Exploring the QCD Phase Diagram at High Baryon Densities:

The CBM experiment at FAIR

Claudia Höhne, GSI Darmstadt

- **FAIR**
- **QCD phase diagram**
- **results from SPS and RHIC**
- **CBM physics topics and observables**
  feasibility studies and R&D

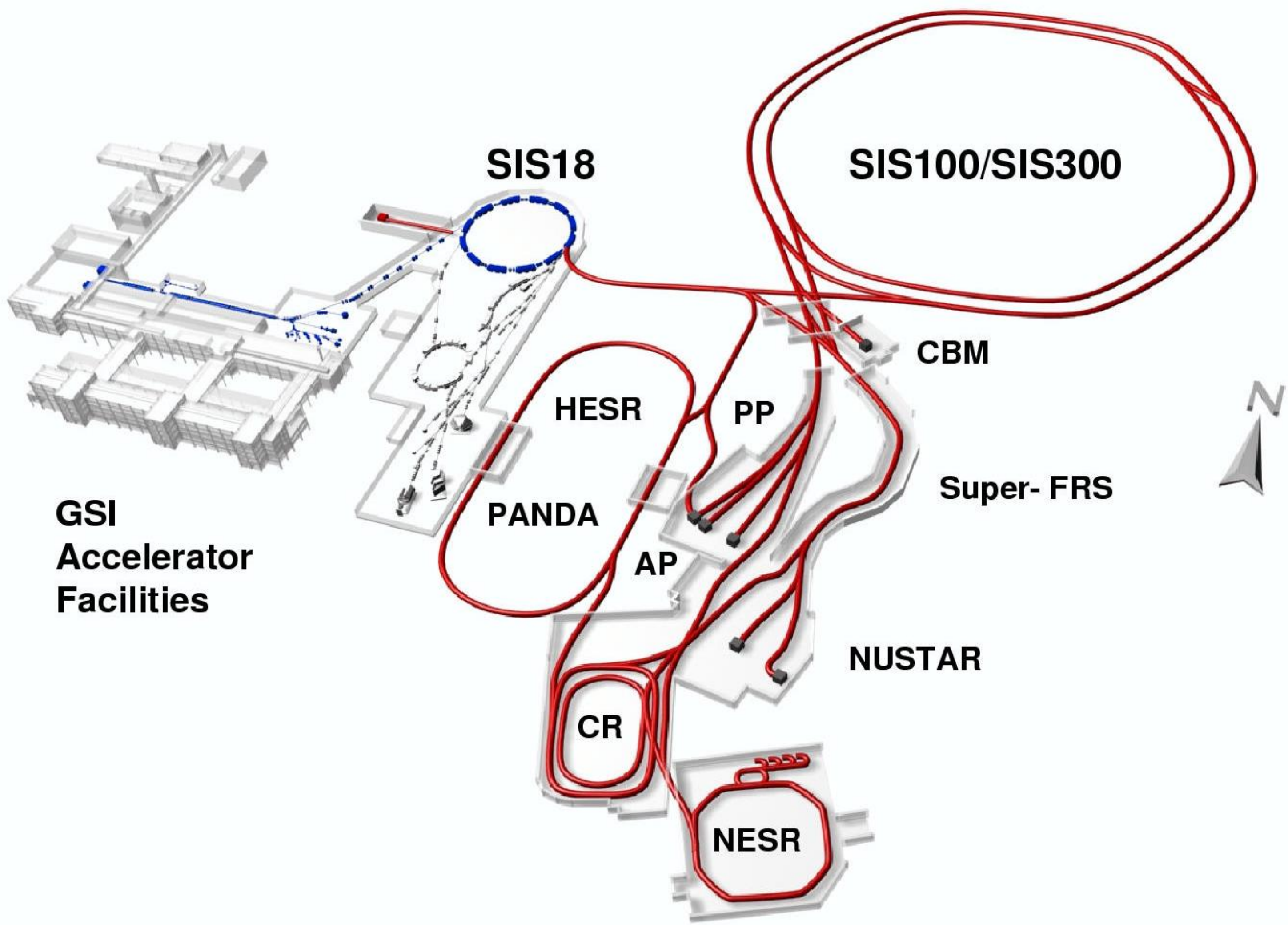
FAIR

Facility for Antiproton and Ion Research

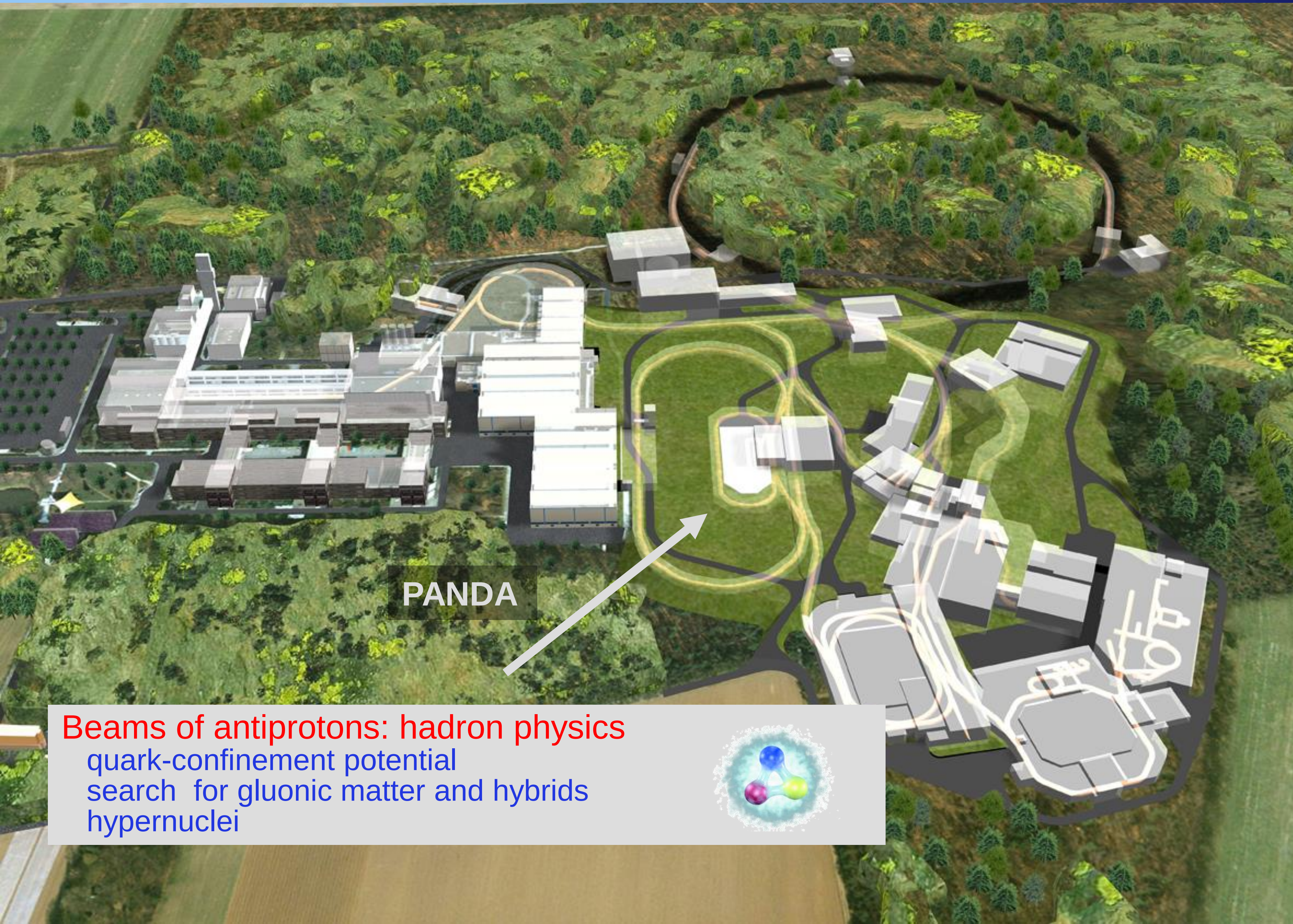
- accelerator complex serving several experiments at a time (up to 5) from a broad community
- highest beam intensities! (e.g. $2x10^{13}$/s 90 GeV protons and 10^{9} 45 AGeV Au ions)
- "working horse": SIS 100 serving a variety of storage rings
- rare isotope beams
- stored and cooled antiprotons
- foundation of FAIR GmbH in summer 2009
- operational ~2016

Observer:
EU, United States, Hungary, Georgia, Saudi Arabia

FAIR accelerator complex

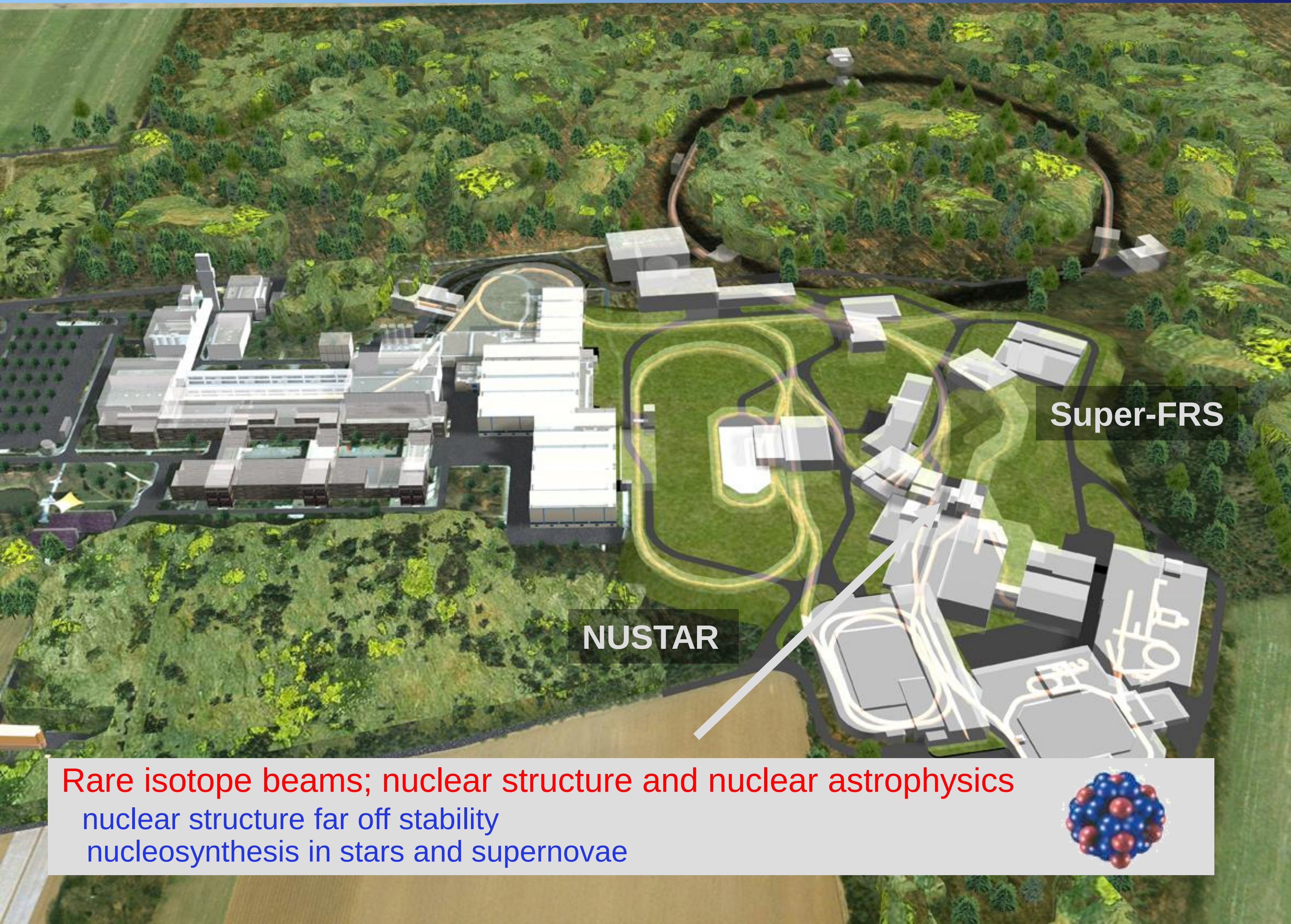


Research programs at FAIR



Beams of antiprotons: hadron physics
- quark-confinement potential
- search for gluonic matter and hybrids
- hypernuclei

Research programs at FAIR



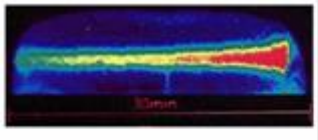
Rare isotope beams; nuclear structure and nuclear astrophysics

nuclear structure far off stability

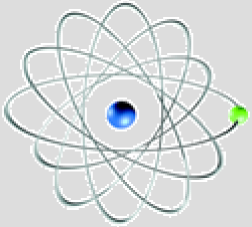
nucleosynthesis in stars and supernovae

Research programs at FAIR

short-pulse heavy ion beams: plasma physics
- matter at high pressure, densities, and temperature
- fundamentals of nuclear fusion

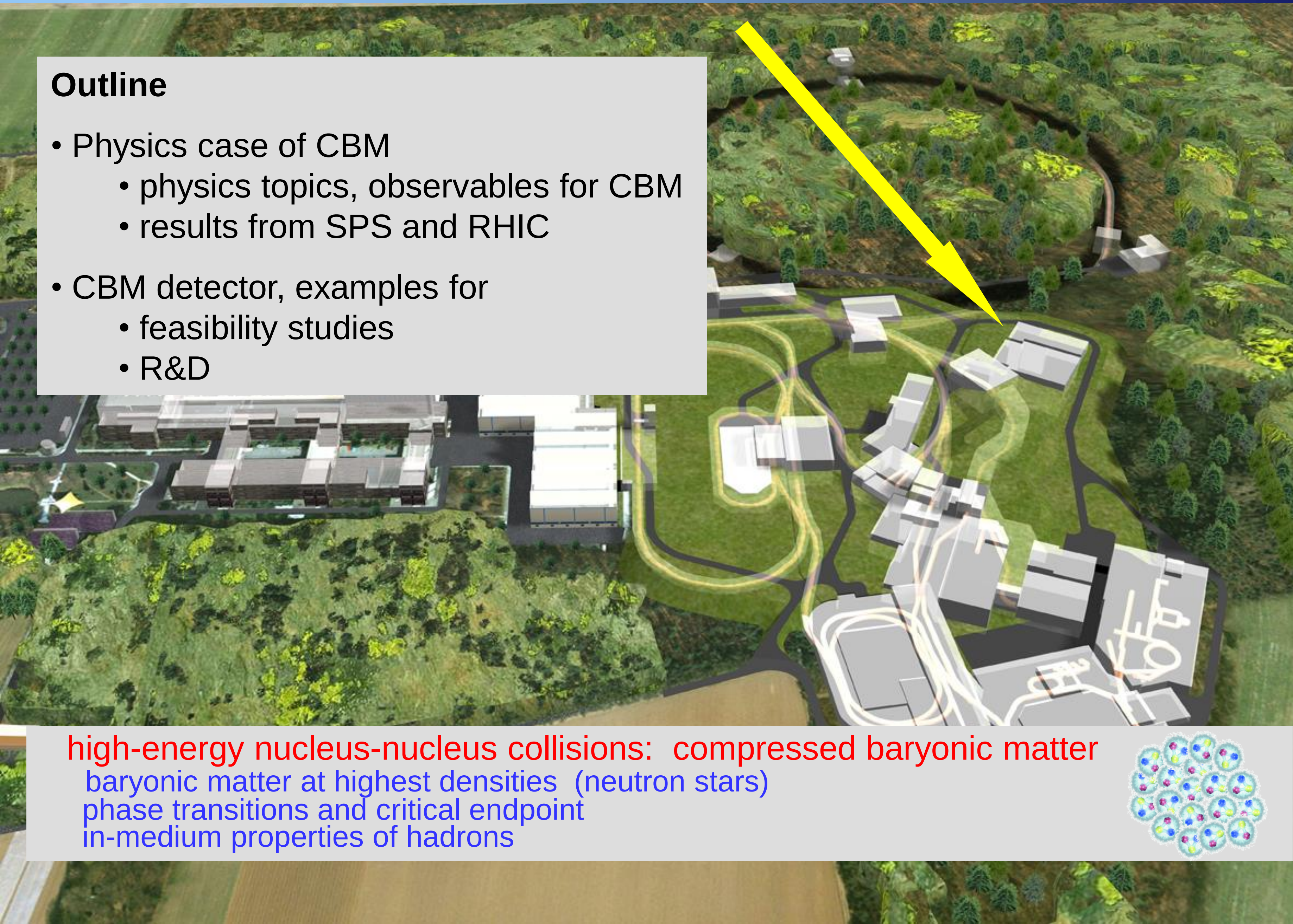


atomic physics and applied research
- highly charged atoms
- low energy antiprotons (anti-hydrogen)
- radiobiology
- materials research



accelerator physics
- high intensive heavy ion beams (vacuum!)
- rapidly cycling superconducting magnets
- high energy electron cooling

CBM @ FAIR



Outline

- Physics case of CBM
  - physics topics, observables for CBM
  - results from SPS and RHIC
- CBM detector, examples for
  - feasibility studies
  - R&D

high-energy nucleus-nucleus collisions: compressed baryonic matter

baryonic matter at highest densities (neutron stars)

phase transitions and critical endpoint

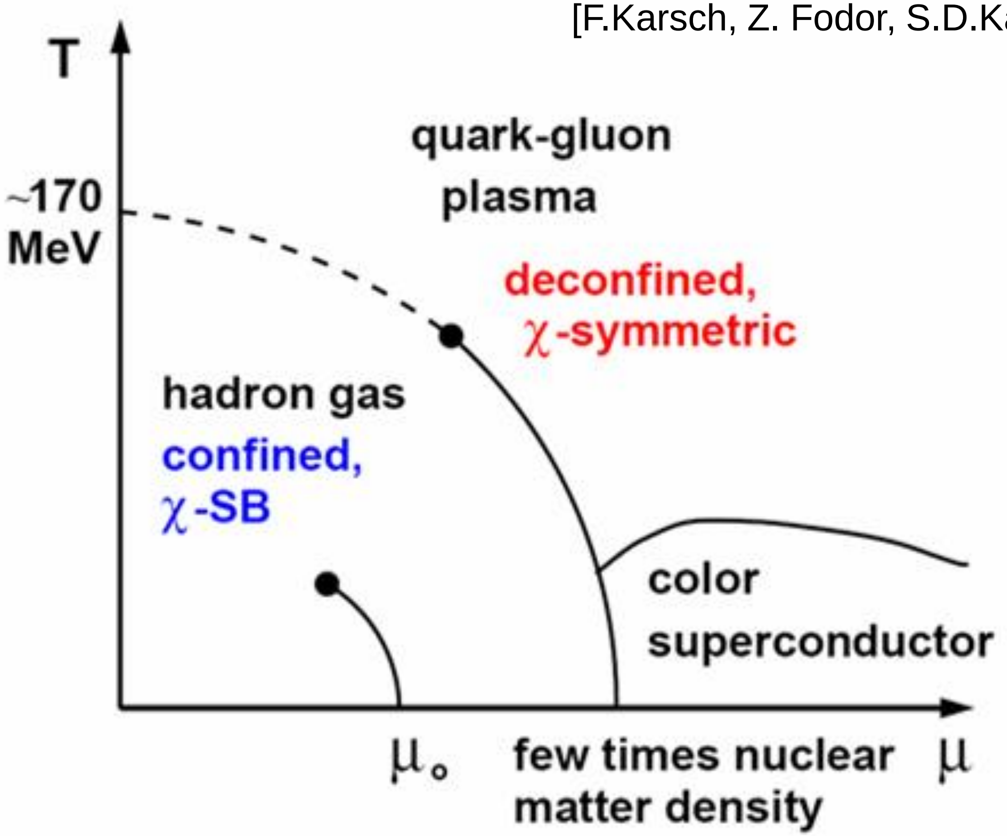
in-medium properties of hadrons

QCD phase diagram at high baryon densities

- intermediate range of the QCD phase diagram with high net-baryon densities of strong interest because of
- expected structures as 1st order phase transition and critical point (2nd order phase tarnsition)
- chiral phase transition

- deconfinement = chiral phase transition ?
- hadrons and quarks at high μ?
- signatures (measurable!) for these structures/ phases?
- how to characterize the medium?

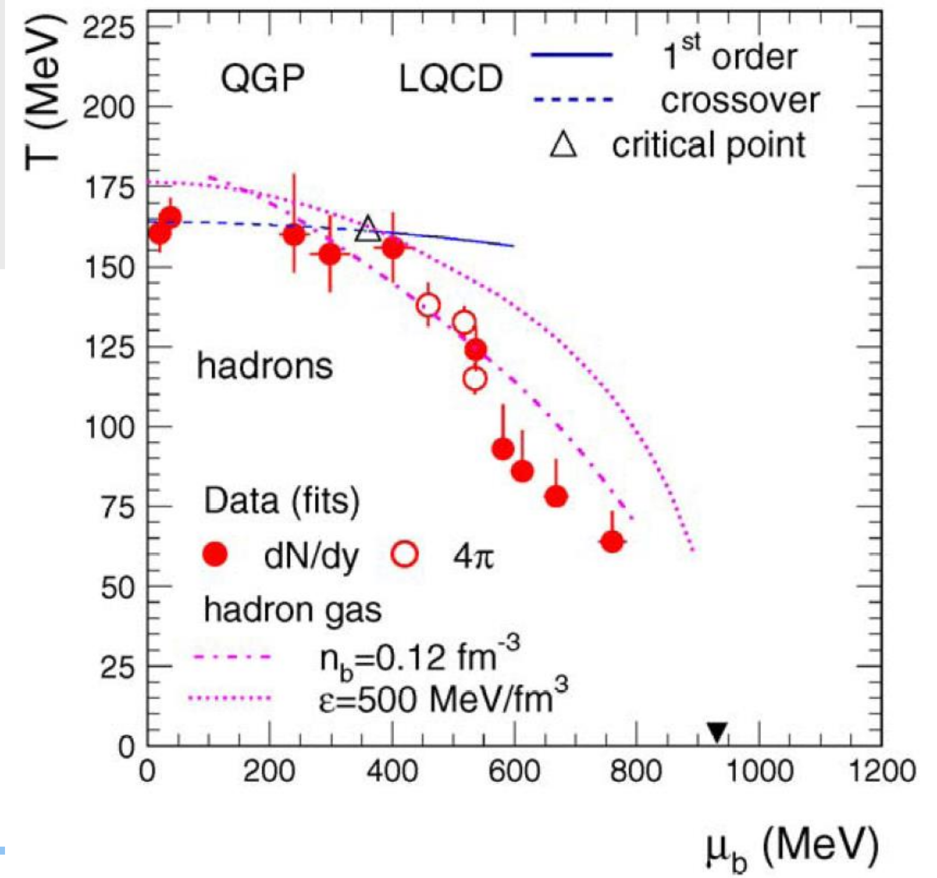
[F.Karsch, Z. Fodor, S.D.Katz]



QCD phase diagram & experiments

What do we know from experiment? → Heavy-ion collisions:

- „chemical freeze-out curve“ = (T, μ_B) from statistical model
- top SPS, RHIC (high T, low μ_B): partonic degrees of freedom, crossover (?)
- RHIC: first steps towards a quantitative characterization of the medium (gluon density, viscosity, energy loss...)
- lower SPS (intermediate T-μ_B): intriguing observations around 30 AGeV!
- SIS, AGS: high density baryonic matter

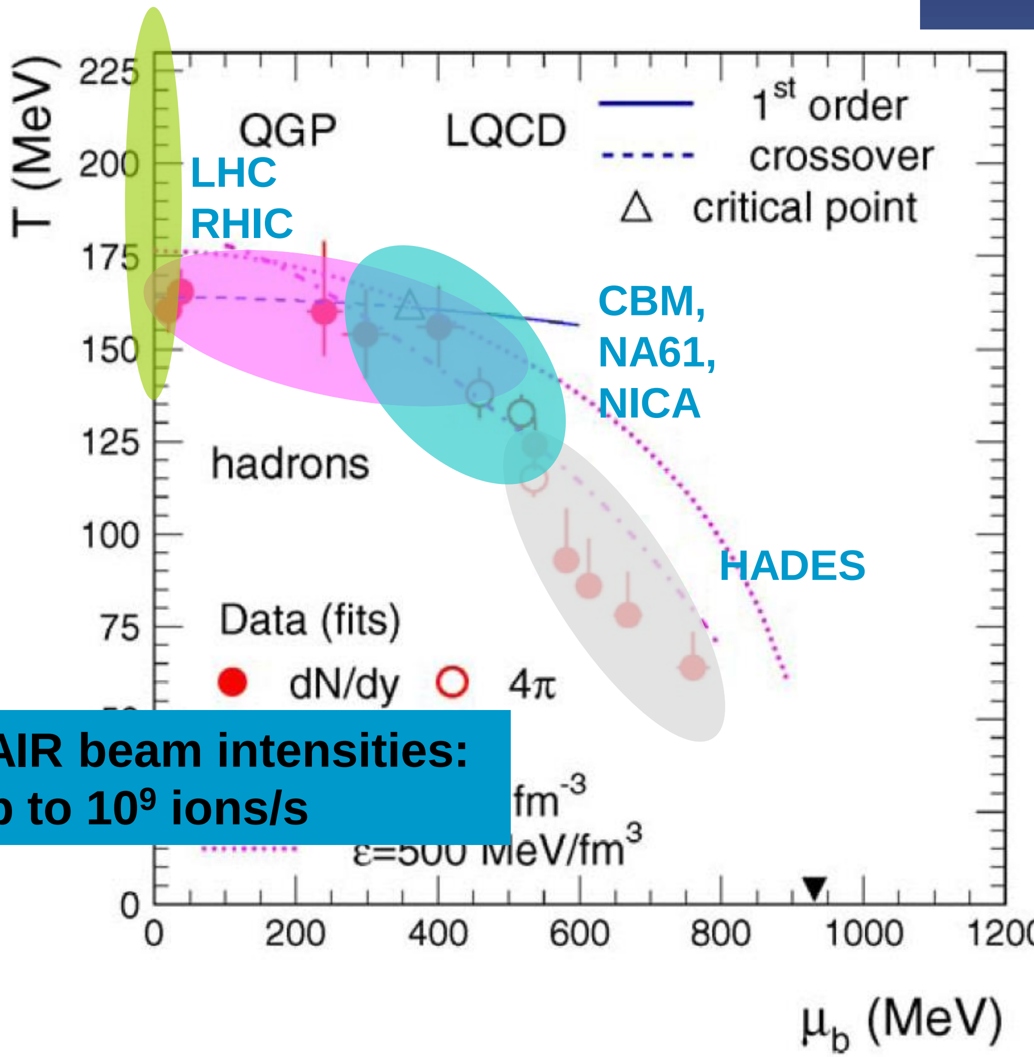


[Andronic et al. Nucl. Phys. A 772, 167 (2006).

Experimental scan of QCD phase diagram

Within the next years we'll get a **complete scan of the QCD phase diagram** with 2nd generation experiments

- **LHC, RHIC**: bulk observables **and** rare probes (charm, dileptons)
- **RHIC** energy scan: bulk observables $\sqrt{s}$ ~ (5)10 GeV – 200 GeV
- **NA61**: focus on fluctuations ($\sqrt{s_{NN}}$ = 4.5 – 17.3 GeV), A < 120
- **NICA**: strangeness, bulk observables ($\sqrt{s_{NN}}$ = 3 – 9 GeV)
- **CBM**: bulk observables **and** rare probes (charm, dileptons) beam energy 10 – 45 GeV/nucleon ($\sqrt{s_{NN}}$ = 4.5 – 9.3 GeV)
- **HADES**: bulk observables, dileptons beam energy 2 – 10 GeV/nucleon



FAIR beam intensities: up to 10^9 ions/s

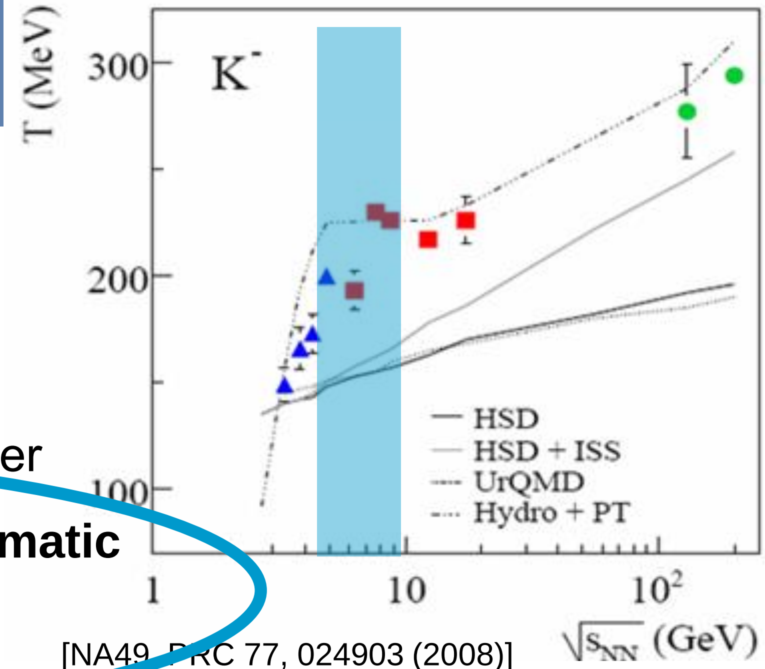
[Andronic et al. Nucl. Phys. A 772, 167 (2006).

SPS results

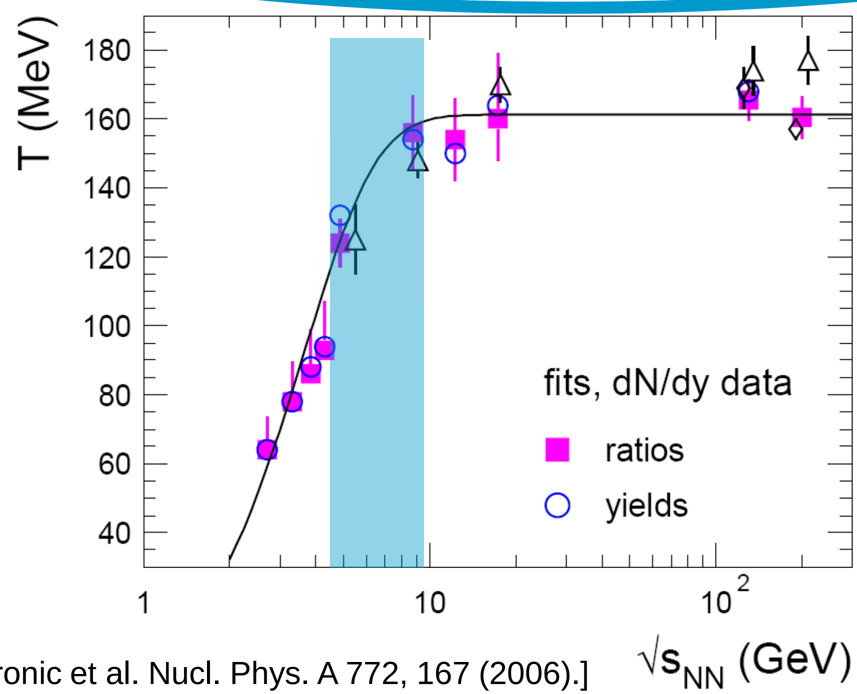
- energy dedendence of hadron production
→ changes in SPS energy regime

- discussions ongoing:
    - hadron gas → partonic phase
    - baryon dominated → meson dominated matter

- **missing: high precision measurements, systematic investigations, correlations, rare probes**
→ quantitative characterization of the medium!



[NA49, PRC 77, 024903 (2008)]



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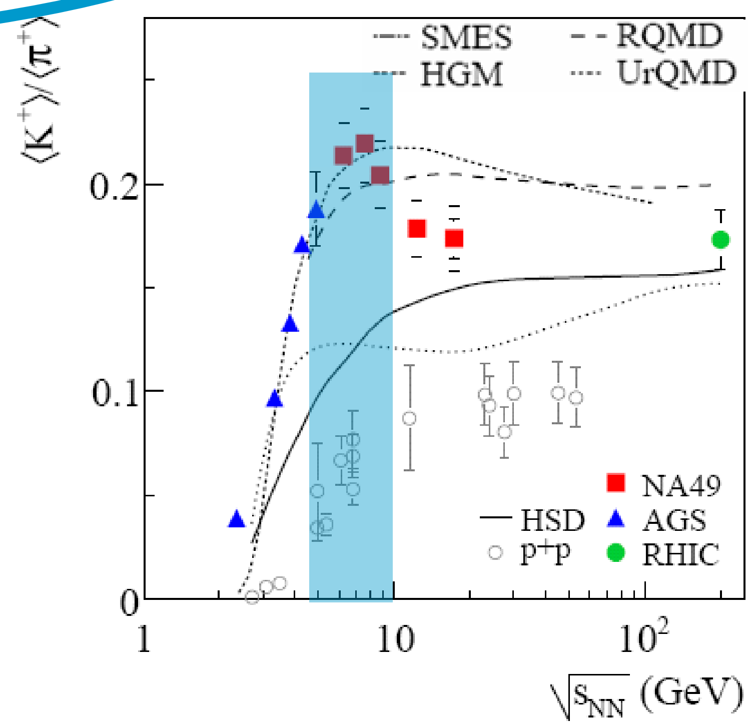
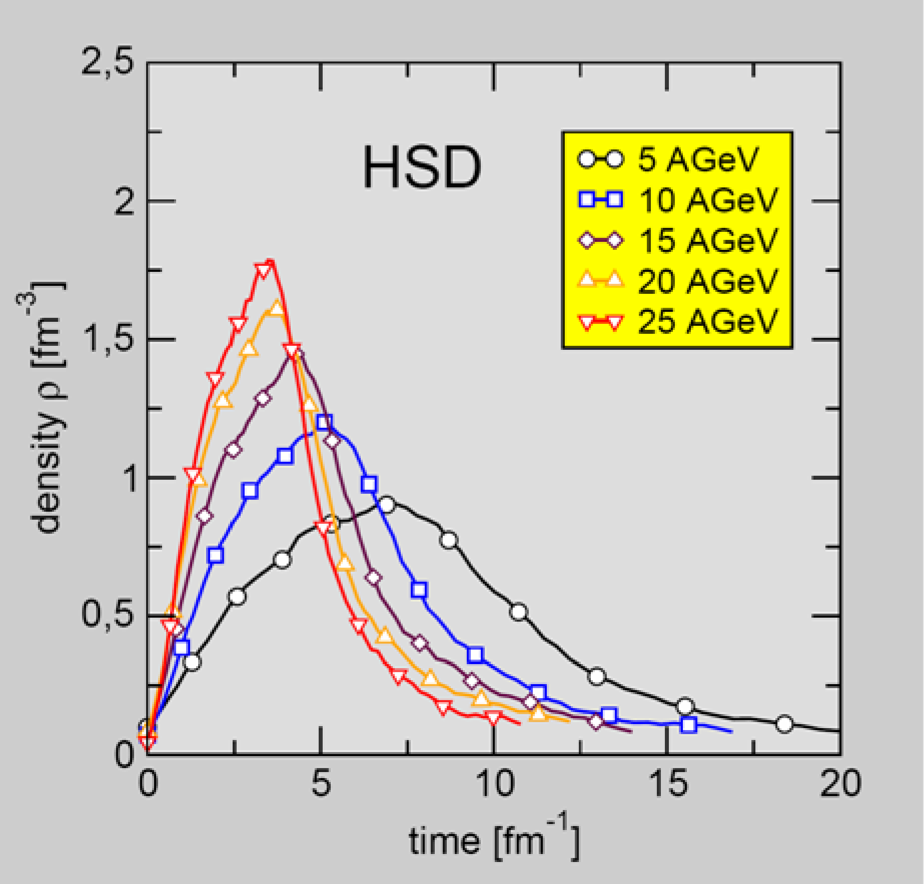


High net-baryon density matter at CBM

• high baryon and energy densities created in central Au+Au collisions

beam energy	max. ρ/ρ_0	max ε [GeV/fm³]	time span ~FWHM
5 AGeV	6	1.5	~ 8 fm/c
40 AGeV	12	> 10	~ 3.5 fm/c

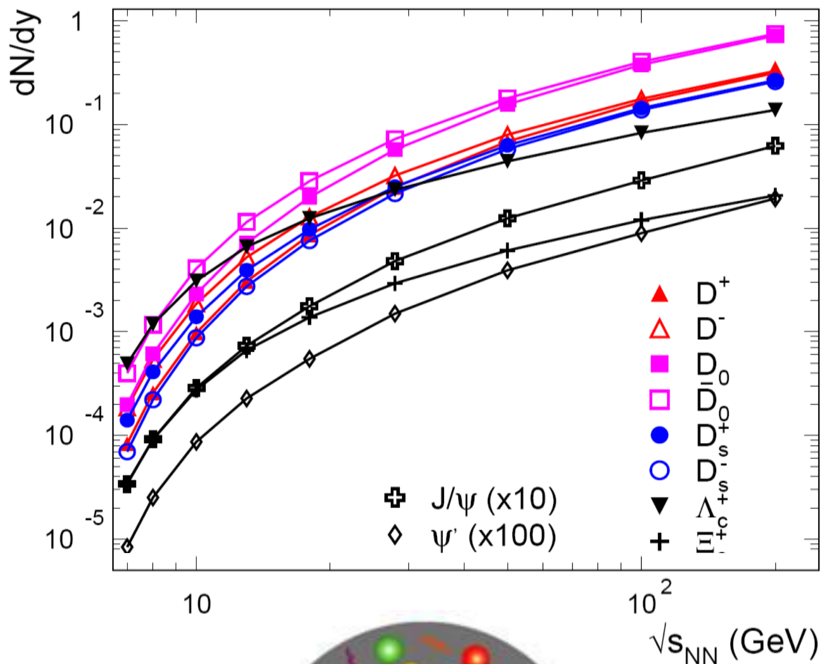


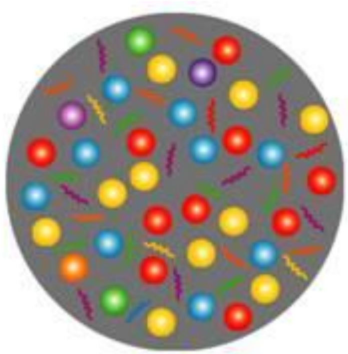
[CBM physics group, C. Fuchs, E. Bratkovskaya priv. com.]

Charm production in hadronic and partonic matter

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

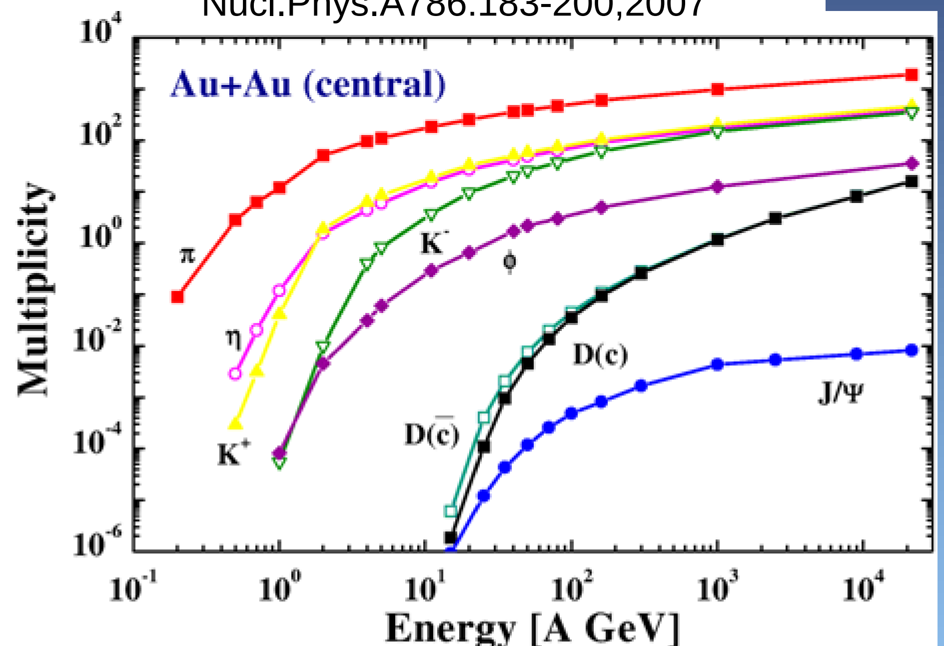
[A. Andronic, P. Braun-Munzinger,
K. Redlich, J. Stachel, arXiv:0708.1488]





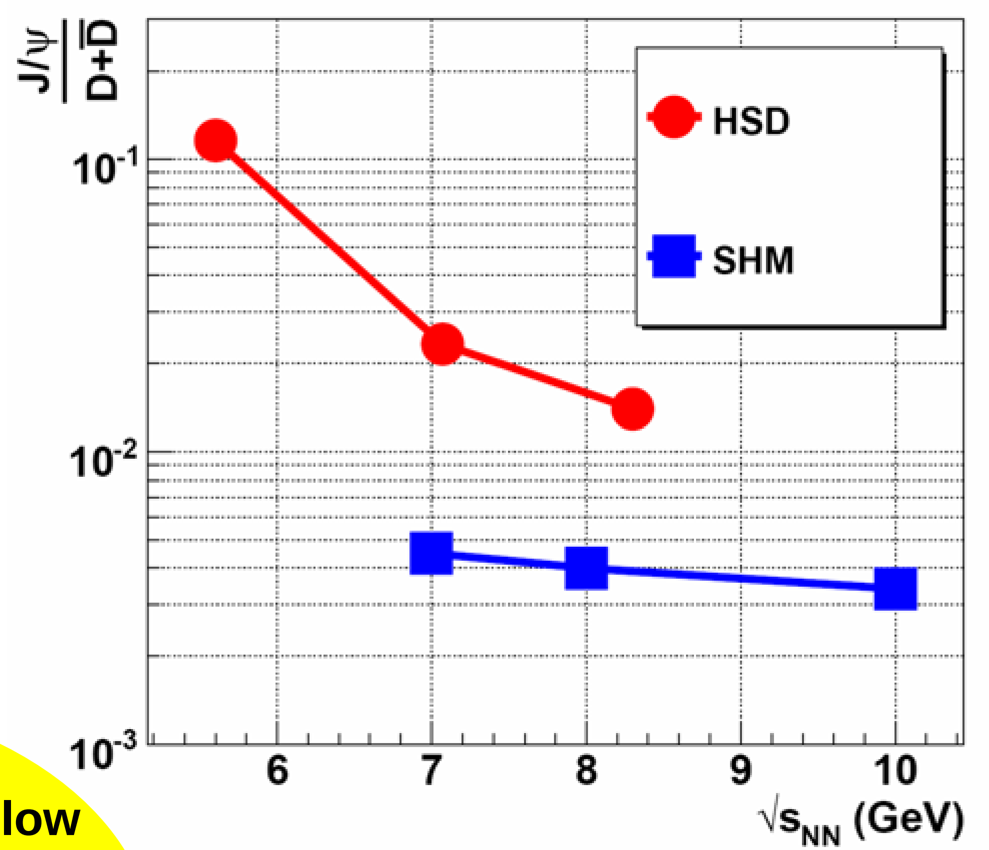
Hadronic model (HSD)

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



$NN \rightarrow D\, \Lambda_c\, N$
$NN \rightarrow DD\, NN$
$NN \rightarrow J/\psi\, NN$

Charm production in hadronic and partonic matter

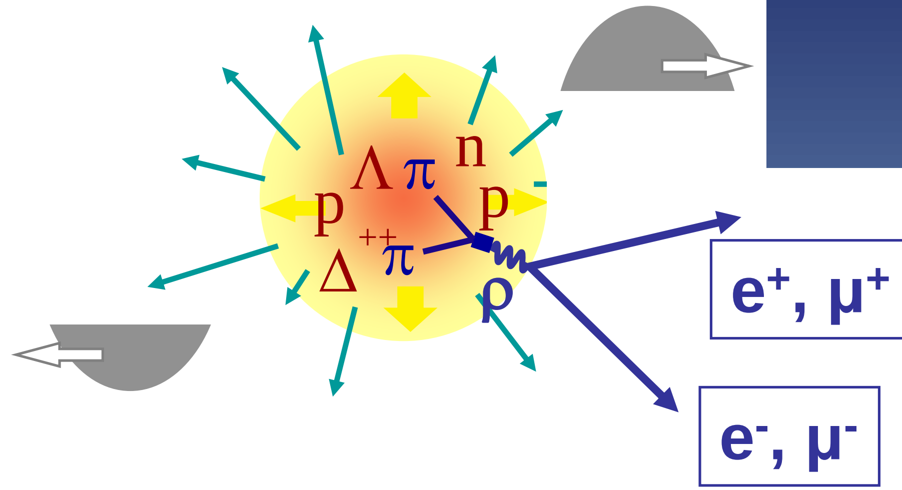


no charm (J/ψ) data below 158 AGeV beam energy

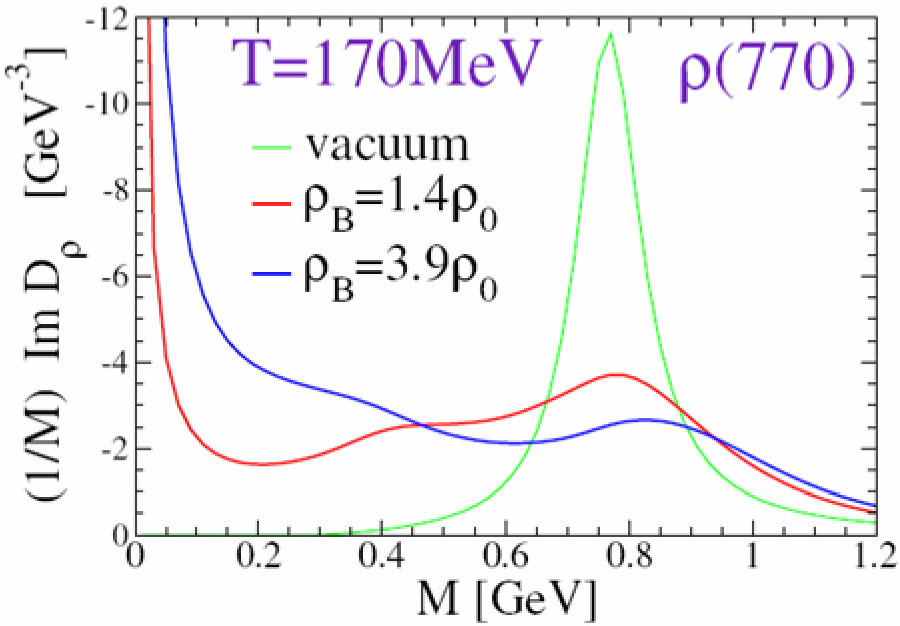
detailed information including phase space distributions!

ρ-meson spectral function

- ρ-meson couples to the medium: "melts" close to T_c and at high μ_B
- vacuum lifetime τ_0 = 1.3 fm/c
- dileptons = penetrating probe
- connection to chiral symmetry restoration?
- particular sensitive to baryon density



"SPS"
"FAIR"



- illustrate sensitivity to modifications caused by the baryonic component of the medium: ρ-meson spectral function weighted by 1/M to resemble the dilepton rate, Bose-factor will further amplify the low-mass part
- m < 0.4 GeV/c^2 of special interest!

no measurement between 2-40 AGeV beam energy yet!

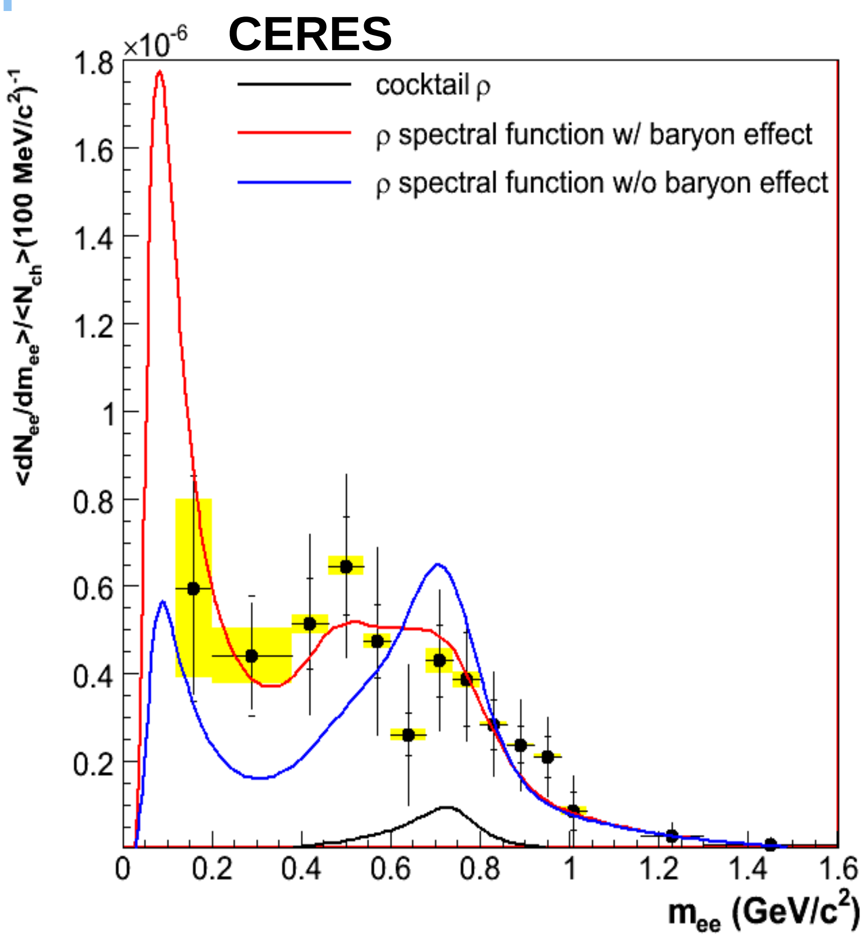
[R. Rapp, priv. com. (CBM physics book)]

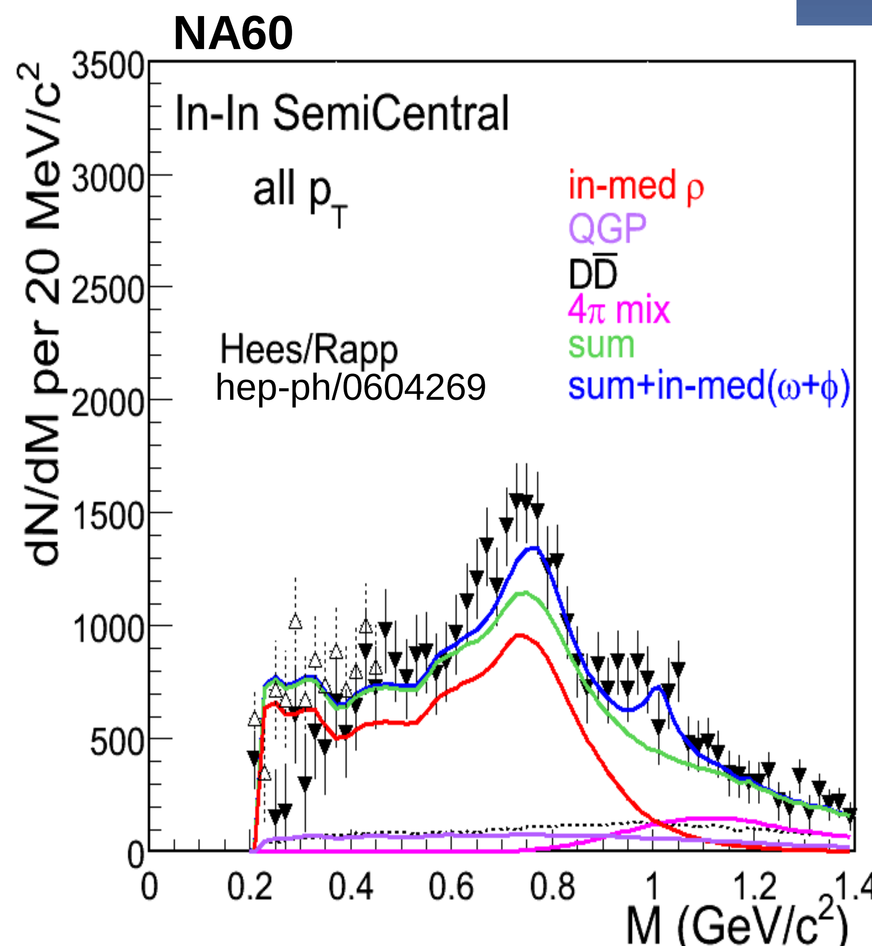
Dileptons

- new results from top SPS energy ($\sqrt{s_{NN}}$ = 17.3 GeV):

→ modification of ρ spectral function, importance of baryons!

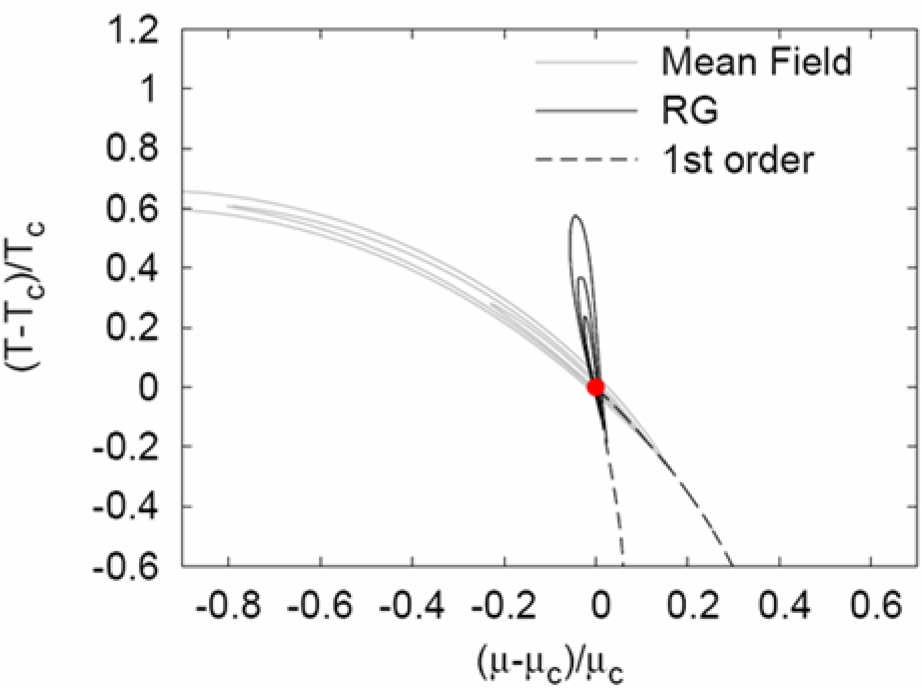
- **measure in dependence on baryon density (energy)!**

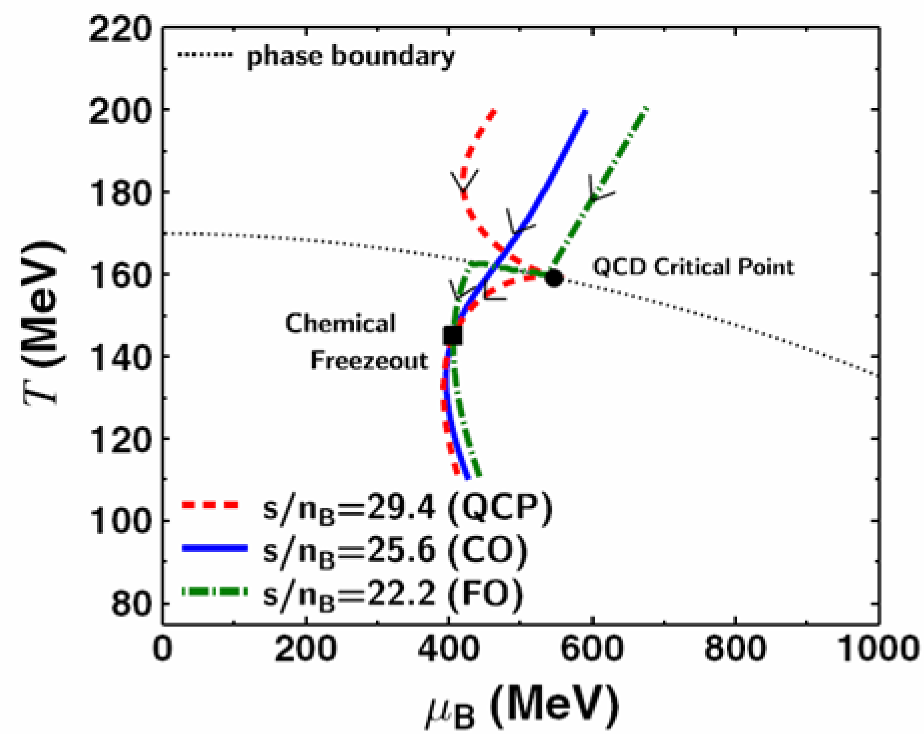




Critical point

- critical point = endpoint of 1st order phase transition: 2nd order phase transition
- critical region might be small, focussing effect?
- fluctuations would need time to develop





[Schaefer, Wambach, PRD75, 085015 (2007)]

[Asakawa, Bass, Mueller, Nonaka, PRL 101, 122302 (2008)]

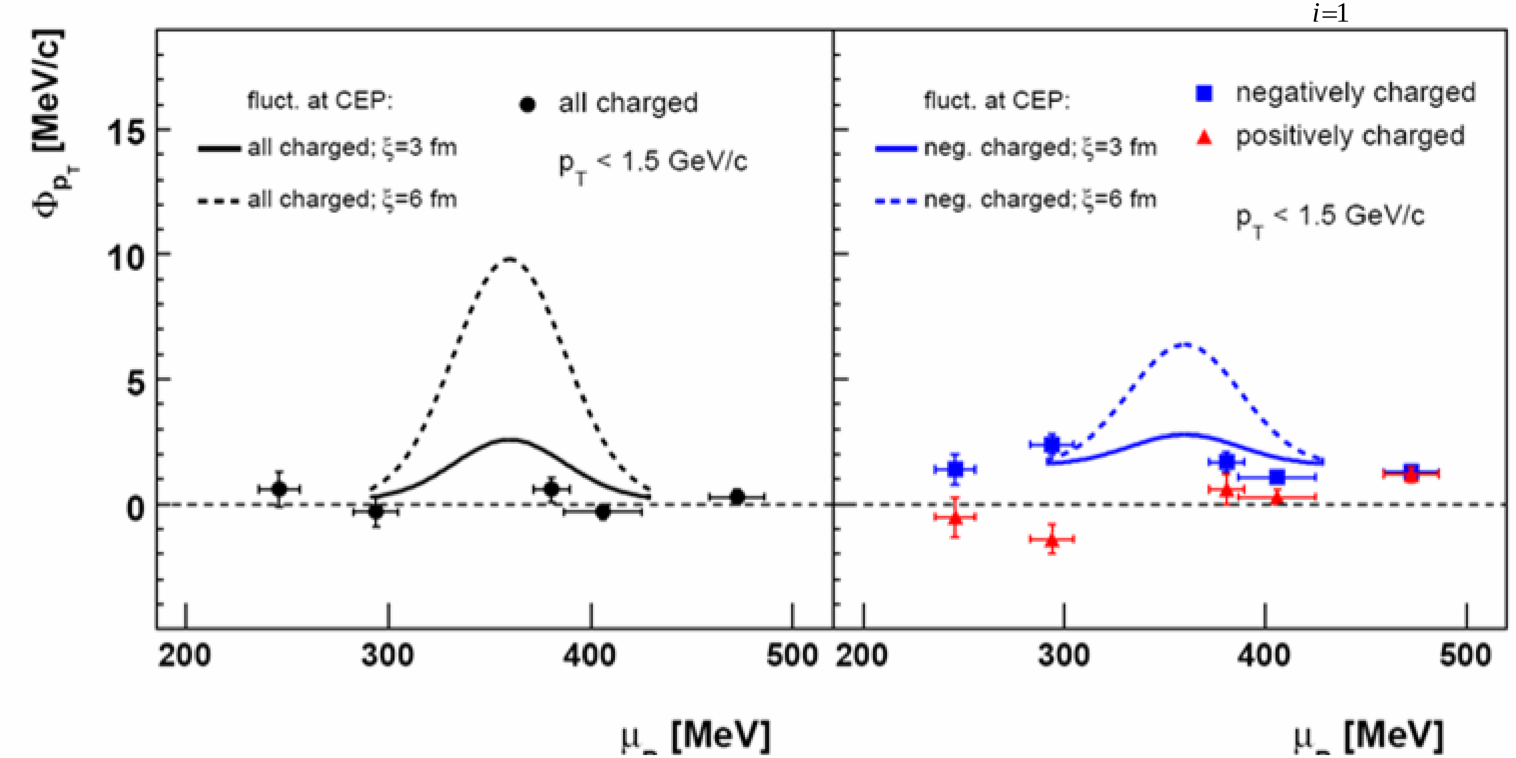
Event-by-event fluctuations

- observation might become enormously difficult
- correlation length ξ of sigma field, may become rather small for a finite lifetime of the fireball
- large acceptance needed!

$$\Phi_{pt} = \sqrt{\frac{\langle Z_{pt}^2 \rangle}{\langle N \rangle}} - \sqrt{\overline{z_{pt}^2}}$$

$$z_{pt} = p_t - \overline{p_t}$$

$$Z_{pt} = \sum_{i=1}^{N} \left(p_{ti} - \overline{p_t} \right)$$



[NA49 collaboration, arXiv:0810.5580v2 [nucl-ex]] [Stephanov, Rajagopal, Shuryak, PRD60, 114028 (1999)]

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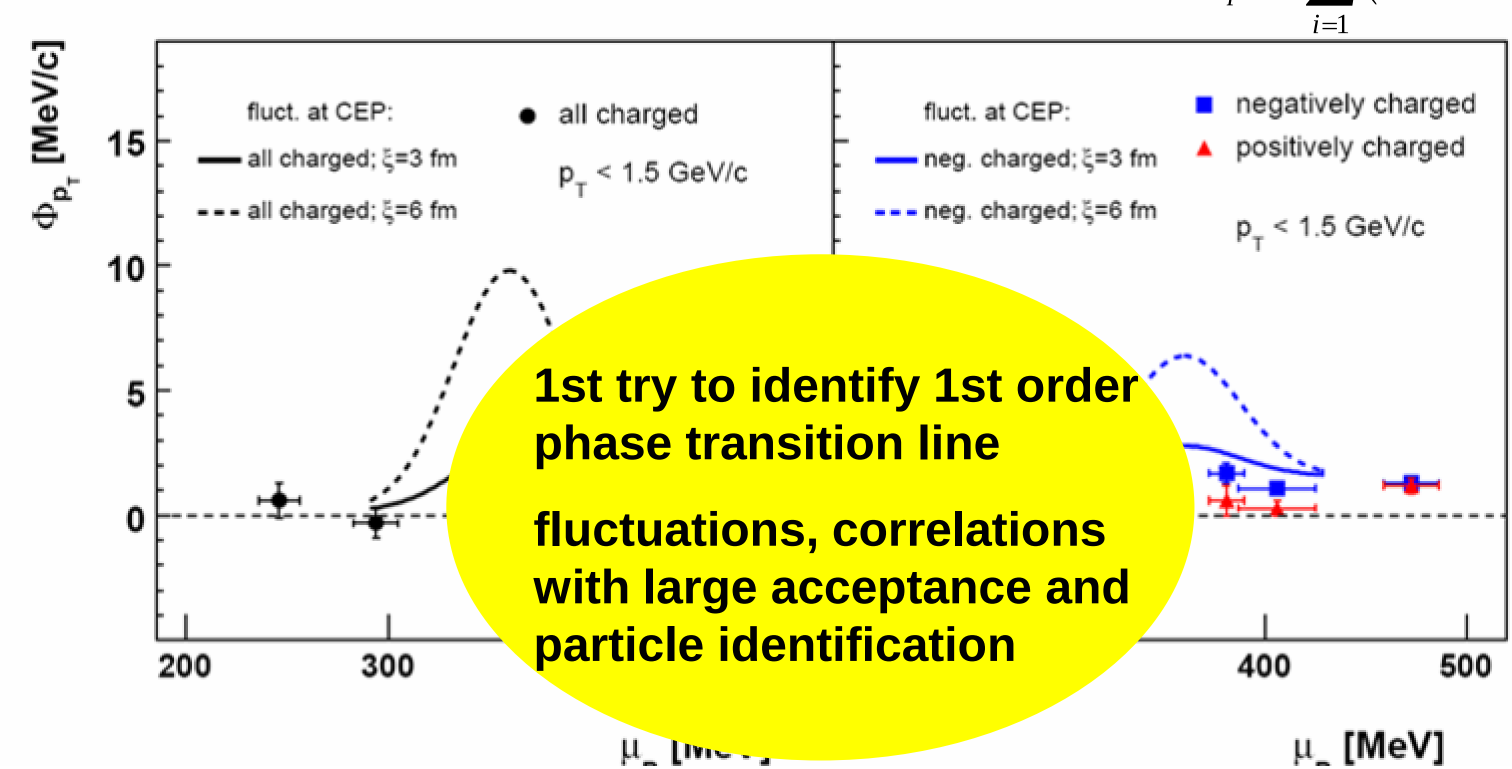


1st try to identify 1st order phase transition line

fluctuations, correlations with large acceptance and particle identification

[NA49 collaboration, arXiv:0810.5580v2 [nucl-ex]] [Stephanov, Rajagopal, Shuryak, PRD60, 114028 (1999)]

CBM: Physics topics and Observables

The equation-of-state at high ρ_B

- collective flow of hadrons
- particle production at threshold energies (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)
- charmonium suppression, sequential for J/ψ and ψ' ?

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)

predictions? clear signatures?
→ prepare to measure "everything" including rare probes
→ systematic studies! (pp, pA, AA, energy)
aim: probe & characterize the medium! - importance of rare probes!!

The CBM experiment

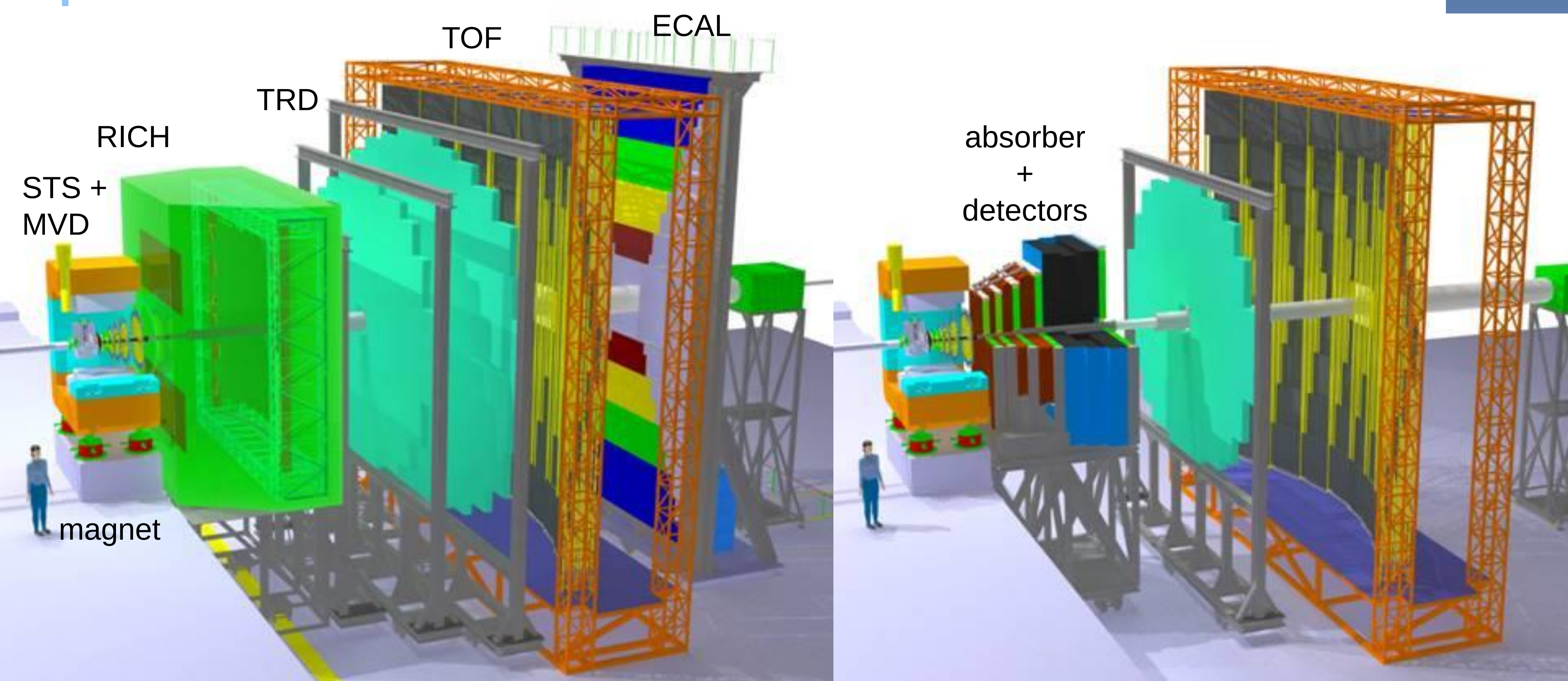
- tracking, momentum determination, vertex reconstruction: radiation hard silicon pixel/strip detectors (STS) in a magnetic dipole field

- hadron ID: TOF (& RICH)
- photons, π^0, η: ECAL

- PSD for event characterization
- high speed DAQ and trigger $\rightarrow$ **rare probes!**

- **electron ID**: RICH & TRD
  $\rightarrow$ π suppression $\geq 10^4$

- **muon ID**: absorber + detector layer sandwich
  $\rightarrow$ move out absorbers for hadron runs

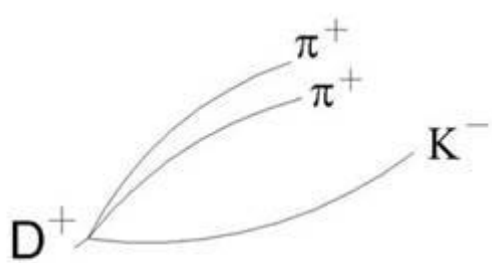


STS tracking – heart of CBM

Challenge: high track density: ≈ 600 charged particles in ± 25° @ 10MHz

Task

- track reconstruction: 0.1 GeV/c < p ≤ 10-12 GeV/c Δp/p ~ 1% (p=1 GeV/c)
- primary and secondary vertex reconstruction (resolution ≤ 50 μm)
- V_0 track pattern recognition



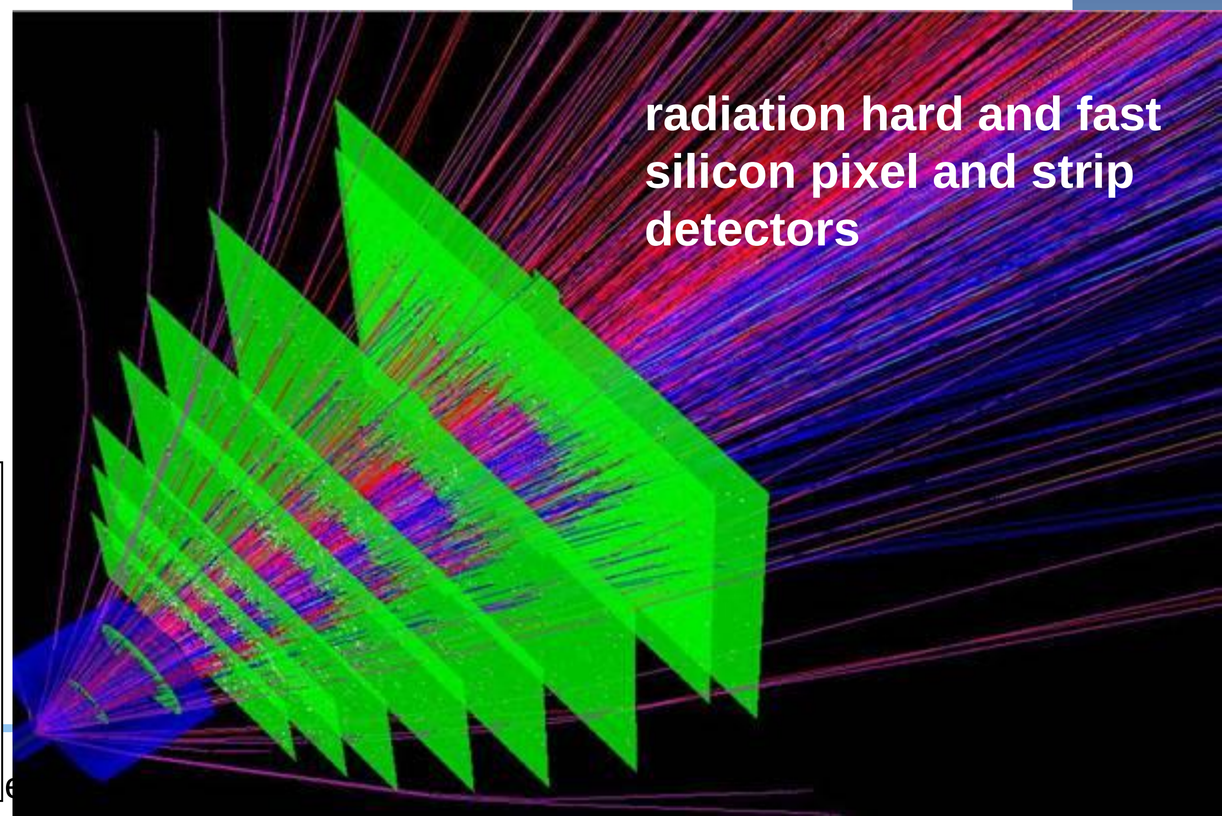
$c\tau$ = 312 μm

self triggered FEE

high speed DAQ and trigger

online track reconstruction!

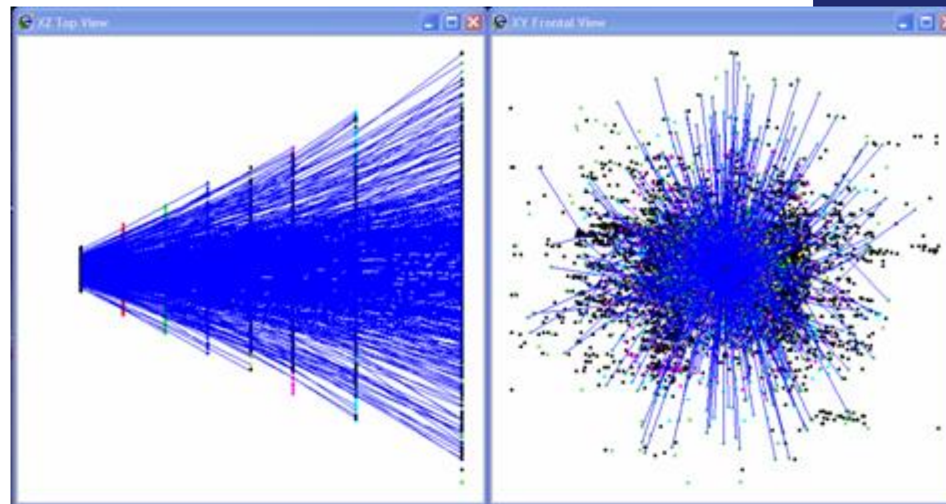
fast & rad. hard detectors!



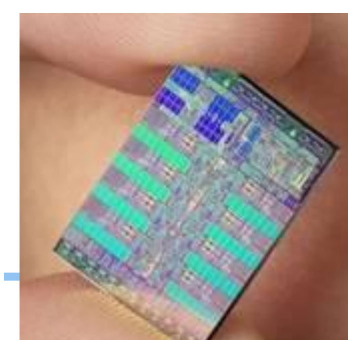
Track reconstruction

- max: up to ~10^9 tracks/s in the silicon tracker (10 MHz, ~100 tracks/event)
- start scenario for D more like 0.1 MHz
  → 10^7 tracks/s

→ **fast track reconstruction!**



- optimize code, port C++ routines to dedicated hardware
- parallel processing → today: factor 120000 speedup of tracking code achieved!
- long term aim: make use of manycore architectures of new generation graphics cards etc.



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

2 Double-sided silicon microstrip detectors

Double and triple GEM detectors

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

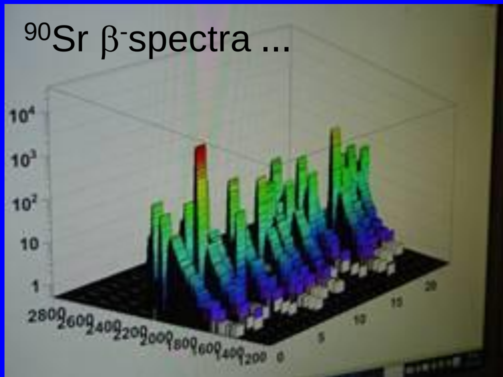
online

Analysis

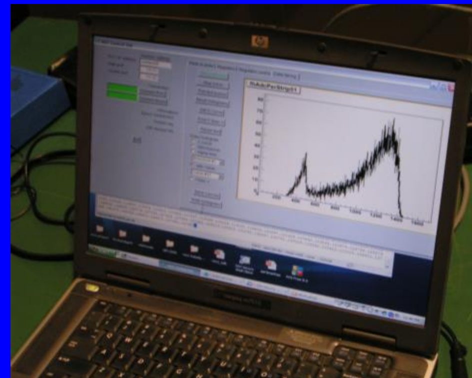
offline

FairRoot

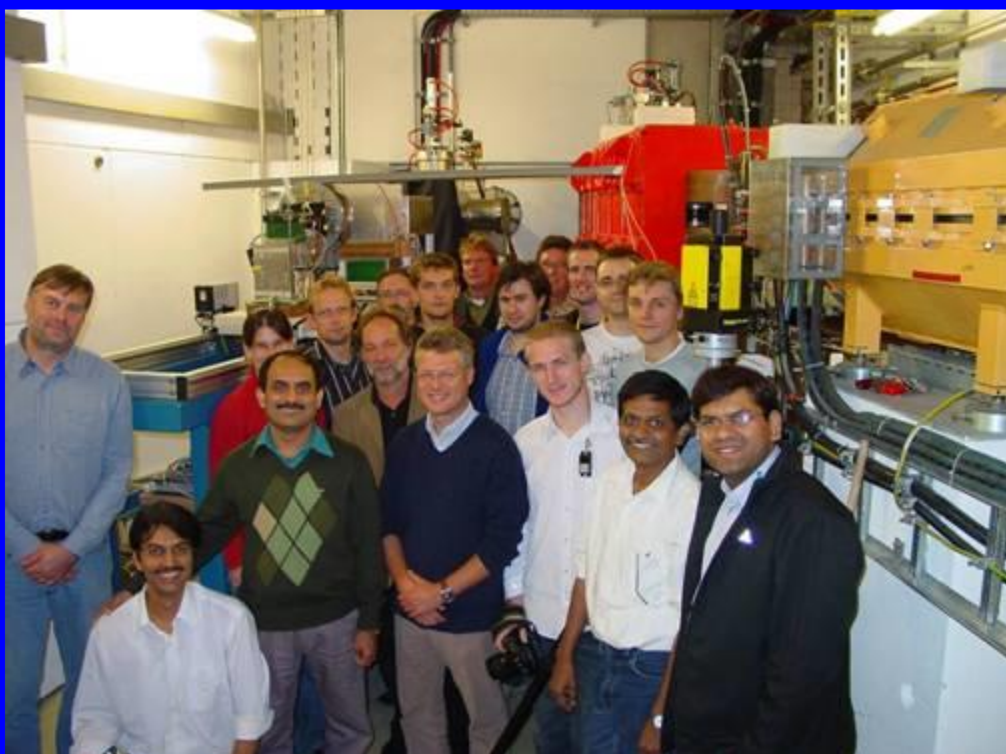
Detector commissioning:



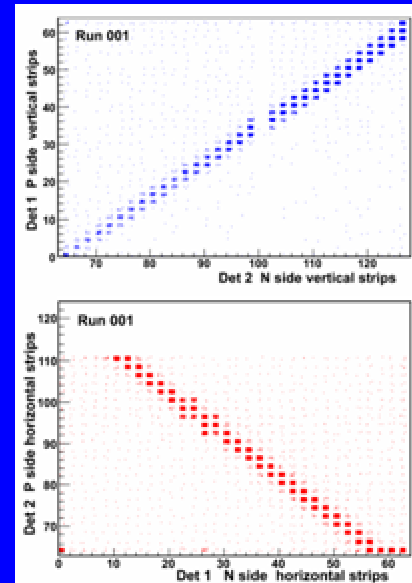
... in several channels of a silicon microstrip detector



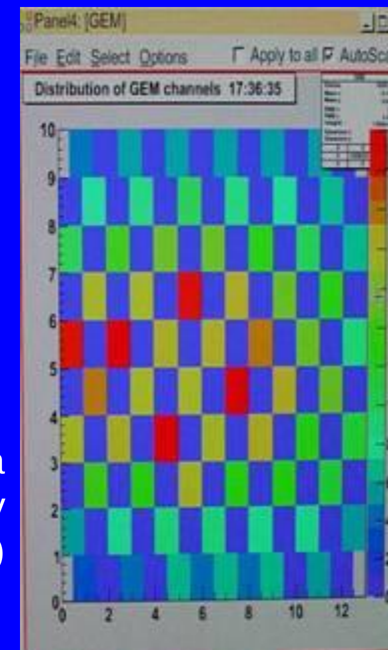
... and in a GEM detector



Operation on the beam line:



Correlation of fired channels in two silicon microstrip detectors



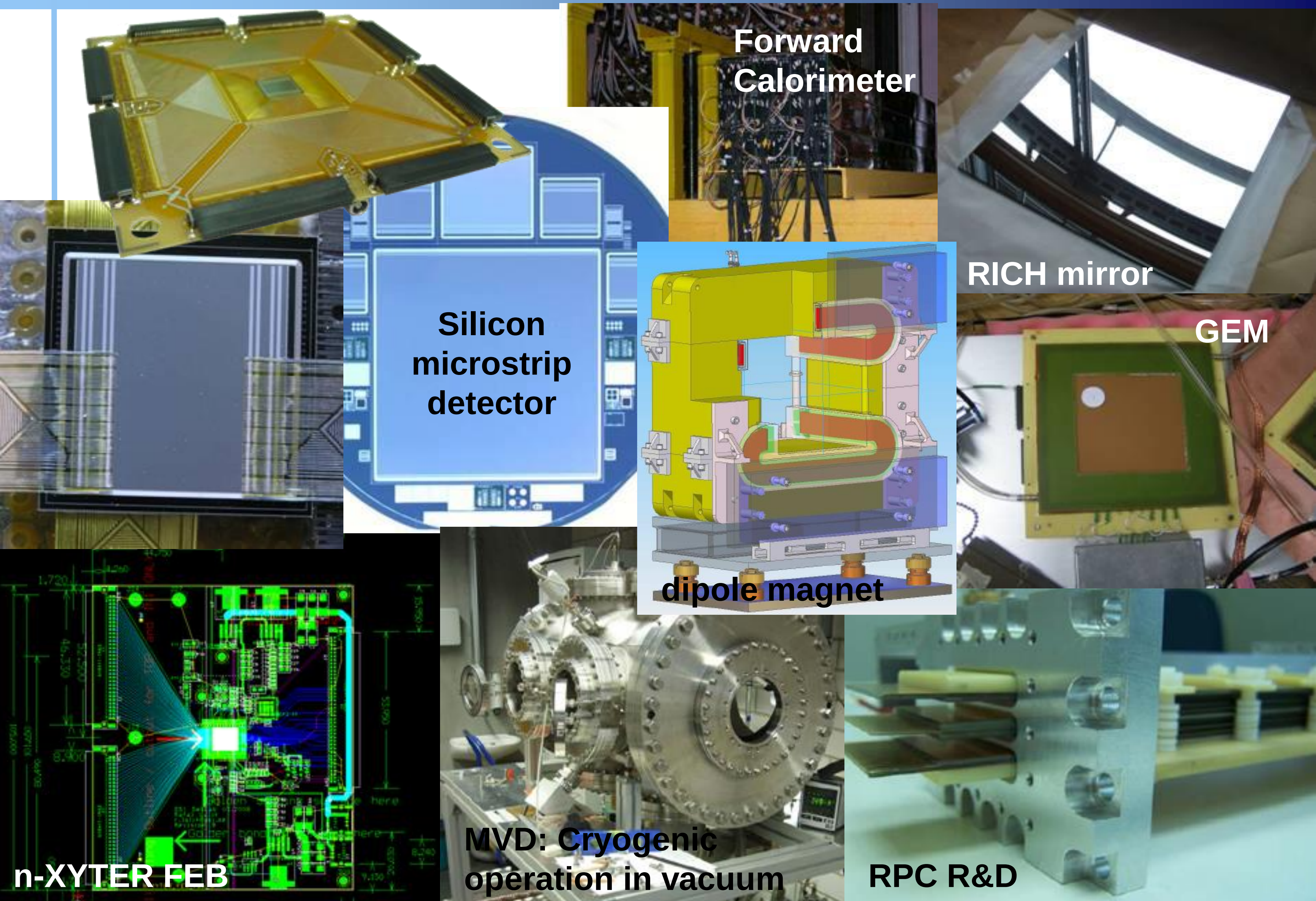
Beam spot seen on a GEM detector (every 2nd channel read out)

Participants:

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

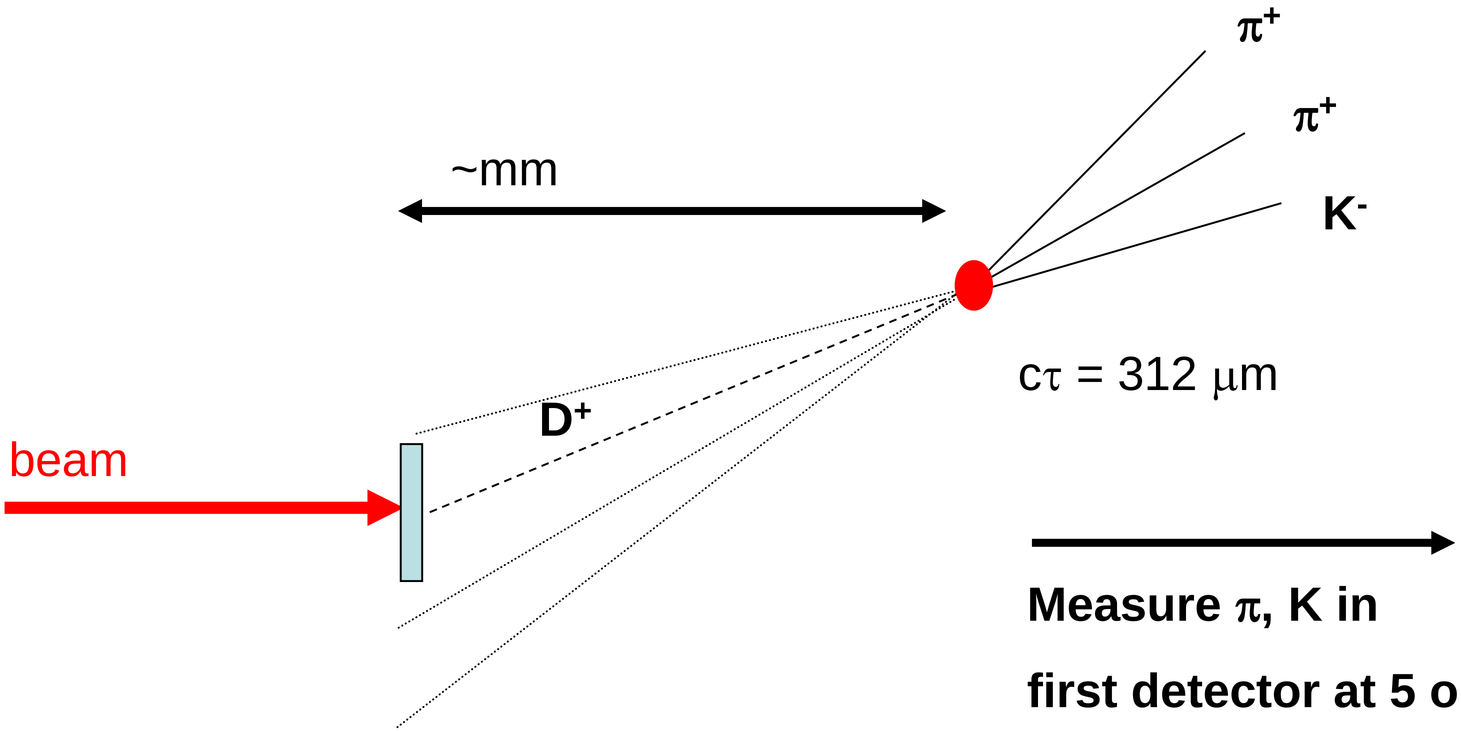
www-cbm.gsi.de

CBM hardware R&D



Open charm reconstruction

- open charm reconstruction via the reconstruction of their 2ndary decay vertex
- most important features for background rejection
  - good position resolution of 2ndary decay vertex (~50 μm)
  - good position resolution for back extrapolation of decay particles to primary vertex plane
- thin high resolution detectors needed which are close to the primary vertex!

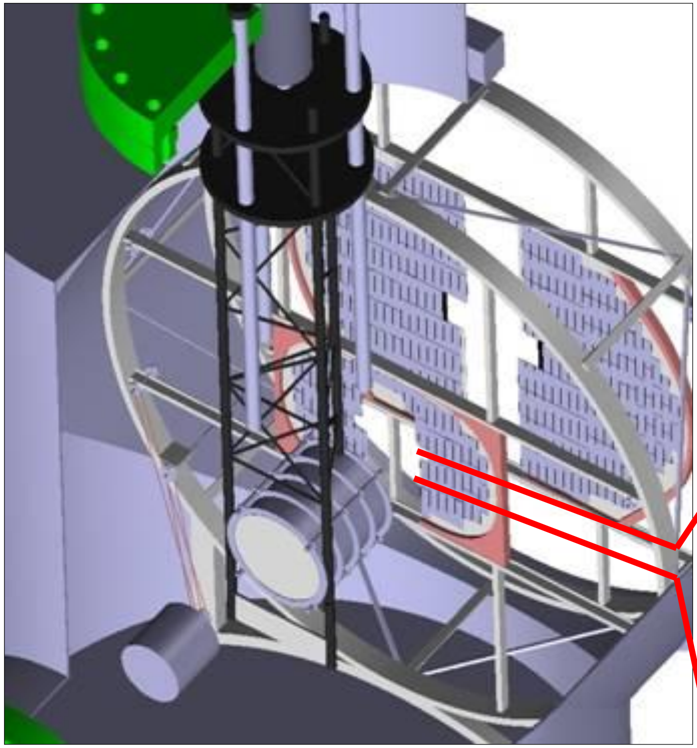


Measure π, K in

first detector at 5 or 10 cm

Micro Vertex Detecor (MVD) Development

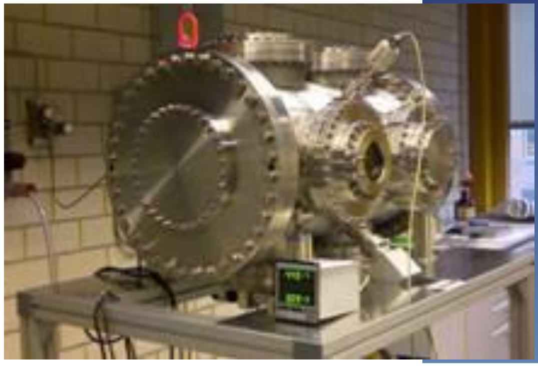
Artistic view of the MVD

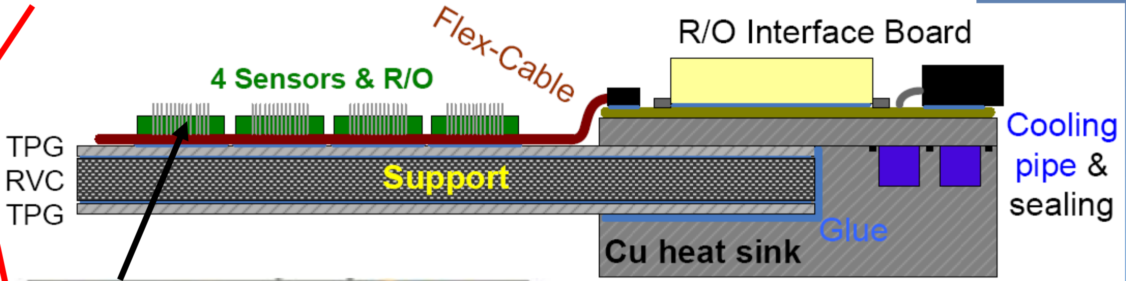


- mechanical system integration
- material for cooling!

→ material budget!

- vacuum compatibility





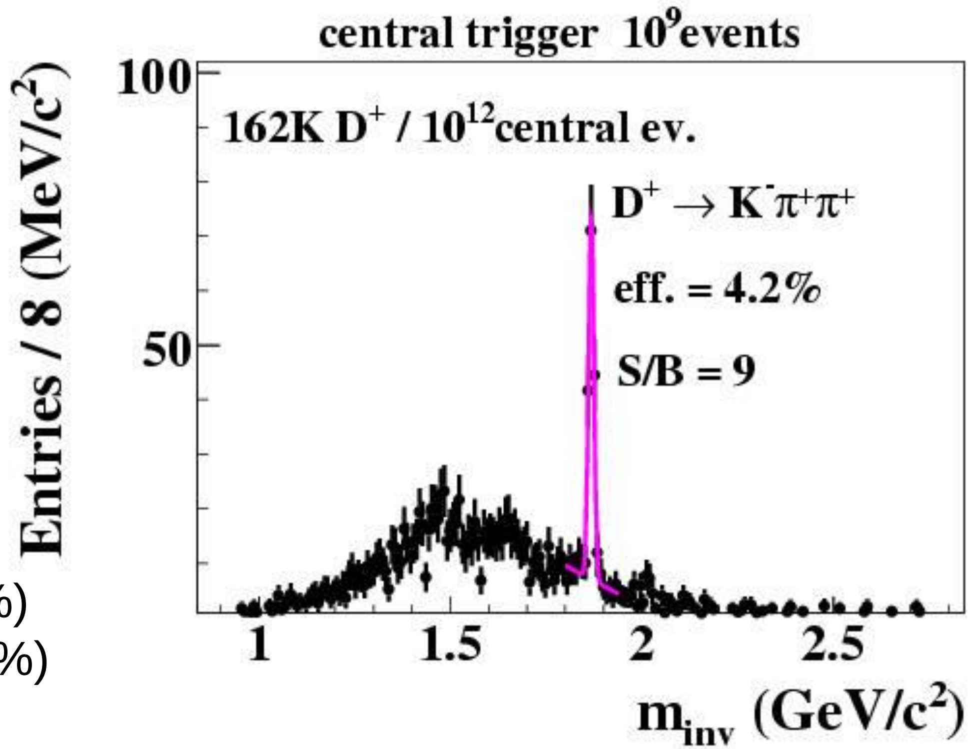
IPHC, Strasbourg (M. Winter et al.)

die thinned to 50 μm glued to support.

Monolithic **A**citive **P**ixel **S**ensors
in commercial CMOS process
10×10 μm² pixels fabricated,
$\varepsilon > 99\%$, $\Delta x \sim 1.5 – 2.5\ \mu m$

D-meson Simulations

- CbmRoot simulation framework, GEANT3 implemented through VMC
- full event reconstruction: track reconstruction, particle-ID (RICH, TRD, TOF), 2ndary vertex finder
- feasibility studies: central Au+Au collisions at 25 AGeV beam energy (UrQMD)
- several channels studied: D^0, $D^\pm$, D_s, Λ_c
- here: 2 MAPS layers (10, 20 cm, 150 μm Si-equivalent each)

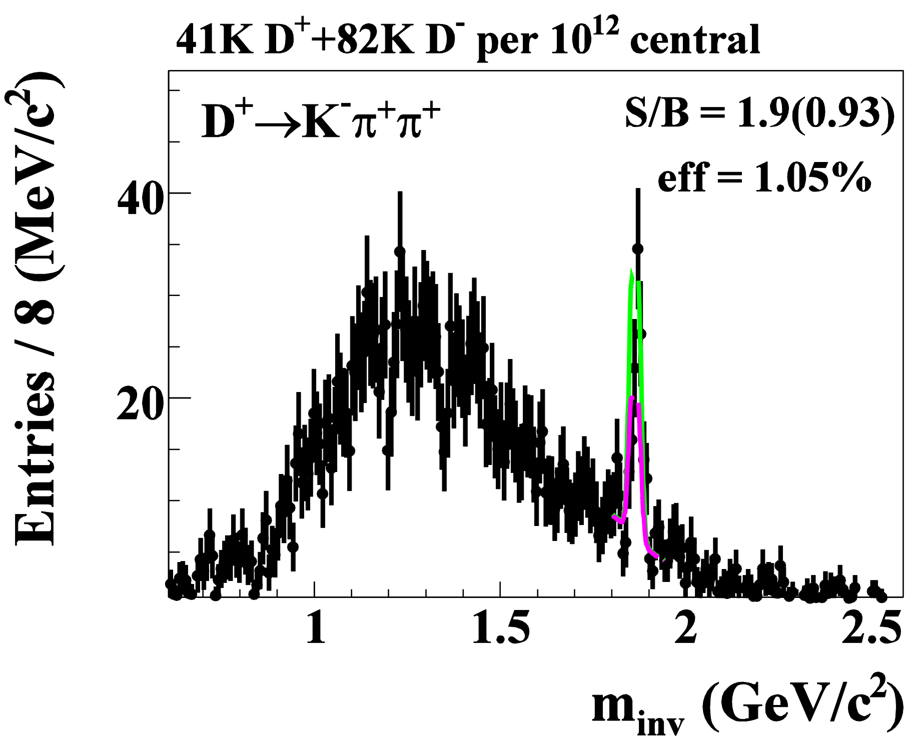


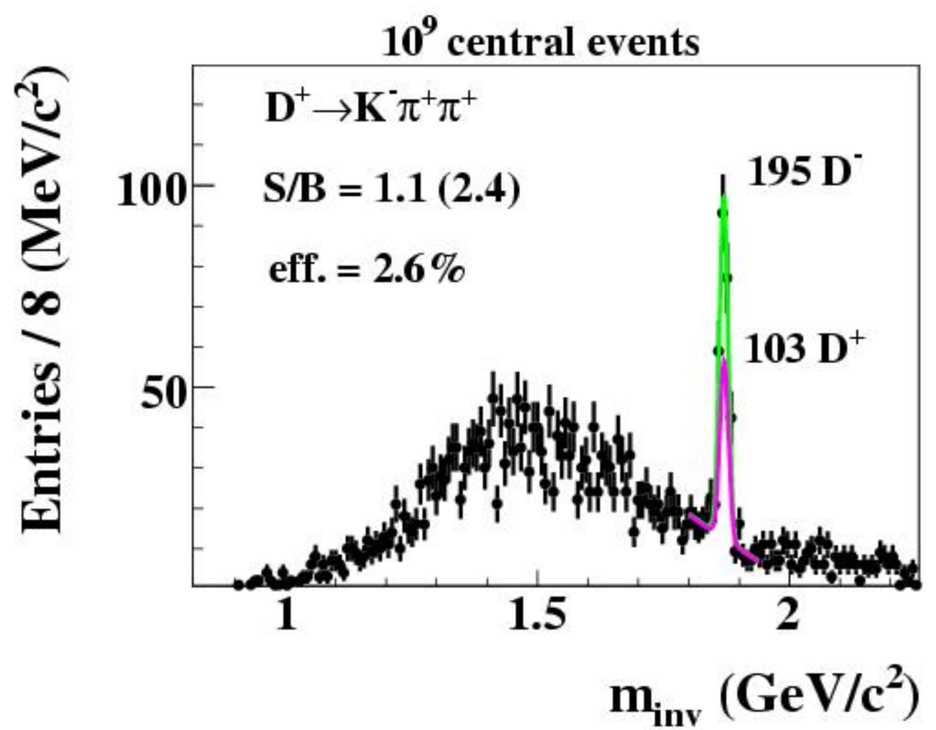
$D^+ \rightarrow \pi^+\pi^+K^-$ ($c\tau$ = 312 μm, BR 9%)
$D^0 \rightarrow K^-\pi^+$ ($c\tau$ = 123 μm, BR 3.85%)
$\Lambda_c \rightarrow pK^-\pi^+$ ($c\tau$ = 60 μm, BR 5%)

D meson reconstruction

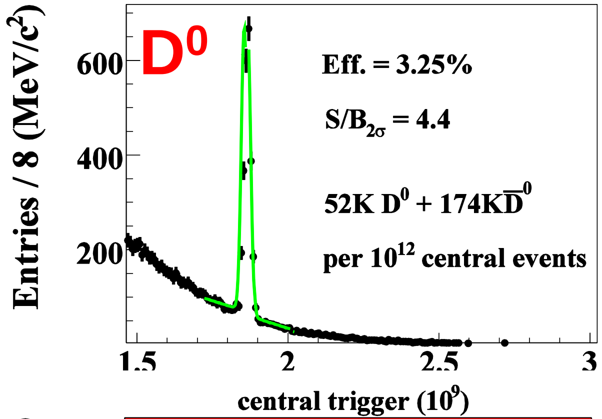
- important layout studies: MAPS position and thickness !
- HSD: <D+> = 4.2 · 10^{-5}/ev
- 10^{12} central events ~ 8-10 weeks running time

1st MAPS thickness	Position of 1st	D+ efficiency	D+ S/B (2σ)	D+ in 10^{12} ev.
150 μm	10 cm	4.2%	9	$162 \cdot 10^3$
500 μm	10 cm	1.05%	0.93	$41 \cdot 10^3$
300 μm	5 cm	2.6%	1.1	$103 \cdot 10^3$

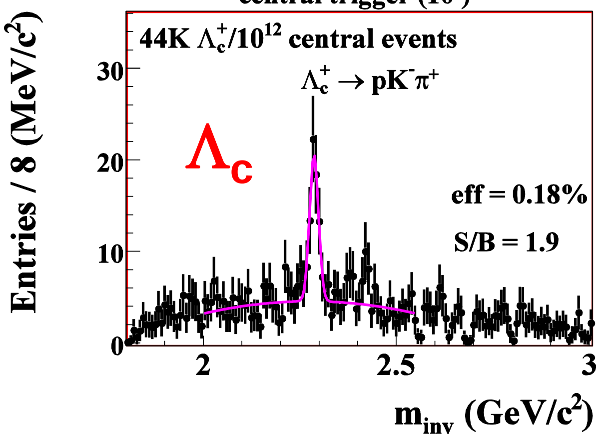




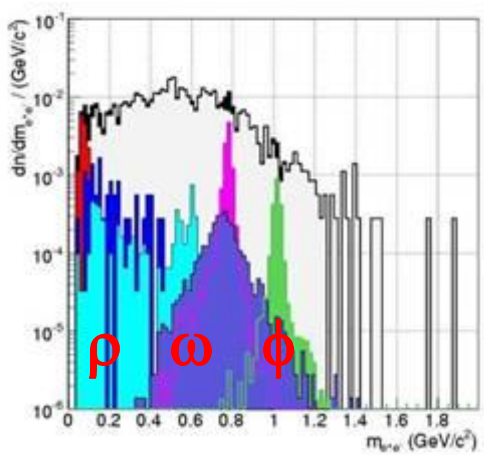
CBM feasibility studies



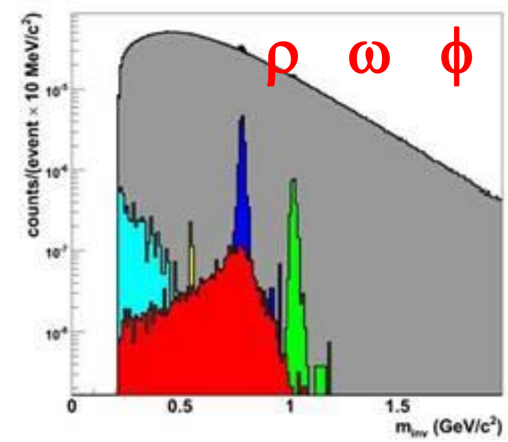
- feasibility studies performed for all major channels including event reconstruction and semirealistic detector setup

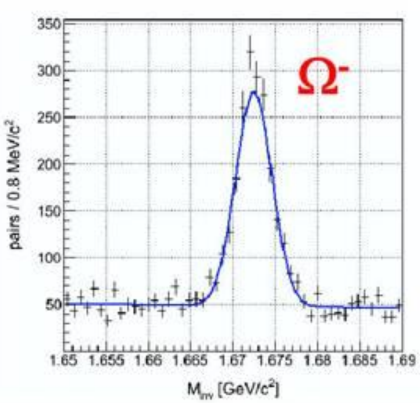


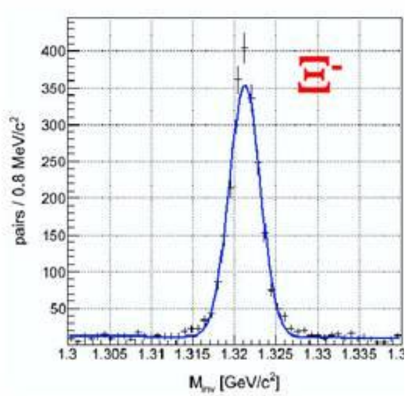
di-electrons

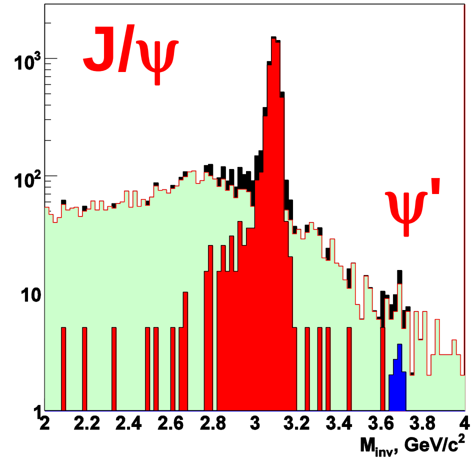


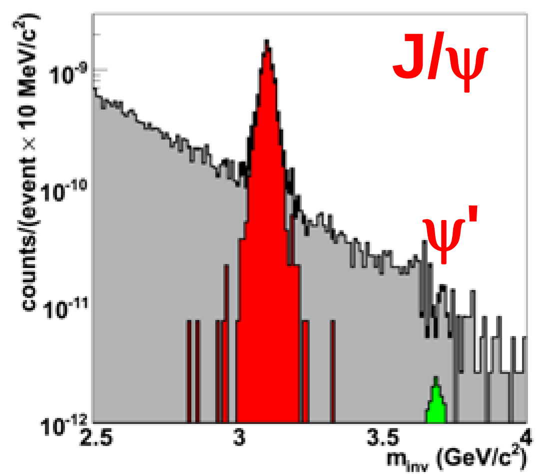
di-muons











Challenges of the di-electron measurement

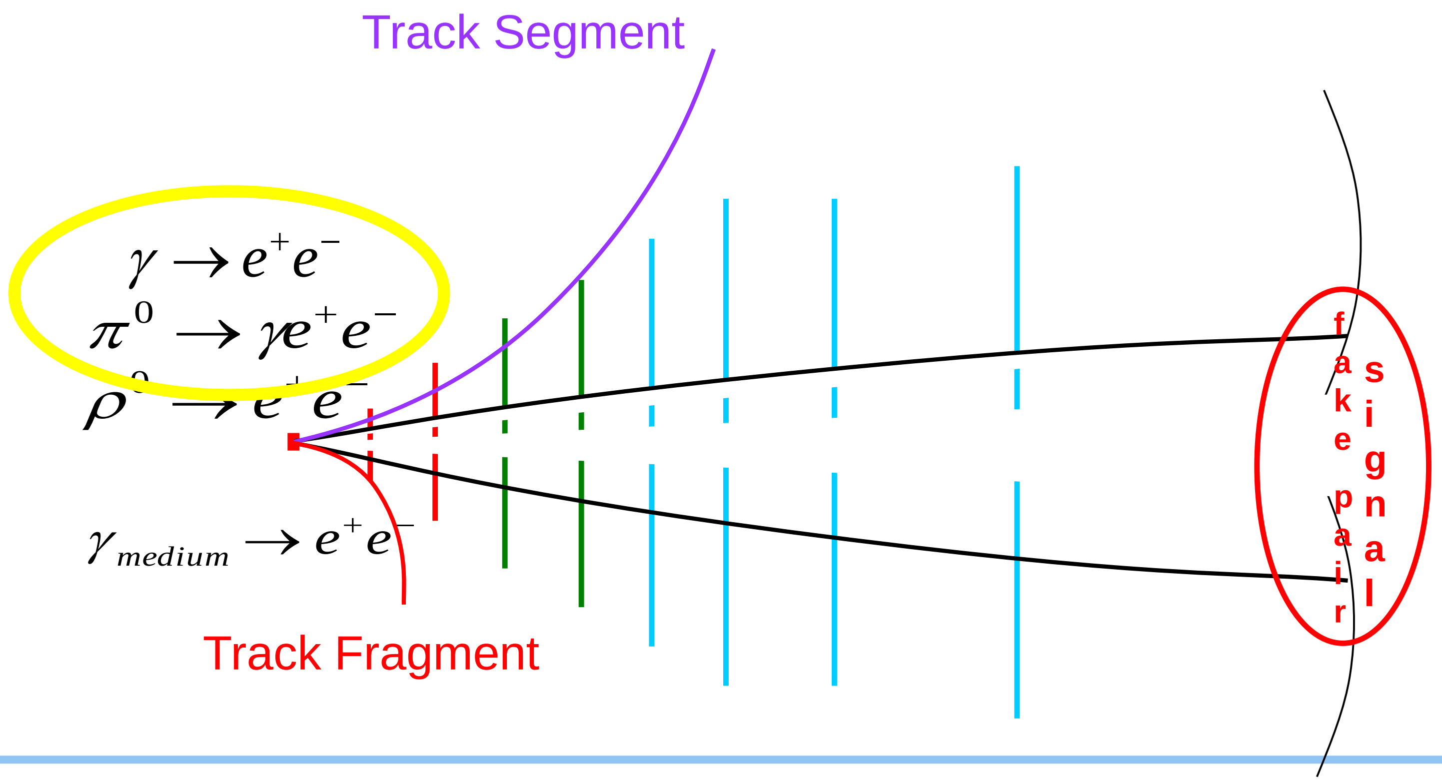
- **clean electron identification** (π suppression ≥ 10^4)
- **large background from physical sources**

RICH & TRD

γ-conversions in target and STS, π^0 Dalitz decays

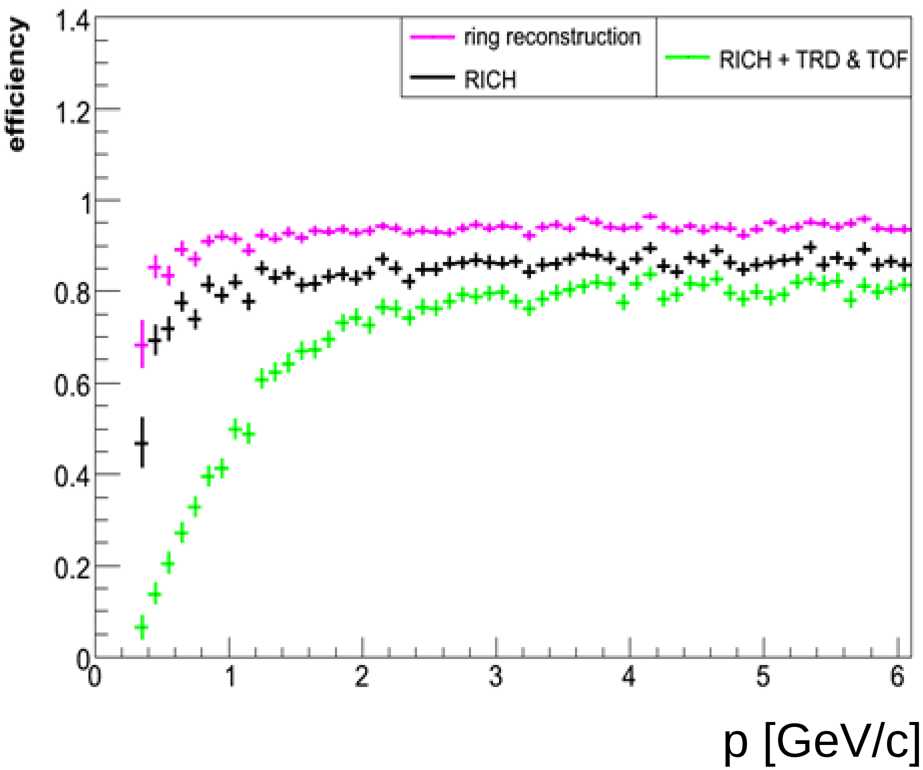
→ use excellent tracking and two hit resolution (≤ 100 μm) in first pixel detectors in order to reject this background:

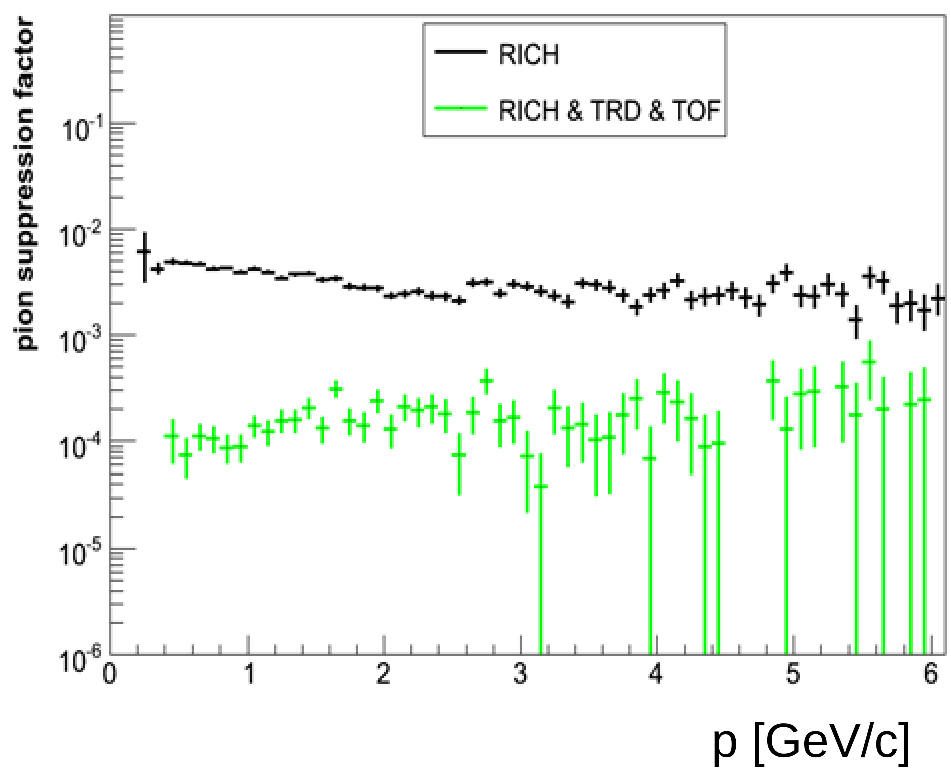
→ optimize detector setup (STS, B-field), use 1‰ interaction target



Performance of combined e-ID

- use RICH, TRD (and TOF) detectors for electron identification
- 10^4 π-suppression at ~75% efficiency
- combined purity of identified electrons ~96%



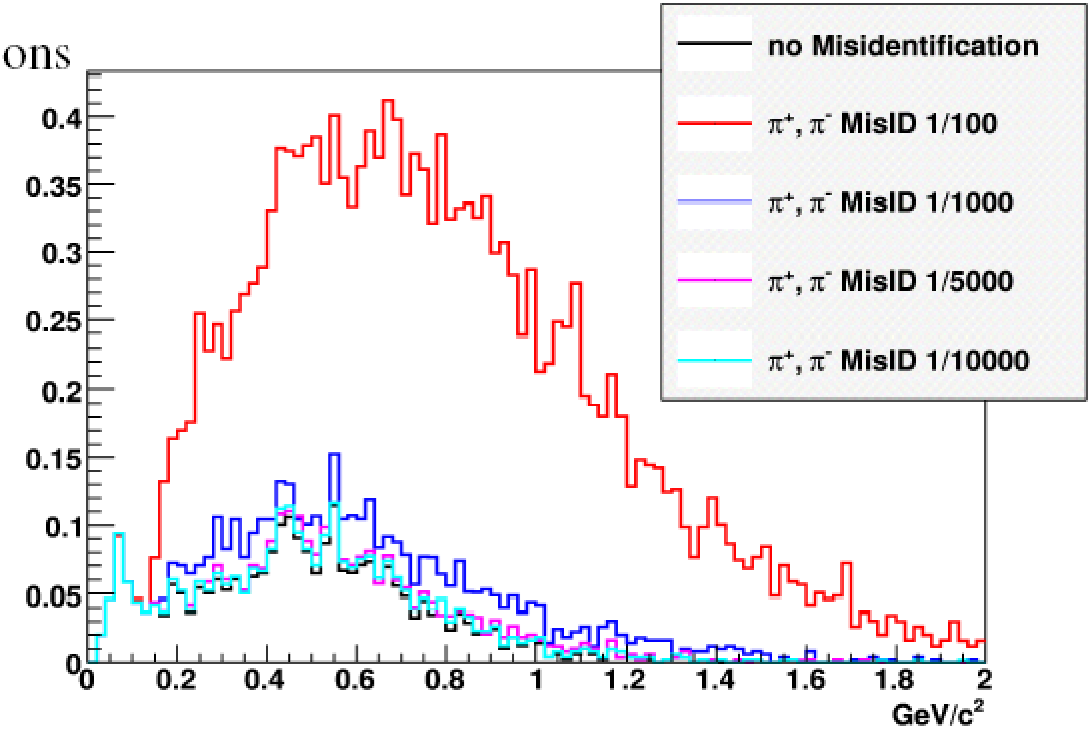


Background in electron measurement

Combinatorial background assuming that every 1/N of pions are misidentified as electron/positron. N = 100, 1000, 5000, 10000

Fraction of misidentified pions

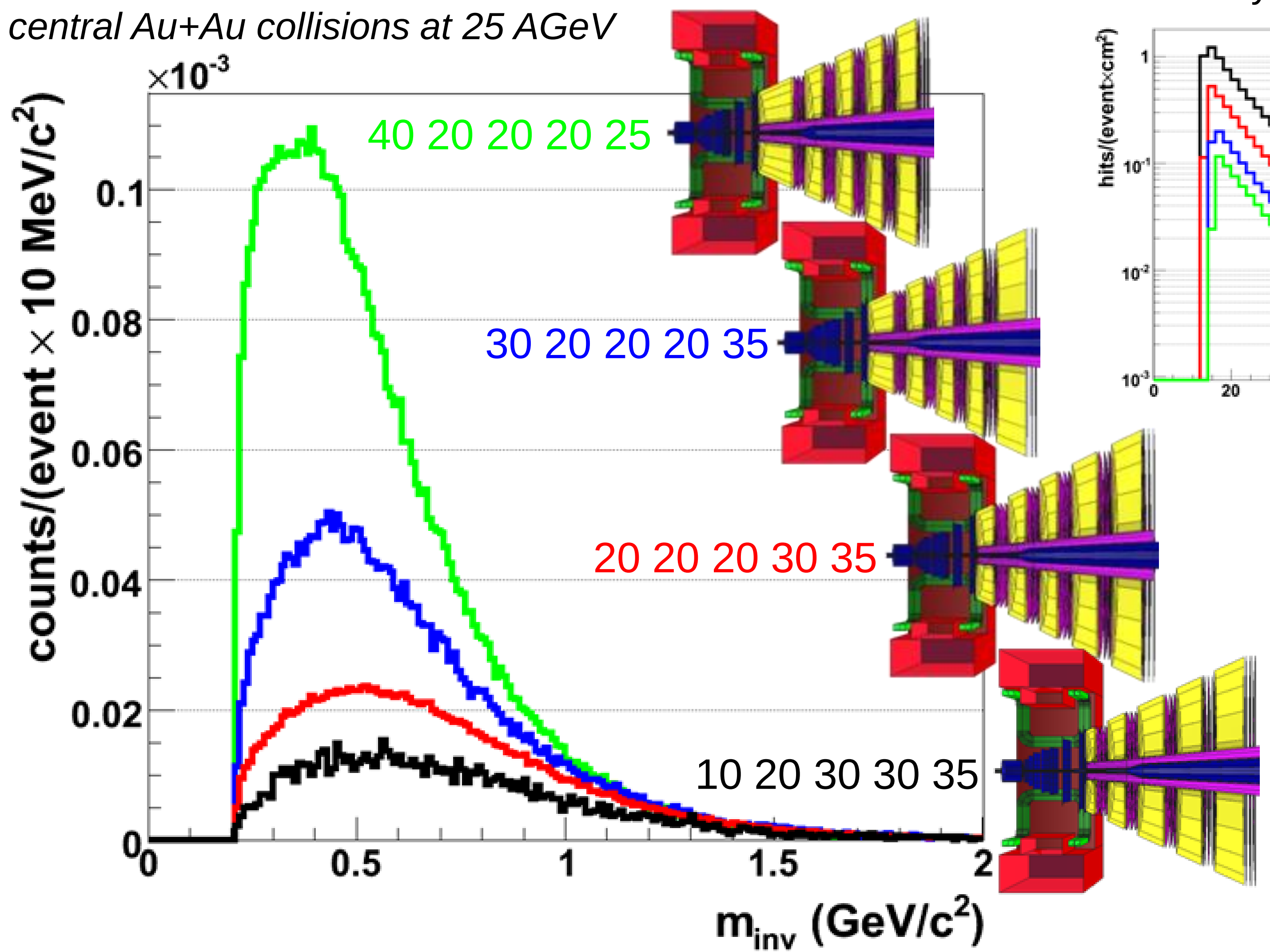
85%	-	1/100
37%	-	1/1000
11.2%	-	1/5000
6.8%	-	1/10000

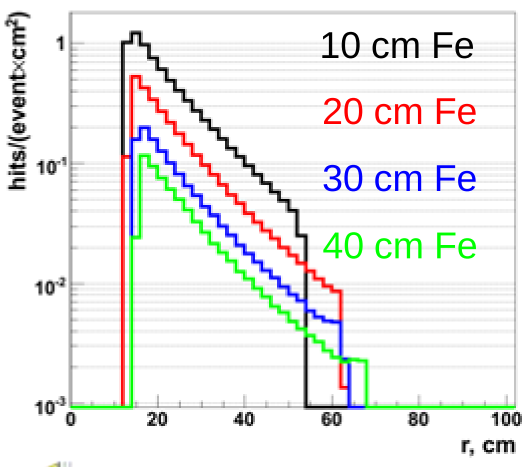


With π-misidentification of 1/5000 the combinatorial background is purely dominated by physical sources (88.8%)

K. Antipin, IKF Frankfurt

Detector layout optimization: Muon absorber

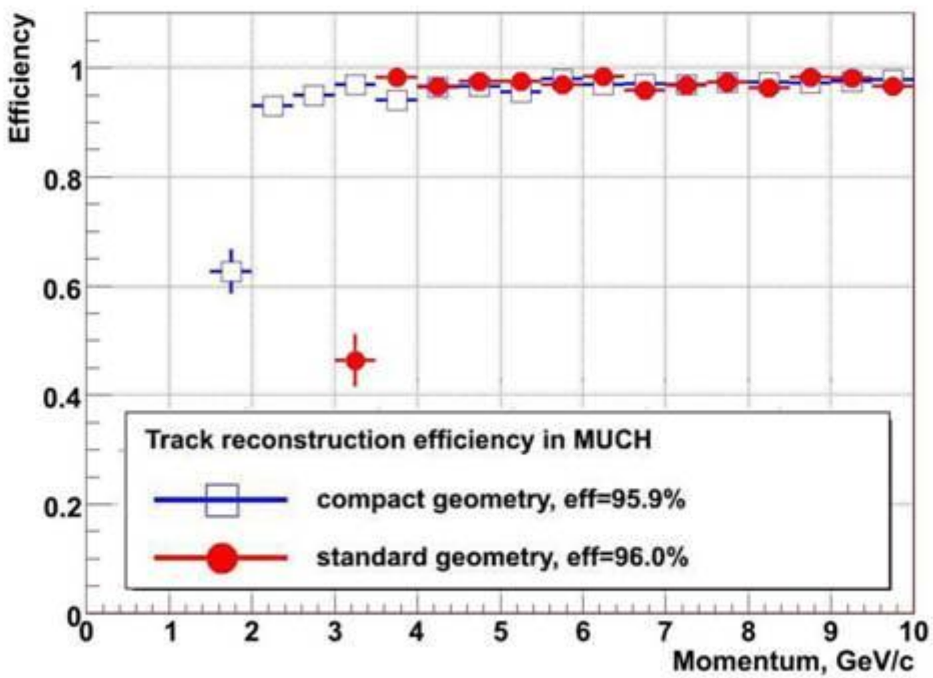


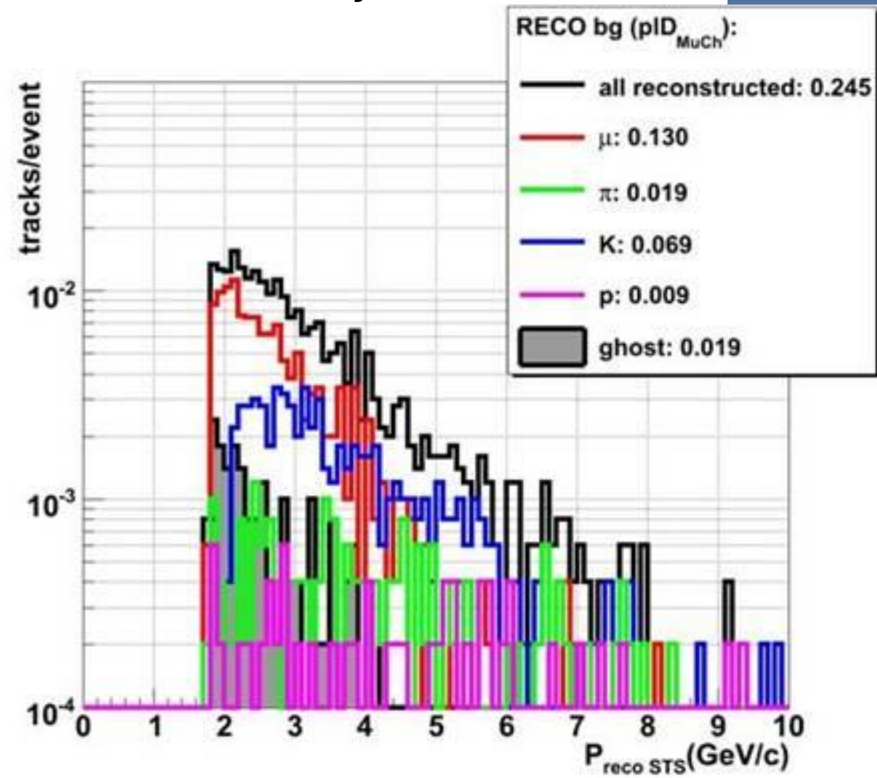


total absorber length 125 cm = 7.5 λ_I

Muon identification

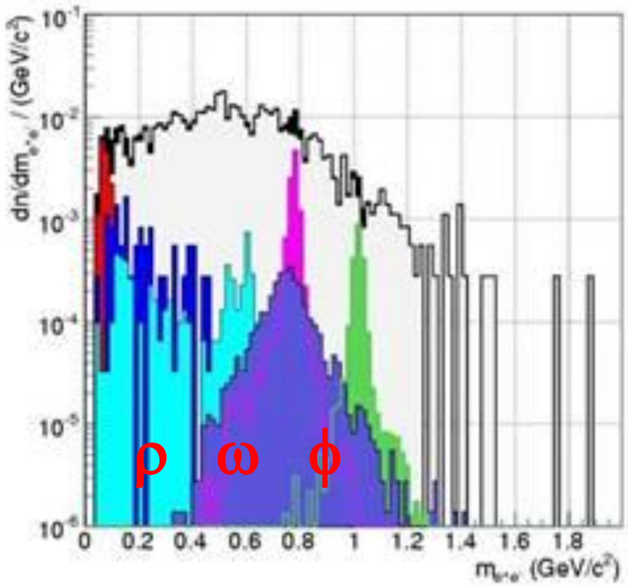
- alternating absorber-detector system allows efficient muon tracking
- central Au+Au collisions, 25 AGeV, absorber layout as (20+20+20+30+35) cm iron, 3 detector stations in between
- certain momentum cutoff depending on absorber length
- main part of remaining background: muons from π, K decays



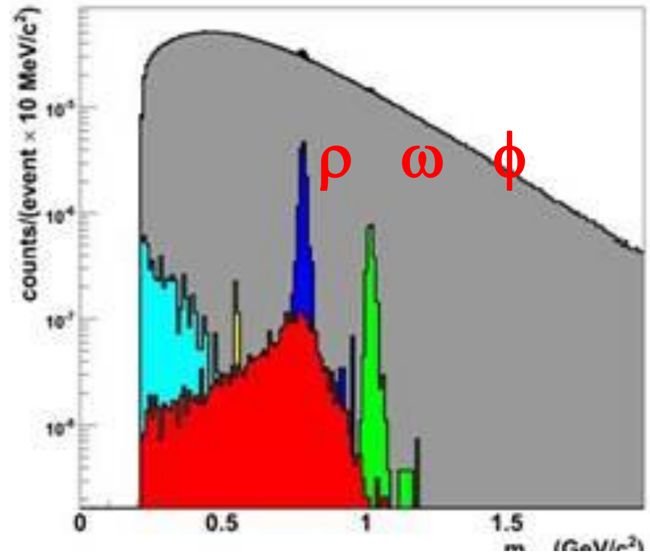


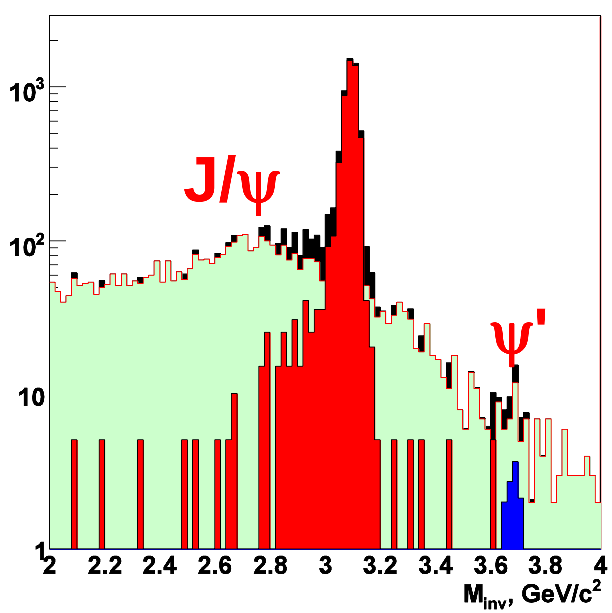
Dileptons

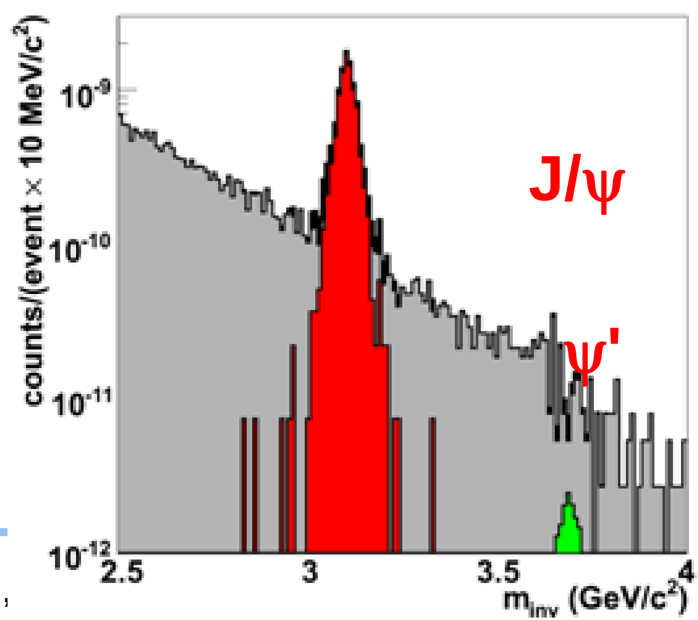
di-electrons



di-muons







very similar performance despite of the different background sources

Summary – physics of CBM

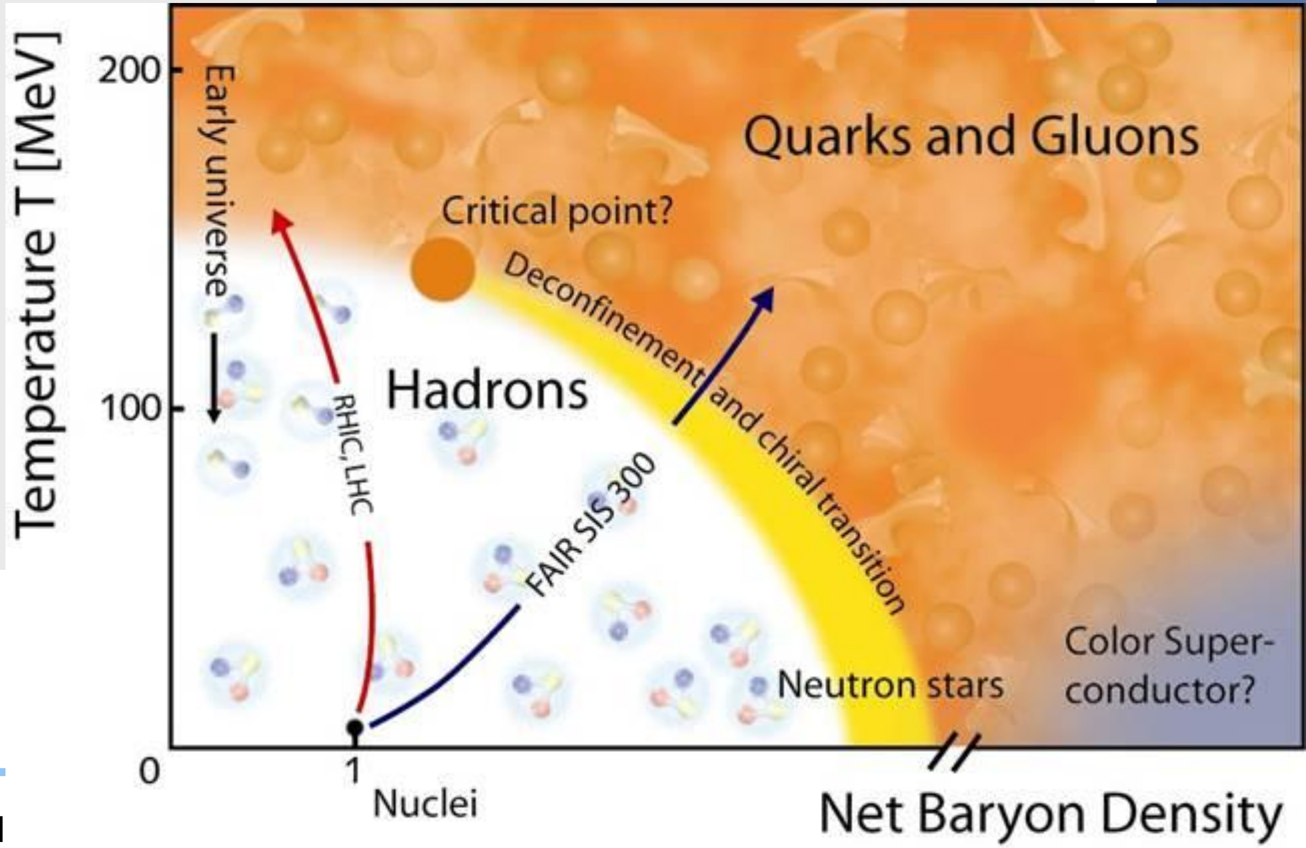
CBM@FAIR – high μ_B, moderate T:

- searching for the landmarks of the QCD phase diagram
  - first order deconfinement phase transition
  - chiral phase transition
  - QCD critical endpoint

→ systematic measurements, rare probes

- characterizing properties of baryon dense matter
- in medium properties of hadrons?

in A+A collisions from 10-45 AGeV ($\sqrt{s_{NN}}$ = 4.5 – 9.3 GeV) starting in 2016 at SIS 300



CBM collaboration

China:
Tsinghua Univ., Beijing
CCNU Wuhan
USTC Hefei

Croatia:
University of Split
RBI, Zagreb

Cyprus:
Nikosia Univ.

Czech Republic:
CAS, Rez
Techn. Univ. Prague

France:
IPHC Strasbourg

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

Hungaria:
KFKI Budapest
Eötvös Univ. Budapest

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

Korea:
Korea Univ. Seoul
Pusan National Univ.

Norway:
Univ. Bergen

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

Portugal:
LIP Coimbra

Romania:
NIPNE Bucharest
Bucharest University

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

Ukraine:
INR, Kiev
Shevchenko Univ. , Kiev

55 institutions, > 400 members