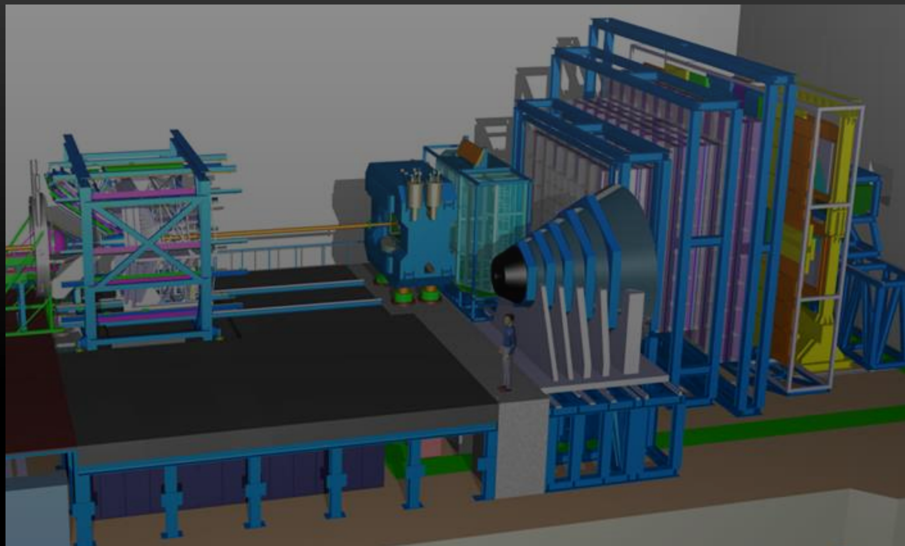


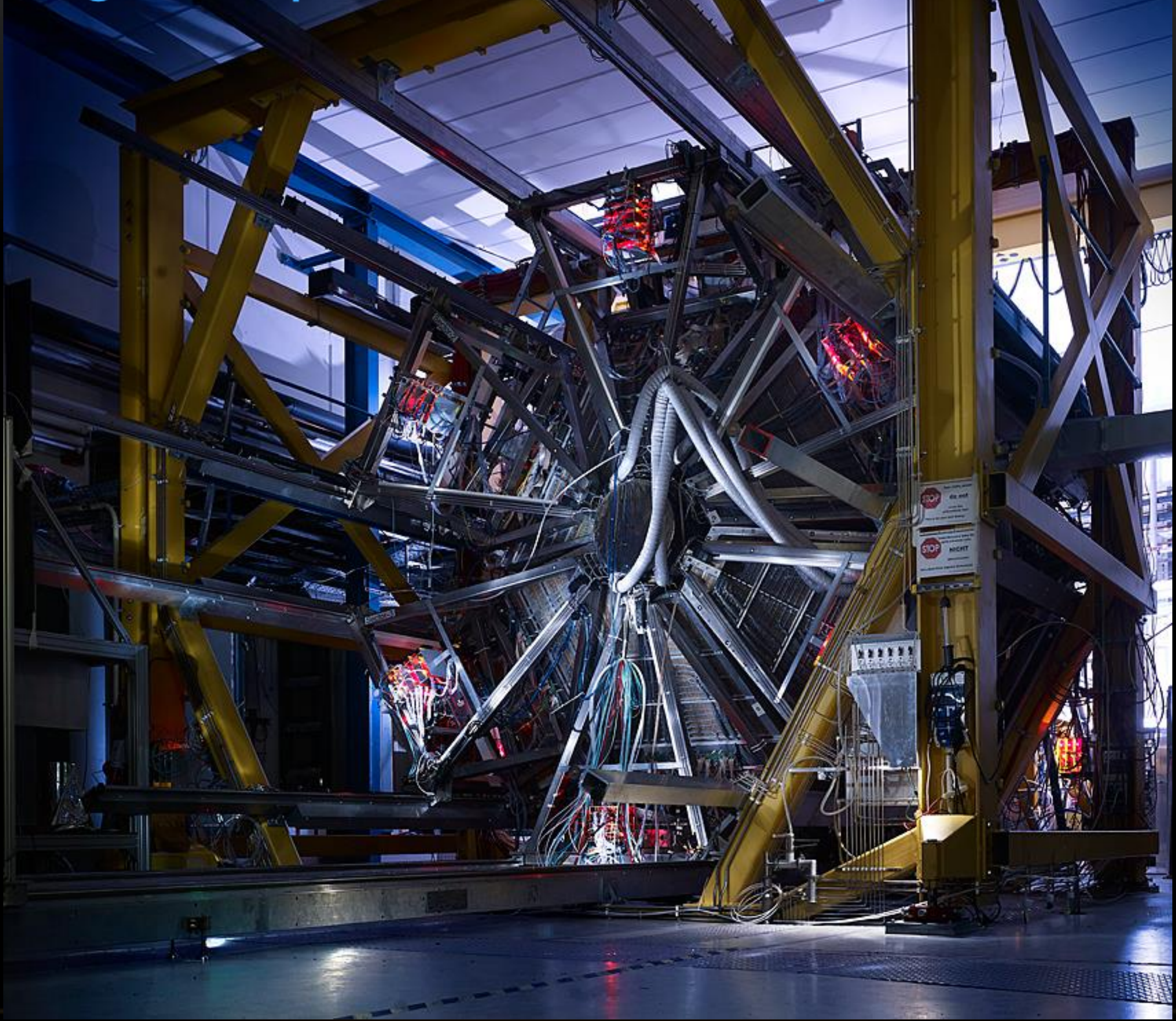
GDR QCD 2016

8-10 novembre 2016
IPN Orsay
Europe/Paris timezone

Future measurements with HADES and CBM at FAIR and FAIR-Phase0 at GSI

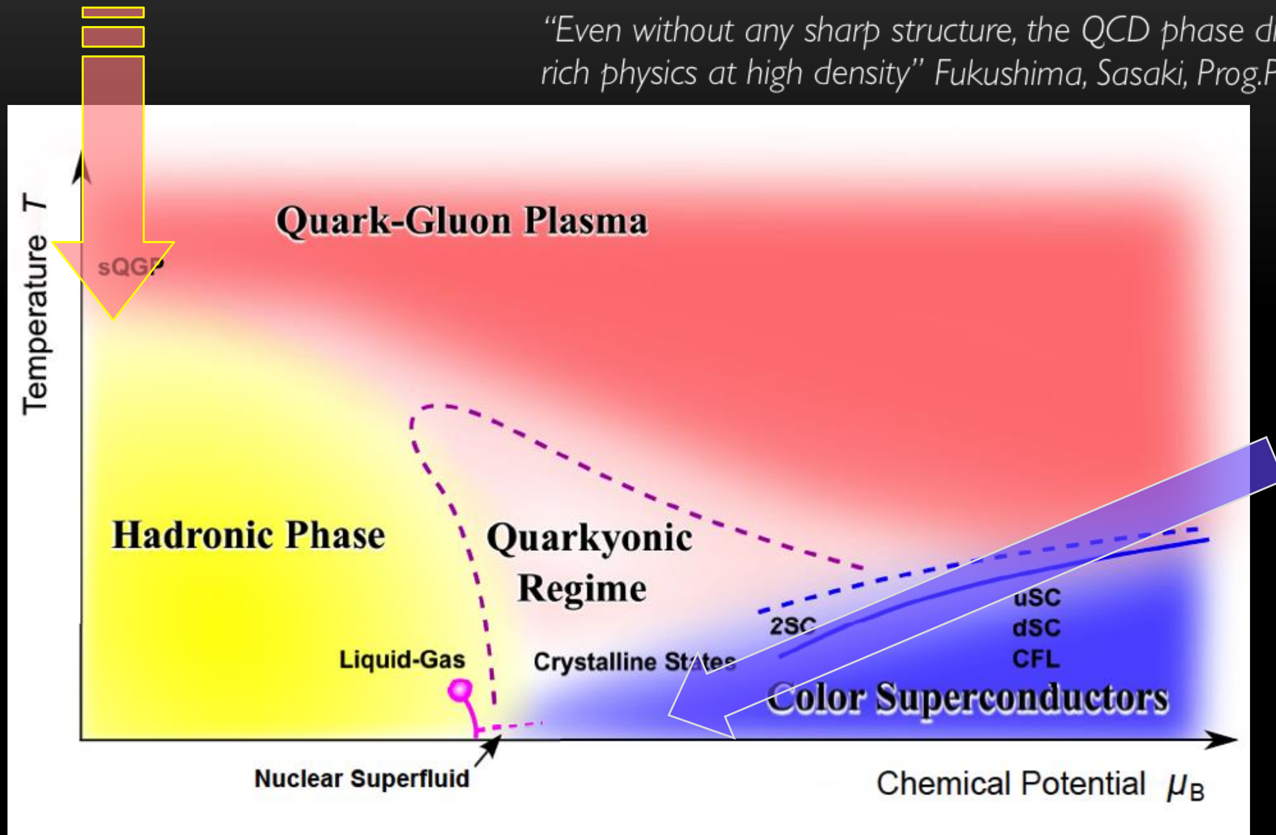
Tetyana Galatyuk
for the HADES and CBM Collaborations
Technische Universität Darmstadt / GSI Helmholtzzentrum für Schwerionenforschung

High Acceptance DiElectron Spectrometer



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)

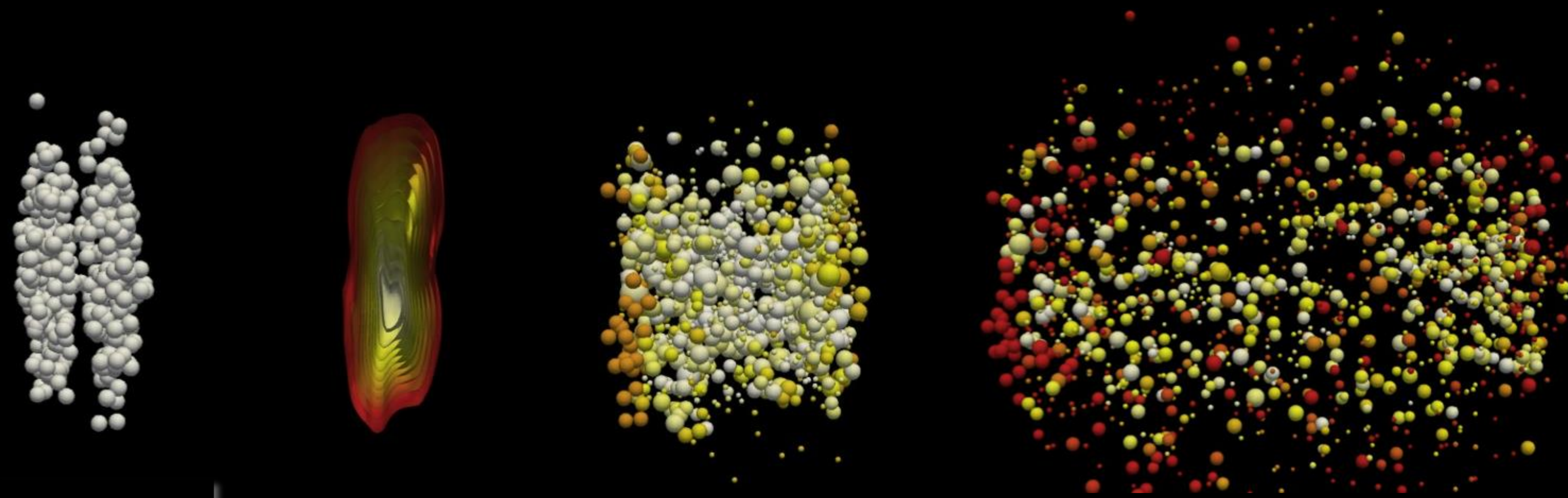


What are the fundamental properties of strongly interacting matter under extreme temperatures and densities?

- 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

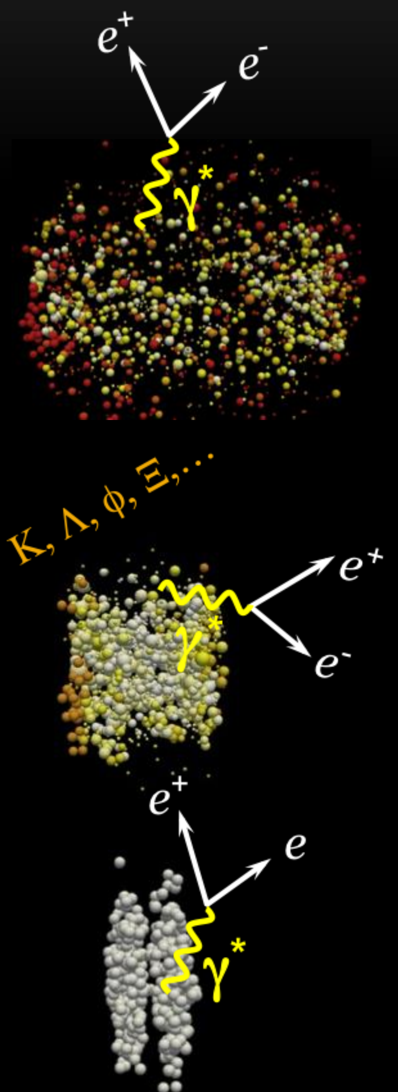


First-chance NN collisions | QGP | Hadronic matter | Freeze-out

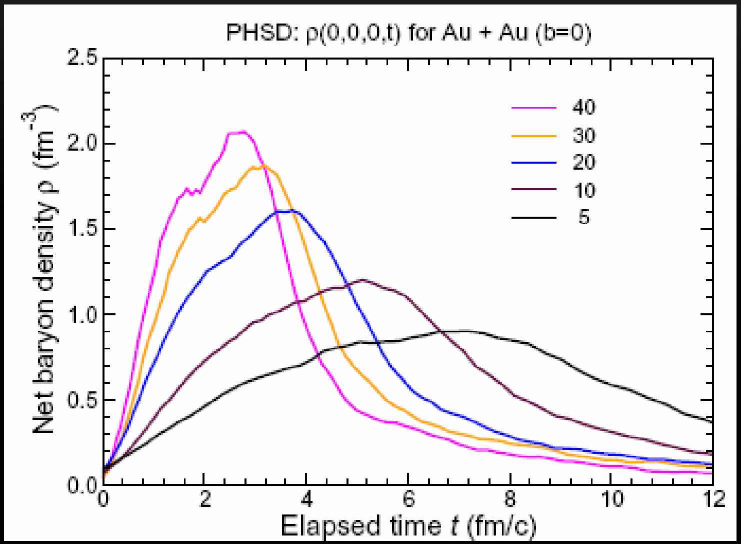
τ ~1 – 20 fm (~10^{-23} s)

Systematic experimental measurements (E_{beam}, A)
→ extract numbers that might be related to the QCD phase diagram

Baryonic matter at SIS beam energies

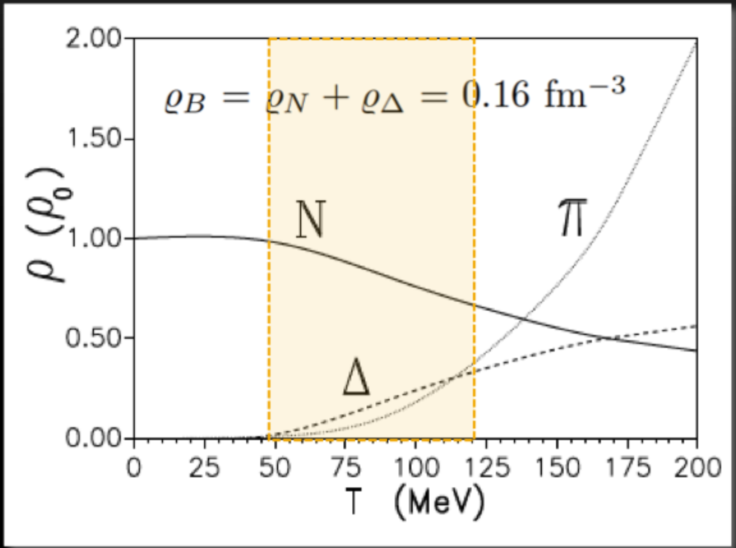


Evolution of net baryon density



CBM Physics Book (2009)

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

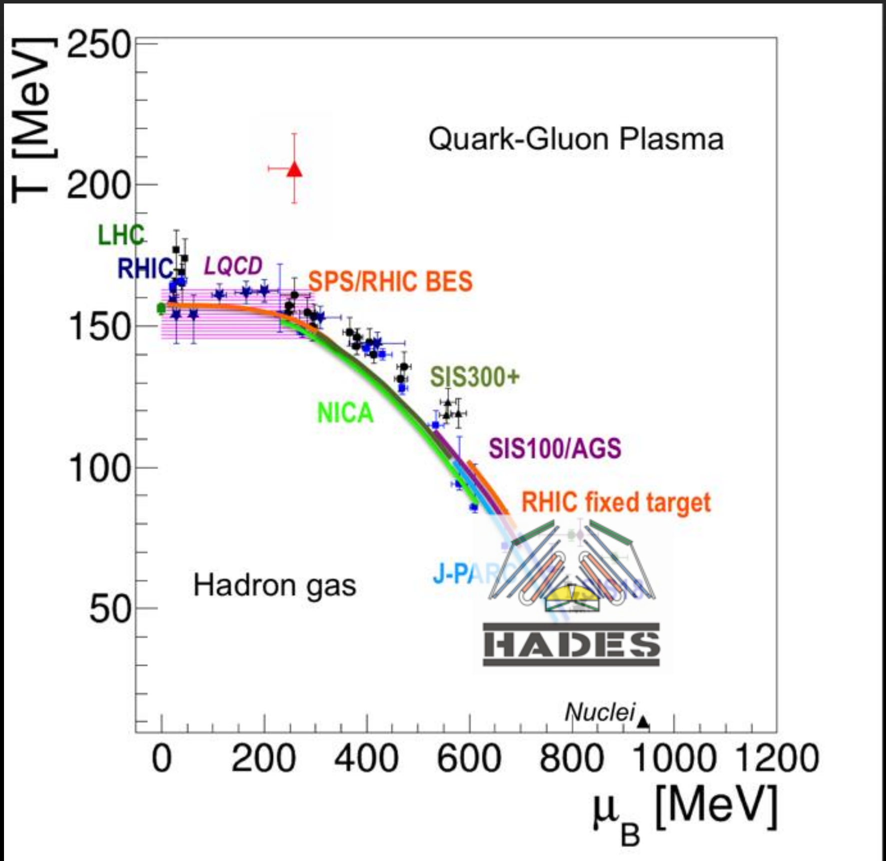


Rapp, Wambach, Adv.Nucl.Phys. 25 (2000)

- High densities: up to 5 ρ_0
- Moderate temperatures: T = 50 – 120 MeV
- System stays above ground state matter density for $\Delta\tau$ ~10 fm/c
- Baryon dominated: N_π/A_{part} ≈ 10% at 1-2A GeV

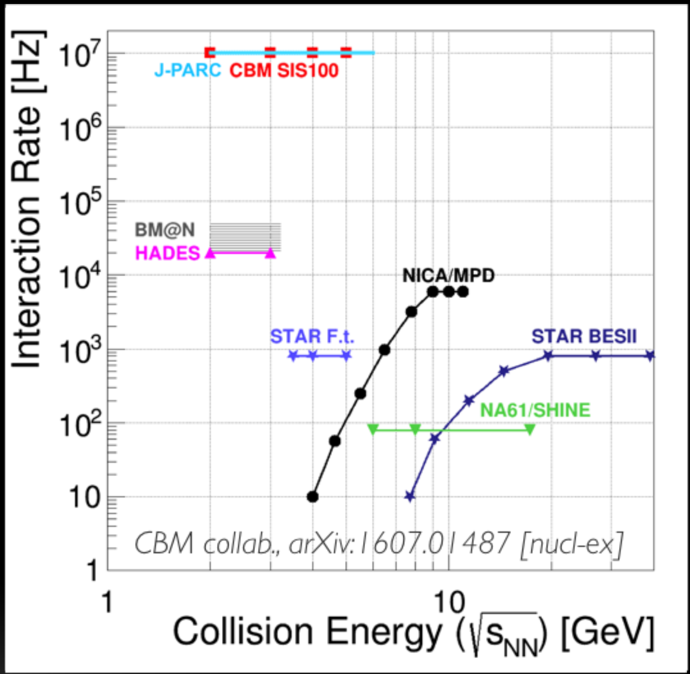
→ Rare and penetrating probes

Searching for landmarks of the QCD phase diagram of matter

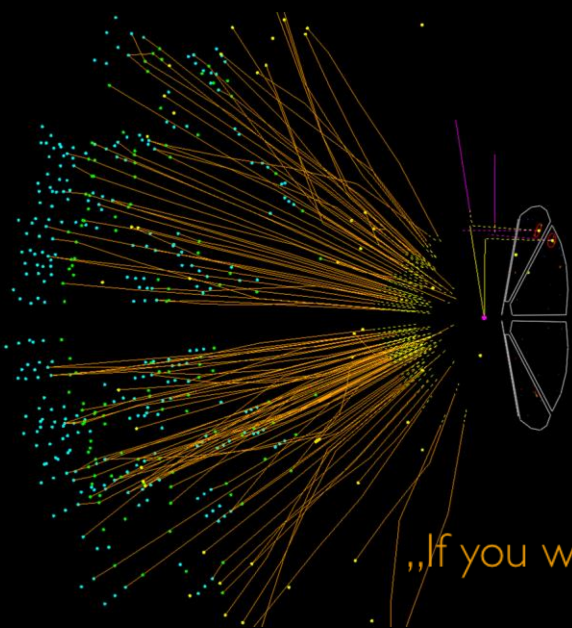


Observables:

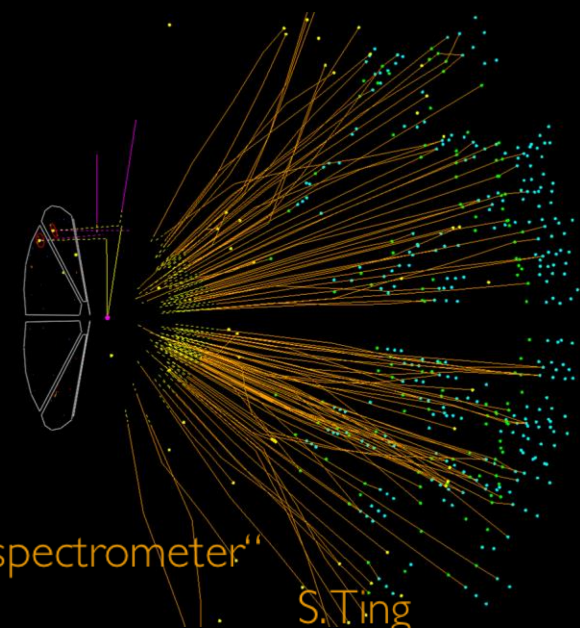
- Emissivity of matter (dileptons)
- Flavor production (multi-strange, *charm*)
- High order correlation functions (B, S, Q)



- 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
- CBM unique w.r.t interaction rate capability



Emissivity of matter

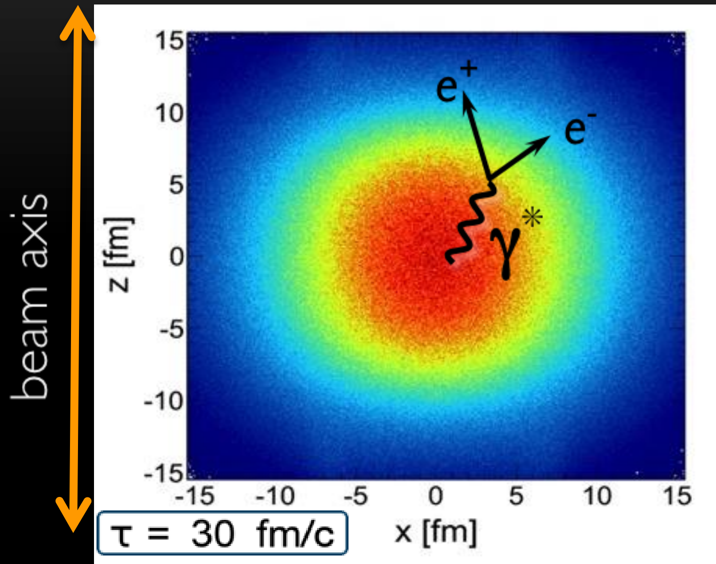


„If you want to detect something new, build a dilepton spectrometer"

S. Ting

Dilepton rate in a strongly interacting medium

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



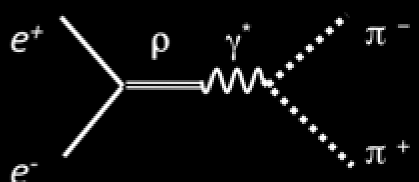
- The dilepton signal contains contributions from throughout the collision
- No strong final state interactions → leave reaction volume undisturbed
- Encodes information on collisions (T, μ_B, τ_{coll})

Unique direct access to in-medium spectral function

Photon self-energy

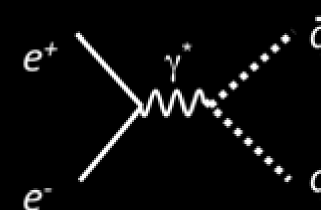
$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{EM}^2}{\pi^3}\frac{L(M)}{M^2} f^B(q_0;T)\, \mathrm{Im}\,\Pi_{EM}^{\mu\nu}(M,q;\mu_B,T)$$

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



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

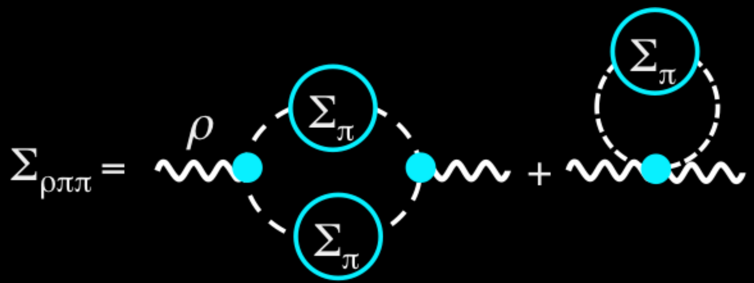
q̄q continuum

ρ meson in hot and dense medium…

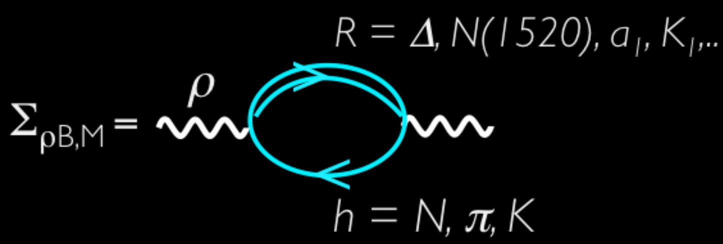
… interacts with hadrons from heat bath → in-medium ρ-propagator

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

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

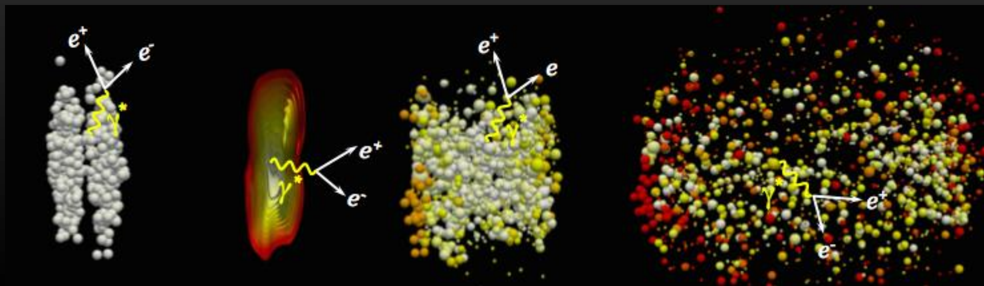


- **Direct ρ-hadron Scattering**
  [Haglin, Friman et al, Rapp et al, Post et al, …]

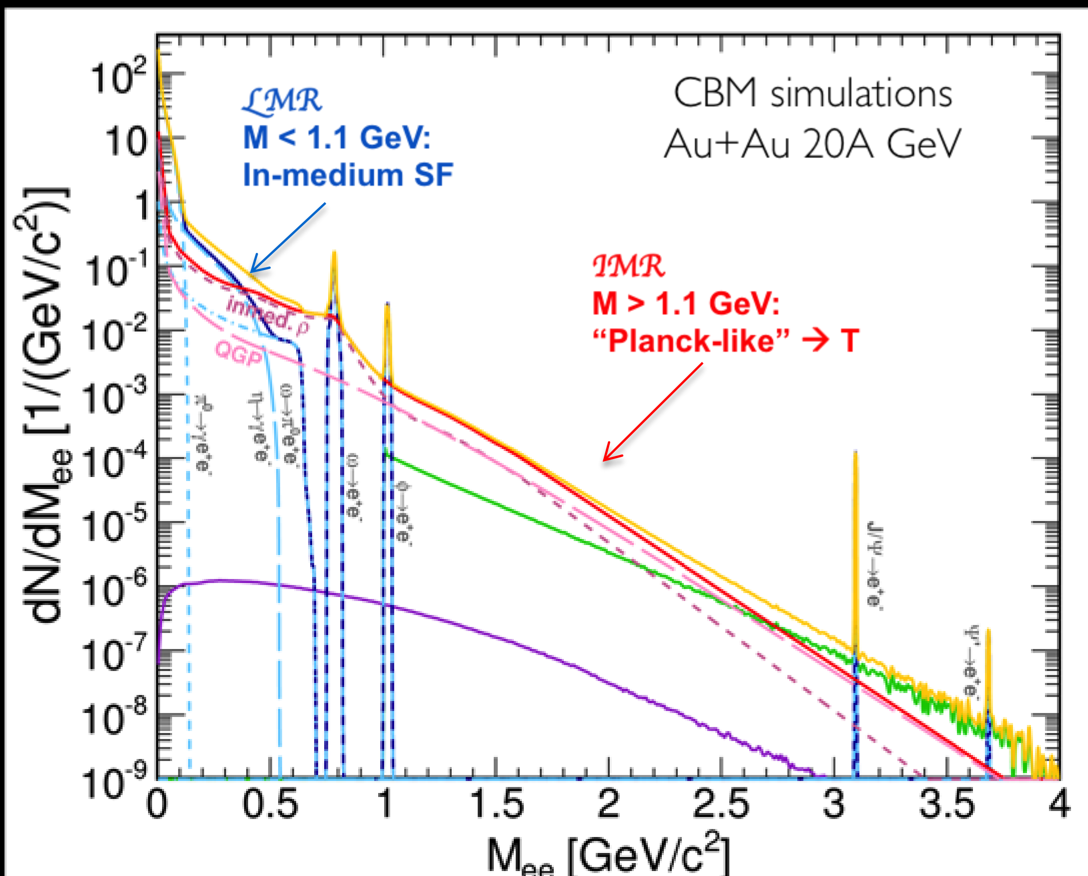


- **Theoretical control:**
  → symmetries (gauge, chiral)
  → empirical constraints: decays R → ρN, scattering data γN/γA, πN → ρN…

Characteristic features of dilepton invariant mass

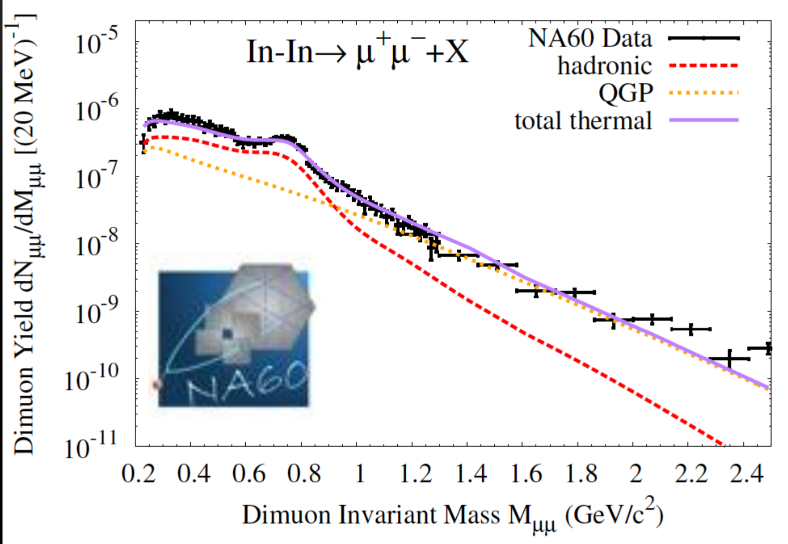


- Dilepton spectra represent the space-time integral of EM radiation
- Mass dependence allows separation of collision stages

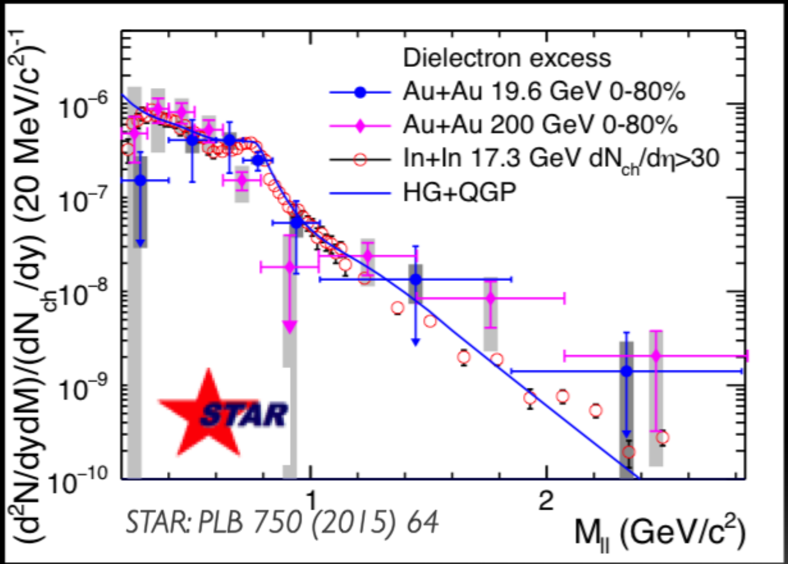


- *Drell-Yan* (NN → l^+l^-X)
- Heavy-flavor: $\bar{c}c \rightarrow l^+l^-$
- Medium radiation (R. Rapp):
  - QGP: $\bar{q}q \rightarrow l^+l^-$
  - In-medium ρ, ω → l^+l^-
  - "4π annihilation": $\pi a_1 \rightarrow l^+l^-$
- Final state decays (hadron cocktail): $\pi^0, \eta \rightarrow \gamma e^+e^-$

What did we learn from UrHIC dileptons?



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



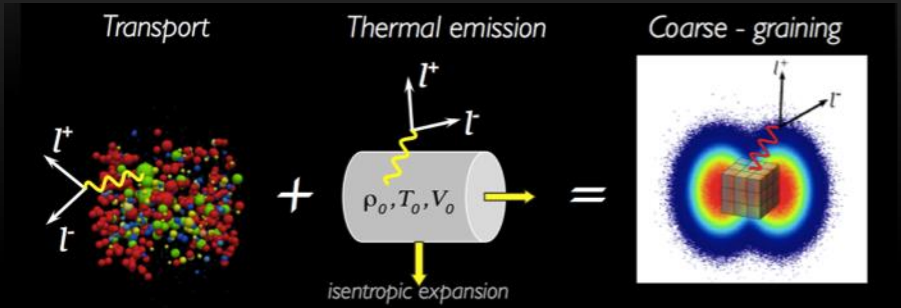
STAR: PLB 750 (2015) 64

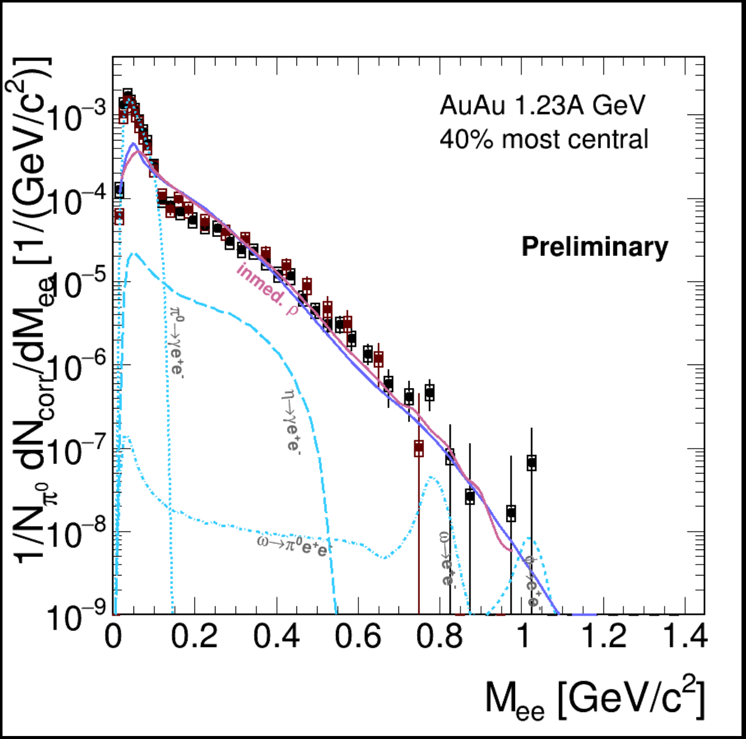
- "Dileptons as chronometer, thermometer, barometer and spectrometer of the field"

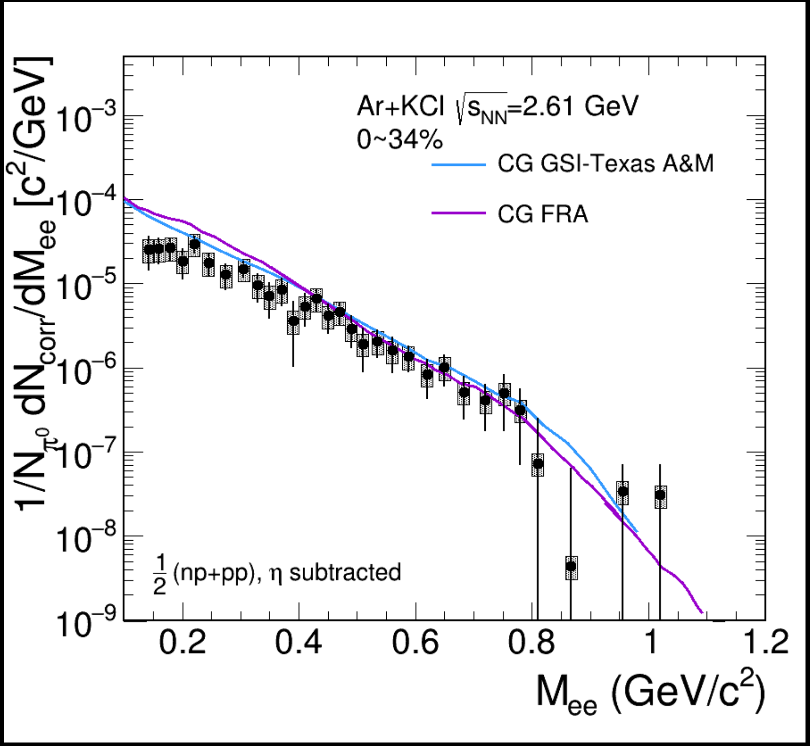
- ρ - Δ/N* couplings play substantial role in ρ melting observed in UrHIC

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





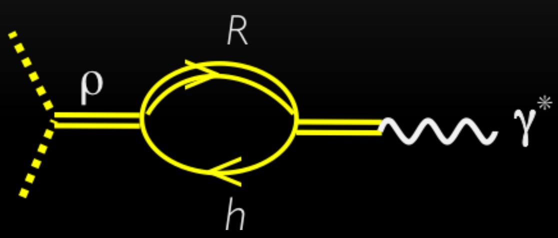


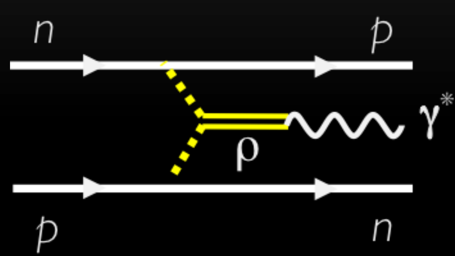
CG FRA: Phys. Rev. C 92, 014911 (2015)
CG GSI-Texas A&M: Eur.Phys.J.A52 (2016) no.5, 131

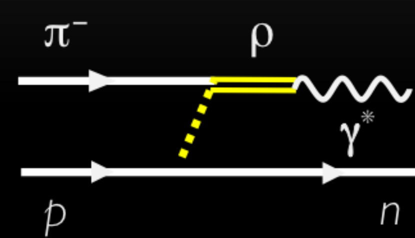
- Coarse-graining method works at low energies
- Supports baryon-driven medium effects at UrHIC (SPS and RHIC)!

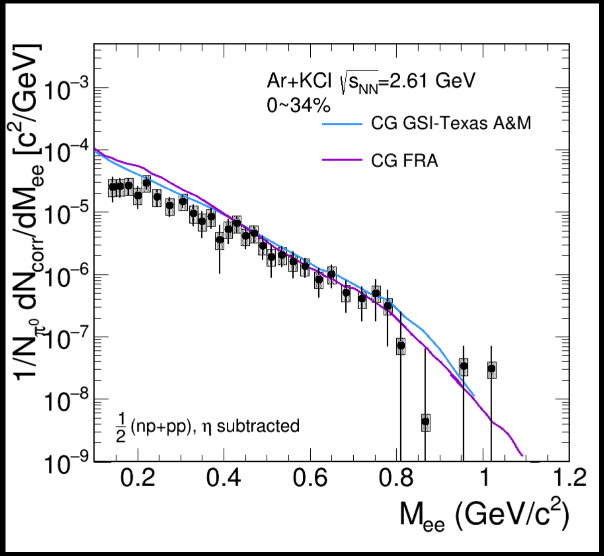
The role of virtual pions in dilepton production

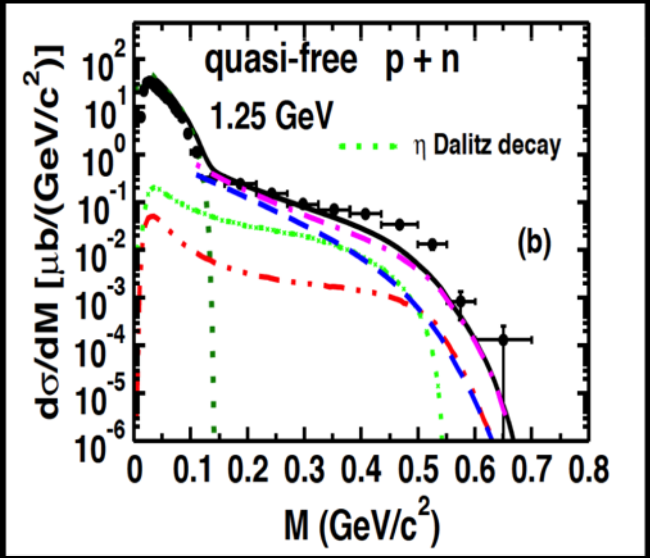
Three different collision systems, three surprises but likely the same underlying mechanism

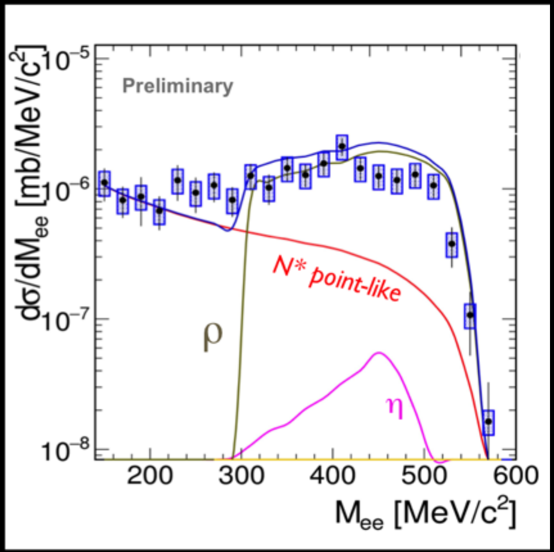












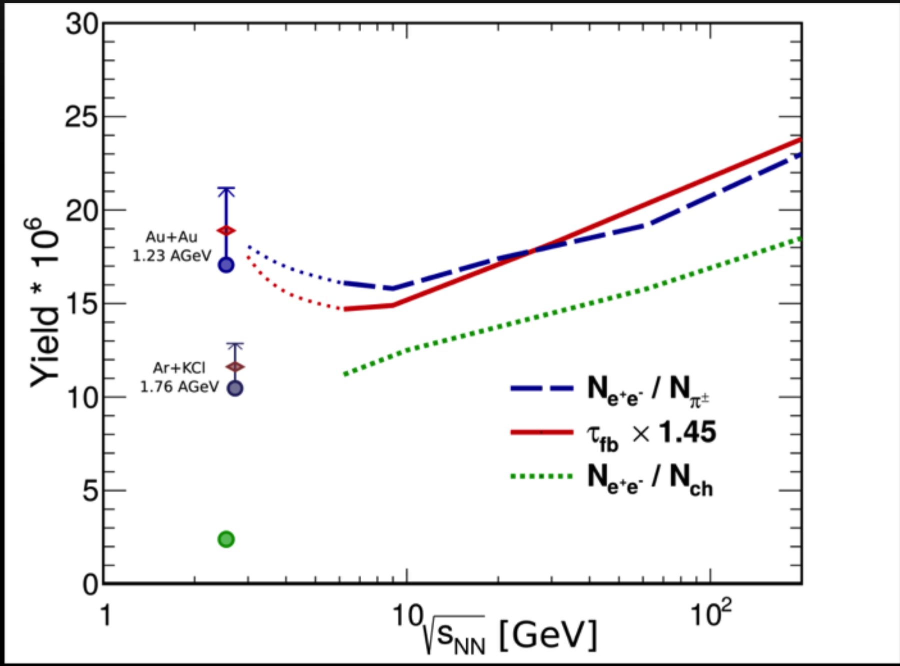
CG FRA: Phys. Rev. C 92, 014911 (2015)
CG GSI-Texas A&M: Eur.Phys.J.A52 (2016) no.5, 131

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)

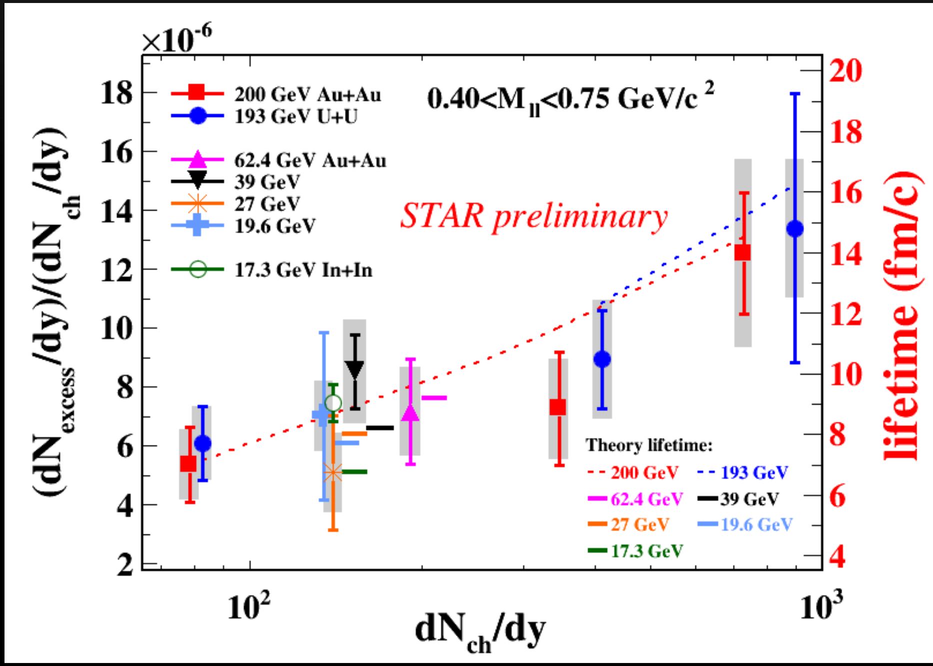
See talk Federico Scozzi, Thu.

Dileptons as chronometer

Excitation Function of Low-Mass Dilepton Excess Yield



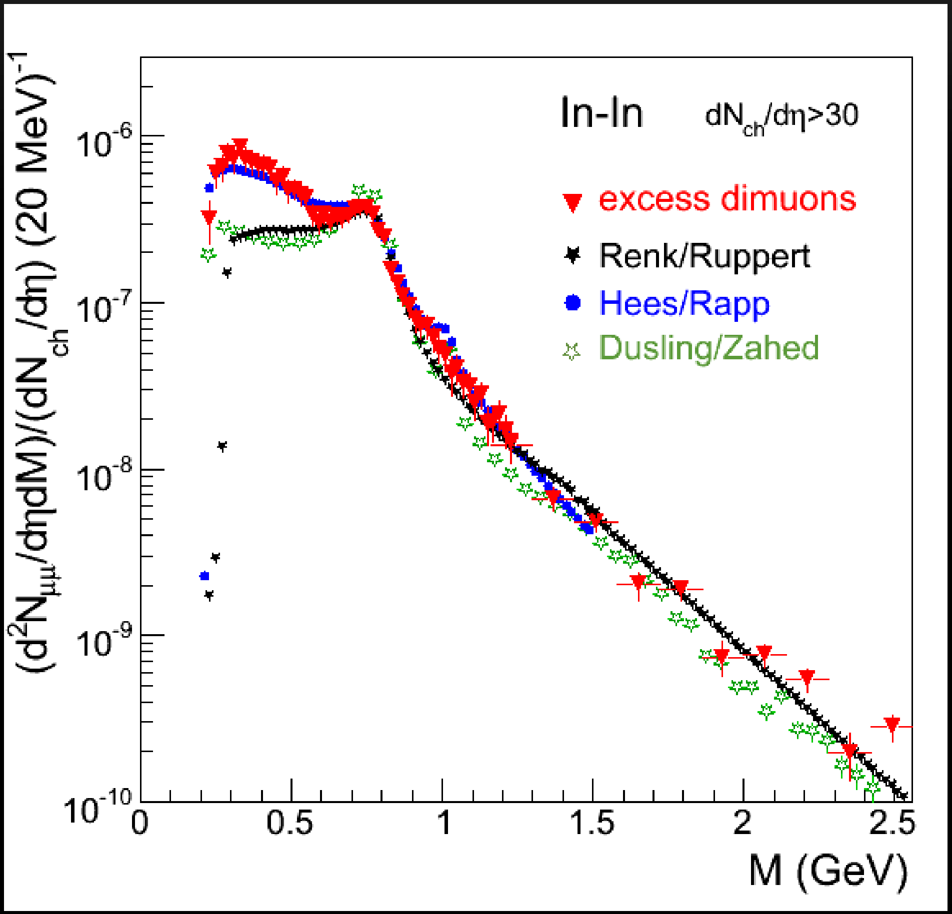
F. Seck et al., proceedings CPOD2016



STAR: PLB750, 64 (2015)
Model: R. Rapp, H. van Hees, Phys. Lett. B 753 (2016) 586

- Low-mass excess tracks lifetime well (medium effects!)
- Robust understanding across QCD phase diagram

Dileptons as thermometer



NA60: Eur. Phys. J. C 59 (2009) 607
→ CERN Courier 11/ 2009, 31-34
Chiral 2010 , AIP Conf.Proc. 1322 (2010) 1

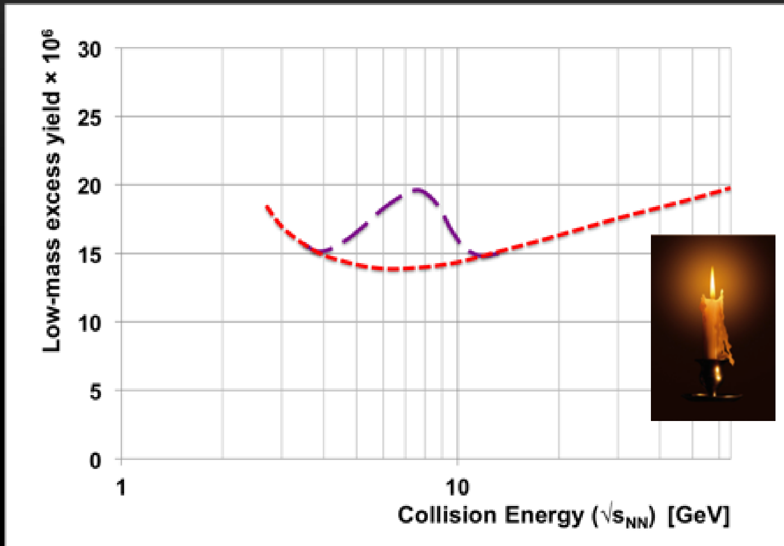
- All physics background sources subtracted
- Integrated over p_T
- Fully corrected for acceptance
- Absolutely normalized

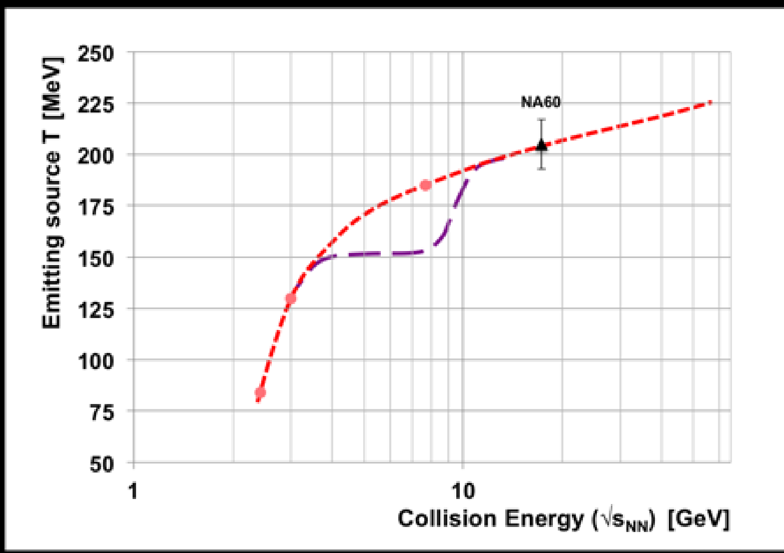
$M > 1$ GeV/c^2
~exponential "fall-off" → "Planck-like"
fit to $dN / dM \propto M^{3/2} \times e^{-M/T}$

Range
1.1-2.0 GeV/c^2: T=205±12 MeV
1.1-2.4 GeV/c^2: T=230±10 MeV

$T > T_c \cong 160$ MeV: partons dominate

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)

Connection to the fundamental properties of the QCD → Chiral symmetry

Weinberg Sum Rules…

Weinberg '67, Das et al '67

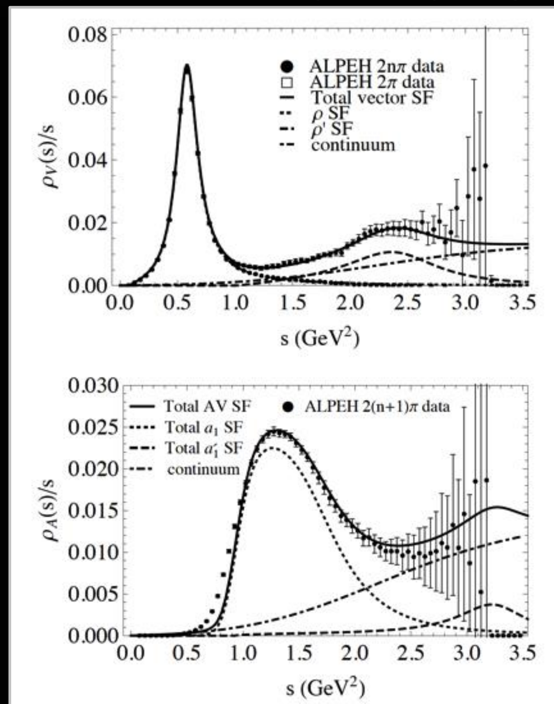
$$\int \frac{ds}{\pi} \frac{1}{s} (\rho_V - \rho_A) = f_\pi^2$$

$$\int \frac{ds}{\pi} (\rho_V - \rho_A) = -m_q \langle \bar{q}q \rangle$$

$$\int \frac{ds}{\pi} s\, (\rho_V - \rho_A) = c\alpha_s \langle (\bar{q}q)^2 \rangle$$

…valid in vacuum

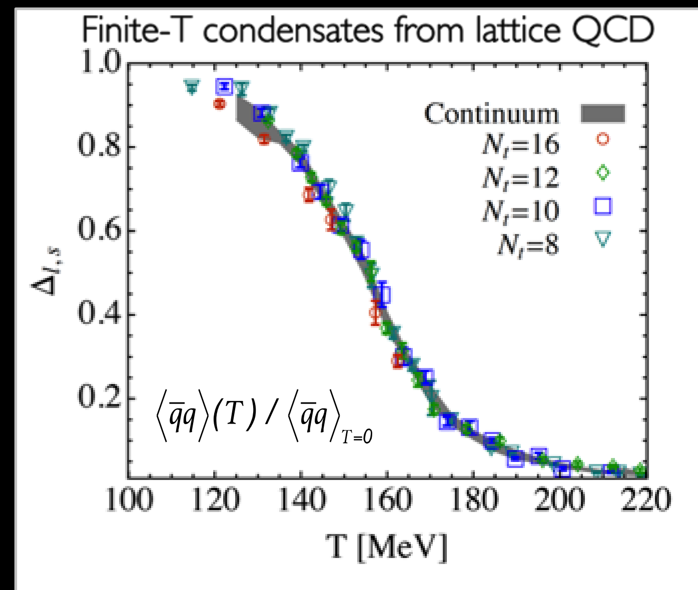
Rapp et al, Annals Phys. 368 (2016)



ρ-a$_1$ mass splitting due to χ_s breaking (~f_π, $<q\bar{q}>$)

… remain valid in medium

J. Kapusta, E. Suryak '94



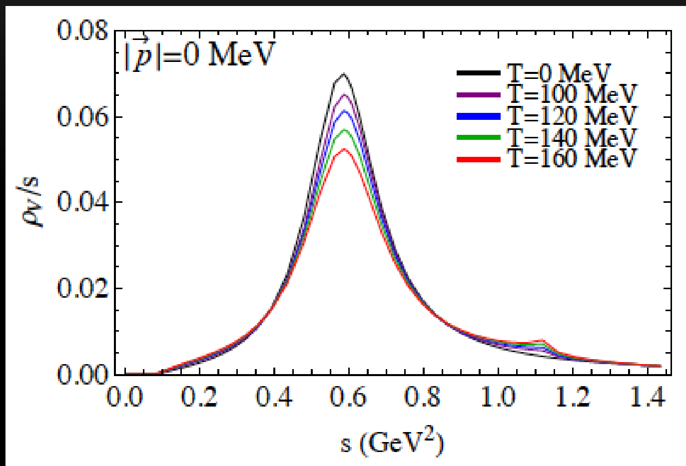
S. Borsanyi et al., JHEP 1009 (2010) 073

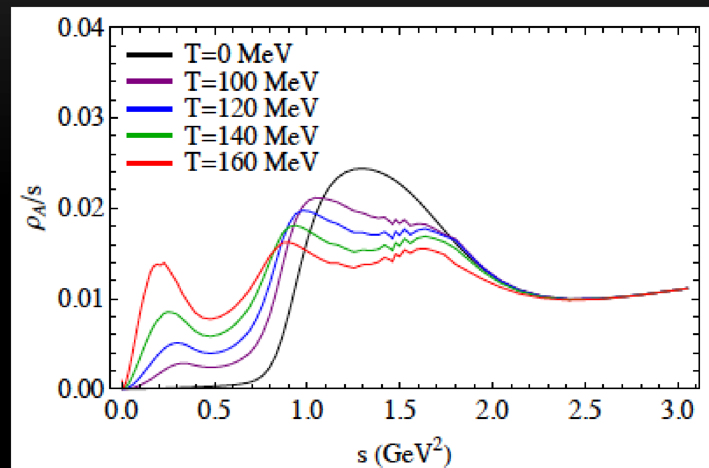
ρ-a$_1$ mass degeneracy

→ Test in-medium ρ spectral function

→ Dropping mass vs. broadening

ρ-a_1 spectral functions at finite T



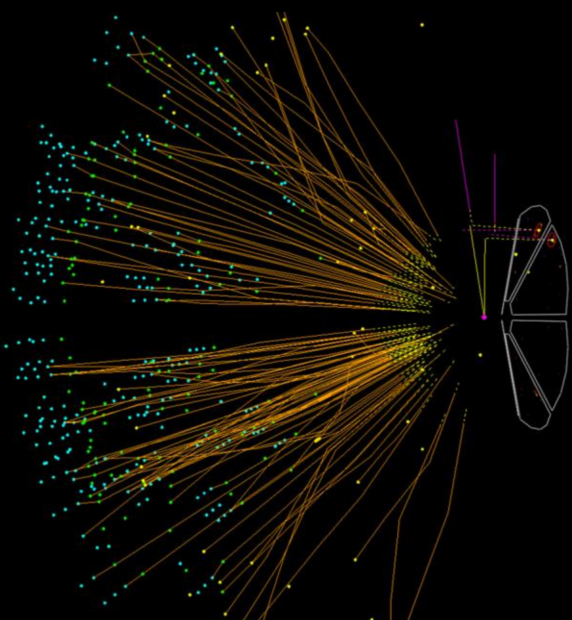


P. Hohler, R.Rapp, arXiv:1510.00454v1 [hep-ph] 2 Oct 2015
See also R.-A. Tripolt et al., arXiv:1605.00771v1 [hep-ph]

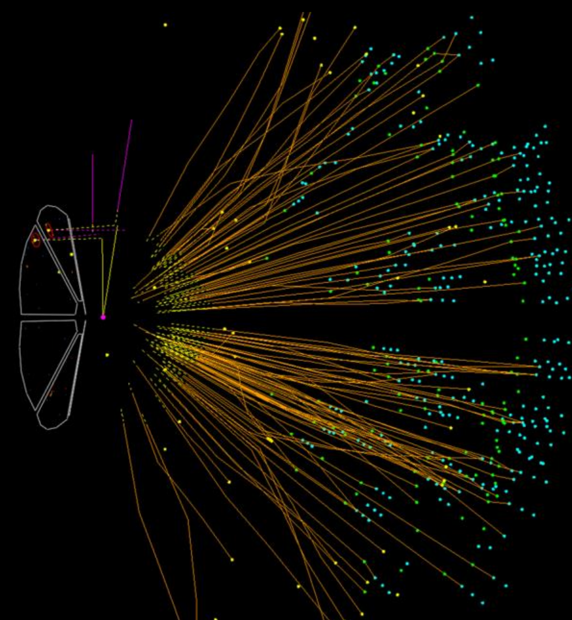
- Vector and axial-vector spectral functions in a pion gas
- No baryon effects accounted for yet

- 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 current and future explorations in HIC

→ Measure changes in yield and shape on M>1.1 GeV/c^2 in high statistic πp & πA; pp & pA; AA

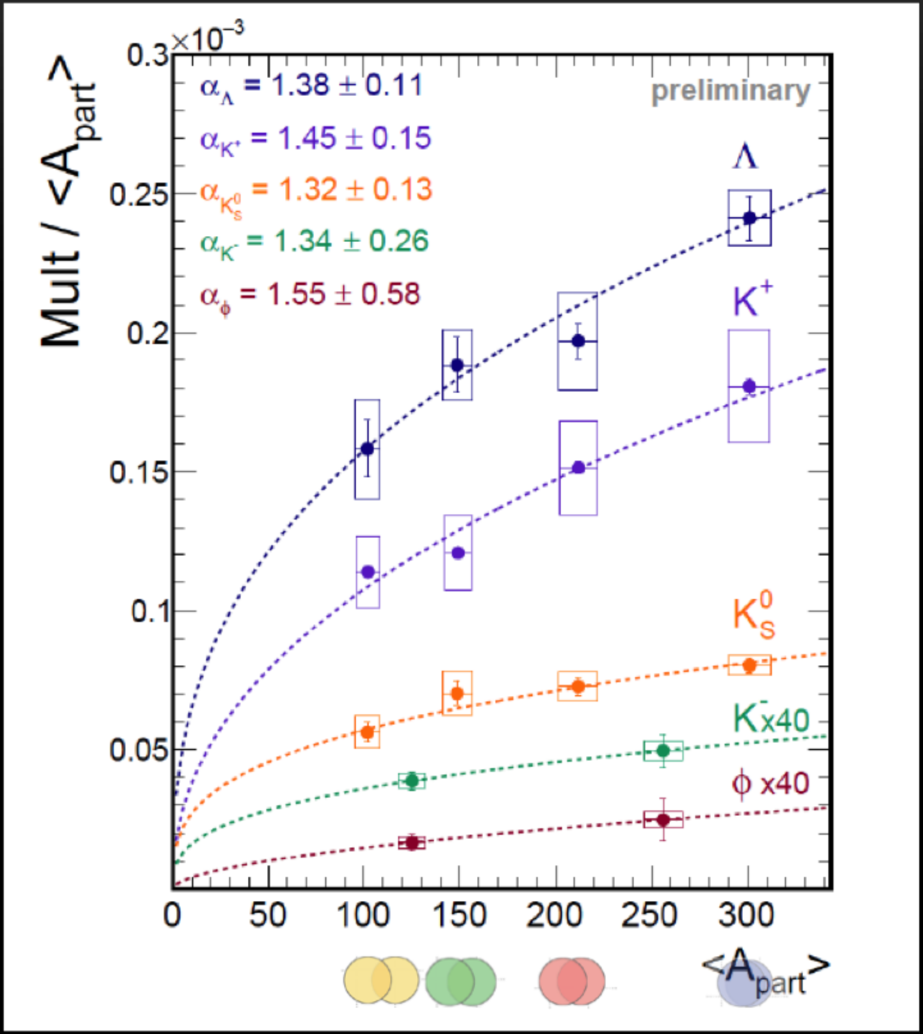


Flavor production
(multi-)strange objects



Strange particle production

Au+Au collisions at 1.23A GeV

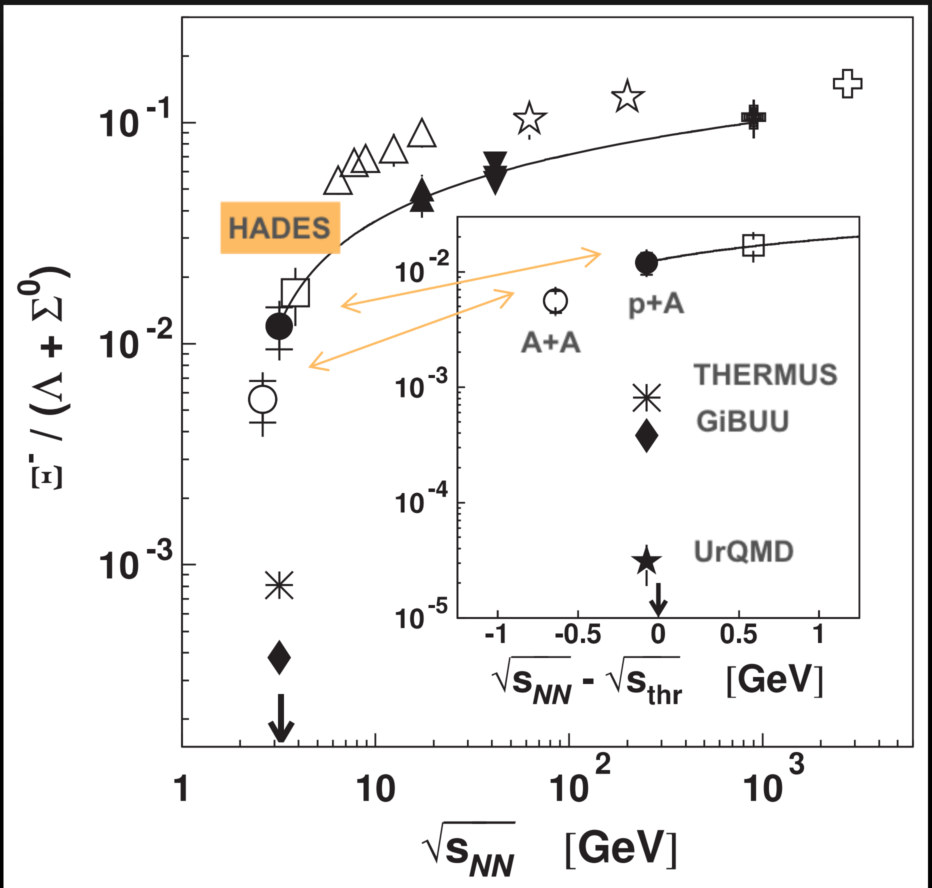


$NN \rightarrow N\Lambda K^+$ $E_{thr} = 1.58$ GeV
$NN \rightarrow NNK^+K^-$ $E_{thr} = 2.49$ GeV
$NN \rightarrow NN\phi$ $E_{thr} = 2.59$ GeV

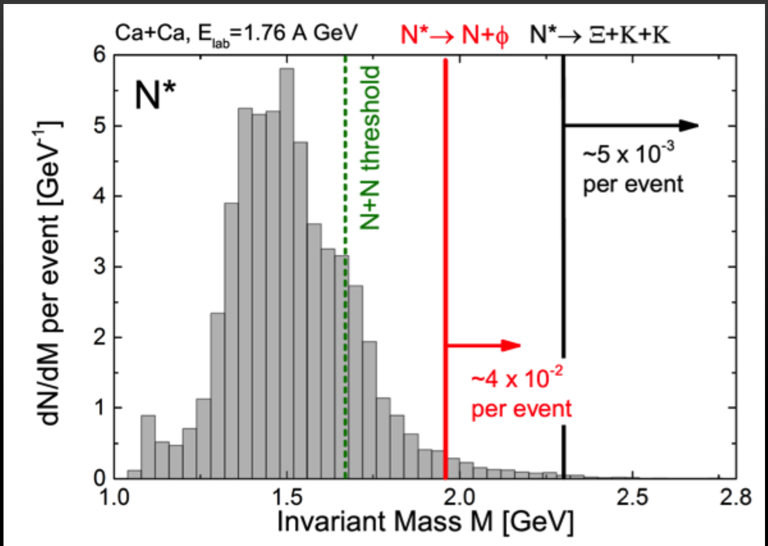
- First comprehensive set of results on strange particle productions from the Au+Au at this low energy
- Far below (free NN) threshold → strong constraints on production mechanism
- Particle yields rise with A_{part} faster than linear ($M \sim A^{\alpha}_{part}$, with $\alpha > 1$)

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

What is so strange about Ξ^-?



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

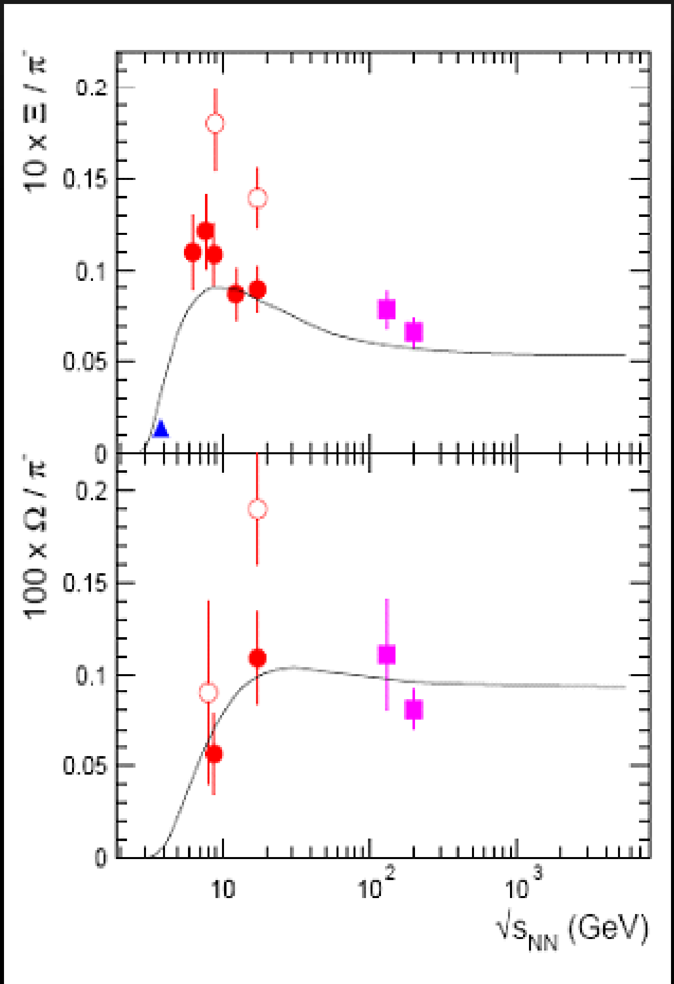


J. Steinheimer et al., J.Phys. G43 (2016) no.1, 015104

- 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?

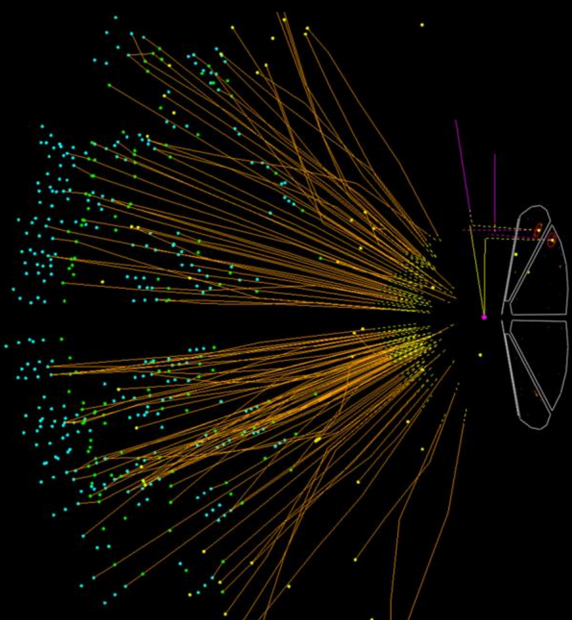
or…

Signatures for exotic phases at high μ_B

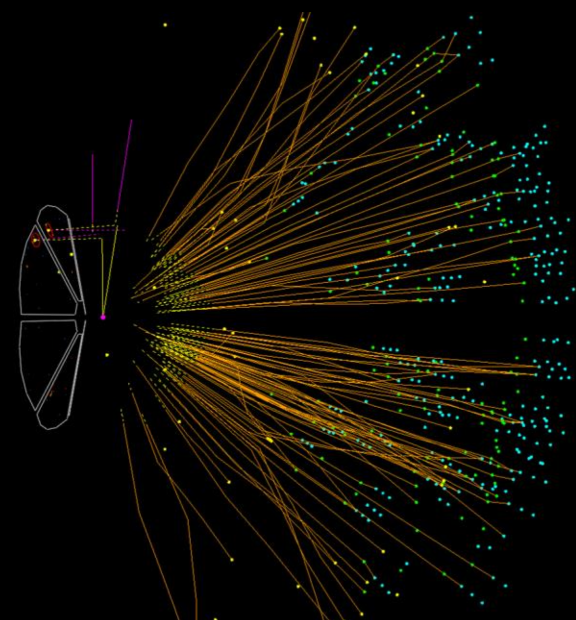


A. Andronic et al., Phys. Lett. B 673 (2009) 142

- Far sub-threshold (multi-) strangeness production → strangeness distillation in quark bubbles
- Compelling result from heavy-ion runs, however
  - FAIR-energy data are missing
  - Reference measurements are needed
    - SIS18: highest proton beam momentum which can be used for stable runs: $B\rho$ = 5.4 GeV/c → E_{kin} = 4.5 GeV ($\sqrt{s}$ = 3.47 GeV) → strangeness production, i.e. cascade



High order correlation functions (B, S, Q)

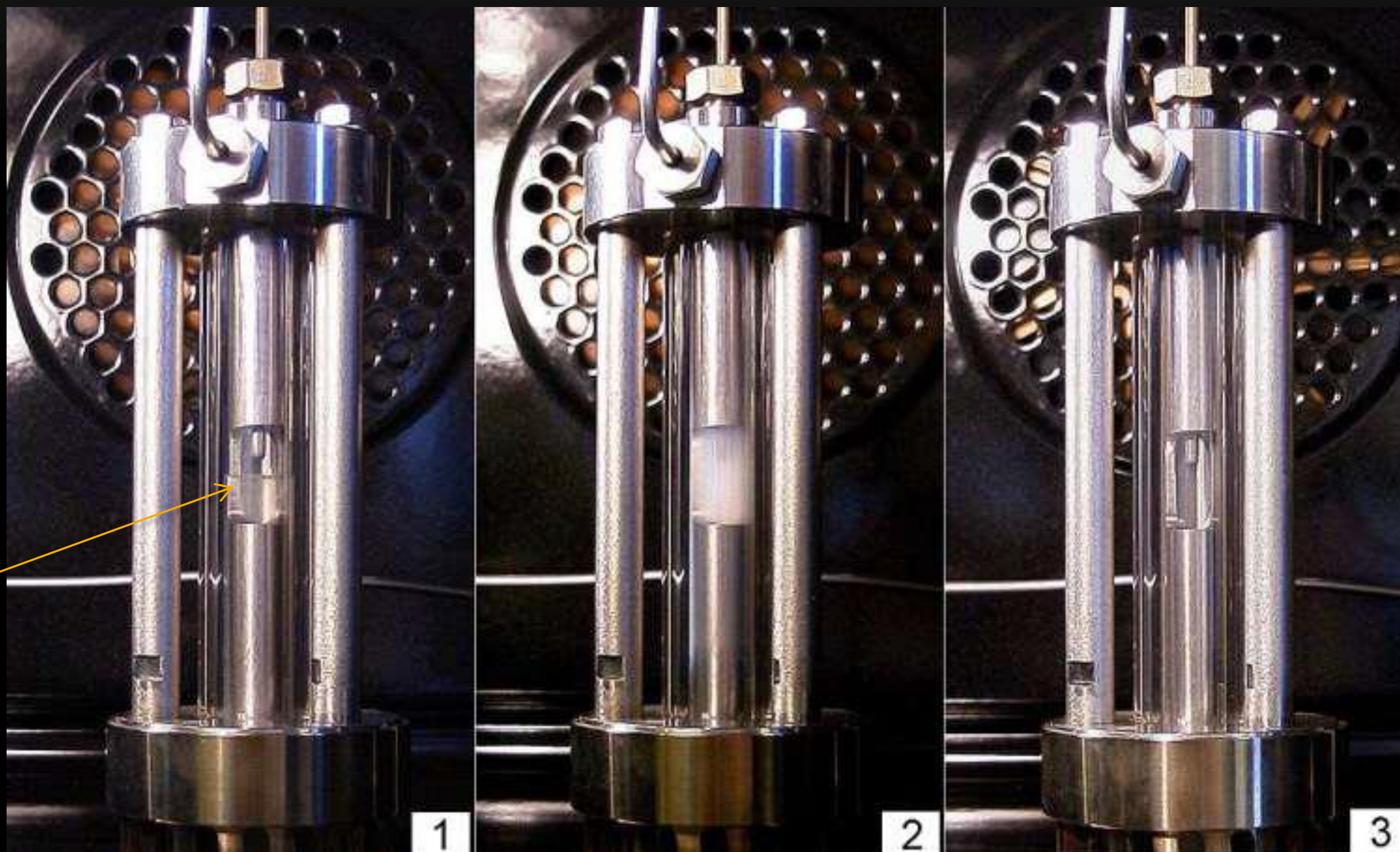


Critical opalescence in ethane

Probing the medium response to external perturbations

V = constant T1, P1 < T2, P2 < T3, P3

C_2H_6



liquid + vapor CP fluid

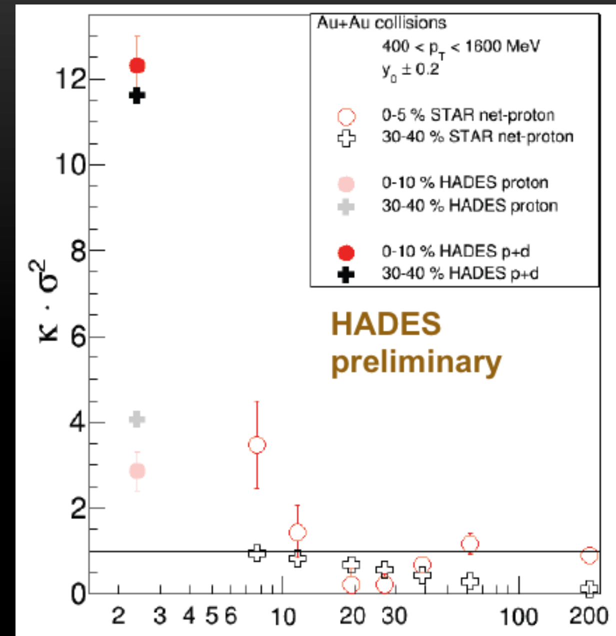
$T_{cr} = 32\ ^{o}C$, $P_{cr} = 49$ bar

Proton number fluctuations

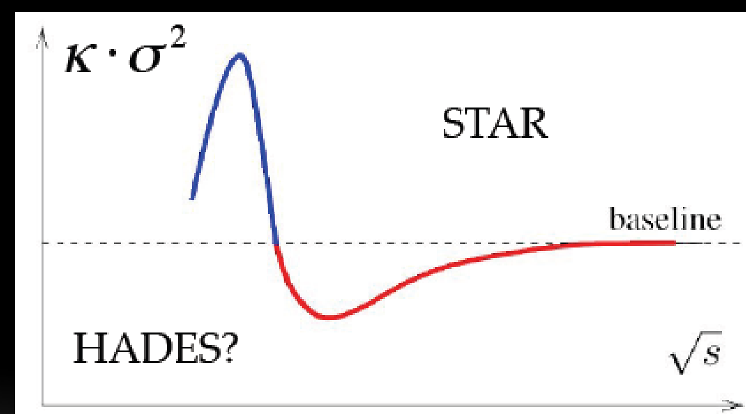
- Related to phase structure of hot and dense matter (e.g. spinodal decomposition of the mixed phase)
- Search for the critical point

- Higher moments probe the tails. Statistics!
  → Striking signal
  → FAIR-energy data are missing

- Need to control:
  - Fluctuations to due baryon stopping
  - Role of heavier fragments
  - Centrality resolution, ect.



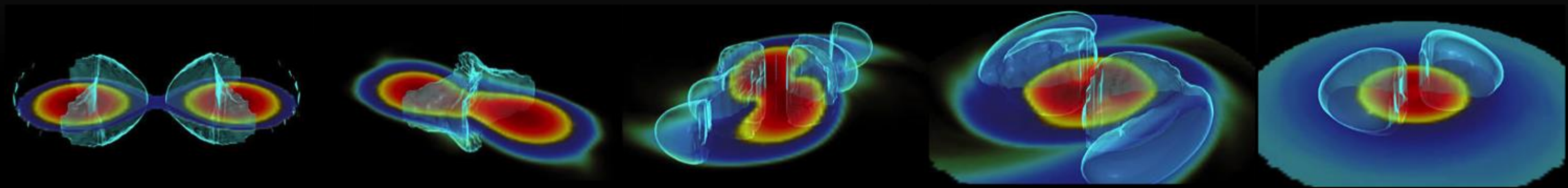
HADES: R. Holtzman, SQM16
STAR: X. Luo et al., PoS (CPOD14) 2016

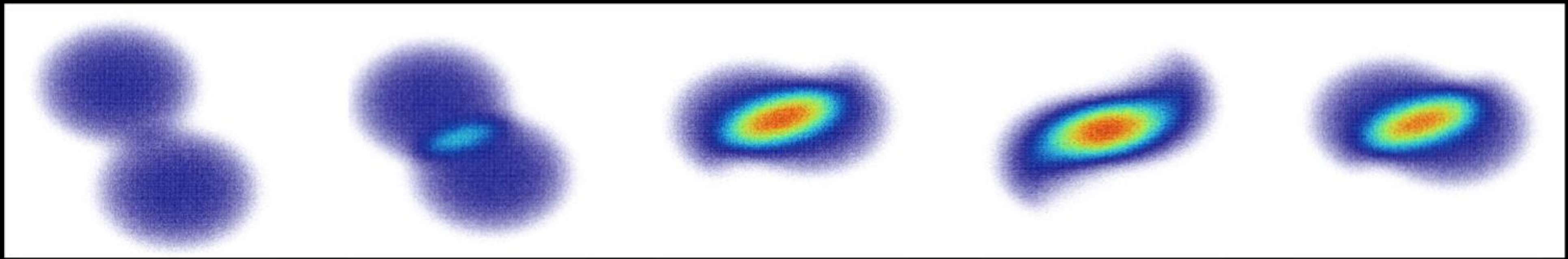


M. Stephanov, Phys. Rev. Lett. 107 (2011) 052301

Cosmic matter in the laboratory

http://flash.uchicago.edu/~calder/neutron.html



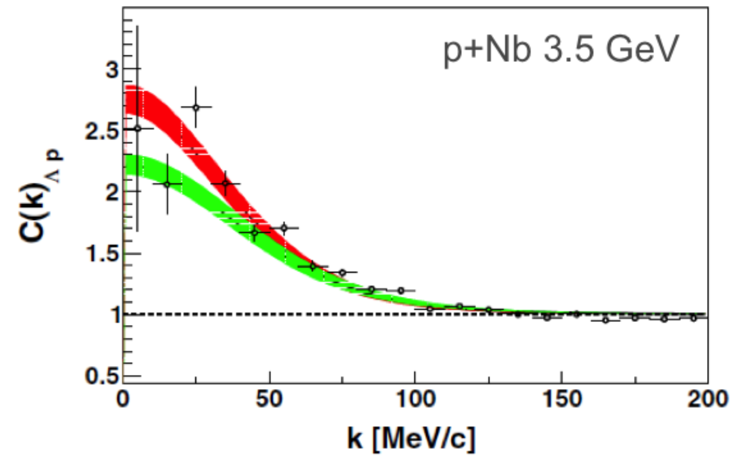


Images: Florian Seck
Bass et al., Prog. Part. Nucl. Phys. 41 (1998)

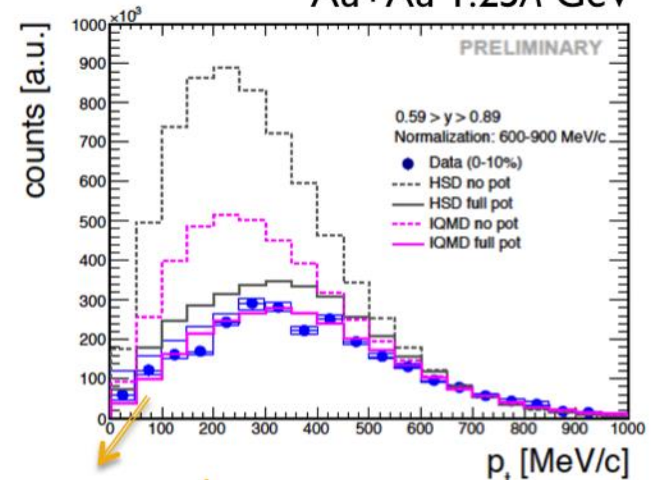
Matter in Compact Stars

- 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, ΛNN further studies in high statistic pp, pA, AA
  - Data support in-medium repulsive vector K^0 potential ~40 MeV *[PRC 82 (2009) 044907; PRC 90 (2014) 054906]*

Λ-N correlation function



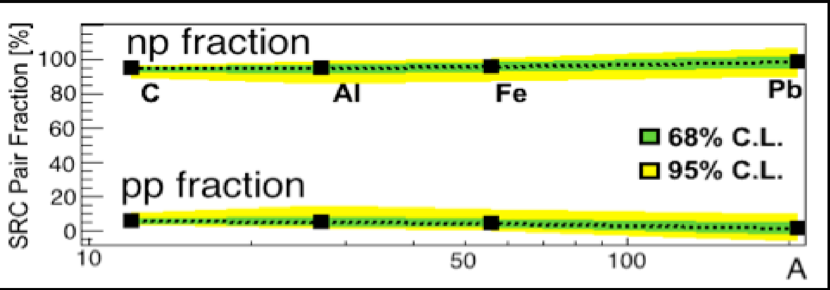
HADES collab., PRC 94 (2016) no.2, 025201



p_t coverage down to zero p_t

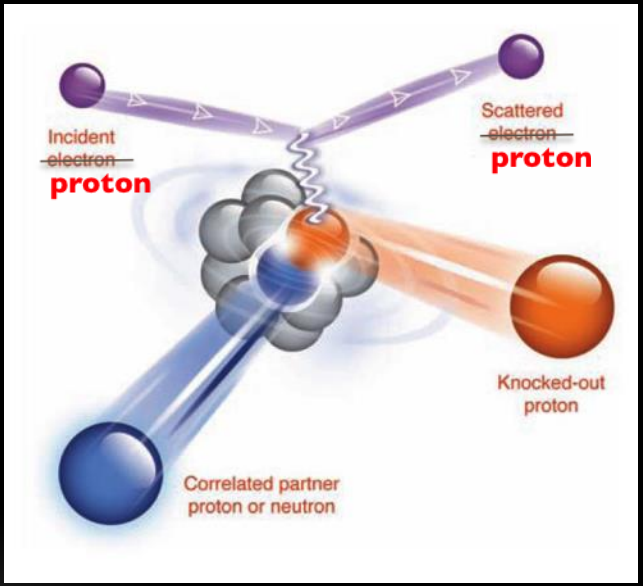
Measuring Short Range Correlations in nuclei

- SRC's lately become a very active field investigated by e- and p scattering
  Review: Arrington et al., Prog. Part. Nucl. Phys. 67 (2012)
- Found that np SRC 10×stronger than for pp!
  → impact on NN force at high densities
- Neutron Star EOS depends on composition and interactions (e.g. NN forces)



O. Hen et al., Science 364 (2014) 614

- So far mainly e scattering but p preferable
- Use max energy of p beam: compare results on C and Ag targets



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

- 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

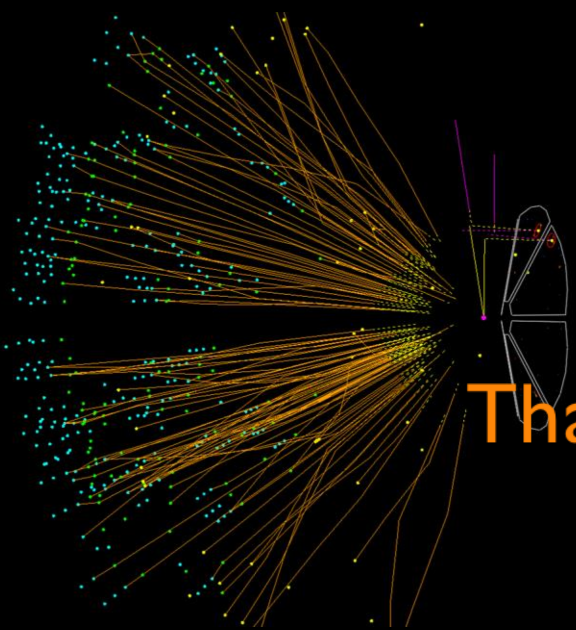
- Roadmap beyond 2016:
  - 2016-18: upgrade HADES: add lead-glass EM calorimeter, add forward straw-tube tracker & RPC, replace RICH photon detector
  - 2018-20: high statistic p+A and A+A (e.g. Ag+Ag at E_{kin}=1.65 GeV), as well as measurements with secondary pion beams (π+N and π+A)
  - 2020/21^{+}: HADES & CBM at SIS100 → Establish complete excitation functions of dileptons, (multi-) strange particles, high order correlation functions

FAIR-

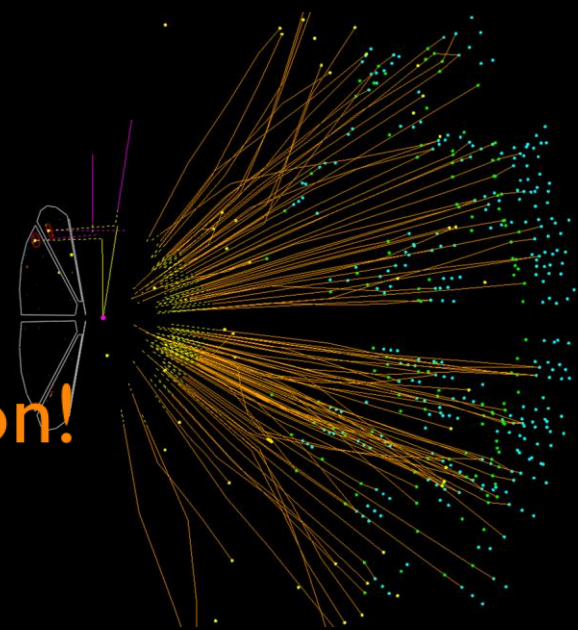
0


CBM collaboration
56 institutions, > 500 members


The HADES Collaboration
14 institutions, ~100 collaborators

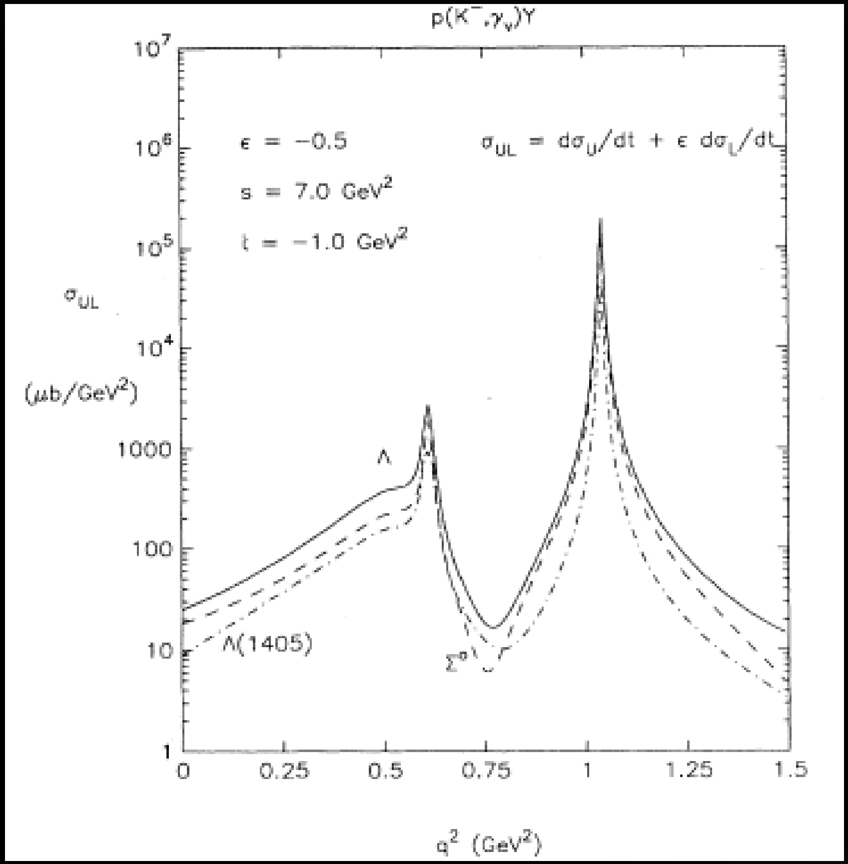


Thank you for your attention!



Cinematically accessible VM resonance enhancement in $p(K^+, e^+e^-)\Lambda, \Sigma^0, \Lambda(1405)$

Two-body virtual photon radiative capture cross section as a function of q^2.



R. Williams et. al. PRC48(1993)1381

- Proposed reaction:
  - $pp \rightarrow p\,K^- Y\,X \rightarrow p\,K^-\,e^+e^-\,X$
    tagging with K^- or Λ (check acceptance?);
    $Y = \Lambda, \Sigma^0, \Lambda(1405)$
  - $BR(Y \rightarrow \Lambda\gamma) \sim 0.5\%$ ($\sim e^+e^-\ 4 \times 10^{-5}$)
- VM have a dramatic effect on hyperon virtual photon production cross section as a function of q^2
- Hyperon production rate increase by 2—4 orders of magnitude relative to the real photon production rate

"You may say I'm a dreamer… but I'm not the only one"

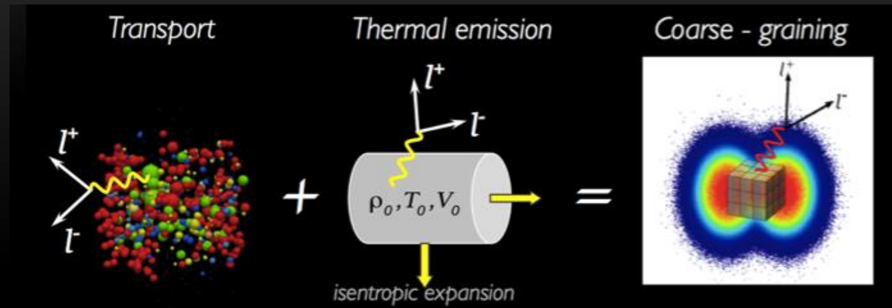
		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
HADES	SIS18			2.5 GeV + pA, πA							
STAR BES	RHIC				8 – 20 GeV			200GeV			
MPD	NICA				4 – 11 GeV						
CBM	SIS100							2 – 5 GeV			
ALICE*	LHC	5.5 TeV					5.5 TeV				
	J-PARC**			pA 8 GeV							2 –5GeV
NA60+	SPS		LOI						6 – 17 GeV		
PHENIX	RHIC	200 GeV									
STAR	RHIC	200 GeV	pp(500)								
sPHENIX								200 GeV			
BM@N	Nuclotron		2 – 3 GeV								

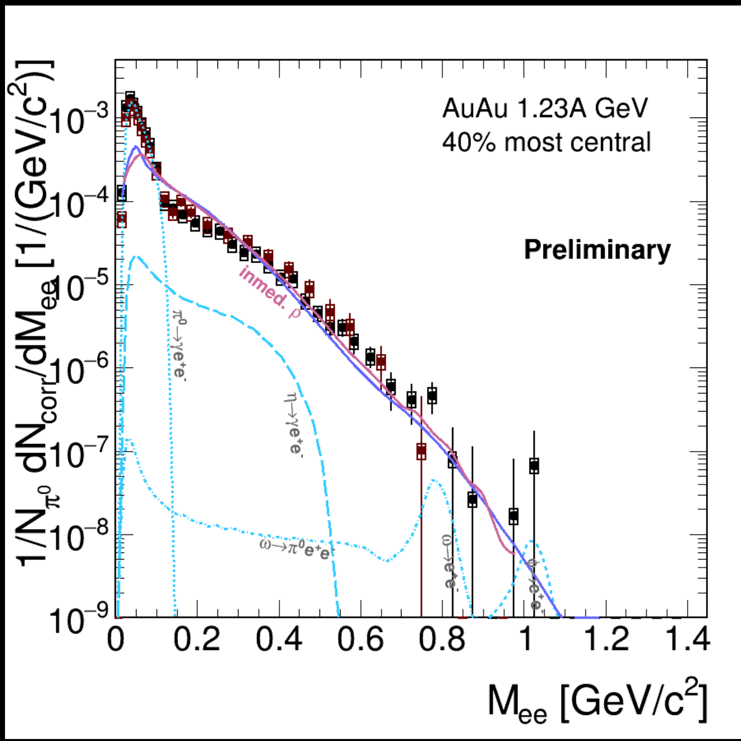
* - ITS, 50kHz, lower field

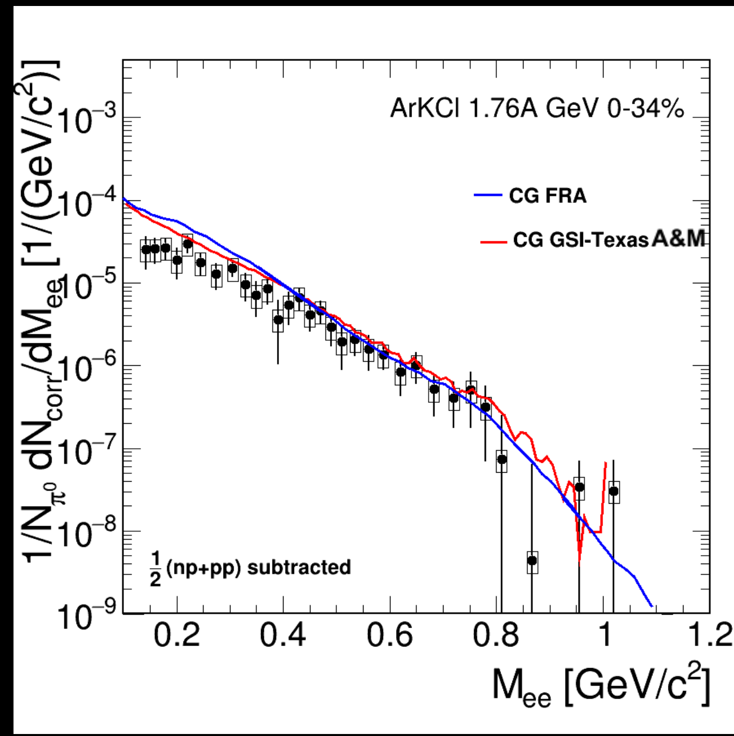
** - Proposal to J-PARC in 2016, If approved, construction of HI injector and detectors in 10 years ?

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



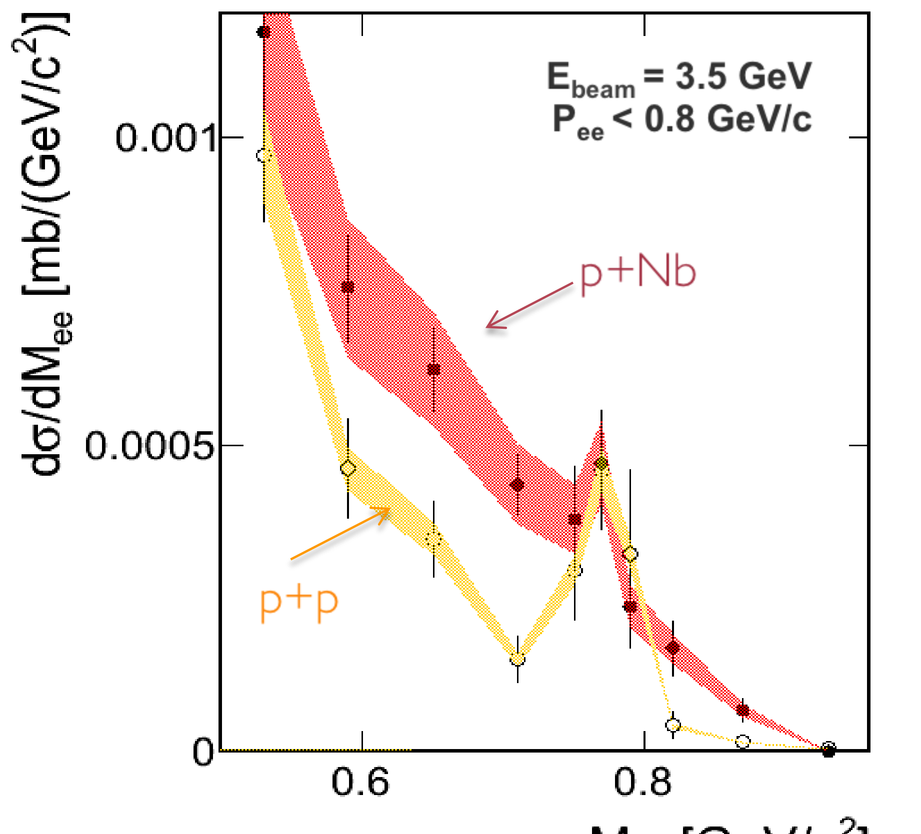




- Coarse-graining method works at low energies
- Supports baryon-driven medium effects at UrHIC (SPS and RHIC)!

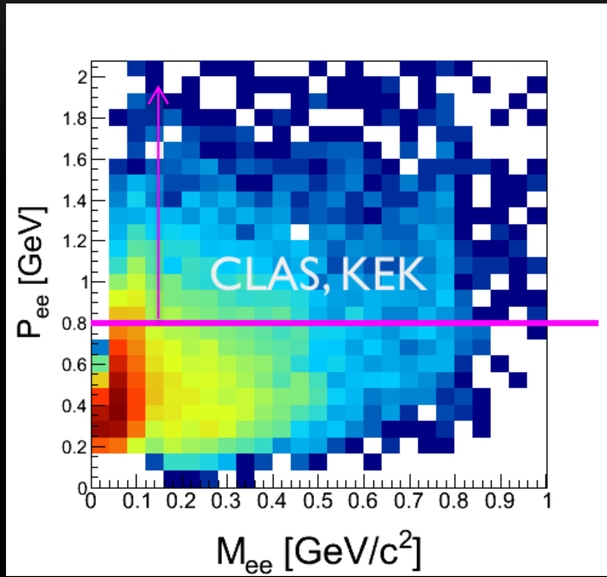
CG FRA: Phys. Rev. C 92, 014911 (2015)
CG GSI-Texas A&M: Eur.Phys.J.A52 (2016) no.5, 131

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



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

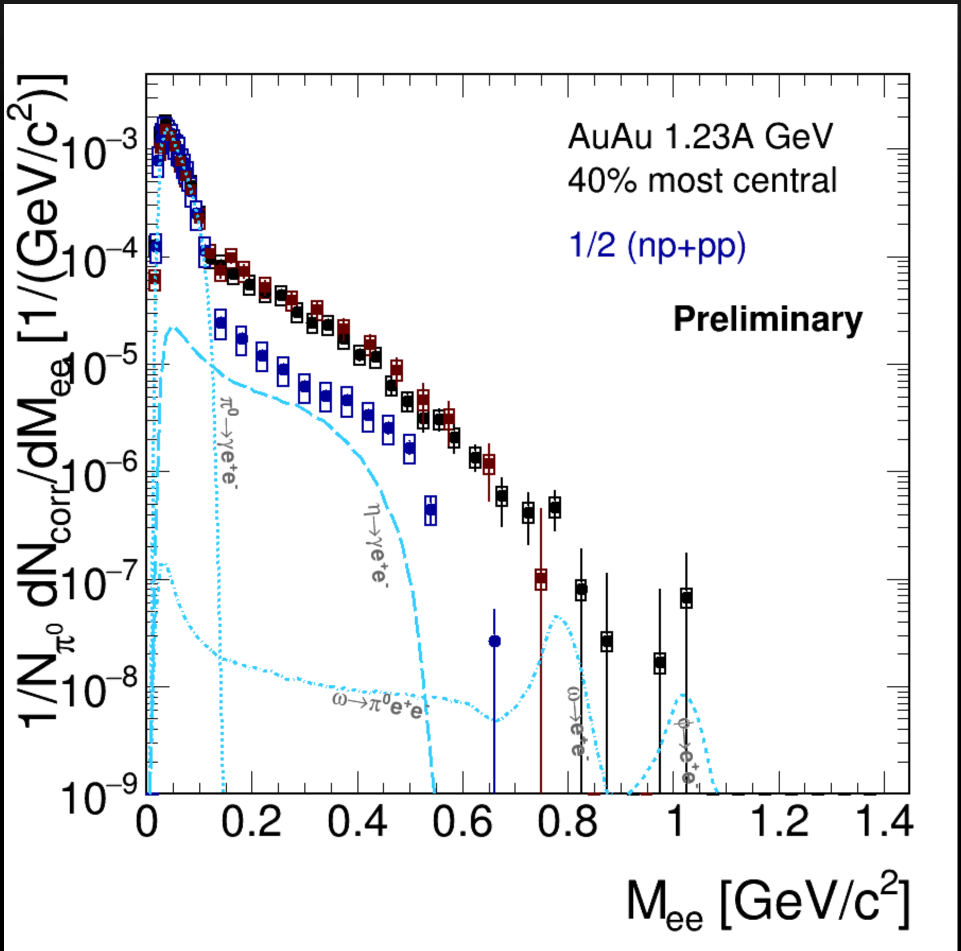
HADES acceptance



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

- 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

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

FAIR- Phase 0 physics with HADES at GSI

- Role of the meson cloud in the emissivity of (dense) baryonic matter
  - Electromagnetic structure of baryons in the time-like region
  - ρ-meson nucleon coupling, a_1 SF
  - In-medium vector meson propagation
- Strangeness production and propagation
  - Production of multi-strange baryons / ϕ-meson
- Studying EoS: SRC, ΛN, ΛNN

π+p

π+A

p+A
A+A

- 3.5 - 4 GeV p+Nb
- 1.65A GeV Ag+Ag seems to be an ideal choice
- Request one run per year with at least 4 weeks beam on target for production