CHARACTERISING THE HOT AND DENSE FIREBALL WITH VIRTUAL PHOTONS AT HADES

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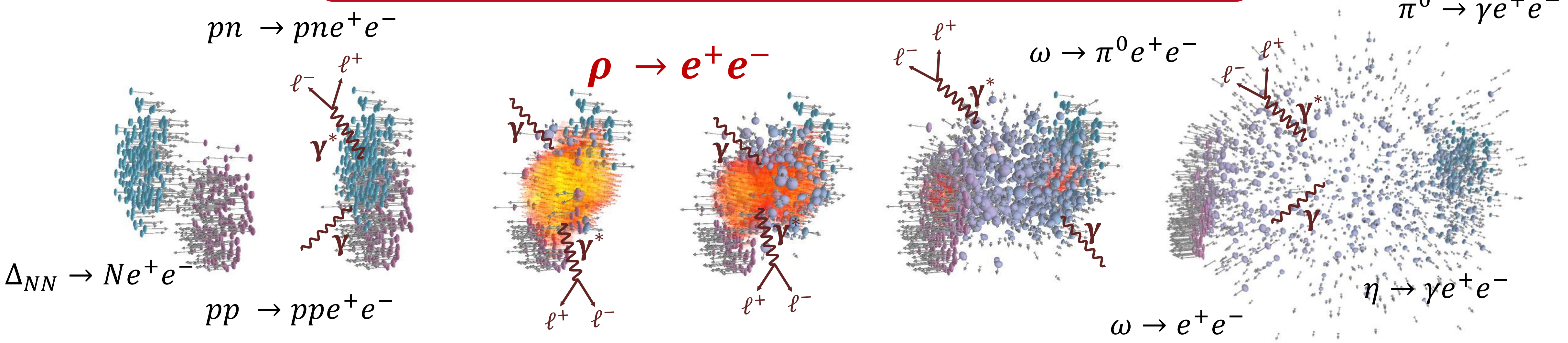
INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS, 46th Course

MOTIVATION - DILEPTONS

Electromagnetic probes (γ, γ^*) penetrate strongly-interacting medium and can bring direct information to the detector



Allows for many unique measurements

Signals of phase transition via lifetime and temperature measurement

Restoration of chiral symmetry

Degrees of freedom of the medium

Transport properties

Yet bring own set of challenges

Need to isolate contribution of interest

Rarity of events (BR ~ 10^{-5})

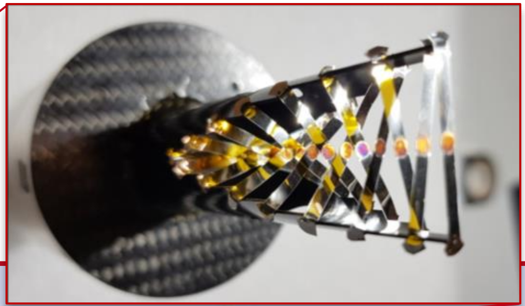
HIGH-ACCEPTANCE-DI-ELECTRON-SPECTROMETER

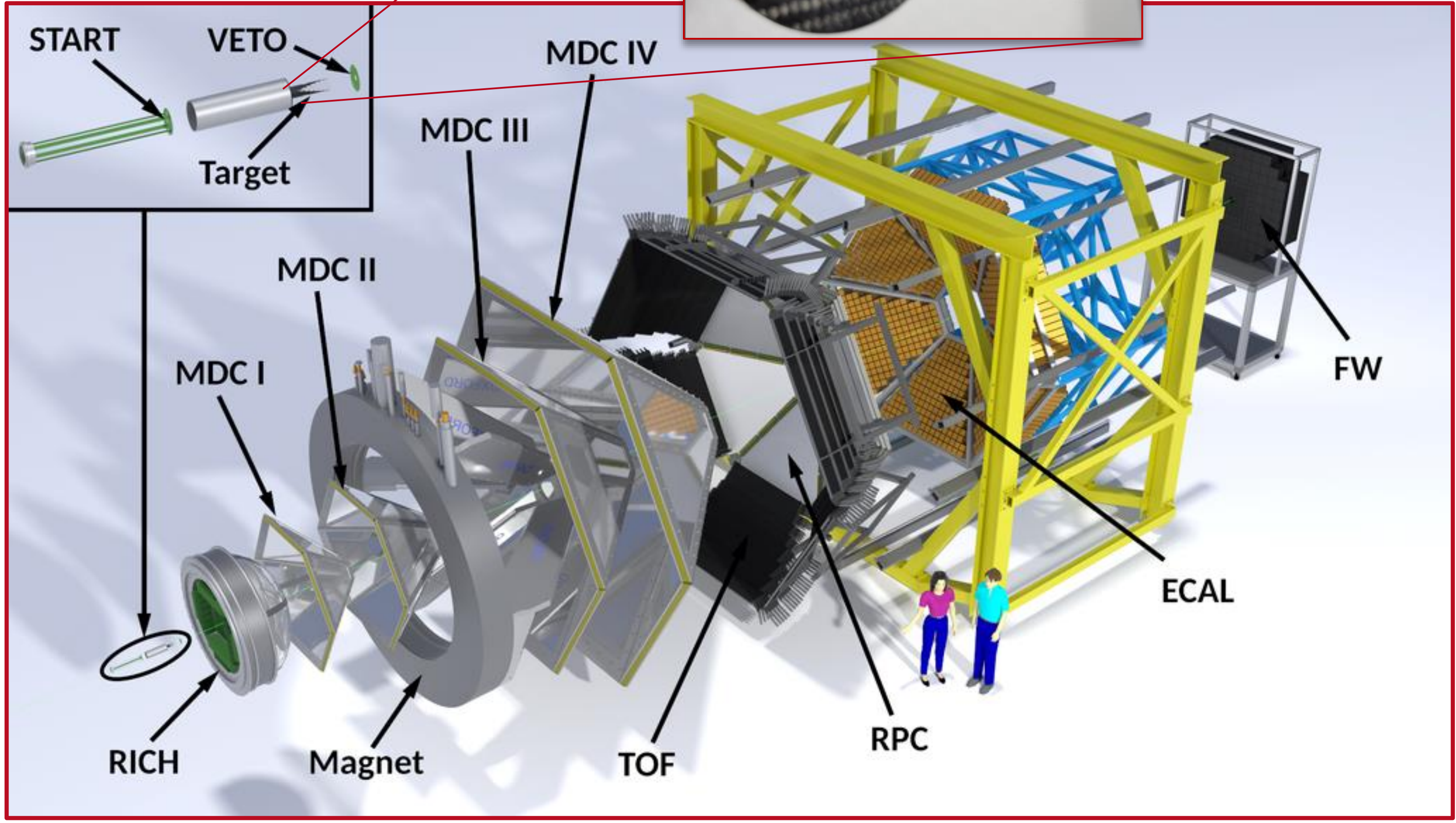
- Designed with minimal material budget to reduce conversion
- Large angular coverage:

$$15° < \theta < 85°$$
$$0° < \phi < 360°$$

- Accepted trigger rate up to:
  ⇝ 16 kHz for heavy-ion collisions
  ⇝ 50 kHz with proton/pion beam
- Dedicated components for e^+/e^-:
  ⇝ Ring-Imaging Cherenkov Detector
  ⇝ Electromagnetic Calorimeter
  ⇝ Time-of-Flight measurements

HADES allows for high effciency and high purity electron sample!



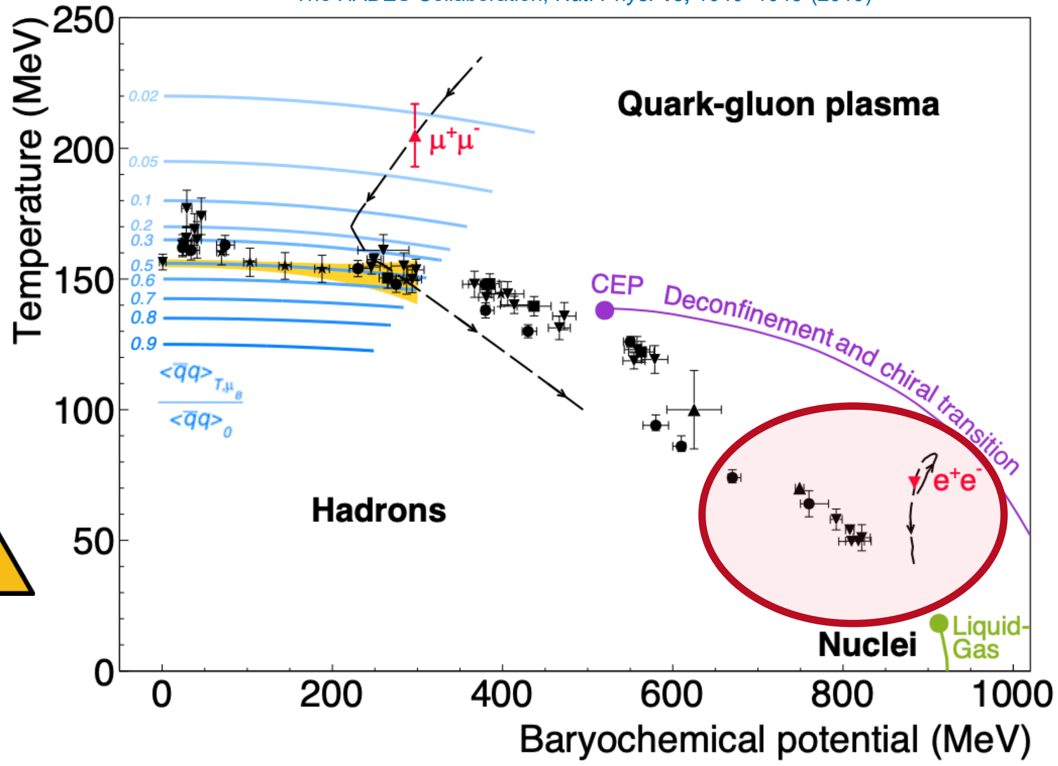


HIGH-ACCEPTANCE-DI-ELECTRON-SPECTROMETER

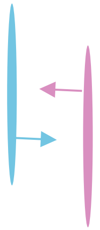
- **Pion and nucleon beams**
  - Reference measurements
  - Inclusive and exclusive measurements
- **Heavy ion collisions (HICs)**
  - Study the medium properties
    - ⚠ Different collision dynamics compared to higher energies ⚠

Explore region of QCD phase diagram with high net-baryon density and moderate temperatures

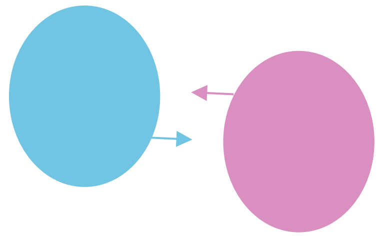
The HADES Collaboration, *Nat. Phys.* **15,** 1040–1045 (2019)



LHC energies $\sqrt{s_{NN}} = 2\ \mathrm{TeV}$
parton+parton collisions
Early Universe in the laboratory



Energies $\sqrt{s_{NN}} \cong 2 * m_N\ \mathrm{GeV}$
nuclear stopping
NS merger matter in the laboratory



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<u>Focus Today</u>

Thermal dilepton radiation in HICs

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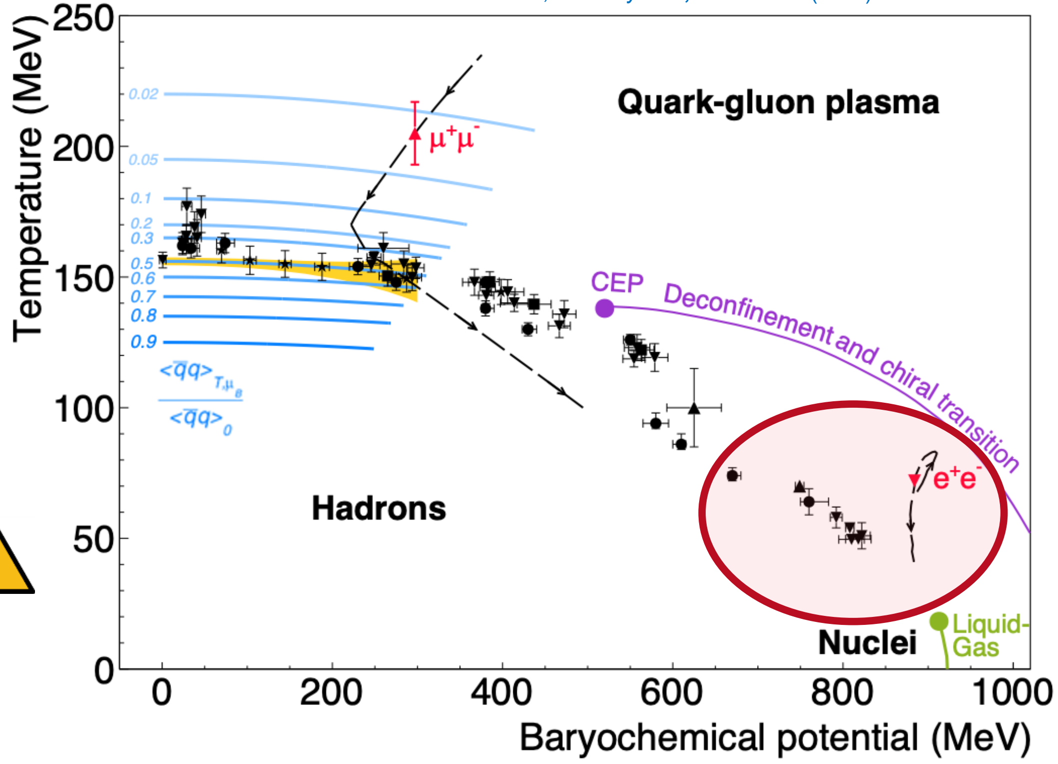

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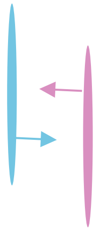

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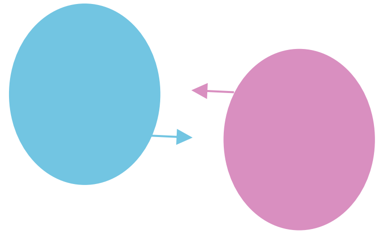
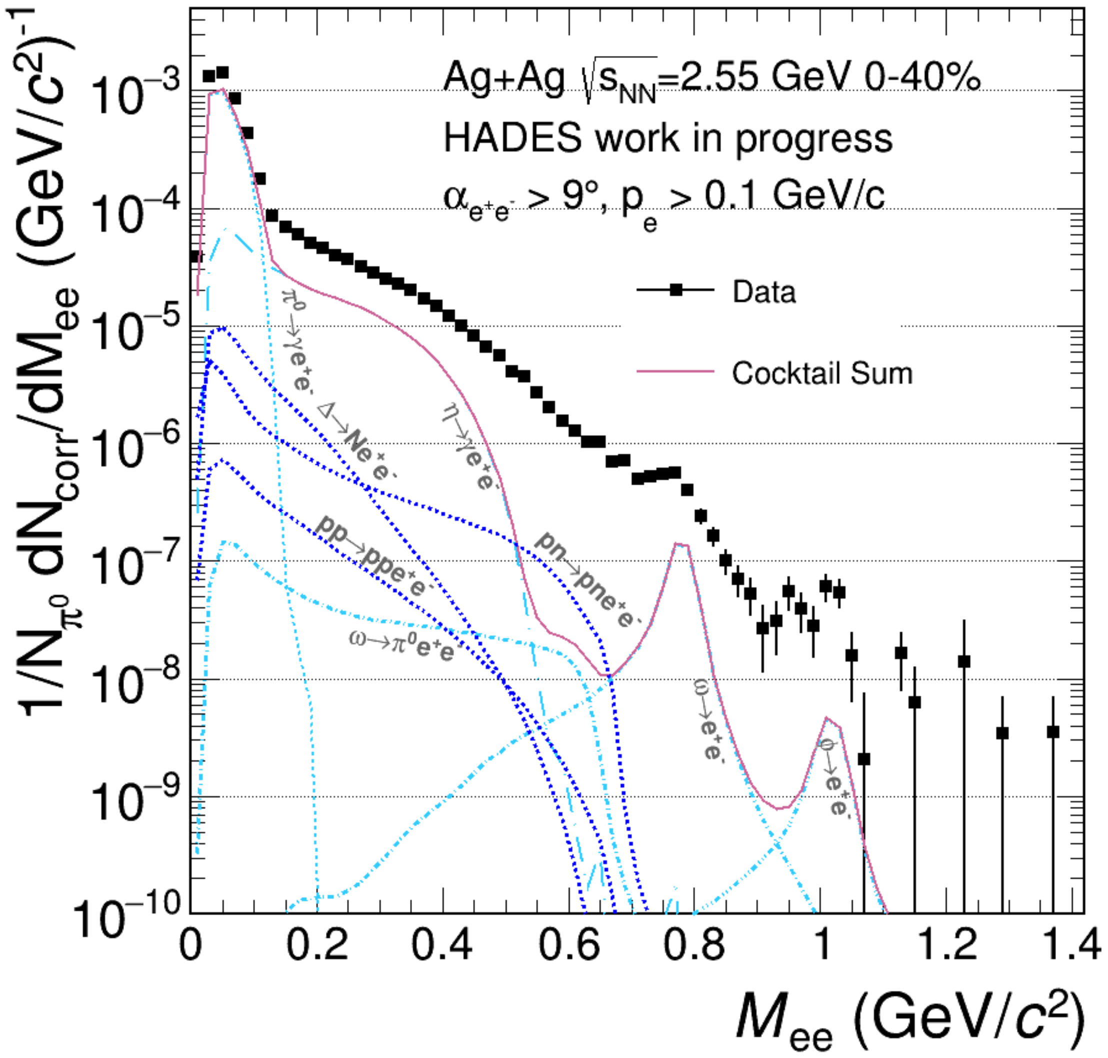
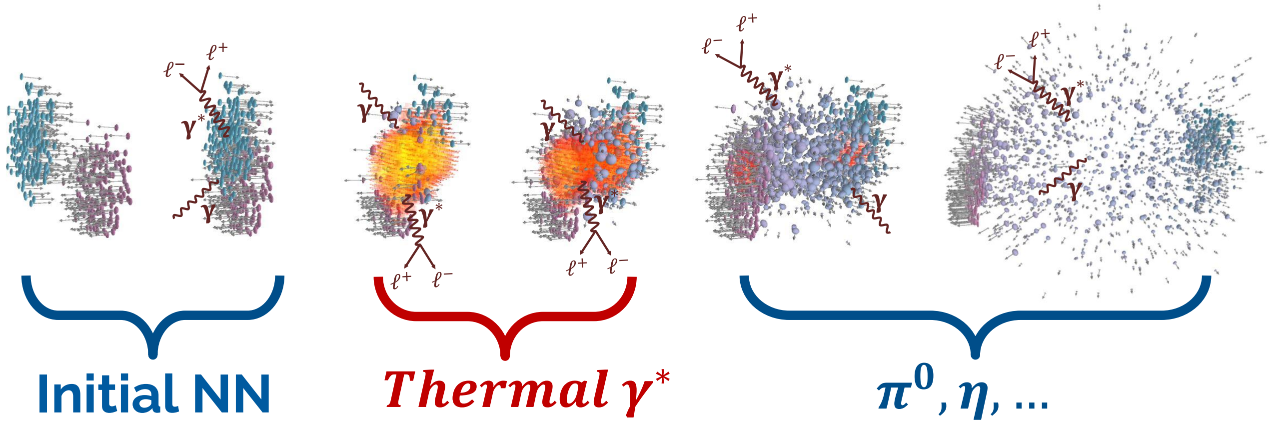


INVARIANT MASS SPECTRUM





Measured signal is integral over whole evolution

Isolate thermal contribution by subtraction of (experimentally measured):

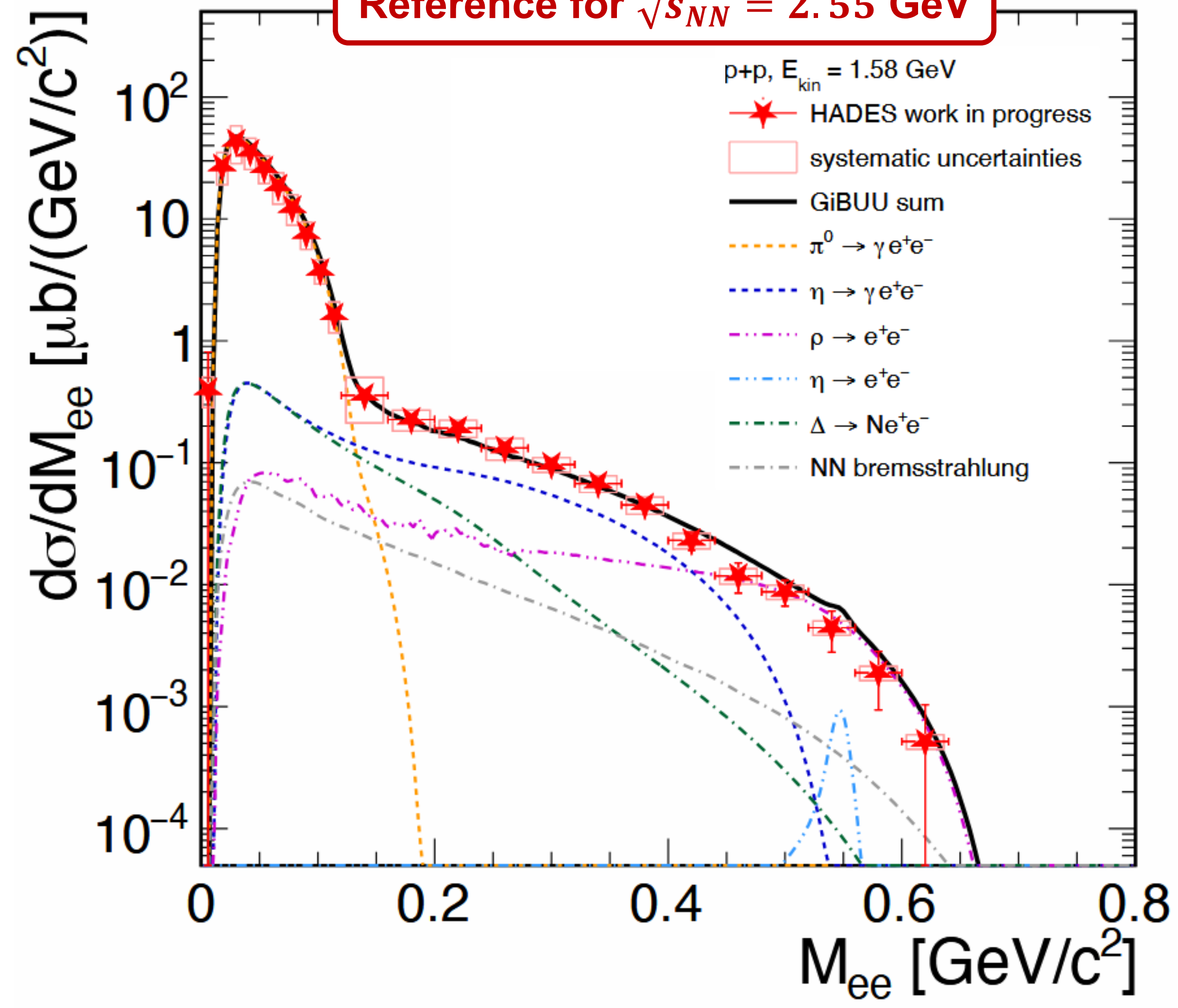
- Freeze-out cocktail $(\pi^0, \eta, \omega, \phi)$
- Initial NN reference spectrum
  - pp and $p(n)$ reactions

NN REFERENCE MEASUREMENT

Ongoing analysis of p+p collisions (2022) at 1.58 GeV

Provides reference to Ag+Ag measurement at $\sqrt{s_{NN}} = 2.55$ GeV

Reference for $\sqrt{s_{NN}} = 2.55$ GeV



- Promising agreement with GiBUU prediction

GiBUU, Phys. Rept. 512 (2012), 1-124

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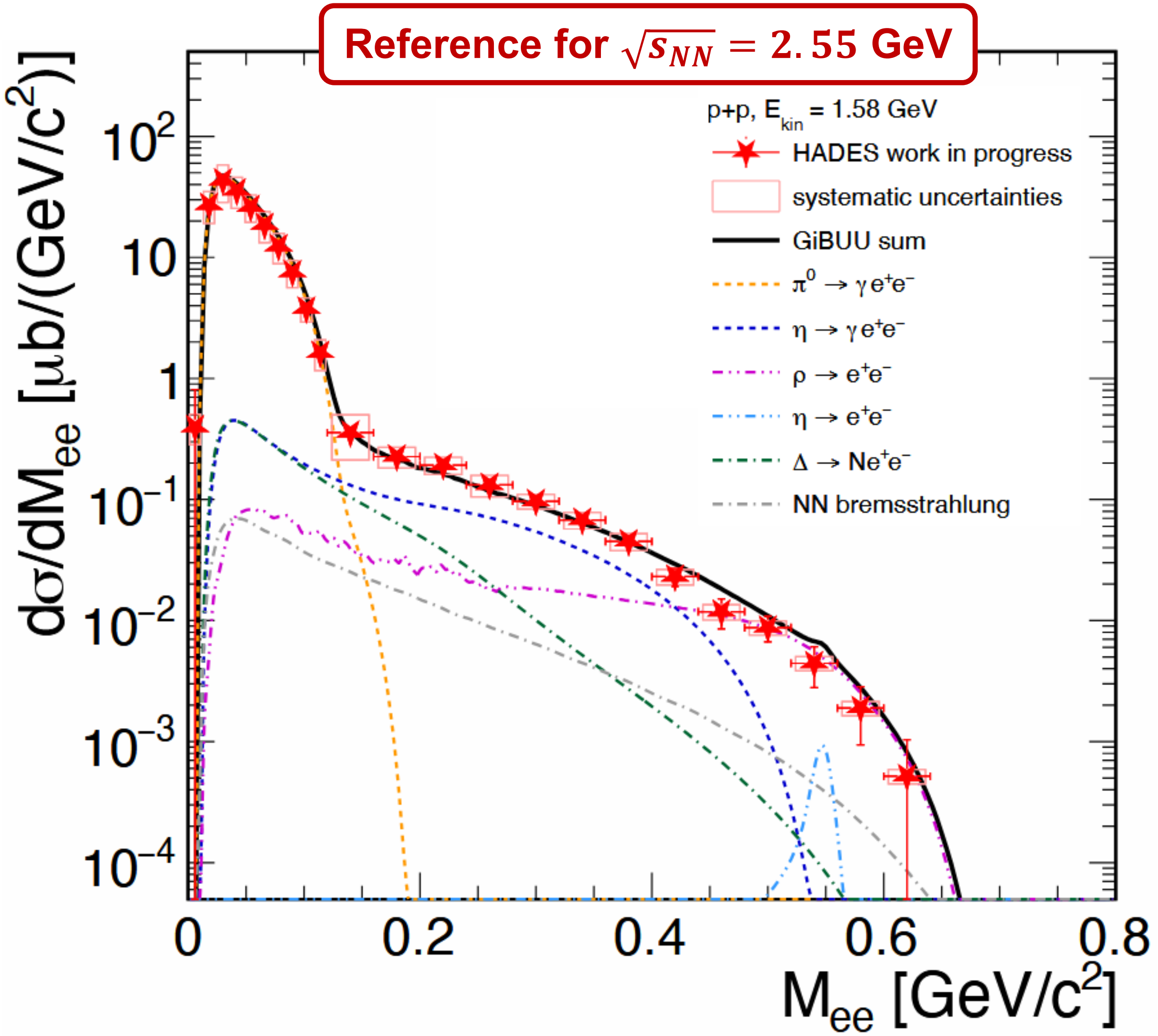
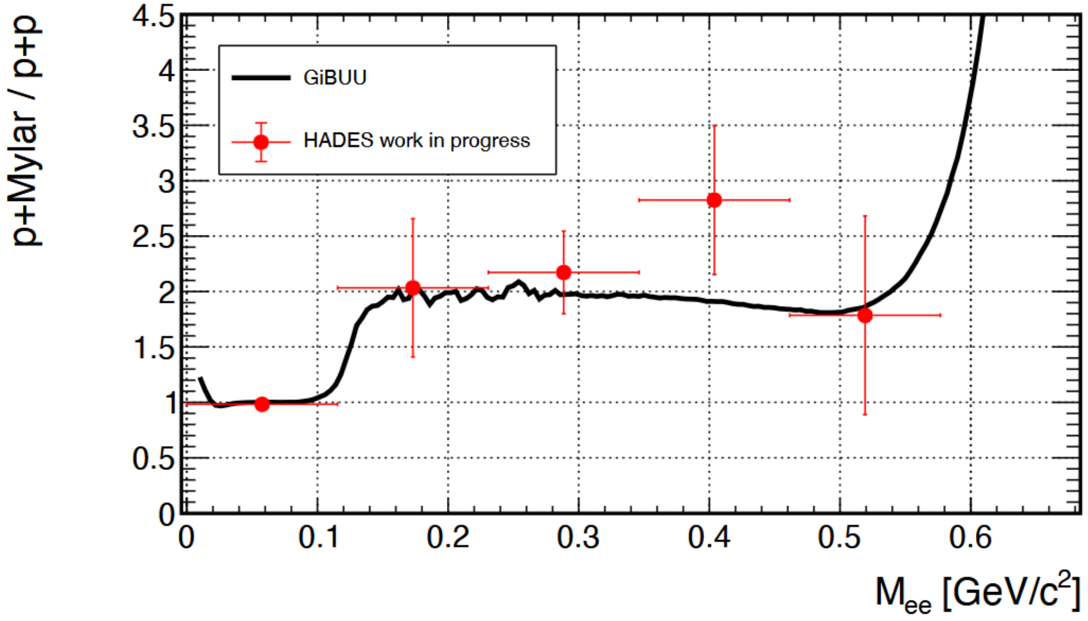


- Promising agreement with GiBUU prediction
- Empty target run with p+Mylar ($C_{10}H_8O_4$) as proxy for (pp/pn)



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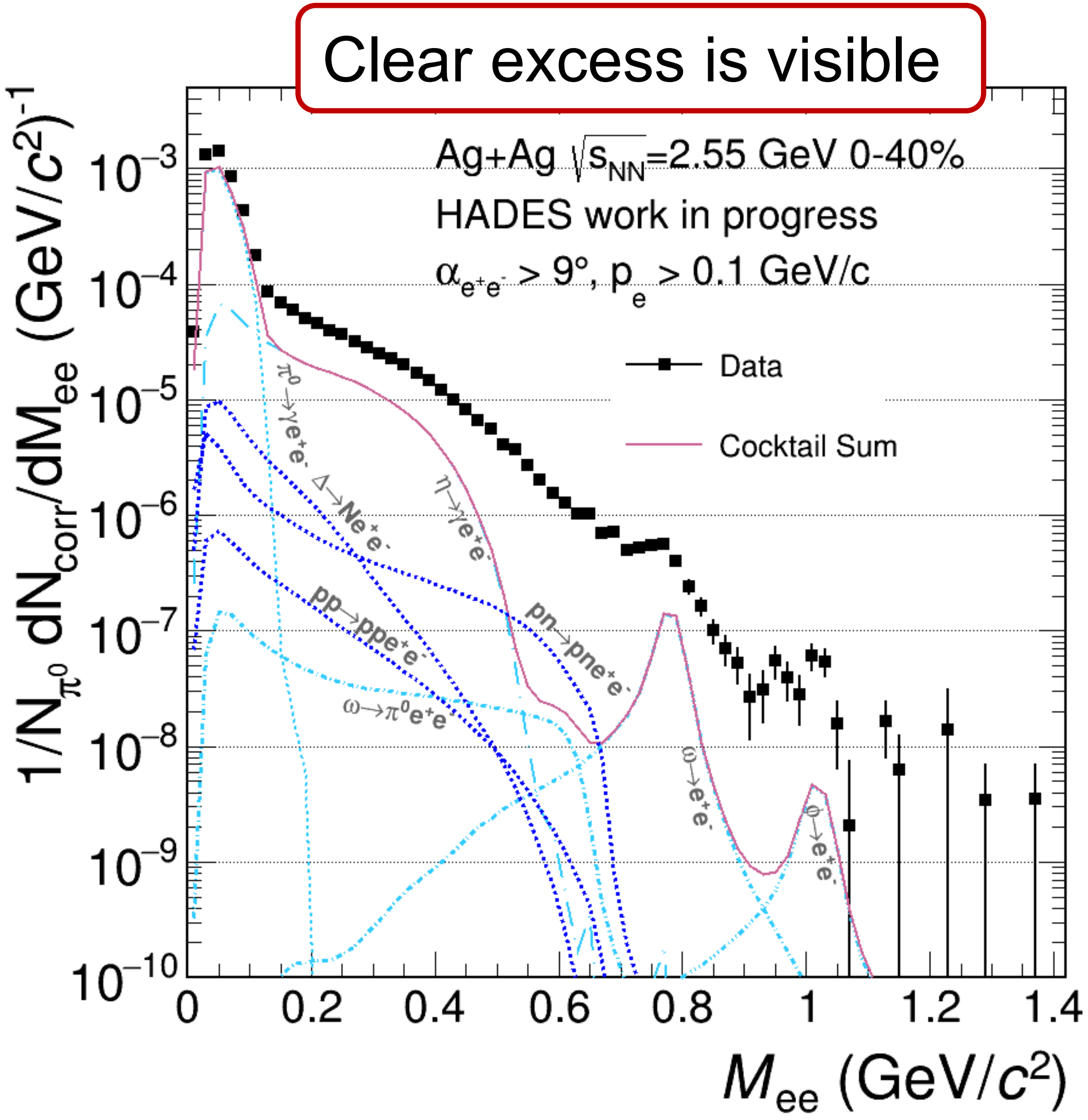
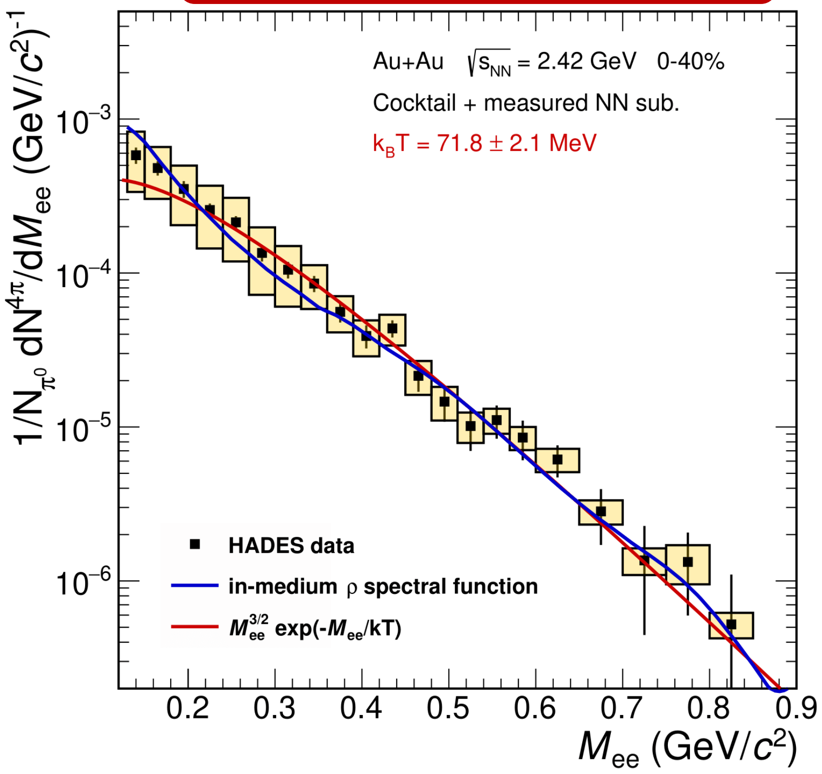


DILEPTON EXCESS

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

- Subtraction of reference and freeze-out sources reveals **thermal dilepton excess**
- Good agreement between data and theory predictions from coarse-grained (CG) UrQMD

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



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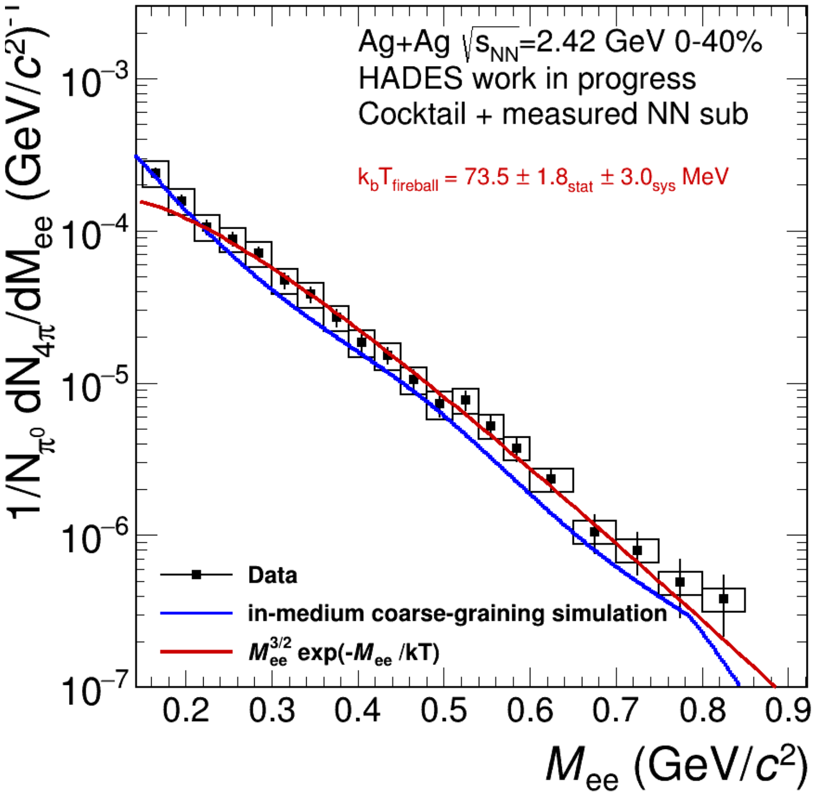

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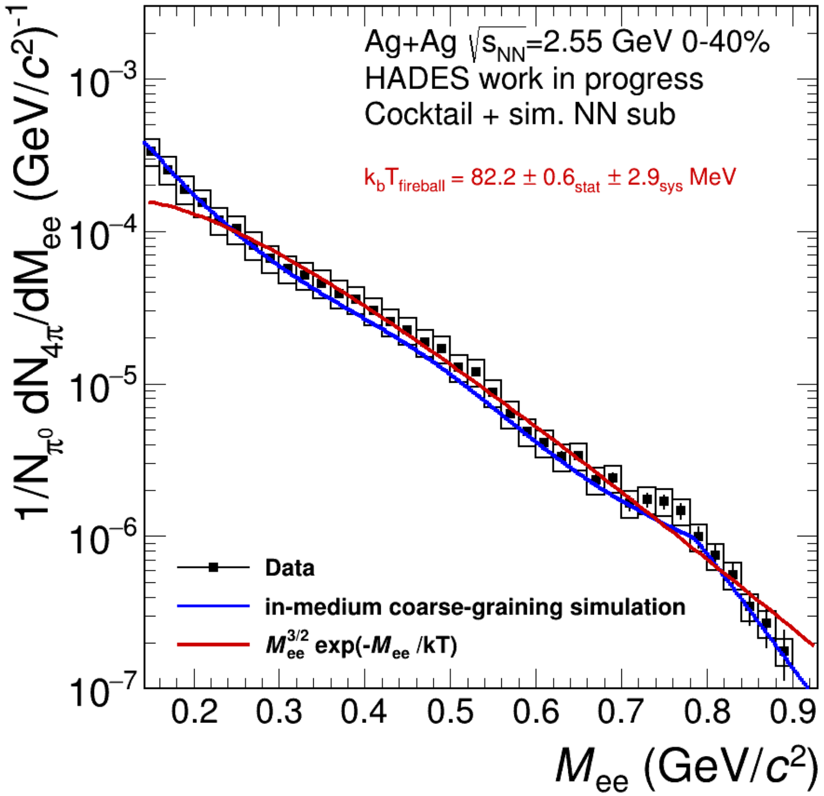
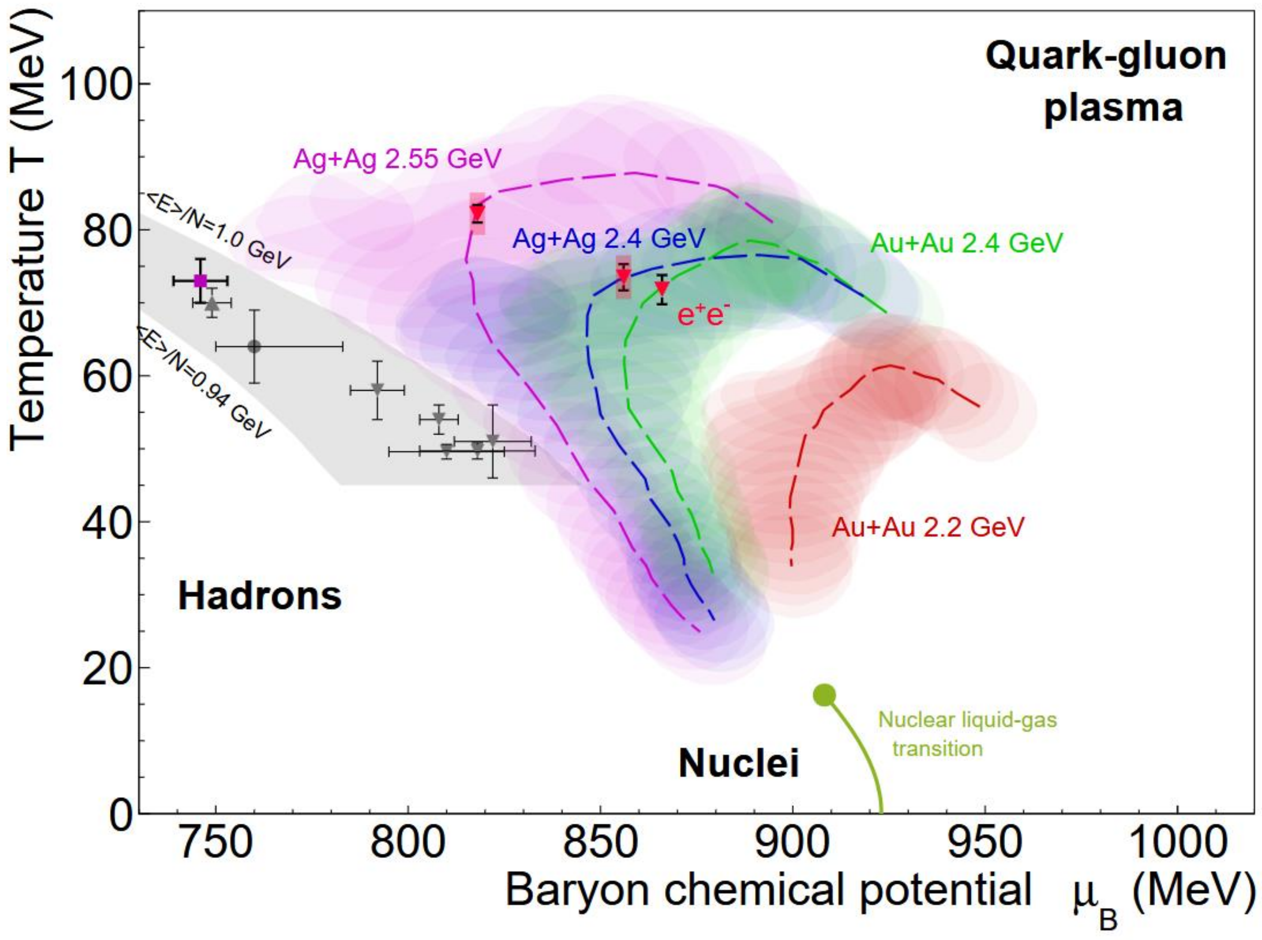


PROBING THE QCD PHASE DIAGRAM

- Trajectories from coarse-grained UrQMD
- Freeze-out points from hadron resonance model (SHM)
- Measured average fireball temperatures from HADES well above universal freeze-out region



FO curve: J. Cleymans, K. Redlich, Nucl. Phys. A 661 (1999) 379
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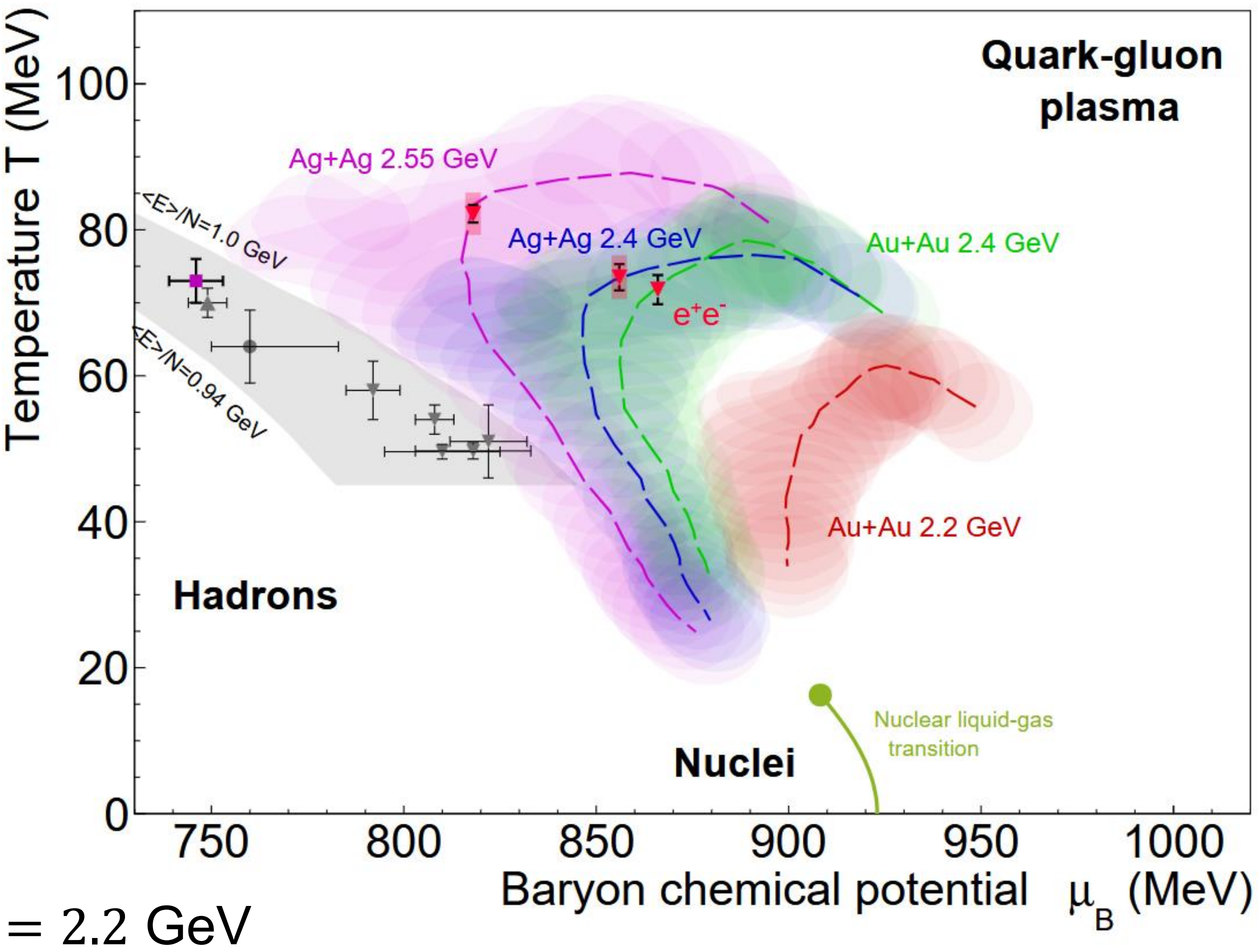

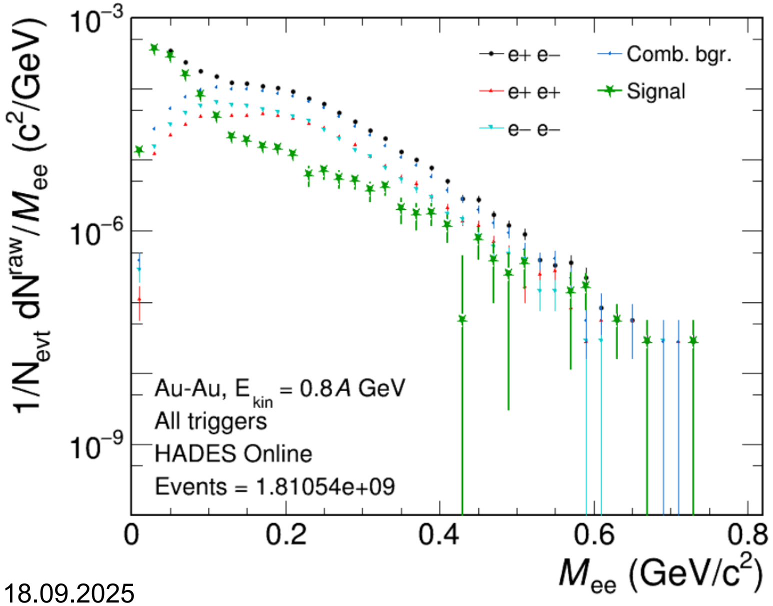

- Au+Au $\sqrt{s_{NN}} = 2.2$ GeV ~4B events collected in Feb'24 and May'25

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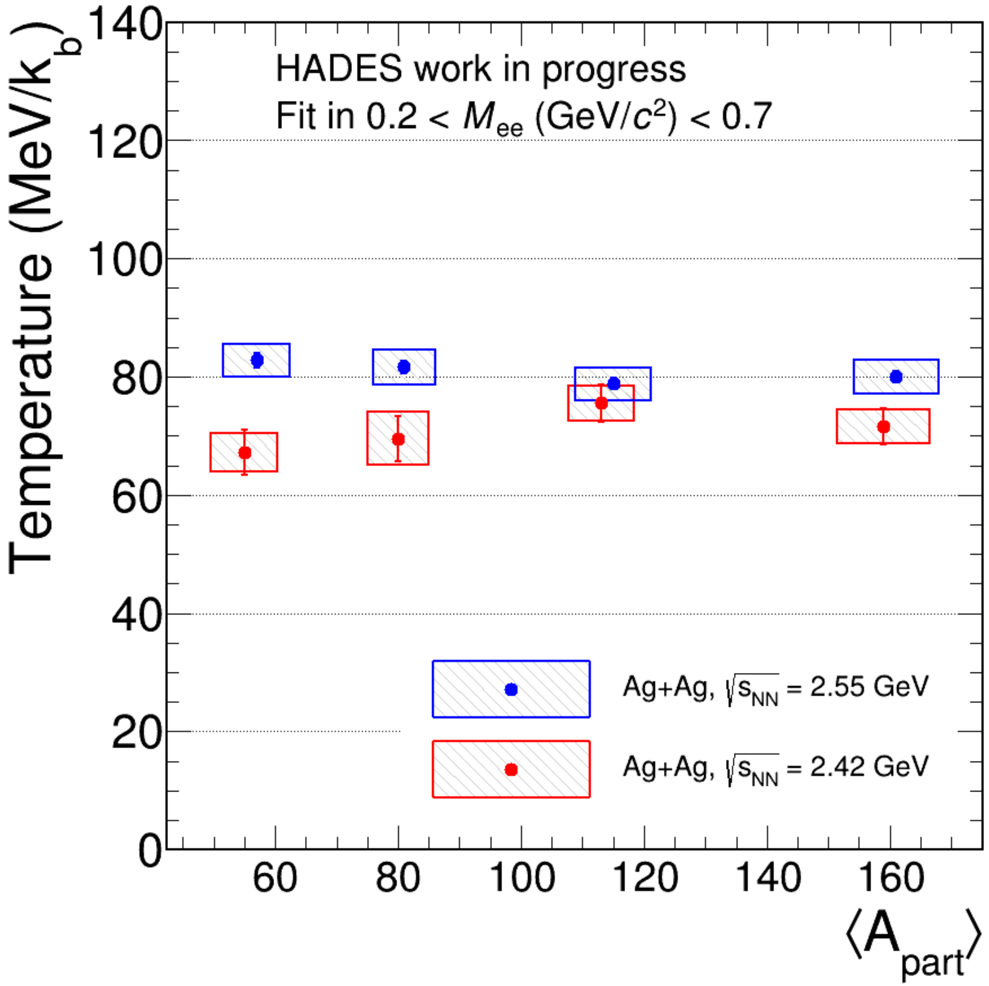
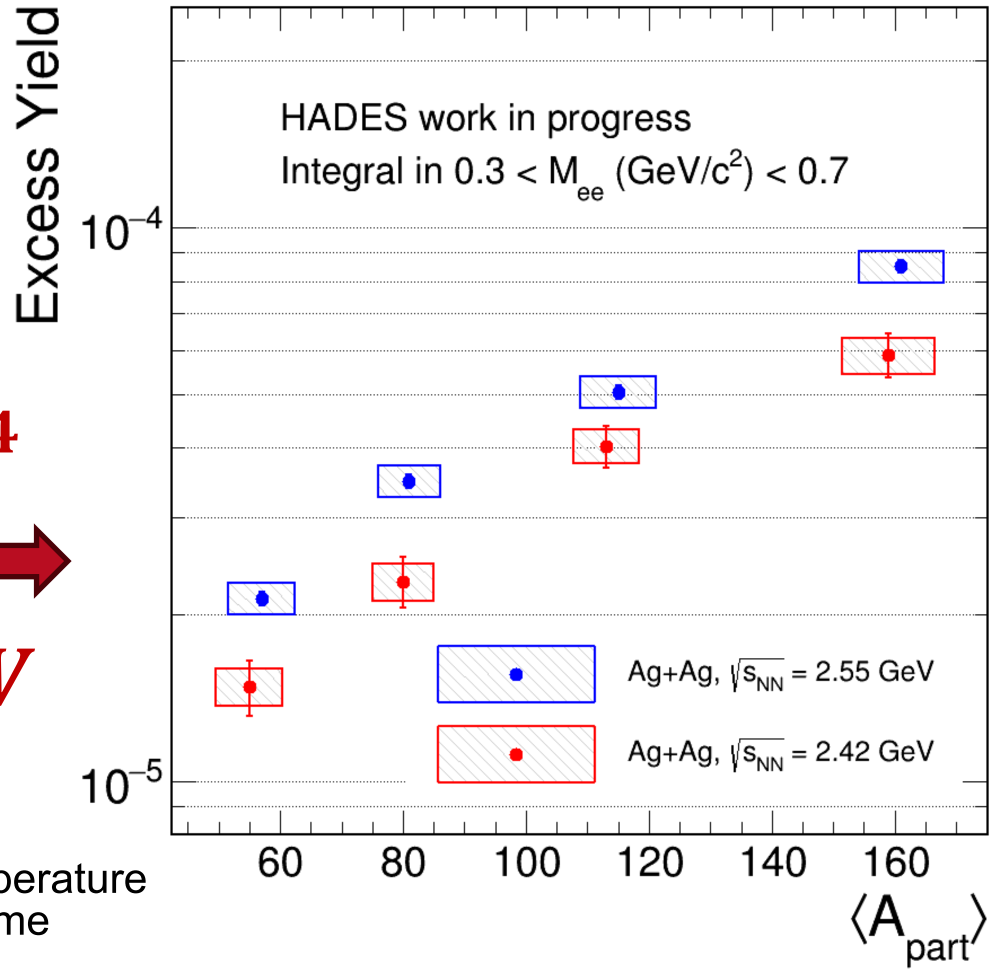
EXCESS - CENTRALITY DEPENDENCE

- Comparison between temperature and excess yield allows investigation of lifetime of the system



$\propto T^4$

$\propto \tau V$



T: Fireball temperature
τ: Fireball lifetime
V: Volume

COLLECTIVITY – ANISOTROPIC FLOW

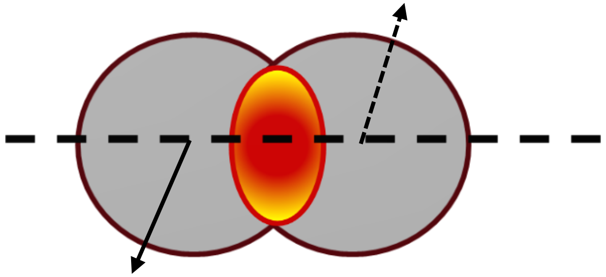
$$\frac{dN}{d\Delta\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n\,\Delta\varphi)$$

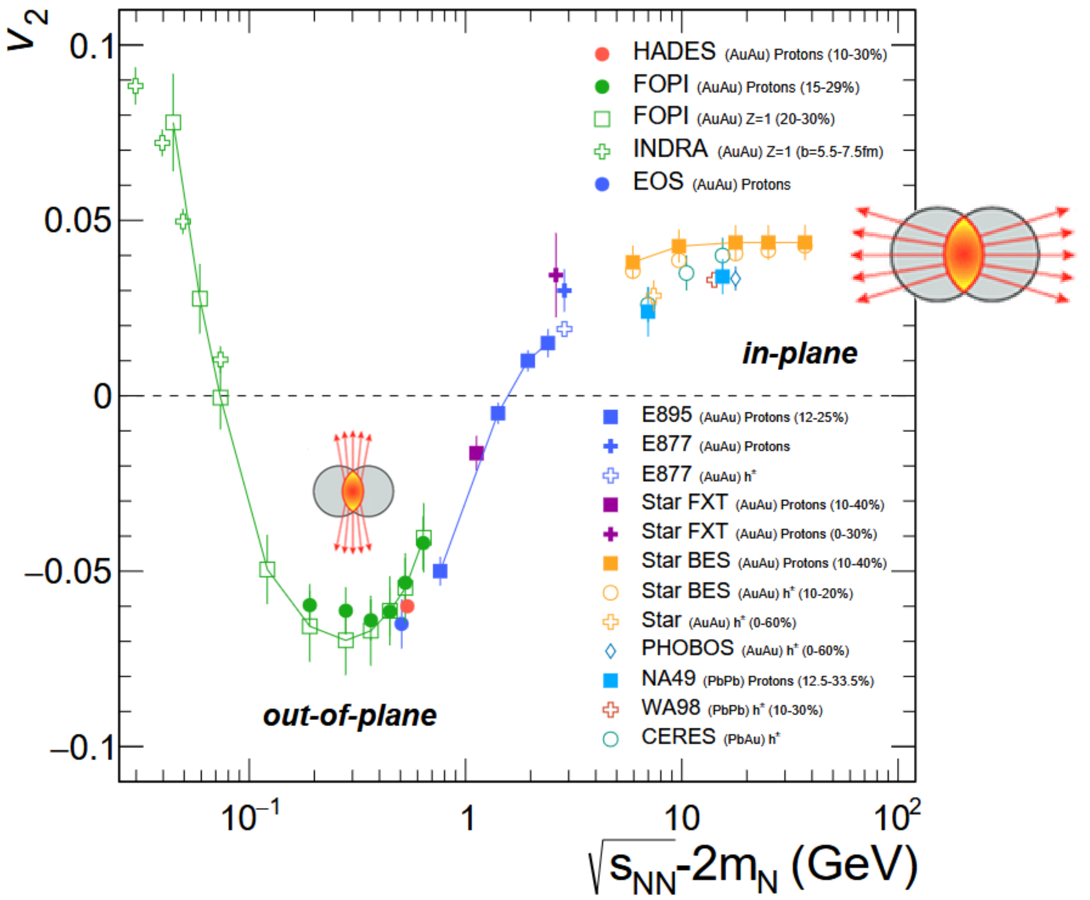
$$\Delta\varphi = \varphi - \Psi_{RP}$$

v_1: Directed Flow

v_2: Elliptic Flow

Reaction Plane Ψ_{RP}





Eur.Phys.J.A 59 (2023) 4, 80

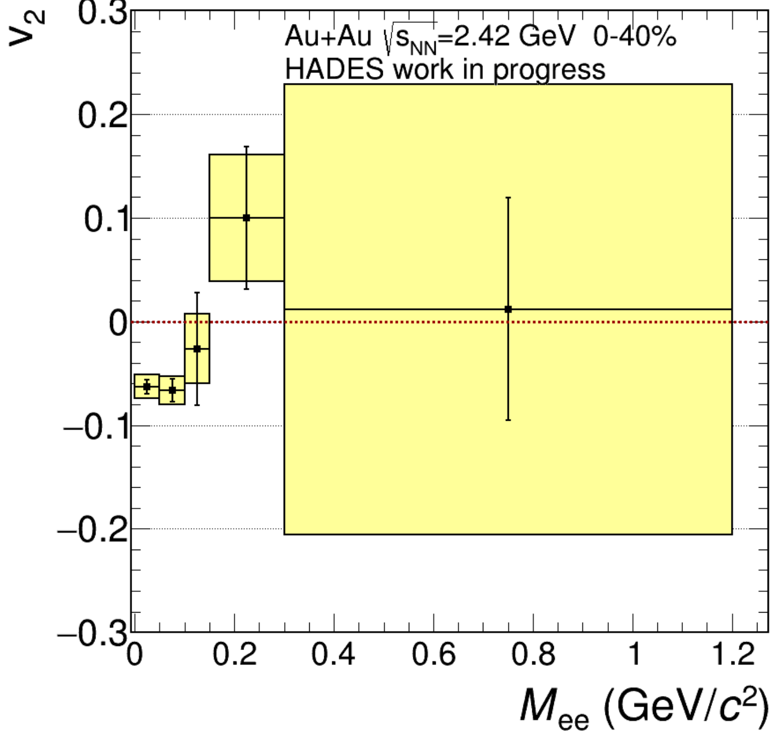
- Azimuthal anisotropies are sensitive to EoS
- Interesting „squeeze-out“ at these energies
- Dileptons may probe evolution of flow over time

Phys.Lett.B 841 (2023) 137947

ANISTROPIC FLOW - DILEPTONS

- Elliptic flow v_2 of dileptons determined for different systems and energies

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



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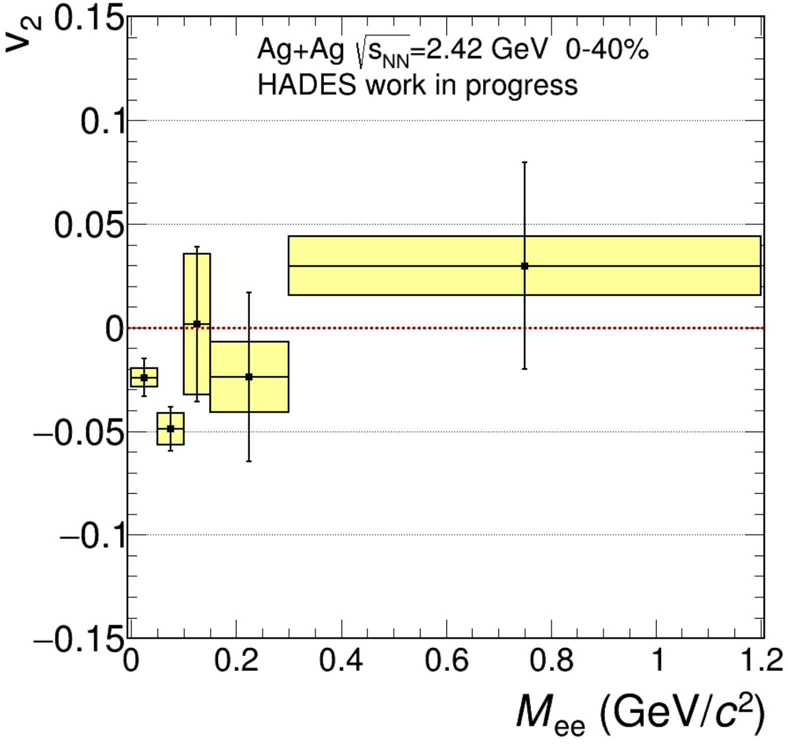

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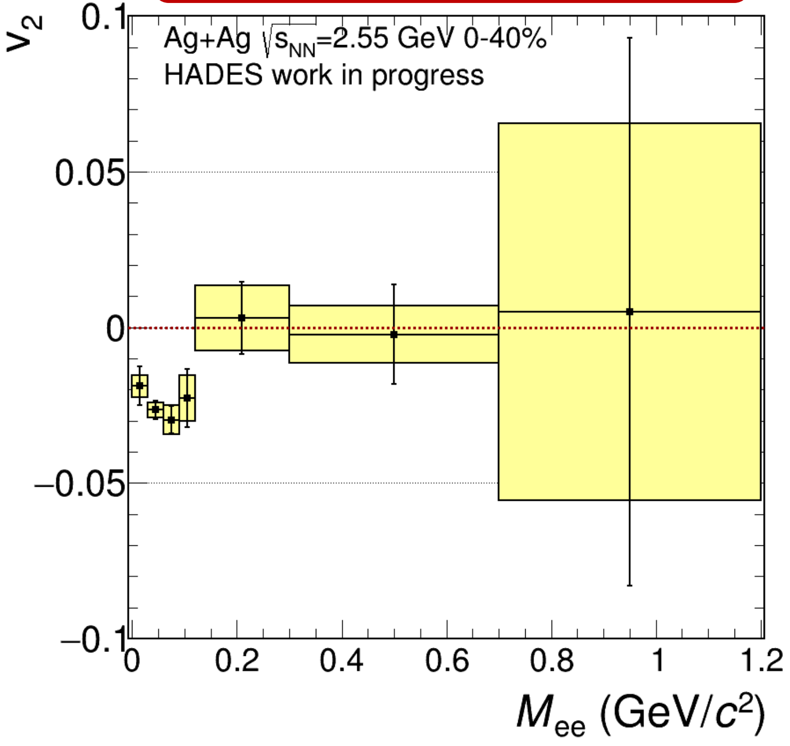
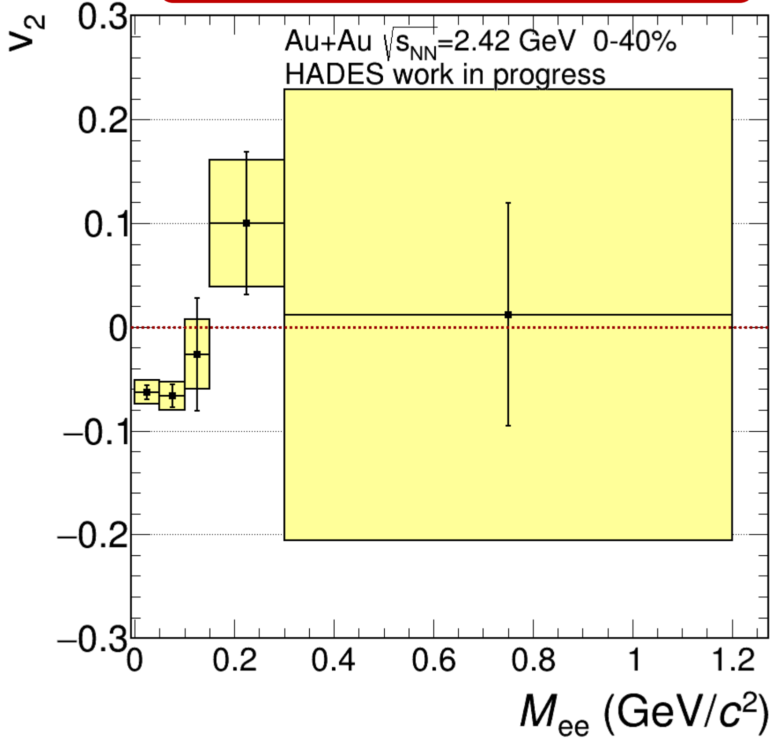


ANISTROPIC FLOW - DILEPTONS

- Elliptic flow v_2 of dileptons determined for different systems and energies
- Change in v_2 in mass regions dominated by **π^0decays (M_{ee} < 0.12 GeV/c^2)** vs region dominated by **thermal radiation (M_{ee} > 0.12 GeV/c^2)**

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



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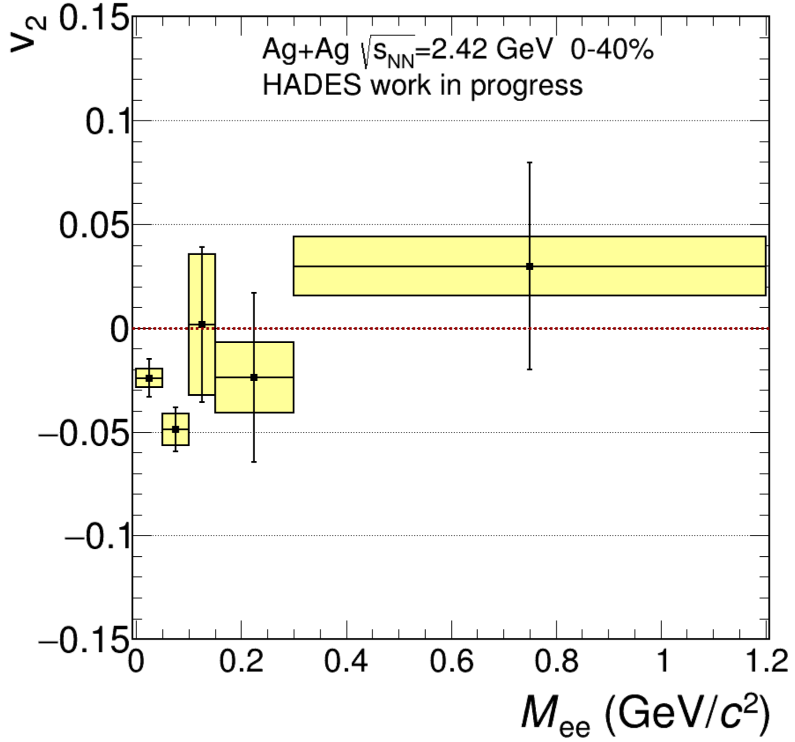

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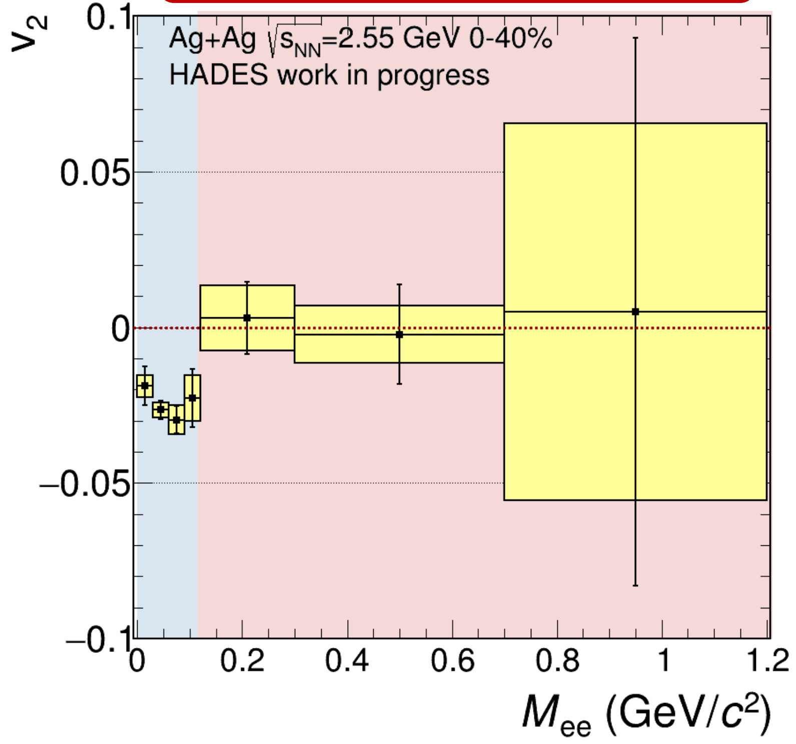

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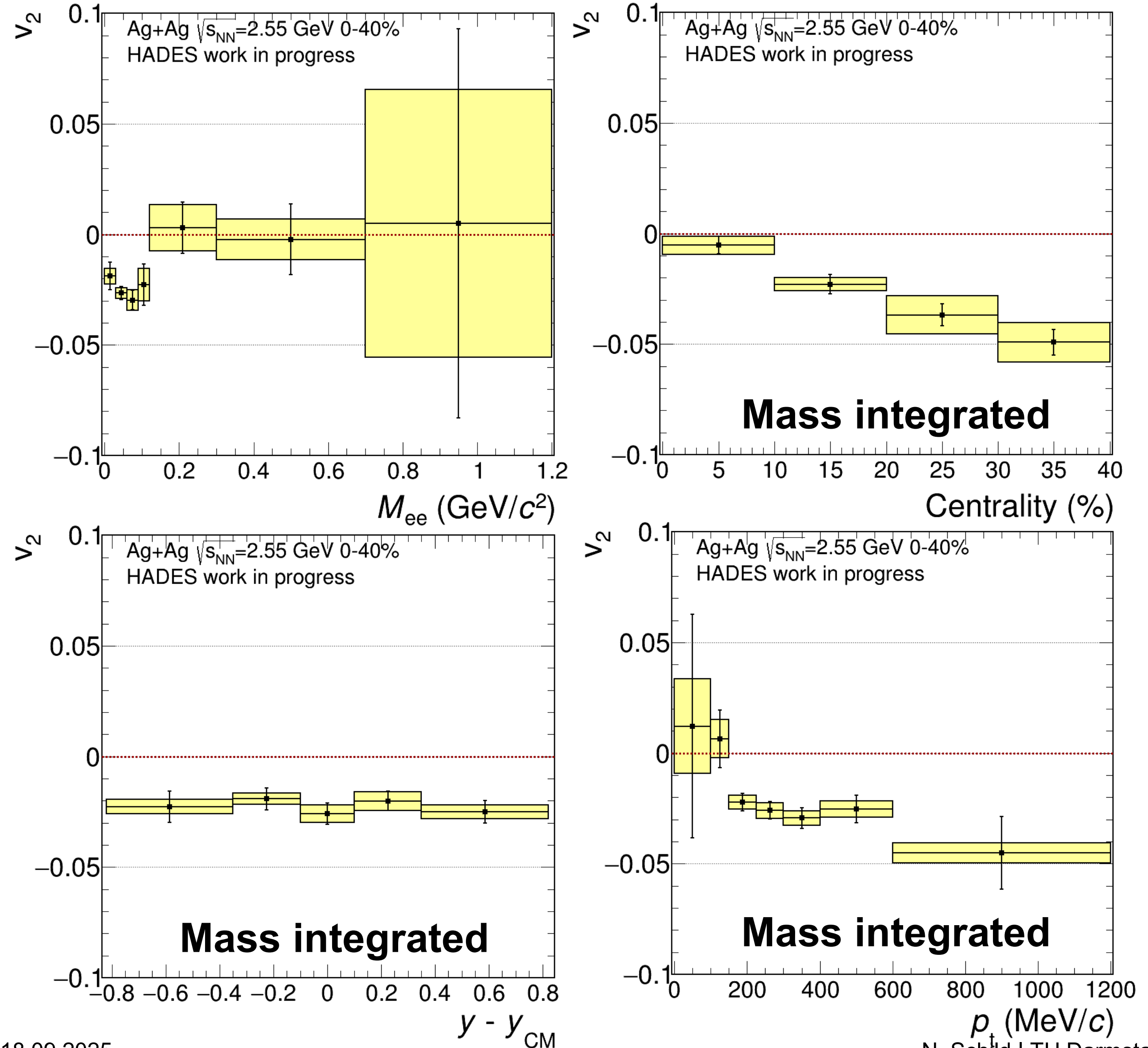


- High-statistics Ag+Ag measurement allows for differential analysis

Isolation of thermal dilepton contribution

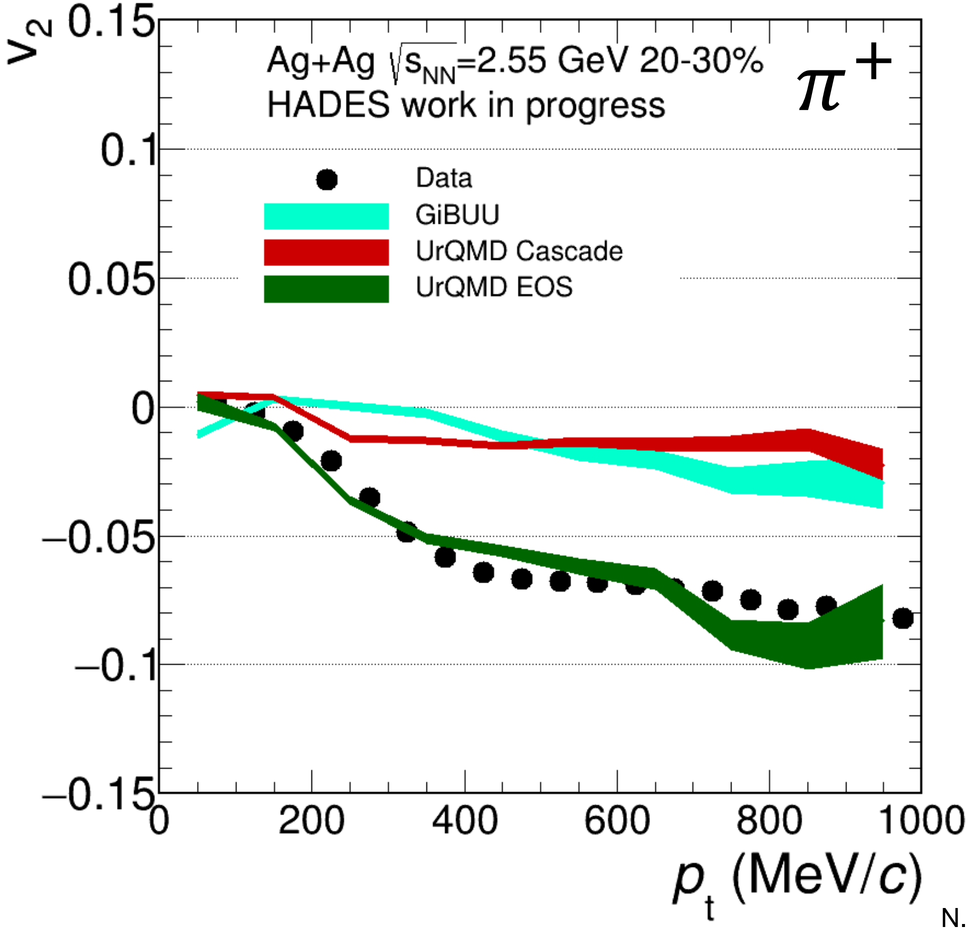
- Need precise flow measurements of freeze-out sources (π^0, η)
- Only limited data available at HADES energies

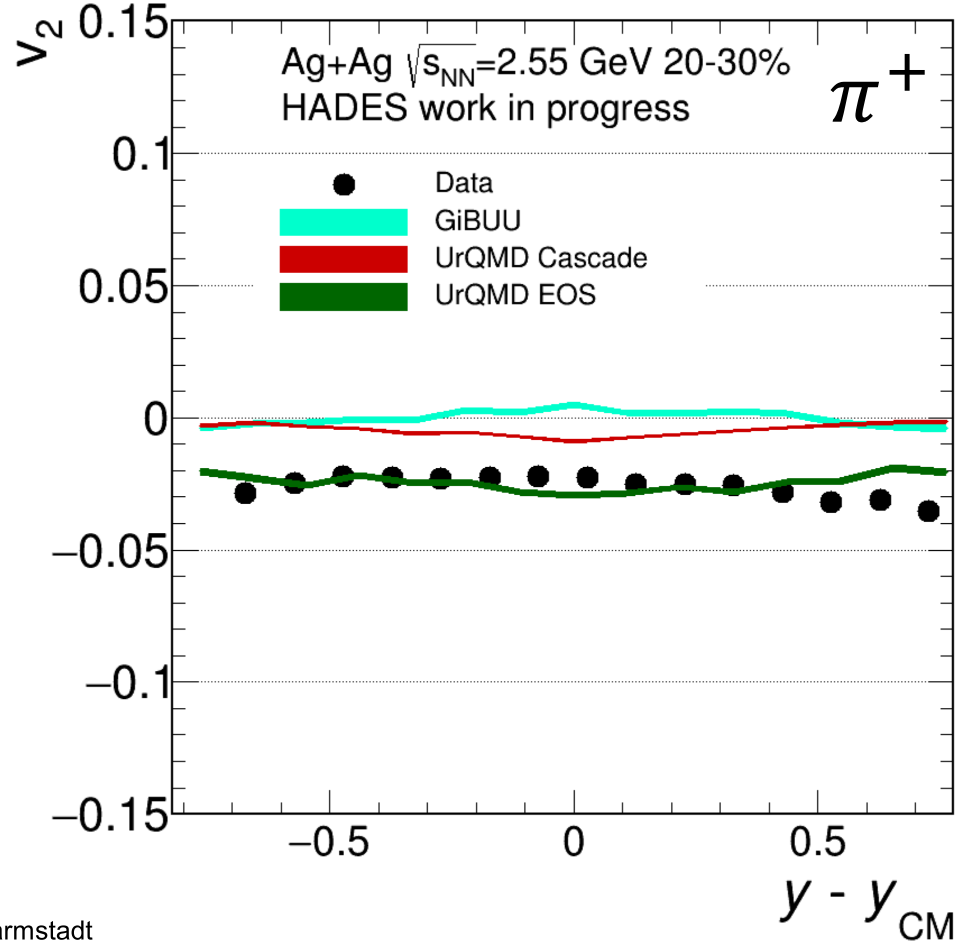
Use model to estimate $v_2^{\pi^0/\eta}$

Constrained by data

ANISTROPIC FLOW – CHARGED PIONS MODEL COMPARISON

UrQMD EOS shows the best description of pion ellitpic flow





ANISTROPIC FLOW ISOLATION

$$v_n^{sig} = v_n^{tot} + \frac{N_{bg}}{N_{sig}}\left(v_n^{tot} - v_n^{bg}\right)$$

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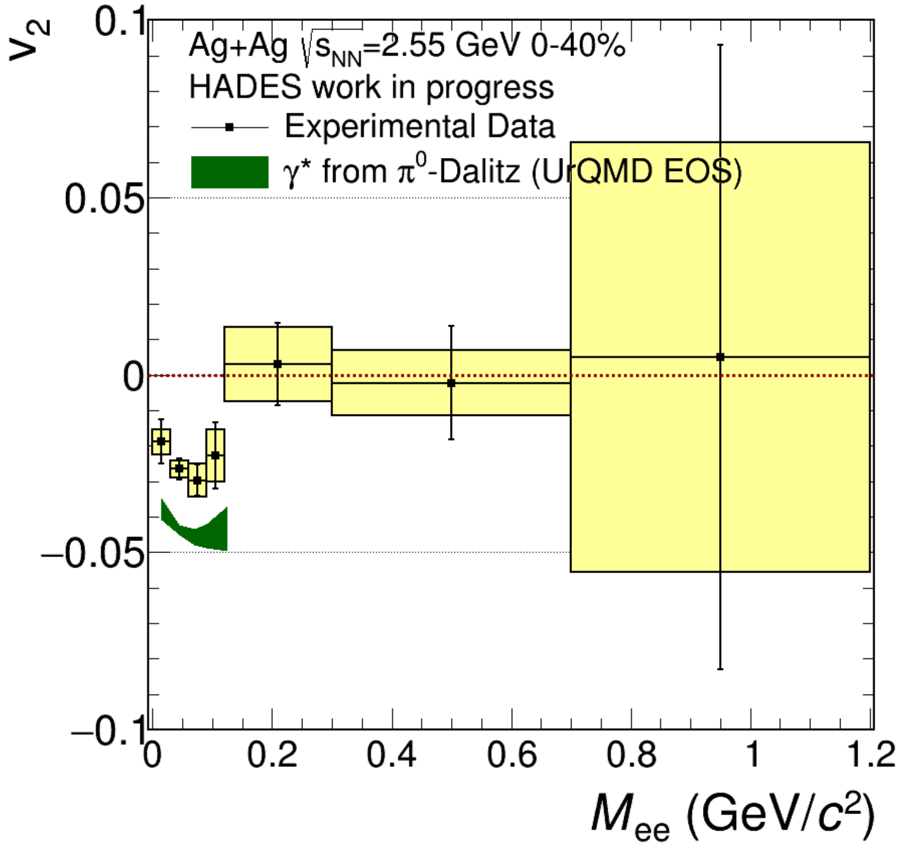
HADES

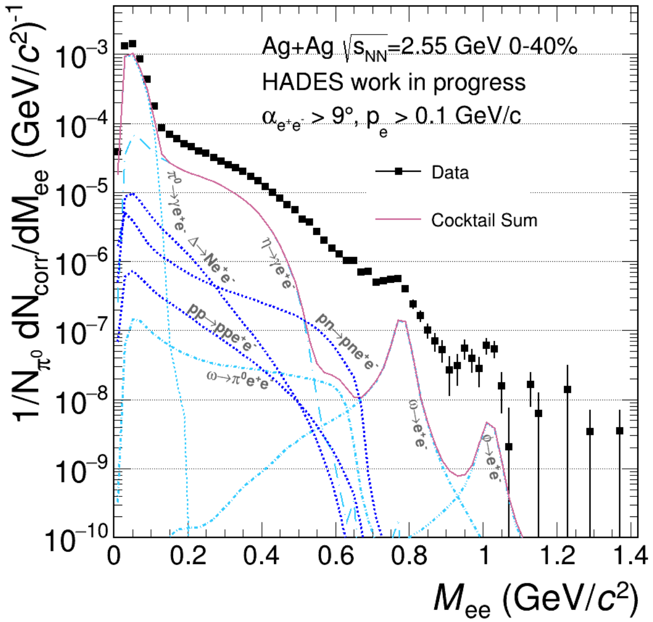
Flow + Yields → Isolated Flow

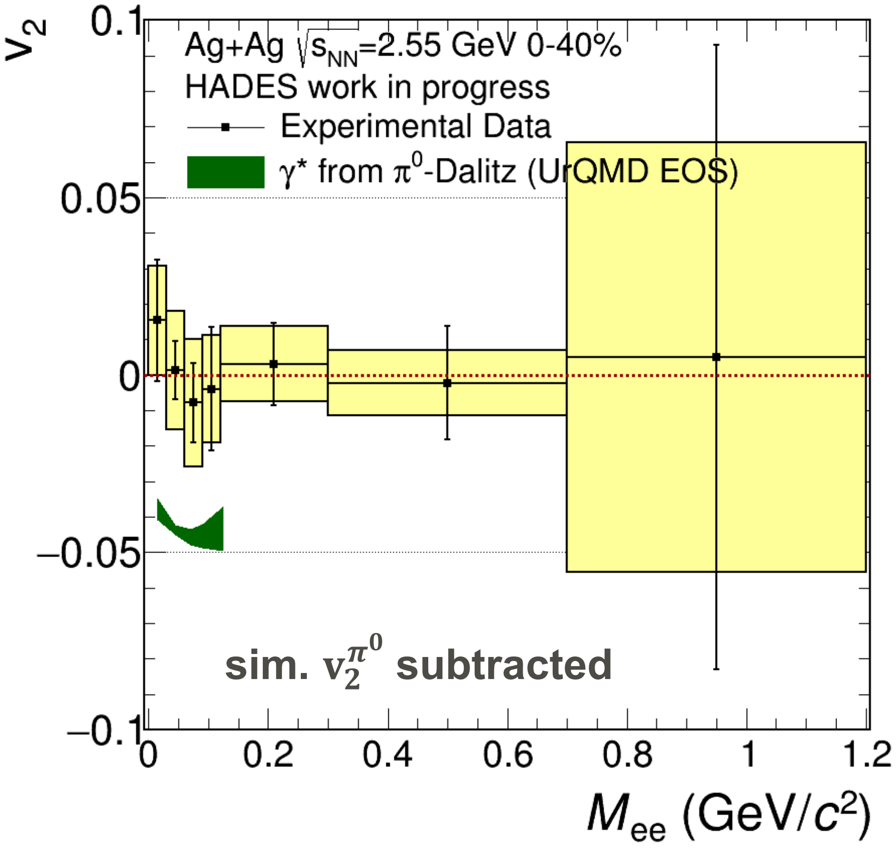
Take v_2 from UrQMD

Take yields from cocktail estimation

Resulting isolated v_2 moves towards positive values







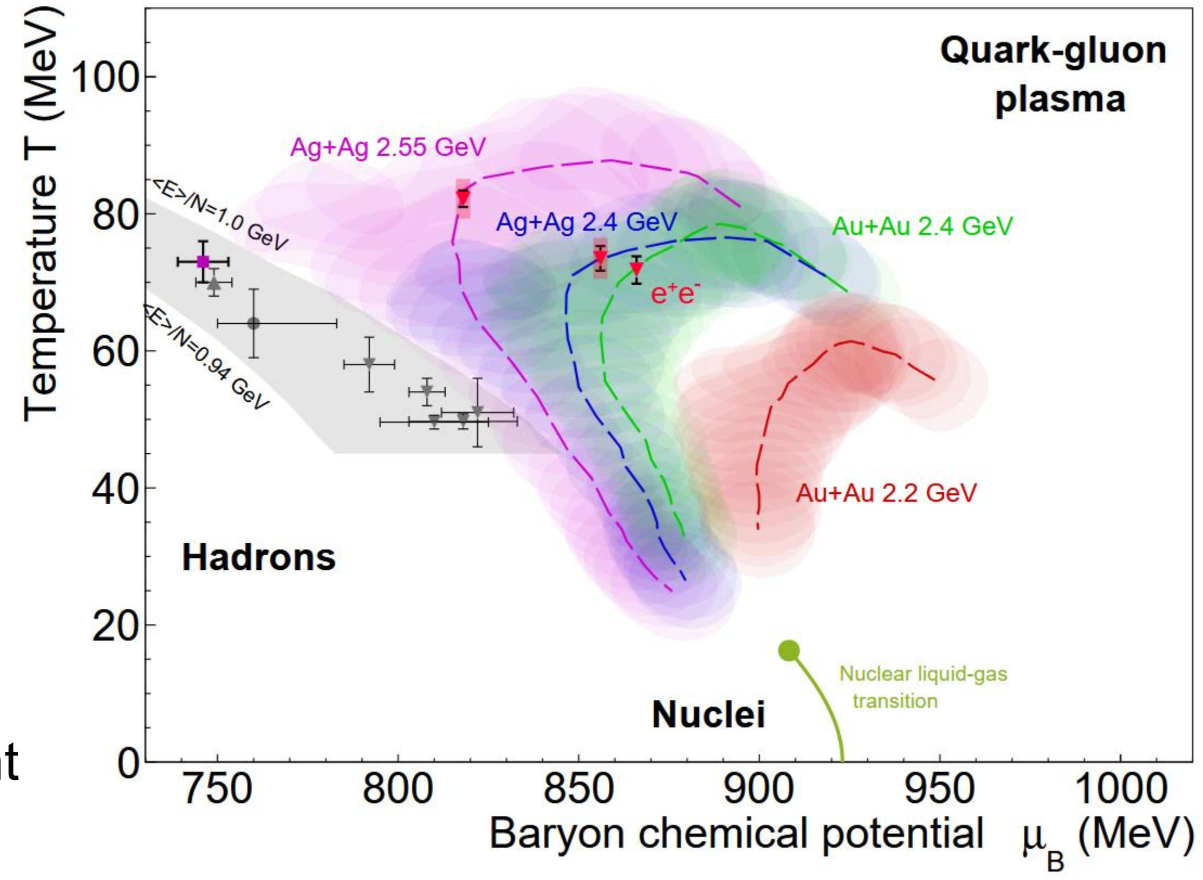
SUMMARY AND OUTLOOK

HADES dilepton program brings unique measurement possiblities to various observalbes

- Establish **thermal nature** of the radiation
- **Flow** to investigate the equation of state

- Production mechanism via **Polarisation**
- **QCD phase structure** at high μ_B with low momentum dileptons at HADES

- Exciting possibilities at future CBM experiment at FAIR with dedicated dilepton program



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