Compressed Baryonic Matter experiments at FAIR

Andrej Kugler for CBM collaboration

- The CBM physics
- FAIR
- CBM performance
- FAIR Phase 0

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

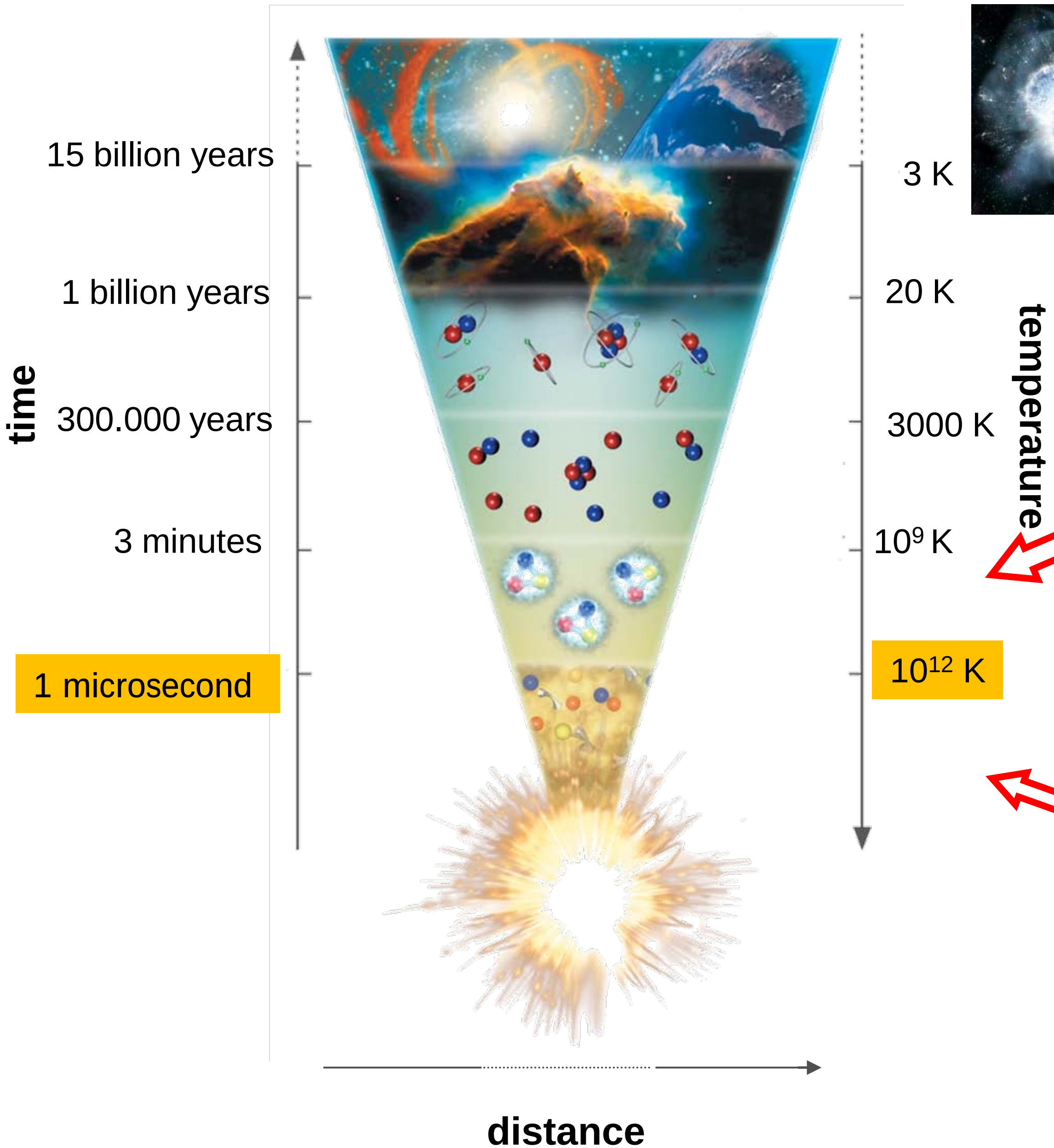
MINISTRY OF EDUCATION, YOUTH AND SPORTS

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

Nuclear Physics Institute of the CAS
public research institution

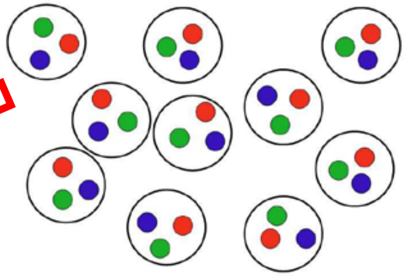
The Czech Academy of Sciences

Evolution of Matter in the Universe

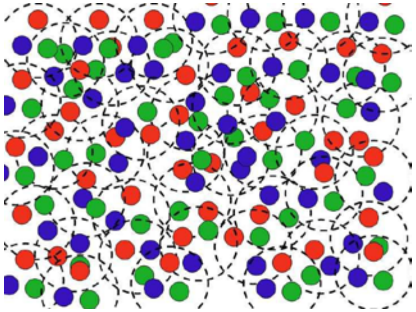


neutron star mergers observed by gravitational waves

Compressed Baryonic Matter

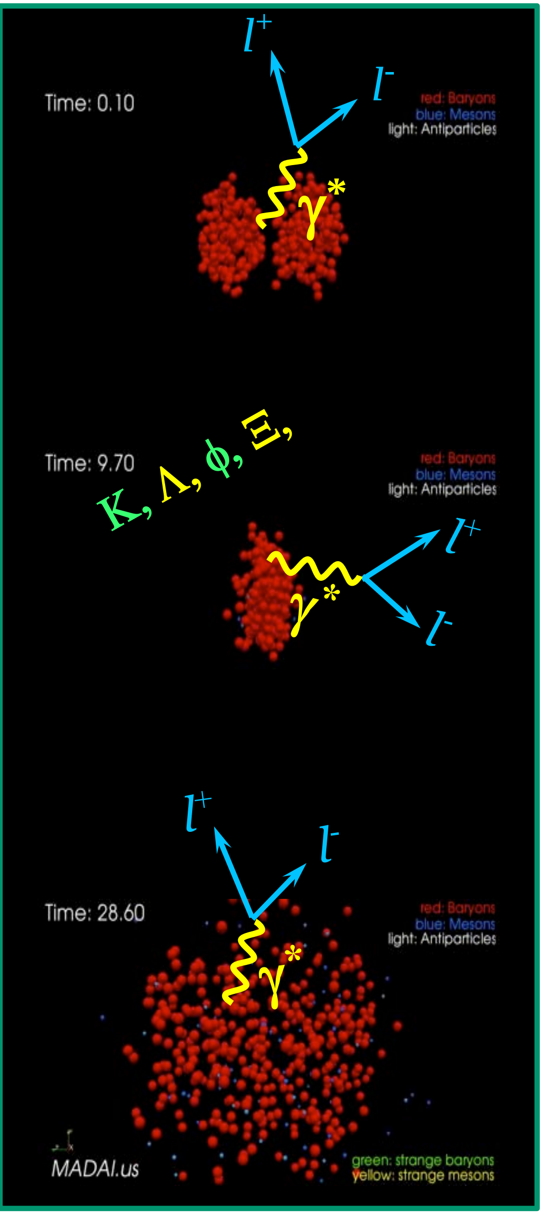


Quark Gluon Plasma (QGP)



Investigation of properties of strong interaction (QCD)

The Compressed Baryonic Matter



Physics cases

- Equation-of-state of matter at neutron star core densities
- Phase transitions from hadronic matter to quarkyonic or partonic matter at high net-baryon densities
- Electro-magnetic radiation from the dense fireball
  (→ temperature, caloric curve)
- Chiral symmetry restoration in dense baryonic matter
- Hypernuclei: Λ-N, Λ-Λ interaction

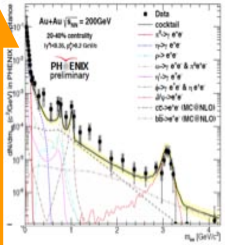
Hadrons incl. Hyperons, Hypernuclei, Dileptons
in Au+Au (C+C) collisions up to 11 (15) A GeV.

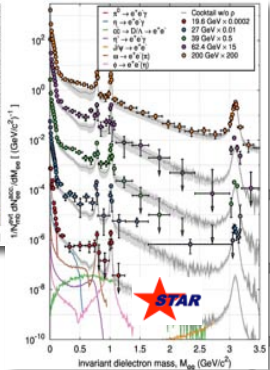
- p,π,K,K*, ρ,ω,φ,Λ,Λ,Λ*,Σ*, Ξ^-,Ξ^+,Ξ*,Ω^- ,Ω^+,Ω*,fragments
- fluctuations, correlations, flow
- determination of centrality and reaction plane.

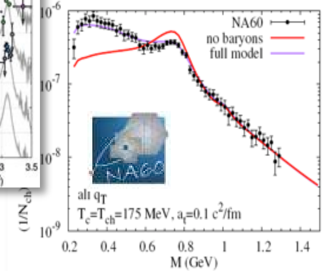
Virtual photon radiation from hot and dense QCD matter

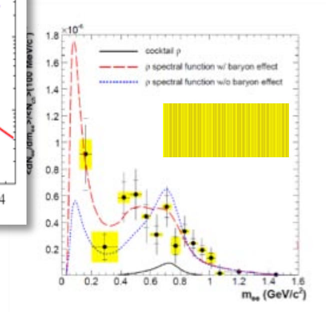
T

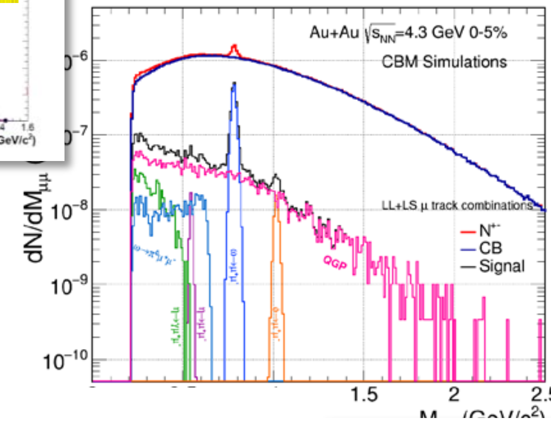
Model: Ralf Rapp
STAR: QM2014,
NA60: EPJC 59 (2009) 607,
CERES: Phys. Lett. B 666 (2006) 425,
HADES: QM2018







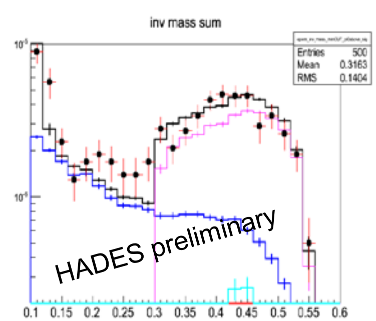


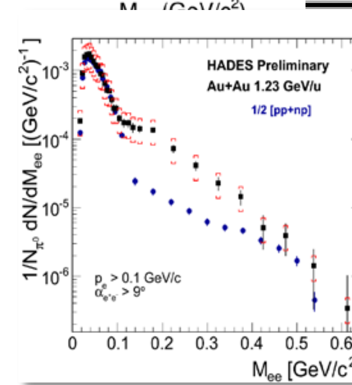


Highly interesting results from RHIC, SPS, SIS18

→ lepton pairs as true messengers of the dense phase

No dilepton data at FAIR energies





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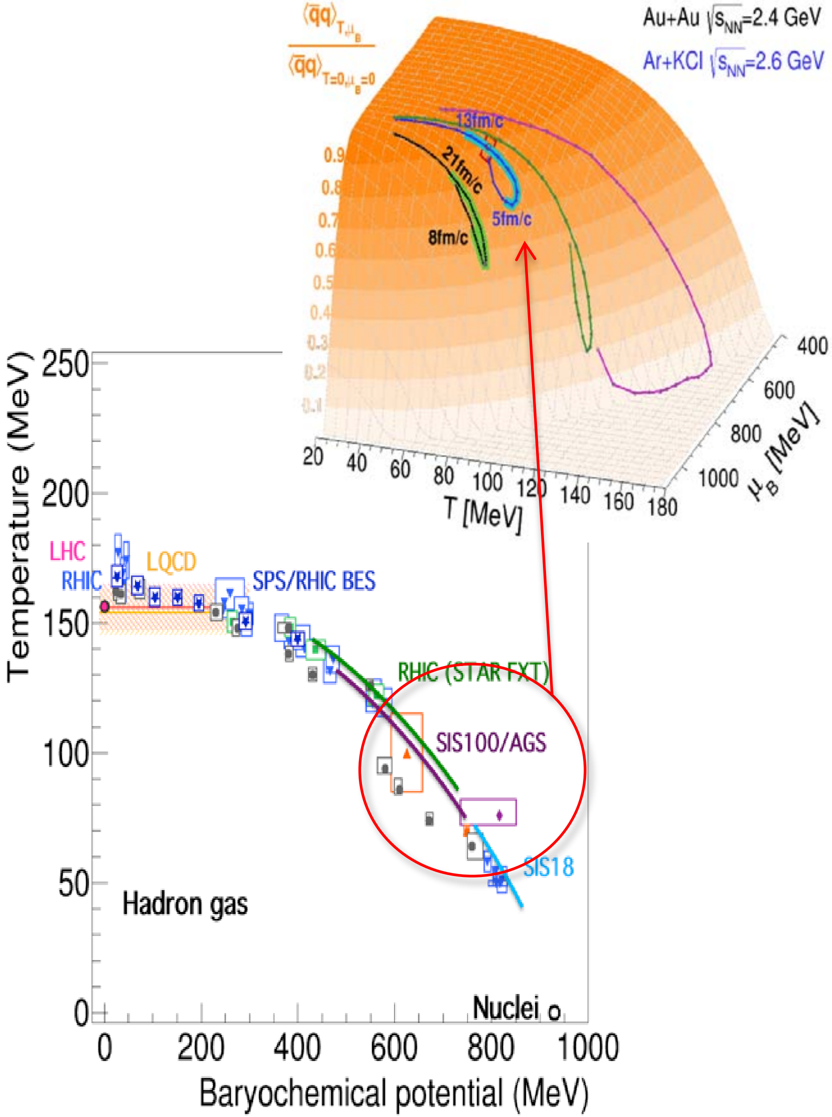
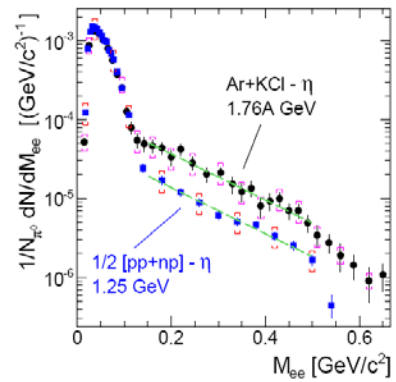
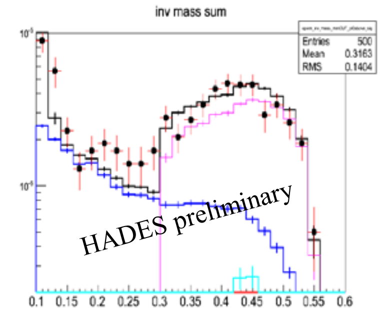
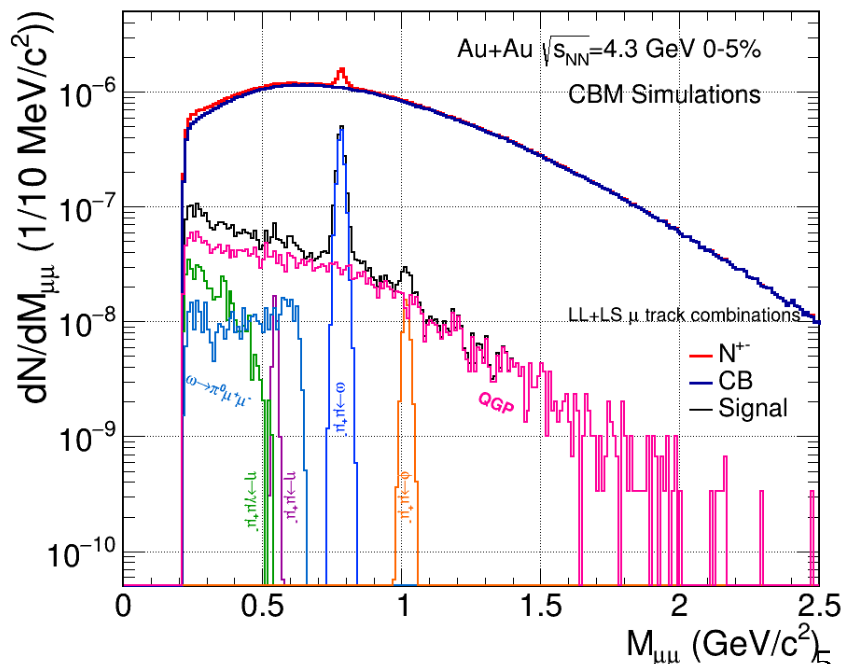
μ_B

Compressed Baryonic Matter: Di-Leptons









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Strangeness

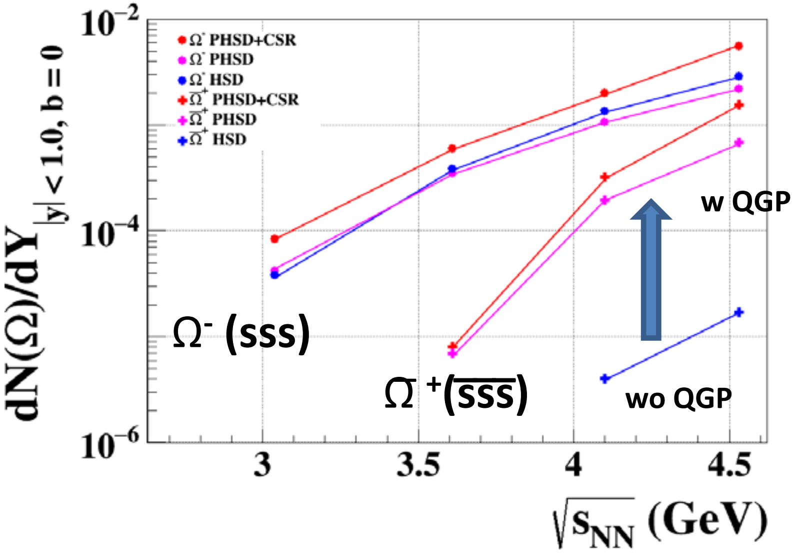
Observables

Excitation function of yields, spectra, and collective flow of (multi-) strange baryons in heavy-ion collisions

Physics case

- Nuclear matter equation-of-state at extremely high net-baryon densities
- Search for quarkyonic matter or for phase coexistence
- Presence of QGP significantly increase yield of Ω+ at FAIR energy
- Chiral Symmetry Restoration effect increase yield of Ω- and Ω+ at FAIR energy

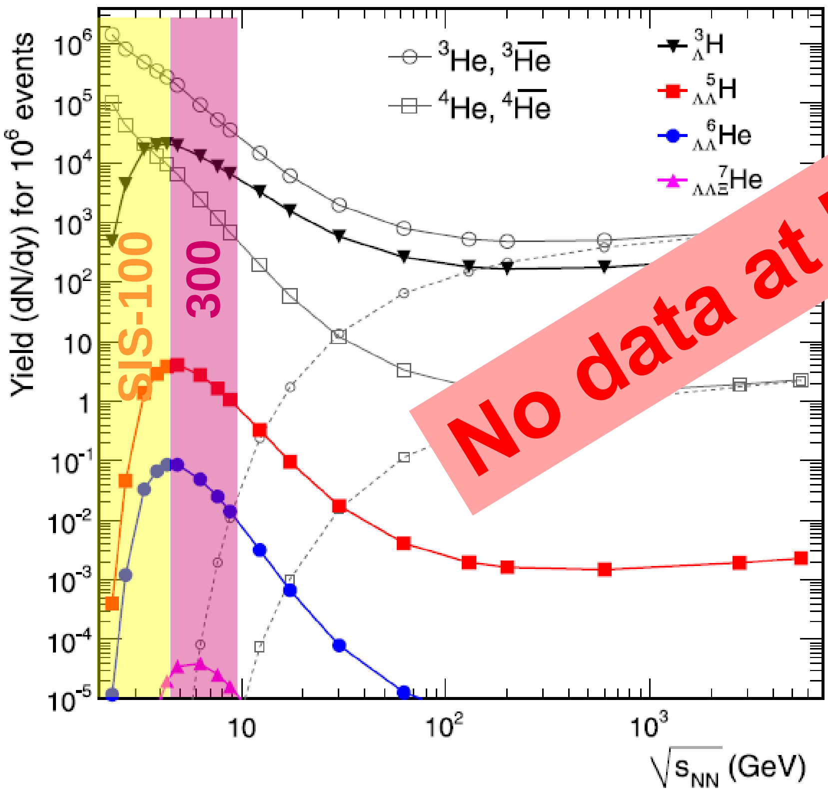
“Chiral symmetry restoration versus deconfinement in heavy-ion collisions at high baryon density”
W. Cassing, A. Palmese, P. Moreau, and E. L. Bratkovskaya Phys.Rev. C93 (2016), 014902, arXiv:1510.04120 [nucl-th]
“Chiral symmetry restoration versus deconfinement in heavy-ion collisions at high baryon density”



Strange Matter

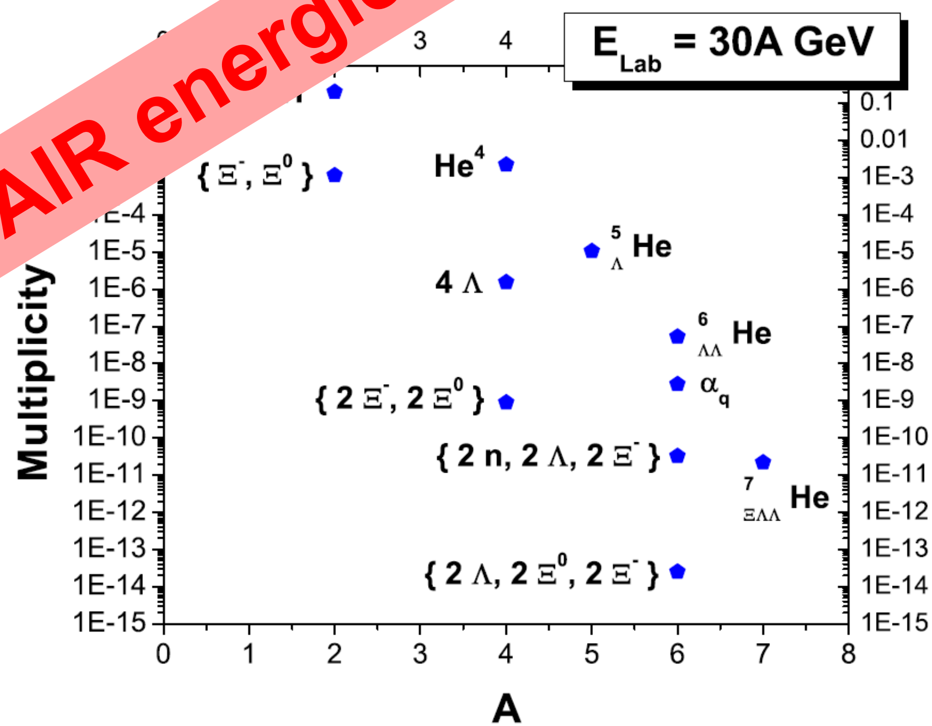
- at FAIR energies maximum in cross section for hypernuclei expected (coalescence between light nuclei and hyperons)
- meta-stable strange objects?

[A. Andronic, Phys. Lett.B 697 (2011) 203]



No data at FAIR energies!

[H. Stöc... ...cl. Phys. A 827 (200) 624c]

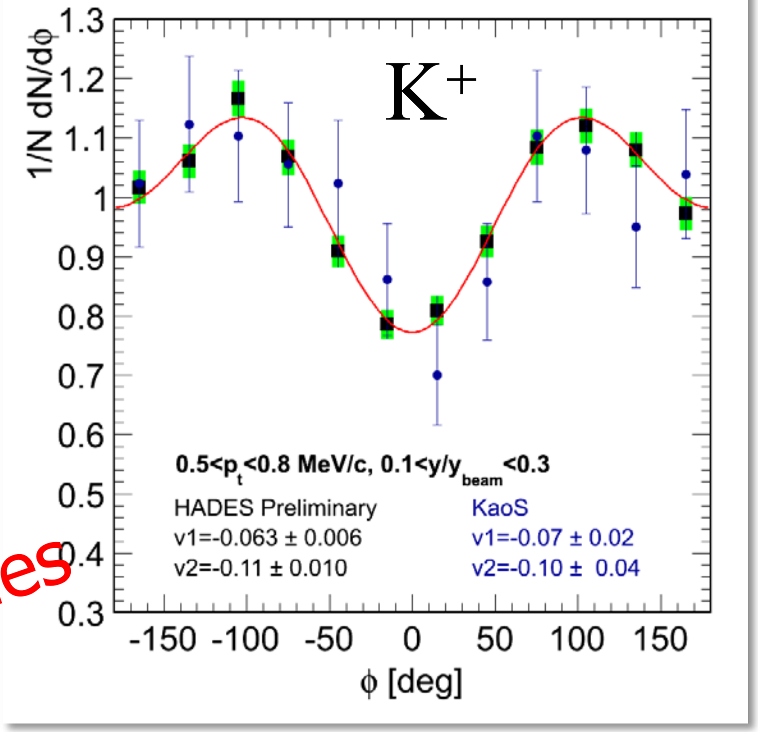


Collective flow, correlations, fluctuations

Observables

- Excitation function of flow of identified particles
- Enhanced production of composite particles, multi-particle correlations (spinodal amplification of density fluctuations)
- Higher moments of net-baryon and net-charge multiplicity distributions

HADES 1.23 *A*GeV Au+Au



Physics case

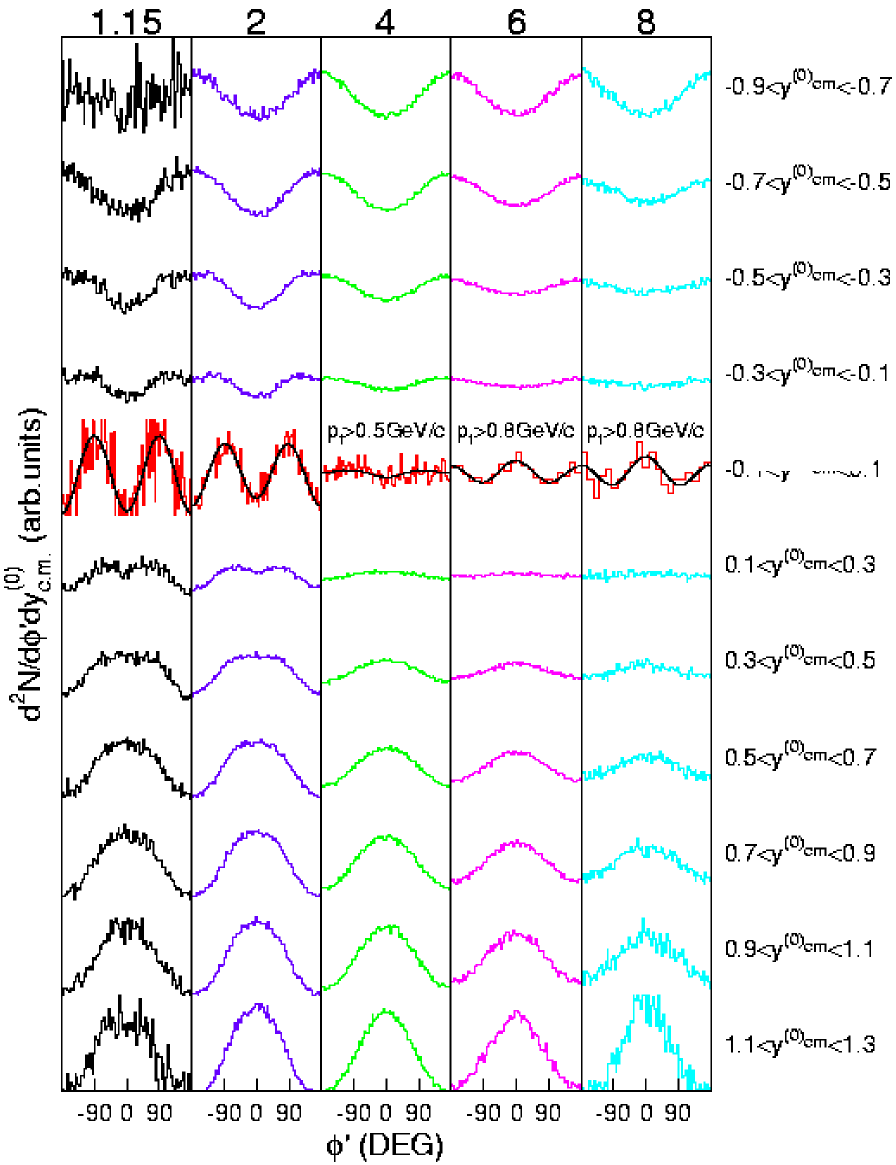
- Equation of state
- Phase coexistence
- Phase transition
- Critical endpoint

Few data at FAIR energies

Proton flow

Azimutal Distributions with respect to the reaction plane

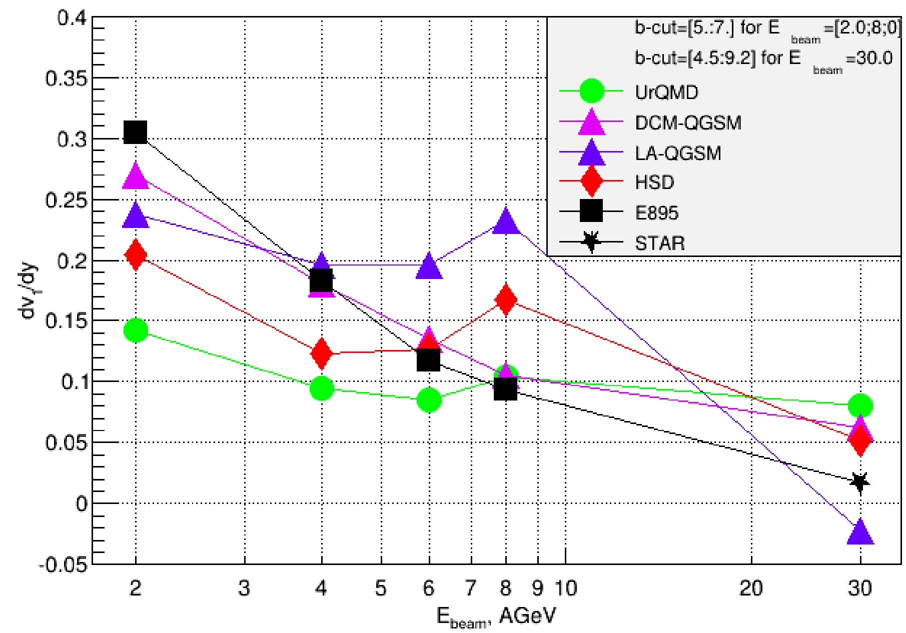
Incident enery (AGeV)



DATA
Reaction: Au + Au
Centrality: 0.5 < Mul< 0.75 Mulmax
(5 fm < b < 7fm)

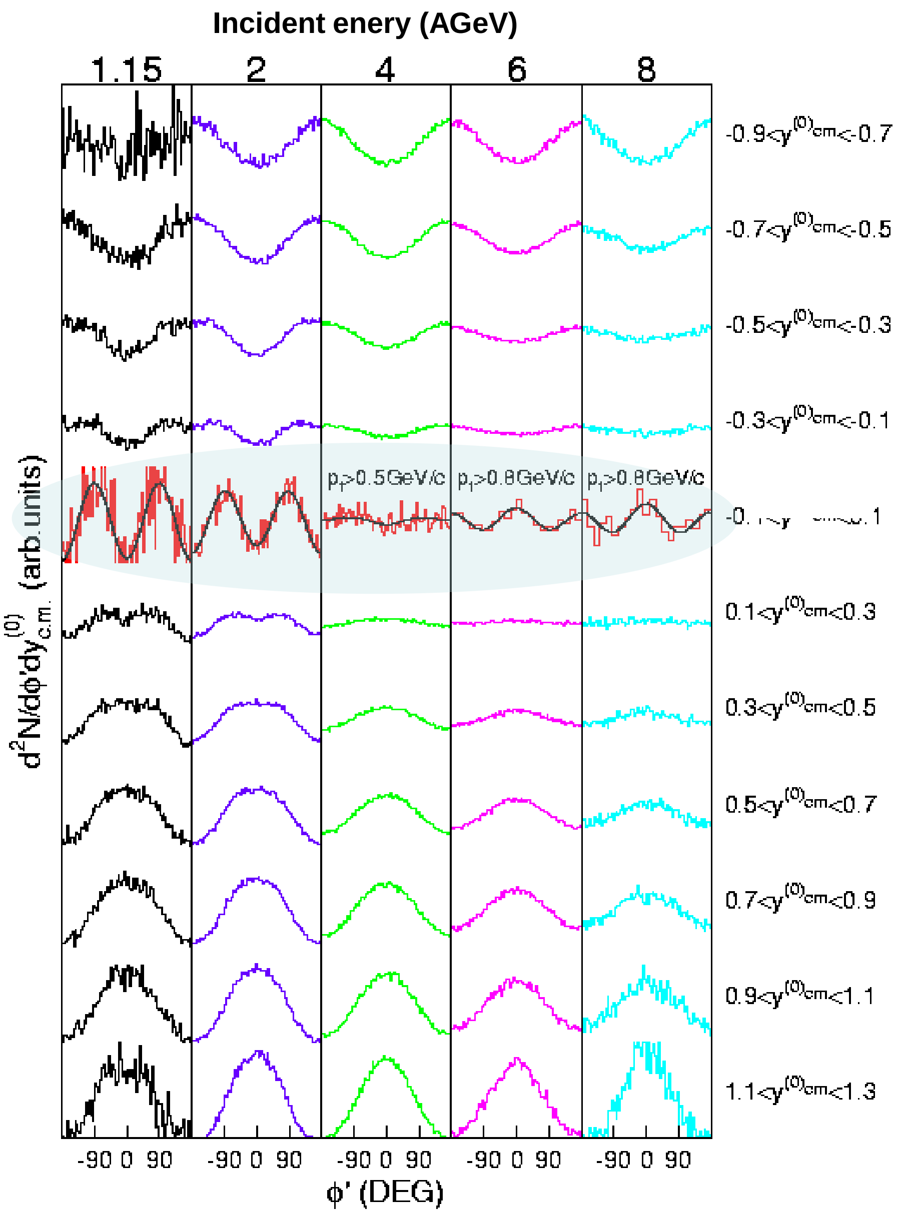
C.Pinkenburget al., (E895),
Phys.Rev.Lett. 83 (1999) 1295
nucl-ex/9903010

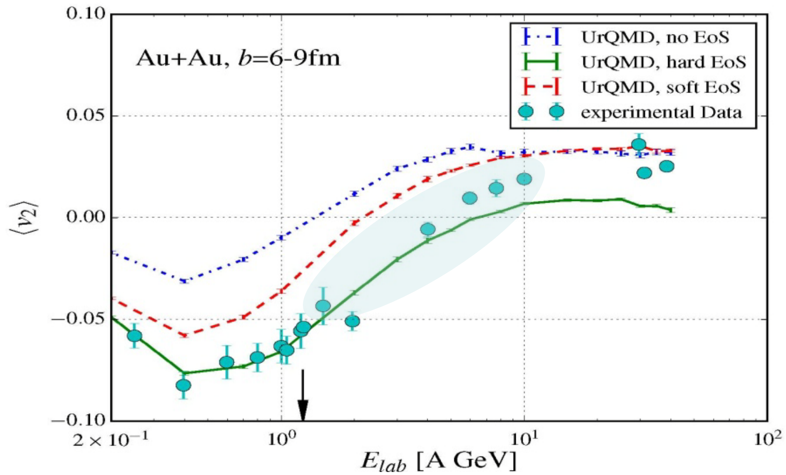
Transport models, see PhD V.Mikhaylov



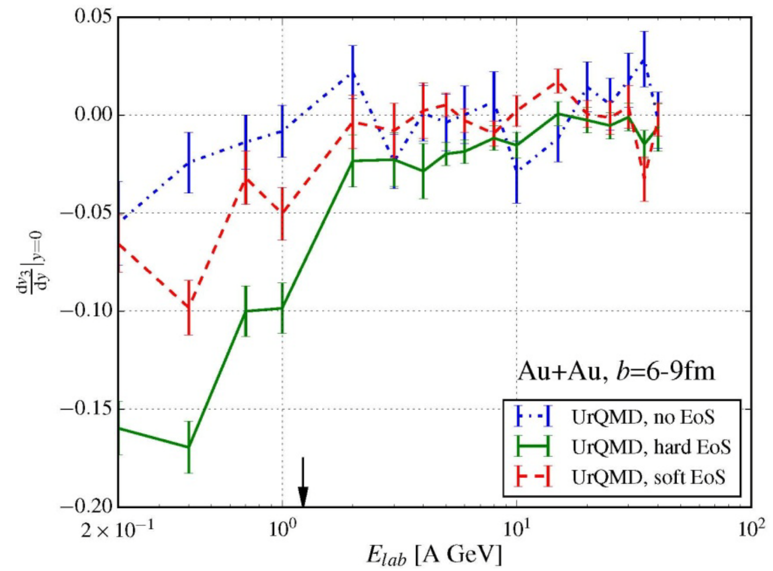
Proton flow

Azimutal Distributions with respect to the reaction plane

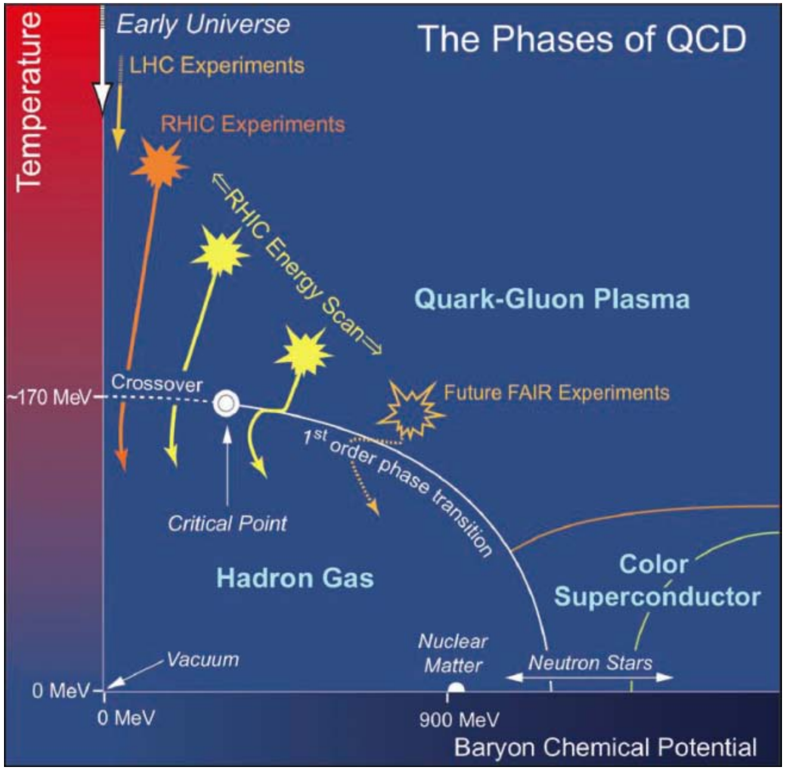




P.Hillmann et al. 2018 J.Phys.G: Nucl.Part.Phys. 45



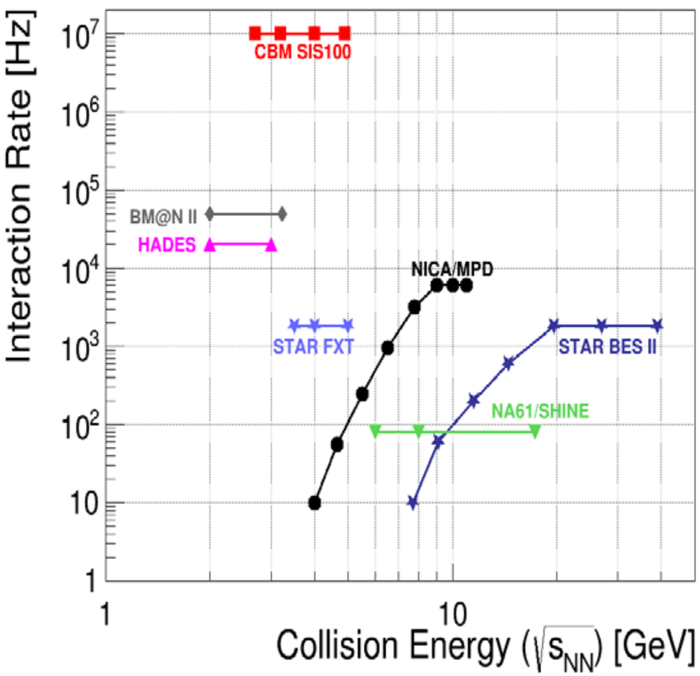
Compressed Baryonic Matter Experiments



Exploration of the QCD phase diagram is possible in heavy-ion collisions:

- at high temperature: RHIC@BNL; LHC@CERN
- at large baryon density: SIS18@GSI;SIS100@FAIR; NICA@Dubna

High Rate at CBM to study Rare Probes



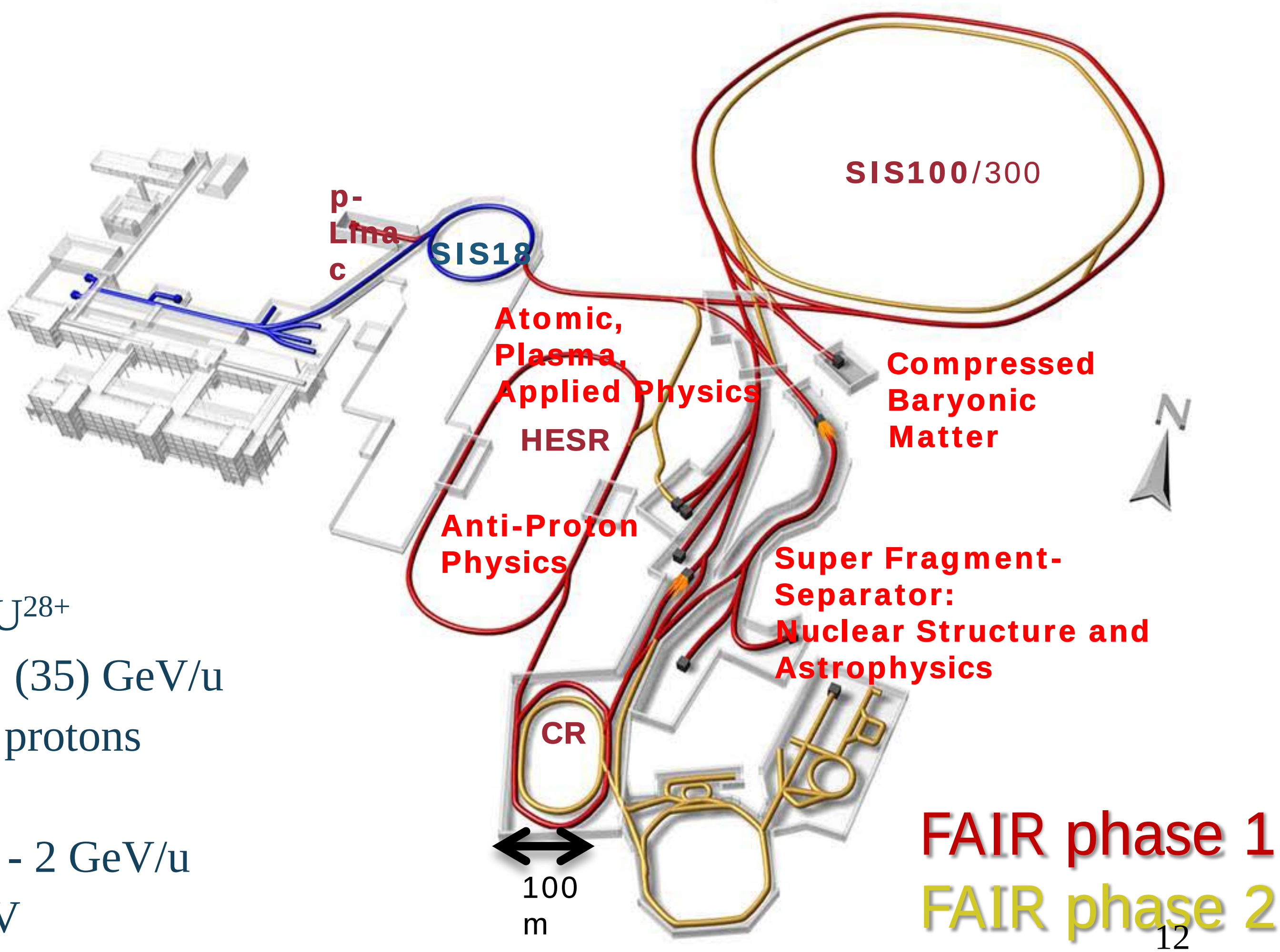
Center of mass energies
of different accelerators (in GeV):

SIS18	1 - 2
SIS100	2 - 6 (10)
NICA	4 - 11
RHIC	7 - 200
LHC:	2760, 5000

FAIR

Facility for **A**ntiproton and **I**on **R**esearch @

Matter at very high densities exists in neutron stars and in the core of supernova explosions.



Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{92+}$ up to 11 (35) GeV/u
- $3x10^{13}$/s 30 (90) GeV protons

Secondary Beams

- radioactive beams 1.5 - 2 GeV/u
- antiprotons 3 - 30 GeV

FAIR

Facility for **A**ntiproton and **I**on **R**esearch @ GSI

FAIR

Matter at very high densities exists in neutron stars and in the core of supernova explosions.

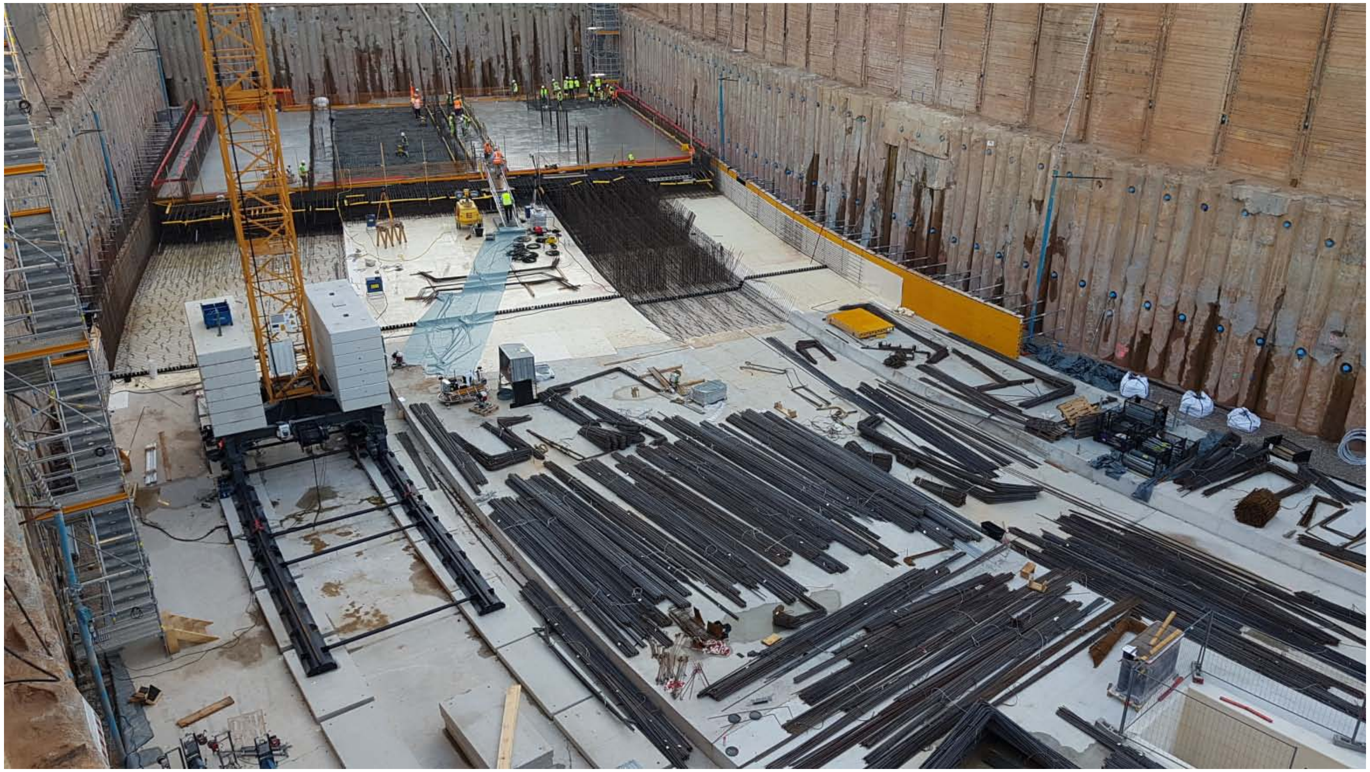
2017

FAIR

Facility for **A**ntiproton and **I**on **R**esearch @ GSI

Matter at very high densities exists in neutron stars and in the core of supernova explosions.

August 2018



FAIR

Facility for **A**ntiproton and **I**on **R**esearch @ GSI

Matter at very high densities exists in neutron stars and in the core of supernova explosions.

2025

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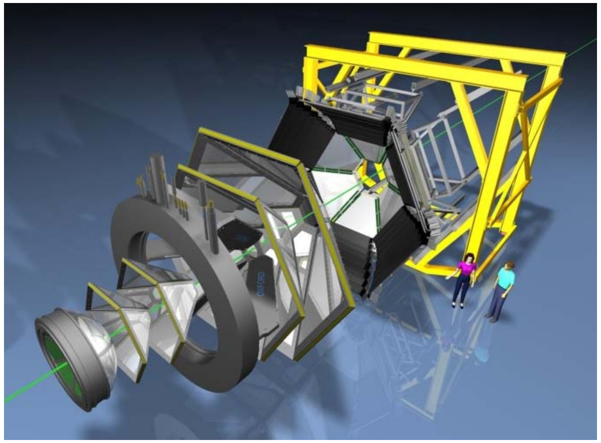
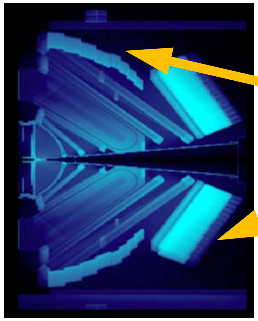
HADES, CBM

High Acceptance Dilepton Spectrometer @ FAIR GSI



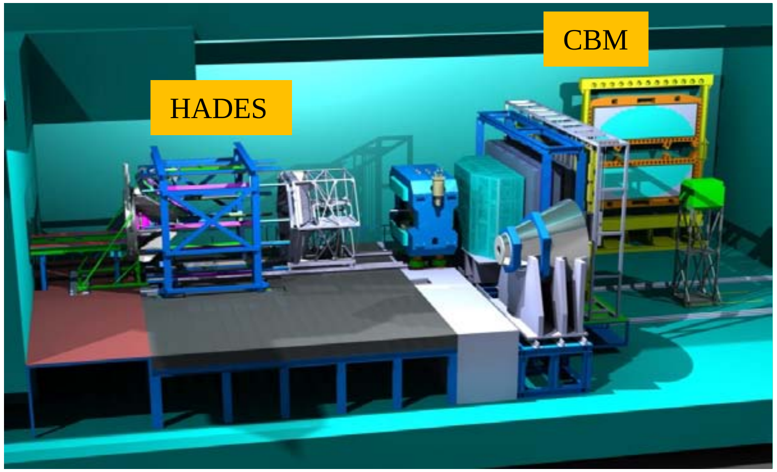


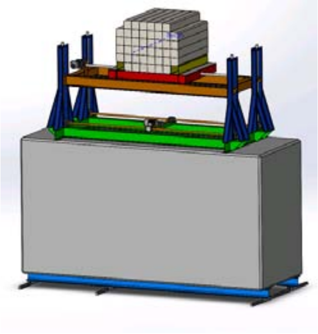
NPI contribution:
Time of Flight detector (TOF)
Electromagnetic Calorimeter (ECAL)

HADES: 23 institutions
9 countries
110 collaborators

In front of HADES ECAL

Compressed Baryonic Matter @ FAIR



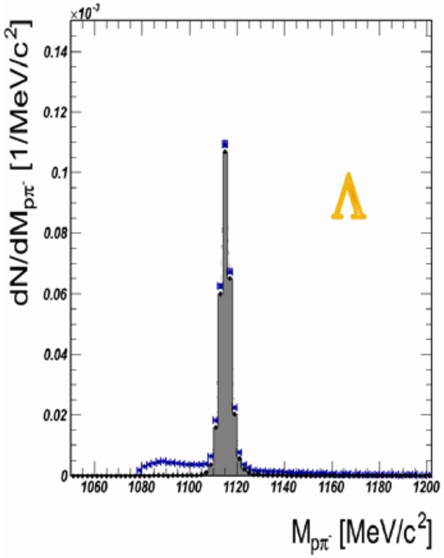


Projectile **S**pectator **D**etector **(PSD)**

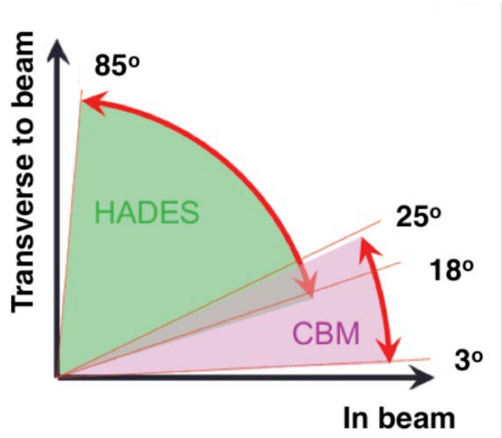
Testing PSD photodiodes at NPI

CBM: 55 institutions
11 countries
476 collaborators

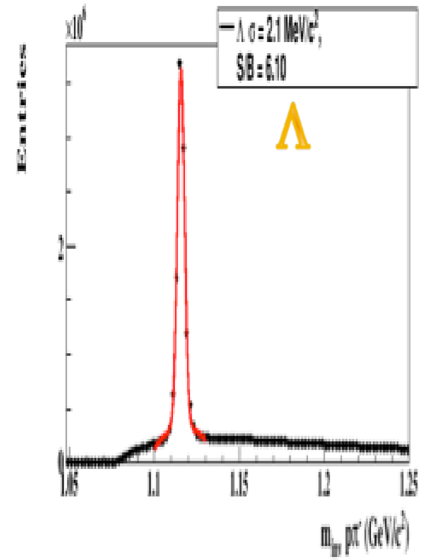
HADES, CBM: Strange matter



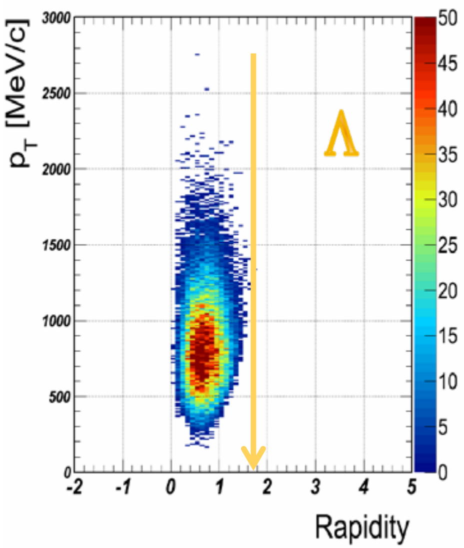
HADES Nb+Nb, 3.5A GeV



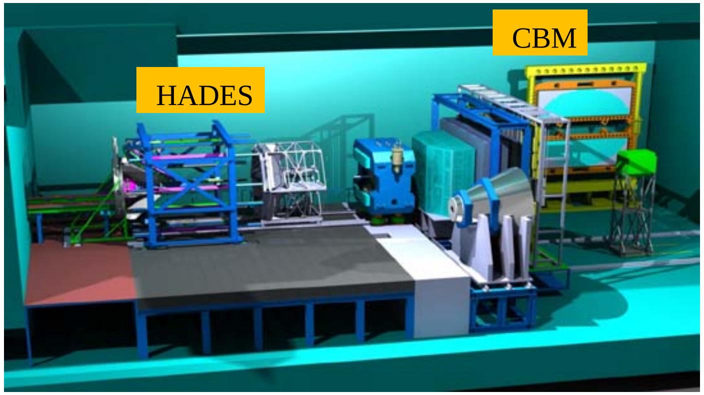
pπ$^-$ invariant mass distributions

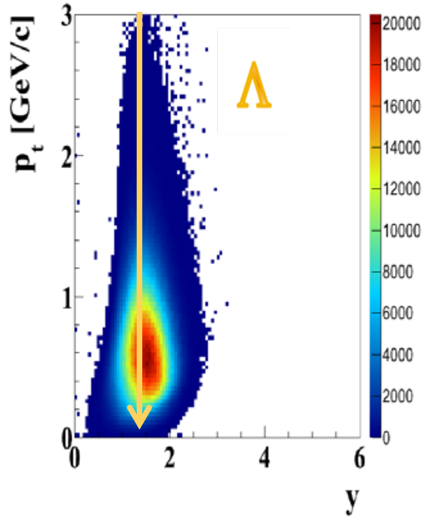


CBM Au+Au, 4A GeV



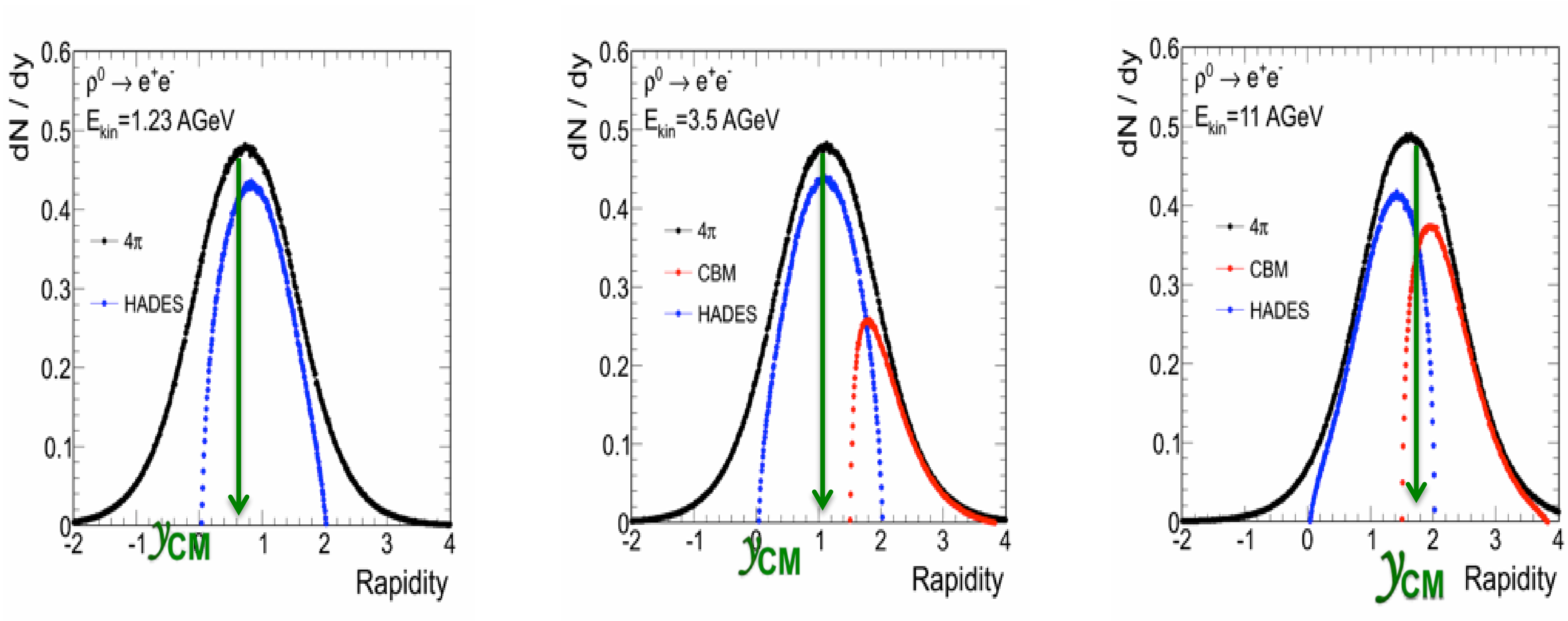
Phase space coverage
(acceptance, reconstruction
efficiency, secondary vertex cuts)





HADES, CBM: Di-Leptons

- Dilepton invariant mass distribution in acceptance
  - ρ spectral function w/o 2π threshold $\otimes$ VDM $\otimes$ Boltzmann phase space factor
  - PLUTO – thermal source with different temperatures
  - Angular cuts only



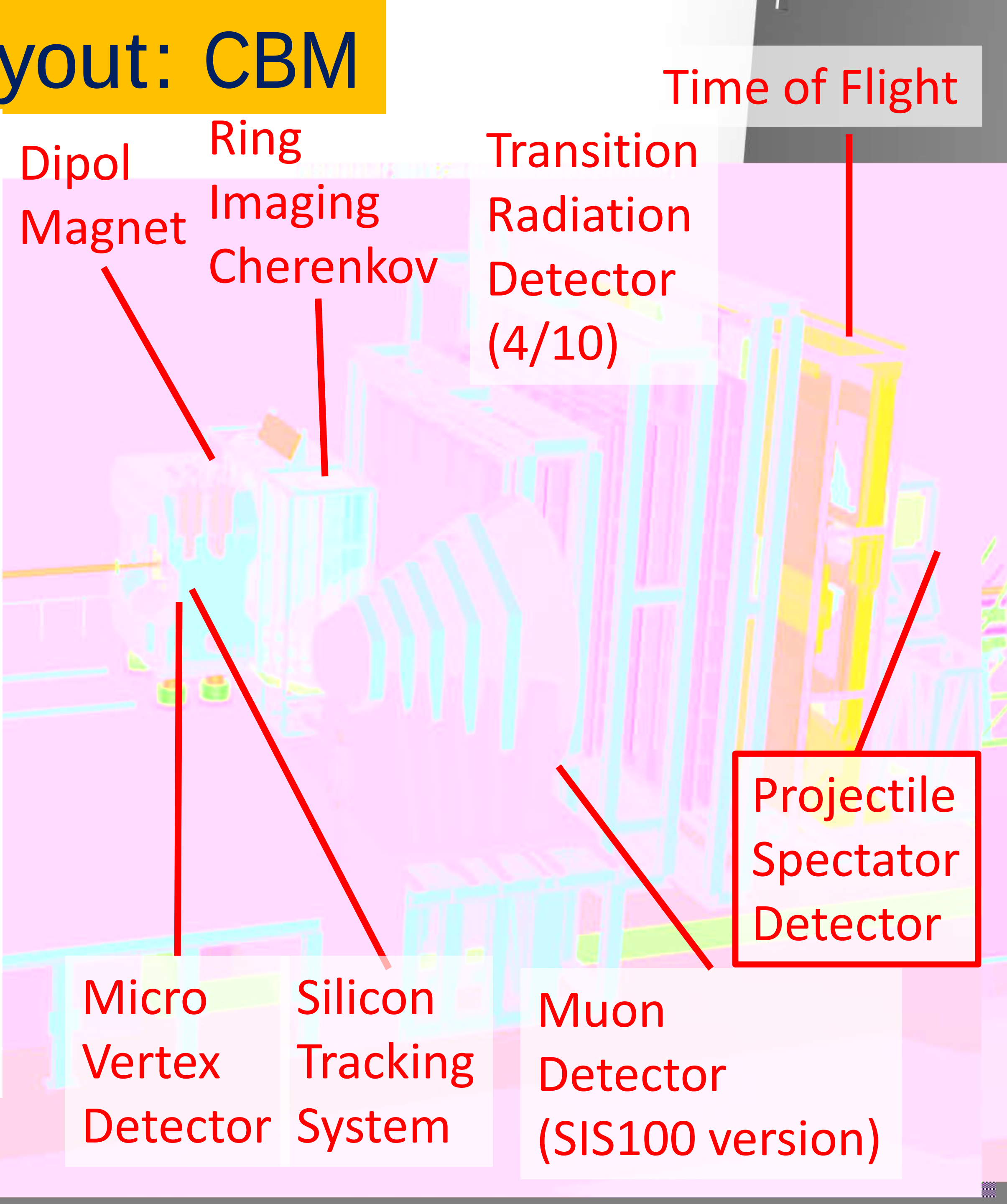
CBM - Experimental requirements

- 10^5 - 10^7 Au+Au reactions/sec
- determination of displaced vertices ($\sigma \approx 50\ \mu m$)
- identification of leptons and hadrons
- fast and radiation hard detectors and FEE
- free-streaming readout electronics
- high speed data acquisition and high performance computer farm for online event selection
- 4-D event reconstruction

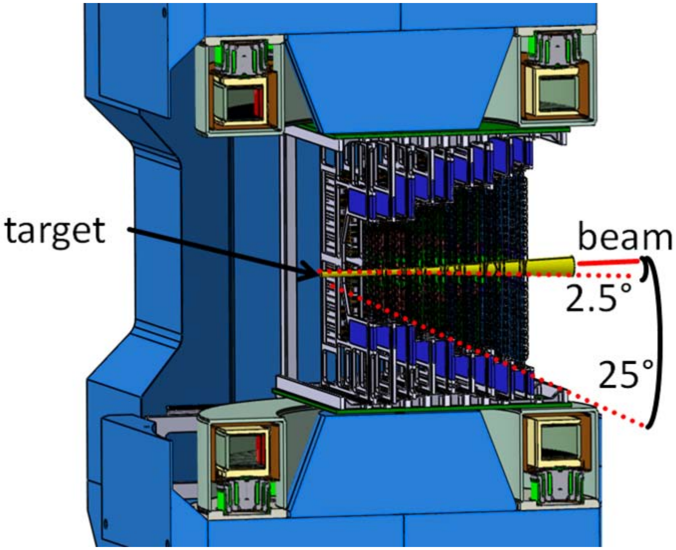
A.Kugler

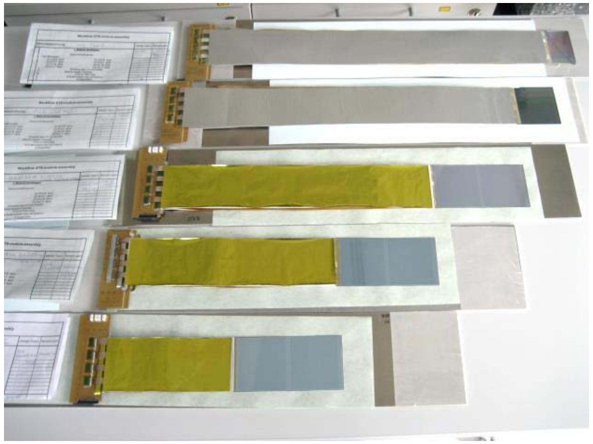
Experimental layout: CBM

- Dipole magnet – for momentum measurement
- MVD – Pixel detector for vertex determination
- STS – Radiation-hard Silicon strip detector for tracking
- RICH – Ring Imaging Cherenkov detector for electron identification
- TRD – Transition Radiation Detectors for electron identification
- RPC – Resistive Plate Chambers for time-of-flight measurement
- Muon – detector for muon identification
- PSD – Projectile Spectator Detector for centrality and reaction plane determination



CBM Silicon Tracking System



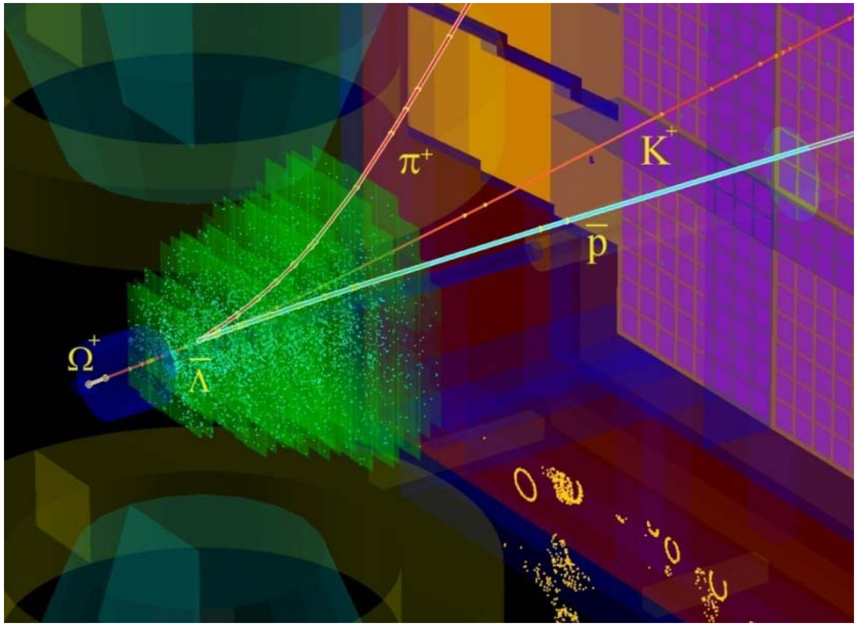


- track point measurement in high-rate collision environment:
  $10^5 - 10^7$/s (A+A), up to 10^9/s (p+A)
- physics aperture :
  $2.5° \leq \Theta \leq 25°$, $0.3\ \mathrm{m} \leq z \leq 1.0\ \mathrm{m}$
- 8 tracking stations
- double-sided silicon microstrip sensors
- hit spatial resolution ≈ 25 µm
- self-triggering front-end electronics
- time-stamp resolution ≈ 5 ns
- material : ≈ 0.3% – 1.5% X_0 per station
- $\Delta p/p \approx 1.8\%$ (p > 1 GeV/c, 1 Tm field)
- Detector construction: 2019 to 2022
- Installation into CBM: 2023

Detector testing at COSY, February 2018:

- ❑ Signal to noise 15±3
- ❑ Hit efficiency > 95 % in 1:7 GeV proton beam

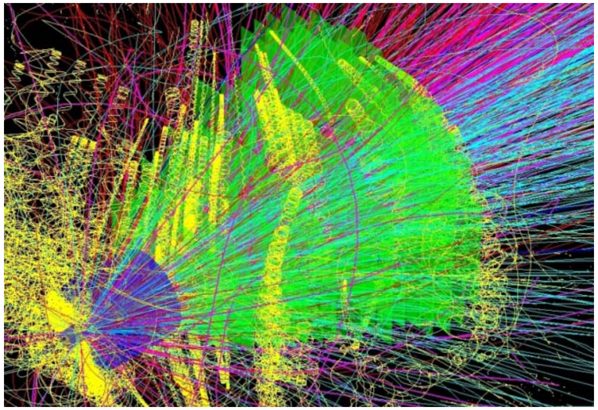
Performance of the CBM track finder



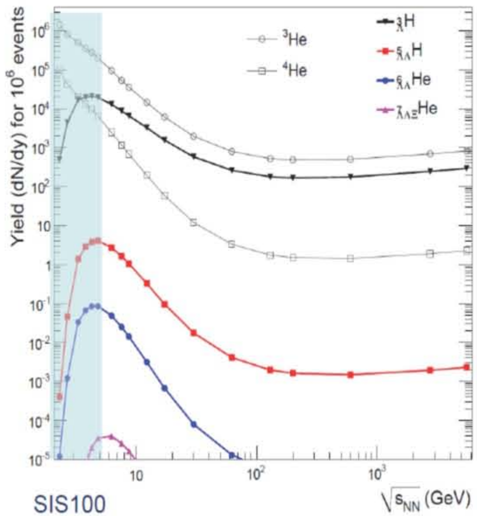
AuAu 10 AGeV/c
165 π; 170 p; 26 K$^+$; 15 Λ; 20 **K$_S^0$; 0.3 Ξ$^-$**

minimum bias : 6ms/core track finder,
1 ms/core particle finder

- For studies several theoretical models like UrQMD and PHSD are used.
- Track finder is based on the Cellular Automaton method.
- High efficiency for track reconstruction of more then 92%, including fast (more then 90%) and slow (more then 65%) secondary tracks.
- Time-based track finder is developed, efficiency is stable with respect to the interaction rate.
- Low level of split and wrongly reconstructed (ghost) tracks.

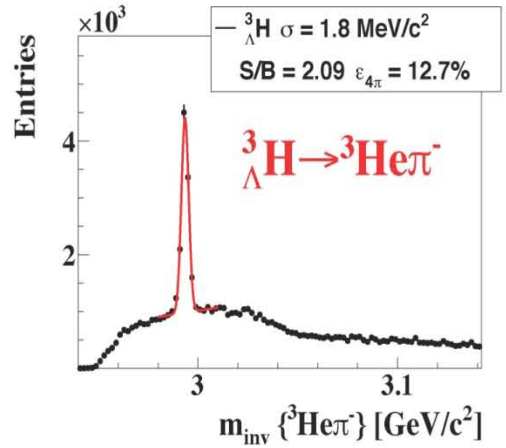


Hypernuclei production in Au+Au collisions at 10 A GeV

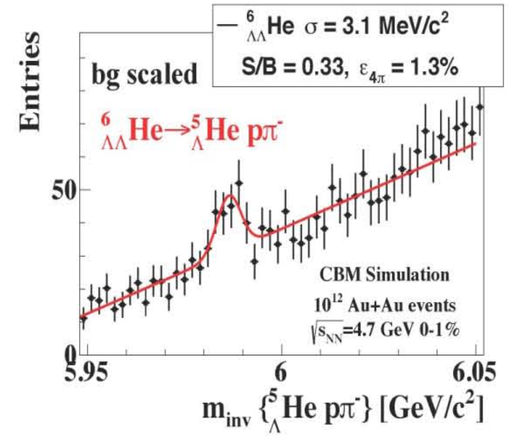


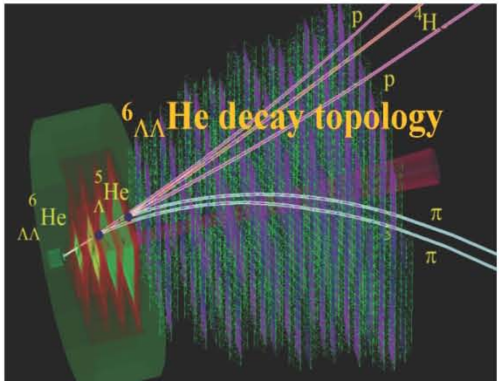
A. Andronic et al., Phys. Lett. B697 (2011) 203

5M mbias events Au+Au at 10AGeV/c
5 sec at 1MHz IR (1.8 k/sec)



Expected collection rate: ~60 $^6_{\Lambda\Lambda}$He
in 1 week at 10MHz IR

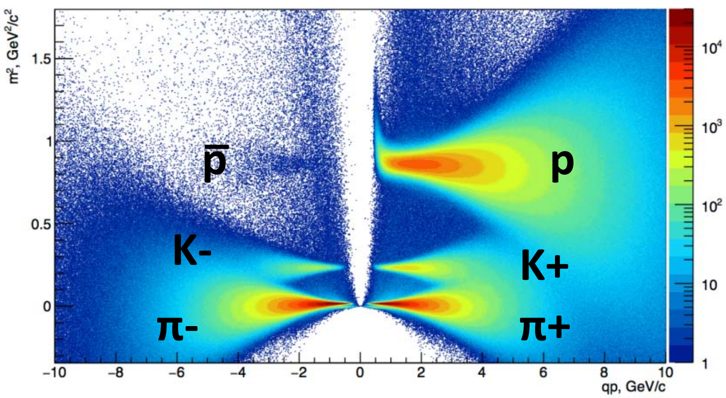




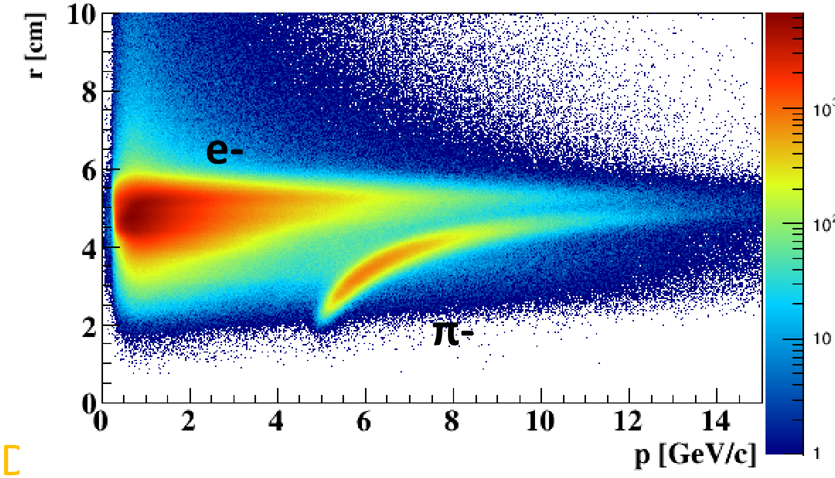
- According to the current theoretical predictions CBM will be able to perform comprehensive study of hypernuclei, including:
  - precise measurements of lifetime;
  - excitation functions;
  - flow.
- It has a huge potential to register and investigate double Λ hypernuclei.

Particle identification with PID detectors

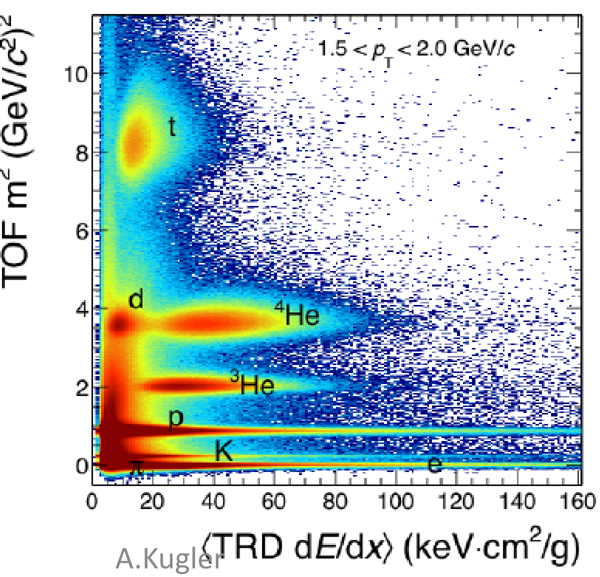
ToF: hadron identification



RICH: electron identification



TRD: d-He separation



PID

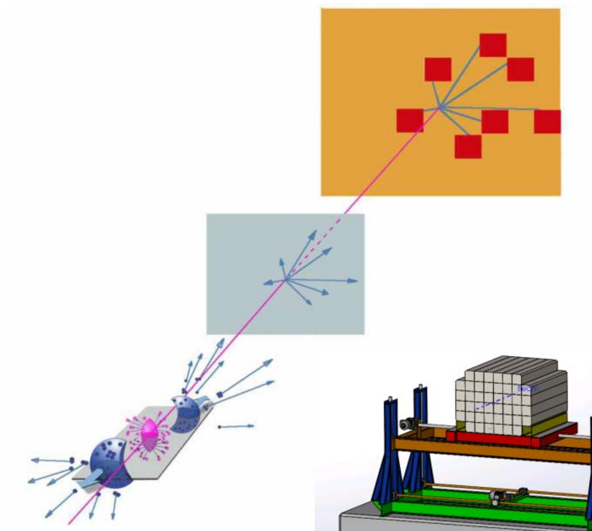
- ToF (Time of Flight) — hadron identification;
- RICH (Ring Imaging CHerenkov detector) —
- electron identification;
- TRD (Transition Radiation detector) —
- electron and heavy fragments identification.

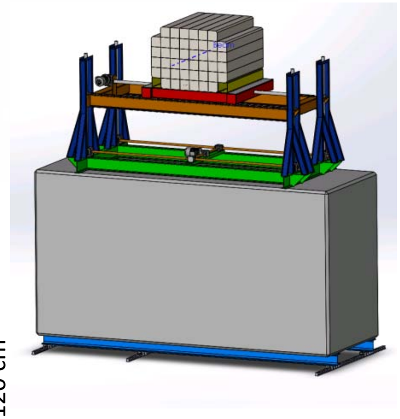
PID detectors of CBM will allow a clear identification of charged tracks.

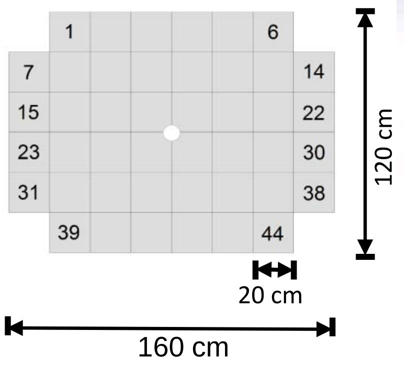
CBM: Projectile Spectator Detector

Full compensating modular lead-scintillator sandwich calorimeter

- Measurement of centrality: $b \sim A - N_{spect}$
- Reconstruction of the reaction plane







Main features:

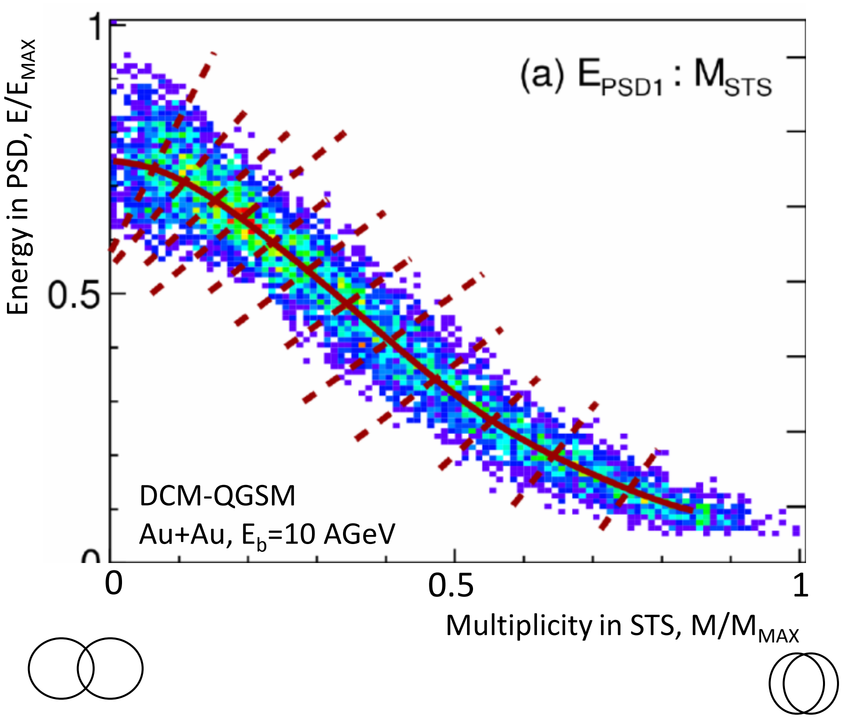
- high transverse granularity
  transverse homogeneity of energy resolution,
  reaction plane measurements
- lead/scintillator sampling ratio 4:1 (16 mm / 4 mm), compensating calorimeter (e/h = 1)
  high energy resolution <60%/√E(GeV)
- longitudinal segmentation (10 sections per module)
  particle identification, calibration, improved energy resolution
- light readout from each section by novel APDs
  large dynamic range up to 10^4 ph.el.,
  no nuclear counting effect
- ability to operate at high count rate and at high radiation dose

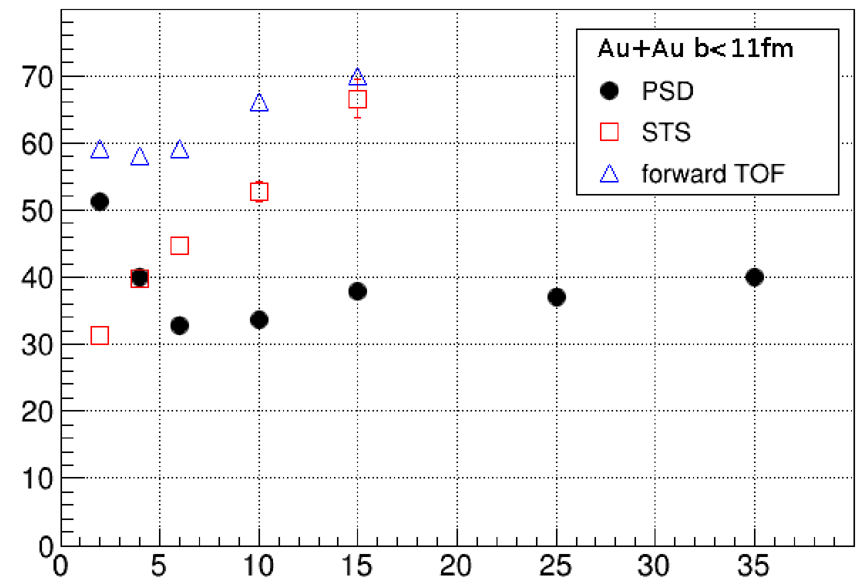
60 sandwiches in one module
45 modules of 20 x 20 x 120 cm^3
Total weight ~ 22 tons, 8 m (SIS100) / 15 m (SIS300) from target
Beam hole (d = 6 cm) for intensity up to 10^9 ions/sec
CBM beam energy up to 11 AGeV (SIS100) / 35 AGeV (SIS300)

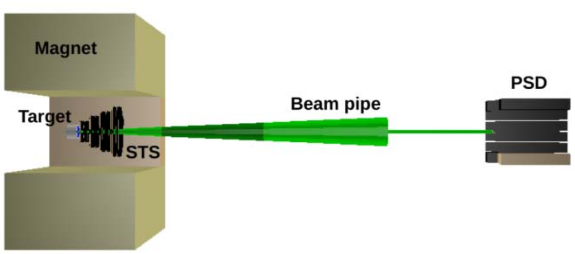
CBM PSD: centrality determination

Centrality determination by correlation between energy deposited in PSD & STS track multiplicity

Reaction plane resolution, σ







- PSD can be used standalone as an independent centrality estimator with a resolution for centrality of 10%
- PSD helps to improve resolution of the STS for (mid-) central collisions

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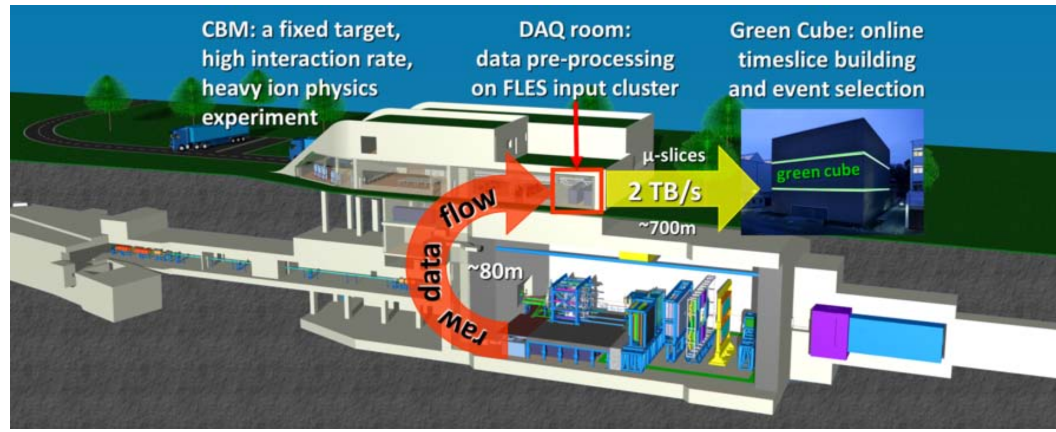
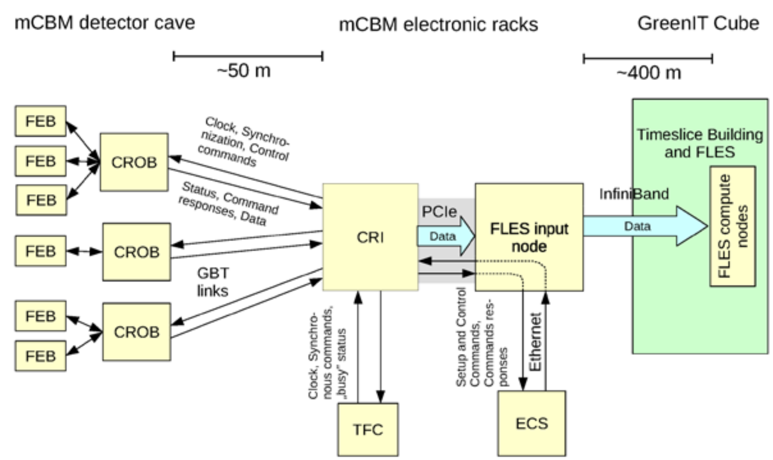
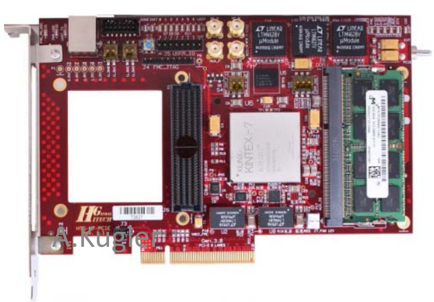
CBM Readout and Computing

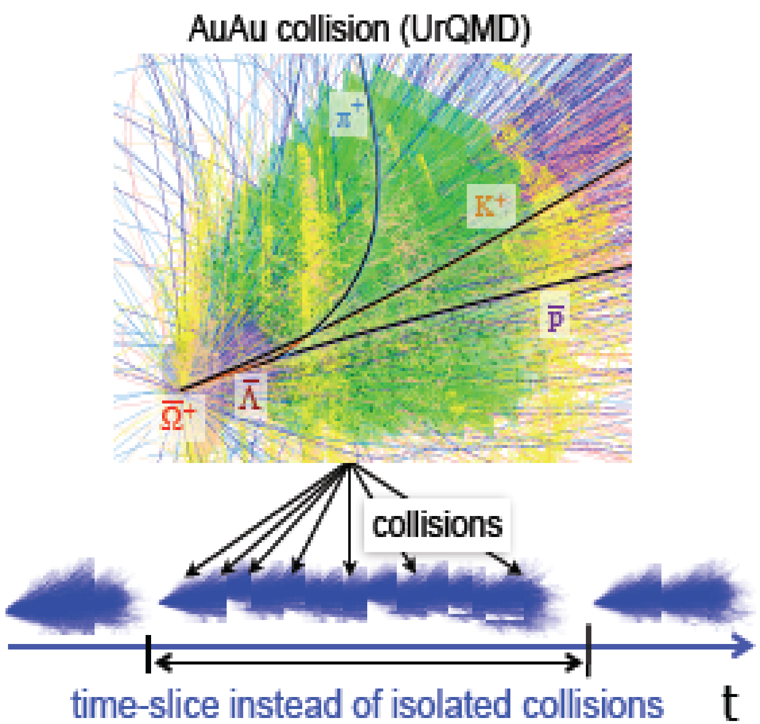
- ❑CBM-DAQ is free-streaming and self-triggered based on innovative frontend electronics
- ❑ Interaction rates resulting in high computing requirements
- ❑ FPGA-based readout chain (feature extraction) complemented by high-performance computing in the Green Cube (2TBytes/sec)
- ❑ Early reconstruction of self-contained units, data processing: in FPGA, FLES, online software
- ❑ Event definition: online in 4D-tracking from overlapping time-slices (First-Level Event Selector)



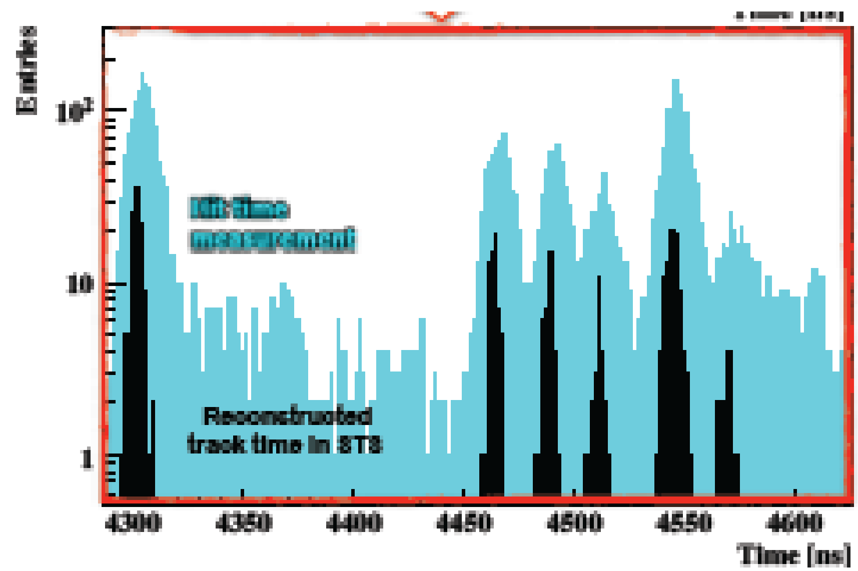




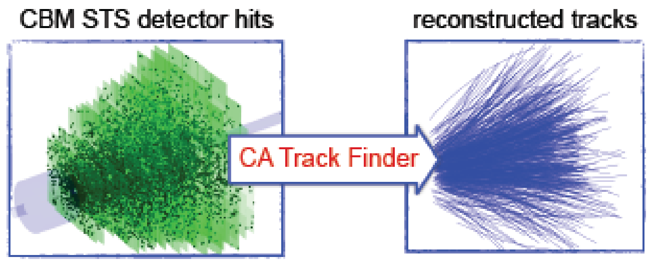
CBM 4D Event Reconstruction



- Free streaming data.
- Continuous time-slices instead of individual collisions.
- On-line time-based collision reconstruction and selection is required in the first trigger level.

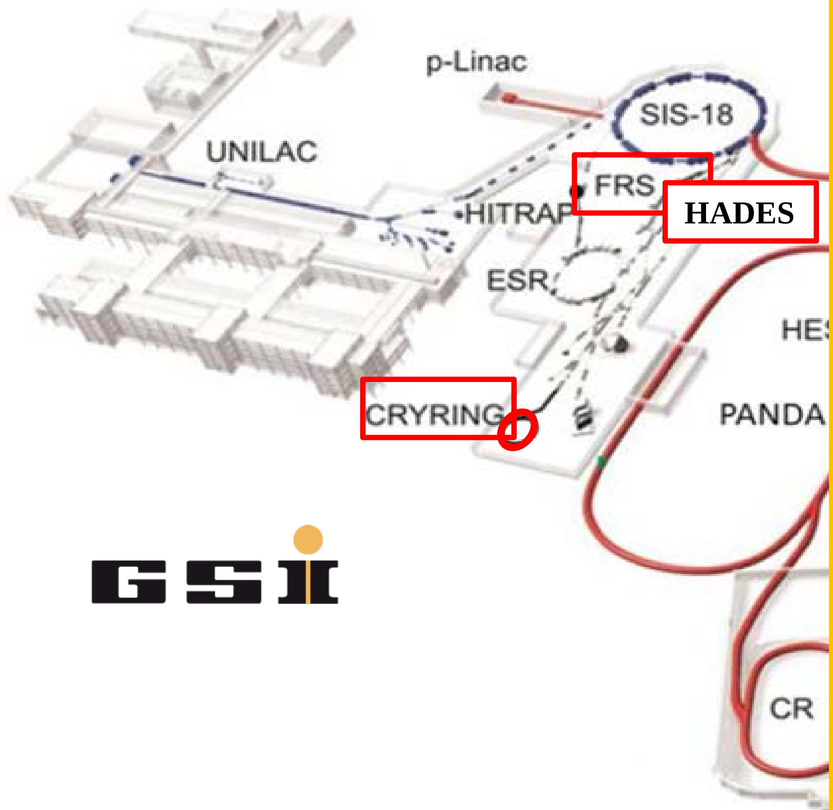


4D Cellular Automaton Track Finder



Efficiency, %	3D	0.1 MHz	10 MHz
All tracks	92.5	93.8	91.7
Ghost level	1.8	0.6	0.6
Time, ms/ev	11.70	11.97	13.60

FAIR Phase 0



Since 2018

- Exploiting upgraded SIS 18 accelerator facilities
- Forefront research by employing and testing new FAIR detectors *(ECAL@HADES, RICH@HADES, mCBM, CRYRING, EXPERT@NuSTAR...)*
- Education of young scientists
- Maintain and extend skills and expertise
- Serve national and international user community

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FAIR Phase 0 – scientific opportunities for the four research pillars of FAIR

APPA	Facility	Research Activity
SPARC	ESR-HITRAP-	Strong field QED, atomic collisions, fundamental
SPARC	CRYRING	symmetries, border to nuclear physics
BIOMAT	M Branch, Z0/ A	Biophysics, heavy ion therapy, Material Science
WDM/HEDgeHOB	HHT/PRIOR	Equation-of-state studies; phase transitions in matter
WDM/HEDgeHOB	PHELIX	Laser plasma interaction and acceleration
CBM		
HADES	HADES@SIS18	Di-lepton production in pion-induced and HI reactions
miniCBM	miniCBM@SIS18	Test of subsystem plus data acquisition of CBM
CBM	External	Beam energy scan at STAR/RHIC (tests/ physics at NICA)
NUSTAR		
NUSTAR	FRS -EXPERT	Separator-/spectrometer expt.'s with exotic nuclei
NUSTAR	FRS-ESR	Nuclear physics with exotic beams in storage rings
NUSTAR	HISPEC/DESPEC	In-beam and stopped-beam spectroscopy experiments
NUSTAR	R3B@SIS18	Reactions with relativistic radioactive beams
NUSTAR	SHIP, TASCA	Physics and chemistry of SHE
PANDA		
PANDA	HADES	Hyperon Dalitz decays with HADES (use of PANDA F-TRK)
PANDA	External	Search for exotic states, charmonium and time-like form factors at BESIII/Beijing/IHEP. Magnetic moment of Δ(1232), e-m universality, multi pi0 prod. at MAMI

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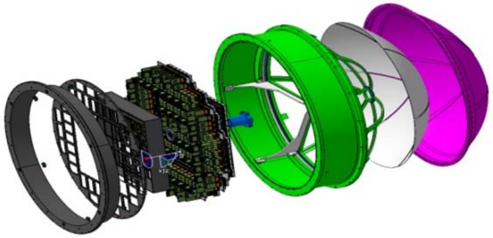
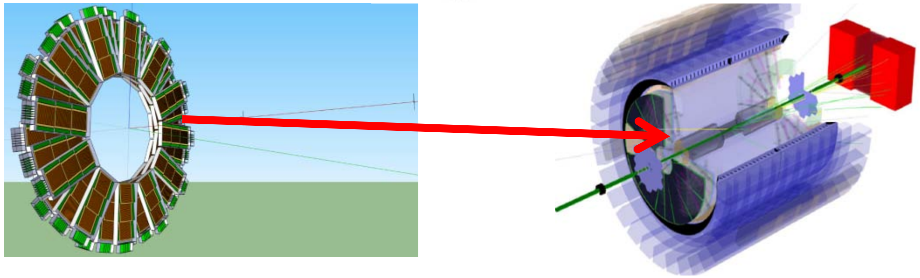
CBM – FAIR Phase 0 projects (2018 – 2022)

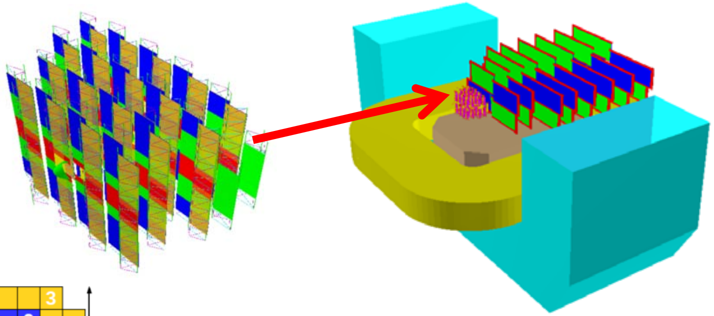
1. Install, commission and use 430 out of 1100 CBM RICH multi-anode photo-multipliers (MAPMT) including FEE in HADES RICH photon detector



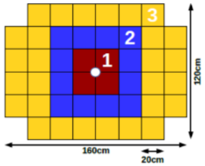
2. Install, commission and use 10% of the CBM TOF modules including read-out chain at STAR/RHIC (BES II 2019/2020)

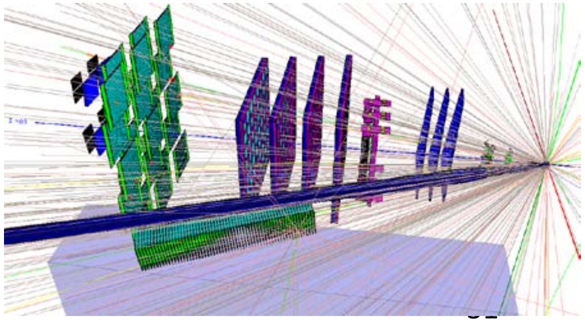


3. Upgrade BM@N experiment with 4 Silicon stations of CBM/STS design in the BM@N experiment at the Nuclotron JINR/Dubna (Au-beams in late 2020)



4. Install, commission and use the Project Spectator Detector at the BM@N experiment





5. mCBM@SIS18: demonstrator for full CBM data taking and analysis chain

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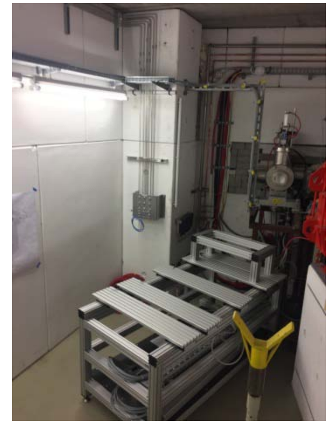
A CBM full-system test-setup at GSI/FAIR: *mCBM@SIS18*

concept:

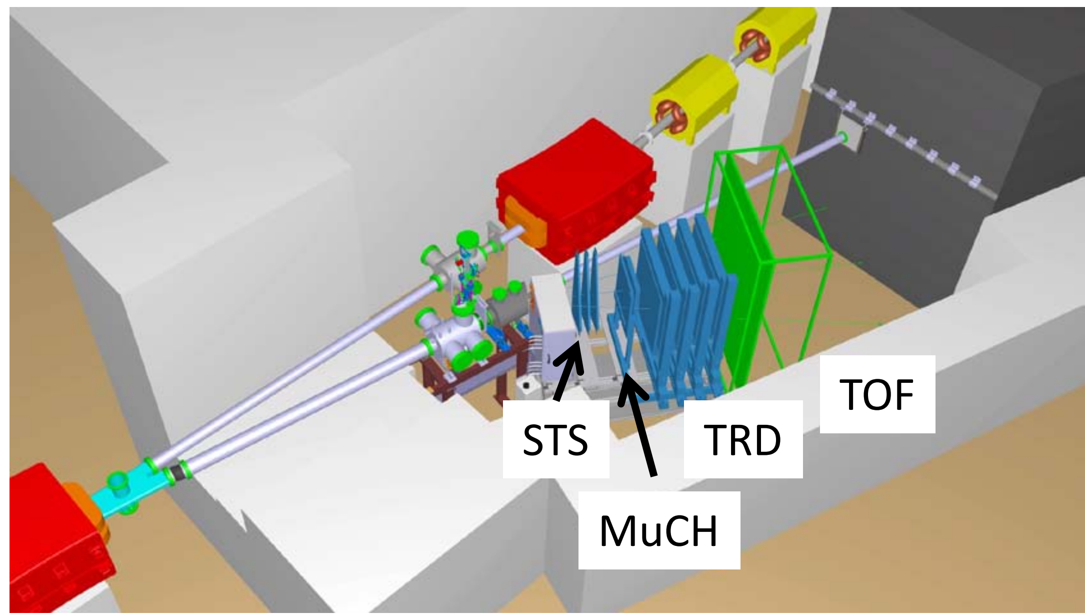
a permanent test-setup at the host lab

- **detector prototypes** at $\theta_{lab} \approx 20°$
- collision rates up to 10 MHz
- compact setup (< 5m)
- no B-field → straight tracks
- high resolution TOF (T_0 – TOF stop wall)



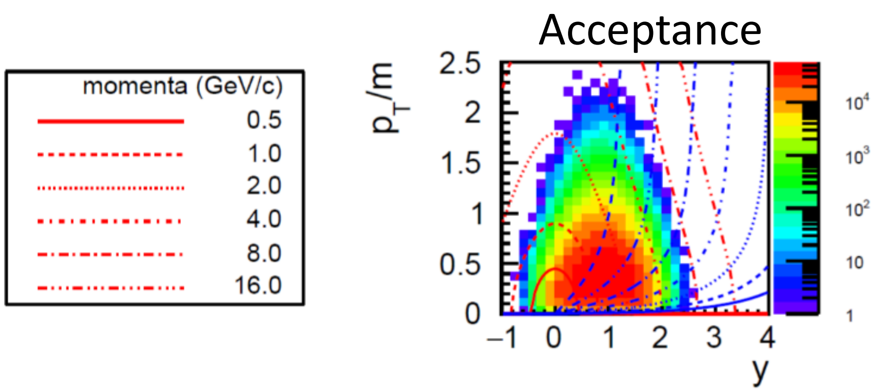
Topics to be addressed

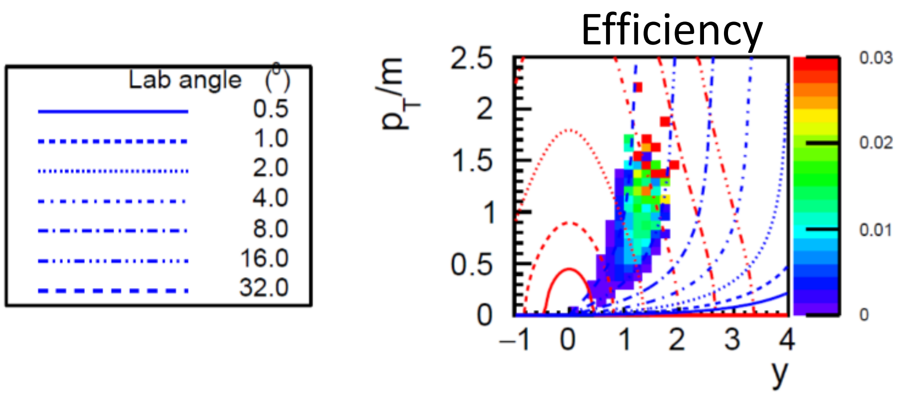
- free streaming read-out and data transport to the mFLES
- online reconstruction
- offline data analysis
- controls
- detector tests of final detector prototypes

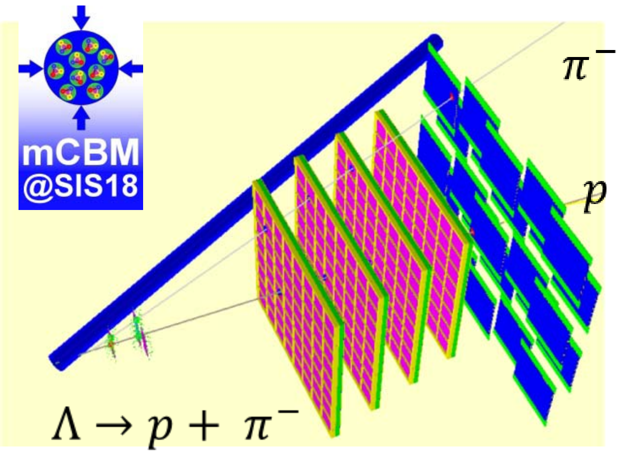


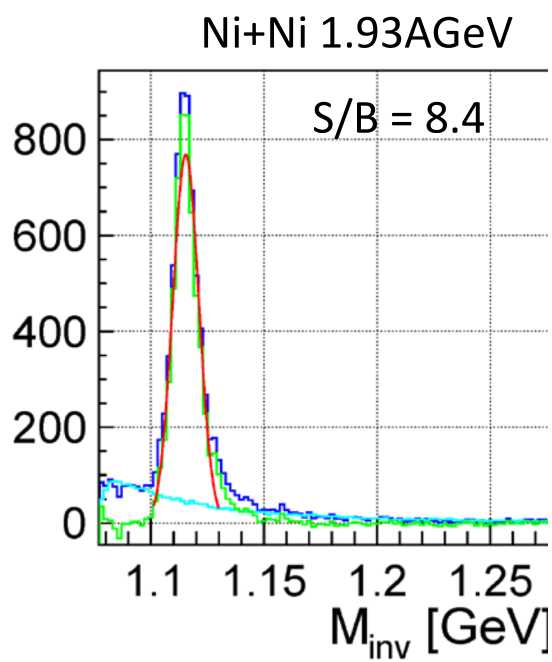
mCBM benchmark observable: Λ reconstruction

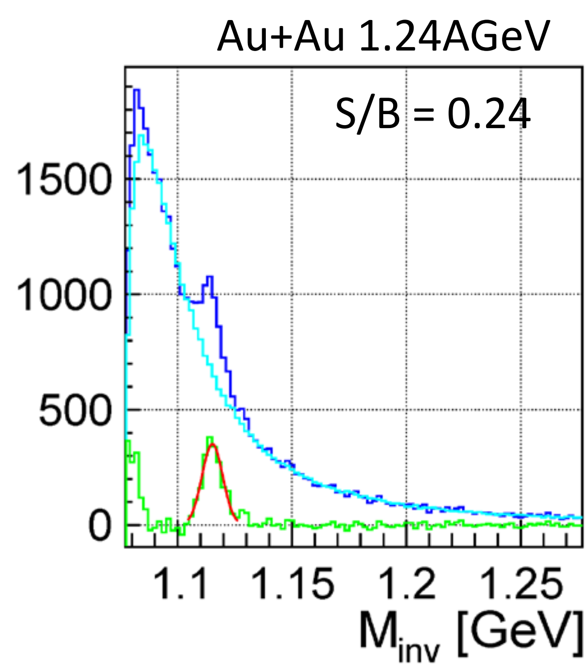
Simulation input: 10^8 UrQMD events, min. bias











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The CBM Collaboration: 60 institutions, 530 members

Croatia:
Split Univ.

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei
CTGU Yichang

Czech Republic:
CAS, Rez
Techn. Univ.Prague

France:
IPHC Strasbourg

Hungary:
KFKI Budapest
Budapest Univ.

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

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

Korea:
Pusan Nat. Univ.

Romania:
NIPNE Bucharest
Univ. Bucharest

Poland:
AGH Krakow
Jag. Univ. Krakow
Silesia Univ. Katowice
Warsaw Univ.
Warsaw TU

Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
Kurchatov Inst., Moscow
LHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
Obninsk Univ.
PNPI Gatchina
SINP MSU, Moscow
St. Petersburg P. Univ.
Ioffe Phys.-Tech. Inst. St. Pb.

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

Summary

- CBM scientific program at SIS100:
  First precision study of the QCD phase diagram in the region of extreme high net-baryon densities → large discovery potential

- Unique measurements of rare diagnostic probes with CBM:
  High-precision multi-differential measurements of hadrons incl. multistrange hyperons and dileptons for different beam energies and collision systems → terra incognita.

- Key experimental requirements: high-rate capability of detectors and DAQ, online event reconstruction and selection
  → Unrivaled feature of CBM

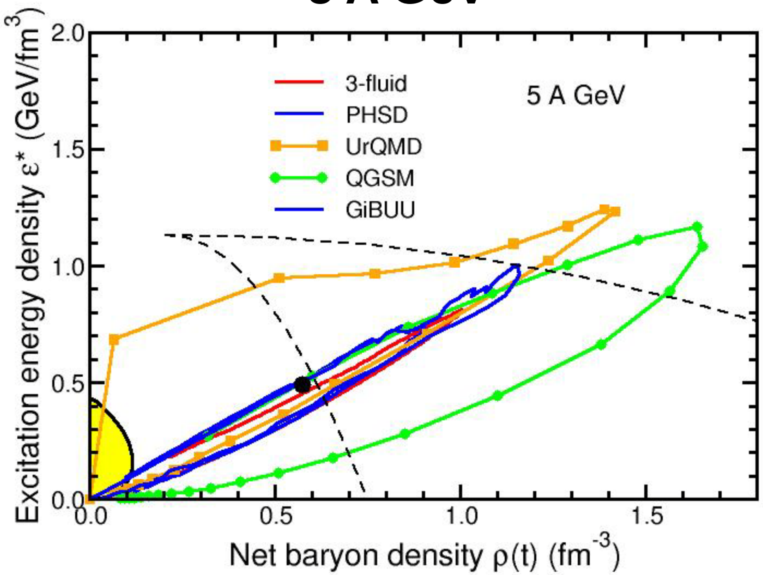
- Status of CBM experiment preparation:
  7 TDRs approved, 4 TDRs in preparation
  Substantial part of the CBM start version is financed

THANK YOU

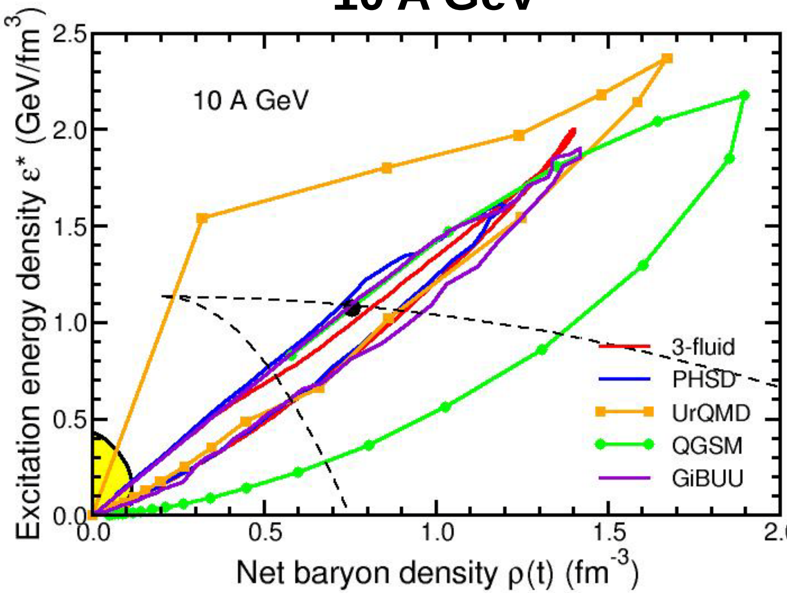
Baryon densities in central Au+Au collisions

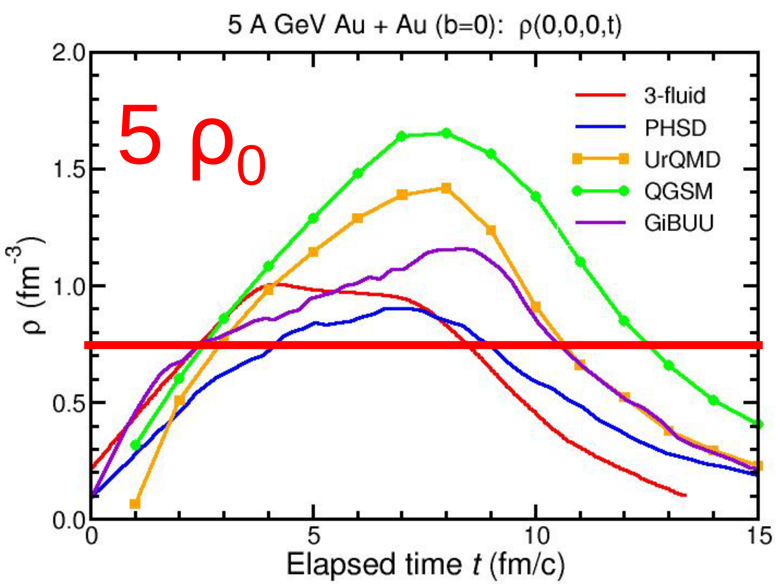
I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007), V. D. Toneev et al., Eur. Phys. J. C32 (2003) 399

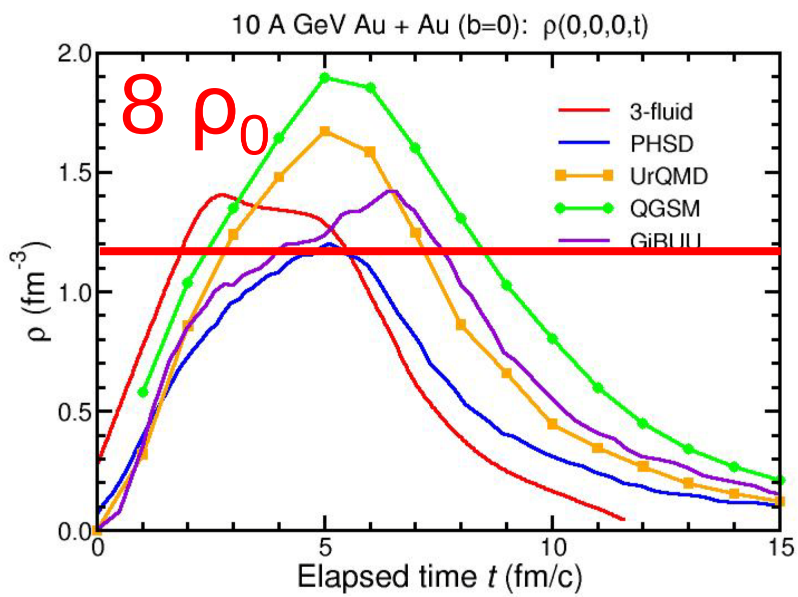
5 A GeV



10 A GeV





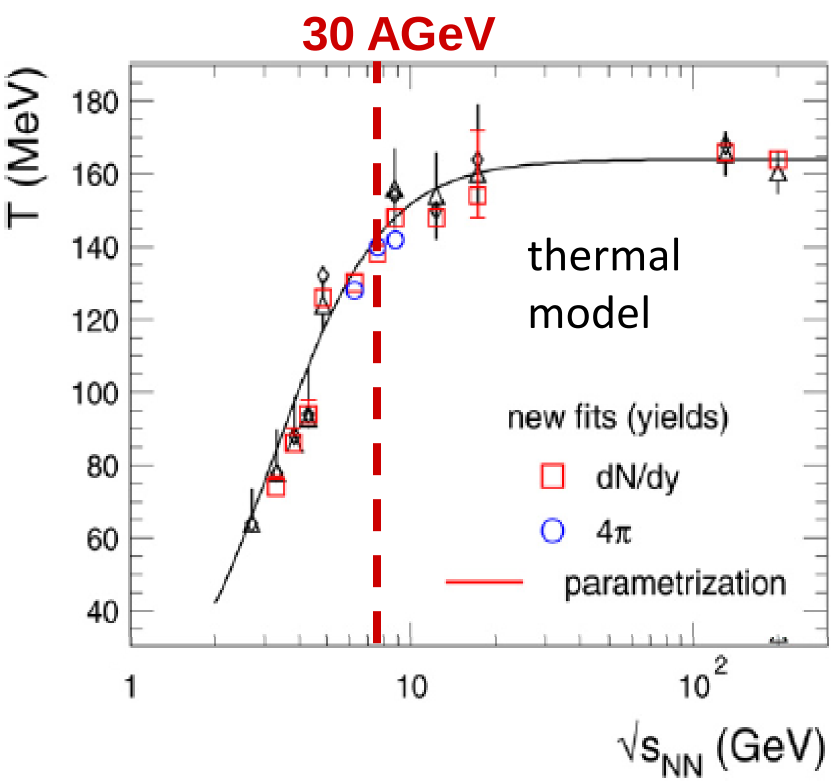


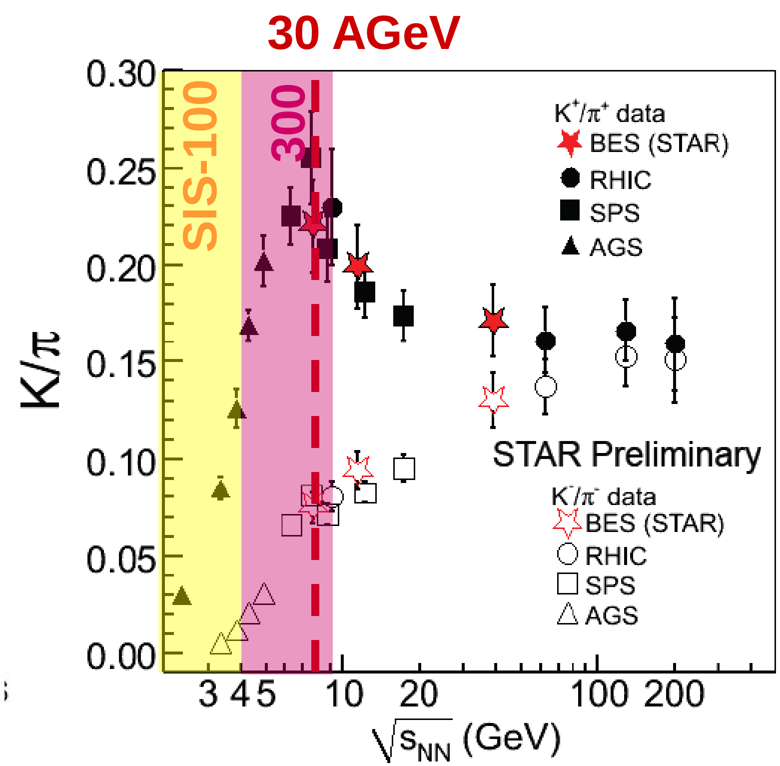
Phase transition at high μ_B?

- Phase transition to partonic phase in heavy-ion collisions at 30 AGeV?
- More/ other phases at lower energies?
- Characteristics of dense baryonic matter?

CBM at FAIR will cover the lower energy – high baryon density side!

[A. Andronic et al., Phys. Lett. B 673 (2009) 142]





[L. Kumar (STAR) QM 2011]

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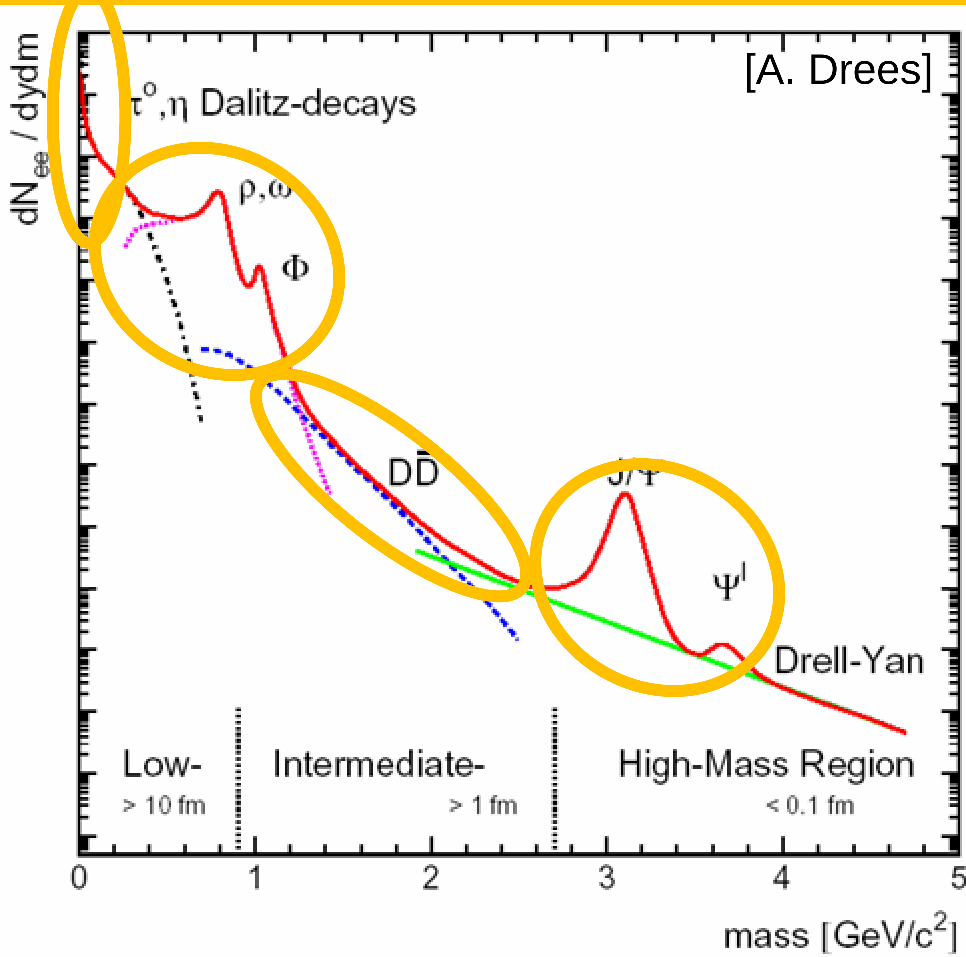
Dileptons



- Photons: access to early temperatures
  → excitation function?
- Low-mass vector mesons: in-medium properties of ρ
  → strength due to coupling to baryons (see HADES)
  → go to real dense matter!
- Intermediate range: acces to fireball radiation (see NA60)
  → quarkyonic phase?
- J/ψ: charm as a probe for dense baryonic / partonic matter
  → propagation of charm?
  → distribution amongst hadrons?