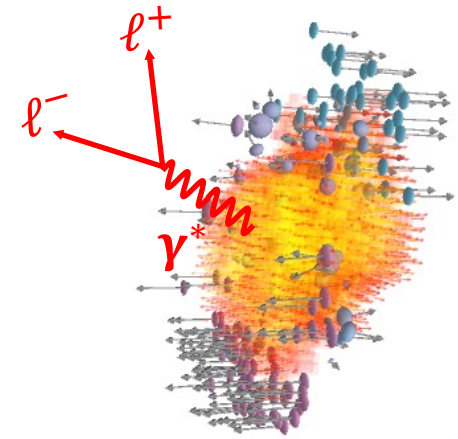


# Thermal dileptons as a probe of QCD matter at high $\mu_B$



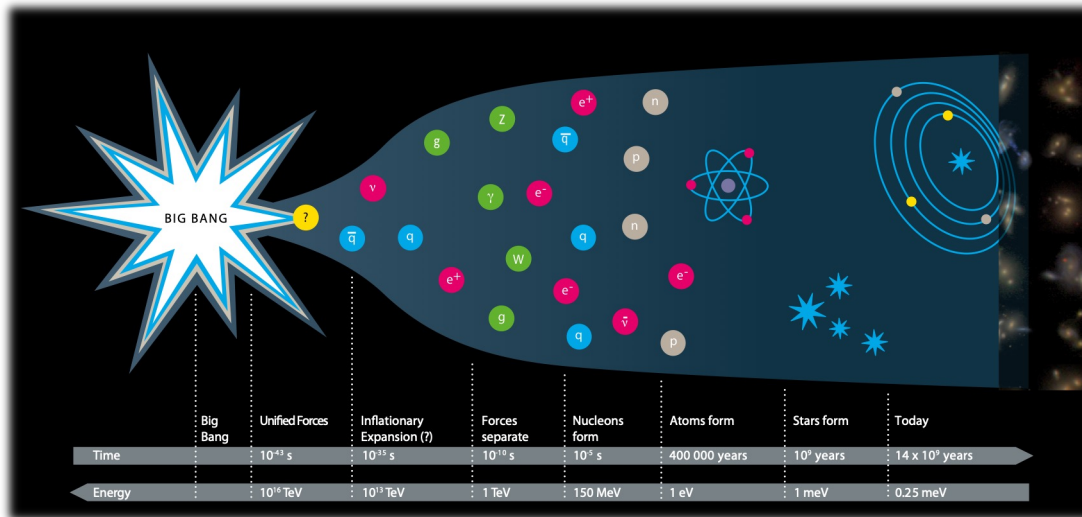
Tetyana Galatyuk, GSI / Technische Universität Darmstadt

66. Cracow School of Theoretical Physics, June 14-19, 2026, Krakow

# Objective

Decode the phases of nuclear matter in the non-perturbative regime of **QCD**

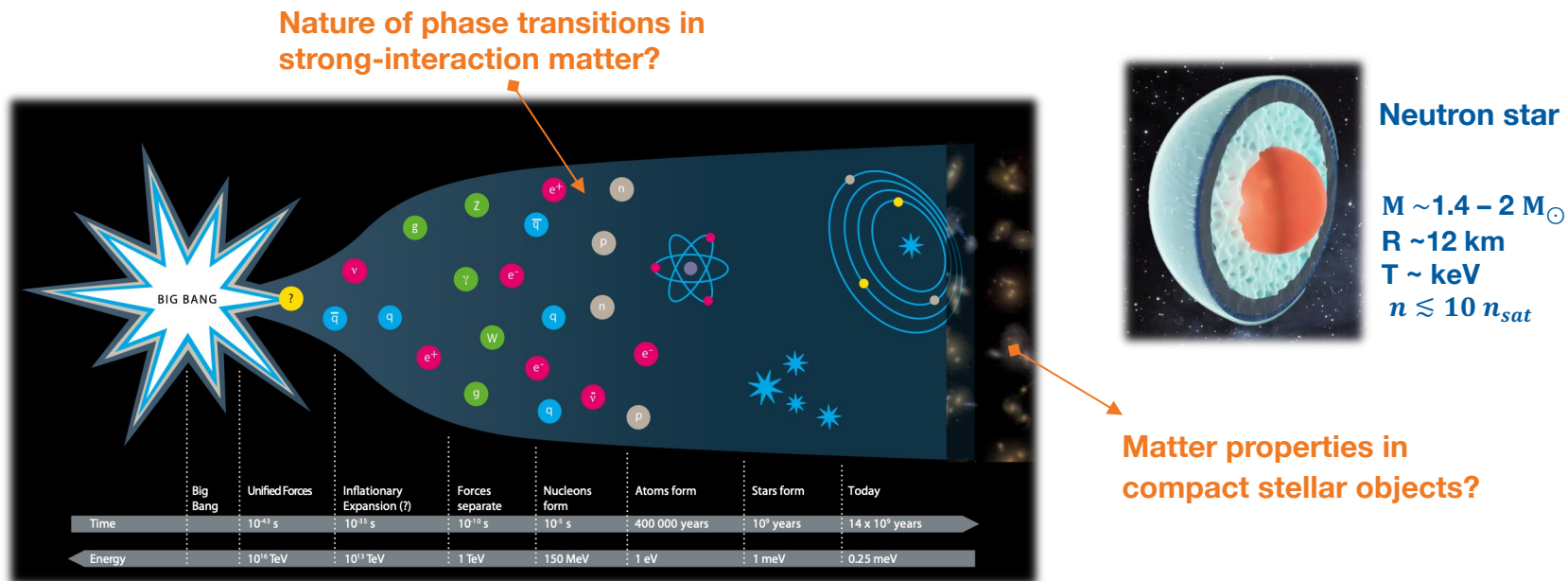
Unravel the role of the strong interaction in the evolution of our universe



# Objective

Decode the phases of nuclear matter in the non-perturbative regime of **QCD**

Unravel the role of the strong interaction in the evolution of our universe



# Method

Recreate various forms of cosmic matter in laboratory → high-energy heavy-ion collisions  
 Investigate transient states of QCD matter under extreme conditions

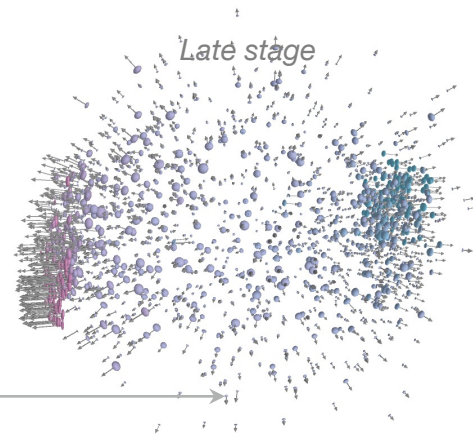
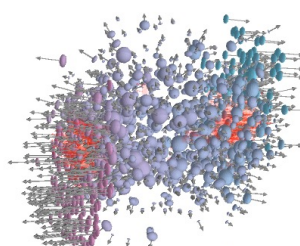
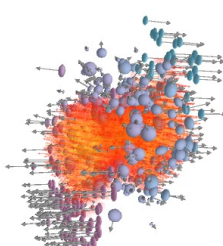
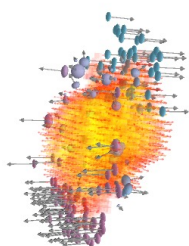
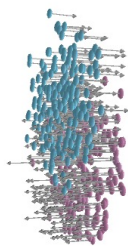
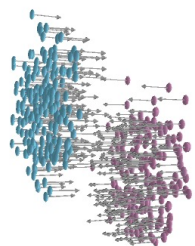
*First chance*

*Pre-equilibrium*

*Fireball*

*Freeze-out*

*Late stage*

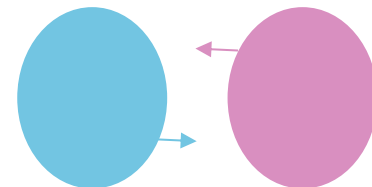


$time \sim 10^{-23} s$

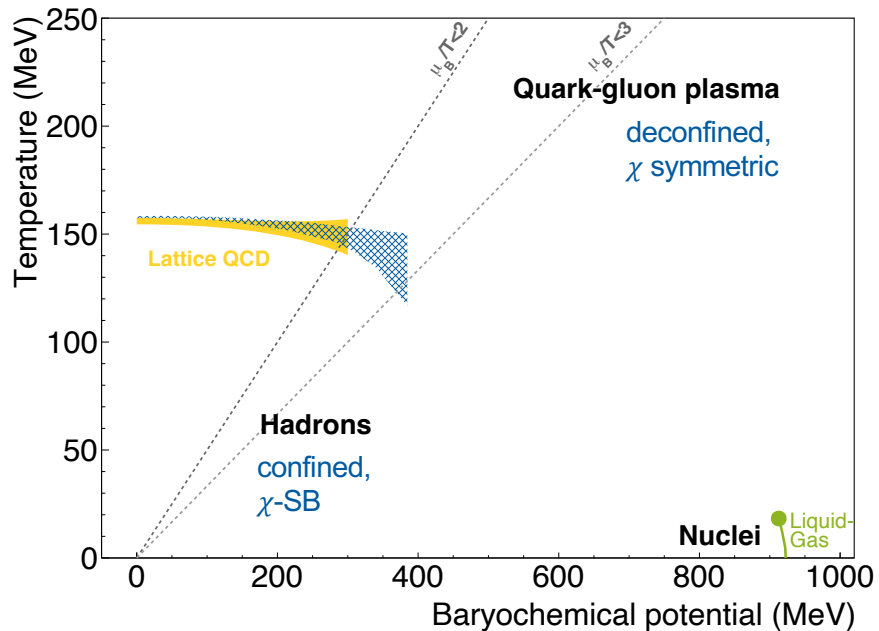


LHC energies  $\sqrt{s_{NN}} = 2 - 5 TeV$   
 parton parton collisions  
 $N_{particles} = N_{anti-particles}$

SIS energies  $\sqrt{s_{NN}} = 2 - 5 GeV$   
 Nuclear stopping  
 $N_{particles} \gg N_{anti-particles}$



# Searching for landmarks of the QCD phase diagram



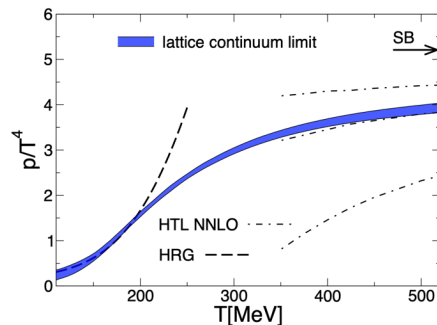
Borsanyi *et al.* [Wuppertal-Budapest], PRL 125 (2020)  
 Borsanyi *et al.* [Wuppertal-Budapest], PLB 730 (2014)  
 Borsanyi *et al.* [Wuppertal-Budapest], JHEP 1009 (2010) 073

## Vanishing $\mu_B$ , high $T$ (lattice QCD):

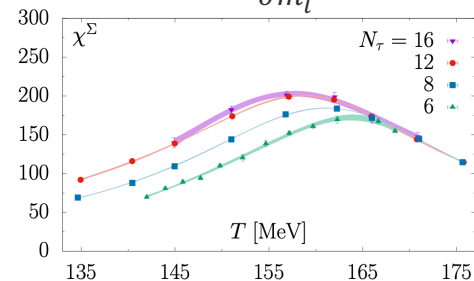
- **crossover** from hadronic to partonic medium
  - $T_{pc} = 156.5 \pm 1.5$  MeV ( $T_c = 132_{-6}^{+3}$  MeV at chiral limit)
  - $T_{pc} = 158.0 \pm 0.6$  MeV
- **no 1<sup>st</sup> order transition** found by IQCD at  $\mu_B^{CEP}/T_c < 3$

Bazavov *et al.* [HotQCD], PLB 795 (2019)  
 Ding *et al.*, [HotQCD], PRL 123 (2019) 062002  
 Dini *et al.*, PRD 105 (2022) 034510

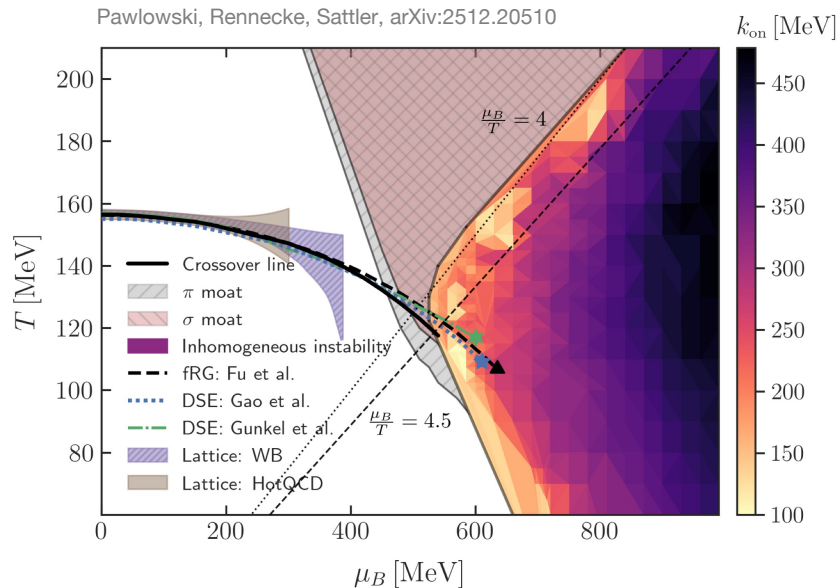
$$\frac{p}{T^4} = \frac{1}{VT^3} \ln Z(V, T, \vec{\mu})$$



$$\chi^\Sigma \sim \frac{\partial^2 \ln Z}{\partial m_l^2}$$



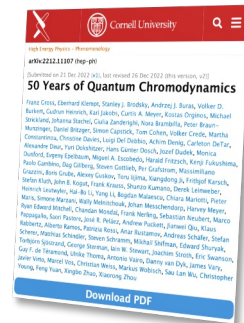
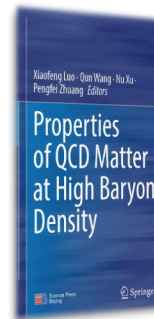
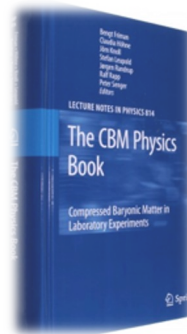
# Searching for landmarks of the QCD phase diagram



## Large $\mu_B$ , moderate $T$ (IQCD inspired effective theories):

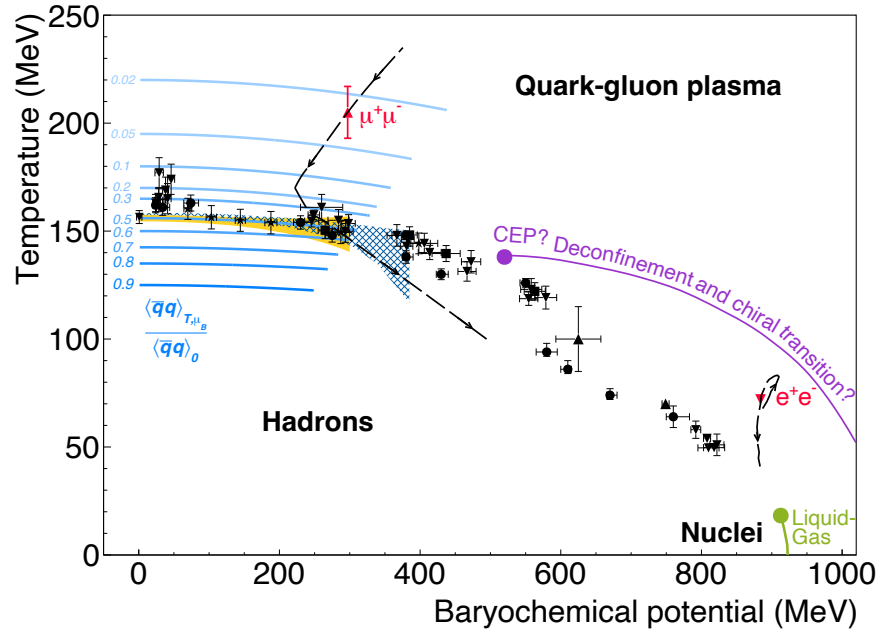
- limits of hadronic existence?
- 1<sup>st</sup> order transition?
- QCD critical point?
- equation-of-state of dense matter?
- what phases (quarkyonic, moat, soft deconfinement)?

**Worldwide experimental and theoretical efforts  
Relevance for astrophysics**



Friman *et al.*, Lect. Notes Phys. 814 (2011) 1  
 Chen, *et al.*, doi:10.1007/978-981-19-4441-3\\_4 (2022)  
 F. Gross *et al.*, Eur.Phys.J.C 83 (2023) 1125

# Searching for landmarks of the QCD phase diagram



## Experimental challenges:

- isolate unambiguous signals of new phases of QCD matter, order of phase transitions, conjectured QCD critical point
- probe microscopic matter properties

## Measure with utmost precision:

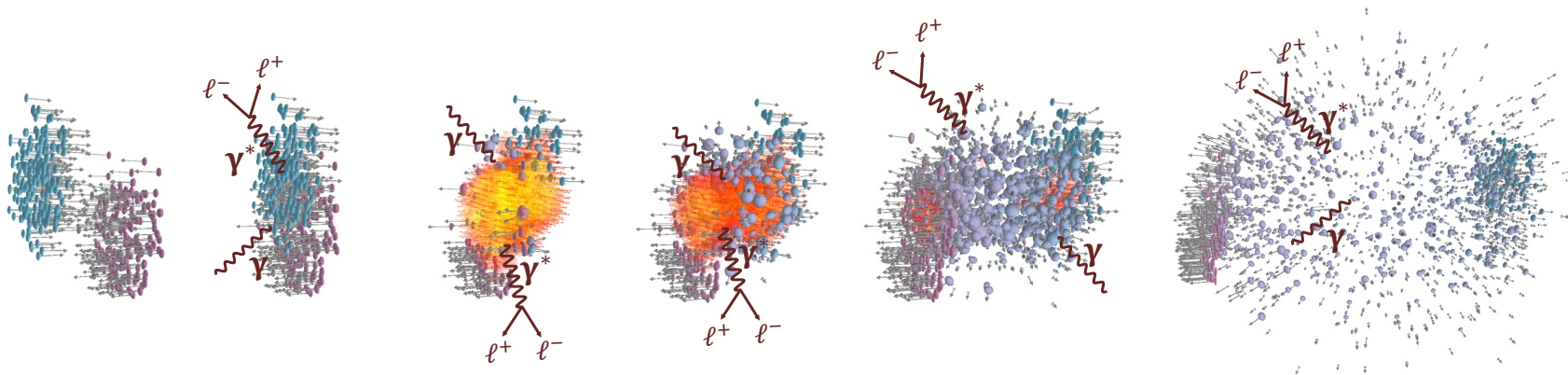
- light flavour (chemistry, vorticity, flow)
- event-by-event fluctuations (criticality)
- charm (transport properties)
- hypernuclei (interaction)
- **dileptons (emissivity)**

Andronic *et al.*, Nature 561 (2018) no.7723

HADES, Nature Phys. 15 (2019) 10, 1040-1045

NA60, Specht *et al.*, AIP Conf.Proc. (2010) 1322

# Electromagnetic radiation as multi-messenger of fireball



Electromagnetic radiation ( $\gamma, \gamma^*$ )

Reflect the whole history of a collision

No strong final state interaction  
 $\leadsto$  leave reaction volume undisturbed

Encodes information on matter properties  
 enabling unique measurements

- degrees of freedom of the medium
- fireball lifetime, temperature, acceleration, polarization
- transport properties
- restoration of chiral symmetry

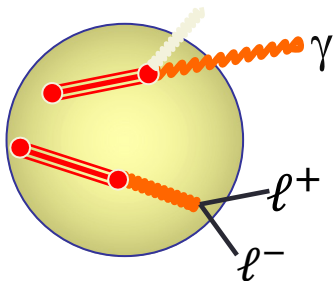
# Electromagnetic production rate

- *em* current-current correlation function

$$\Pi_{em}^{\mu\nu}(q_0, q) = -i \int d^4x e^{iq \cdot x} \theta(x^0) \langle [j^\mu(x), j^\nu(0)] \rangle$$

- Photons characterized by “transverse” momentum:

$$q_0 \frac{dN_\gamma}{d^4x d^3q} = -\frac{\alpha_{em}}{\pi^2} f^B(q \cdot u; T) \text{Im} \Pi_{em}(q_0 = q; \mu_B, T)$$



**spectral  
function**

determines both  
photon and  
dilepton rates

- Dileptons carry extra information: invariant mass  
→ unique direct access to in-medium spectral function

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

lepton phase  
space factor

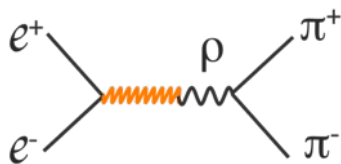
thermal Bose  
distribution

# Electromagnetic correlator in the vacuum

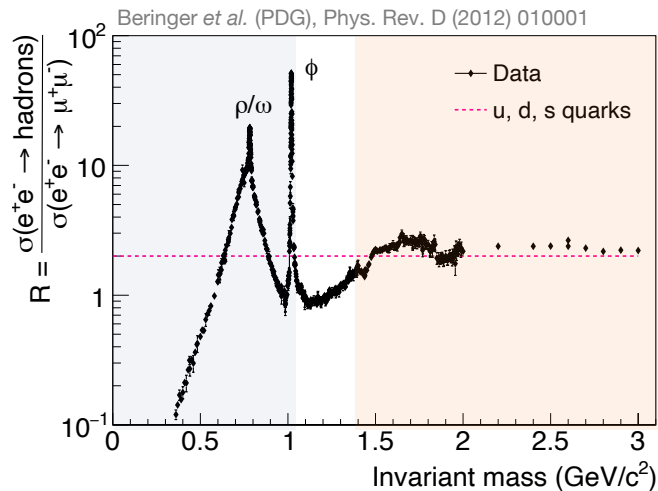
accurately known from  $e^+e^-$  annihilation  $R \propto \frac{\text{Im}\Pi_{em}^{vac}}{M^2}$

## Low-mass region (LMR)

$em$  spectral function is saturated by light vector mesons (VMD  $J^P = 1^-$  for both  $\gamma^*$  and VM,  $\rho$  playing the dominant role)

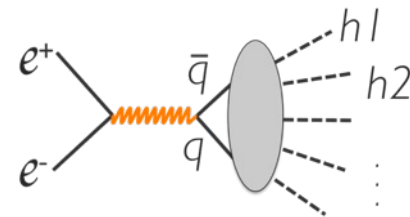


$$\text{Im}\Pi_{em}^{vac} = \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 \text{Im}D_v^{vac}(M)$$



## Intermediate-mass region (IMR)

perturbative QCD continuum (quark degrees of freedom)



$$\text{Im}\Pi_{em}^{vac} = -\frac{M^2}{12\pi} \left(1 + \frac{\alpha_s(M)}{\pi} + \dots\right) N_c \sum_{q=u,d,s} (e_q)^2$$

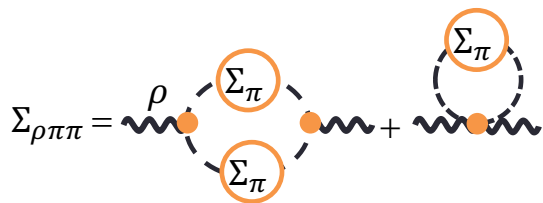
# In-medium SF from hadronic many body theory

→  $\rho$  meson in medium interacts with hadrons from heat bath

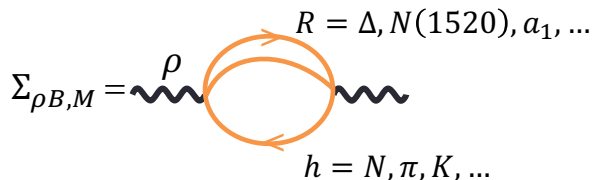
additional contributions to the  $\rho$ -meson self-energy

$$D_\rho(M, q, T, \mu_B) = \frac{1}{[M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}]}$$

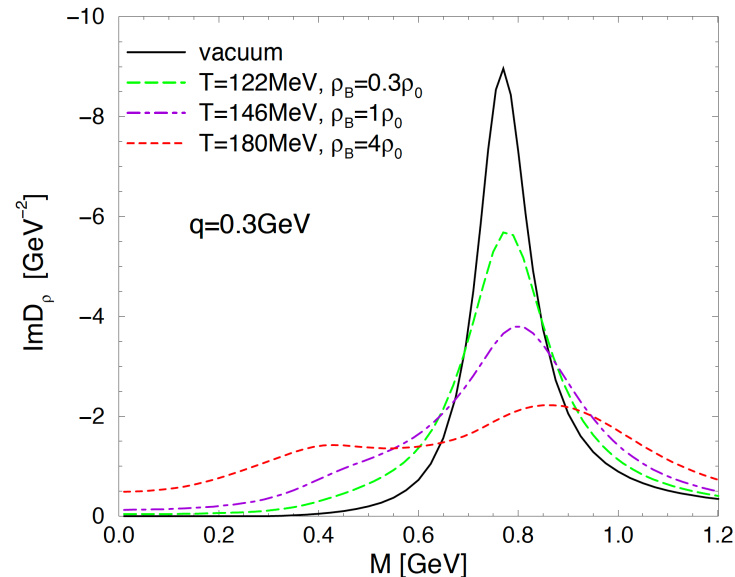
In-medium pion cloud



direct  $\rho$ -hadron scattering



Rapp and Wambach, EPJA 6 (1999) 415

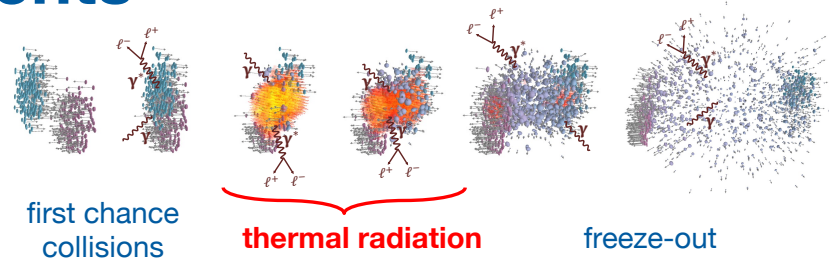
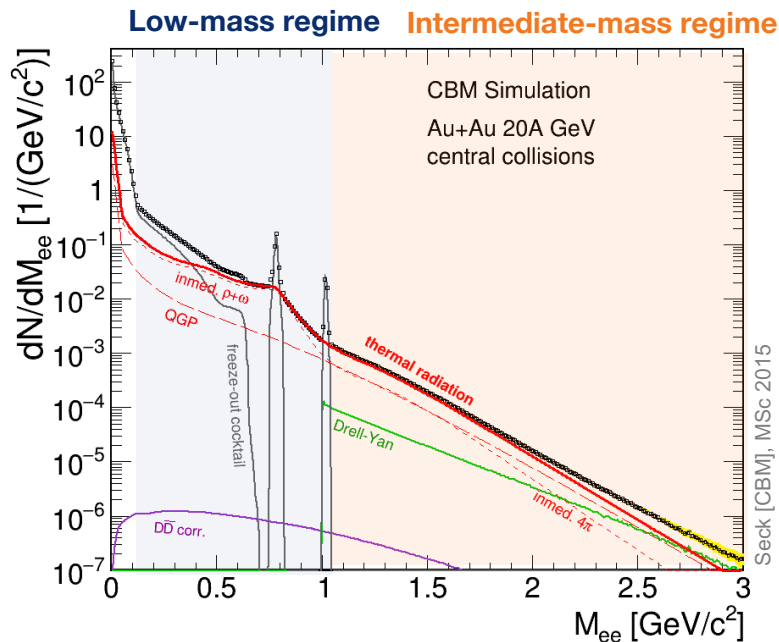


→  $\rho$ -peak undergoes a strong broadening

→ baryon effects important

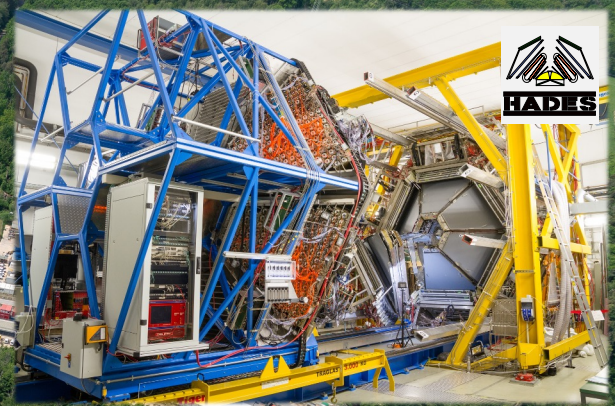
(even at  $\rho_{Bnet} = 0!$  sensitive to  $\rho_{Btot} = \rho_B + \rho_{\bar{B}}$ )

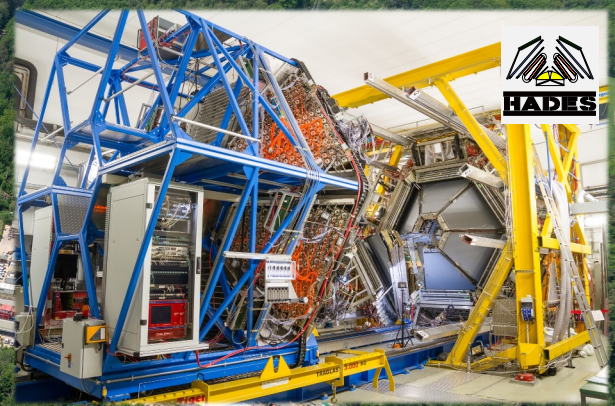
# Thermal dilepton measurements



- Dileptons are rare probes
- Decisive parameters for data quality:  
interaction rates ( $IR$ ) and signal-to-combinatorial background ratio ( $S/CB$ ): effective signal size:  $S_{eff} \sim IR \times S/CB$
- Needs coverage of mid-rapidity, low- $M_{\ell\ell}$ , and low- $p$
- Isolation of thermal radiation by subtraction of measured decay cocktail ( $\pi^0, \eta, \omega, \phi$ ), Drell-Yan,  $c\bar{c}$  ( $b\bar{b}$ )



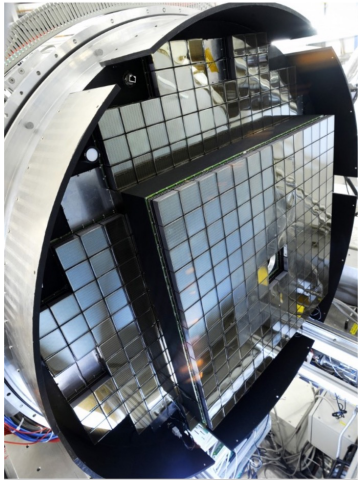
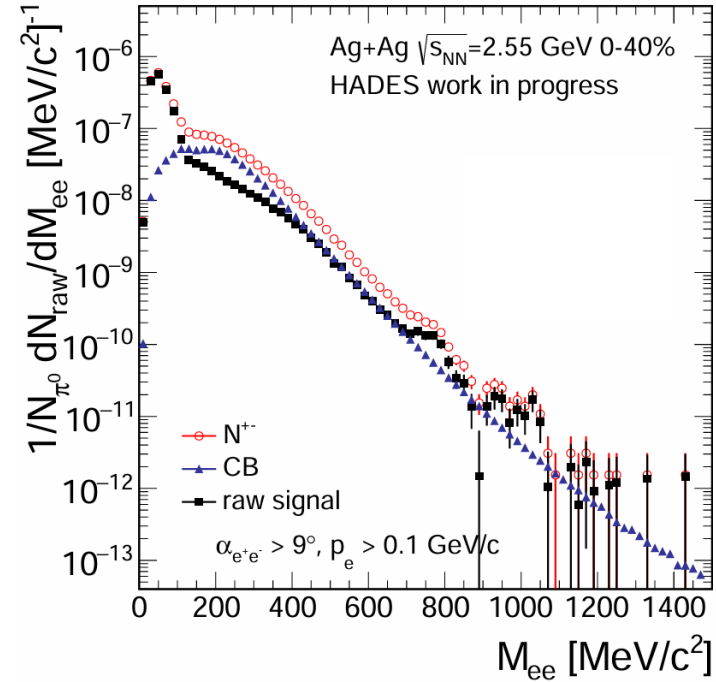
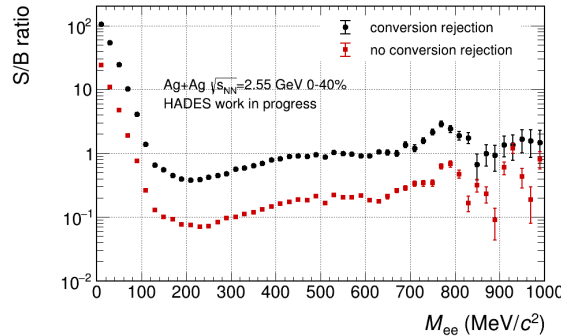
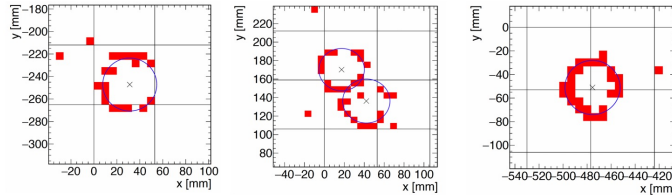




# Electron pairs reconstruction

RICH photo camera upgrade, employing CBM at FAIR technology

- Significantly improved lepton detection efficiency
- Pion suppression factor  $> 10^4$
- Excellent double ring detection (factor of 8 better signal-to-background ratio)

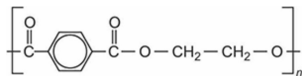


# Measurement of NN reference in HADES

- p+p and d+p collisions at  $E_{kin} = 1.25$  GeV
  - n+p reaction tagged by triggering on proton spectator

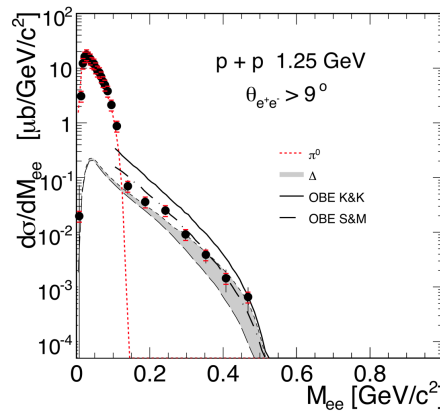
HADES, PLB 690 (2010) 118

- Analysis of p+p at  $E_{kin} = 1.58$  GeV and 4.5 GeV
  - empty target run p+C/p/O as proxy for p+p/p+n

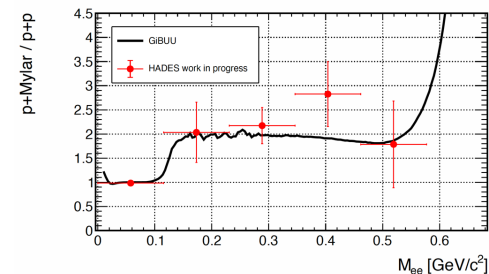
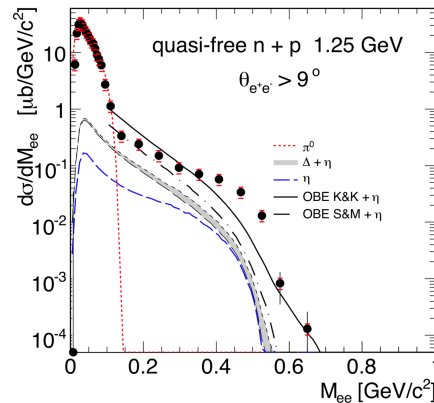
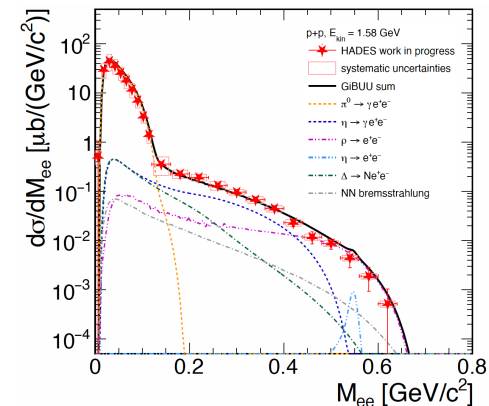


Mylar

NN ref. for  $\sqrt{s_{NN}} = 2.42$  GeV



NN ref. for  $\sqrt{s_{NN}} = 2.55$  GeV

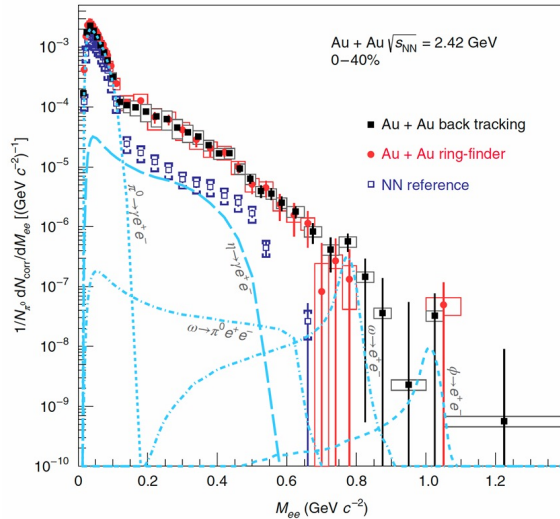


HADES, in preparation  
GiBUU: Larionov *et al.*,  
PRC 102 (2021) 064913

# Dilepton invariant mass spectra from HADES

→ Clear excess visible above contributions from initial NN reference and freeze-out cocktail

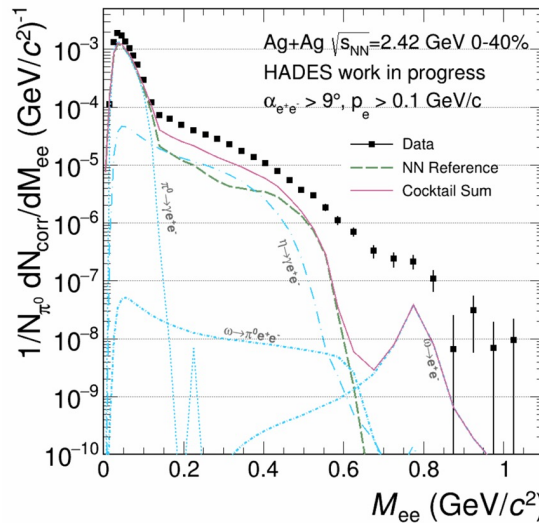
Au+Au at  $\sqrt{s_{NN}} = 2.42$  GeV



HADES, Nature Phys. 15 (2019) 1040

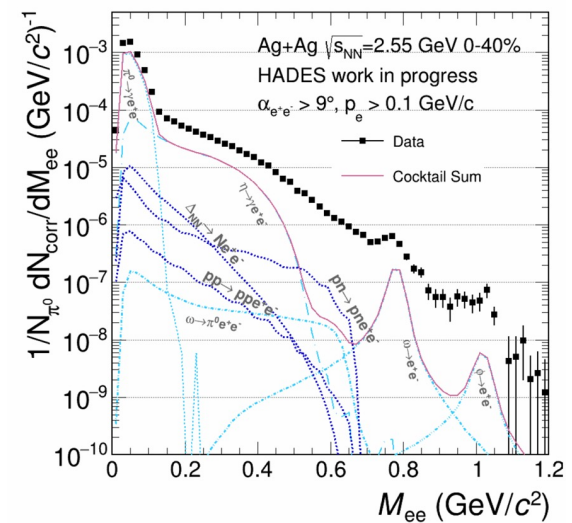
strongest isospin effect seen in  $np$  vs  $pp$   
→ measured NN reference

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



strongest isospin effect seen in  $np$  vs  $pp$   
→ measured NN reference

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



simulated reference (GiBUU)  
→ measured NN in preparation

# Thermal dileptons at few GeV energies?

- Necessary ingredients to understand dilepton production in HIC:
  - accurate description of fireball evolution
  - realistic emission rates
  - sensitivity studies for the Equation of State

## Coarse-Grained transport approach

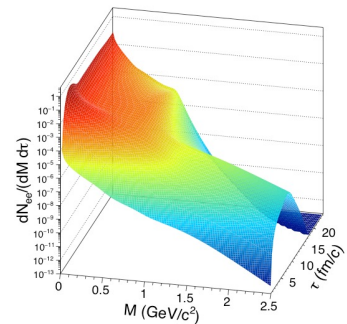
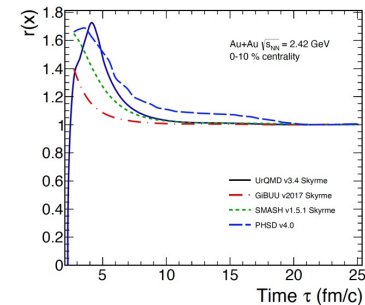
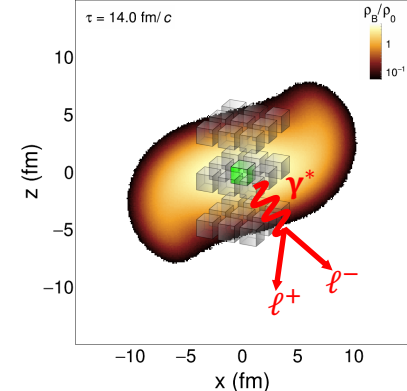
- ➔ bulk evolution from microscopic transport
- ➔ apply equilibrium rates locally

CG GSI-Texas A&M: TG *et al.*, EPJ A52 (2016) no.5, 131

Rapp and Wambach, Adv.Nucl.Phys. (2000) 25  
 Jung, Rennecke, Tripolt, *et al.*, PRD95 (2017) 036020  
 Sasaki, PLB 801 (2020) 135172

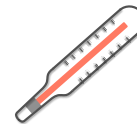
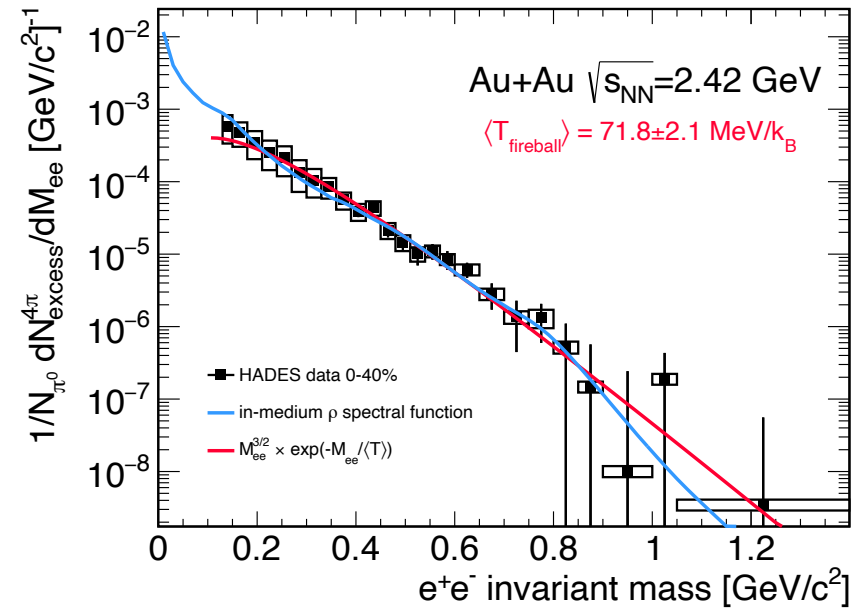
- Simulate events with a transport model  
 ↪ ensemble average to obtain smooth space-time distributions
- Divide space-time into 4-dim. cells
- Check if cell is thermalized (→ enough interactions)
- Determine baryon density  $\rho_B$ , medium velocity  $\vec{u}$ , and temperature  $T$  (→  $m_T$  spectra of pions)
- Use in-medium spectral functions to compute EM emission rates

Huovinen *et al.*, PRC 66 (2002) 014903  
 CG FRA: Endres *et al.*, PRC 92 (2015) 014911  
 CG SMASH: PRC 98 (2018) 5, 054908



# Thermal dileptons from baryon-rich matter

HADES, Nature Phys. 15 (2019) 1040



'Planck-like'



In-medium spectral function

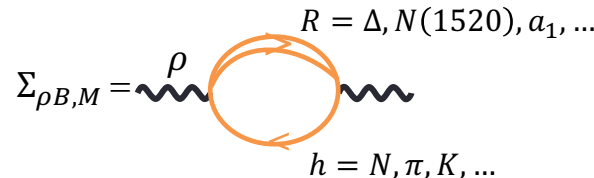
$$\frac{dN_{ll}}{d^4q d^4x} = -\frac{\alpha_{em}^2 L(M^2)}{\pi^3 M^2} f^B(q_0, T) Im\Pi_{em}(M, q, T, \mu_B)$$

McLerran - Toimela formula, PRD 31 (1985) 545

- Thermal excess radiation established at HADES
  - $\rho$ -meson peak undergoes a strong broadening in medium
  - in-medium spectral function from many-body theory consistently describes SIS18, SPS, RHIC, LHC energies

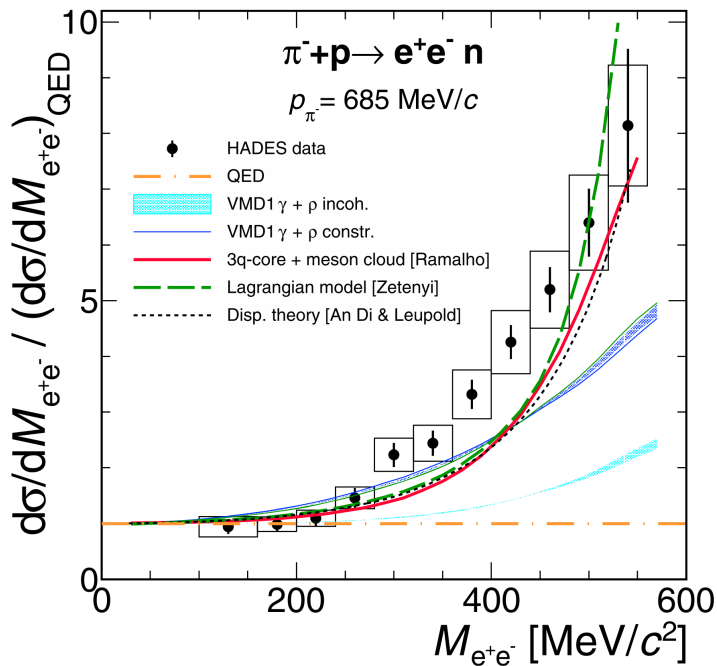
Rapp and Wambach, Adv.Nucl.Phys. (2000) 25

- Baryonic effects are crucial

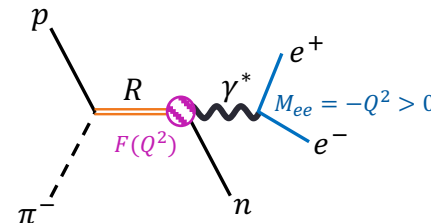
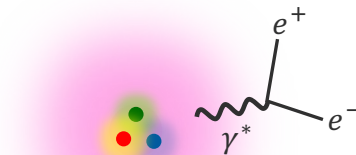


# First measurement of massive $\gamma^*$ emission from $N^*$ baryon resonances (exclusive analysis $\pi^- p \rightarrow e^+ e^- n$ )

HADES, PRC 111 (2025) 024908  
 HADES, PLB 875 (2026) 140338



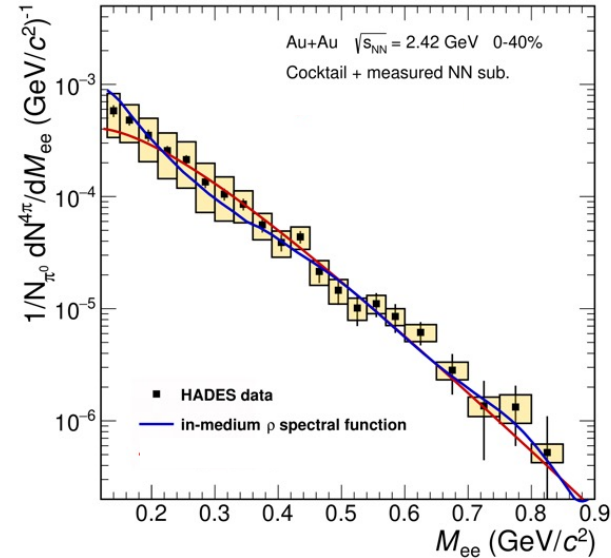
- Study the structure of the nucleon as an extended object (quark core and meson cloud)
- Dominance of the  $N^*(1520)$  resonance at  $\sqrt{s_{NN}} = 1.49 \text{ GeV}$ 
  - $\rho$  meson as "excitation" of the meson cloud
  - **Vector Meson Dominance - basis of emissivity calculations for QCD matter**



# Thermal dileptons HADES systematics

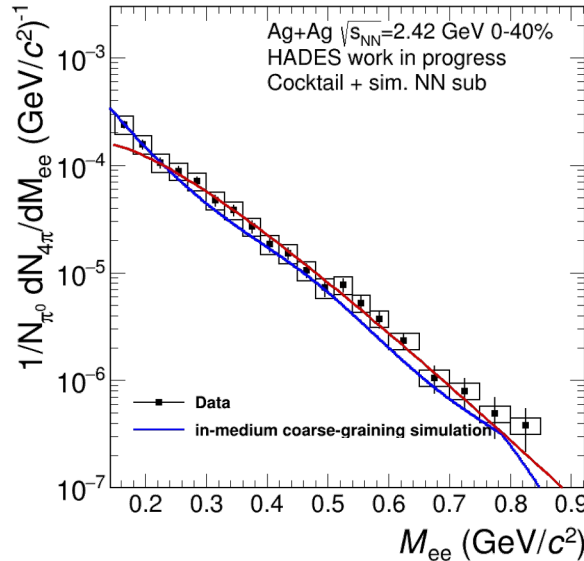
→ very good agreement between experiment and theory for excess radiation

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



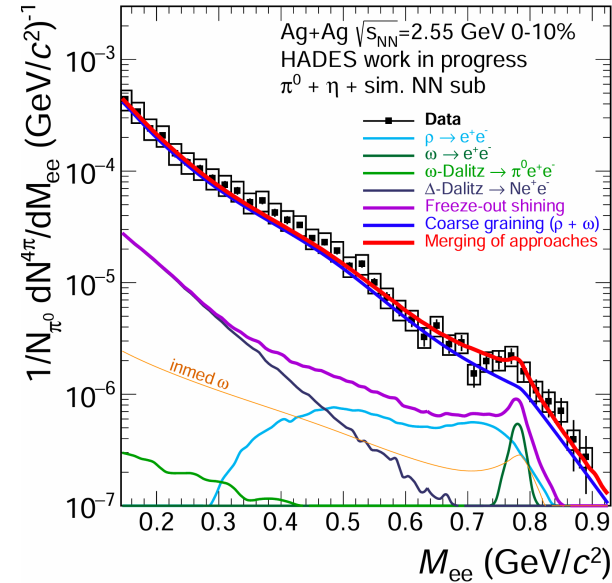
HADES, Nature Phys. 15 (2019) 1040

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



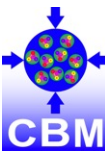
HADES, in preparation

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



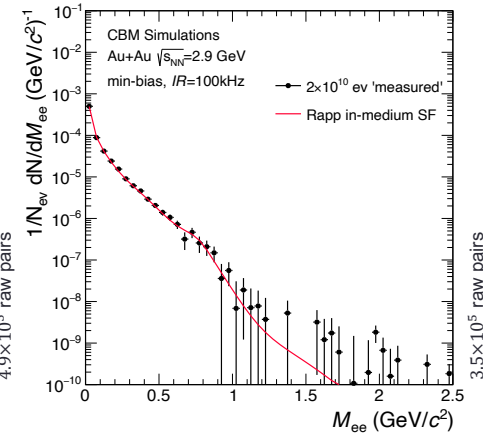
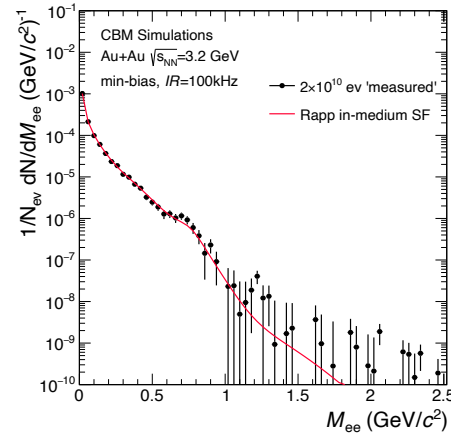
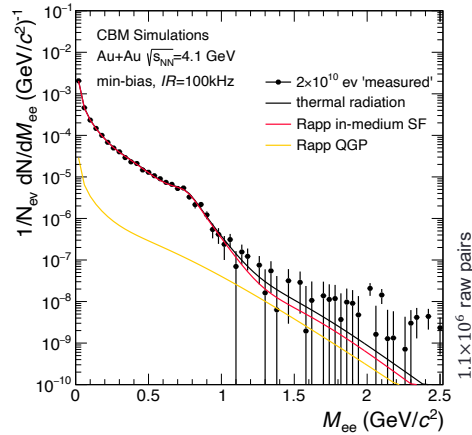
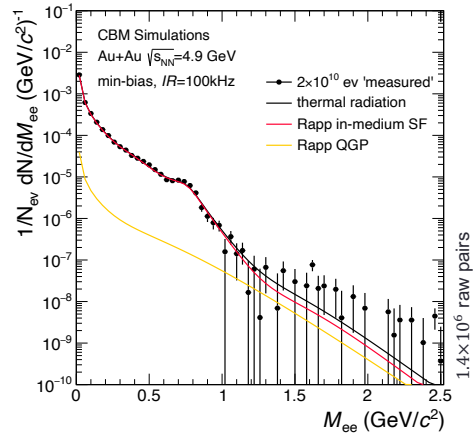
Refined coarse-graining: treat the “corona” of the fireball separately

Ou Ya Vogel, Seck, et al., in preparation



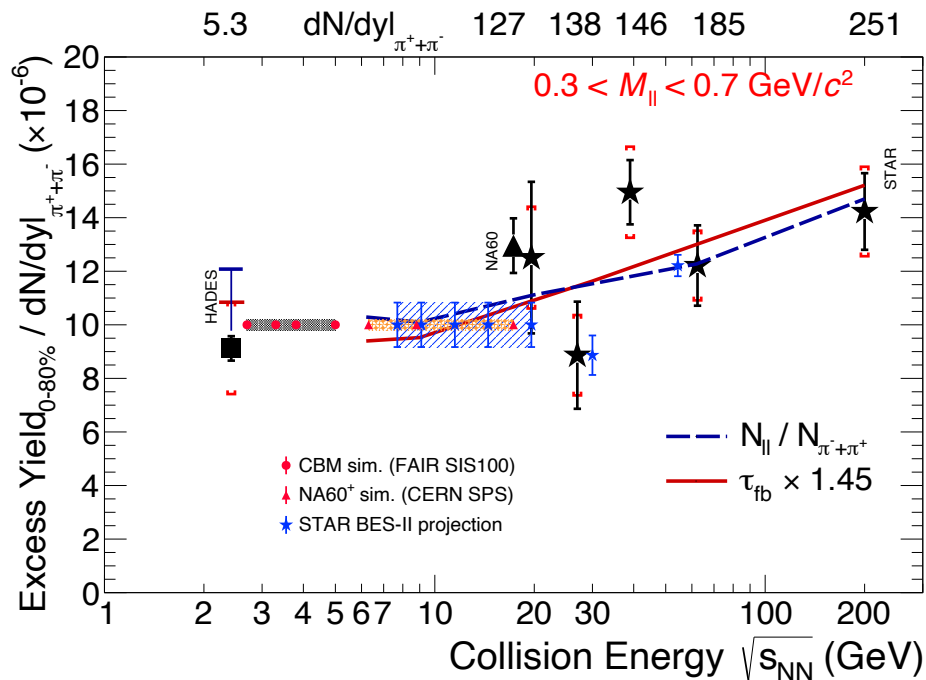
# CBM dielectron performance (first year, 5 days / energy)

- CBM performance studies with realistic detector geometries, material budget, response, S/B and statistics
- Isolated dielectron thermal radiation yield, corrected for acceptance  $\times$  efficiency:
  - dominated by  $\rho$  contribution at low mass ( $M_{\ell\ell} < 1 \text{ GeV}/c^2$ ); can be reconstructed with precision of  $\sim 5\%$



$T$  vs. baryon density effects  
 from partonic to hadronic fireballs

# Lifetime of the interacting medium



## Integrated low-mass excess yield radiation 0.3 < $M < 0.7$ GeV/c<sup>2</sup> tracks the fireball lifetime

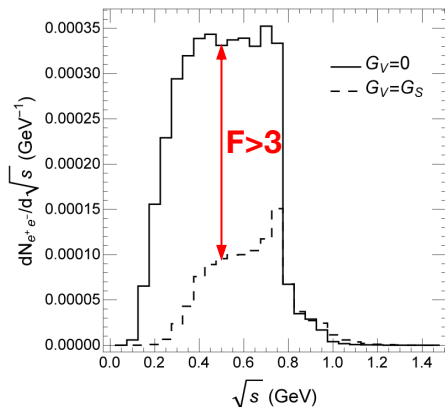
Heinz and Lee, PLB 259, 162 (1991)  
Barz, Friman, Knoll and Schulz, PLB 254, 315 (1991)  
Rapp, van Hees, PLB 753, 586 (2016)

Search for emerging signatures indicative of a  
1<sup>st</sup> order **phase transition** (and critical point?):

- prolonged lifetime of the system due to latent heat  
→ “**excess excess-radiation**”?

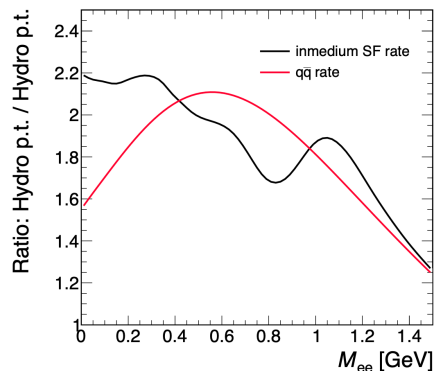
# Dilepton signature of a 1<sup>st</sup> order phase transition

Li and Ko, PRC 95 (2017) 055203



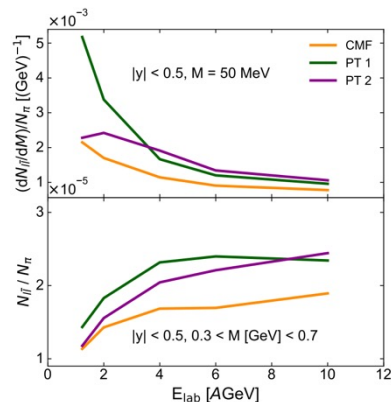
Spinodal instabilities of baryon-rich quark matter

Seck, TG, *et al.*, PRC 106 (2022) 014904



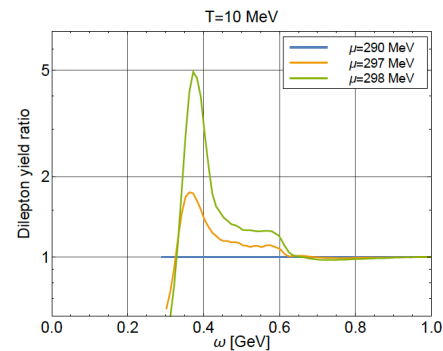
Ideal hydro simulations

Savchuk, TG, *et al.*, JPG 50 (2023) 125104



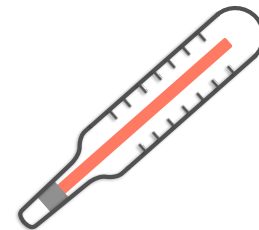
Chiral Mean Field EoS in UrQMD

Jung, *et al.*, PRD 95 (2017) 036020  
Tripolit *et al.*, NPA 982 (2019) 775

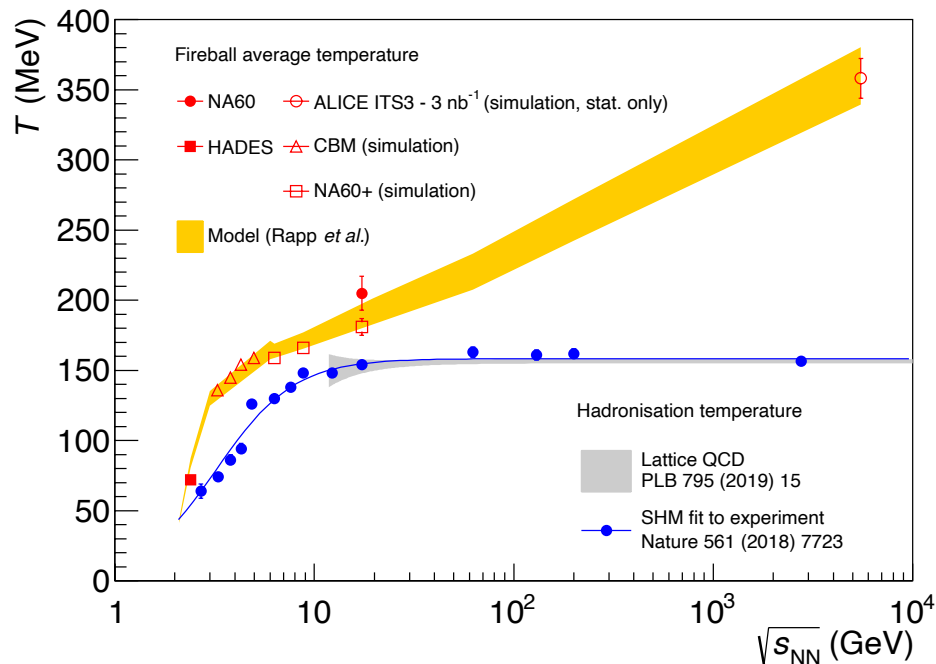


Functional Renormalization Group

Dilepton emission shows a significant effect: factor  $\sim 2$  enhancement of dilepton emission due to extended “cooking”



# Mapping the QCD “caloric curve” ( $T$ vs $\varepsilon$ )



[https://github.com/tgalatyuk/QCD\\_caloric\\_curve](https://github.com/tgalatyuk/QCD_caloric_curve)

- Invariant mass slope measures radiating source  $\langle T \rangle$  (free from blue-shift effects)

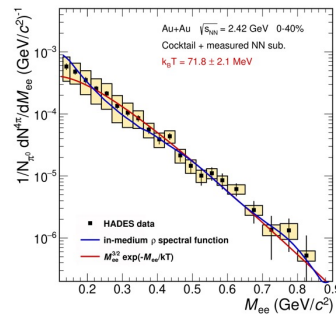
$$\frac{dR_{ll}}{dM} \propto (MT)^{\frac{3}{2}} \exp\left(-\frac{M}{T}\right)$$

Rapp, van Hees, PLB753 (2016)

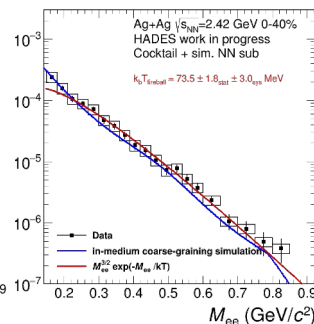
- Assumption:  $\frac{Im\Pi_{EM}}{M^2} \sim const.$
- **Flattening** of caloric curve ( $T$  vs  $\varepsilon$ )  $\rightarrow$  evidence for a **phase transition**

# High $\mu_B$ region of QCD phase diagram probed with dileptons

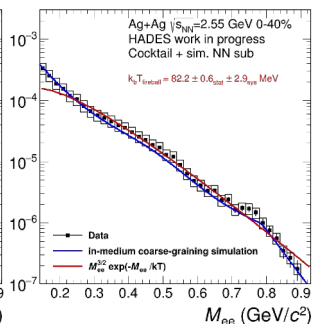
**Au+Au**  
 $\sqrt{s_{NN}} = 2.42$  GeV



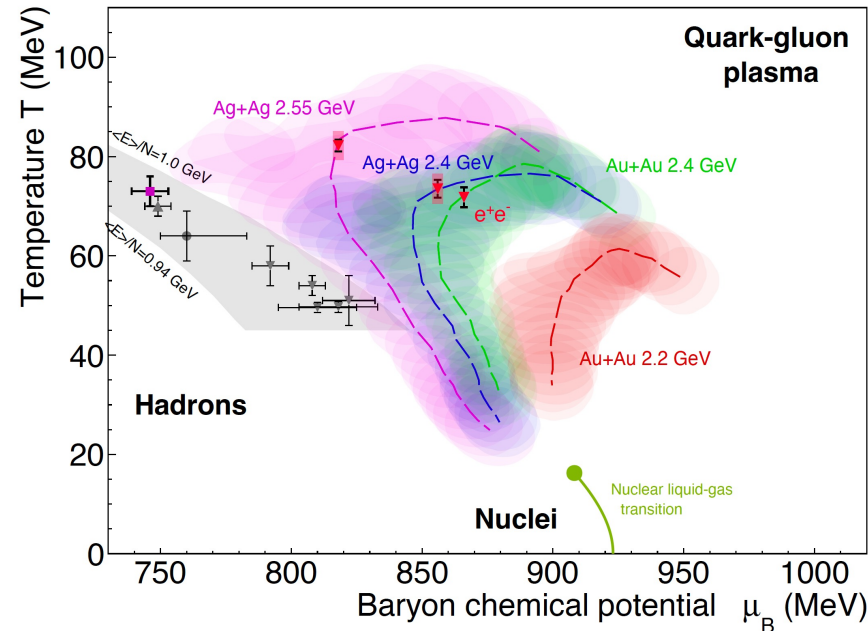
**Ag+Ag**  
 $\sqrt{s_{NN}} = 2.42$  GeV



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



- Measured by HADES average **temperatures** from ‘Planck-like’ fit to **invariant mass** Ag+Ag, Au+Au
- Trajectories from coarse-grained UrQMD
- Probe time dependence of fireball  $T$ :  $M_{\ell\ell}$  versus  $v_2$



Freeze-out curve: J. Cleymans, K. Redlich, NPA 661 (1999) 379  
 Au+Au 2.4 GeV: HADES, Nature Phys. 15 (2019) 1040  
 Ag+Ag 2.4 GeV, 2.55 GeV: HADES in preparation

# Dilepton flow

- Azimuthal anisotropies with respect to reaction plane

$$\frac{dN}{d\phi} \propto (1 + 2 \sum_n v_n \cos(n\phi)), \text{ with } v_n = \langle \cos(n\phi) \rangle$$

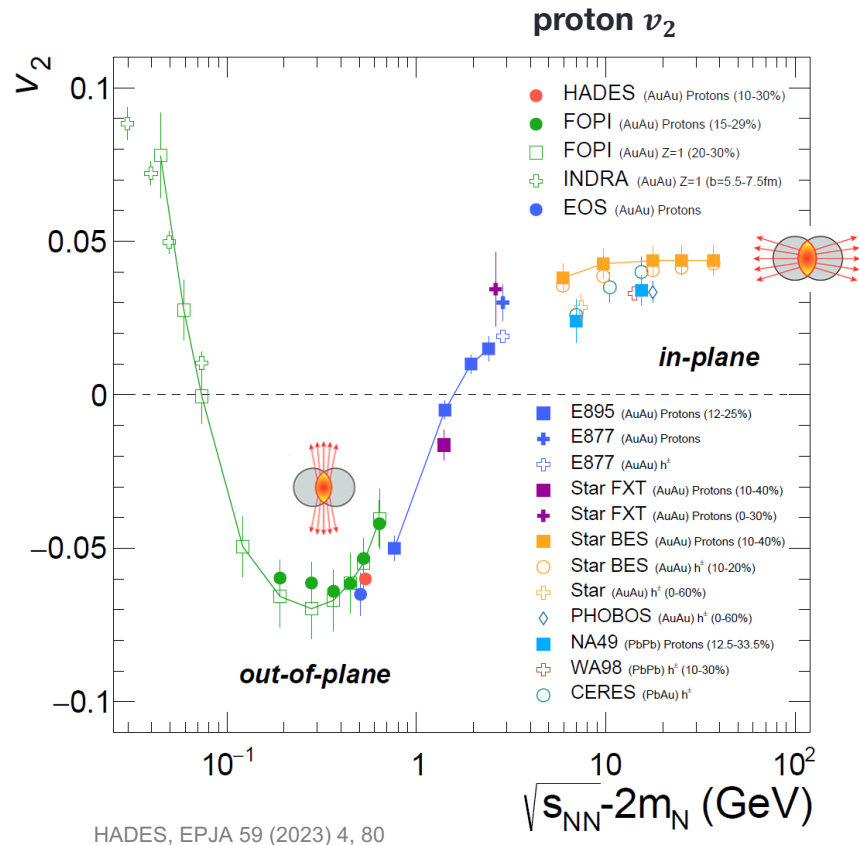
- Interplay between medium 4-velocity  $u$  and temperature  $T$

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

Chatterjee *et al.*, PRC 75 (2007) 054909  
Vujanovic *et al.*, PRC 89 (2014) 034904

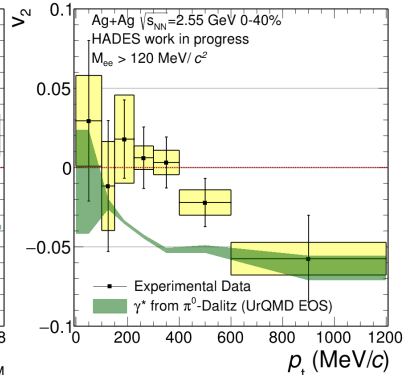
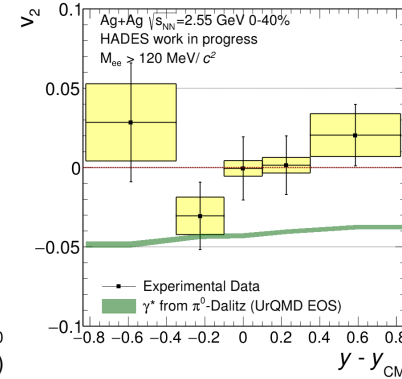
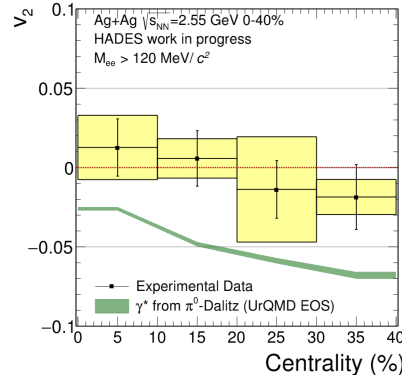
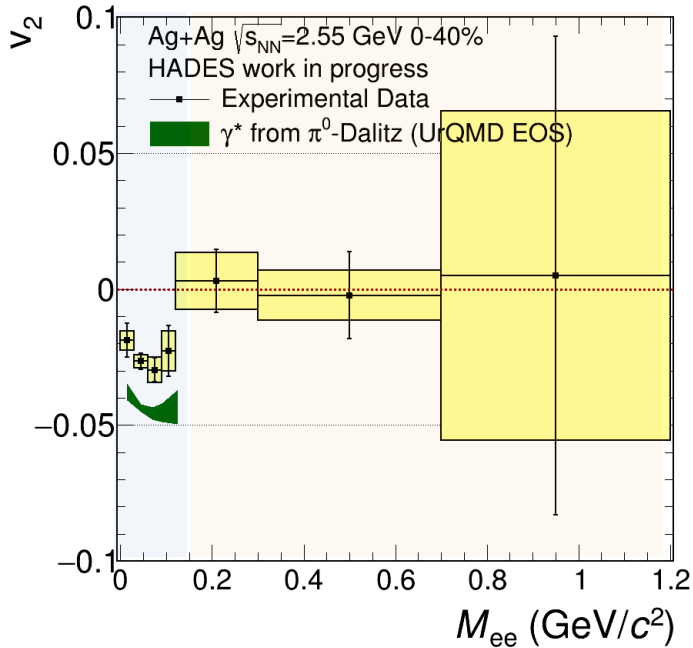
- Pressure anisotropies in underlying space-time evolution  
→ collective velocities of medium cells
- Dileptons probe earlier times (high  $\rho_B$ , high  $T$ )  
compared to hadron flow

Possible sensitivity to the EoS at high  $\mu_B$



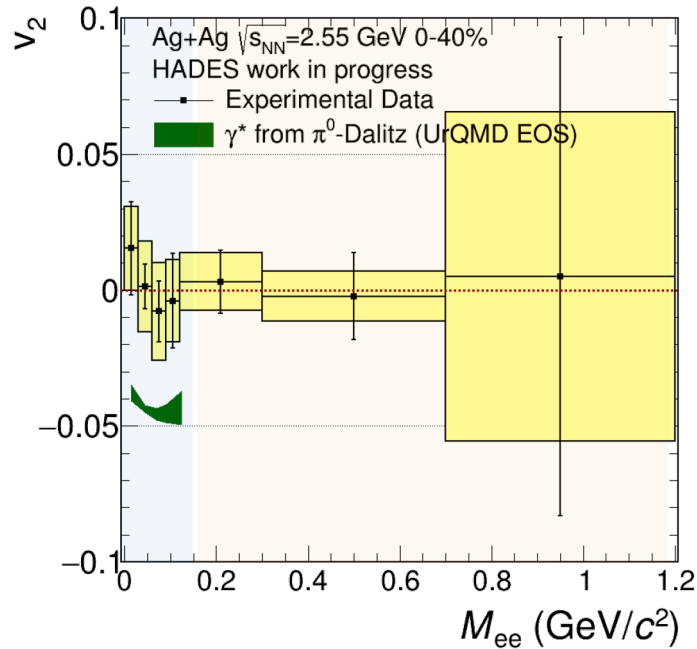
# Dilepton $v_2$ in Ag+Ag collisions

- $M_{ee} < 0.12 \text{ GeV}/c^2$ : inclusive yield dominated by  $\pi^0$  decays  
 $\leadsto$  dilepton  $v_2$  consistent with charged pion  $v_2$
- $M_{ee} > 0.12 \text{ GeV}/c^2$ : inclusive yield dominated by thermal radiation  
 $\leadsto$  dilepton  $v_2$  consistent with zero  $\rightarrow$  early emission

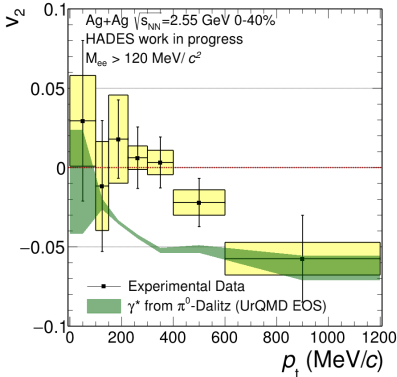
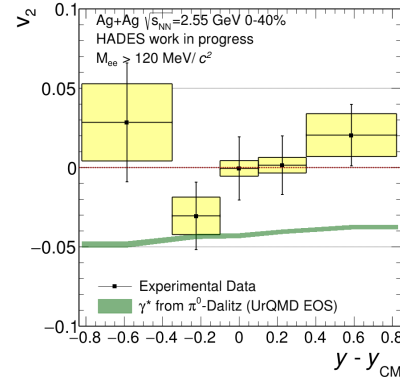
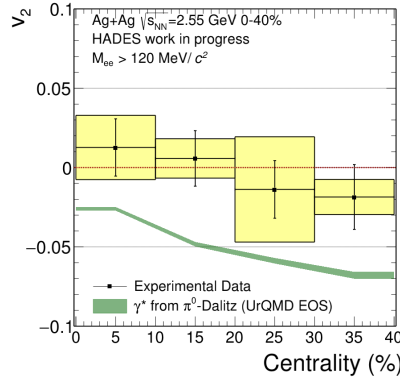


# Dilepton $v_2$ in Ag+Ag collisions

## Simulated $v_2^{\pi^0}$ subtracted



- $M_{ee} < 0.12 \text{ GeV}/c^2$ : inclusive yield dominated by  $\pi^0$  decays  
 $\leadsto$  dilepton  $v_2$  consistent with charged pion  $v_2$
- $M_{ee} > 0.12 \text{ GeV}/c^2$ : inclusive yield dominated by thermal radiation  
 $\leadsto$  dilepton  $v_2$  consistent with zero  $\rightarrow$  early emission



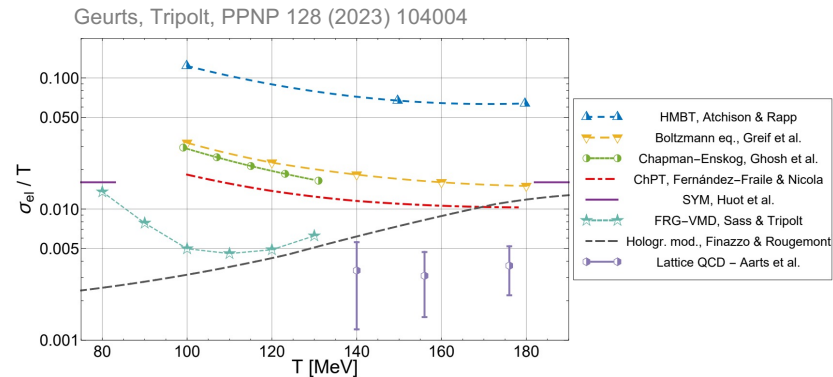
# Transport properties of the medium

Kubo, J. Phys. Soc. Jap. 12 (1957) 570-586  
 Moore, Robert, arXiv:hep-ph/0607172 (2006)  
 Atchison, Rapp, NPA 1037 (2023) 122704  
 Flörchinger *et al.*, PLB 837 (2023) 137647

- **Electric conductivity** - can be directly obtained from the low-energy limit of the EM spectral function (at vanishing momentum)

$$\sigma_{el}(T) = -e^2 \lim_{q_0 \rightarrow 0} \frac{1}{q_0} \text{Im} \Pi_{em}(q_0, q = 0; T, \mu_B)$$

Non-monotonic trend of  $\sigma_{el}$  as the phase transition occurs?



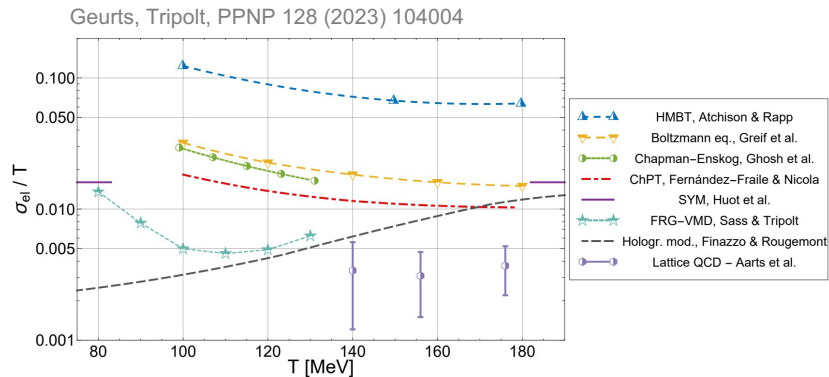
# Transport properties of the medium

Kubo, J. Phys. Soc. Jap. 12 (1957) 570-586  
 Moore, Robert, arXiv:hep-ph/0607172 (2006)  
 Atchison, Rapp, NPA 1037 (2023) 122704  
 Flörchinger *et al.*, PLB 837 (2023) 137647

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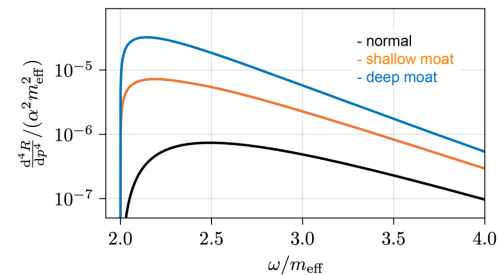
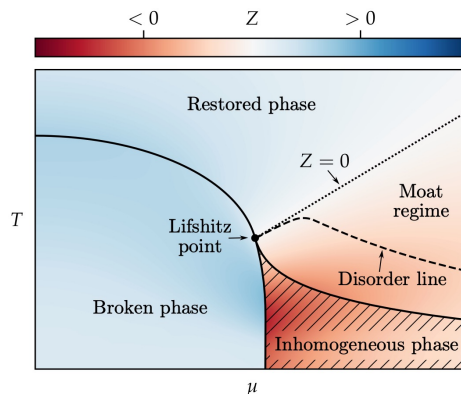
$$\sigma_{el}(T) = -e^2 \lim_{q_0 \rightarrow 0} \frac{1}{q_0} \text{Im} \Pi_{em}(q_0, q = 0; T, \mu_B)$$

Non-monotonic trend of  $\sigma_{el}$  as the phase transition occurs?



- Enhanced yield for soft dileptons predicted for **exotic QCD phases**
  - color superconducting phase
  - moat regime

Experimental constraints highly desirable

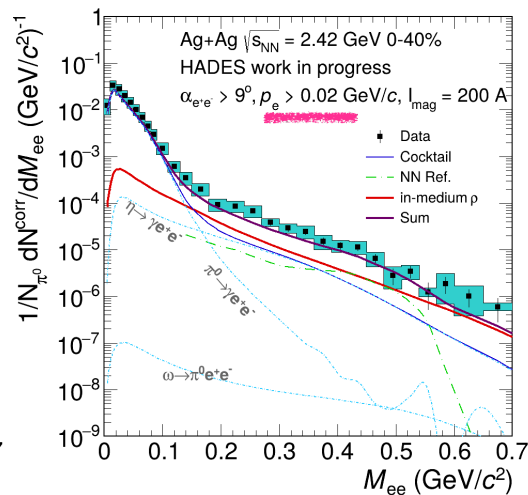
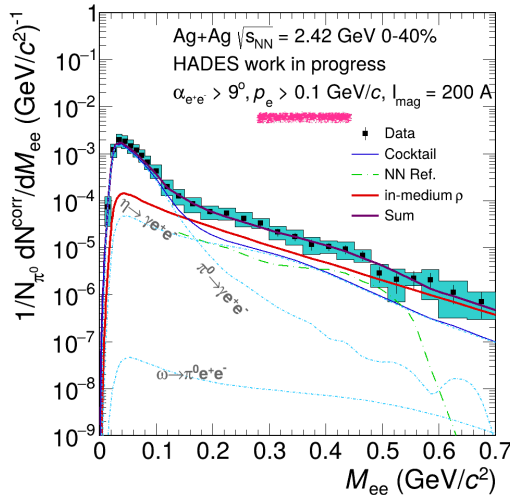


Nussinovet *et al.*, PRL135 (2025) 101904  
 Nishimura *et al.*, EPJA 60 (2024) 82

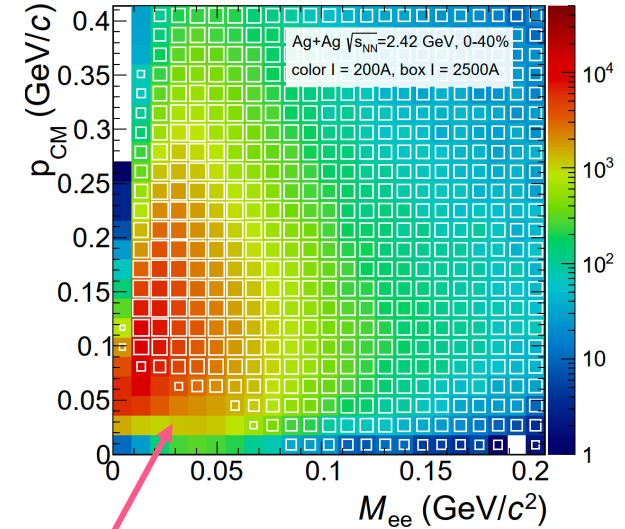
# Low-mass low-momentum dileptons

- Low field pilot run (6h of data taking)
  - 106 million Ag+Ag events
  - Low Field  $I_{\text{mag}} = 200$  A (6% out of  $I_{\text{max}}$ )

**Efficiency corrected spectra: agreement between data and model calculations when in-medium  $\rho$  included**



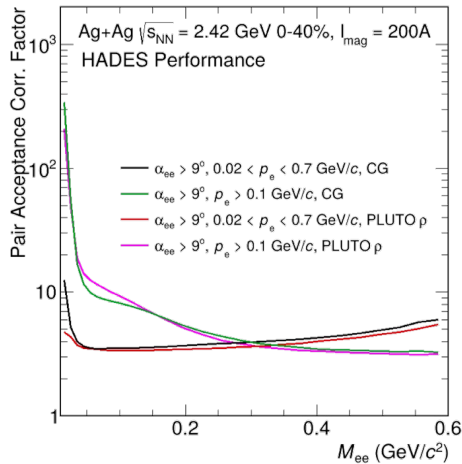
**Measured signal  $e^+e^-$  spectra of raw counts**



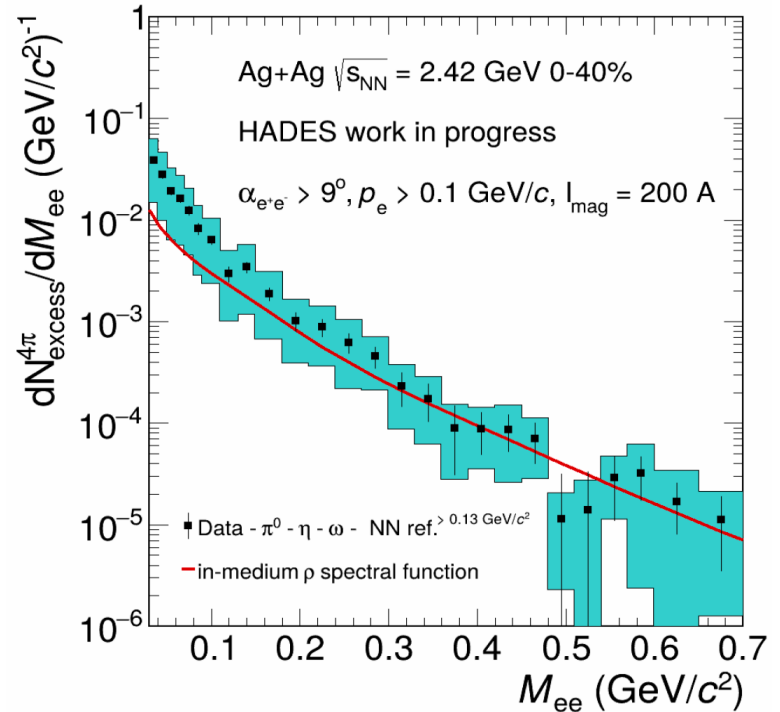
region of interest

# Excess yield extraction, low field Run

- Isolation of the excess by subtracting the experimentally measured NN reference and freeze-out contributions
- Acceptance corrections applied to pair spectra
- **Careful evaluation of systematic uncertainties is ongoing**
- New Au+Au at  $\sqrt{s_{NN}} = 2.23$  GeV low-field data recorded in 2025



Acceptance correction factor calculated based on various approaches, difference taken into systematics

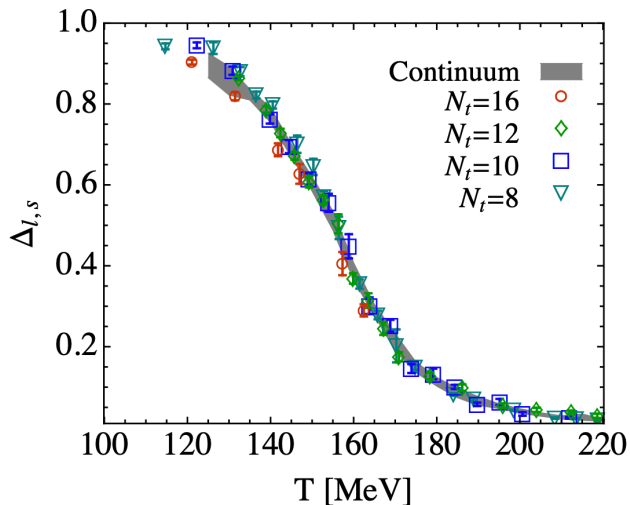


# Dileptons and chiral symmetry of QCD

**Spontaneously broken** in the vacuum

$$\langle 0 | \bar{q}q | 0 \rangle = \langle 0 | \bar{q}_L q_R + \bar{q}_R q_L | 0 \rangle \neq 0$$

Condensates  $\langle \bar{q}q \rangle$  calculated by lattice QCD

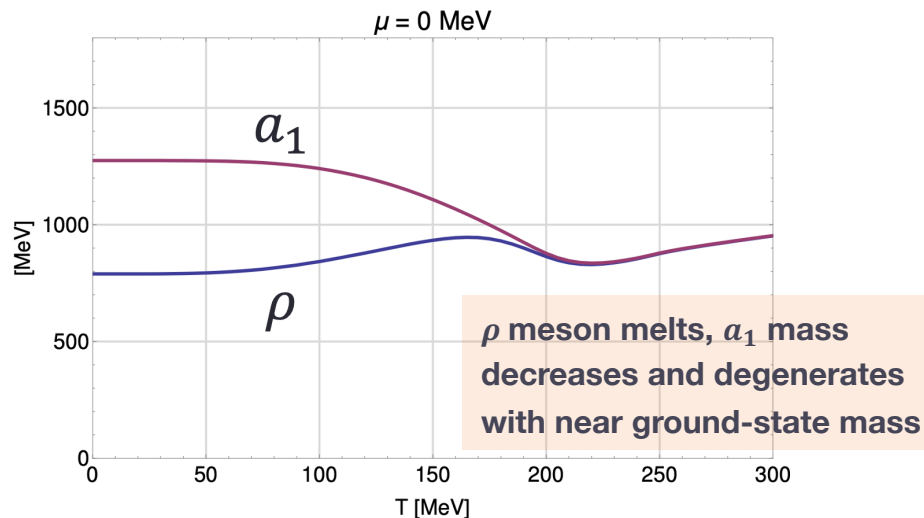


Bazavov *et al.* [Hot QCD Coll.], PRD90 (2014) 094503

S. Weinberg, PRL 18 (1967) 507

$$\int_0^\infty \frac{ds}{\pi} [\Pi_V(s) - \Pi_{AV}(s)] = m_\pi^2 f_\pi^2 = -2m_q \langle \bar{q}q \rangle$$

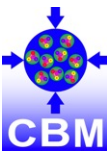
**Restoration** at finite  $T$  and  $\mu_B$  manifests itself through mixing of vector and axial-vector correlators



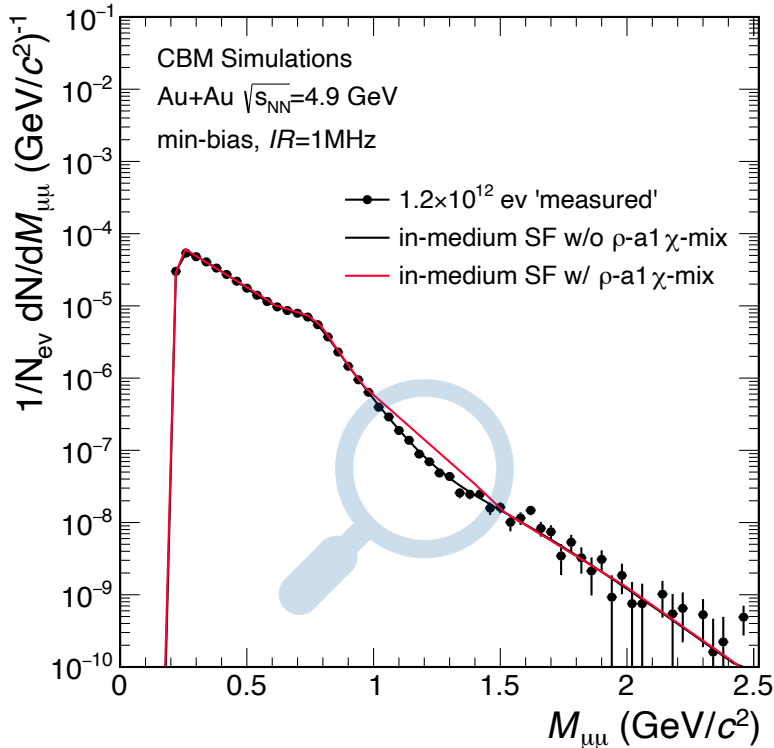
**Hadronic many-body theory** Hohler and Rapp, PLB 731 (2014)

**FRG** Jung, Rennecke, Tripolt, v. Smekal, Wambach, PRD95 (2017) 036020

**Light mesons and baryons from lattice QCD**, Aartz, QM2022, April 2022



# (additional) Signature for chiral symmetry restoration



- Changes in yield and shape at  $M_{\ell\ell} > 1.1$  GeV/ $c^2$  due to **chiral  $\rho - a_1$  mixing**
- $\pi a_1 \rightarrow \gamma^* \rightarrow \ell^+ \ell^-$  (chiral mixing) is a dominant hadronic source in IMR
- **20-30% enhancement** w.r.t. no chiral mixing is **predicted**

Dey, Eletsky, Ioffe, PLB252 (1990)  
 Rapp, Wambach, ANP 25 (2000)  
 Sakai *et al.*, arXiv:2308.03305 [nucl-th]

## Experimental challenge: physics background ( $M_{\ell\ell} > 1$ GeV/ $c^2$ )

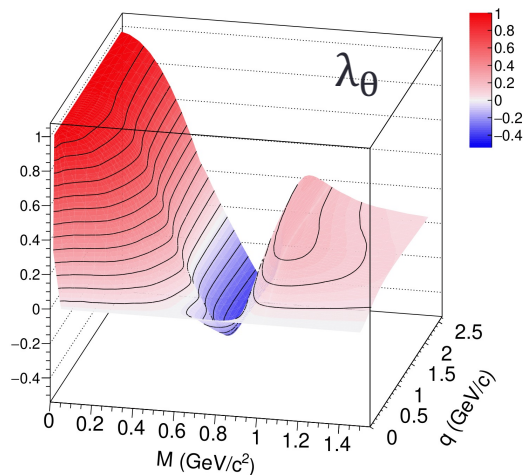
- correlated charm: excellent vertex resolution  $\rightarrow$  topological separation of prompt and non-prompt source employing DCA cut
- QGP: decrease towards lower energy
- Drell-Yan: pp, pA measurements
- **Sensitivity** to detect a signal (CBM, NA60+/DiCE, ALICE3) is **demonstrated**

# Virtual photon polarization

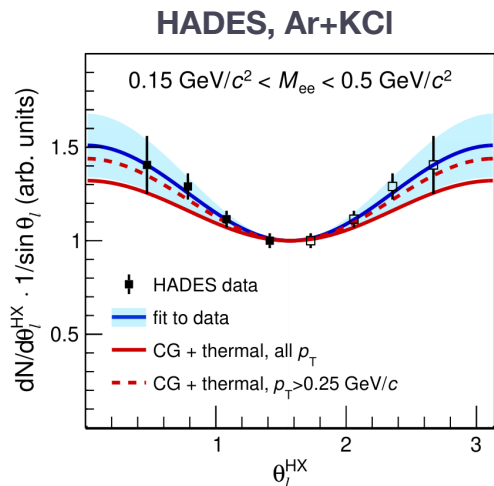
- Angular distribution of single lepton in  $\gamma^*$  rest frame depends on polarization of  $\gamma^*$

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

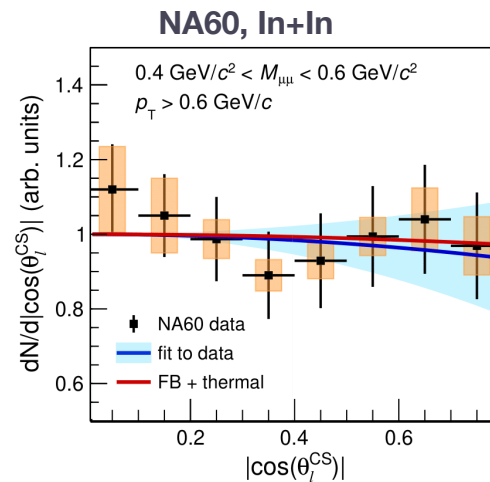
- $\lambda$  coefficients related to **difference** between **longitudinal and transverse** spectral function components  $\lambda_\theta = \frac{e_T - e_L}{e_T + e_L}$
- Different virtual photon **production mechanisms** imprint different anisotropy parameters  $\lambda$



Seck *et al.*, arXiv: 2309.03189



data points: HADES, PRC 84 (2011) 014902



data points: NA60, PRL 102 (2009) 222301

# Disentangling hadronic and partonic sources

## Polarization plays important role in exploring the mechanisms underlying EM emission

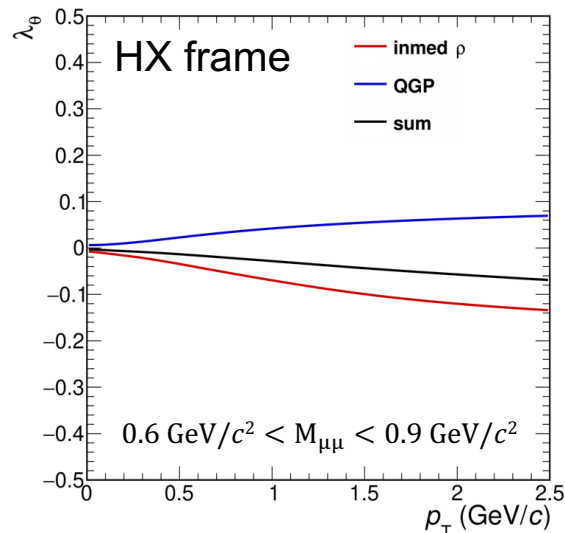
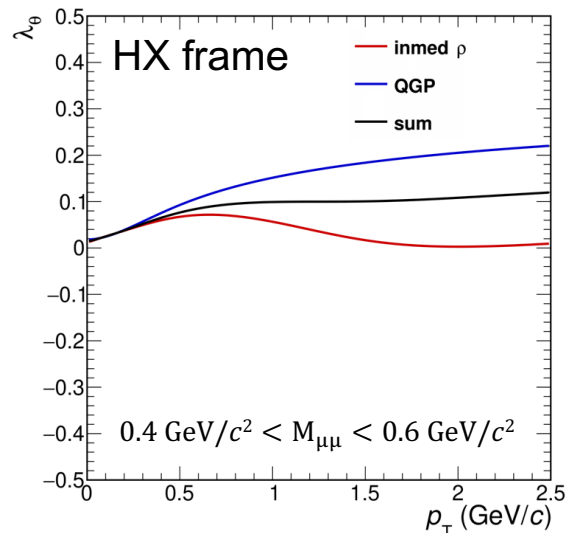
Seck *et al.*, arXiv: 2309.03189

Coquet, Winn, Du, Ollitrault, Schlichting, PRL132 (2024) no.23, 232301

Speranza *et al.*, PLB 782, 395 (2018)

Baym *et al.*, PRC95, 044907(2017)

Bratkovskaya *et al.*, PLB 376, 12 (1996)



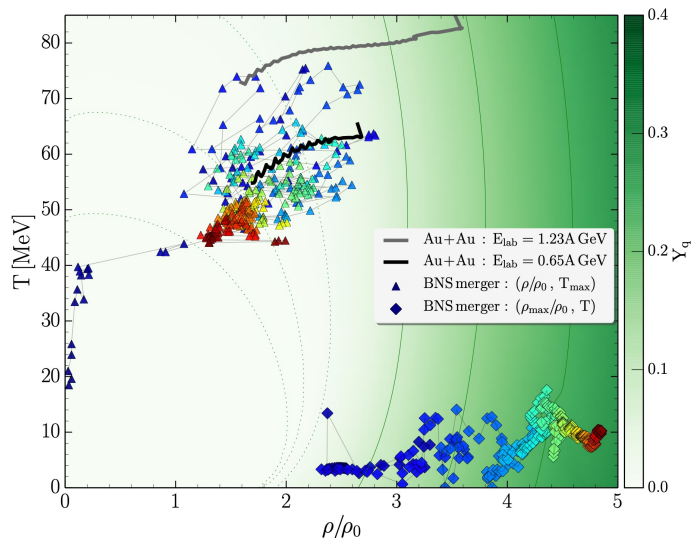
### Multi-differential measurements of the $\gamma^*$ polarization

- resolve mass,  $p_T$ , rapidity, lepton emission angles  $\theta_l, \varphi_l \rightarrow$  large datasets needed
- future high-rate experiments CBM, NA60+ and ALICE3
- search for onset of QGP
- important in disentangling  $\rho - a_1$  chiral mixing from QGP around  $M_{ll} \sim 1.2 \text{ GeV}/c^2$

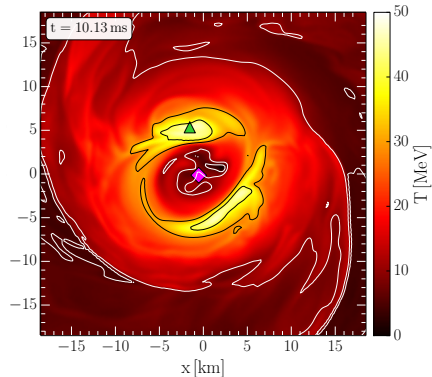
# The QCD phase structure at high $\mu_B$

QCD phase transition in **binary neutron star mergers**:

- Affect neutron star cooling and merger dynamics
- Potential impact on nucleosynthesis and kilonovae

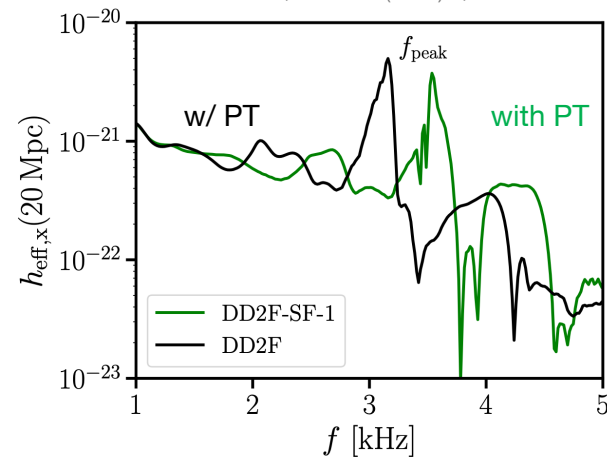


Hanuske *et al.*, Particles 2 (2019) no.1  
Rezzolla *et al.*, PRL 122 (2019) no. 6, 061101



Study the possible occurrence of the hadron-quark phase transition and its signature in Gravitational Waves

Bauswein *et al.*, PRL 122 (2019) 6, 061102



- NS mergers probe bulk properties of EoS – microphysics only accessible through combined effort

Blacker *et al.*, PRD 109 (2024) 4, 043015  
Vijayan *et al.*, PRD 108 (2023) 2, 023020

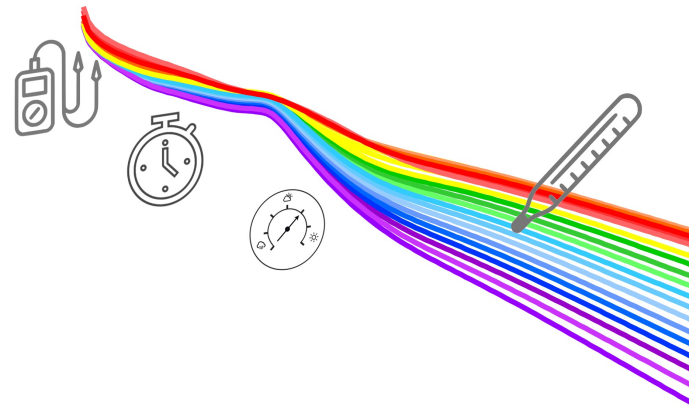
- Consistency between EOS infer from observables from BNS mergers and new high precision HIC

Most *et al.*, PRD 107 (2023) 043034

# Résumé: The future is bright

## Unique possibility of characterizing properties of hot and dense QCD matter with dileptons

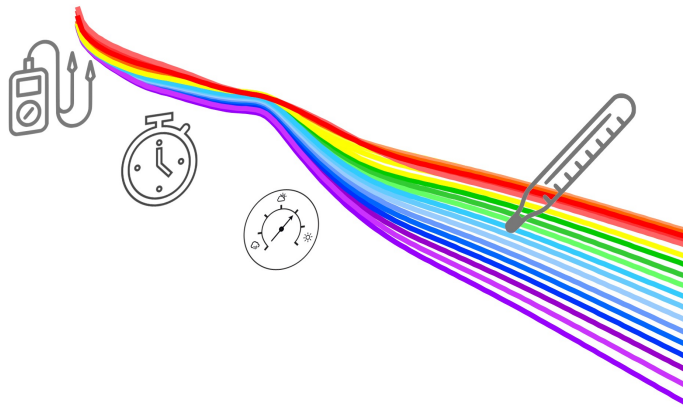
- Robust understanding of low-mass dilepton excess radiation through  $\rho$ -baryon coupling (at LHC, RHIC, SPS and SIS18 energies)
- 1<sup>st</sup> order phase transition and QCD critical point is awaiting discovery  
→ might be detected in dileptons excitation functions
- Complementary program on exclusive measurements in  $\pi$ , p induced reactions
- Thermal dileptons enable unique measurements
  - degrees of freedom of the medium
  - restoration of chiral symmetry
  - transport properties
  - fireball lifetime, temperature, acceleration, polarization
- To fully exploit this observable, measurement at unprecedented precision and statistics are needed



# Résumé: The future is bright

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**Thank you  
for your attention!**

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# BONUS SLIDES

# Multi-differential ( $M_{\ell\ell}, p_T, v_n, \lambda_\theta$ ) emission probability of dileptons, current and future

ALICE, Run3 & Run4



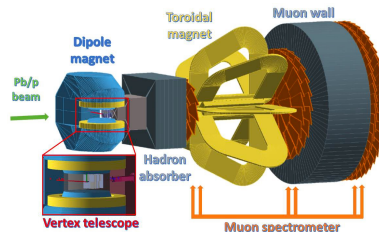
<https://cds.cern.ch/record/2703140>

STAR



NA60+DiCE at SPS

LoI, <http://arxiv.org/abs/arXiv:2212.14452>

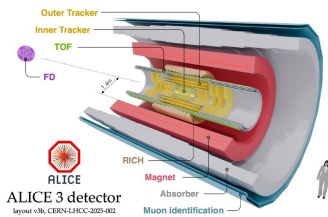


CBM / HADES at FAIR



© GSI/FAIR, Zeitrausch

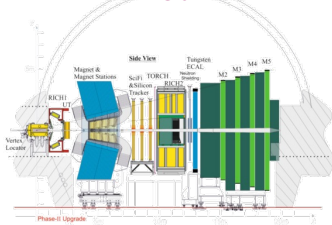
ALICE 3



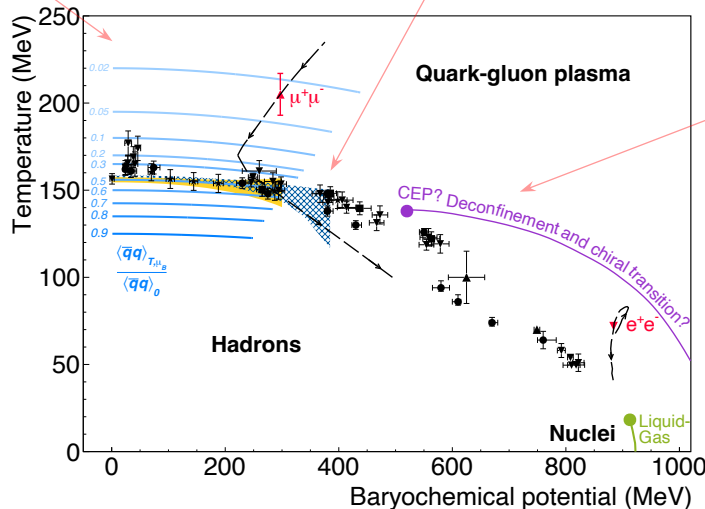
ALICE 3 detector layout v36, CERN-LHCC-2025-002

<http://cds.cern.ch/record/2803563>

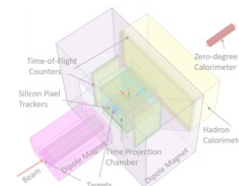
LHCb-II



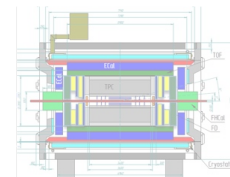
CERN-LHCC-2021-012



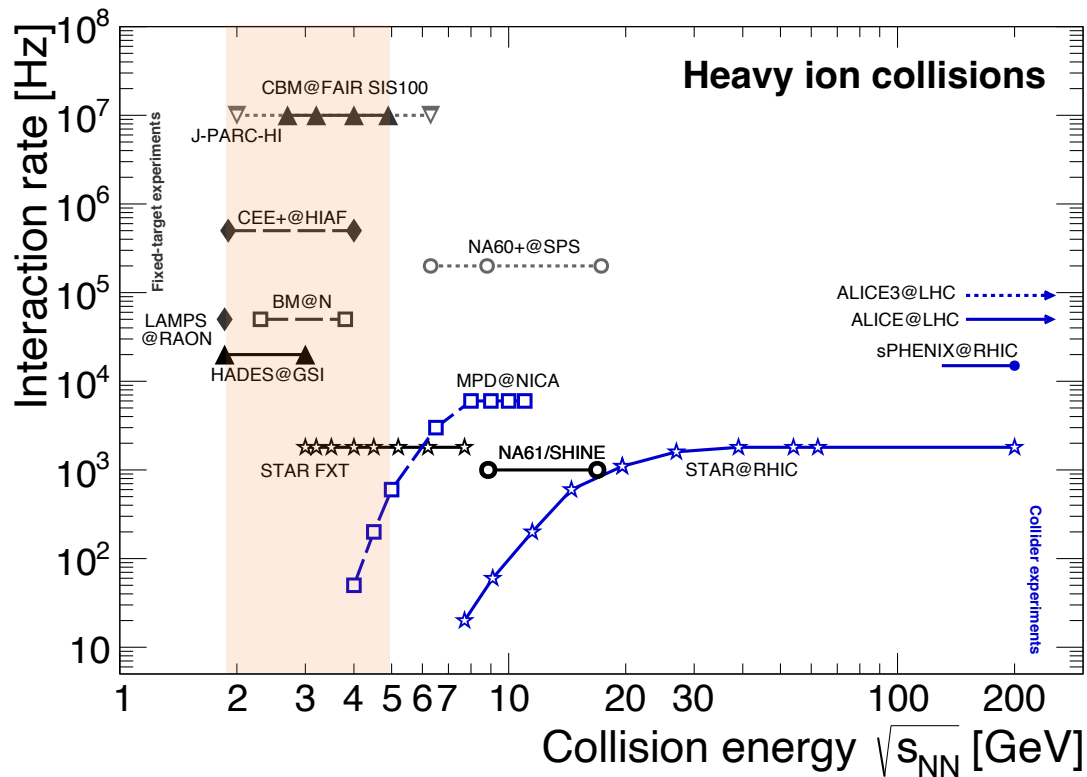
J-PARC-HI



MPD



# Exploring the “terra incognita” with EM probes



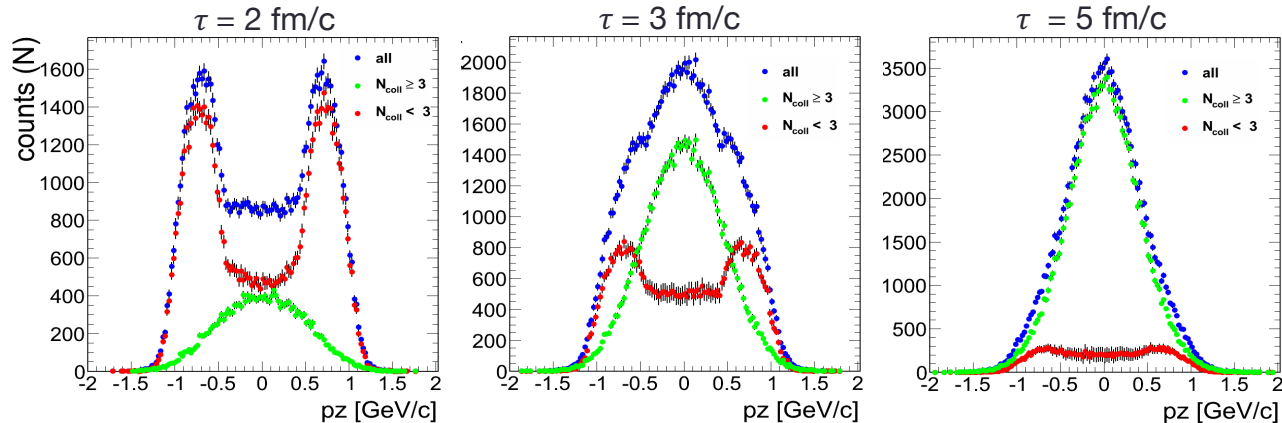
- **CBM** will play a unique role in the exploration of the QCD phase diagram in the region of high  $\mu_B$  with rare and electromagnetic probes: high rate capability, **energy range**  $3 < \sqrt{s_{NN}} < 5$  GeV
- **HADES**: established thermal radiation at high  $\mu_B$ , limited to 20 kHz and  $\sqrt{s_{NN}}=2.4$  GeV
- **STAR FXT@RHIC**: BES program completed; limited capabilities for rare probes
- **NA60+ proposal**: dimuon spectrometer at SPS, energy range  $6 < \sqrt{s_{NN}} < 17$  GeV,  $>10^5$  Hz rate capability
- **ALICE / ALICE 3**: exploit the forefront detector technologies and high luminosity potential of the LHC for ions

**Program needs ever more precise data and sensitivity for rare signals**

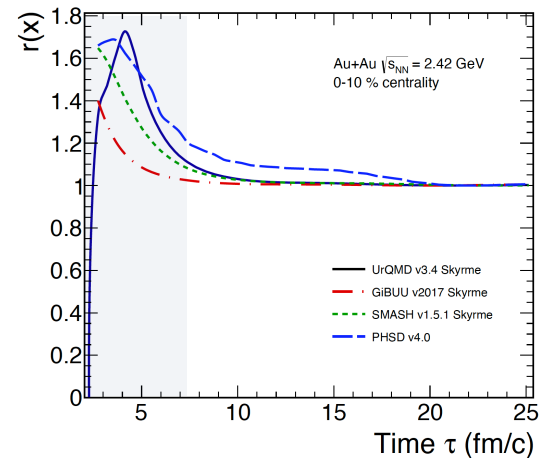
# Justifying local thermal equilibrium

Au+Au  $\sqrt{s_{NN}} = 2.42$  GeV, central cell

## Momentum distributions of nucleons



## Relaxation function $r(x)$ vs time

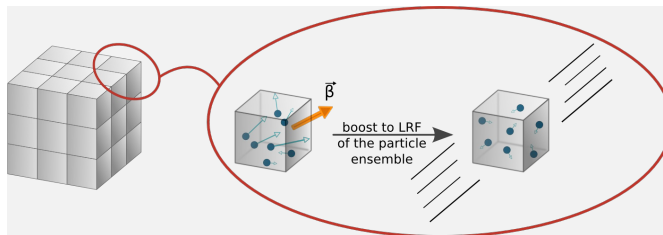


Check for every cell:

- Gaussian shaped  $p_z$  distribution builds up for nucleons with  $N_{\text{coll}} \geq 3$
- $r(x)$  deviates from 1 by  $< 5\%$
- $m_T$  spectra have exponential shape

# Determination of bulk properties

- Baryon density via 4-current
- Lorentz-boost to local rest frame (LRF) where the baryon current vanishes



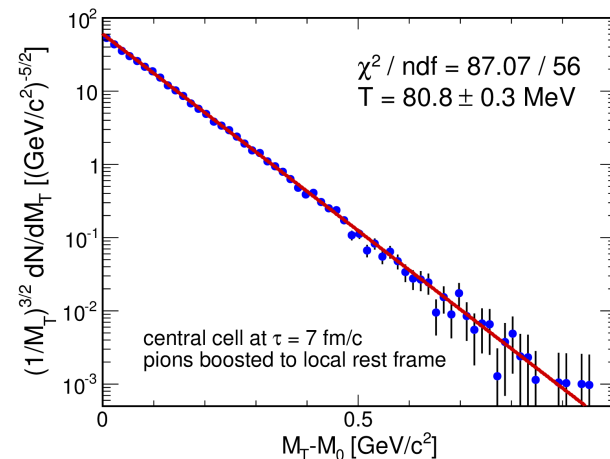
- In Boltzmann approximation

$$\frac{d^3N}{d\vec{p}} = \frac{d^3N}{dp_z p_T dp_T d\theta} \propto \exp(-E/T)$$



$$\frac{1}{m_T^{3/2}} \frac{dN}{dm_T} \propto \exp(-m_T/T)$$

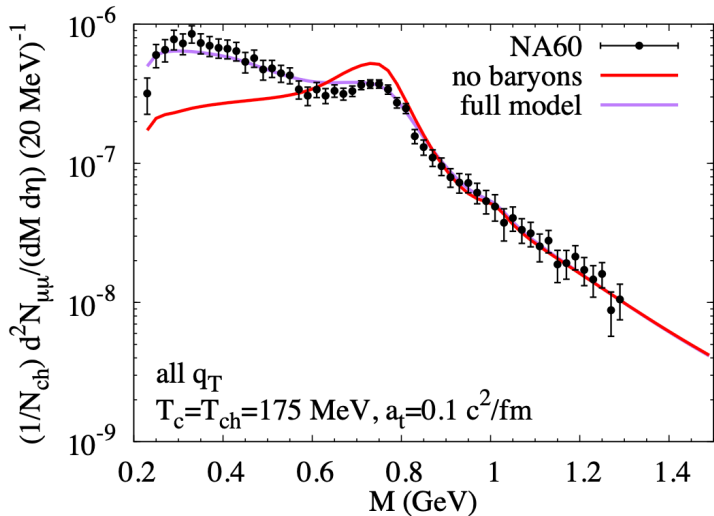
- Fill  $m_T$  spectra with particle momenta in LRF (mean flow  $v_{coll}$  vanishes)
- Fit exponential function to extract T (species of choice: pions)



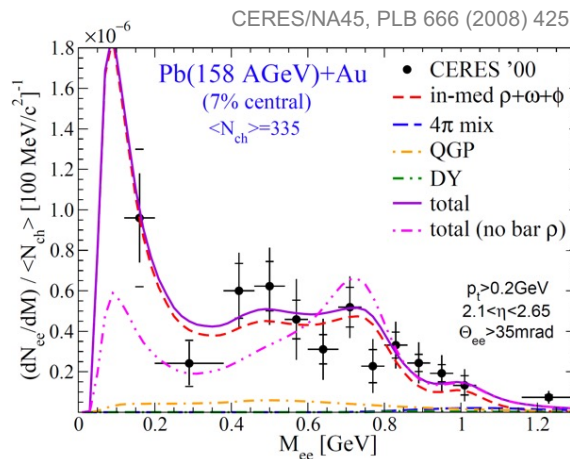
# Measured excess dilepton spectra

NA60, EPJC 61(2009) 711

NA60, Chiral 2010, AIP Conf.Proc. 1322 (2010)



Strongly supports melting of  $\rho$ , in particular due to baryon-induced effects



STAR, PRL 113 (2014) 022301;  
 PRC 92 (2015) 024912; PLB 750 (2015);  
 PRC107 (2023) L061901 → BES 62.4 – 27 GeV

