System size and centrality dependence of e^+e^- radiation at E_{beam} = 1.23*A* GeV ($(s_{NN})^{1/2}$ = 2.42 GeV) with HADES

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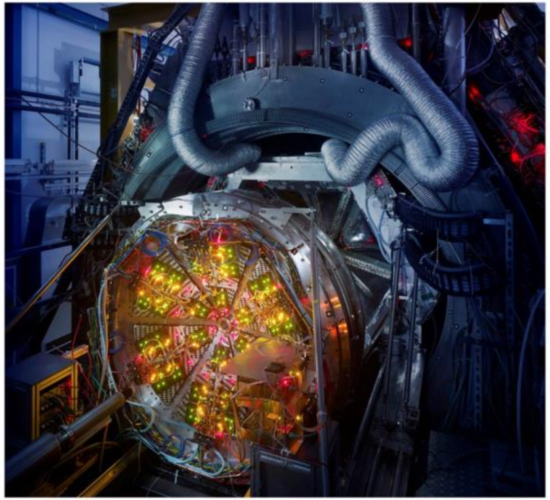
Szymon Harabasz for the HADES Collaboration



- Introduction
- Data Analysis
- Differential Spectra
- Comparison Au+Au vs. Ag+Ag
- Future
- Summary

Meet the HADES

(High Acceptance Di-Electron Spectrometer)

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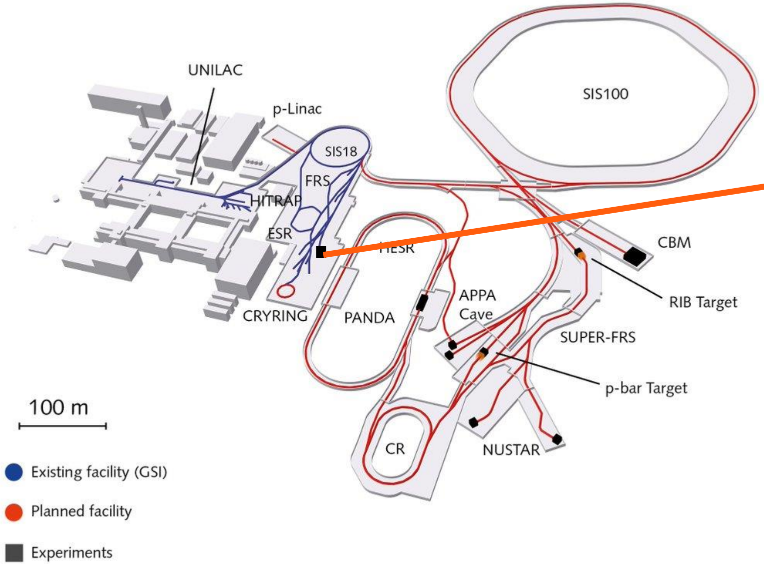
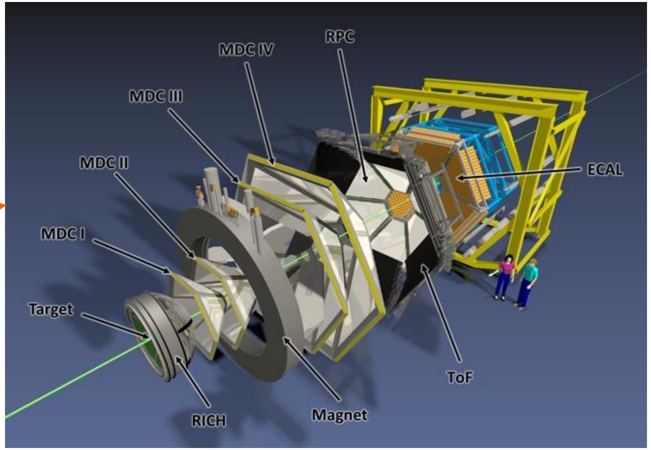




Heavy ion collisions possible *now* at $(s_{NN})^{1/2}$ = 2-3 GeV in fixed-target mode

Interaction rate:

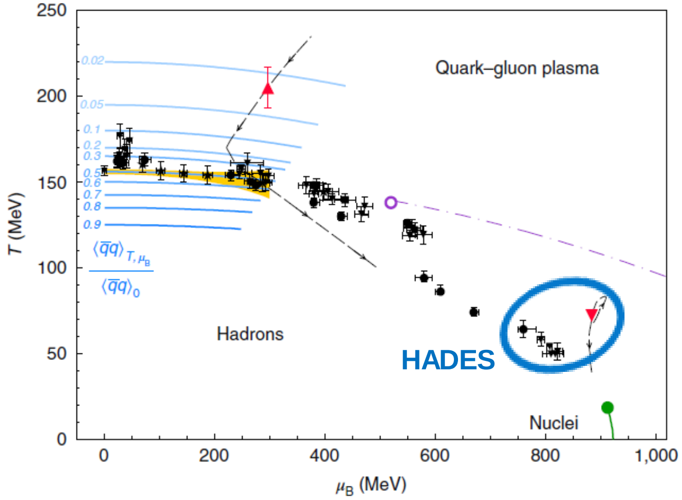
- 8 kHz in Apr 2012 Au+Au $(s_{NN})^{1/2}$ = 2.42 GeV
- 16kHz in Mar 2019 Ag+Ag $(s_{NN})^{1/2}$ = 2.42 GeV and 2.55 GeV

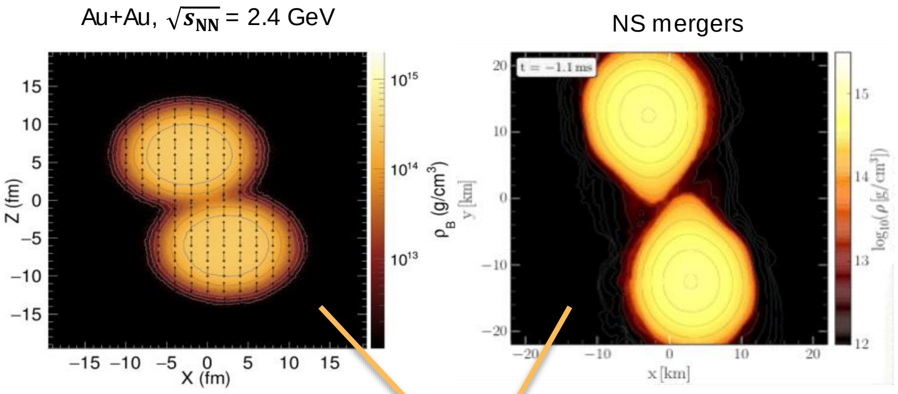
Pion and nucleon beams:

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

The HADES physics case

[HADES Collab., Nature Physics 15 (2019) 1040]



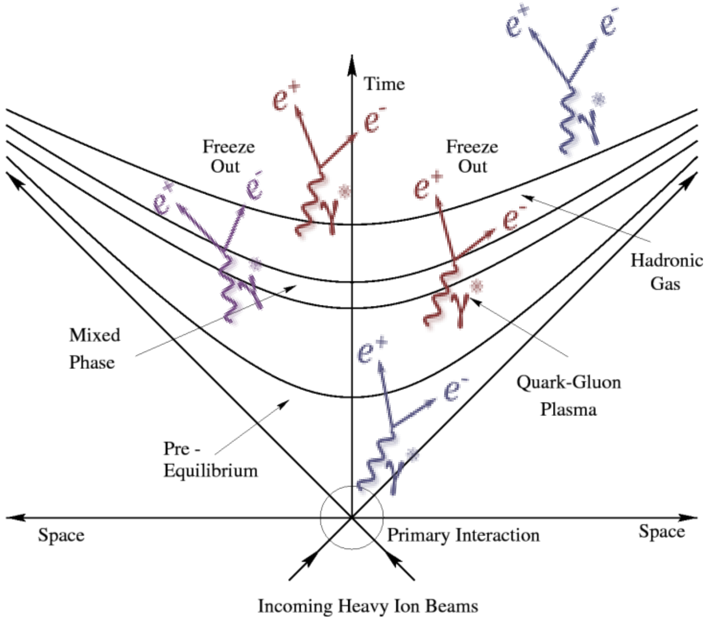


[Universe 5 (1019) 129, Fig. credit: T. Galatyuk, M. Hanauske, F. Seck]

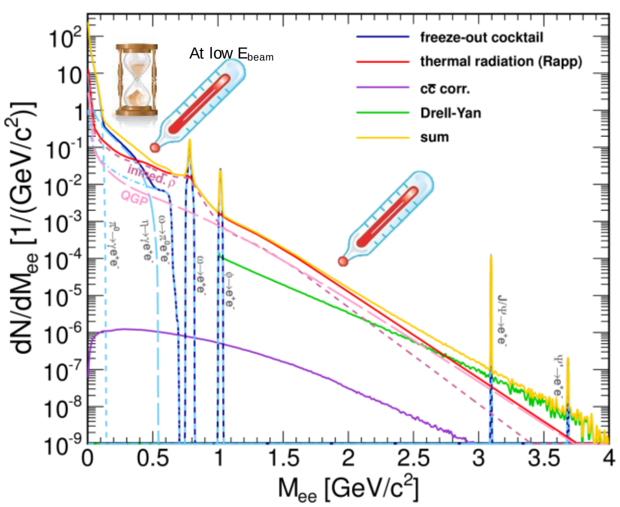
T < 70 MeV, $\rho \approx 3\rho_0$ in both cases

- High μ_B region of QCD phase diagram
- Properties of matter occuring in neutron star mergers

Electromagnetic probes of strongly interacting matter



Schematic spectral distribution of lepton pairs emitted in ultra-relativistic heavy ion collisions



Describing the electromagnetic rate

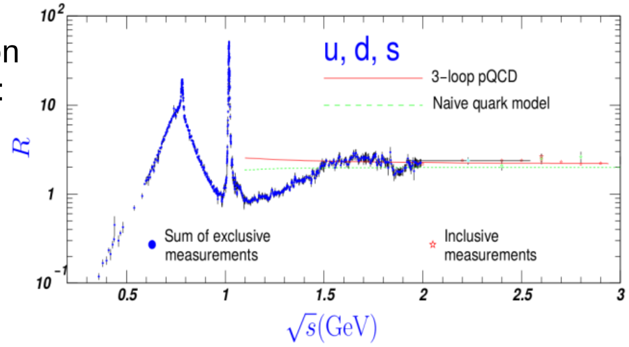
$$\frac{dR_{ll}}{d^3p} = -\frac{\alpha_{EM}^2}{\pi^3 M^2} f^B(p_0;T) \frac{1}{3} g_{\mu\nu} \operatorname{Im}\Pi^{\mu\nu}_{EM}(M,p;\mu_B,T)$$

Boltzmann factor — Spectral function

$$\Pi^{\mu\nu}_{EM}(M,p;\mu_B,T) = -i \int d^4x\, e^{ip\cdot x}\, \Theta(x_0)\, \langle\langle [j^{\mu}_{EM}(x), j^{\nu}_{EM}(0)] \rangle\rangle$$

In vacuum the spectral function has been precisely measured:

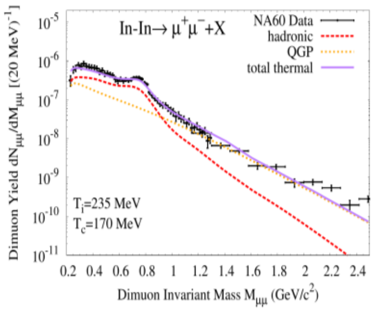
$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \propto \frac{\operatorname{Im}\Pi^{vac}_{EM}}{M^2}$$



In-medium parametrization of the spectral function

[R. Rapp, J. Wambach: Eur. Phys. J. A 6 (1999) 415]

Coupling to baryons → strong broadening of the SF



[Data: NA60 Collab., AIP Conf. Proc. 1322 (2010) 1-10,
Model: H. v. Hees, R. Rapp, NPA 608 (2008) 339-387]

Describes the dilepton spectra from:

- ALICE
  [Phys.Rev.C 99 (2019) 2, 024002]
- STAR
  [Phys.Lett.B 750 (2015) 64-71]
  [arXiv:1810.10159 [nucl-ex]]
- NA60
  [Phys.Rev.Lett. 96 (2006) 162302]
- CERES
  [Phys.Lett.B 666 (2008) 425-429]
- HADES
  [Nature Phys. 15 (2019) 10, 1040-1045]

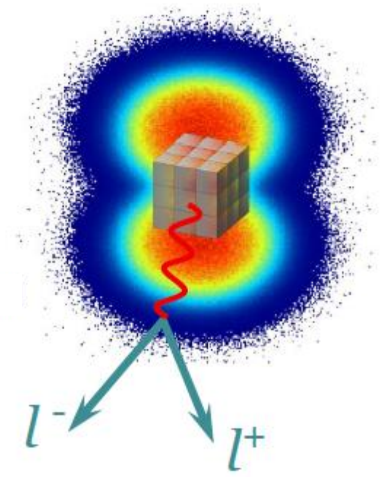
Towards the few-GeV energy regime

Lower beam energy:

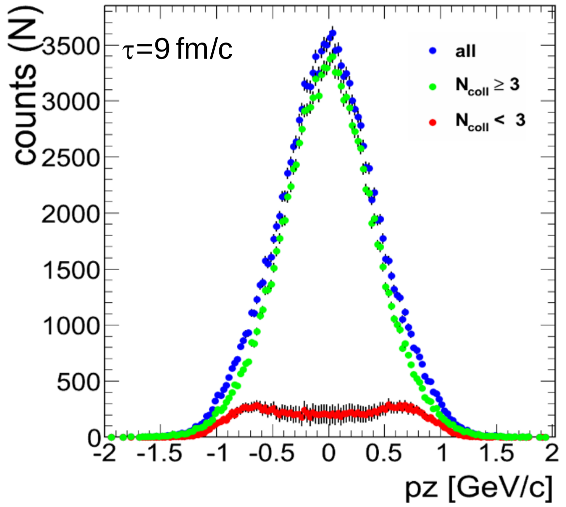
- Lower temperature
- Less abundant meson production
- Slower thermalization
- Local thermal equilibrium at best

Possibilities:

- Microscopic transport models
- Coarse graining of the hadronic transport
  - Simulate (ensemble average of) events with transport model
  - Divide the evolution in 4D spacetime cells
  - Calculate bulk properties in each cell (T, ρ_B, v_{coll})
  - Calculate thermal dilepton rates for these parameters
  - Add up the contributions of all the cells



Momentum distribution of nucleons
(based on UrQMD)



Phys. Rev. C 66, 014903 (2002)
Phys. Rev. C 92, 014911 (2015)
Eur. Phys. J. A, 52 5 (2016) 131
Phys. Rev. C 98, 054908 (2018)

DATA ANALYSIS

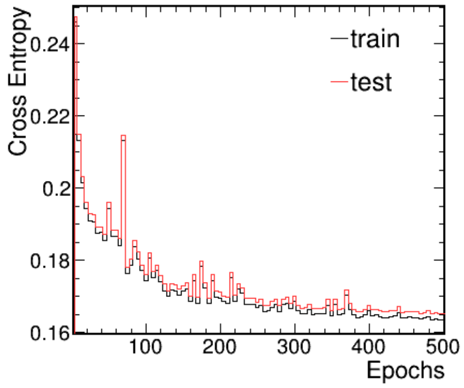
Electron Identification

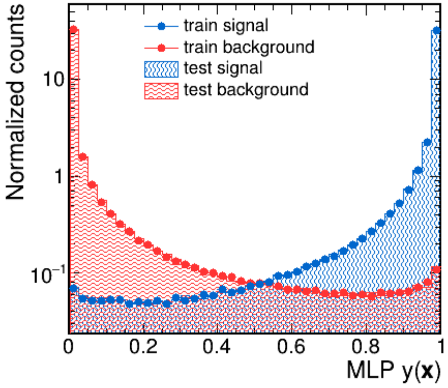
- Track quality selection
- Energy loss
- Particle velocity
- Electromagnetic shower
- Cherenkov radiation

} Correlated with momentum

- All combined in a multivariate analysis (neural networks)
- Purity of single lepton identification at least 98 %

PID with multi-layer perceptron (MLP)



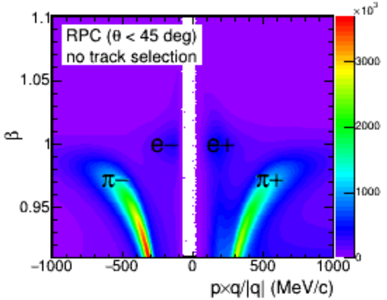


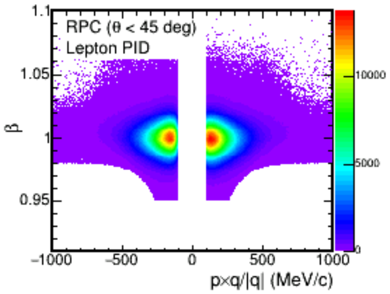
- Train and test do no split
  → No signal of overtraining
- Plateau reached
  → Sufficient number of training epochs

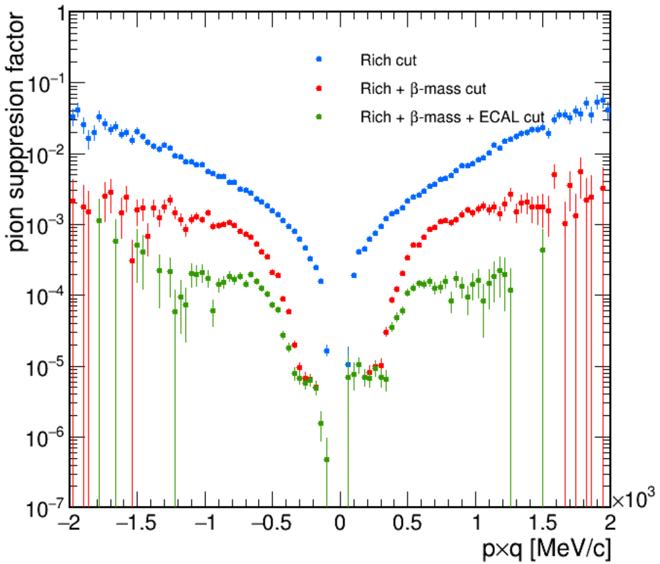
- Distributions drop rapidly
  → Good discrimination power
- Train and test overlap
  → Ability of the model to generalize for unseen data

Selection of Signal Leptons

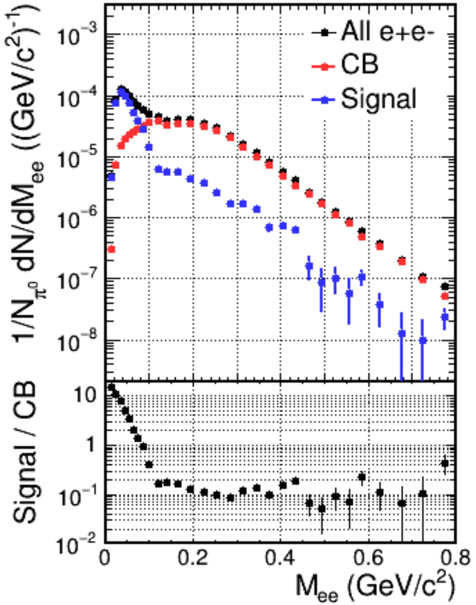
Identification of single e^+ and e^-





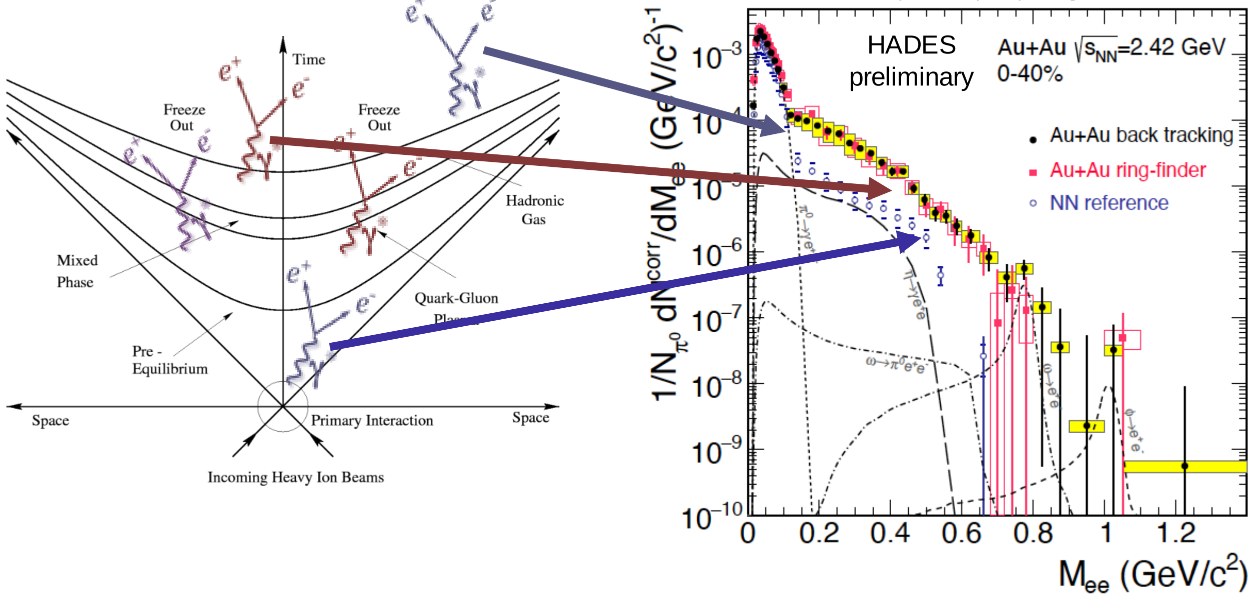


Building of e^+e^- pair signal



Extracting in-medium radiation

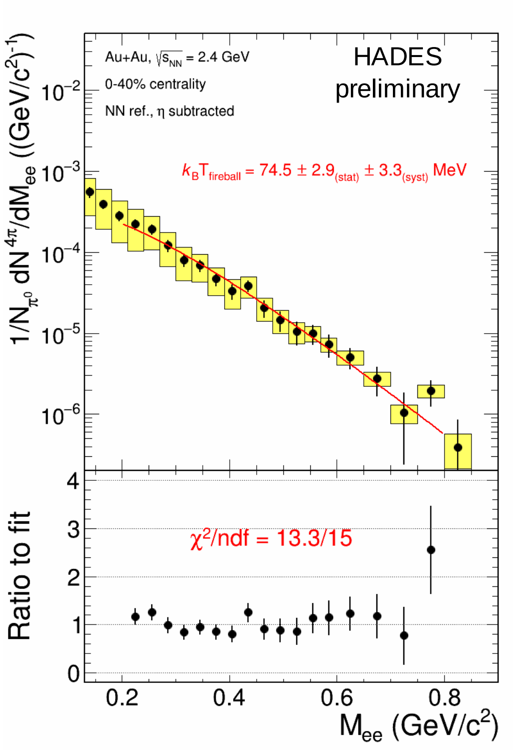
[HADES Collab., MS in preparation, cf. also Nature Physics 15 (2019) 1040]



- pp and np measured at the same beam energy account for primary interaction
- Cocktail of long-lived meson sources is simulated
- After subtracting the two one gets in-medium radiation
- This can be extrapolated to 4π without much systematics

DIFFERENTIAL SPECTRA

Thermal dileptons at high μ_B



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

- Thermal dilepton production rates

$$\frac{dR_{ll}}{d^3p} = -\frac{\alpha_{\rm EM}^2}{\pi^3 M^2} f^B(p_0;T) \frac{1}{3} g_{\mu\nu} \; {\rm Im}\,\Pi^{\mu\nu}_{\rm EM}(M,p;\mu_B,T)$$

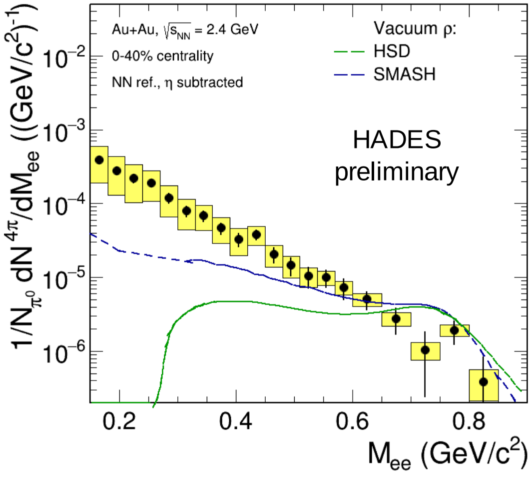
Boltzmann factor

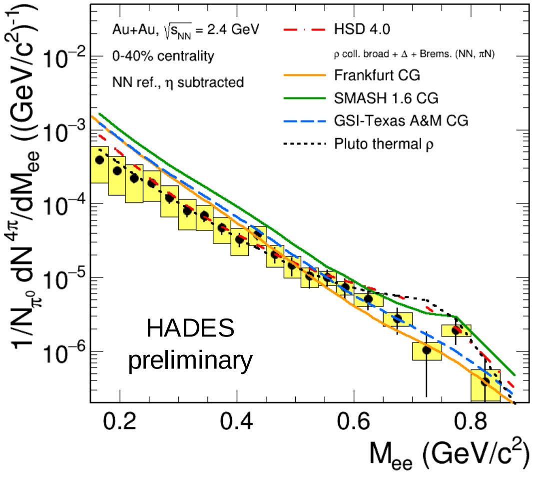
- Boltzmann factor dominates the exponential shape of the spectrum if $\mathrm{Im}\Pi_{EM}/M^2$ does not change much with M
- Slope of the invariant mass not affected by the fireball expansion
- True measure of the (average) source temperature

Thermal dileptons at high μ_B

$$\frac{dR_{ll}}{d^3p} = -\frac{\alpha_{EM}^2}{\pi^3 M^2} f^B(p_0;T)\, \frac{1}{3}\, g_{\mu\nu}\, \boxed{\mathrm{Im}\,\Pi^{\mu\nu}_{EM}(M,p;\mu_B,T)}$$

Spectral function





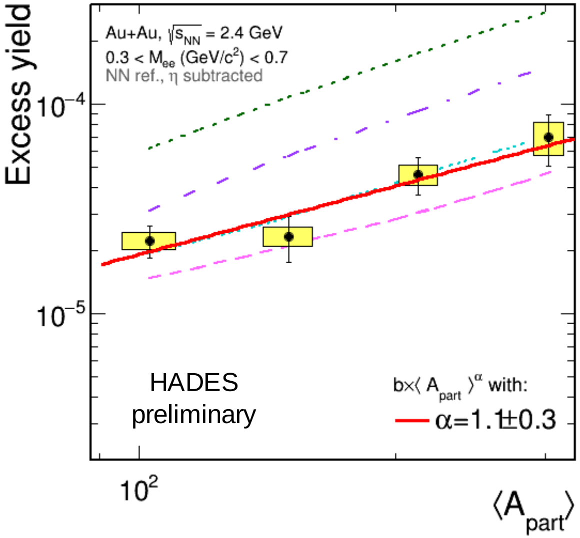
- Melting of ρ clearly visible
- Collisional broadening is not sufficient to account for that

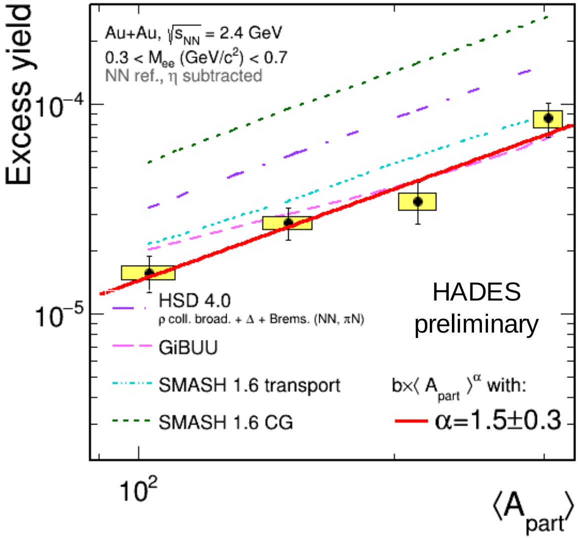
ρ melting handled properly by local equilibrium (CG) approach

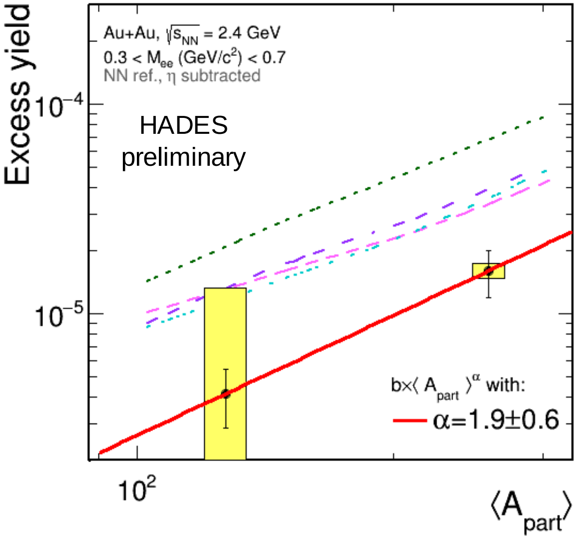
CG FRA: Phys. Rev. C 92, 014911 (2015)
CG GSI-Texas A&M: Eur. Phys. J. A, 52 5 (2016) 131
CG SMASH: Phys. Rev. C 98, 054908 (2018)
HSD: Phys. Rev. C 87, 064907 (2013)
PLUTO: J. Phys. Conf. Ser 219, 032039 (2010)

Excess yield

Dependence on the centrality and p_t



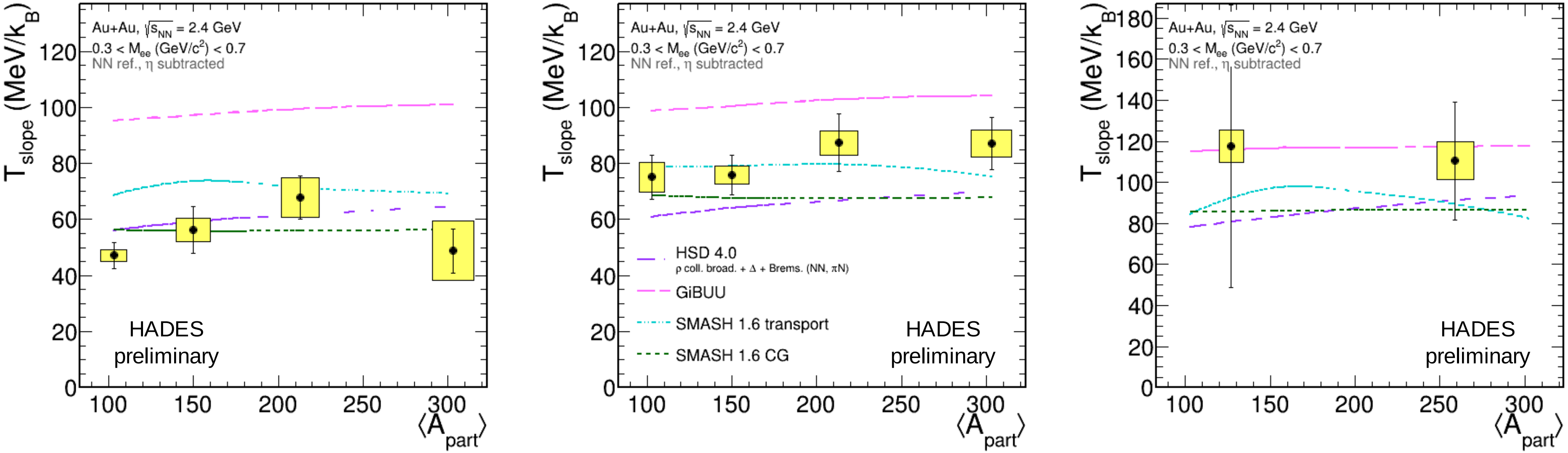




- Stronger dependence at higher p_t
- None of the models describes all the trends fully

Temperature

Dependence on the centrality and p_t



- Stronger dependence at higher p_t
- None of the models describes all the trends fully

Boltzmann fits to transverse momentum

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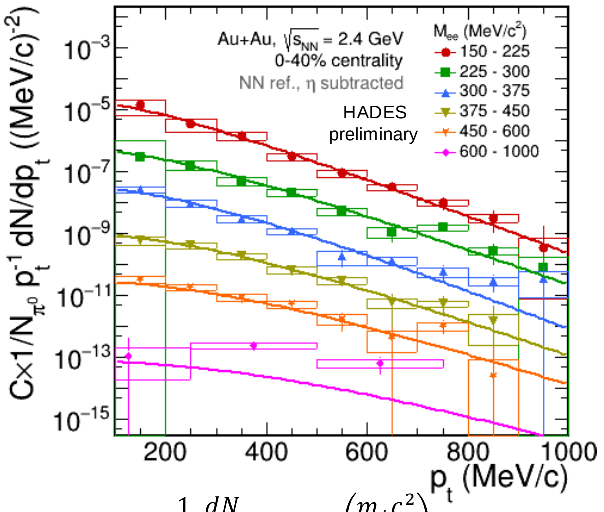
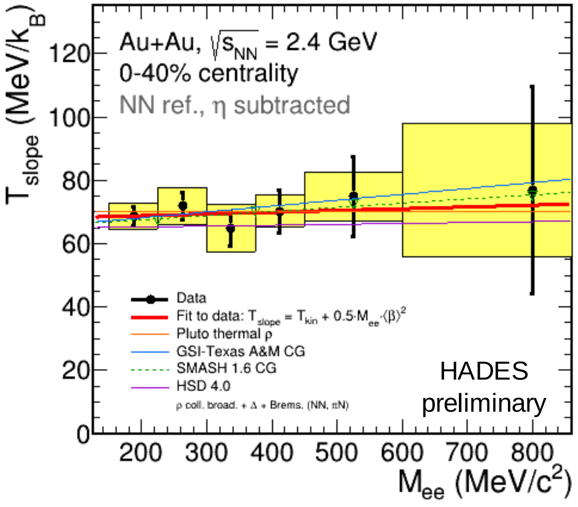


$$\frac{1}{p_t}\frac{dN}{dp_t} \propto m_t K_1\left(\frac{m_t c^2}{k_B T}\right)$$

Assumes pure Boltzmann nature of the source:

$$\frac{d^3N}{d\vec{p}} \propto \exp\left(-\frac{E}{k_B T}\right)$$

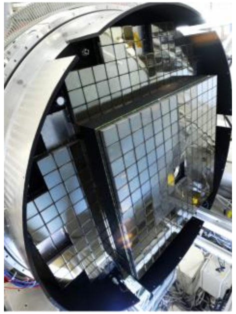


$$k_B T_{\text{slope}} = k_B T_{\text{kin}} + \tfrac{1}{2} M_{ee} c^2 \langle\beta\rangle^2$$

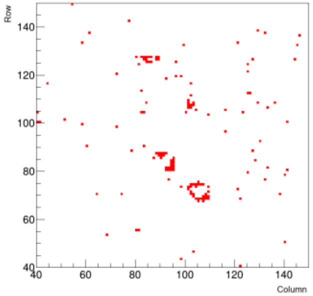
- Fit to the model points:
  - CG: $T_{\text{kin}} = 65\ \text{MeV}/k_B, \langle\beta\rangle = 0.19$
  - HSD: $T_{\text{kin}} = 74\ \text{MeV}/k_B, \langle\beta\rangle = 0.05$

TOWARDS THE DILEPTON EXCITATION FUNCTION

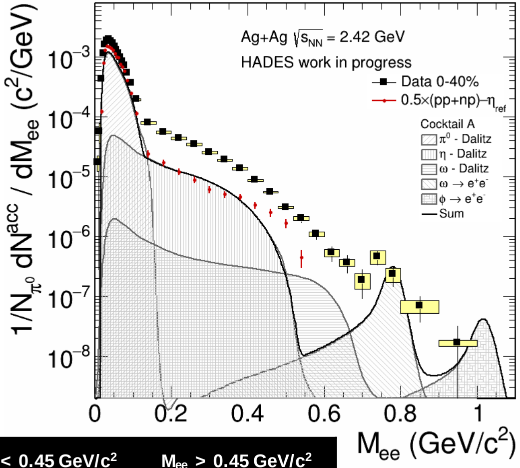
New data set from March 2019 beam time



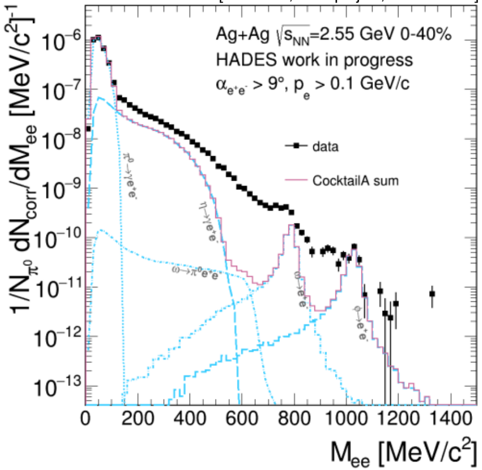
PMT-based photodetector for HADES RICH



Event display of the RICH detector



[J. H. Otto, PhD project, JLU Gießen]

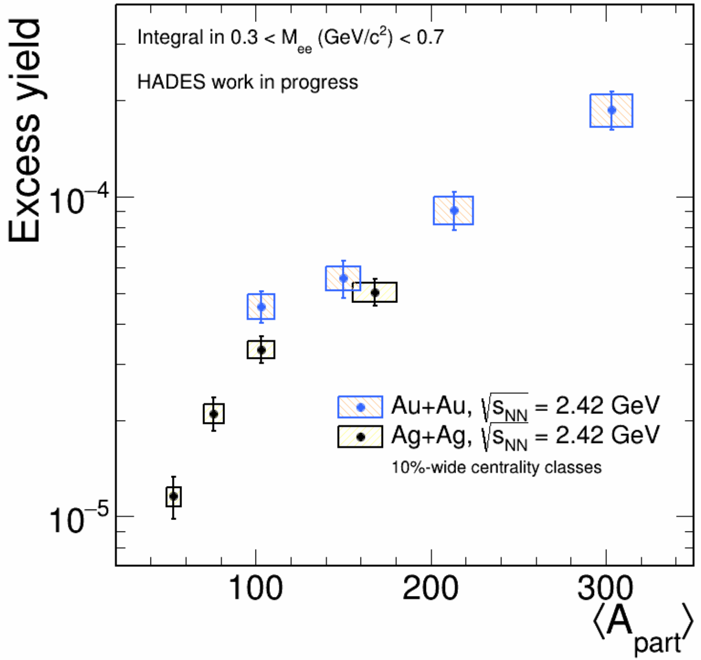


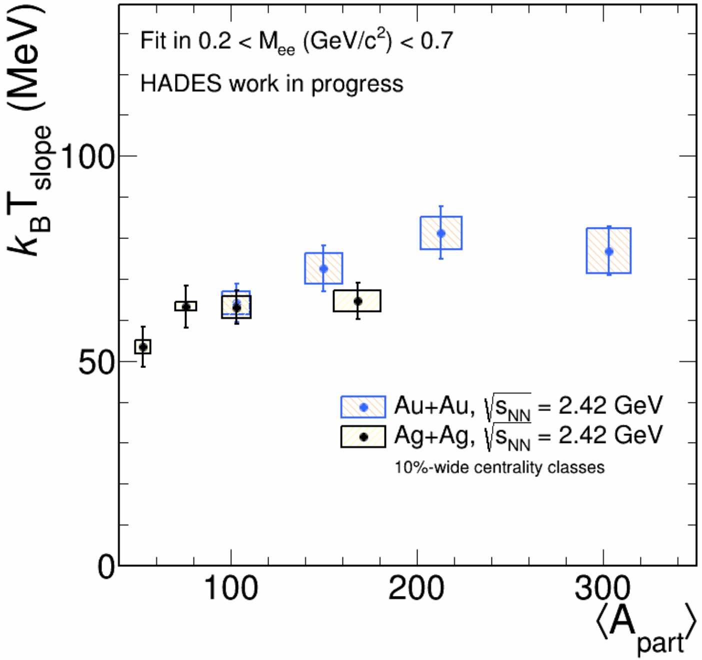
Number of raw signal pairs

Experiment	# analyzed events	M_{ee} < 0.12 GeV/c²	0.12 < M_{ee} < 0.45 GeV/c²	M_{ee} > 0.45 GeV/c²
Au+Au $(s_{NN})^{1/2}$ = **2.42** GeV	2.4×10^9	1.15×10^5	1.53×10^4	581
Ag+Ag $(s_{NN})^{1/2}$ = **2.42** GeV	5.9×10^8	1.12×10^5	1.59×10^4	901
Ag+Ag $(s_{NN})^{1/2}$ = **2.55** GeV	4.0×10^9	8.80×10^5	1.53×10^5	10916

Very high quality of the data!

Exciting physics around the corner





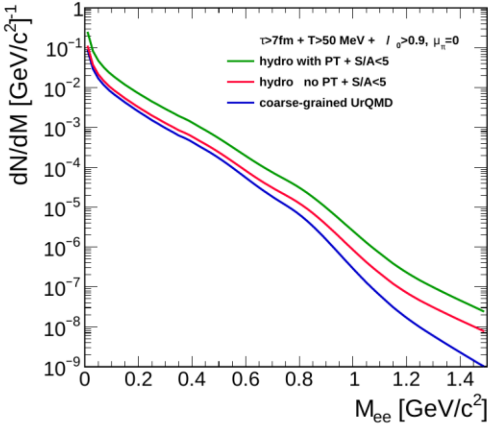
Conclusions

- HADES explores baryon rich matter at SIS 18
- Properly extracted dilepton excess yield agrees well with theory predictions
- Differential spectra depending on p_t and rapidity have been presented
- Boltzmann temperature and characteristics of the spectra function are studied
- Upgraded RICH photodetector (FAIR Phase 0, together with CBM) allows for unprecedented precision of dielectron data

Stay tuned for...

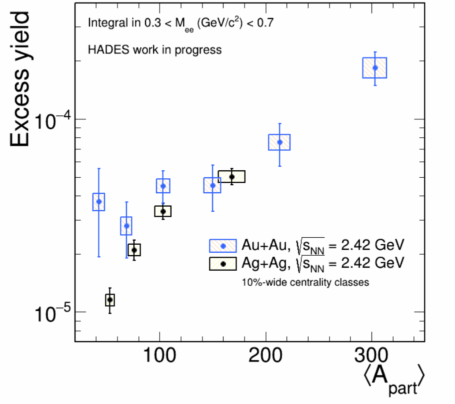
Sensitivity of dilepton yield to a phase transition

[F. Seck *et al.*, arXiv:2010.04614]



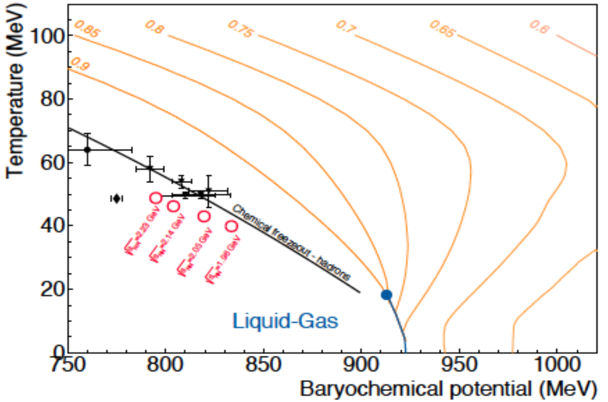
Extension of the Au+Au analysis to peripheral events

[N. Schild, Master's project at TU Darmstadt]



HADES BES 0.2-0.8*A* GeV

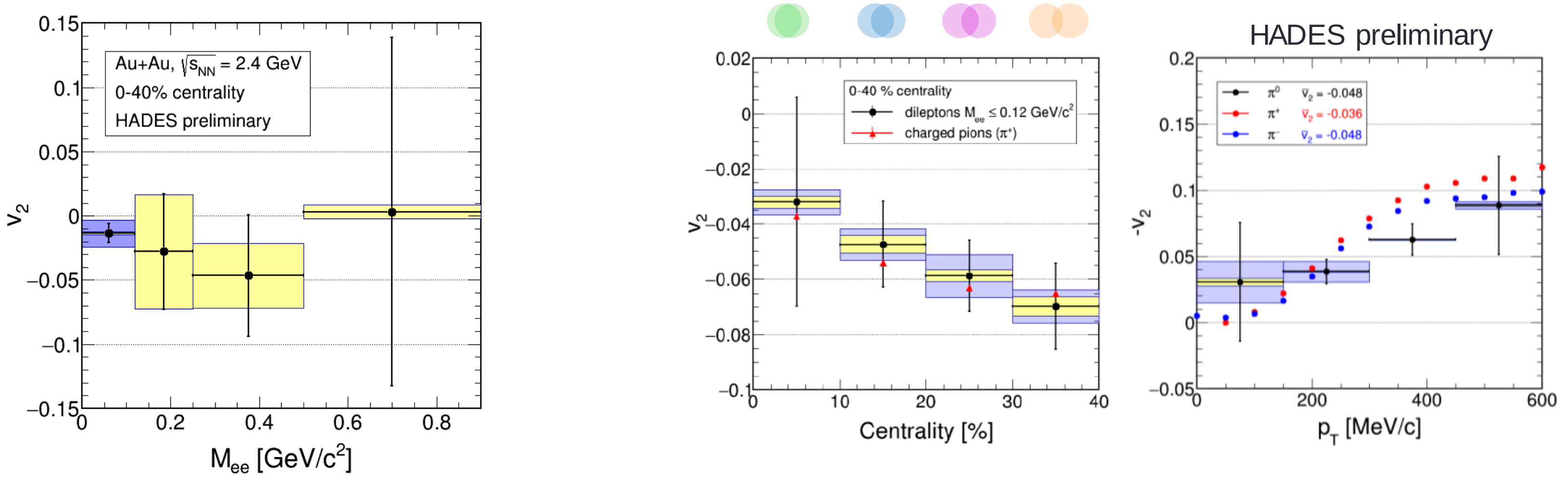
[New beam time proposal]



THANK YOU FOR YOUR ATTENTION

EXTRA SLIDES

Azimuthal anisotropy of virtual photons



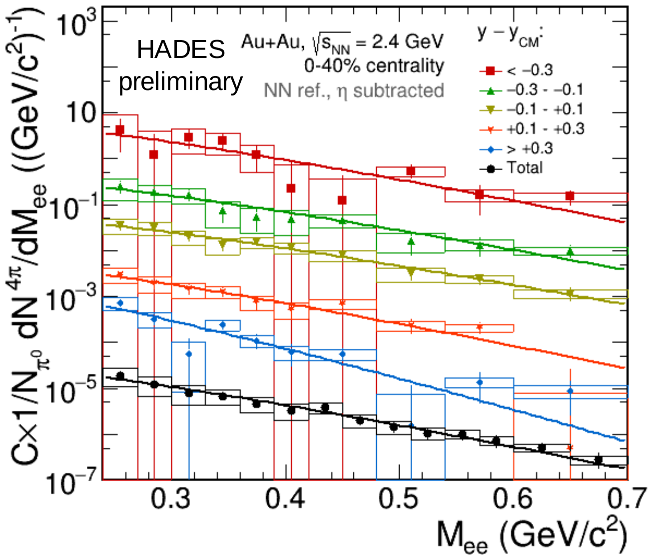
- Calculate the flow of the excess radiation $v_2^{ex} = \frac{1+r}{r} \cdot v_2^{in} - \frac{1}{r} \cdot v_2^{bg}$
- Estimate hadron flow contribution:

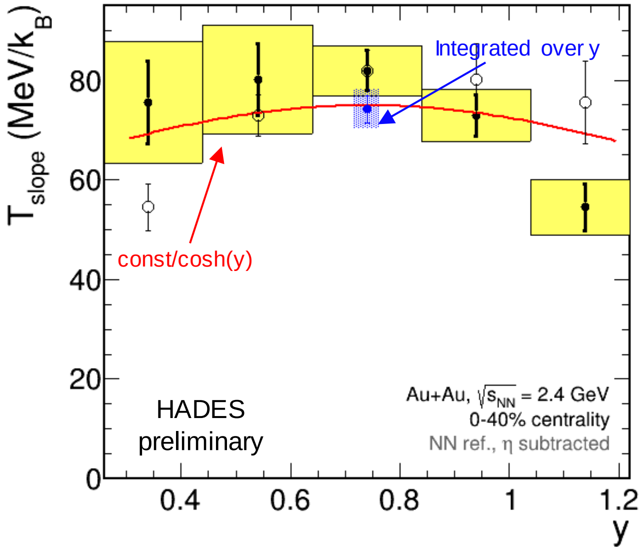
π^0:90% $\rightarrow r = \frac{1-0.9}{0.9}, v_2^{\pi} = -0.051614$

η: 10% -- assume the same value v_2^{π}

- HADES is capable of extracting v_2 of thermal dileptons
- For more conclusive results larger statistics is needed

Boltzmann fits to M_{ee} as a function of rapidity





Consistent (within uncertainties) with thermal ansatz
$T_{slope} \propto 1/\cosh(y)$

NA60 excess p_t dependent