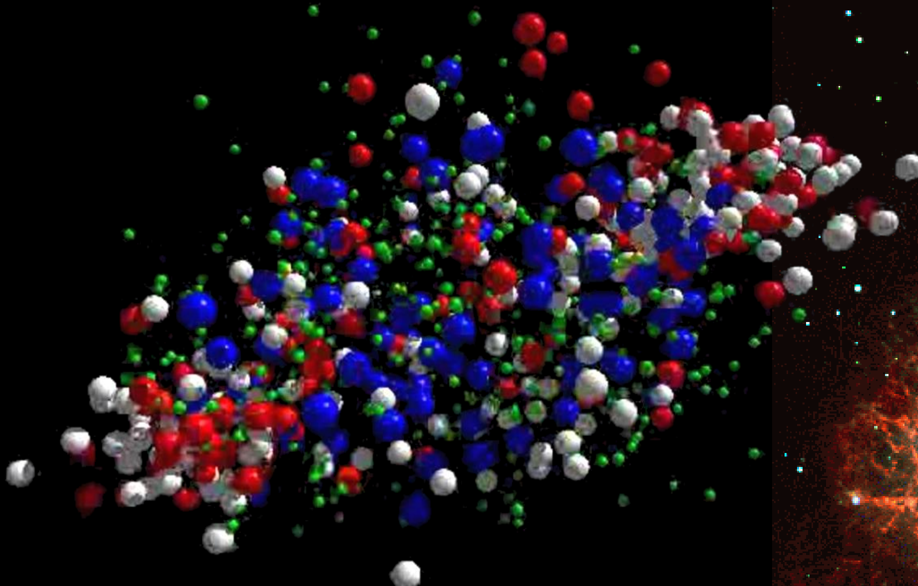
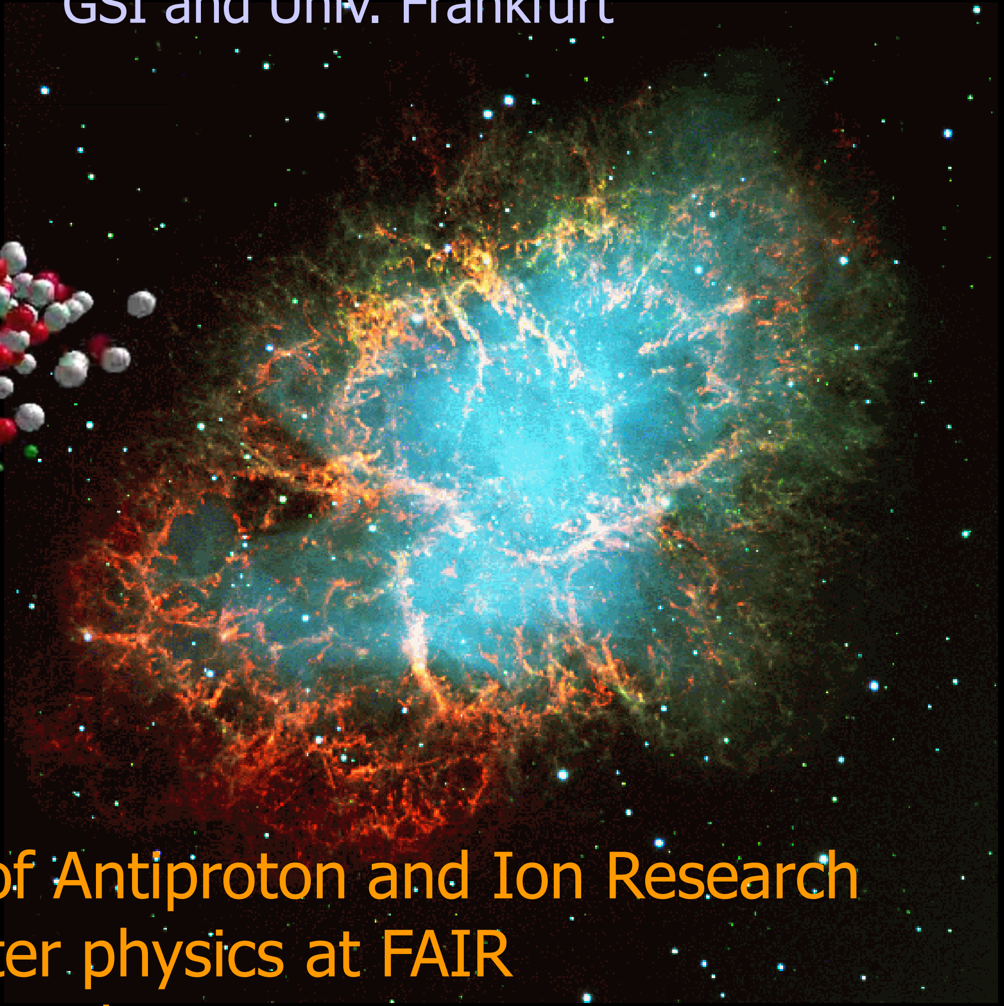
Nuclear Matter physics at FAIR

Peter Senger GSI and Univ. Frankfurt





Outline:

- The Facility of Antiproton and Ion Research
- Nuclear matter physics at FAIR
- The Compressed Baryonic Matter Experiment

31st Reimei WorkShop on Hadron Physics in Extreme Conditions at J-PARC
Tokai, Japan, 18 - 20 January 2016

Facility for Antiproton & Ion Research

FAIR is the largest upcoming fundamental science project worldwide this decade.

Forefront research in nuclear, hadron, atomic, plasma and applied physics.

- First beam in 2022
- 10 member states up to date
- 2500 - 3000 users
- Total cost ~1.6 Billion € (German funds 70%, rest from international partners)

Germany
Russia
Finland
France
India
Poland
Romania
Slovenia
Sweden
UK (associated)

FAIR Signatory Countries

Facility for Antiproton & Ion Research

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

Technical Challenges

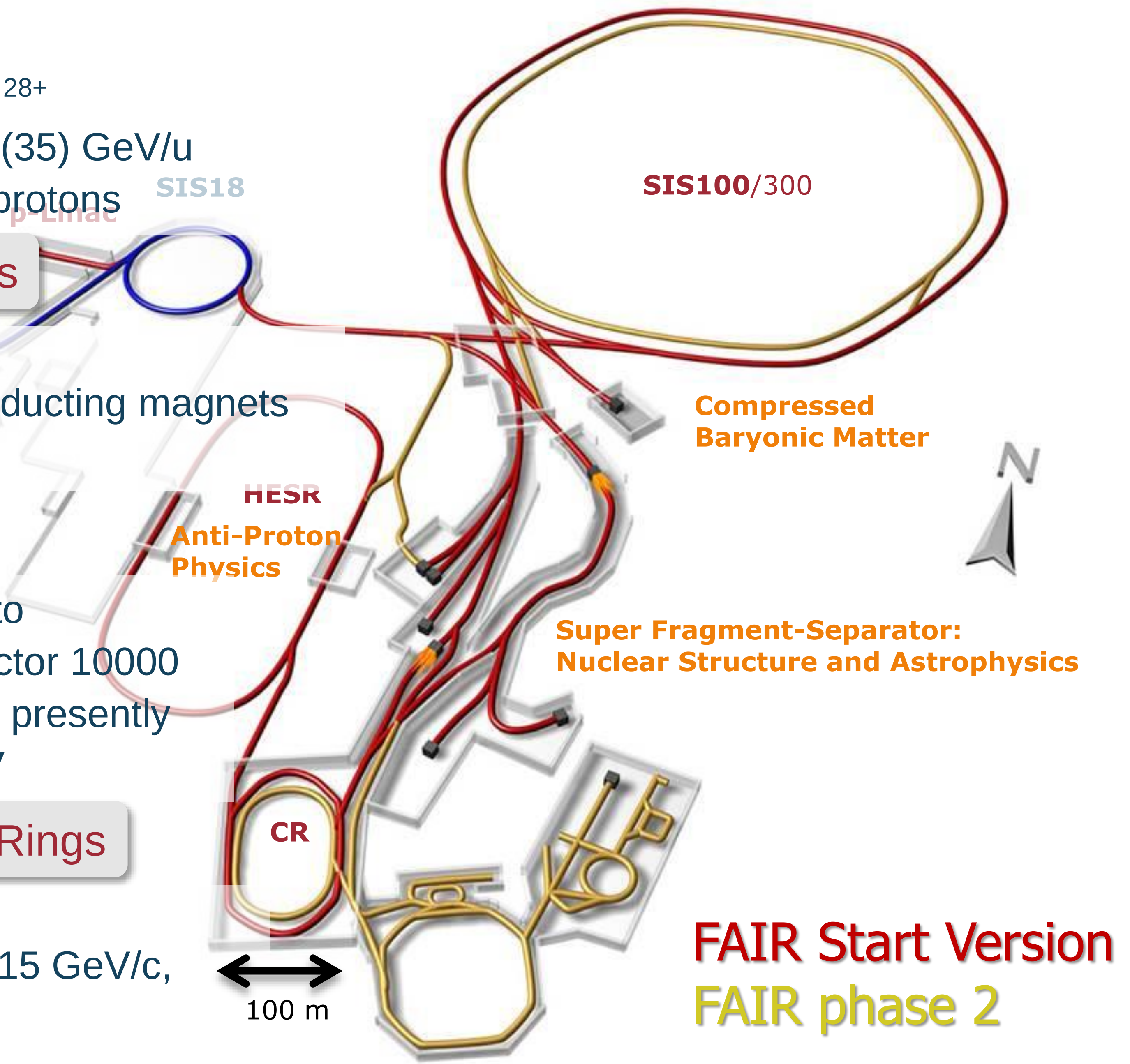
- cooled beams
- rapid cycling superconducting magnets
- dynamical vacuum

Secondary Beams

- radioactive beams up to 1.5 - 2 GeV/u; up to factor 10000 higher in intensity than presently
- antiprotons 3 - 30 GeV

Storage and Cooler Rings

- radioactive beams
- 10^{11} antiprotons 1.5 - 15 GeV/c, stored and cooled



Civil construction

The four most powerful drilling machines worldwide put down 1350 reinforced concretd pillars of 60 m depth and 1.2 m diameter.

Status of FAIR

2014:

Announcement of a time delay and cost increase caused by civil construction

2015:

Evaluation by an international committee:

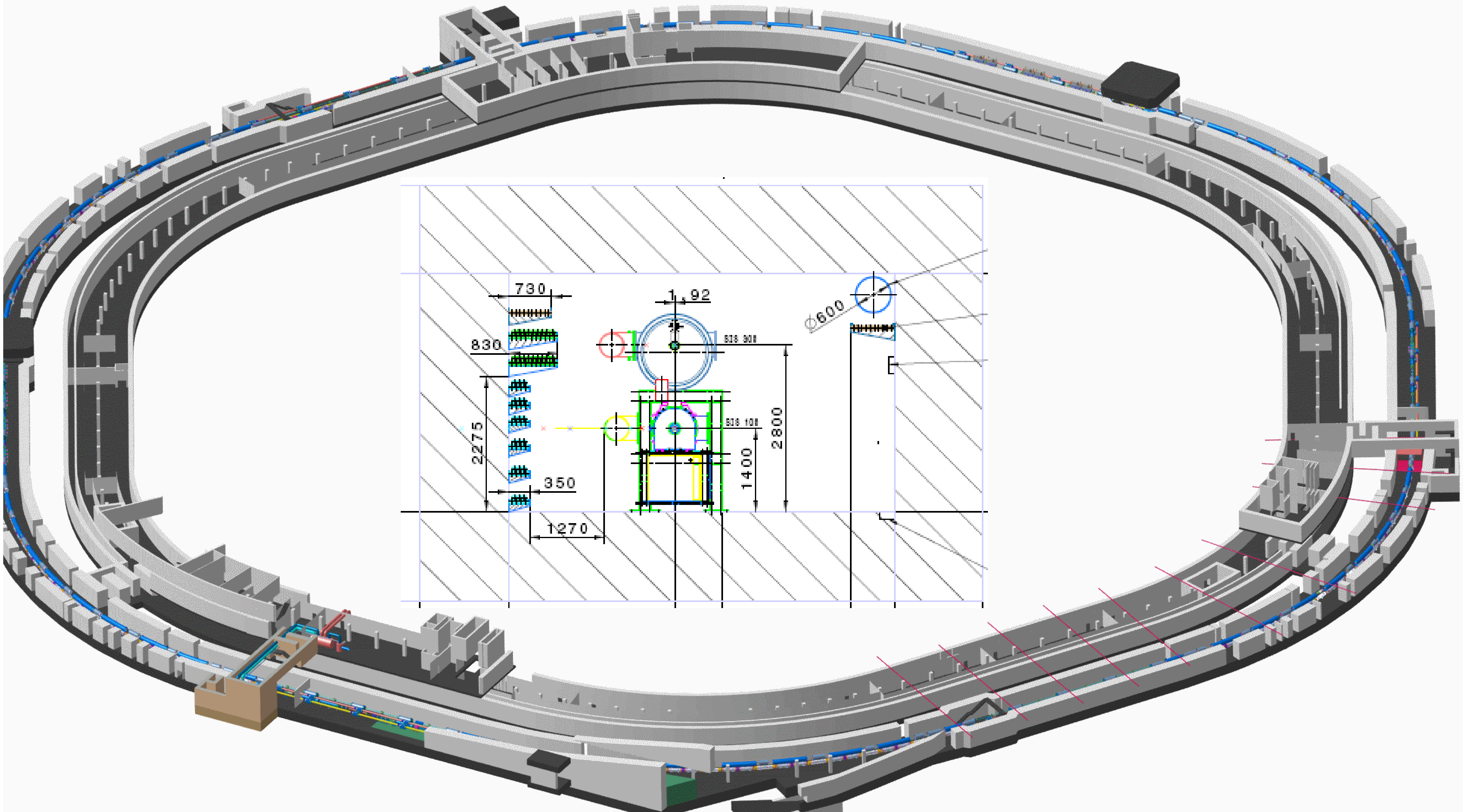
- Recommendation to restructure the FAIR management,
- Confirmation of the FAIR science program.

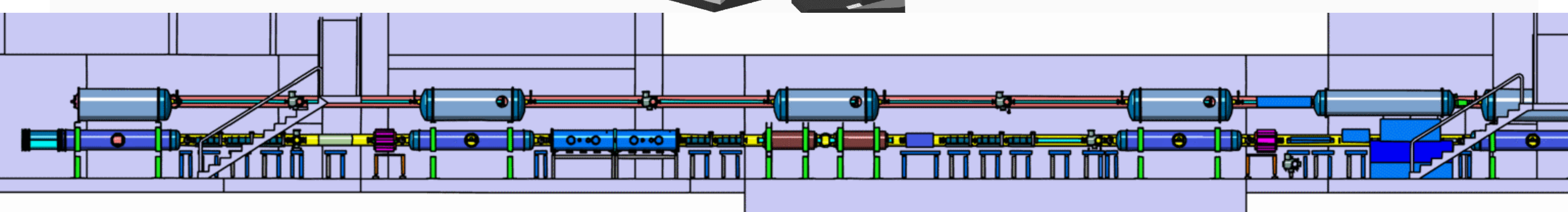
Decision of the FAIR shareholders:

- Build Start Version within staged approach and a cost cap.
- No reduction of the scientific scope.
- Commitment for 2/3 of missing funding in June 2016
- Status review in 2019
- Commitment for 1/3 of missing funding 2019

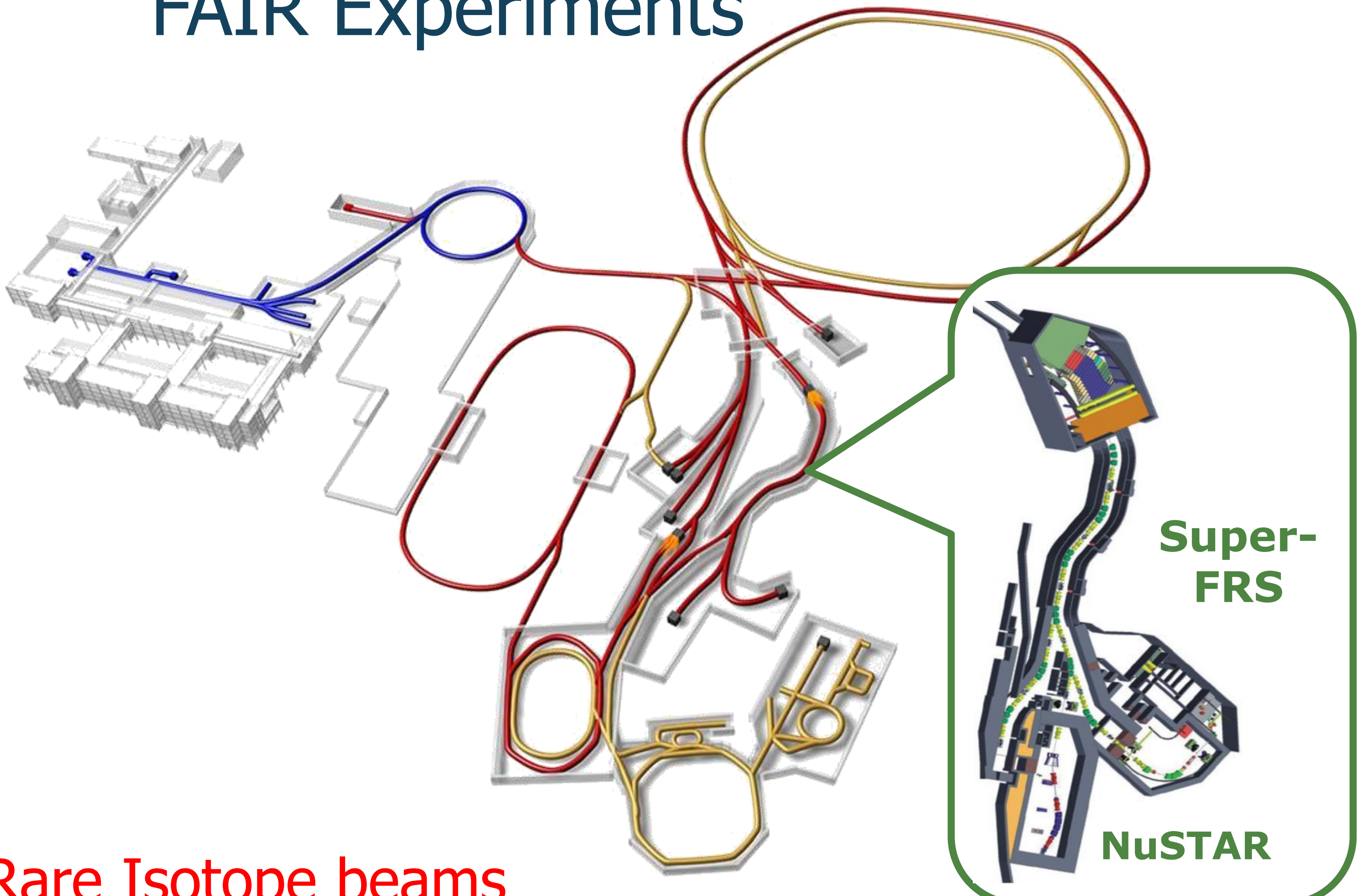
Application for the construction permit for the SIS100/300 tunnel submitted end of 2015. Goal: first beams in 2022.

Tunnel for SIS100/300





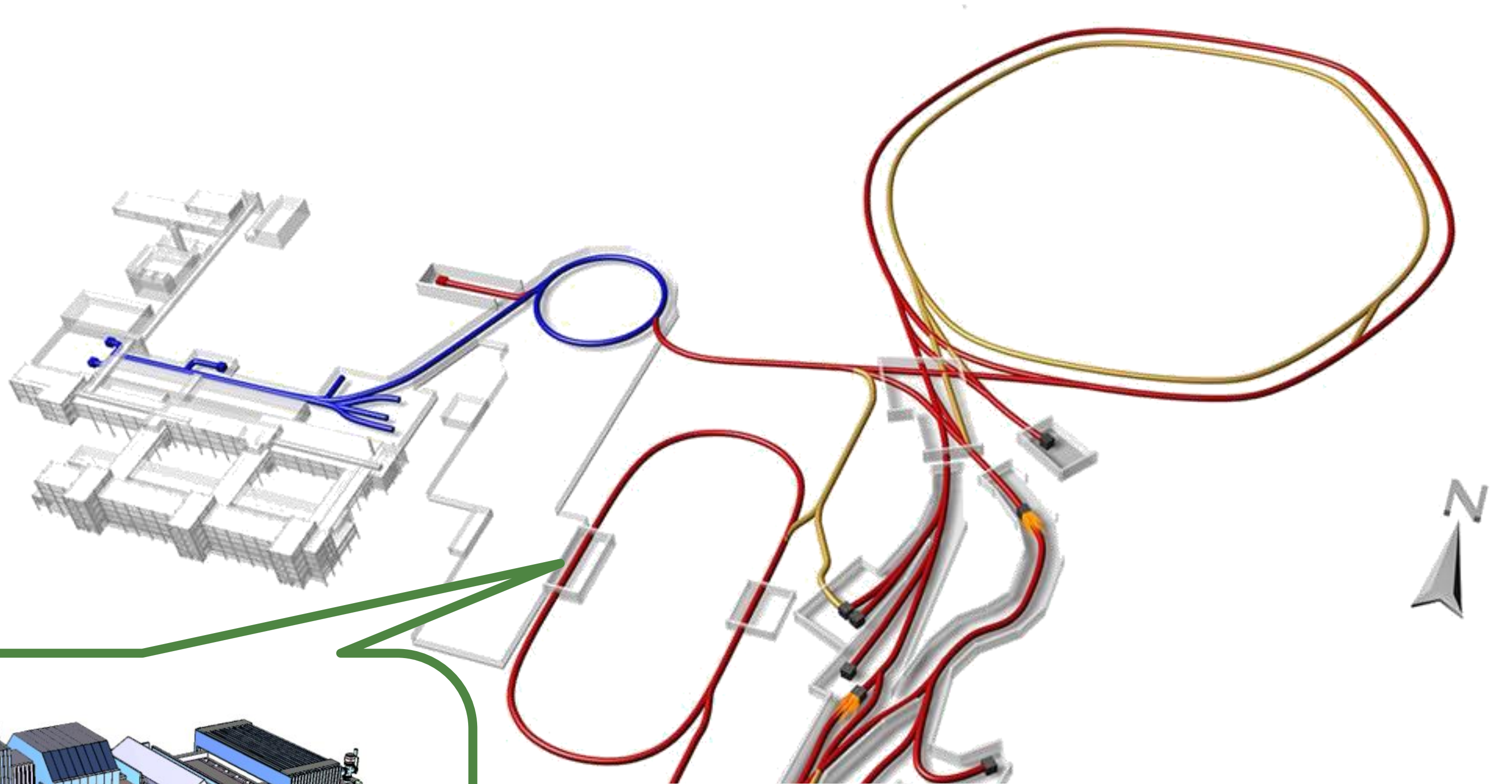
FAIR Experiments

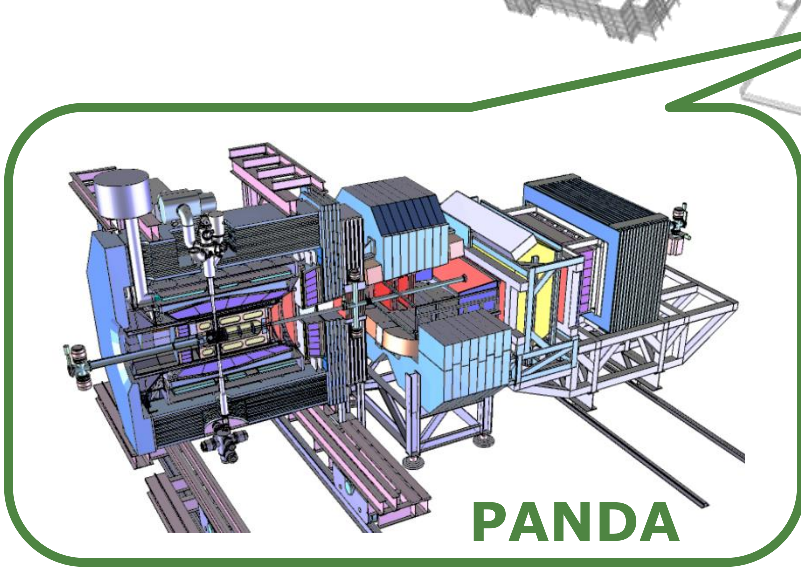


Rare Isotope beams

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

FAIR Experiments

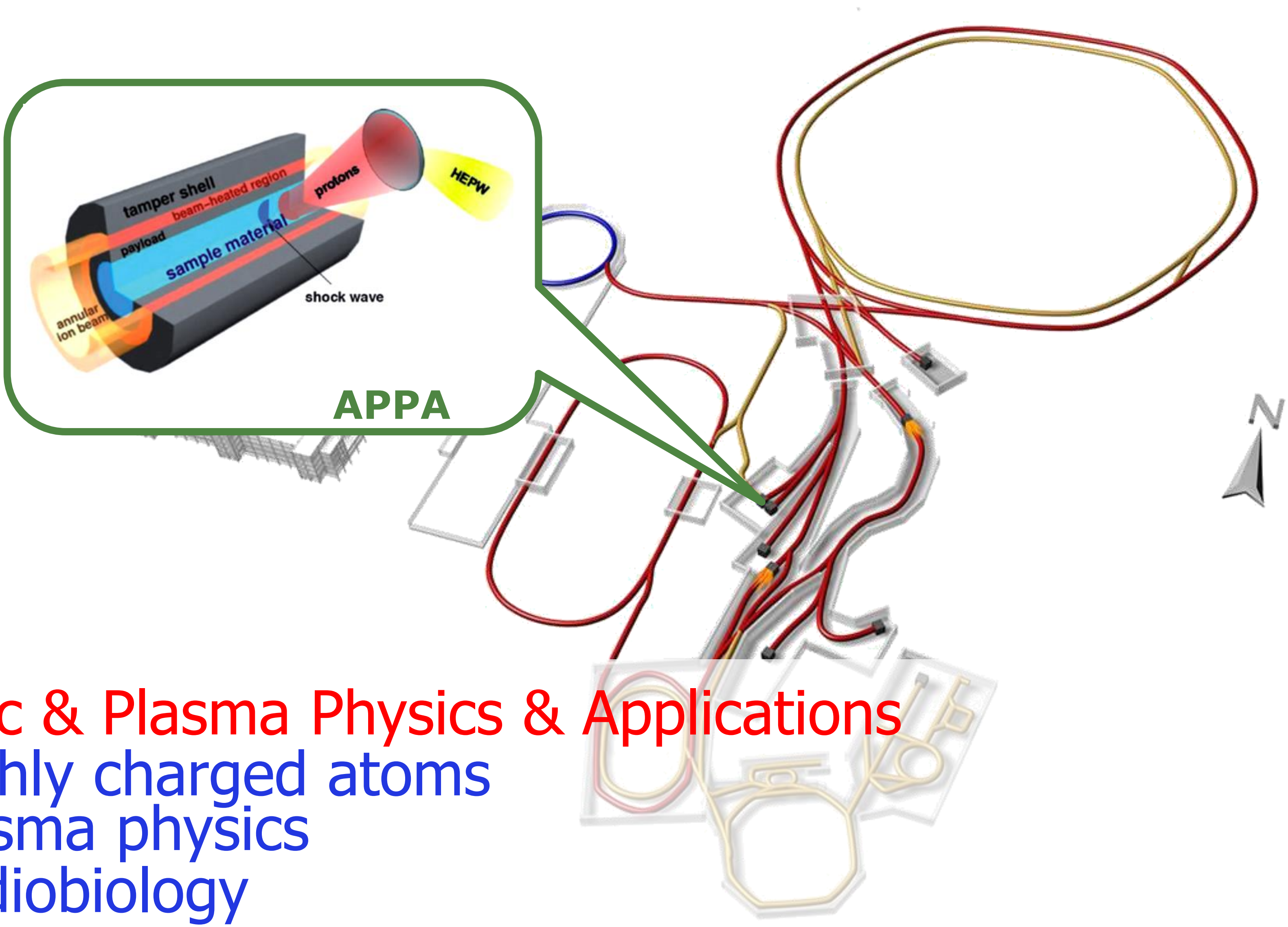




Antiproton-proton collisions:

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

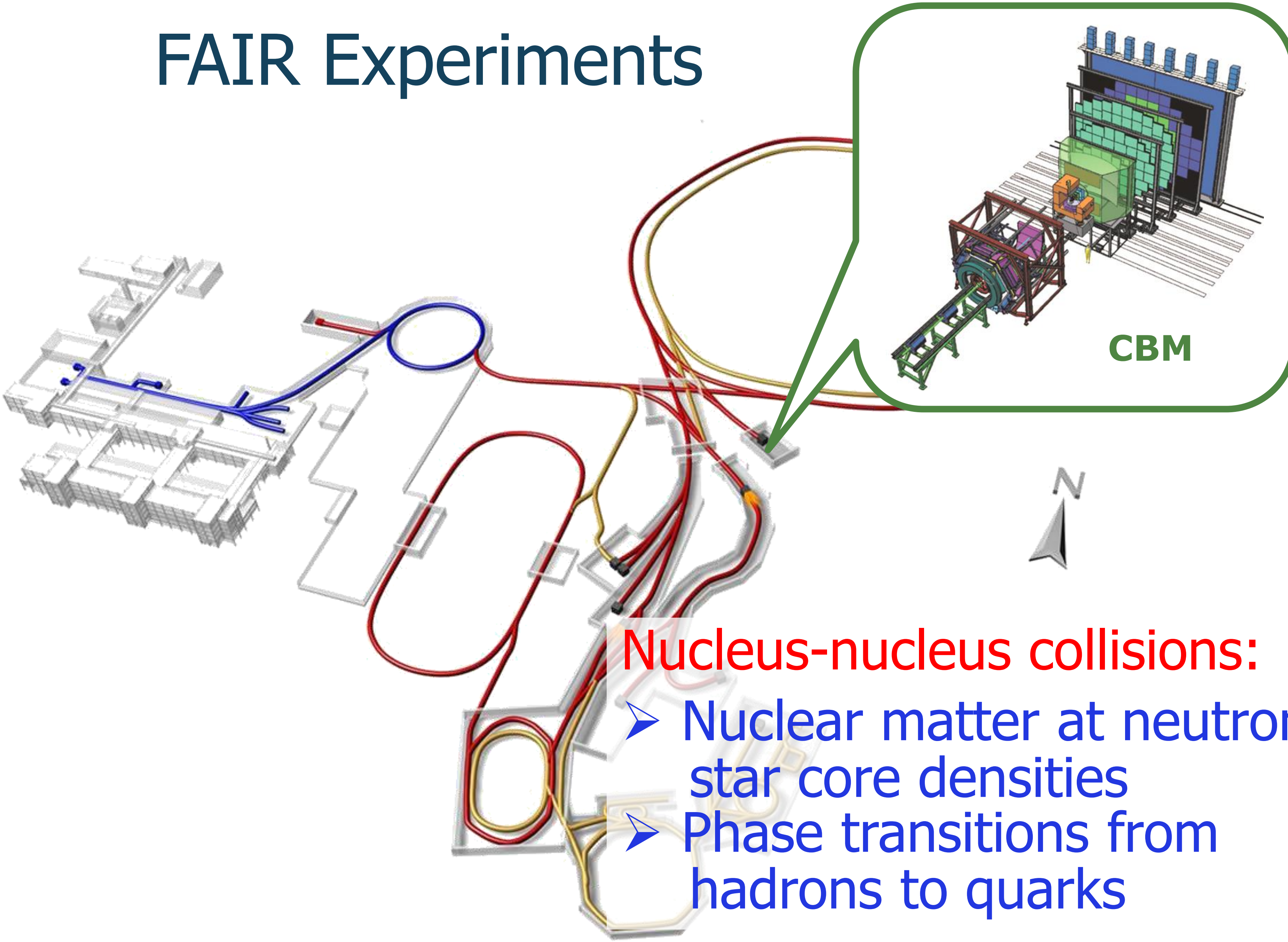
FAIR Experiments



Atomic & Plasma Physics & Applications

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

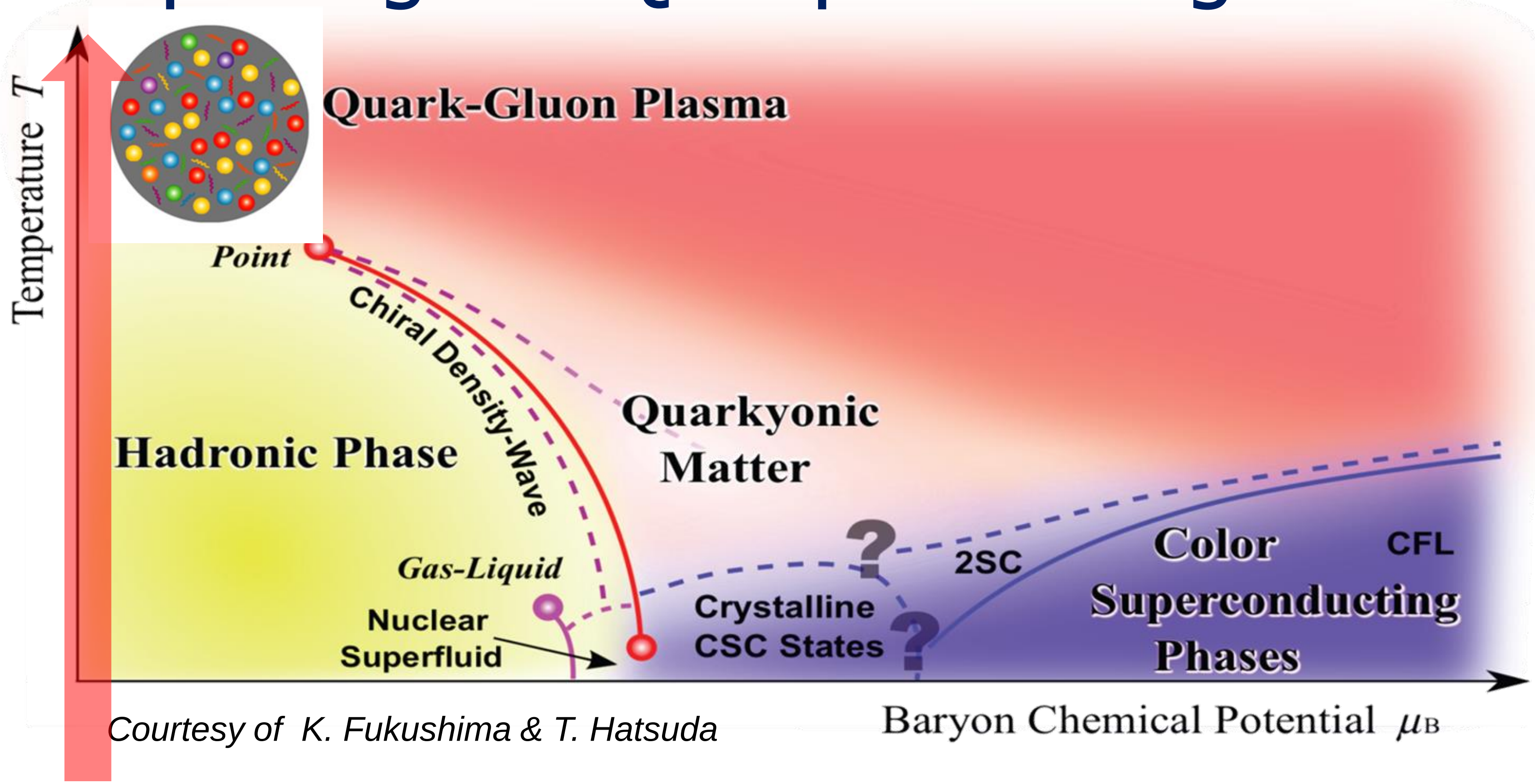
FAIR Experiments



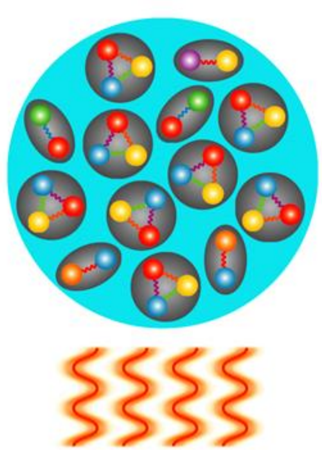
Nucleus-nucleus collisions:

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

Exploring the QCD phase diagram



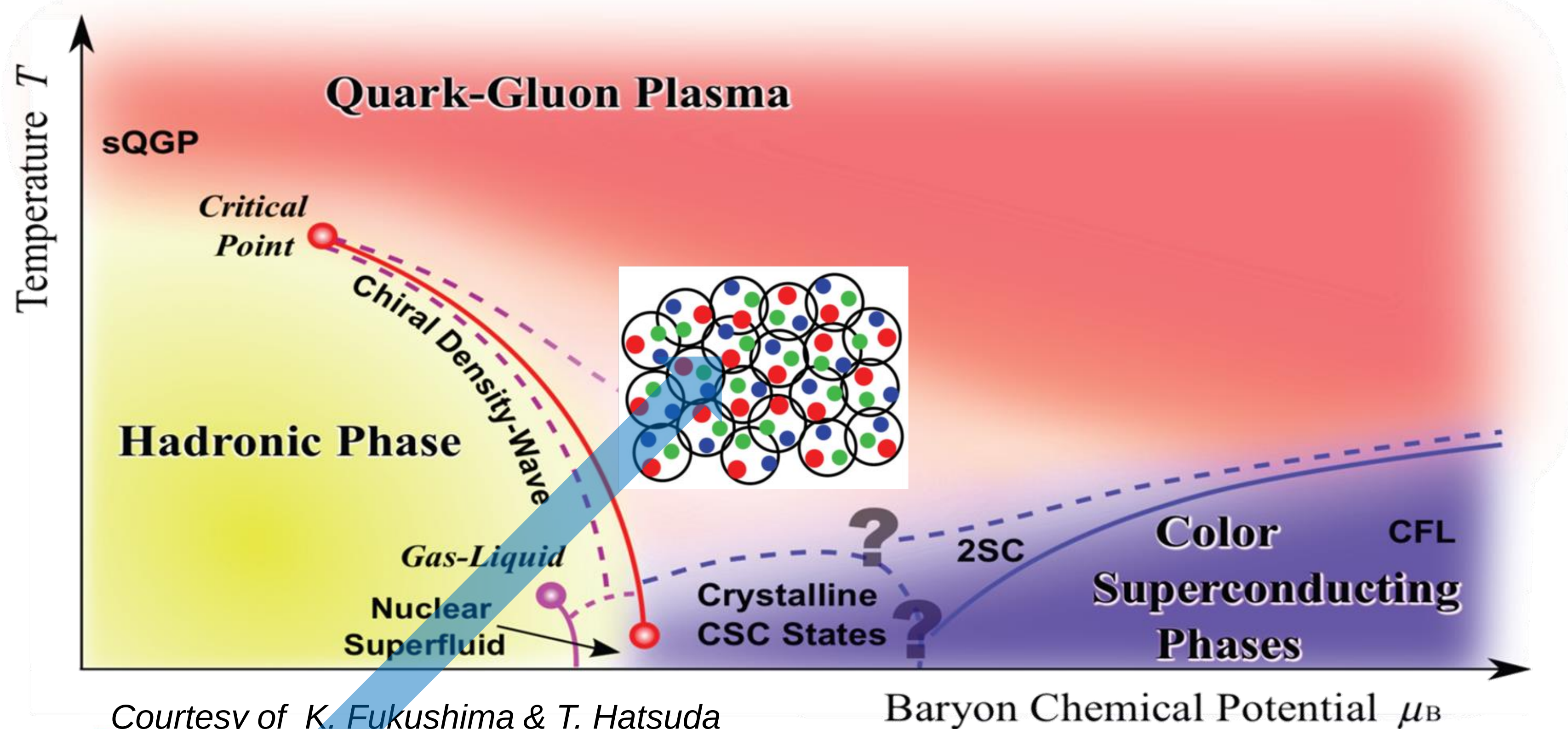
Courtesy of K. Fukushima & T. Hatsuda



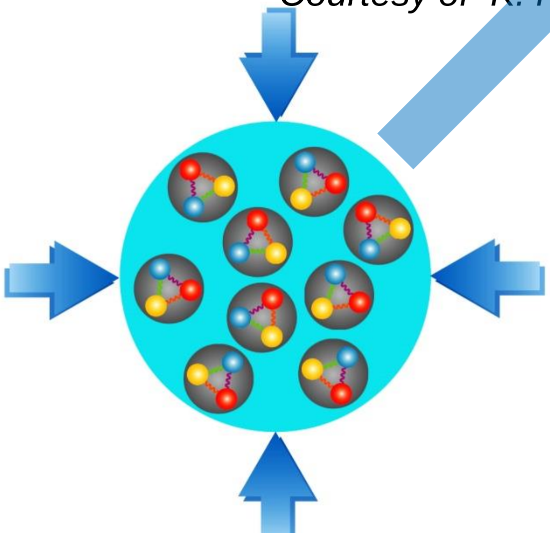
<u>At very high temperature:</u>

- N of baryons ≈ 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



Courtesy of K. Fukushima & T. Hatsuda



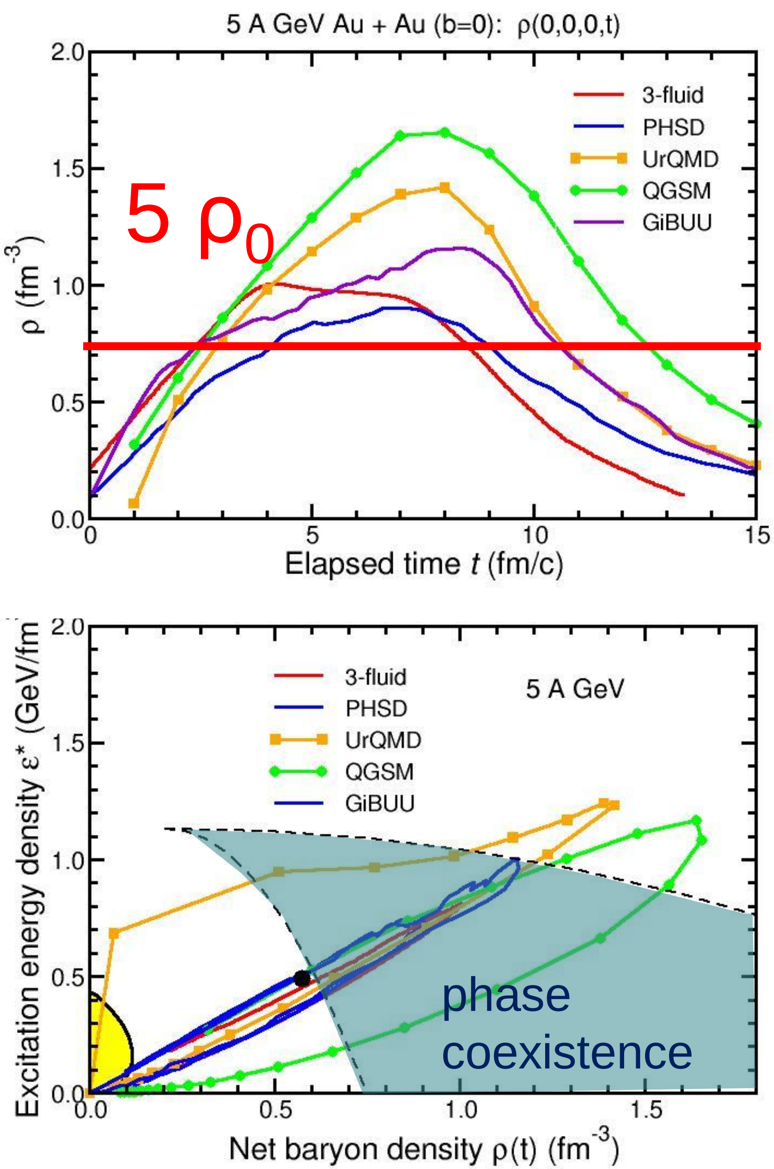
<u>At high baryon density:</u>

- N of baryons >> 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

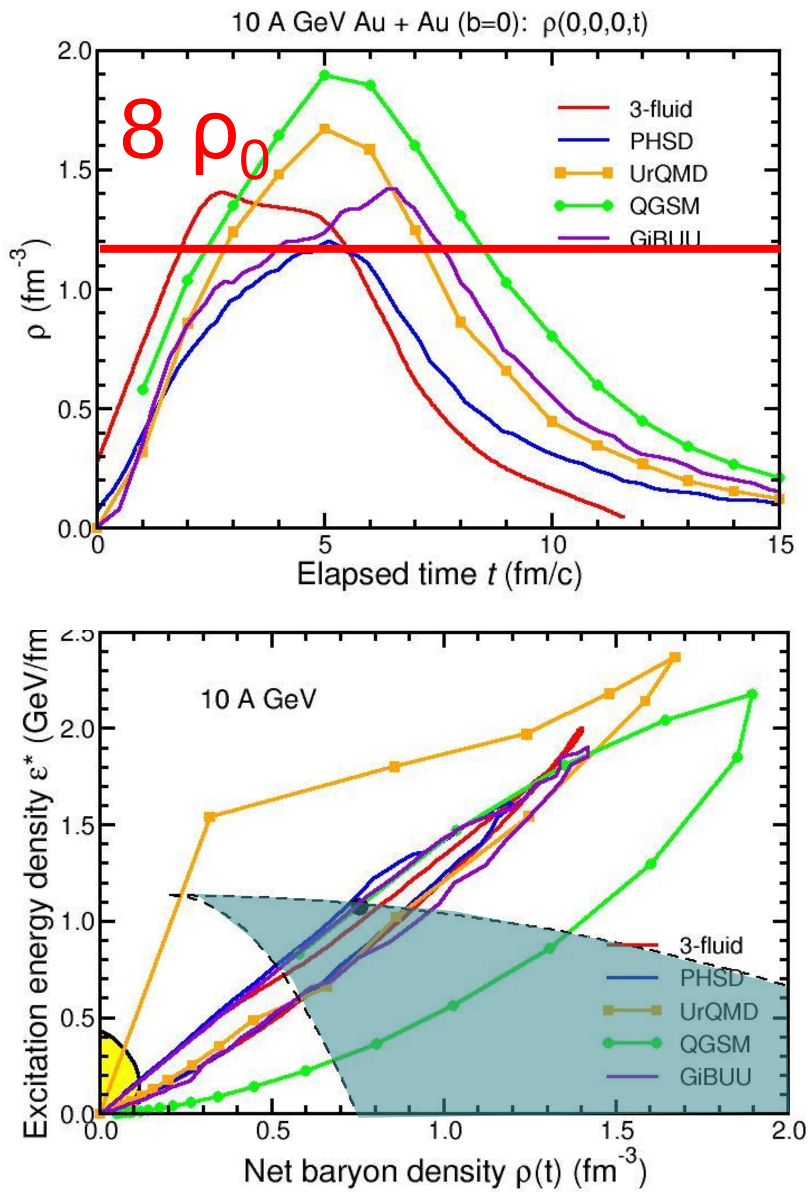
Baryon densities in central Au+Au collisions

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

5 A GeV

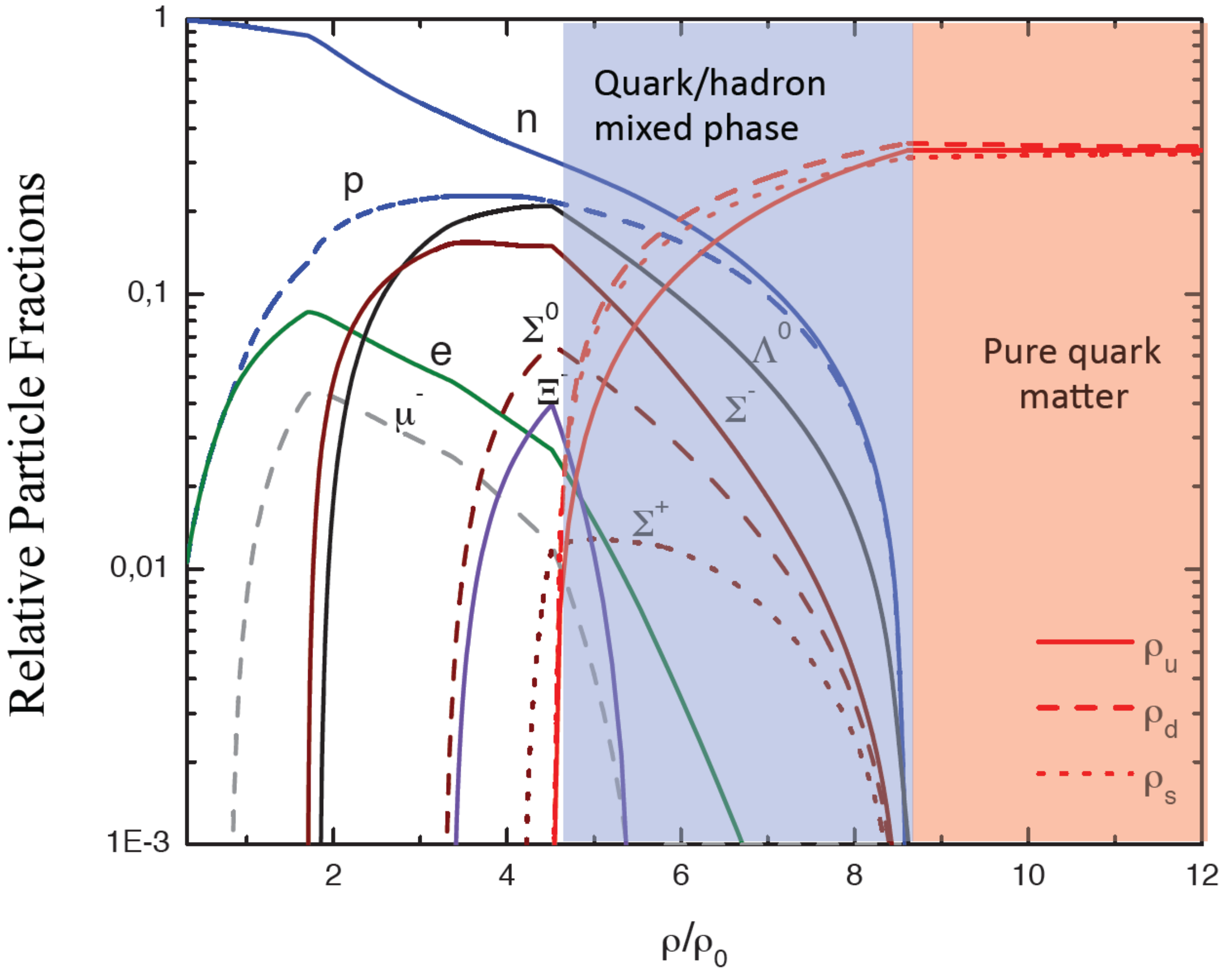


10 A GeV



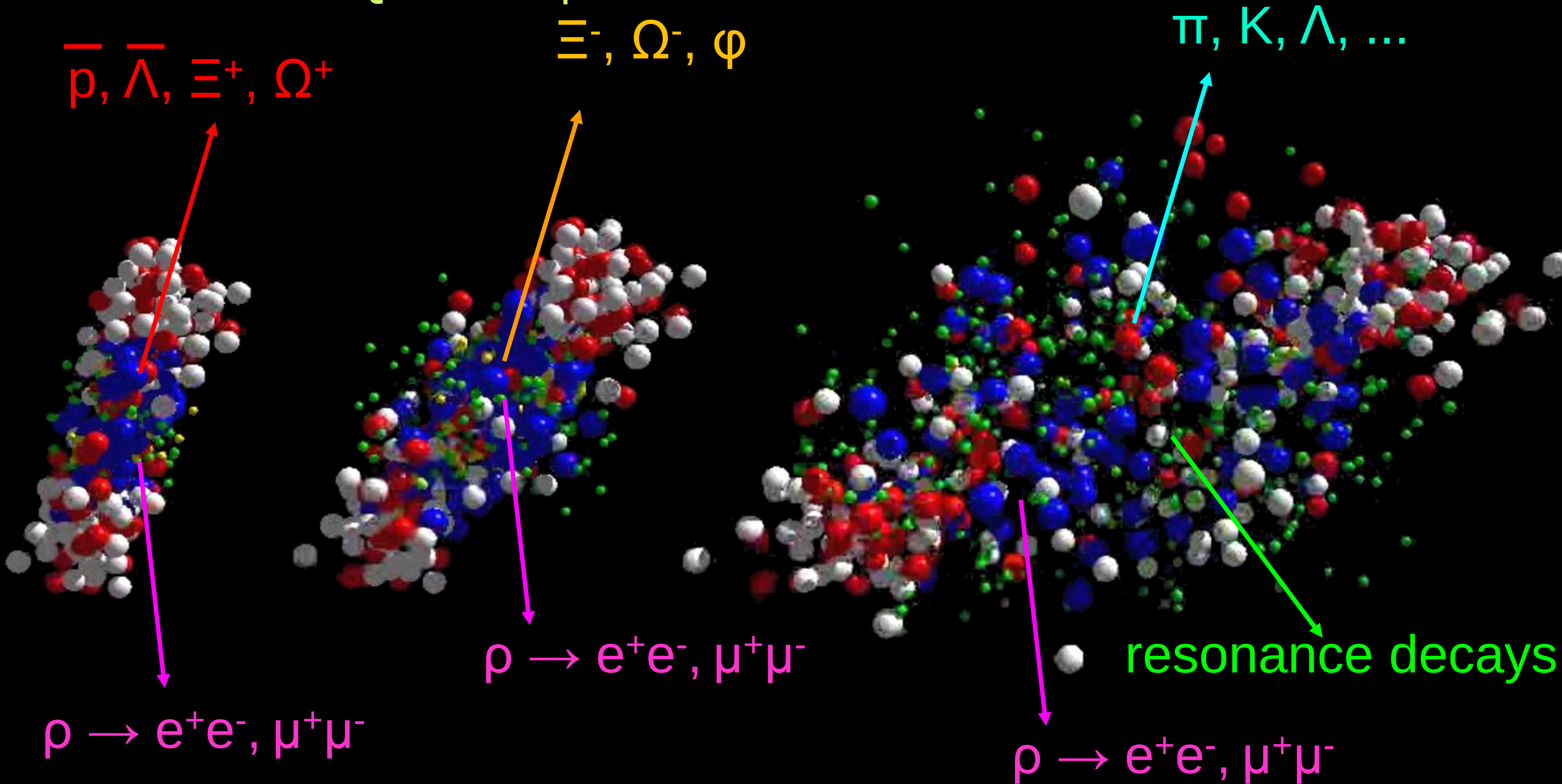
Quark matter in massive neutron stars?

M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657
Phys. Rev. C 89, 015806, 2014



Messengers from the dense fireball: CBM at FAIR

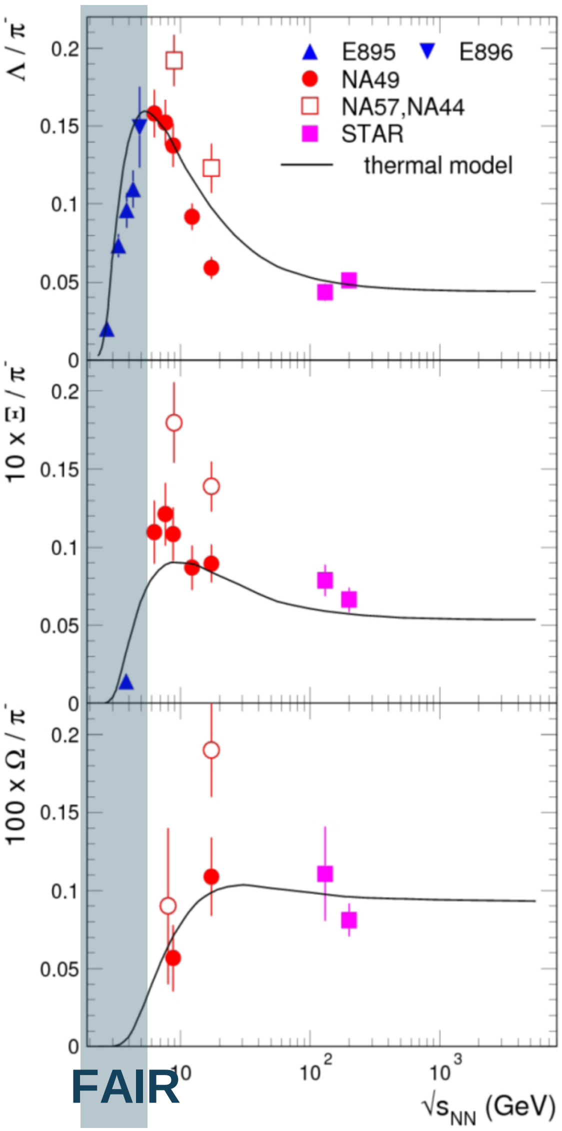
UrQMD transport calculation Au+Au 10.7 A GeV



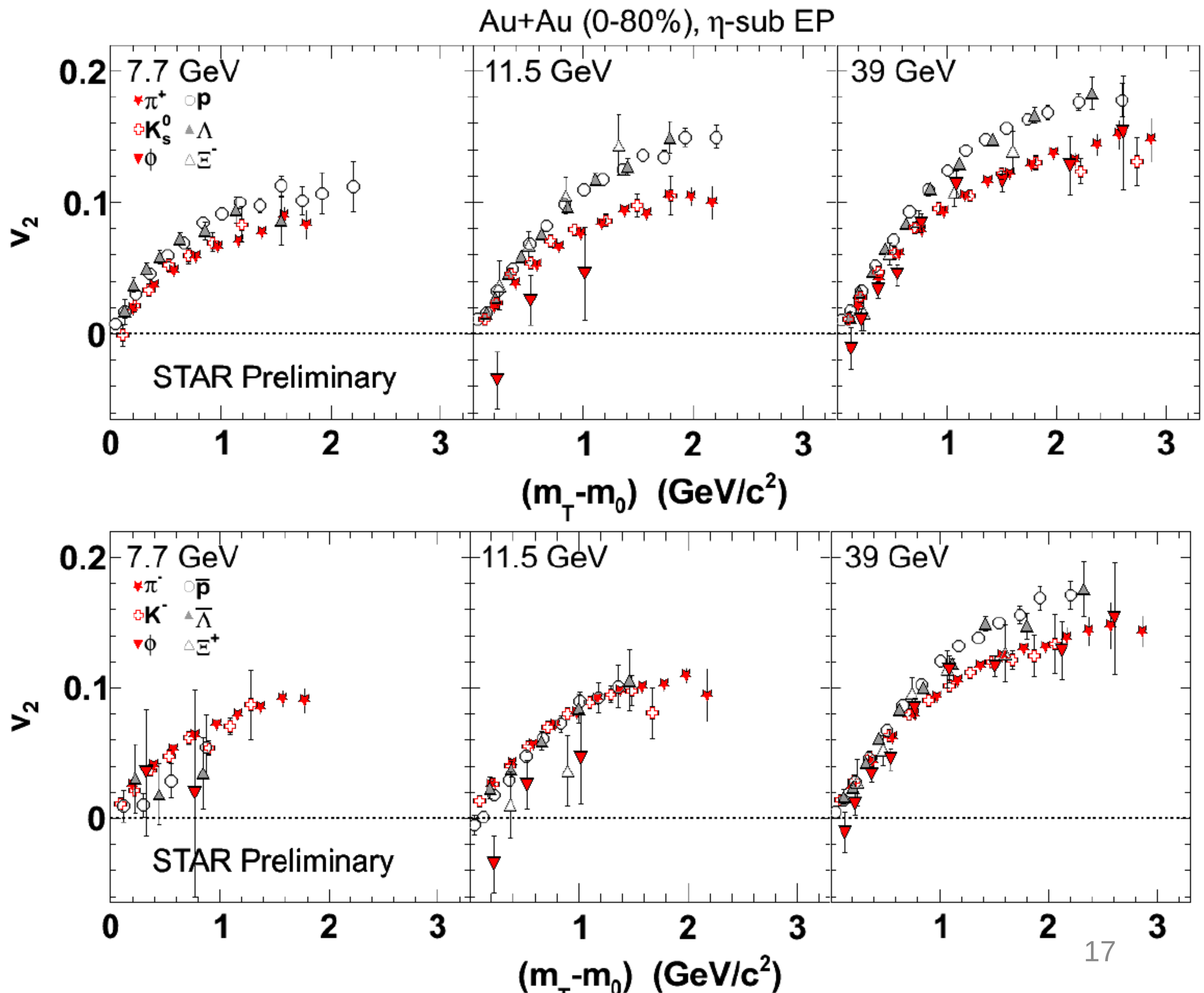
Strangeness
Data situation

very few data at FAIR energies

Pb+Pb, Au+Au (central)



RHIC beam energy scan

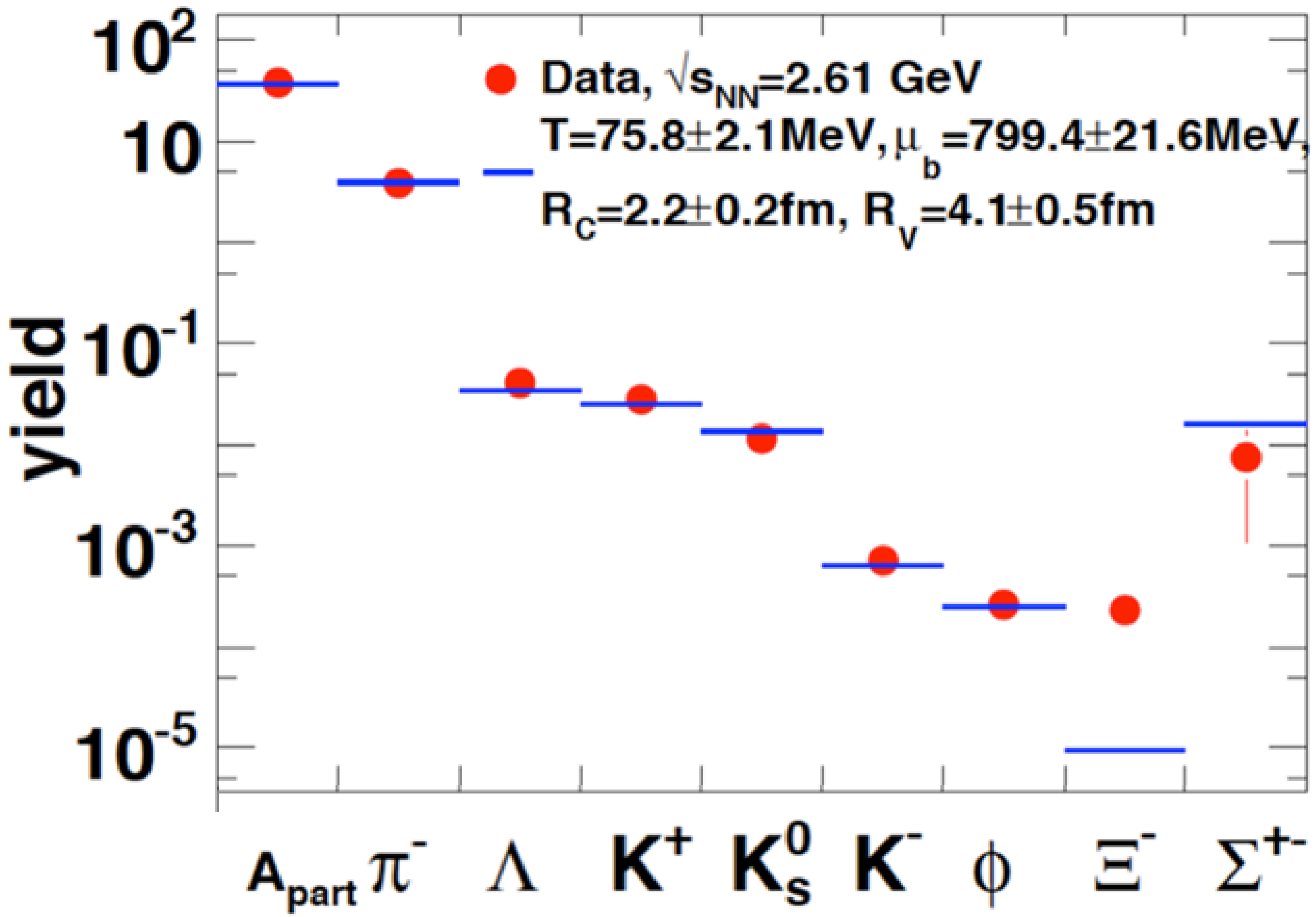


Strangeness

Data situation

HADES: Ar + KCl 1.76 A GeV

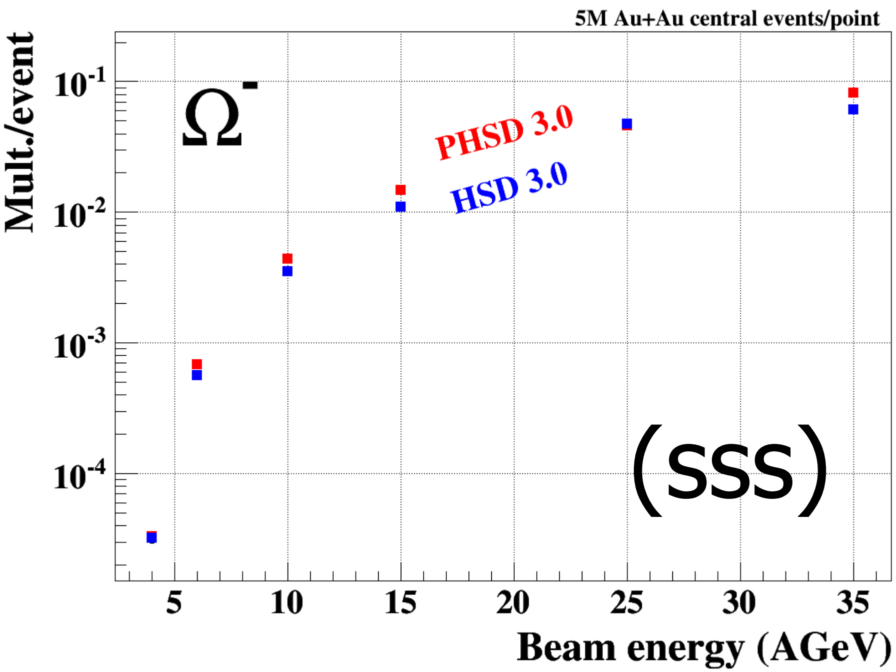
Phys. Rev. Lett. 103 (2009) 132301

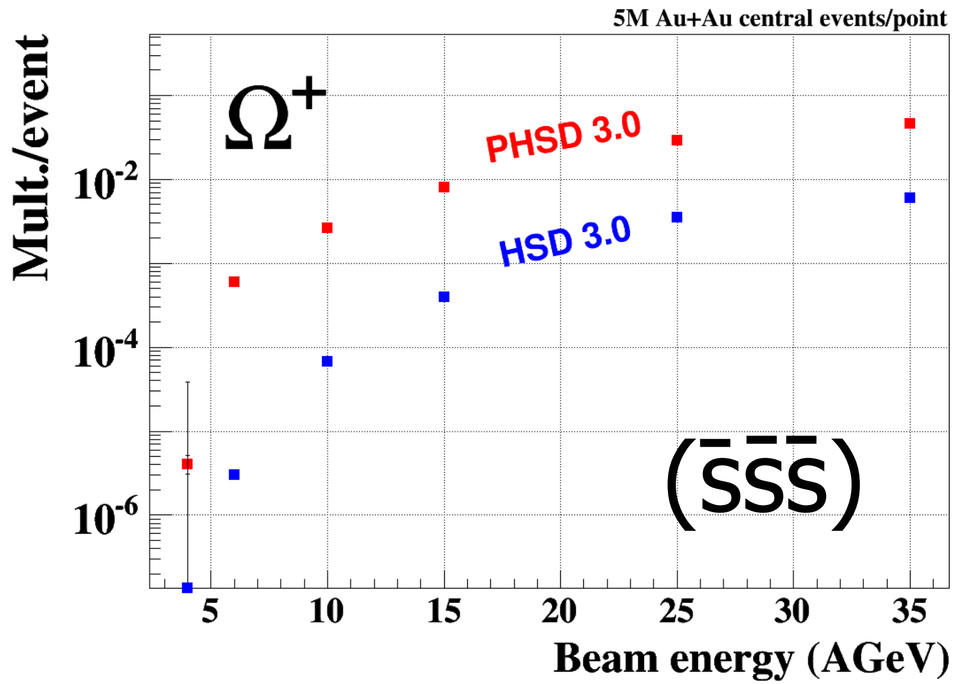


Strangeness and anti-strangeness

Multistrange (anti-)hyperon production in HSD and PHSD transport codes at FAIR energies

I. Vassiliev, E. Bratkovskaya, preliminary results





HSD: Hadronic transport code

PHSD: Hadronic transport code with partonic phase ($\varepsilon > 1$ GeV/fm^3)

Strangeness at CBM

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

Transport codes:

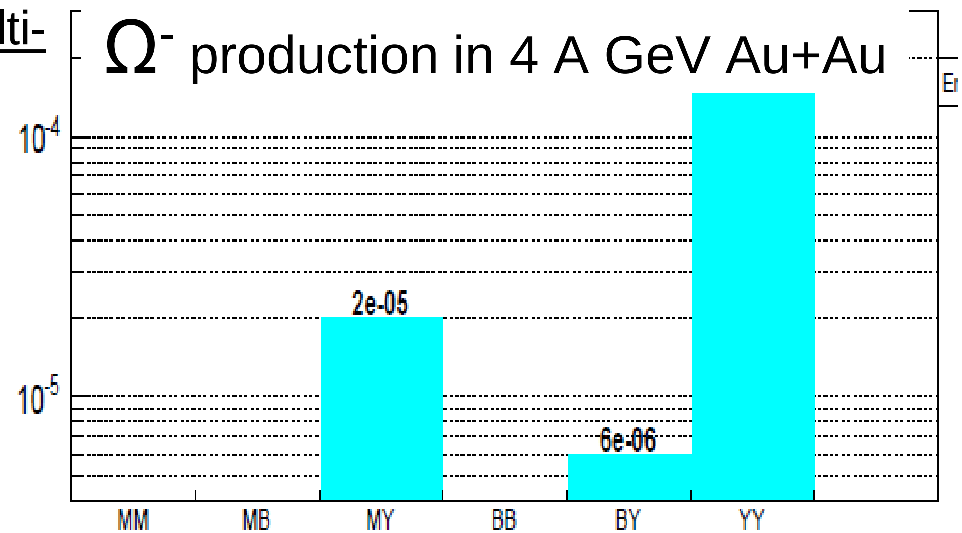
Multi-strange hyperon production via multi-step strangeness exchange reactions:

Hyperons (s quarks):

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

Antihyperons (anti-s quarks):

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



HYPQGSM calculations , K. Gudima et al.

Dileptons

Observables

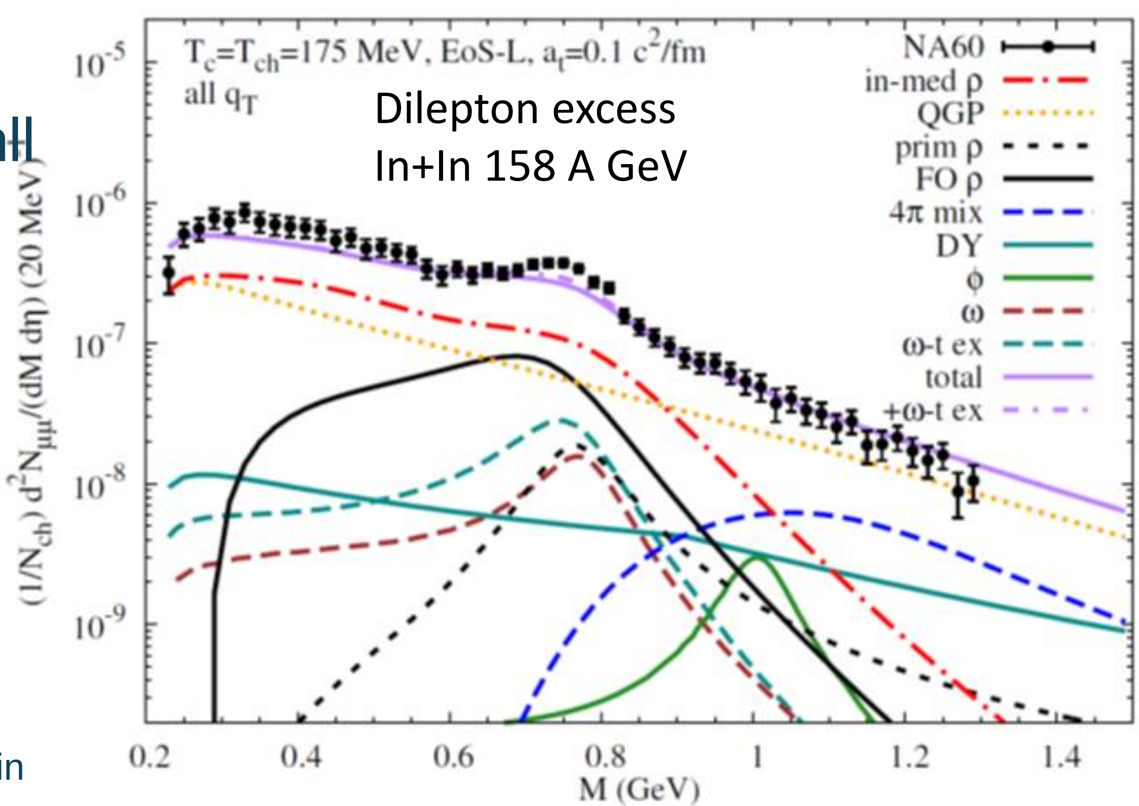
Excitation function of yields, emitting source temperature and phase-space distributions of lepton pairs in heavy-ion collisions.

No dilepton data at FAIR energies

Physics case

- In-medium modifications of hadrons

- $1 < M_{inv} < 2.5$ GeV/c^2 :
- Temperature of the fireball
- 4π mix. $\rightarrow$ ρ-a_1 chiral mixing
- Onset of QGP radiation



Experiment:
R. Arnaldi et al. [NA60 Coll.], Phys. Rev. Lett. 96, (2006) 162302,
Theory:
R. Rapp, J. Wambach and H. van Hees, in arXiv:0901.3289 hep-ph

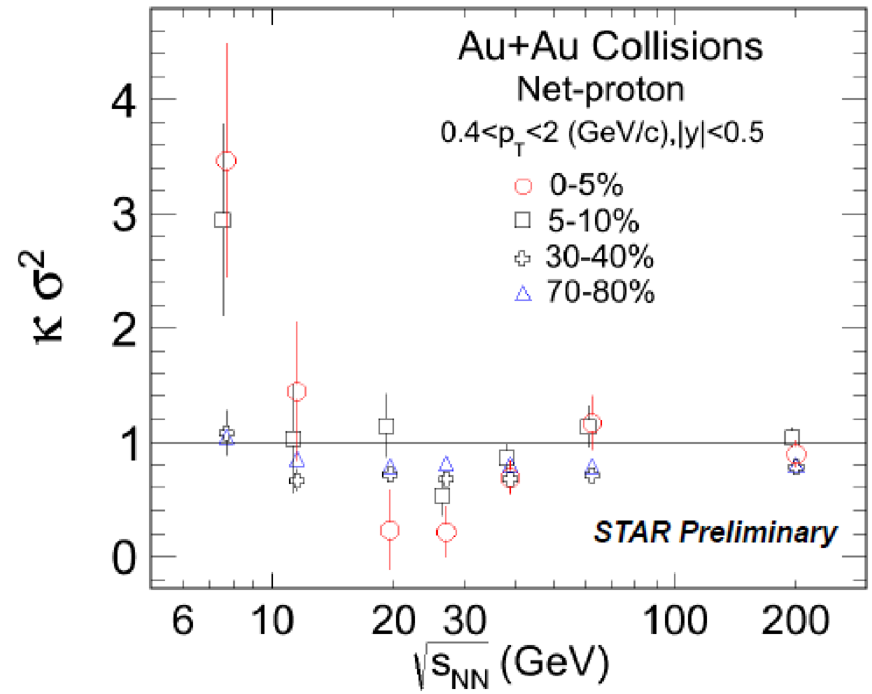
Collective flow, correlations, fluctuations

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

Physics case

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



Few data at FAIR energies

Charm at CBM (SIS100)

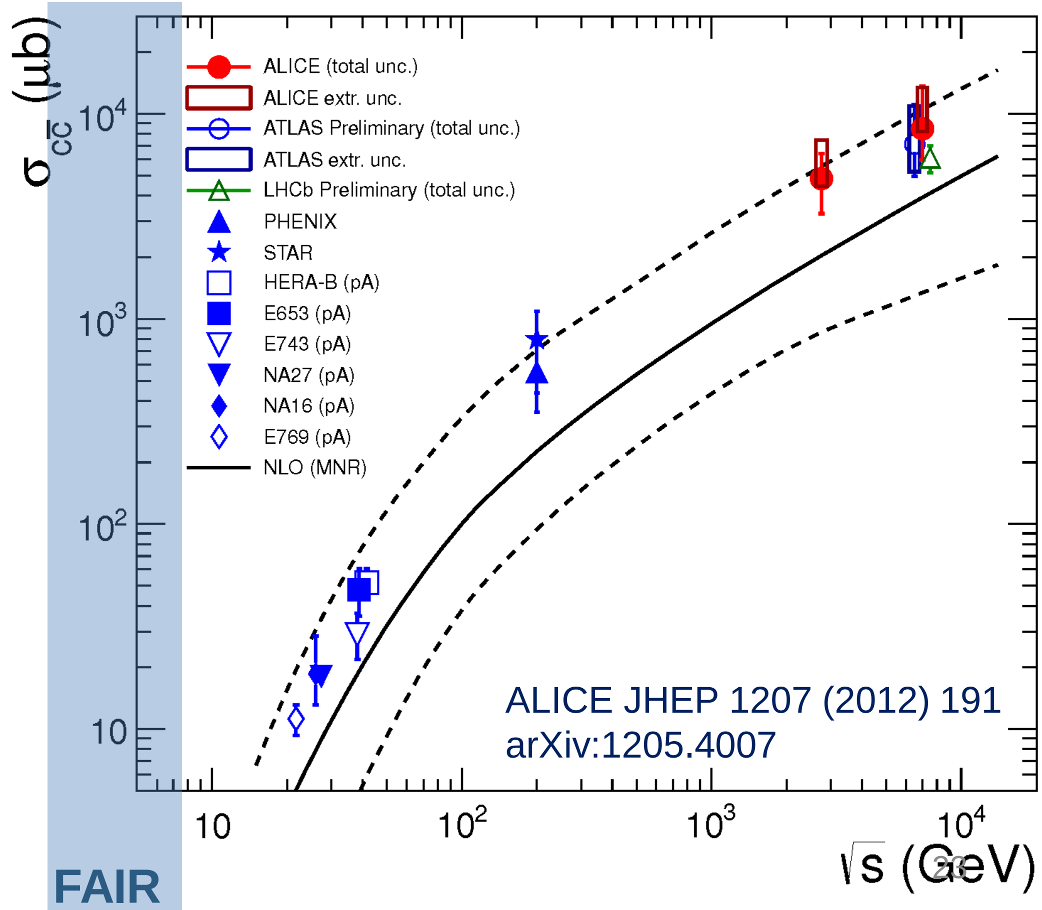
Observables

Cross sections and phase-space distributions of open and hidden charm in proton-nucleus collisions (p+A up to 30 GeV) and nucleus-nucleus collisions (Ni+Ni up to 15 A GeV).

Physics case

- Charm production at threshold energies
- Charm production in cold nuclear matter
- Charm propagation in dense QCD matter

No charm data at FAIR energies

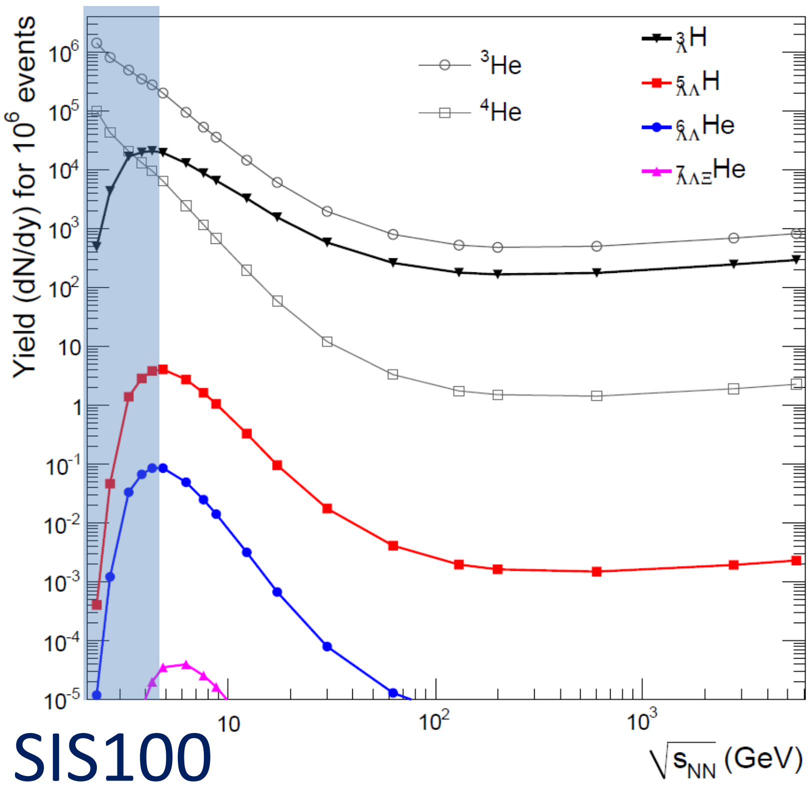


Strange Matter

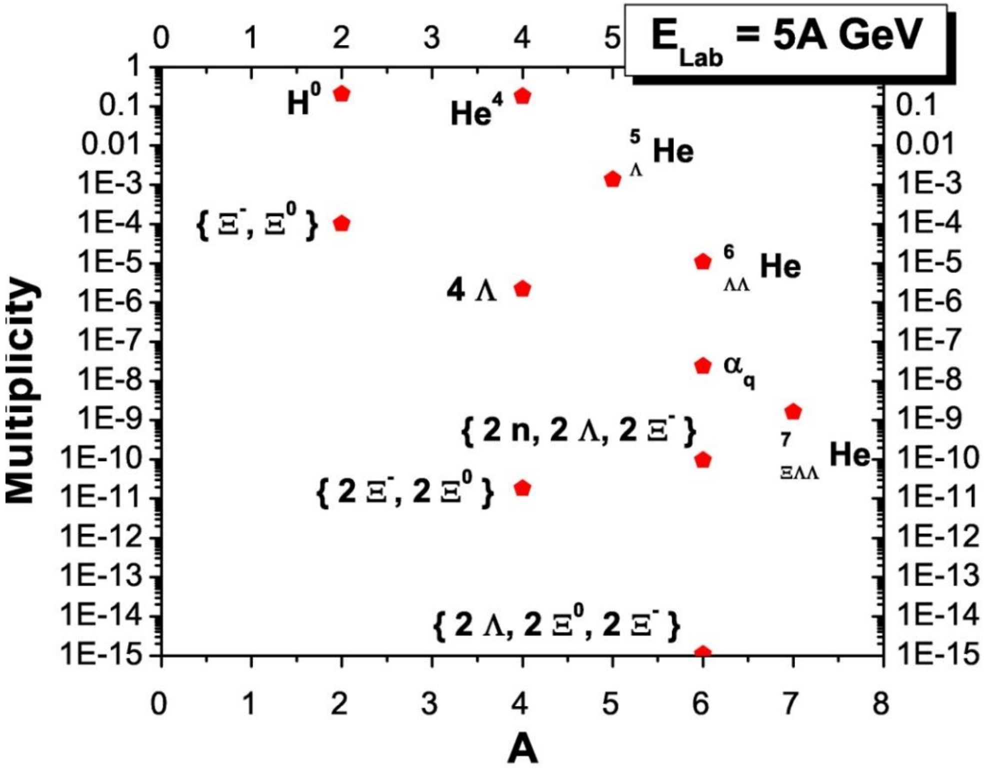
No data at FAIR energies

Observables

Hypernuclei, strange dibaryons and massive strange objects



SIS100

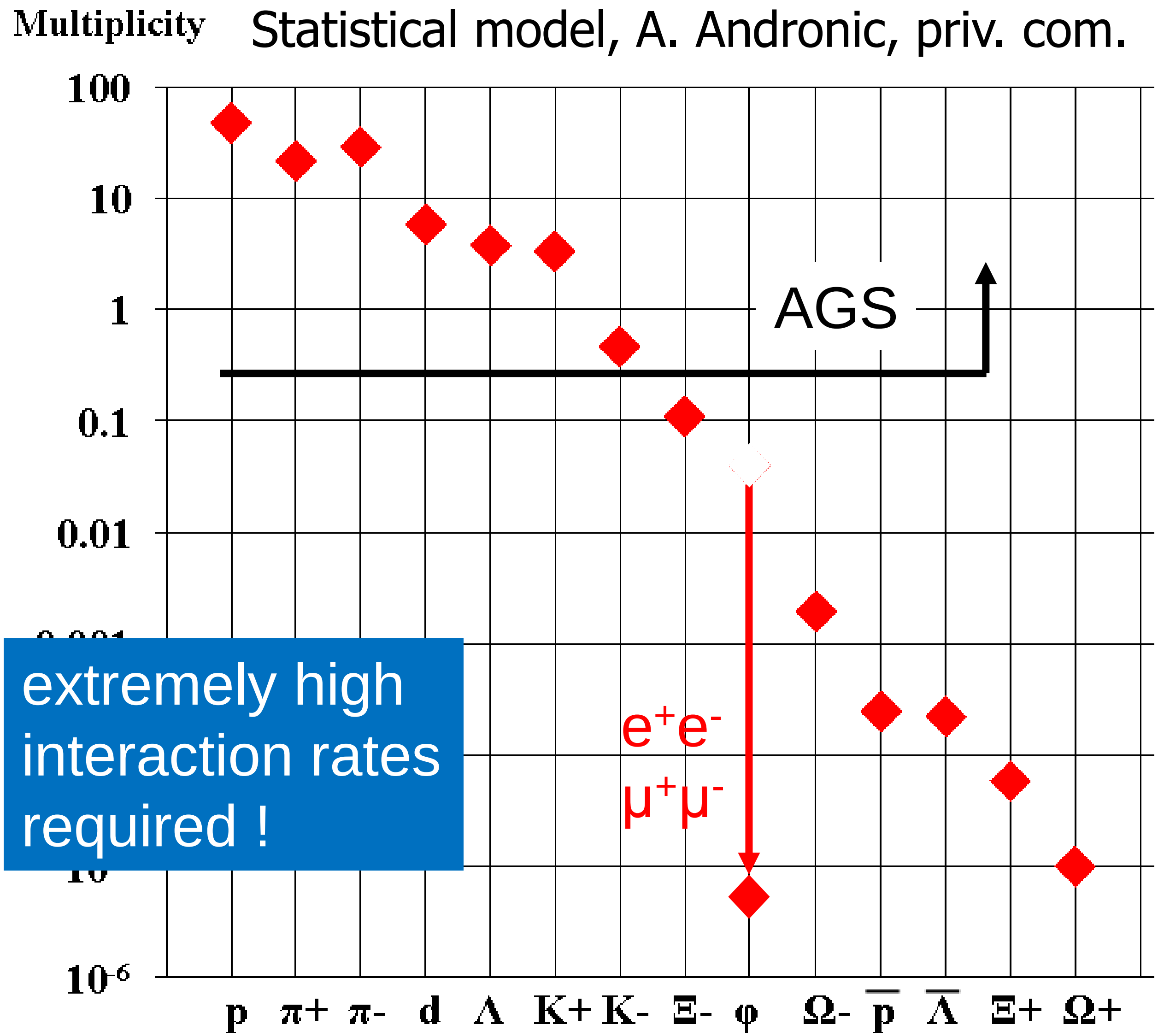


A. Andronic et al., Phys. Lett. B697 (2011) 203

H. Stöcker et al., Nucl. Phys. A 827 (2009) 624c

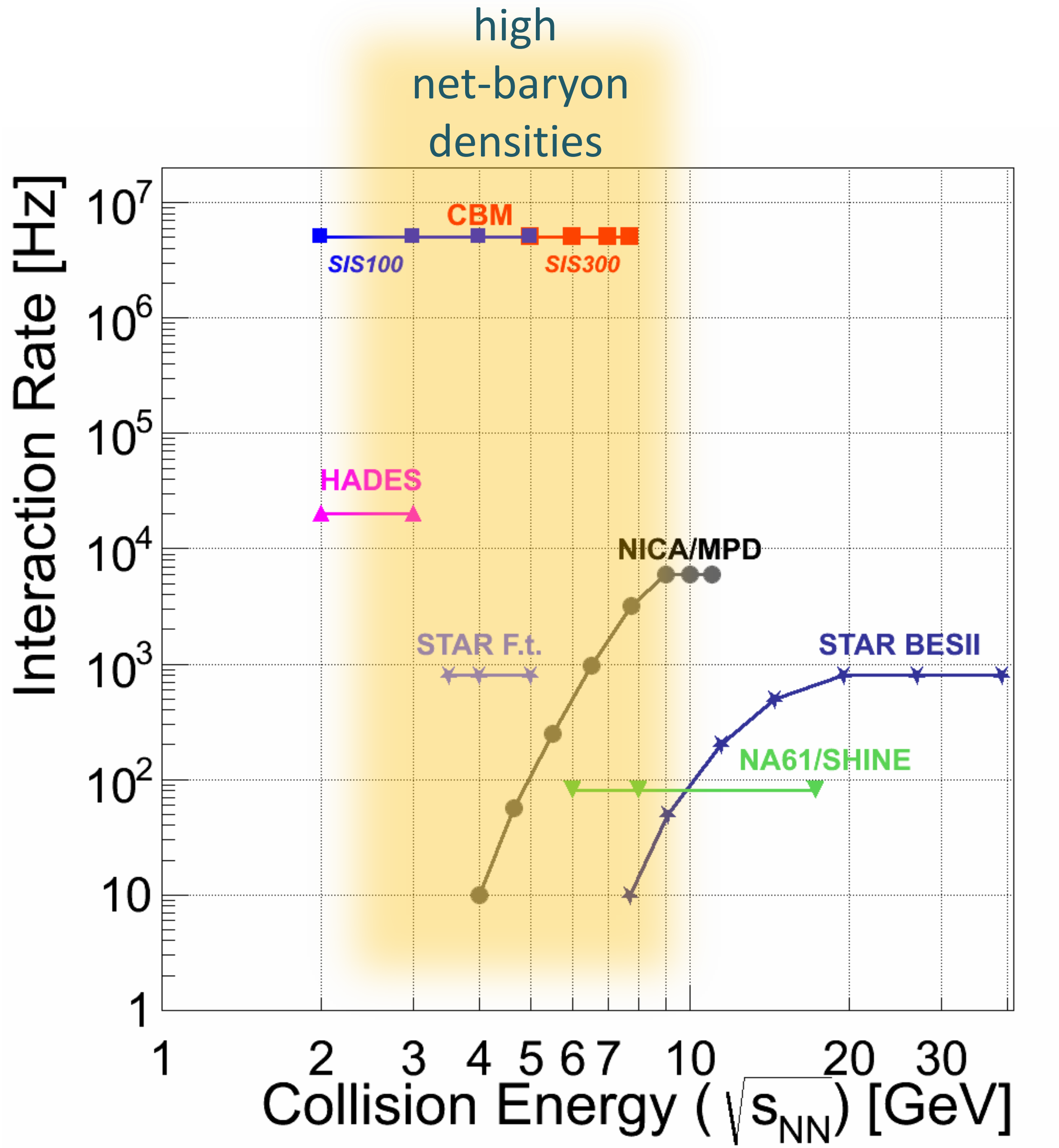
Experimental challenges

Particle yields in central Au+Au 4 A GeV



extremely high interaction rates required !

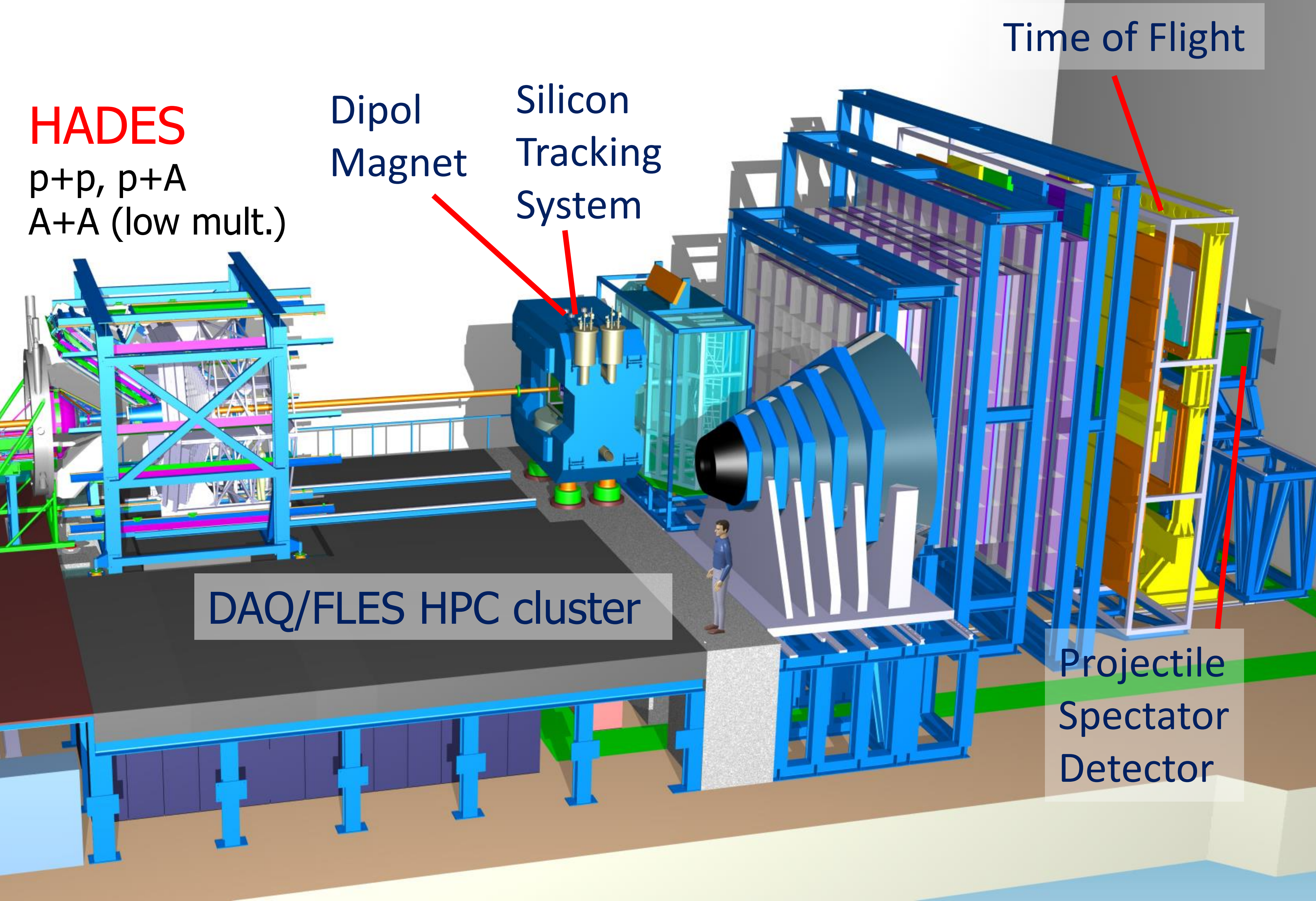
Experiments exploring dense QCD matter



Experimental requirements

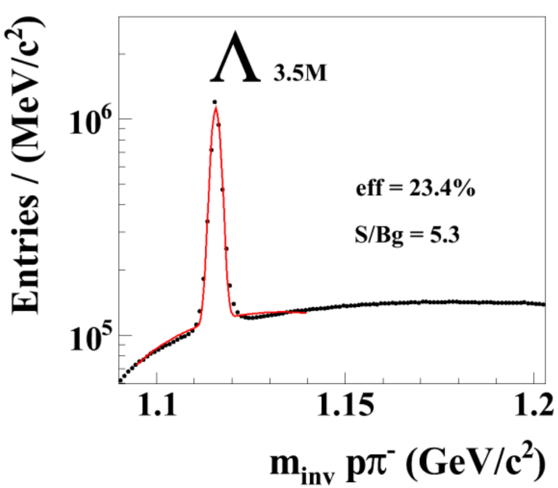
- 10^5 - 10^7 Au+Au reactions/sec
- determination of displaced vertices ($\sigma \approx 50$ μm)
- identification of leptons and hadrons
- fast and radiation hard detectors and FEE
- free-streaming readout electronics
- high speed data acquisition and high performance computer farm for online event selection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

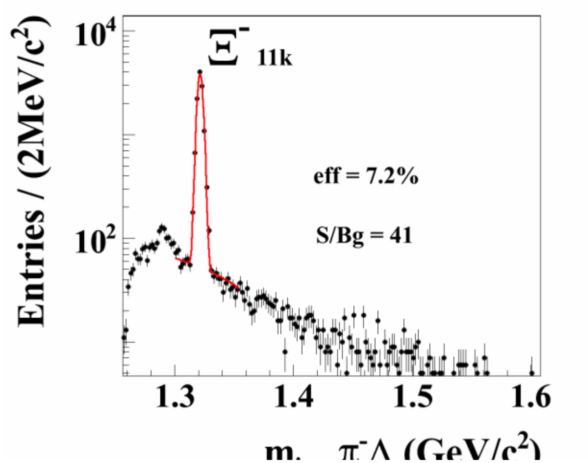
Experimental requirements

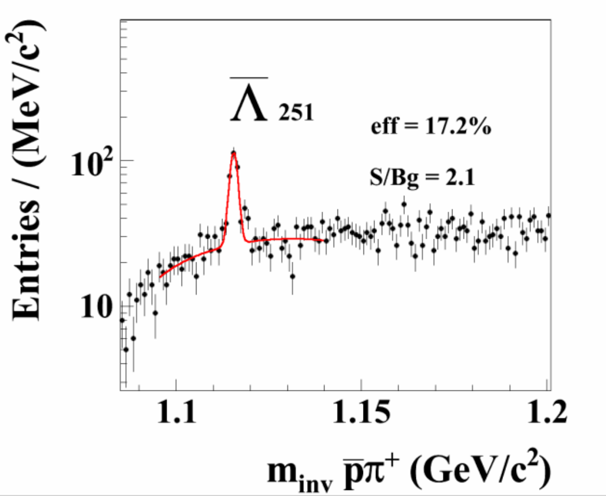


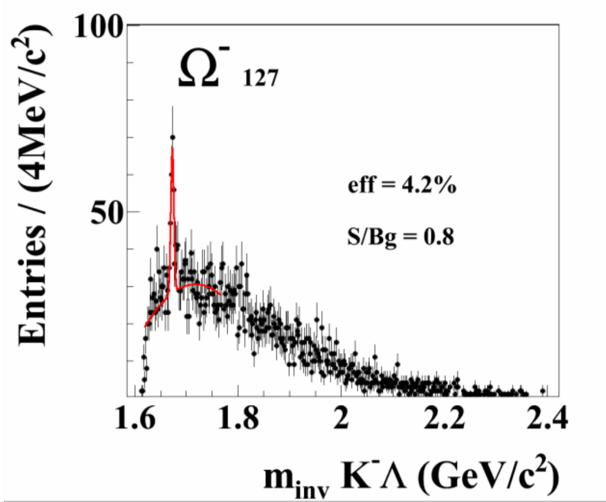
Hyperons in CBM at SIS100

Example: Au+Au at 8 A GeV, 10^6 central collisions (UrQMD)









- In addition:

  K*,Λ*,Σ*,Ξ*,Ω*

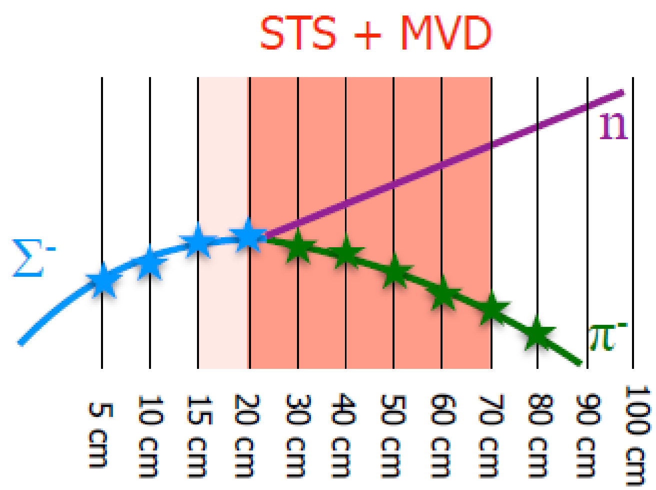
- Event rate:

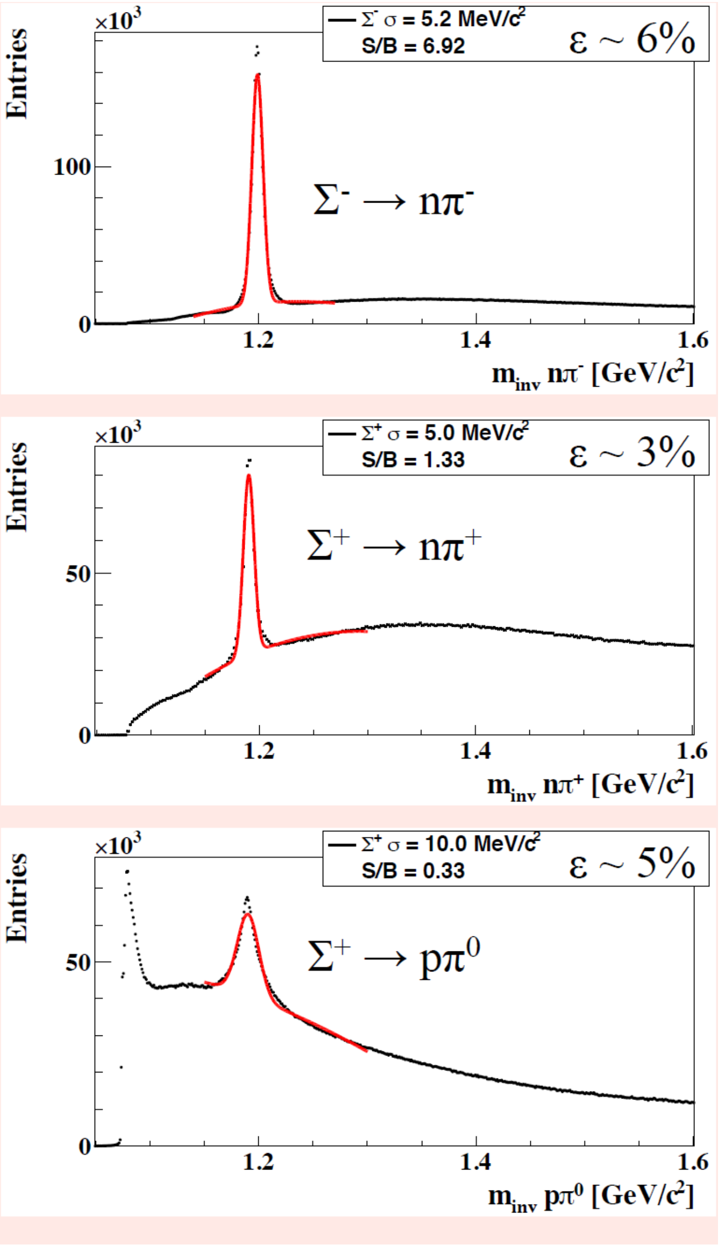
  100 kHz to 1 MHz

Hyperons in CBM at SIS100

Au+Au at 10 A GeV
$5 \cdot 10^6$ central collisions
(UrQMD)

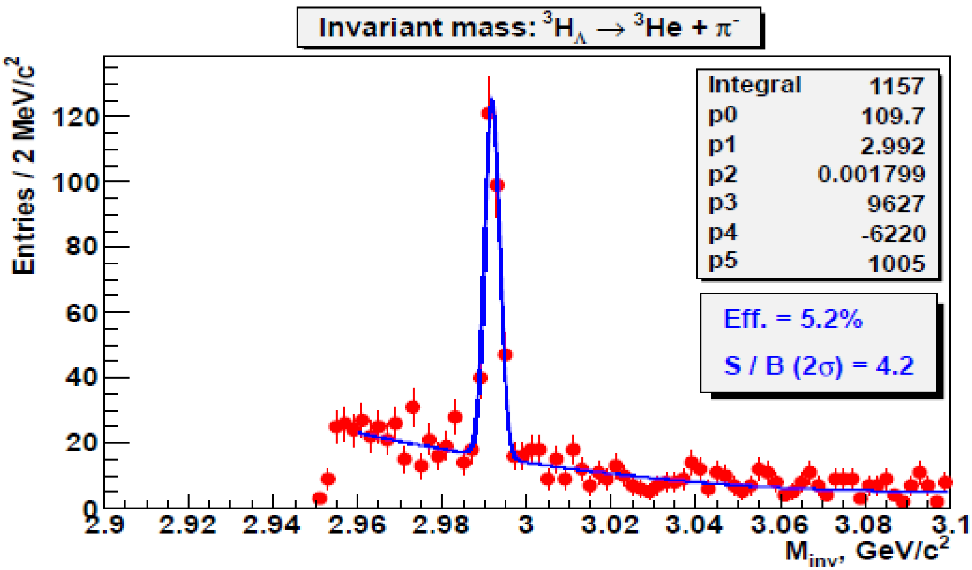
missing mass analysis:

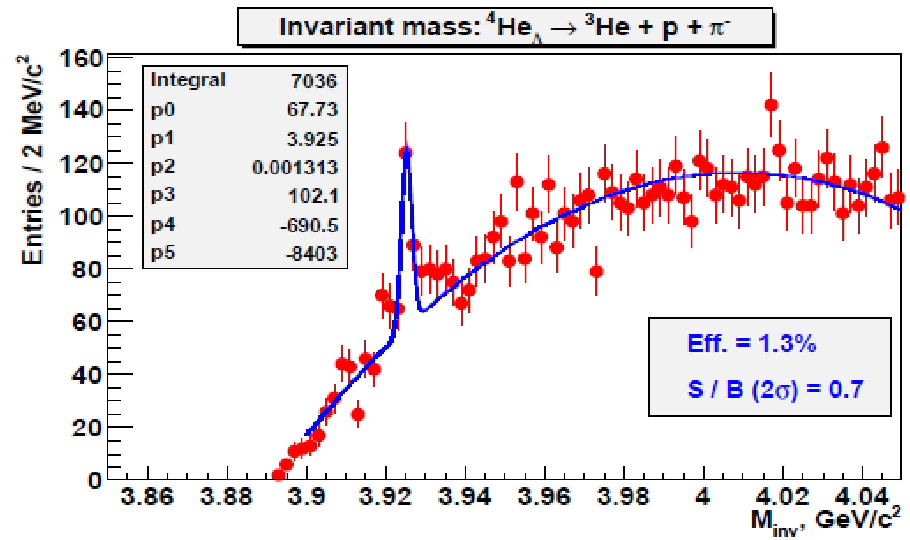


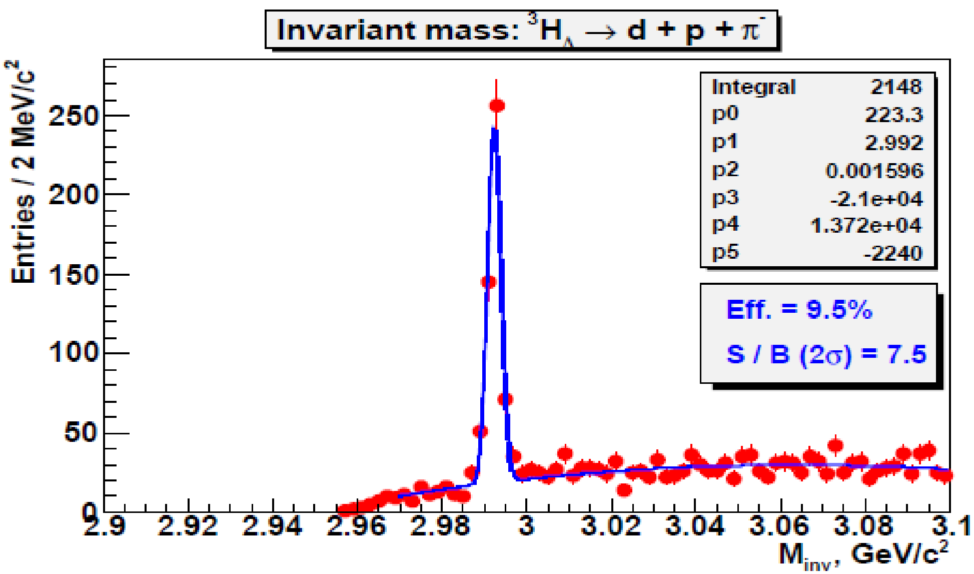


Hypernuclei in CBM at SIS100

Au+Au at 10 A GeV







Hyper nuclei	M central	BR	ε %	Yield/week central
${}_{\Lambda}{}^{3}H$	$2\cdot10^{-2}$	0.6	7	$4.6\cdot10^{7}$
${}_{\Lambda\Lambda}{}^{5}H$	$6\cdot10^{-6}$	0.36	1	1300

central collision rate 100 kHz

BR = 36% for double lambda hypernuclei is a guess

Reconstruction of a multistrange di-baryon

Signal: strange dibaryon

$(\Xi^0\Lambda)_b \rightarrow \Lambda\Lambda$ (cτ=3cm)

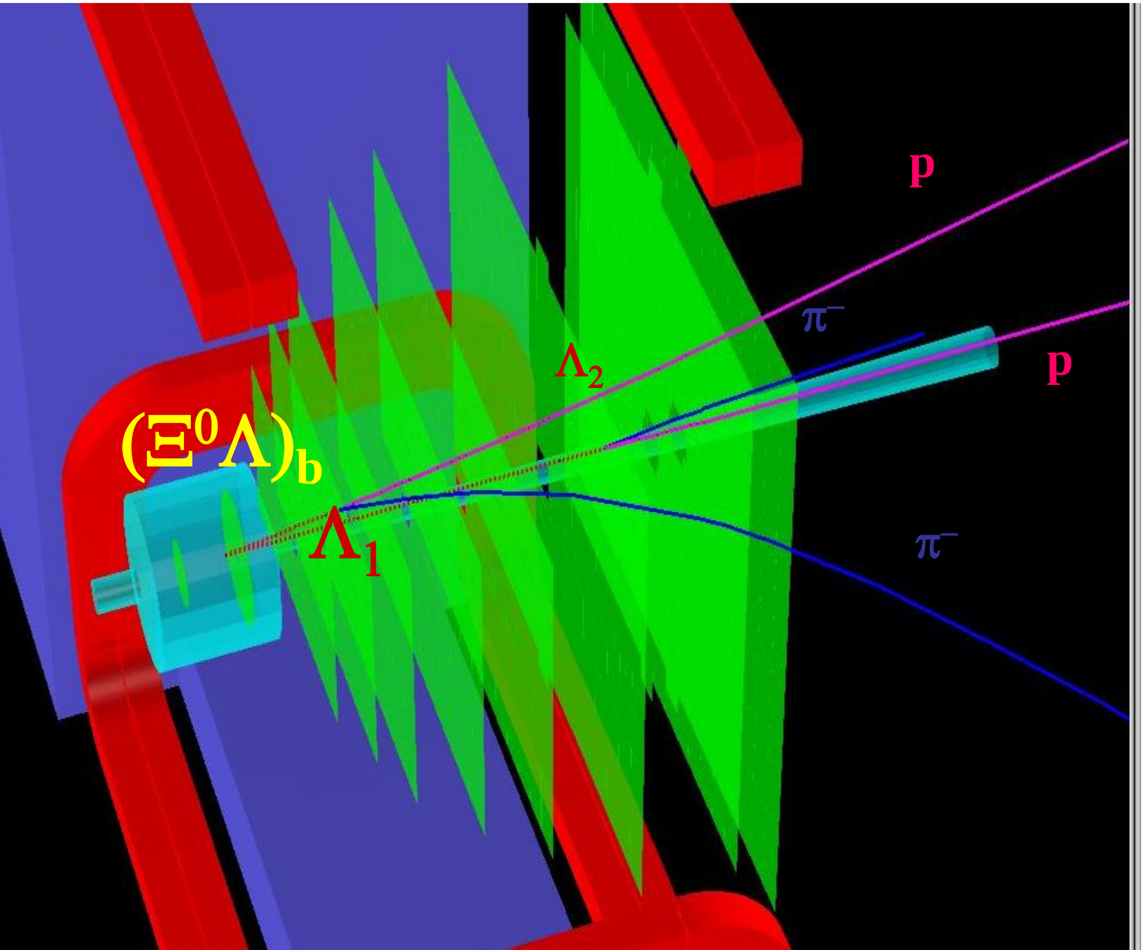
M= 10^{-6}, BR = 5%

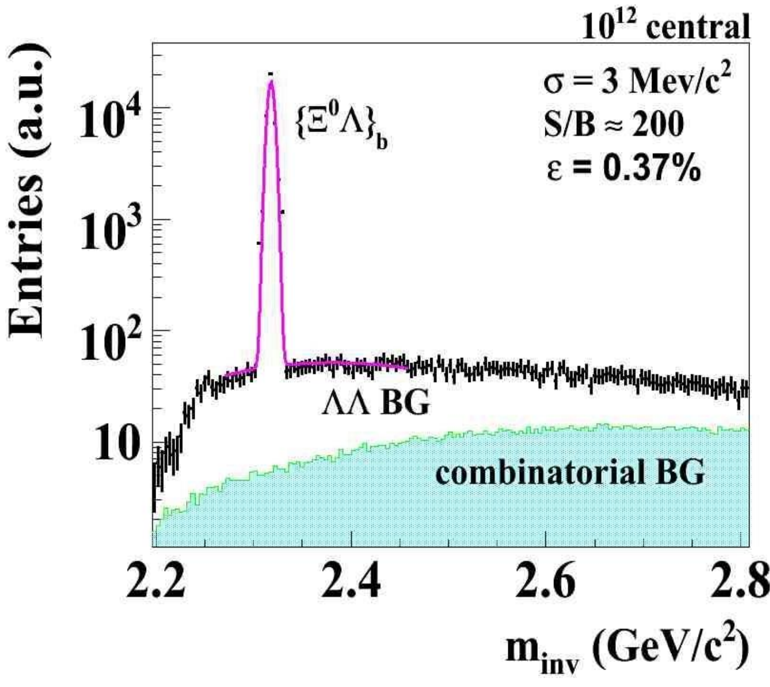
Background:

central Au+Au collision

32 Λ per central event

11 Λ reconstructable



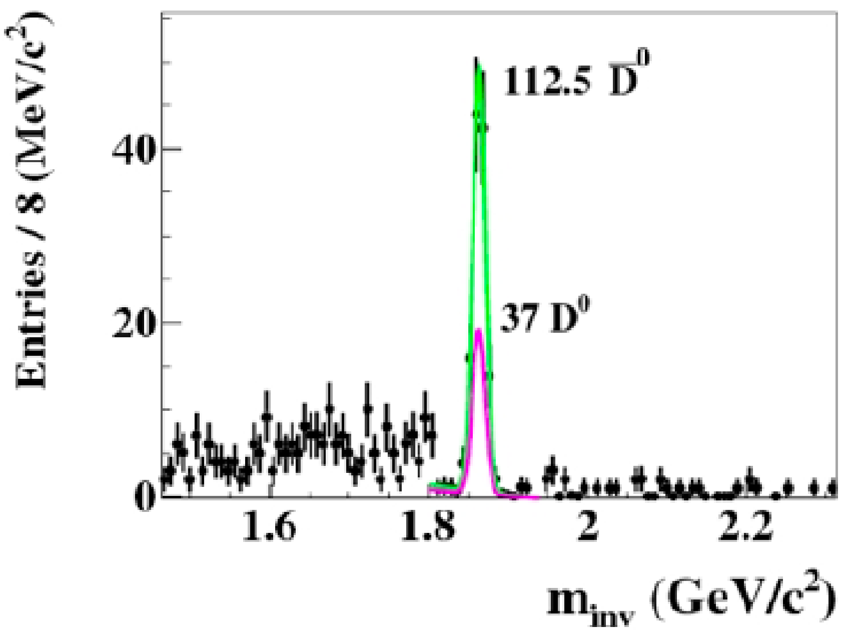


Open charm in CBM at SIS100

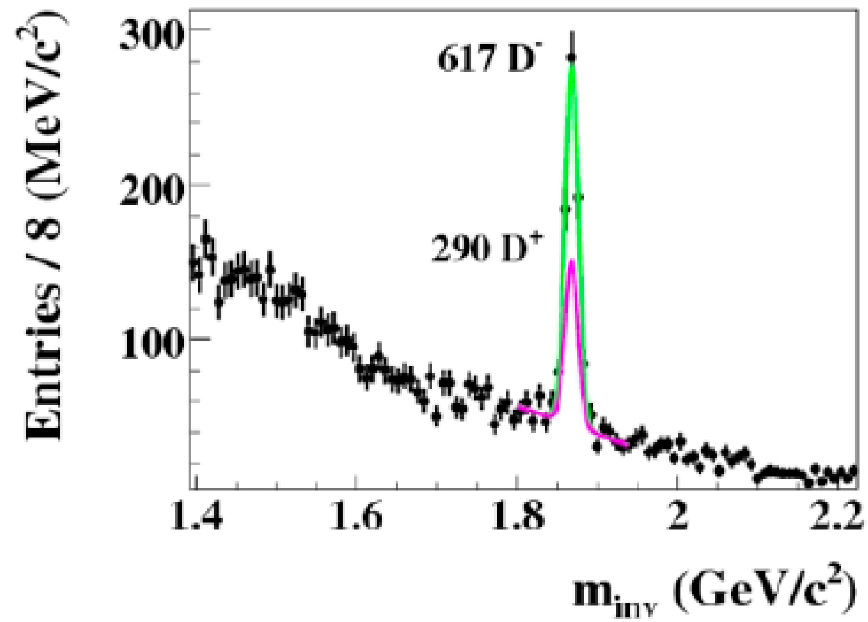
- Charm production cross sections at threshold energies
- Charm propagation in cold nuclear matter

30 GeV p + C

$D^0 \rightarrow K\pi\pi\pi$

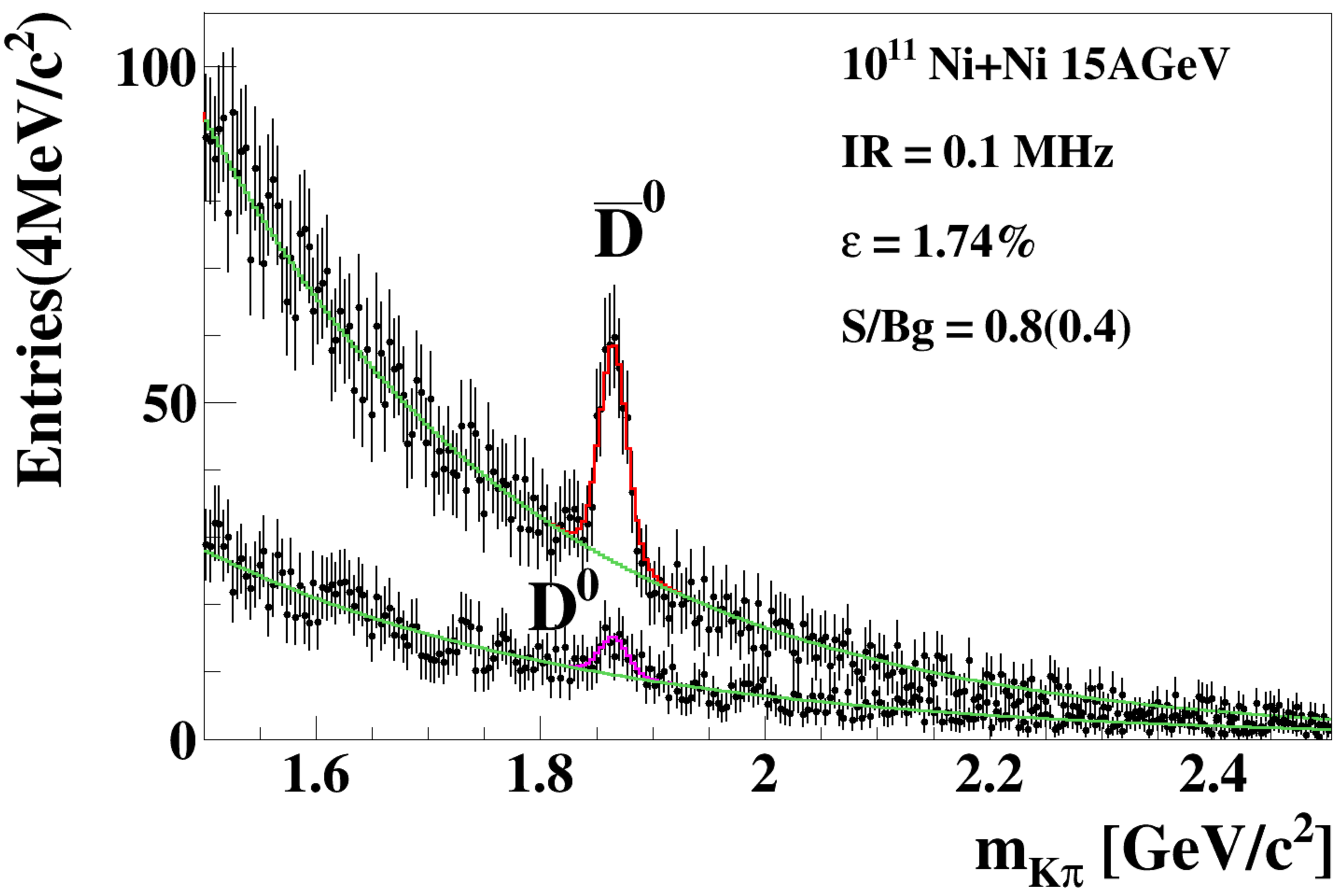


$D^{\pm} \rightarrow K\pi\pi$

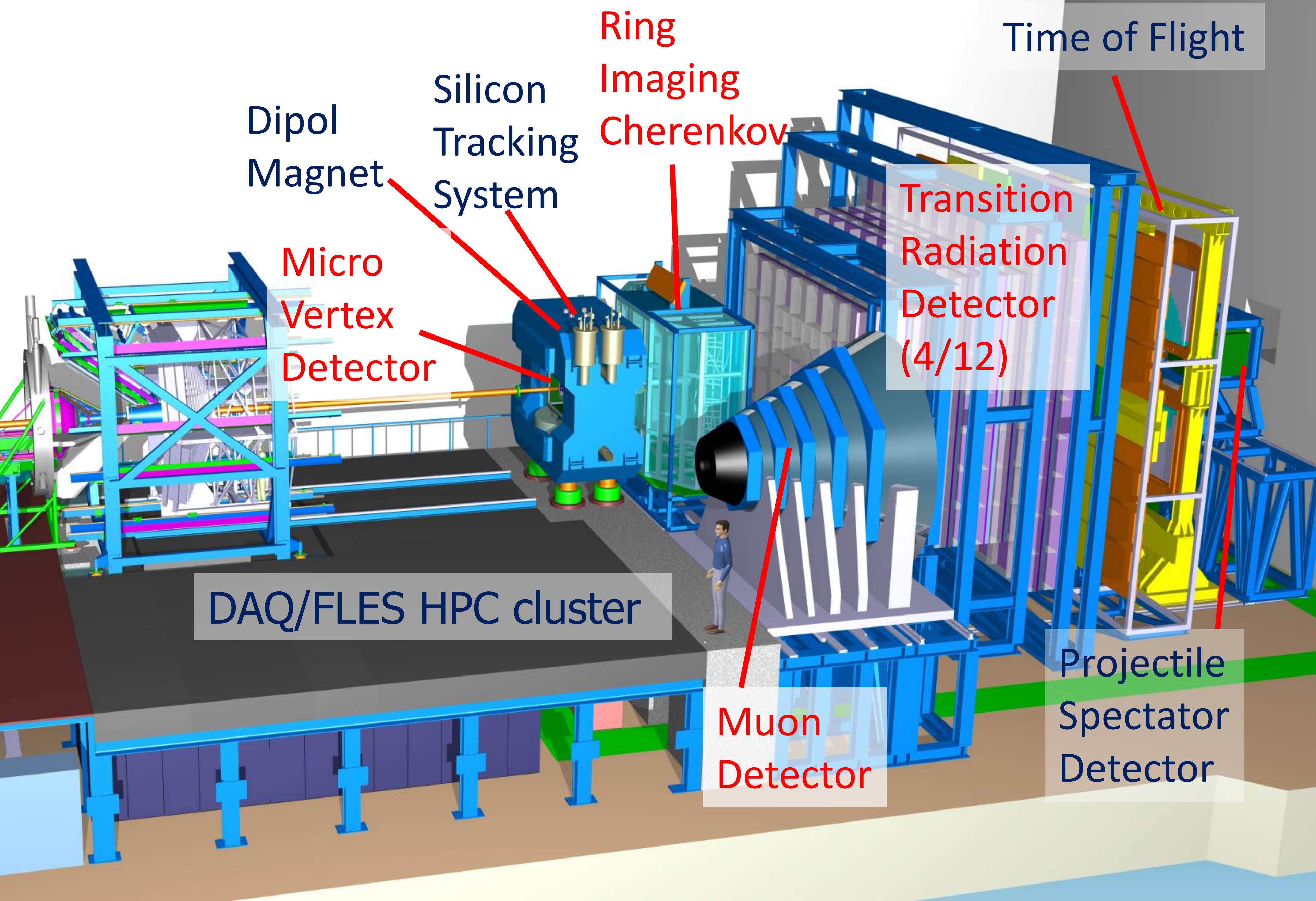


Open charm in CBM at SIS100

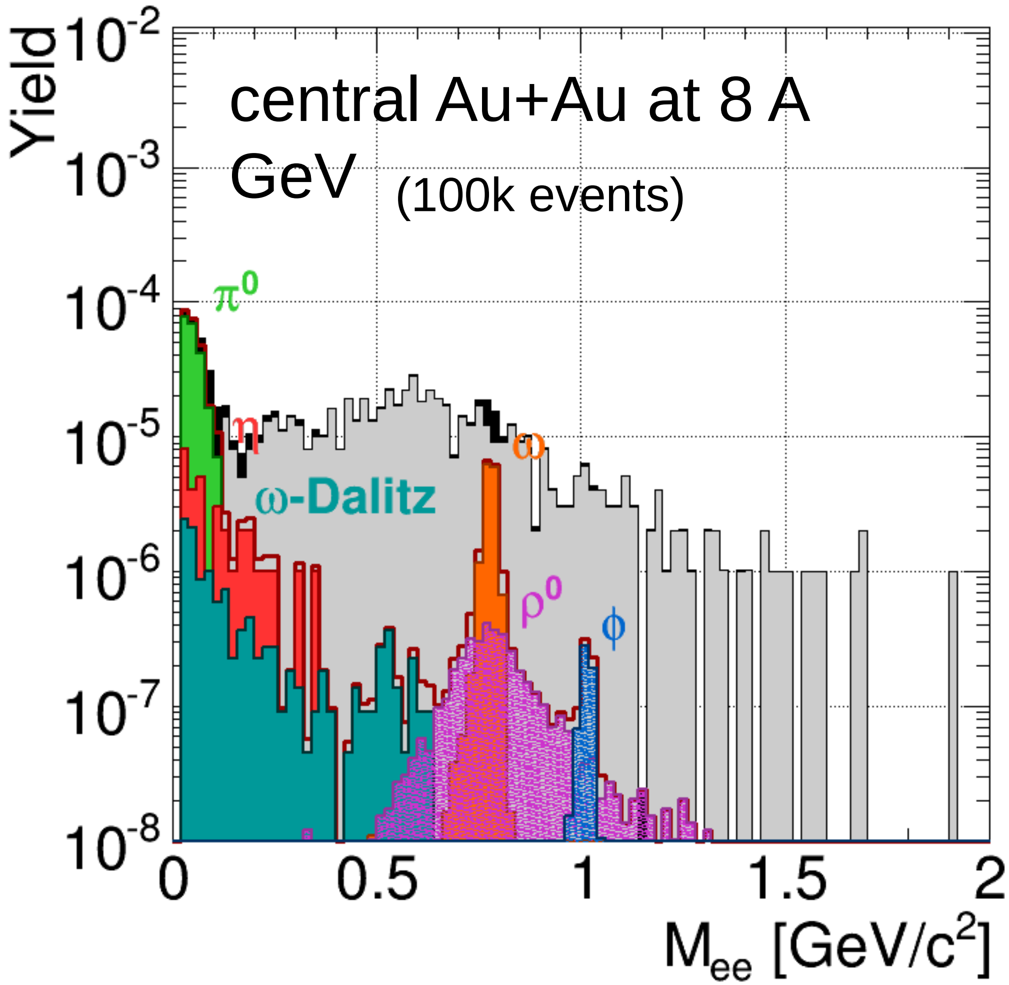
- Charm production and propagation in hot nuclear matter
- D multiplicities from thermal model (V. Vovchenko)
- 2 weeks Ni + Ni at 15 A GeV: 260 $\overline{D}^0$, 45 D^0



Experimental requirements



Electrons in CBM at SIS100



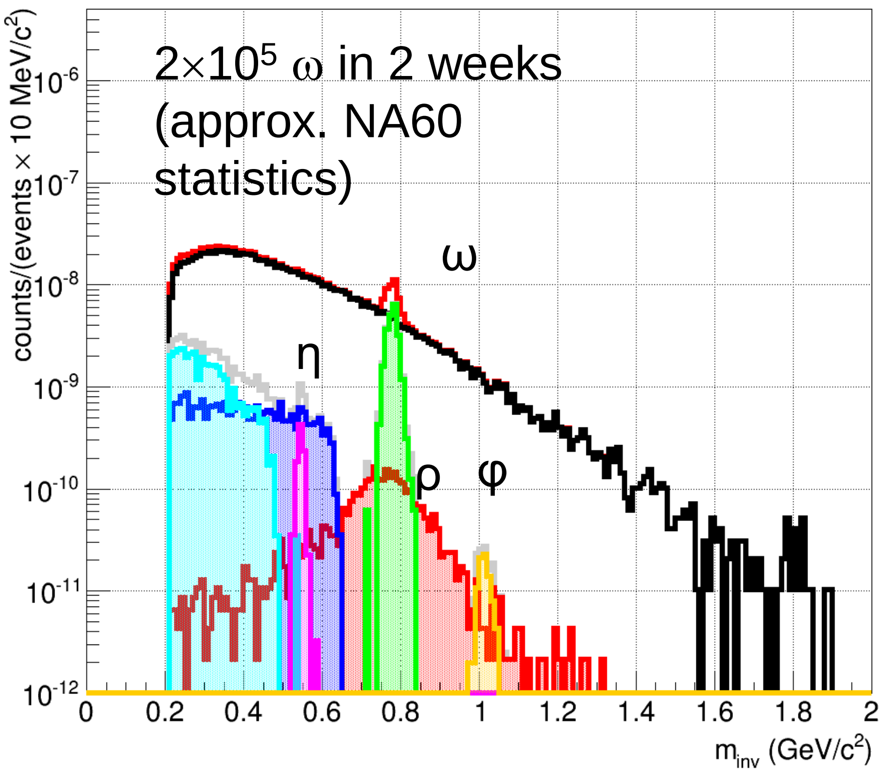
8 A GeV:
2×10^6 ω in 2 weeks

Simulation:
Signal yields from HSD
Background from UrQMD

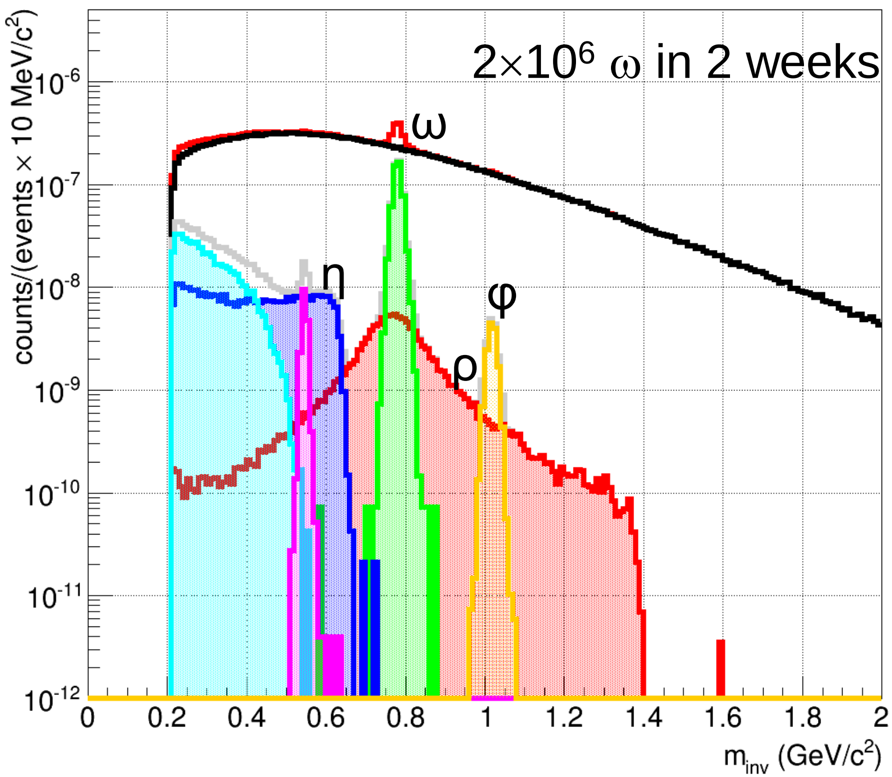
Muons in CBM at SIS100

Simulation: Signal yields from HSD, Background from UrQMD

central Au+Au at 4 A GeV

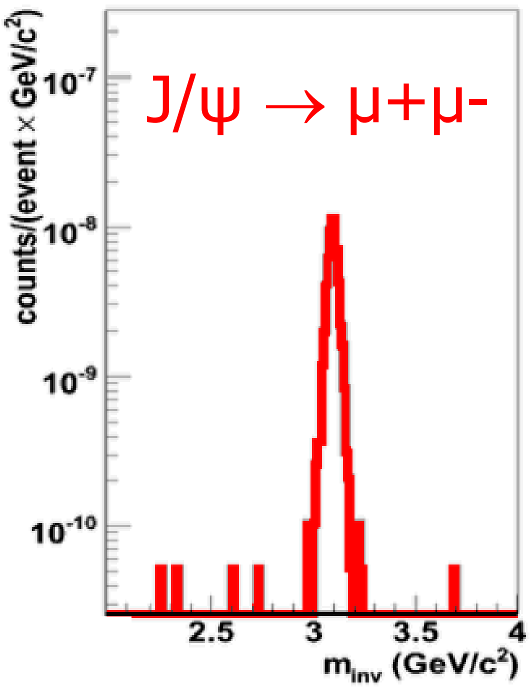


central Au+Au at 8 A GeV



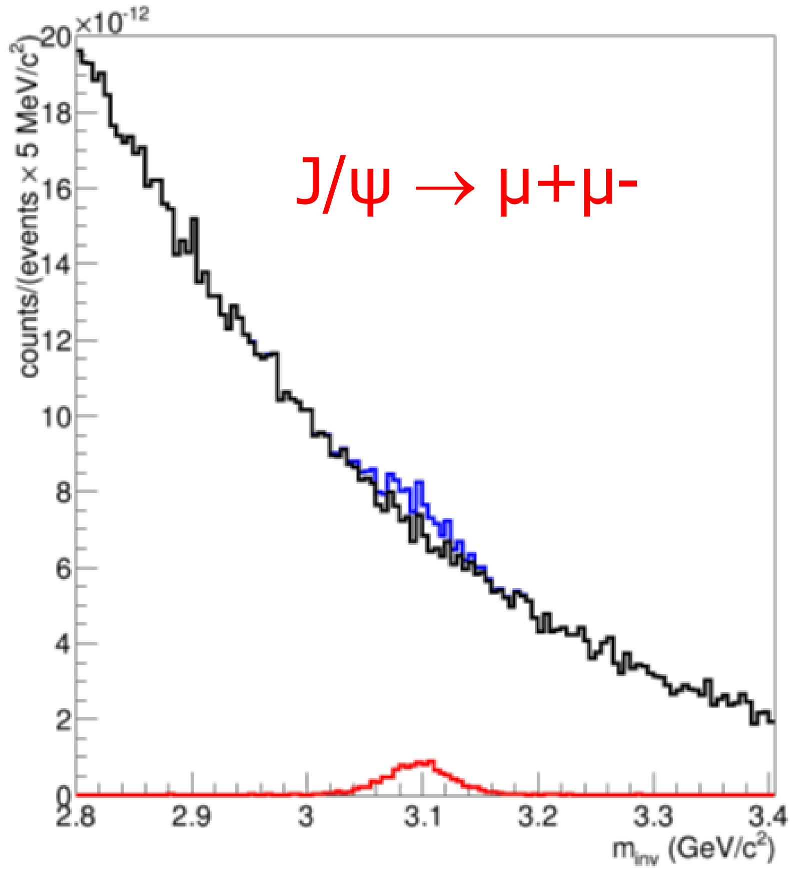
Hidden charm in CBM at SIS100

30 GeV p + Au



1000 J/ψ in 10^{12} events (1 day)
(multiplicity from HSD)

central Au+Au at 10 A GeV



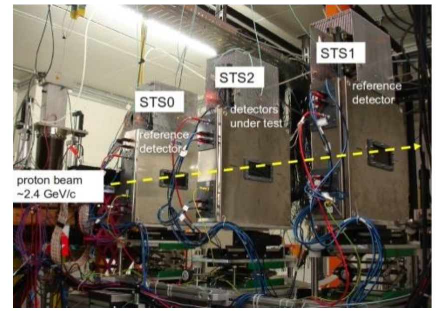
1000 J/ψ in 10^{13} events (10 days)
(multiplicity from HSD)

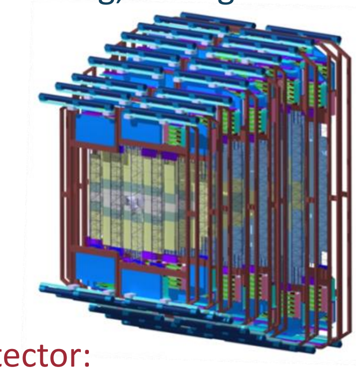
CBM Technical Developments

SC Magnet: JINR Dubna

Micro-Vertex Detector:
Frankfurt, Strasbourg

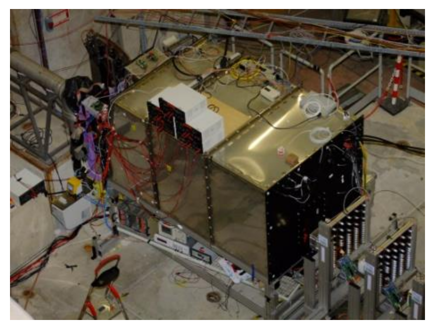
Silicon Tracking System: Darmstadt, Dubna, Krakow, Kiev, Kharkov, Moscow, St. Petersburg, Tübingen



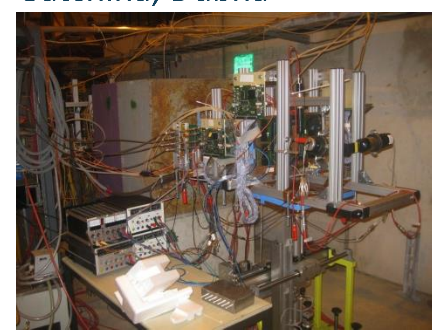


MRPC ToF Wall: Beijing, Bucharest, Darmstadt, Frankfurt, Hefei, Heidelberg, Moscow, Rossendorf, Wuhan

RICH Detector:
Darmstadt, Giessen, Pusan, St. Petersburg, Wuppertal

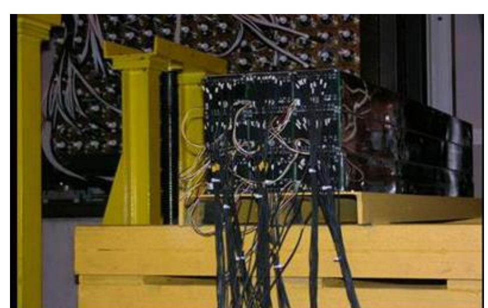


Muon detector:
Kolkata + 13 Indian Inst., Gatchina, Dubna

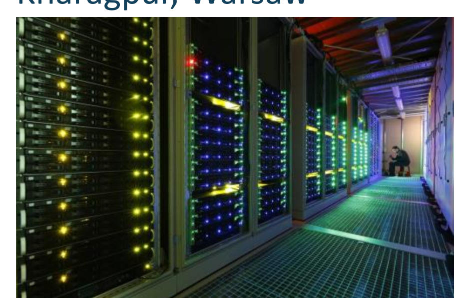


Transition Radiation Detector:
Bucharest, Dubna, Frankfurt, Heidelberg, Münster

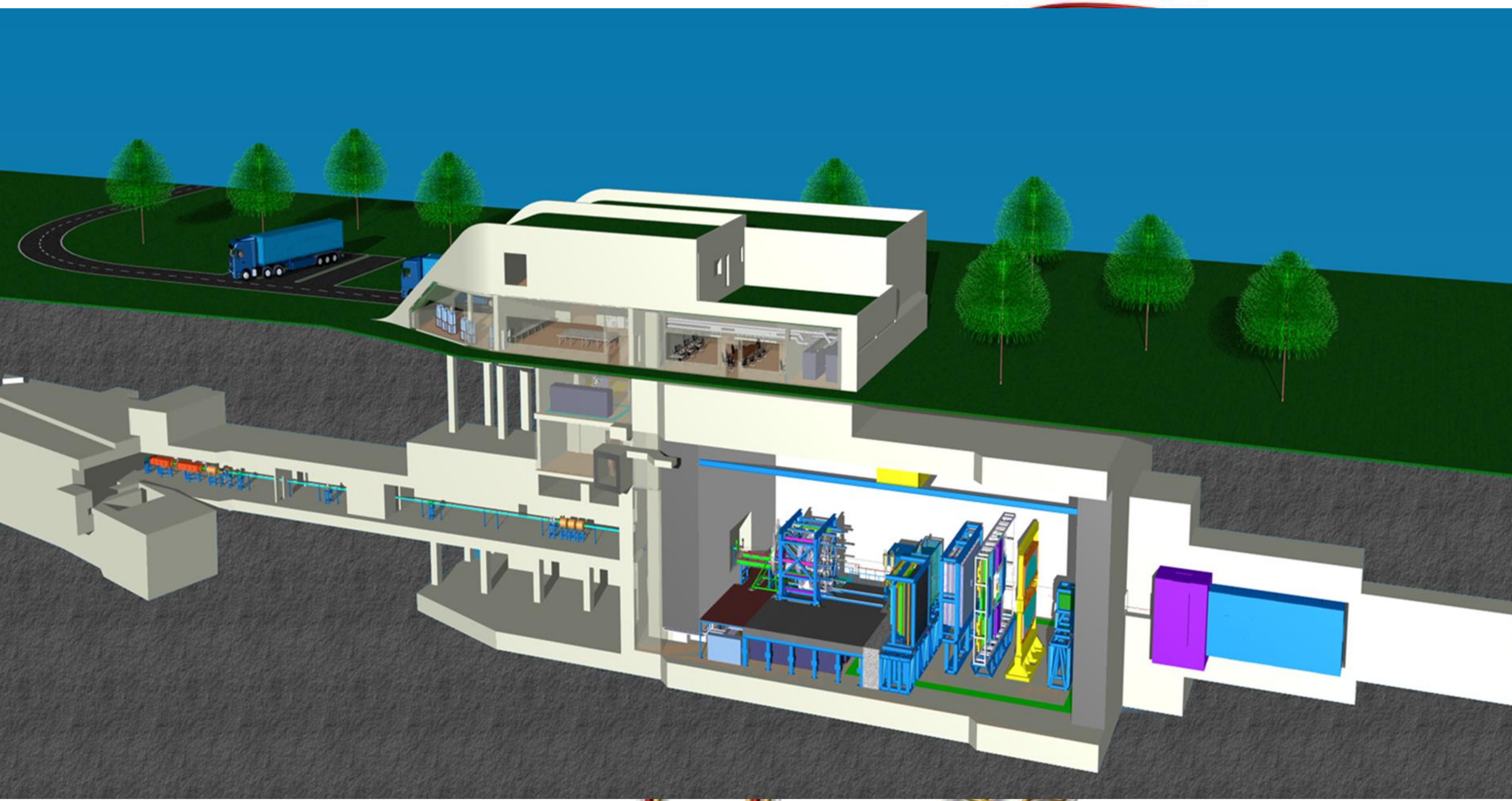
Forward calorimeter:
Moscow, Prague, Rez



DAQ and online event selection:
Darmstadt, Frankfurt, Heidelberg, Kharagpur, Warsaw



Facility for Antiproton & Ion Research



- 10^9/s Au up to 11 GeV/u
- 10^9/s C, Ca, ... up to 14 GeV/u
- 10^{11}/s p up to 29 GeV

FAIR phase 1
FAIR phase 2

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.

日本国 ？

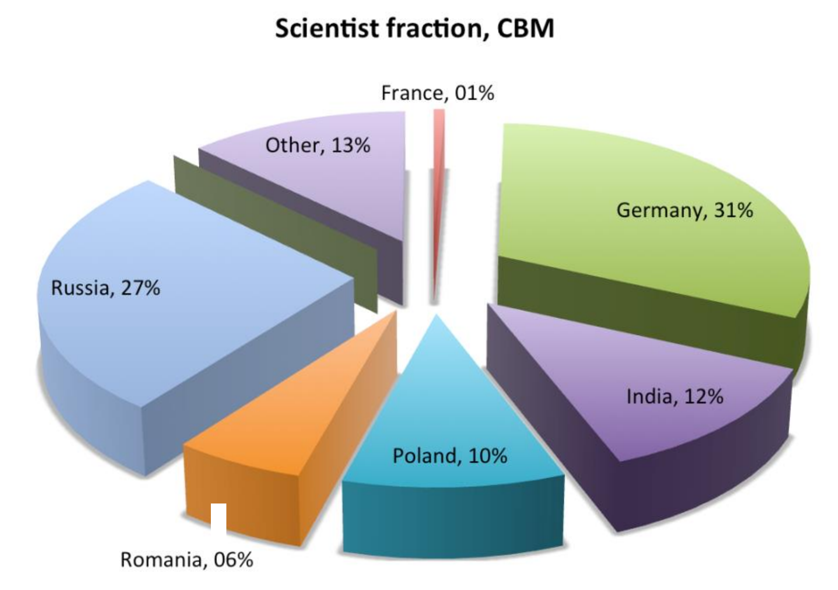
Korea:
Pusan Nat. Univ.

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

Romania:
NIPNE Bucharest
Univ. Bucharest

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

- The experiments at FAIR address fundamental questions in hadron, nuclear, atomic and plasma physics, and explore new frontiers in material and bio physics.
- The unique features of the FAIR accelerators are high-intensity primary and secondary beams.
- CBM scientific program at SIS100:
  Exploration of the QCD phase diagram in the region of neutron star core densities $\rightarrow$ 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 $\rightarrow$ terra incognita.
- Participation of Japanese scientists is most welcome