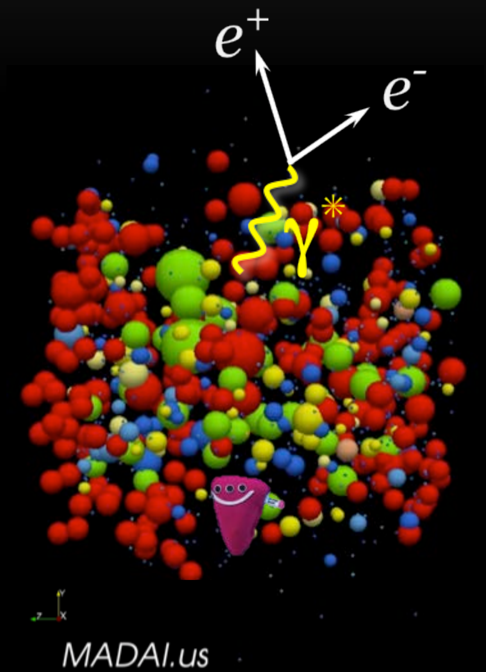
INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
38th Course
Nuclear matter under extreme conditions -
Relativistic heavy-ion collisions
Erice-Sicily: September 16-24, 2016



Exploring baryon rich matter with virtual photons

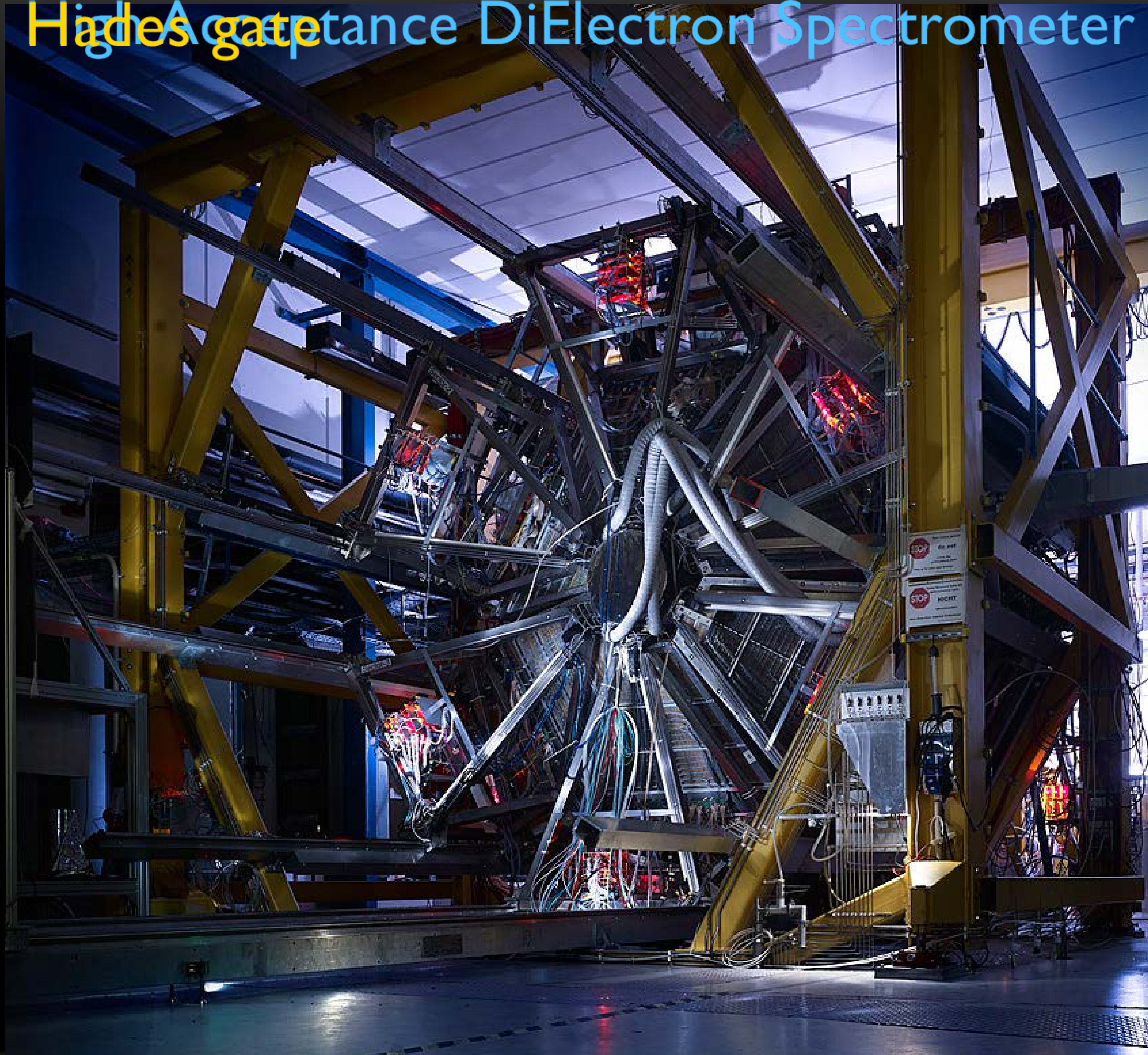
- The electromagnetic response of resonance matter and
- Other strange observations

Tetyana Galatyuk for the HADES Collaboration

Technische Universität Darmstadt / GSI Helmholtzzentrum für Schwerionenforschung

High Acceptance DiElectron Spectrometer

Hades gate



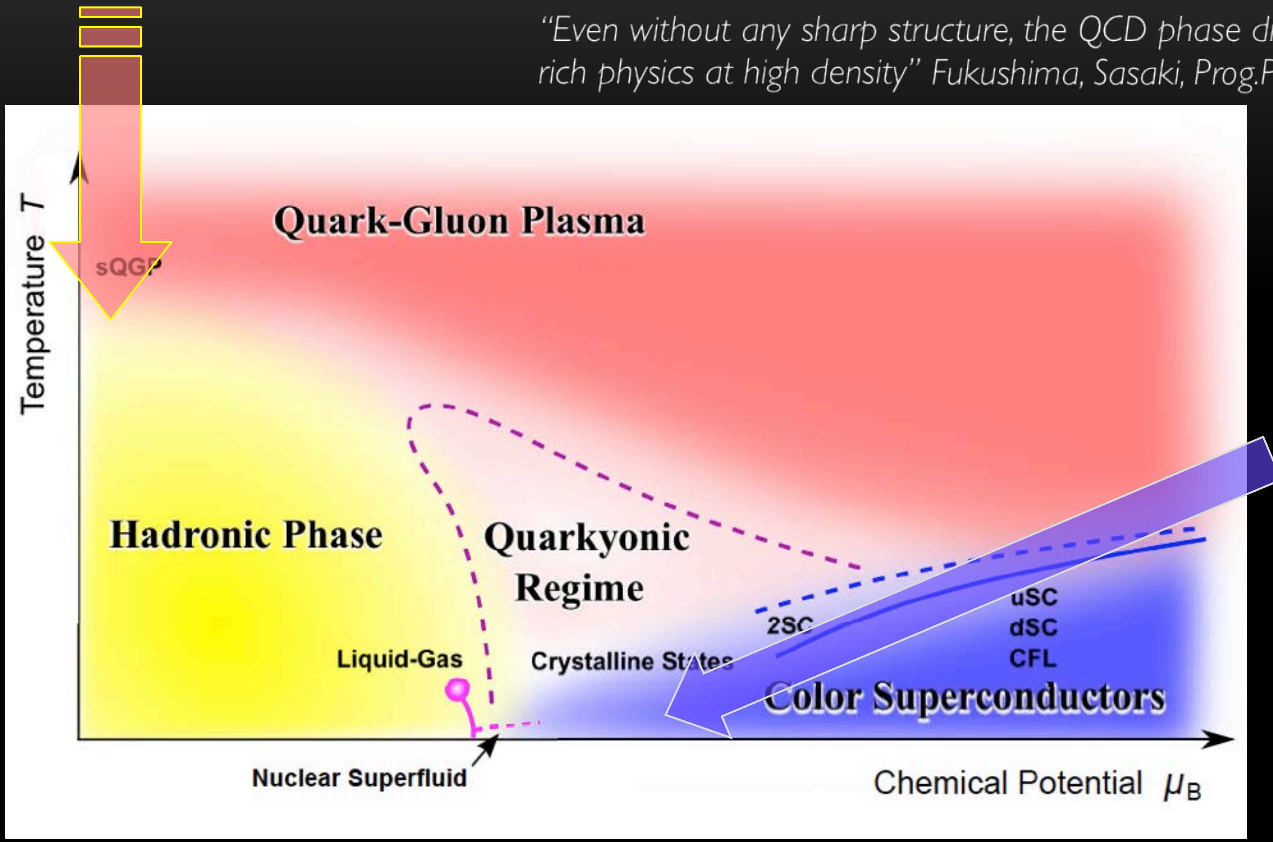
The HADES Collaboration

- Coimbra, Portugal
- Cracow, Poland
- GSI Damstadt, Germany
- TU Darmstadt, Germany
- Dresden, Germany
- Dubna, Russia
- Frankfurt, Germany
- Giessen, Germany
- Lisboa, Portugal
- München, Germany
- Moscow, Russia
- Nicosia, Cyprus
- Orsay, France
- Rez, Czech Rep.

14 institutions
~100 collaborators

Exploring the phase diagram of QCD matter

"Even without any sharp structure, the QCD phase diagram contains rich physics at high density" Fukushima, Sasaki, Prog.Part.Nucl.Phys. 72 (2013)

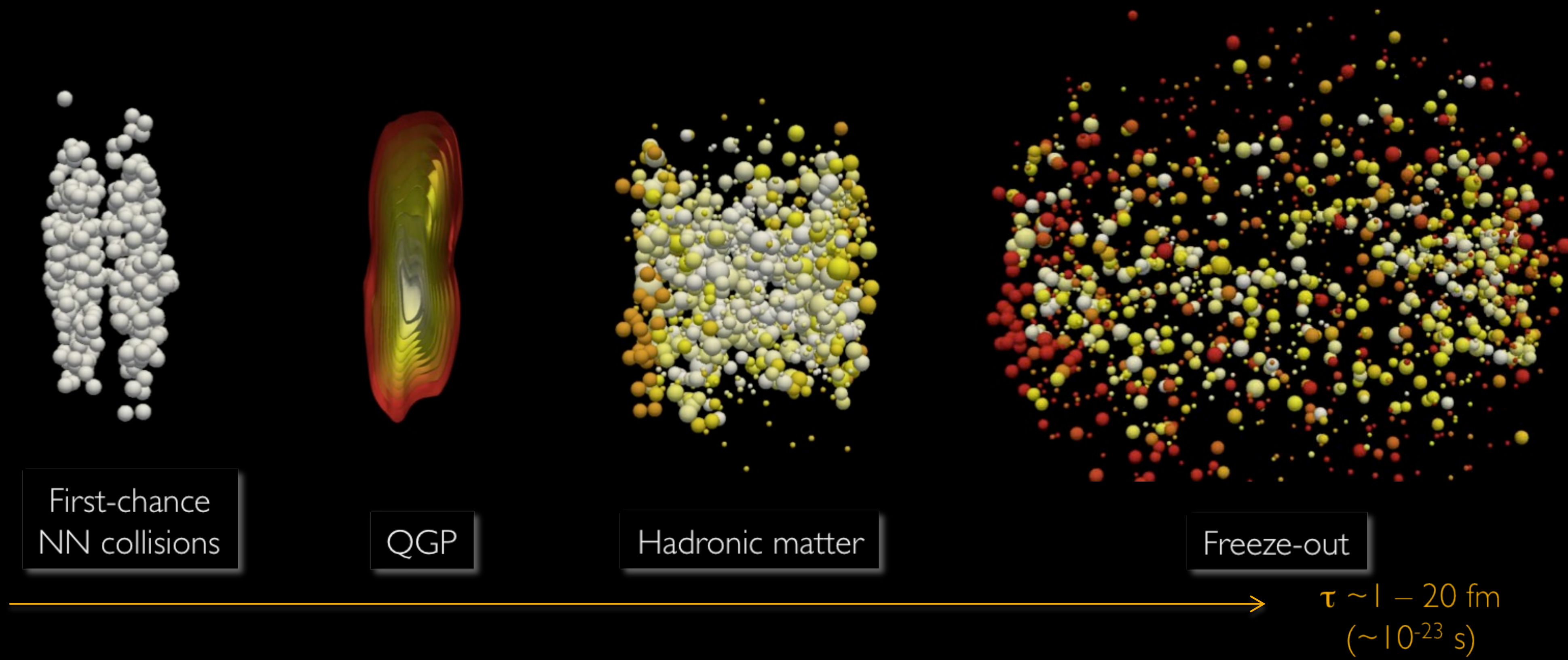


What are the fundamental properties of strongly interacting matter under extreme temperatures and densities?

- Macroscopic: equation of state, transport coefficients
- Microscopic: degrees of freedom (hadronic vs. partonic), spectral functions
- Phase structure and role of condensates

Experimental approach:
high energy heavy-ion collisions

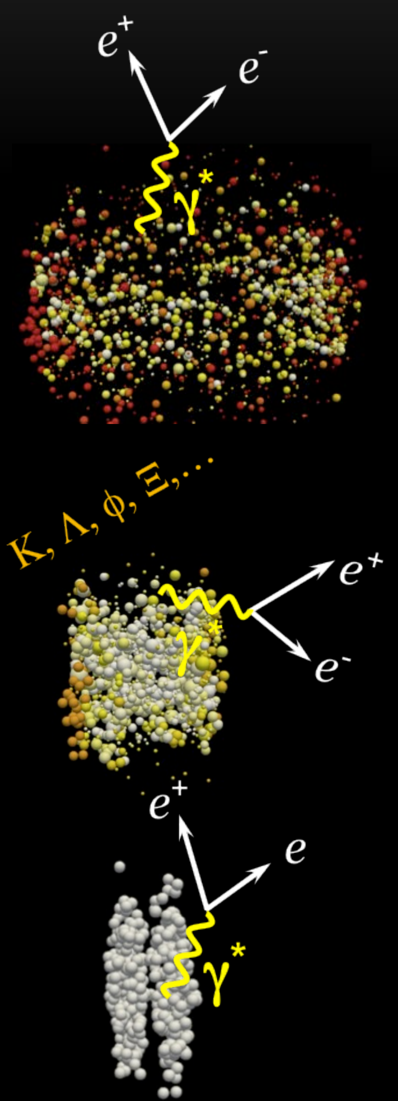
MADAI.us



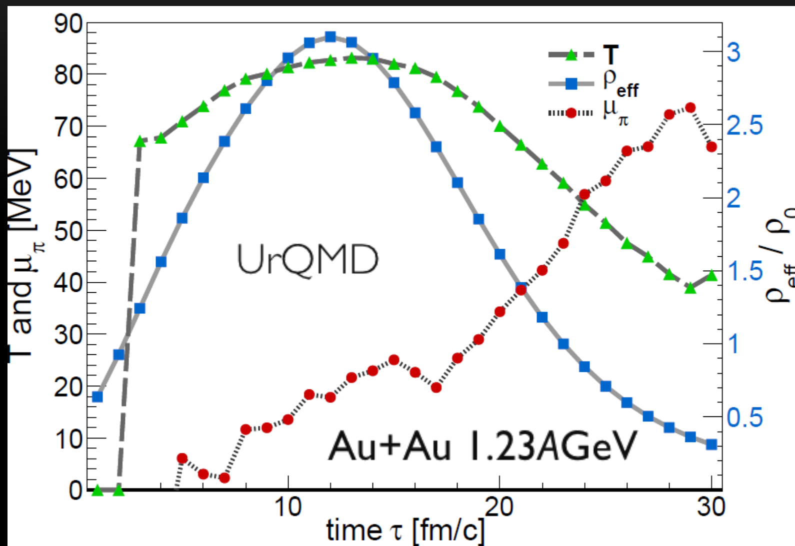
Systematic experimental measurements (E_{beam}, A)

→ extract numbers that might be related to the QCD phase diagram

Baryonic matter at 1-2*A* GeV beam energy

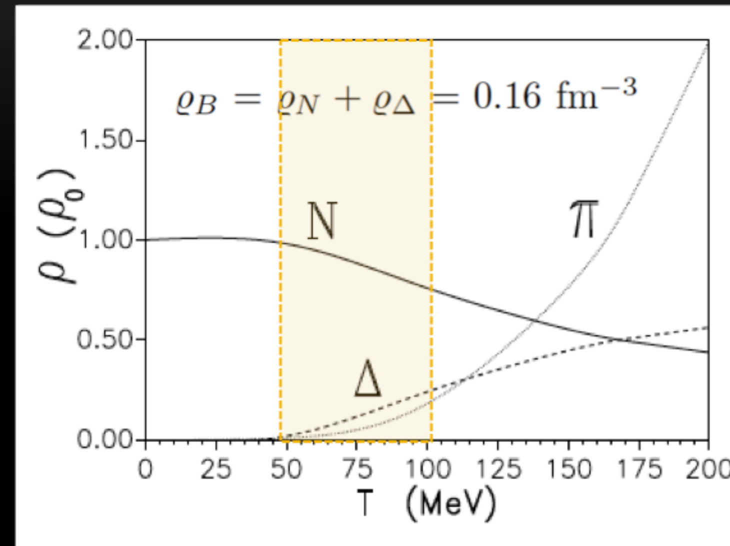


Evolution of average T and ρ_{eff}



TG, et al., Eur. Phys. J. A 52 (2016) 131
Basset al., Prog. Part. Nucl. Phys. 41 (1998)

Composition of a hot $\pi\Delta N$ gas

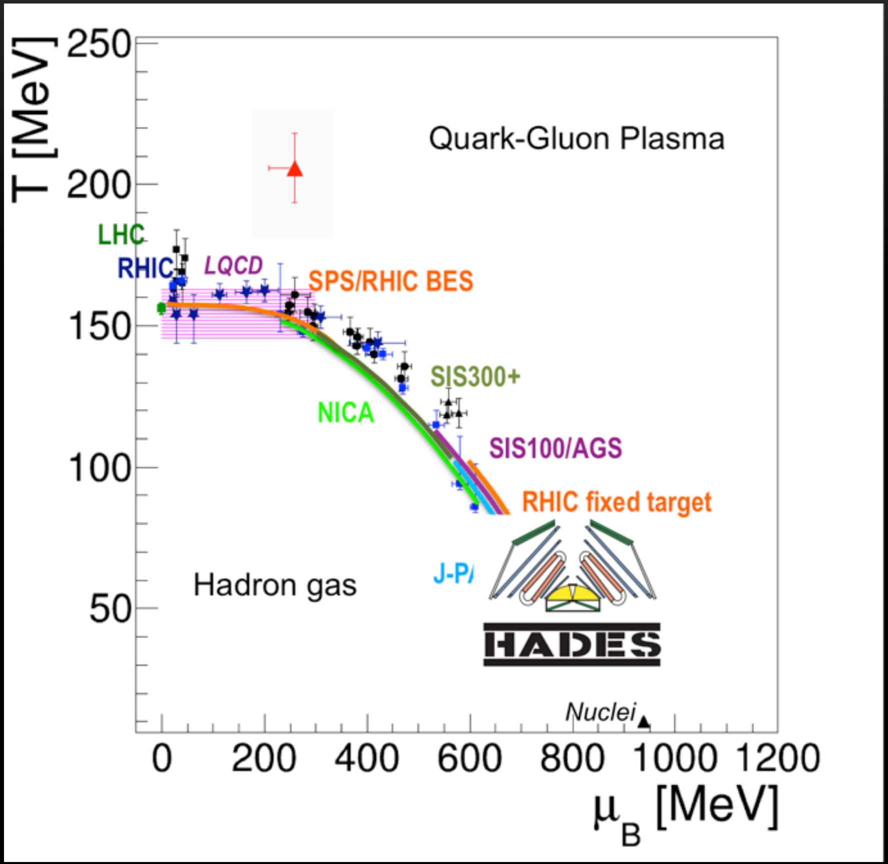


Rapp, Wambach, Adv.Nucl.Phys. 25 (2000)

- High densities: ρ_{max} = 1-3 ρ_0
- Moderate temperatures: T = 50 – 100 MeV
- System stays above ground state matter density for $\Delta\tau$~15fm/c
- Baryon dominated: N_π/A_{part} ≈ 10%

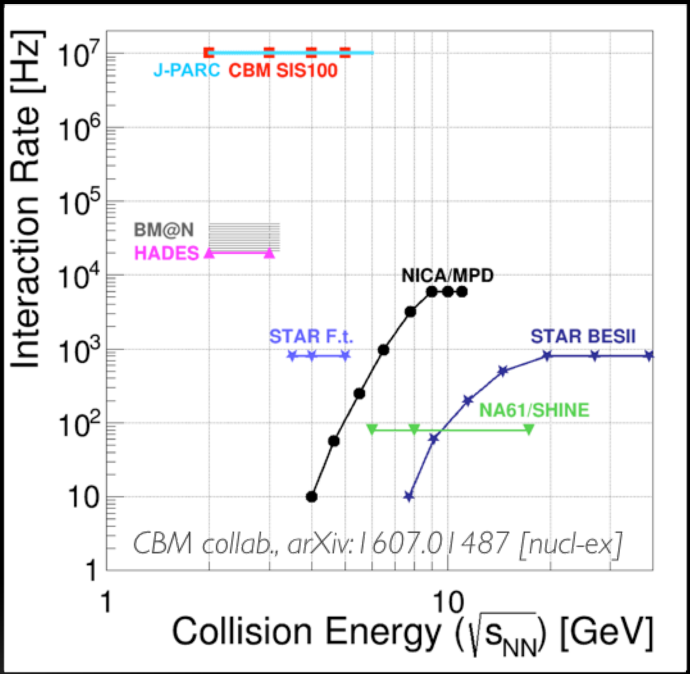
Rare and penetrating probes

Searching for landmarks of the QCD phase diagram of matter



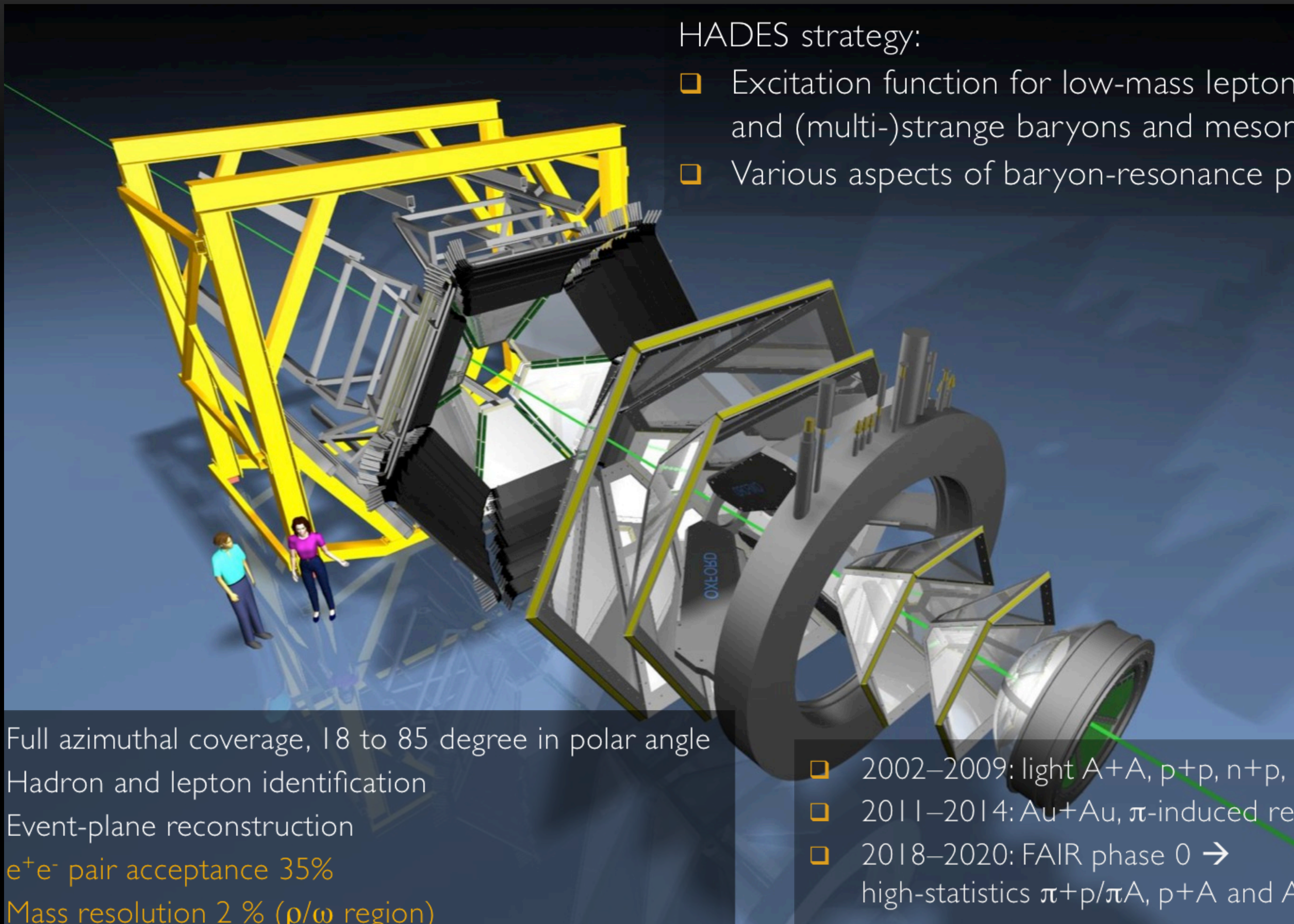
Observables:

- Flavor production (multi-strange, *charm*)
- Emissivity of matter (dileptons)
- High order correlation functions (B, S, Q)



- HADES currently explores the high-μ_B region
- Very competitive w.r.t. interaction rate capability
- HADES is part of the beam energy scan
  → marks lowest point of the excitation function

The HADES at GSI, Darmstadt, Germany



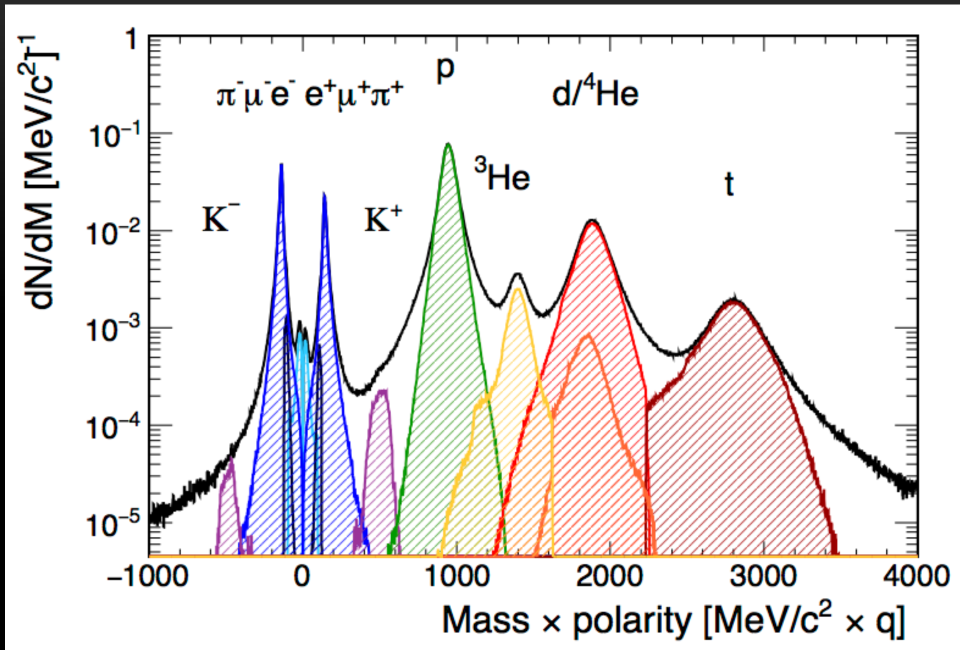
HADES strategy:

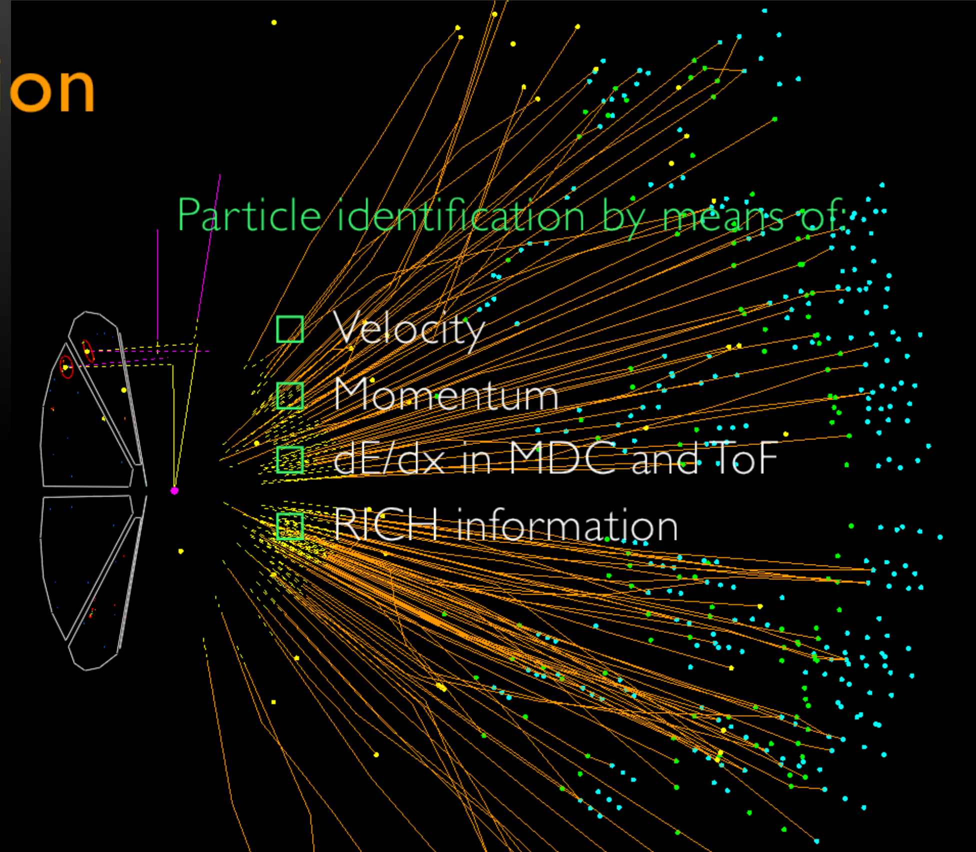
- Excitation function for low-mass lepton pairs and (multi-)strange baryons and mesons
- Various aspects of baryon-resonance physics

- Full azimuthal coverage, 18 to 85 degree in polar angle
- Hadron and lepton identification
- Event-plane reconstruction
- e^+e^- pair acceptance 35%
- Mass resolution 2 % (ρ/ω region)

- 2002–2009: light A+A, p+p, n+p, p+A
- 2011–2014: Au+Au, π-induced reactions
- 2018–2020: FAIR phase 0 → high-statistics π+p/πA, p+A and A+A

HADES event reconstruction

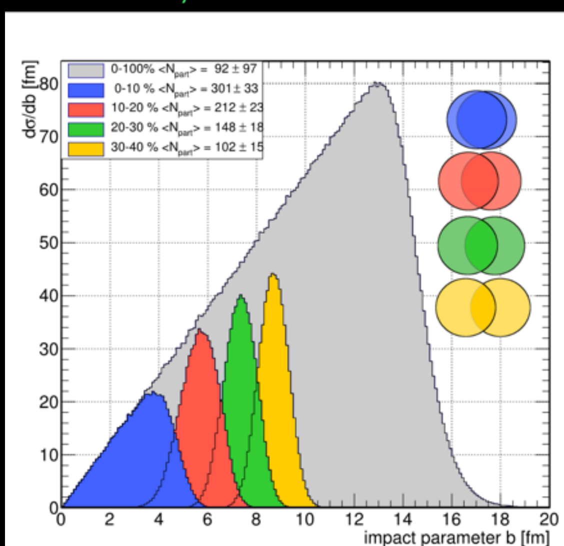




Particle identification by means of:

- Velocity
- Momentum
- dE/dx in MDC and ToF
- RICH information

Centrality: Glauber calculation



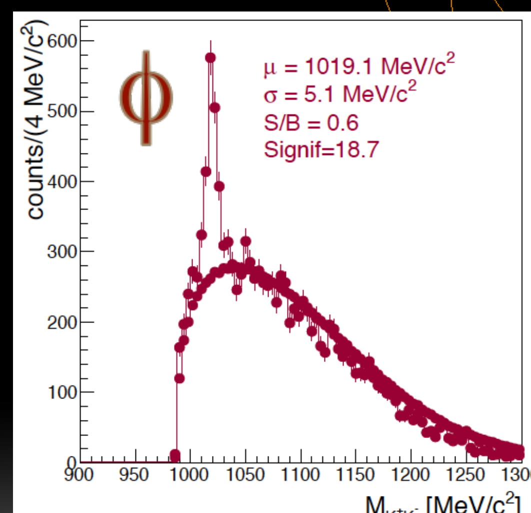
$\langle A_{part} \rangle$

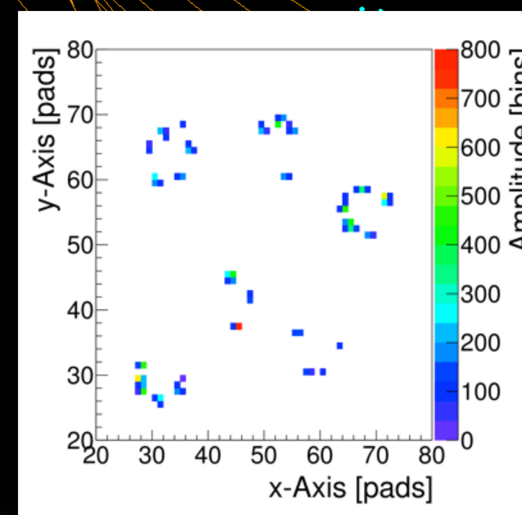
0-10% - 301

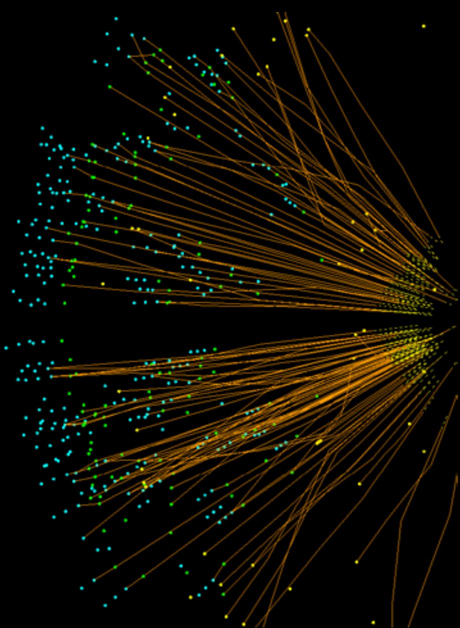
10-20% - 212

20-30% - 148

30-40% - 102

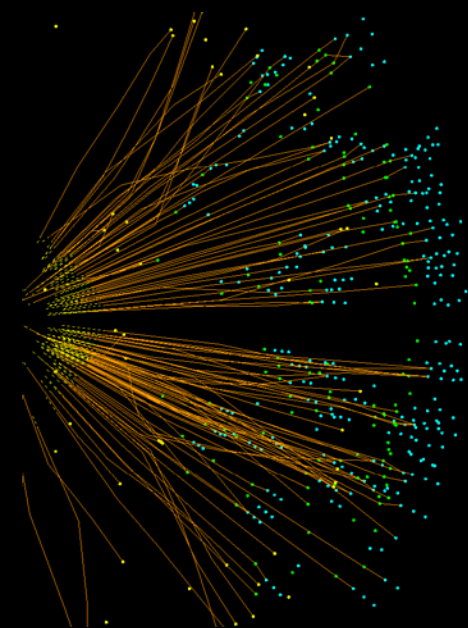






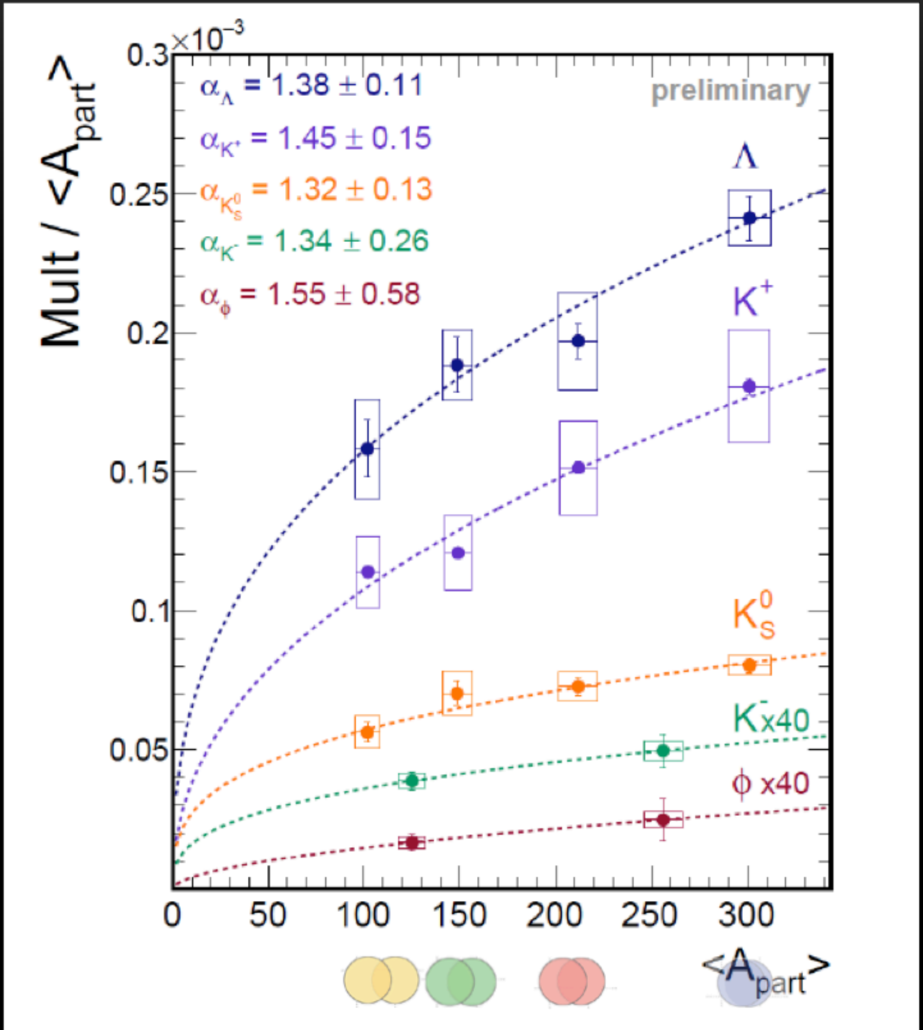
Final state

“Hadron-chemistry”



Strange particle production

Au+Au collisions at 1.23AGeV



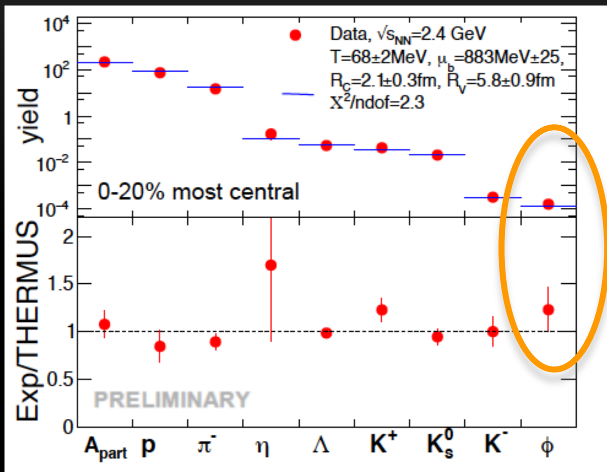
$NN \rightarrow N\Lambda K^+ E_{thr}$ = 1.58 GeV
$NN \rightarrow NNK^+K^- E_{thr}$ = 2.49 GeV
$NN \rightarrow NN\phi E_{thr}$ = 2.59 GeV

- First comprehensive set of results on strange particle productions from the Au+Au at this low energy
- Far below (free NN) threshold → strong constraints on production mechanism
- Particle yields rise with A_{part} faster than linear ($M \sim A^{\alpha}_{part}$, with $\alpha > 1$)

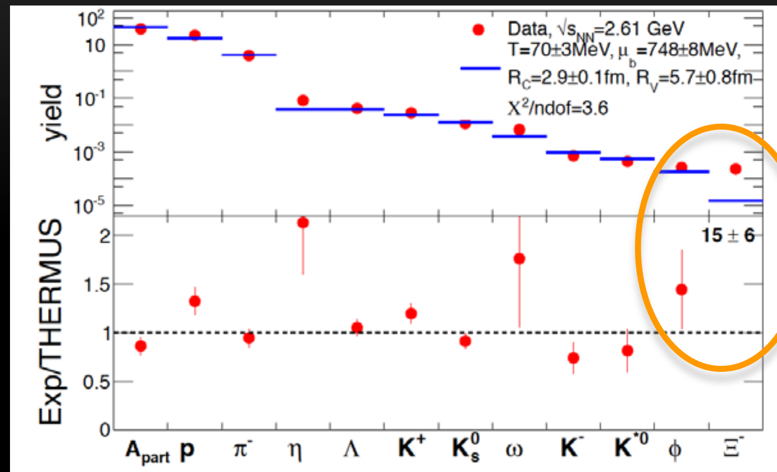
→ Large sensitivity to
  → Multi-particle interactions
  → Medium modifications

Comparing hadron yields with a statistical model

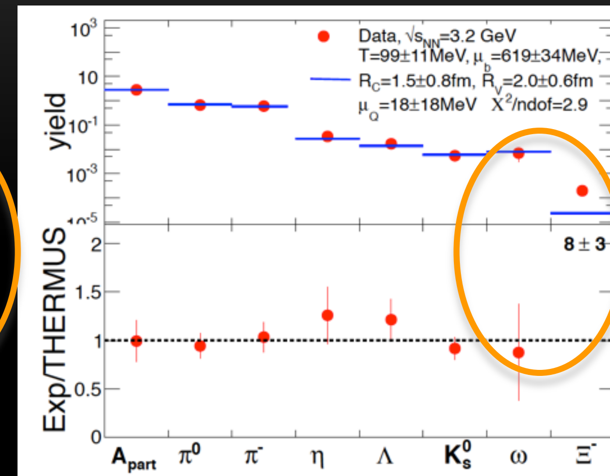
Au+Au at $\sqrt{s_{NN}}$= 2.42 GeV



Ar+KCl at $\sqrt{s_{NN}}$= 2.61 GeV



p+Nb at $\sqrt{s_{NN}}$= 3.2 GeV

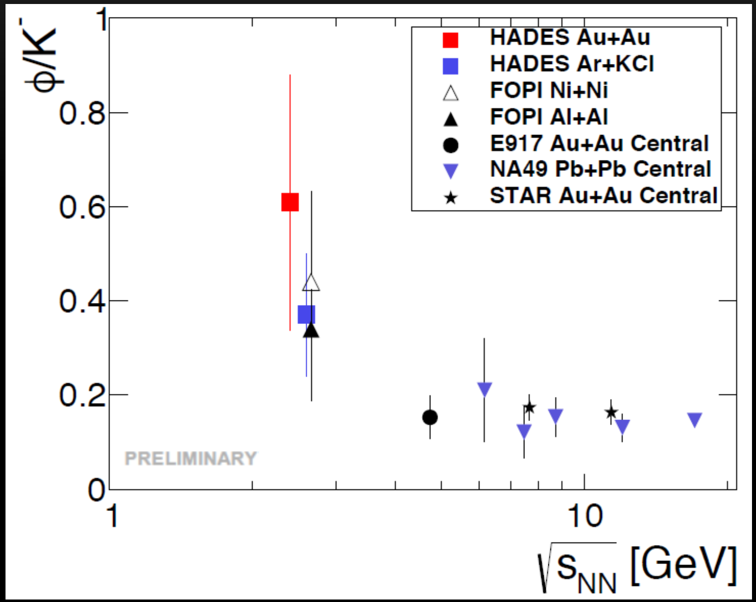


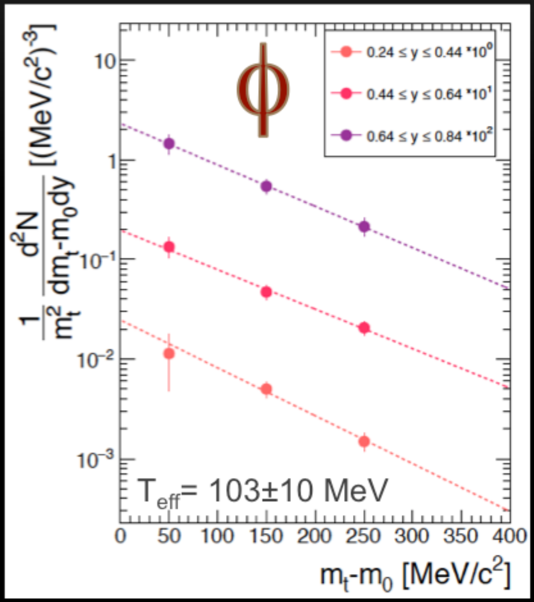
Thermus v2.3 S. Wheaton, J. ClеymansComput.Phys.Commun. (2009) 180
HADES collab. Eur.Phys.J.A52 (2016) no.6, 178

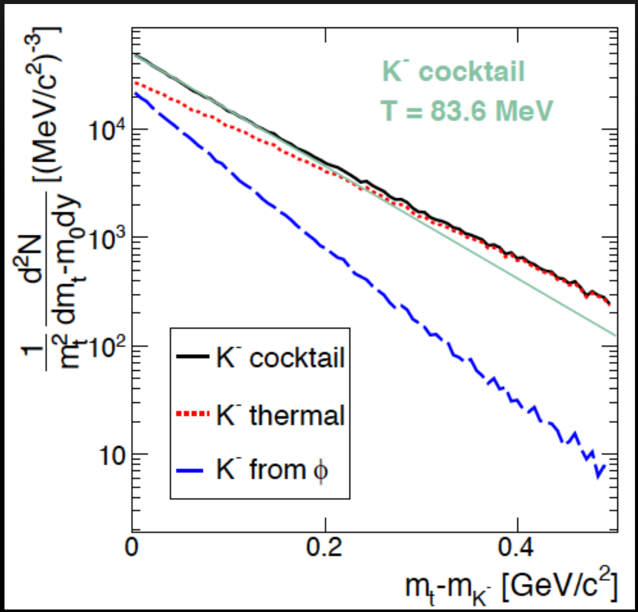
Thermal equilibrium also at low energies (high μ_B)?
What is the mechanism responsible for system thermalization?

- Grand canonical ensemble (T, μ_B, V and sometimes γ_s)
- Strangeness canonically suppressed at low temperatures → needs additional parameter: $R_c < R_V$
- Hadron abundances described by T, μ_B, R_V, R_c
- Surprises:
  - ϕ meson (hidden strangeness) not suppressed
  - Ξ^- ($s = -2$) yield "enhanced"

The role of ϕ meson: do K^+, K^- freeze-out sequentially?







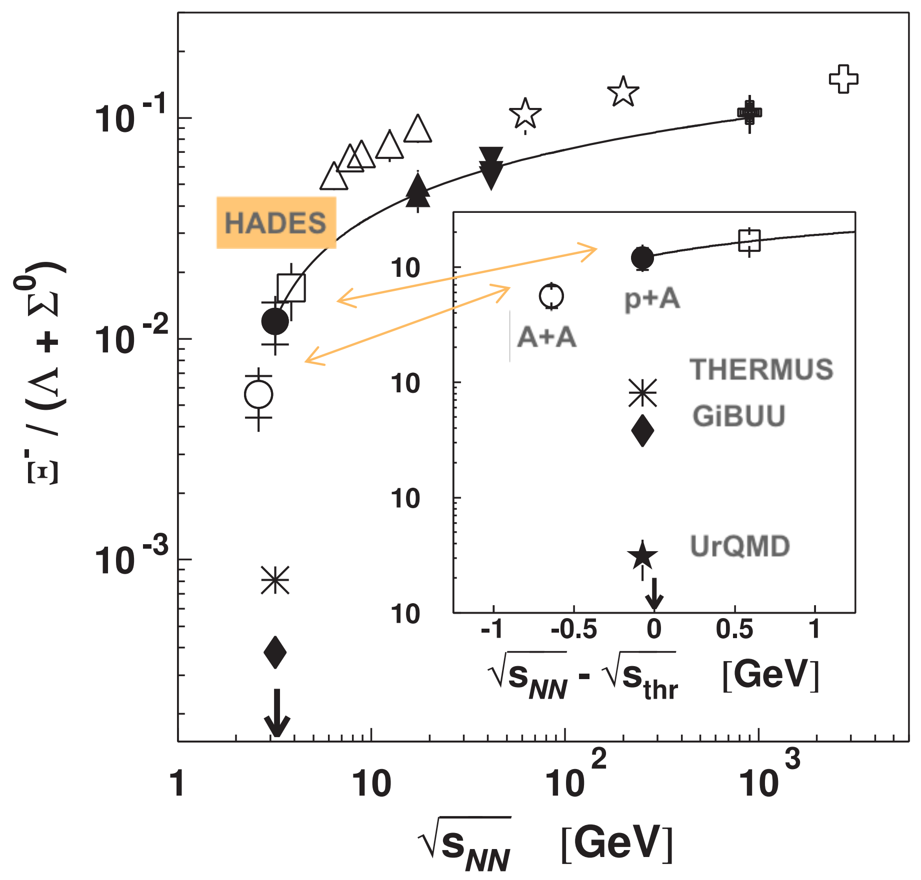
- Sizeable increase of ϕ meson to K^- ratio around production threshold 30% of K^- are from ϕ decays

- Sufficient statistics to perform multi-differential analysis for K^+, K^- and ϕ
  - $T_{eff}(K^+) = 105 \pm 4$ MeV
  - $T_{eff}(K^-) = 82 \pm 9$ MeV

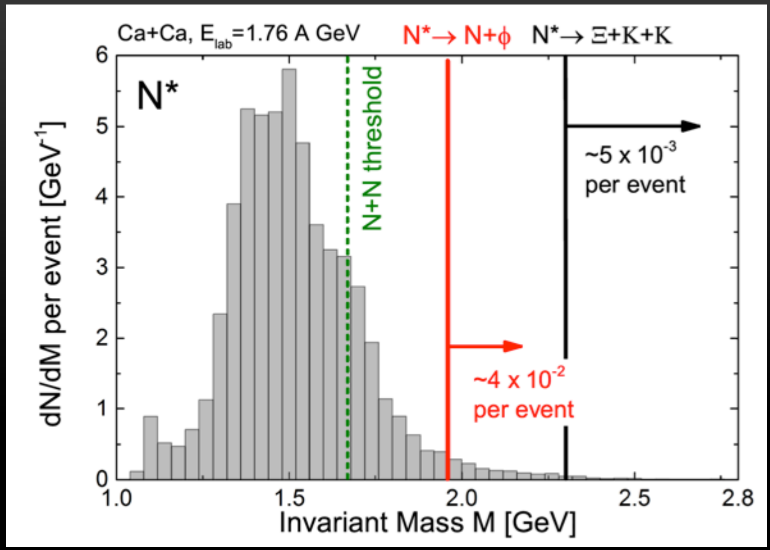
- Unique freeze-out criteria when ϕ decay kinematics is taken into account → no evidence for sequential freeze-out of K^+, K^- → support for statistical model

See also
Ar+KCl in HADES: PRC 86 (2010)
Al+Al in FOPI: EPJA 52 (2016)

What is so strange about Ξ^-?



HADES collab. PRL 103 (2009) 132310
HADES collab. PRL 114 (2015) 212301



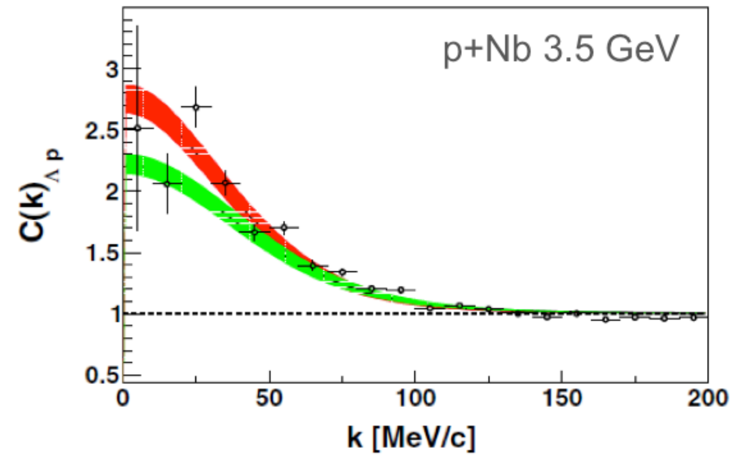
J. Steinheimer et al., J.Phys. G43 (2016) no.1, 015104

- Multi-strange baryons (Ξ, Ω) are expected to be a sensitive probe for compressed baryonic matter
- HADES observes unexpectedly large production cross sections inAr+KCl and p+Nb collisions
- UrQMD microscopic transport models → dominant role of high mass baryonic resonances?
  - N* → N+ϕ is fixed by ANKE data
    Y. Maeda et al. [ANKE collab.], PRC 77, 015204 (2008)
  - Spectroscopy of N* → Ξ+K+K is badly needed

Matter in Compact Stars

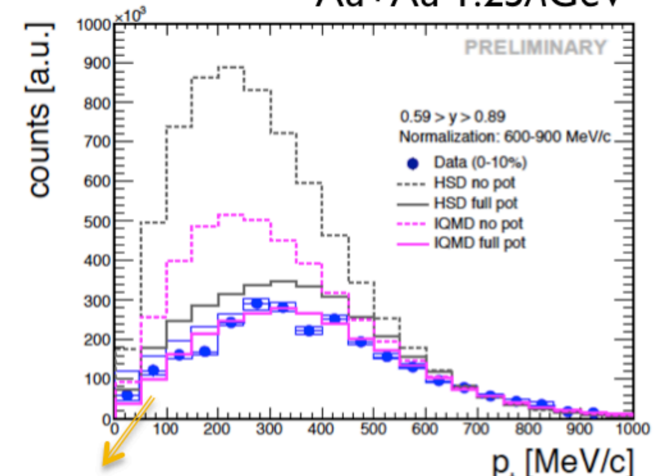
- Hyperons in neutron stars: new vistas?
  - Many models with hyperons fail to describe a $2M_{\odot}$ pulsar mass
  - Breakdown of baryonic models at high densities?
  - Onset of a new phase not based on baryon d.o.f.?
- QCD matter in compact stars
  - NASA news release 02-082: Cosmic X-rays reveal evidence for new form of matter" → a quark star?
  - Composition of high-density neutron star cores: unknown (green band)
  - Input needed from relativistic heavy-ion experiments
- HADES
  - ΛN, ΞN further studies in high statistic p+Ag in 2018
  - Data support in-medium repulsive vector K^0 potential ~40 MeV *[PRC 82 (2009) 044907; PRC 90 (2014) 054906]*

Λ-N correlation function

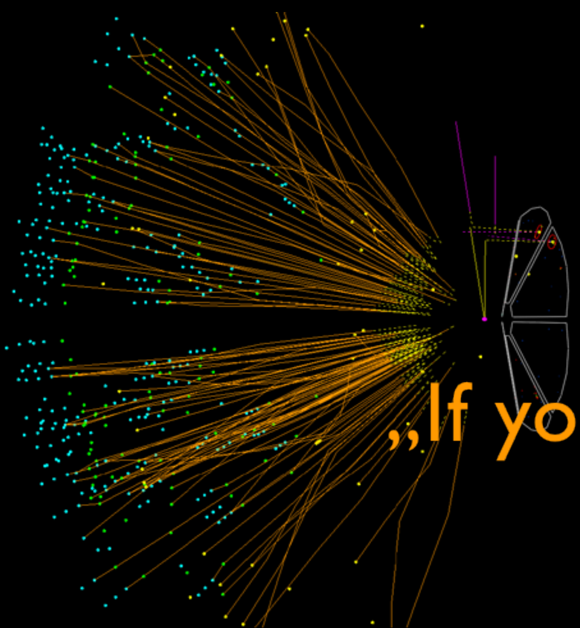


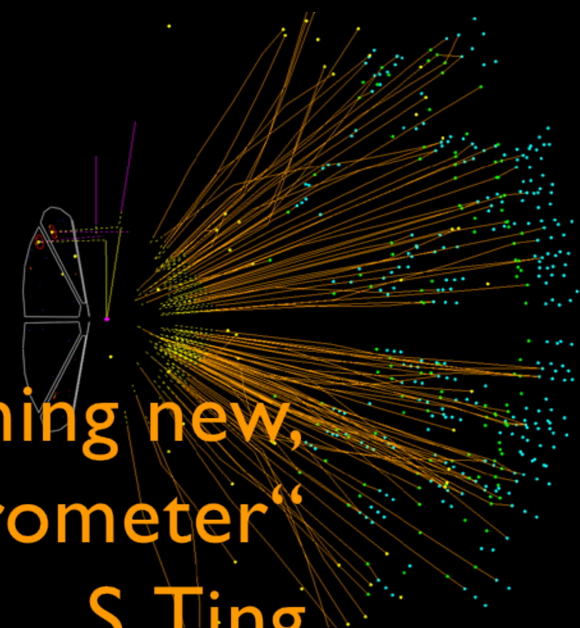
HADES collab., PRC 94 (2016) no.2, 025201

Au+Au 1.25AGeV



p_t coverage down to zero p_t



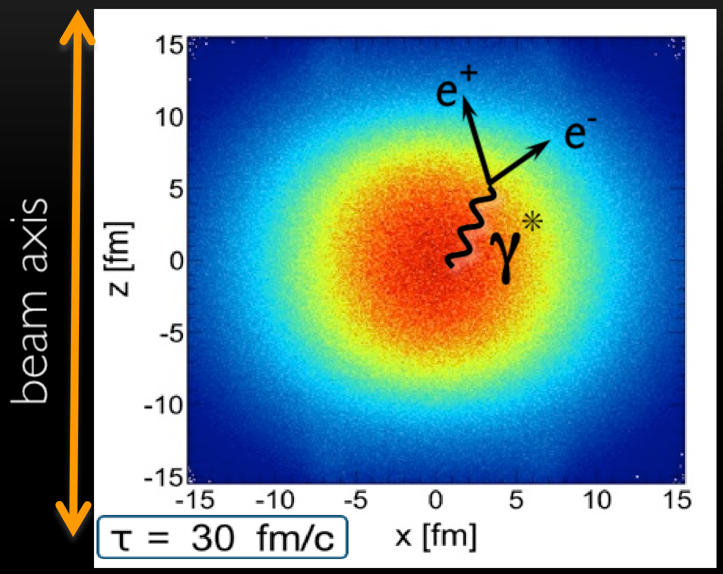


„If you want to detect something new,
build a dilepton spectrometer"

S. Ting

Electromagnetic radiation

Photons and lepton pairs probe the interior of fireballs – "PET" of the fireball



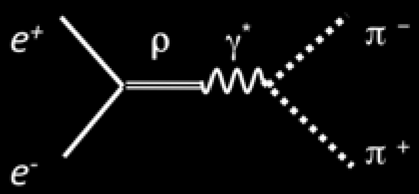
- The dilepton signal contains contributions from throughout the collision
- No strong final state interactions → leave reaction volume undisturbed
- Encodes information on collisions (T, μ_B, τ_{coll})

Unique direct access to in-medium spectral function

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

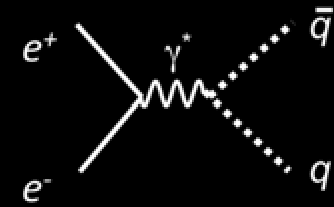
Photon self-energy

$$\mathrm{Im}\,\Pi_{EM} \sim \left[\mathrm{Im}\,D_\rho + \frac{1}{9}\mathrm{Im}\,D_\omega + \frac{2}{9}\mathrm{Im}\,D_\phi\right]$$



Low-mass region, $M_{ll} \leq 1.1$ GeV/c^2

Strong coupling of γ^* to ρ → VMD



Intermediate-mass region, $M_{ll} > 1.1$ GeV/c^2

$\bar{q}q$ continuum

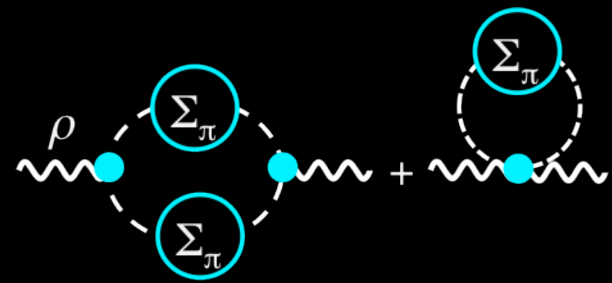
ρ meson in hot and dense medium…

… interacts with hadrons from heat bath → in-medium ρ-propagator

$$D_\rho(M,q;\mu_B,T) = \frac{1}{\left[M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}\right]}$$

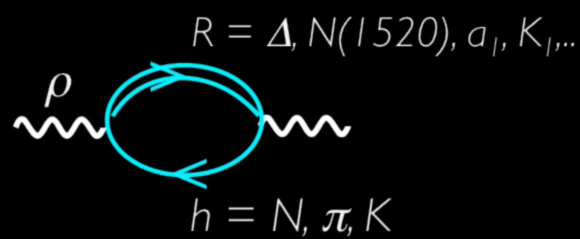
- **In-medium pion cloud**
  [Chanfray et al, Herrmann et al, Urban et al, Weise et al, Osetet al, …]

$\Sigma_{\rho\pi\pi} =$



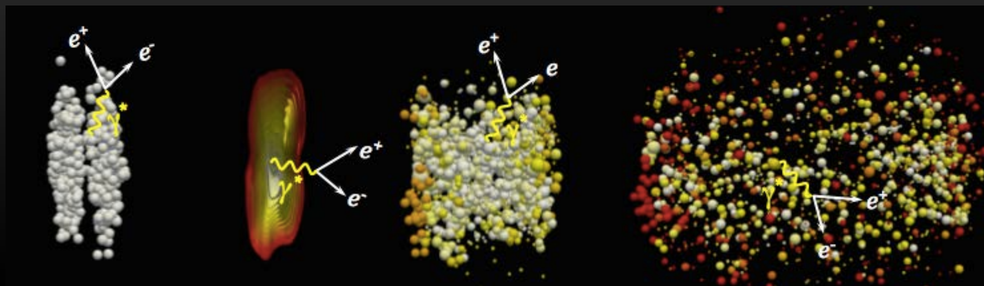
- **Direct ρ-hadron Scattering**
  [Haglin, Friman et al, Rapp et al, Post et al, …]

$\Sigma_{\rho B,M} =$

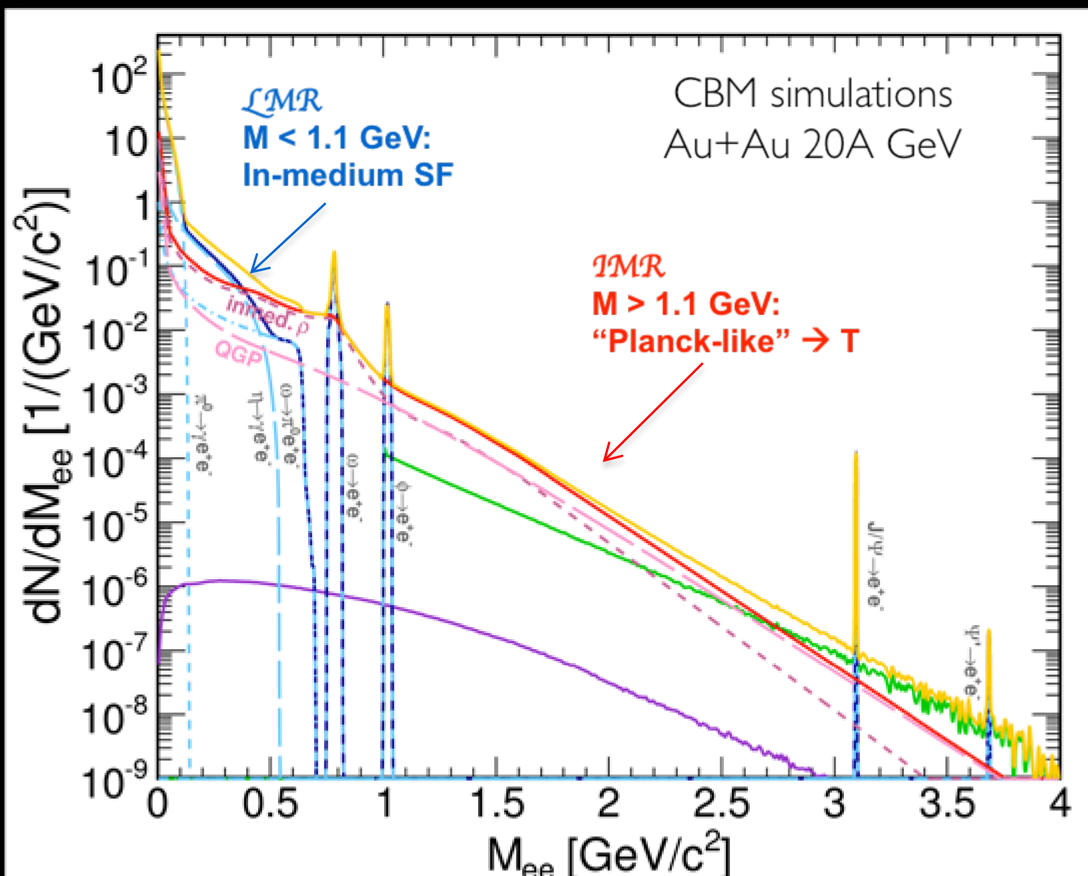


- **Theoretical control:**
  → symmetries (gauge, chiral)
  → empirical constraints: decays R → ρN, scattering data γN/γA, πN → ρN…

Characteristic features of dilepton invariant mass

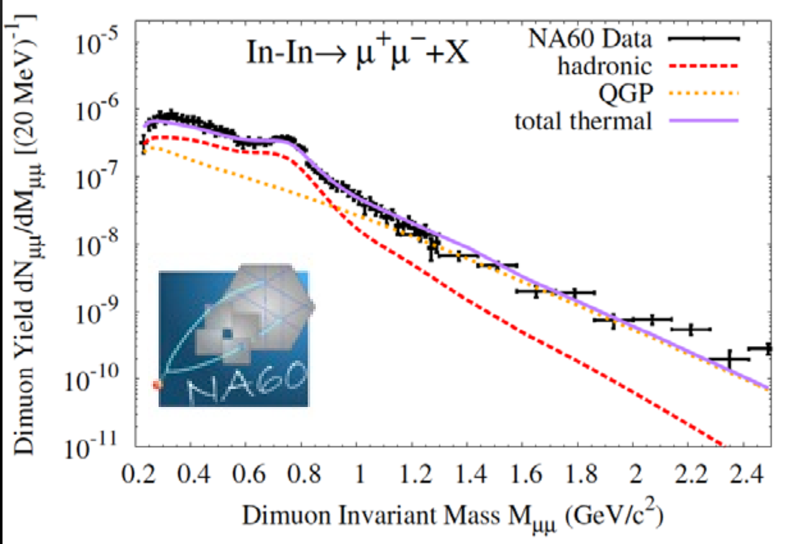


- Dilepton spectra represent the space-time integral of EM radiation
- Mass dependence allows separation of collision stages

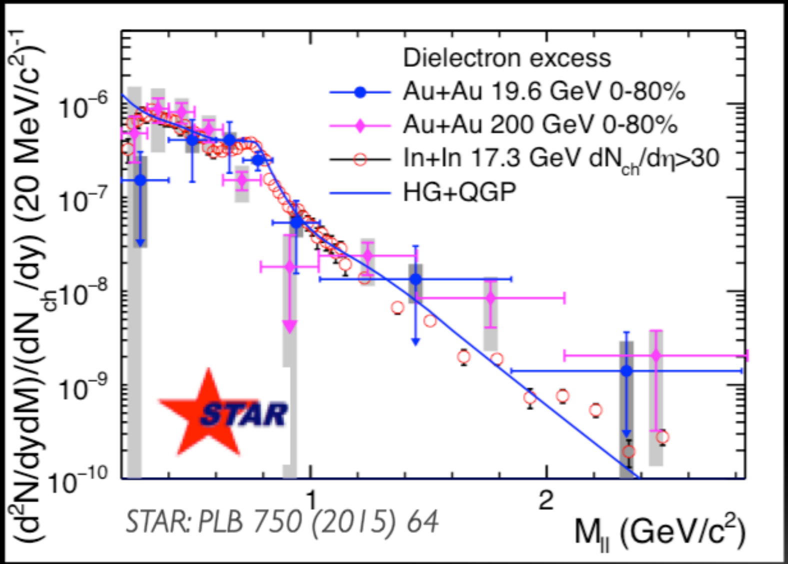


- *Drell-Yan* (NN → l^+l^-X)
- Heavy-flavor: $c\bar{c} \rightarrow l^+l^-$
- Medium radiation (R. Rapp):
  - QGP: $q\bar{q} \rightarrow l^+l^-$
  - In-medium ρ, ω → l^+l^-
  - "4π annihilation": $\pi a_1 \rightarrow l^+l^-$
- Final state decays (hadron cocktail): $\pi^0, \eta \rightarrow \gamma e^+e^-$

What did we learn from UrHICdileptons?

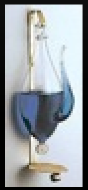


NA60: H.J. Specht, AIP Conf.Proc. 1322 (2010) 1
Model: R. Rapp, H. van Hees, PLB 753 (2016) 586



STAR: PLB 750 (2015) 64

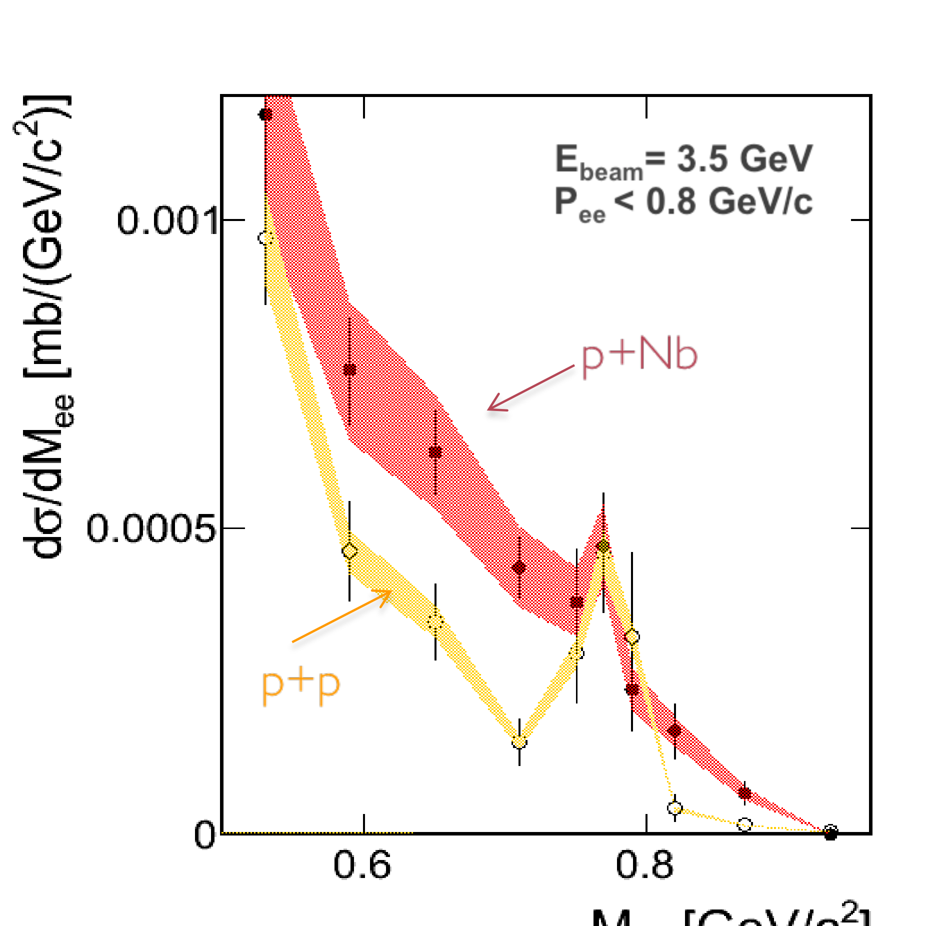
- "Dileptons as chronometer, thermometer, barometer and spectrometer of the field"



R.Rapp '14

- ρ - Δ/N* couplings play substantial role in ρ melting observed in UrHIC

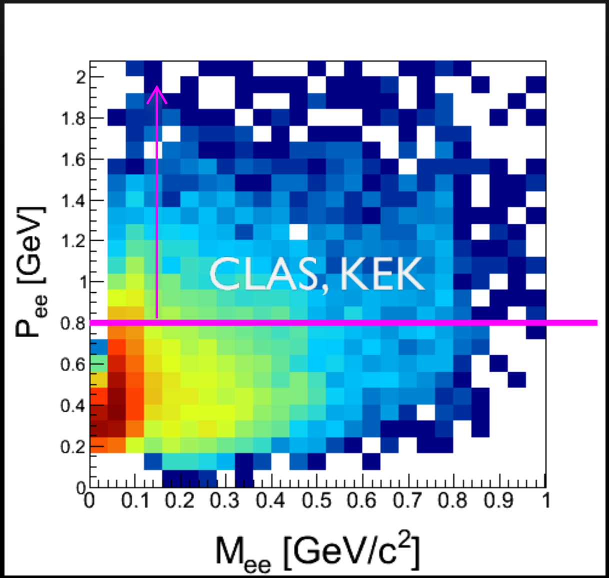
Are there narrow in-medium vector meson states with substantially shifted pole mass?



HADES collab.: Phys.Lett. B715 (2012)

PDG Entry 2012, 2014
BR($\eta \rightarrow e^+e^-$) < 2.5x10^{-6} (90% CL)

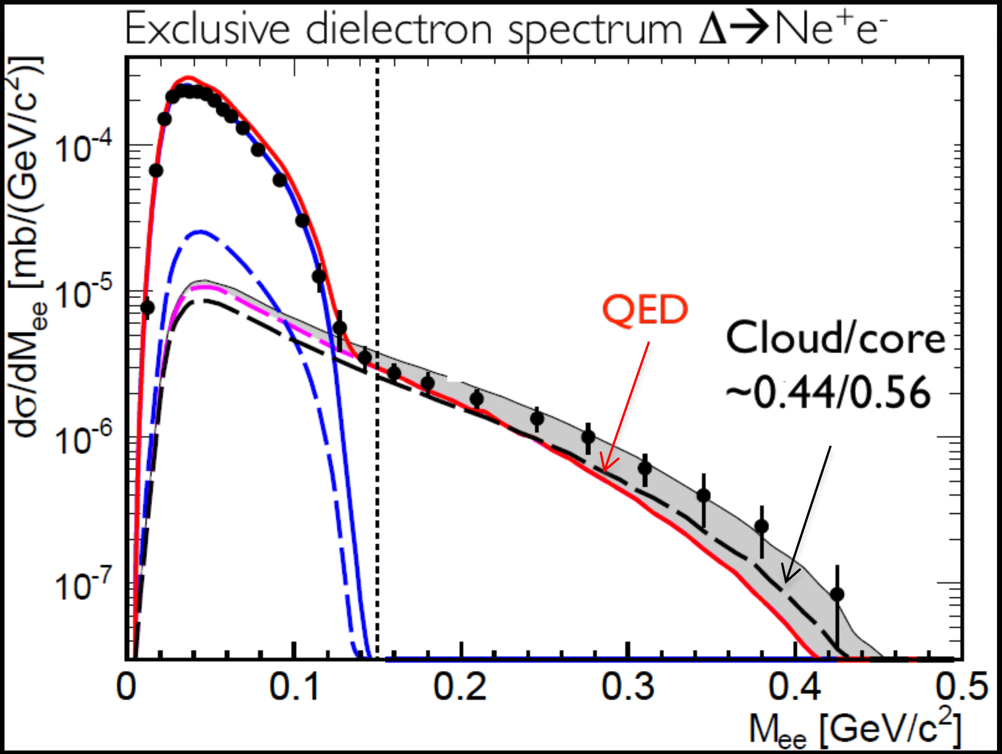
HADES acceptance



- First measurement of in-medium vector meson decays in the relevant momentum region (P_{ee} down to 0.2 GeV/c)
- HADES sees rather a melting than a shift
- p+p reactions: significant contribution from higher (than Δ) mass resonances

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

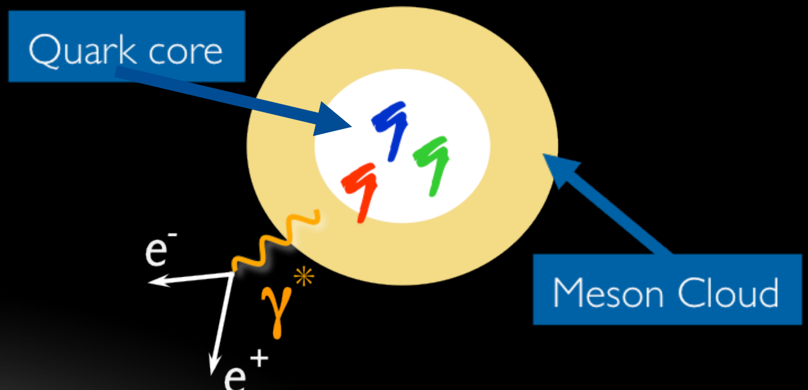
- Reference measurement for Au+Au
- Exploring hadron electromagnetic structure



pp reactions 1.25 GeV (below free NN η production threshold)

- First direct access to the Δ transition form factor in the time-like region
  BR = 4.42×10^{-5} ± 20%(syst.) ± 9%(stat.)

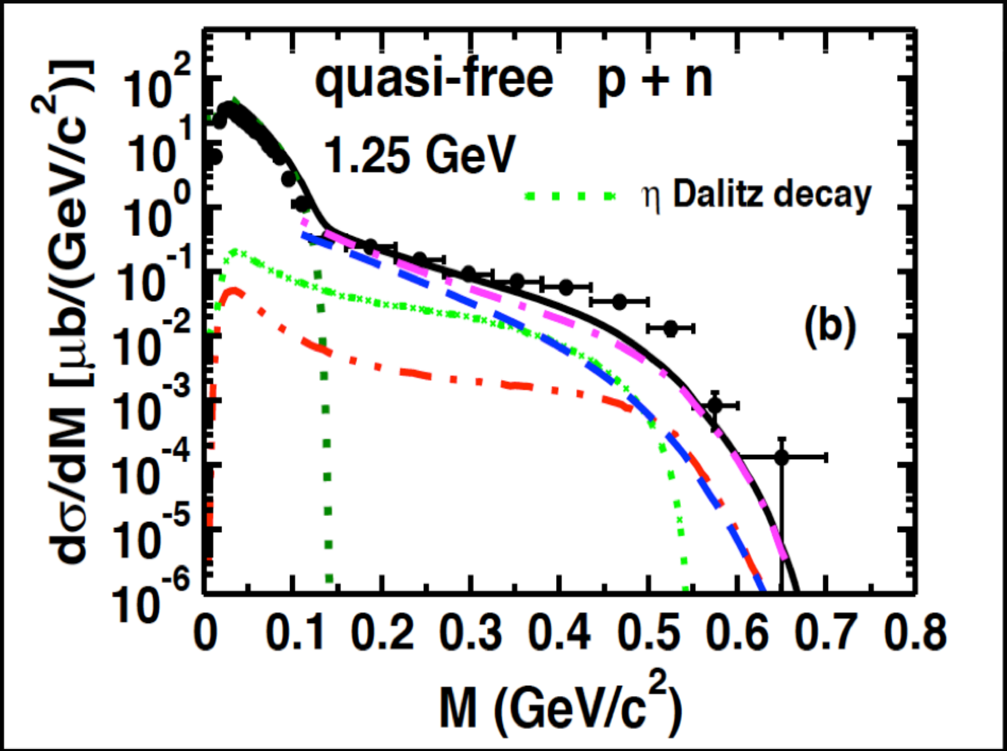
- Excitation of a baryon can be carried by the meson cloud *[I.G. Aznauryan, V.D. Burkert Prog. Part. Nucl. Phys. 67, 1 (2012)) 1846]*



Data: HADES collab., in preparation
QED: M.I. Krivoruchenko et al. Phys. Rev. D65(2002) 017502
Cloud/core: G. Ramalho, M.T. Peña Phys. Rev. D85(2012) 113014

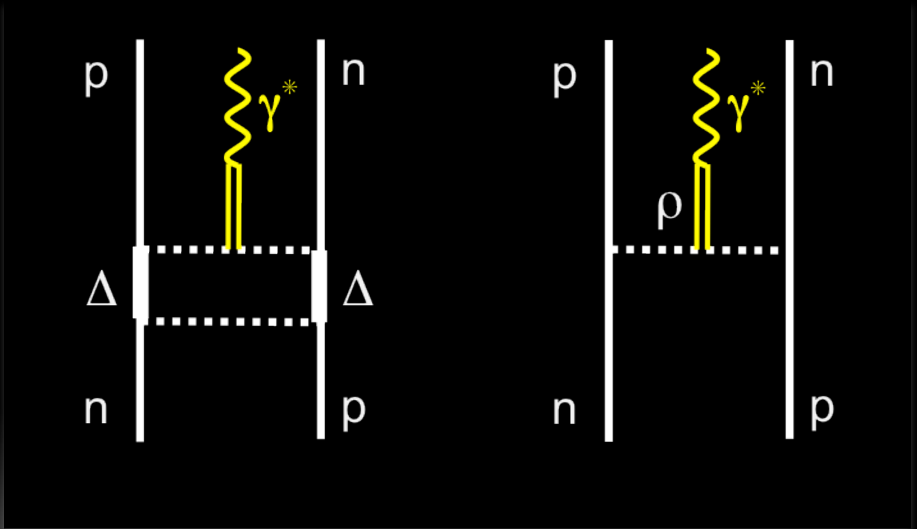
e^+e^- pairs from pp and np (tagged n) reactions

- Reference measurement for Au+Au
- Exploring hadron electromagnetic structure



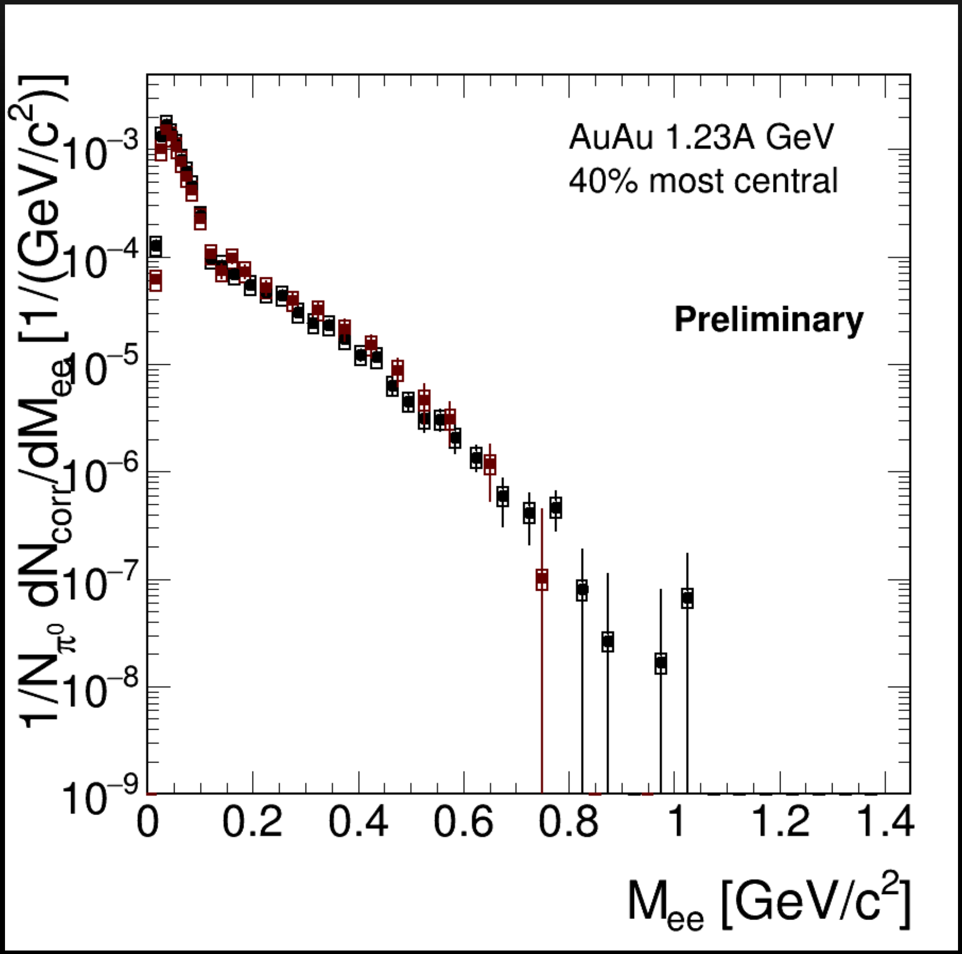
np reactions 1.25 GeV

- Remarkable isospin effect
- Radiation from the internal line yields enhanced emission at high invariant masses → off-shell (cloud-cloud) $\pi\pi$ collision



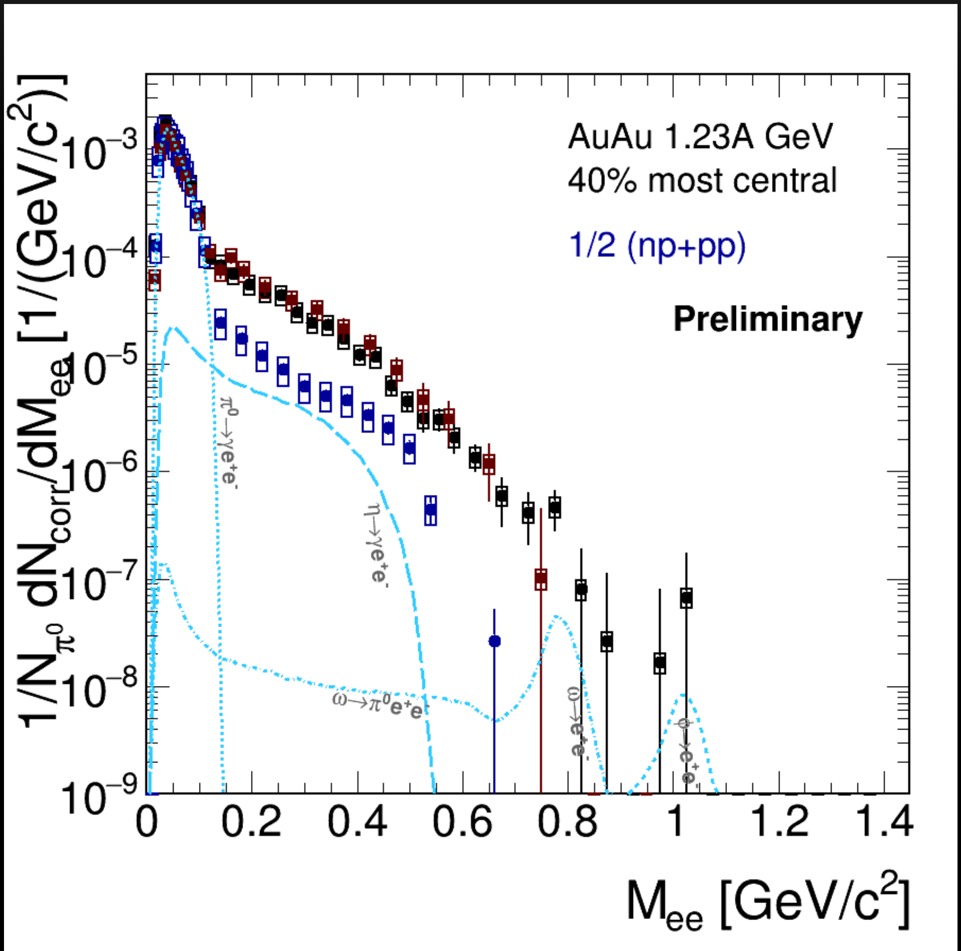
Data: HADES collab., PLB 690 (2010) 118
R. Shyam and U. Mosel, PRC 82:062201, 2010
M. Bashkanov, H. Clement, Eur. Phys. J. A50, 107, (2014)

Virtual photon emission in Au+Au collisions



- Normalization to number of neutral pions N_π
  - Fireball dominated by incoming nucleons at lower energies
  - Number of charged particles N_{ch} not a good proxy for thermal excitation energy
- Almost exponential spectrum up to vector meson region!

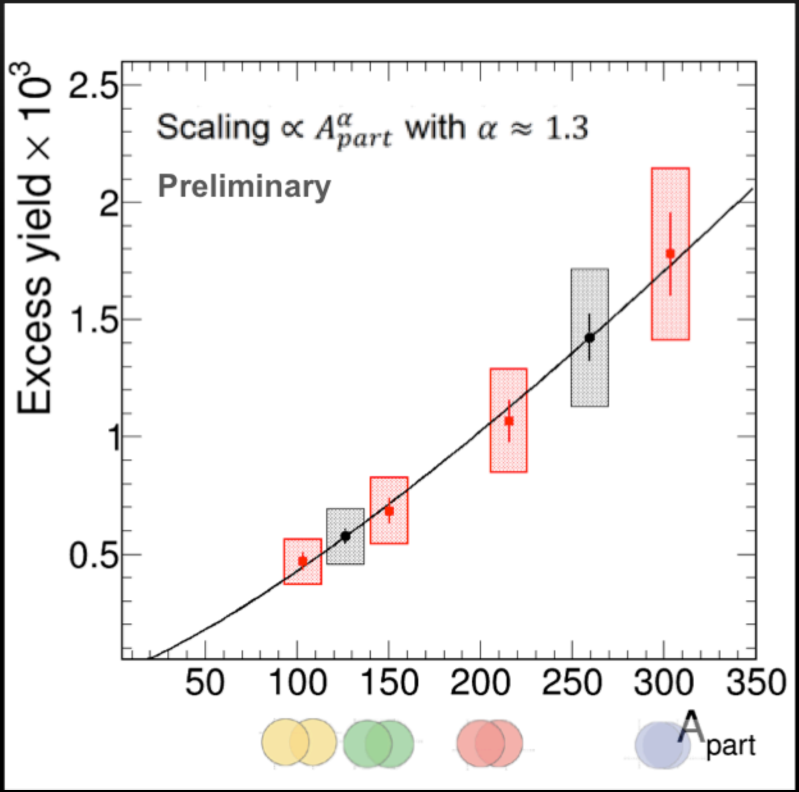
Virtual photon emission in Au+Au collisions

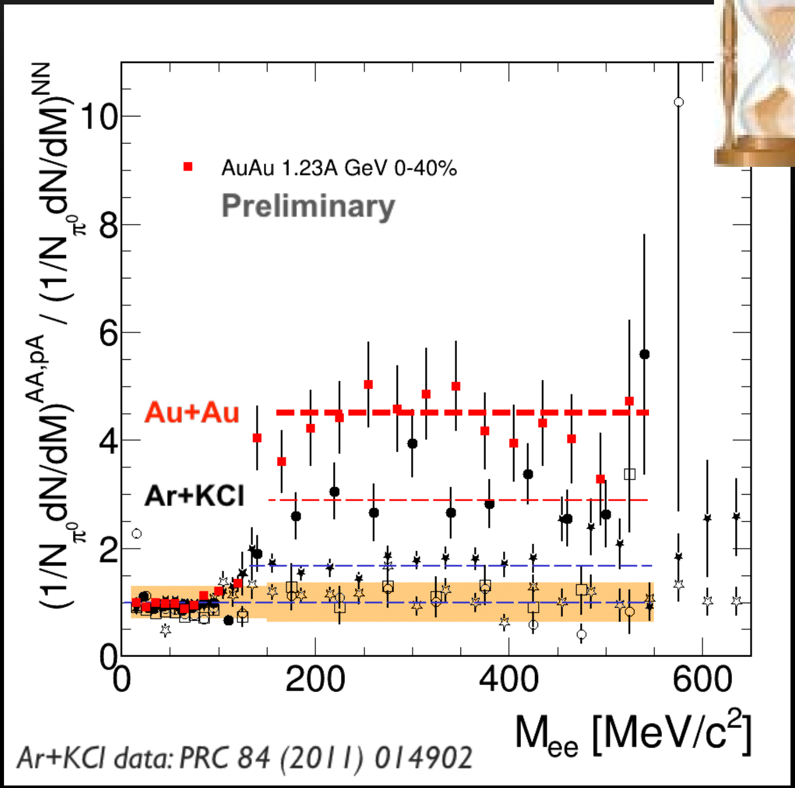


- Comparison to e^+e^- cocktail accounting for decays of mesons (π^0, η, ω, ϕ) at freeze-out
- Strong enhancement above π^0 (in-medium radiation, baryons..)
- Comparison to e^+e^- measured in NN collisions scaled to same A_{part}
- Excess yield $0.2<M<0.5$ GeV/c^2 → true in-medium effect

Centrality and system size dependence of the excess

Excess radiation 0.3 < M < 0.7 GeV/c²

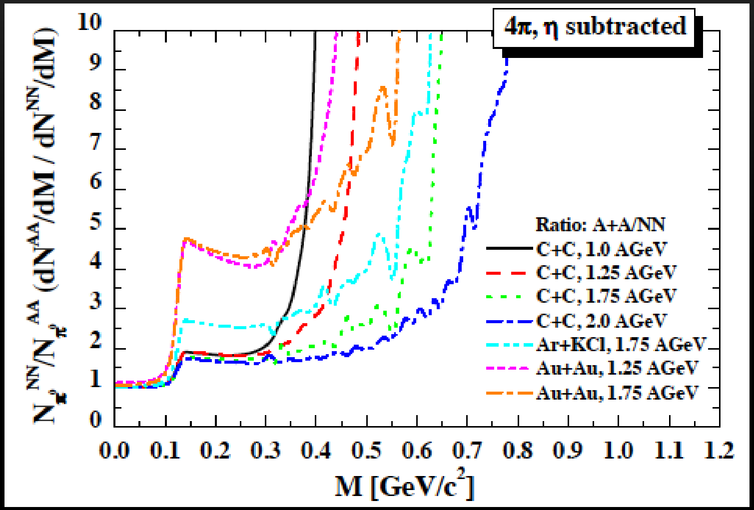




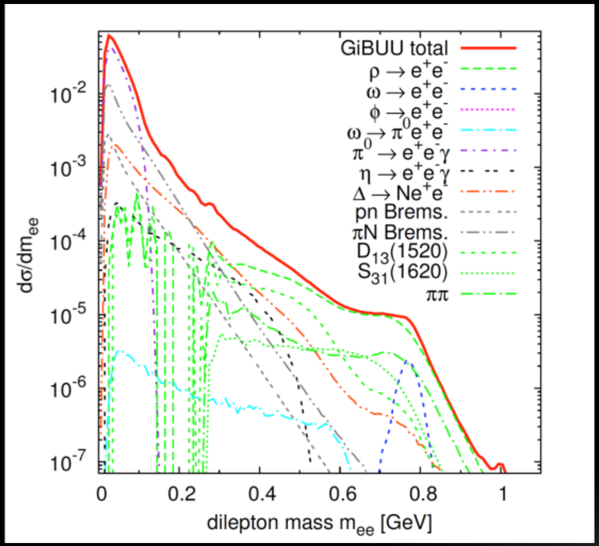
- Strong excess ($\sim A_{part}^{1.3}$, interplay $V \otimes \tau_{coll}$)
- Dilepton chronometer of the collision time

- Medium radiation goes beyond what is expected from a superposition of incoherent NN collisions
  - → Regeneration of baryonic resonances
  - → Subsummed into spectral functions

Transport treatment of e^+e^- production



Bratkovskaya, Aichelin, et al., PRC 87 (2013) 064907



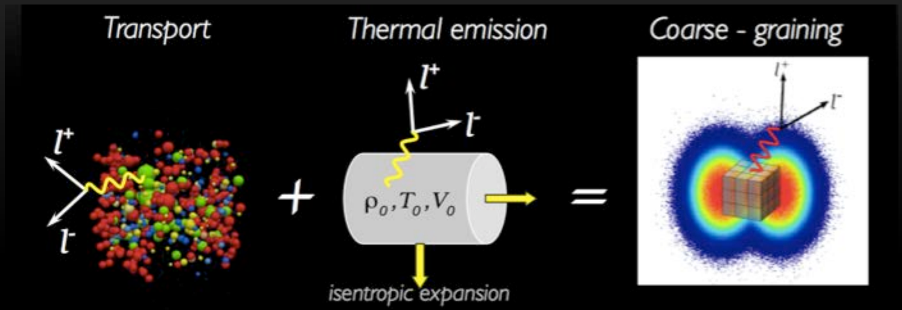
GiBUUJ. Weil et al.

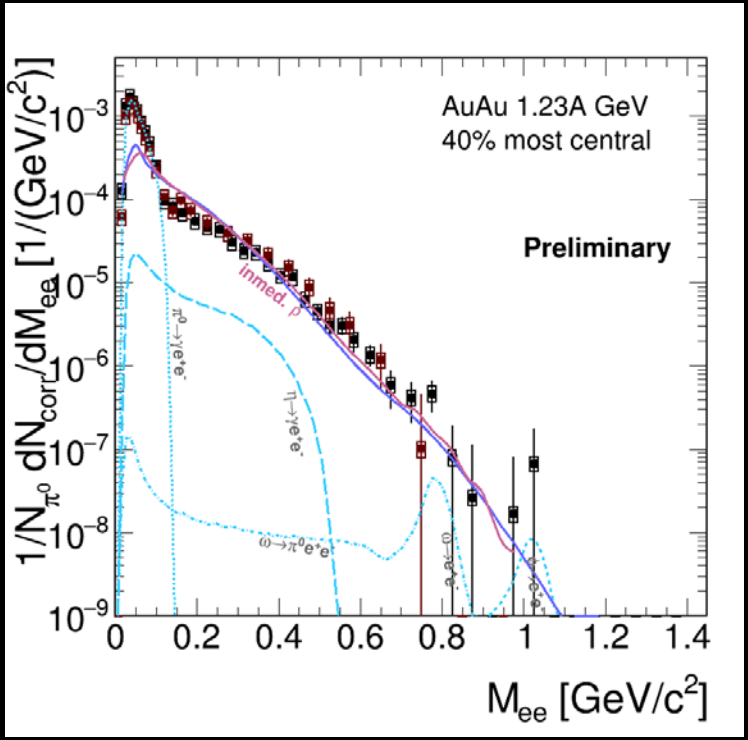
- In HSD, dilepton excess above NN due mostly to Δ regeneration & decay
- In GiBUU more baryon resonances are included, e.g. N*(1520)
- The interference of elastic and inelastic channels is neglected
- Difficulties to incorporate in-medium physics - vacuum SFs used

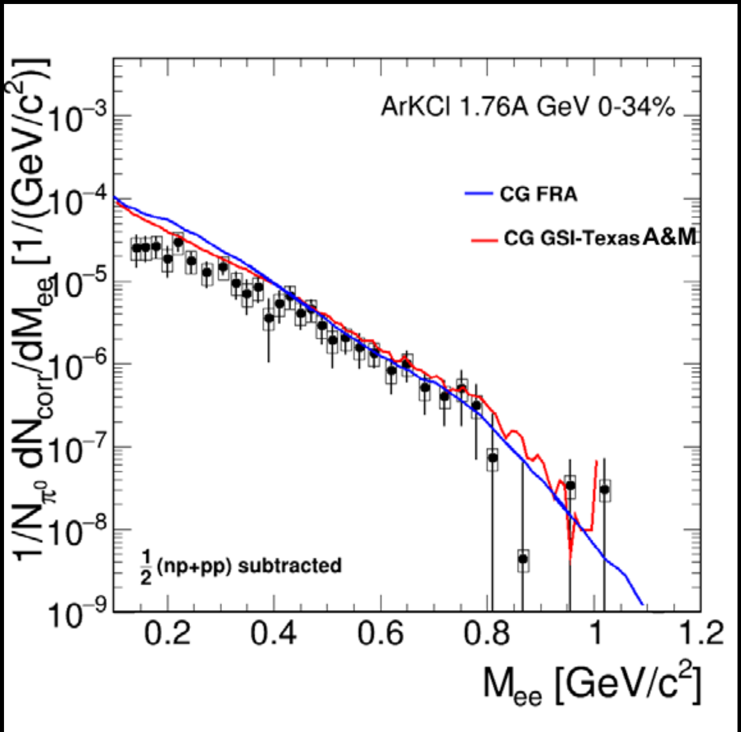
→ comparison with data in preparation

Thermal dilepton emission at SIS18?

- Bulk evolution from microscopic transport
  - Coarse graining in space-time cells → extract T, μ_B, μ_π, collective velocity…
- Apply in-medium ρ&ω spectral functions to compute EM emission rates







- Coarse-graining method works at low energies
- Supports baryon-driven medium effects at UrHIC (SPS and RHIC)!

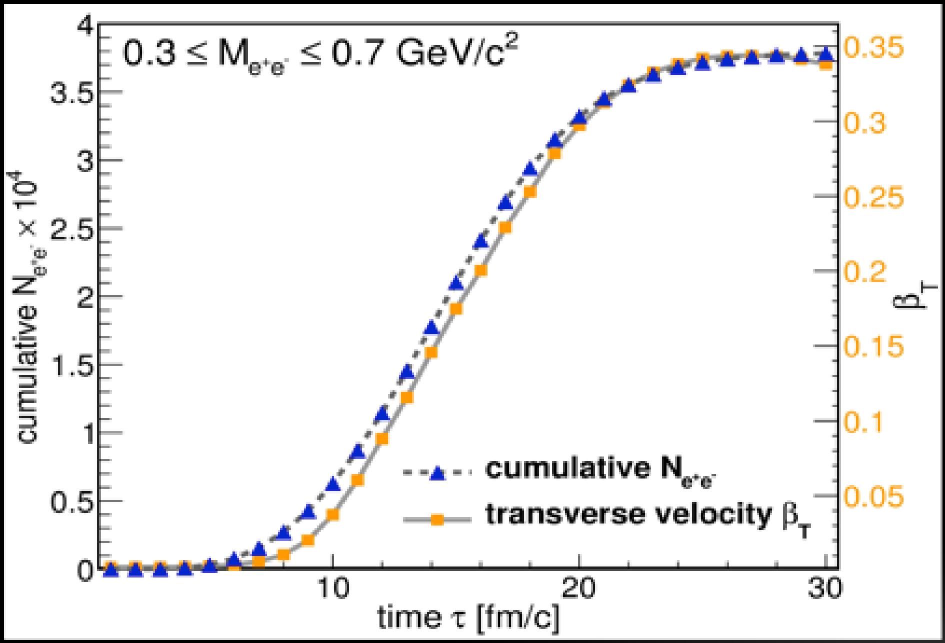
CG FRA: Phys. Rev. C 92, 014911 (2015)
CG GSI-Texas A&M: Eur.Phys.J.A52 (2016) no.5, 131

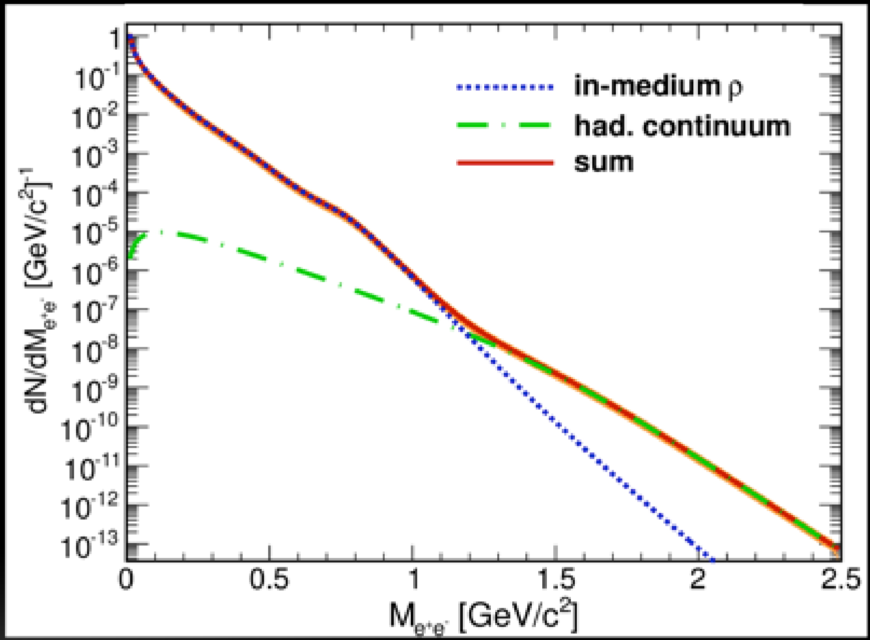
Dileptons as fireball probes

- Time evolution of cumulative dilepton yield in mass window M = 0.3-0.7 GeV/c^2
- Active radiation window ~13 fm/c follows build-up of collective medium flow ➡ fireball lifetime
- Strong medium effects on ρ-meson ➡ remarkably structure-less low-mass spectrum

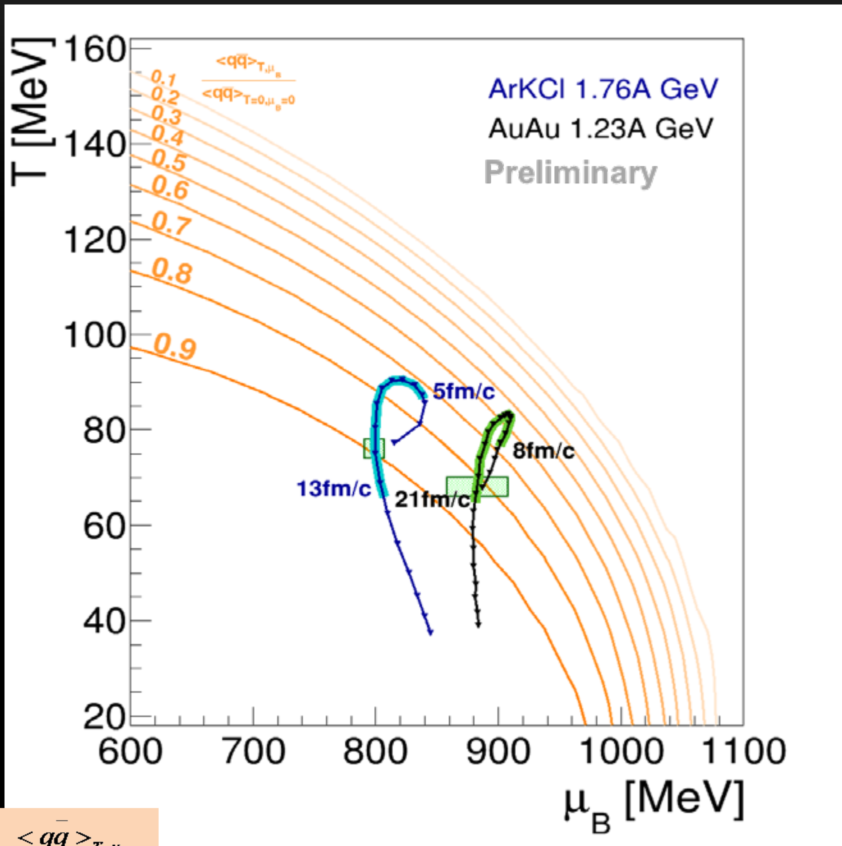
$$\mathrm{d}R_{ll}/\mathrm{d}M \propto (MT)^{3/2}\exp(-M/T)$$

- Inverse slope parameter: T_S = 88 ± 5 MeV in IMR, T_S = 64 ± 5 MeV in LMR





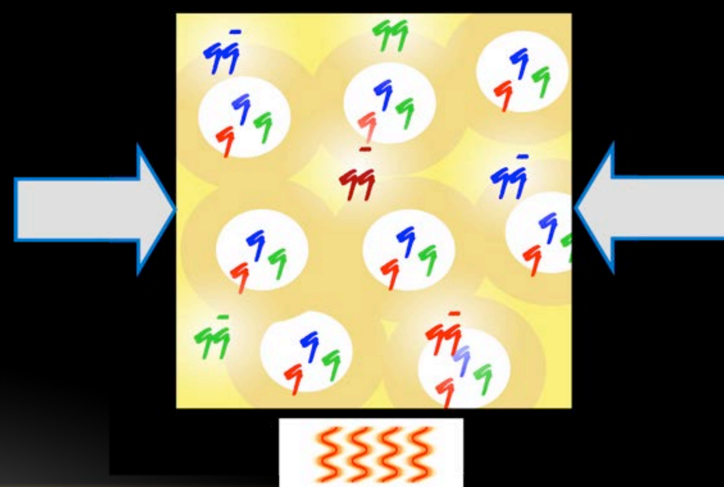
HADES and QCD phase diagram of matter



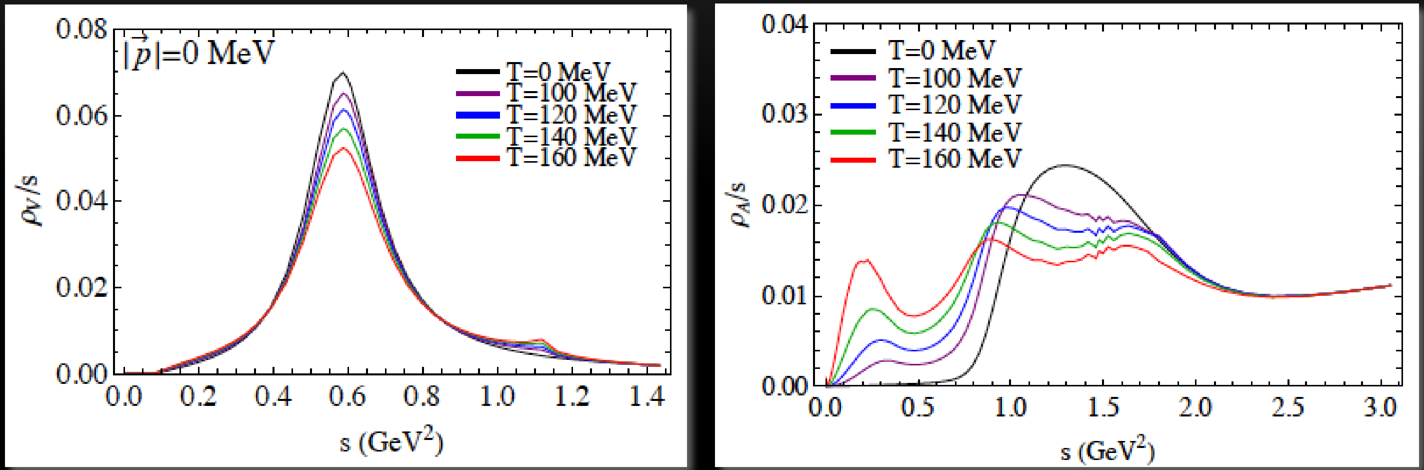
$\frac{<q\bar{q}>_{T,\mu_B}}{<q\bar{q}>_{T=0,\mu_B=0}}$: *B.J. Schaefer and J. Wambach*

HADES Ar+KCl data: Nucl. Phys. A931 (2014) c785

- Chemical freeze-out from measured particle yields analyzed with SHM
- Trajectories extracted from inner cube of cells with coarse-grained UrQMD
- Time-window of dilepton emission
  - Radiation stops shortly after chemical freeze-out
  - Access to hot and dense stage of the heavy-ion collision
- Excitation of the vacuum (melting of condensate) matches spectral medium effects!



ρ-a₁ spectral functions and chiral symmetry



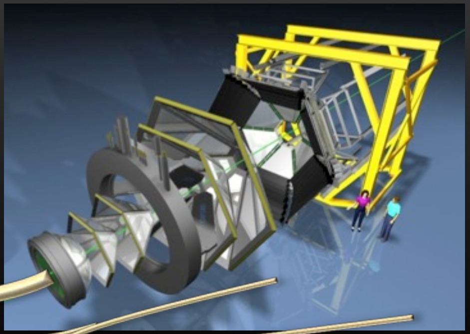
P. Hohler, R.Rapp, arXiv:1510.00454v1 [hep-ph] 2 Oct 2015

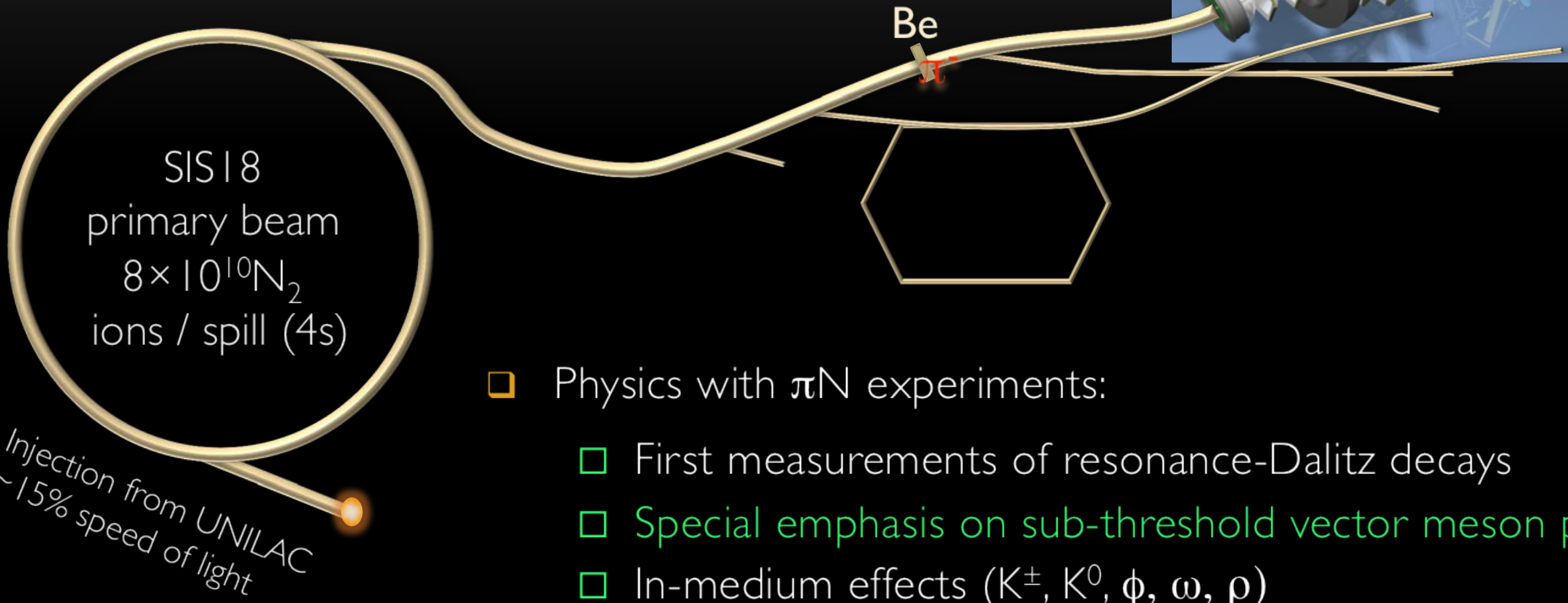
- Vector and axial-vector spectral functions in a pion gas
- No baryon effects accounted for yet

- 4π processes: $\pi a_1 \rightarrow \gamma^* \rightarrow$ *l+l-* (chiral mixing) is a dominant hadronic source in IMR
  - No correlated charm contribution!
  - No Drell-Yan!
  - No QGP!
- Results in elementary collisions provide an important baseline for future explorations in HIC
  → HADES: high statistic p+p and p+Ag in 2018

HADES π-beam

"If you are out to describe the truth, leave elegance to the tailor"
A. Einstein





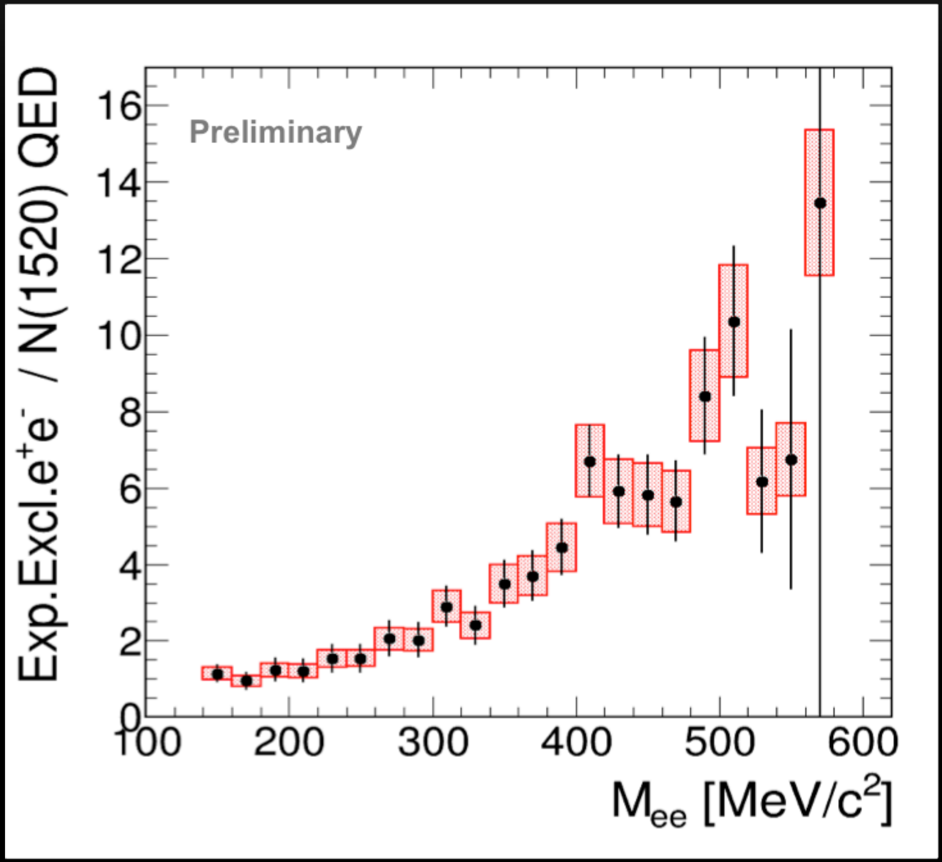
- Physics with πN experiments:
  - First measurements of resonance-Dalitz decays
  - Special emphasis on sub-threshold vector meson production
  - In-medium effects ($K^{\pm}$, K^0, ϕ, ω, ρ)

- π-beam 5×10^5 / spill
  - HADES starts from $\sqrt{s}$ = 1.46-1.55 GeV
    → $N^*(1520)$ resonance region
  - Pion tracking with two double-sided silicon strip detectors in the beam line $\delta p/p$ = 0.3%

HADES collab., Nucl.Phys.News25 (2015) no.2

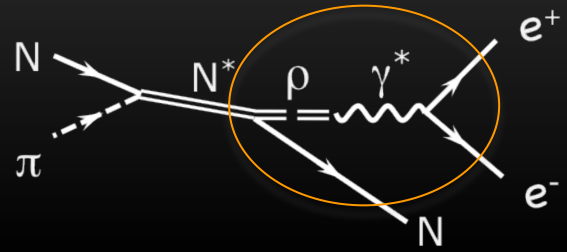
Verify the ρ-baryon coupling mechanism

Exclusive $\pi^- p \rightarrow n e^+ e^-$ at $\sqrt{s}$= 1.49 GeV



ρ meson contribution from the measured $\pi^+\pi^-$ channel and using the strict VMD:

$$\frac{d\sigma}{dM_{ee}} = \frac{d\sigma}{dM_{\pi\pi}} c_p \left(\frac{m_\rho}{m_{ee}}\right)^3$$

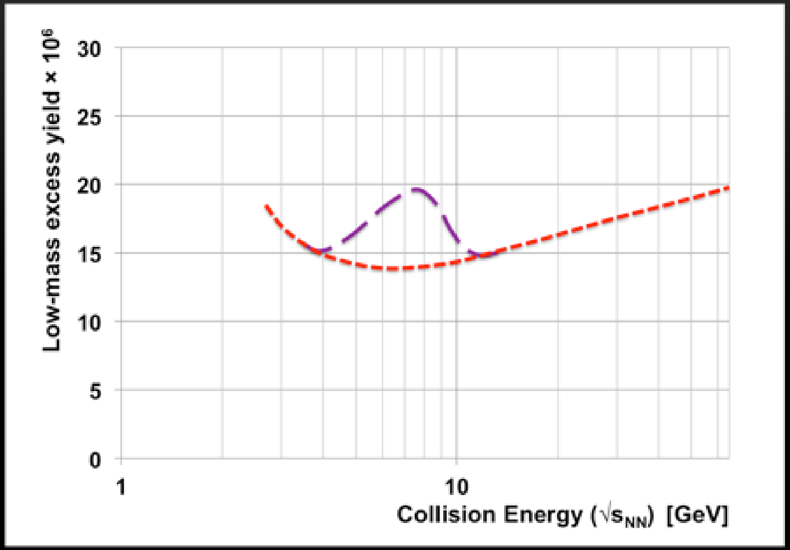


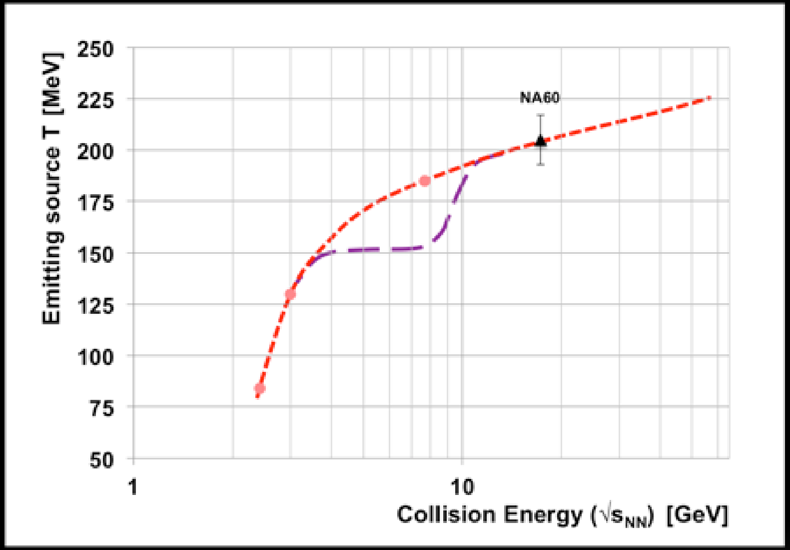
- Vector Meson Dominance: the basis of emissivity calculations for QCD matter.
- Crucial to support the validity of the model by elementary reactions

→ Virtual excitation of ρ-meson states in the baryons' meson cloud?

→ Strong deviation from unity show the time-like contribution to the resonance decay and along strict VMD!

Mapping QCD phase diagram with dileptons





Dashed violet curve corresponds to a speculated shape with phase transition

- Yield in low-mass window tracks fireball lifetime
  - Measure excitation function of ρ spectral function
  - Search for anomalous fireball lifetime around phase transition & CP

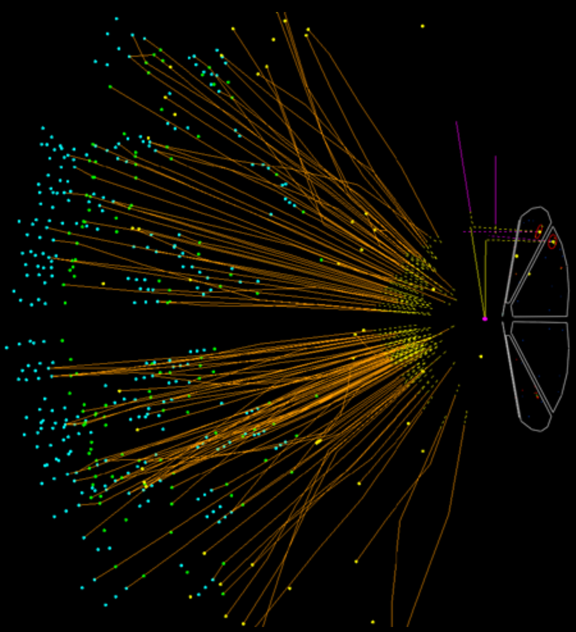
- Intermediate mass slope measures the emitting source temperature (true, no blue shift)
  - Measure T_{slope} (note, $T_{slope} < T_{initia}$)"caloric curve"
  - Plateau around onset of deconfinement?
    (see e.g. M. D'Agostino et al. NPA 749 (2005) 5533)

Future experiments allow for overlap and independent confirmation of results!

Encouraging prospects for studying QCD matter in the region of finite μ_B with HADES

- Unique possibility of characterizing properties of baryon dominated matter with rare and penetrating probes:
  - Long-lived states of compressed resonance matter are produced in heavy-ion collisions in the few-GeV energy regime
  - This state of matter might be much more exotic than a hadron gas

- Roadmap beyond 2016:
  - 2016-18: upgrade HADES: add lead-glass EM calorimeter, add forward straw-tube tracker & RPC, replace RICH photon detector
  - 2018-20: high statistic p+A and A+A (e.g. Ag+Ag at E_{kin}=1.65 GeV), as well as measurements with secondary pion beams (π+N and π+A)
  - 2020/21$^+$: move HADES to SIS100 → continuation at higher beam energies



Thank you!