# Highlights from the HADES experiment

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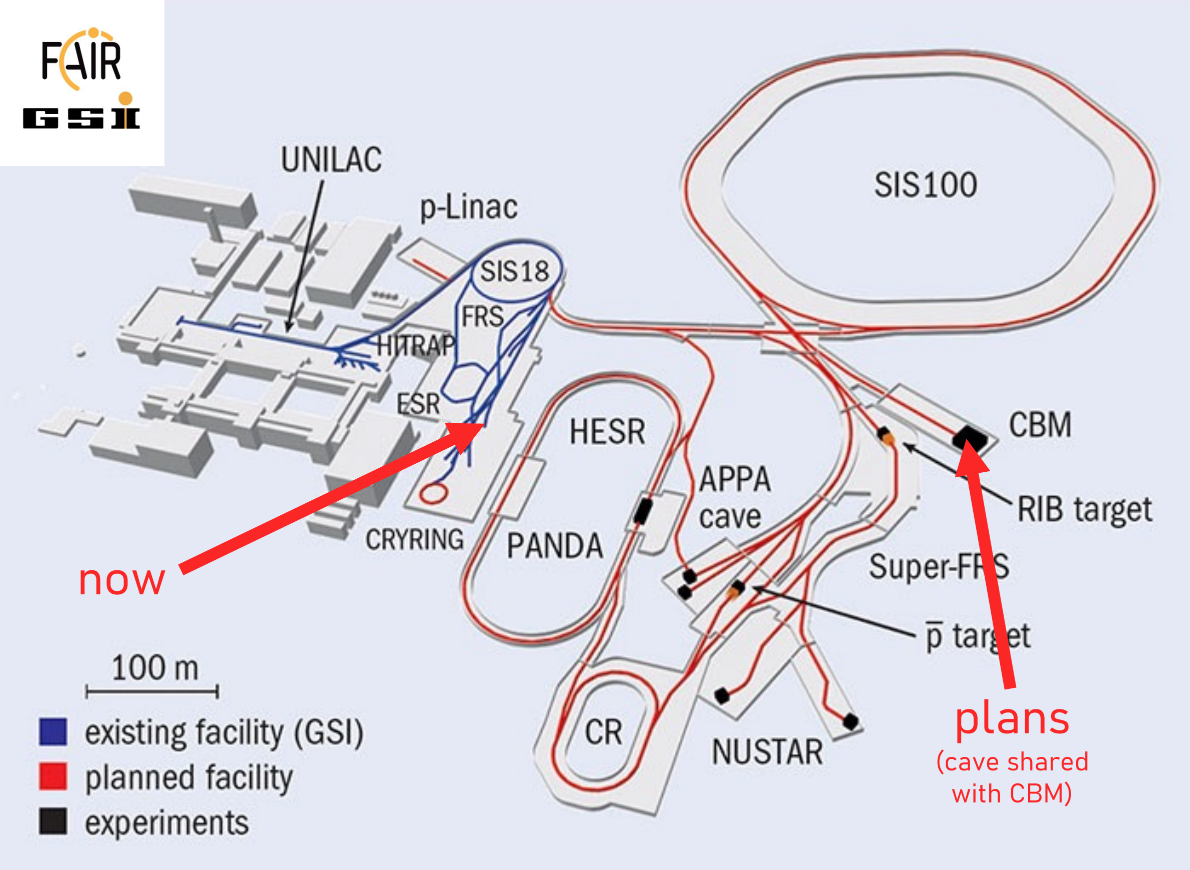
for the HADES collaboration


FAIR GSI HADES TECHNISCHE UNIVERSITÄT DARMSTADT

# On behalf of the HADES Collaboration

~170 members
~26 institutions
~10 countries

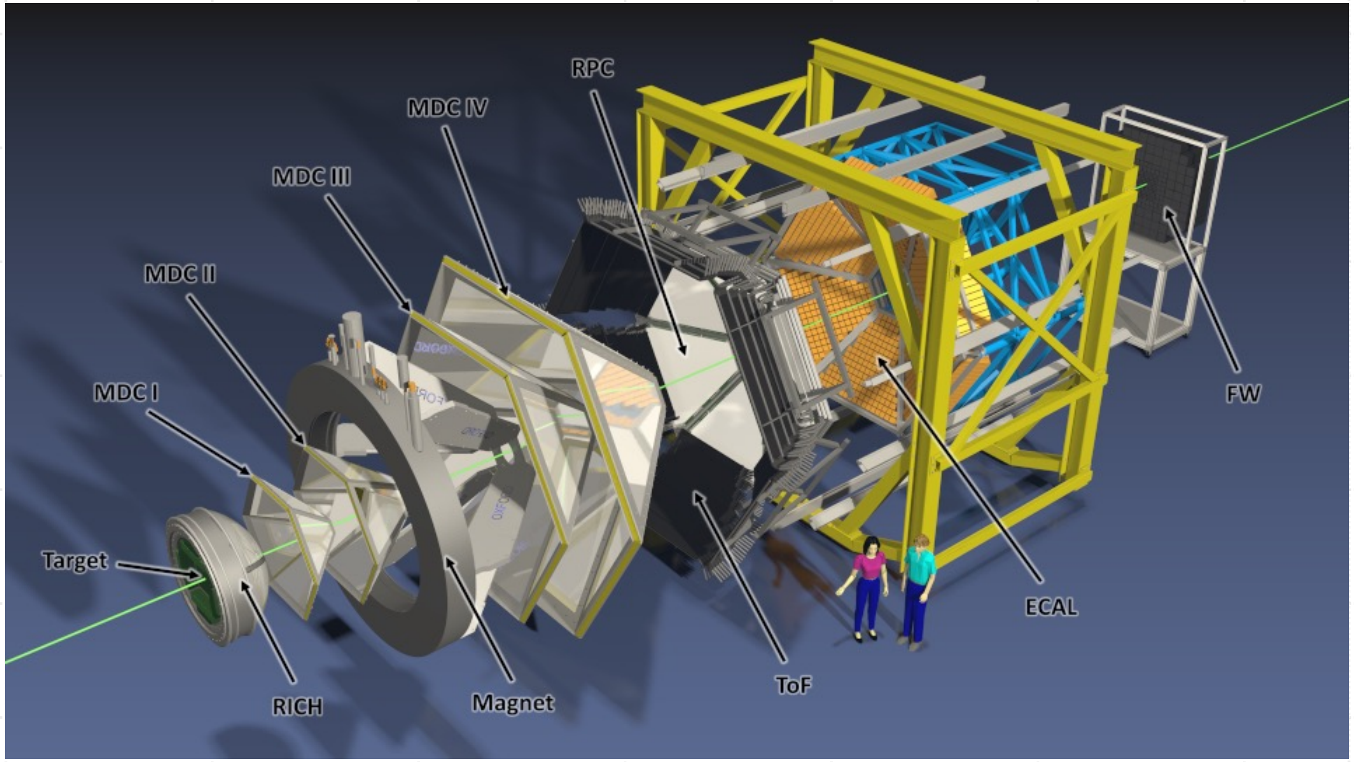
# Space-time coordinates




- **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** $\pi^-$ + 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

# High Acceptance Di-Electron Spectrometer

- Fixed target setup
  - Higher interaction probability than in the collider mode
  - Challenges: δ rays, γ conversion, interactions of beam with the surrounding material
- Accepance
  - Full in the azimulhal angle
  - From 18° to 85° in the polar angle: adjusted for good coverage around mid-rapidity



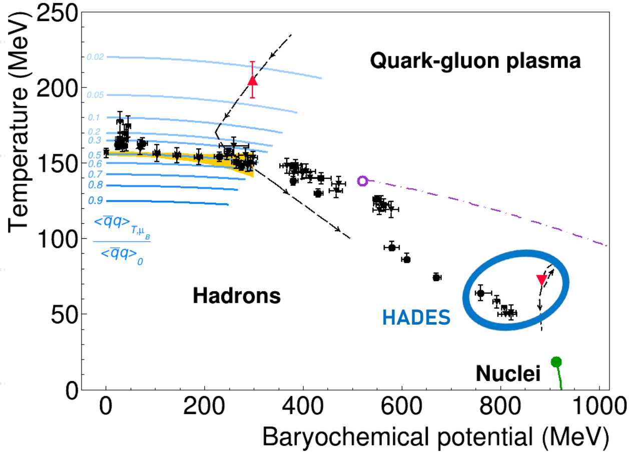

New detectors installed since 2019:

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

# Two-fold physics goal

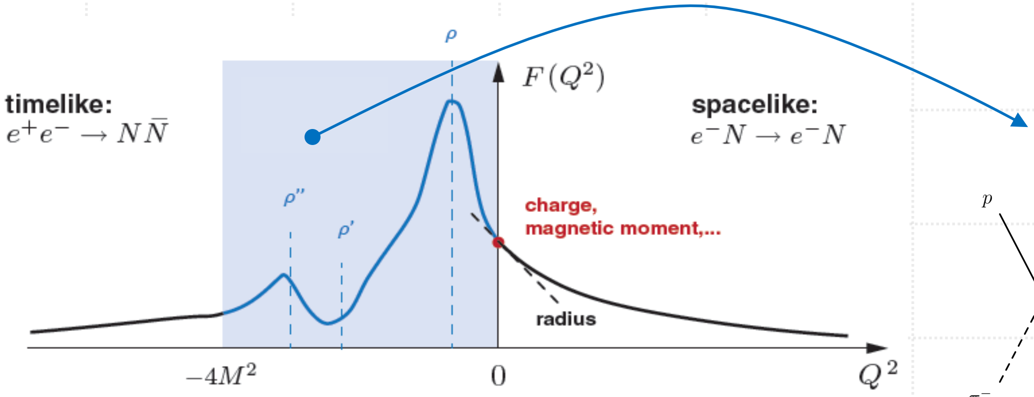
Not fully clear how it was in the Antiquity, but the modern era imagines Hades holding a ***bident***

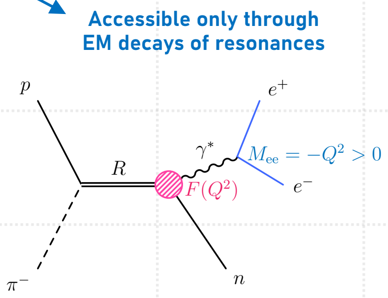
Hades (Pluto). From a Statue in the Vatican.




**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:**

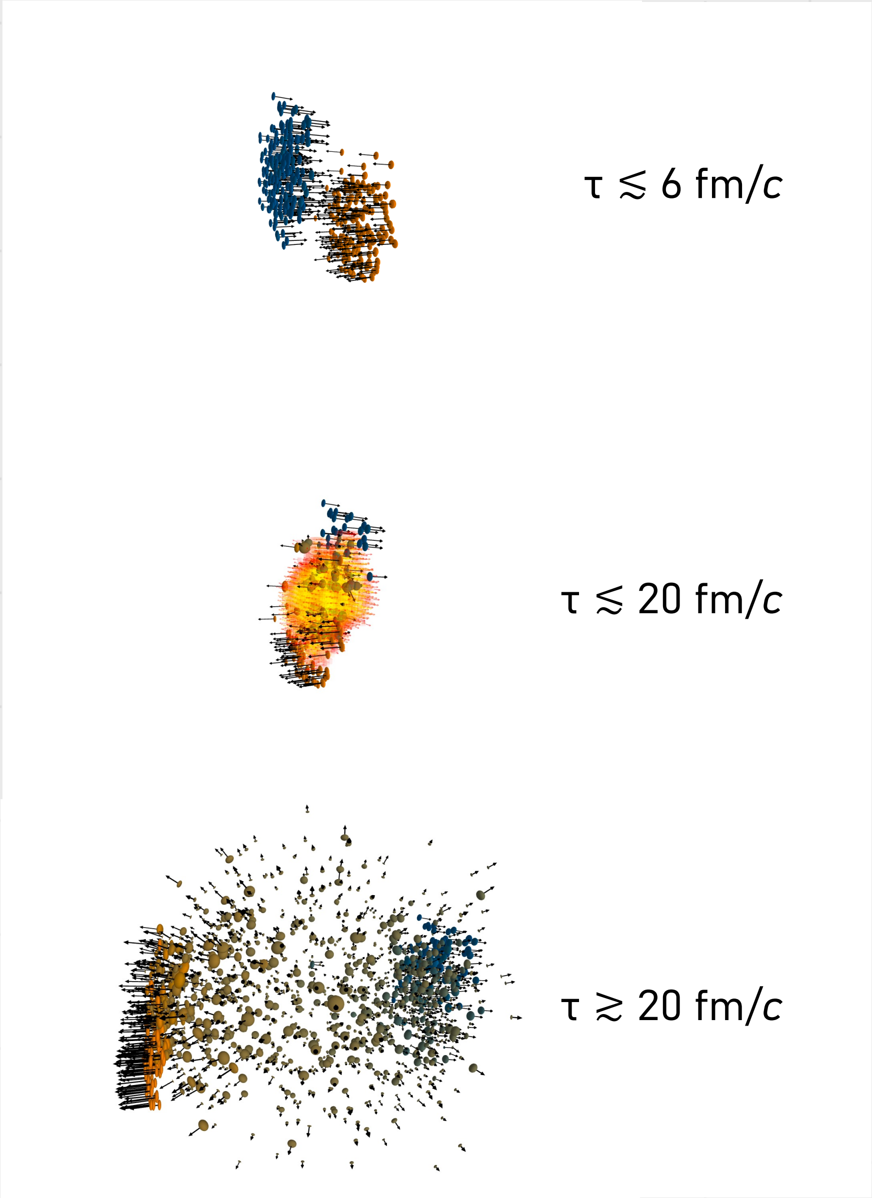
- Reference measurements (vacuum, cold QCD matter)
- Electromagnetic structure of baryons and hyperons

# Contents

- Electromagnetic probes
  - Spectra
  - Azimuthal anisotropy
- Hadrons
  - Influence of the final-state EM interaction
  - Azimuthal anisotropy
  - Global spin polarization
- Strangeness
  - Lifetime of hypernuclei
  - Multiplicities
- Spectra of correlated pion-proton pairs

# Electromagnetic probes

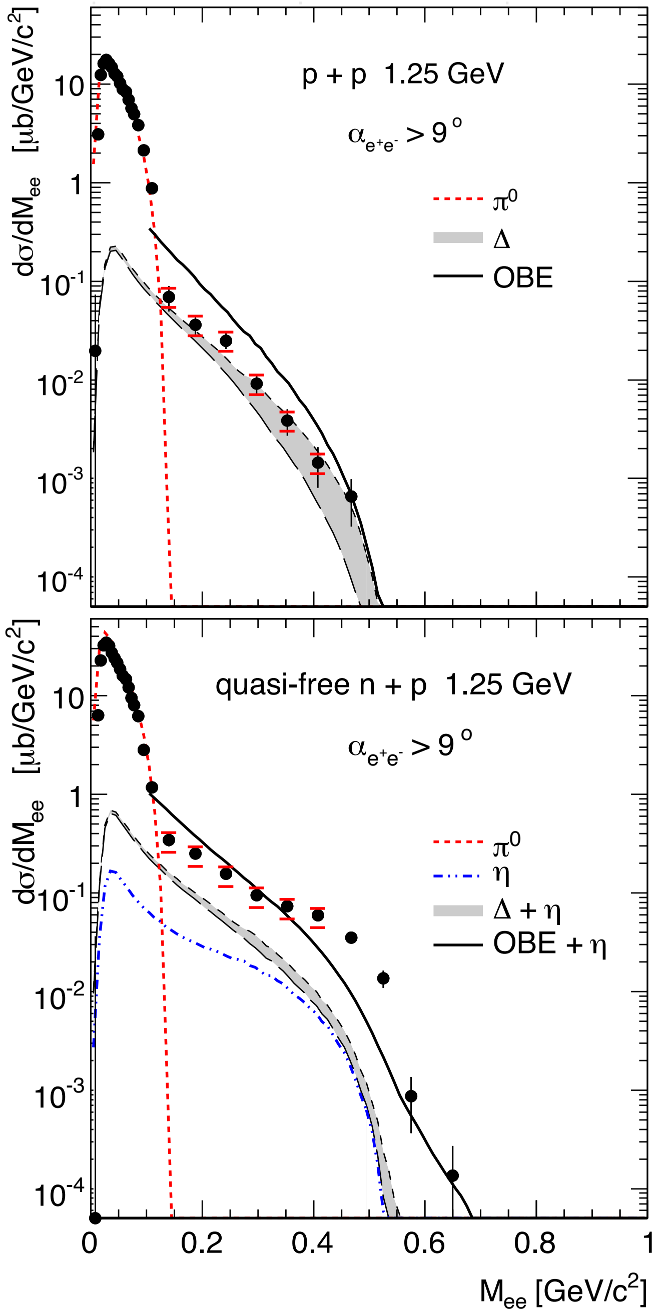
- Photons (virtual and real):
  - Don’t undergo strong interaction
  - Probe all the stages of heavy-ion collisions
- Radiation from hot and dense matter is isolated by subtracting:
  - First-chance NN collisions
  - Meson decays at the freeze-out



# Constraining the pre-equilibrium contribution

- Equivalent to (properly normalized) collisions of single nucleons or not-too-heavy ions
- Can be:
  - Directly measured
  - Simulated
- For $\sqrt{s_{NN}} = 2.42$ GeV we have well established data from 2006 and 2007
- For $\sqrt{s_{NN}} = 2.55$ GeV a dedicated measurement during the Feb 2022 beam time

HADES Collab., PRC **95**, 065205 (2017)
HADES Collab., PLB **690**, 118 (2010), EPJA **53**, 149 (2017)

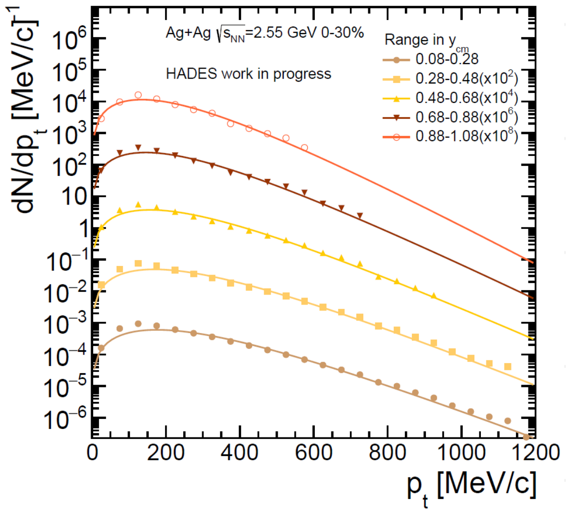


# Constraining the freeze-out contribution

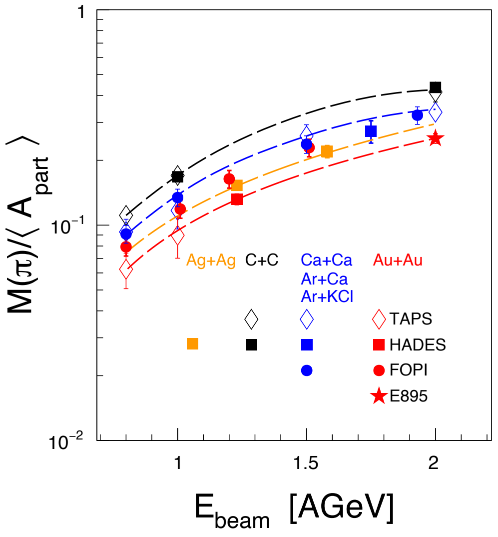
Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV
0-30% centrality

- Photon conversion method:
  $\pi^0 / \eta \rightarrow \gamma\gamma \rightarrow e^+e^- e^+e^-$
- Electromagnetic calorimeter:
  $\pi^0 / \eta \rightarrow \gamma\gamma$
- Isospin symmetry:
  $N(\pi^0) \cong 0.5\ (\ N(\pi^+) + N(\pi^-)\ )$
- Hadron multiplicity:
  $\phi \rightarrow K^+K^-$
- Cross-section from the spectra:
  $\omega \rightarrow e^+e^-$

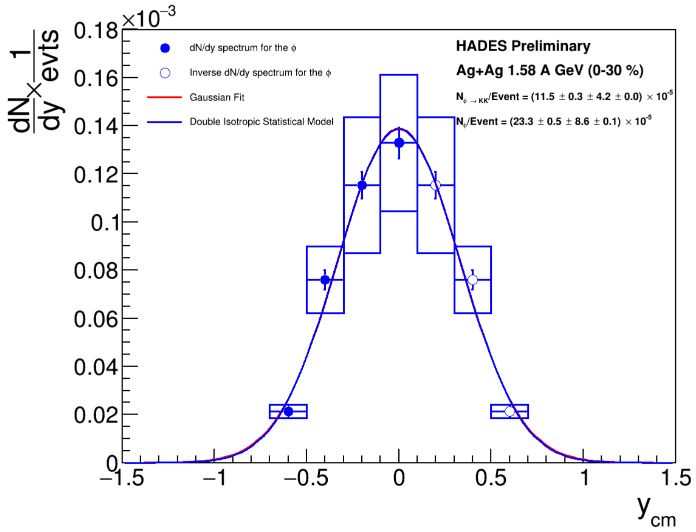
π




**Alexandr Prozorov, poster, session 1 T14_1 (Wed)**

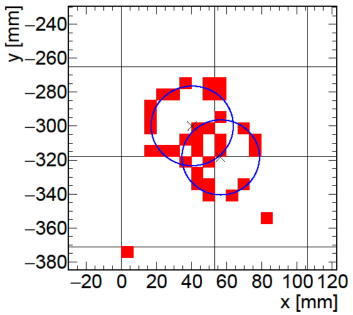



ϕ

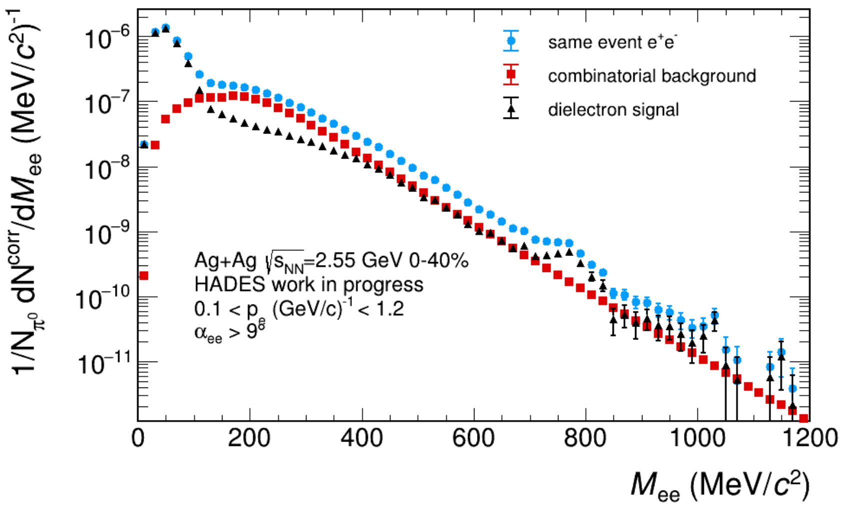


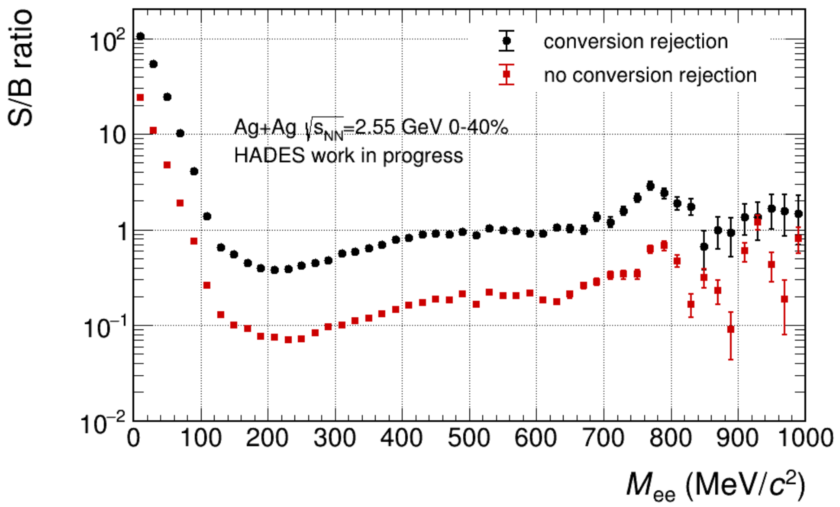

**Simon Spies, talk, Thu 16:50**

# Dilepton reconstruction performance




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



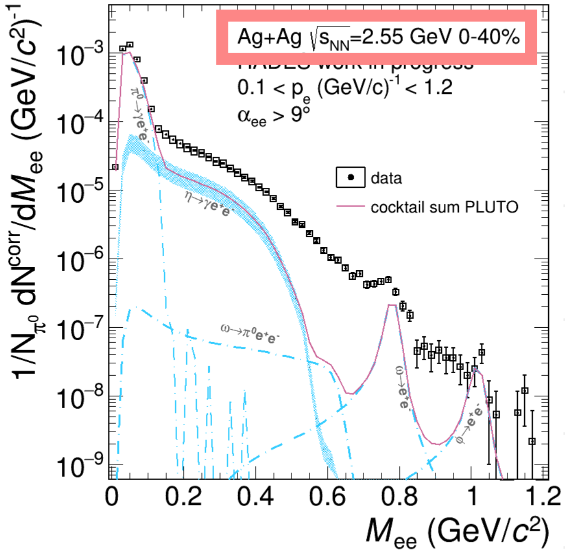

- Very large statisics due to high detection efficiency
- Suppressing γ conversion
  - Only very small mass
  - Produces combinatorial background at all masses

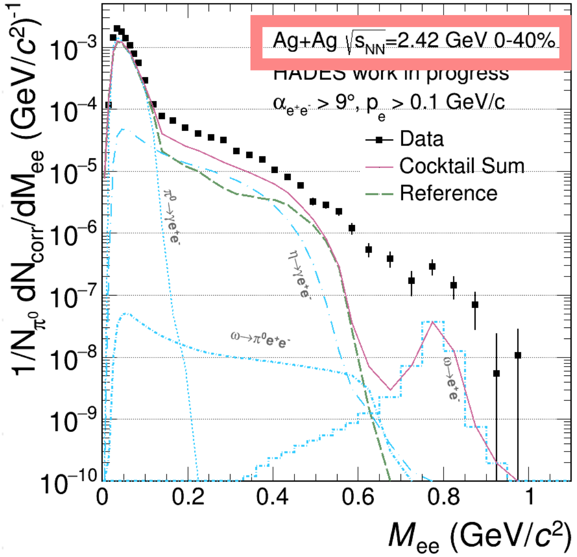


**Jan-Hendrik Otto, talk, Thu 18:50**

# 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")

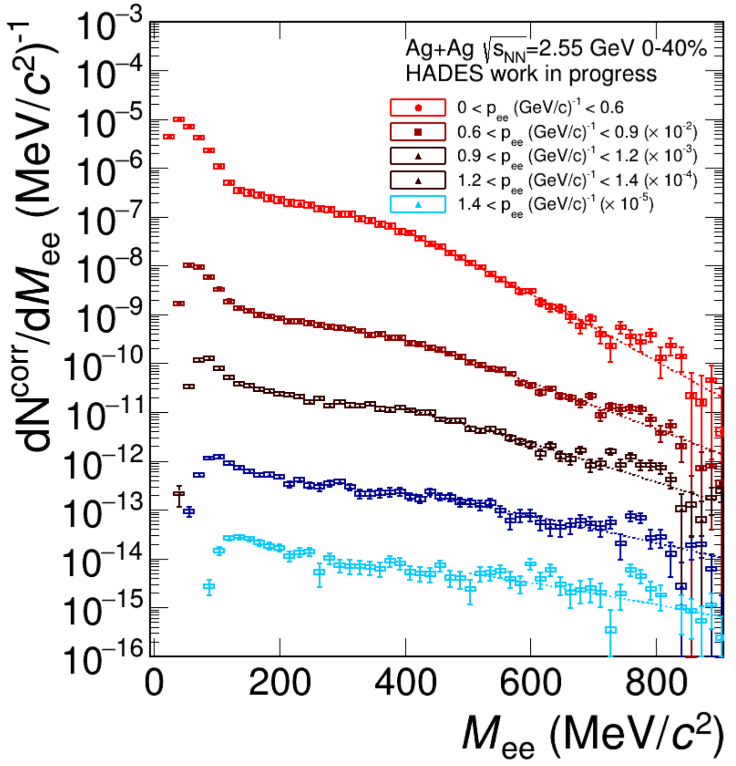
**Ag+Ag at $\sqrt{s_{NN}} = 2.42$ GeV**

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

**Jan-Hendrik Otto, talk, Thu 18:50**
**Niklas Schild, poster, session 2 T05 / T13 (Wed)**

# Momentum-dependent dilepton spectra

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



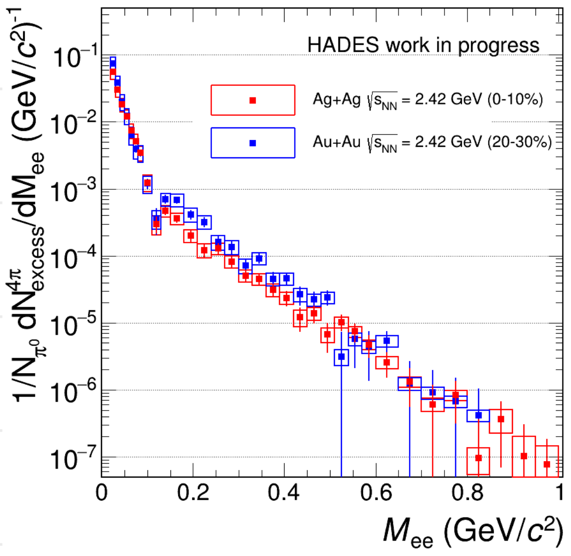

- Possibility for multi-differential analysis
- ω meson clearly visible at high momentum
- “Disappears” at lower momentum:
  - Overwhelmed by the ρ contribution?
  - Broadened by medium effects?
  - Dedicated theory calculations needed to study the effect



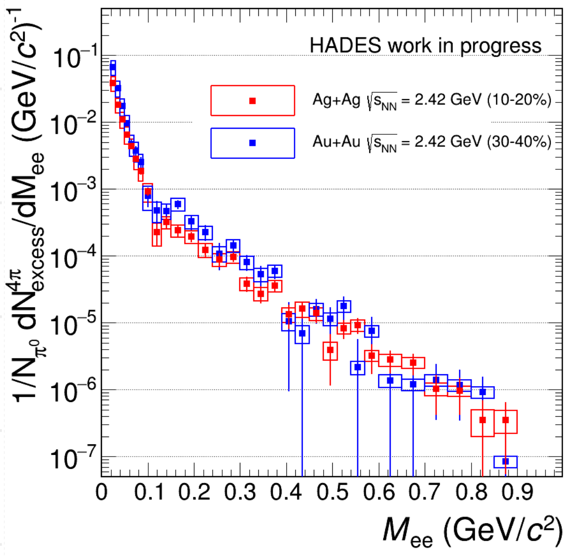
**Jan-Hendrik Otto, talk, Thu 18:50**

# System size dependence of dilepton production

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




Comparable $\langle A_{part} \rangle$




Comparable $\langle A_{part} \rangle$

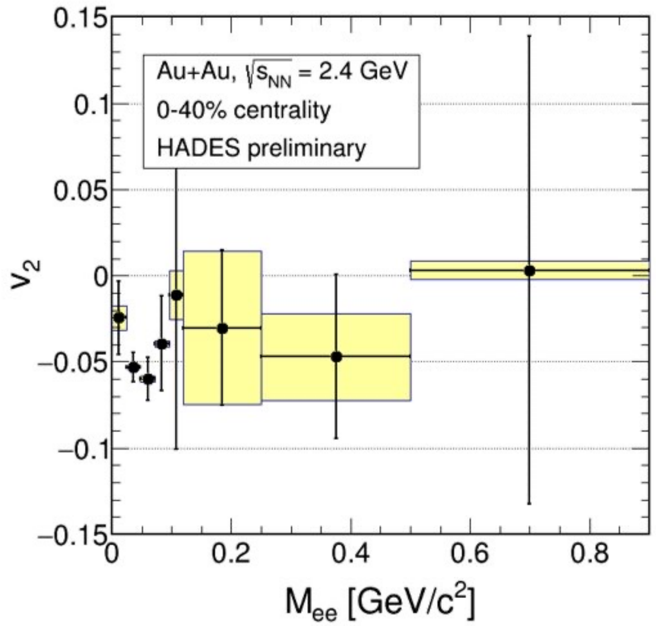
- Same collision energy
- Pairs of centrality classes with similar participant numbers
- Possibility to isolate the system size dependence

**Niklas Schild, poster, session 2 T05 / T13 (Wed)**

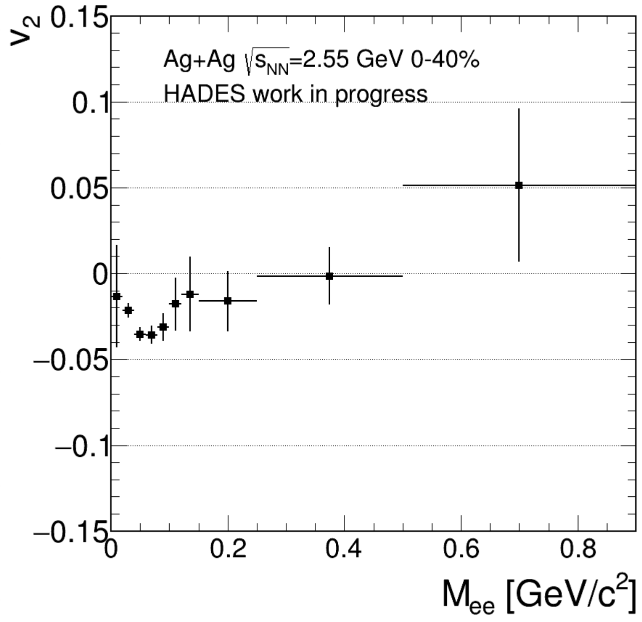
# Dilepton azimuthal anisotropy

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

Au+Au (QM 2019)




Ag+Ag (new)



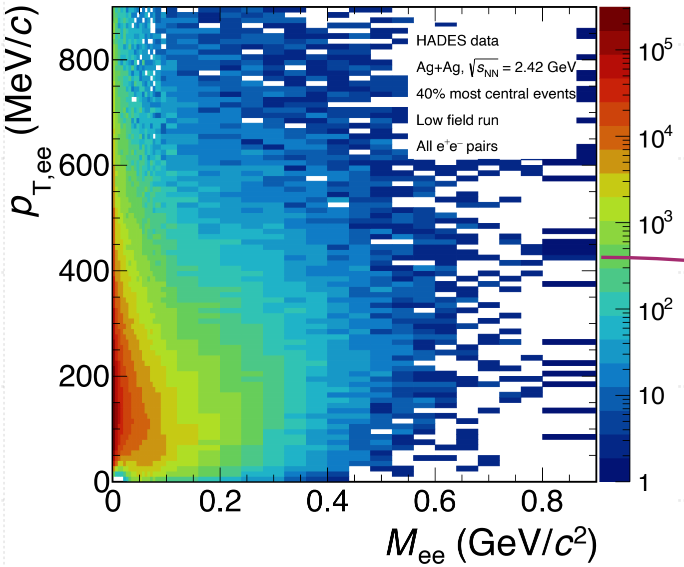

- In the region below 0.14 GeV/$c^2$ dominated by $\pi^0$ Dalitz decay
  - Consistent with charged pion results
- At higher mass $v_2$ consistent with 0
  - Confirms dileptons as penetrating probes of hot and dense medium

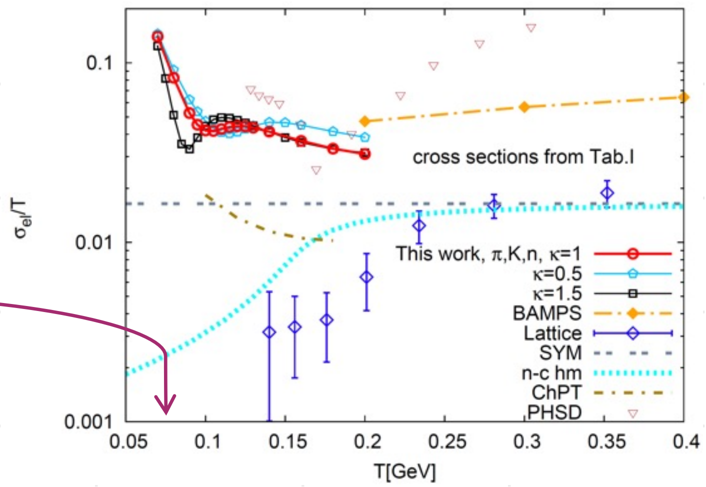


**Niklas Schild, poster, session 2 T05 / T13 (Wed)**

# Dilepton perspectives: extracting electrical conductivity

Existing 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)

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

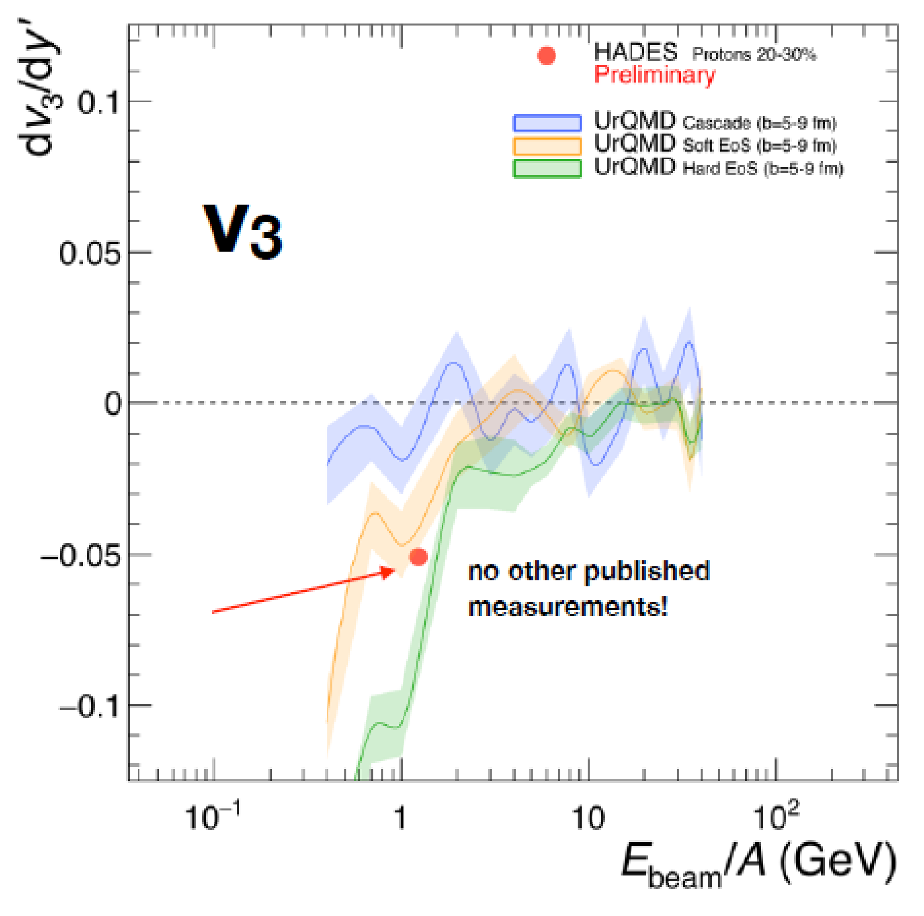
Spectral function

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

# Hadron production and collectivity

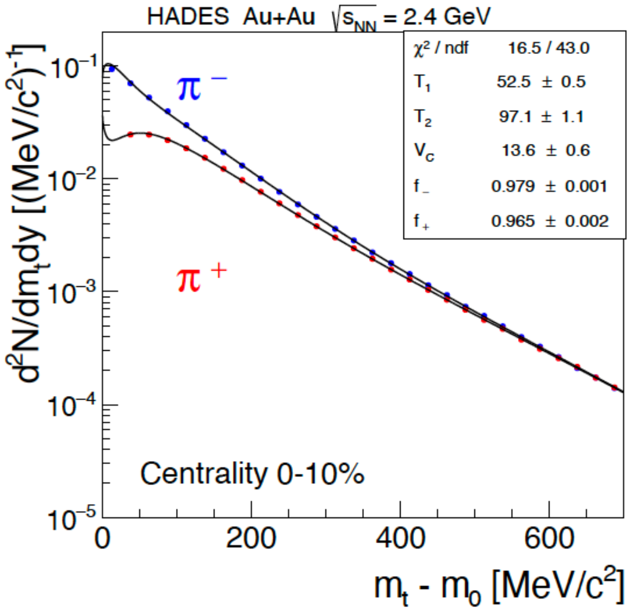
**Sensitivity to:**

- QCD equation of state
- Nuclear symmetry energy [$v_2(y_{cm})$ for protons]
  Y. Wang *et al.*, PLB 802 (2020) 135249

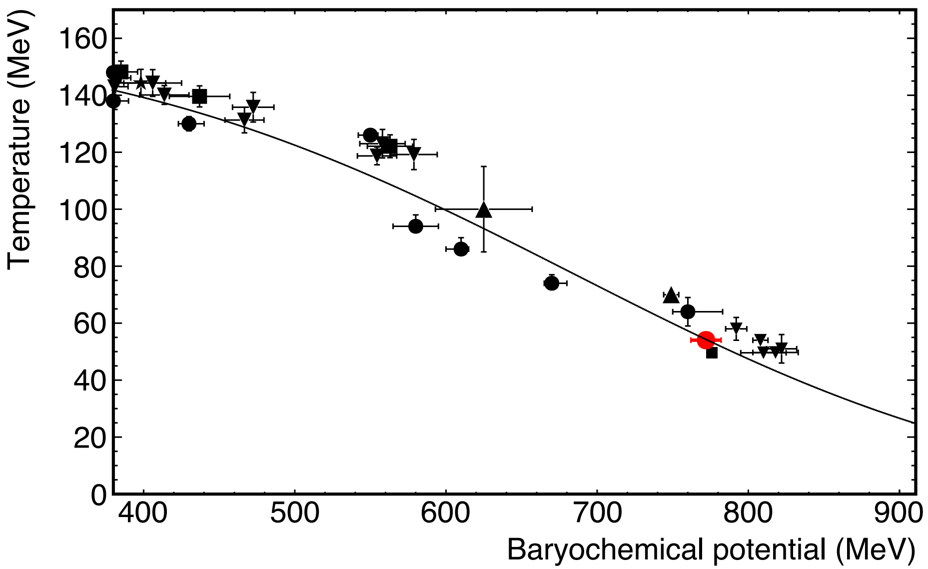


# Shift of the pion energy by the Coulomb potential

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV
0-10% centrality




HADES Collaboration, arXiv:2202.12750

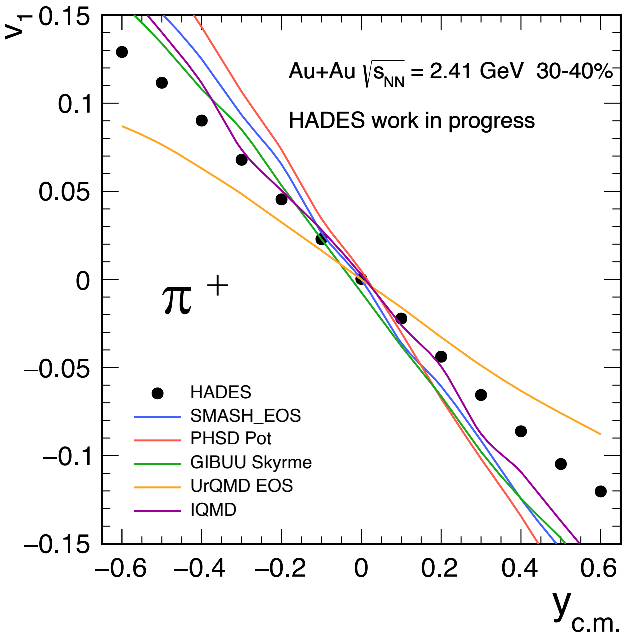


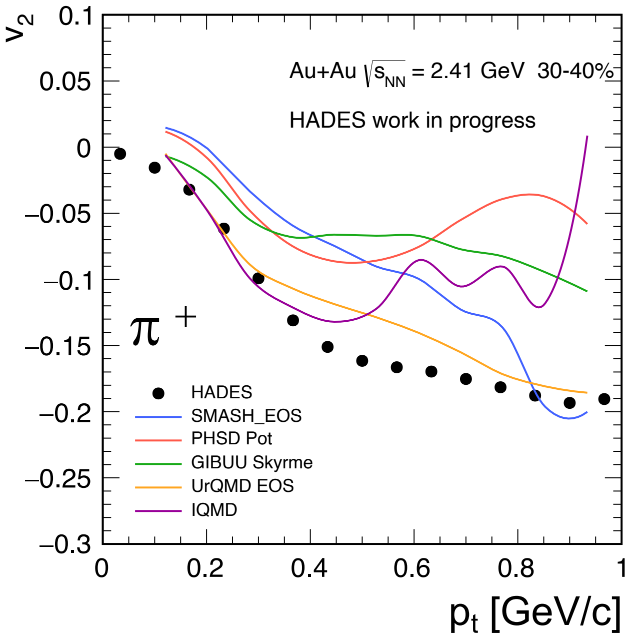

Black data points, SHM fits:
Nature **561** no.7723, 321-330 (2018), also the black curve
PLB **764**, 241-246 (2017)
PRC **73**, 034905 (2006)
PRC **96**, 044904 (2017)
PRC **76**, 052203 (2007)
EPJA **52** no.6, 178 (2016)

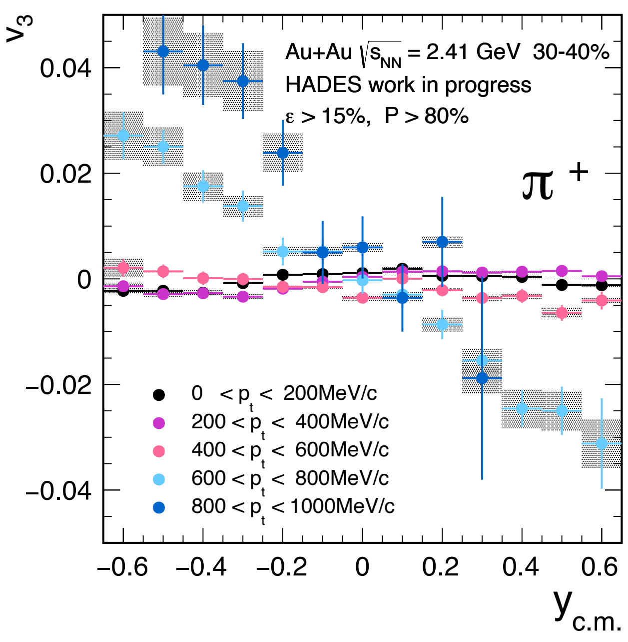
- More accurate extrapolation to low $p_t/m_t$
- Extracting the average value of the Coulomb potential energy
  - Improved formalism compared to previous works
- Translating it to the fireball size at the freeze-out → density → $\mu_B$
  - Method independent from SHM fits
  - Result in good agreement

# Pion anisotropy in Au+Au

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV
30-40% centrality



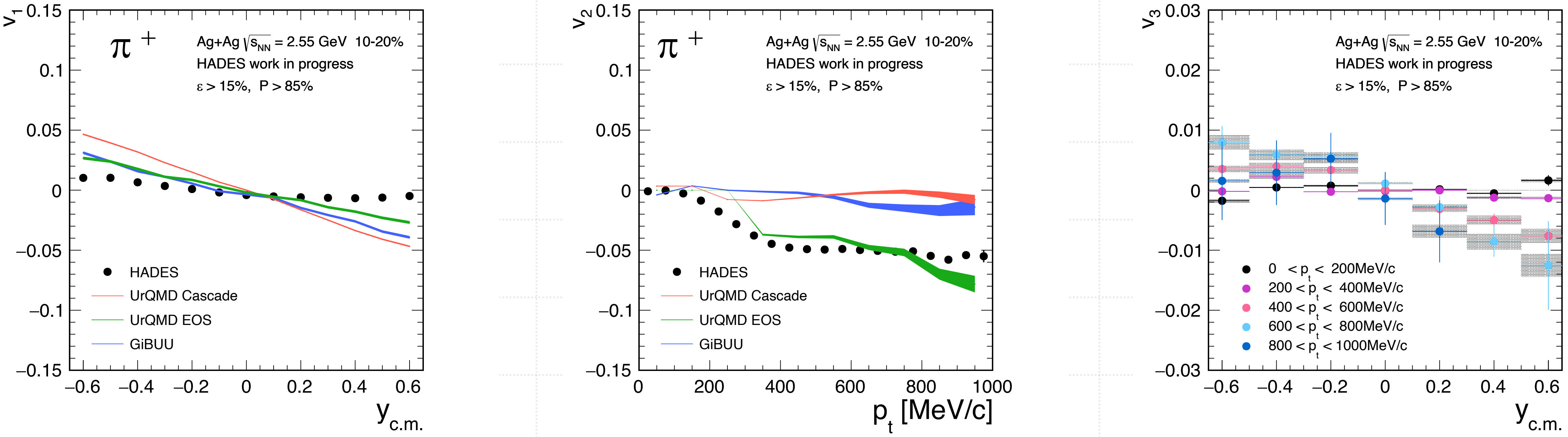




- Good statistics to constrain models and equation of state
- There is room for improvement in the models

# Pion anisotropy in Ag+Ag

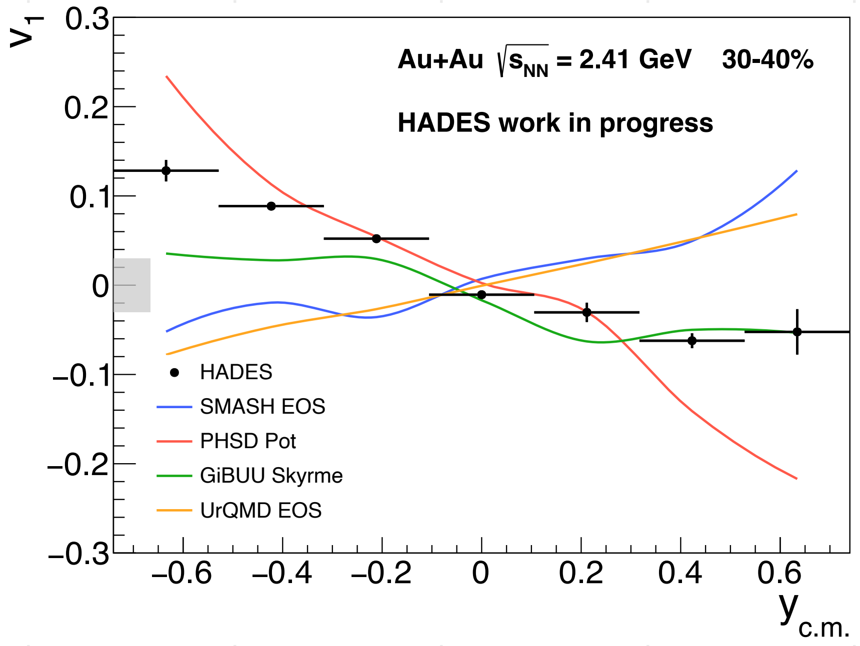
Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV
10-20% centrality

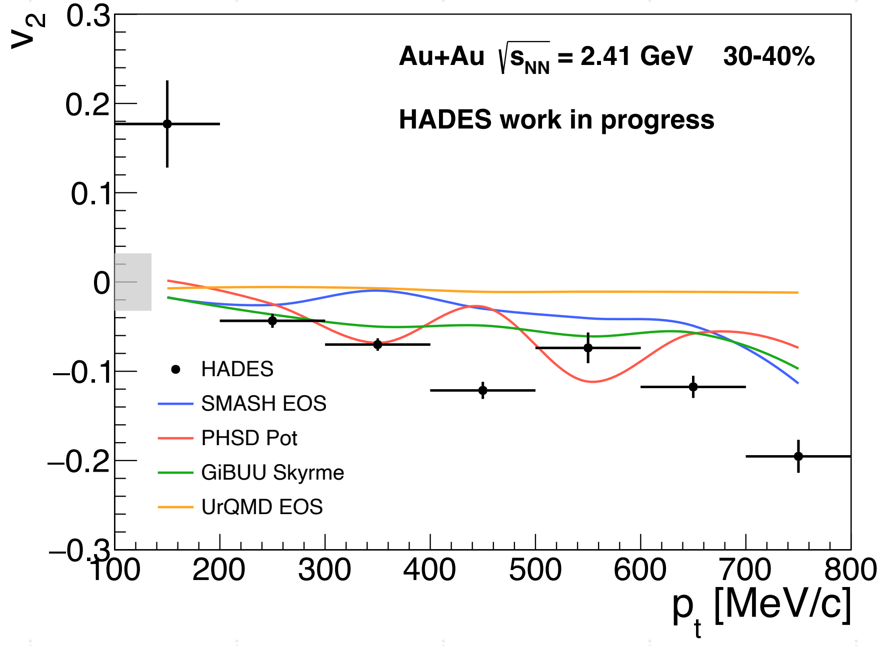



- Good statistics to constrain models and equation of state
- There is room for improvement in the models
- Energy and system size dependence allows for more global study

# Kaon anisotropy in Au+Au

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV
30-40% centrality




- Good statistics to constrain models and equation of state
- There is room for improvement in the modeling

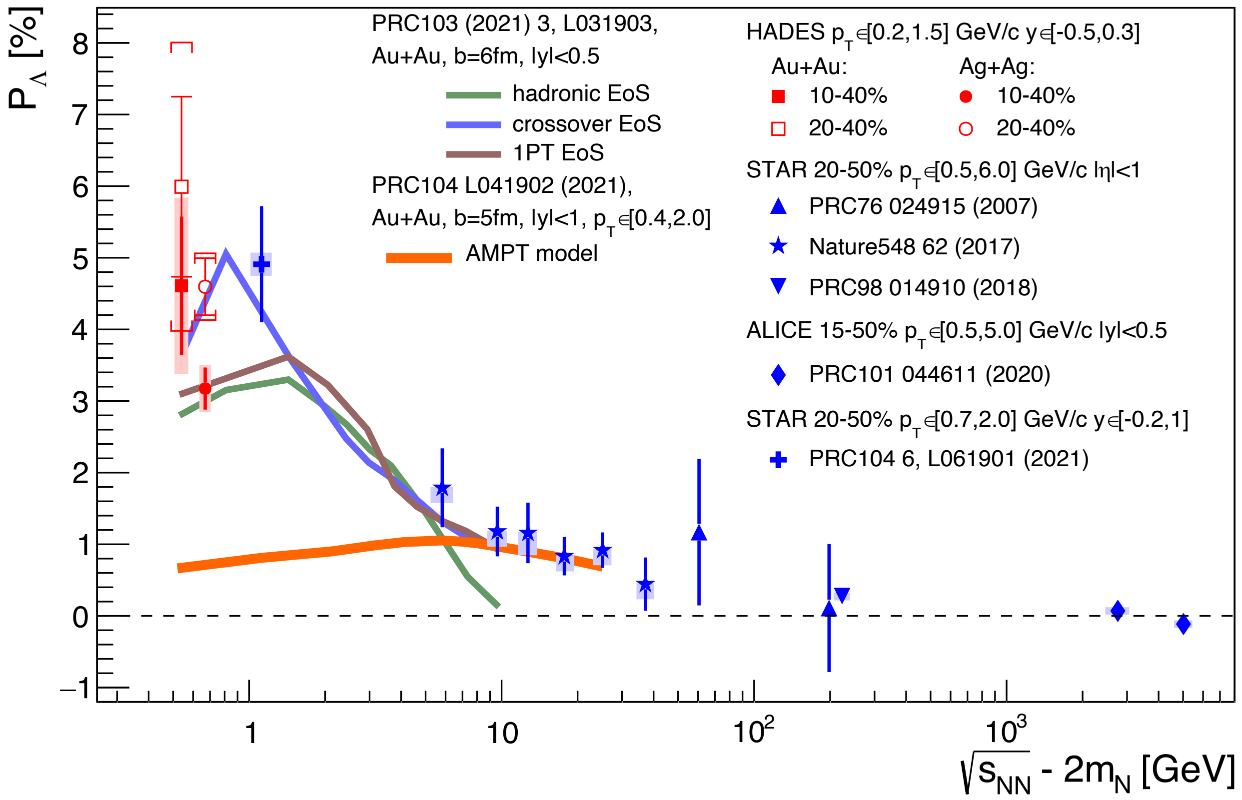
**Lukáš Chlad, poster, session 2 T14_1 (Wed)**

# Global spin polarization

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV
Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV
Various centralities

- First observed at RHIC: "most vortical fluid"
- What is the mechanism of converting $\vec{L}$ to $\vec{S}$?
- Now: thorough systematics study and support from Ag+Ag data
- Note that $|\vec{L}|$ is substantially lower in Ag+Ag than in Au+Au:

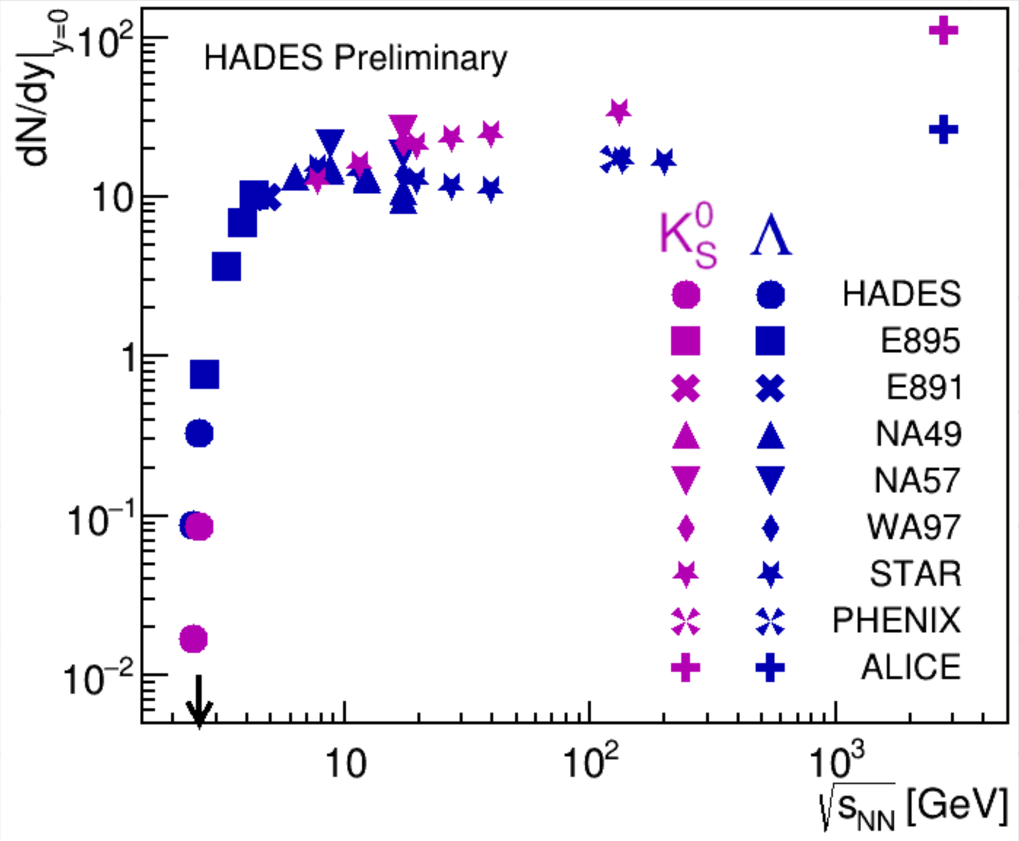
$$L_y \approx \frac{1}{2} Ab \sqrt{s} \sqrt{1 - (2M/\sqrt{s})^2}$$



Data compilation: C. Blume, C. Markert, Progr.Part.Nucl.Phys. 66 (2011) 834-879

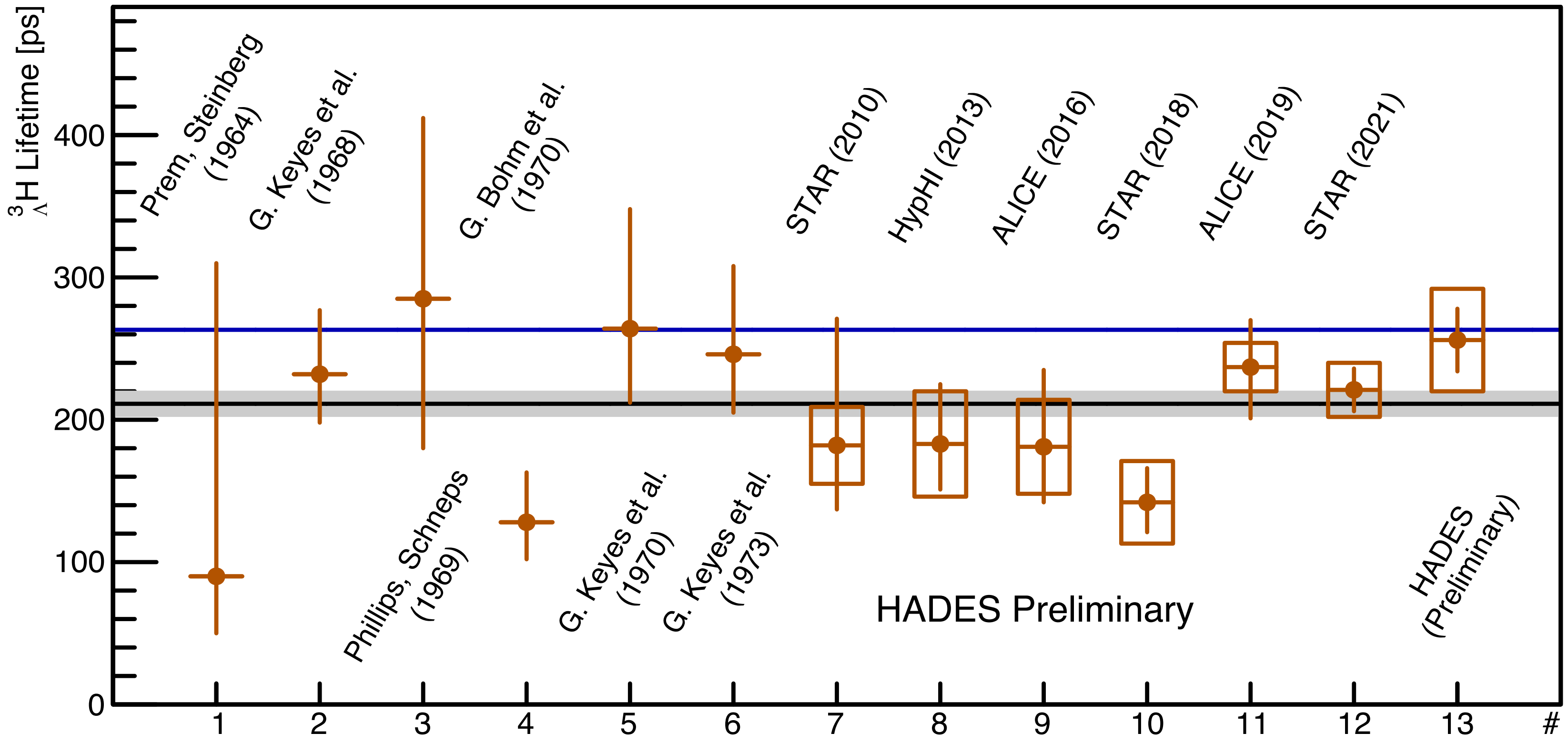
# Strangeness

- SIS18 collision energies around the strangeness production threshold
- Strange quark mass comparable to the expected temperature: “heavy flavor”



# Hypernuclei lifetime

Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV
0-30% centrality



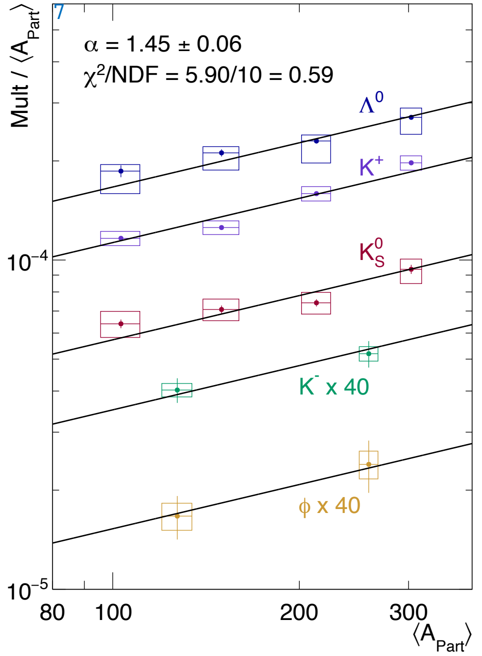

**Simon Spies, talk, Thu 16:50**

# System with Multi-Particle Correlations?

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV
Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV
Various centralities

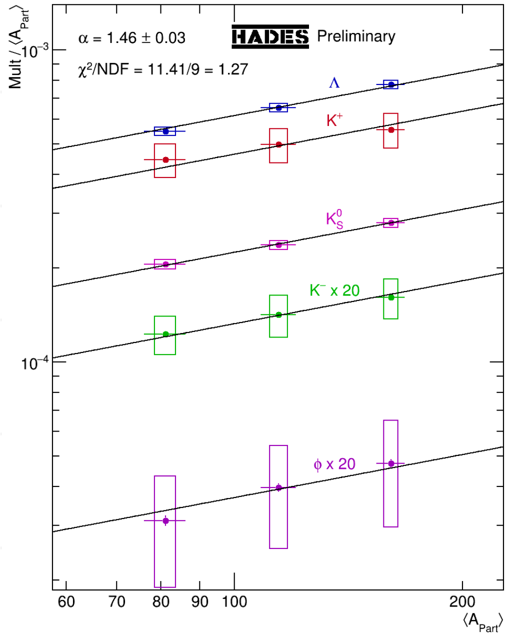
Au+Au

HADES Collaboration, PLB 793 (2019) 457
https://www.hepdata.net/record/ins1707




Ag+Ag

**Simon Spies, talk, Thu 16:50**




- Different particles
- Different production mechanisms
- Different thresholds

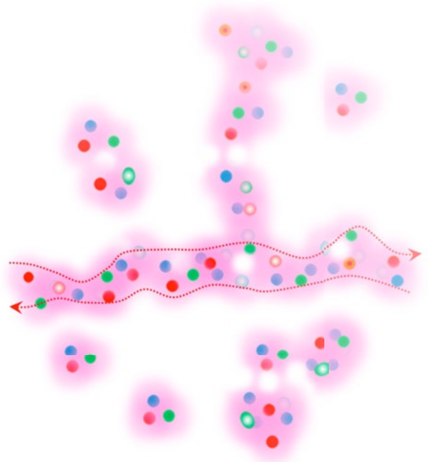
**but**

- Common scaling with participant number

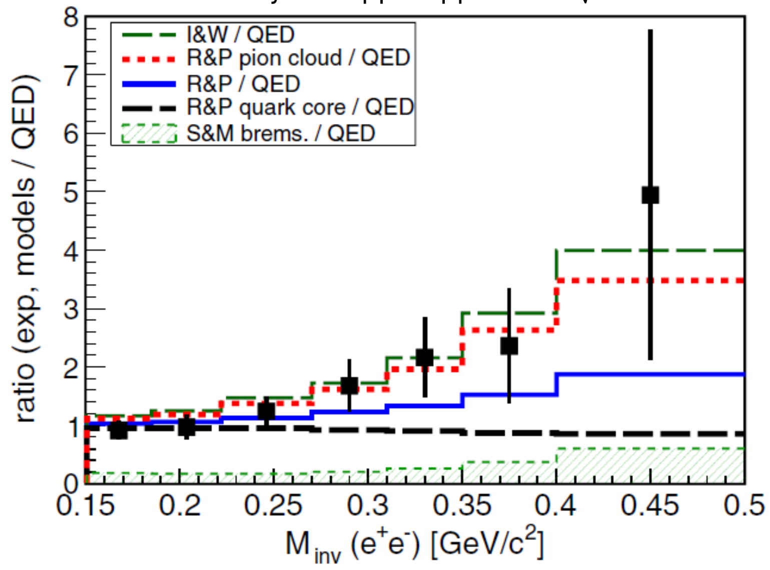
- Quarks are easily reshuffled between hadron states?

Quantum percolation at $\rho \sim 1.8\rho_0$

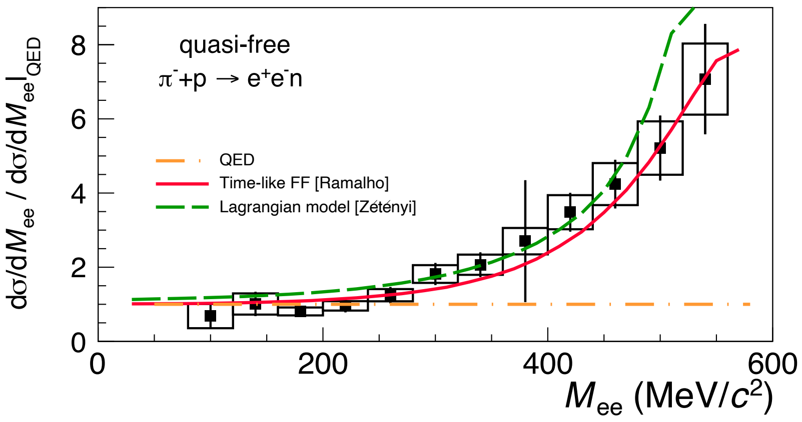
K. Fukushima, T. Kojo, W. Weise, PRD **102**, 096017 (2020)



Exclusive analysis of pp → pp $e^+e^-$ at $\sqrt{s}$ = 2.42 GeV




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




# Baryons as extended objects

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

- Ratios to the case with the point-like form factor ("QED")
- Rising with the dilepton invariant mass
- Related to the pion cloud
- Same conclusion as in the earlier p+p $\sqrt{s}$ = 2.42 GeV run

pp:
Data: PRC **95**, 065205 (2017)
QED: point like γ*NR, Heavy Ion Phys. **17**, 27 (2003)
I&W: two component quark model, PRC **69**, 055204 (2004)
R&P: covariant constituent quark model, PRD **93**, 033004 (2016)
S&M brems.: PRC **82**, 062201 (2010)

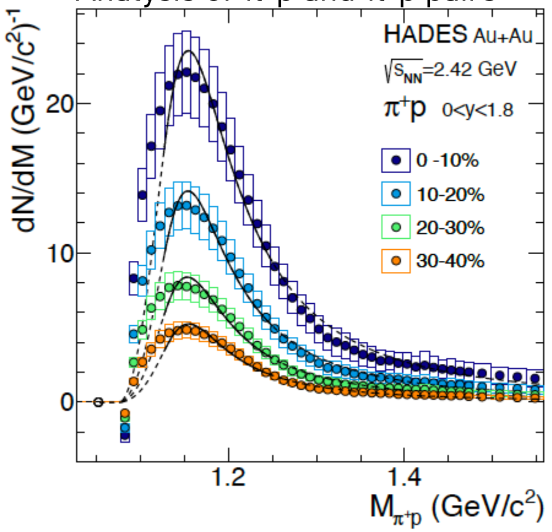
$\pi^-p$:
Data: MS in preparation
Zétényi: PRC **104**, 015201 (2021)
Ramalho: PRD **95**, 014003 (2017), PRD **101**, 114008 (2020)

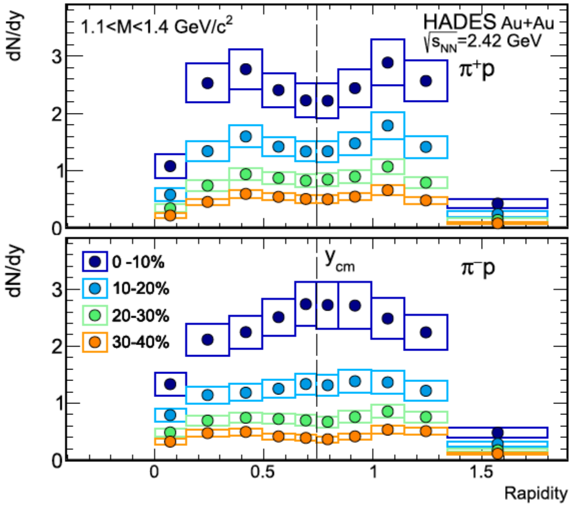
# Correlated pion-proton pairs

HADES Collaboration, PLB **819**, 136421 (2021)

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

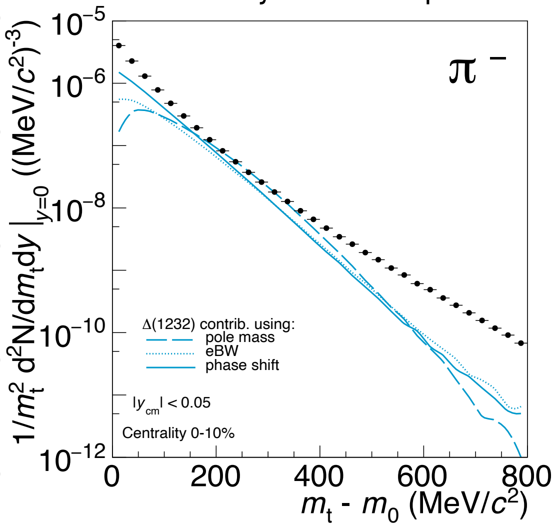
Analysis of $\pi^+p$ and $\pi^-p$ pairs




- Dominant source of particle production at SIS18
- High statistics allows multi-differential analysis
- Understanding of “kinematical” mass shift with S-matrix formalism
- Comparison to theory

Sensitivity to the shape




Phase shift: P. M. Lo, B.Friman, M. Marczenko, K. Redlich, C. Sasaki, PRC **96**, 015207 (2017)

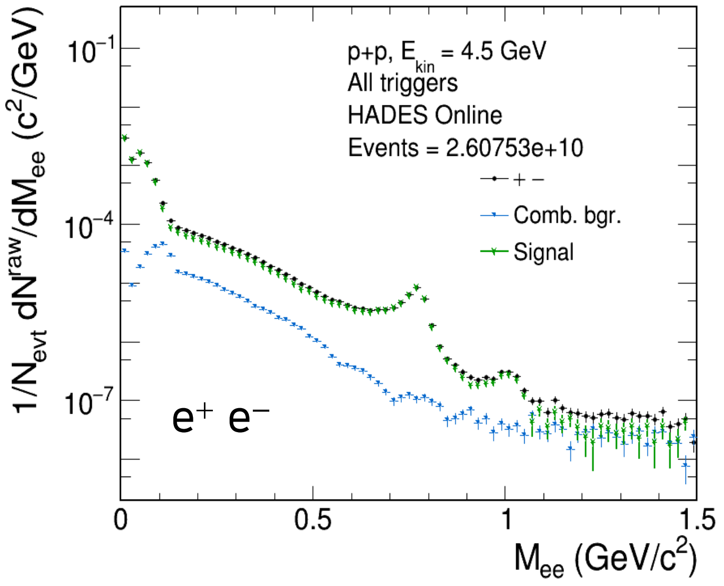
SHM parameters: A. Motornenko, J. Steinheimer, V. Vovchenko, R. Stock, H. Stoecker, PLB **822**, 136703 (2021)

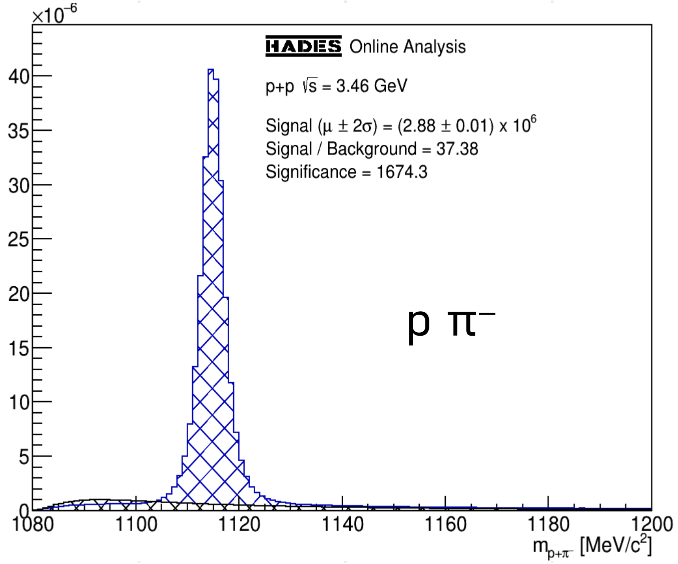
Event generator: M.Cojnacki, A.Kisiel, W.Florkowski, W.Broniowski, Comput.Phys.Comm **181**, 746–773 (2012)

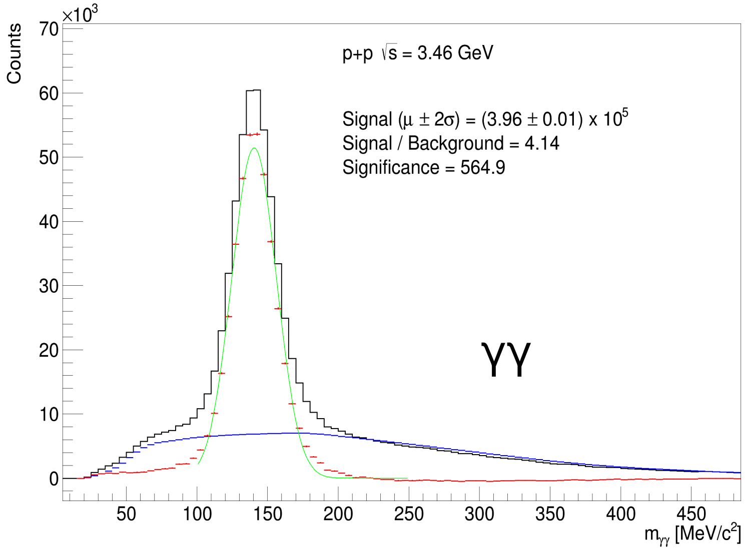
Adapting to HADES energies: SH *et al.*, PRC **102**, 054903 (2020), see also Jędrzej Kołaś, poster, session 2 T14_1 (Wed)

# New Feb 2022 data

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




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

# Summary

- Electromagnetic probes:
  - Dilepton excess yield
  - It has no signature of azimuthal anisotropy
- Hadron production:
  - Influence of final-state EM interactions
  - No global description of azimuthal anisotropy by available models
  - $\Lambda$ polarization the largest at the moment
- Strangeness:
  - Measurement of hypernuclei lifetime
  - Common scaling with participant number
- High precision data on correlated pion-proton pairs available

All HADES contributions:
**Simon Spies, talk, Thu 16:50**
**Jan-Hendrik Otto, talk, Thu 18:50**
**Niklas Schild, poster, session 2 T05 / T13 (Wed)**
**Lukáš Chlad, poster, session 2 T14_1 (Wed)**
**Alexandr Prozorov, poster, session 1 T14_1 (Wed)**
**Mateusz Grunwald, poster, session 2 T07_1 (Wed)**
**Marten Becker, poster, session 3 T11_5 (Fri)**