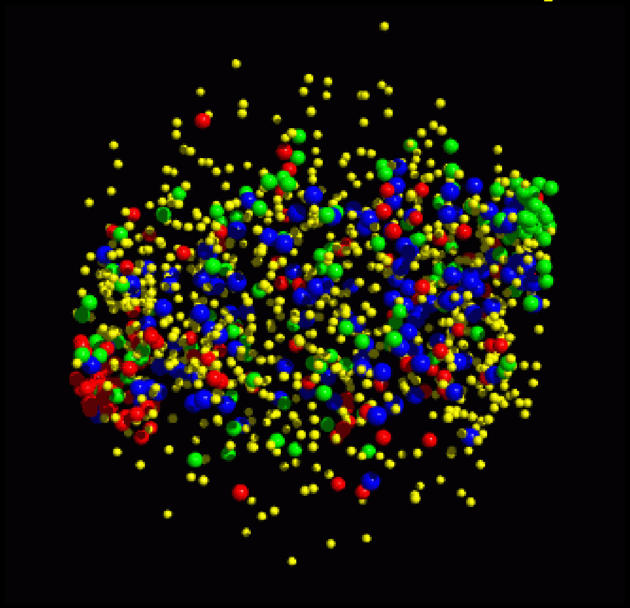
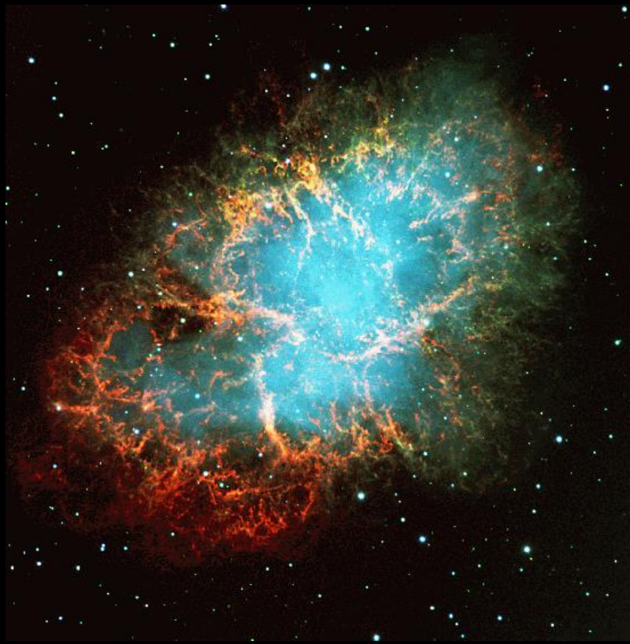
The Compressed Baryonic Matter experiment at the Facility for Antiproton and Ion Research



Peter Senger (GSI)



Outline:

- Introduction to FAIR
- The CBM experiment:
  - Physics case and observables
  - (Simulations and technical challenges: Volker Friese)

Heavy Ion Meeting, Hanyang University, Seoul, Korea, Oct. 31, 2009

FAIR: the big challenge

FAIR is the largest fundamental science project worldwide for the next decade!

Forefront research in nuclear, hadron, atomic, anti-matter, plasma, and applied physics.

- **Construction until 2016**
- **Total cost 1.2 B€**
- **16 member states up to date**
- **Scientific users: 2500 - 3000 per year**

Financing:

- **65 % Federal Government of Germany**
- **10 % State of Hessen**
- **25 % Partner Countries**

→FAIR GmbH with International Shareholders

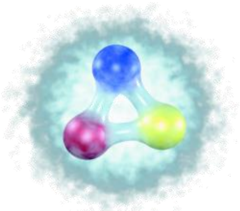
Observer

Austria China Finnland France Germany Greece India Italy Poland Slovakia Slovenia Spain Sweden Romania Russia UK

Research programmes at FAIR

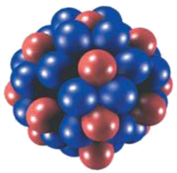
Beams of antiprotons: hadron physics

quark-confinement potential
search for gluonic matter and hybrids
hypernuclei



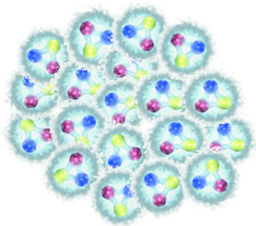
Rare isotope beams: nuclear structure and nuclear astrophysics

nuclear structure far off stability
nucleosynthesis in stars and supernovae



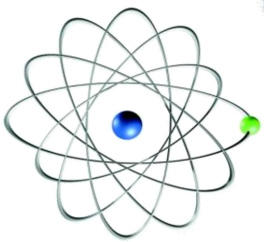
Nucleus-nucleus collisions: compressed baryonic matter

baryonic matter at highest densities (neutron stars)
phase transitions and critical endpoint
in-medium properties of hadrons



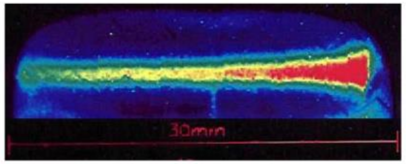
Atomic physics, FLAIR, and applied research

highly charged atoms
low energy antiprotons
radiobiology



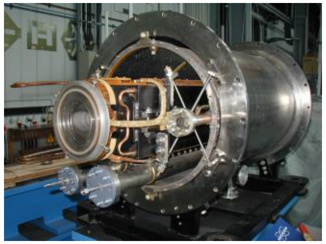
Short-pulse heavy ion beams: plasma physics

matter at high pressure, densities, and temperature
fundamentals of nuclear fusion

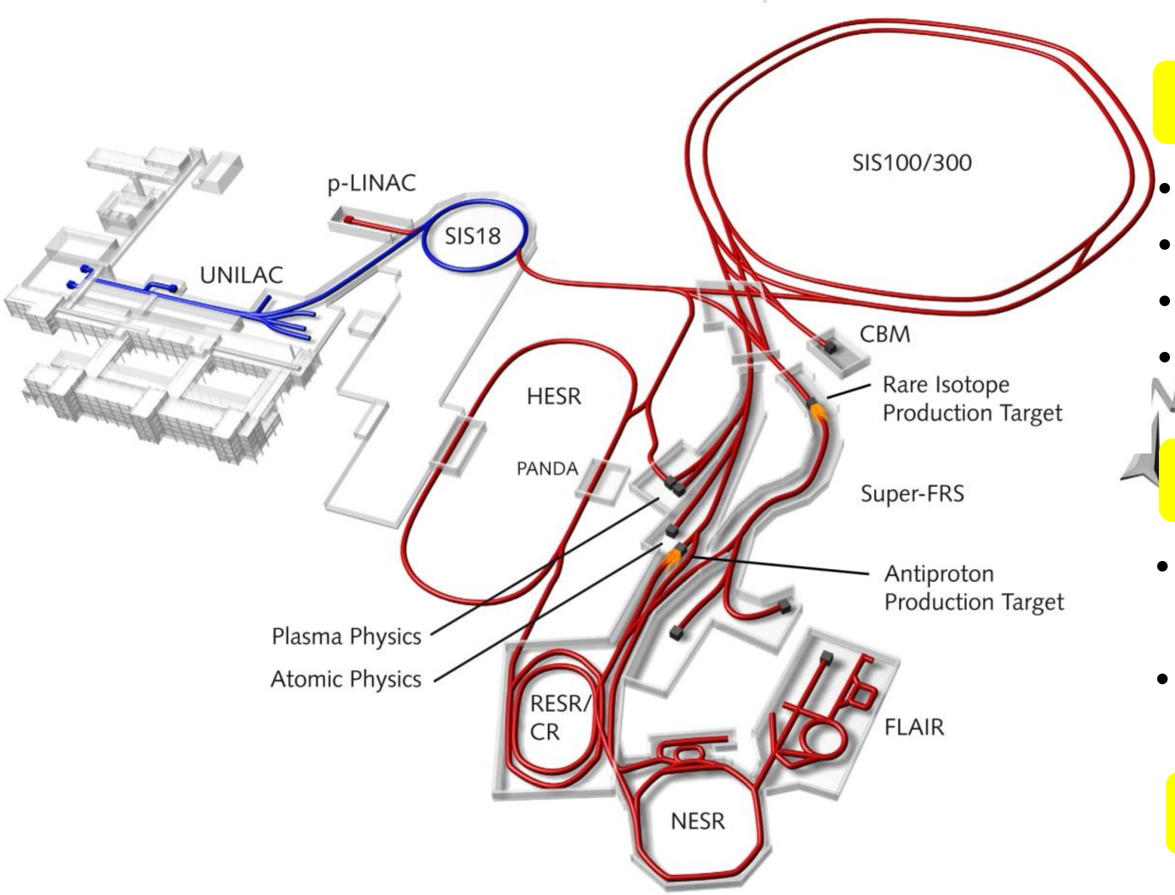


Accelerator physics

high intensive heavy ion beams
dynamical vacuum
rapidly cycling superconducting magnets
high energy electron cooling



Facility for Antiproton and Ion Research (FAIR)



primary beams

- **5x10^{11}/s; 1.5-2 GeV/u; $^{238}U^{28+}$**
- **factor 100-1000 increased intensity**
- **4x10^{13}/s 90 GeV protons**
- **10^{10}/s ^{238}U 35 GeV/u (Ni 45 GeV/u)**

secondary beams

- **rare isotopes 1.5 - 2 GeV/u; factor 10 000 increased intensity**
- **antiprotons 3(0) - 30 GeV**

storage and cooler rings

- **beams of rare isotopes**
- **e – A Collider**
- **10^{11} stored and cooled antiprotons 0.8 - 14.5 GeV**

accelerator technical challenges

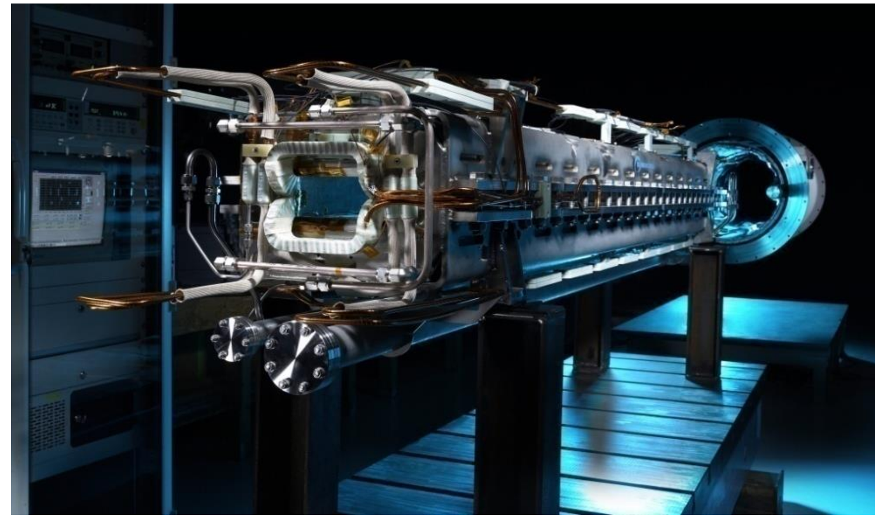
- **Rapidly cycling superconducting magnets**
- **high energy electron cooling**
- **dynamical vacuum, beam losses**

R&D on magnets for SIS100

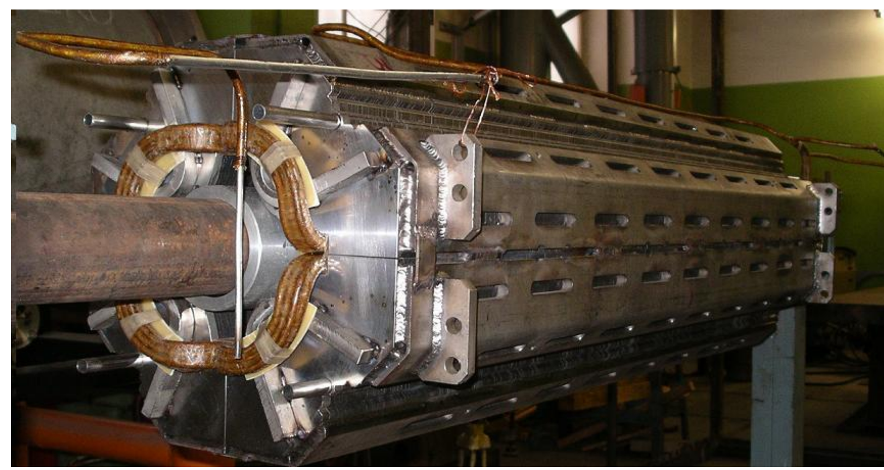
- Design and construction of superconducting prototype magnets in collaboration with external partners and industry.

BABCOCK NOELL

Joint Institute for Nuclear Research



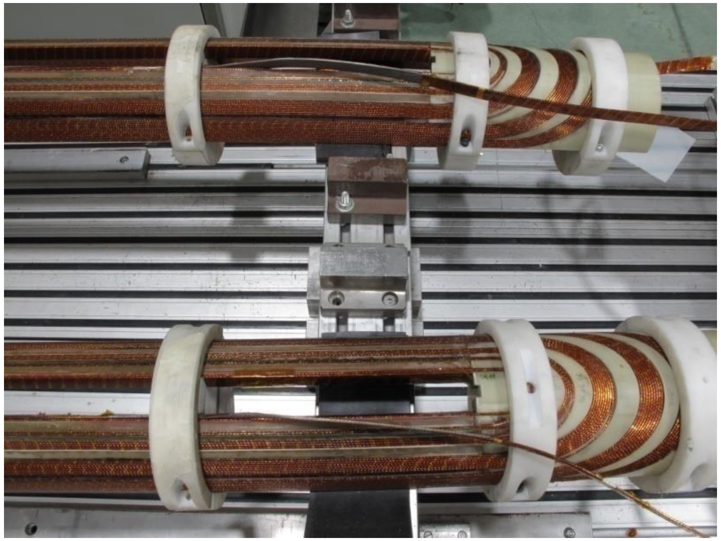
SIS100 superferric dipole prototype

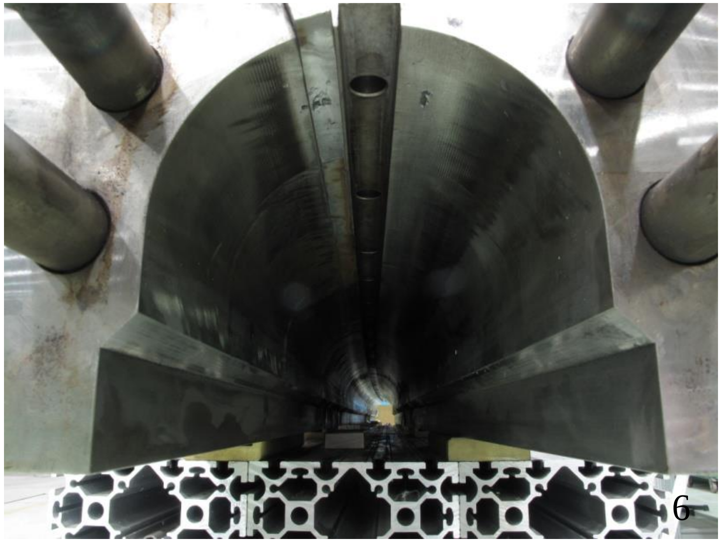


SIS100 superferric quadrupole prototype

R&D on dipole magnets for SIS300

two superconducting curved coils and poles produced using innovative tooling





Ansaldo Superconduttori

INFN Istituto Nazionale di Fisica Nucleare

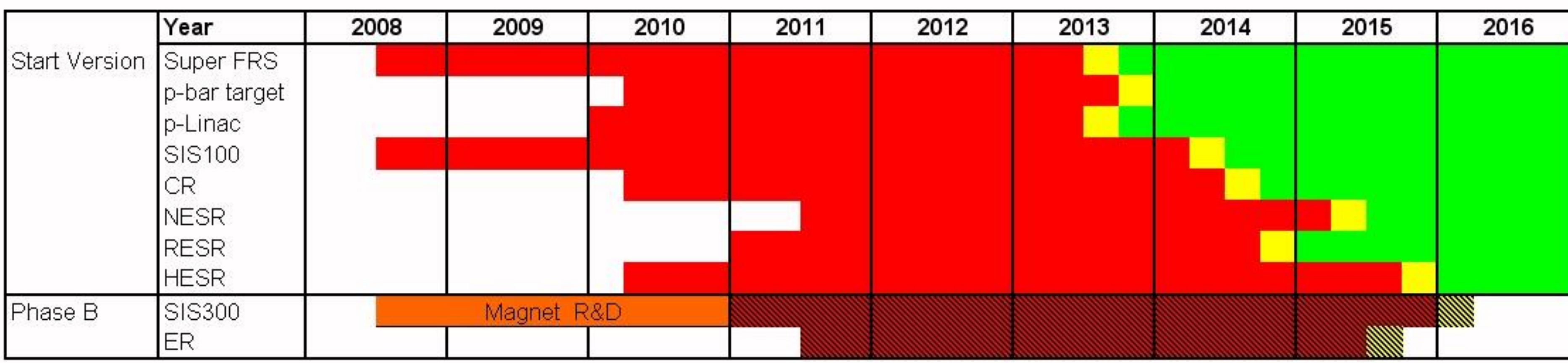
Overall schedule (FAIR accelerator sections)

2000: International Workshop at GSI (physics discussions, 300 participants)

2005: Evaluation of accelerators and experiments by international experts

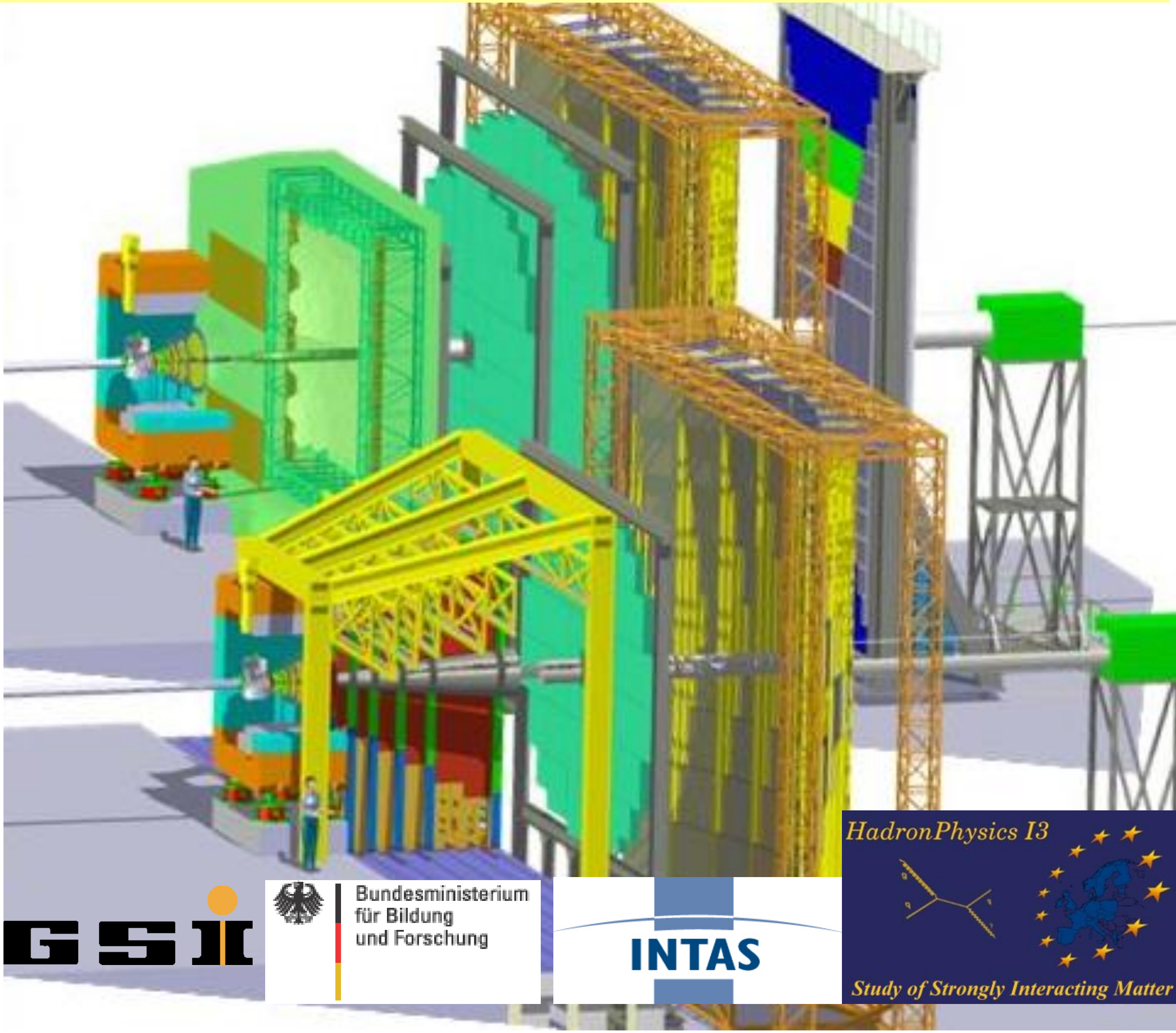
2006: FAIR Baseline Technical Report

(6 volumes with more than 3500 pages and more than 2600 authors



Project requires ~ 700 accelerator physicists and engineers

The Compressed Baryonic Matter experiment at FAIR



GSI

Bundesministerium für Bildung und Forschung

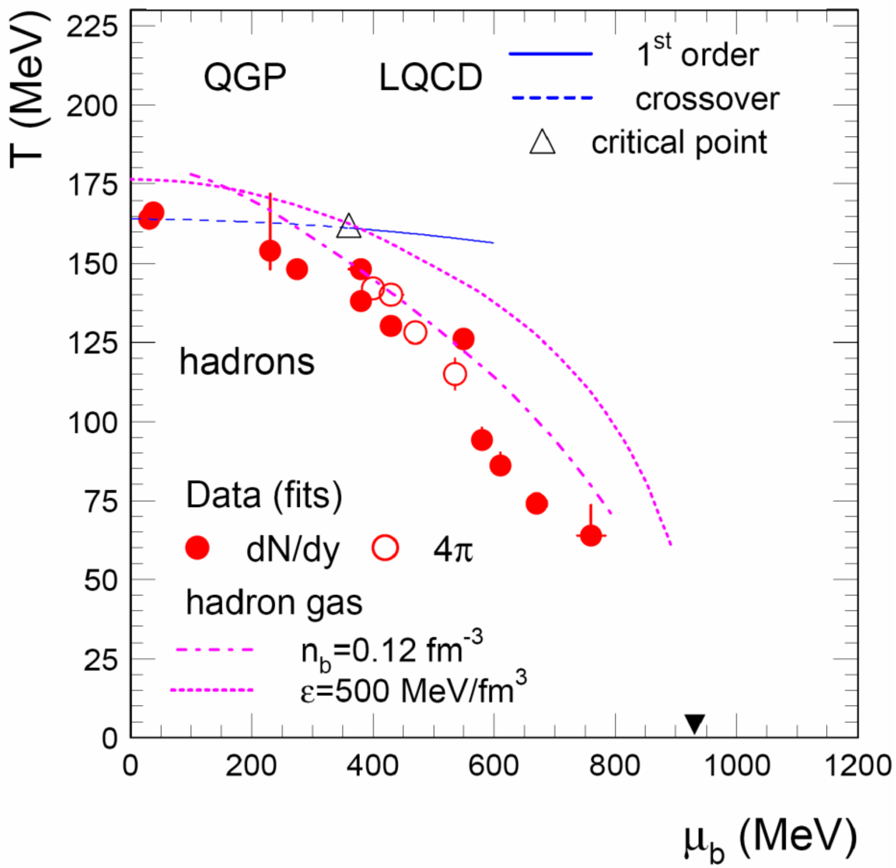
INTAS

HadronPhysics I3

Study of Strongly Interacting Matter

The QCD Phase diagram: facts and speculations

A. Andronic et al., Phys. Lett. B 673 (2009).



Experimental results:

- Freeze-out curve (T, μ_B)
- T_{fo} = 161±4 MeV at (μ_B=0)
- new state of matter = partonic dof?

L-QCD Predictions:

- T_C = 151 ± 7 ± 4 MeV
  (Z. Fodor, arXiv:0712.2930 hep-lat)
- T_C = 192 ± 7 ± 4 MeV
  (F. Karsch, arXiv:0711.0661 hep-lat)
- crossover transition at μ_B=0
  (Z. Fodor, arXiv:0712.2930 hep-lat)
- 1. order phase transition with critical endpoint at $\mu_B > 0$

Exploring the QCD phase diagram at large μ_B with heavy-ion collisions:

RHIC energy-scan: search for QCD-CP with bulk observables

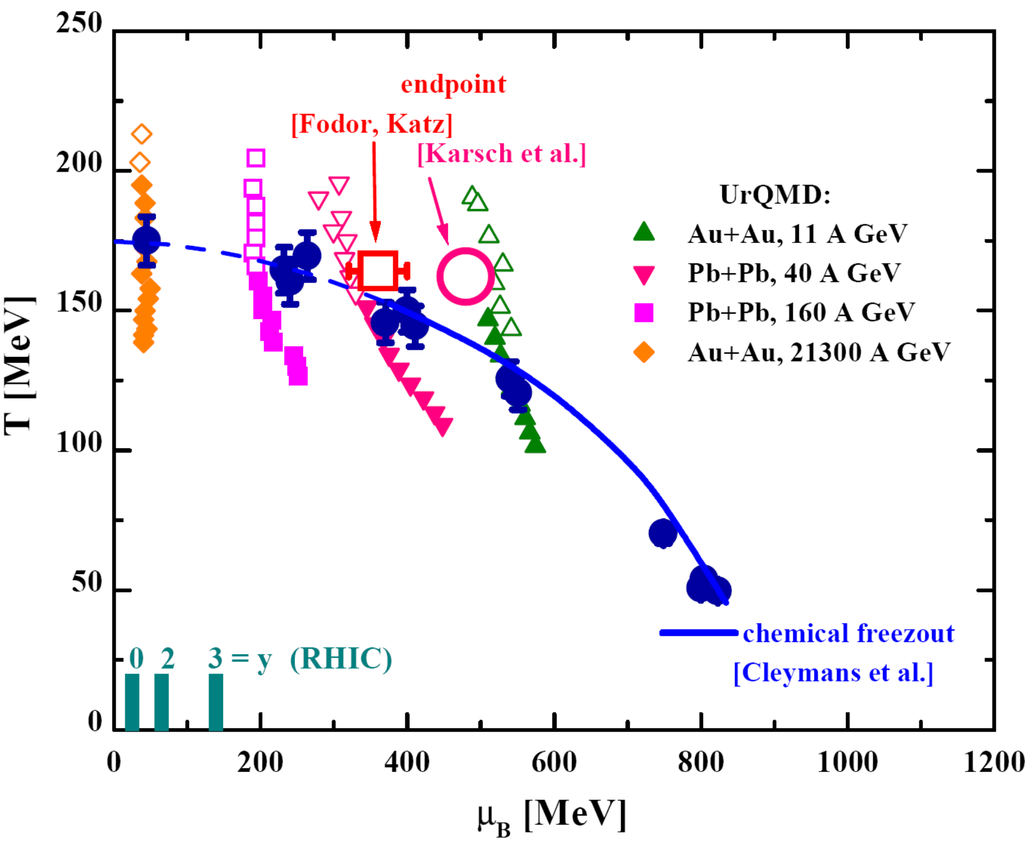
NA61@SPS: search for QCD-CP with bulk observables

MPD@NICA: search for the QCD mixed phase with bulk observables

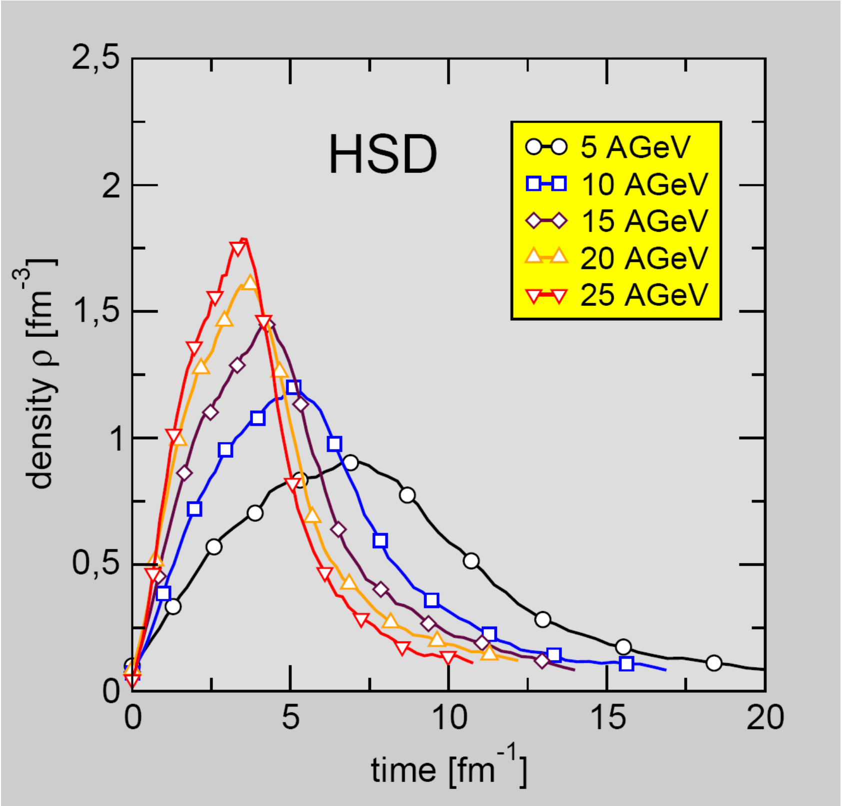
CBM@FAIR: scan of the phase diagram with bulk and rare observables

Heavy-ion collisions at SIS100: Transport model predictions

<u>UrQMD:</u> L.V. Bravina et al., Phys. Rev. C60 (1999) 044905



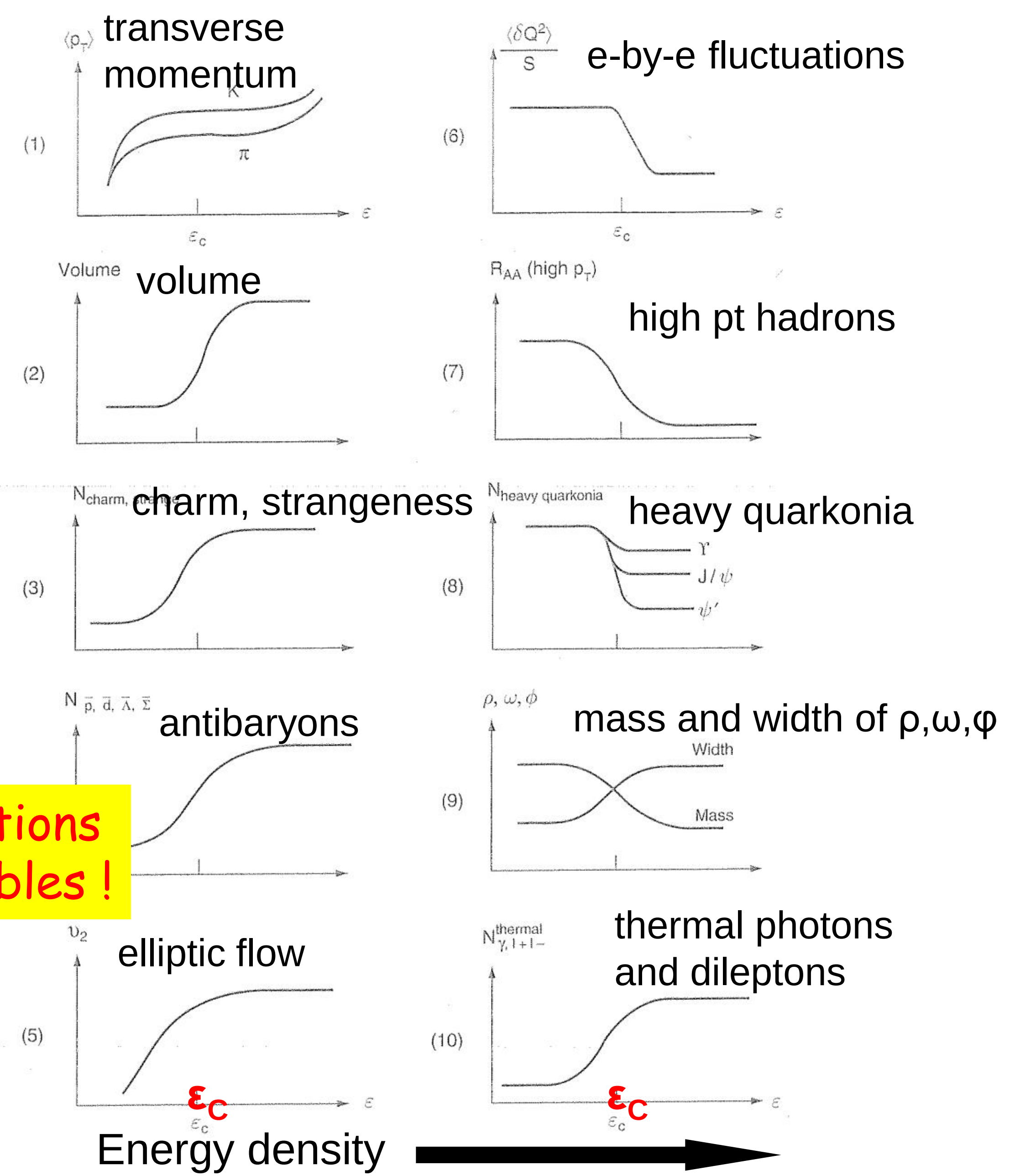
E. Bratkovskaya, W. Cassing



Signatures for phase transitions in heavy-ion collisions

taken from the book:
Quark-Gluon-Plasma:
from big bang to little bang
by K. Yagi, T. Hatsuda,
Y. Miake (2006)

Measure excitation functions of bulk and rare observables !



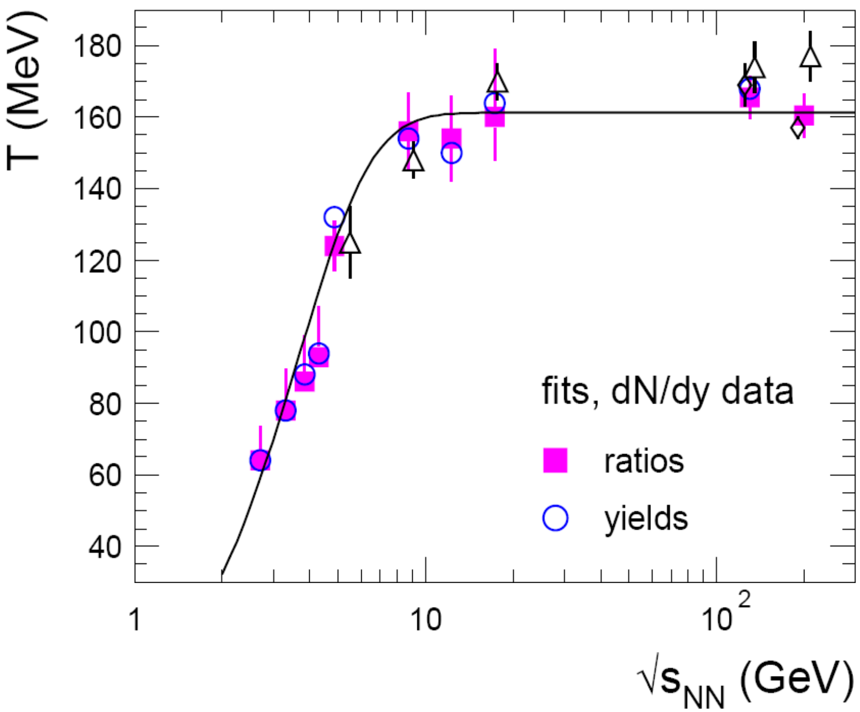
Signatures for phase transitions ?

Structures in excitation functions of observables at low SPS energies:

- limiting chemical freeze-out temperature
- limiting collective flow
- limiting radial flow and kinetic freeze-out temperature
- maximum in the strangeness/entropy ratio
- enhanced dynamical event-by-event fluctuations

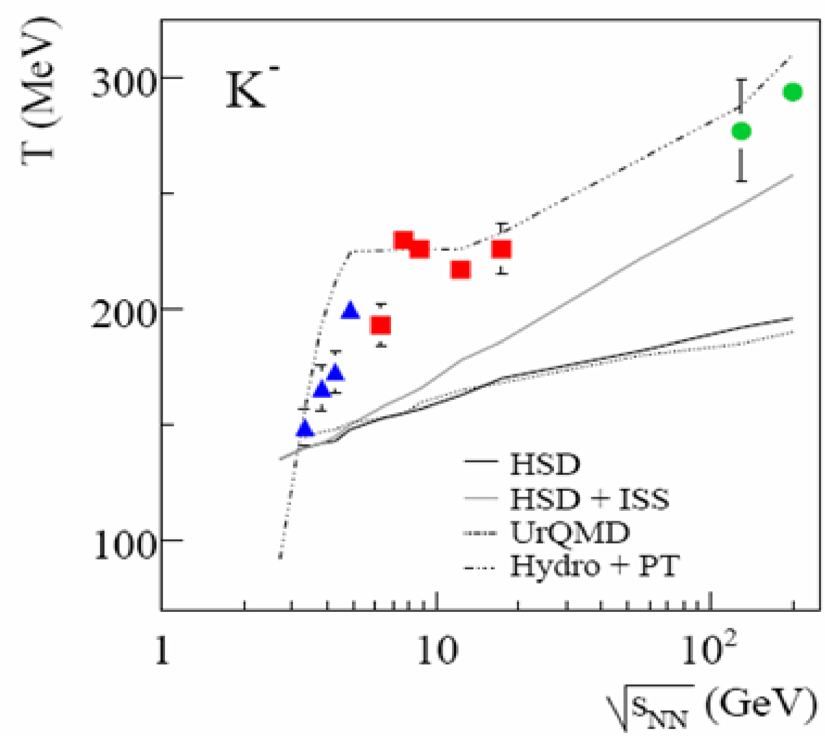
chemical freeze-out temperature

A. Andronic et al. Nucl. Phys. A 772, 167 (2006).



inverse slope parameter

[NA49, PRC 77, 024903 (2008)]



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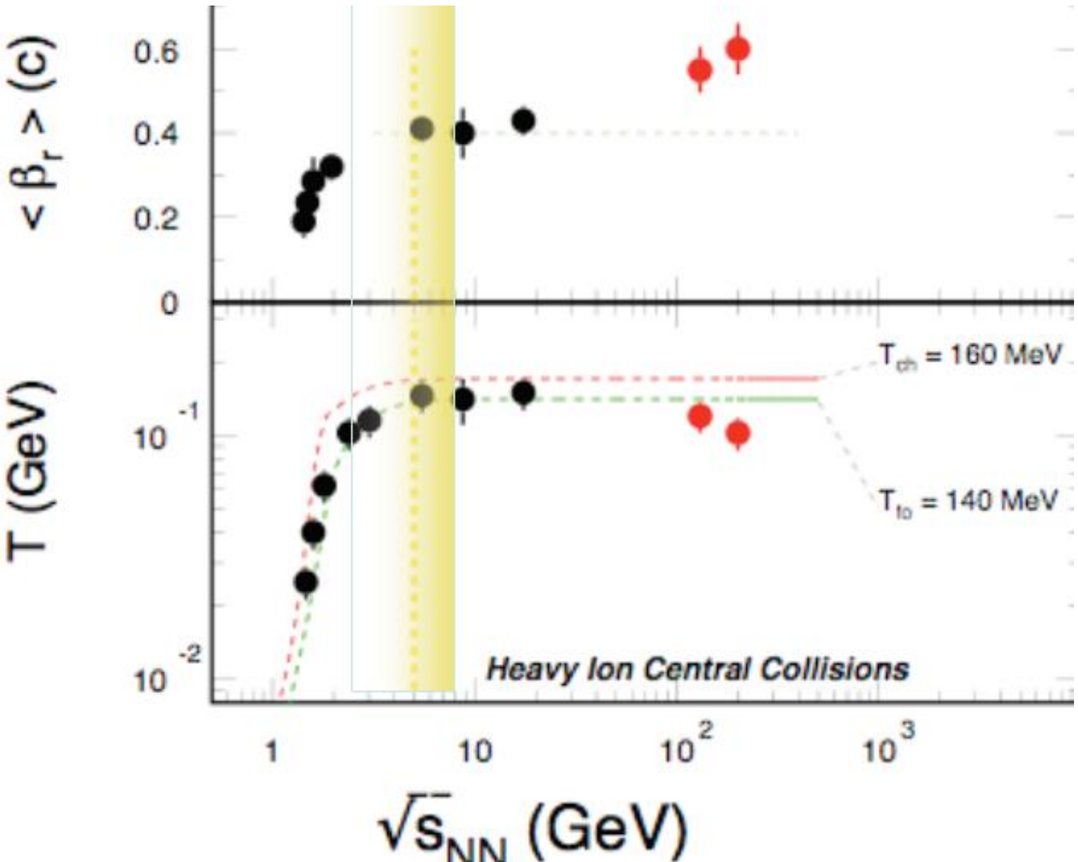

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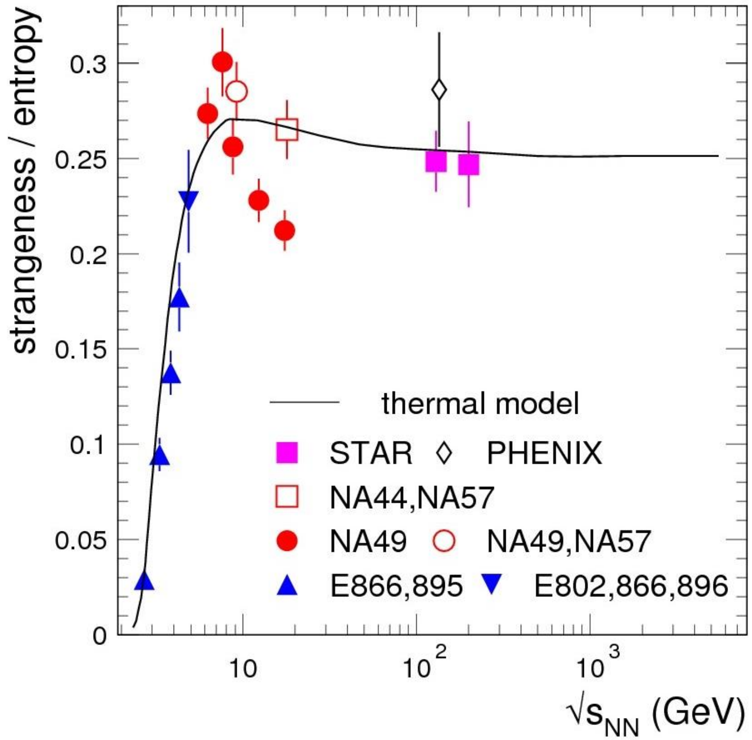
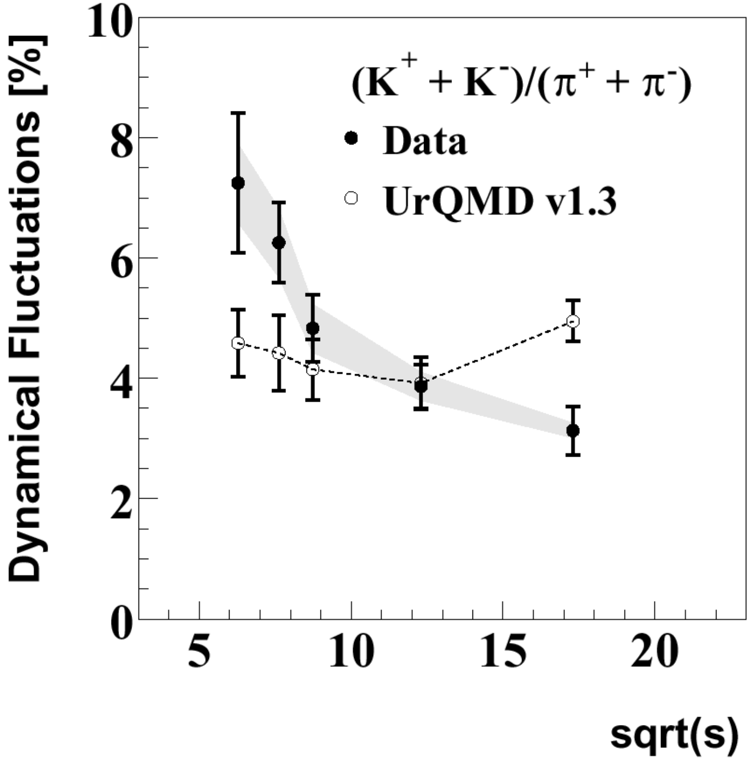
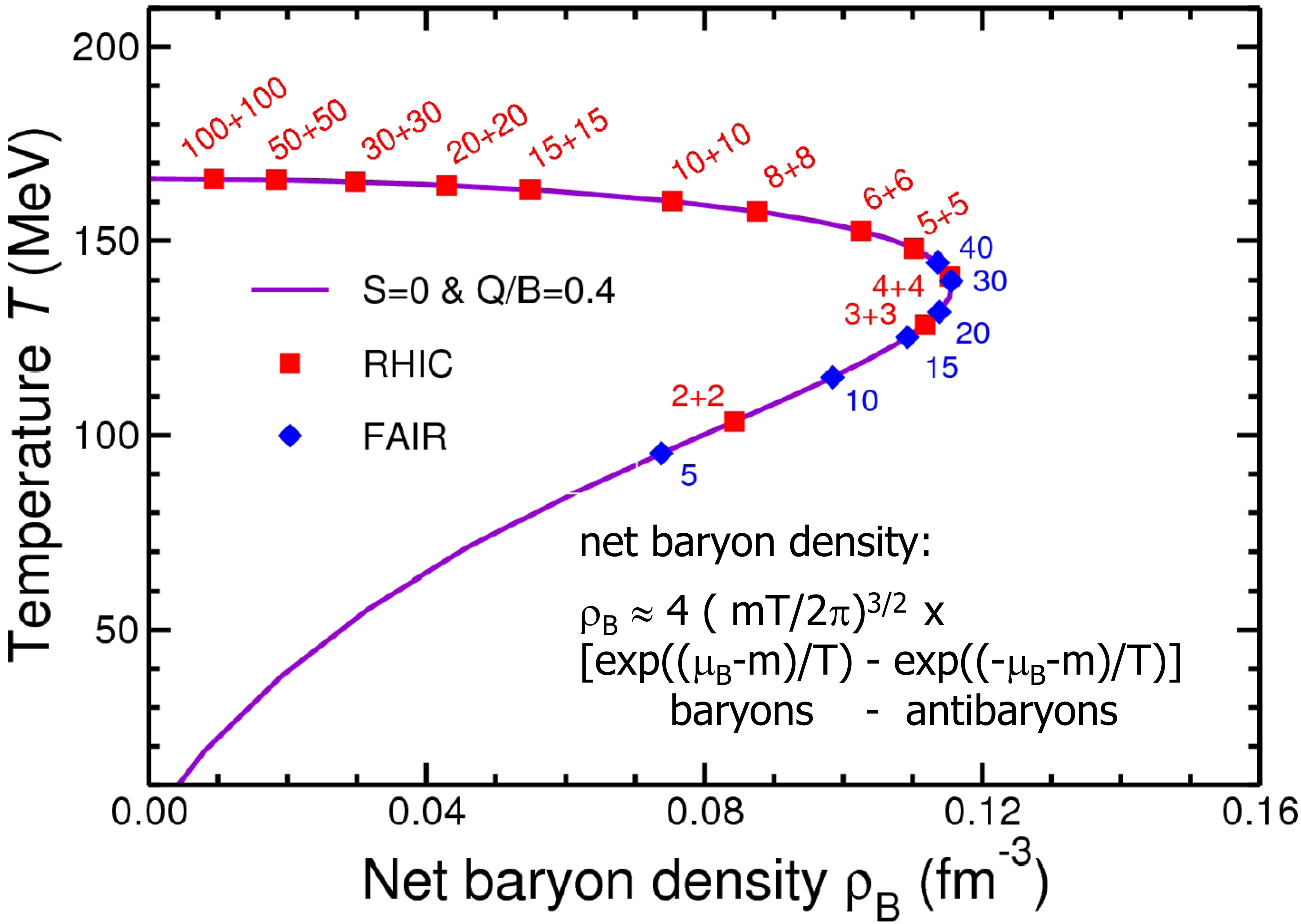


NA49 arXiv:0808.1237



What happens around $\sqrt{s_{NN}}$ = 5 -10 GeV?



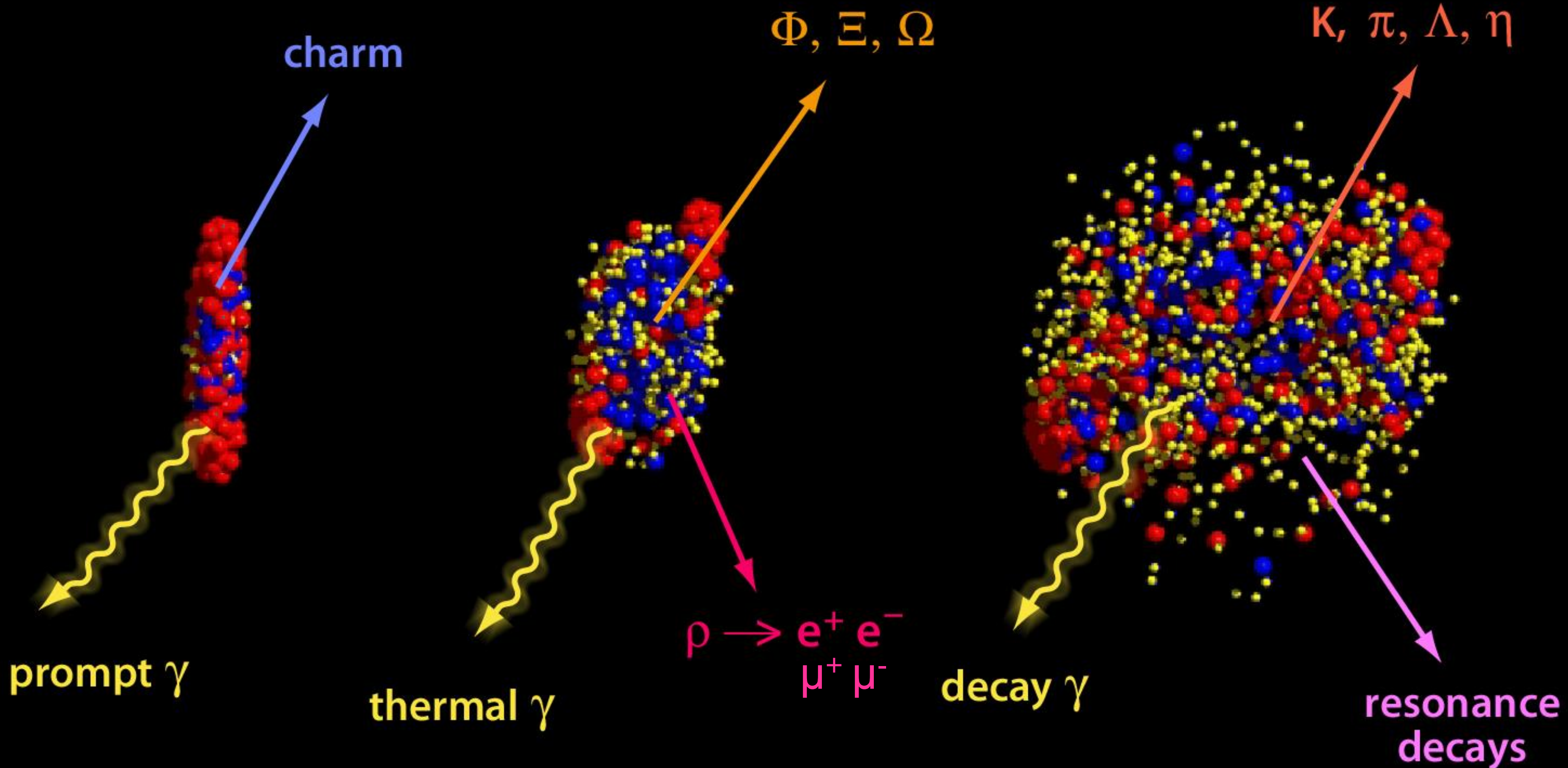
net baryon density:

$$\rho_B \approx 4\,(\,mT/2\pi)^{3/2}\ x$$
$$[\exp((\mu_B\text{-}m)/T) - \exp((-\mu_B\text{-}m)/T)]$$

baryons - antibaryons

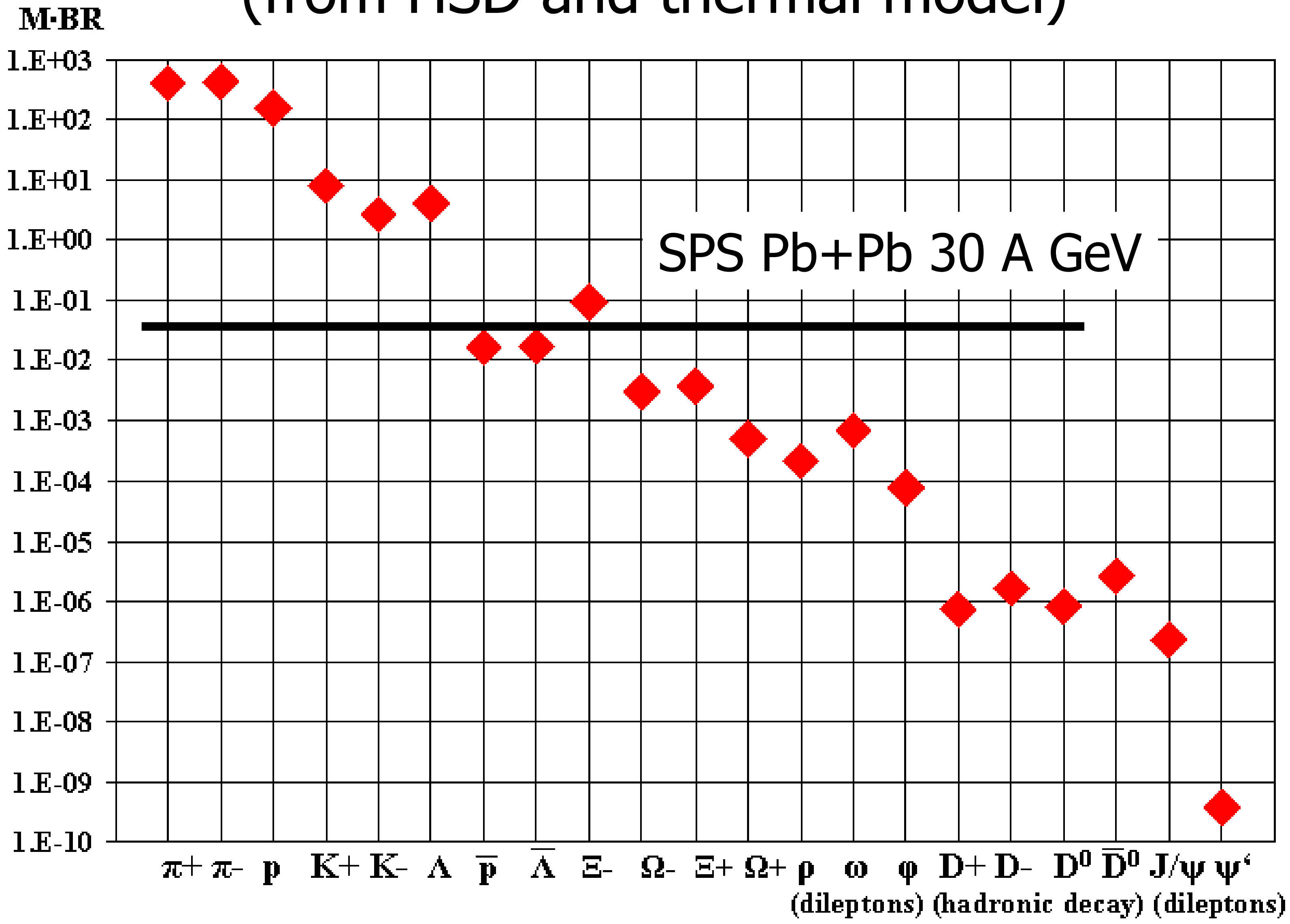
Messengers from the dense fireball ?

UrQMD transport calculation U+U 23 AGeV



Up to date only freeze-out probes have been measured in A+A collisions at 2 - 40 AGeV

Particle multiplicity x branching ratio for min. bias Au+Au collisions at 25 GeV (from HSD and thermal model)



CBM physics topics and observables

The equation-of-state at high ρ_B

- collective flow of hadrons
- particle production at threshold energies (multistrange hyperons, open charm?)

Deconfinement phase transition at high ρ_B

- excitation function and flow of strangeness (K, Λ, Σ, Ξ, Ω)
- excitation function and flow of charm (J/ψ, ψ', D^0, $D^{\pm}$, Λ_c) (e.g. melting of J/ψ and ψ')
- excitation function of low-mass lepton pairs
- disappearance of quark-number scaling of elliptic flow

QCD critical endpoint

- excitation function of event-by-event fluctuations (K/π,...)

Onset of chiral symmetry restoration at high ρ_B

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

The equation-of-state of (symmetric) nuclear matter

Equation of state:

$P = \delta E/\delta V \,|_{T=const}$

$V = A/\rho$

$\delta V/ \delta\rho = - A/\rho^2$

$P = \rho^2 \; \delta(E/A)/\delta\rho \,|_{T=const}$

T=0: $E/A = 1/\rho \int U(\rho)d\rho$

Effective NN-potential:

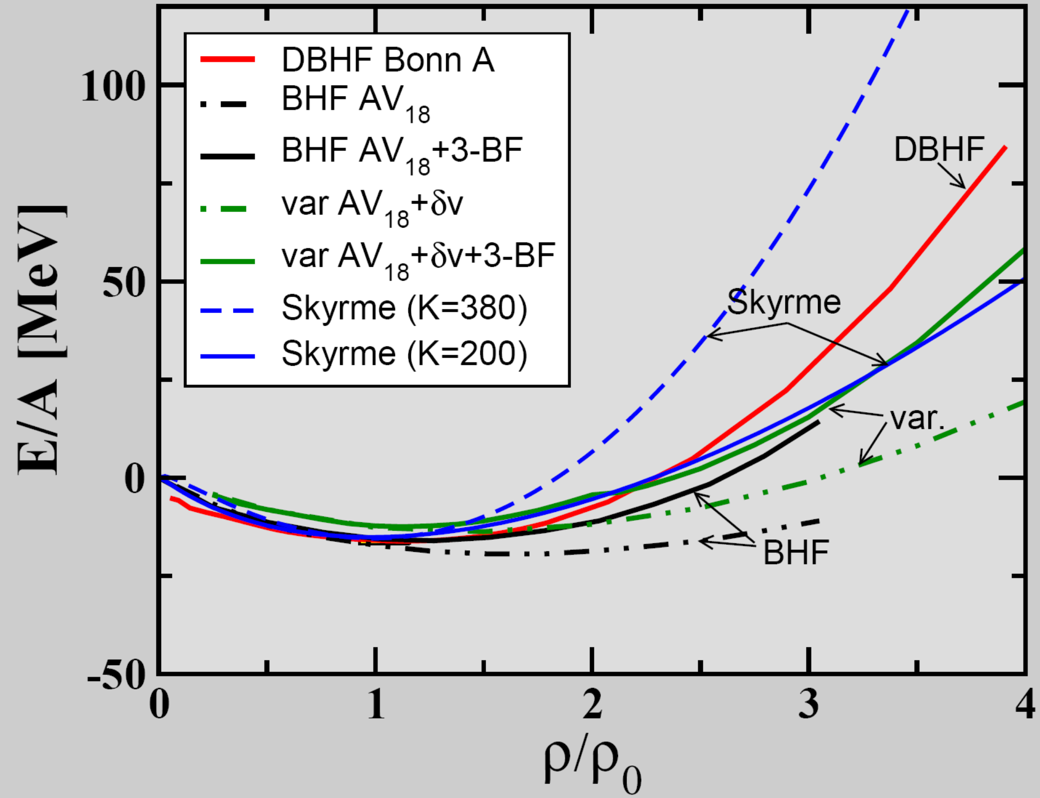
$U(\rho)=\alpha\rho+\beta\rho^{\gamma}$

$E/A(\rho_o) = -16$ MeV

- $\delta(E/A)(\rho_o)/\delta\rho = 0$
- Compressibility:

$\kappa = 9\rho^2 \; \delta^2 (E/A)/ \delta\rho^2$

C. Fuchs, Prog. Part. Nucl. Phys. 56 (2006) 1

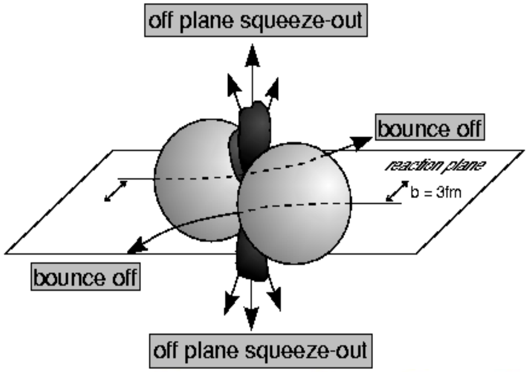


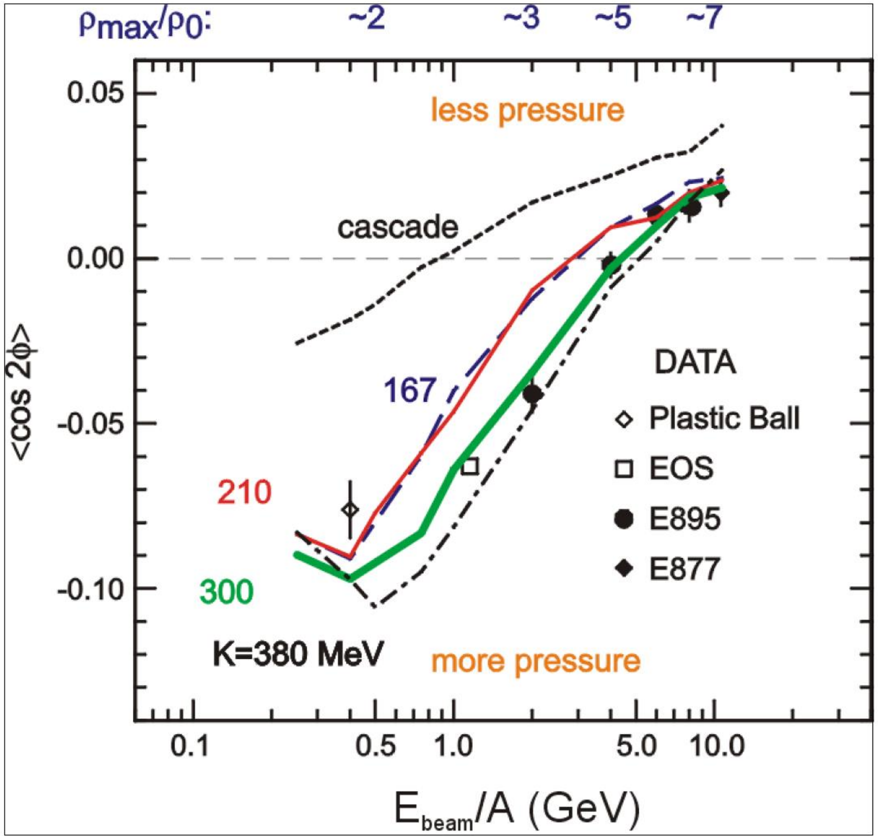
κ = 200 MeV: "soft" EOS

κ = 380 MeV: "stiff" EOS

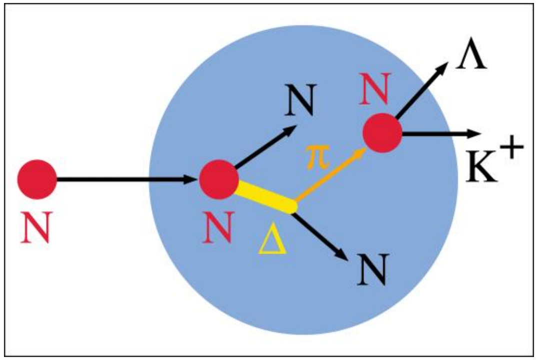
How to measure pressure or density?

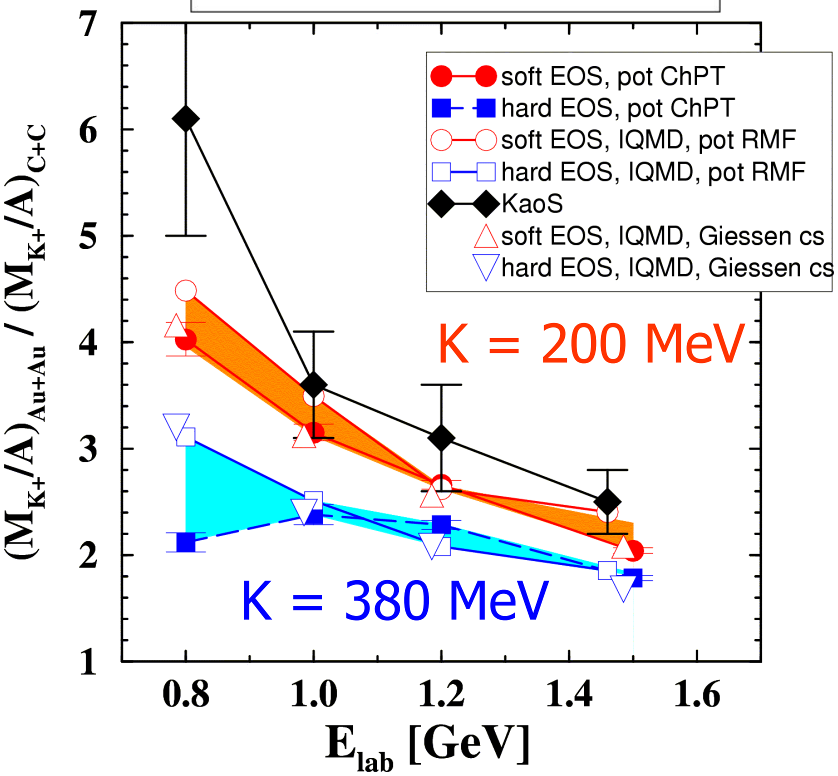
Pressure drives collective flow



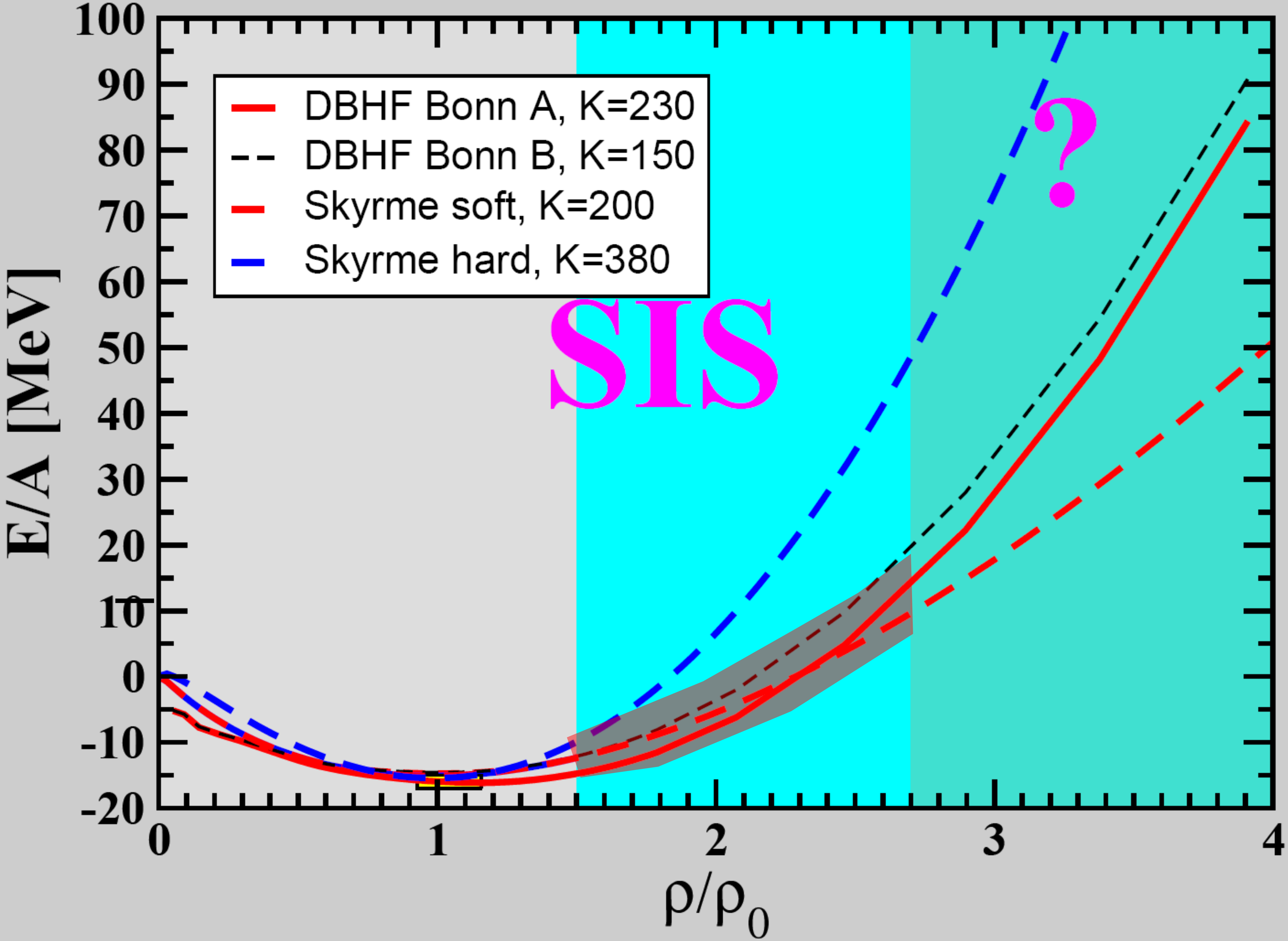


High densities favor multiple collisions and subthreshold particle production





nuclear matter EOS



Exploring the "nuclear" EOS at $3\rho_0 < \rho < 7\rho_0$ with (sub)threshold production of multistrange hyperons

Direct production:

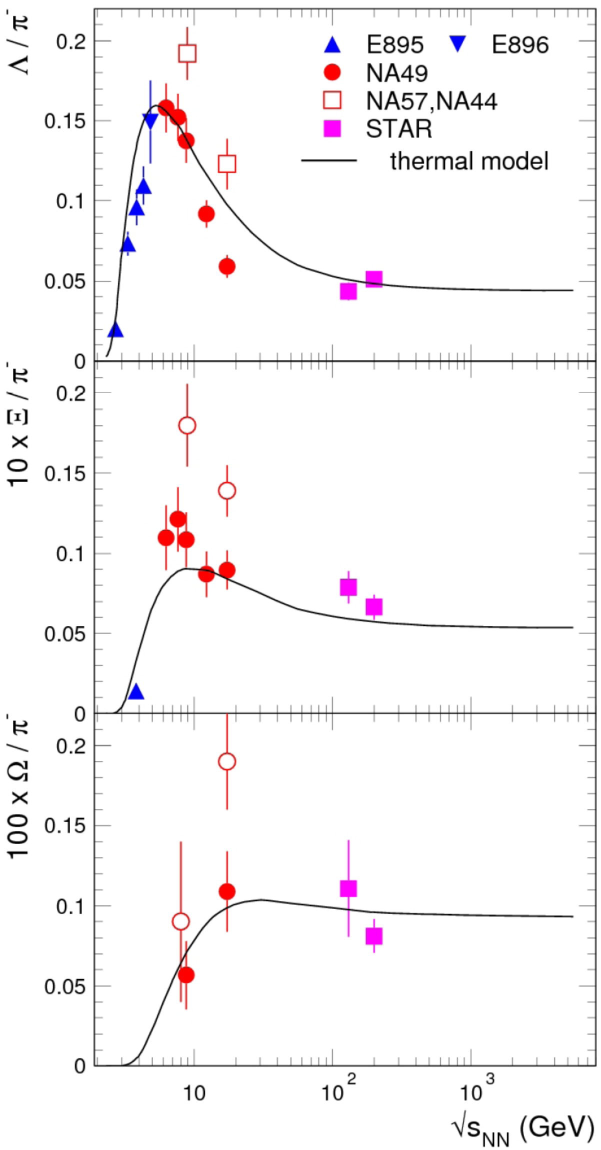
$NN \rightarrow \Lambda^0\overline{\Lambda}^0 NN$ (E_{thr} = 7.1 GeV)
$NN \rightarrow \Xi^+ \Xi^- NN$ (E_{thr} = 9.0 GeV)
$NN \rightarrow \Omega^+ \Omega^- NN$ (E_{thr} = 12.7 GeV)

Production via multiple collisions:

Hyperons (s quarks):
1. $NN \rightarrow K^+\Lambda^0 N$, $NN \rightarrow K^+K^- NN$,
2. $\Lambda^0\Lambda^0 \rightarrow \Xi^- p$, $\Lambda^0 K^- \rightarrow \Xi^- \pi^0$
3. $\Lambda^0 \Xi^- \rightarrow \Omega^- n$, $\Xi^- K^- \rightarrow \Omega^- \pi^-$

Antihyperons (anti-s quarks):
1. $\overline{\Lambda}^0 K^+ \rightarrow \Xi^+ \pi^0$,
2. $\Xi^+ K^+ \rightarrow \Omega^+ \pi^+$.

Measure excitation function for multi-strange hyperons in light and heavy collision systems



Measuring net baryon density fluctuations via multistrange hyperons

<u>Direct production:</u>

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<u>Production via multiple collisions:</u>

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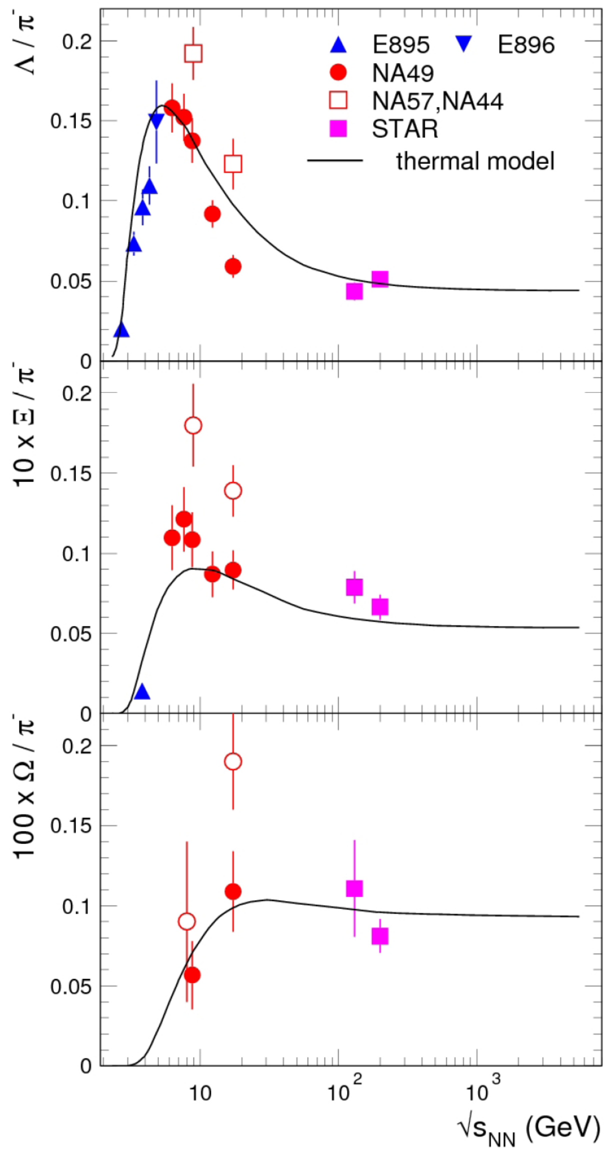
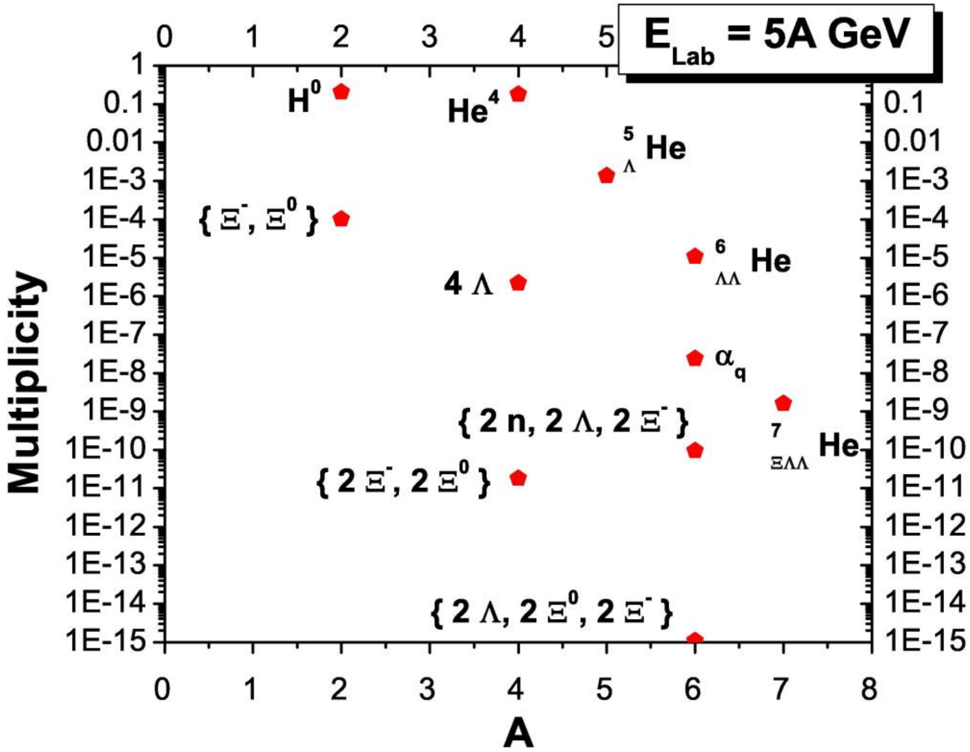


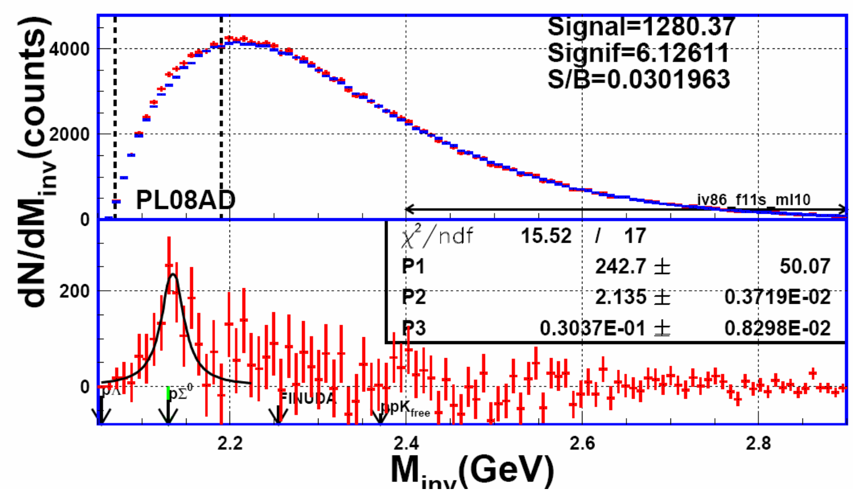
Search for structures in the excitation function of Ω/Λ

Search for metastable strange objects: experimental reconstruction of (multi)strange dibaryons

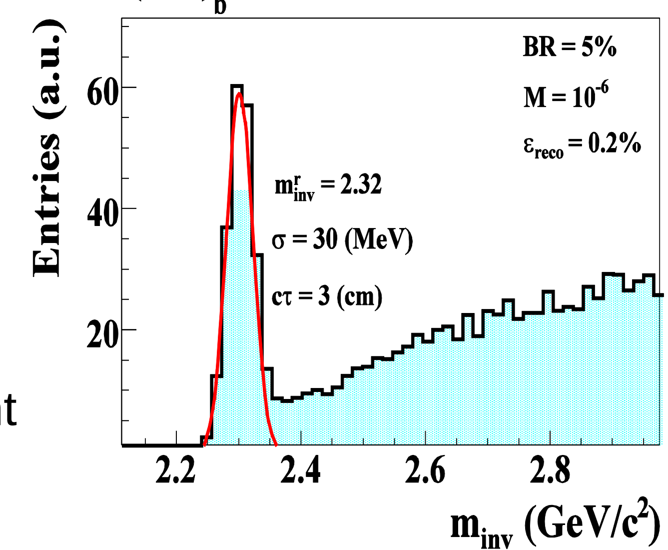
H. Stöcker et al., Nucl. Phys. A 827 (2009) 624c



FOPI: strange dibaryon
Λp–invariant mass in Ni+Ni at 1.91AGeV



$(\Xi^0\Lambda)_b \rightarrow \Lambda\Lambda$



Simulation for CBM:

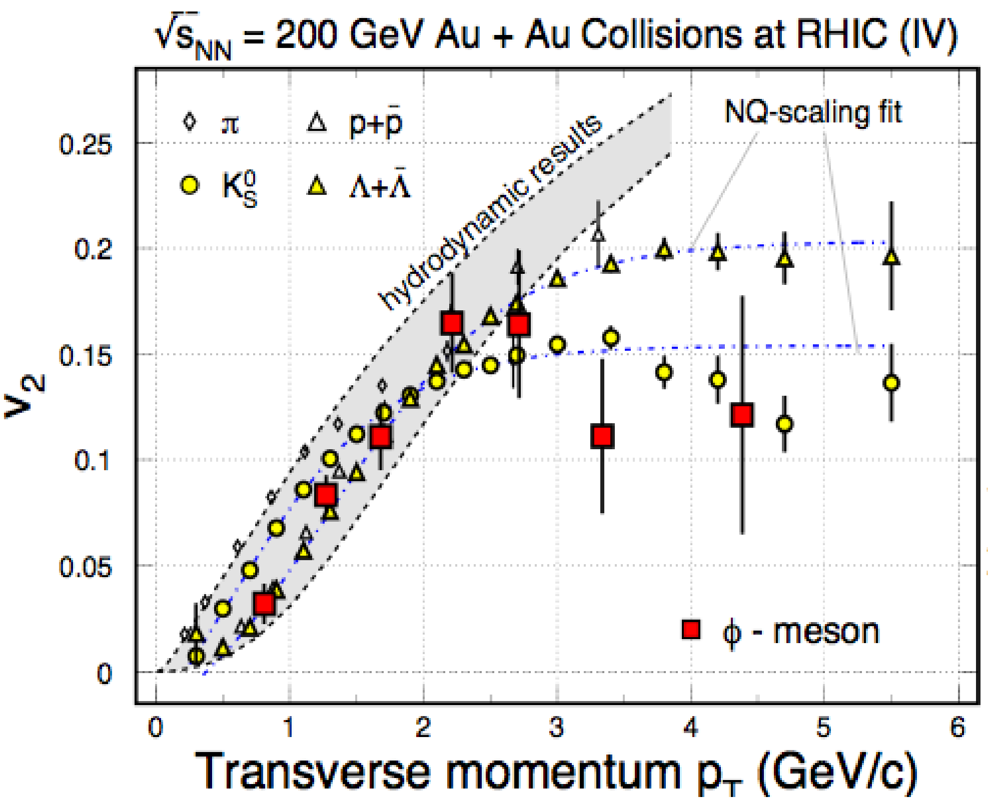
$(\Xi^0\Lambda)_b \rightarrow \Lambda\Lambda$ (cτ=3cm)

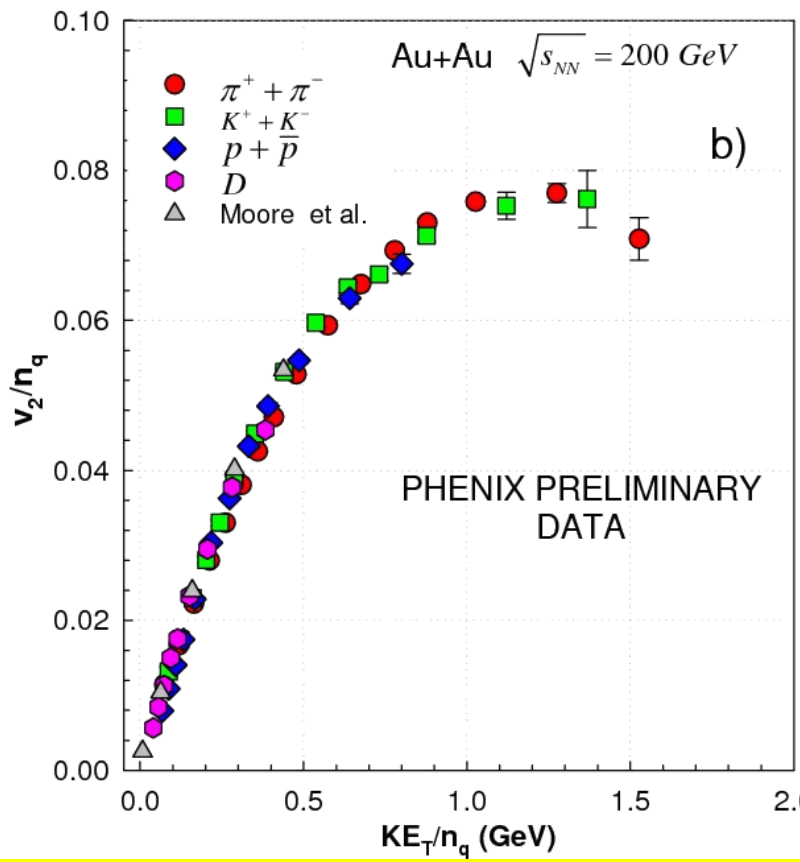
M= 10^{-6}, BR = 5%

Background:
Au+Au @ 25 AGeV
32 Λ per central event
11 Λ reconstructable

Signatures for partonic collectivity at RHIC

- Large elliptic flow
- elliptic flow scales with number of participant quarks
- suppression of high momentum hadrons (jet quenching)





Measure excitation function of elliptic flow for φ, Ω, D, and J/ψ.

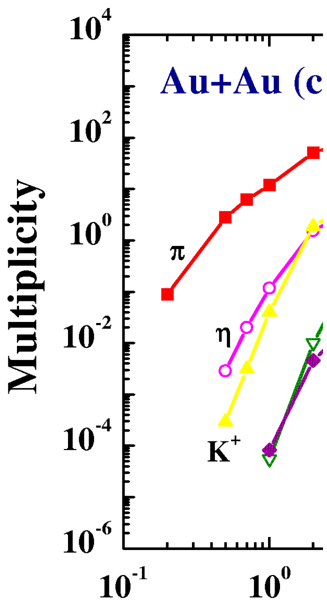
Searching for the deconfinement phase transition: Charm production in hadronic and partonic matter

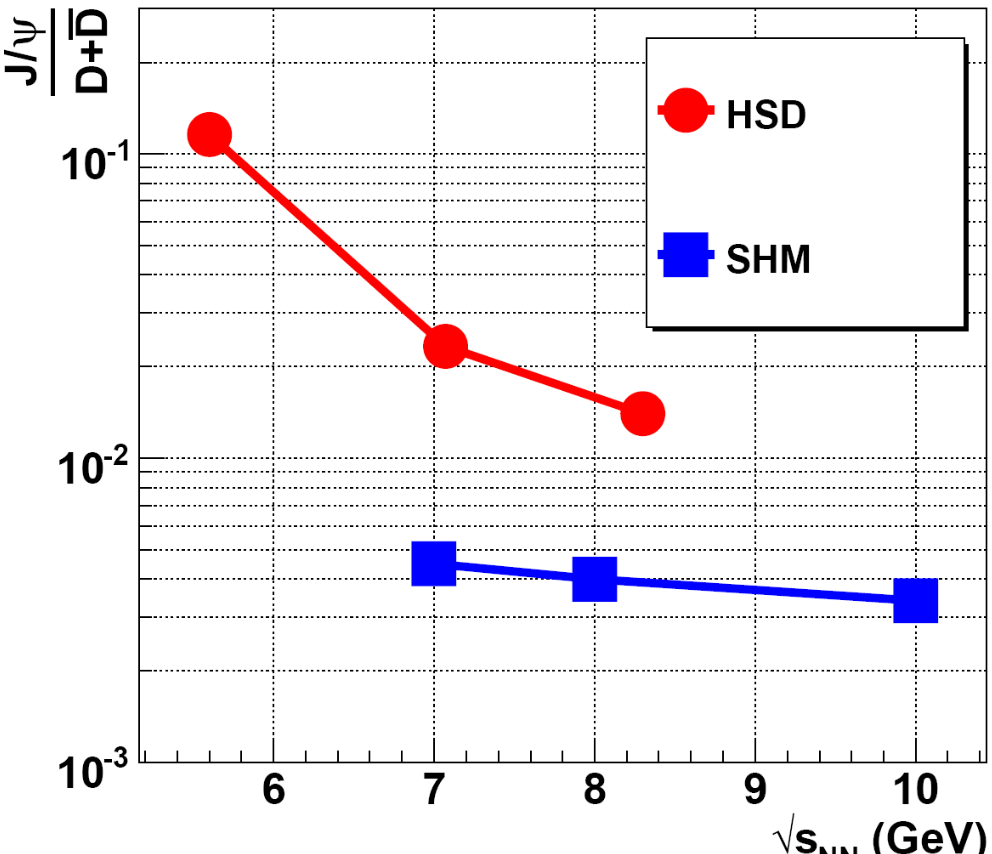
Hadronic model (HSD)

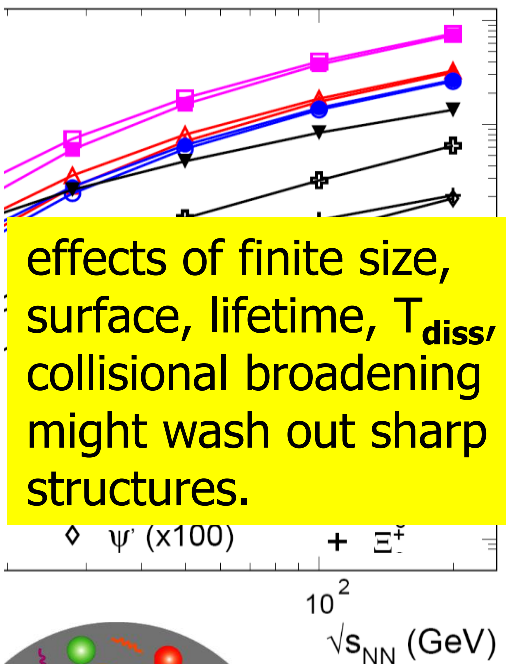
O. Linnyk, E.L. Bratkovskaya, W. Cassing, H. Stöcker, Nucl.Phys.A786:183-200,2007

Statistical hadronization model (SHM) (c-cbar production in partonic phase)

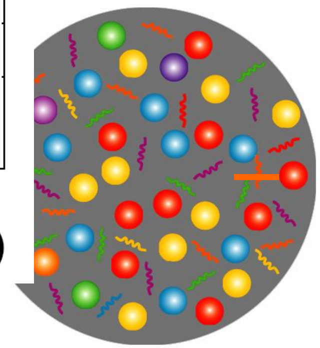
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, arXiv:0708.1488







effects of finite size, surface, lifetime, T_{diss}, collisional broadening might wash out sharp structures.

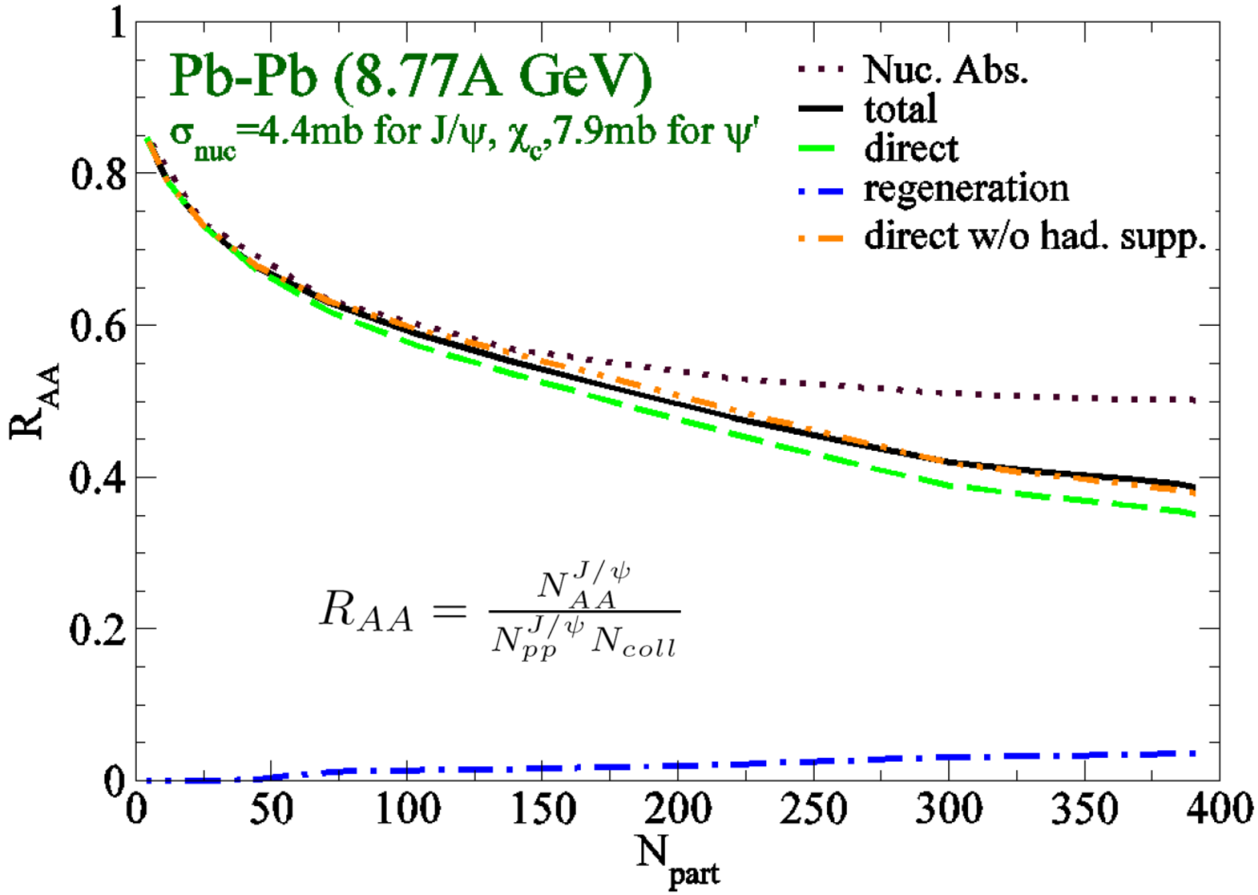


NN –

NN –

NN → J/ψ NN

Charmonium suppression at FAIR energies



Xingbo Zhao,
Ralf Rapp

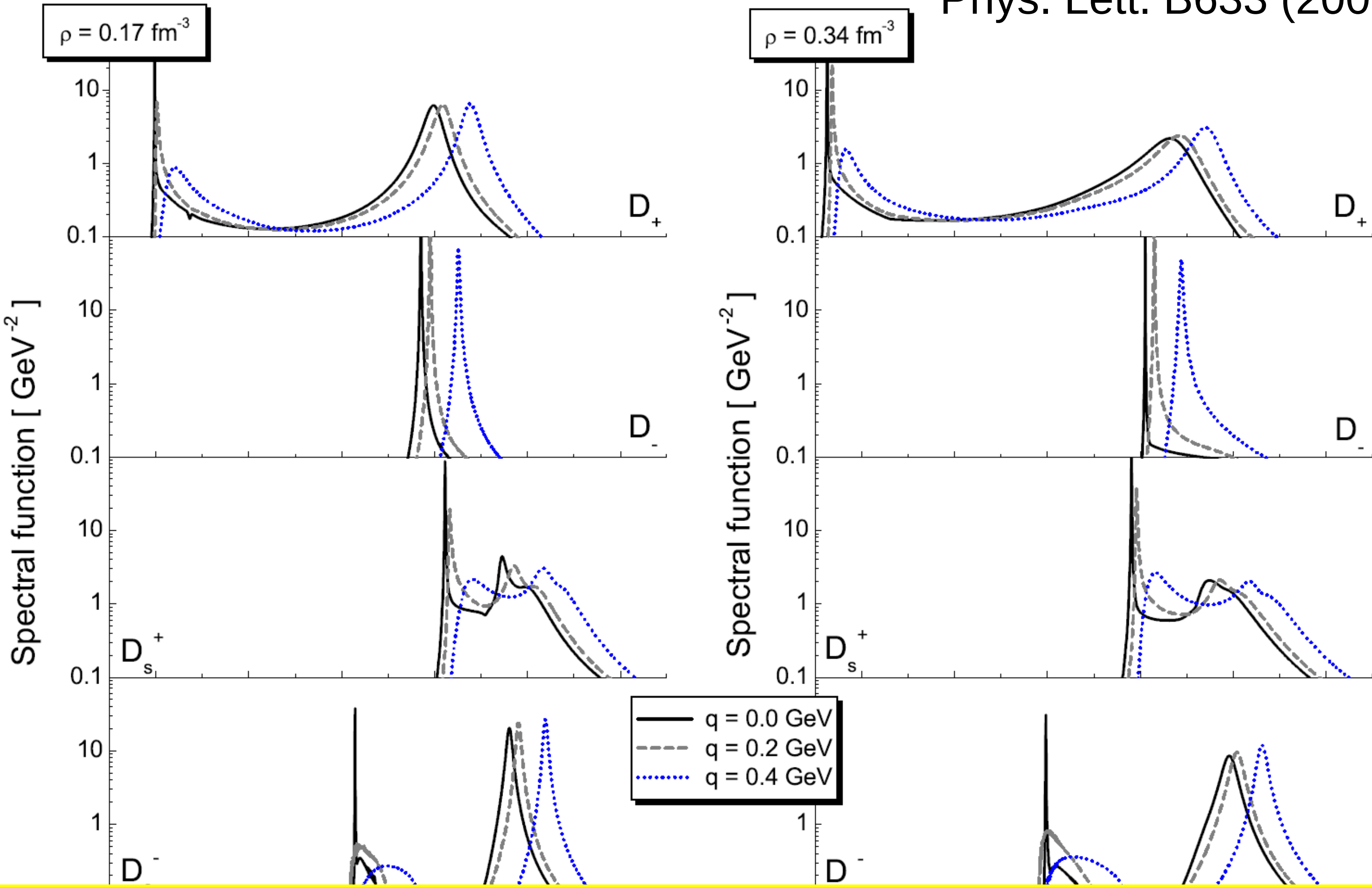
new NA60 data: 158 GeV p+A
E. Scomparin, QM2009

$\sigma_{abs}^{J/\psi}$ (158 GeV) = 7.6 ± 0.7 ± 0.6 mb
$\sigma_{abs}^{J/\psi}$ (400 GeV) = 4.3 ± 0.8 ± 0.6 mb

Measure excitation function of R_{AA},
i.e. $p+p \rightarrow J/\psi+X$, $p+A \rightarrow J/\psi+X$, $A+A \rightarrow J/\psi+X$

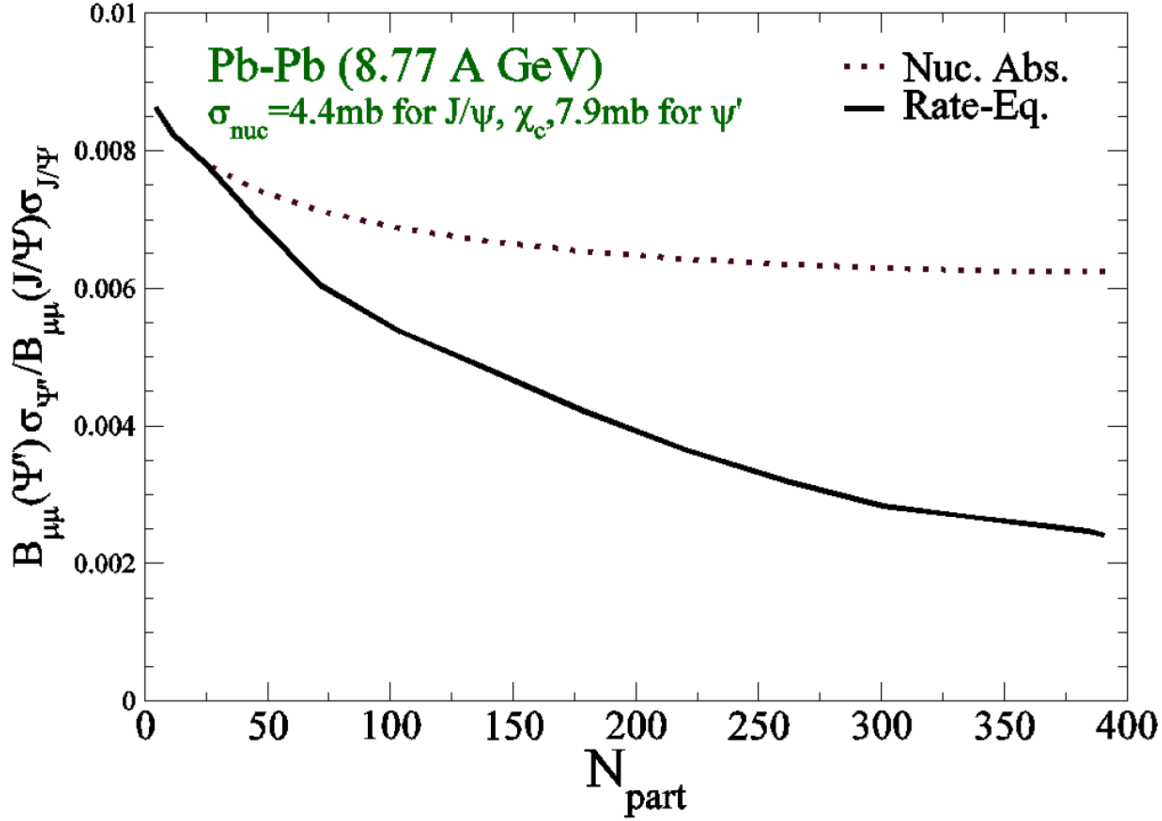
In-medium properties of D-mesons

M.F.M. Lutz and C.L. Korpa, Phys. Lett. B633 (2006) 43



Measure collective flow (v_1, v_2) of D^+ and D^- mesons

In-medium properties of D-mesons



Xingbo Zhao and Ralf Rapp

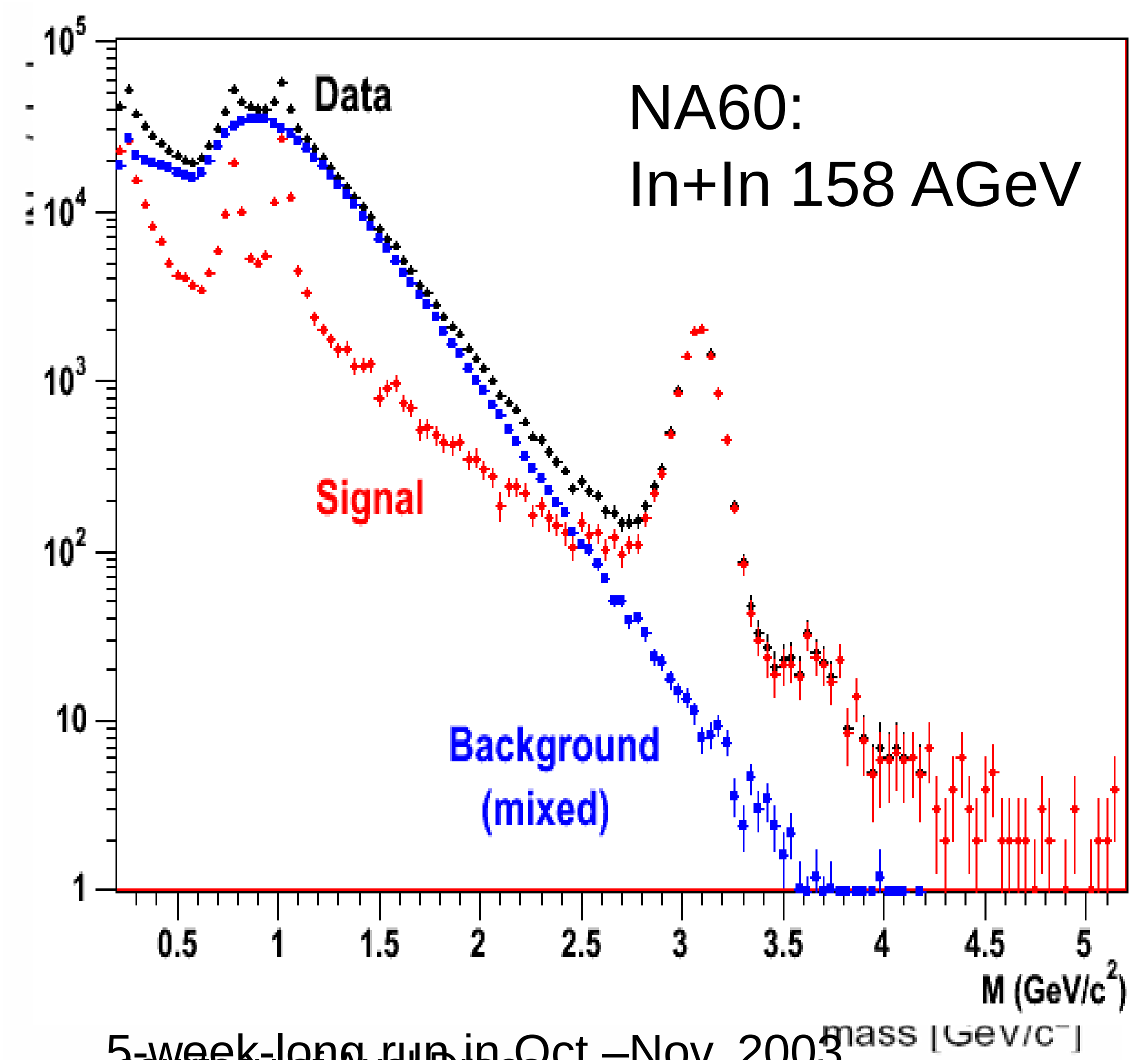
D meson mass modification affects the ψ'/(J/ψ) ratio

New absorption mechanism in nuclear medium
if D meson mass reduced: $\psi' \rightarrow D^+D^-$

Not possible in vacuum: ψ'(3686 MeV) < D^+D^-(3738 MeV)

Measure: $p + A \rightarrow J/\psi,\ \psi'$ $A + A \rightarrow J/\psi,\ \psi'$

Dilepton production in heavy-ion collisions

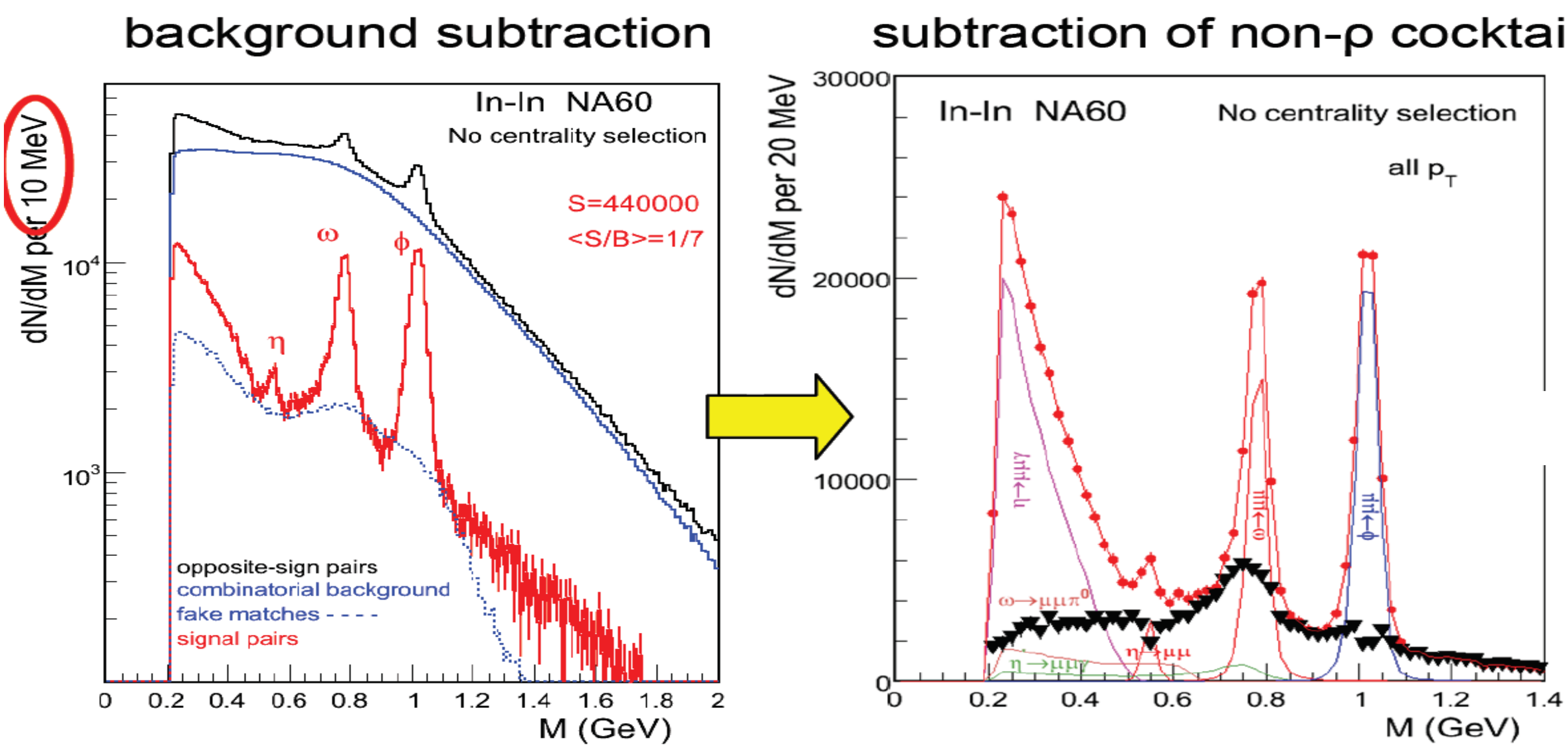


5-week-long run in Oct.–Nov. 2003

~ 4 × 10^{12} ions delivered in total

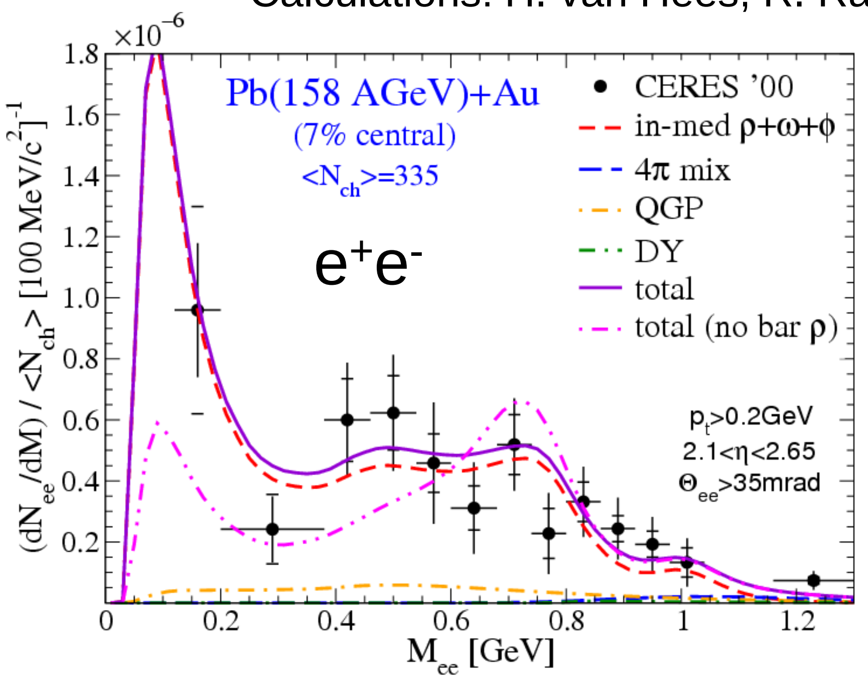
Digging out the signal

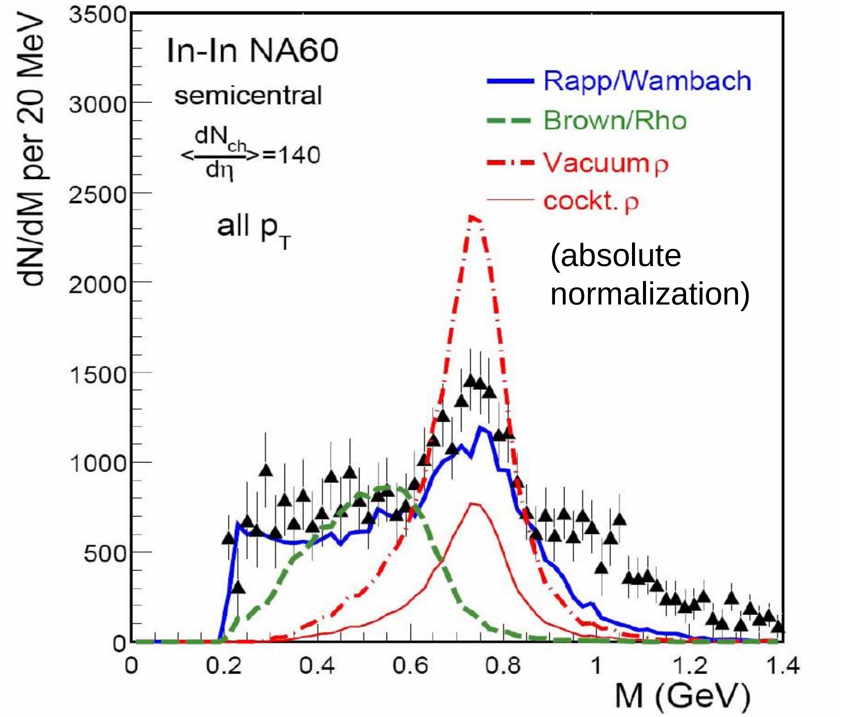
Substraction of combinatorial background and known sources of $\mu^+\mu^-$ pairs in the region of low invariant masses:



Searching for the modification of hadron properties via dilepton measurements

Calculations: H. van Hees, R. Rapp, arXiv:0711.3444v1 [hep-ph]





Electrons: access to M_{inv} < 200 MeV/c^2 Muons: better statistics (trigger)

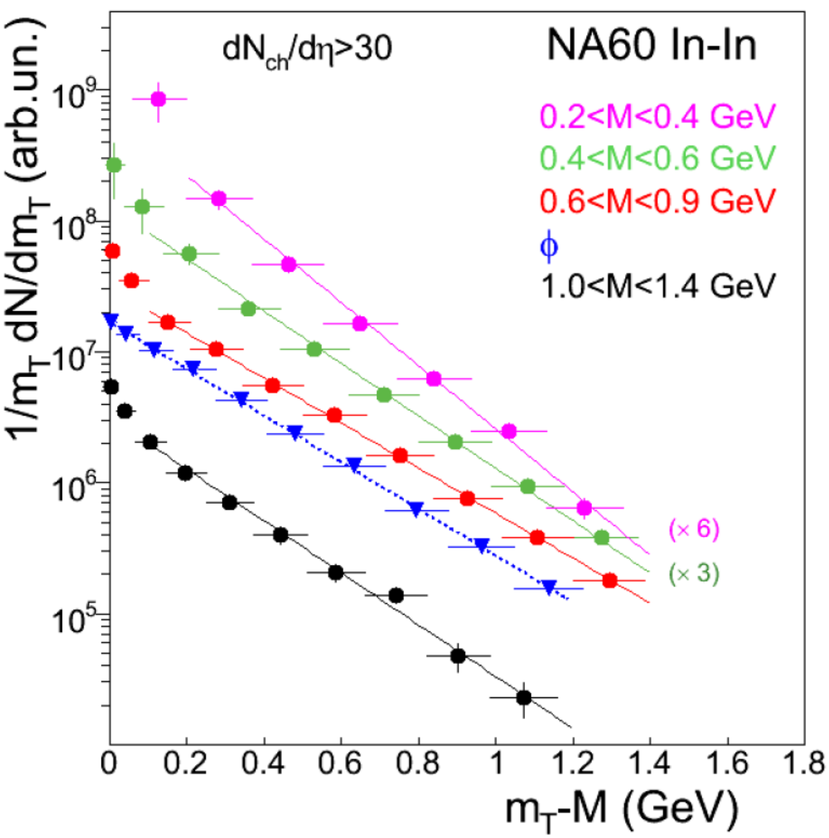
no ρ,ω,φ → e^+e^- ($\mu^+\mu^-$) data between 2 and 40 AGeV

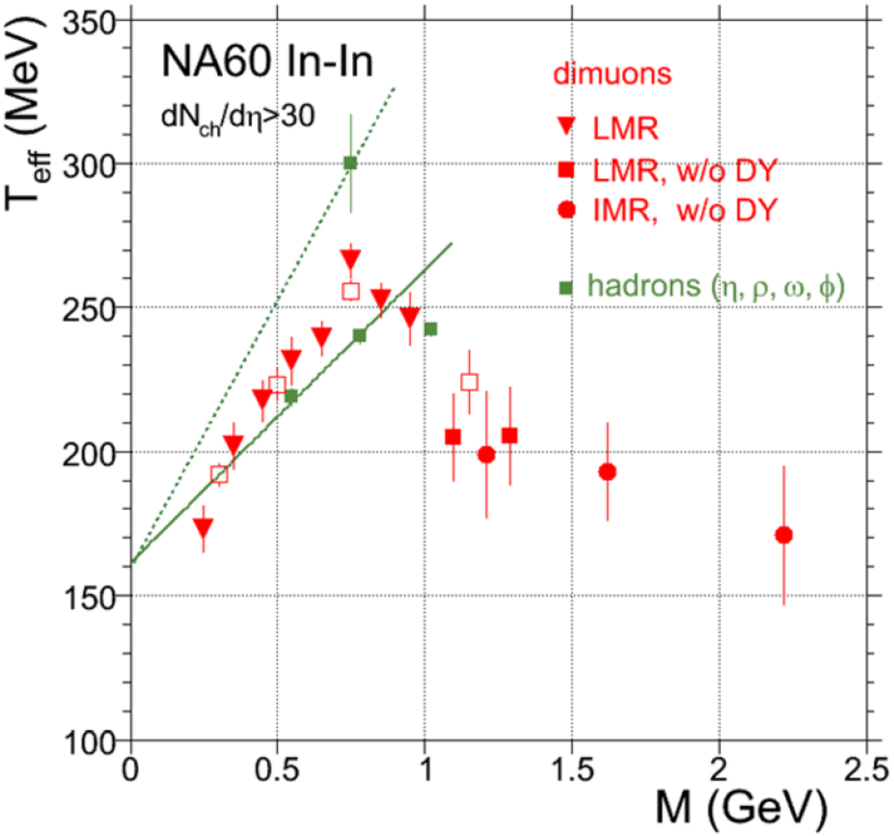
no J/ψ, ψ' → e^+e^- ($\mu^+\mu^-$) data below 160 AGeV

More information: the spectral slope as function of invariant mass

parameterisation $\frac{1}{m_T}\frac{dN}{dm_T} \sim \exp\left(-m_T/T_{eff}\right)$

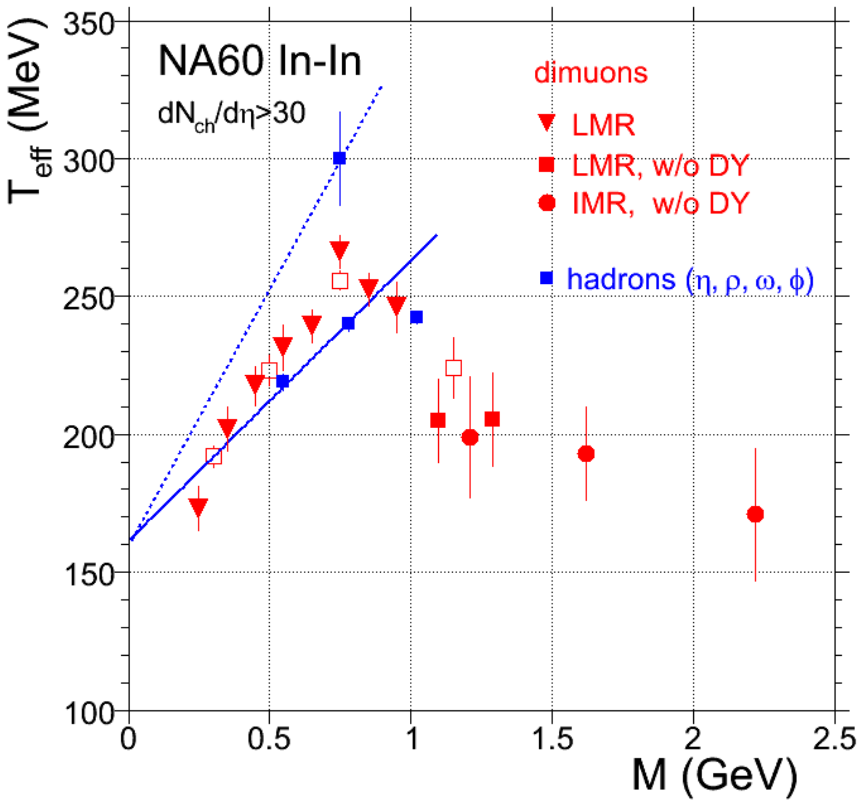
NA60: PRL 100,022302(2008)



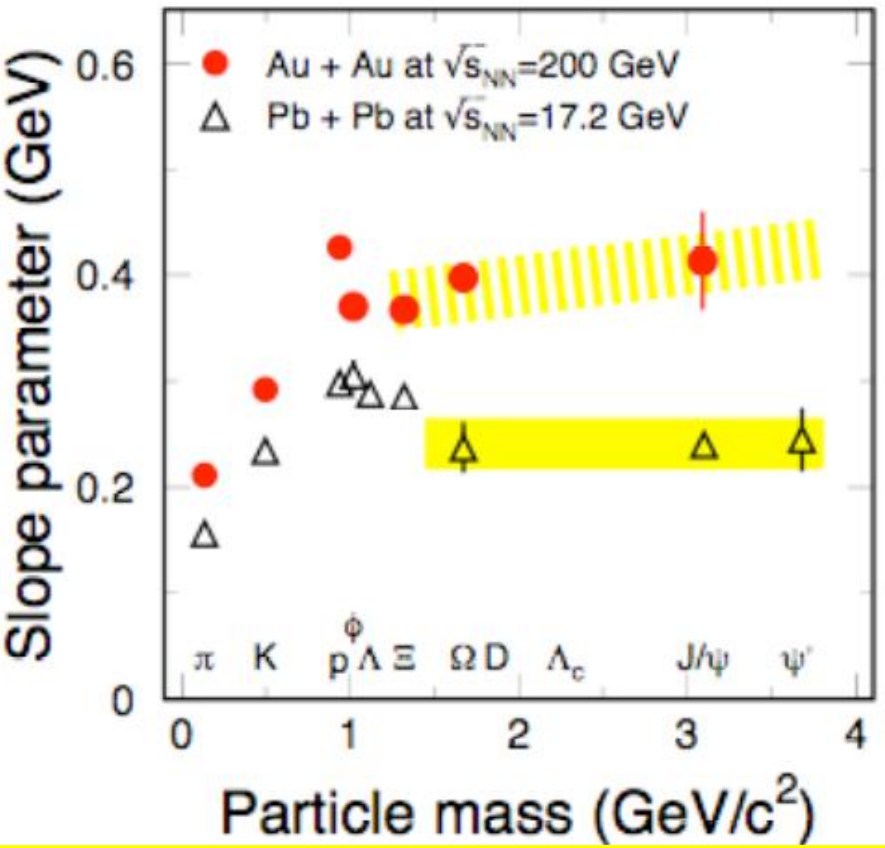


Radial flow as function of particle mass: probing the early phase of the fireball evolution

R. Arnaldi et al., (NA60), PRL 100 (2008) 022302



N. Xu, Int. J. Mod. Phys. E16 (2007) 715



Measure excitation function of dilepton and hadron yields and slope parameters (e^+e^-, $\mu^+\mu^-$, Ω, D, J/ψ, ψ')

CBM Physics Book

Content:

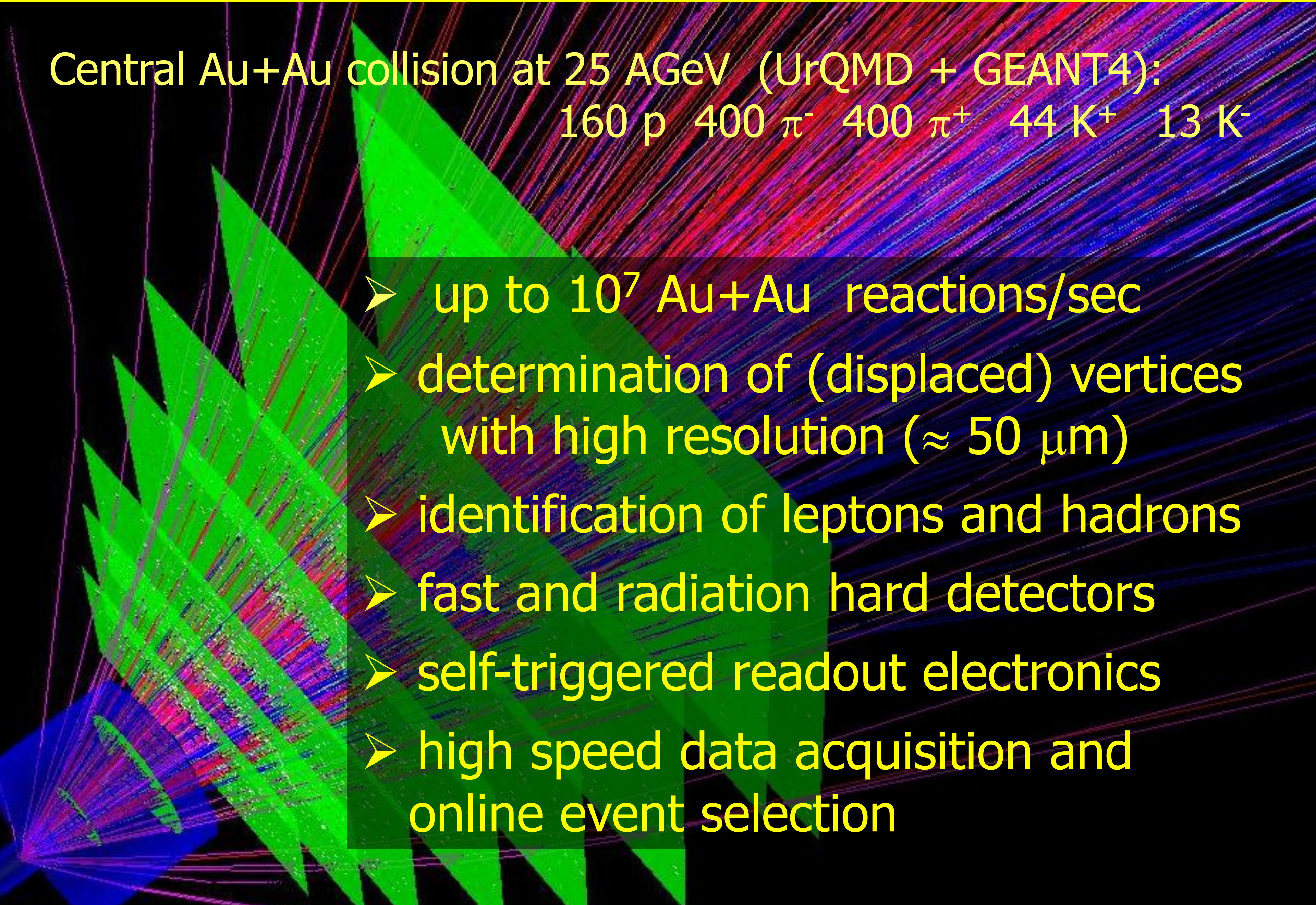
- Bulk Properties of Strongly Interacting Matter
- In-Medium Excitations
- Collision Dynamics
- Observables and Predictions
- The CBM Experiment
- Appendix: Overview on heavy-ion experiments

1000 pages, about 60 authors,

Submitted Sept. 2009 to Springer as "Lecture Notes in Physics"

Electronic version will be available on document servers once an official version is approved by Springer.

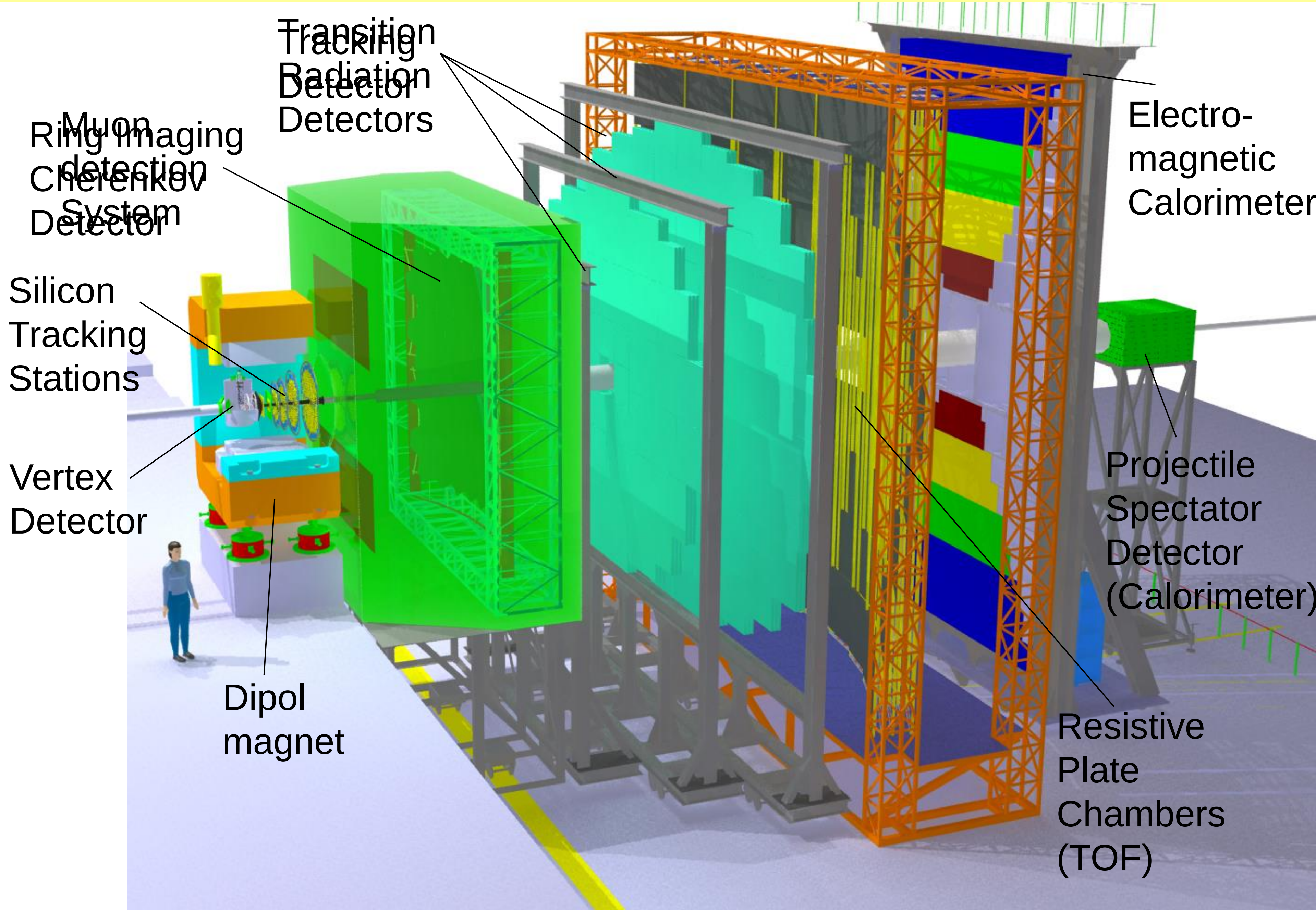
Experimental challenges



Central Au+Au collision at 25 AGeV (UrQMD + GEANT4):
160 p 400 π^- 400 π^+ 44 K^+ 13 K^-

- up to 10^7 Au+Au reactions/sec
- determination of (displaced) vertices with high resolution ($\approx$ 50 μm)
- identification of leptons and hadrons
- fast and radiation hard detectors
- self-triggered readout electronics
- high speed data acquisition and online event selection

The Compressed Baryonic Matter Experiment



The CBM Collaboration: 55 institutions, 450 members

Croatia:
RBI, Zagreb
Split Univ.

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei

Czech Republic:
CAS, Rez
Techn. Univ.Prague

France:
IPHC Strasbourg

Hungaria:
KFKI Budapest
Budapest Univ.

Norway:
Univ. Bergen

India:
Aligarh Muslim Univ.
Panjab Univ.
Rajasthan Univ.
Univ. of Jammu
Univ. of Kashmir
Univ. of Calcutta
B.H. Univ. Varanasi
VECC Kolkata
SAHA Kolkata
IOP Bhubaneswar
IIT Kharagpur
Gauhati Univ.

Korea:
Korea Univ. Seoul
Pusan Nat. Univ.

Germany:
Univ. Heidelberg, P.I.
Univ. Heidelberg, KIP
Univ. Heidelberg, ZITI
Univ. Frankfurt IKF
Univ. Frankfurt, FIAS
Univ. Münster
FZ Dresden
GSI Darmstadt
Univ. Wuppertal

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

Portugal:
LIP Coimbra

Romania:
NIPNE Bucharest
Univ. Bucharest

Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
KRI, St. Petersburg
Kurchatov Inst., Moscow
LHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
Obninsk State Univ.
PNPI Gatchina
SINP MSU, Moscow
St. Petersburg P. Univ.

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

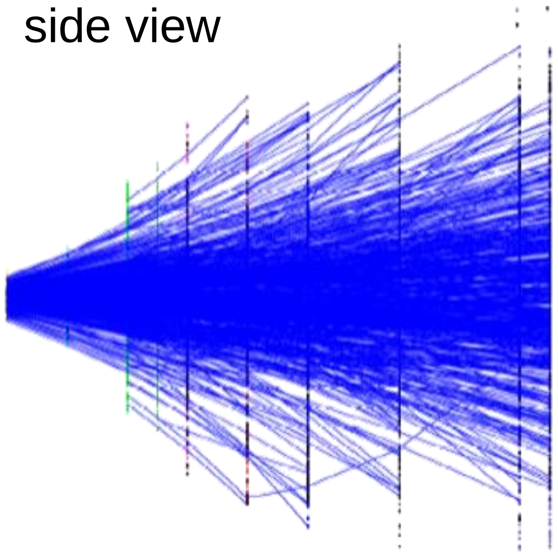
Conceptual design and feasibility studies

- Framework FAIRroot: Root + Virtual Monte Carlo
  Transport codes GEANT 3 & 4, FLUKA
  Event generators UrQMD, HSD, PLUTO
- Fast ("SIMDized") track reconstruction algorithms for online event selection using many-core architectures
- Realistic detector layouts and response functions

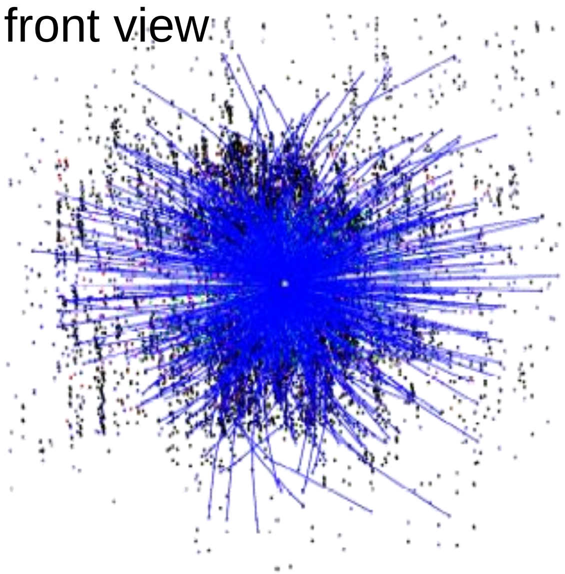
Example: Silicon Tracking System

Central Au+Au collision 25 AGeV (UrQMD): 770 reconstructed tracks

side view



front view



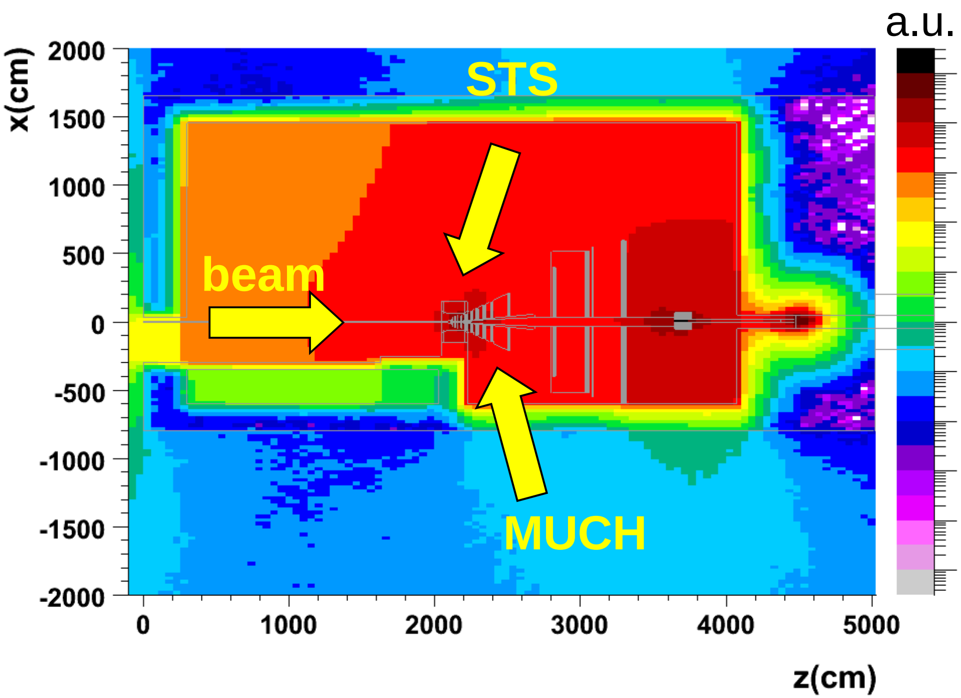
Fast track reconstruction algorithms running graphic processing units:

- fitting: 22 million tracks/s
- track reconstruction efficiency > 96 %
- momentum resolution $\Delta p/p < 1.5$ %

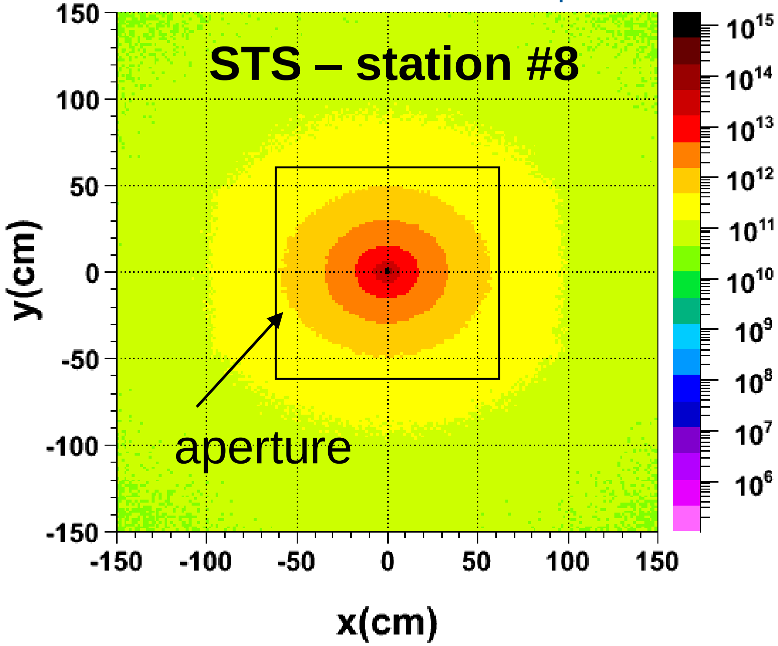
CBM — Radiation environment

Neutron fluence in CBM cave

UrQMD + FLUKA simulation,
25 GeV Au beam on Au target



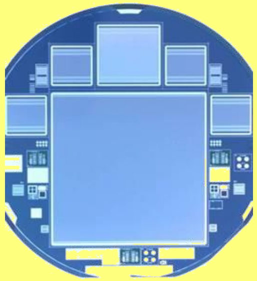
Neutron fluence through Silicon Tracking System



Typical operation scenario: 6 years ⇒ up to 10^{15} n_{eq}/cm^2

⇒ radiation hardness regime of LHC/SuperLHC experiments

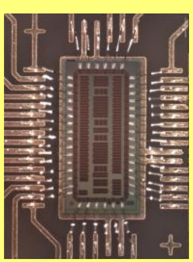
CBM hardware developments

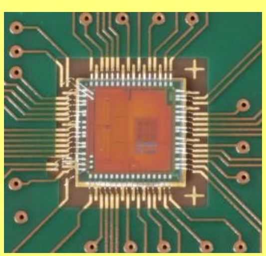


radiation hard silicon microstrip detectors:

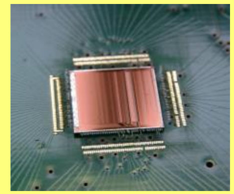
- double-sided
- 300 µm thick,
- 60 µm strip pitch
- stereo angle 15^{o}
- radiation-hard up to 10^{15} $n_{eq}cm^{-2}$

Readout ASICs for RPC Time-of-flight system: 25 ps time resolution

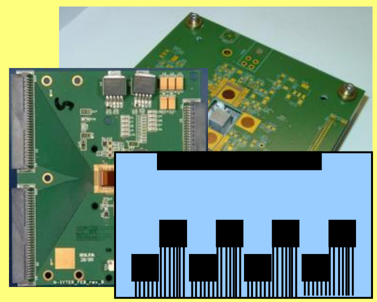




self-triggering read-out chip 128 ch, 32 MHz



high-density front end boards



Data Acquisition System

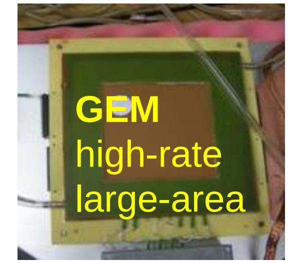
throughput 500 MB/s/node

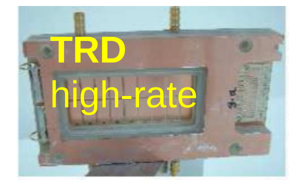
GSI DABC

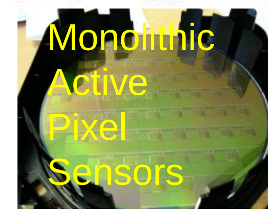
fast on-line event selection + track reconstruction

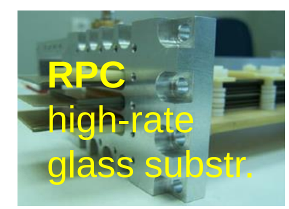
exploitation of many-core architectures (CELL, LRB, GPUs)

GPU farm

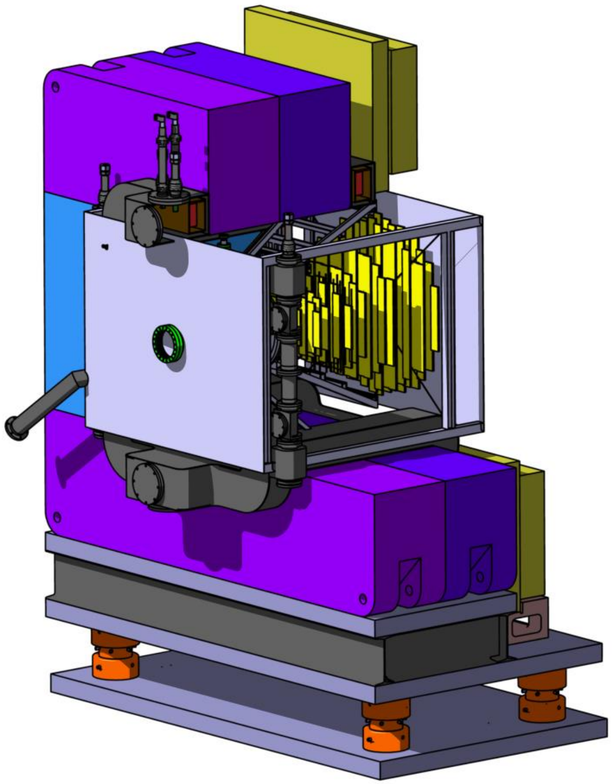




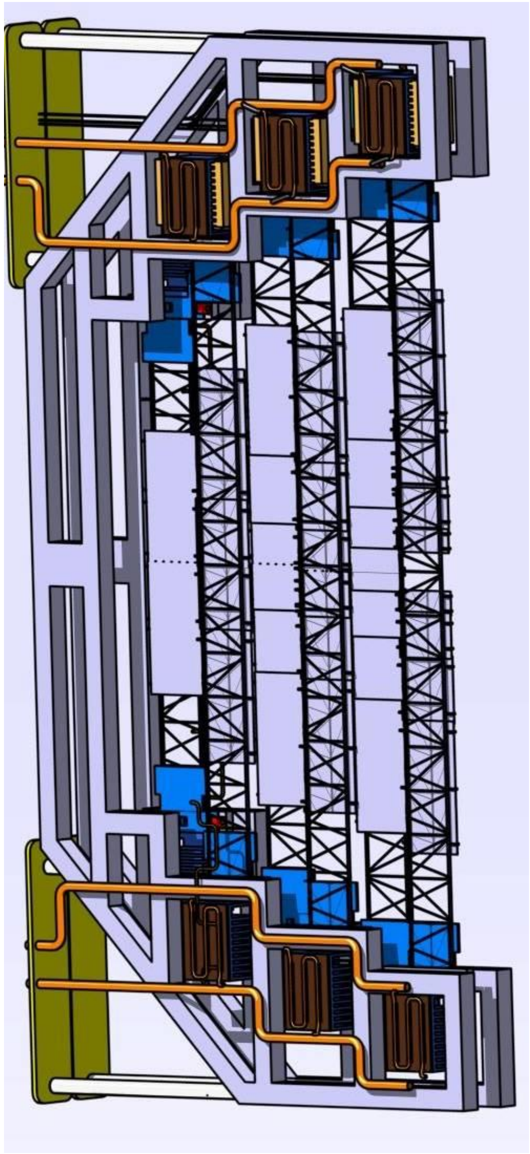




Development of the Silicon Tracking System (STS)



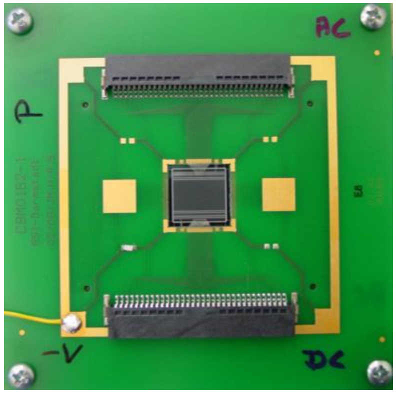
STS in thermal enclosure

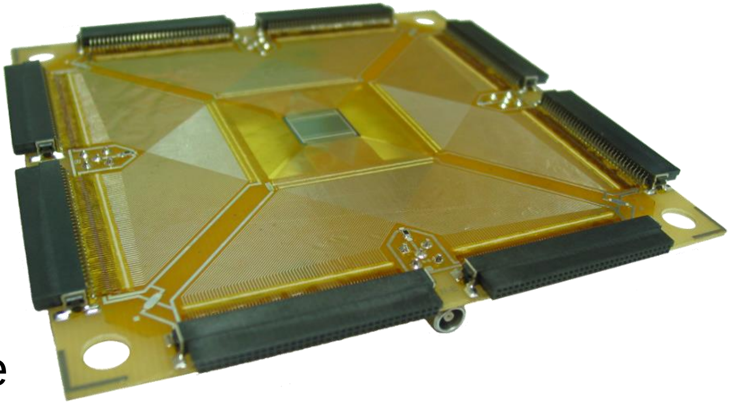


Detector planes:
ultra-light weight ladder structure

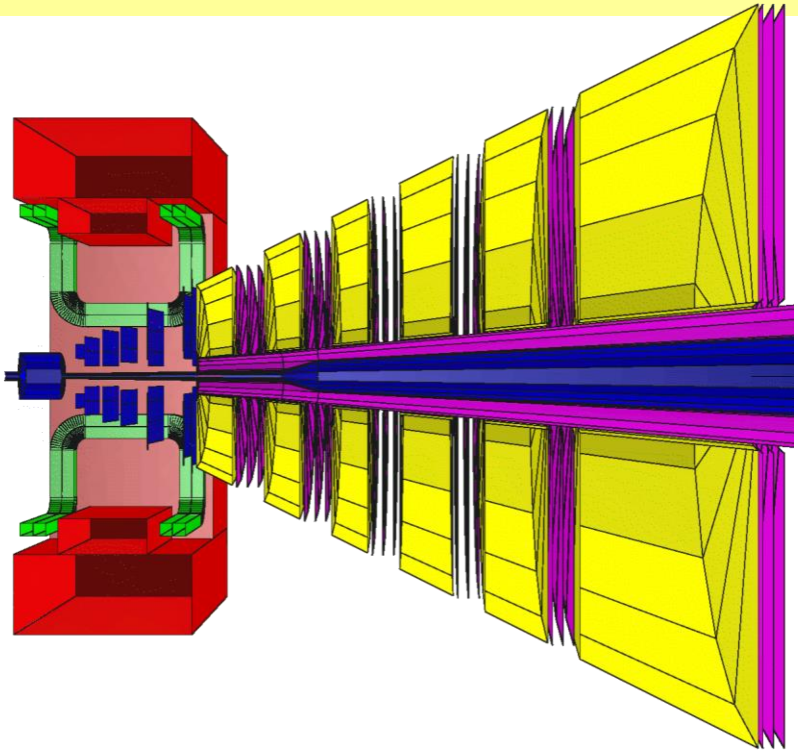
<u>Sensor development:</u>
double-sided micro-strips,
stereo angle 15^{o}, pitch 60 µm
300 µm thick, bonded to
ultra-thin micro-cables

Prototypes for beam tests:





The CBM Muon Detection system

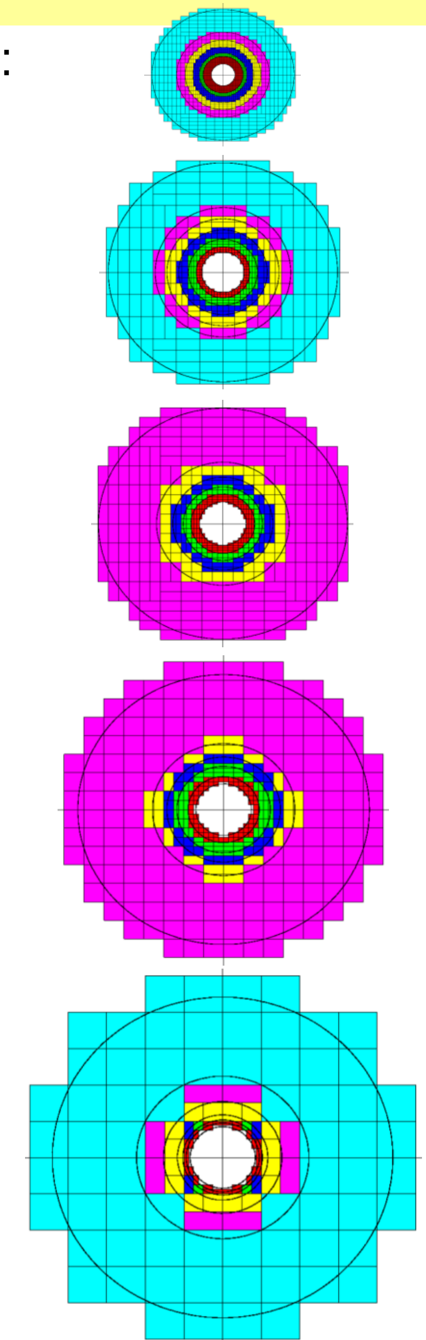


6 segmented absorber layers:
225 cm Fe: 13.5 λ_I
18 tracking detector layers

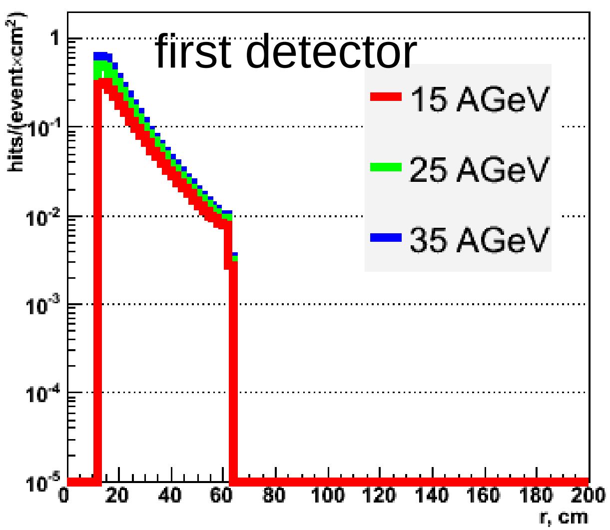
Detector segmentation:
5% occupancy

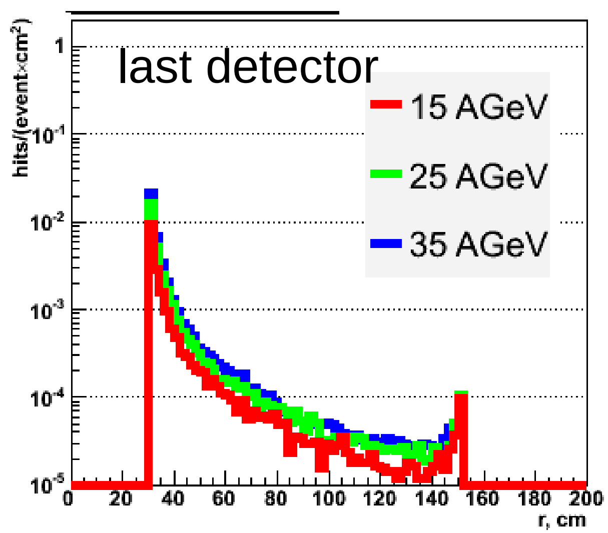
min pad 1.4 × 2.8 mm²
space resolution:
x – 400 μm, y – 800 μm

max pad 44.8 × 44.8 mm²
space resolution:
x – 12.8 mm, y – 12.8 mm

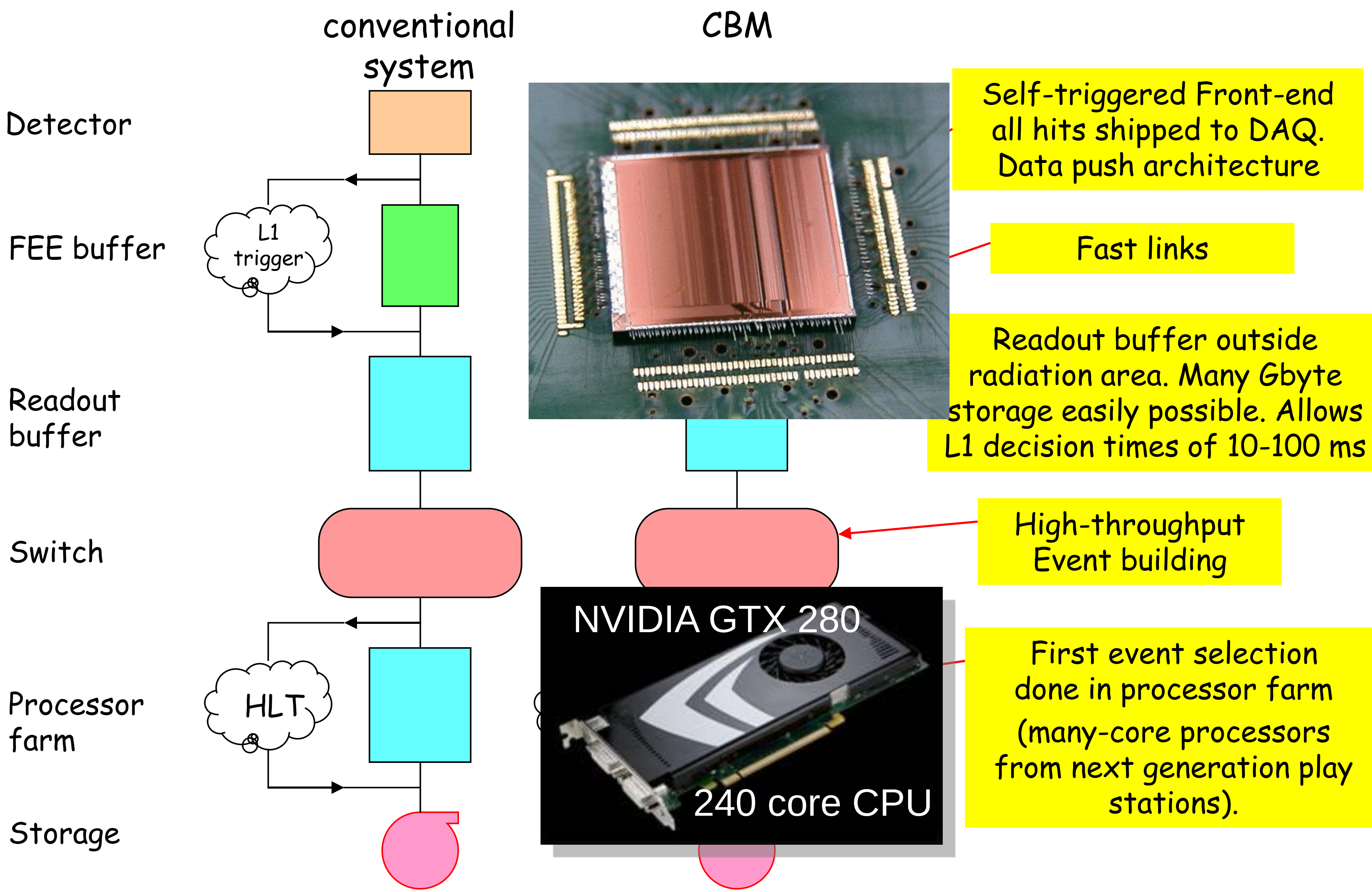


Simulations Au+Au central collisions at 25 AGeV :





CBM DAQ architecture: free-streaming data flow



Successful test of CBM prototype detector systems with free-streaming read-out electronics using proton beams at GSI, September 28-30, 2008


GSI and AGH Krakow

2 Double-sided silicon microstrip detectors


VECC Kolkata

Double and triple GEM detectors


KIP Heidelberg

Radiation tolerance studies for readout electronics

Full readout and analysis chain:

Detector signals


Front-end board with self-triggering *n-XYTER* chip


Readout controller

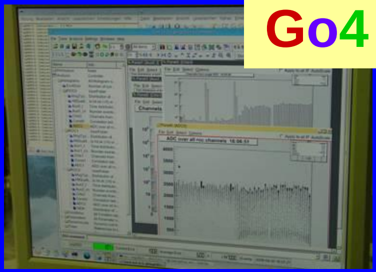
GSI DABC

Data Acquisition System

online

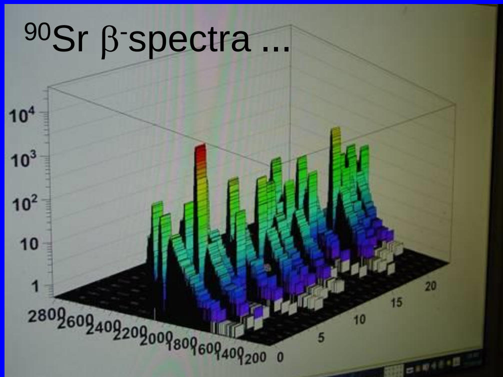
Analysis

offline

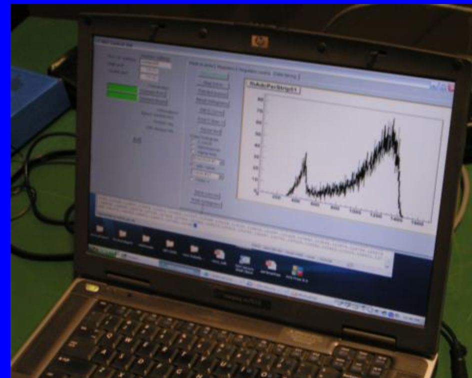

Go4

FairRoot

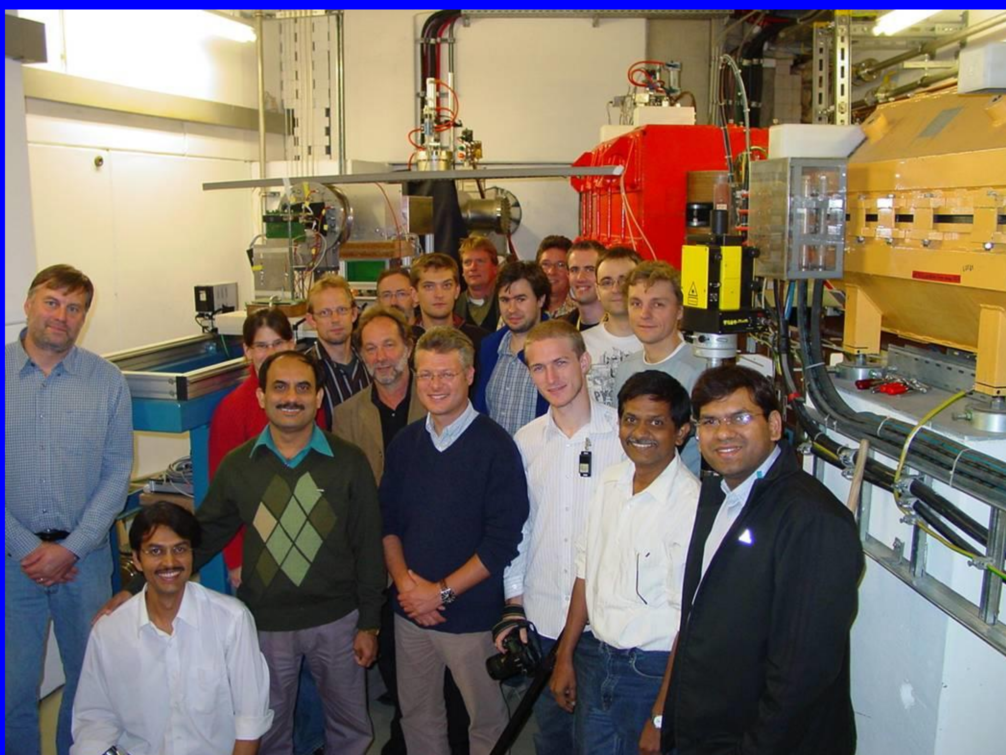
Detector commissioning:



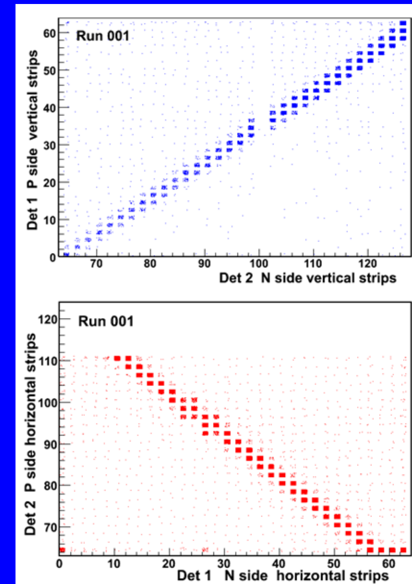
... in several channels of a silicon microstrip detector



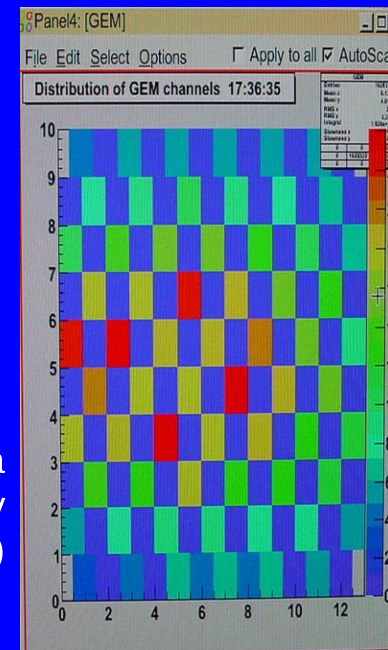
... and in a GEM detector



Operation on the beam line:



Correlation of fired channels in two silicon microstrip detectors



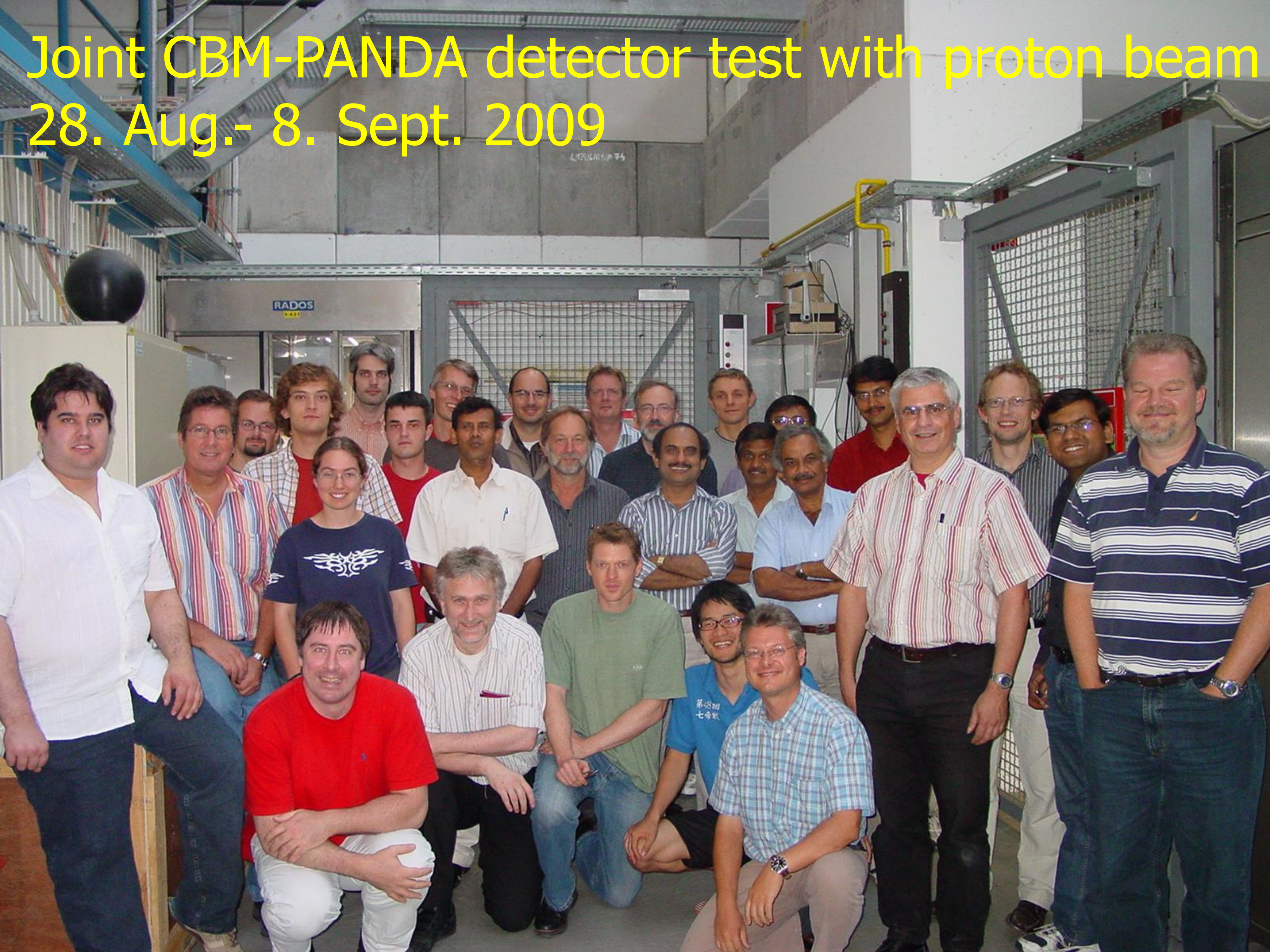
Beam spot seen on a GEM detector (every 2nd channel read out)

Participants:

GSI, Darmstadt, Germany
JINR, Dubna, Russia
KIP, Heidelberg, Germany
VECC, Kolkata, India
AGH, Krakow, Poland

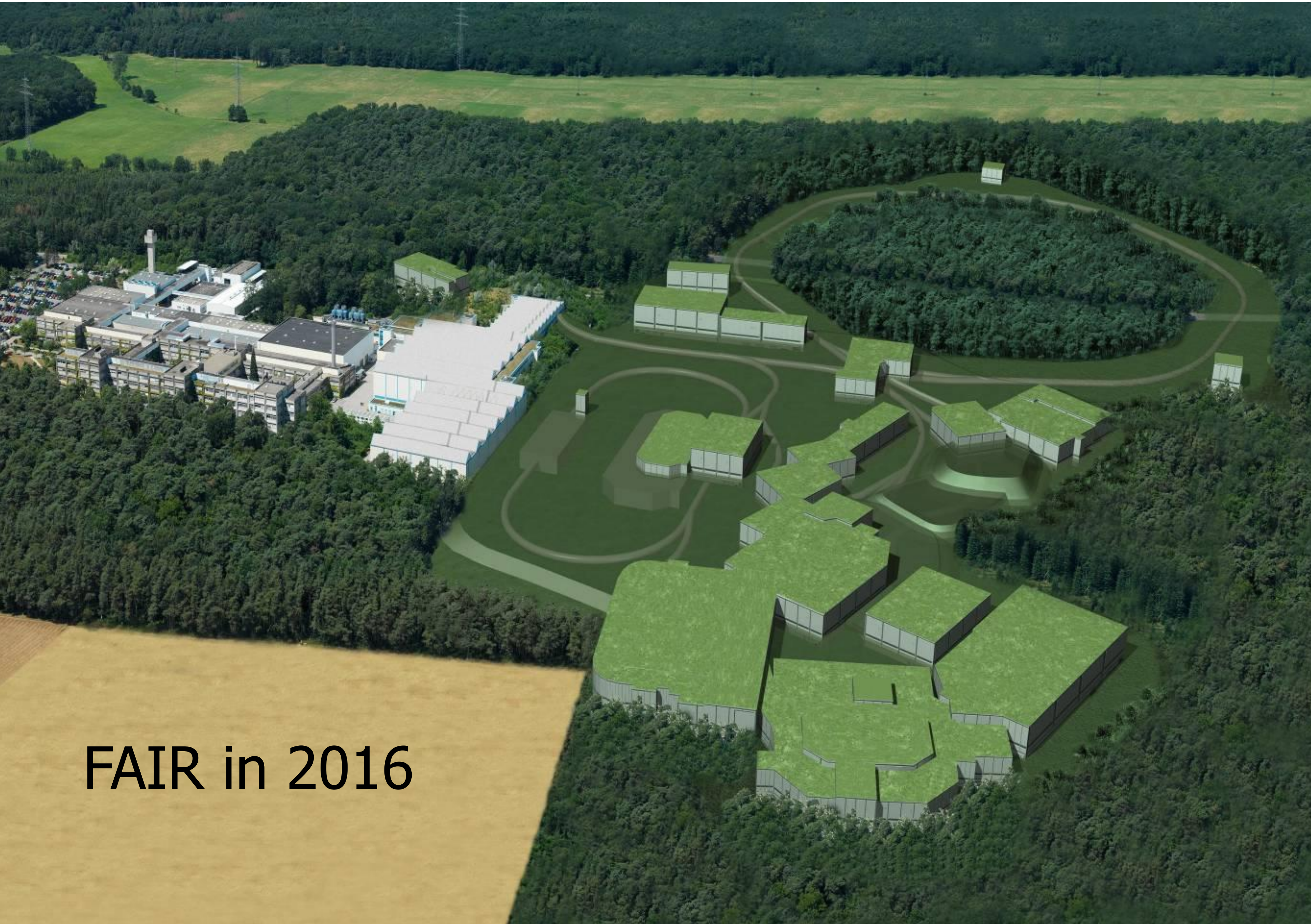
www-cbm.gsi.de

Joint CBM-PANDA detector test with proton beam
28. Aug.- 8. Sept. 2009



CBM-RPC tests with proton beam

Beijing-Bucharest-GSI-Hefei-Heidelberg

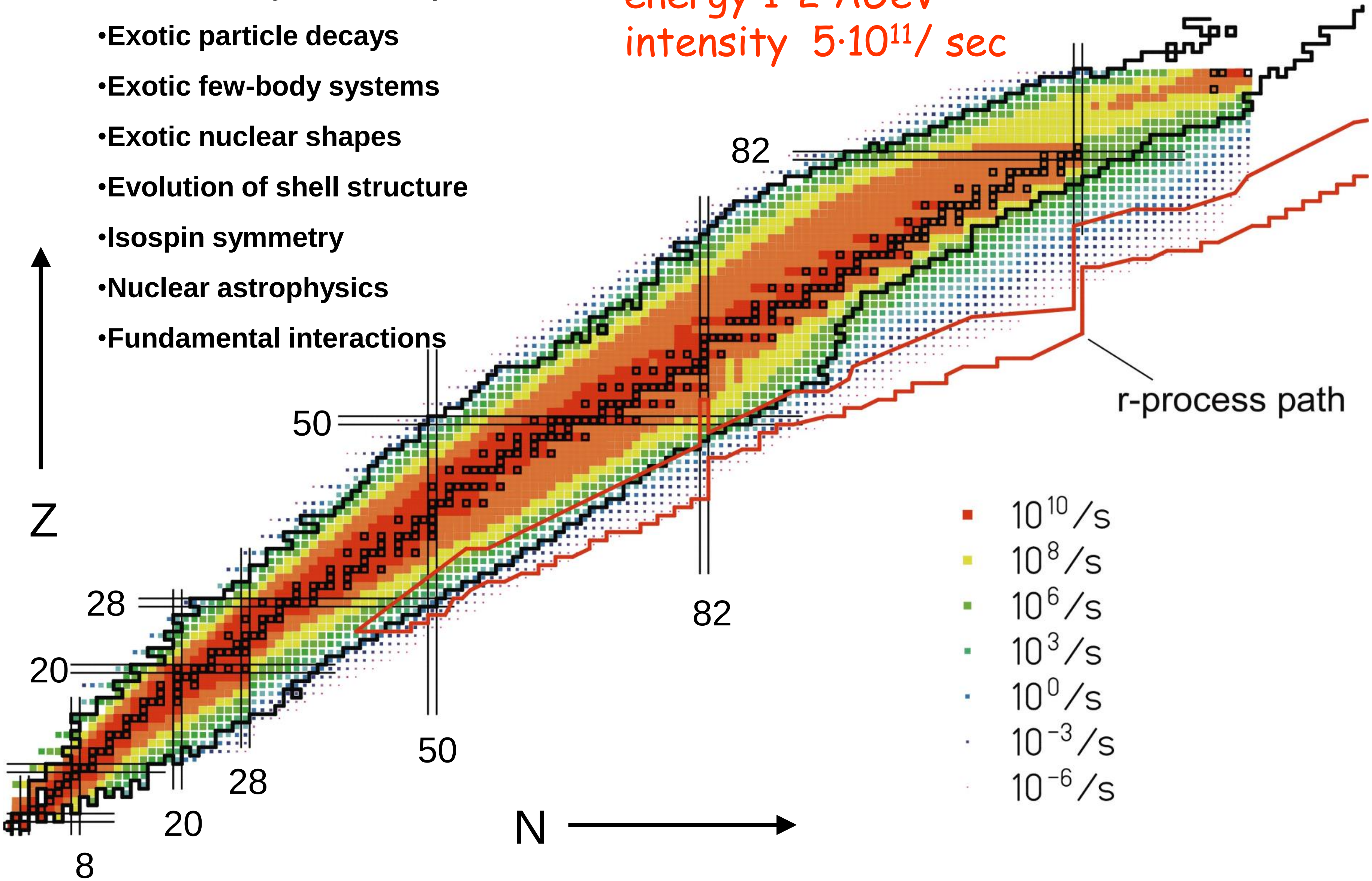

FAIR in 2016

NuSTAR: Nuclear Structure, Astrophysics, Reactions

Physics topics:

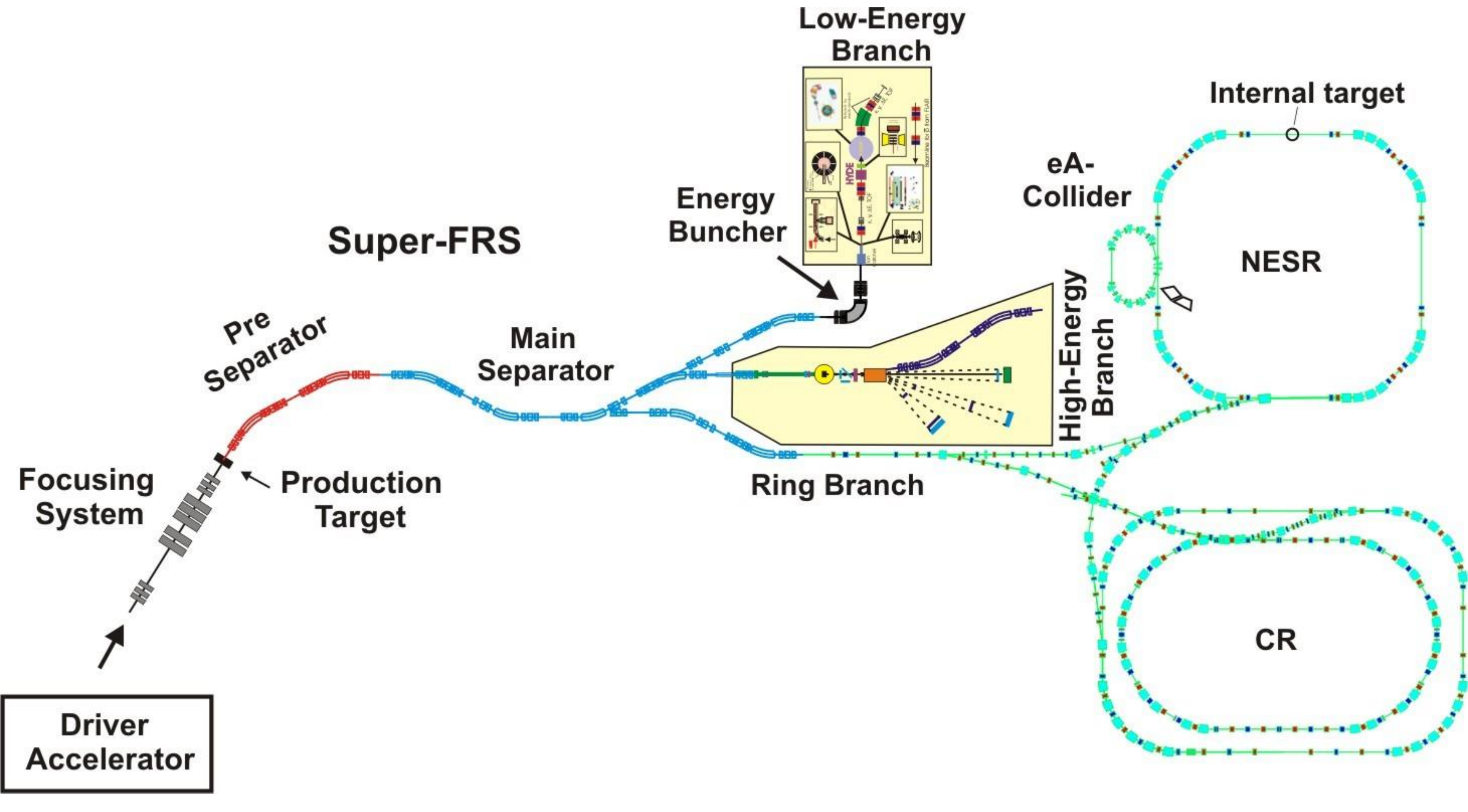
- Structure beyond the driplines
- Exotic particle decays
- Exotic few-body systems
- Exotic nuclear shapes
- Evolution of shell structure
- Isospin symmetry
- Nuclear astrophysics
- Fundamental interactions

Uranium beam at SIS100:
energy 1-2 AGeV
intensity $5 \cdot 10^{11}$/ sec



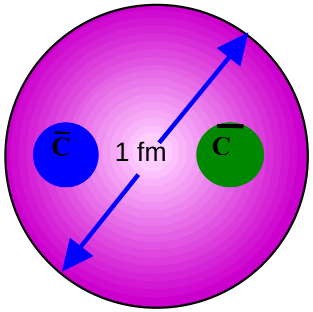
The NUSTAR experimental facility:

- Production of intensive rare isotope beams by in-flight projectile fragmentation/fission (access to short-lived isotopes)
- Detailed investigations, large variety of experimental techniques

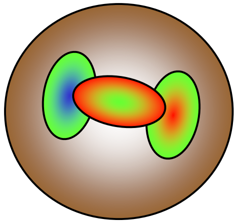


Hadron physics with high energy antiprotons

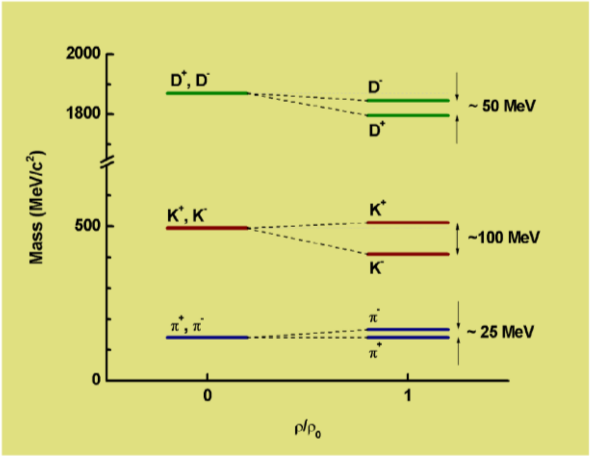
Study of the confinement potential with charmonium spectroscopy:



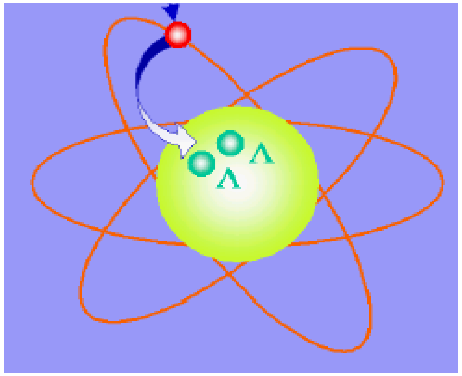
Search for gluonic excitations:



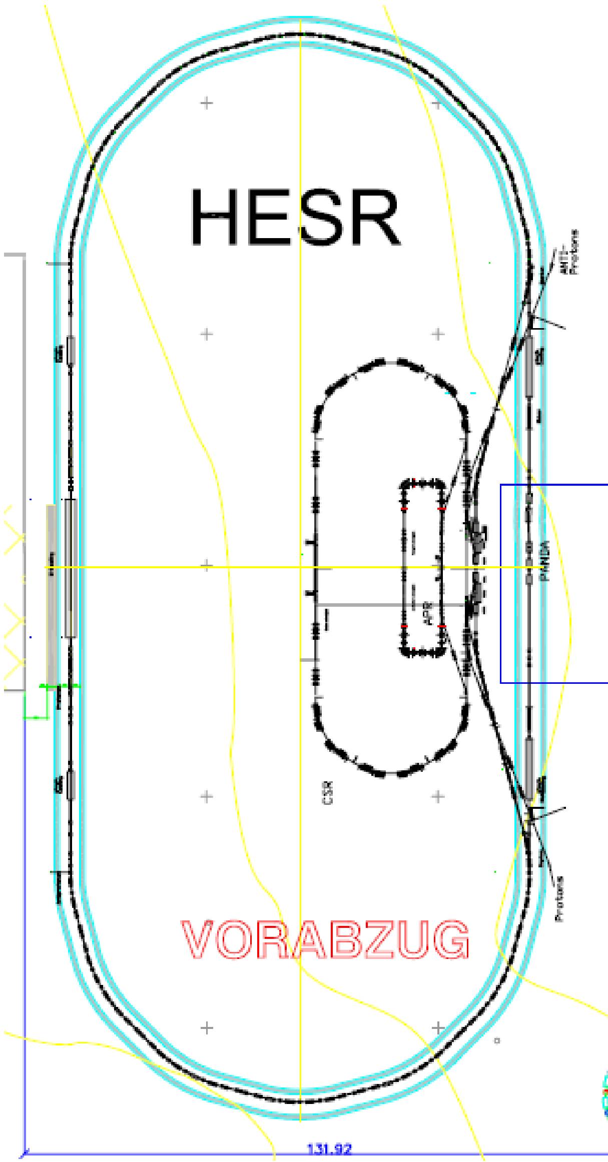
Search for in-medium modifications of hadron properties

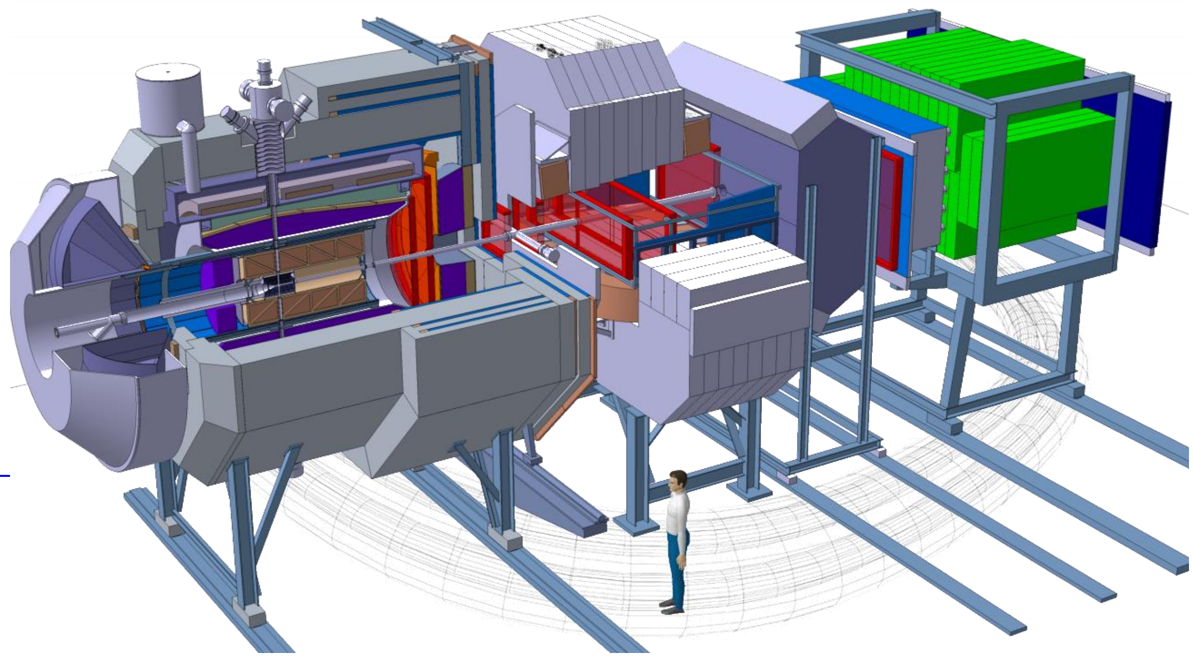


Precision γ-spectroscopy of single and double hypernuclei



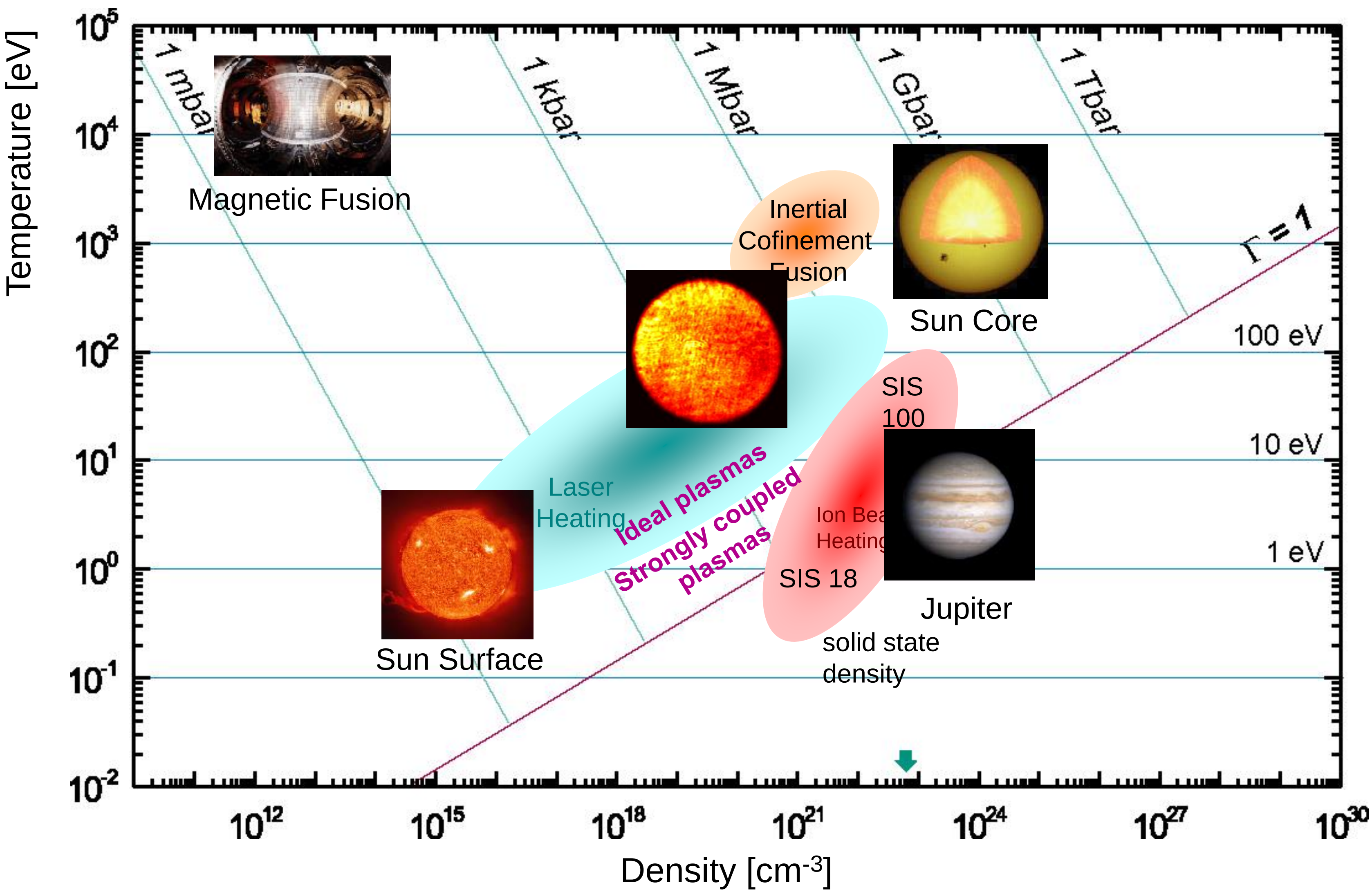
Antiproton-Proton-Annihilation in Darmstadt





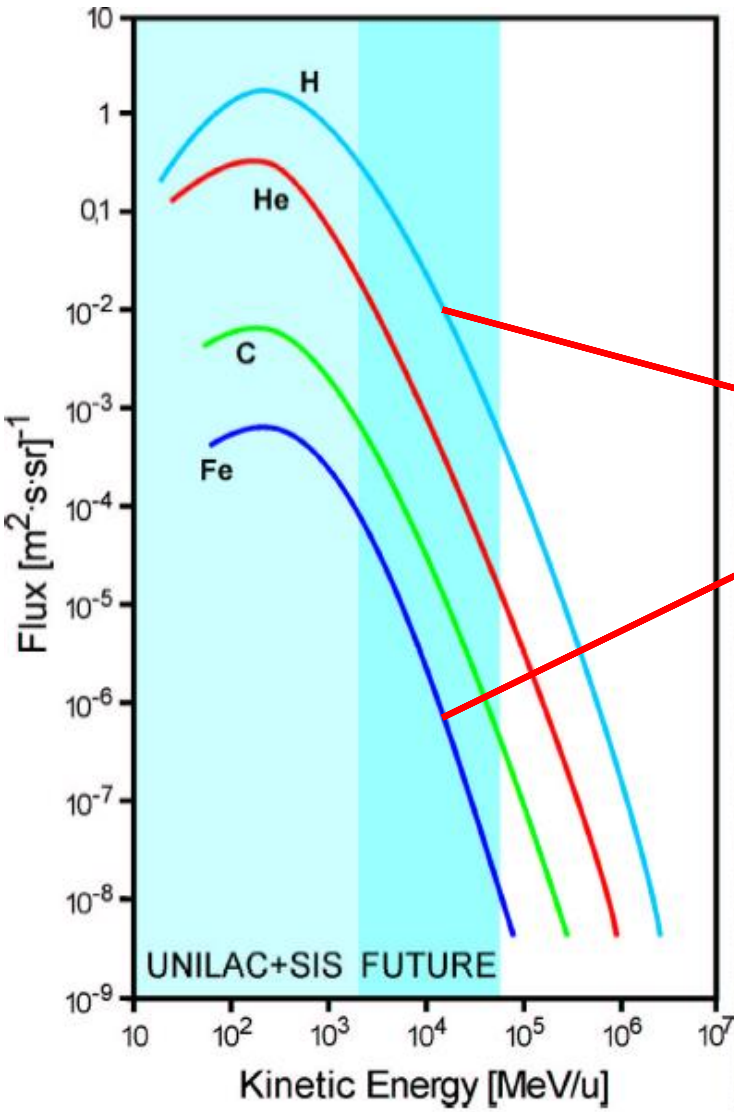
- High luminosity mode
  - Luminosity = 2 x 10^{32} $cm^{-2}s^{-1}$
  - $\delta p/p \sim 10^{-4}$ (stochastic cooling)
- High resolution mode
  - $\delta p/p \sim$ few 10^{-5} (+electron cooling)
  - Luminosity > 10^{31} $cm^{-2}s^{-1}$
- Gas-Jet/Pellet/Wire Target

Hot electro-magnetic plasmas:
high intensity ion bunches hitting petawatt laser pulses
(PHELIX and heavy-ion beams)



Radiobiology:
Radiation dose during long-term space missions ?

Cosmic radiation in space



within factor of 10