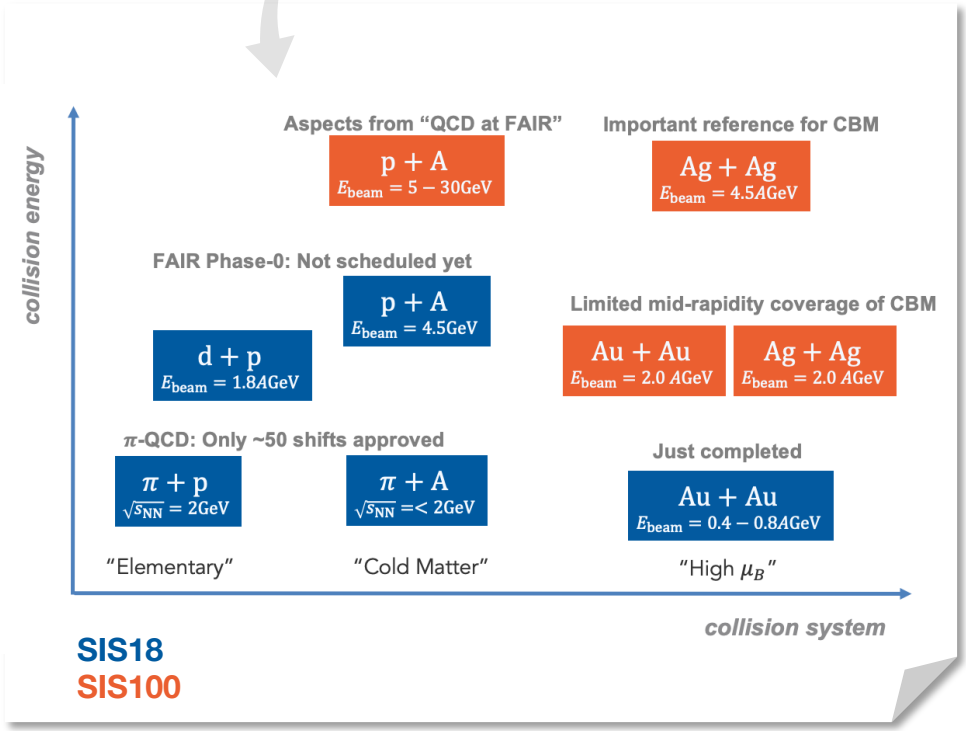
# HADES Physics Runs: past and future

Reduced annual run periods at GSI due to preparation of GSI facility as injector for FAIR



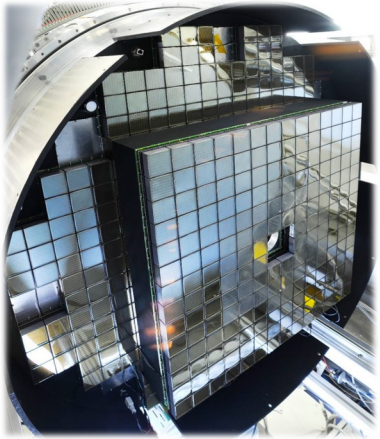

Substantial increase of events/d (log scale!!!)



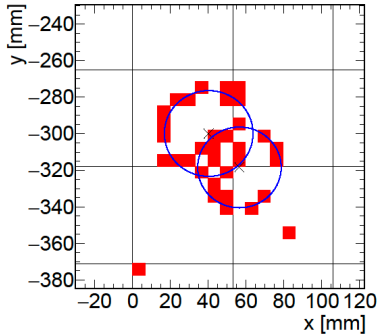



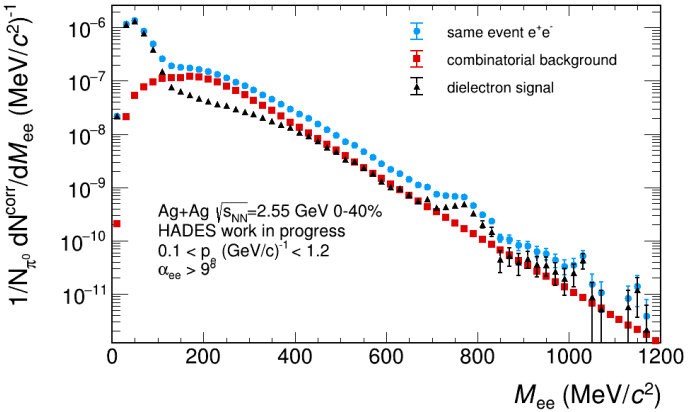
# Electron pairs

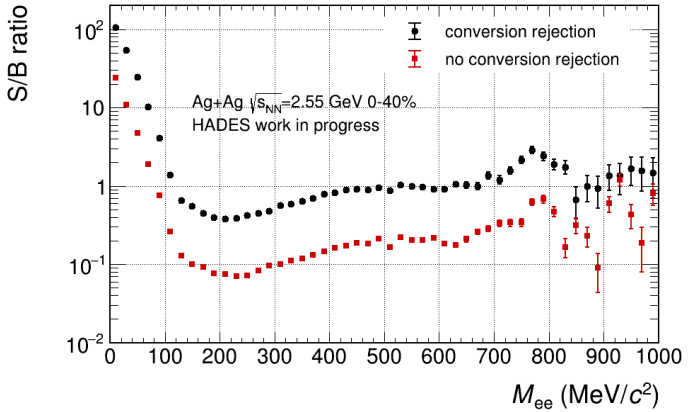
## RICH photo camera upgrade, employing CBM at FAIR technology



- Significantly improved lepton detection efficiency
- Pion suppression factor >$10^4$
- Excellent double ring detection
  (factor of 8 better signal-to-background ratio)



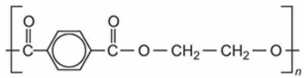



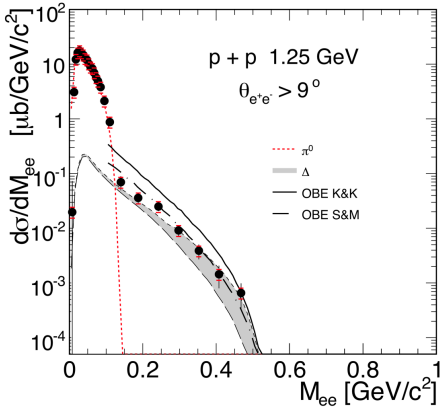
# Measurement of NN reference in HADES

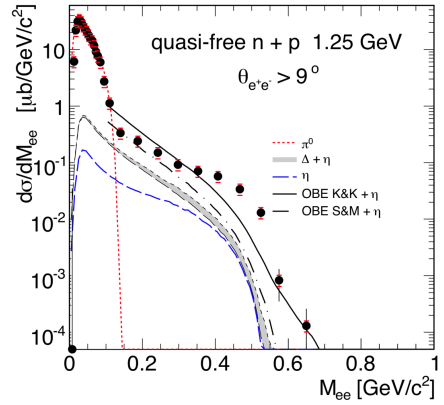
- p+p and d+p collisions at $E_{kin}$ = 1.25 GeV
  - n+p reaction tagged by triggering on proton spectator

NN ref. for $\sqrt{s_{NN}}$ = 2.42 GeV

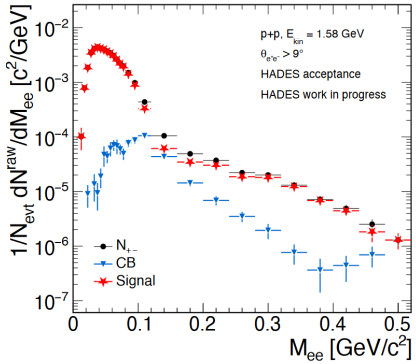
- ongoing analysis of p+p at $E_{kin}$ = 1.58 GeV and 4.5 GeV
  - empty target run p+C/p/O as proxy for p+p/p+n



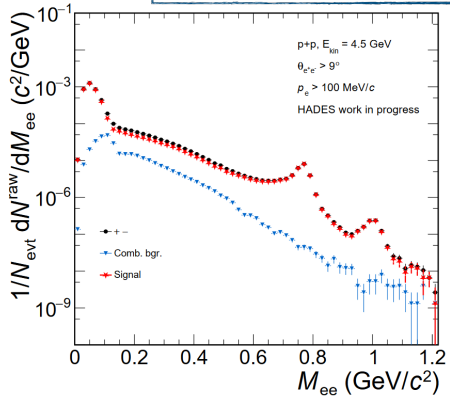



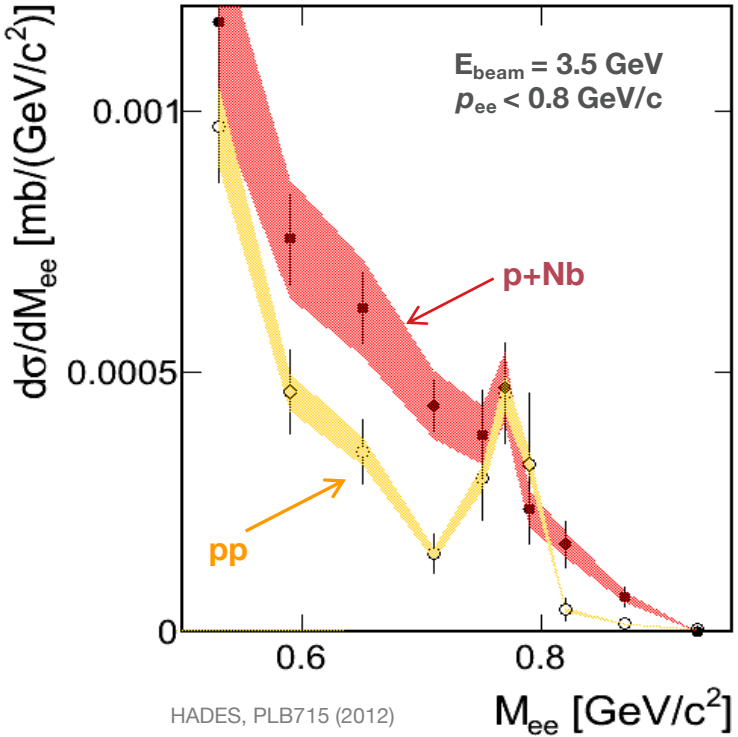

NN ref. for $\sqrt{s_{NN}}$ = 2.55 GeV




NN ref. for future FAIR

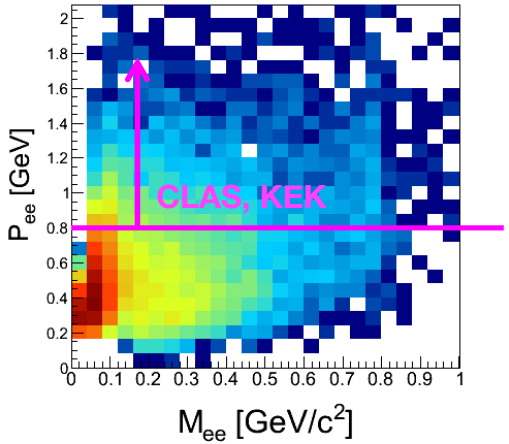


# Are there narrow in-medium vector meson states with substantially shifted pole mass?




HADES, PLB715 (2012)

HADES acceptance

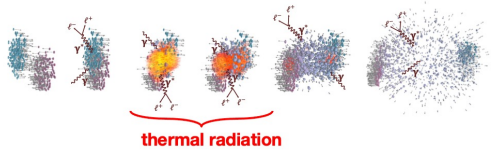


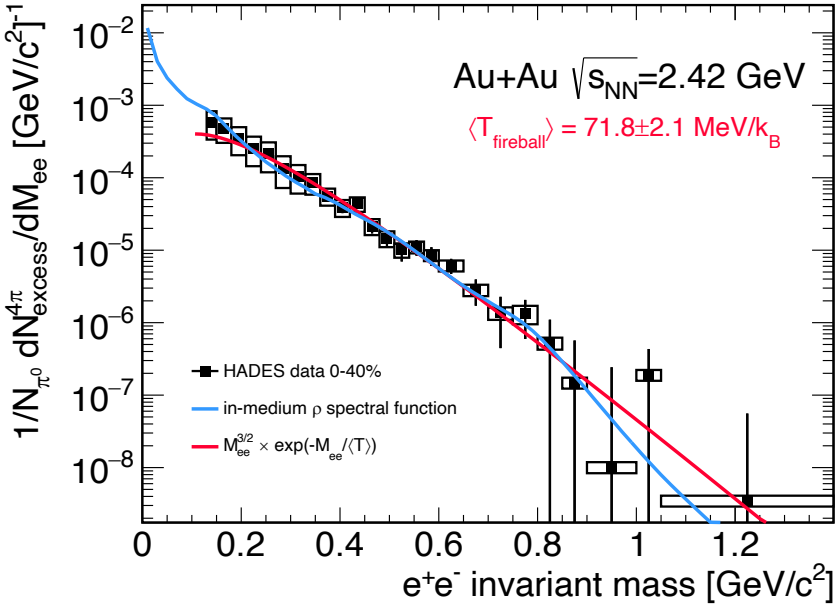

- Ideal probe to monitor possible mass shifts
- Low relative momentum to medium needed to increase sensitivity

- First measurement of in-medium vector meson decays in the relevant momentum region
- HADES sees rather a broadening than a shift

**PDG Entry 2012, 2014**
**BR($\eta \rightarrow e^+e^-$) < 2.5x10$^{-6}$ (90% CL)**

# Thermal dileptons from baryon rich matter




HADES, Nature Phys. 15 (2019) 1040

'Planck-like'

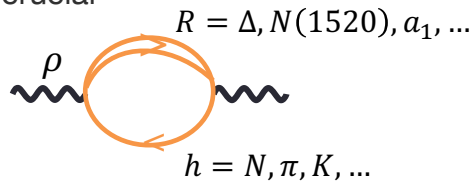
In-medium spectral function

$$\frac{dN_{ll}}{d^4q\,d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^B(q_0,T)\, Im\Pi_{em}(M,q,T,\mu_B)$$

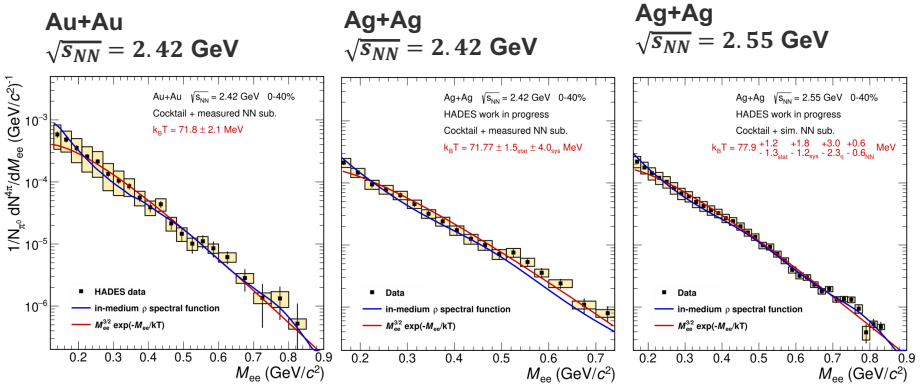
- Thermal excess radiation established at HADES (Au+Au, Ag+Ag)
  - $\rho$-meson peak undergoes a strong broadening in medium
  - in-medium spectral function from many-body theory consistently describes SIS18, SPS, RHIC, LHC energies

Rapp and Wambach, Adv.Nucl.Phys. (2000) 25

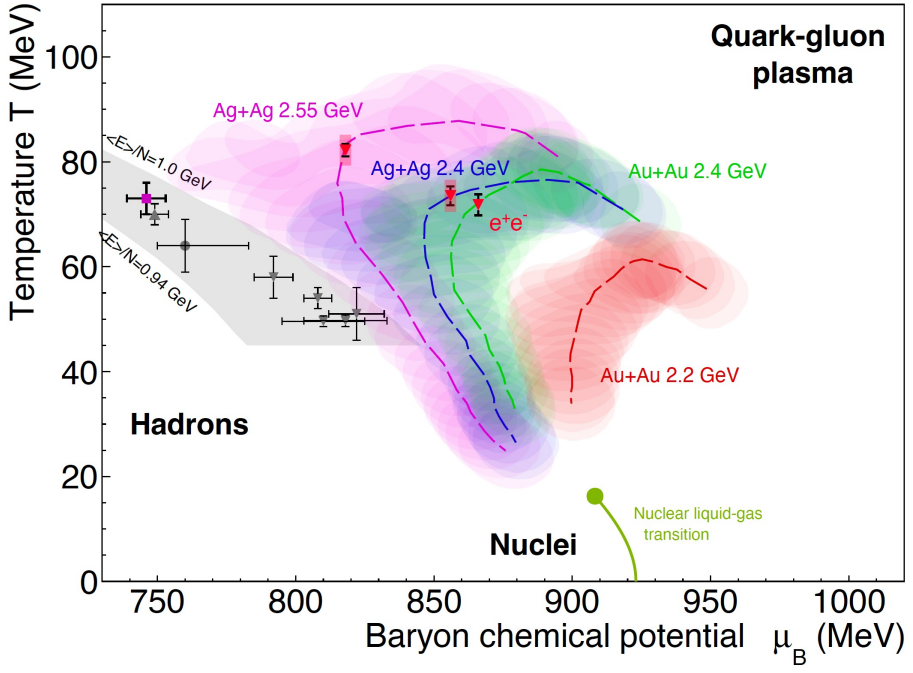
- Baryonic effects are crucial



# Mapping QCD phase diagram with dileptons



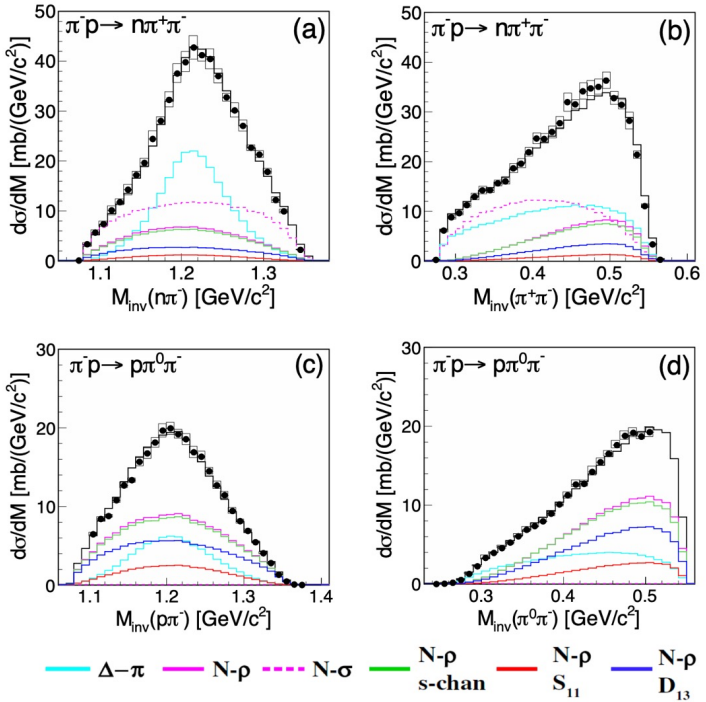

- Trajectories from coarse-grained UrQMD
- Measured average temperatures from HADES well above universal freeze-out region




Freeze-out curve:J. Cleymans, K. Redlich, NPA 661 (1999) 379
Au+Au 2.4 GeV: HADES, Nature Phys. 15 (2019) 1040
Ag+Ag 2.4 GeV, 2.55 GeV: HADES in preparation

# The HADES pion beam facility

- Direct excitation of baryon resonance and exclusive reconstruction of final states
- Combination with dilepton spectrometer world-wide unique (in few GeV energy regime)



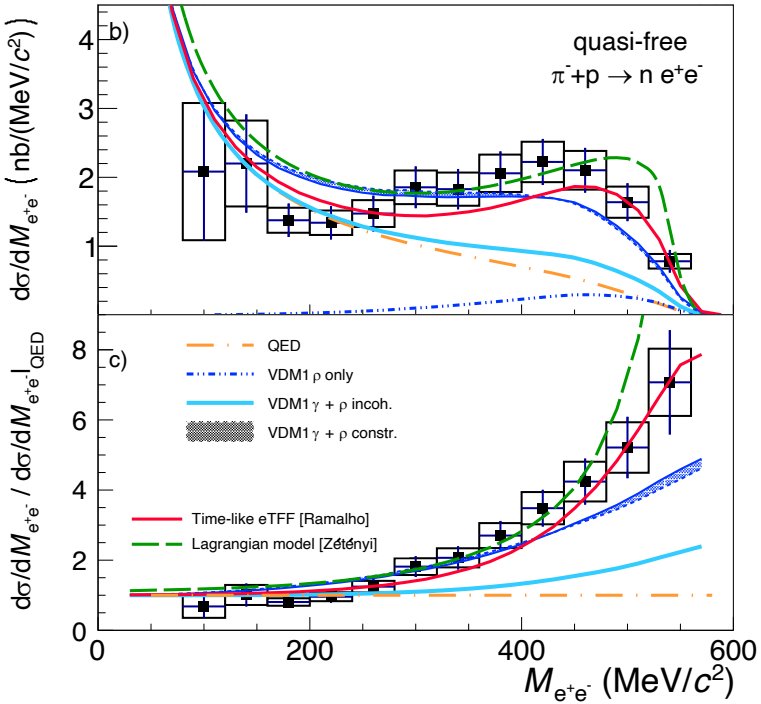

- $p_\pi = [0.66, 0.69, 0.75, 0.8]\ GeV/c$
- $\pi^- + p \rightarrow \pi^- + \pi^+ + n$
  - hadronic final states used in PWA (Bonn/Gatchina code)
  - use invariant masses, and angular distribution
- $\pi^- + p \rightarrow e^- + e^+ + n$
  - prediction for dilepton invariant mass assuming strict VMD
  - comparison to two-component model by Pena & Ramalho

HADES, PRC 102 (2020) 2, 024001
HADES, PRC 95 (2017) 065205

**4 first entries ($N\rho$)**
**4 additional entries**
**first entry BR $\Delta \rightarrow pe^+e^-$**

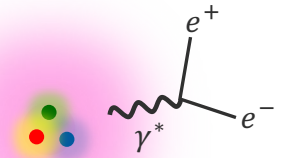
# First measurement of massive $\gamma^*$ emission from $N^*$ baryon resonances (exclusive analysis $\pi^- p \to e^+ e^- n$)

HADES, arXiv:2205.15914 [nucl-ex], with PLB
HADES, arXiv:2309.13357 [nucl-ex], accepted PRC

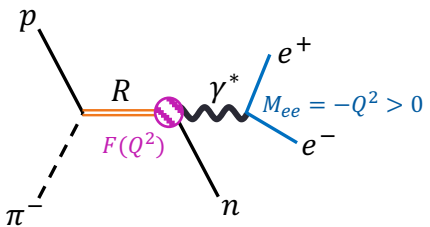



Ramalho, Pena, PRD95 (2017) 014003
Zetenyi, Nitt, Buballa, TG, PRC 104 (2021) 1, 015201
Speranza *et al.*, PLB764 (2017) 282

- Study the structure of the nucleon as an extended object (quark core and meson cloud)




- Dominance of the $N^*(1520)$ resonance at $\sqrt{s_{NN}} = 1.49$ GeV
  - $\rho$ meson as "excitation" of the meson cloud
  - **Vector Meson Dominance - basis of emissivity calculations for QCD matter**

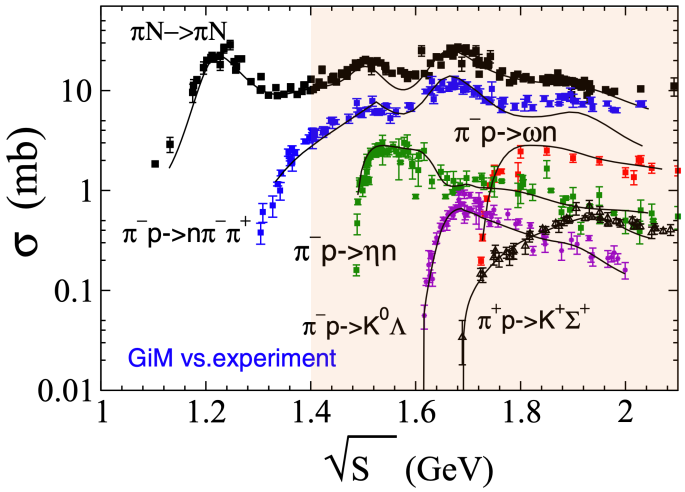


# HADES physics with pion beam (>2025)

**π-beam energy scan $\sqrt{s} = 1.37 - 2.3$ GeV**

- Baryon |S|=0,1 spectrosc
  *f.e. N** in 3rd resonance
- Polarisation studies in h
  $\pi^- p \to \vec{\Lambda} K^0 / \vec{\Sigma}^0 K^0$ / … (s
- Vector-meson productio
- Strangeness production,
- Electromagnetic structure
- Light meson dynamics, *f.e*
- Rare (BSM) decays of mes

- Hypernuclei studies
- Particle production cross sec
  reconstruction in T2K, DUNE

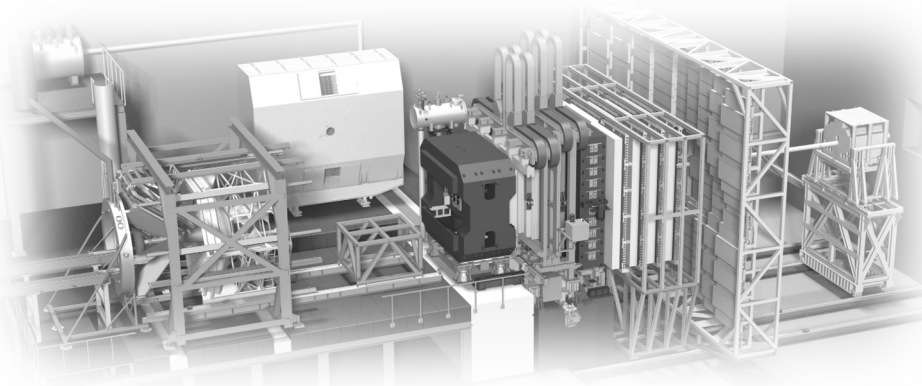

**Wide physics opportunities, strong interest from hadron structure community, crucial input to PWA**


315 members
57 institutions from 10 countries

**71 PhDs ongoing**

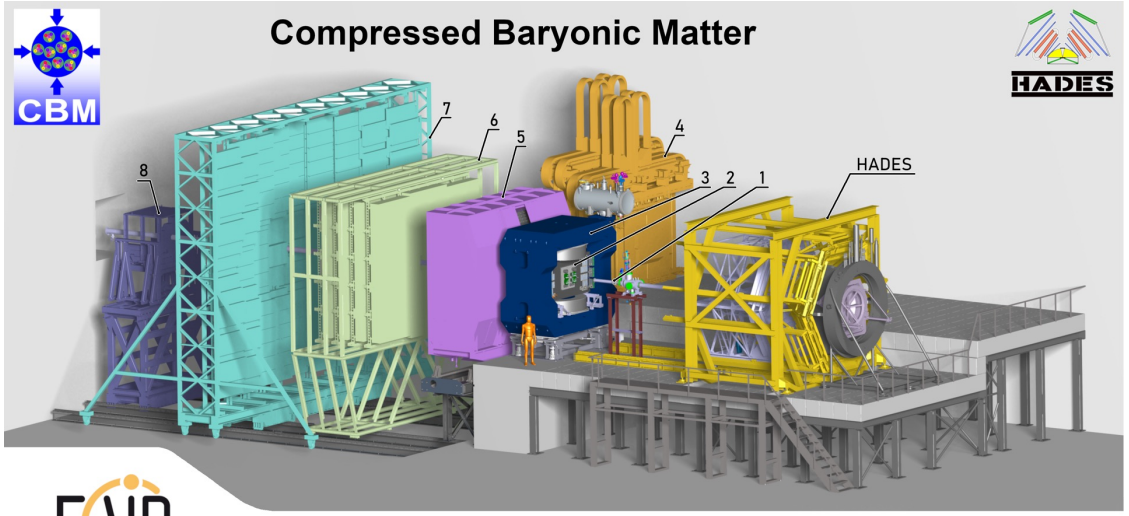
# Compressed Baryonic Matter experiment

## CBM



# Compressed Baryonic Matter experiment

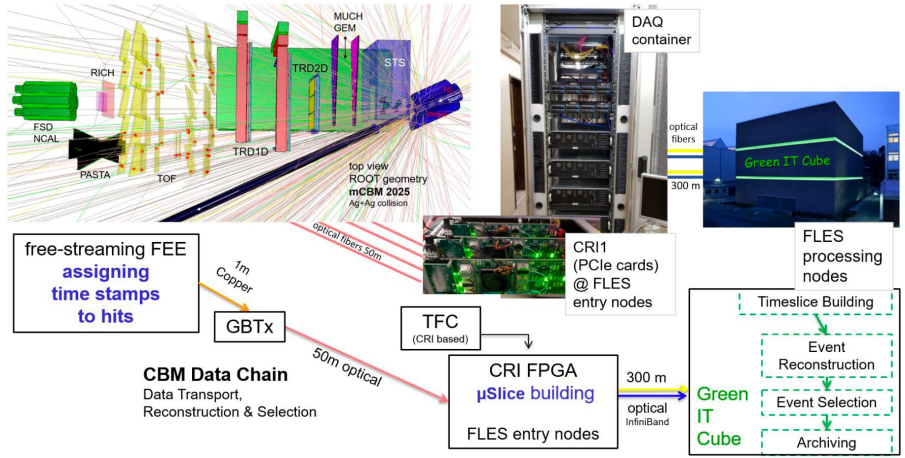
- Fixed target experiment
  → obtain highest luminosities
- Versatile detector systems
  → lepton and hadron identification
  → optimal setup for given observable
- Tracking based entirely on silicon
  → fast and precise track reconstruction
- Free-streaming FEE
  → nearly dead-time free data taking
- On-line event selection
  → highly selective data reduction

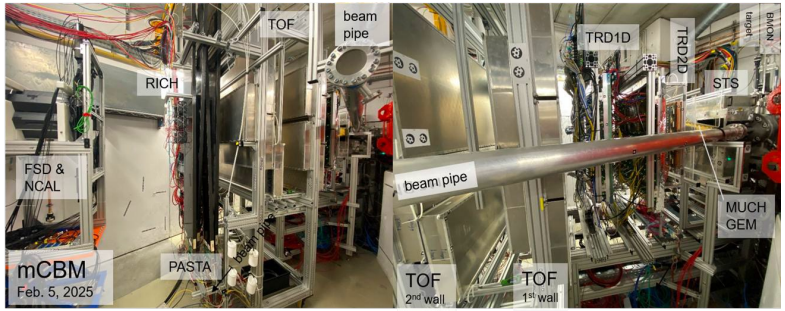



1: Time-Zero Detector & Beam Diagnostics
2: Silicon Tracking System / Micro Vertex Detector
3: Superconducting Dipole Magnet
4: Muon Chambers
5: Ring Imaging Cherenkov Detector
6: Transition Radiation Detector
7: Time of Flight Detector
8: Forward Spectator Detector

# Prototype of CBM online data processing with mini-CBM

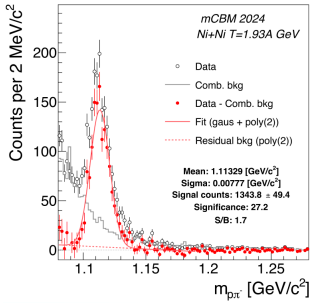
- Full system test, verification of the triggerless-streaming read-out and data transport of CBM
- High-rate detector tests with up to 10 MHz collision rates




Full system test with SIS18 beam

- Detector pre-series modules
- Free-streaming readout implemented and commissioned
- Connection scheme and hardware close to the final CBM DAQ

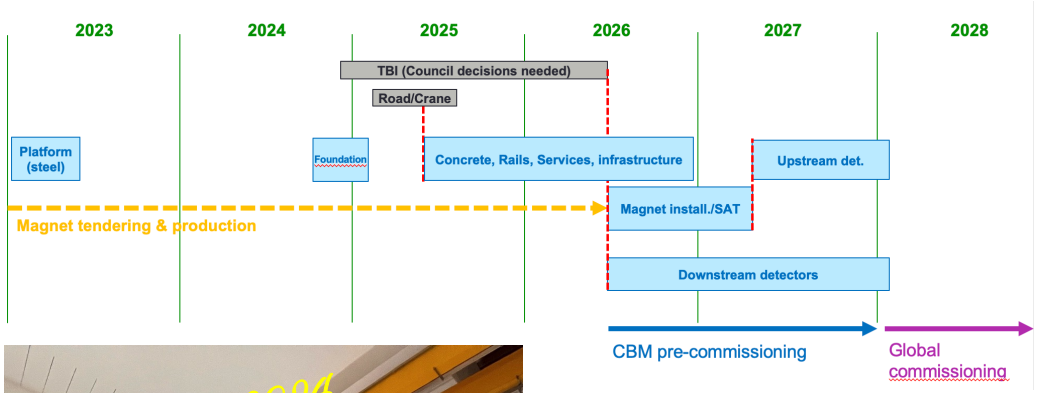



- Gained experience in operations, calibration and alignment
  → speed up of commissioning of CBM
- Λ reconstruction with CA track reconstruction and KFParticle package

# CBM installation / commissioning

## CBM Cave

- a dedicated cave with a massive beam dump for high-intensity, high-energy beams
- CBM cave/building shell completed
- Technical Building Infrastructure in 2025/2026



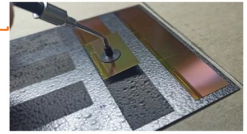

## CBM Installation

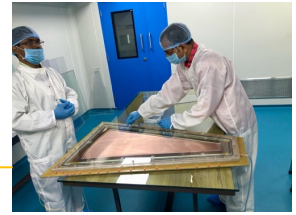
- CBM installation activities (platform)
- started in June 2023
- CBM ready for beam by 2028, ~12 months contingency for CBM global commissioning


# CBM subsystems are on the verge of series production

➥ **pre-production is ongoing in all systems**

**Micro Vertex Detector**
*sensor/module integration*

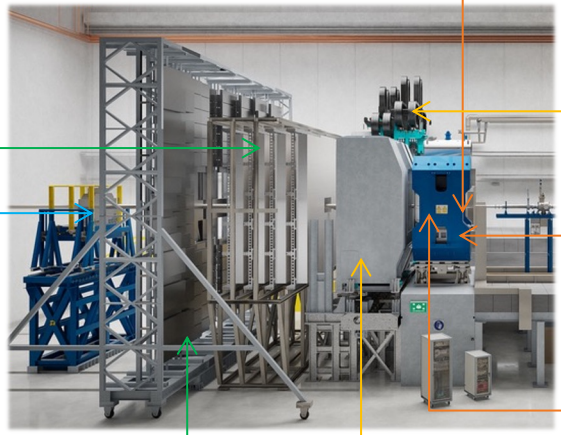


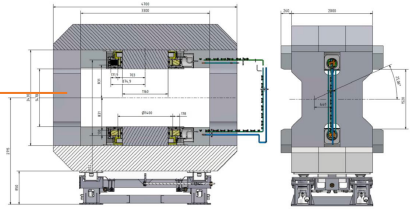
*series production of station 1 GEM chambers starts soon*

**Transition Radiation Detector**

*pre-production modules of 1D and 2D options ready*

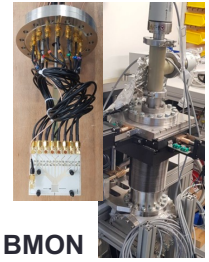


**Superconducting dipole magnet**
*production readiness review ongoing*



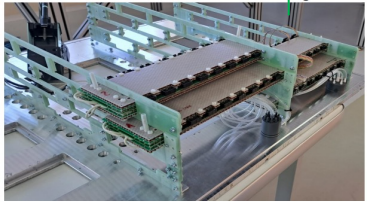
**Forward Spectator Detector**

*test modules*



**BMON**
*T0 manipulator X/Y/Z*
*Vacuum test – done*

**Time of flight detector**



*20% counters assembled, module pre-production ongoing*

**Ring Imaging Cherenkov detector**

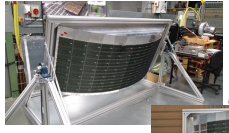
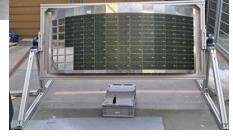


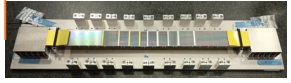
*photo camera 1*

*photo camera 2*



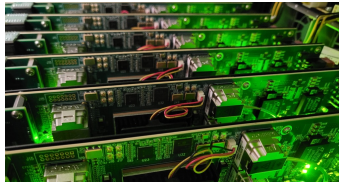
*preparations for final batch of 1500 DIRICH FEBs*

**Silicon Tracking System**



*> 400 modules assembled*

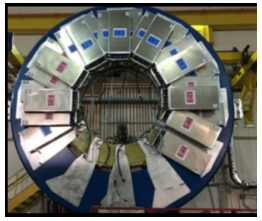
*8 ladders assembled*

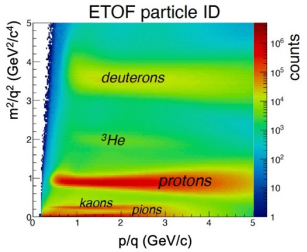


**DAQ / FLES** *TFC2 (Timing and Fast Control system) demonstrator setup*

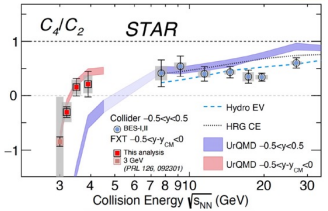
# Towards world-leading science with FS+

- Most of the CBM subsystems are on the verge of series production, two major subsystems are in the series production
- **Successful Phase-0: HADES, STAR, E16, mCBM**
  - demonstrate performance of major components
  - physics results with CBM devices and software packages



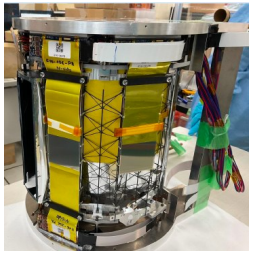


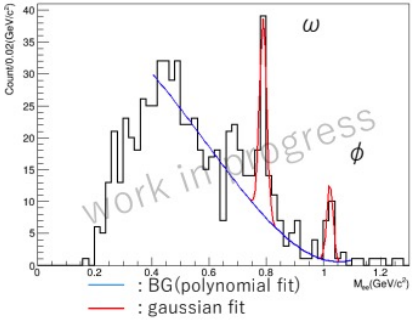

*eTOF provided by CBM-FAIR, crucial for BES-II, especially for the FXT program*




Zachary Sweger, QM25

*10 pre-series STS modules were built, assembled and tested at GSI and are installed as innermost tracking detector of the **E16** experiment at J-PARC*





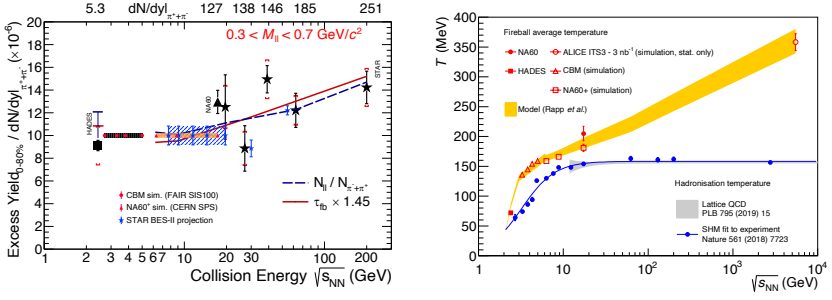

*Result of E16 pilot run (p+A collision) ~20h data taking*

Yuhei Morino, QM25

# Anticipated CBM physics performance

See for details

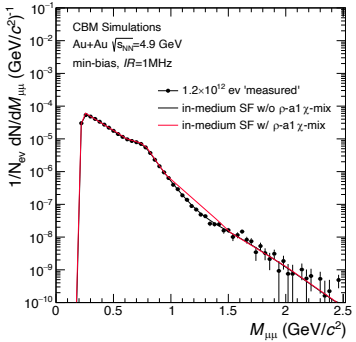
## Emissivity



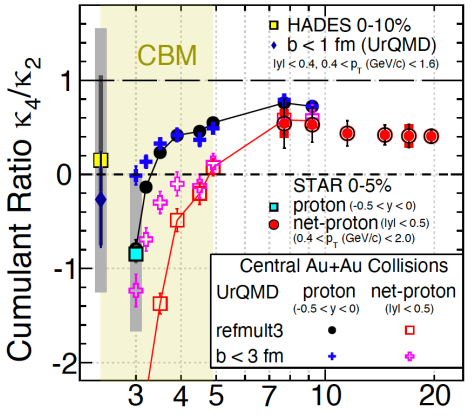




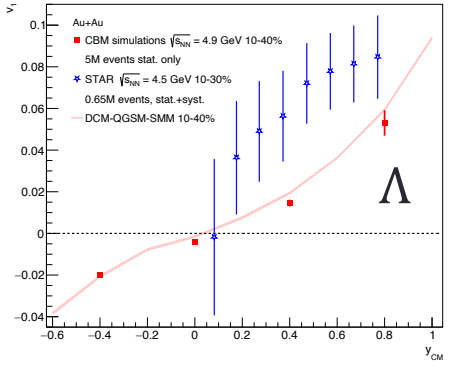
## Chirality



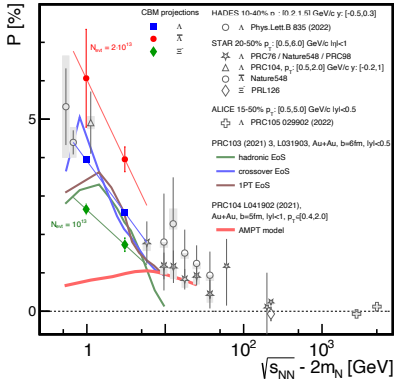

## Criticality



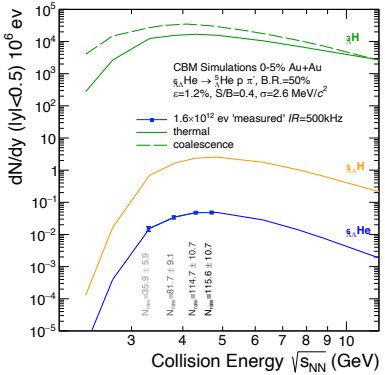

## Collectivity



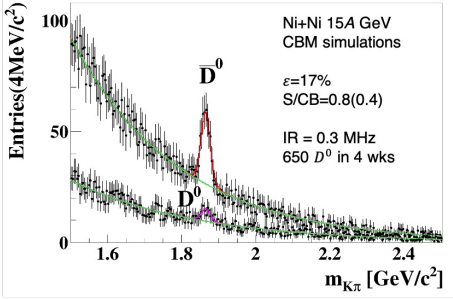

## Vorticity




## Interactions




## Transport properties



Hadron physics

# INCLUSIVE & EXCLUSIVE

# Physics perspectives with hadron beams at GSI/FAIR

**SIS18 $\pi^-$, $p$ 4.5 GeV with HADES**

structure, spectroscopy,
EM transition formfactors
of $N^*$ and hyperons

**SIS100 $p$ 29 GeV with CBM/HADES**

multi-strangeness,
charm degree of freedom

**$p\bar{p}$ with PANDA**

enhanced sensitivity to
gluonic degrees of freedom

- Initiative (2022) from FAIR-motivated group from within CBM, HADES, PANDA (building up on success of PANDA Phase-0 at HADES)
- Promote the realisation of First Science+ at FAIR (at zero extra cost)
- Identify a QCD-inspired physics program with SIS100 proton beams
- Evaluate its complementarity with programs at other facilities
- Strengthen collaborations among hadron-, nuclear- and heavy-ion communities
- Reach out for new collaborators from both experiment and theory!

# From SIS18 to SIS100

## …what could that add in strong-QCD physics?

**Energy upgrade:**

- from max 4.7 GeV (SIS18) to 29 GeV (SIS100) proton energy
- opening new realm:
  - production, spectroscopy and interactions of double and triple strangeness
  - charm production and interactions close to production threshold
- significant increase in production yield of hyperons

**Intensity upgrade:**

- from max $10^{12}$ (SIS18) to $2\times10^{13}$ (SIS100) protons/cycle
- even with $10^{10}$ p/cycle and 1% LH2 target: ~10 $pb^{-1}$ / day

**Detector enrichment:**

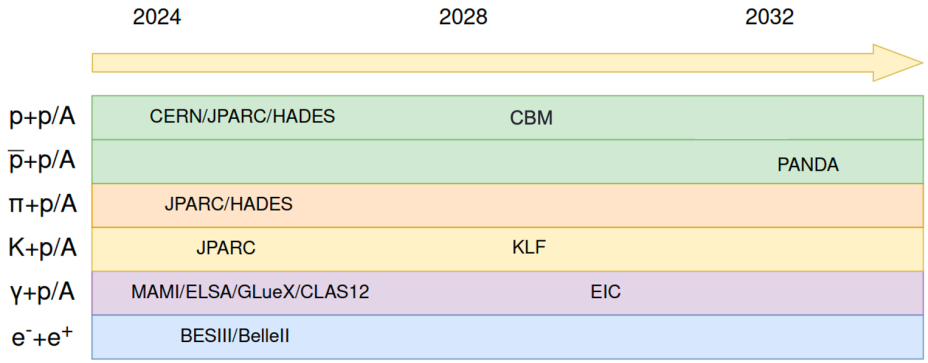
- towards high-rate capabilities and free-streaming DAQ's
- excellent mass resolution (~2%)
- excellent coverage for exclusive channels

**Theory enrichment:**

- terra incognita: theoretically complicated region to describe, transition from resonance to string production
- important new insight into hadron structure (hyperon spectrum, study intrinsic charm component of the hadron wave function on)

Vogt, PRC 106 (2022) 2, 025201
NNPDF, Nature 608 (2022) 7923, 483-487

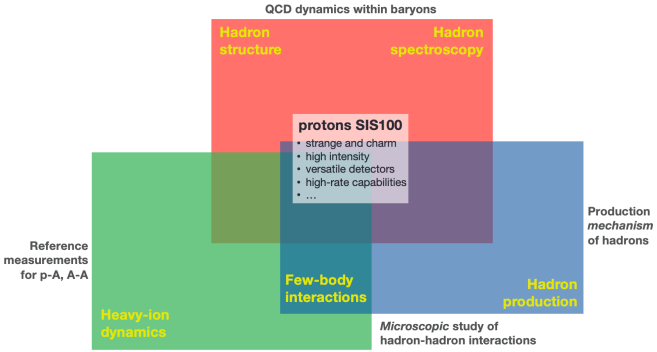
**Competitive and complementary program to other facilities world-wide**

# Hadron Physics at GSI and FAIR: Prospects for the Next Decades

- High potential for hadron physics with proton beam from SIS100
- Importance of physics with pion beams strongly emphasised by the community

- Series of workshops took place already:
  - Kraków, Poland, Jun 21, 2023: https://indico.gsi.de/event/17693/
  - Wuppertal, Germany, Feb 6–9, 2024: https://indico.gsi.de/event/18475/
  - Darmstadt, Germany, Nov 11–14, 2024: https://indico.gsi.de/event/20301/
  - Catania, Italy, Jun 23-27, 2025: https://indico.gsi.de/event/21757/




***White Paper in preparation***
***Over 50 contributors, 200+ pages!***

Physics Opportunities at FAIR with Proton and Pion Beams

Editors[a,b], Contributors (alphabetical order)[c,1], Endorsers (alphabetical order)[d,1]

[a]*RU Bochum, GU Frankfurt*
[b]*GSI Darmstadt*
[c]*Institutions*
[d]*Institutions*

Abstract

This white paper outlines a coordinated, decade-spanning programme of hadron and QCD studies anchored at the GSI/FAIR accelerator complex. By exploiting intense proton and pion beams coupled with high-rate capable detectors and an international theory effort, the initiative addresses five challenges: (i) elucidating confinement and dynamical mass generation, (ii) mapping the complete baryon–meson spectrum—including exotic states, (iii) quantifying baryon–baryon and meson–baryon interactions, (iv) constraining neutron-star structure through terrestrial data. A phased roadmap with SIS100 accelerator start-up, and envisaged detector upgrades—will yield precision cross-sections, transition form factors, in-medium spectral functions and validated lattice/EFT inputs. Synergies with JLab 12 GeV, J-PARC, the EIC and RHIC/LHC are foreseen. The programme is expected to bring about decisive advances in non-perturbative QCD, astrophysics topics, such as questions related to the equation of state of neutron stars, and high-rate detector and data-science technology.

*Keywords:* keyword1, keyword2, keyword3, keyword4, keyword5

Contents



# Charm-nucleon interactions

## $pp \rightarrow ppJ/\psi$ final state

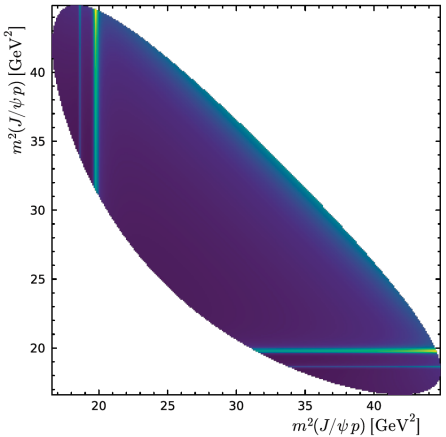
- (Near-threshold) charm production in NN scattering contains rich info: PDFs, multi-gluon dynamics, …
- Search for “LHCb” pentaquarks
- Input to nucleon-structure studies (“controversial”):
  - role of intrinsic charm of nucleon? (claim LHCb, NNPDF)
  - trace anomaly contribution to mass of nucleon?
  - mass radius of the nucleon, “gravitational form factor”?

**Prerequisites:**

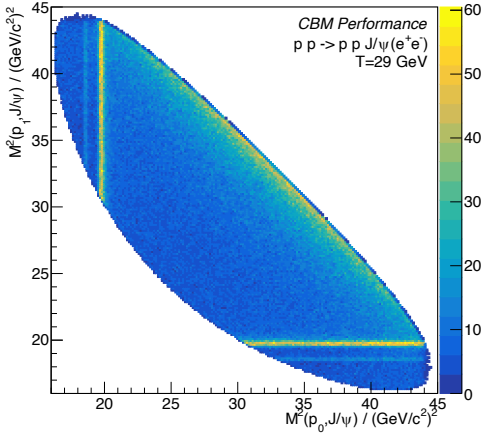
- coverage of the Dalitz plot of the three-body final state → **Excellent coverage for exclusive channels**
- excellent mass resolution → **$\sigma_M$< 10 MeV**

**3 body phase space + Pentaquark Model**

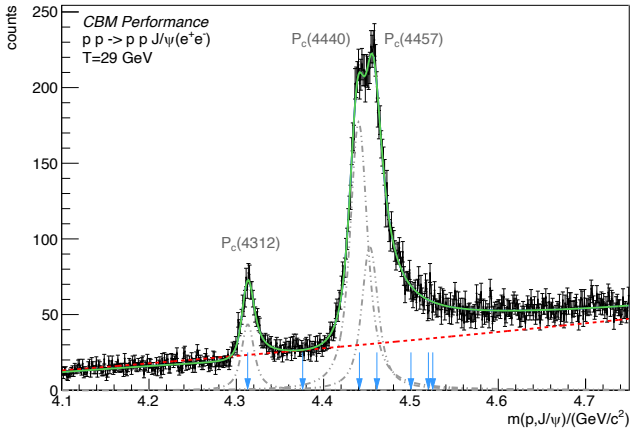
**input**




**reconstructed**




p J/ψ mass (5C fitted)



# Summary: The future is bright!

https://www.nupecc.org/lrp2024/Documents/nupecc_lrp2024.pdf


## Recommendations for Nuclear Physics Infrastructures

The NuPECC Long Range Plan 2024 resulted in the following main recommendations for infrastructures of importance for nuclear physics:

- The first phase of the international **FAIR** facility is expected to be operational by 2028, facilitating experiments with SIS100 using the High-Energy Branch of the Super-FRS, the CBM cave and the current GSI facilities. Completing the full facility including the **APPA, CBM, NUSTAR** and **PANDA** programmes will provide European science with world-class opportunities for decades and is highly recommended.

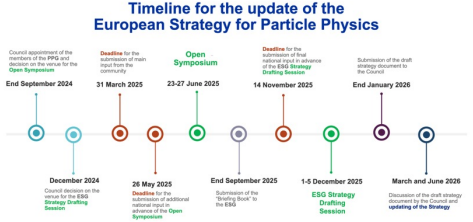
## Recommendations for Fundamental Nuclear Physics

**Future flagship facilities and experiments**

- To investigate nuclear matter at high baryonic density, the timely completion of **SIS-100** at **FAIR** and the completion of the **CBM** experiment are of utmost importance. Efforts should continue to support R&D activities related to advanced **CBM** silicon vertexing and tracking devices.
- The full exploitation of the existing detectors and facilities, in particular **HADES** and **R3B** at **SIS-18/SIS-100**, should receive full support.

- **Input to European Strategy for Particle Physics 2026 (as part of the KHuK input)**
  - The full exploration of the phase diagram towards high $\mu_B$ will be a central recommendation
  - It will be on equal footing to the full exploitation of the HL-LHC

Town meeting: heavy ion and QGP physics at CERN
Monday 17 Feb 2025, 10:30 → 18:55 Europe/Zurich
503/1-001 - Council Chamber (CERN)



Thank you for your attention!