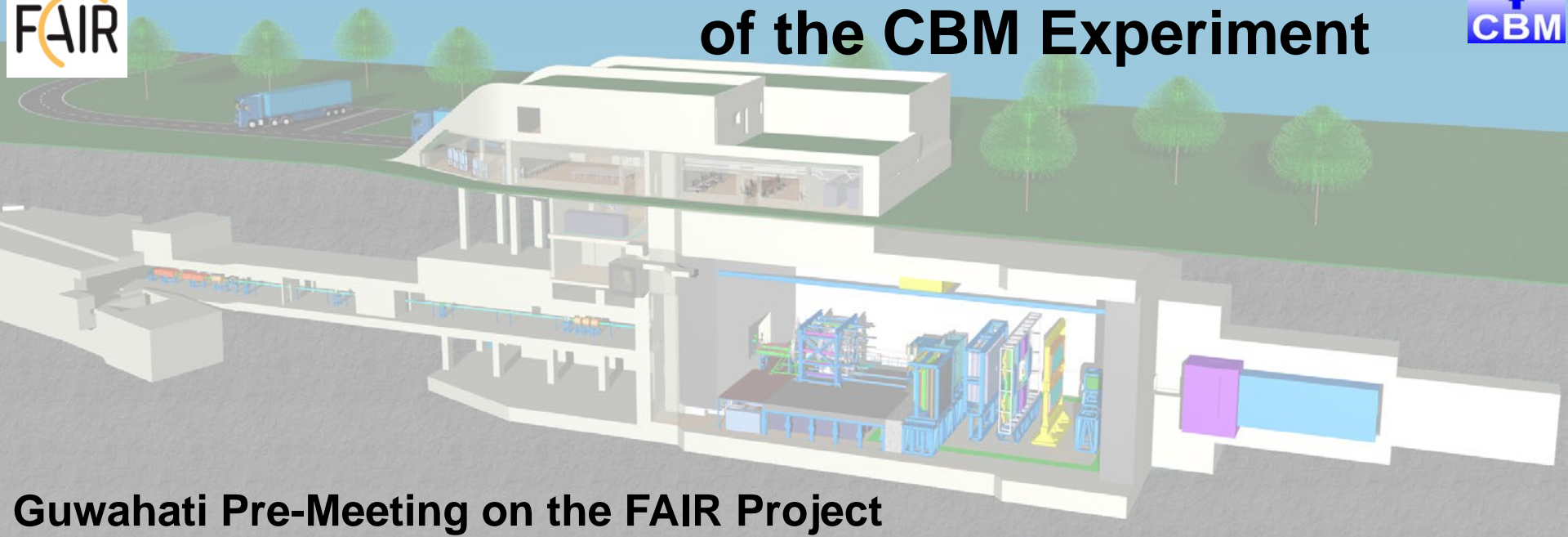


# Goals and Perspectives of the CBM Experiment



## Guwahati Pre-Meeting on the FAIR Project

Guwahati, India

September 28, 2019

*Christian Sturm, GSI  
for the CBM Collaboration*

### Outline

CBM physics program

The CBM experiment

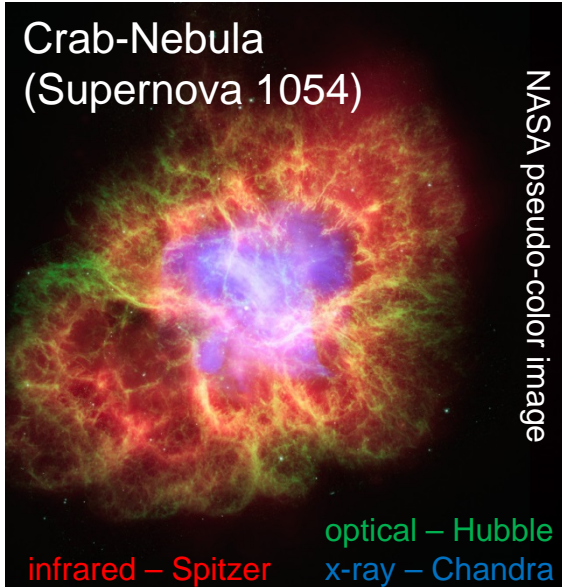
The full system test-setup mCBM@SIS18

## Neutron stars

Temperature  
 $T < 20 \text{ MeV}$

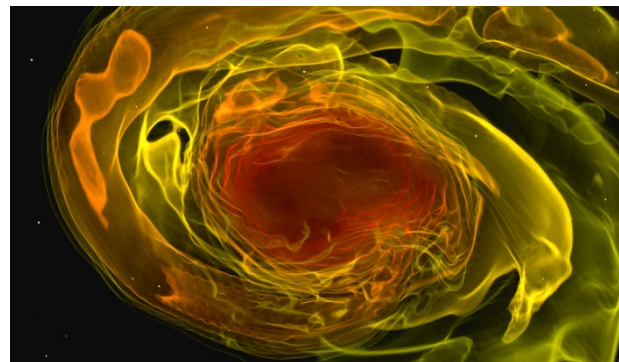
Core density  
 $\rho < 10 \rho_0$

Lifetime  
 $\Delta t \sim \text{infinity}$



Crab pulsar  $T = 33.4 \text{ ms}$ , Mass  $\sim 1.5 M_\odot$

## Neutron star merger



numerical simulation, GW170817

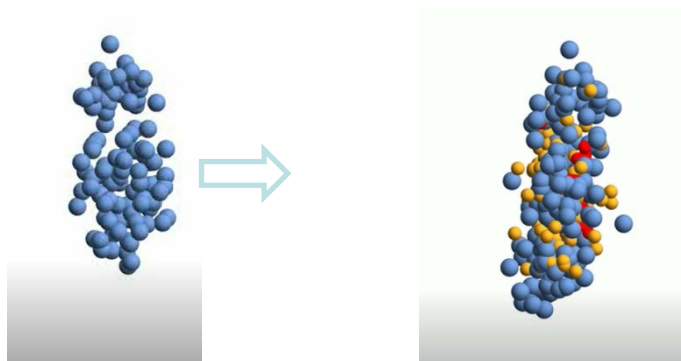
T. Dietrich (Max Planck Institute for Gravitational Physics)

Temperature  
 $T < 70 \text{ MeV}$

Density  
 $\rho < 2 - 6 \rho_0$

Reaction time  
 $\Delta t \sim 10 \text{ ms}$

## Relativistic nucleus-nucleus collisions at SIS100

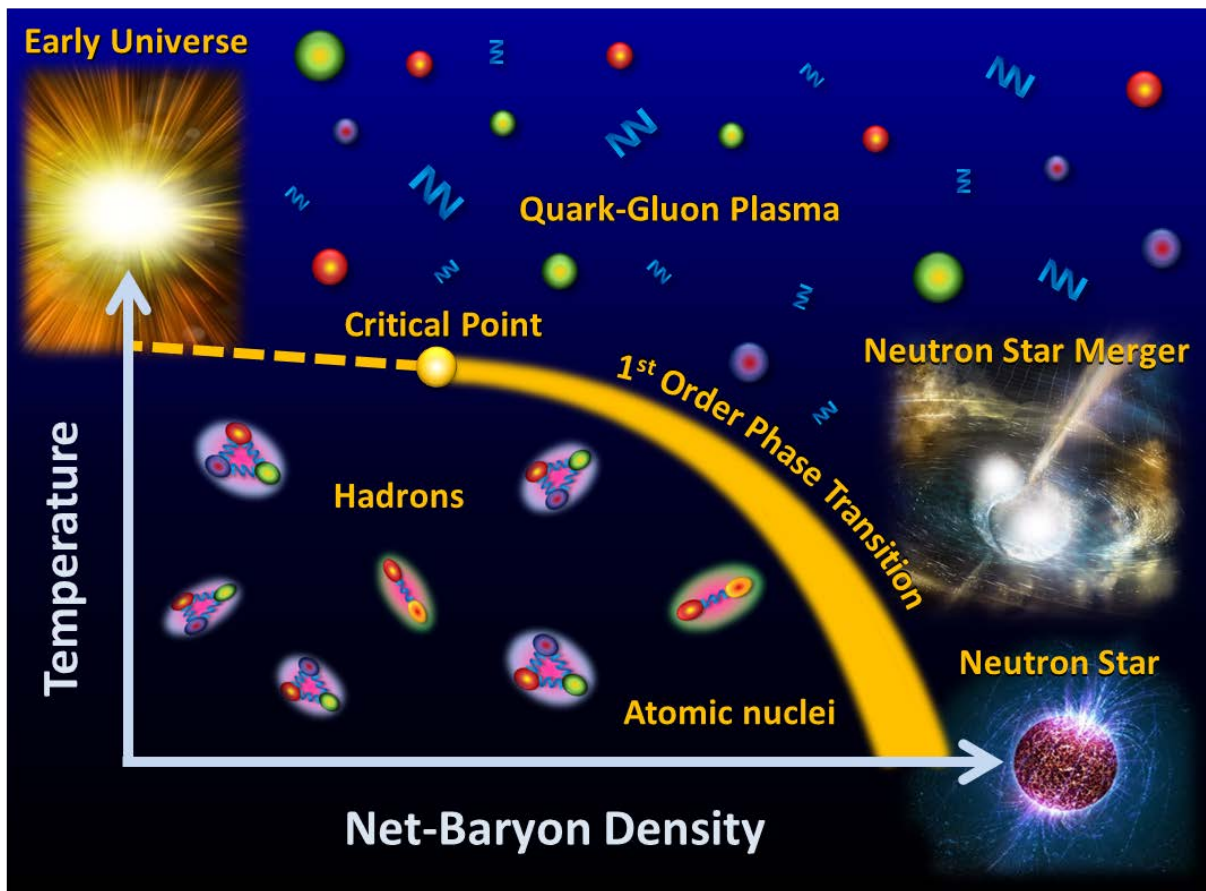


Temperature  
 $T < 120 \text{ MeV}$

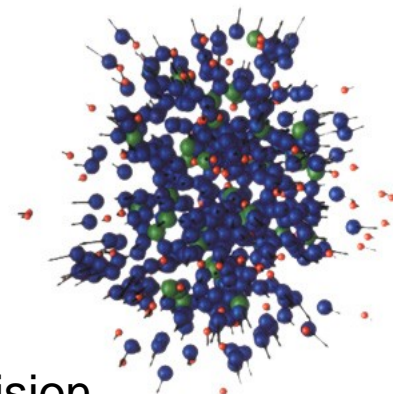
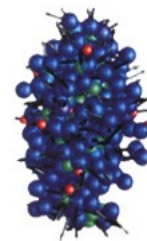
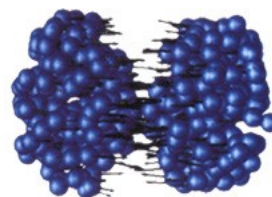
Density  
 $\rho < 8 \rho_0$

Reaction time  
 $\Delta t \sim 10^{-23} \text{ s}$

# Exploring the QCD phase diagram

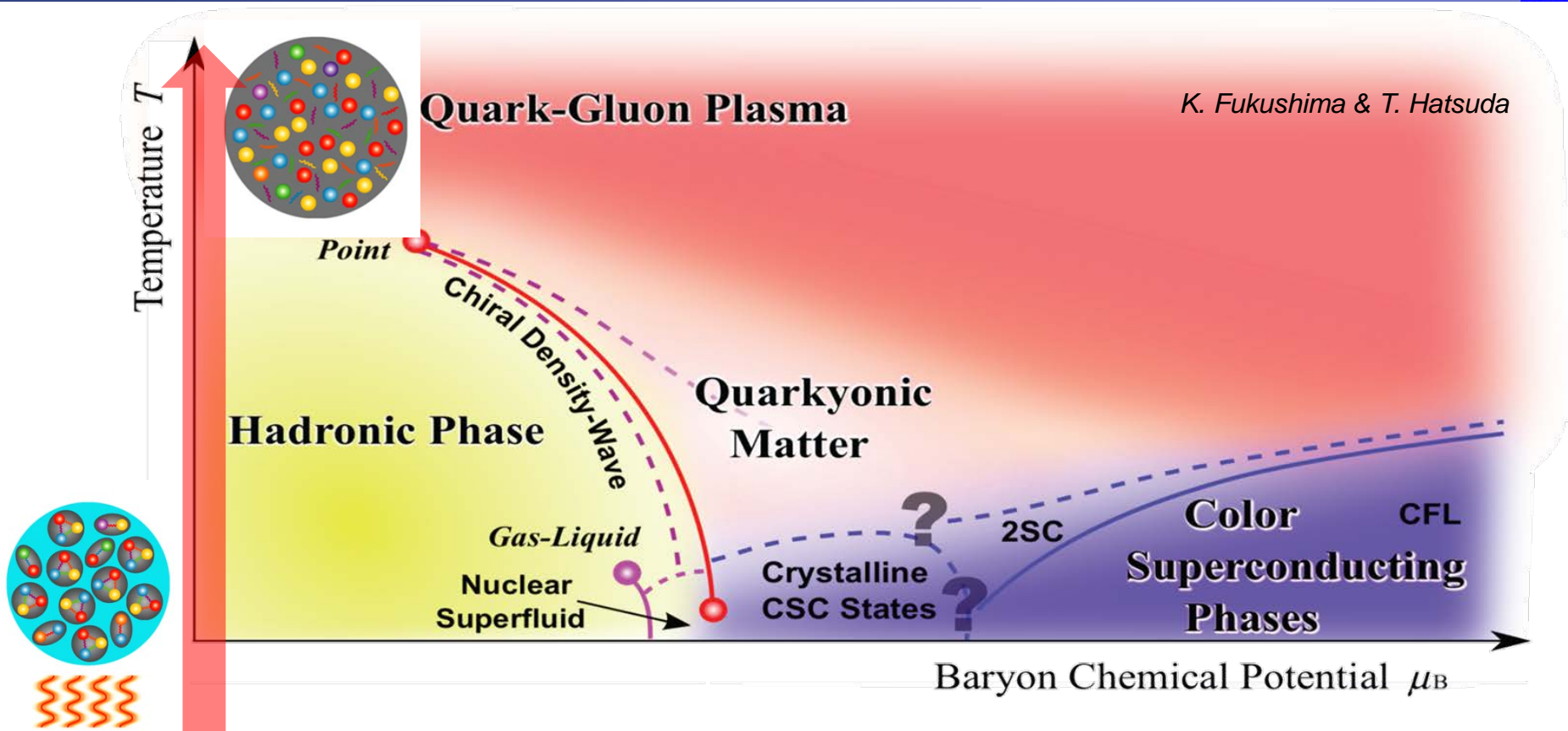


in the **laboratory**:  
nucleus-nucleus collisions



Au + Au collision

# Exploring the QCD phase diagram



## At very high temperature:

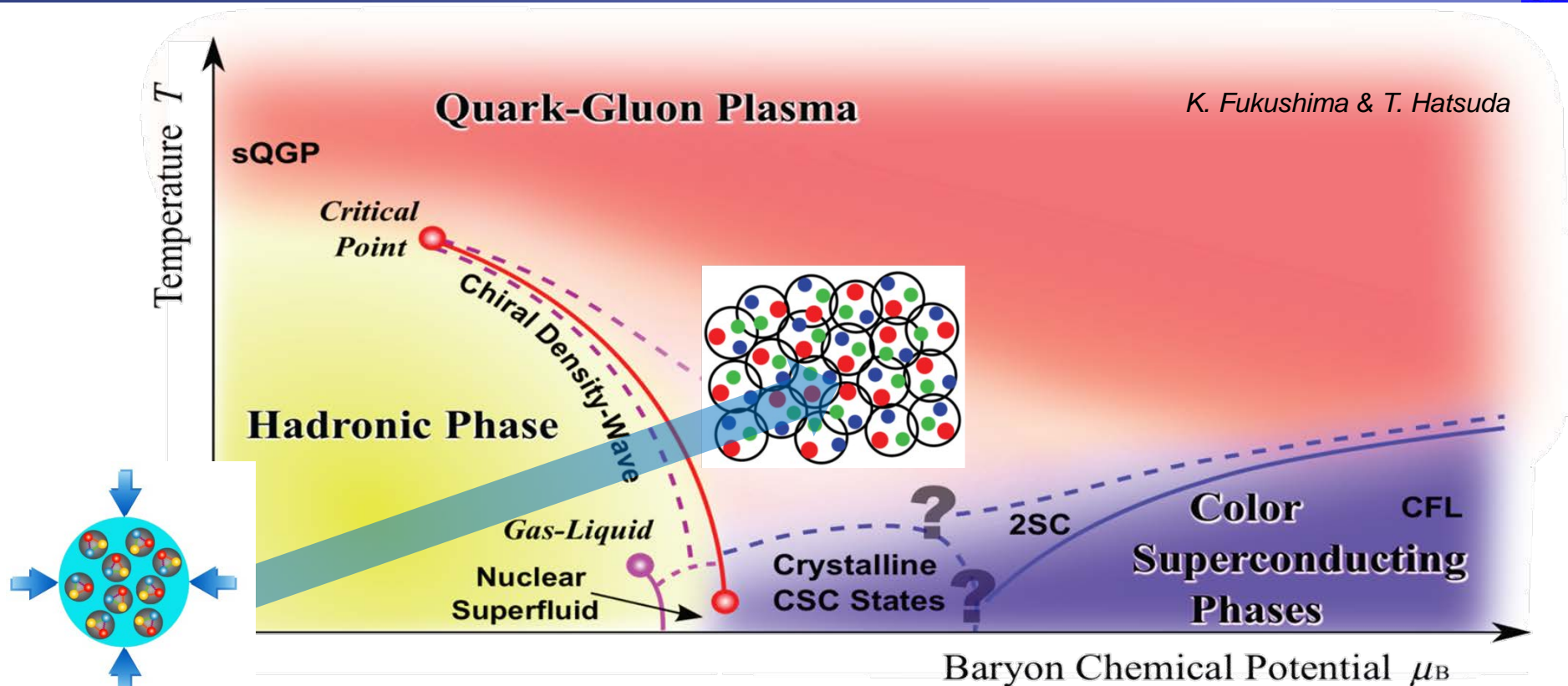
$N$  of baryons  $\approx N$  of antibaryons  $\rightarrow$  situation similar to early universe

Lattice QCD: crossover transition Hadronic Matter  $\rightarrow$  Quark-Gluon Plasma

Experiments:

ALICE, ATLAS and CMS at LHC & STAR and PHENIX at RHIC

# Exploring the QCD phase diagram



## At high baryon density:

$N$  of baryons  $\gg$   $N$  of antibaryons, densities like in neutron star cores

→ Lattice QCD not (yet) applicable

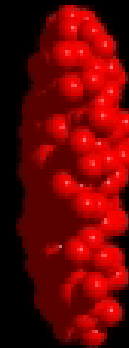
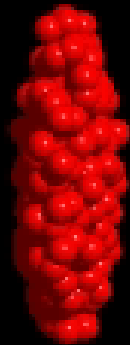
→ Models predict first order phase transition with mixed or exotic phases

Experiments:

BES at RHIC, NA61 at CERN SPS, NICA at JINR and **CBM at FAIR**

Relativistic nucleus-nucleus collision  
U + U 23 GeV per nucleon

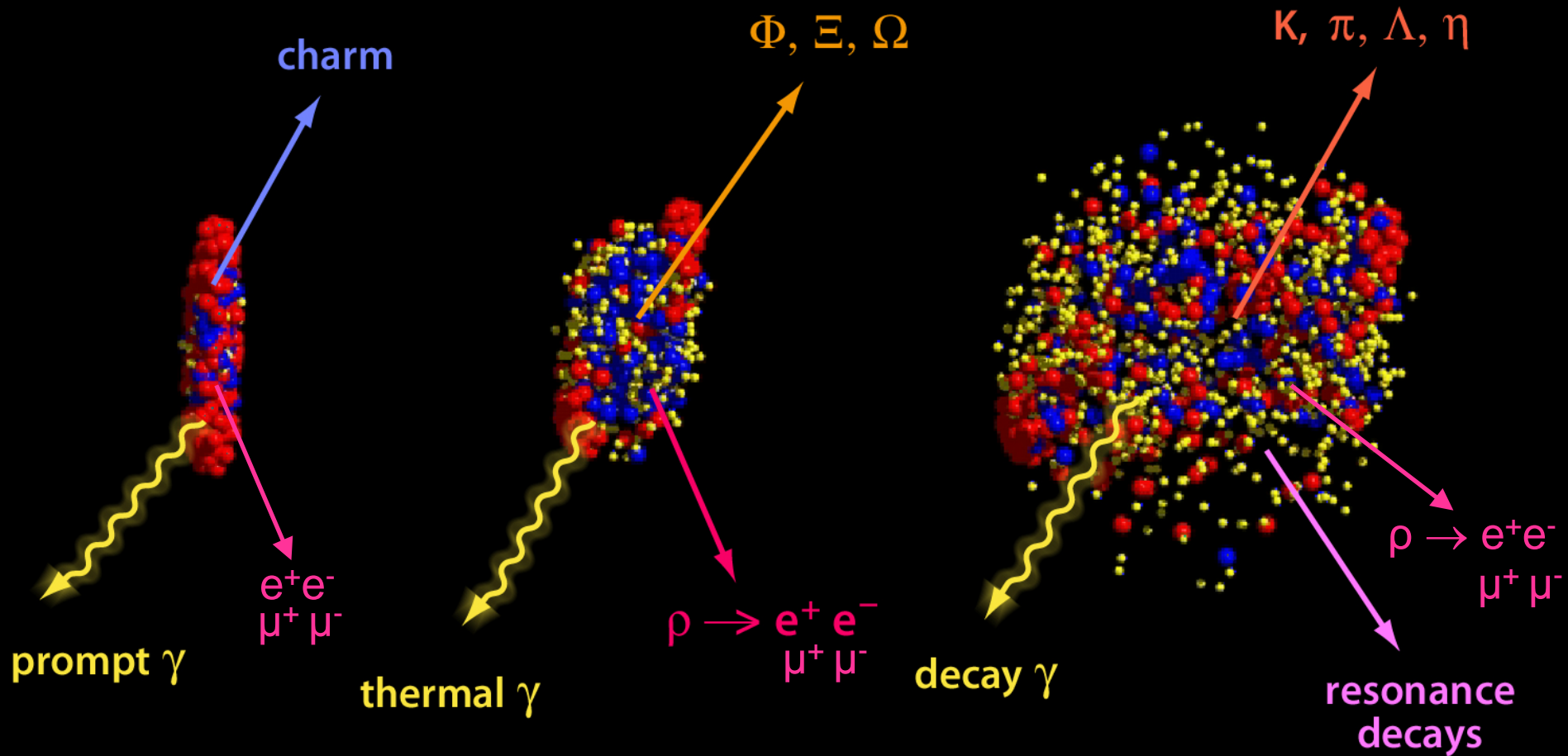
$t = -17.14 \text{ fm/c}$



microscopic transport model calculation

UrQMD Frankfurt/M

# Messengers



UrQMD transport calculation U+U 23 AGeV

# CBM physics case and observables

New phases of strongly-interacting matter ?

- excitation function and flow of lepton pairs
- excitation function and flow of strangeness ( $K$ ,  $\Lambda$ ,  $\Sigma$ ,  $\Xi$ ,  $\Omega$ )

Deconfinement phase transition at high  $\rho_B$  ?

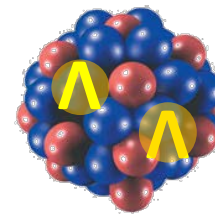
- excitation function and flow of charm ( $J/\psi$ ,  $\psi'$ ,  $D^0$ ,  $D^\pm$ ,  $\Lambda_c$ )
- anomalous charmonium suppression
- event-by-event fluctuations of conserved quantities

Onset of chiral symmetry restoration at high  $\rho_B$  ?

- in-medium modifications of hadrons ( $\rho, \omega, \phi \rightarrow e^+e^-(\mu^+\mu^-)$ )

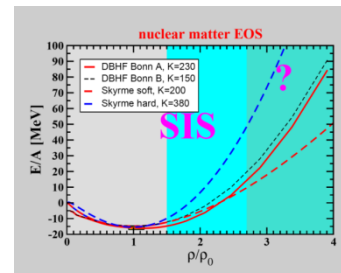
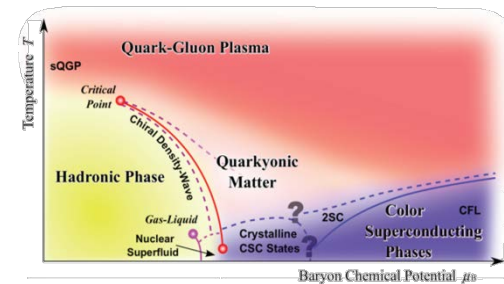
Strange matter

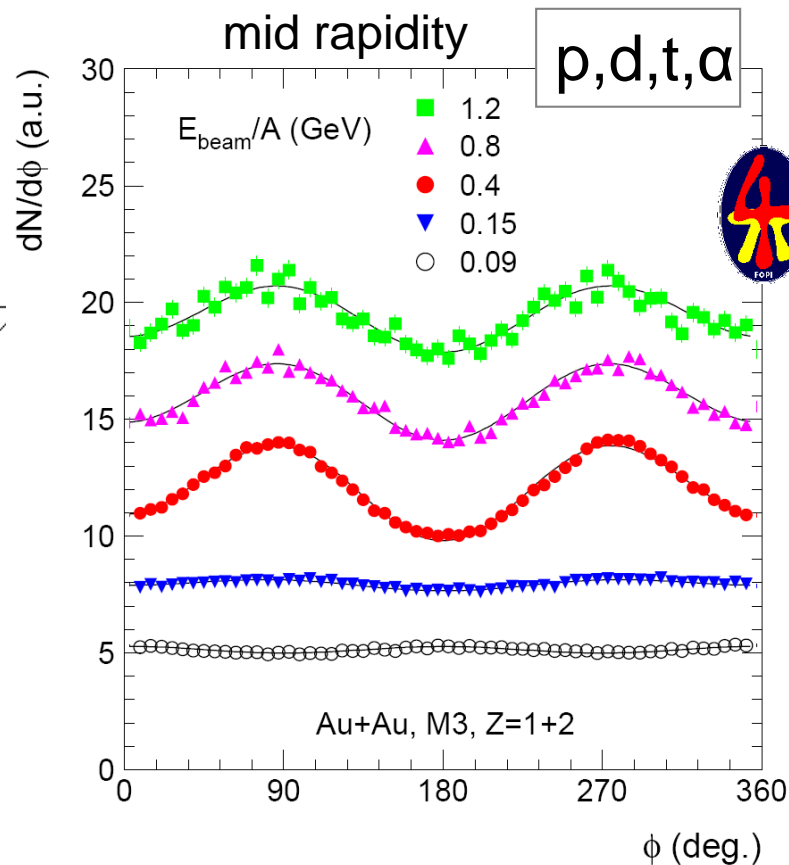
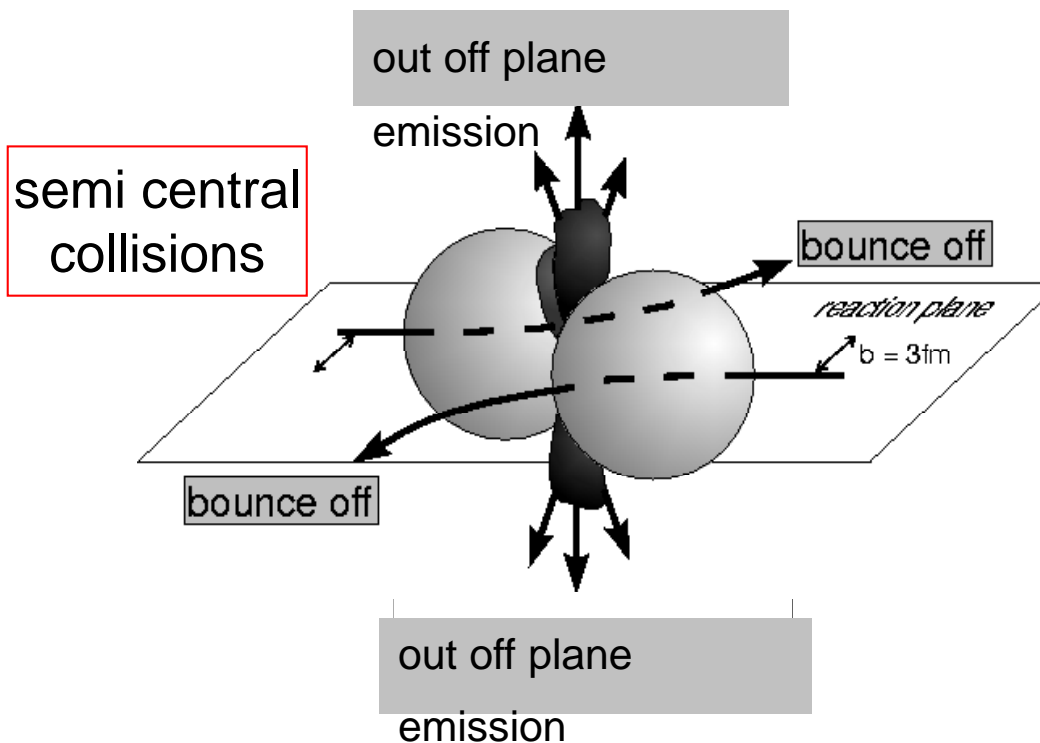
- (double-) lambda hypernuclei
- strange meta-stable objects (e.g. strange dibaryons)



The equation-of-state at neutron star core densities

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





Fourier expansion of the  $dN/d\phi$  distribution:

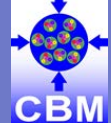
$$\frac{dN}{d\phi} \sim [1 + 2v_1 \cdot \cos(\phi) + 2v_2 \cdot \cos(2\phi)]$$

the coefficients quantify :

- $v_1$  the **in-plane** and
- $v_2$  the **elliptic** emission pattern

named as well as:  $v_1$  directed flow ,  $v_2$  elliptic flow

# Introducing the nuclear equation-of-state



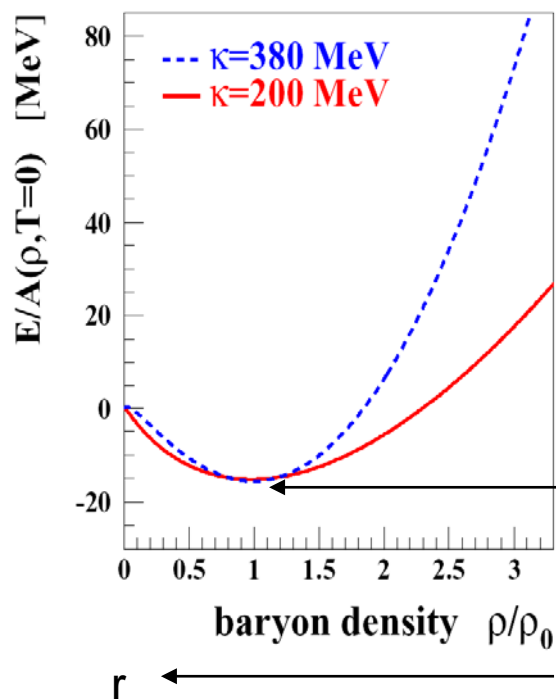
$$\varepsilon(\rho, T) = \varepsilon_T(\rho, T) + \varepsilon_C(\rho, T=0) + \varepsilon_0$$

( $\varepsilon = E/A$ )    thermal    compressional    ground state energy

**thermodynamical  
concept**

nuclear equation-of-state at  $T = 0$  : the "compressional"

$$E/A(\rho, T=0) = \frac{1}{\rho} \int U(\rho) d\rho \quad U(\rho): \text{ density dependent local potential}$$



curvature at saturation density:  
compression modulus

$$\kappa = \left( 9\rho^2 \frac{\partial^2 E/A(\rho, T=0)}{\partial \rho^2} \right)_{\rho=\rho_0}$$

example for an  
effective NN-Potential  
(Skyrme type)

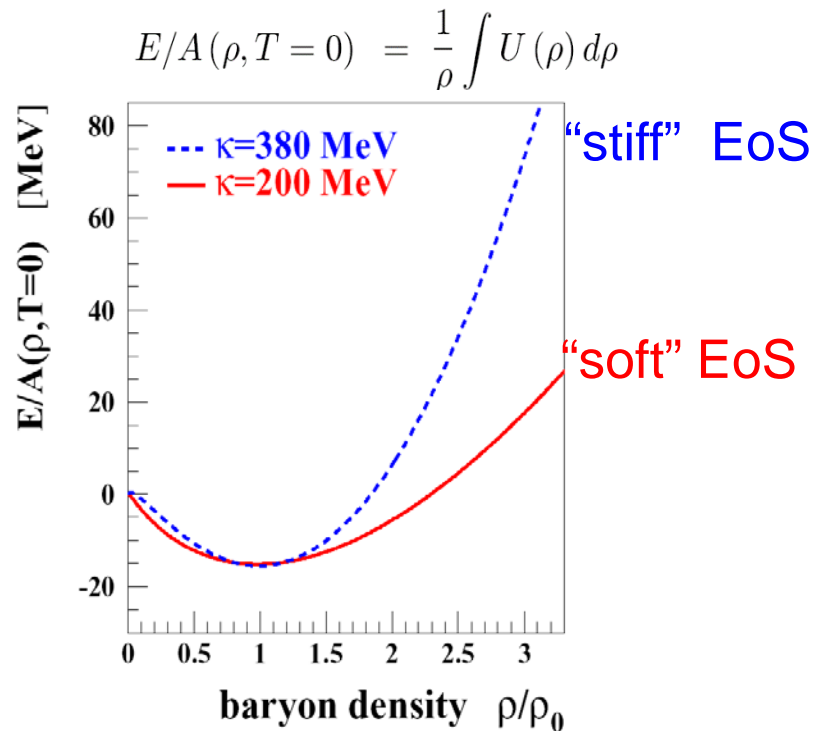
$$U(\rho) = \alpha \left( \frac{\rho}{\rho_0} \right) + \beta \left( \frac{\rho}{\rho_0} \right)^\gamma$$

constraints for the parameters  
of the potential :

$$\varepsilon(\rho = \rho_0, T = 0) = -16 \text{ MeV}$$

$$\left( \frac{\partial \varepsilon(\rho, T = 0)}{\partial \rho} \right)_{\rho = \rho_0} = 0$$

	$\alpha$ [MeV]	$\beta$ [MeV]	$\gamma$
$\kappa = 380 \text{ MeV}$	-124	70.5	2
$\kappa = 200 \text{ MeV}$	-356	303	7/6



$$\kappa = \left( 9\rho^2 \frac{\partial^2 E/A(\rho, T = 0)}{\partial \rho^2} \right)_{\rho = \rho_0}$$

compression modulus

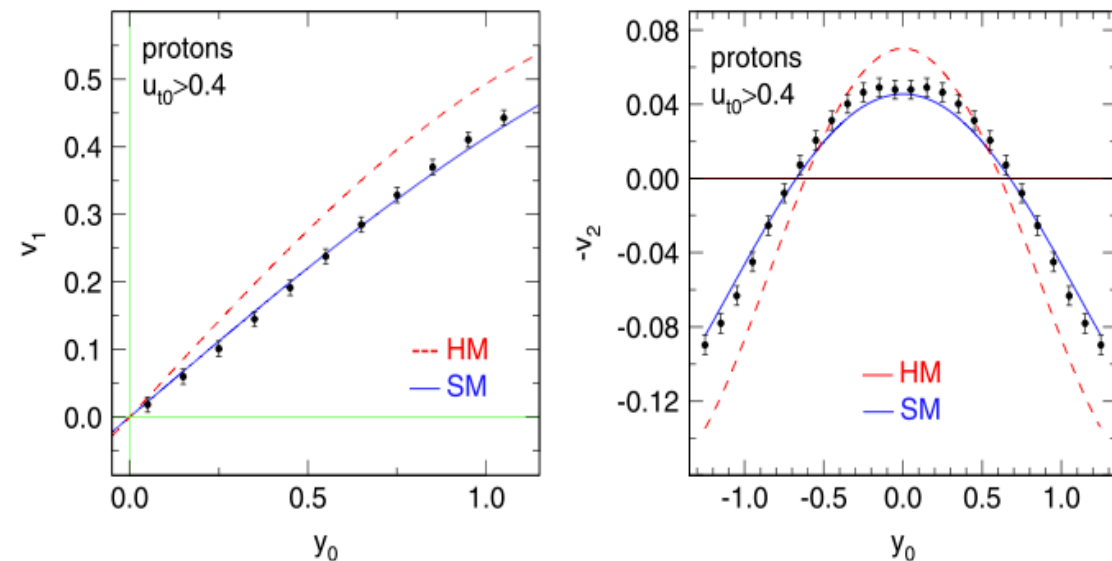
# Nuclear equation-of-state at high (net) baryon densities



FOP1

Au+Au 1.5 AGeV

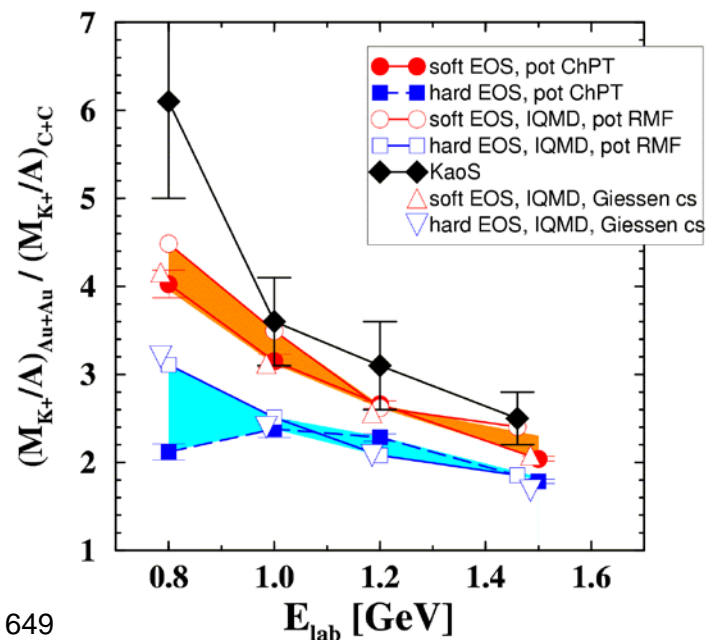
W. Reisdorf et al. (FOP1), Nucl. Phys. A 876 (2012) 1



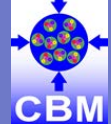
Experiment: CS et al., Phys. Rev. Lett. 86 (2001) 39

Theory: RQMD C. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974

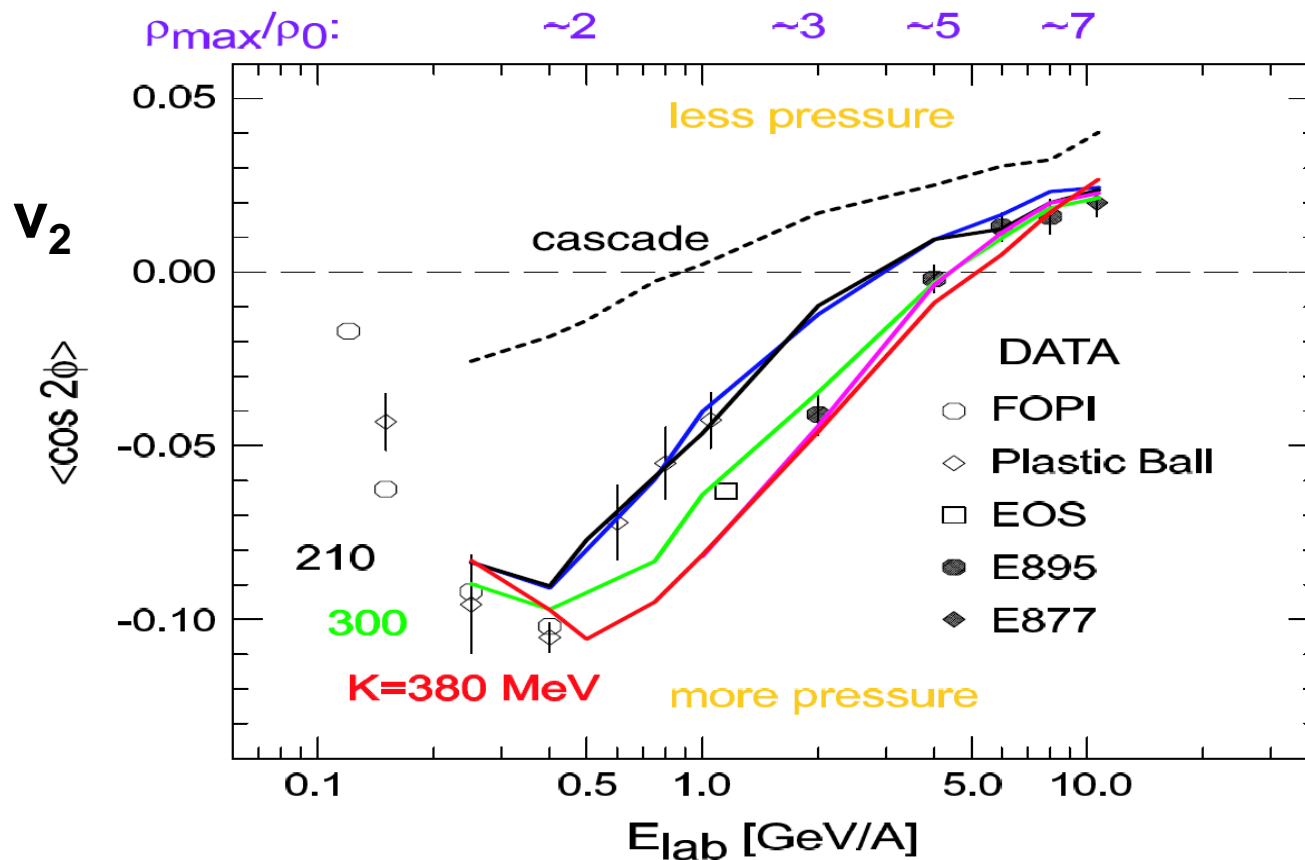
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649



# Nuclear equation-of-state at high (net) baryon densities



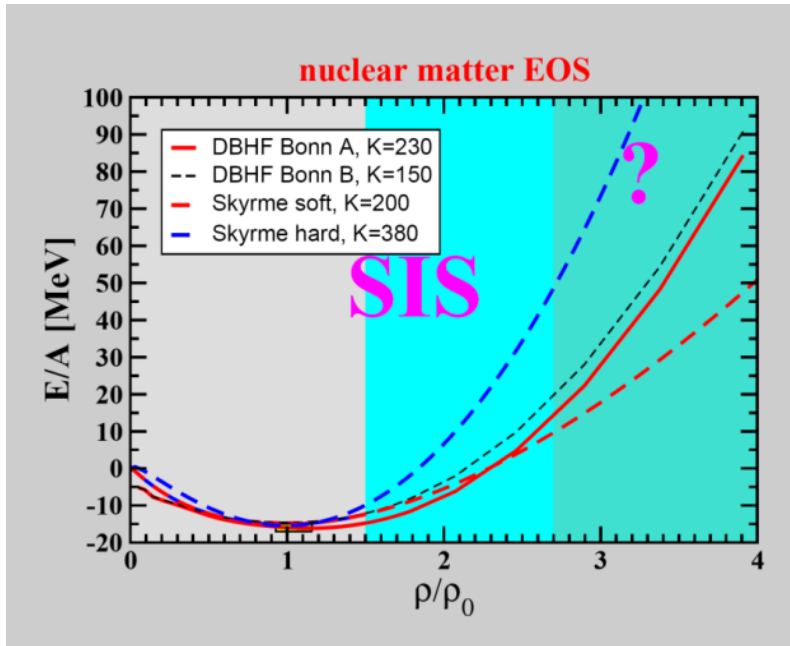
P. Danielewicz et al., Science 298 (2002) 1592



consistent picture at  
SIS18 energies ( $1.5 < \rho / \rho_0 < 3.0$ )

inconclusive at AGS energies

# Nuclear equation-of-state at the **highest** (net) baryon densities



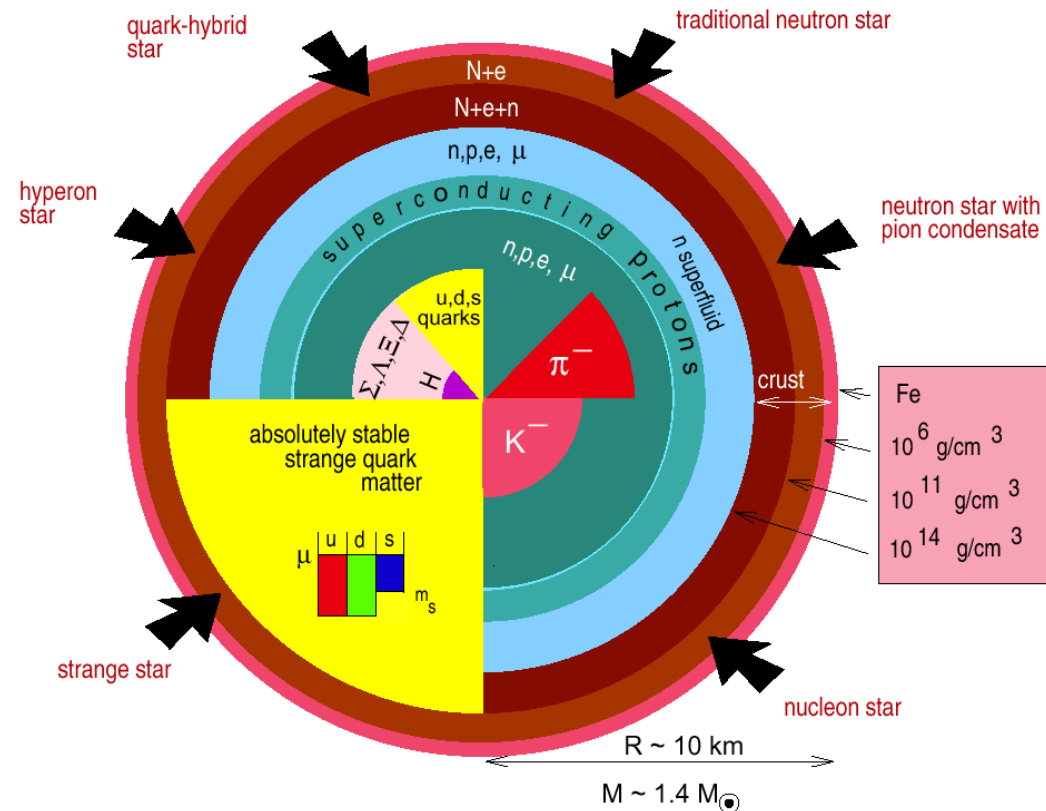
DBHF: E. N. E. van Dalen, C. Fuchs, A. Faessler  
 EPJ. A 31,29 (2007)

F. Weber,  
 J.Phys. G27 (2001) 465

equation-of-state at neutron star core densities ?

→ (sub-threshold) production  
 of  $\Omega^+(\bar{s}\bar{s}\bar{s})$  at FAIR energies ?

- refined to the high-density phase
- small final-state interaction

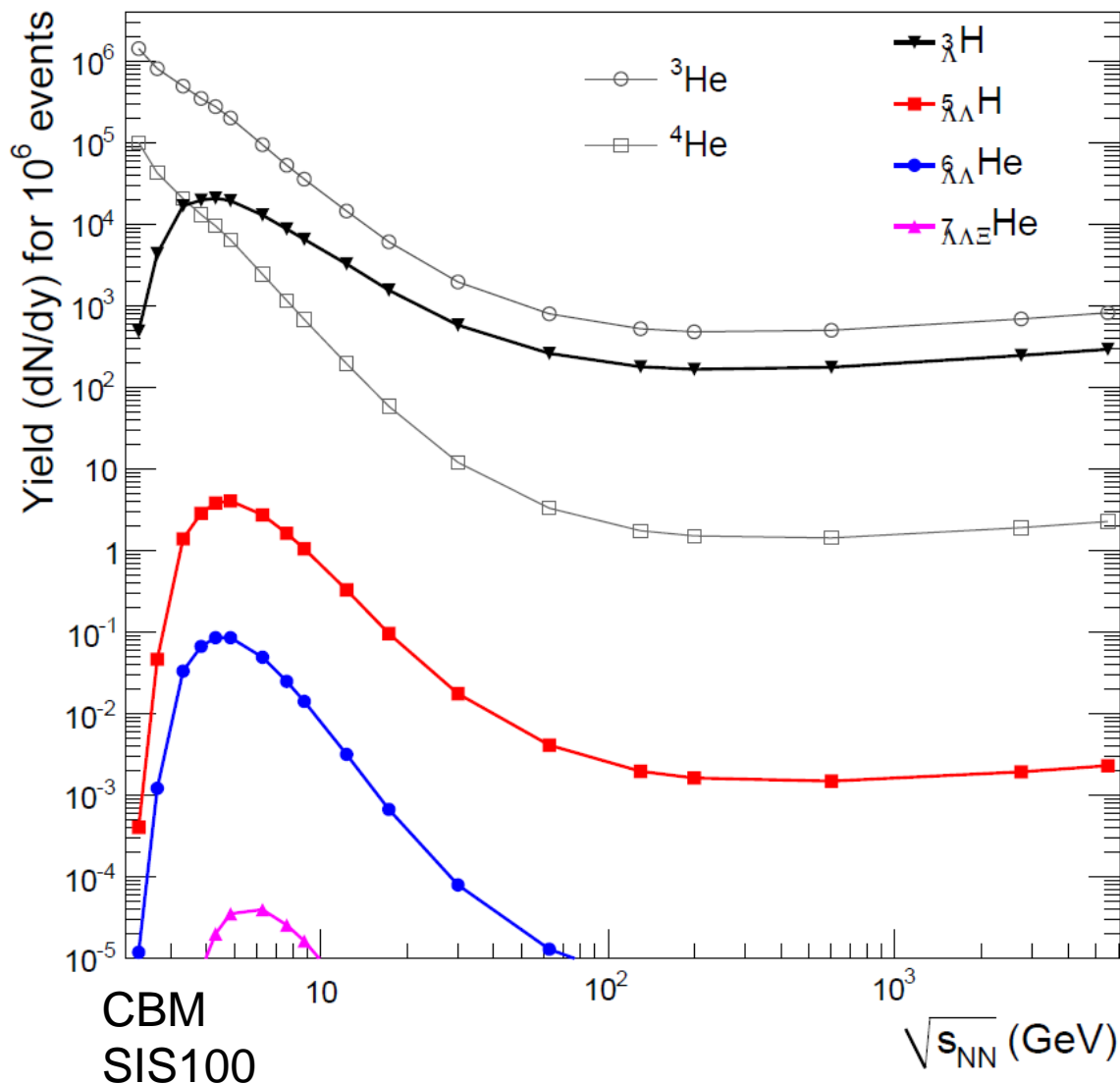


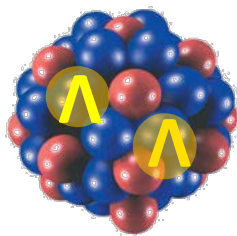


## Statistical hadronisation model:

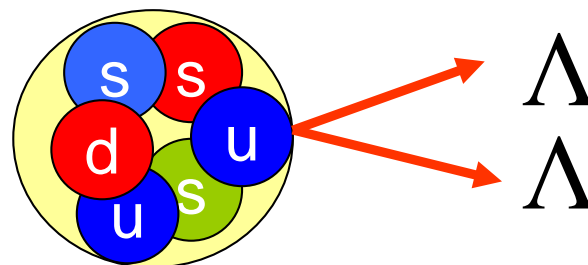
production of light nuclei and hypernuclei

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker,  
B. Phys. Lett. B697 (2011) 203





double hypernuclei



strange dibaryon

Search for strange matter in the form of strange dibaryons and heavy multi-strange short-lived objects

Production in nucleus-nucleus collisions via coalescence of hyperons and light nuclei

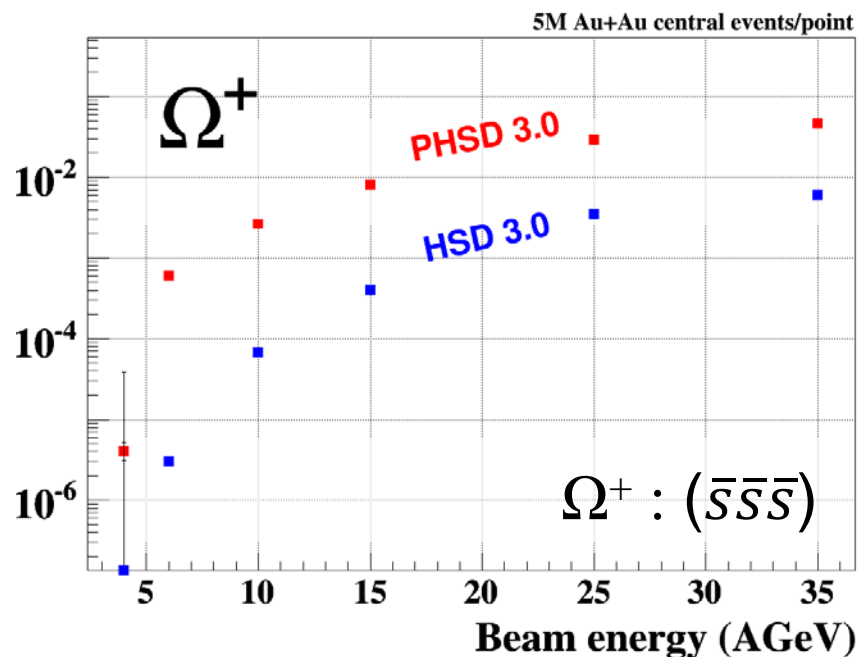
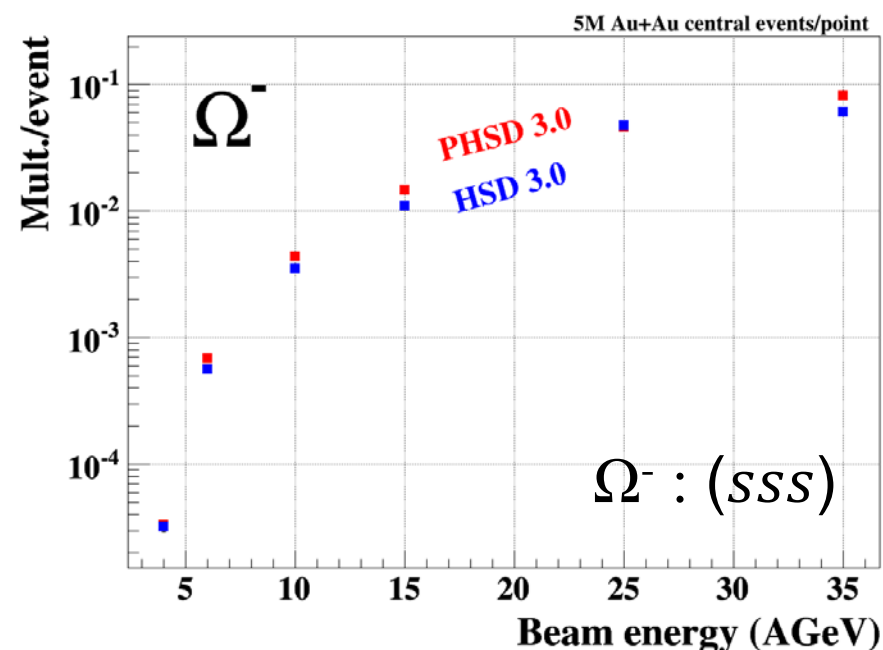
- existence and yield of (exotic) strange objects ?
- $\Lambda\Lambda$ ,  $N\Lambda$  interactions ?
- remnants of dense (chirally restored?) matter?

## Multi-strange (anti-) hyperons at FAIR energies

Prediction by microscopic transport calculations:

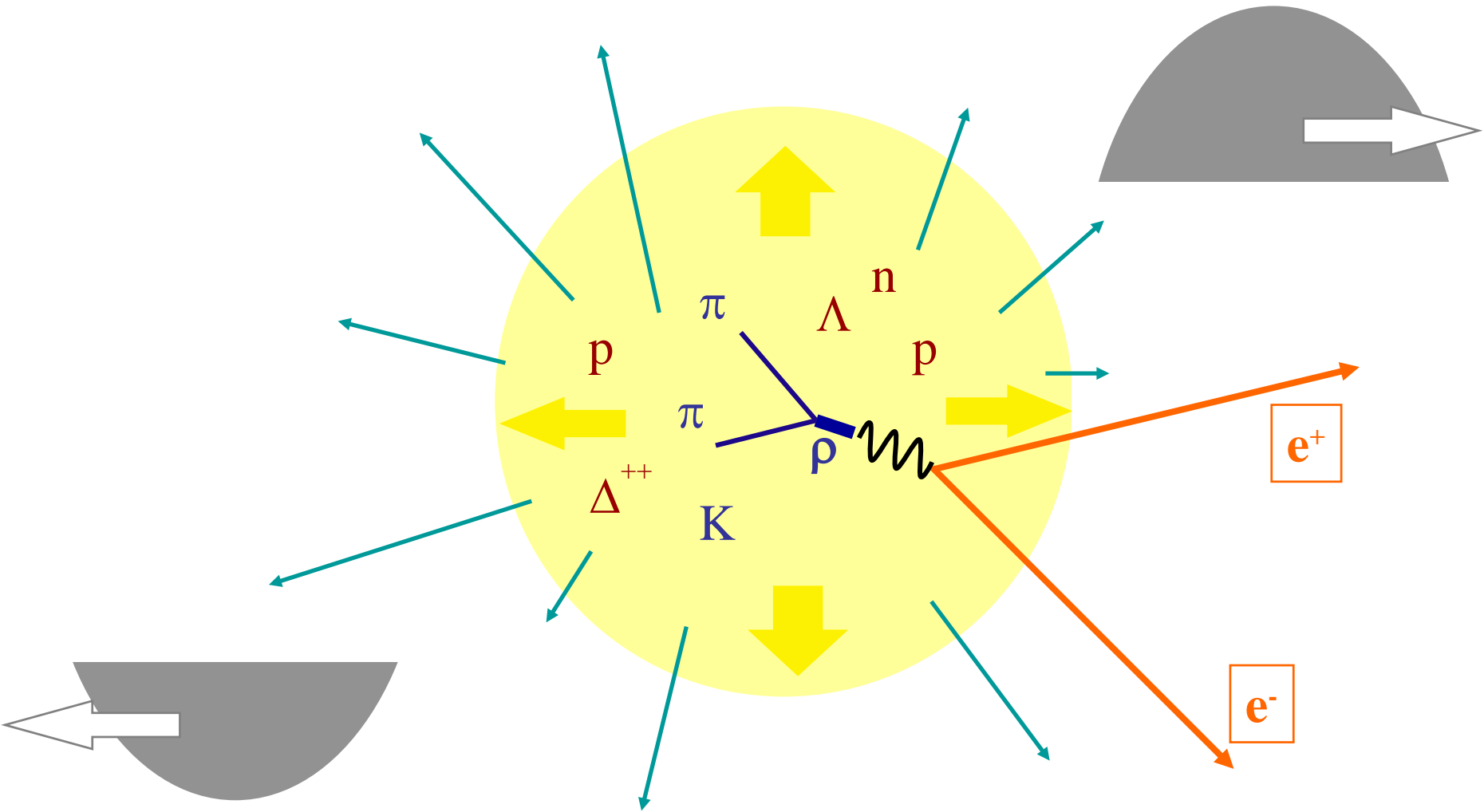
PHSD: transport code with partonic phase ( $\epsilon > 1 \text{ GeV/fm}^3$ )

HSD: hadronic transport code

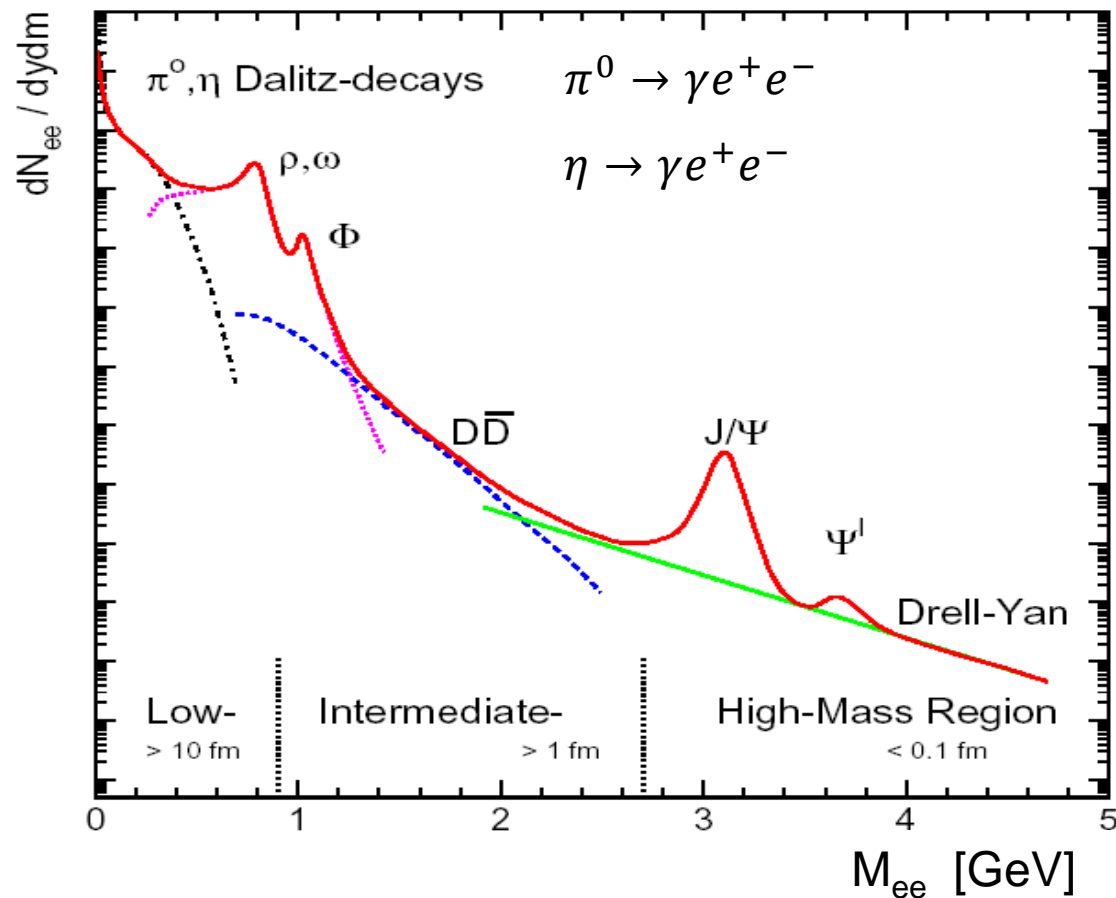


I. Vassiliev, E. Bratkovskaya, preliminary results

# $e^+e^-$ pairs (dileptons) – penetrating probes



# Sources of $e^+e^-$ pairs (dileptons)



invariant mass

$$M_{ee} = \sqrt{p_{e^+} p_{e^-}} \sin \frac{\vartheta_{e^+ e^-}}{2}$$

	mass [MeV/c <sup>2</sup> ]	$c\tau$ [fm]	dominating decay	$e^+e^-$ branching ratio
$\rho$	768	1.3	$\pi\pi$	$4.4 \times 10^{-5}$
$\omega$	782	23.4	$\pi^+\pi^-\pi^0$	$7.2 \times 10^{-5}$
$\Phi$	1019	44.4	$K^+K^-$	$3.1 \times 10^{-4}$

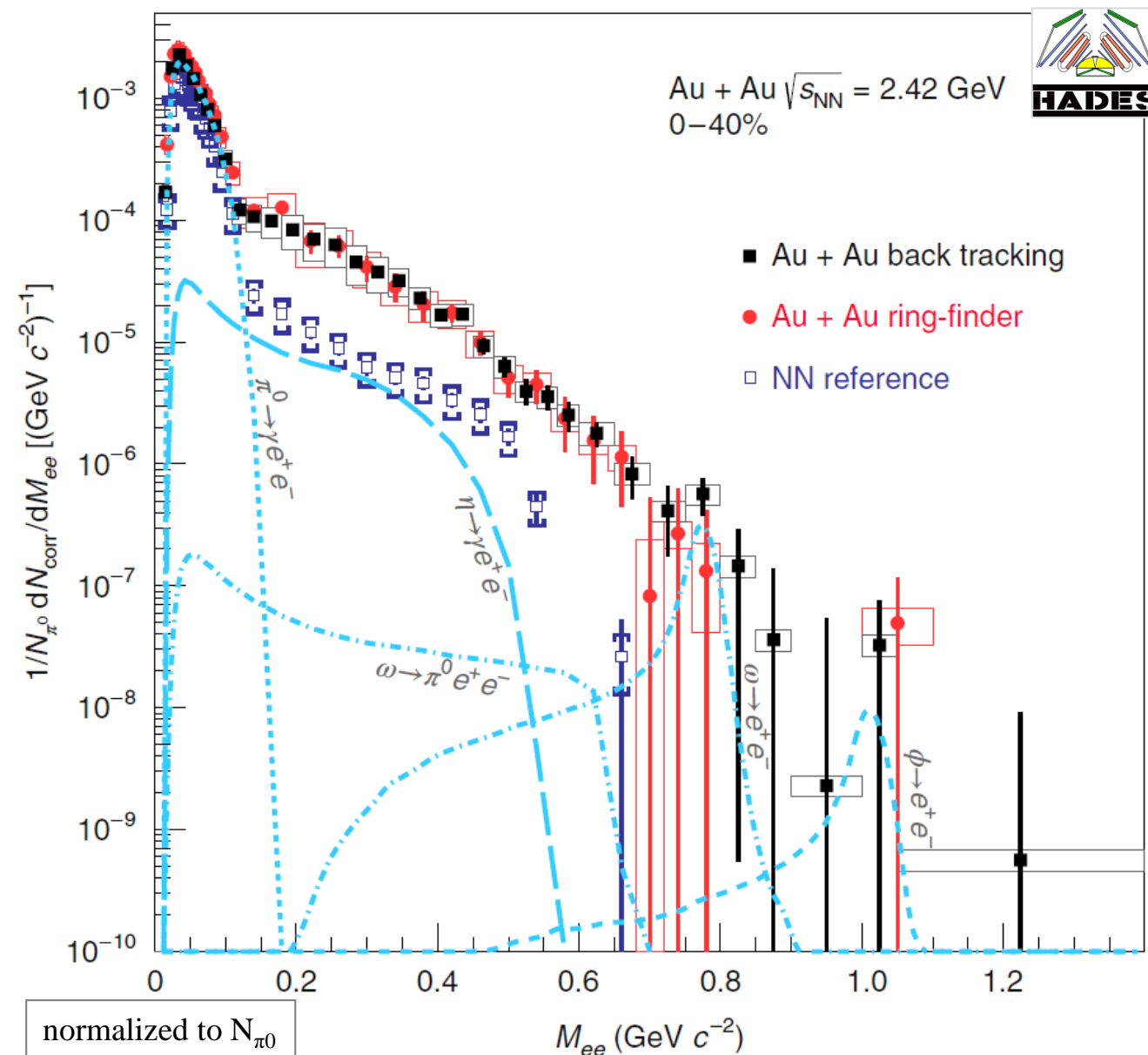
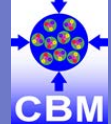
$E_{\text{thr,lab}} \text{ (NN)}$

1.7 GeV

1.8 GeV

2.6 GeV

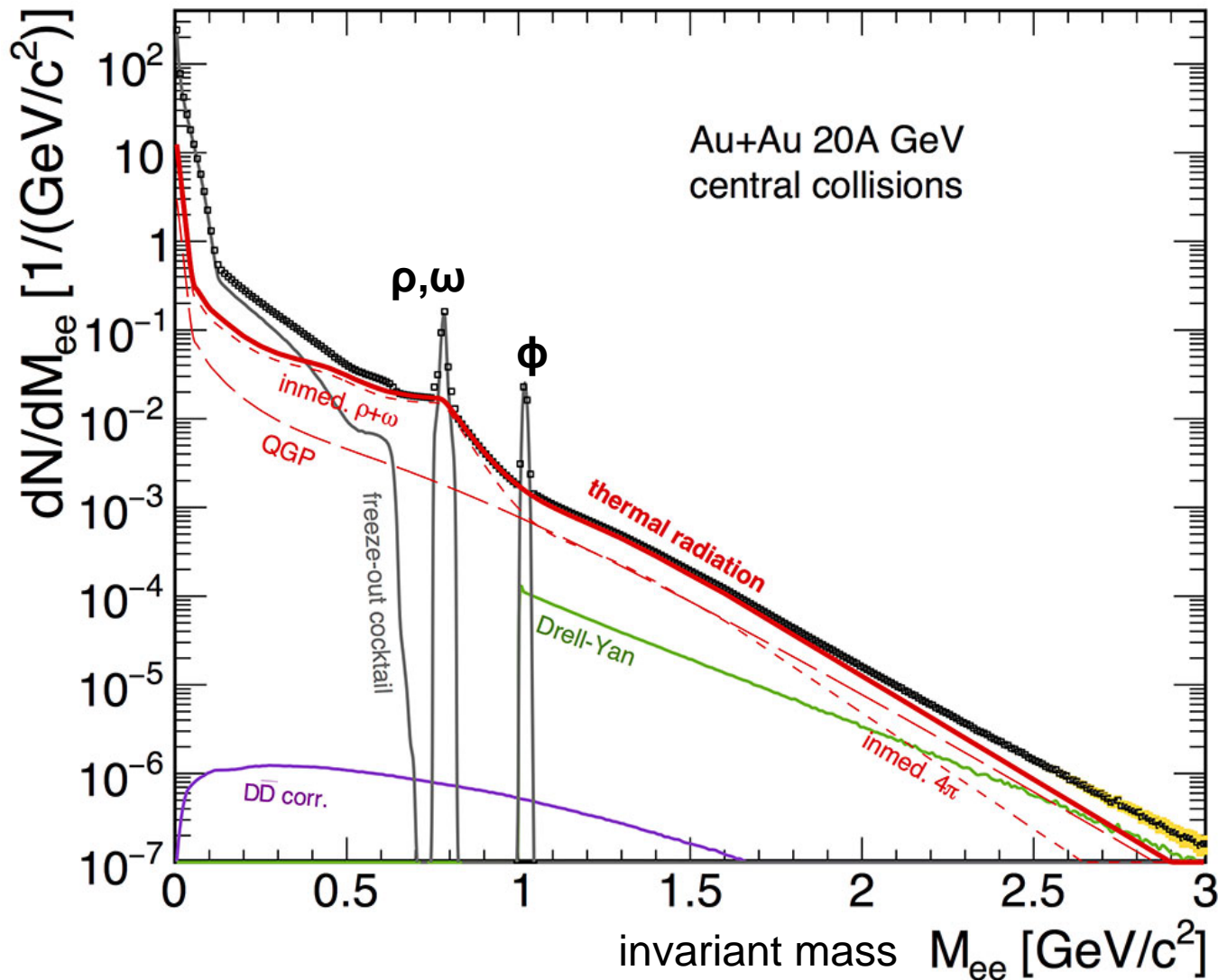
# Dileptons in nucleus-nucleus collisions at SIS18



HADES,  
 Nature Physics, 2019,  
<https://doi.org/10.1038/s41567-019-0583-8>

$$M_{ee} = \sqrt{p_{e^+} p_{e^-}} \sin \frac{\theta_{e^+ e^-}}{2}$$

## $e^+e^-$ pairs



simulation

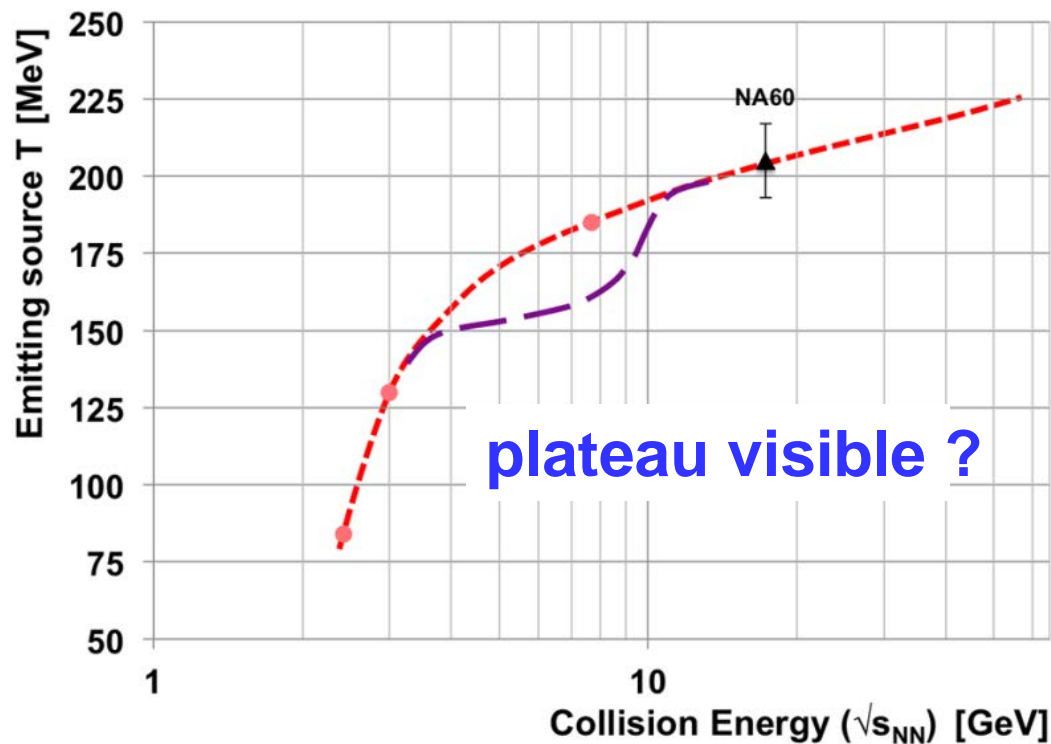
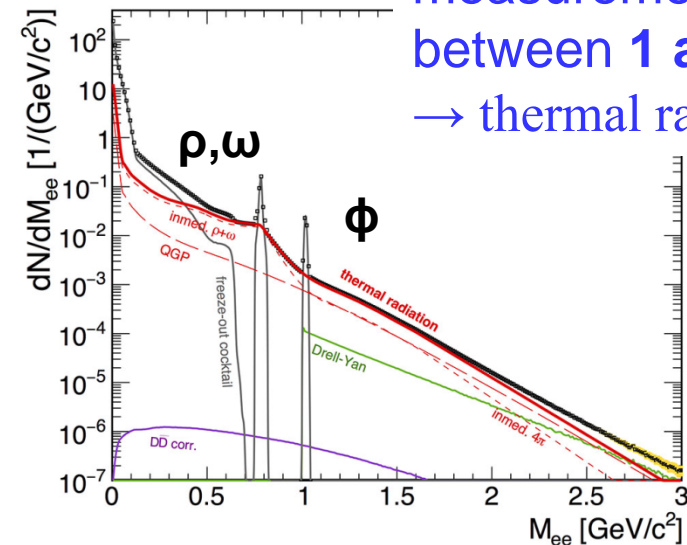
within  
CBM acceptance

$$M_{ee} = \sqrt{p_{e^+} p_{e^-}} \sin \frac{\vartheta_{e^+e^-}}{2}$$

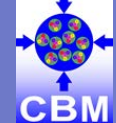
# Deconfinement phase transition at high $\mu_B$ ?

$e^+e^-$  pairs

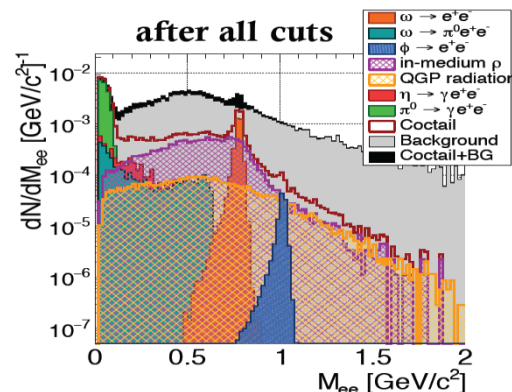
measurement of the di-lepton invariant-mass distribution  
between 1 and 2.5  $\text{GeV}/c^2$  for different beam energies  
→ thermal radiation T



# Summary: unique measurements with CBM at day 1

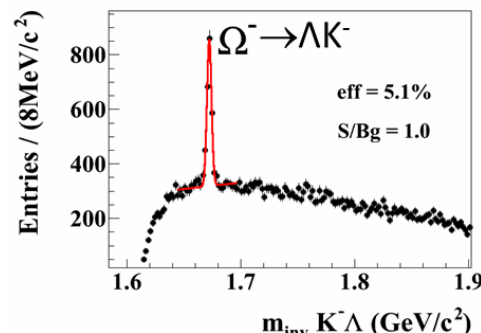


**Di-electron** measurement  
Full performance,  
(uses MVD, limited to 100 kHz)

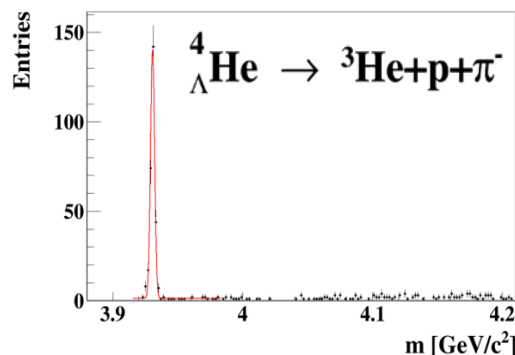


Au+Au, 8A GeV,

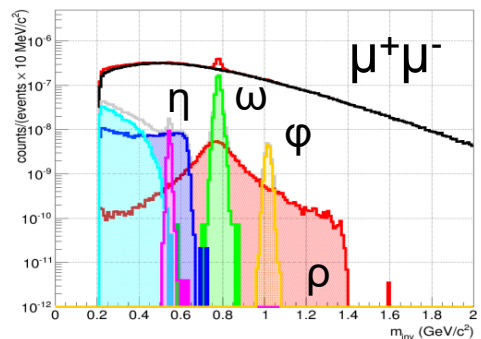
**Hyperon** measurements, e.g. Au+Au at 10A GeV :



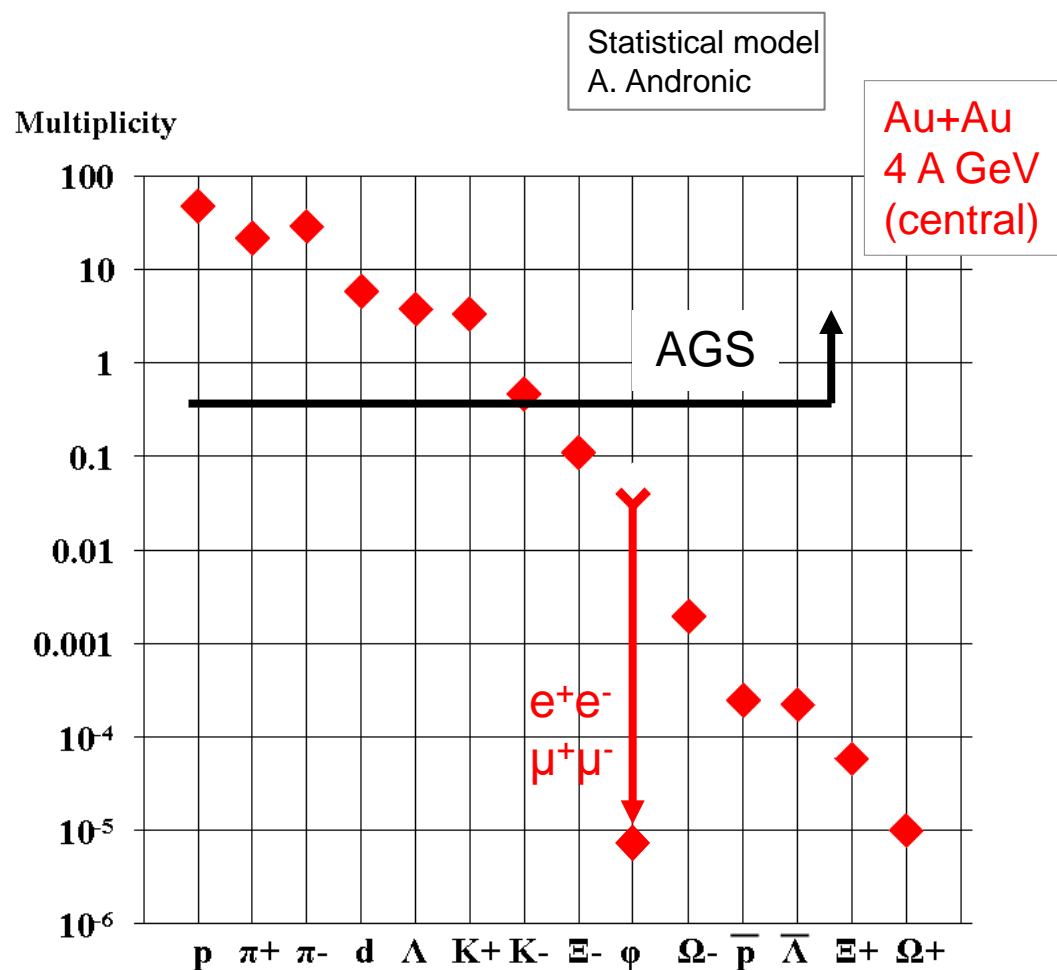
**Hypernuclei** measurement,  
e.g. Au + Au at 10A GeV



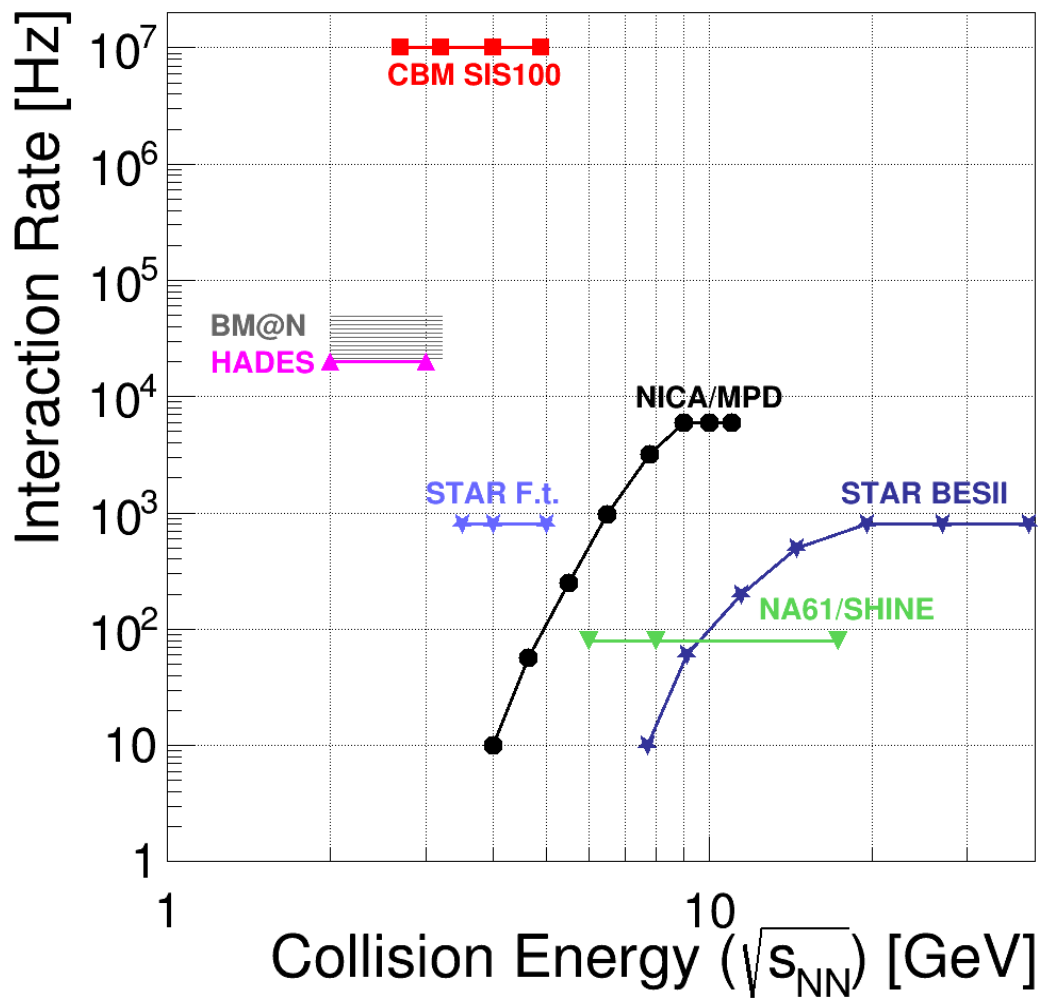
**Di-muon**  
LM measurement at 8A GeV  
= complementary measurement to  $e^+e^-$   
with different systematic errors



# Experimental challenge ?

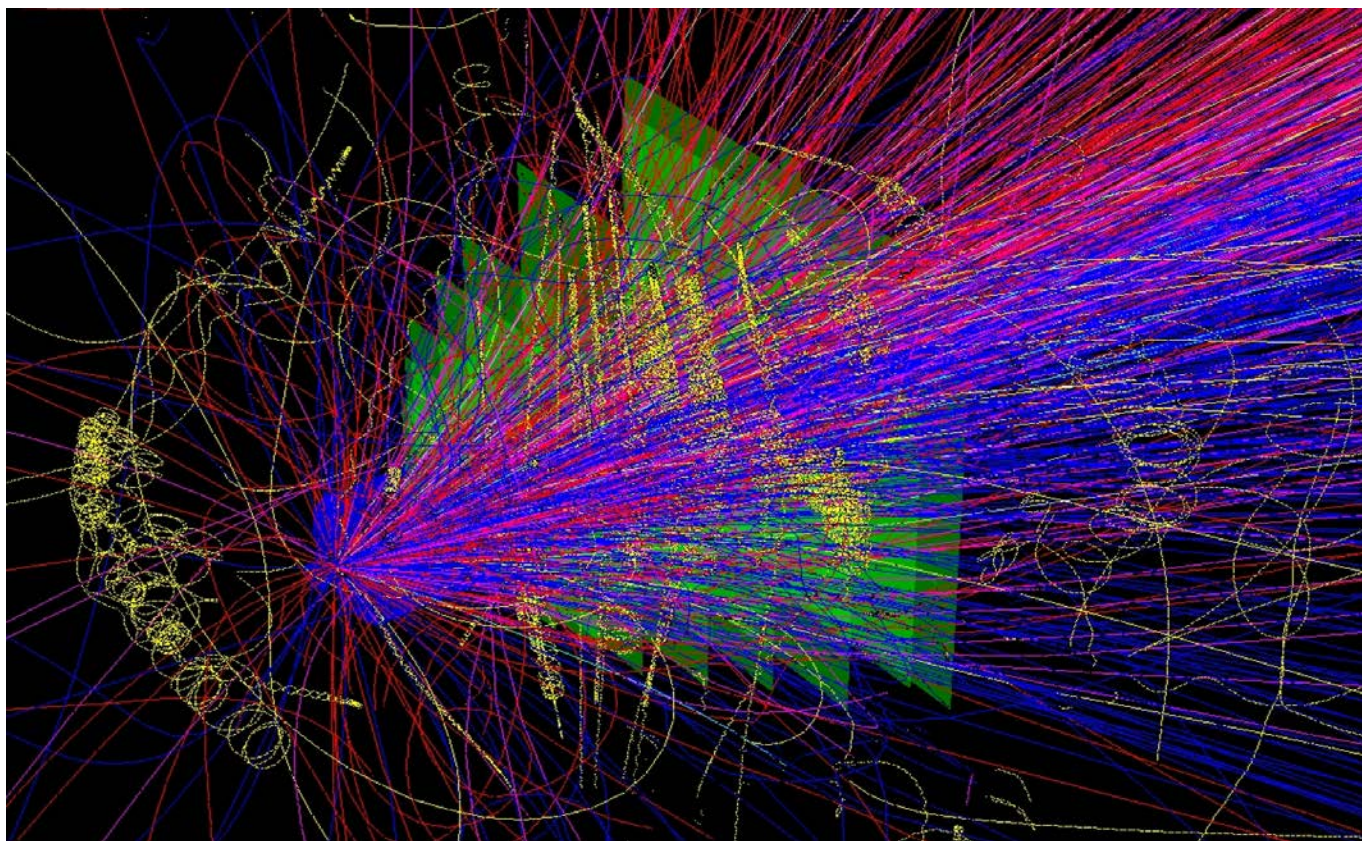


Rare probes  $\rightarrow$  extremely high interaction rates required !



## FAIR energies (Au ions)

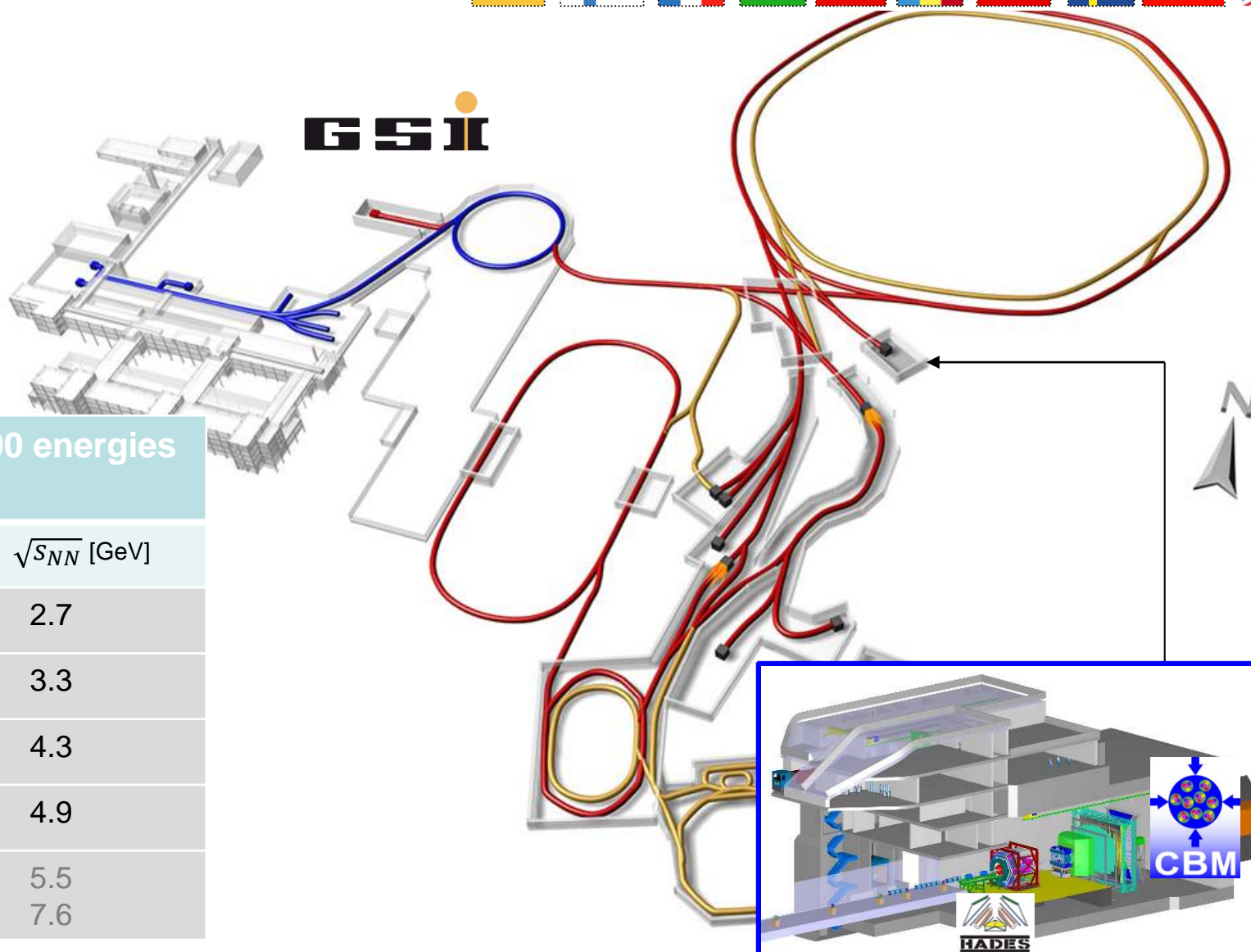
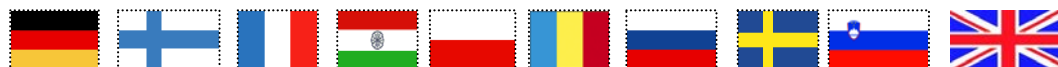
$E_{kin}^{lab}$ [A·GeV]	$\sqrt{s_{NN}}$ [GeV]
2	2.7
11	4.9
14 (Ca @ SIS100)	5.5
29 (p @ SIS100)	7.6
phase 2 (SIS300):	
30	7.7
35	8.3
44 (Ca @ SIS300)	9.3
89 (p @ SIS300)	13.0



Simulation  
Au+Au at 25 AGeV  
UrQMD+GEANT4:  
160 p,  
400  $\pi^+$ , 400  $\pi^-$ ,  
44  $K^+$ , 13  $K^-$

**Unprecedented collision rates:**  $10^5 - 10^7$  Au+Au collisions / sec

- fast and radiation hard detectors
- free-streaming read-out electronics
- high speed data acquisition and  
high performance computer farm for online event reconstruction and selection
- 4-D event reconstruction



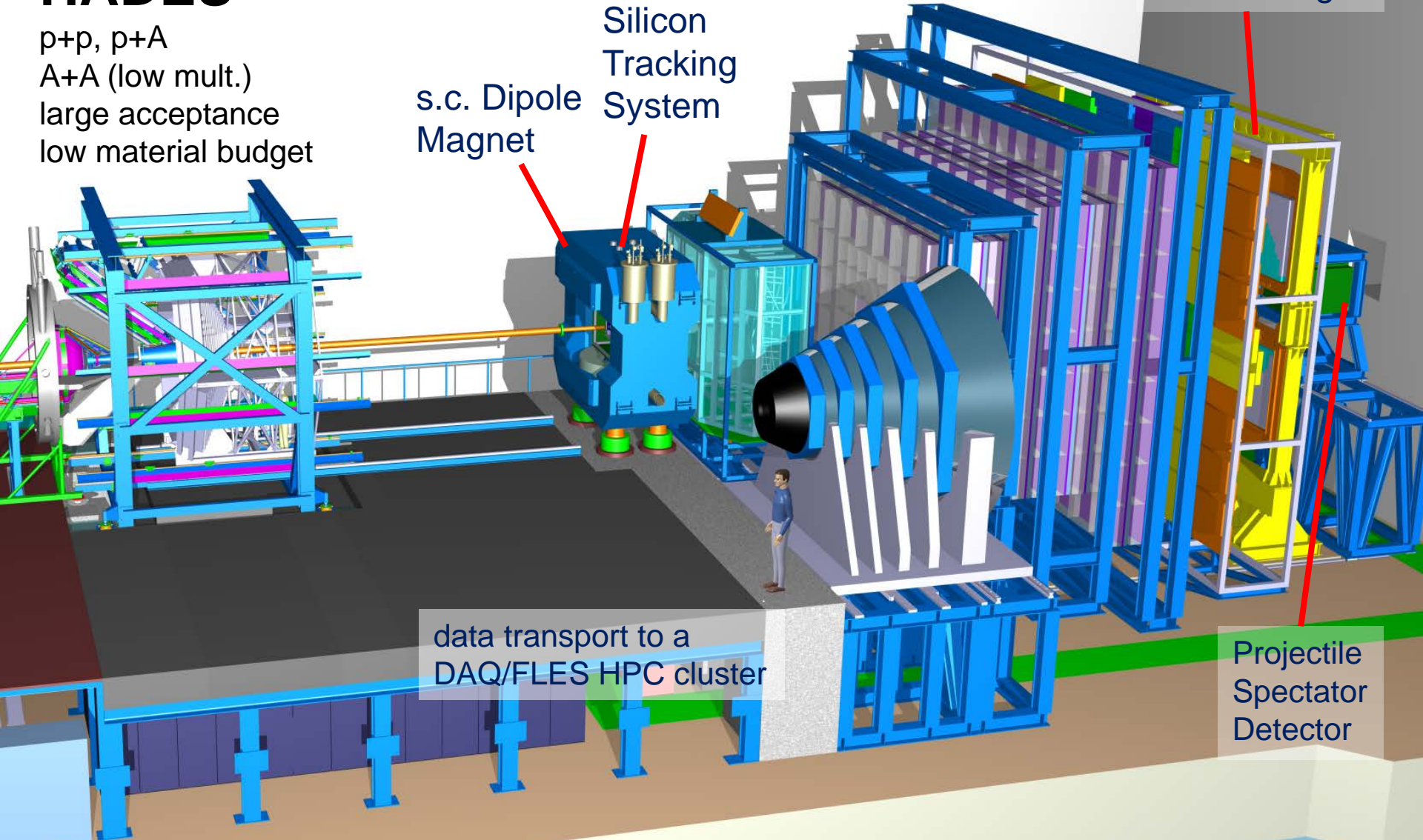
**FAIR SIS100 energies**  
(Au ions)

$E_{kin}^{lab}$ [A·GeV]	$\sqrt{s_{NN}}$ [GeV]
2	2.7
4	3.3
8	4.3
11	4.9
14 (Ca)	5.5
29 (p)	7.6

# CBM hadrons

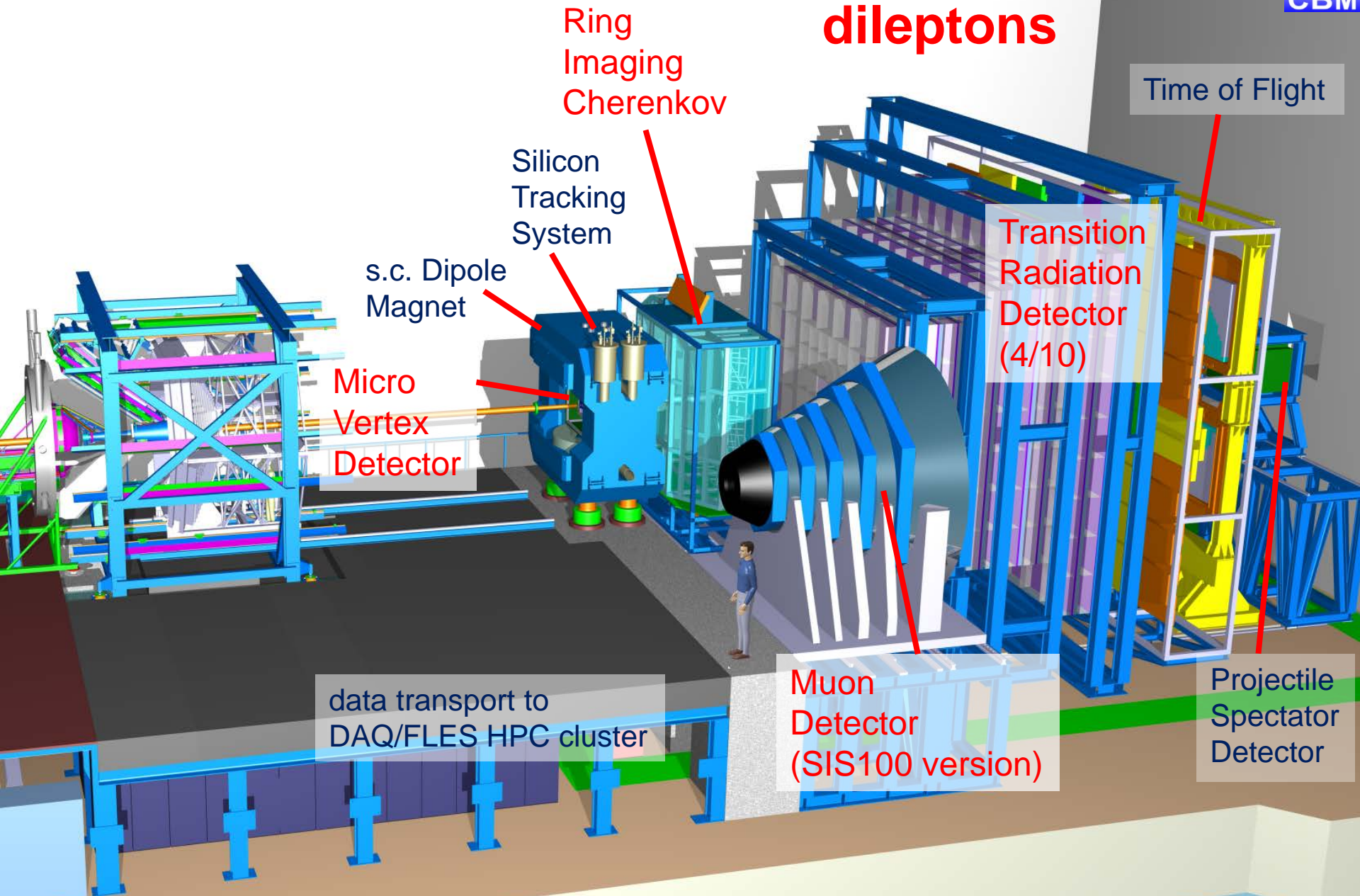
## HADES

p+p, p+A  
A+A (low mult.)  
large acceptance  
low material budget

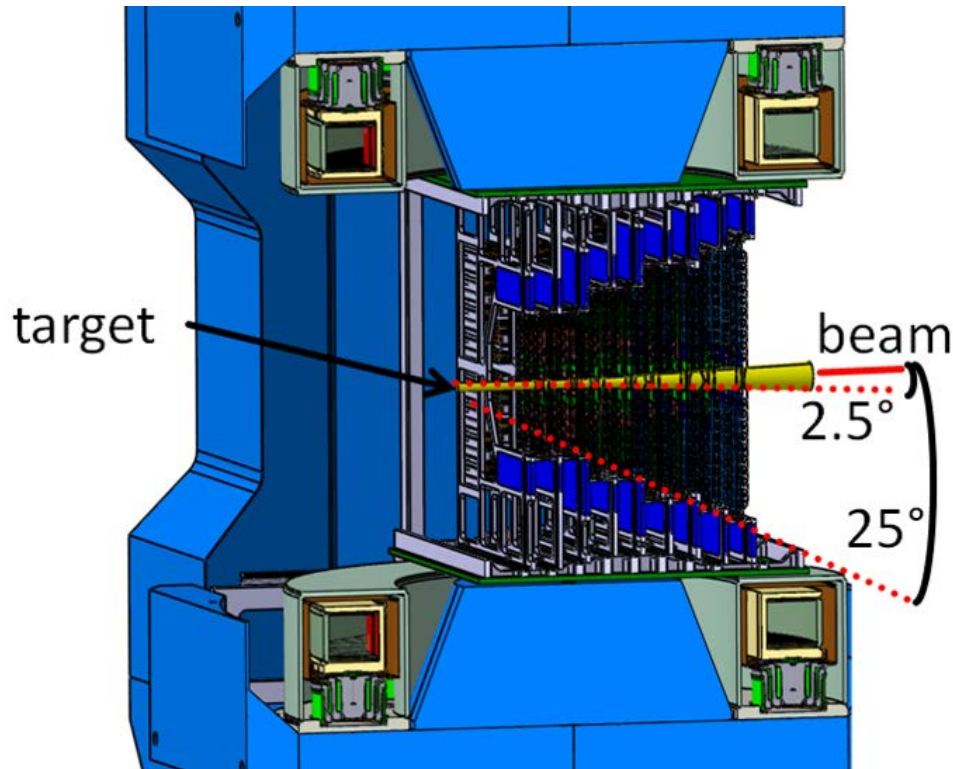
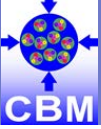


# CBM

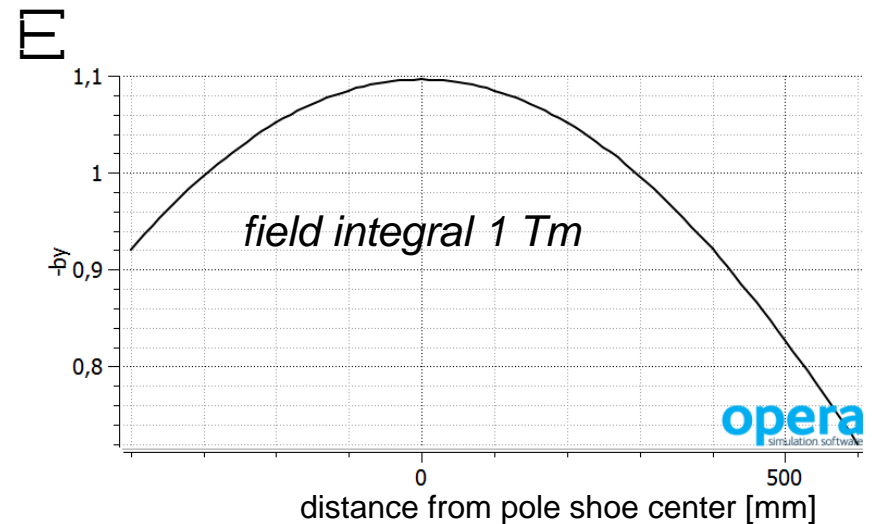
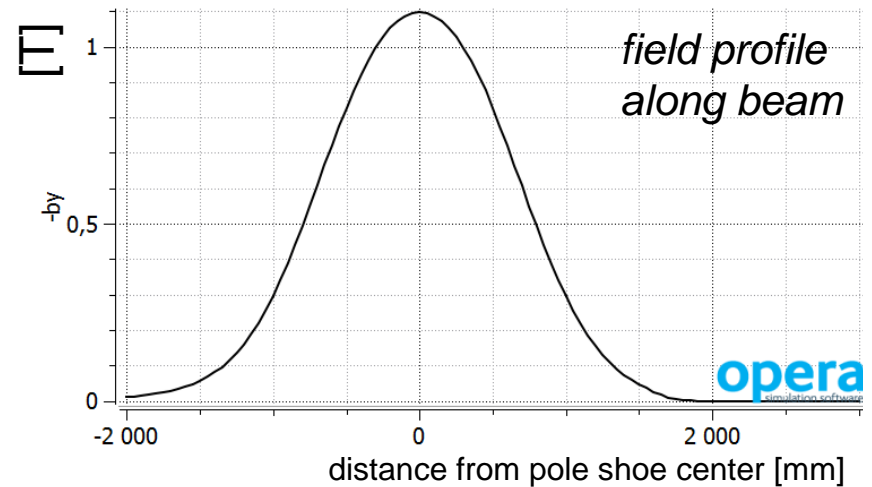
## dileptons

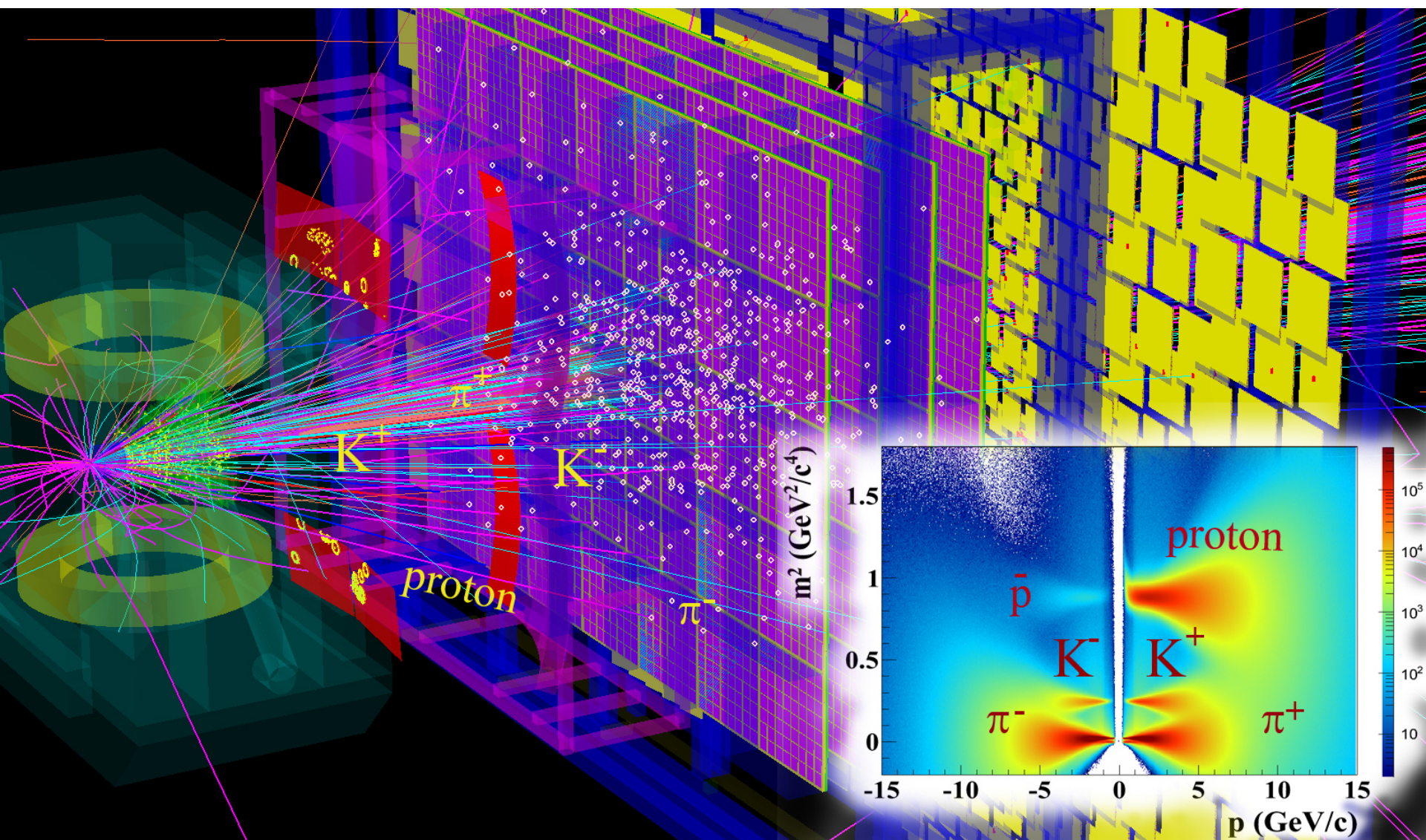


# The Silicon Tracking System (STS) inside the s.c. Dipole Magnet



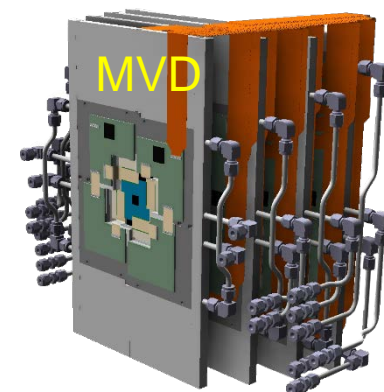
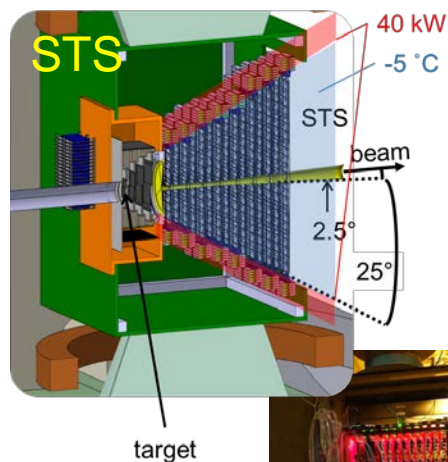
superconducting dipole magnet



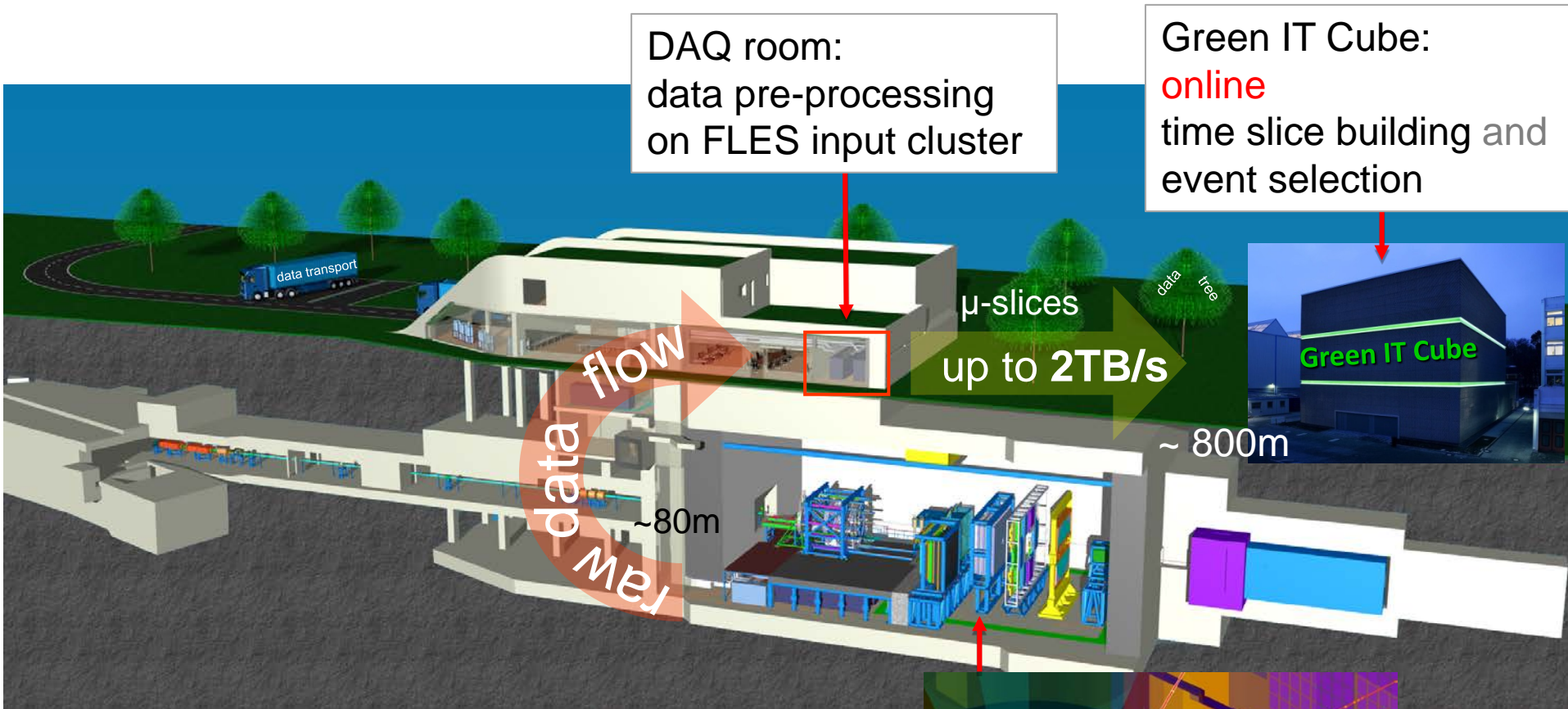


# Status of the experiment preparation

#	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 in 2020
9	DAQ/FLES	submission in 2023
10	TRD	approved
11	ECAL	submission in 2020



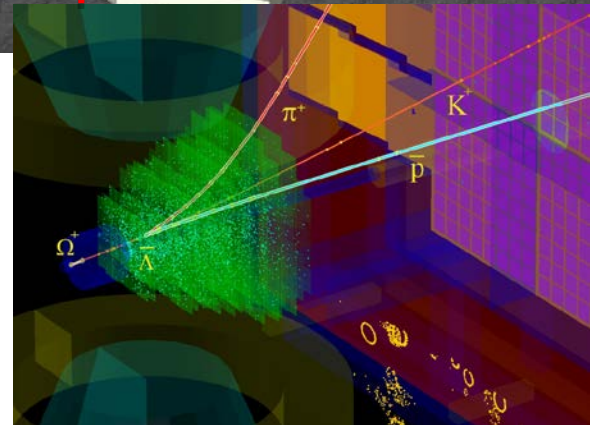
# The high-performance free-streaming DAQ system of CBM

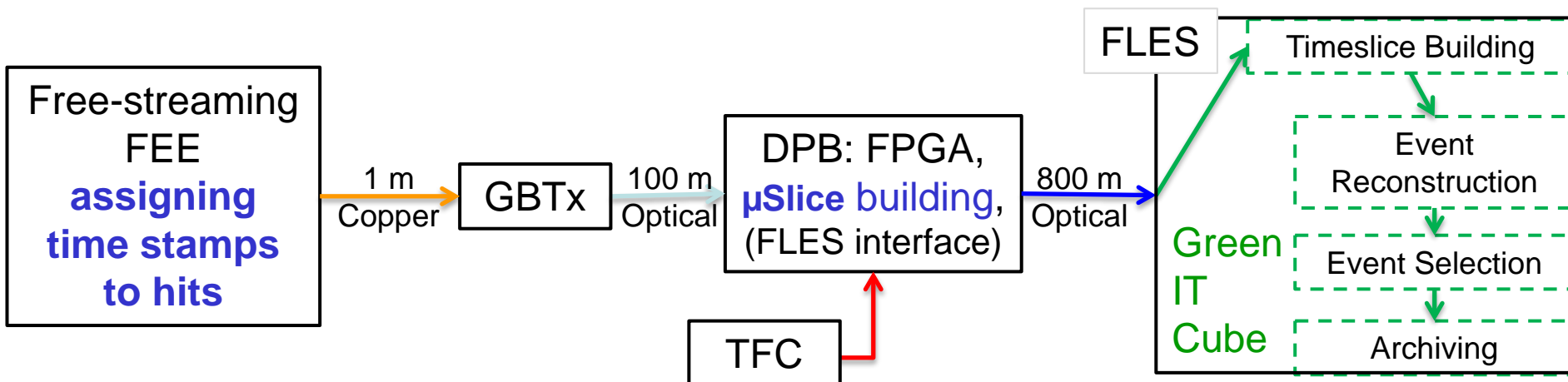


## Main feature:

free-streaming DAQ system

- all detector hits with time stamps,
- software based event selection





**FPGA :** Field Programmable Gate Array

Acronyms

**DPB :** Data Processing Board

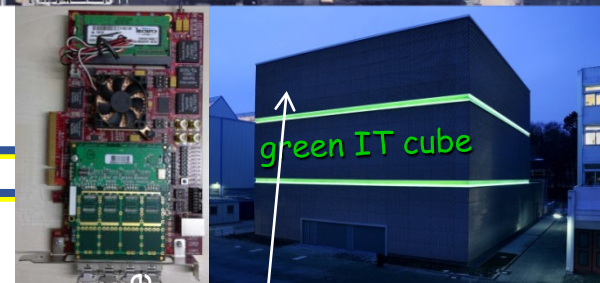
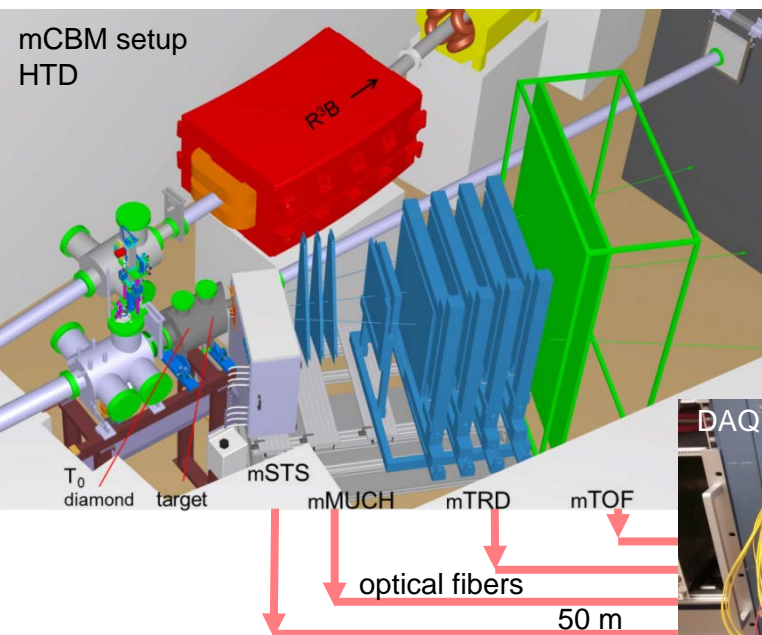
**TFC :** Timing and Fast Control Syst.

**FLES :** First Level Event Selector

**GBTx :** CERN rad.-hard interface ASIC

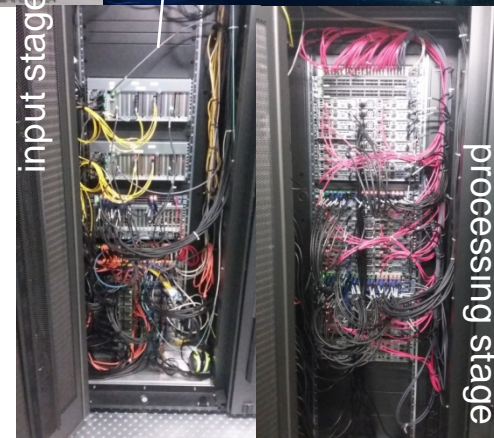
**$\mu$ Slice ( $\mu$ S) :** self contained data block for a subset of the experiment, minimal size depends on degree of data time sorting

**Timeslice :** collection of  $\mu$ S, self contained data block for the full experiment and a given time interval, includes overlap to avoid edge losses



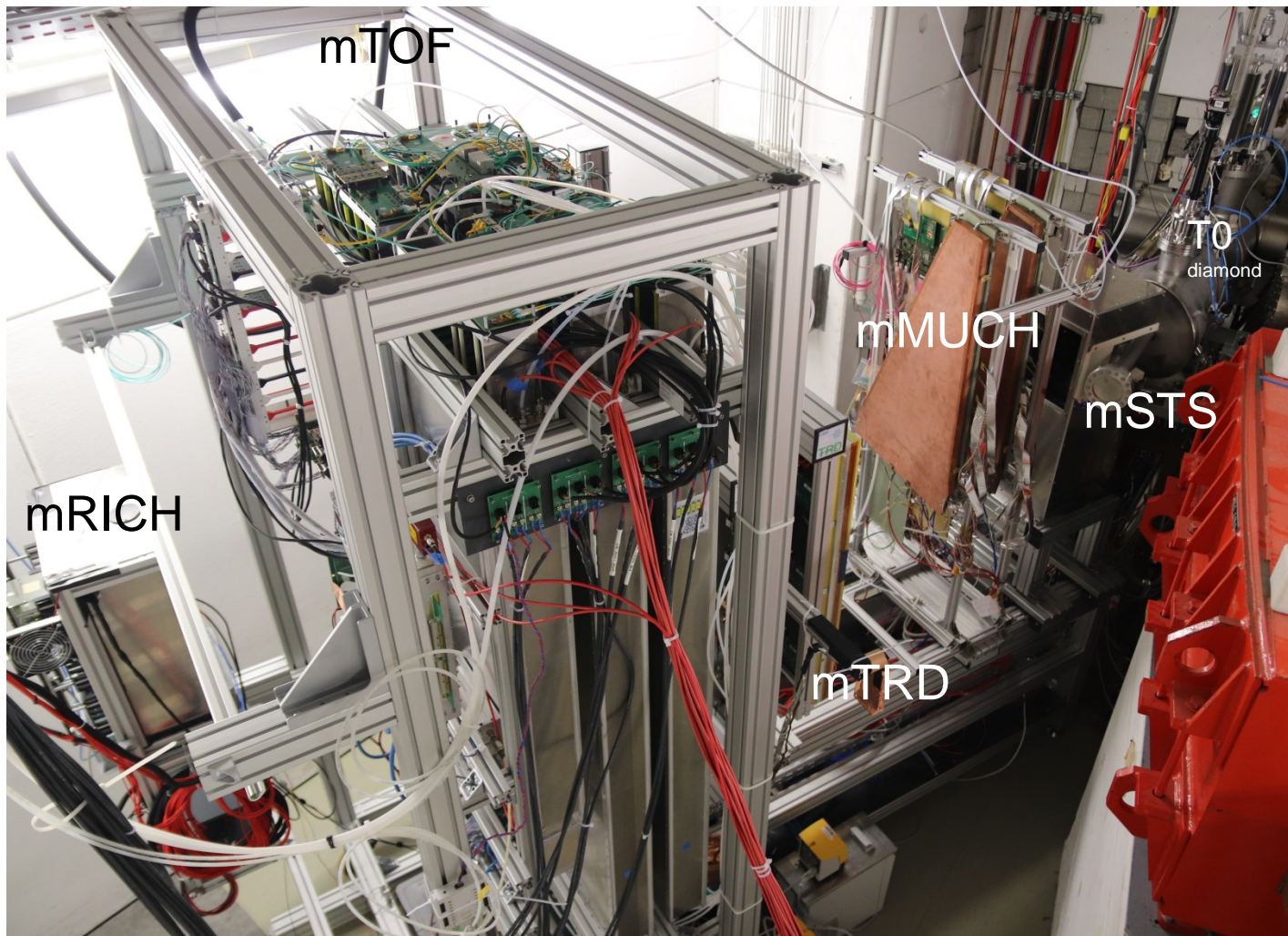
## *mCBM@SIS18* - a CBM full system test-setup for high-rate nucleus-nucleus collisions at GSI/FAIR

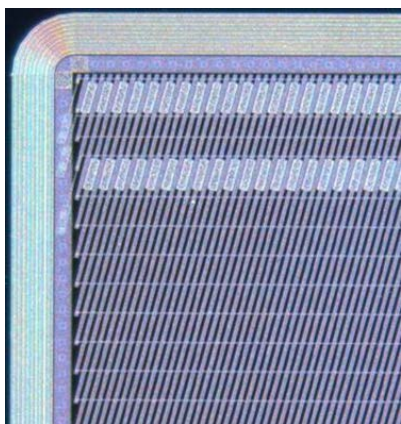
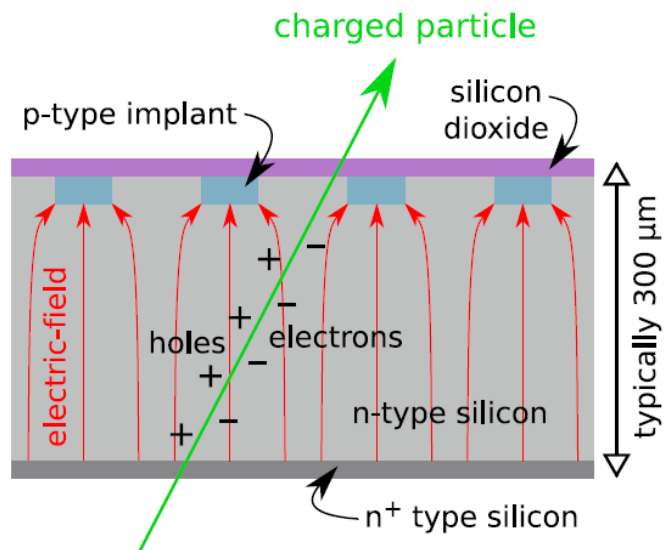
- CBM prototype detector systems
- free-streaming read-out and data transport to the mFLES inside the GreenITCube
- online event reconstruction and selection
- up to 10 MHz collision rate
- **first successful commissioning with beam in Dec. 2018 and March 2019**



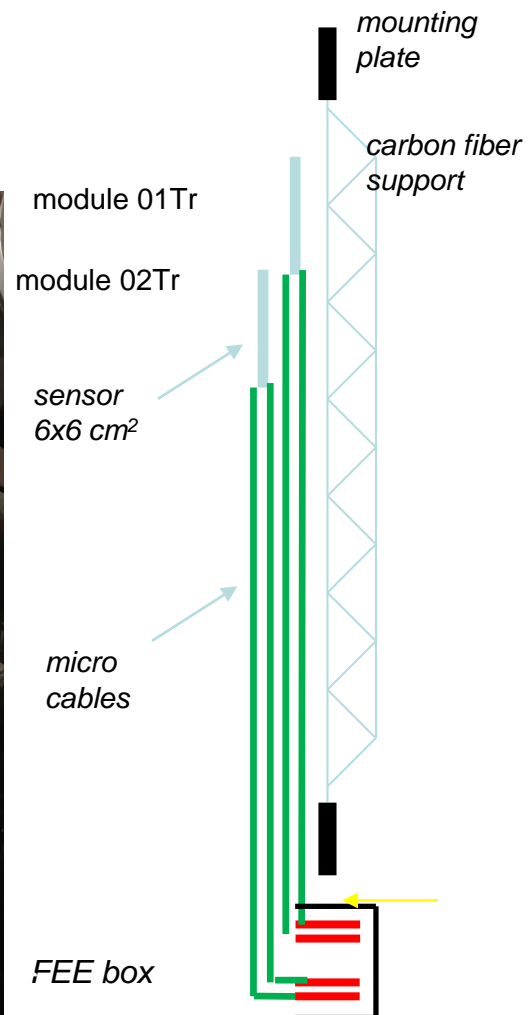


## mCBM setup at March 2019

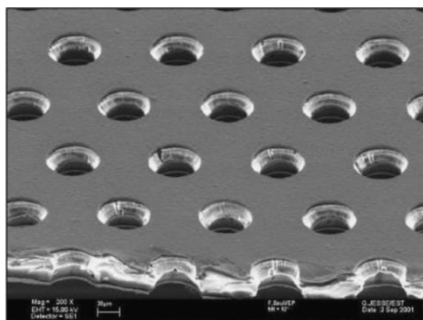
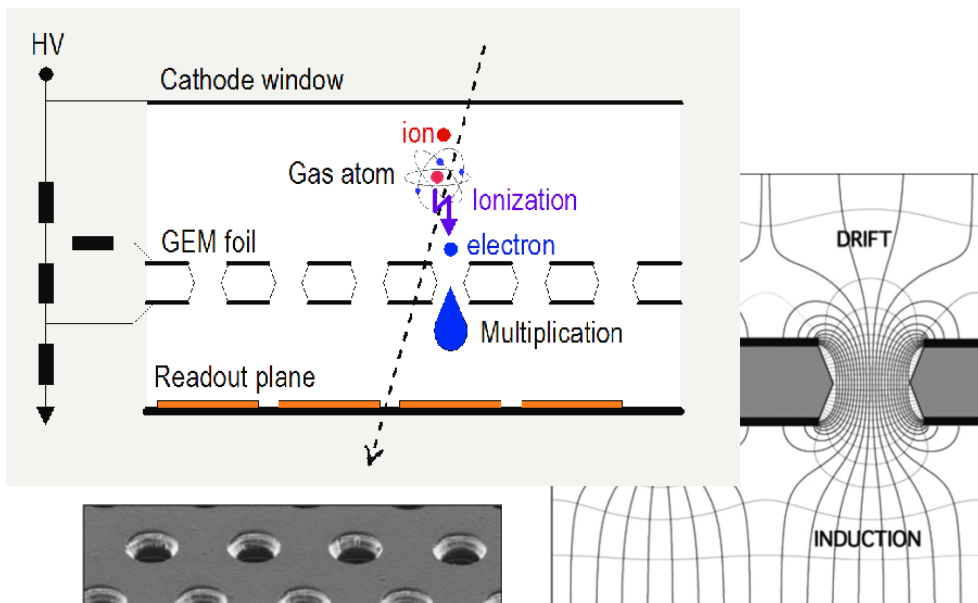




Double-sided  
silicon micro strip sensor  
(58  $\mu\text{m}$  pitch,  
300  $\mu\text{m}$  thickness)

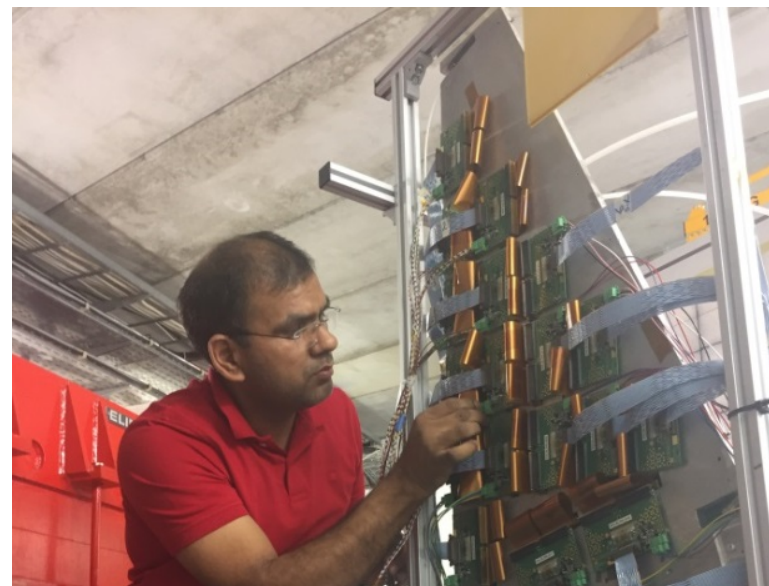


## Gas Electron Multiplier (GEM)



F.Sauli,  
NIM A805(2016) 2–24

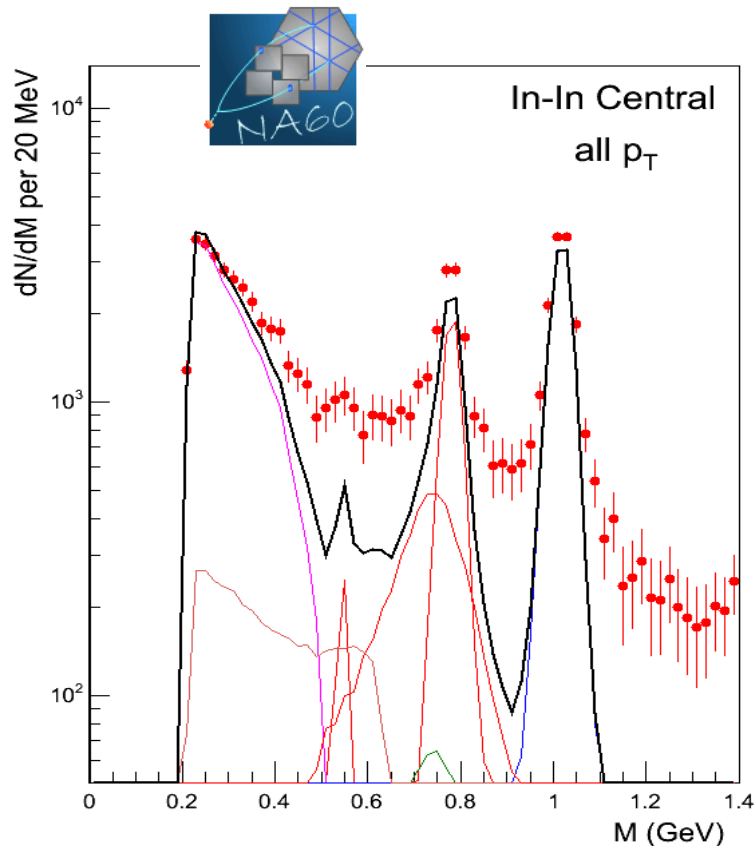
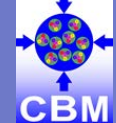
GEM foil, 50 μm thick



real-size GEM modules  
2000 pads (3mm – 2cm)

**contribution by India**

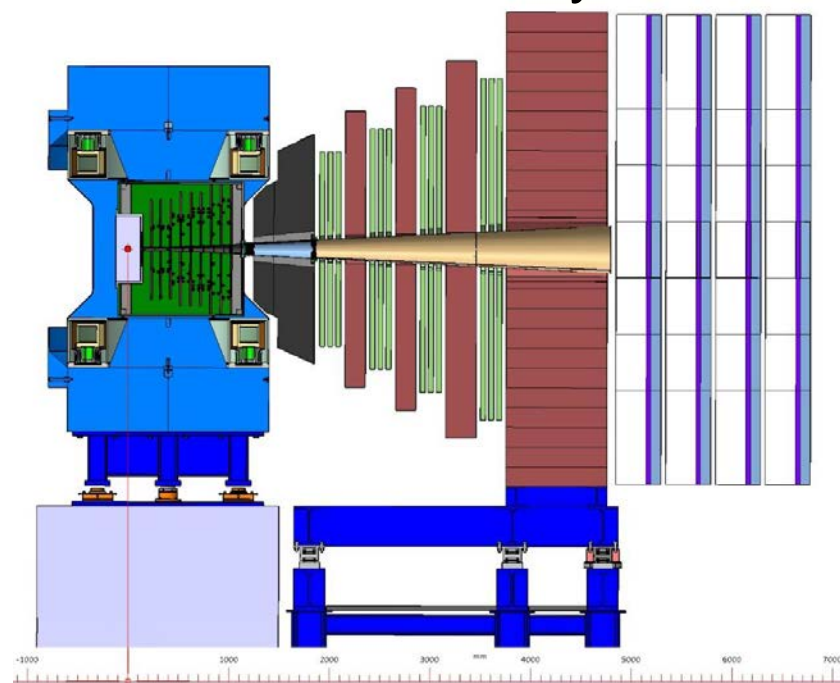
# The CBM Muon Chamber (MuCh) System



NA60  
In + In collisions at 158 AGeV (SPS)

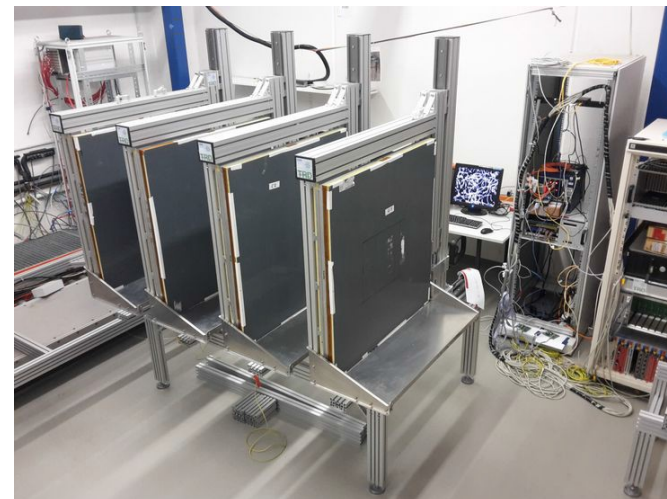
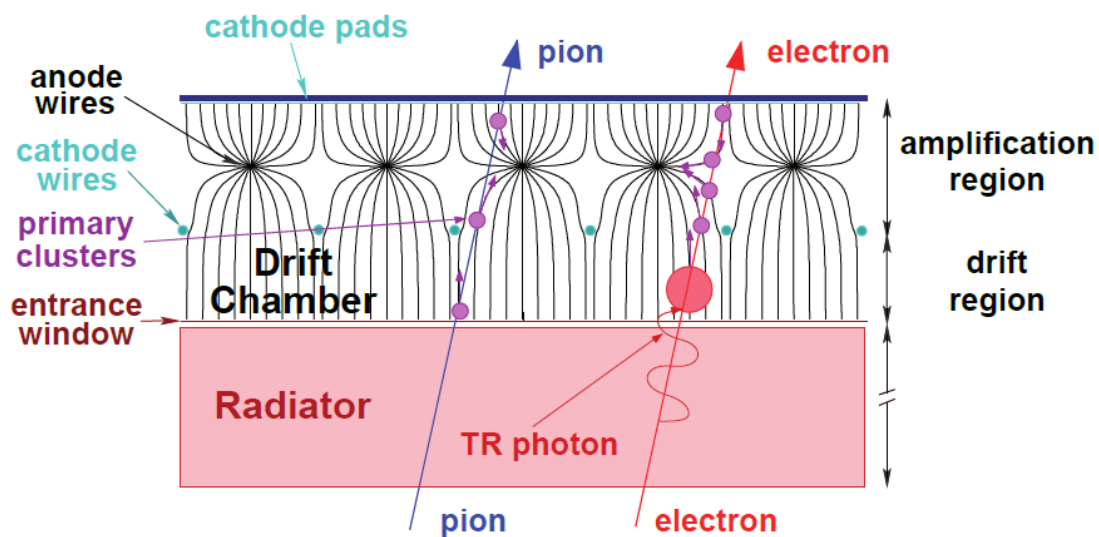
$\mu^+\mu^-$  pairs

at FAIR energies:  
 $\mu$  pairs @ CBM  
contribution by India

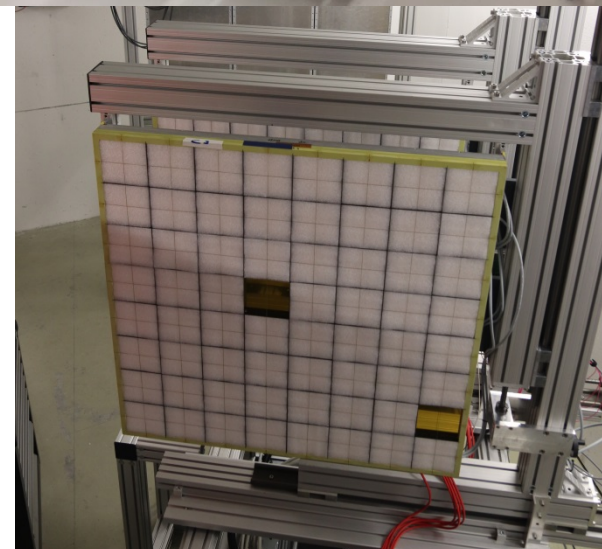
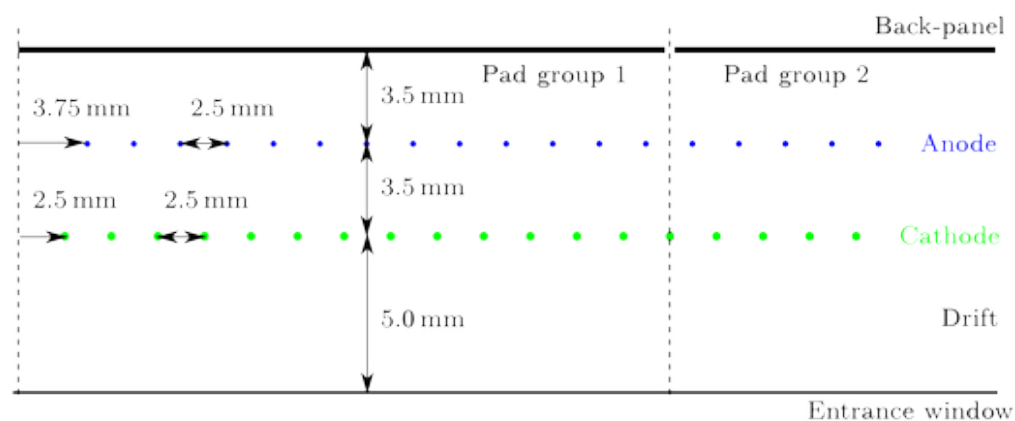


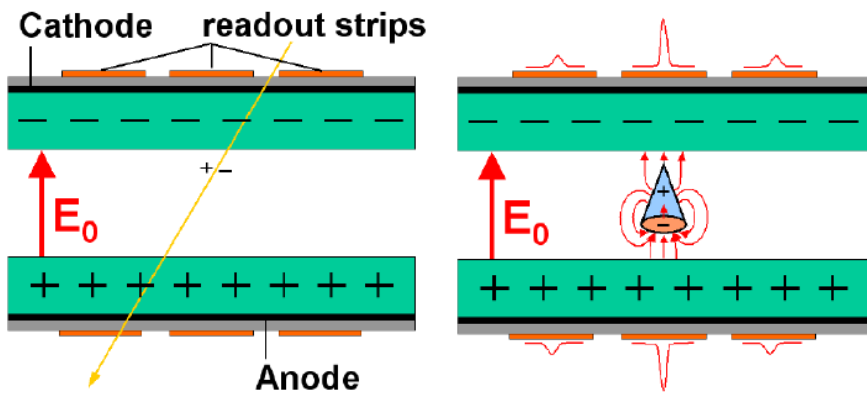
“active absorber system”  
1<sup>st</sup> and 2<sup>nd</sup> stations: GEM  
3<sup>rd</sup> and 4<sup>th</sup> stations: RPCs (?)

backside

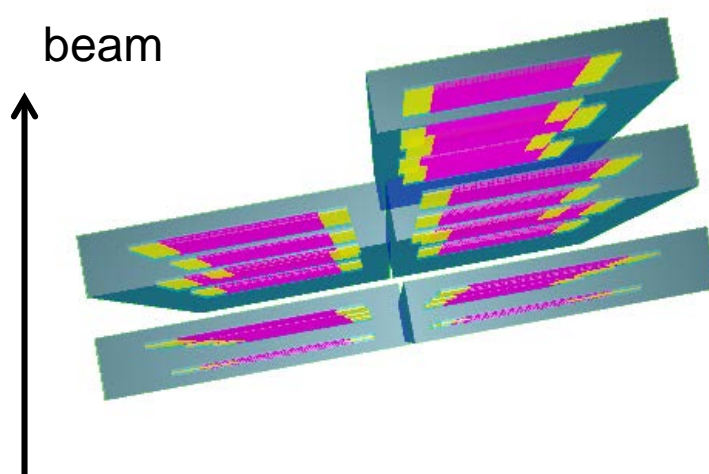
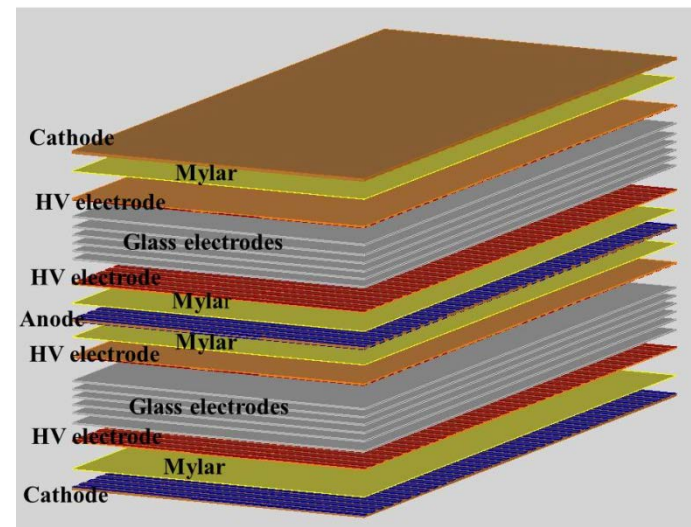


front



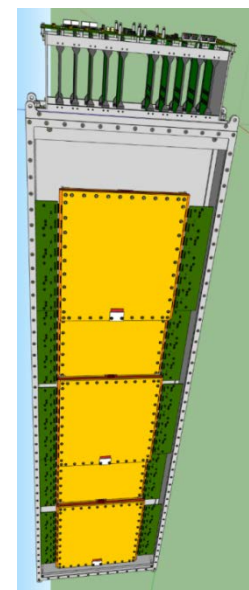


**MRPCs:**  
amplification  
by  
multiple  
gaps  
(2 x 5 gaps)

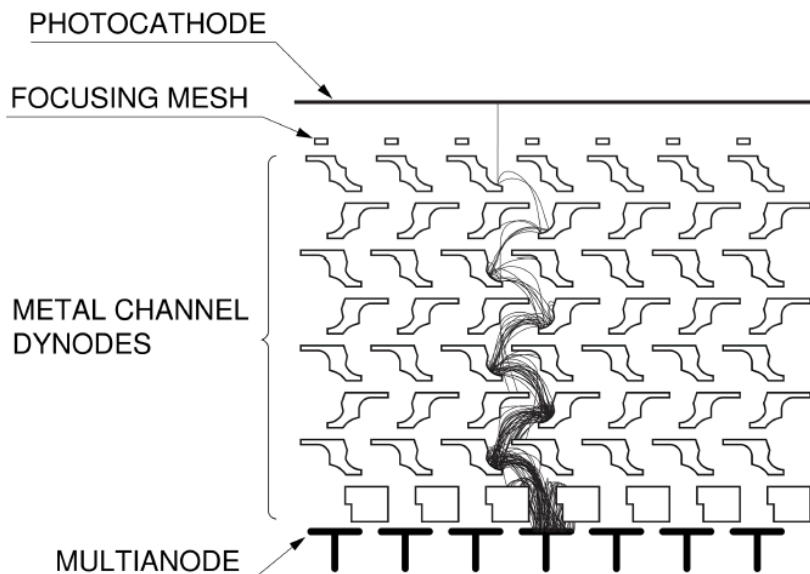


configuration:  
double stack  
triple stack

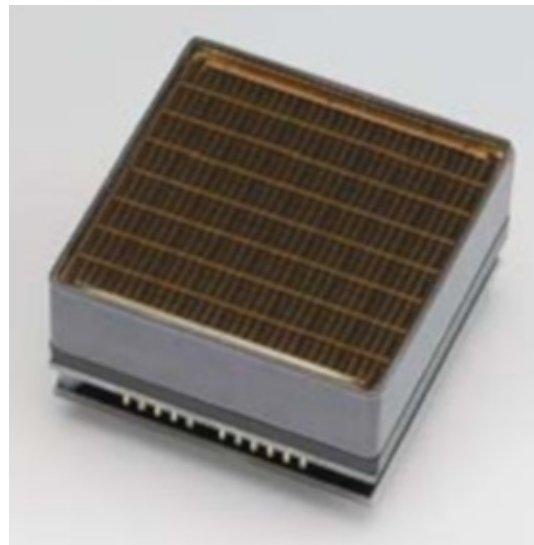
1600 channels:  
 $32(\text{channels}) \times 2(\text{sides}) \times 5(\text{MRPCs}) \times 5(\text{modules})$



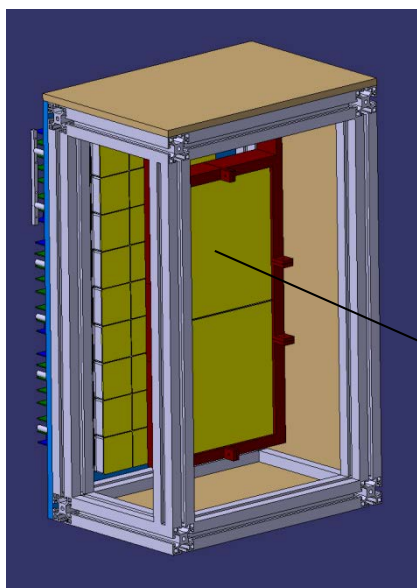
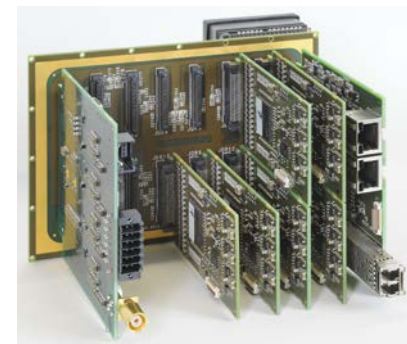
# The mRICH subsystem



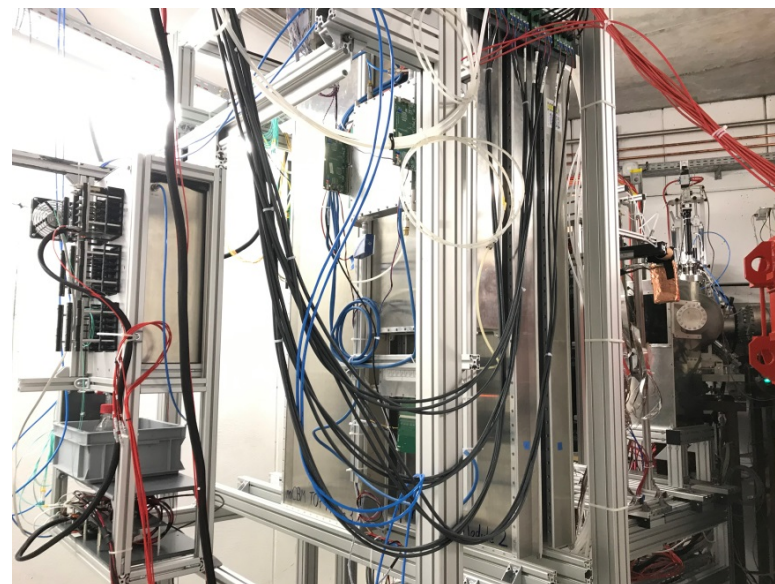
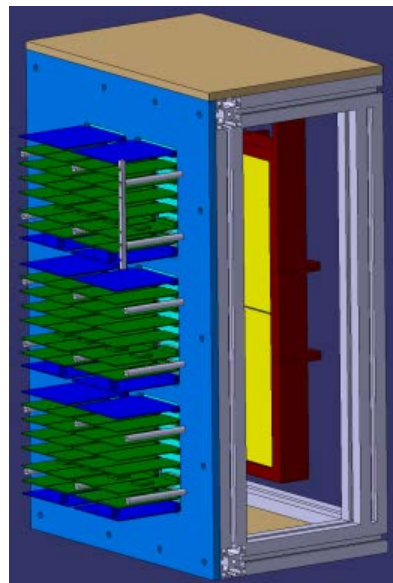
## Multi Anode Photo Multiplier Tube



6 × 6  
H12700  
64ch **MAPMT**



aerogel  
pads



## New Hardware

### Login Node

- 2x Xeon Gold 6140: 18 cores, 2,3 - 3,7 GHz
- 192 GB RAM, 2x 2 TB NVMe SSD
- 10 G ethernet uplink to GSI

### Processing Nodes

- 2x Xeon Gold 6130: 16 cores, 2,1 - 3,7 GHz
- 192 GB RAM, 2x 2 TB NVMe SSD
- Infiniband HDR (200 Gbit/s)

### Network

- 40 port Infiniband HDR switch
- 4 dual socket HDR HCAs (200 GBit/s)

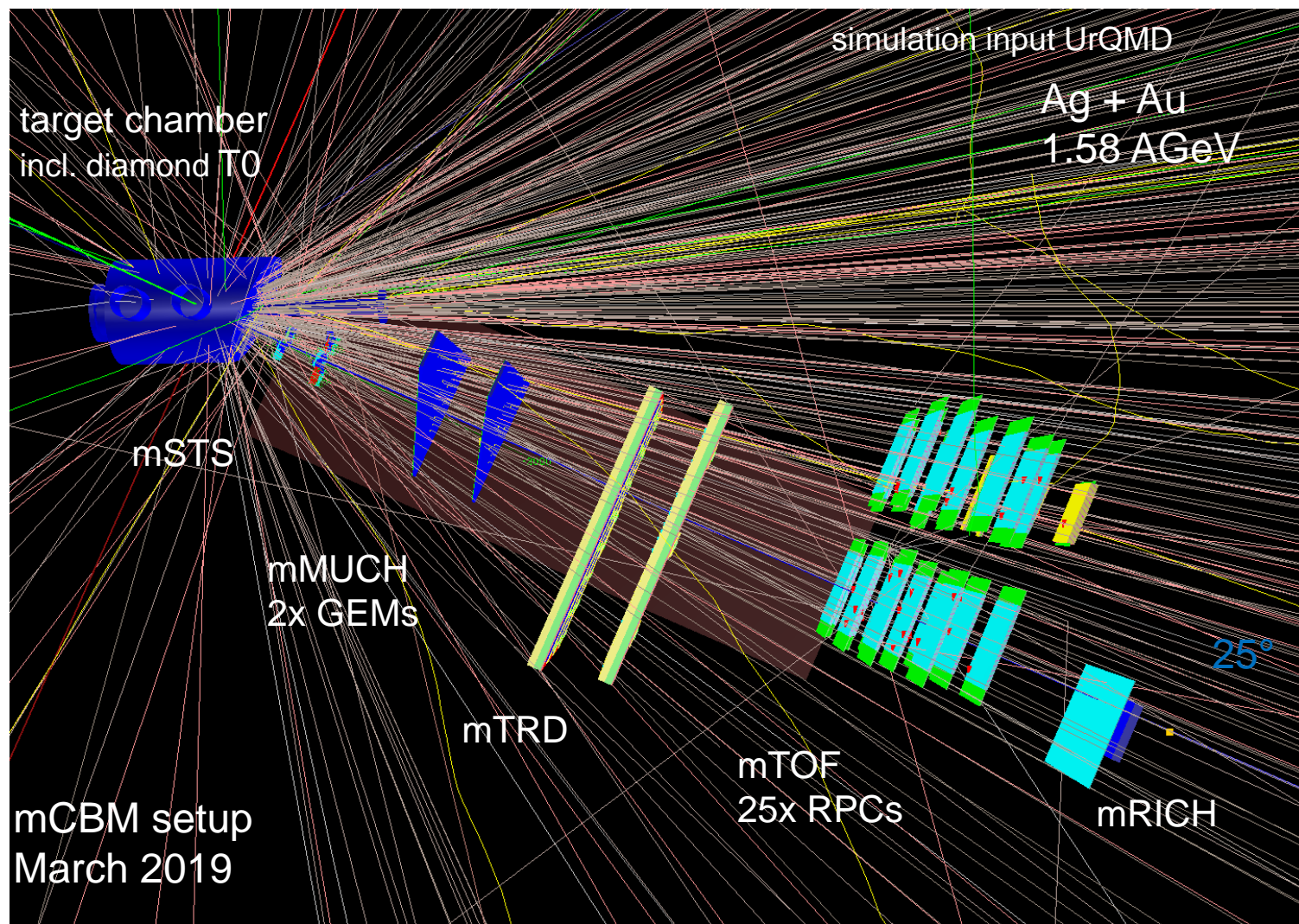
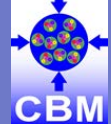


## New mFLES Run Control

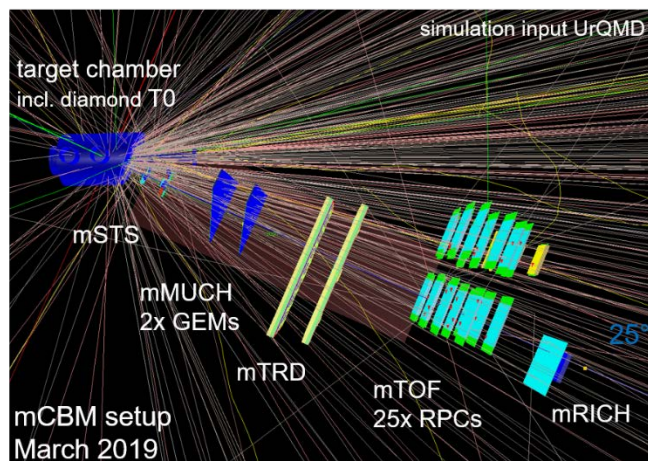
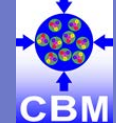
- Aim: switch gears to common data taking with a realistic FLES
  - Reproducible data taking, independent of control node
  - Support for multiple operators
  - Use of multiple nodes, timeslice building from EN to PN
- All run parameters are described in a configuration file
  - Configurations are stored as a tag
- Configuration includes:
  - Set of entry and processing nodes
  - FLIB parameters
  - Timeslice building parameters
  - Archival parameters
- Globally installed on mFLES cluster

```
$ flesctl
Usage:
  flesctl list
  flesctl add <config_file> <tag>
  flesctl show <tag>
  flesctl start <tag>
  flesctl stop
  flesctl monitor | mon
  flesctl status
  flesctl logbook
  flesctl info <run>
  flesctl -h | --help
  flesctl --version
```

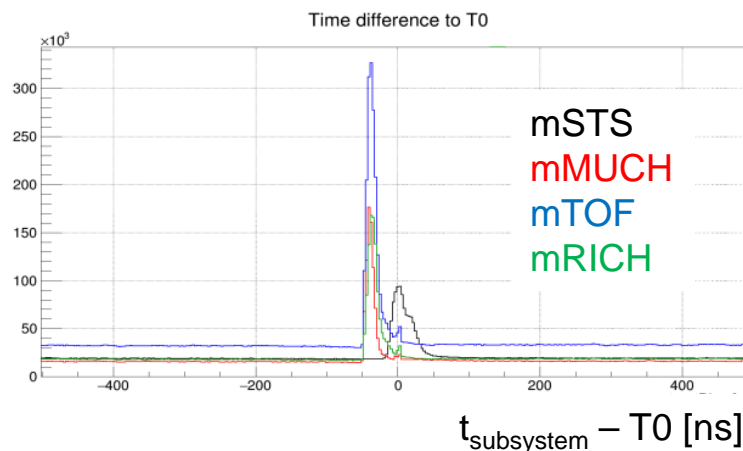
# Start of mCBM commissioning



# Start of mCBM commissioning

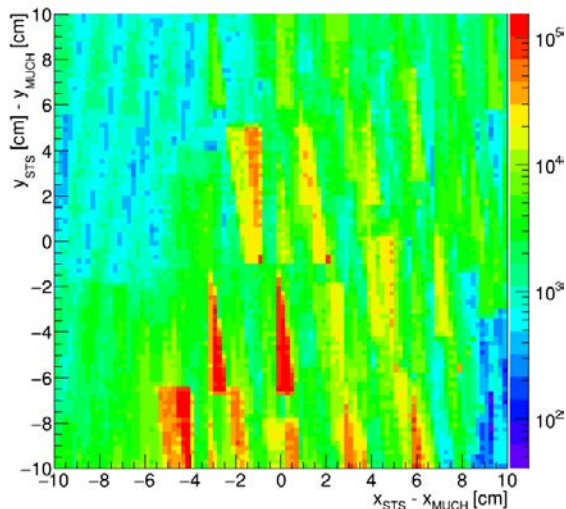


**very preliminary results** data taken in March 2019

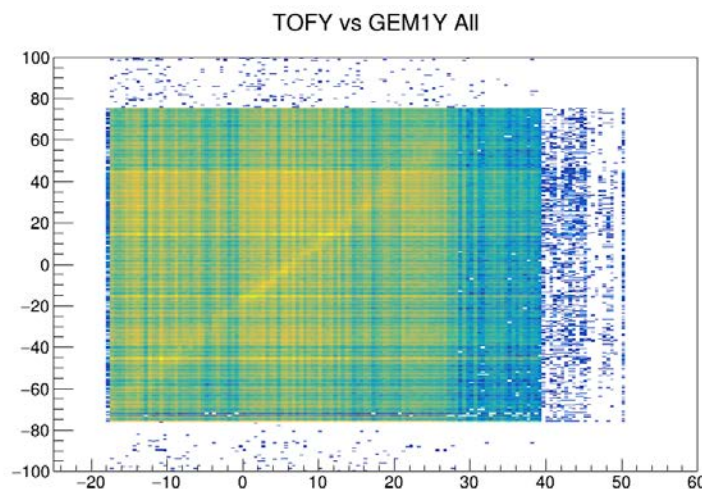


subsystem  
time offset  
in the common,  
synchronized  
data stream

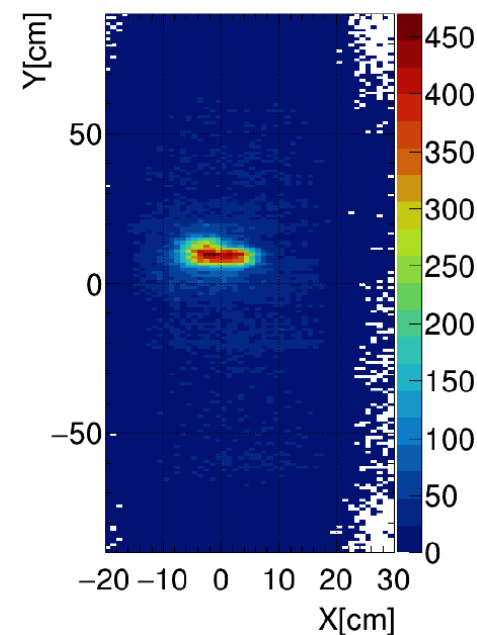
mSTS ↔ mMUICH



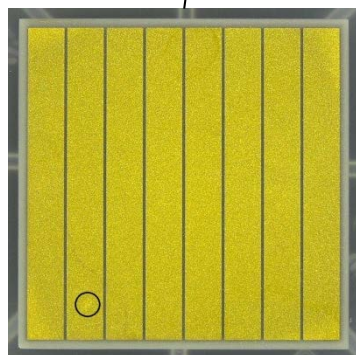
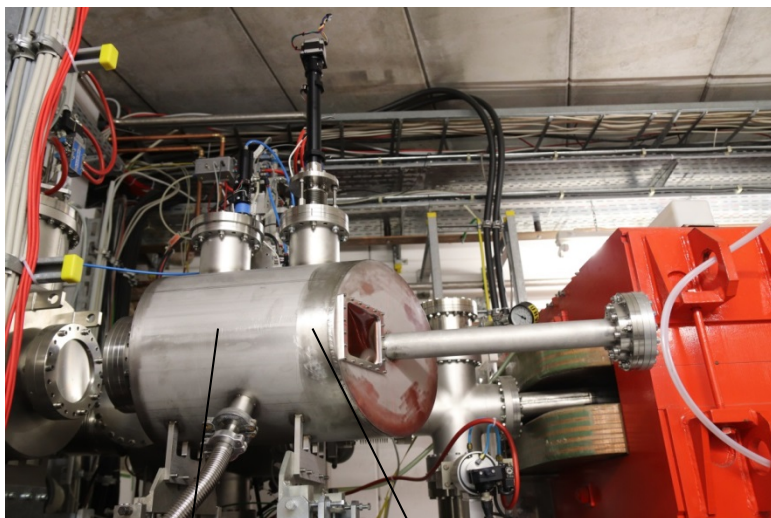
mMUICH ↔ mTOF



mTOF ↔ mRICH



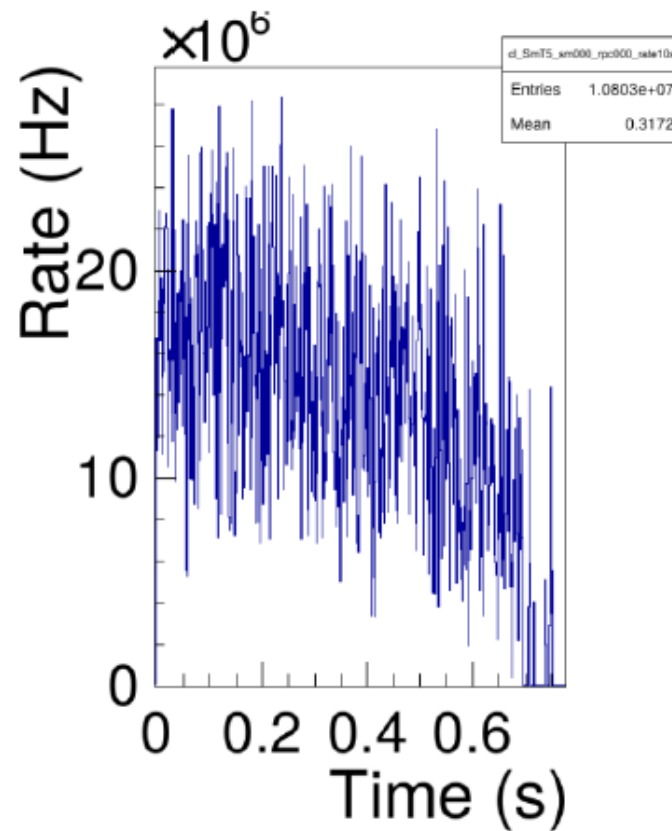
# Start of mCBM commissioning



diamond counter:  
8x strips  
2mm width each

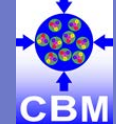


target  
ladder

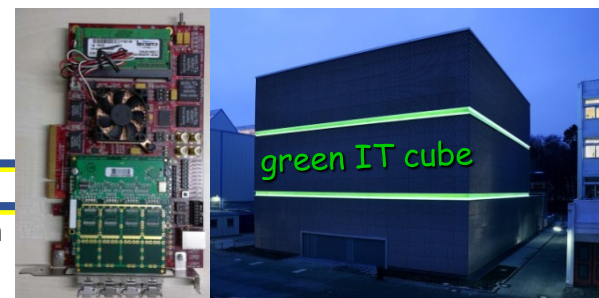
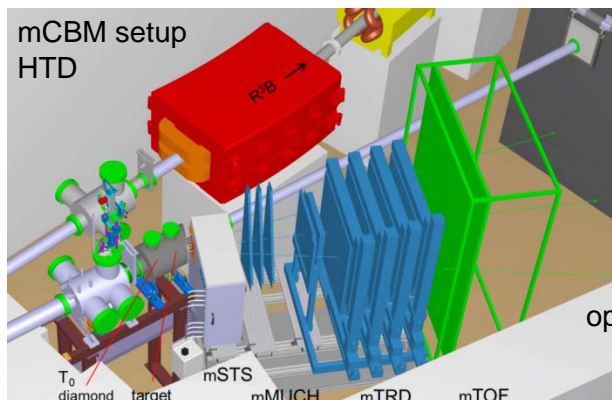


March 30, 2019:  
beam intensity  $\approx 10^8$  Ag ions / s  
T0 saturation ?  
radiation damage ?

# Start of mCBM commissioning



March 2019 :  $10^8$  Ag ions/s (1.58 AGeV) + Au (2.5mm)  $\rightarrow$  10 MHz collision rate

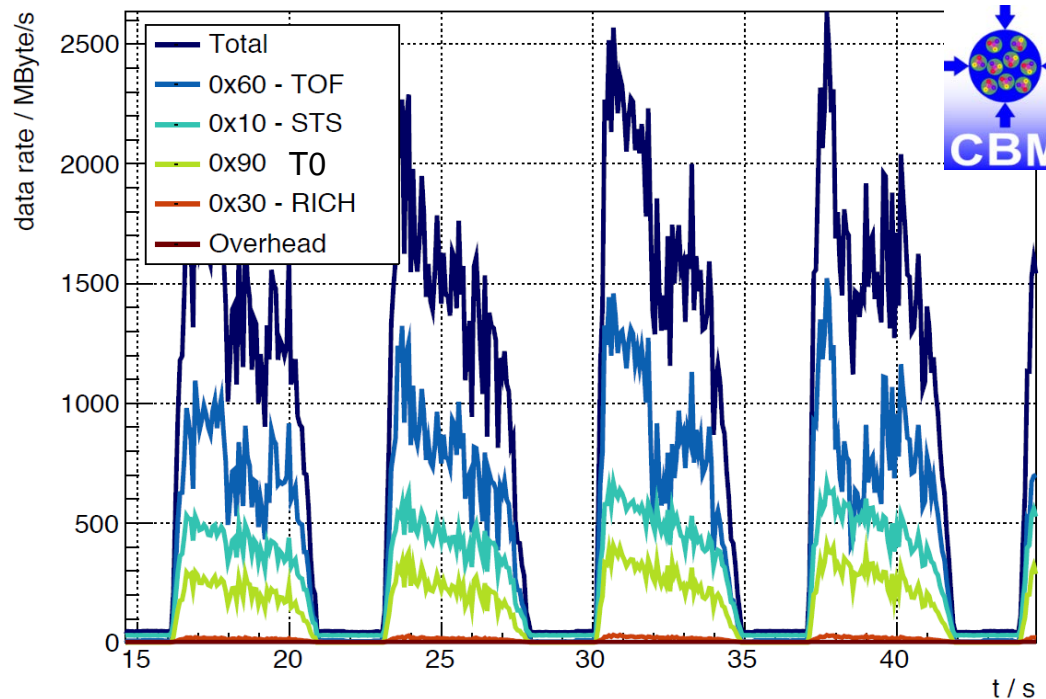


50 m

300 m

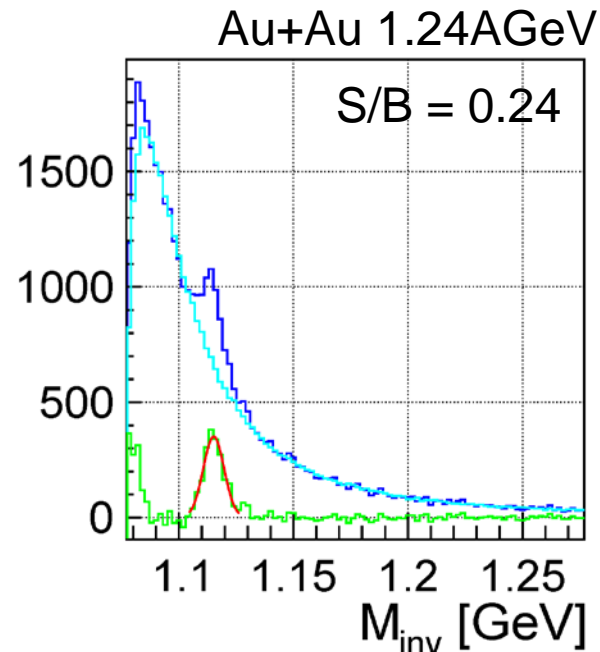
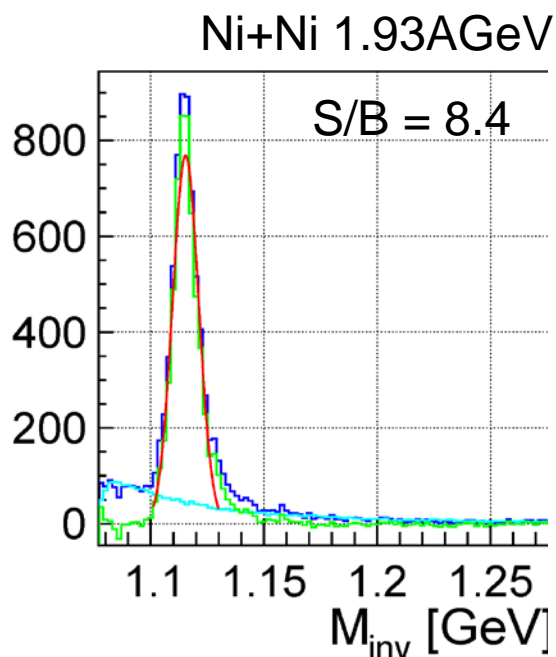
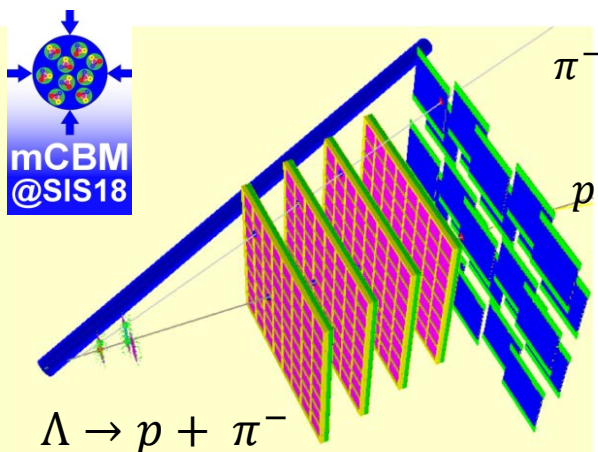
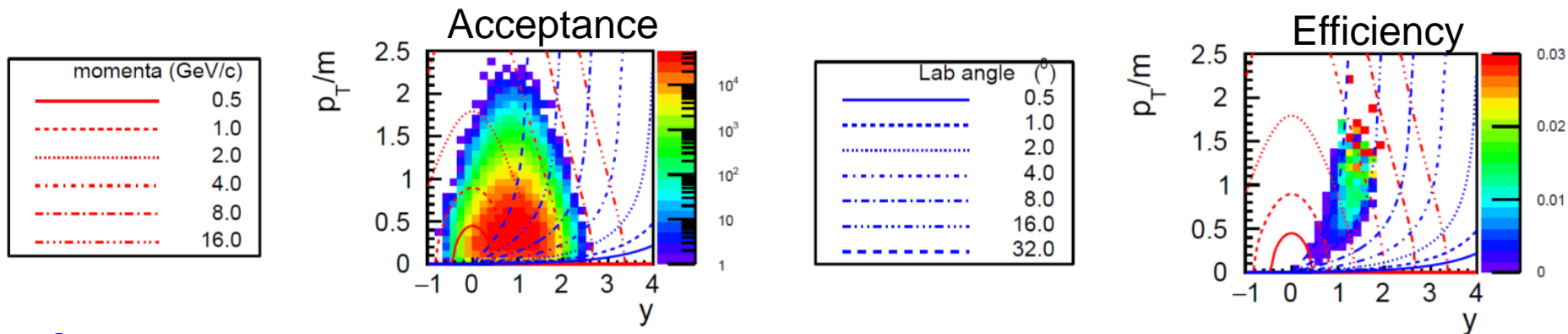
total data rate  
online

2.5 GB/s (max.)



# mCBM benchmark observable: $\Lambda$ reconstruction

Simulation input:  $10^8$  UrQMD events, min. bias



---

2018 development & commissioning  
→ data transport, data analysis, detector tests

2019

---

2019 approaching full performance  
→ subsystems completed, high-rate data transport / processing

2020 → online reconstruction and selection

---

requested  
beamtime  
was fully  
granted  
by GSI/FAIR  
G-PAC

---

2021 1<sup>st</sup> benchmark run  
 $\Lambda$  reconstruction production runs  
benchmark coll. systems:  
Ni+Ni 1.93 AGeV & Au+Au 1.24 AGeV

---

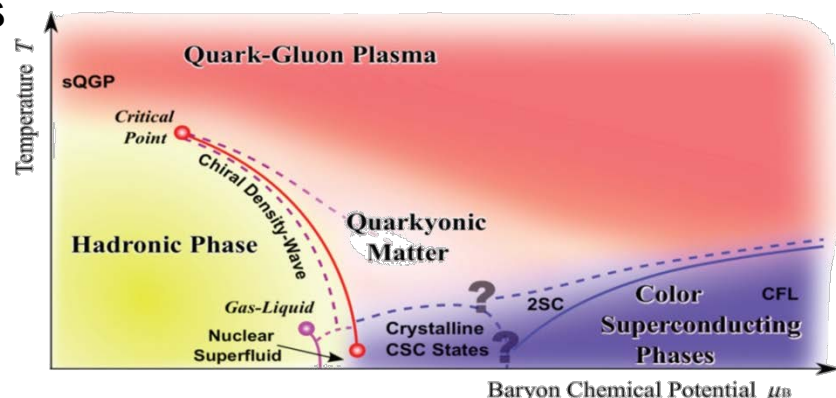
2022 2<sup>nd</sup> benchmark run  
 $\Lambda$  reconstruction in Ni+Ni and Au+Au collisions  
at various projectile energies  
→  $\Lambda$  production excitation function

---

proposal  
to be  
submitted  
in 2019/20

## Open questions at high net baryon densities

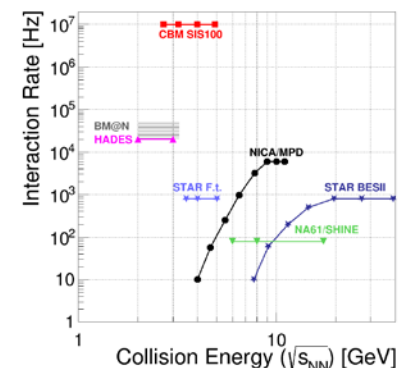
- Phase transition from hadronic matter to quarkyonic or partonic matter ?
- Chiral phase transition ? Chiral restoration ?
- In-medium modification of hadrons ?
- Nuclear equation-of-state at neutron star core densities ?



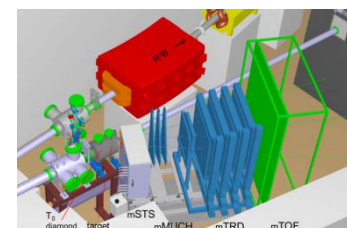
→ **substantial discovery potential with CBM at FAIR**

Extremely rare probes

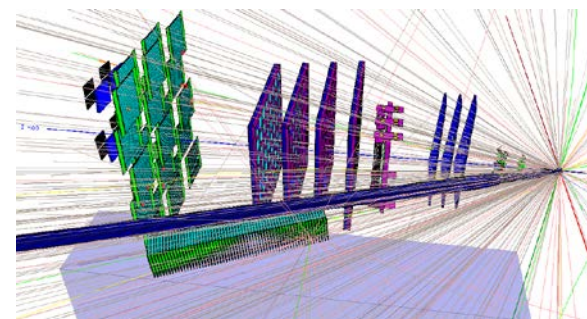
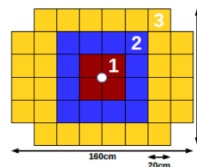
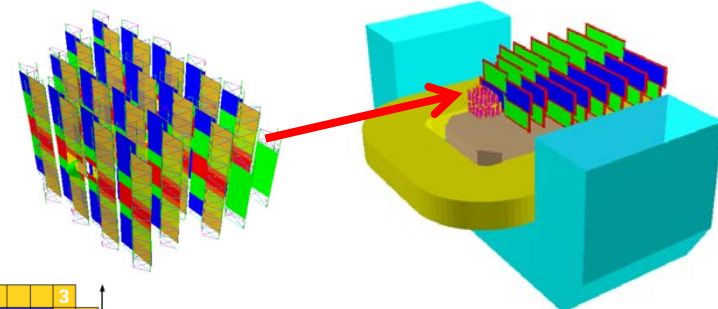
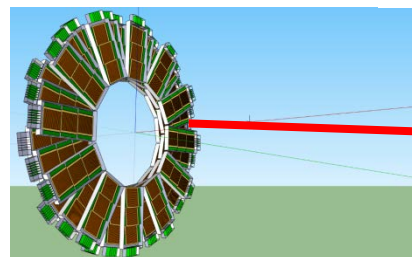
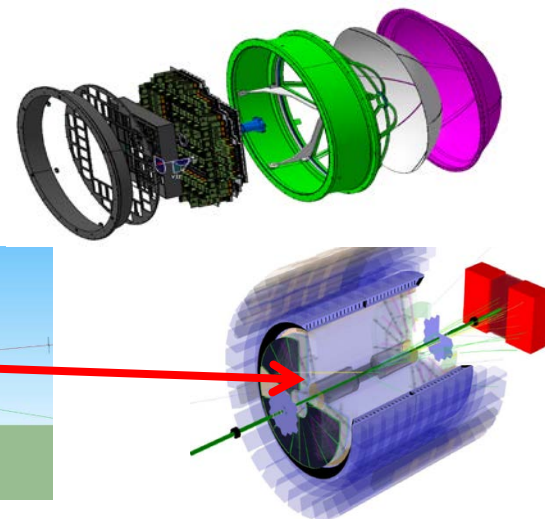
→ CBM high-tec developments  
to achieve unprecedented collision rates (10 MHz)



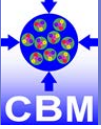
Commissioning of a precursor experiment, full-system test mCBM@SIS18 (“mini-CBM”) has started → planned program until 2023, potential physics results



1. Install, commission and use 430 out of 1100 CBM RICH multi-anode photo-multipliers (MAPMT) including FEE in HADES RICH photon detector
2. Install, commission and use 10% of the CBM TOF modules including read-out chain at STAR/RHIC (BES II 2019/2020)
3. Upgrade BM@N experiment with 4 Silicon stations of CBM/STS design in the BM@N experiment at the Nuclotron JINR/Dubna (Au-beams in late 2020)
4. Install, commission and use the Project Spectator Detector at the BM@N experiment
5. mCBM@SIS18:  
demonstrator for full CBM data taking and analysis chain



# CBM Collaboration: 55 institutions, 470 members



## China:

CCNU Wuhan  
Tsinghua Univ.  
USTC Hefei  
CTGU Yichang  
Chongqing Univ.

## Czech Republic:

CAS, Rez  
Techn. Univ. Prague

## France:

IPHC Strasbourg

## 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.  
Univ. of Jammu  
Univ. of Kashmir  
Univ. of Calcutta  
B.H. Univ. Varanasi  
VECC Kolkata  
IOP Bhubaneswar  
IIT Kharagpur  
IIT Indore  
Gauhati Univ.

## Korea:

Pusan Nat. Univ.

## Poland:

AGH Krakow  
Jag. Univ. Krakow  
Warsaw Univ.  
Warsaw TU

## Romania:

NIPNE Bucharest  
Univ. Bucharest

## Hungary:

KFKI Budapest  
Eötvös Univ.

## Russia:

IHEP Protvino  
INR Troitzk  
ITEP Moscow  
Kurchatov Inst., Moscow  
VBLHEP, JINR Dubna  
LIT, JINR Dubna  
MEPHI Moscow  
PNPI Gatchina  
SINP MSU, Moscow

## Ukraine:

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

## 33<sup>th</sup> CBM Collaboration meeting at GSI, April 2019

