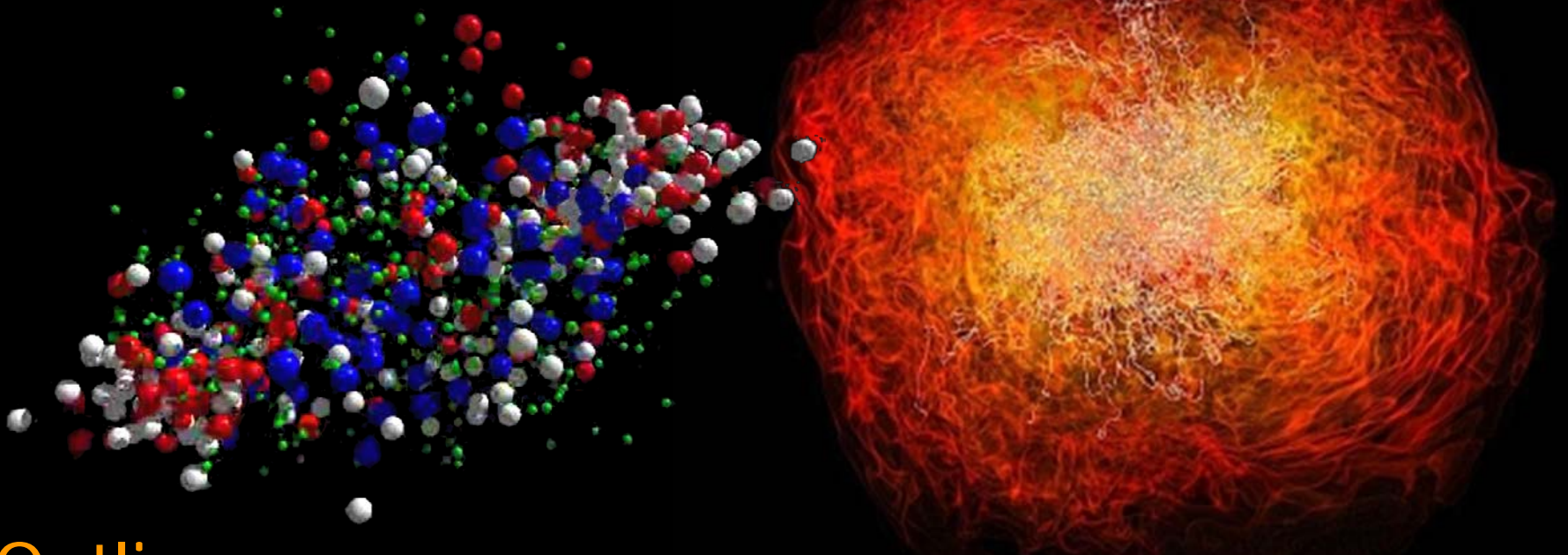


The CBM experiment: status and program

Peter Senger

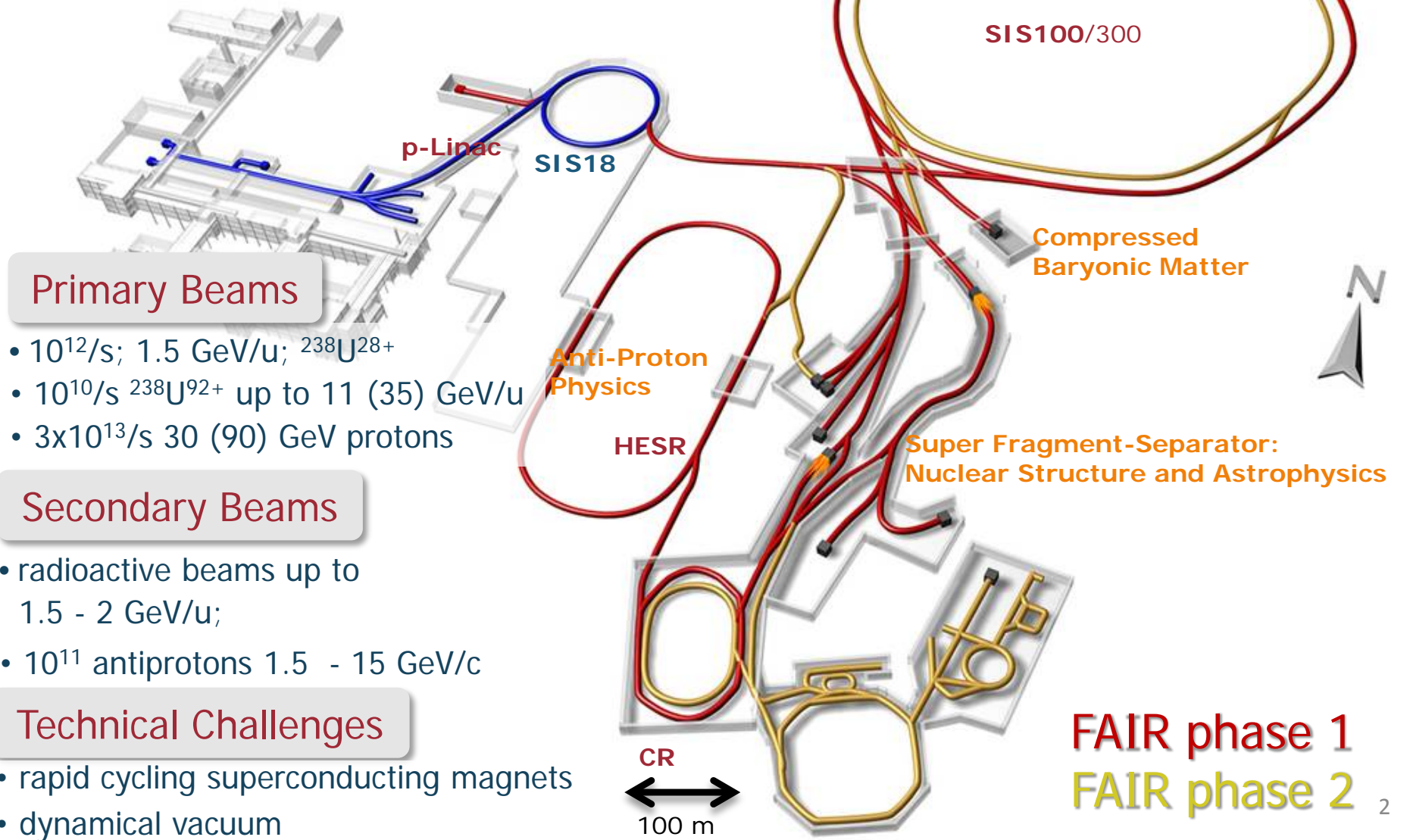
GSI and Univ. Frankfurt



- Outline:**
- The Facility of Antiproton and Ion Research
 - The CBM physics case: QCD matter at large μ_B
 - The Compressed Baryonic Matter experiment

Workshop of the Study of high-density nuclear matter with hadron beams
March 28-31, 2017, Weizmann Institute of Science, Israel

Facility for Antiproton & Ion Research



Primary Beams

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

Secondary Beams

- radioactive beams up to 1.5 - 2 GeV/u;
- 10^{11} antiprotons 1.5 - 15 GeV/c

Technical Challenges

- rapid cycling superconducting magnets
- dynamical vacuum

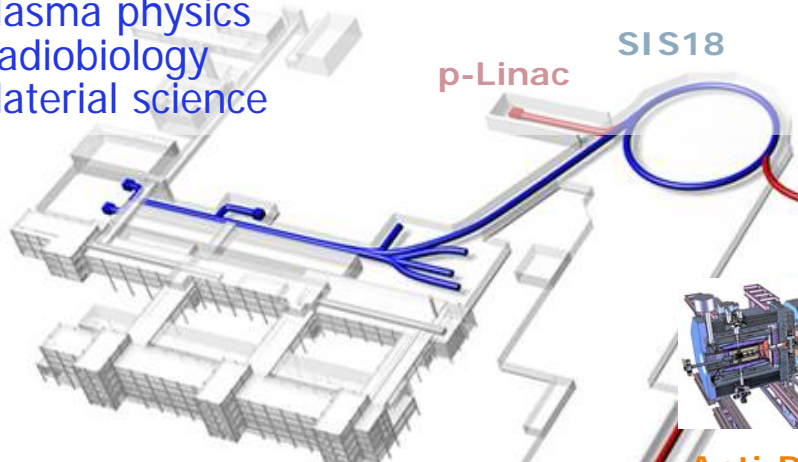
FAIR phase 1
FAIR phase 2

Facility for Antiproton & Ion Research

Experimental programs:

APPA: Atomic & Plasma Physics & Applications

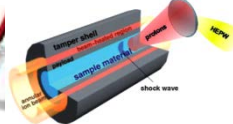
- Highly charged atoms
- Plasma physics
- Radiobiology
- Material science



CBM: Nucleus-nucleus collisions

- Nuclear matter at neutron star core densities
- Phase transitions from hadrons to quarks

Anti-Proton Physics



Compressed Baryonic Matter



Super Fragment-Separator: Nuclear Structure and Astrophysics



NUSTAR: Rare Isotope beams

- Nuclear structure far off stability
- Nucleosynthesis in stars and supernovae

CR

PANDA: Antiproton-proton collisions:

- Charmed hadrons (XYZ)
- Gluonic matter and hybrids
- Hadron structure
- Double Lambda hypernuclei



FAIR phase 1
FAIR phase 2



In 2014: Four worldwide largest drilling machines put down 1350 reinforced concrete pillars of 60 m depth and 1.2 m diameter.



Status of FAIR

On Sept. 13, 2016, BMBF gave green light and 203 M€ to start civil construction.

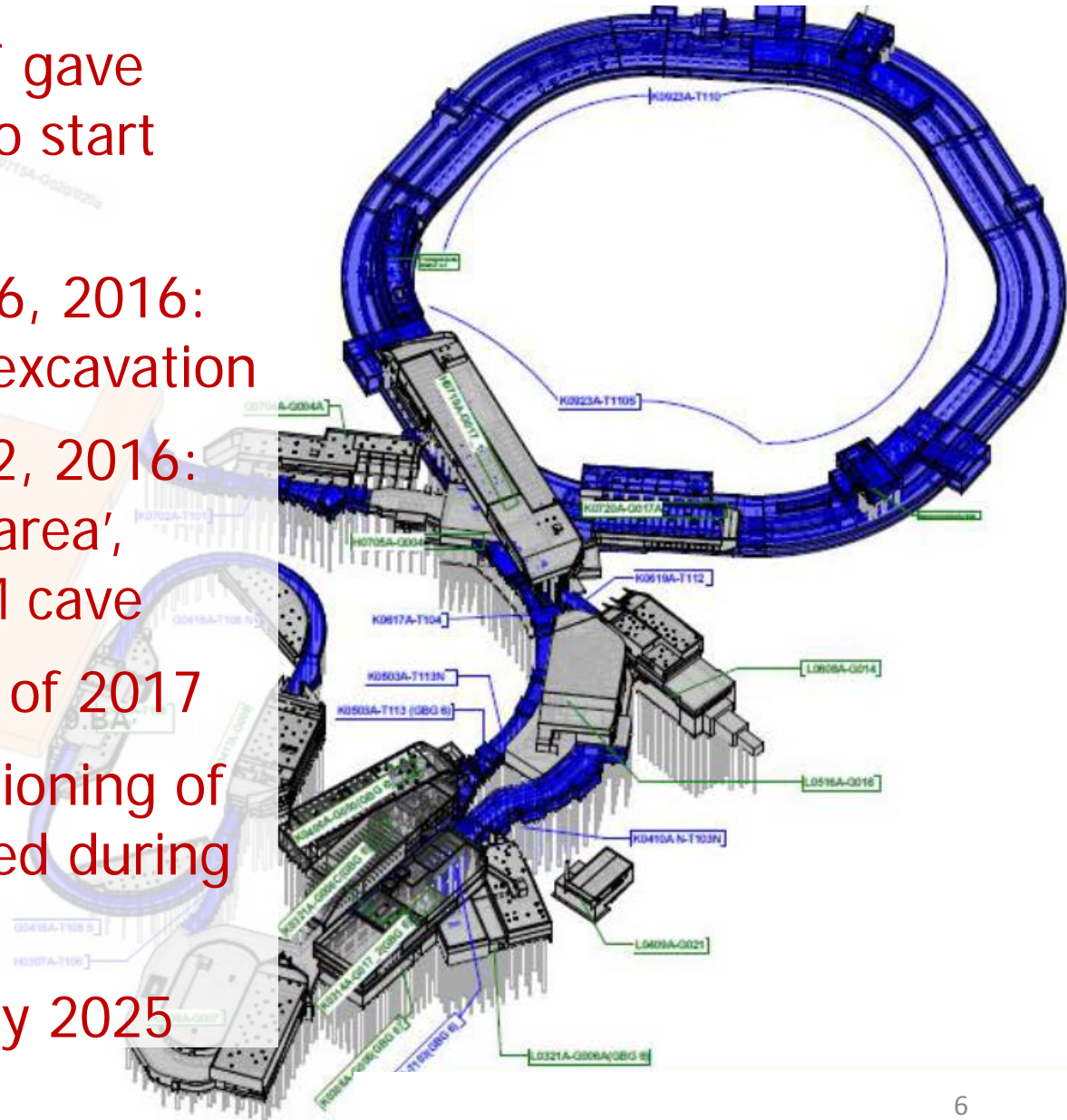
1st call for tender Sept. 26, 2016: water management and excavation

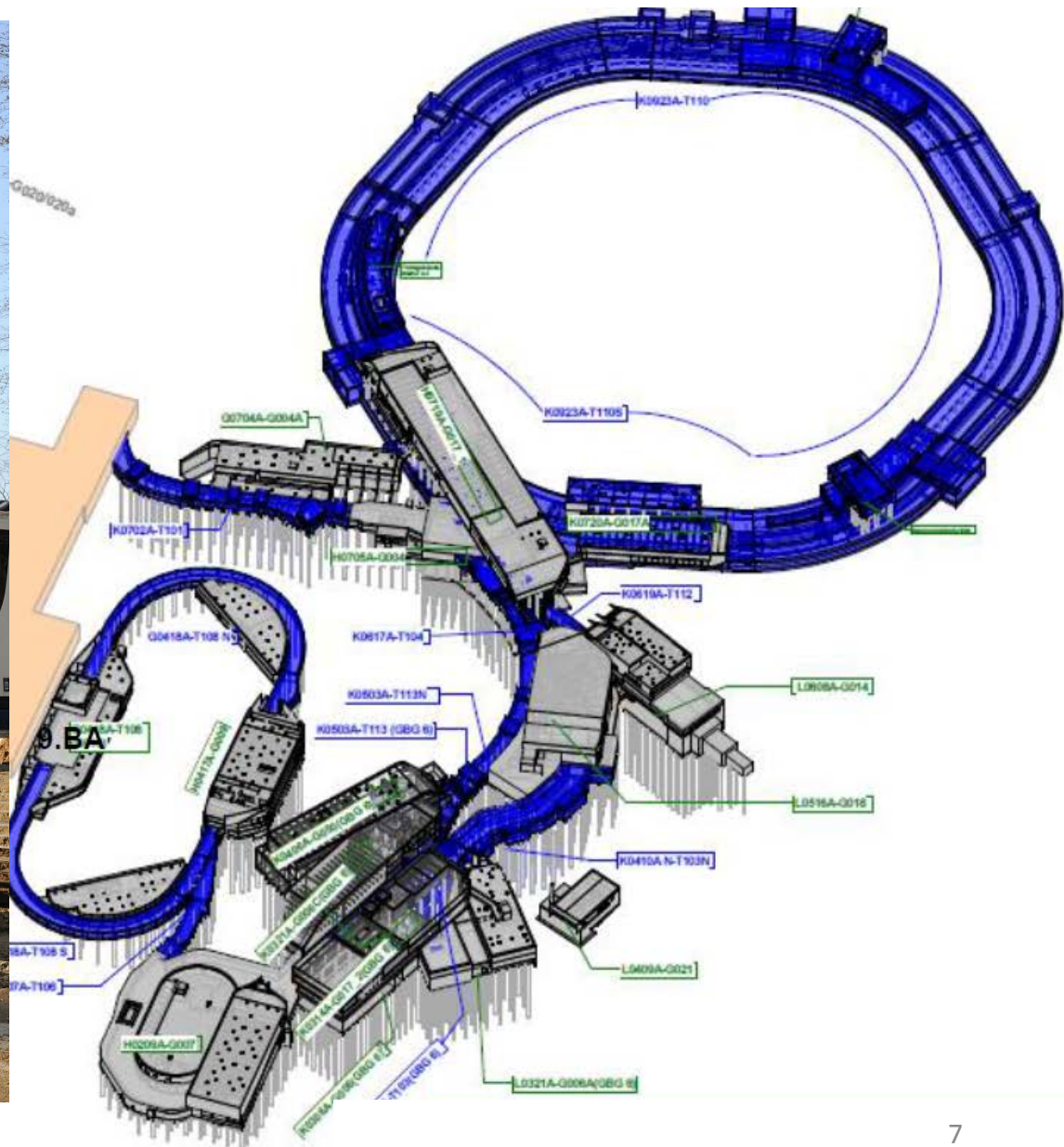
2nd call for tender Nov. 22, 2016: shell construction 'north area', includes SIS100 and CBM cave

Start of construction mid of 2017

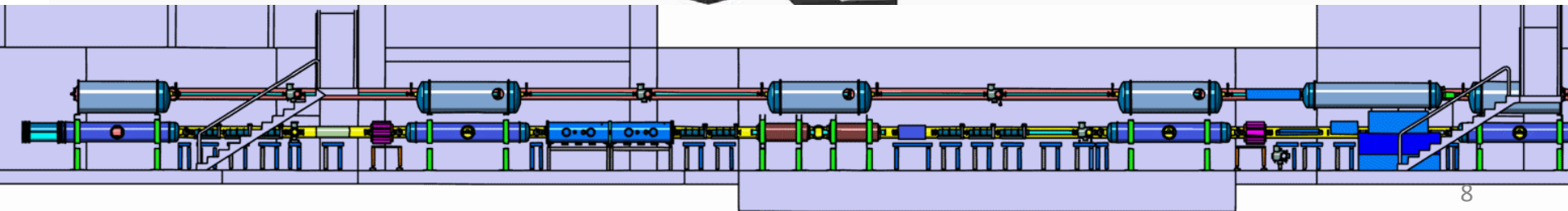
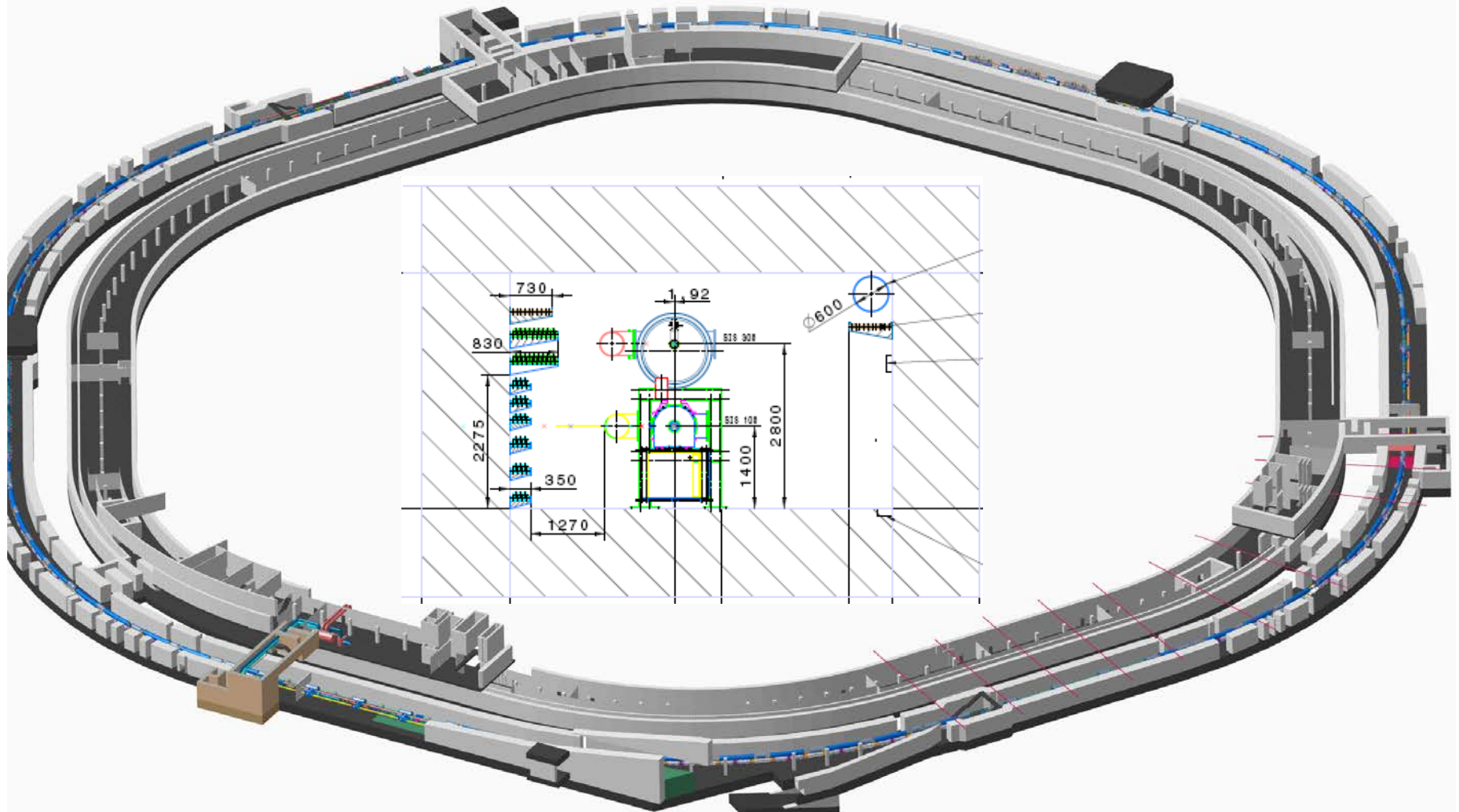
Installation incl. commissioning of the experiments is planned during 2021-2024

Full completion of FAIR by 2025





Tunnel for SIS100/300



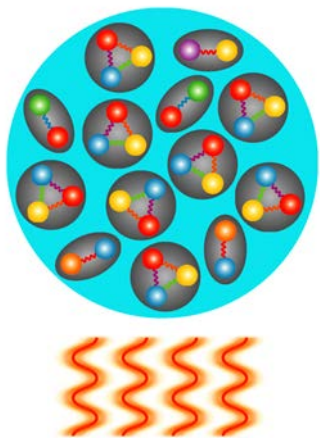
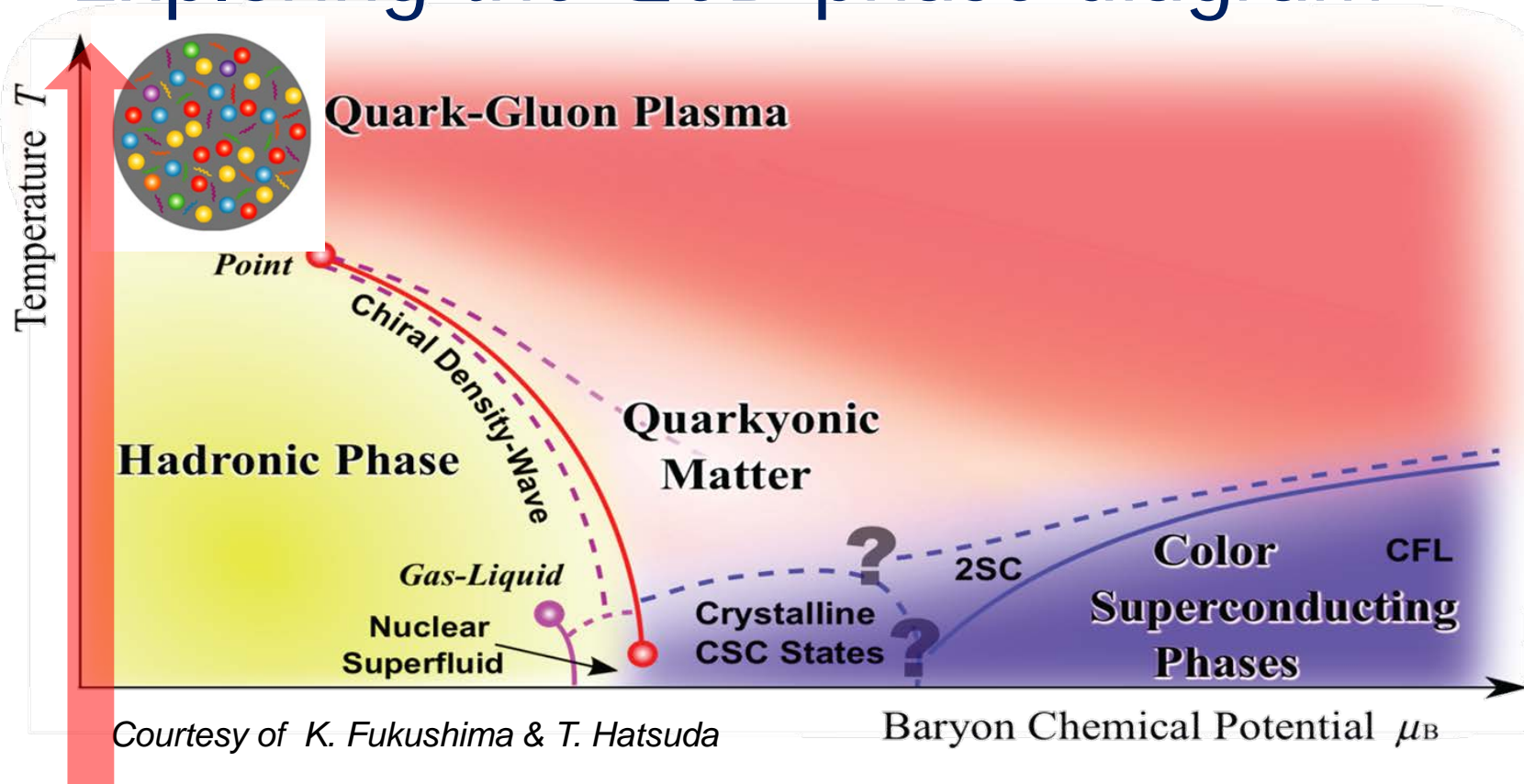
The Compressed Baryonic Matter (CBM) experiment



4000 tons of steel plates
transported from KIT to FAIR
for the CBM beam dump



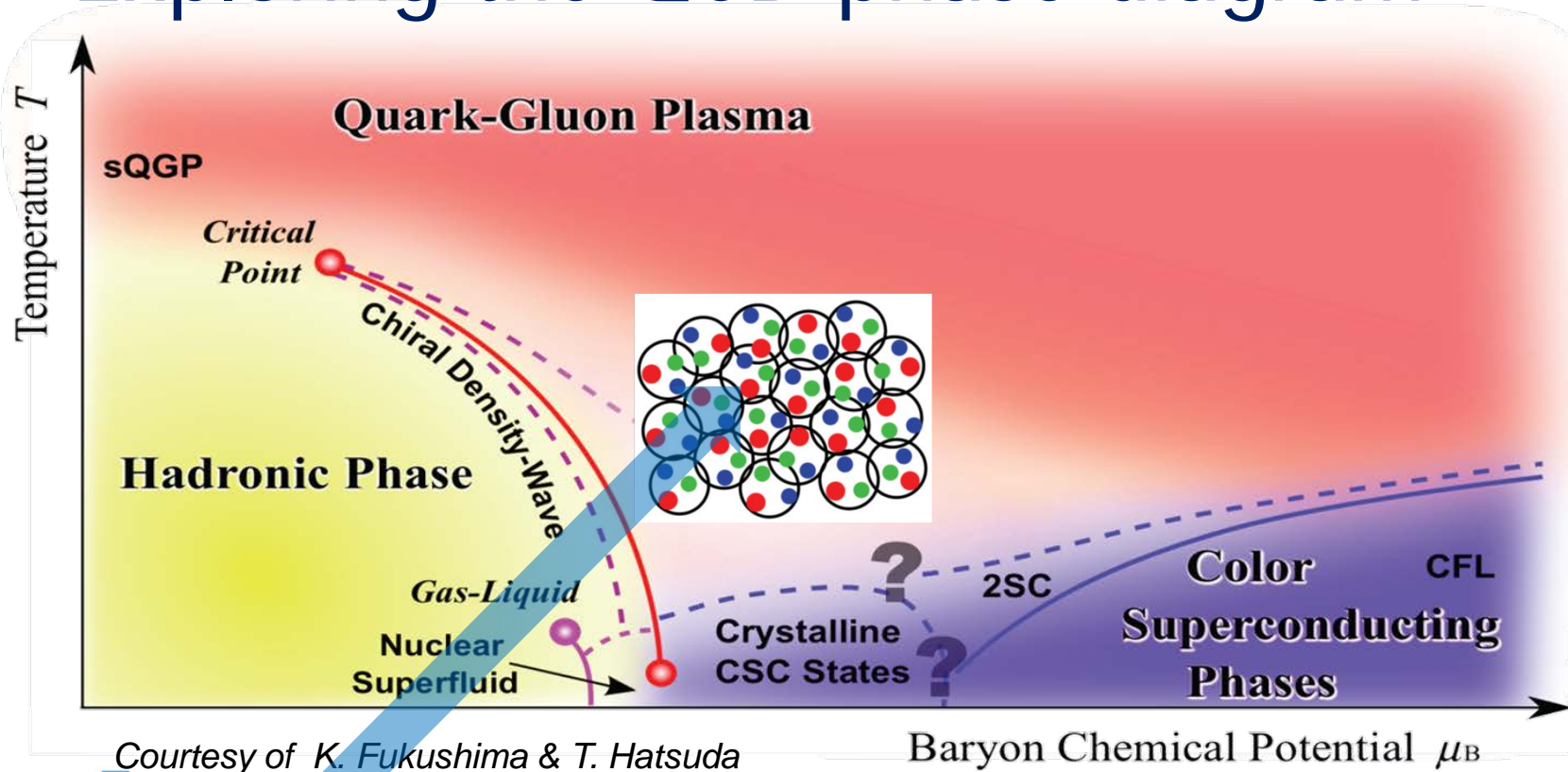
Exploring the QCD phase diagram



At very high temperature:

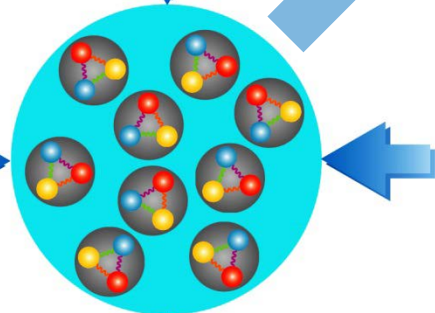
- N of baryons $\approx N$ of antibaryons
Situation similar to early universe
- L-QCD finds crossover transition between hadronic matter and Quark-Gluon Plasma
- Experiments: [ALICE](#), [ATLAS](#), [CMS](#) at LHC
[STAR](#), [PHENIX](#) at RHIC

Exploring the QCD phase diagram



At high baryon density:

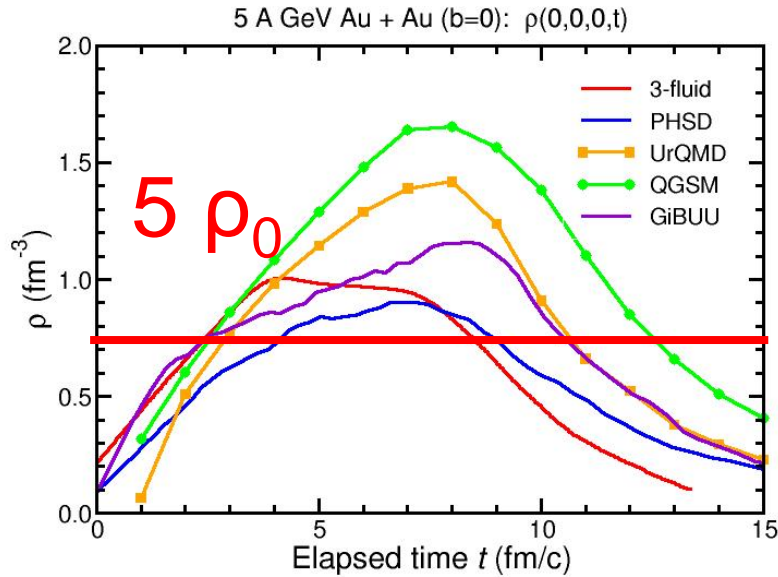
- N of baryons \gg N of antibaryons
Densities like in neutron star cores
- L-QCD not (yet) applicable
- Models predict first order phase transition with mixed or exotic phases
- Experiments: **BES at RHIC, NA61 at CERN SPS, CBM at FAIR, NICA at JINR, J-PARC**



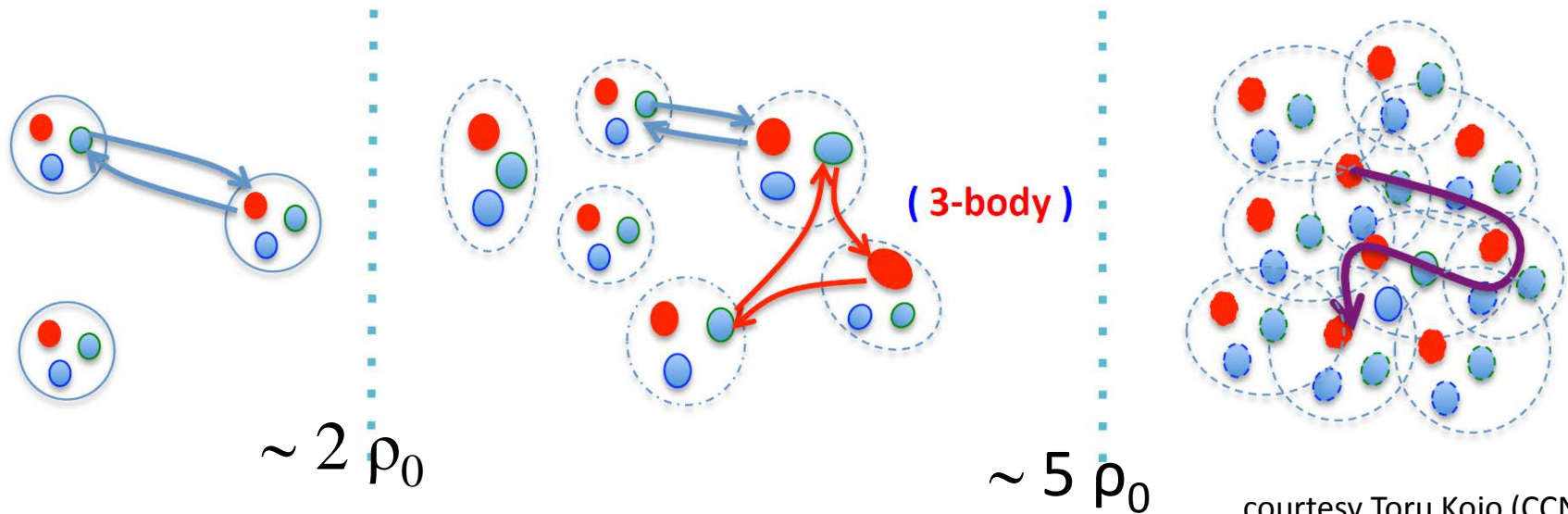
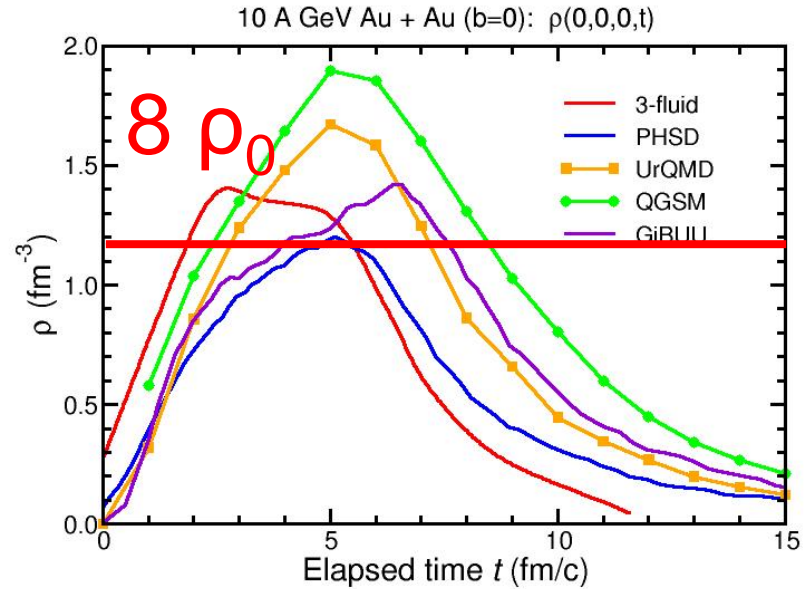
Baryon densities in central Au+Au collisions

I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007)

5 A GeV



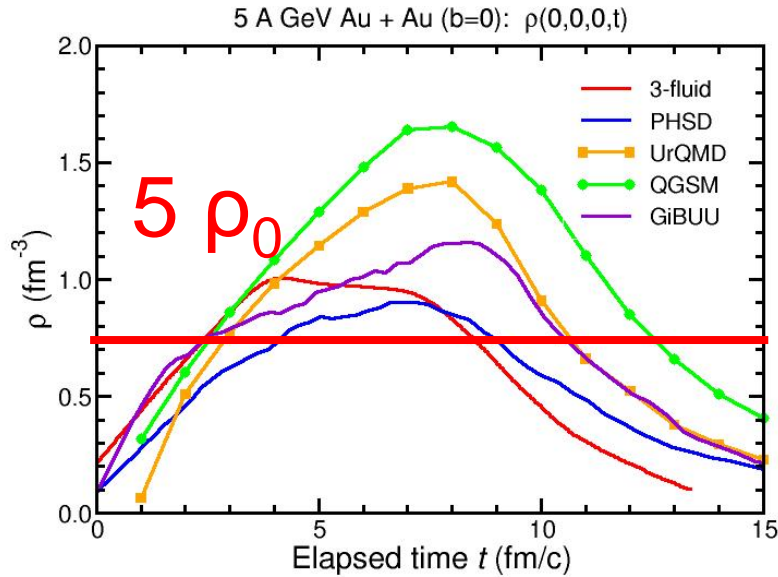
10 A GeV



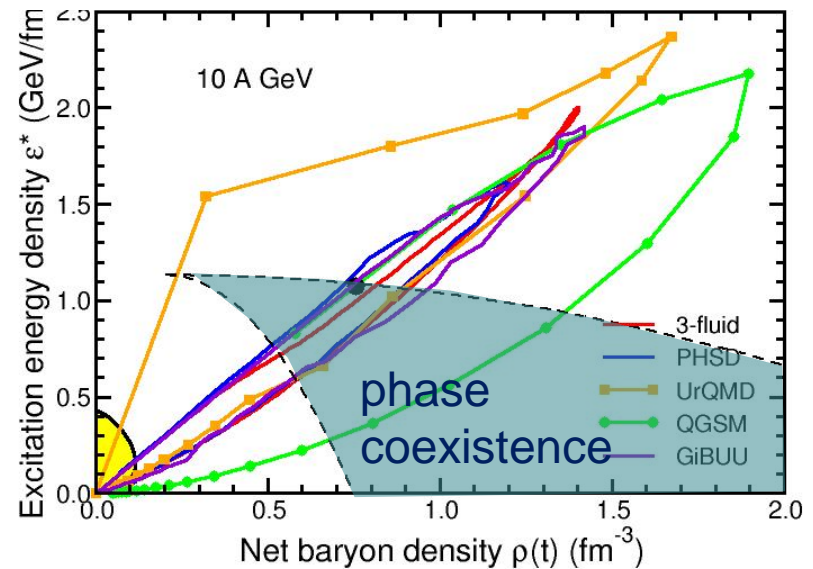
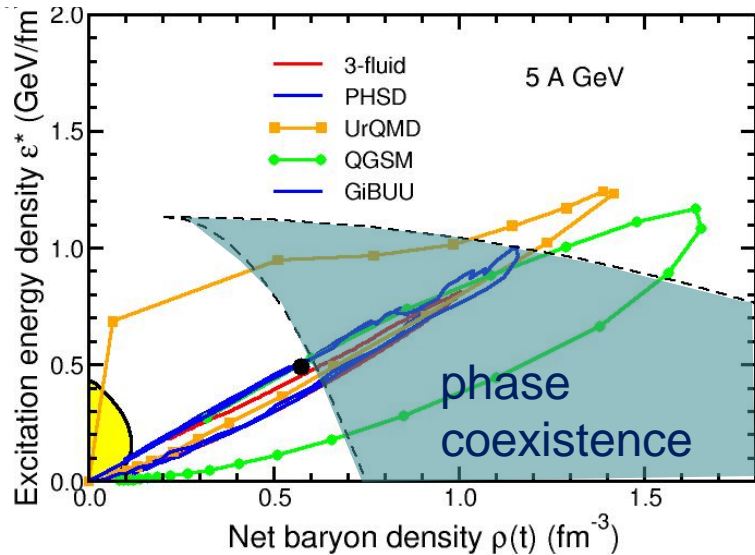
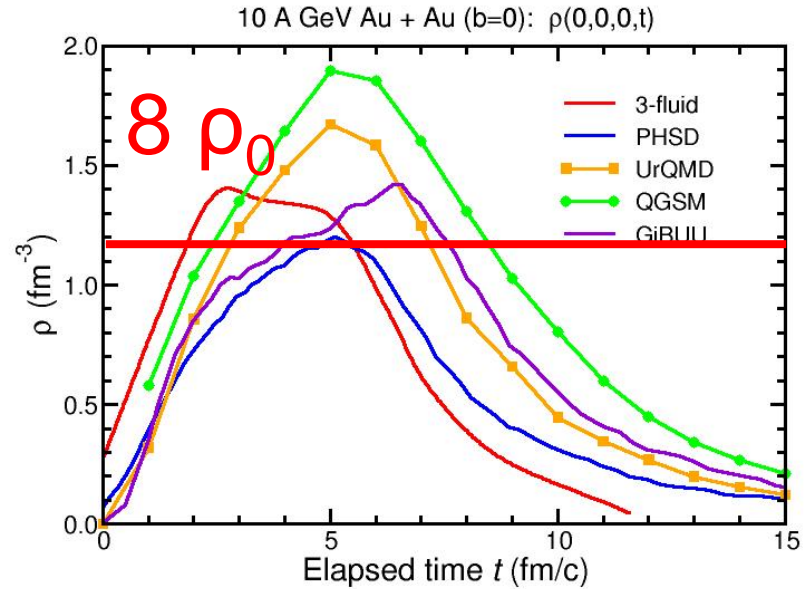
Baryon densities in central Au+Au collisions

I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007)

5 A GeV



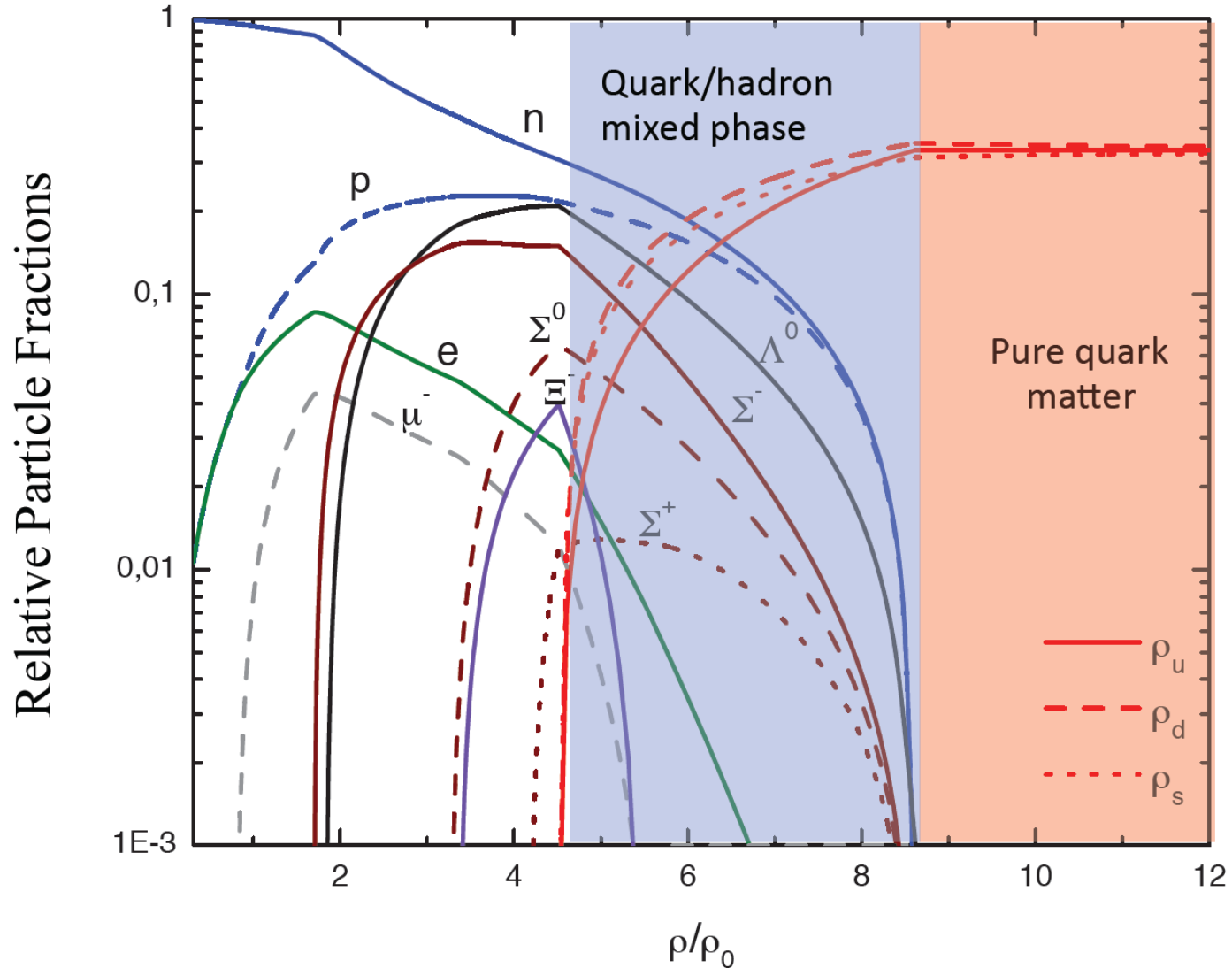
10 A GeV



Quark matter in massive neutron stars?

M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657

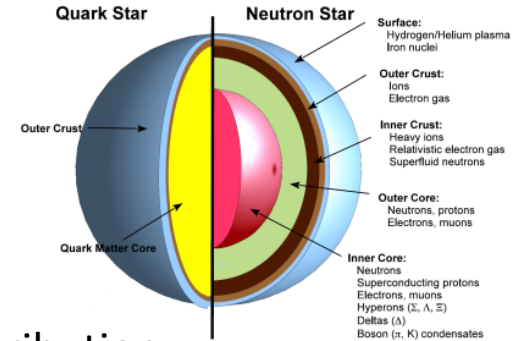
Phys. Rev. C 89, 015806, 2014



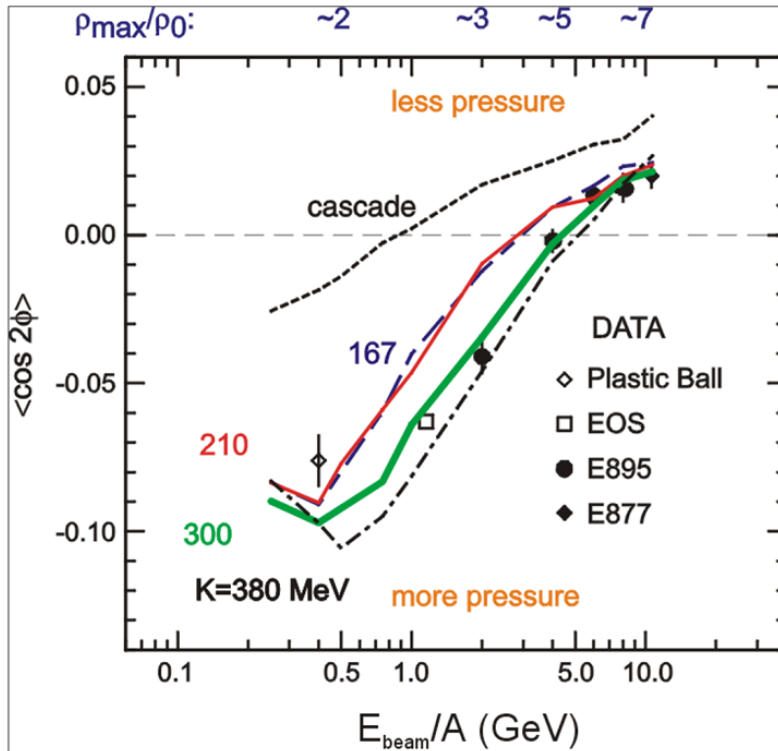
CBM physics case and observables

The QCD matter equation-of-state at neutron star core densities

- collective flow of identified particles ($\pi, K, p, \Lambda, \Xi, \Omega, \dots$) driven by the pressure gradient in the early fireball

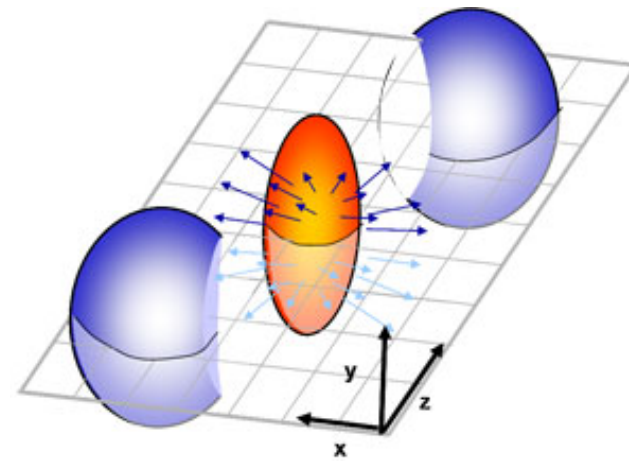


AGS: proton flow in Au+Au collisions



Azimuthal angle distribution:

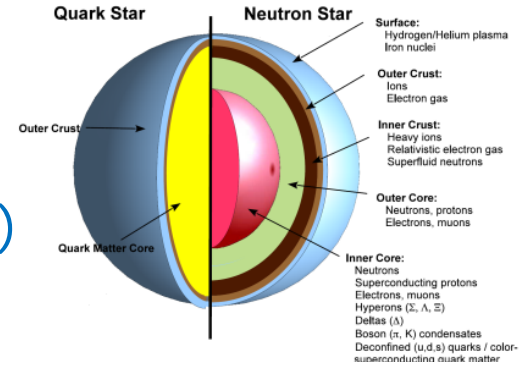
$$dN/d\phi = C (1 + v_1 \cos(\phi) + v_2 \cos(2\phi) + \dots)$$



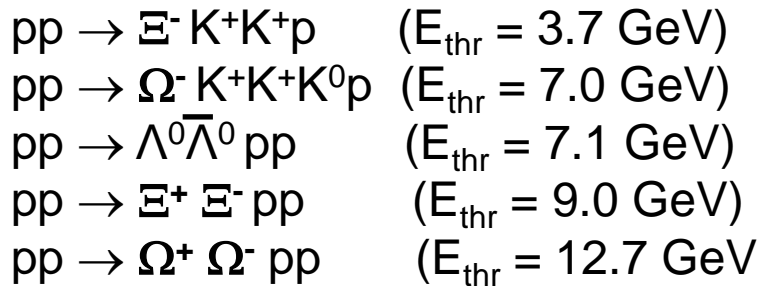
CBM physics case and observables

The QCD matter equation-of-state at neutron star core densities

- collective flow of identified particles ($\pi, K, p, \Lambda, \Xi, \Omega, \dots$) driven by the pressure gradient in the early fireball
- particle production at (sub)threshold energies via multi-step processes (multi-strange hyperons, charm)



Direct multi-strange hyperon production:



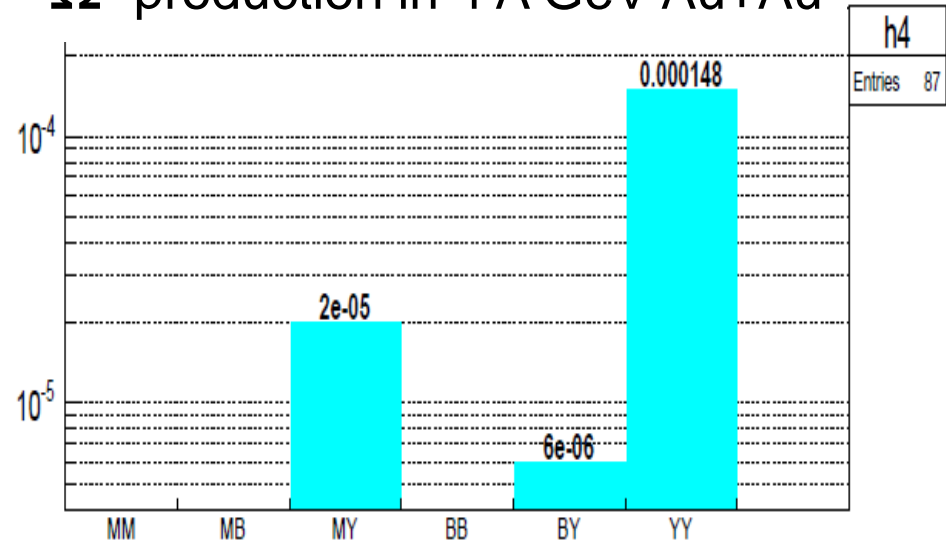
Hyperon production via multiple collisions

- $pp \rightarrow K^+ \Lambda^0 p, \quad pp \rightarrow K^+ K^- pp,$
- $p \Lambda^0 \rightarrow K^+ \Xi^- p, \quad \pi \Lambda^0 \rightarrow K^+ \Xi^- \pi,$
 $\Lambda^0 \Lambda^0 \rightarrow \Xi^- p, \quad \Lambda^0 K^- \rightarrow \Xi^- \pi^0$
- $\Lambda^0 \Xi^- \rightarrow \Omega^- n, \quad \Xi^- K^- \rightarrow \Omega^- \pi^-$

Antihyperons

- $\bar{\Lambda}^0 K^+ \rightarrow \Xi^+ \pi^0,$
- $\Xi^+ K^+ \rightarrow \Omega^+ \pi^+.$

Ω^- production in 4 A GeV Au+Au

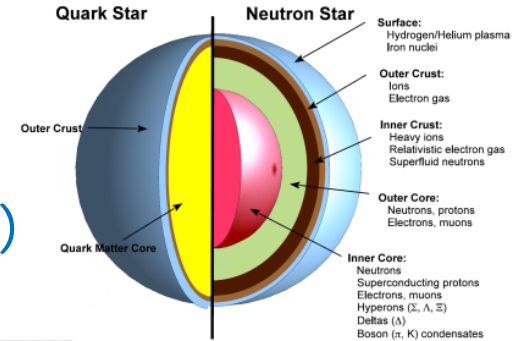


HYPOGSM calculations, K. Gudima et al.

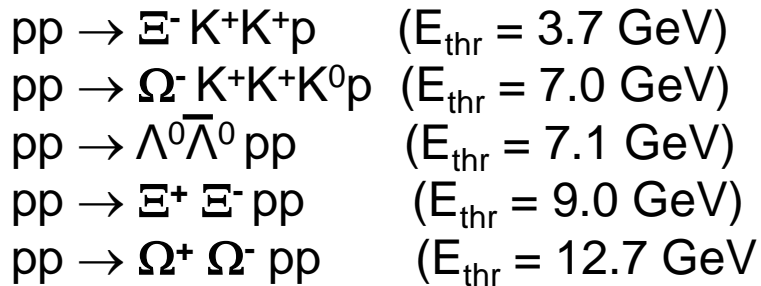
CBM physics case and observables

The QCD matter equation-of-state at neutron star core densities

- collective flow of identified particles ($\pi, K, p, \Lambda, \Xi, \Omega, \dots$) driven by the pressure gradient in the early fireball
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Direct multi-strange hyperon production:

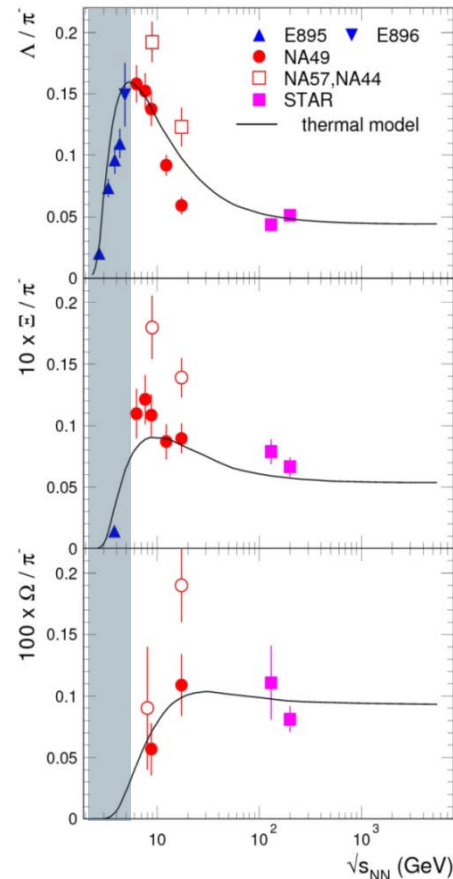


Hyperon production via multiple collisions

1. $pp \rightarrow K^+ \Lambda^0 p$, $pp \rightarrow K^+ K^- pp$,
2. $p \Lambda^0 \rightarrow K^+ \Xi^- p$, $\pi \Lambda^0 \rightarrow K^+ \Xi^- \pi$,
 $\Lambda^0 \Lambda^0 \rightarrow \Xi^- p$, $\Lambda^0 K^- \rightarrow \Xi^- \pi^0$
3. $\Lambda^0 \Xi^- \rightarrow \Omega^- n$, $\Xi^- K^- \rightarrow \Omega^- \pi^-$

Antihyperons

1. $\bar{\Lambda}^0 K^+ \rightarrow \Xi^+ \pi^0$,
2. $\Xi^+ K^+ \rightarrow \Omega^+ \pi^+$.



CBM physics case and observables

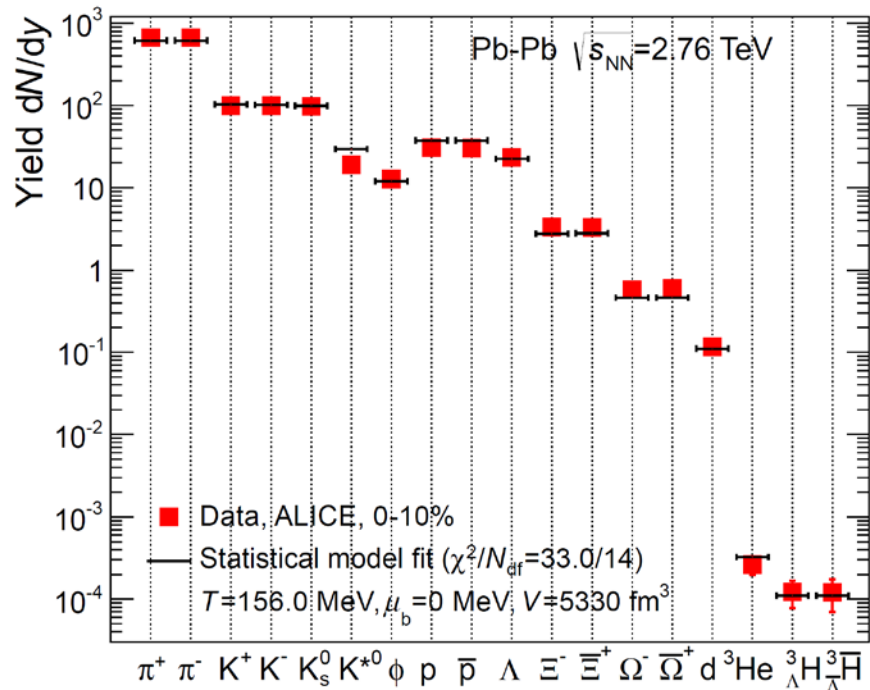
Phase transitions from partonic to hadronic matter

- excitation function of strangeness: $\Xi^-(dss), \Xi^+(\bar{d}\bar{s}\bar{s}), \Omega^-(sss), \Omega^+(\bar{s}\bar{s}\bar{s})$
 → chemical equilibration at the phase boundary

Particle yields and thermal model fits

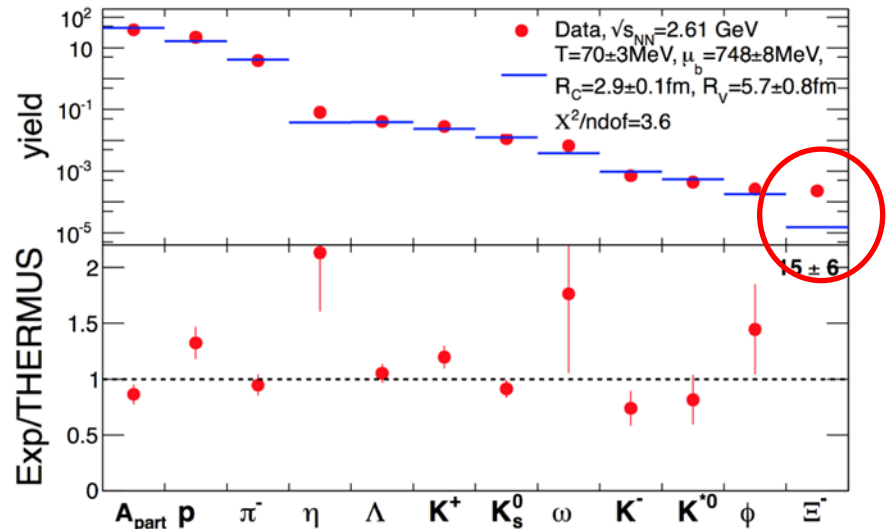
$$n_i = N_i/V = -\frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_i)/T] \pm 1}$$

A. Andronic et al., Jour. Phys. G38 (2011)



HADES: Ar + KCl 1.76 A GeV

G. Agakishiev et al., arXiv:1512.07070



CBM physics case and observables

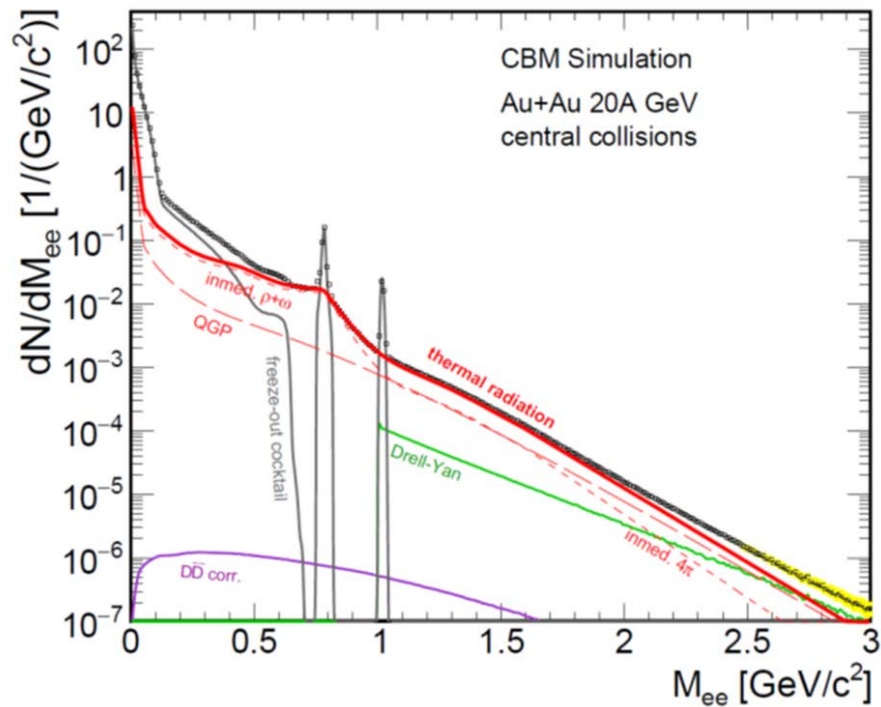
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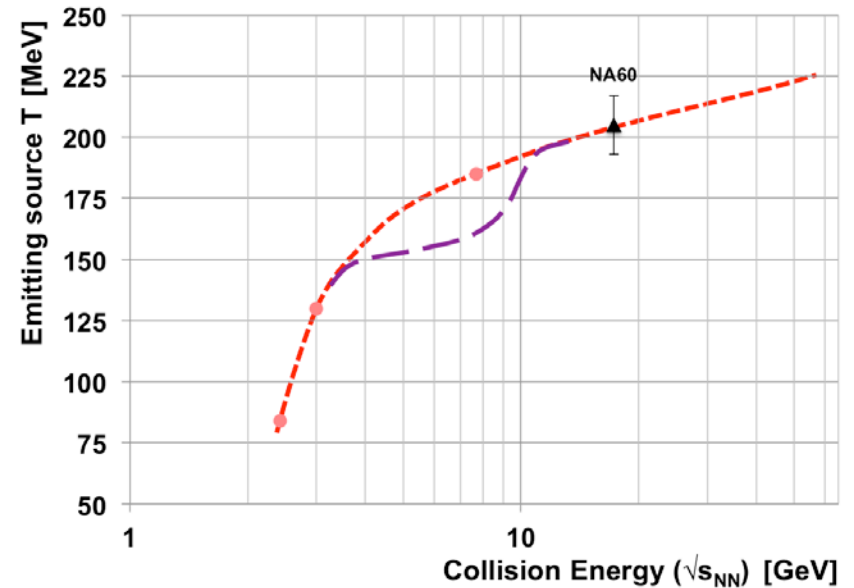
Phase coexistence

- excitation function (invariant mass) of lepton pairs:
thermal radiation from QGP, caloric curve

Invariant mass distribution of lepton pairs



Slope of dilepton invariant mass spectrum
 $1 GeV/c^2 < M_{inv} < 2.5 GeV/c^2$



CBM physics case and observables

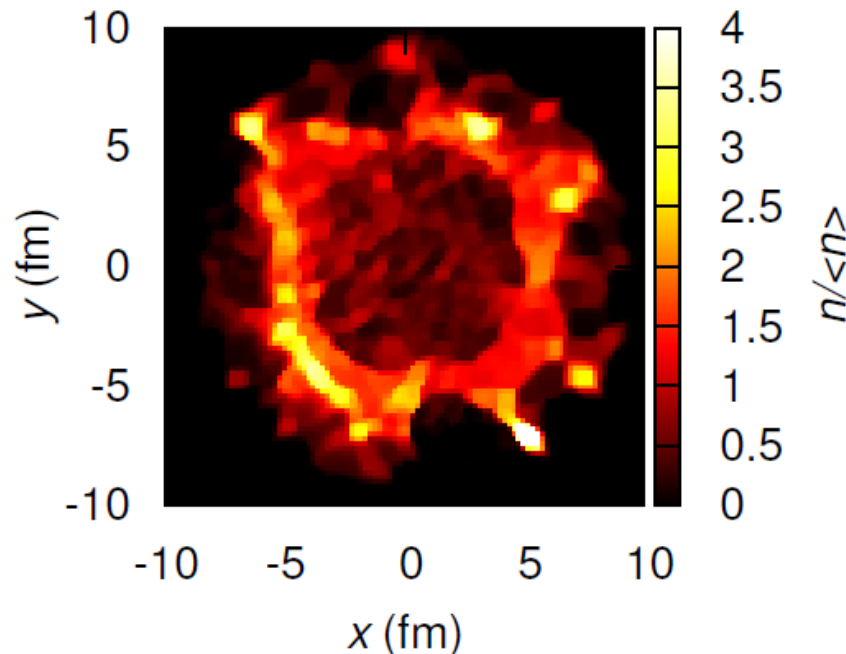
Phase transitions from partonic to hadronic matter

- excitation function of strangeness: $\Xi^-(dss), \Xi^+(\bar{d}\bar{s}\bar{s}), \Omega^-(sss), \Omega^+(\bar{s}\bar{s}\bar{s})$
→ chemical equilibration at the phase boundary

Phase coexistence

- excitation function (invariant mass) of lepton pairs:
thermal radiation from QGP, caloric curve
- anisotropic azimuthal angle distributions: “spinodal decomposition”

Spinodal decomposition of the mixed phase: net baryon number density fluctuations



C. Herold, M. Nahrgang, I. Mishustin, M. Bleicher
Nuclear Physics A 925 (2014) 14

Jan Steinheimer, Jorgen Randrup
Phys. Rev. C 87, 054903 (2013)
Eur. Phys. J. A (2016) 52: 239

CBM physics case and observables

Phase transitions from partonic to hadronic matter

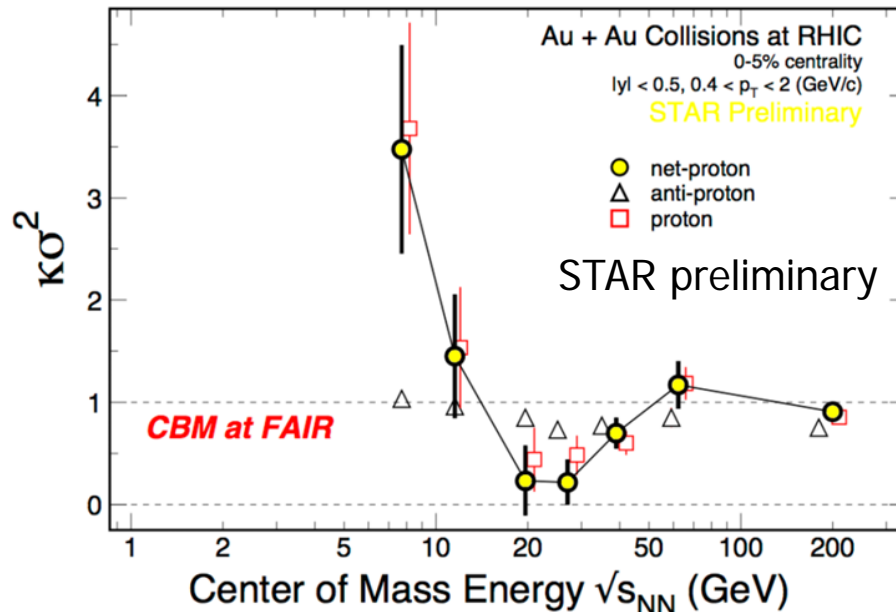
- excitation function of strangeness: $\Xi^-(dss), \Xi^+(dss), \Omega^-(sss), \Omega^+(sss)$
→ chemical equilibration at the phase boundary

Phase coexistence

- excitation function (invariant mass) of lepton pairs:
thermal radiation from QGP, caloric curve
- anisotropic azimuthal angle distributions: “spinodal decomposition”

Critical point

- event-by-event fluctuations of conserved quantities (B,S,Q)
“critical opalescence”

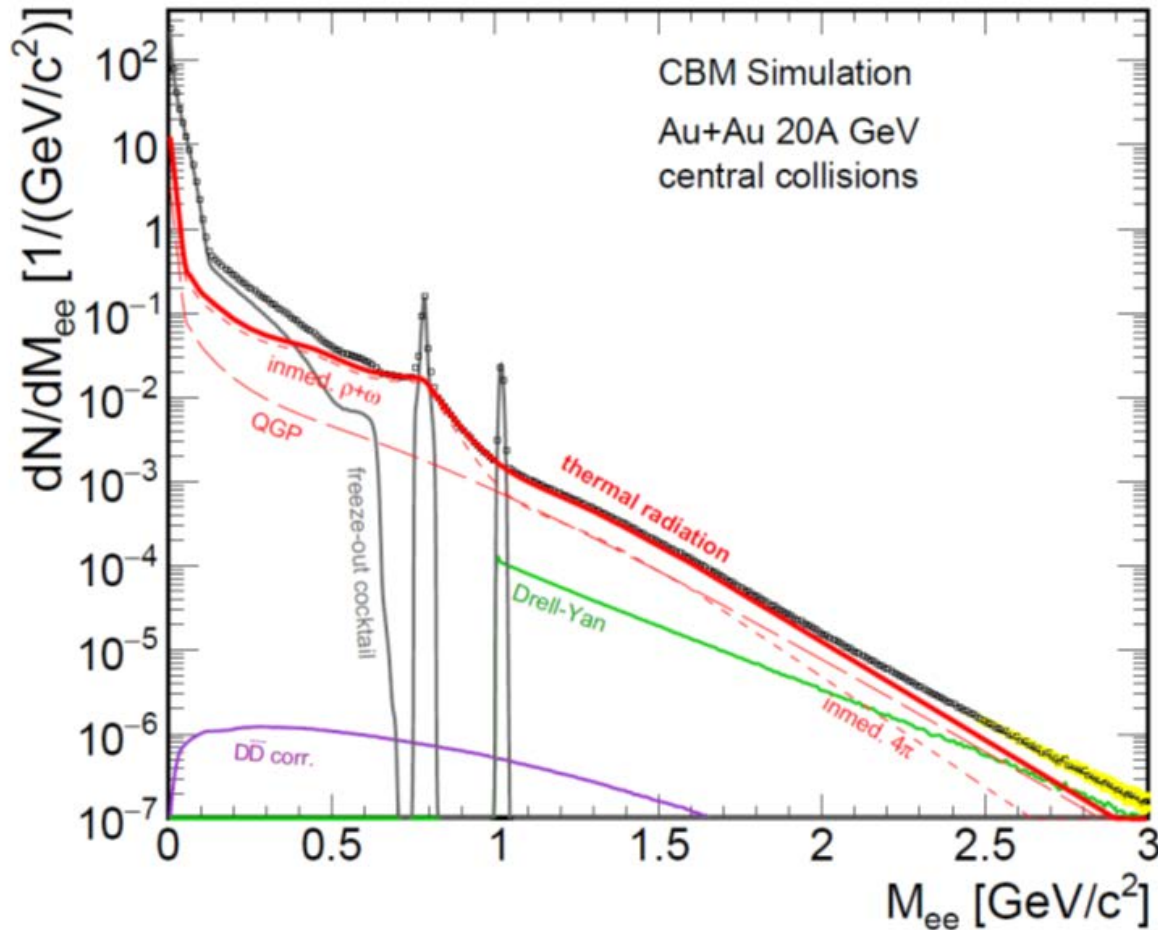


4th moment of net-proton
multiplicity distribution:
critical fluctuations

CBM physics case and observables

Onset of chiral symmetry restoration at high ρ_B

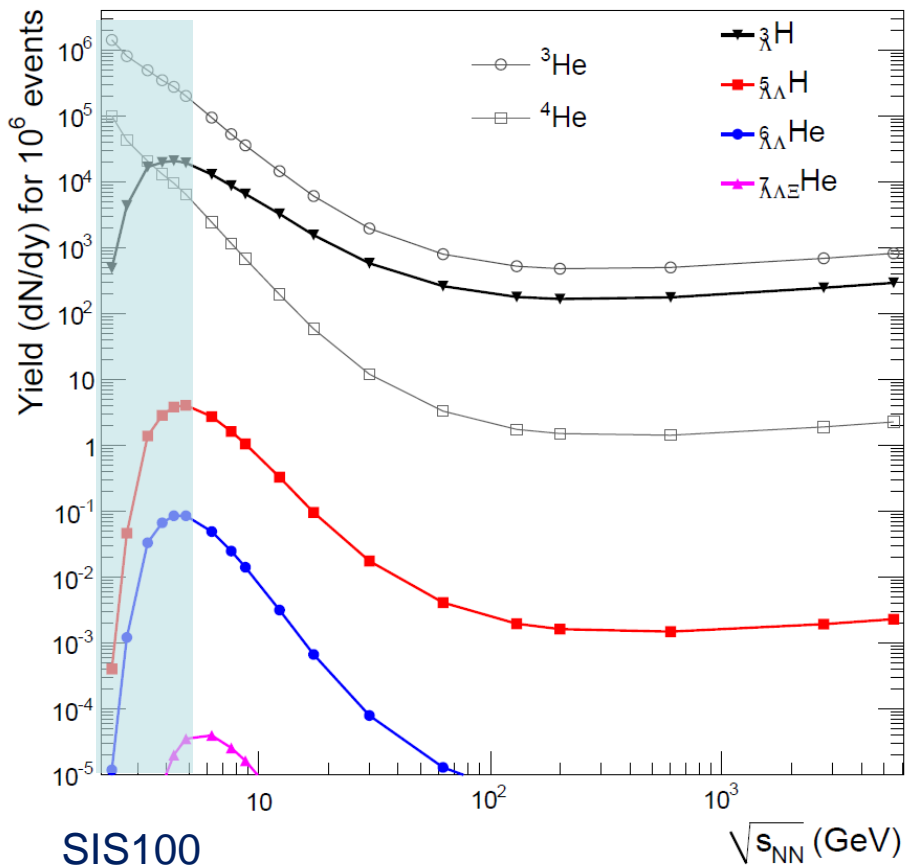
- in-medium modifications of hadrons: $\rho, \omega, \phi \rightarrow e^+e^-(\mu^+\mu^-)$
- dileptons at intermediate invariant masses: $4\pi \rightarrow \rho\text{-}a_1$ chiral mixing



CBM physics case and observables

N- Λ , Λ - Λ interaction, strange matter?

- (double-) lambda hypernuclei
- meta-stable objects (e.g. strange dibaryons)



Double lambda hypernuclei production in central Au+Au collisions at 10 A GeV:

	Multiplicity	Yield in 1 week
${}^5_{\Lambda\Lambda}\text{H}$	$5 \cdot 10^{-6}$	3000
${}^6_{\Lambda\Lambda}\text{He}$	$1 \cdot 10^{-7}$	60

Assumption for yield calculation:

Reaction Rate 1 MHz

BR 10% (2 sequential weak decays)

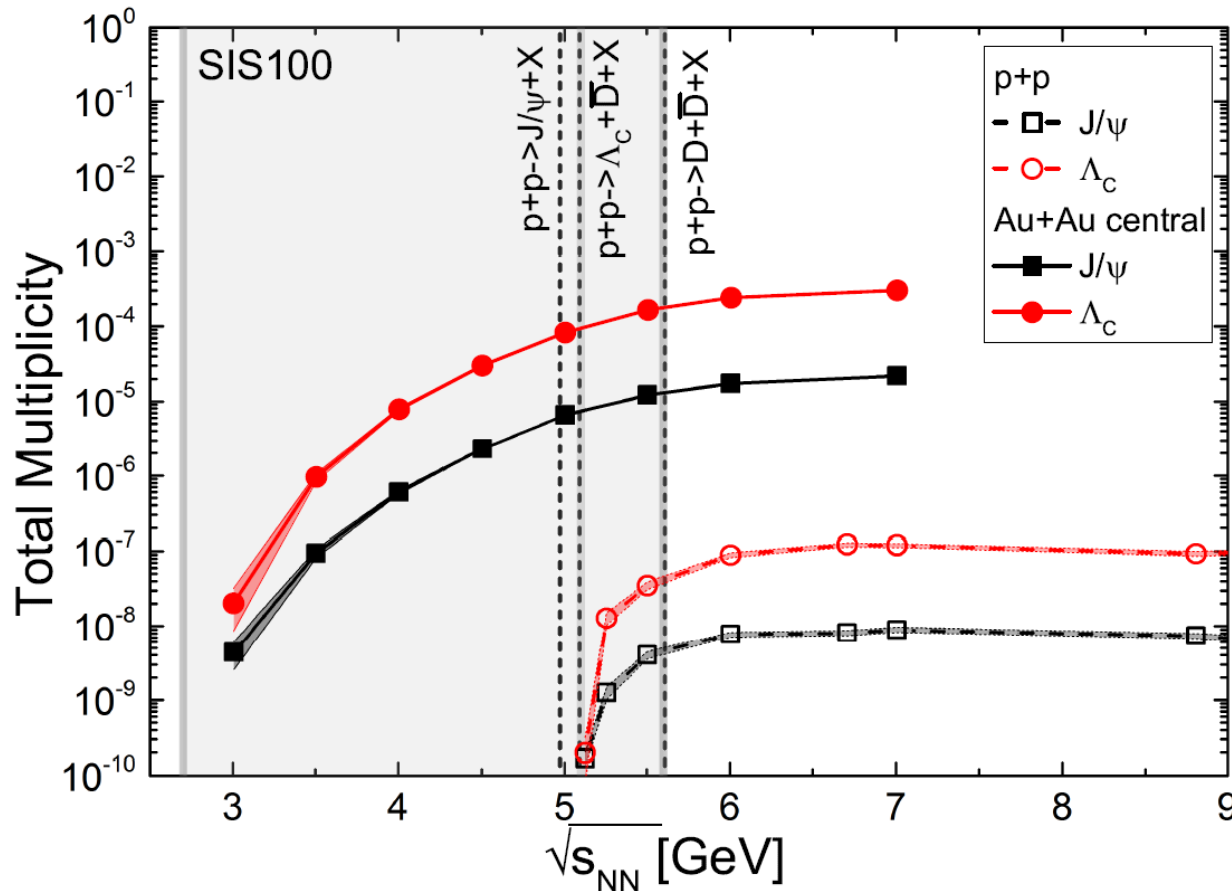
Efficiency 1%

CBM physics case and observables

Charm production at threshold energies in cold and dense matter

➤ excitation function of charm production in p+A and A+A (J/ψ , D^0 , D^\pm)

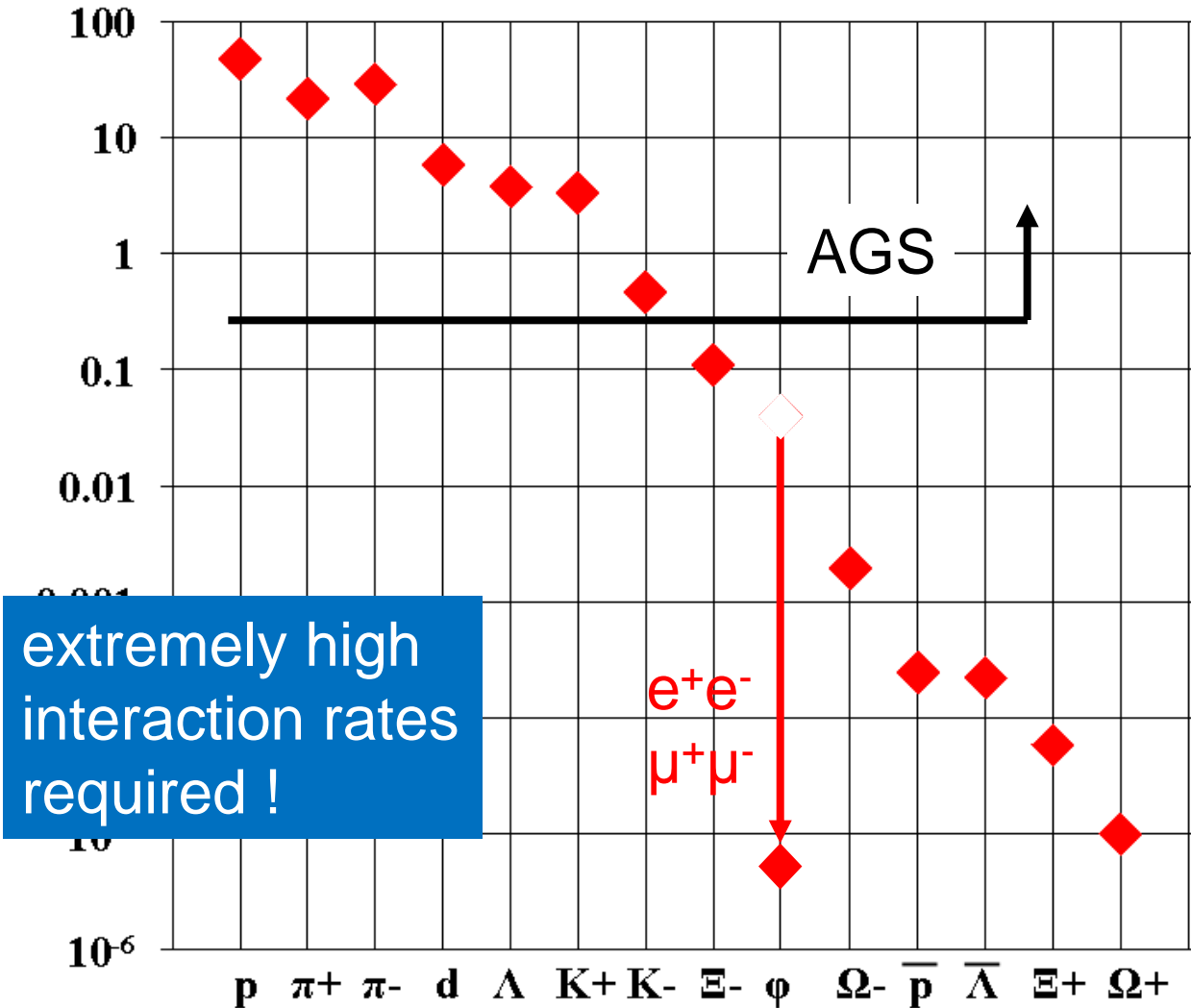
UrQMD calculation including subthreshold charm production via
 $N^* \rightarrow \Lambda_c + D$ and $N^* \rightarrow N + J/\psi$



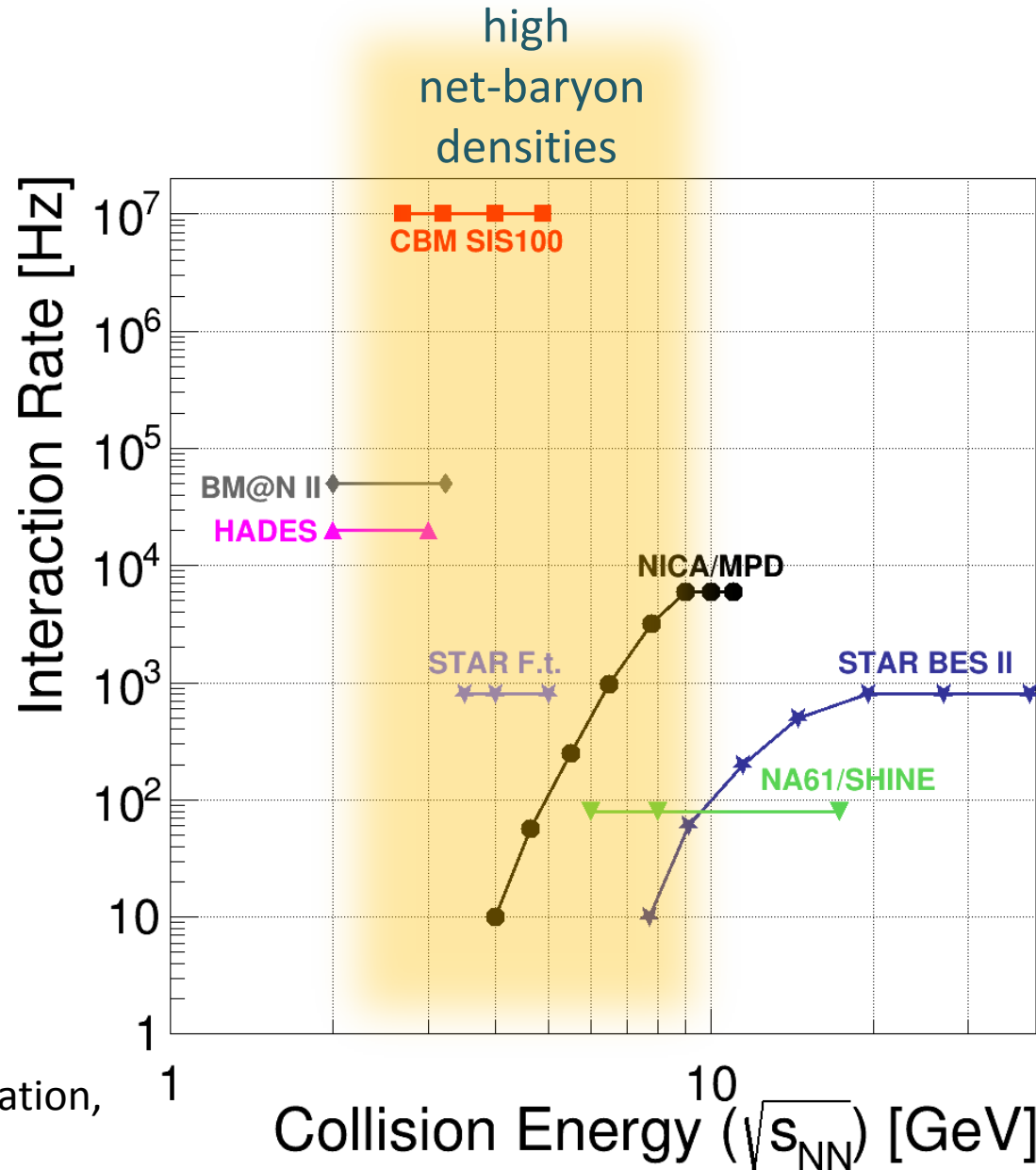
Experimental challenges

Particle yields in central Au+Au 4 A GeV

Multiplicity Statistical model, A. Andronic, priv. com.



Experiments exploring dense QCD matter



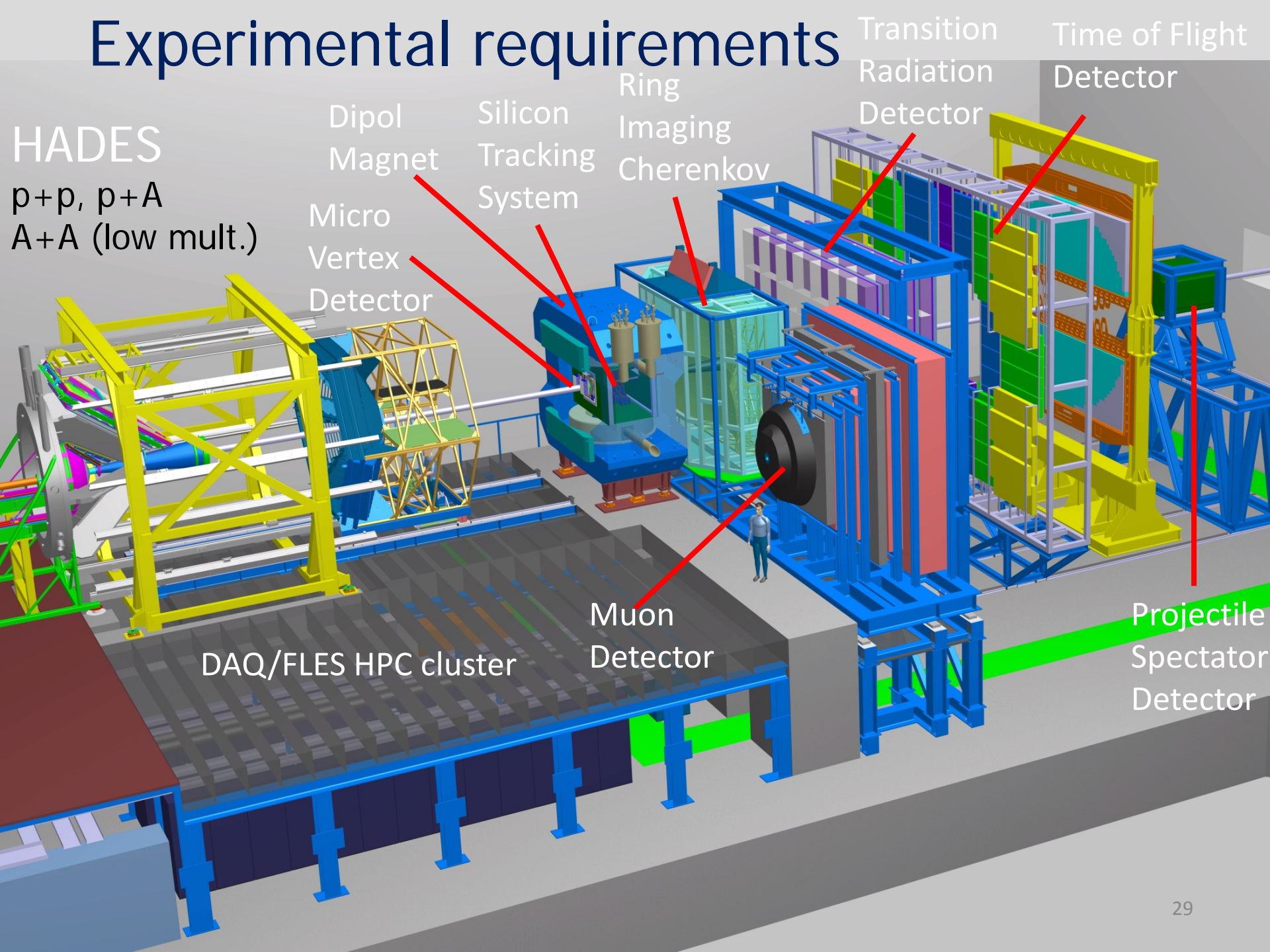
Experimental requirements

- $10^5 - 10^7$ Au+Au reactions/sec
- determination of displaced vertices ($\sigma \approx 50 \mu\text{m}$)
- 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

Experimental requirements

HADES

$p+p$, $p+A$
 $A+A$ (low mult.)



Dipol Magnet

Micro Vertex Detector

Silicon Tracking System

Ring Imaging Cherenkov

Transition Radiation Detector

Time of Flight Detector

DAQ/FLES HPC cluster

Muon Detector

Projectile Spectator Detector

Status experiment preparation

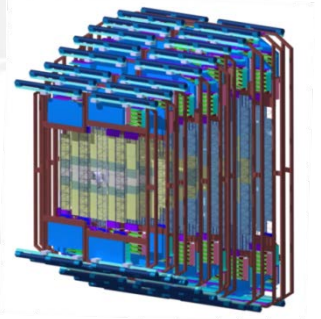
Superconducting Dipole Magnet

- TDR approved
- Funding: Russia
- JINR Dubna, BINP Novosibirsk



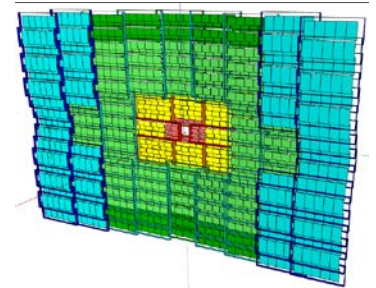
Silicon Tracking System

- TDR approved
- Funding: Germany, Russia, Poland
- GSI, JINR Dubna, KIT, INR Kiev, AGH and UJ Krakow, Univ. Tübingen, Warsaw UT



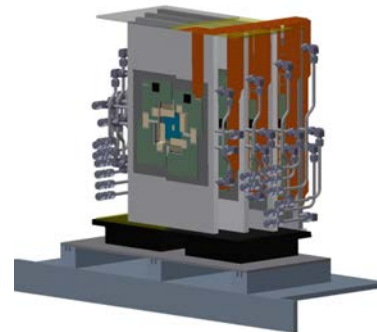
High-rate MRPC TOF wall

- TDR approved
- Funding: Germany, Romania, China, Russia
- THU Beijing, NIPNE Bucharest, GSI Darmstadt, TU Darmstadt, Ifl Frankfurt, USTC Hefei, Univ. Heidelberg, ITEP Moscow, HZDR Rossendorf, CCNU Wuhan



Micro-Vertex Detector

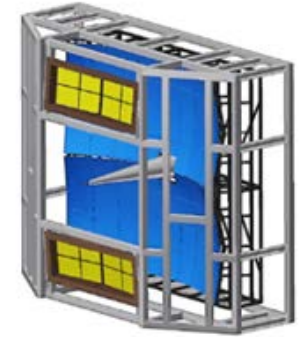
- Funding: Germany, France
- Univ. Frankfurt, IPHC Strasbourg



Status experiment preparation

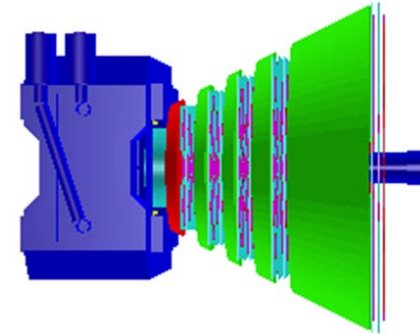
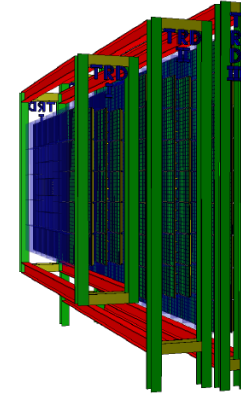
Ring Imaging Cherenkov Detector

- TDR approved
- Funding: Germany, Russia
- Univ. Gießen, Univ. Wuppertal, PNPI Gatchina



Transition Radiation Detector

- Funding: Germany, Romania
- NIPNE Bucharest, Univ. Frankfurt, Univ. Heidelberg, Univ. Münster, WI Budapest

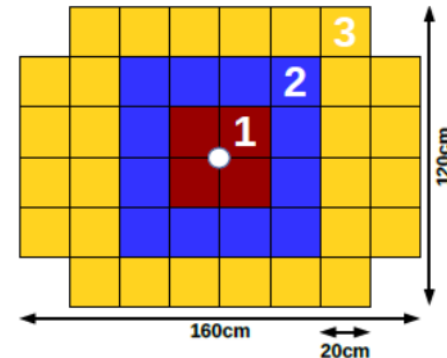


Muon Chambers

- TDR approved
- Funding: India, Russia
- VECC Kolkata + 12 Indian Inst., PNPI Gatchina, JINR Dubna

Projectile-Spectator Detector

- TDR approved
- Funding: Russia, Czechia, Germany
- INR Moscow, Prague, Rez, TU Darmstadt

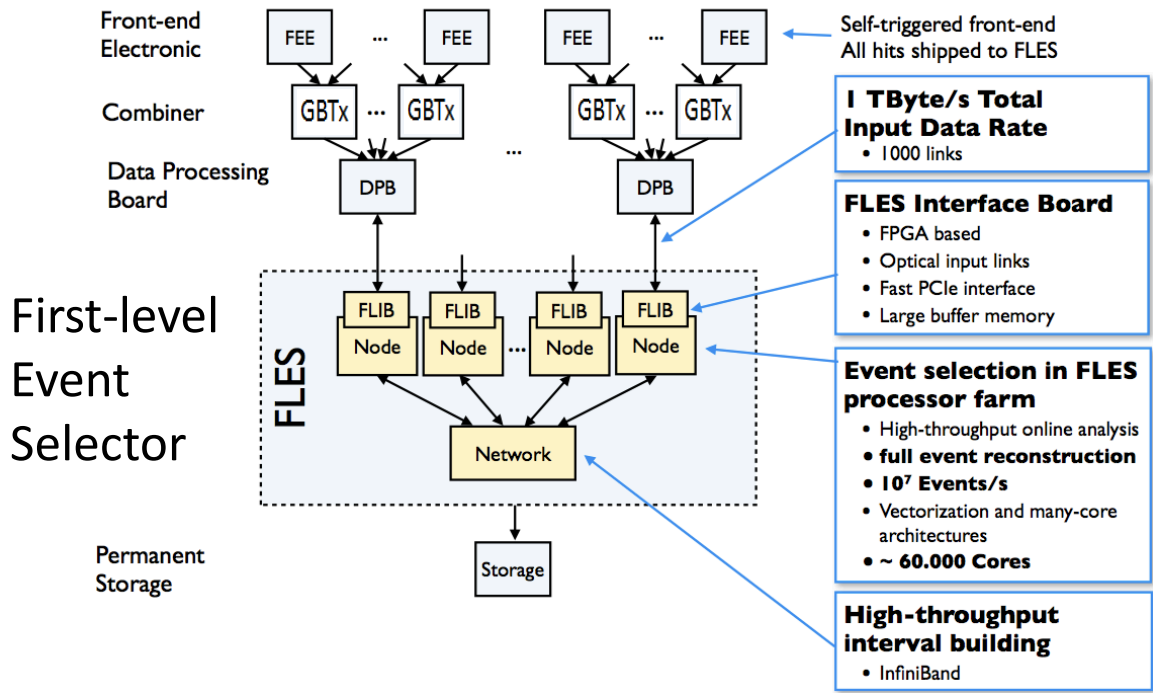


Test beam at CERN Nov. - Dec. 2016

- Prototype TOF, GEM, TRD and diamond detectors with common free-streaming readout system and DAQ successfully tested.
- Pb+Pb collisions with energies of 13, 30 and 160 A GeV.
- Teams from China, Germany, India, Romania



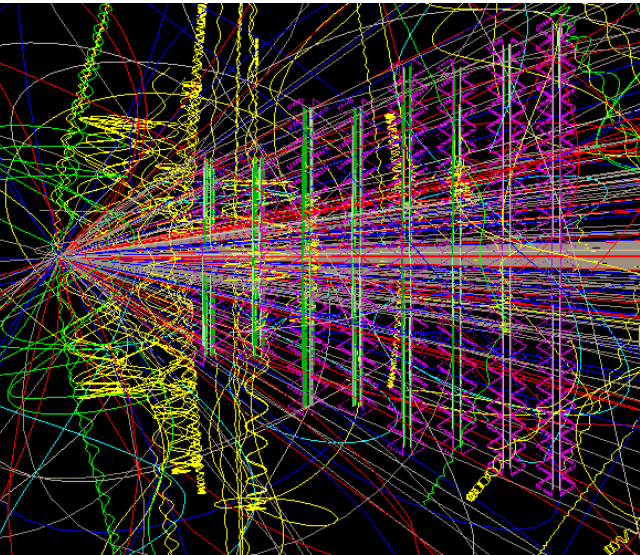
CBM DAQ and online event selection



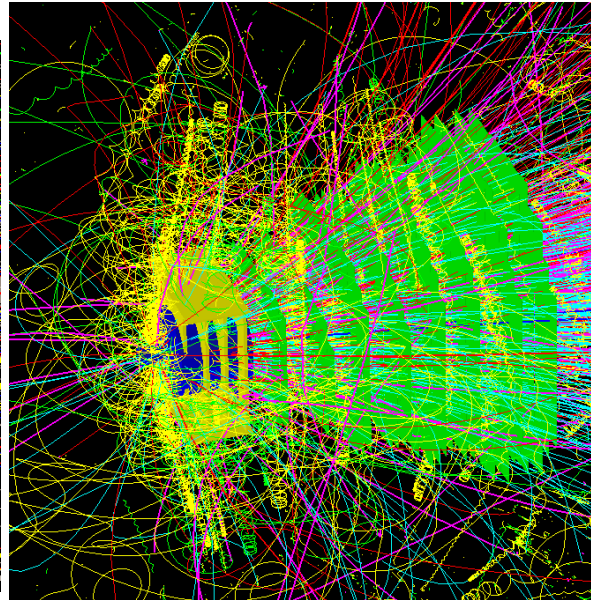
Novel readout system: no hardware trigger on events, detector hits with time stamps, full online 4-D track and event reconstruction.

4D reconstruction

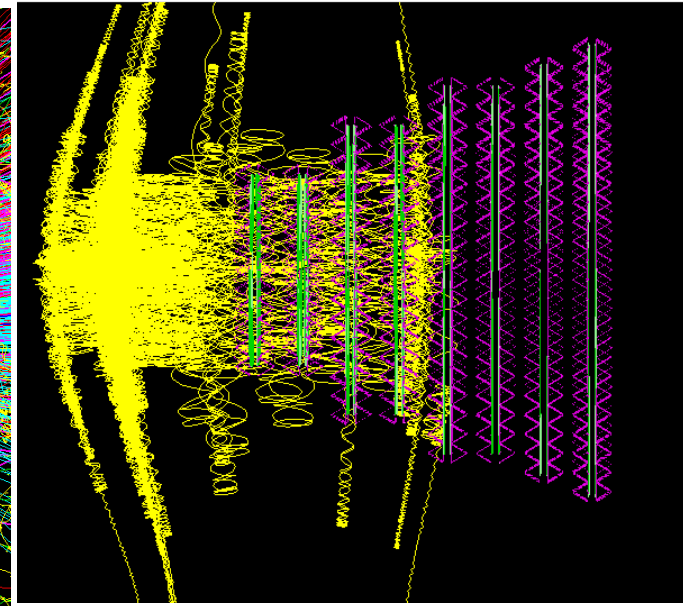
Au+Au 8 A GeV
peripheral collision
UrQMD + GEANT3



Au+Au 8 A GeV
central collision
UrQMD + GEANT3

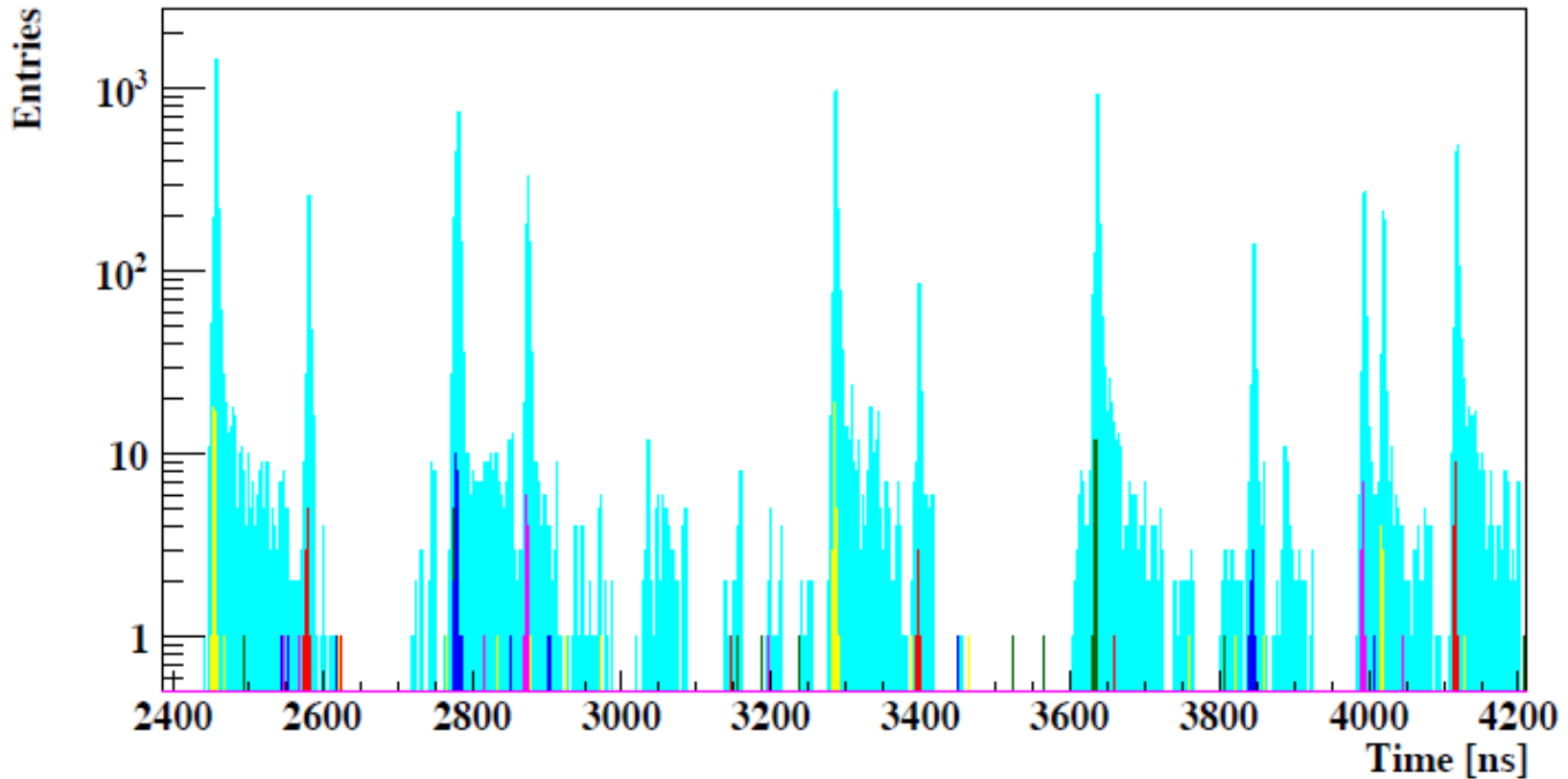


Au beam 8 A GeV
one single ion
passing the target
FairIon + GEANT3



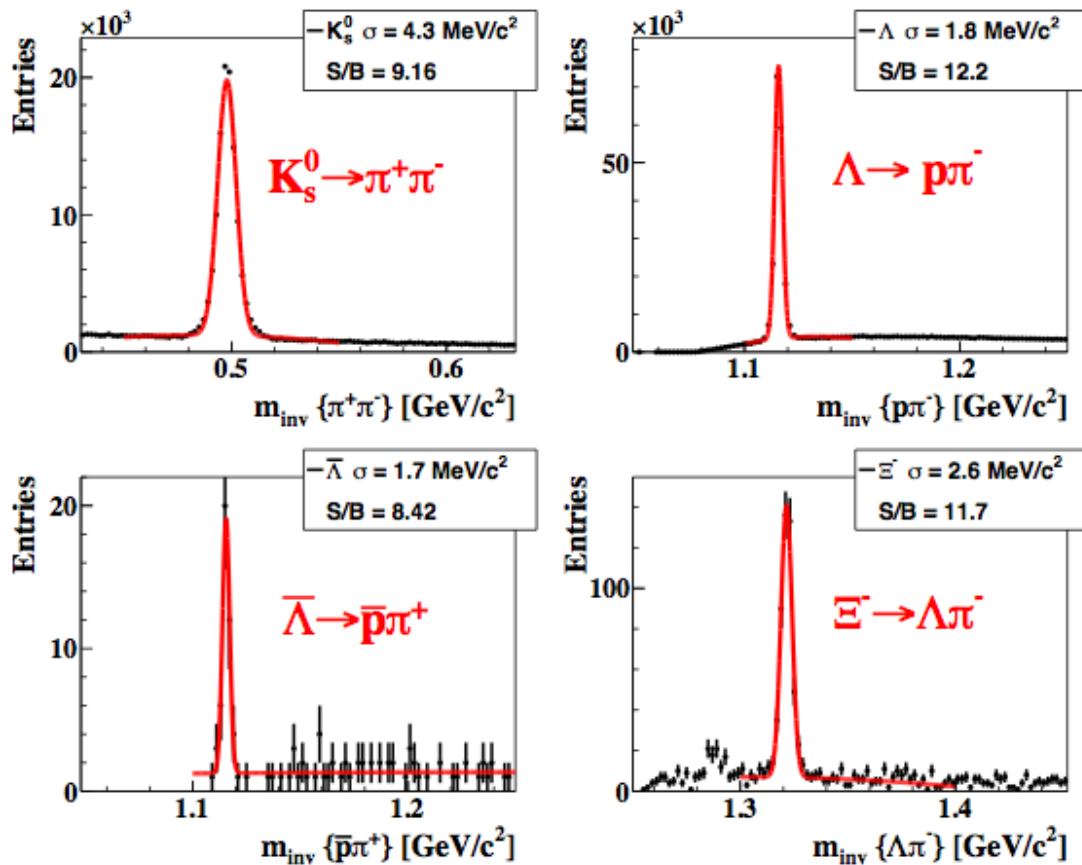
4D reconstruction

Hit and track time distribution for
Au+Au 10 AGeV mbias events at 10 MHz (UrQMD)



4D reconstruction

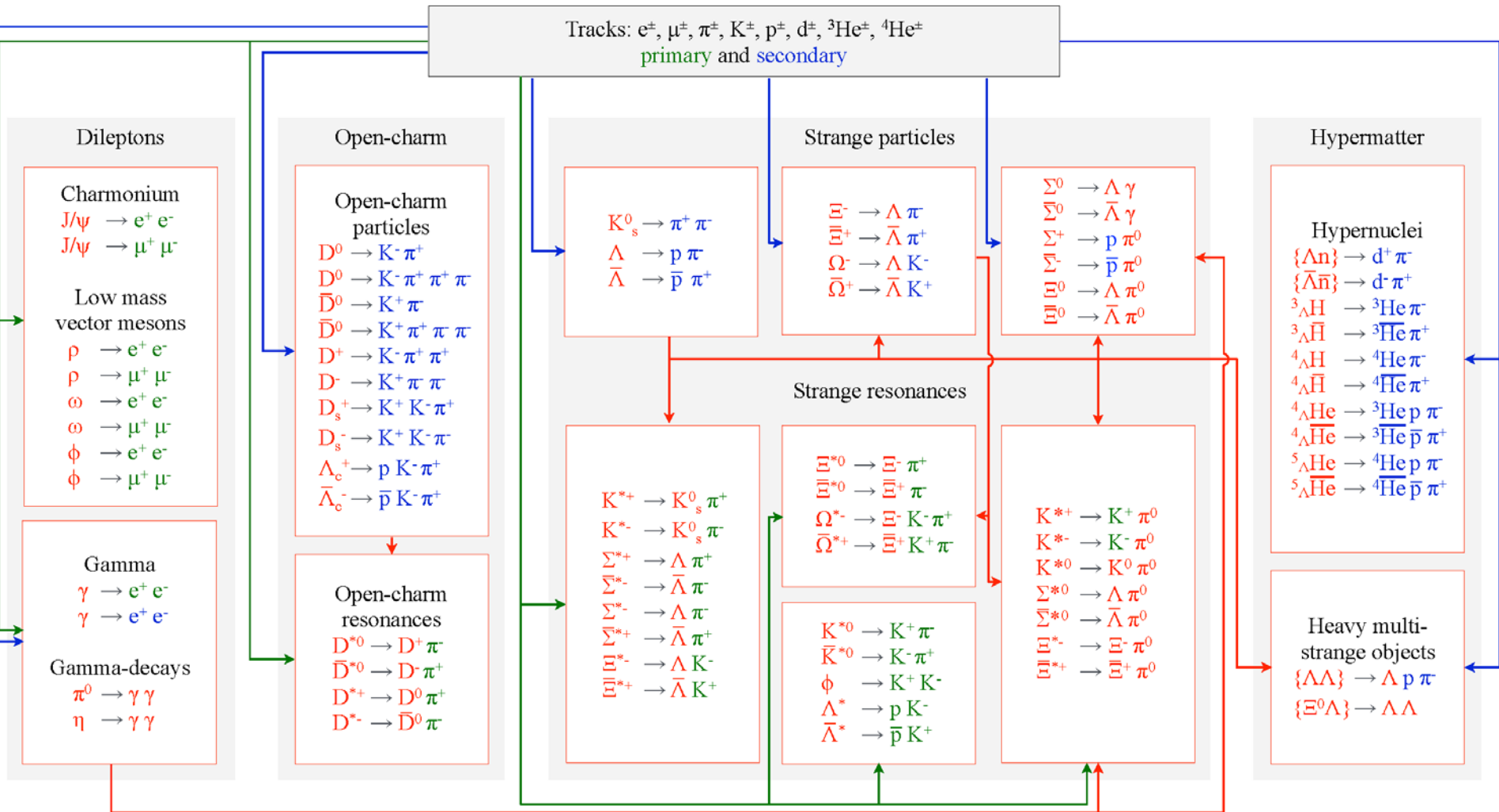
10 MHz Au+Au, 10 AGeV,
300k mbias UrQMD events, ideal PID



		K^0_s	Λ	$\bar{\Lambda}$	Ξ^-
3 D	$\epsilon_{\text{method}}, \%$	68.6	61.2	67	46.7
	$\epsilon_{4\pi}, \%$	20.7	19.4	28	10.5
	S/B	10.6	23.7	12.7	21.8
0.1 MHz	$\epsilon_{\text{method}}, \%$	68.5	62.0	62	45.2
	$\epsilon_{4\pi}, \%$	21.1	20.6	32	11.7
	S/B	9.8	12.9	10	14.2
1 MHz	$\epsilon_{\text{method}}, \%$	67.5	60.9	59	46.0
	$\epsilon_{4\pi}, \%$	19.4	18.7	26	10.6
	S/B	9.3	12.5	10	12.3
10 MHz	$\epsilon_{\text{method}}, \%$	66.8	60.0	64	41.8
	$\epsilon_{4\pi}, \%$	17.6	16.7	28	8.2
	S/B	9.2	12.2	8	11.7

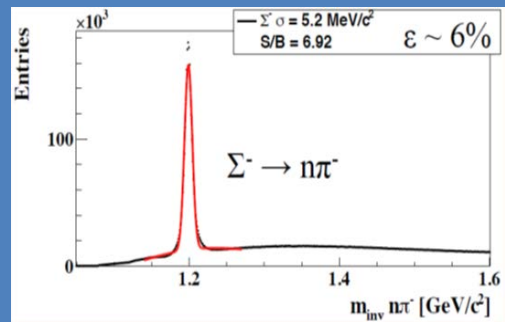
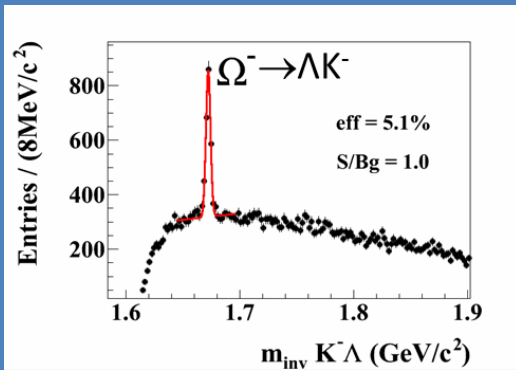
all mother particles emitted from one primary vertex

Online particle identification in CBM: The KF Particle Finder

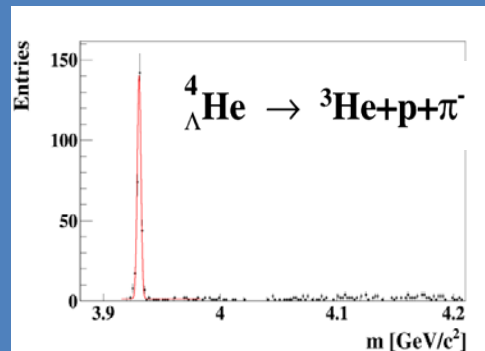


Simulations: central Au+Au collisions at 8A GeV and 10A GeV

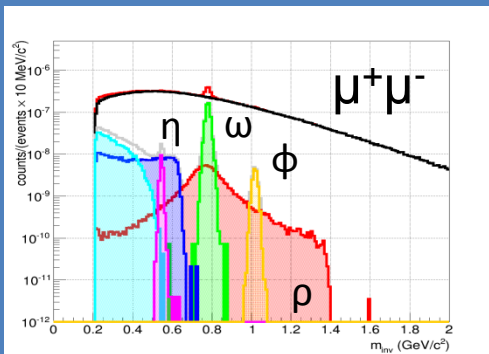
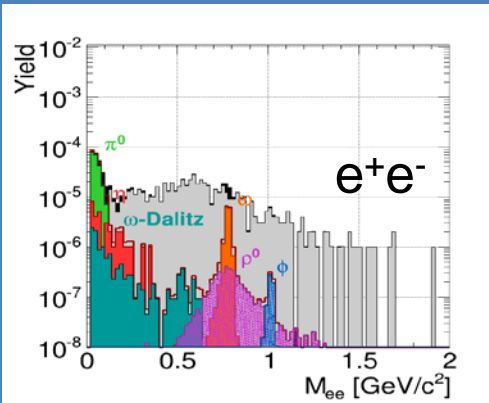
Hyperons at 10 A GeV



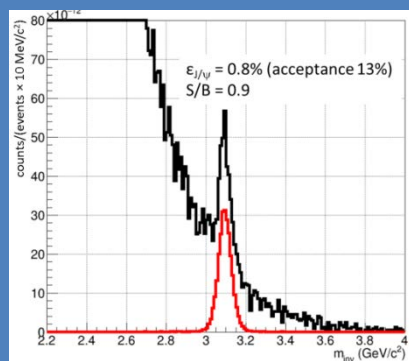
Hypernuclei at 10 A GeV



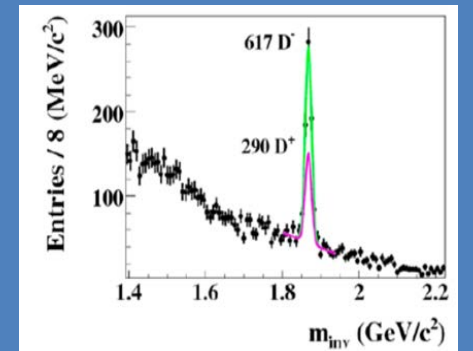
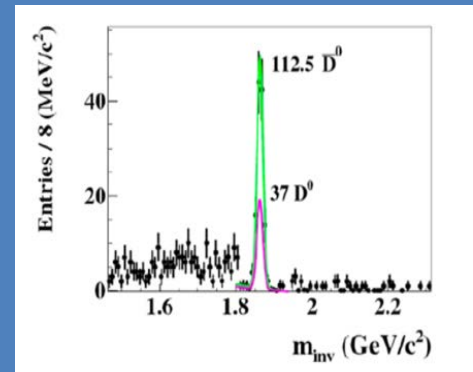
Dileptons 8A GeV



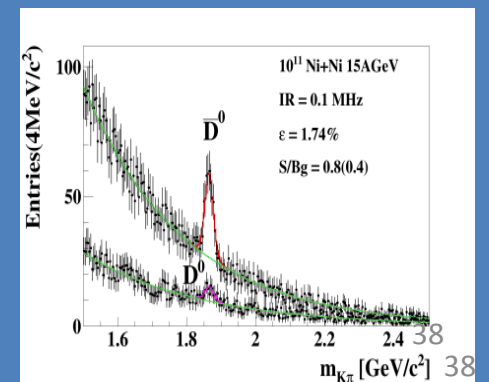
Charmonium at 10 A GeV



D mesons 30 GeV p+Au

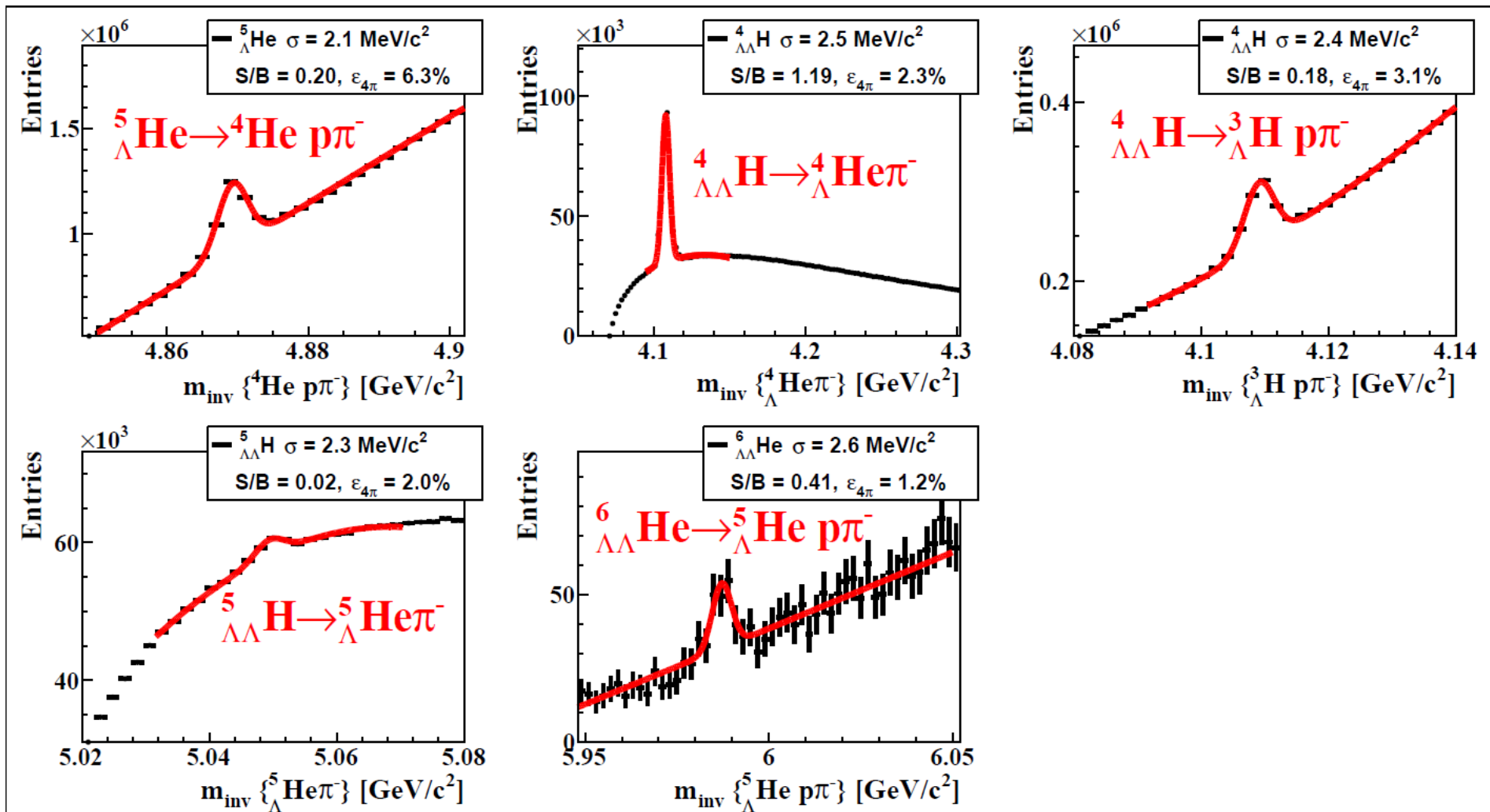


D mesons Ni+Ni 15A GeV



Simulation and reconstruction

Hypernuclei in central Au+Au 10 AGeV



For further reading ...



“Challenges in QCD Matter Physics – the scientific programme of the Compressed Baryonic Matter Experiment at FAIR”

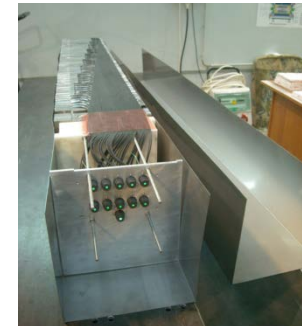
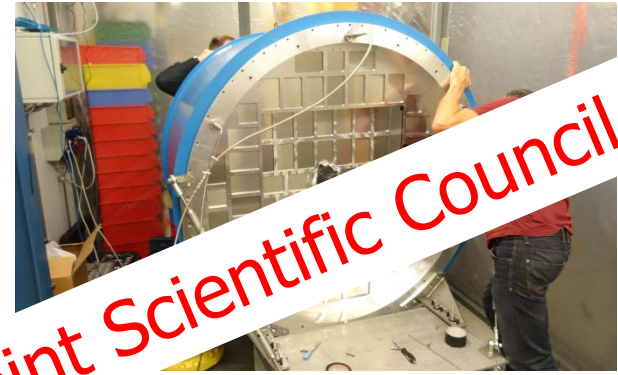
Ablyazimov, T. et al. Eur. Phys. J. A (2017) 53: 60. doi:10.1140/epja/i2017-12248-y

135 contributions, 220 pages
ISBN 978-3-9815227-4-7.

[https://repository.gsi.de/record/186952/files/CBM-PR-2015%20\[pdf\].pdf](https://repository.gsi.de/record/186952/files/CBM-PR-2015%20[pdf].pdf)

FAIR phase 0 experiments on dense QCD matter

1. Install, commission and use 430 out of 1100 CBM RICH multi-anode photo-multipliers (MAPMT) 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)
3. Install and use 4 Silicon detectors in the BM@N experiment at the Nuclotron in JINR/Dubna (start 2019 with Au-beams up to 4.5 A GeV)
4. Install, commission and use the Project Spectator Detector at the BM@N experiment



Strongly endorsed by the 2nd FAIR/GSI Joint Scientific Council

The CBM Collaboration: 55 institutions, 460 members

China:

CCNU Wuhan
Tsinghua Univ.
USTC Hefei
CTGU Yichang

Czech Republic:

CAS, Rez
Techn. Univ. Prague

France:

IPHC Strasbourg

Hungary:

KFKI Budapest
Eötvös 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.

Poland:

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

Romania:

NIPNE Bucharest
Univ. Bucharest

Russia:

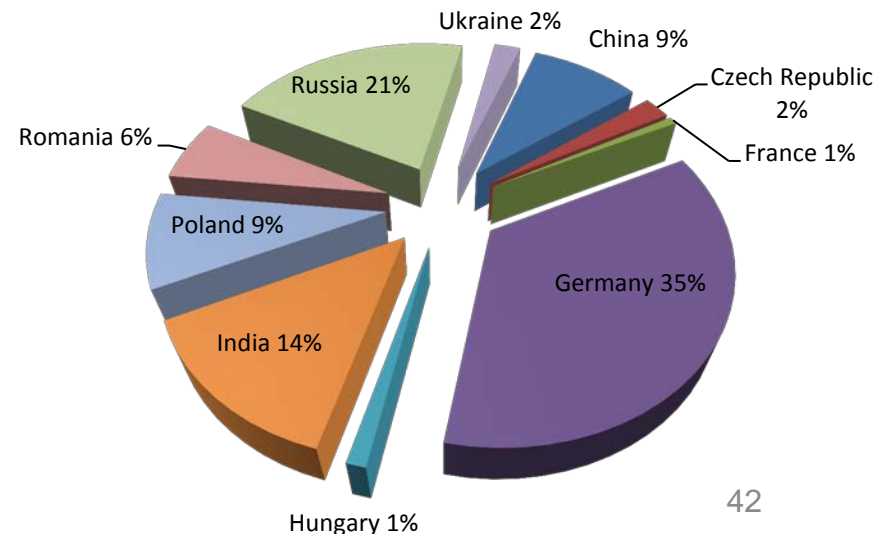
IHEP Protvino
INR Troitzk
ITEP Moscow
Kurchatov Inst., Moscow
VBLHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
PNPI Gatchina
SINP MSU, Moscow

Ukraine:

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



CBM Scientists



29th CBM Collaboration meeting at GSI
20-24 March 2017

Summary

- Status FAIR: Procurement of accelerator components ongoing. Civil construction starts mid 2017. FAIR Phase 1 full operational in 2025. Installation/commissioning of experiments planned during 2021-2024.
- CBM scientific program at SIS100: Exploration of the QCD phase diagram in the region of neutron star core densities → large discovery potential.
- First measurements with CBM: High-precision multi-differential measurements of hadrons incl. multistrange hyperons, hypernuclei and dileptons for different beam energies and collision systems → terra incognita.
- Status of experiment preparation: Prototype detectors fulfill CBM requirements. 7 out of 11 TDRs approved.
- FAIR Phase 0: HADES experiments with CBM RICH photon detector, use CBM detectors at STAR/BNL and BM@N/JINR

