The CBM Experiment at FAIR and its Silicon Tracking System:

Physics case, Experimental approach, Status of development

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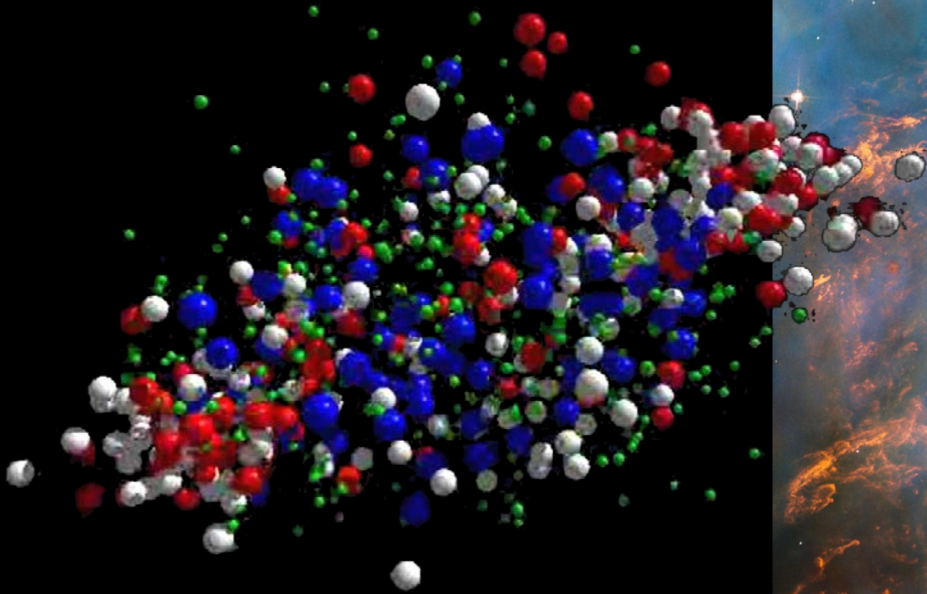
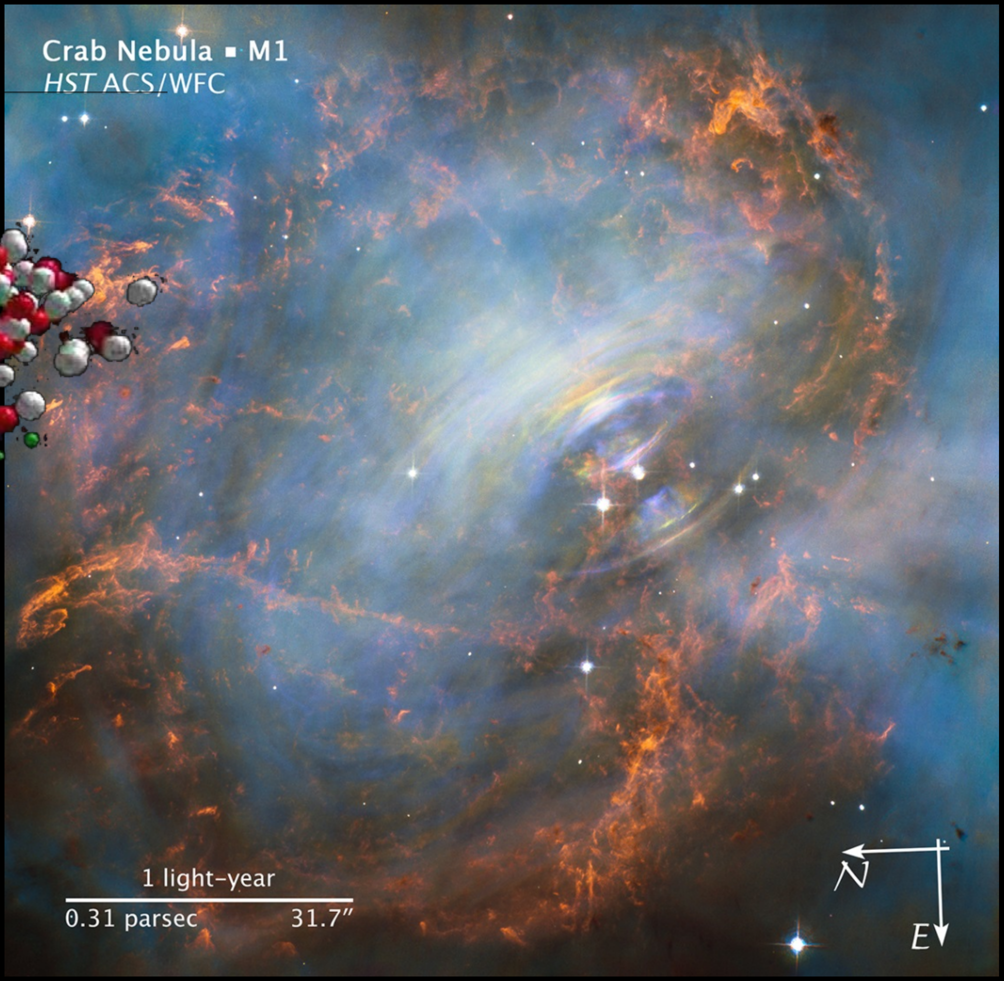
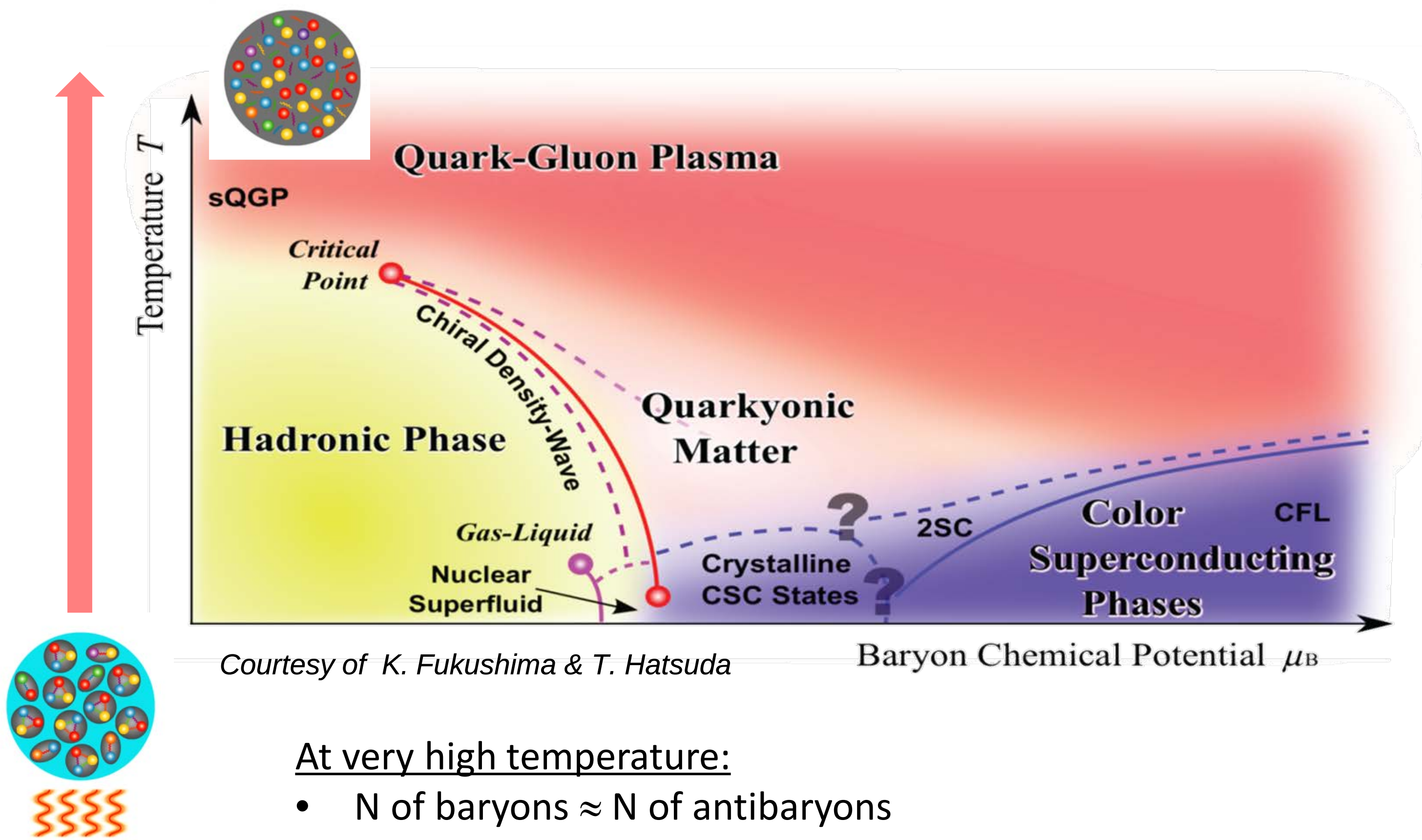
JAEA Advanced Scientific Research Center, Tokai, Japan, 4 August 2016

Compressed Baryonic Matter





Exploring the QCD phase diagram

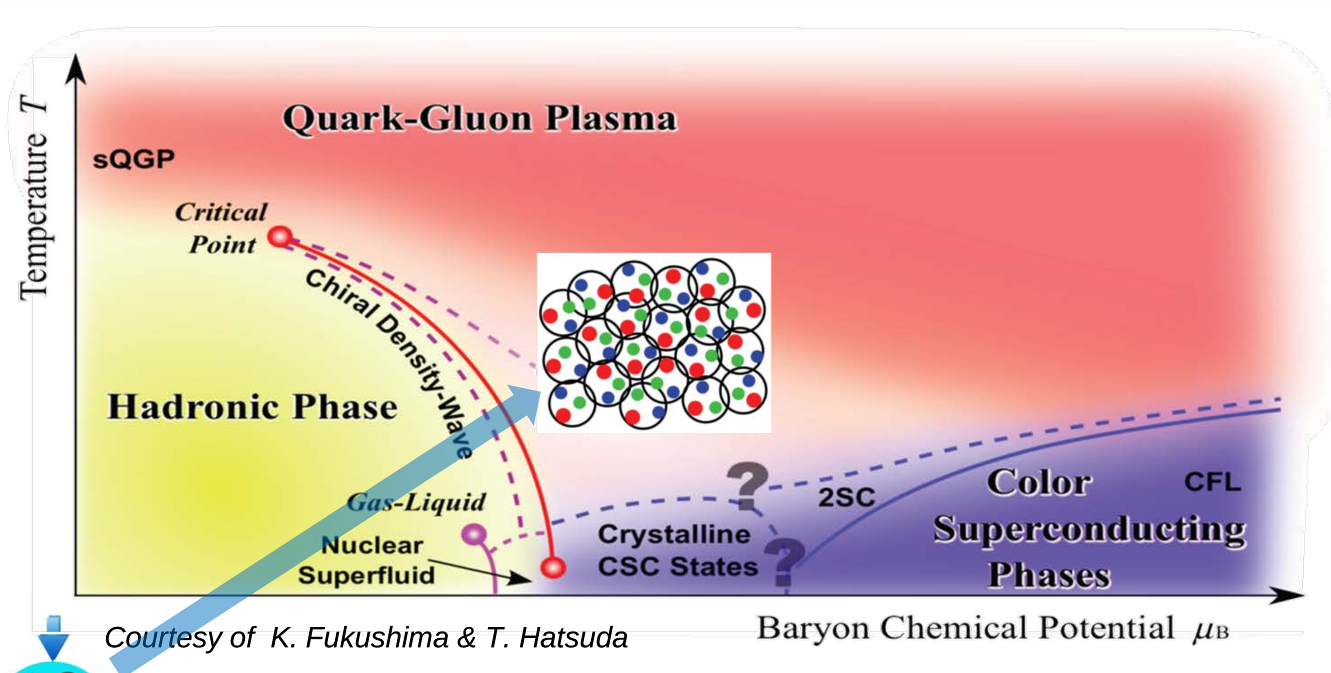


Courtesy of K. Fukushima & T. Hatsuda

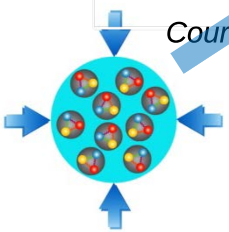
<u>At very high temperature:</u>

- N of baryons ≈ N of antibaryons
  Situation similar to early universe
- L-QCD finds crossover transition between hadronic matter and Quark-Gluon Plasma
- Experiments: ALICE, ATLAS, CMS at LHC
  STAR, PHENIX at RHIC

Exploring the QCD phase diagram



Courtesy of K. Fukushima & T. Hatsuda



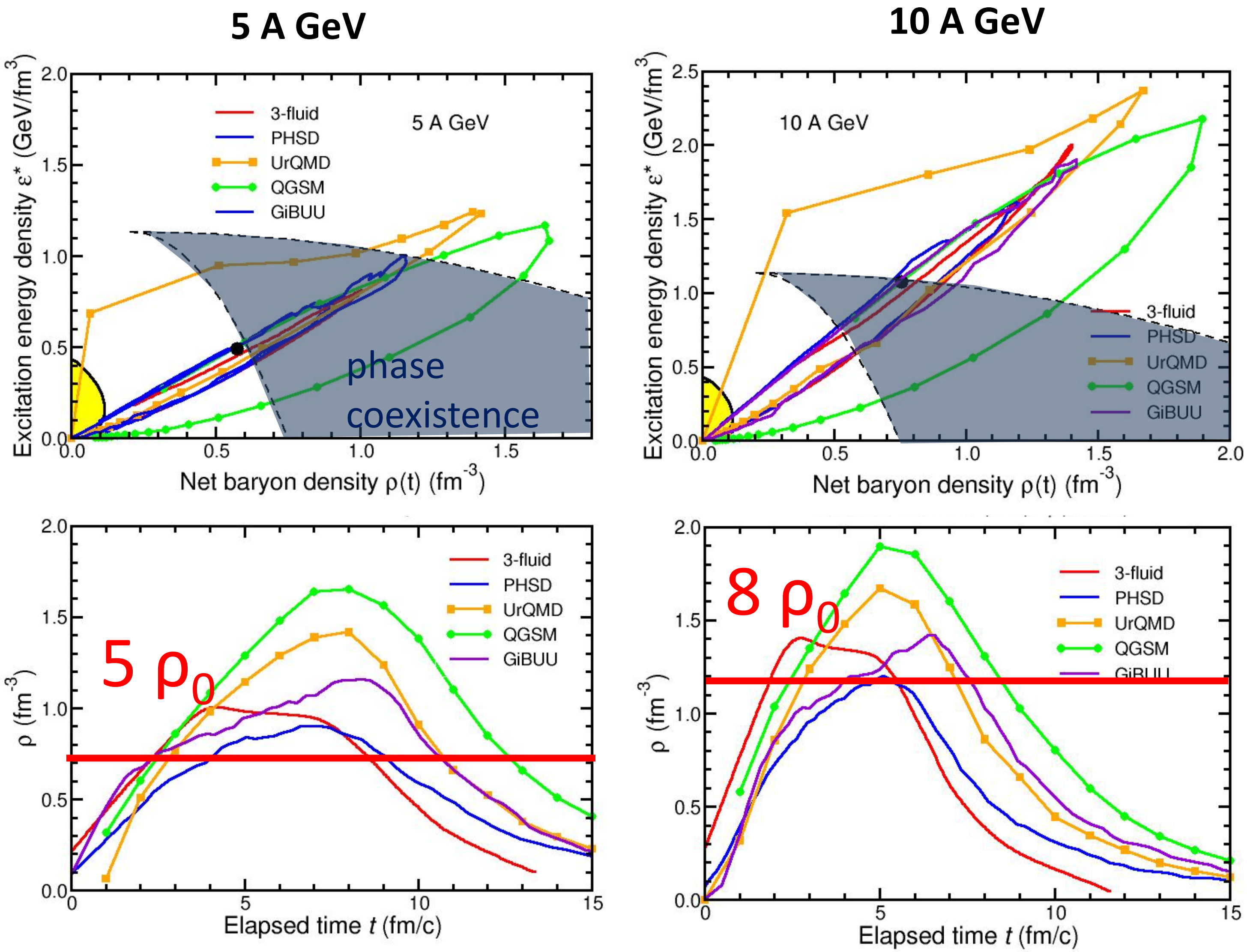
<u>At high baryon density:</u>

- N of baryons >> N of antibaryons; Densities like in neutron star cores
- L-QCD not (yet) applicable

  Models predict 1st order phase transition with mixed or exotic phases
- Experiments: BES at RHIC, NA61 at CERN SPS, CBM at FAIR, NICA at JINR

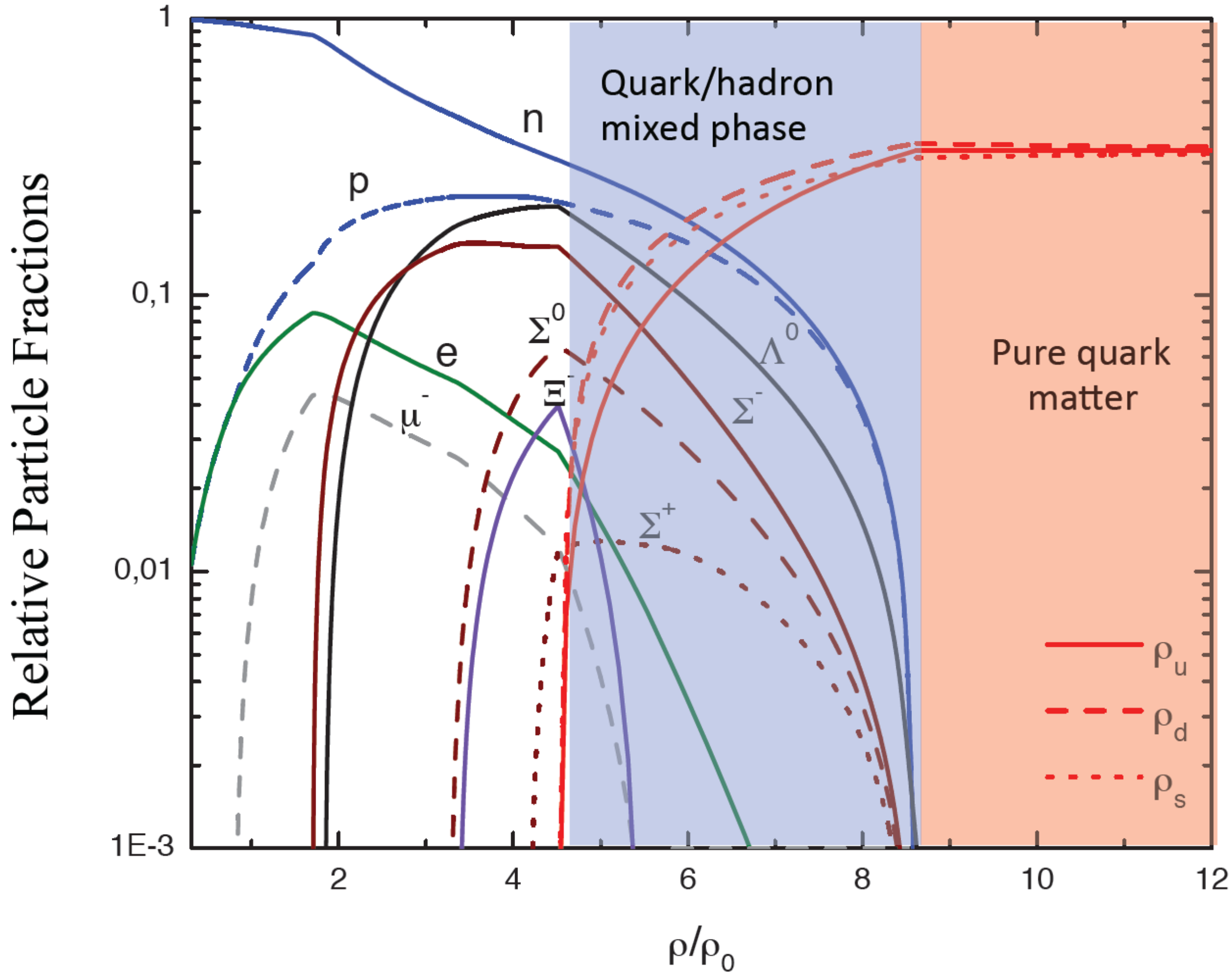
Baryon densities in central Au+Au collisions

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



Quark matter in massive neutron stars?

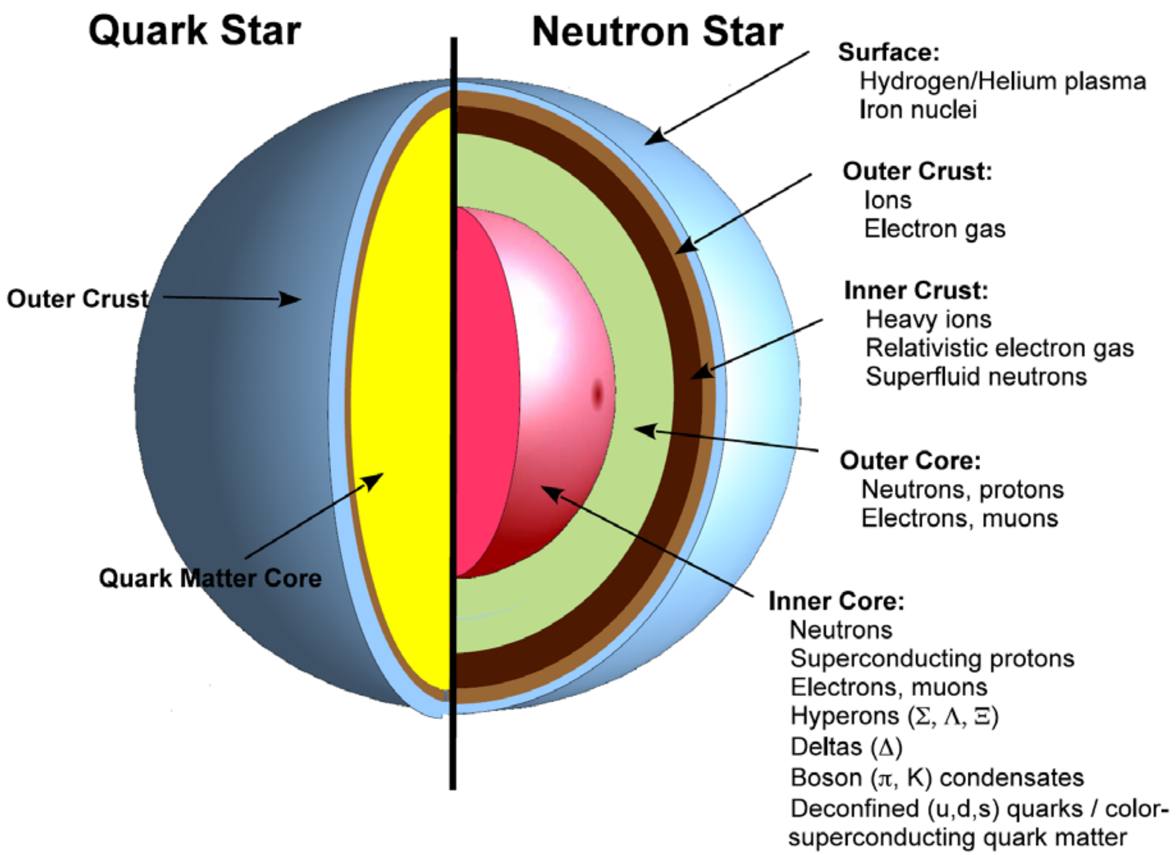
Equation-of-state: Non-local SU(3) NJL with vector coupling
M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657



CBM physics case and observables

The equation-of-state at neutron star core densities

- collective flow of hadrons (driven by pressure)
- particle production at threshold energies (multi-strange hyperons)



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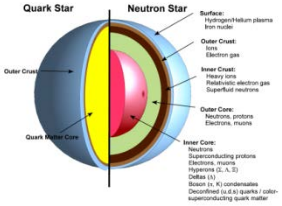
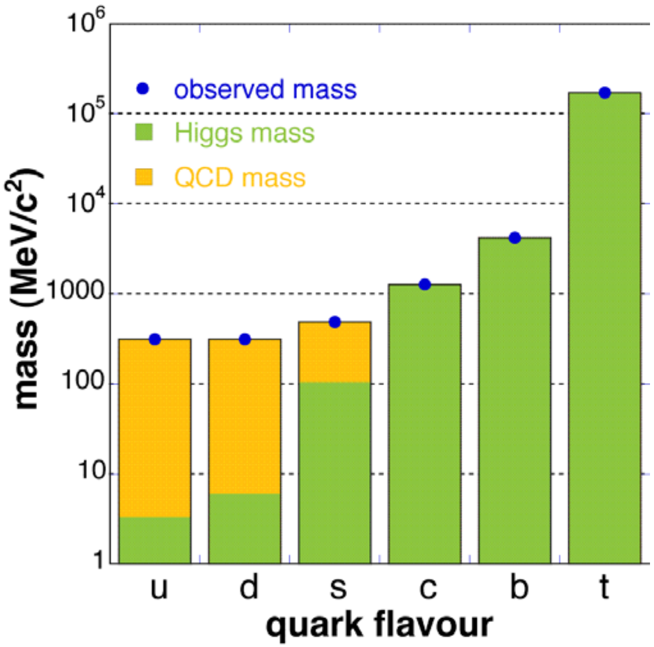


The equation-of-state at neutron star core densities
- collective flow of hadrons (driven by pressure)
- particle production at threshold energies (multi-strange hyperons)

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: ρ-a_1 chiral mixing



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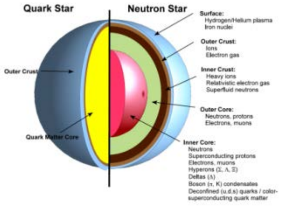

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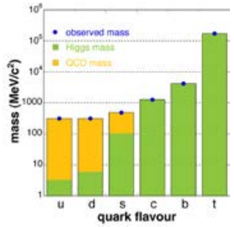
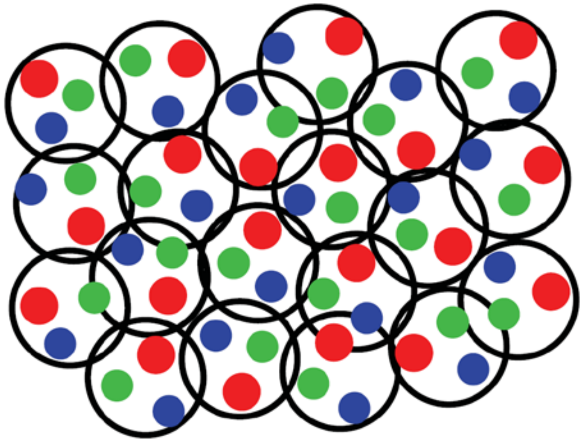


New phases of strongly-interacting matter

- excitation function and flow of lepton pairs
- excitation function and flow of strangeness (K, Λ, Σ, Ξ, Ω)



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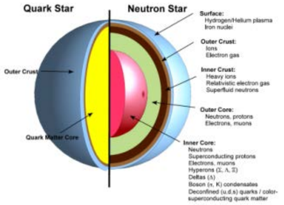

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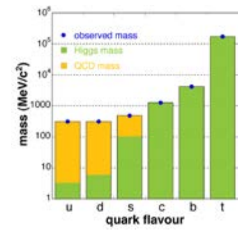

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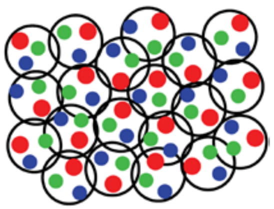

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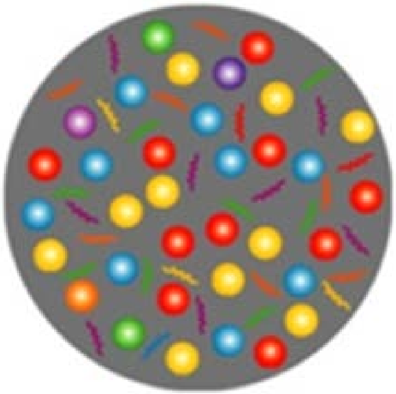
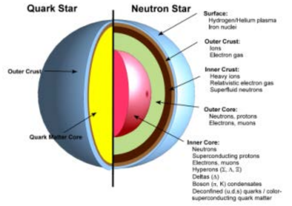


Deconfinement phase transition at high ρ_B

- excitation function and flow of charm (J/ψ, ψ', D^0, $D^\pm$, Λ_c)
- anomalouus charmonium suppression

CBM physics case and observables



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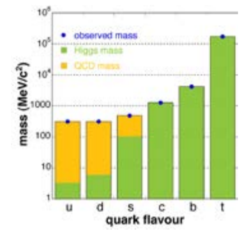

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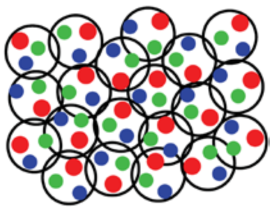

New phases of strongly-interacting matter

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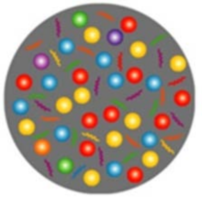
- excitation function and flow of strangeness (K, Λ, Σ, Ξ, Ω)



Deconfinement phase transition at high ρ_B

- excitation function and flow of charm (J/ψ, ψ', D^0, $D^\pm$, Λ_c)
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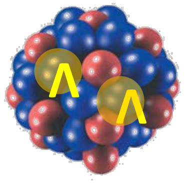
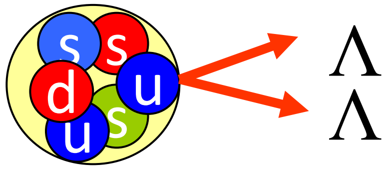
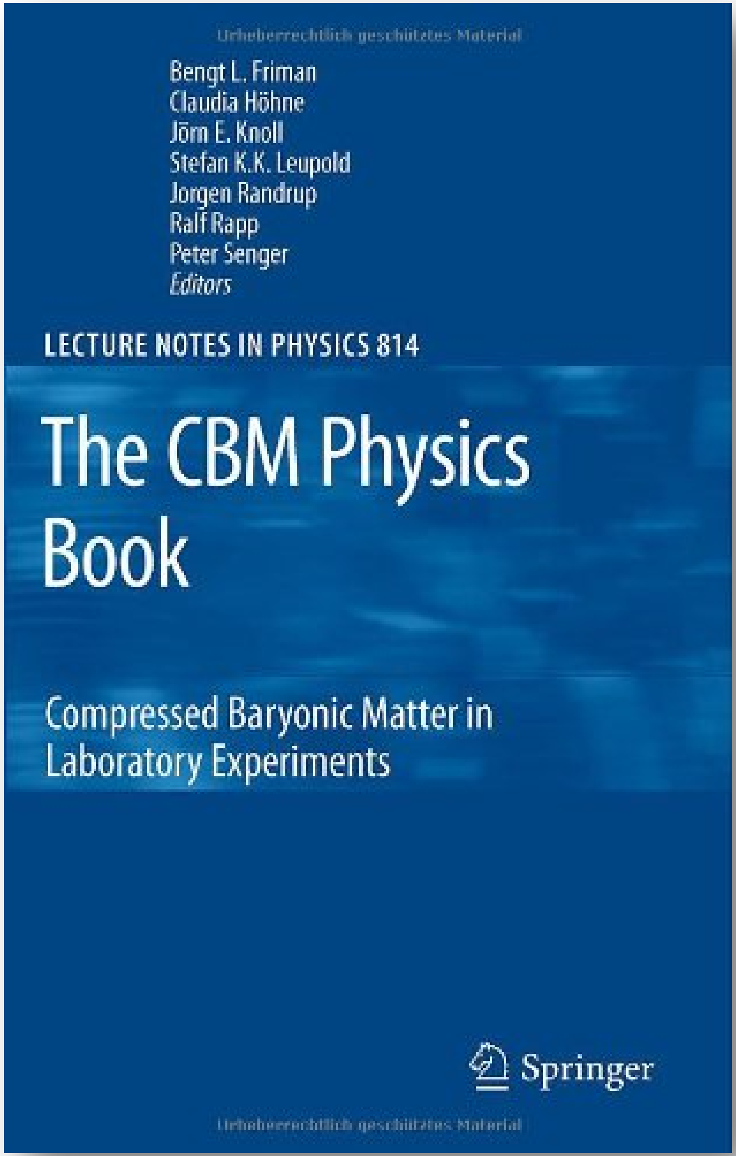
Strange matter

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





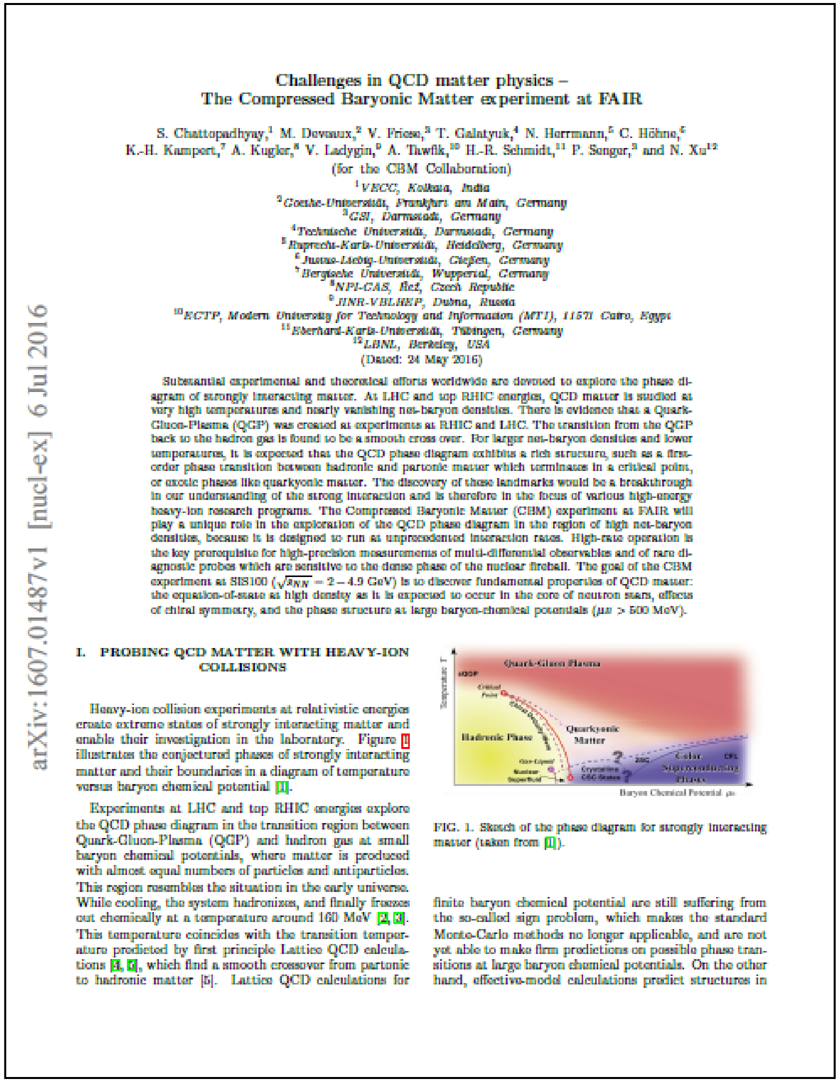


The CBM Physics Book

Foreword by Frank Wilczek

Springer Series:
Lecture Notes in Physics, Vol. 814
1st Edition., 2011, 960 p., Hardcover
ISBN: 978-3-642-13292-6

Electronic Authors version:
http://www.fair-center.eu/fileadmin/fair/experiments/CBM/documents/PhysBook_A4.rar



arXiv:1607.01487v1 [nucl-ex] 6 Jul 2016

Challenges in QCD matter physics –
The Compressed Baryonic Matter experiment at FAIR

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(Dated: 24 May 2016)

Substantial experimental and theoretical efforts worldwide are devoted to explore the phase diagram of strongly interacting matter. At LHC and top RHIC energies, QCD matter is studied at very high temperatures and nearly vanishing net-baryon densities. There is evidence that a Quark-Gluon-Plasma (QGP) was created at experiments at RHIC and LHC. The transition from the QGP back to the hadron gas is found to be a smooth cross over. For larger net-baryon densities and lower temperatures, it is expected that the QCD phase diagram exhibits a rich structure, such as a first-order phase transition between hadronic and partonic matter which terminates in a critical point, or exotic phases like quarkyonic matter. The discovery of these landmarks would be a breakthrough in our understanding of the strong interaction and is therefore in the focus of various high-energy heavy-ion research programs. The Compressed Baryonic Matter (CBM) experiment at FAIR will play a unique role in the exploration of the QCD phase diagram in the region of high net-baryon densities, because it is designed to run at unprecedented interaction rates. High-rate operation is the key prerequisite for high-precision measurements of multi-differential observables and of rare diagnostic probes which are sensitive to the dense phase of the nuclear fireball. The goal of the CBM experiment at SIS100 ($\sqrt{s_{NN}} = 2 - 4.9$ GeV) is to discover fundamental properties of QCD matter: the equation-of-state at high density as it is expected to occur in the core of neutron stars, effects of chiral symmetry, and the phase structure at large baryon-chemical potentials ($\mu_B > 500$ MeV).

I. PROBING QCD MATTER WITH HEAVY-ION COLLISIONS

Heavy-ion collision experiments at relativistic energies create extreme states of strongly interacting matter and enable their investigation in the laboratory. Figure 1 illustrates the conjectured phases of strongly interacting matter and their boundaries in a diagram of temperature versus baryon chemical potential [1].

Experiments at LHC and top RHIC energies explore the QCD phase diagram in the transition region between Quark-Gluon-Plasma (QGP) and hadron gas at small baryon chemical potentials, where matter is produced with almost equal numbers of particles and antiparticles. This region resembles the situation in the early universe. While cooling, the system hadronizes, and finally freezes out chemically at a temperature around 160 MeV [2, 3]. This temperature coincides with the transition temperature predicted by first principle Lattice QCD calculations [4, 5], which find a smooth crossover from partonic to hadronic matter [5]. Lattice QCD calculations for finite baryon chemical potential are still suffering from the so-called sign problem, which makes the standard Monte-Carlo methods no longer applicable, and are not yet able to make firm predictions on possible phase transitions at large baryon chemical potentials. On the other hand, effective-model calculations predict structures in

FIG. 1. Sketch of the phase diagram for strongly interacting matter (taken from [1]).

Challenges in QCD matter physics – The Compressed Baryonic Matter experiment at FAIR

CBM Collaboration

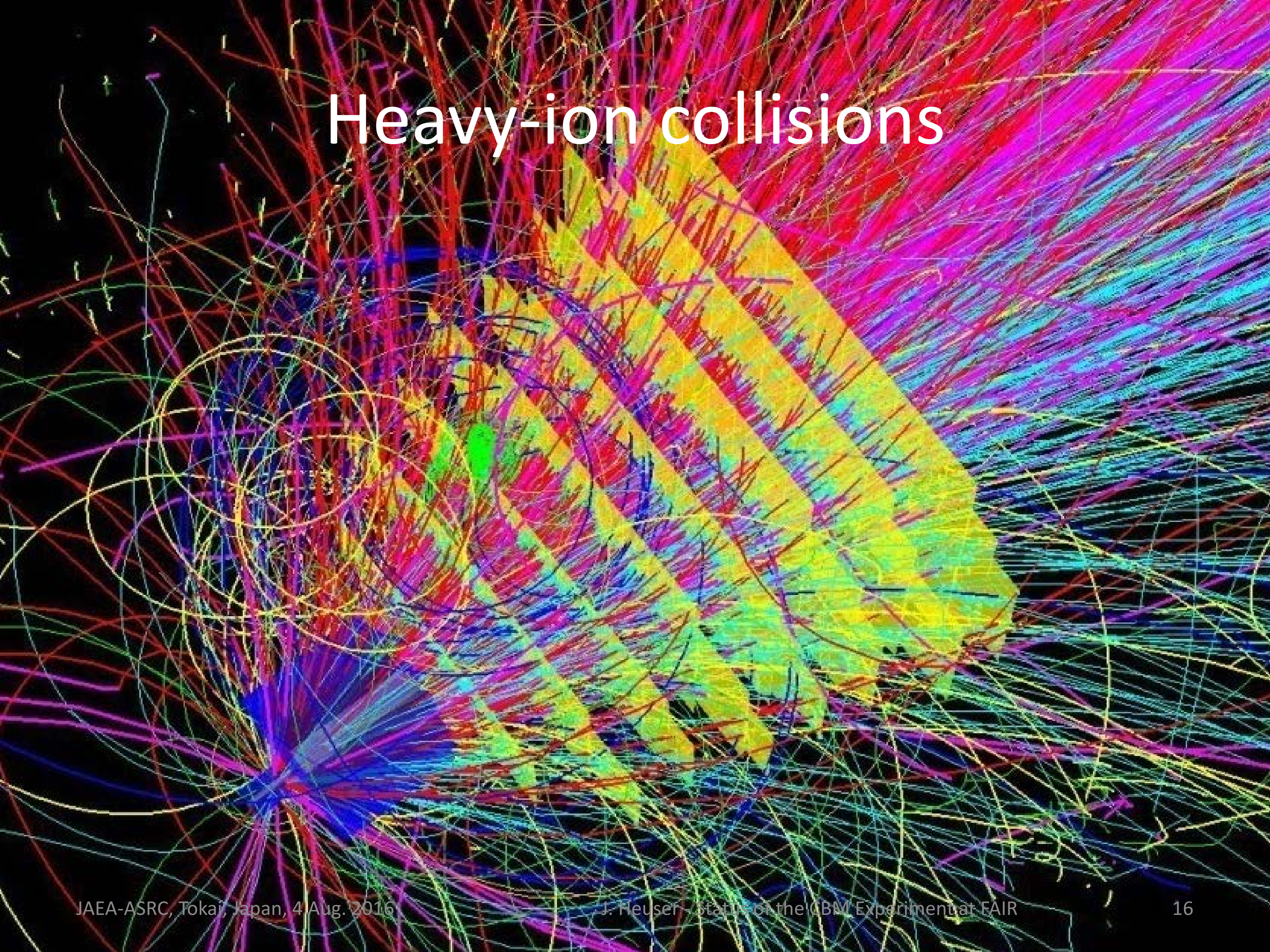
arXiv:1607.01487 [nucl-ex]
6 July 2016

to be published in a refereed journal

Heavy-ion collisions

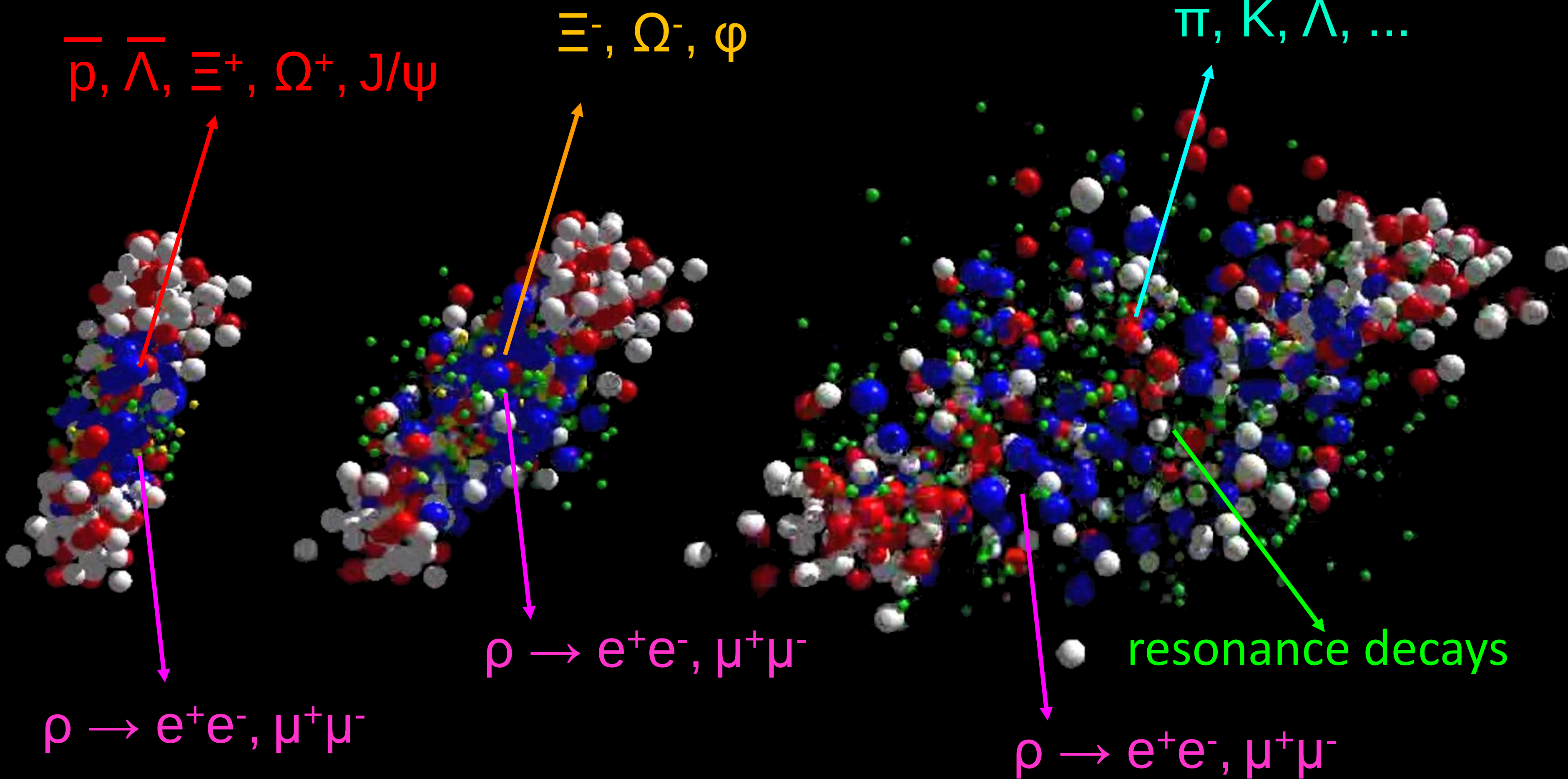
Heavy-ion collisions

Heavy-ion collisions



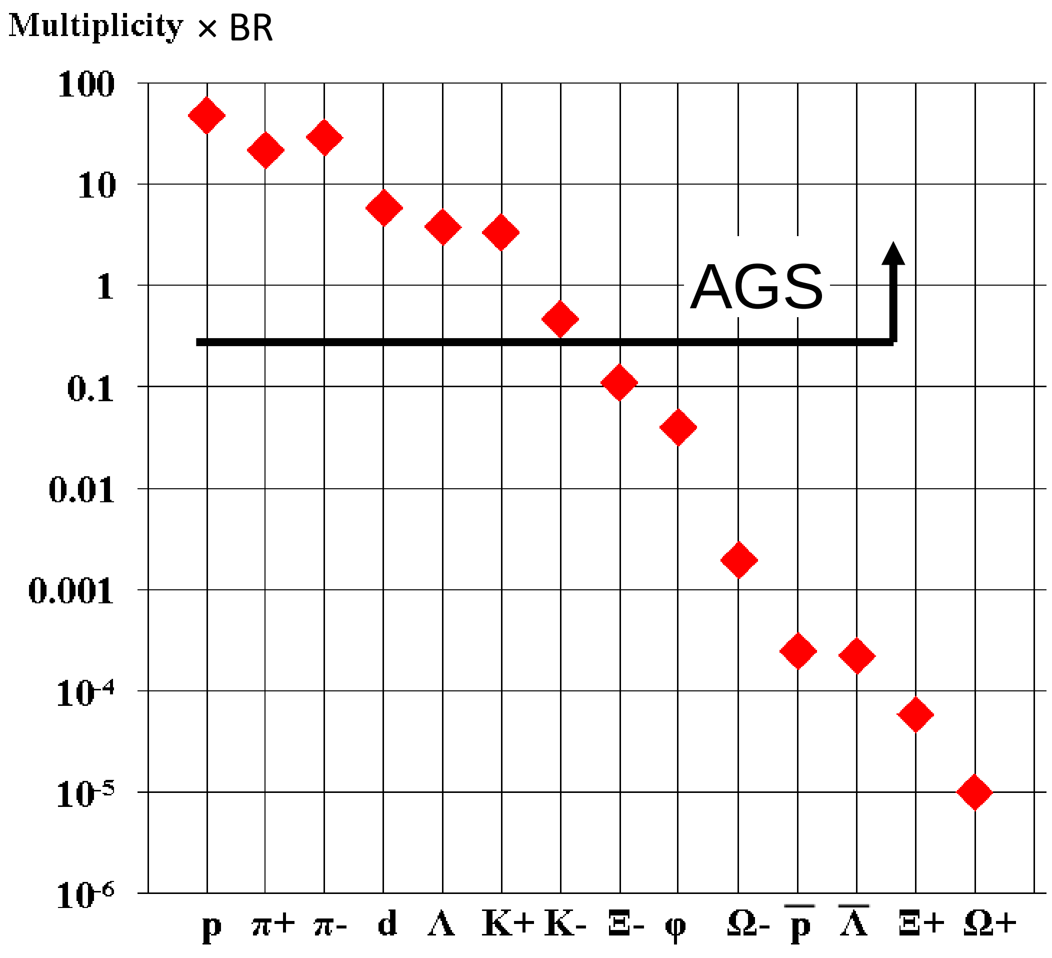
Messengers from the dense fireball: CBM at SIS100

UrQMD transport calculation Au+Au 10.7 A GeV

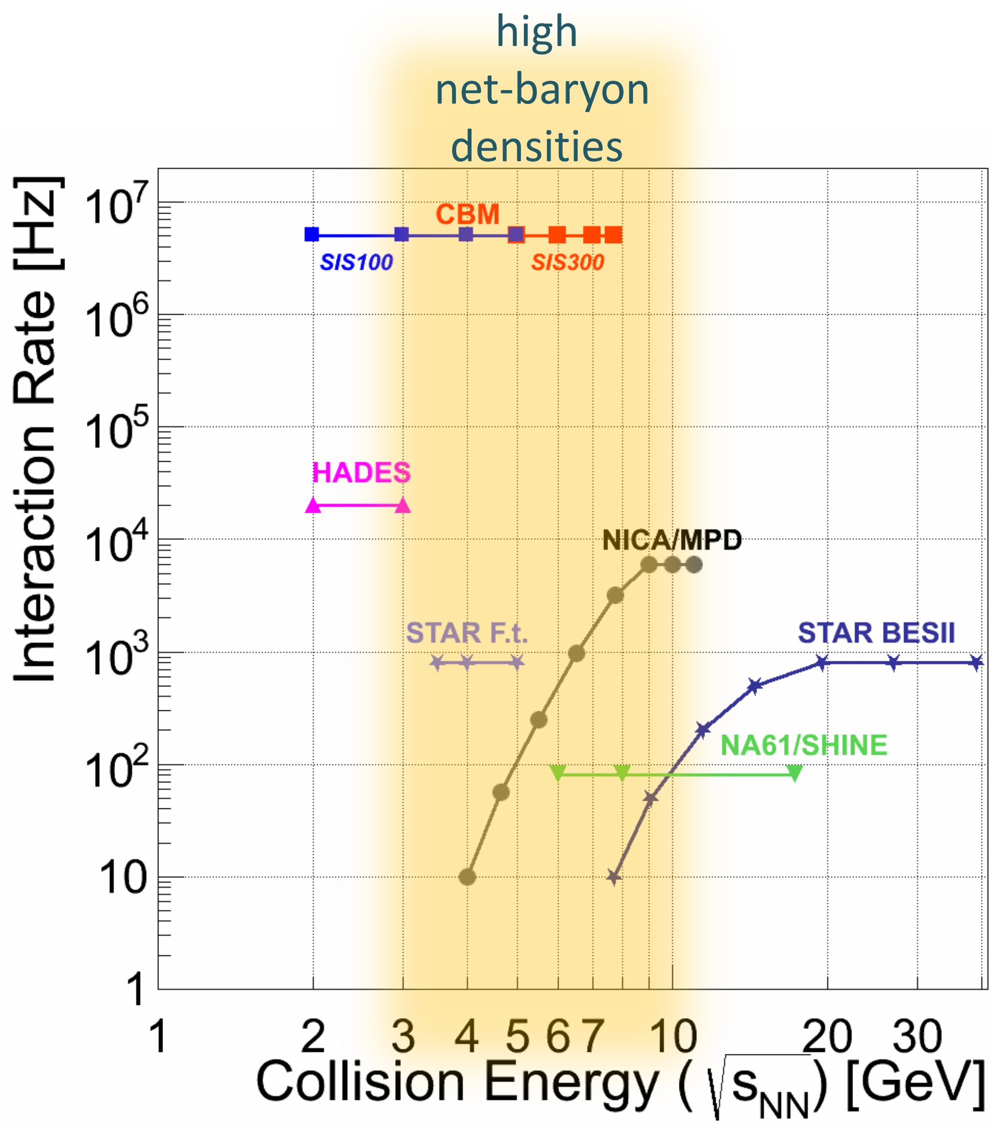


Experimental challenges

Particle yields in central Au+Au 4 A GeV



Experiments exploring dense QCD matter

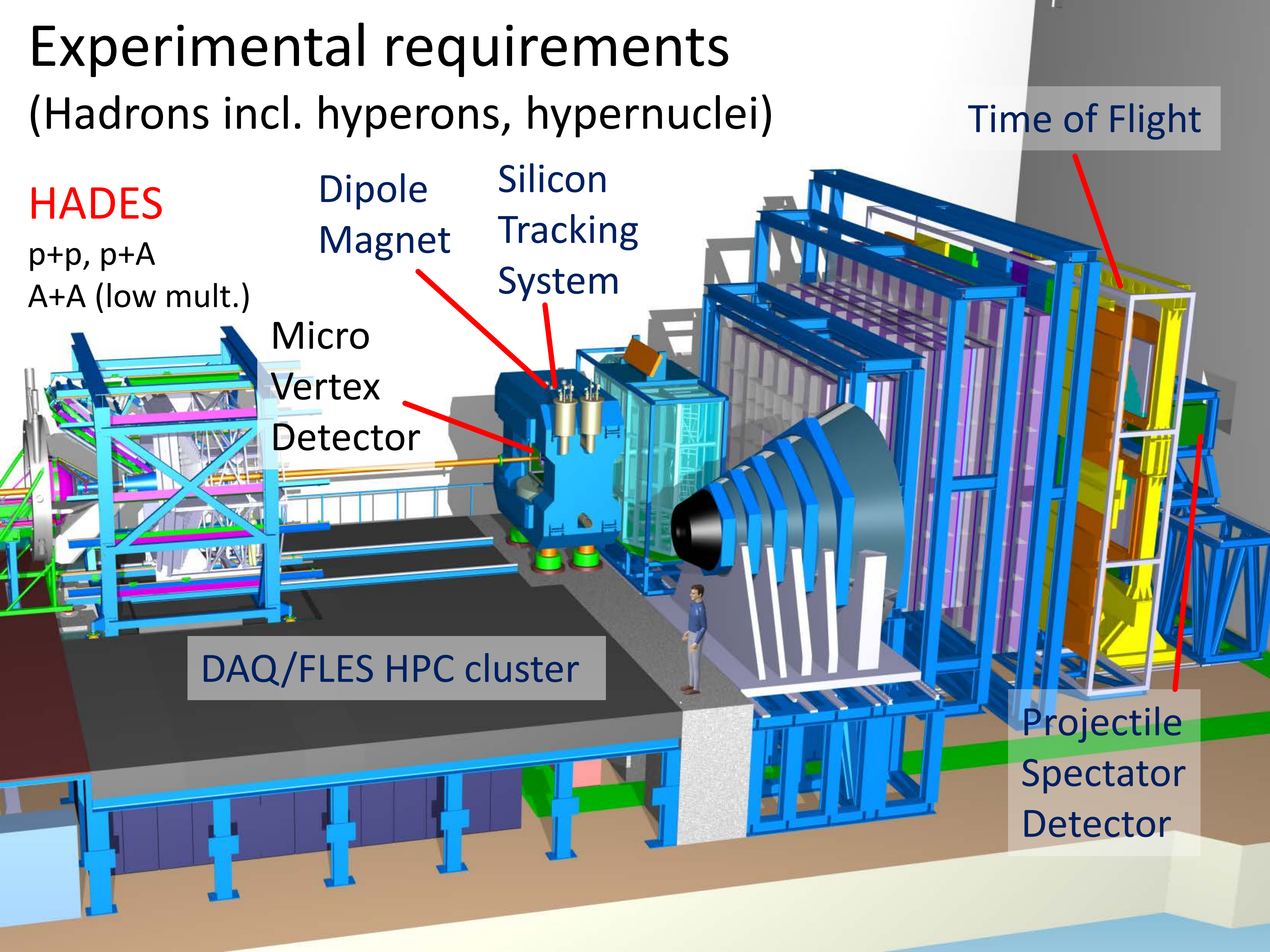


Experimental requirements

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

Experimental requirements

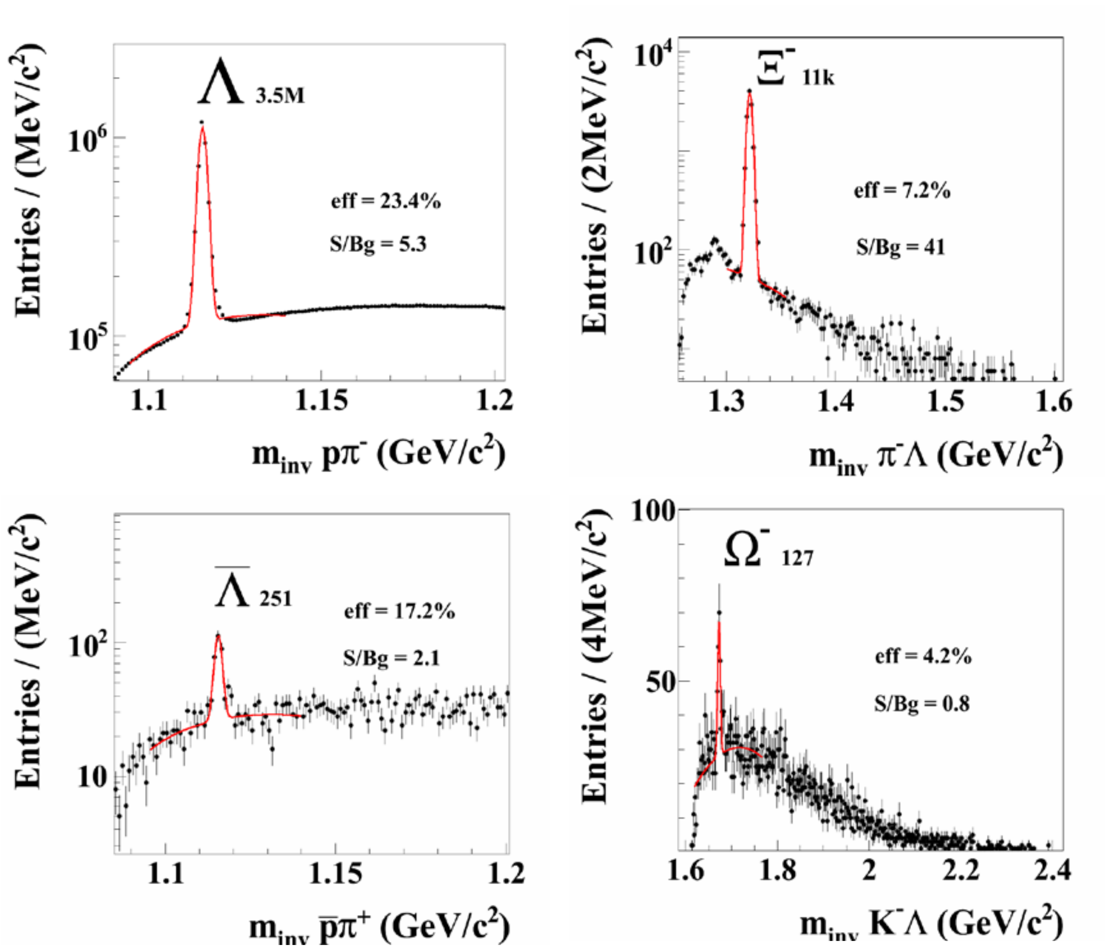
(Hadrons incl. hyperons, hypernuclei)



Hyperons in CBM at SIS100

Running scenario: Au+Au, C+C at 4, 6, 8, 10 A GeV

Example: Au+Au at 8 A GeV, 10^6 central collisions



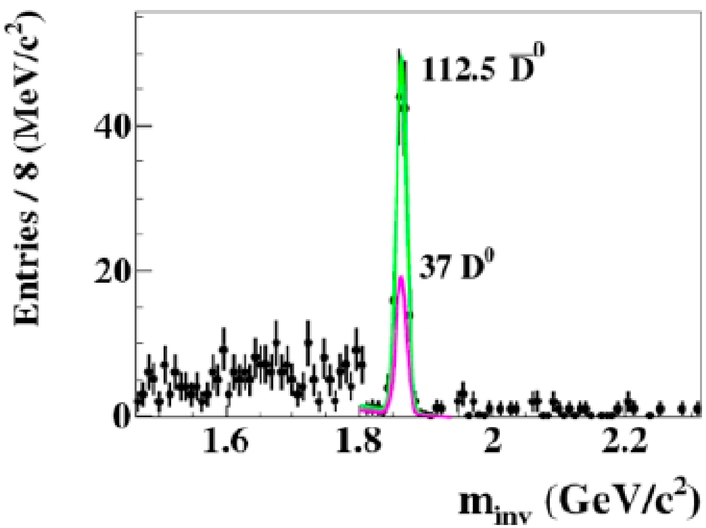
- In addition: K*,Λ*,Σ*,Ξ*,Ω*
- Event rate: 100 kHz to 1 MHz

Open charm in CBM at SIS100

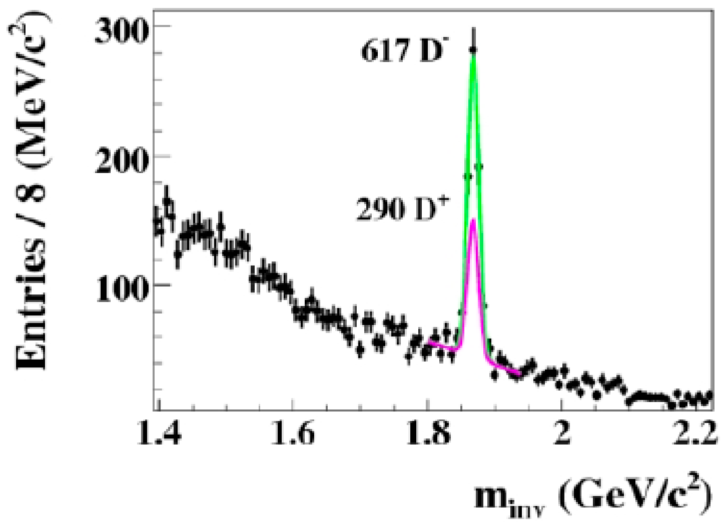
- Charm production cross sections at threshold energies
- Charm propagation in cold nuclear matter

30 GeV p + C

$D^0 \rightarrow K\pi\pi\pi$

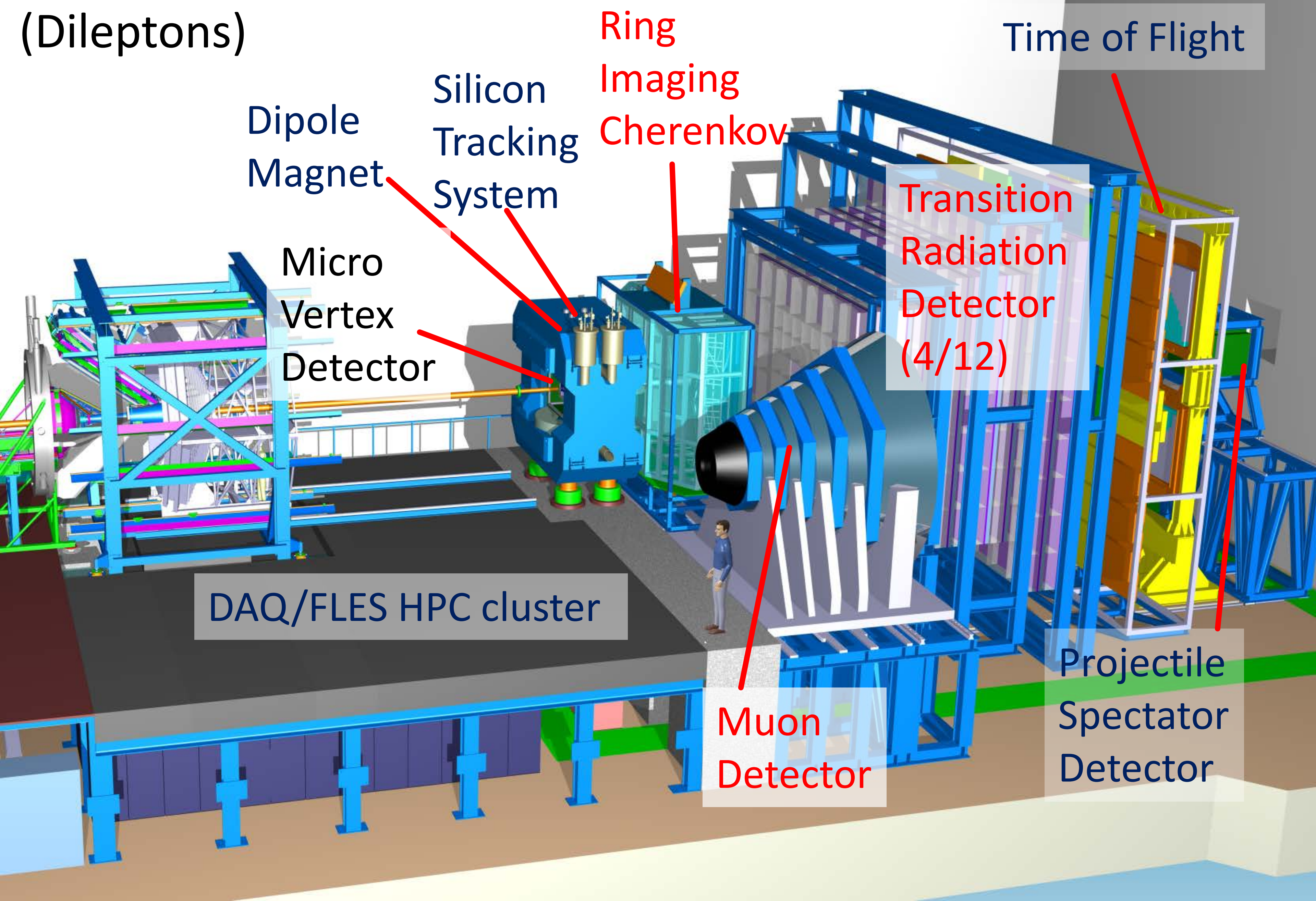


$D^{\pm} \rightarrow K\pi\pi$



Experimental requirements

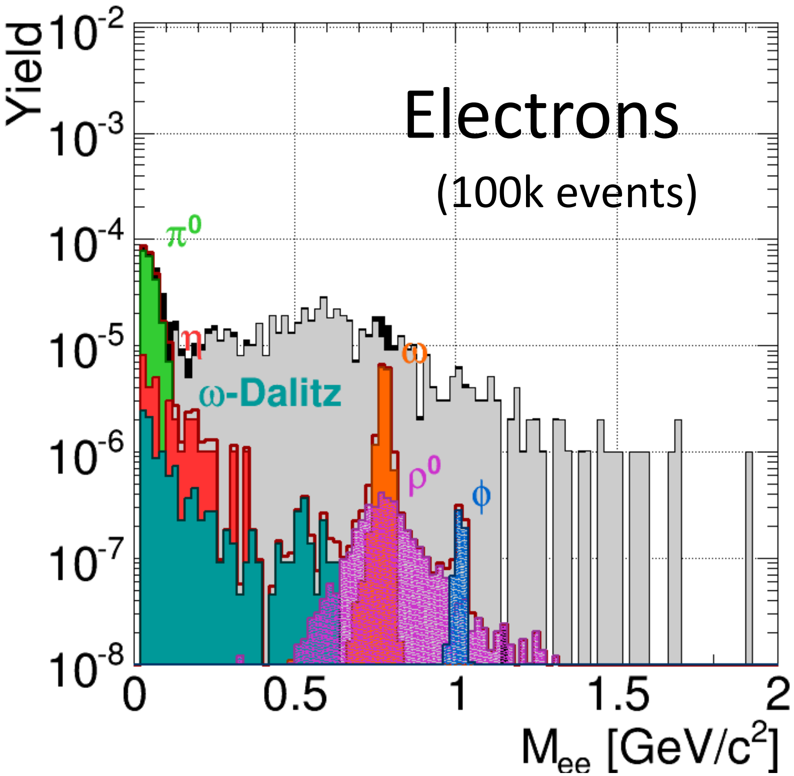
(Dileptons)

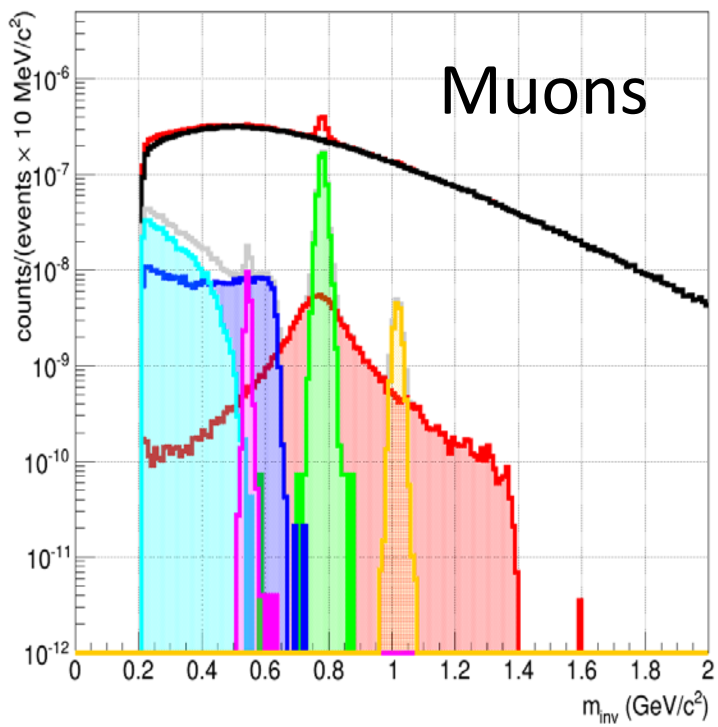


Leptons in CBM at SIS100

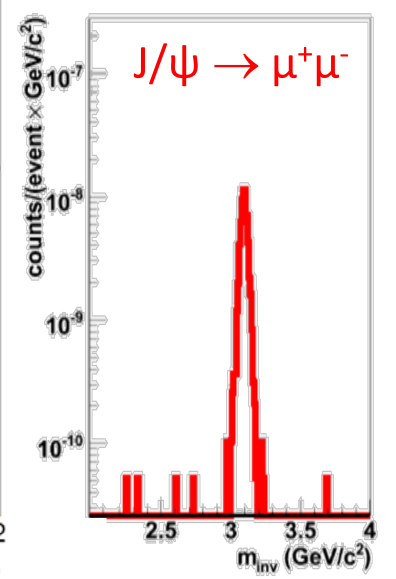
Simulation: Signal yields from HSD, Background from UrQMD

central Au+Au at 8 A GeV: 2×10^6 ω in 2 weeks





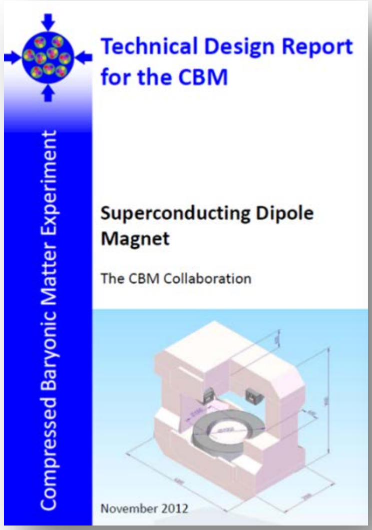
30 GeV p+Au

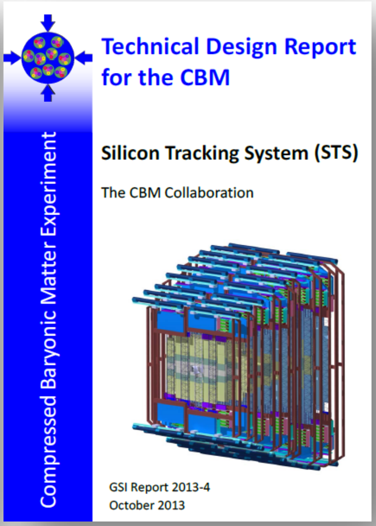


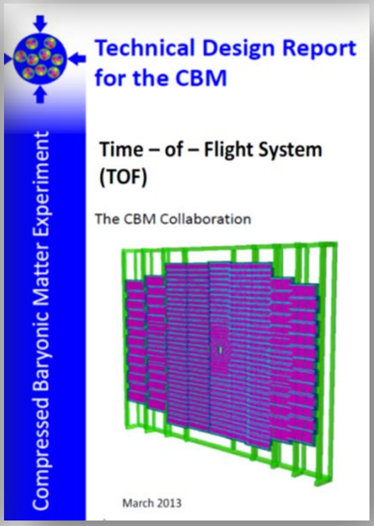
1000 J/ψ
in 10^{12} events
(1 day)

CBM Technical Design Reports

#	Project	TDR Status
1	**Magnet**	approved
2	**STS**	approved
3	**RICH**	approved
4	**TOF**	approved
5	**MuCh**	approved
6	**HADES ECAL**	approved
7	**PSD**	approved
8	**MVD**	submission 2016
9	**TRD**	submission 2016
10	**ECAL**	submission 2016
11	**DAQ/FLES**	submission 2017







More on technical developments in:

CBM Progress Report 2015

CBM Collaboration

progress in the fields of

- *detectors*
- *electronics*
- *DAQ*
- *computing*
- *simulations*

http://www.fair-center.eu/en/for-users/experiments/cbm/documents.html

On-line event reconstruction

- There is no a-priori event definition possible:
  - no simple trigger signatures: e.g. $J/\psi \rightarrow e^+e^-$ and $D,\Omega \rightarrow$ charged hadrons.
  - extreme event rates set strong limits to trigger latency.
  - therefore data from all detectors come asynchroneously.
  - events may overlap in time.

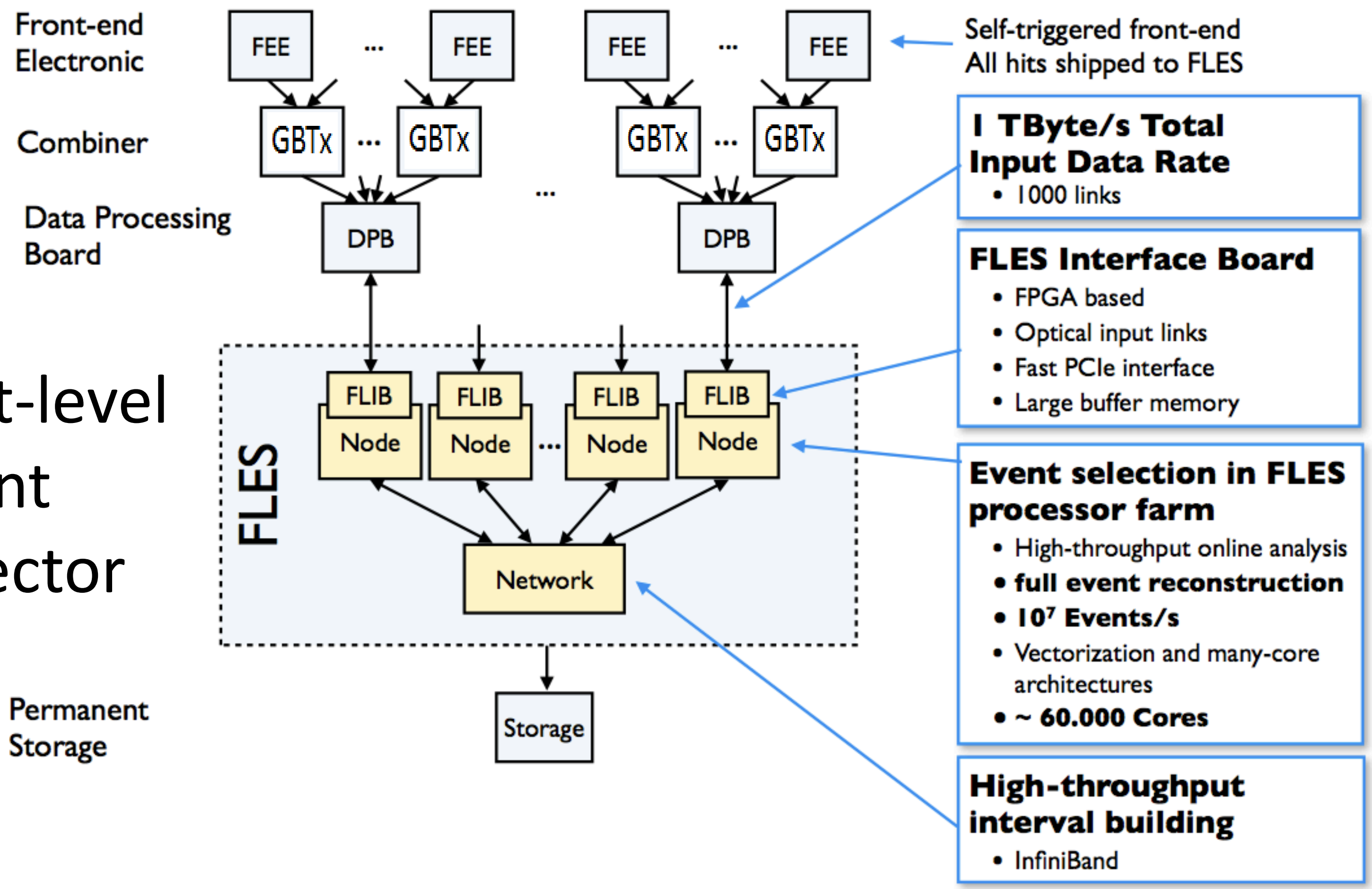
- The classical DAQ task of „event building“ is now rather a „time-slice building“. Physical events are defined later in software.

- Data reduction is shifted entirely to software:
  - Complex signatures involve secondary decay vertices; difficult to implement in hardware.
  - maximum flexibility w.r.t. physics.

- The system is limited only by the throughput capacity and by the rejection power of the on-line computing farm.

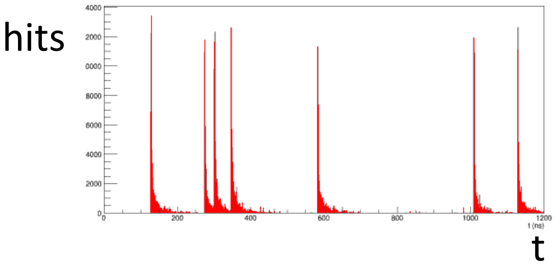
CBM online data flow

First-level Event Selector

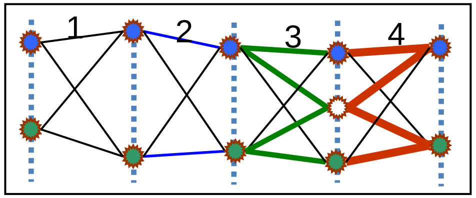


Steps of event reconstruction

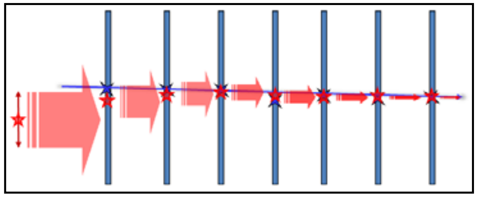
1. Time-slice sorting of detector hits:
   First step in "pre-event" definition.



2. Track finding – Cellular Automaton:
   Which hits in the detector layers belong to the same track?
   – large combinatorial problem
   – well to be parallelized
   – applicable to many-core CPU/GPU systems

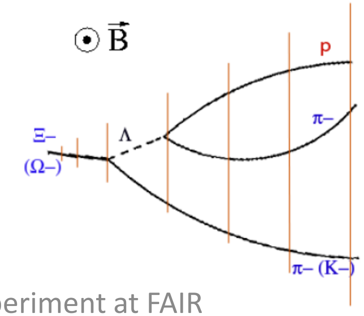


3. Track fitting – Kalman Filter:
   Optimization of the track parameters.
   – recursive least squares method, fast



4. Event determination
   Which tracks belong to same interaction?

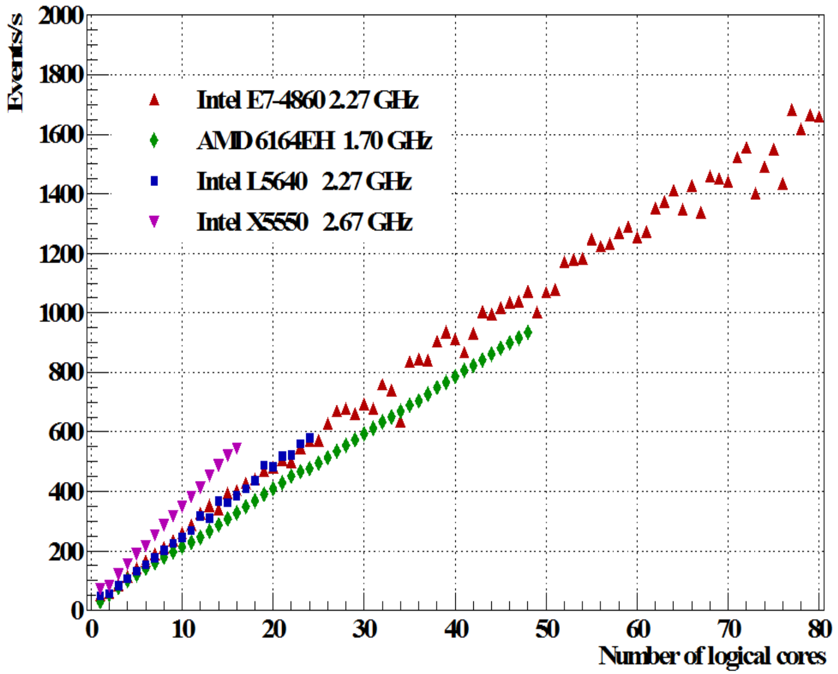
5. Particle finding:
   Identify decay topologies and other signatures.



Parallelization of event reconstruction

On “event” level:

- reconstruction with independent processes
- Exploit many-core systems with multi-threading: 1 thread per logical core, 1000 events per core.



On “task” level:

- digitizer, finder, fitter, analysis tasks: current readiness of parallelization
- employing different computing techniques and architectures

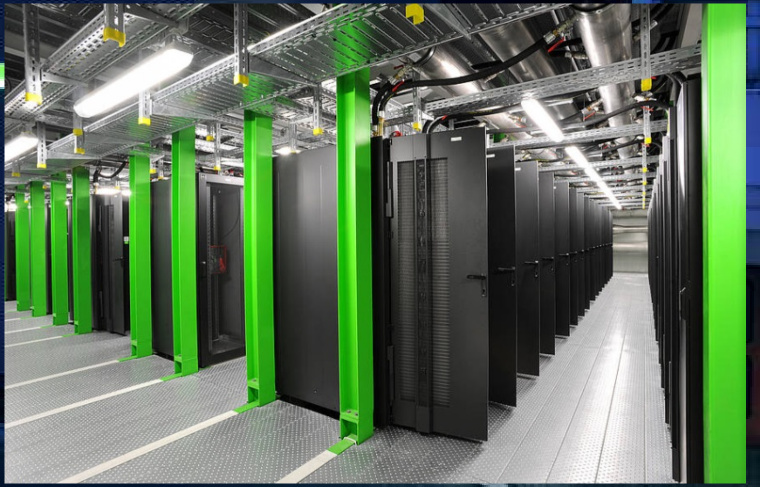
Algorithm	Vector SIMD	Multi Threading	CUDA	OpenCL CPU/GPU
Digitizers				
STS KF Track Fit	✓	✓	✓	✓/✓
STS CA Track Finder	✓	✓		
MuCh Track Finder	✓	✓	✓	
TRD Track Finder	✓	✓	✓	
RICH Ring Finder	✓	✓		✓/✓
Vertexing (KF Particle)	✓	✓		
Off-line Physics Analysis	✓			
FLES Analysis and Selection	✓	✓		

Green IT Cube, January 2016
new high-performance computing center at GSI

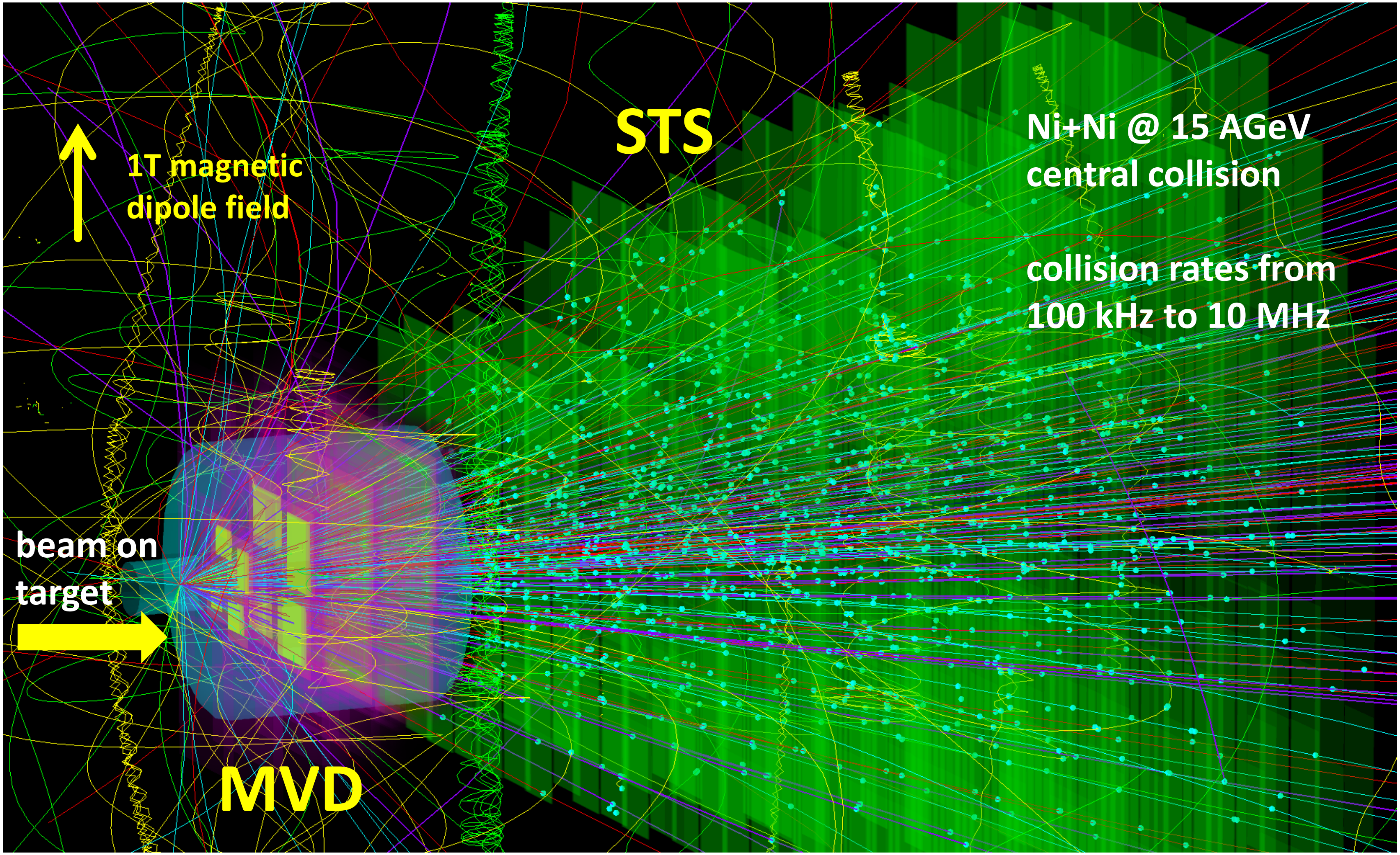
- physics simulations, detector development for FAIR
- Data processing and analysis from experiments in the accelerator facilities of GSI, and FAIR

Space and cost effective

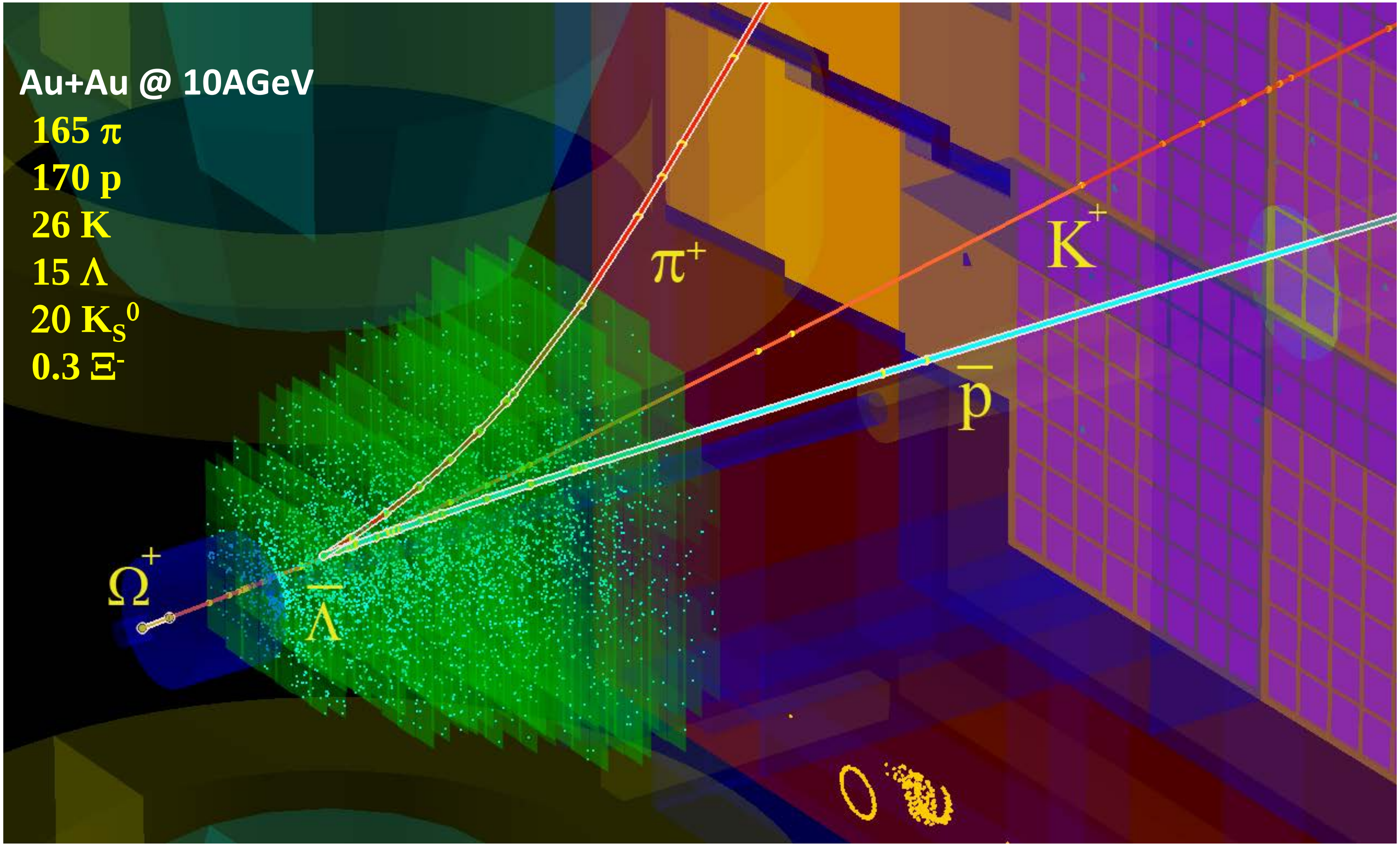
- 768 computer cabinets on six floors (1/3 now)
- 300,000 CPUs
- 12 MW cooling power
- 100 petabytes to store experiment data
- data link from experiments: one terabyte/s



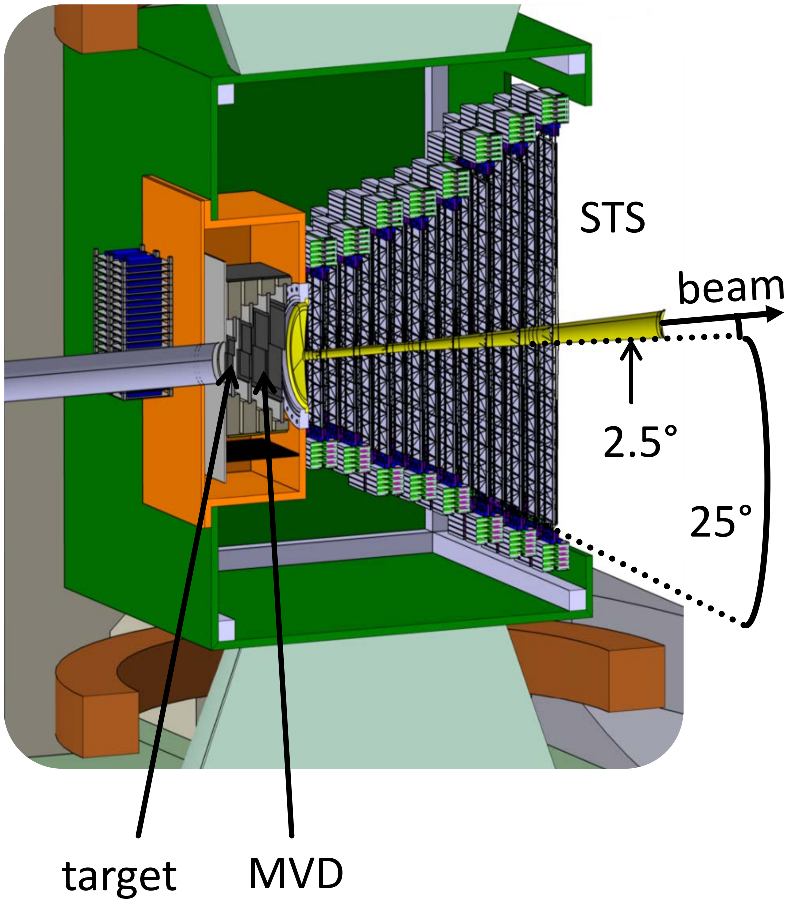
Tracking nuclear collisions

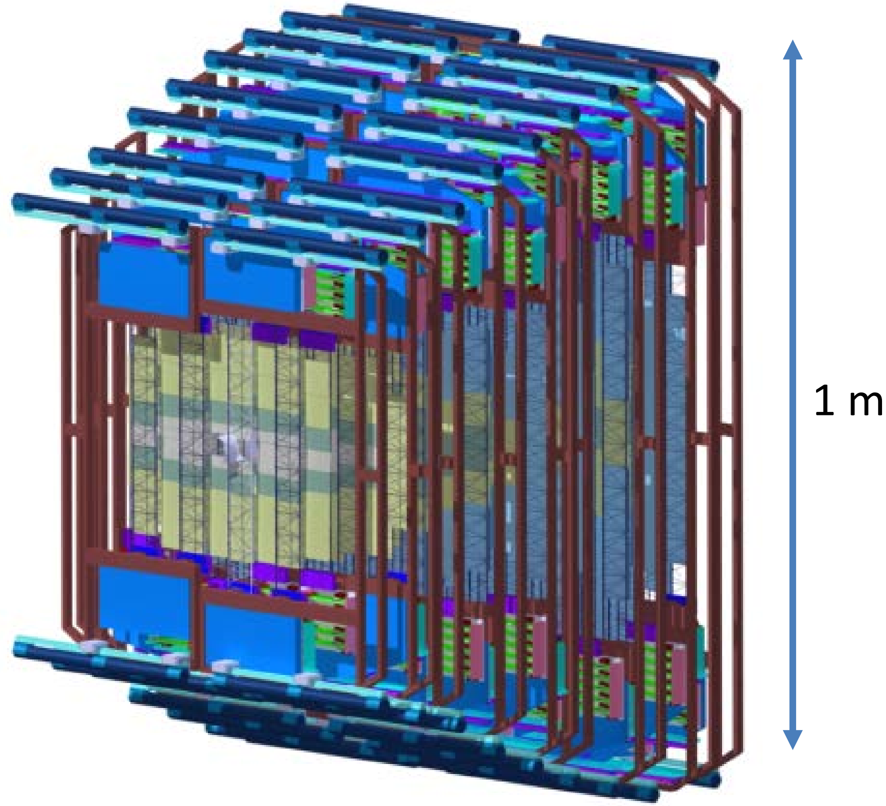


Search for physics signatures

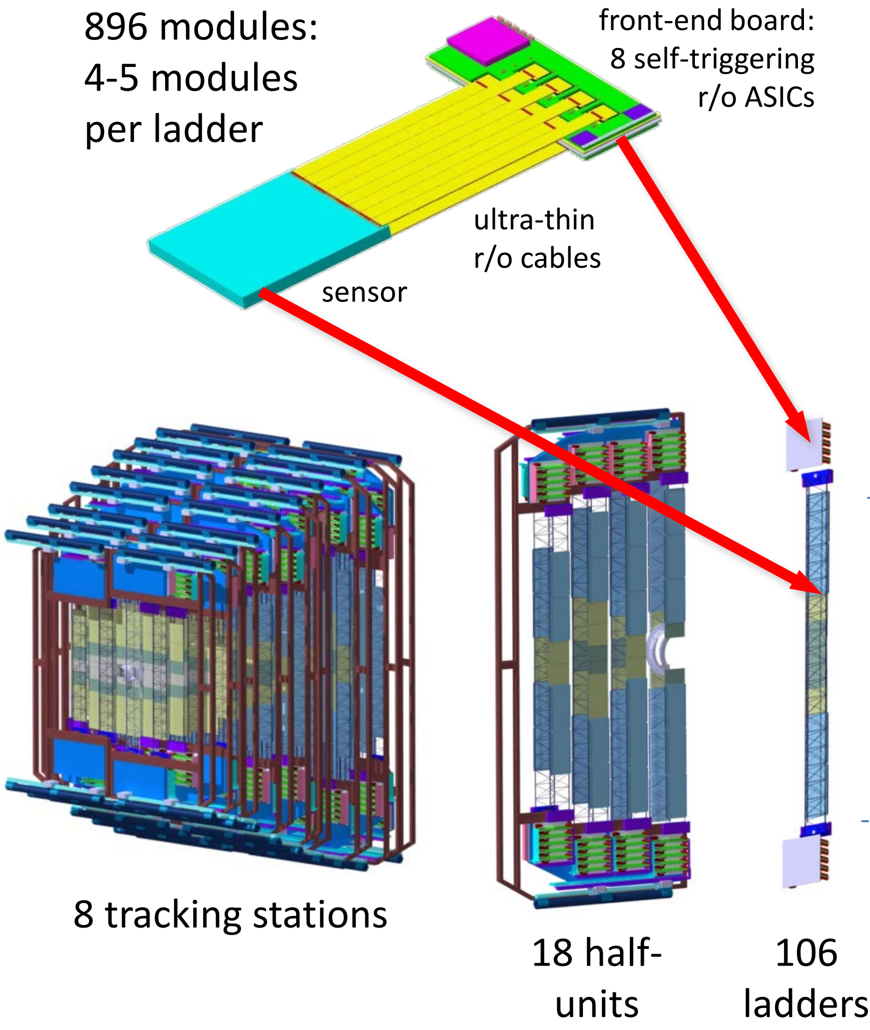


Silicon Tracking System

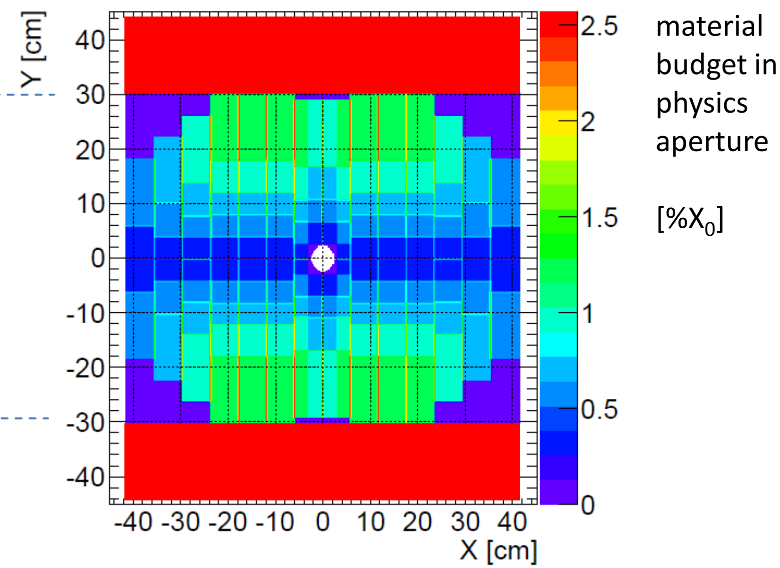




STS integration



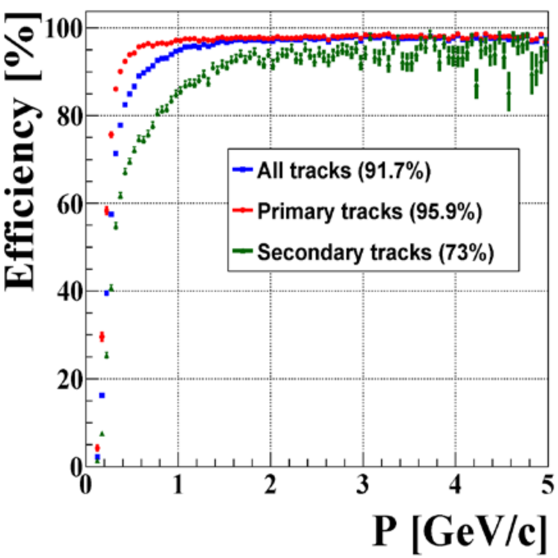
- 8 stations, volume 2 m^3, area 4 m^2
- 896 detector modules
  - 1220 double-sided microstrip sensors
  - ~ 1.8 million read-out channels
  - ~ 16 000 r/o STS-XYTER ASICs
  - ~ 58 000 ultra-thin r/o cables
- 106 detector ladders with 4-5 modules
- power dissipation: 42 kW (CO_2 cooling)

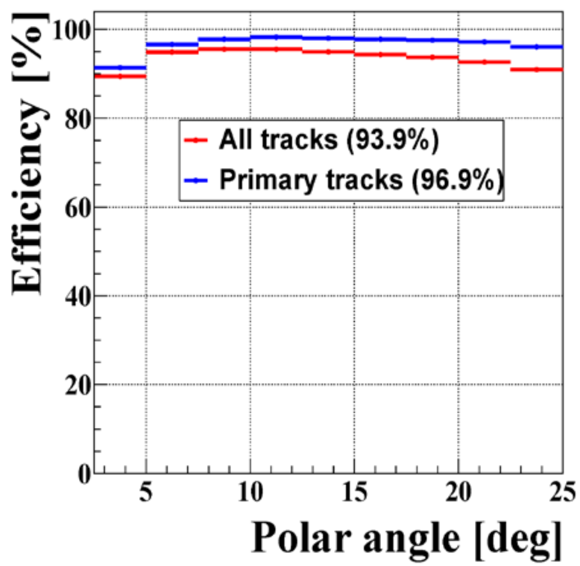


STS performance simulation

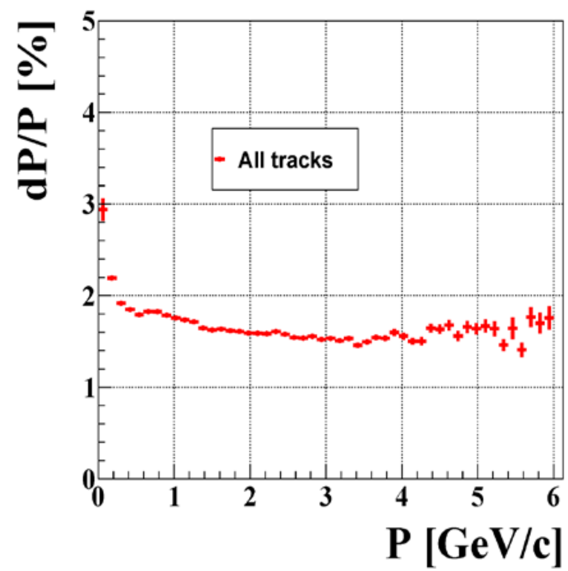
- detailed, realistic detector model based on tested prototype components
- CbmRoot simulation framework
- using Cellular Automaton / Kalman Filter algorithms

track reconstruction efficiency





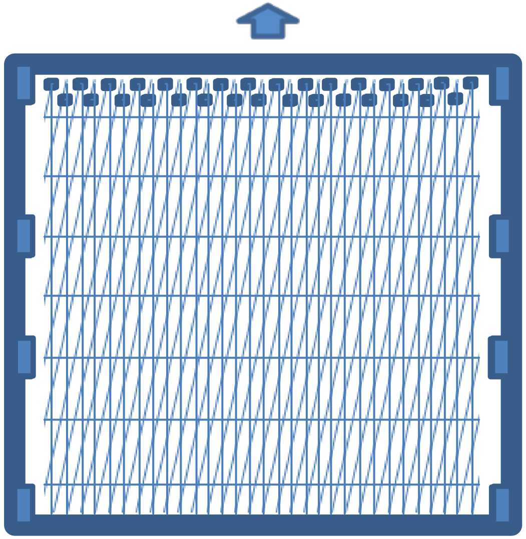
momentum resolution

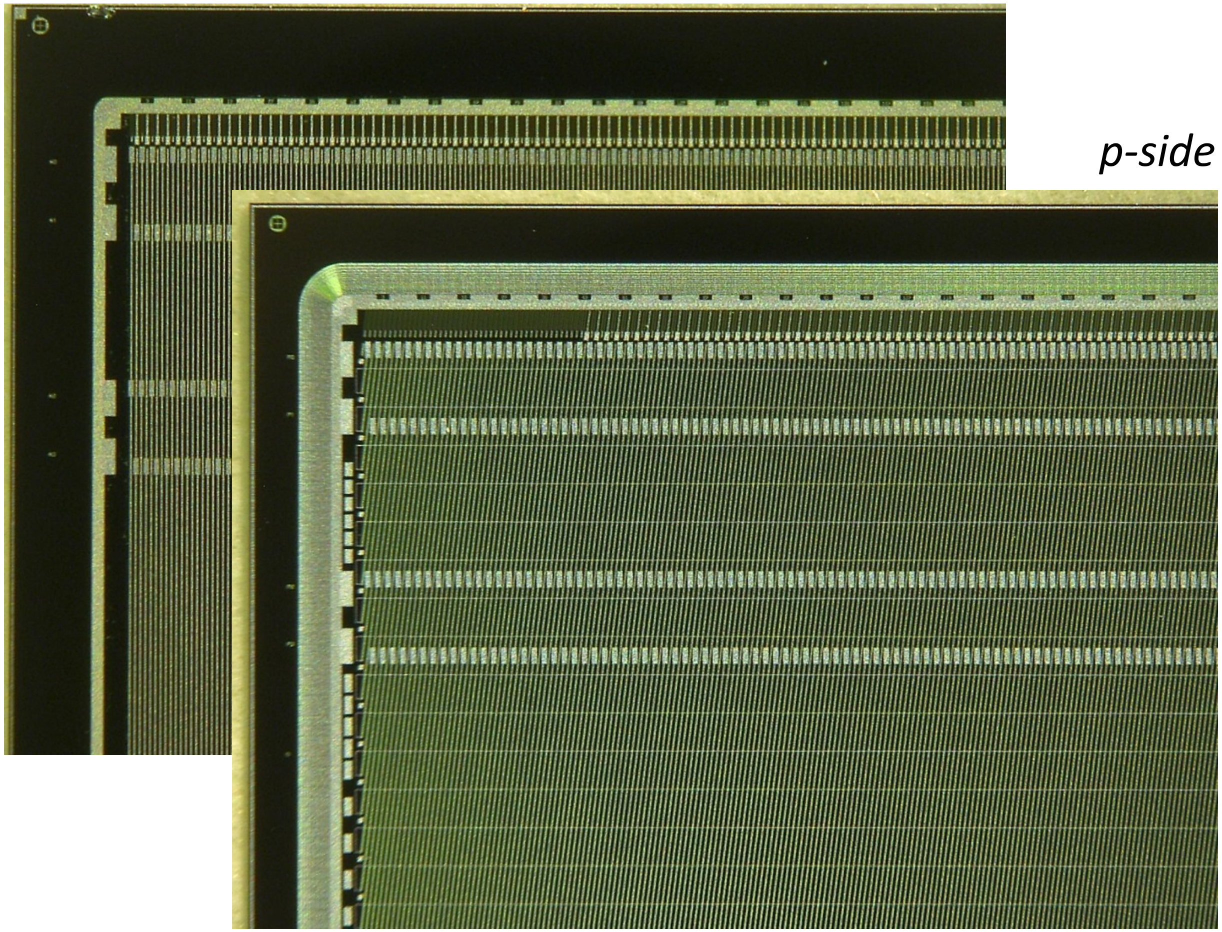


Silicon microstrip sensors

sensor structure:

- 285/320 ± 15µm thick
- n-type silicon
- double-sided segmentation
- 1024 strips of 58 µm pitch
- strip length 2/4/6/12 cm
- angle front/back: 7.5 deg
- read-out from top edge
- rad. tol. up to 10^{14} n_{eq}/cm^2





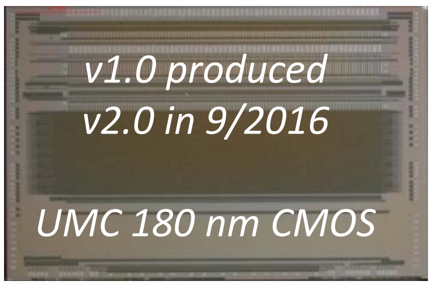
prototypes from CiS, Germany and Hamamatsu, Japan

Read-out electronics

- *purely data driven read-out*
- *time-stamped data elements*

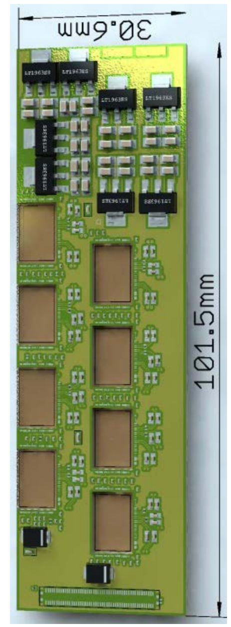
STS-XYTER ASIC

128 sensor channels



channels	128, polarity +/-
noise	< 1ke$^-$ at 20-50pF load
ADC range	linear up to12 fC, 5 bit
clock	250 MHz
power	< 10 mW/channel
timestamp	< 10 ns resolution
out interface	5 × 500 Mbit/s LVDS

Front-end Board



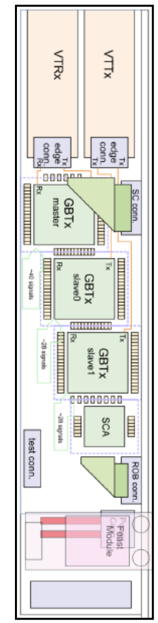
time-stamped data

8 STS-XYTER chips
à 1/2/5 LVDS links out

under development

copper link

Read-Out Board



data combining

GBTx chip-set (CERN):
3 GBTx, 1 VTRx, 1 VTTx, 1 SCA

42 E-links à 320 Mb/s
3 GBT optical uplinks à 4.48 Gb/s

under development /production

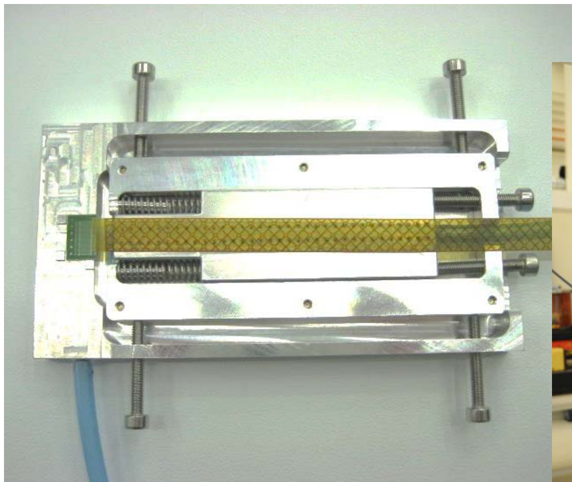
optical link

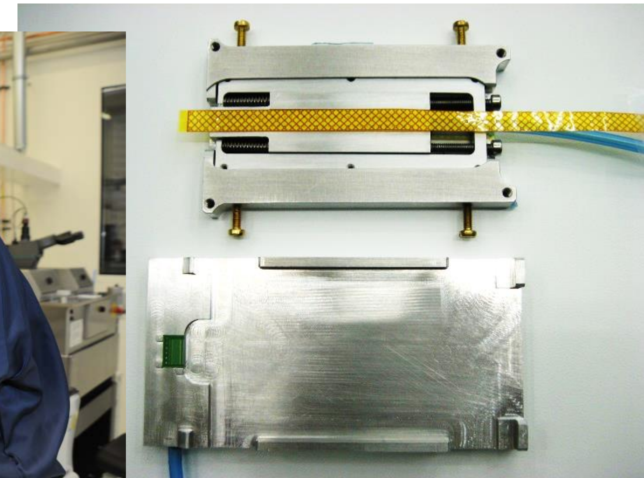
Data Processing Board
time-slicing

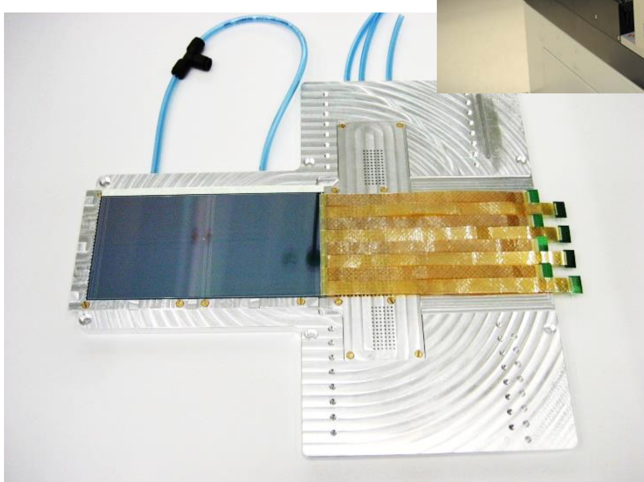
FLES farm
online event computing

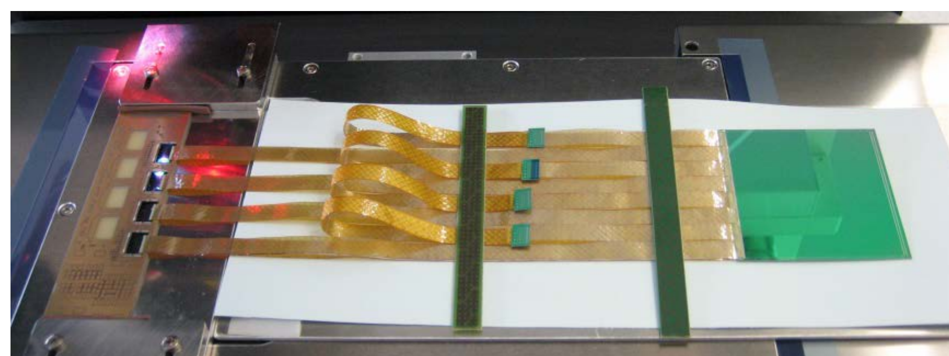
Module assembly

GSI-Detector Lab

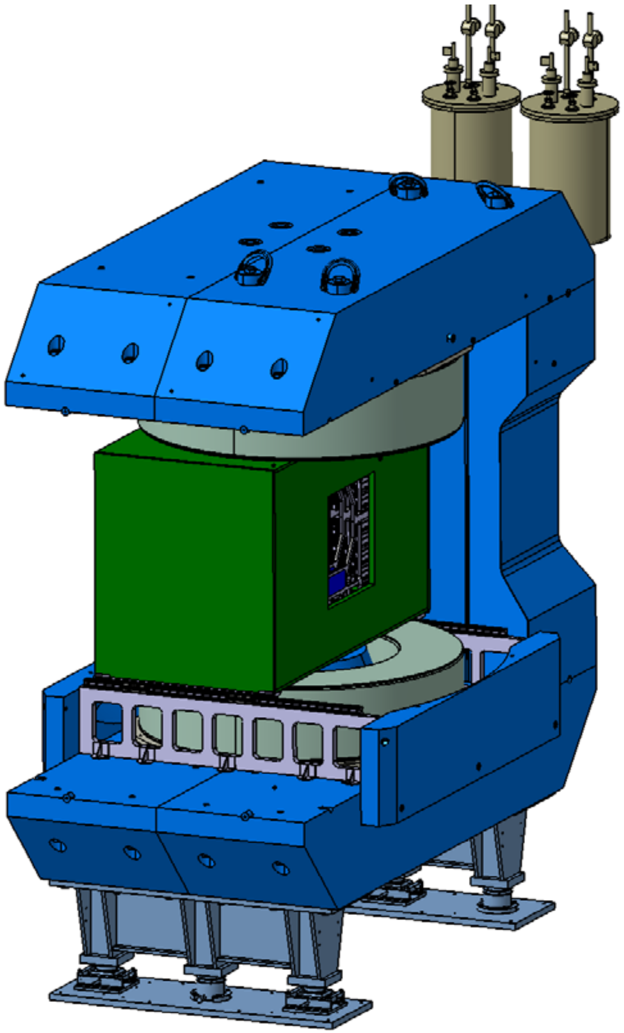


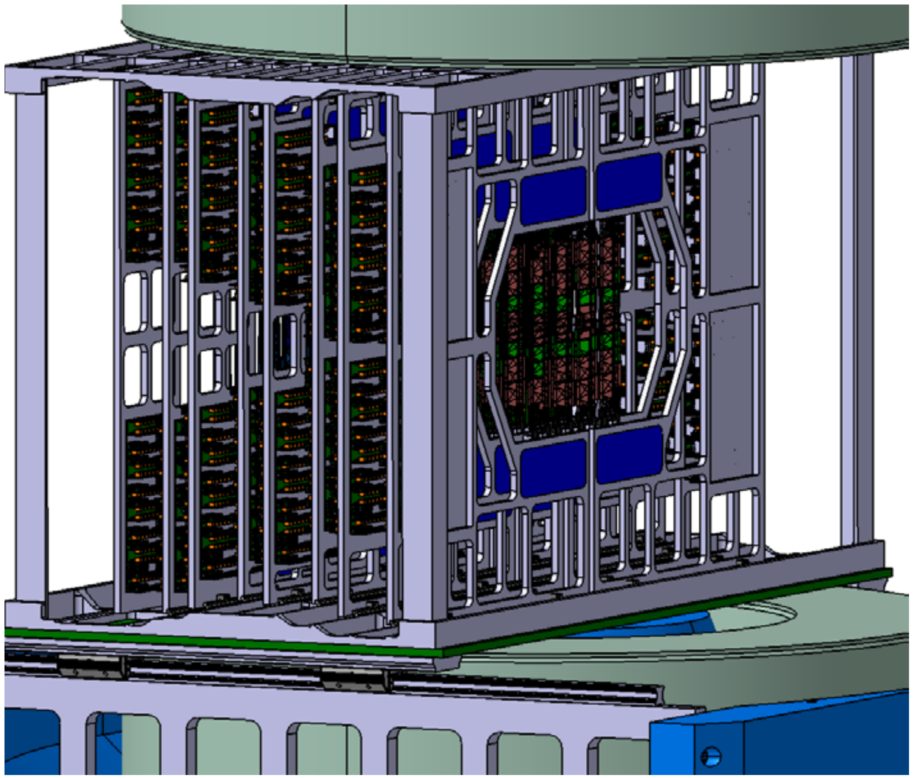






System Integration





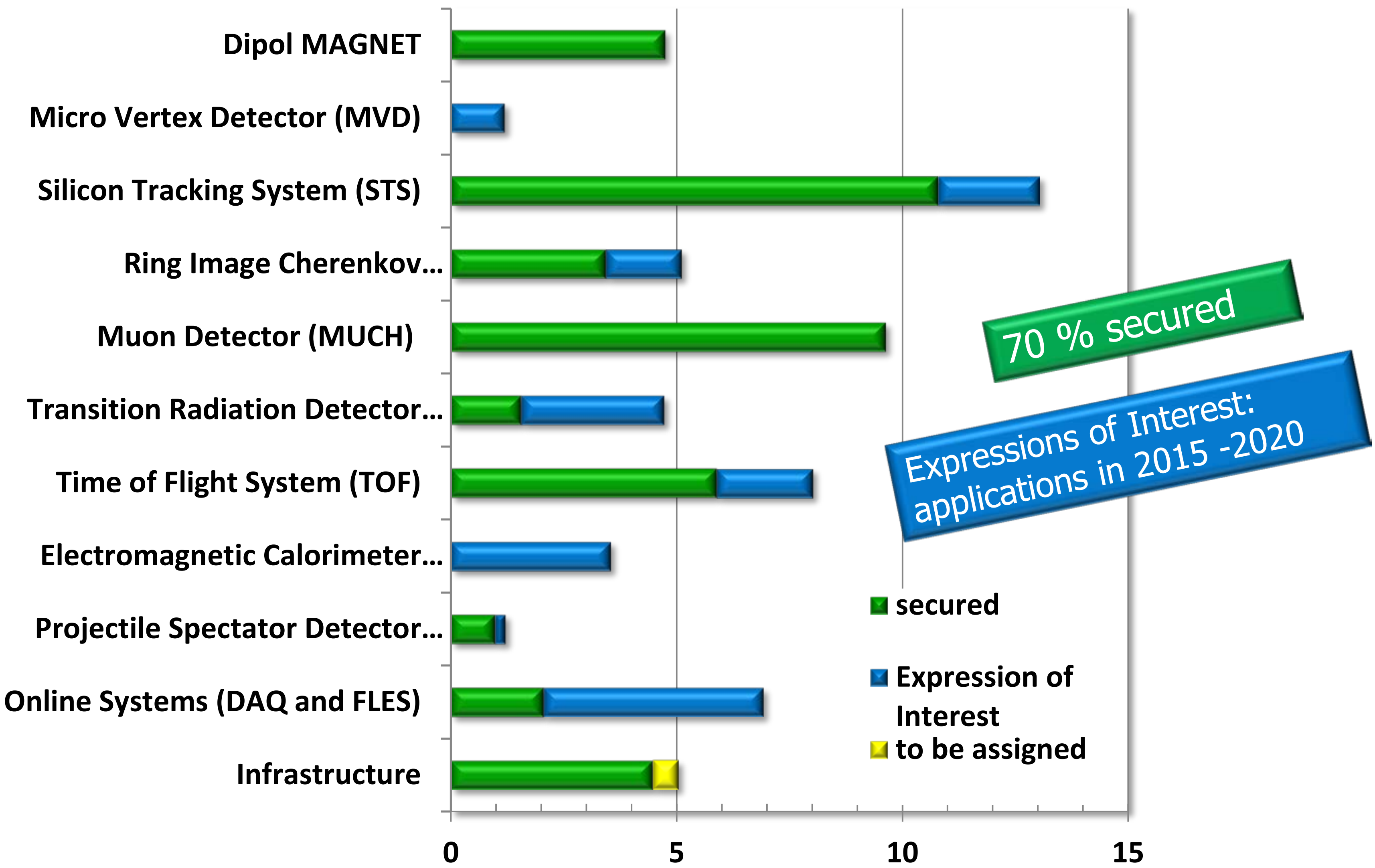
Current topics in STS development

- *signal-to-noise in module:*
  detailed understanding of sensor (degrading with irradiation), microcables, ASIC: capacitive + resistive load
- *read-out with final electronics/DAQ*
- *system integration: powering, cooling, final dimensions of modules, ladders, support structures, board stack-up, routing integration of target-MVD-STS into dipole magnet*
- *preparing for production readiness:*
  assembly centers, tasks, component yields,
  quality assurance specifications and procedures,
  determination of timelines, contracts with industry (sensors)
- *…*

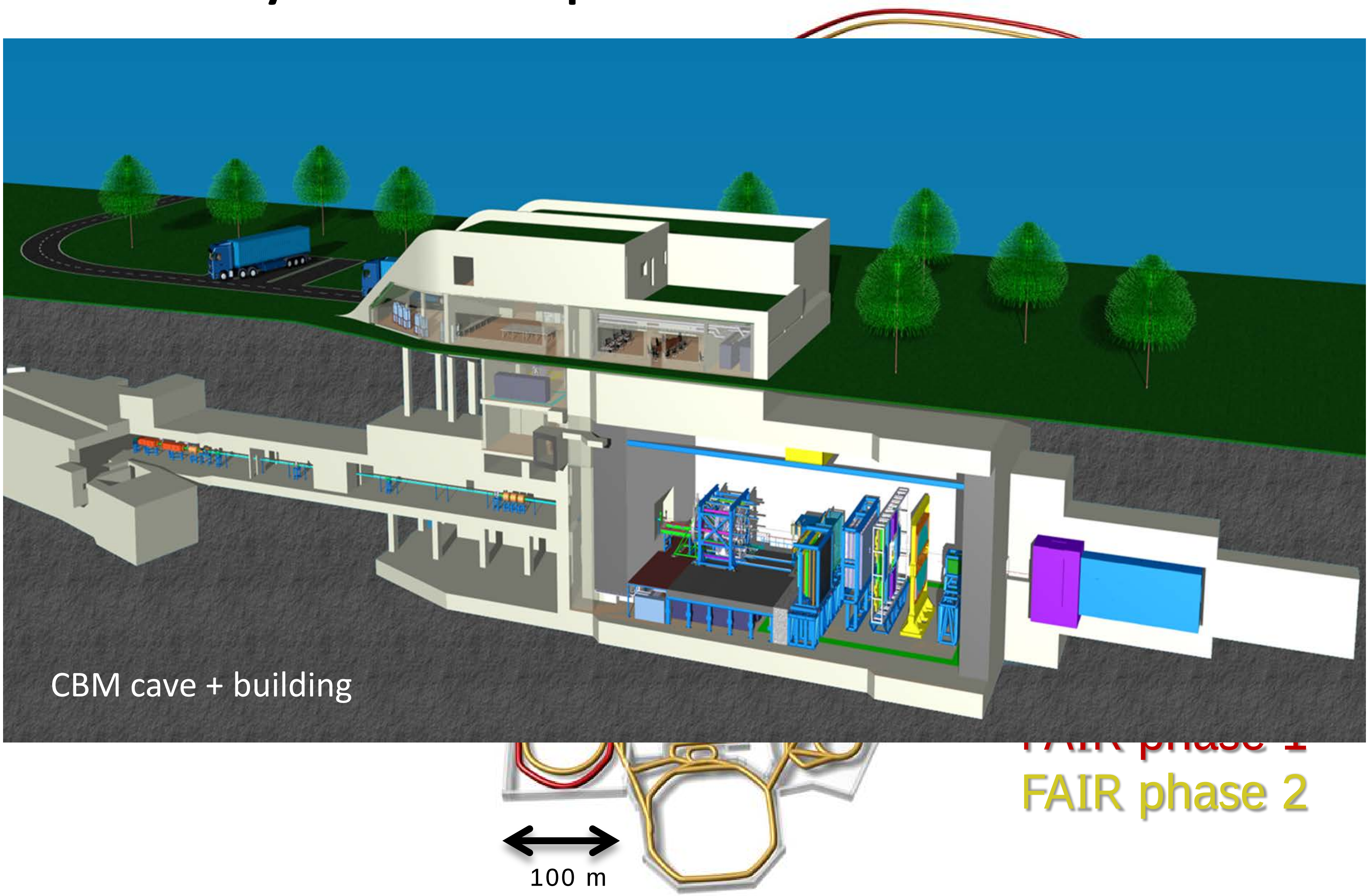
CBM time line

- TDRs: 2013 – 2017
- production readiness of the sub-systems: 2016 – **2017** – 2018
- construction: until 2020
- ready for beam: 2021

Costs and funding – CBM Start version



Facility for Antiproton & Ion Research



Facility for Antiproton & Ion Research

Aerial photo - April 2015

FAIR phase 0

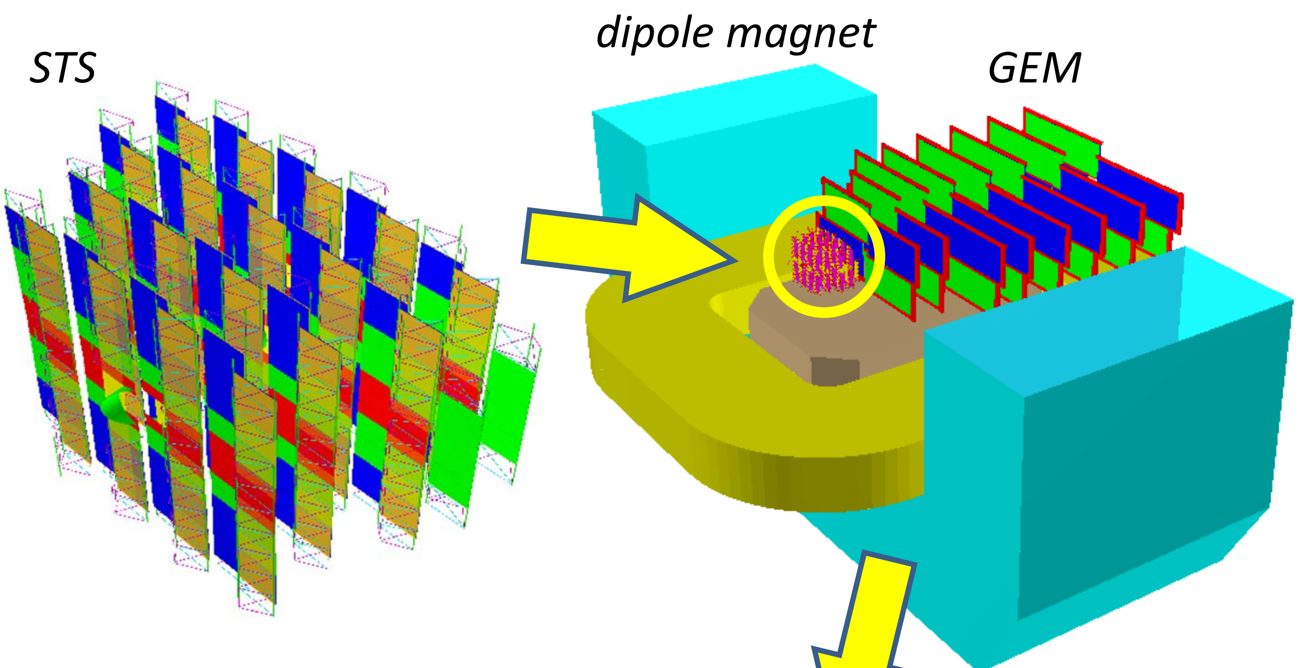
CBM plans to operate prototype sub-systems already before the start of FAIR:

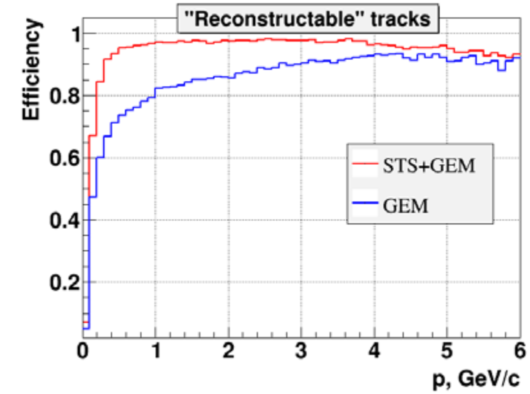
TOF:	*in STAR experiment at RHIC/BNL*
RICH:	*in HADES experiment at SIS-18/GSI*
STS:	*in BM@N experiment at Nuclotron/JINR*
DAQ/FLES:	*in mCBM set-up at SIS-18*

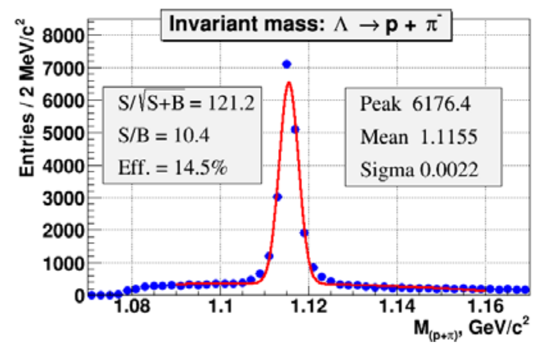
Aim:
- – commissioning of detectors under real exp. conditions
- – physics measurements
- – training of the teams

STS in BM@N experiment at Nuclotron

Mutual interest by CBM groups from Germany and Russia to install, commission and use 4 CBM-like Silicon Tracking Stations in BM@N in 2018 – 2021







The CBM Collaboration: 60 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.

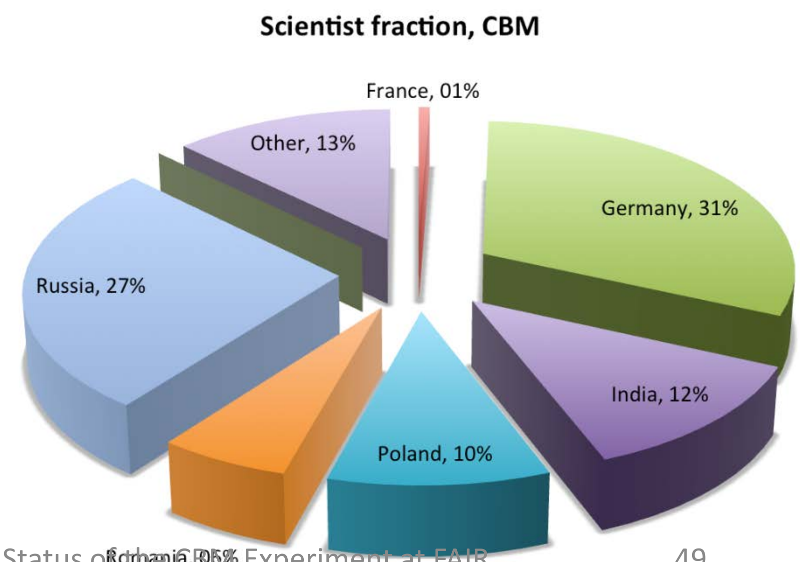
Korea:
Pusan Nat. Univ.

Romania:
NIPNE Bucharest
Univ. Bucharest

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

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

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

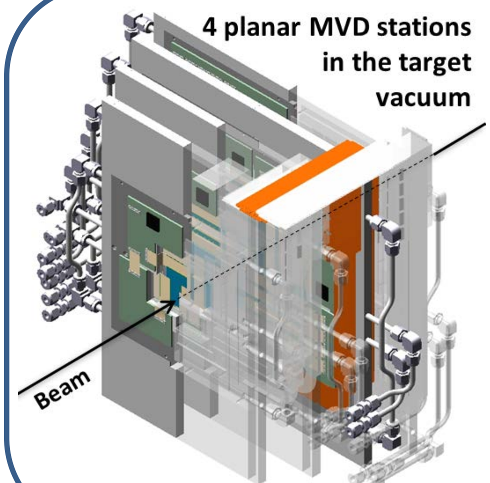


Summary

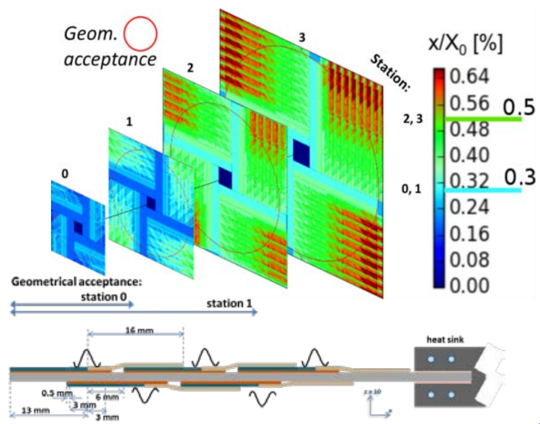
- **CBM scientific program at SIS100:**
  Exploration of the QCD phase diagram in the region of neutron star core densities
  $\rightarrow$ large discovery potential.
- **First measurements with CBM:**
  High-precision multi-differential measurements of hadrons incl. multistrange hyperons, hypernuclei and dileptons for different beam energies and collision systems $\rightarrow$ terra incognita.
- **Status of experiment preparation:**
  Prototype detector performances fulfill CBM requirements.
  7 TDRs approved, 4 TDRs in preparation.
- **e.g. Silicon Tracking System:**
  Central detector of the experiment: charged-particle tracking, momentum measurement.
  Development and construction in close cooperation of GSI and JINR. Electronics from Poland.
  Using part of the STS detector for system tests at GSI and/or physics runs at external labs is under consideration: $\rightarrow$ BM@N, JINR (FAIR0 phase, 2018 – 2020)
- **Funding:**
  Substantial part of the CBM start version is financed (including Expressions of Interest).
- **CBM time line:**
  Resource loaded schedules for most of the detectors.
  Aim: Detectors ready for beam end of 2020.

back-up slides

CBM Micro-Vertex Detector

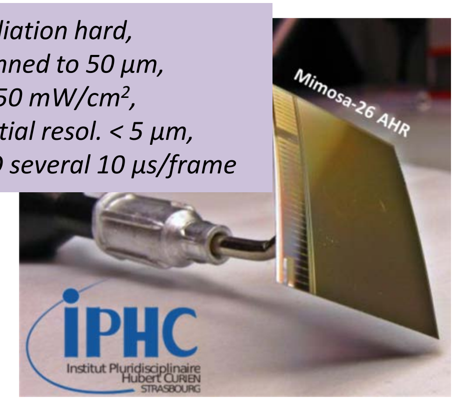


Ultra-thin: CVD diamond, TPG



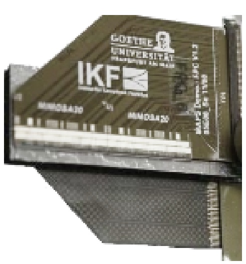
Sensors: CMOS MAPS

- *Radiation hard,*
- *Thinned to 50 µm,*
- *< 150 mW/cm², *
- *spatial resol. < 5 µm,*
- *R/O several 10 µs/frame*



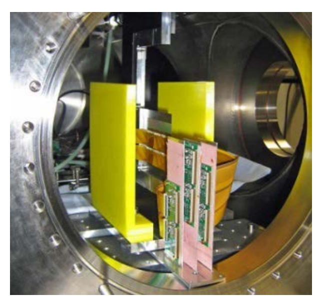
Prototyping & test

MVD demonstrator



MVD prototype

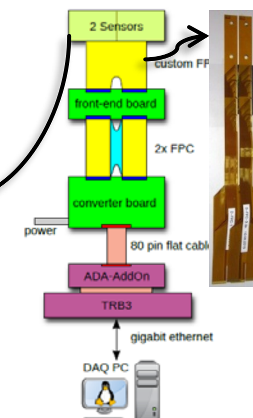
PRESTO



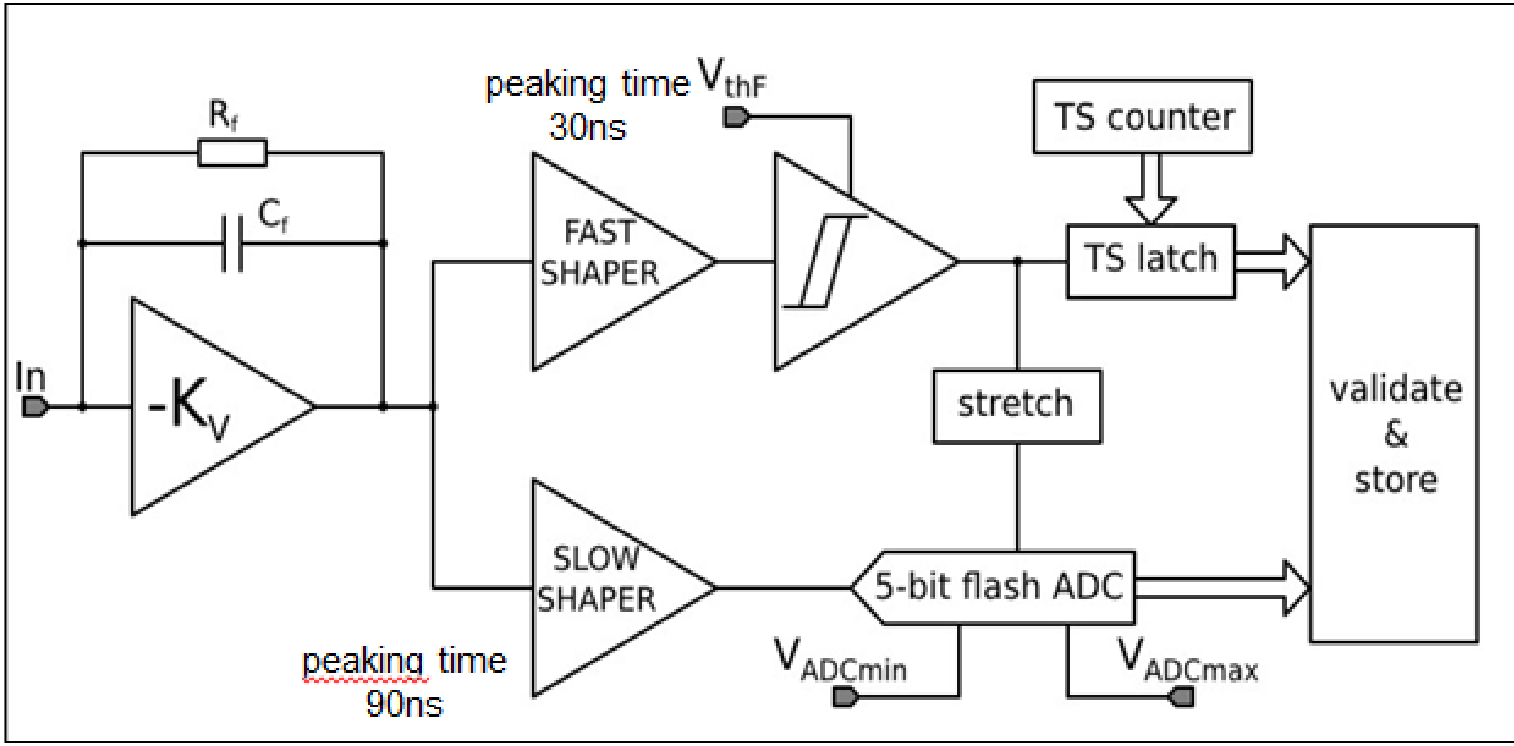
MOMENTIVE

Thermal Pyrolytic Graphite

Customized FEE & DAQ: TRB-based



Structure of *STS-XYTER* front-end

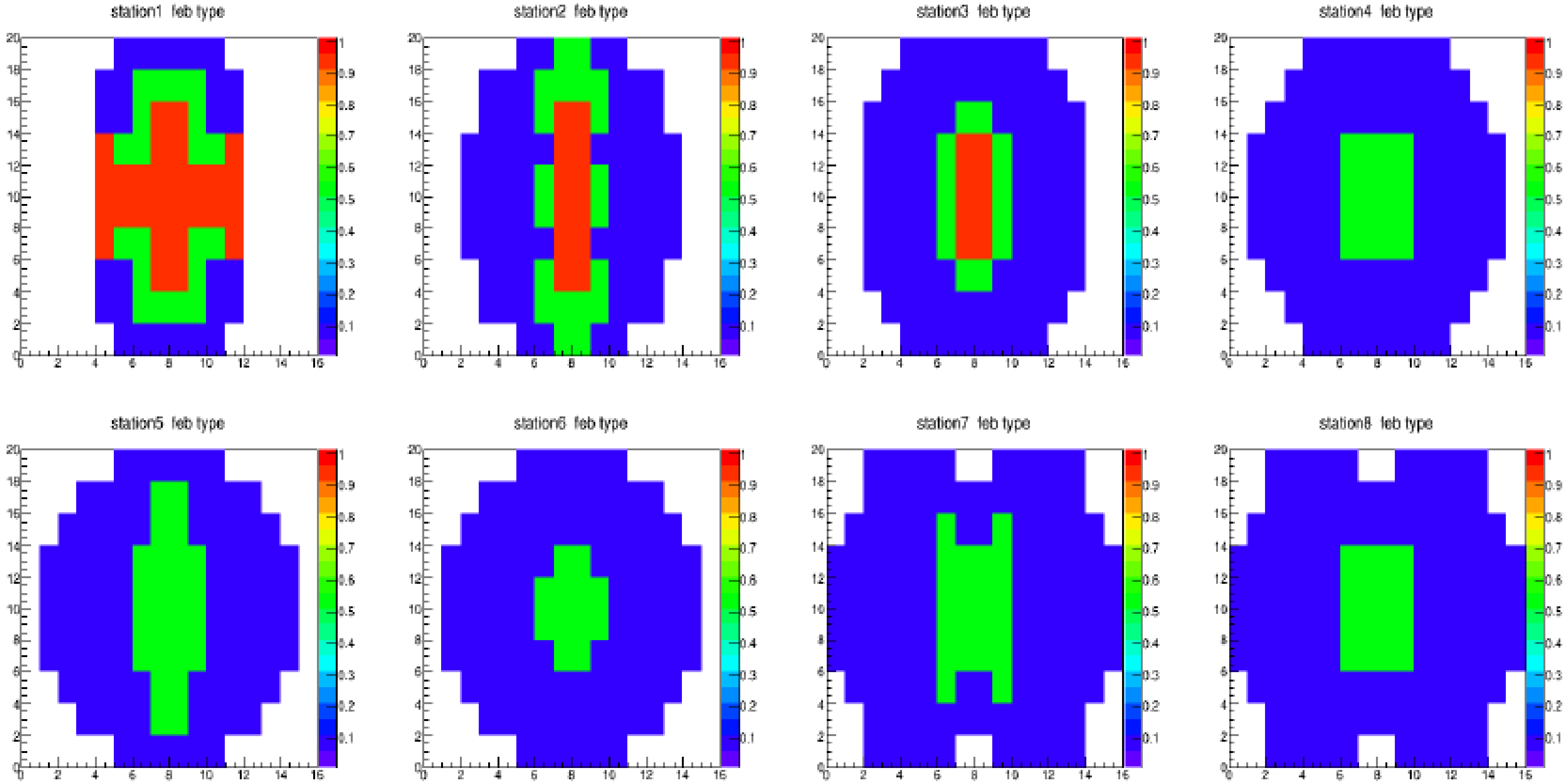


- Two-stage trigger allows fast time stamp and low trigger level
- $V_{thF} < V_{ADCmin}$ → the time measurement is validated by the energy measurement – worst cases (noise) dropped

FEB Types @ 10 MHz, Au+Au, 10 AGeV

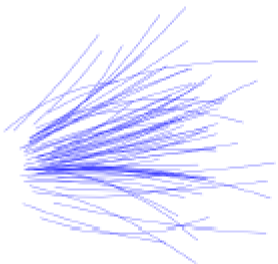
FEB-1: 1 x 320 Mbps / STS-XYTER
FEB-2: 2 x 320 Mbps / STS-XYTER
FEB-5: 5 x 320 Mbps / STS-XYTER

preliminary

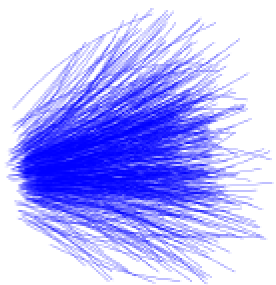


CA Track Finder at High Track Multiplicity

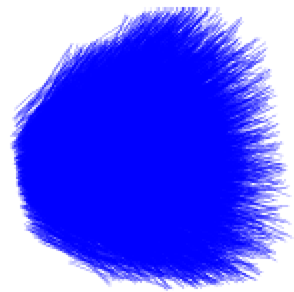
A number of minimum bias events is gathered into a group (super-event), which is then treated by the CA track finder as a single event



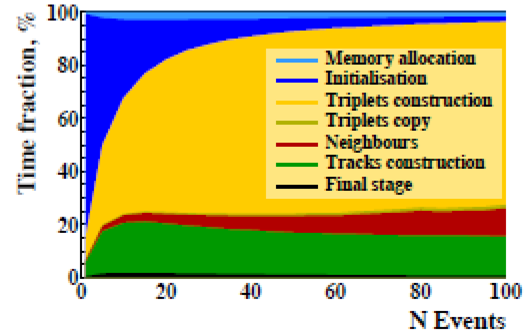
1 mbias event, $\langle N_{reco} \rangle$ = 109

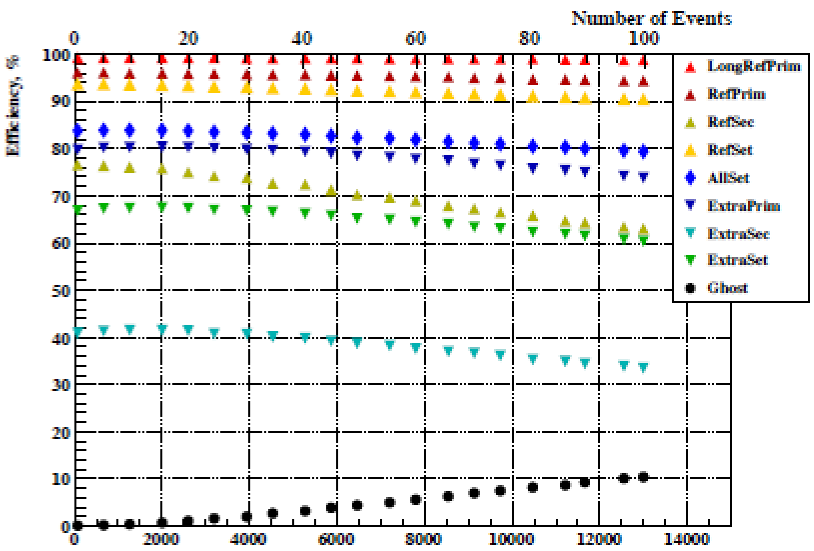


5 mbias events, $\langle N_{reco} \rangle$ = 572

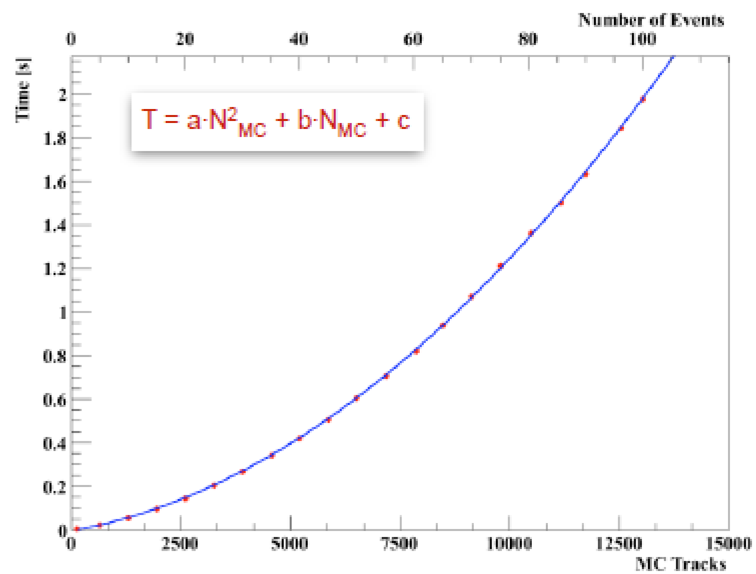


100 mbias events, $\langle N_{reco} \rangle$ = 10340



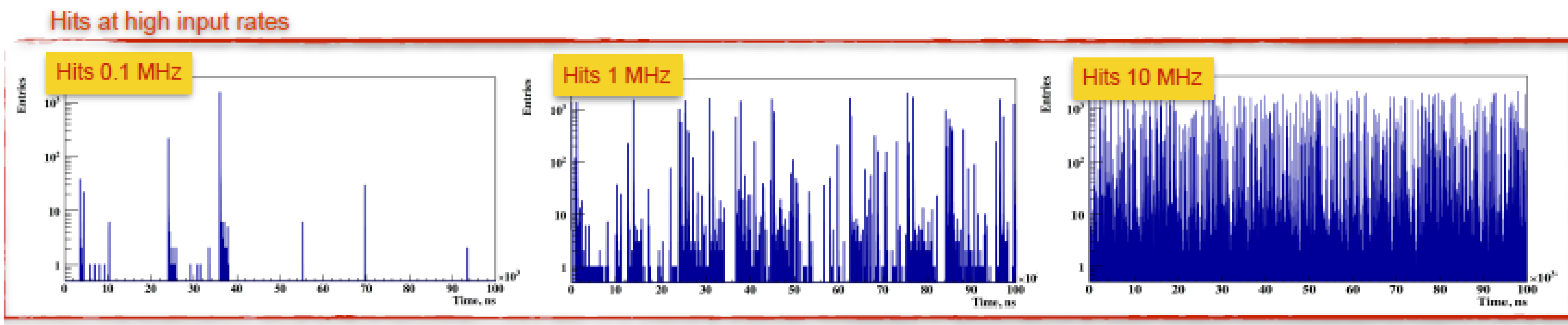


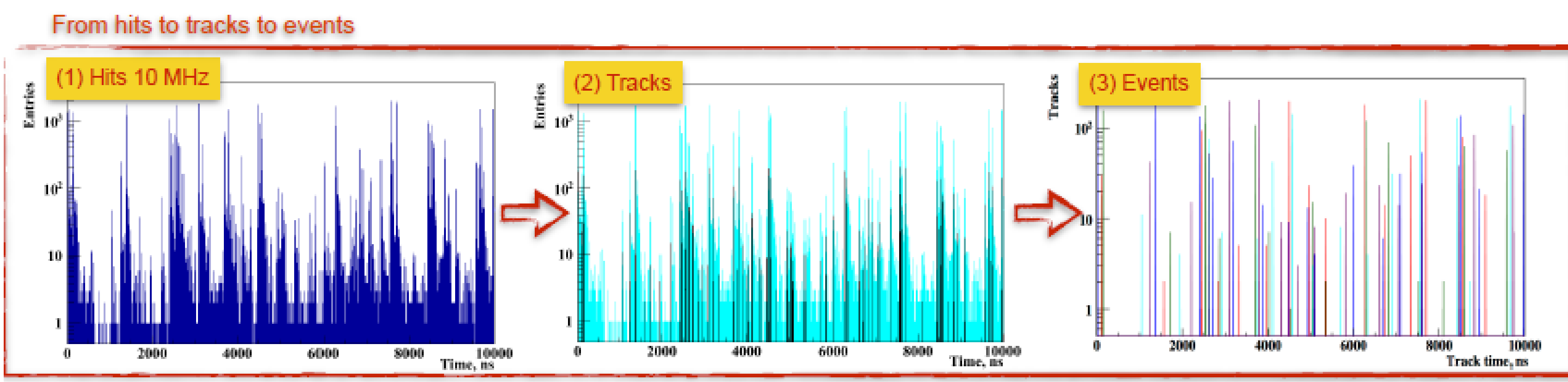
Au+Au mbias events at 25 AGeV



Stable reconstruction efficiency and time as a second order polynomial w.r.t. to track multiplicity

4D Event Building at 10 MHz





Reconstructed tracks clearly represent groups, which correspond to the original events
83% of single events, no splitted events, further analysis with TOF information at the vertexing stage