CHARACTERISING THE HOT AND DENSE FIREBALL WITH VIRTUAL PHOTONS AT HADES

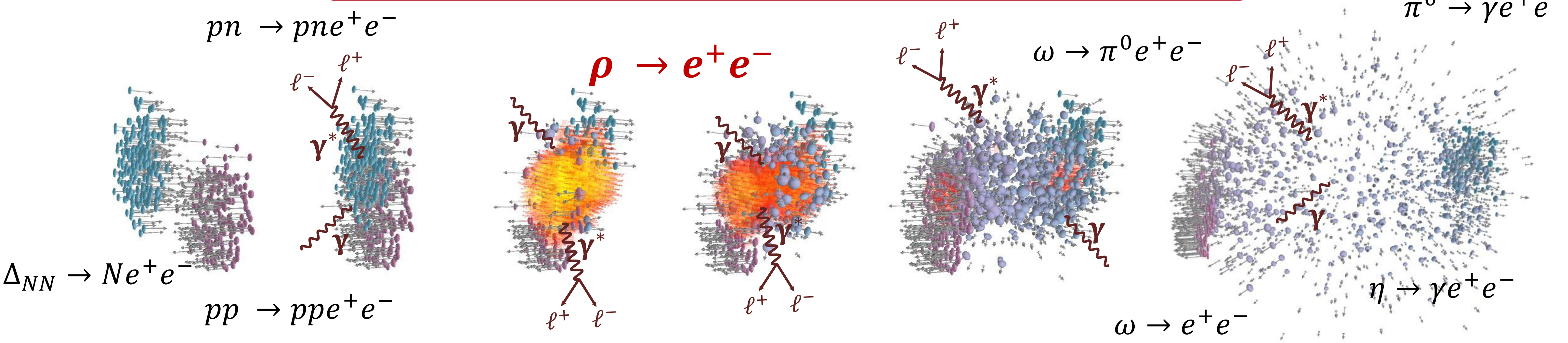
Niklas Schild

(TU Darmstadt)

EMMI Workshop: Collective phenomena and the Equation-of-State of dense baryonic matter

MOTIVATION - DILEPTONS

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



<u>Allows for many unique measurements</u>

Signals of phase transition via lifetime and temperature measurement

Restoration of chiral symmetry

Degrees of freedom of the medium

Transport properties

<u>Yet bring own set of challenges</u>

Need to isolate contribution of interest

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

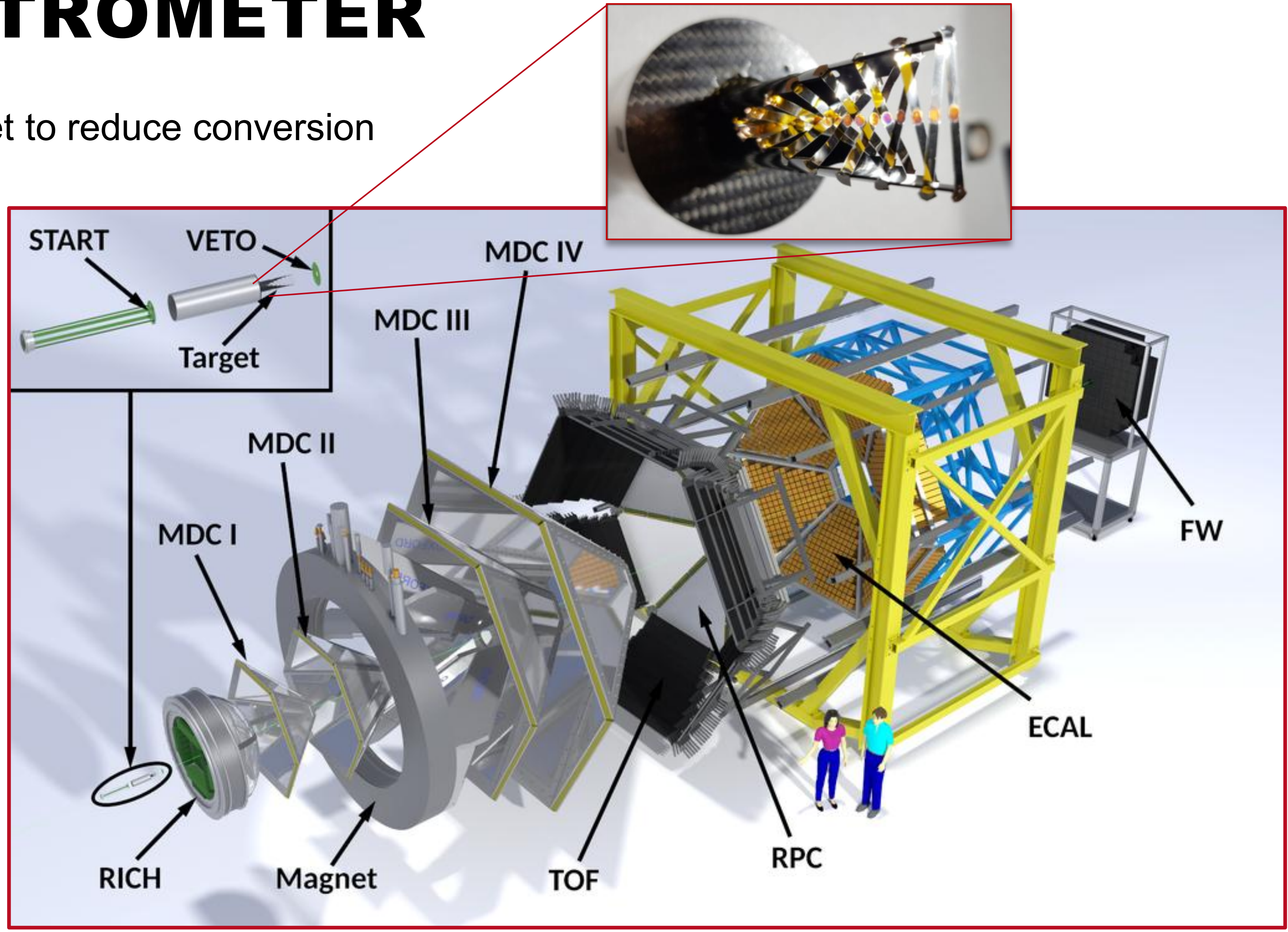
HIGH-ACCEPTANCE-DI-ELECTRON-SPECTROMETER

- 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!



HIGHLIGHTED BEAMTIMES

HADES, Nature Phys. 15(2019) 1040

Time

2001 — 2012 — 2019 — 2022 — Today

2012: Au+Au
$1.23A$ GeV

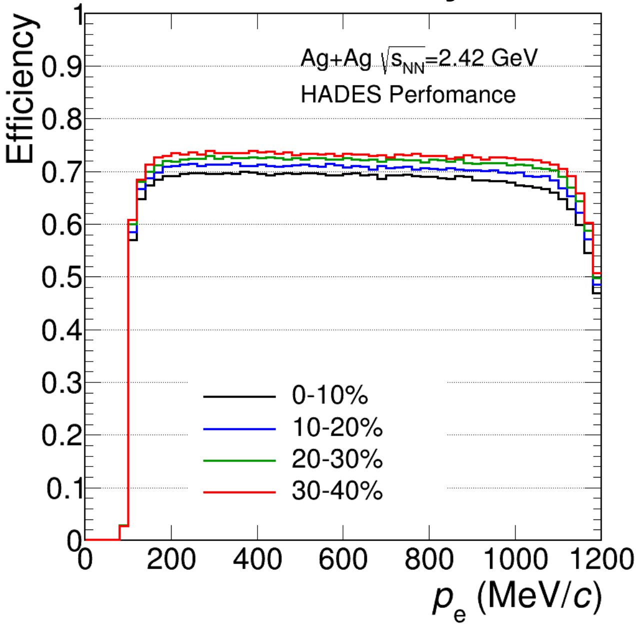
2019: Ag+Ag
$1.58A$ GeV ($\sqrt{s_{NN}} = 2.55$ GeV)
$1.23A$ GeV ($\sqrt{s_{NN}} = 2.42$ GeV)

2022: p+p
4.50 GeV
1.58 GeV

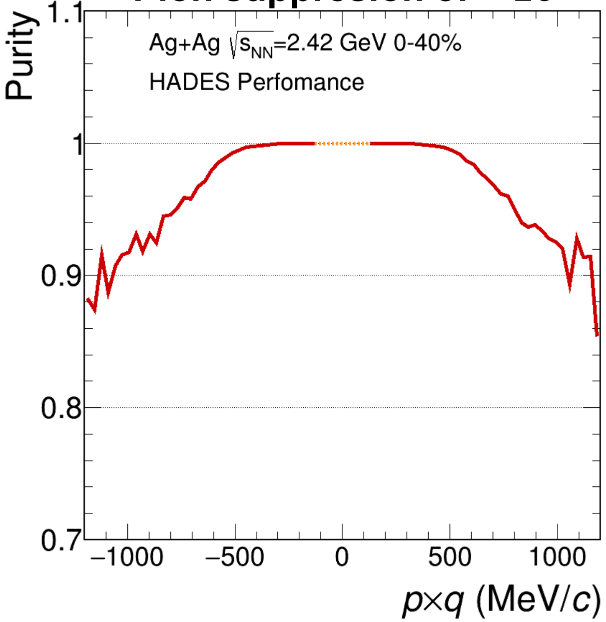
Today: Au+Au, C+C
$0.8A$ GeV

- Various upgrades improved detector capablities over time
  - ⇝ Photodetection plane in RICH
  - ⇝ Installation of ECAL

Reconstruction efficiency ~ 60-90%



Purity above 90%
Pion suppresion of ~ 10^{-5}



HIGHLIGHTED BEAMTIMES

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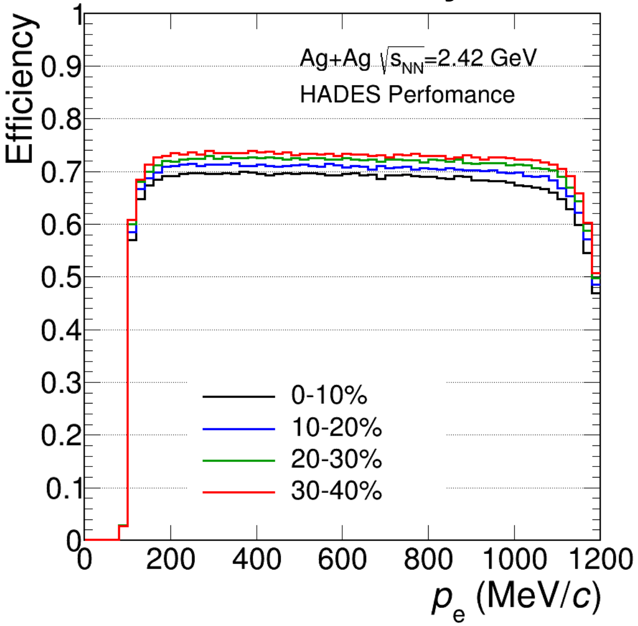
Focus Today

Thermal dilepton radiation from the hot and dense medium

Reconstruction efficiency ~ 60-90%



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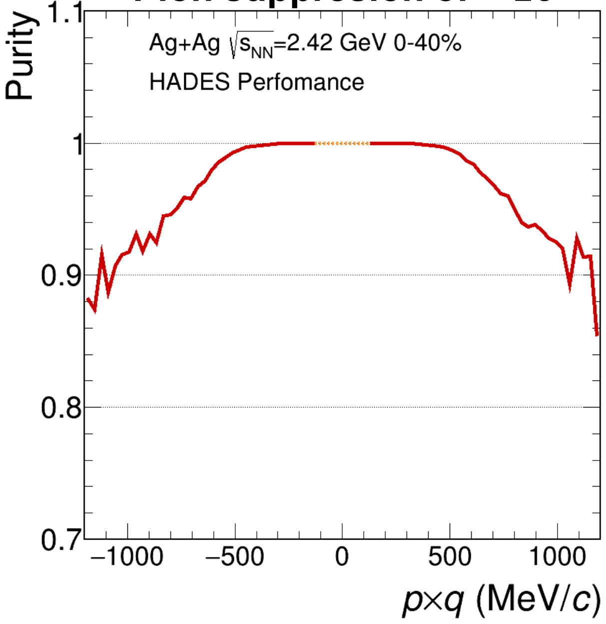
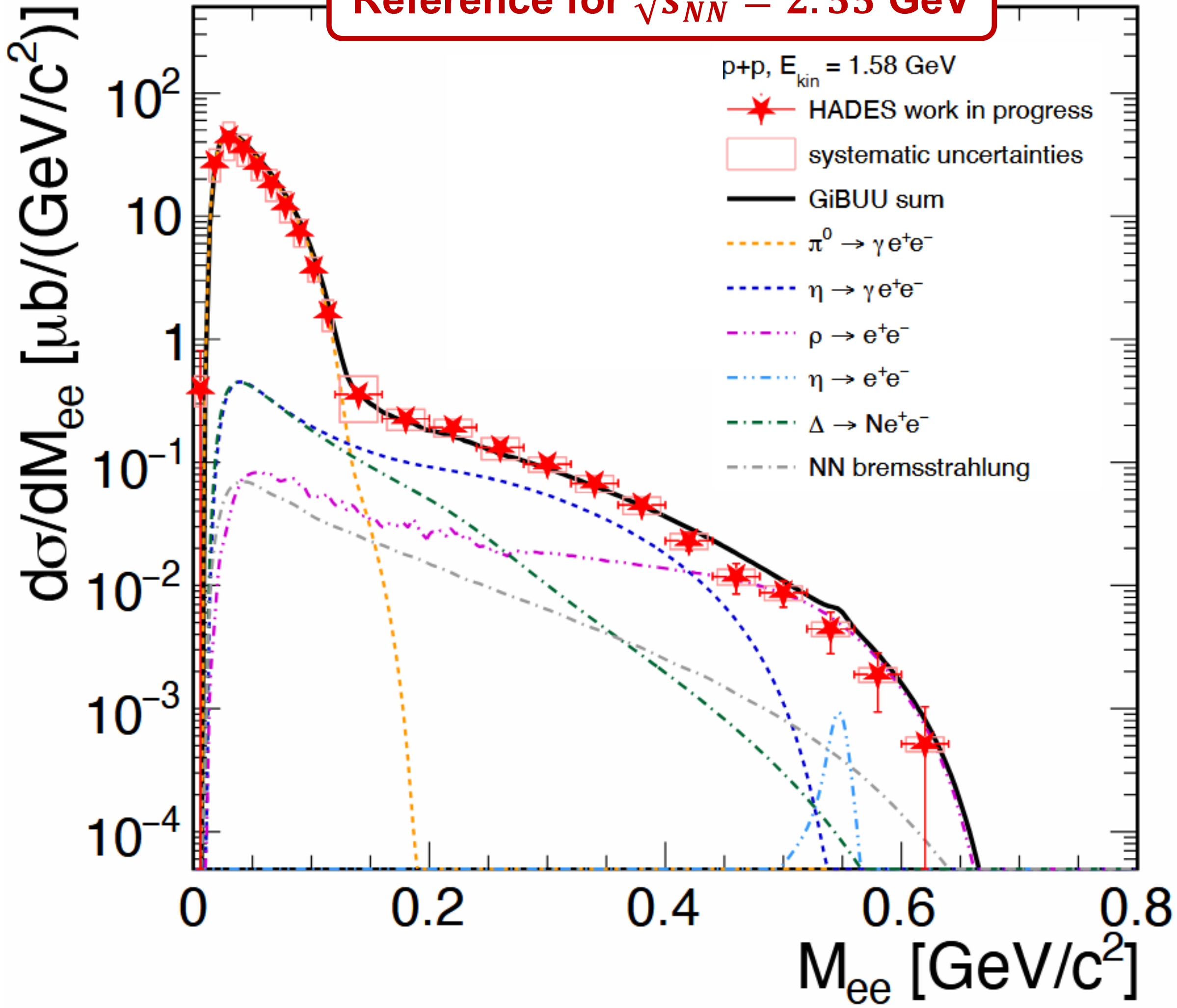


NN REFERENCE MEASUREMENT

Measurement of p+p collisions (2022) at 1.58 GeV

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



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

- Very good agreement with GiBUU prediction

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

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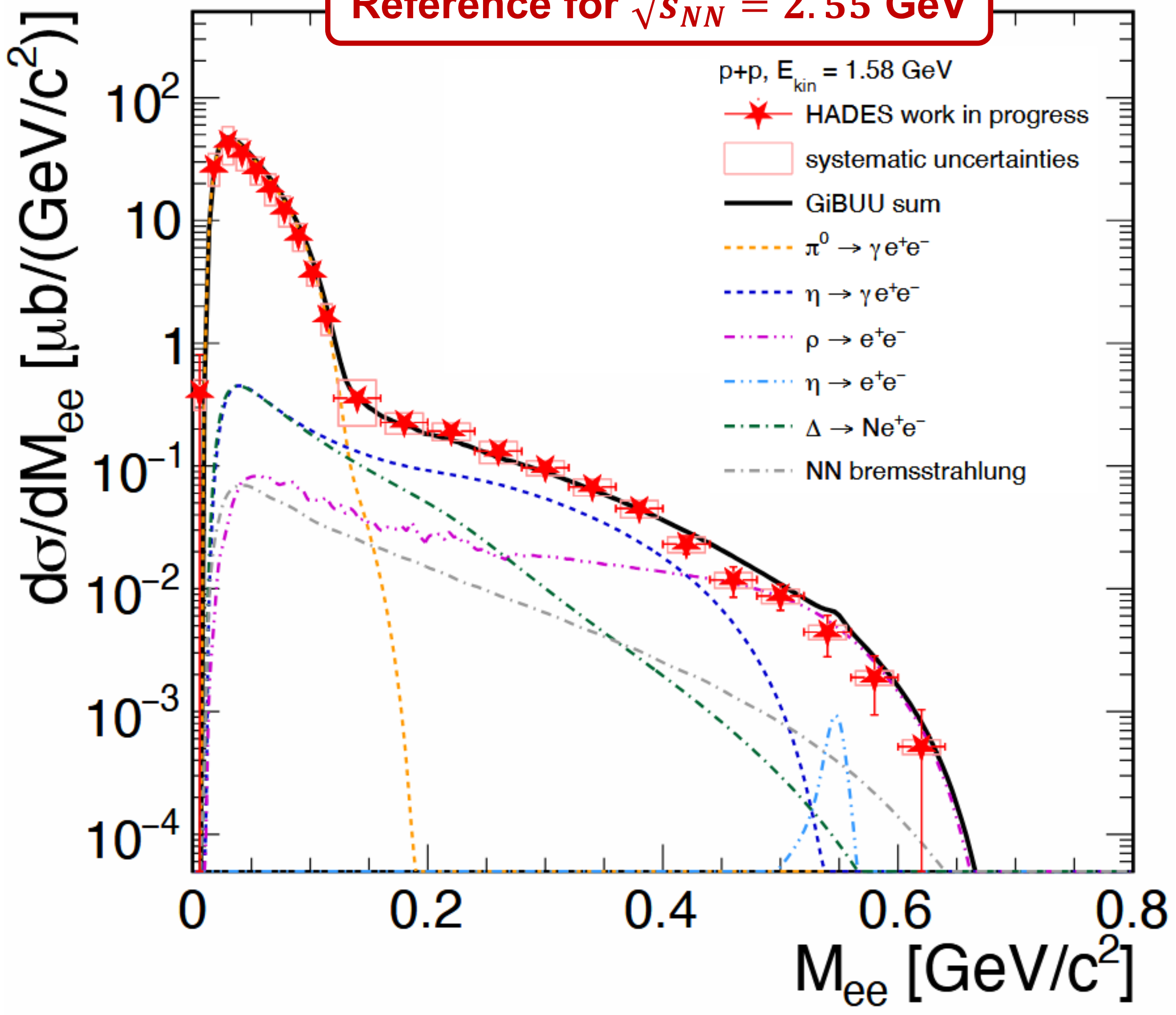
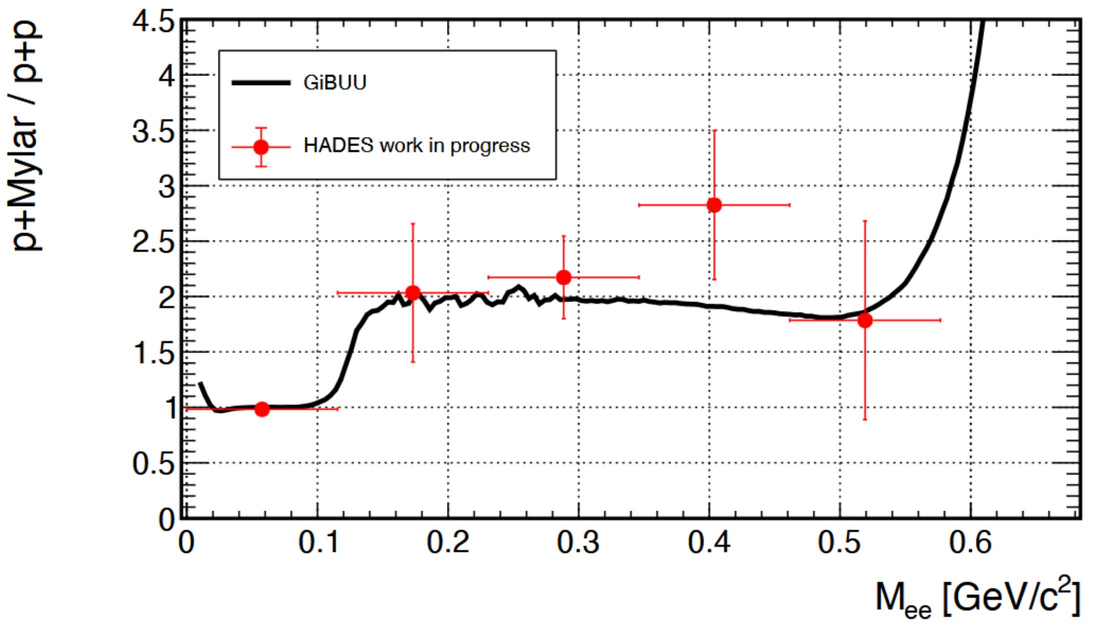


Provides reference to Ag+Ag measurement at $\sqrt{s_{NN}} = 2.55$ GeV

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



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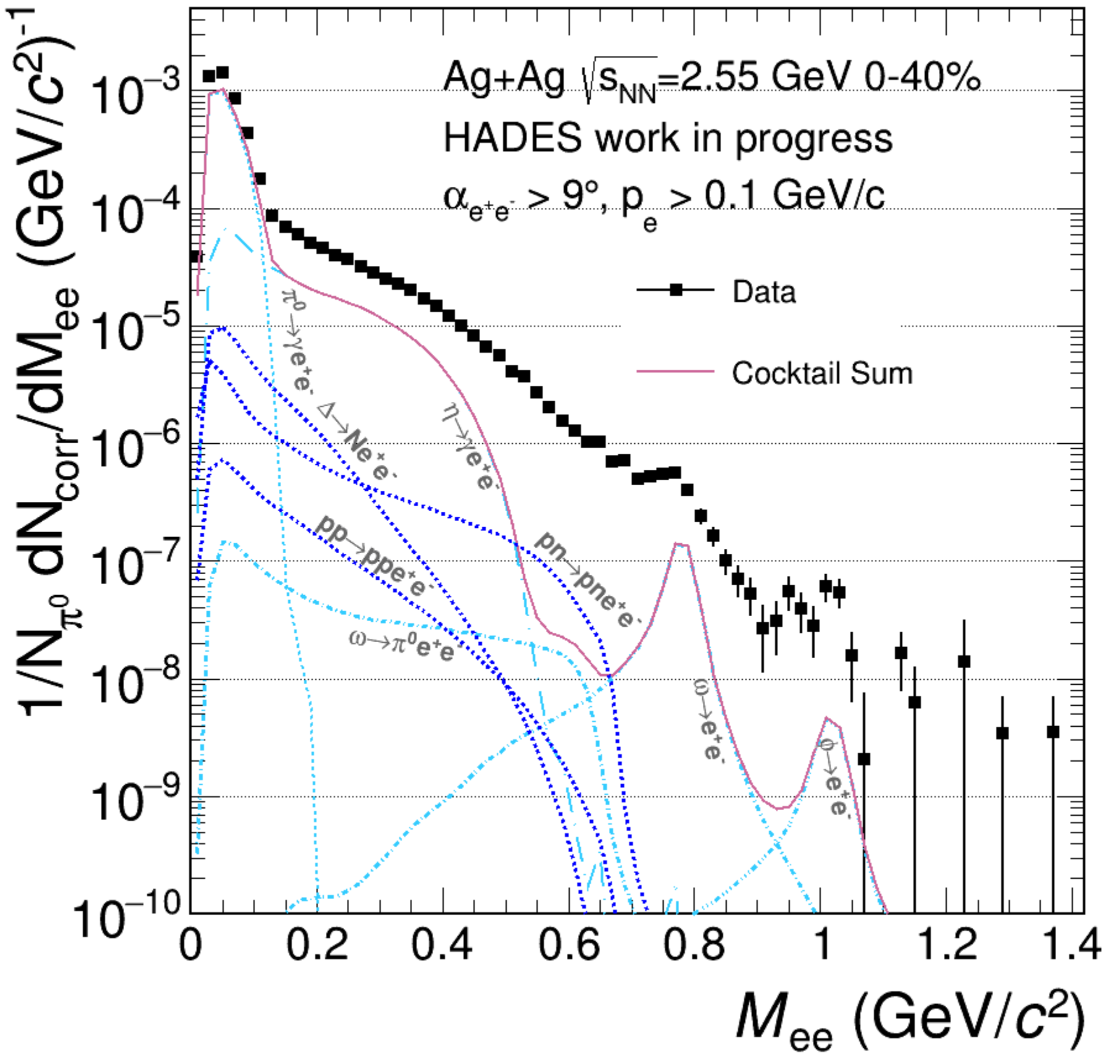
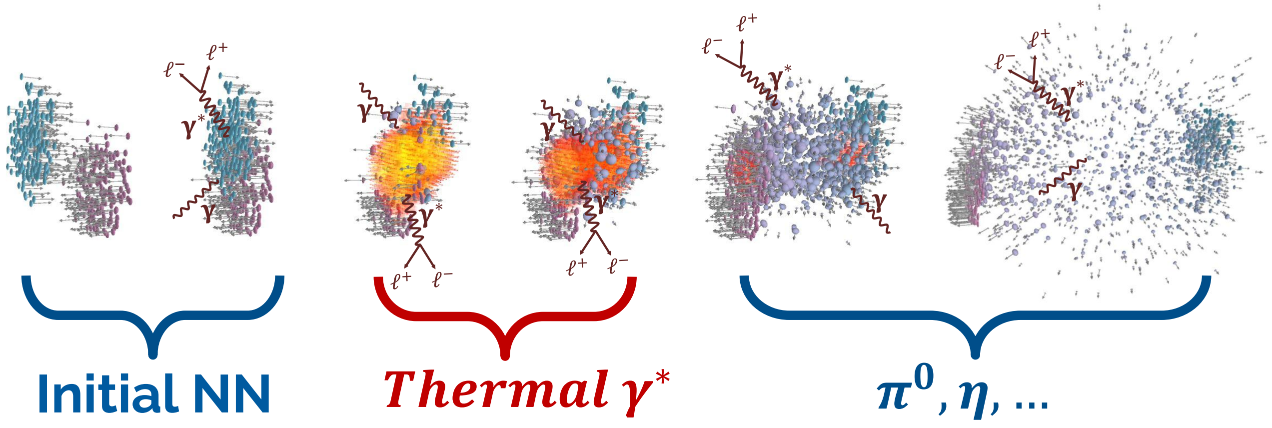
INVARIANT MASS SPECTRUM





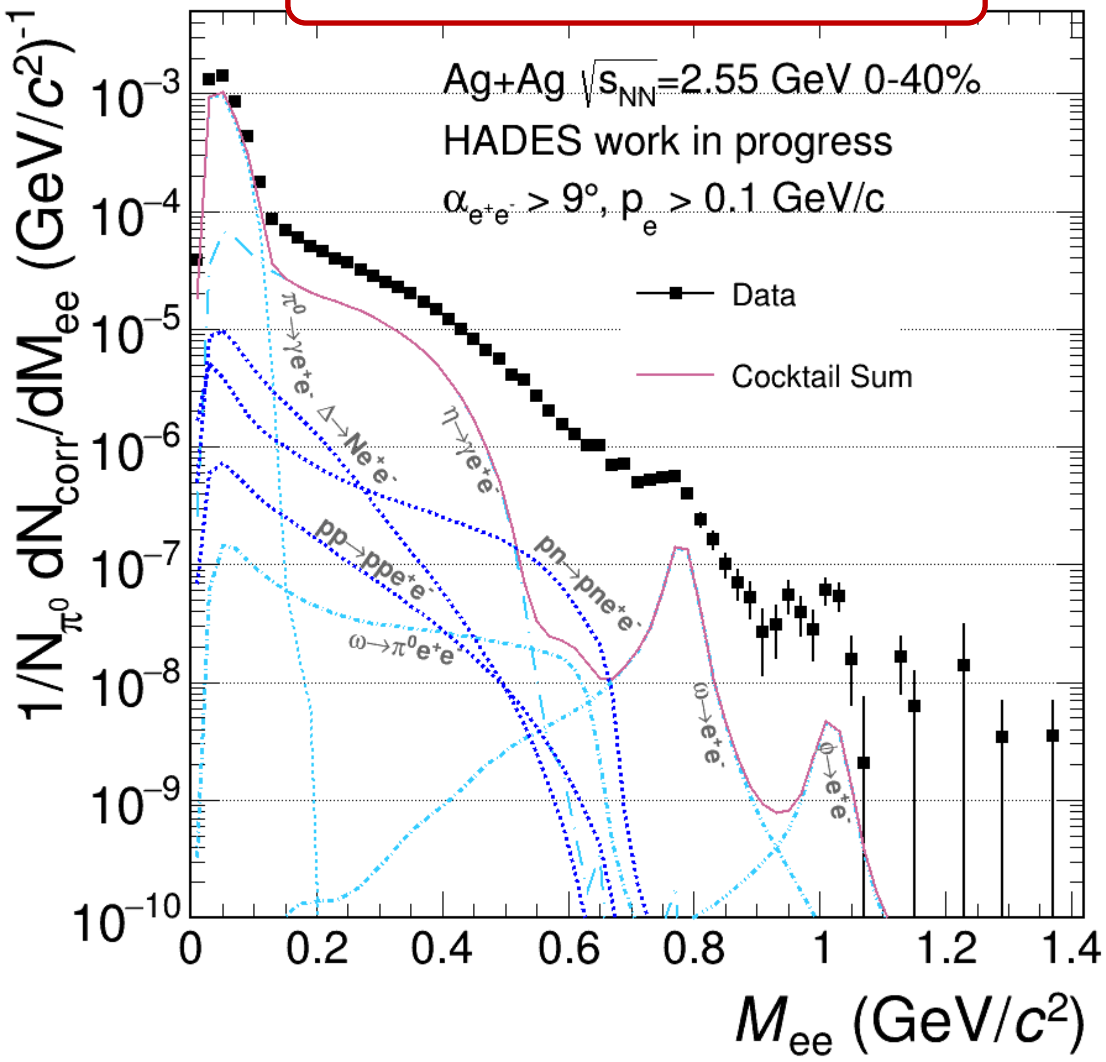
Measured signal is integral over whole evolution

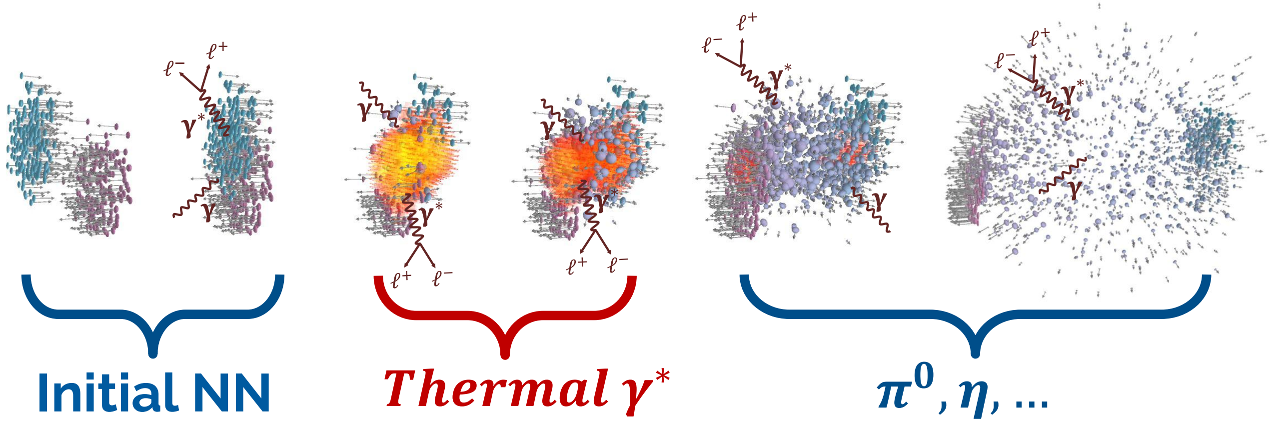
Isolate thermal contribution by subtraction of (experimentally measured):

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

INVARIANT MASS SPECTRUM

Clear excess is visible





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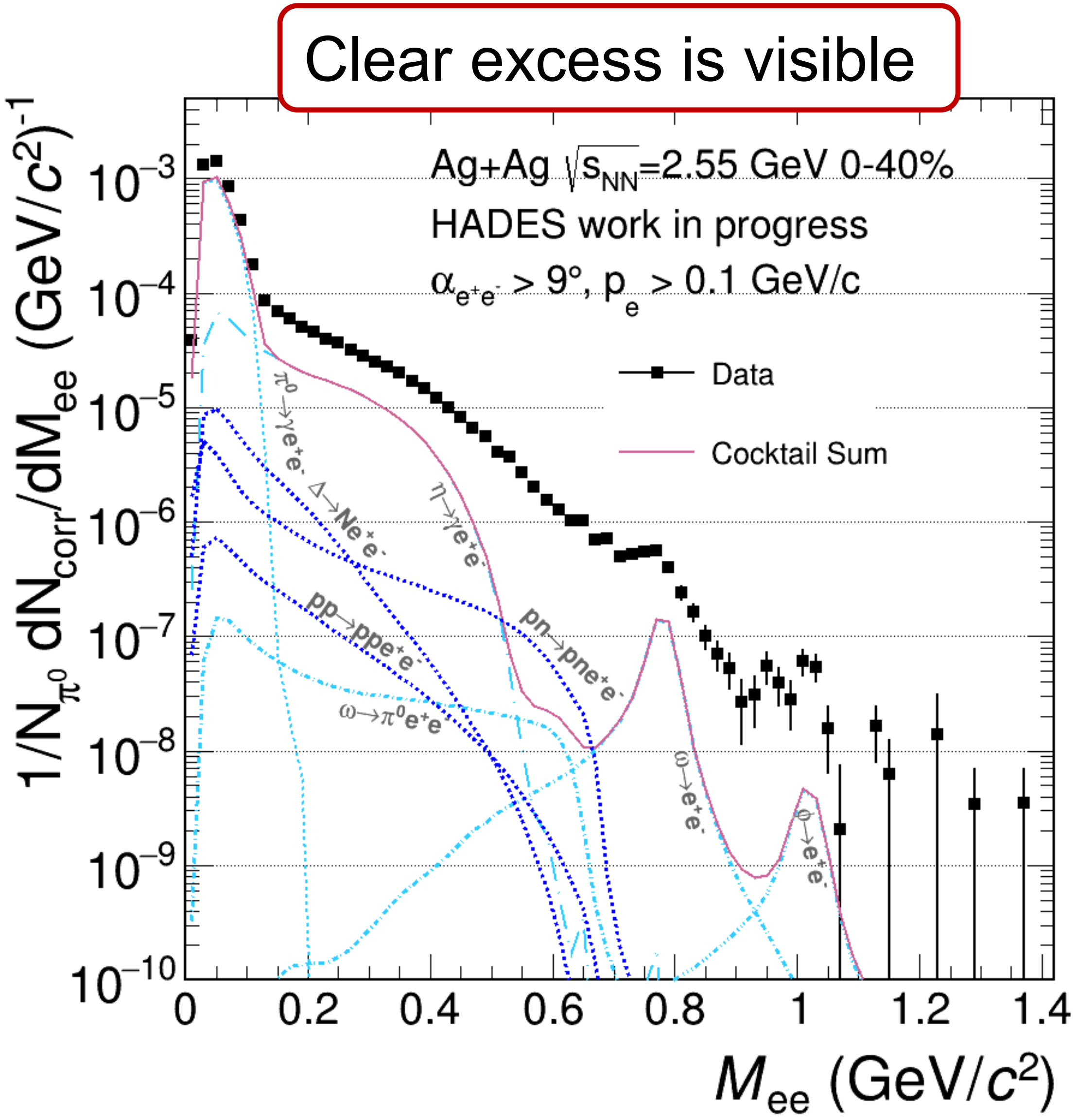

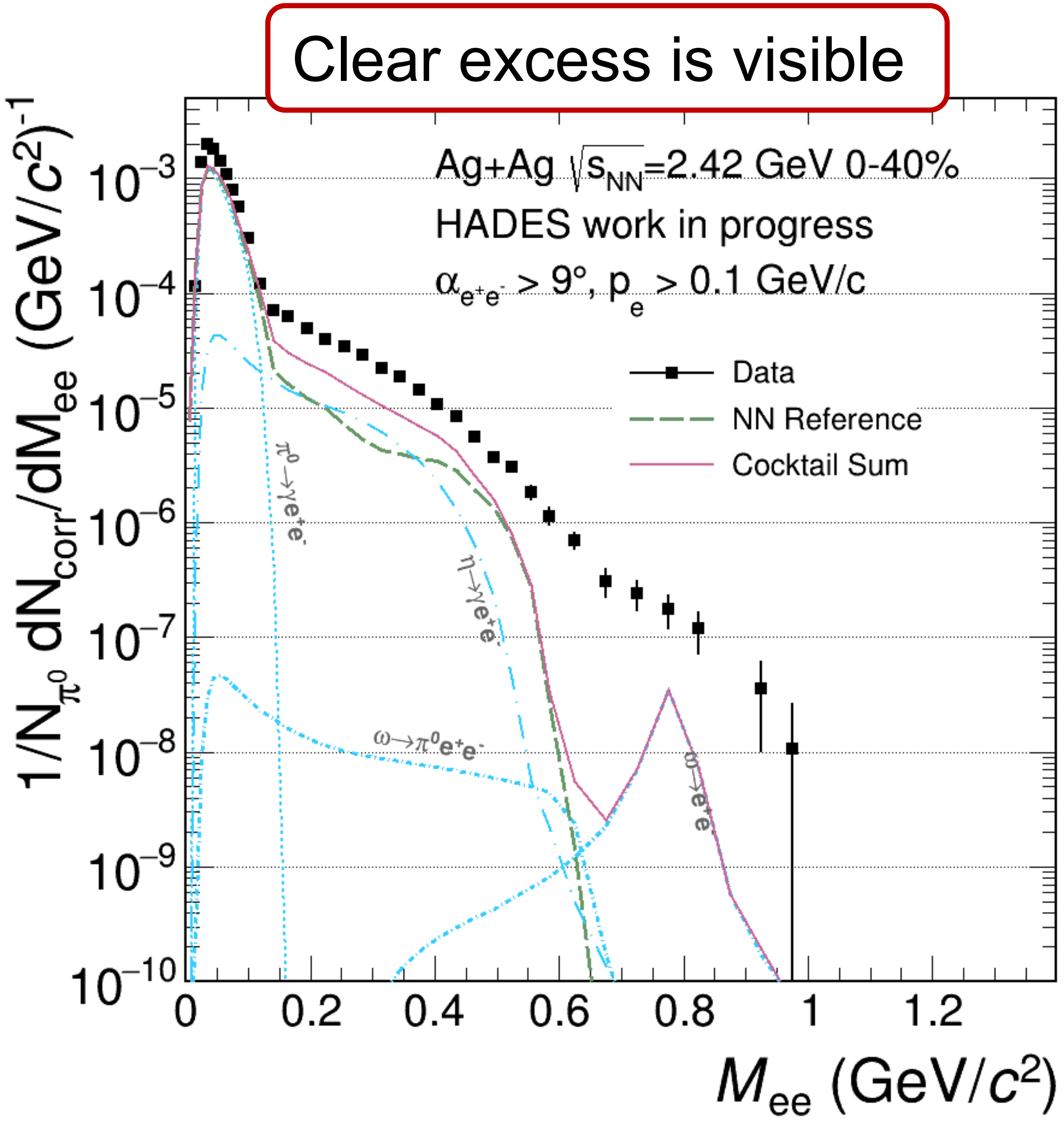

DILEPTON EXCESS

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

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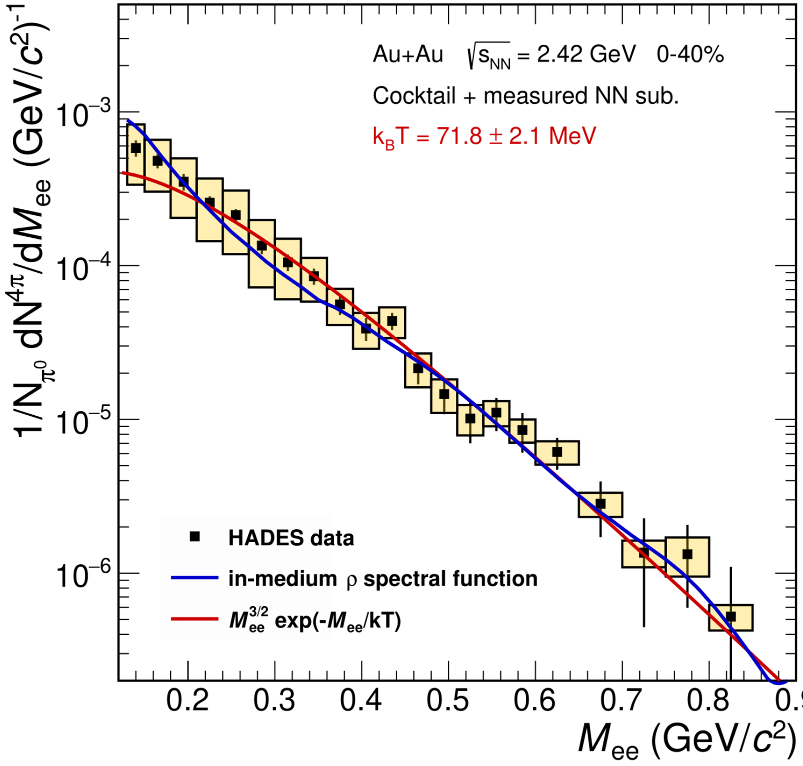
HADES

- 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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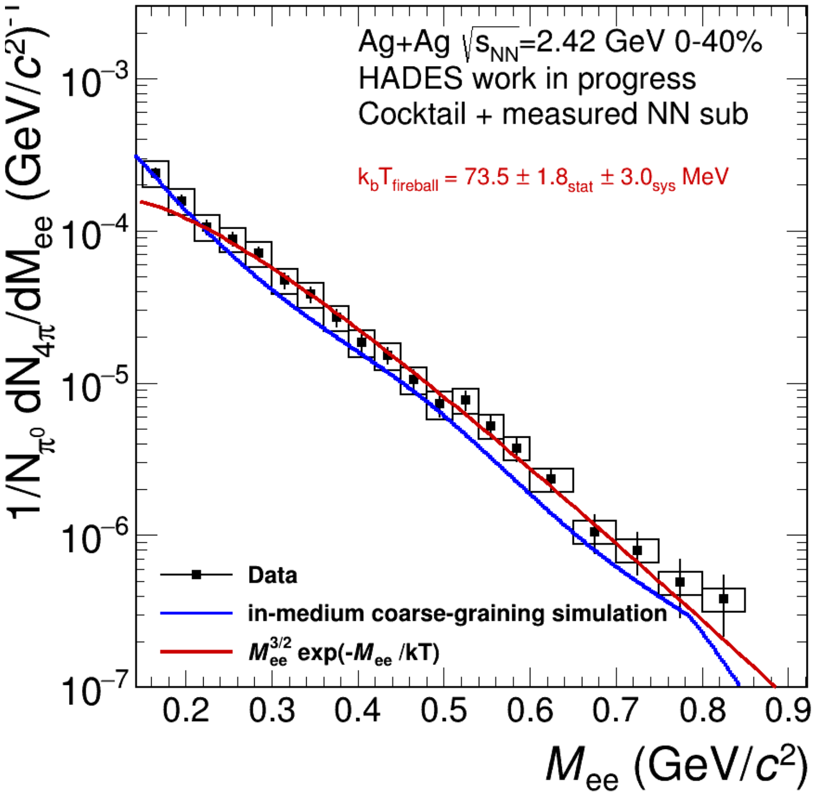
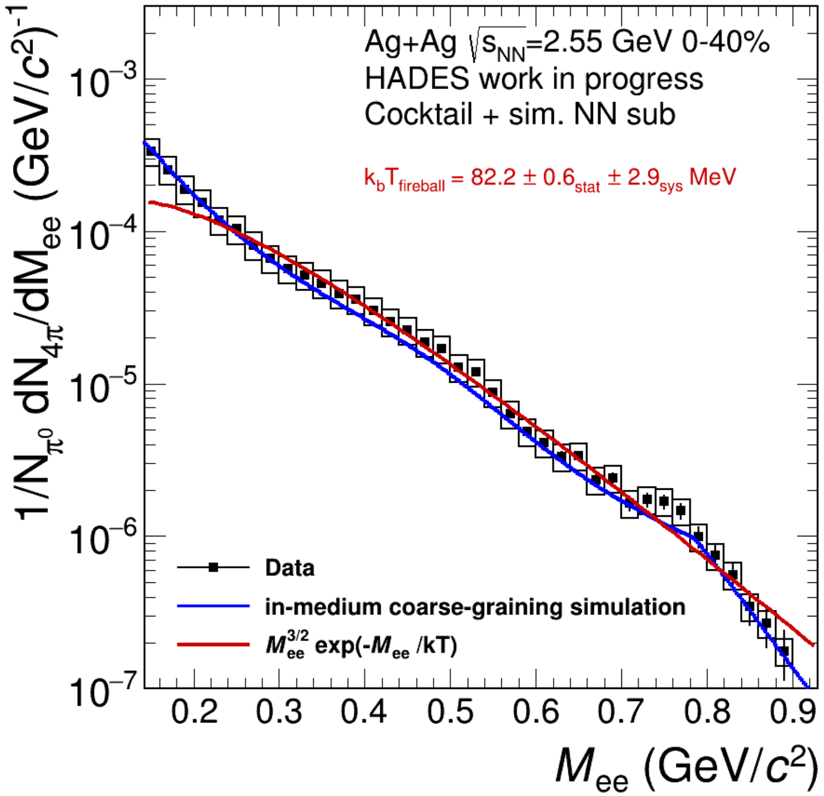
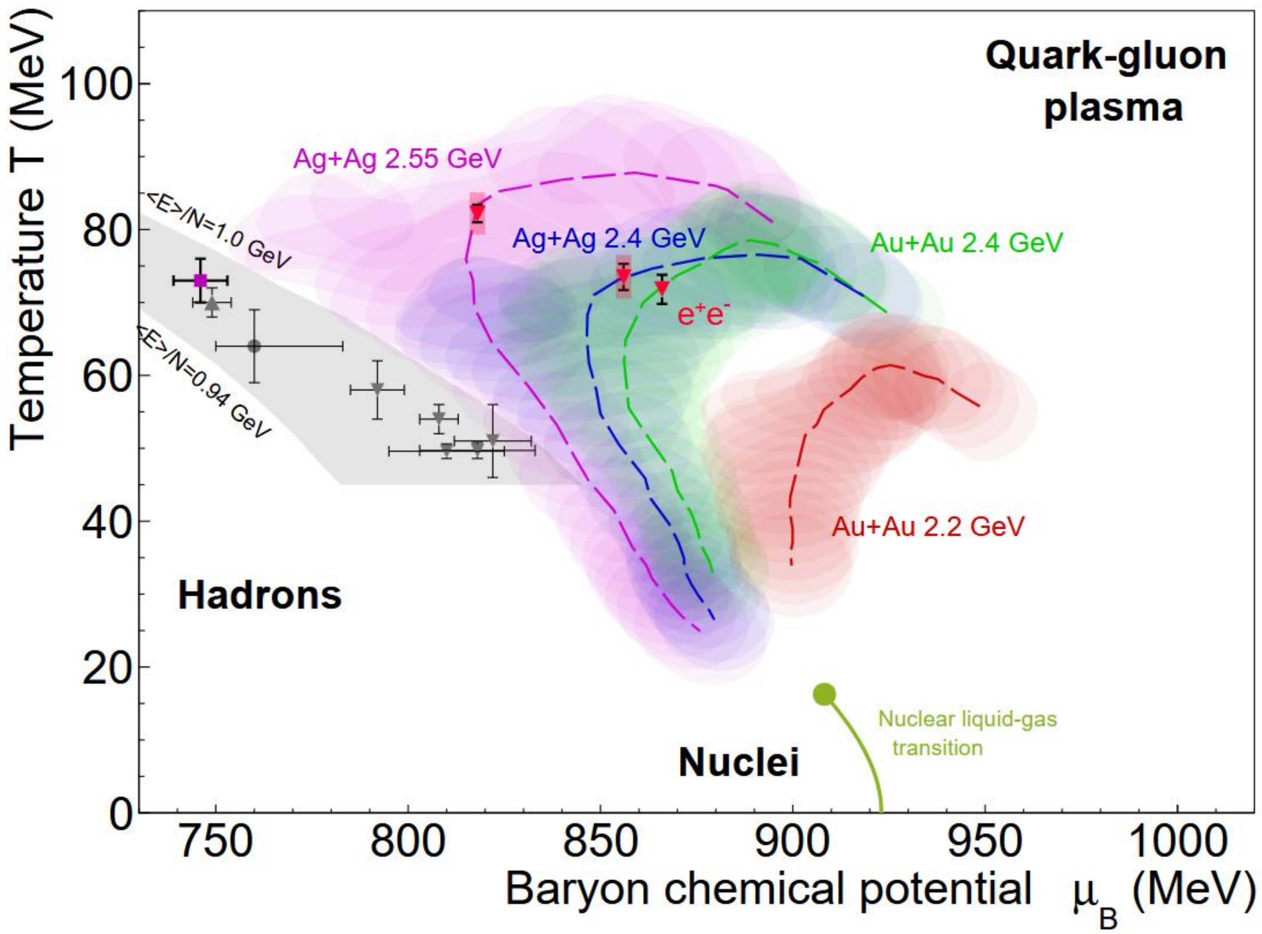


Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV



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
Au+Au 2.4 GeV data: HADES, Nature Phys. 15(2019) 1040
Eur.Phys.J.A 52 (2016) 5, 131
Phys.Rev.C 106 (2022) 1, 014904
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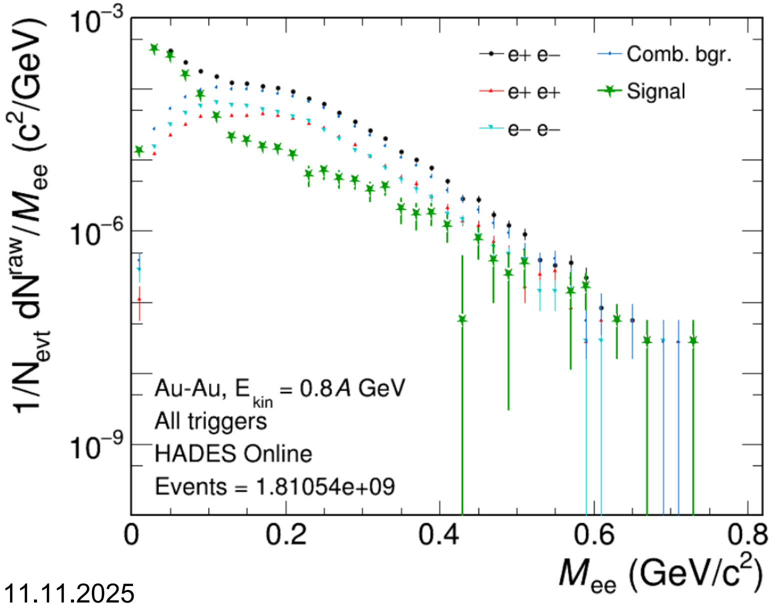

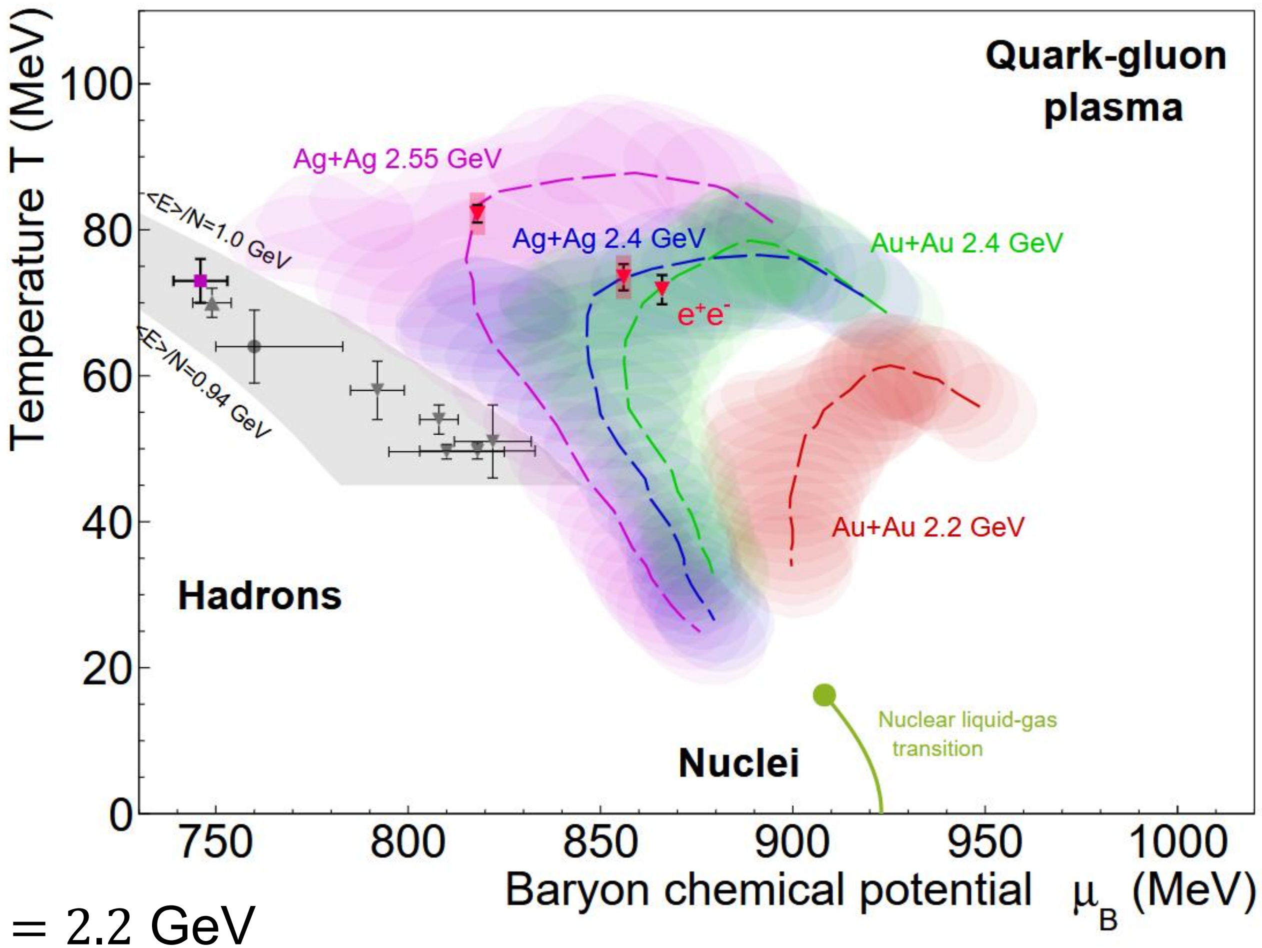

- Au+Au $\sqrt{s_{NN}} = 2.2$ GeV
  ~4B events collected
  in Feb'24 and May'25

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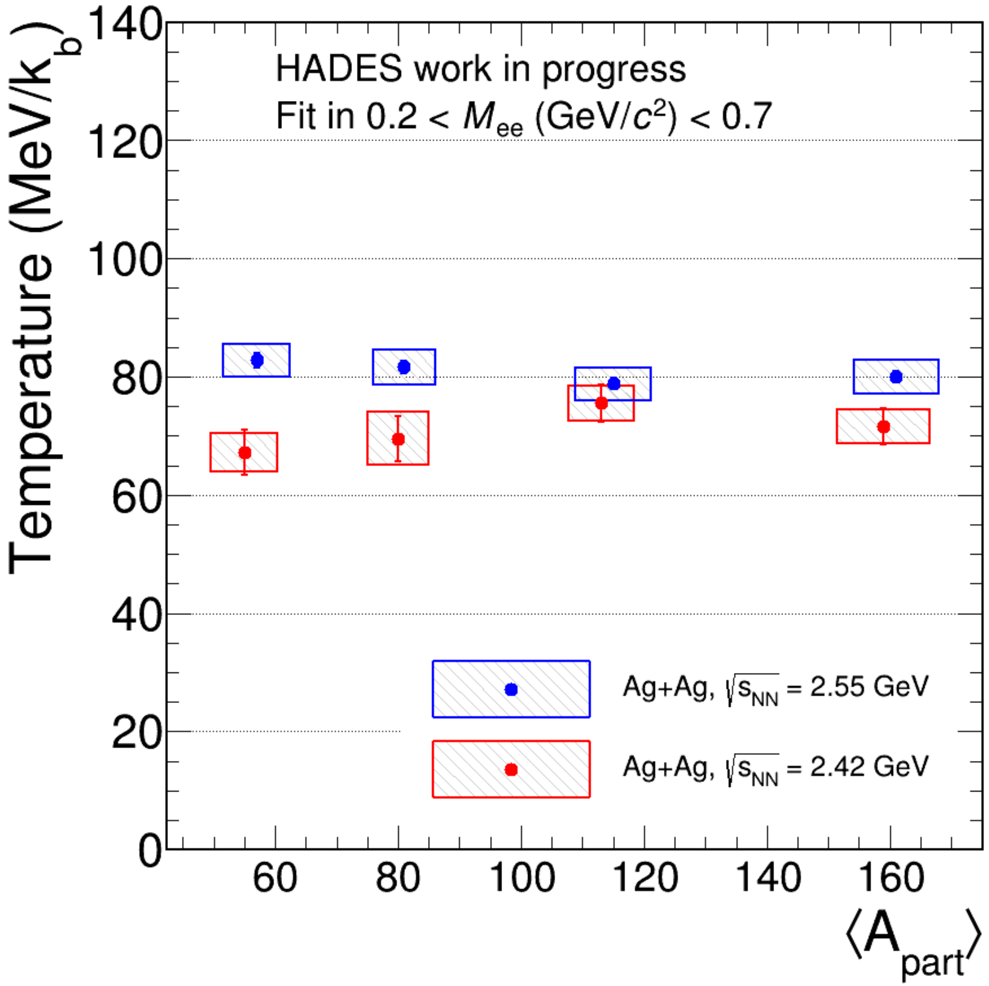
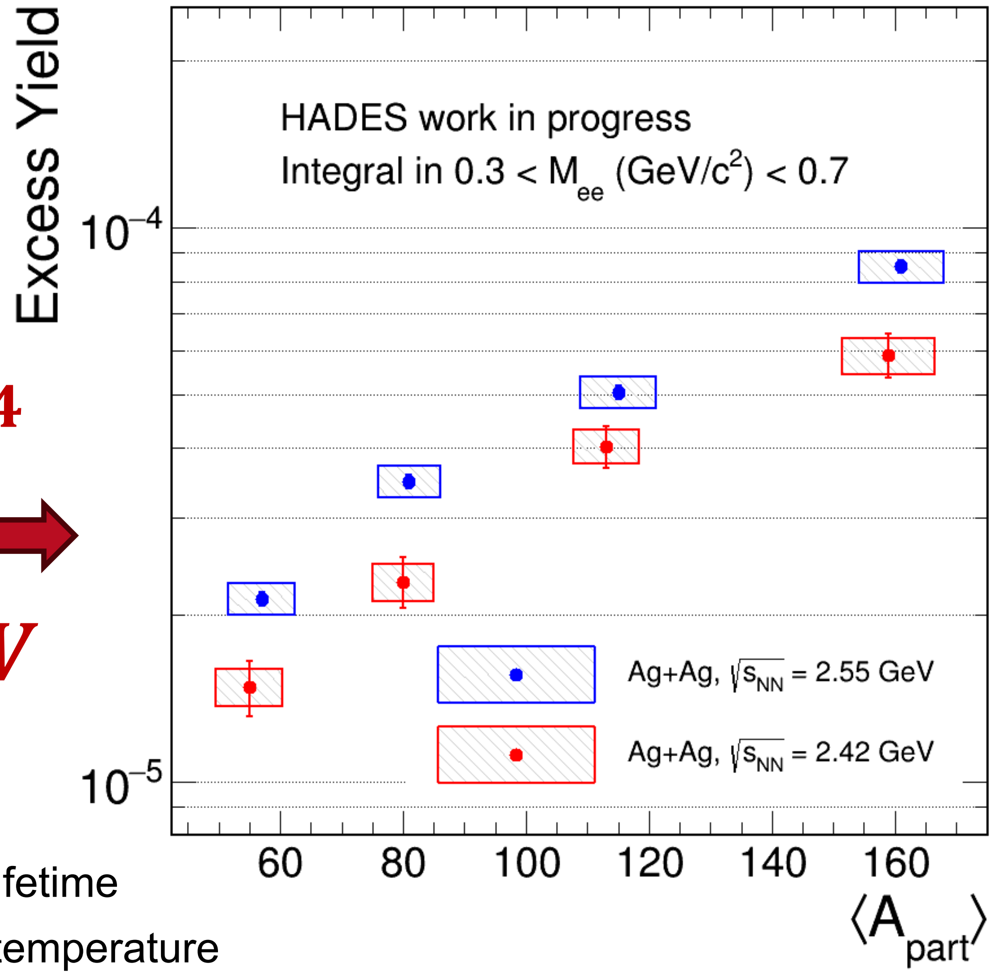
EXCESS - CENTRALITY DEPENDENCE

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



$\sim T^4$

$\sim \tau V$



V: Volume

τ: Fireball lifetime

T: Fireball temperature

FIREBALL CHARACTERISATION

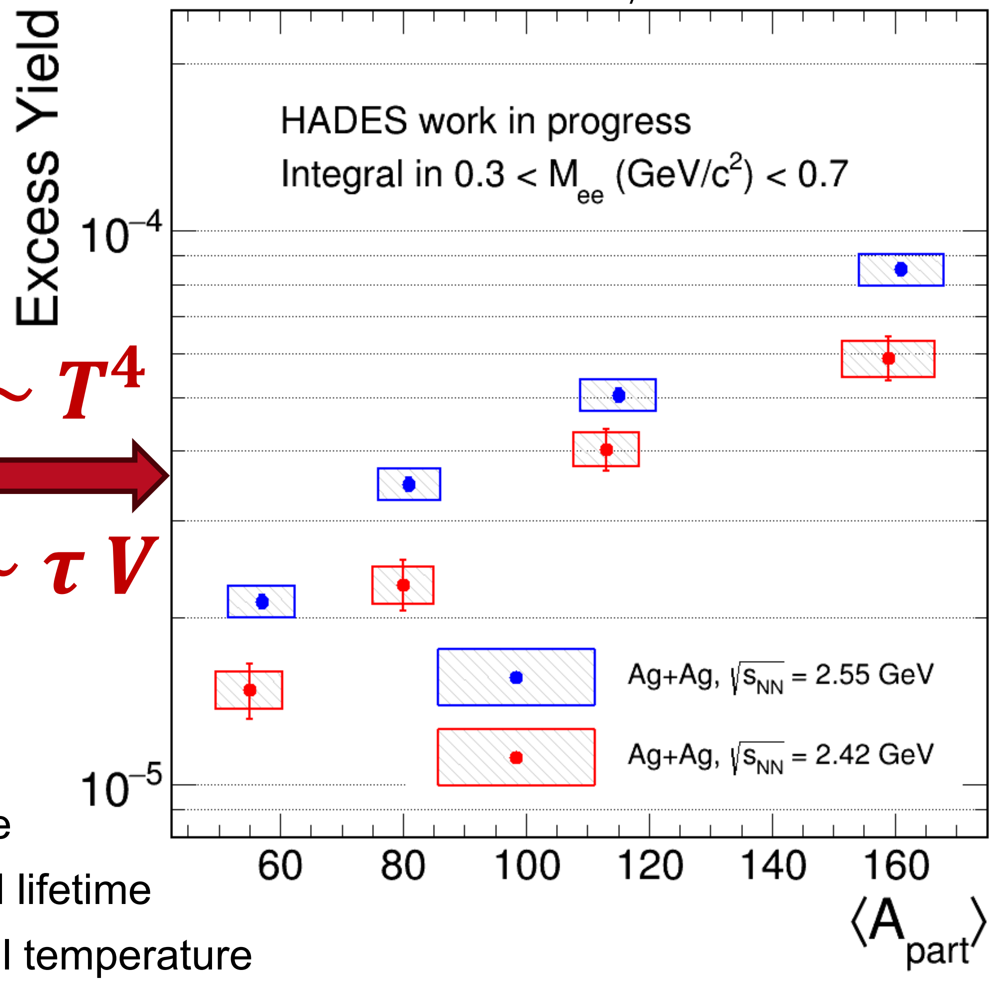
Assume:

- $\boldsymbol{T}$ constant across $\langle \mathrm{A}_{\mathrm{part}} \rangle$
- $\boldsymbol{V}$ follows linear $\langle \mathrm{A}_{\mathrm{part}} \rangle$ scaling
- Nonlinear scaling associated with $\boldsymbol{\tau}$

$$\mathrm{N}_{\mathrm{excess}} = \int_{0.3\ \mathrm{GeV}/c^2}^{0.7\ \mathrm{GeV}/c^2} \frac{dN}{dM}\, dM$$

$\sim \boldsymbol{T}^4$

$\sim \boldsymbol{\tau}\, \boldsymbol{V}$



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Fitting $N_{excess} \propto \langle A_{part} \rangle^{\alpha}$ yields:

$$\alpha^{AgAg}_{\sqrt{s_{NN}}=2.55\ GeV} = 1.39 \pm 0.04_{stat} \pm 0.13_{sys}$$

$$\alpha^{AgAg}_{\sqrt{s_{NN}}=2.42\ GeV} = 1.33 \pm 0.14_{stat} \pm 0.15_{sys}$$

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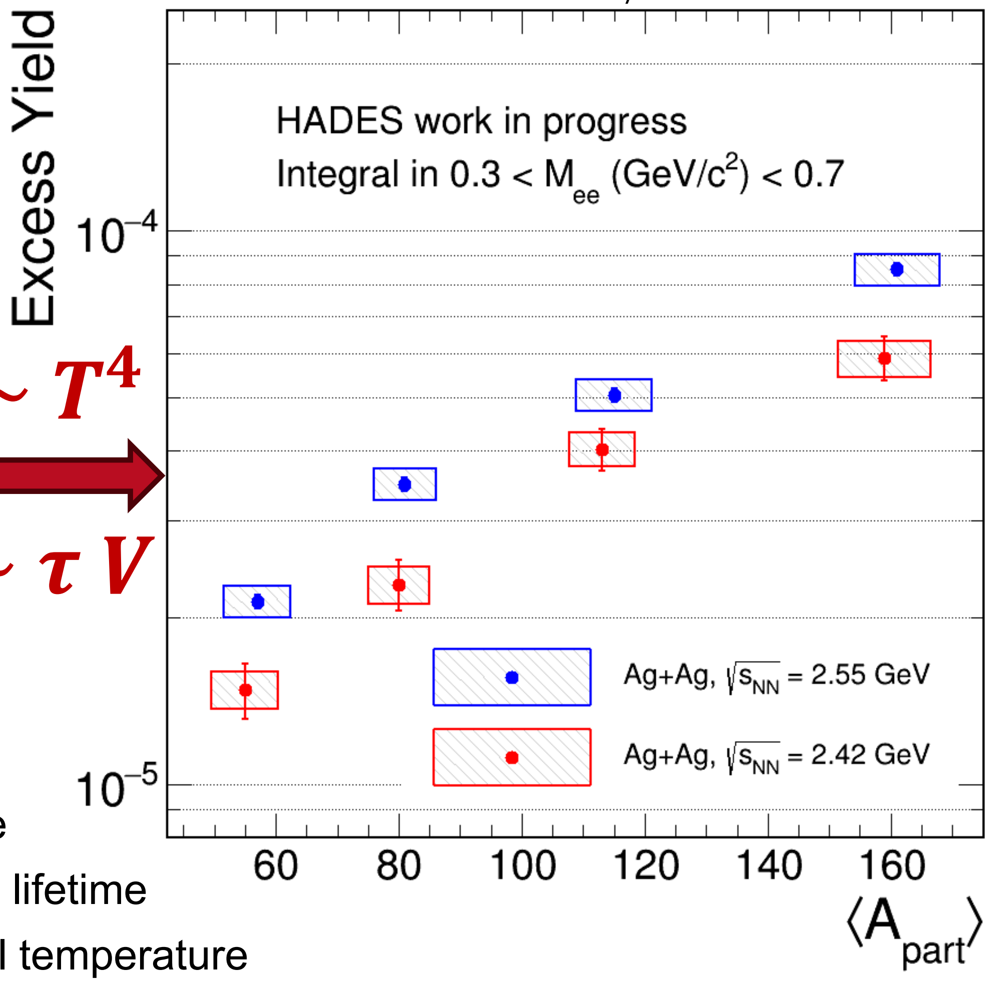

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Characterising the hot and dense fireball

Signals of phase transition (latent heat)

Phys.Rev.C 106 (2022) 1, 014904

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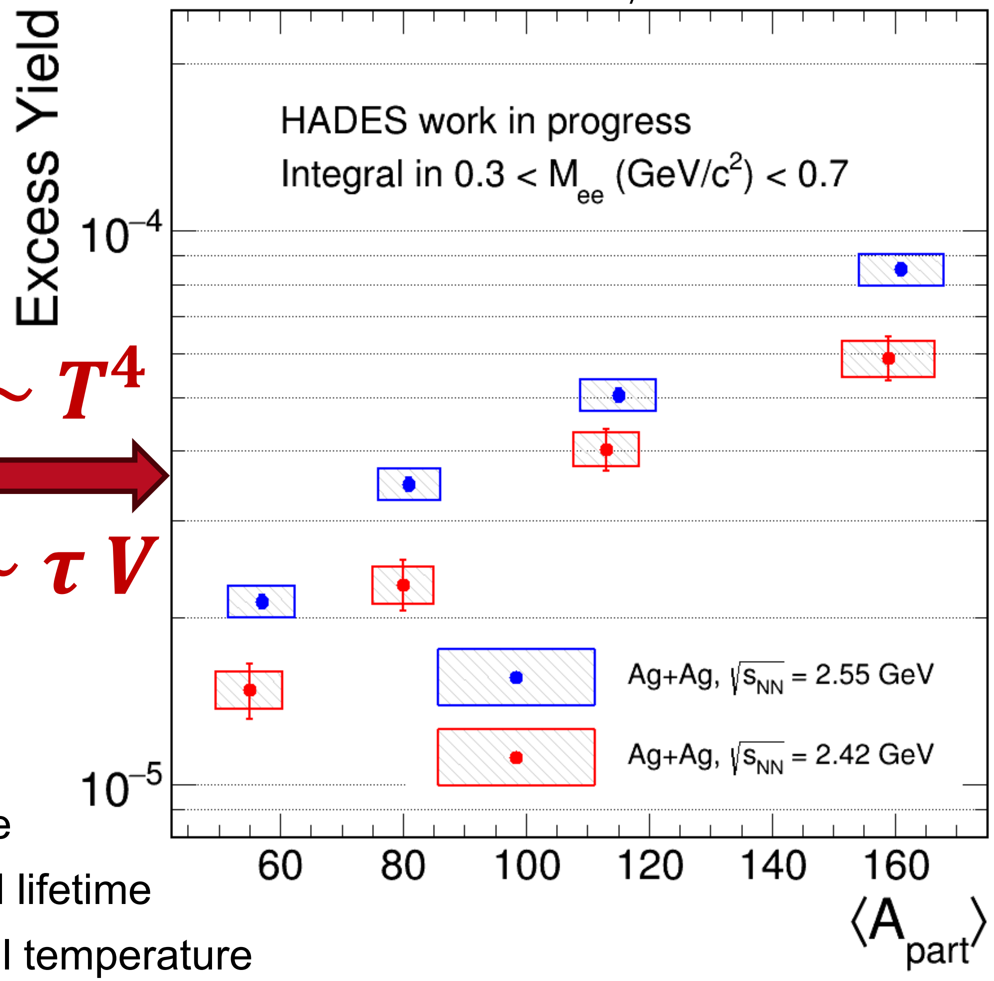

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COLLECTIVITY ANISOTROPC FLOW

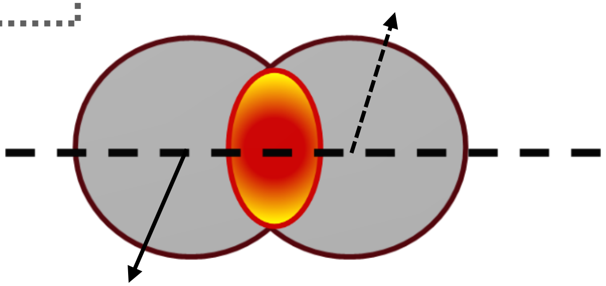
$$\frac{dN}{d\Delta\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n\,\Delta\varphi)$$

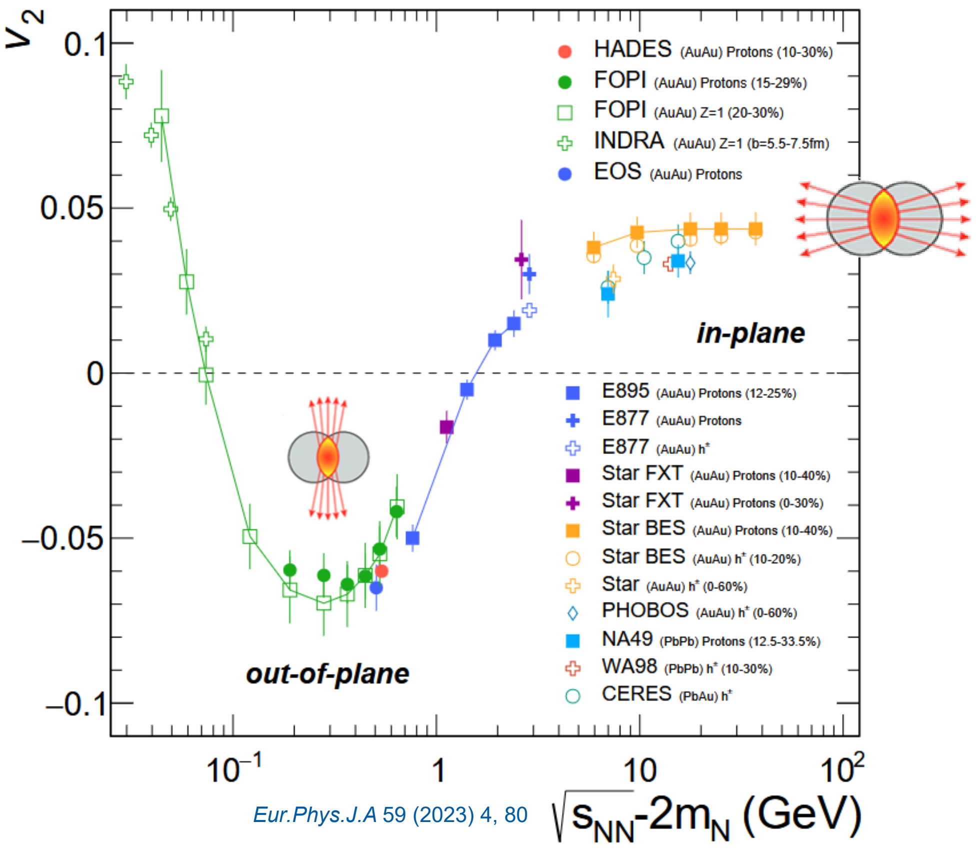
$$\Delta\varphi = \varphi - \Psi_{RP}$$

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

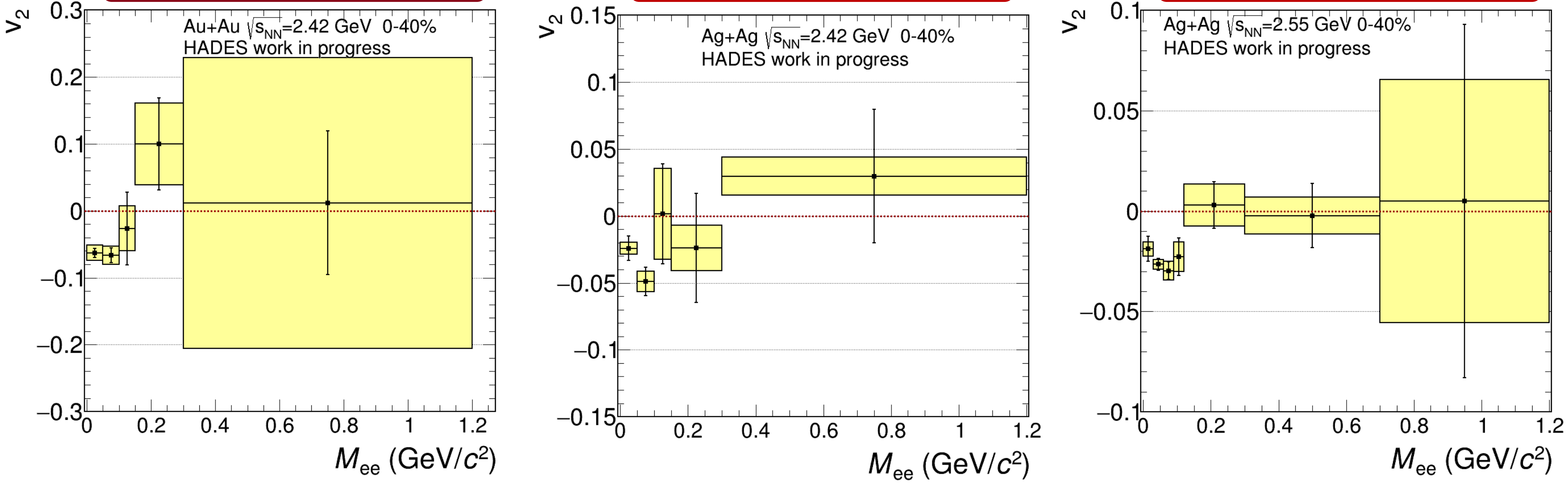
ANISTROPIC FLOW - DILEPTONS

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

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

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

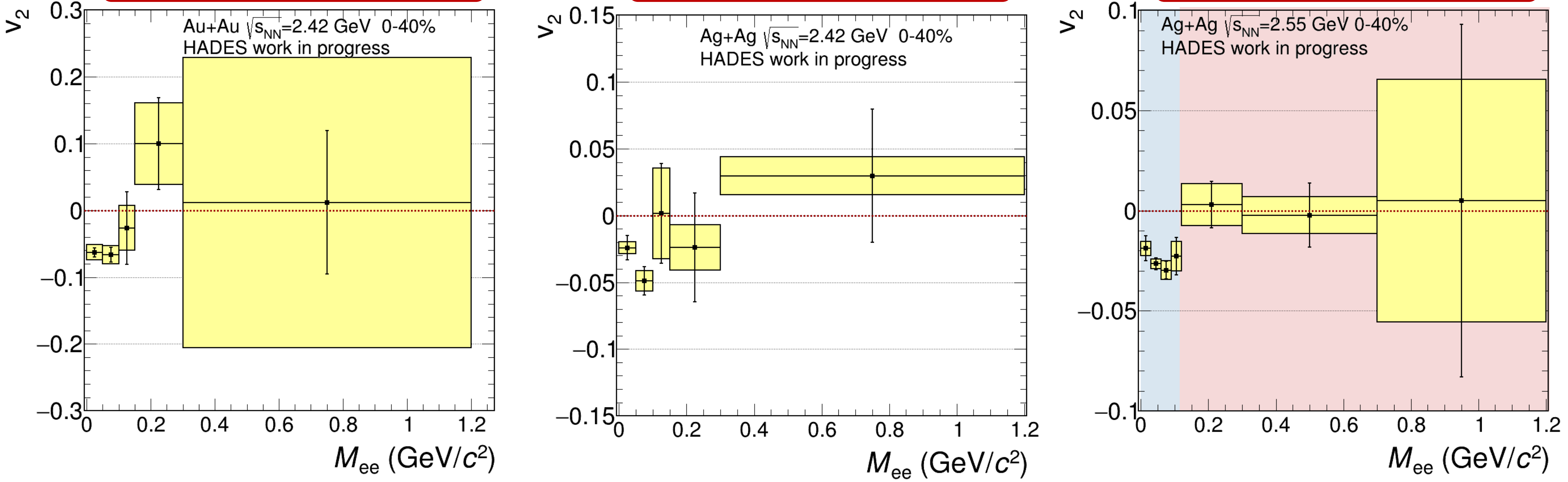
Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV



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/c²)** vs region dominated by **thermal radiation (M_{ee} > 0.12 GeV/c²)**

Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV | **Ag+Ag at $\sqrt{s_{NN}} = 2.42$ GeV** | **Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV**



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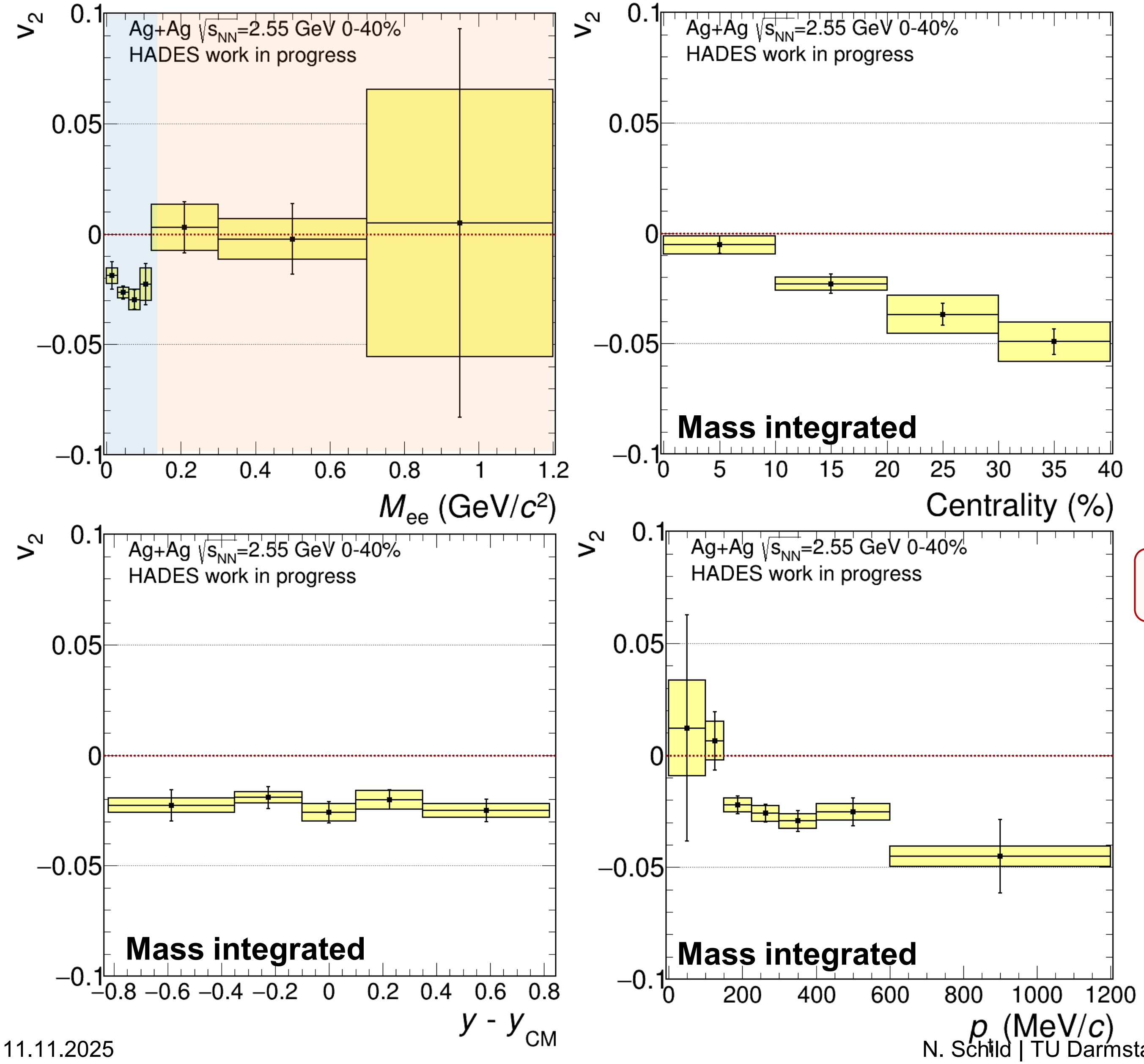
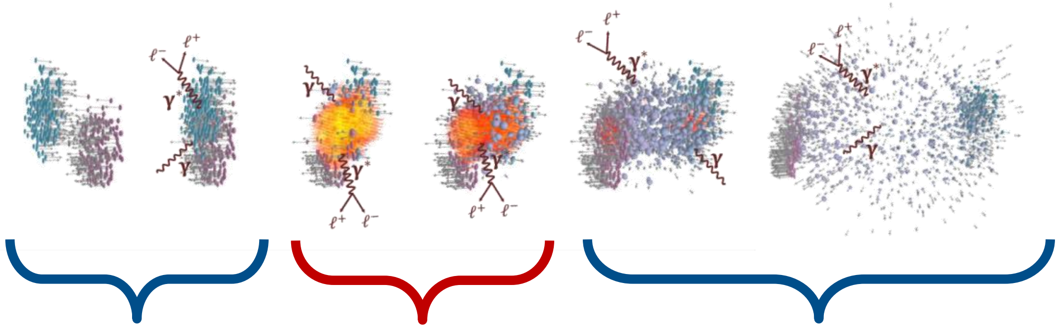


- High-statistics Ag+Ag measurement allows for differential analysis



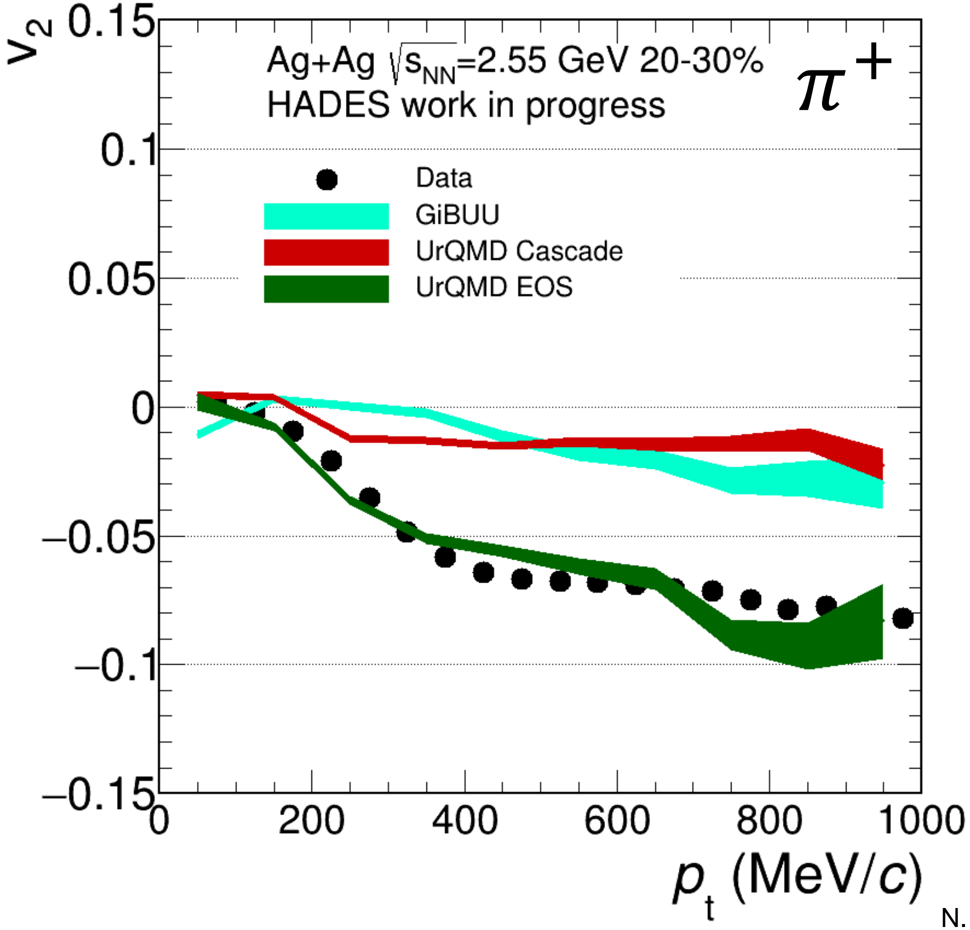
Measured signal is integral over whole evolution

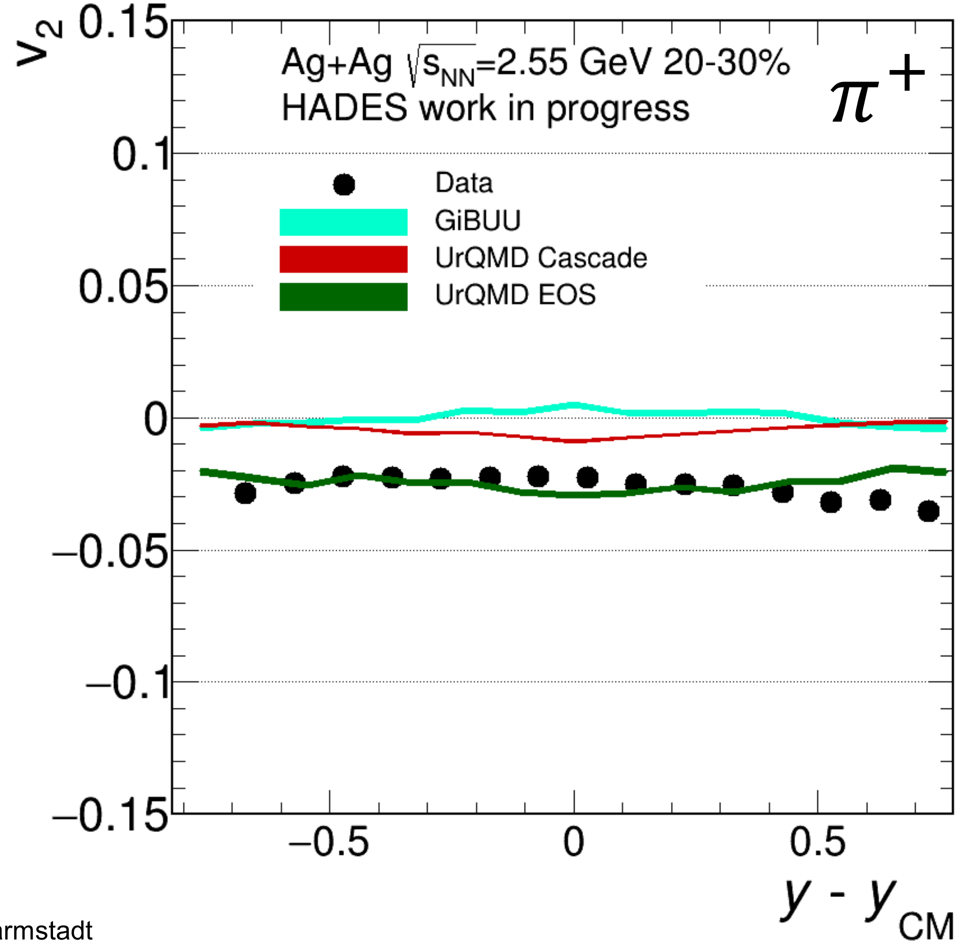
- Need precise flow measurements of freeze-out sources (π^0, η)
- Only limited data available at HADES energies

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

ANISTROPIC FLOW – CHARGED PIONS MODEL COMPARISON

UrQMD EOS shows the best description of pion ellitpic flow





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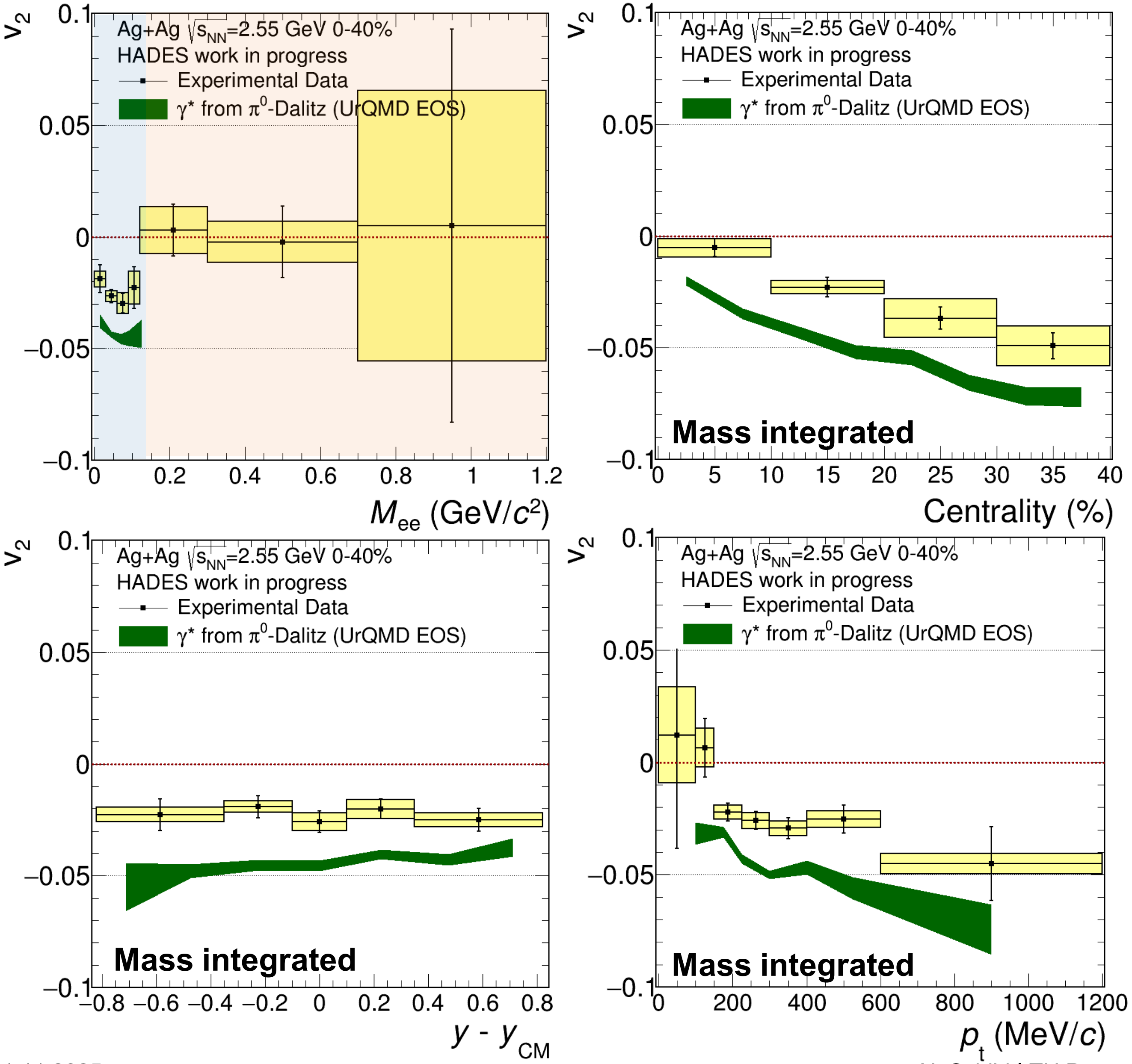

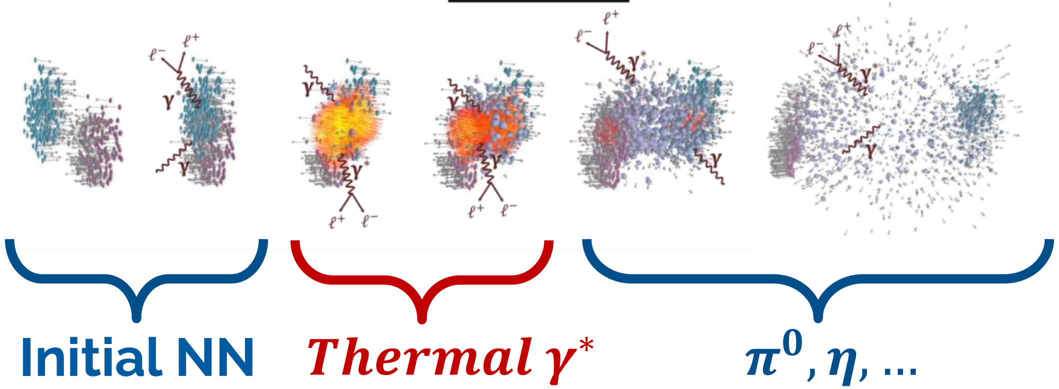

Measured signal is integral over whole evolution

- Need precise flow measurements of freeze-out sources (π^0, η)
- Model used to estimate $v_2^{\pi^0/\eta}$

➡ Serves as a baseline to understand observed behavior

➡ Helps to disentangle the various dielectron contributions

ELLITPIC FLOW BY MASS RANGES

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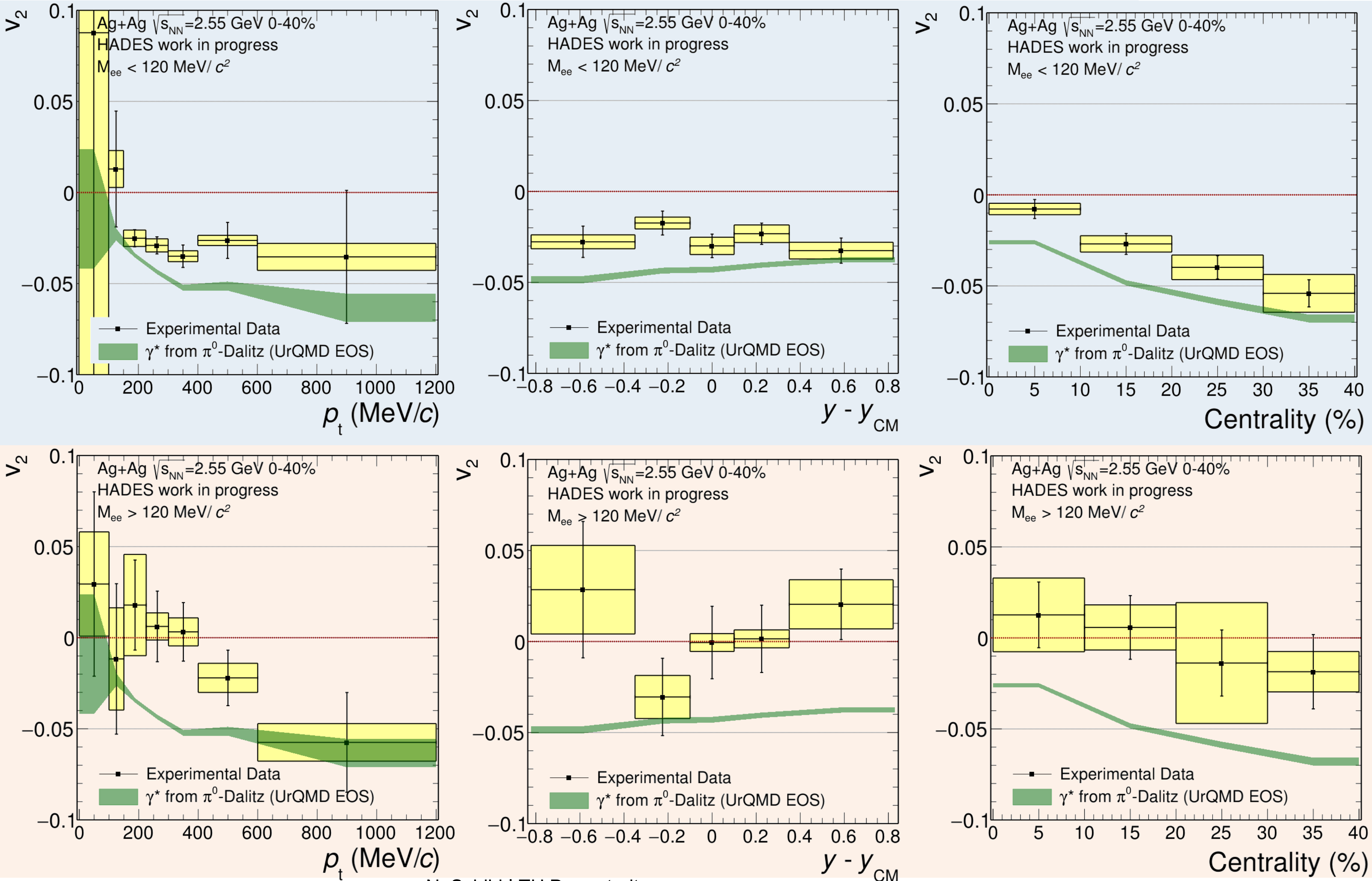
M_{ee} < 0.12 GeV/c^2

Dominated by π^0-Dalitz decay

M_{ee} > 0.12 GeV/c^2

Dominated by thermal radiation



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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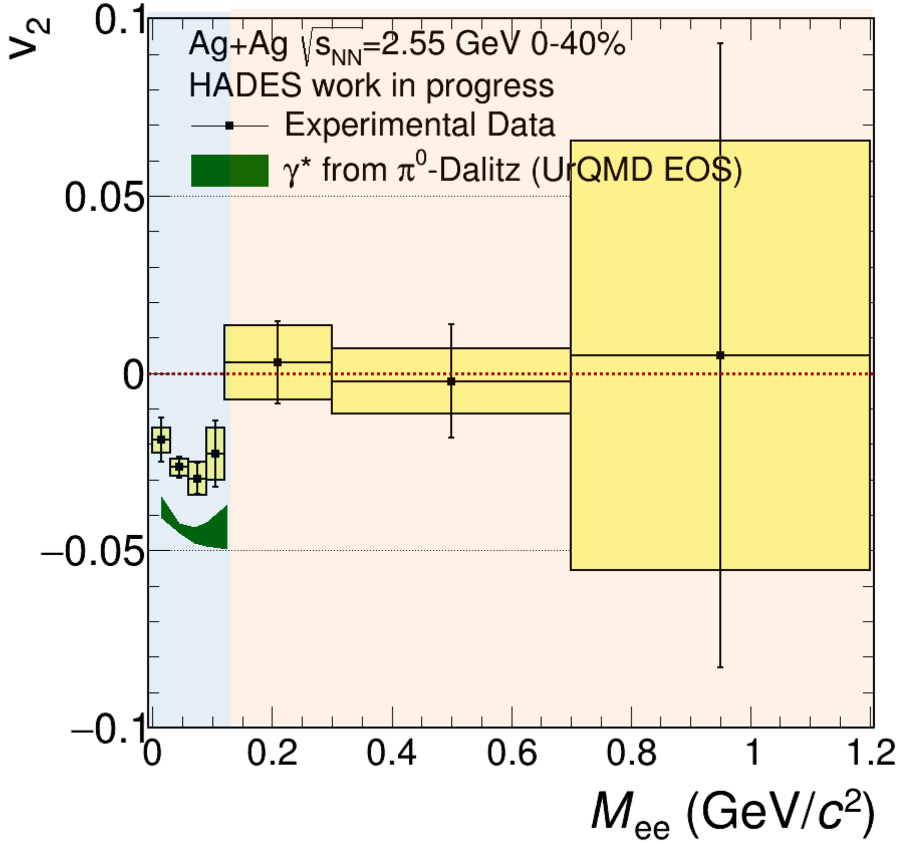
HADES

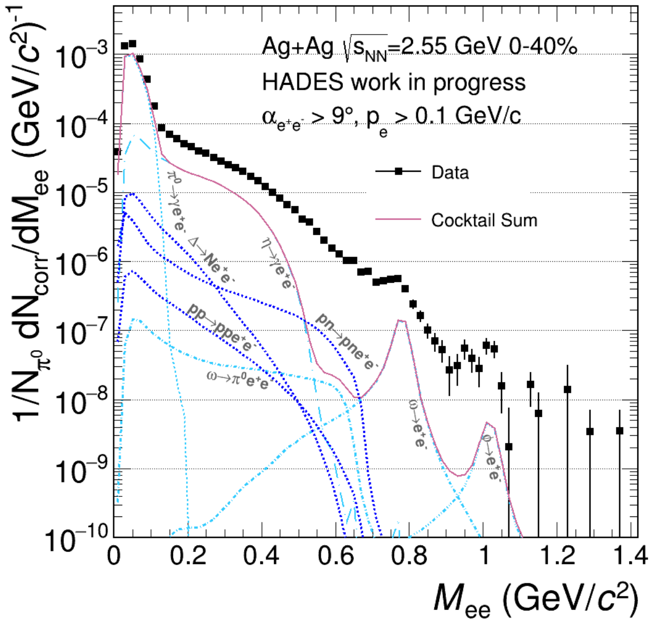
Flow + Yields → Isolated Flow

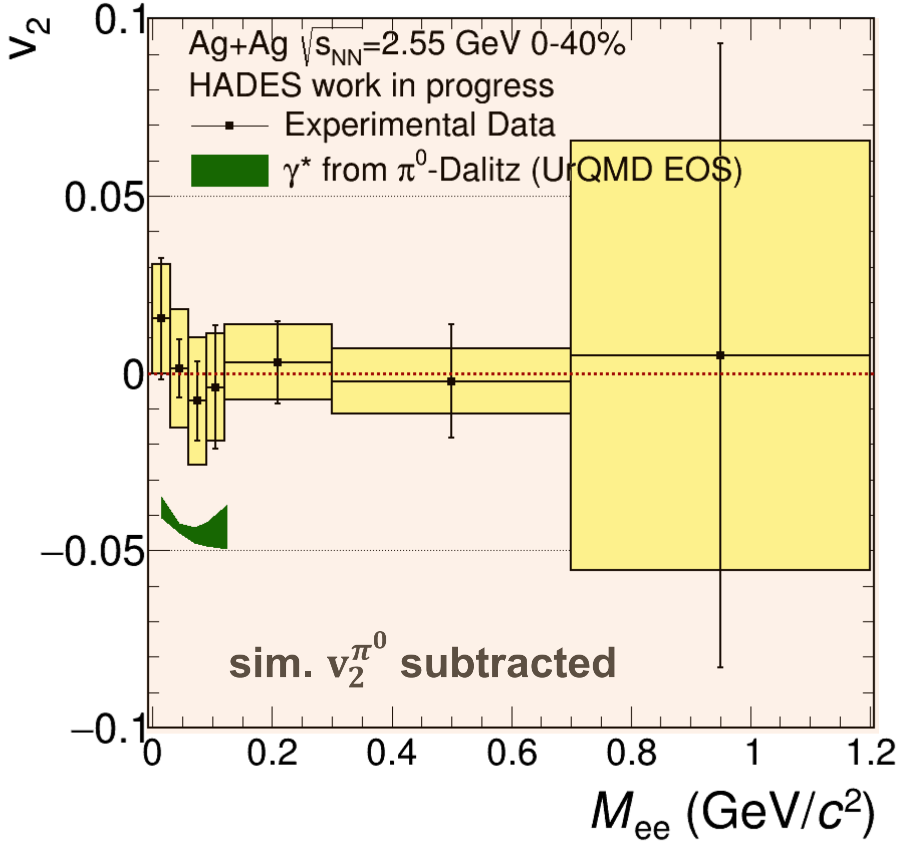
Take v_2 from UrQMD

Take yields from cocktail estimation

Resulting isolated v_2 moves towards positive values



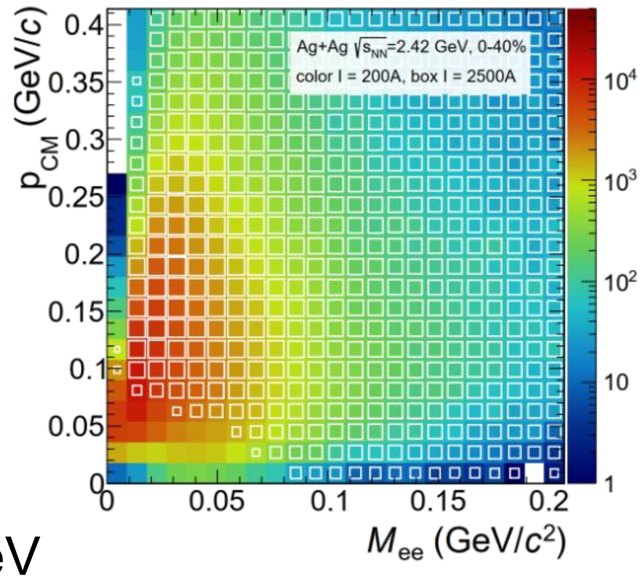




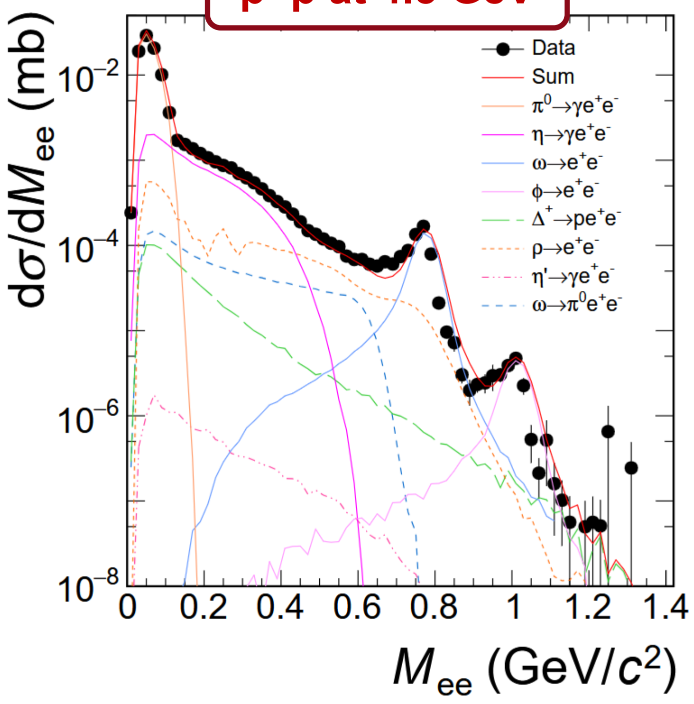
PERSPECTIVES

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

➡ Gain insights into the electrical conductivity



p+p at 4.5 GeV



- High-statistics **p+p measurement** at 4.5 GeV

➡ Allows for multi-differential studies of production mechanisms

➡ Can serve as reference for future measurement at CBM

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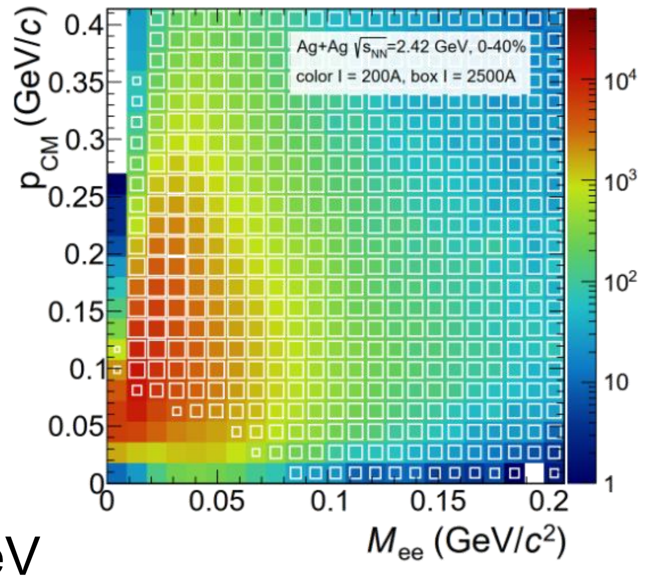

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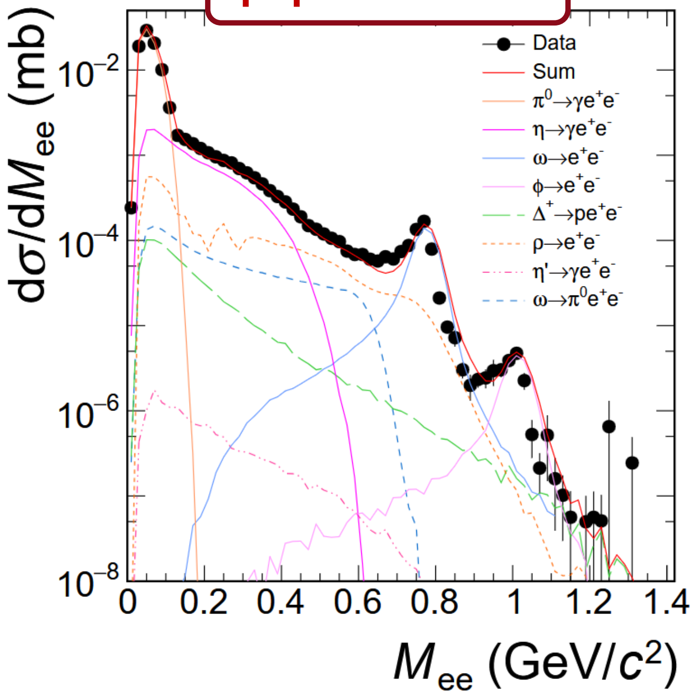


- High-statistics **p+p measurement** at 4.5 GeV

➡ Allows for multi-differential studies of production mechanisms

➡ Can serve as reference for future measurement at CBM

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

SUMMARY

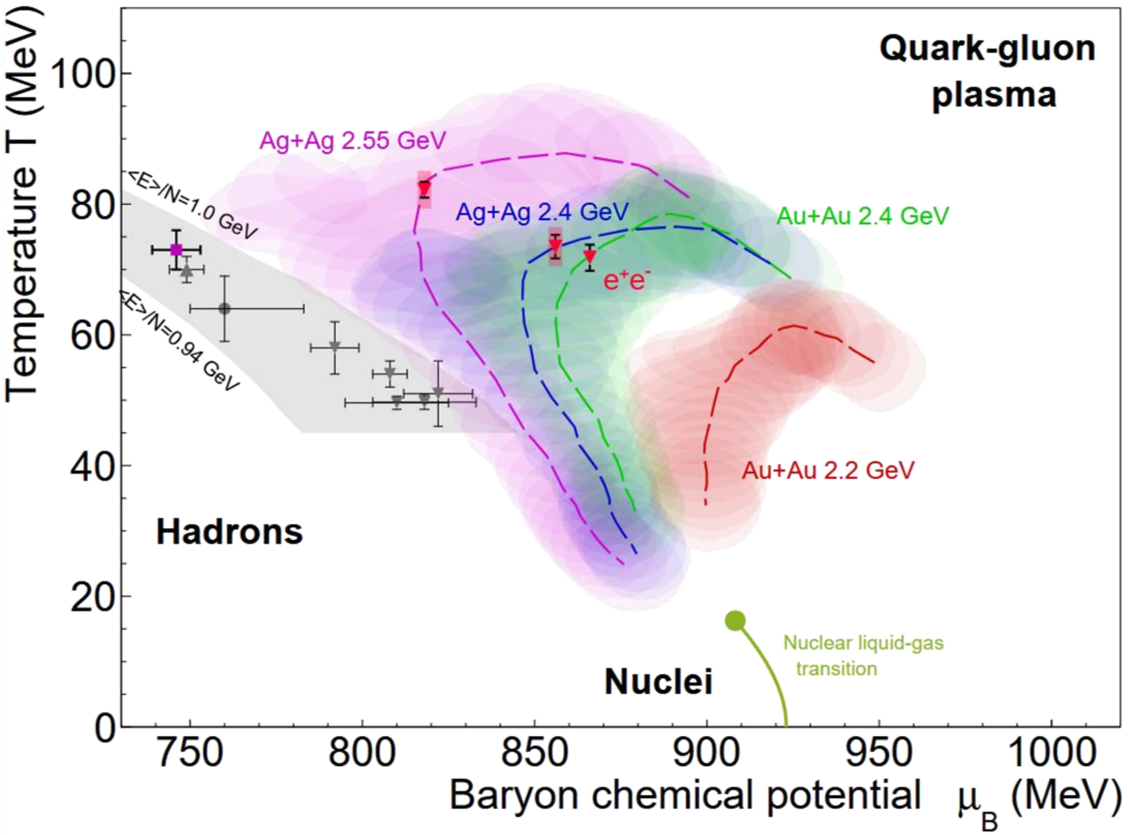
Dileptons bring unique measurement possiblities to various observalbes

- Establish **thermal nature** of the radiation

➡ Characterise the hot and dense fireball

- Collectivity measurements in terms of **anisotropic flow**

➡ Probe the time evolution of the system



FO curve: J. Cleymans, K. Redlich, Nucl. Phys. A 661 (1999) 379
Au+Au 2.4 GeV data: HADES, Nature Phys. 15(2019) 1040
Eur.Phys.J.A 52 (2016) 5, 131
Phys.Rev.C 106 (2022) 1, 014904
Ag+Ag data: HADES preliminary
figure: F.Seck, T.Galatyuk

- Promising **perspectives** with new studies and new data

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