CBM: Experiment, Physics and Trigger

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Triggering Discoveries in High-Energy Physics II

Puebla, 29 January - 2 February 2018

Outline

I. Heavy-Ion Collisions and the CBM Experiment
II. The Physics of CBM
III. Trigger Concept

I. Setting the Stage

Heavy-Ion Collisions and the CBM Experiment

Intro

Compressed

We study hot and dense matter

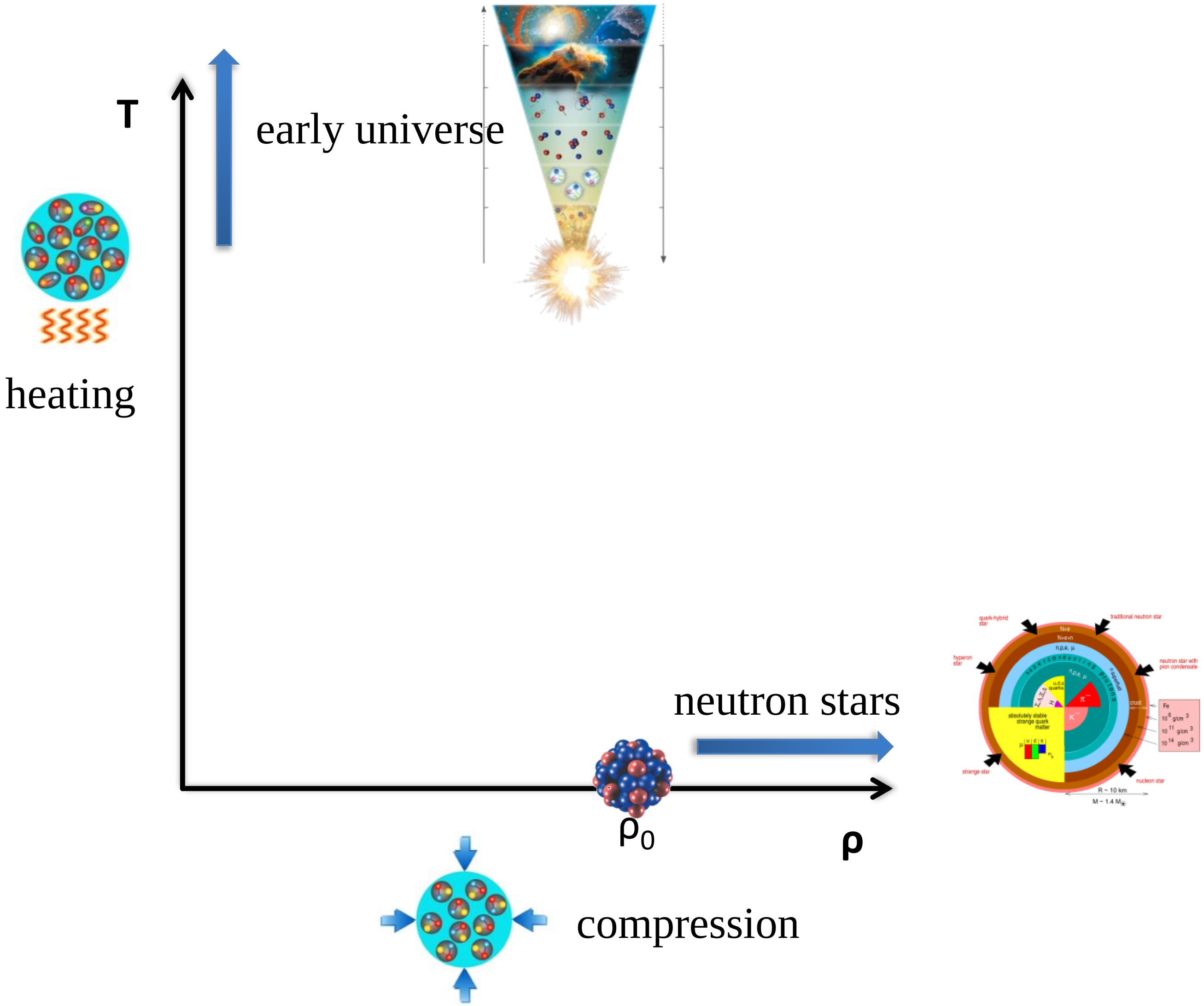
Baryonic

Strongly interacting, baryon-rich matter

Matter

We study extended matter,
not particles

Matter at extreme conditions



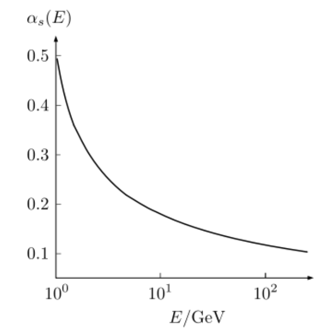
Strongly Interacting Matter

To understand matter, one needs to know

- The basic constituents: quarks and gluons
- The force between them: strong interaction
  - The theory of the strong interaction is QCD
  - Which is unfortunately in general not calculable

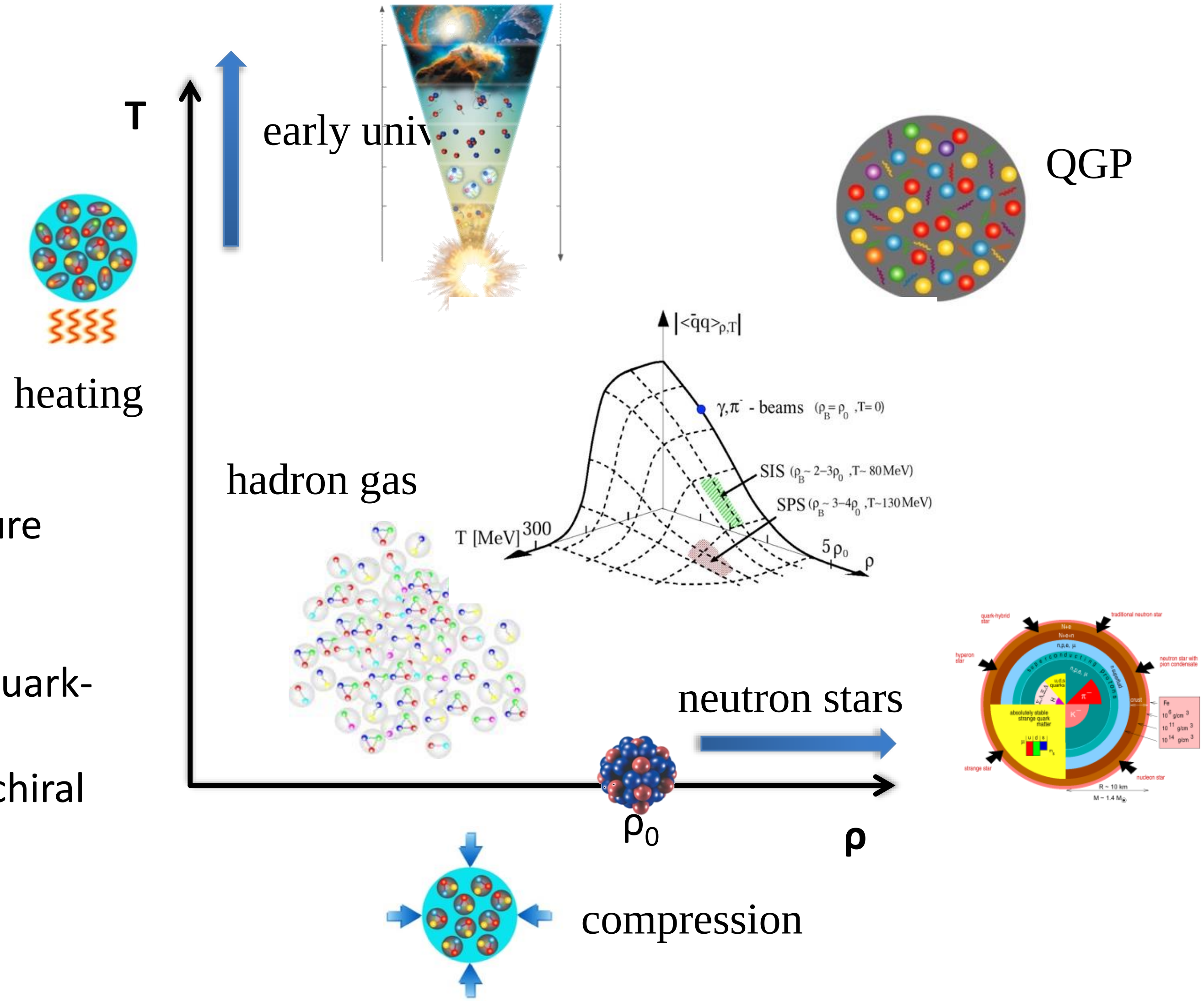
Properties of the strong interaction in vacuum:

- Asymptotic freedom: the interaction is weak at small distances (large energies)
- Confinement: in vacuum, quarks are bound into hadrons; no free colour charges
- Chiral symmetry breaking: compound objects (hadrons) are much heavier than the sum of their constituents



Driving question: do these properties change with temperature and/or density?

Matter at extreme conditions



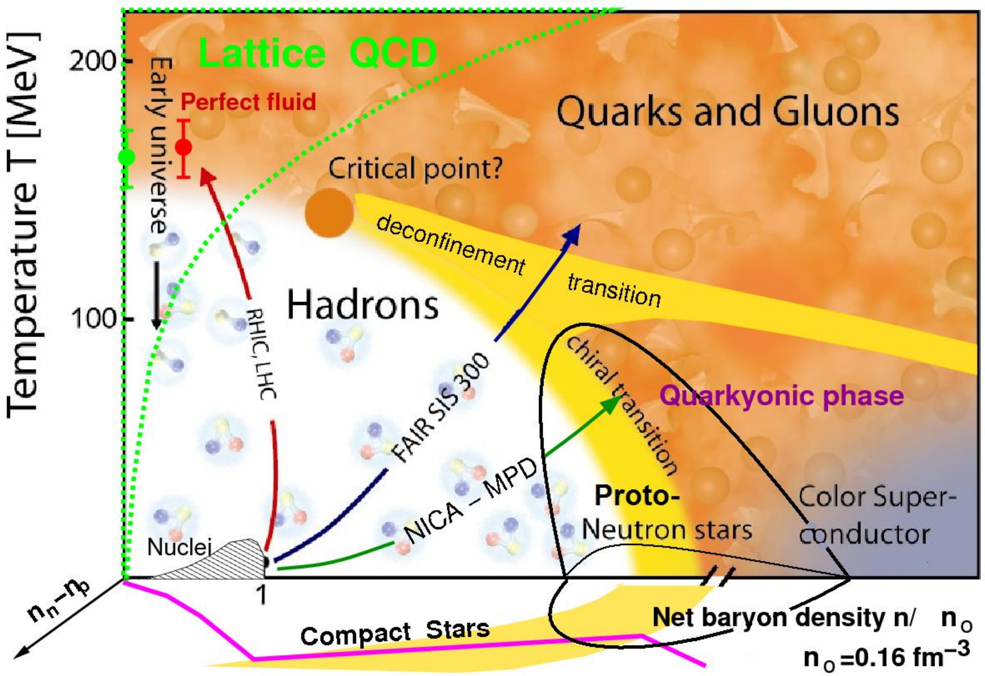
We expect at high enough temperature and / or density:

- Breakdown of confinement (quark-gluon plasma)
- Restoration of chiral symmetry

Theoretical Access

- Perturbation Theory
  - only possible for large momentum transfer (some observables)
- Lattice QCD: statistical sampling of QCD on a discrete space-time grid
  - Restricted to small densities
- Effective QCD models: simplified Lagrangian
  - Tuned to LQCD; hope that behaves like real QCD where LQCD not applicable

The Phase Diagram of QCD Matter

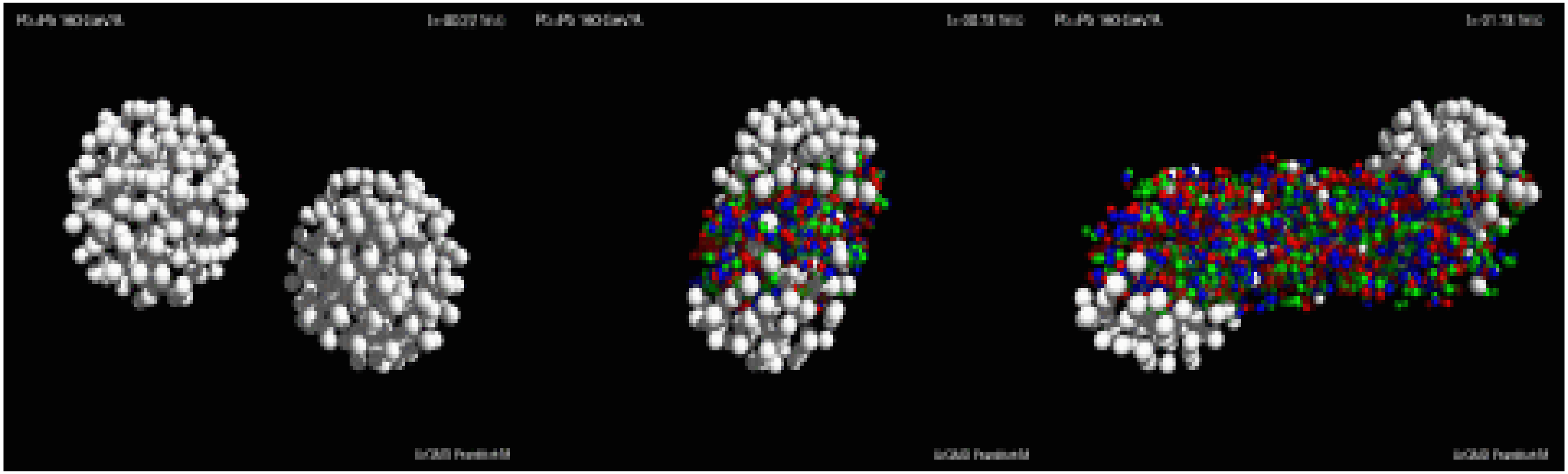


Possibly a very complex structure!

Landmarks:

- Cross-over at low densities,
- first-order (?) transition at high densities,
- both separated by a critical point.
- Chiral transition / quarkyonic matter ?
- Exotic phases at extreme densities

Experimental Access



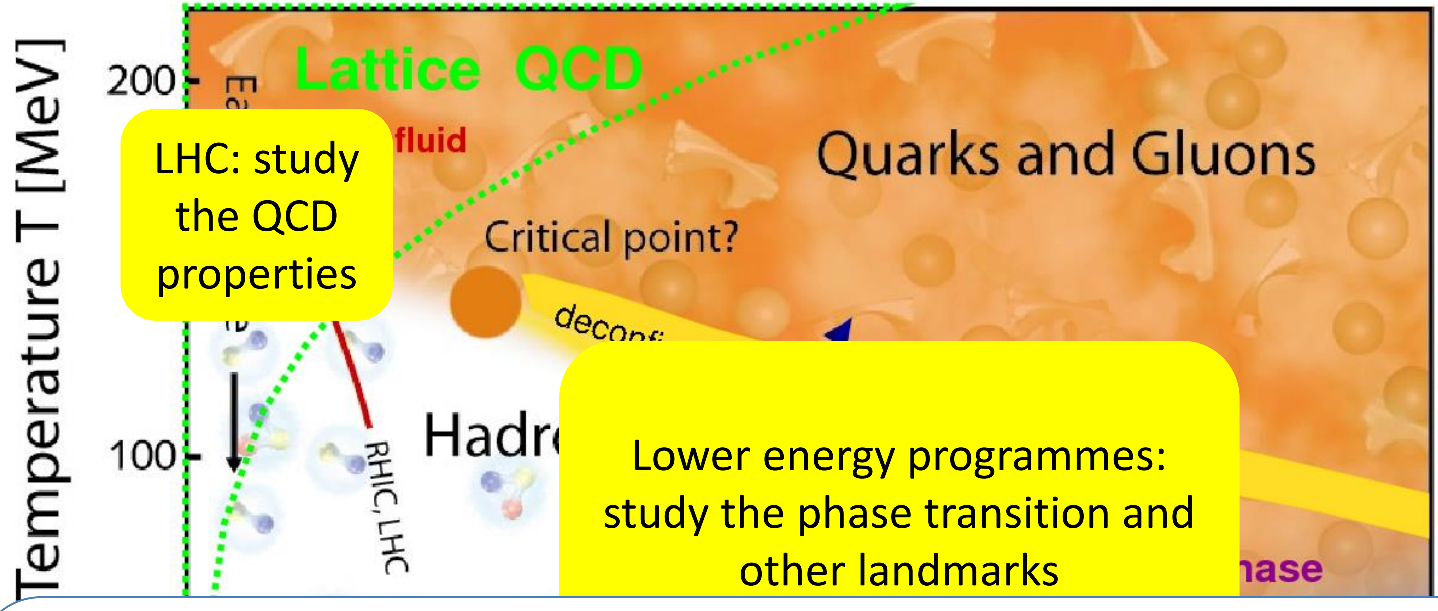
In high-energy collisions of heavy nuclei, matter at high energy densities (hot and dense) is created – for a very short time and in a very limited volume.

Control parameters:
- Collision energy
- System size (ion species / collision centrality)

Exploring the QCD Phase Diagram

- Nuclear collisions at high energies (LHC, RHIC):
  - Incoming nucleons leave the reaction zone (transparency) after depositing a part of their kinetic energy
  - No baryon number transfer to the fireball
  - Produce a medium with high temperature and vanishing net-baryon density
- At lower energies (SPS, FAIR, NICA):
  - A part (or all) of the baryon number is transferred into the fireball (stopping)
  - Create a medium with moderate temperature but high net-baryon density
- Variation of the collision energy, allows to study different parts of the phase diagram

Exploring the QCD Phase Diagram



LHC: study the QCD properties

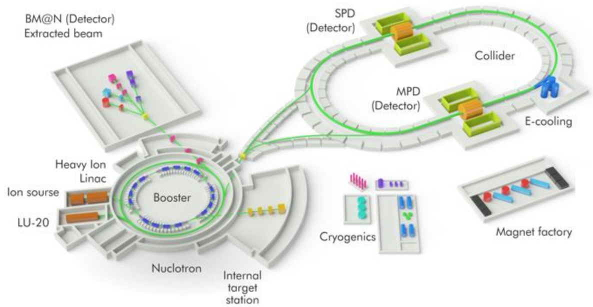
Lower energy programmes: study the phase transition and other landmarks

Key questions:

- Is there a critical point, and if yes, where?
- Where is deconfinement first reached?
- Is there a first-order phase transition?
- Is there a difference between chiral and deconfinement transition?

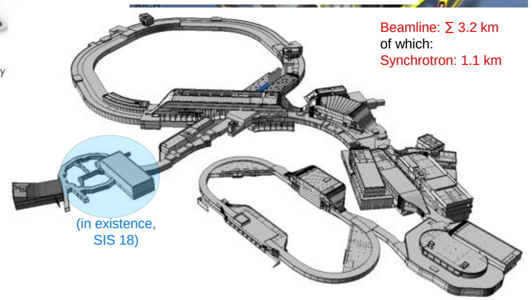
Facilities for Baryon-Rich Matter

NICA (JINR, Russia)
under construction

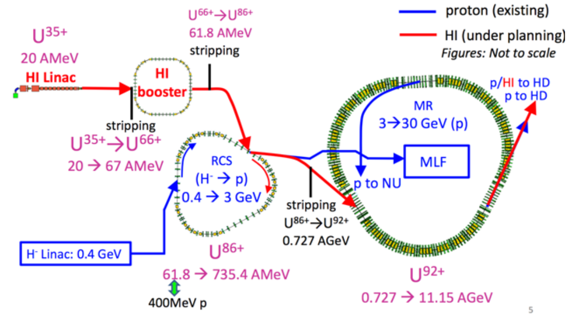


HADES (GSI, Germany)
running

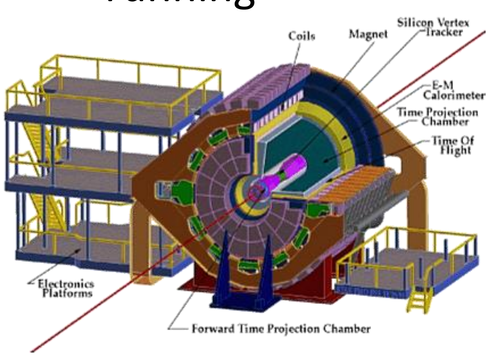
FAIR (Germany)



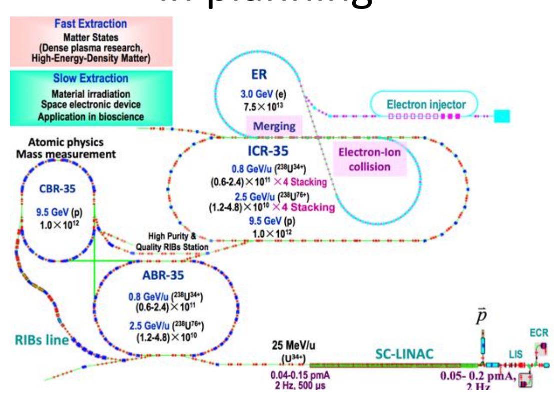
JPARC (Japan)
proposed



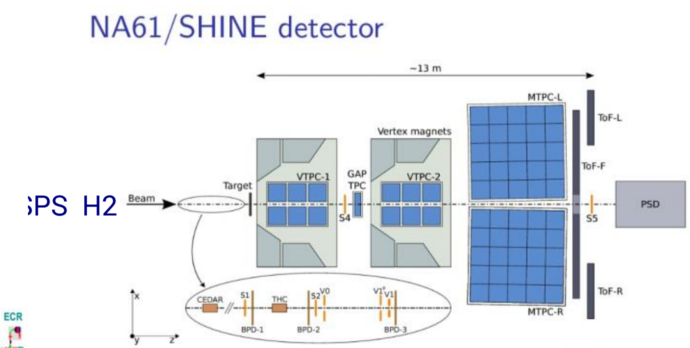
STAR (BNL, USA)
running



in planning



NA61 (SPS, CERN)
running



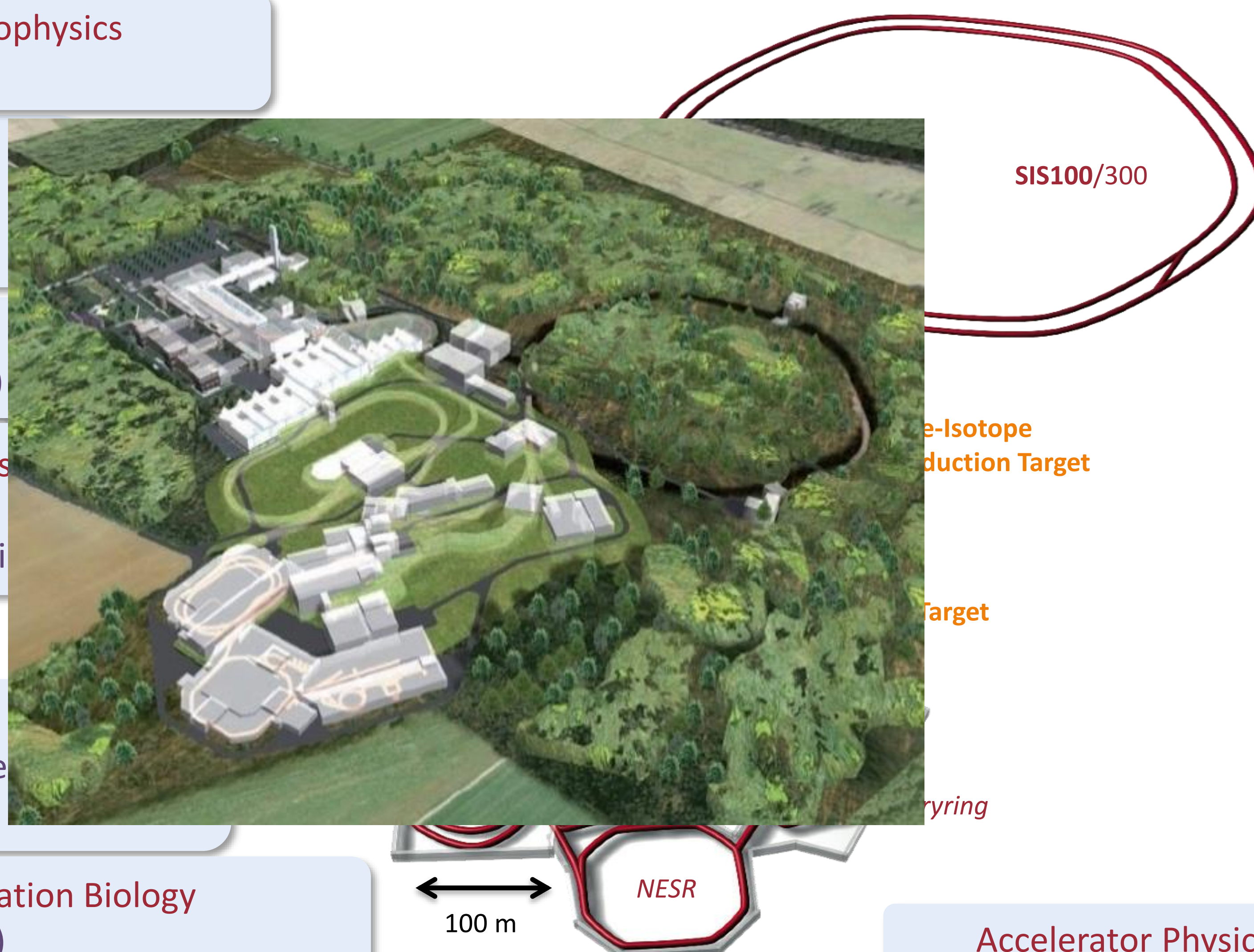
The FAIR Project

Nuclear Structure & Astrophysics
(Rare-isotope beams)

Hadron Physics
(Stored and cooled
14 GeV/c anti-protons)

QCD-Phase Diagram
(HI beams 2 to 45 GeV/u)

Fundamental Symmetries
& Ultra-High EM Fields
(Antiprotons & highly stri



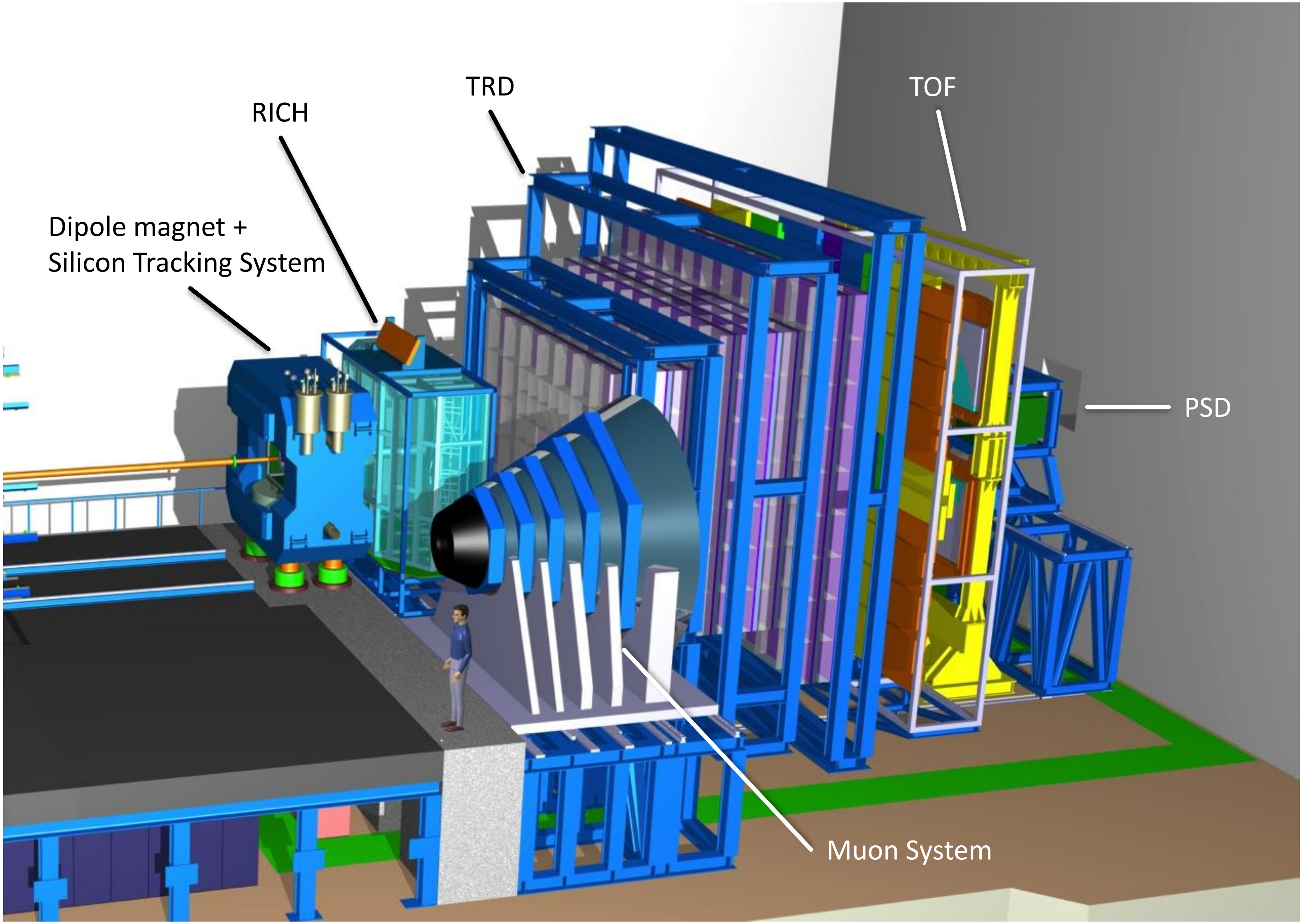
Dense Bulk Plasmas
(Ion-beam bunch compre
& petawatt-laser)

Materials Science & Radiation Biology
(Ion & antiproton beams)

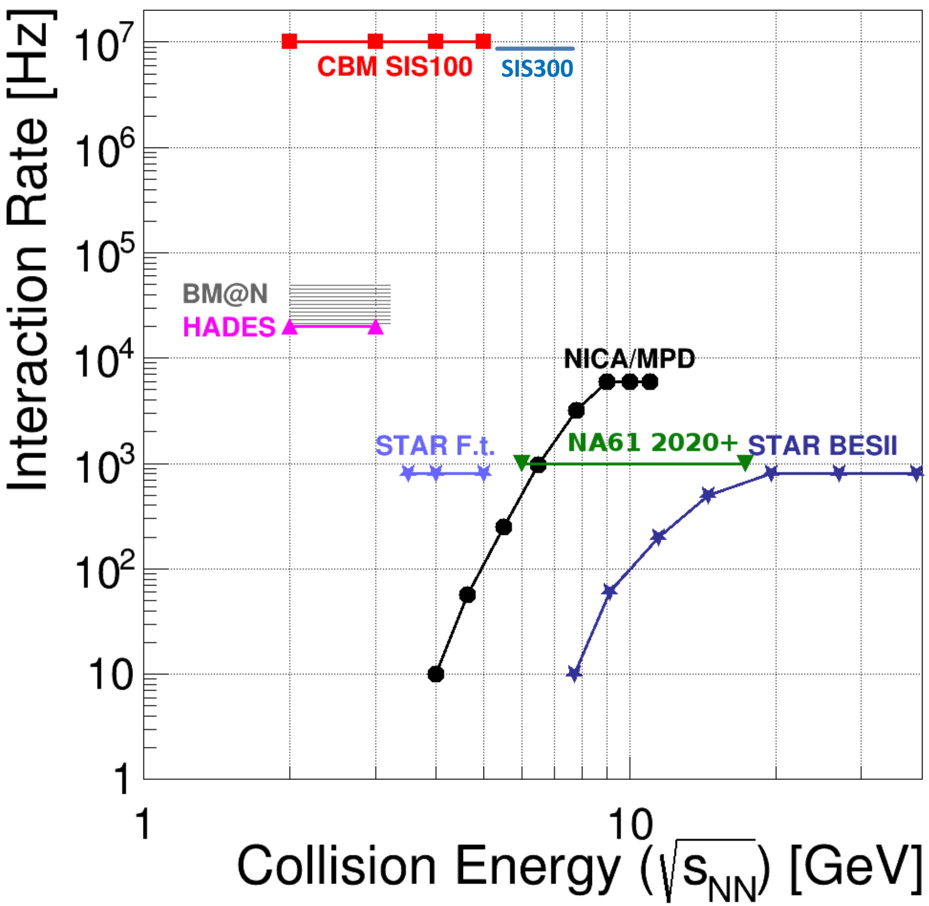
Accelerator Physics

FAIR Accelerator Complex and CBM

CBM: Experiment Systems



CBM in the experimental landscape



Uniqueness of CBM: very high rate capability

Comes with huge challenges in terms of:

- Speed and radiation hardness of detectors and read-out electronics
- Data processing on- and offline

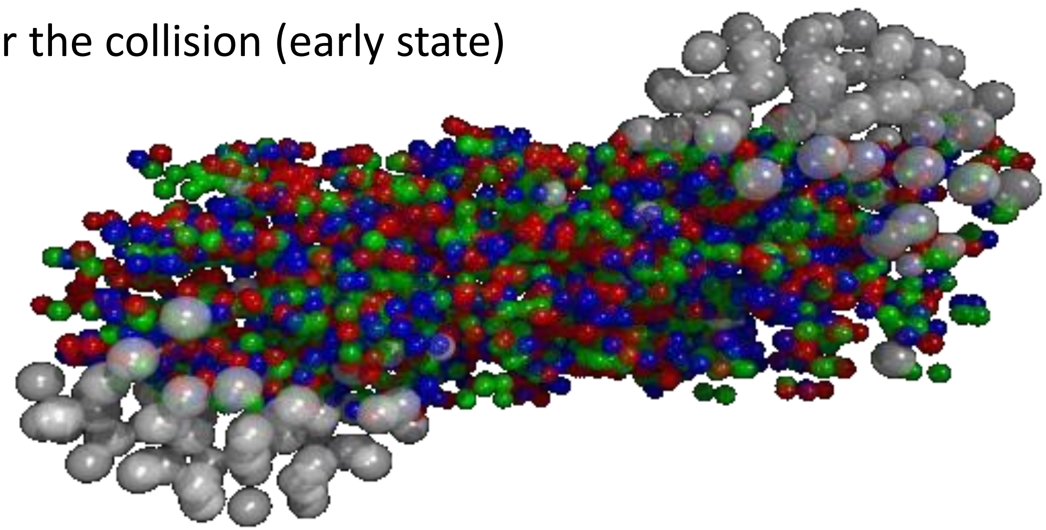
II. CBM Physics

(parforce, not exhaustive)

The Experimental Task

The Hope:

Learn from the multitude of emitted particles (final state) about the state of the matter immediately after the collision (early state)

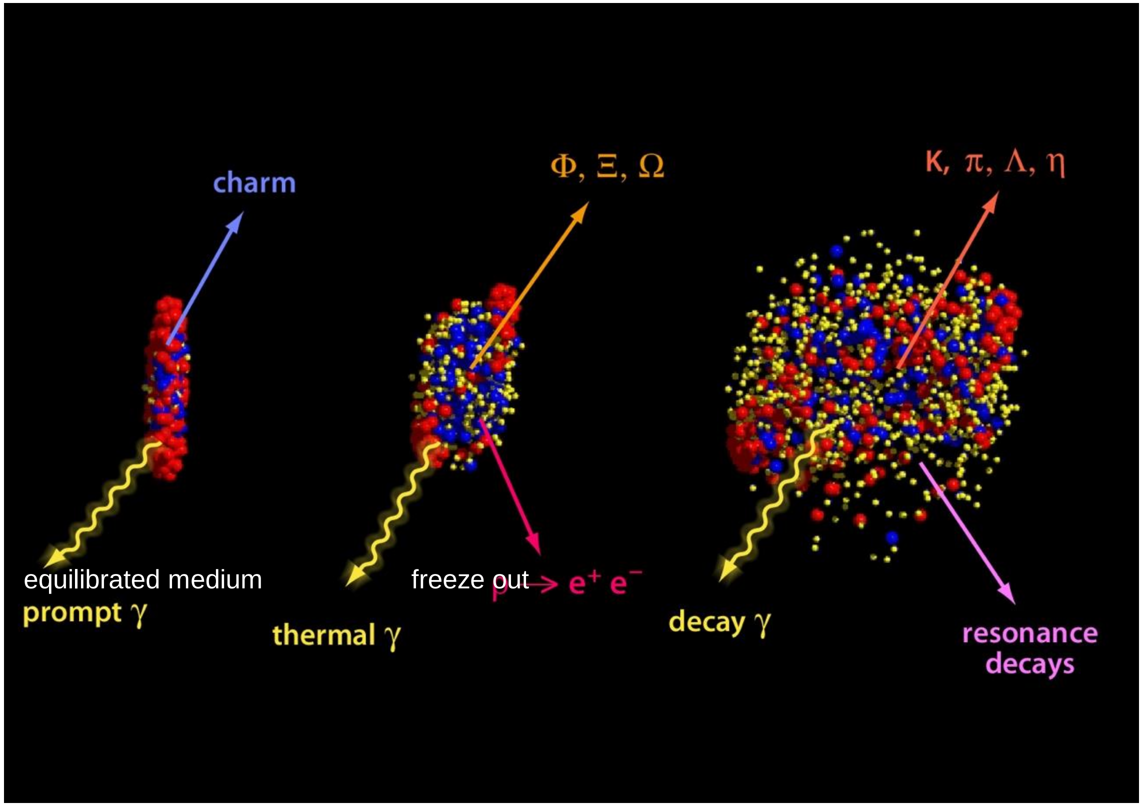


The Task:

Detect the final-state particles as completely as possible and characterise them w.r.t. momentum and identity (π, K. p, …)

Observables

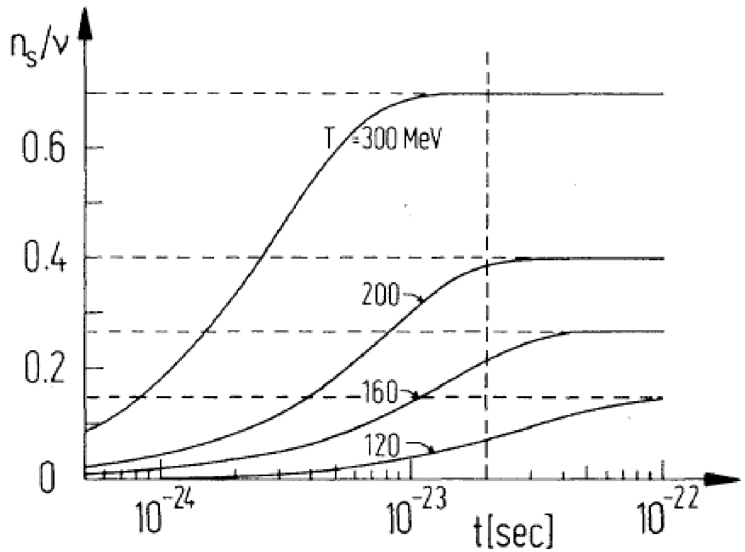
U+U collision at 23A GeV from UrQMD



Different probes give access to various stages of the collision

Strangeness is interesting

- No strangeness in entrance channel (nucleons): strangeness is produced in the reaction
- Hadronic production (e. g. p+p -> KΛp): $m_K \approx 500$ MeV >> T_H
- Partonic production (e.g. g + g -> s sbar): $m_s \approx 100$ MeV <= T_H



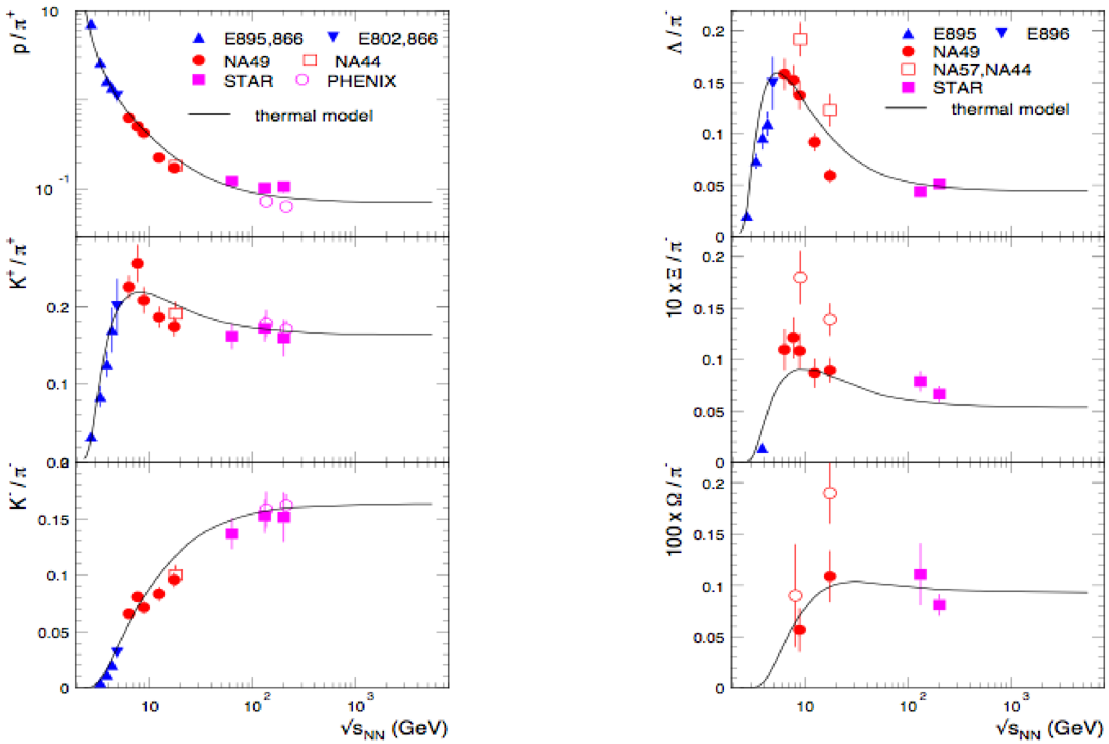
Koch, Müller, Rafelski, Phys. Rep. 142 (1986) 167

Relaxation of s-Quarks in a QGP within few fm/c ≈ lifetime of the fireball

Expectation: More strangeness production in A+A relative to p+p, if QGP was formed

„Strangeness enhancement“

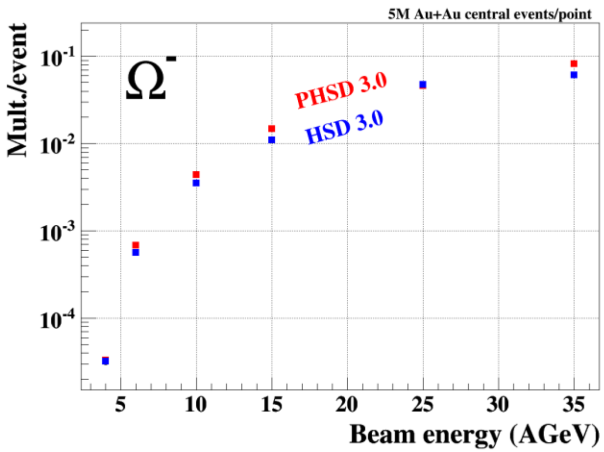
Multi-Strange Hyperons



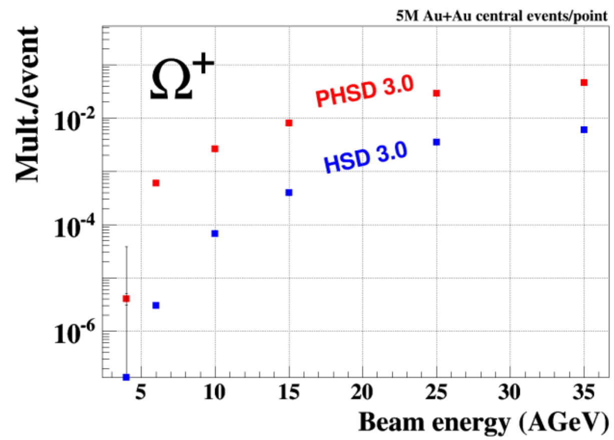
A long-lasting debate: pure hadronic description or signal of drastic change in matter properties?

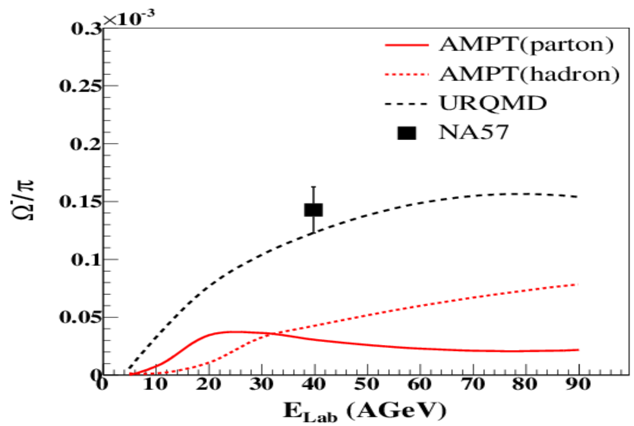
Data on multi-strange baryons will be decisive!

Strange Anti-Baryons

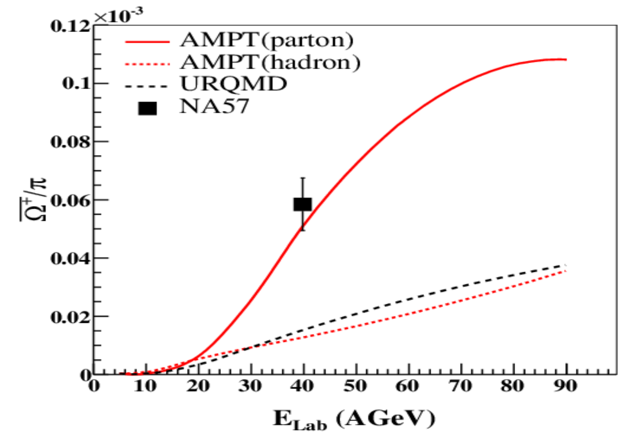


HSD / pHSD





AMPT

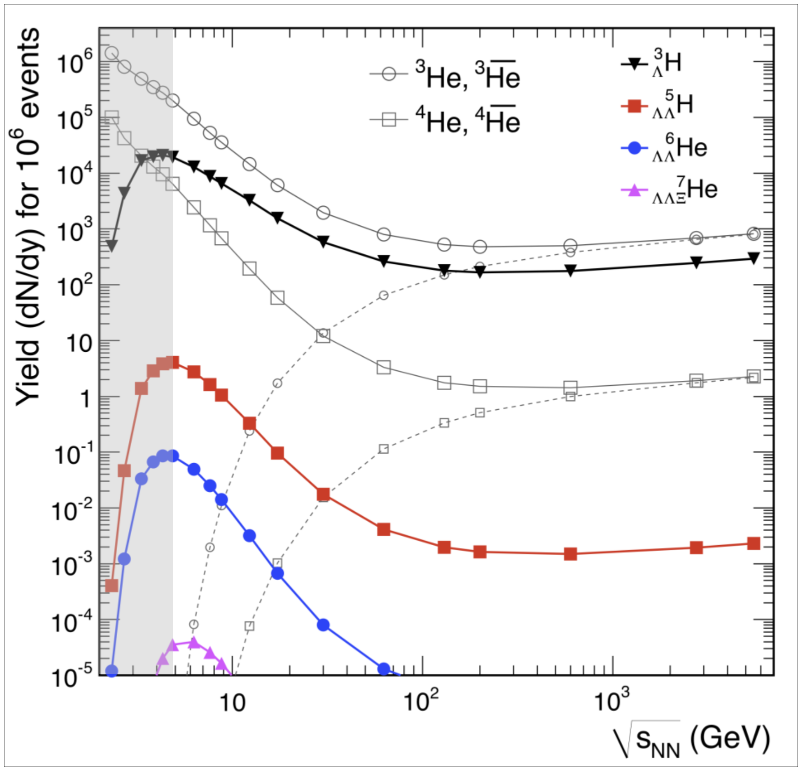


Microscopic models (including partonic production) predict the anti-hyperons to be very sensitive to partonic production mechanisms (hyperons much less)

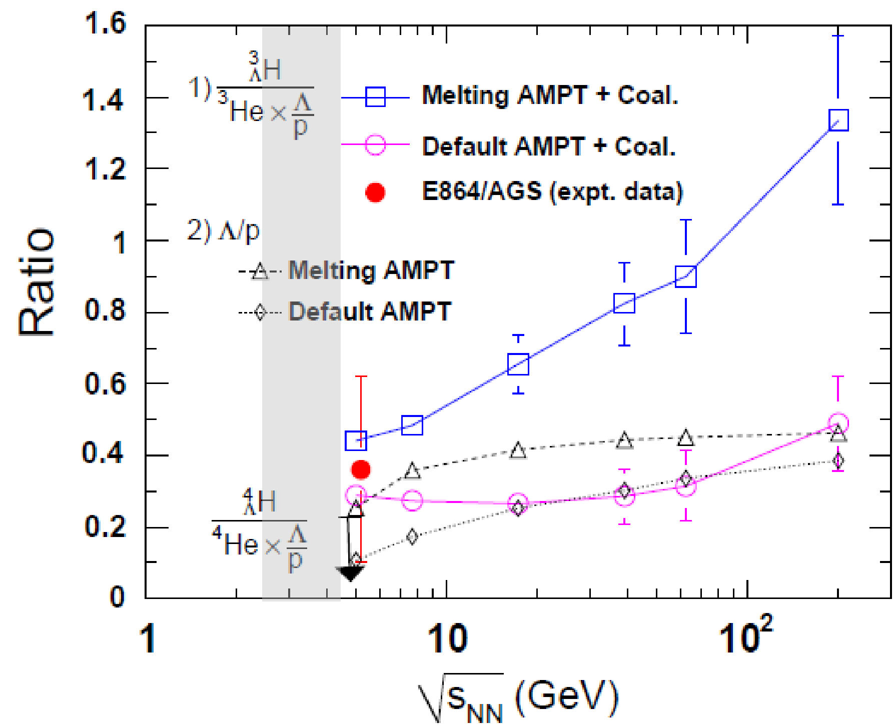
CBM Physics: Hyper-Matter

In heavy-ion collisions: produced through capture of Λ in light nuclei

A. Andronic et al., PLB 697 (2011) 203



S. Zhang et al., PLB 684 (2010) 224

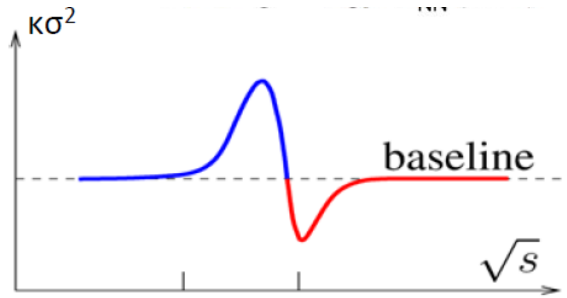


Thermal model: maximum production at CBM energies

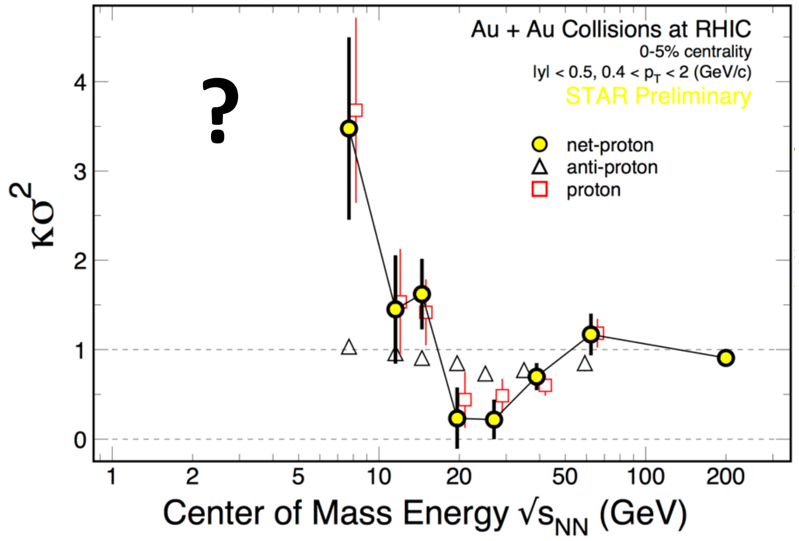
Transport: sensitive to medium properties (correlation of strangeness and baryon number)

Fluctuations

Should signal the critical point...

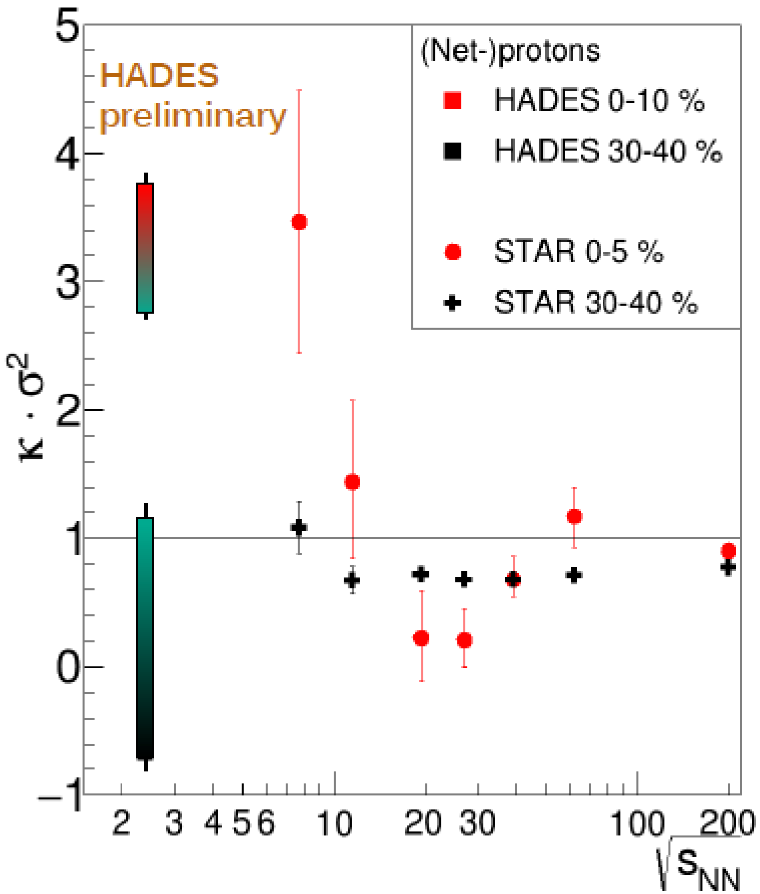


M. Stephanov. J. Physics G.: Nucl. Part. Phys. ***38*** (2011) 124147



STAR, NPA 956 (2016) 320c

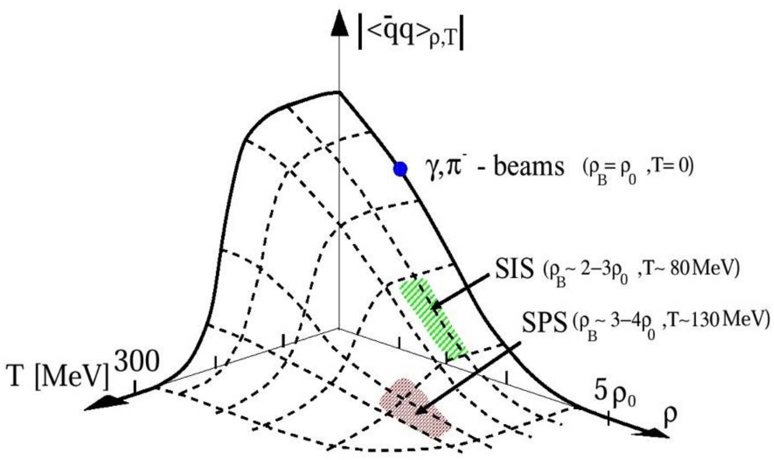
M. Lorentz, QM 2017



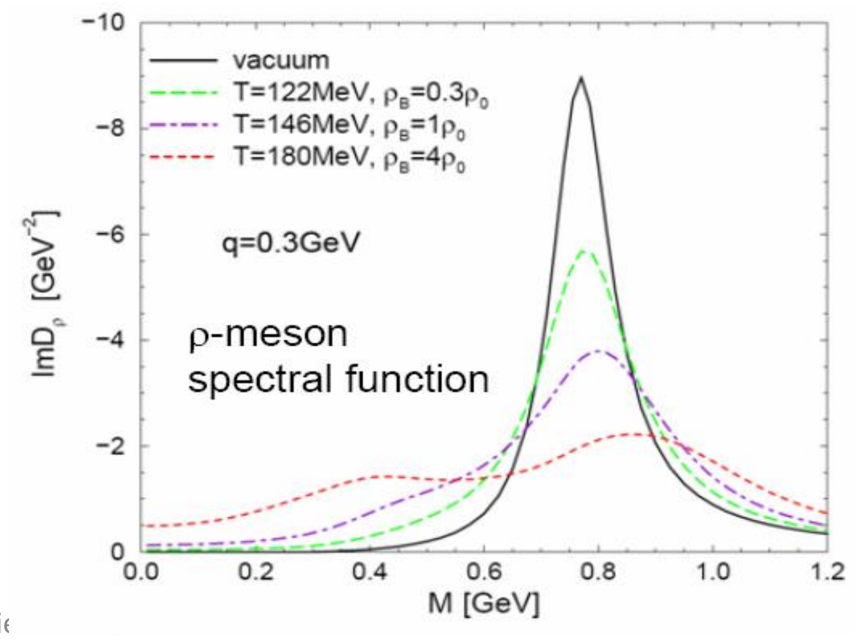
...or spinodial decomposition of a mixed phase?

Vector Mesons and the Generation of Mass

- Hadrons are expected to change their properties (mass / width) in presence of dense medium
  - vanishing of chiral condensate; restoration of chiral symmetry (?)
- Experimental access: short-lived vector mesons (ρ)
  - decay inside the fireball -> retain information on dense environment
  - decay into lepton pairs: no strong interaction, carry information out of the medium



R. Rapp and J. Wambach, Act. Nucl. Phys. 28 (2000) 1

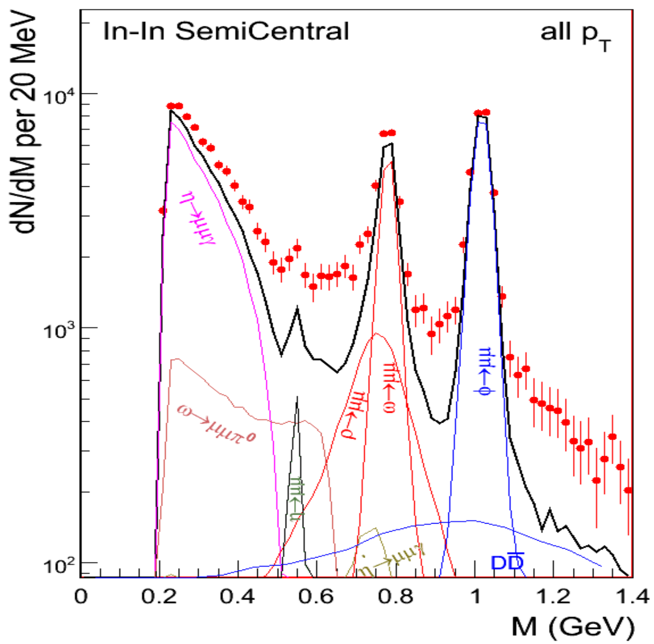


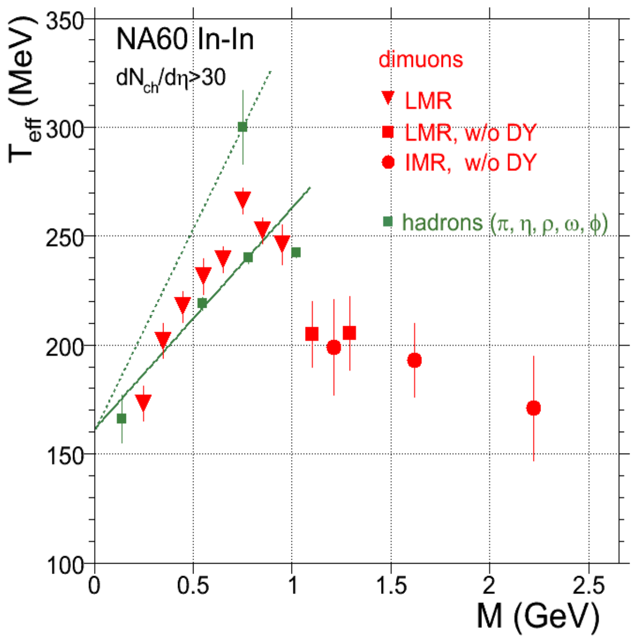
CBM Physics: Lepton Pairs

Emitted throughout the lifetime of the fireball: probe its space-time evolution

Low mass (< 1 GeV): in-medium properties of rho meson; excess yield (over vacuum hadronic cocktail) is sensitive to the lifetime of the system

Intermediate mass (1 – 2.5 GeV): no hadronic sources; measure directly the temperature of the fireball.



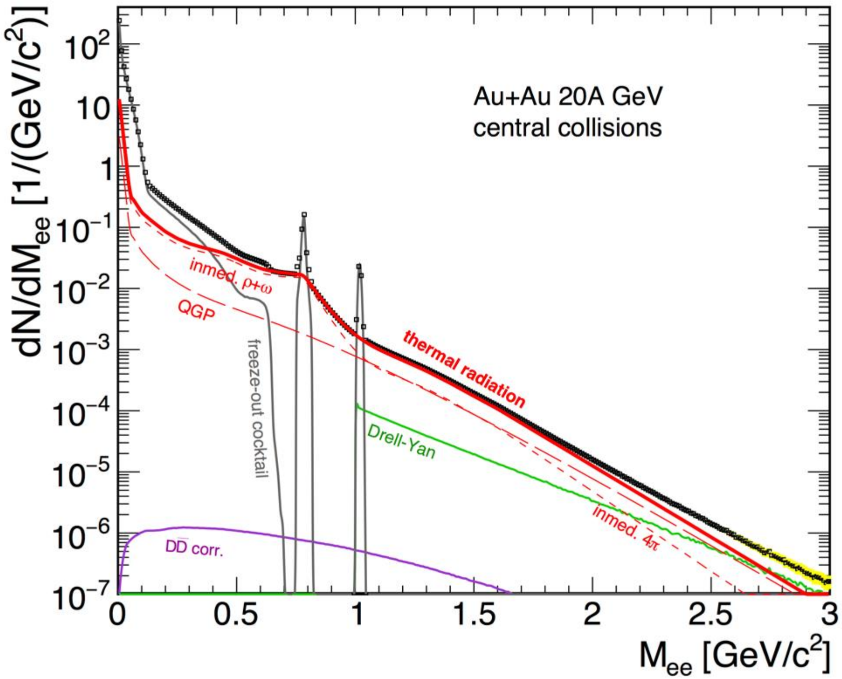


NA60, EPJC 59 (2009) 607

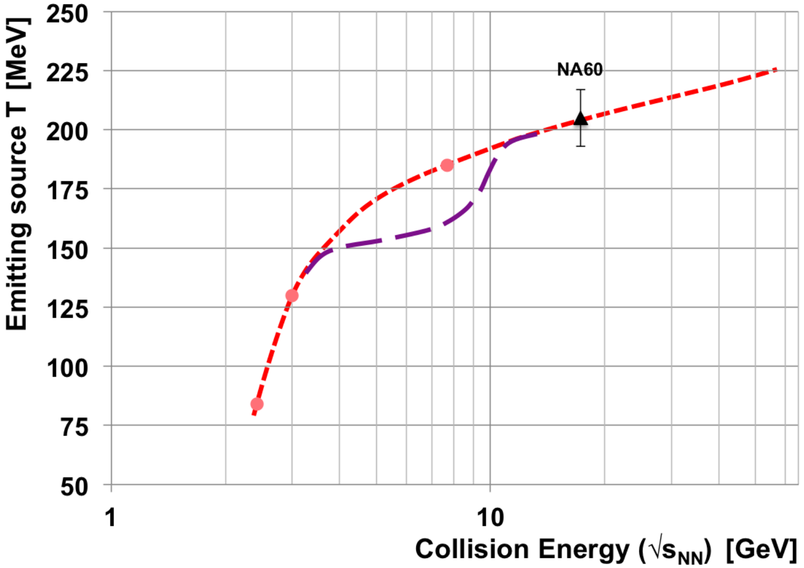
CBM Physics: Lepton Pairs

No di-lepton data exist between HADES and NA60!

CBM will provide di-lepton mass spectra and measure the caloric curve in the FAIR energy range. Interpretation almost model-independent!



CBM Simulation



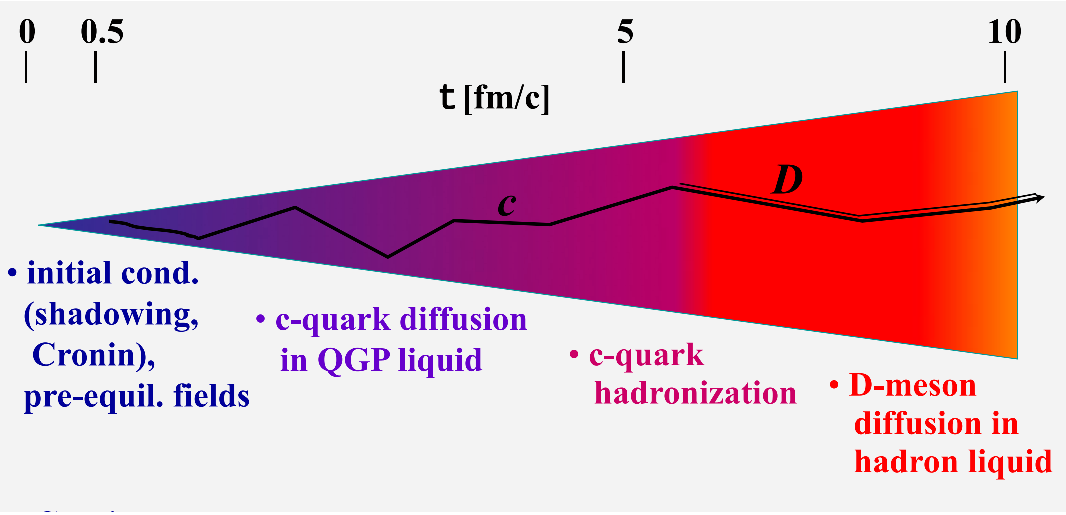
Extracted temperature at intermediate masses; violet: speculated signature of a mixed phase

Charm

- Important (if not decisive) probe of the created medium
  - that holds at all energies!
- Fraction of charm hadronising in J/psi is sensitive to the medium properties (e.g. suppression in QGP)
- Particular at lower energies (below top SPS):
  - $N_{ccbar} << 1$ -> no regeneration, ”clean” probe
  - Softer J/psi, longer-lived fireball: charm has a chance to see the medium
- Proper interpretation of data requires the measurement of both open and hidden charm
  - Important part of the CBM physics programme

Charm in Heavy-Ion Collisions

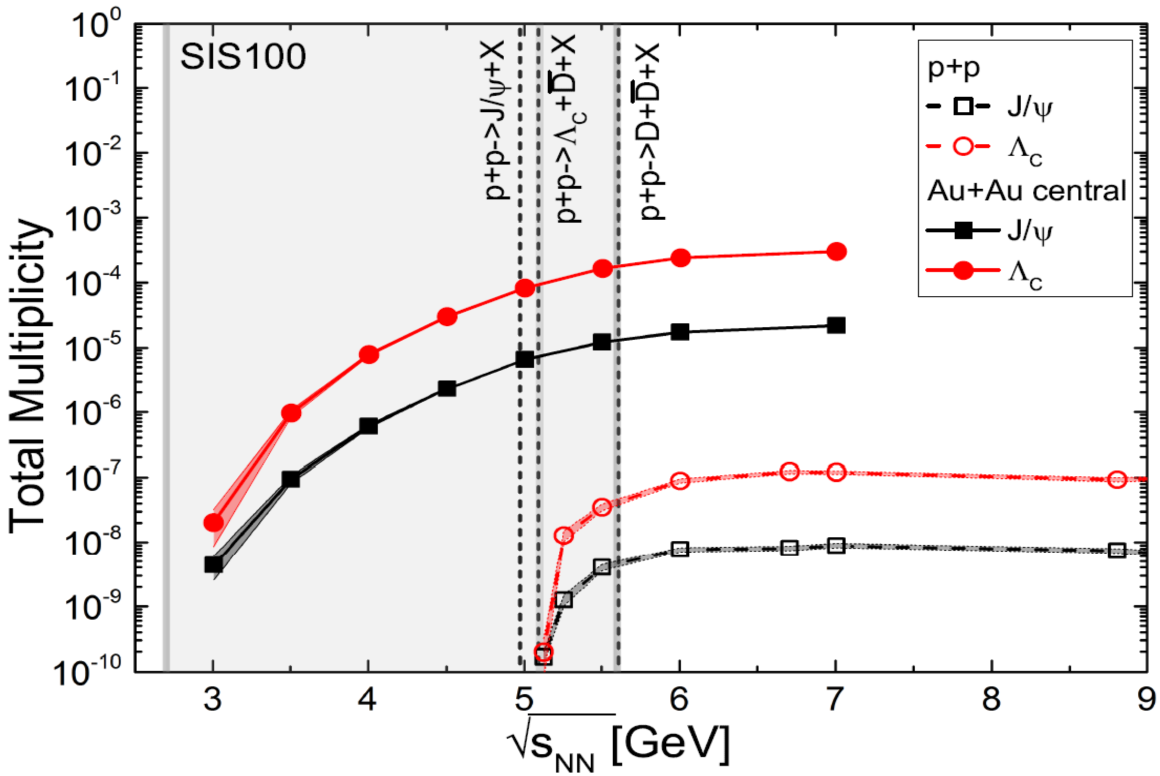
- Unlike lighter quarks, $m_c >> T$
  - thermal production of charm negligible
  - production of charm in first-chance N-N collisions
  - charm probes the produced medium
    - c quark diffusion in QGP
    - D meson / J/ψ propagation in hadronic medium



courtesy R. Rapp

Open Charm Below Threshold

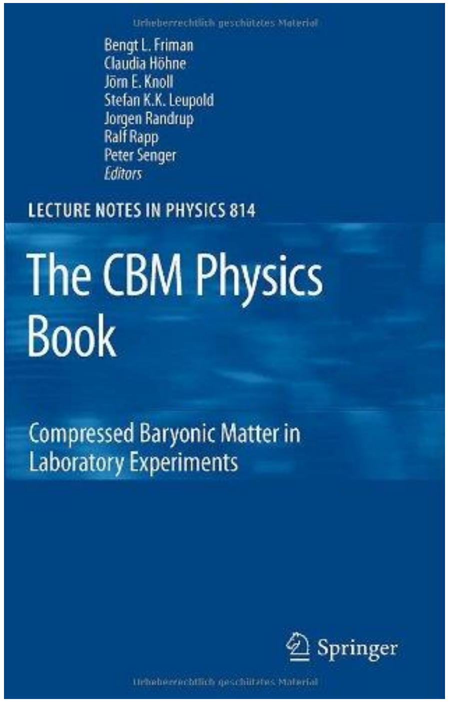
J. Steinheimer et al., PRC 95 (2017) 014911

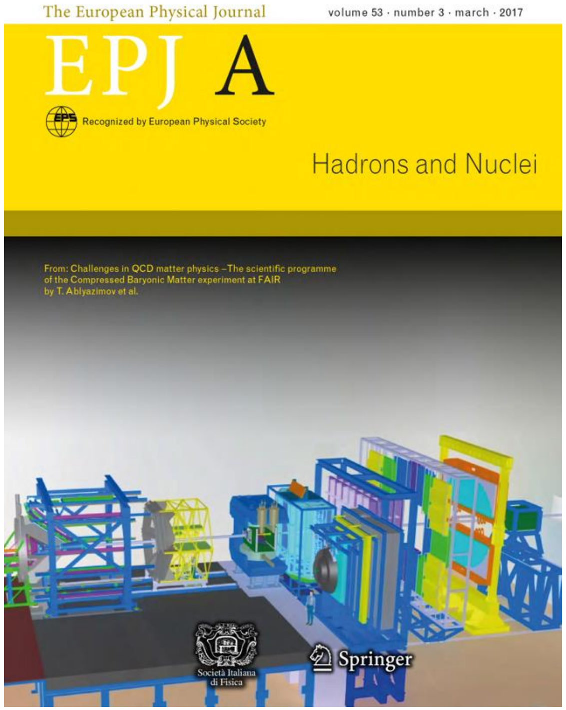


Sub-threshold production through heavy baryonic resonances:
$N^* \rightarrow \Lambda_c + D$ and $N^* \rightarrow N + J/\psi$

CBM Physics Programme

- A long menu of observables from strange hadrons over lepton pairs to charmed hadrons
- For more exhaustive information:



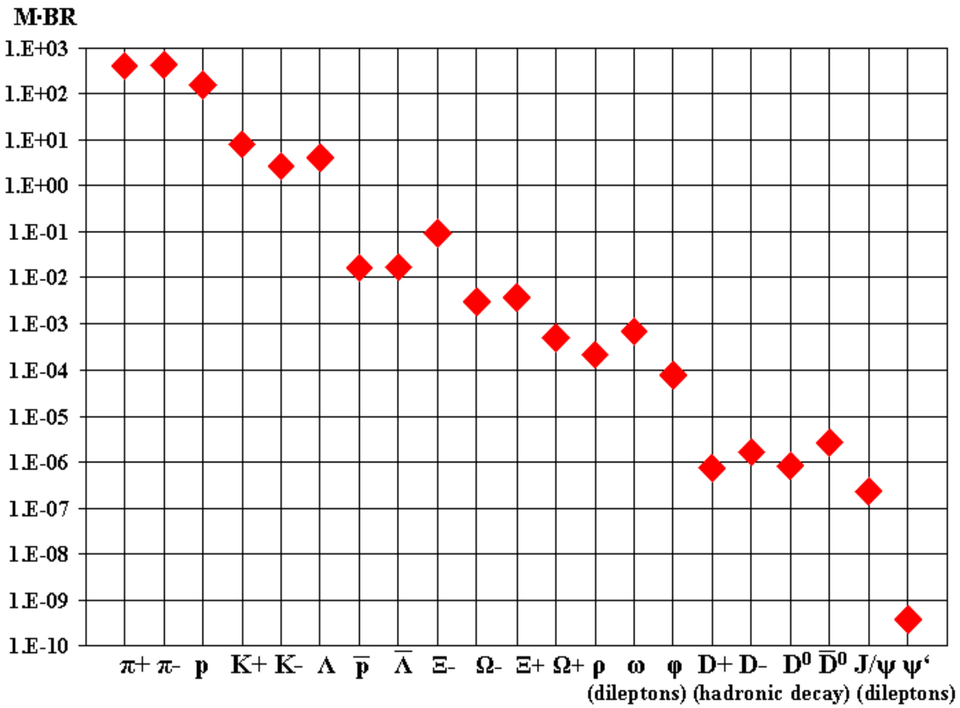


III. Online Data Selection

(in order to avoid the term “trigger”)

Rare Observables

Model predictions of particle multiplicities (x branching ratio)
(central Au+Au, 25A GeV)



- Some of the (most interesting) probes are extremely rare.
- Decent measurement in reasonable time necessitates high interaction rates.
- Current heavy-ion experiments run with very moderate rates (100 Hz - several kHz).
- When designing a new experiment: what is the rate limit?

Rate Limitations

The measured interaction rates are limited by:

- what the accelerator can deliver: beam luminosity (collider) or intensity (fixed-target)
- what the experiment can take:
  - speed of detectors (fast: e.g. ECAL, solid-state detectors; slow: e.g. gas drift detectors)
  - speed of read-out electronics (e.g. shaping time of the ADC)
  - trigger latency
  - DAQ throughput
  - archival rate

Current experimental upgrade plans usually target higher interaction rates (LHC experiments, STAR, NA61)

CBM is designed as a high-rate experiment from the beginning.

Natural Time Scales

Considerations for the design interaction rate:

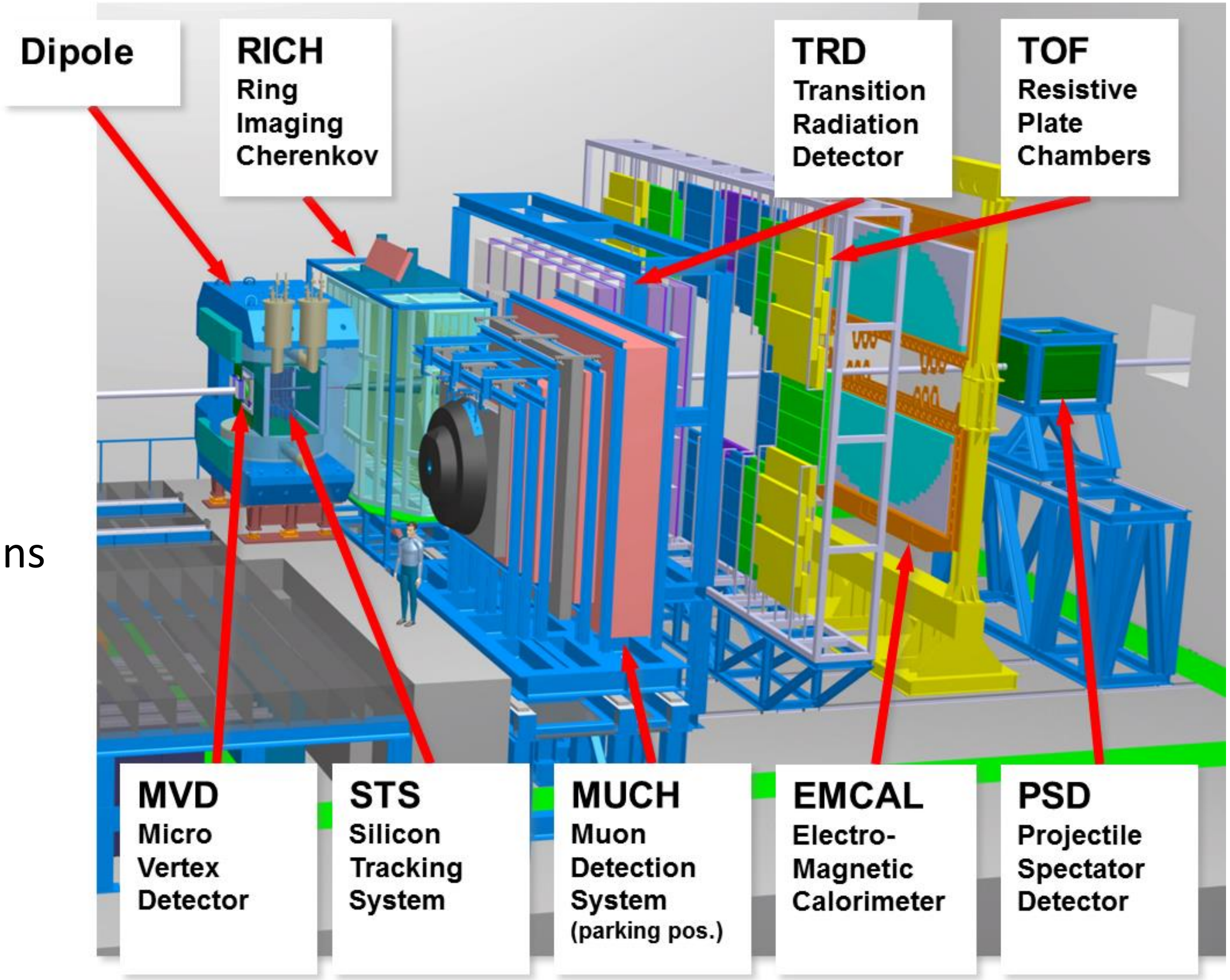
- The accelerator promises 2 x 10^9 ions/s. With a (typical) 1% target, this would give 20 MHz interaction rate -> 50 ns on average between collisions.
- Event duration
  - typical experiment size 10m
  - Difference of time-of-flight through the setup between $\beta = 1$ and $\beta = 0.7$ particles is 20 ns
- Event pile-up should be avoided
  - hard to resolve different events in fixed-target mode (are all within several 100 µm inside the target)

CBM design rate: 10 MHz

Experimental Setup

Mission: build a

- a fixed-target heavy-ion experiment
- for collisions in the FAIR energy range
- which can measure hadrons, electrons, muons and open charm
- at event rates up to 10 MHz.



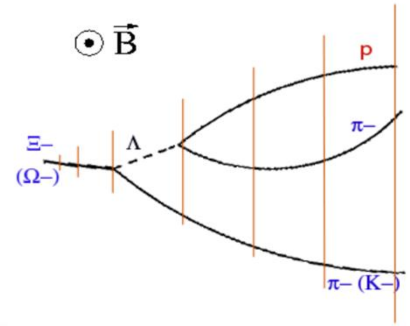
Data Rates

- Raw data event size: 100 kB / min. bias event (Au+Au)
- At 10 MHz event rate: raw data rate 1 TB/s

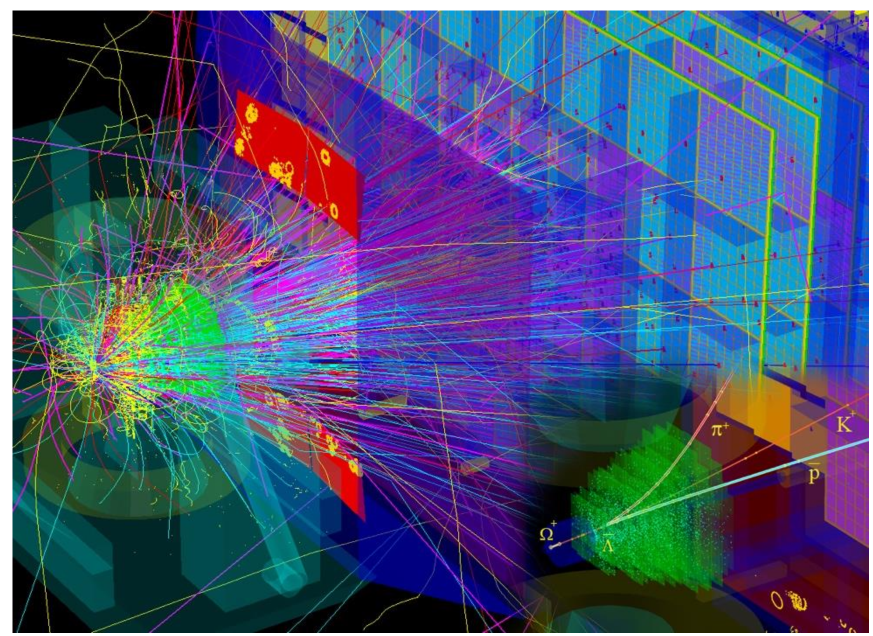
- Archival rate:
  - technologically possible are rates of 100 GB/s and above
  - limiting factor are the storage costs
  - typical runtime scenario 2 effective months / year (5×10^6 s)
  - At 1 GB/s: gives a storage volume of 5 PB/year

We aim at an data archival rate of a few GB/s, meaning that the raw data volume has to be suppressed online by factors 300 - 1000.

Selecting Data Online

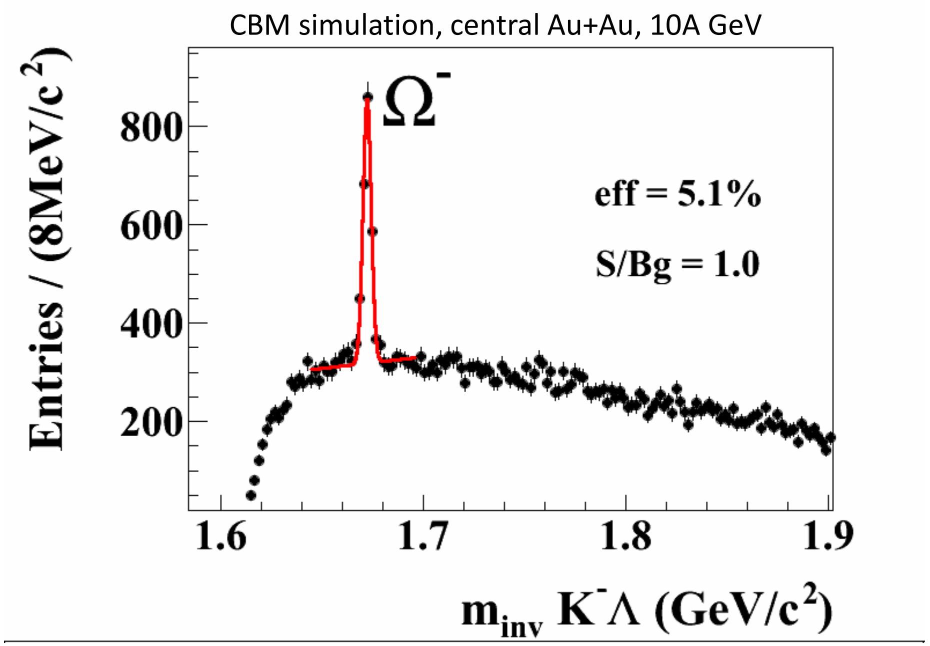


- Some (not all) of the rare probes have a complex signature. Example: $\Omega \to \Lambda K^+ \to p\pi^- K^+$
- In the background of several hundreds of charged tracks
- No simple primitive to be implemented in trigger logic



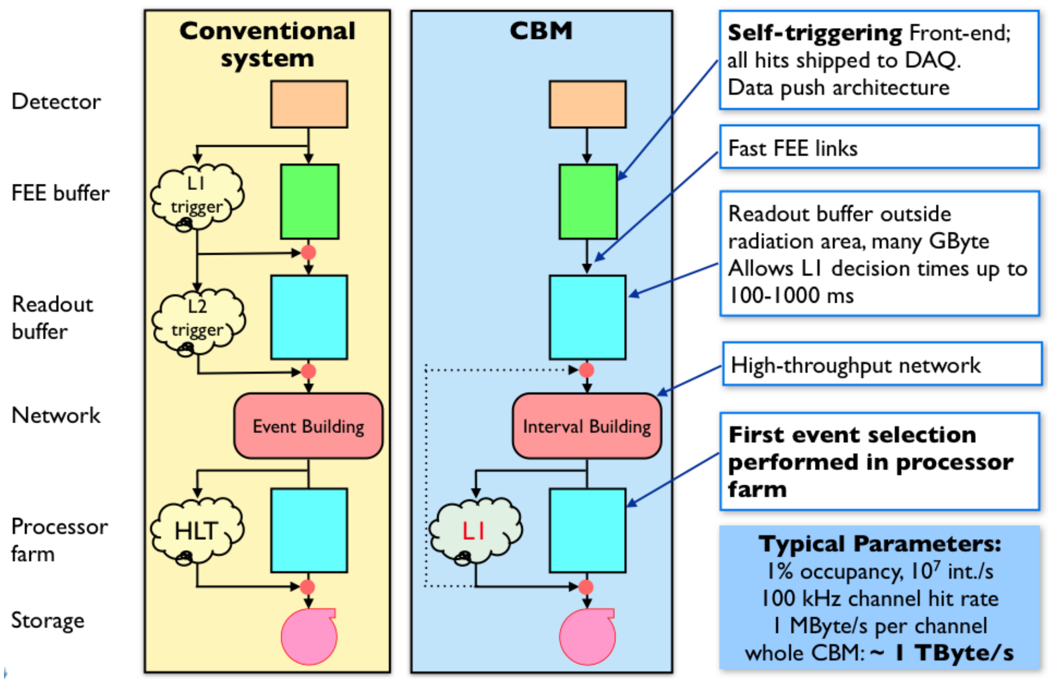
Selecting Data Online

- Selection requires reconstruction of all tracks plus combinatorial search for two decay vertices: typical software task
- Offline performance for Omega: S/B ~1
- If realisable online: excellent software trigger



- Similar argument for many topology-based observables (hyper-nuclei, exotic strange objects, charm)
- Simpler patterns e.g. for lepton pairs (J/ψ or low-mass)
- R/O design must be based on the most challenging case

DAQ and Trigger Concept



- No hardware trigger at all
- Continuous readout by autonomous FEE
- FEE sends data message on each signal above threshold ("self-triggered")
- Hit message come with a time stamp; readout system is synchronised by a central clock
- DAQ aggregates messages based on their time stamp into "time slices"
- Time slices are delivered to the online computing farm (FLES)
- Decision on data selection is done in the FLES (in software)

Triggered and Free-Running Readout

Trigger: snapshots of the detector

Trigger-less: a movie of the detector

N.b.: Too large to be stored! Will be cut into pieces (events) in the photo lab (= FLES).

Advantages

- no latency issues; the system is limited by throughput
- no buffers on FEE ASICS (inside radiation zone) needed
- data selection is shifted to software
  - in principle, everything which is usually done in the offline analysis can be implemented for online data selection
  - very flexible: easy to switch between triggers, to use different triggers in parallel
  - assessing the trigger efficiency is straightforward: no emulation of trigger logic needed

So, why was it not done before?

- Requires an online compute farm powerful enough to process the entire data stream
- Throughput is defined by the size of the compute farm and the speed of the algorithms.
- CBM estimate: equivalent to ~10^5 CPU cores needed
- Some years ago, this was the entire LHCgrid
- Nowadays (let alone in some years), feasible to finance and to host close to the experiment

Issues of a Trigger-less System

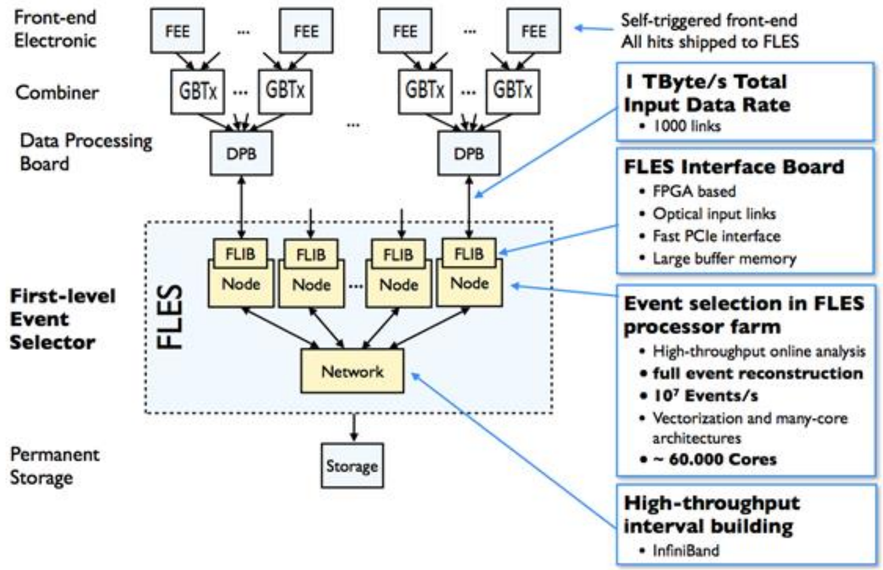
- Noise from detectors and electronics
  - tight threshold in order to suppress the contribution of noise to the total data rate
  - good signal-to-noise ratios in detectors are needed in order not to lose signals

Example: fraction of noise from the STS

M.b. event rate	10 MHz	1 MHz	100 kHz	10 kHz
Threshold / noise = 3	40 %	86 %	98 %	99.8 %
Threshold / noise = 3.5	11 %	55 %	92 %	99.2 %
Threshold / noise = 4	2 %	15 %	65 %	95 %

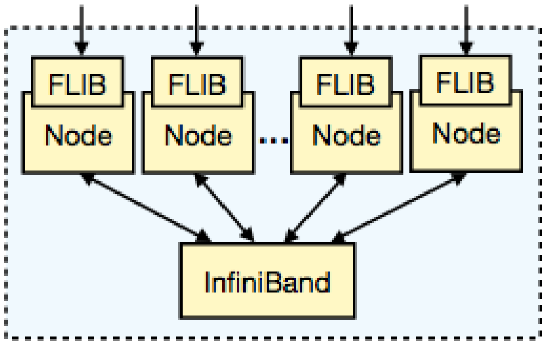
- No events given to software
  - Unlike in conventional HLTs, where events are build before by DAQ
  - Online reconstruction starts from time-sorted data stream
  - Algorithms have to take into account time coordinate (“4D reconstruction”)

Online Data Flow



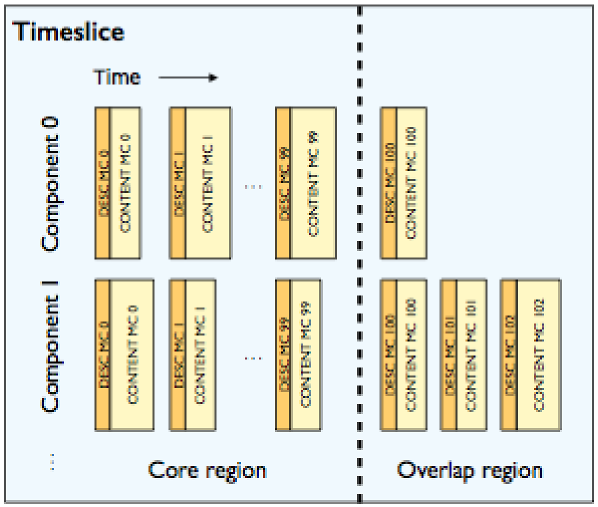
Green Cube, GSI

FLES Architecture



- FLES is designed as an HPC cluster
  - Commodity PC hardware
  - GPGPU accelerators
  - Custom input interface
- Total input data rate ~1 TB/s
- InfiniBand network for interval building
  - High throughput, low latency switched fabric communications
  - Provides RDMA data transfer, very convenient for interval building
  - Most-used system interconnect in latest TOP500 (224 systems)*
- Flat structure w/o dedicated input nodes
  Inputs are distributed over the cluster
  - Makes use of full-duplex bidirectional InfiniBand bandwith
  - Input data is concise, no need for processing before interval building
- Decision on actual commodity hardware components as late as possible
  - First phase: full input connectivity, but limited processing and networking

Time Slice: Interface to Online Reconstruction



Timeslice

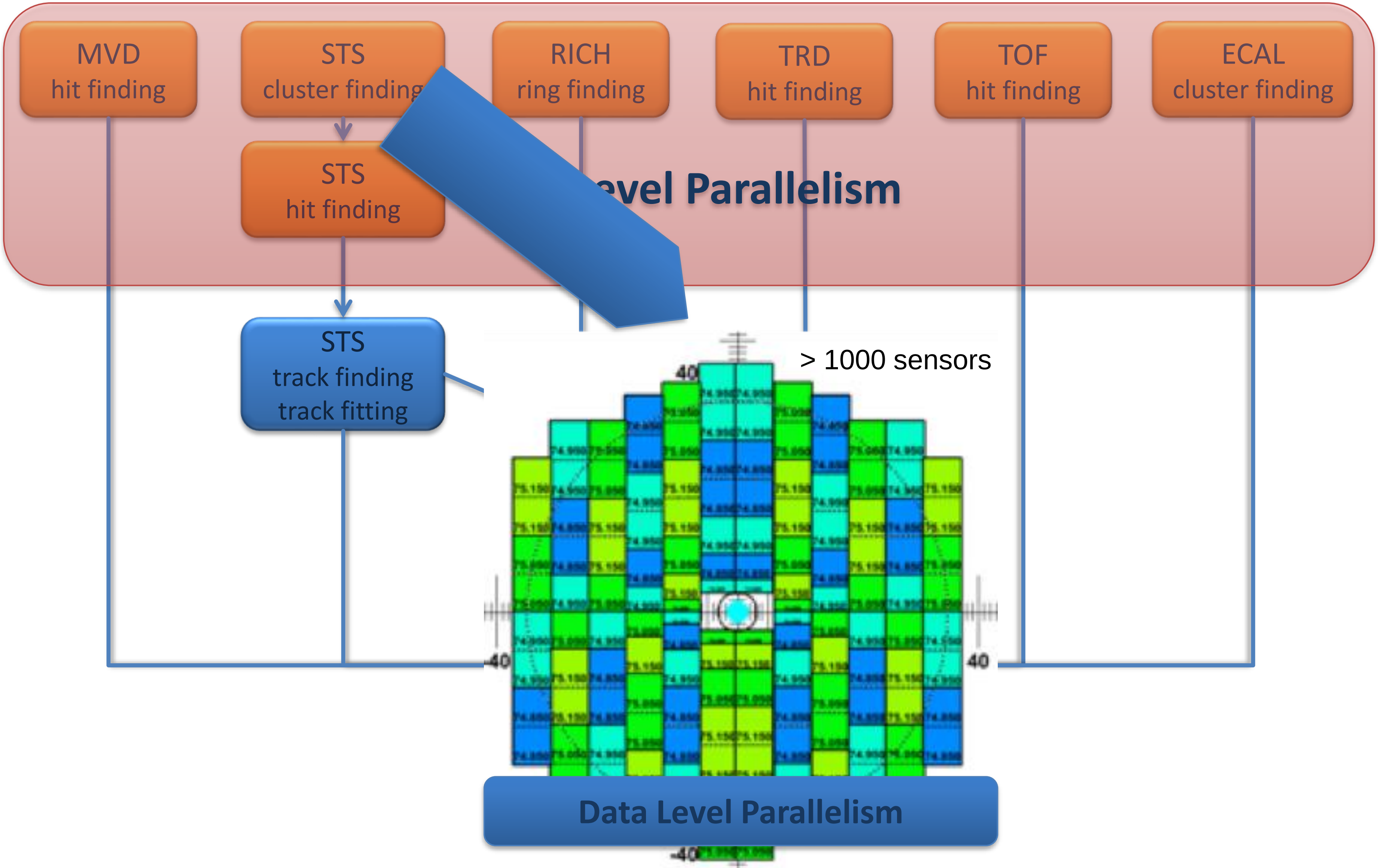
- Two-dimensional indexed access to microslices
- Overlap according to detector time precision
- Interface to online reconstruction software

- Basic idea: For each timeslice, an instance of the reconstruction code...
  - is given direct indexed access to all corresponding data
  - uses detector-specific code to understand the contents of the MCs
  - applies adjustments (fine calibration) to detector timestamps if necessary
  - finds, reconstructs and analyzes the contained events

Real-Time Reconstruction

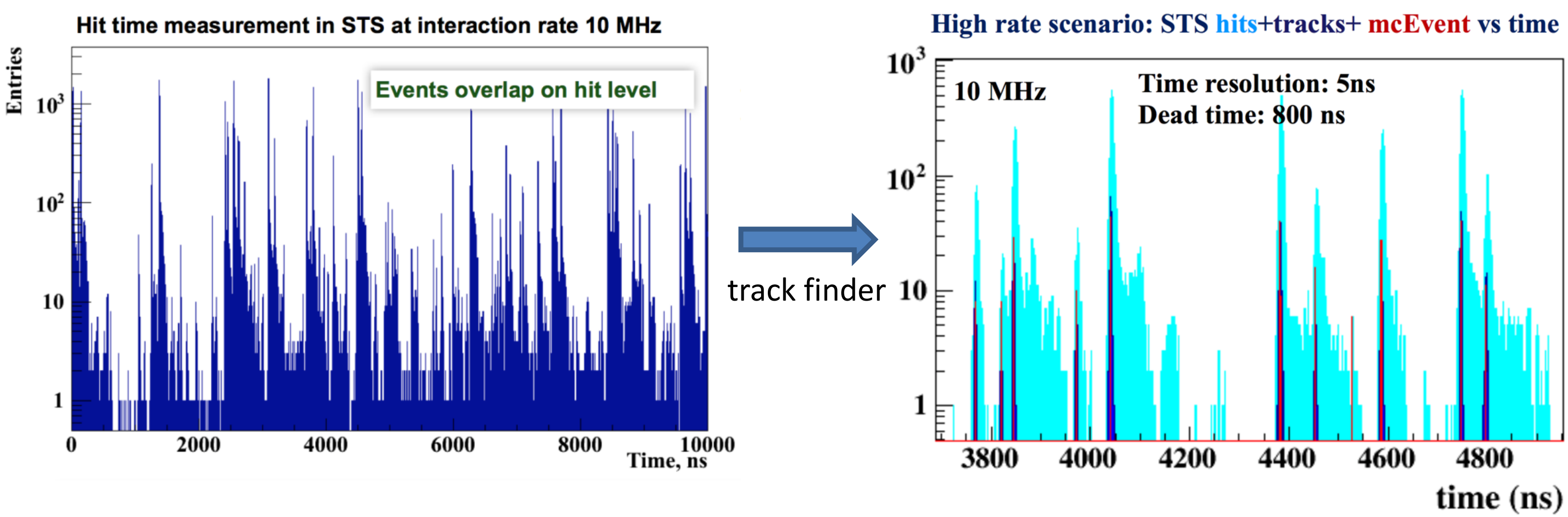
- In our concept, the task of online data selection is shifted from electronic engineering to software engineering.
- For a given event / data rate, the speed of the algorithms determines the required size of the online compute farm.
- For a given financial budget / size of the online farm, the speed of the algorithms determine the physics output of the experiment.
- High-performance online software is a pre-requisite for the successful operation of CBM.
  - Make optimal use of available parallel computer architectures: many-core, GPU, accelerators
  - Be flexible to upcoming new architectures
- Parallelism is the key word
  - Data-level parallelism: one time slice per compute node
  - Task-level and data-level parallelism within time slice

Parallelisation within time-slice



Track Finding

- Usually, the most compute-intensive task in reconstruction
- Approach: Cellular Automaton, operating on time-ordered stream of detector hits (no event association)



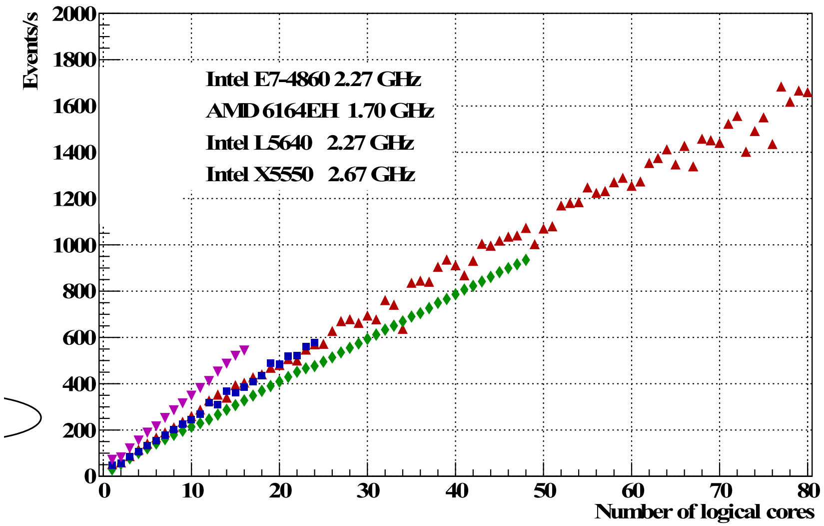
- After track finding, events can be defined as time-clusters of tracks

CA track finder: performance and scalability

100 AuAu minimum bias events at 10 AGeV

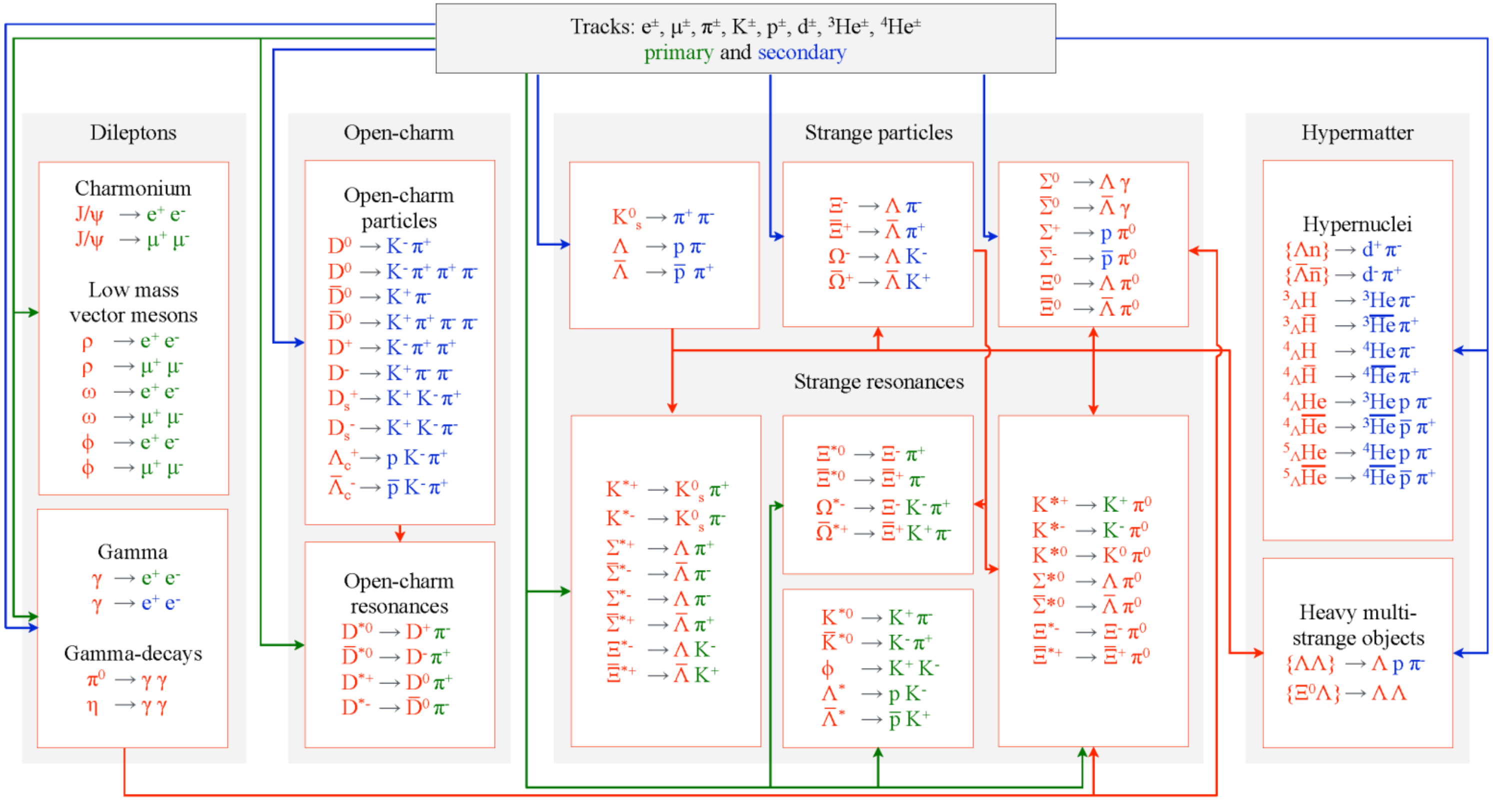
Efficiency, %	3D	4D 0.1MHz	4D 1MHz	4D 10MHz
All tracks	92.5 %	93.8 %	93.5 %	91.7 %
Primary high-p	98.3 %	98.1 %	97.9 %	96.2 %
Primary low-p	93.9 %	95.4 %	95.5 %	94.3 %
Secondary high-p	90.8 %	94.6 %	93.5 %	90.2 %
Secondary low-p	62.2 %	68.5 %	67.6 %	64.3 %
Clone level	0.6 %	0.6 %	0.6 %	0.6 %
Ghost level	1.8 %	0.6 %	0.6 %	0.6 %
True hits per track	92%	93 %	93 %	93%
Hits per MC track	7.0	7.0	6.97	6.70

High efficiency for primary tracks
Rate effects become visible above 1 MHz interaction rate



Good scaling behaviour: well suited for many-core systems

Particle Reconstruction in Real-Time



KFParticleFinder: Simultaneous access to multitude of particles
Real-time reconstruction allows online selection of rare probes.

Real-Time Reconstruction - Status

Not all problems yet solved - but the major hurdles are taken.

Results so far give confidence that online event reconstruction and selection will be possible on a computer farm of < 10^5 cores.

Summary

- CBM: A heavy-ion experiment to investigate baryon-rich QCD matter at energies from 2A to 45A GeV at FAIR/Darmstadt
- The physics programme comprises a suite of observables including very rare ones. The design punchline is thus to be capable to take interaction rates in the MHz range.
- Novel read-out concept without hardware trigger; real-time data selection exclusively on CPU.
- Timeline: Facility under construction; experiment starts mass production of components soon; operation from 2024 on.