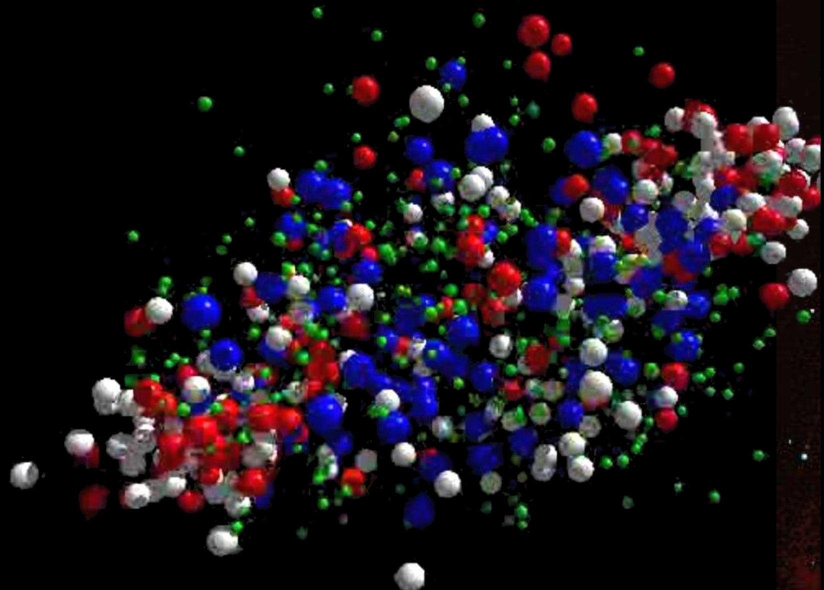
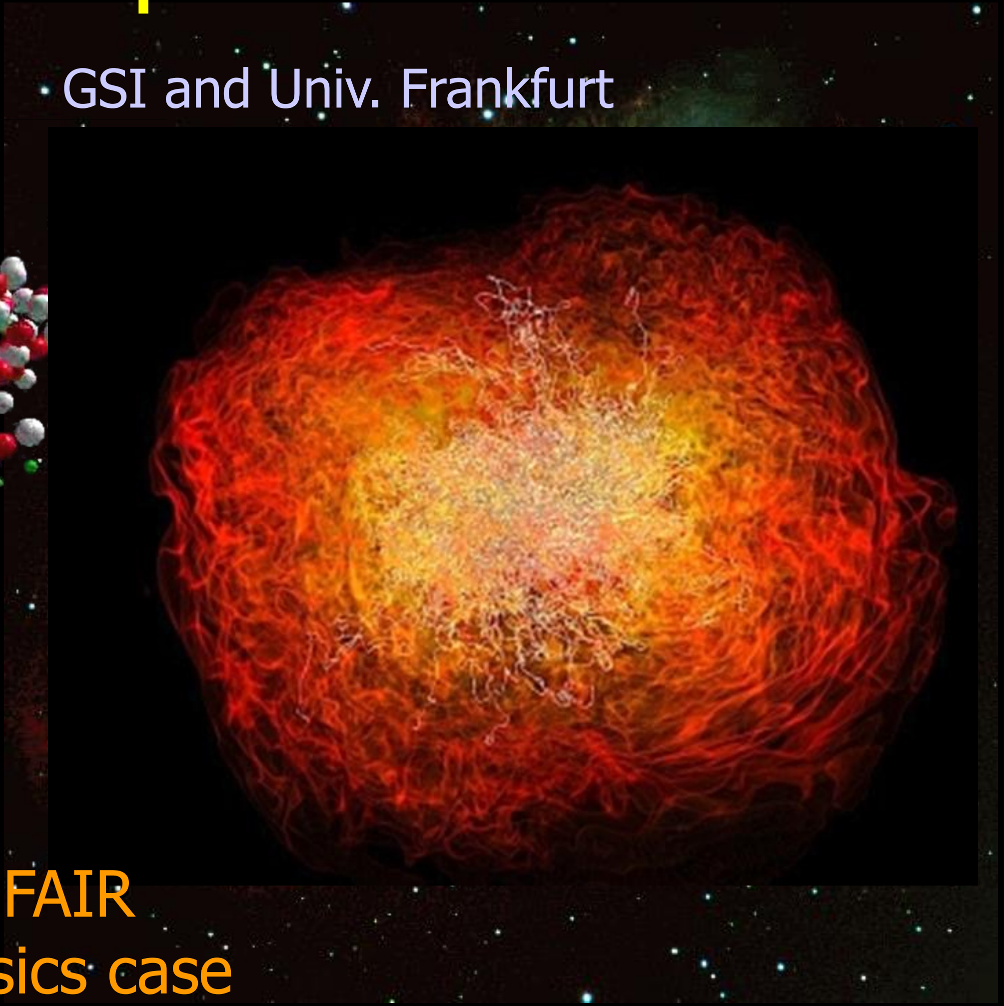
QCD matter physics at FAIR
The CBM experiment

Peter Senger GSI and Univ. Frankfurt





Outline:

- The status of FAIR
- The CBM physics case
- The CBM experiment

BES workshop, INT Seattle, October 3 – 7, 2016

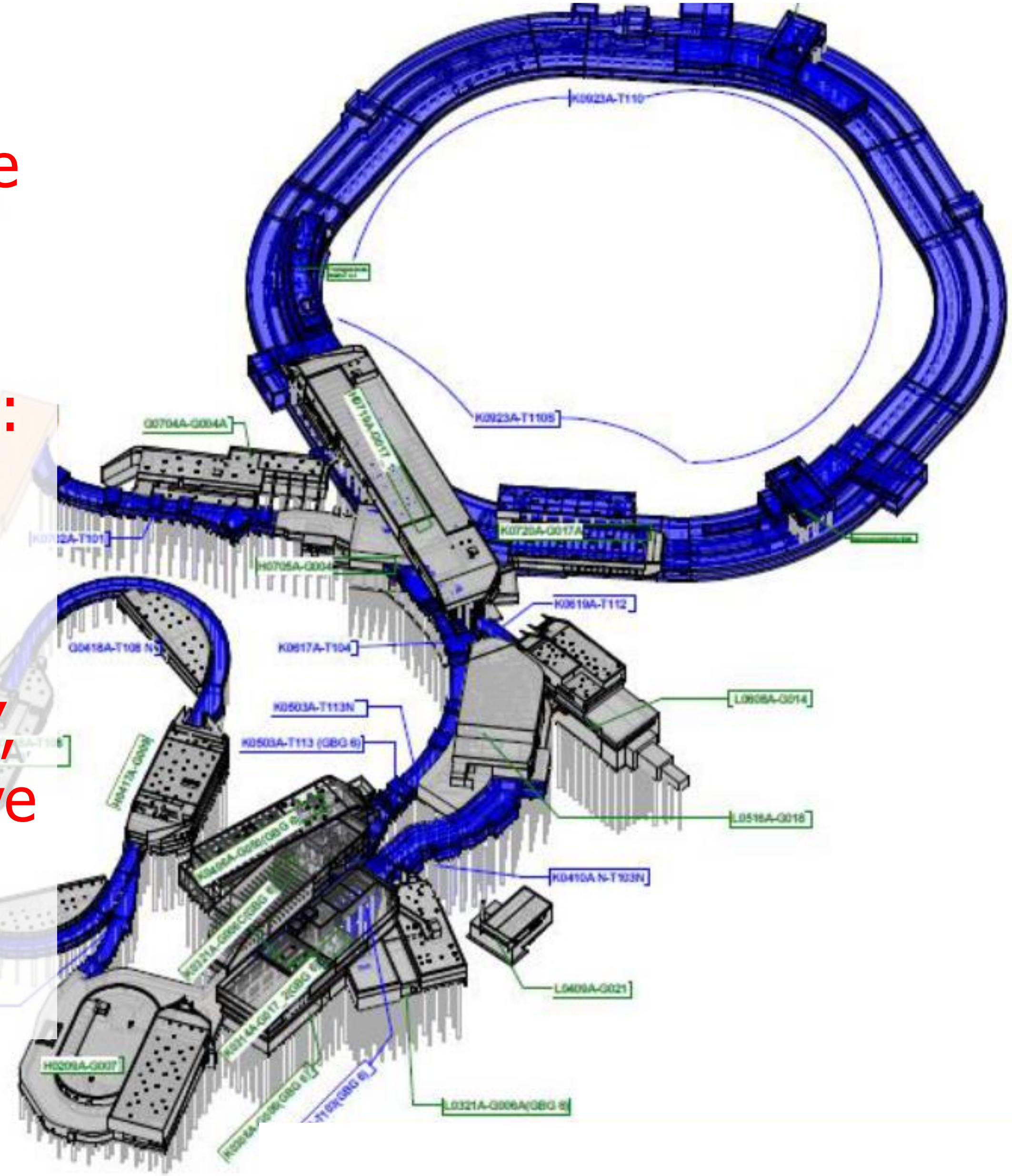
Status of FAIR

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

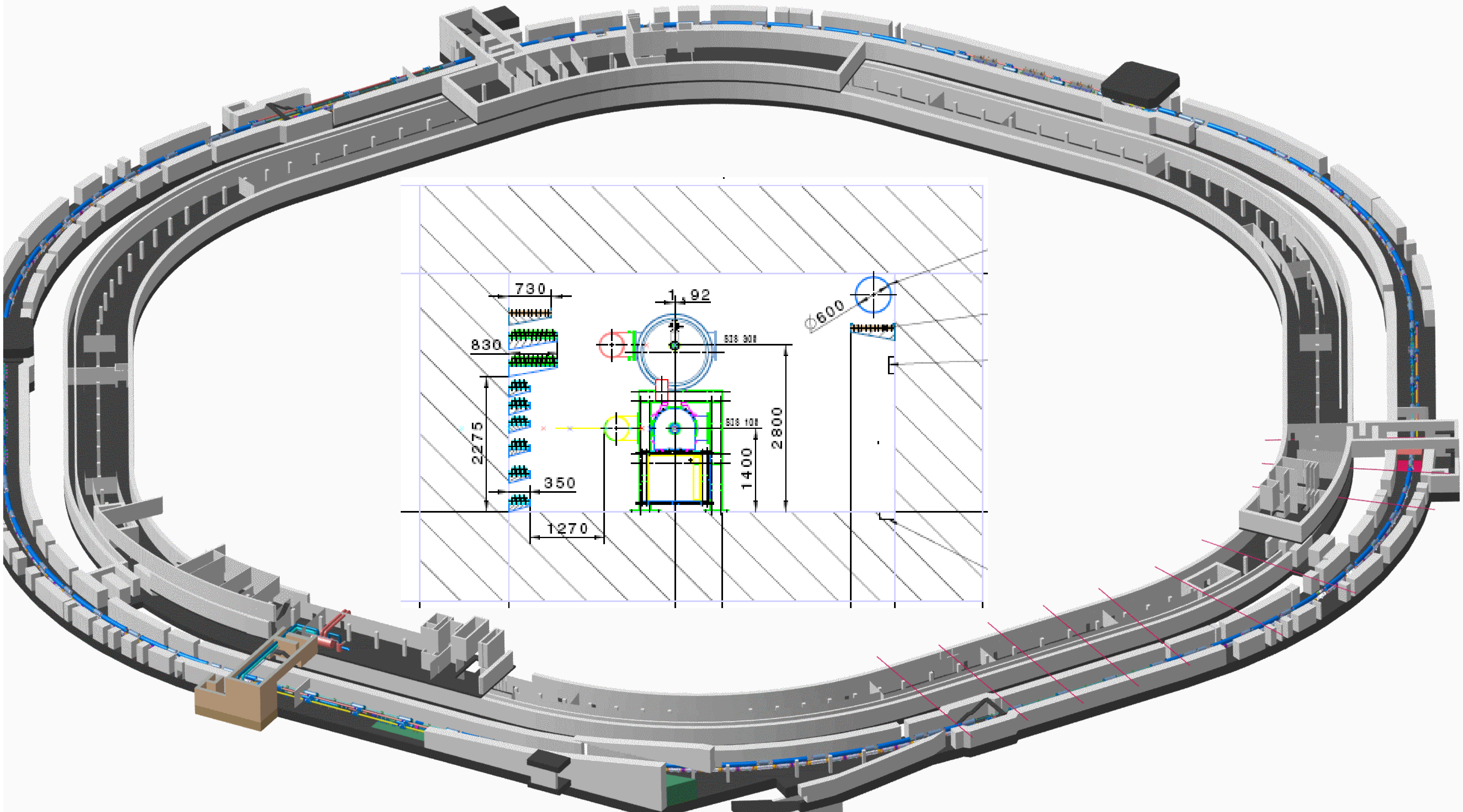
1st call for tender on Sept. 22: water management and excavation

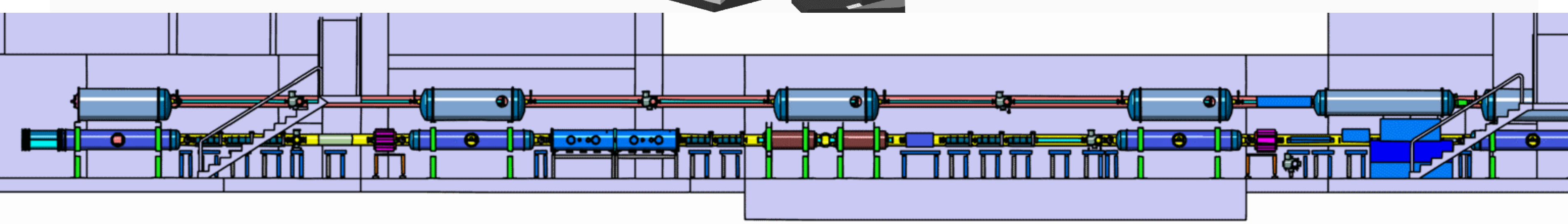
2nd call for tender in Nov.: shell construction 'north area', includes SIS100 and CBM cave

Start of construction mid of 2017



Tunnel for SIS100/300



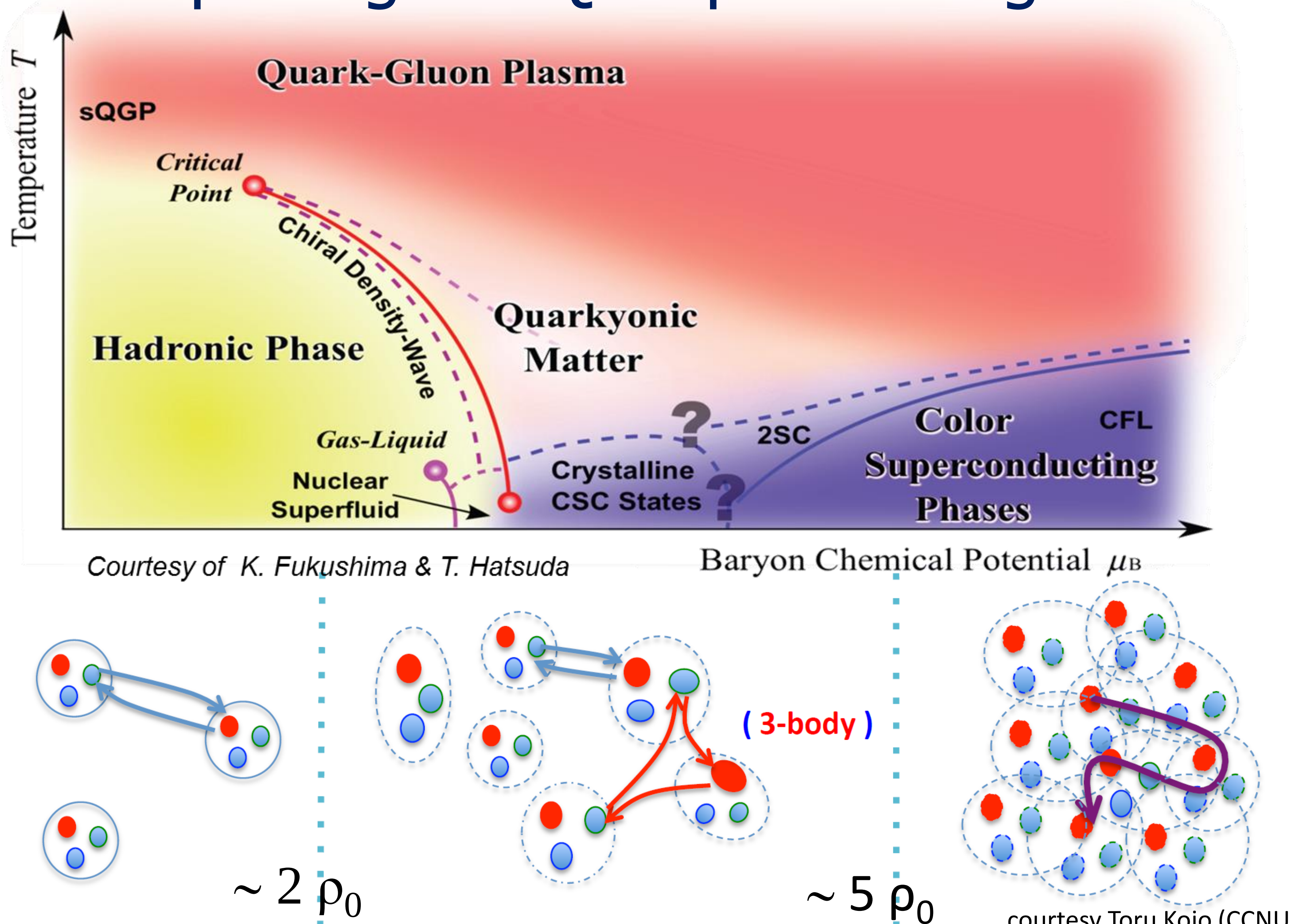


The CBM cave

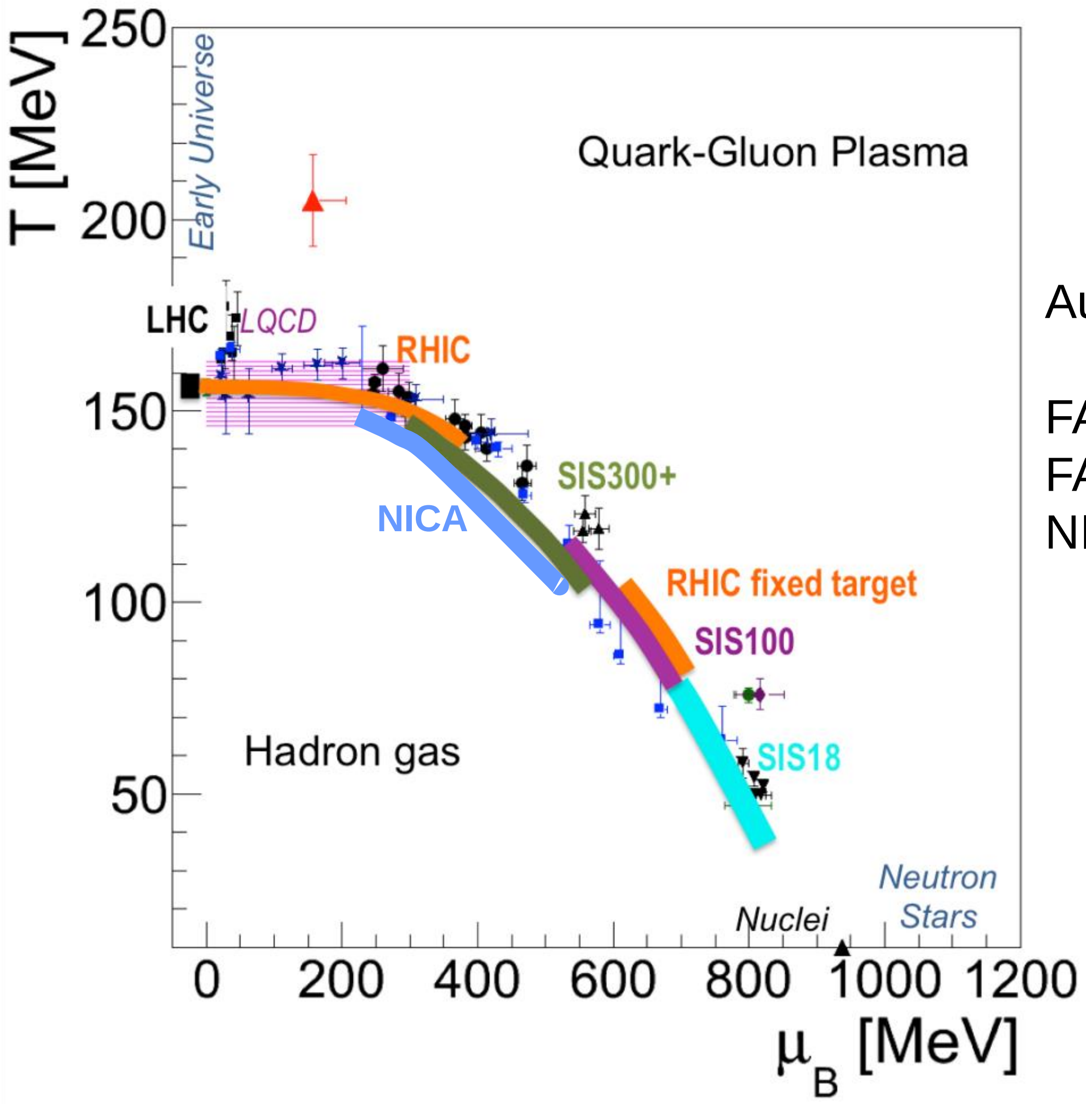
CBM will take first beam from SIS100

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

Exploring the QCD phase diagram



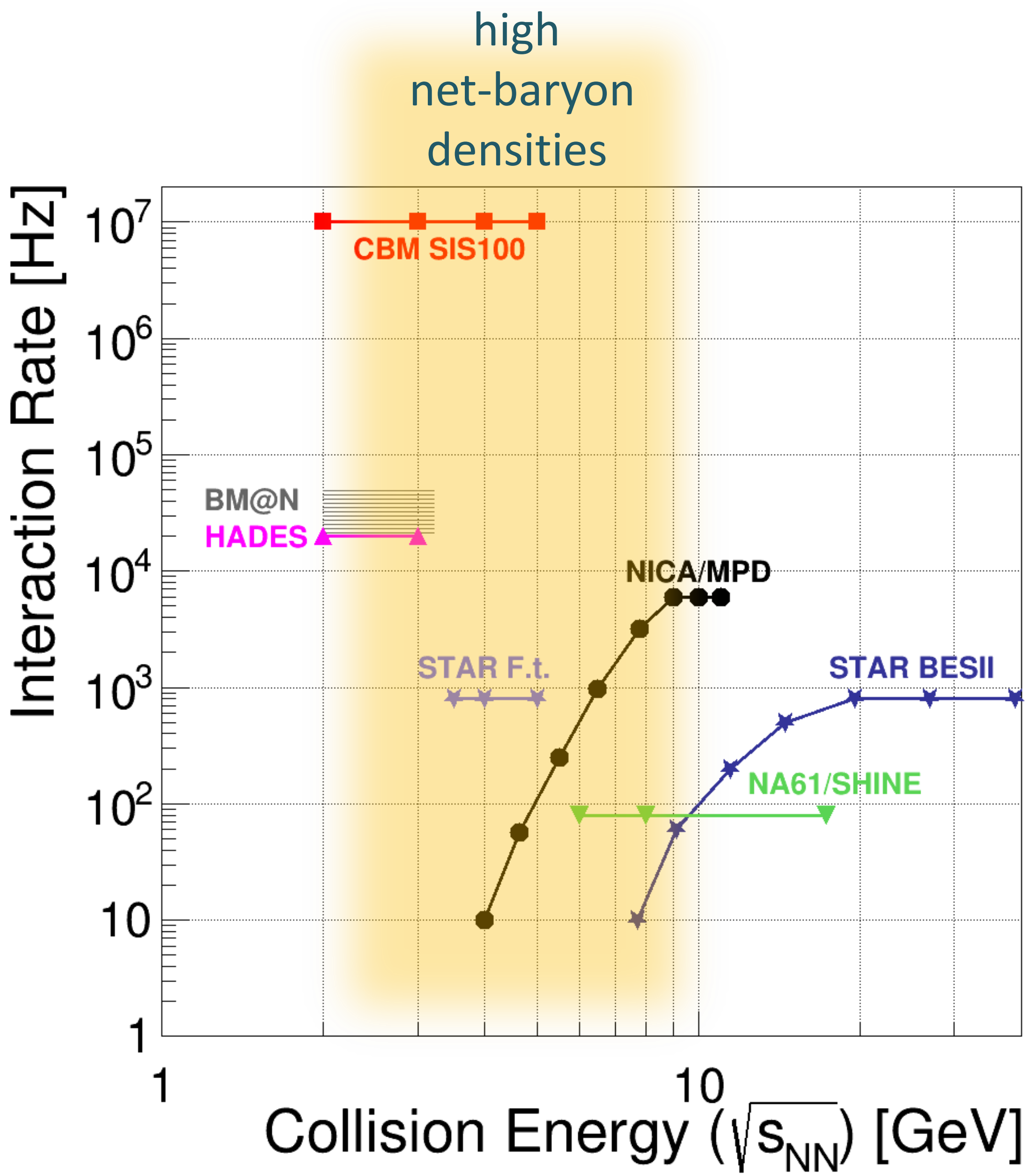
Exploring the QCD phase diagram



Au beam energies:

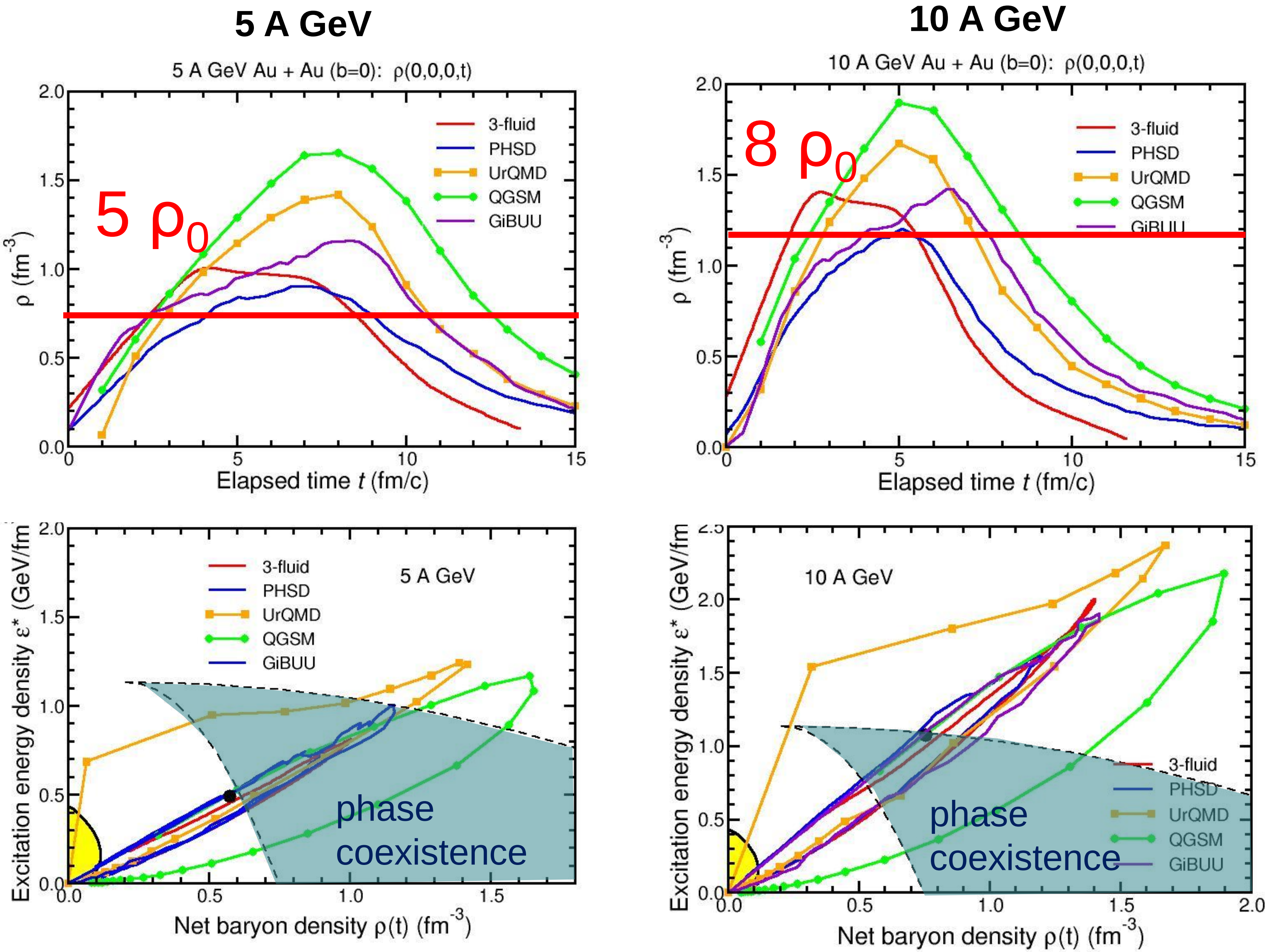
FAIR SIS100: $\sqrt{s_{NN}}$ = 2.7 – 4.9 GeV
FAIR SIS300: $\sqrt{s_{NN}}$ = 4.9 – 8.3 GeV
NICA: $\sqrt{s_{NN}}$ = 4.5 – 11 GeV

Experiments exploring dense QCD matter



Baryon densities in central Au+Au collisions

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

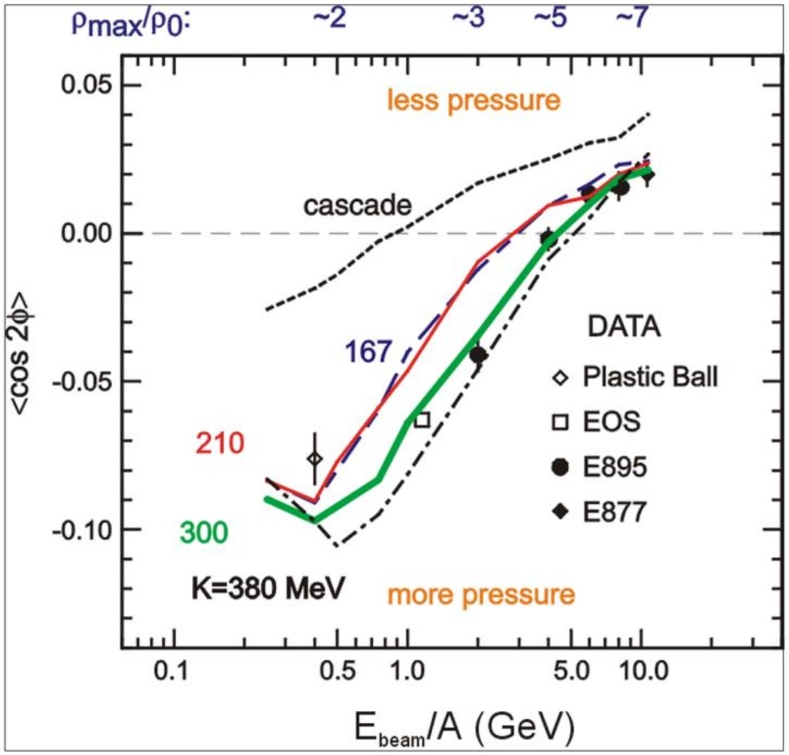


CBM physics case and observables

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

- collective flow of identified particles (π,K,p,Λ,Ξ,Ω,...) driven by the pressure gradient in the early fireball

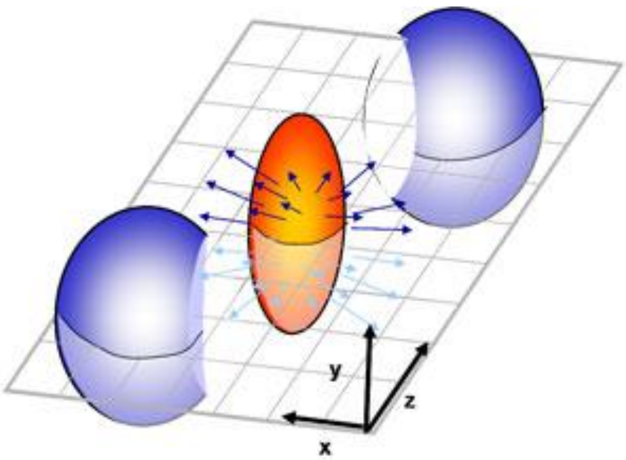
AGS: proton flow in Au+Au collisions



P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

Azimuthal angle distribution:

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



CBM physics case and observables

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- collective flow of identified particles (π,K,p,Λ,Ξ,Ω,...) 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:

$pp \rightarrow \Xi^- K^+K^+p$ (E_{thr} = 3.7 GeV)
$pp \rightarrow \Omega^- K^+K^+K^0p$ (E_{thr} = 7.0 GeV)
$pp \rightarrow \Lambda^0\bar{\Lambda}^0 pp$ (E_{thr} = 7.1 GeV)
$pp \rightarrow \Xi^+ \Xi^- pp$ (E_{thr} = 9.0 GeV)
$pp \rightarrow \Omega^+ \Omega^- pp$ (E_{thr} = 12.7 GeV

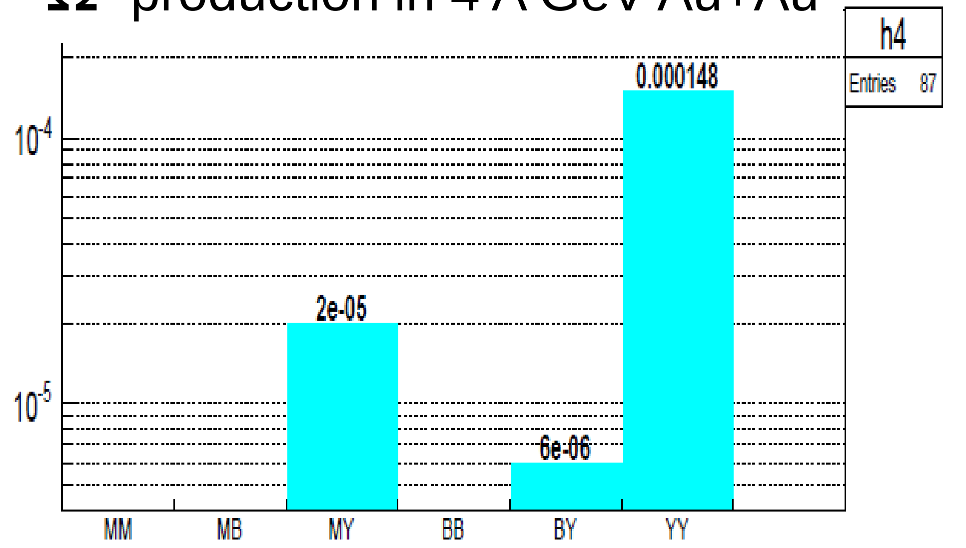
Hyperon production via multiple collisions

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. $\Xi^+ K^+ \rightarrow \Omega^+ \pi^+$.

Ω^- production in 4 A GeV Au+Au



HYPQGSM calculations , K. Gudima et al.

CBM physics case and observables

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

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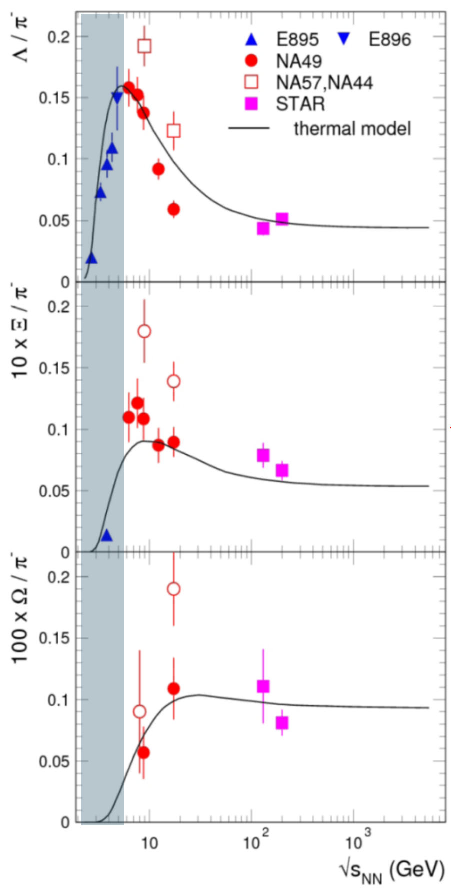


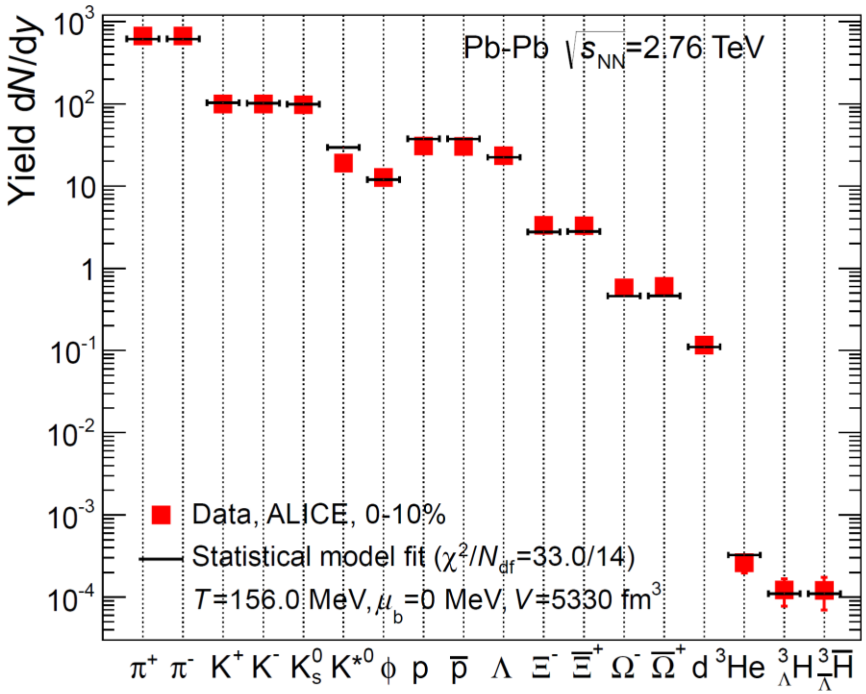
Very few data at FAIR energies

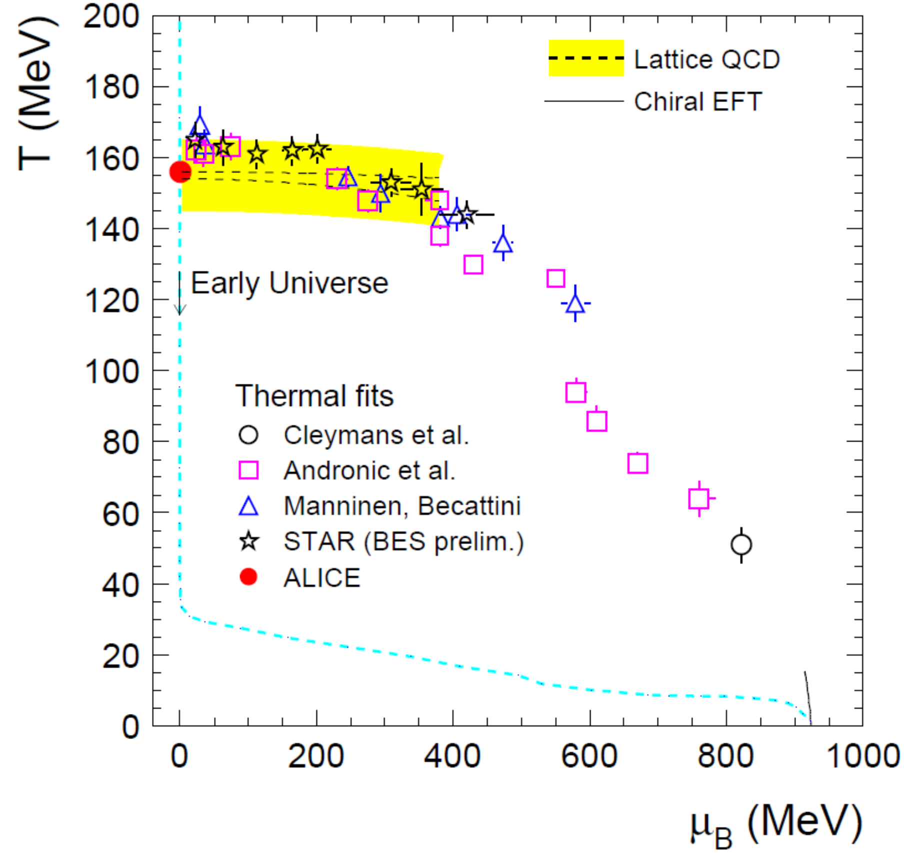
CBM physics case and observables

Phase transitions from partonic to hadronic matter

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

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





A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Jour. Phys. G38 (2011)

CBM physics case and observables

Phase transitions from partonic to hadronic matter

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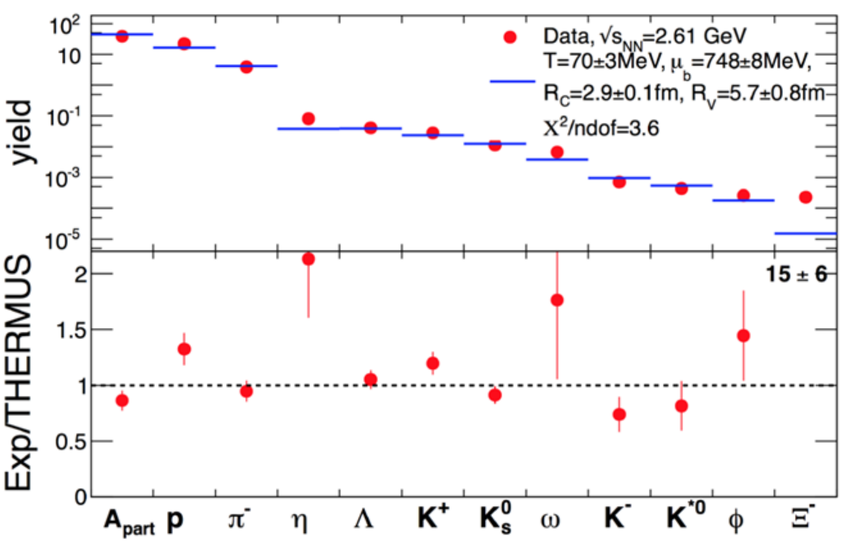
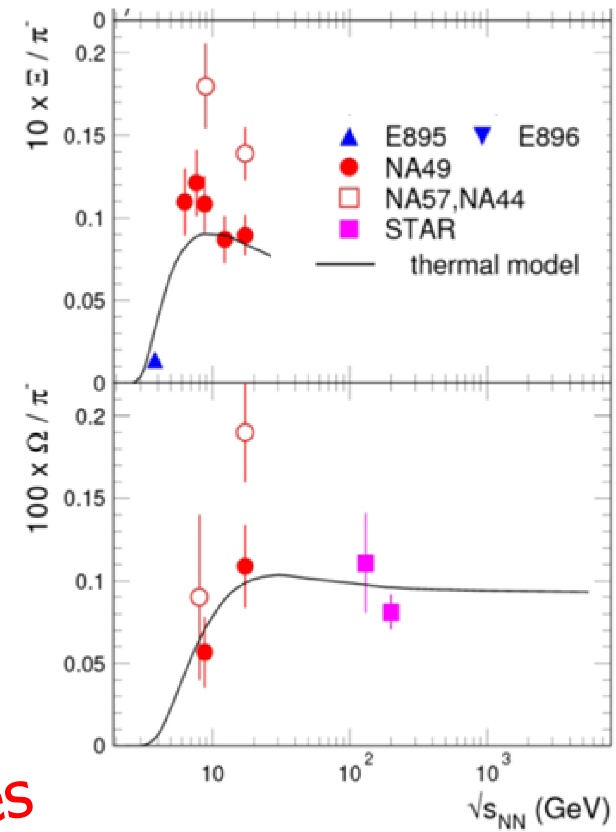
  $\rightarrow$ chemical equilibration at the phase boundary

Particle yields and thermal model fits

HADES: Ar + KCl 1.76 A GeV

G. Agakishiev et al., arXiv:1512.07070





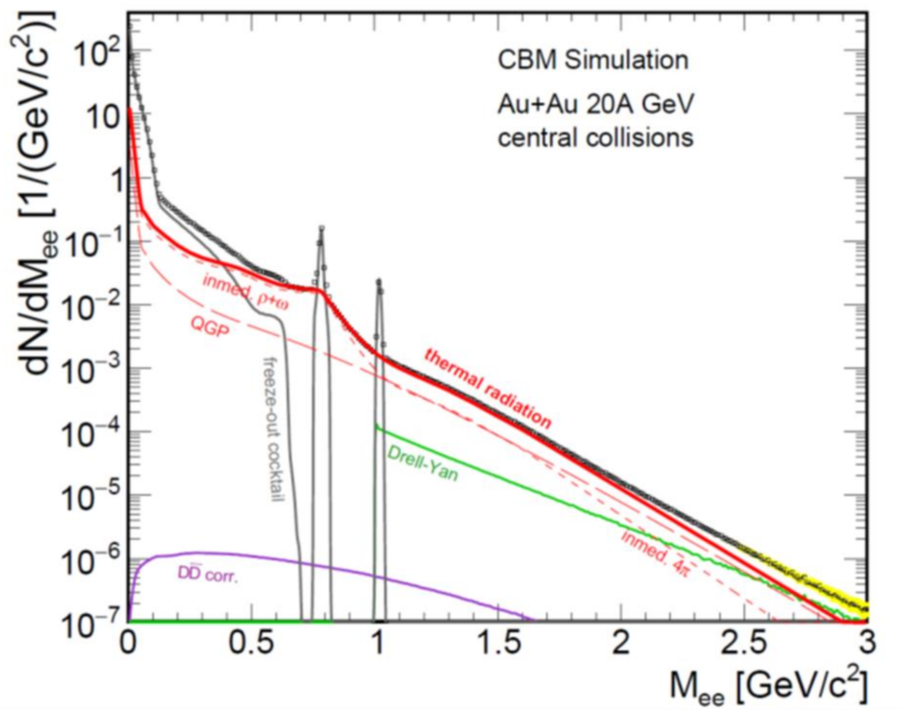
Very few data at FAIR energies

CBM physics case and observables

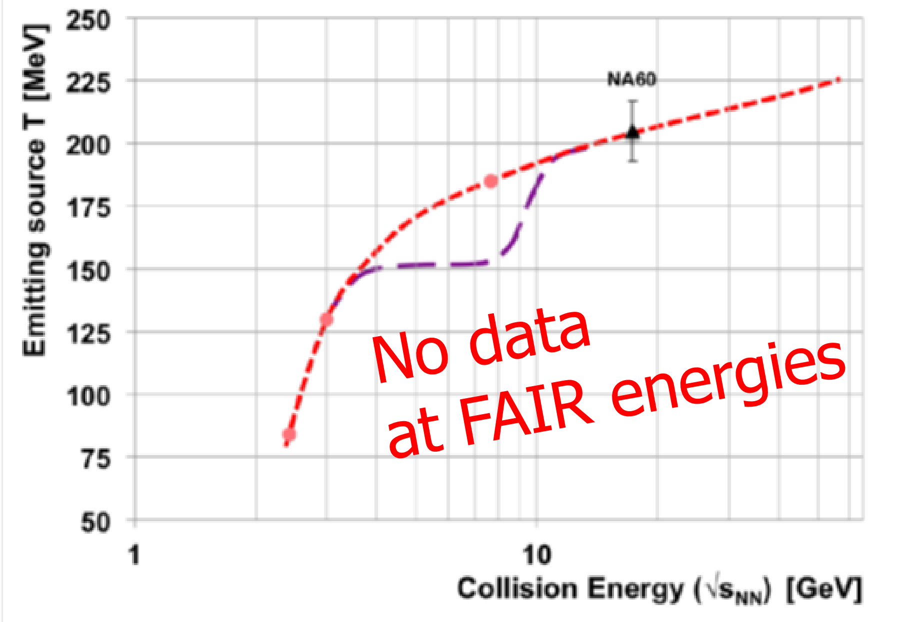
Phase transitions from partonic to hadronic matter, phase coexistence

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

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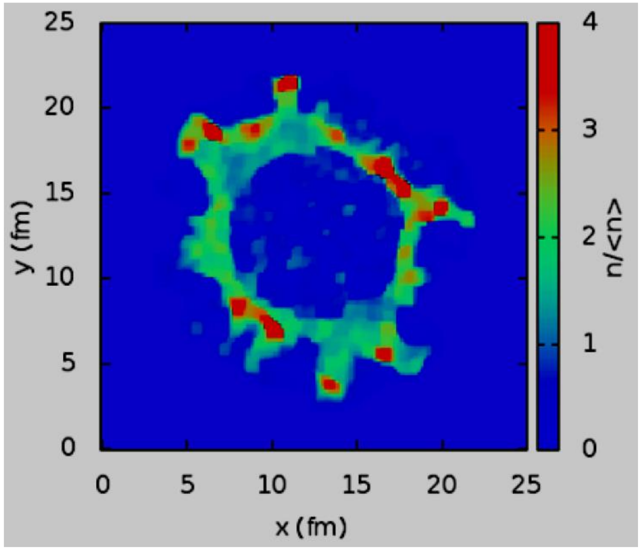
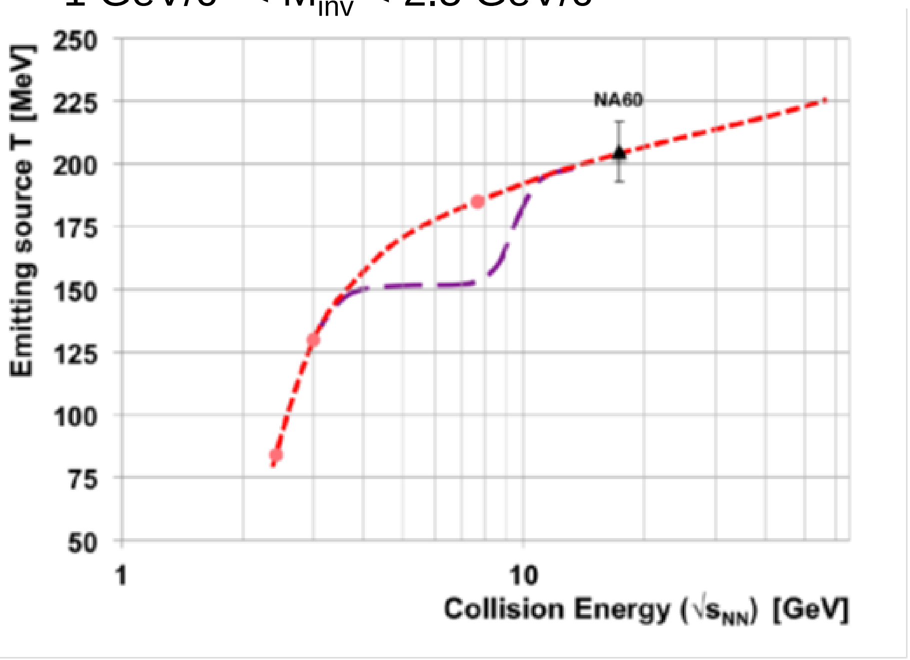
- excitation function (invariant mass) of lepton pairs:
  thermal radiation from QGP, caloric curve
- anisotropic azimuthal angle distributions: “spinodal decomposition”

Spinodal decomposition of the mixed phase



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

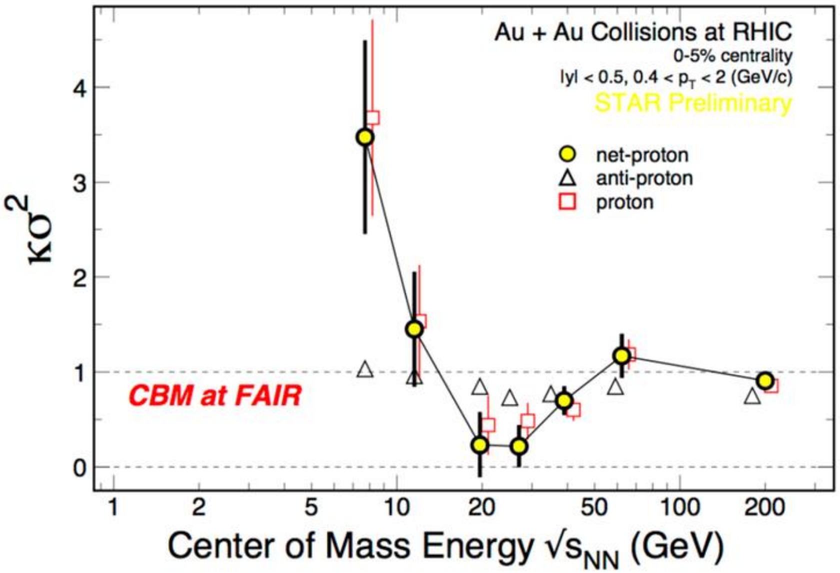


CBM physics case and observables

Phase transitions from partonic to hadronic matter, phase coexistence, critical point

- excitation function of strangeness: $\Xi^-(dss)$,$\Xi^+(\overline{dss})$,$\Omega^-(sss)$,$\Omega^+(\overline{sss})$
  $\rightarrow$ chemical equilibration at the phase boundary
- excitation function (invariant mass) of lepton pairs:
  Thermal radiation from QGP, caloric curve
- anisotropic azimuthal angle distributions: "spinodal decomposition"
- event-by-event fluctuations of conserved quantities (B,S,Q)

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

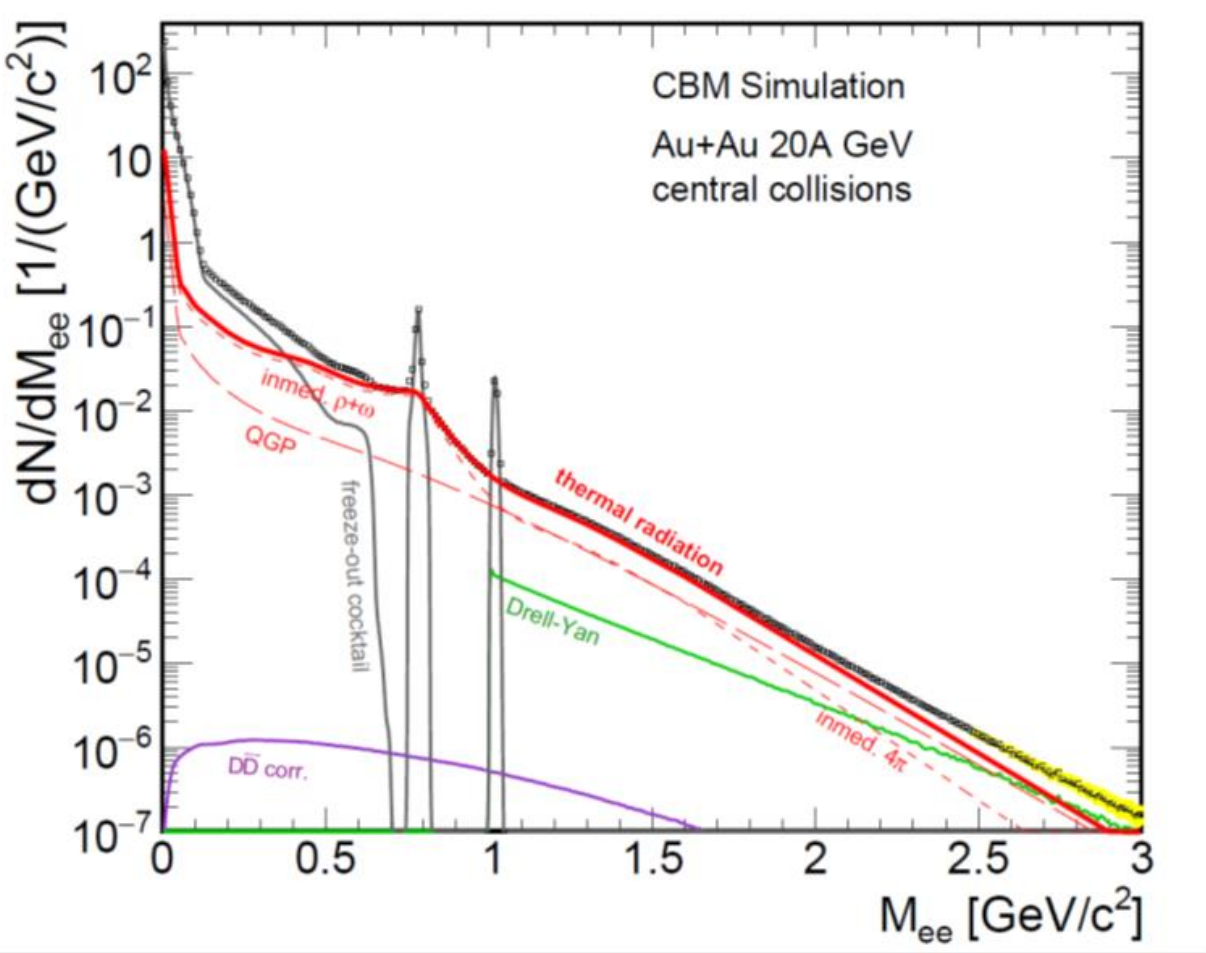


No data
at FAIR energies

CBM physics case and observables

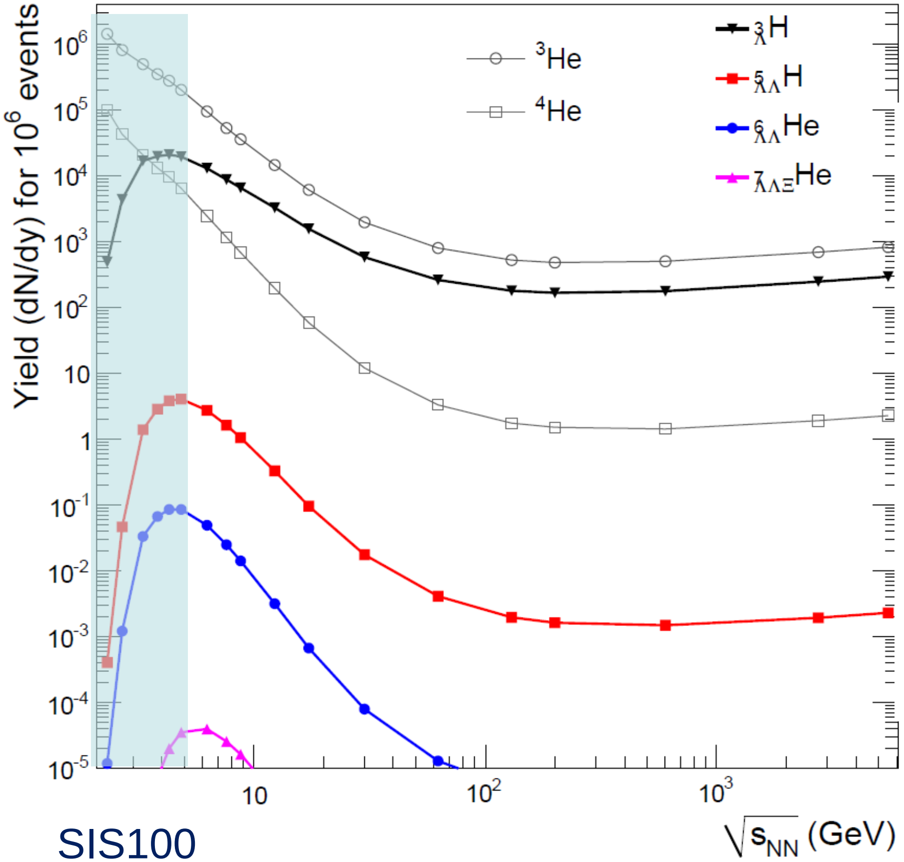
Onset of chiral symmetry restoration at high ρ_B

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

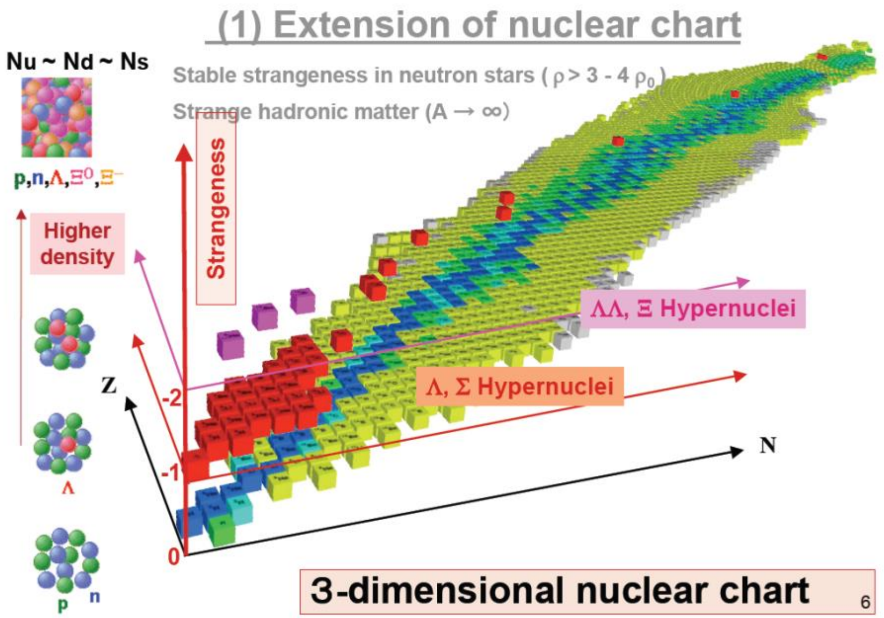


CBM physics case and observables

N-Λ, Λ-Λ interaction, strange matter?
- (double-) lambda hypernuclei
- meta-stable objects (e.g. strange dibaryons)



SIS100



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

CBM physics case and observables

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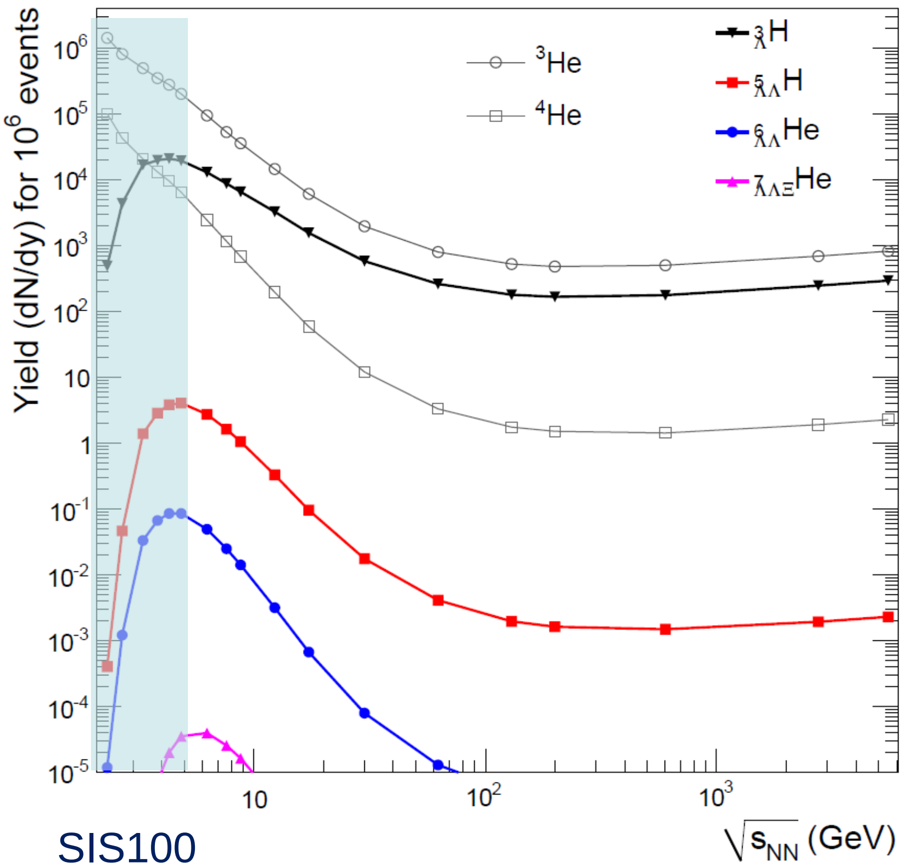


A. Andronic et al., Phys. Lett. B697 (2011) 203

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

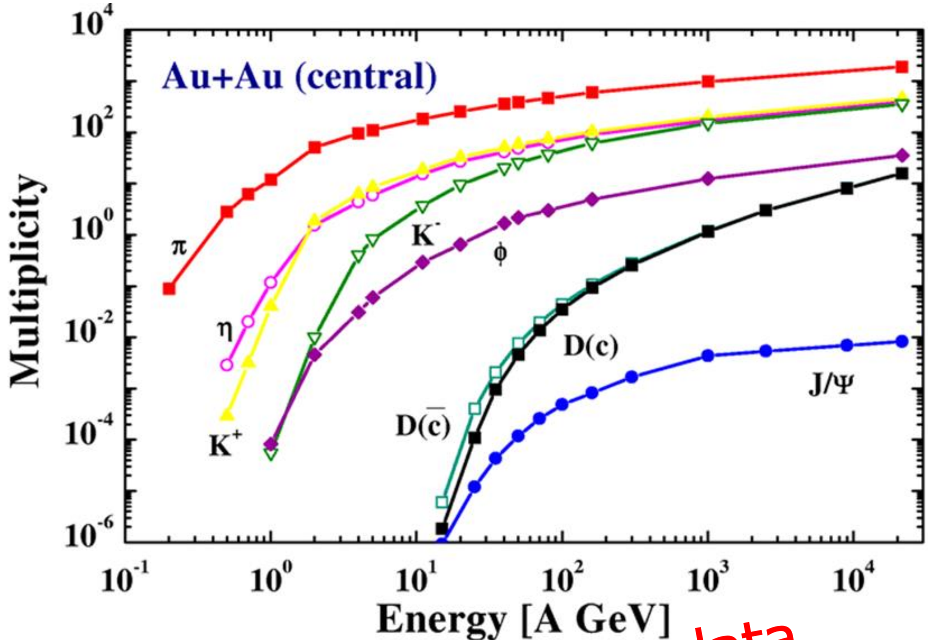
	Multiplicity	Yield in 1 week
$^5_{\Lambda\Lambda}H$	$5 \cdot 10^{-6}$	3000
$^6_{\Lambda\Lambda}He$	$1 \cdot 10^{-7}$	60

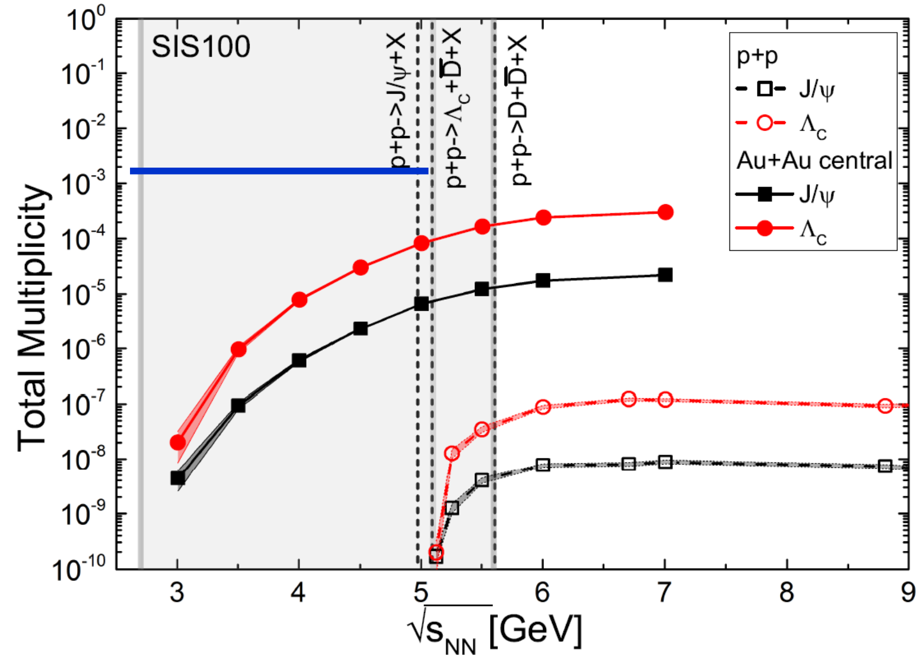
Assumption for yield calculation:
Reaction Rate 1 MHz
BR 10% (2 sequential weak decays)
Efficiency 1%

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, $D^{\pm}$)





No data at FAIR energies

HSD calculation

Central coll. Au+Au 10 A GeV :
$M_{J/\psi} = 1.7 \cdot 10^{-7}$

W. Cassing, E. Bratkovskaya, A. Sibirtsev, Nucl. Phys. A 691 (2001) 753

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

Central Au+Au collisions 10 A GeV:
$M_{J/\psi} = 5 \cdot 10^{-6}$

J. Steinheimer, A. Botvina, M. Bleicher, arXiv:1605.03439v1

Highly appreciated: support from theory

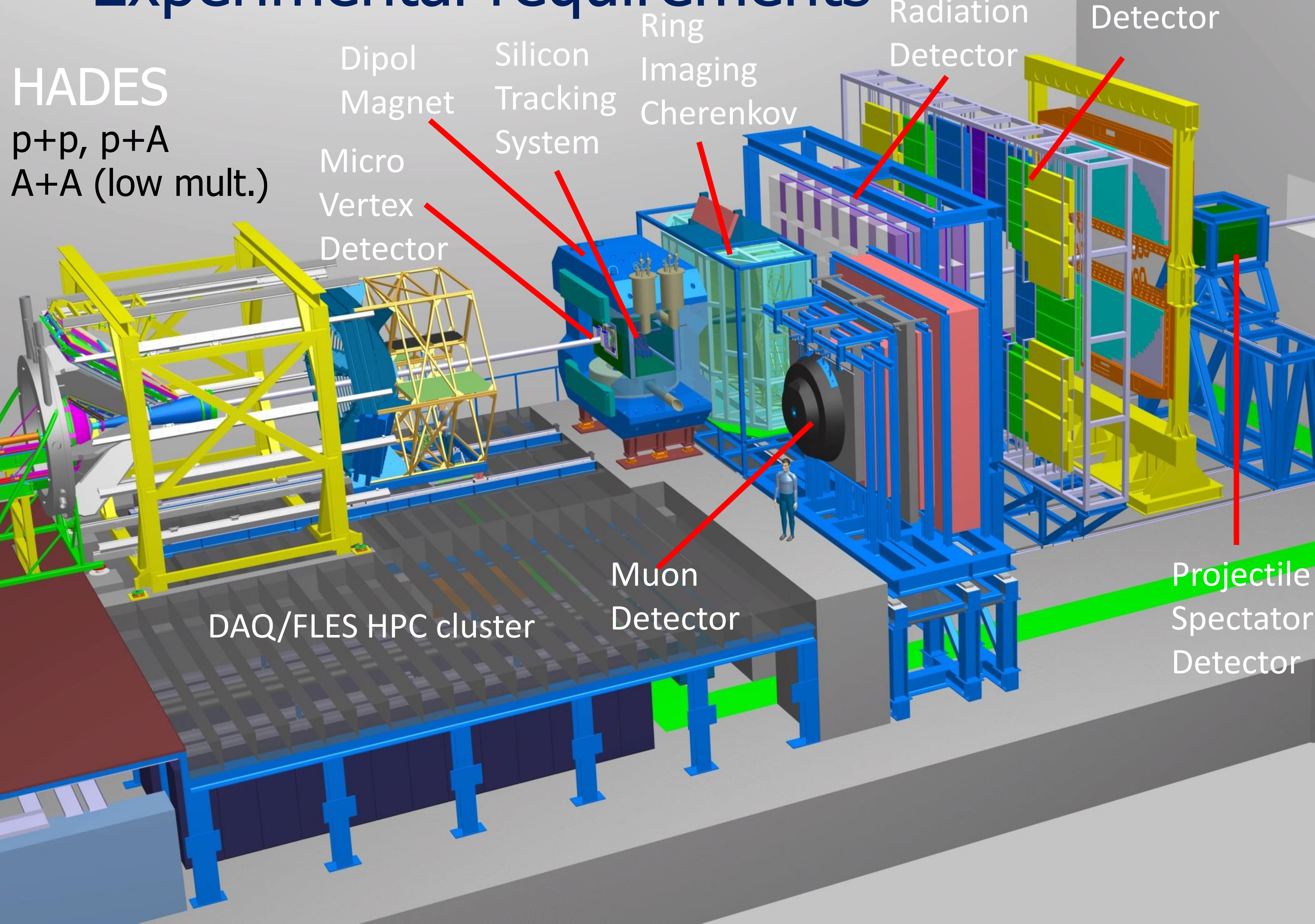
- Realistic description of heavy-ion collisions at high net-baryon densities (energies of 4 – 40 A GeV)
- Quantitative relation between physics case and observables

Physics case	**Diagnostic probe**
Equation-of-state	Flow, Particle production ?
Phase transition	Chemical equilibration of φ, Ξ, Ω, ... ? Open and hidden charm ?
First order phase transition: - Spinodal decomposition - Caloric curve - Critical point	 Fragments, flow power spectrum? Intermediate mass dileptons? E-b-e fluctuations of B, S, Q
Chiral symmetry restoration	Dilepton invariant mass spectra ?
NΛ and ΛΛ interaction	Hypernuclei (yield, lifetime)

Experimental requirements

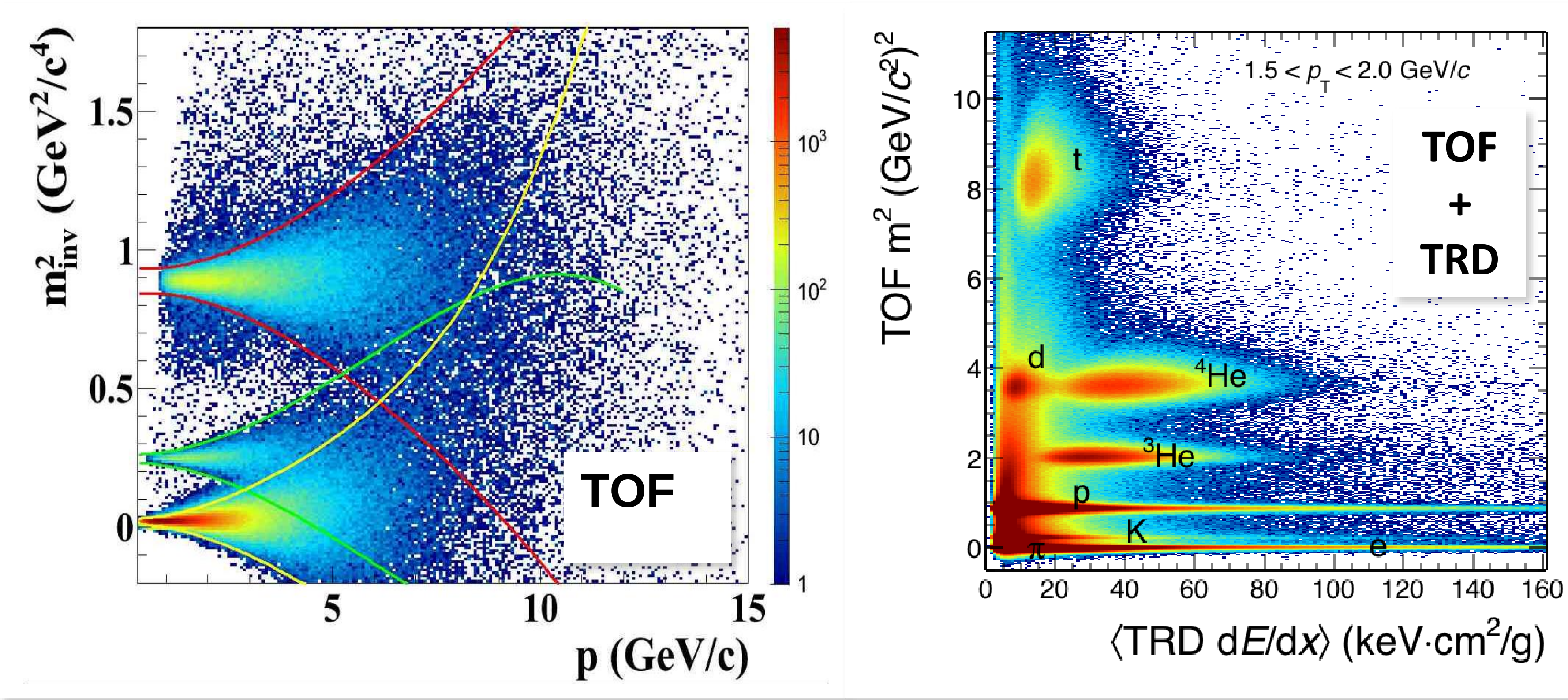
- 10^5 - 10^7 Au+Au reactions/sec
- determination of displaced vertices ($\sigma \approx 50\ \mu m$)
- identification of leptons and hadrons
- fast and radiation hard detectors and FEE
- free-streaming readout electronics
- high speed data acquisition and high performance computer farm for online event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

Experimental requirements

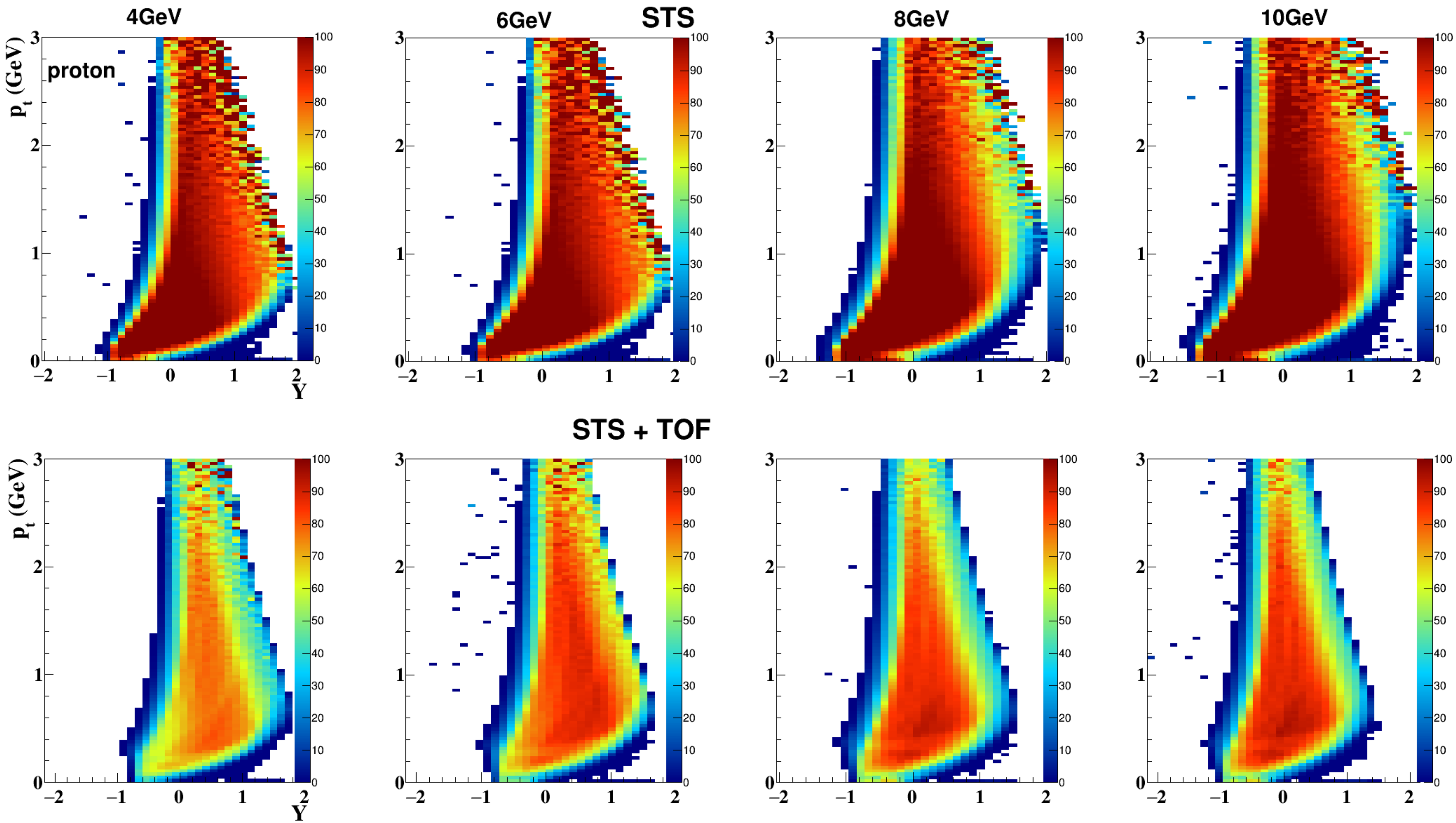


Particle Identification

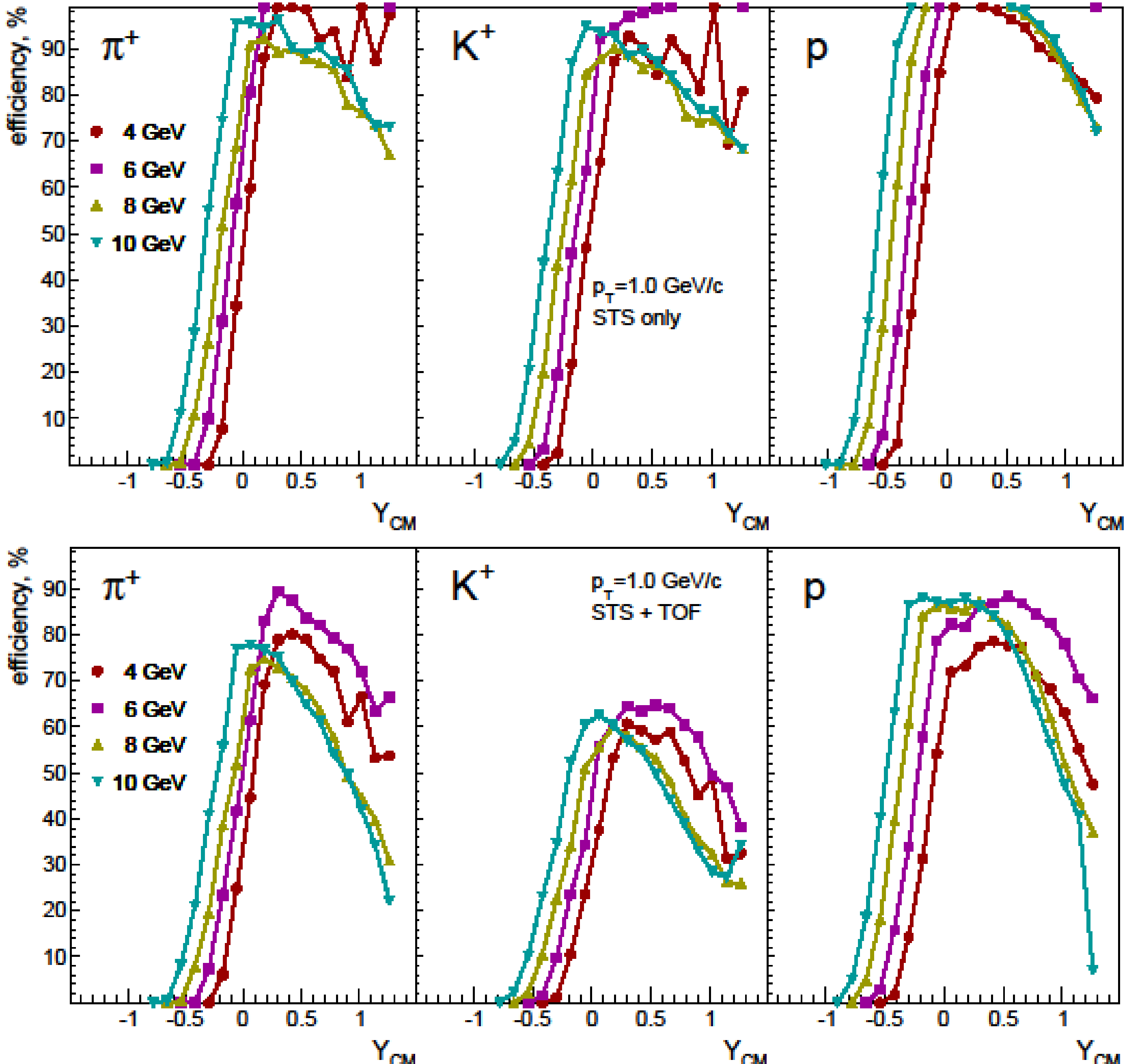
Detectors used: STS, TOF, TRD



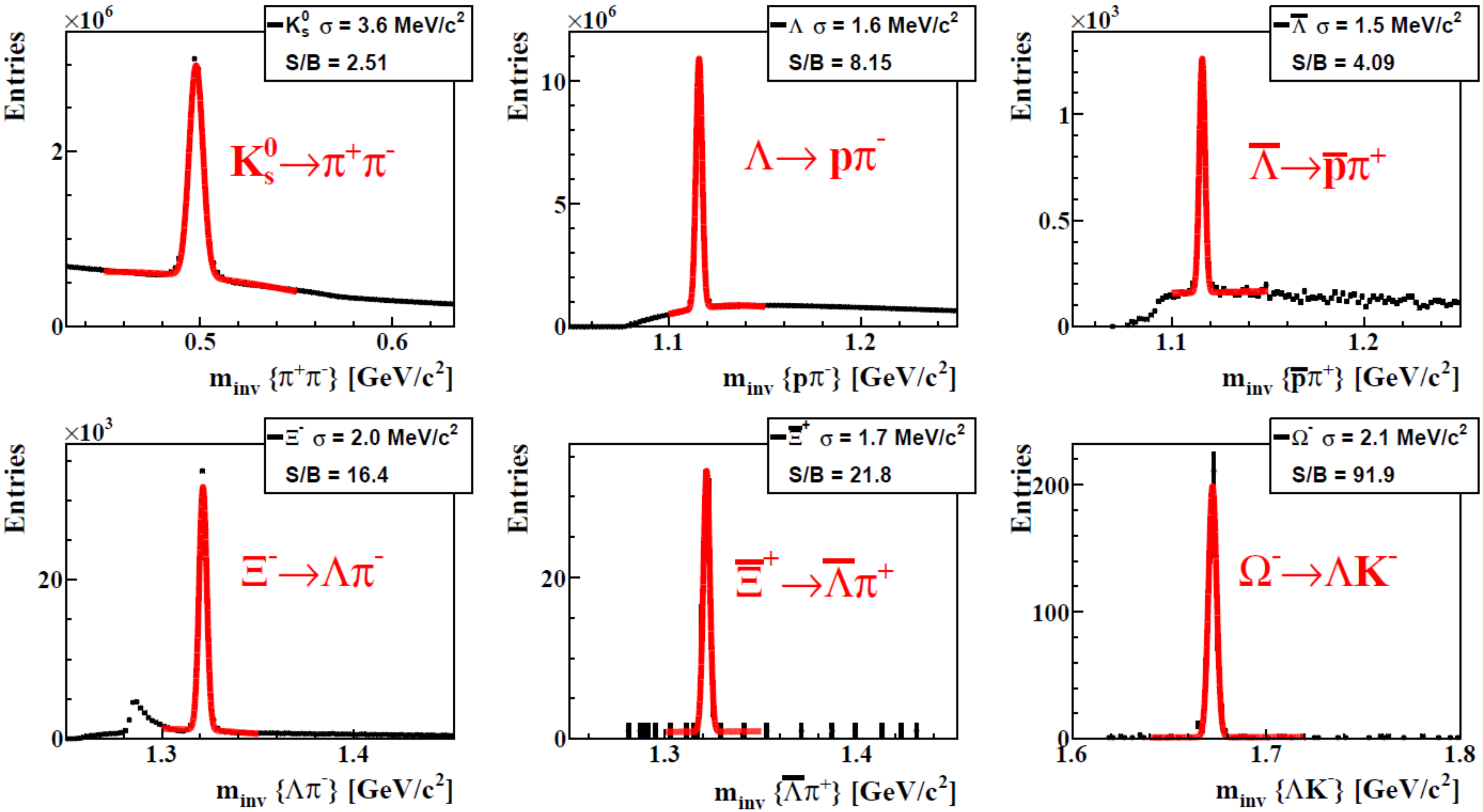
p reconstruction efficiency



π^+, K^+, and p reconstruction efficiency

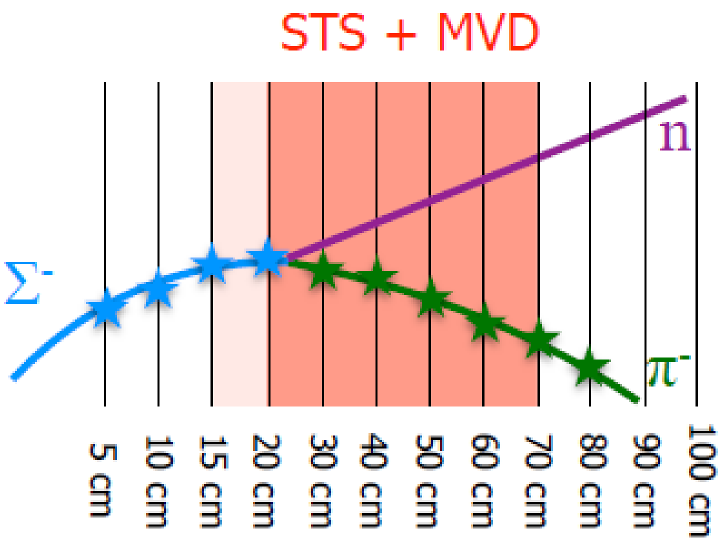


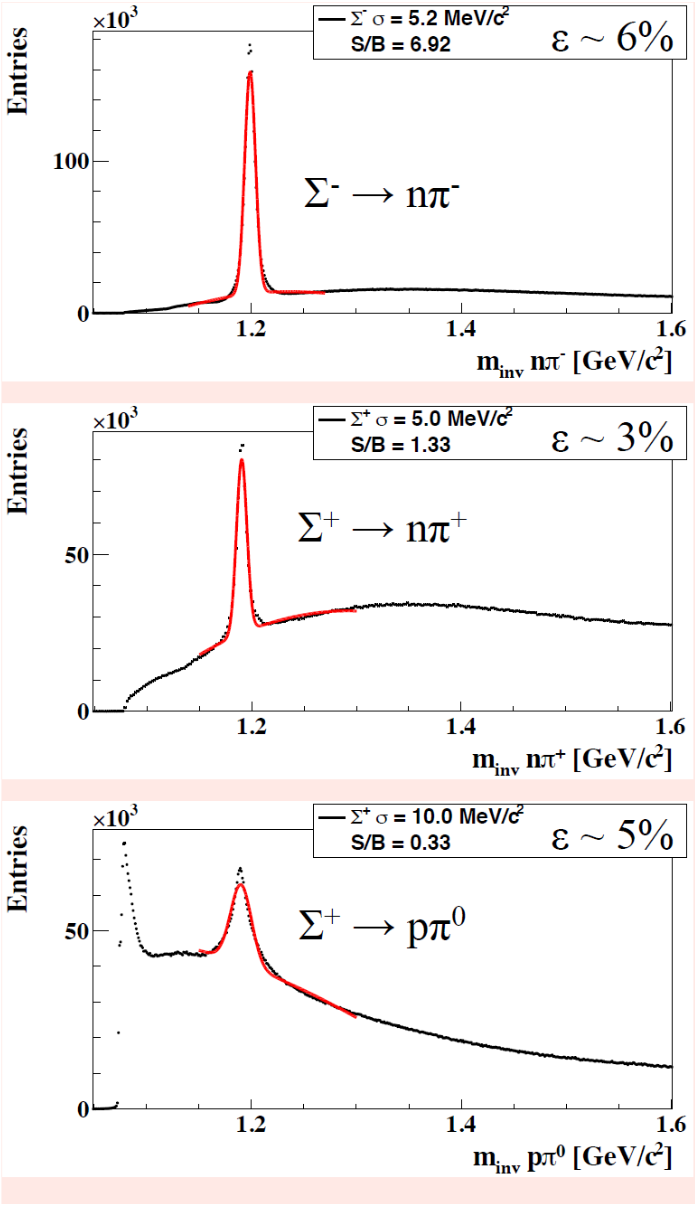
Strange hadrons in central Au+Au 10 AGeV



Hyperons in Au+Au 10 AGeV

missing mass analysis

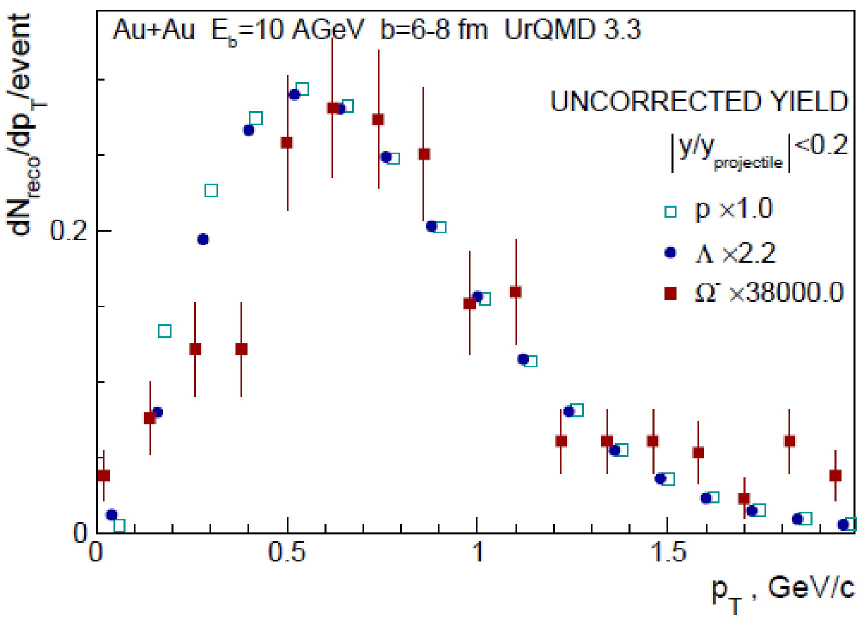




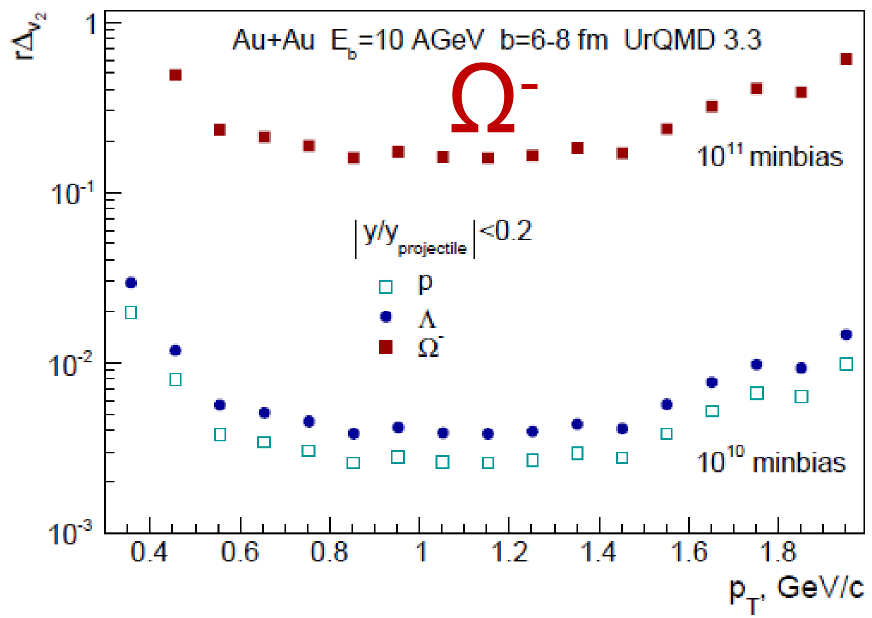
Simulations

Elliptic flow measurements in Au+Au collisions
at 10 A GeV at b = 6 – 8 fm

1 day: 10^6 min. bias events/s x $8.6 \cdot 10^4$ s = $8.6 \cdot 10^{10}$ events

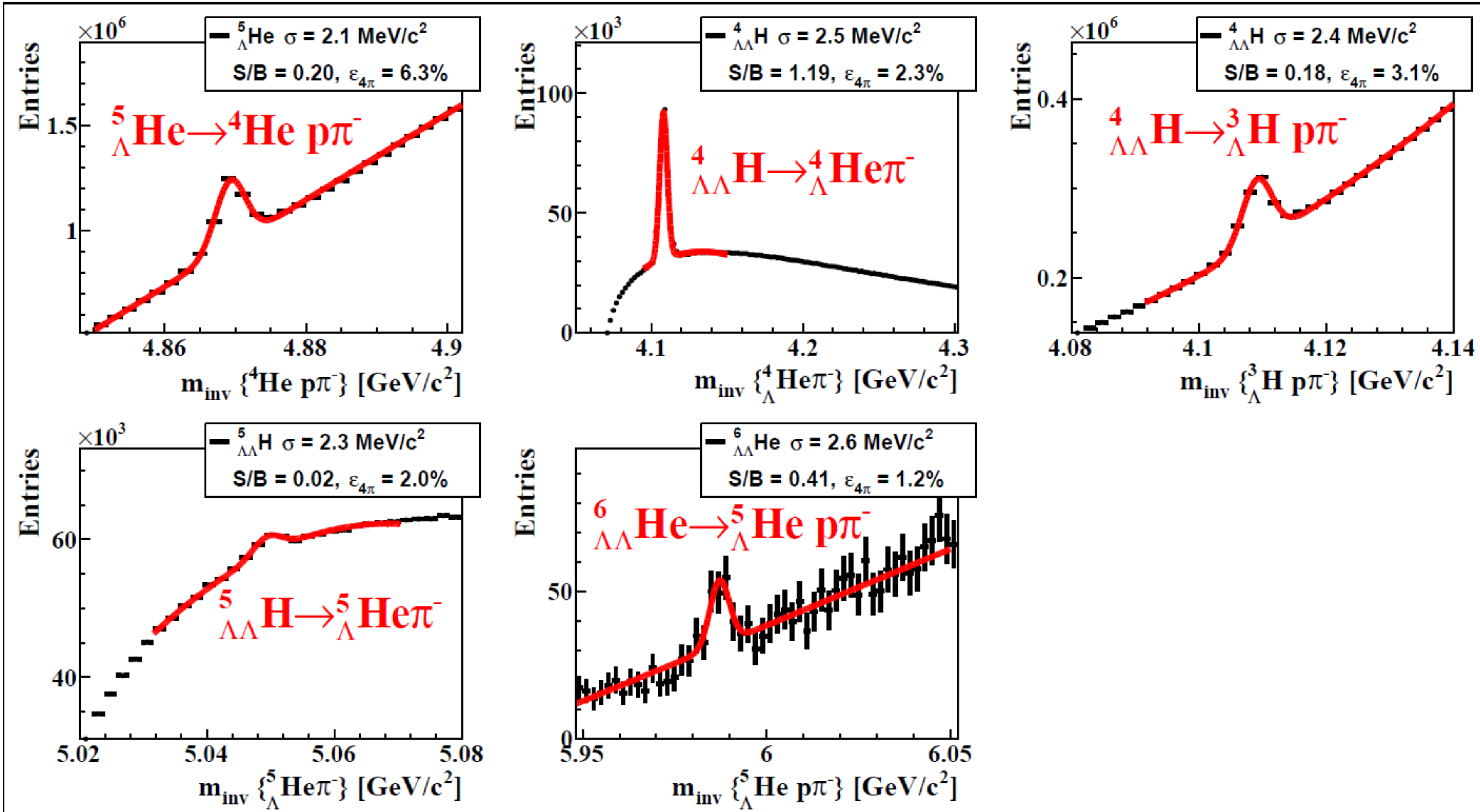


Yield of p, Λ, and Ω^- vs. p_T



Relative statistical error of v_2
for p, Λ, and Ω^-

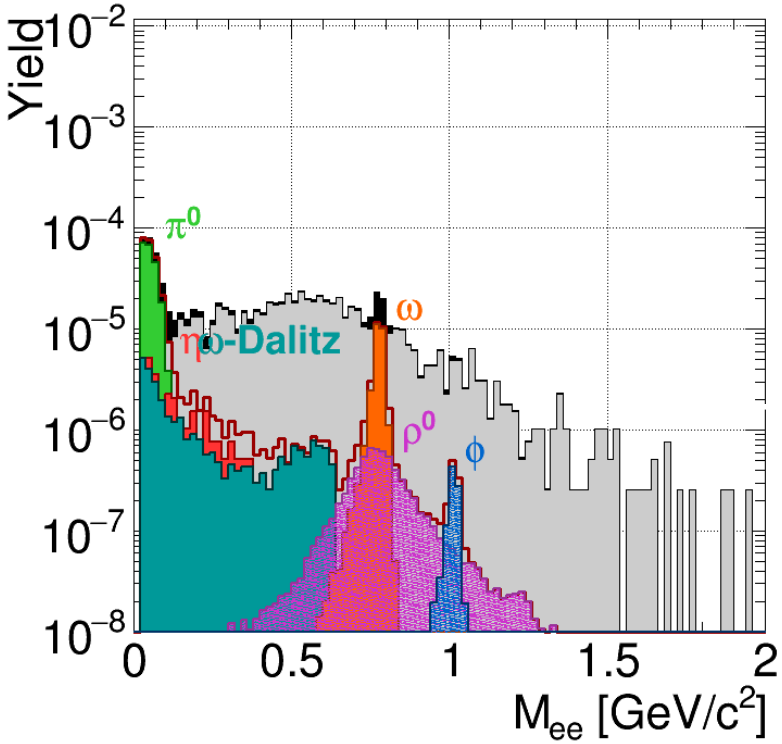
Hypernuclei in central Au+Au 10 AGeV



Simulations

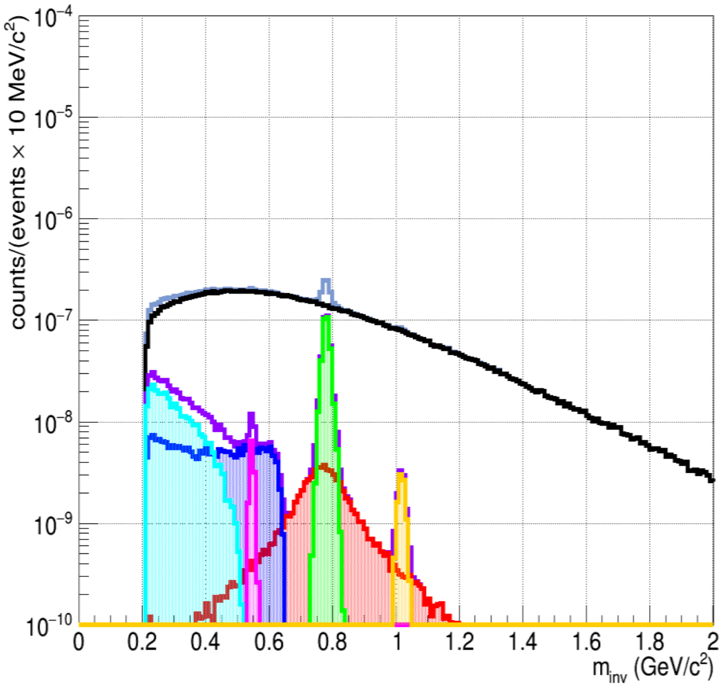
Dileptons in central Au+Au collisions at 8 A GeV

Electrons



Simulation STS, RICH, TRD, TOF:
RICH with mechanical structure
Hit smearing in TRD (4 layers)

Muons

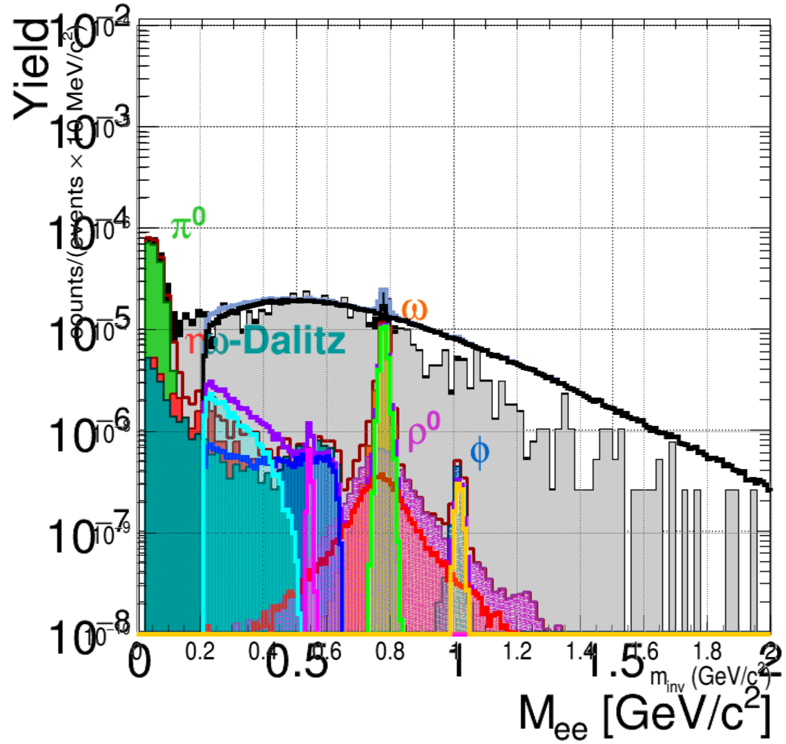


Simulation STS, MUCH with TRD, TOF:
Clustering in all detectors
(3 GEM stations + 4 layers TRD)

Simulations

Dileptons in central Au+Au collisions at 8 A GeV

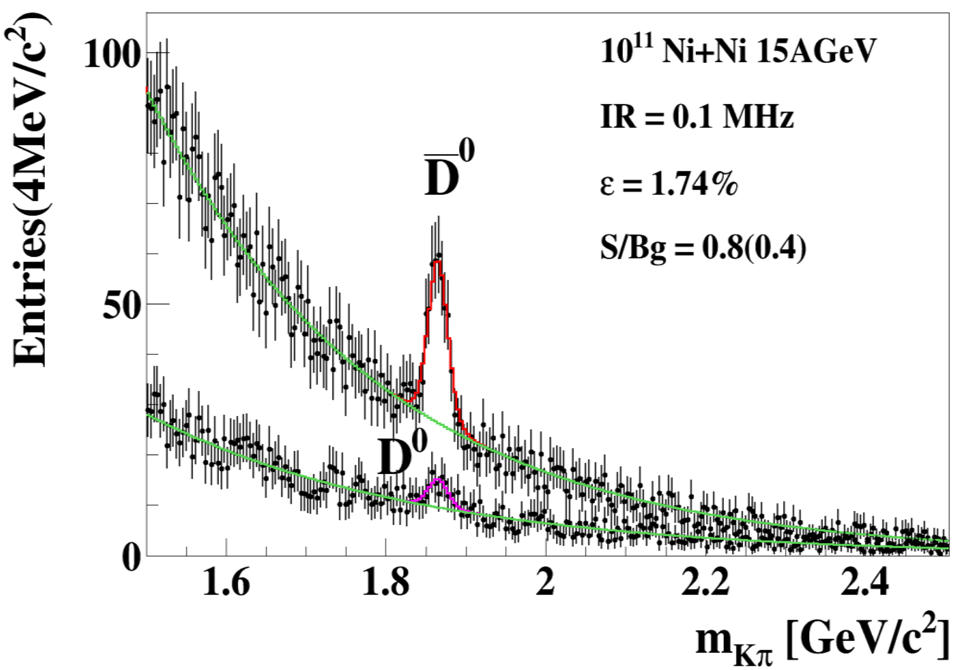
Electrons + Muons



Open and hidden charm in CBM at SIS100

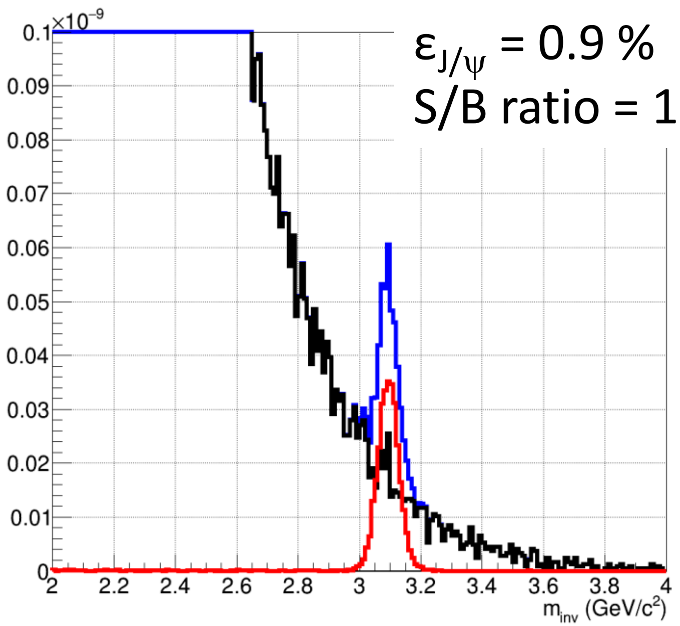
Ni + Ni central collisions at 15 A GeV

260 $\bar{D}^0$ and 45 D^0 in 2 weeks at IR = 0.1 MHz



Au + Au central collisions at 10 A GeV

6480 J/ψ in 2 weeks at IR = 10 MHz



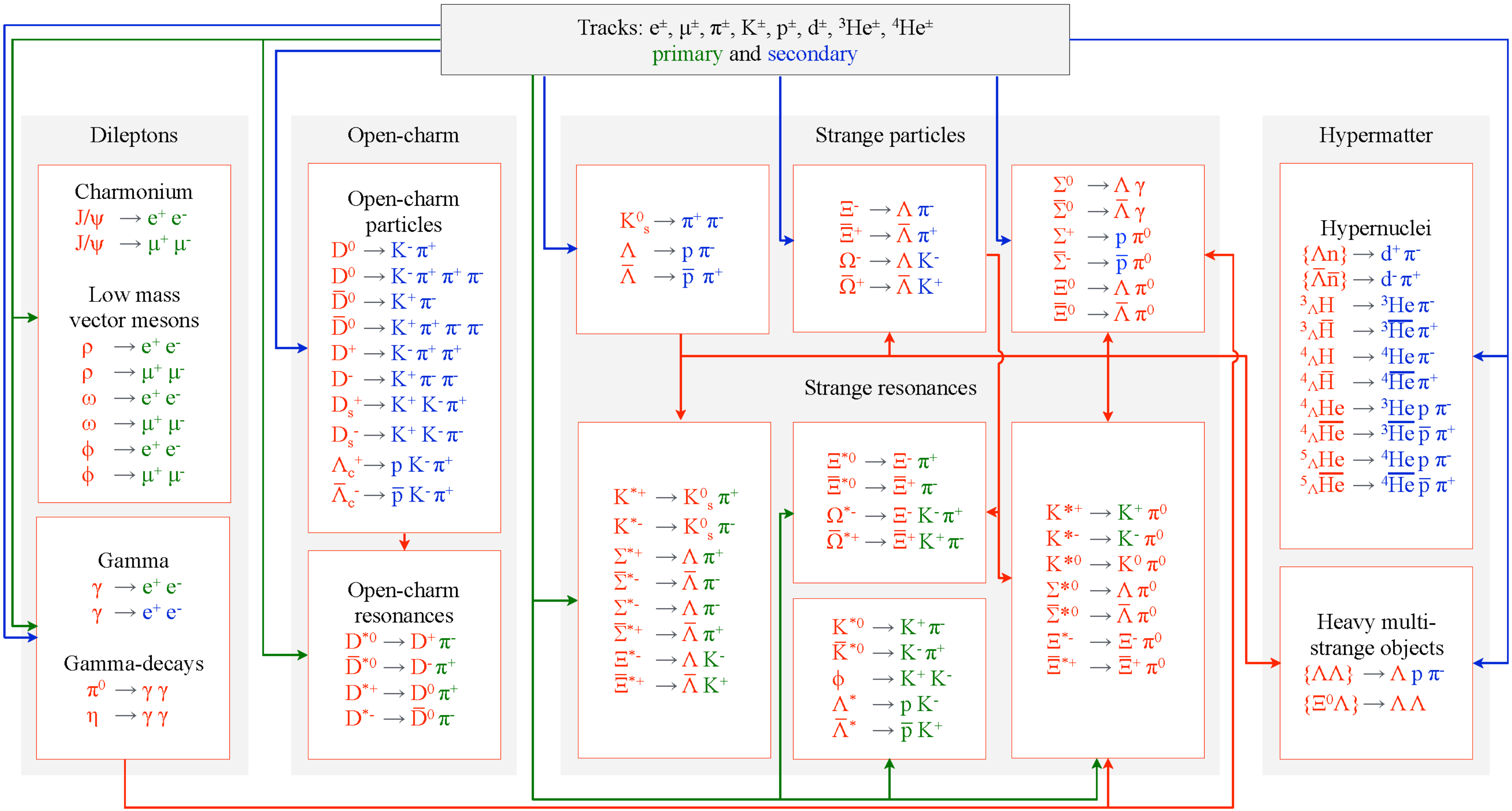
$\varepsilon_{J/\psi}$ = 0.9 %

S/B ratio = 1.0

UrQMD multiplicity ~ 5×10^{-6}*

* *Sub-threshold charm production in nuclear collisions* J. Steinheimer, A. Botvina, M. Bleicher arXiv:1605.03439

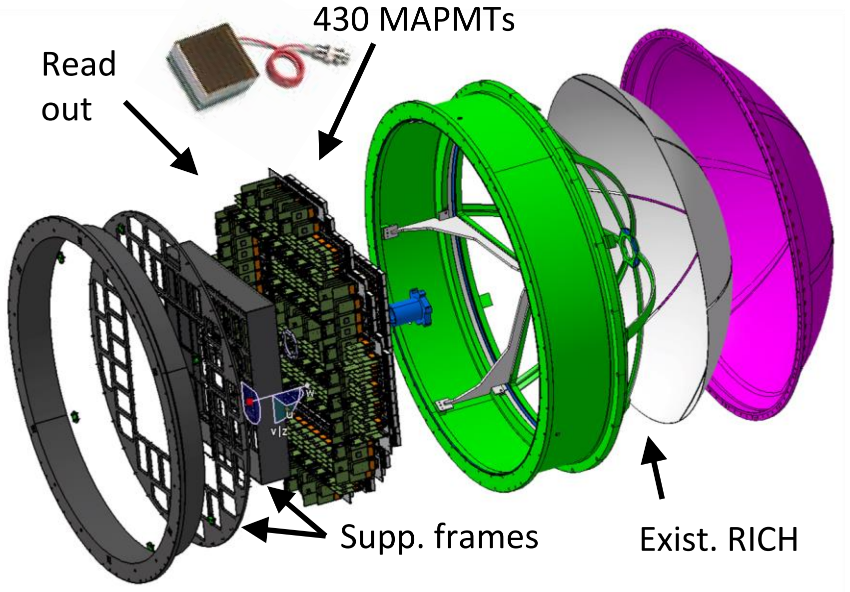
Online particle identification in CBM: The KF Particle Finder



successfully used online in the STAR experiment

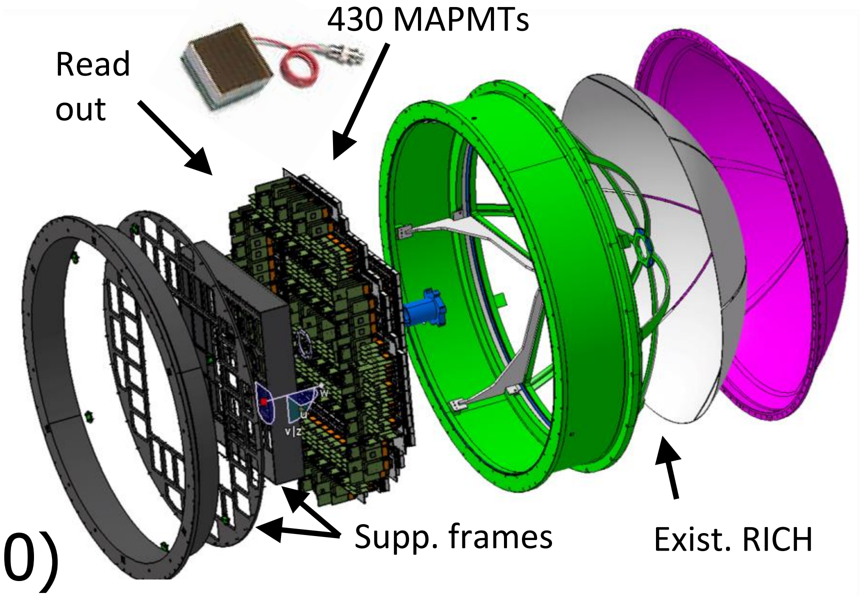
FAIR Phase 0 experiments

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

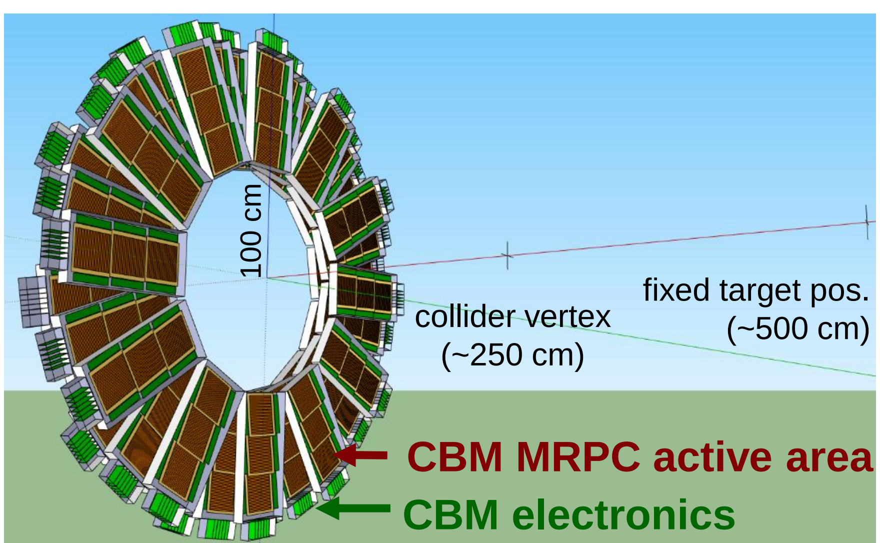


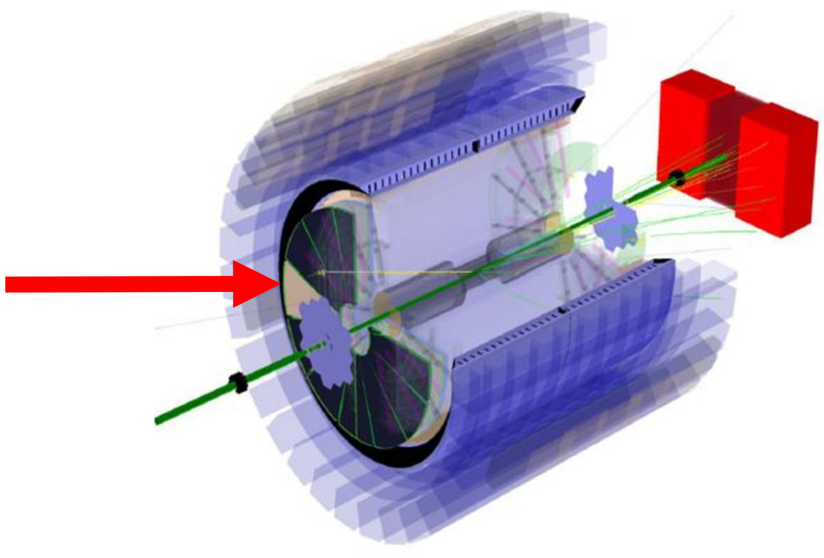
FAIR Phase 0 experiments

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



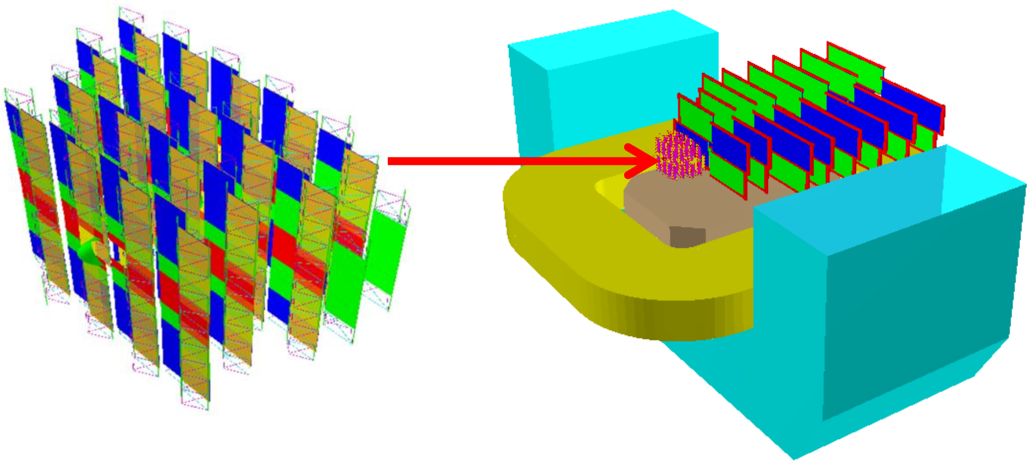
2. Install, commission and use 10% of the CBM TOF modules including read-out chain at STAR/RHIC (BES II 2019/2020)

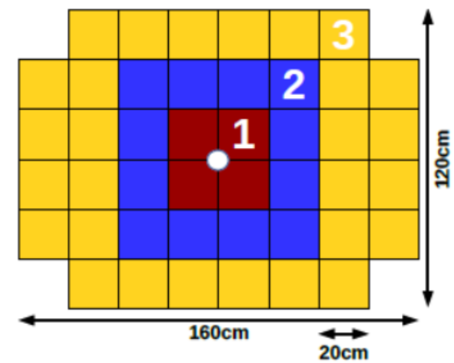




FAIR Phase 0 experiments

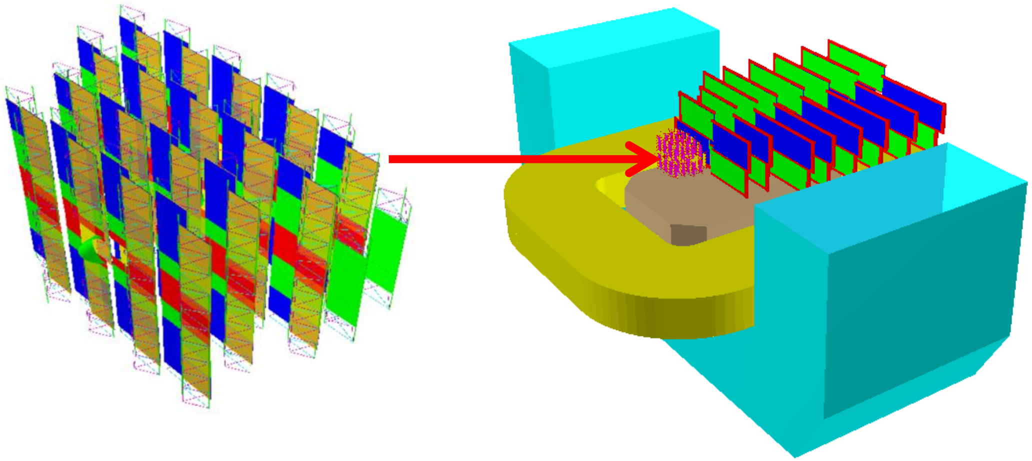
3. Install, commission and use 4 Silicon tracking layers and the Project Spectator Detector at the BM@N experiment at the Nuclotron in JINR/Dubna (Au-beams up to 4.5 A GeV in 2018/19)

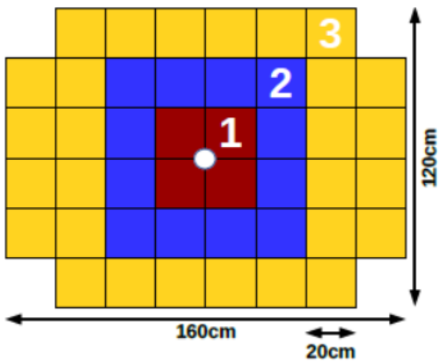




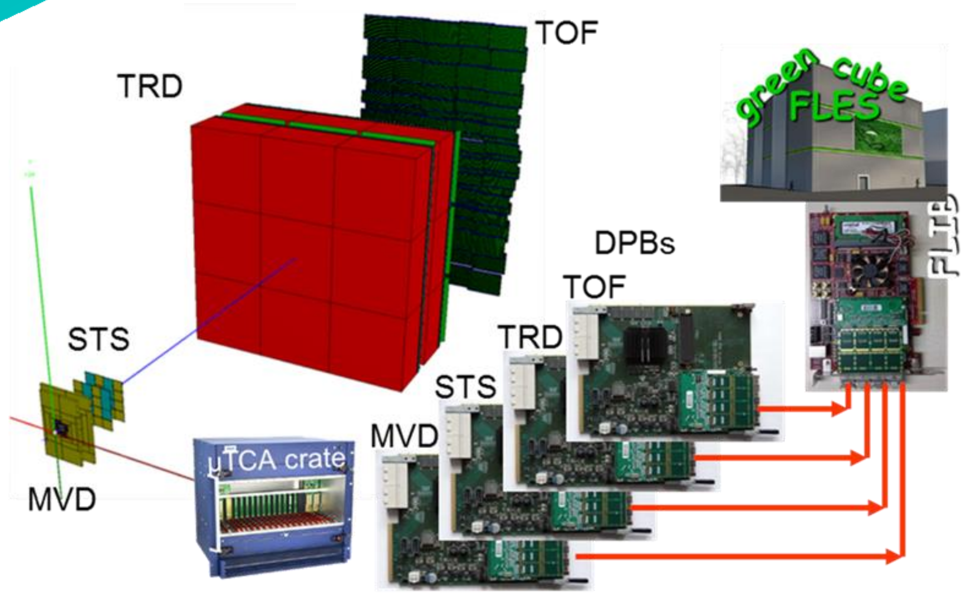
FAIR Phase 0 experiments

3. Install, commission and use 4 Silicon tracking layers and the Project Spectator Detector at the BM@N experiment at the Nuclotron in JINR/Dubna (Au-beams up to 4.5 A GeV in 2018/19)





4. Build mCBM at GSI/SIS18 for a full system test with high-rate nucleus-nucleus collisions from 2018 - 2020



The CBM Collaboration: 59 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.

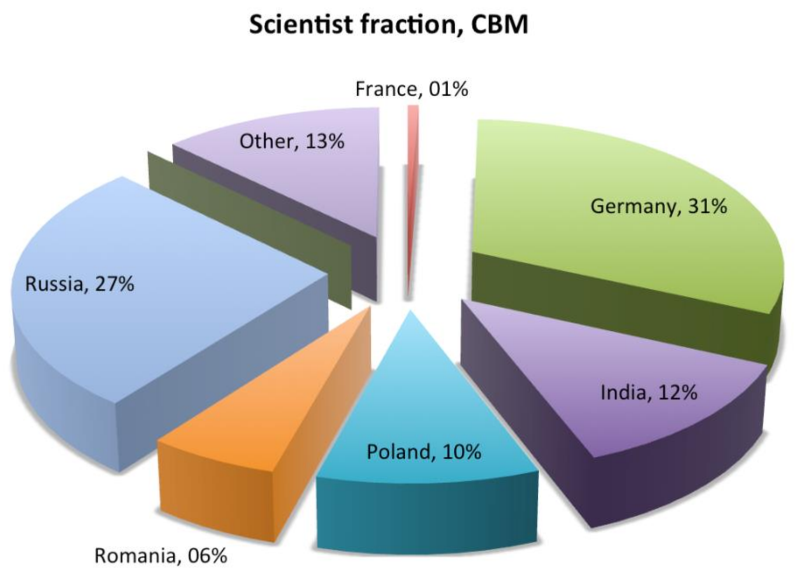
Poland:
AGH Krakow
Jag. Univ. Krakow
Silesia Univ. Katowice
Warsaw Univ.
Warsaw TU

Romania:
NIPNE Bucharest
Univ. Bucharest

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

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

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



Summary

- 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 detector performances fulfill CBM requirements.
  7 TDRs approved, 4 TDRs in preparation.
- Funding:
  CBM start version is financed by about 2/3 (+ EoI).
- FAIR Phase 0:
  HADES with CBM RICH photon detector,
  use CBM detectors at STAR/BNL and BM@N/JINR