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The Compressed Baryonic Matter experiment at FAIR

Experimental program and status

Christian Pauly, BU Wuppertal
for the CBM collaboration

FAIR –
Facility for Antiproton and Ion Research

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Research communities from more than 50 countries

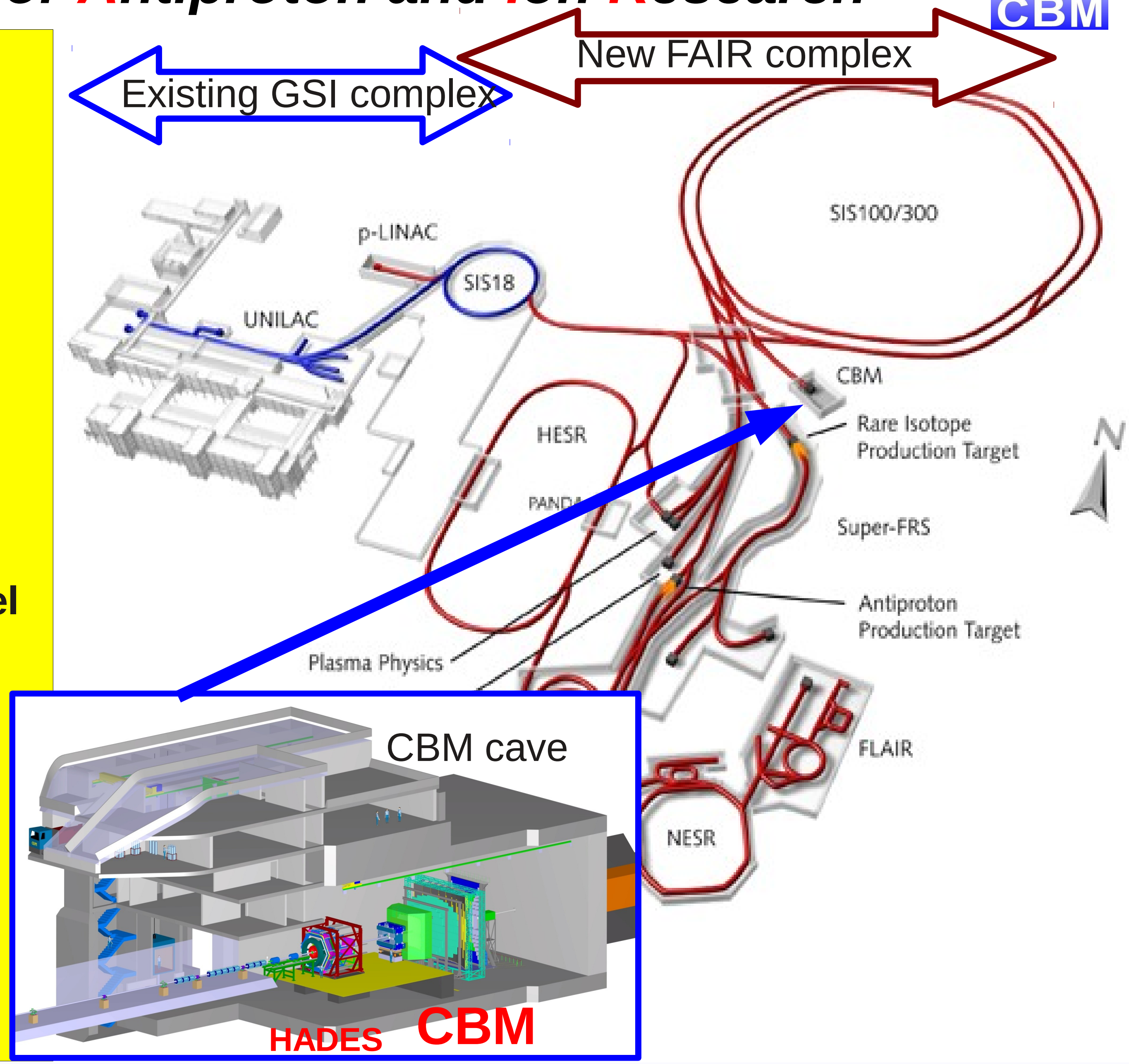
covering **many different aspects of physics:**

- Hadron spectroscopy with anti-protons (PANDA)
- Rare Isotope beams
- Plasma Physics
- **Heavy-Ion Physics with the CBM experiment and HADES**

Using beams from two parallel synchrotrons:

SIS100: (starting 2018)
2-29 GeV (protons)
2-11 A GeV (Au)

SIS300: (few years later)
2-89 GeV (protons)
2-35 A GeV (Au)



Exploring the QCD phase diagram in region of high net baryon density

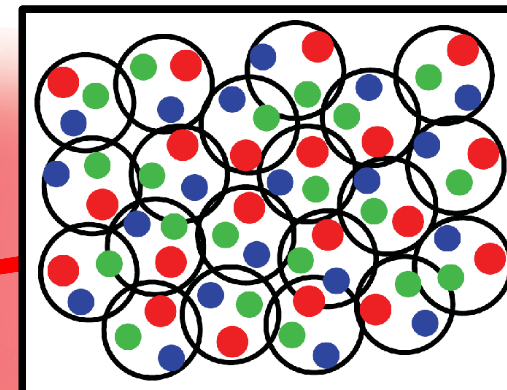
Probing the QCD diagram at very high T and $\rho_B \approx 0$ (early universe):

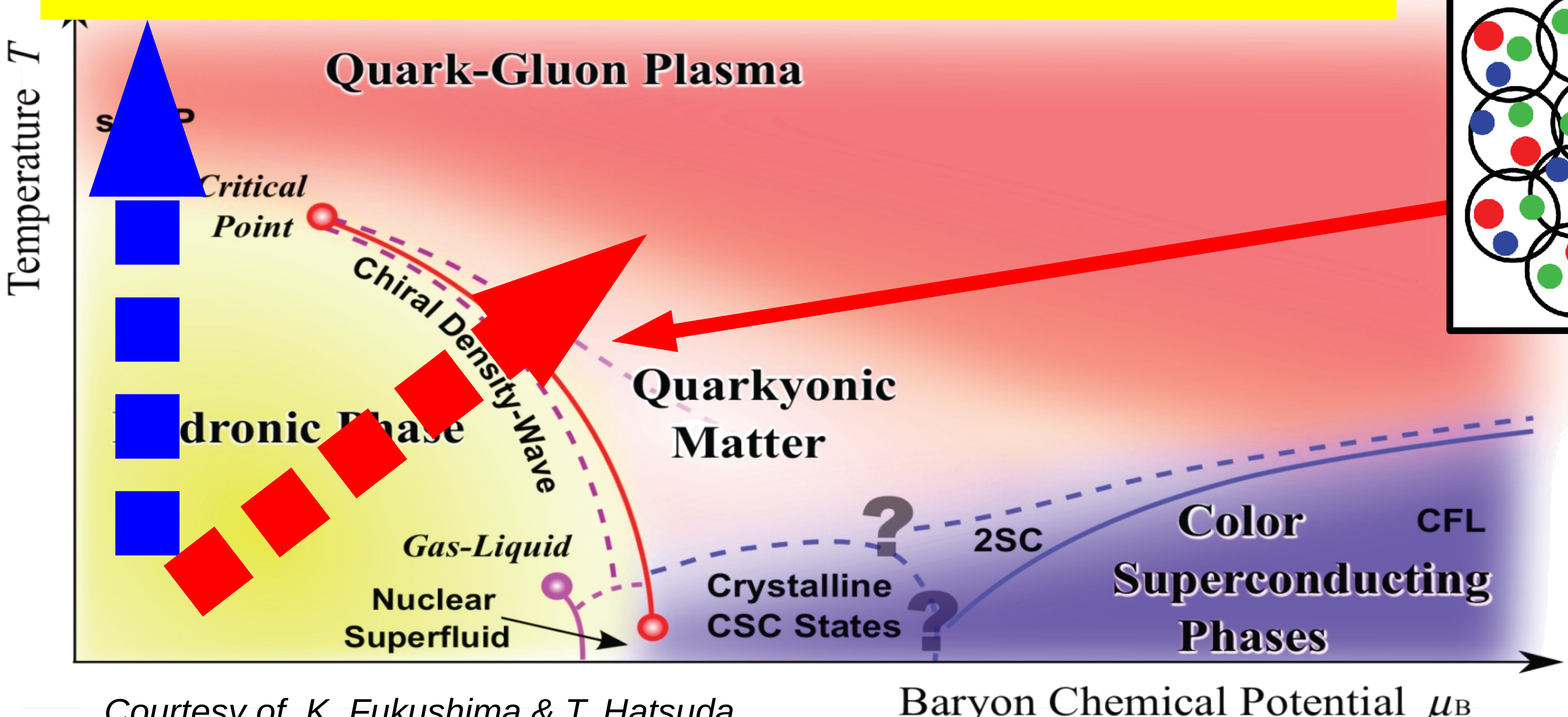
ALICE, ATLAS, CMS at LHC
STAR, PHENIX at top RHIC energies,

Probing the QCD phase diagram at moderate T and (very) high ρ_B:

Beam energy scan at RHIC, NA61 at CERN SPS
(but limited statistics, observables)
CBM at FAIR, MPD at NICA

density $\rho \geq 6x\ \rho_0$
ρ_0 nucl.matter density



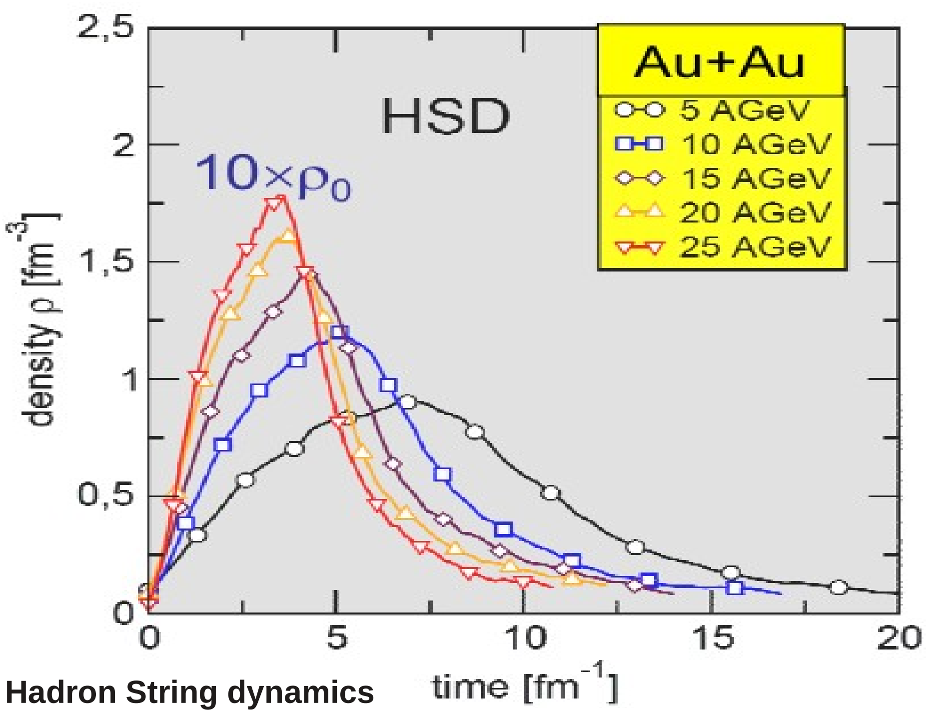


Courtesy of K. Fukushima & T. Hatsuda

How to produce dense matter in the lab ?

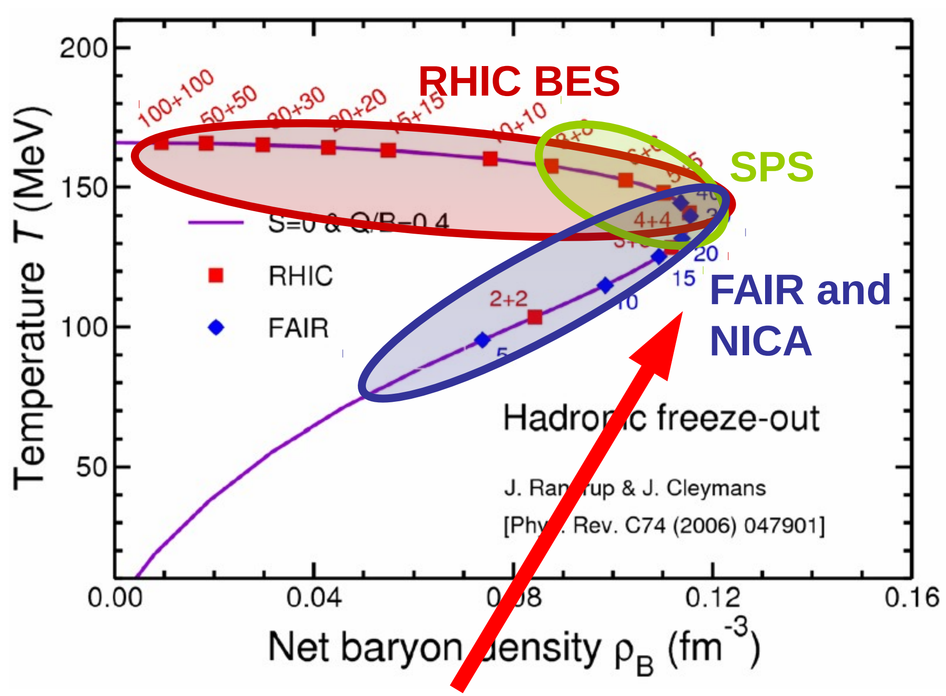
At FAIR / CBM: **Au+Au** collisions at **medium energies**, fixed target
SIS 100: Ekin 2.0 – 11 AGeV, $\sqrt{S_{NN}}$ = 2.7 – 4.7 GeV
SIS 300: Ekin 2.0 – 35 AGeV, $\sqrt{S_{NN}}$ = 2.7 – 8.3 GeV
contrary to "high T" physics at LHC: Pb+Pb collisions at highest energy

density as function of time according to transport calculations



Hadron String dynamics
W. Ehehalt, W. Cassing
Nucl. Phys. A 602(1996) 449

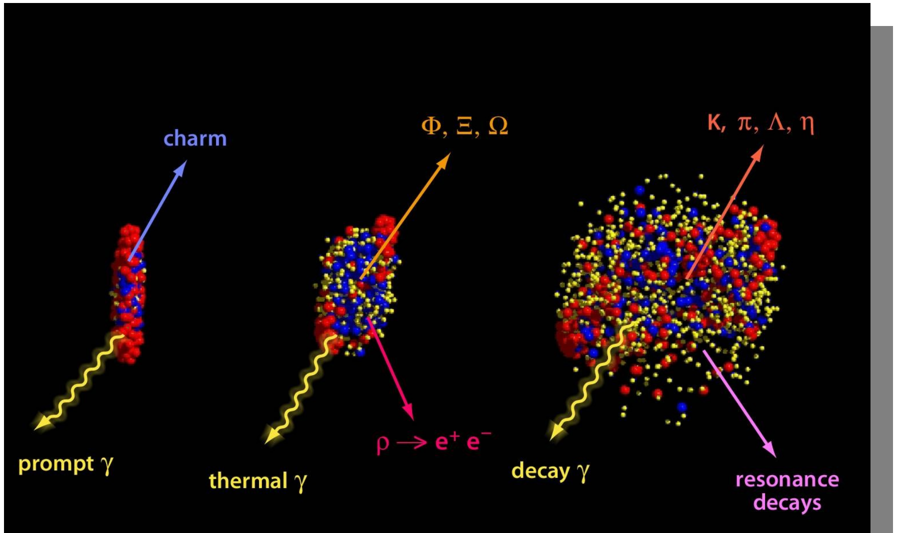
density and **temperature at freezeout** for different beam conditions



Maximum freezeout density reached at 30 AGeV, well within SIS300 range

How to probe dense matter ?

- need penetrating probes sensitive to the early, high-density phase of fire ball evolution !
- CBM: di-lepton decays of light vector mesons and charm
  - **light vector mesons**
    $\rho, \omega, \Phi \rightarrow e^+ e^- / \mu^+\mu^-$
  - **Charmonium**
    $J/\Psi, \Psi' \rightarrow e^+ e^- / \mu^+\mu^-$
  - **open charm**
    $D^{+-}, D^0 \rightarrow K + \pi$
    $K + \pi\ \pi$
    $K + \pi\ \pi\ \pi$
- measure **both di-electron and di-muon** channels
  - same physics, but different detection methods
  - good control over systematic errors
- **Rare probes !**
  → high luminosity
  → reaction rate up to 10MHz (J/Psi)
  → good particle ID (pion suppression better 10^{-4})

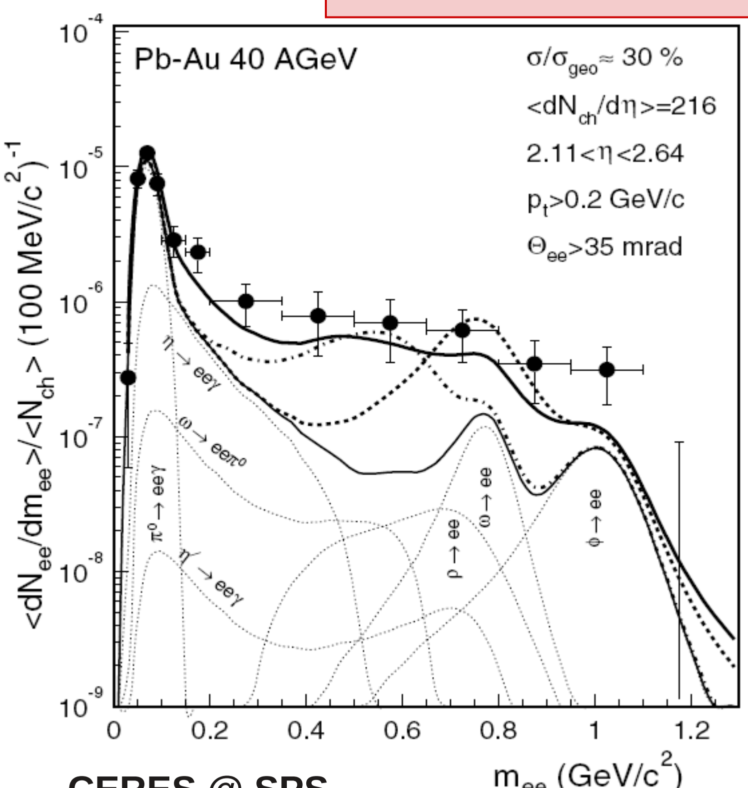


U – U collision at 23 AGeV, evolution in time

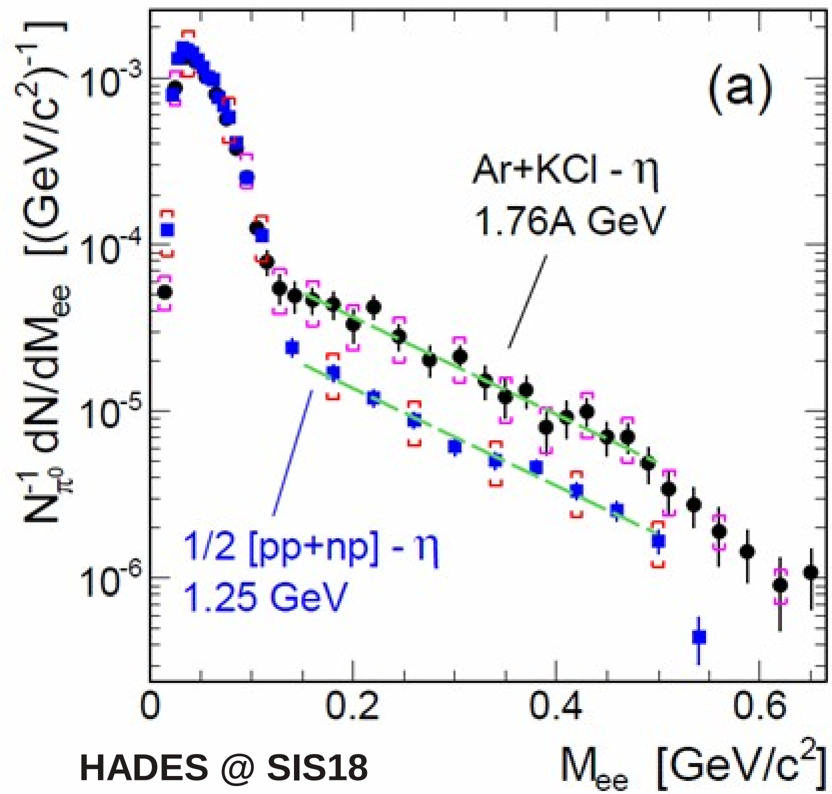
Dileptons as probe of high density phase

- CERES data at 40 AGeV and 158 AGeV: excess higher at lower energy
  → connection to baryon density
- HADES: excess in C+C can be understood from elementary processes
  (pn-> pnγ Bremsstrahlung, Δ decay, ...)
  but: additional excess in more dense system Ar+KCl (1.76 AGeV)
  in-medium effects ???

No data between 2 and 40 AGeV beam energy!



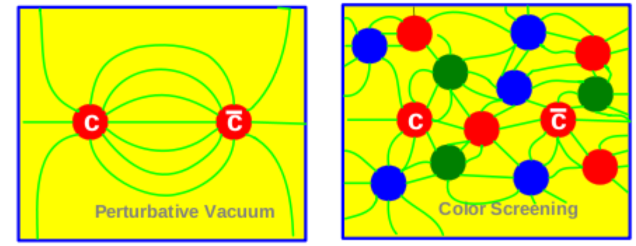
CERES @ SPS
Eur. Phys.J. C41, 475(2005)



HADES @ SIS18
G. Agakishiev et al., Phys. Rev. C 84 (2011) 014902

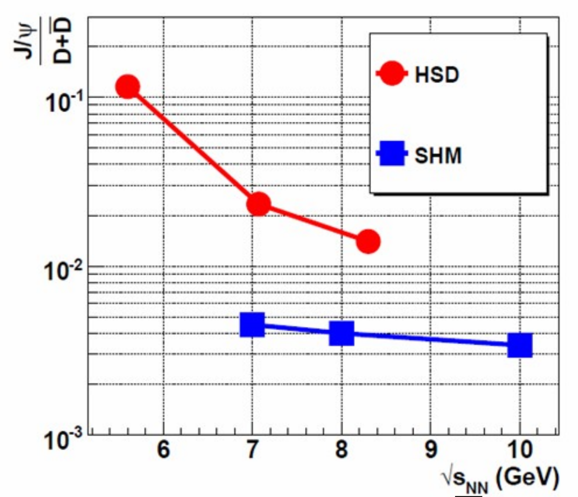
charmonium (J/Ψ, $c\bar{c}$) production

- J/Ψ produced in hard collisions at initial stage of collision
  - → probing dense medium on higher energy scale
- If the medium is partonic (and not hadronic):
  - → formation suppressed due to Debye screening
  - → increased formation of open charm (D mesons)
  - → ratio: charmonium / open charm
- **But:** J/Ψ can also be absorbed in cold nuclear matter !



Debye color screening

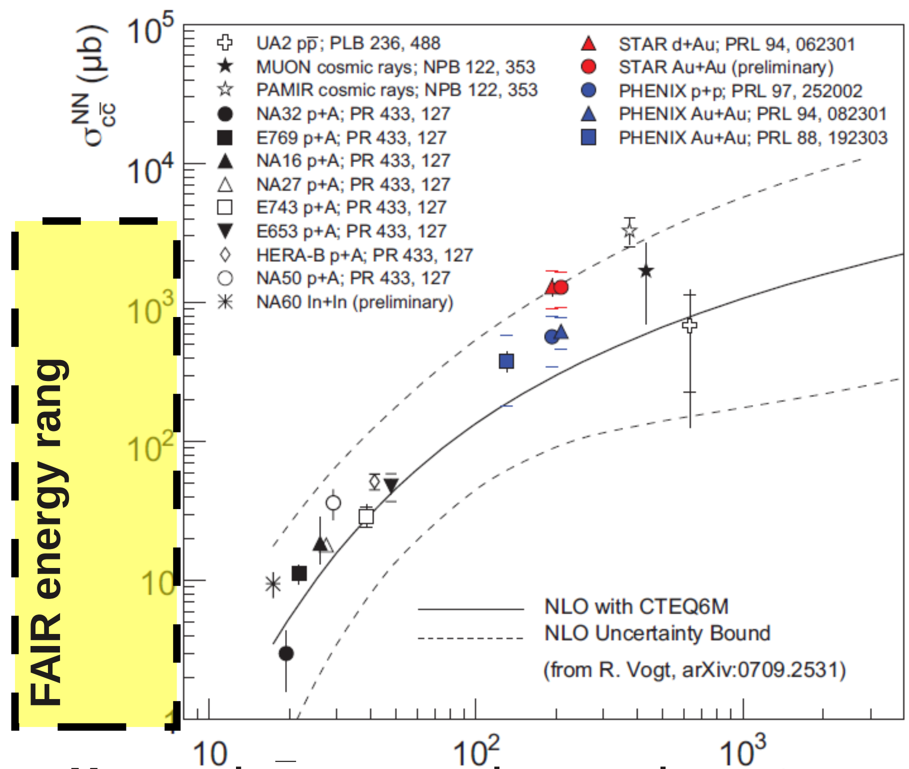
Need for **precise multi-differential data**, both **p-N** and **N-N** to disentangle absorption in nuclear matter from dissociation in partonic matter(QGP)



Predictions for J/Ψ over D,$\bar{D}$ ratio, two different models: quark like or (pre) hadron like medium

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

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



√s (GeV)

Measured $c\bar{c}$ cross section overview
no data at FAIR energy range

Multi strange hyperon production

- **direct production:**
  pp → $\Xi^- K^+K^+p$ E_{thr}=3.7 GeV
  pp → $\Omega^- K^+ K^+ K^0 p$ E_{thr}=7.0 GeV

- **Multistep, sub-threshold production** in nuclear collisions via strangeness exchange:

  pp → π $K^+ \Lambda$ E_{thr}=1.6 GeV
  pp → p p $K^+ K^-$ E_{thr}=2.5 GeV

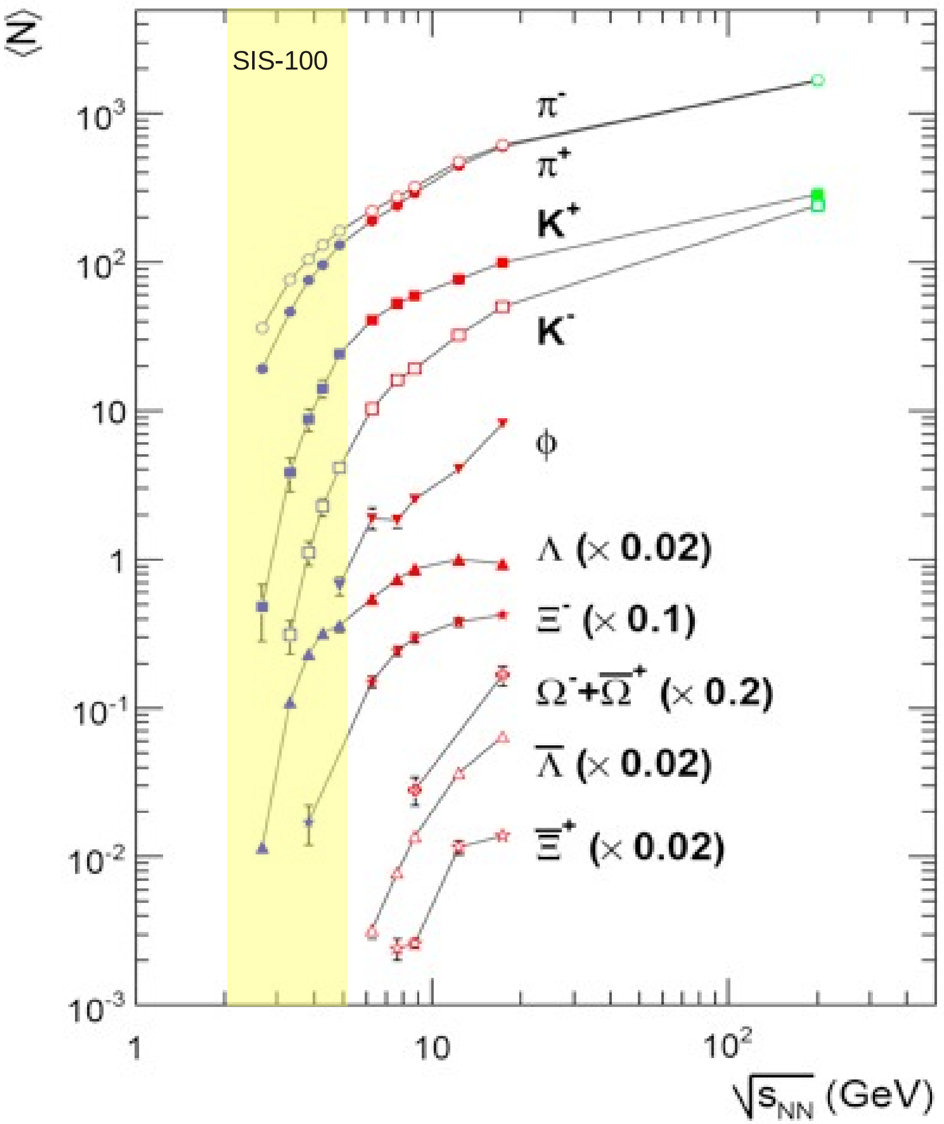
  followed by:
  $\Lambda\Lambda \rightarrow \Xi^- \pi$, $\Lambda\ \Xi^- \rightarrow \Omega^- n$ or
  $\Lambda K^- \rightarrow \Xi^- \pi^0$, $\Xi^- K^- \rightarrow \Omega^- \pi^-$

  or even **three-body collisions involving Λ and K**

- Production cross section depends on density
  → enhanced production in dense medium

- systematic study of Ξ^- and Ω^- production as function of beam energy and size of nuclei:
  → study the nuclear matter equation of state, EoS

C. Blume, J. Phys. G 31 (2005) S57



Available data in SIS100 range very scarce,
no data on Ω production below 40 AGeV

Ξ^- with HADES, Ar+KCl

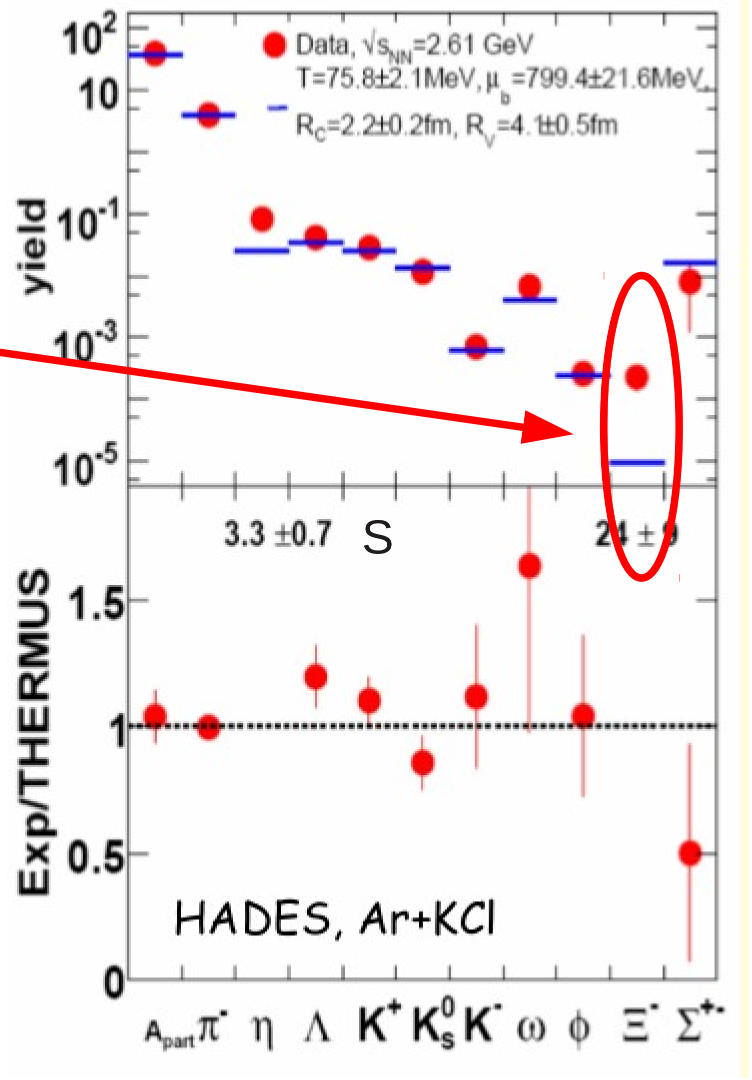
- Particle yields as measured with HADES
- **Ar+KCl, 1.76 A GeV**, $\sqrt{S_{NN}}$=2.61 GeV

- Comparison with thermal fit: THERMUS

- **Ξ^- yield off by factor 25 !!!**

- Can not be described by Statistical Hadronization Model, SHM

S. Wheaton and J. Cleymans, Comp. Phys. Comm. 180 (2009) 84



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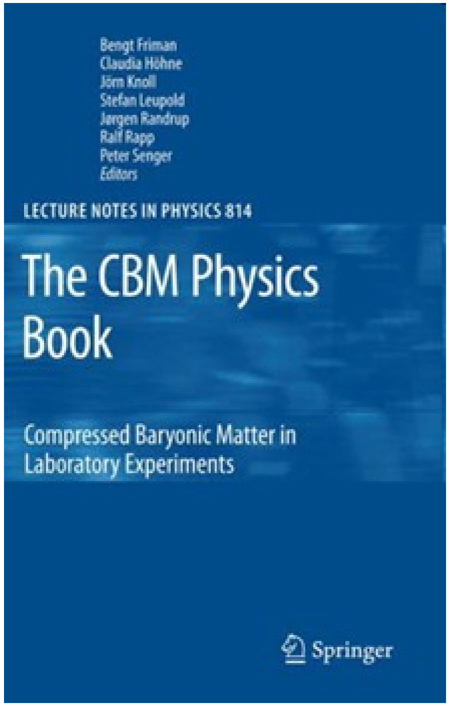
Summary: Observables to be studied with CBM

- **Particles containing charm quarks** (D mesons, charmonium: J/Psi)
  - Access to early, dense phase of collisions
- **Low-mass vector mesons** decaying into dilepton pairs (ρ,ω,φ)
  - Hadron properties within dense phase of fireball evolution
- Collective flow of identified hadrons
  - Obtain information on the equation-of-state, EoS of dense matter
- Kaons, **hyperons** and hadronic resonances
  - Strangeness is sensitive probe for fireball evolution
- Hyper-Nuclei, exotic particles
  - Strange dimension of chart of nuclei,
  - hyperon-nucleon and hyperon-hyperon interaction
- Dynamical fluctuations of particle multiplicities, momenta
  - Indication for first order phase transition, search for critical point
- Photons
  - Direct radiation from the early fireball
- Two-particle correlations, hadronic femtoscopy
  - Determine source size, space-time characteristics of source

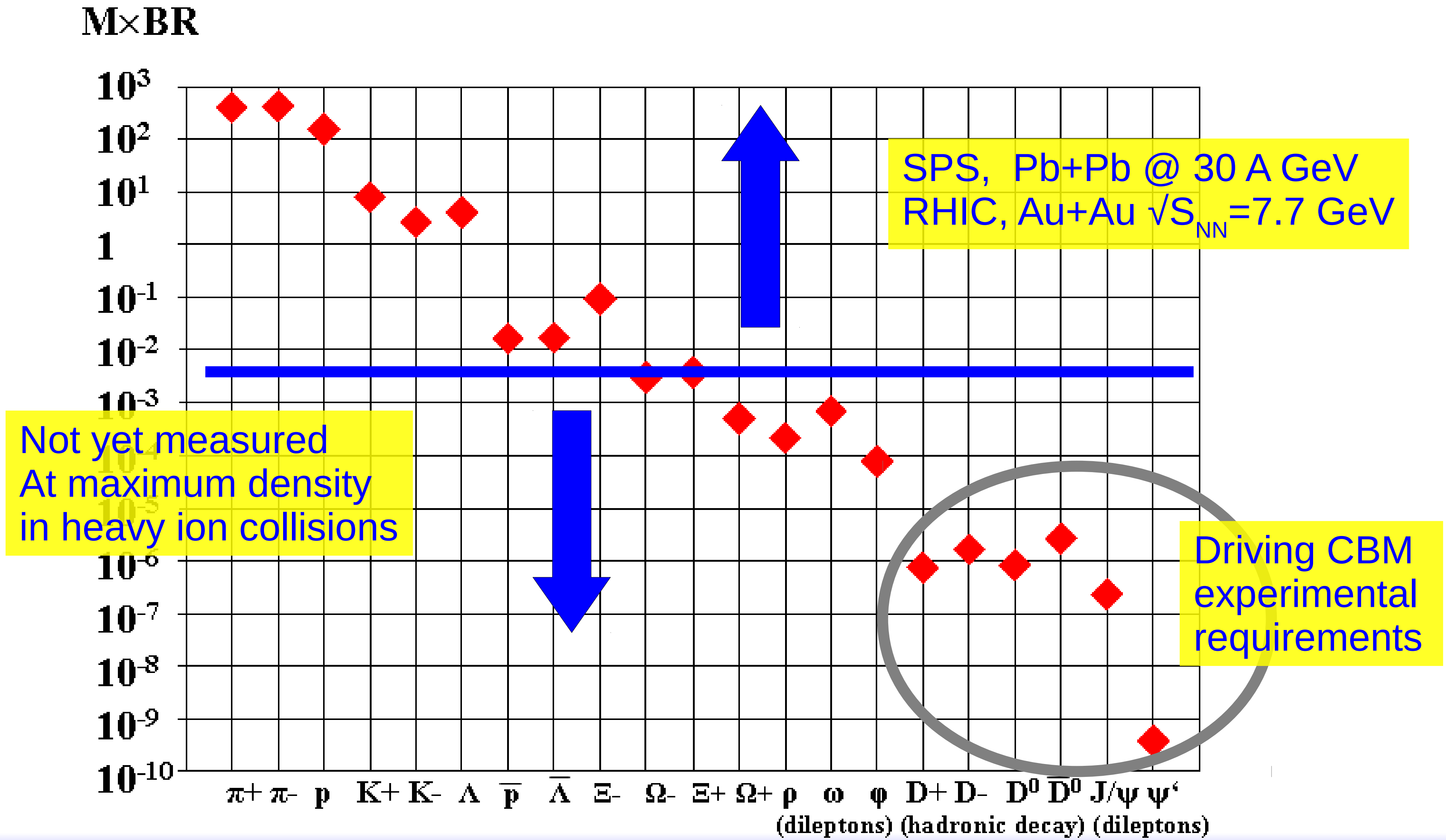


these (and more) observables can be studied with CBM providing **unprecedented statistics**

Experimental challenge (i)

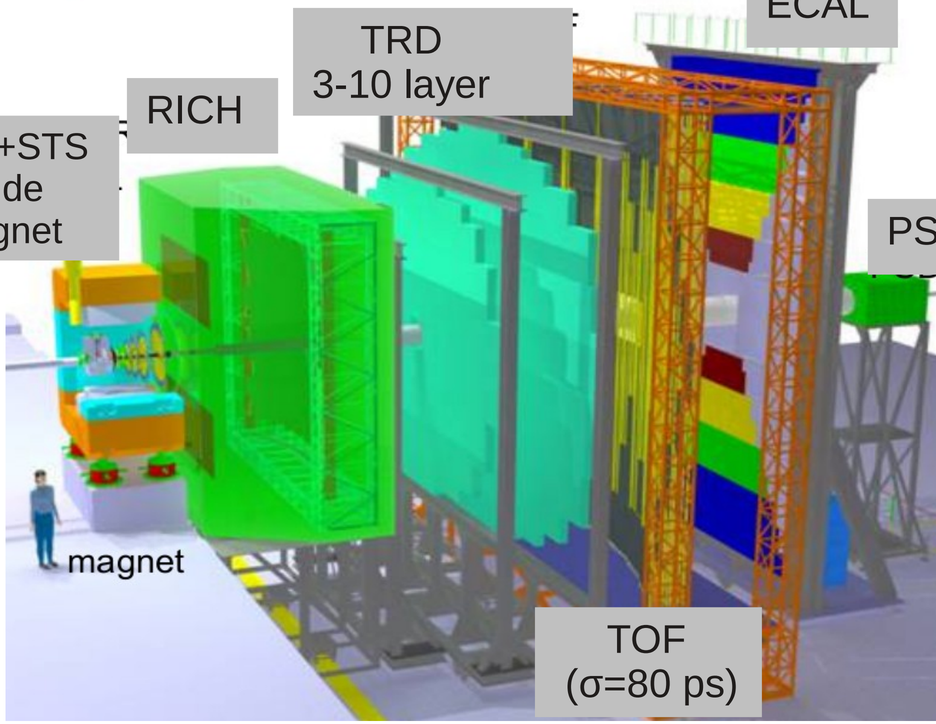
Particle multiplicity x Branching ratio

for min bias Au+Au collisions at 25 A GeV (from HSD and thermal model)

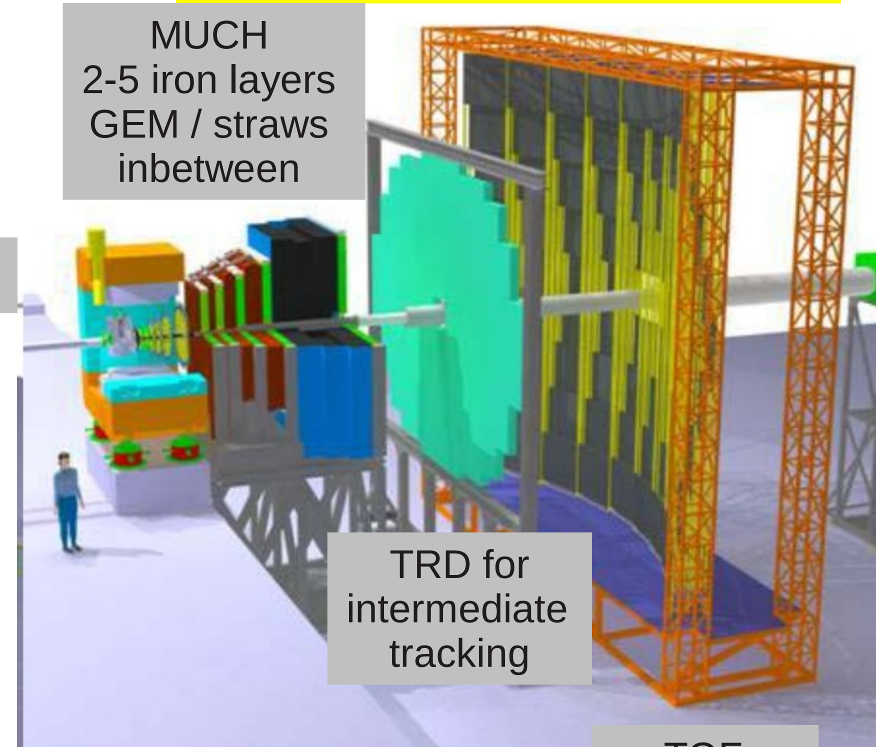


The CBM detector setup

Electron setup
RICH and TRD for electron-ID
pion suppression >10^4

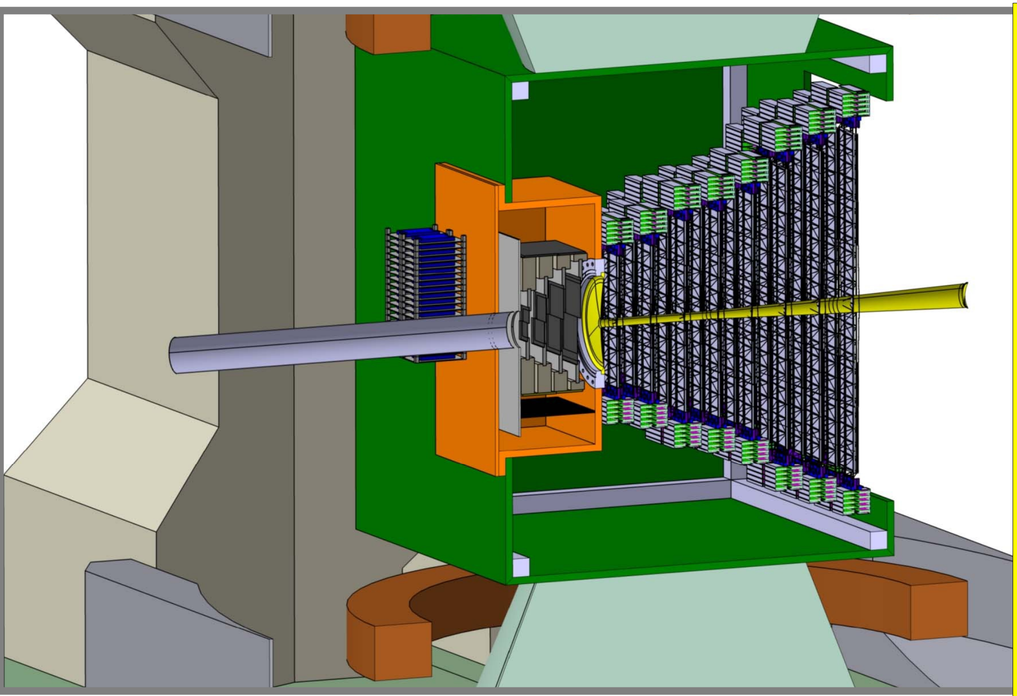


Muon setup
instrumented iron absorber



- **Exceptional high rate** capability (up to 10 MHz for J/Ψ)
- Hadron- and lepton reconstruction/ID with **large acceptance**
- **Displaced vertex reconstruction** (open charm, strangeness)
- Fully **self-triggered readout**, no hardware triggering
- Online event reconstruction and selection
- **excellent fast tracking** inside 1Tm superconducting magnet

STS+MVD – the heart of CBM



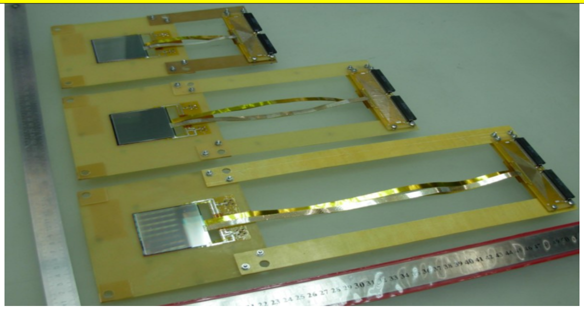
STS thermal enclosure (-5°C) inside CBM magnet

STS: Silicon Tracking Station
- Double-sided silicon strip sensors
- Track reconstruction for momenta >0.1 GeV
- Momentum resolution: Δp/p ~ 1% (p=1 GeV)

- ~100 individual "ladders", ~1200 indiv. detectors
- **> 2mio channels (!)**

MVD: Micro Vertex Detector
- **Monolithic Active Pixel Sensors, MAPS**
- **5 / 60 µm primary/secondary vertex resolution**
  (→ open charm, hyperon reconstruction)

Detector layers:
Low-weight carbon structures



Sensor development:
Double-sided microstrips
60 µm pitch, 300 µm thick

Experiments studying dense baryonic matter

Experiment	Energy range (Au/Pb beams)	Reaction rates Hz
STAR, PHENIX@RHIC BNL	$\sqrt{s_{NN}}$ = 7 – 200 GeV	1 – 800 (limitation by luminosity)
NA61@SPS CERN	E_{kin}= 20 – 160 A GeV $\sqrt{s_{NN}}$= 6.4 – 17.4 GeV	80 (limitation by detector)
MPD@NICA Dubna	$\sqrt{s_{NN}}$= 4.0 – 11.0 GeV	~1000 (design luminosity of 10^{27} $cm^{-2}s^{-1}$ for heavy ions)
HADES@SIS100 Darmstadt	E_{kin} = 1.5 AGeV Au+Au E_{kin} = 8 AGeV Ni + Ni	5x 10^4 (limitation by detector and DAQ)
CBM@FAIR Darmstadt	E_{kin}= 2.0 – 35 A GeV $\sqrt{s_{NN}}$= 2.7 – 8.3 GeV	**10^5 – 10^7** (limitation by detector)

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CBM online event reconstruction, running scenarios

- Key to achieve interaction rates up to 10 MHz:
  very effective event selection (up to factor 1000)
  using **fast online full event reconstruction**
  no hardware triggers

- All data transferred to computer cluster (up to 1TB/sec)
  - fast reconstruction algorithms
  - parallel processing on ~60k cores, GPU processing

- Different running scenarios depending on physics measurements
  - maximum rates / data reduction not possible for all channels
  - rate limit of vertex pixel detector (→ displaced vertices, hyperons)

„GreenIT cube“: planned FAIR Tier-0 data center

Untriggered 10^4 ev/sec	1 GB/sec raw data 1GB/sec to disk No online event selection possible	**- Pions, kaon, proton, hyperon yields spectra and flow** **- low-mass dileptons**
Medium rate 10^5-10^6 ev/sec	**<100 GB/sec raw data** **1GB/sec to disk** **online data reduction: 10-100**	**- low-mass di-muons** **- open charm (limited by vertex det)**
Maximum rate 10^7 ev/sec	1 TB/sec raw data, 1GB/sec to disk online **data reduction: 1000**	**- charmonium ($e^+ e^-$, $\mu^+ \mu^-$)**

CBM performance (i): Charm / charmonium

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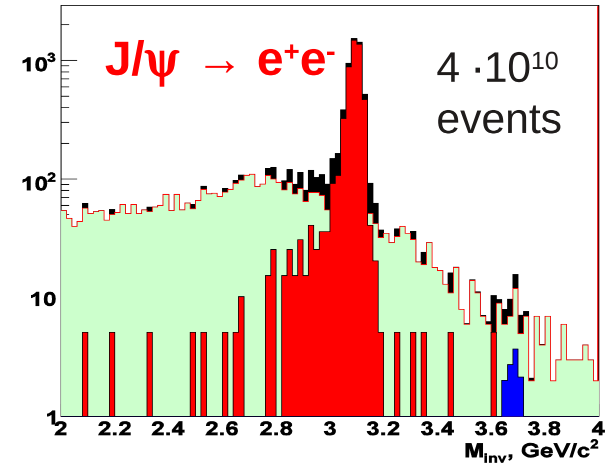
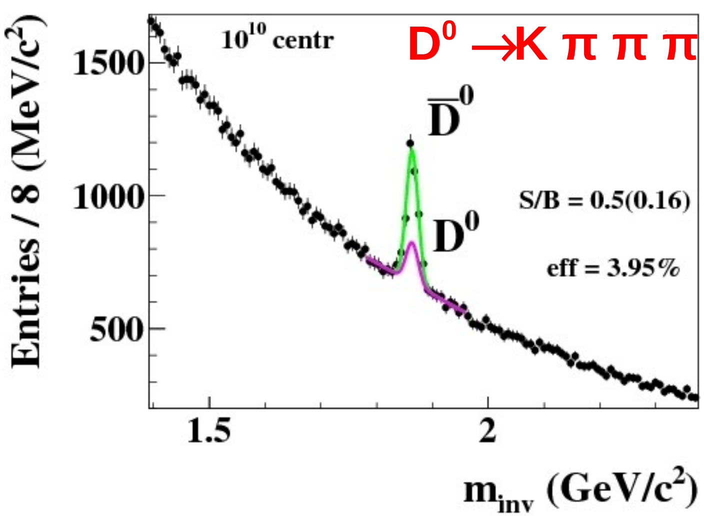
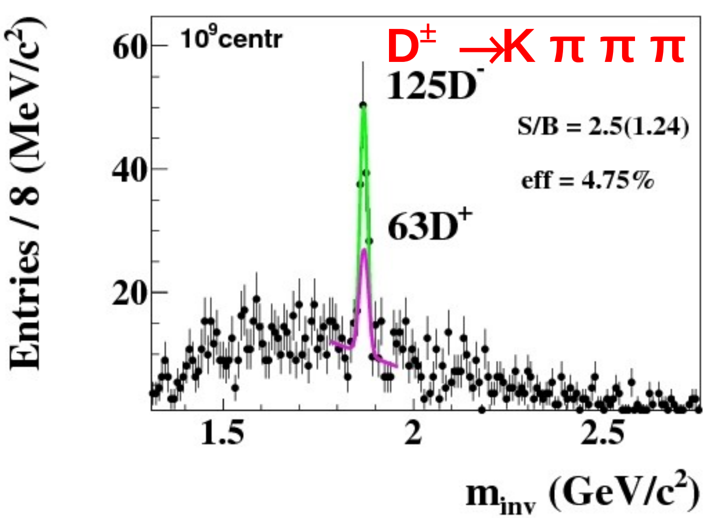
- All performance simulations:
  - → realistic detector geometry
  - → event generator: UrQMD (+PLUTO)
  - → GEANT3
- J/Ψ will be running at maximum event rate:
  - → 10 MHz minimum bias event rate
- Open charm at reduced rate:
  - → 100 kHz – 1MHz
  - → limited by Micro Vertex Detector MVD
  - → reconstruction of displaced vertices

Au+Au 25 AGeV (SIS300)



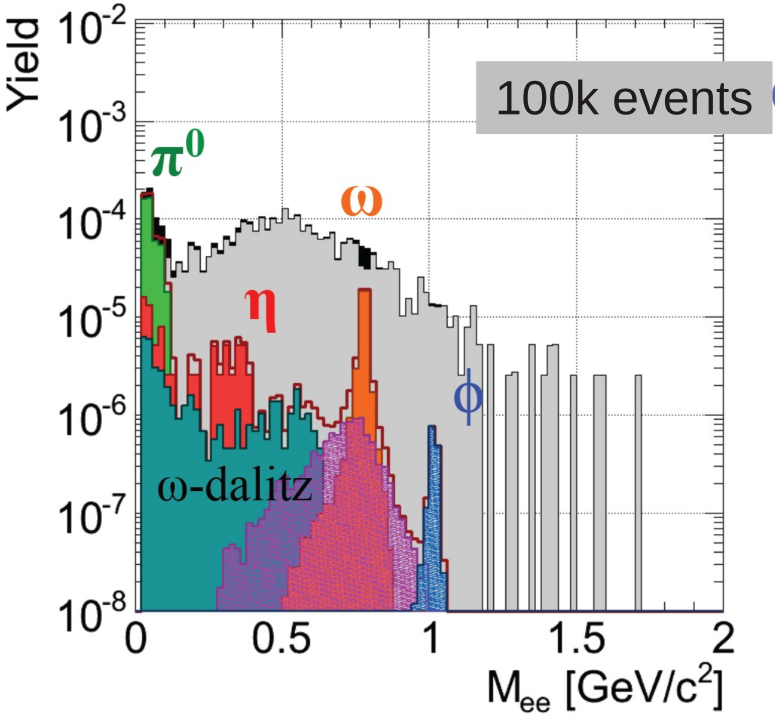




CBM performance (ii): di-electron decays of vector mesons

@SIS100: **8 AGeV**

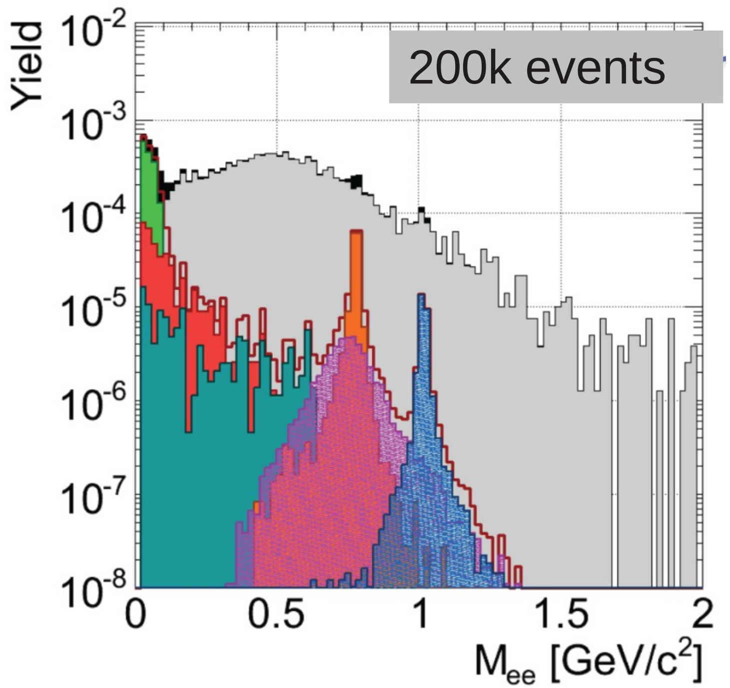
Using STS, RICH and TOF



	ρ	ω	φ
eff. [%]	3.12	4.11	4.89
S/BG	-	0.64	0.04

@SIS300: **25 AGeV**

Using STS, RICH, TRD and TOF



	ρ	ω	φ
eff. [%]	4.39	5.53	7.08
S/BG	-	0.31	0.11

CBM performance (iii): (multi strange) hyperon production

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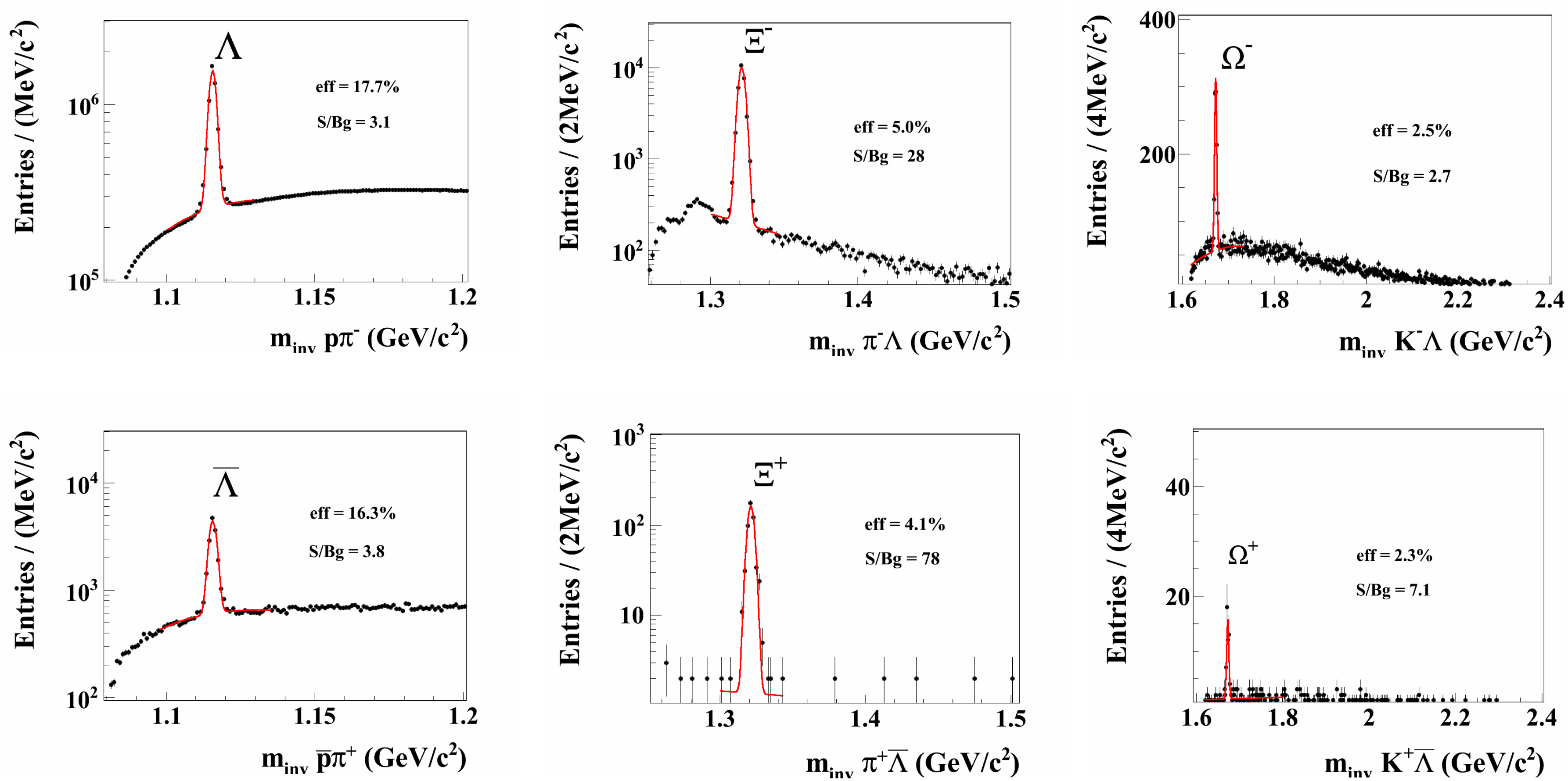
Hyperon yields in 10s CBM run at maximum interaction rate 10 MHz

1M central events

Au+Au 25 A GeV (SIS300)

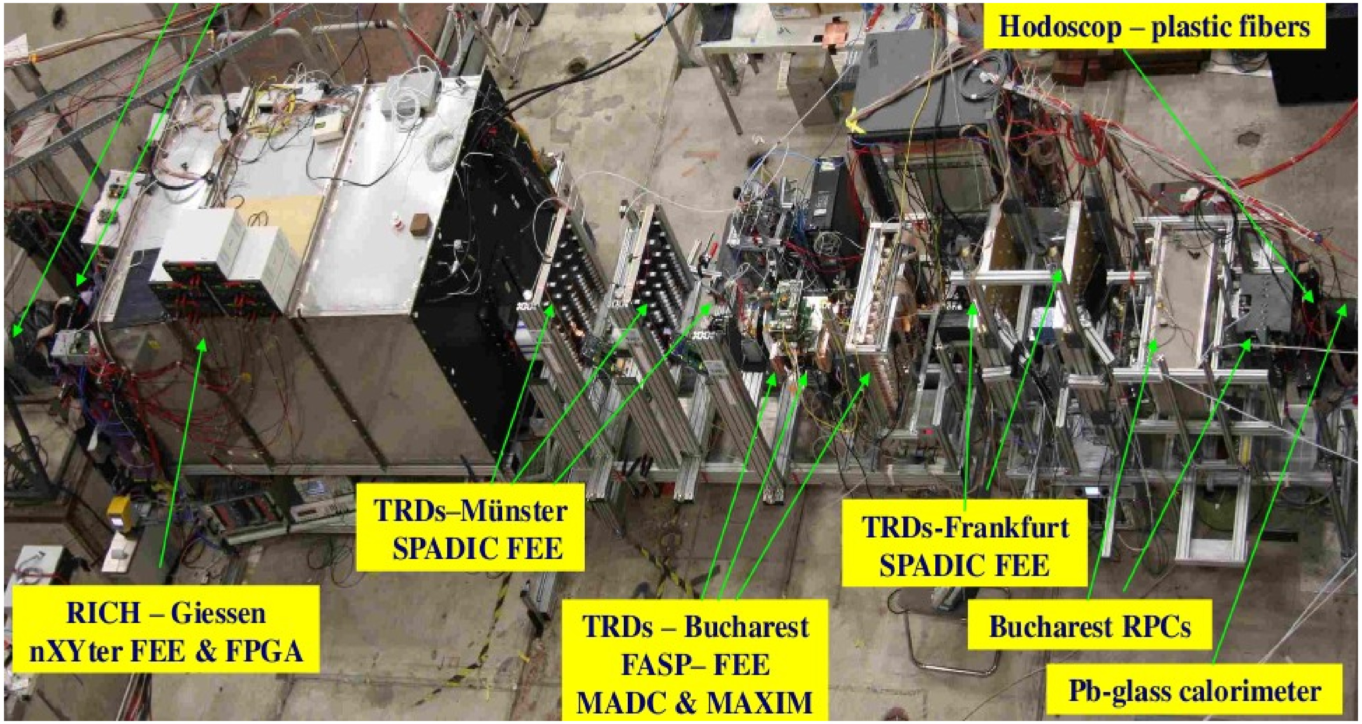


Detector development and design

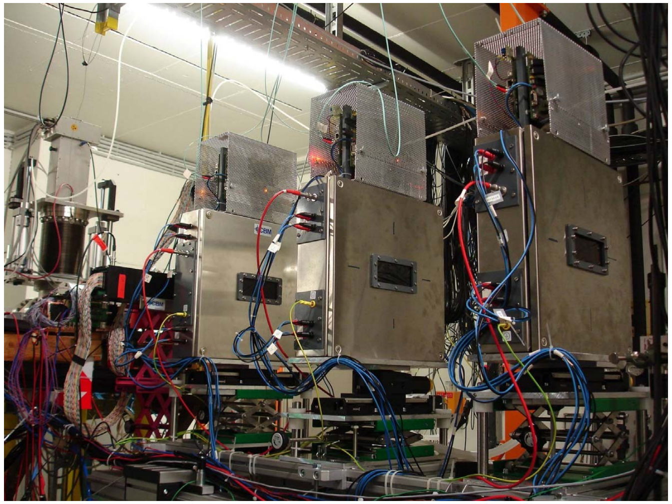
- CBM detector design in advanced stage
- Technical design reports for several detector systems submitted

- Real size prototype systems of all major components
- Tested in test beams at CERN PS, CERN SPS, COSY and GSI

Silicon Pixel sensors MAPS for Micro Vertex detector beamtest at CERN SPS, 2012



Combined RICH, TRD and RPC beam test CERN PS, 2011 and 2012



Silicon strip sensor stations for STS beam test at COSY, FZ-Jülich 2011 and 2012

some results from RICH beam tests

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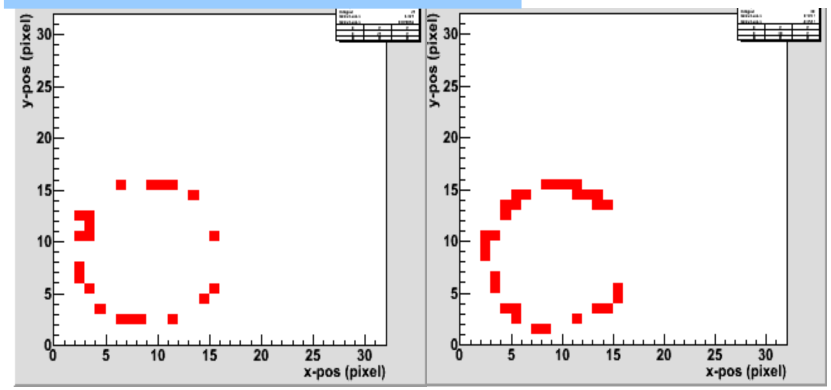
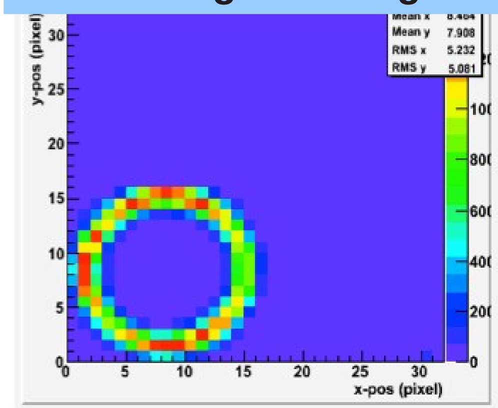
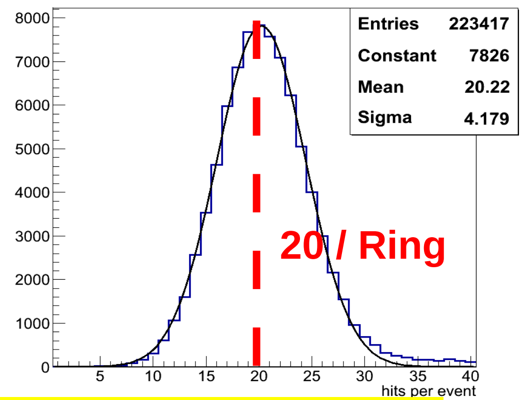
CBM

typical single event rings



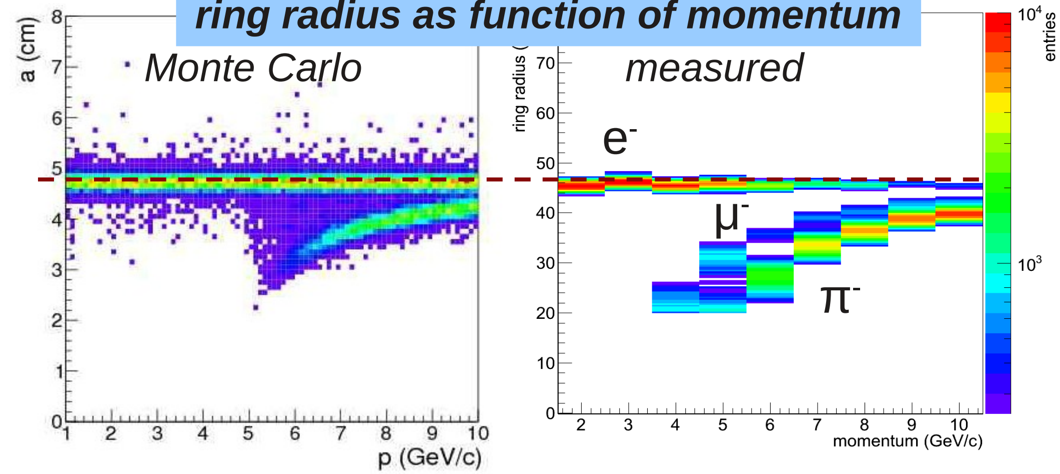
event-integrated ring image and hit multiplicity



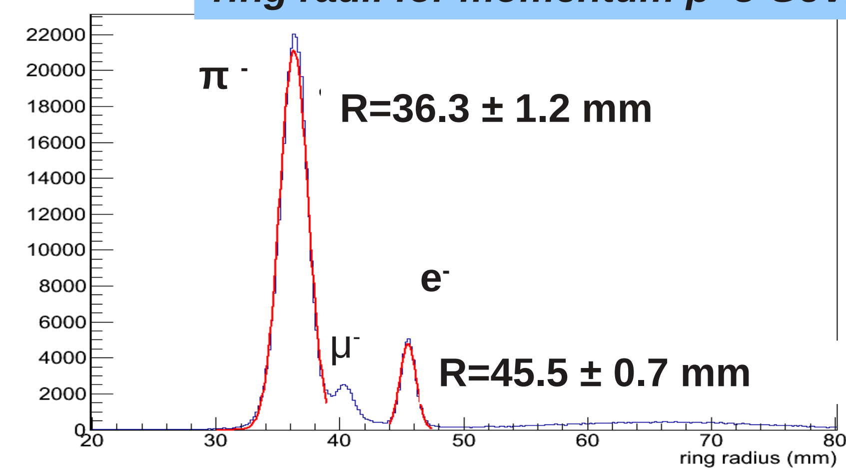


- very clean single event rings
- in averag e **~20 photons/ring** (electrons) in agreement with Monte Carlo
- nearly no uncorrelated background noise ~ **10Hz / channel**

ring radius as function of momentum



ring radii for momentum p=8 GeV/c



- ring radii for electrons and pions corresponding to Monte Carlo expectation
- **> 7σ e^- / π^- separation at p=8 GeV/c**

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The CBM collaboration

China:
Tsinghua Univ., Beijing
CCNU Wuhan
USTC Hefei

Croatia:
University of Split
RBI, Zagreb

Cyprus:
Nikosia Univ.

Czech Republic:
CAS, Rez
Techn. Univ. Prague

France:
IPHC Strasbourg

Germany:
Univ. Gießen
Univ. Heidelberg, Phys. Inst.
Univ. HD, Kirchhoff Inst.
Univ. Frankfurt
Univ. Mannheim
Univ. Münster
FZ Rossendorf
GSI Darmstadt
Univ. Tübingen
Univ. Wuppertal

Hungaria:
KFKI Budapest
Eötvös Univ. Budapest

India:
Aligarh Muslim Univ., Aligarh
IOP Bhubaneswar
Panjab Univ., Chandigarh
Gauhati Univ., Guwahati
Univ. Rajasthan, Jaipur
Univ. Jammu, Jammu
IIT Kharagpur
SAHA Kolkata
Univ Calcutta, Kolkata
VECC Kolkata
Univ. Kashmir, Srinagar
Banaras Hindu Univ., Varanasi

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Korea Univ. Seoul
Pusan National Univ.

Norway:
Univ. Bergen

Poland:
Krakow Univ.
Warsaw Univ.
Silesia Univ. Katowice
Nucl. Phys. Inst. Krakow

Portugal:
LIP Coimbra

Romania:
NIPNE Bucharest
Bucharest University

Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
KRI, St. Petersburg
Kurchatov Inst. Moscow
LHE, JINR Dubna
LPP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
Obninsk State Univ.
PNPI Gatchina
SINP, Moscow State Univ.
St. Petersburg Polytec. U.

Ukraine:
INR, Kiev
Shevchenko Univ. , Kiev

56 institutions, 450 members

summary and outlook

- CBM@FAIR:
  - explore the QCD phase diagram of nuclear matter
  - at high net baryon density
  - using in particular rare, penetrating probes (dileptons, charm, …)
  - starting at SIS100, later continued at SIS300
- CBM detector design in very advanced stage
  - Detailed simulations proof feasibility of physics program
  - prototype detector performances fulfill CBM requirements
  - first TDRs submitted for external review
- Substantial part of CBM startversion for SIS100 in financed
- ordering of first components (eg PMTs for RICH) will start 2014

Backup slides

Expected particle yields: hyperons and hypernuclei

Strange baryon yields measured per week
for $2 \cdot 10^4$/s min. bias Au+Au collisions.
M(min. bias) $\approx$ 0.25 M(central)
Efficiency is 15% for anti-Λ and 3%
for the multi-strange hyperons.

Beam energy A GeV	Ξ^-	Ω^-	anti-Λ	Ξ^+	Ω^+
4.0	$9 \cdot 10^6$	$1.8 \cdot 10^5$	$3.6 \cdot 10^3$	$5.2 \cdot 10^3$	$9.0 \cdot 10^2$
6.0	$2.6 \cdot 10^7$	$5.0 \cdot 10^5$	$2.4 \cdot 10^5$	$1.4 \cdot 10^4$	$2.8 \cdot 10^3$
8.0	$4.0 \cdot 10^7$	$1.4 \cdot 10^6$	$3.6 \cdot 10^6$	$2 \cdot 10^5$	$6.0 \cdot 10^4$
10.7	$5.4 \cdot 10^8$	$2.2 \cdot 10^6$	$6.8 \cdot 10^6$	$3.8 \cdot 10^5$	$1.2 \cdot 10^5$

Hyper nuclei	M central	BR	ε %	Yield/s central	Yield/week central
${}_{\Lambda}^{3}H$	$2 \cdot 10^{-2}$	0.6	7	7.6	$4.6 \cdot 10^6$
${}_{\Lambda\Lambda}^{5}H$	$6 \cdot 10^{-6}$	0.36	1	$2.2 \cdot 10^{-4}$	130
${}_{\Lambda\Lambda}^{6}He$	$1 \cdot 10^{-7}$	0.36	1	$1 \cdot 10^{-6}$	2

central collision rate 10 kHz

BR = 36% for double lambda hypernuclei is a guess

Expected particle yields: open charm, charmonium->$\mu^+\mu^-$

Particle	Multiplicity central	Multiplicity Min. bias	BR [%]	ε [%]	Yield/week Min bias
D^+	$2.7\cdot10^{-8}$	$9.0\cdot10^{-9}$	9.5	13	97
D^-	$5.5\cdot10^{-8}$	$1.8\cdot10^{-8}$	9.5	13	206
D^0	$2.9\cdot10^{-8}$	$9.7\cdot10^{-9}$	8.1	1.7	12
Anti-D^0	$8.8\cdot10^{-8}$	$3\cdot10^{-8}$	8.1	1.7	37

M(min. bias) ≈ 1/3 M(central)
min. bias reaction rate 1.5 MHz, pile up of 50 central events in the MVD.

Collision system	Energy	Multiplicity Central*	Multiplicity Min. bias	ε [%]	Yield/week Min bias
p+C	30 GeV	$5.0\cdot10^{-8}$	$1.7\cdot10^{-8}$	13	700
p+Au	30 GeV	$1.2\cdot10^{-7}$	$4.0\cdot10^{-8}$	13	1800
Au+Au	10 A GeV	$1.7\cdot10^{-7}$	$3.4\cdot10^{-8}$	3.3	400

* taken from HSD. Min.bias ≈ 1/3 central for p+A, and 0.2 for A+A

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relevance: dense nuclear matter in neutron stars

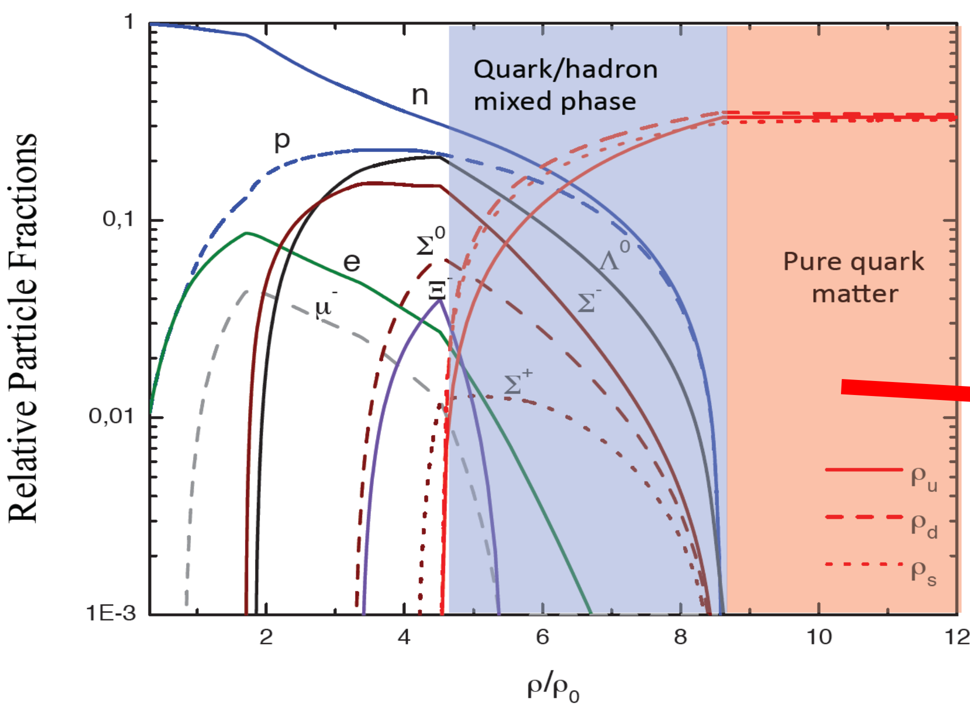
CBM

- How is the inner core of a neutron star composed ?
  Strange matter ? Hyperons ? Quark matter ? → many different models

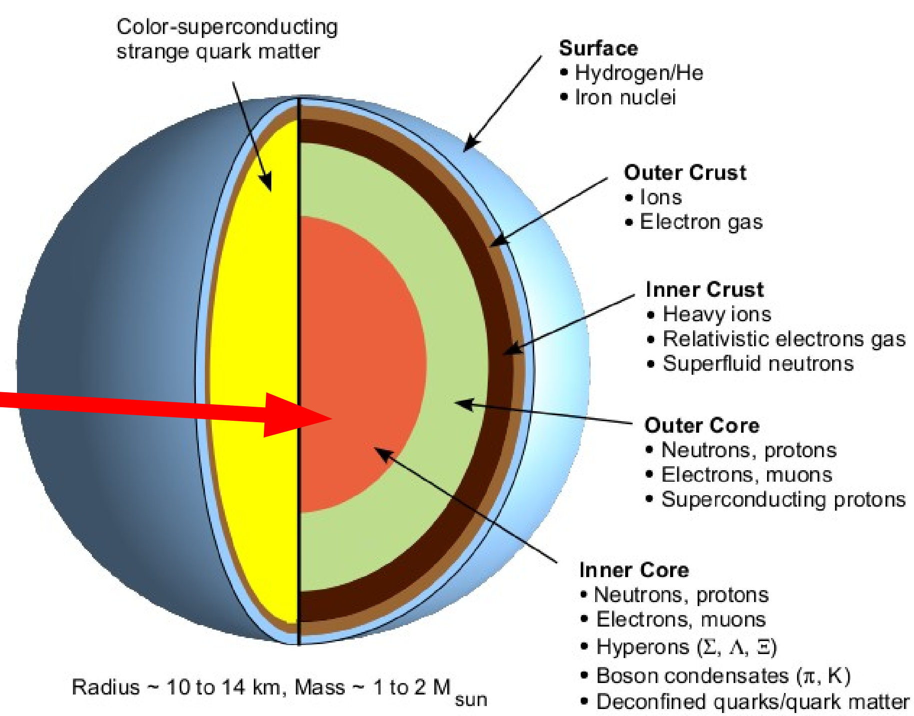
- What is the Equation-of-State (EOS) of such dense matter ?

- Recent mass determination of massive neutron star challenging models
  PSR J1614-2230 with **mass ~ 1.97±0.04 * M_{sun}**

P.Demorest et al, **Nature 467**, 1081-1083(2010)



M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera (August 2012)
Non-local SU(3) NJL with vector coupling



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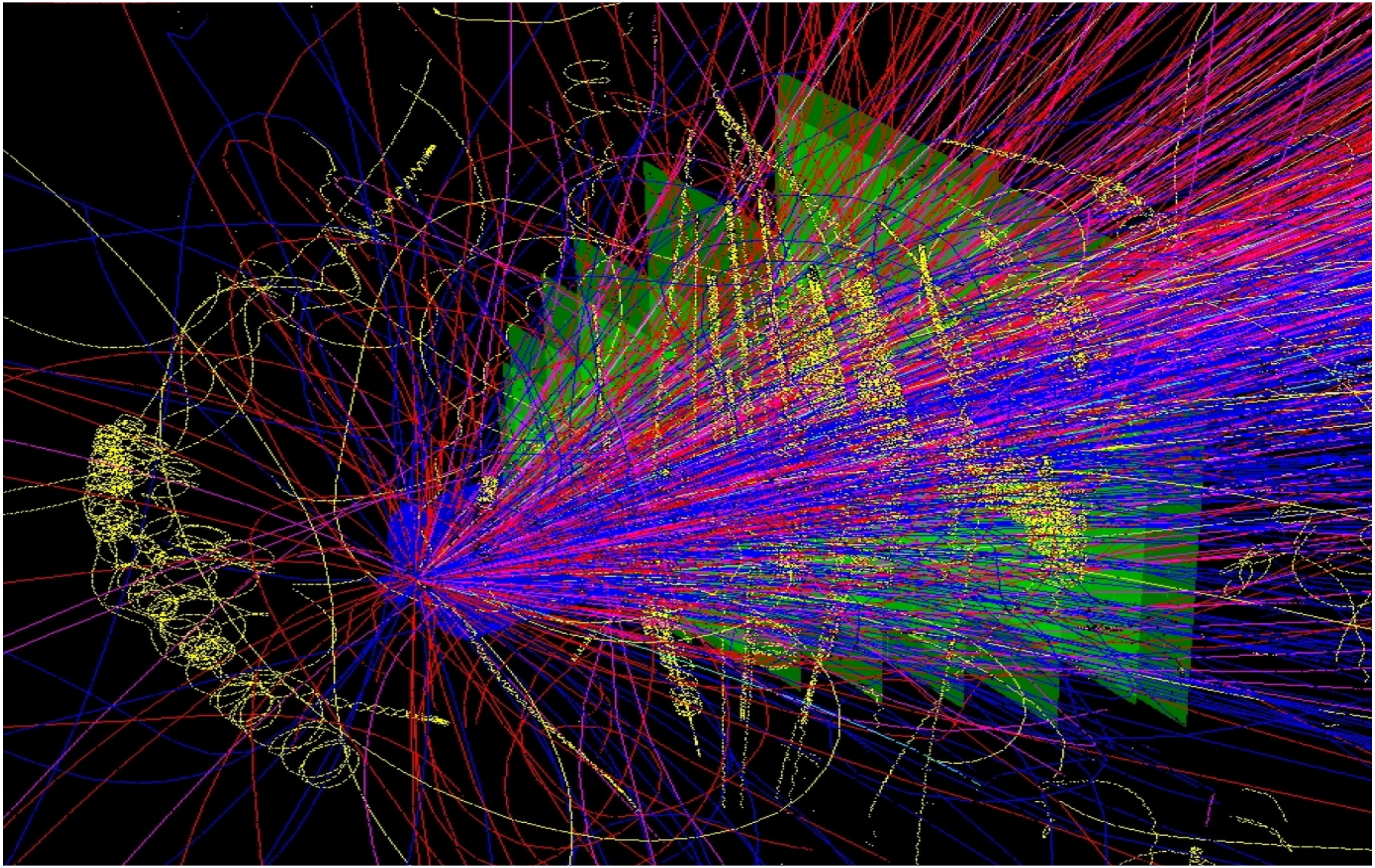
Experimental challenge (ii)

Simulated central Au+Au collision, 25 A GeV, UrQMD+GEANT4
160 p, 400 π^+, 400 π^+, 44 K^+, 13 K^-



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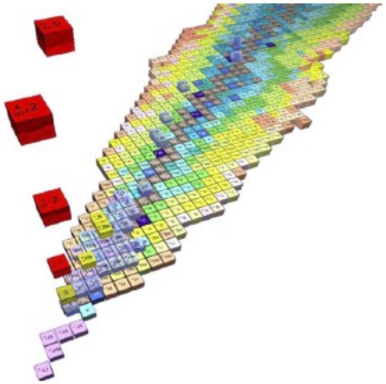
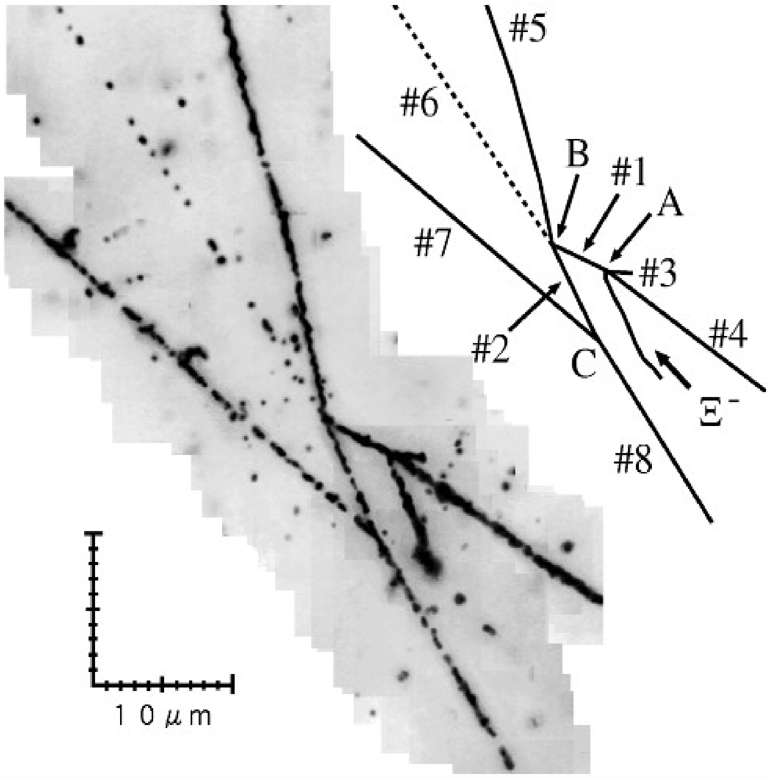
search for double hyper nuclei



- Hypernuclei: Nuclei containing one or more hyperons **in addition** to nucleons
  example: **$^{5}_{\Lambda\Lambda}$H, $^{6}_{\Lambda\Lambda}$He**

- explore third, strange dimension of the chart of nuclei
- information on **hyperon-nucleon** and **hyperon-hyperon interaction**,
  → important role for **neutron star models**

H. Takahashi et al., Phys. Rev. Lett. 87 (2001) 212502



- So far:
  produced using K- beams bombarding light nuclei:
  strangeness-exchange: s-quark transferred to nucleon forming a Λ trapped in nucleus
  Kaon+Nucleus → Pion+Hypernucleus

- only few double hyper-nuclei found so far

- mostly in emulsions
  (displaced decay vertices on 10mu scale !)

(double) hyper-nuclei production with CBM:

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CBM

- alternative approach CBM:

  production of (double) hyper-nuclei in heavy ion collisions
  via **coalescence** of Λ with nucleons or light nuclei

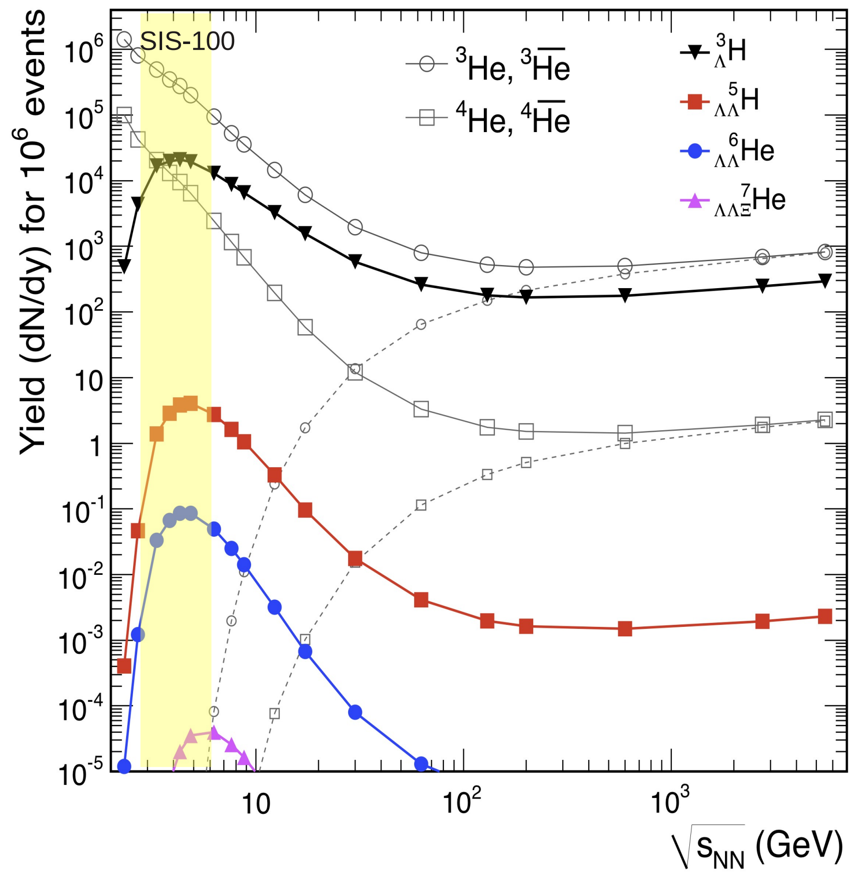
- Λ produced abundantly,
  ~50 per (Pb+Pb) collision above 40 AGeV,
  still 4 Λ per (Au+Au) collision at 4 AGeV

- yield of light nuclei increases rapidly
  with decreasing beam energy !

- coalescence probability should have
  maximum at 7 – 11 AGeV: SIS100 energy !
  (according to statistical model)

- reconstruction and tagging via decay chain:
  $^{5}_{\Lambda\Lambda}H \rightarrow {}^{5}_{\Lambda}He + \pi^-$
  $^{5}_{\Lambda}He \rightarrow {}^{4}He + p + \pi^-$

A. Andronic et al., Phys. Lett. B 697 (2011) 203



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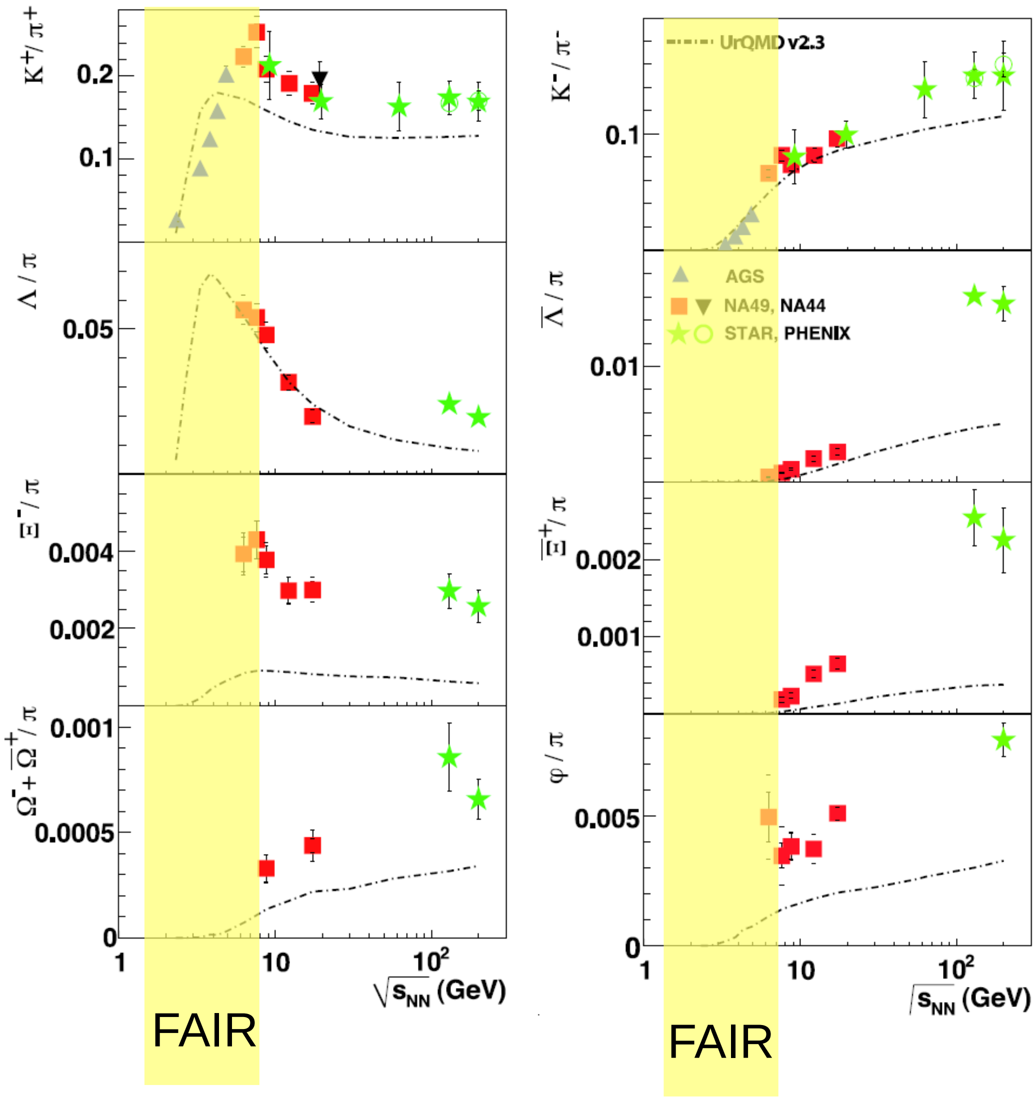
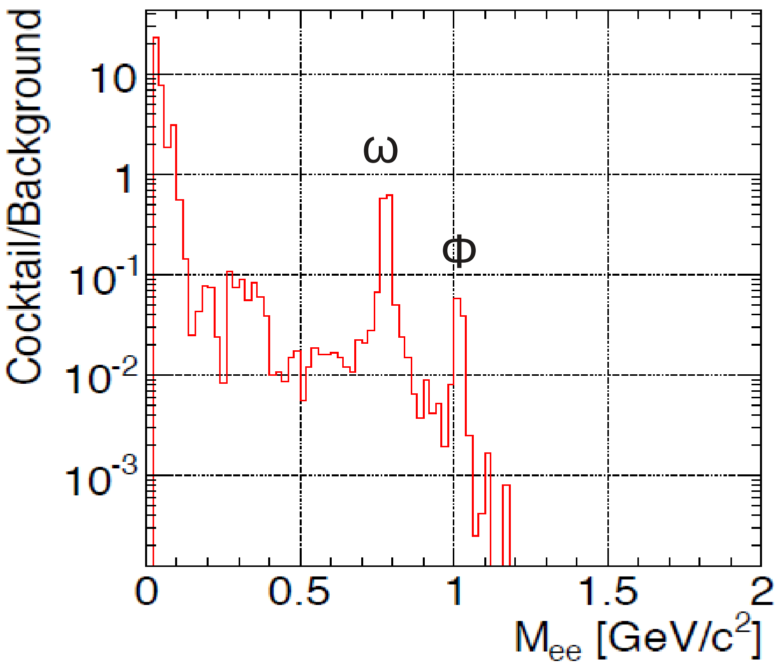
Strangeness production

- Excitation funcion of yields, spectra and collective flow of strange particles as indication for phase transition
- Non-monotonic behaviour of K^+ / π^+ ratio
- Strangeness production changes at ~30 AGeV



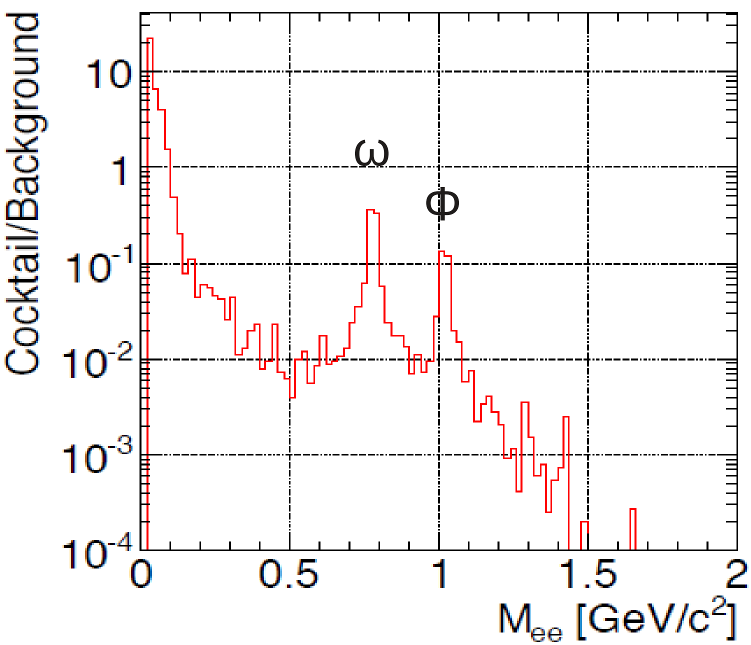
Dileptons with CBM : performance

@SIS100: **8 AgeV**



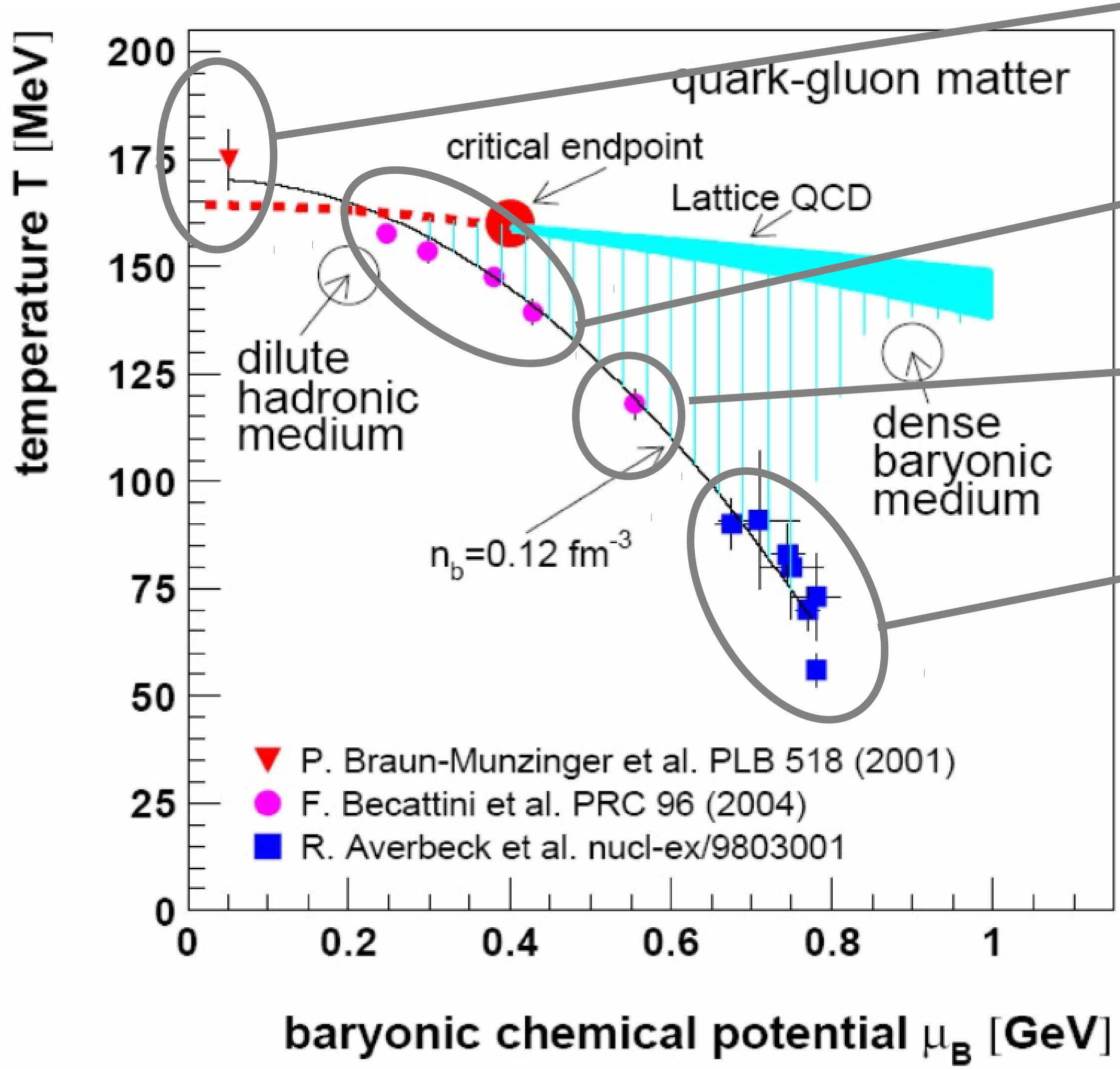
	ρ	ω	φ
eff. [%]	3.12	4.11	4.89
S/BG	-	0.64	0.04

@SIS300: **25 AgeV**



	ρ	ω	φ
eff. [%]	4.39	5.53	7.08
S/BG	-	0.31	0.11

Current status of measurements



R. Averbeck et al, PRC 67(2003) 024903

RHIC Brookhaven
√s = 130 – 200 GeV/Nukleon
additional data from **LHC**

SPS CERN
20-160 GeV/Nukleon

AGS Brookhaven
2-10 GeV/Nukleon

SIS18 GSI
<2 GeV/Nukleon

"freezeout points" determined for different conditions

Possible critical point
Z. Fodor, S.D. Katz,
JHEP 404, 50(2004)

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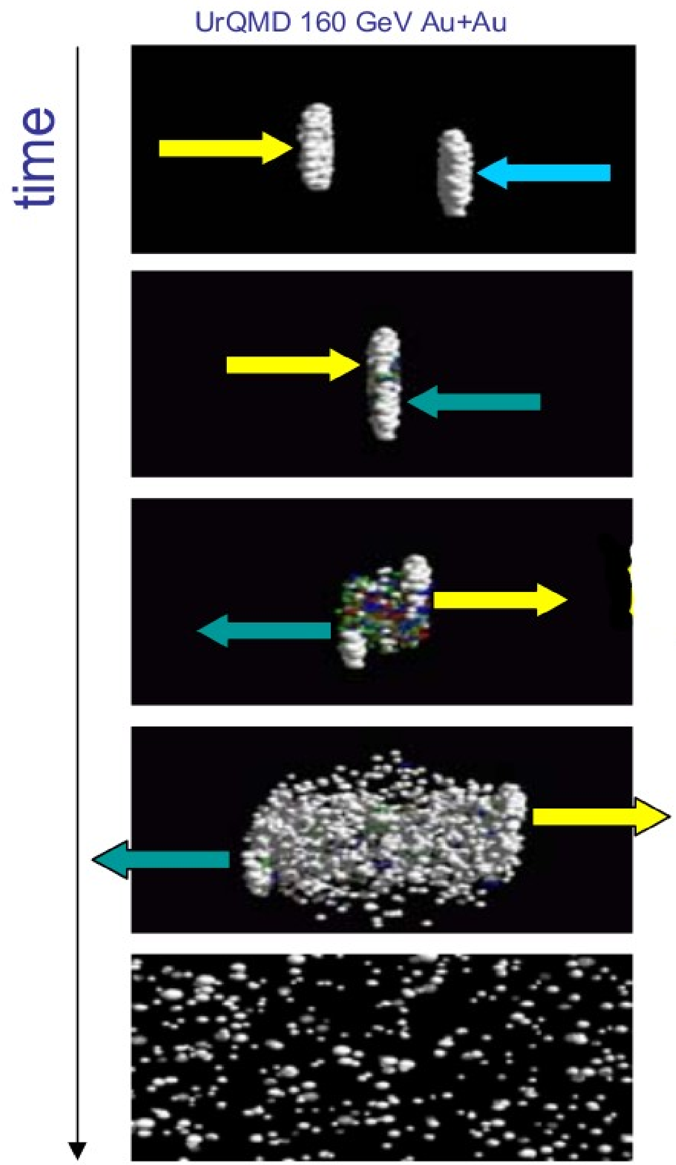
Different steps of a heavy ion collision

CBM



Before the collision
two Lorenz-contracted nuclei approaching

Moment of collision:
compression and heating, $T >> T_{chem}$ ~ 160 MeV

Thermalization of the “fireball”
(high T and ρ reached for ~10 fm/c= $3.3\text{x}10^{-23}$ s

Expansion of fireball, cool-down

Chemical freezeout (number and type of particles frozen)
kinematical freezeout (particle spectra frozen)

T_{chem} ~ 160 MeV, $\sim 2\text{x}10^{12}$ K

The Muon Detection System

Requirements:

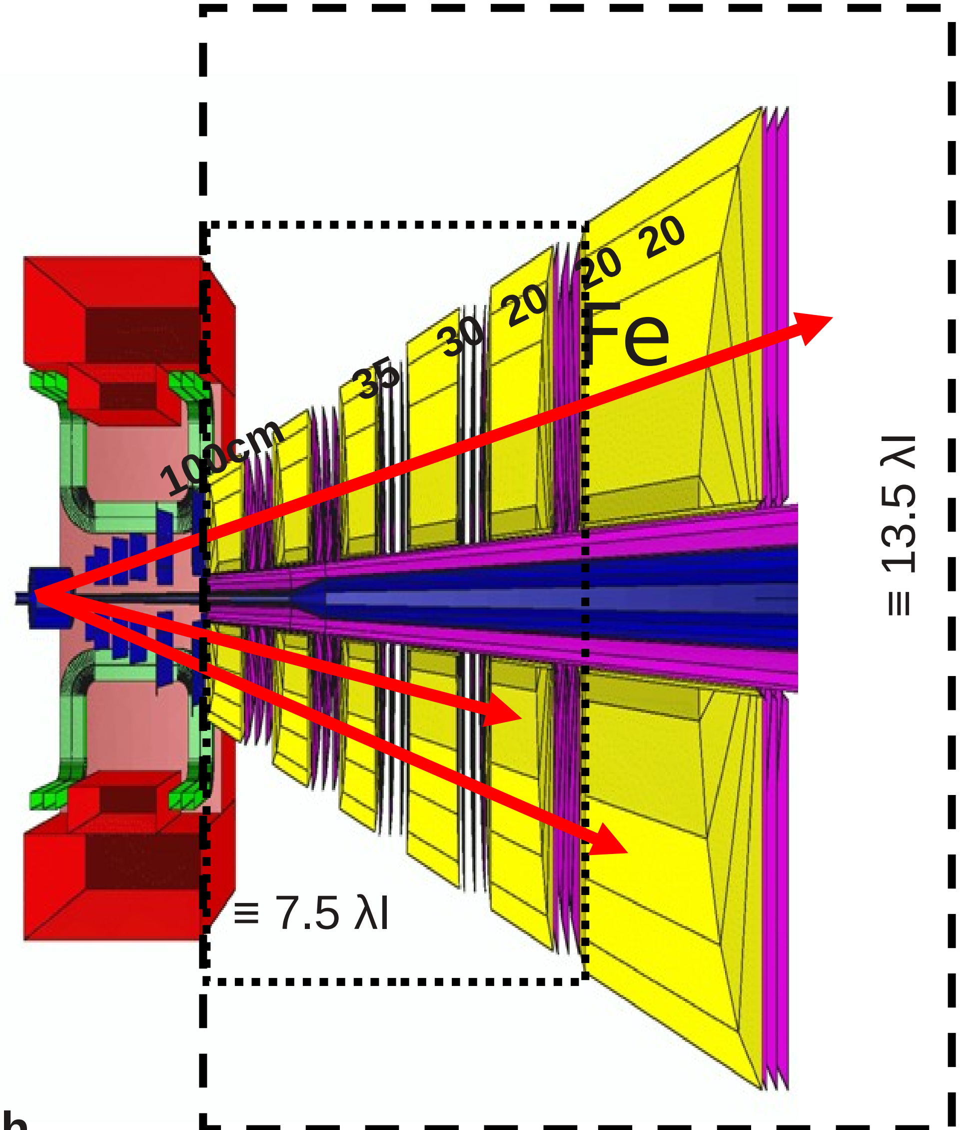
- Muon reconstruction and identification
- High particle- and dose rates
-

Realisation

- “instrumented” iron absorber

- Front 3 gaps, small area:
  “Gas electron Multiplier”, GEM-detectors

- Backward 2 gaps:
  Strawtube layers



Extensive prototype testing at COSY/Jülich