

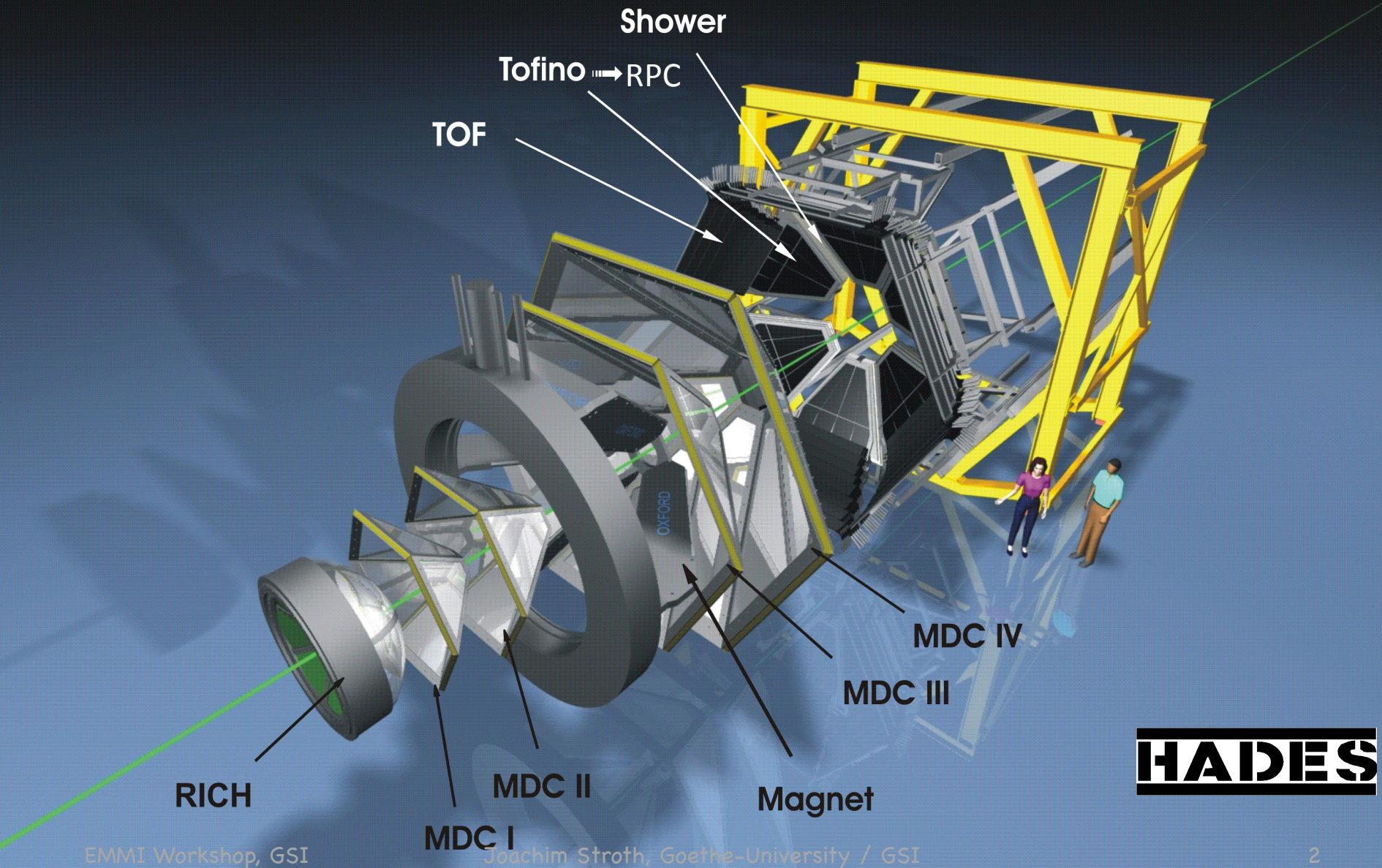
Recent Results of HADES

"Cold dense nuclear matter"

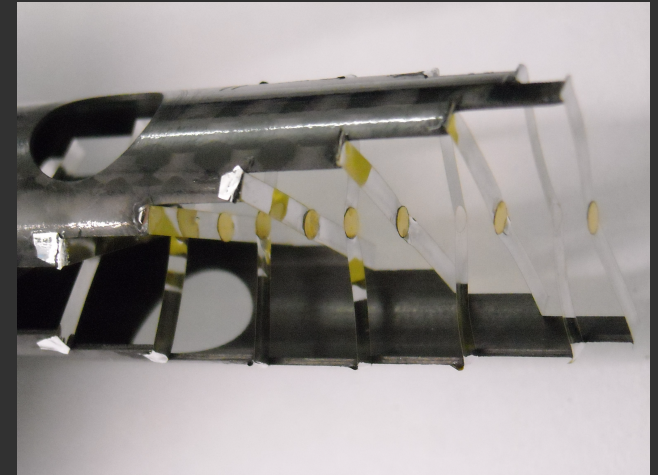
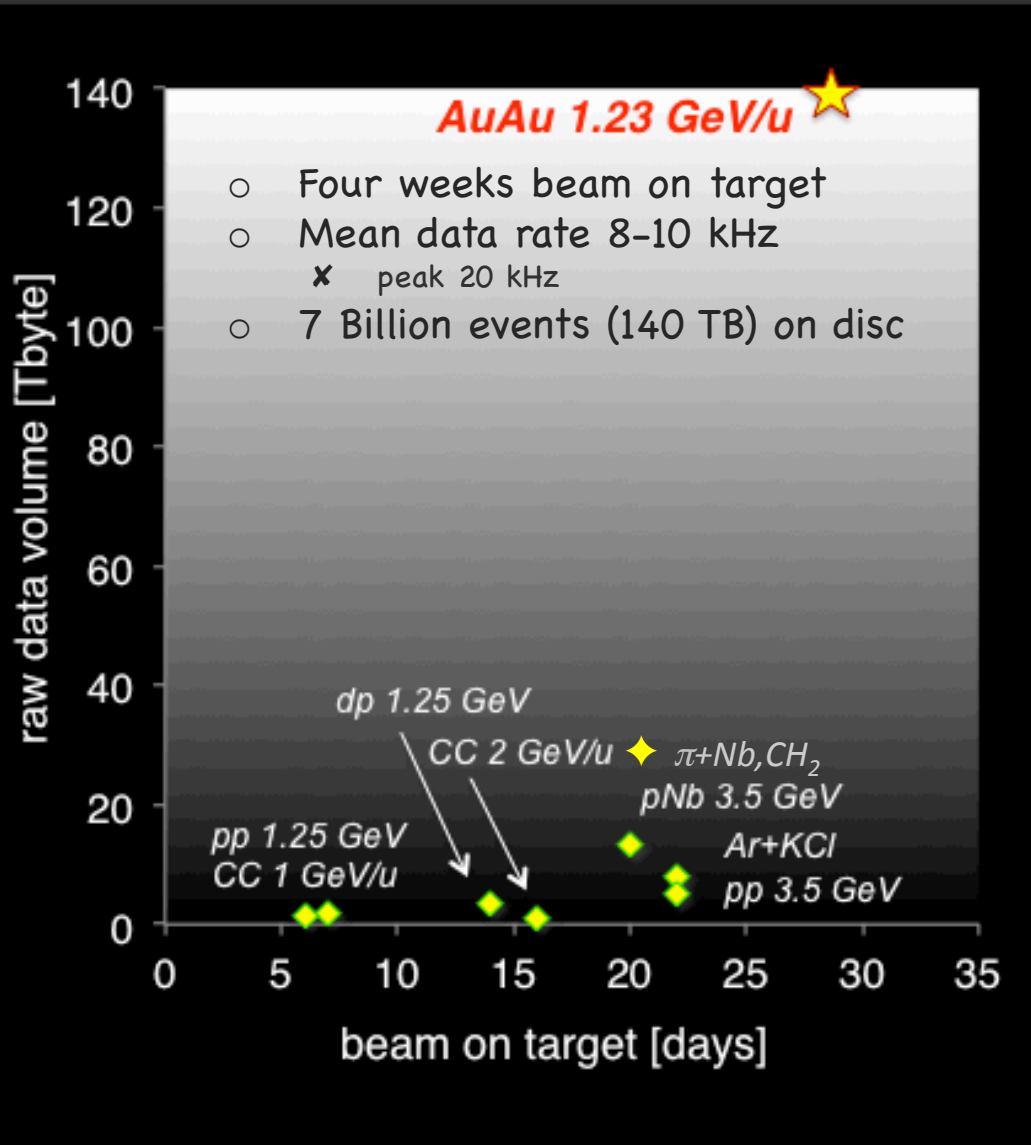
EMMI workshop, GSI, October 15, 2015

Joachim Stroth, Goethe-University Frankfurt / GSI
for the HADES collaboration

The HADES experiment @ GSI



Data taken so far



Still to come at SIS18:

- Ag + Ag 11.65 AGeV
- more π + p/A
(“the mother of dilepton measurements” VK)

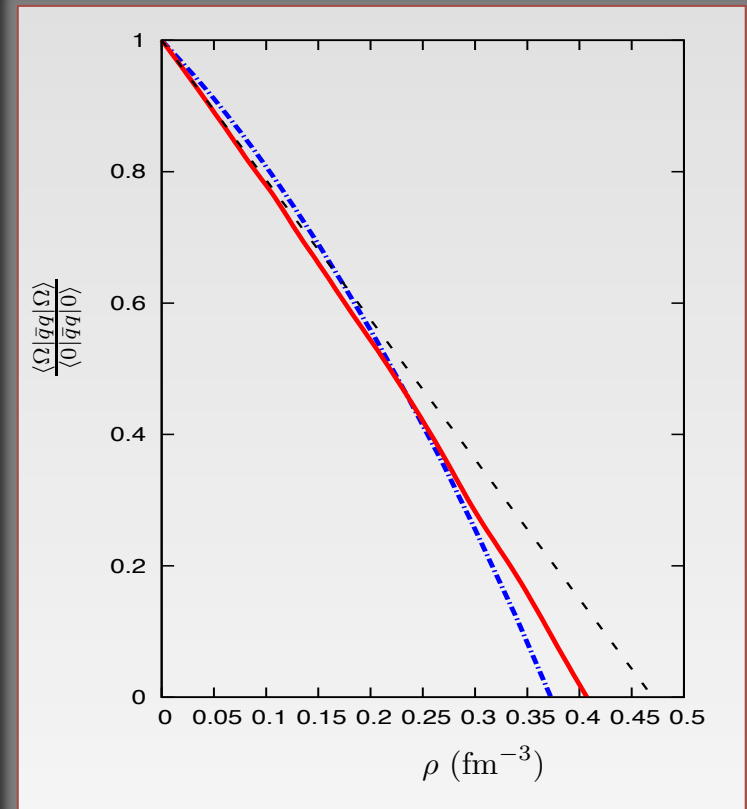
Motivation came from theory!

- R. Pisarski (1982): connection of phase-transition to modification of the ρ mass (dileptons) (PLB 110, 1982).
- G.E. Brown / M. Rho: Scaling of masses with χ -condensate (PRL 1989, 1991)

$$m^* \approx m \left[\frac{\langle \bar{q}q^* \rangle}{\langle \bar{q}q \rangle} \right]^u$$

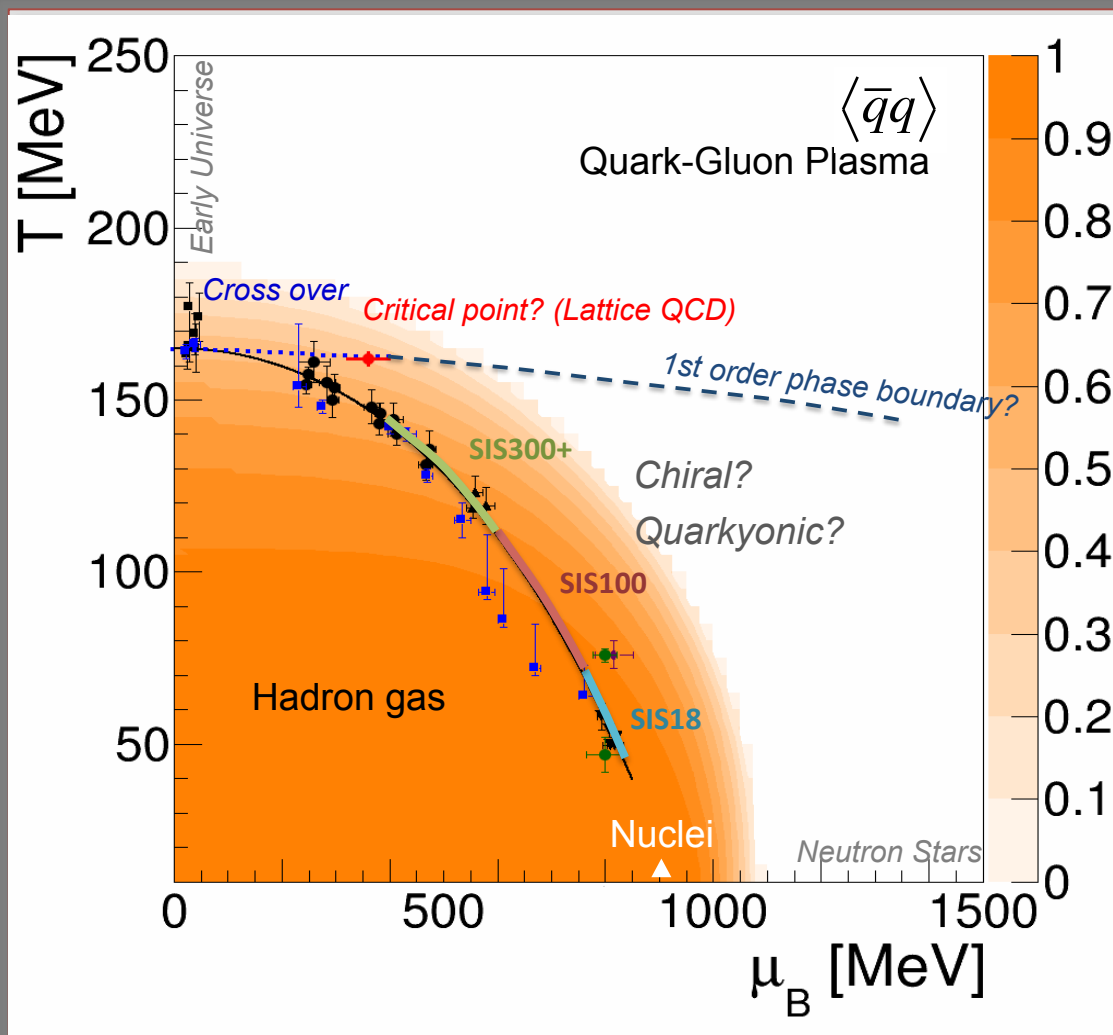
- T. Hatsuda / S. Lee: operator product expansion (PRC 46, 1992)

$$m^* = m(1 - \alpha \rho / \rho_0)$$



$\bar{q}q$ expectation in chiral power counting
by U. Meissner et al. [arXiv:1007.2574]

C.B.M. Mission



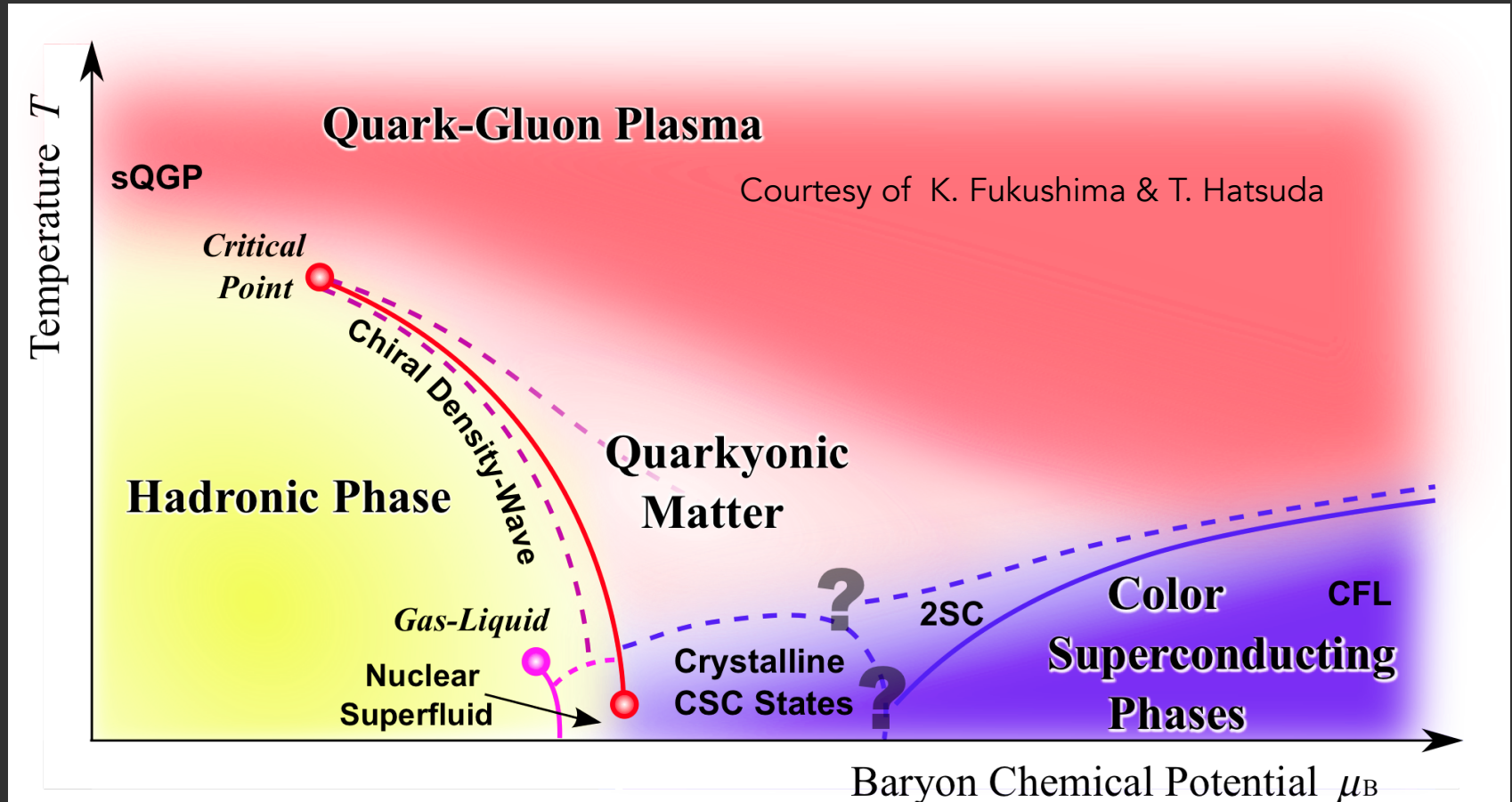
- Search for new phases of strongly interacting matter in the region of high net-baryon density

○ **Discovery potential**

- Emphasis on
 - ✗ Multi-strange baryons
 - ✗ Dileptons
 - ✗ **Fluctuations**
 - ✗ Charm
- ... systematics!

$\langle \bar{q}q \rangle$ from PQM: B.J. Schaefer, J. Wambach, priv. comm.

The (conjectured) phases of QCD

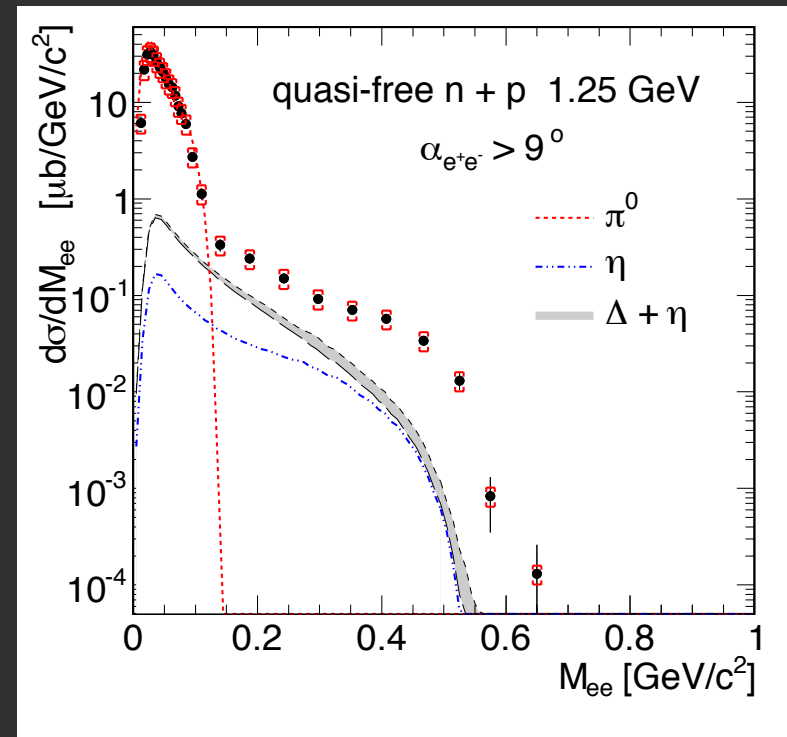
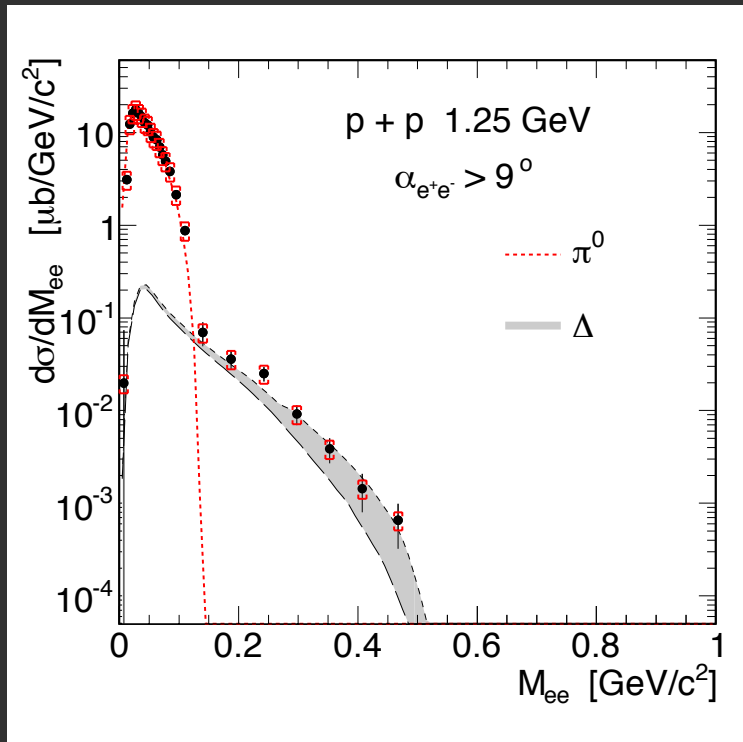


Dilepton results from HADES - elementary reactions

e^+e^- pairs from pp and np reactions (HADES)

Data from HADES pp and dp (tagged n) at 1.25 AGeV

- Remarkable isospin effect
- Beam energy dependence observed

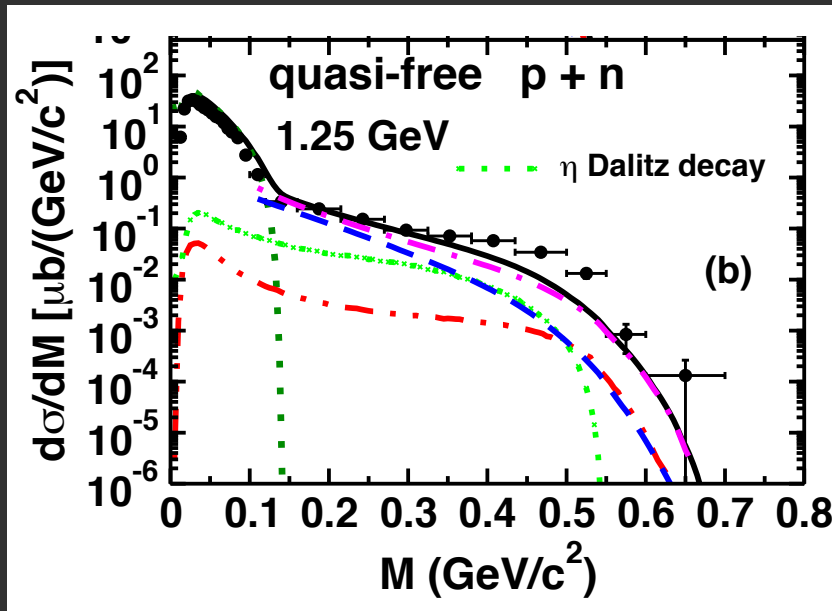
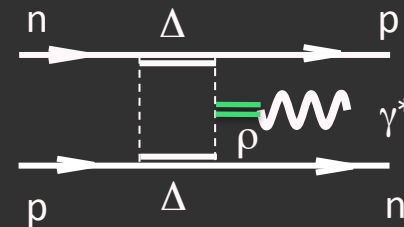
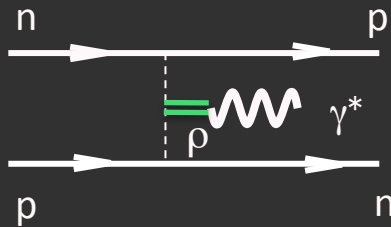


HADES collaboration (PLB 690, 2010)

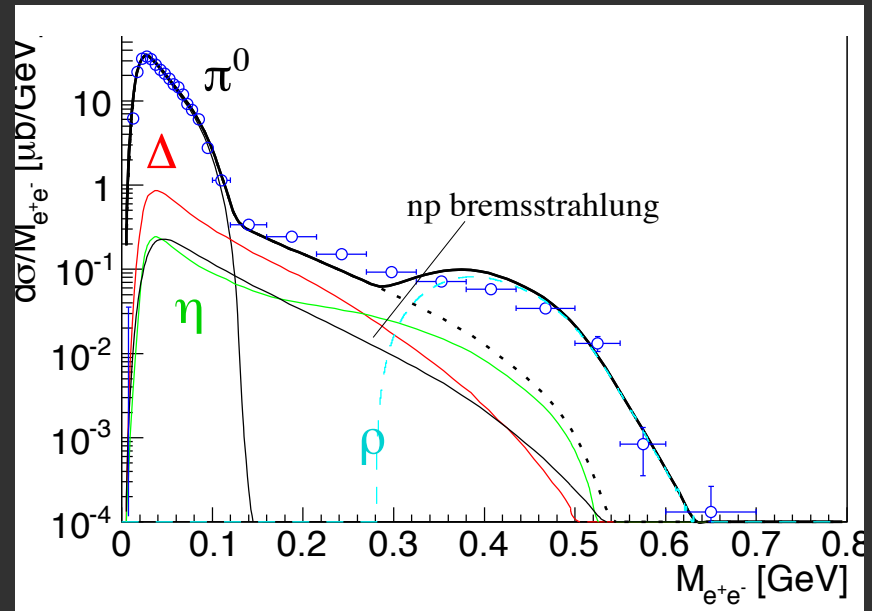
theoretical interpretation of the "Isospin Effect"

Radiation from the internal line yields enhanced emission at high invariant mass.

→ can also be understood as **off-shell** (cloud cloud) $\pi\pi$ **collision**!!



R. Shyam, U. Mosel [arXiv:1003.3343]



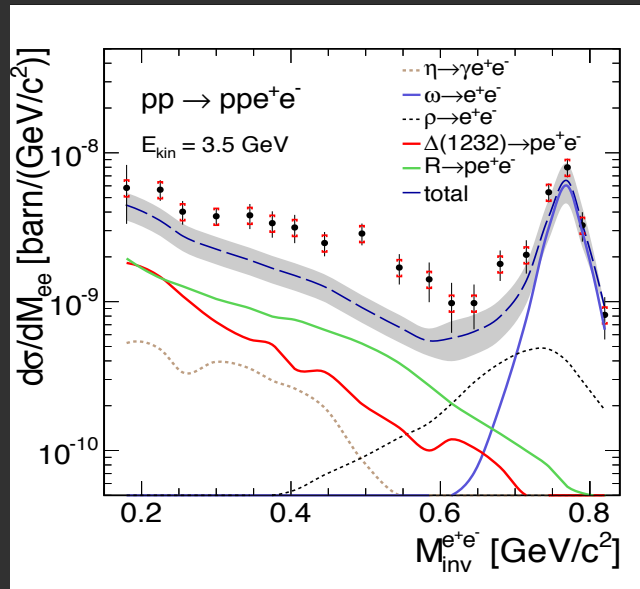
M. Baskkanov, H. Clement [arXiv:1312.2810]

Dilepton results from HADES - cold matter

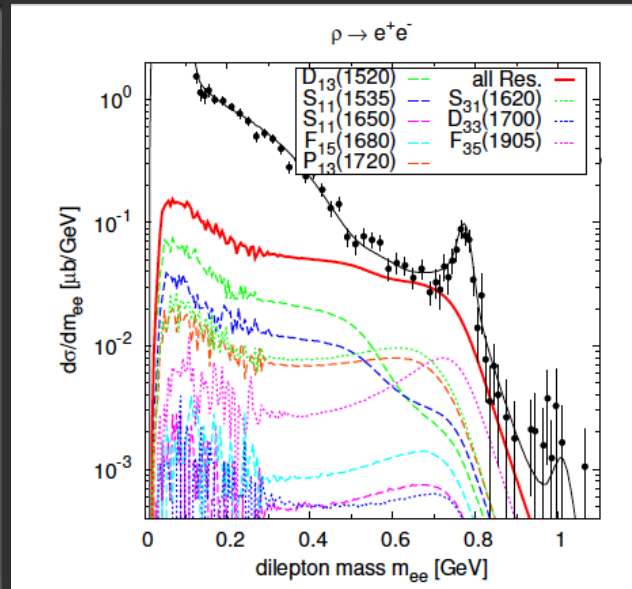
dileptons from p+p and p+Nb @ 3.5 GeV collisions

Radiation from Dalitz-decays of regenerated Deltas

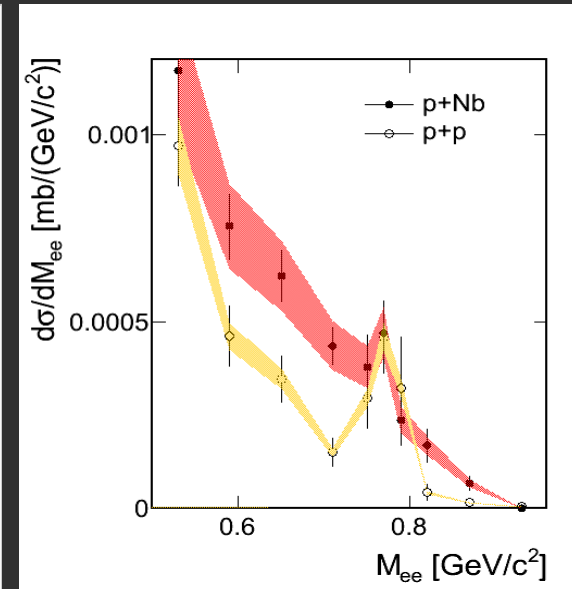
p + p



p + p (GiBUU)



p + p/Nb ($p_l < 800$ MeV)

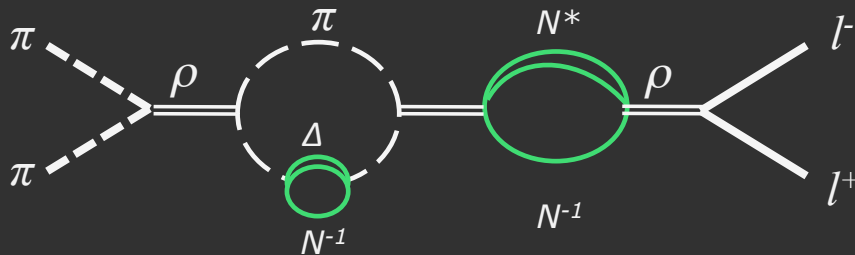


Decay of **off-shell ρ's** formed in **the meson cloud!**

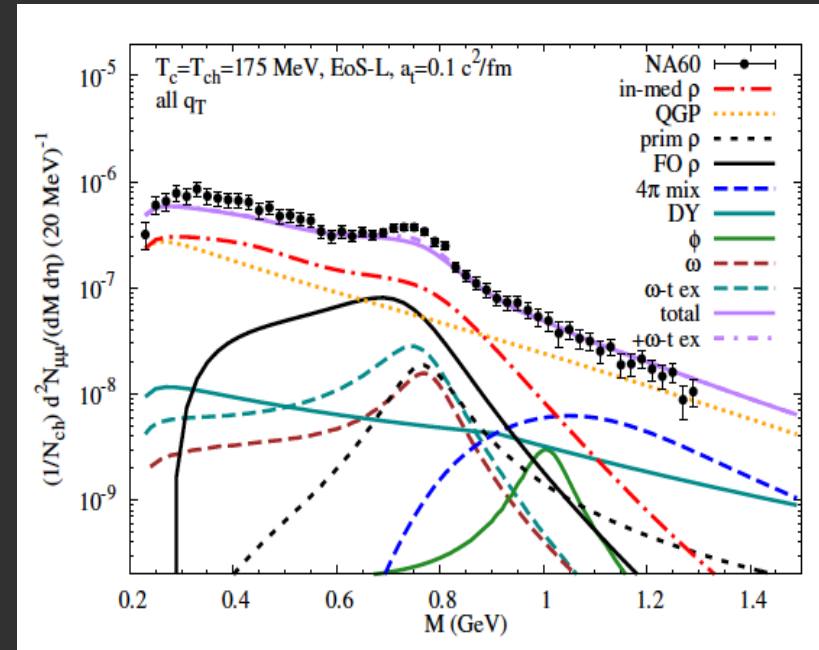
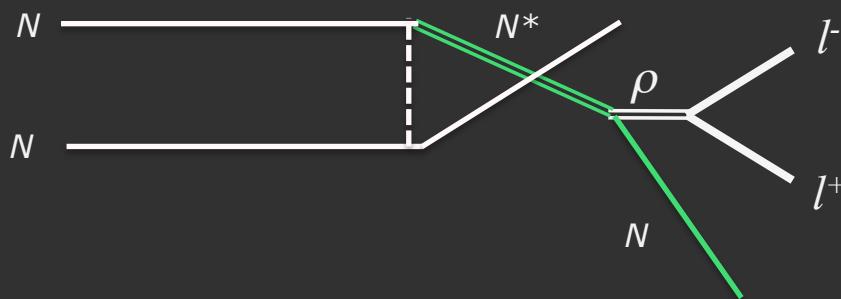
Medium radiation

the thermal dilepton signal

SPS, RHIC



SIS18, Bevalac



Data: NA60, Cocktail: R. Rapp et al.

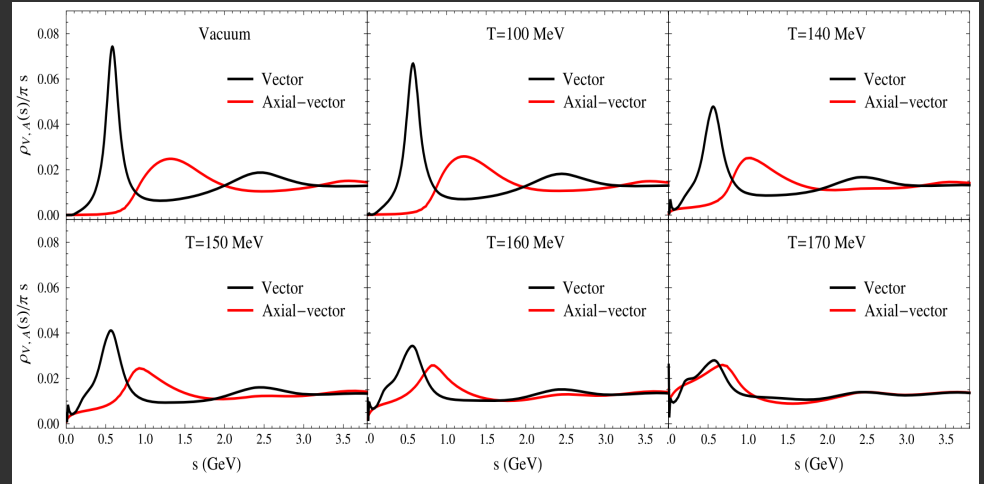
Thermal dilepton rate:

$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{EM}^2}{\pi^3} \frac{L(M)}{M^2} f^B(q_0; T) \text{Im} \Pi_{EM}^{\mu\nu}(M, q; \mu_B, T)$$

thermal rate and χ symmetry restoration

○ Weinberg sum rules (2nd)

$$\int_0^\infty ds \Delta\rho(s) = f_\pi^2 m_\pi^2 = -2m_q \langle \bar{q}q \rangle$$



○ Chiral condensate and HRG

$$\frac{\langle \bar{q}q \rangle_T}{\langle \bar{q}q \rangle_0} = 1 - \frac{\varrho_s^\pi}{2m_\pi f_\pi^2} - \frac{\varrho_s^K}{4m_K f_K^2} - \frac{\varrho_s^\eta}{6m_\eta f_\eta^2} - \frac{\varrho_s^{\eta'}}{3m_{\eta'} f_{\eta'}^2} - \sum_B \frac{\sigma_B}{f_\pi^2 m_\pi^2} \varrho_s^B - \sum_M \frac{\sigma_M}{f_\pi^2 m_\pi^2} \varrho_s^M - \alpha T^{10}.$$

$$\sigma_h = \sigma_q^{\text{bare}} + \sigma_\pi^{\text{cloud}}$$

Paul Hohler and Ralf Rapp, arXiv:1311.2921

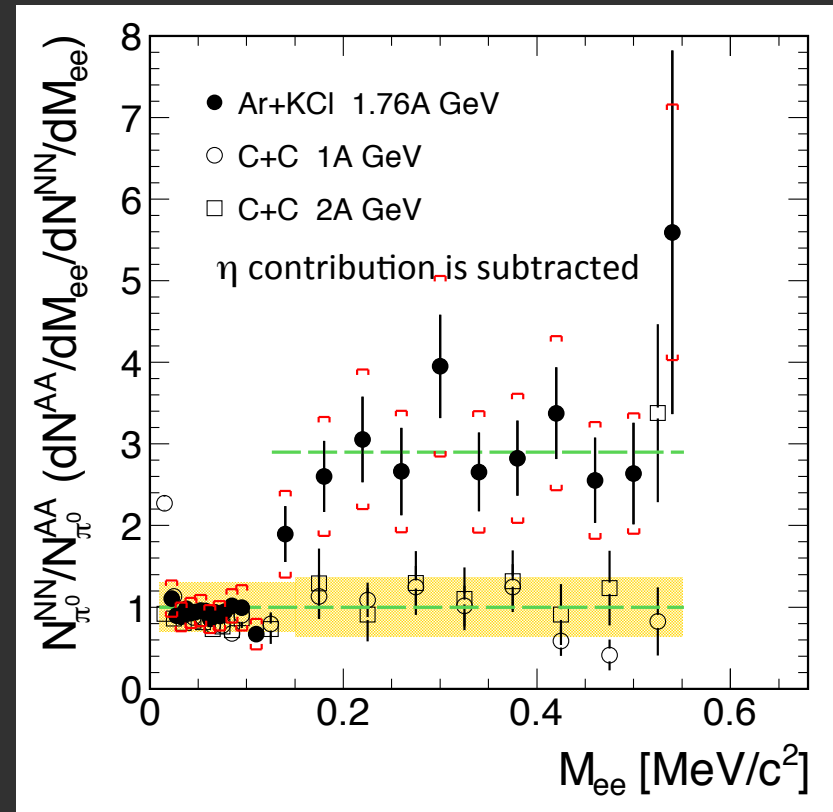
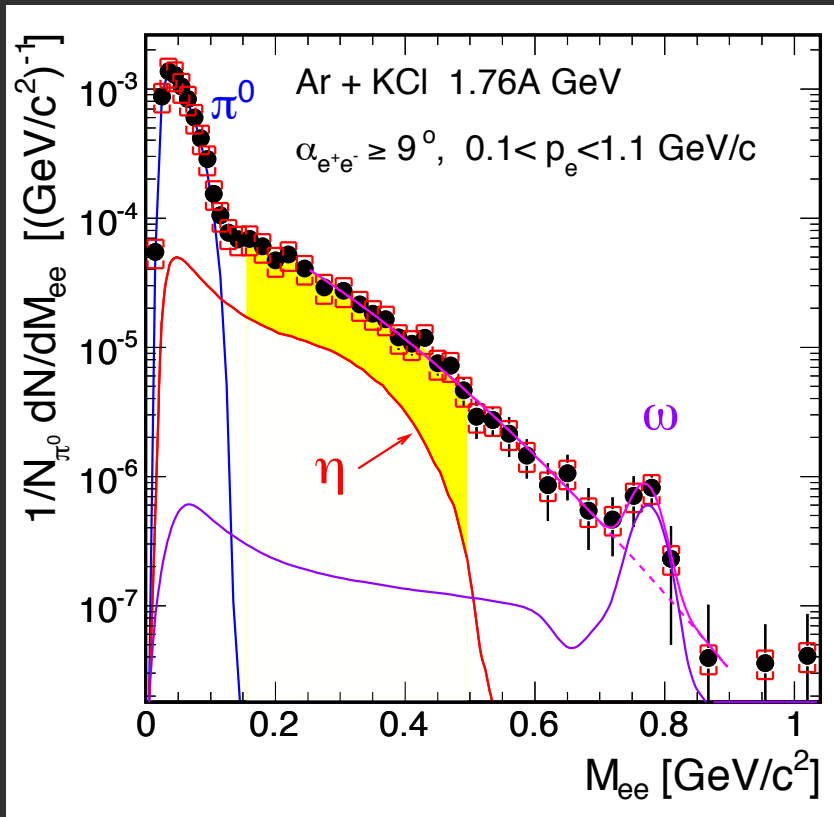
Dilepton results from HADES - Medium radiation

e^+e^- pairs from Ar+KCl at 1.76 GeV/u

First observation of ω mesons in HI collisions at these low energies.

„True“ excess (\sim factor 3)

➤ The **HADES „Delta“ clock**



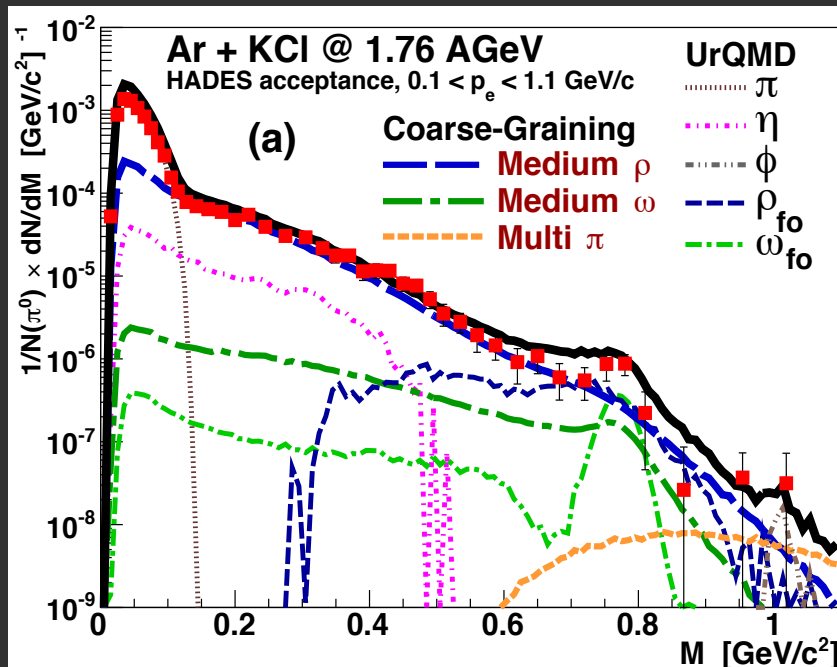
HADES collaboration, Nucl.Phys.A830:483C-486C,2009

low-mass dilepton excess

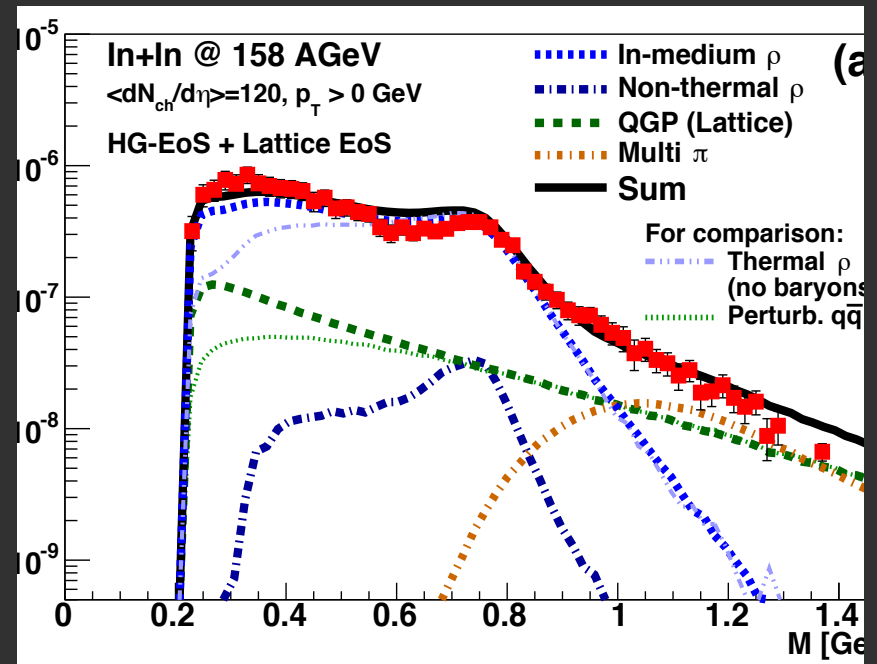
Understood as thermal radiation off the evolving fireball

- Seems to describe data measured for 1.7 AGeV up to the highest energies (RHIC)
- But there are open questions:
 - ? Is the emissivity description complete → Constrain theory by πN reactions
 - ? How to properly describe the expansion → Compare hadronic collective observables

HADES data



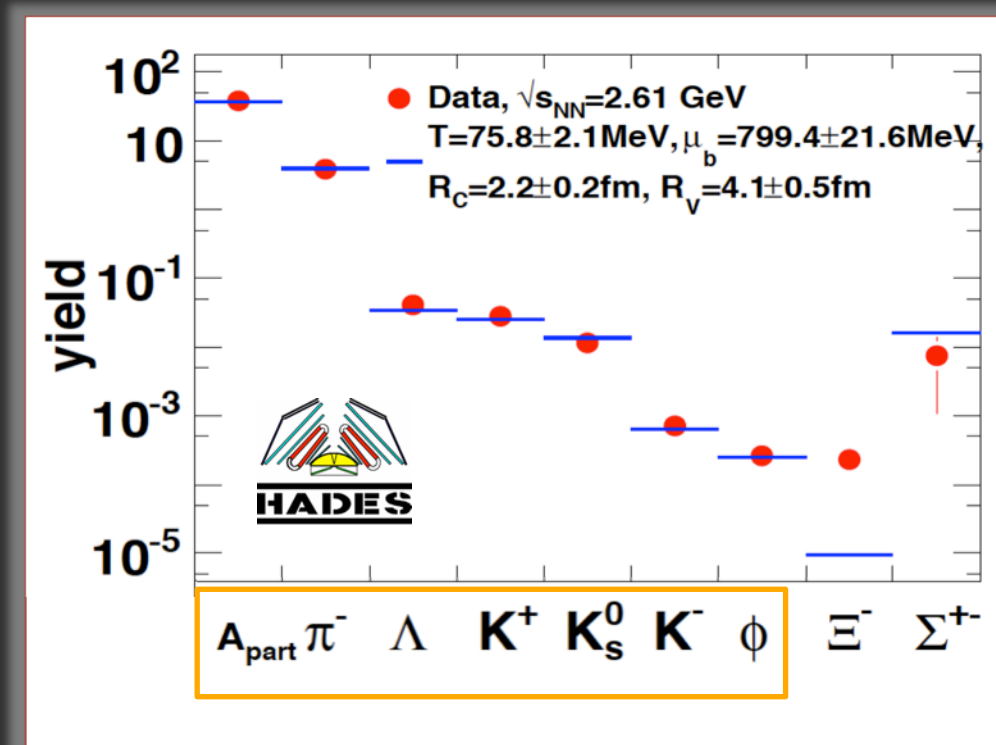
NA60 data



S. Endres_et al. UrQMD [arXiv:1505.06131]

S. Endres et al. UrQMD [arXiv:1412.1965]

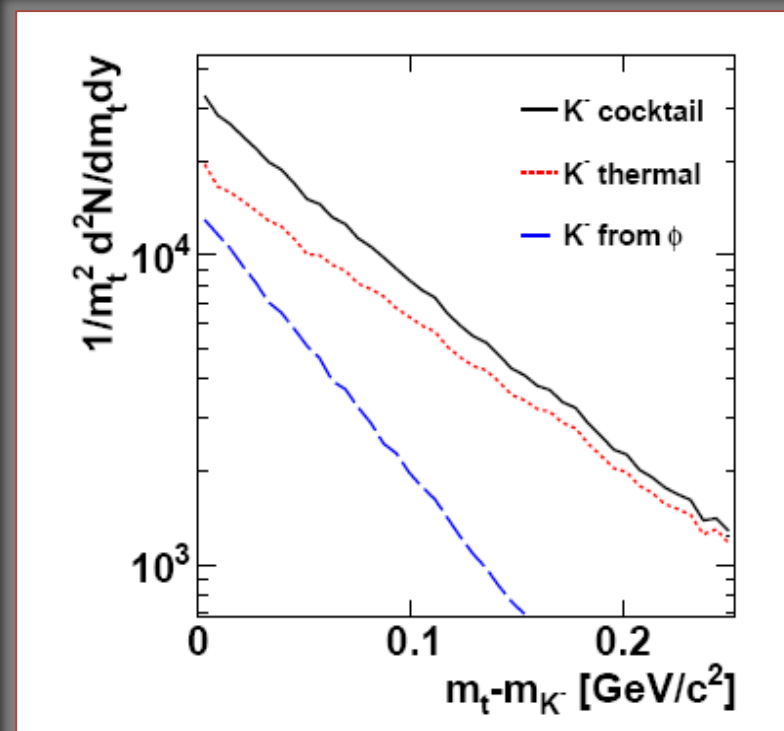
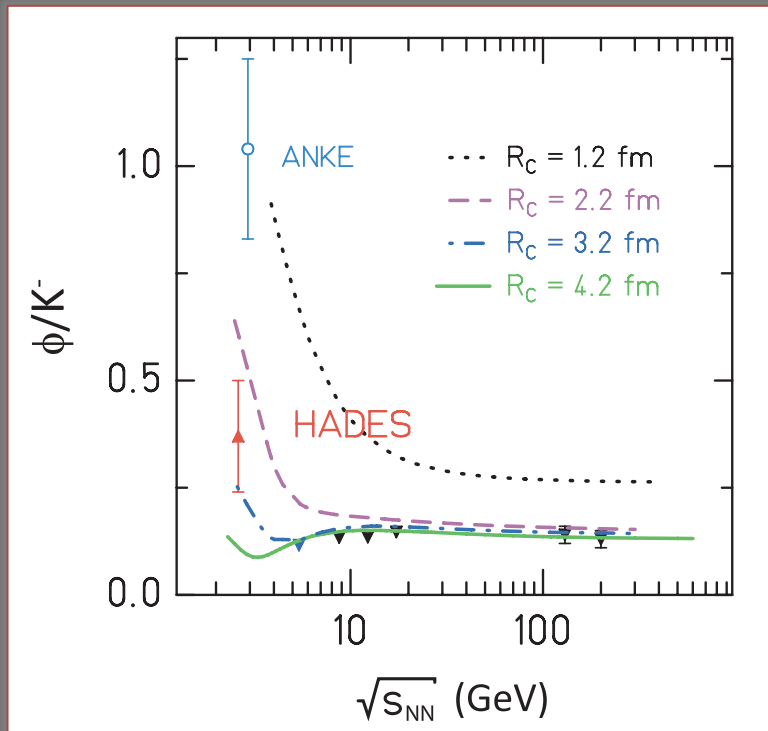
Hadron production in Ar+KCl collisions



ϕ production as source of K^-

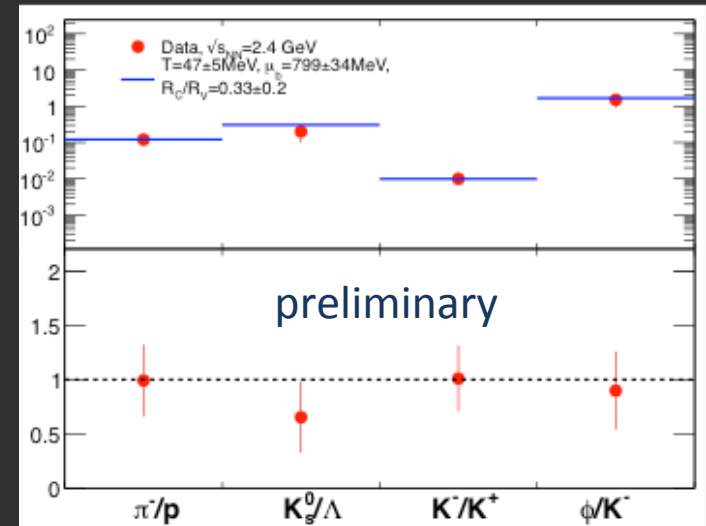
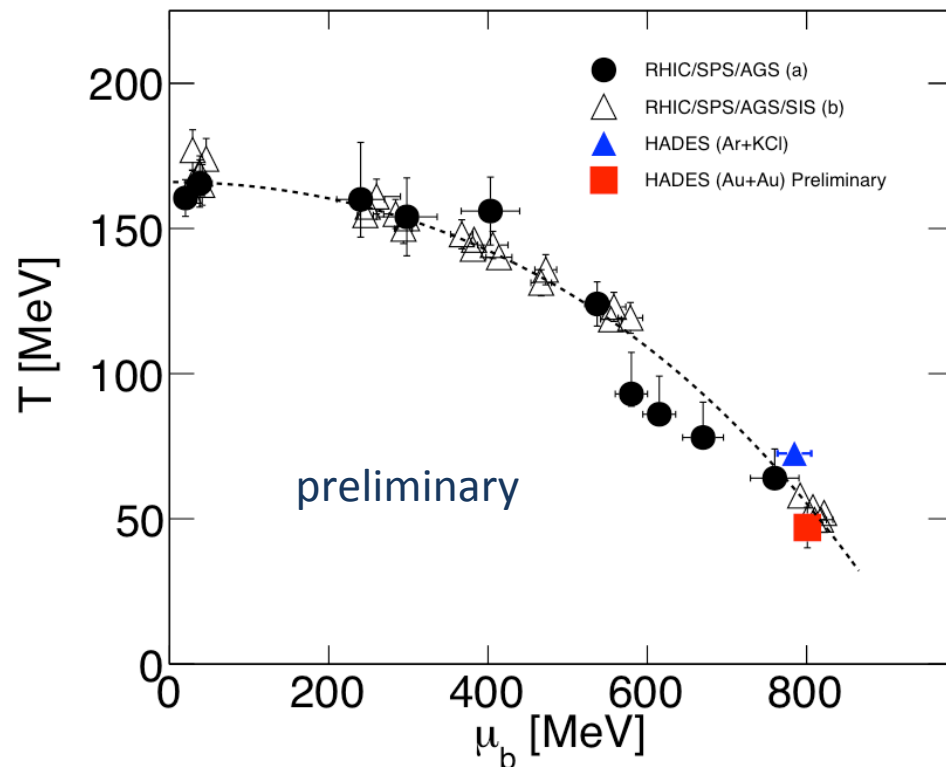
ϕ production in Ar+KCl @ 1.76 AGeV

- Multiplicity consistent with thermal production
- No OZI suppression
- K^- transverse mass slope identical to K^+ after correcting feed down



hadron yields from Au+Au @ 1.23 AGeV

Statistical "hadronization" also working at high μ_B and low temperature.



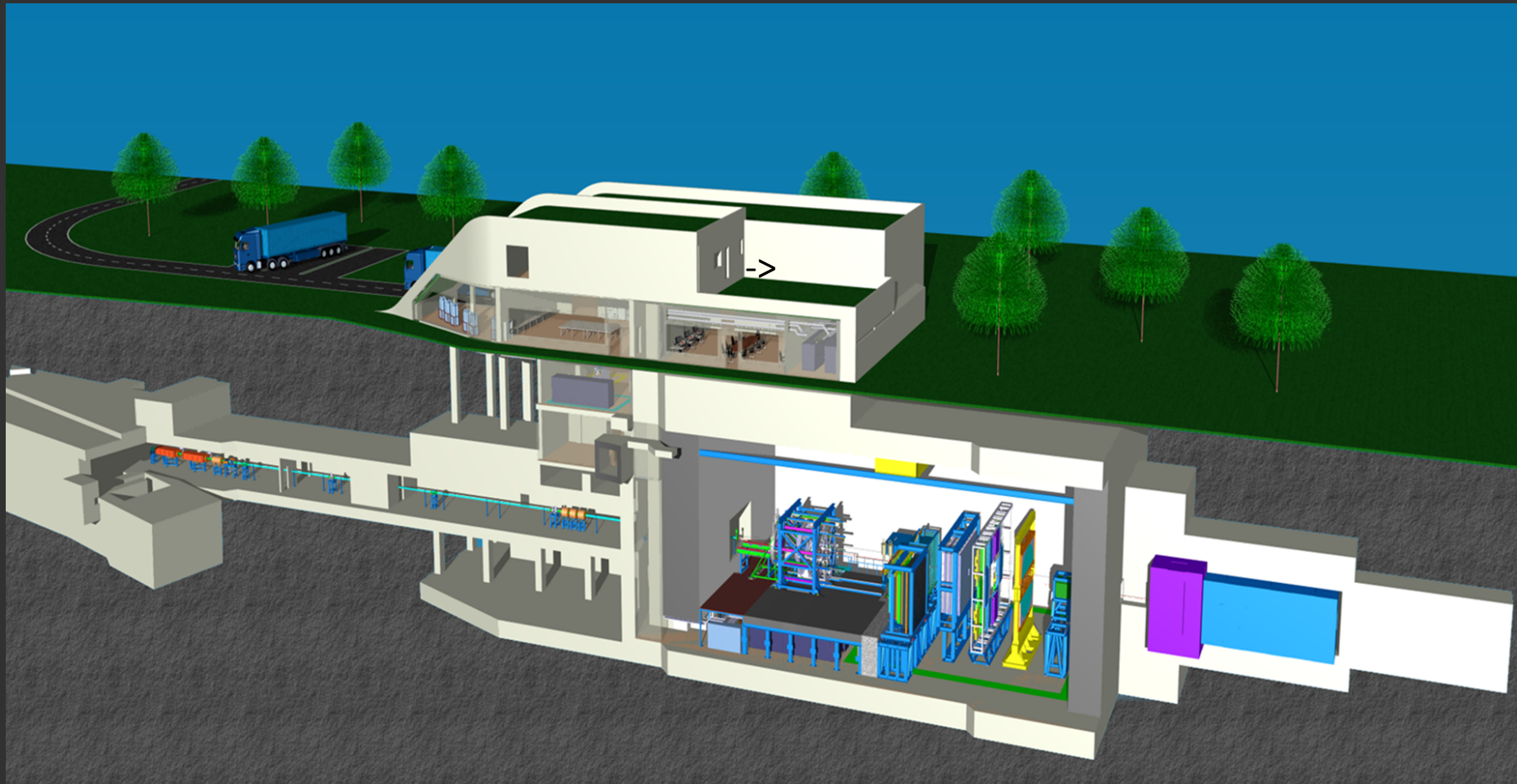
-- THERMUS fit: J.Cleymans, J.Phys.G31(2005)S1069

• HADES Au+Au data at 1.25 AGeV PRELIMINARY,
Ar+KCl: Phys.Rev.C80:025209,2009

The future: C.B.M. experimental hall

HADES and CBM at SIS100

Exceptional conditions to study QCD matter under extreme conditions



Summary and Outlook

- HADES has collected **high-quality data** on dilepton emission from A+A and elementary collisions, including exclusive channels.
- **No evidence for mass shifts** of ρ/ω
- Contributions from the **dense/early phase** are quite **featureless** → strong broadening of in-medium states!(?)
- Interesting observations in strangeness production → full understanding of reaction mechanism missing.
- Missing at SIS18: more data on pion induced reactions and second HI run
- And even more exciting physics possible ;)