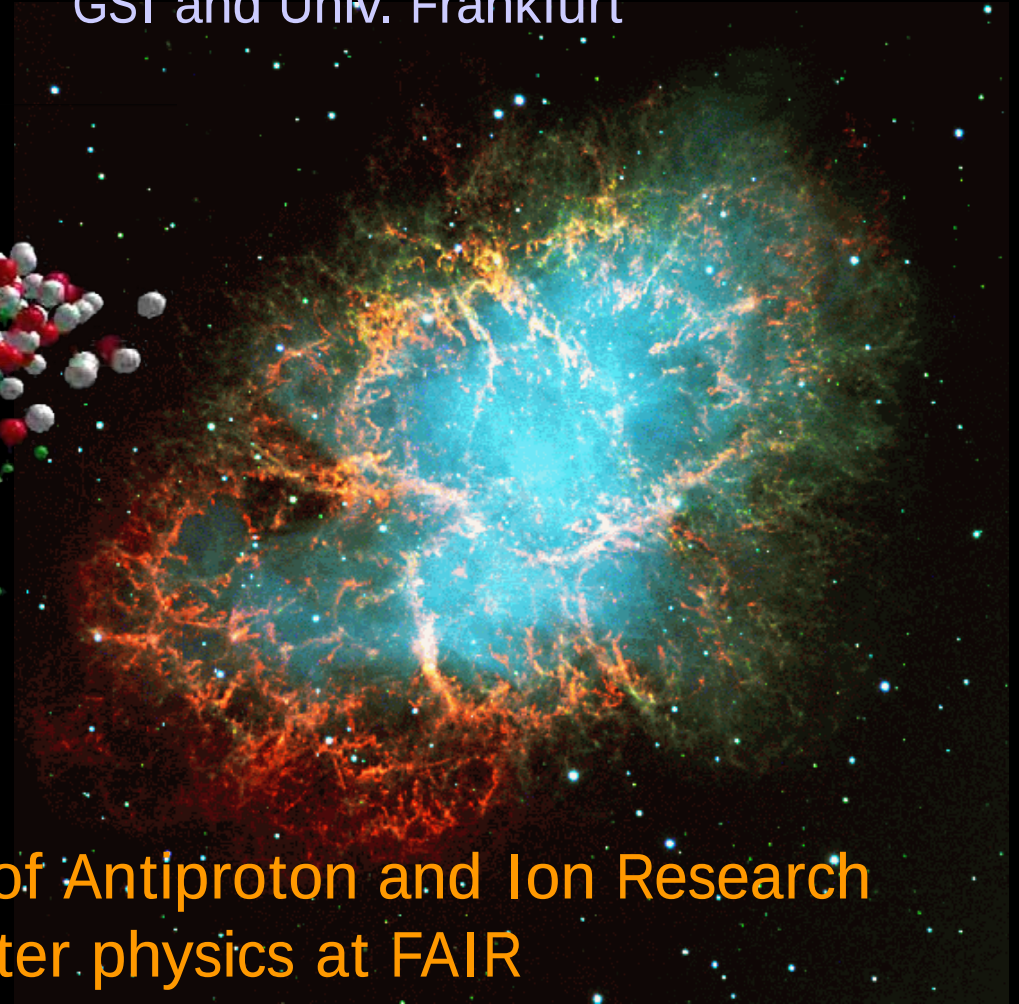
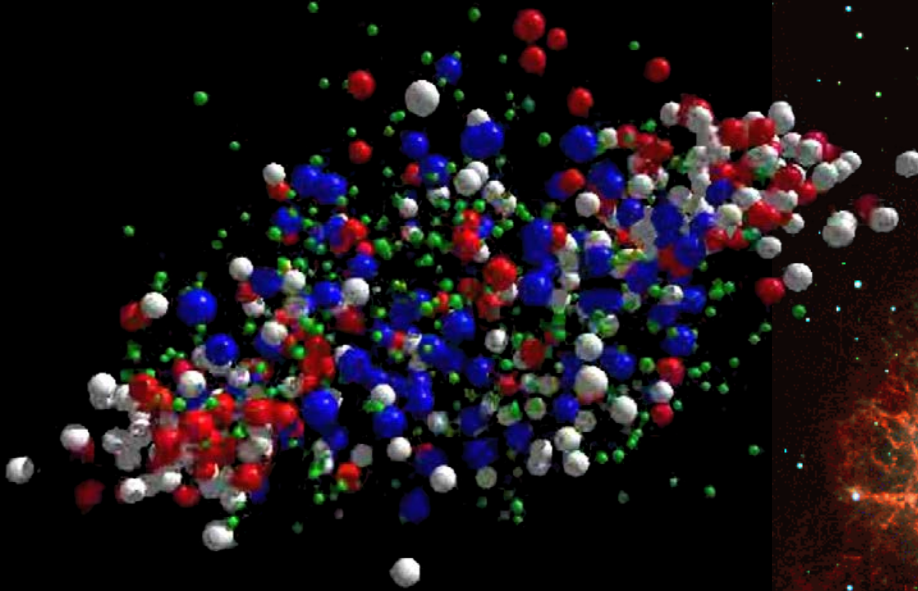


Nuclear Matter physics at FAIR

Peter Senger

GSI and Univ. Frankfurt



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

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

Technical Challenges

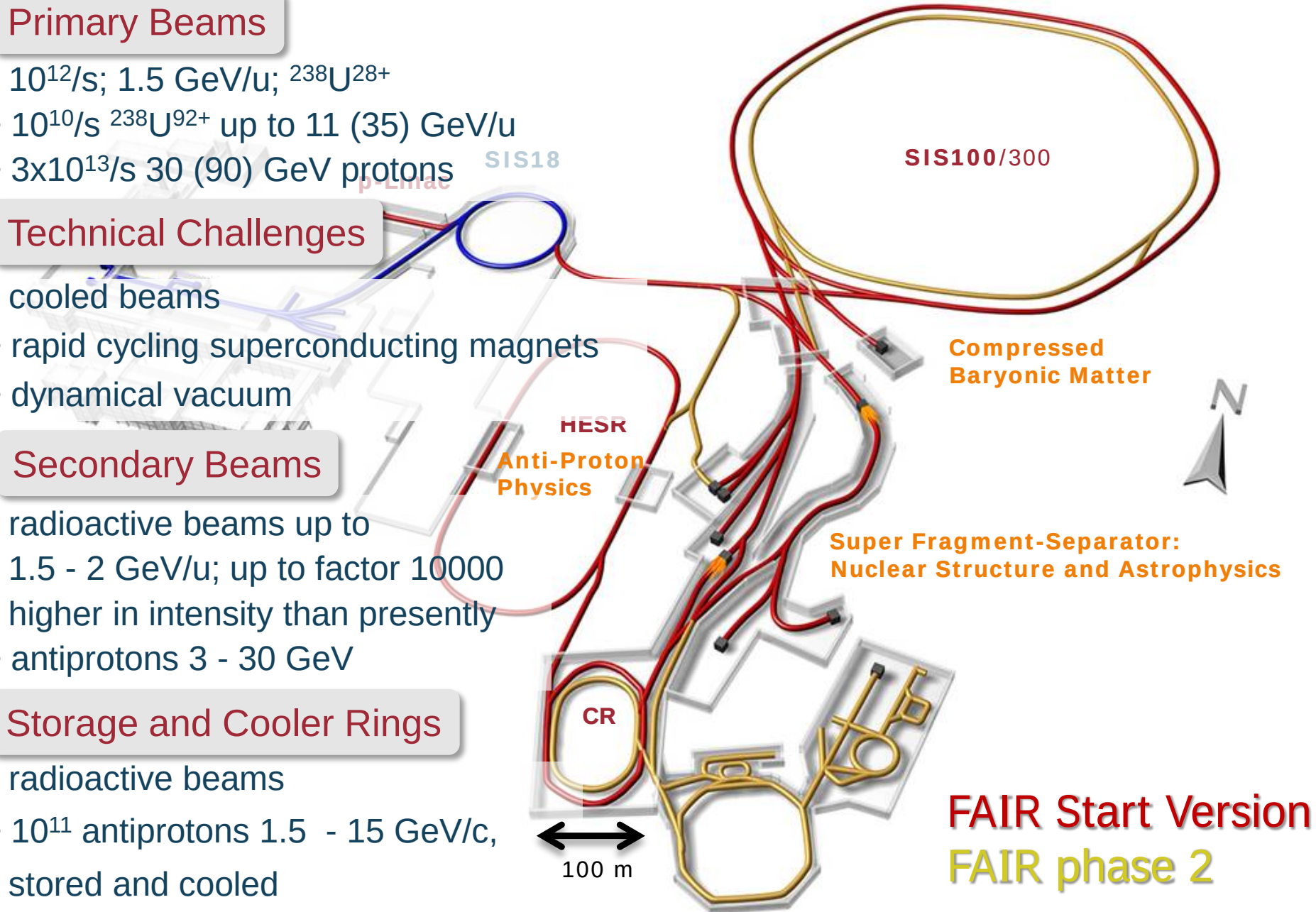
- cooled beams
- rapid cycling superconducting magnets
- dynamical vacuum

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 concrete 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:

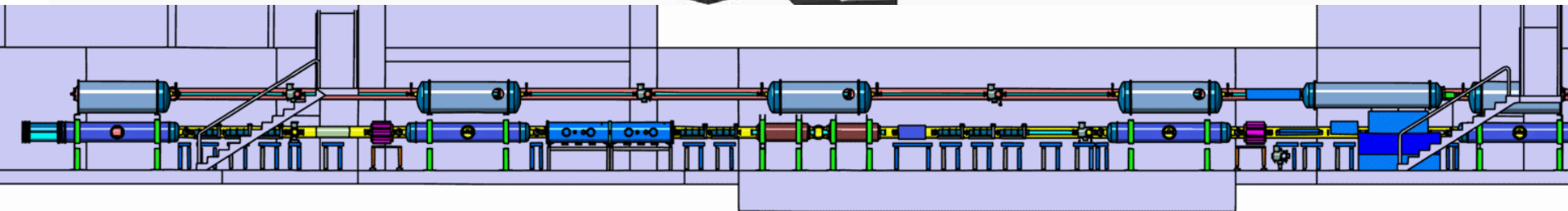
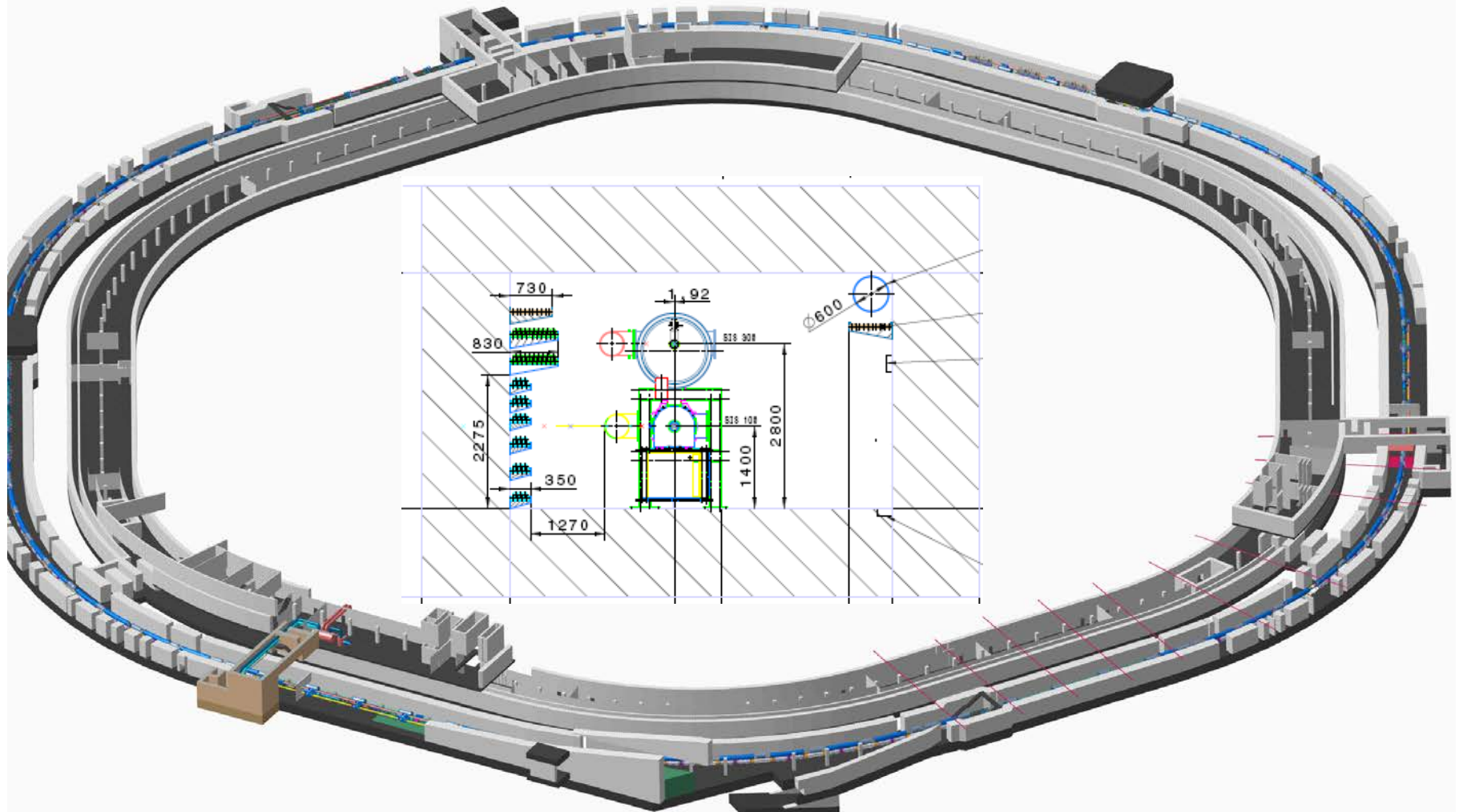
- Recommendation to restructure the FAIR management,
- Confirmation of the FAIR science program.

Decision of the FAIR shareholders:

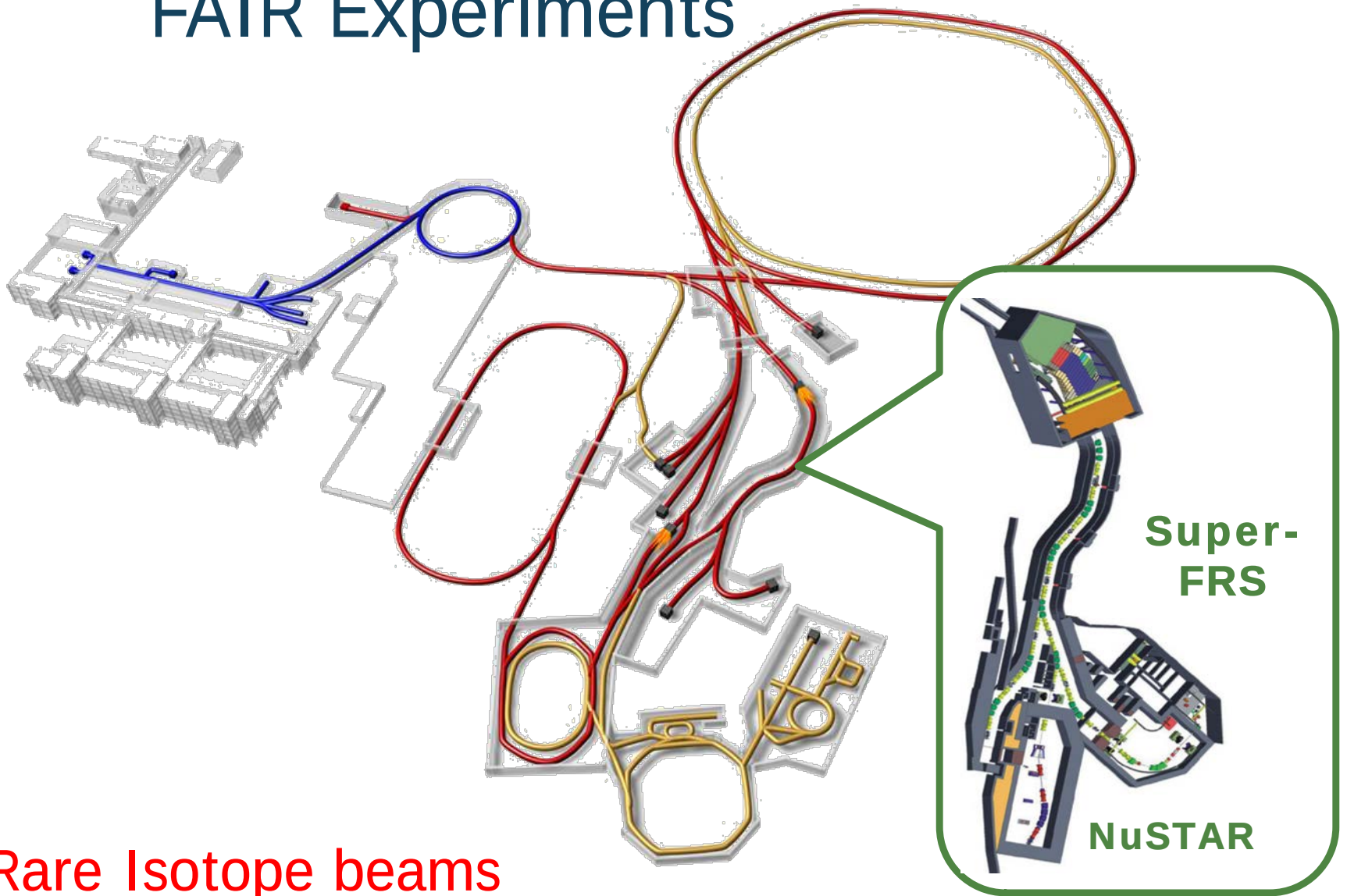
- Build Start Version within staged approach and a cost cap.
- No reduction of the scientific scope.
- Commitment for 2/3 of missing funding in June 2016
- Status review in 2019
- Commitment for 1/3 of missing funding 2019

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

Tunnel for SIS100/300



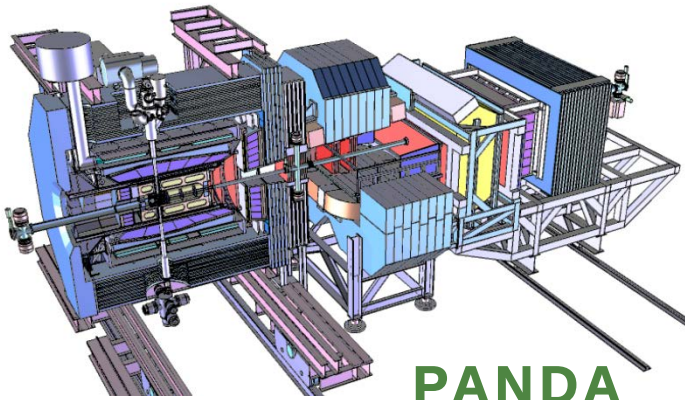
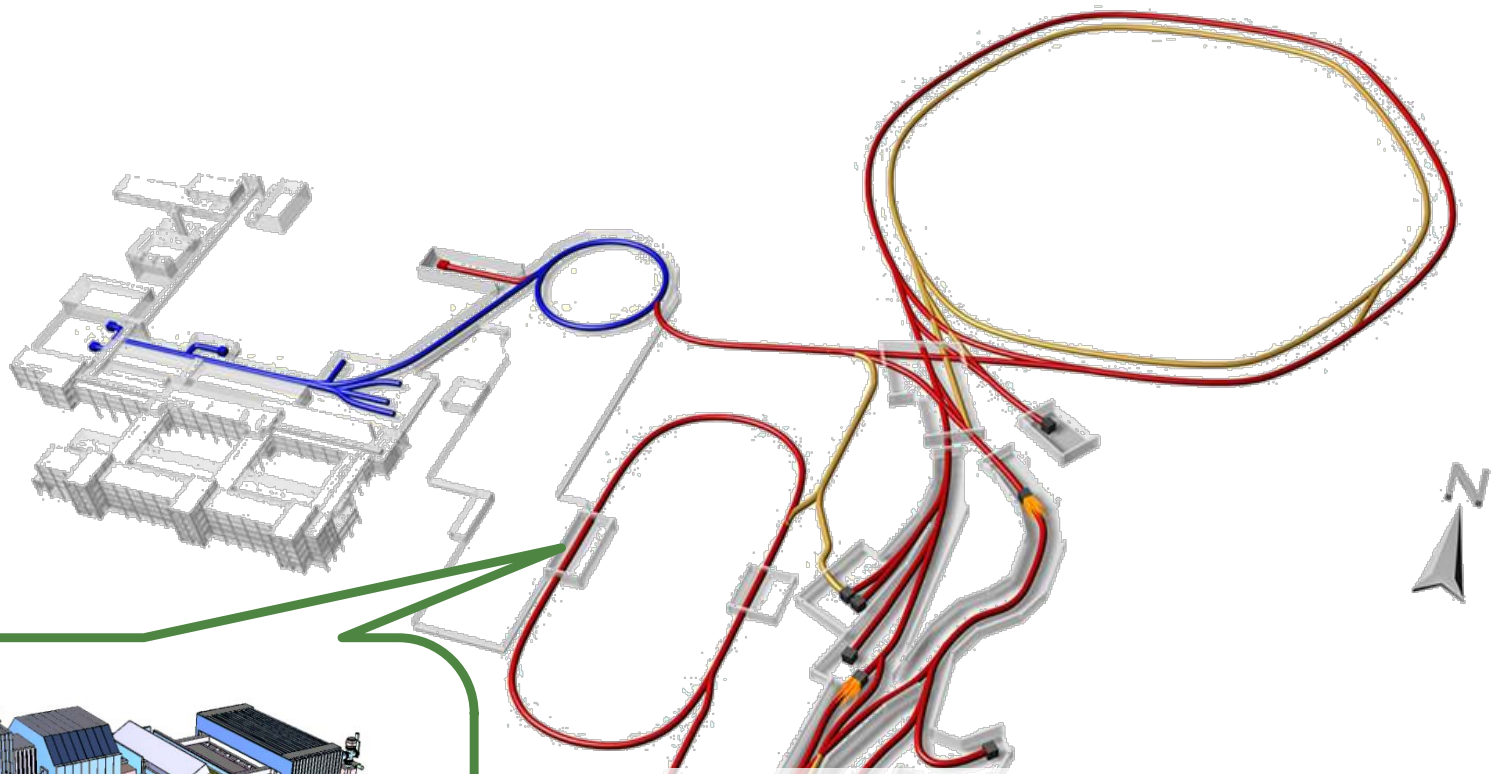
FAIR Experiments



Rare Isotope beams

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

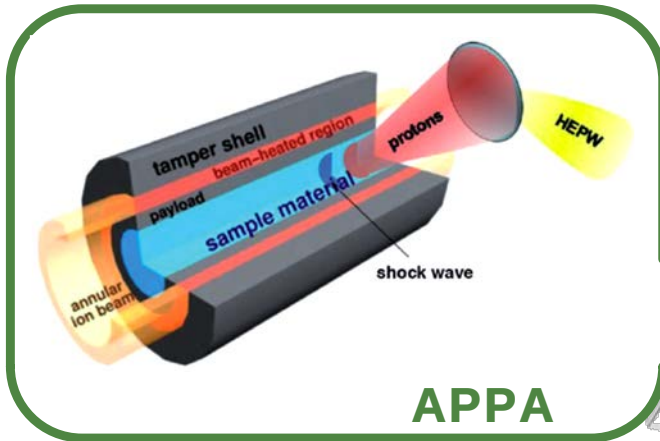
FAIR Experiments



Antiproton-proton collisions:

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

FAIR Experiments

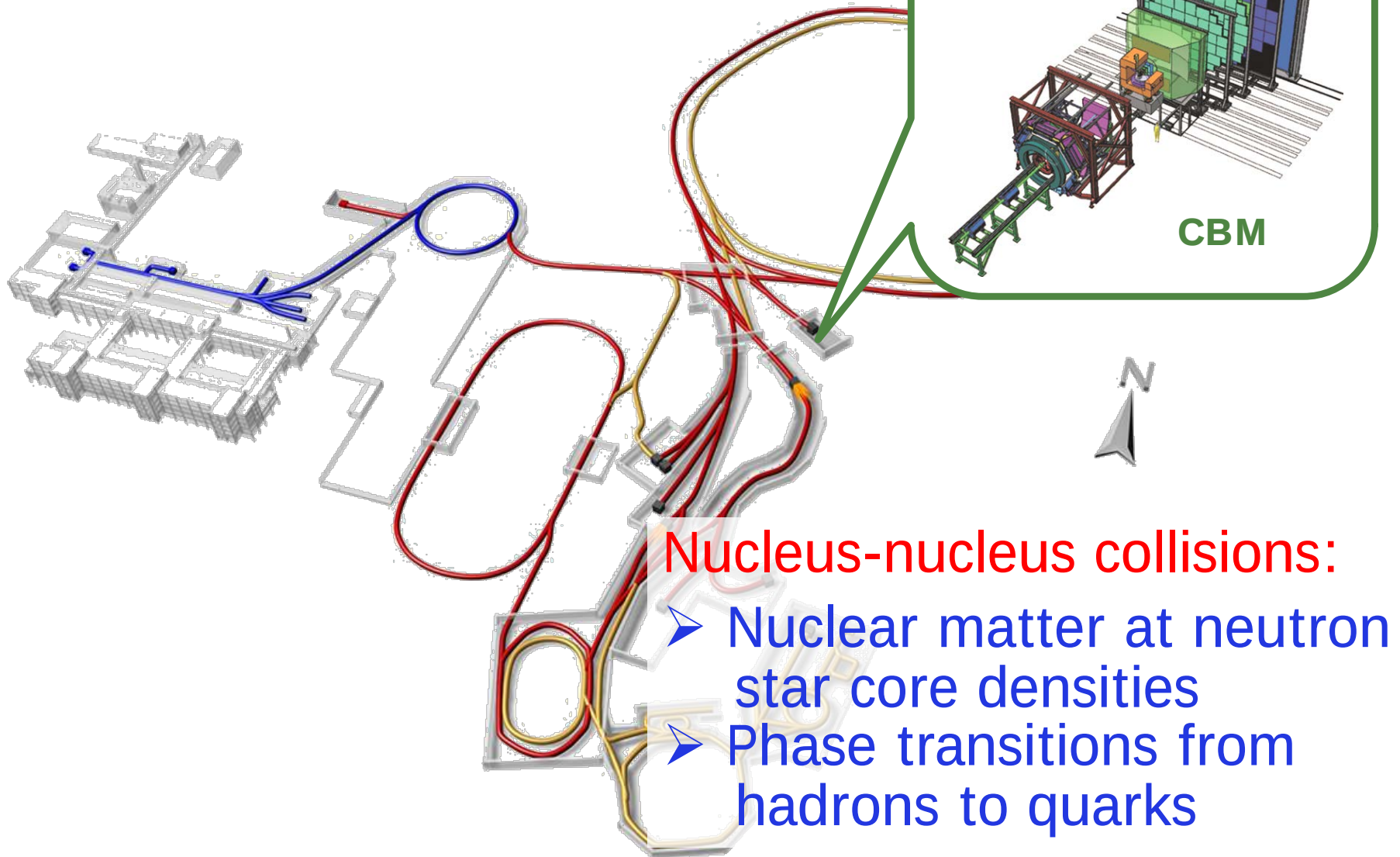


APPA

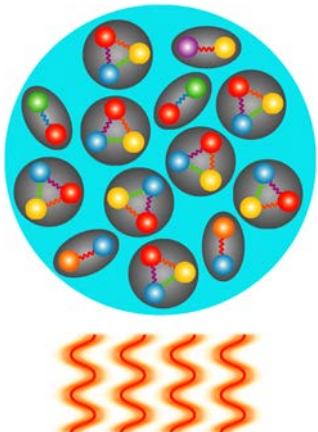
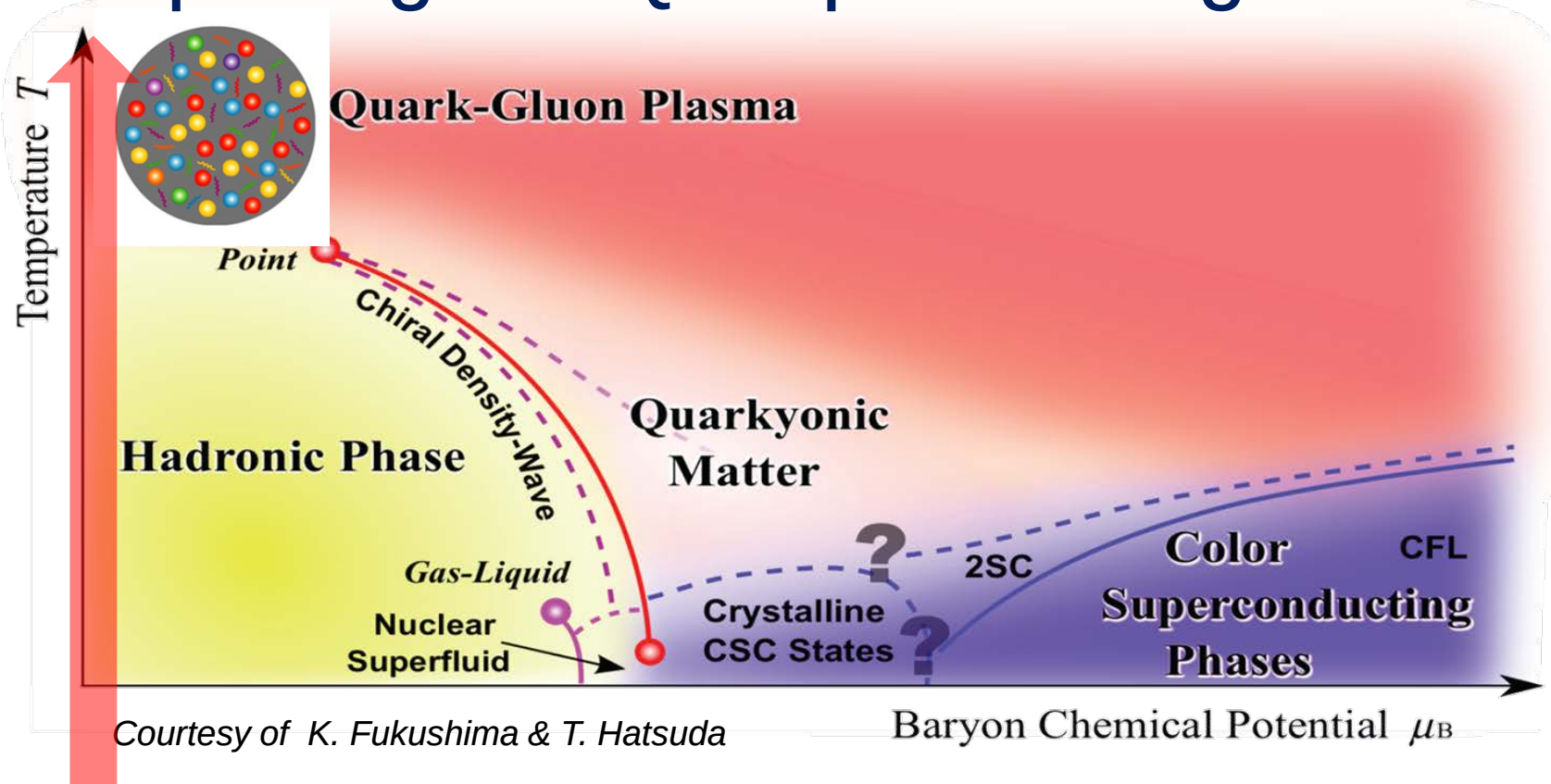
Atomic & Plasma Physics & Applications

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

FAIR Experiments



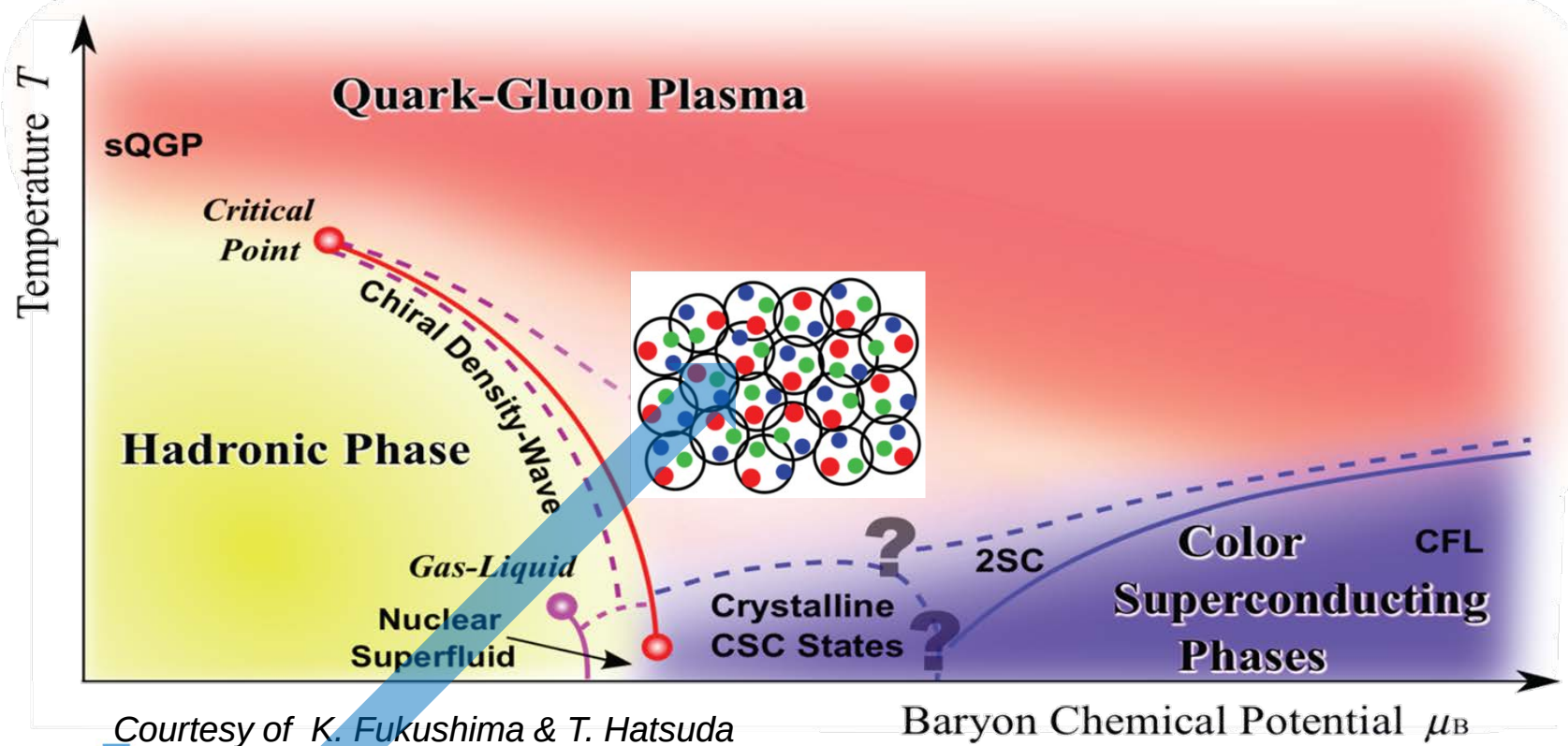
Exploring the QCD phase diagram



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



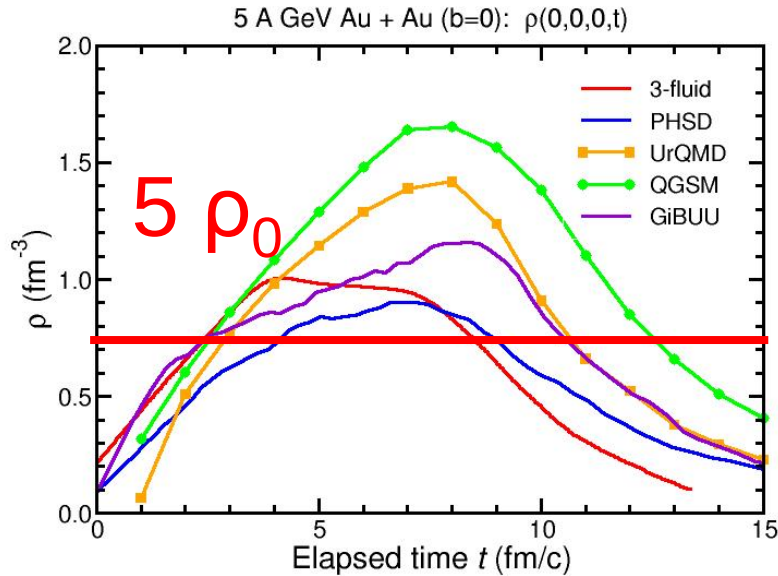
At high baryon density:

- 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](#)

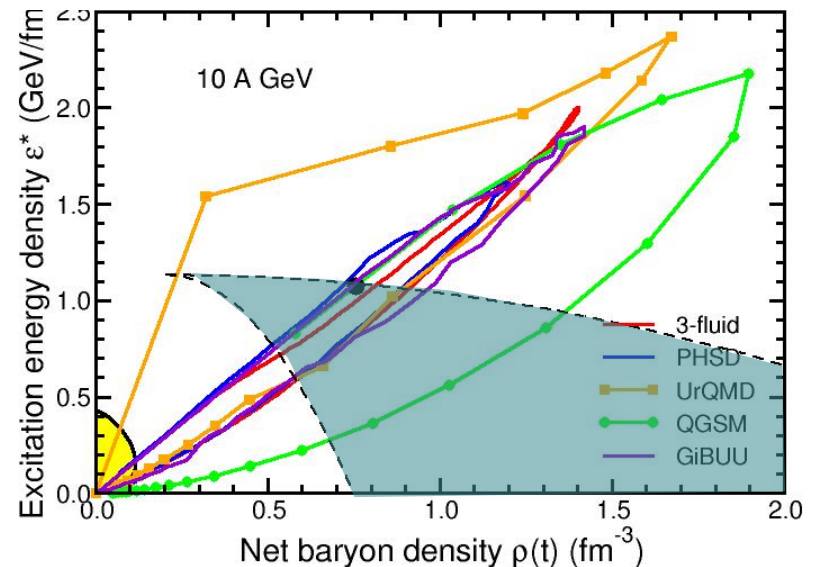
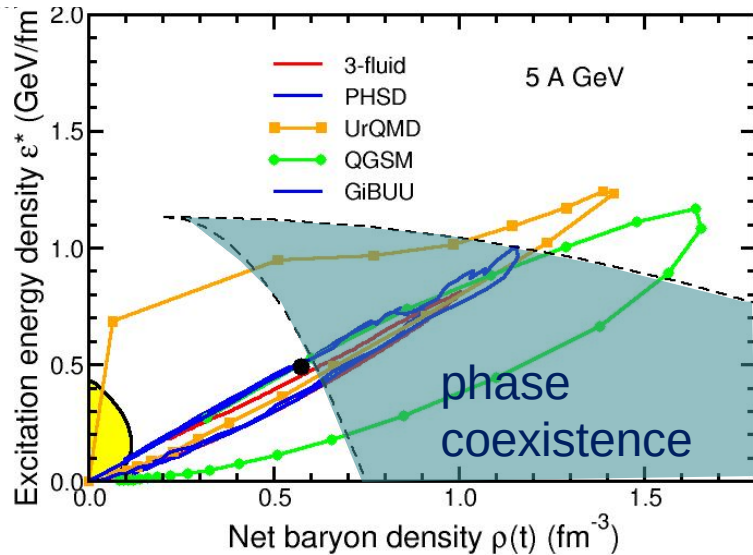
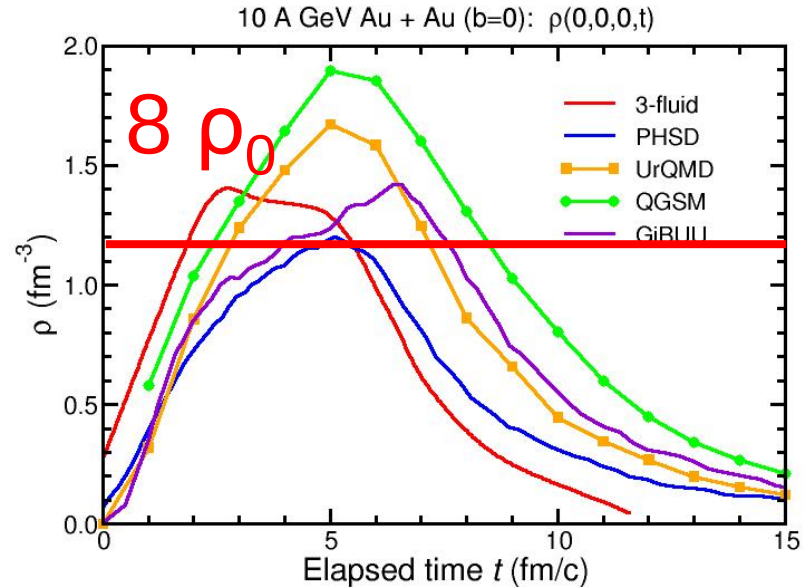
Baryon densities in central Au+Au collisions

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

5 A GeV



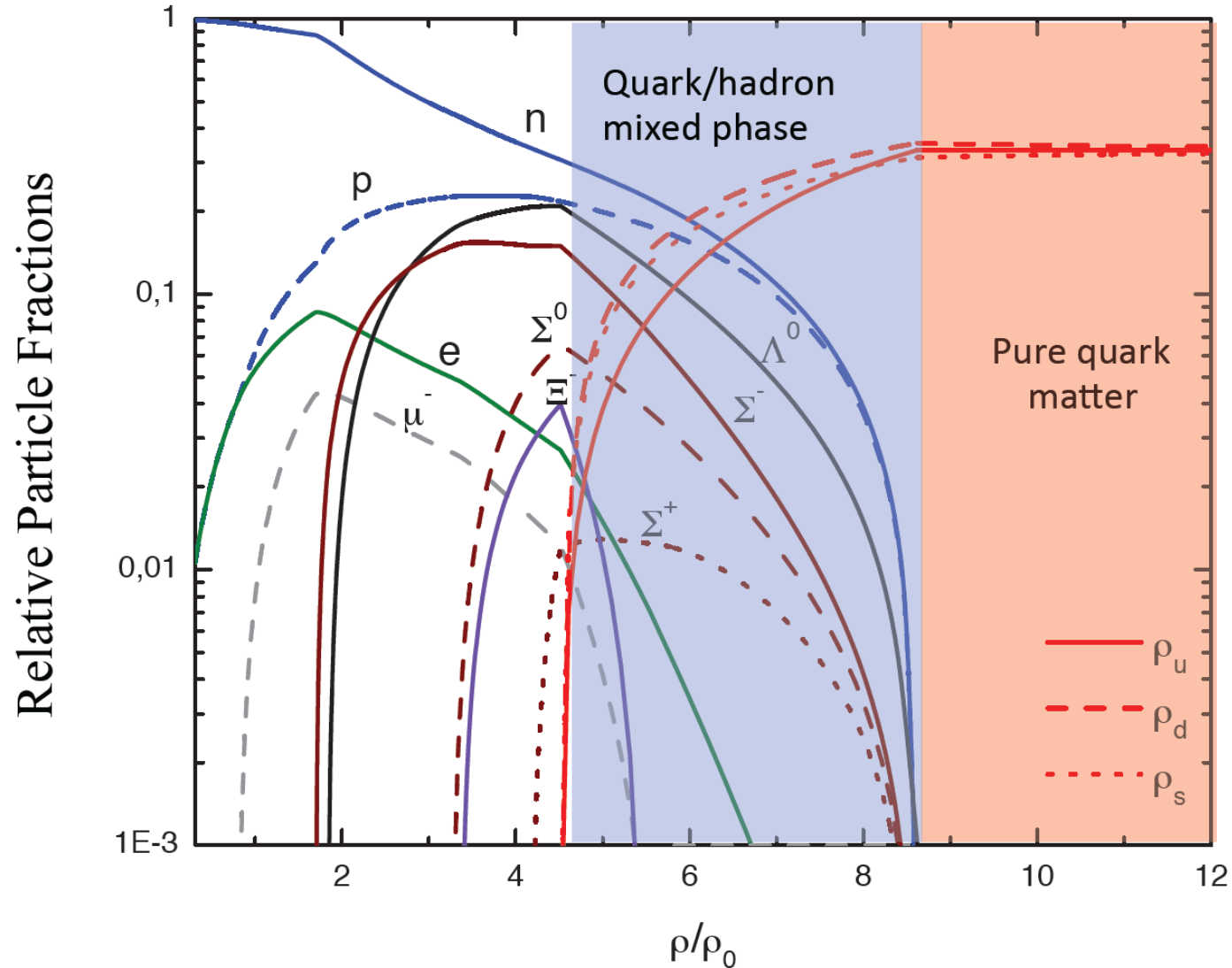
10 A GeV



Quark matter in massive neutron stars?

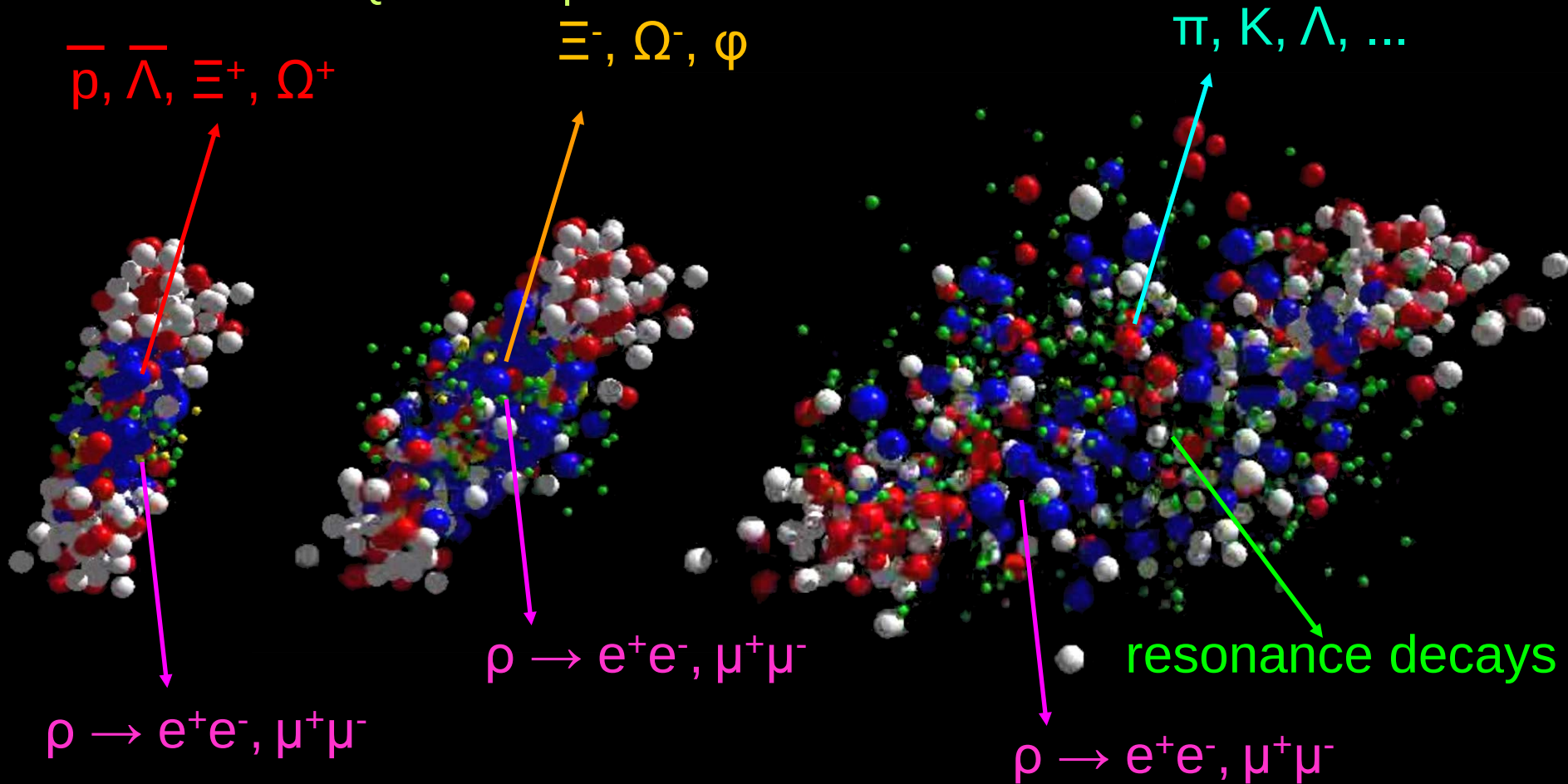
M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657

Phys. Rev. C 89, 015806, 2014



Messengers from the dense fireball: CBM at FAIR

UrQMD transport calculation Au+Au 10.7 A GeV

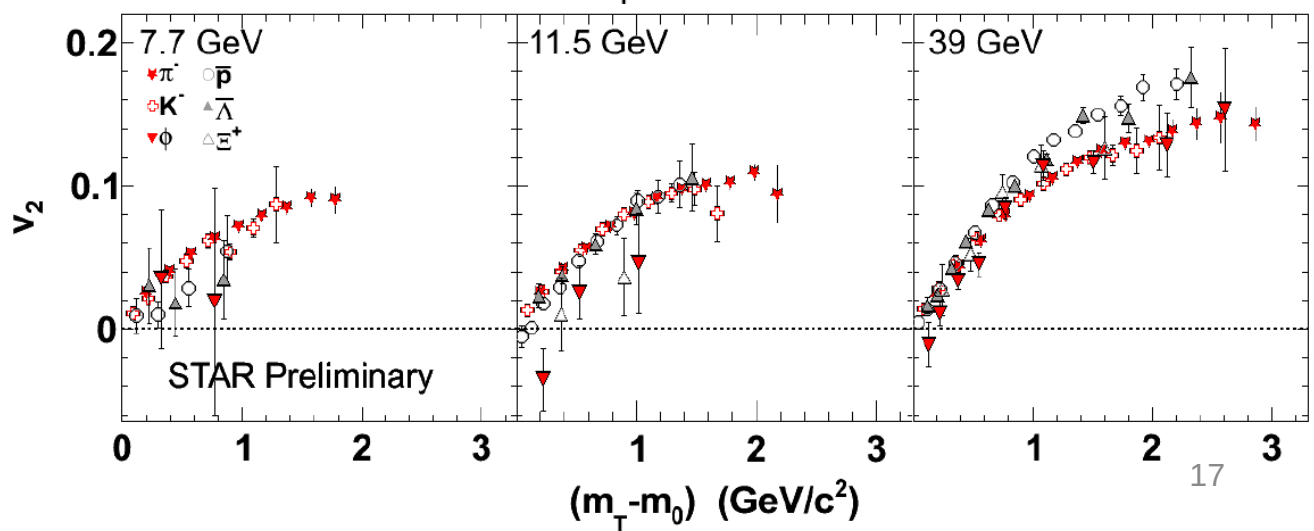
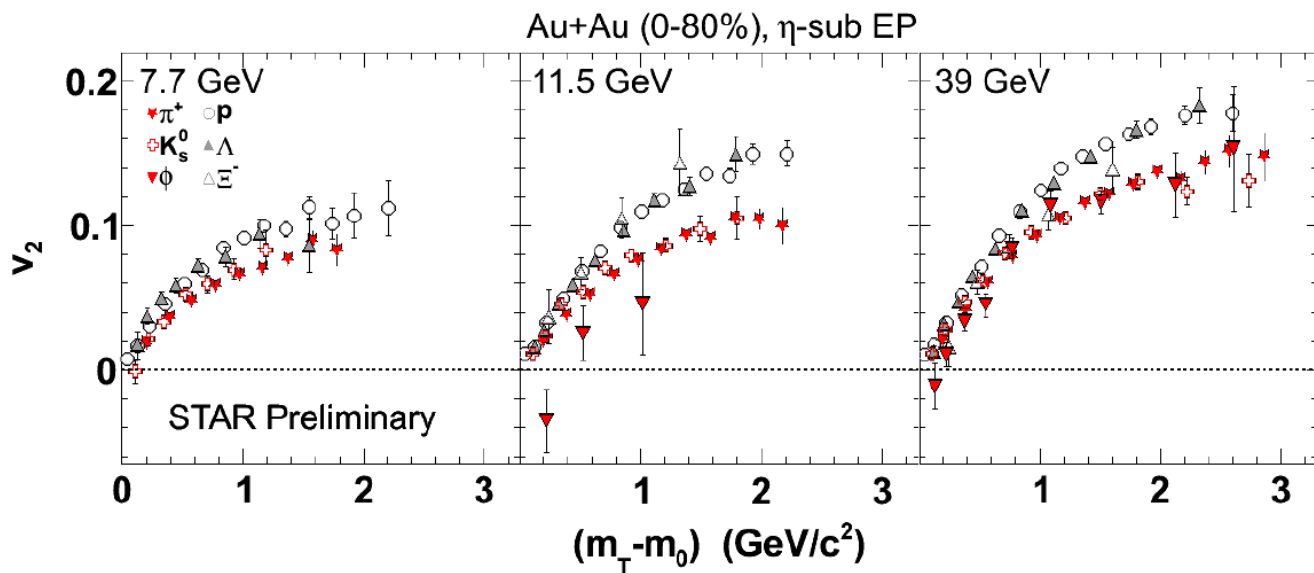
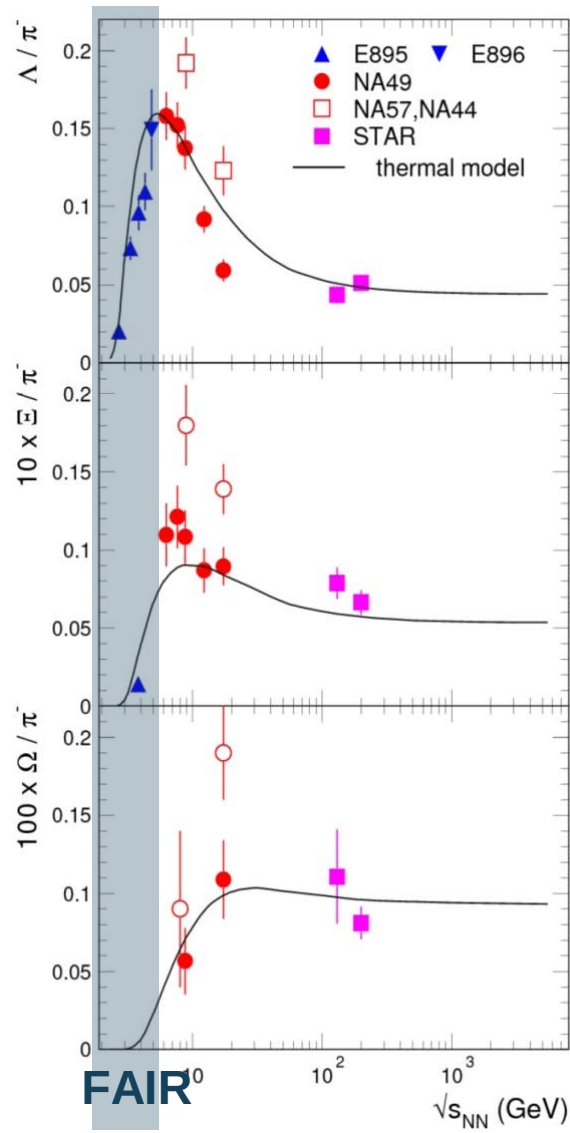


Strangeness Data situation

very few data
at FAIR energies

Pb+Pb, Au+Au (central)

RHIC beam energy scan

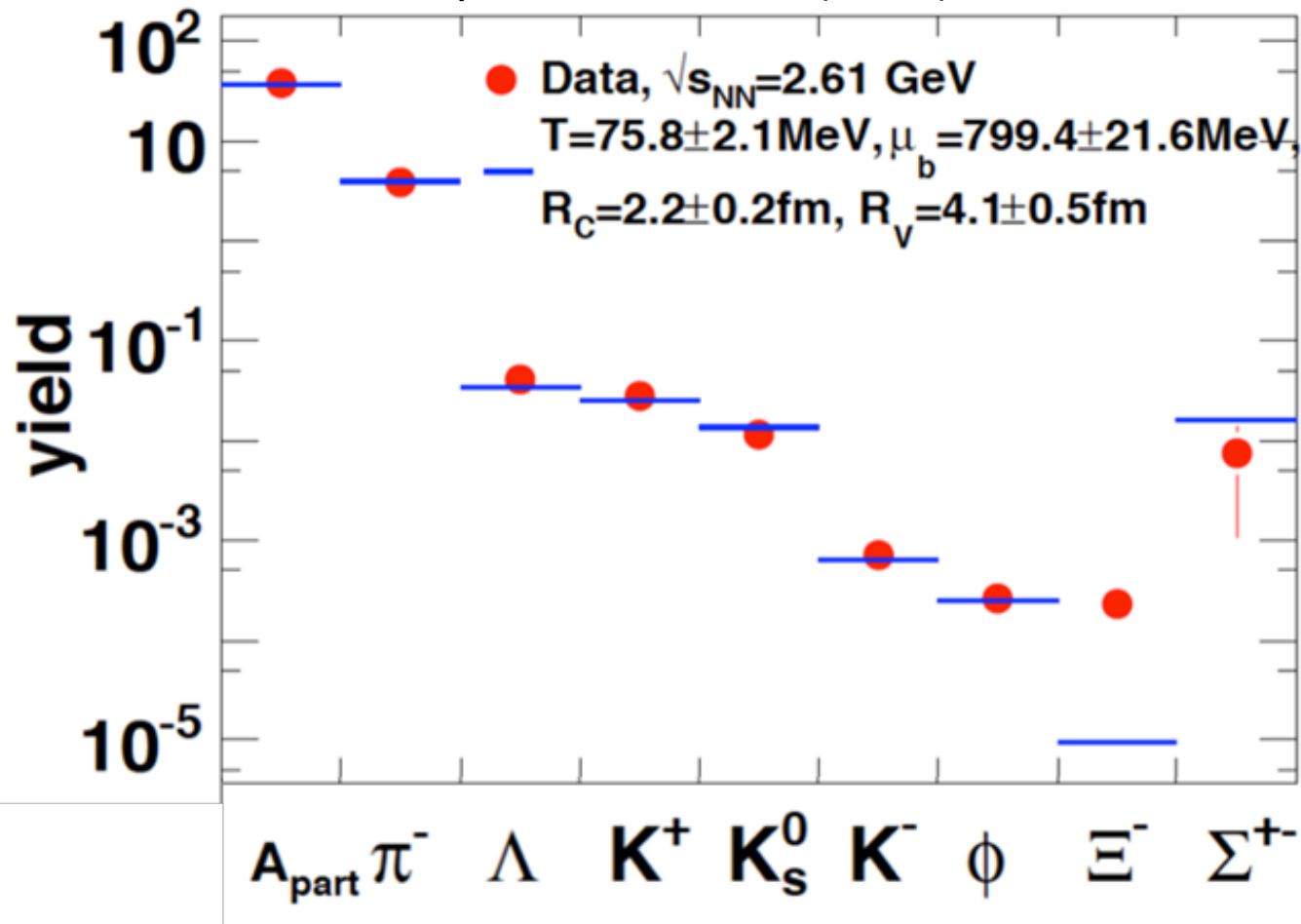


Strangeness

Data situation

HADES: Ar + KCl 1.76 A GeV

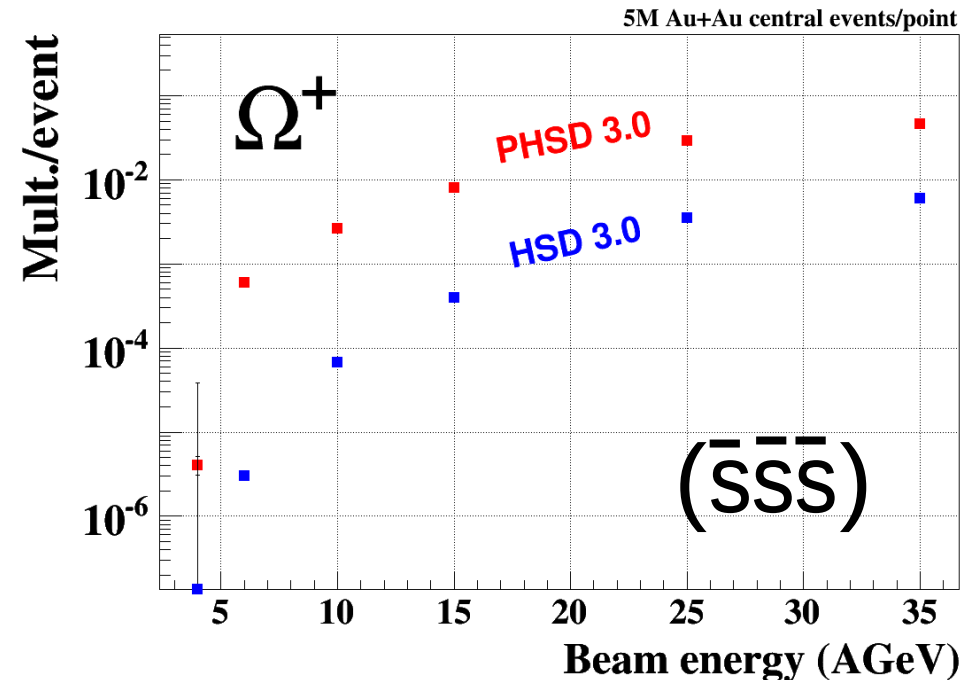
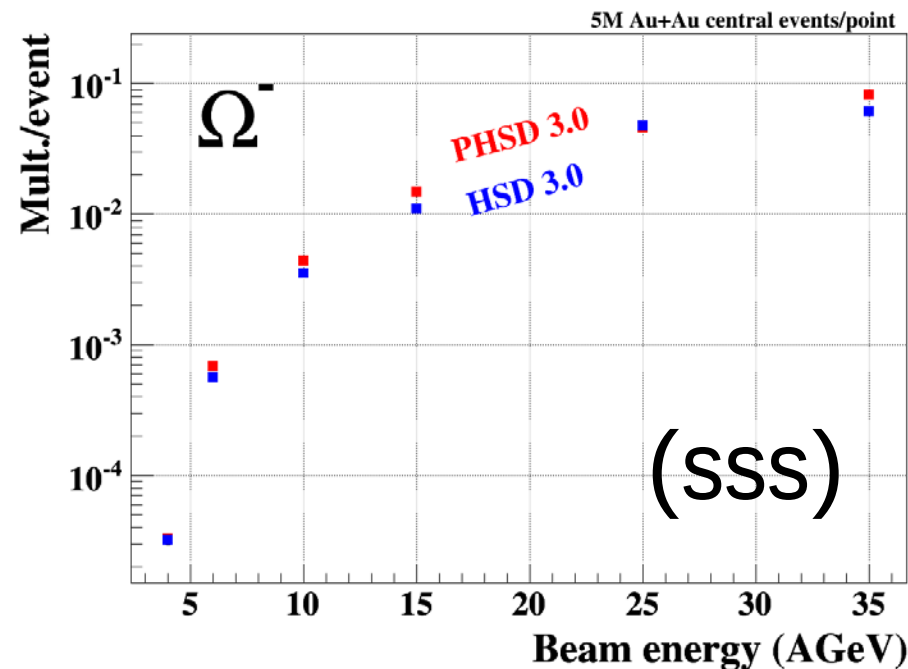
Phys. Rev. Lett. 103 (2009) 132301



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 ($\epsilon > 1 \text{ GeV/fm}^3$)

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:

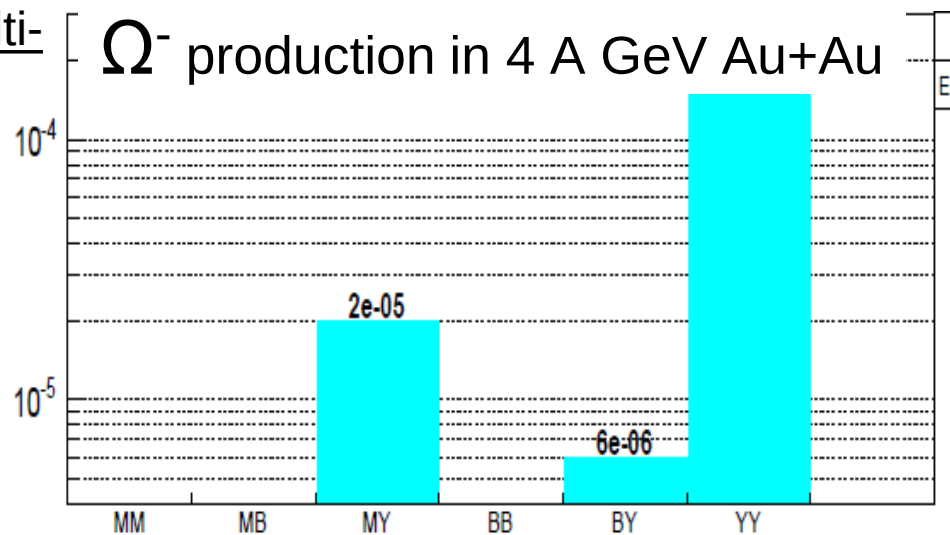
Multi-strange hyperon production via multi-step strangeness exchange reactions:

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. $\Lambda^0 K^+ \rightarrow \Xi^+ \pi^0$,
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

Physics case

➤ In-medium modifications of hadrons

➤ $1 < M_{\text{inv}} < 2.5 \text{ GeV}/c^2$:

- Temperature of the fireball
- 4π mix. $\rightarrow$
 ρ - a_1 chiral mixing
- Onset of QGP radiation

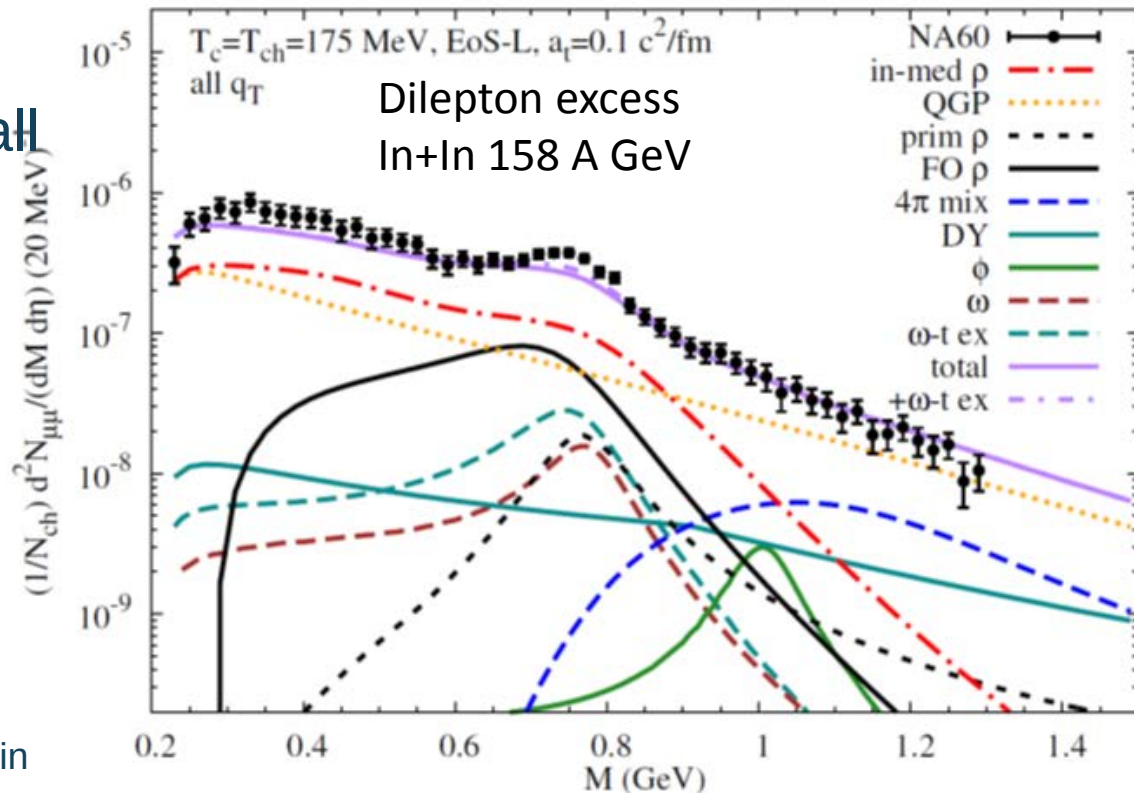
Experiment:

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

No dilepton data
at FAIR energies



Collective flow, correlations, fluctuations

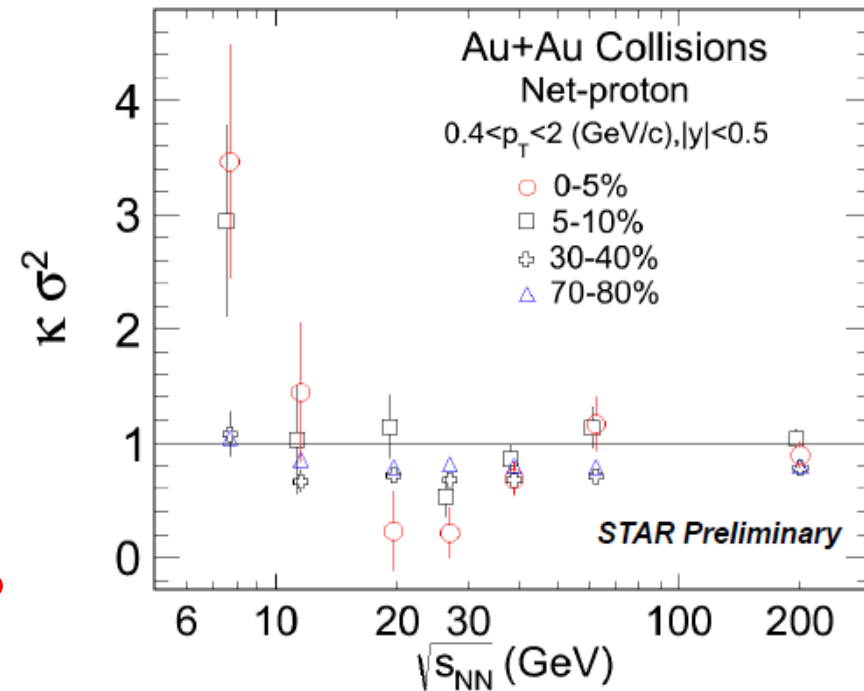
Observables

- 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)

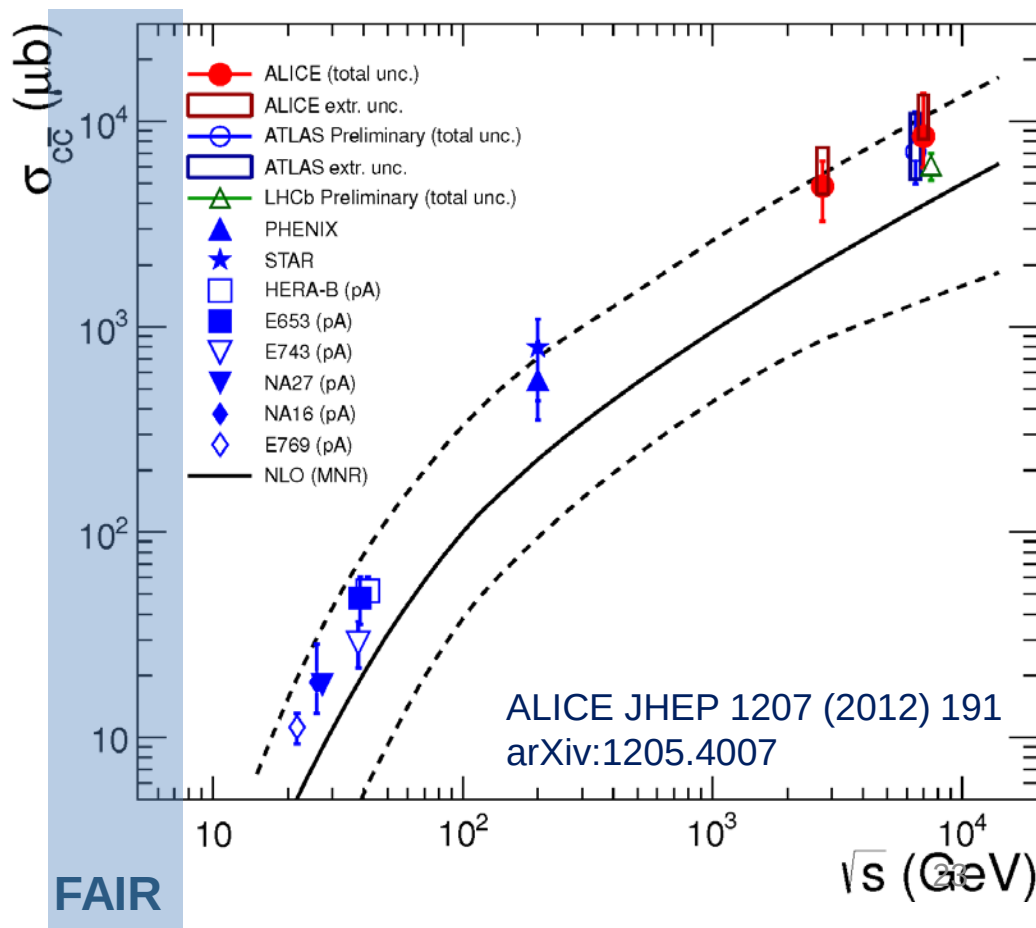
Observables

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

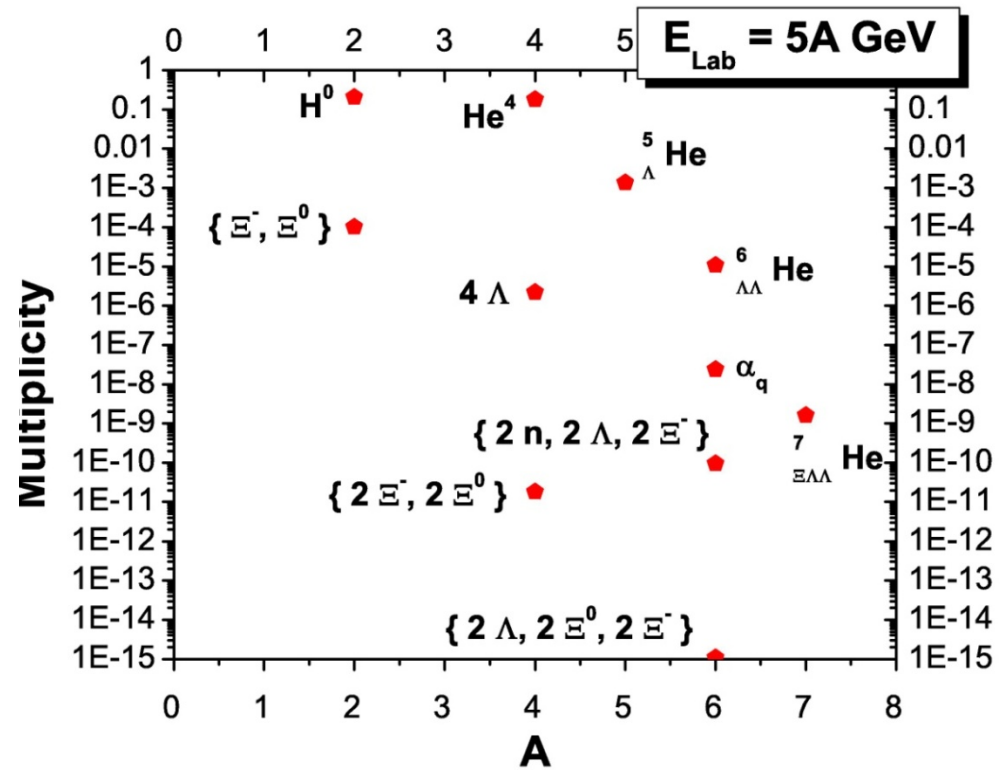
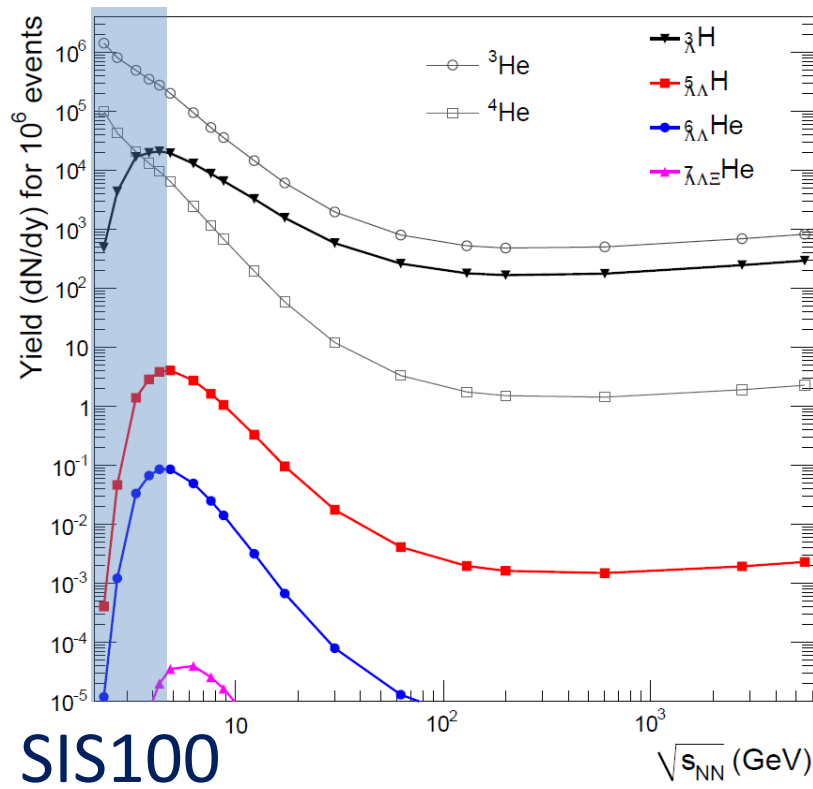


Strange Matter

Observables

Hypernuclei, strange dibaryons and massive strange objects

No data at FAIR energies



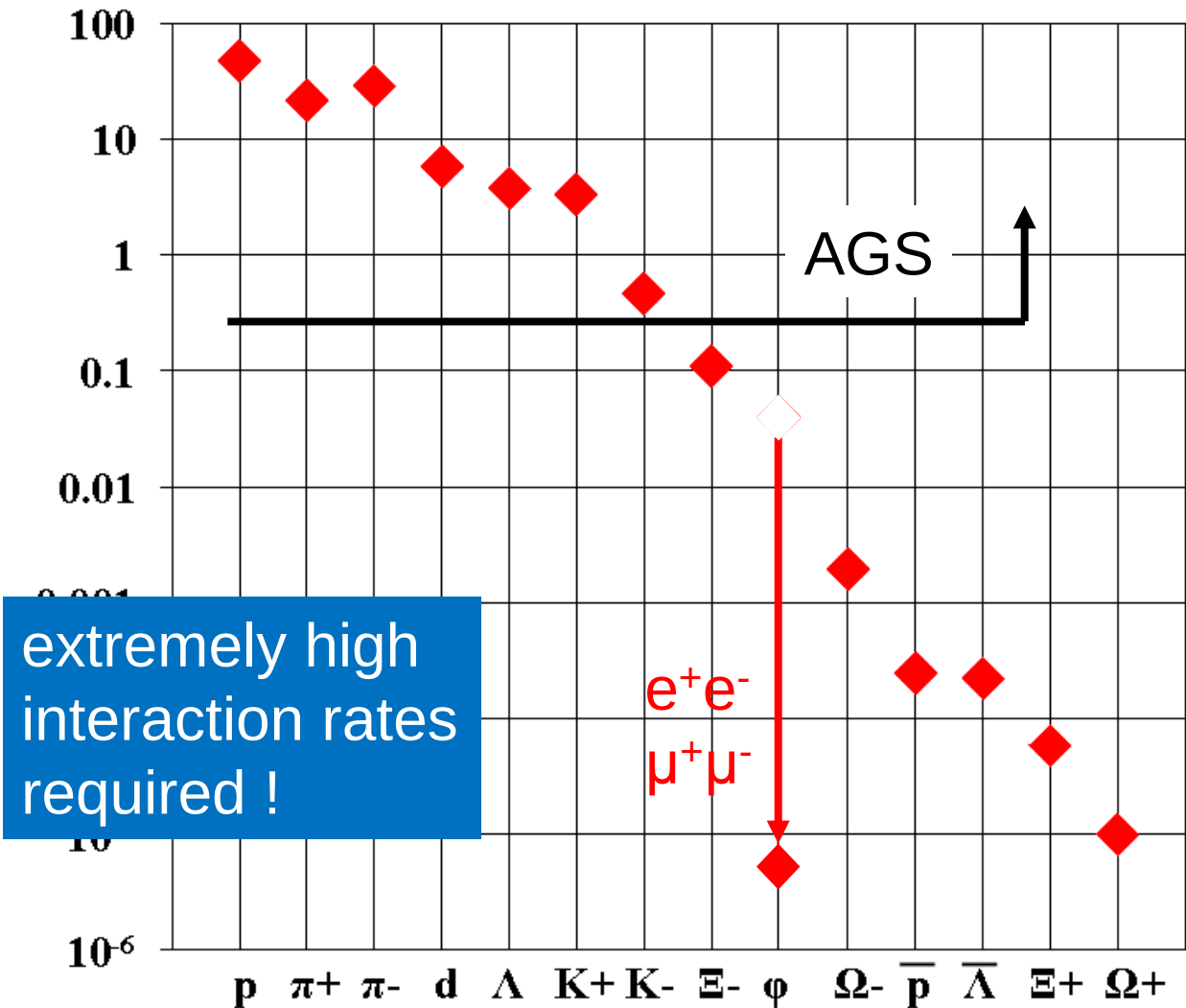
A. Andronic et al., Phys. Lett. B697 (2011) 203

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

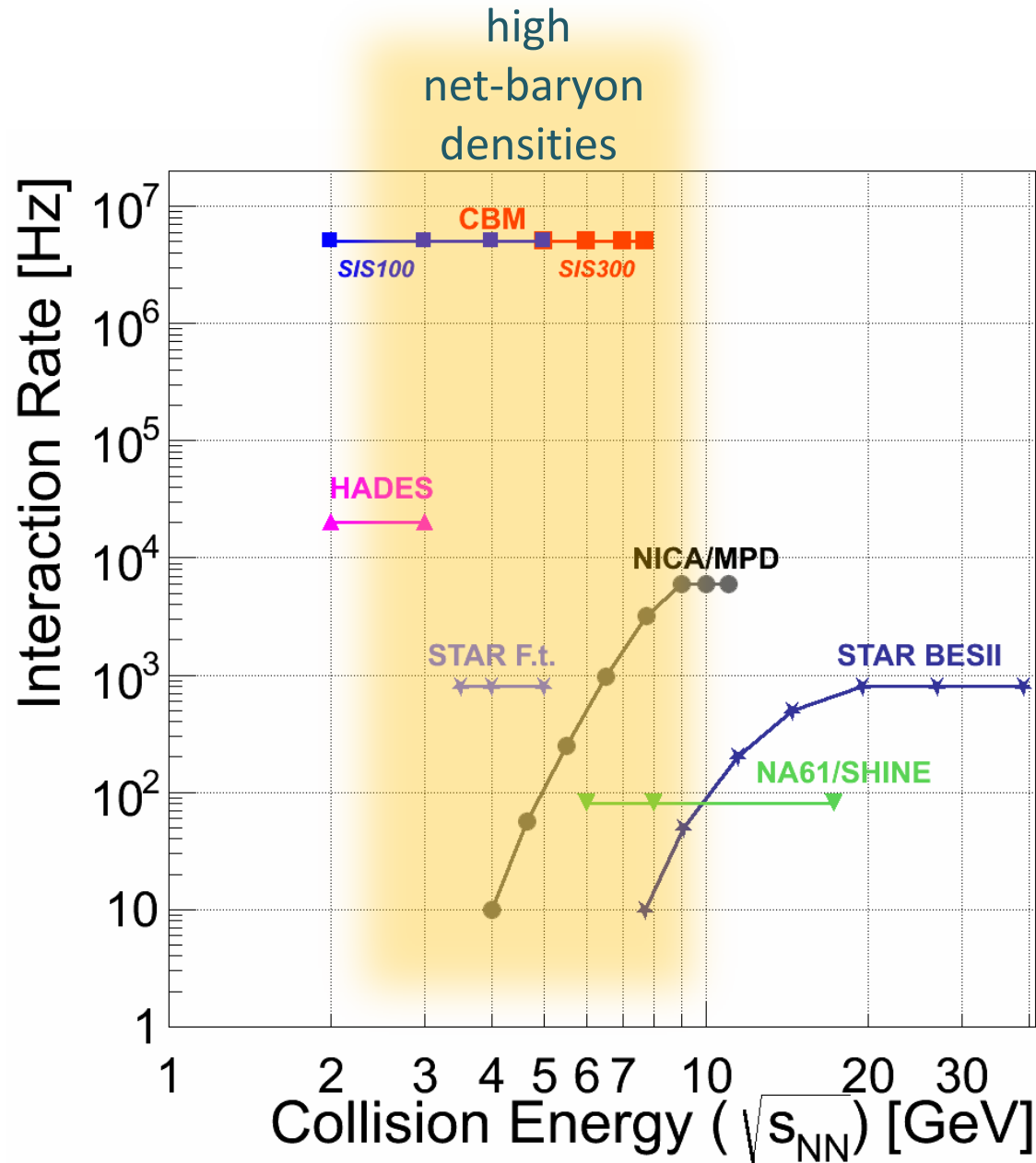
Experimental challenges

Particle yields in central Au+Au 4 A GeV

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.)

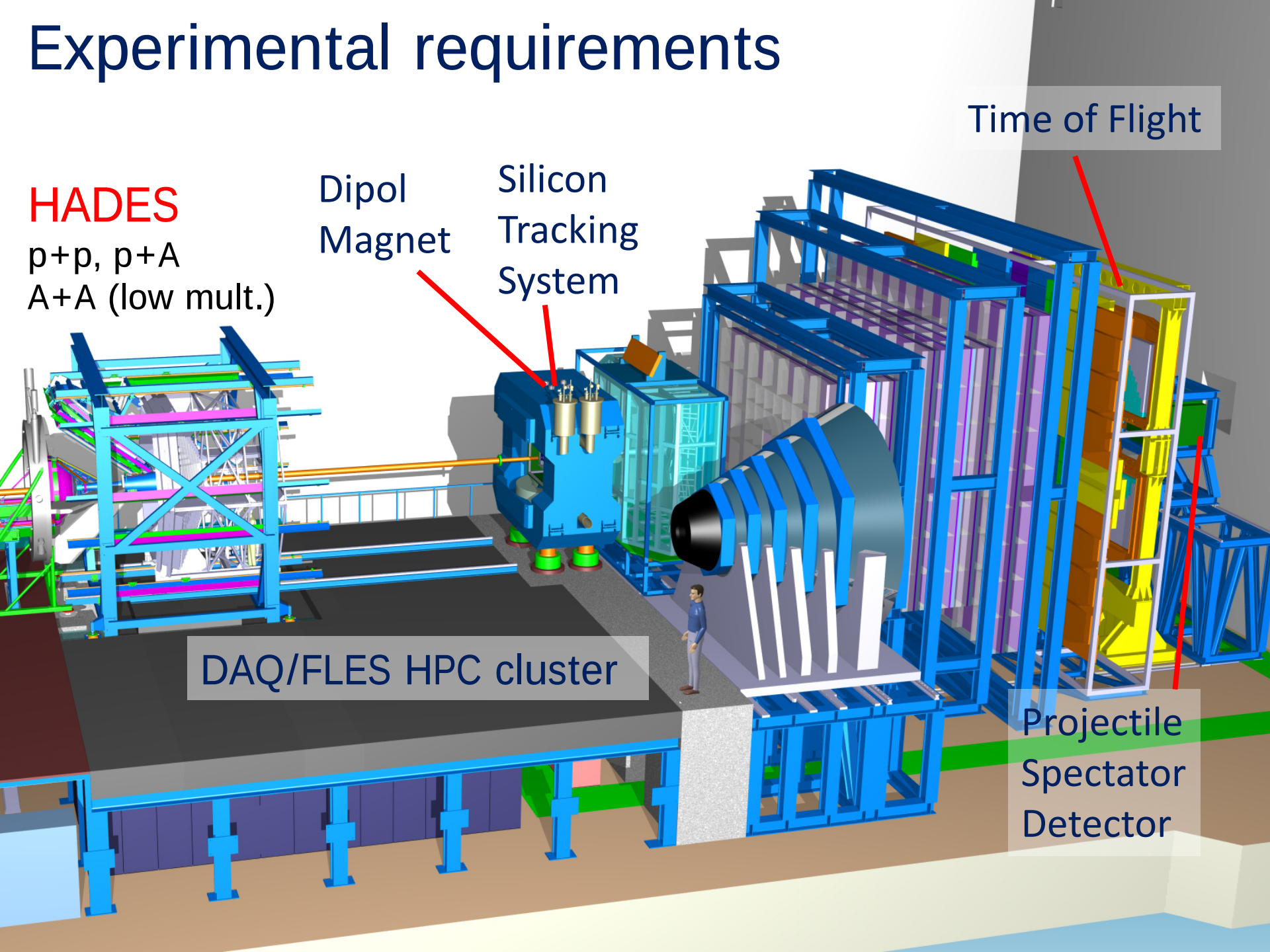
Dipol
Magnet

Silicon
Tracking
System

Time of Flight

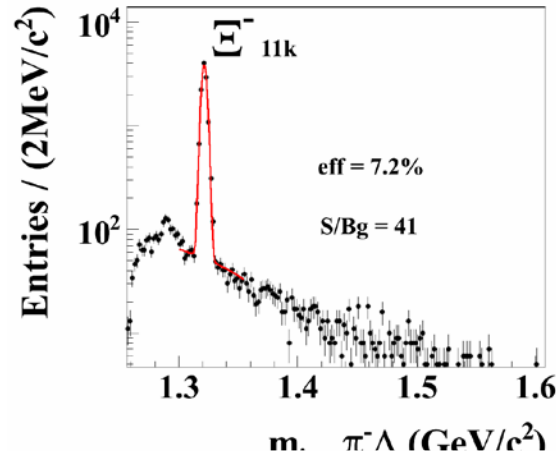
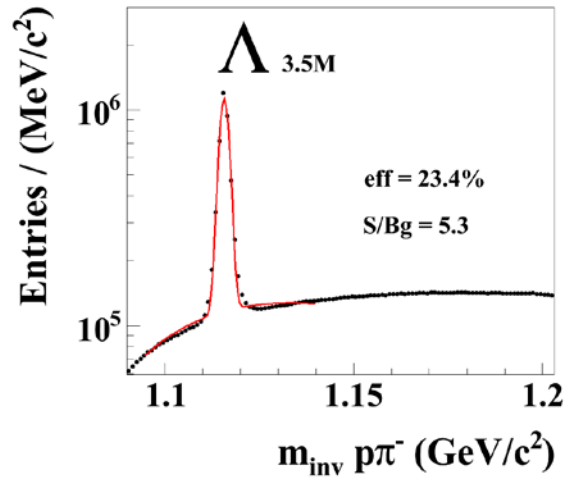
DAQ/FLES HPC cluster

Projectile
Spectator
Detector



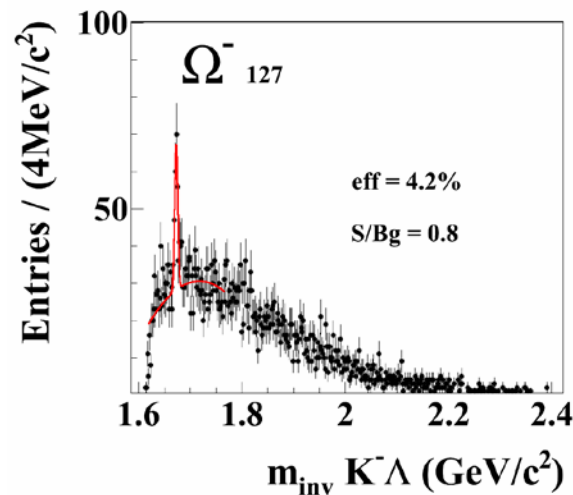
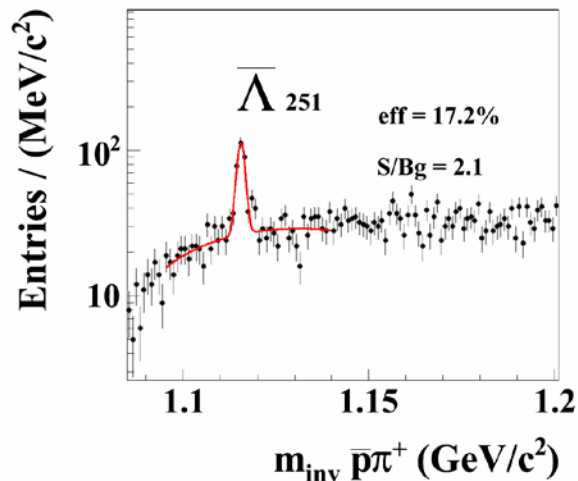
Hyperons in CBM at SIS100

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



- In addition:
 $K^*, \Lambda^*, \Sigma^*, \Xi^*, \Omega^*$

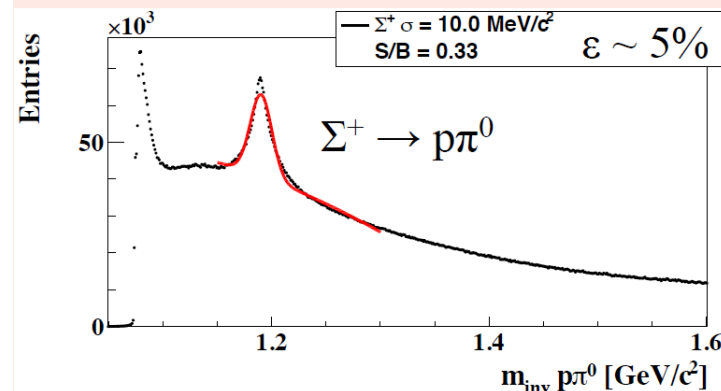
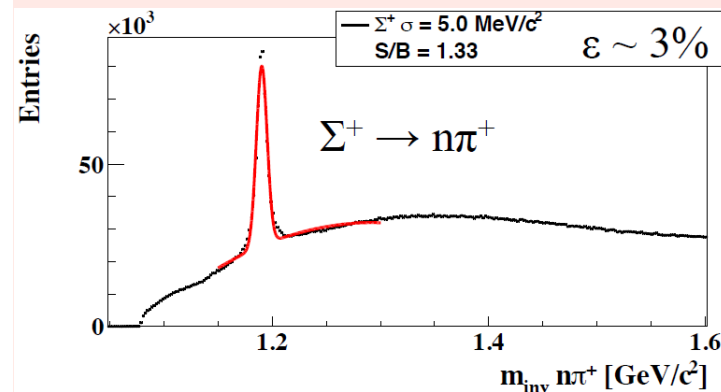
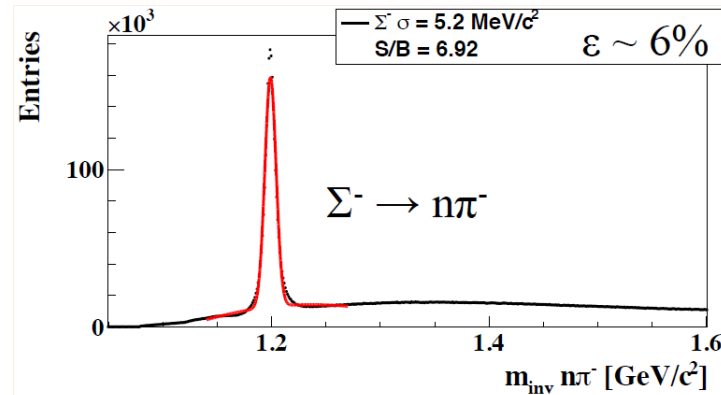
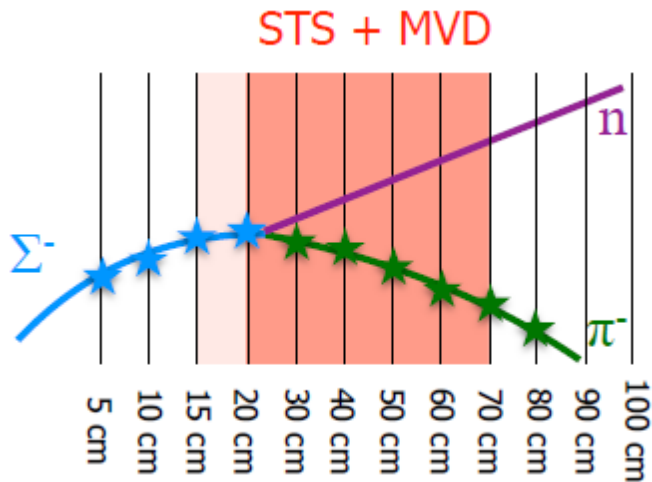
- Event rate:
100 kHz to 1 MHz



Hyperons in CBM at SIS100

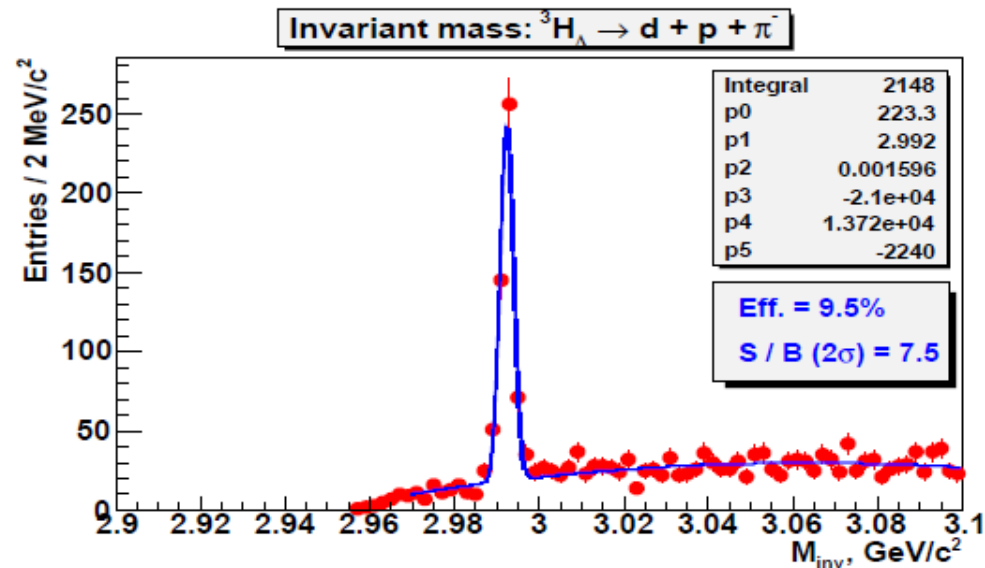
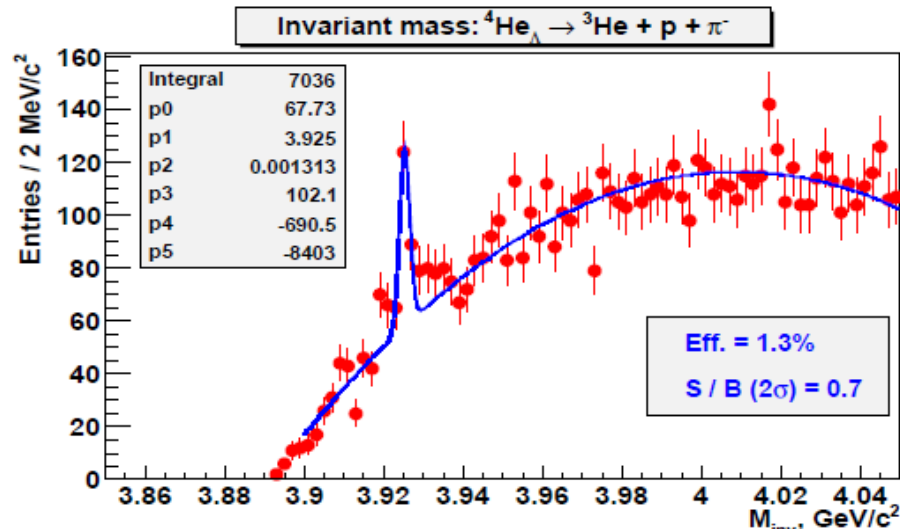
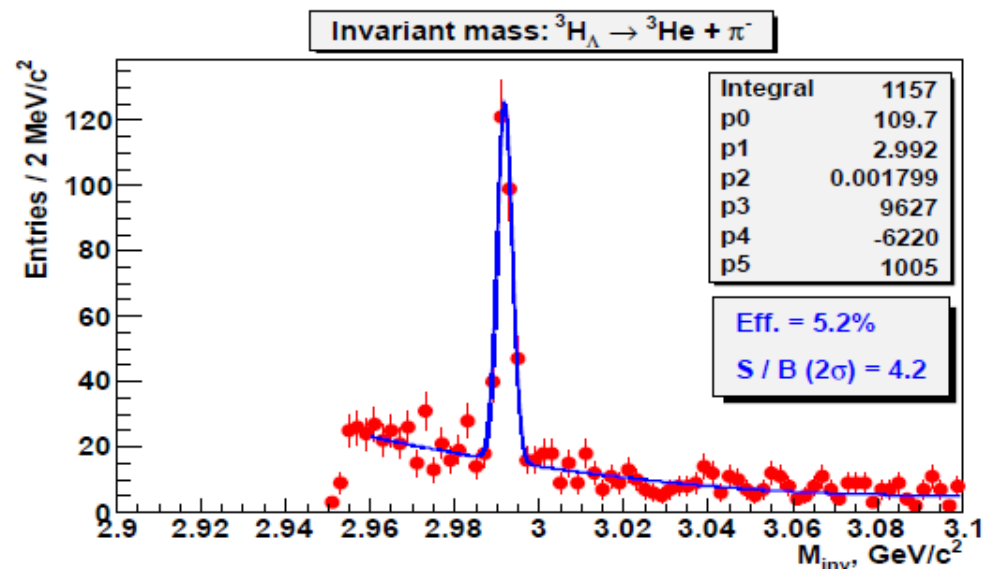
Au+Au at 10 A GeV
 $5 \cdot 10^6$ central collisions
 (UrQMD)

missing mass analysis:



Hypernuclei in CBM at SIS100

Au+Au at 10 A GeV



Hyper nuclei	M central	BR	ε %	Yield/week central
$\Lambda^3\text{H}$	$2 \cdot 10^{-2}$	0.6	7	$4.6 \cdot 10^7$
$\Lambda\Lambda^5\text{H}$	$6 \cdot 10^{-6}$	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

$(\Xi^0 \Lambda)_b \rightarrow \Lambda \Lambda$ ($c\tau=3\text{cm}$)

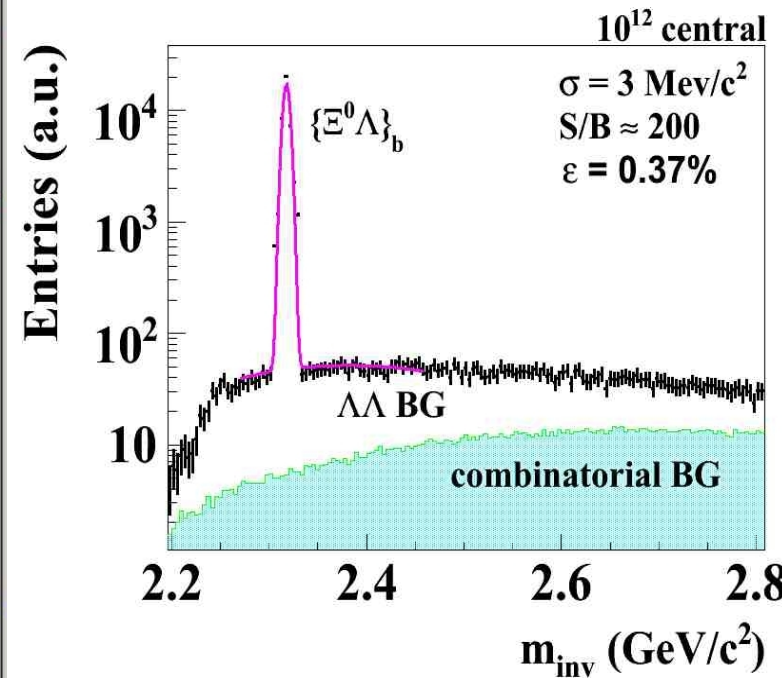
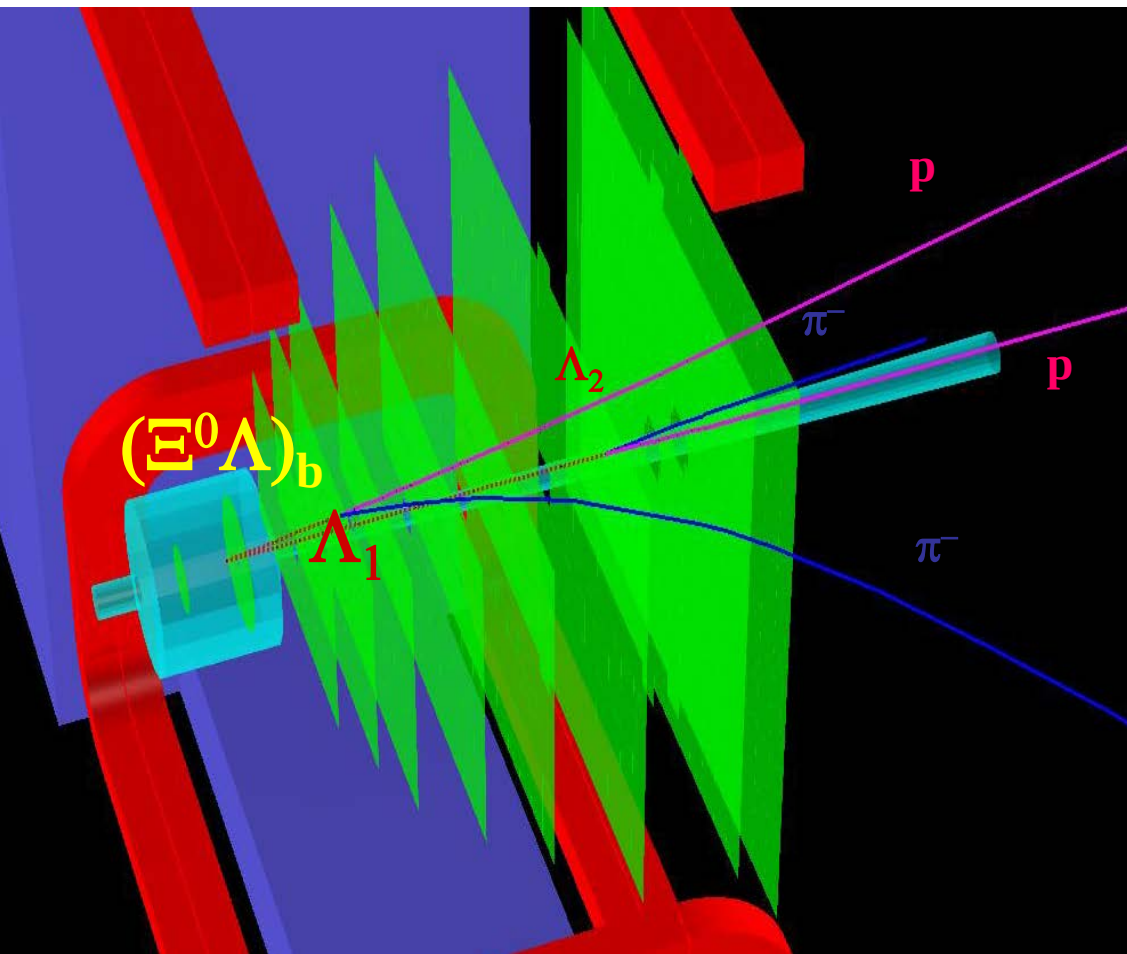
$M = 10^{-6}$, $\text{BR} = 5\%$

Background:

central Au+Au collision

32 Λ per central event

11 Λ reconstructable

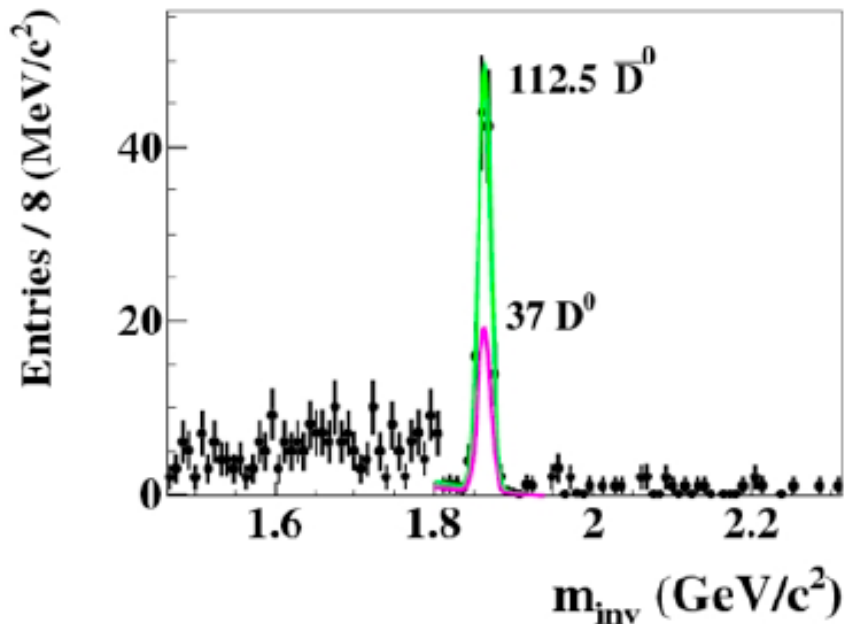


Open charm in CBM at SIS100

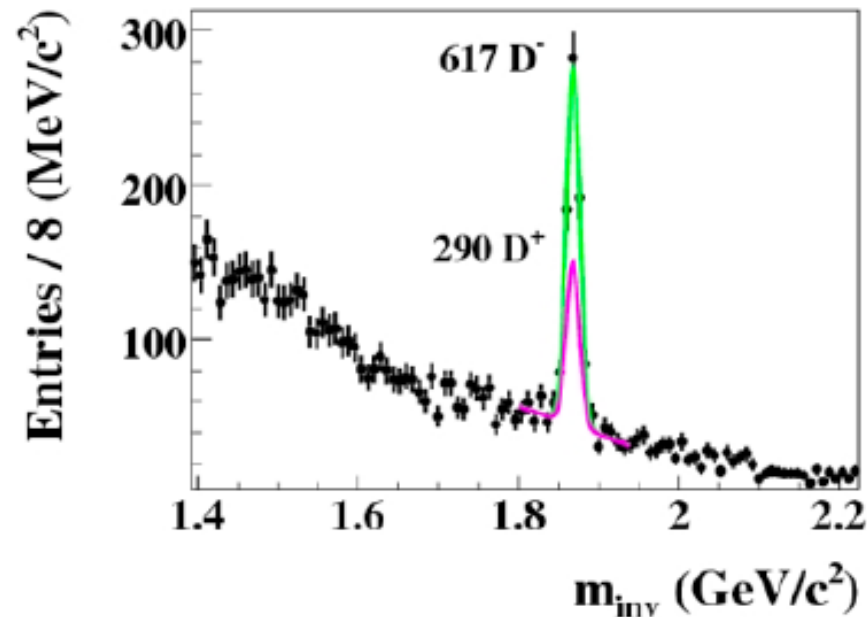
- Charm production cross sections at threshold energies
- Charm propagation in cold nuclear matter

30 GeV p + C

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

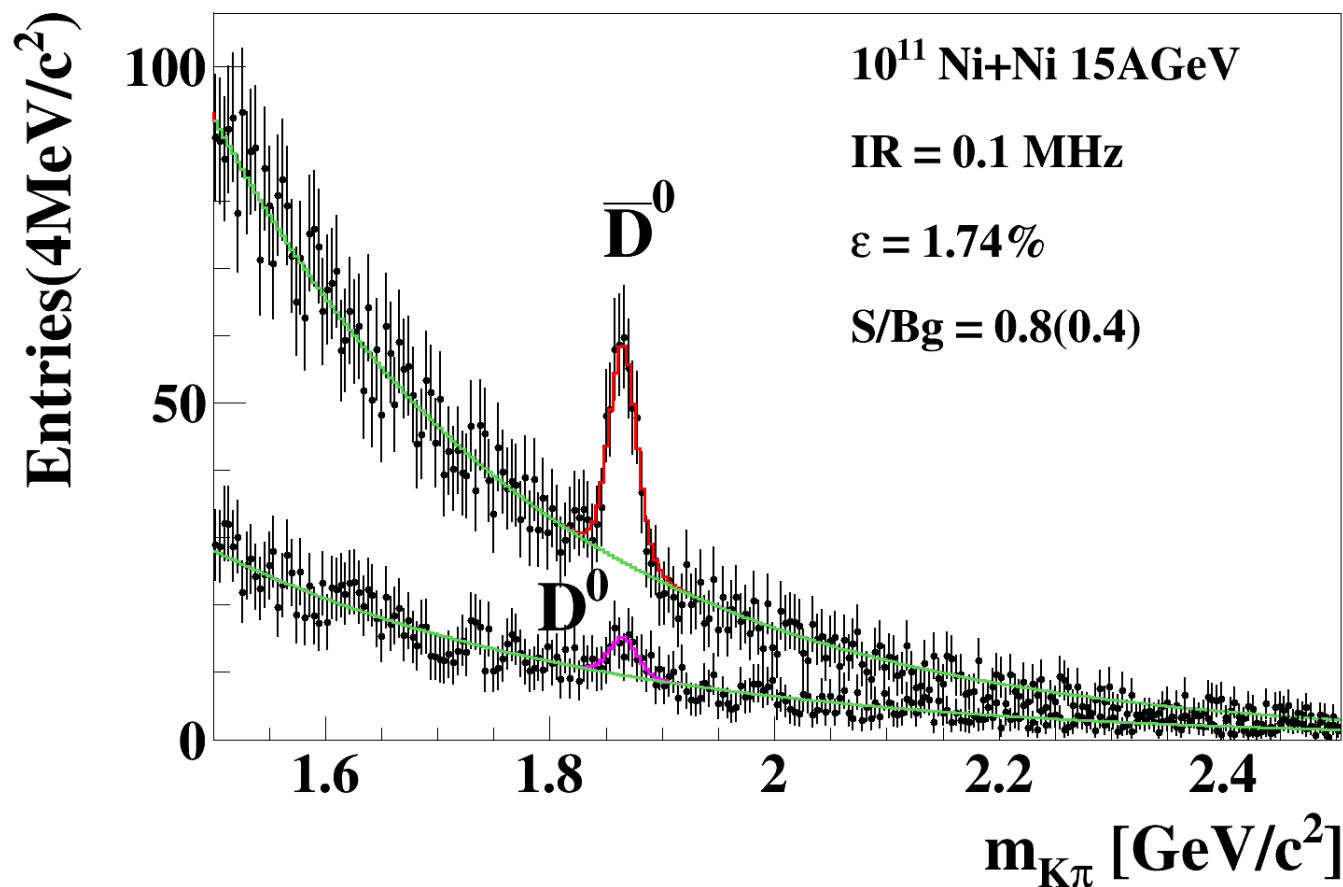


$D^\pm \rightarrow K\pi\pi\pi$

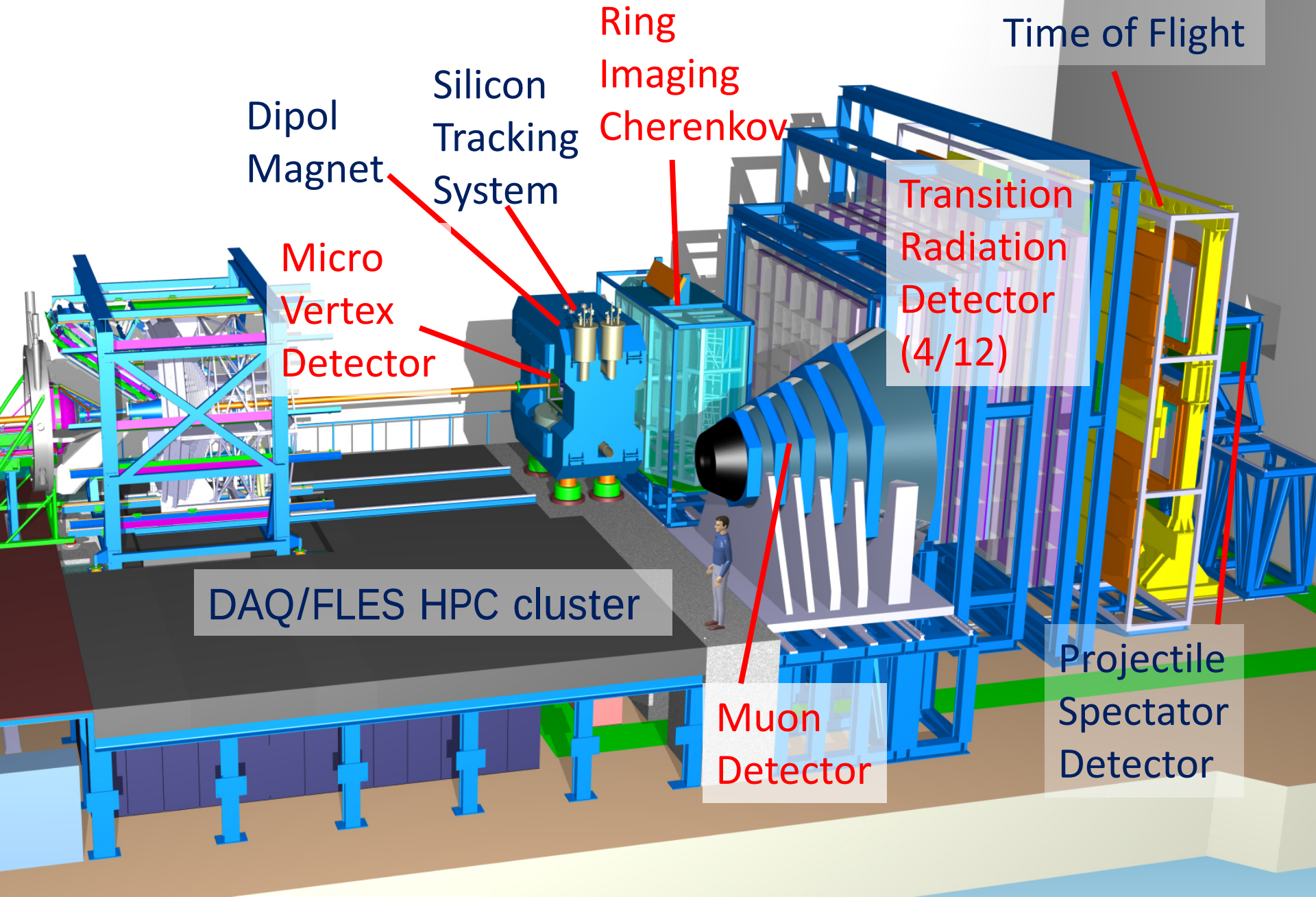


Open charm in CBM at SIS100

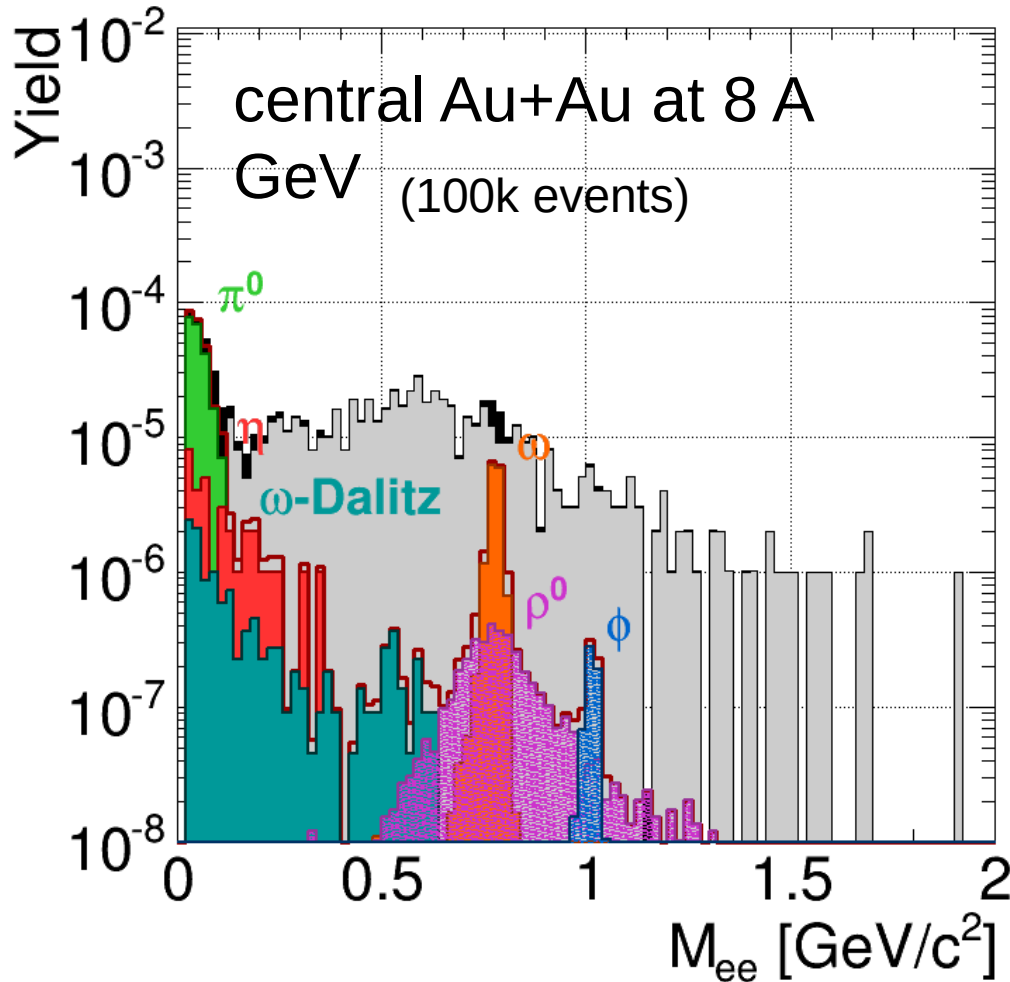
- Charm production and propagation in hot nuclear matter
- D multiplicities from thermal model (V. Vovchenko)
- 2 weeks Ni + Ni at 15 A GeV: 260 $\bar{D}^0$, 45 D^0



Experimental requirements



Electrons in CBM at SIS100



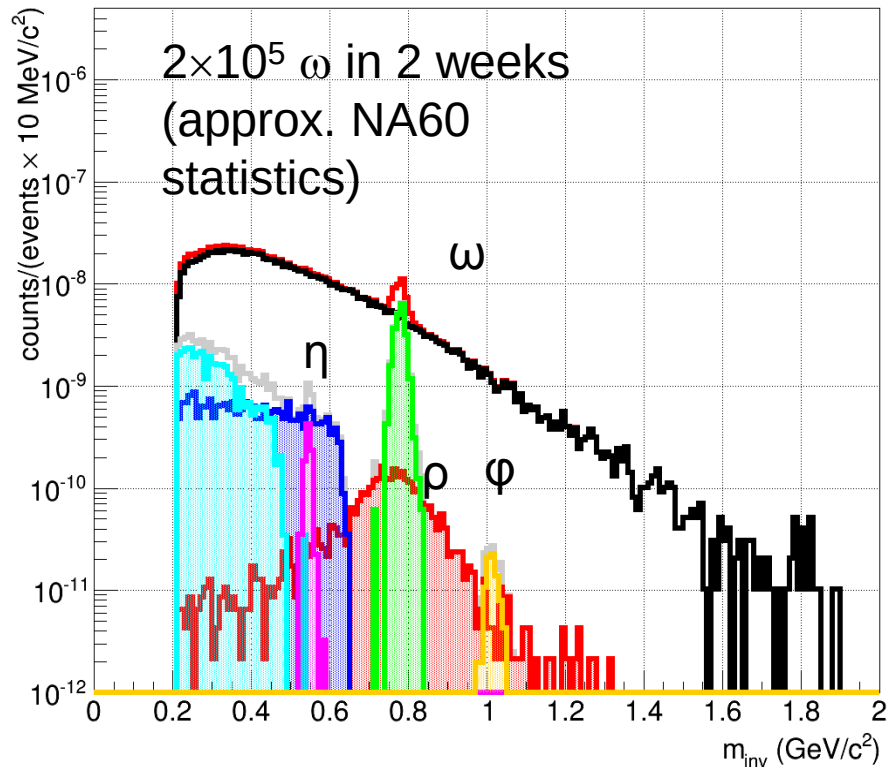
8 A GeV:
 2×10^6 ω in 2 weeks

Simulation:
Signal yields from HSD
Background from UrQMD

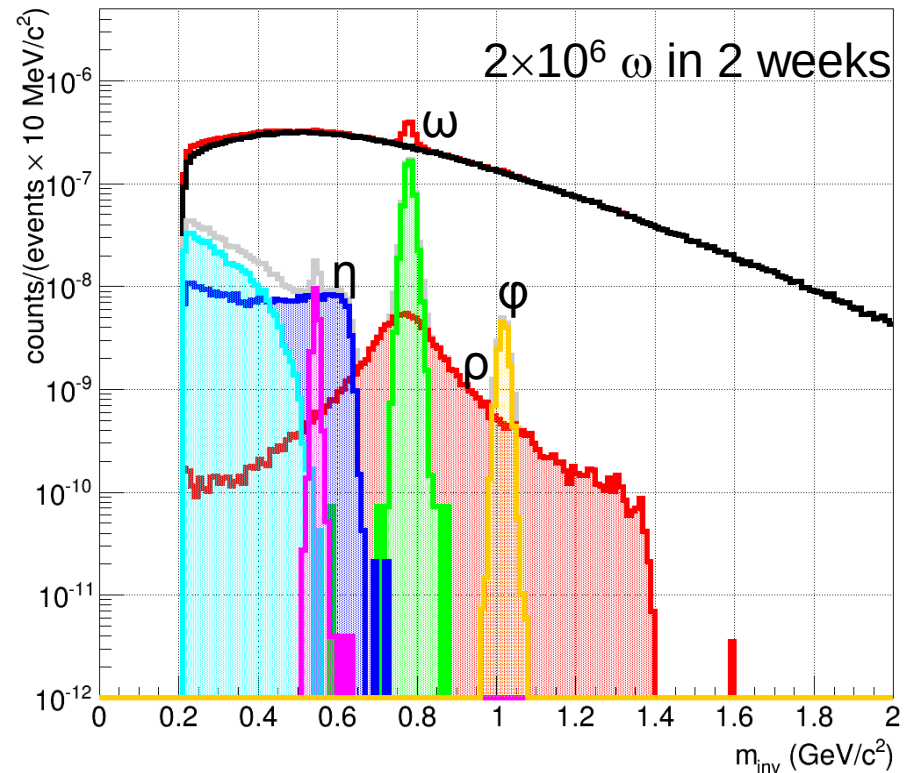
Muons in CBM at SIS100

Simulation: Signal yields from HSD, Background from UrQMD

central Au+Au at 4 A GeV

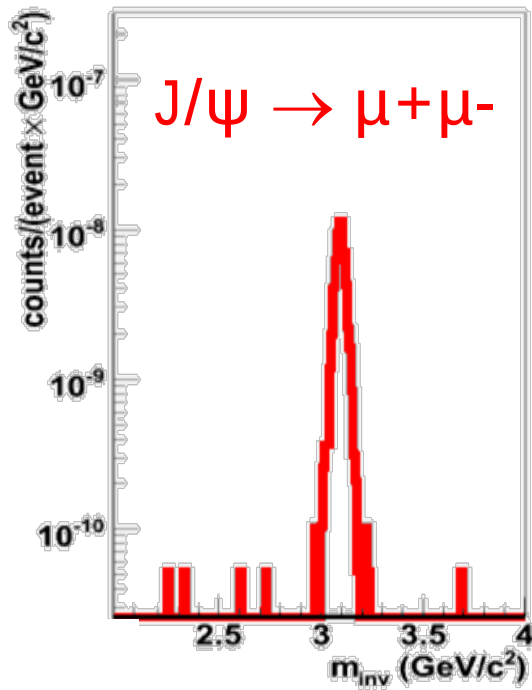


central Au+Au at 8 A GeV



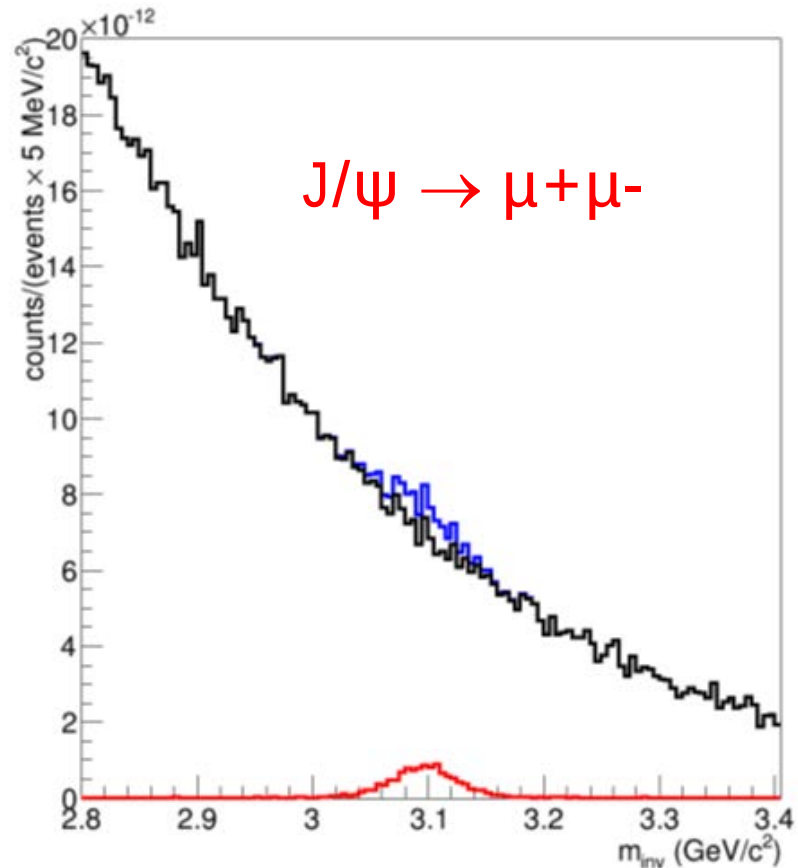
Hidden charm in CBM at SIS100

30 GeV p + Au



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

central Au+Au at 10 A GeV



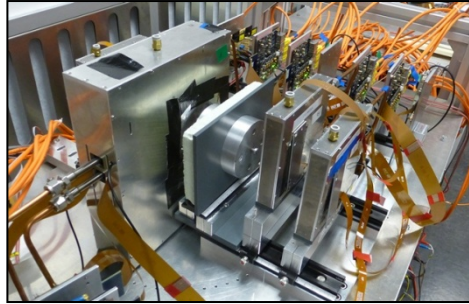
1000 J/ψ in 10^{13} events (10 days)
(multiplicity from HSD)

CBM Technical Developments

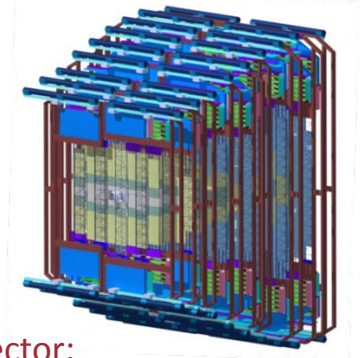
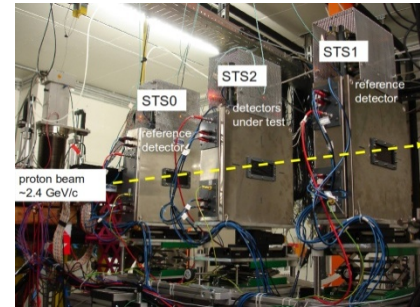
SC Magnet: JINR Dubna



Micro-Vertex Detector:
Frankfurt, Strasbourg



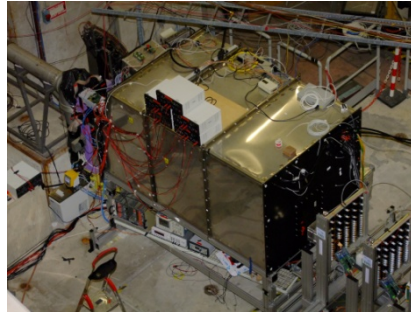
Silicon Tracking System: Darmstadt, Dubna, Krakow,
Kiev, Kharkov, Moscow, St. Petersburg, Tübingen



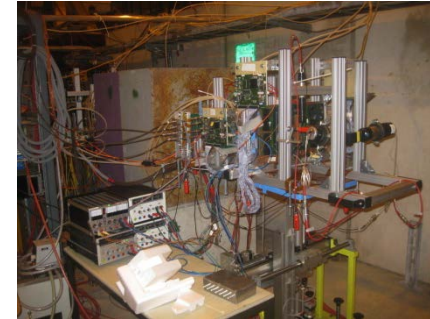
MRPC ToF Wall: Beijing, Bucharest,
Darmstadt, Frankfurt, Hefei, Heidelberg,
Moscow, Rossendorf, Wuhan



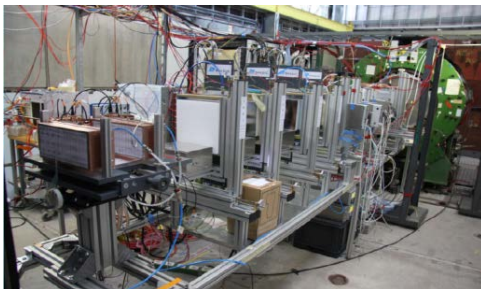
RICH Detector:
Darmstadt, Giessen, Pusan,
St. Petersburg, Wuppertal



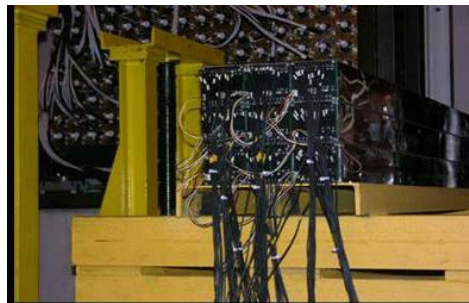
Muon detector:
Kolkata + 13 Indian Inst.,
Gatchina, Dubna



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



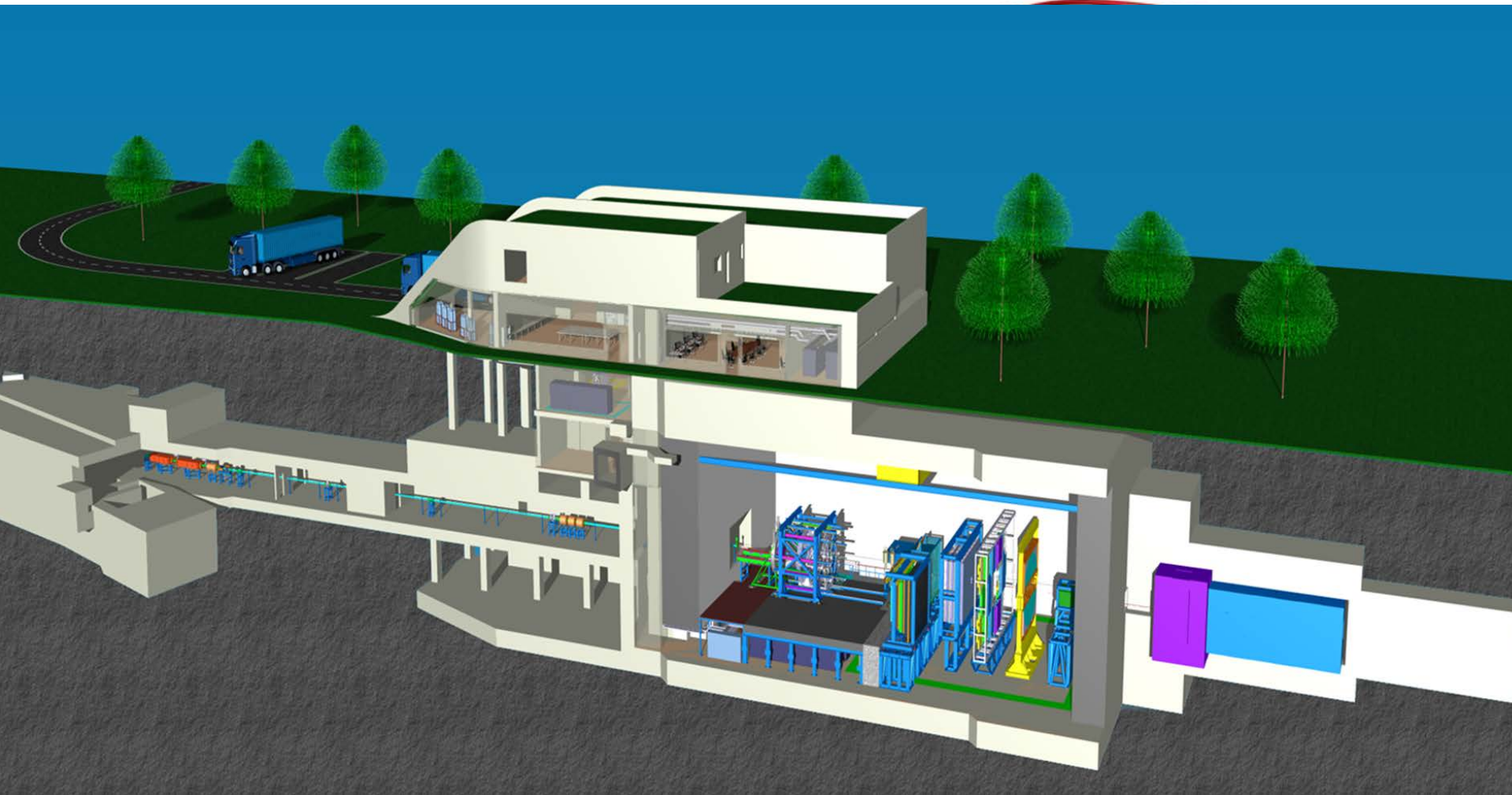
Forward calorimeter:
Moscow, Prague, Rez



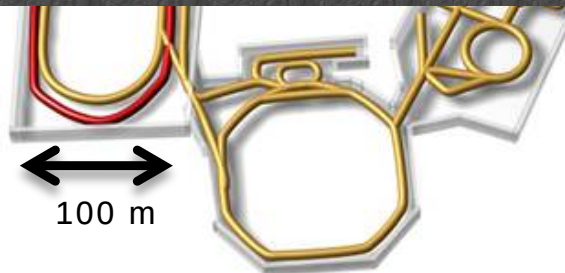
DAQ and online event selection:
Darmstadt, Frankfurt, Heidelberg,
Kharagpur, Warsaw



Facility for Antiproton & Ion Research



- $10^9/\text{s}$ Au up to 11 GeV/u
- $10^9/\text{s}$ C, Ca, ... up to 14 GeV/u
- $10^{11}/\text{s}$ 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.

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

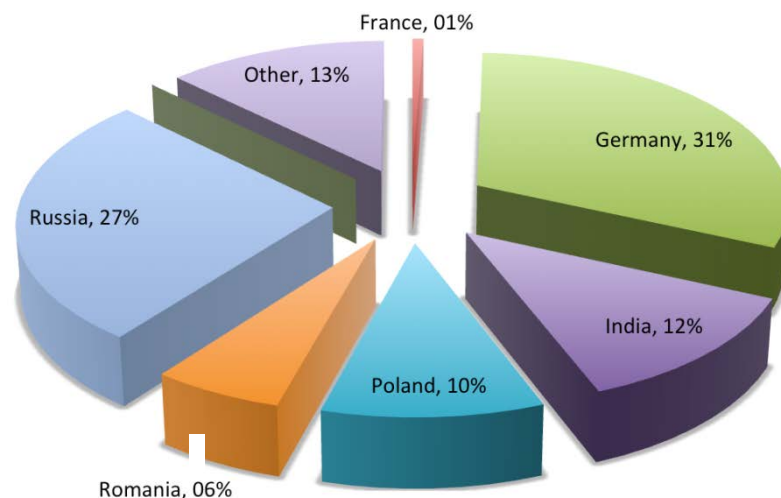
Kiev Inst. Nucl. Research

日本国 ?

26th CBM Collaboration meeting in Prague, CZ
14 -18 Sept. 2015



Scientist fraction, CBM



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 → 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.
- Participation of Japanese scientists is most welcome

