HADES Experimental Highlights

Szymon Harabasz
for the HADES collaboration

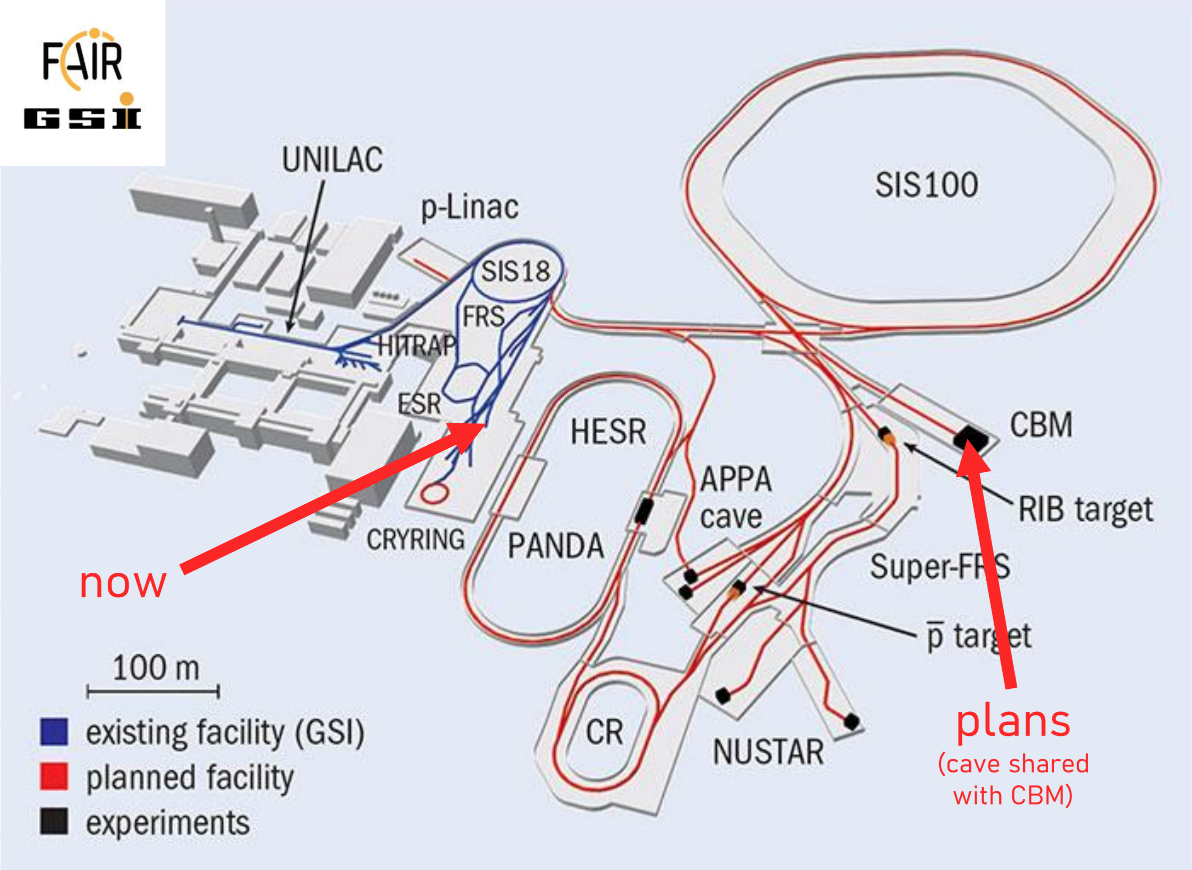
11th International Conference
on Hard and Electromagnetic Probes
of High-Energy Nuclear Collisions

TECHNISCHE
UNIVERSITÄT
DARMSTADT

On behalf of the HADES Collaboration

~170 members
~26 institutions
~10 countries

Space-time coordinates

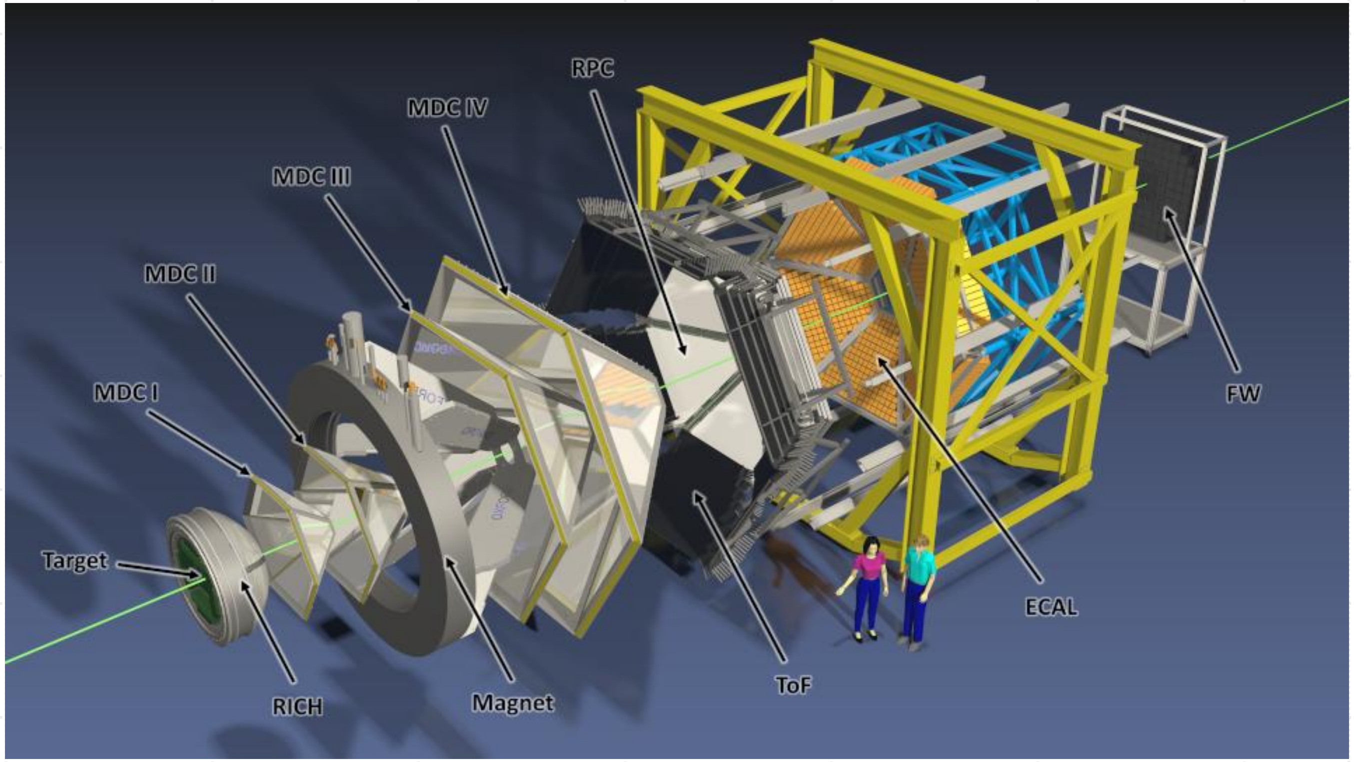


- **Nov 2002** C+C at $\sqrt{s_{NN}} = 2.7$ GeV
- **Jan 2004** p+p at $\sqrt{s} = 2.77$ GeV
- **Aug 2004** C+C at $\sqrt{s_{NN}} = 2.32$ GeV
- **Sep 2005** Ar+KCl (~Ca+Ca) at $\sqrt{s_{NN}} = 2.61$ GeV
- **Apr 2006** p+p at $\sqrt{s} = 2.42$ GeV
- **Apr 2007** p+p at $\sqrt{s} = 3.18$ GeV, d+p at $\sqrt{s_{NN}} = 2.42$ GeV
- **Sep 2008** p+Nb at $\sqrt{s_{NN}} = 2.7$ GeV
- **Apr 2012** Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV
- **Jul-Aug-Sep 2014** π^- + W/C/polyethylene
- **Mar 2019** Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV and 2.42 GeV
- **Feb 2022** p+p at $\sqrt{s} = 3.46$ GeV

Color: data shown in this talk

High Acceptance Di-Electron Spectrometer

- Fixed target setup
- Acceptance
  - Full in the azimuthal angle
  - From 18° to 85° in the polar angle: adjusted for good coverage around mid-rapidity



New detectors installed since 2019:

- RICH photodetection plane in cooperation with CBM
- Electromagnetic calorimeter
- Set of forward detectors in cooperation with PANDA

Two-fold physics goal

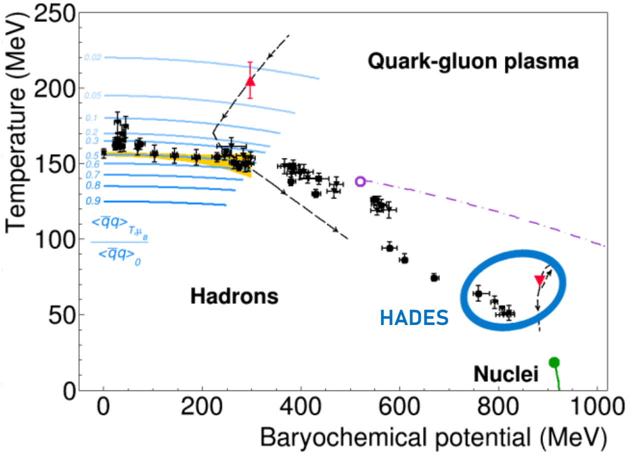
Not fully clear how it was in the Antiquity, but the modern era imagines Hades holding a ***bident***

Hades (Pluto). From a Statue in the Vatican.

Two-fold physics goal

Not fully clear how it was in the Antiquity, but the modern era imagines Hades holding a ***bident***

Hades (Pluto). From a Statue in the Vatican.



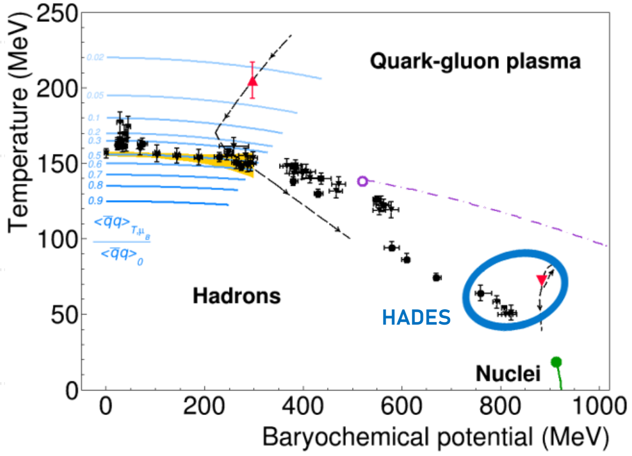
Heavy-ion collisions at $\sqrt{s_{NN}}$ = 2-2.4 GeV:

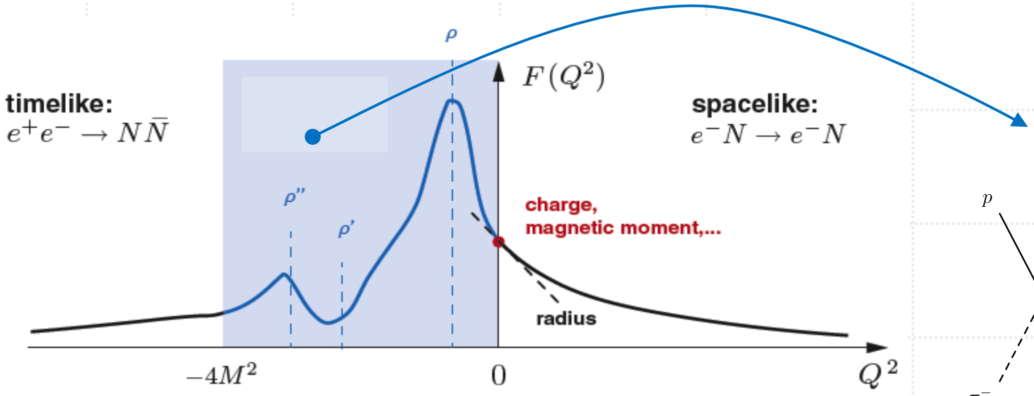
- Microscopic properties of baryon dominated matter
- Equation-of-State
- Observables
  - E-b-e correlations and fluctuations
  - Strangeness production and collective effects
  - Dileptons

Two-fold physics goal

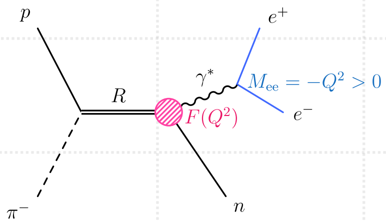
Not fully clear how it was in the Antiquity, but the modern era imagines Hades holding a ***bident***

Hades (Pluto). From a Statue in the Vatican.





Accessible only through EM decays of resonances



Heavy-ion collisions at $\sqrt{s_{NN}}$ = 2-2.4 GeV:

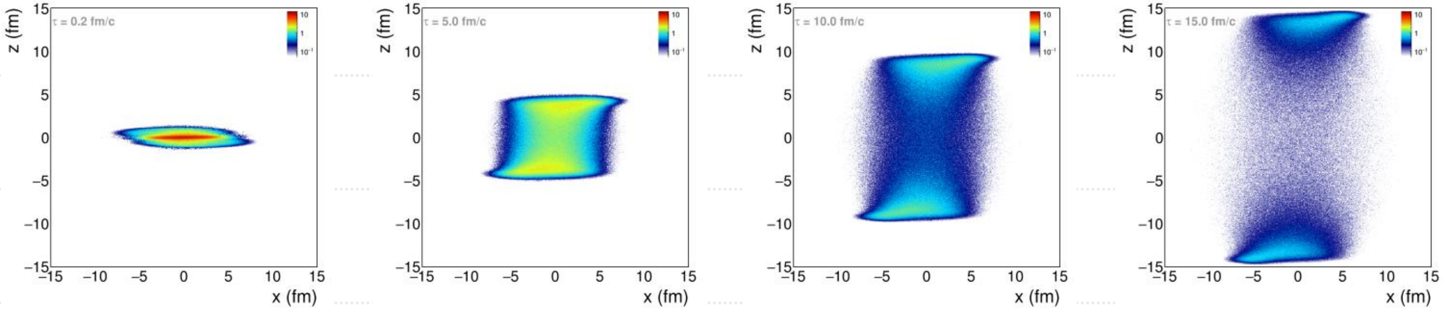
- Microscopic properties of baryon dominated matter
- Equation-of-State
- Observables
  - E-b-e correlations and fluctuations
  - Strangeness production and collective effects
  - Dileptons

Pion and nucleon beams:

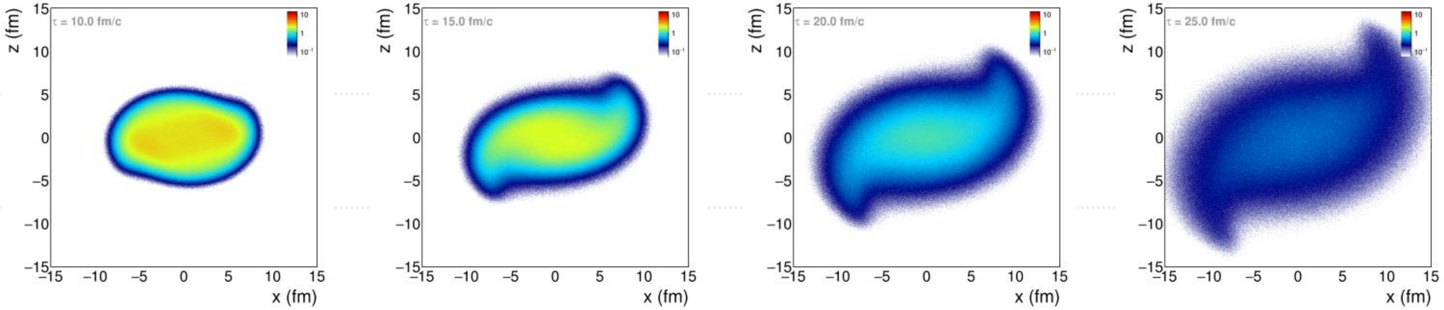
- Reference measurements (vacuum, cold QCD matter)
- Electromagnetic structure of baryons and hyperons

Strong interaction matter at extreme conditions

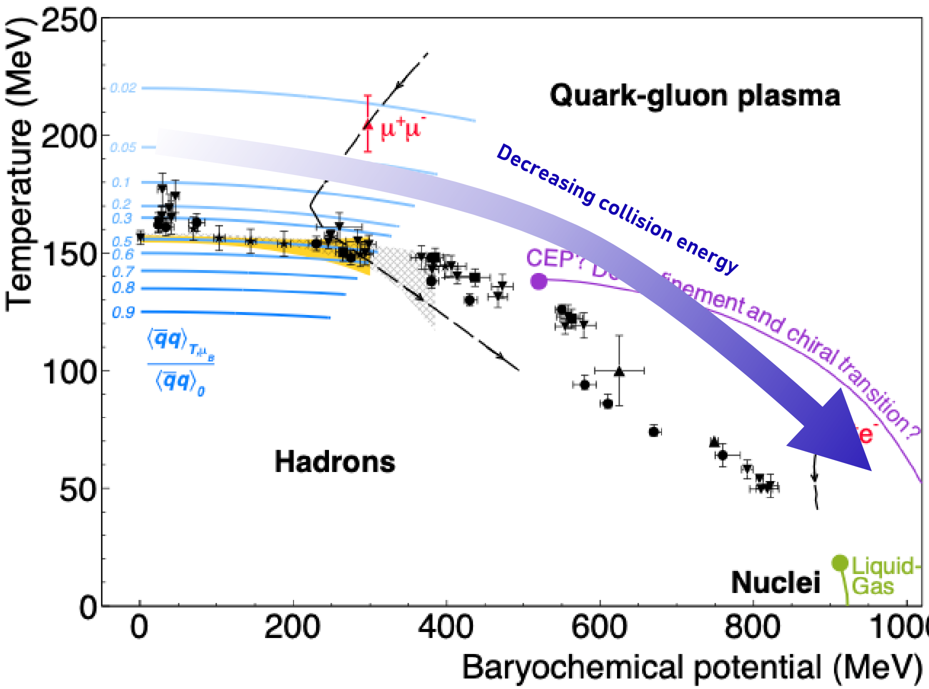
In+In at 158*A* GeV



Au+Au at 1.23*A* GeV



T. Galatyuk et al., EPJA 52 (2016) 5, 131



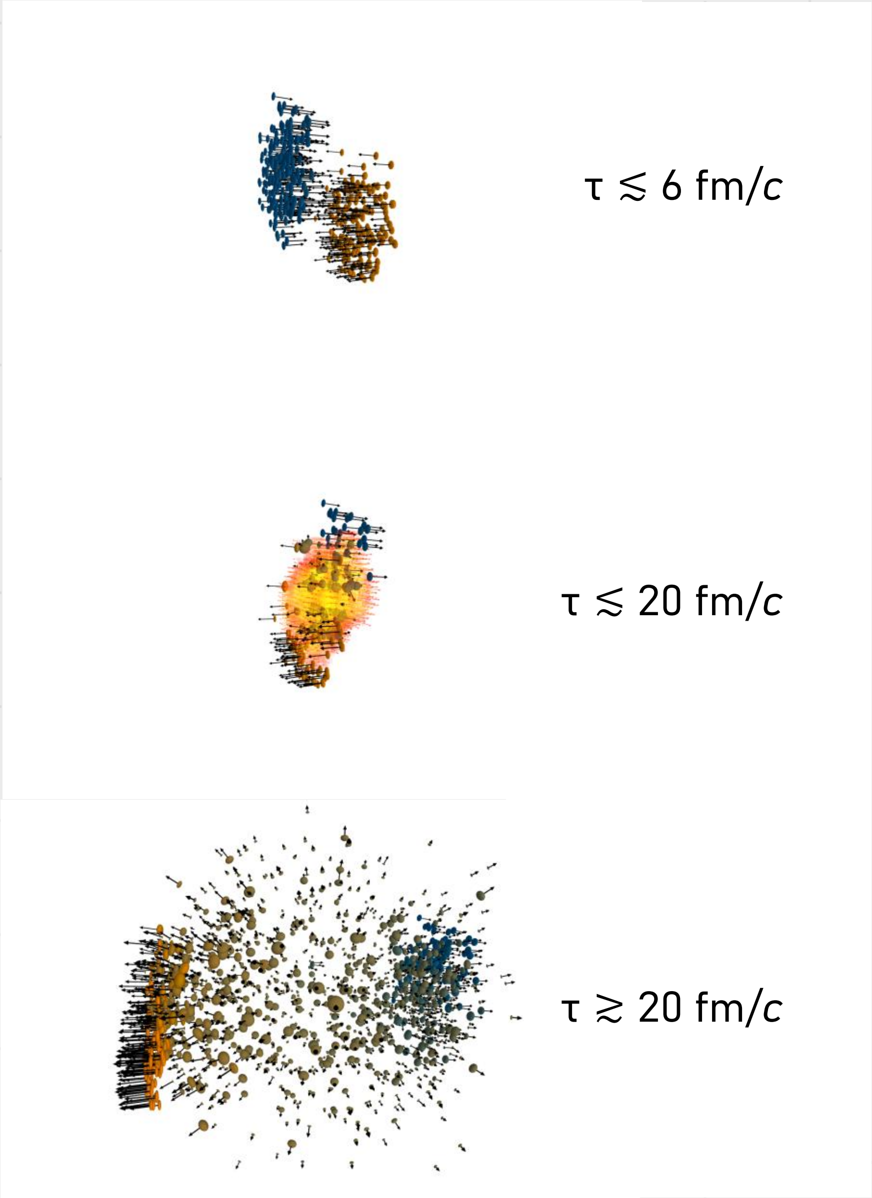
Statistical Hadronization Model of particle production

Borsanyi *et al.* [Wuppertal-Budapest Collab.], JHEP **1009** 073 (2010)
Isserstedt, Buballa, Fischer, Gunkel, PRD **100** 074011 (2019)
Gao, Pawlowski, PLB **820** 136584 (2021)
Cuteri, Philipsen, Sciarra, JHEP **11** 141 (2021)
McLerran, Pisarski, NPA **796** 83 (2007)
Glozman, Philipsen, Pisarski, arXiv:2204.05083 [hep-ph]

HADES, Nature Phys. **15** 10, 1040-1045 (2019)
NA60, Specht *et al.*, AIP Conf.Proc. **1322** 1, 1-10 (2010)
Andronic *et al.*, Nature **561** no.7723 (2018)

Electromagnetic probes

- Photons (virtual and real):
  - Don’t undergo strong interaction
  - Probe all the stages of heavy-ion collisions
- Radiation from hot and dense matter is isolated by subtracting:
  - First-chance NN collisions
  - Meson decays at the freeze-out



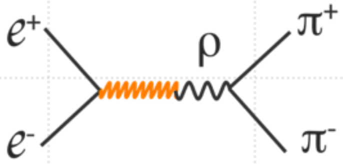
Electromagnetic spectral function

In vacuum, it is measured in e^+e^- annihilation experiments:

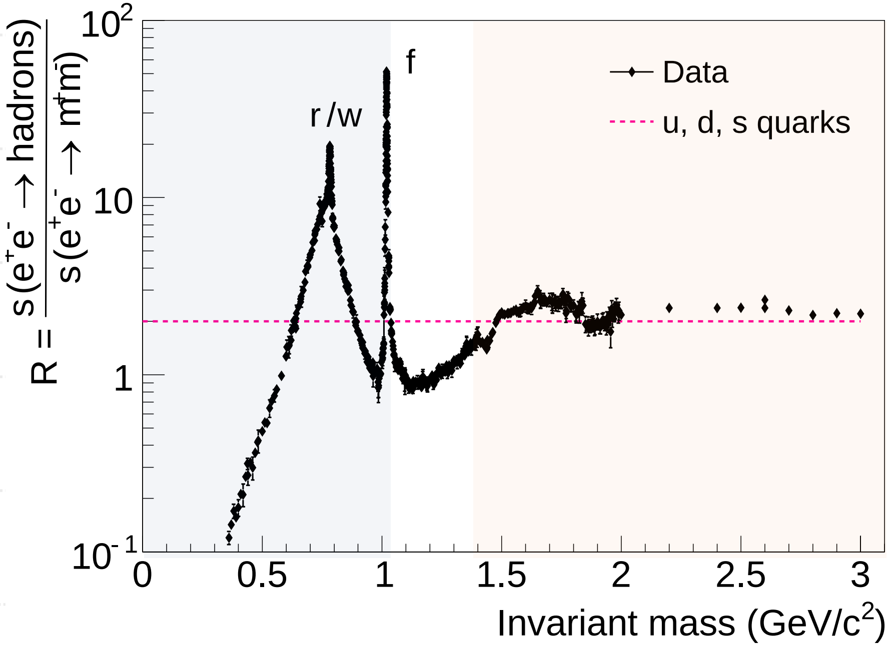
$$R \propto \frac{Im\Pi_{em}}{M^2}$$

Low mass region LMR

EM spectral function is saturated by light vector mesons – with $J^P = 1^-$, same as for (virtual) photon, mainly ρ^0

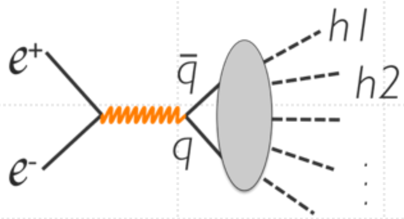


Beringer *et al.* (PDG), PRD **86** 010001 (2012)



Intermediate mass region IMR

Perturbative QCD continuum, quark degrees of freedom



Thermal dileptons at high μ_B

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV
0-40% centrality

- Thermal dilepton production rates
  L. D. McLerran, T. Toimela, PRD **31** 545 (1985)

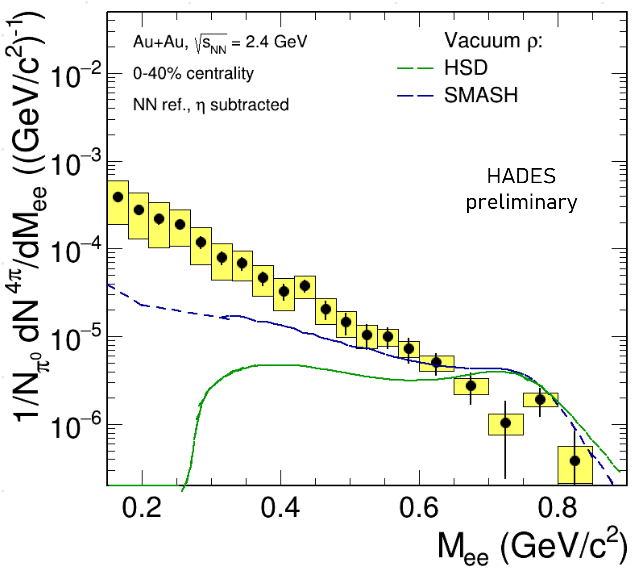
$$\frac{dN_{ll}}{d^4q d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^B(q_0,T) Im\Pi_{em}(M,q,T,\mu_B)$$

Spectral function

CG FRA: PRC **92** 014911 (2015)
CG GSI-Texas A&M: EPJA, **52** 5 131 (2016)
CG SMASH: PRC **98** 054908 (2018)
HSD: PRC **87** 064907 (2013)
PLUTO: J. Phys. Conf. Ser **219** 032039 (2010)

Thermal dileptons at high μ_B

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV
0-40% centrality



- Thermal dilepton production rates

L. D. McLerran, T. Toimela, PRD **31** 545 (1985)

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

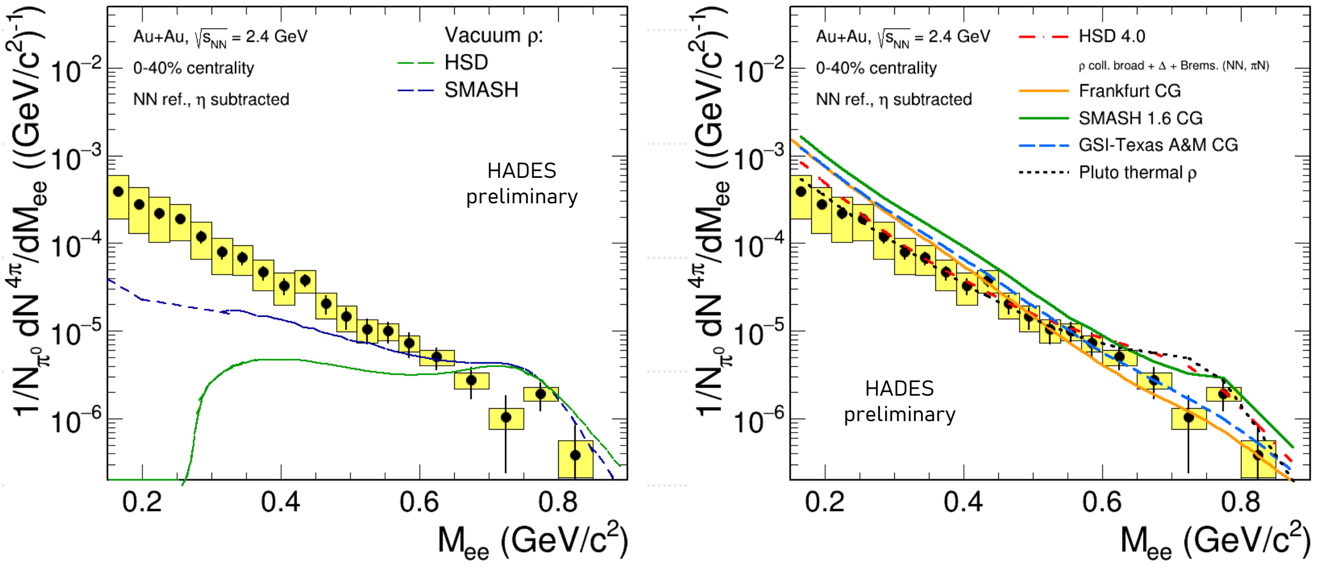
Spectral function

CG FRA: PRC **92** 014911 (2015)
CG GSI-Texas A&M: EPJA, **52** 5 131 (2016)
CG SMASH: PRC **98** 054908 (2018)
HSD: PRC **87** 064907 (2013)
PLUTO: J. Phys. Conf. Ser **219** 032039 (2010)

Thermal dileptons at high μ_B

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV
0-40% centrality

HADES Collab., MS in preparation, cf. also Nature Physics **15** 1040 (2019)



- Thermal dilepton production rates

L. D. McLerran, T. Toimela, PRD **31** 545 (1985)

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

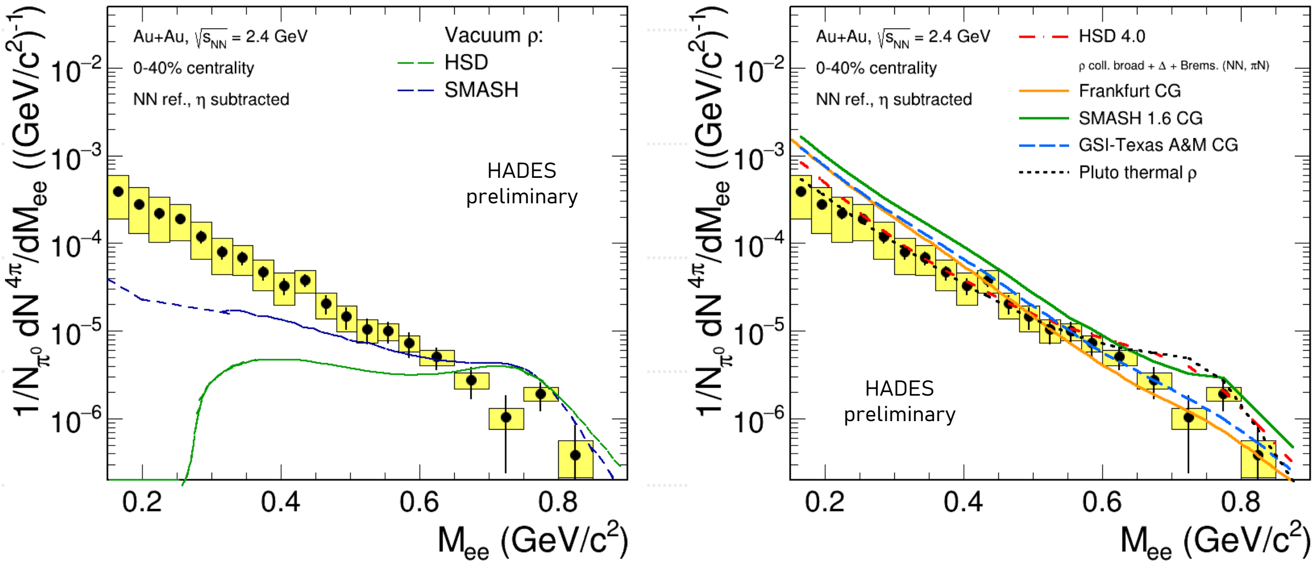
Spectral function

CG FRA: PRC **92** 014911 (2015)
CG GSI-Texas A&M: EPJA, **52** 5 131 (2016)
CG SMASH: PRC **98** 054908 (2018)
HSD: PRC **87** 064907 (2013)
PLUTO: J. Phys. Conf. Ser **219** 032039 (2010)

Thermal dileptons at high μ_B

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV
0-40% centrality

HADES Collab., MS in preparation, cf. also Nature Physics **15** 1040 (2019)



- Thermal dilepton production rates

L. D. McLerran, T. Toimela, PRD **31** 545 (1985)

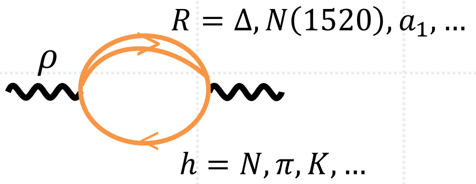
$$\frac{dN_{ll}}{d^4qd^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^B(q_0,T) Im\Pi_{em}(M,q,T,\mu_B)$$

Spectral function

- Melting of ρ clearly visible
- Collisional broadening is not sufficient to account for that

ρ melting handled properly by the local thermal equilibrium approach (CG)

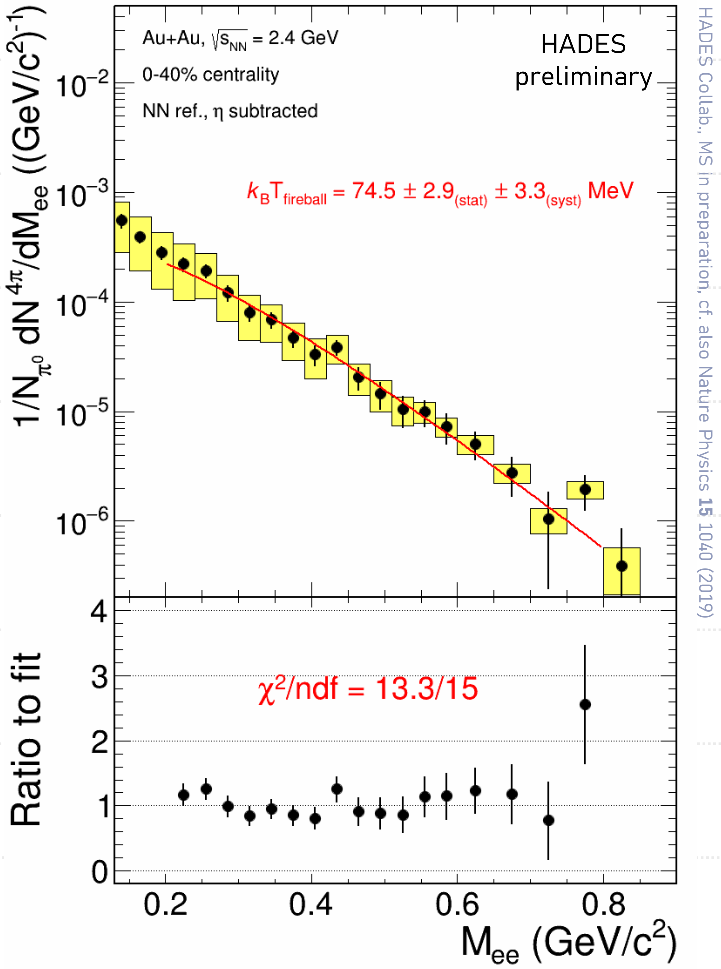
Role of medium effects - coupling of ρ to resonances



CG FRA: PRC **92** 014911 (2015)
CG GSI-Texas A&M: EPJA, **52** 5 131 (2016)
CG SMASH: PRC **98** 054908 (2018)
HSD: PRC **87** 064907 (2013)
PLUTO: J. Phys. Conf. Ser **219** 032039 (2010)

Thermal dileptons at high μ_B

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV
0-40% centrality



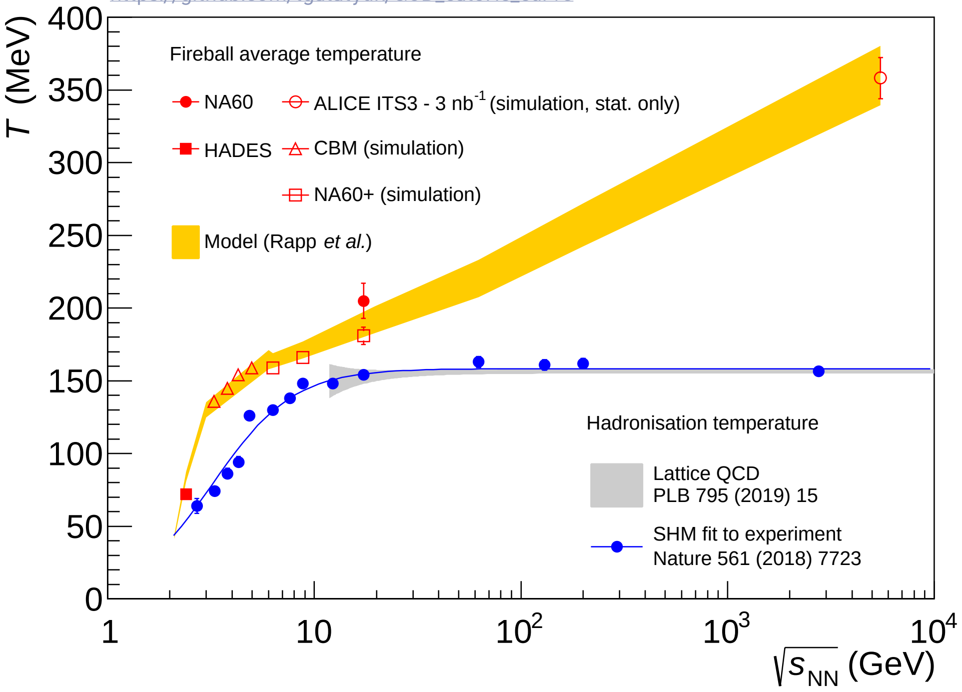
$$\frac{dN_{ll}}{d^4q d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^B(q_0,T) Im\Pi_{em}(M,q,T,\mu_B)$$

Boltzmann factor

- Boltzmann factor dominates the exponential shape of the spectrum if $\mathrm{Im}\Pi_{EM}/M^2$ does not change much with M
- True (average) source temperature – not affected by the blue shift

Discovering the QCD "caloric curve"

Rapp and v. Hess, PLB **753** 586 (2016)
Galatyuk *et al.*, EPJA **52** 131 (2016)
https://github.com/tgalatyuk/QCD_caloric_curve



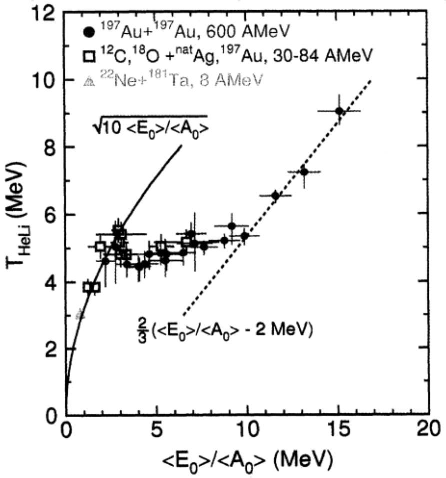
Temperature vs. energy density (collision energy as a proxy)

Up to now, only published data from HADES and NA60

Phase transition may manifest itself as a plateau

Nuclear liquid-gas phase transition

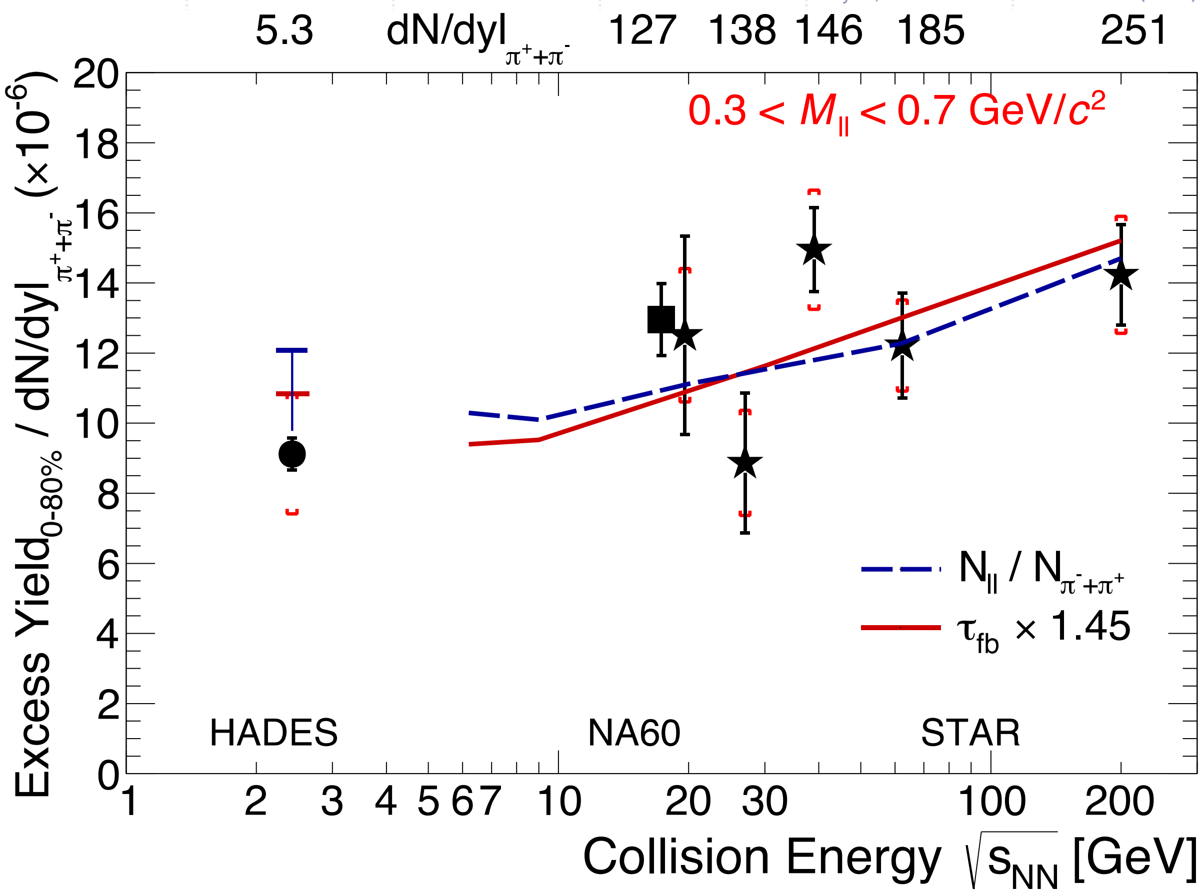
Pochodzalla *et al.*, PRL **75** 1040-1043 (1995)



Lifetime of the fireball

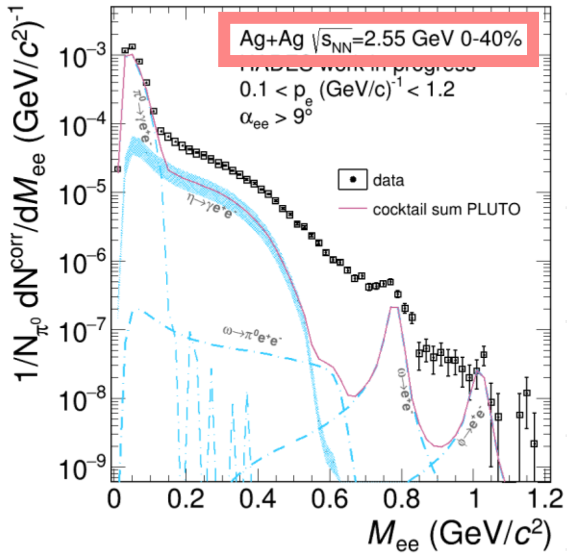
- Thermal radiation is emitted during the whole lifetime of the system
- The integrated yield in $0.3 < M_{ee} / (\text{GeV}/c^2) < 0.7$ is the most sensitive to measure the lifetime
  Heinz and Lee, PLB 259, 162 (1991)
  Barz, Friman, Knoll and Schulz, PLB 254, 315 (1991)
  Rapp, van Hees, PLB 753 (2016) 586
- At a phase transition "production" of the latent heat would increase the lifetime

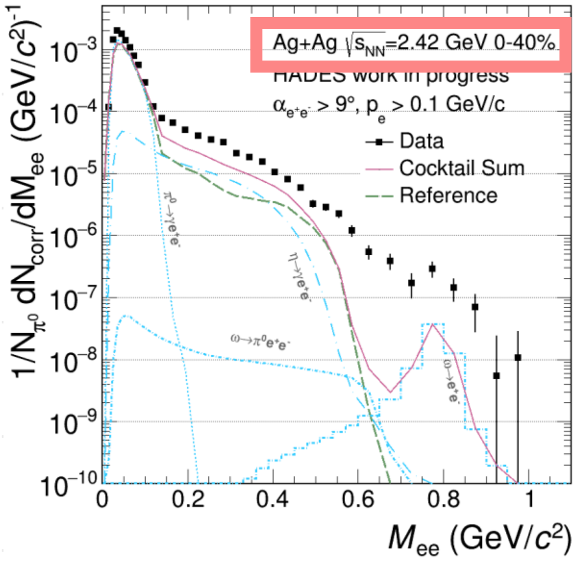
T. Galatyuk, JPS Conf.Proc. **32** 010079 (2020)



High-quality dilepton data

Ag+Ag $\sqrt{s_{NN}}$ = 2.42 GeV
$\sqrt{s_{NN}}$ = 2.55 GeV
0-40% centrality





Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV

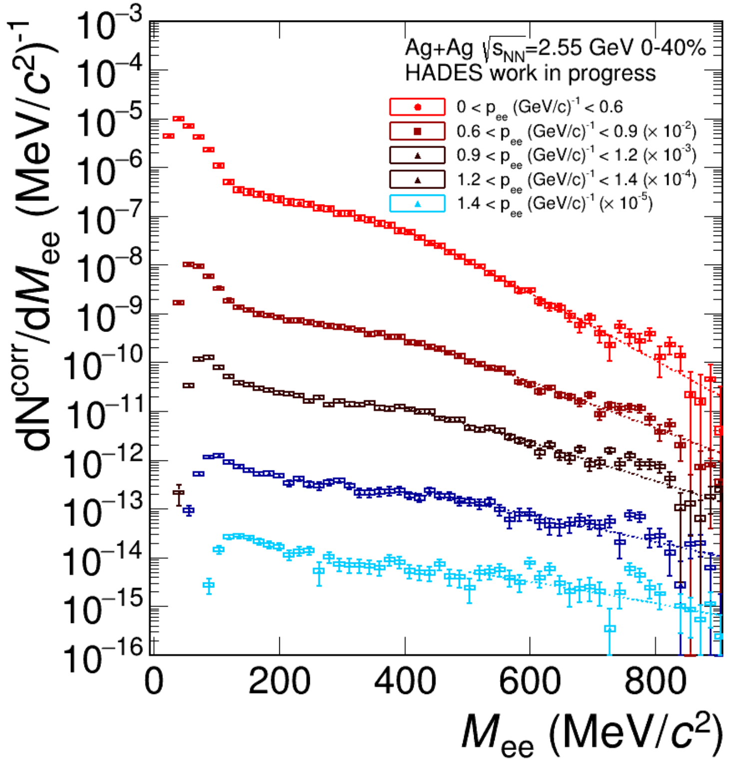
- Vector mesons peaks (ω, ϕ) visible
- Possibility to study cross-sections and in-medium modifications of the spectral shape
- First measurement of the yield above vector meson masses ("Intermediate Mass Region")

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

- Energy, system size and centrality dependence of the hot and dense medium probed by dileptons

Momentum-dependent dilepton spectra

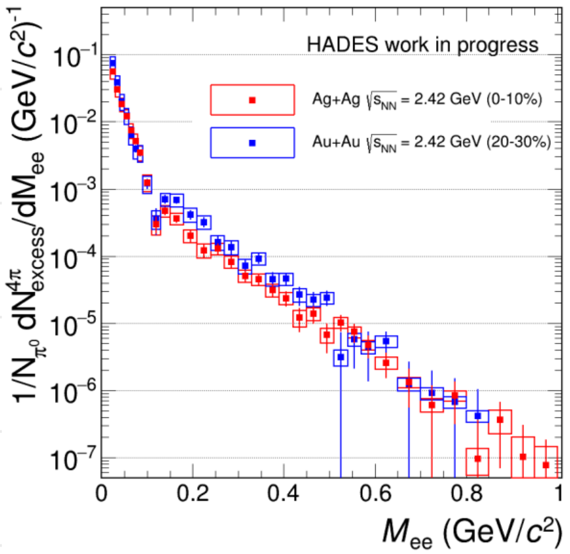
Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV
0-40% centrality



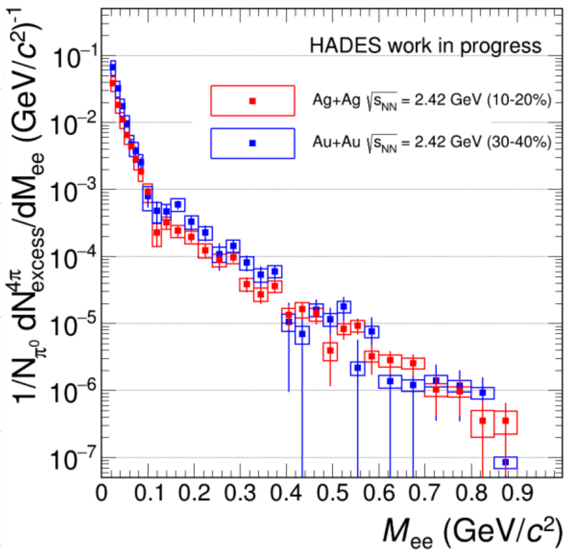
- Possibility for multi-differential analysis
- ω meson clearly visible at high momentum
- "Disappears" at lower momentum:
  - Overwhelmed by the ρ contribution?
  - Broadened by medium effects?
  - Dedicated theory calculations needed to study the effect

System size dependence of dilepton production

Au+Au & Ag+Ag $\sqrt{s_{NN}}$ = 2.42 GeV
Various centralities



Comparable $\langle A_{part} \rangle$



Comparable $\langle A_{part} \rangle$

- Same collision energy
- Pairs of centrality classes with similar participant numbers
- Possibility to isolate the system size dependence

Dilepton polarization

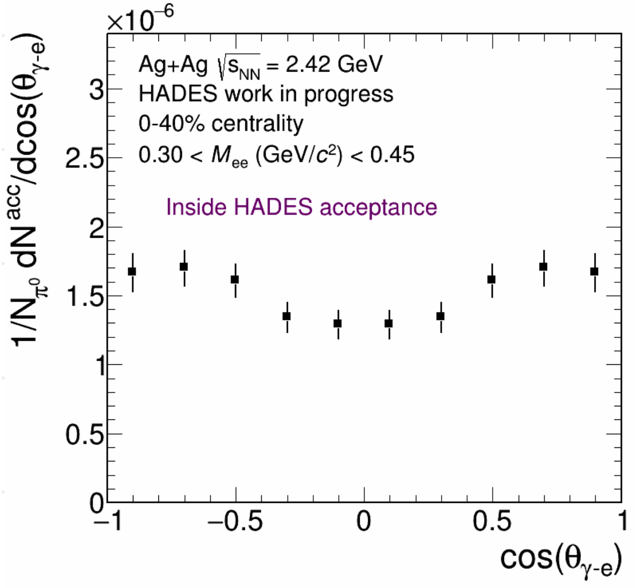
- Angular distribution of l^+l^- in γ^* rest frame depends on the polarization of γ^*:

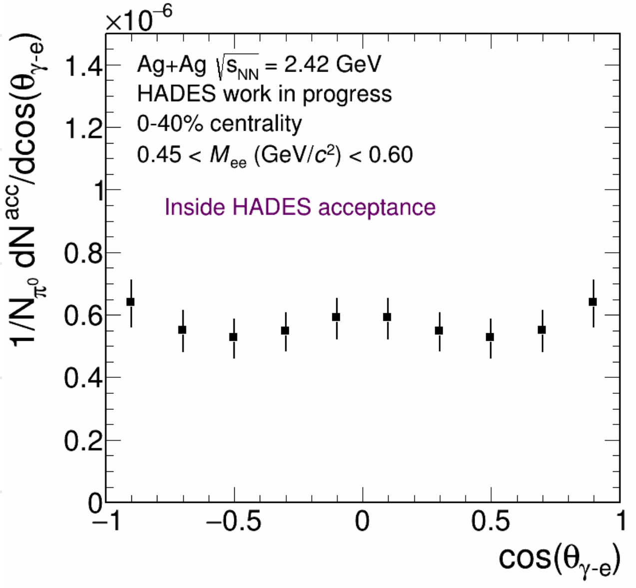
$$\frac{dN}{d^4x d^4q d\Omega} = \mathcal{N}(1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi^\perp \sin^2\theta \sin 2\varphi + \lambda_{\theta\varphi}^\perp \sin 2\theta \sin\varphi)$$

- Distinct polarization patterns for different γ^* sources
- For thermal dileptons: $\lambda_\theta = \frac{\Pi_T - \Pi_L}{\Pi_T + \Pi_L}$, all other coefficients are zero

Dilepton polarization

Ag+Ag $\sqrt{s_{NN}}$ = 2.42 GeV
0-40% centrality





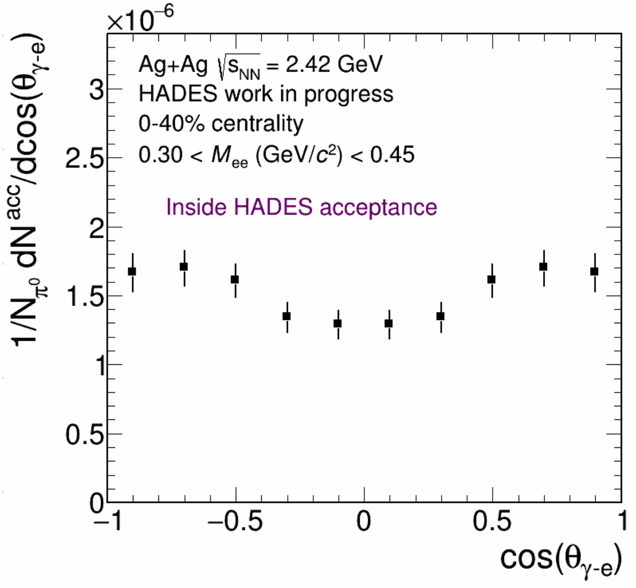
- Angular distribution of l^+l^- in γ^* rest frame depends on the polarization of γ^*:

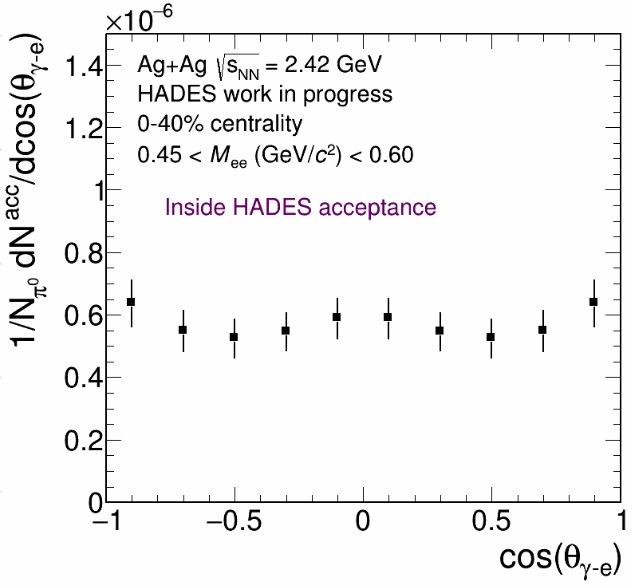
$$\frac{dN}{d^4xd^4qd\Omega} = \mathcal{N}(1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi^\perp \sin^2\theta \sin 2\varphi + \lambda_{\theta\varphi}^\perp \sin 2\theta \sin\varphi)$$

- Distinct polarization patterns for different γ^* sources
- For thermal dileptons: $\lambda_\theta = \frac{\Pi_T - \Pi_L}{\Pi_T + \Pi_L}$, all other coefficients are zero

Dilepton polarization

Ag+Ag $\sqrt{s_{NN}}$ = 2.42 GeV
0-40% centrality





- Angular distribution of l^+l^- in γ^* rest frame depends on the polarization of γ^*:

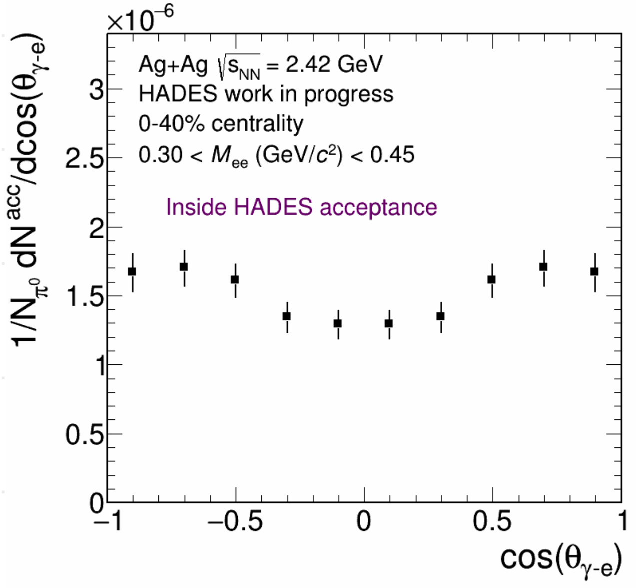
$$\frac{dN}{d^4x d^4q d\Omega} = \mathcal{N}(1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi^\perp \sin^2\theta \sin 2\varphi + \lambda_{\theta\varphi}^\perp \sin 2\theta \sin\varphi)$$

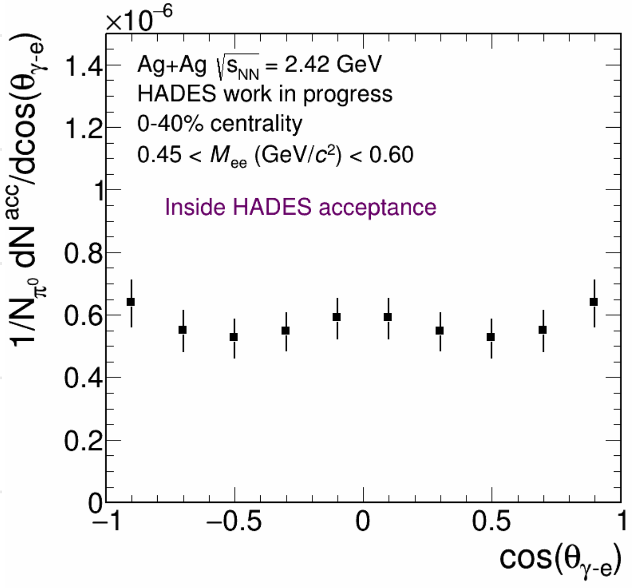
- Distinct polarization patterns for different γ^* sources
- For thermal dileptons: $\lambda_\theta = \frac{\Pi_T - \Pi_L}{\Pi_T + \Pi_L}$, all other coefficients are zero

- Reasonable statistics for lower energy data (10% of all)
- Ongoing study of acceptance corrections
- Flip of the polarization already visible?

Dilepton polarization

Ag+Ag $\sqrt{s_{NN}}$ = 2.42 GeV
0-40% centrality



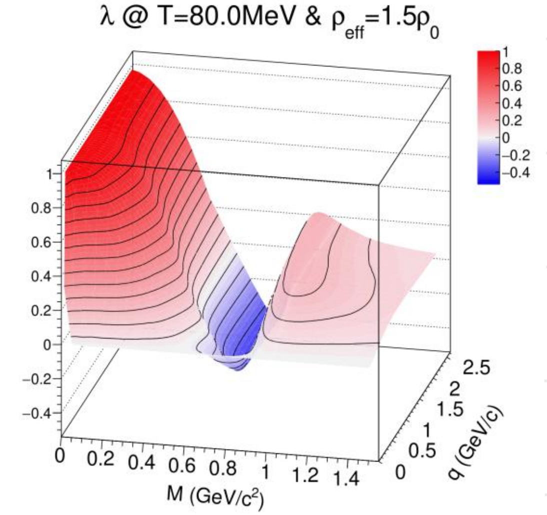


- Angular distribution of l^+l^- in γ^* rest frame depends on the polarization of γ^*:

$$\frac{dN}{d^4x d^4q d\Omega} = \mathcal{N}(1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi^\perp \sin^2\theta \sin 2\varphi + \lambda_{\theta\varphi}^\perp \sin 2\theta \sin\varphi)$$

- Distinct polarization patterns for different γ^* sources
- For thermal dileptons: $\lambda_\theta = \frac{\Pi_T - \Pi_L}{\Pi_T + \Pi_L}$, all other coefficients are zero

- Reasonable statistics for lower energy data (10% of all)
- Ongoing study of acceptance corrections
- Flip of the polarization already visible?

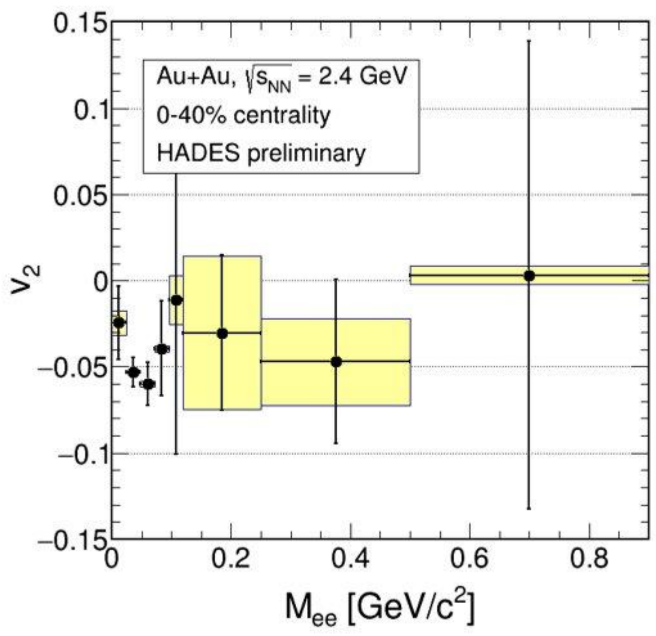


Predictions: N. Schwarz, Bachelor's thesis, Technical University Darmstadt (2023)

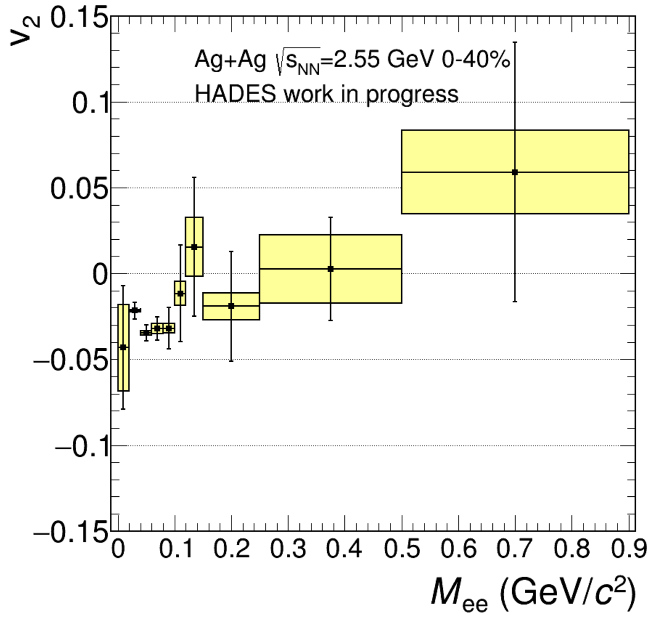
Dilepton azimuthal anisotropy

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV
Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV
0-40% centrality

Au+Au



Ag+Ag



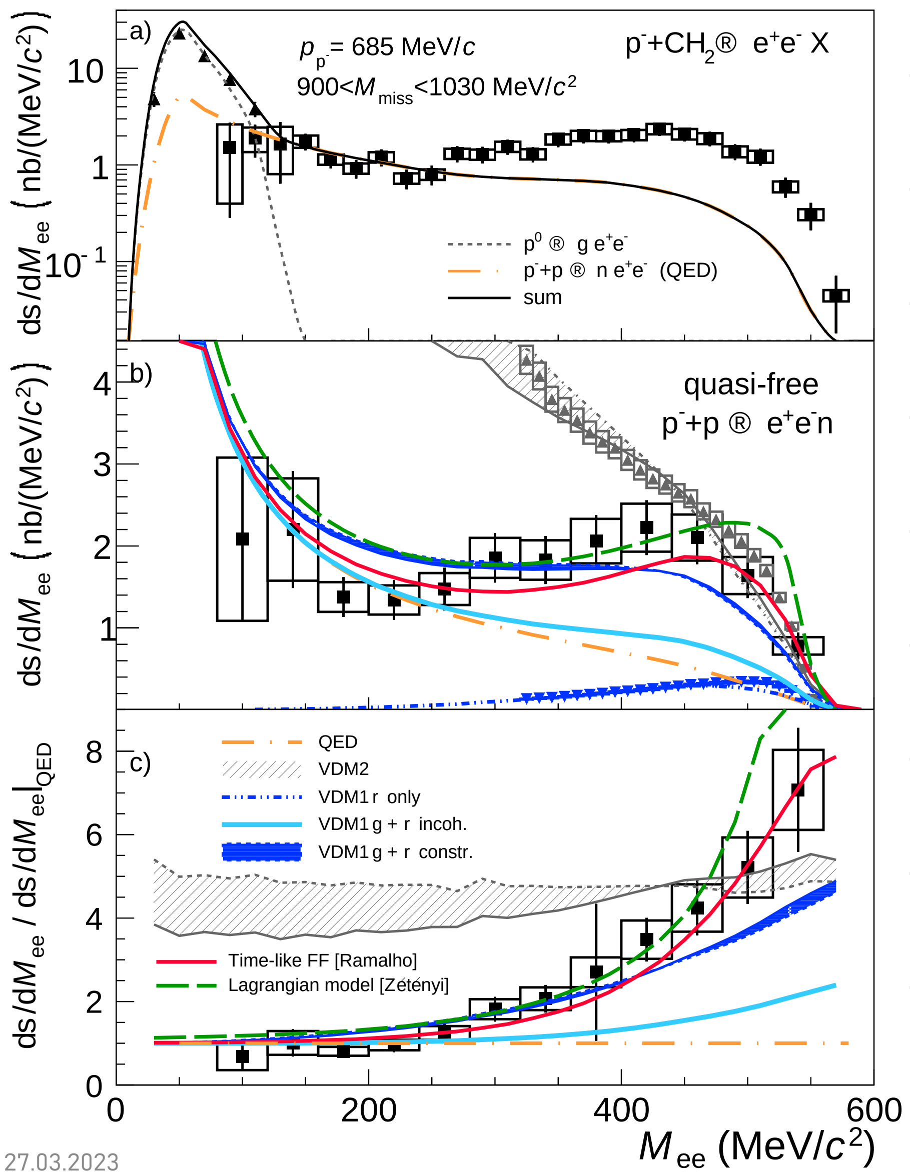
- In the region below 0.14 GeV/c^2 dominated by π^0 Dalitz decay
  - Consistent with charged pion results
- At higher mass v_2 consistent with 0
  - Confirms dileptons as penetrating probes of hot and dense medium

Niklas Schild, talk, 30 Mar 2023, 10:20

Baryons as extended objects

pp $\sqrt{s}$ = 2.42 GeV
π^-p $\sqrt{s}$ = 1.49 GeV

Exclusive analysis of $\pi^- p \to n\, e^+e^-$ at $\sqrt{s}$ = 1.49 GeV

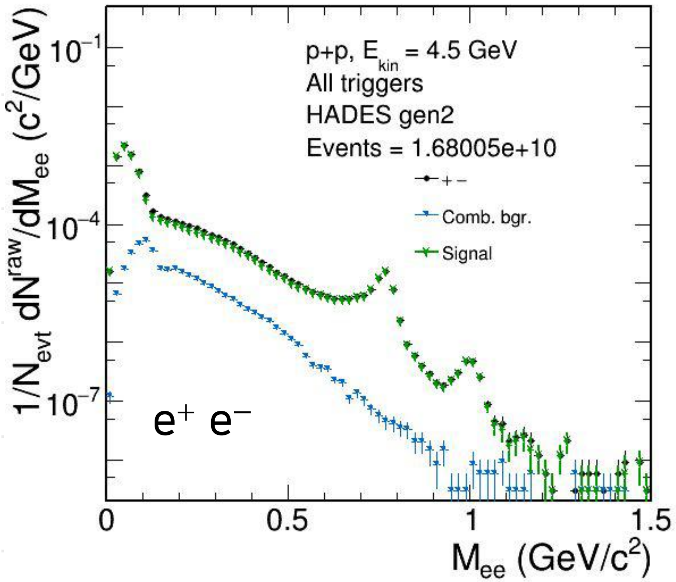


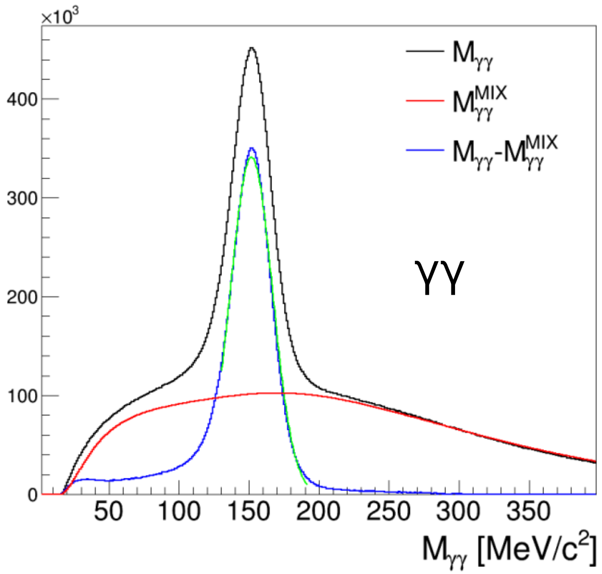
- Ratios to the case with the point-like form factor ("QED")
- Rising with the dilepton invariant mass
- Vector Meson Dominance:
  - VMD2 has $\Gamma = \Gamma_0 \left(\frac{M_0}{M_{ee}}\right)^2$ and overshoots the data at low M_{ee}
  - VMD1 has $\Gamma = \Gamma_0 \frac{M_{ee}}{M_0}$ and leaves room for a contribution of direct $N - \gamma^*$ coupling
  - Therefore the "strict VMD" is excluded

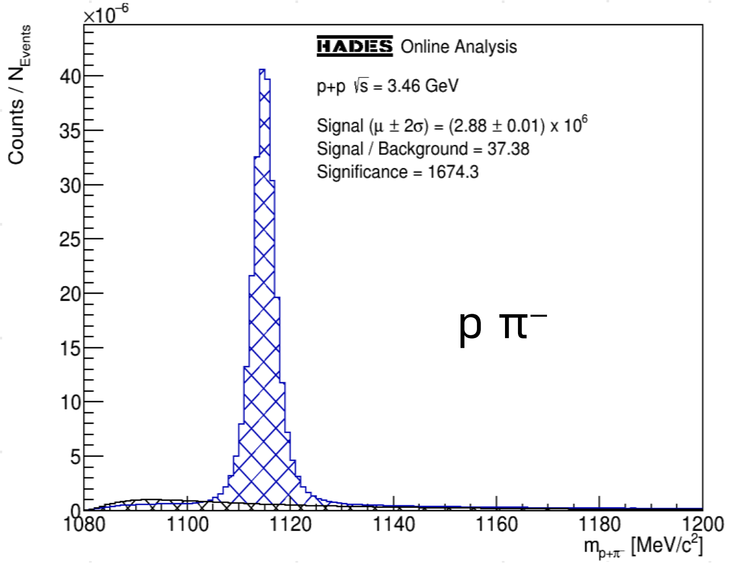
Data: arXiv:2205.15914 [nucl-ex]
Zétényi: PRC **104**, 015201 (2021)
Ramalho: PRD **95**, 014003 (2017), PRD **101**, 114008 (2020)

New Feb 2022 data

p+p $\sqrt{s}$ = 3.46 GeV



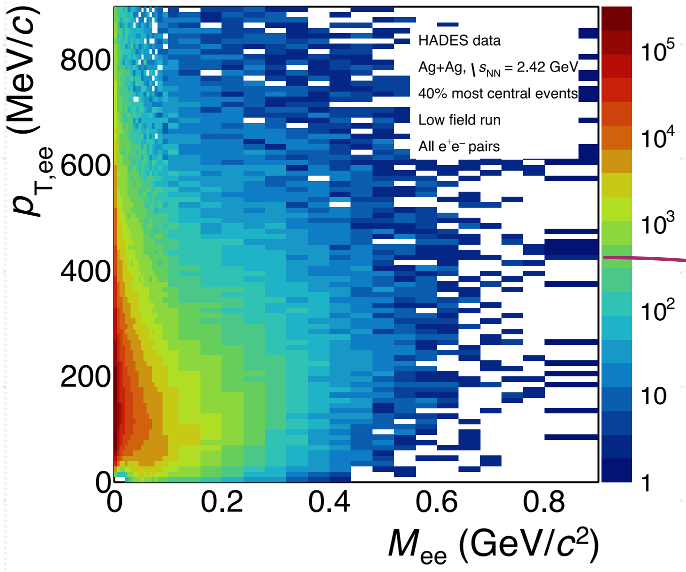


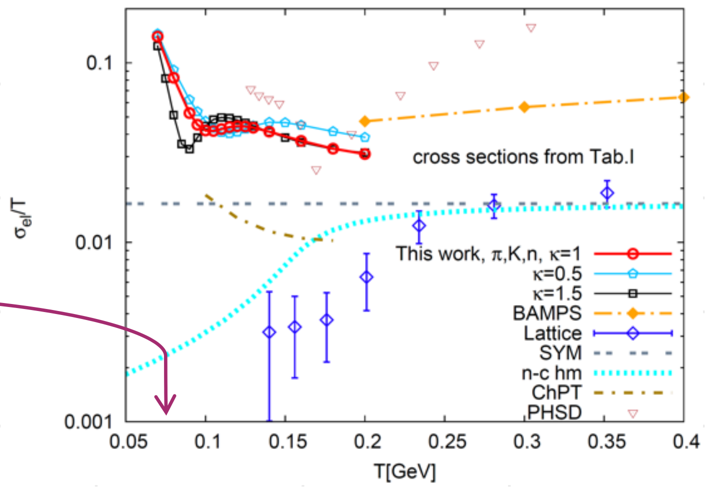


- Ingredients for reconstruction and study of hyperons
- Study ρ, a_1, ω, and ϕ mesons, form-factors
- Data will serve as a baseline for CBM and STAR FXT (fluctuations, correlations, dileptons, etc.)

Dilepton perspectives: extracting electrical conductivity

Raw HADES data





Greif, Greiner, Denicol, PRD **93**, 096012 (2016)
Atchison, Rapp, JPCS **832**, 012057 (2017)

- Related to the spectral function:

$$\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} \mathrm{Im}\Pi_{em}(q_0, \mathbf{q} = 0; T)$$

where:

L. D. McLerran, T. Toimela, PRD **31**, 545 (1985)

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

Spectral function

- Studies at different T are complementary
- Plan:
  - Validate spectral function with dilepton data at lowest possible M_{ee}, $p_{t,ee}$
  - Extract the number

Summary

- Electromagnetic probes allow studying the hot and dense medium
- They measure the temperature and lifetime of the fireball
- Structures in the excitation function will signify a phase transition
- HADES provides high-precision data on dilepton multi-differential spectra and flow harmonics with collision energy, system size, and centrality dependence
- Further studies:
  - Dilepton polarization
  - Electrical conductivity of the medium