Physics of Compressed Baryonic Matter and the CBM Experiment

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HIC for FAIR
Helmholtz International Center

Outline

- **Introduction & Motivation**
  - QCD phase diagram & experimental results
    → fundamental questions of QCD

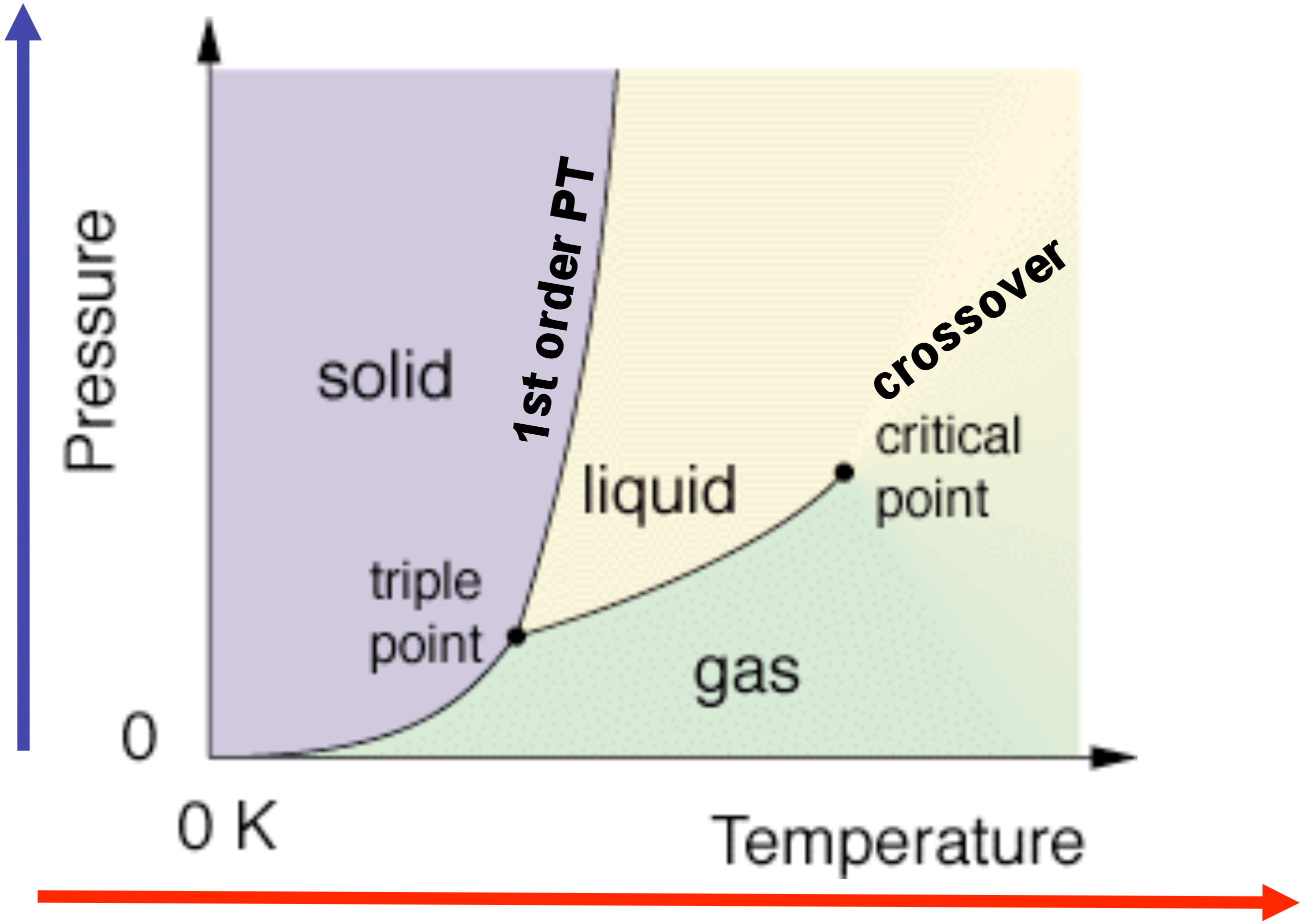
- Equation of state of strongly interacting matter?
- Structure of strongly interacting matter as function of T and ρ_B?
- In medium properties of hadrons as function of T and ρ_B?

→ **address with heavy-ion collisions**

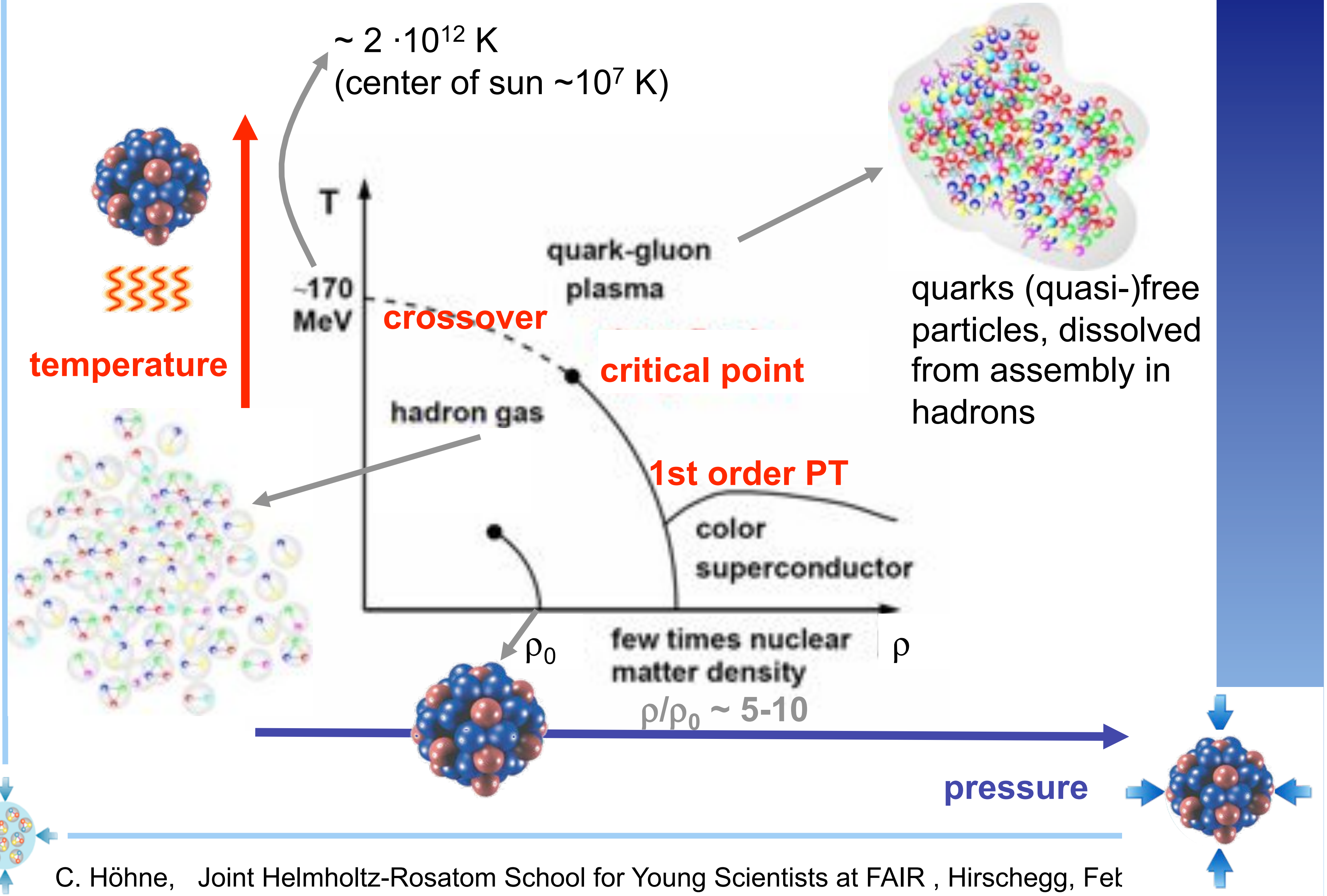
- **CBM experiment at FAIR**
  - examples for
    - feasibility studies
    - detector R&D

Phasediagram

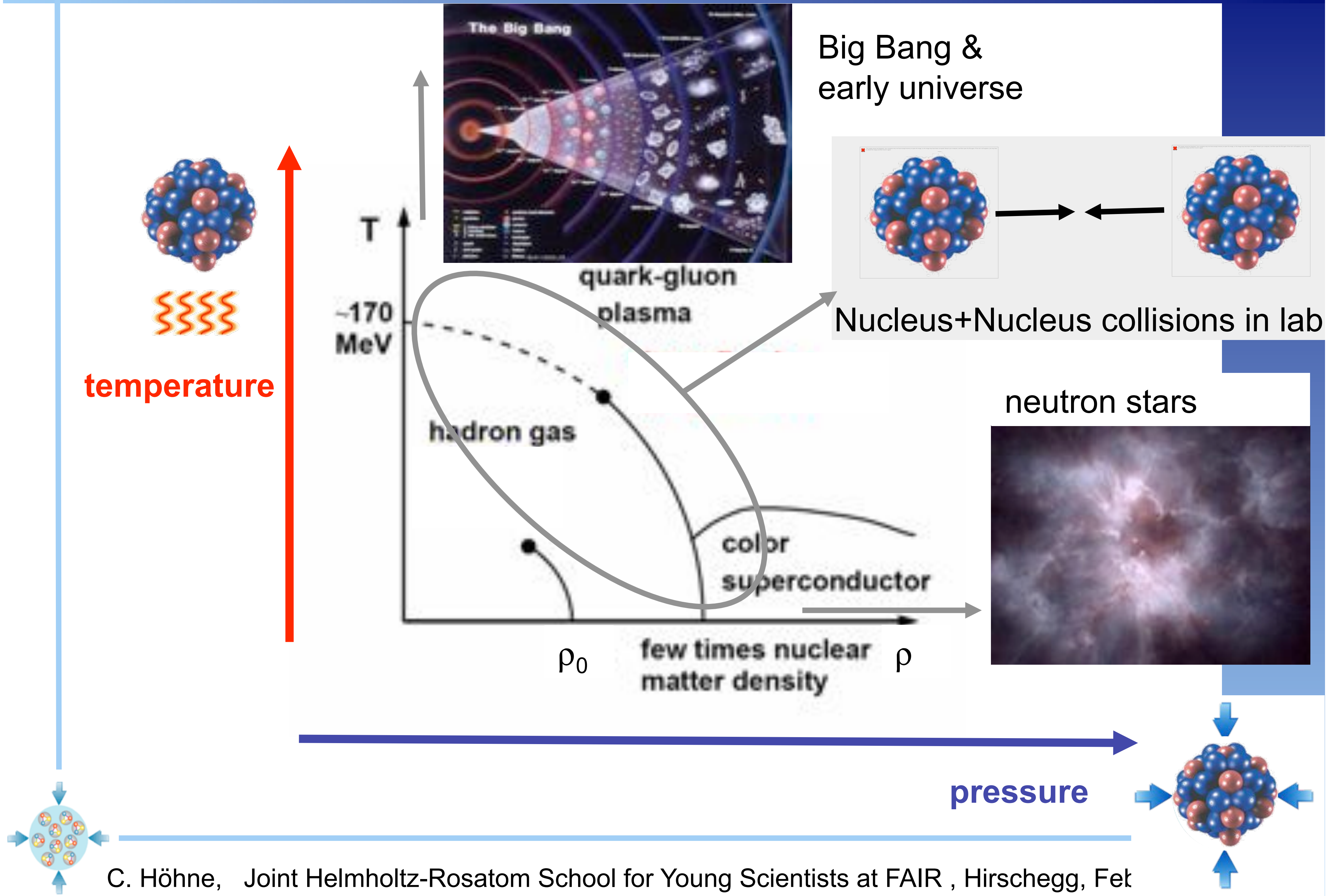
- normal matter exists in different phases depending on p,T
- phasediagram for hot and dense nuclear matter?



Phasediagram of strongly interacting matter



Phasediagram of strongly interacting matter



Phasediagram of strongly interacting matter

Fundamental questions of QCD

- Equation of state of strongly interacting matter?
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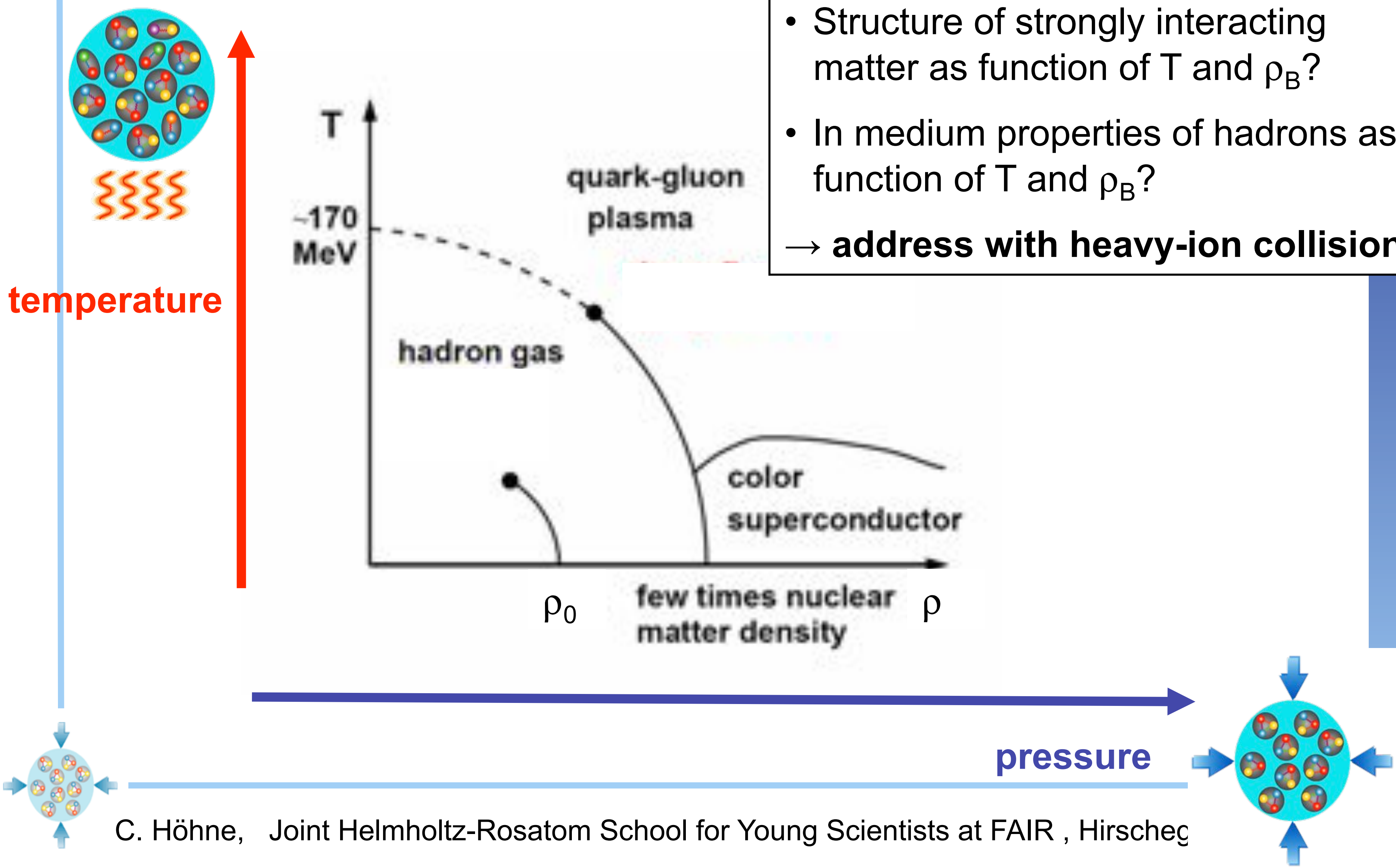
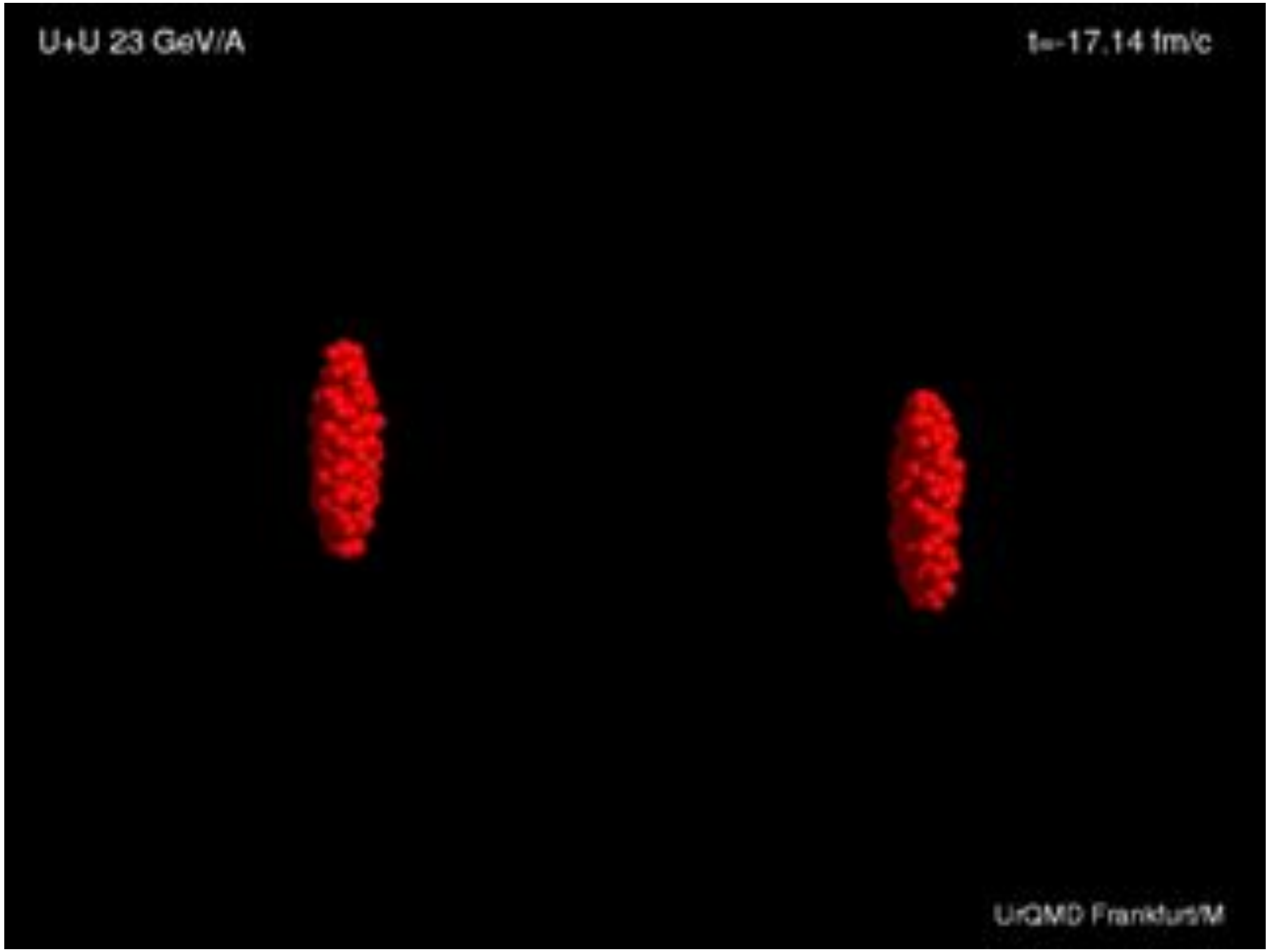
- In medium properties of hadrons as function of T and ρ_B?

→ **address with heavy-ion collisions**



Heavy ion collisions

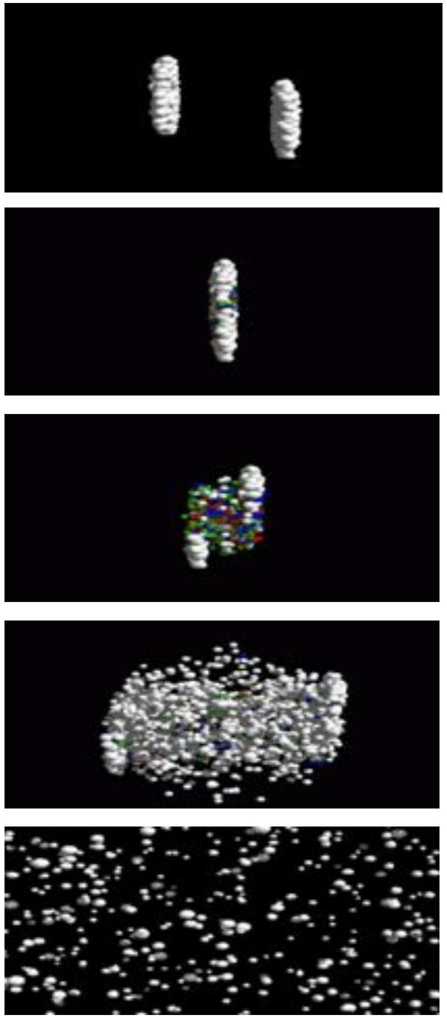
simulation of a U+U collision at 23 GeV/A (UrQMD)



nucleons mesons excited baryons

Phases of a heavy ion collision

UrQMD 160 GeV Au+Au



before collision

compression and heating

thermalization of the "fireball"
(high T and ρ reached for ~10fm/c = 3.3 10^{-23} s)

expansion

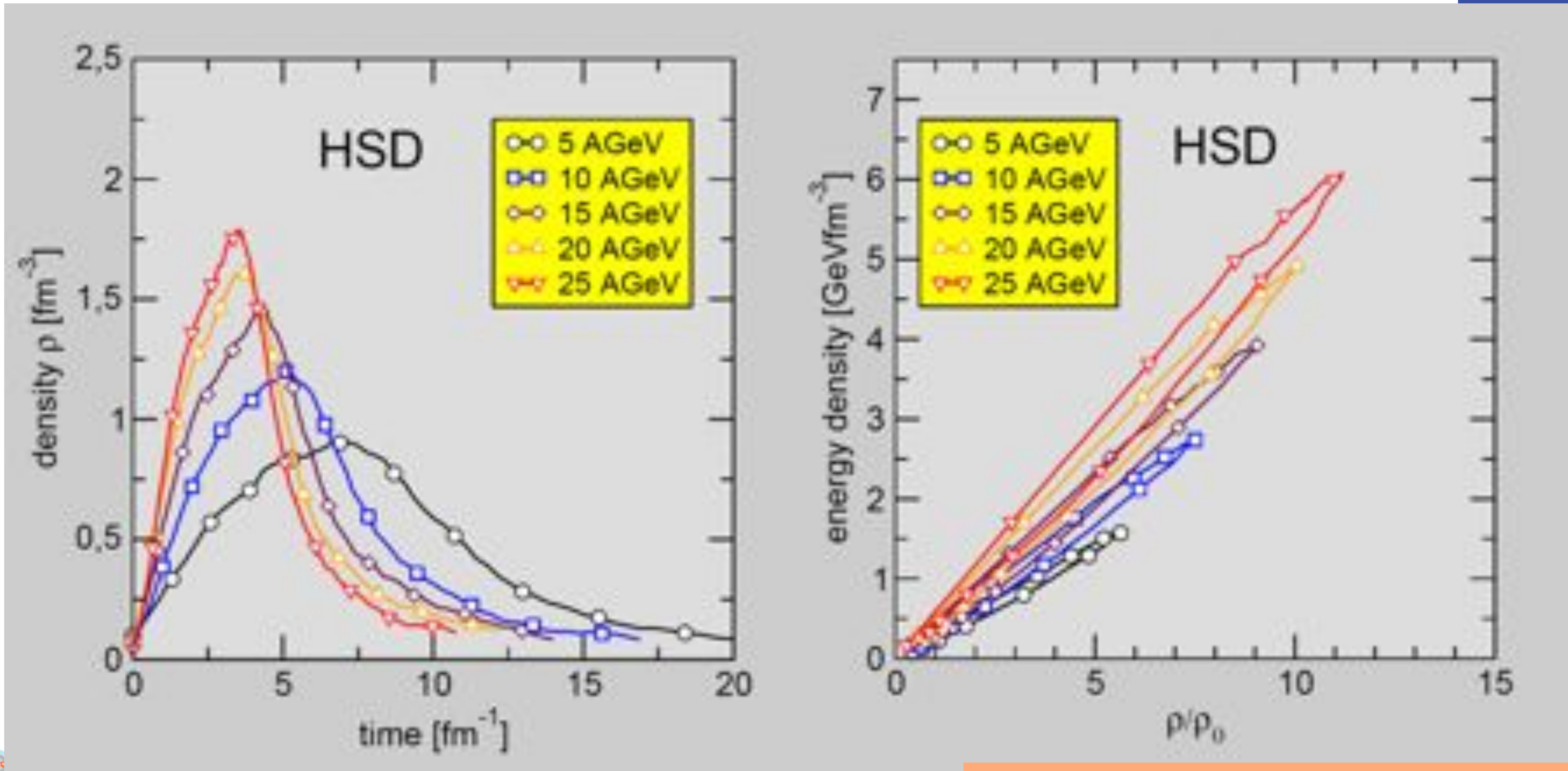
chemical freezeout (number and type of particles frozen)
kinetic freezeout (particle momenta frozen)

Heavy ion collisions (II)

simulation of Au+Au collisions at different beam energies

→ maximum baryon densities ρ increase with beam energy

→ energy densities also increase with beam energy



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

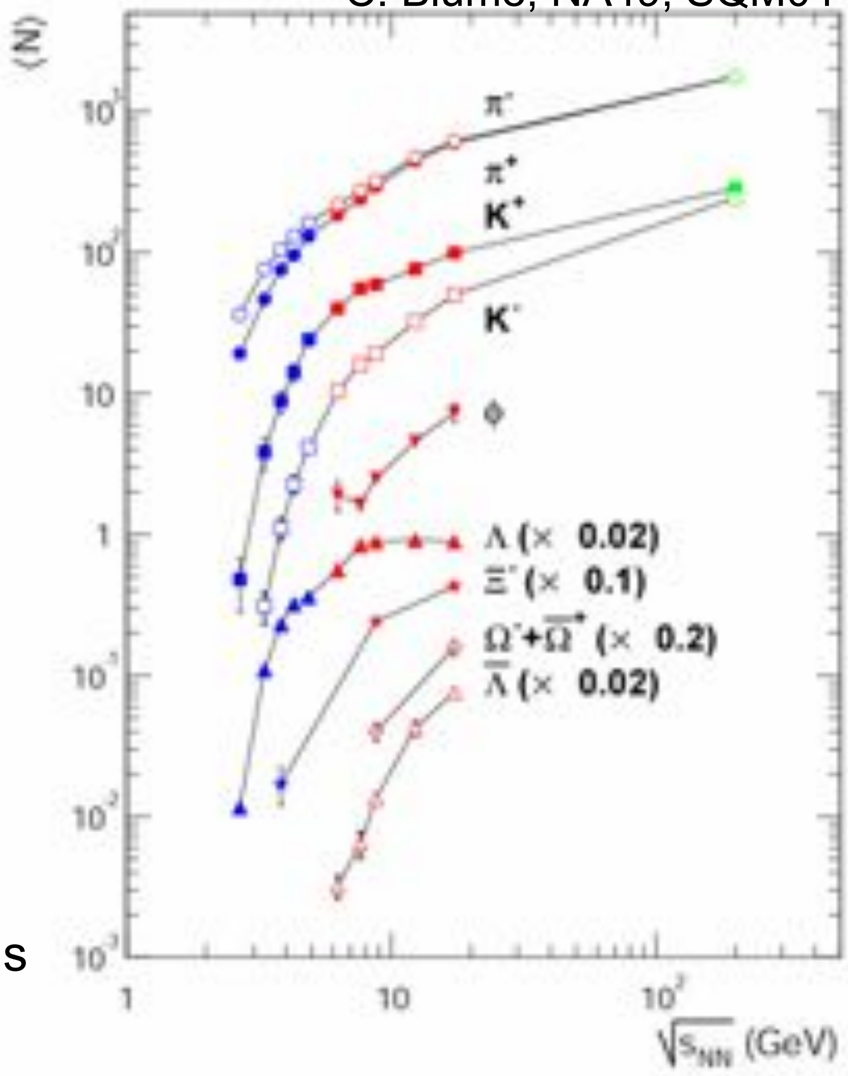
Particle production

~ 90% of all produced particles are pions

~10% kaons

one of the most rare ones are e.g. Ω baryons (sss)

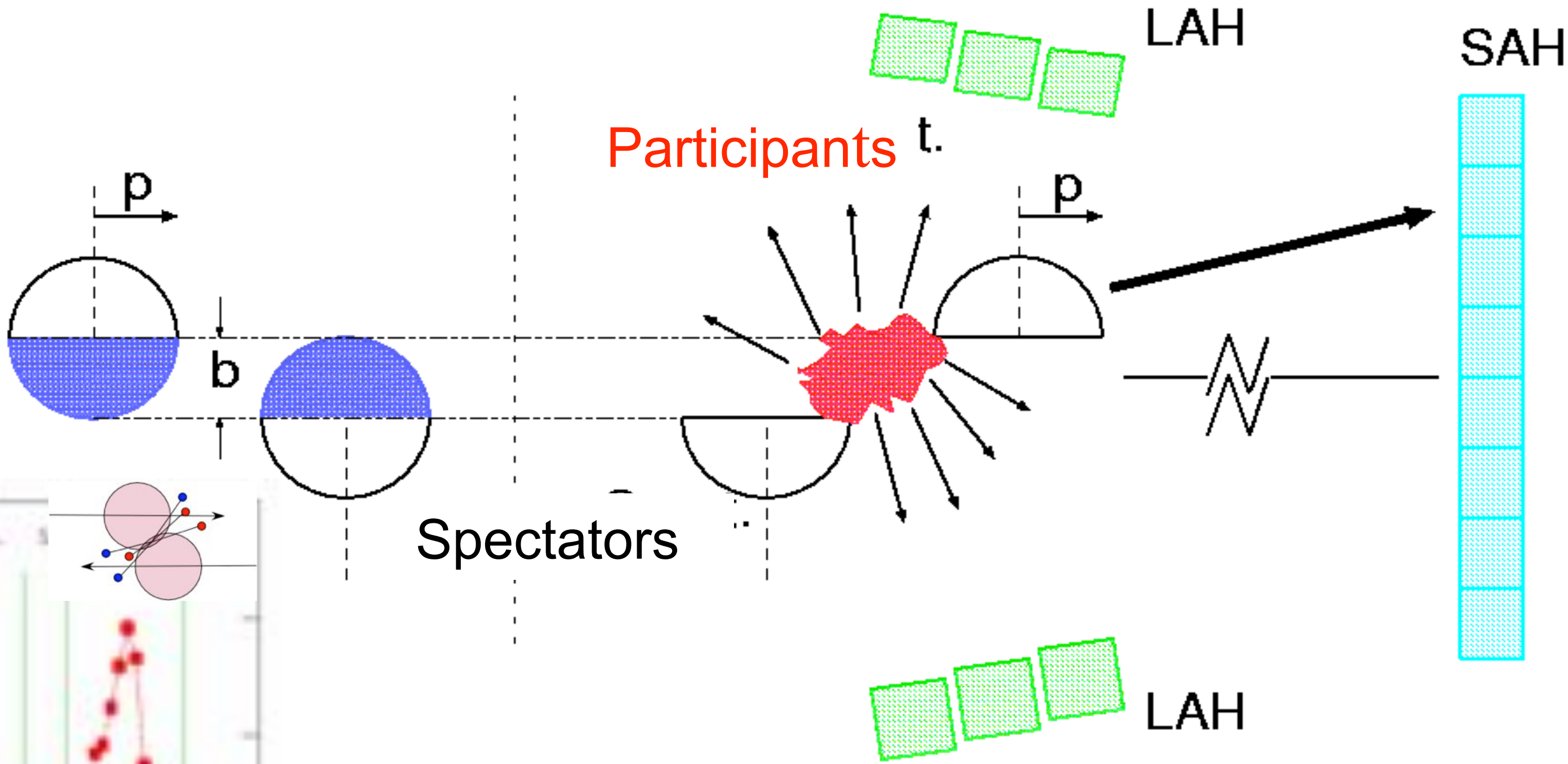
C. Blume, NA49, SQM04

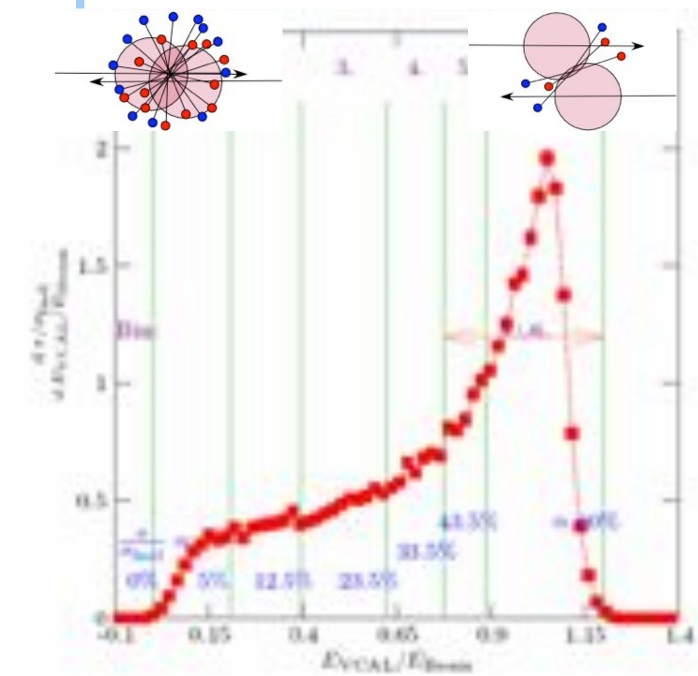


total particle multiplicities in central Au+Au / Pb+Pb collisions

A+A collisions (II)

- centrality of the collision can be measured by measuring the energy of the "spectators" → N_{spec} → extract also number of participating nucleons N_{part}





interaction cross section in dependence on the energy of the spectators

Particle production and statistical model

• number and type of produced particles can be nicely described with a statistical ansatz

ρ_i = density of particle of type i

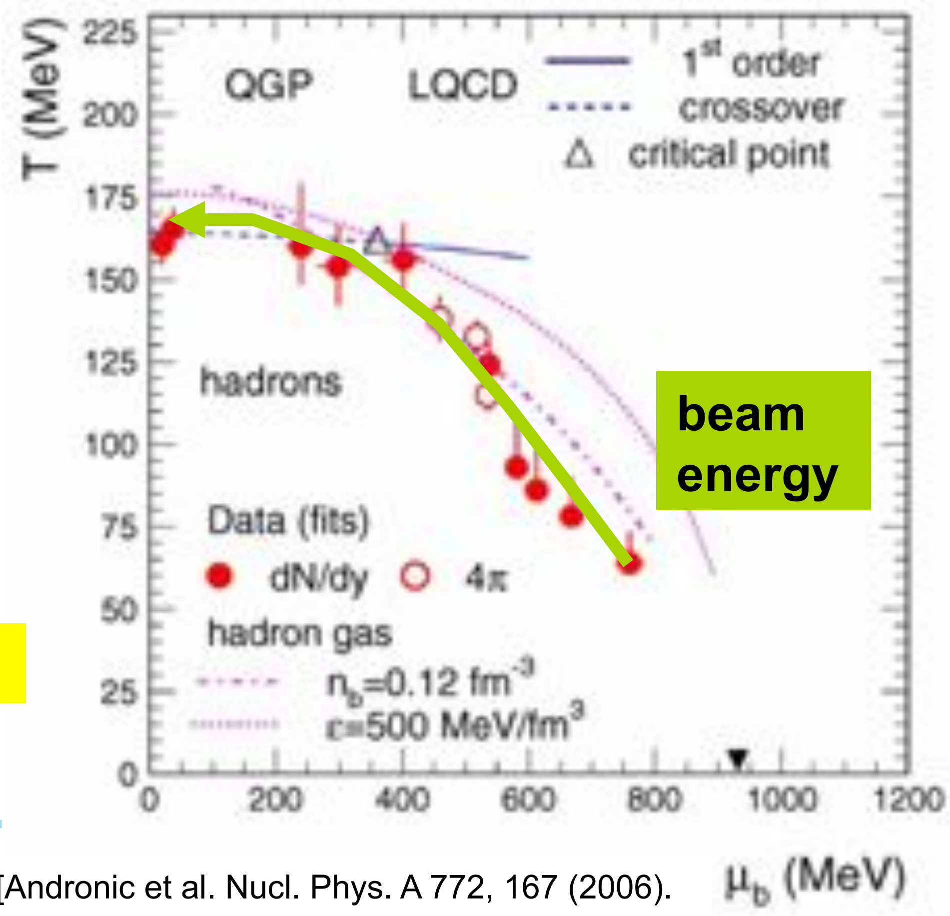
$$\rho_i = \frac{g_i}{2\pi^2}\int \frac{p^2 \mathrm{d}p}{\exp\left\{\frac{1}{T}(E_i - \mu_B B_i - \mu_S S_i)\right\} \pm 1}$$

• assumption: all particles stem from a thermalized fireball at temperature T and baryon chemical potential μ_b

• depending on the volume (e.g. p+p, central Au+Au) a (micro)canonical or canonical partition function is used

• with three parameters: V, T, μ_b particle yields can be explained

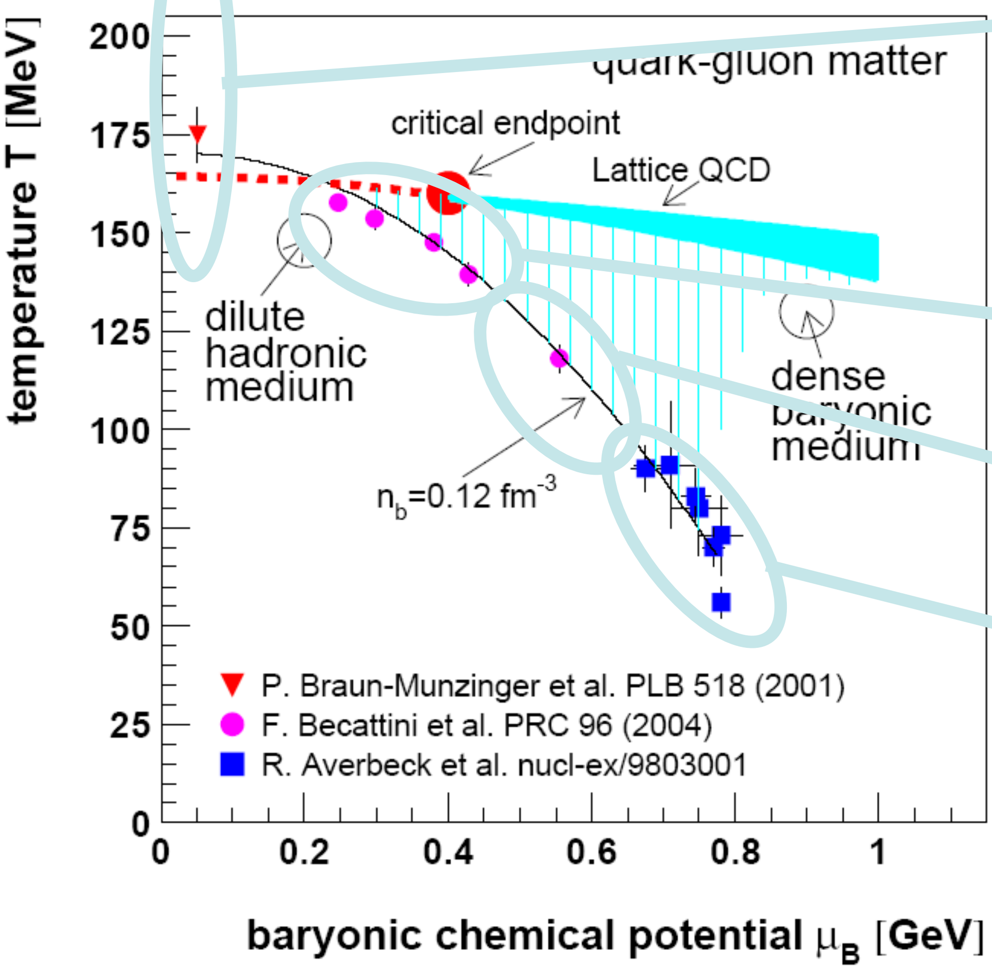
very successful model!



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

What do we know from experiment?

- since 1980s heavy ion collision experiments at AGS, SPS
- 2000 start of RHIC, 2009 LHC
- ongoing experiments at SIS exploring „resonance matter“



R. Averbeck et al., PRC 67 (2003) 024903

RHIC Brookhaven
√s = 130 - 200 GeV/nucleon
future: LHC

SPS CERN
20 -160 GeV/nucleon

AGS Brookhaven
2-10 GeV/nucleon

SIS18 GSI
< 2 GeV/nucleon

●▼■ “freeze-out” points: final hadron yields described by statistical model: T, μ_B, V

Phasediagram of strongly interacting matter

Fundamental questions of QCD

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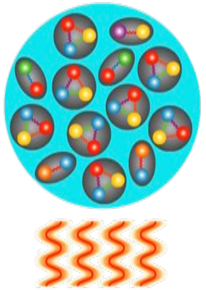
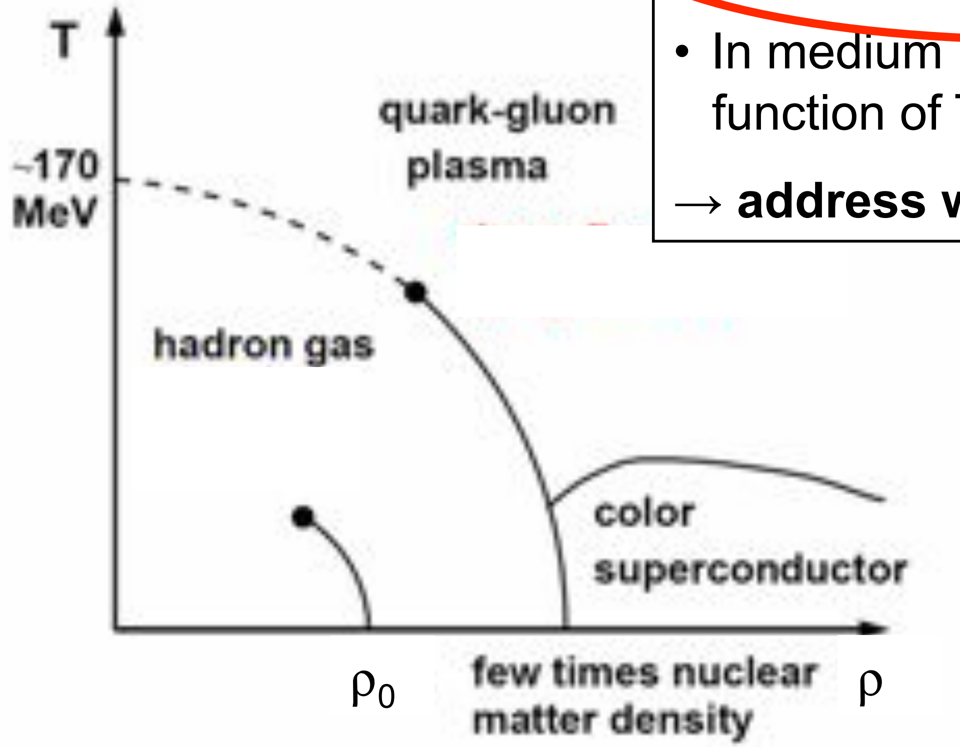
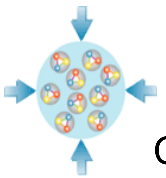
→ **address with heavy-ion collisions**

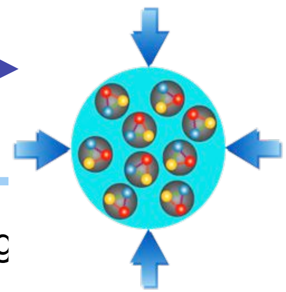


temperature



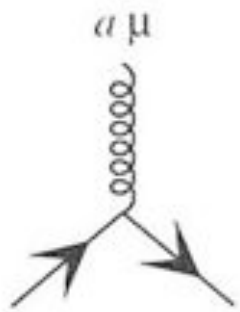
pressure

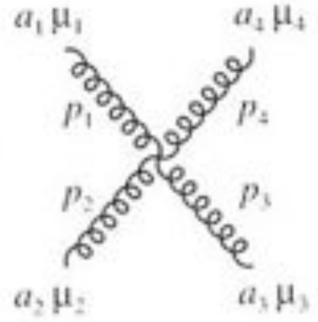


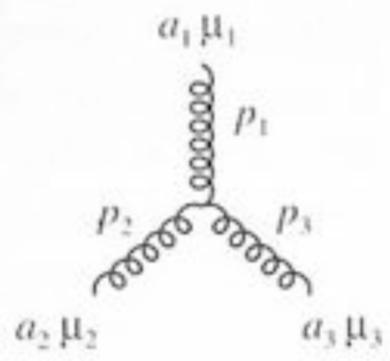


The nature of the strong force

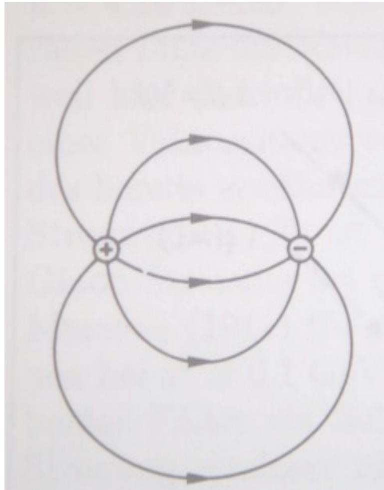
- interaction described by the exchange of gluons
- gluons carry color charge! → selfinteraction





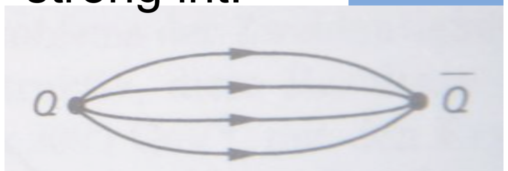


electromagn. int.



Property	QED	QCD
Charge	electric	colour
Bosons	photon (carries no charge)	gluons (carry charge)
Mass of boson	0	0
Screening	reduces bare charge	amplifies bare charge
Strength	α	$\alpha_s(q^2) \propto \ln(q^2)^{-1}$

strong int.



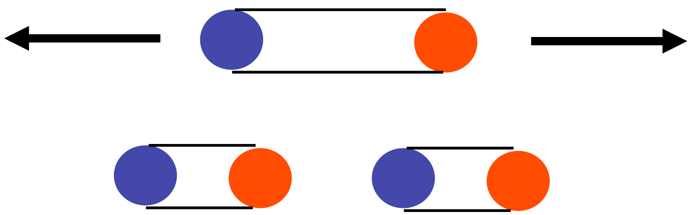
→ flux tube, string

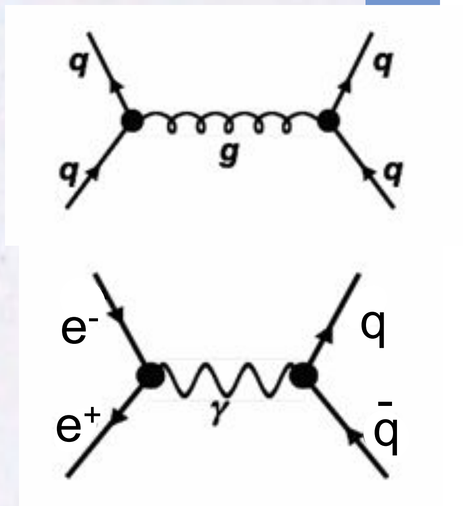
QCD: Confinement

- small distances (large q^2): $V(r) \sim 1/r$ ← e.g. jets, spectroscopy of "charmonium" ($c\bar{c}$)
  → perturbative calculations applicable ("pQCD")
- larger distances (small q^2): $V(r) \sim r$ ← e.g. $J(M^2)$, string model of hadrons
  → perturbative ansatz does not converge!: phenomenological methods, LQCD

$$V(r) = -\frac{4\alpha_s \hbar c}{3r} + Kr$$

- with increasing distance of the quark more and more energy is stored in the "string" until it becomes favorable to produce a new pair of quarks





- "confinement": no free quarks
- "asymptotic freedom" for $r \to 0$

Lattice - QCD

• because of the "running coupling constant" α_s which is small only at large q^2, i.e. small distances, perturbative treatment of QCD is only applicable at small distances ("pQCD")

• numerical method to treat larger distances "lattice QCD":

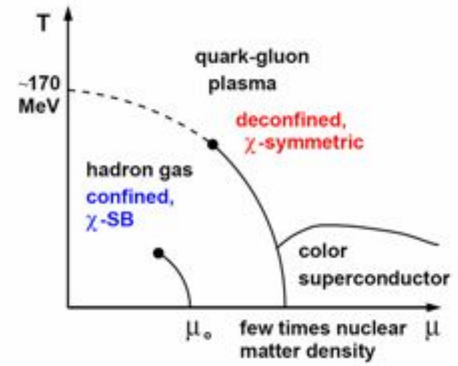
  • 4dim space-time lattice of size N_σ^3 x N_τ with lattice spacing a

  • finally extrapolate to the continuum case: a → 0 and $N_\tau \to \infty$

→ calculations need large computer memory and speed!

Lattice-QCD (II)

• calculations limited to certain observables and regions of the QCD phase diagram



• in particular calculations for $\mu \neq 0$ are difficult and conceptual problems could only be solved a few years ago!

• $\mu_b = 0$

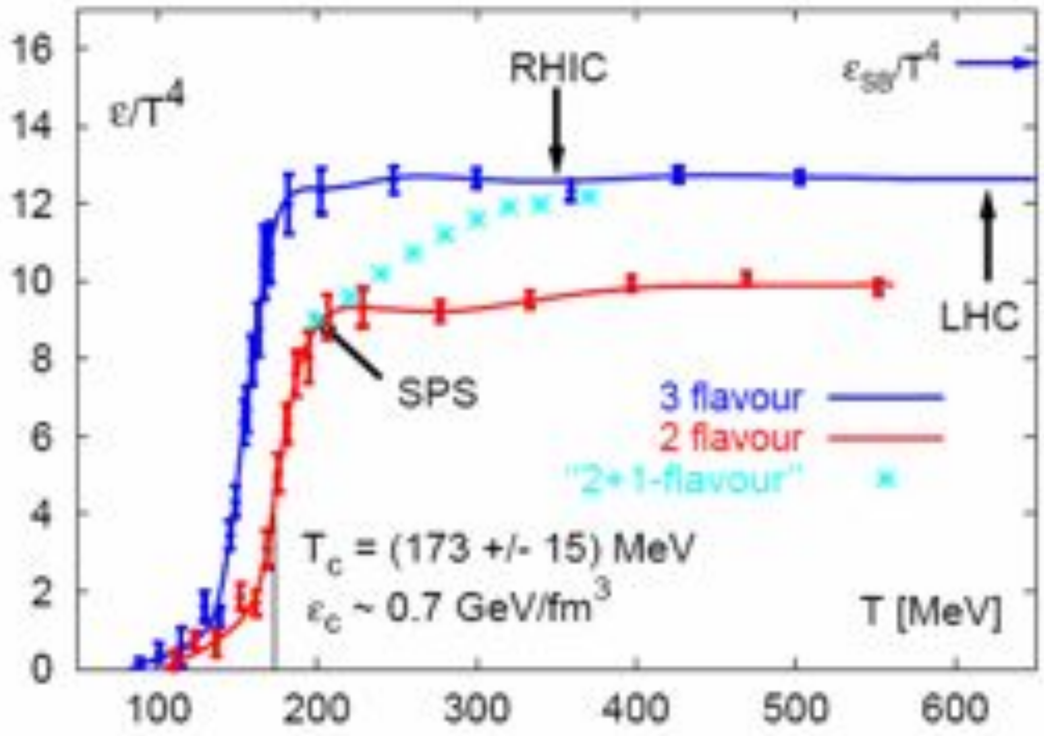
→ transition to deconfinement above a certain T_c!

$T_c \sim 175$ MeV

driven by energy density

$\varepsilon_c \sim 1$ GeV/fm^3

• quarks and gluons become relevant degrees of freedom



Lattice - QCD (III)

- phase transition at $\mu_b = 0$: crossover
  = rapid change of properties but no clearly defined phase boundary
- $\mu_b > 0$ not yet completely settled ... but:
- first order phase transition at large μ_b

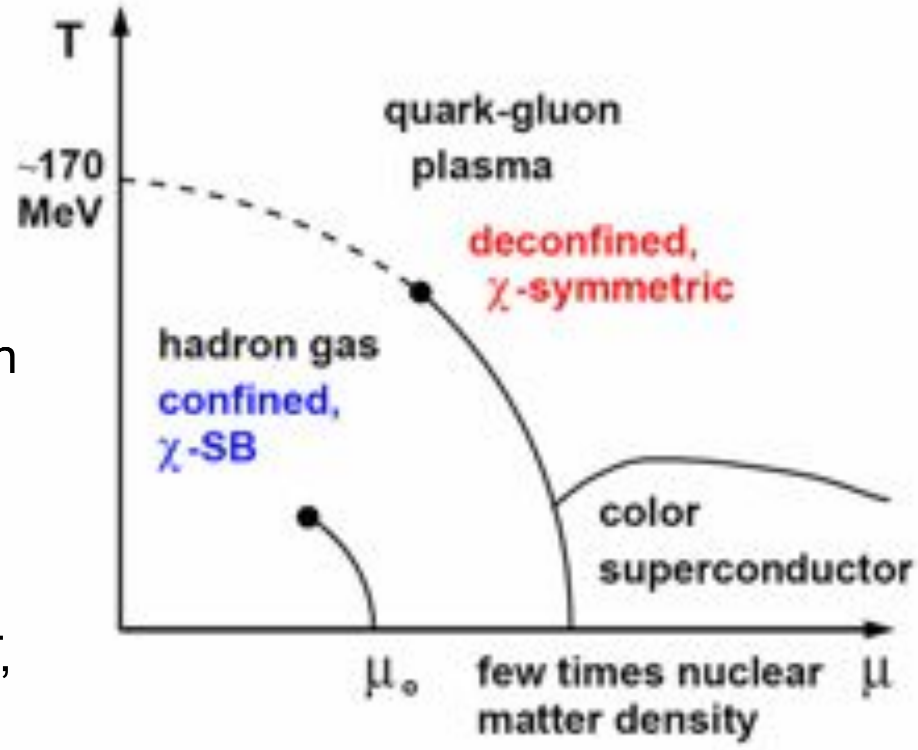
→ e.g. latent heat
   phase coexistence region

- critical point

  $T_{crit} \sim 160$ MeV $\mu_{crit} \sim 360$ MeV

- low T, $\sim\rho_0$: liquid gas phase transition
  nuclei → hadron gas
- low T, high μ_b: color superconductor
  (quarks form Cooper pairs)
- chiral symmetry restoration at high T, large μ_b

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



Experiments – Signatures ?

How to characterize the produced hot & dense matter?

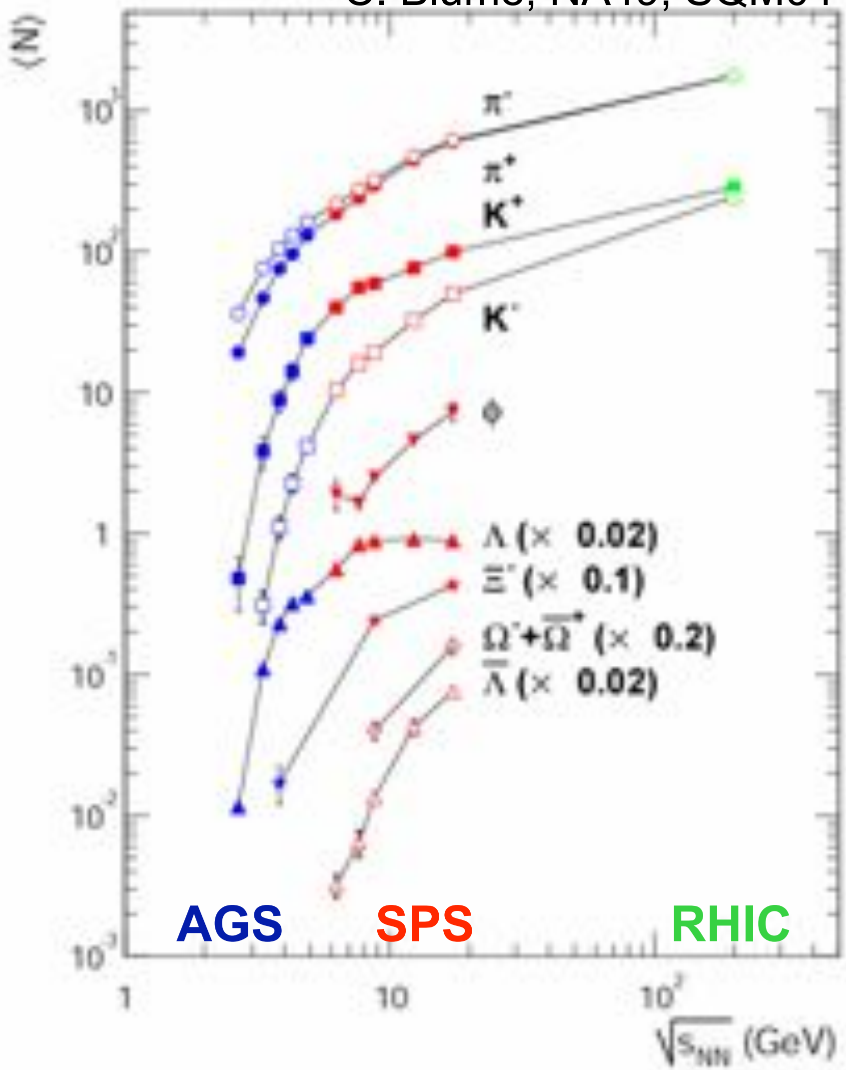
Signatures for phase transition?

- 90% of all measured particles are pions
- multiplicities increase smoothly

→ **look for special probes, e.g:**

- relative production of “new” quarks: strangeness, charm
- penetrating probes: di-leptons
- collective behaviour, e.g. flow, fluctuations
- energy loss of high momentum particles

C. Blume, NA49, SQM04



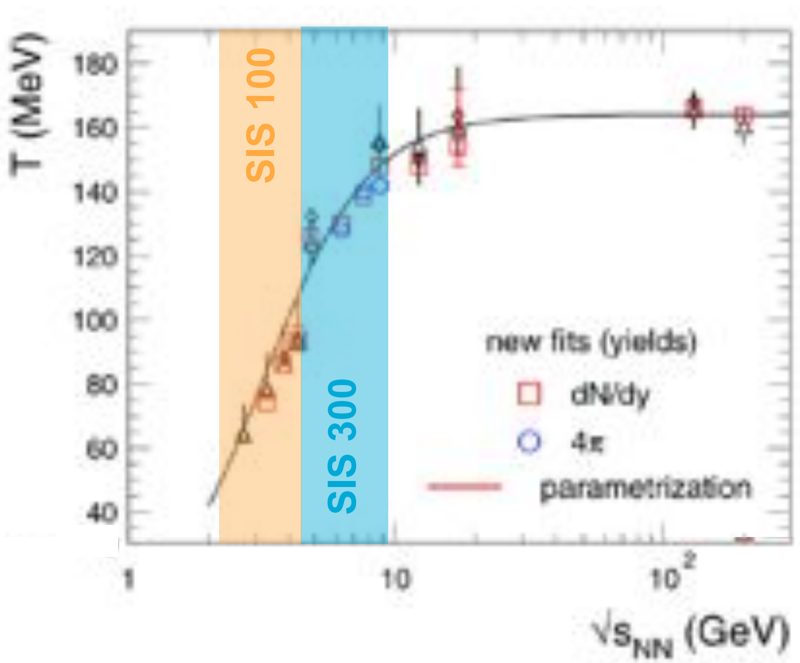
total particle multiplicities in central Au+Au / Pb+Pb collisions

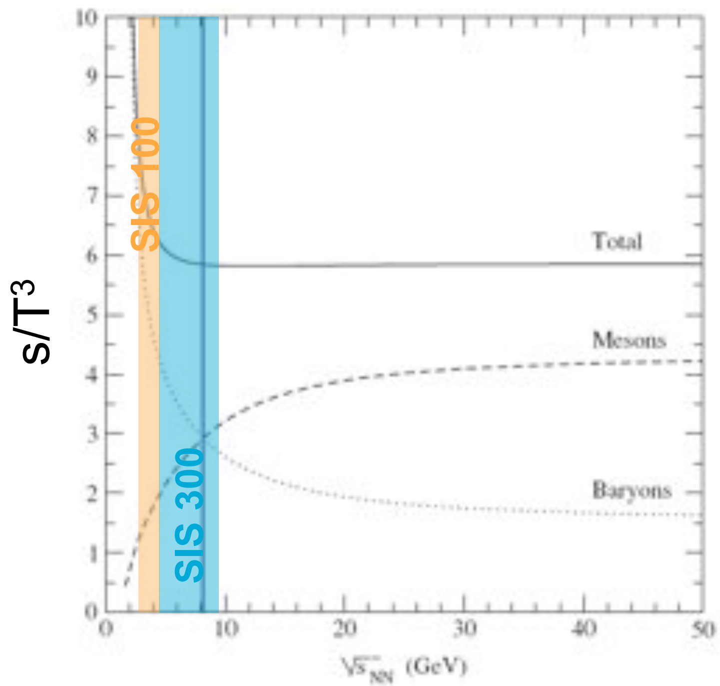
Limiting temperature at $\sqrt{s_{NN}}$ ~ 10 GeV

- statistical model fit: T, μ_B, V: **temperature saturates** for $\sqrt{s_{NN}}$ > 10 GeV although energy density (and initial T) still increases

→ **deconfinement phase boundary reached, additional energy goes into heating the QGP**

- occurs at the same energy at which mesons start to carry the larger part of the entropy





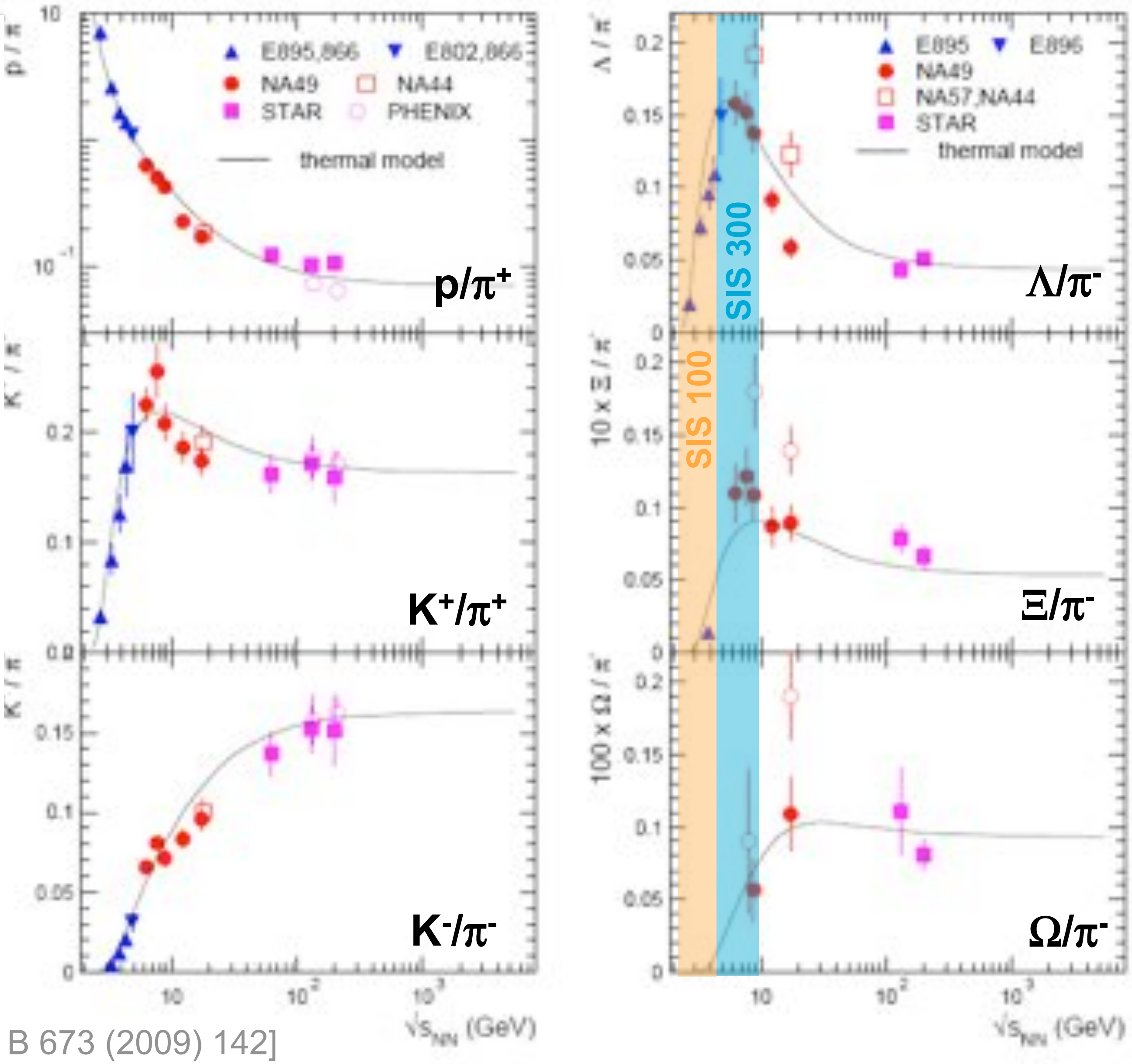
[A. Andronic et al., Phys. Lett. B 673 (2009) 142]   [H.Oeschler et al., J.Phys.G 32, 223 (2006)]

Structures in particle ratios

- statistical model: very succesful description of particle yields
- equilibrated hadron gas!
- multistrange hadrons are important – very sensitive!

  vicinity of phase boundary required?

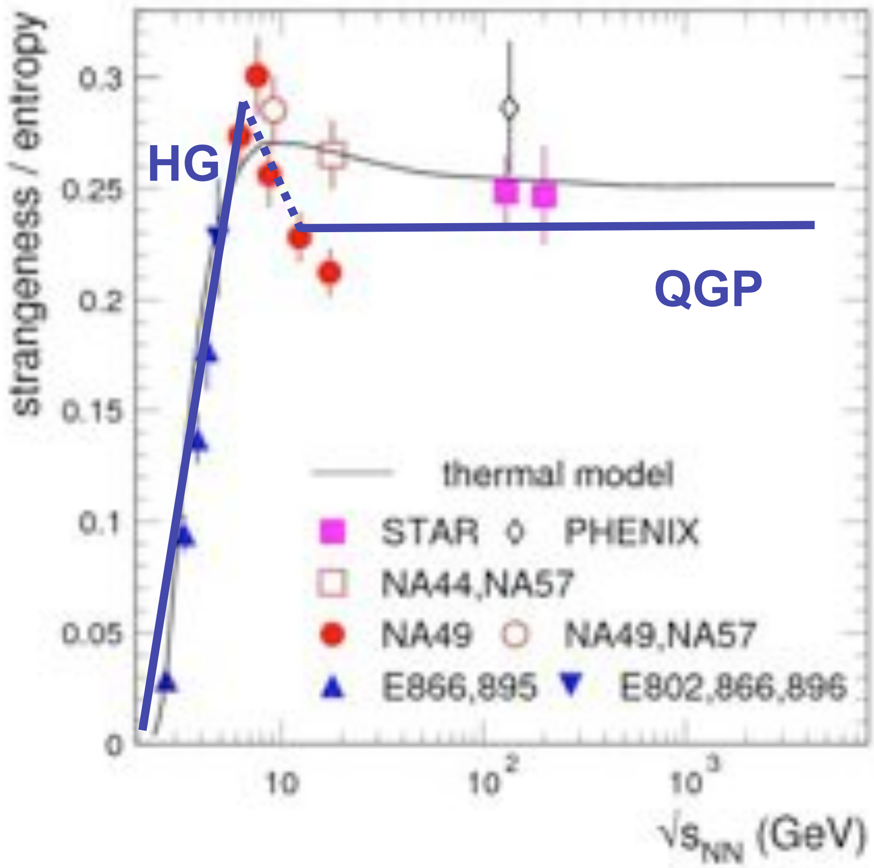
- however: for low energies multistrange hadrons are missing!
- also freeze-out at phase boundary? or rescattering hadron gas?



[A. Andronic et al., Phys. Lett. B 673 (2009) 142]

Maximum in relative s-production

- maximum in relative strangeness production
- different energy dependence than in pp
- details of dependence not captured by statistical hadron gas model
- data best described assuming a phase transition: prediction of SMES



[A. Andronic priv. com., analysis in Phys. Lett. B 673 (2009) 142]

Statistical model of the early stage (SMES)

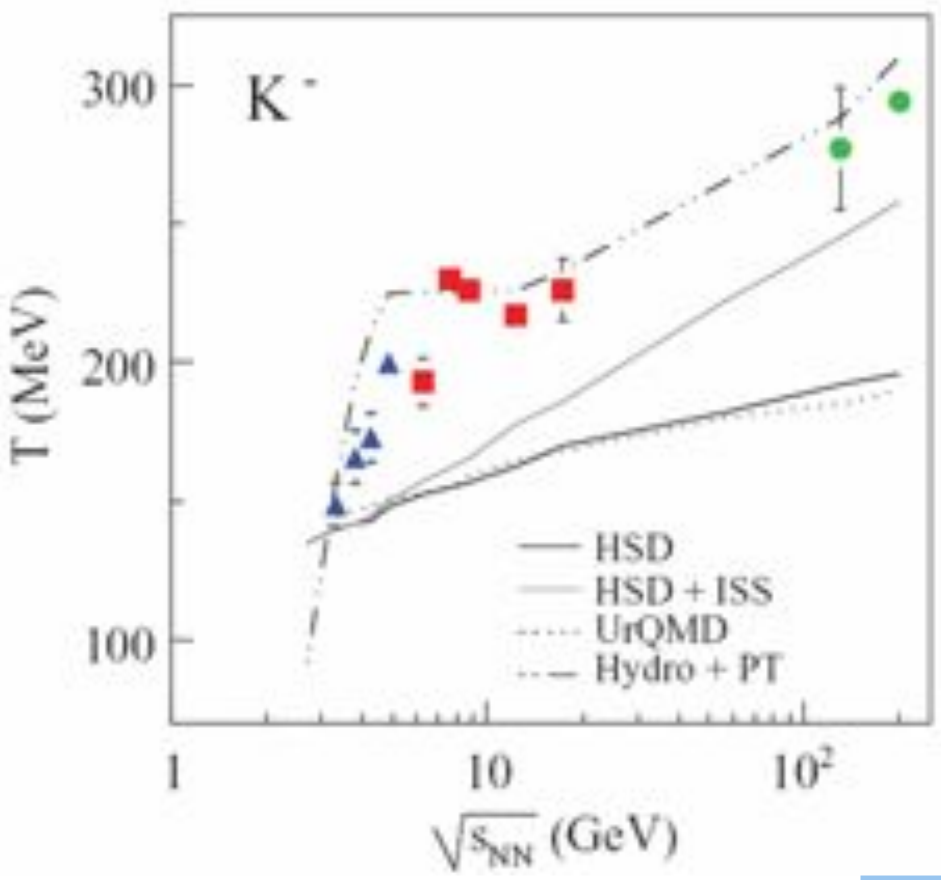
[Gazdzicki, Gorenstein, Acta. Phys. Polon. B30, 2705 (1999)]

Plateau in slopes of pt-distributions

- mixed phase: pressure and T independent of ε → weak increase of slopes of p_t-spectra [L. van Hove, Phys.Lett.B 118, 138 (1982)] [M. Gorenstein et al., Phys. Lett. B 567, 175 (2003)]
- behavior can only be explained assuming a phase transition

- similar behavior in <m_t> seen for other particles: π, K, p, Λ, Ξ, ϕ
- however: low energy data missing

- hydrodynamic calculation including a phase transition [M. Gazdzicki et al, Braz. J. Phys. 34, 322 (2004)]
- bag model EoS with a strong 1st order phase transition (UrQMD + hydro) [H. Petersen et al., arXiv:0902.4866]

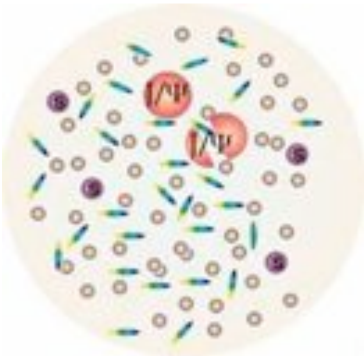


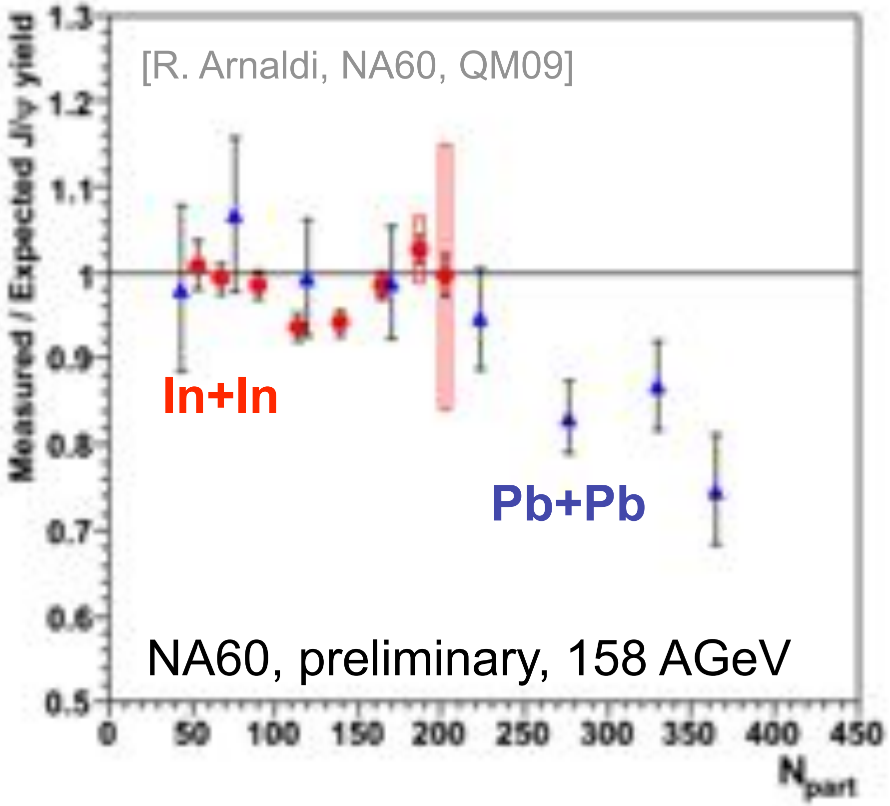
[NA49: Phys.Rev.C77:024903,2008]

Charmonium suppression

- charm newly produced: m_c ~ 1.3 GeV ! → new scale, production in initial hard scattering
- distribution among charmed hadrons depending on medium
- appealing early idea: charmonia will be dissolved in QGP

→ suppressed yield compared to hadron gas

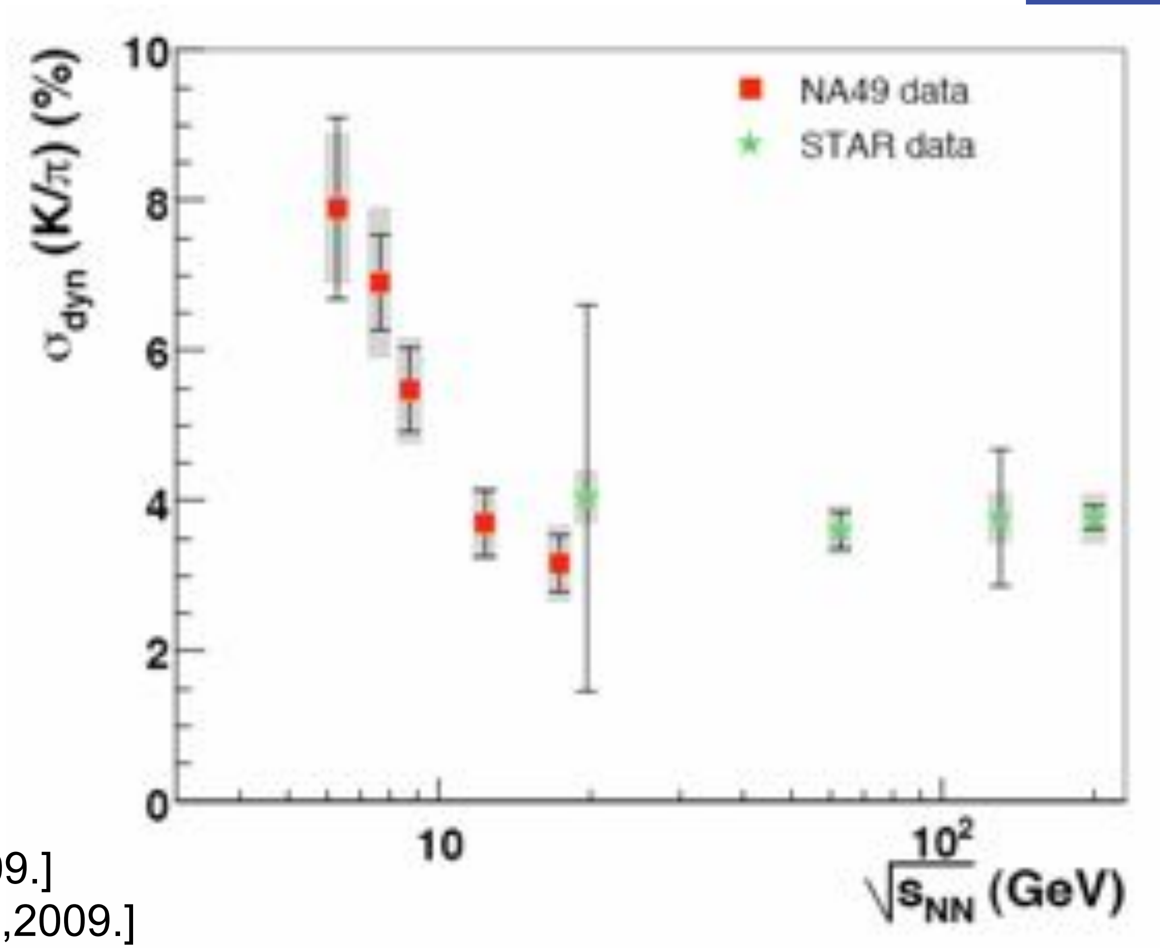




- J/ψ suppression measured
- difficult corrections, many open questions
- no good open-charm (D-meson) measurement
- no data at lower energies

Search for the critical point: Event-by-event fluctuations

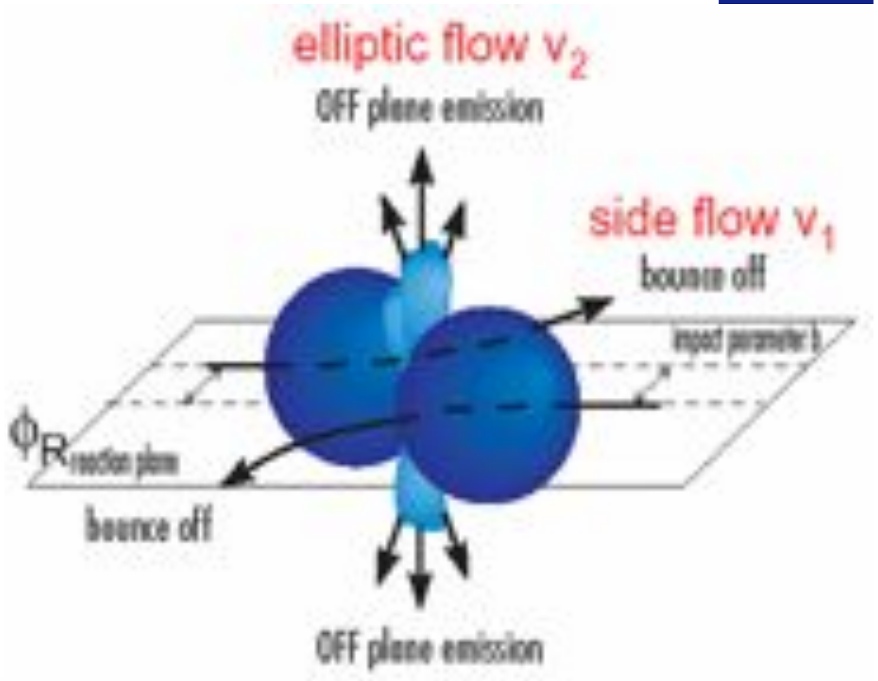
- phase transition of 2nd order at critical point: fluctuations?
- study of event-by-event fluctuations of
  - mean-pt
  - multiplicity
  - net electric charge
  - particle ratios
- experimentally difficult, many contributions can contribute
- no data for lower energies
- **not conclusive**



[NA49: Phys.Rev.C79:044910,2009.]
[STAR: Phys.Rev.Lett.103:092301,2009.]

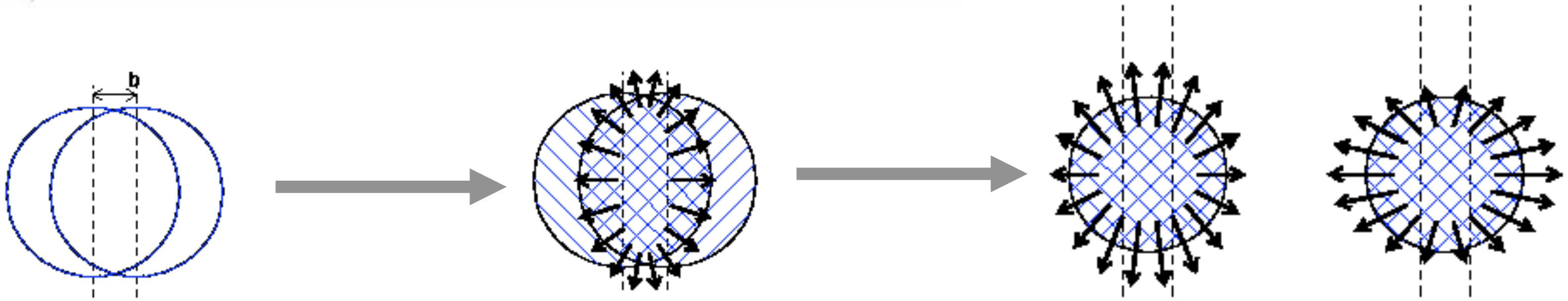
elliptic flow v2

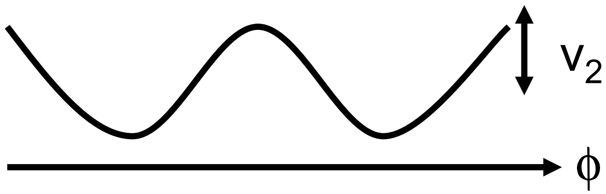
- particle emission pattern in plane transverse to the reaction plane
- initial overlap eccentricity is transformed in momentum anisotropy
- driven by pressure from overlap region



Fourier expansion of the dN/dϕ distribution:

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





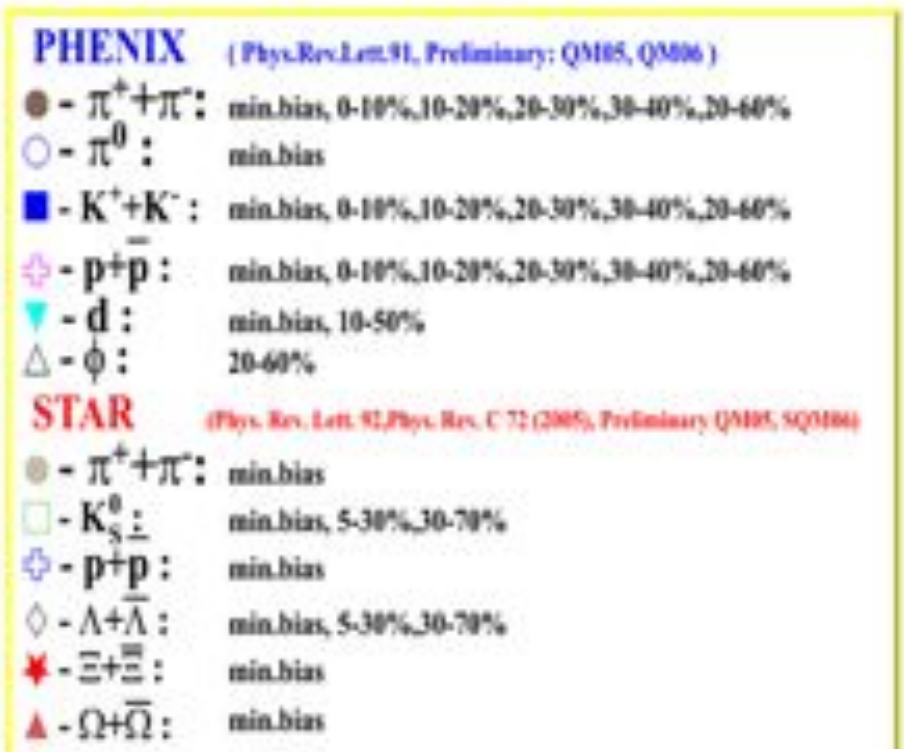
Quark number scaling of v2 at RHIC

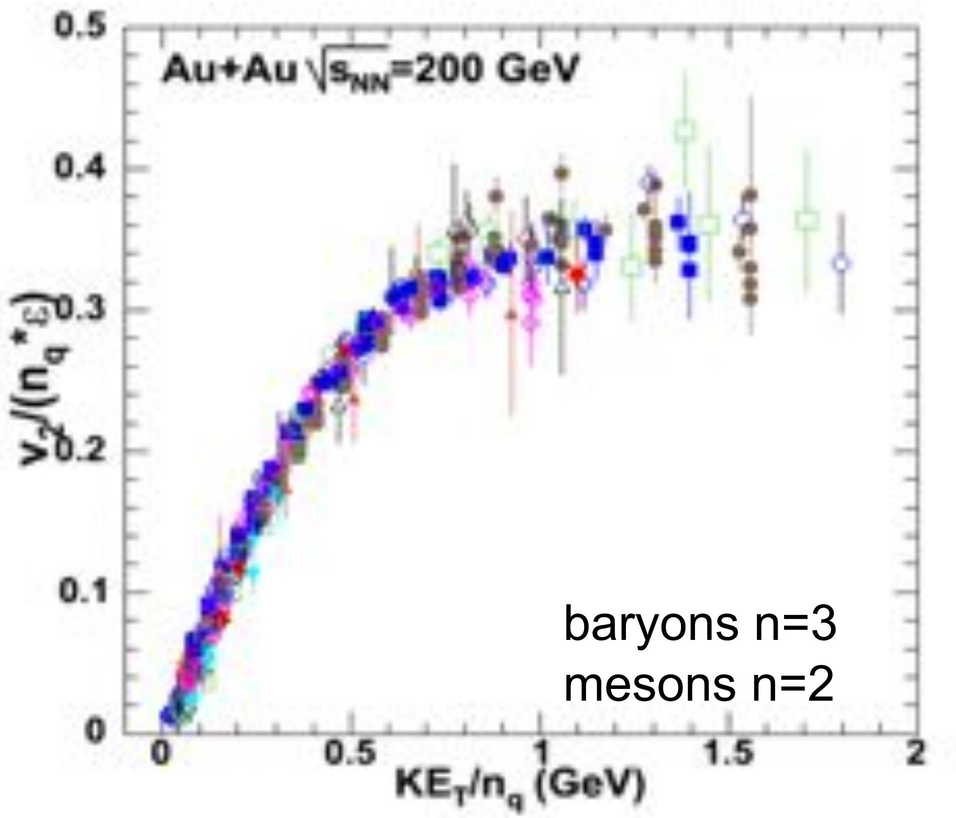
• all flow observations scale extremely well if taking the underlying number of quarks into account!

→ like (all!) quarks flow and combine to hadrons at a later stage (hadronisation)

• data can only be explained assuming a large, early built up pressure in a nearly ideal liquid (low viscosity!)

• breakdown of this feature at a certain energy??





$$KE_T = m(\gamma_T - 1) = m_T - m$$

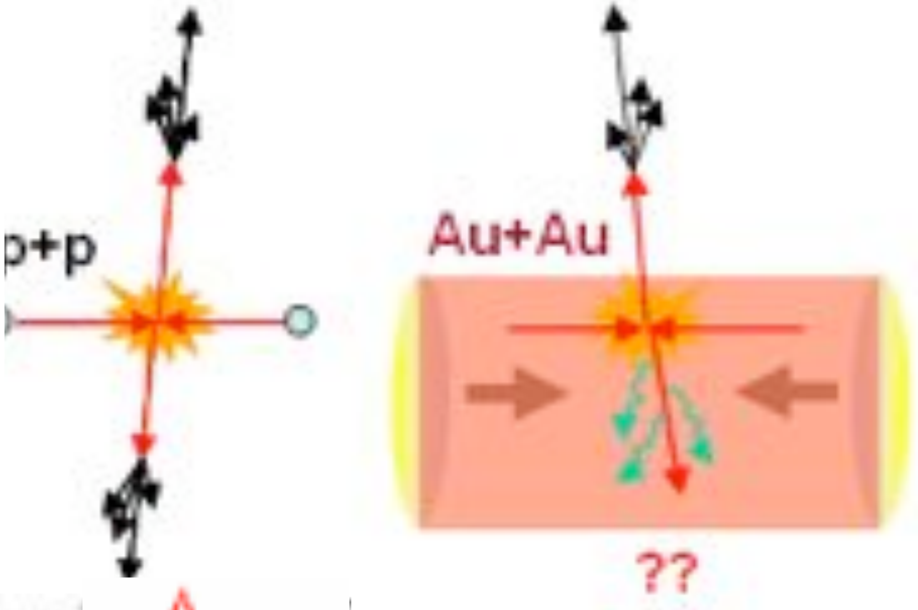
Jet quenching

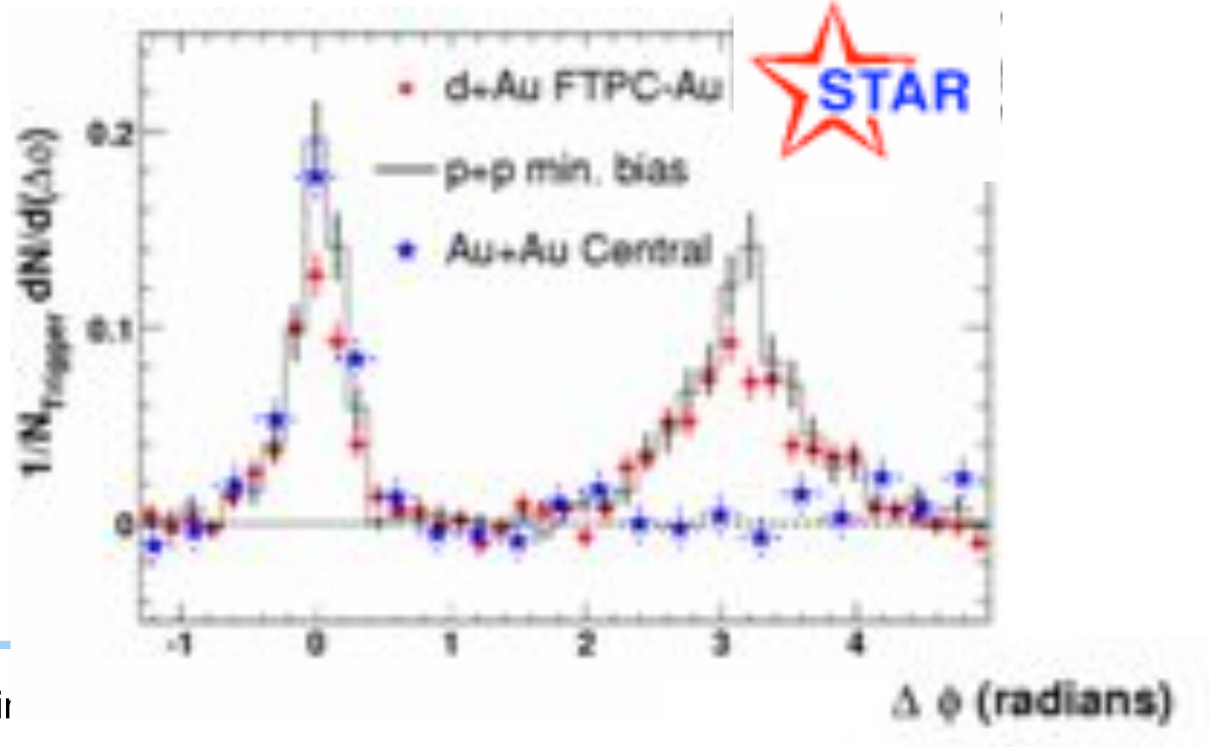
• partons should loose energy in a dense and hot medium

→ jet suppression!

→ results imply huge gluon densities corresponding to an initial temperature of ~2T_{crit} and ε ~ 14-20 GeV/fm^{-3} in the fireball!

→ breakdown of this phenomenon at a certain energy?



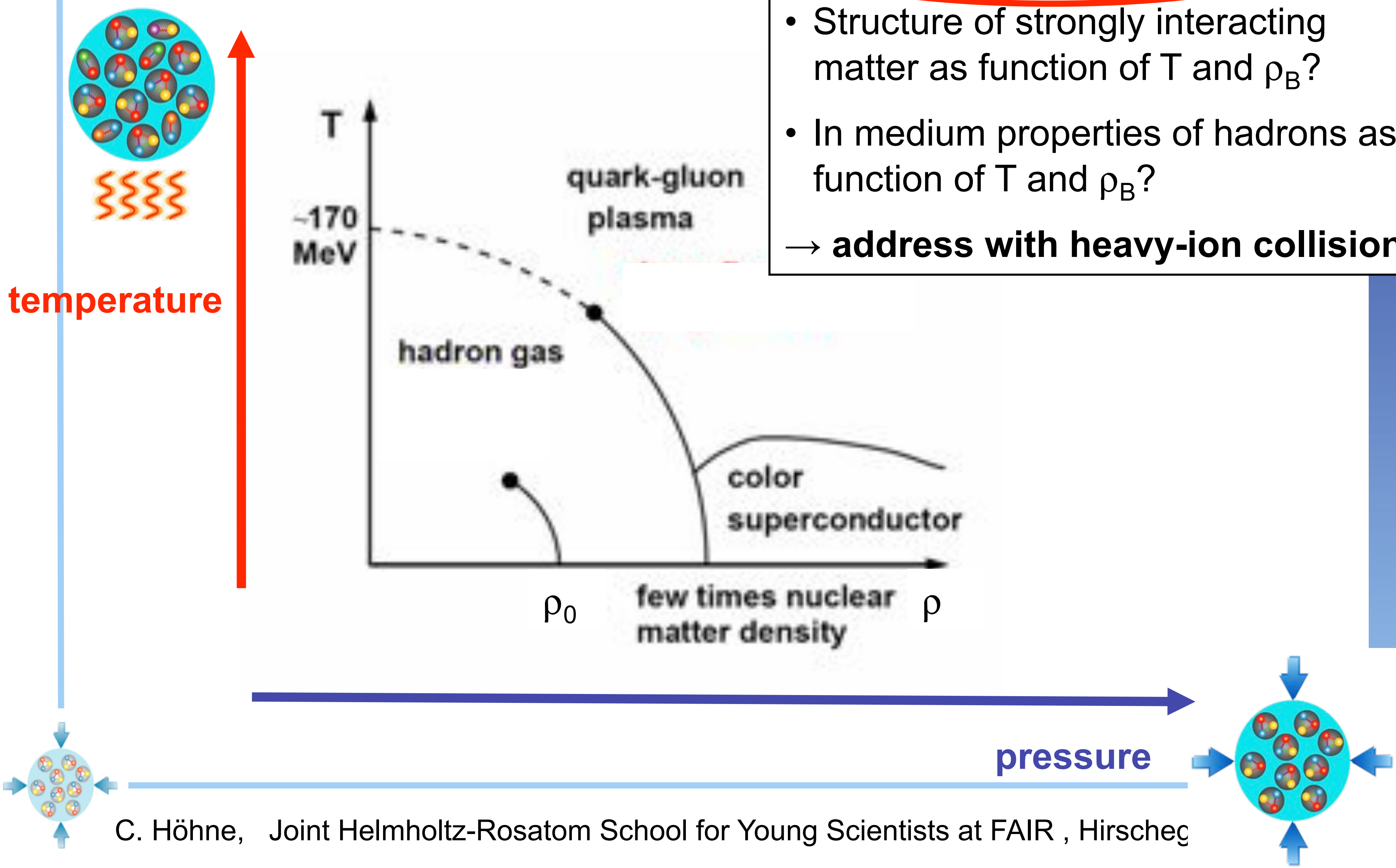


Phasediagram of strongly interacting matter

Fundamental questions of QCD

- Equation of state of strongly interacting matter?
- Structure of strongly interacting matter as function of T and ρ_B?
- In medium properties of hadrons as function of T and ρ_B?

→ **address with heavy-ion collisions**



The equation of state

- thermodynamic relation between state variables; most prominent: ideal gas law → relation between energy density ε and T, ρ etc.

$$P = \frac{F}{A} = \frac{F \cdot d}{A \cdot d} = \frac{E}{V}$$

- thermodynamics for an ideal gas (liquid):

$$P = \frac{\partial E}{\partial V}\Big|_{T=\mathrm{const}} \qquad V = \frac{N}{\rho} \qquad \partial V = -\frac{1}{\rho^2}\partial\rho$$

$$P = \rho^2 \frac{\partial\, E/N}{\partial\rho}\Big|_{T=\mathrm{const}} = \rho^2 \frac{\partial\varepsilon}{\partial\rho}(\rho)\Big|_{T=\mathrm{const}}$$

- the function $\varepsilon(\rho,P,T)$, which satisfies this equation is called the Equation of State (EOS)

- different depending on the degrees of freedom of the investigated matter
  - nuclear matter
  - neutron matter (→ neutron stars)
  - quark matter

The nuclear equation of state (EOS)

- "**equation of state**" (EOS): energy/nucleon vs. density

$$\varepsilon(\rho,T) = \varepsilon_T(\rho,T) + \varepsilon_C(\rho,T=0) + \varepsilon_0 \qquad (\varepsilon = E/A)$$

thermal **compressional** **ground state energy**

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

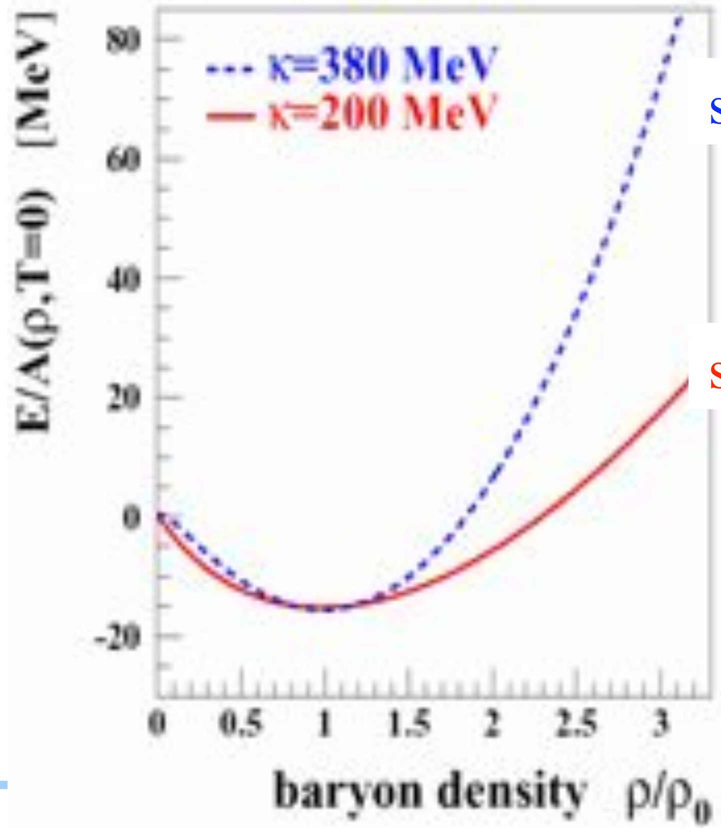
$$E/A(\rho, T=0) = \frac{1}{\rho}\int U(\rho)\, d\rho$$

- U(ρ) density dependent local potential
- compression modulus κ

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

- constraints $\varepsilon(\rho=\rho_0, T=0) = -16MeV$

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



stiff EoS

soft EoS

Analogy: Electrons in a lattice

• free electrons (no interaction with other e^-, no potential)

→ dispersion relation = parabola

$$E(\vec{k}) = \frac{(\hbar \vec{k})^2}{2m}$$

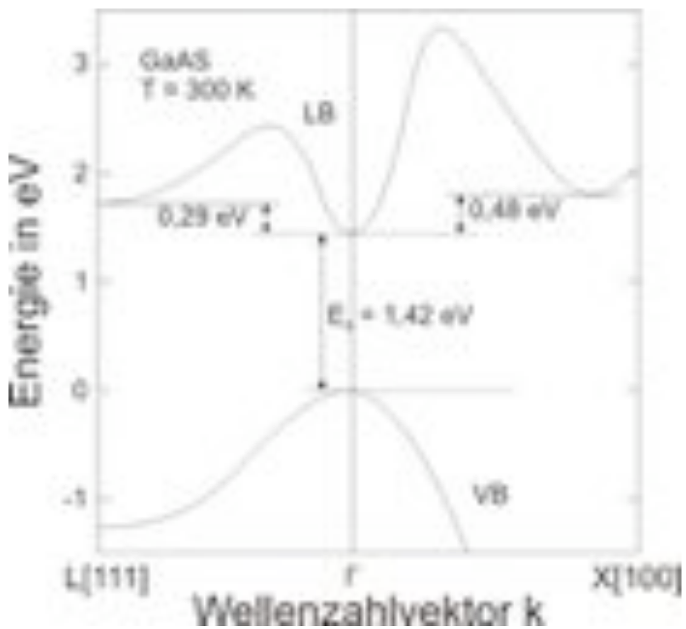
• electrons in a solid

→ due to the lattice not all energies/ frequencies are possible

→ introduction of the concept of an effective mass m_{eff} for electrons allows a simpler description / handling of the electrons in the lattice

$$m_{eff} = \hbar^2 \left(\frac{\partial^2 E}{\partial k^2} \right)^{-1}$$

→ m_{eff} describes dispersion $E(\vec{k})$ of e^- in an external potential



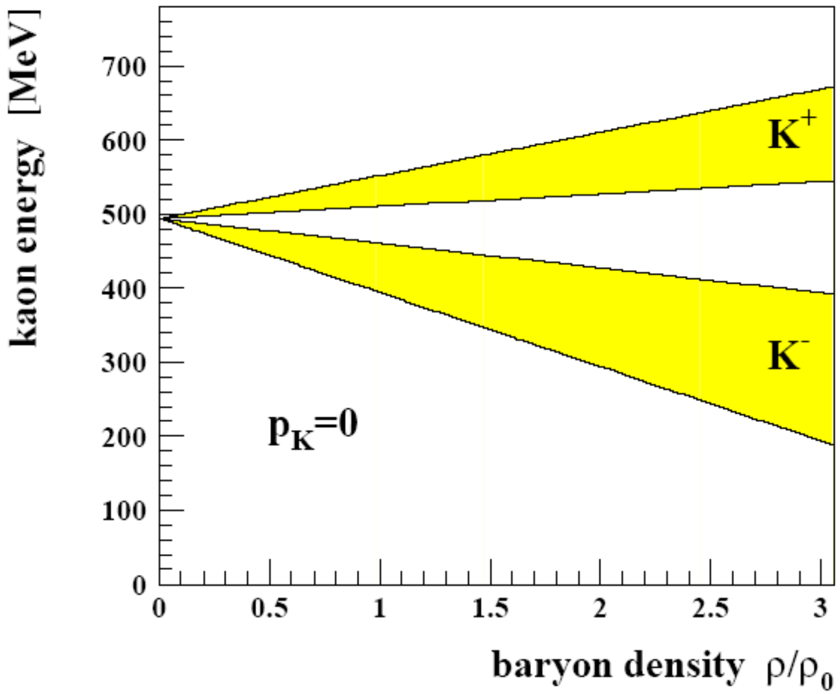
Kaons in dense nuclear matter

• What happens if kaons are place inside nuclear matter (=external potential, density given by ρ or ρ/ρ_0)?

→ dispersion relation for kaons!

→ define m_{eff} in order to describe kaon energy in the nuclear medium

$$m_{eff} = \varpi(\vec{k}=0,\rho) = \varpi(\rho)$$



repulsive K^+ N potential

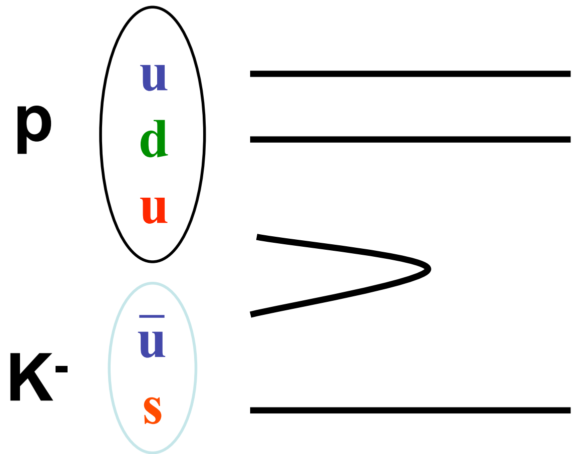
attractive K^- N potential

→ different for K^+ and K^- !
→ kaons sensitive to medium!

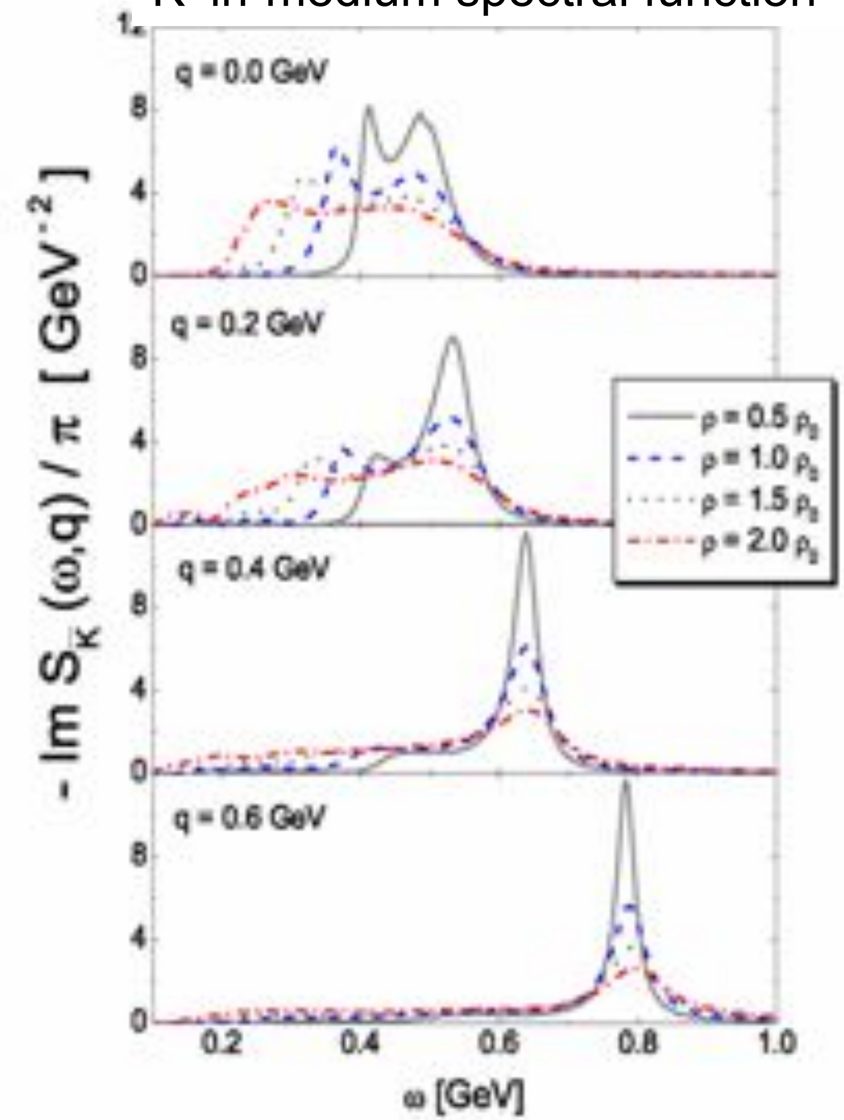
(yellow area: envelope of several microscopic calculations: all predict the same trend !)

Kaons in dense nuclear matter (III)

- in particular for K⁻ the nuclear medium is "attractive"

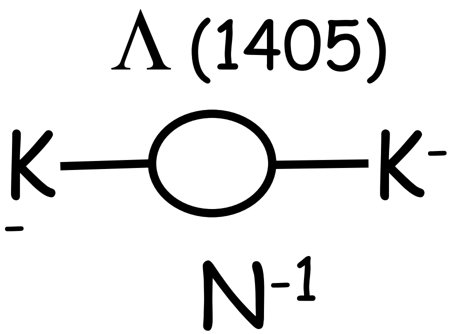


K⁻ in-medium spectral function



[M. Lutz, GSI, Coupled channels calculation]

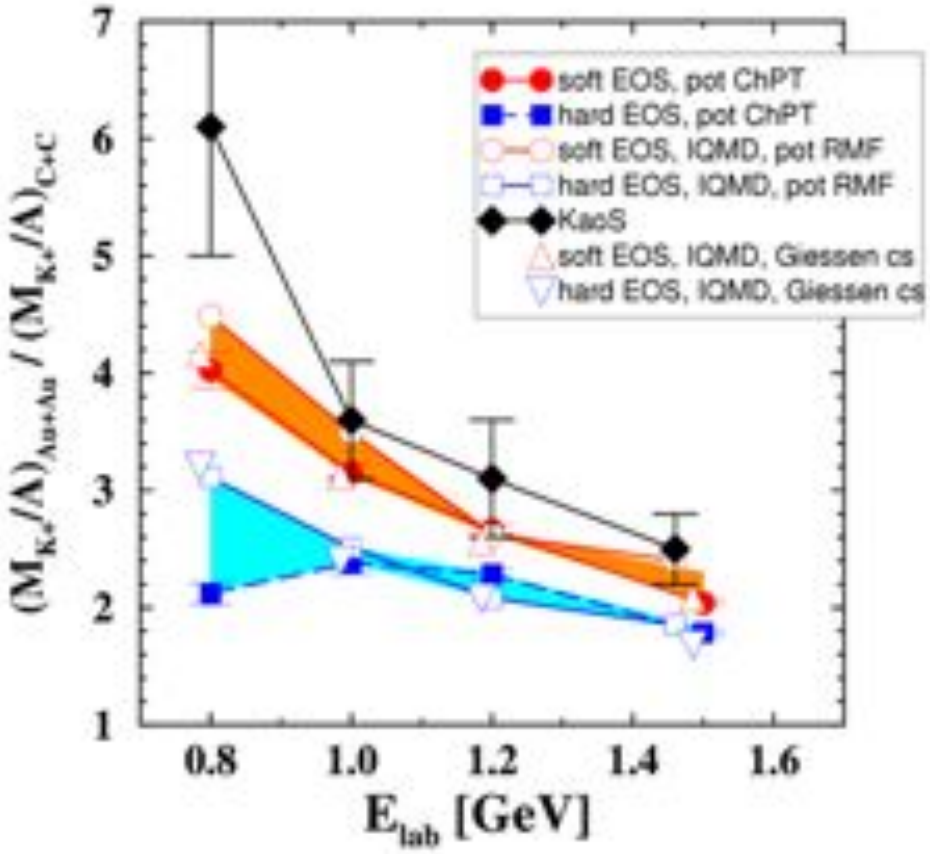
- resonant state close to the K⁻N threshold: Λ(1405)

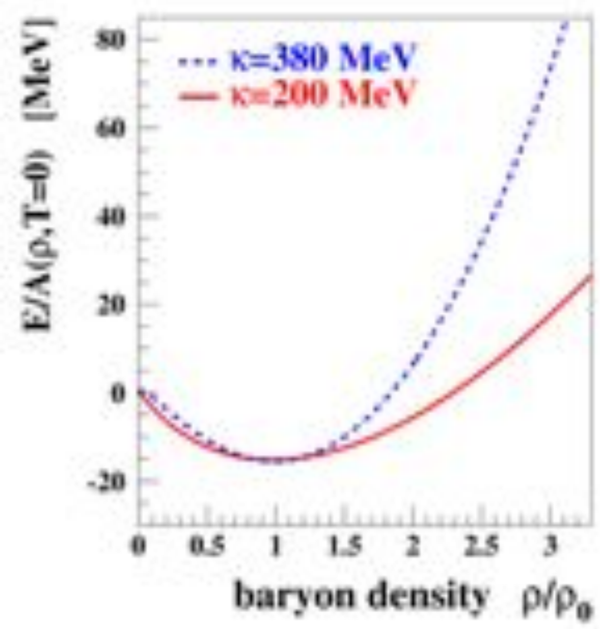


- for K+ ($u\bar{s}$) the nuclear medium is "repulsive"

The compressibility of nuclear matter

.... and indeed: effect seen in K production in Au+Au and C+C collisions at at SIS





soft nuclear equation of state:
κ ~ 200 MeV

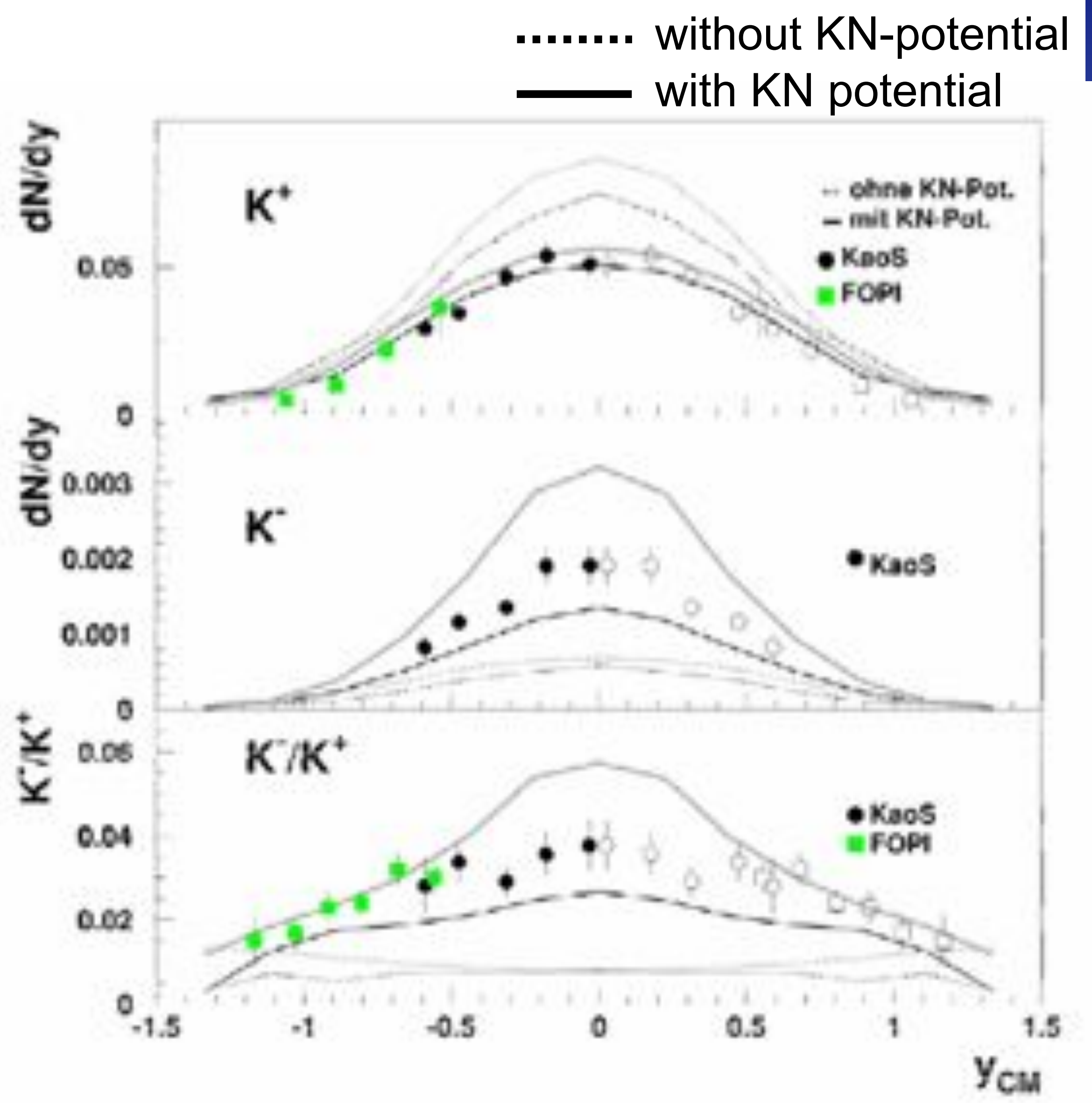
Experiment: C. Sturm et al., Phys. Rev. Lett. 86 (2001) 39

Theory: QMD C. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649

Figure by C. Fuchs

In medium kaons

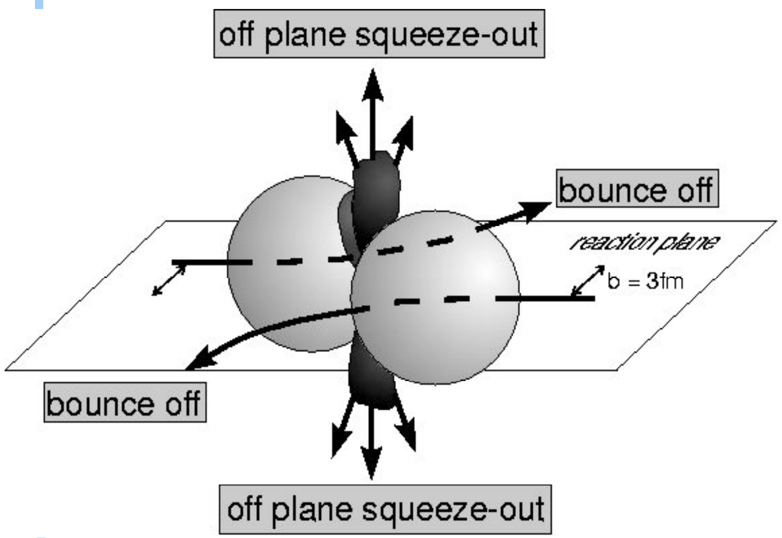
Clear effect of the nuclear medium on kaon production also seen in rapidity distributions.

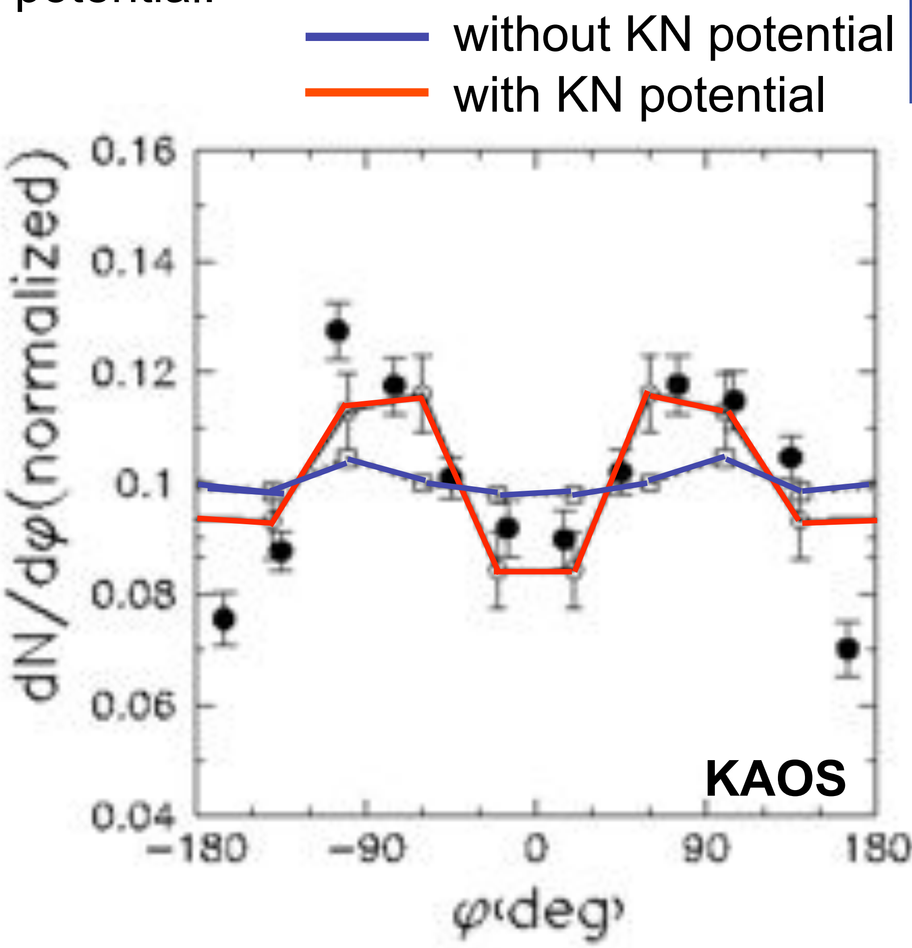


K$^+$ "squeeze out"

- angular distributions of produced K+

→ squeeze out due to repulsive KN potential!

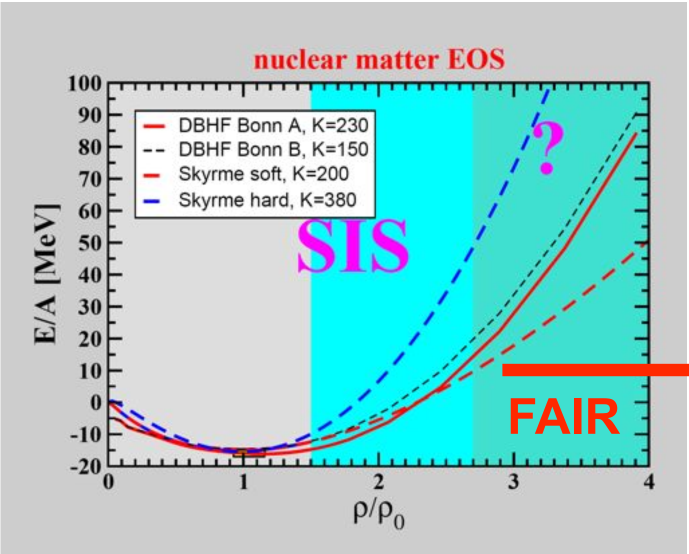


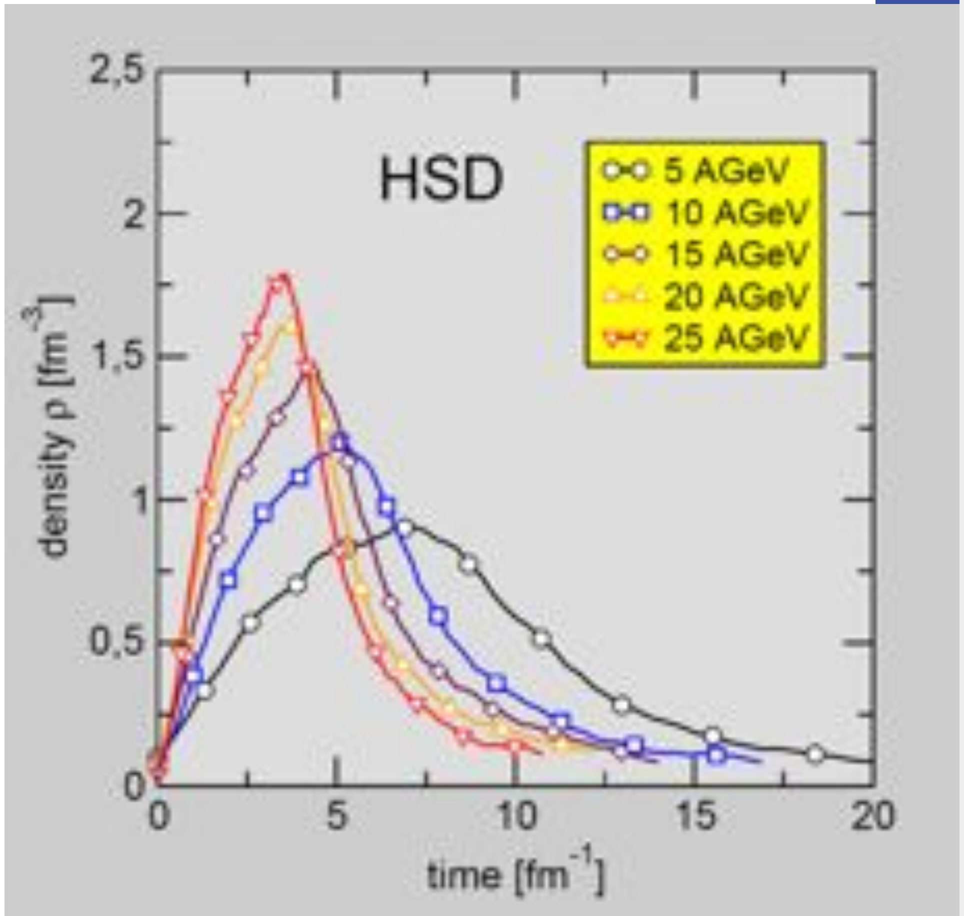


High net-baryon density matter in A+A collisions

- **high baryon and energy densities created in central Au+Au collisions**
- agreement between different models (not shown)

beam energy	max. ρ/ρ_0	max ε [GeV/fm^3]	time span ~FWHM
5 AGeV	6	1.5	~ 8 fm/c
40 AGeV	12	> 10	~ 3.5 fm/c





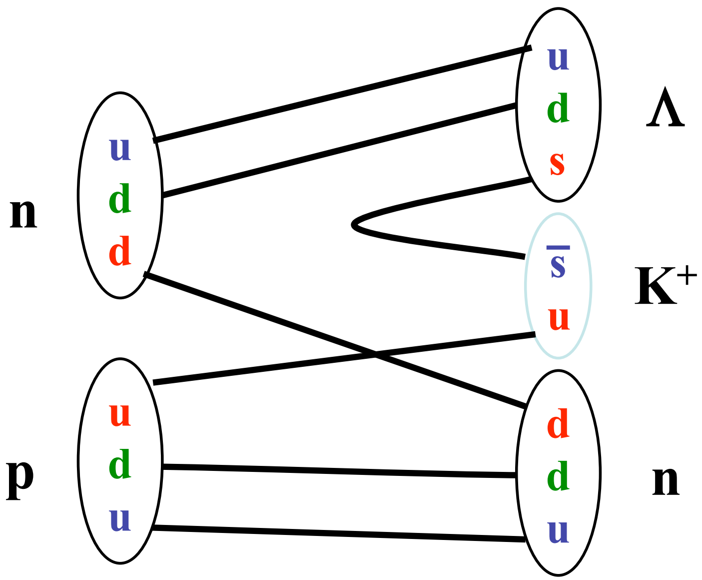
[CBM physics group, C. Fuchs, E. Bratkovskaya priv. com.]

Production in elementary interactions

.... can this be understood qualitatively?

• elementary production process of kaons in NN collisions:

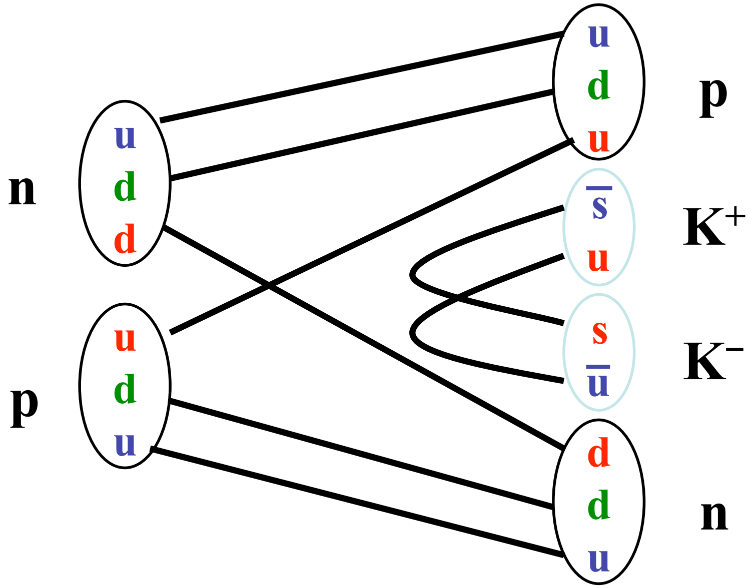
K^+ mesons



production threshold

$E_{lab} = 1.58\ GeV$

K^- mesons

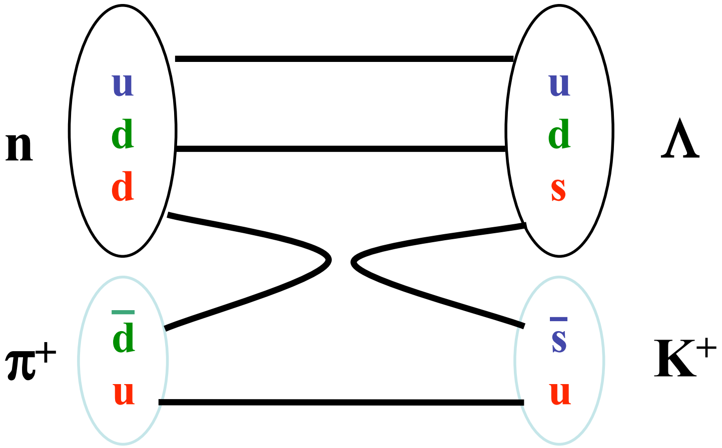


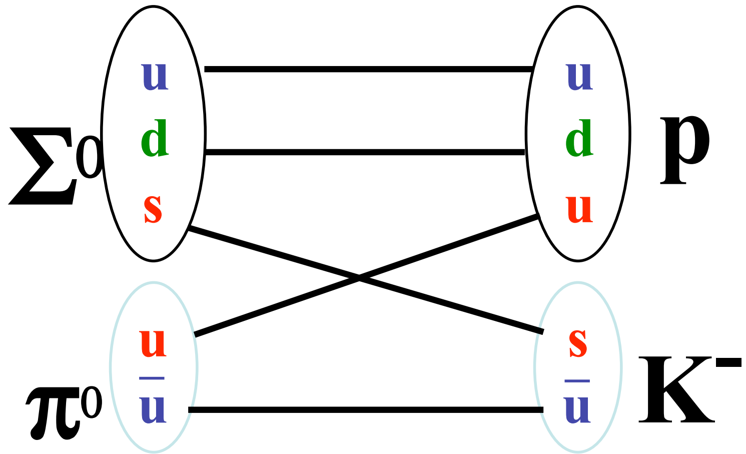
production threshold

$E_{lab} = 2.5\ GeV$

Kaons in dense nuclear matter (II)

• in a nuclear medium/ the vicinity of many more hadrons more processes become available, for example:





→ "rescattering":

• multistep processes for production

$$NN \rightarrow N\Delta$$

$$N\Delta \rightarrow NK^+Y$$

$$\pi N \rightarrow K^+Y$$

(Y=Λ,Σ)

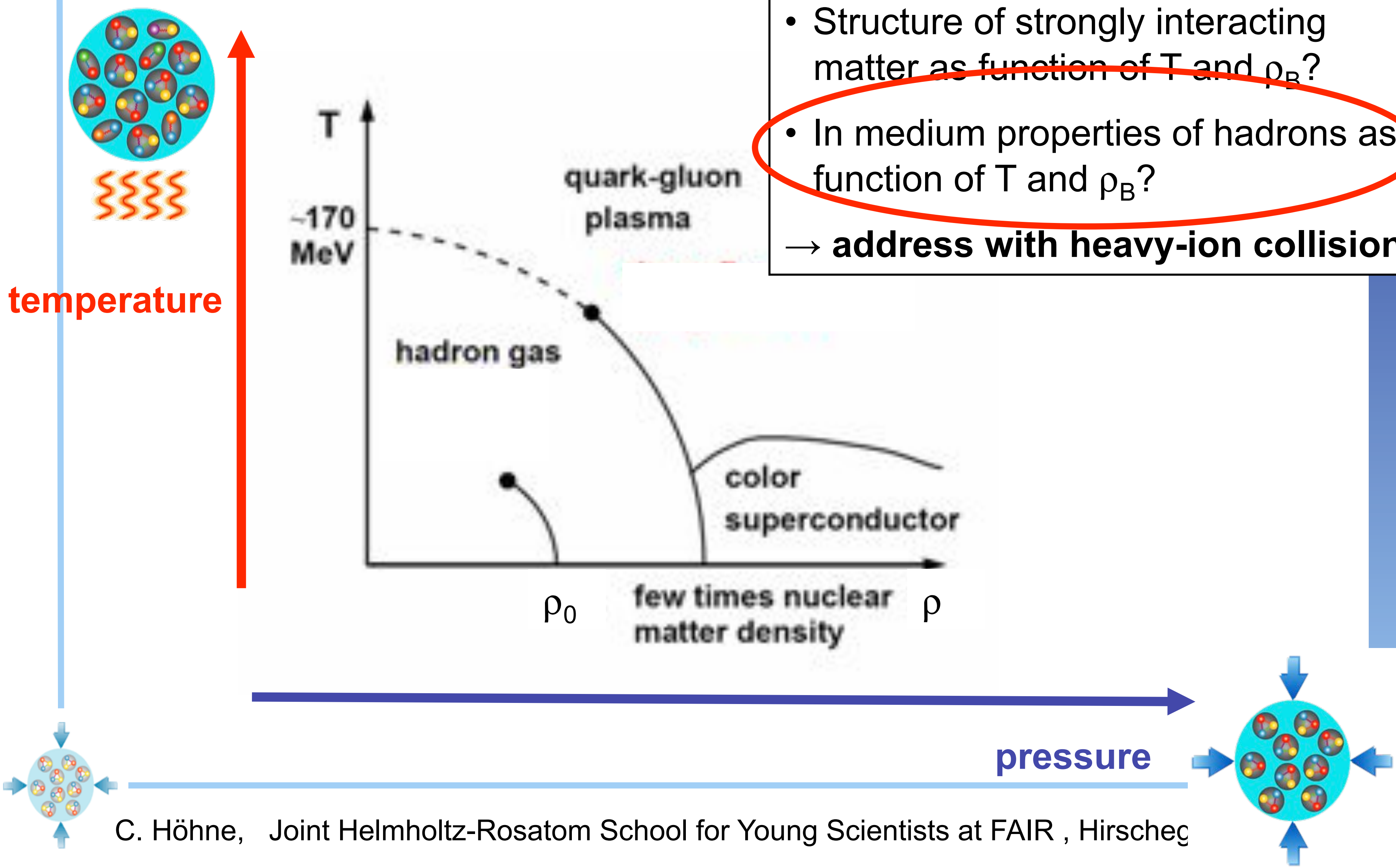
• ... but also absorption (processes are time reversal)

Phasediagram of strongly interacting matter

Fundamental questions of QCD

- Equation of state of strongly interacting matter?
- Structure of strongly interacting matter as function of T and ρ_B?
- In medium properties of hadrons as function of T and ρ_B?

→ **address with heavy-ion collisions**

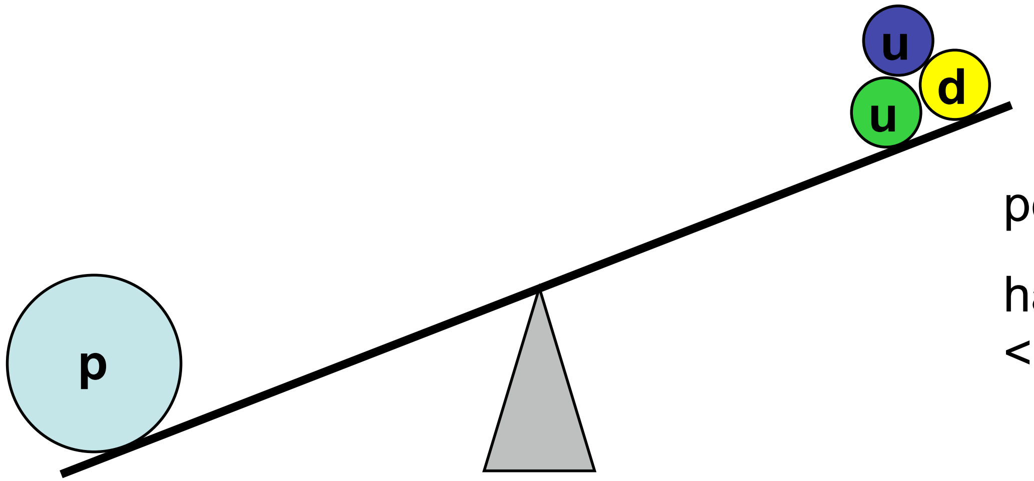


Chiral symmetry restoration

several effects occur at the phase transition:

- confinement/ deconfinement of quarks
- chiral symmetry restoration

relation to generation of hadron masses!



pedestrian explanation:

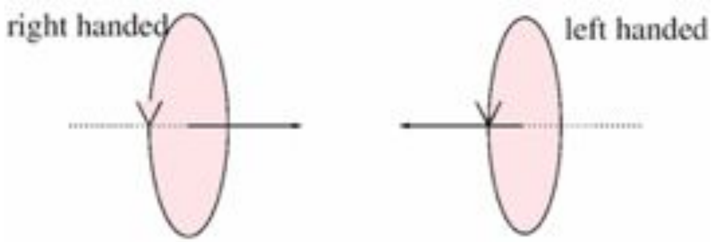
hadrons "dressed" with <$q\bar{q}$> pairs

m = 938 MeV/c^2

m ~ 3·10 MeV/c^2

Chiral symmetry

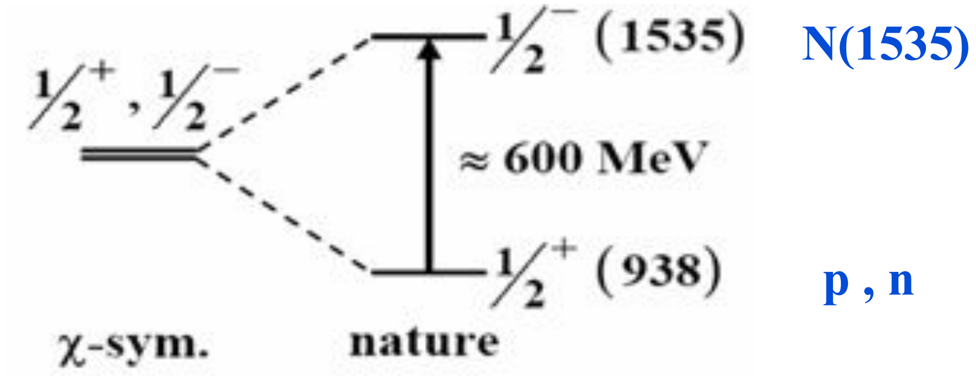
• Chiral symmetry = fundamental symmetry of QCD



helicity = projection of spin onto the direction of momentum

• in case of mass less quarks, the chirality corresponds to the (conserved) helicity

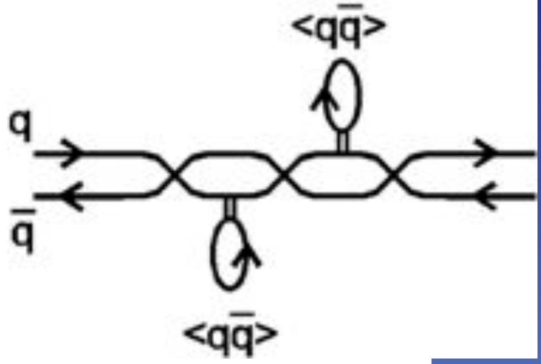
• the QCD Lagrangian is chirally symmetric but in "nature" Chiral symmetry is broken !



- explicit breaking by small but finite quark masses
- spontaneously broken due to the existence of a mass less mode ("Goldstone-boson"): the pion .

Chiral symmetry restoration (II)

• the groundstate of QCD is characterized by a non-vanishing field of quark – anti-quark pairs, the so-called chiral condensate.

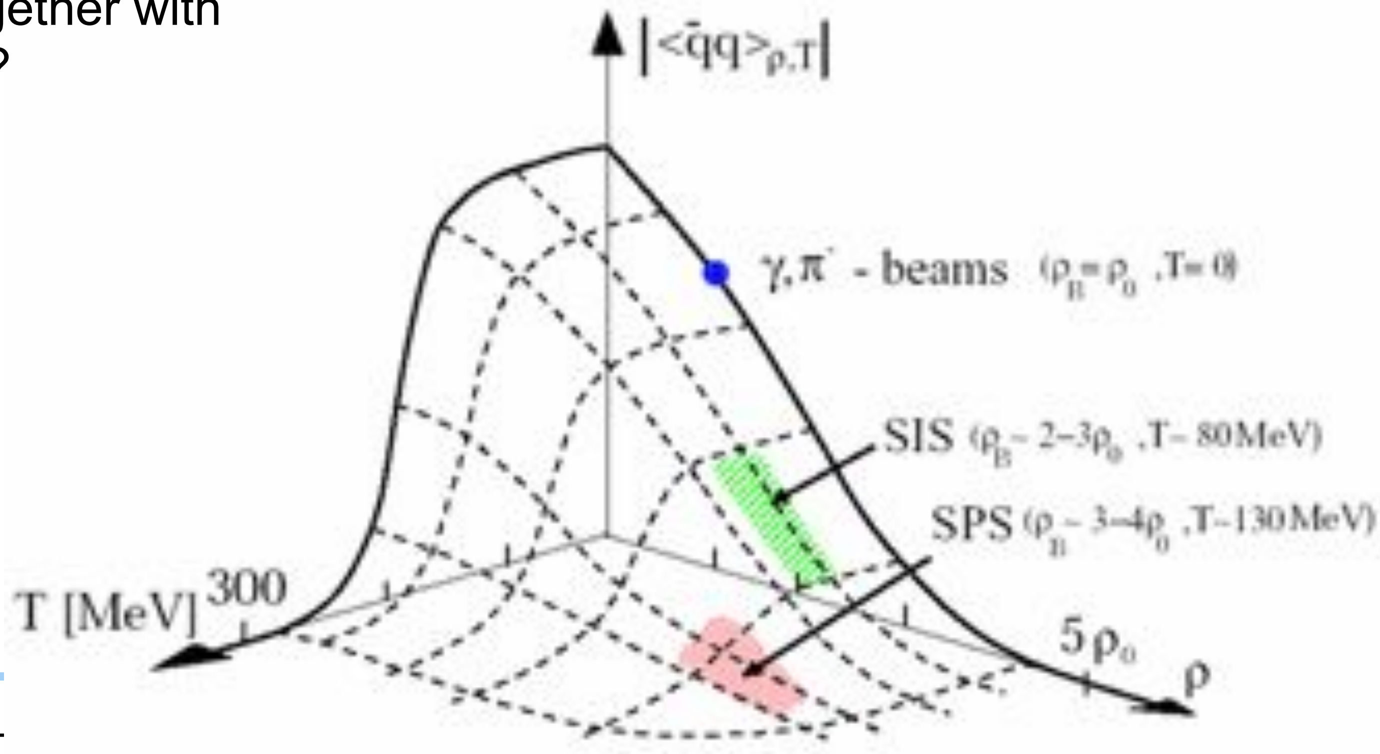


• this is a non-perturbative effect of QCD

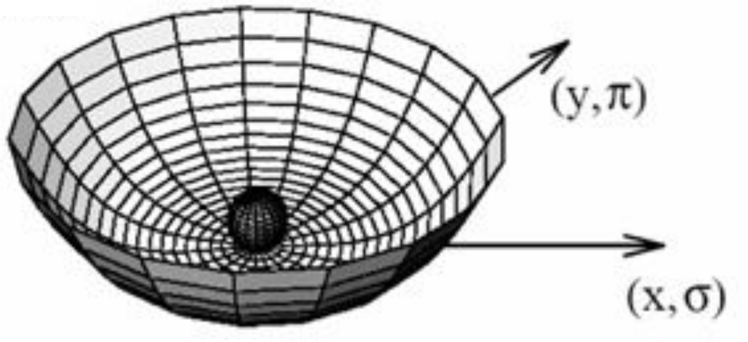
• already in ordinary nuclei the condensate is reduced as compared to vacuum

• prediction: chiral symmetry can be restored at high temperature or large baryon density

• restoration together with deconfinement?

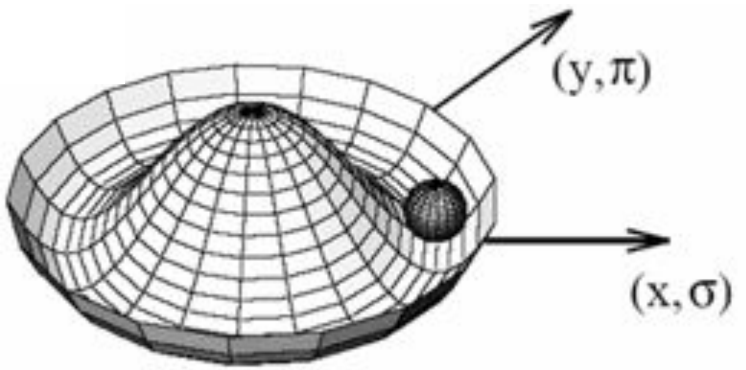


Analogy: classical mechanics



rotational symmetry

ground state: symmetric



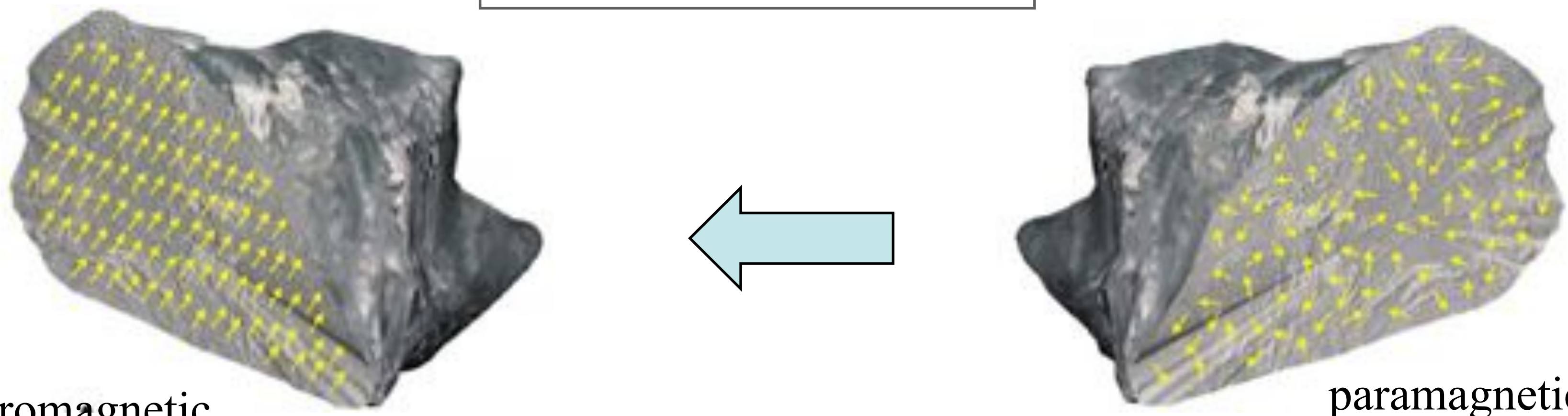
spontaneously broken rotational symmetry

ground state: not symmetric

potential still symmetric, but any (spontanously) chosen ground state breaks the symmetry

Analogy: Ferromagnet

spontaneous breaking
of full rotational symmetry

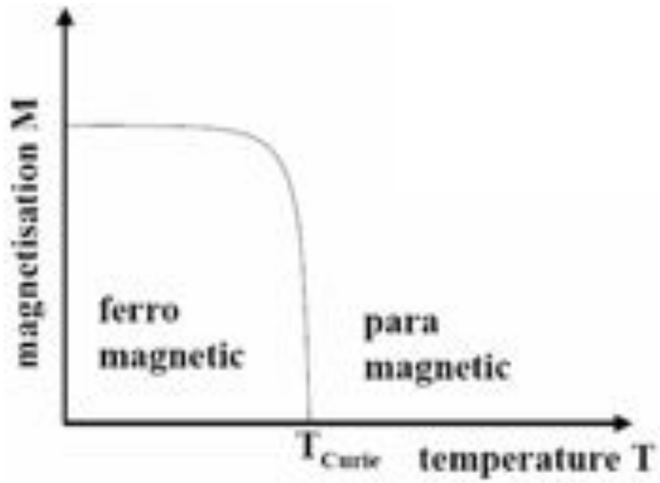


ferromagnetic

paramagnetic

Ferromagnet:

Below a certain temperature (T_{Curie}) all elementary magnets tend to align into on arbitrary, spontanously chosen direction.



Chiral symmetry restoration (III)

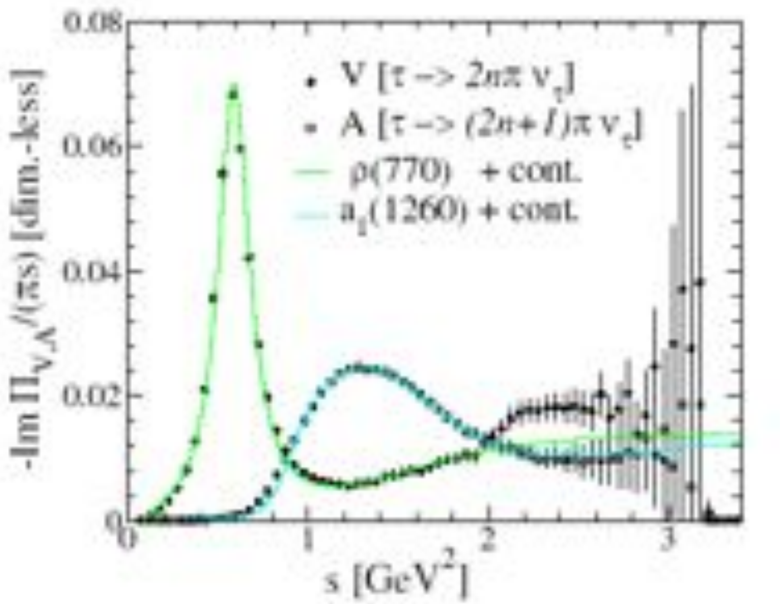
• chiral broken world:

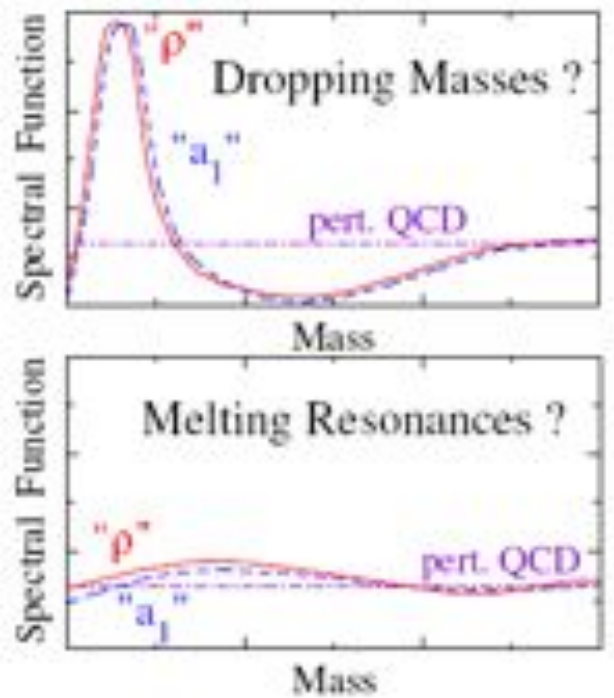
→ chiral partners show different spectral functions!

for example: nonstrange I=J=1 multiplet: ρ- and a_1 - meson

• chiral symmetry restoration requires that vector and axialvector spectral functions become degenerate

→ dramatic reshaping of spectral functions expected!



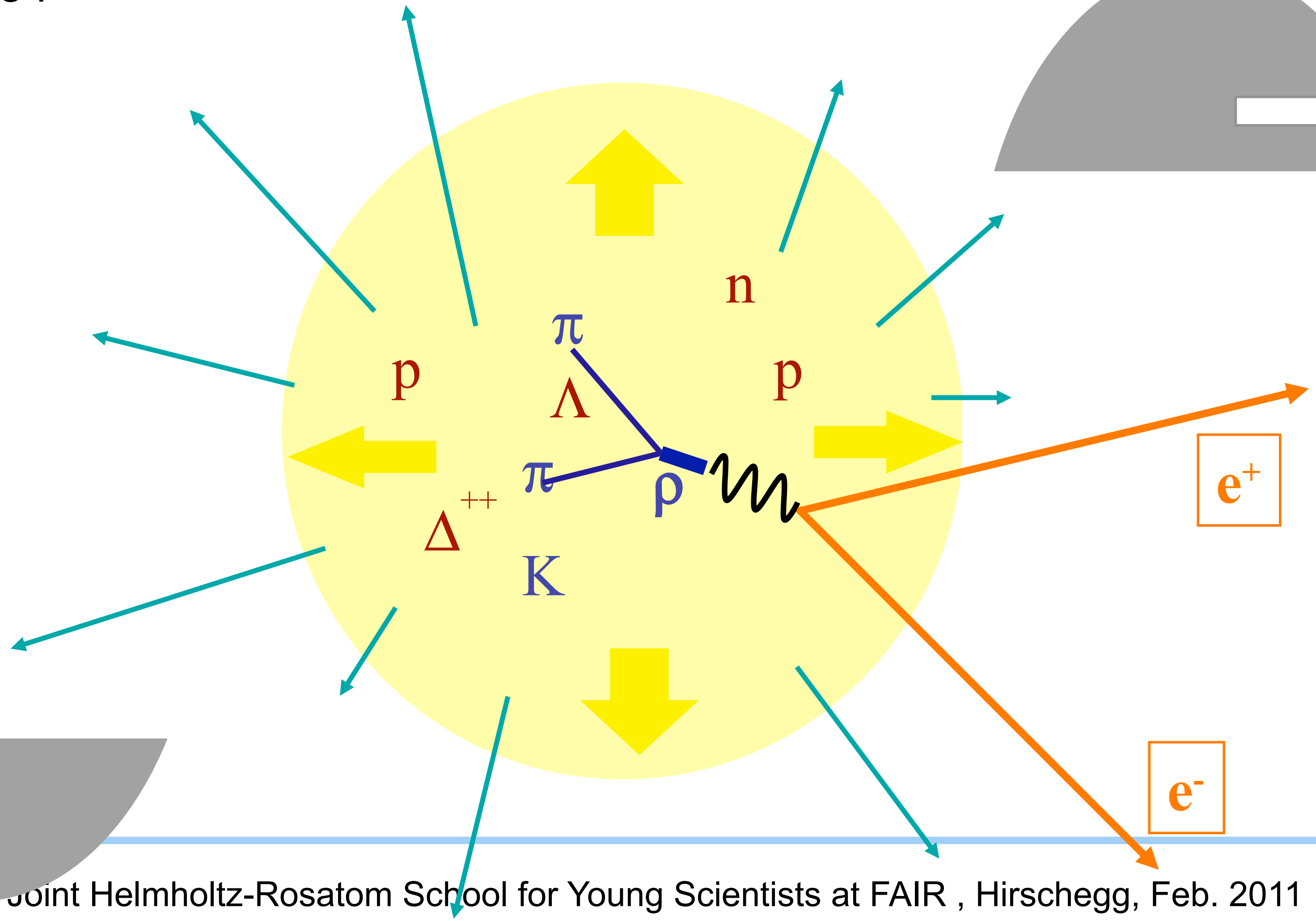


ρ-meson in A+A collisions

• lifetime in vaccum 1.3 fm/c

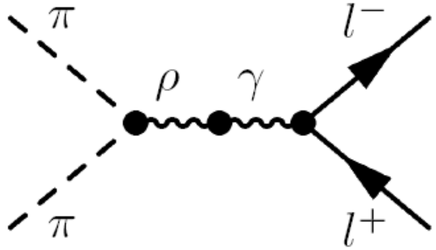
→ formation and decay inside the "fireball"

→ e^+e^- pair carries undistorted information of the fireball conditions to the outside: "penetrating probe"



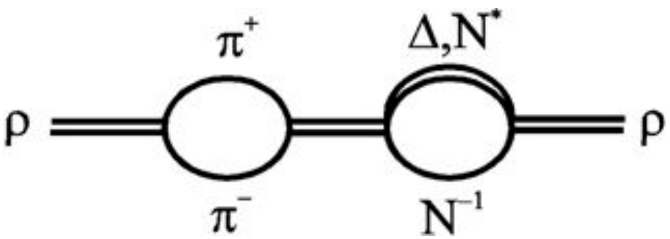
ρ-meson in dense nuclear matter

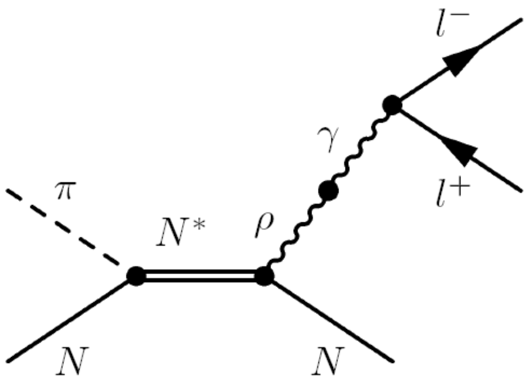
- ρ-meson in vacuum

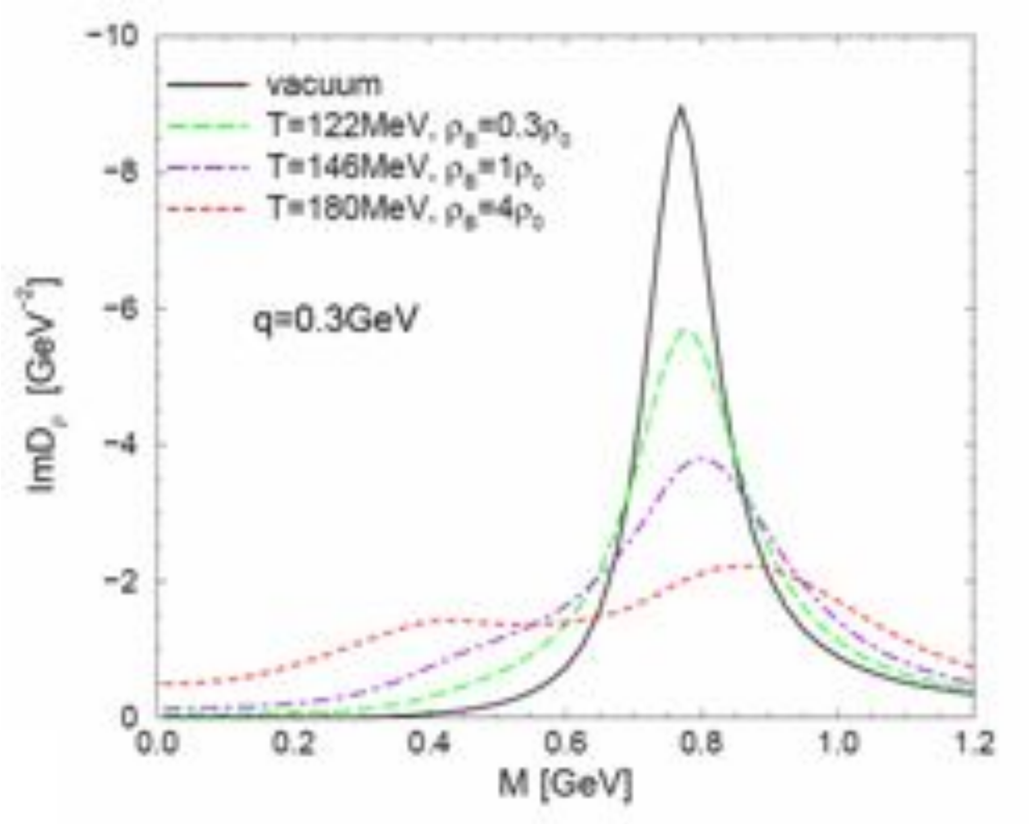


- in (dense) nuclear matter the ρ-meson might undergo a lot of rescattering

→ broadens spectral function!



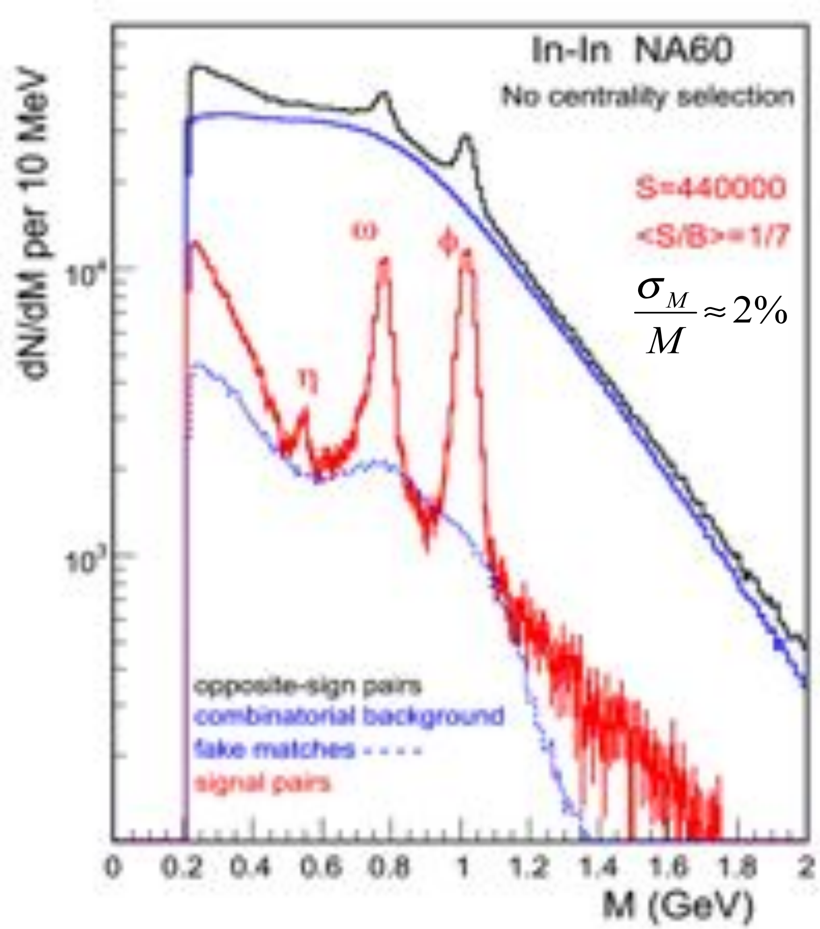




[Rapp, Wambach, Adv. Nucl. Phys. 25 (2000) 1, hep-ph/9909229]

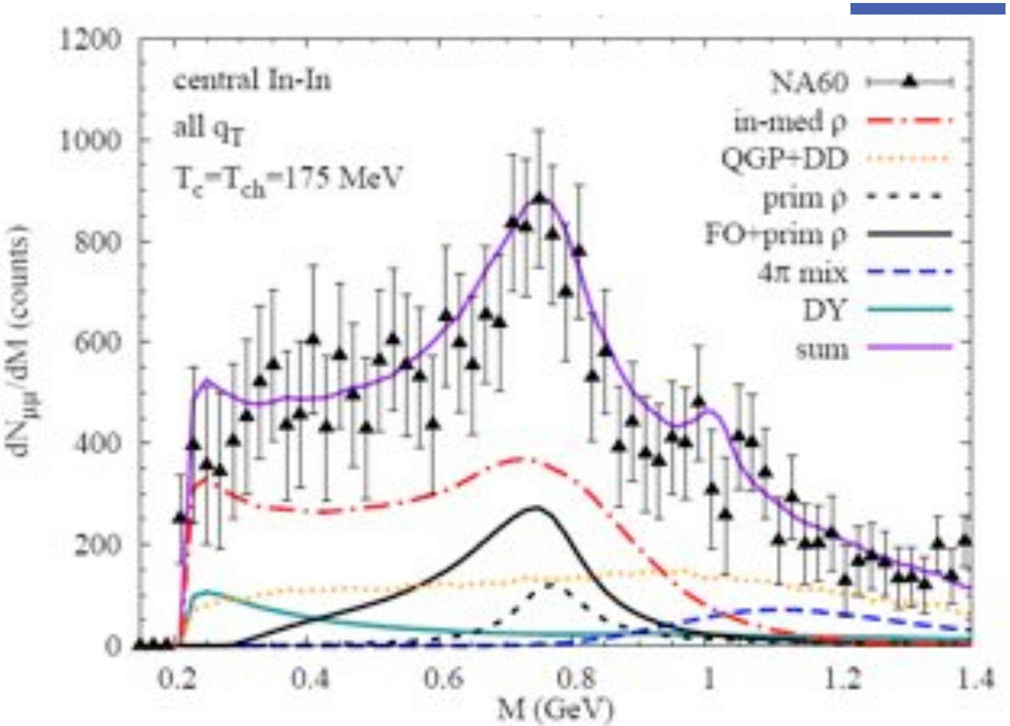
Exploring nuclear matter with penetrating probes

- SPS: dilepton spectra measured by NA60 (μ+μ-) and CERES (e+e-)
- excess spectrum shows strong modification of ρ-meson in medium



NA60: Phys.Rev.Lett. 96 (2006) 162302

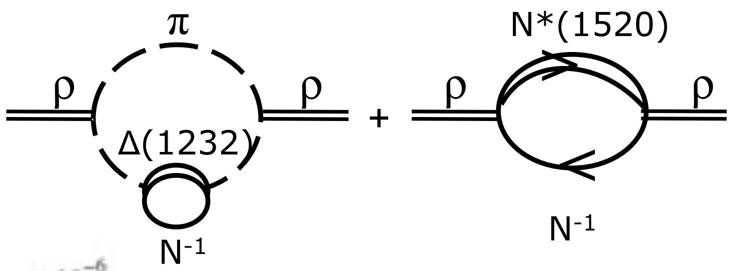
"excess spectrum": di-lepton radiation from the high-density phase

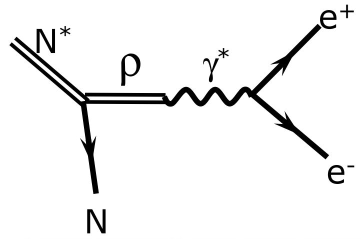


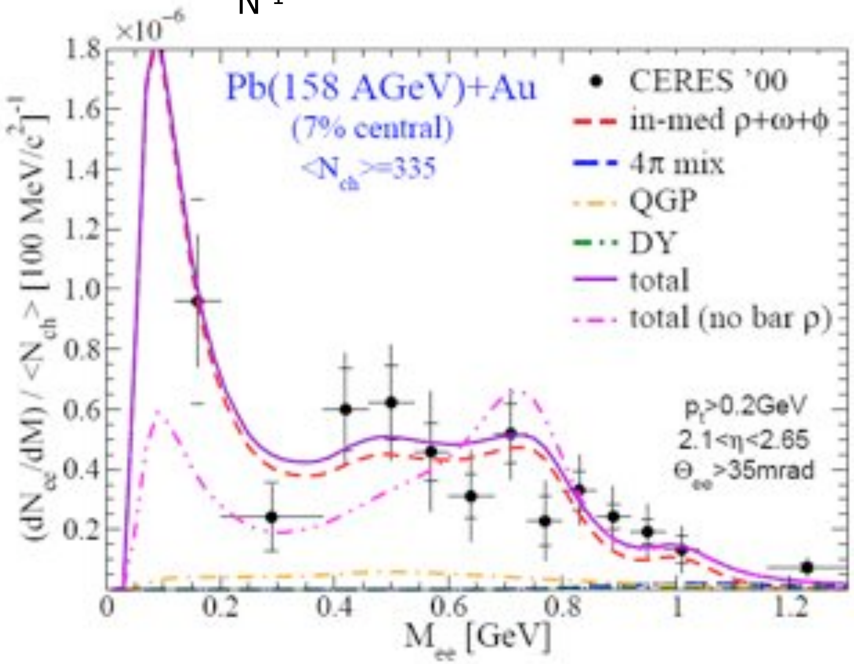
calculations: H. v. Hees, R. Rapp, Nucl.Phys.A806:339,2008

Exploring nuclear matter with penetrating probes

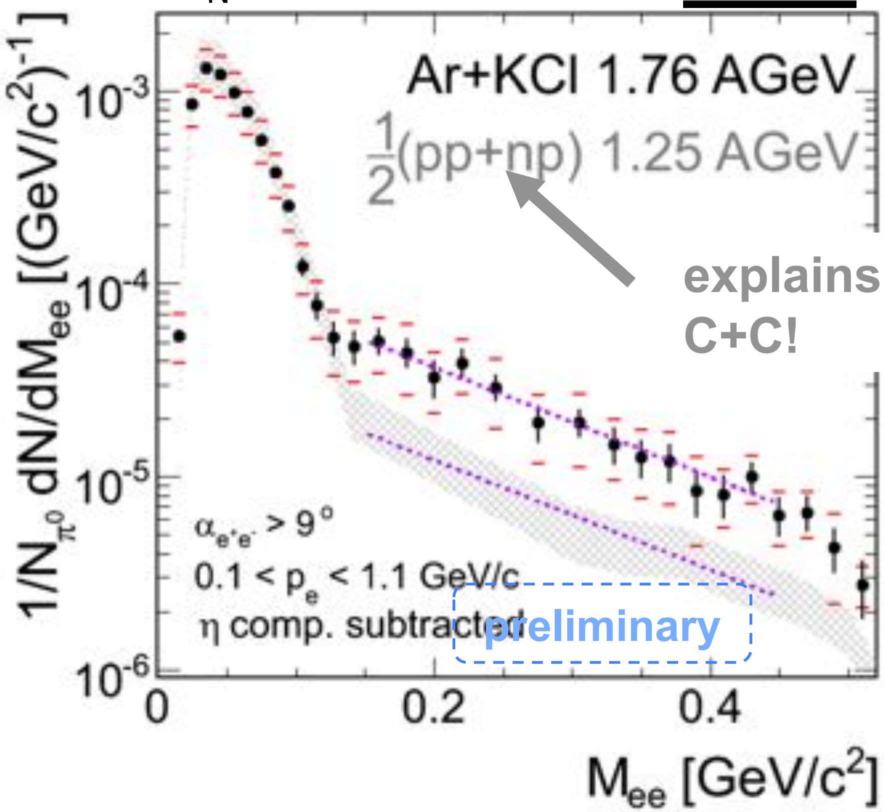
- measurement of di-electron channel: access to lowest masses
  → strength of dilepton yield at low masses is due to coupling to baryons!
- importance of baryon density: data at 40 show higher excess than at 158 AGeV!





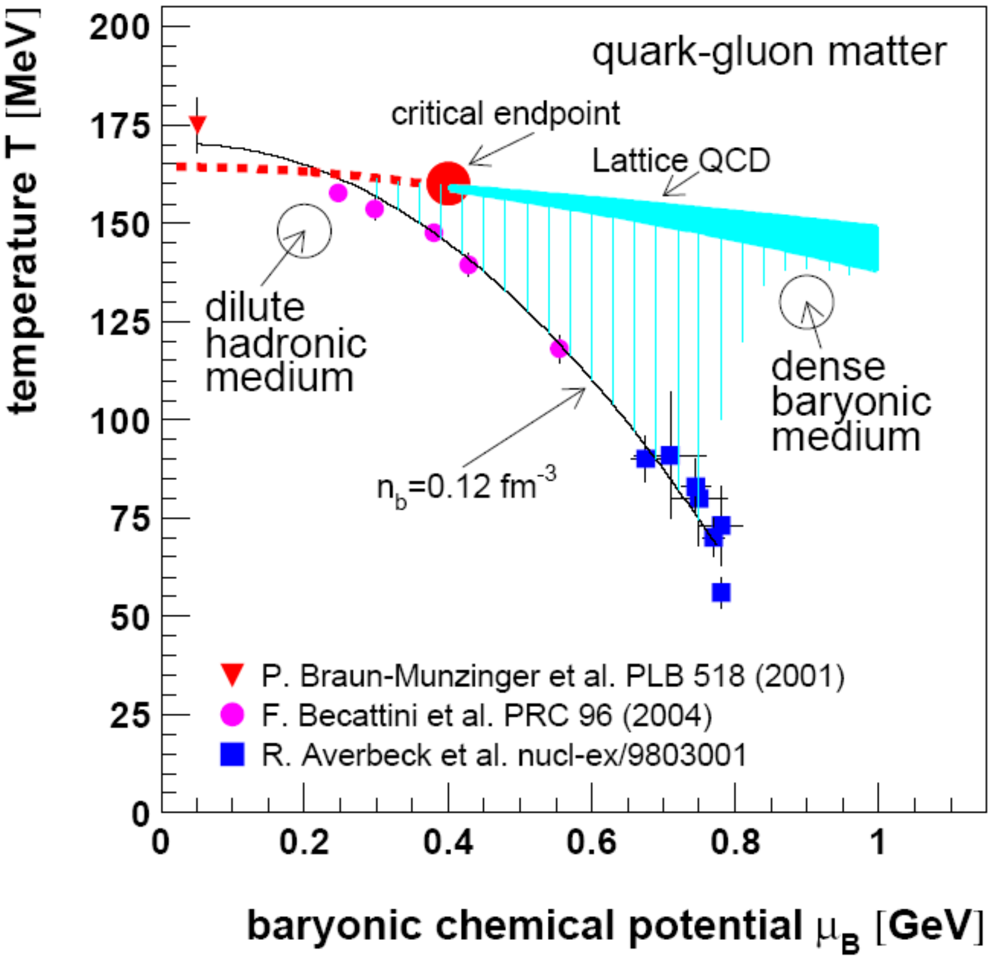


[CERES: Phys.Lett.B 666, 425 (2008)]
[calculations: H. v. Hees, R. Rapp, Nucl.Phys.A806:339,2008]



HADES, arXiv: 0907.3690 – QM09

Summary: What do we know from experiment?



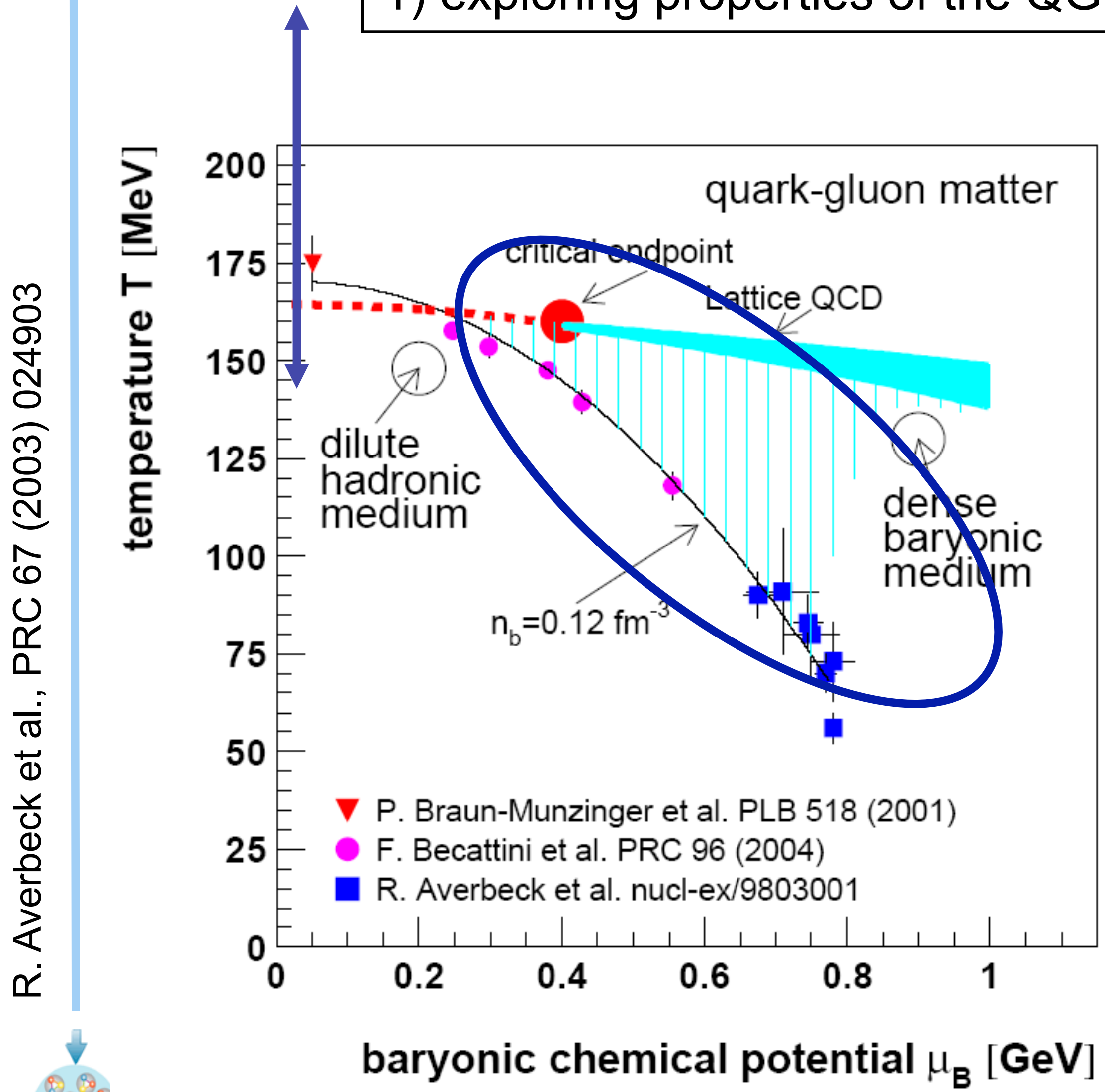
R. Averbeck et al., PRC 67 (2003) 024903

- freeze out curve
- μ_B=0 MeV: T=164 MeV
- partonic degrees of freedom at RHIC and top SPS
- evidence for onset of deconfinement at lower SPS energies (30 AGeV)
- modifications of hadronic properties in the medium
  - Kaons (SIS)
  - ρ-meson

●▼■ "freeze-out" points: final hadron yields described by statistical model: T, μ_B, V

Future experimental programs

1) exploring properties of the QGP at highest T and μ_B=0: LHC



2) searching for structures in the QCD phase diagram at high net-baryon densities; characterization of this matter

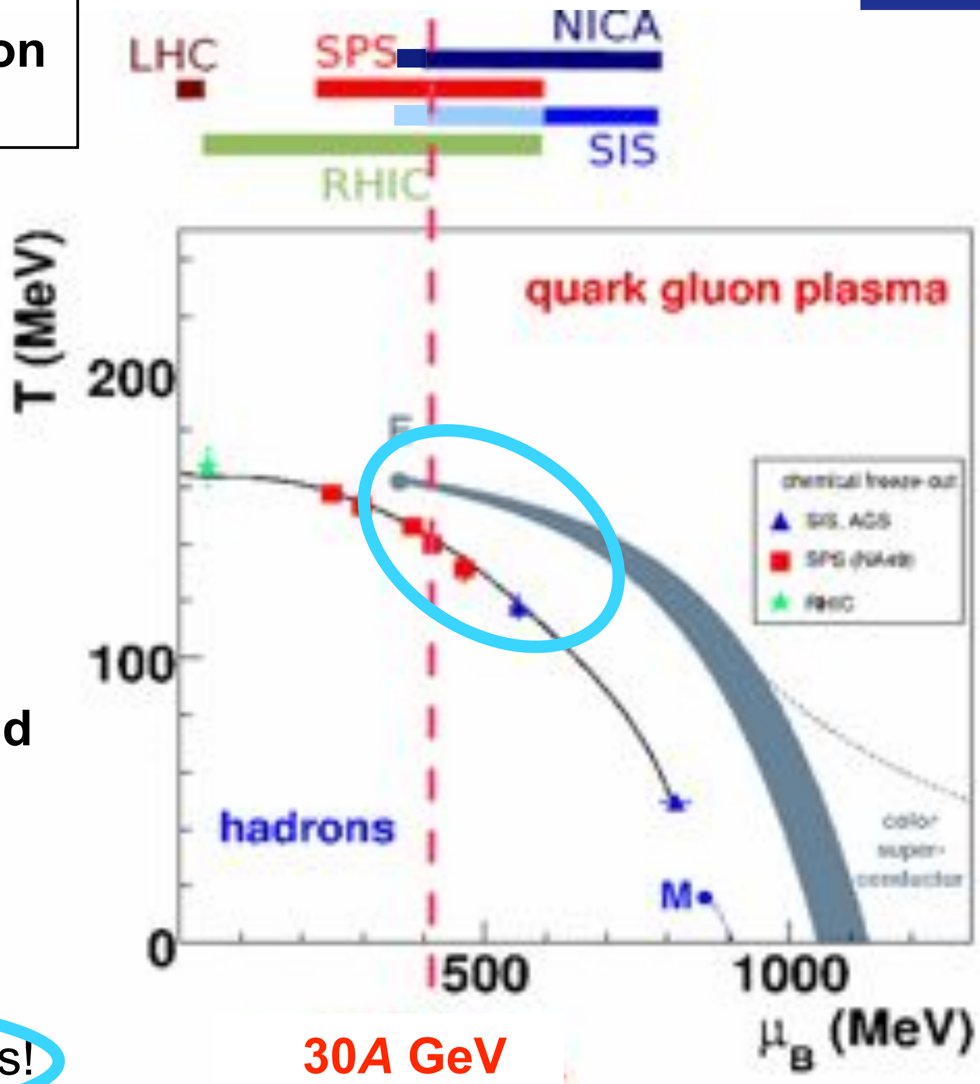
field driven by experimental data!

need to enter an era with quantitative characterizations!
(first steps done at RHIC)

Future explorations

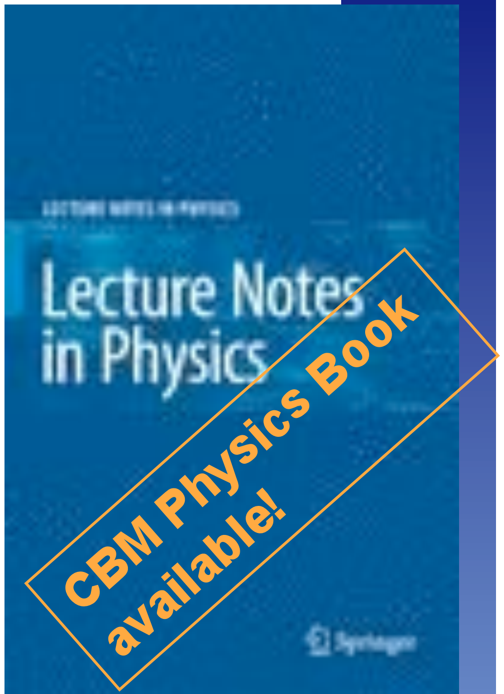
complete scan of the QCD phase diagram with modern, 2nd generation experiments on the horizon!

- **RHIC beam energy scan**
  - evolution of medium properties
  - "turn-off" of established signatures
  - search for CP and PT
- **NA61 at SPS**
  - search for CP and PT in energy-system size scan
- **both essentially limited to high yield observables**
- **FAIR and NICA**
  - new accelerator projects
  - FAIR: high intensities! → rare probes!



30*A* GeV

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,...)

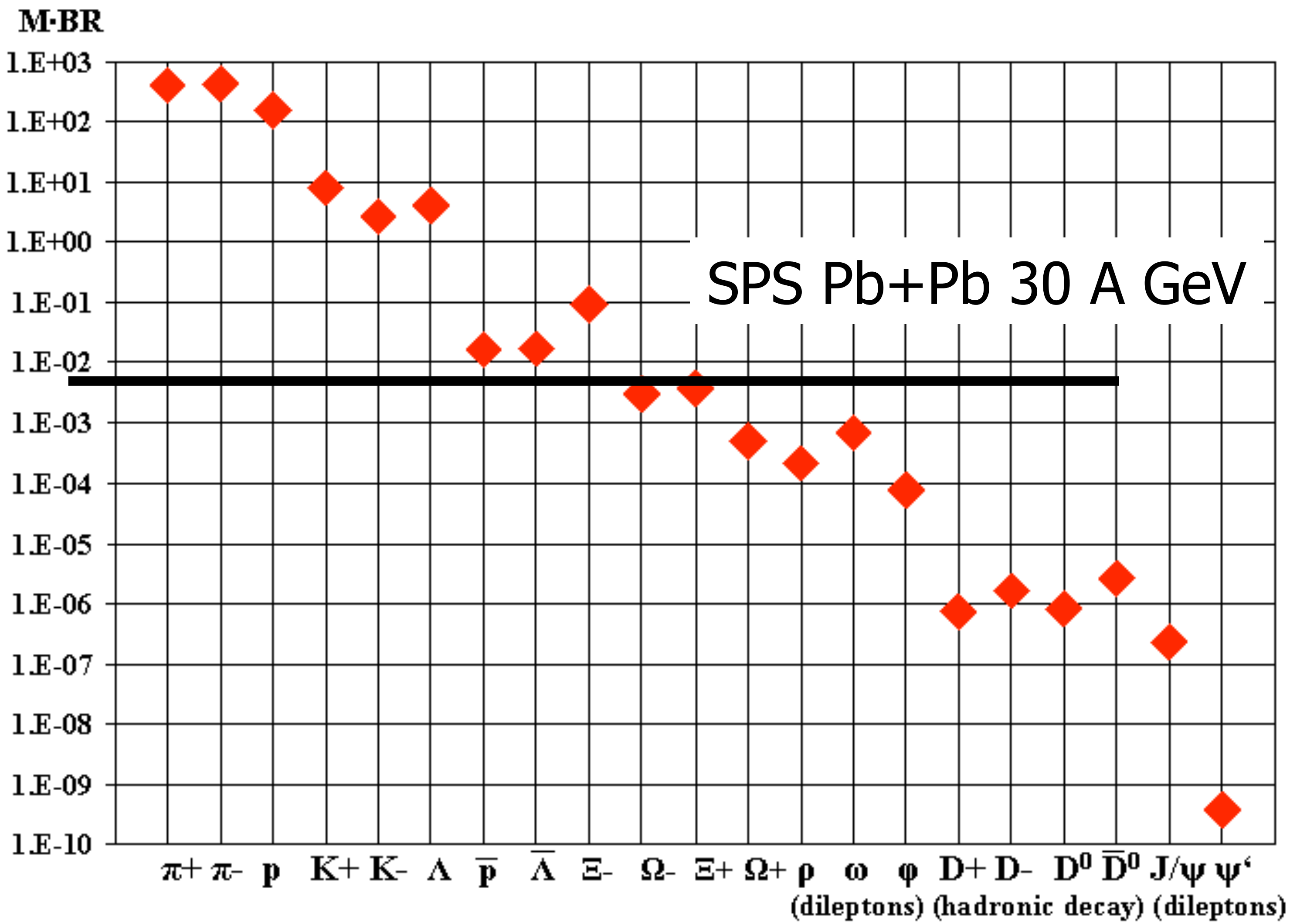
Onset of chiral symmetry restoration at high ρ_B
- in-medium modifications of hadrons ($\rho,\omega,\phi \rightarrow e^+e^-(\mu^+\mu^-)$, D)

Systematics & precision!!

→ characterization of the created medium!

Particle multiplicities

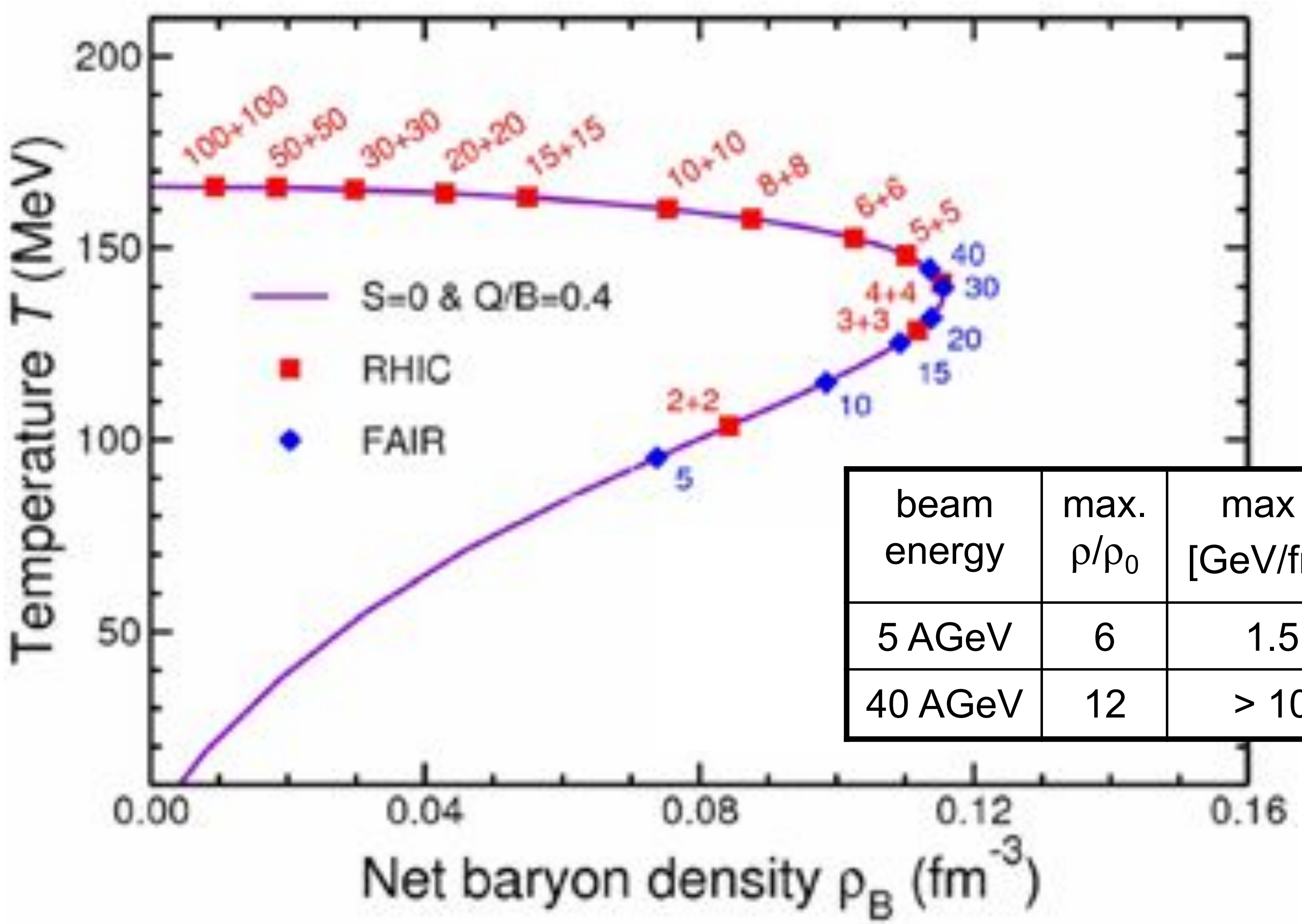
Particle multiplicity · branching ratio for min. bias Au+Au collisions at 25 GeV (from HSD and thermal model)



Highest net-baryon densities at FAIR

• high (net-)baryon and energy densities created in central Au+Au collisions

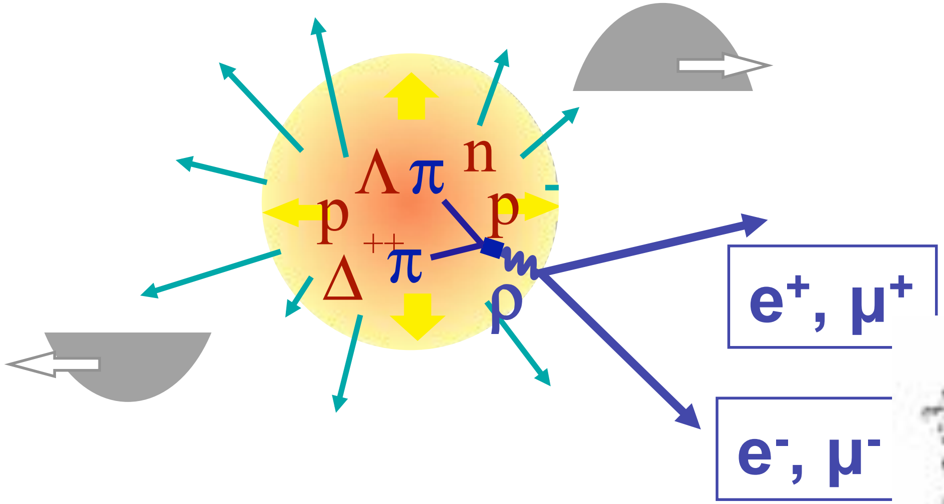
[J. Randrup, J. Cleymans PRC74, 047901 (2006)]



beam energy	max. ρ/ρ_0	max ε [GeV/fm^3]	time span ~FWHM
5 AGeV	6	1.5	~ 8 fm/c
40 AGeV	12	> 10	~ 3.5 fm/c

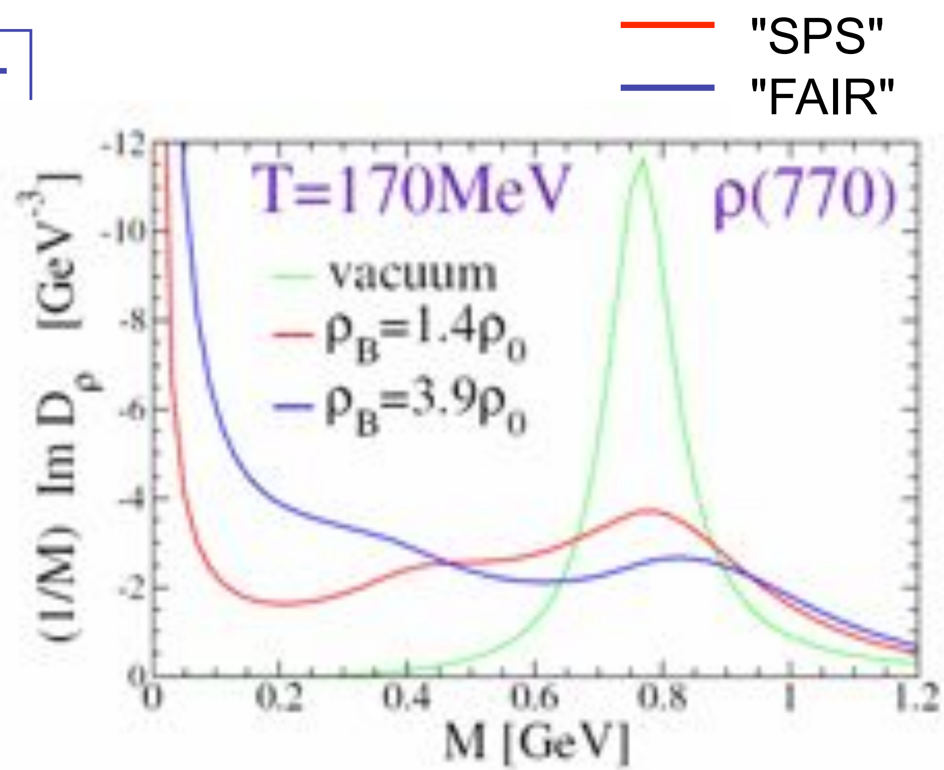
Exploring nuclear matter with penetrating probes

- dileptons are penetrating probes – direct radiation from the created hot and dense matter



ρ - meson

- vacuum lifetime τ_0 = 1.3 fm/c
- couples to the medium → change of hadronic properties:
  ρ "melts" close to T_c and at high μ_B
- connection to chiral symmetry restor



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

Charm production at threshold

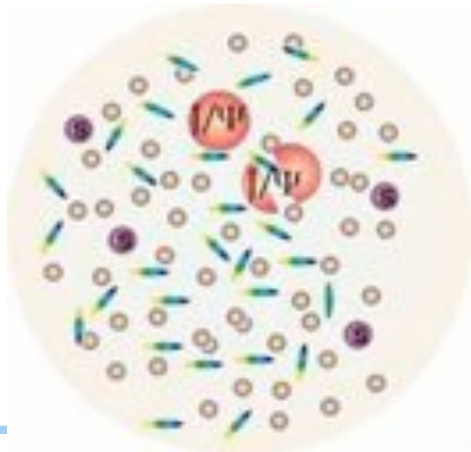
- CBM will measure charm production at threshold

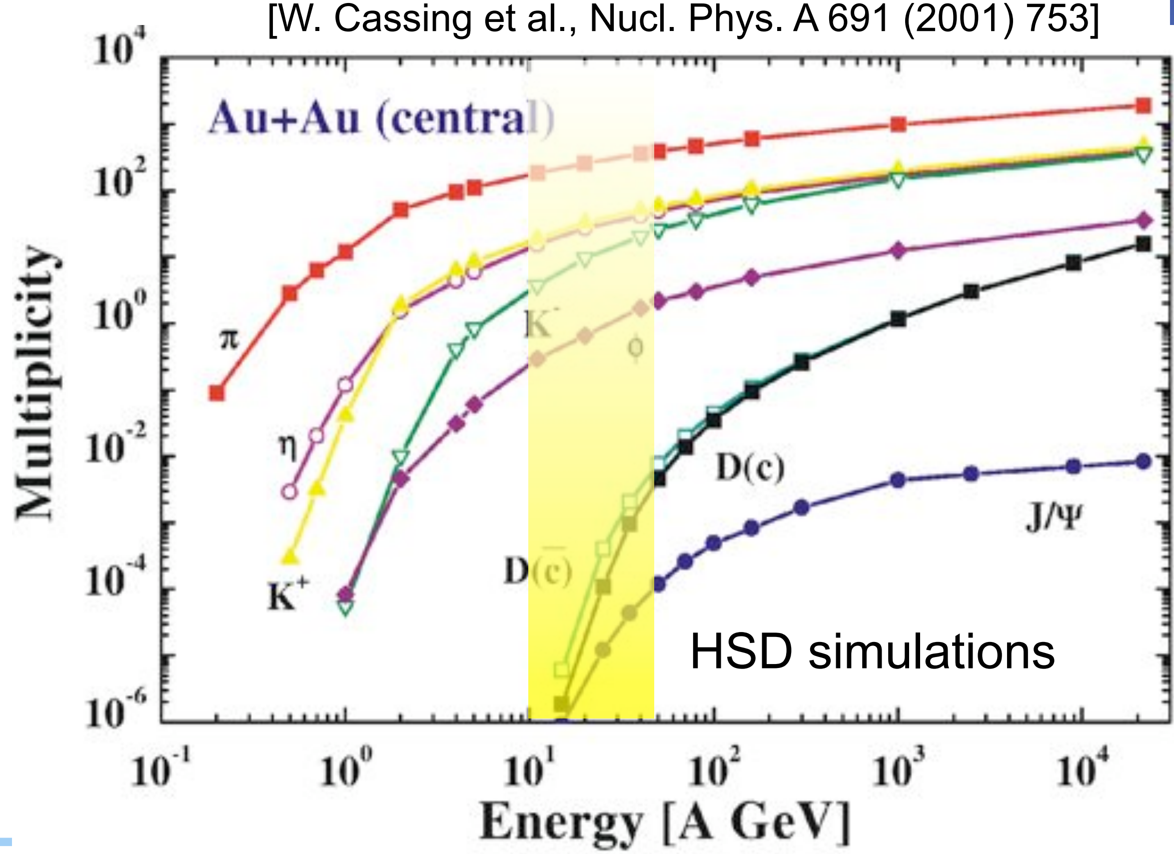
→ after primordial production, the survival, momentum and distribution amongst different hadrons of charm depends on the interactions with the dense and hot medium!

→ direct probe of the medium!

[W. Cassing et al., Nucl. Phys. A 691 (2001) 753]

- charmonium in hot and dense matter?
- relation to deconfinement?
- relation to open charm?

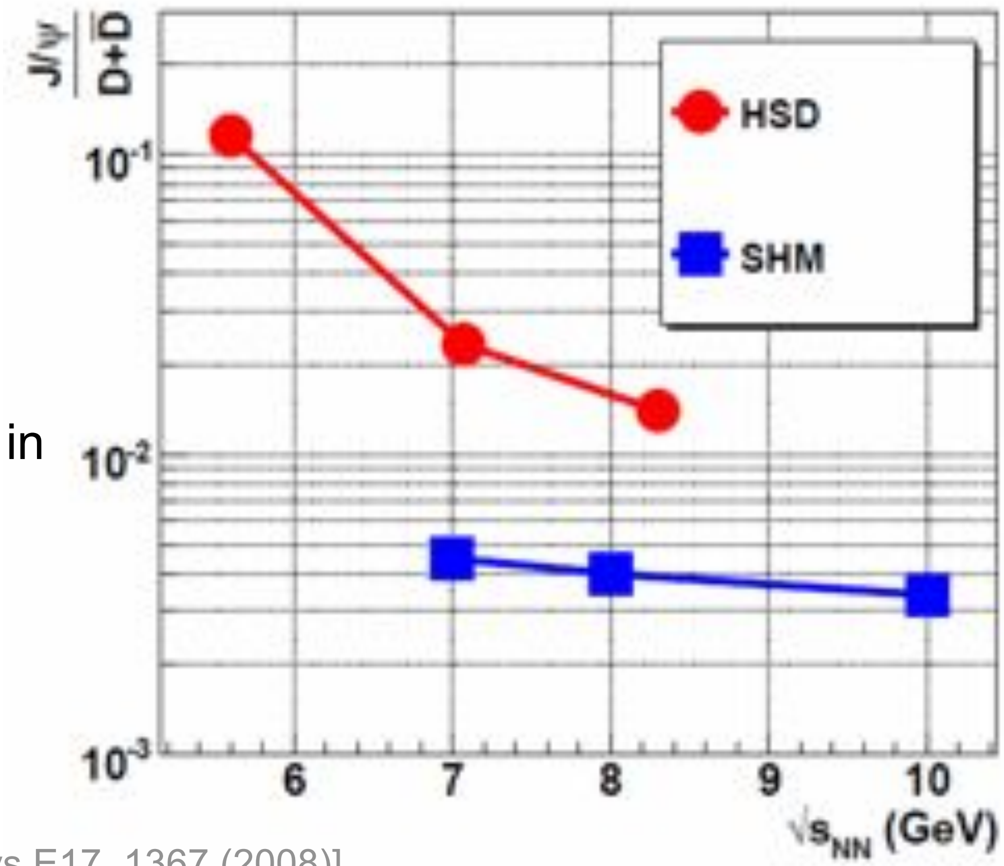




Charm propagation

Propagation of produced charm quarks in the dense phase – quark like or (pre-)hadron like?

- charmonium to open charm ratio as indicator – **measure both!**
- indications of collectivity?



- first charm measurements in A+A below 158 AGeV!
- aim at detailed information including phase space distributions, flow!

[HSD: O. Linnyk et al., Int.J.Mod.Phys.E17, 1367 (2008)]
[SHM: A. Andronic et al., Phys. Lett. B 659 (2008) 149]

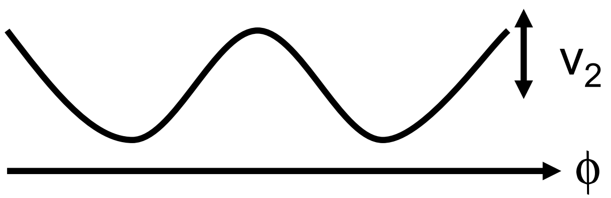
A+A collisions (IV)

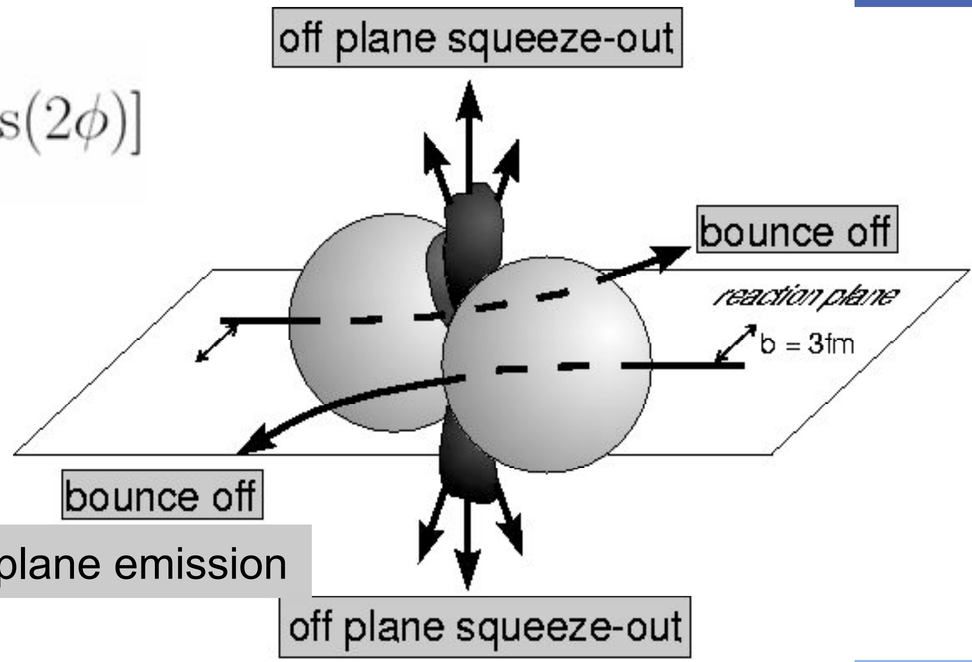
• the geometry of the colliding nuclei determines another important measure, the reaction plane

• relative to the reaction plane particle emission patterns (flow) can be measured, rich structure!

Fourier expansion of the dN/dϕ distribution:

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

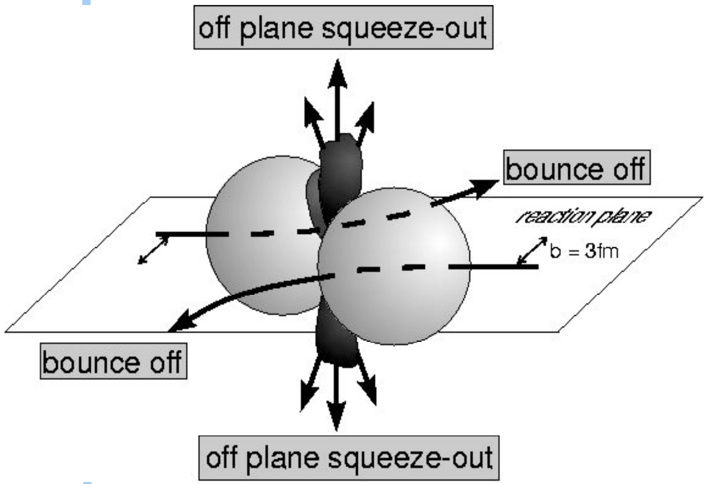




out off plane emission

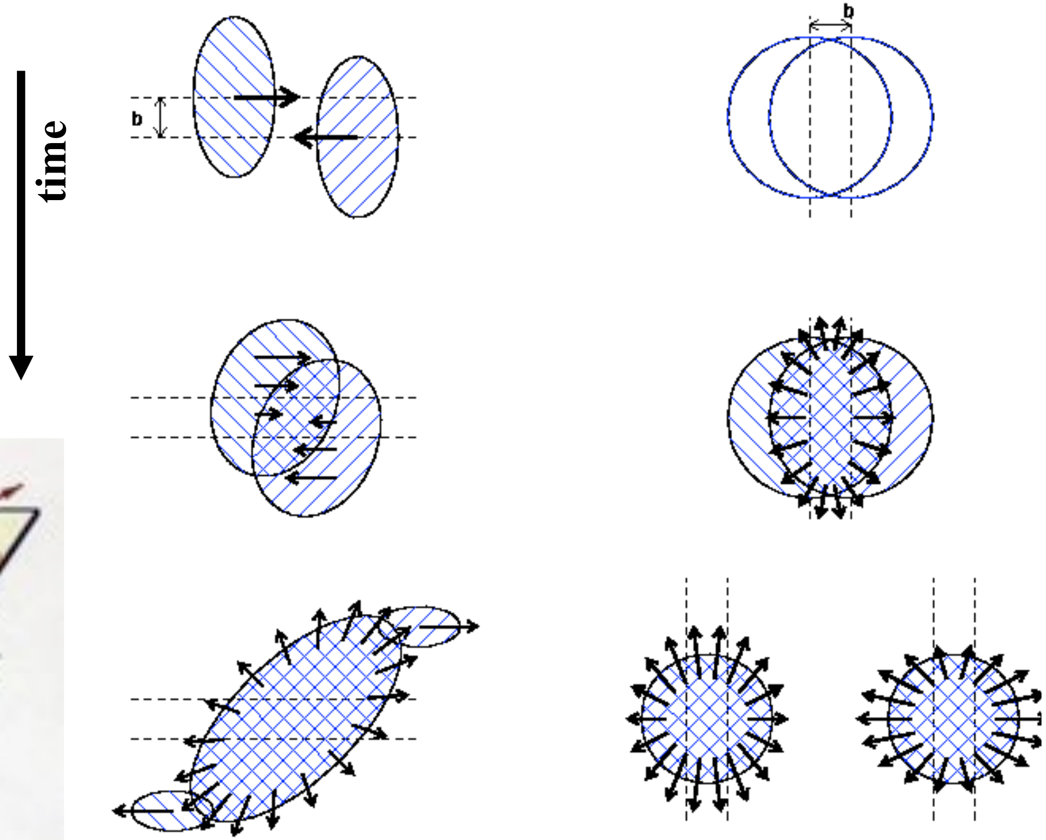
the coefficients quantify :
- v_1 the in-plane and
- v_2 the elliptic emission pattern

Sideflow versus elliptic flow



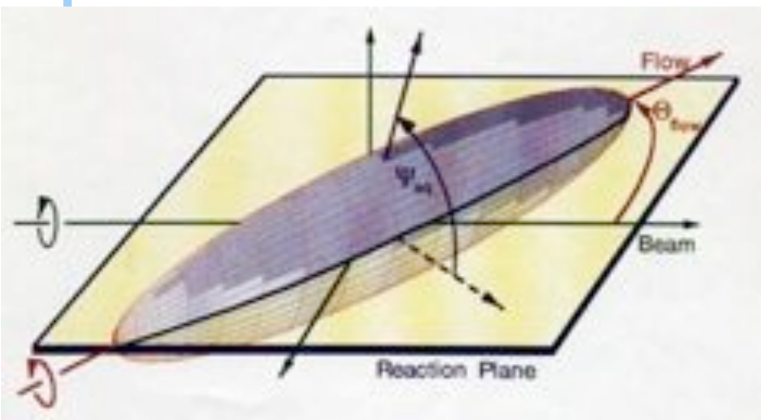
reaction plane

transverse plane (at midrapidity)



spacial overlap eccentricity

momentum anisotropy



$$\frac{d\sigma}{d\Psi} \propto \left[1 + 2v_1 \cos(\Psi) + 2v_2 \cos(2\Psi)\right]$$

$v_1<0$ $v_1>0$

sideflow

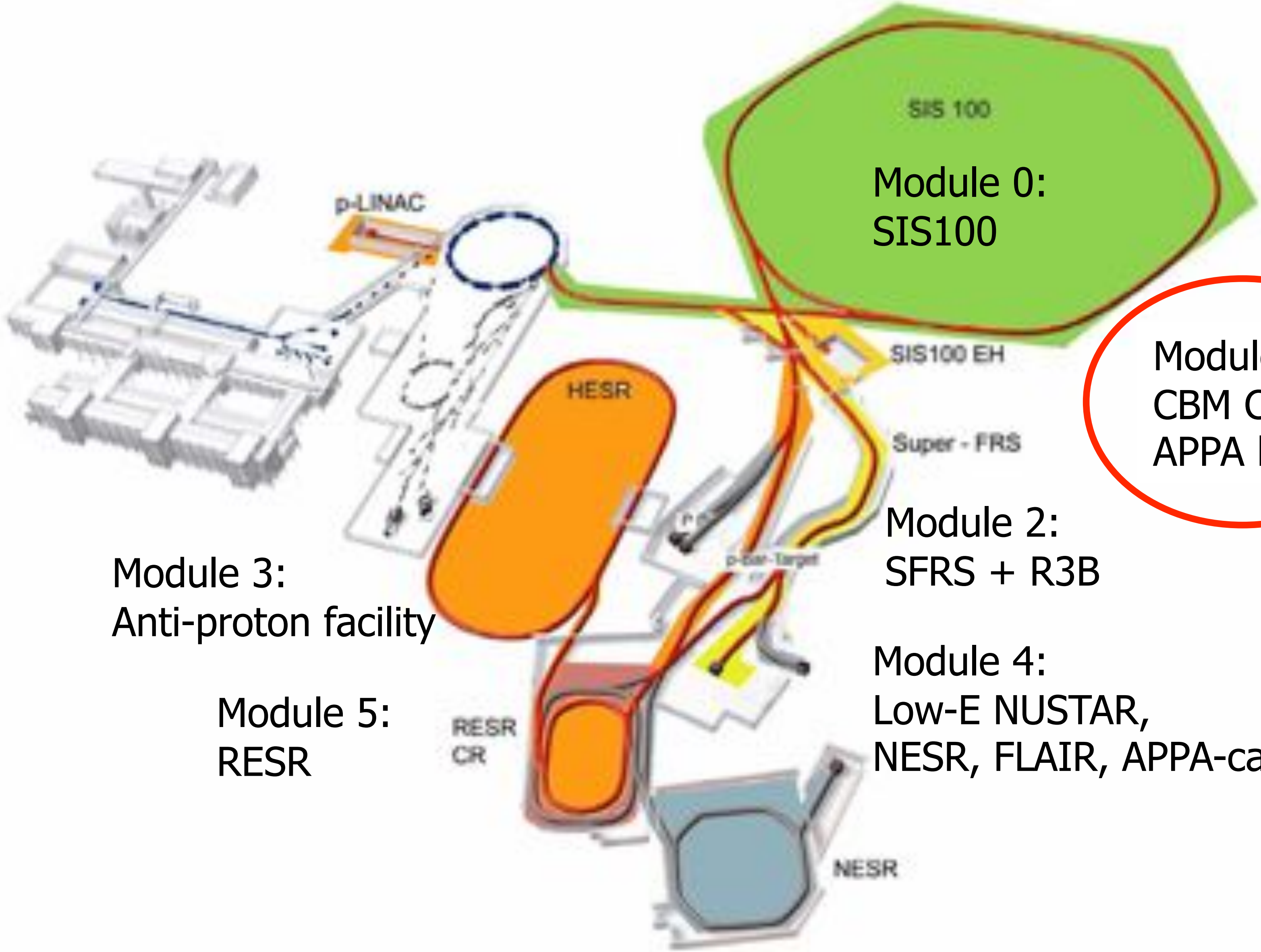
$p_x = v_1 p_t$

$v_2<0$ $v_2>0$

elliptic flow

$R_N=(1+v_2)/(1-v_2)$

HADES and CBM startversion at SIS 100



Module 0:
SIS100

Module 1:
CBM Cave,
APPA hall

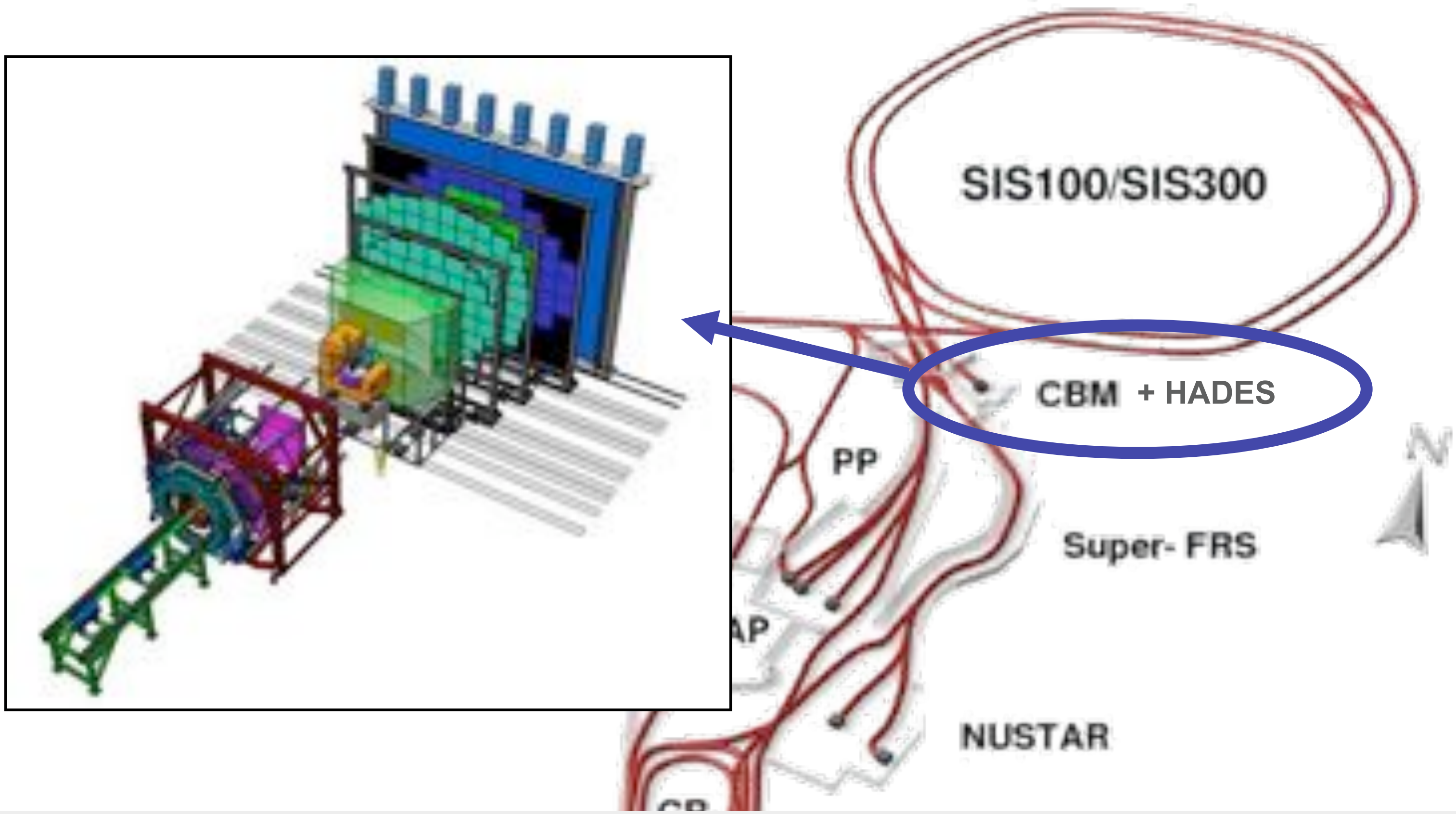
Module 2:
SFRS + R3B

Module 3:
Anti-proton facility

Module 4:
Low-E NUSTAR,
NESR, FLAIR, APPA-cave

Module 5:
RESR

CBM @ FAIR



CBM and HADES at SIS 100 and SIS 300

- systematic exploration of high baryon density matter in A+A collisions from 2 – 45 AGeV beam energy with 2nd generation experiments
- explore the QCD phase diagram, chiral symmetry restauration

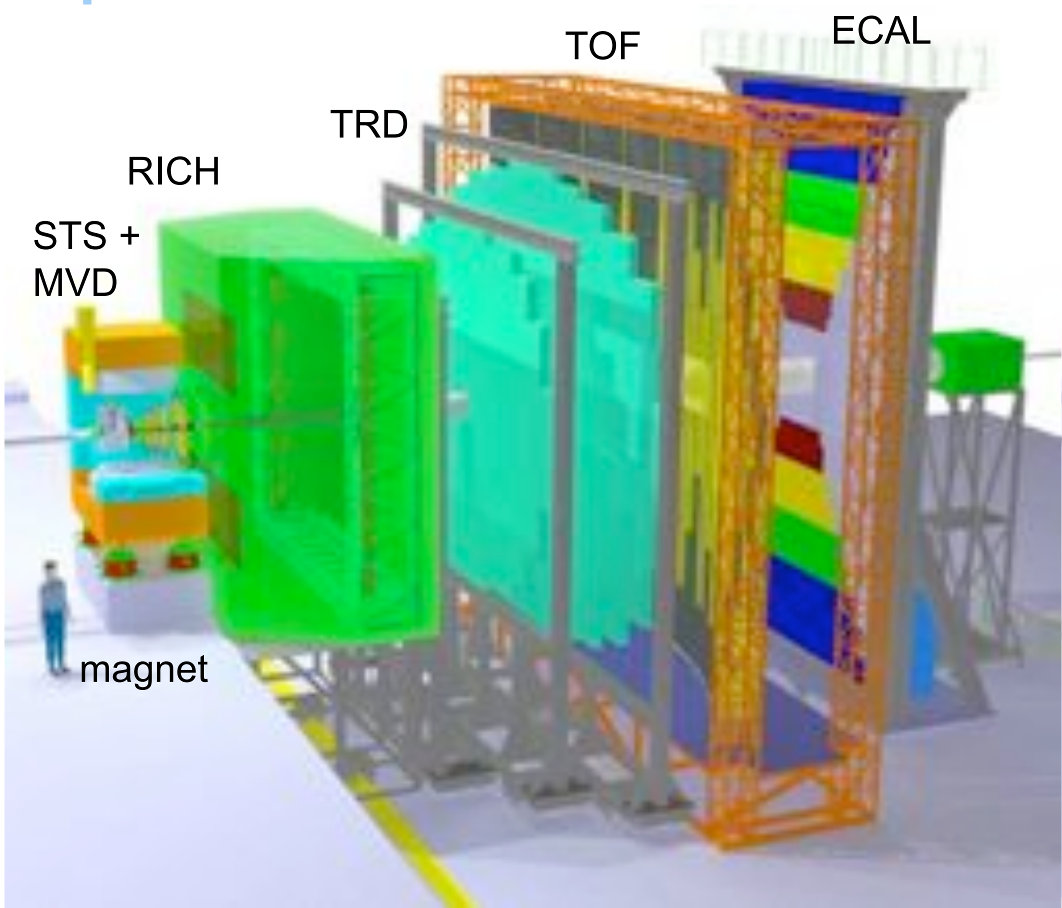
The CBM experiment

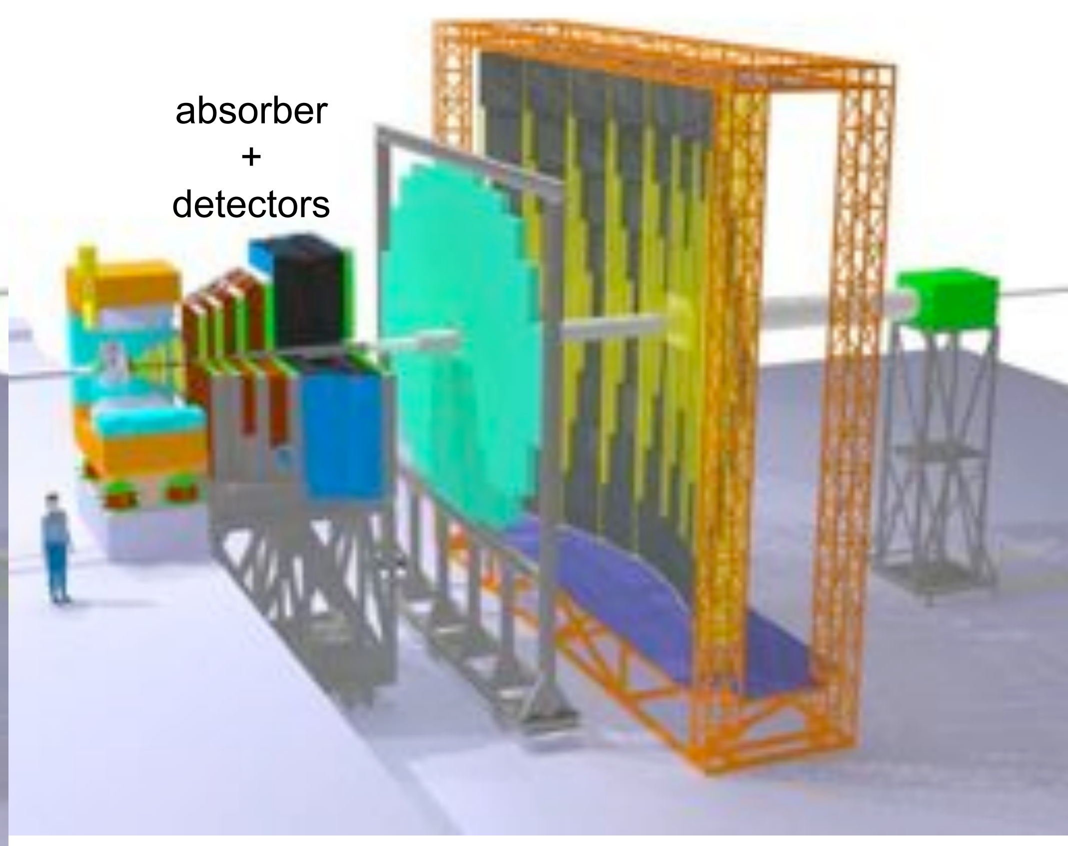
- tracking, momentum determination, vertex reconstruction: radiation hard silicon pixel/strip detectors (STS) in a magnetic dipole field

- 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



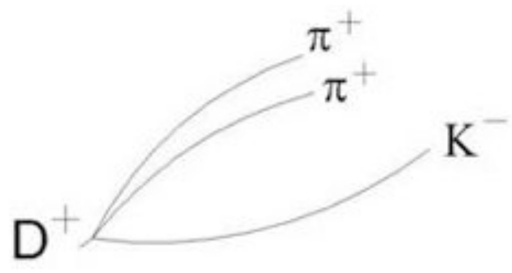


STS tracking – heart of CBM

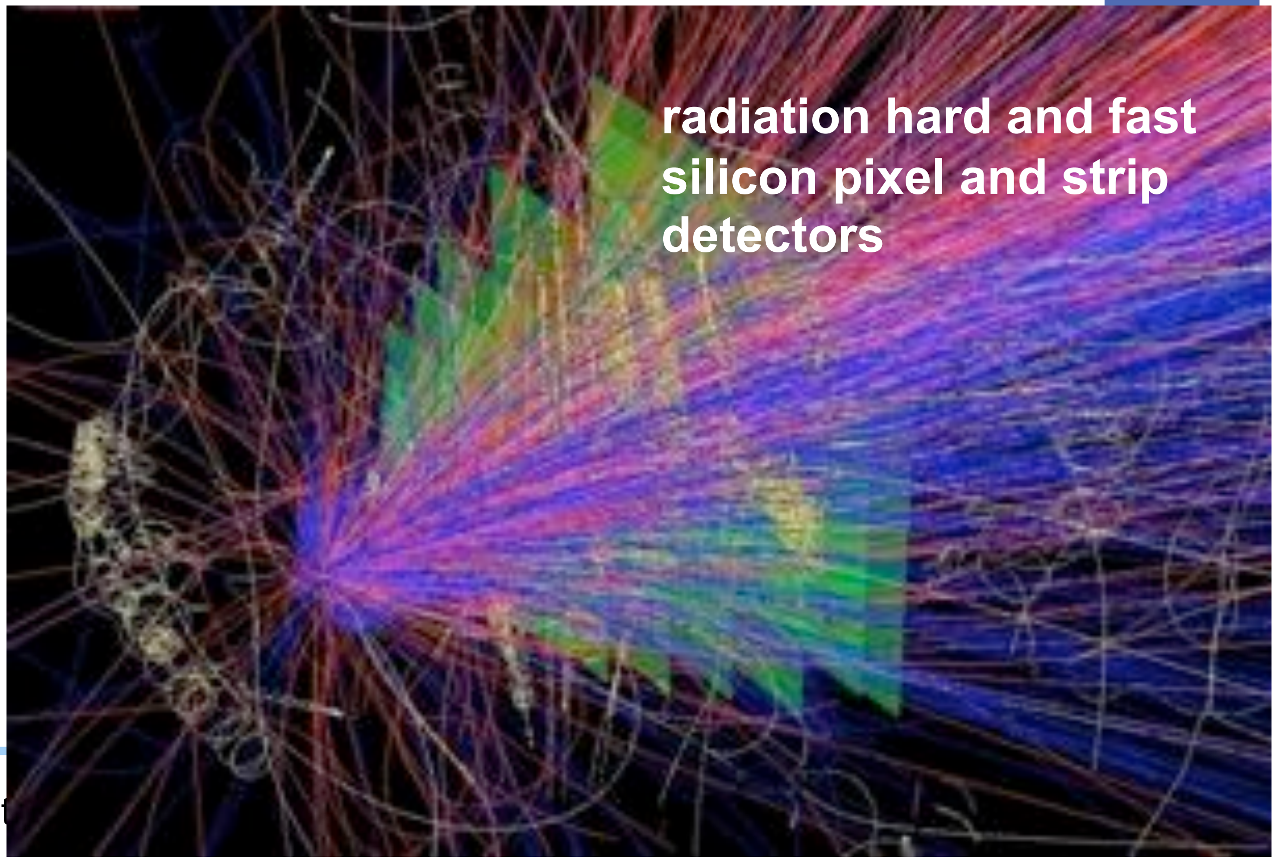
Challenge: high track density: ≈ 600 charged particles in ± 25° @ 10MHz

Task

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



$c\tau$ = 312 μm



self triggered FEE

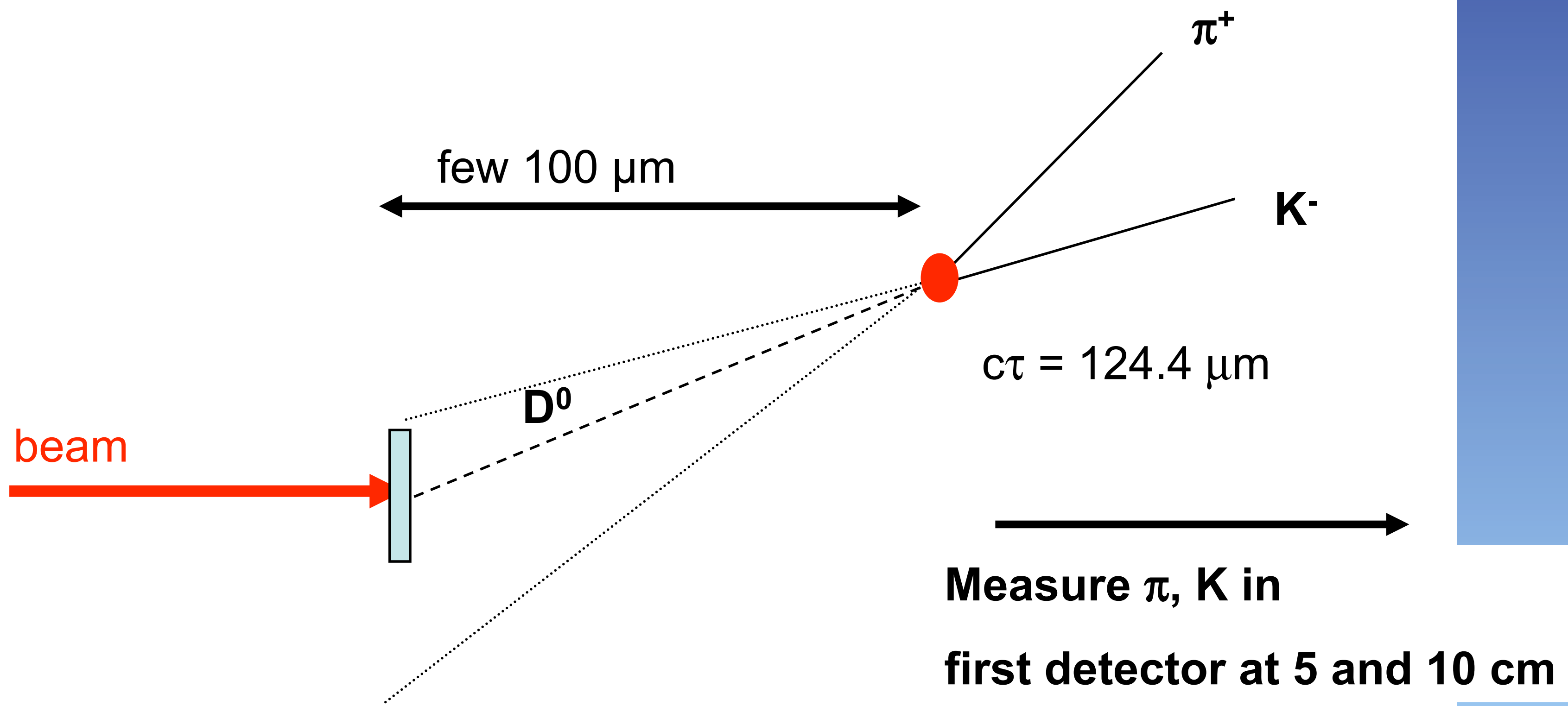
high speed DAQ and trigger

online track reconstruction!

fast & rad. hard detectors!

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
  - 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!



CBM – detector concept

• fixed target experiment, "medium" energies

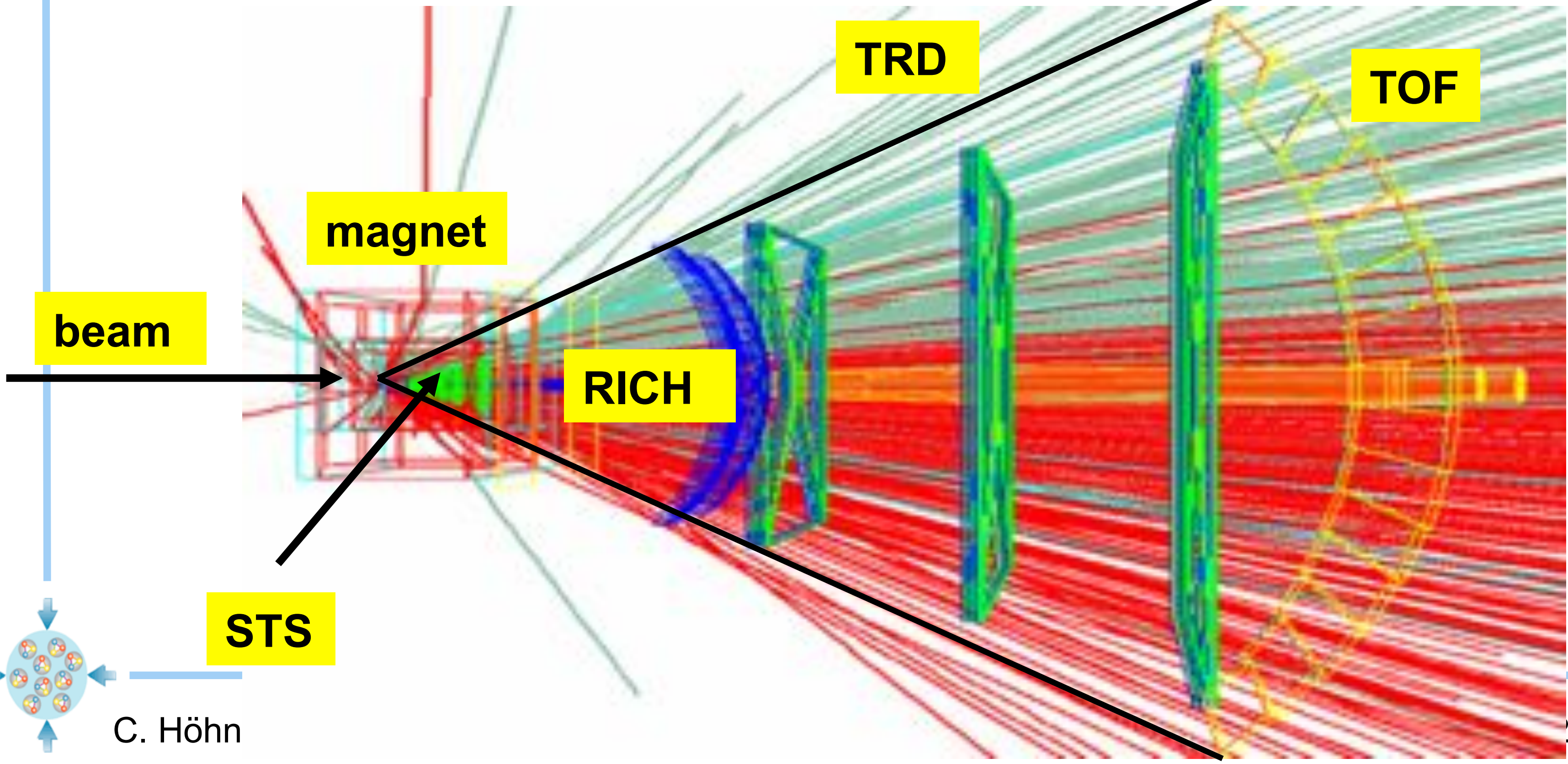
→ large solid angle to be covered

• high rate, multipurpose detector including open charm reconstruction

drives layout

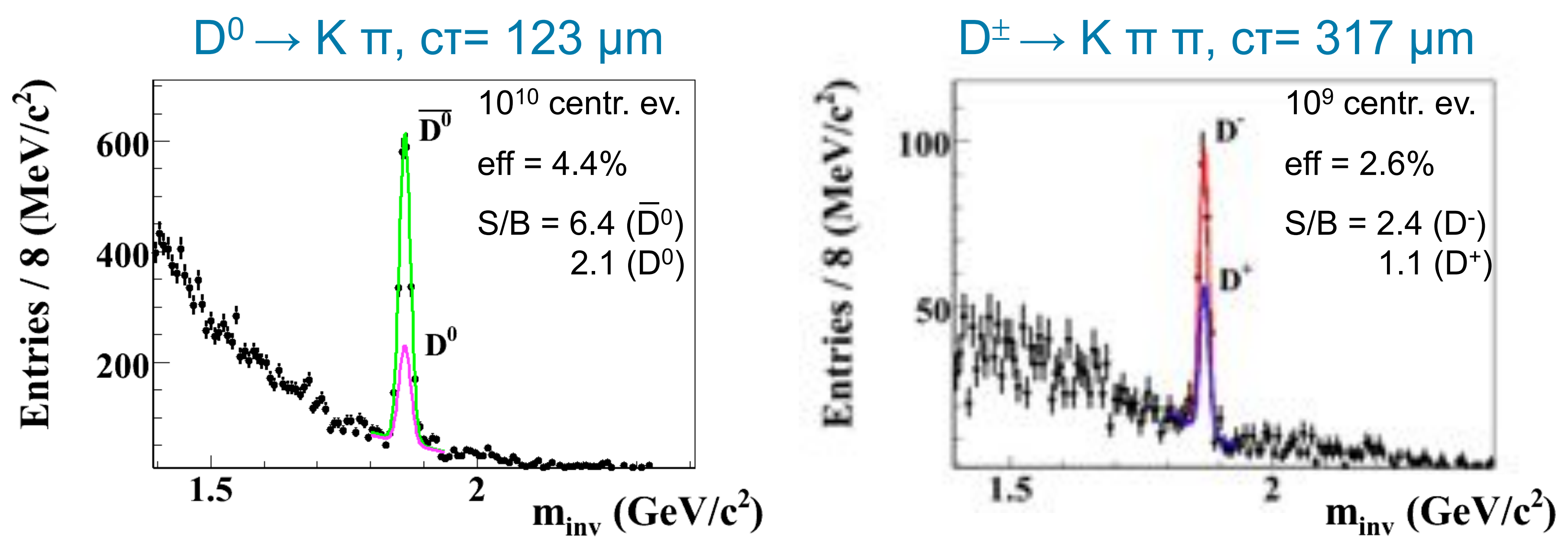
→ fast, excellent tracking based on silicon pixel and strip detectors directly behind the target and inside a magnetic field

→ add particle identification afterwards (leptons, hadrons)



Simulation of open charm reconstruction

- STS – 8 double-sided Si micro-strip sensor stations (each 400 μm Si equ.)
- MVD – 2 MAPS pixel sensors (300 μm, 500 μm) at z = 5 cm, 10 cm
- no K, π id.; p rejection via TOF; 2ndary vertex resolution ~ 50 μm
- semi-realistic detector response



10^{12} minbias events
25*A* GeV Au+Au

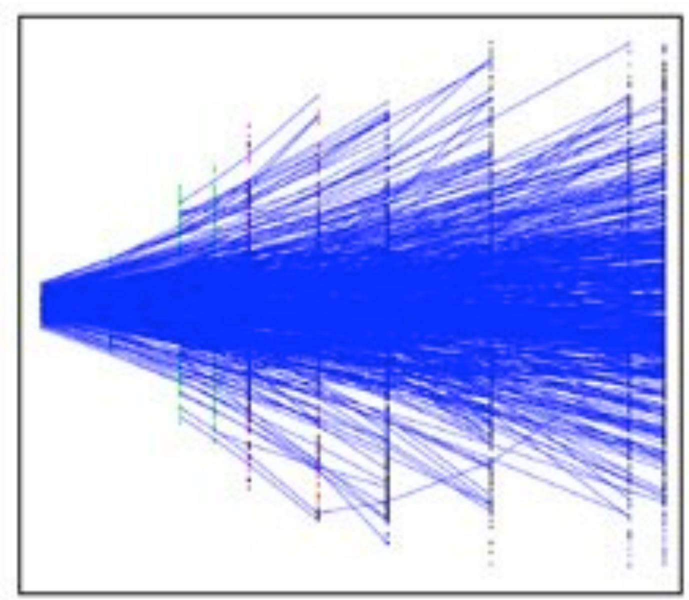
~ 7k D_0 + 20k $\bar{D}_0$

~ 12k D^+ + 26k D^-

Parallelization in CBM Reconstruction !

- fast event reconstruction is a **must** for CBM!

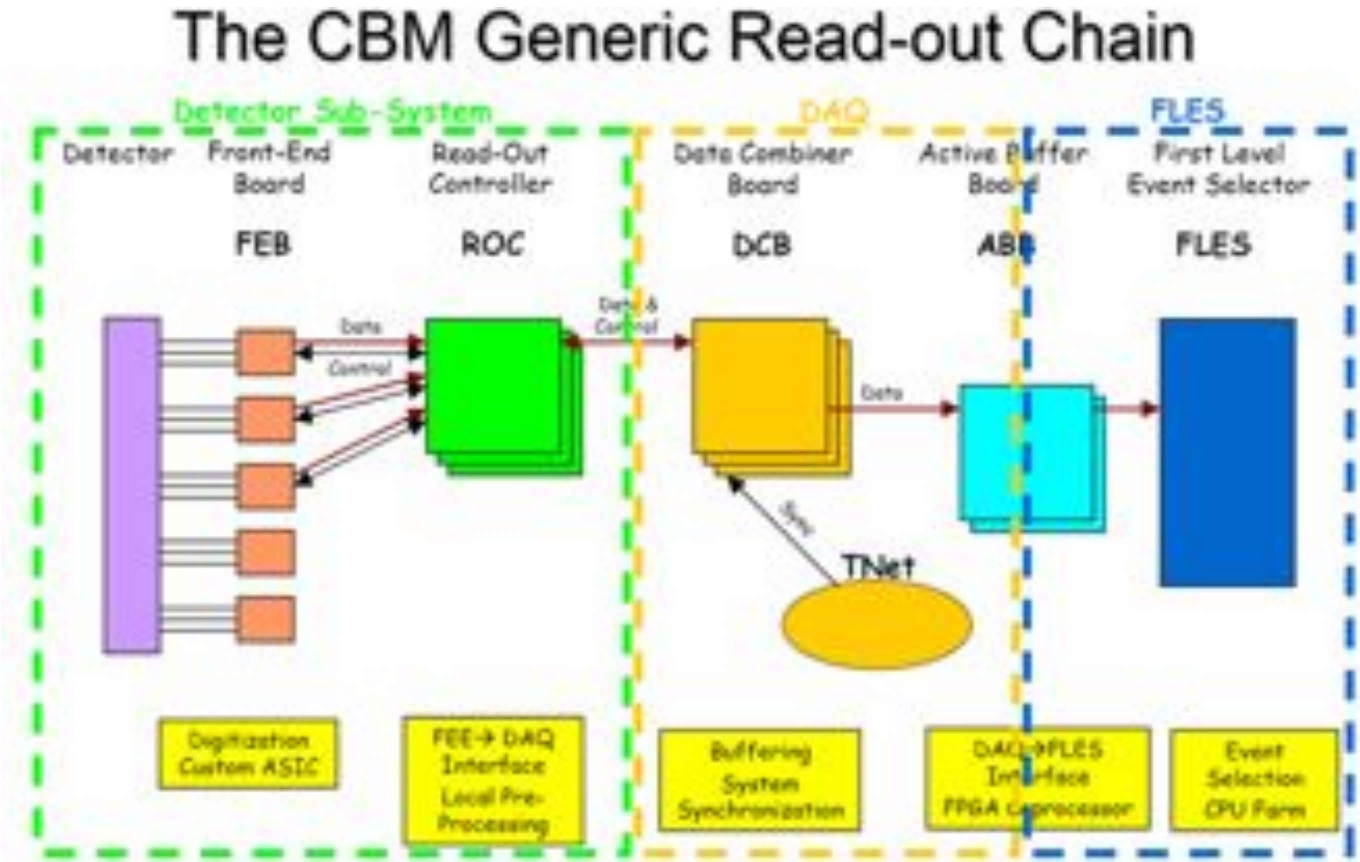
	Vector SIMD	MultiThreading	NVIDIA CUDA	OpenCL
STS	+	+	+	+
MuCh	+	+		
RICH	+	+		
TRD	+	+		
Vertexing	+			
Open Charm Analysis	+			



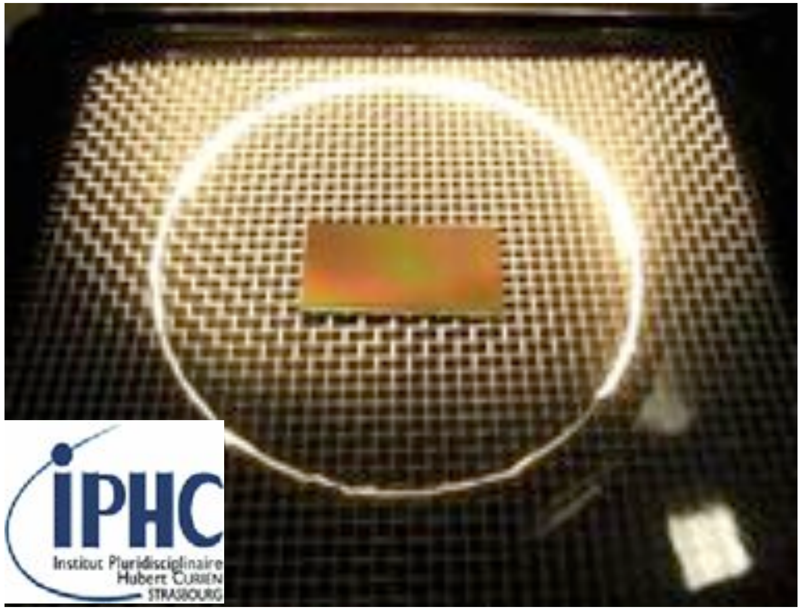
DELL Server with:
- **Core i7/Nehalem 2**x(Xeon X5550 **4**x2.66 GHz, 8 MB L3 cache)
- DDR3-1333 **36 GB** main memory
- **NVIDIA** GTX 295 **2x240 FPUs**, 1792 MB
- optional **LRB**

Self-triggered readout electronics

- self-triggered readout electronics
- data-push architecture
- trigger evaluation with online tracking on large PC farm



Sensors for the MVD

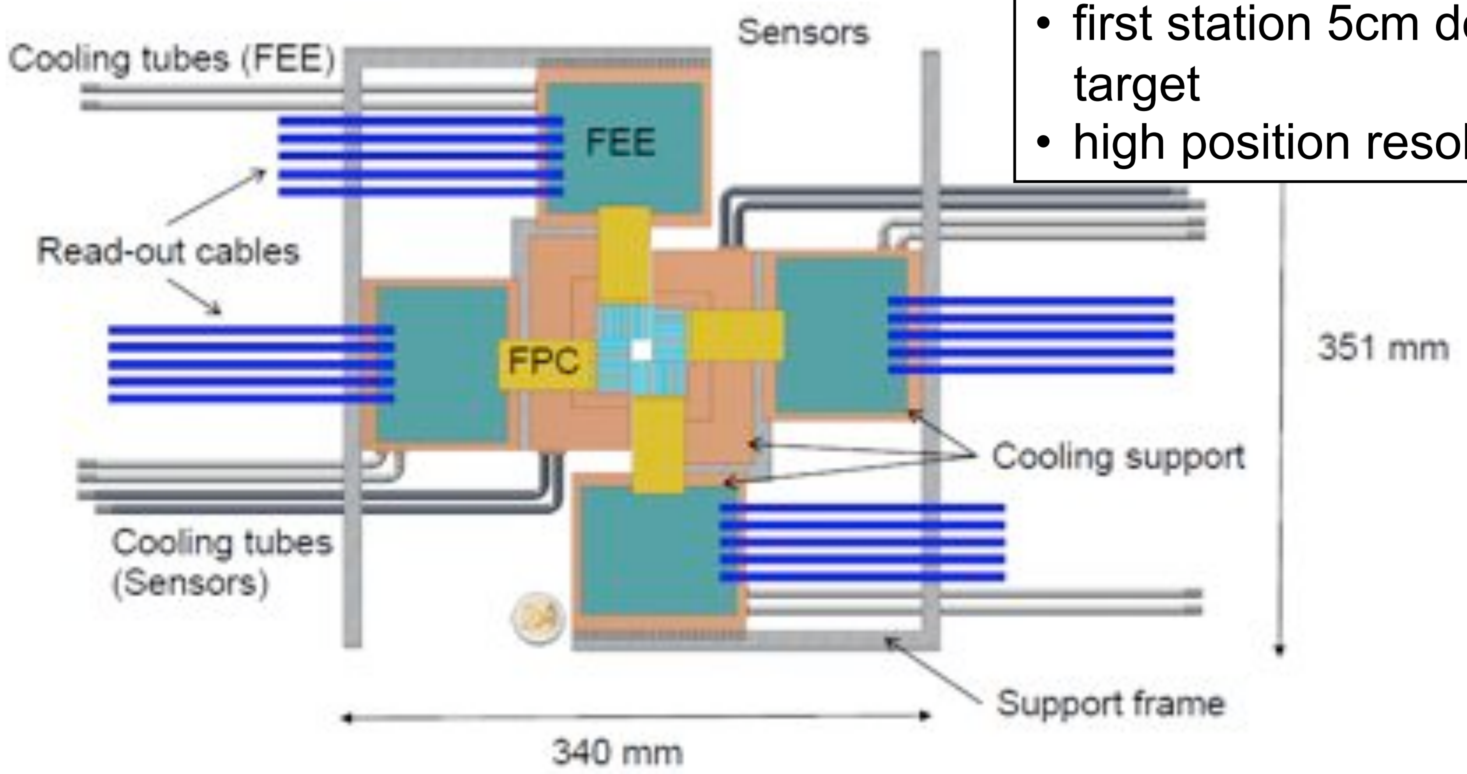


Monolithic Active Pixel Sensors
(MAPS, also CMOS-Sensors)

- Invented by industry (digital camera)
- Modified for charged particle detection since 1999 by IPHC Strasbourg
- Also foreseen for ILC, STAR…

		Best values reached		Current compromise
	CBM wish list	MAPS* (2003)	MAPS* (2009)	MIMOSA-26 Binary, ∅
Single point res.	**~ 5 µm**	**1.5 µm**	**1 µm**	**4 µm**
Material budget	**< 0.3% X_0**	**~ 0.1% X_0**	**~ 0.05% X_0**	**~ 0.05% X_0**
Rad. hard. non-io.	**>10^{13} n_{eq}**	**10^{12} n_{eq}/cm^2**	**>3x10^{13} n_{eq}**	few 10^{13} n_{eq}
Rad. hard. io	**> 3 Mrad**	**200 krad**	**> 1 Mrad**	**> 300 krad**
Time resolution	**< 30 µs**	**~ 1 ms**	**~ 25 µs**	80 µs

Micro Vertex Detecor (MVD) Development

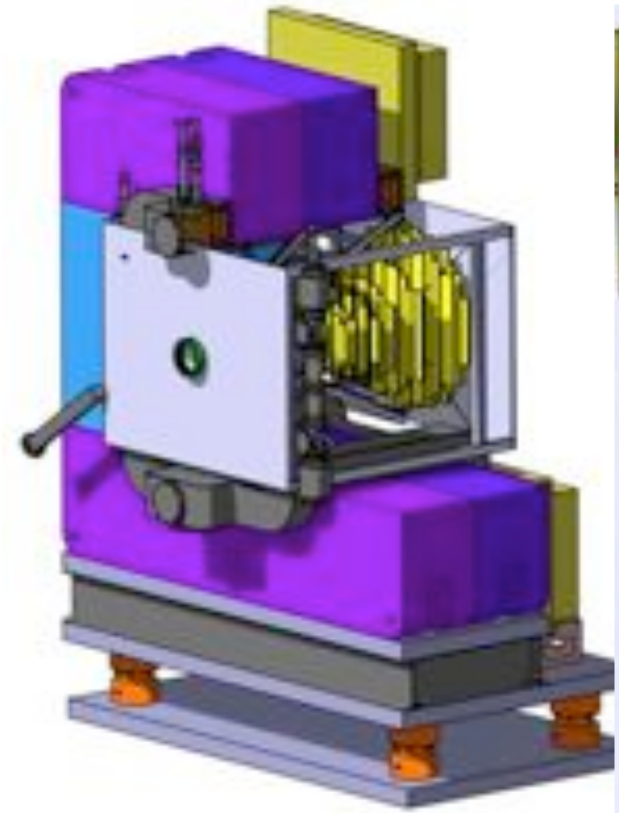


- first station 5cm downstream of target
- high position resolution!

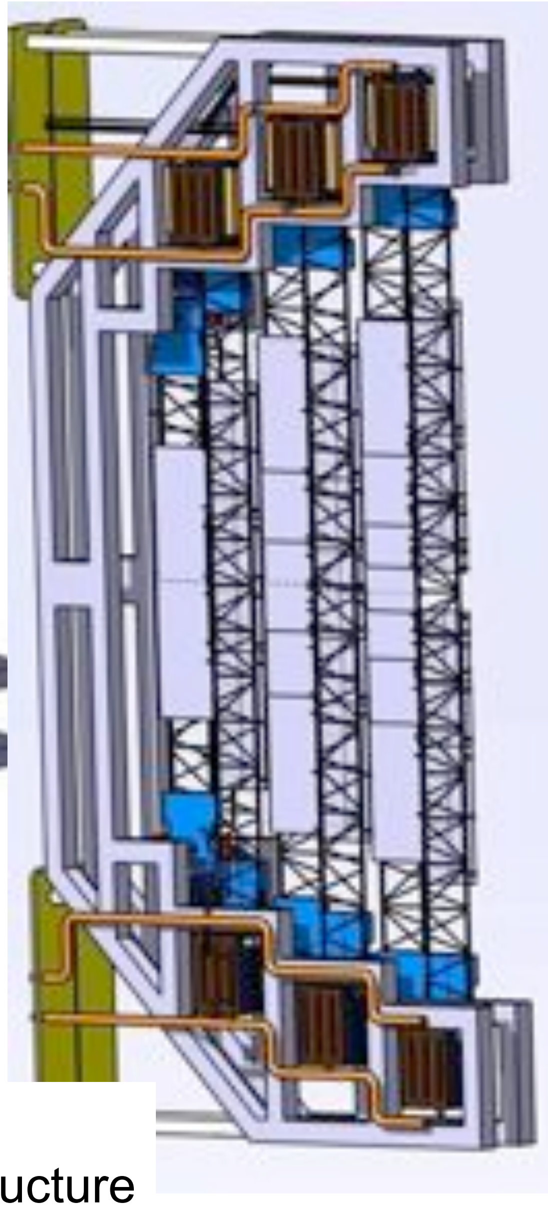
first demonstrator tested in beam!

Monolithic **A**citive **P**ixel **S**ensors
in commercial CMOS process
CBM: 5 µm single point resolution

Development of the Silicon Tracking System (STS)



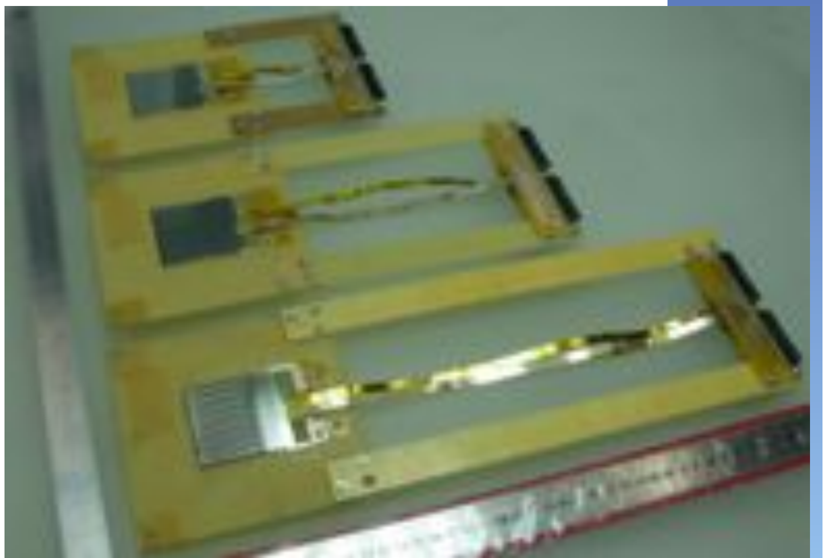
STS in thermal enclosure



Detector planes:
ultra-light weight ladder structure

<u>Sensor development:</u>
double-sided micro-strips, stereo angle 15°, pitch 60 μm
300 μm thick, bonded to ultra-thin micro-cables, radiation hardness

Prototypes: full CBM sensor, ultrathin cables

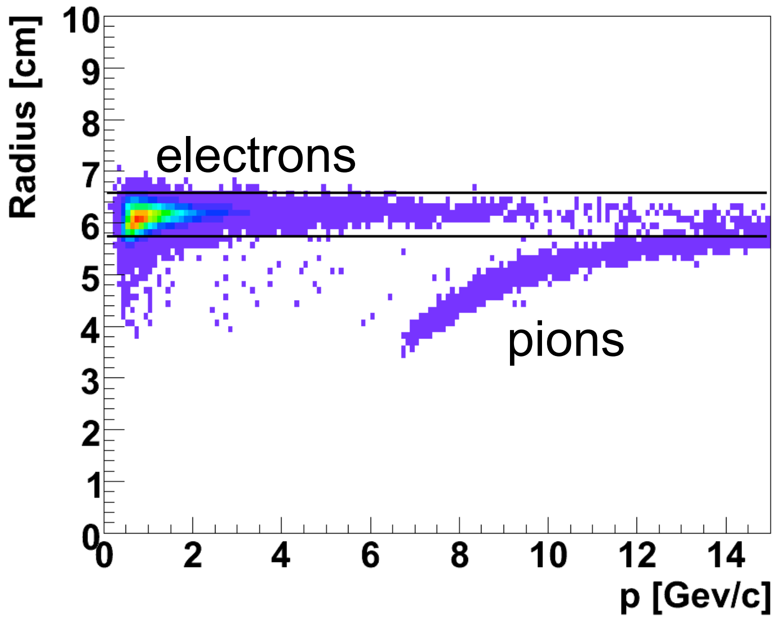


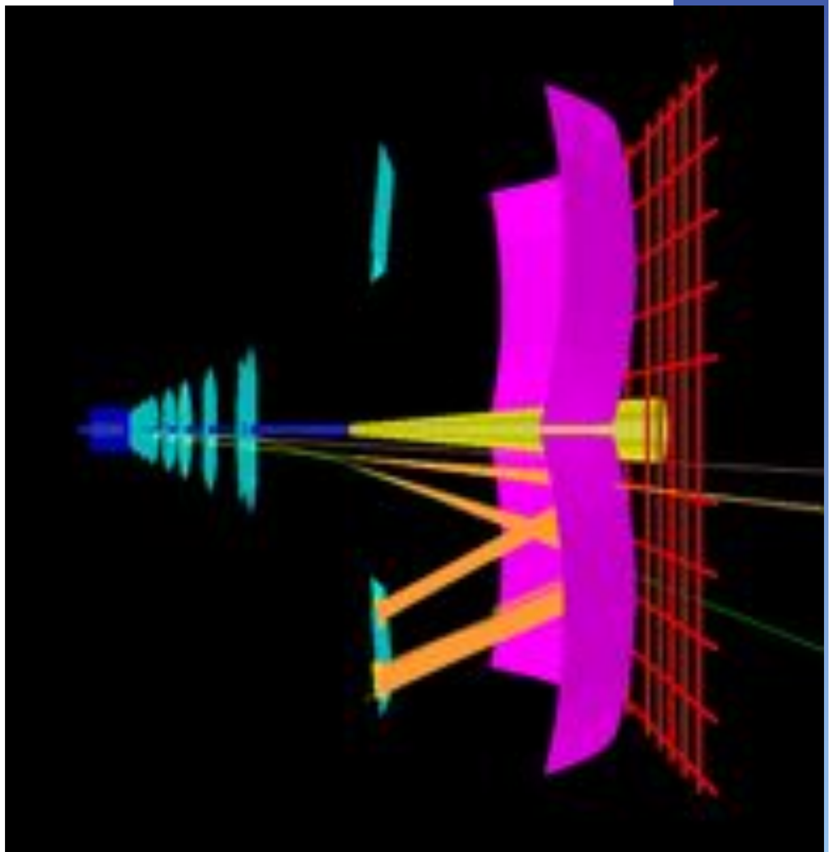
RICH detector

aim: clean electron identification for momenta below 8 GeV/c, robust and stable detector running at high rates!

concept: RICH with gas radiator (CO_2), glass mirrors coated with $Al+MgF_2$, H8500 MAPMTs

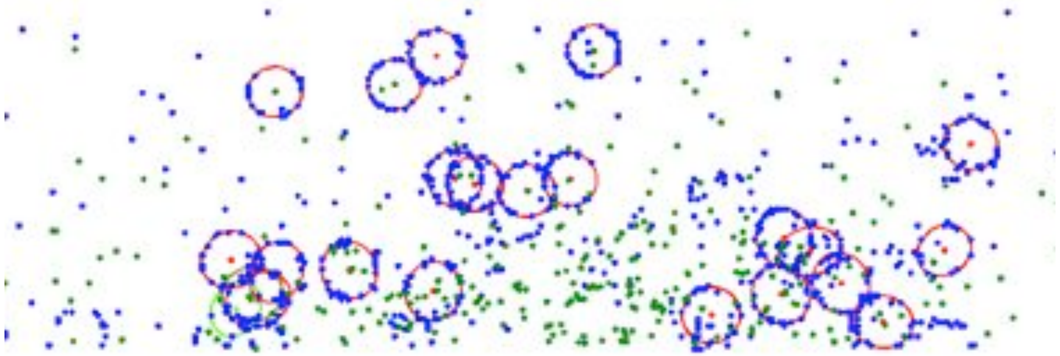
Cherenkov threshold for pions in CO_2 p=4.65 GeV/c





RICH detector (II)

event display of part of photodetector plane
~ 20 photons/ ring!

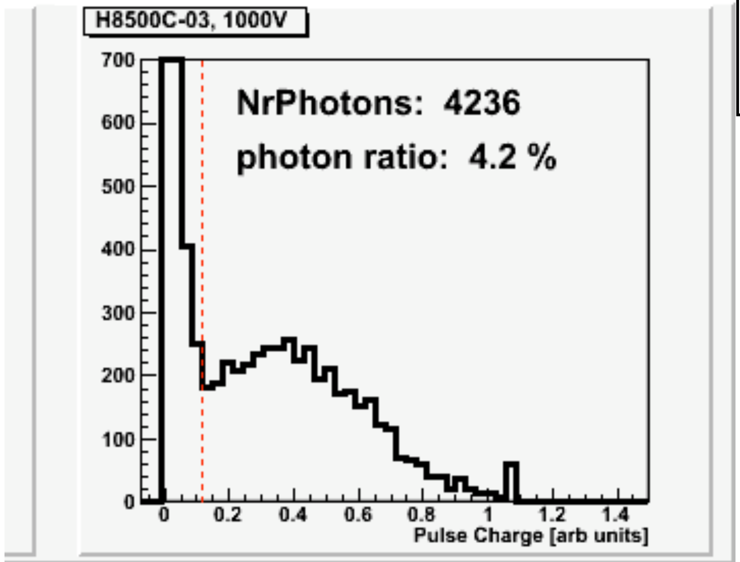


green – track projections

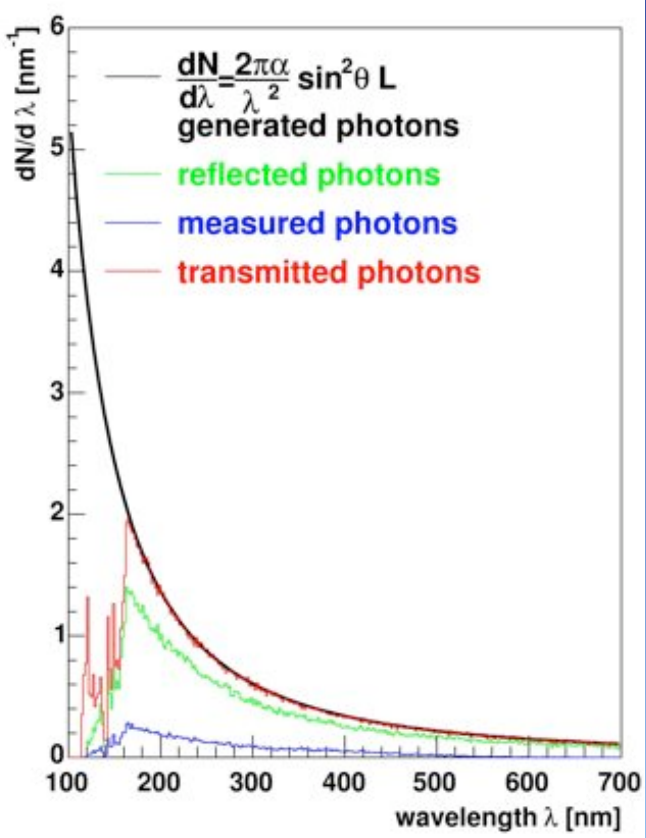
blue – hits

red – found rings

PMTs with single photon counting capability!

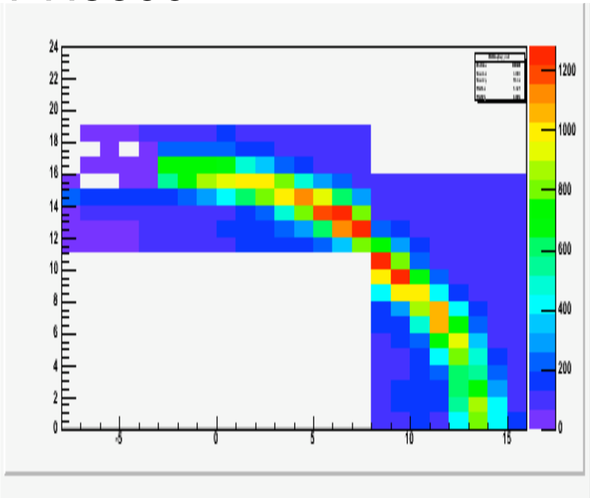


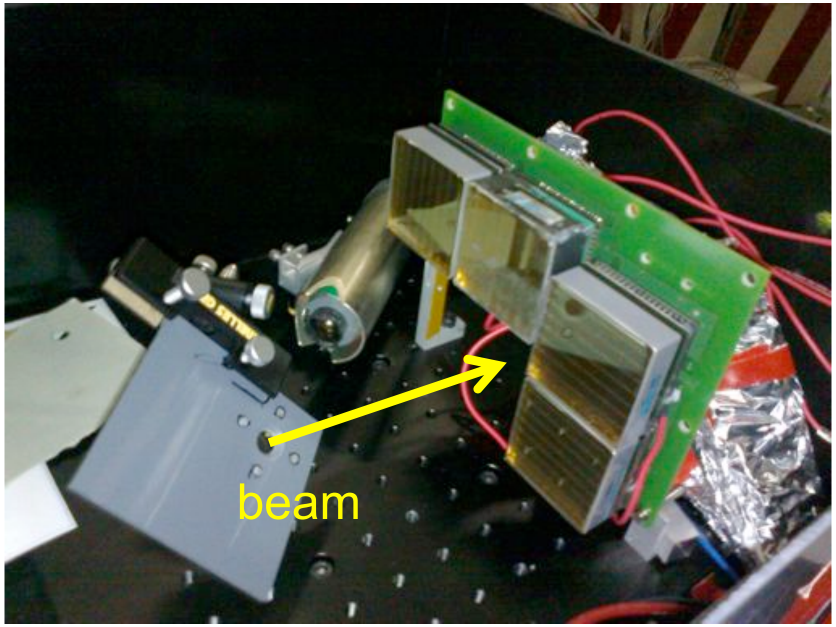
~ 100 rings per central Au+Au collision at 25 GeV/nucleon

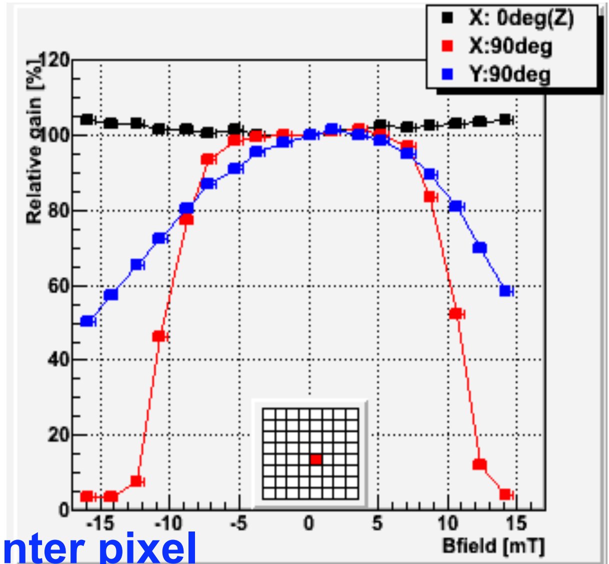


RICH detector (III)

testbeam measurements, labtests
of MAPMT H8500

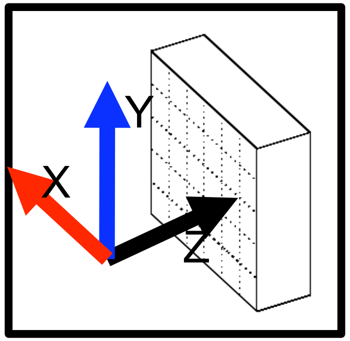






center pixel

response in
magnetic field



Mirrors

- glass mirrors: ≤ 6 mm thickness, R ≈ 3 m, Al+MgF_2 coating
- search for provider from industry with sufficient quality on surface homogenity and reflectivity

- **FLABEG** GmbH, Germany:

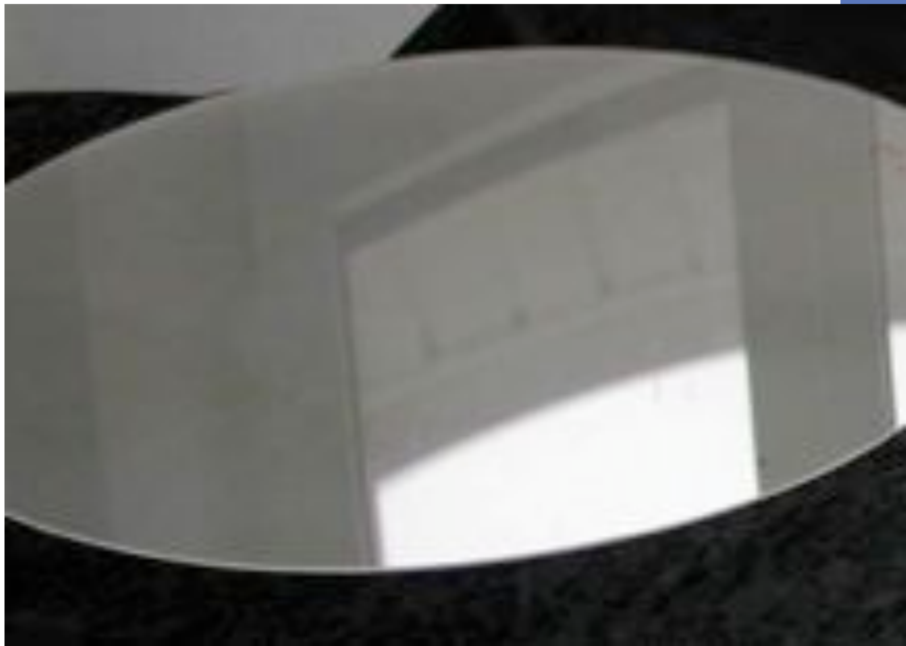
d = 6 mm, r_0 = 3.2m
size A = 40 x 40 cm^2

Coating:	Al:	d = 70 nm (55)
	MgF_2:	d = 90 nm (120)

- **Compas**, Czech Republic

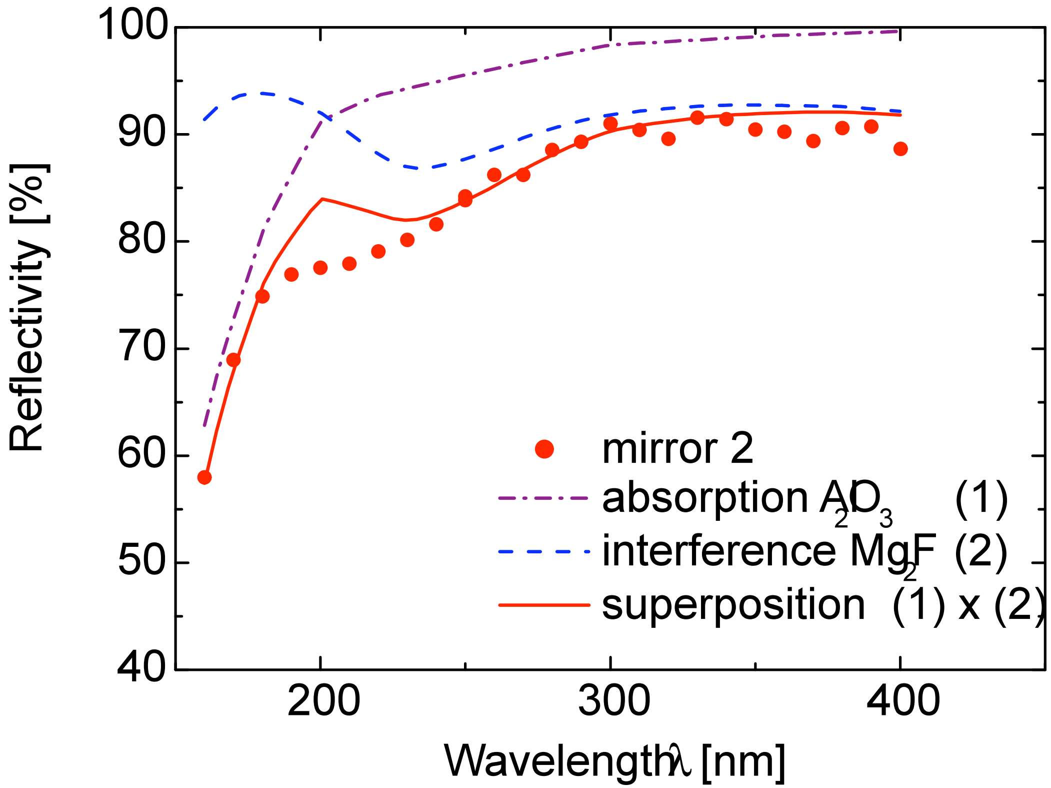
d = 3 and 6 mm, r_0 = 3 m
size R = 30 cm

Coating:	Al:	d = 80 nm
	MgF_2:	d = 30 nm



Reflectivity measurements

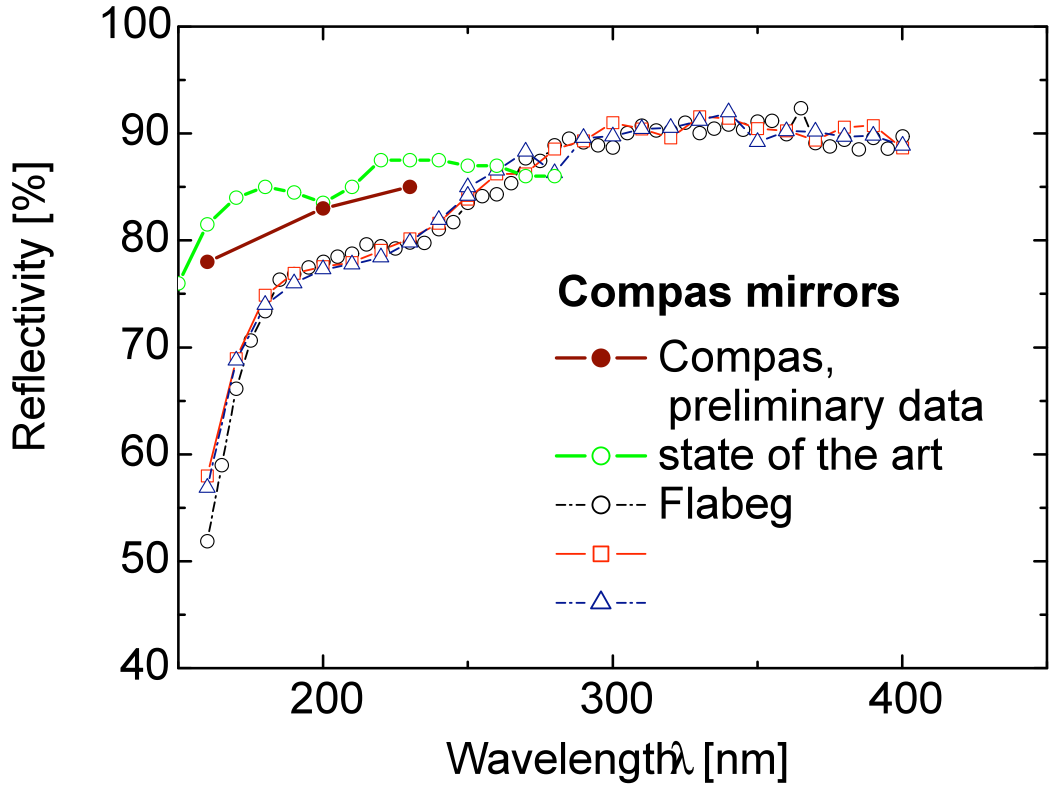
- **FLABEG**: very good reflectivity between 400 nm and 270 nm
  first drop around 250 nm: influence of aluminum oxide
  second drop at about 180 nm: interference at MgF_2 layer



Measurements done in cooperation with CERN, A. Braem and C. Joram

Reflectivity measurements

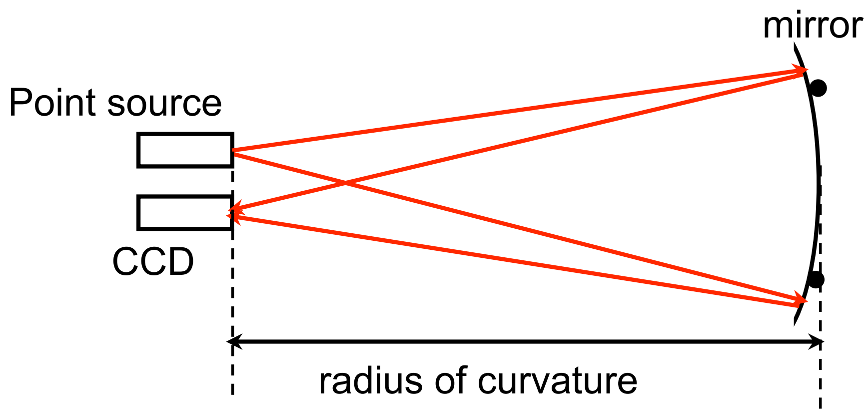
- **FLABEG**: very good reflectivity between 400 nm and 270 nm
  first drop around 250 nm: influence of aluminum oxide
  second drop at about 180 nm: interference at MgF_2 layer
- **Compas**: good reflectivity in the UV, full range to be measured



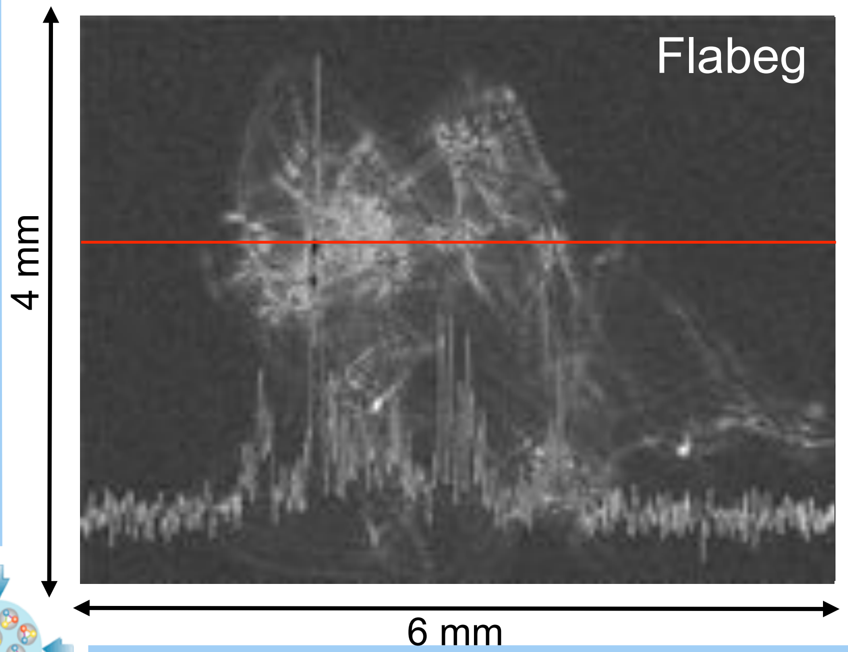
Measurements done in cooperation with CERN, A. Braem and C. Joram

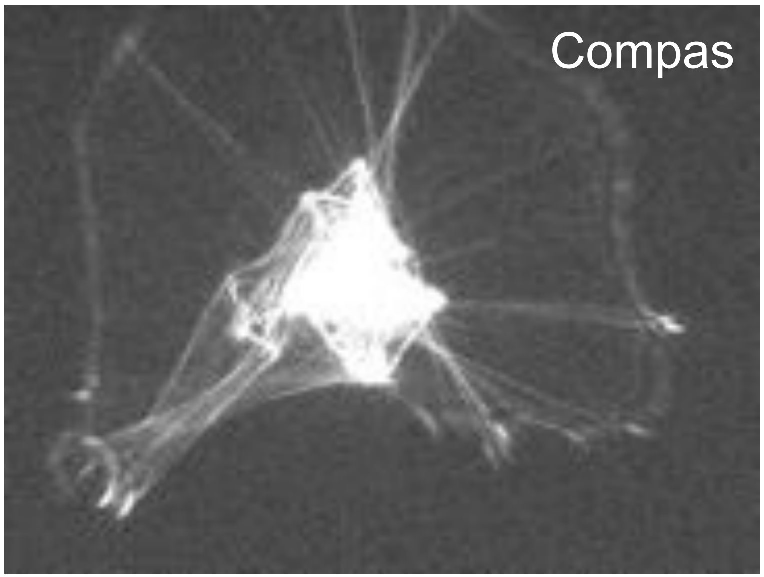
Radius of curvature and surface homogenity

- **FLABEG**: very broad feature, most of the intensity in the background; pronounced irregularities on the cm-scale
- **Compas**: $D_0 \cong 2.3$ mm (95 % intensity)



at CERN – Carmelo D'Ambrosio

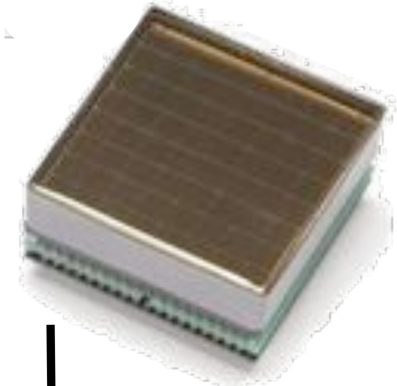




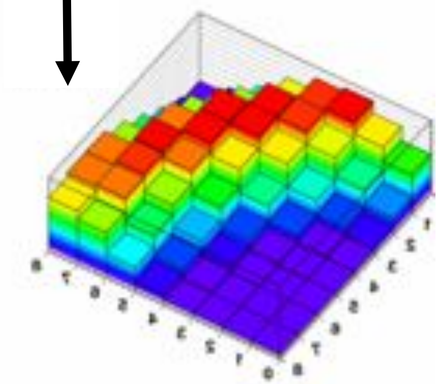
RICH – TRD – TOF development

- RICH and TRD detectors for electron identification
- large size time-of-flight detector (RPCs) for hadron identification

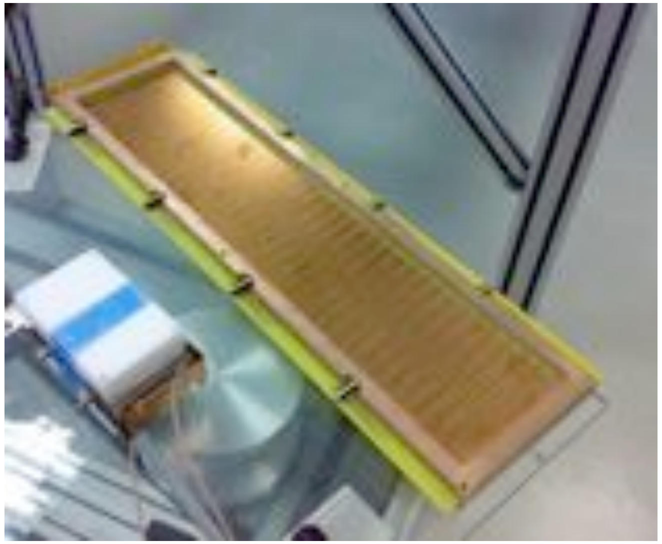
MAPMT H8500



testbeam

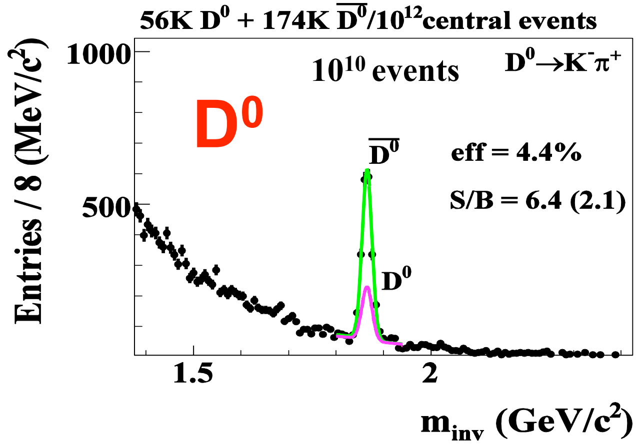


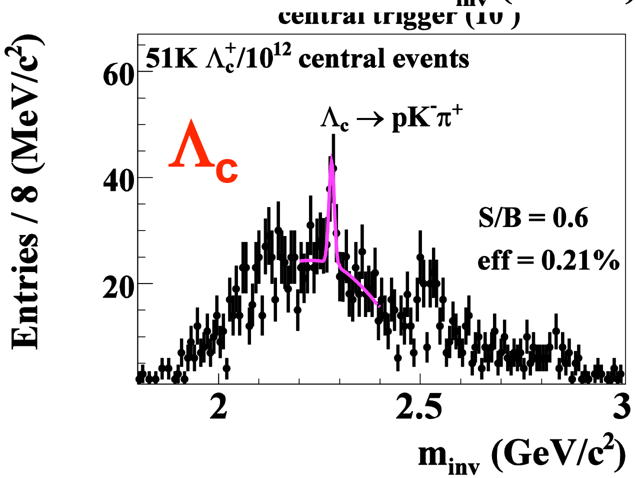
double-sided TRD prototypes



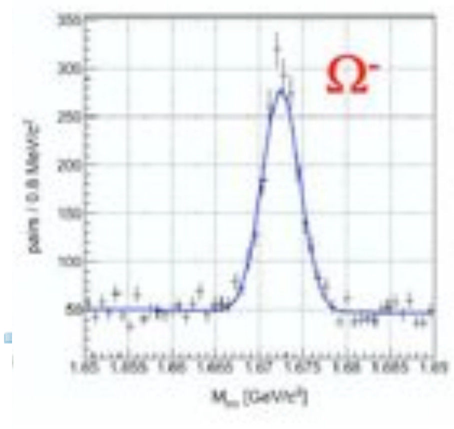
fast readout electronics

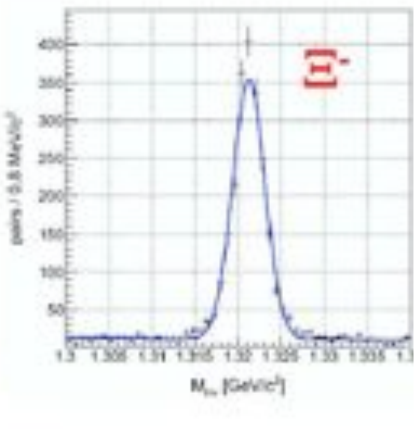
CBM feasibility studies



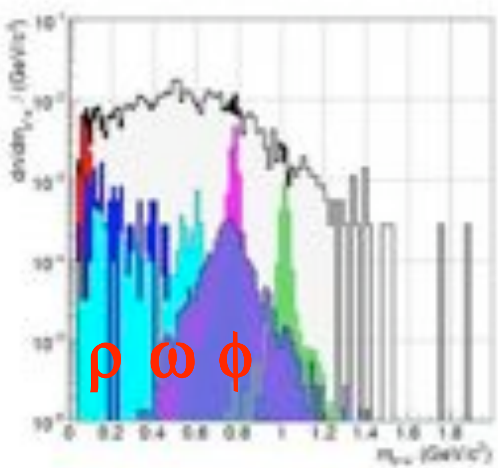


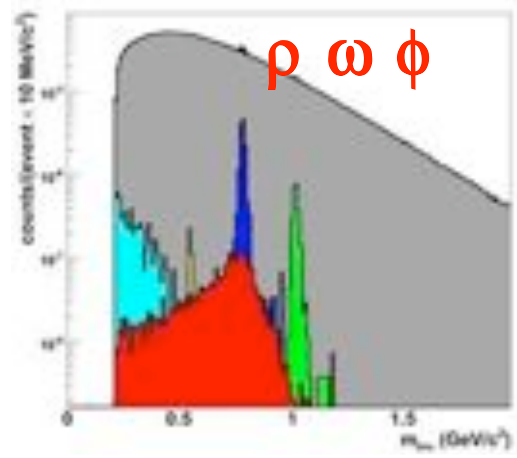
• feasibility studies performed for all major channels including event reconstruction and semirealistic detector setup

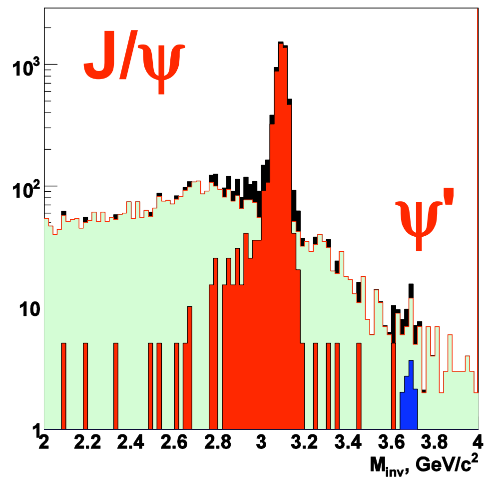


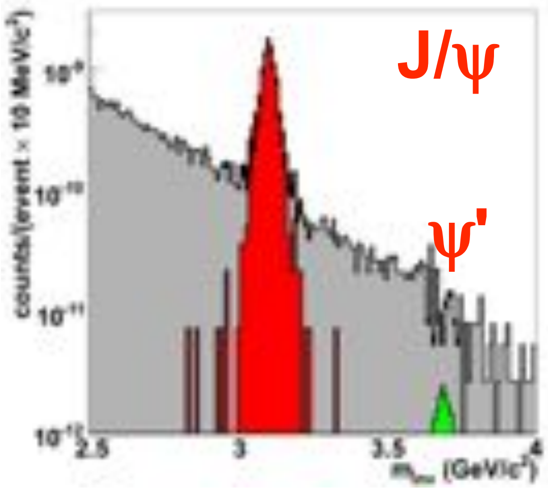


di-electrons **di-muons**









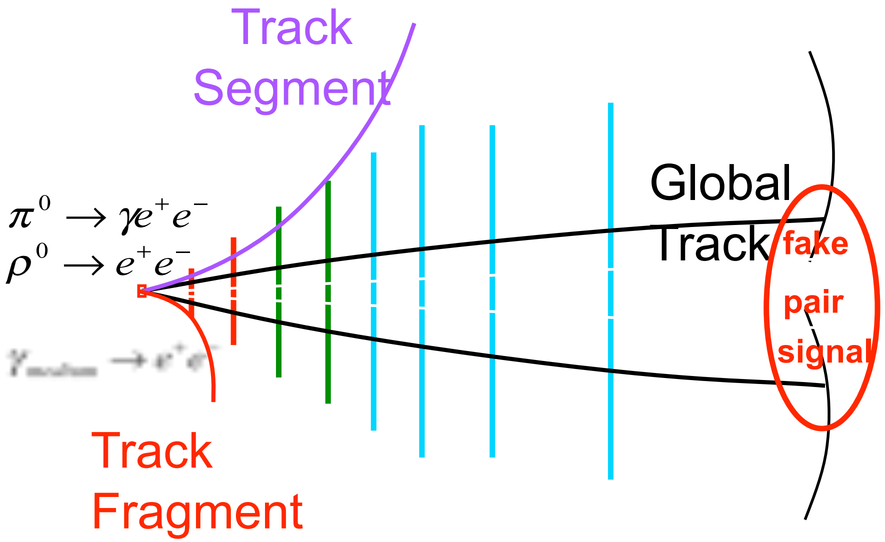
Challenge of di-electron measurement

- **clean electron identification** (π suppression ≥ 10^4)
- no e-ID in front of B-field and material budget of STS
- **large background from physical sources (low-mass vector mesons!)**

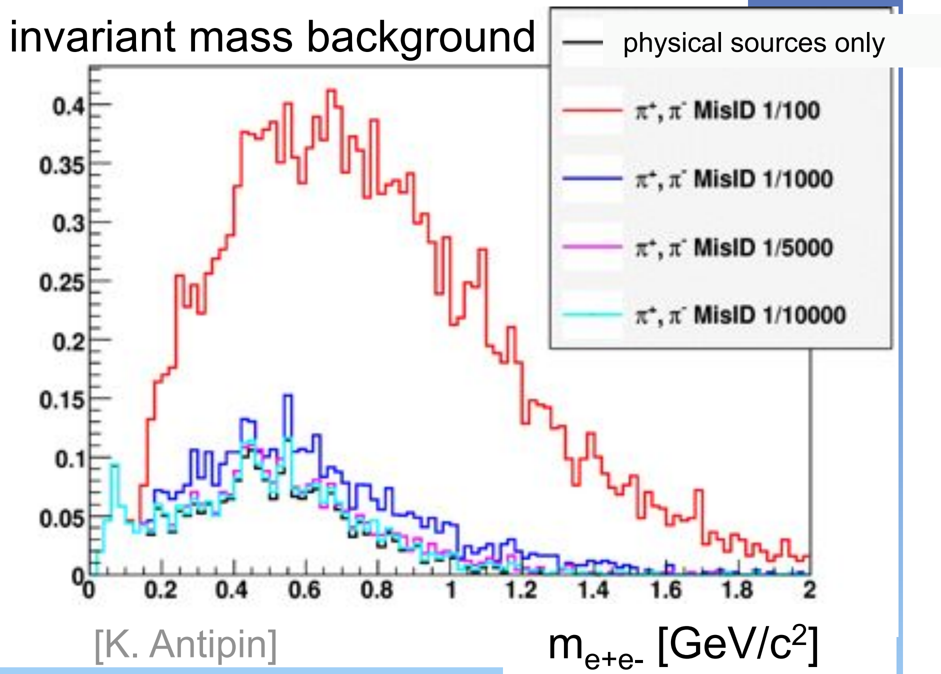
  γ-conversions in target and STS, π^0 Dalitz decays

  → use reduced B-field (70%), use 1‰ interaction target

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



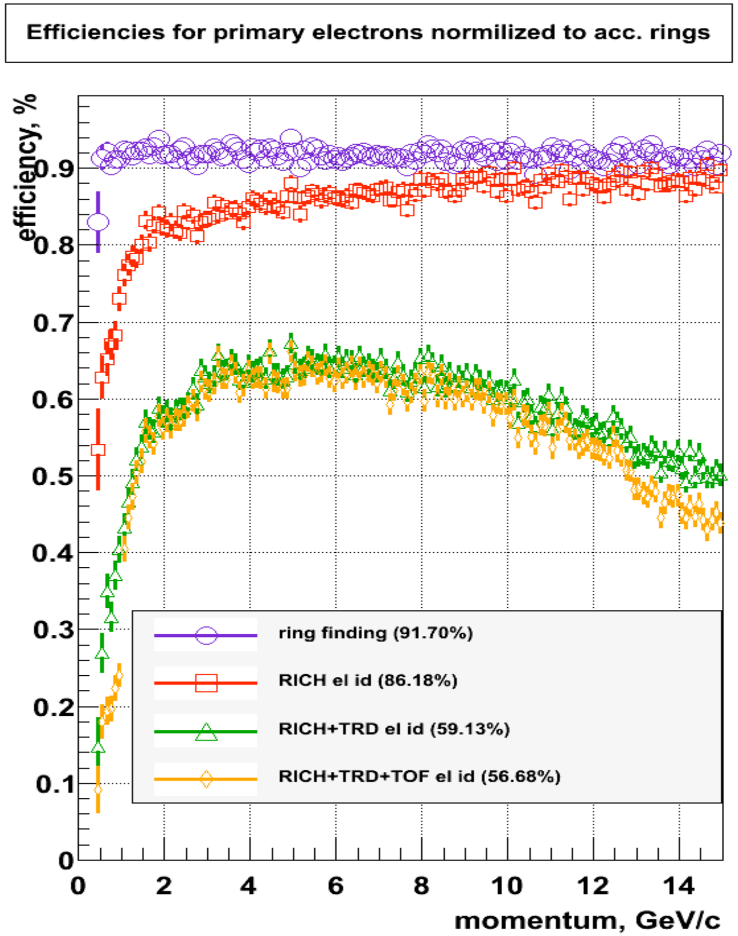
[T. Galatyuk]

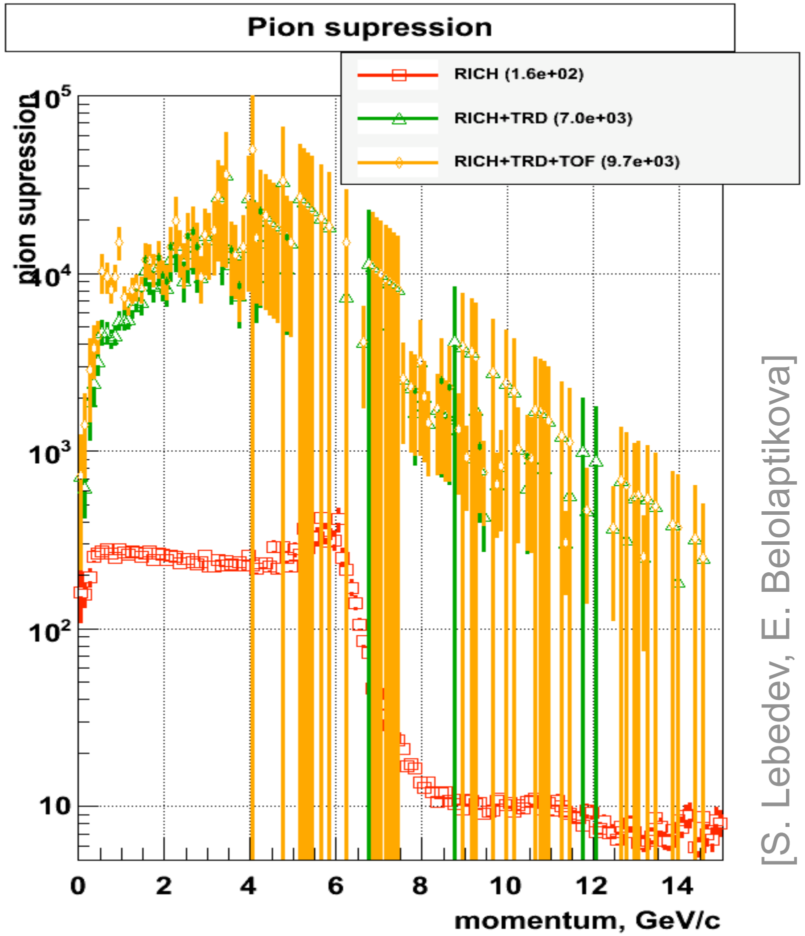


[K. Antipin]

Electron identification

- electron identification studies, N_{hit}/ring ~22 (H8500, UV extended window)
- background: central UrQMD events, 25 GeV Au+Au collisions
- 10^4 π suppression with RICH + TRD for ~60% electron effciency





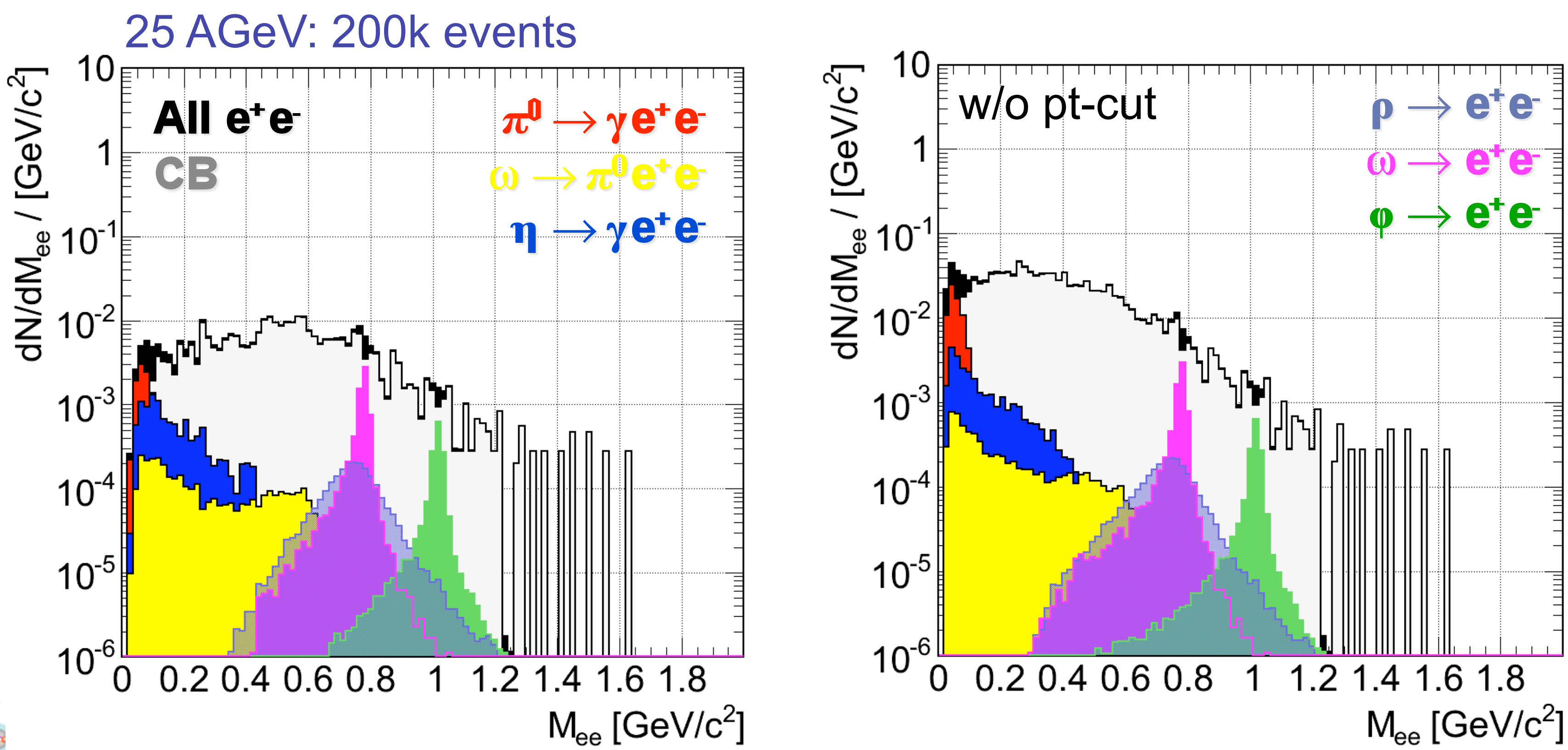
[S. Lebedev, E. Belolaptikova]

Low mass vector mesons

[T. Galatyuk]

invariant mass spectra in central Au+Au collisions at

- 25 AGeV (SIS 300): pt > 0.2 GeV/c
  background dominated by physical sources (80%),
  1‰ int. target, 70% B-field

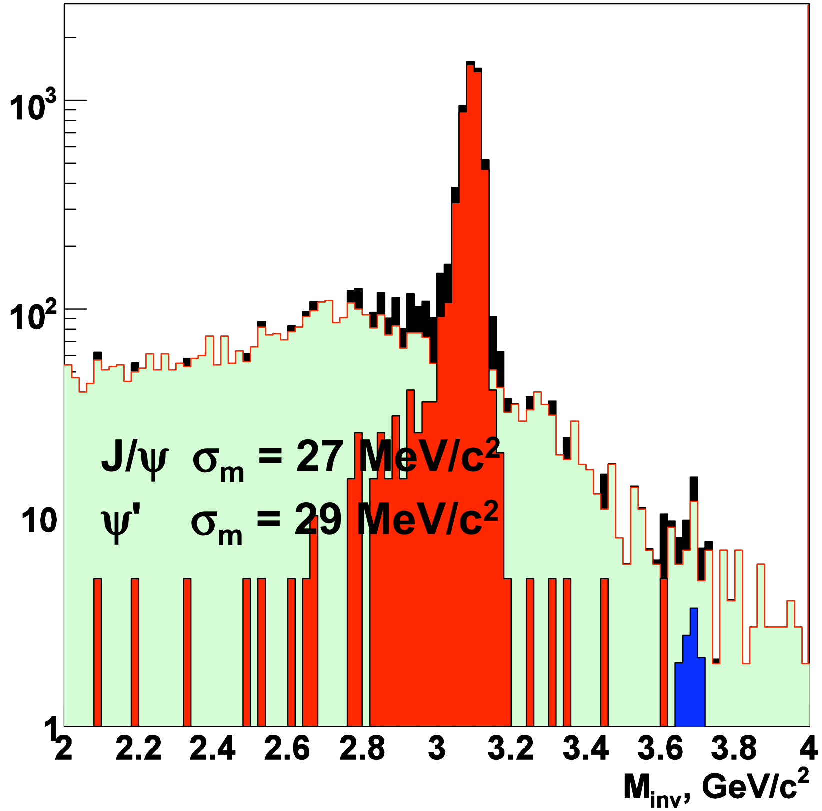


J/ψ and ψ'

25 AGeV
central AuAu

- electrons: p < 13 GeV/c, pt > 1.2 GeV, 1‰ interaction target (25 μm Au, need segmented target for sufficient event rate)
- S/B ratio ~2.4 for 250 μm Au target
- trigger: TRD standalone trigger feasible? full STS + TRD tracking needed?

electrons: $4 \cdot 10^{10}$ events



[A. Maevskaya]

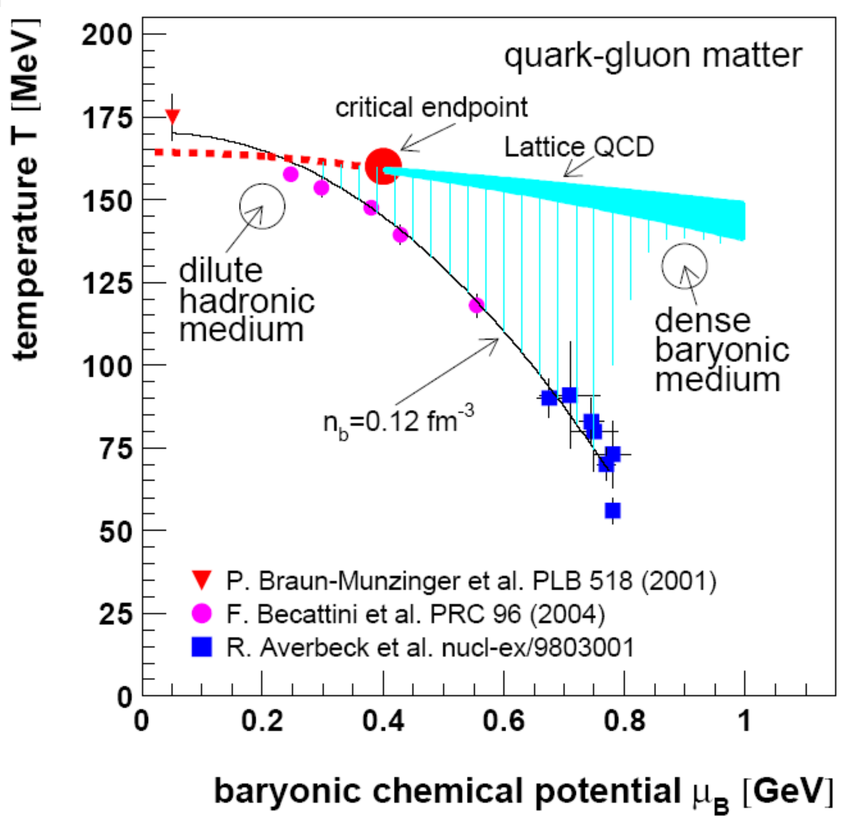
Summary

Experimental knowledge of the QCD phase diagram at high μ_B:

- evidence for onset of deconfinement
- medium properties? – medium influences seen: more data, statistics missing → characterization of medium needed!
- evidence for critical point? – not conclusive

CBM@FAIR – high μ_B, moderate T:

- exploration of QCD phase diagram at high baryon densities at SIS 100 and SIS 300 (2-45 AGeV beam energy)
- together with HADES unique possibility of characterizing properties of baryon dense matter



CBM collaboration

* tba

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CCNU Wuhan
USTC Hefei

Croatia:
University of Split
RBI, Zagreb

Cyprus:
Nikosia Univ.

Czech Republic:
CAS, Rez
Techn. Univ. Prague

France:
IPHC Strasbourg

Germany:
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