Heavy-Ion Physics at High Baryon Densities

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Helmholtzzentrum für Schwerionenforschung

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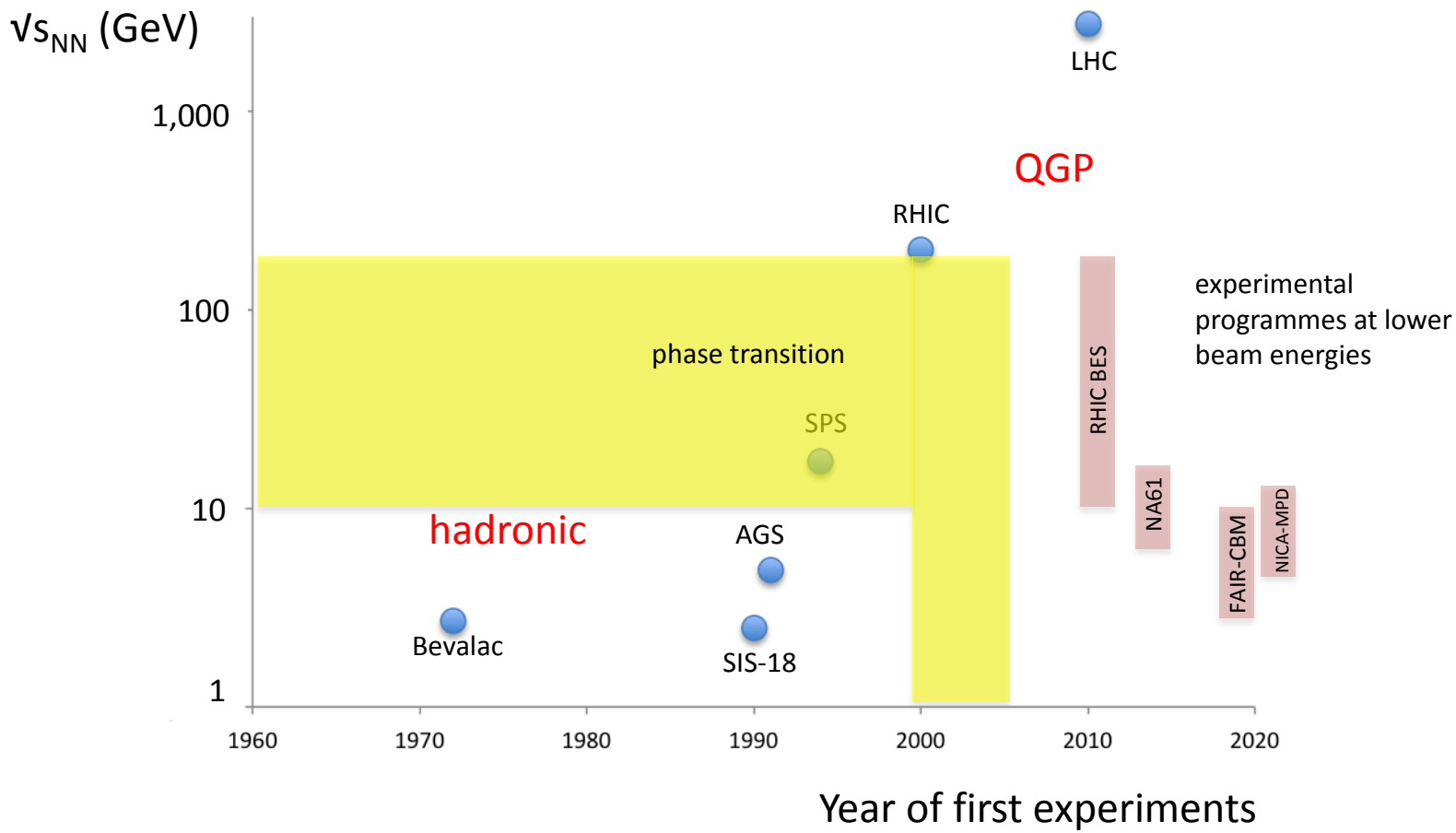
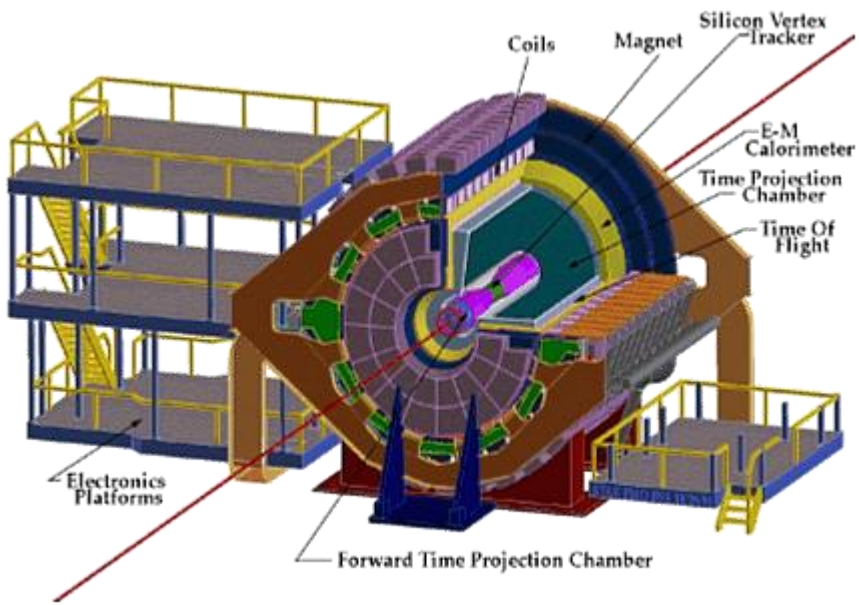
The Phase Diagram of Heavy-Ion Experiments



RHIC Beam Energy Scan

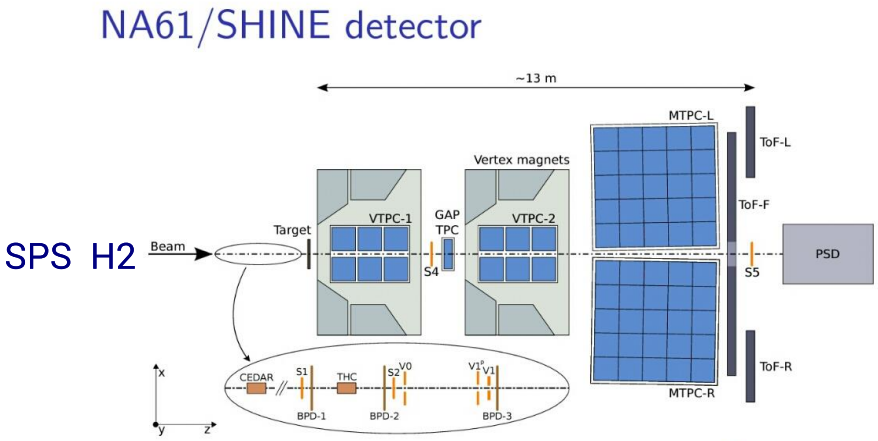
- STAR (and PHENIX) experiments @ RHIC
- phase 1: 2010 – 2014
- phase 2 planned for 2018 - 2019

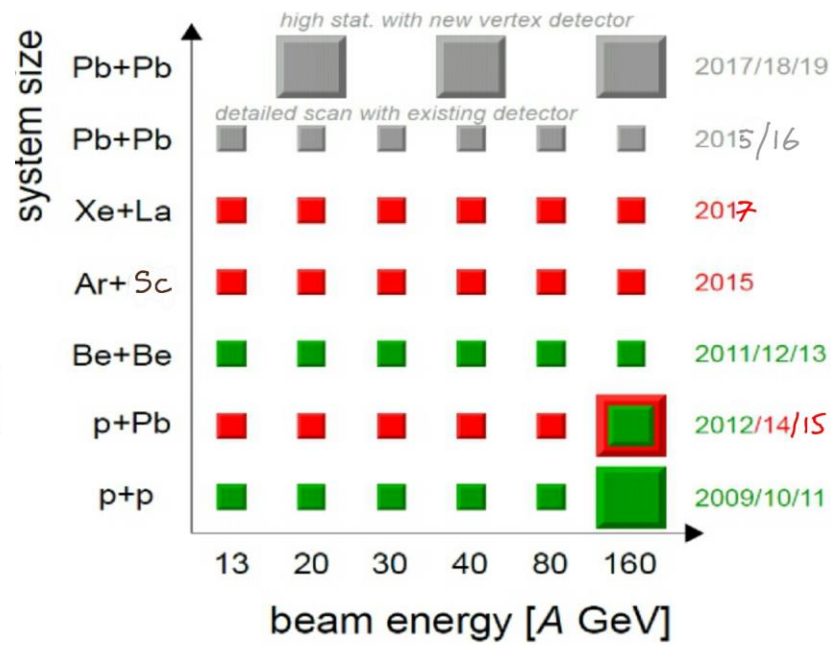


Energy (GeV)	Events (Millions)	Time (Weeks)
200	350	11
62.4	67	1.5
39.0	130	2
27.0	70	1
19.6	36	1.5
14.5	20	3
11.5	12	2
7.7	4	4

NA61

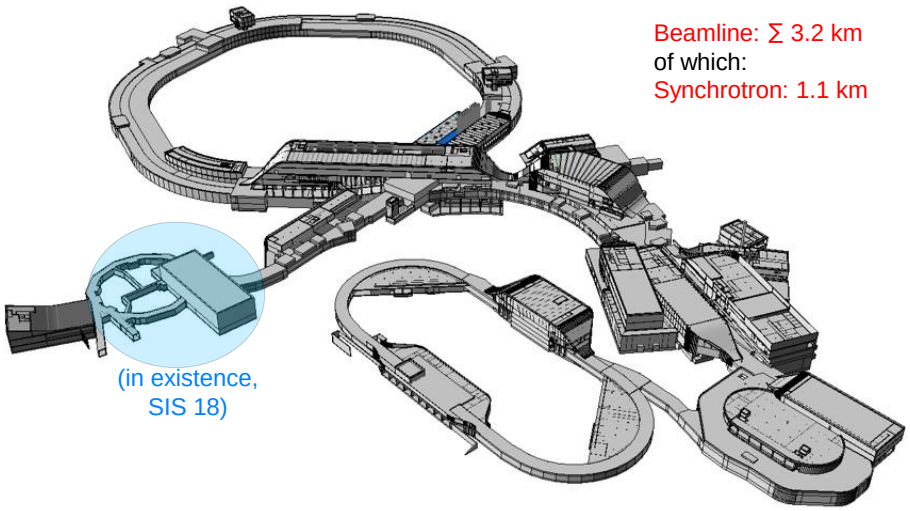
- upgrade of the NA49 detector at CERN-SPS; recently first ion data (Be+Be)
- 2-d scan: beam energy and system size

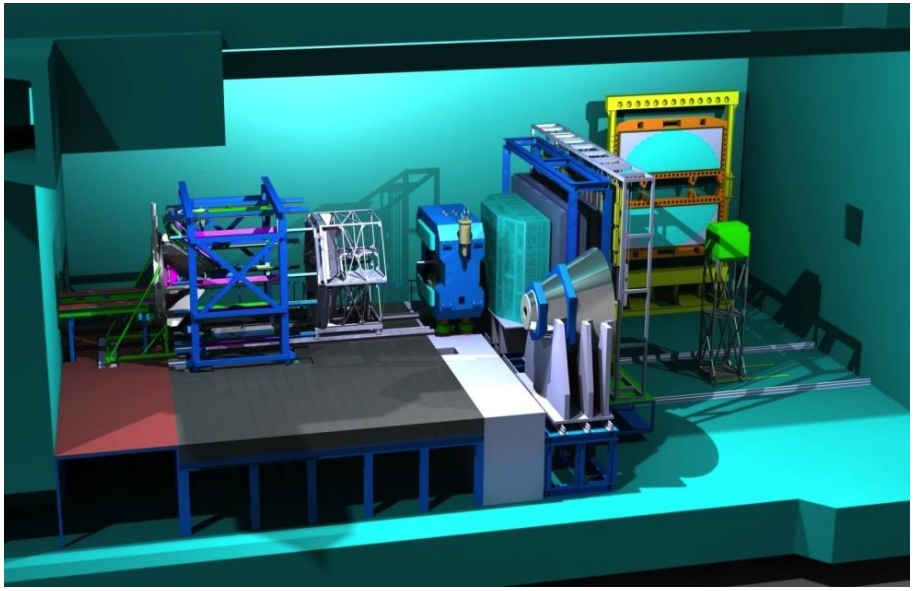




CBM

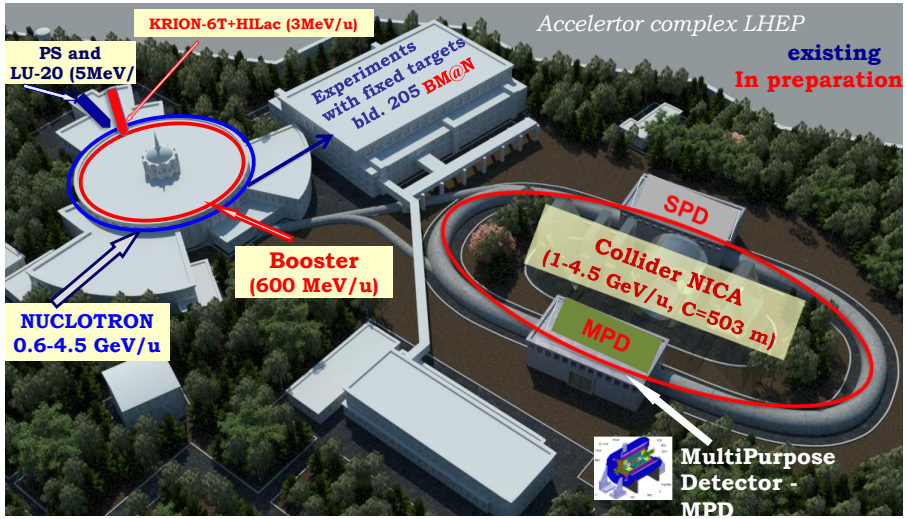
- next-generation fixed-target experiment at the FAIR centre, Darmstadt (under construction)
- hadron, lepton and photon detector with large acceptance
- beam energy range 2A – 45A GeV
- programme includes HADES at the new beam line
- operation from 2019 on

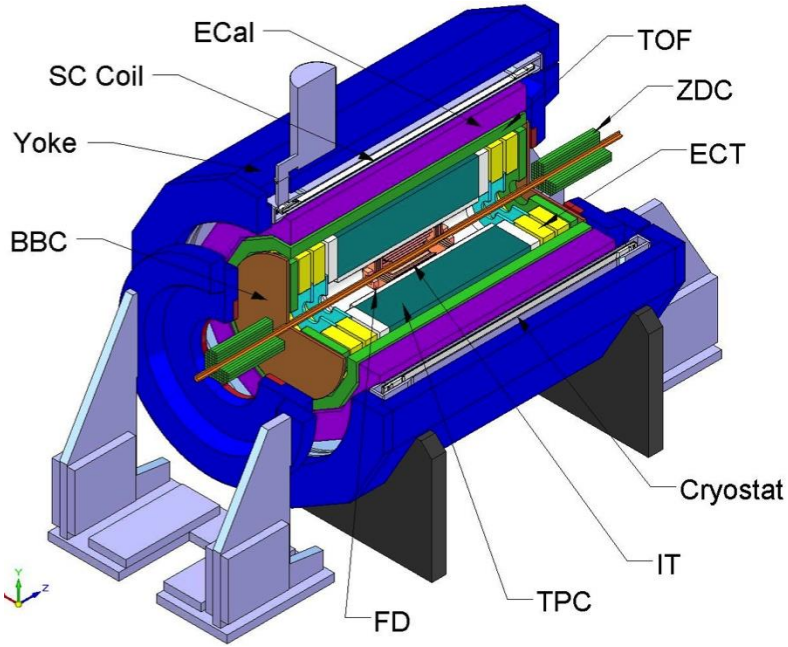




MPD

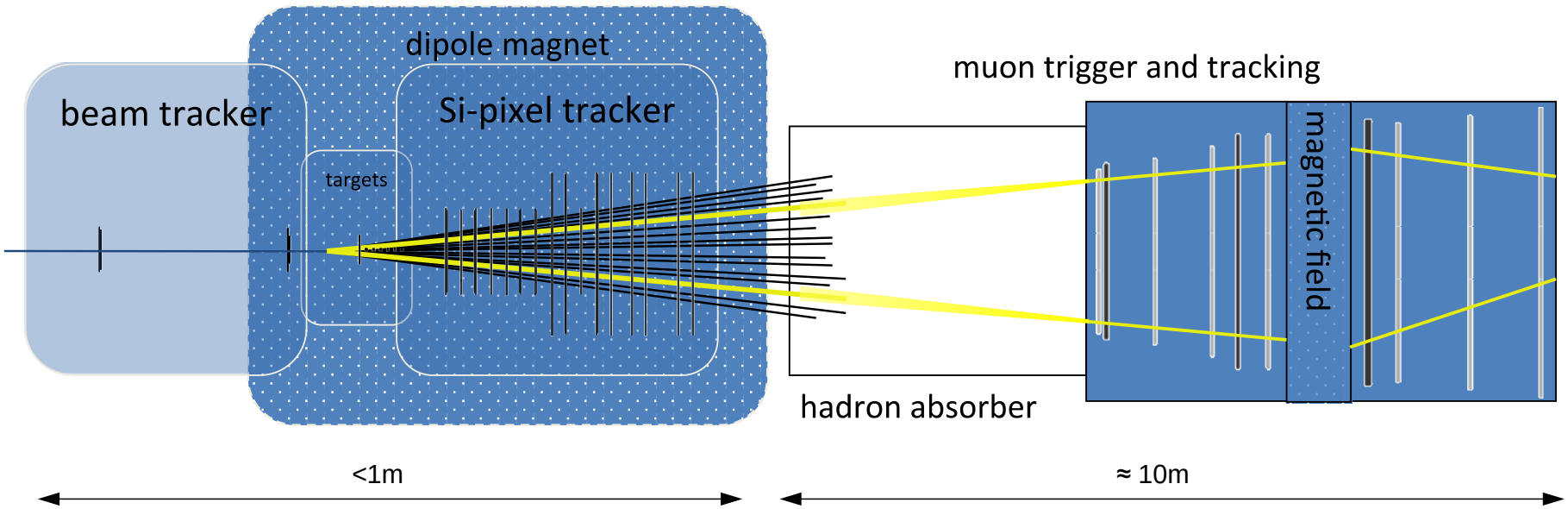
- collider experiment at the NICA accelerator complex at JINR / Dubna (under construction)
- hadronic and leptonic probes
- collision energies: $\sqrt{s_{NN}}$ = 4 – 11 GeV
- operation from 2019 on





NA60+

- dedicated fixed-target muon experiment proposed for CERN-SPS
- detector concept similar to NA60 (two spectrometers before and after the absorber), but adapted to conditions at lower energies
- low- and intermediate-mass di-muons down to 20A GeV, charmonium down to 60A GeV
- letter of intent in preparation



G. Usai, FAIR Workshop, this conference

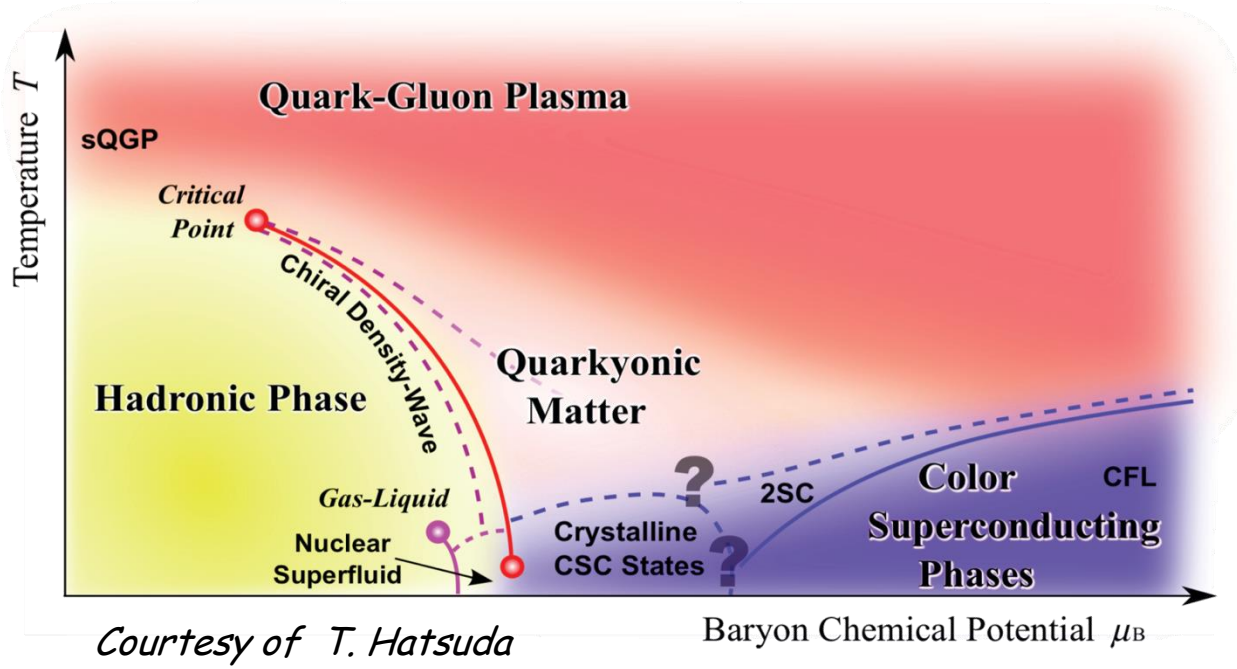
Motivation – in a Nutshell

- Assuming a deconfined state is created in nuclear collisions at top SPS energy and above:
  - when (at which beam energy) is such a state first reached (onset of deconfinement)?
  - of what nature is the phase transition?

- This calls for a systematic study in terms of collision energy (and, also, system size) – at energies below top SPS (158A GeV $\cong \sqrt{s_{NN}}$=17.3 GeV
  - looking for discontinuities / non-monotonic behaviour in the energy dependence of observables

- Why does that mean “high baryon density”?

Finally: The QCD Phase Diagram

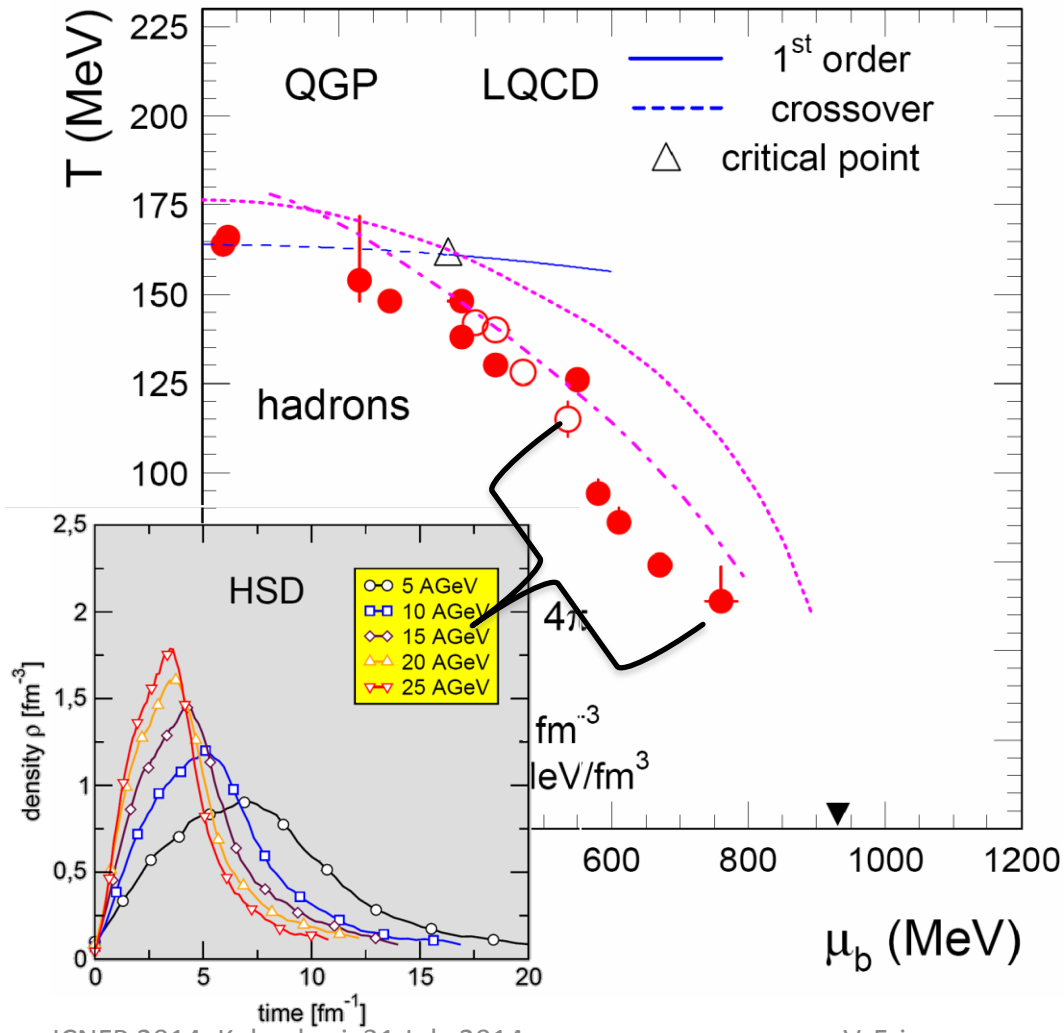


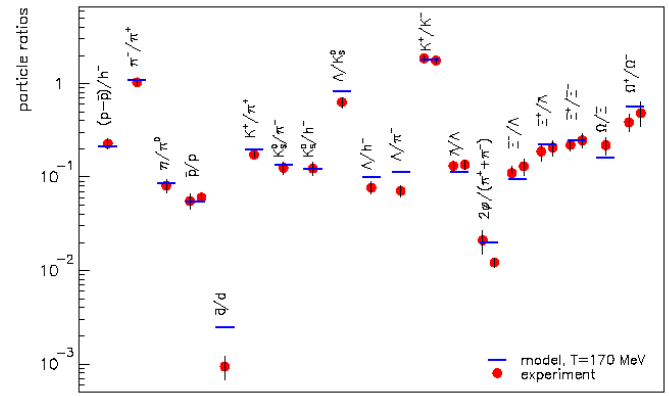
Courtesy of T. Hatsuda

Features:

- deconfined at high T / μ_B
- at μ_B = 0: no phase transition (cross-over)
- at high μ_B: first-order phase transition
- both domains separated by a critical point
- potentially rich structure near T=0 axis

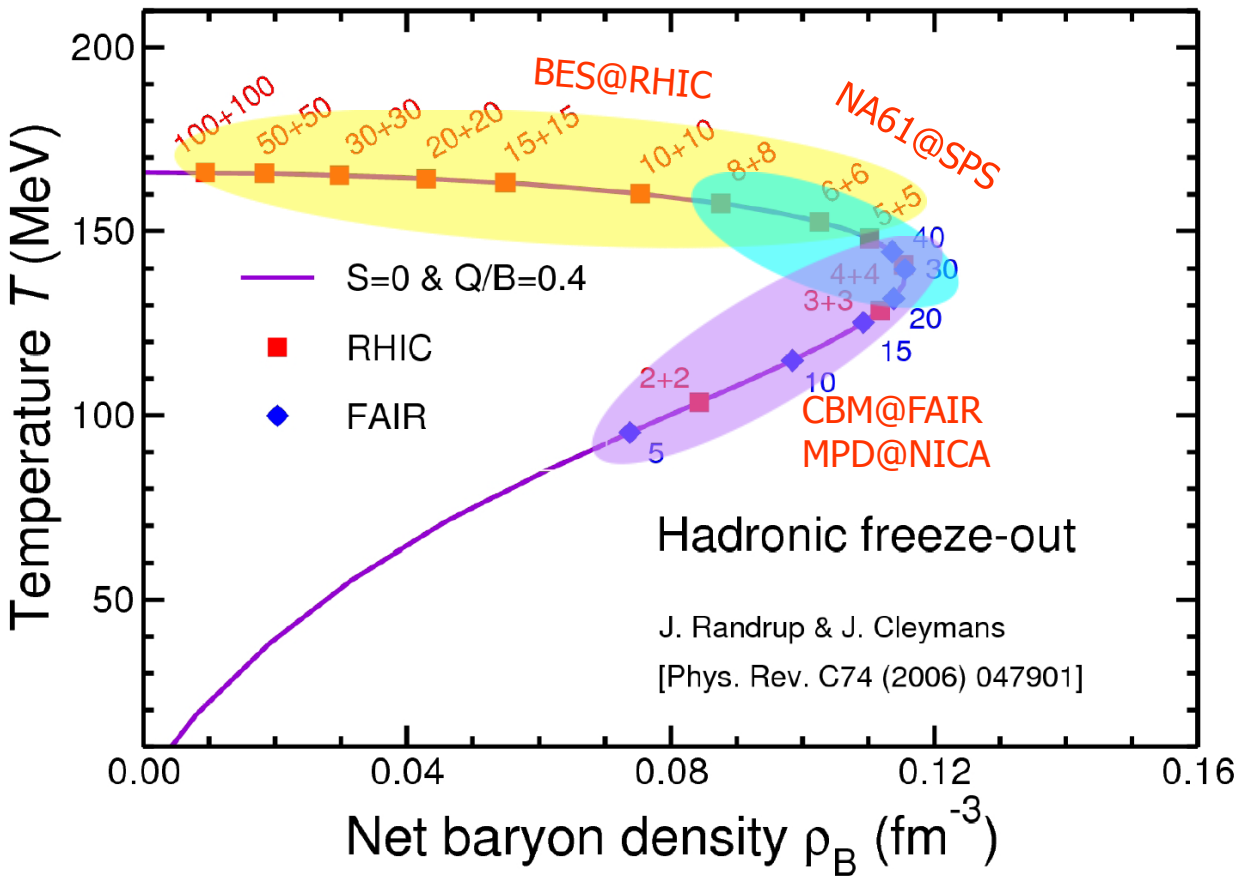
Experimental Access



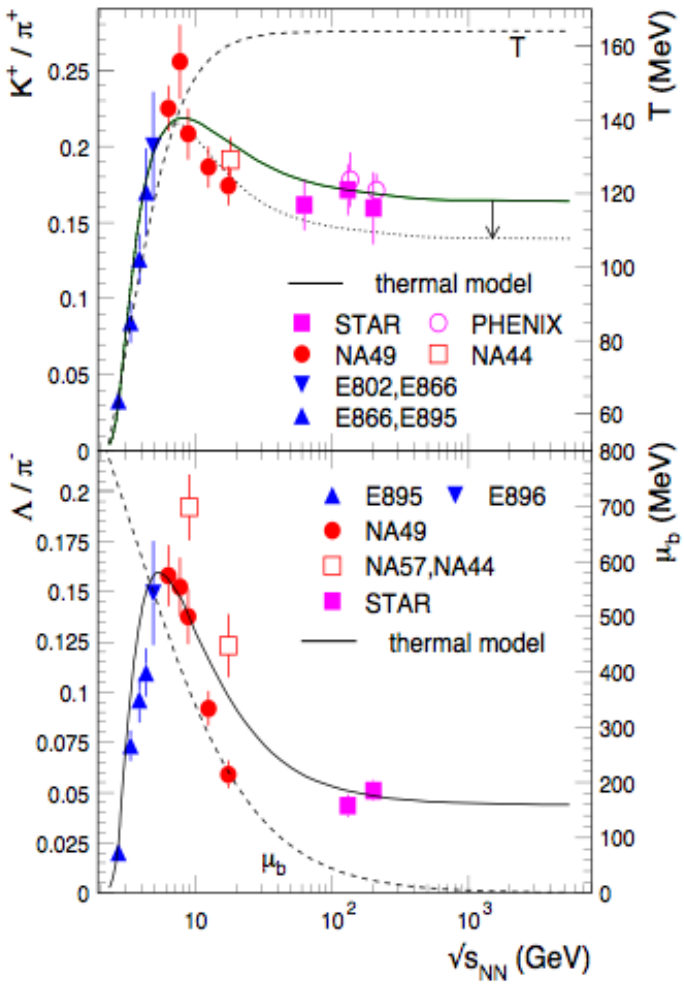


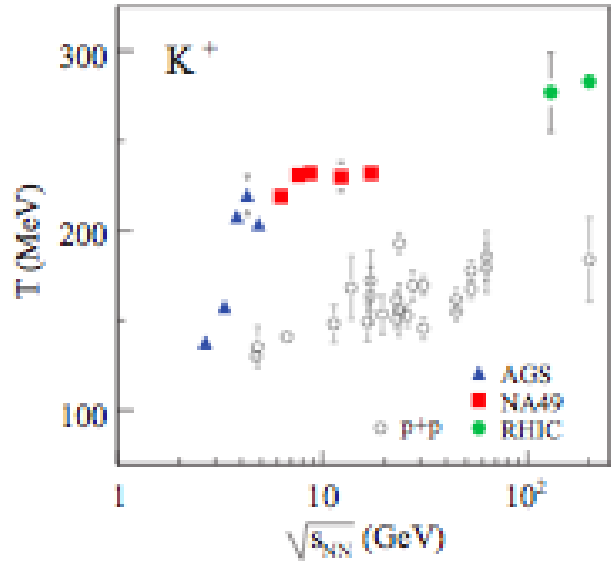
- The hadronic final state resembles a hadron gas in equilibrium.
- Different collision energies probe different regions of the phase diagram.
- Microscopic models confirm to reach a high-density state with medium energies.

Probing Highest Net-Baryon Densities



A First Flavour

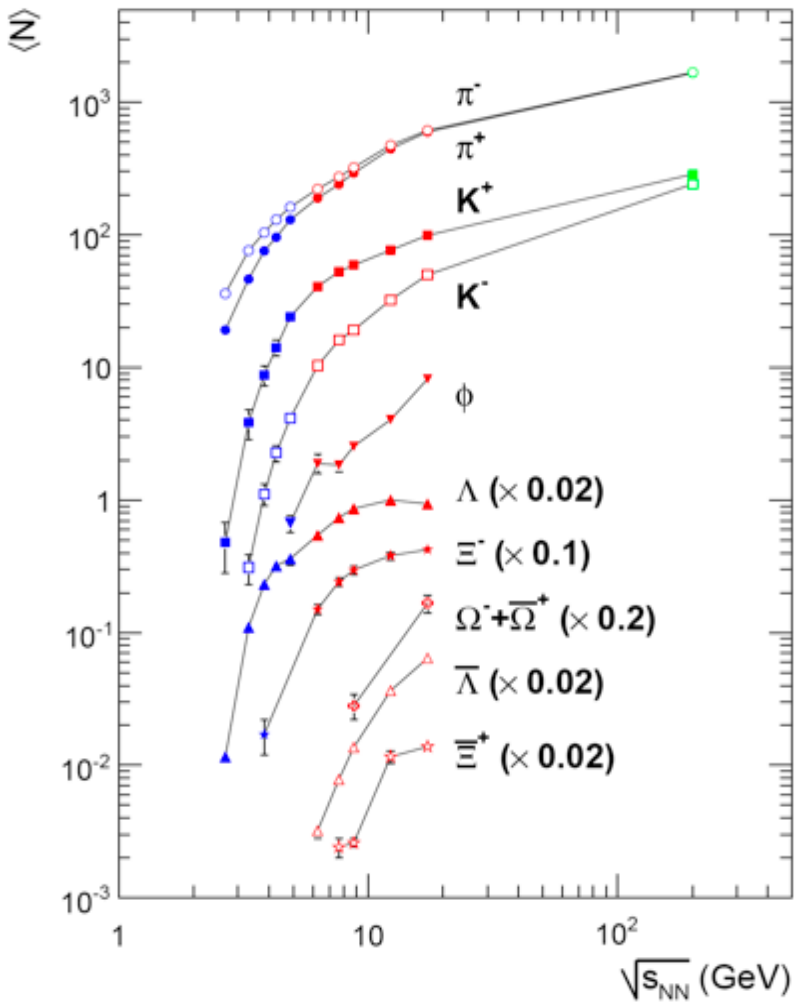




- Results of the beam energy scan by NA49 (1999-2002)
  - maximum in K/pi at 30A GeV
    - explained by statistical model (?)
  - plateau in apparent temperature above 30A GeV
    - inidicative of 1st order phase transition (latent heat) ?
- might be an interesting energy region to look further into

Characterising the Hadronic Final State

C. Blume, J. Phys. G 31 (2005) S57



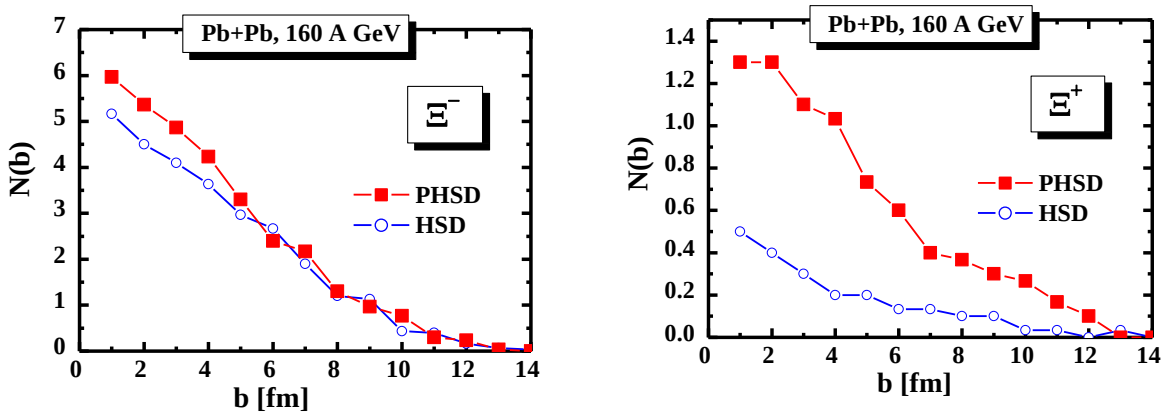
- Number of measured hadron species decreases when going to lower energies.
- Does the statistical model still work here, also with rare species?
- Puzzling observations:
  - ϕ well described at SIS-18 (sub-threshold!) and RHIC, but not so at SPS
  - Ξ at SIS-18 (also deep sub-threshold) off by factor of 20 from SHM.
- Is strangeness production really understood?

Multi-Strange (Anti-)Hyperons

- Particularly interesting near threshold (Ξ: 3.7 GeV, Ω: 7.0 GeV)
- Can be produced in nuclear collisions also sub-threshold:
  - multi-step processes like $\Lambda K \rightarrow \Xi\pi$ $\Xi K \rightarrow \Omega\pi$
  - many-body collisions with K or Λ in entry channel
- Sensitive to both strangeness and baryon density
- Quantitative predictions: need microscopic models

Multi-Strange (Anti-)Hyperons

- Predictions from pHSD: anti-Hyperons are particularly sensitive to the production scenario
  - much easier to be produced in QGP: relaxes strong constraints due to high baryon density



- Very recent high-statistics calculations: Ω^+ is enhanced by a factor of 8 in pHSD (partonic) compared to HSD (hadronic) in Au+Au at 25A GeV

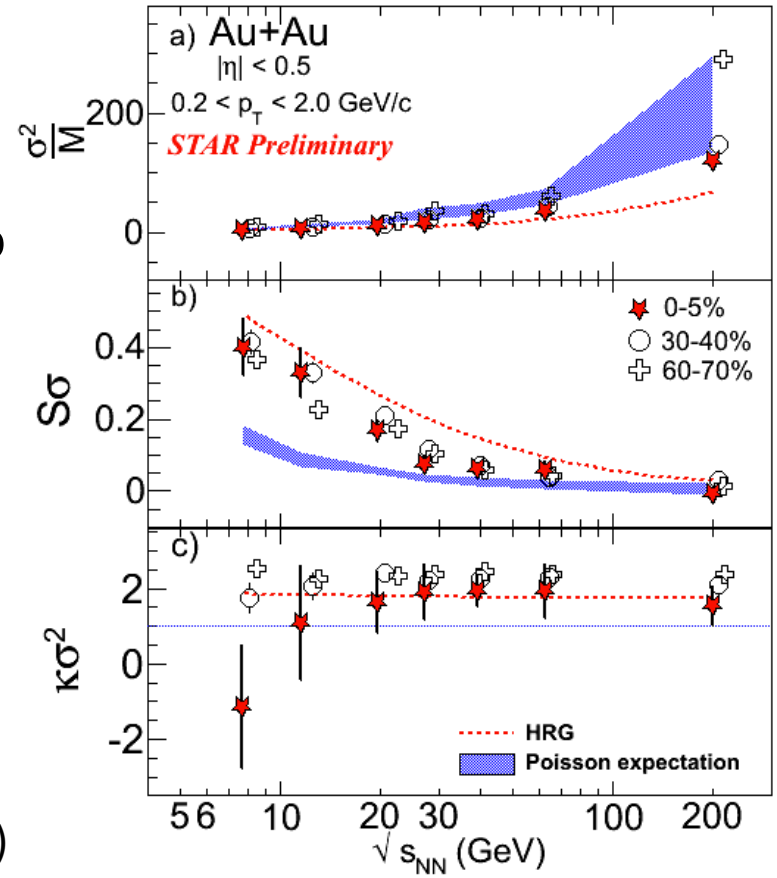
Anti-Hyperons: Experimental Prospects

Needs very high statistics and good secondary vertexing to identify (anti-)cascade decays

- CBM/FAIR: 4A - 45A GeV
- MPD/NICA: $\sqrt{s}$ = 4A – 11A GeV (E = 6A – 60A GeV)
- BM@N (NICA fixed target): 2A – 5.5A GeV

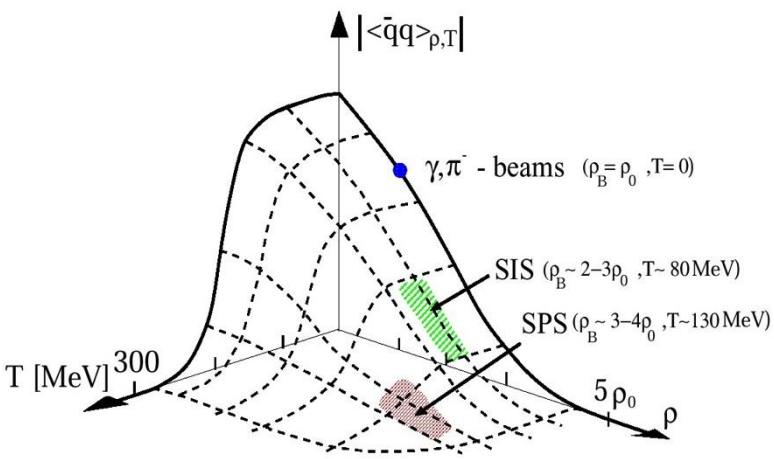
The Search for the Critical Point

- Criticality would express in non-statistical event-by-event fluctuation of conserved quantities: e.g., net charge, net baryon
- Beautiful data delivered by STAR: but no conclusive indication of a critical point yet
  - n.b.: theory gives little guidance as to how close to the critical point fluctuations should be observable
    - finite size and lifetime of system
  - data at lower energies suffer from low statistics
    - improvement to be expected from BES phase II (improved beam, detector upgrade)

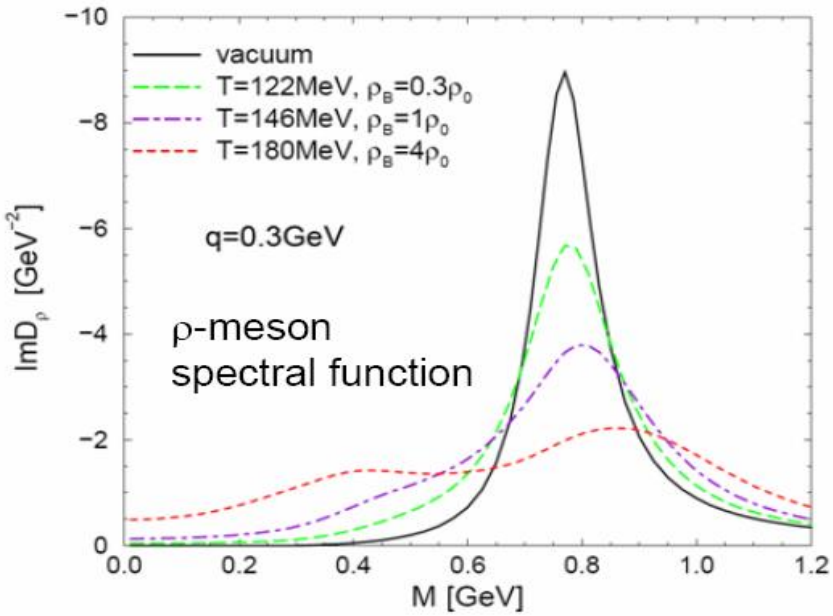


Vector Mesons and the Generation of Mass

- Hadrons are expected to change their properties (mass / width) in presence of dense medium
  - vanishing of chiral condensate; restoration of chiral symmetry (?)
- Experimental access: short-lived vector mesons (ρ)
  - decay inside the fireball -> retain information on dense environment
  - decay into lepton pairs: no strong interaction, carry information out of the medium

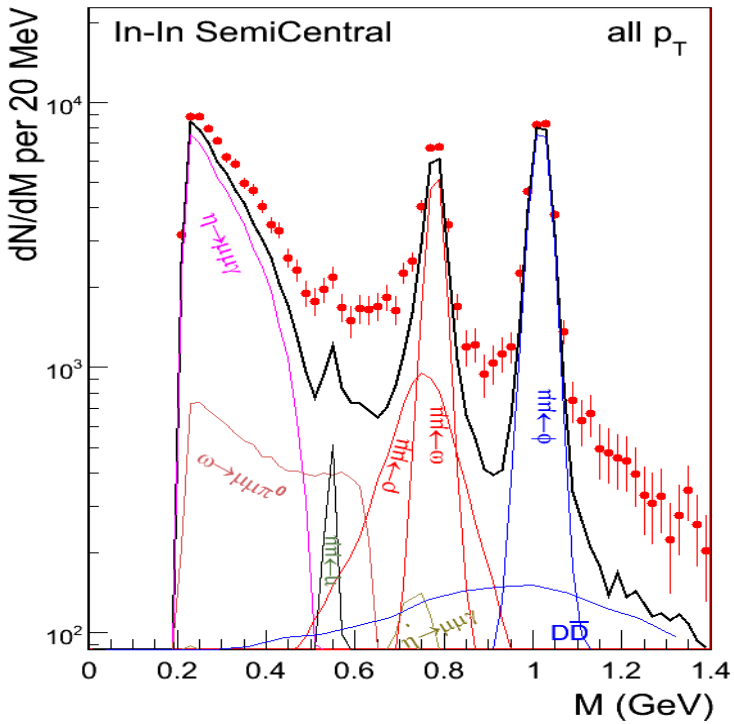


R. Rapp and J. Wambach, Act. Nucl. Phys. 28 (2000) 1

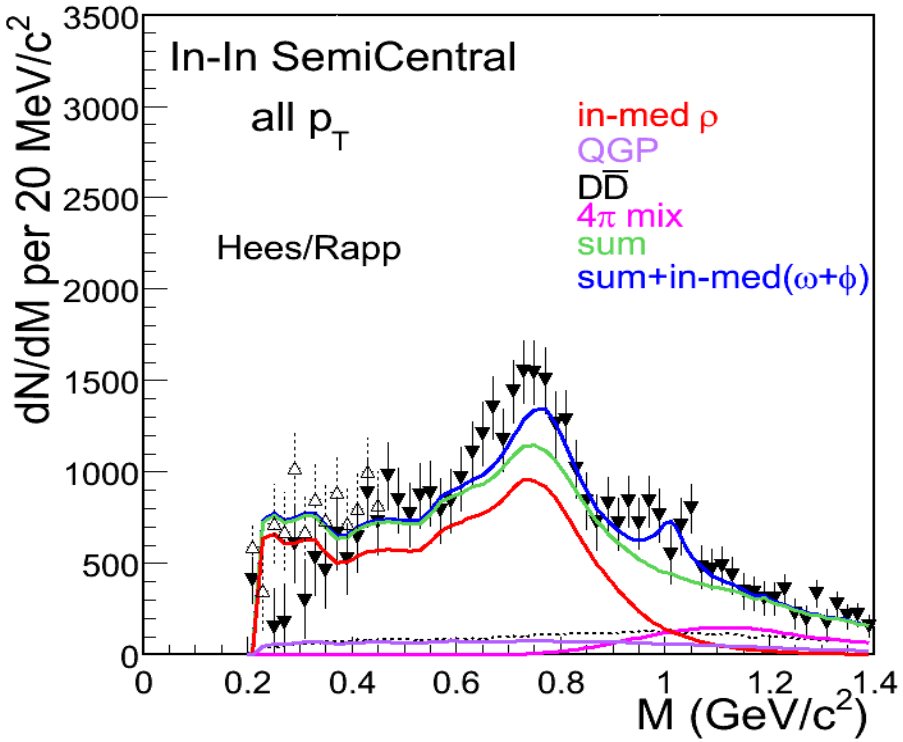


The Melting of the ρ

- Observation of excess over spectrum expected from hadronic cocktail was observed at SPS by CERES (e^+e^-) and NA50/NA60 ($\mu^+\mu^-$)
- Landmark measurement: NA60 (In+In): consistent with broadening of the ρ meson

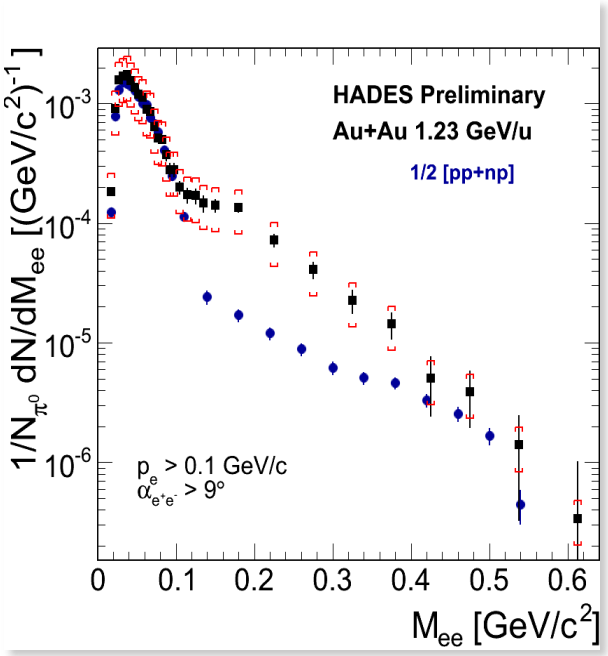


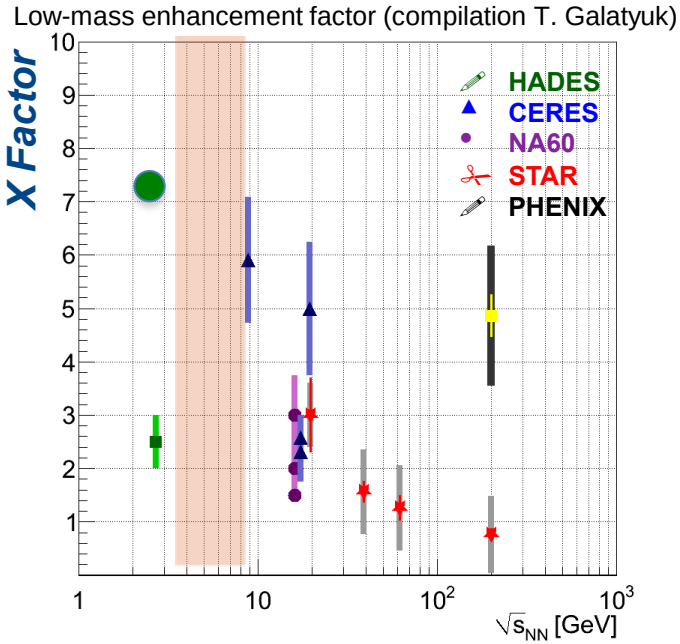
Data: NA60, EPJC 59 (2009) 607



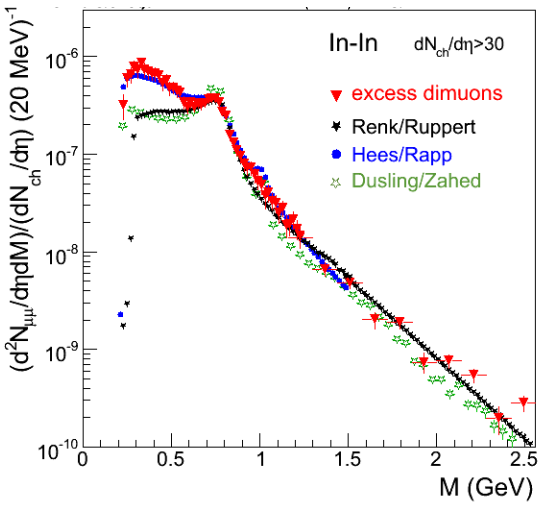
Messages from HADES

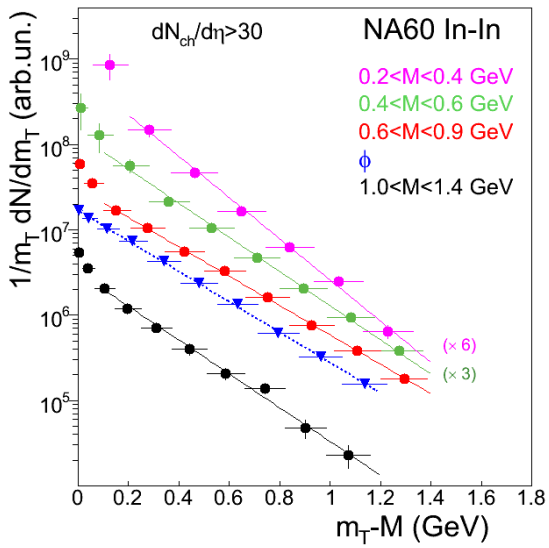
- Excess already present at beam energies as low as 1.76A GeV and systems as small as Ar+KCl! Can this have to do with chiral symmetry restoration?
  - Need the proper baseline: p+p is not enough.
  - Can coupling of ρ to baryons explain everything?
  - Newest results: excess of factor of 8 in Au+Au at 1.23A GeV!
- Data in the high density region utterly desirable!

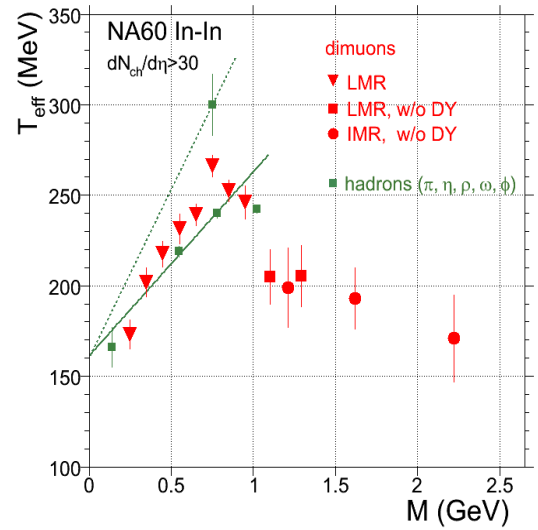




The Intermediate Mass Region







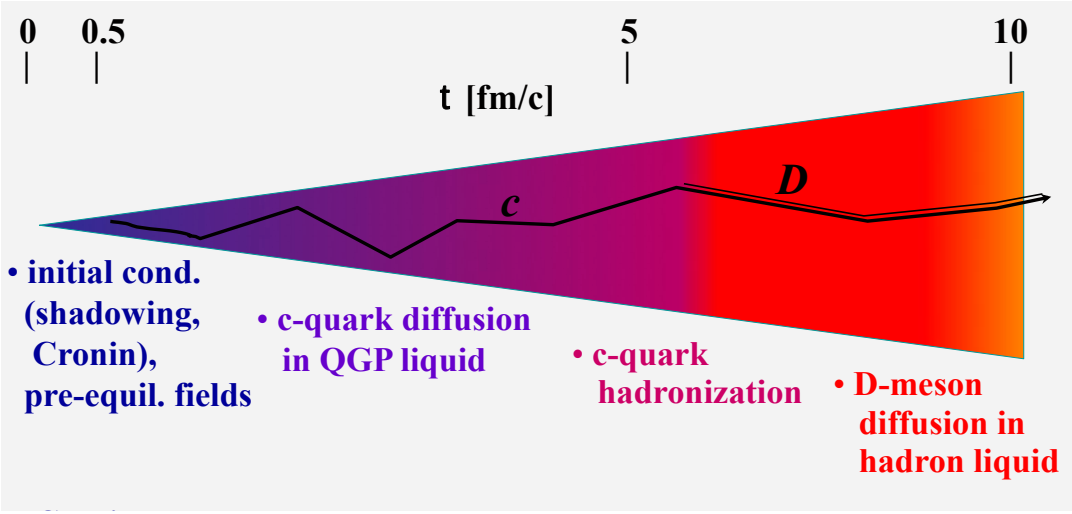
- Between ϕ and J/ψ: no hadronic sources
  - processes: Drell-Yan, thermal radiation (QGP / hadron gas)
- Apparent temperature of excess yield (through transverse spectra) as function of mass:
  - rise for m < 1 GeV: hadronic sources, radial flow
  - constant for m > 1 GeV: early source with low flow -> direct radiation from the QGP?
- Calls for systematic investigation at lower energies!

Low-Mass Lepton Pairs: Experimental Prospects

- HADES/FAIR: e^+e^-, up to 4A GeV (Au+Au), 8A GeV (Ni+Ni)
- CBM/FAIR: e^+e^- and $\mu^+\mu^-$, 4A - 45A GeV
- MPD/NICA: e^+e^-, $\sqrt{s}$ = 4A – 11A GeV (E = 6A – 60A GeV)
- NA60+/SPS: $\mu^+\mu^-$, 20A - 158A GeV

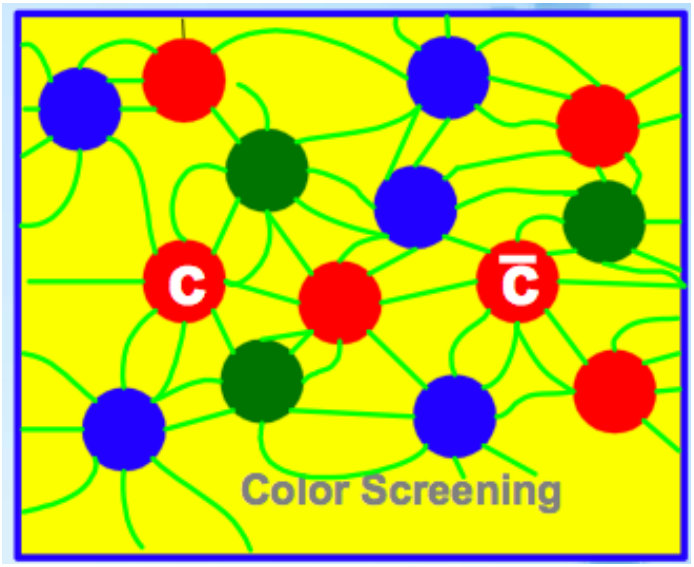
Charm in Heavy-Ion Collisions

- Unlike lighter quarks, $m_c >> T$
  - thermal production of charm negligible
  - production of charm in first-chance N-N collisions
  - charm probes the produced medium
    - c quark diffusion in QGP
    - D meson / J/ψ propagation in hadronic medium

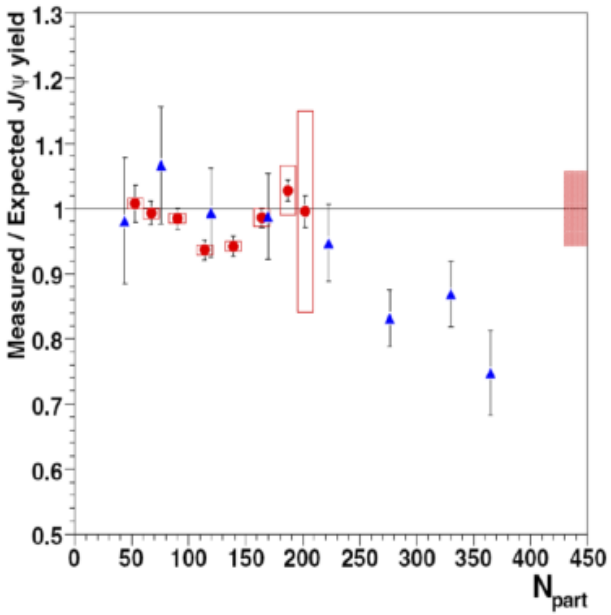


courtesy R. Rapp

Charmonium Suppression: The QGP Signal



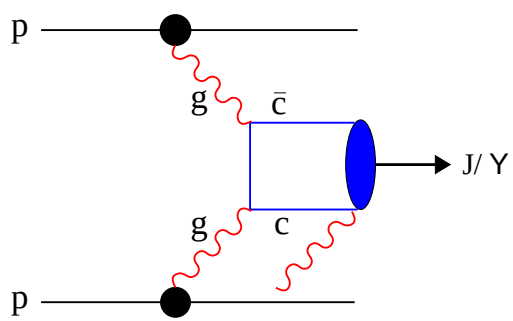
R. Arnaldi et al. (NA60), Nucl. Phys. A 830 (2009) 345c

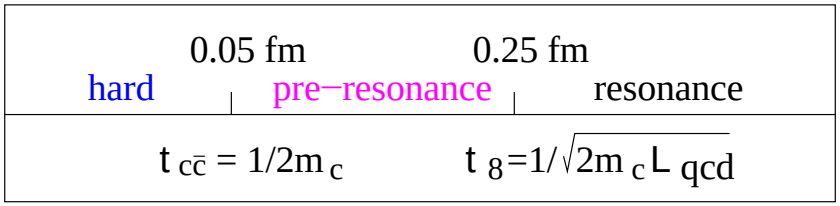


- Dissociation of charmonium states by free colour charges in a deconfined medium
- observed at SPS (NA50) for very central Pb+Pb collisions (not in In+In / NA60)
- need to control additional effects:
  - absorption in cold nuclear (spectator) matter -> p+A
  - absorption in hot hadronic (co-mover) matter
  - regeneration: only at high collision energies (RHIC, LHC)

Charmonium Below Top SPS Energy

- Can an „onset“ of charmonium suppression be observed below top SPS energy (160A GeV)?
- $N_{ccbar} << 1$: re-generation negligible
- Many questions:
  - how do quarkonia interact with normal hadrons?
  - what is the effect of nuclear matter on the binding of c-cbar to charmonia?
  - how is the overall c-cbar production rate modified in dense matter?

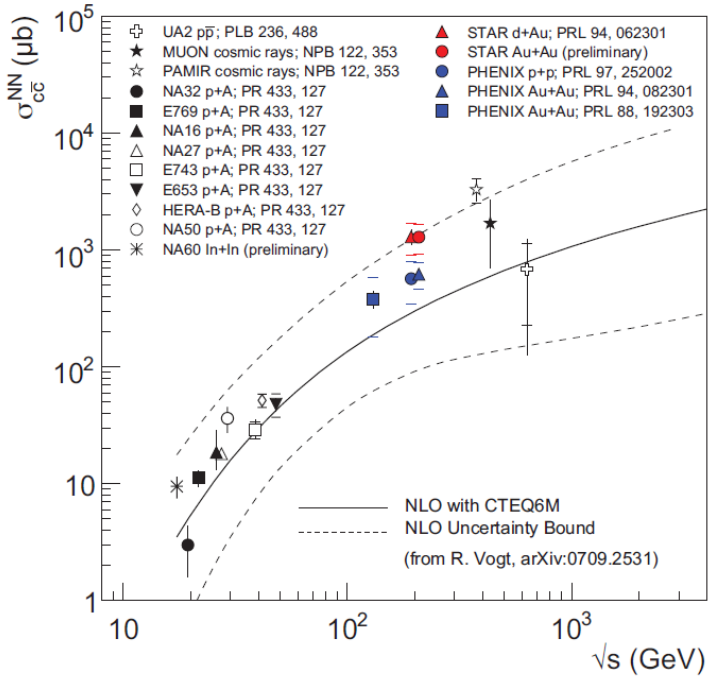




H. Satz, Heavy-Flavour Workshop, 24 May 2014

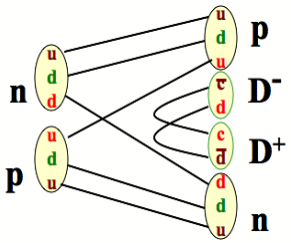
Charm Cross Section

- For the interpretation of charmonium data, the total c-cbar production cross section is required: need to measure also open charm.
  - cave: near threshold, $N_{J/\psi} << N_D$ not necessarily true
- Charm cross section close to threshold is experimentally unknown below √s = 20 GeV even in elementary reactions (let alone A+A)!
- pQCD calculations also come with large uncertainties.

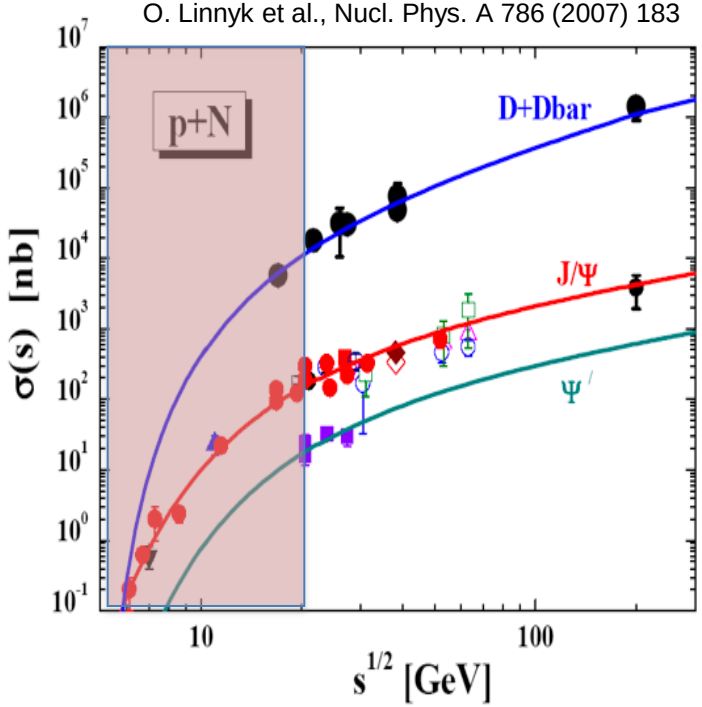


Model Predictions for Charm in A+A

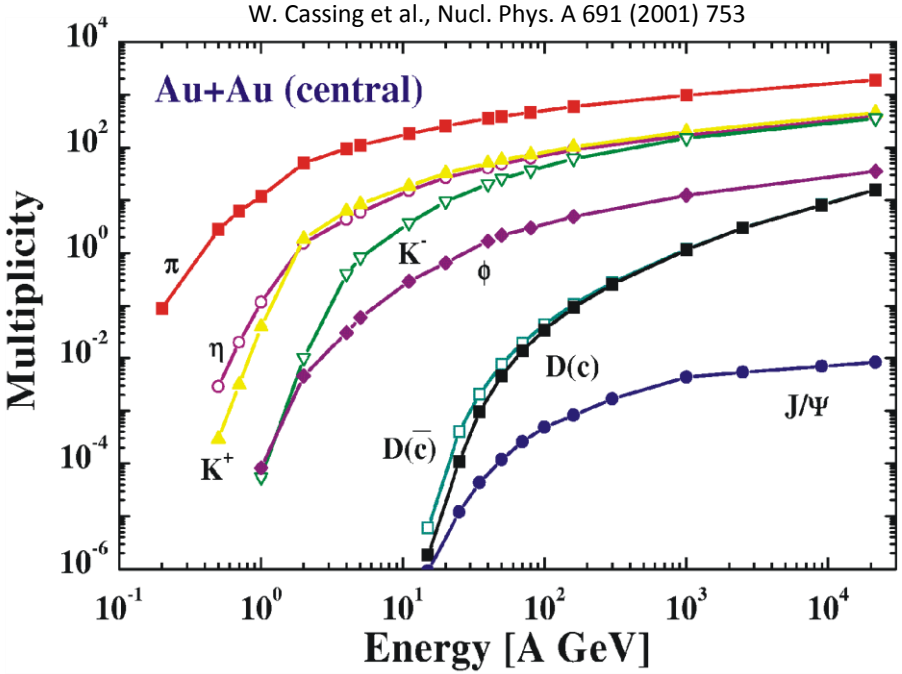
HSD: hadronic picture
(based on extrapolation of elementary cross sections to threshold)



O. Linnyk et al., Nucl. Phys. A 786 (2007) 183



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

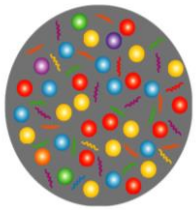


Very low predicted rates: experimentally quite challenging!

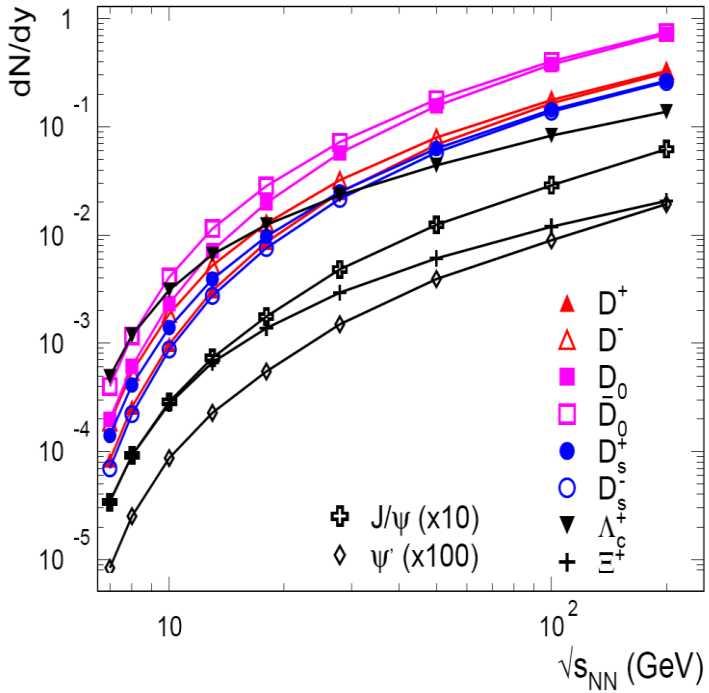
Charm Predictions for A+A: Partonic Picture

Statistical Model:

- fixed c-cbar multiplicity (e.g., from pQCD)
- statistical hadronisation: implicitly assumes thermalisation of charm quarks in QGP
- works well for RHIC and LHC

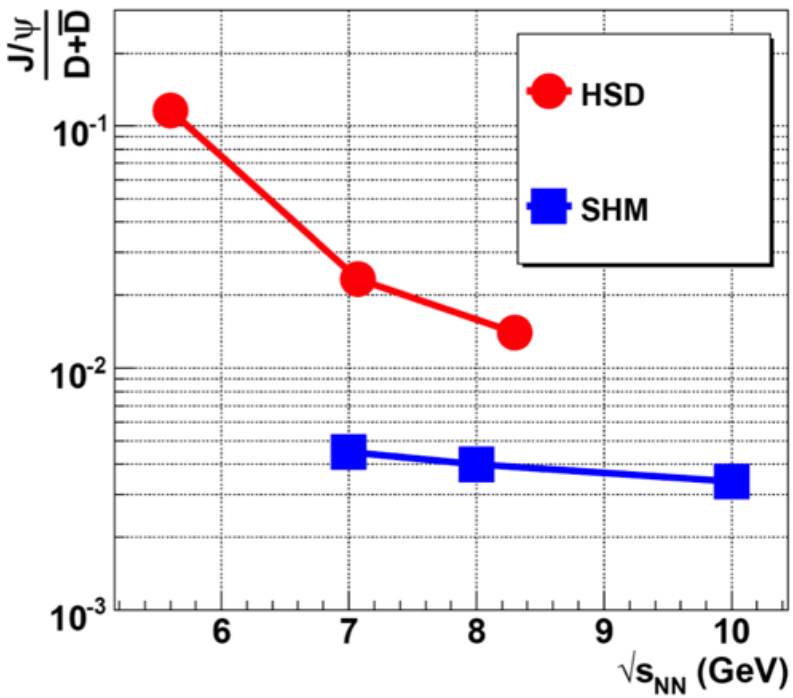


A. Andronic, et al., PLB 659 (2008) 149



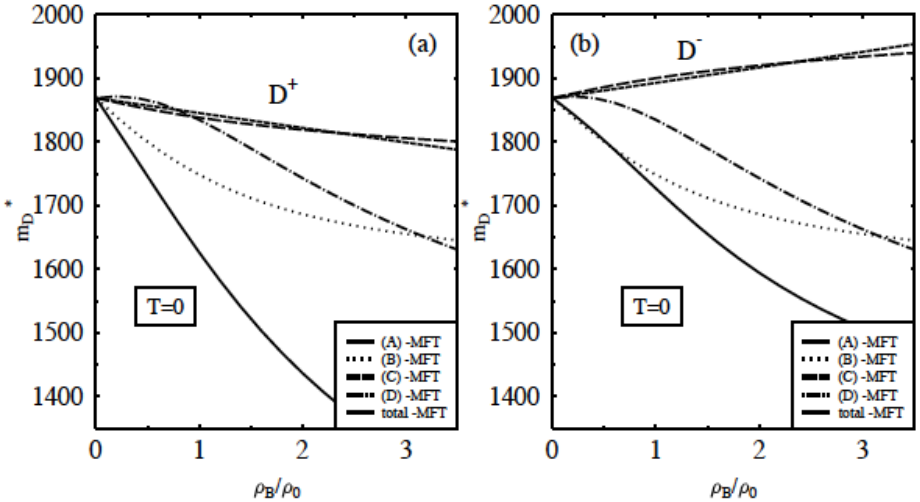
The Sensitivity of Charm

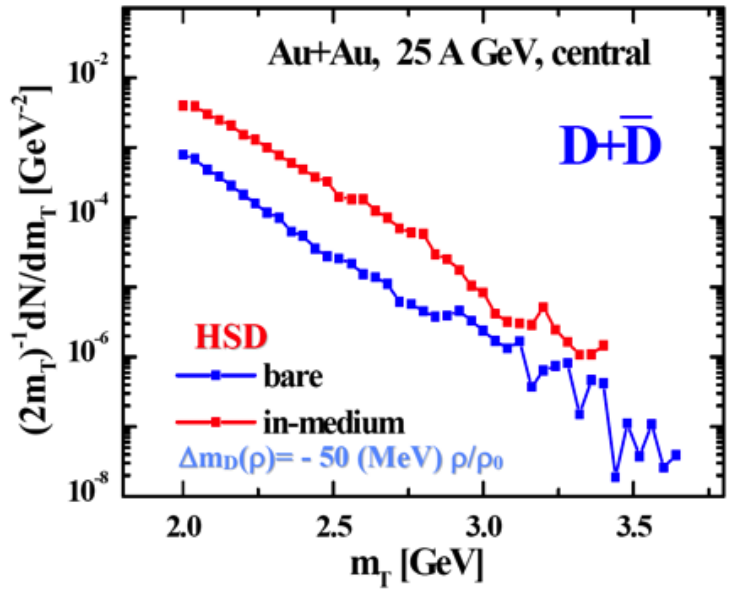
- Model predictions (hadronic / partonic) differ significantly: charm production near threshold is sensitive to the production scenario!
- Particularly promising: ratio hidden to open charm (reduces uncertainty due to c-cbar cross section).



Charm in Medium

A. Mishra et al., Phys. Rev. C 69 (2004) 015202

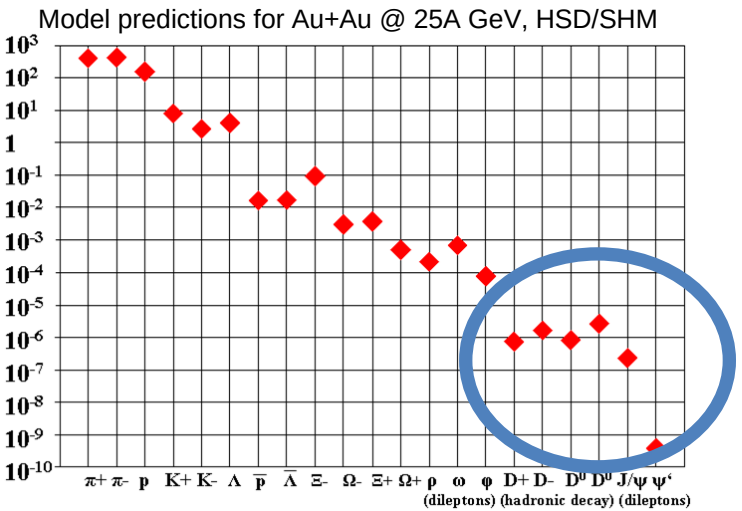




- Open charm is expected to change properties in dense medium (coupling to light-quark condensate)
- Can have large effect on production cross section!
- Unclear: formation time of open charm vs. life time of dense fireball

Charm at Lower Energies: Experimental Prospects

- exciting physics with many open issues calls for a comprehensive experimental programme including p+p and p+A collisions
- low yields: needs high-rate experiments plus micro-vertexing capabilities for open charm.
- charmonium
  - NA60 down to 60A GeV
  - CBM up to 45A GeV
- open charm
  - NA61: down to ~ 80A GeV
  - CBM: up to 45A GeV



Summary

- Experimental programmes are ongoing or in preparation worldwide to explore strongly interacting matter at highest achievable net-baryon densities.
- The aim is to find and study the structures in the QCD phase diagram:
  - first-order deconfinement phase transition
  - critical point
  - hypothetical new phases at high baryon densities
- These programmes are complementary to the study of the QGP which are performed at top RHIC and LHC.
- New accelerator facilities will become available around 2019.
- The future of heav-ion physics seems bright and promising!