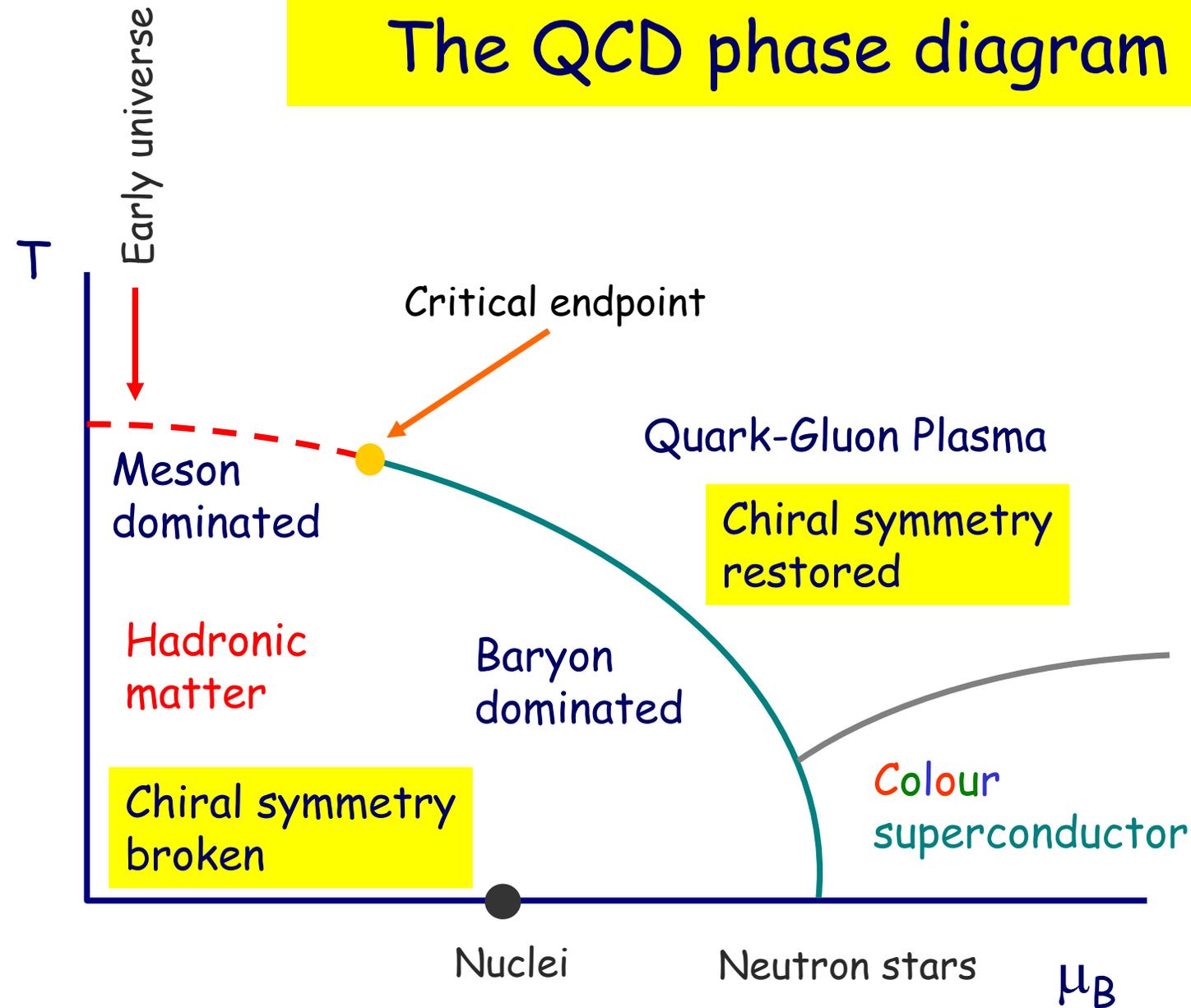


The Physics of high ^(and not so high) baryon densities

B. Friman, GSI

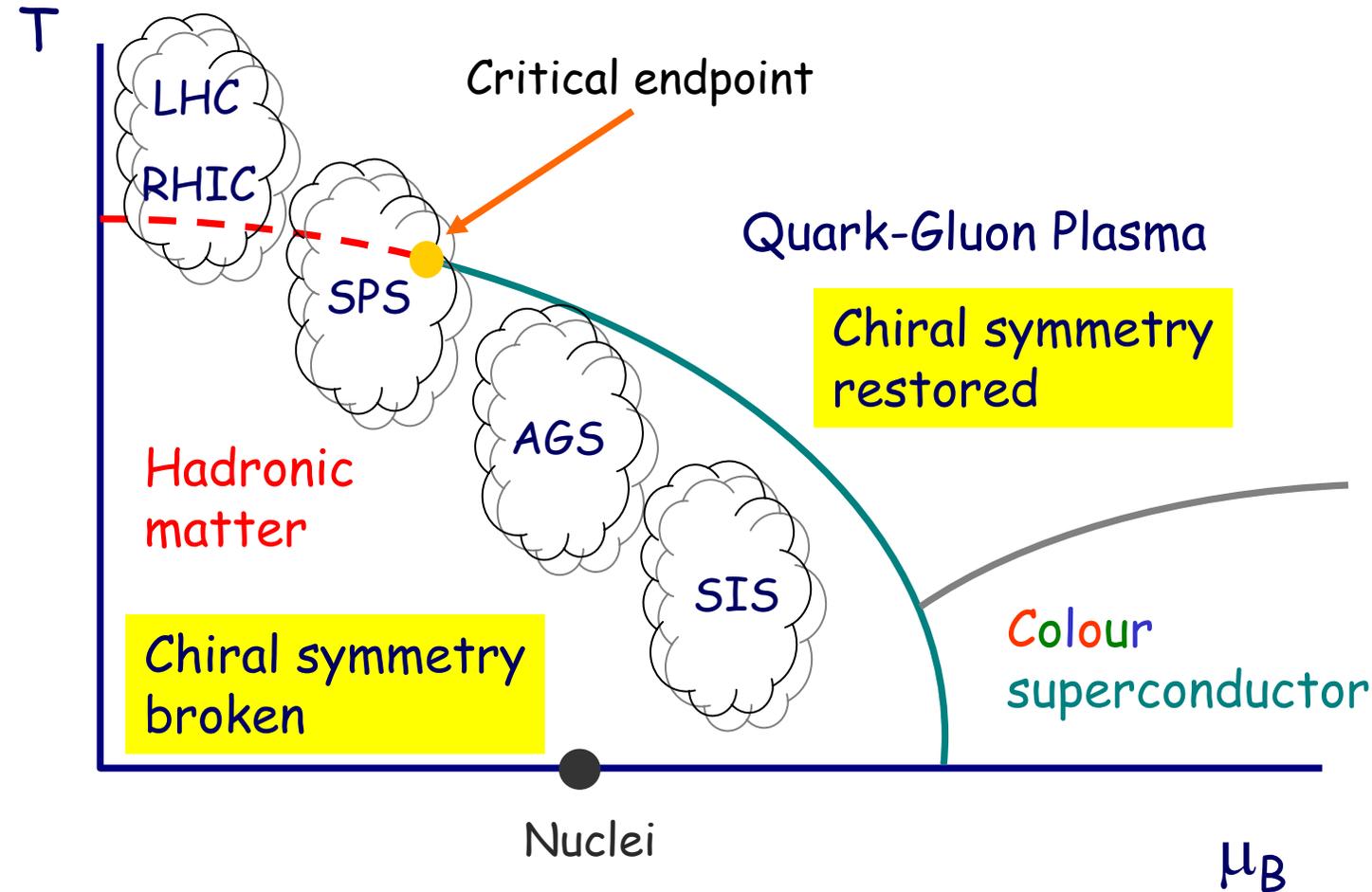
- Probing the QCD phase diagram
- The critical end point
- Properties of mesons in matter
 - Baryon density vs. temperature
- Probing cold dense matter
- Conclusions

The QCD phase diagram



Neutron stars:
-low T
-high μ_B
-strangeness
-quark matter
(CSC?)

The QCD phase diagram

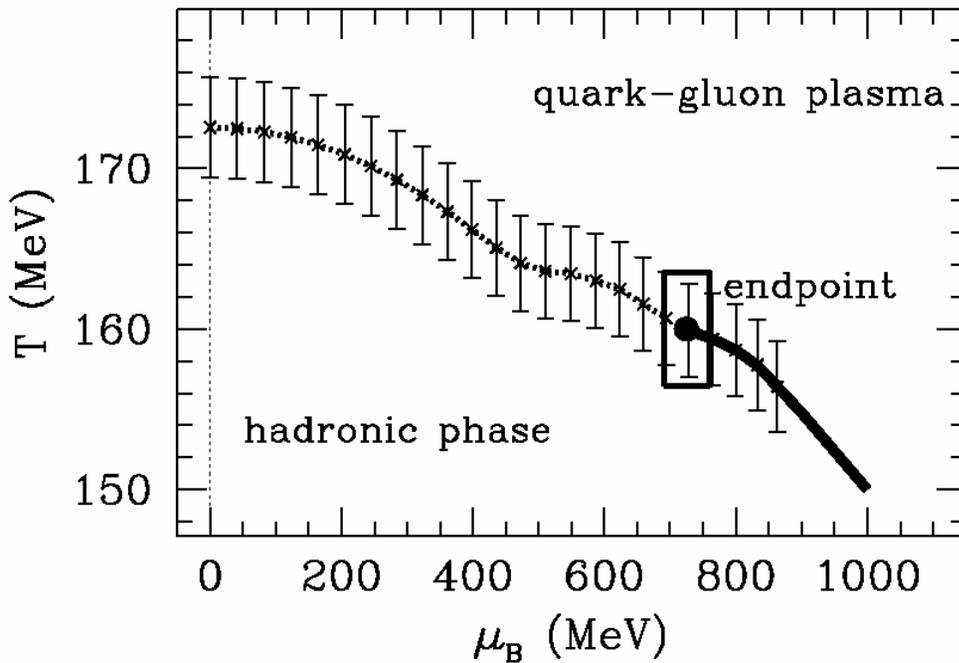


Need:

High, low and intermediate energies

Different reactions
 $AB, pA, \gamma A..$

The critical end point

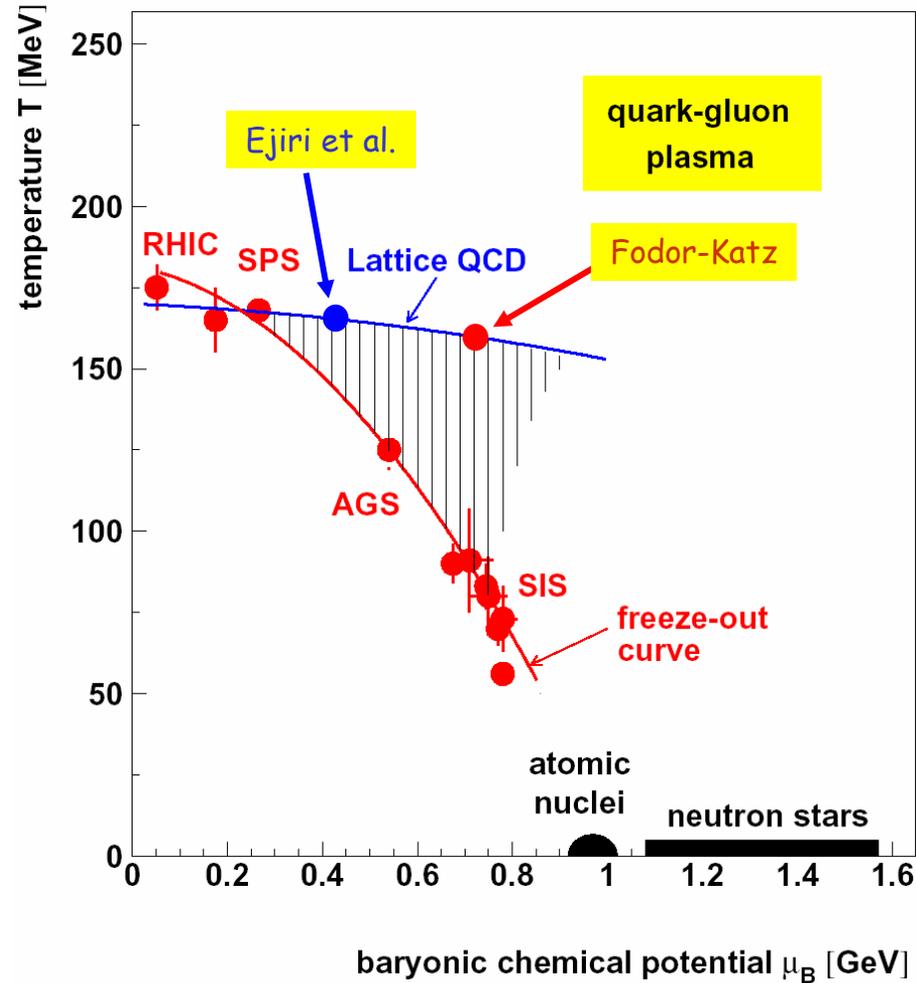


Fodor & Katz:

$$T^c \approx 160 \text{ MeV}, \mu_B^c \approx 720 \text{ MeV}$$

Adiabatic extrapolation to
freeze-out curve: $E \sim 10 \text{ AGeV}$

Critical point expected to move
to smaller μ_B for realistic m_q



Ejiri et al. (Bielefeld-Swansea):
 $\mu_B^c \approx 420 \text{ MeV}$
 $E \approx 40 \text{ AGeV}$

Signatures of the critical end point?

Critical point: **fluctuations of the order parameter are soft**

Look for rise and fall of fluctuations! (E-by-E)
(Stephanov, Rajagopal, Shuryak)

E-by-E fluctuations of:

- transverse momentum (SRS)
- pion multiplicity (SRS)
- proton number (Hatta, Stephanov)

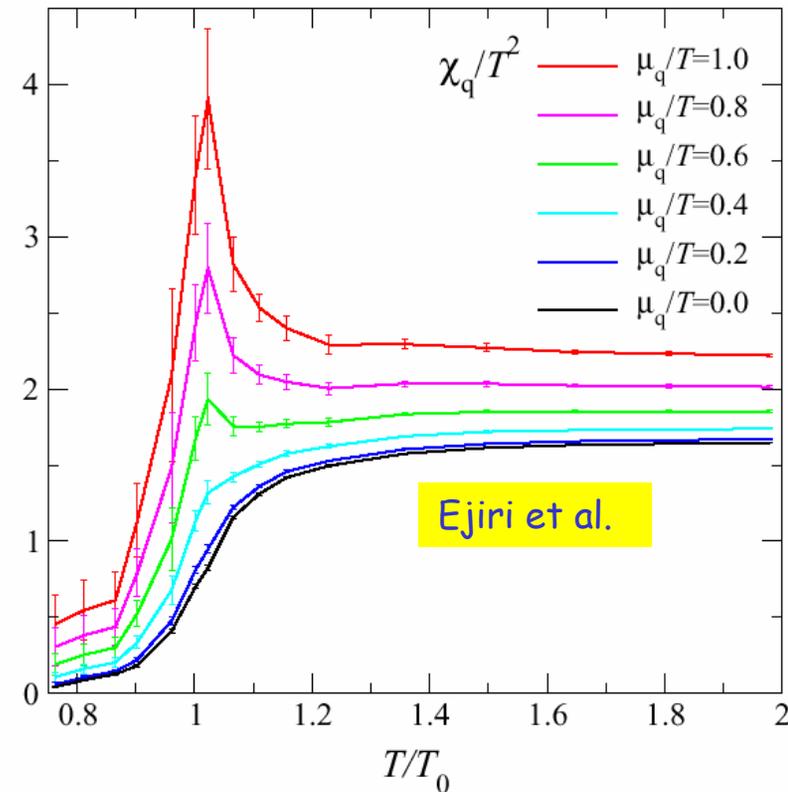
.....

Take care of finite time and finite size effects (Berdnikov, Rajagopal)

Exciting prospects, but still many unknowns!

So far no convincing experimental evidence for the nuclear matter gas-liquid critical point

Quark number susceptibility



Effects of baryon density

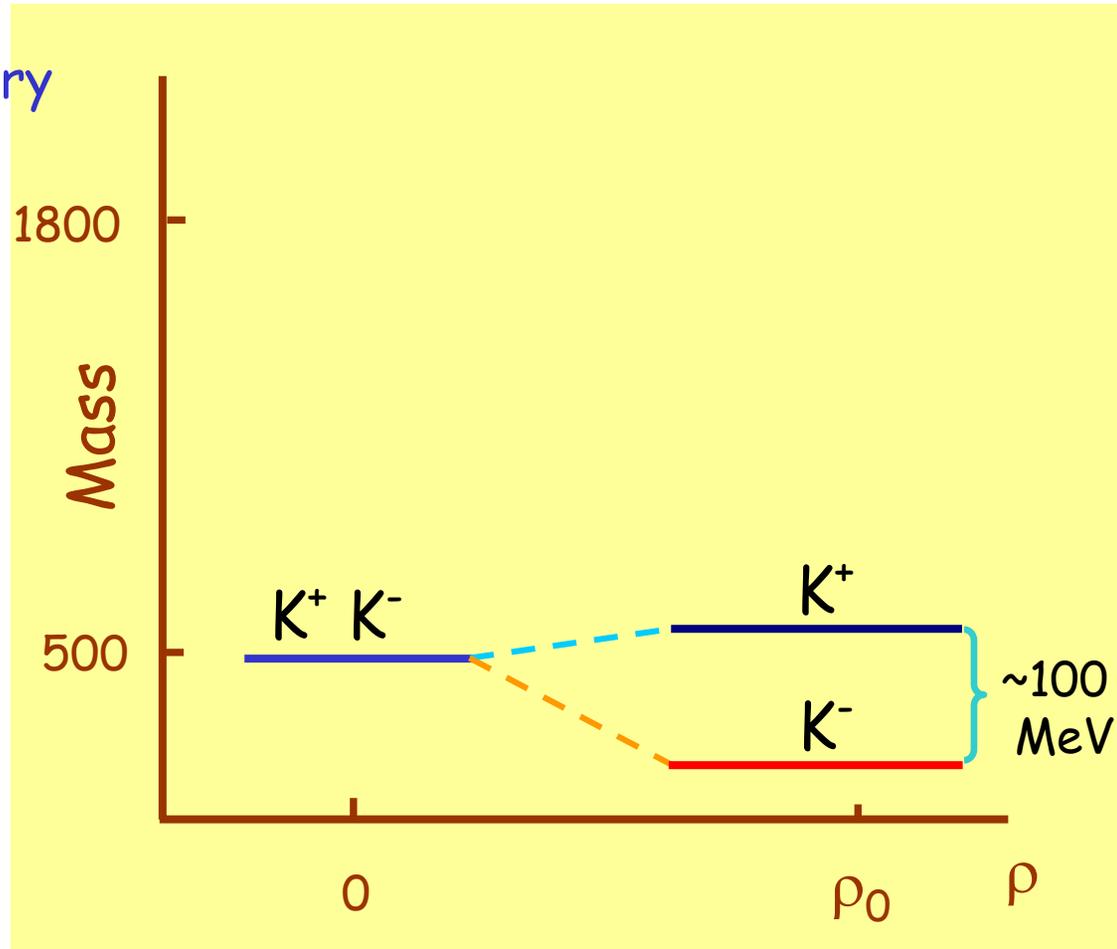
Mass splittings because charge conjugation symmetry broken at $n_B \neq 0$

$$|K^+\rangle = |u\bar{s}\rangle$$

$$|K^-\rangle = |s\bar{u}\rangle$$

Overall attraction due to scalar interaction: KN sigma term

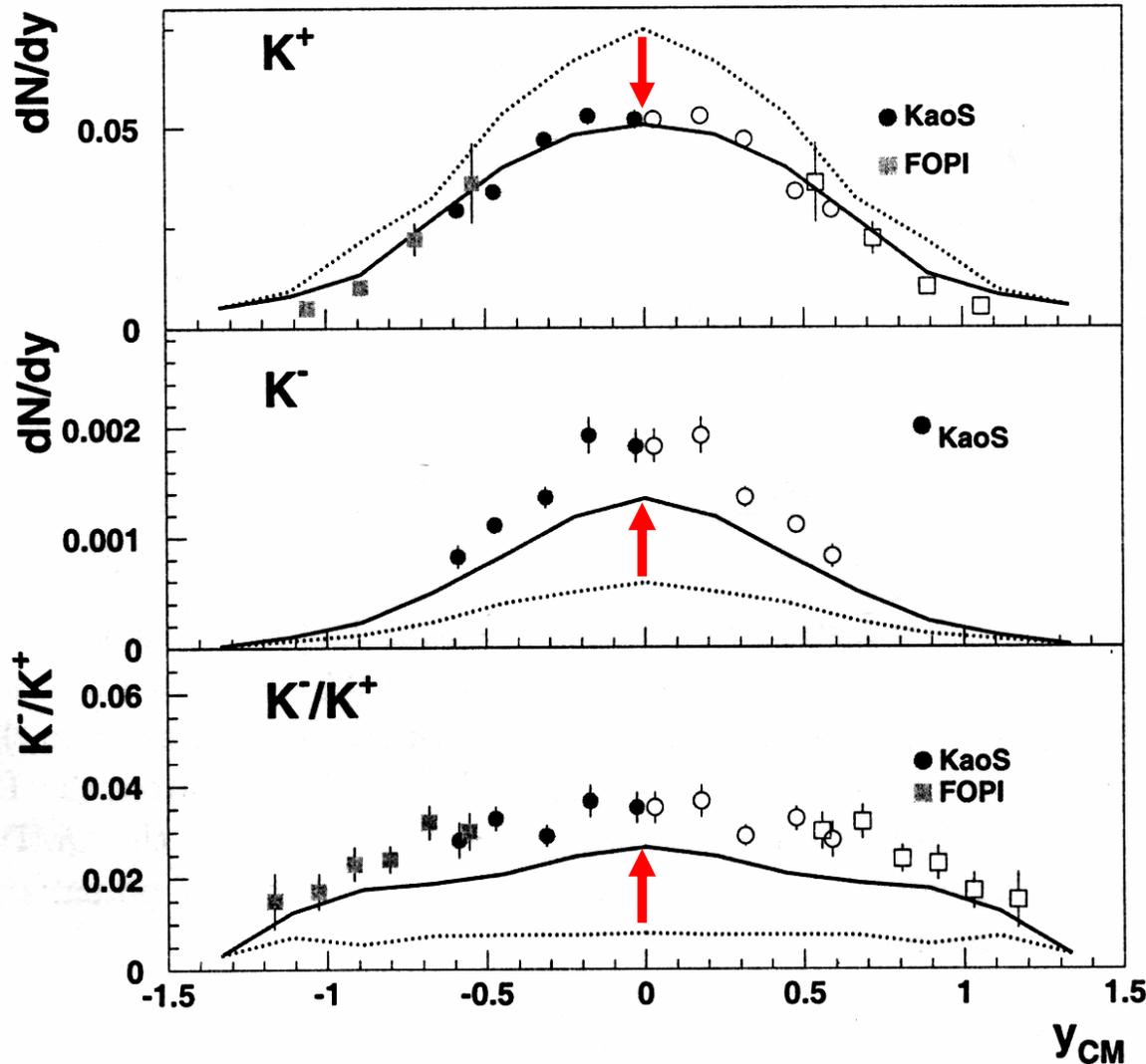
Mass splitting due to vector interaction: Weinberg-Tomozawa



Easier to produce K^- in dense matter

Kaon production near threshold

Ni+Ni (1.93 GeV) KaoS & FOPI @ GSI



Repulsive potential

Suppression of K^+

Attractive potential

Enhancement of K^-

Calculation:
Cassing & Bratkovskaya

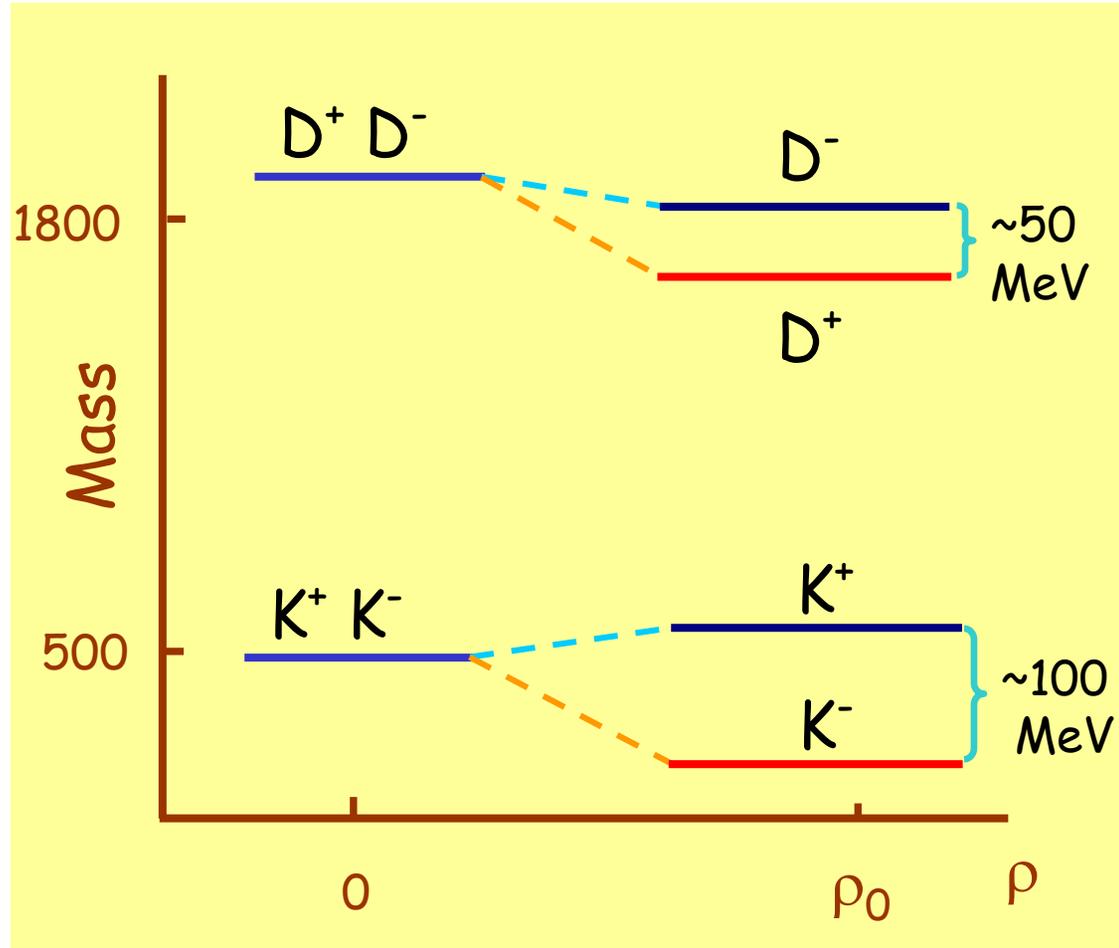
Effects of baryon density (2)

D-Meson mass splitting
at $n_B \neq 0$

$$|D^- \rangle = |d\bar{c} \rangle$$

$$|D^+ \rangle = |c\bar{d} \rangle$$

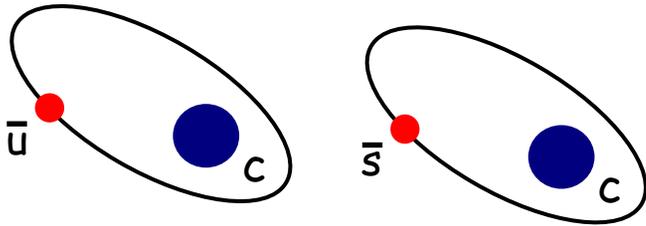
Explore D-meson
properties in dense
matter at energies
around charm threshold
 $E \approx 10\text{-}20 \text{ AGeV}$



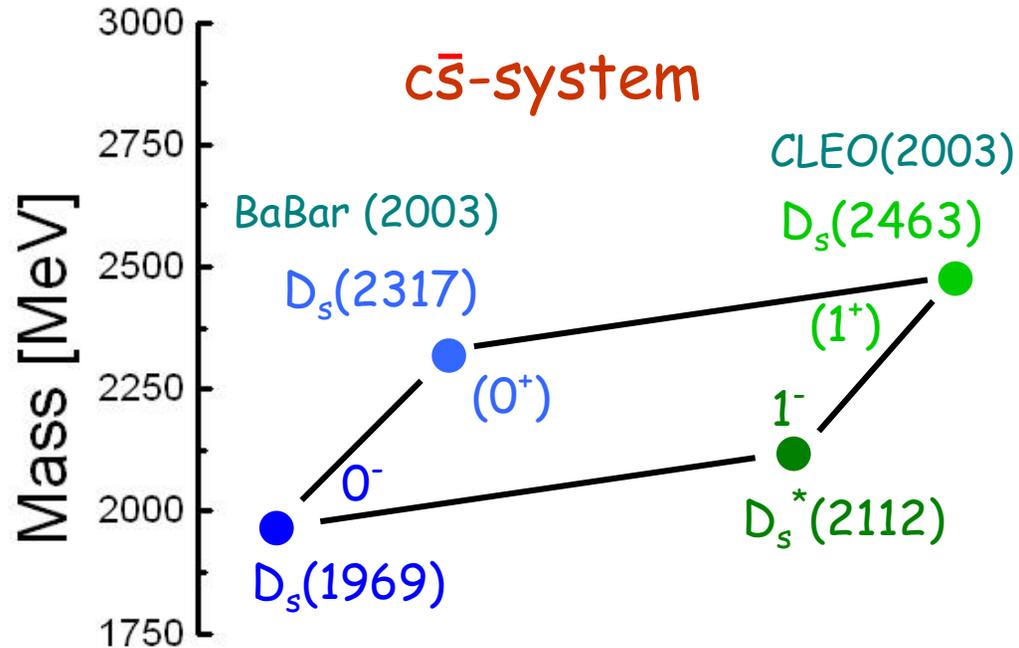
Chiral partners of D-mesons?

D-mesons:

- heavy-light system
- hydrogen atom of QCD



Light-quark-cloud probes chiral symmetry



Chiral mass shifts ≈ 350 MeV

Heavy-quark-symmetry

+ chiral symmetry:

chiral doubling of D-mesons

(Nowak-Rho-Zahed and Bardeen-Hill, 92-93)

$$D_s(0^+) \not\rightarrow D(0^-) + K$$

$$D_s(0^+) \rightarrow D_s(0^-) + \pi$$

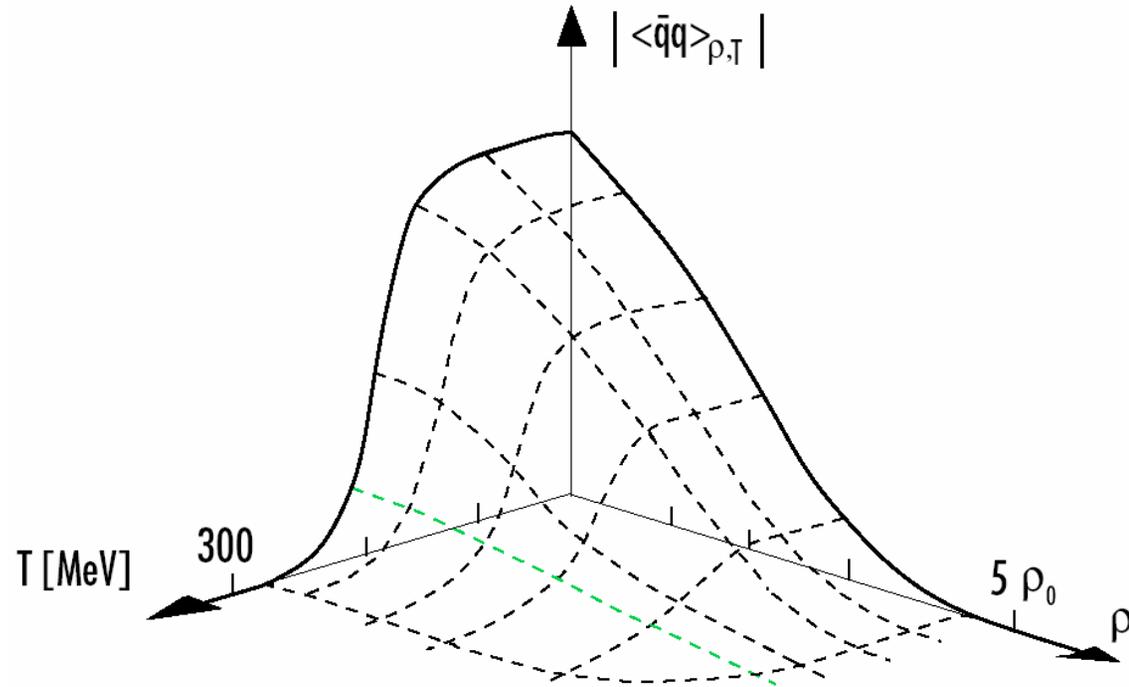
Restoration of Chiral Symmetry

at non-zero baryon density and temperature

Chiral partners become degenerate

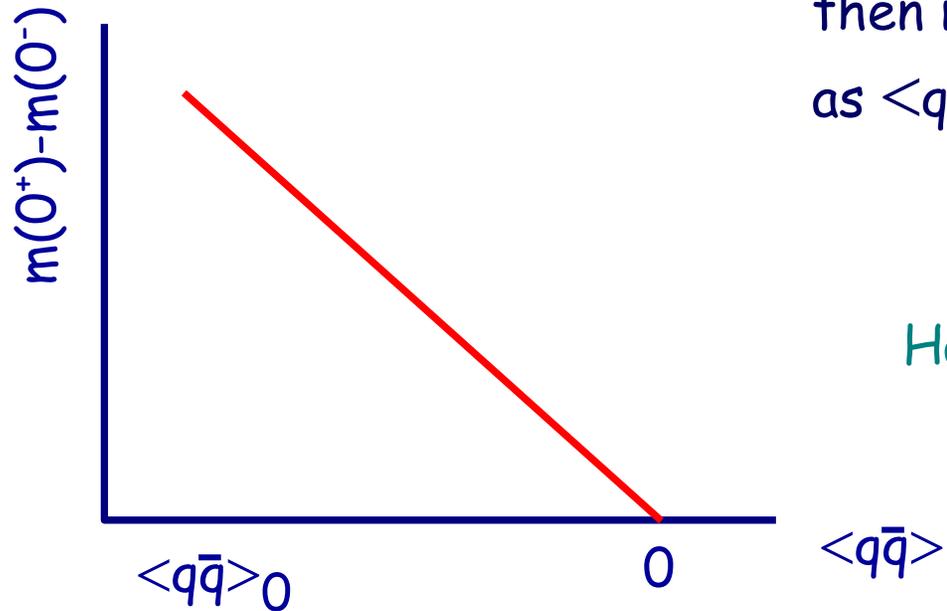
Explore dependence of hadron properties on quark condensate

Role of chiral symmetry for hadron masses?



D mesons in matter

If chiral doubling scenario for D mesons correct



then $m(0^+) - m(0^-) \rightarrow 0$ etc.
as $\langle q\bar{q} \rangle \rightarrow 0$ (chiral limit)

Harada, Rho, Sasaki (2003)

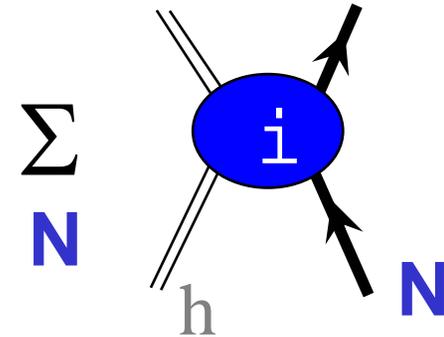
D-meson production in nuclear collisions offer a unique opportunity to explore chiral dynamics in dense matter

Beyond mean-field approximation

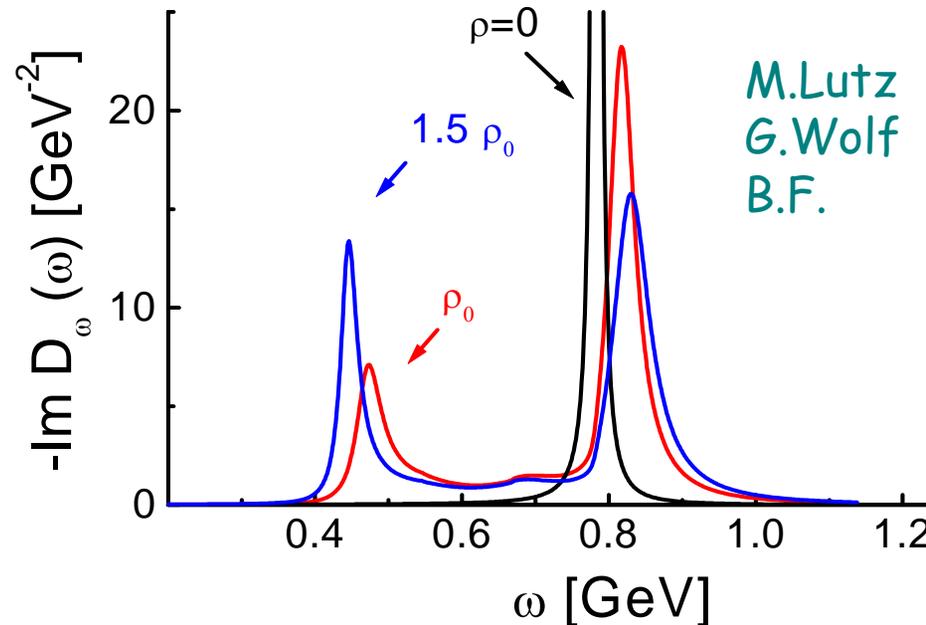
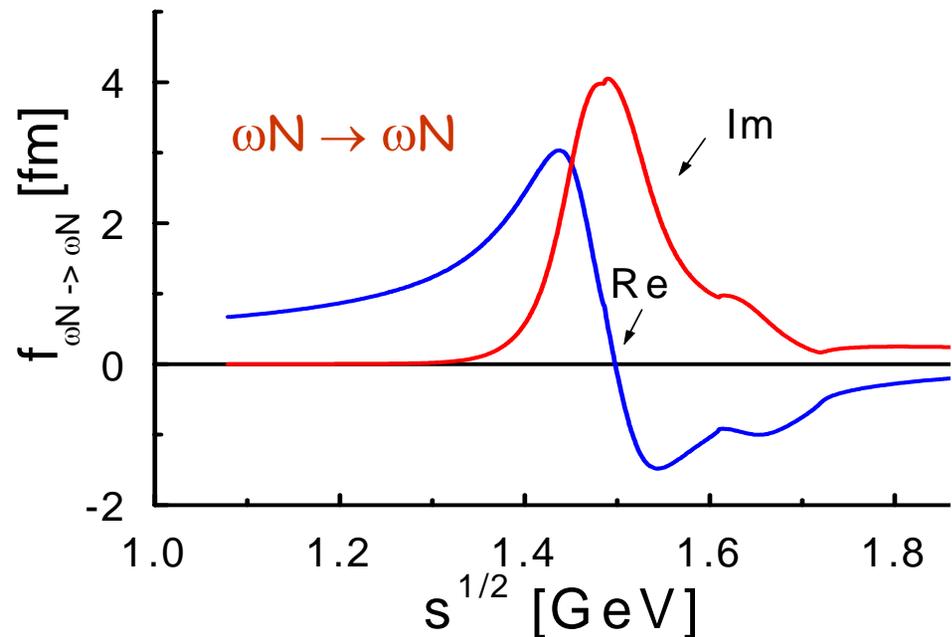
Spectral functions change due to interactions

Low-density expansion:

$$\Sigma_h(\rho_N) = -4\pi \left(1 + \frac{m_h}{m_N}\right) \bar{f}_{hN} \rho_N + \dots$$



Resonances in scattering amplitude:
peaks in spectral function



M.Lutz
G.Wolf
B.F.

Baryon density vs. temperature

Baryon dominated matter:
meson spectral functions
determined by **baryon resonances**

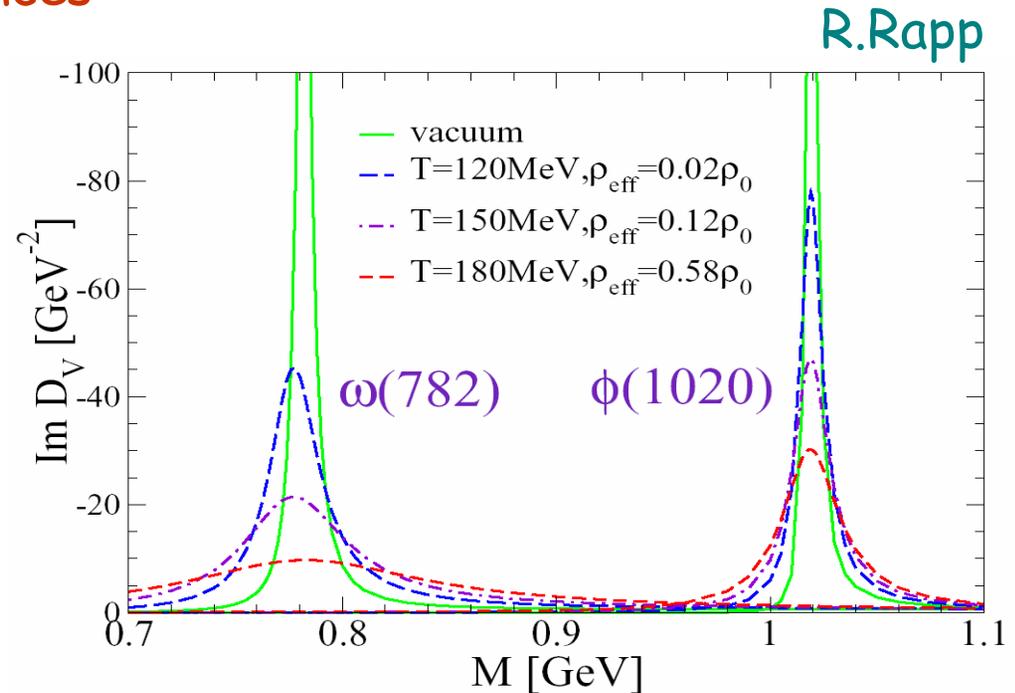
Meson dominated matter:
meson spectral functions
determined by
meson resonances

Meson mixing at $\mu_B \neq 0$

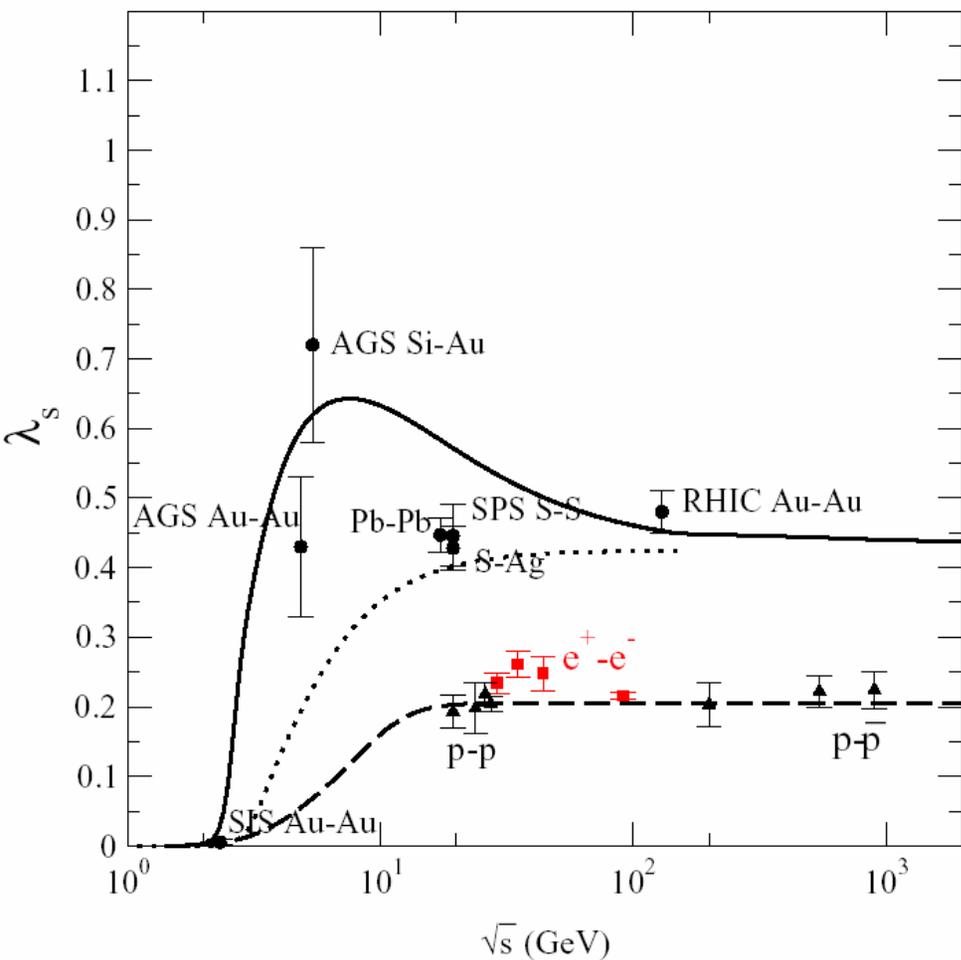
Resonances
smeared by
collision broadening

These effects must be unfolded before one can draw
conclusions on chiral symmetry and masses

Need high resolution, high statistics data at
a wide range of energies (T vs. μ_B)

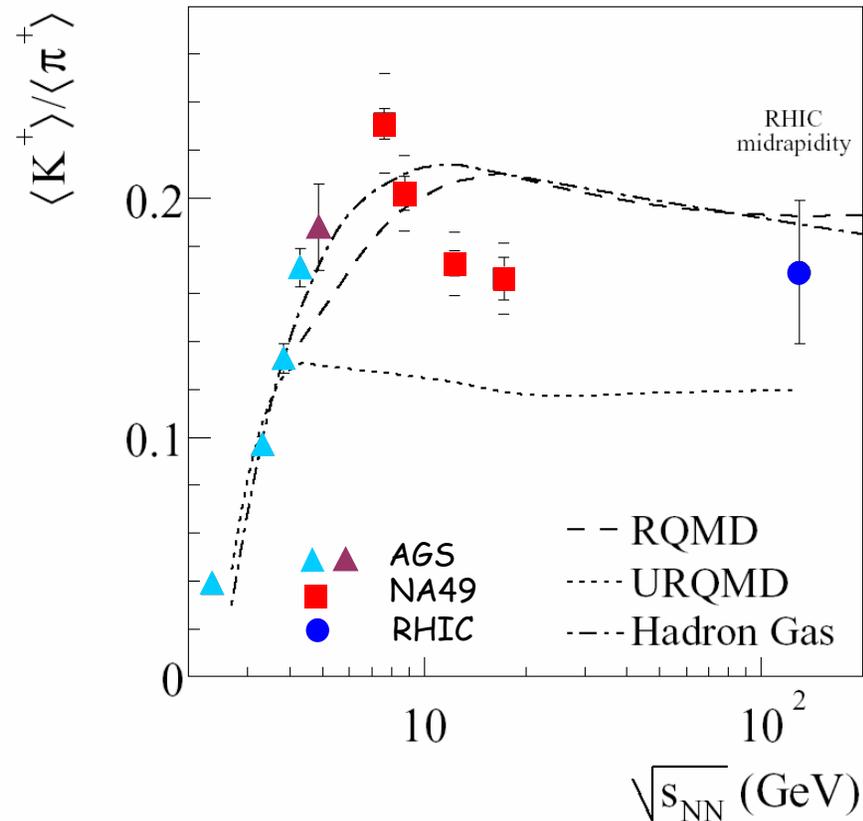


Strangeness and baryon density



Braun-Munzinger, Cleymans,
Oeschler and Redlich

No peak for $\mu_B = 0$!



Sharp maximum in K^+/π^+

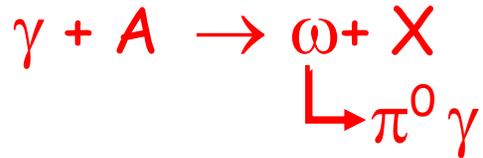
Not understood!

Probing cold dense matter in nuclei

Complementary information from

$p A, \bar{p} A, \pi A, \gamma A \dots$

Photo induced ω production



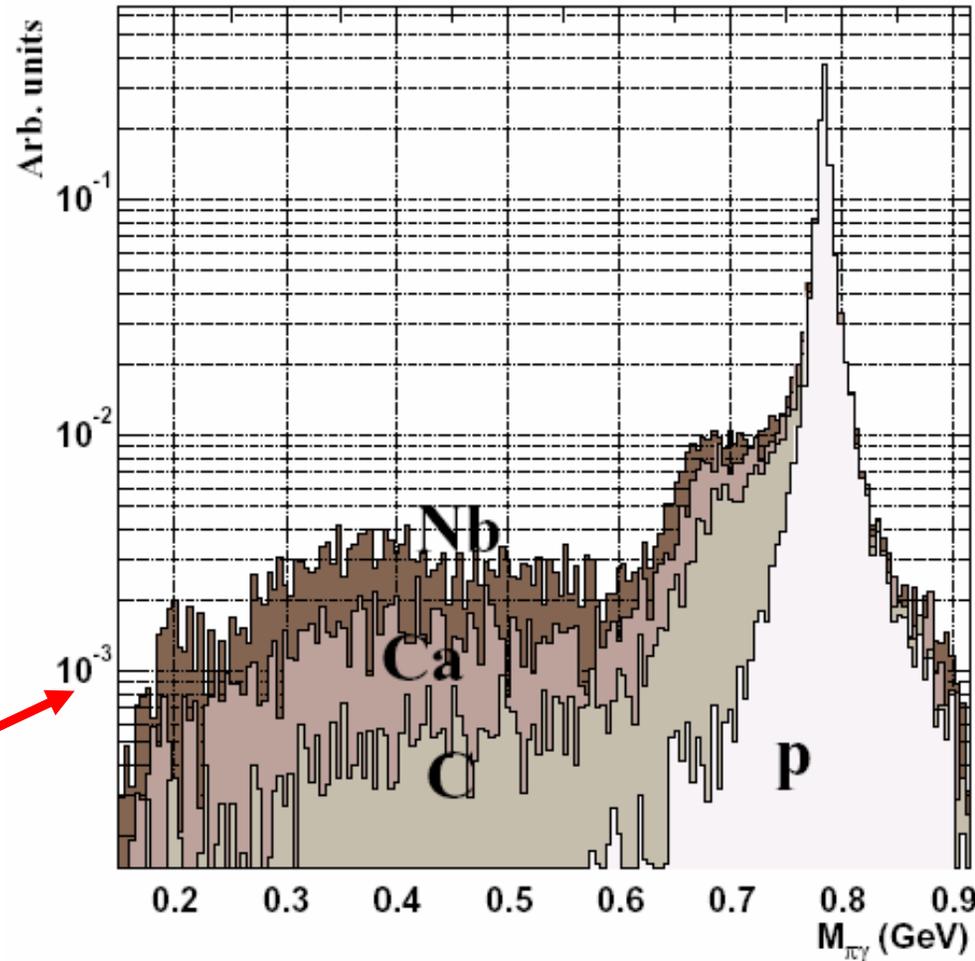
Measured at ELSA by
TAPS collaboration

Data analysis in progress

Simulation by
Meschendorp et al.

Assume at $\rho = \rho_0$:

$m_\omega \approx 660 \text{ MeV}$, $\Gamma_\omega \approx 60 \text{ MeV}$



Summary

- Critical endpoint: fluctuations
- Light-heavy mesons: mass splitting
- Chiral partners become degenerate
 - New D mesons
- Data at different energies/different μ_B/T useful for unraveling meson/baryon resonances, meson mixing etc.
- pA , πA , γA etc. provide complementary information

Some of these issues are being addressed at CERN SPS.

Most of them can be explored at the
GSI Future Facility

Protons	$E \leq 90 \text{ GeV}$
Heavy ions (N=Z)	$E \leq 45 \text{ AGeV}$
Pb	$E \leq 35 \text{ AGeV}$
Stored antiprotons	$E \leq 15 \text{ GeV}$

Comprehensive heavy-ion program with strangeness, charm, lepton pairs and photons