The CBM physics program

Christian Sturm, GSI
for the CBM Collaboration

Outline

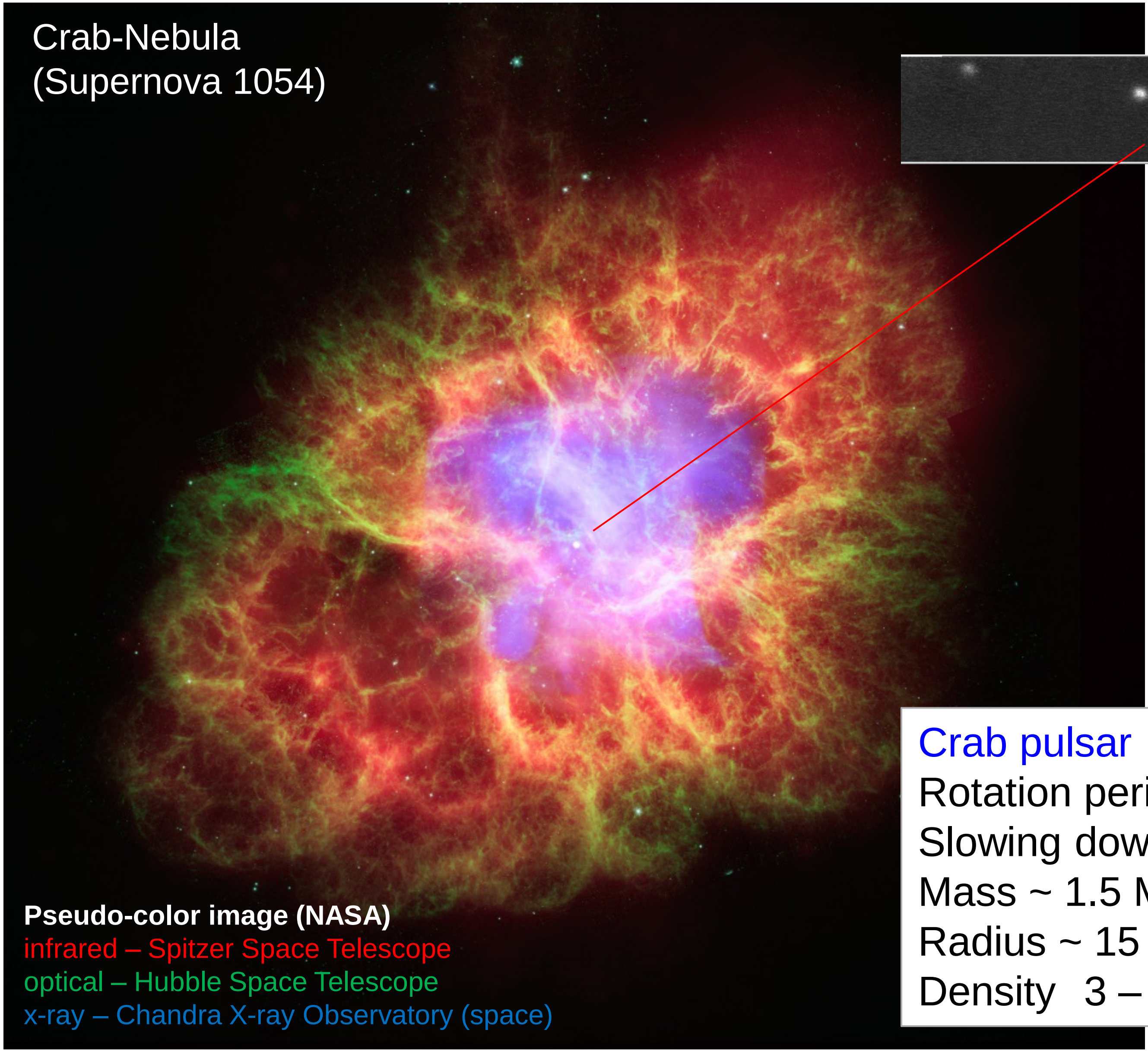
CBM physics at SIS100

Outlook to FAIR phase 2

Experiment preparation and activities during FAIR phase 0

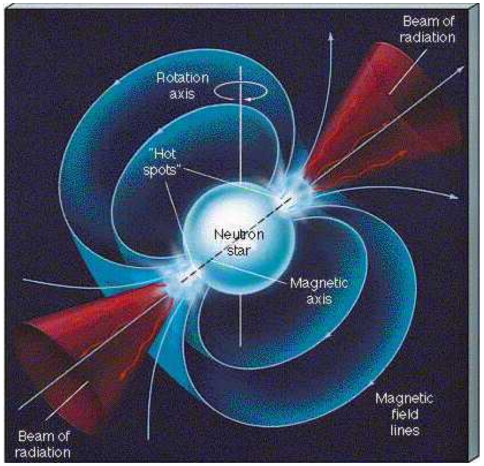
Compressed baryonic matter – neutron stars

Crab-Nebula
(Supernova 1054)



Pseudo-color image (NASA)
infrared – Spitzer Space Telescope
optical – Hubble Space Telescope
x-ray – Chandra X-ray Observatory (space)

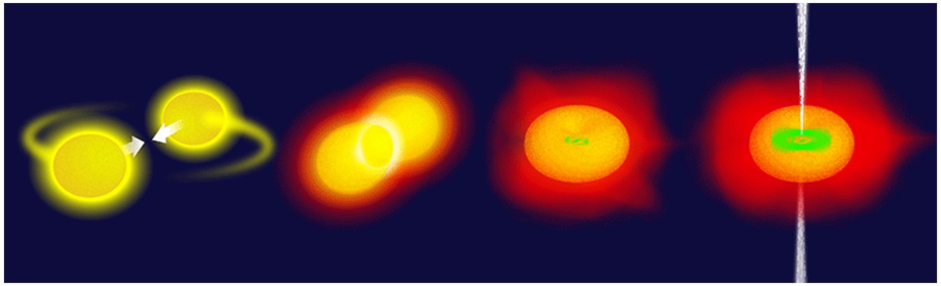
slow motion

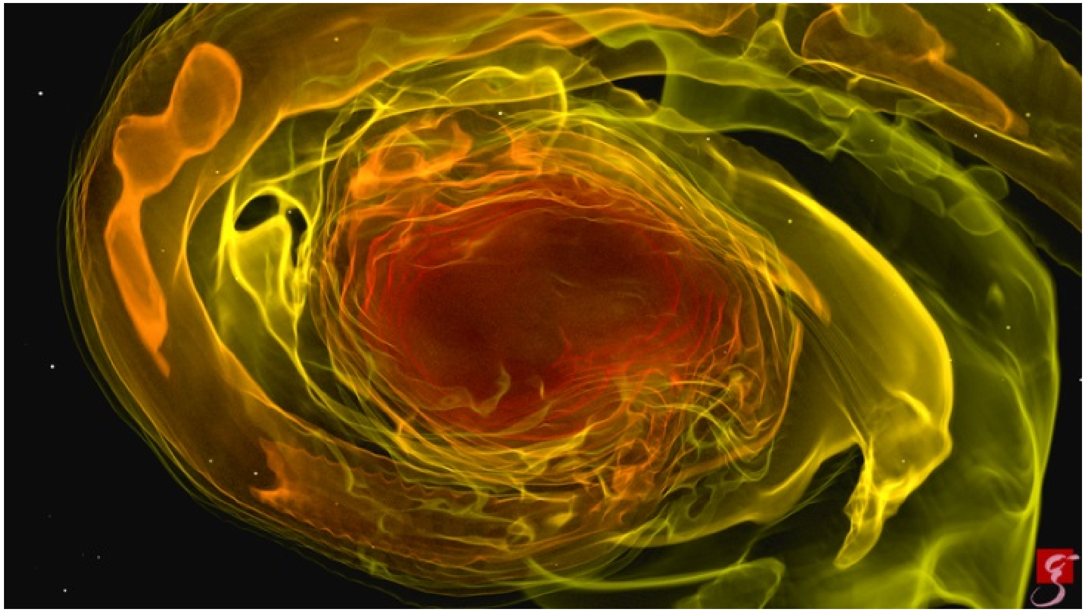


Crab pulsar
Rotation period T = 33.4 ms
Slowing down rate $\Delta T/\Delta t = 3 \cdot 10^{-8}$ s/a
Mass ~ 1.5 $M_\odot$
Radius ~ 15 km
Density 3 – 10 ρ_0

Compressed baryonic matter – collision of neutron stars

Neutron star merger





numerical simulation, GW170817
T. Dietrich (Max Planck Institute for Gravitational Physics)

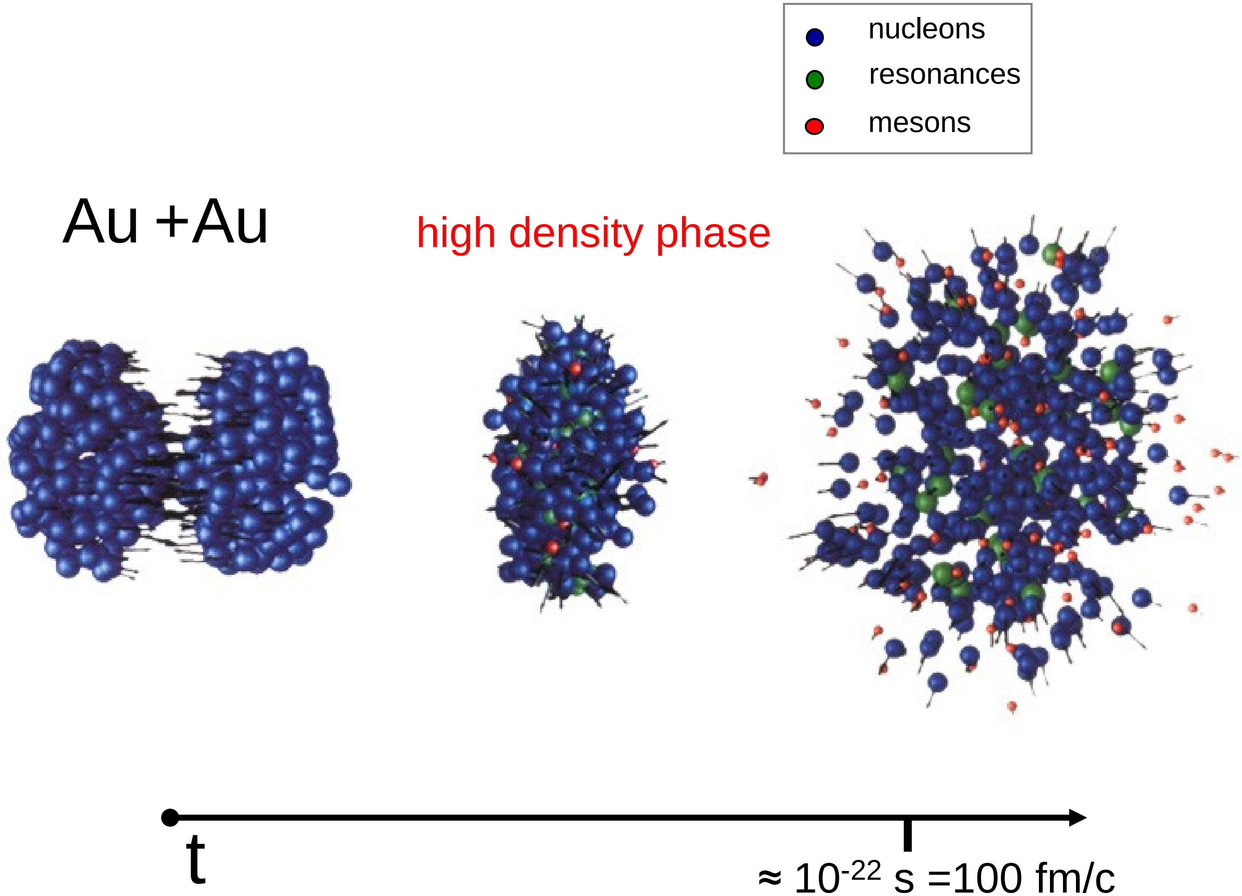
Temperature
$T < 70$ MeV

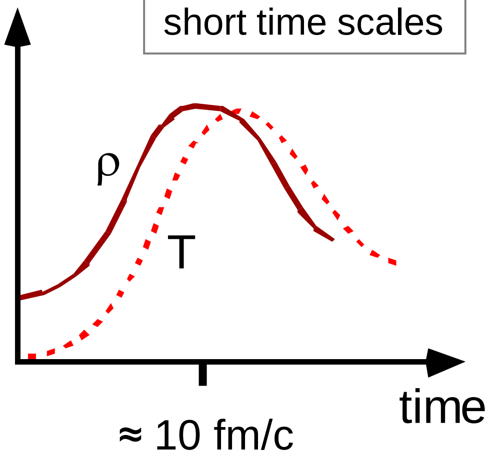
Density
$\rho < 2 - 6\ \rho_0$

Reaction time
$\Delta t \sim 10$ ms

Compressed baryonic matter – collision of (heavy) nuclei

QMD , S. Bass , Uni. Frankfurt



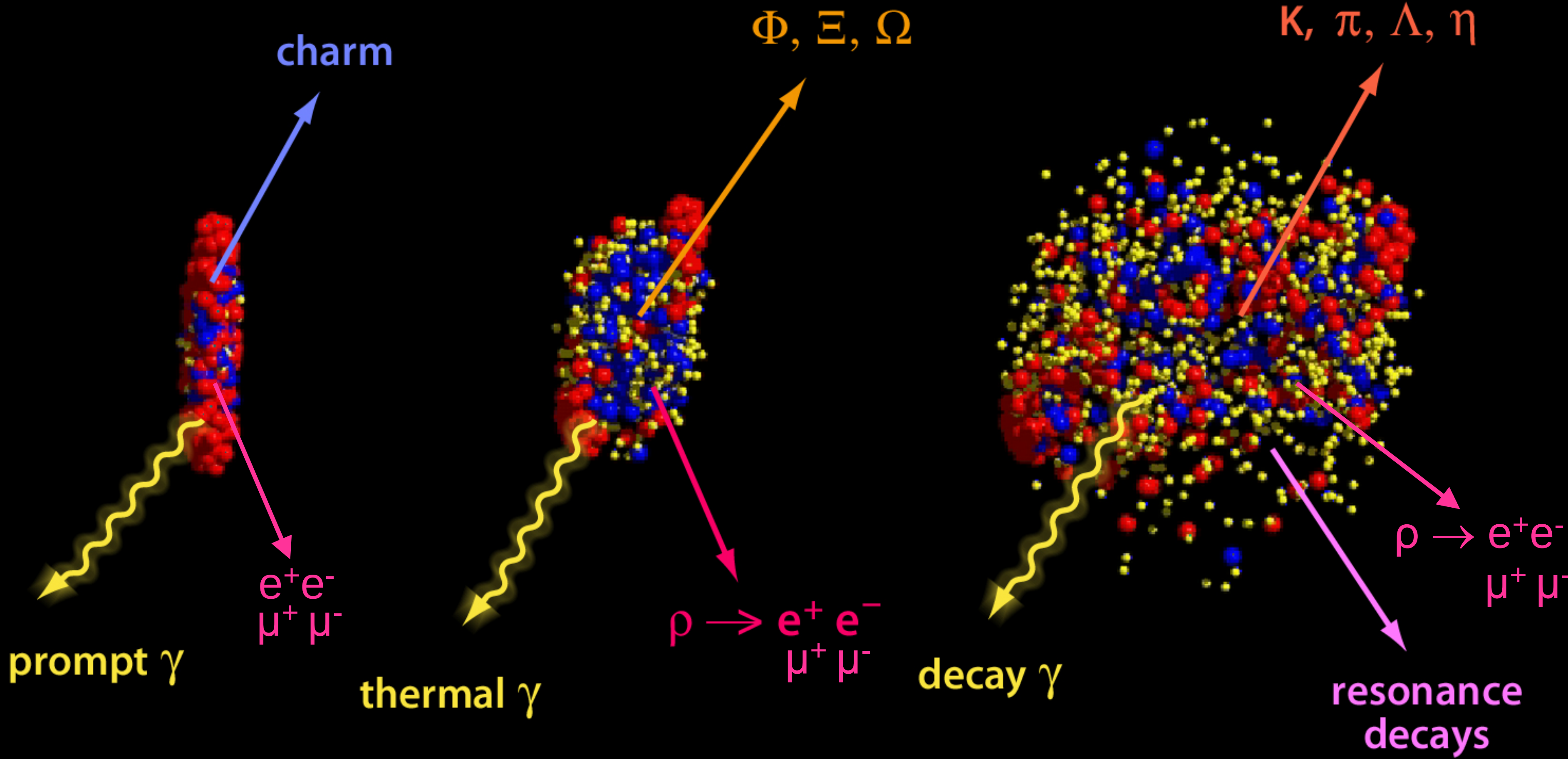


at SIS18:
$\rho_B \approx 1 - 3\ \rho_0$
$T \approx 70 - 100$ MeV

<u>note:</u>
system not necessarily equilibrated

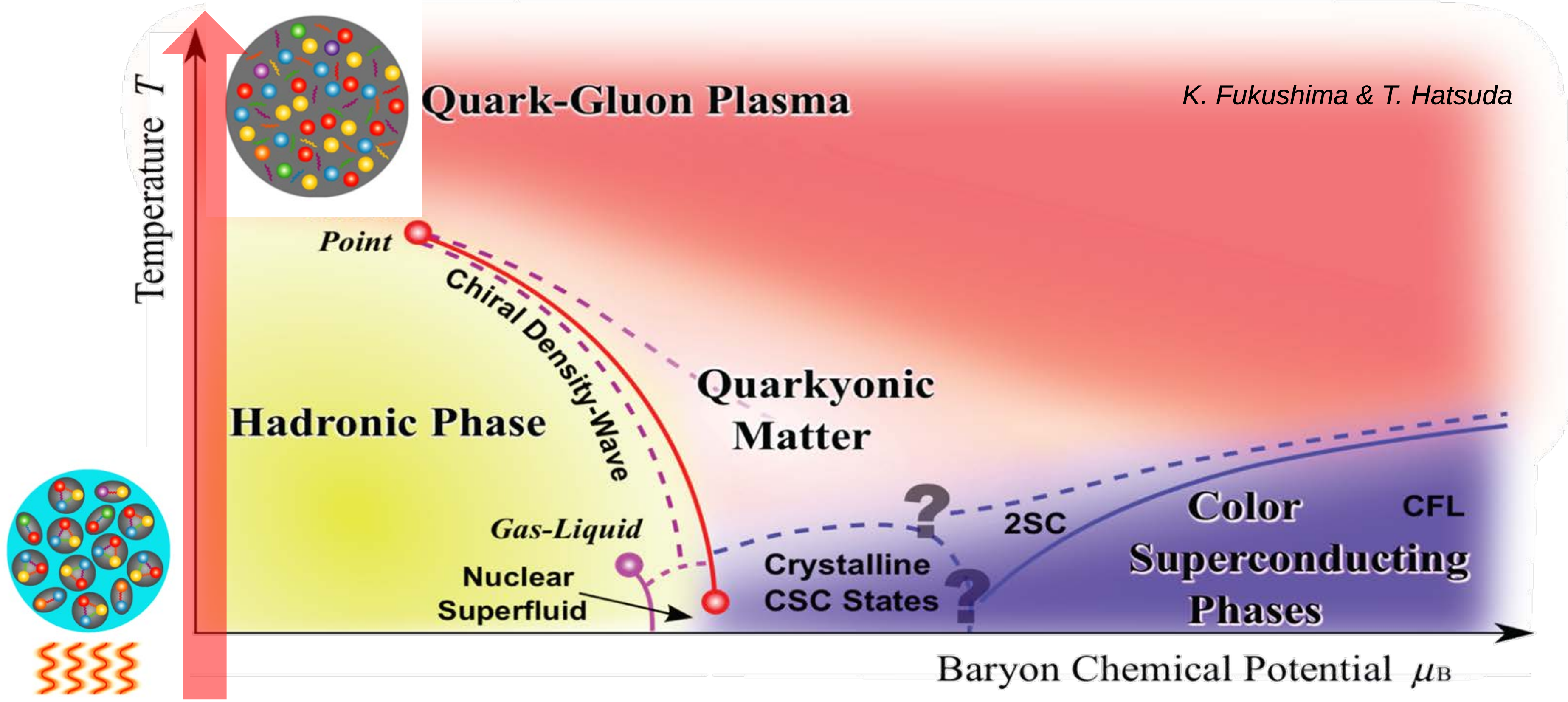
transport models: $\rho_{max} \cong 3\rho_0$

Messengers at FAIR energies



UrQMD transport calculation U+U 23 AGeV

Exploring the QCD phase diagram



At very high temperature:

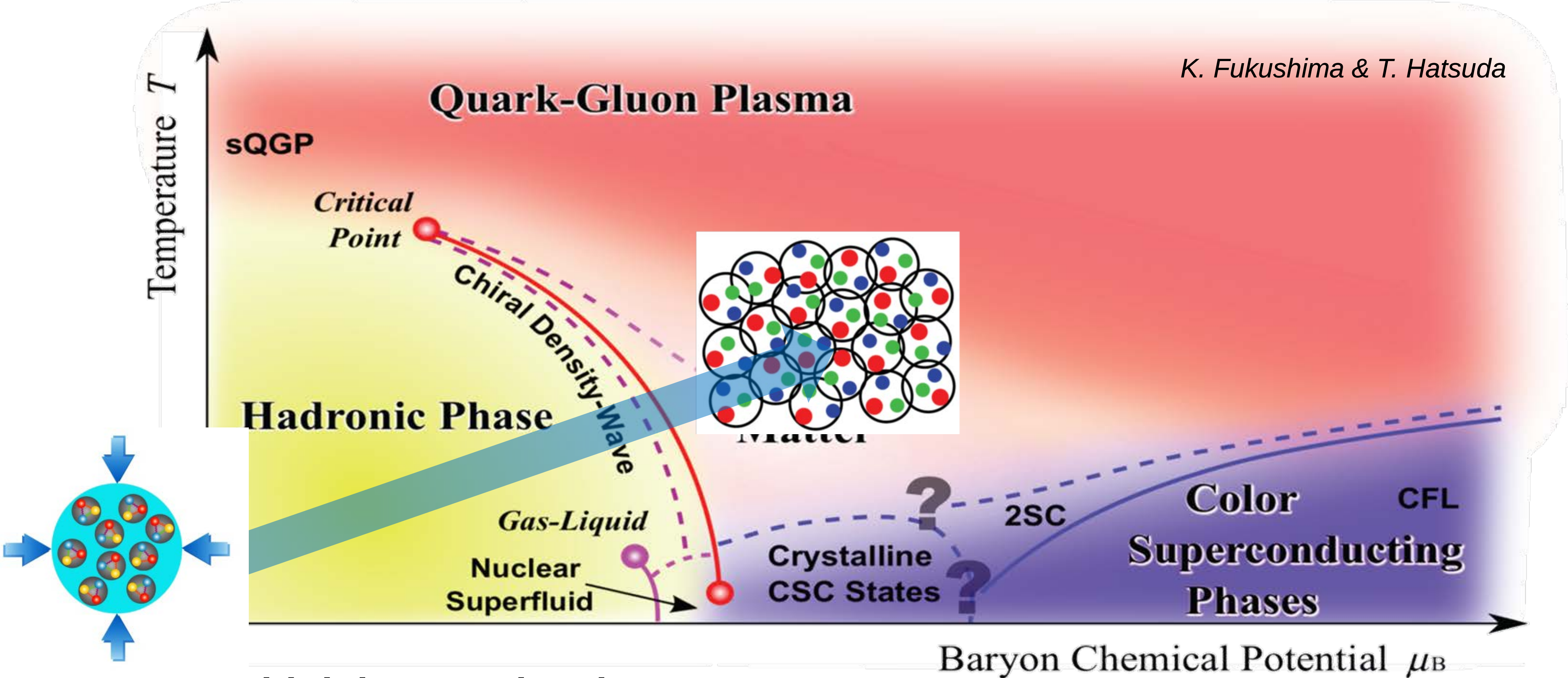
N of baryons ≈ N of antibaryons → situation similar to early universe

Lattice QCD: crossover transition Hadronic Matter → Quark-Gluon Plasma

Experiments:

ALICE, ATLAS and CMS at LHC & STAR and PHENIX at RHIC

Exploring the QCD phase diagram



At high baryon density:

N of baryons >> N of antibaryons , densities like in neutron star cores

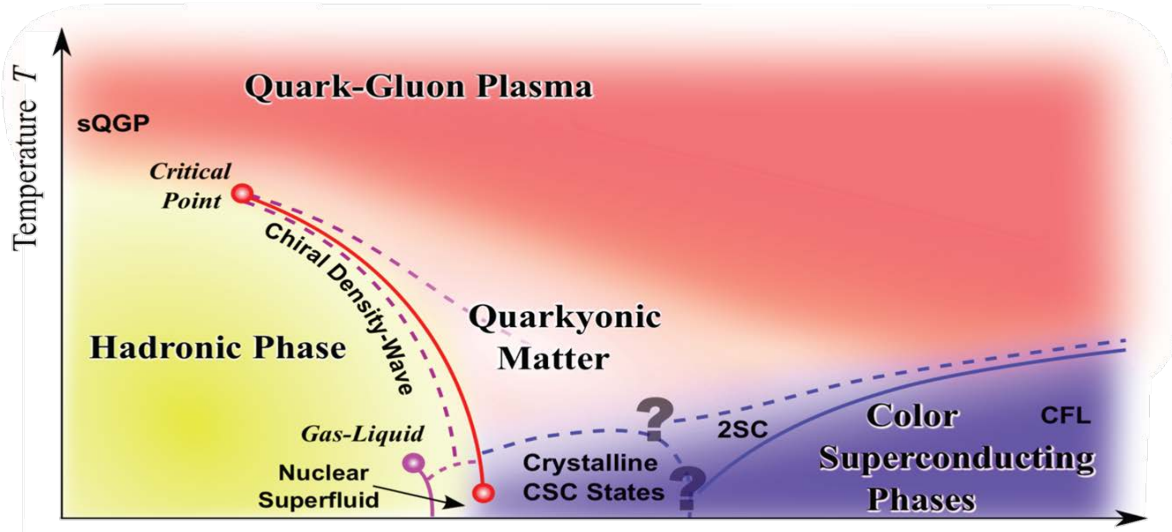
→ Lattice QCD not (yet) applicable

→ Models predict first order phase transition with mixed or exotic phases

Experiments:

BES at RHIC, NA61 at CERN SPS, NICA at JINR and **CBM at FAIR**

CBM – Goals



Courtesy of K. Fukushima & T. Hatsuda

Mission:

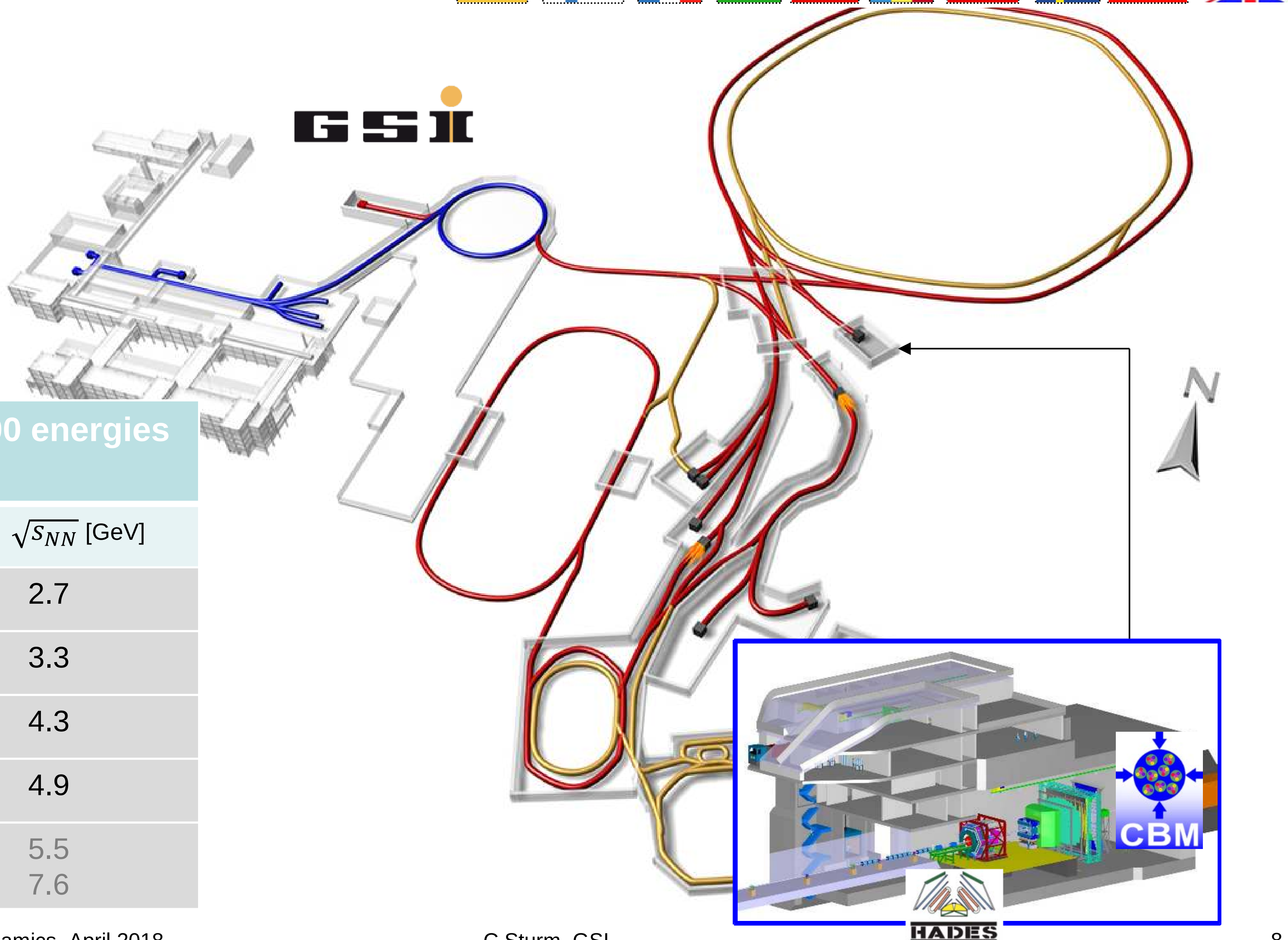
Systematically explore QCD matter at large baryon densities with high accuracy and rare probes.

Fundamental questions:

Equation-of-state of QCD matter at neutron star core densities
Phase structure of QCD matter
Chiral symmetry restoration at large densities
Bound states with strangeness

Field driven by experimental data !

The Facility for Antiproton and Ion Research

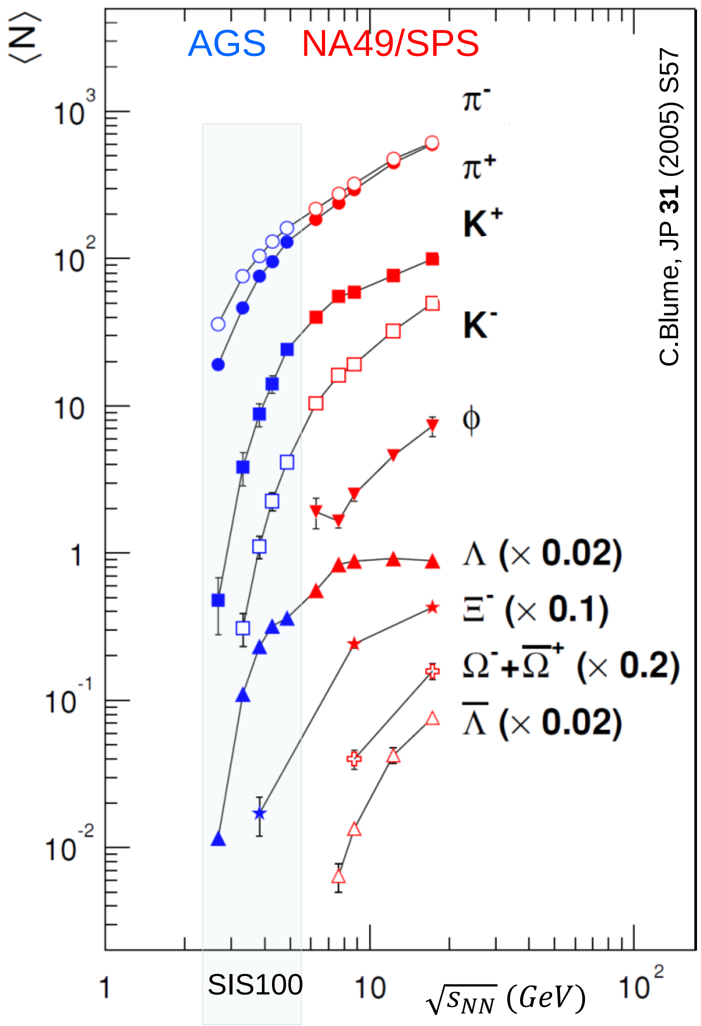


FAIR SIS100 energies
(Au ions)

E_{kin}^{lab} [A·GeV]	$\sqrt{s_{NN}}$ [GeV]
2	2.7
4	3.3
8	4.3
11	4.9
14 (Ca) 29 (p)	5.5 7.6

Strangeness at FAIR energies

Particle yields
from central Au + Au collisions



Particle production thresholds in pp - collisions

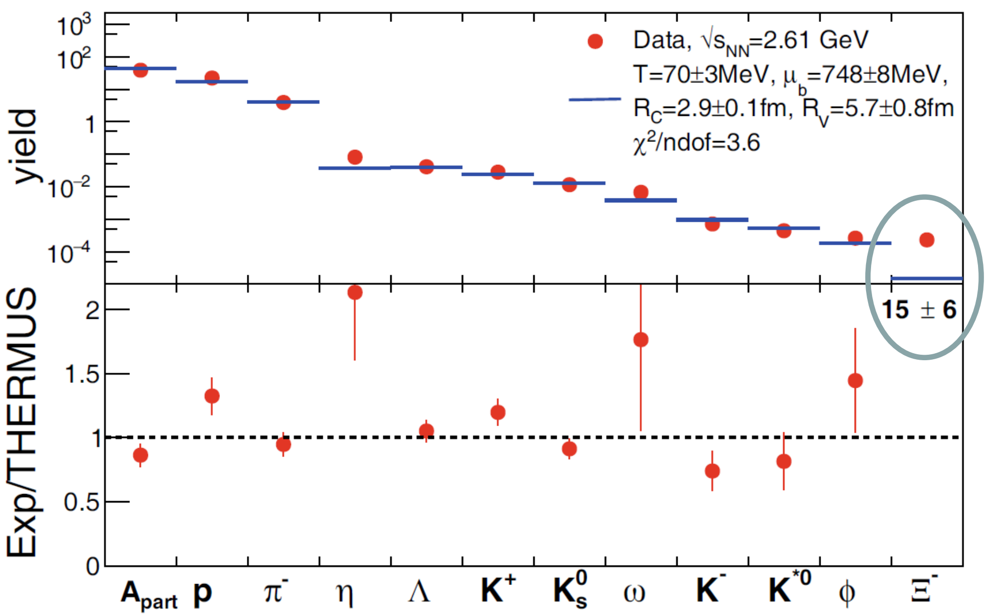
reaction	$\sqrt{s}$ (GeV)	T_{lab}(GeV)
$pp \rightarrow K^+ \Lambda p$	2.548	1.6
$pp \rightarrow K^+ K^- pp$	2.864	2.5
$pp \rightarrow K^+ K^+ \Xi^- p$	3.247	3.7
$pp \rightarrow K^+ K^+ K^+ \Omega^- n$	4.092	7.0
$pp \rightarrow \Lambda \bar{\Lambda} pp$	4.108	7.1
$pp \rightarrow \Xi^- \bar{\Xi}^+ pp$	4.520	9.0
$pp \rightarrow \Omega^- \bar{\Omega}^+ pp$	5.222	12.7

Little knowledge on **multi-strange hyperons** at energies T_{lab} < 10 AGeV

→ multi-step production ?
→ production via strangeness exchange channels ?
→ enhanced production in dense medium ?

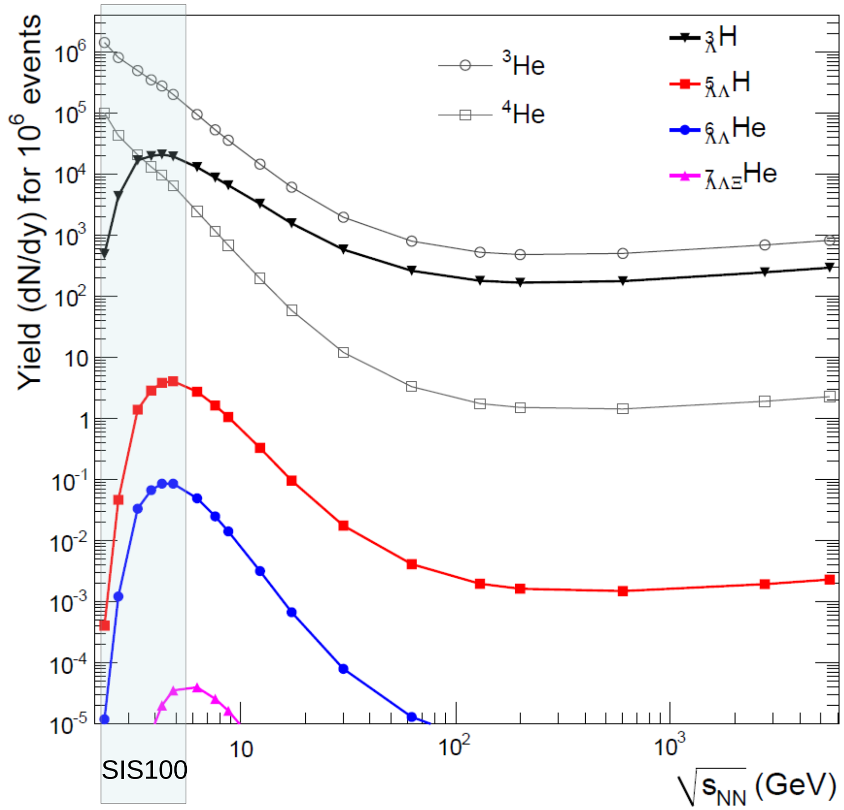
Multi-strange hyperons and hypernuclei at FAIR energies

HADES data
Ar + KCl 1.76 A GeV
Phys. Rev. Lett. 103 (2009) 132301



Statistical model fit, THERMUS v3.0
Eur. Phys. J. A (2016) 52 178

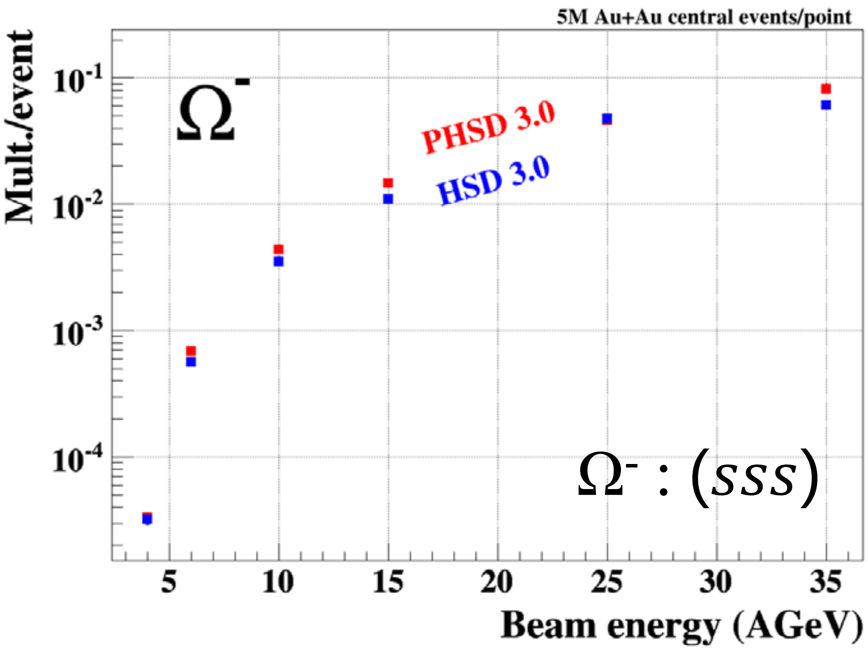
Statistical hadronisation model:
production of light nuclei and hypernuclei

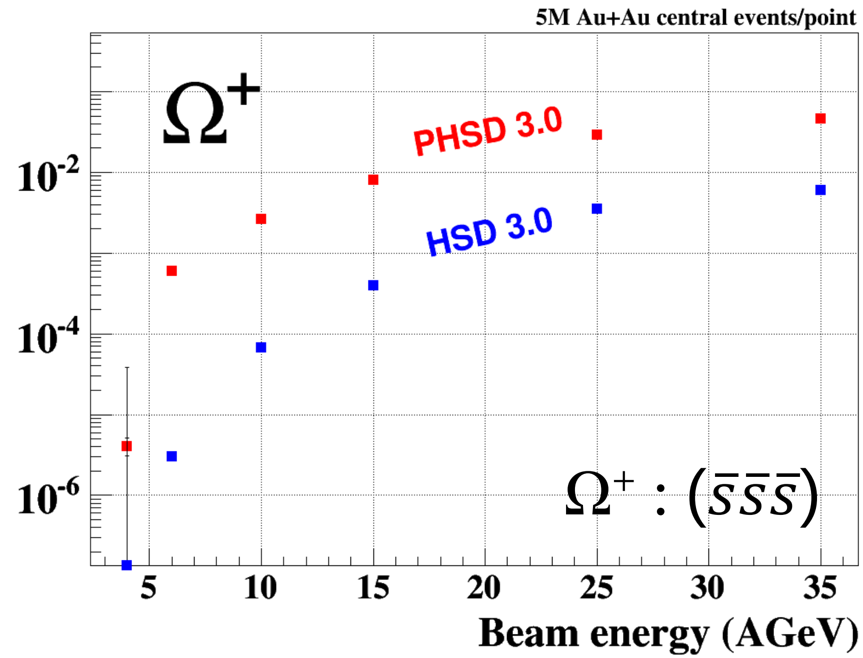


A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker
Phys. Lett. B697 (2011) 203

Multi-strange (anti-) hyperons at FAIR energies

PHSD: Transport code with partonic phase (ε > 1 GeV/fm³)
HSD: Hadronic transport code

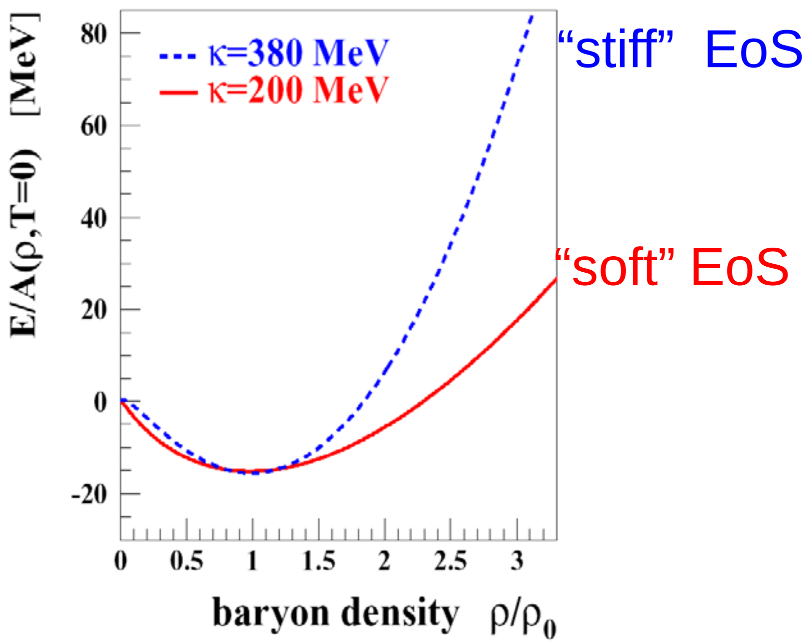




I. Vassiliev, E. Bratkovskaya, preliminary results

Transport calculations and the nuclear Equation-of-State

$$E/A\,(\rho, T=0) \;=\; \frac{1}{\rho}\int U\,(\rho)\,d\rho$$



$$\kappa \;=\; \left(9\rho^2\,\frac{\partial^2 E/A(\rho, T=0)}{\partial \rho^2}\right)_{\rho=\rho_0}$$

compression modulus

In transport code included effective NN potential (Skyrme):

$$U\,(\rho) \;=\; \alpha\left(\frac{\rho}{\rho_0}\right) \;+\; \beta\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

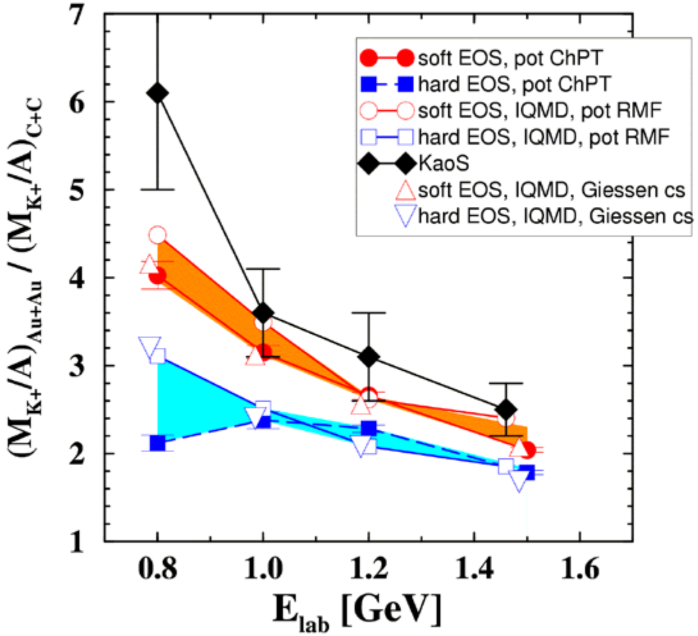
constraints for the parameters of the potential :

$$\varepsilon(\rho=\rho_0, T=0) = -16 MeV$$

$$\left(\frac{\partial\varepsilon(\rho, T=0)}{\partial\rho}\right)_{\rho=\rho_0} = 0$$

Corresponding EoS with	α [MeV]	β [MeV]	γ
κ = 380 MeV	**-124**	**70.5**	**2**
κ = 200 MeV	**-356**	**303**	**7/6**

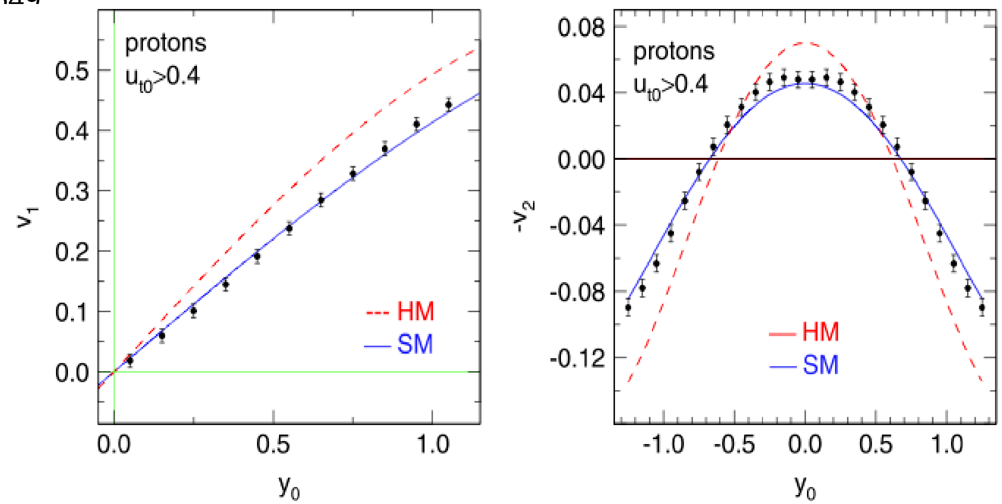
Experiment: CS et al., Phys. Rev. Lett. 86 (2001) 39
Theory: RQMD C. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649

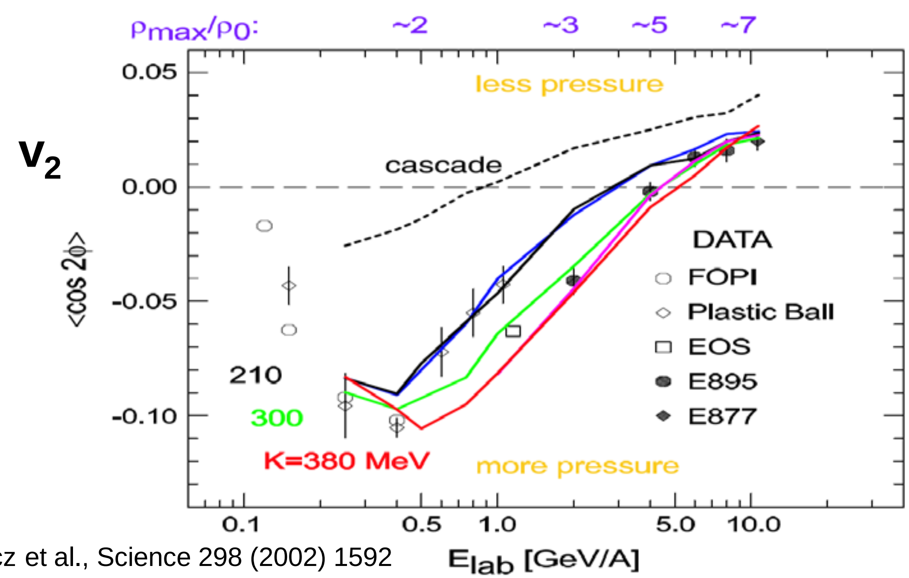


FOPI

Au+Au 1.5 AGeV

W. Reisdorf et al. (FOPI), Nucl. Phys. A 876 (2012) 1





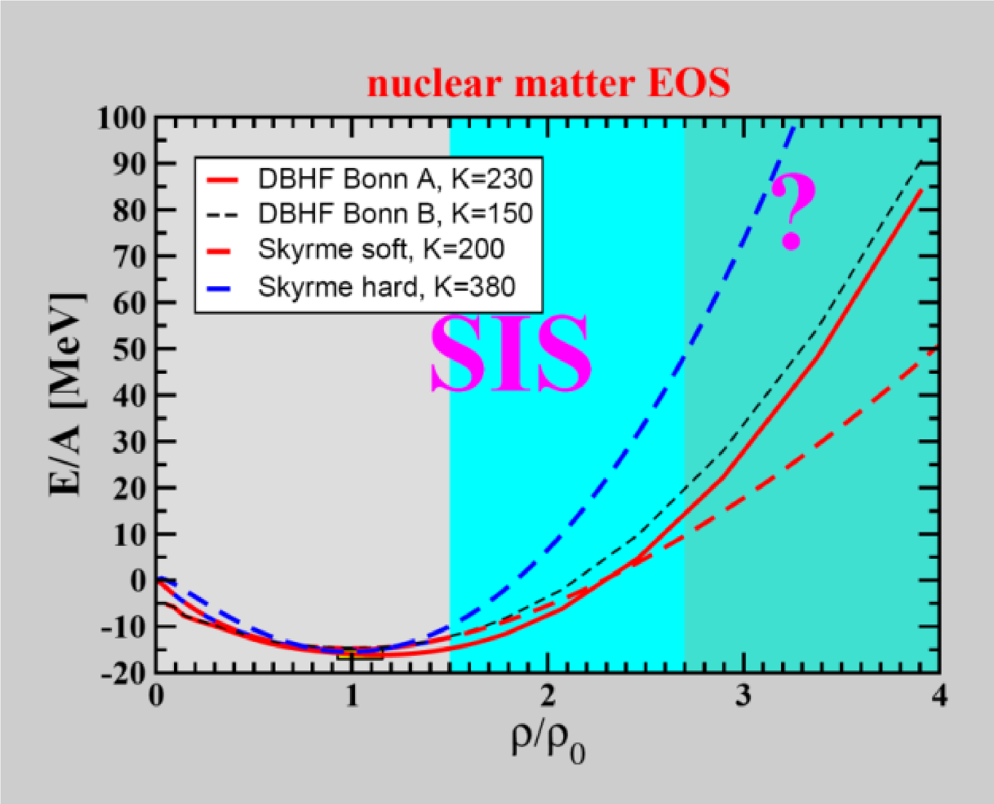
P. Danielewicz et al., Science 298 (2002) 1592

consistent picture at
SIS18 energies ($1.5 < \rho / \rho_0 < 3.0$)

inconclusive at AGS energies

Nuclear equation-of-state at FAIR energies

DBHF: E. N. E. van Dalen, C. Fuchs, A. Faessler
EPJ. A 31,29 (2007)

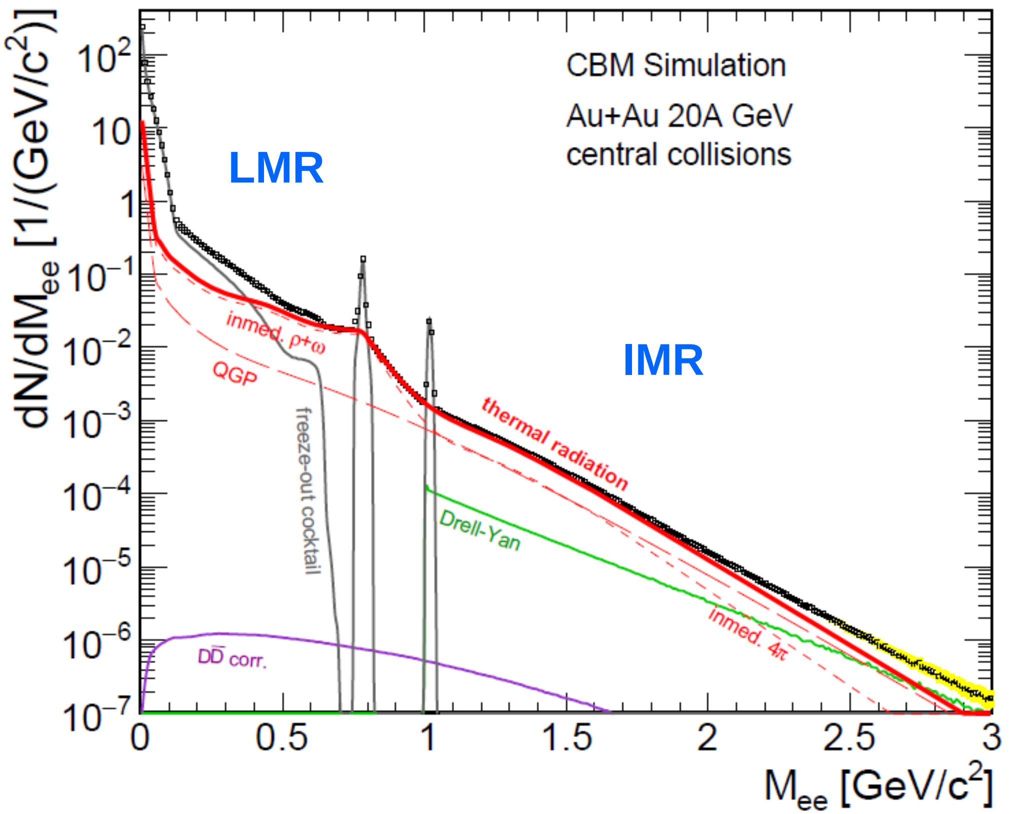


equation-of-state
at
neutron star core densities ?

→ (sub-threshold) production
of $\Omega^+(\bar{s}\bar{s}\bar{s})$ at FAIR energies
- refined to the high-density phase
- small final-state interaction

Dileptons
Electromagnetic radiation from the fireball

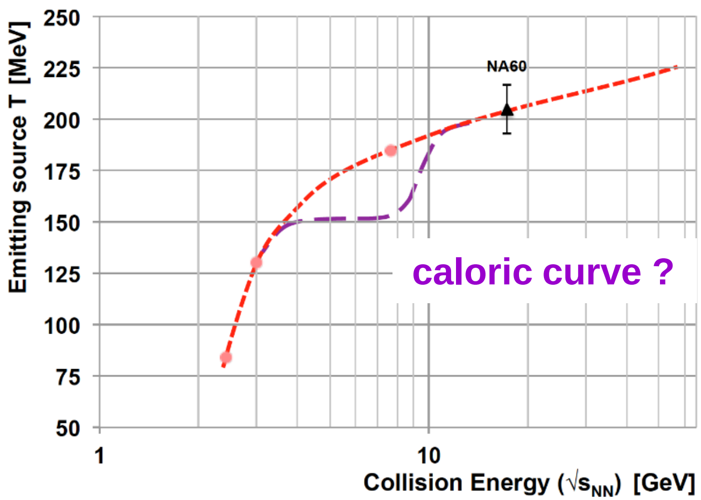
R. Rapp, H. v.Hees, PLB 753 (2016) 586



LMR (low mass region) **:**
ρ – chiral symmetry restoration

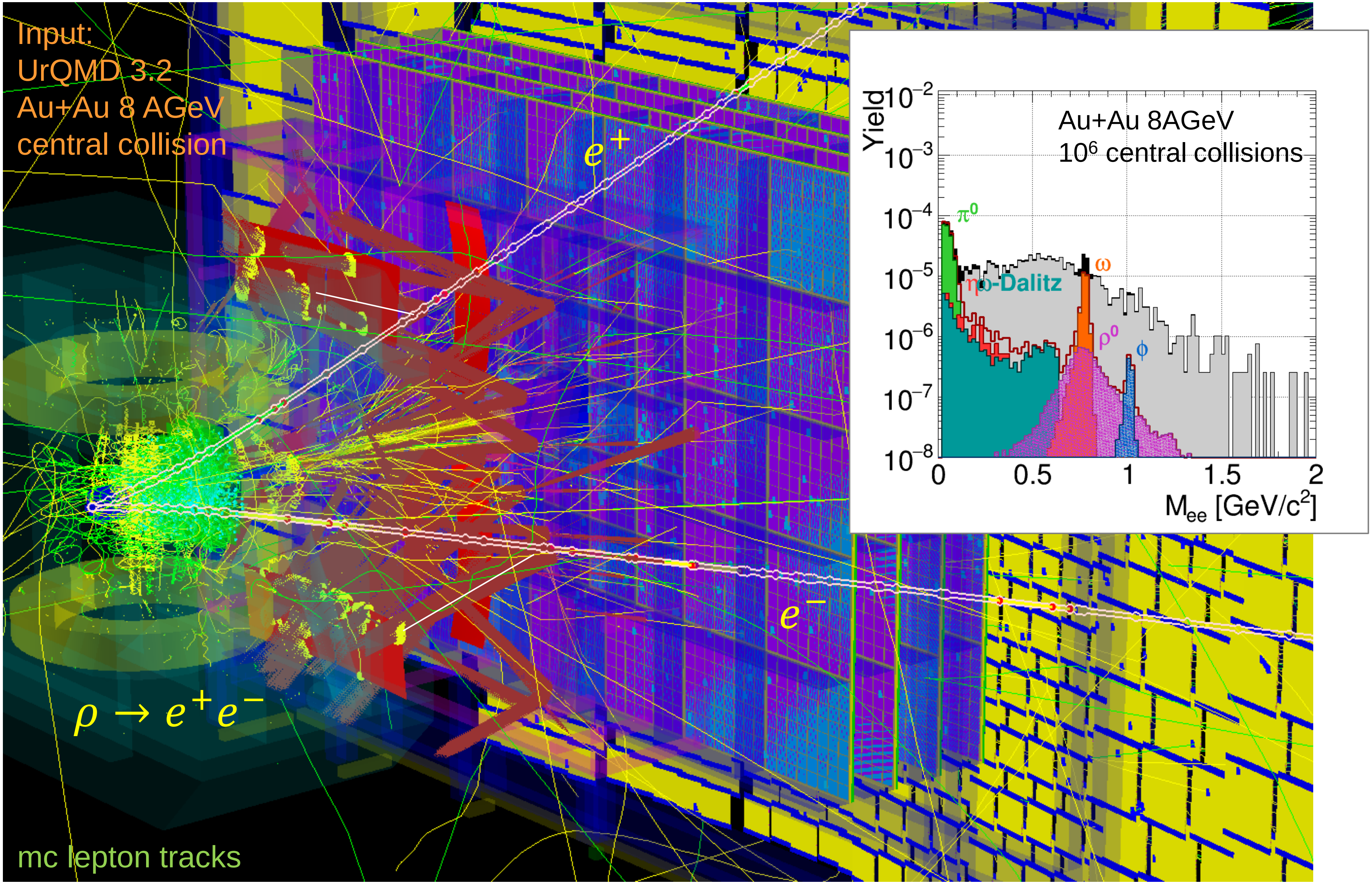
IMR (intermediate mass region) **:**
access to fireball temperature
ρ-a_1 chiral mixing

Fig. by T.Galatyuk &
EPJA 52 (2016) 131



Measurement program:
e.g. excitation function of IMR–slope

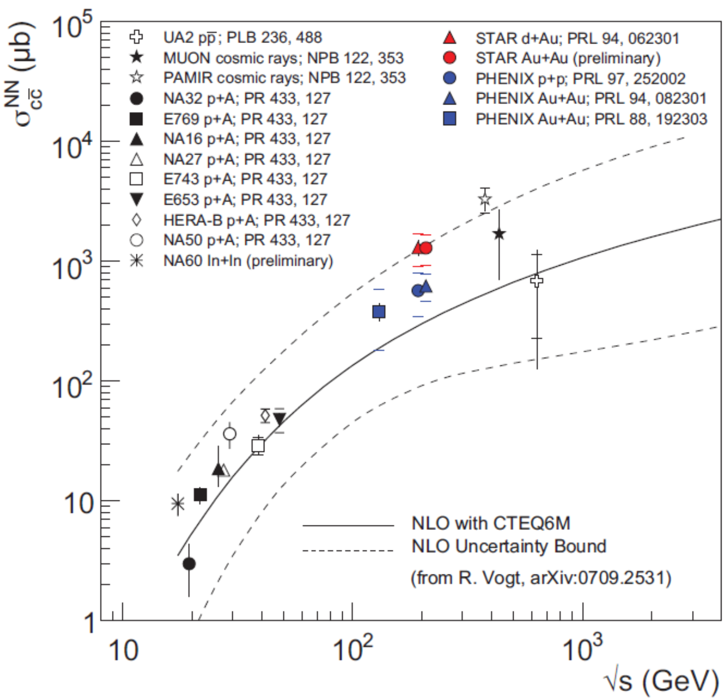
Di-electron reconstruction



CBM Physics: Charm @ SIS100

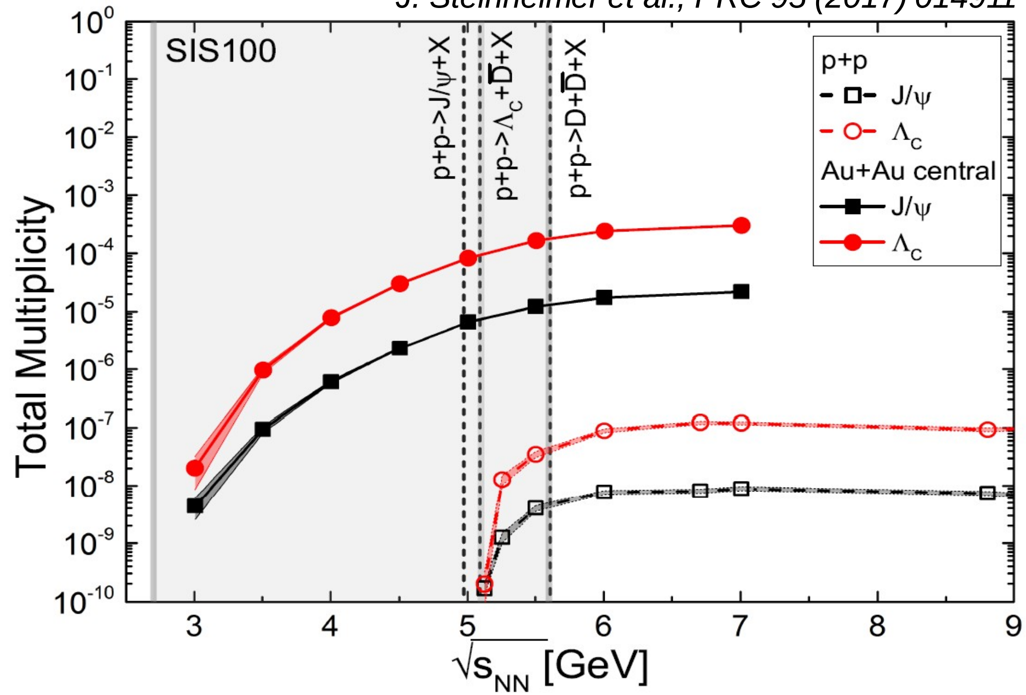
Charm cross section
in elementary collisions:

A.Frawley,T.Ulrich,R.Vogt Phys.Rept.462:125-175,2008



UrQMD transport calculation:

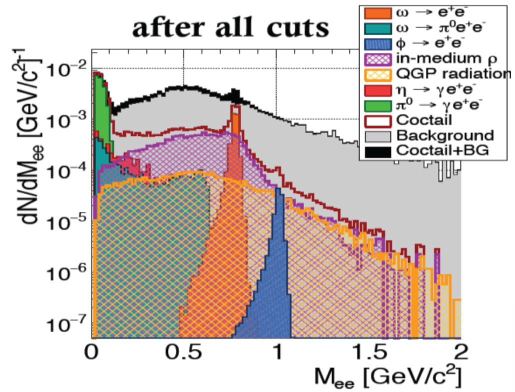
J. Steinheimer et al., PRC 95 (2017) 014911



Sub-threshold production
through heavy baryonic resonances:

N* → Λ_c + D and N* → N +J/ψ

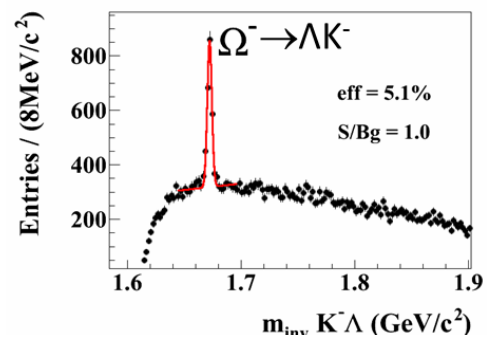
Summary: unique measurements with CBM at day 1



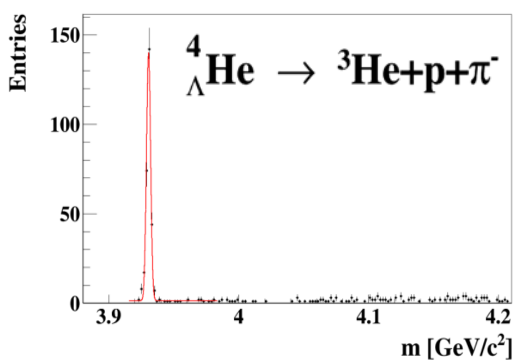
Au+Au, 8A GeV,

Di-electron measurement
Full performance,
(uses MVD, limited to 100 kHz)

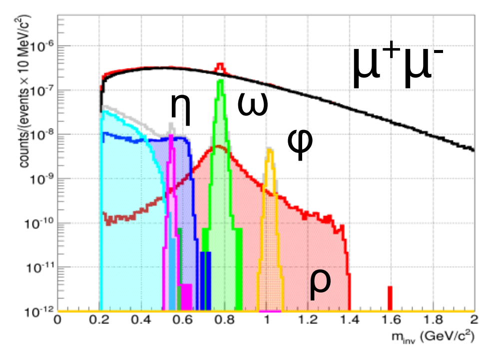
Hyperon measurements, e.g. Au+Au at 10A GeV :



Hypernuclei measurement,
e.g. Au + Au at 10A GeV

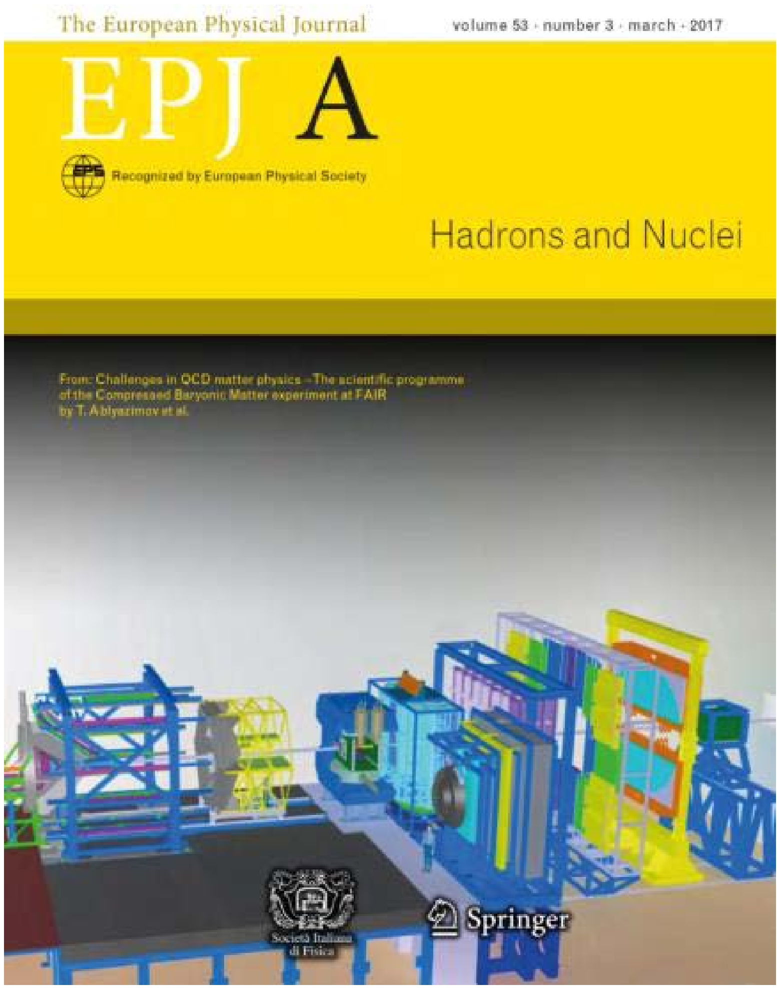


Di-muon
LM measurement at 8A GeV
= complementary measurement to e^+e^-
with different systematic errors



CBM physics and observables

Eur.Phys.J. A53 (2017) 60



QCD equation-of-state

- collective flow of identified particles
- particle production at threshold energies

Phase transition

- excitation function of hyperons
- excitation function of LM lepton pairs

Critical point

- event-by-event fluctuations of conserved quantities

Chiral symmetry restoration at large ρ_B

- in-medium modifications of hadrons
- dileptons at intermediate invariant masses

Strange matter

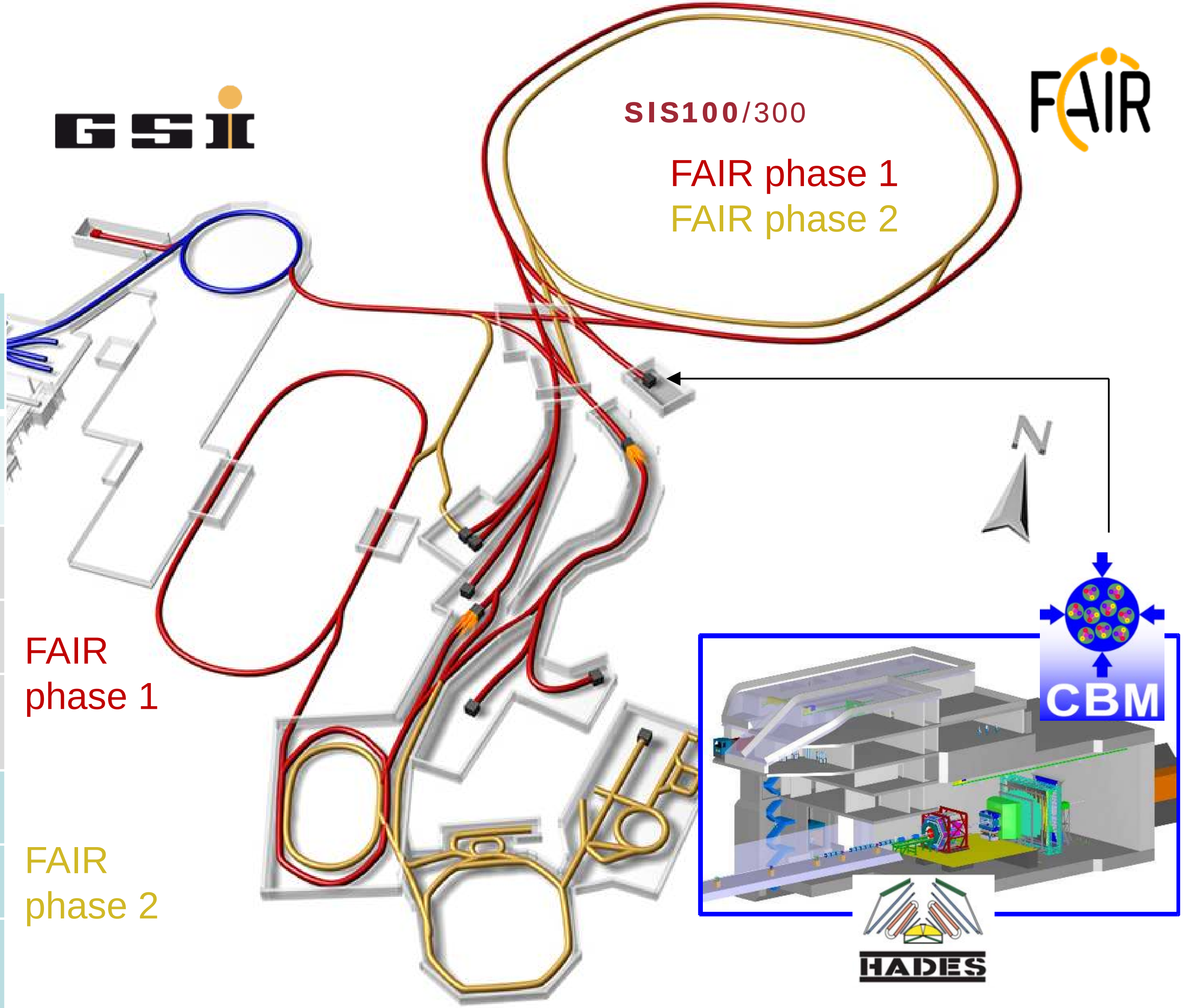
- (double-) lambda hypernuclei
- Search for meta-stable objects (e.g. strange dibaryons)

Heavy flavour in cold and dense matter

- excitation function of charm production

The Facility for Antiproton and Ion Research

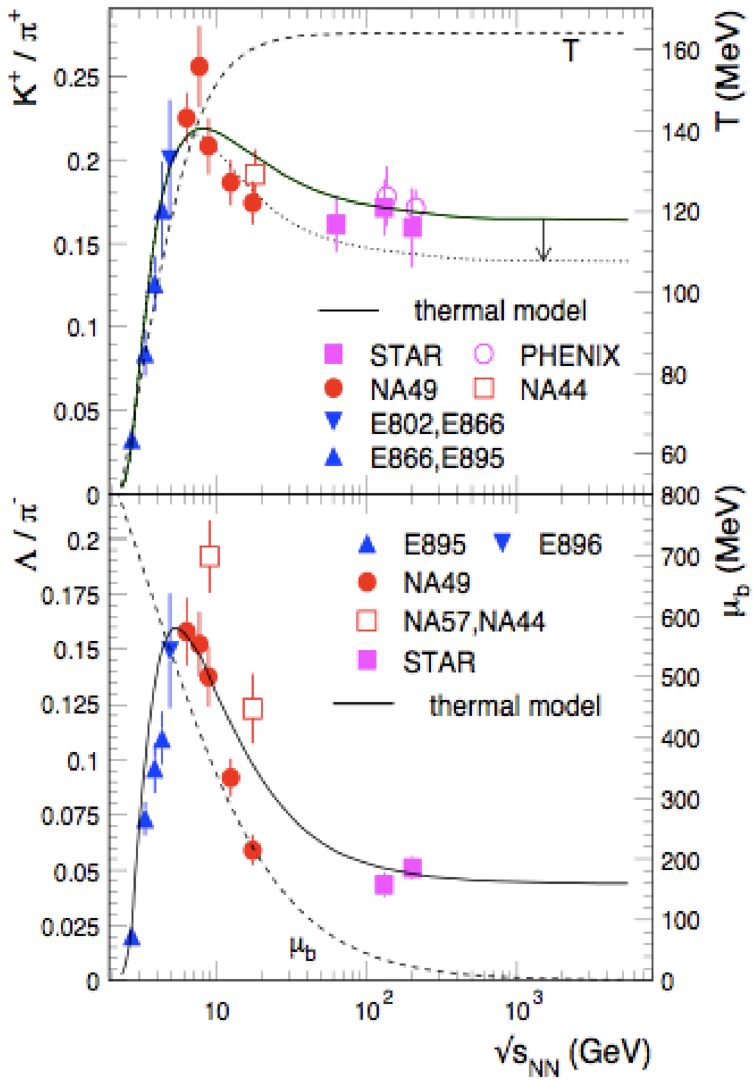
Using beams from two synchrotrons for parallel operation !



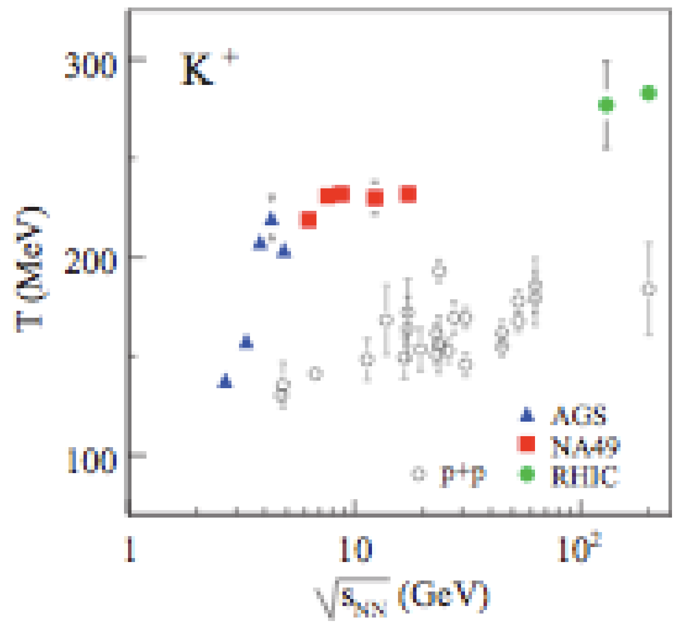
FAIR energies
(Au ions)

E_{kin}^{lab} [A·GeV]	$\sqrt{s_{NN}}$ [GeV]
2	2.7
11	4.9
14 (Ca @ SIS100) 29 (p @ SIS100)	5.5 7.6
30	7.7
35	8.3
44 (Ca @ SIS300) 89 (p @ SIS300)	9.3 13.0

CBM physics: particle yields @ FAIR phase 2



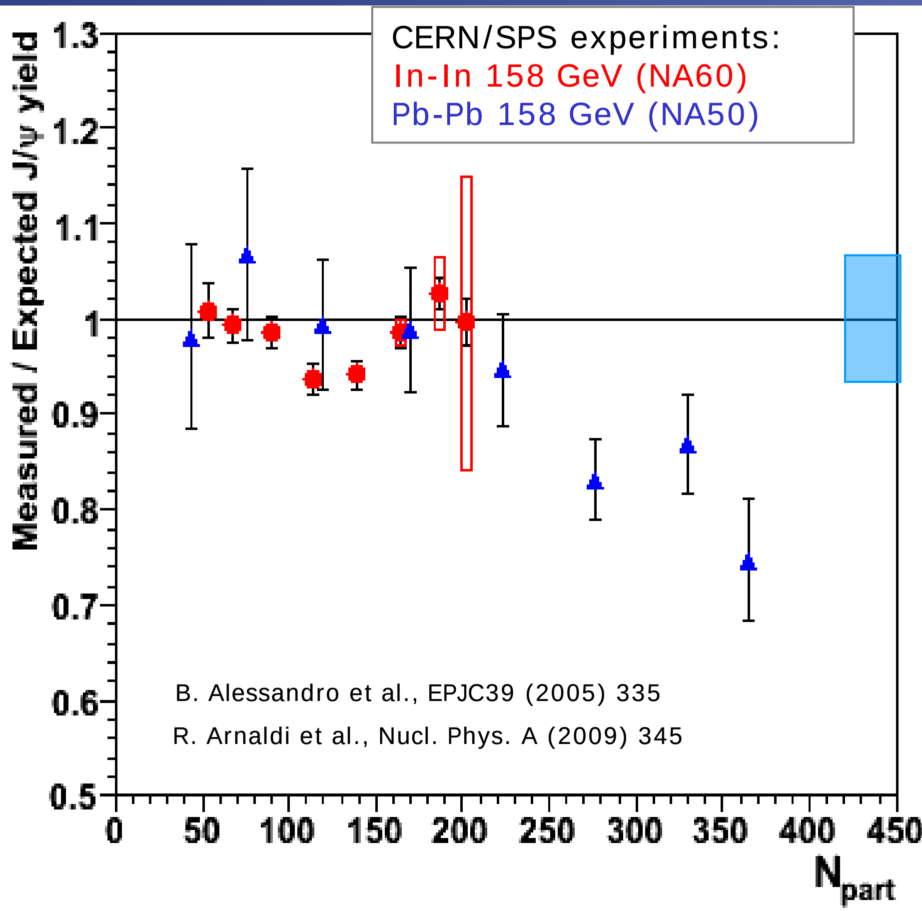
Maximum in K/π at 30 AGeV



Plateau in apparent temperature above 30 AGeV

indication of 1st order phase transition (latent heat) ?

CBM physics: Charm @ FAIR phase 2



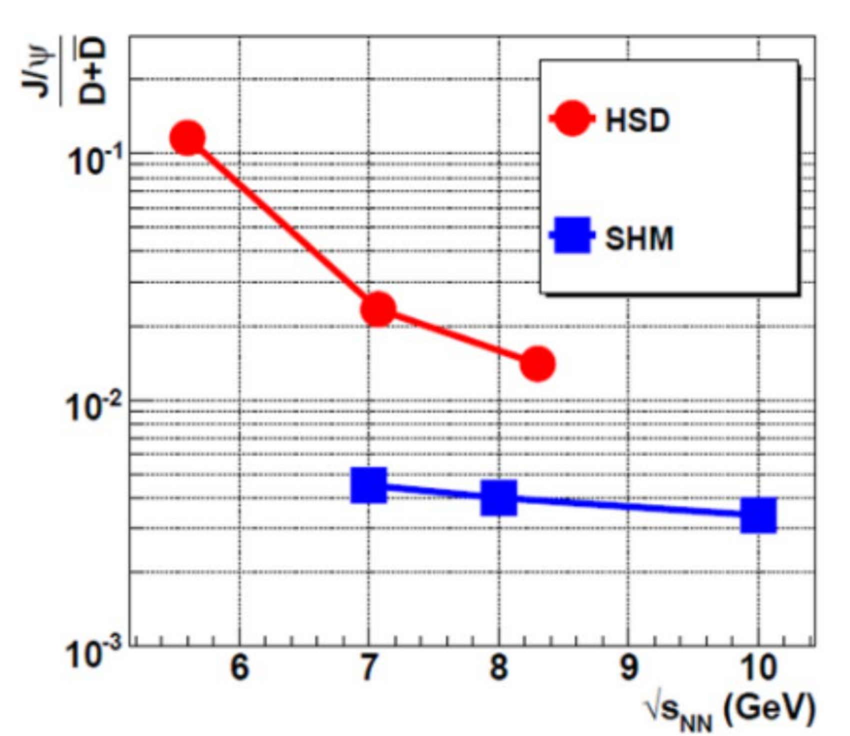
No data available below top SPS energies !

Excitation function of J/ψ production at FAIR energies

→ production mechanism ?

→ J/ψ suppression ?

CBM physics: Charm @ FAIR phase 2



HSD "hadronic"
O. Linnyk et al.,
Int.J.Mod.Phys. E17, 1367 (2008)

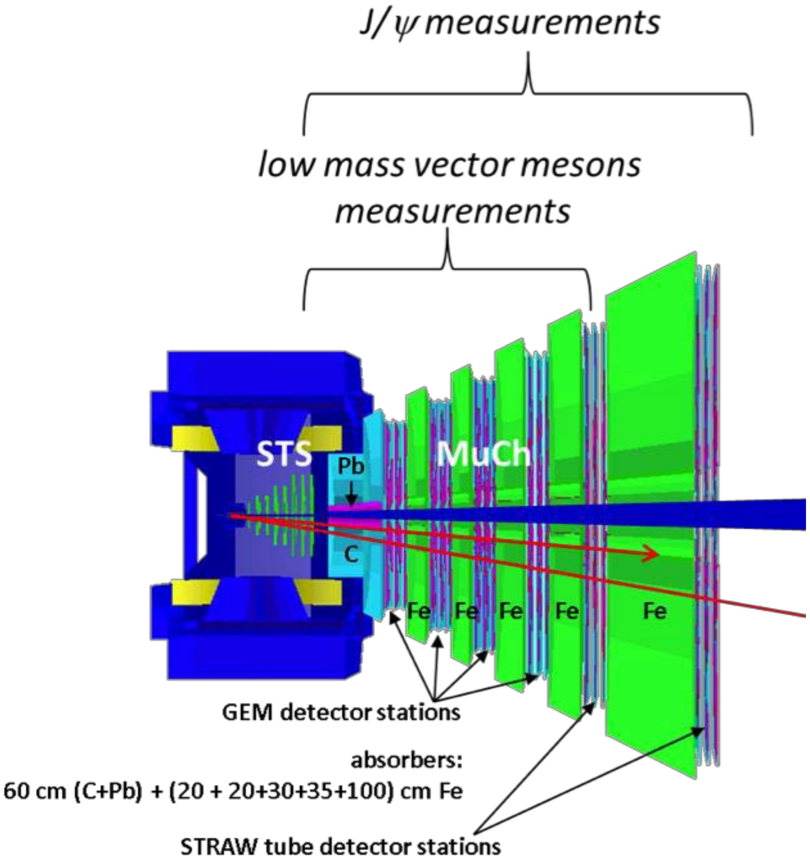
SHM "partonic"
A. Andronic et al.,
Phys. Lett. B 659 (2008) 149

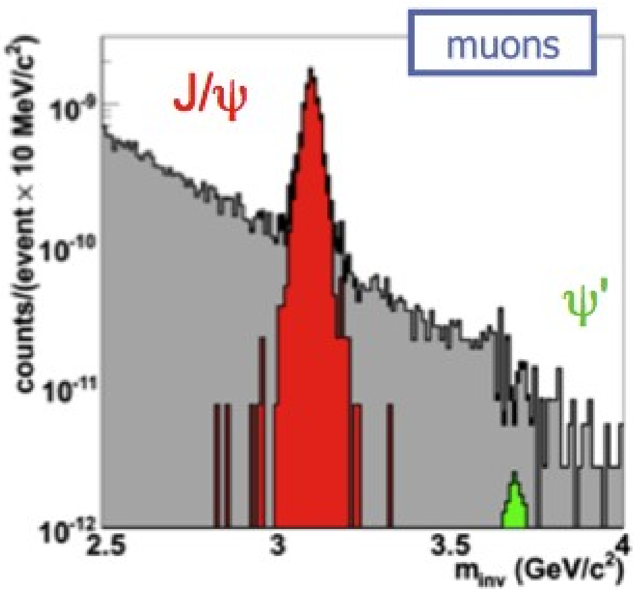
Excitation function of J/ψ production at FAIR energies

→ production mechanism ?
→ J/ψ suppression ?

CBM physics: Charm @ FAIR phase 2

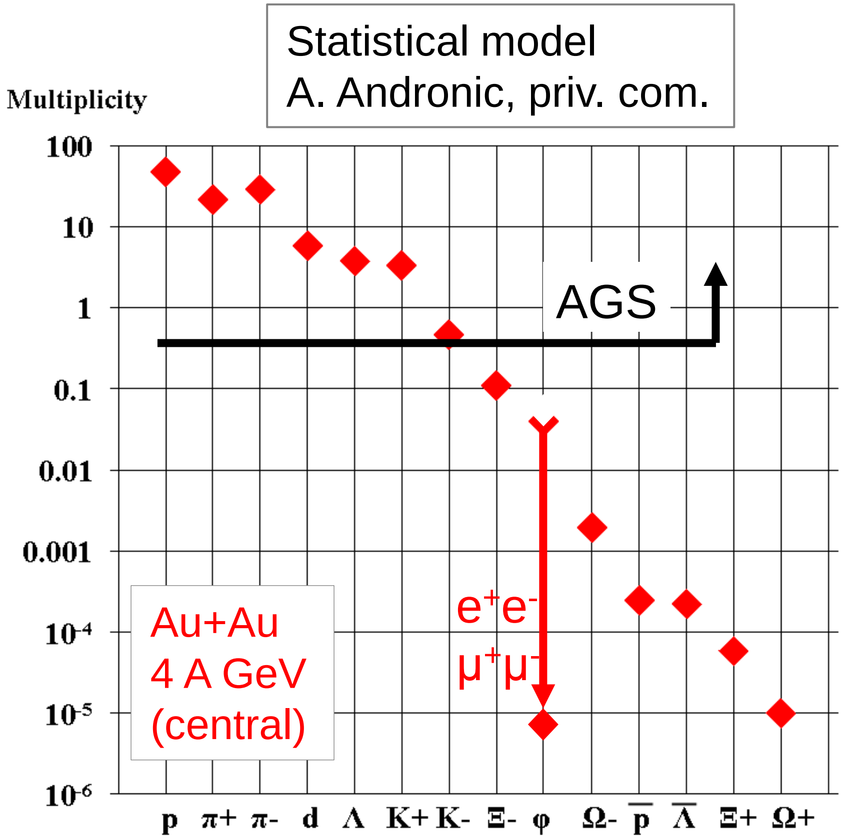
active absorber system with tracking detectors (GEM / straw tubes) sandwiched between absorber slices

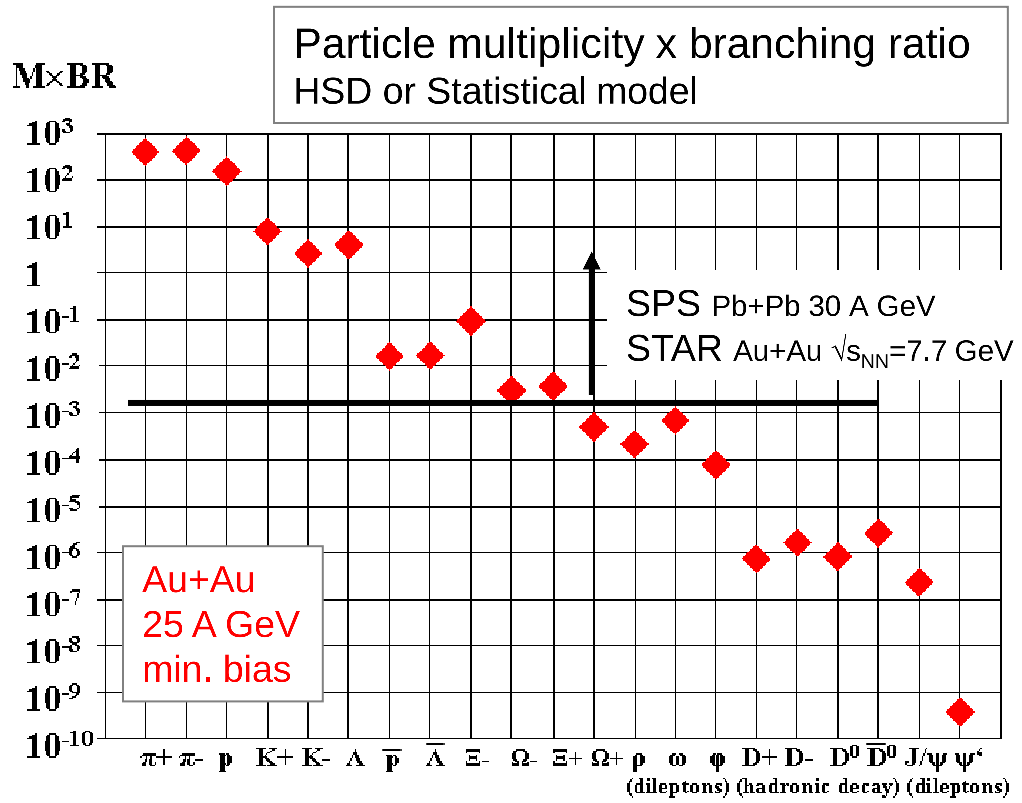




CBM Simulation
Au+Au @ 25 AGeV

Experimental challenges



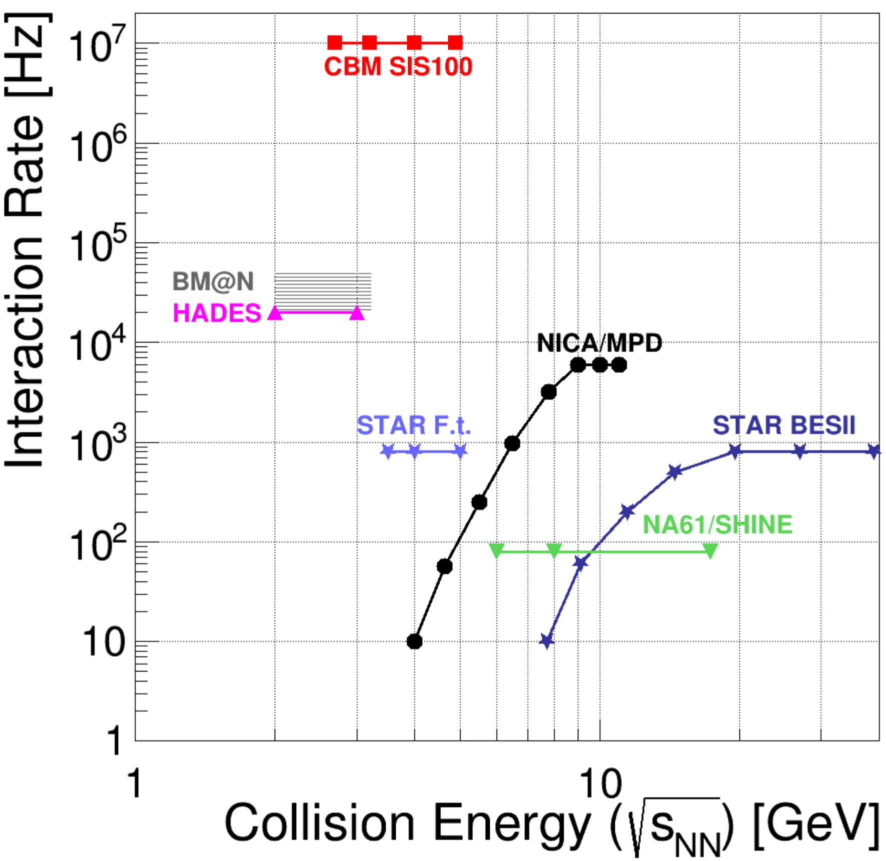


rare probes → extremely high interaction rates required !

CBM strategy

Exploration of the QCD phase diagram as international effort:

NA61	@ SPS / CERN
BM@N	@ Nuclotron / JINR
STAR (F.t.)	@ RHIC / BNL
MPD	@ NICA / JINR

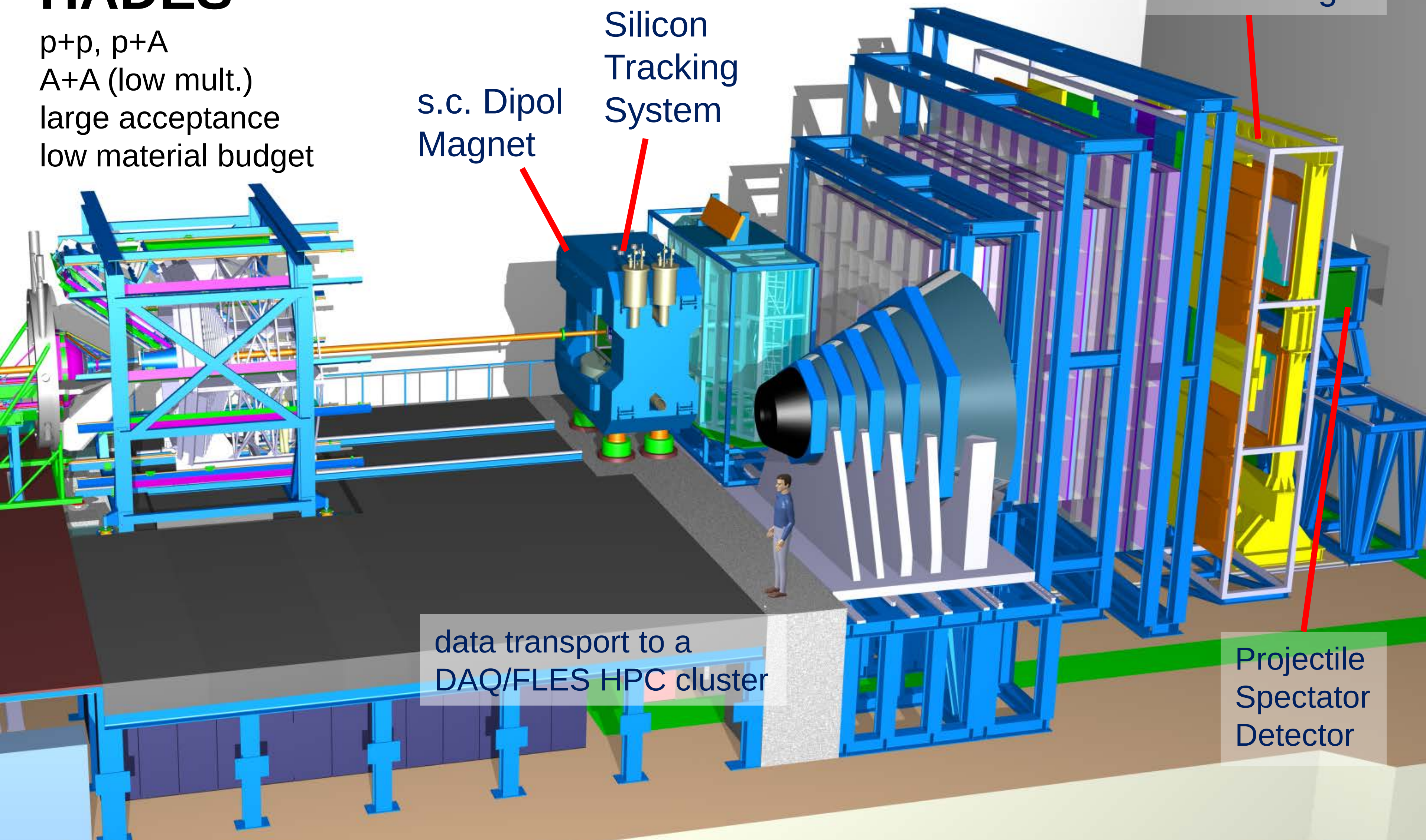


<u>CBM's unique feature:</u>
ultimate rate capability for
high statistics measurement of rare probes

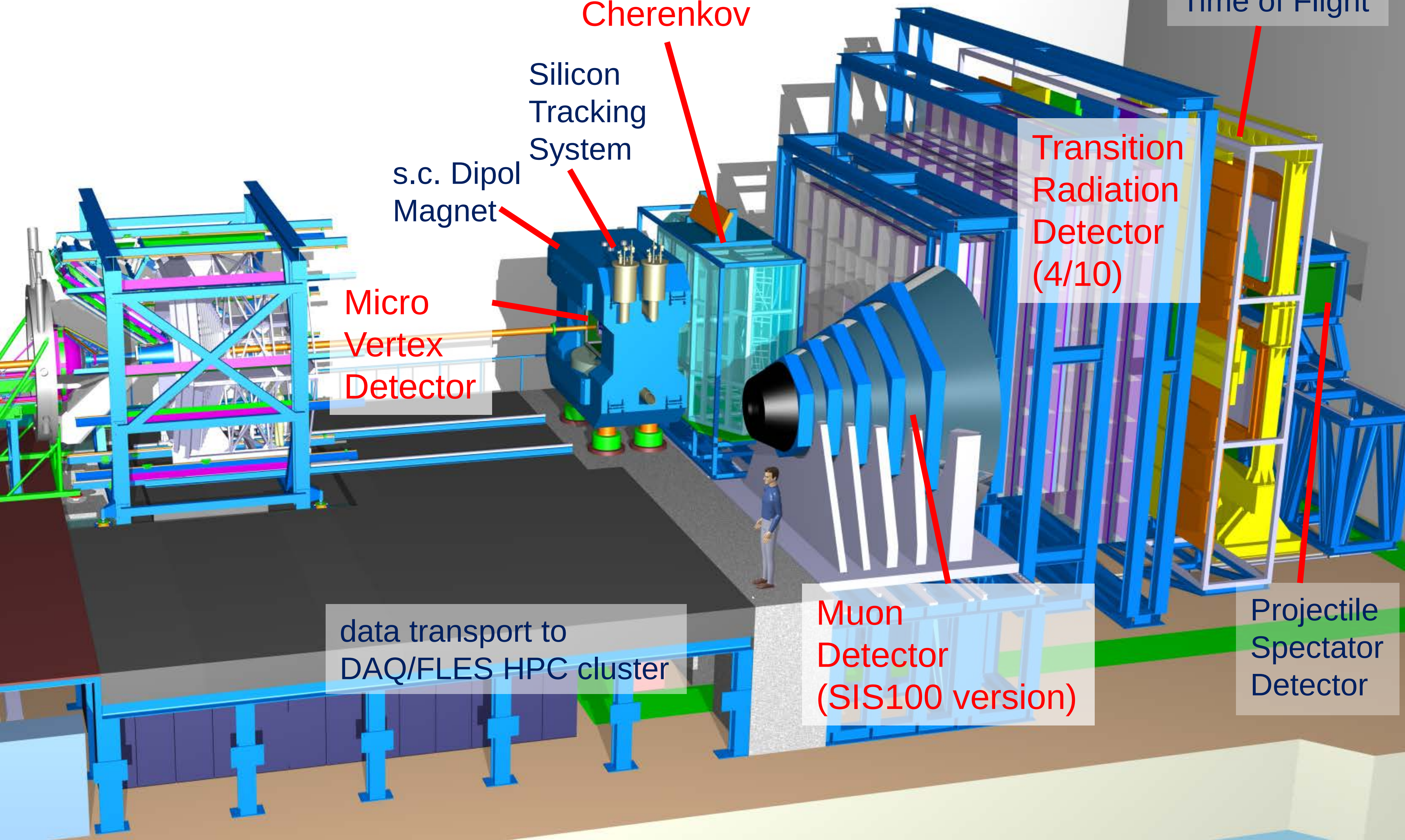
→ fast and radiation tolerant detectors
→ free-streaming read-out electronics
→ high speed data acquisition and
high performance computer farm
for online event reconstruction and selection

CBM
hadrons

HADES
p+p, p+A
A+A (low mult.)
large acceptance
low material budget



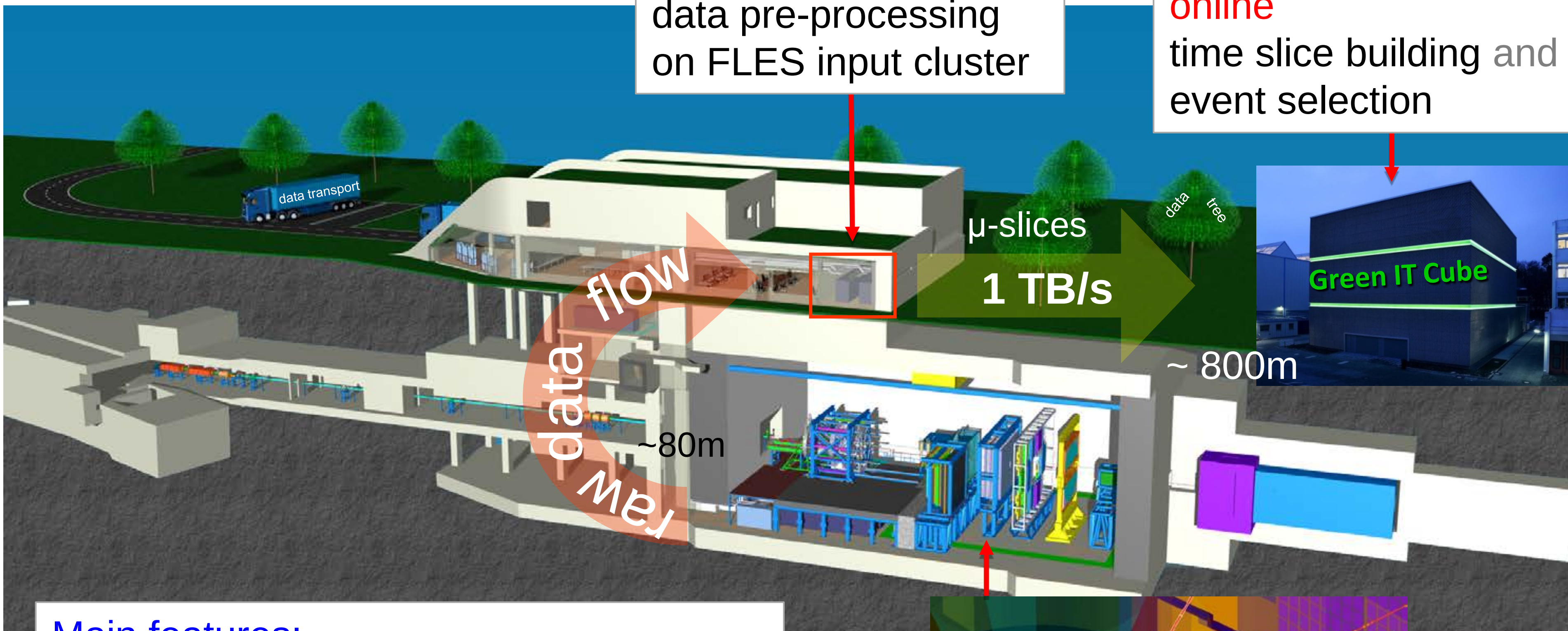
CBM
dileptons

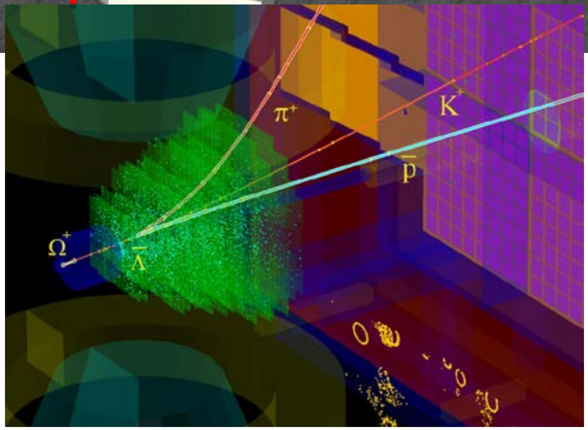


The high-performance free-streaming DAQ system of CBM

DAQ room:
data pre-processing
on FLES input cluster

Green IT Cube:
online
time slice building and
event selection

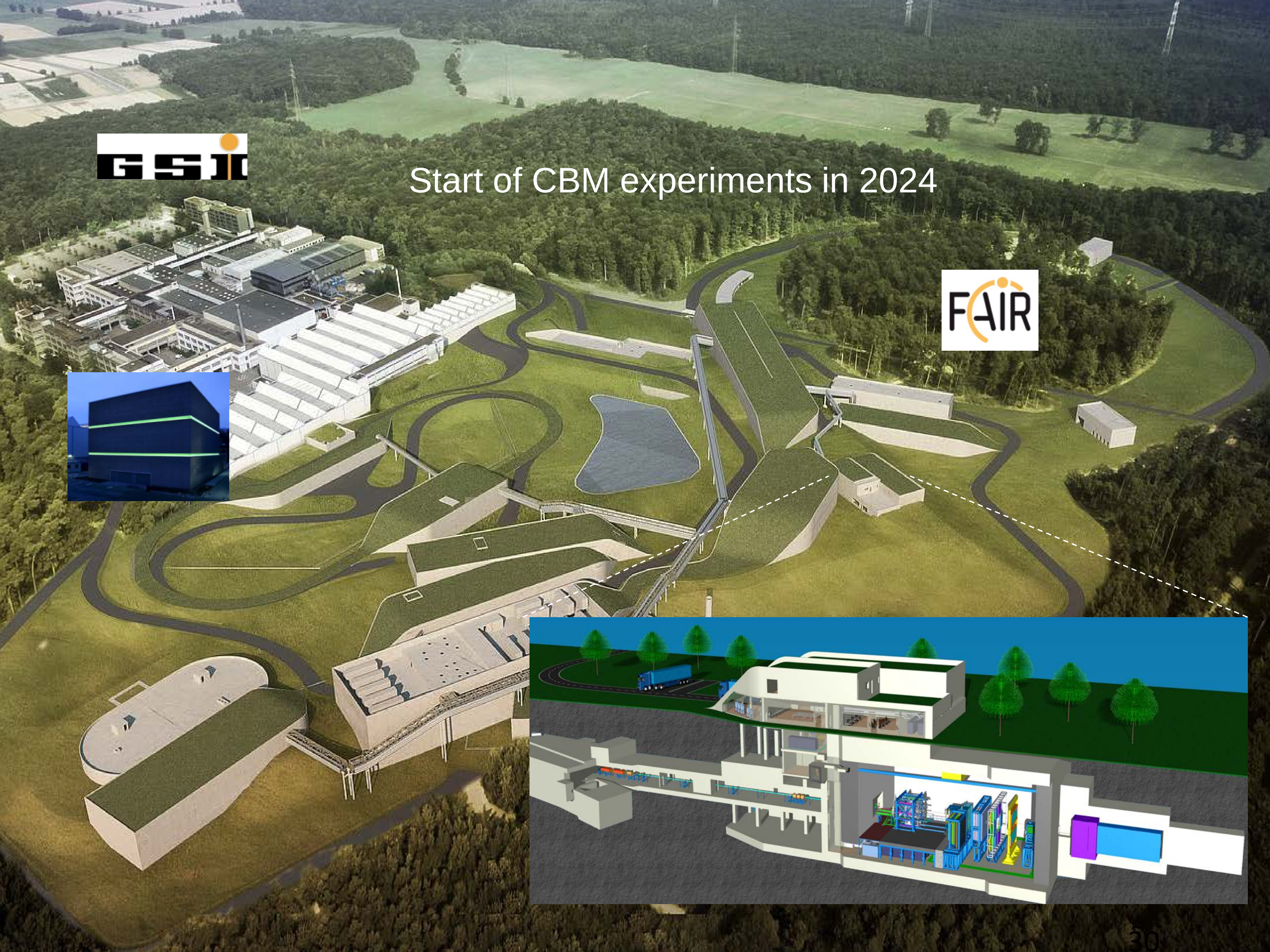




Main features:

- radiation tolerant detectors and front-end electronics
- free-streaming DAQ system
    - all detector hits with time stamps,
    - software based event selection

Start of CBM experiments in 2024



Status of the FAIR construction

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

<u>concept:</u>

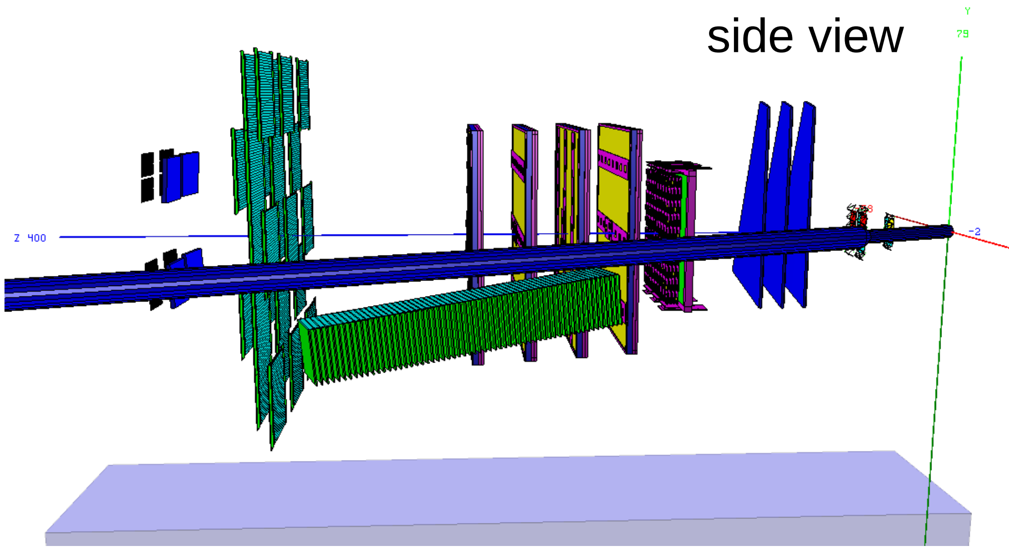
a permanent test-setup at the host lab

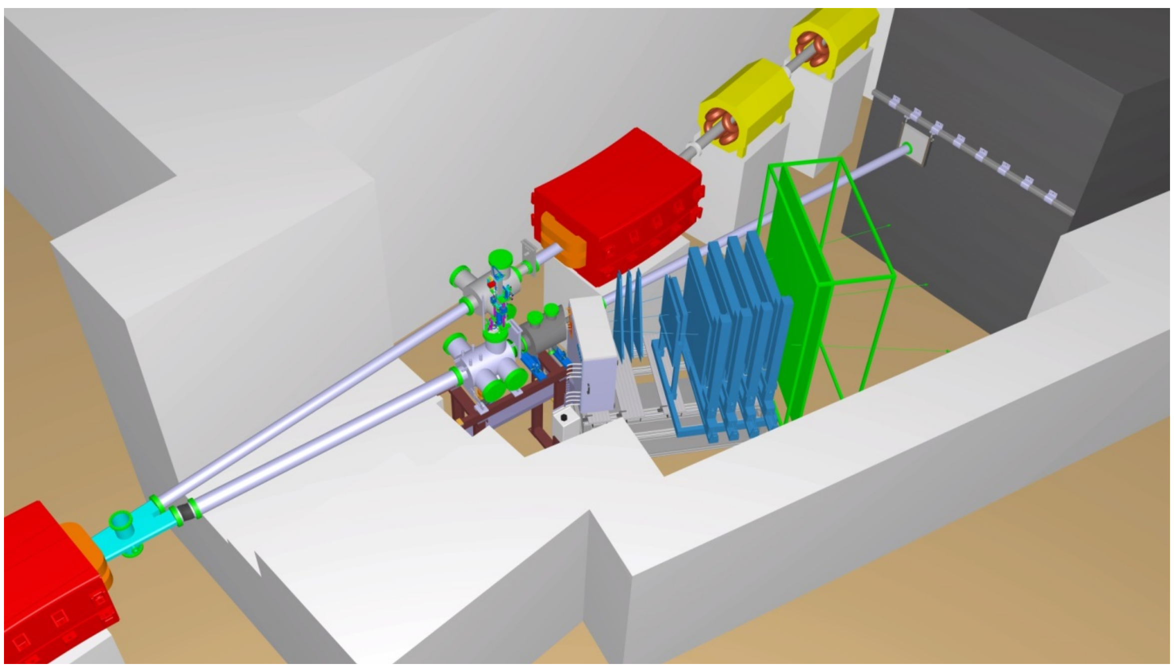
- **detector prototypes** at $\theta_{lab} \approx 20°$
- collision rates up to 10 MHz
- compact setup (< 5m)
- no B-field → straight tracks
- high resolution TOF (T_0 – TOF stop wall)

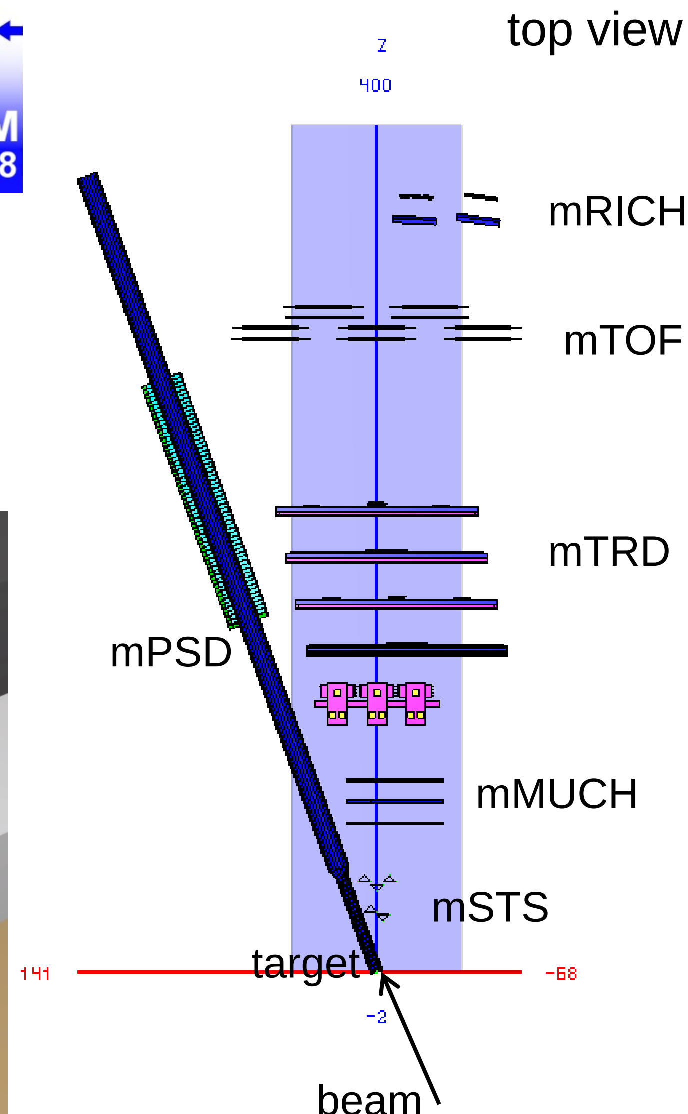
Topics to be addressed

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

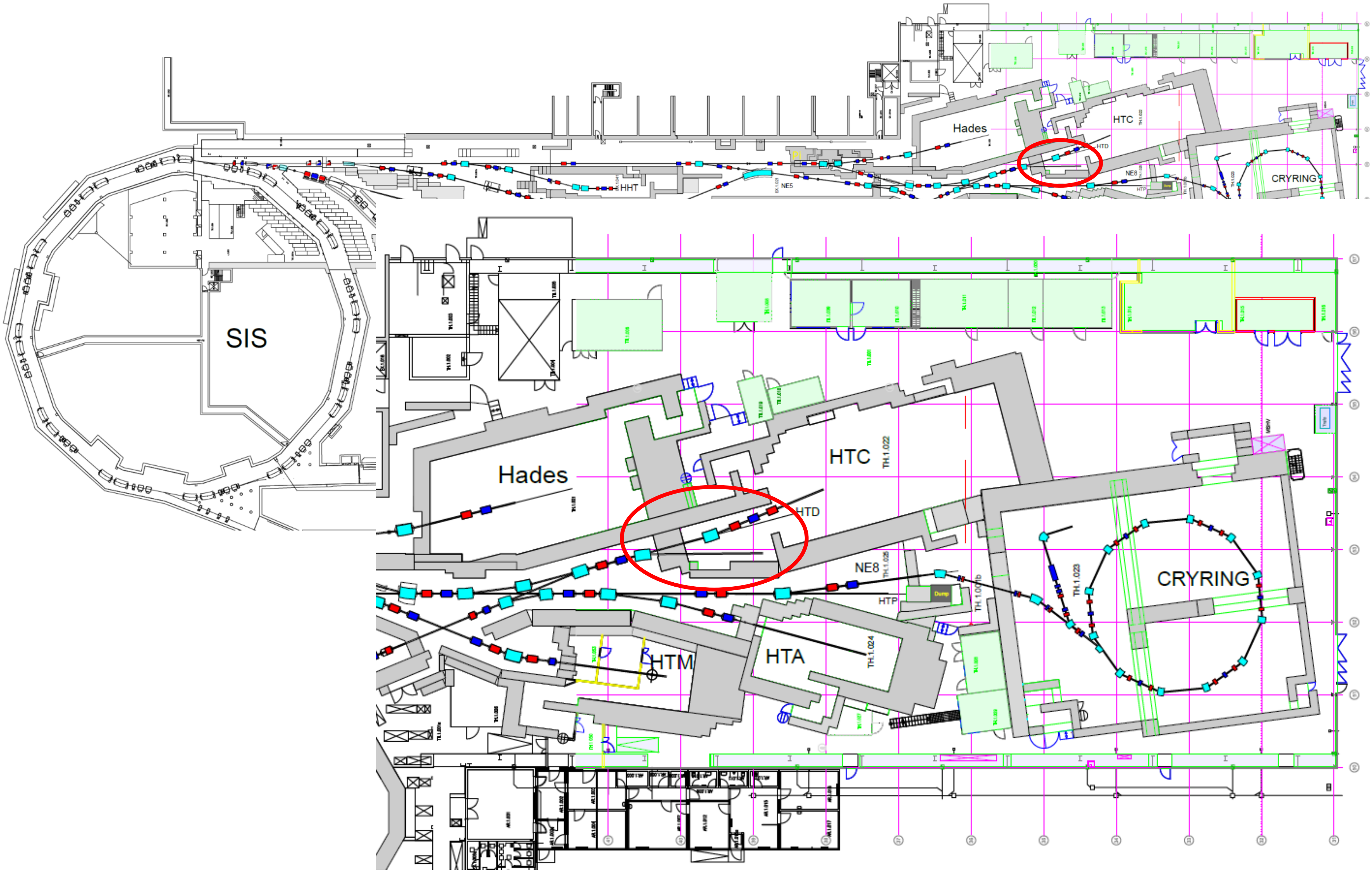
Design of the mCBM test-setup



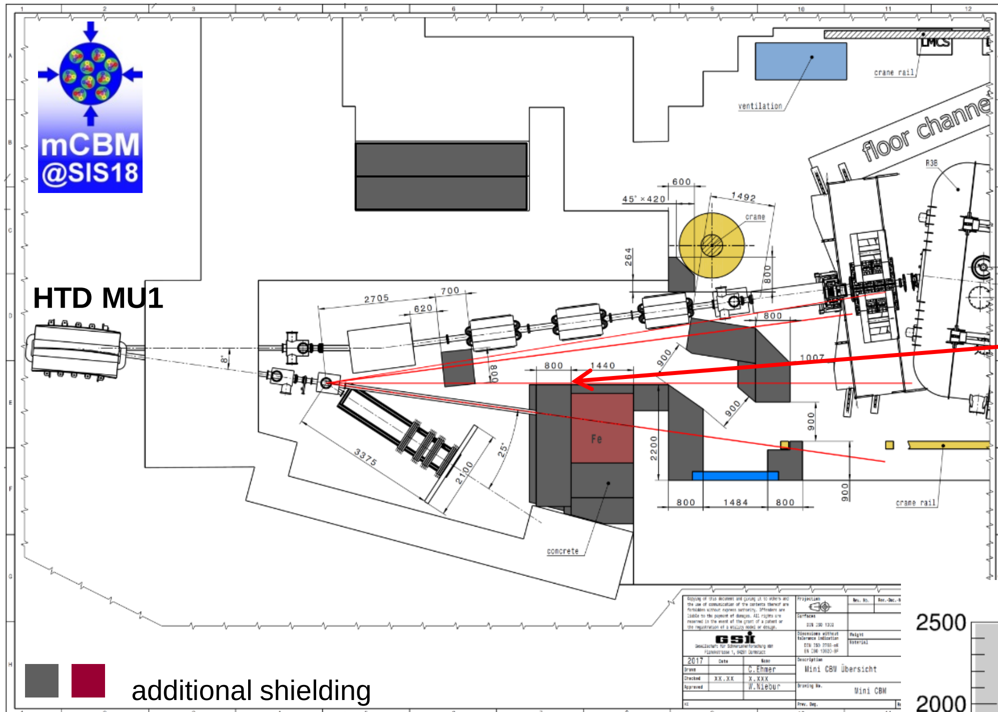




mCBM @ SIS18 facility

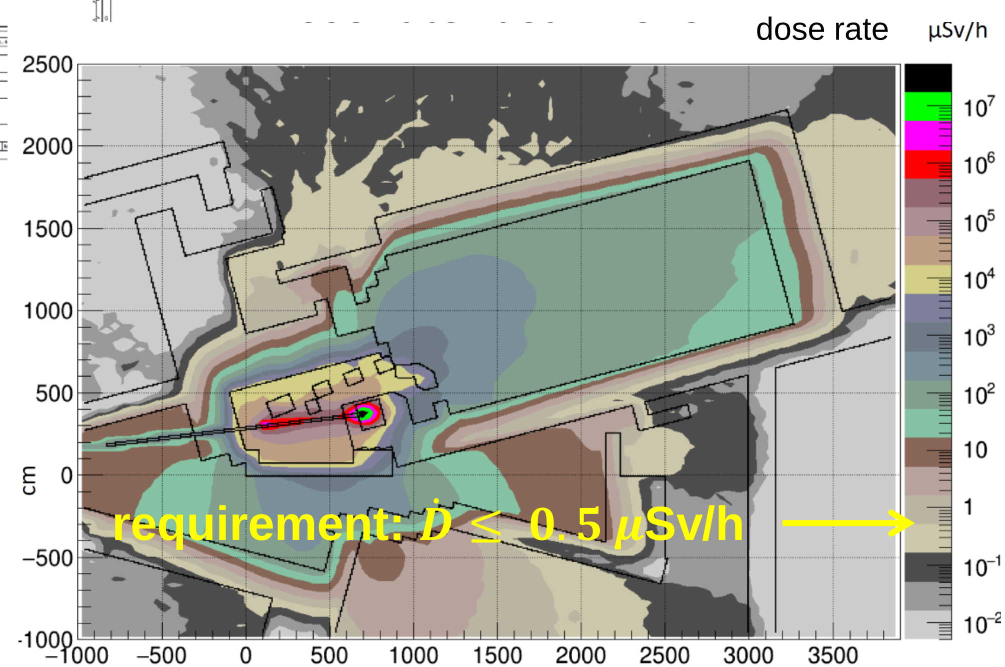


mCBM Cave (HTD @ SIS18 facility)

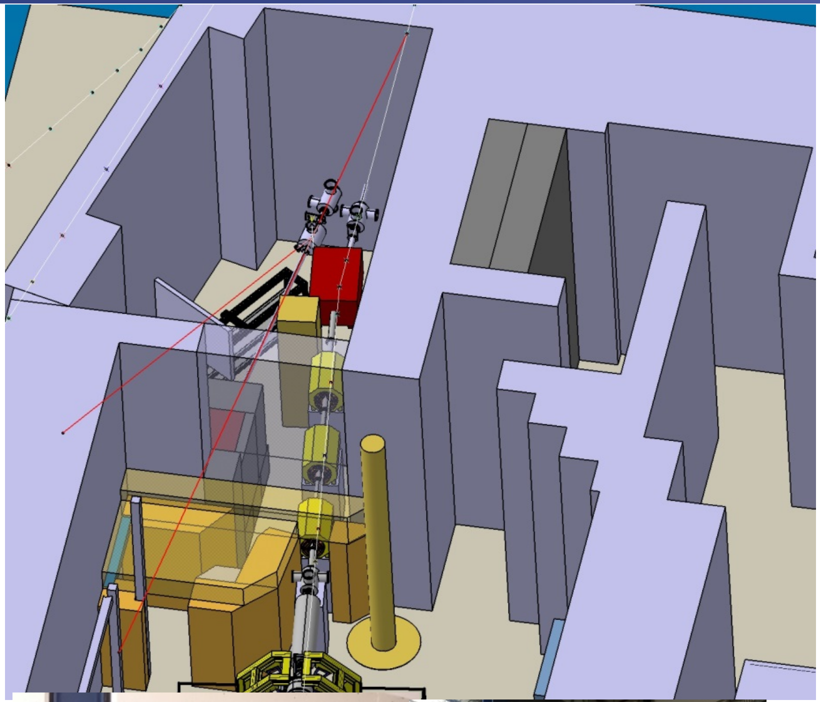


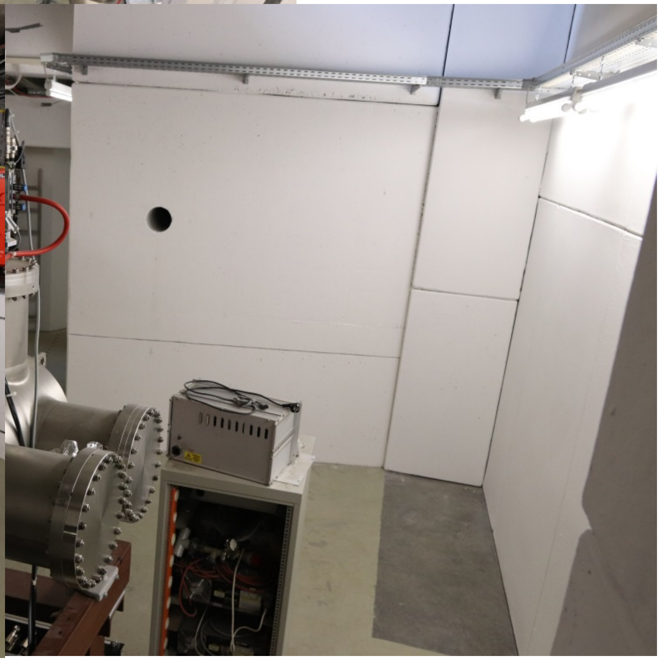
- modified switching magnet (HTD MU1)
- new beam dump
- additional shielding

FLUKA calculations (right fig.):
10^8 Au ions s^{-1}, 1.24 AGeV,
2.5 mm Au target (P_{int} = 10%)
vertical section: **beam level**



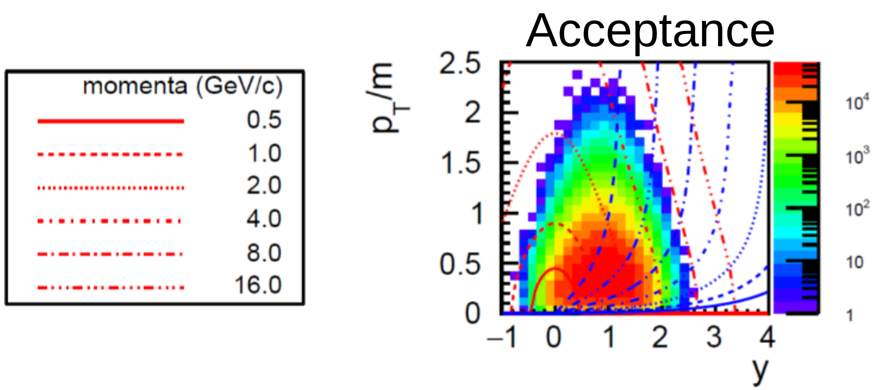
Status of the cave reconstruction

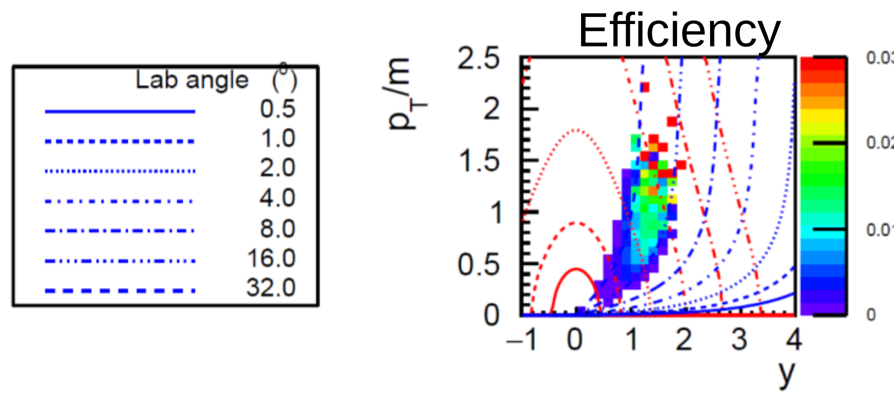


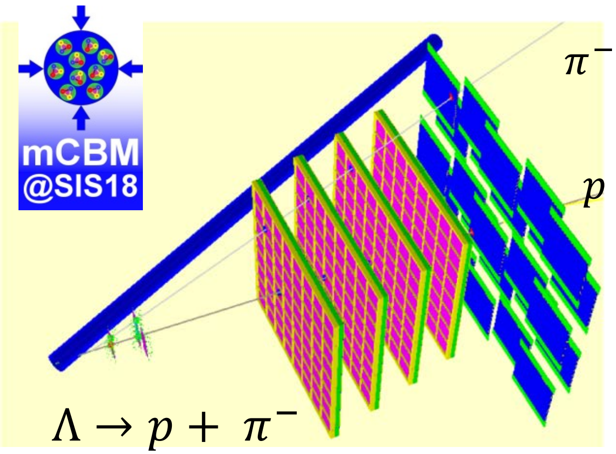


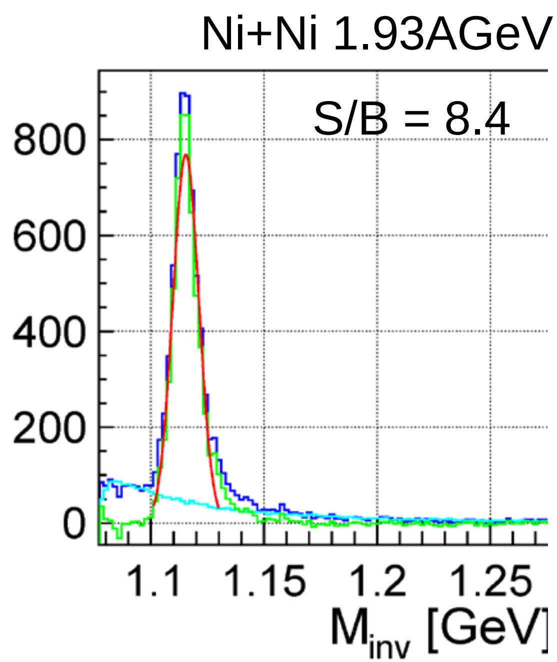
mCBM benchmark observable: Λ reconstruction

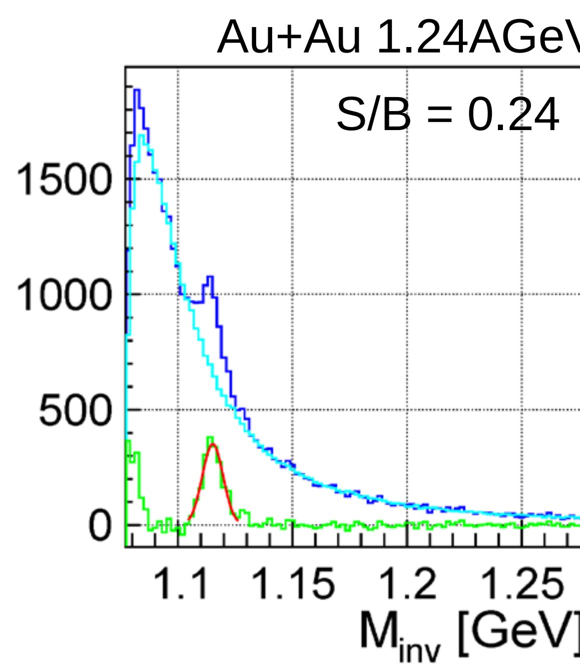
Simulation input: 10^8 UrQMD events, min. bias







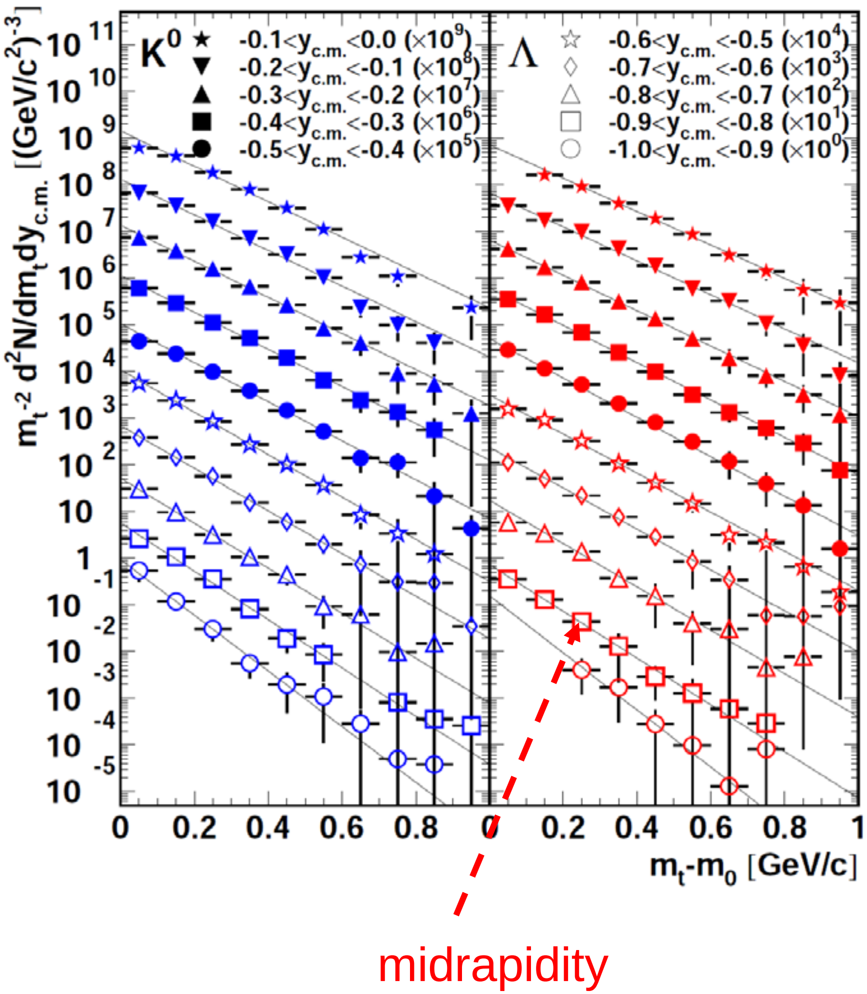




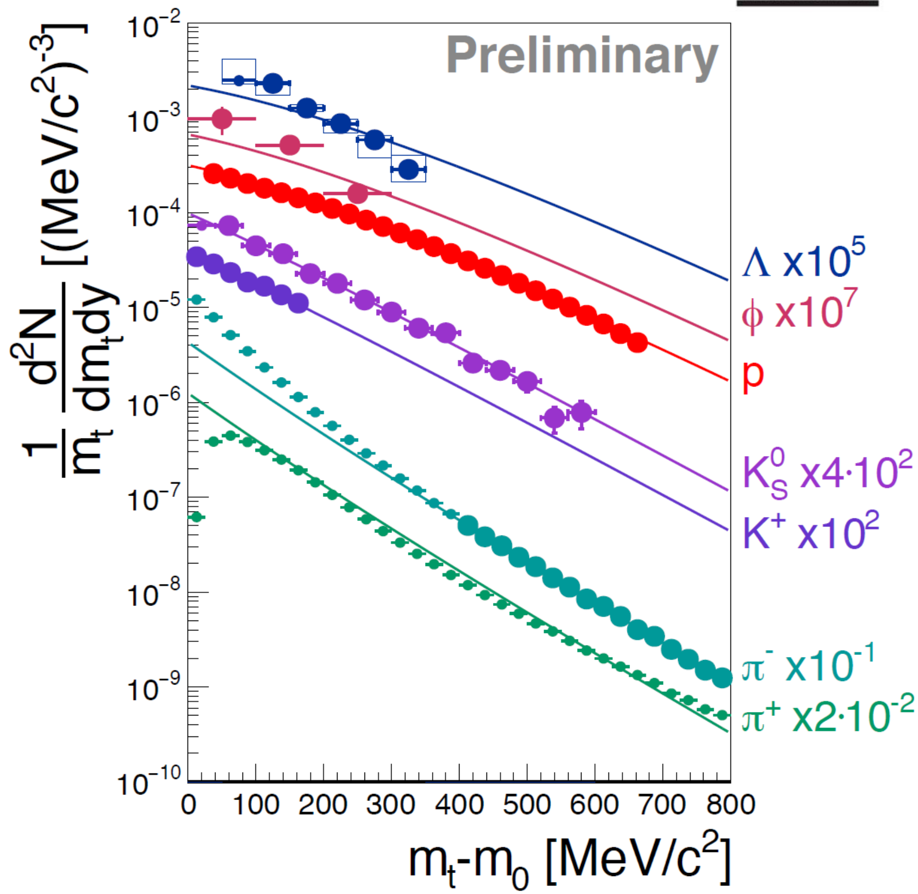
Λ production at SIS18 energies – mCBM reference data

Ni + Ni 1.93 AGeV

M. Merschmeyer et al. (FOPI), PRC 76, 024906 (2007)



Au + Au 1.23 AGeV



H. Schuldes et al. (HADES)
EPJ Web of Conferences 171, 01001 (2018), SQM2017

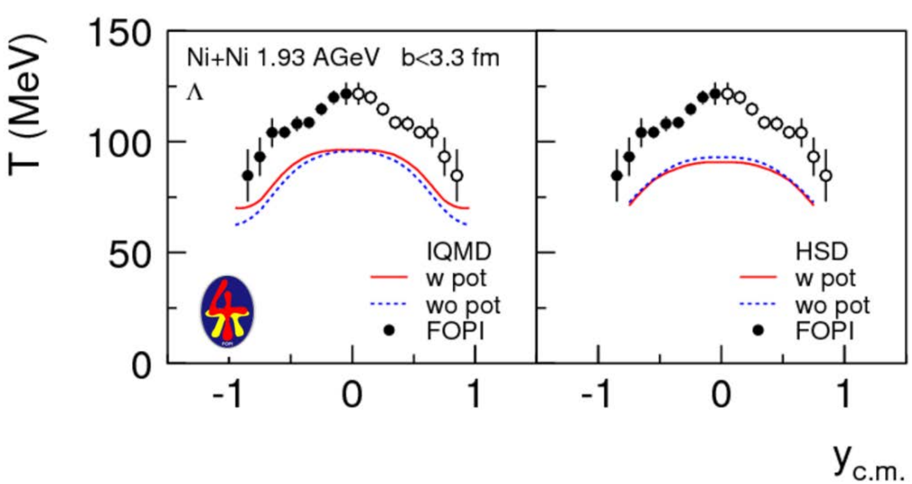
mCBM data taking

2018	development & commissioning data transport, data analysis, detector tests
2019	approaching full performance subsystems completed, high-rate data transport / processing → online reconstruction

requested beamtime was fully granted by GSI/FAIR G-PAC

2020	1st benchmark run Λ reconstruction production runs benchmark coll. systems: Ni+Ni 1.93AGeV & Au+Au 1.24AGeV
2021	2nd benchmark run Λ reconstruction in Ni+Ni and Au+Au collisions at various projectile energies → Λ production excitation function

proposal to be submitted in 2019



Λ - slope parameter:
- smaller than proton
- not explained by transport models

  reason unclear:
  - rescattering cross section ?
  - repulsive potential ?

CBM Collaboration: 55 institutions, 470 members

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei
CTGU Yichang
Chongqing Univ.

Czech Republic:
CAS, Rez
Techn. Univ. Prague

France:
IPHC Strasbourg

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.
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

Hungary:
KFKI Budapest
Eötvös Univ.

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