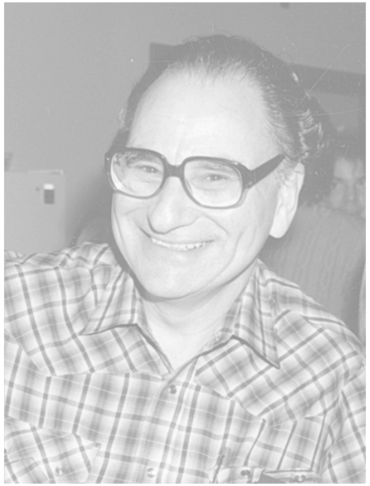


FROM VMD TO THERMAL RADIATION TO FAIR

Joachim Stroth

Symposium on Collective Flow in Nuclear Matter

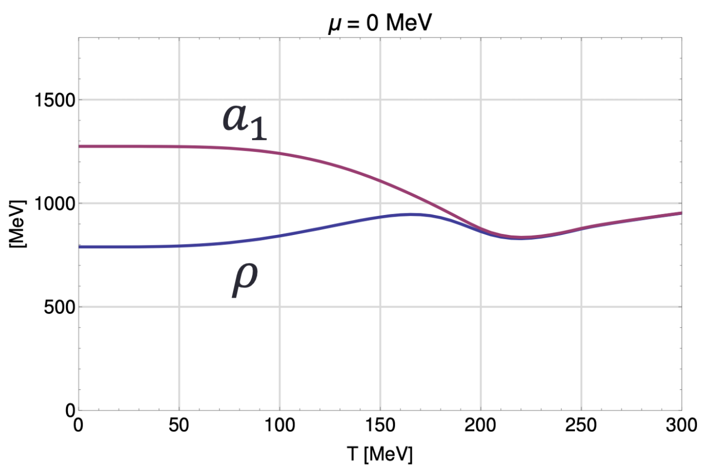
A celebration of Art Poskanzer's Life and Career

December 9–10, 2022

Vector mesons as probe for the QCD condensates

The role of QCD condensates in the generation of mass

- **Gluon condensate**: Dynamical mass generation (trace anomaly)
- **Chiral condensate**: Parity doublet splitting



C. Jung et al.: 1610.08754 [hep-ph]
P. Hohler and R. Rapp: 1311.2921 [hep-ph]

Experimental approach:

- "Modify" condensates by embedding states of interest in a hadronic medium
- Rely on **Vector Meson Dominance (VMD)** and use ρ meson as probe (penetrating probe)

Original idea, following the work of:
Brown & Rho *(PRL 1989, 1991)* /
Hatsuda & Lee *(PRC46(1992)R34)*:

- Search for **mass modifications** of vector mesons in medium → "dropping mass"

But $\rho \rightarrow e^+e^-$ in HIC at $1\ A\ GeV$ is an extremely rare probe ☹

"Not everything which drops is chiral symmetry restoration"

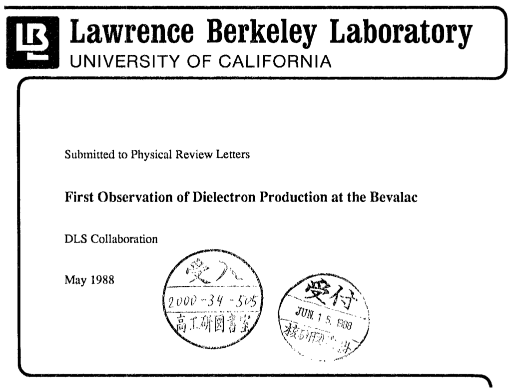
V.K. Trento, 2005

"Not everything which drops is chiral symmetry restoration"

V.K. Trento, 2005

100 % **left handed** amino acids. Guaranteed

The DLS at LBNL

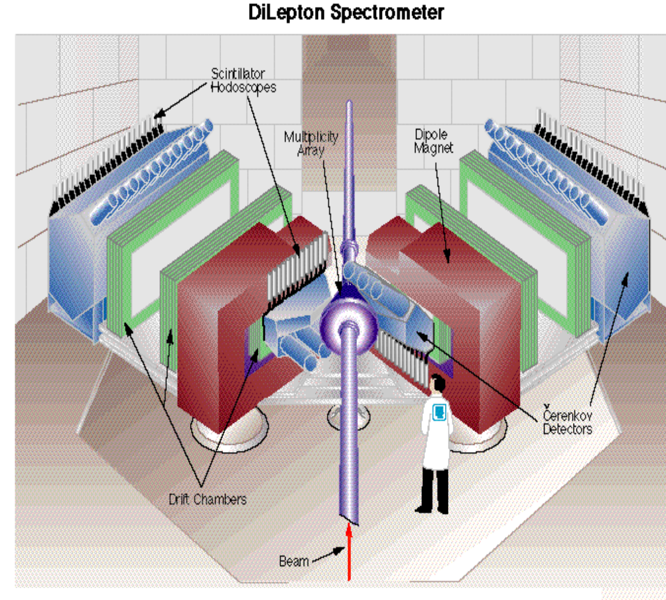

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to Physical Review Letters

First Observation of Dielectron Production at the Bevalac

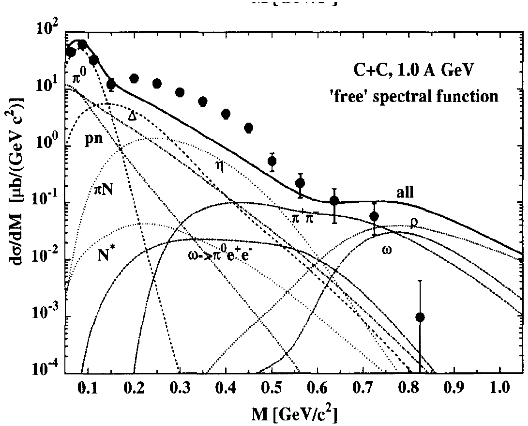
DLS Collaboration

May 1988

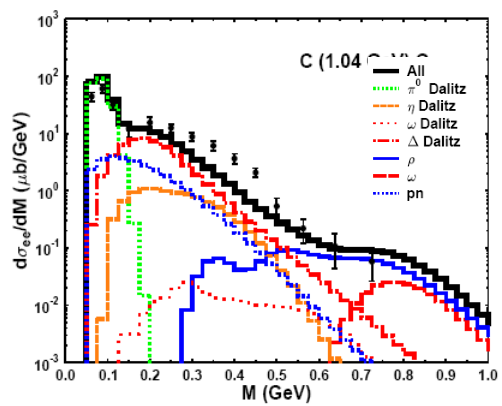


The DLS puzzle !

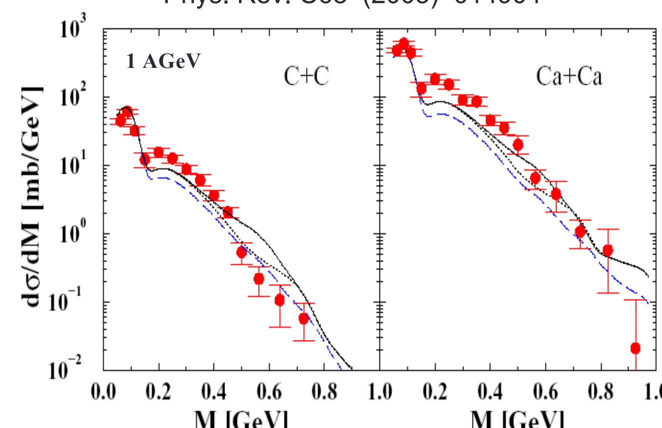
Calculation: **E.L.Bratkovskaya et al.**
Phys. Lett. B445 (1999) 265



Calculation: **Ernst et al.**
Phys. Rev. C58 (1998) 447

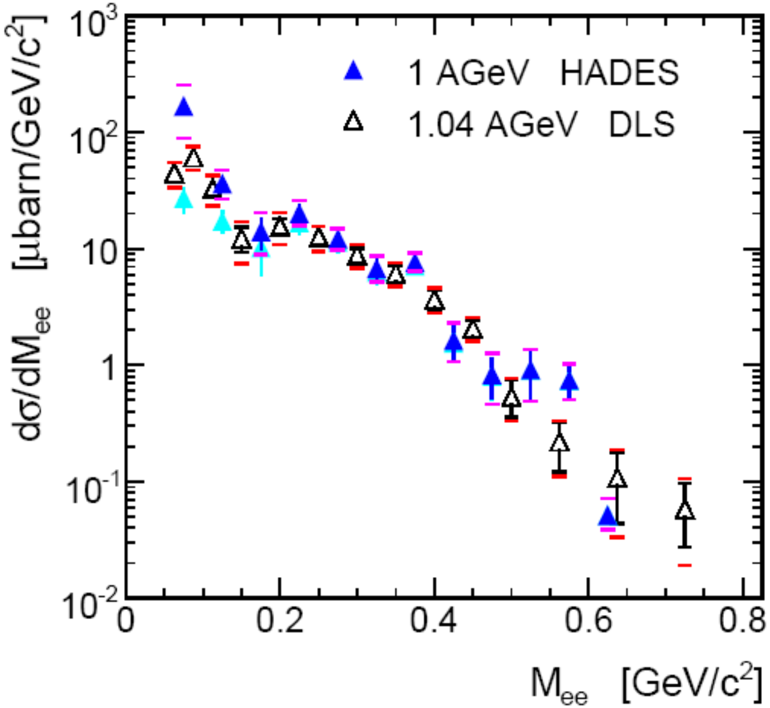


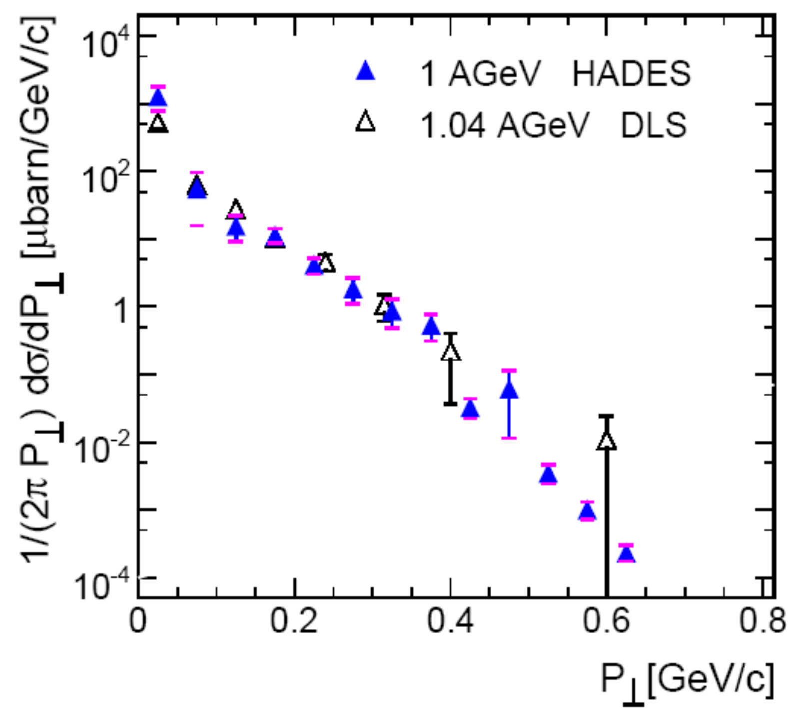
Calculation: **C. Fuchs et al.**
Phys. Rev. C68 (2003) 014904



DLS and HADES (in DLS Acceptance)

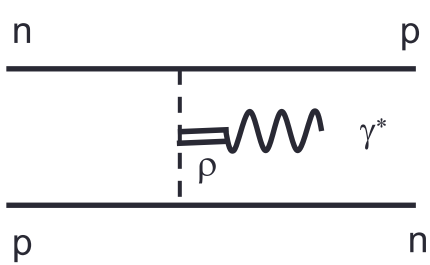
- Large acceptance of HADES enabled direct comparison with DLS w/o acceptance correction
- Measurements are in good agreement – no "DLS Puzzle"





Elementary reference from $p+p$ and $n+p$ with HADES

- $n+p$ shows enhanced radiation beyond additional dipole contribution
- Virtual photon can couple to the internal pion line only if charged pion is exchanged
  - Final state interaction of ρ with N?
- Was not taken into account in microcopic transport calculations

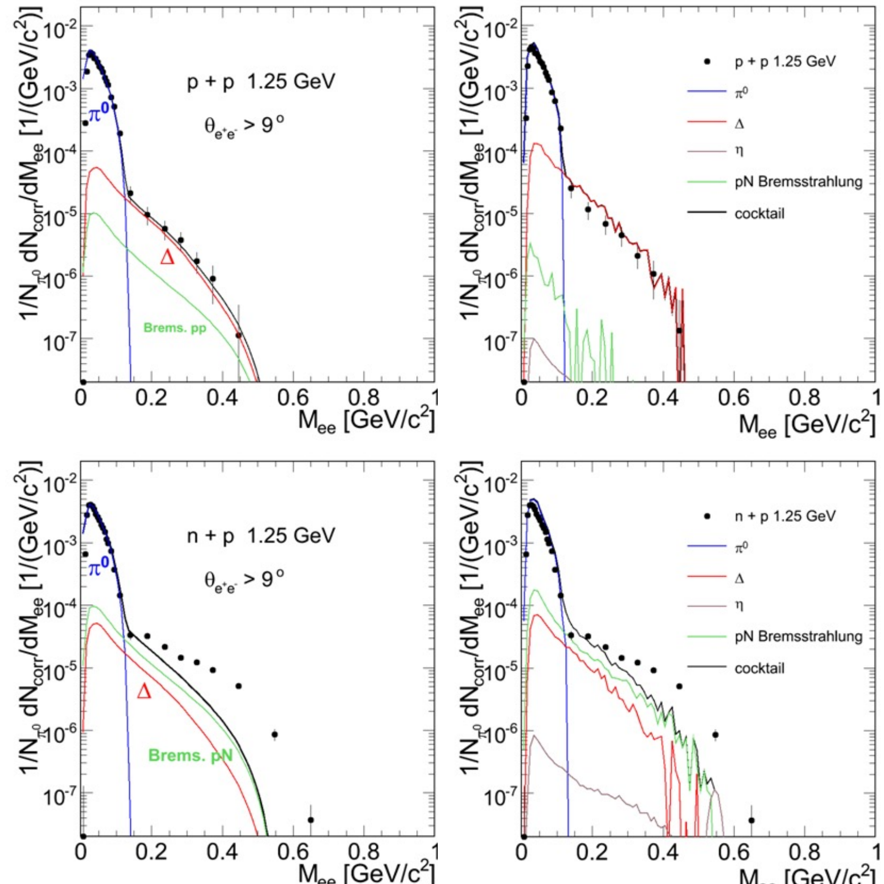


HADES PLB 690 (2010) 118

HSD IQMD

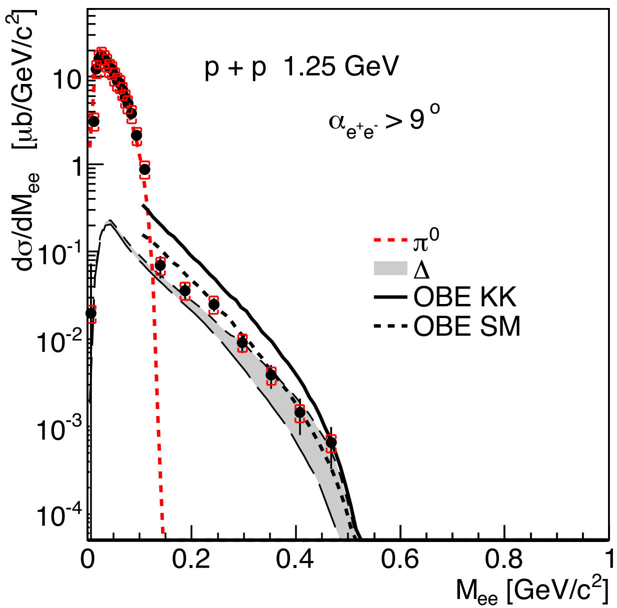
p+p

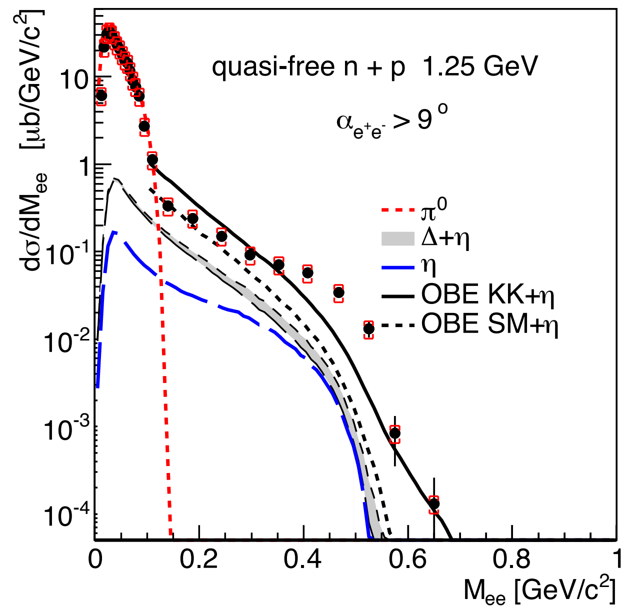
n+p



One Boson Exchange calculations

- Data from HADES pp and dp (tagged n) at 1.25 GeV/u
- One-boson exchange (OBE) calculations catch the the strong isospin effect - almost





R. Shyam, U. Mosel; 1006.3873 [hep-ph]
L.P. Kaptari, B. Kampfer; 0903.2466 [nucl-th]

The upgraded HADES spectrometer (> 2018)

Geometry

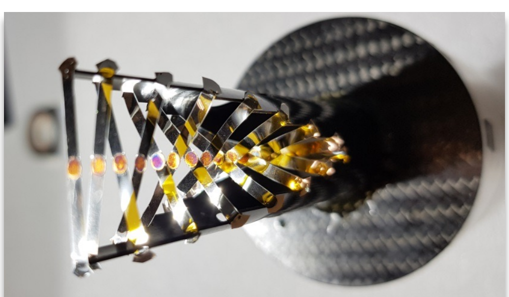
- Full azimuth identical sectors, polar angles 18° - 85°
- Pair acceptance ≈ 0.35

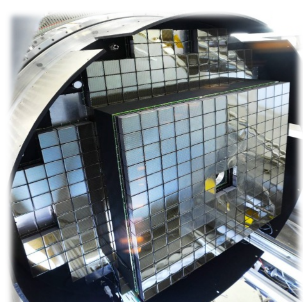
Particle identification

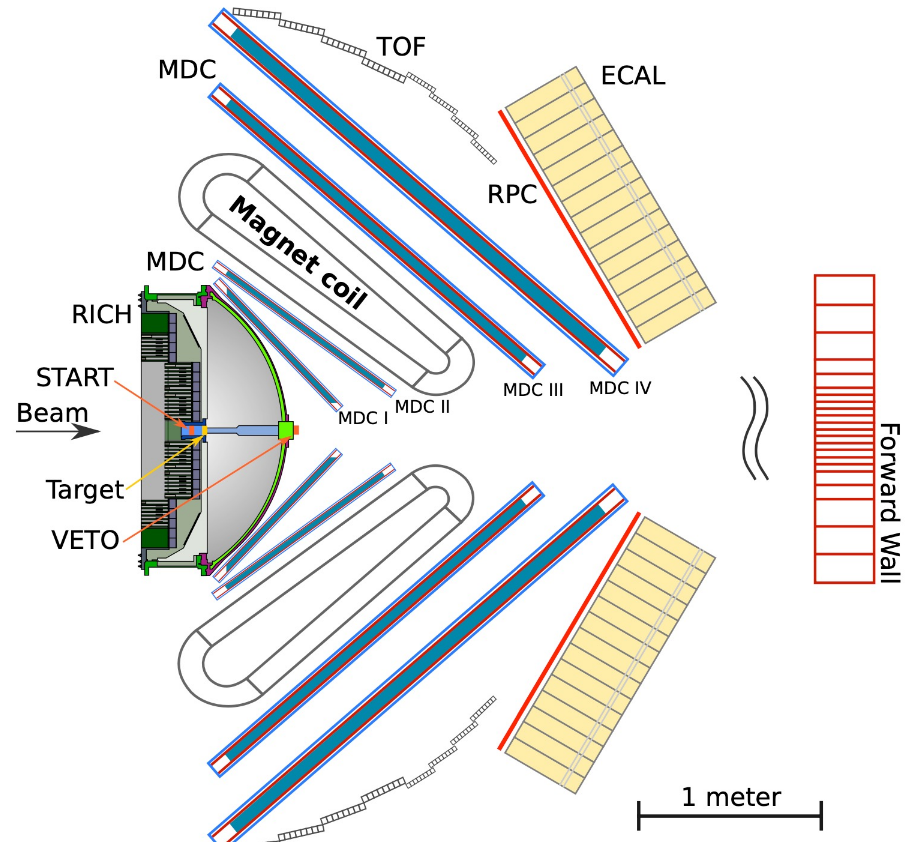
- RICH – MAPMT based photo detector
- TOF – scintillator rods ($\sigma_t \simeq 150\ ps$)
- RPC – 2 layers of shielded cells ($\sigma_t \simeq 70\ ps$)
- ECAL – lead-glass ($\sigma_E \simeq 150\ ps$)
- START – segmented CVD or LGAD

Low-mass tracking

- 6-coils super conducting toroid $B\rho\ => 0.36\ \mathrm{Tm}$
- MDC – 4 planes of mini-drift chamber (~30.000 cells)

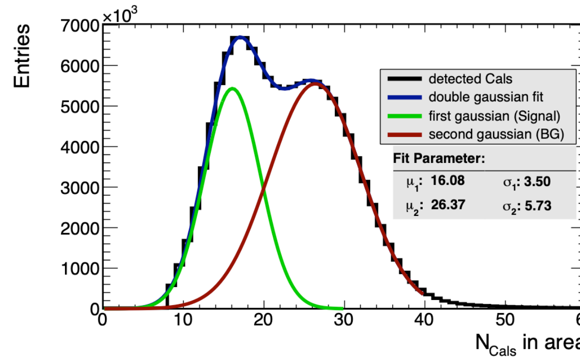


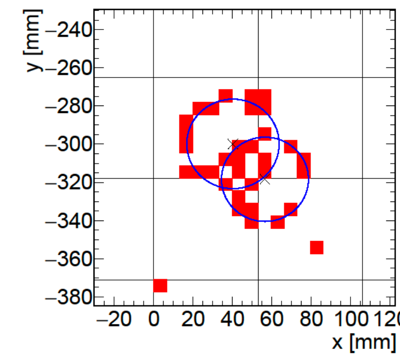


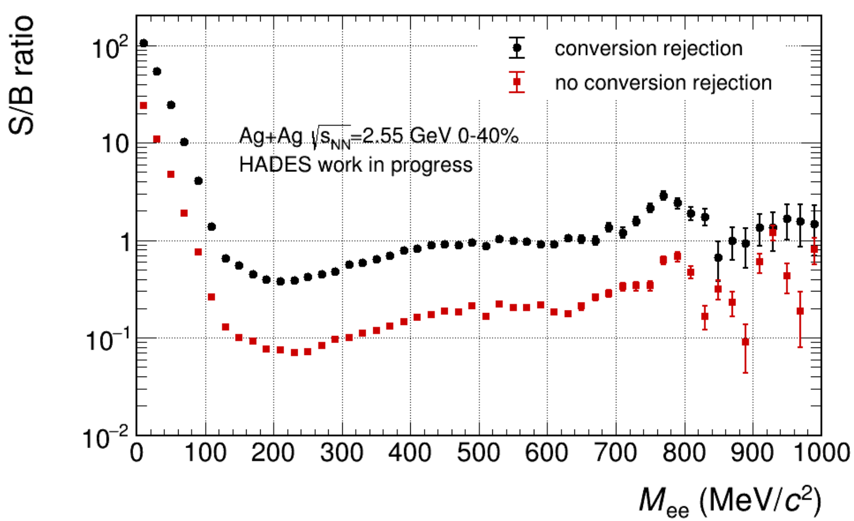


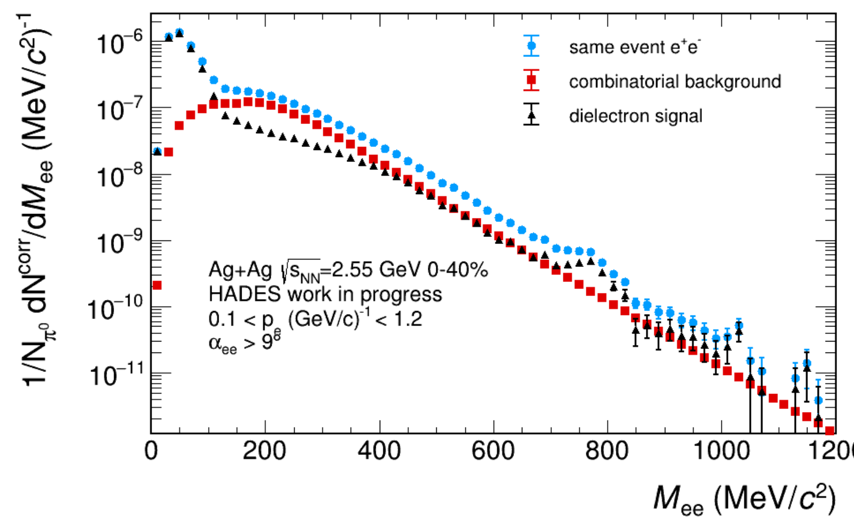
Improved dilepton performance with MAPMT (CBM)

- Nearly **background-free images** after narrow time coincidence
- Large number of fired pads per ring provides **excellent conversion rejection**









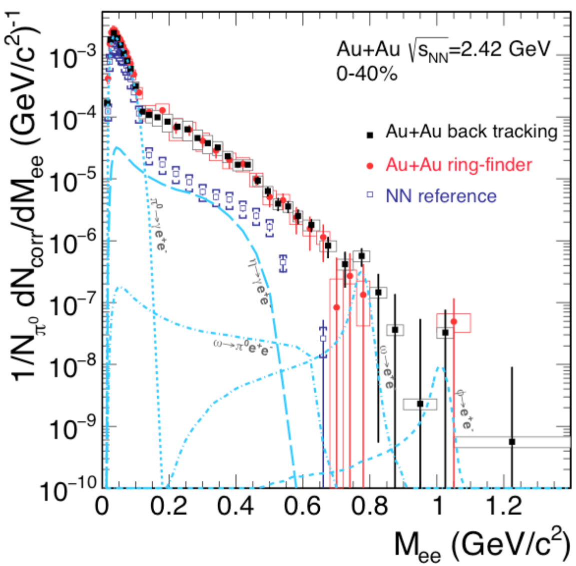
Dileptons from central HI collisions

Extraction of the **excess radiation**:

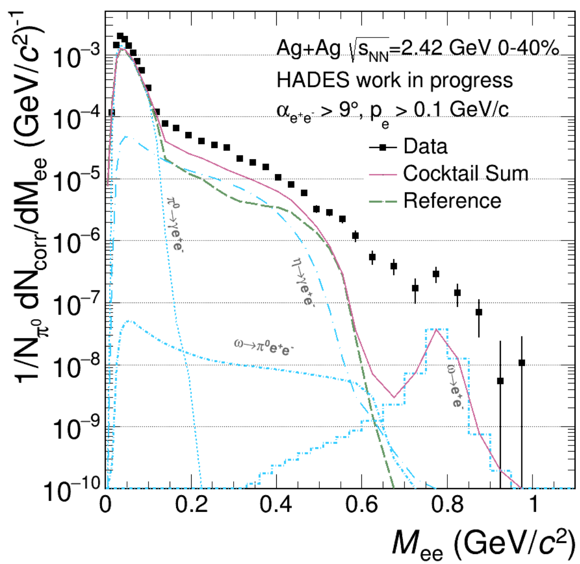
- Pre-equillibrium from reference measurements
- Hadronic cocktail from $\pi^{-/+}$ or $\gamma\gamma$ measurement
- Implicit scaling to π^0 yield
- Reference for $\mathrm{Ag}+\mathrm{Ag}$ $(2.55\ A\ \mathrm{GeV})$ in progress

[HADES] Nature Phys. 15(2019) 1040

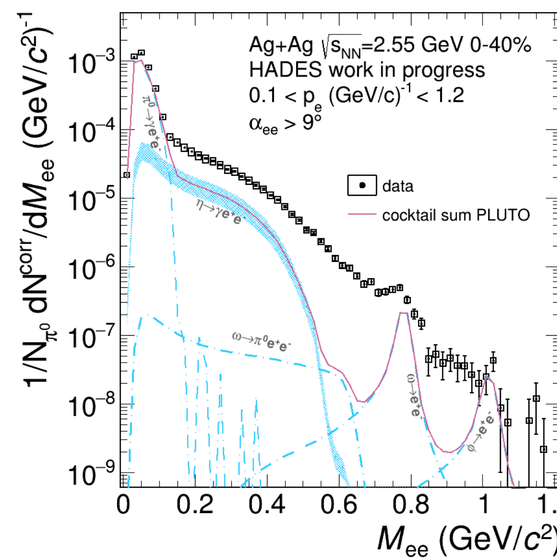
Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



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



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



Vector Meson Dominance in Hot & Dense Matter

Generalized „Bremsstrahlung" – EM spectral function from Fourier transform of current-current correlation function $\langle \mathrm{j(x), j(0)} \rangle$ (thermal average):

$$\Pi^{\mu\nu}_{EM}(q) = \int d^4x e^{iqx}\, \Theta(x_0) \langle [j^{\mu}_{EM}(x), j^{\nu}_{EM}(0)] \rangle_T$$

L. McLerran, K. Toimela, Phys. Rev. D31 (1985)

See also: Ralf Rapp arXiv-1110-4345

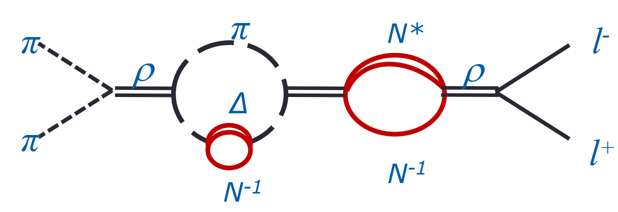
Extension of the Gounaris-Sakurai formula to a thermal pion gas: C. Gale, J. Kapusta: Nucl. Phys. B357 (1991)

$$j^{\mu}_{EM} = \frac{1}{2}(\bar{u}\gamma^{\mu}u - \bar{d}\gamma^{\mu}d) + \frac{1}{6}(\bar{u}\gamma^{\mu}u + \bar{d}\gamma^{\mu}d) - \frac{1}{3}\bar{s}\gamma^{\mu}s = \frac{1}{\sqrt{2}}j^{\mu}_{\rho} + \frac{1}{3\sqrt{2}}j^{\mu}_{\omega} - \frac{1}{3}j^{\mu}_{\phi}$$

Hadronic current can be approximated by the imaginary part of the in-medium ρ propagator. Inclusion of meson-baryon coupling, ρ only:

$$\mathrm{Im}\, \Pi^{med.}_{EM}(M) = \left(\frac{m^2_{\rho}}{g_{\rho}}\right)^2 \mathrm{Im}\, D(M)$$

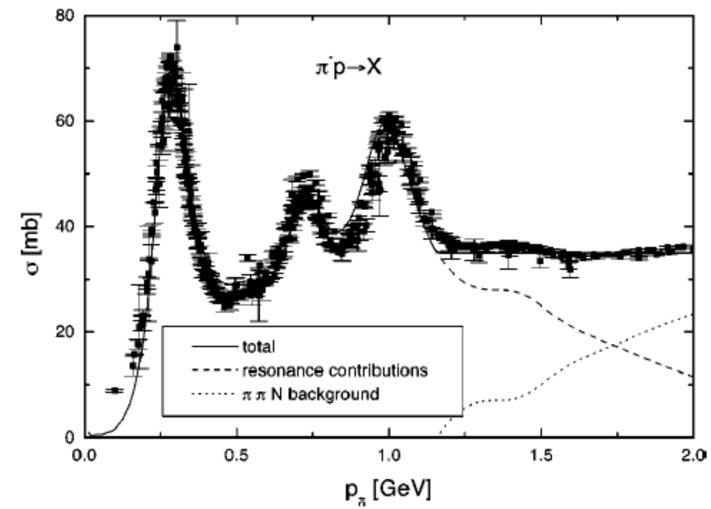
$$D_{\rho}(M, q; \mu_B, T) = \frac{1}{(M^2 - m^2_{\rho} - \Sigma_{\rho\pi\pi} - \Sigma_{\rho M} - \Sigma_{\rho B})}$$

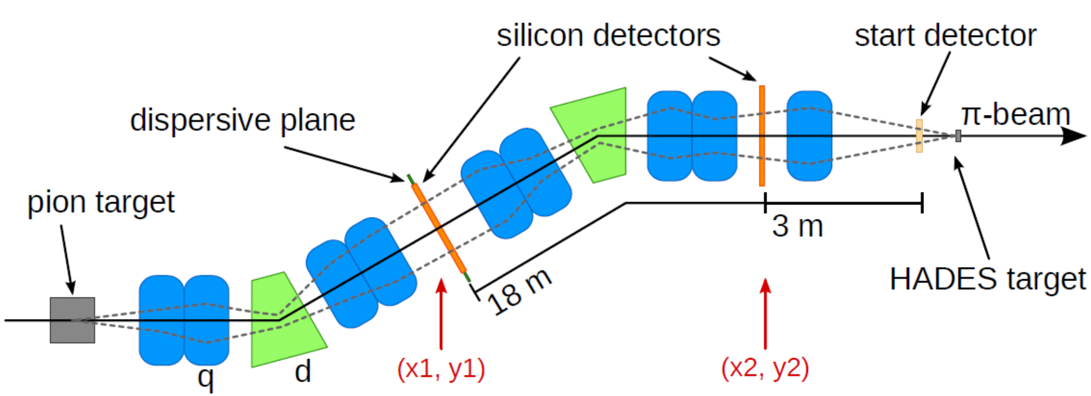


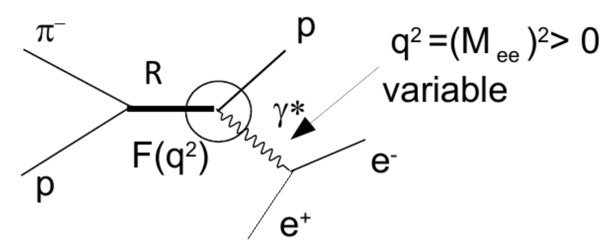
R. Rapp, J. Wambach: Adv. Nucl. Phys. 25 (2000) 1
B. Friman, Nucl. Phys. A610 (1996) 358c;
B. Friman and H.J. Pirner, Nucl. Phys. A617 (1997) 496

The HADES Pion Beam Facility

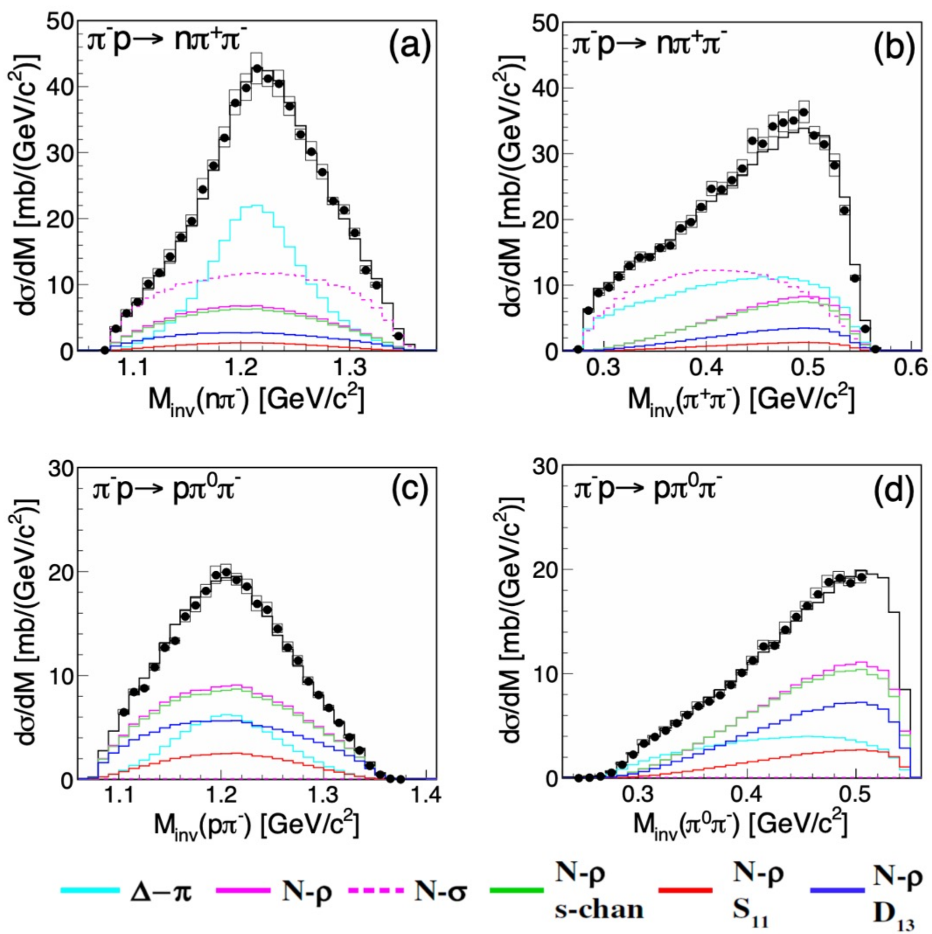
- Pion production target 40 m upstream the experiment target position
- Direct excitation of baryon resonance and exclusive reconstruction of final states
- Combination with dilepton spectrometer world-wide unique







Extraction of partial waves from two-pion channel



$p_\pi = [0.66, 0.69, 0.75, 0.8]\ GeV/c$

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

- Hadronic final states used in PWA (Bonn/Gatchina code)
- Use invariant masses, and angular distribution (not shown here)

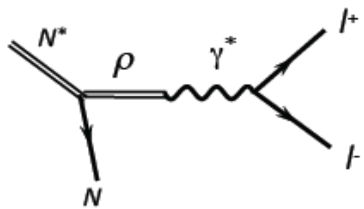
$\pi^- + p \rightarrow e^- + e^+ + n$

- Prediction for dilepton invariant mass assuming strict VMD
- Comparison to two-component model by Pena & Ramalho

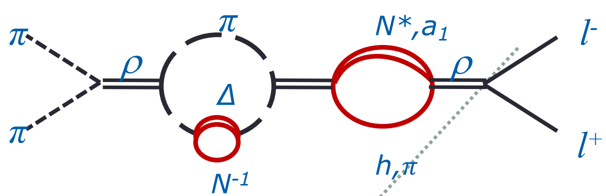
HADES Phys. Rev. C 102 (2020) 2, 024001

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

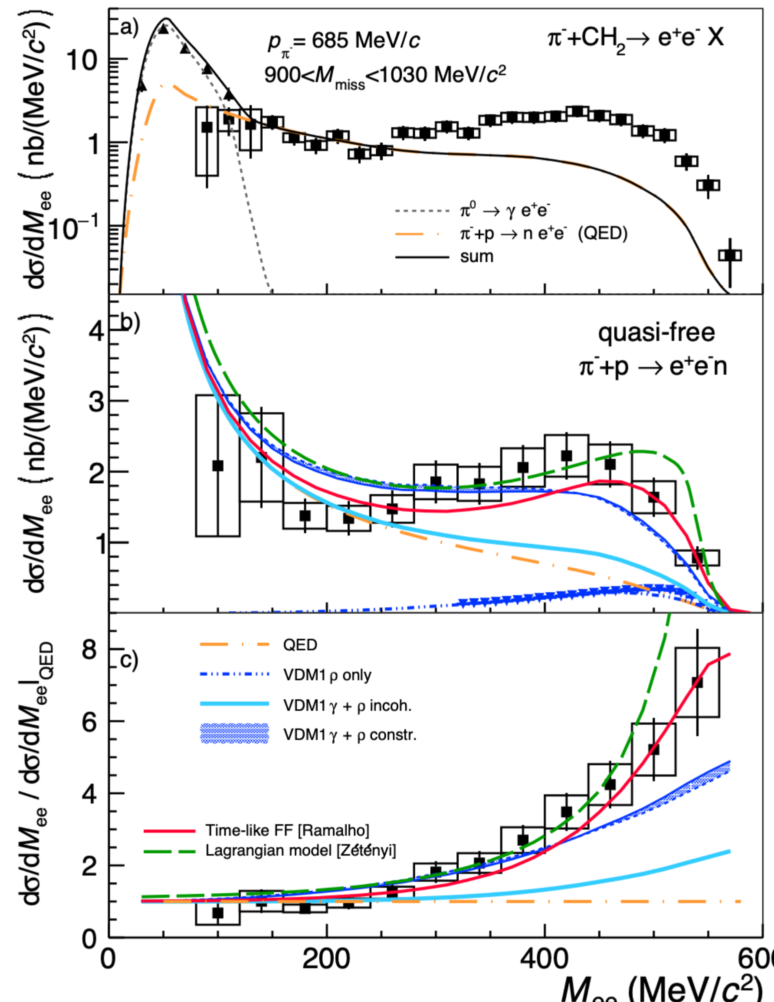
- Resonance-Dalitz decay (a la VMD) …



… is analogous to baryonic contribution to in-medium ρ selfenergy (**emissivity**)



- Effective **transition form factor** (time-like) extracted by subtracting QED expectation from exclusive invariant mass distribution.



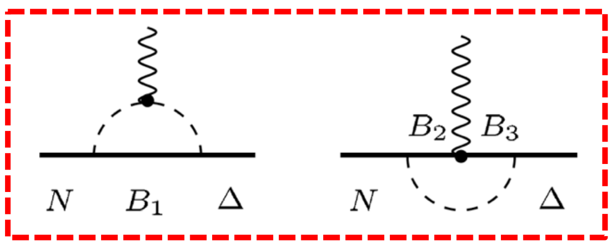
HADES arXiv:2205.15914

$p + p \rightarrow e^{+}e^{-} + p + p \quad (\sqrt{s} = 2.4\,GeV)$

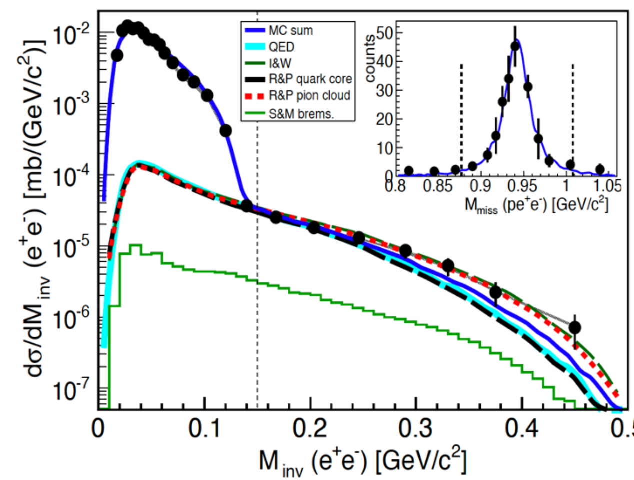
- Effect of the pion cloud observed in the time-like electromagnetic transition using two-component model

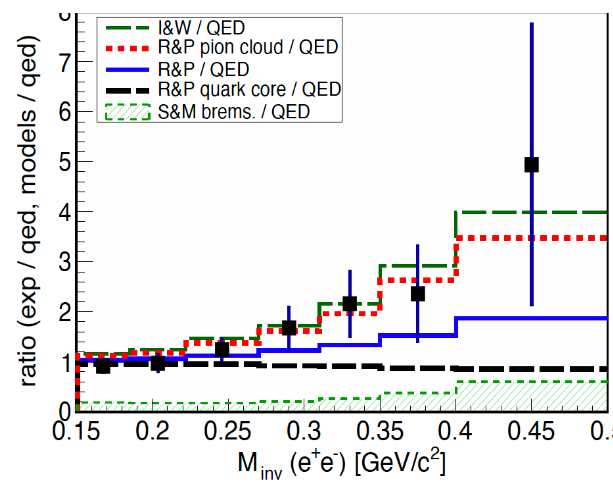
  Peña, Ramalho; arXiv:1205.2575 ($\Delta(1232)$)
  Peña, Ramalho + GiBUU.; arXiv:1512.03764
  Peña, Ramalho; arXiv: 1610.08788 ($N(1520)$)
  Peña, Ramalho; arXiv: 2003.04850 ($N(1535)$)

- Two component model: green line (sum of core and cloud contributions)



- Modified Bremsstrahlung (S&M brems.)





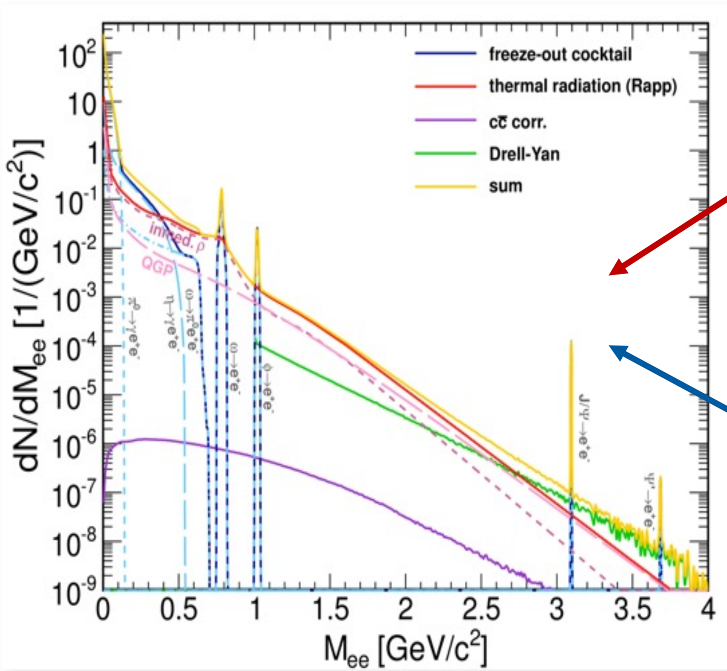
HADES: arXiv:1703.07840 [nucl-exp]

Theoretical approaches to medium radiation

Medium (excess) radiation from ***Thermal Emission Rates*** **(ϵ)** ("standard candle"):

$$\frac{d^4N}{dM\,dy\,dp_t\,d\alpha} = \int \frac{\alpha^2}{\pi^3 M^2}\frac{L(M^2)}{M^2}\, f_B(q\cdot u;\ T)\,\mathrm{Im}\Pi_{\mathrm{EM}}[M,q;T,\mu_B]\,d\boldsymbol{x}$$

$$\equiv \int \frac{d^4\epsilon}{d\boldsymbol{q}}[T(\boldsymbol{x}),\mu_B(\boldsymbol{x}),\vec{v}(\boldsymbol{x})]\,d\boldsymbol{x}$$



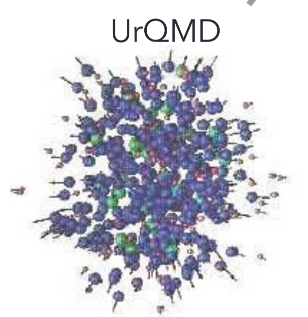
F. Seck, MSc 2015

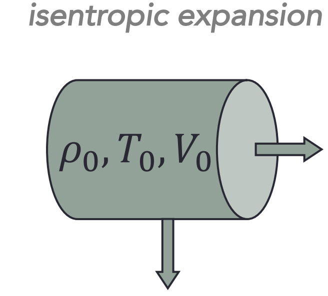
shining

coarse graining

or

isentropic expansion

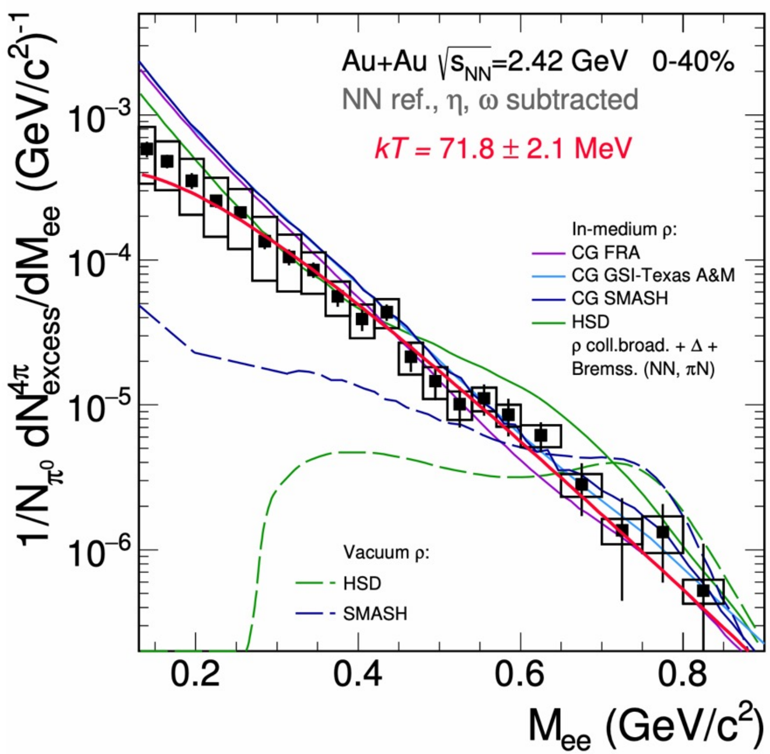




Fluid expansion (local thermal equilibrium)

Microscopic transport

Thermal dileptons Au+Au ($\sqrt{s} = 2.4\,A$ GeV)



HADES, Nat. Phys. 15(2019) 1040

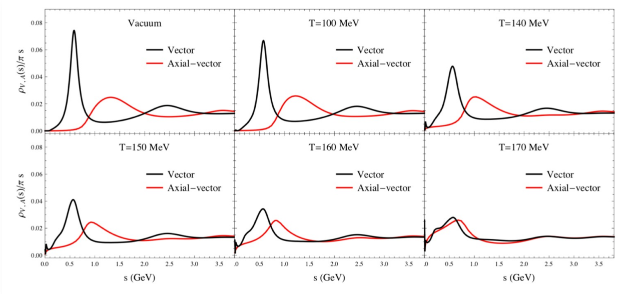
- Microscopic transport[2]:
  - Vacuum ρ spectral function and Δ regeneration
  - Explicit broadening and density dependent mass shift
- Coarse-grained UrQMD[3]
  - Thermal emissivity with in-medium propagator [4]
  - $\rho - a_1$ chiral mixing[5] (not measured so far)

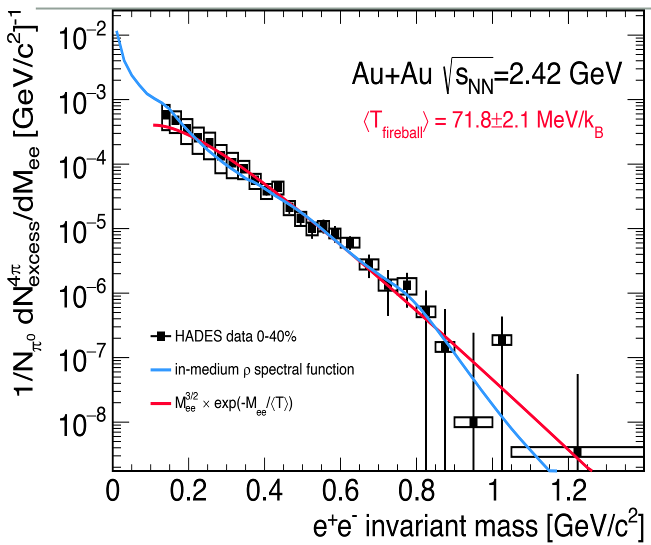
(4) Rapp, van Hees; arXiv:1411.4612v
(2) E. Bratkovskaya;
(3) CG FRA Endres, van Hees, Bleicher; arXiv:1505.06131
CG GSI-TAMU; Galatyuk, Seck, et al. arXiv:1512.08688
(4) Rapp, Wambach, van Hees; arXiv:0901.3289
(5) Rapp, Hohler; arXiv:1311.2921v

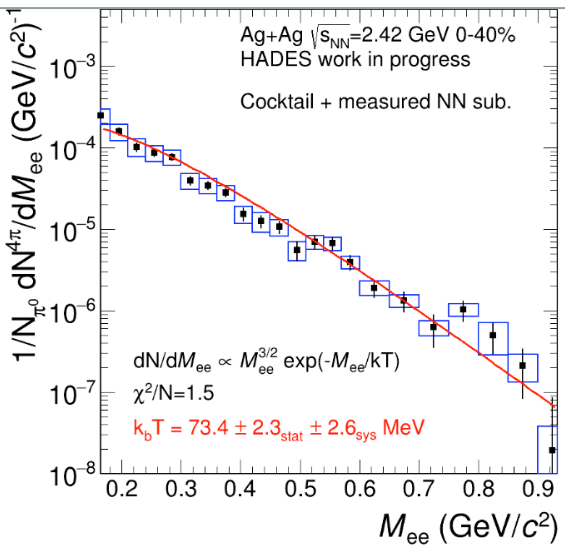
Exccess radiation

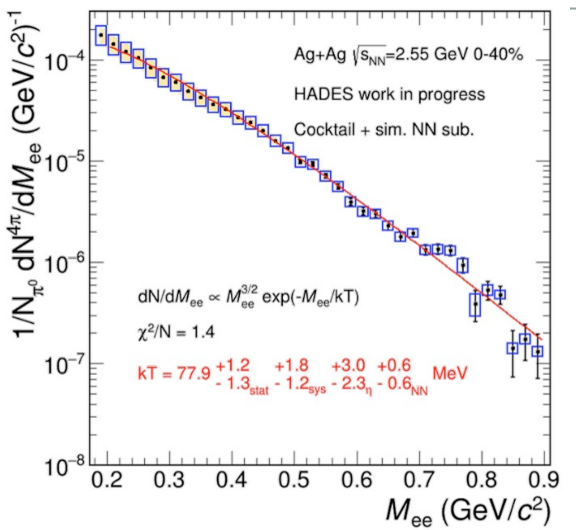
- Spectral distribution reproduced by a fit assuming thermal radiation
- Significantly higher temperature at higher collision energy
- No indication of a bump at the lower energy → strong melting

P. Hohler, R. Rapp; arXiv:0311.2921



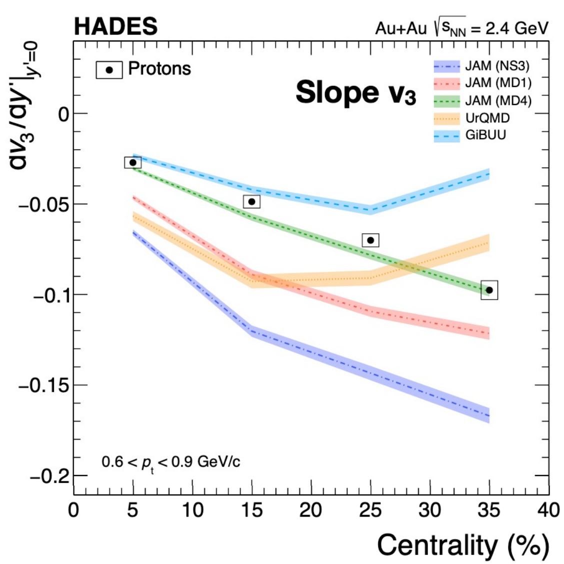


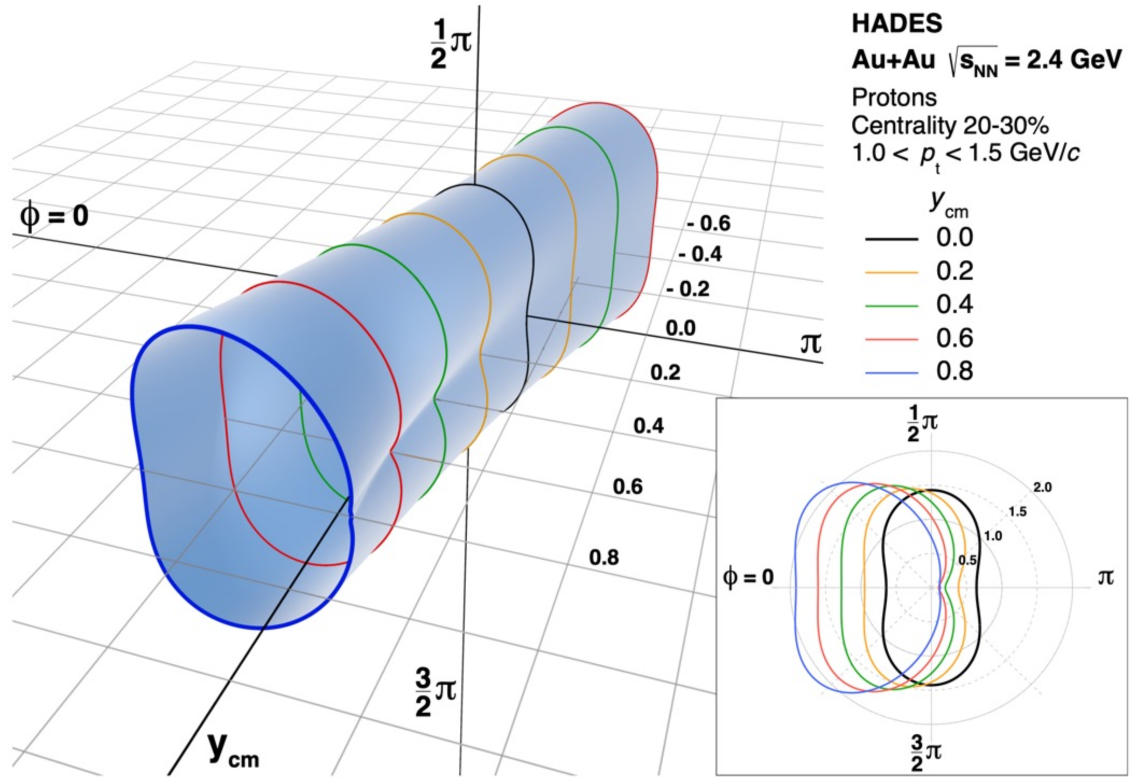




Proton higher-order flow components ($Au + Au\ \sqrt{s} = 2.4$ AGeV)

- Double differential (y,p) flow harmonics up 6th order for p, d, t
- Detailed measurement of the flow profile; higher order coefficients aligned with EP
- Expect high sensitivity to the EOS used in transport calculations

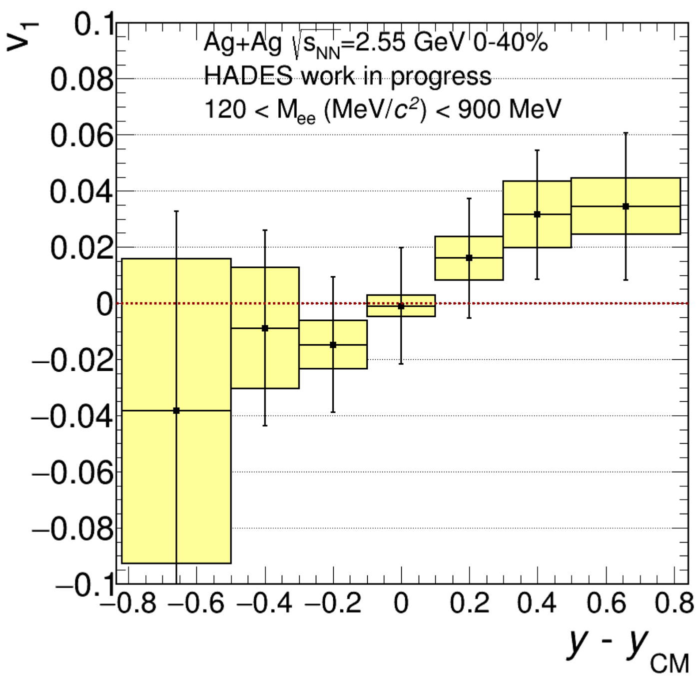


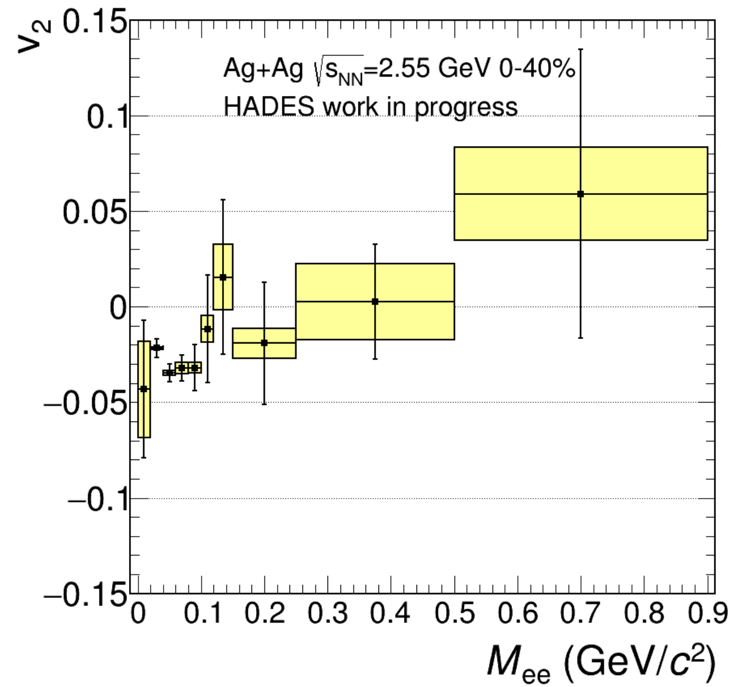


HADES, *Phys. Rev. Lett.* 125 (2020) and 2208.02740 [nucl-ex]

Dilepton flow from Ag+Ag collisions

- First attempt of HADES to extract flow harmonics from excess radiation
- Needs more statistics and will come to bloom at CBM





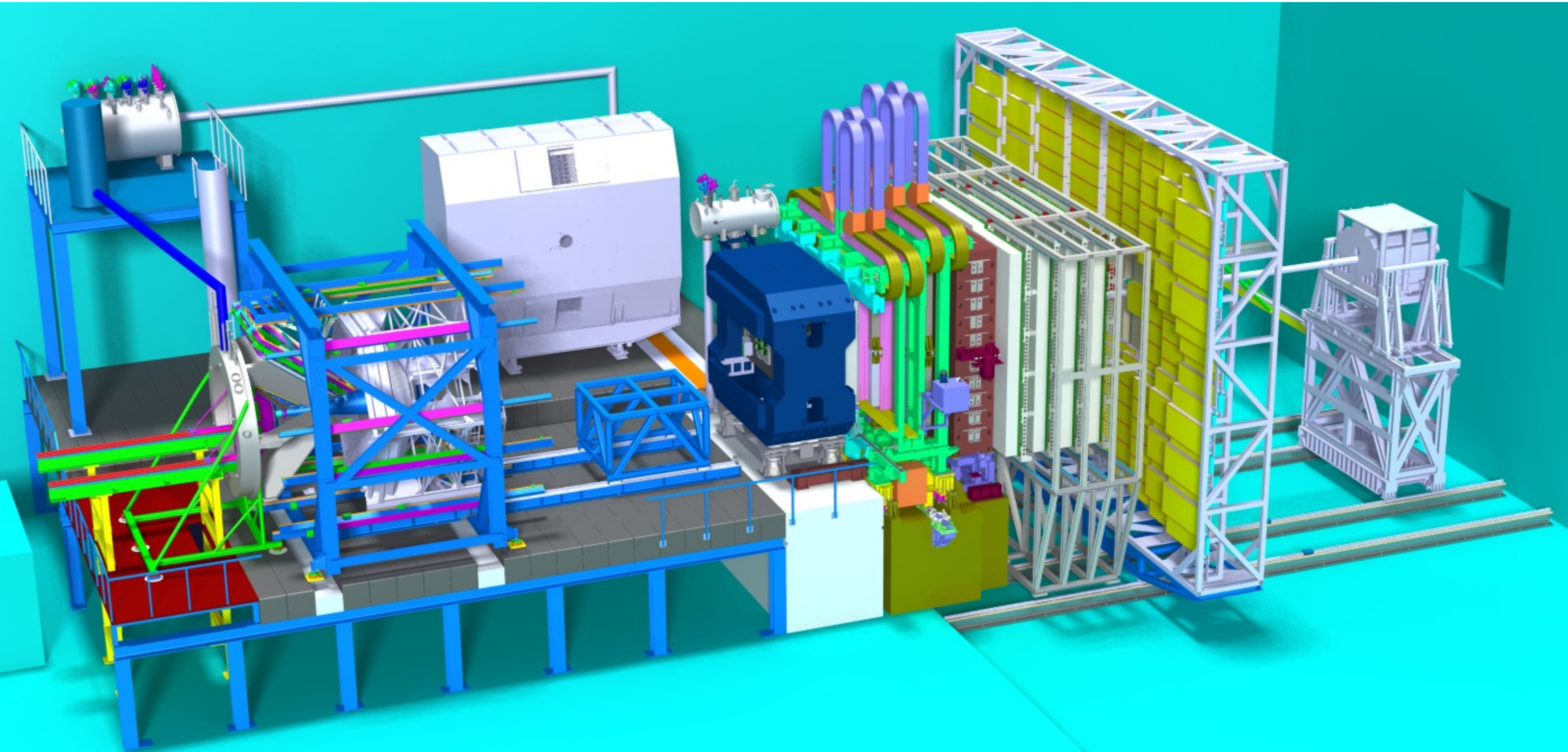
The Future at FAIR

Shell construction accelerator tunnel finished

Installation of technical building equipment has begun

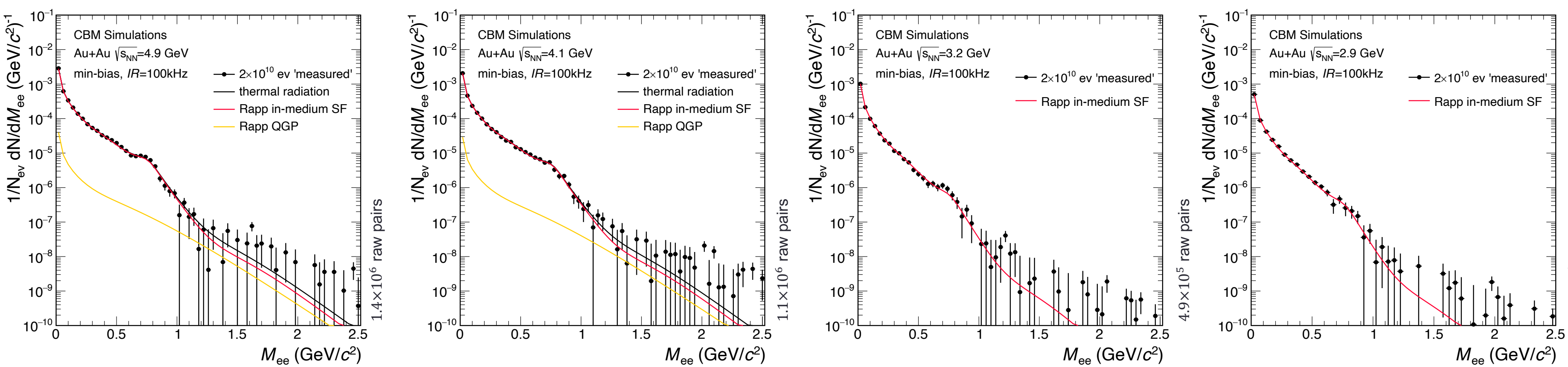
The C.B.M. experiments

Systematic exploration of baryon dominated matter in A+A collisions from $2 - 11\ A\ \mathrm{GeV}$ beam energy



CBM dielectron performance (first 3 years, 5 days / energy)

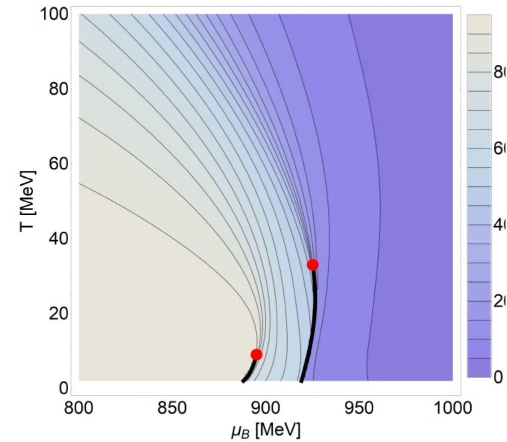
- Dielectron thermal radiation yield, corrected for acceptance x efficiency:
  - Dominated by ρ contribution at low mass ($M_{\ell\ell}$ <1GeV/c^2); can be reconstructed with precision of 1.5 – 4.5%
  - Intermediate mass range ($M_{\ell\ell}$>1GeV/c^2) accessible, statistics will not (yet) be sufficient to extract physics

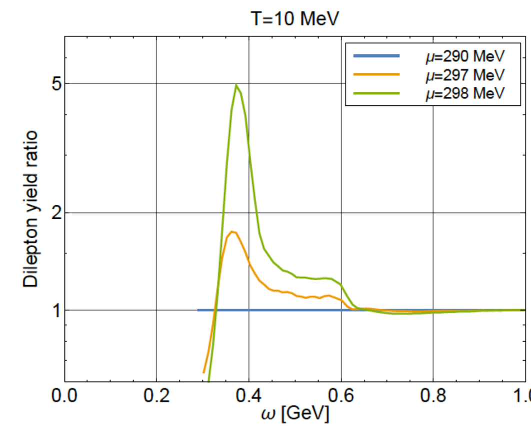


Dilepton Signature of a First-order Phase Transition

- EM spectral function from FRG flow equations
- Dilepton rates at CEP

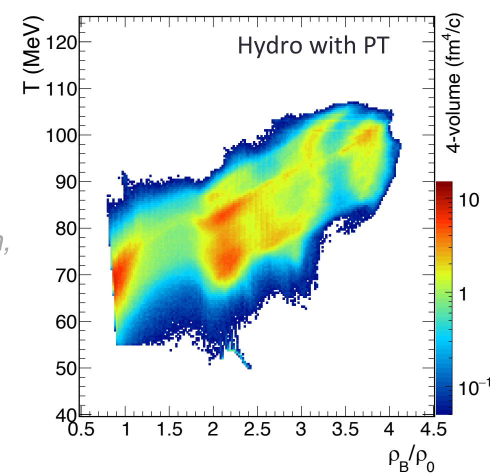
Tripolt, Jung, Tanji, v. Smekal, Wambach, Nucl. Phys. A982 (2019) 775
Jung, Rennecke, Tripolt, v. Smekal, Wambach, Phys. Rev. D 95 (2017) 036020

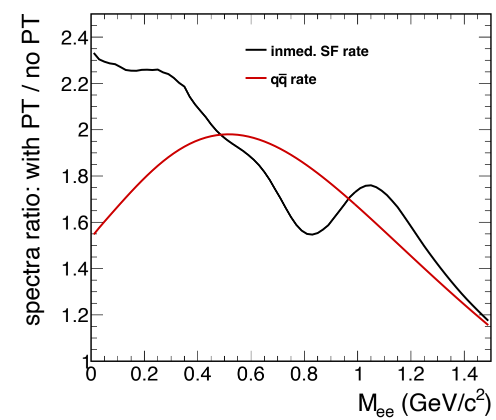




- dilepton radiation in hydrodynamical simulations
- factor of ~2 extra radiation in case of hydro with PT

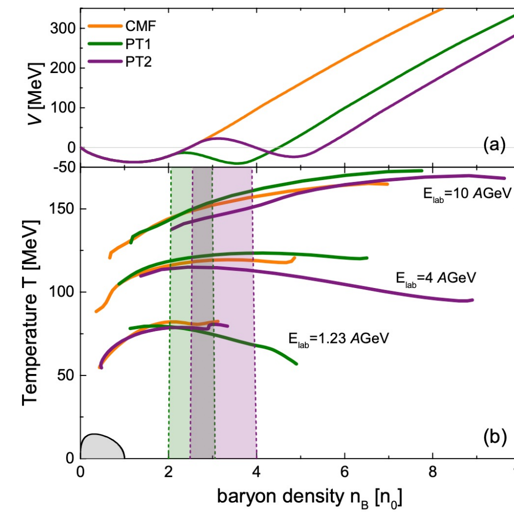
Seck, Galatyuk, Mukherjee, Rapp, Steinheimer, Stroth, Phys.Rev.C 106 (2022) 014904
Feng Li and Che Ming Ko, Phys. Rev. C 95 (2017) no.5, 055203



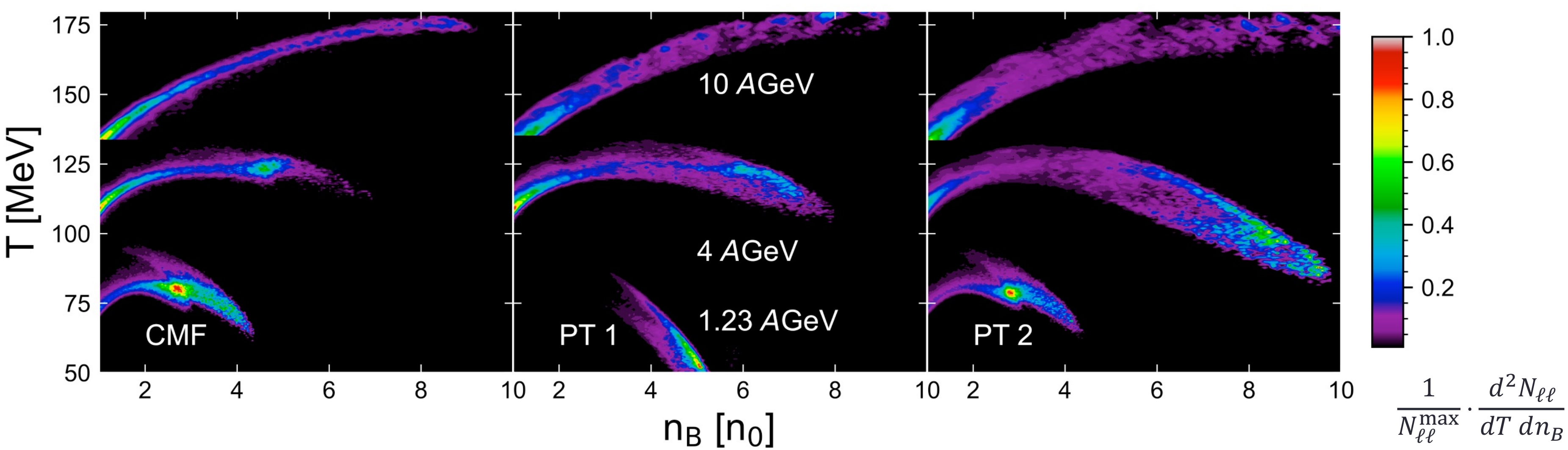


Respective emissivity maps

- "Phase space trajectories" from coarse grained UrQMD involving various equation of states
- Space-time integrated double differential dilepton yield for HADES and lower/upper CBM beam energies ($Au + Au$)



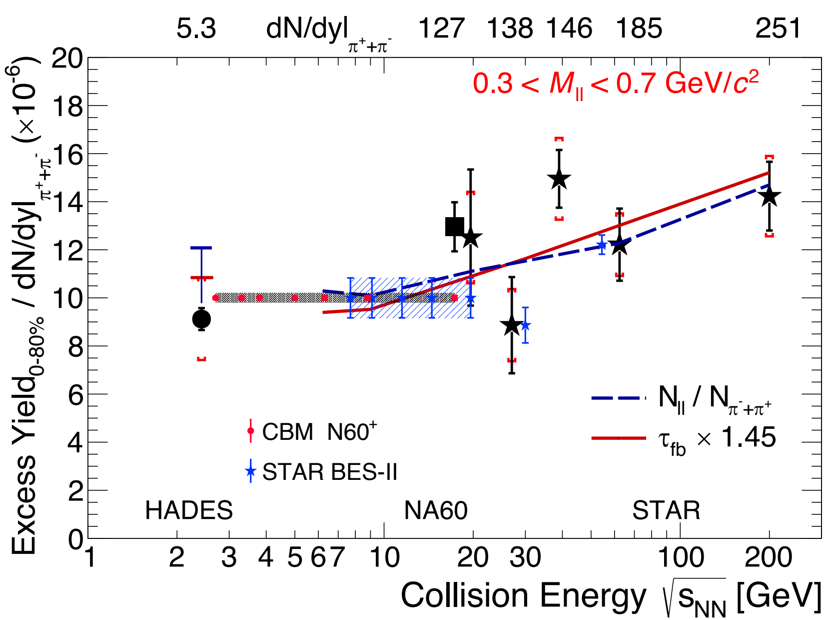
Oleh Savchuk et al. (AM, VV, MG, TG); arXiv:2209.05267 "powered by UKRAINE"

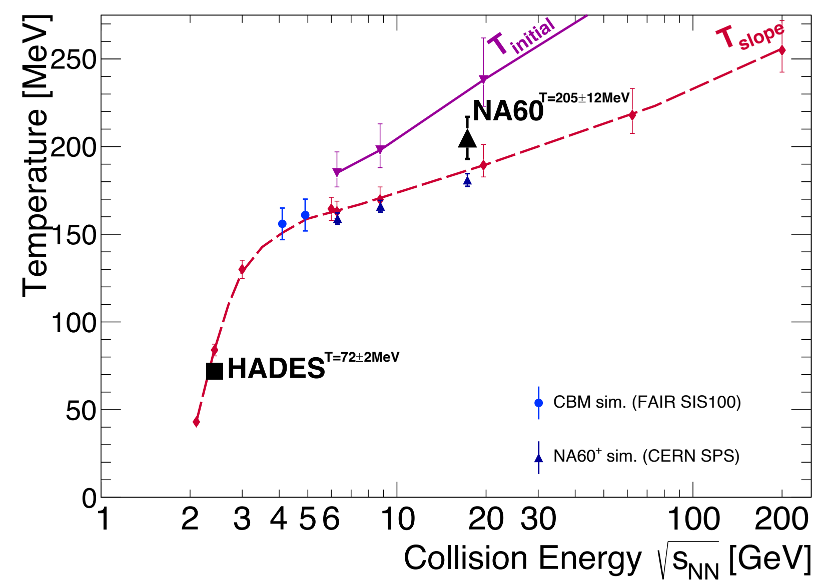


Dielepton excitation functions

Search for emerging signatures indicative of a first-order phase transition:

- prolonged lifetime of the system → "excess excess-radiation"?
- limiting temperature → "hadronic caloric curve"?





T. Galatyuk: JPS Conf.Proc. 32 (2020) 010079 and https://github.com/tgalatyuk/QCD_caloric_curve

THANK YOU