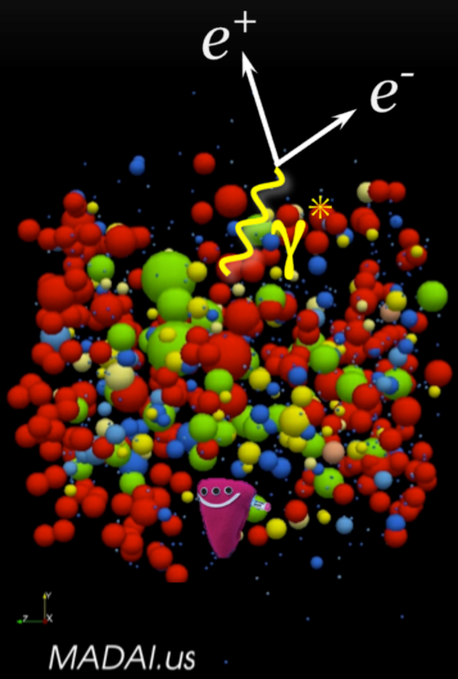
RHIC & AGS
Annual Users' Meeting
From Protons to Heavy Ions, and Back Again
Hosted By Brookhaven National Laboratory



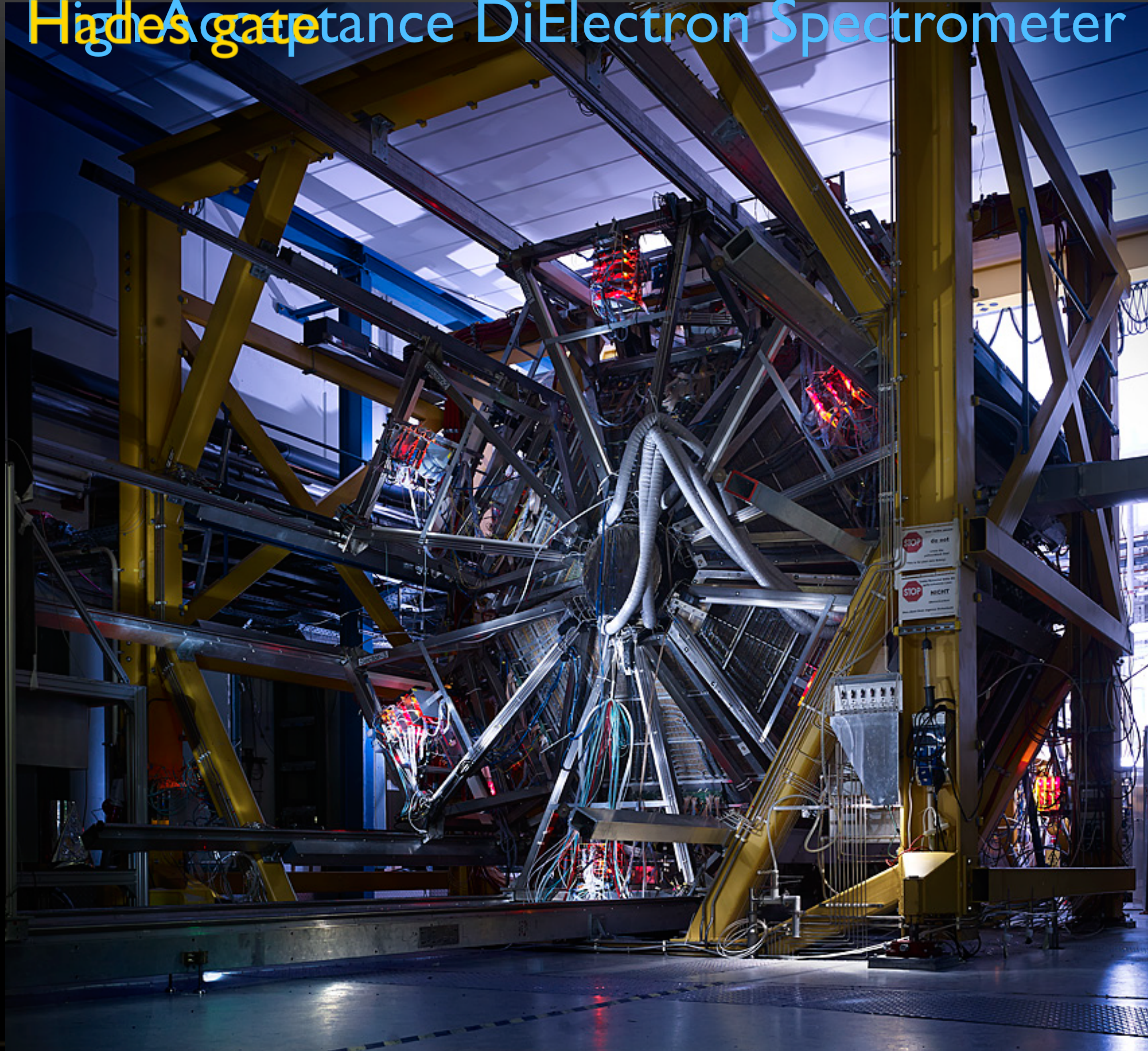
The electromagnetic response of resonance matter and other strange observations

Tetyana Galatyuk for the HADES Collaboration

Technische Universität Darmstadt / GSI Helmholtzzentrum für Schwerionenforschung

High Acceptance DiElectron Spectrometer

Hades gate



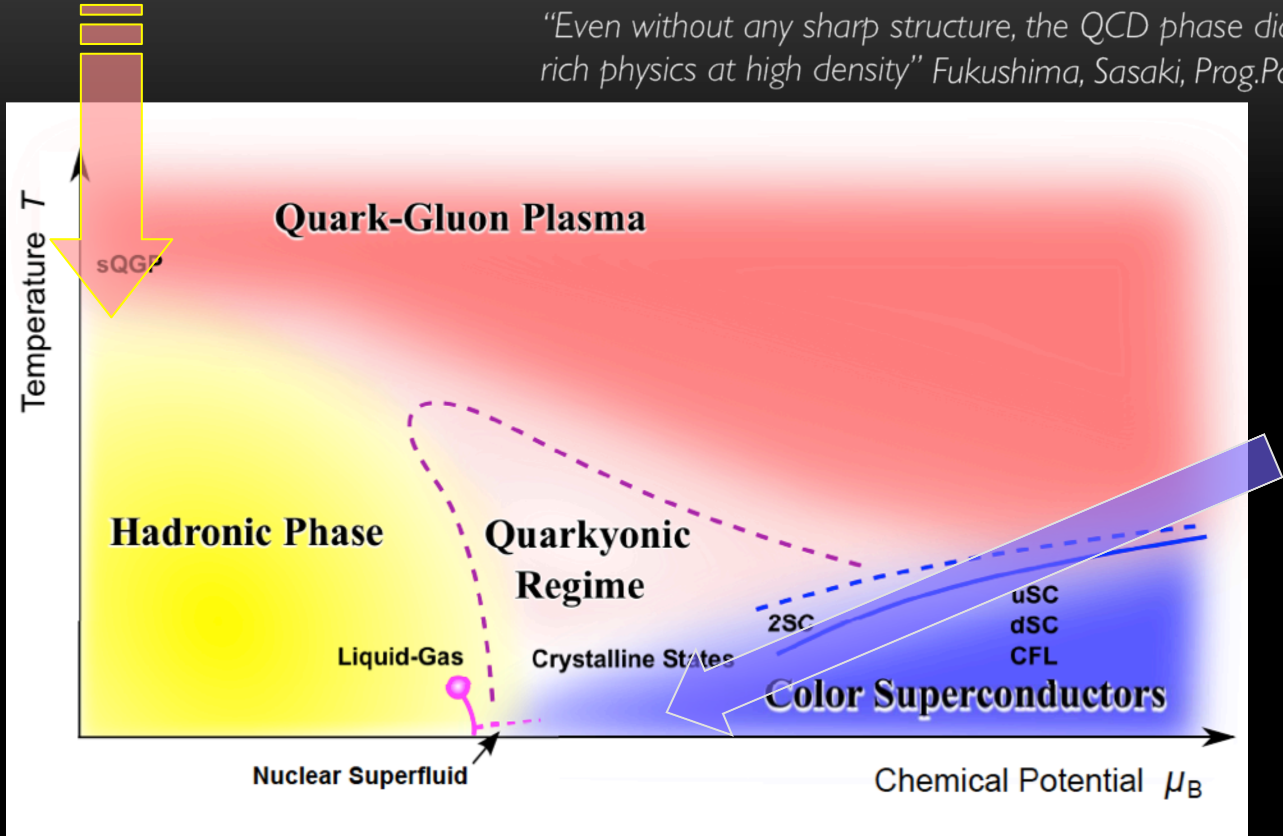
The HADES Collaboration

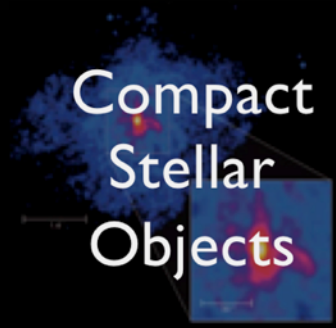
- IOP SAS, Bratislava, Slovakia
- INR & ITEP & MEPHI, Moscow, Russia
- LIP & ISEC, Coimbra, Portugal
- SIP JUC Cracow, Poland
- GSI, Damstadt, Germany
- TU Darmstadt, Germany
- HZDR, Dresden, Germany
- JINR Dubna, Russia
- GU Frankfurt, Germany
- JLU Giessen, Germany
- TU München, Germany
- Lisboa, Portugal
- Nicosia, Cyprus
- IPN Orsay, France
- NPI CAS, Rez, Czech Rep.
- USC – S. de Compostela, Spain
- FZ Jülich, Germany (James Ritman)
- U Wuppertal, Germany (Karl-Heinz Kampert)

~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)

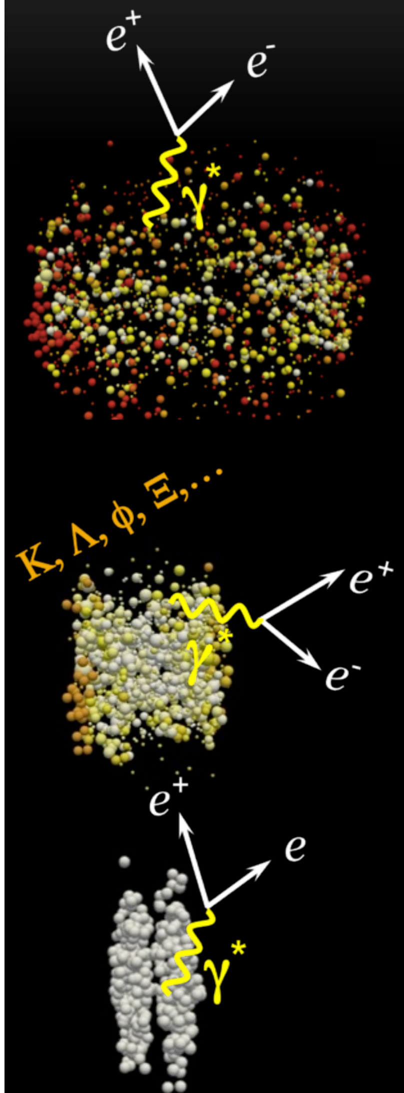




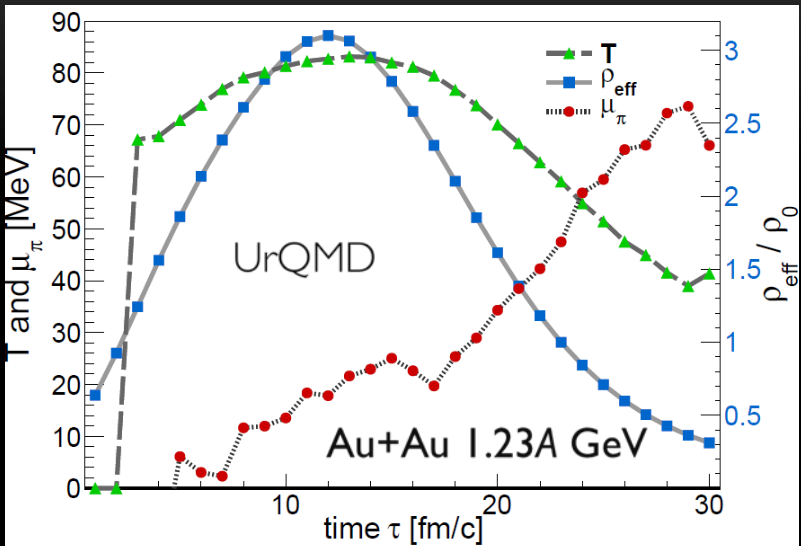
What are the fundamental properties of strongly interacting matter under extreme temperatures and densities?

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

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

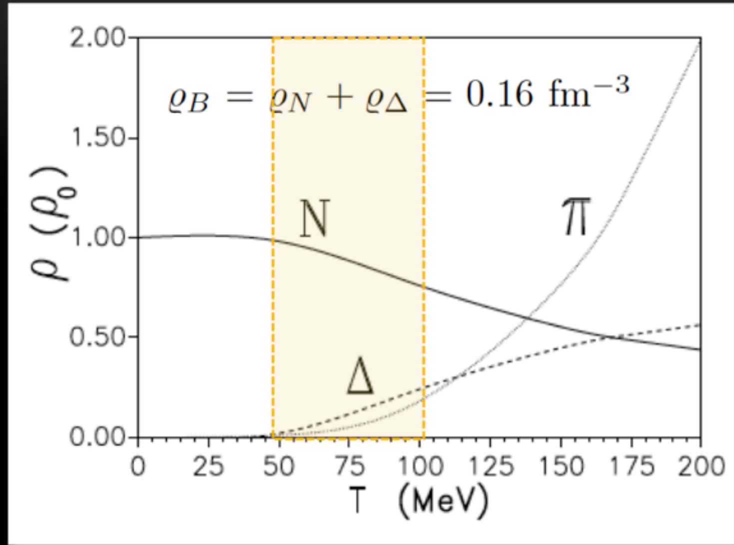


Evolution of average T and ρ_{eff}



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

Composition of a hot πΔN gas

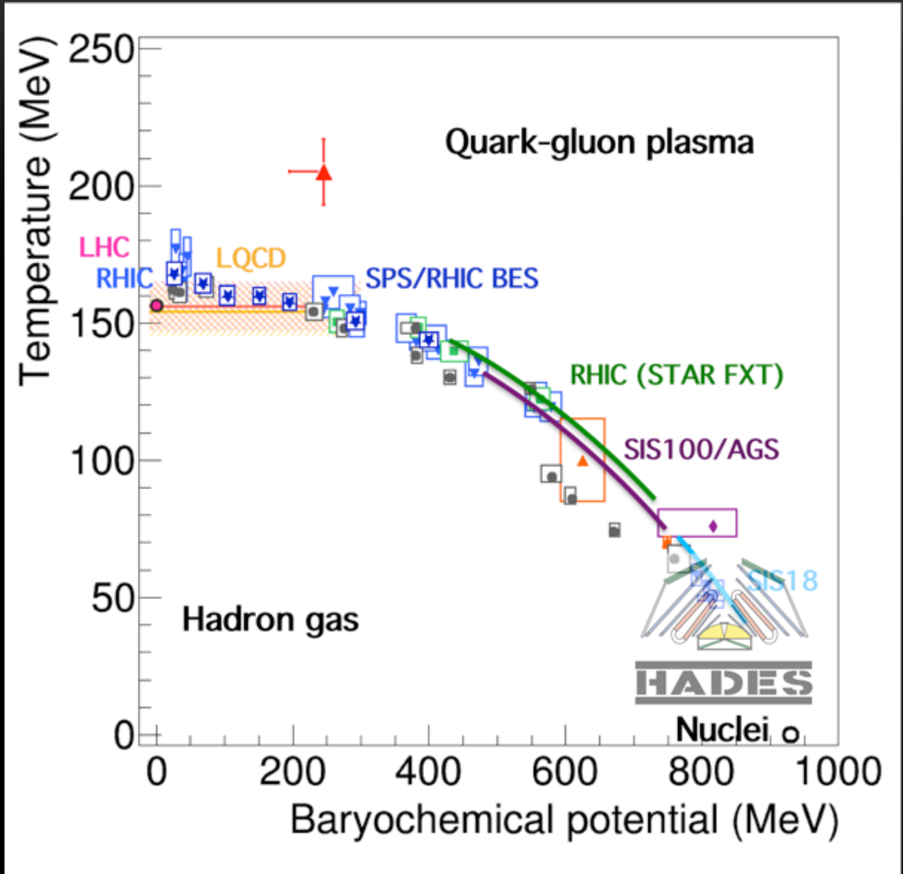


Rapp, Wambach, Adv.Nucl.Phys. 25 (2000)

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

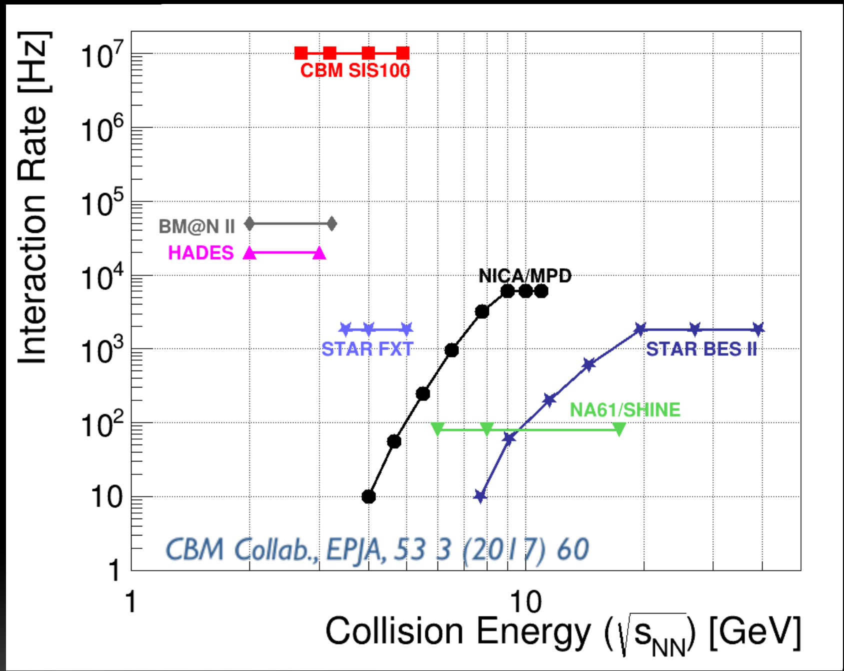
Rare and penetrating probes

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)

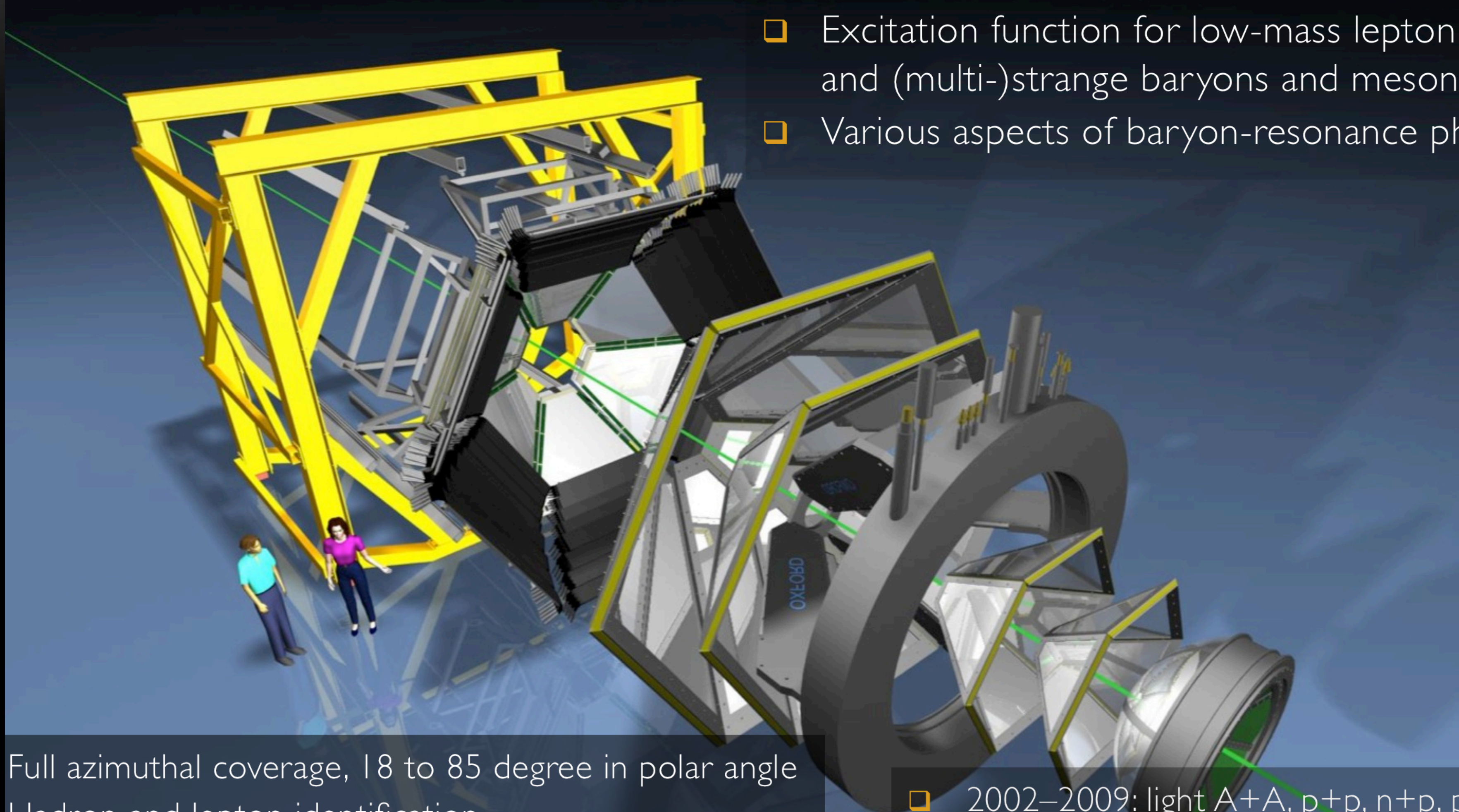


- HADES currently explores the high-μ_B region
- Very competitive w.r.t. interaction rate capability
- HADES is part of the beam energy scan
  → marks lowest point of the excitation function

The HADES at GSI, Darmstadt, Germany

HADES strategy:

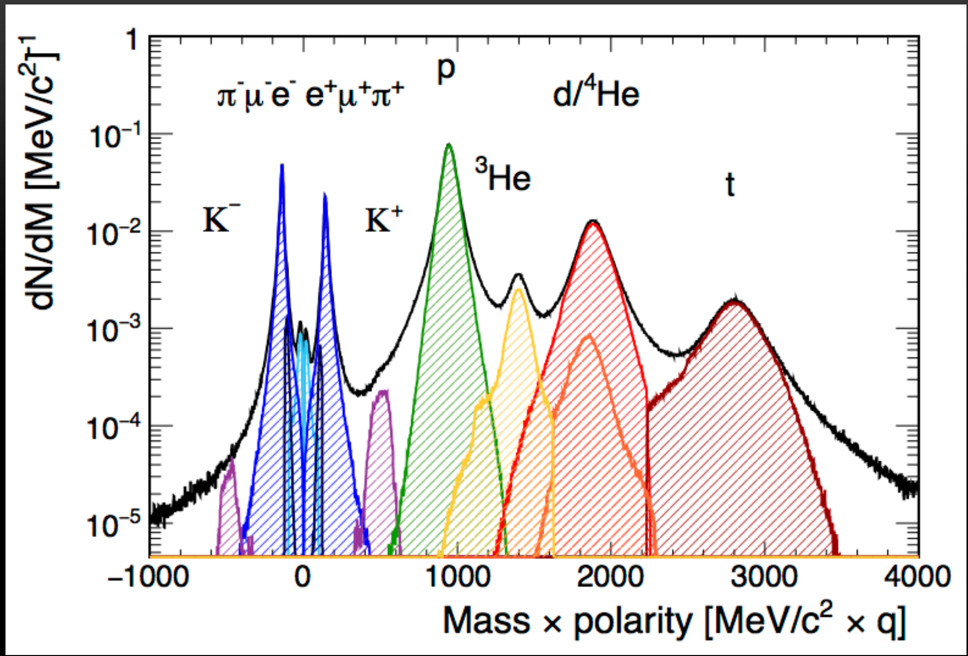
- Excitation function for low-mass lepton pairs and (multi-)strange baryons and mesons
- Various aspects of baryon-resonance physics

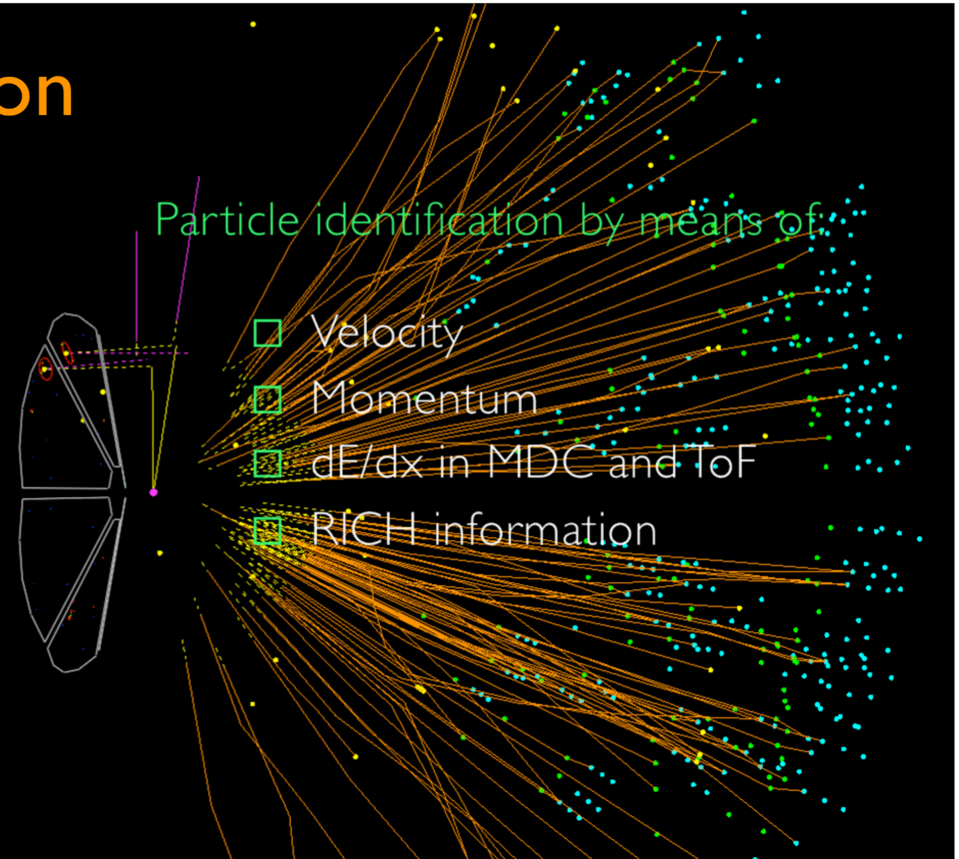


- Full azimuthal coverage, 18 to 85 degree in polar angle
- Hadron and lepton identification
- Event-plane reconstruction
- e^+e^- pair acceptance 35%
- Mass resolution 2 % (ρ/ω region)

- 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

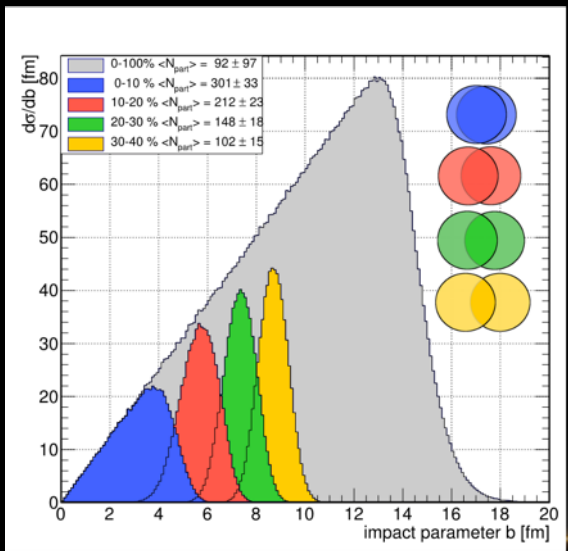




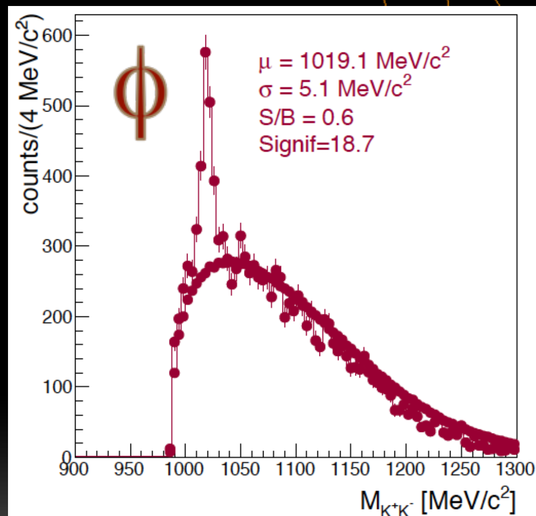
Particle identification by means of:

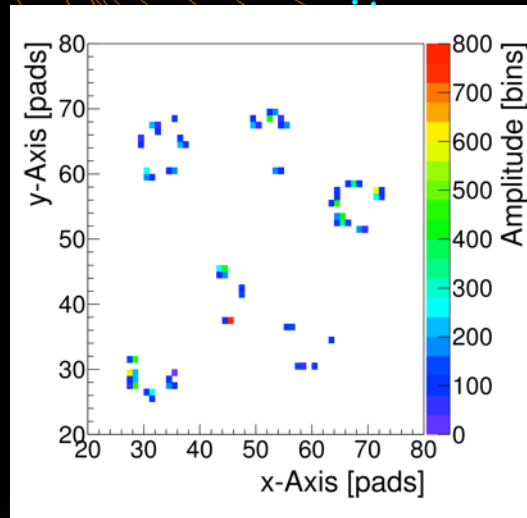
- Velocity
- Momentum
- dE/dx in MDC and ToF
- RICH information

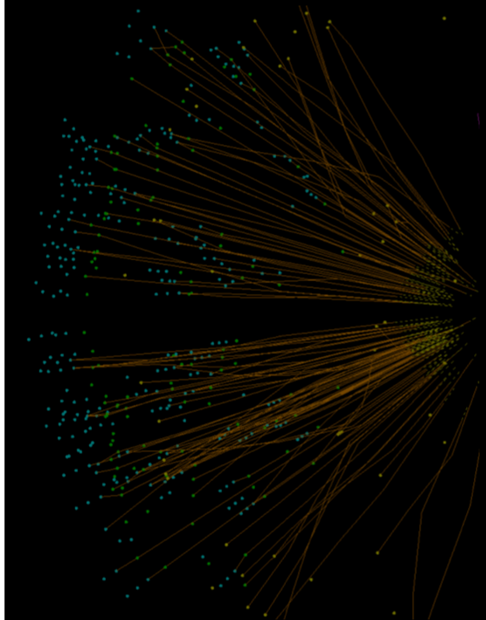
Centrality: Glauber calculation



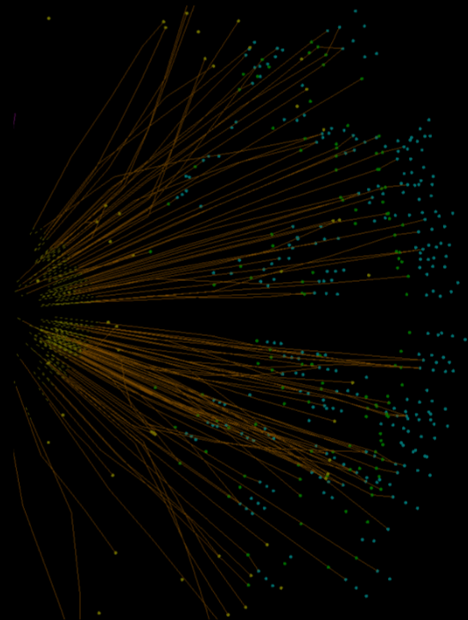
	$\langle A_{part} \rangle$
0-10%	301
10-20%	212
20-30%	148
30-40%	102



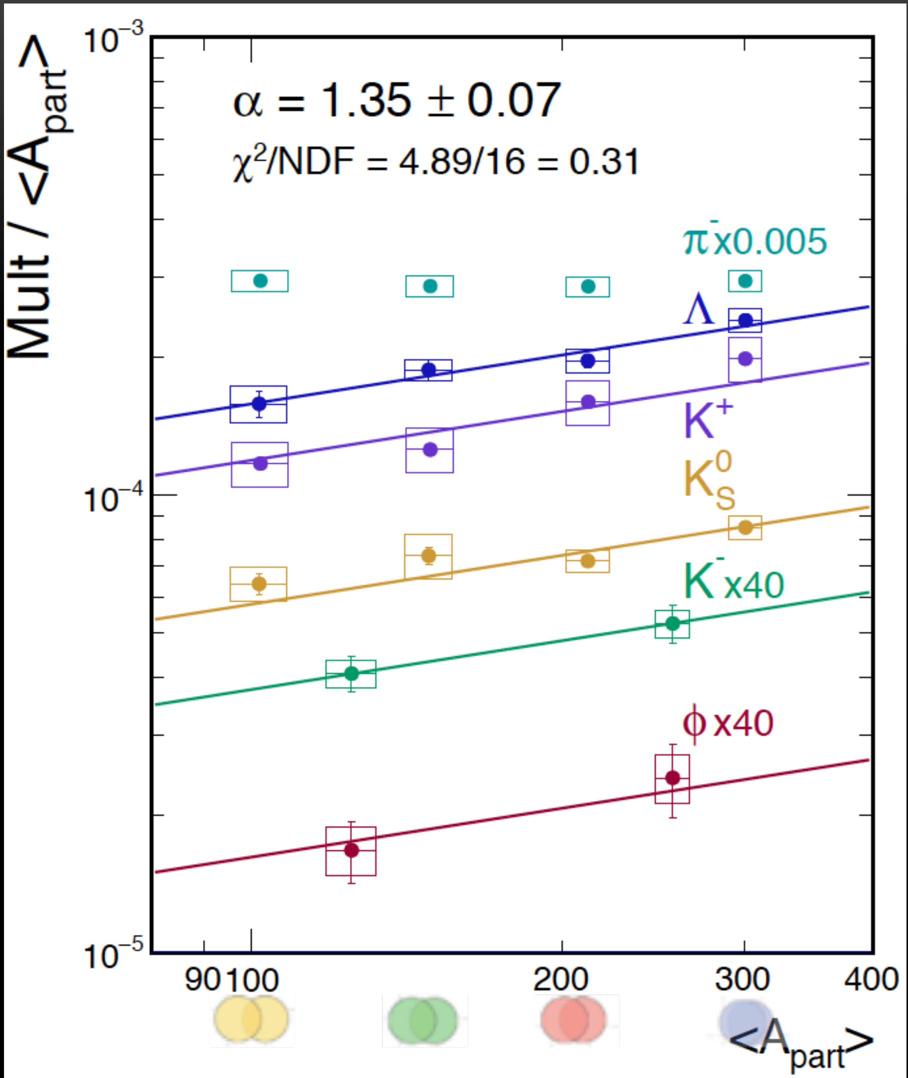




Final state
“Hadron-chemistry”



Strange particle production
Au+Au collisions at 1.23*A* GeV



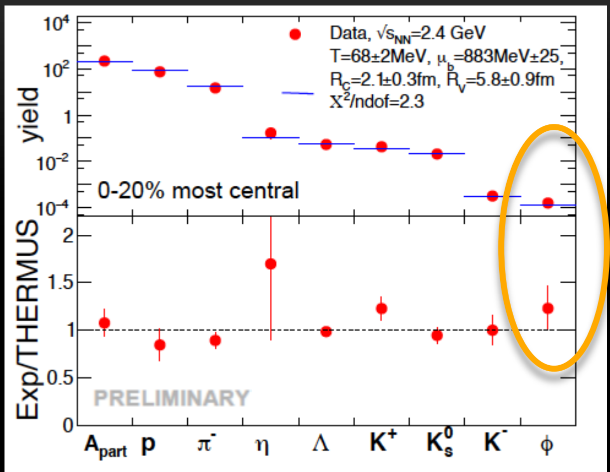
NN → NΛK⁺ E_{thr} *= 1.58 GeV*
NN → NNK⁺K⁻ E_{thr} *= 2.49 GeV*
NN → NNϕ E_{thr} *= 2.59 GeV*

- 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 $\alpha > 1$)

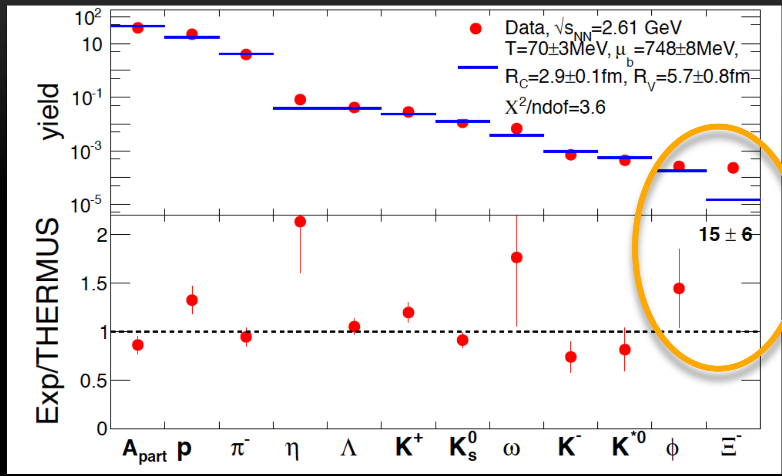
→ Large sensitivity to
  - → Multi-particle interactions
  - → Medium modifications

Comparing hadron yields with a statistical model

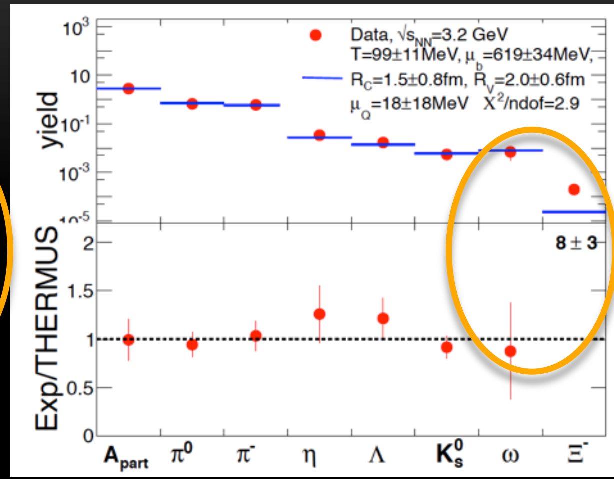
Au+Au at $\sqrt{s_{NN}}$= 2.42 GeV



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



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



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

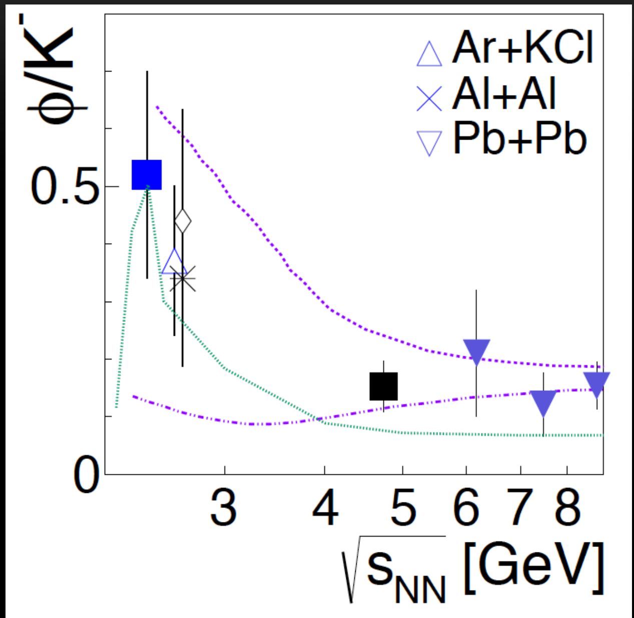
Thermal equilibrium also at low energies (high μ_B)?
What is the mechanism responsible for system thermalization?

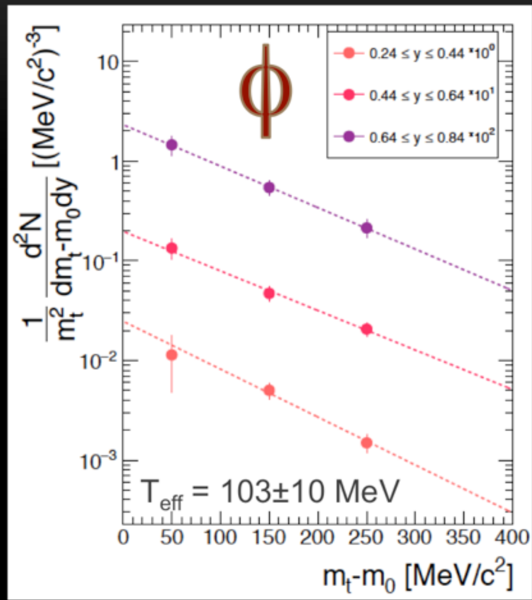
- Grand canonical ensemble (T, μ_B, V and sometimes γ_s)
- Strangeness canonically suppressed at low temperatures → needs additional parameter: $R_c < R_V$

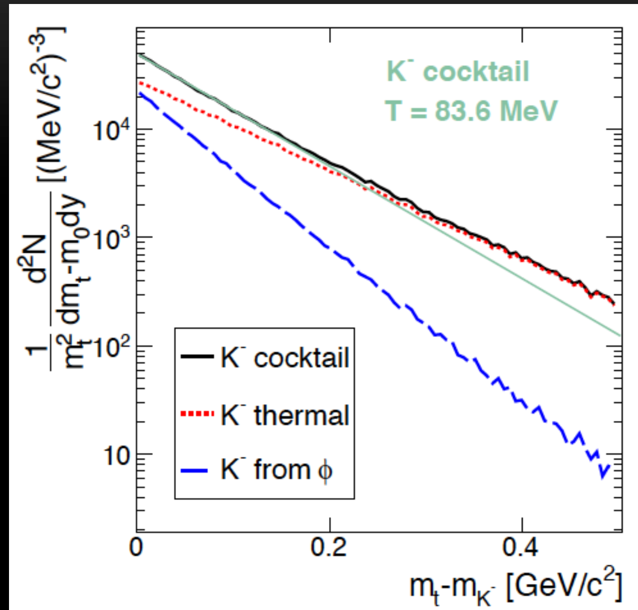
- Hadron abundances described by T, μ_B, R_V, R_c
- Surprises:
  - ϕ meson (hidden strangeness) not suppressed
  - Ξ^- (s = -2) yield "enhanced"

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

HADES Collab.: arXiv:1703.08418v1 [nucl-ex]







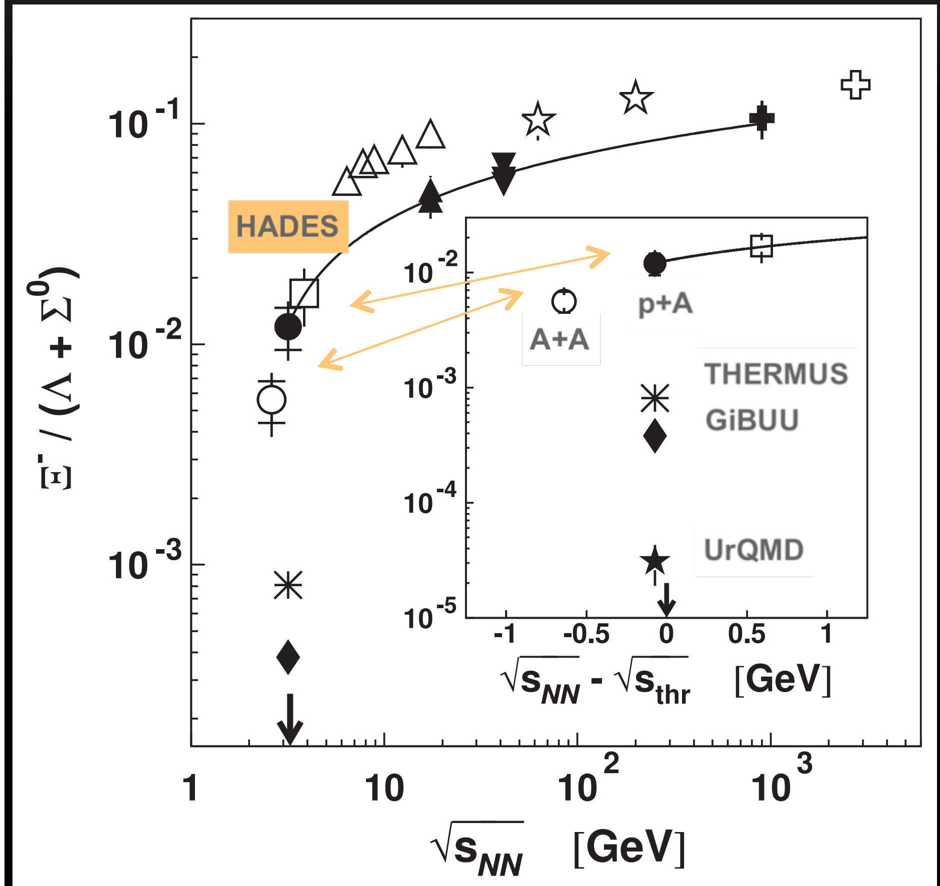
- Sizeable increase of ϕ meson to K^- ratio around production threshold 30% of K^- are from ϕ decays

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

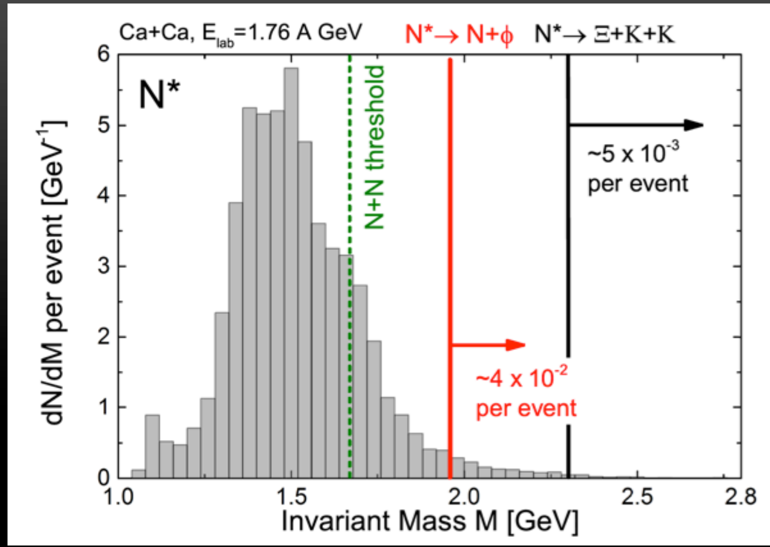
- Unique freeze-out criteria when ϕ decay kinematics is taken into account → no evidence for sequential freeze-out of K^+, K^- → support for statistical model

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



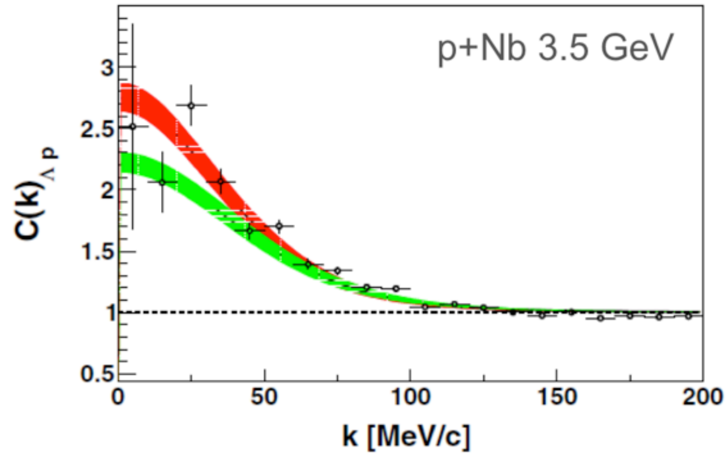
J. Steinheimer et al., J.Phys. G43 (2016) no.1, 015104

- Multi-strange baryons (Ξ, Ω) are expected to be a sensitive probe for compressed baryonic matter
- HADES observes unexpectedly large production cross sections in Ar+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

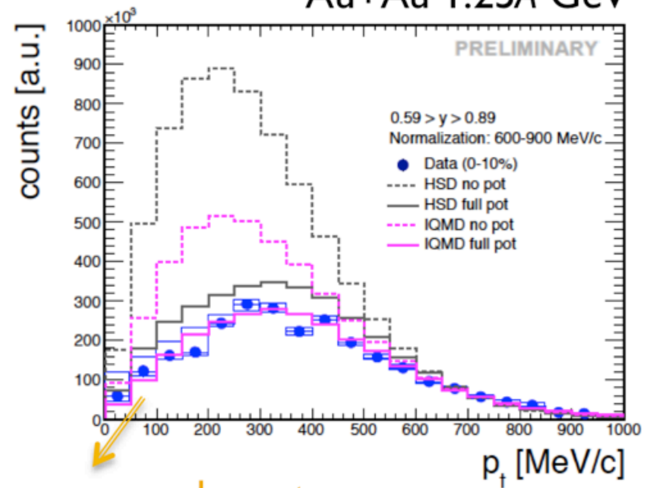
- Hyperons in neutron stars: new vistas?
  - Many models with hyperons fail to describe a $2M_{\odot}$ pulsar mass
  - Breakdown of baryonic models at high densities?
  - Onset of a new phase not based on baryon d.o.f.?
- QCD matter in compact stars
  - Composition of high-density neutron star cores: 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

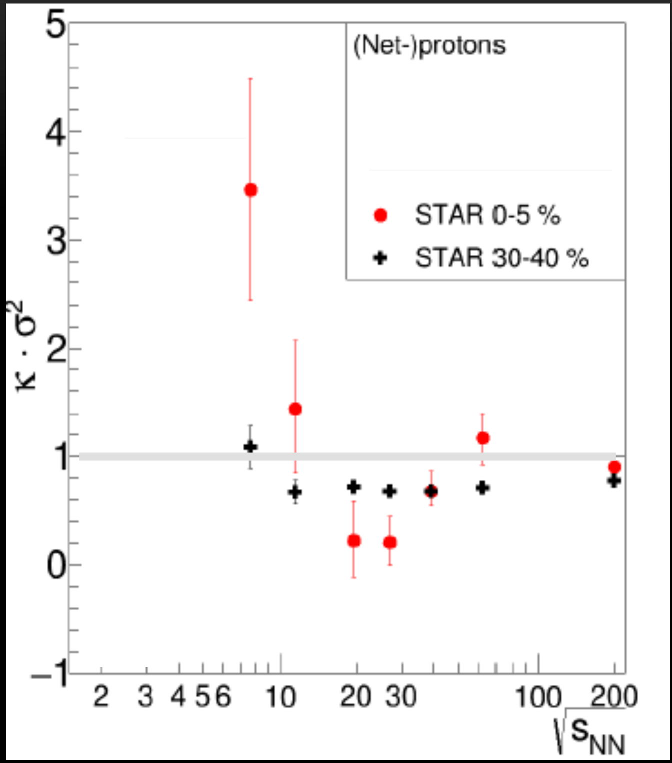
Au+Au 1.25*A* GeV



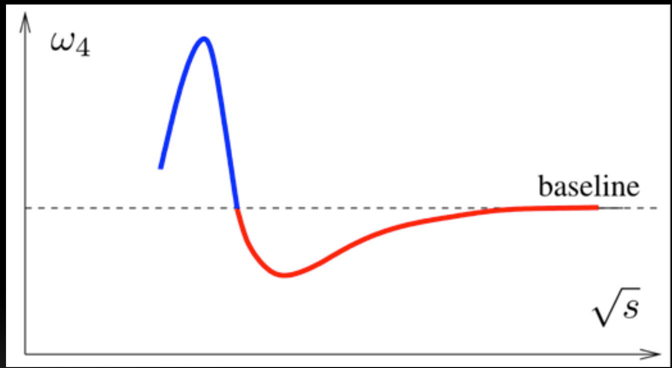
p_t coverage down to zero p_t

Fluctuations probe features of QCD phase diagram

STAR Collab., arXiv:1503.02558v2



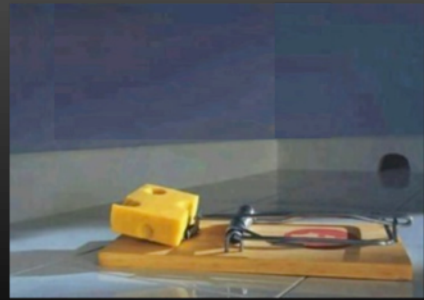
- Crossing features of the QCD phase-diagram (phase boundaries, CEP) is expected to result in:
- Diverging susceptibilities and correlation length
- „Extra" fluctuations of conserved quantities (e.g. baryon number, charge, strangeness)
- Observable discontinuities of the higher moments of particle number distributions, visible e.g. in a beam energy scan



see e.g. B. Friman et al, EPJC 71 (2011) 1694

M. Stephanov, PRL. 107 (2011) 052301

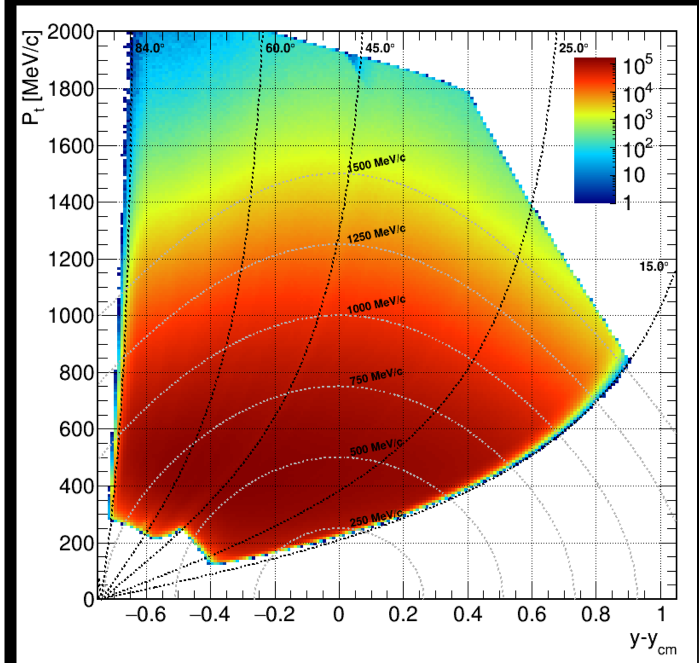
(Net)-Proton Number Fluctuations
The experimental challenge …



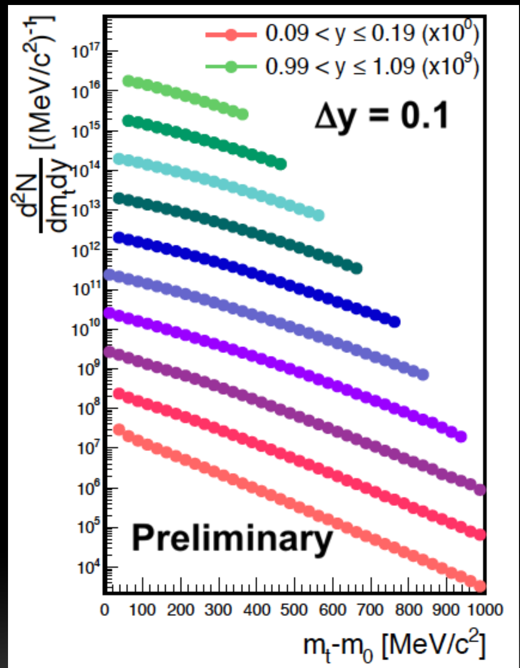
There is no such thing as a free lunch

- Phase space region, not to large not to small
- Data need efficiency corrections! Note that efficiency = acc × det.eff. × rec.eff.
  → Two methods tested and validated with full MC simulations with realistic detector response
- Volume number fluctuations of centrality selection, no antiprotons, no terms cancel!
- Various effects and their impact on the corrected moments systematically studied

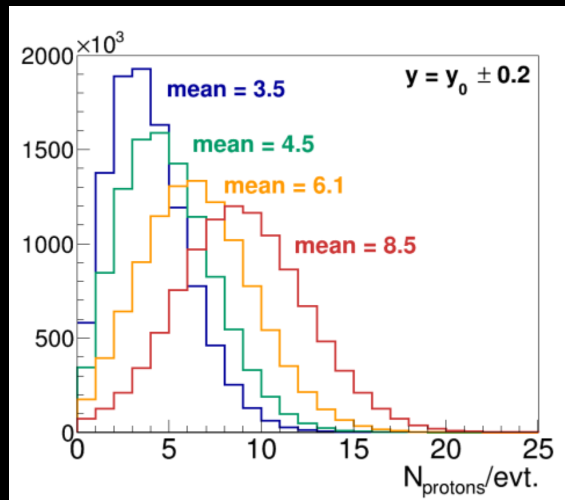
HADES y – p_t coverage for protons



Proton m_t spectra

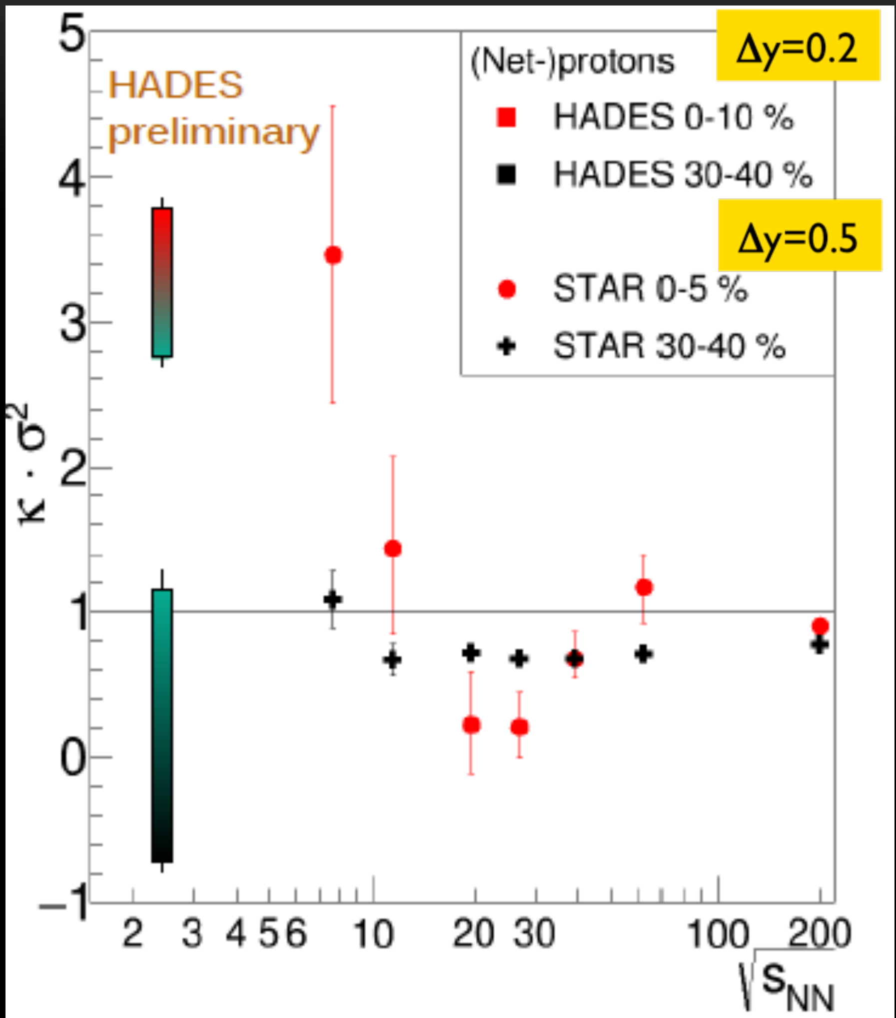


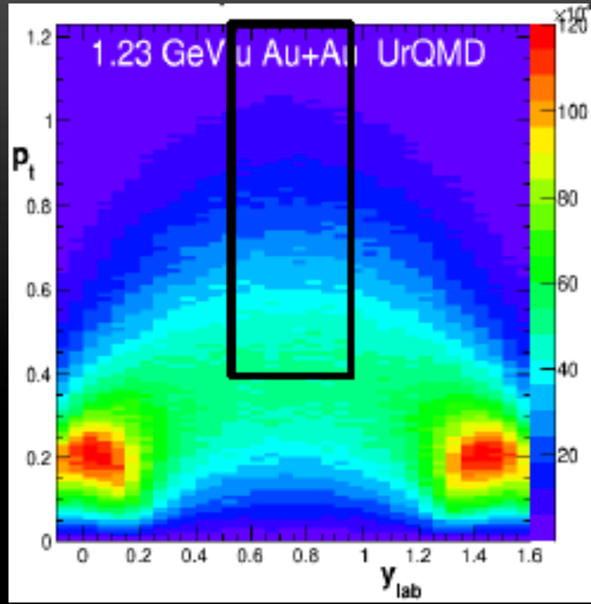
Proton multiplicity distributions



Analysis based on 40×10⁶ Au+Au evts divided into 4 centrality classes (determined with FW)

Comparison with STAR BESI





Rapidity gap = 1.5 units!

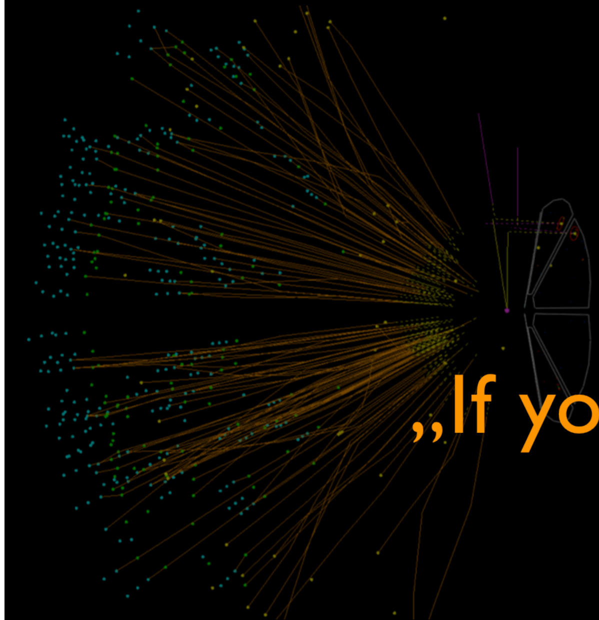
Need to select a phase-space bite which avoids spectators and stays within the HADES acceptance, but far enough from Poisson limit!
→ Δy=0.2

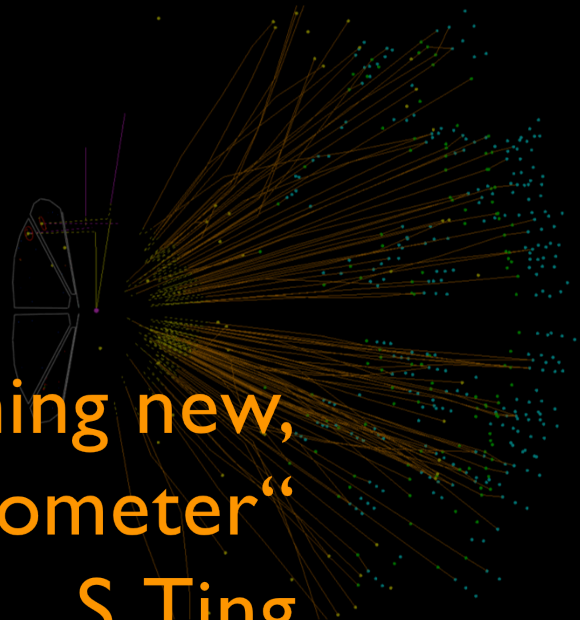
How about bound protons? d/p = 0.3 – 0.4
→ deuteron fluctuation analysis is ongoing

red/black = unfolding (preferred method) + vol. flucs. corr.

green = evt-by-evt eff correction of factorial moments + vol. flucs. corr.

See details QM talk R. Holzmann

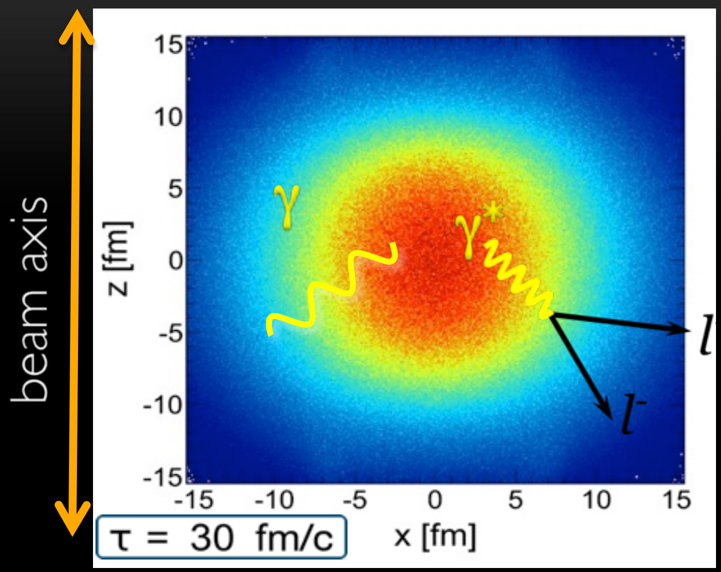




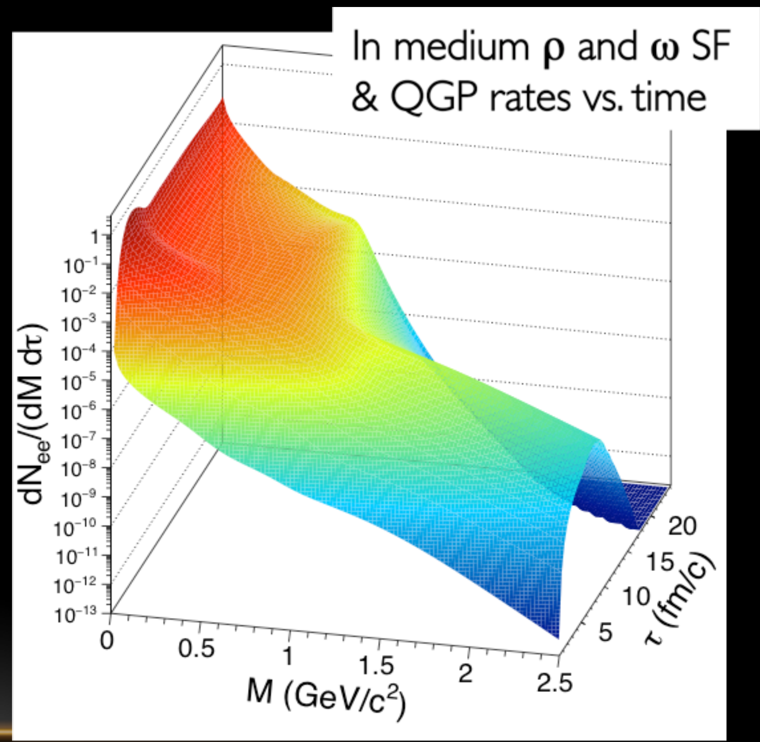
„If you want to detect something new,
build a dilepton spectrometer“
S. Ting

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})



The vector correlator is directly accessible in HIC:

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

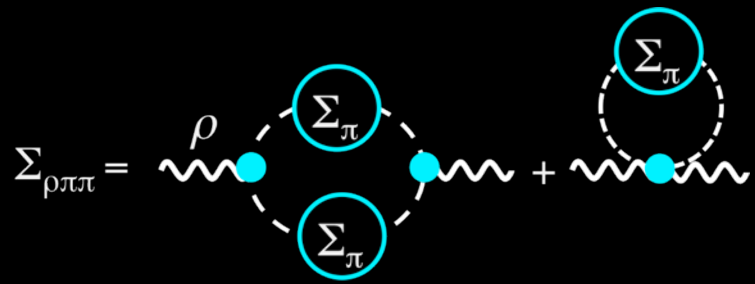
→ Unique direct access to in-medium spectral function

ρ meson in hot and dense medium…

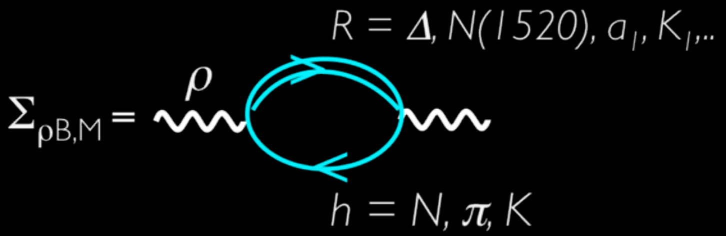
… interacts with hadrons from heat bath → in-medium ρ-propagator

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

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



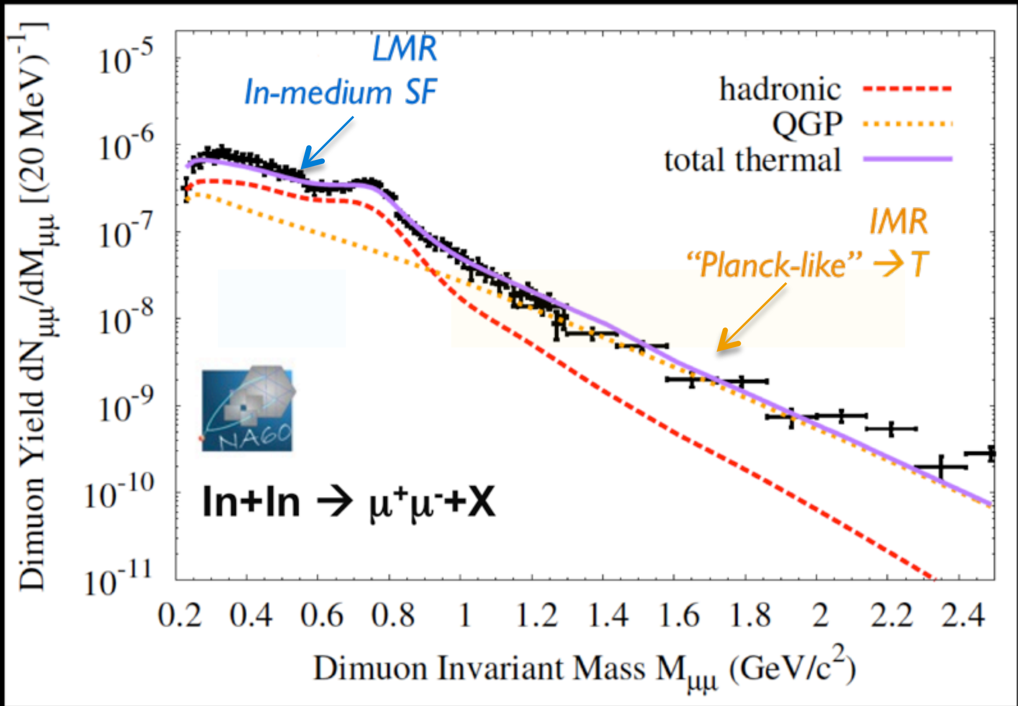
- Direct ρ-hadron Scattering
  [Haglin, Friman et al, Rapp et al, Post et al, …]



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

Characteristic features of excess radiation

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



Chronometer

- LMR dilepton yield
  → fireball lifetime

Thermometer

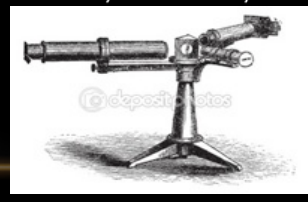
- IMR slope → emitting source temperature (true T, no blue shift)

Barometer

- Inverse-slope analysis, v_2
  → fireball acceleration

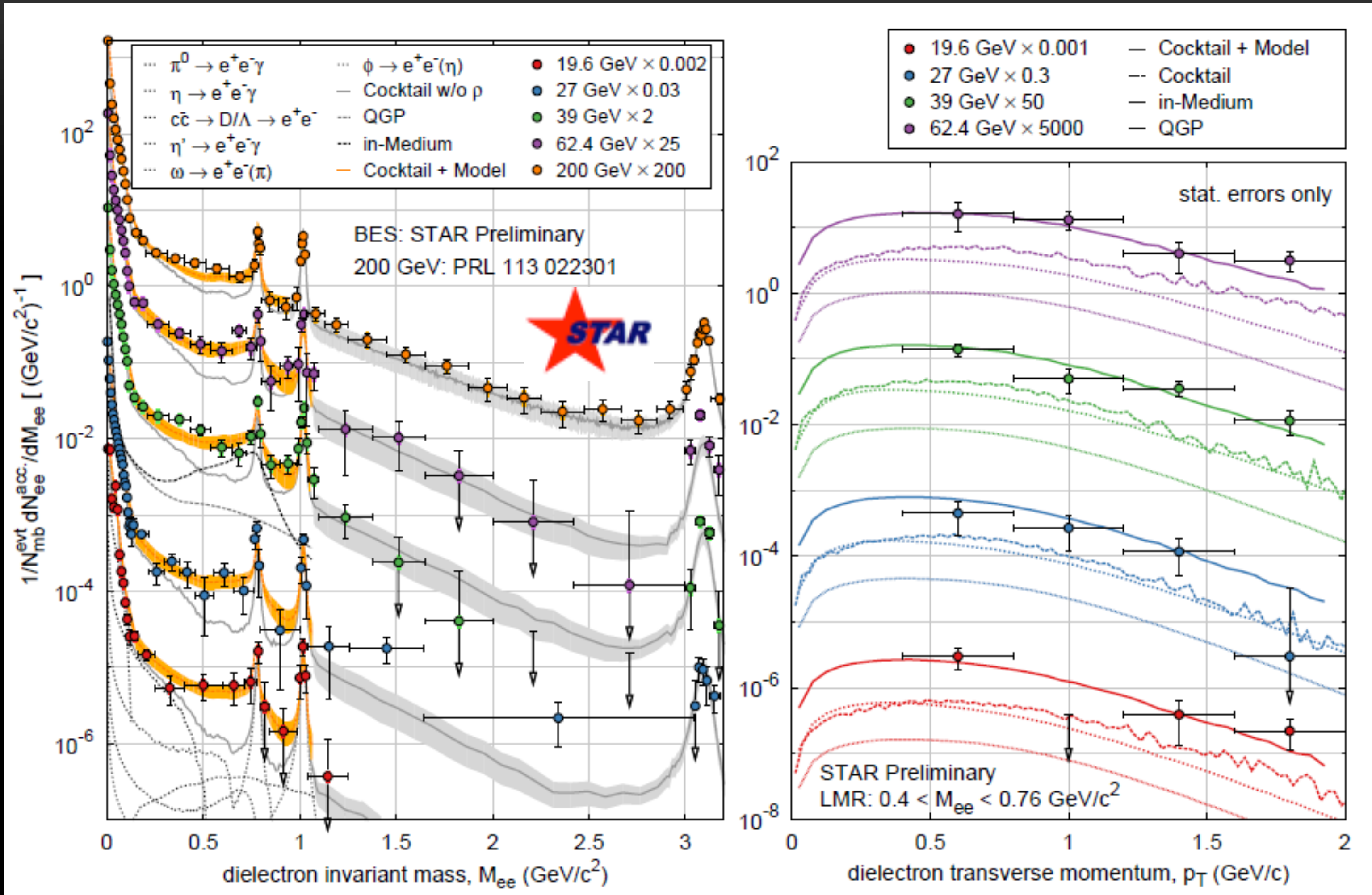
Spectrometer

- Shape and yield
  → restoration of chiral symmetry



Low-mass dileptons (LMR) M<1.1 GeV/c^2
Intermediate-mass dileptons (IMR) M<1.1 GeV/c^2

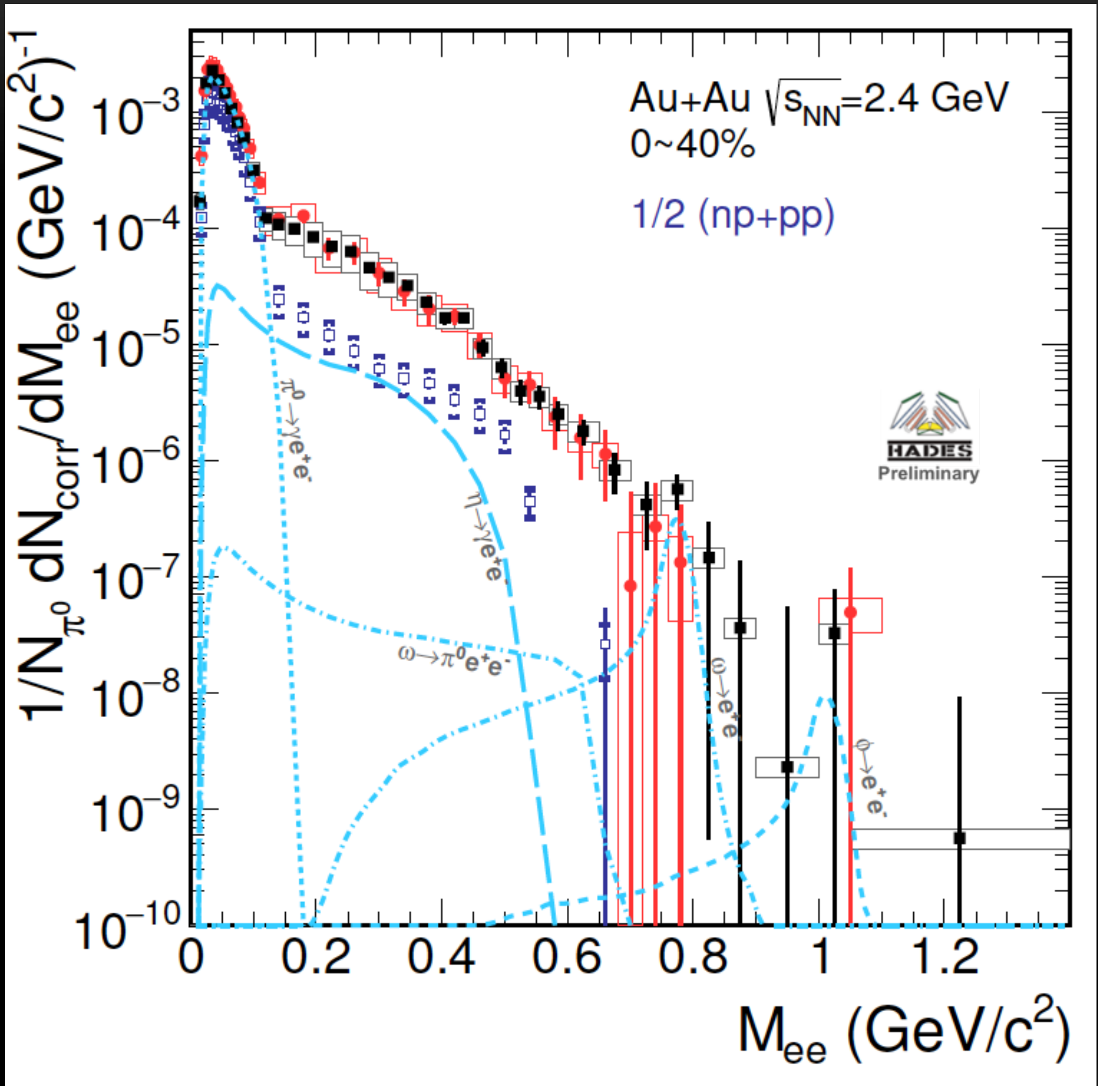
Low-Mass e^+e^- Excitation Function: 19.6-200 GeV



STAR data: P. Huck et al., Nucl.Phys.A931 (2014)
Model: Rapp/Wambach/Hees

- Compatible with predictions from melting ρ meson
- Should get maximal at low energy

Virtual photon emission in Au+Au collisions

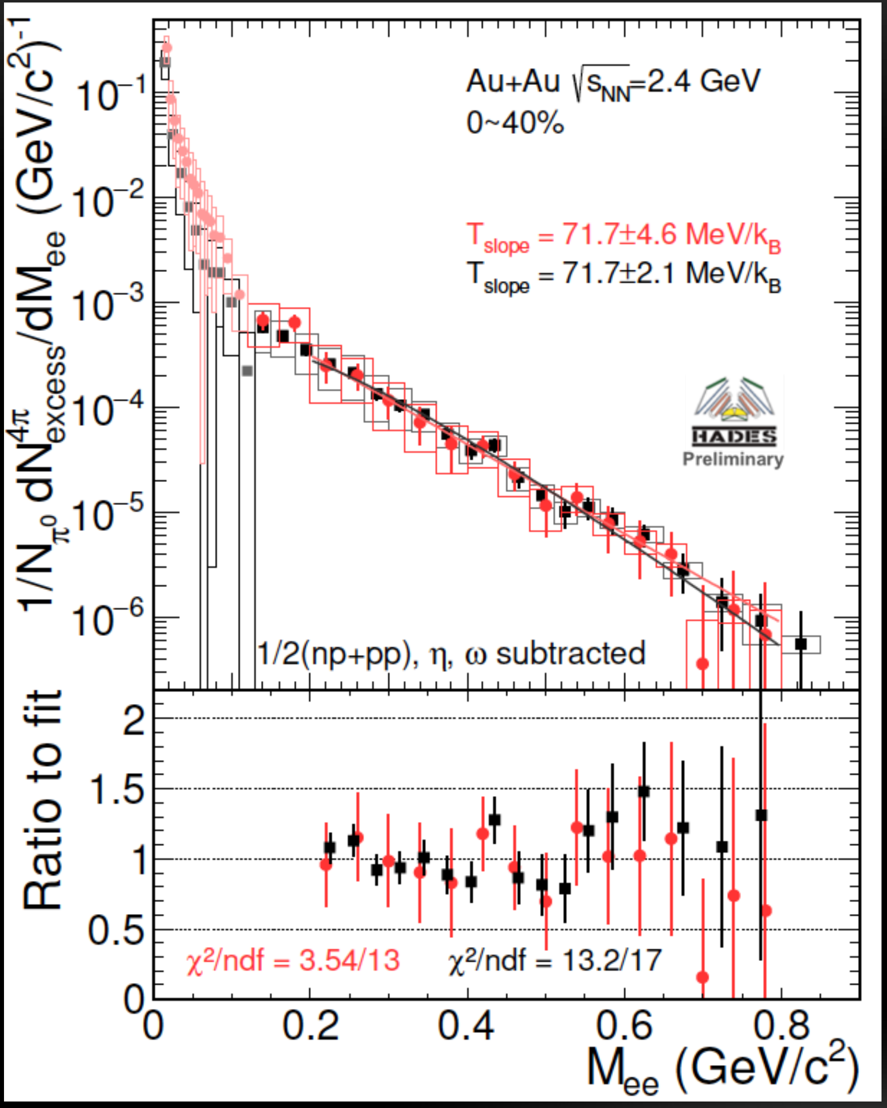


HADES collab., under the collaboration review

- Normalization to number of neutral pions N_π
- 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 $0.15<M<0.7$ GeV/c^2 → true in-medium effect

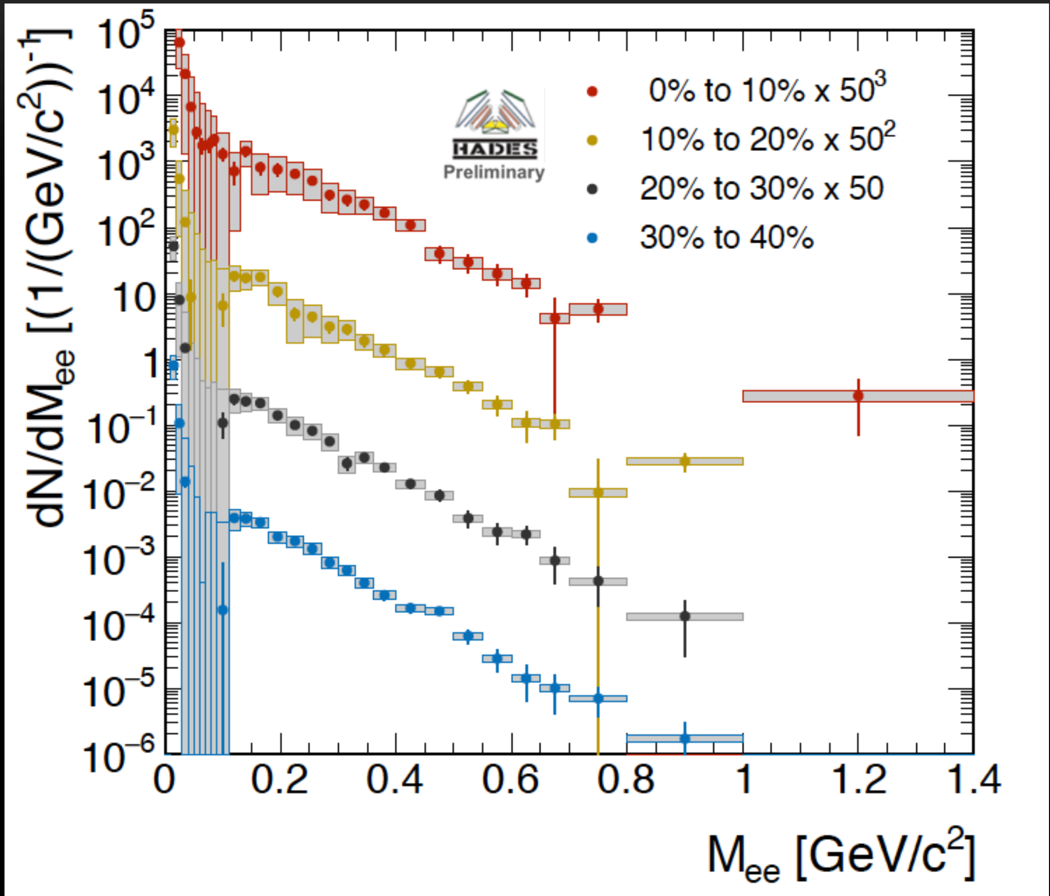
Dileptons as thermometer

Measurement of radiating source temperature

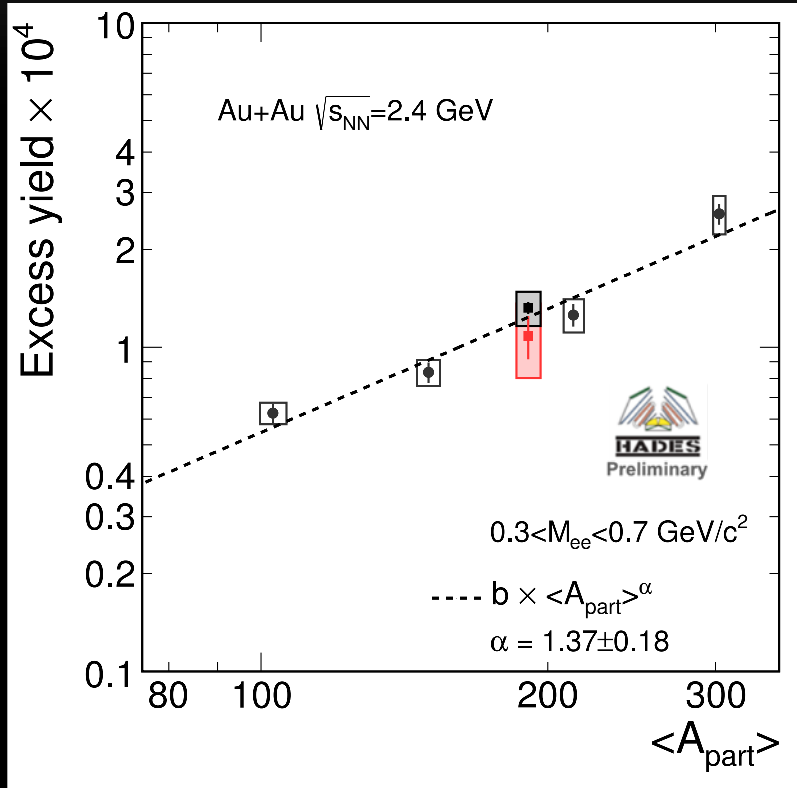


- ❑ Almost exponential spectrum up to vector meson region!
- ❑ M_{ee}<1 GeVc² ~ exponential fall-off
  → 'Planck-like'
- → fit $\frac{dN}{dM} \sim M^{\frac{3}{2}} \times \exp\left(-\frac{M}{T}\right)$ to range M=**0.1−0.8** GeV
- → T=72±4 MeV
- ✓ Agrees with coarse-grained approach

Centrality and system size dependence of the excess



Excess radiation $0.3 < M < 0.7$ GeV/c^2



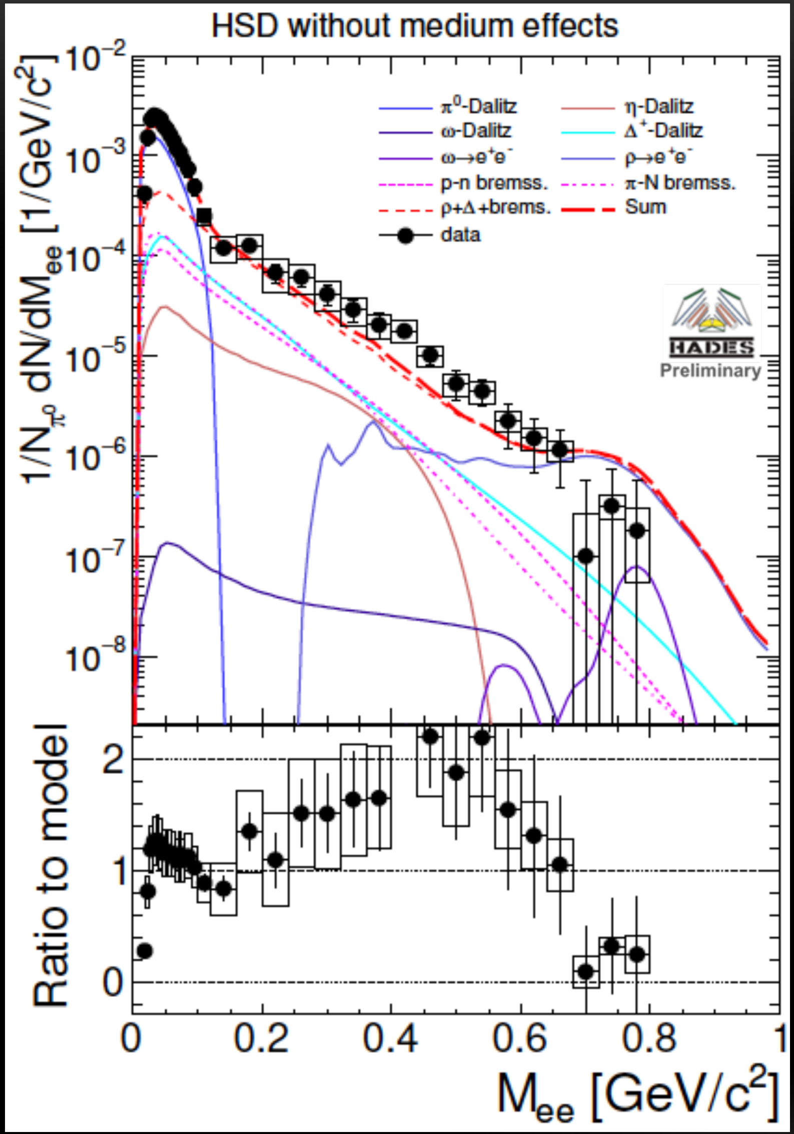
What is the nature of the excess?

→ Regeneration of baryonic resonances

→ Subsumed into spectral functions

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

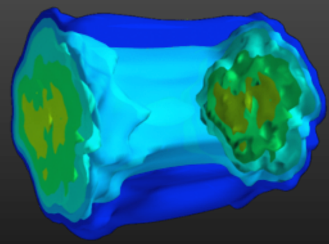
Comparison to microscopic transport models

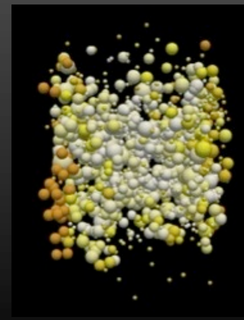


- In PHSD, dilepton excess above NN due mostly to Δ regeneration & decay
  E. Bratkovskaya et al., Phys.Rev. C87 (2013) 064907
- In GiBUU more baryon resonances are included, e.g. N*(1520)
  → comparison to data is on-going
  J. Weil et al., Phys.Rept. 512 (2012) 1-124
- Incoherent sum of dilepton production channels
- Model with vac. SF misses data
  → room for medium modifications!

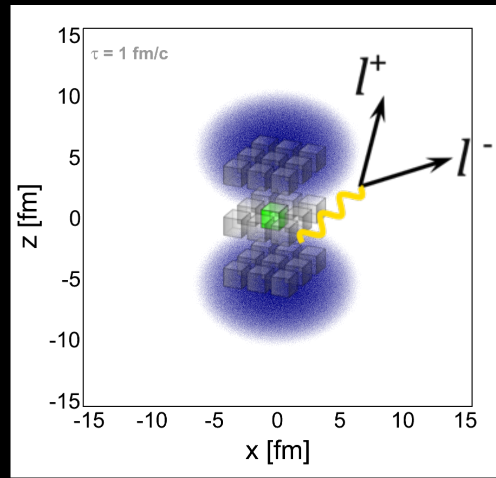
PHSD33_source_code.zip as of October 16th 2016

Coarse-grained transport approach

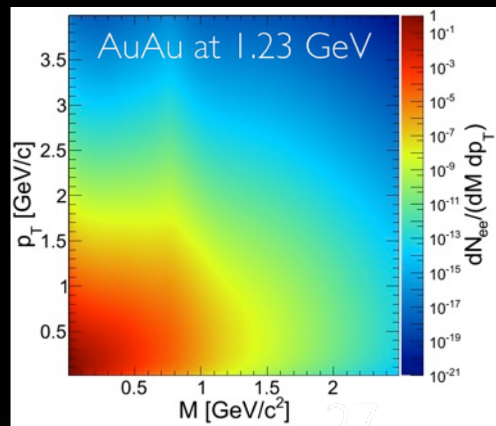




- "Combine" the advantages of two descriptions: hydrodynamics & transport
- Simulate events with a transport model
  → ensemble average to obtain smooth space-time distributions



- Divide space-time evolution into 4-dimensional cells
  21 x 21 x 21 space cells (1fm^3), 30 time steps → ~ 280 k cells
- Determine for each cell the bulk properties like T, μ_B, μ_π, collective velocity

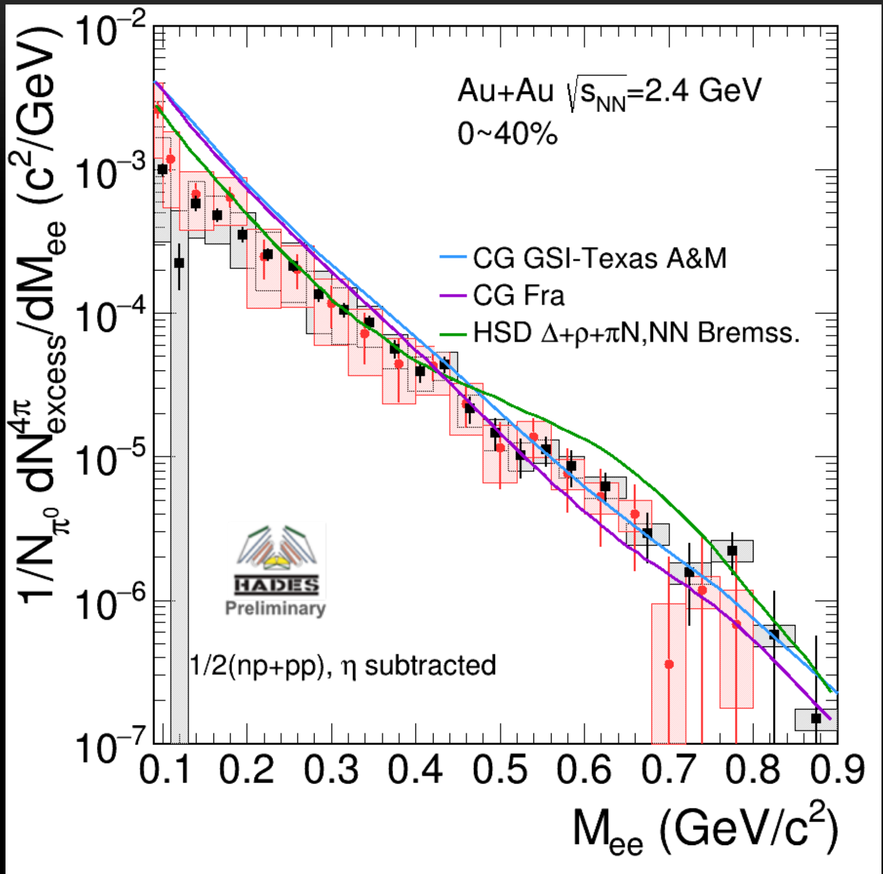


- Apply in-medium ρ & ω spectral functions to compute EM emission rates
  → parameterization of RW in-medium spectral function
- Sum up contributions of all cells

Huovinen et al., PRC 66 (2002) 014903
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J.A52 (2016) no.5, 131

Thermal dileptons at SIS18?

Excess yield fully corrected for acceptance



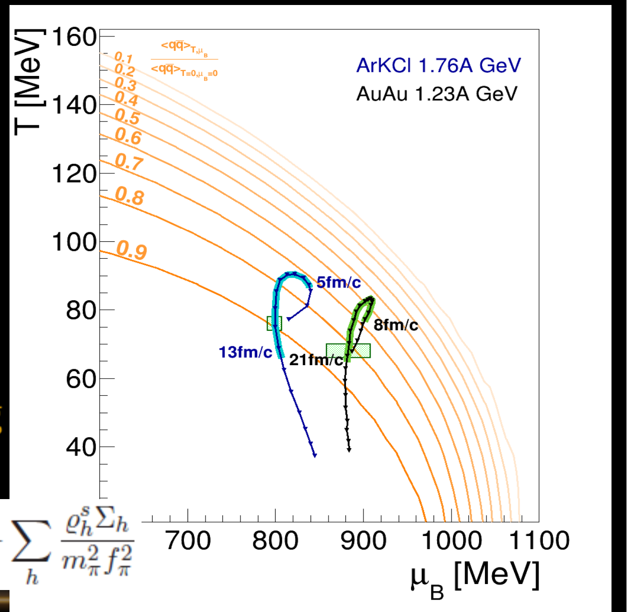
HADES collab., under the collaboration review

- Excess yield driven by temperature and size/ lifetime (four-volume integral)
- Almost exponential spectrum
  - → Strong broadening of the in-medium ρ
  - → Supports baryon-driven medium effects at UrHIC (SPS and RHIC)!
- <*T*>emitting source = 72 ± 2 MeV/kB

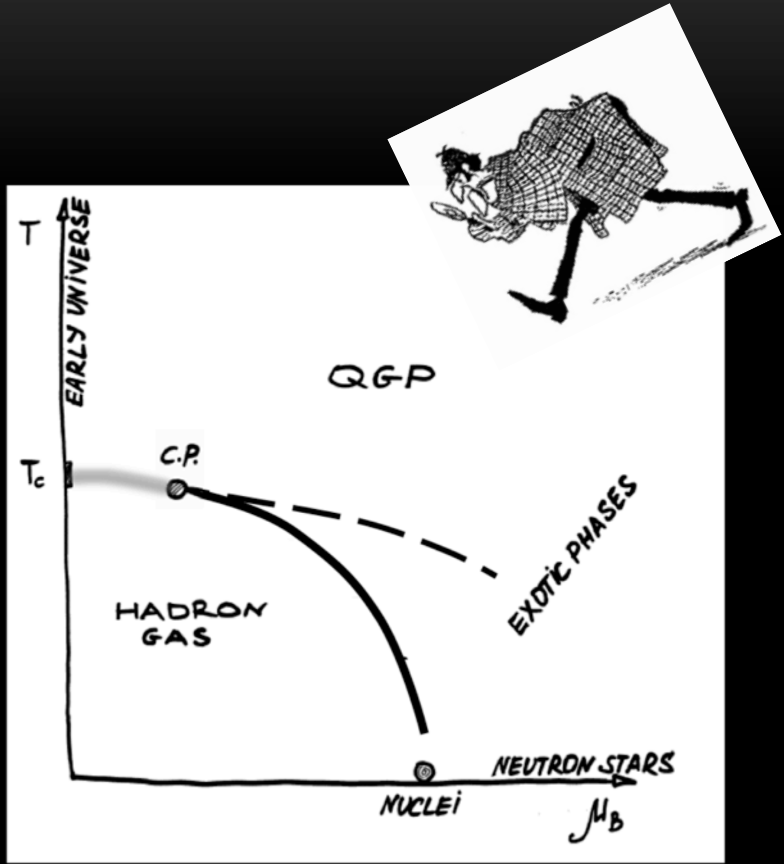
T_{max} = 85 MeV, ρ = 3 ρ_0

→ Excitation of the vacuum (melting of condensate) matches spectral medium effects!

$$\frac{\langle\langle\bar{q}q\rangle\rangle(T,\mu_B)}{\langle\bar{q}q\rangle} = 1 - \sum_h \frac{\varrho_h^s \Sigma_h}{m_\pi^2 f_\pi^2}$$



Dileptons and QCD phase diagram of matter

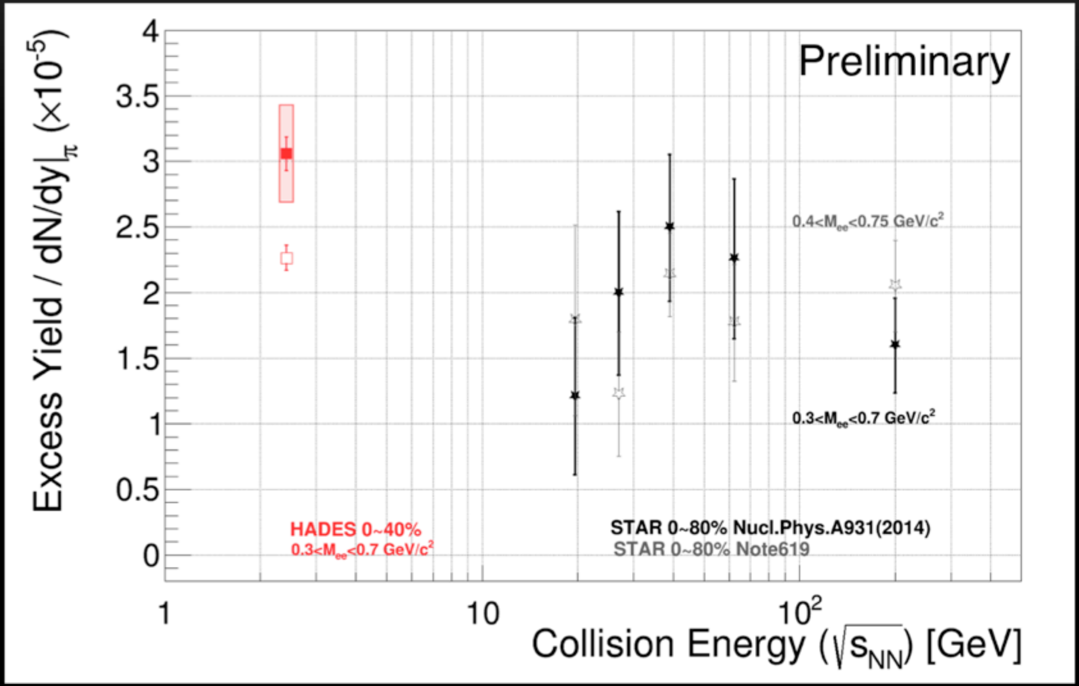


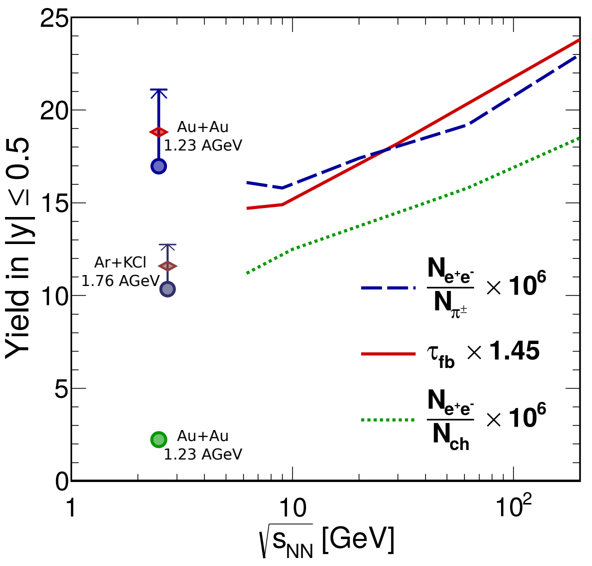
Excitation functions

- Fireball lifetime
- Emitting source temperature

Energy dependence of low-mass excess

F. Seck et al., proceedings CPOD2016
R. Rapp, H. van Hees: PLB 753 (2016)



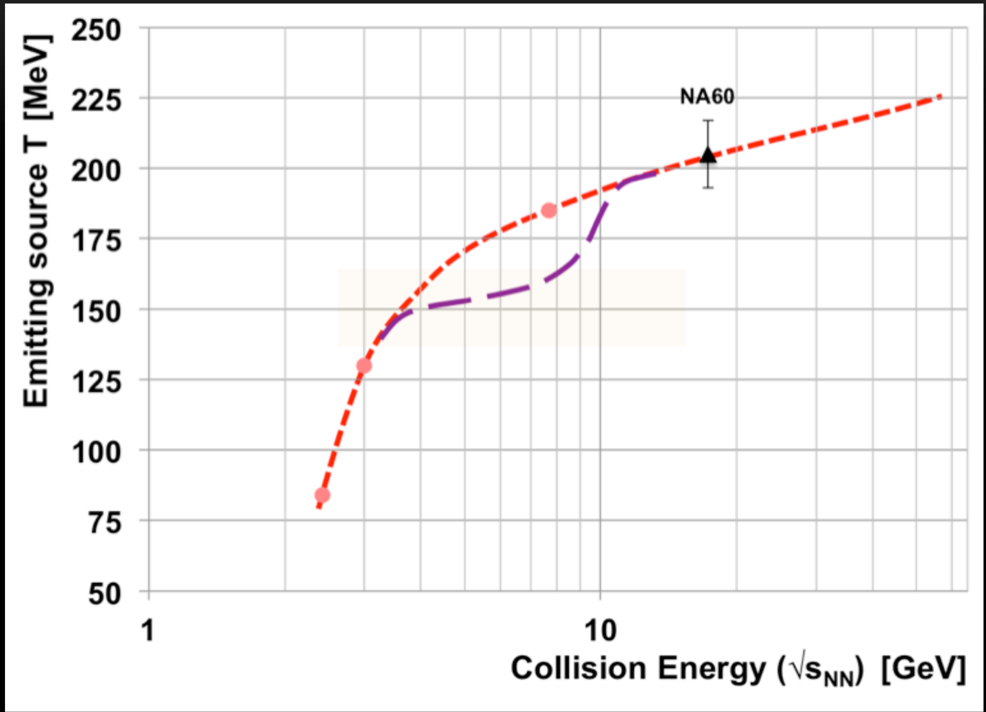


Integrated yield of thermal radiation in the mass range 0.3-0.7 GeV/c^2 is sensitive to the lifetime of the fireball

→ Search for anomalous fireball lifetime around phase transition & critical point

- Quite moderate energy dependence
- Note the very similar A_{part} scaling independently of $\sqrt{S_{NN}}$
- Dilepton yield determined by interplay between temperature and $V \otimes \tau_{coll}$

Energy dependence of intermediate mass slope



Dashed violet curve corresponds to a speculated shape with phase transition

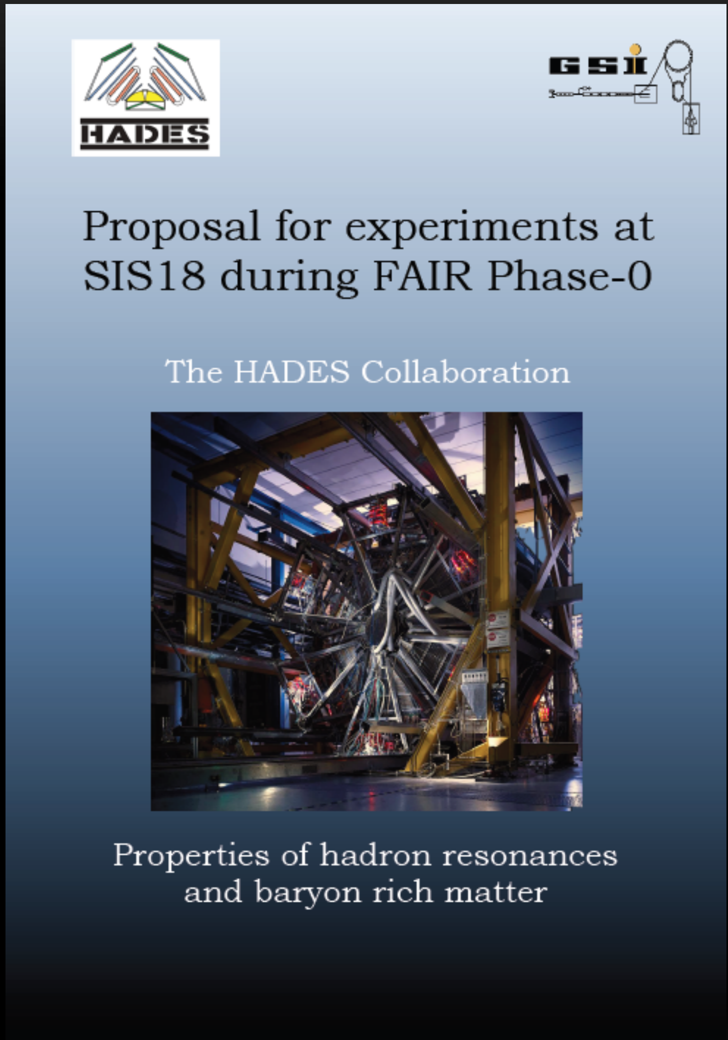
- Measures the emitting source temperature (true, no blue shift)

→ Measure T_s (note, $T_s < T_{initial}$) "caloric curve"

→ Plateau around onset of deconfinement?
[see e.g. M. D'Agostino et al. NPA 749 (2005) 5533]

- Precision measurements are the key

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


HADES

Proposal for experiments at SIS18 during FAIR Phase-0

The HADES Collaboration

Properties of hadron resonances and baryon rich matter

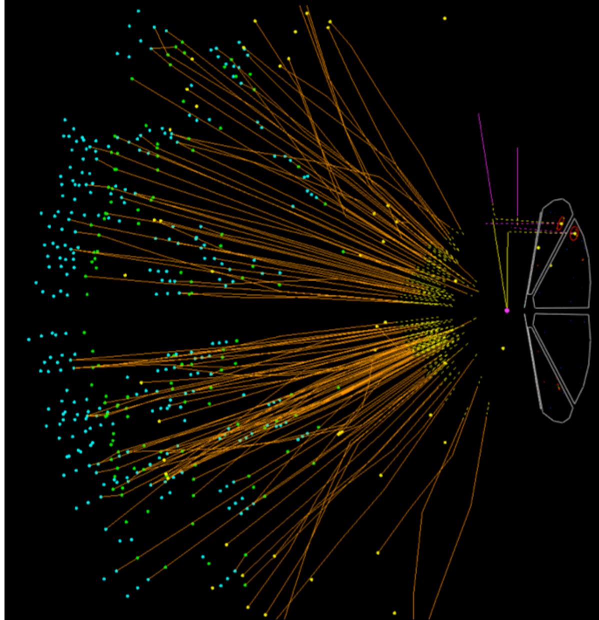
- High statistics π+p, π+A, p+A, A+A
- Results in elementary collisions provide an important baseline for current and future explorations in HIC
- Submitted to PAC on June 19, 2017

Résumé and prospects

There is no mission impossible

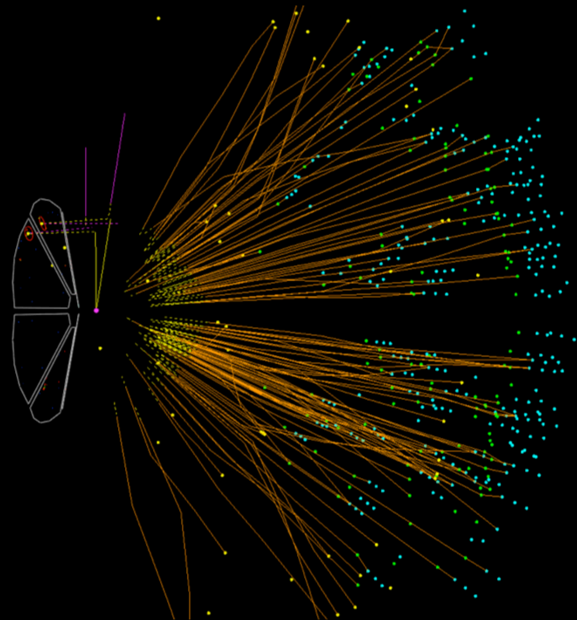
- First measurement of acceptance corrected excess spectrum at low energies → Robust understanding of low-mass dilepton excess radiation by ρ-baryon coupling (at top RHIC, RHIC BES, SPS and SIS18 energies coarse-grained transport approach + Rapp/Wambach SF)
- Analyzed proton nb fluctuations.
  → HADES data allow to extend RHIC results towards low $\sqrt{S_{NN}}$, but interpretation needs input from theory.
- Unexpectedly high ϕ multiplicities. Feed down correction important when interpreting Kaon spectra.
- Completion of the excitation functions of flow, T_{ch}, T_{kin} and β_T
- Exciting results from Au+Au collisions at $\sqrt{S_{NN}}$=2.42 GeV
  → suggest "thermalize" strongly interacting medium created

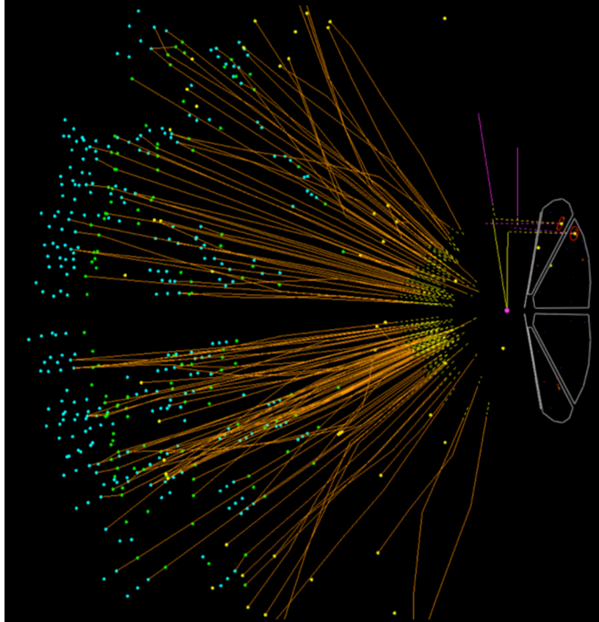
- Strong scientific program for FAIR Phase-0
- Important measurements to complement the exploration of the phase diagram and to provide a valuable reference measurements



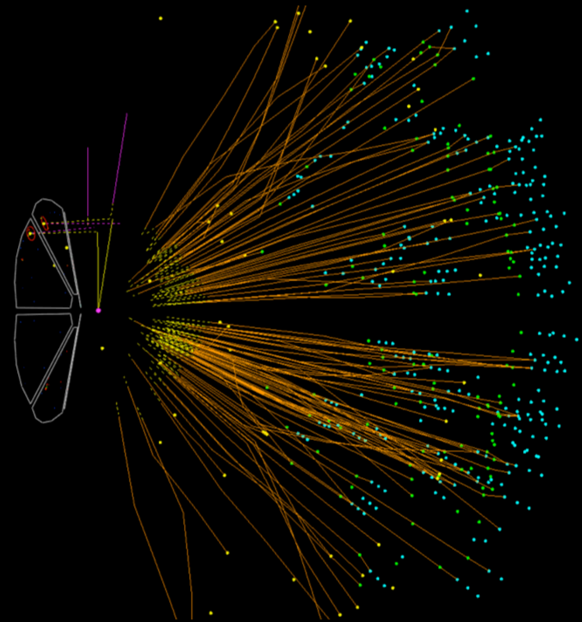
Thank you

for your attention!





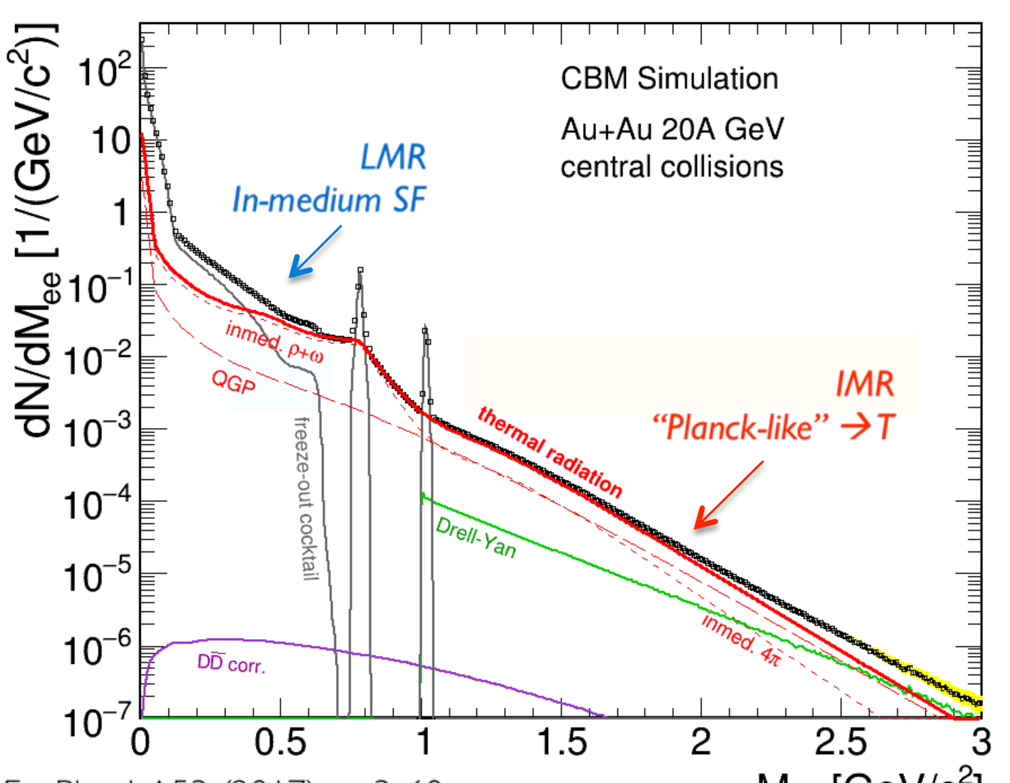
Bonus slides



Characteristic features of dilepton invariant mass spectra

→ Dilepton spectra represent the space-time integral of EM radiation

→ Mass dependence allows separation of collision stages



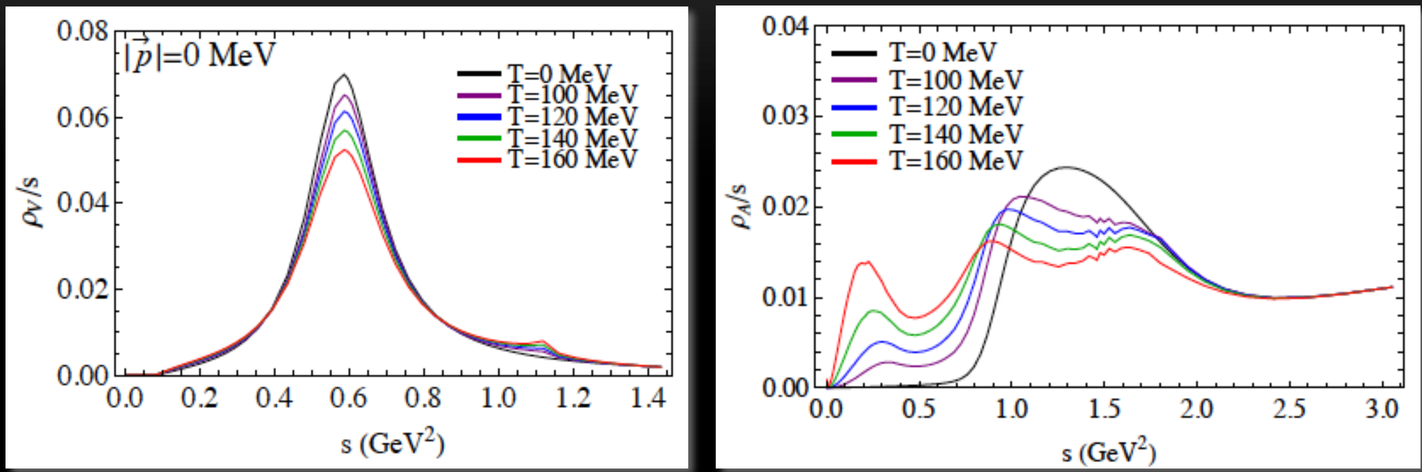
Eur.Phys.J. A53 (2017) no.3, 60

- Drell-Yan (NN → l^+l^-X)
- Heavy-flavor: $c\bar{c}$ → l^+l^-
- Medium radiation (R. Rapp):
  - QGP: $\bar{q}q$ → l^+l^-
  - In-medium ρ, ω → l^+l^-
  - "4π annihilation": πa_1 → l^+l^-
- Final state decays (hadron cocktail): π^0, η → γe^+e^-

Low-mass dileptons (LMR) M<1.1 GeV/c²

Intermediate-mass dileptons (IMR) M<1.1 GeV/c²

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