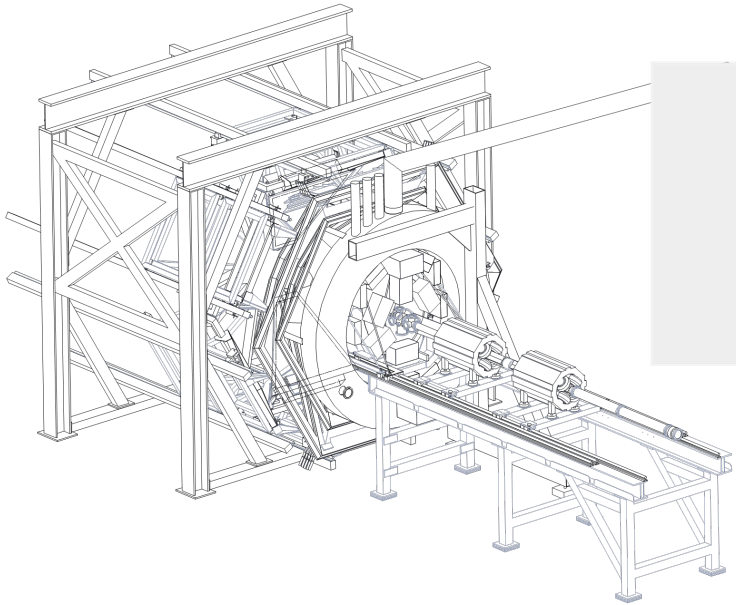
HADES results on emissivity of QCD matter at SIS18

TECHNISCHE UNIVERSITÄT DARMSTADT

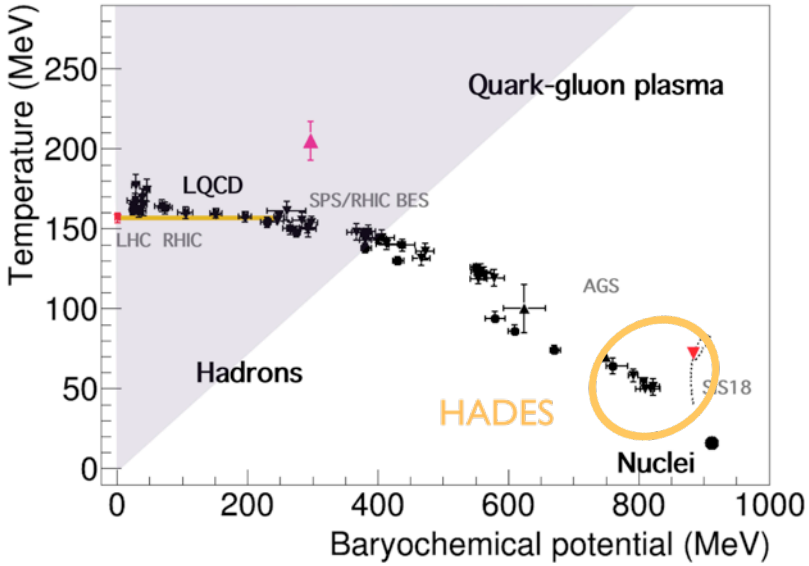


Tetyana Galatyuk
for the HADES Collaboration

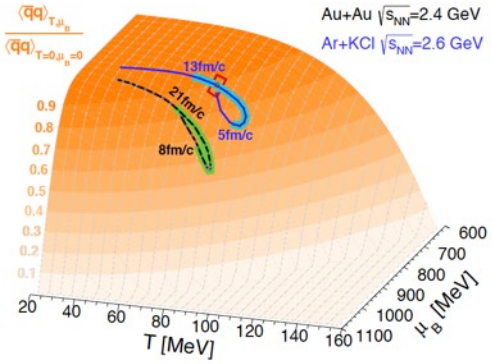
ECT* 2018, Trento, Italy, 26th Nov 2018

GSI FAIR HADES

The HADES Physics Case

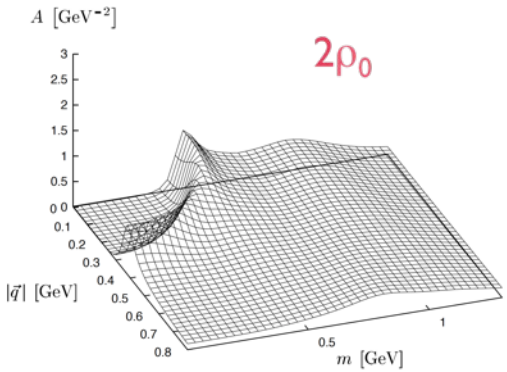


chiral condensate



F. Seck *et al.*, JPCS 1024 (2018) 012011

in-medium ρ spectral function



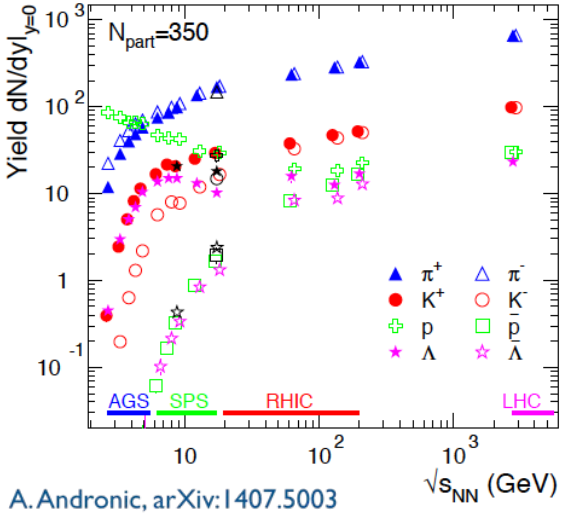
W. Peters *et al.*, Nucl.Phys. A632 (1998)

- Explore the high-μ_B region of the QCD phase diagram
- Focus on rare and penetrating probes
- Address various aspects of baryon-meson coupling

- Heavy-ion collisions: properties of matter occurring in neutron star mergers
- π, p beams:
  - Reference measurements (vacuum, cold QCD matter)
  - Explore electromagnetic structure of baryons/hyperons in time-like region

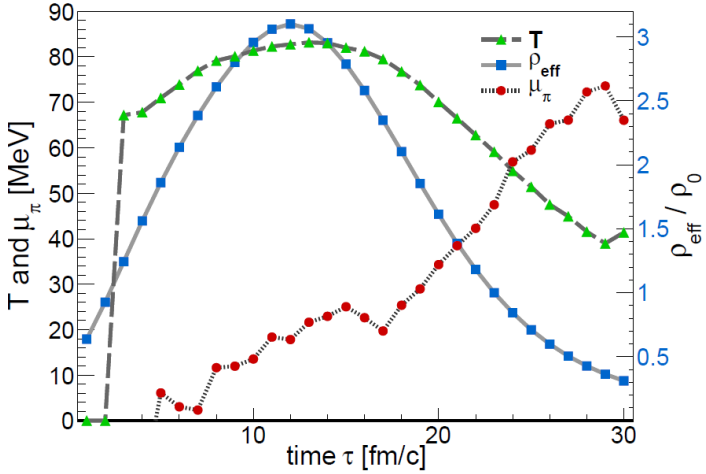
Baryonic matter at few GeV beam energy

Hadron yields at freeze out

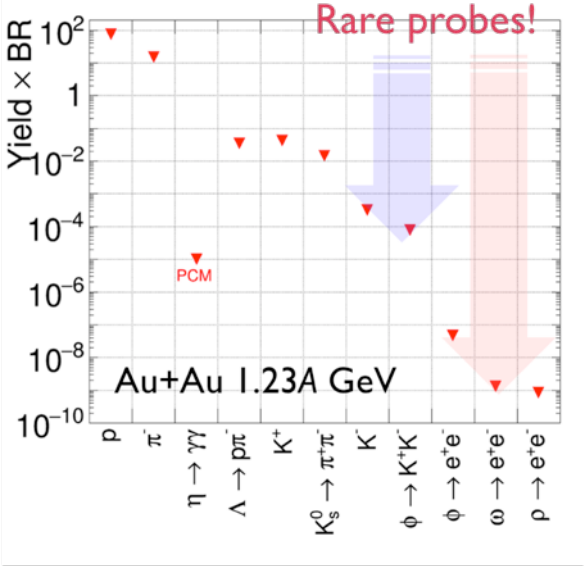


A. Andronic, arXiv:1407.5003

Central cell (3x3x3 fm^3) thermodynamic properties from coarse graining UrQMD



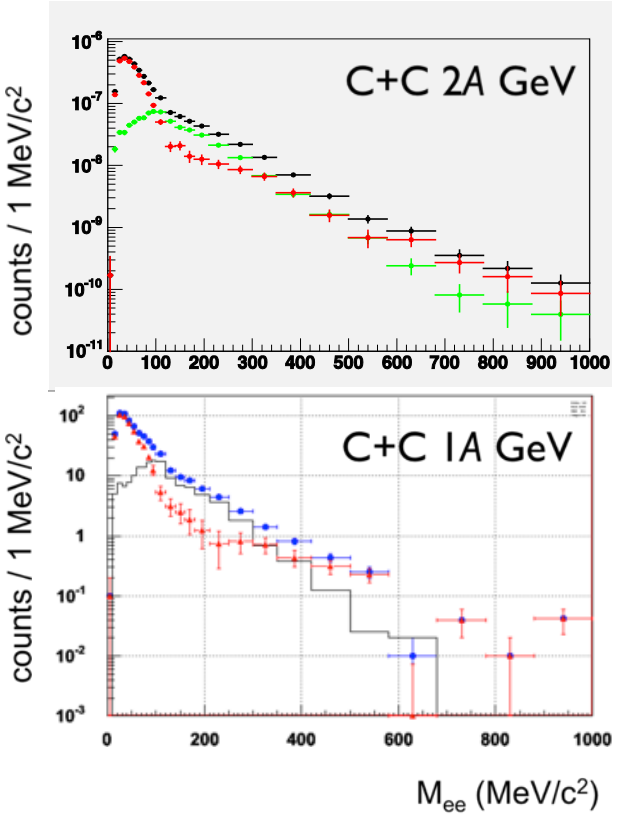
TG, F. Seck, R. Rapp, J. Stroth, Eur. Phys. J. A 52 (2016) 131



- Baryon-dominated system throughout the evolution ($N_\pi/A_{part} \approx 10\%$)
- π densities a factor ~50 lower as compared to SPS regime!
- ~6 fm interpenetration times
- ~13 fm lifetime of the dense fireball: $\rho_{max} \approx 3\ \rho_0$; T < 80 MeV

HADES at ECT* 2005

No Eff/Acc Correction!

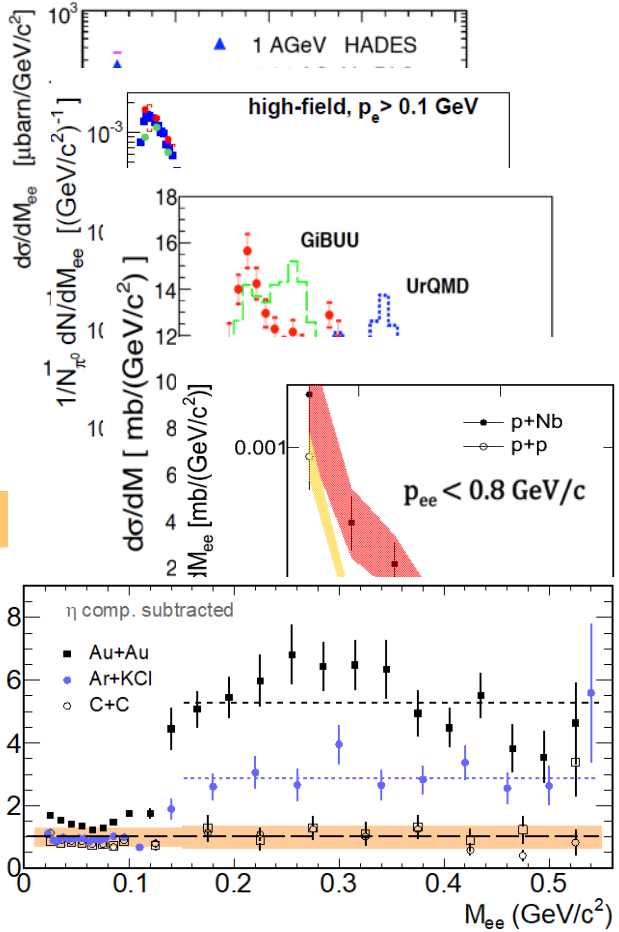


Dileptons from HADES

- C+C at 1 and 2*A* GeV
  - The DLS results are correct
- *p+p* & *n+p* 1.25 GeV
  - Experimental solution of the „DLS puzzle“
  - First direct access to the Δ transition form factor in the time-like region

  PDG Entry 2018
- *p+p* 2.2, 3.5 GeV
  - Constraints on higher lying resonances: electromagnetic channels

  PDG Entry 2012, 2014
- *p+Nb 3.5 GeV*
  - Cold matter effects - indication for strong broadening of the ω
- *Ar+KCl, Au+Au*
  - First evidence for radiation from the “medium” in this energy regime!
- π+*p*/*A*
  - Verify the ρ-baryon coupling mechanism



Phys.Rev.Lett. 98 (2007) 052302
Phys.Lett. B663 (2008)

Phys.Lett. B690 (2010)
Phys.Rev. C95 (2017) 065205
Eur.Phys.J.A53 (2017)

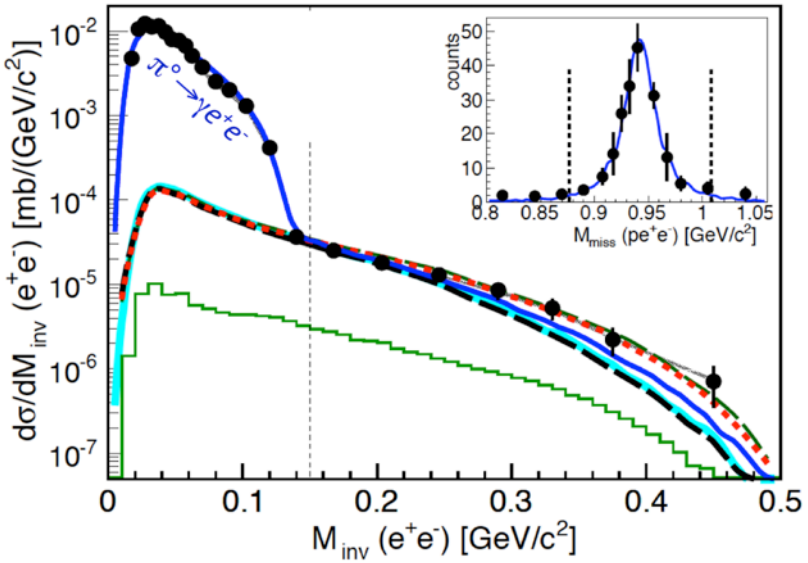
Phys.Rev. C85 (2012) 054005
Eur.Phys.J.A48 (2012) 64
Eur.Phys.J.A48 (2012) 74
Eur. Phys. J.A (2014) 50

Phys.Lett. B715 (2012)
Phys.Rev. C88 (2013) 024904

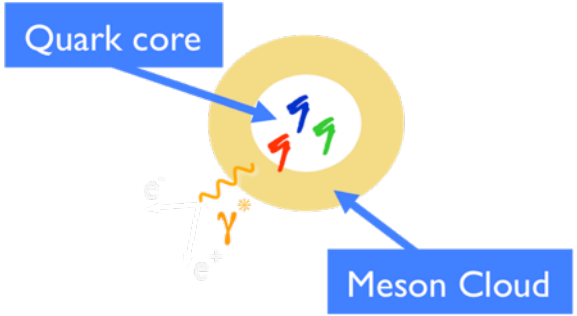
Phys.Lett. B715 (2012)
Phys.Rev. C88 (2013) 024904

Exploring electromagnetic structure of hadrons

Exclusive dielectron spectrum $p(1.25\ GeV)p \rightarrow ppe^+e^-$



- First direct access to the Δ electromagnetic transition form factor in the time-like region
  - Deviation from «point-like» transition
  - Excitation of a baryon can be carried by the meson cloud



HADES Collab. Phys.Rev. C95 (2017) 065205

Krivoruchenkoet al. Phys. Rev. D65(2002) 017502
Iachello, Wan Int. J Mod. Phys. A20 (2005) 1846
Ramalho, Peña, Phys. Rev. D85(2012) 113014
Shyam, Mosel, PRC82 (2010)062201

QED
I&W
R&P quark core
R&P pion cloud
S&M brems.

First measurement:

PDG Entry 2018

Δ(1232) BRANCHING RATIOS

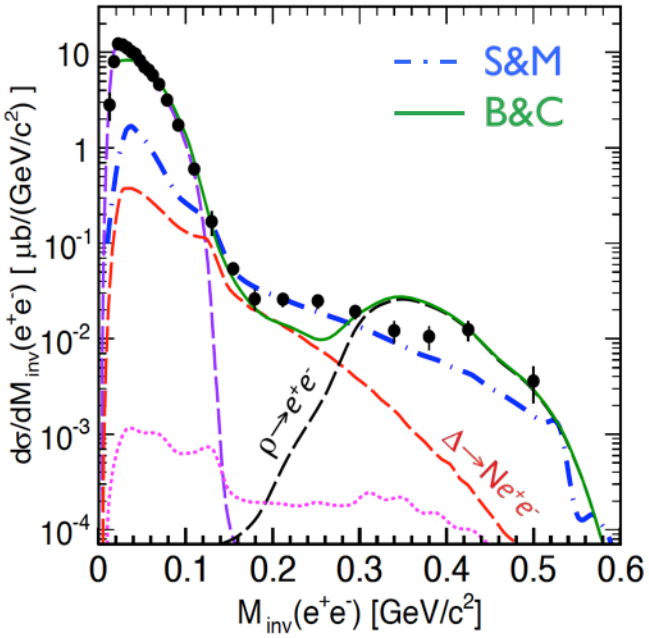
$\Gamma(pe^+e^-)/\Gamma_{total}$

VALUE (units 10^{-5})	*DOCUMENT ID*
4.19±0.34±0.62	[1] ADAMCZEW... 17

[1] The systematic uncertainty includes the model dependence.

Virtual photon emission from charged currents

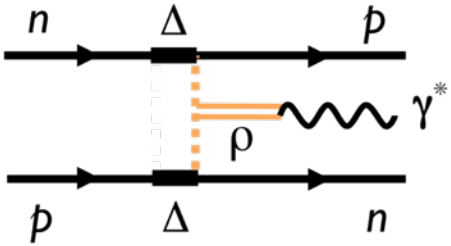
Exclusive dielectron spectrum $n(1.25\ GeV)p \rightarrow pne^+e^-$

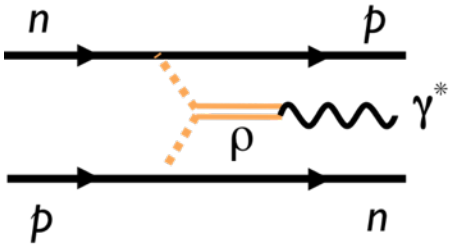


HADES Collab., Eur.Phys.J.A53 (2017) 149

S&M: R. Shyam and U. Mosel, PRC 82 (2010) 062201
B&C: M. Bashkanov, H. Clement, Eur. Phys. J.A50 (2014) 107

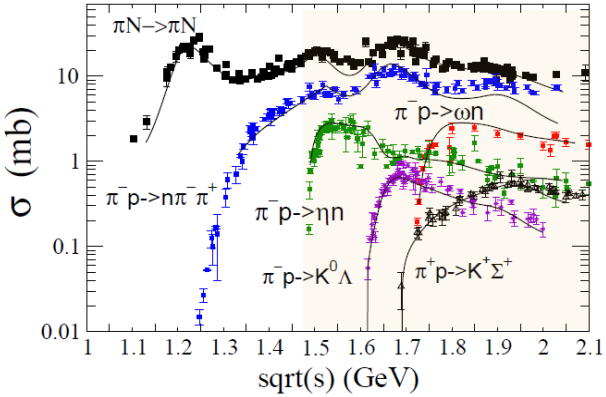
- Remarkable isospin effect: much larger e^+e^- yield at large M_{ee} than in *pp*
- Radiation from the internal line yields enhanced emission at high invariant masses
  → off-shell (cloud-cloud) ππ collision



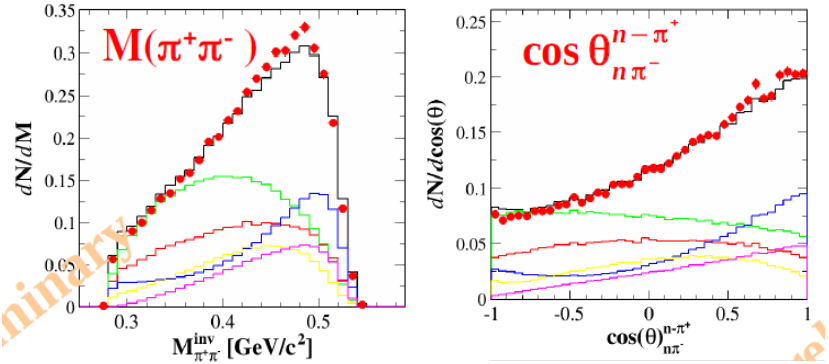


HADES $\pi^- + p \rightarrow \pi^+ + \pi^- + n$

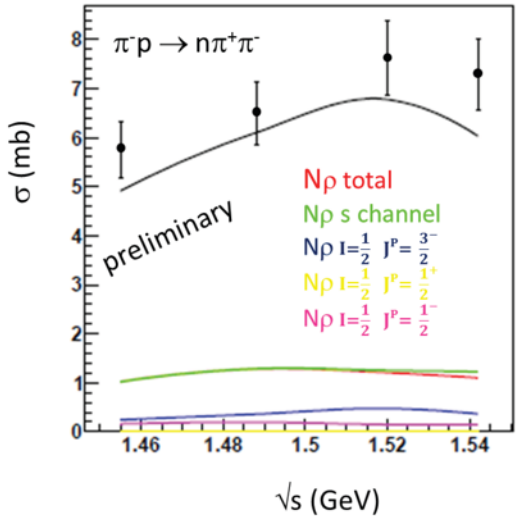
- GSI π^- momentum range 0.65–2.5 GeV/c
- HADES final states: $2\pi N$, πN, e^+e^- (wordwide unique)
- No results on ρ production due to lack of data
  (only D. Manley analysis PRD30 (1984) 904 based on ~200k events)



HADES data and PWA results

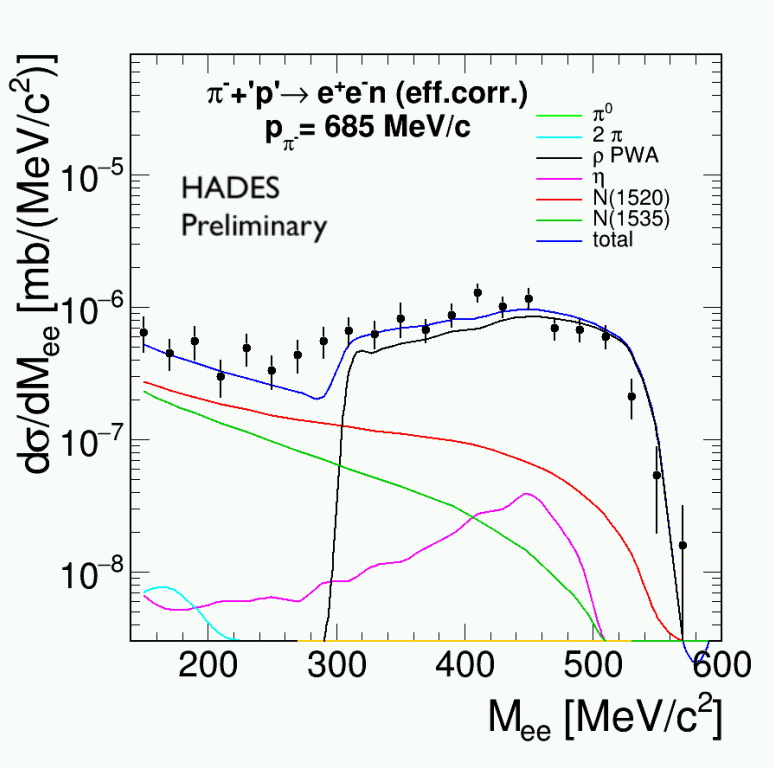


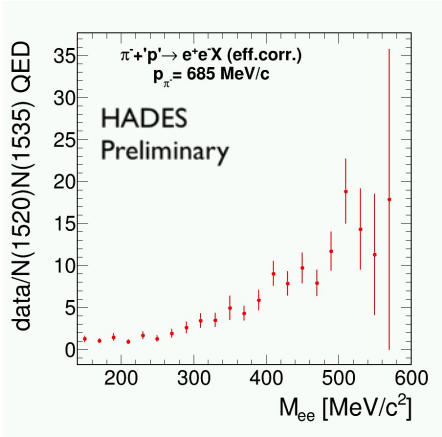
σN Δπ P_{11} D_{13} ρN

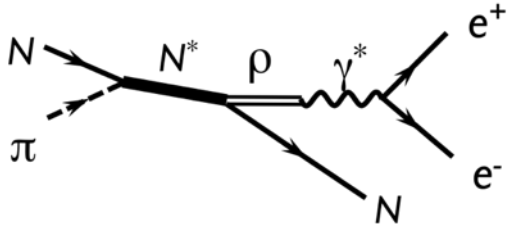


- Hadronic final states used in PWA (A. Sarantsev; Bonn/Gatchina)
- p_π = [656, 690, 748, 800] MeV/c

HADES $\pi^- + p \rightarrow e^+ + e^- + n$ at $\sqrt{s} = 1.49$ GeV







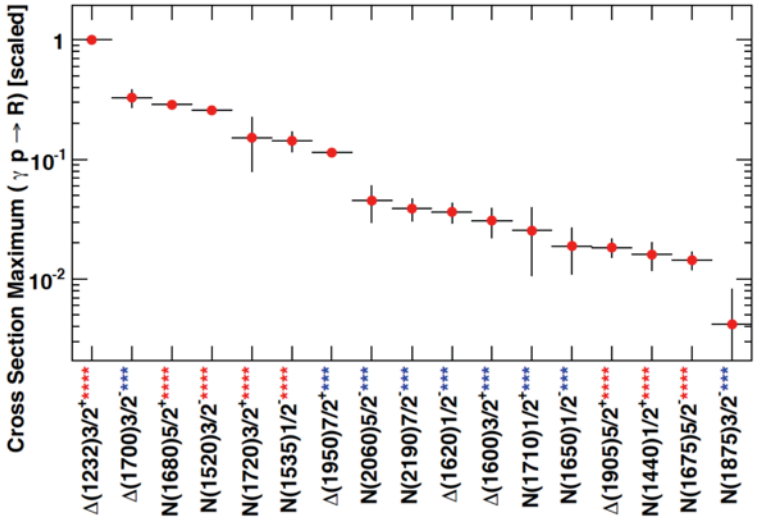
In accordance with strict VMD (the basis of emissivity calculations for QCD matter)

- Convert bin-by-bin $M_{\pi\pi}$ to M_{ee} using: $\frac{d\sigma}{dM_{ee}} \propto \frac{1}{M_{ee}^3} \times \frac{d\sigma}{dM_{\pi\pi}}$
- Evidence for intermediate ρ propagation in both *s*- (baryon resonance) and *t*-channel

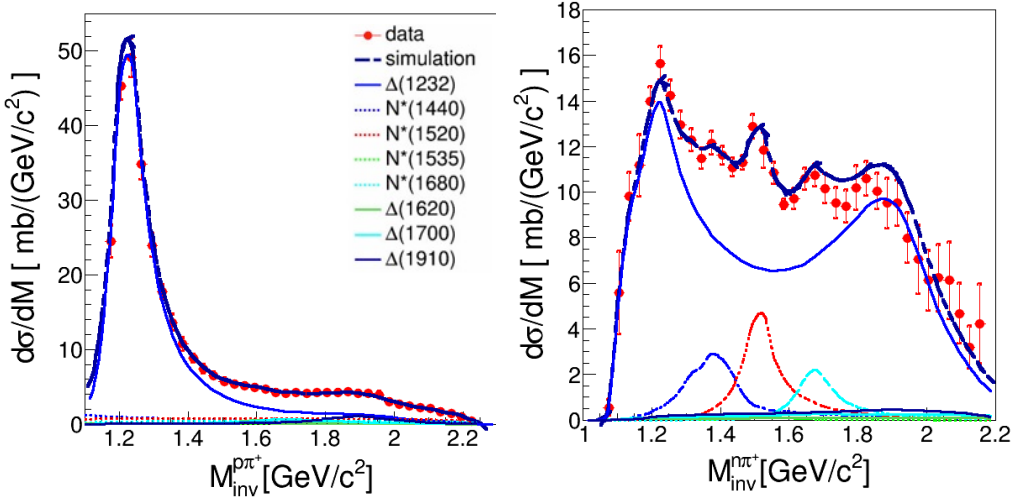
In progress comparison to:
E. Speranza, B. Friman et al., Phys. Lett. B764 (2017) 282
Ramalho, Peña, Phys.Rev. D95 (2017) 014003

Exclusive analysis of $p+p$ at E_{kin} = 3.5 GeV

BoGa PWA, A.V. Anisovichet al, Eur. Phys. J. A 48 (2012)



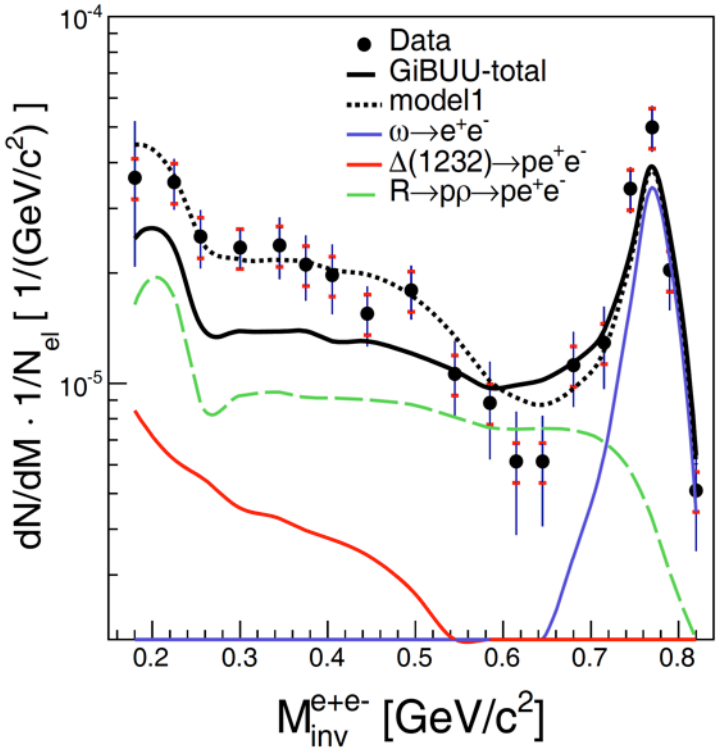
HADES $np\pi^+$



HADES Collab., Eur. Phys. J. 50 A (2014) 82

- Resonance model: production amplitude is given by incoherent sum of R contributions, isospin relations
- Resonance parametrization *S. Teis et al., Z. Phys. A356 (1997) 421*
- Take 4* resonances and empirical angular distributions

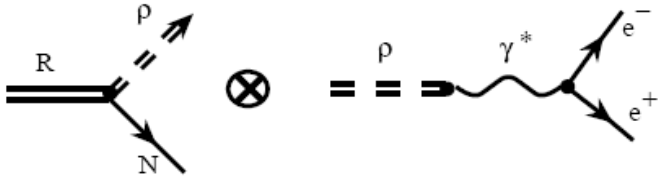
Exclusive dilepton production $pp \rightarrow pp\ e^+e^-$



HADES Collab., Eur. Phys. J. 50 A (2014) 82

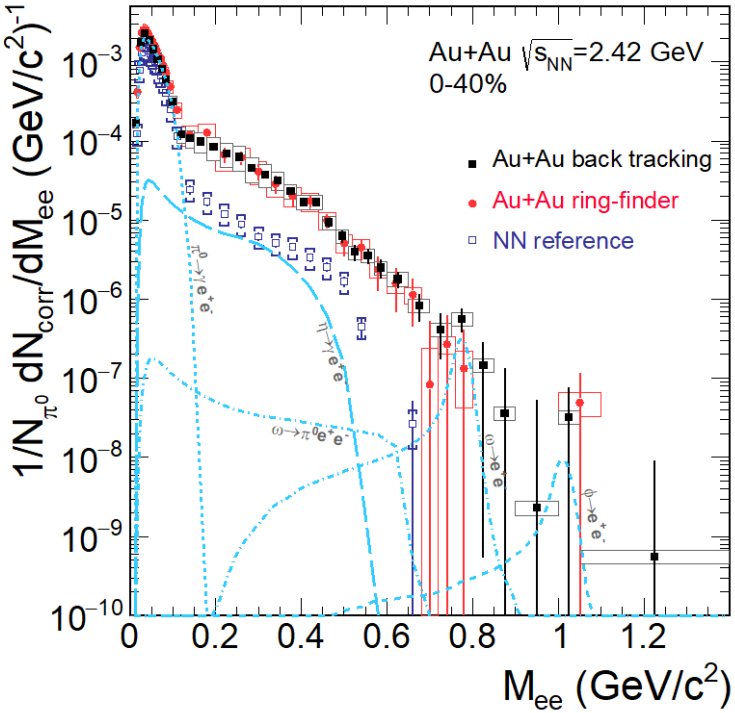
- Significant contribution from higher (than Δ) mass resonances
- „QED" point like R→Nγ* vertex not sufficient to explain measured data

- Good description of data when strict VDM with ρ dominance is used



Heavy-ion collisions

Virtual photon emission from Au+Au at $\sqrt{s_{NN}}$ = 2.42 GeV



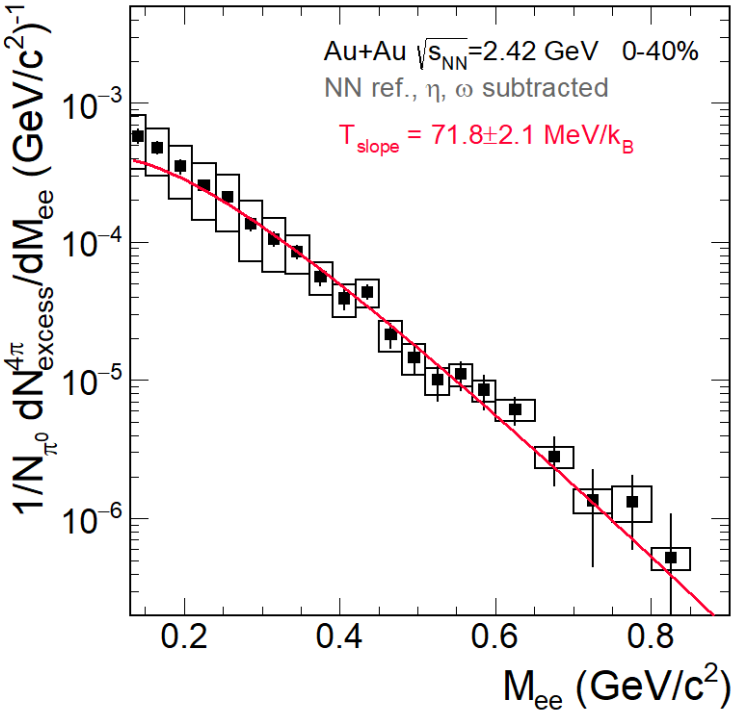
HADES Collab., submitted

- Efficiency corrected dilepton mass spectra normalized to the number of neutral π
- Comparison to
  - e^+e^- cocktail accounting for decays of mesons (π^0, η, ω, ϕ) at freeze-out measured in the same experiment
  - e^+e^- measured in *NN* collisions (*NN* reference)

$$\frac{dN_{ref}^{NN}}{dM_{ee}} = \left(0.54\frac{dN^{pp}}{dM_{ee}} + 0.46\frac{dN^{np}}{dM_{ee}}\right)\langle A_{part}\rangle$$

- Excess yield 0.15<M_{ee}<0.7 GeV/c^2
  → true in-medium radiation

Excess e^+e^- spectrum from *Au+Au at* $\sqrt{s_{NN}}$ = 2.42 GeV



HADES Collab., submitted

- Isolation of excess yield by subtracting the experimentally measured
  - Freeze-out contributions
  - *NN* reference
- Correct for acceptance

Dileptons as thermometer

- Mass spectrum falls exponentially
- Fit $\frac{dN}{dM} \sim M^{3/2} \times exp\left(-\frac{M}{T}\right)$ in range *M*=0.2-0.8 GeV/c^2
- $\langle T \rangle_{emitting\ source}$ = 72 ± 2 MeV/k_B

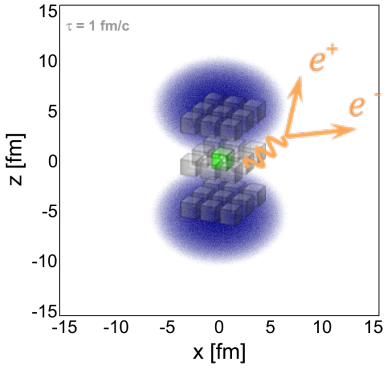
Coarse-grained transport approach

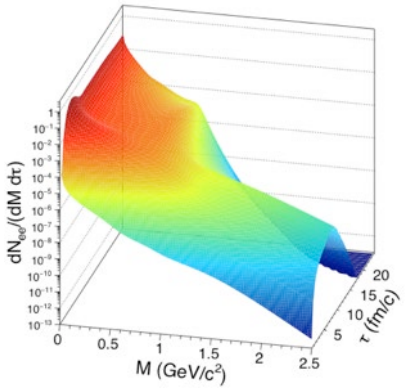
- Bulk evolution from microscopic transport
- Apply equilibrium rates locally

  - Simulate events with a transport model
    → ensemble average to obtain smooth space-time distributions

  - Divide space-time in 4-dimensional cells
    21×21×21 space cells (1fm^3), 30 time steps → ~ 280 k cells
  - Determine for each cell the bulk properties like T, ρ_B, μ_π, collective velocity

  - Use in-medium ρ & ω spectral functions to compute EM emission rates
    → parameterization of RW in-medium spectral function

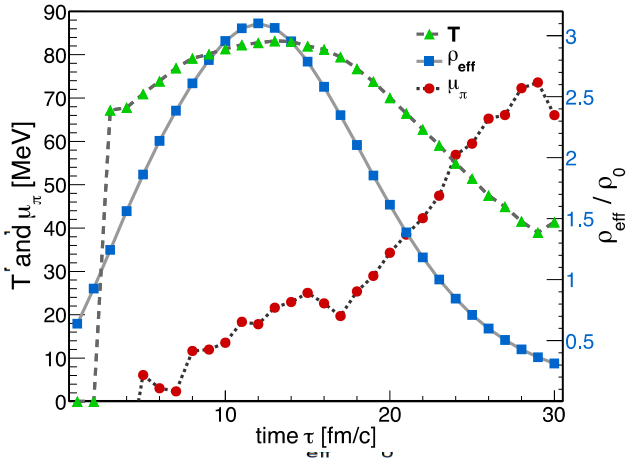


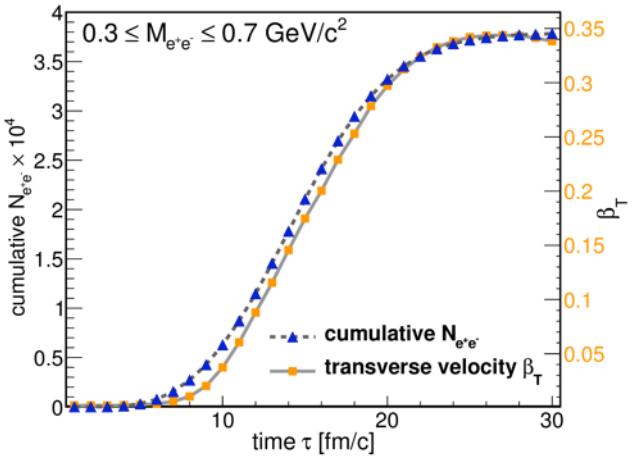


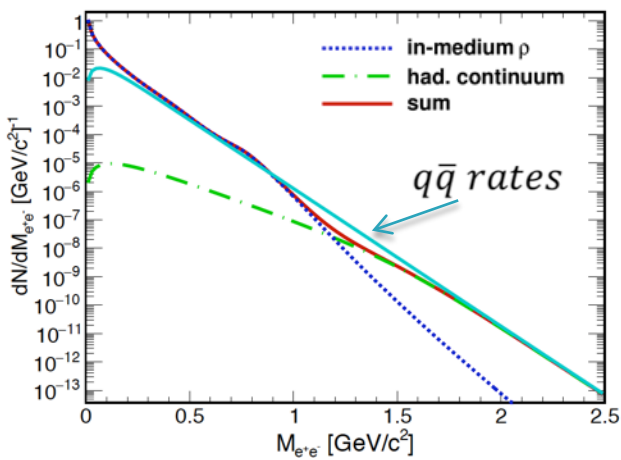
Huovinen et al., PRC 66 (2002) 014903
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J. A52 (2016) no.5, 131
CG SMASH: J. Staudenmaier et al., arXiv:1711.10297v1

Dileptons as fireball probes

- Central cell (3x3x3 fm3) thermodynamic properties from coarse graining UrQMD
- Time evolution of cumulative dilepton yield in mass window M = 0.3-0.7 GeV/c^2
- Active radiation window ~13 fm/c follows build-up of collective medium flow ⇨ fireball lifetime
- Strong medium effects on ρ-meson ⇨ remarkably structure-less low-mass spectrum



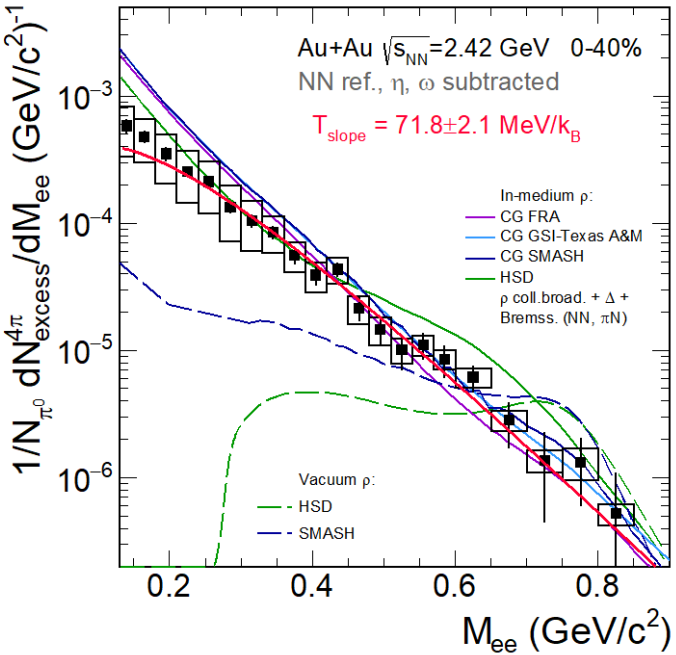




TG, F. Seck, R. Rapp, J. Stroth, Eur. Phys. J. A 52 (2016) 131

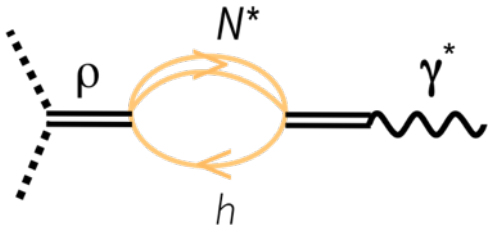
Thermal dielectrons *Au+Au at* $\sqrt{s_{NN}}$ = *2.42 GeV*

Excess yield fully corrected for acceptance



HADES Collab., submitted
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J.A52 (2016) no.5, 131
CG SMASH: J. Staudenmaier et al., arXiv:1711.10297v1
HSD: Phys. Rev. C 87, 064907 (2013)

- Strong broadening of the in-medium ρ due to direct ρ-hadron scattering



- Thermal rates folded over coarse-grained UrQMD medium evolution works at low energies
- Supports baryon-driven medium effects at SPS, RHIC, LHC

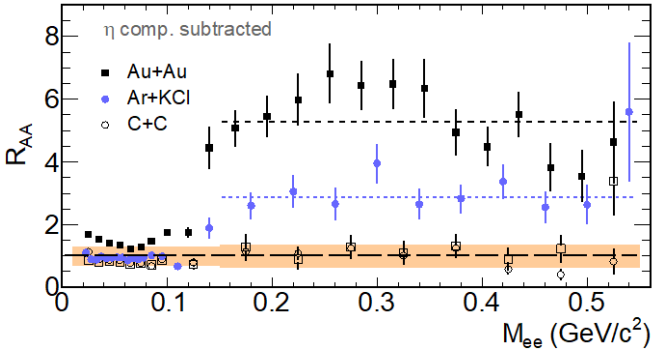
Robust understanding across QCD phase diagram

Dileptons as chronometer

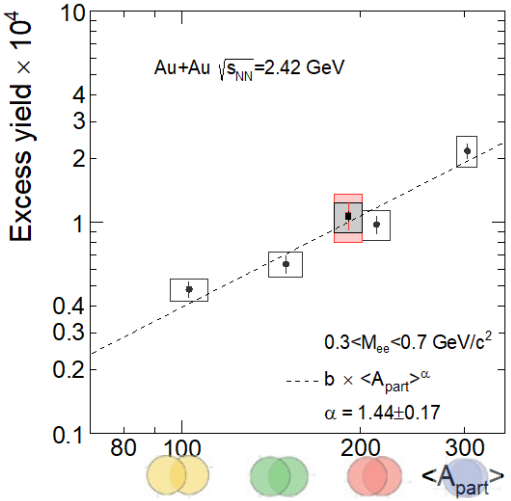
- Excess radiation $0.3 < M < 0.7$ GeV/c² tracks fireball lifetime

U.W. Heinz and K. S. Lee, PLB 259, 162 (1991)
H.W. Barz, B. L. Friman, J. Knoll and H. Schulz, PLB 254, 315 (1991)
R. Rapp, H. van Hees, PLB 753 (2016) 586

System size dependence of the excess

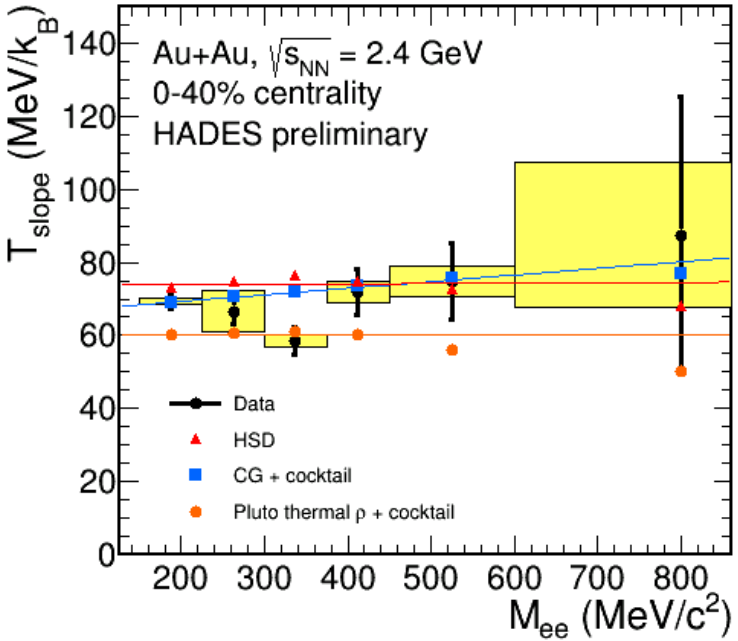


Centrality dependence of the excess



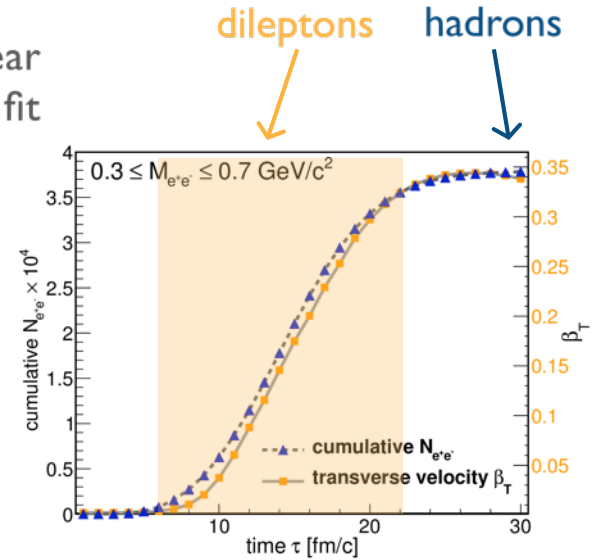
- Rapid increase of relative yield reflects the number of ρ's / R's regenerated in fireball
- Excess yield scales stronger than linear with mean number of participants
- $N_{excess} \sim A_{part}^{1.3}$ → interplay V × τ_{coll}

How the collectivity develops



S. Harabasz *on Friday*

- Analysis of p_t spectra in M_{ee} bins $\frac{1}{p_t}\frac{dN}{dp_t} \propto m_t K_1\left(\frac{m_t c^2}{k_B T}\right)$
- Fit to model calculations: $k_B T = k_B T_{kin} + \frac{1}{2} M_{ee} c^2 \langle\beta^2\rangle$
  - CG: T_{kin}= 65 MeV, $<\beta_{ee}>$=0.19
  - HSD: T_{kin}= 74 MeV, $<\beta_{ee}>$=0.05
- Blast wave model with linear radial flow velocity profile fit to hadron spectra
  - T_{kin}=66±8 MeV, $<\beta_h>$=0.34±0.04



Helicity angle (in the γ* rest frame)…

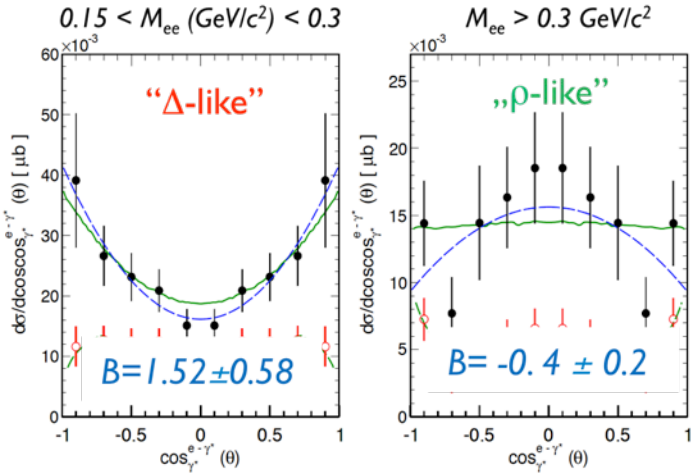
- … measures the photon polarization

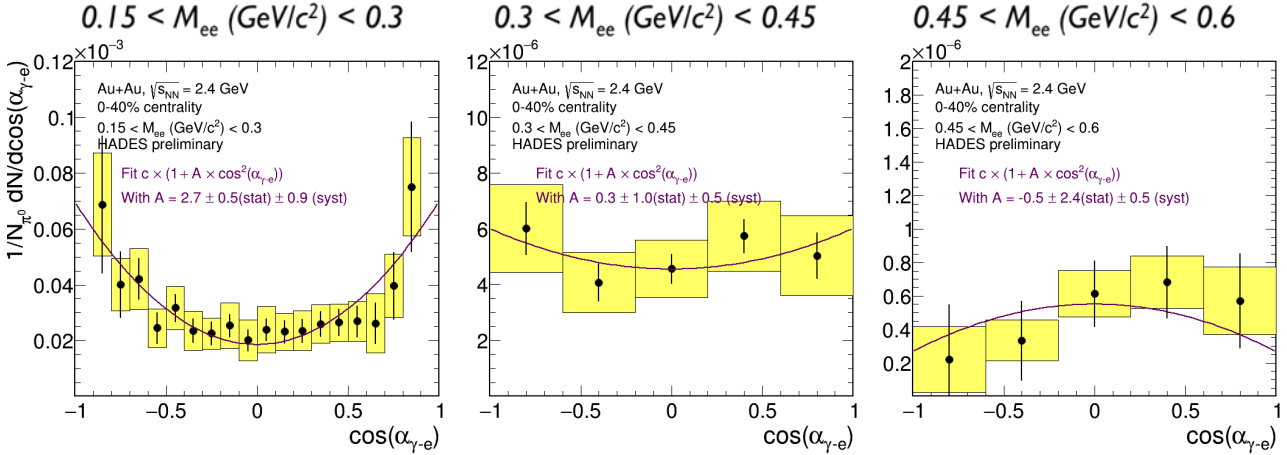
  NA60: PRL 96 (2009) 222301
  HADES: PRC 84 (2011) 014902

- Lack of anisotropy → hint for thermalized source?

  E. Speranza et al., Phys.Lett. B782 (2018)

HADES n+p $\sqrt{s}$=2.4 GeV

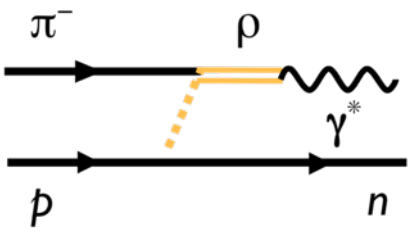


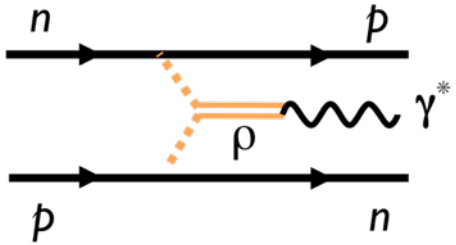


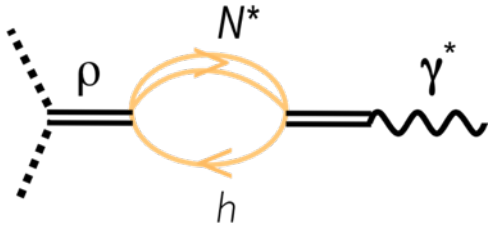
E. L. Bratkovskaya *et al.*
Phys. Lett. B 348 (1995) 325

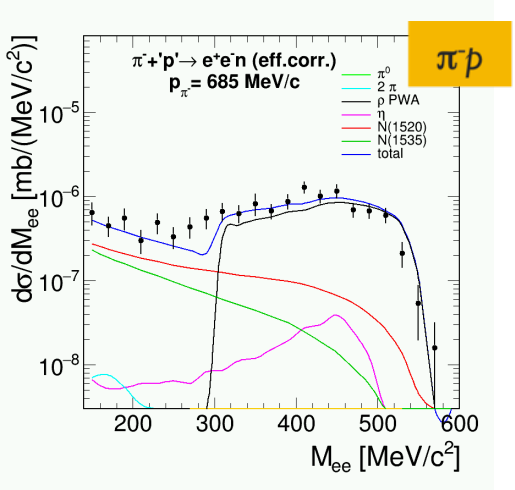
For $\pi^+\pi^- \rightarrow \rho \rightarrow e^+e^-$ expected B=-1 → hint for vector meson contribution

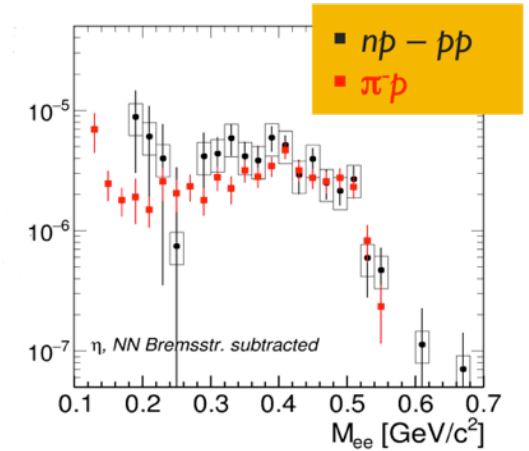
The role of virtual pions in dilepton production

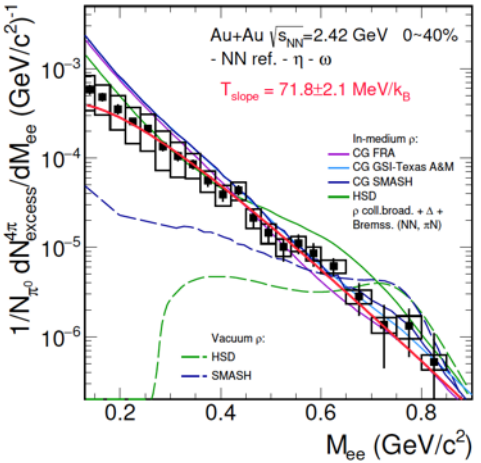










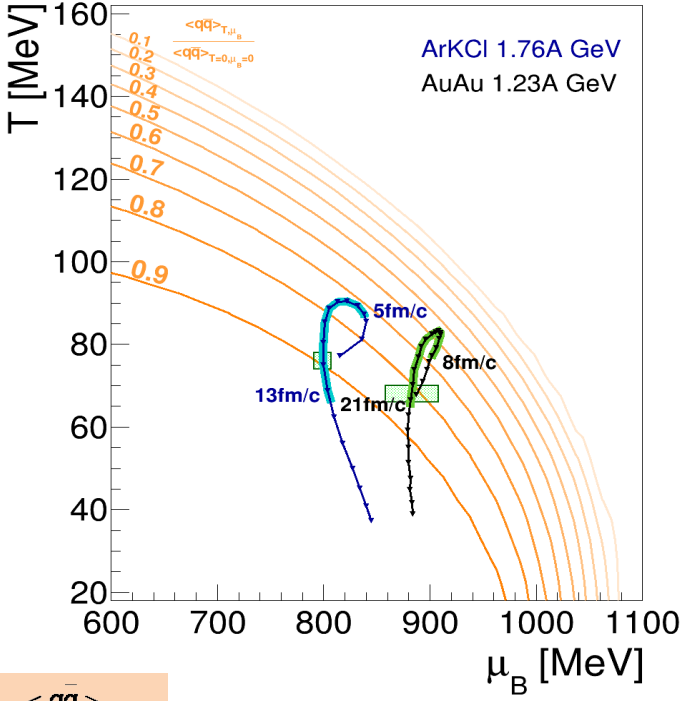


HADES Coll., EPJ A53 (2017) 149
HADES Coll., PRC 95 (2017) 065205

HADES Collab., submitted

Dileptons and phase diagram of matter

HADES and QCD phase diagram of matter



$\frac{<q\bar{q}>_{T,\mu_B}}{<q\bar{q}>_{T=0,\mu_B=0}}$: B.J. Schaefer and J. Wambach

- Trajectories extracted from inner cube of cells with coarse-grained UrQMD
- Time-window of dilepton emission → Access to hot and dense stage of the heavy-ion collision
- Excitation of the vacuum (squeezing out of condensate) matches spectral medium effects!

$$\frac{\langle\bar{q}q\rangle(T,\mu_B)}{\langle\bar{q}q\rangle_0} = 1 - \sum_h \frac{\varrho_h^s \Sigma_h}{m_\pi^2 f_\pi^2}$$

Quark core

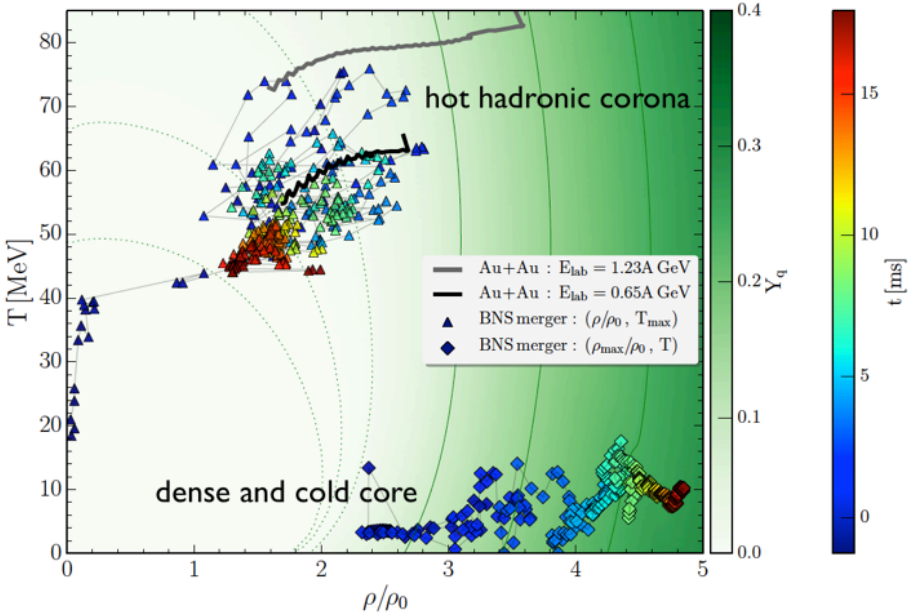
"Meson cloud"

Strong broadening of in-medium ρ spectral function – link to chiral symmetry restoration?

P. Hohler and R. Rapp, PLB 731 (2014) 103

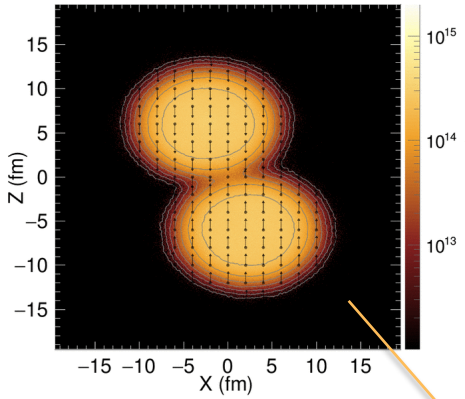
Heavy-Ion Collisions and Merging Neutron Stars

Chiral Mean Field Models enable to treat HIC and NS mergers on the same footing

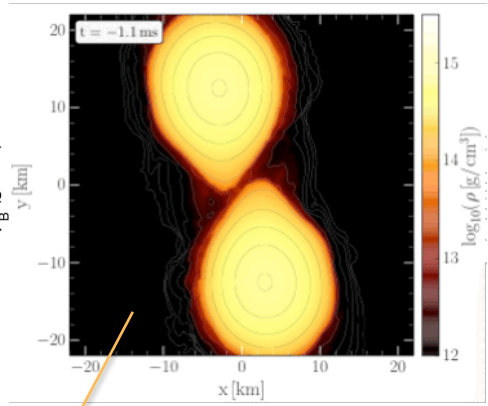


M. Hanauske, J Steinheimer (priv. com.)
L. Rezzolla et al., arXiv:1807.03684 [astro-ph.HE]

Au+Au 1.25A GeV



NS mergers

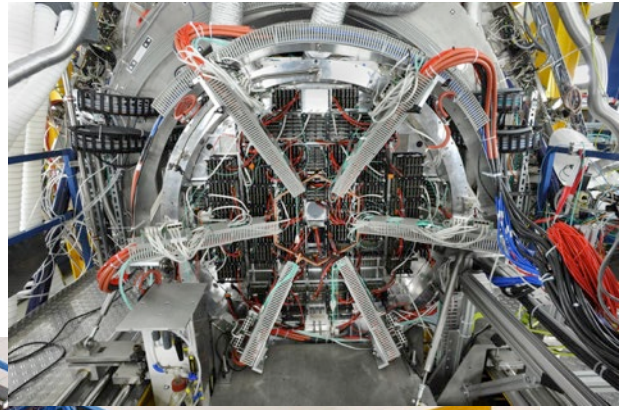


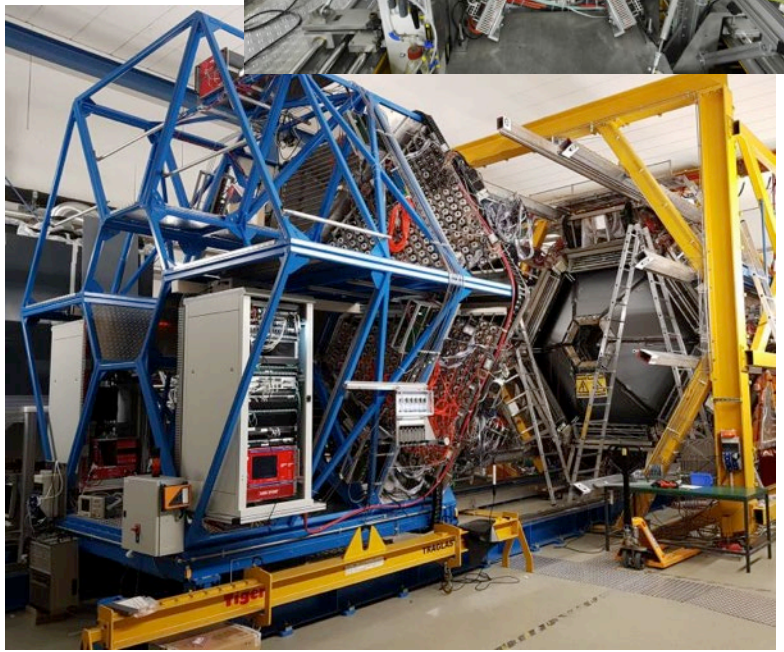
- T<70 MeV, $\rho \cong 3\rho_0$ for both
- Dileptons sensitive to dense phase
- Potential to constrain the EoS of dense matter

Future

HADES near and far future

This is already ½ of the CBM RICH photon detector

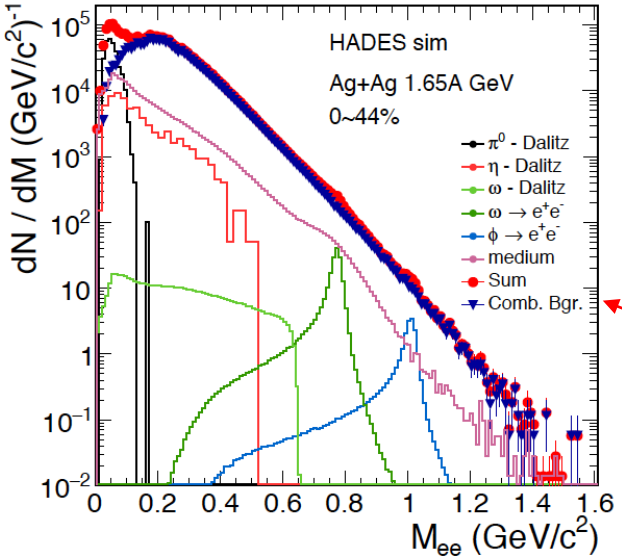




- 2018 (upgrade) – completed
  - Installation of MAPMT-based RICH UV-detector together with CBM
  - Installation of ECAL
- 2019-202x
  (experiment campaign at SIS18 – FAIR Phase-0)
  - Ag+Ag at $\sqrt{s_{NN}}$ = 2.6 GeV and π+N/A BES
  - Upgrades (2019):
    - DAQ upgrade – 200 kHz interaction rate
    - Forward tracking with PANDA
    - Backward neutron detector with R3B
- 202x on (HADES at SIS100)

Dielectrons from Ag+Ag at 1.65*A* GeV

Expected dielectron invariant mass spectra expected after 4 weeks running

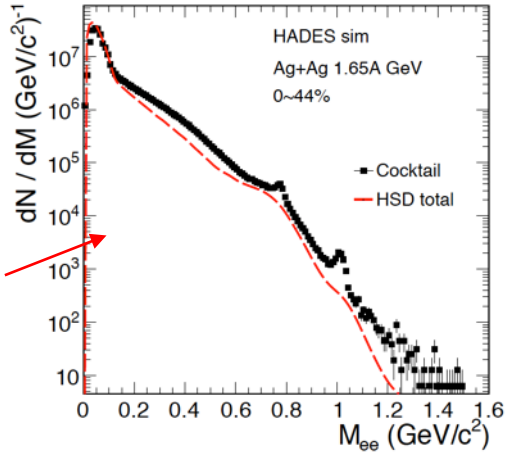


All Pairs
Combinatorial background
Signal contributions (colored)

- Quantify lifetime and baryon density dependence of the ρ spectral function
- Goal: Access for the first time at this collision energies intermediate mass range
  - Learn about ρ-a_1 chiral mixing
  - Access (hottest) fireball temperature
- Disentangle various model calculations

Coarse-grained transport with thermal electromagnetic rates

Conventional transport model

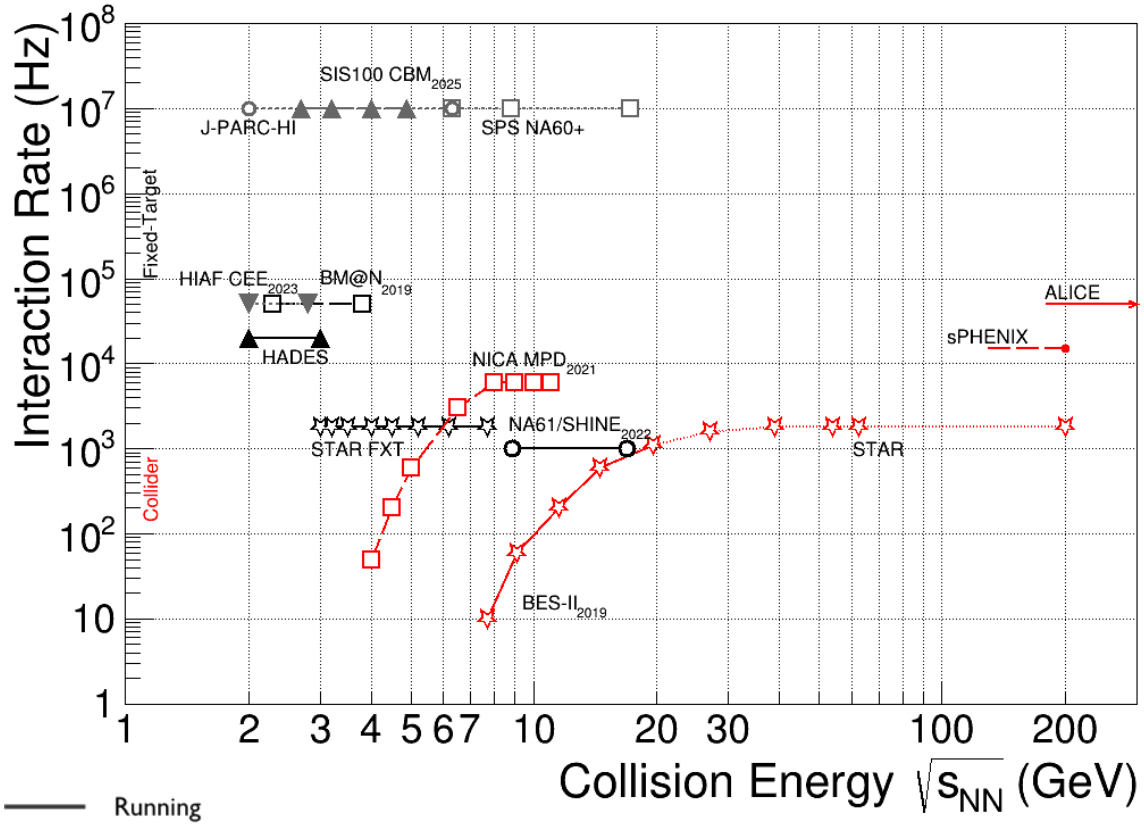


M_{ee} range	<0.15 GeV/c^2	0.15-0.45 GeV/c^2	0.3-0.7 GeV/c^2	>1 GeV/c^2
Rate [84 shifts]	$2.89 \cdot 10^6$	$7.1 \cdot 10^5$	$2.1 \cdot 10^5$	107

Mesons	$\pi^0 \rightarrow \gamma e^+e^-$	$\eta \rightarrow \gamma e^+e^-$	$\omega \rightarrow e^+e^-$	$\phi \rightarrow e^+e^-$
Rate [84 shifts]	$1.5 \cdot 10^6$	$7.32 \cdot 10^5$	179	62

Towards FAIR Phase-I

Explore QCD phase structure through energy scan

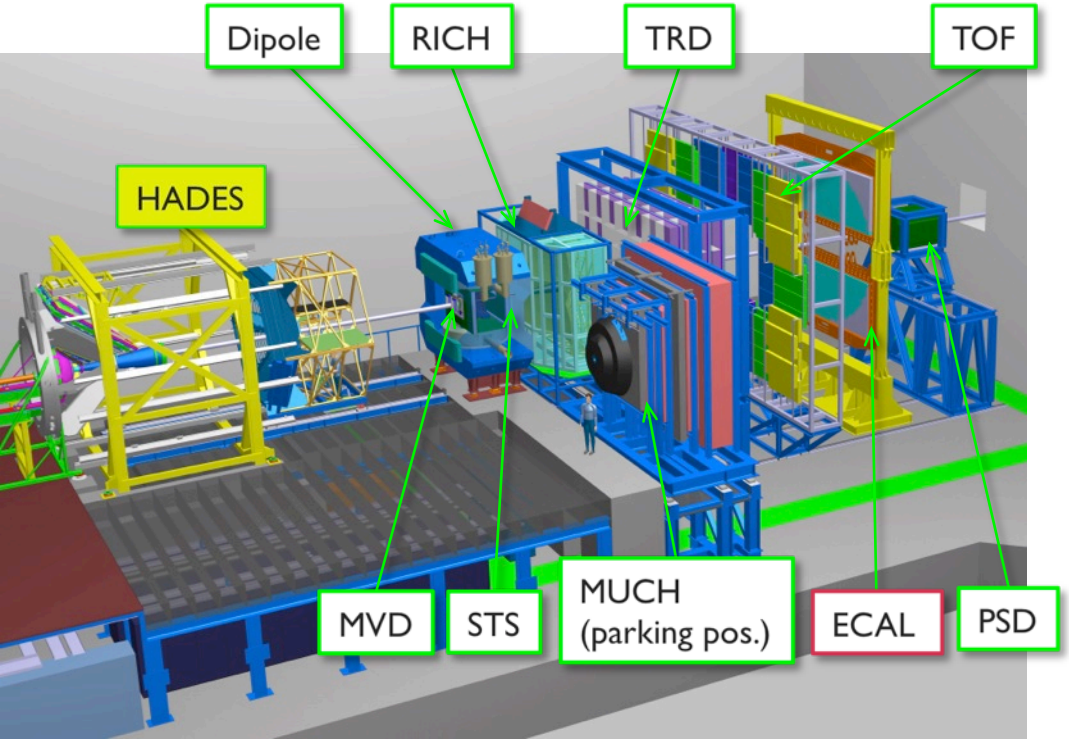


CBM Collab., EPJA 53 3 (2017) 60

- High rates (fixed-target experiments)
  - T_{slope}, excess yield and shape,
    T_{eff} vs mass,
    v_2 vs mass,
    polarization
- Physical background (M_{ll}>1GeV/c^2) towards lower energy
  - Negligible correlated charm contribution
  - Significant reduction of $\mathcal{D}$rell-$\mathcal{Y}$an (pA measurements!)
  - Decrease of QGP

The CBM strategy

~20 years progress in technology since AGS



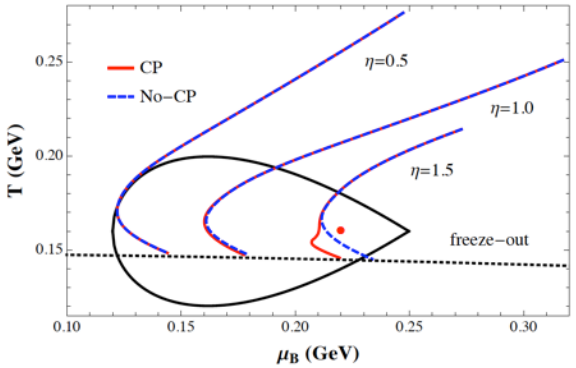
- Fixed target experiments
  → obtain highest luminosities
- Versatile detector systems
  → optimal setup for given observable
- Tracking based entirely on silicon
  → fast and precise track reconstruction
- Free-streaming FEE
  → nearly dead-time free data taking
- On-line event selection
  → high-selective data reduction

Day-1 setup: R_{int} = 0.5 MHz (0.1 MHz with MVD)
Phase-1 setup: Day-1+ECAL+Compute Performance → R_{int} = 10 MHz

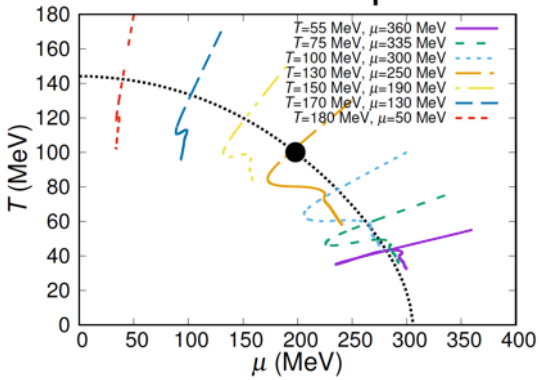
Day-1 funding ~90% secured

Mapping the QCD phase diagram with dileptons

Hydrodynamic evolution trajectories near the critical point



A. Monnai, S. Mukherjee, Y. Yin, PRC95 (2017) 034902



C. Herold, CPOD 2018

What are the possible signatures in dilepton radiation?

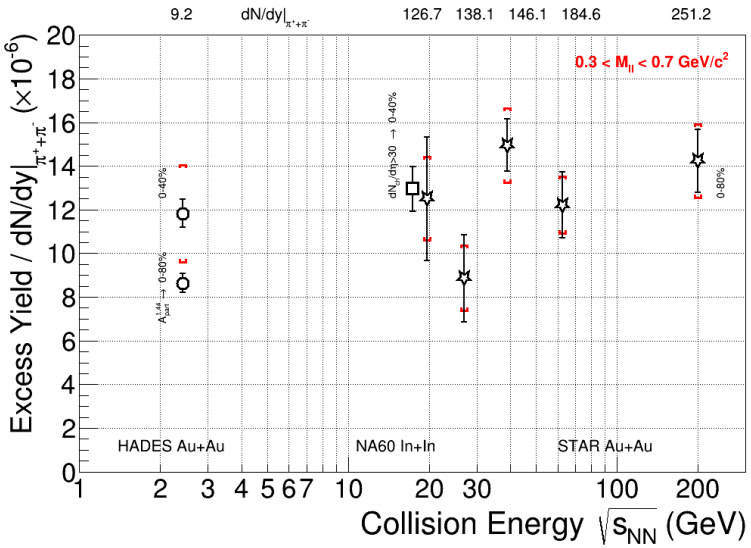
- Phase transition (and QCD critical point)
  - Excitation functions
    - Low-mass excess yield → "Extra radiation" system lives longer
    - Emitting source temperature → QCD caloric curve (plateau around onset of deconfinement?)

- Chiral symmetry restoration
  - Isolation of dilepton spectrum from ρ-a_1 chiral mixing

Hohler and Rapp, Phys.Lett. B731 (2014)
Jung, Tripolt, *et al.*, Phys.Rev. D95, 036020 (2017)

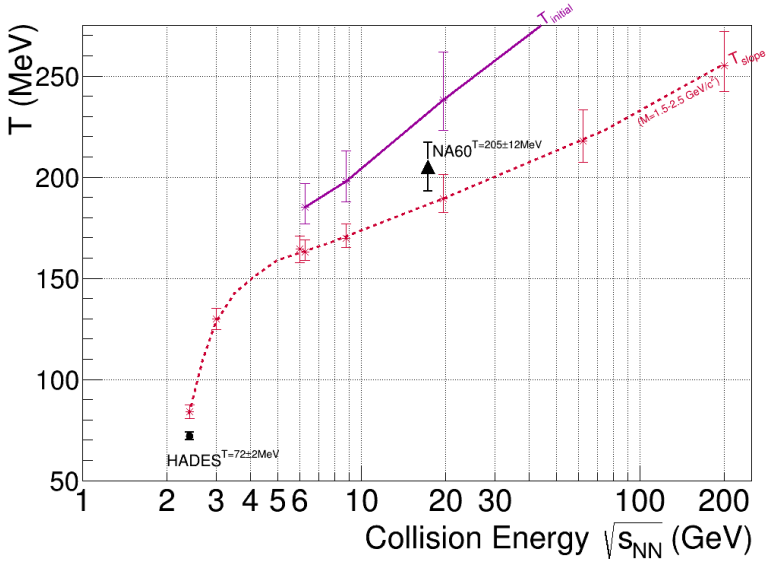
Thermal dileptons excitation functions

Low-mass excess yield per pion



NA60 Collab., Chiral 2010, AIP Conf.Proc. (2010) 1322
HADES Collab., QM2018
STAR: PLB 750 (2015), arXiv:1612.05484 [nucl-ex]

Emitting source T



NA60 Collab., Chiral 2010, AIP Conf.Proc. (2010) 1322
HADES Collab., QM2018

$\sqrt{s}$ > 6 GeV R. Rapp, H. van Hees, PLB 753 (2016) 586
$\sqrt{s}$ < 6 GeV TG, *et al.*: Eur.Phys.J.A52 (2016) no.5, 131

Résumé

Dileptons carry invaluable information in terms of their four-momentum

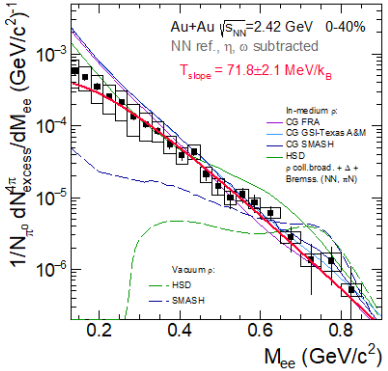
- Spectrometer
  - M_{ll} of excess pairs
- Chronometer

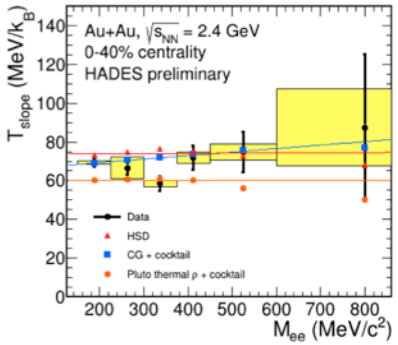
$$\int_{0.3GeV}^{0.7GeV} \frac{dN_{ll}}{dM} \sim \tau_{fireball}$$

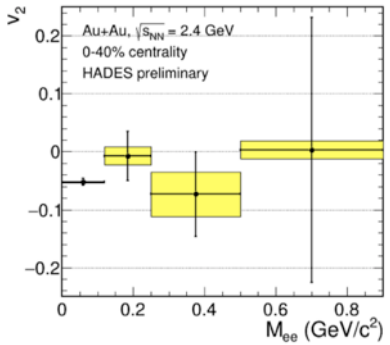
- Thermometer

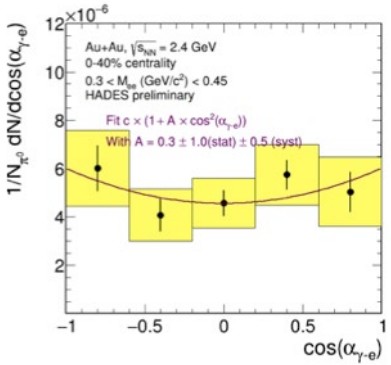
$$if \ \frac{\mathrm{Im}\,\Pi_{EM}^{\mu\nu}}{M^2} \sim const.$$

- Barometer
  - T_{eff} vs. M_{ll}
  - v_2 vs. M_{ll}
- Polarimeter
  - γ^* polarization via lepton angular distribution





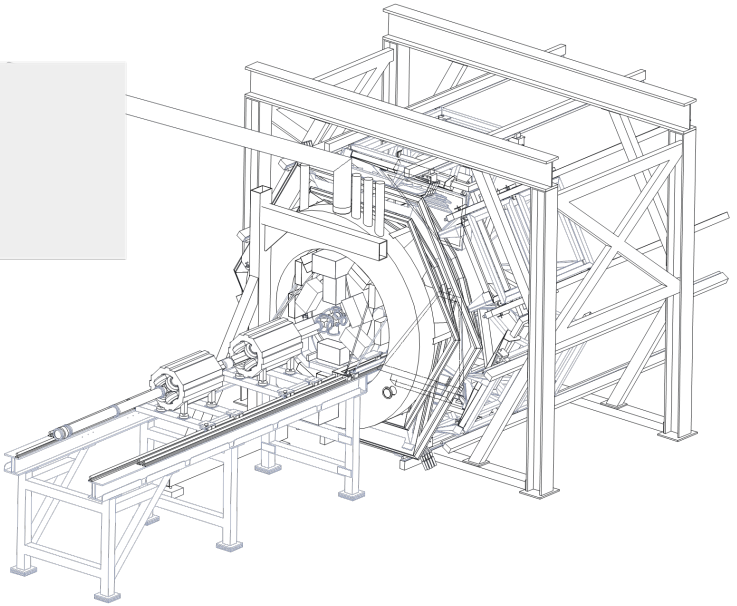




The HADES Collaboration

9 countries, 16 institutions, 150 Collaborators

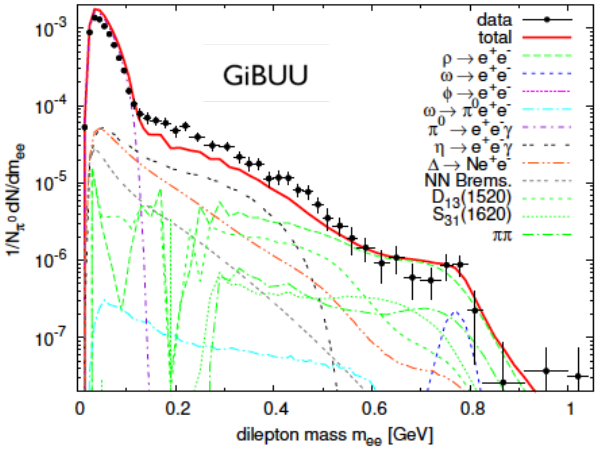
Thank you for your attention!



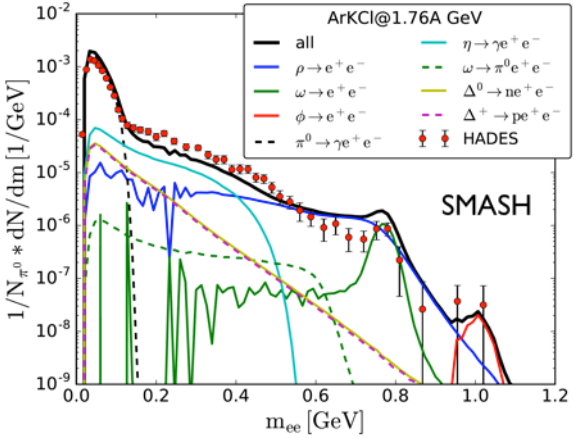
Résumé and prospects

- Encouraging prospects for studying baryon rich QCD matter with HADES
  - HADES marks lowest point of the excitation function
- Results from Au+Au collisions suggest a "thermalized" strongly interacting medium created at $\sqrt{s_{NN}}$=2.42 GeV:
  - Thermal origin of e^+e^- excess spectrum at low energies
- Complementary program on exclusive measurements in π induced reactions:
  - Strong evidence for validity of VDM in electromagnetic decays of baryons
- Strong scientific program for FAIR Phase-0

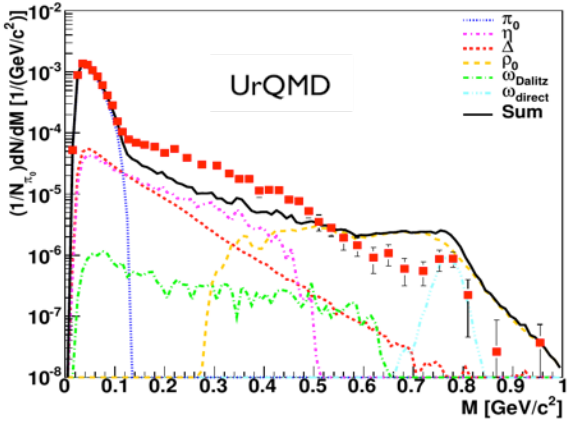
Virtual photon emission in Ar+KCl collisions and transport



J. Weil., J.Phys.Conf.Ser. 426 (2013) 012035



J. Staudenmaier et al., arXiv:1711.10297v1



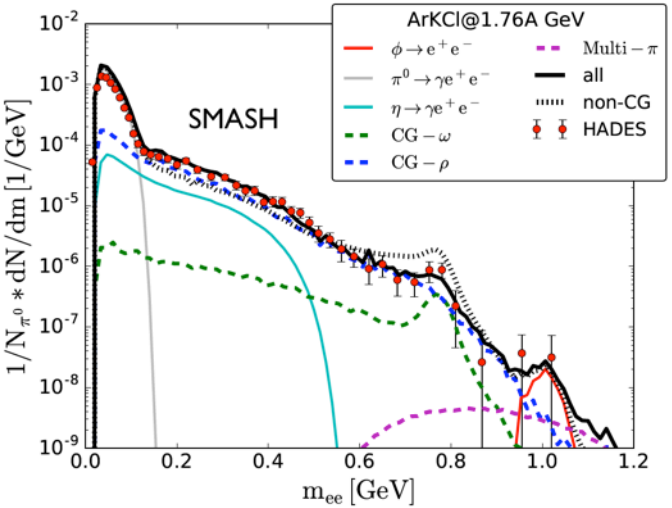
S. Endres, J.Phys.Conf.Ser. 426 (2013) 012033

- Models with vacuum spectral function miss data
  → room for medium modifications!

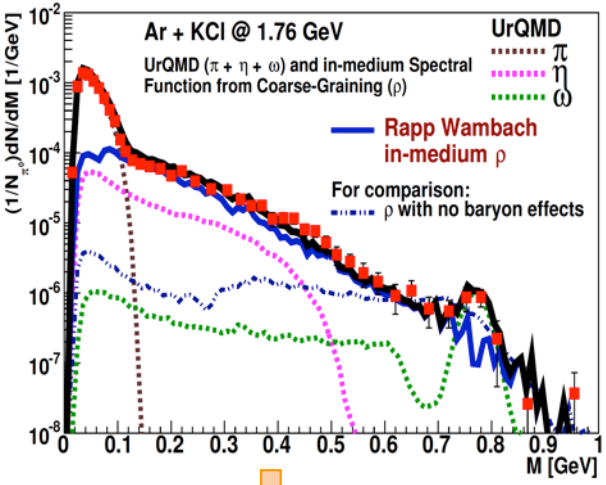
c.f. off-shell transport E. Bratkovskaya *et al.*, Phys.Rev. C87 (2013) 064907
J.Weil *et al.*, Phys.Rept. 512 (2012)

Thermal dielectrons *Ar+KCl at* $\sqrt{s_{NN}}$ = 2.6 GeV

J. Staudenmaier *et al.*, arXiv:1711.10297v1



S. Endres *et al.*: PRC 92 (2015) 014911



F. Seck *et al.*, J. Phys. Conf. Ser. 1024 (2018) 012011