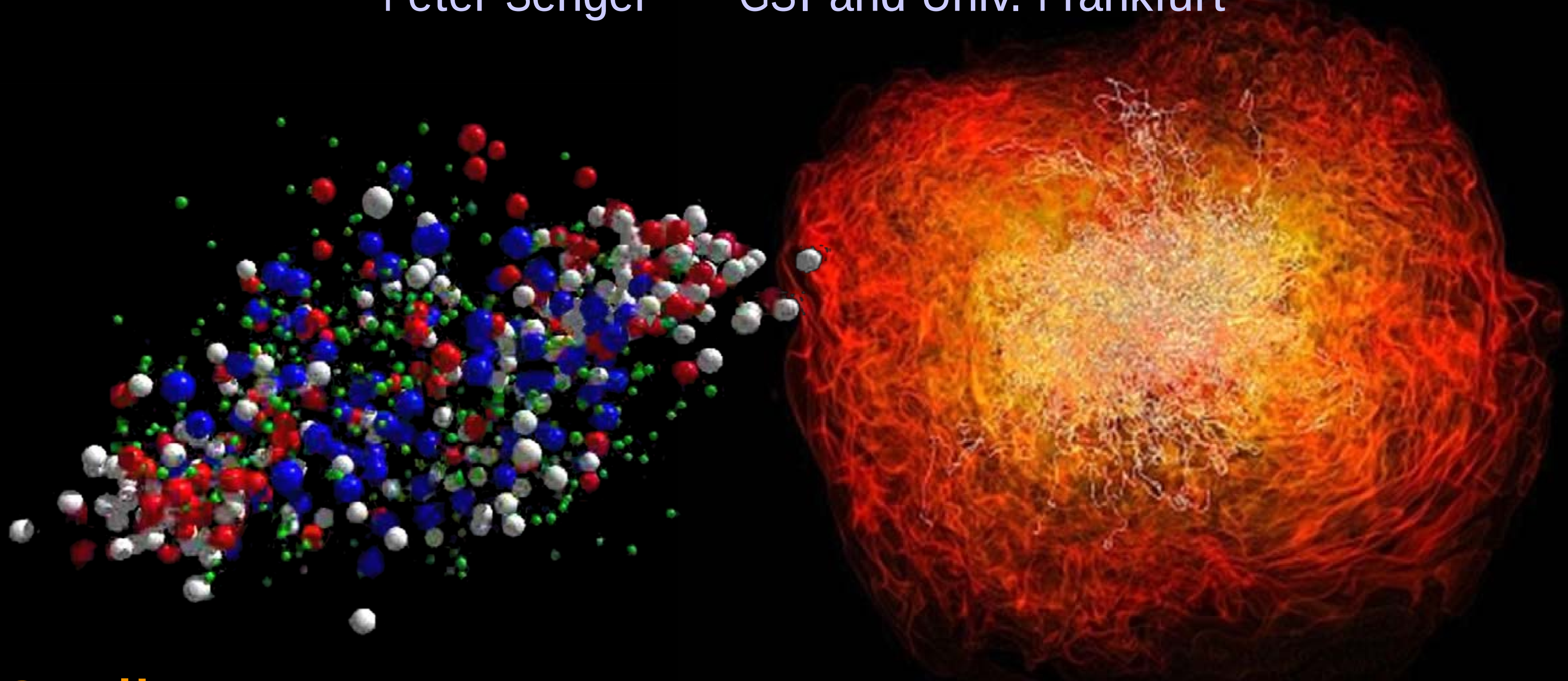
QCD matter physics at FAIR

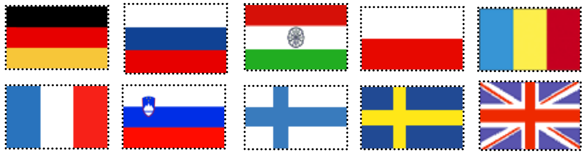
Peter Senger GSI and Univ. Frankfurt

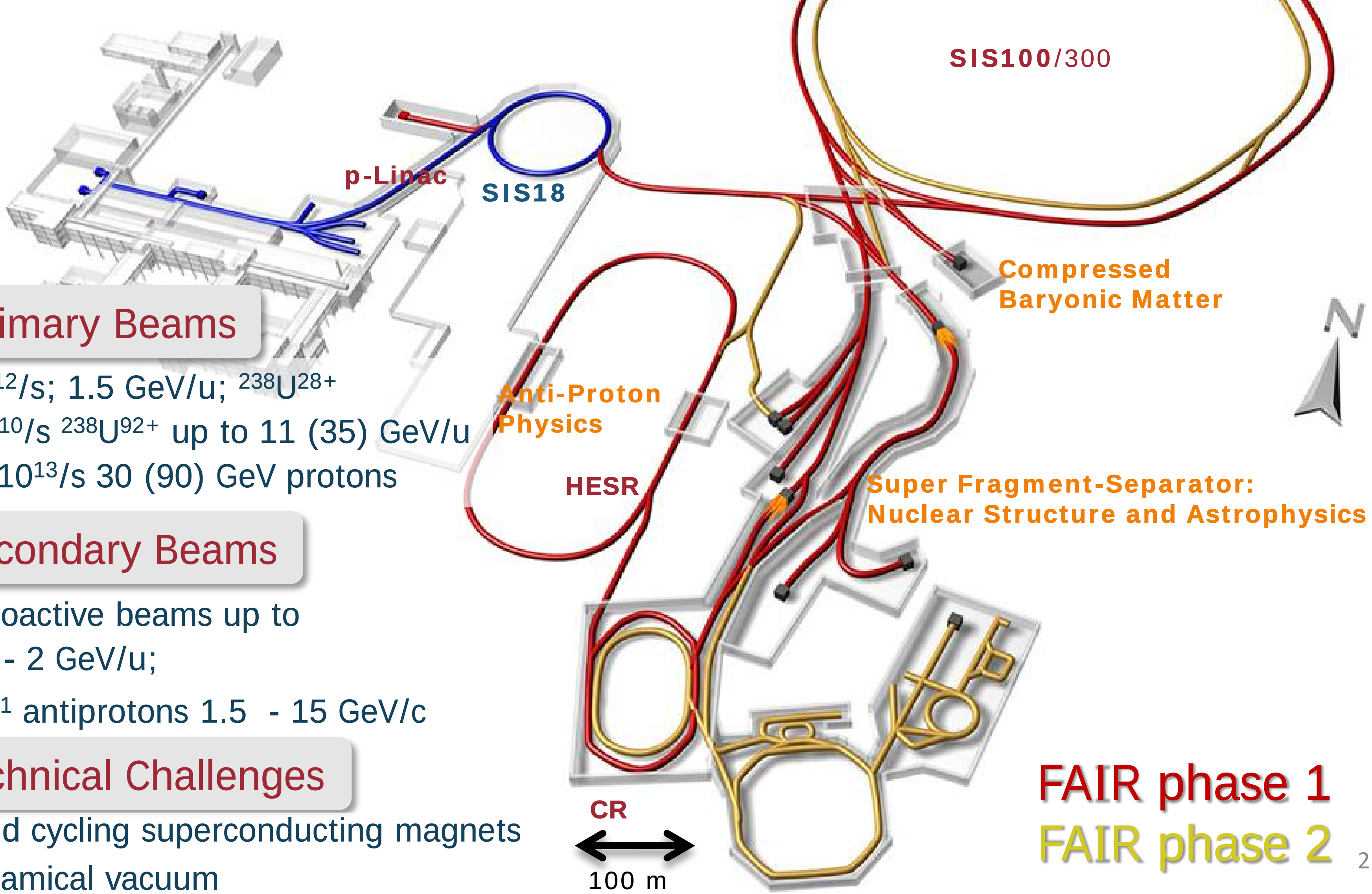


Outline:
- ➢ The Facility of Antiproton and Ion Research
- ➢ The CBM physics case: QCD matter at large μ_B
- ➢ The Compressed Baryonic Matter experiment
- ➢ CBM Phase 0

Quark Matter 2017, Chicago, 5-11 February 2017

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
- 3×10^{13}/s 30 (90) GeV protons

Secondary Beams

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

Technical Challenges

- rapid cycling superconducting magnets
- dynamical vacuum

Facility for Antiproton & Ion Research

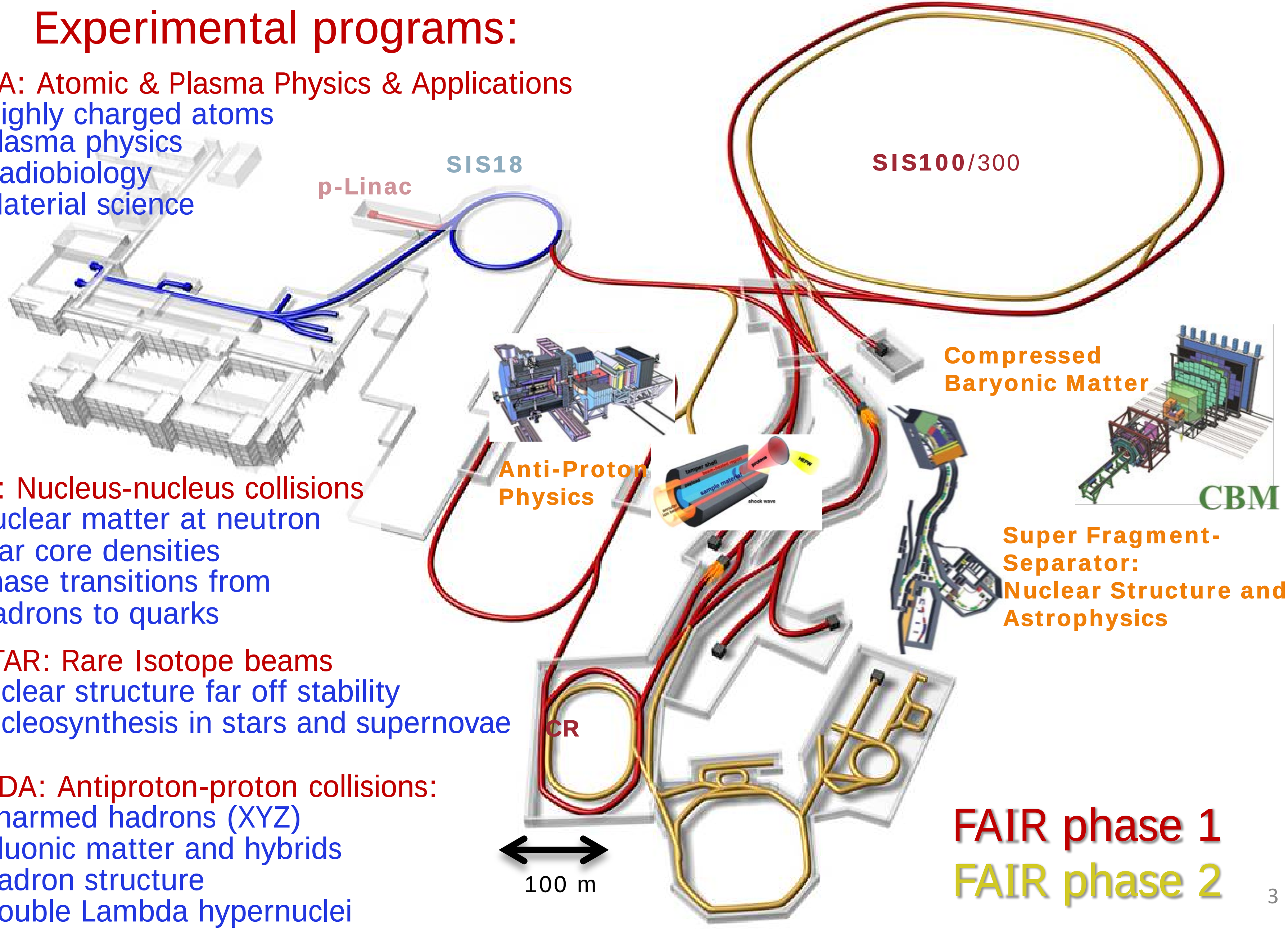
Experimental programs:

APPA: Atomic & Plasma Physics & Applications
- Highly charged atoms
- Plasma physics
- Radiobiology
- Material science

CBM: Nucleus-nucleus collisions
- Nuclear matter at neutron star core densities
- Phase transitions from hadrons to quarks

NUSTAR: Rare Isotope beams
- Nuclear structure far off stability
- Nucleosynthesis in stars and supernovae

PANDA: Antiproton-proton collisions:
- Charmed hadrons (XYZ)
- Gluonic matter and hybrids
- Hadron structure
- Double Lambda hypernuclei



Status of FAIR

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

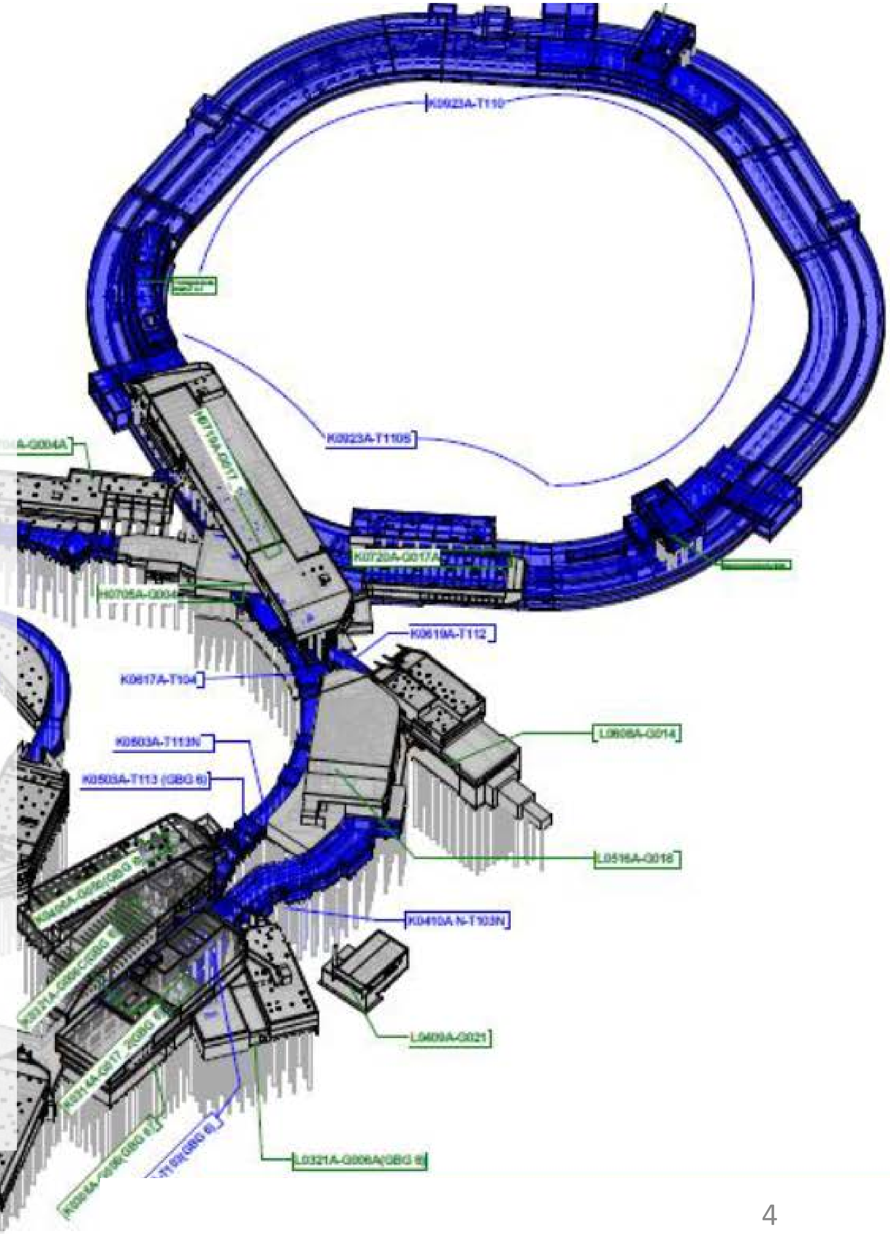
1st call for tender Sept. 26, 2016: water management and excavation

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

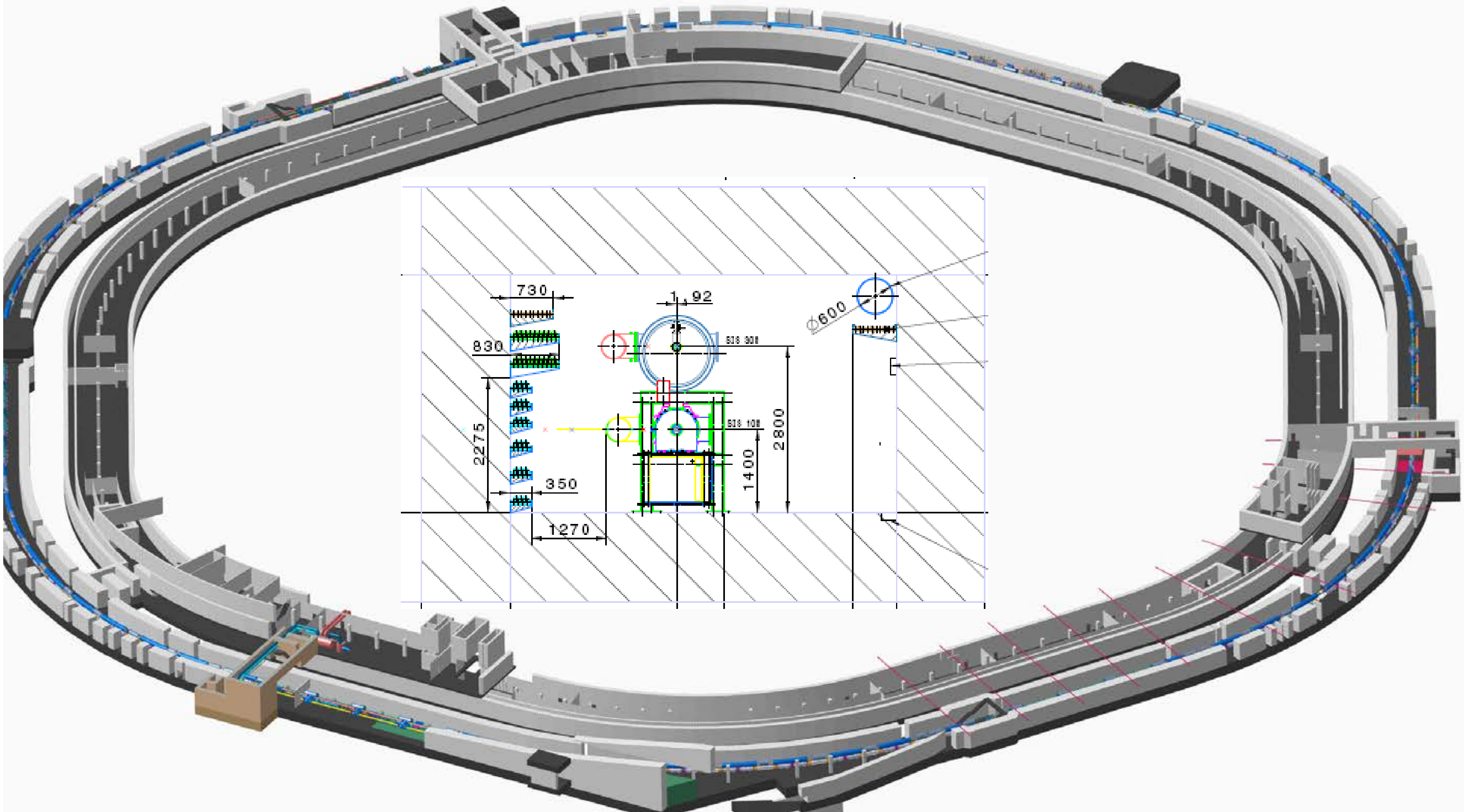
Start of construction mid of 2017

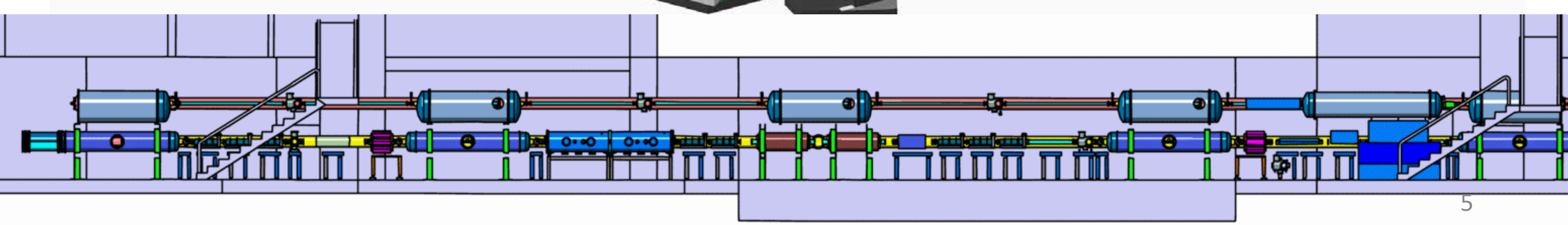
Installation incl. commissioning of the experiments is planned during 2021-2024

Full completion of FAIR by 2025



Tunnel for SIS100/300

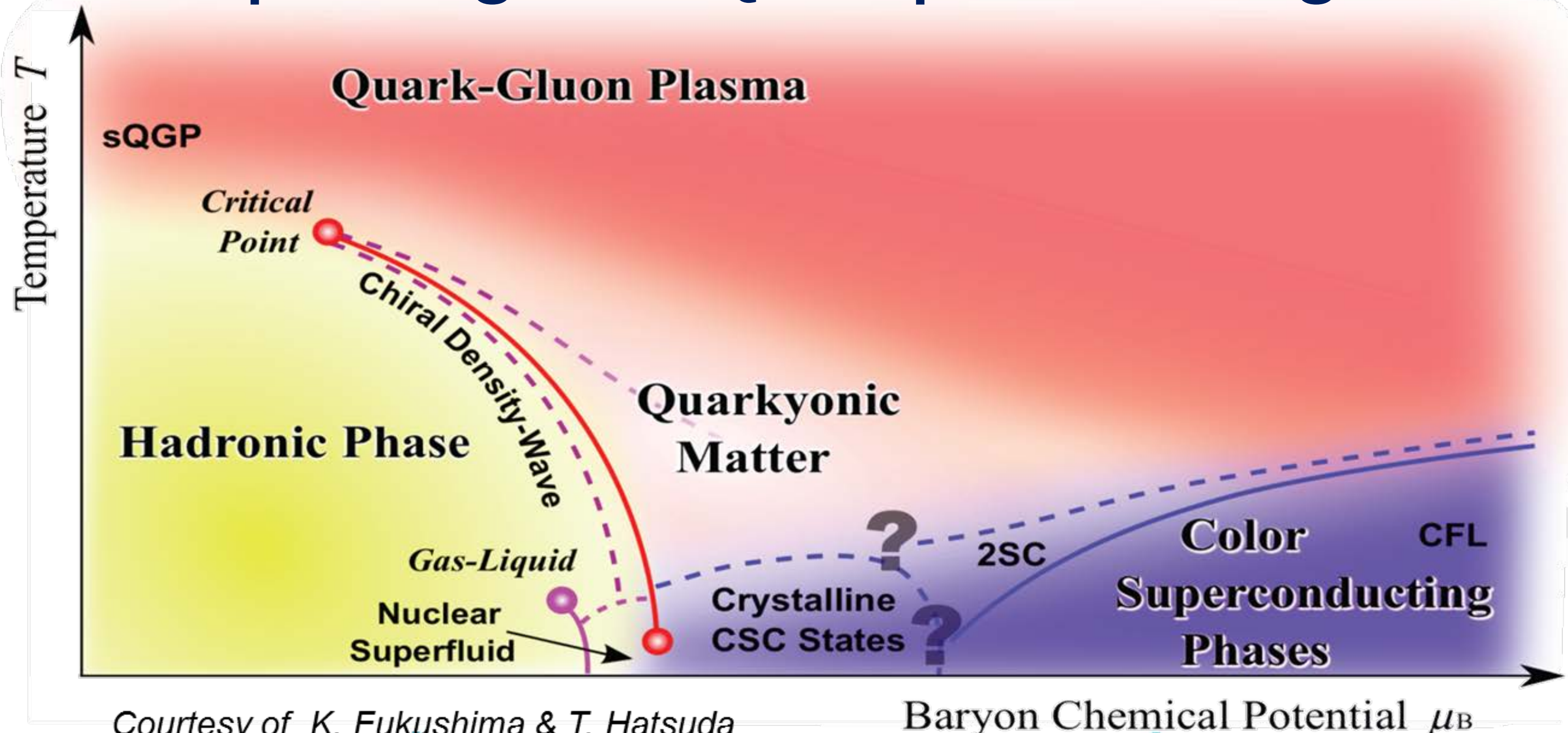




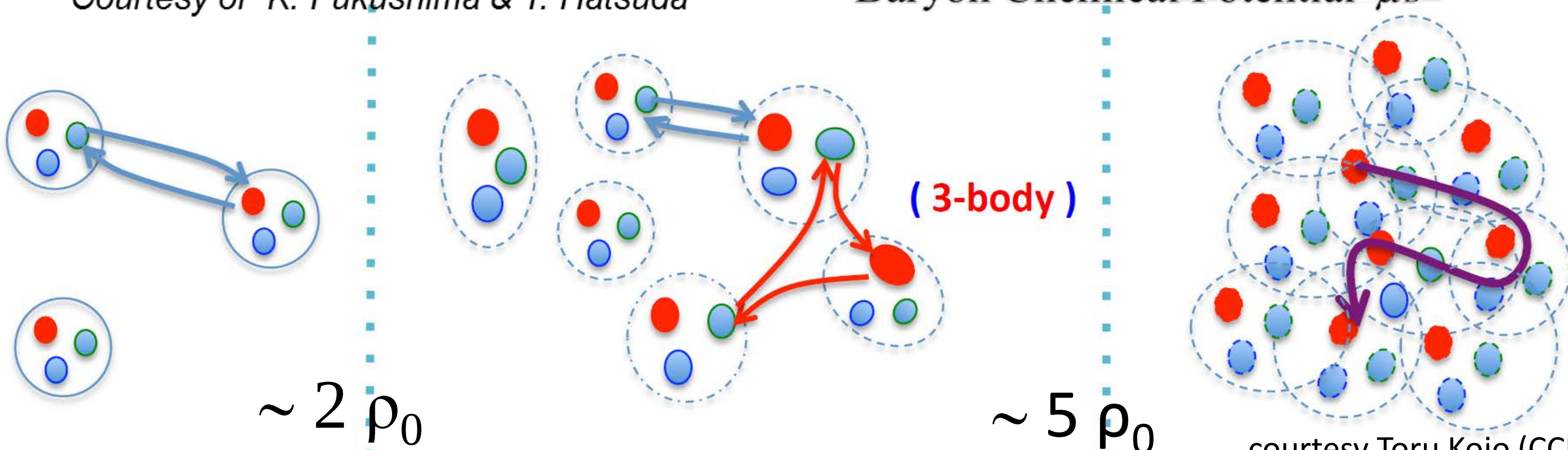
The Compressed Baryonic Matter (CBM) experiment


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

Exploring the QCD phase diagram



Courtesy of K. Fukushima & T. Hatsuda



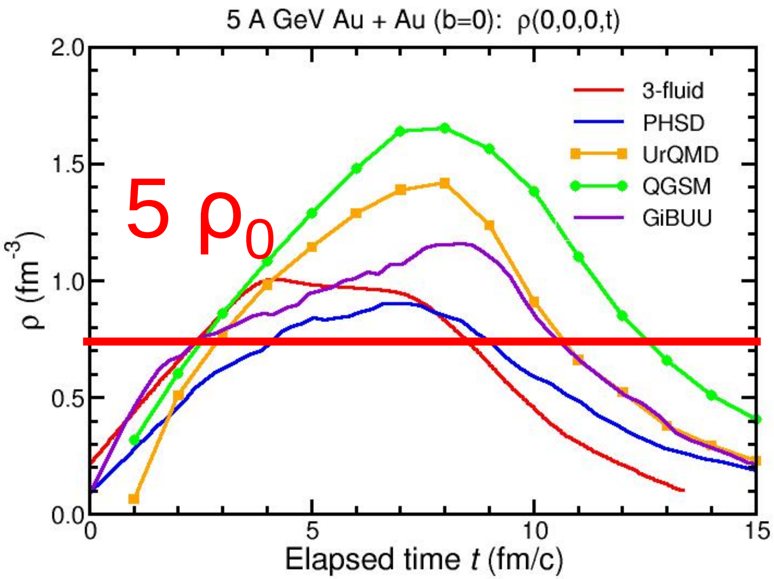
$\sim 2\,\rho_0$ $\sim 5\,\rho_0$

courtesy Toru Kojo (CCNU)

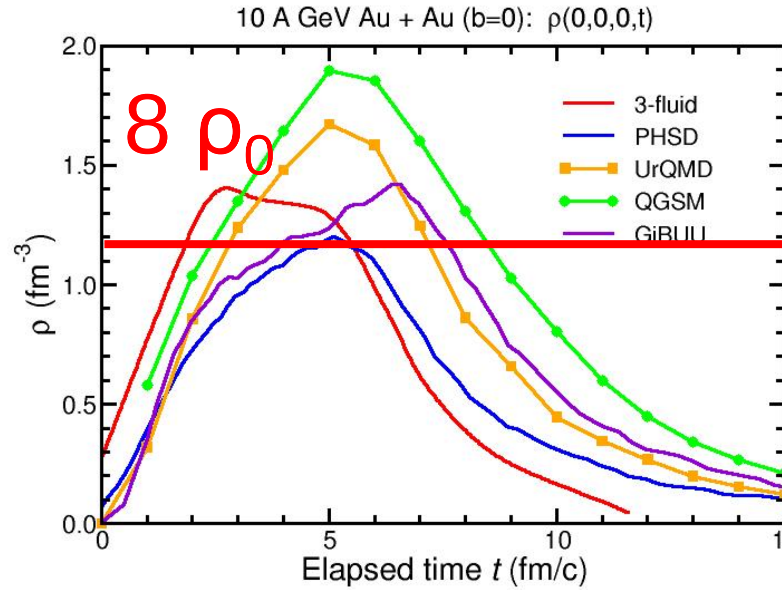
Baryon densities in central Au+Au collisions

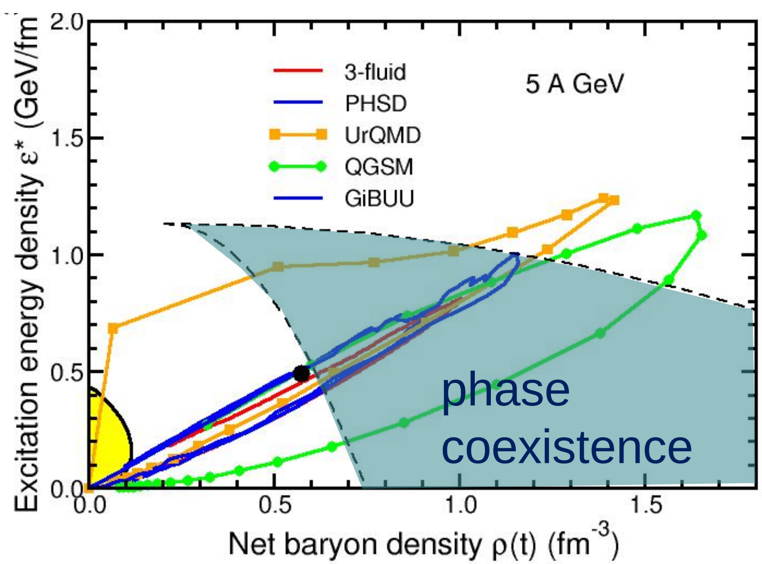
I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007)

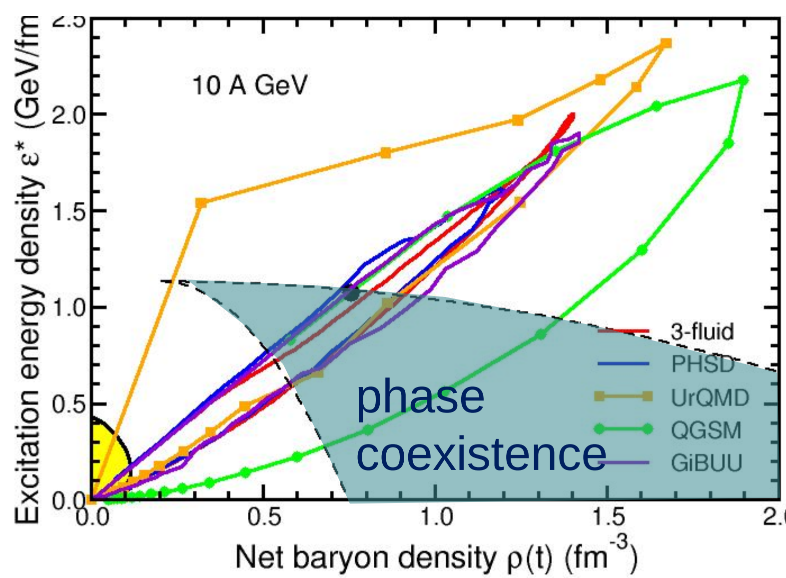
5 A GeV



10 A GeV



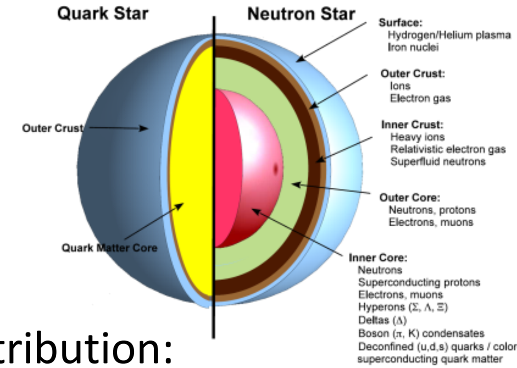




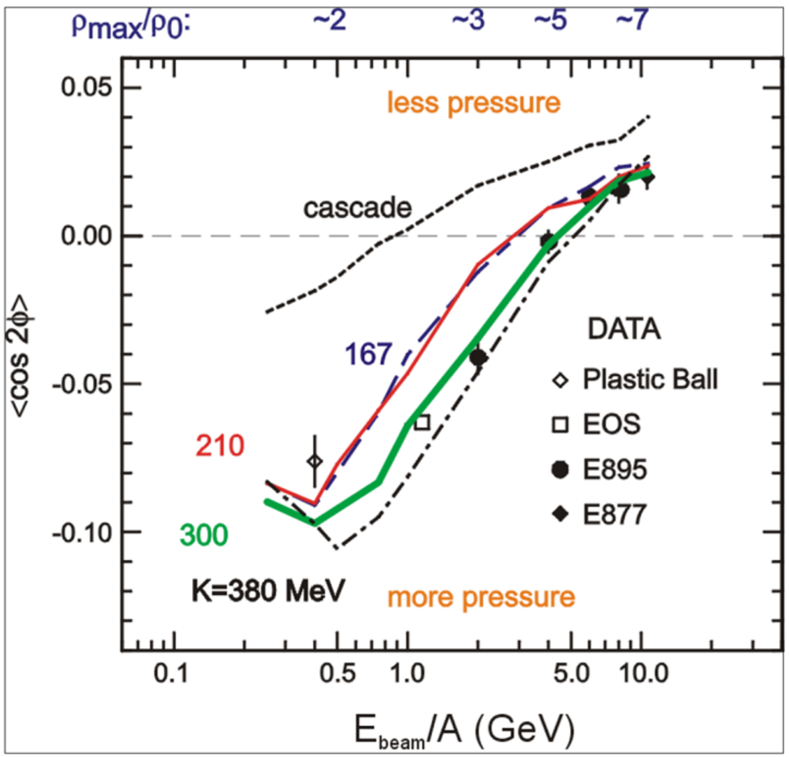
CBM physics case and observables

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

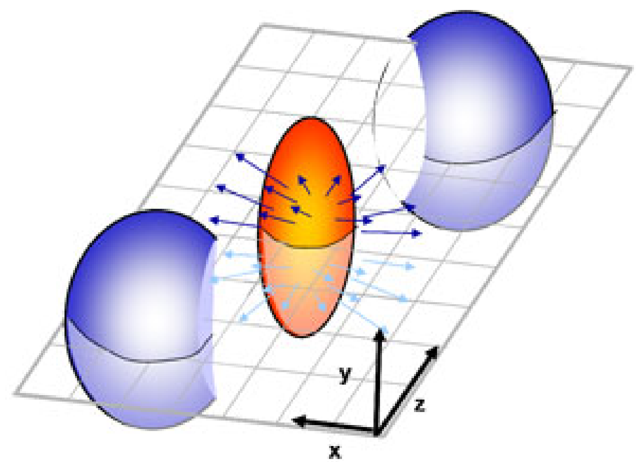


AGS: proton flow in Au+Au collisions



Azimuthal angle distribution:

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

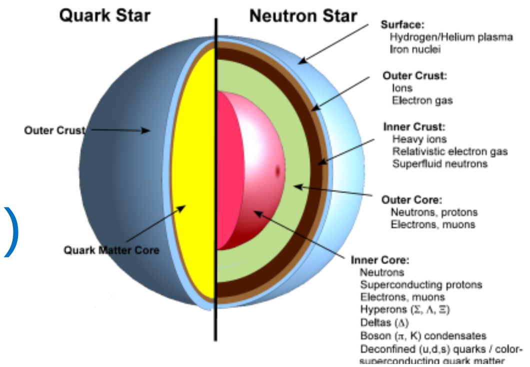


P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

CBM physics case and observables

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

- collective flow of identified particles ($\pi, K, p, \Lambda, \Xi, \Omega, \ldots$) 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

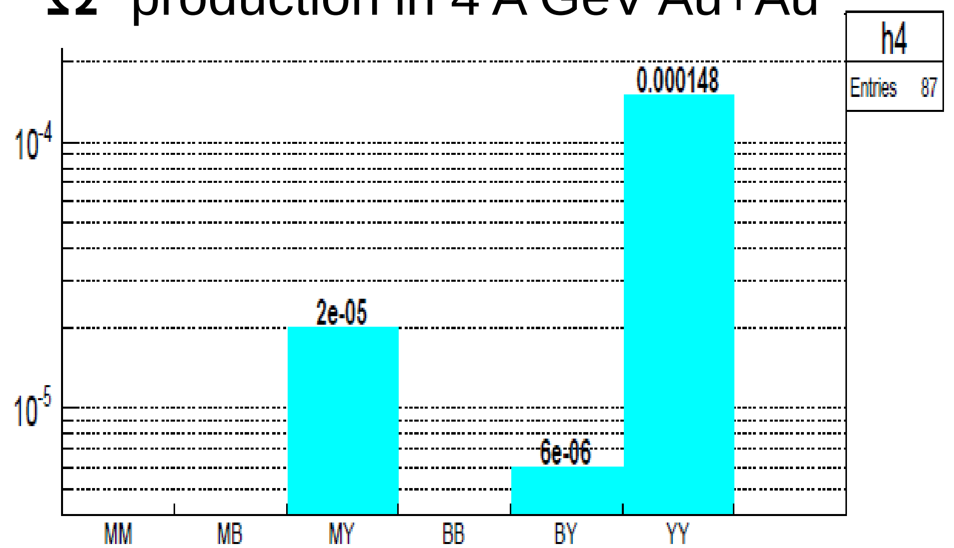
Hyperon production via multiple collisions

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

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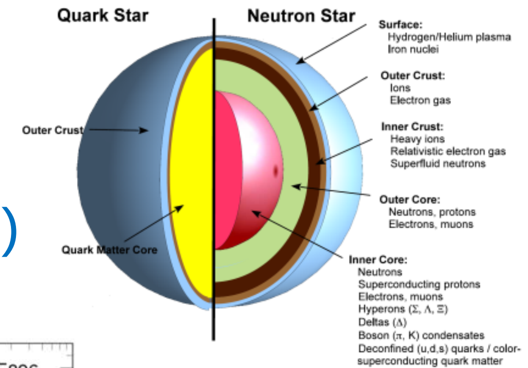

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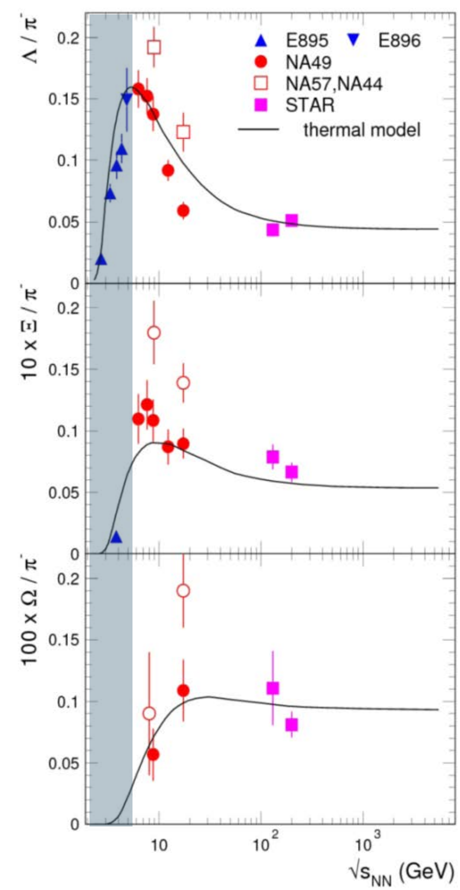


CBM physics case and observables

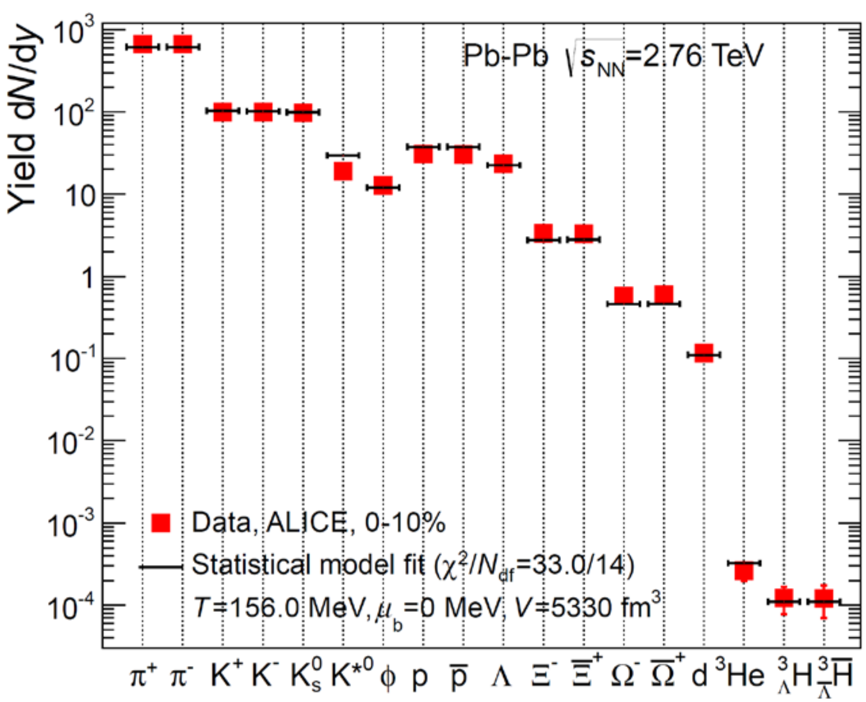
Phase transitions from partonic to hadronic matter

- excitation function of strangeness: Ξ^-(dss), Ξ^+($\overline{\mathrm{dss}}$), Ω^-(sss), Ω^+($\overline{\mathrm{sss}}$)
  - $\rightarrow$ chemical equilibration at the phase boundary

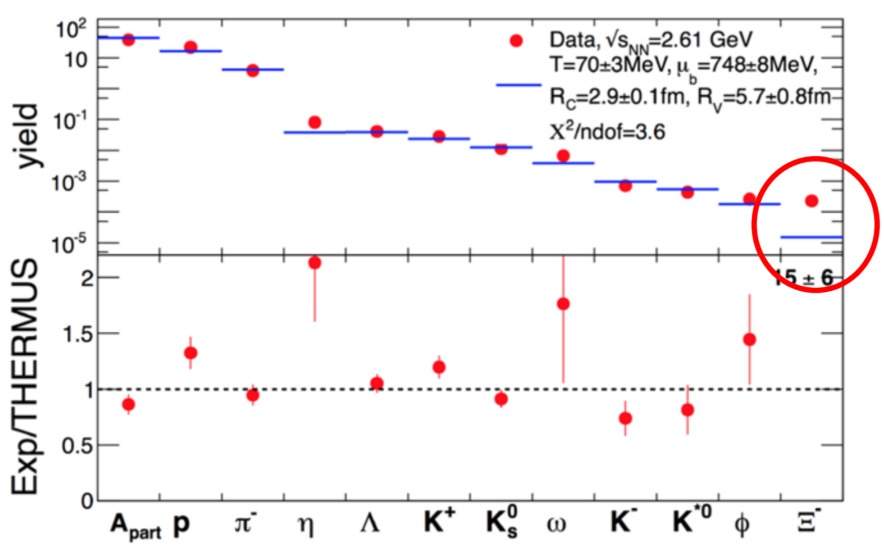
Particle yields and thermal model fits

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

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



HADES: Ar + KCl 1.76 A GeV
G. Agakishiev et al., arXiv:1512.07070



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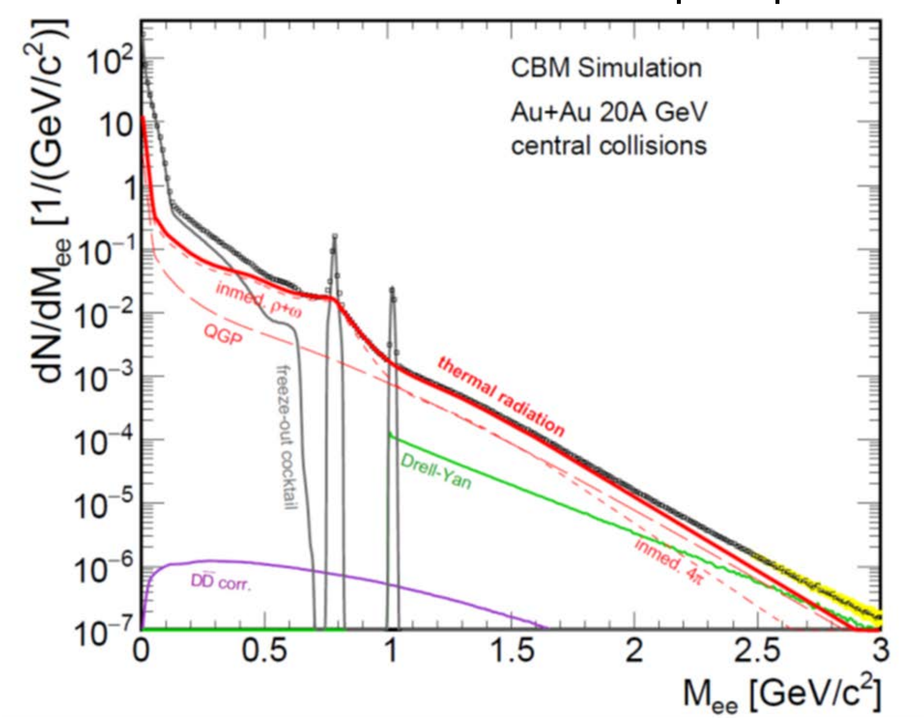
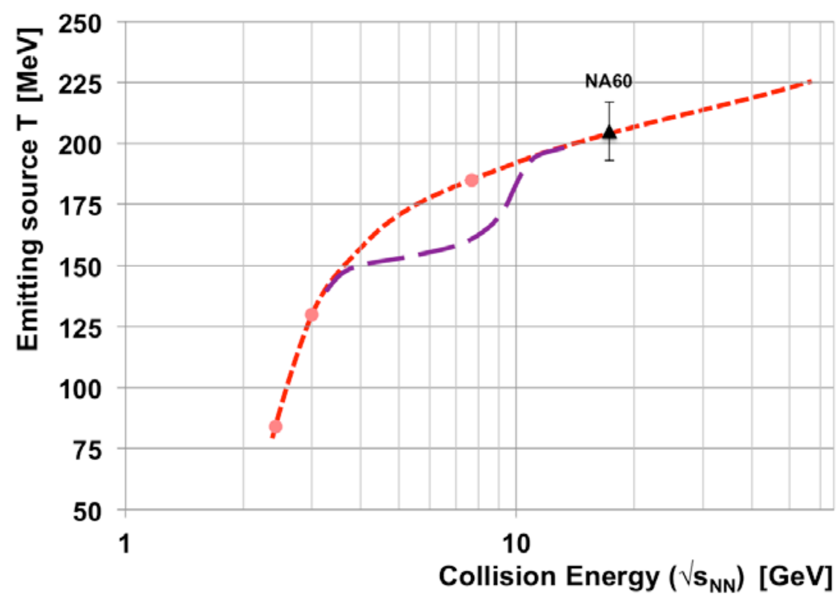
Phase coexistence

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

Invariant mass distribution of lepton pairs



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



The CBM Collaboration, arXiv:1607.01487

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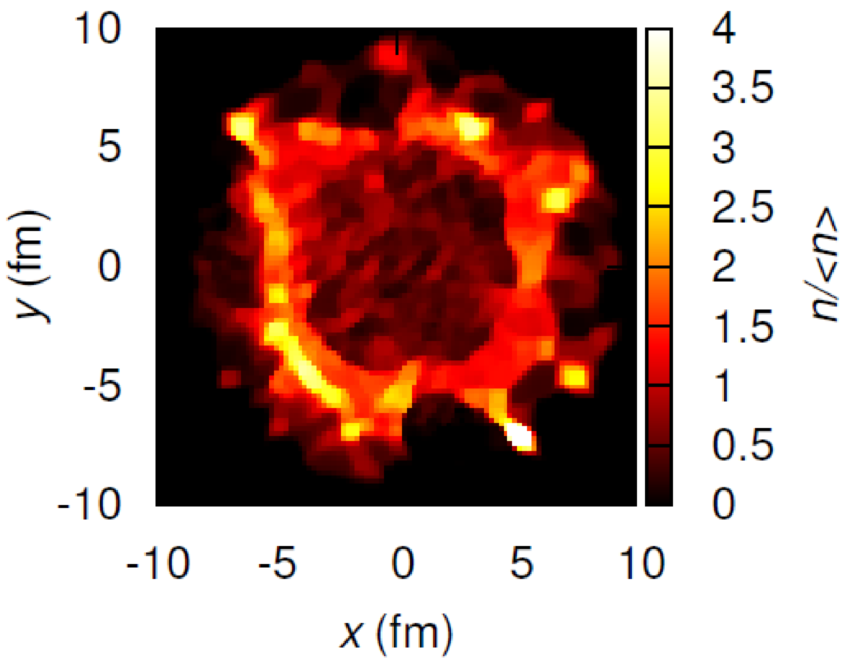
Phase coexistence

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

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



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

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

CBM physics case and observables

Phase transitions from partonic to hadronic matter

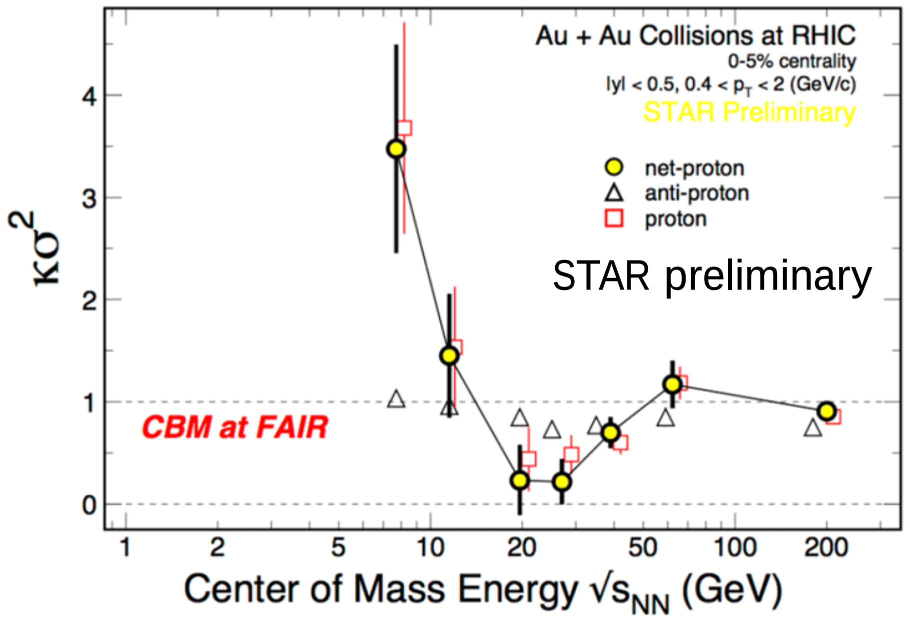
- excitation function of strangeness: $\Xi^-(dss)$,$\Xi^+(\bar{d}\bar{s}\bar{s})$,$\Omega^-(sss)$,$\Omega^+(\bar{s}\bar{s}\bar{s})$
  → chemical equilibration at the phase boundary

Phase coexistence

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

Critical point

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

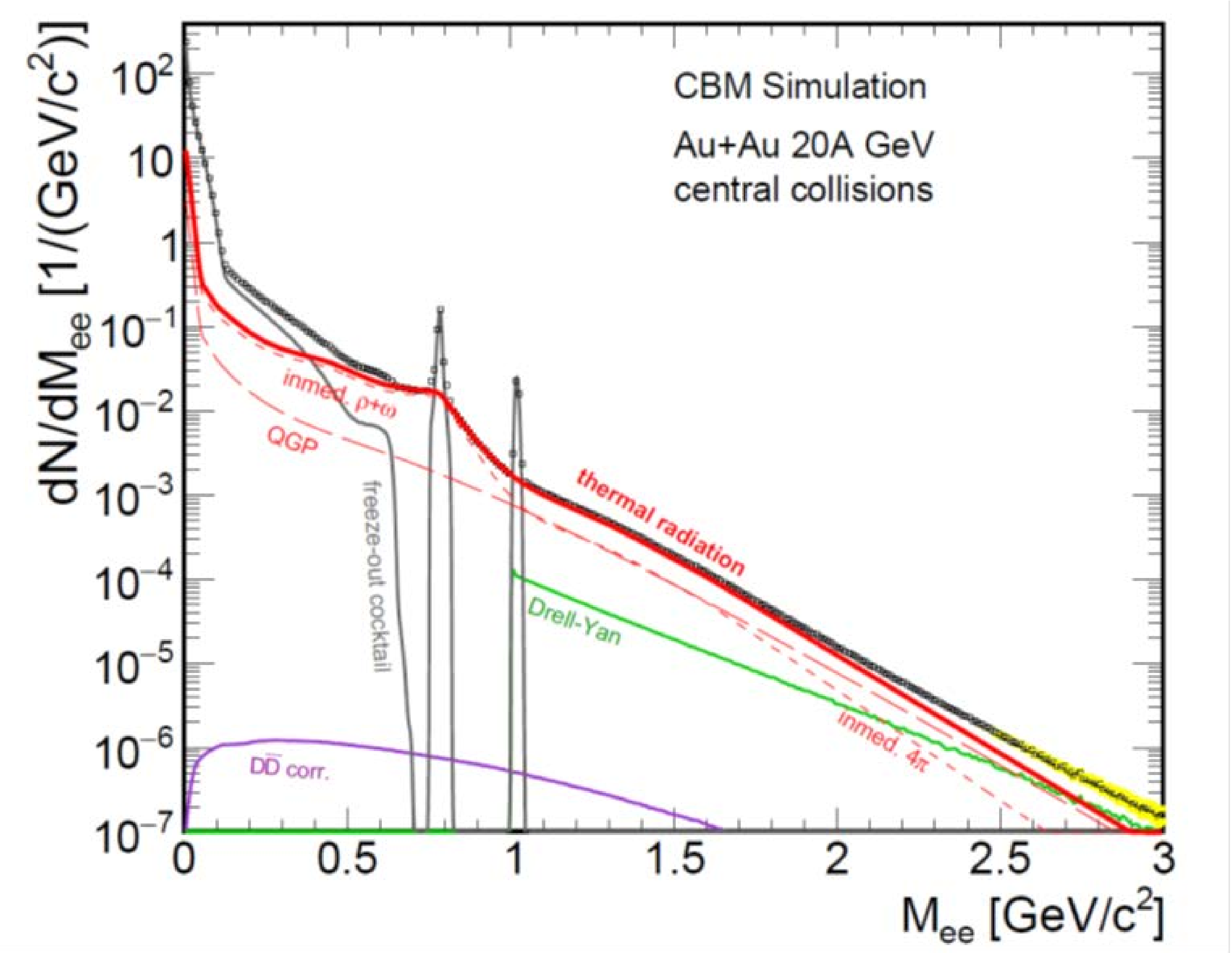


4^{th} moment of net-proton multiplicity distribution: critical fluctuations

CBM physics case and observables

Onset of chiral symmetry restoration at high ρ_B

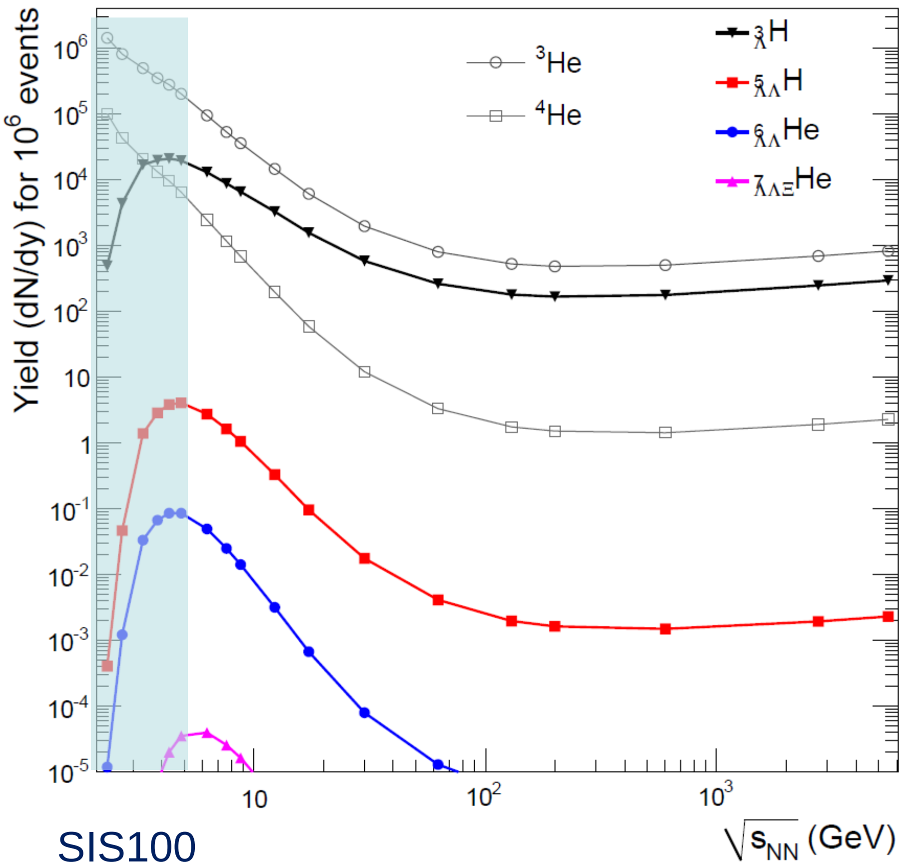
- in-medium modifications of hadrons: $\rho,\omega,\phi \rightarrow e^+e^-(\mu^+\mu^-)$
- dileptons at intermediate invariant masses: $4\pi \rightarrow \rho\text{-}a_1$ chiral mixing



CBM physics case and observables

N-Λ, Λ-Λ interaction, strange matter?

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



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

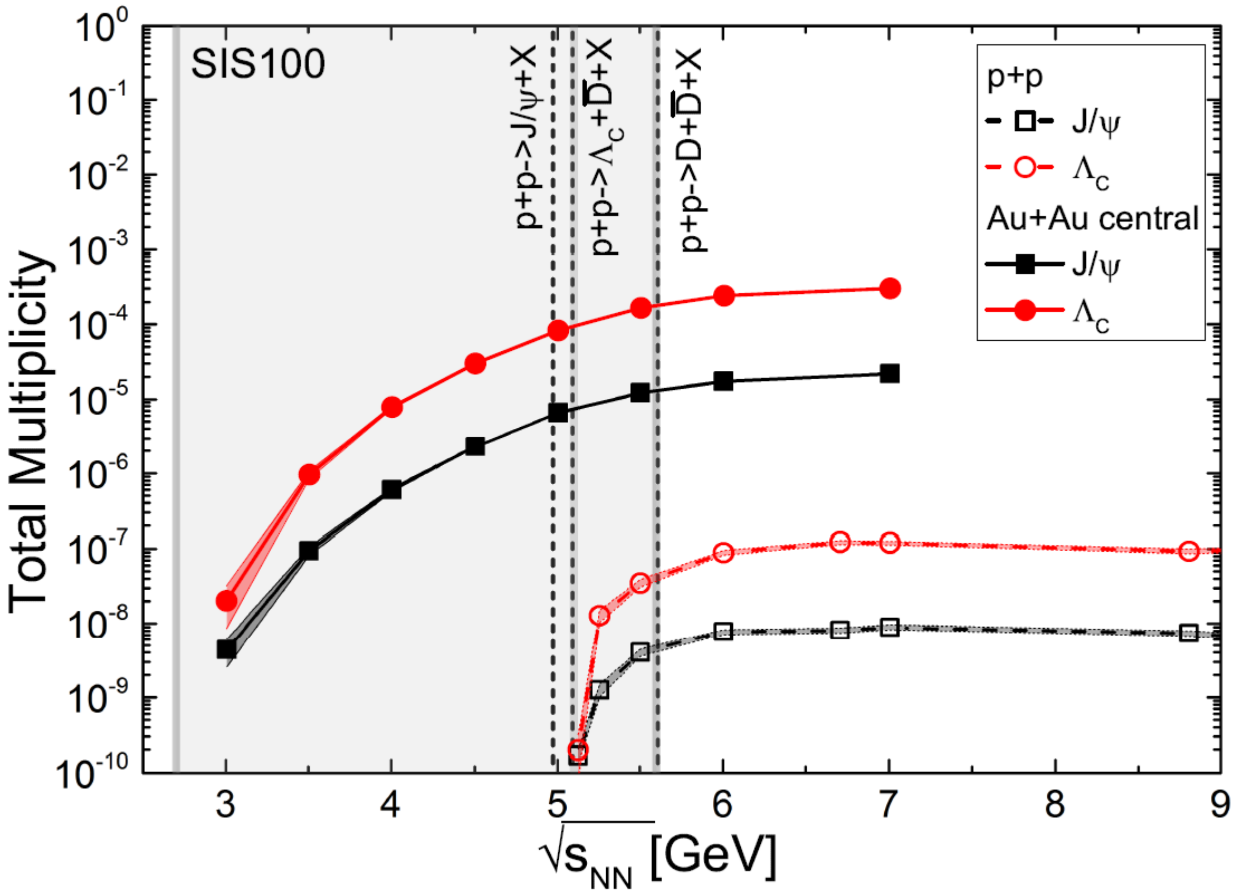
Assumption for yield calculation:
Reaction Rate 1 MHz
BR 10% (2 sequential weak decays)
Efficiency 1%

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, $D^{\pm}$)

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

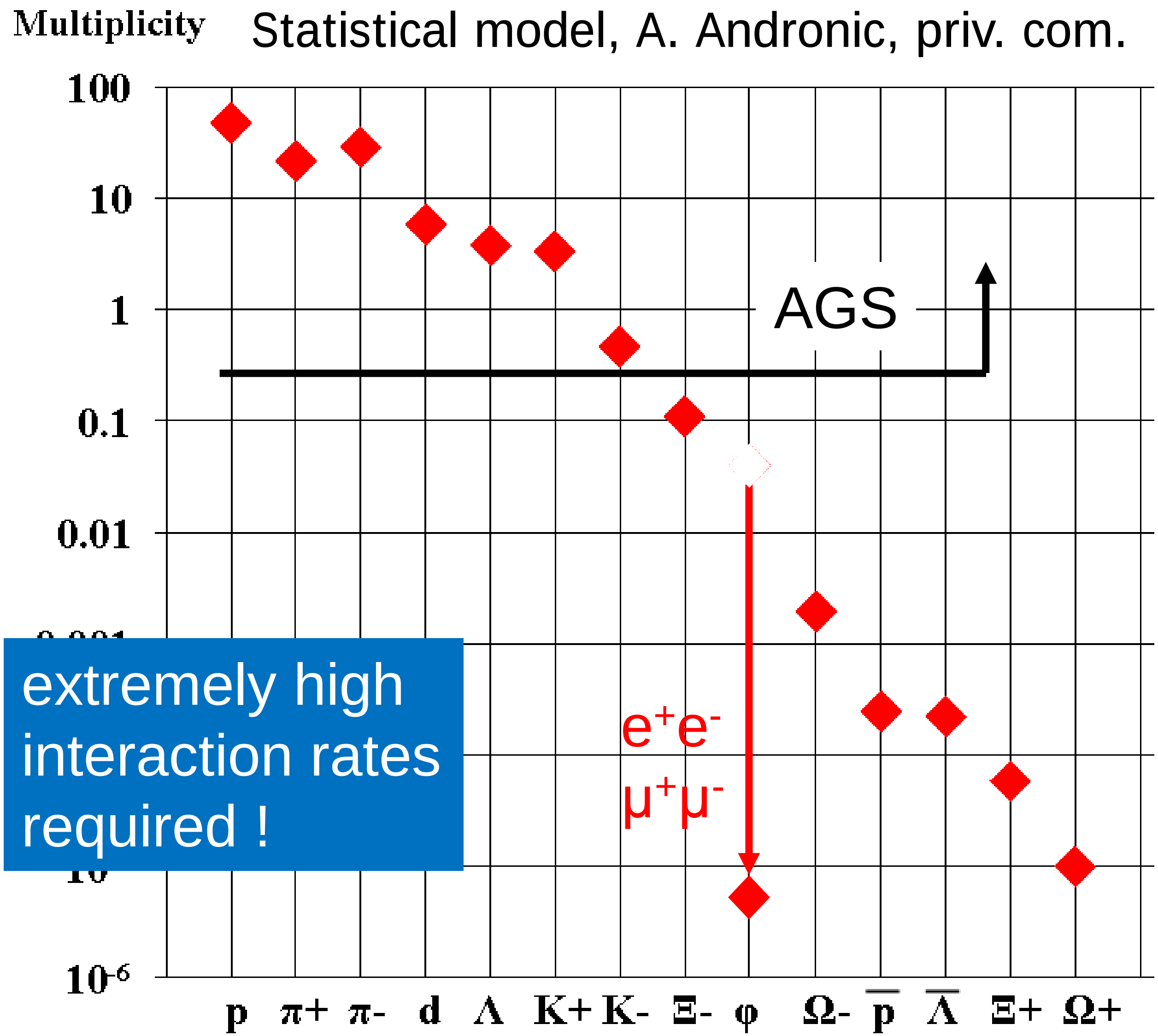


J. Steinheimer, A. Botvina, M. Bleicher, Phys. Rev. C 95, 014911 (2017), arXiv:1605.03439v1

Experimental challenges

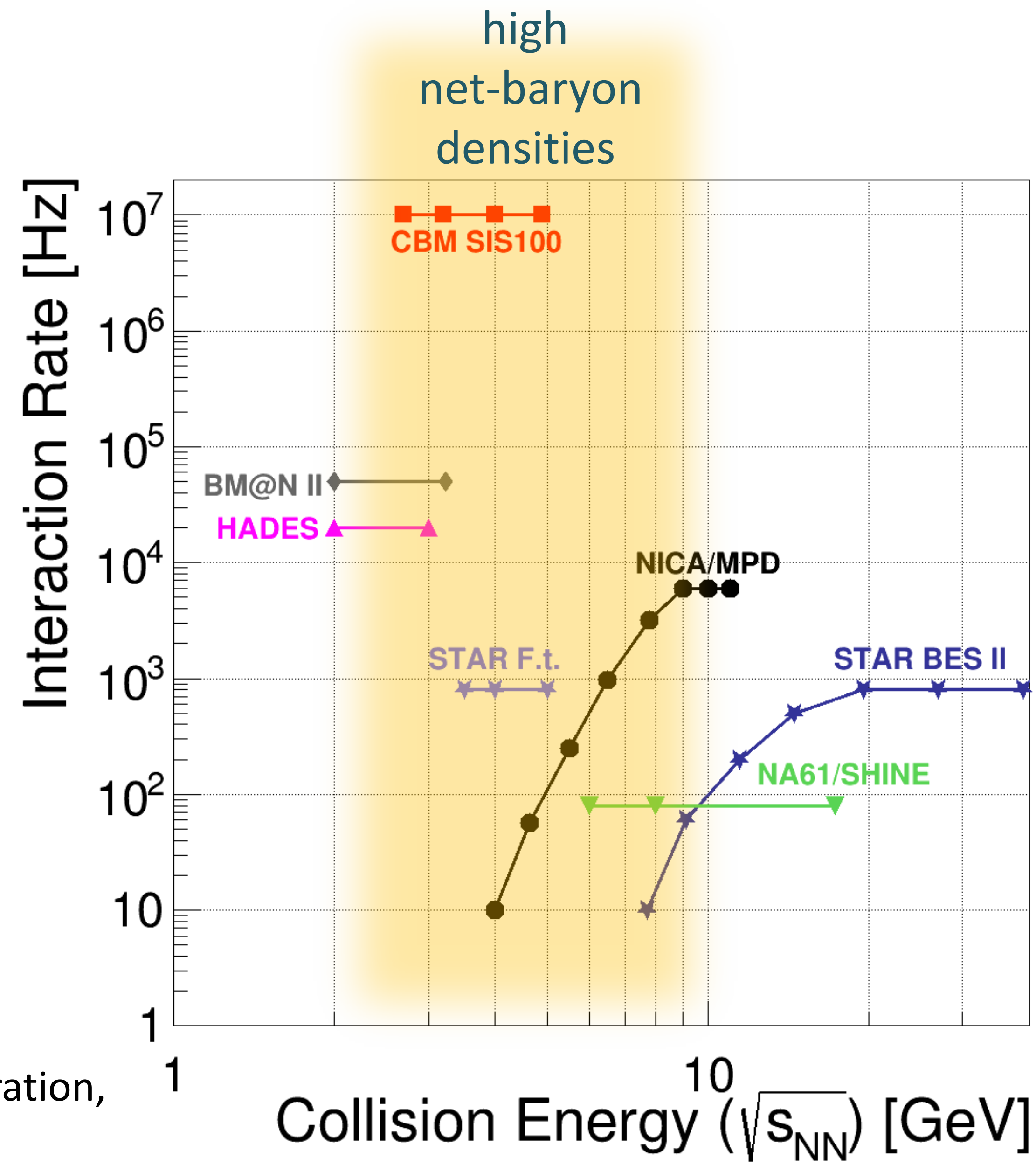
Particle yields in central Au+Au 4 A GeV

Statistical model, A. Andronic, priv. com.



extremely high interaction rates required !

Experiments exploring dense QCD matter



The CBM Collaboration,
arXiv:1607.01487

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

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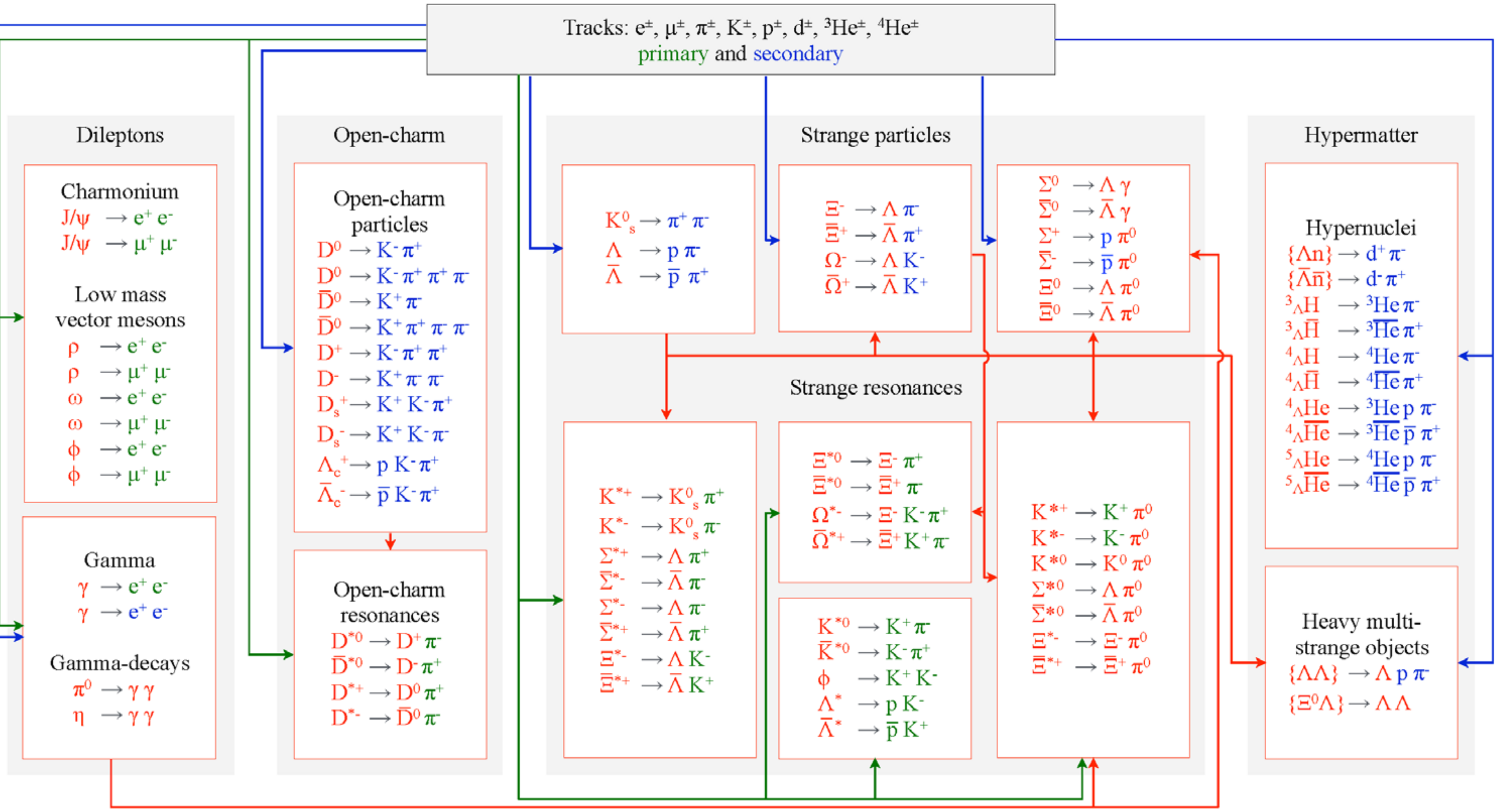
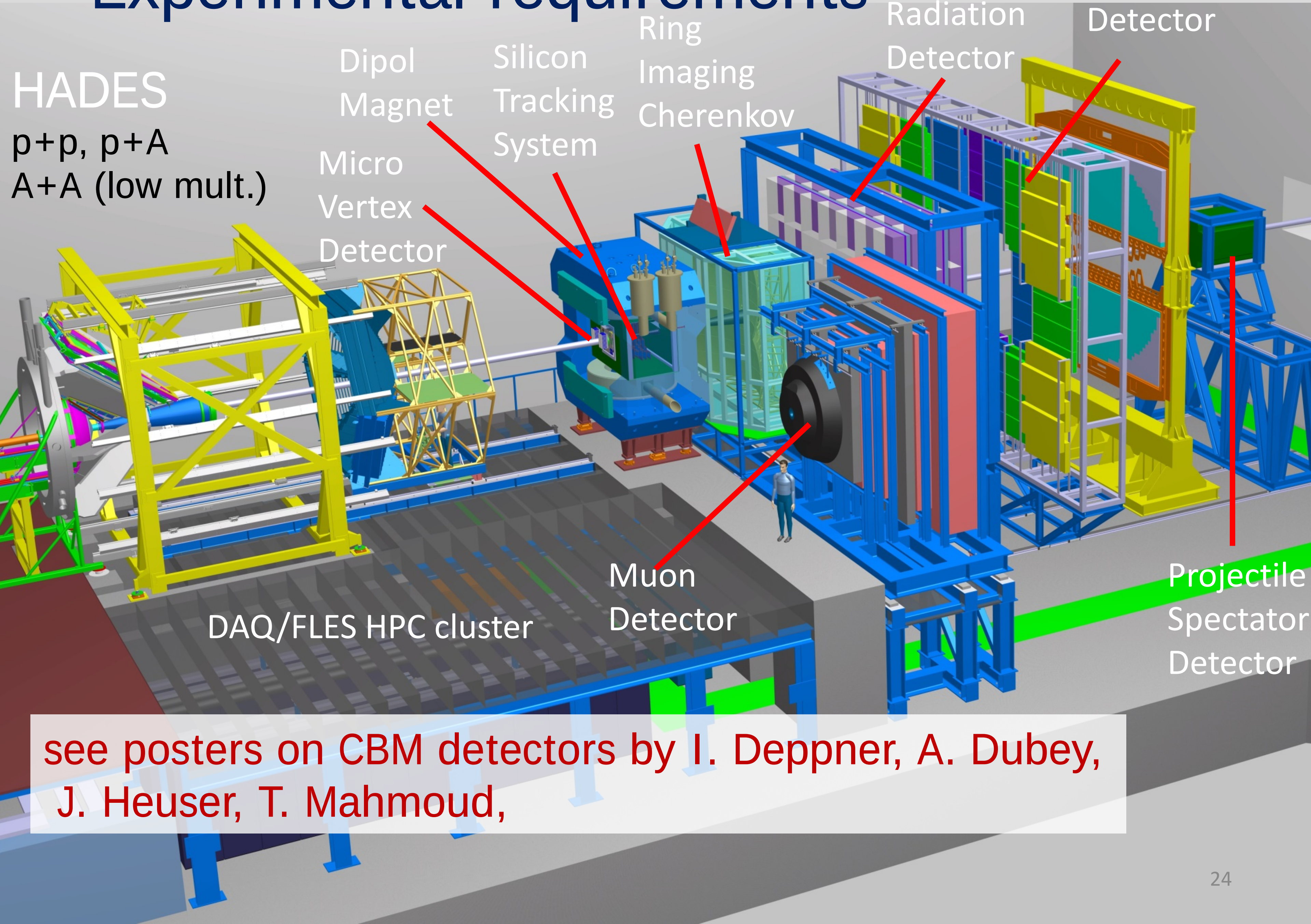
Online particle identification in CBM: The KF Particle Finder



see poster by M. Zyzak

Experimental requirements



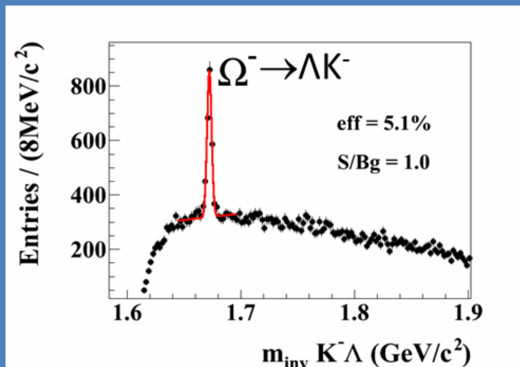
see posters on CBM detectors by I. Deppner, A. Dubey, J. Heuser, T. Mahmoud,

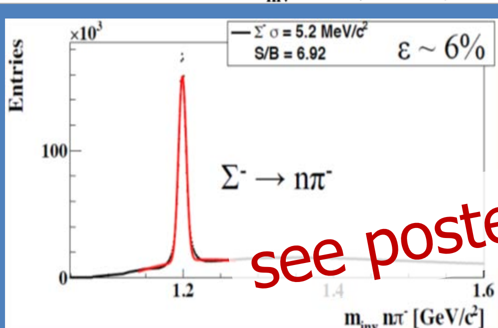
Test beam at CERN Nov. - Dec. 2016

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

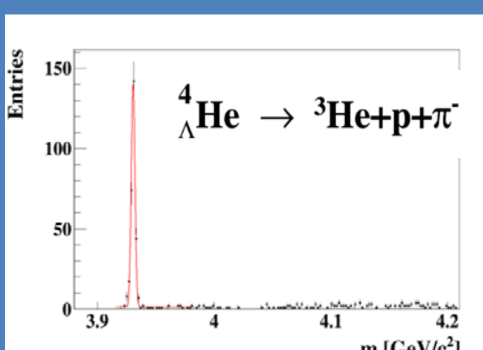
Simulations: central Au+Au collisions at 8A GeV and 10A GeV

Hyperons at 10 A GeV

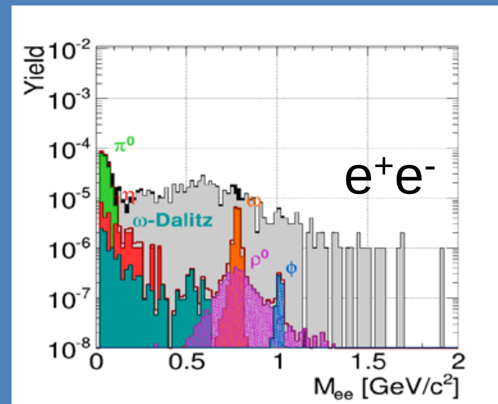


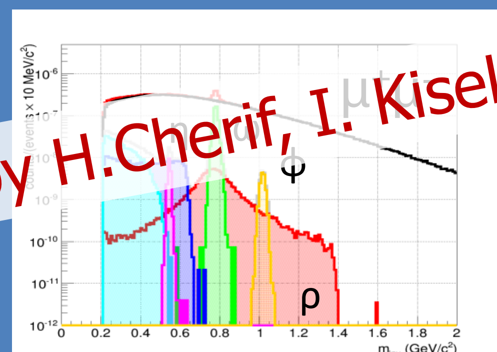


Hypernuclei at 10 A GeV

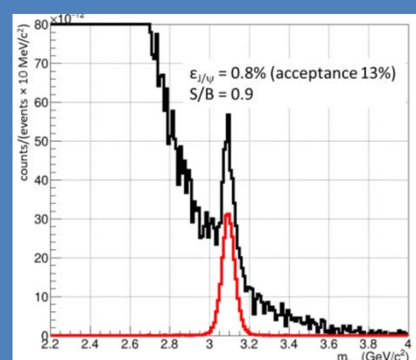


Dileptons 8A GeV

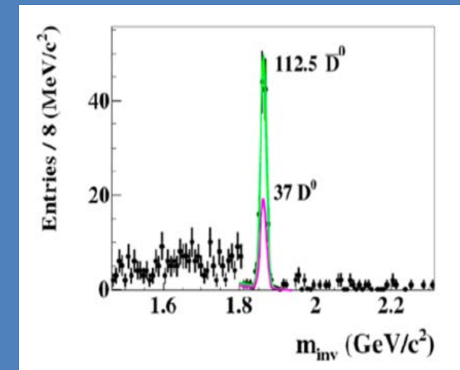


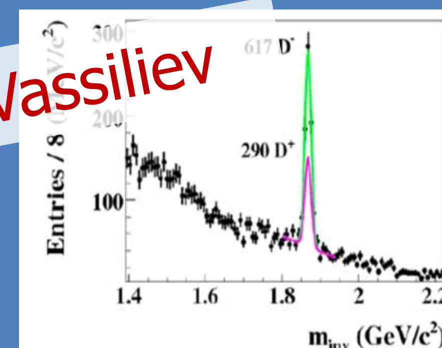


Charmonium at 10 A GeV

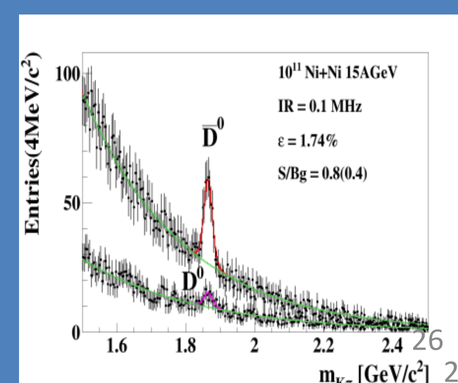


D mesons 30 GeV p+Au





D mesons Ni+Ni 15A GeV



see posters by H.Cherif, I. Kisel, I. Vassiliev

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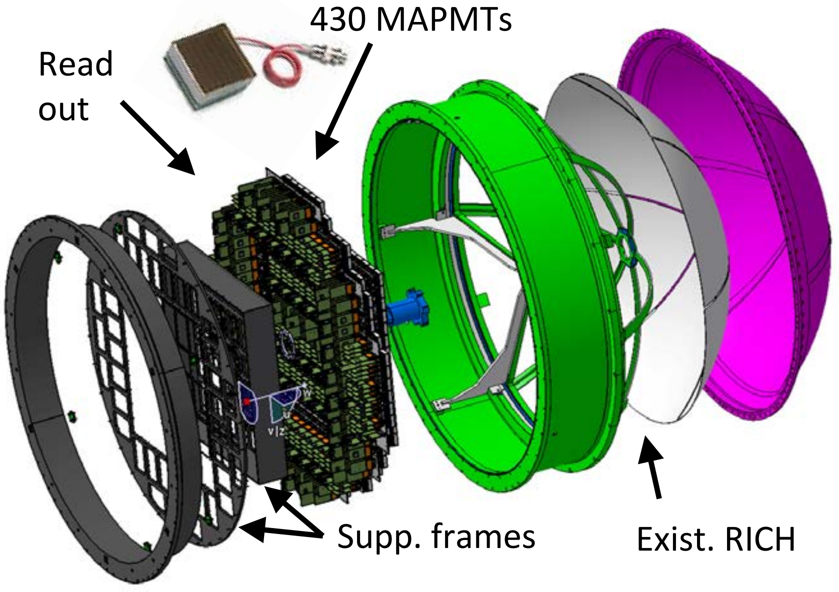
CBM Phase 0 experiments

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



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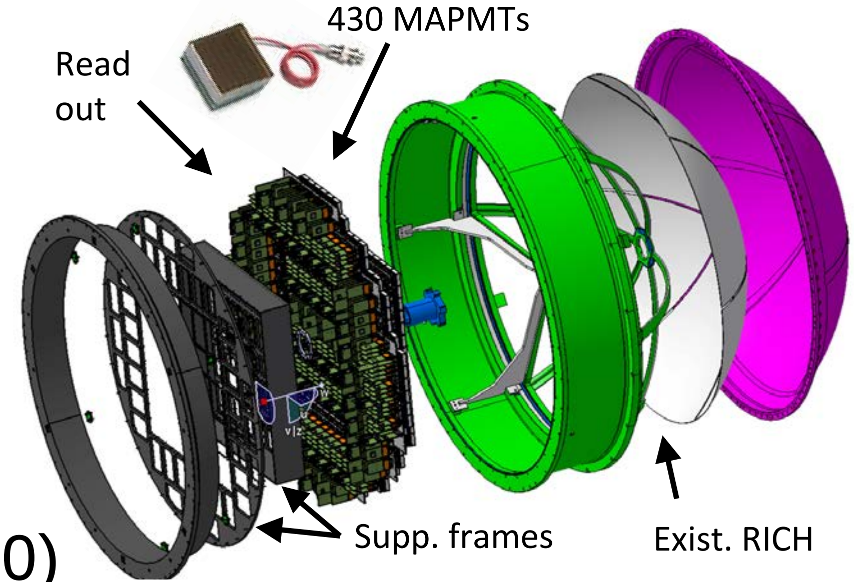
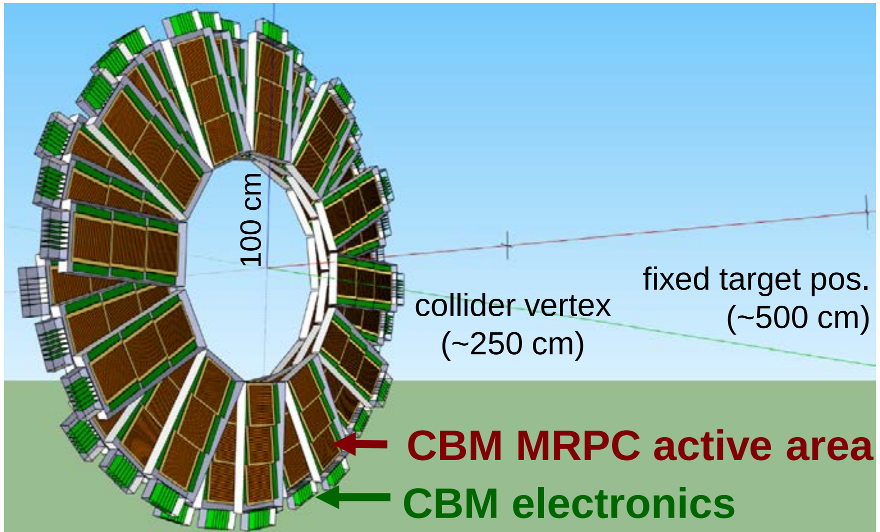
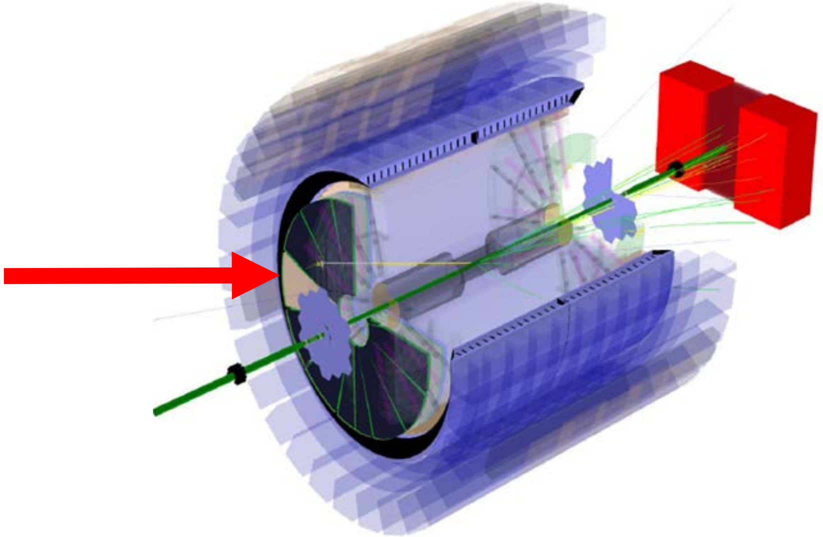


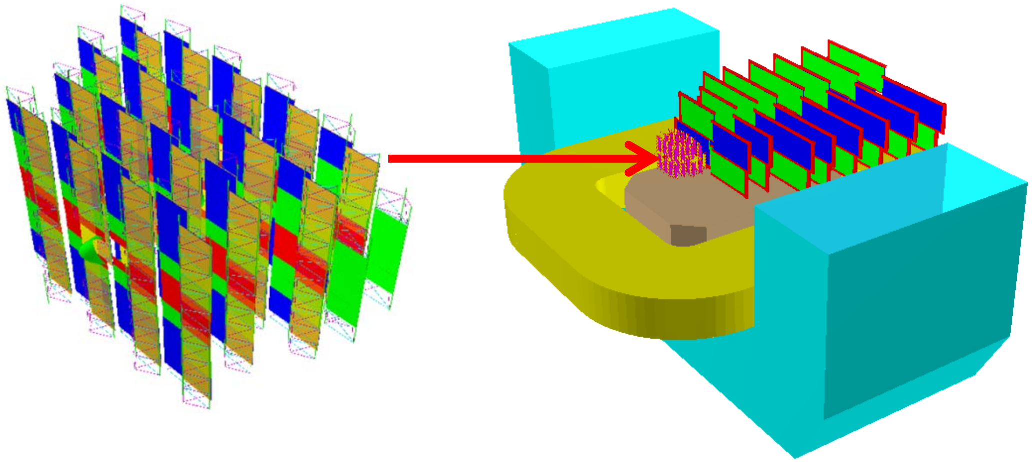
2. Install, commission and use 10% of the CBM TOF modules including read-out chain at STAR/RHIC (BES II 2019/2020)

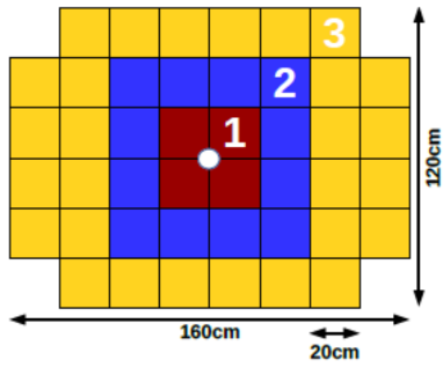




CBM Phase 0 experiments

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)





CBM Phase 0 experiments

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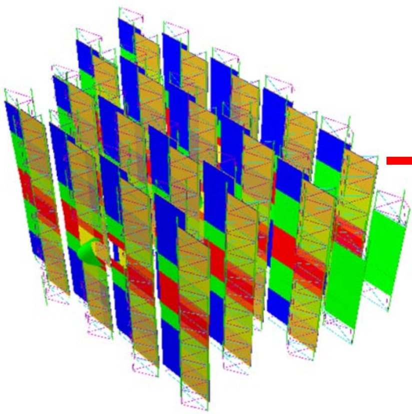
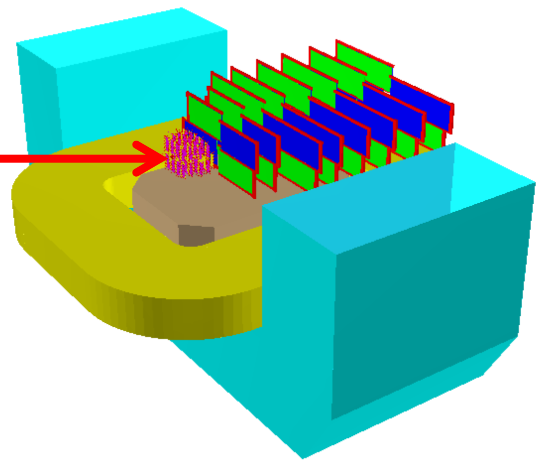
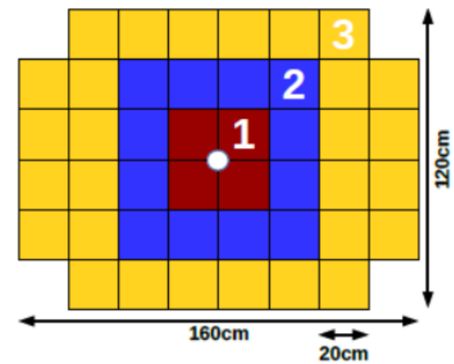
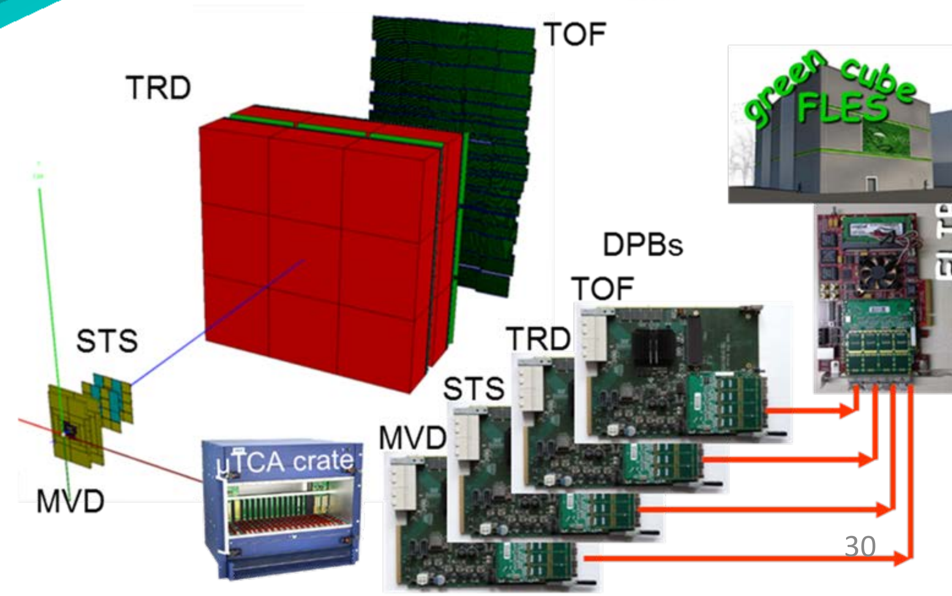






4. Build miniCBM at GSI/SIS18 for a full system test with high-rate nucleus-nucleus collisions from 2018 - 2021



The CBM Collaboration: 55 institutions, 460 members

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei
CTGU Yichang

Czech Republic:
CAS, Rez
Techn. Univ. Prague

France:
IPHC Strasbourg

Hungary:
KFKI Budapest
Eötvös Univ.

Germany:
Darmstadt TU
FAIR
Frankfurt Univ. IKF
Frankfurt Univ. FIAS
Frankfurt Univ. ICS
GSI Darmstadt
Giessen Univ.
Heidelberg Univ. P.I.
Heidelberg Univ. ZITI
HZ Dresden-Rossendorf
KIT Karlsruhe
Münster Univ.
Tübingen Univ.
Wuppertal Univ.
ZIB Berlin

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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.

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Jag. Univ. Krakow
Warsaw Univ.
Warsaw TU

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SINP MSU, Moscow

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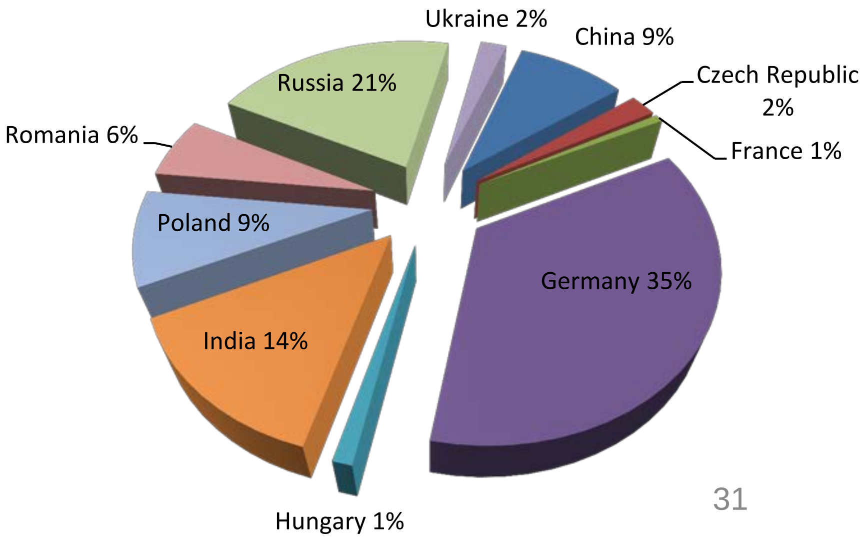
Kiev Inst. Nucl. Research

28th CBM Collaboration meeting in Tübingen
26-30 September 2016

CBM Scientists



Summary

- Status FAIR: Procurement of accelerator components ongoing. Civil construction starts mid 2017. FAIR Phase 1 full operational in 2025. Installation/commissioning of experiments planned during 2021-2024.
- CBM scientific program at SIS100: Exploration of the QCD phase diagram in the region of neutron star core densities
- $\rightarrow$ 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.
- Status of experiment preparation: Prototype detectors fulfill CBM requirements. 7 out of 11 TDRs approved.
- FAIR Phase 0:
  HADES experiments with CBM RICH photon detector,
  use CBM detectors at STAR/BNL and BM@N/JINR

Particle yields based on HSD calculations

10% most central Au+Au collisions at 6 and 10 A GeV

Particle (mass MeV/c^2)	Multi-plicity 6 A GeV	Multi-plicity 10 A GeV	decay mode	BR	ε (%)	yield (s^{-1}) 6 A GeV	yield (s^{-1}) 10 A GeV	yield in 10 weeks 6 A GeV	yield in 10 weeks 10 A GeV	IR MHz
K^+ (494)	12.5	20	-	-	31	$3.9\cdot10^{5}$	$6.2\cdot10^{5}$	$2.4\cdot10^{12}$	$3.7\cdot10^{12}$	1
K^- (494)	1.4	3	-	-	27	$3.8\cdot10^{4}$	$8.1\cdot10^{4}$	$2.3\cdot10^{11}$	$4.8\cdot10^{11}$	1
ρ (770)	5	9	L^+L^-	$4.7\cdot10^{-5}$	4.6	1.1	2.0	$6.5\cdot10^{6}$	$1.2\cdot10^{7}$	1
ω (782)	3.3	6	L^+L^-	$7.1\cdot10^{-5}$	5.2	1.2	2.2	$7.4\cdot10^{6}$	$1.3\cdot10^{7}$	1
φ (1020)	0.07	0.12	L^+L^-	$3\cdot10^{-4}$	6.0	$1.3\cdot10^{-1}$	$2.2\cdot10^{-1}$	$7.6\cdot10^{5}$	$1.3\cdot10^{6}$	1
Λ (1115)	10.4	17.4	$p\pi^-$	0.64	18	$1.2\cdot10^{5}$	$2.0\cdot10^{5}$	$7.2\cdot10^{11}$	$1.2\cdot10^{12}$	1
$\bar{\Lambda}$ (1115)	$4.6\cdot10^{-4}$	0.034	$\bar{p}\pi^+$	0.64	11	1.1	81.3	$6.6\cdot10^{6}$	$2.2\cdot10^{8}$	10
Ξ^- (1321)	0.054	0.222	$\Lambda\pi^-$	1	6	$3.2\cdot10^{3}$	$1.3\cdot10^{4}$	$1.9\cdot10^{10}$	$7.8\cdot10^{10}$	10
Ξ^+ (1321)	$3.0\cdot10^{-5}$	$5.4\cdot10^{-4}$	$\Lambda\pi^+$	1	3.3	$9.9\cdot10^{-1}$	17.8	$5.9\cdot10^{6}$	$1.1\cdot10^{8}$	10
Ω^- (1672)	$5.8\cdot10^{-4}$	$5.6\cdot10^{-3}$	ΛK^-	0.68	5	17	164	$1.0\cdot10^{8}$	$9.6\cdot10^{8}$	10
Ω^+ (1672)	-	$7\cdot10^{-5}$	ΛK^+	0.68	3	-	0.86	-	$5.2\cdot10^{6}$	10
J/ψ (3097)	-	$1.74\cdot10^{-7}$	L^+L^-	0.06	5	-	$5.2\cdot10^{-4}$	-	3100	10
$^{3}_{\Lambda}H$ (2993)	$4.2\cdot10^{-2}$	$3.8\cdot10^{-2}$	$^{3}He\pi^-$	0.25	19.2	$2\cdot10^{3}$	$1.8\cdot10^{3}$	$1.2\cdot10^{10}$	$1.1\cdot10^{10}$	10
$^{4}_{\Lambda}He$ (3930)	$2.4\cdot10^{-3}$	$1.9\cdot10^{-3}$	$^{3}Hep\pi^-$	0.32	14.7	110	87	$6.6\cdot10^{8}$	$5.2\cdot10^{8}$	10

p + A collisions at 20 and 30 GeV

Particle (mass MeV/c^2)	Multi-plicity 20 GeV	Multi-plicity 30 GeV	decay mode	BR	ε (%)	yield (s^{-1}) 20 GeV	yield (s^{-1}) 30 GeV	yield in 10 weeks 20 GeV	yield in 10 weeks 30 GeV	IR MHz
$D^{\pm}$ (1869)	$3.4\cdot10^{-7}$	$1.3\cdot10^{-6}$	$K^+\pi^-\pi^-$	0.09	13	$4.0\cdot10^{-2}$	$1.5\cdot10^{-1}$	$2.4\cdot10^{5}$	$9.2\cdot10^{5}$	10
D^0 (1865)	$5.1\cdot10^{-7}$	$2.0\cdot10^{-6}$	$K^+\pi^-\pi^-\pi^+$	0.08	2	$8.2\cdot10^{-3}$	$3.2\cdot10^{-2}$	$4.9\cdot10^{4}$	$1.9\cdot10^{5}$	10
J/ψ (3097)	$7.5\cdot10^{-8}$	$2.9\cdot10^{-6}$	L^+L^-	0.06	5	$2.3\cdot10^{-3}$	$8.7\cdot10^{-2}$	$1.4\cdot10^{4}$	$5.2\cdot10^{5}$	10