REVIEW OF EXPERIMENTAL RESULTS ON DILEPTONS

Joachim Stroth

Exploring high-μ_B Matter with Rare Probes

ECT* Trento

October 11–15, 2021

Topics discussed

HIC phenomenology

„Get your reference right“

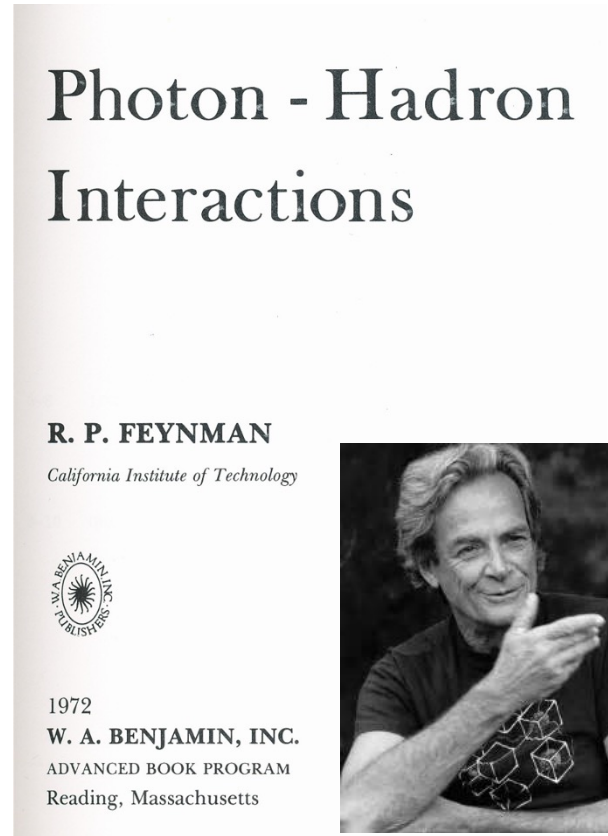
In-medium ρ and SBχS

Thermal radiation (standard candle?)

Cold matter

Vacuum

Future


Photon - Hadron Interactions

R. P. FEYNMAN

California Institute of Technology

W. A. BENJAMIN, INC. PUBLISHERS

1972

W. A. BENJAMIN, INC.

ADVANCED BOOK PROGRAM

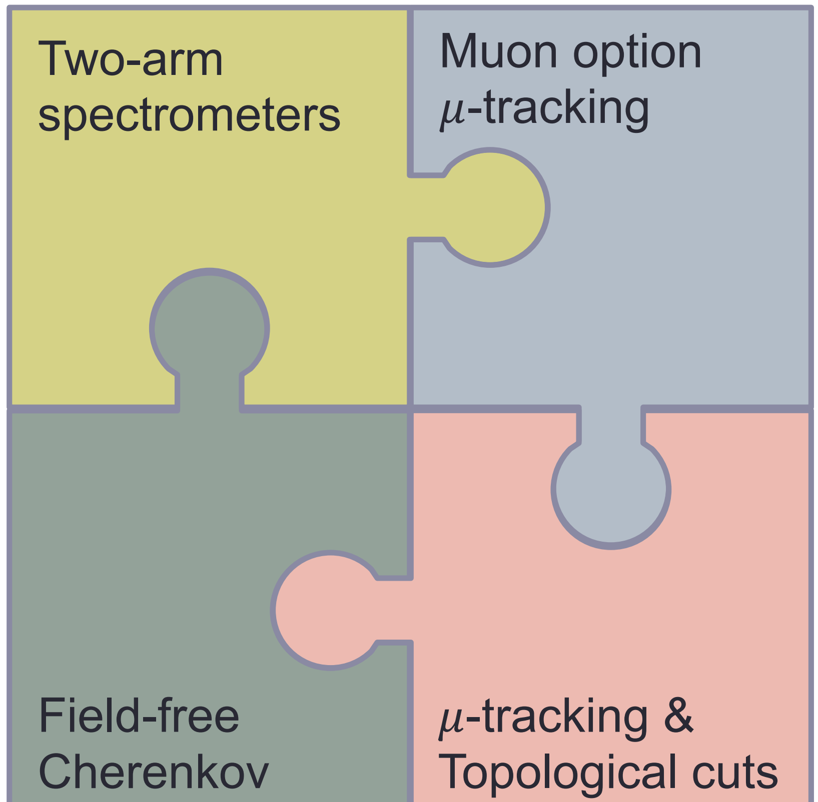
Reading, Massachusetts

Dilepton spectrometer concepts

Technology has driven the transformation from specialized to multi-purpose detectors

DLS
KEK-325

CBM-MUCH
NA60, NA60+
(LHC)



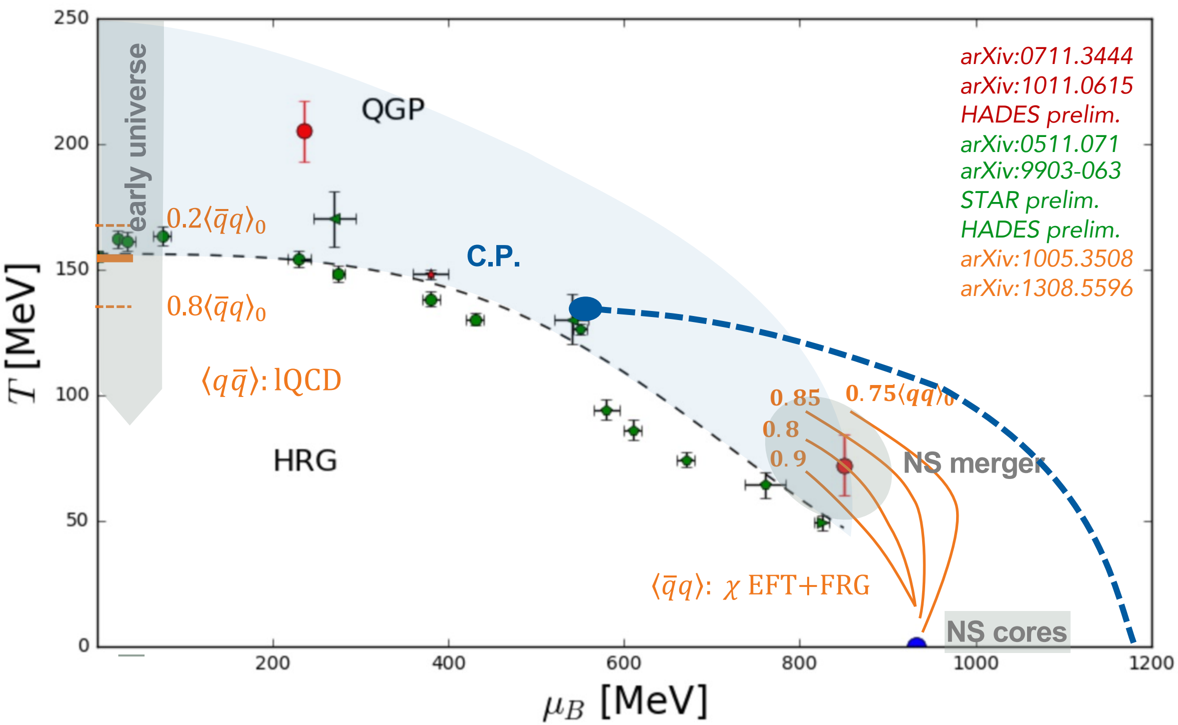
ALICE
CBM
(STAR)
sPHENIX

CERES
HADES
(PHENIX)

;)

INTRODUCTION

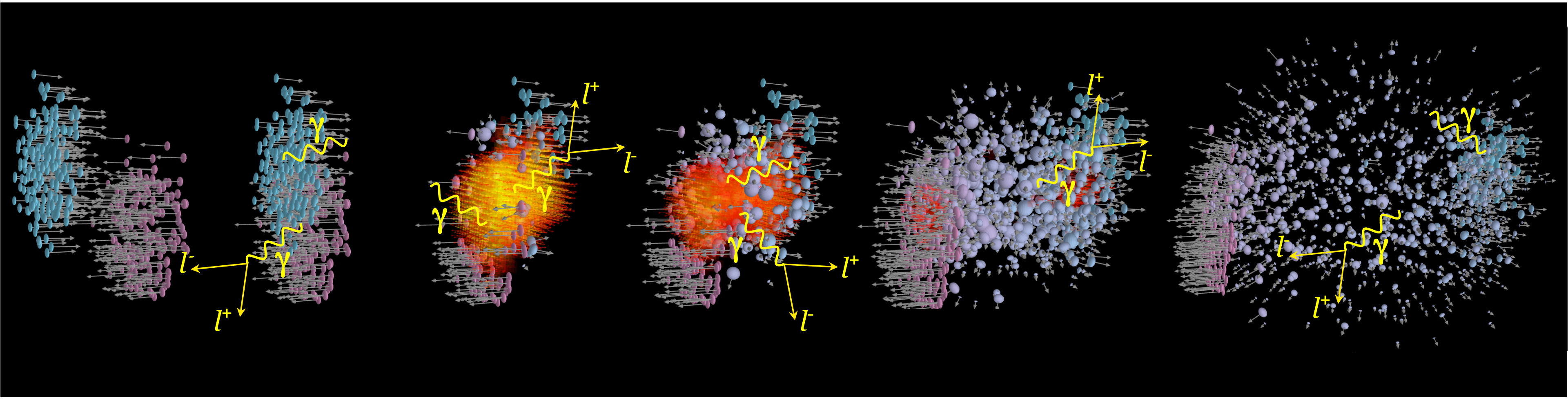
Exploring the QCD phase diagram



- Astrophysical relevance
  - Hadronization in the early universe
  - Neutron stars
  - Neutron star mergers
- lQCD / χEFT landmarks
  - Chiral cross over at $\mu_B = 0$ with pseudo critical temperature ($T_c = 154(9)$ MeV)
  - Chiral condensate
- „Observations“
  - Freeze-out conditions (SHM)
  - „Mean“ fireball temperatures ("Planck"radiation)
  - Liquid gas phase transition
- Conjectures
  - 1st order chiral/deconfinement phase transitions @ high μ_B
  - Exotic phases

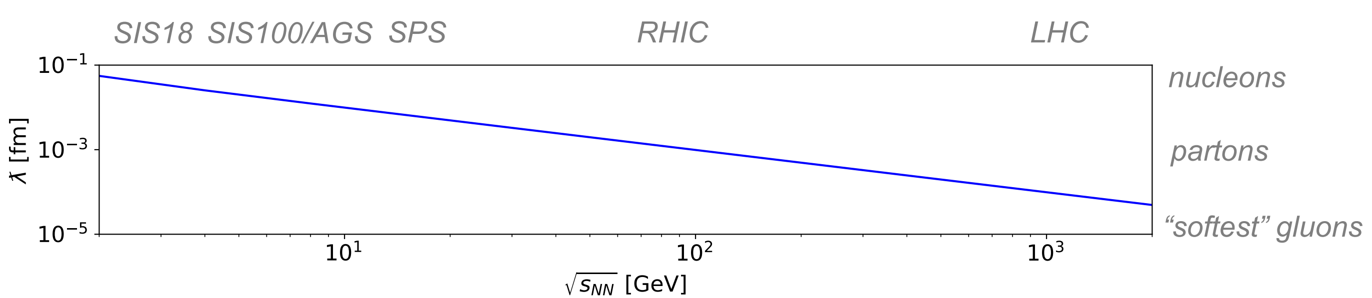
The (U)RHIC Standard Model

„First chance“ „Pre-equillibrium“ Fireball Freeze-out Late stage



Very different a.f.o. $\sqrt{s_{NN}}$

Drell/Yan,
correl. semi-leptonic
decay of heavy flavor

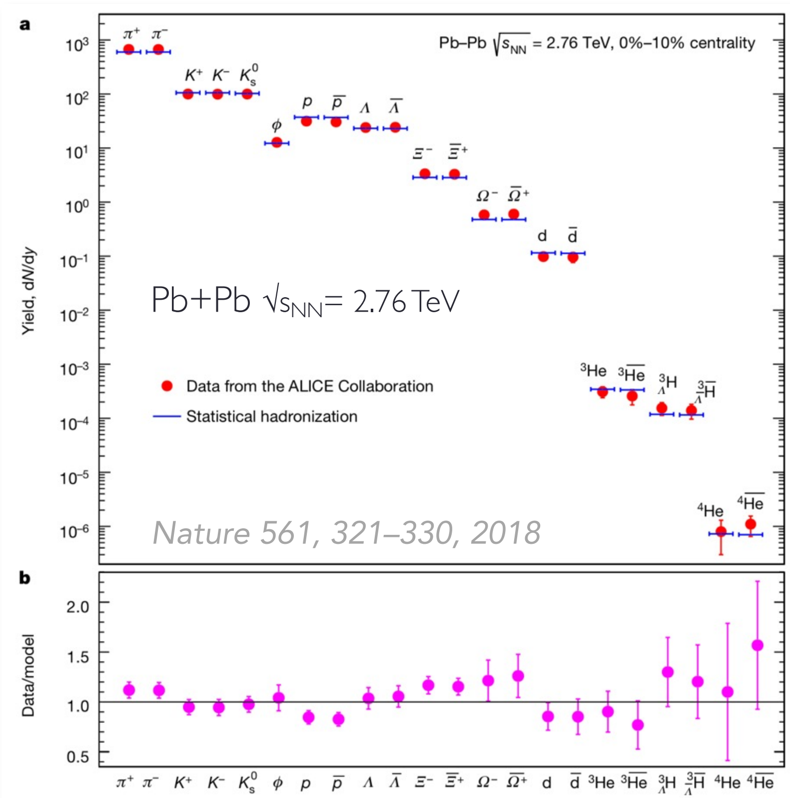


Freeze-out conditions from SIS18 to LHC

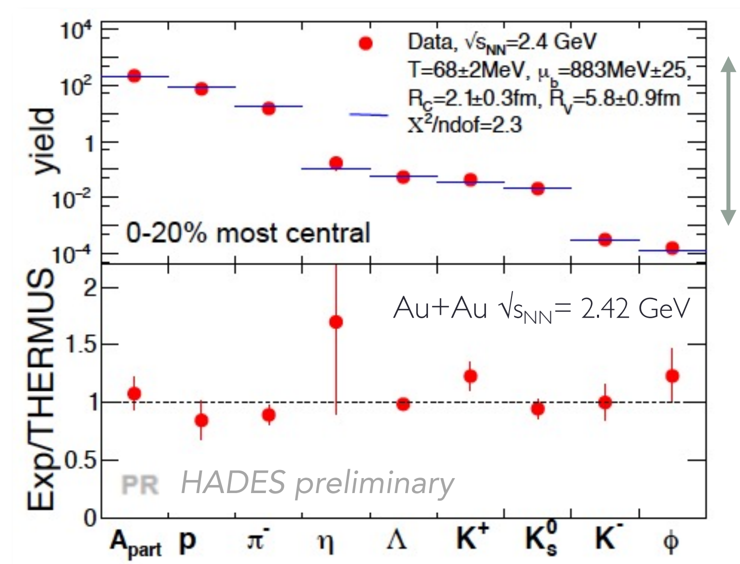
ALICE ($\sqrt{s} = 2.76\ A\text{TeV}$): $\boldsymbol{T_{ch} = 156.5\ (1.5);\ \mu_B = 0.7\ (3.8)}$

HADES ($\sqrt{s} = 2.4\ A\text{GeV}$): $\boldsymbol{T_{ch} = 68.2\ (1.5);\ \mu_B = 883\ (25)}$

- Factor 1000 in beam energy / factor ~2 in temperature
  - Strangeness canonical treatment at low beam energies!
  - Calculation carried out with vacuum masses!



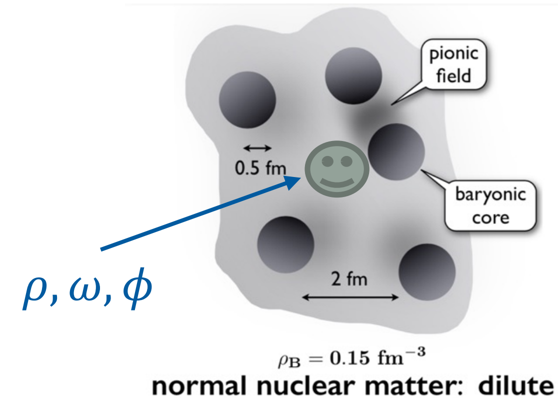
1 ppm



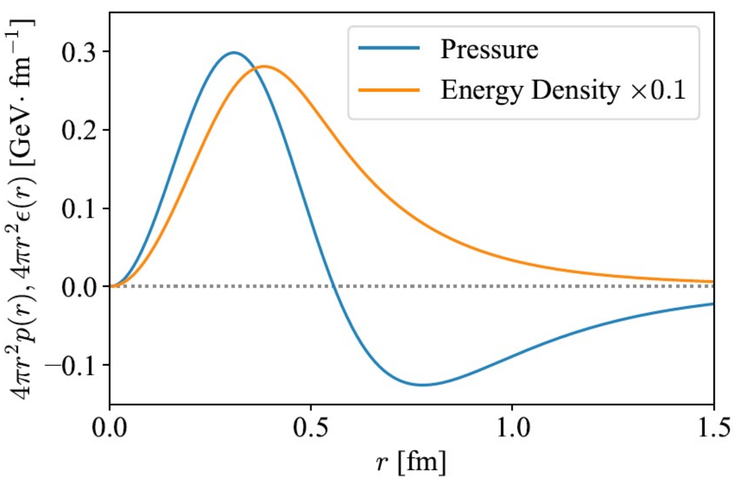
1 ppm

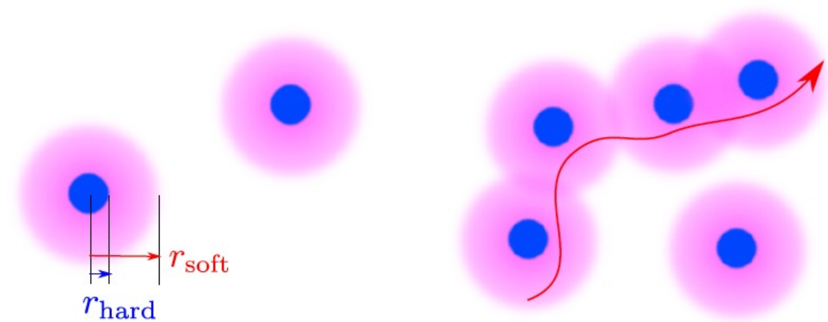
Hadron spectrum and QCD condensates

- Dynamical mass generation due to QCD condensates:
  - Hadron masses: breaking of scale invariance (trace anomaly, gluon condensate)
  - Parity splitting, Goldstone modes: breaking of χ symmetry (chiral condensate)
- Is quantum entanglement the origin of phase space "driven" particle yields?



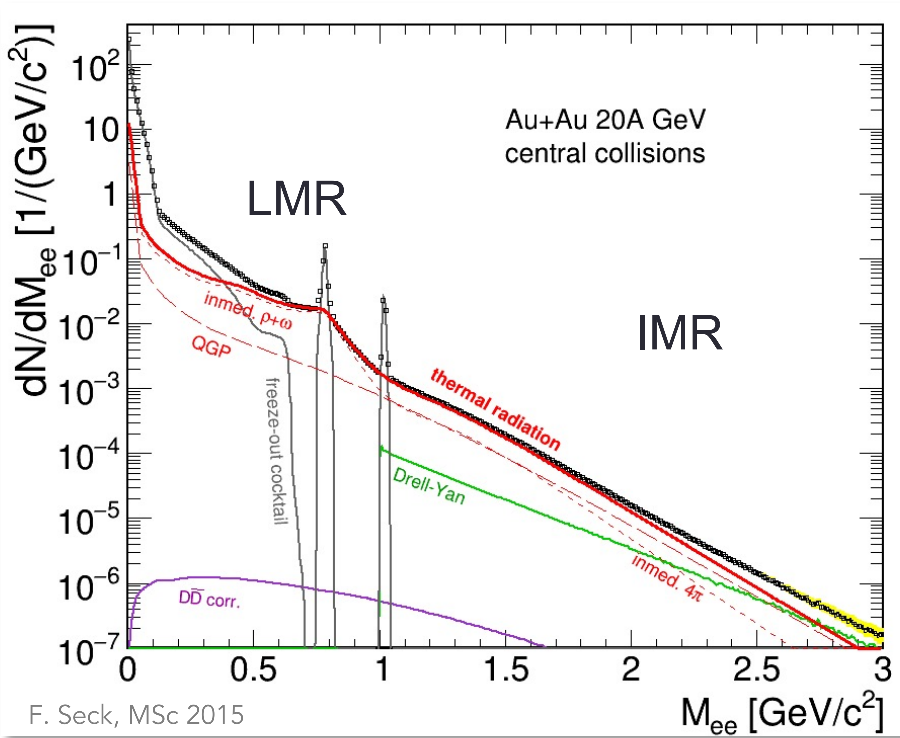
W. Weise, QNP2018





K. Fukushima, T. Kojo, W. Weise; arXiv:2008.08436v2 (also G. Baym, QNP2018)

The dilepton invariant mass distribution



1) „First chance“, pre-equillibrium:
   - $NN \rightarrow e^+e^-X$
   - Drell/Yan
   - Open-charm

2) Excess (thermal) radiation from QGP and hadronic matter:
   - $q\bar{q} \rightarrow e^+e^-$ (QGP)
   - In-medium ρ
   - Multi-meson processes (‘4π’): $\pi\rho, \pi\omega, \pi a_1, \ldots$ $\rho - a_1$ mixing

3) Decays of long-lived mesons (cocktail):
   - $\pi^0, \eta, \omega, \varphi, \ldots$
   - Correlated $D\bar{D}$ pairs – yield fixed from (1), effect of the medium?

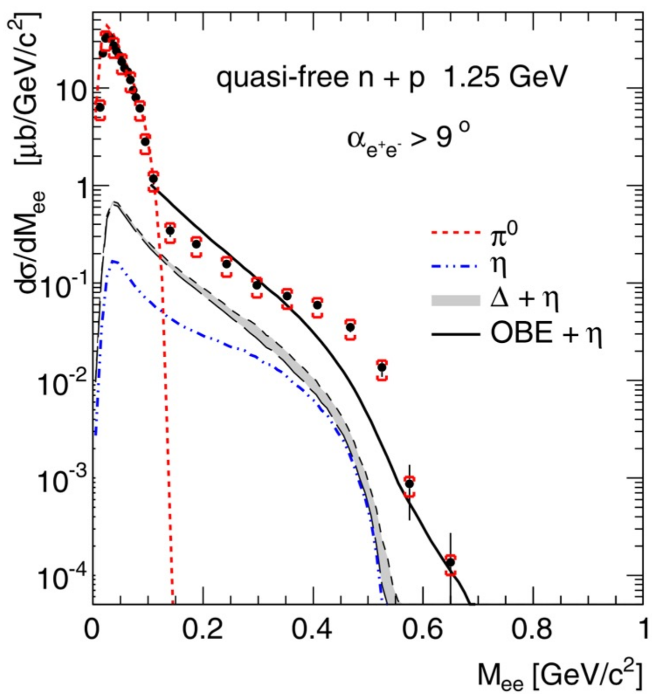
Excess radiation = remainder after subtraction of (1) and (3)

EXCESS RADIATION

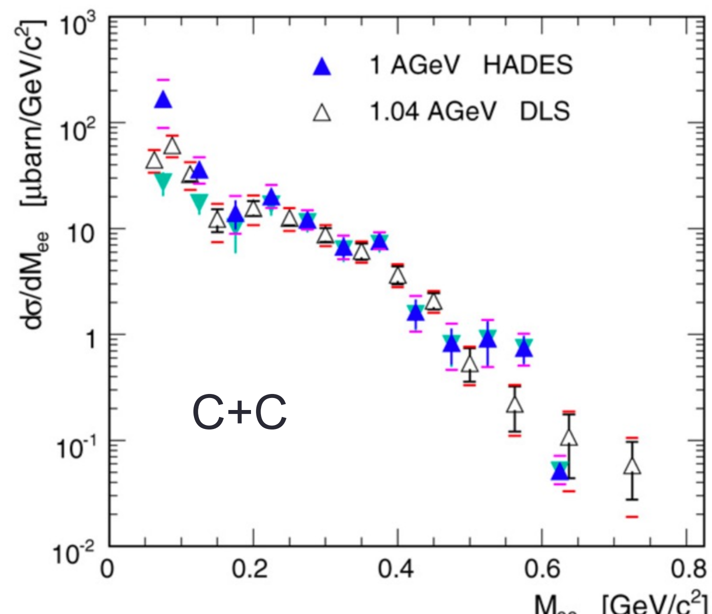
Establishing excess radiation at Bevalac/SIS18 …

… and the solution to the so-called DLS puzzle.

- Strong enhancement of dilepton yield from p+n “bremsstrahlung” – first glimpse on the ρ meson!



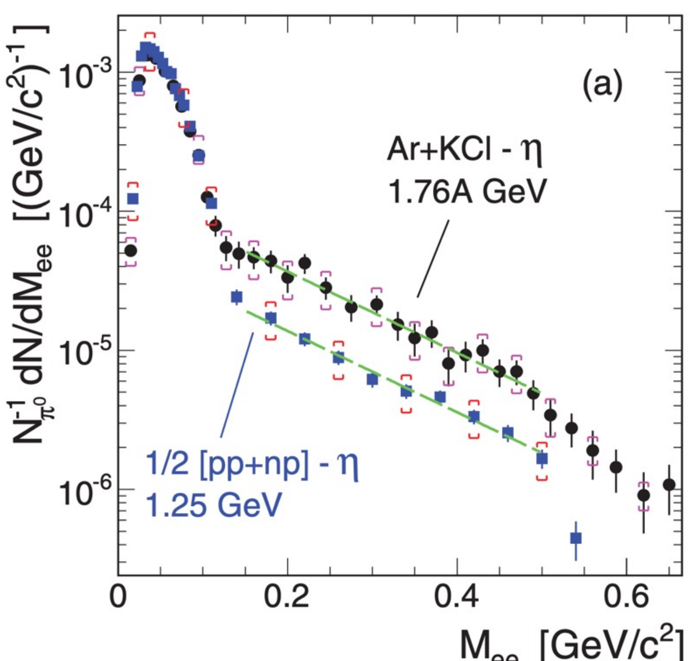
HADES, PLB 690 (2010) 118–122



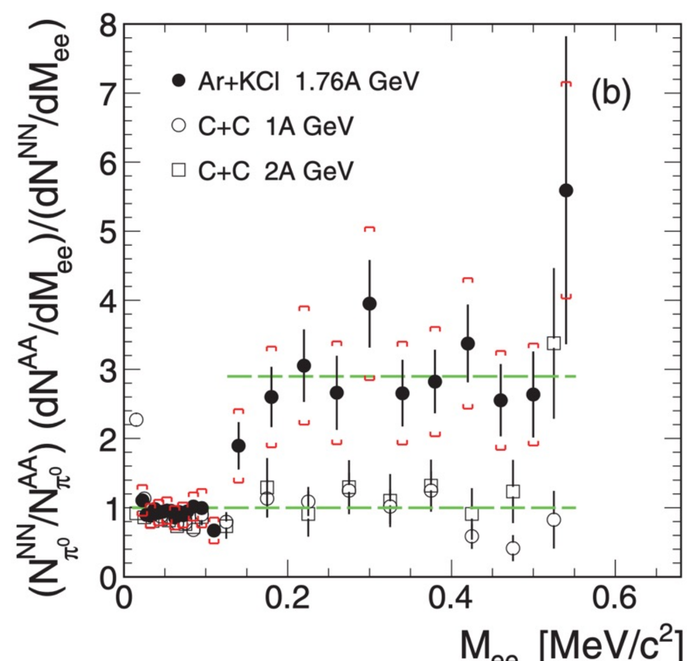
HADES, PLB 663 (2008) 43–48

Dileptons from 1.76 *A* GeV Ar+KCl collisions

- The excess radiation is evidenced after subtraction of a proper approximation for the contributions from first-chance NN collisions – the NN reference.
- Note the normalization to the π^0 multiplicity.



HADES, PRC 84, 014902 (2011)

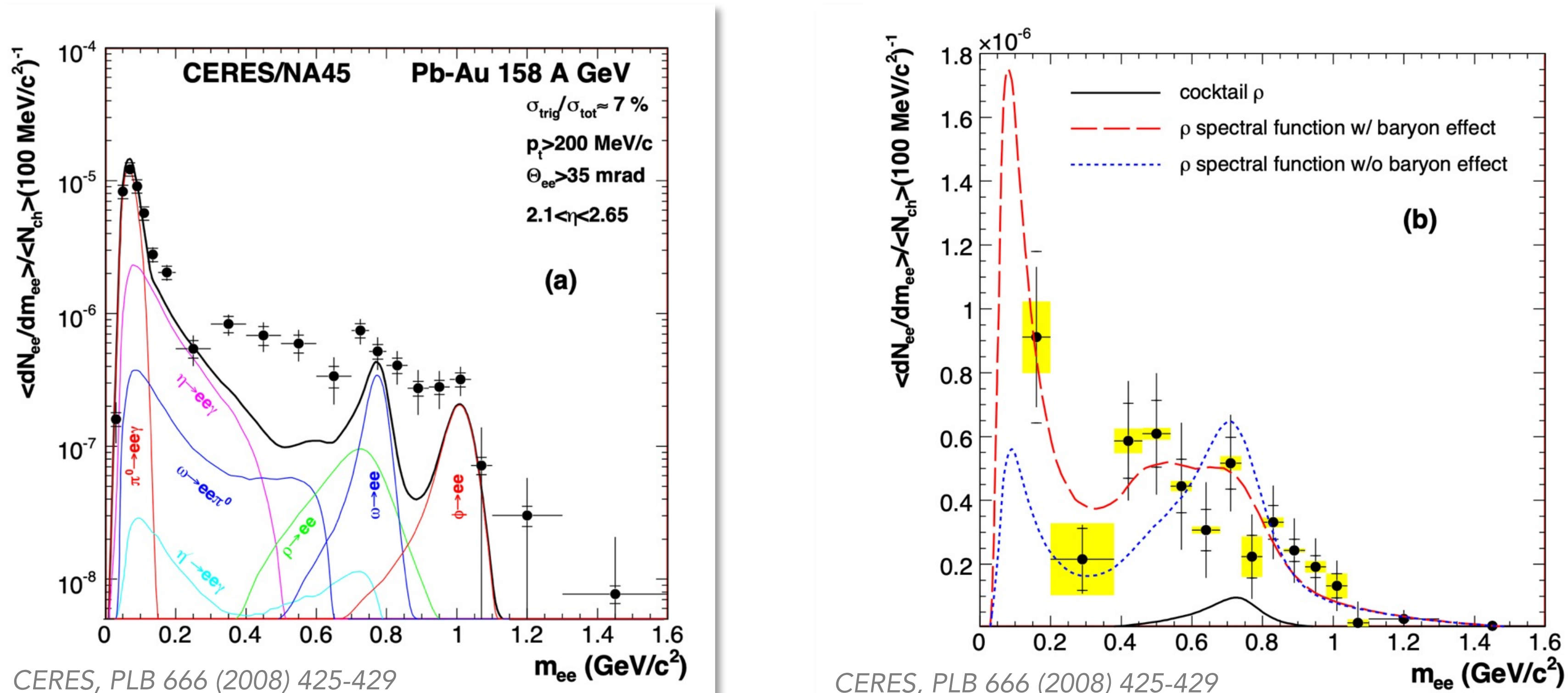


HADES, PRC 84, 014902 (2011)

IN-MEDIUM ρ-MESON

Dileptons from 158 A GeV Pb+Au collisions

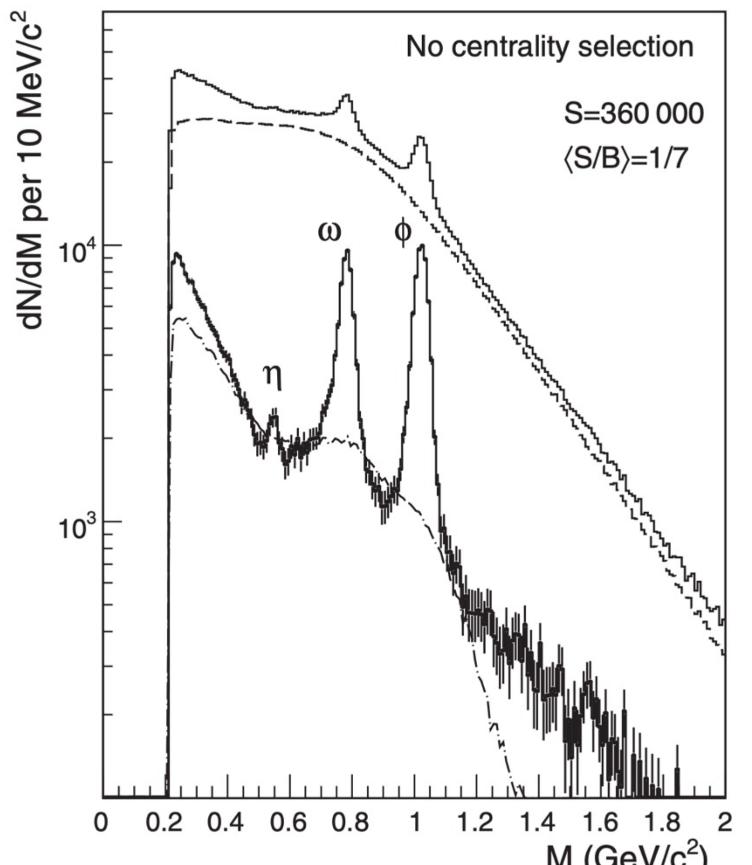
- First low-mass dilepton spectrum from a heavy collision system.
- Indications for strong baryonic effects on the in-medium ρ spectral function.



CERES, PLB 666 (2008) 425-429

CERES, PLB 666 (2008) 425-429

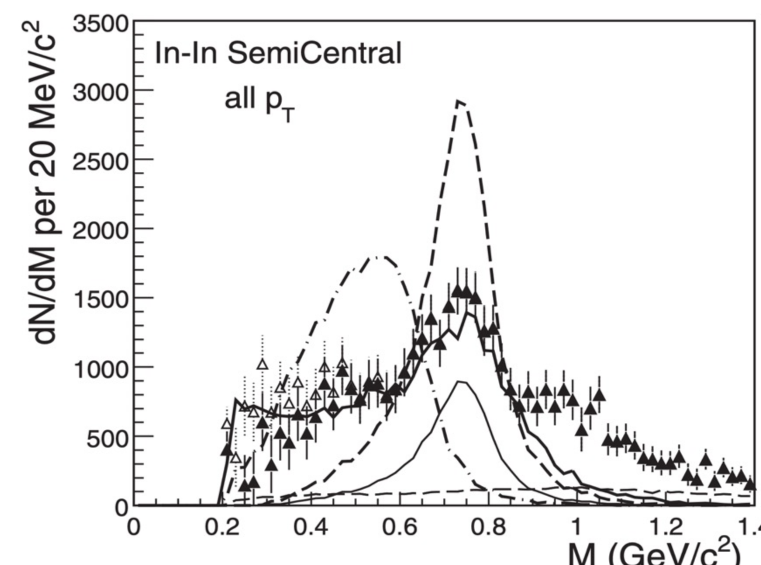
The ground breaking NA60 dimuon measurement



NA60, PRL 96 (2006) 162302

- … and the success of the in-medium ρ plus emission from a thermal source.

L. McLerran and T. Toimela, Phys.Rev.D 31 (1985) 545
J. Kapusta and C. Gale, Phys.Rev.C 35 (1987) 2107-2116
G. Chanfray, R. Rapp, and J. Wambach, PRL 76 (1996) 368.
R. Rapp, G. Chanfray, and J. Wambach, Nucl. Phys. A617 ((1997) 472.
R. Rapp and J. Wambach, Adv. Nucl. Phys. 25, (2000) 1.



NA60, PRL 96 (2006) 162302

Vector Meson Dominance in hot & dense matter

Generalized „Bremsstrahlung" – Fourier transform of current-current correlation function $\langle j(x), j(0)\rangle$:

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

L. McLerran, K. Toimela, Phys. Rev. D31 (1985)
See also: Ralf Rapp arXiv-1110-4345

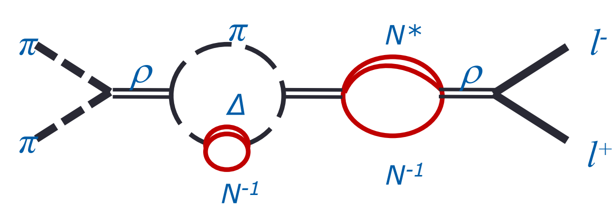
Extension of the Gounaris-Sakurai formula to a thermal pion gas: *C. Gale, J. Kapusta: Nucl. Phys. B357 (1991) 65*

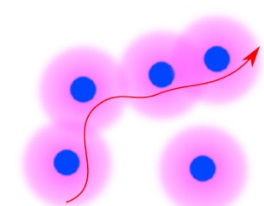
$$j^{\mu}_{EM} = \tfrac{1}{2}(\bar{u}\gamma^{\mu}u - \bar{d}\gamma^{\mu}d) + \tfrac{1}{6}(\bar{u}\gamma^{\mu}u + \bar{d}\gamma^{\mu}d) - \tfrac{1}{3}\bar{s}\gamma^{\mu}s \implies \mathrm{Im}\Pi_{EM} \sim \mathrm{Im\,D}_{\rho} + \tfrac{1}{9}\mathrm{Im\,D}_{\omega} + \tfrac{2}{9}\mathrm{Im\,D}_{\phi}$$

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

$$\mathrm{Im}\Pi_{EM}(M) = \left(\frac{m_\rho^2}{g_\rho}\right)^2 \mathrm{Im}D_\rho(M) \qquad D_\rho(M, q; \mu_B, T) = \frac{1}{(M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho M} - \Sigma_{\rho B})}$$

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
M. Asakawa, C-M. Ko et al., PRC 46 (1992) R1159

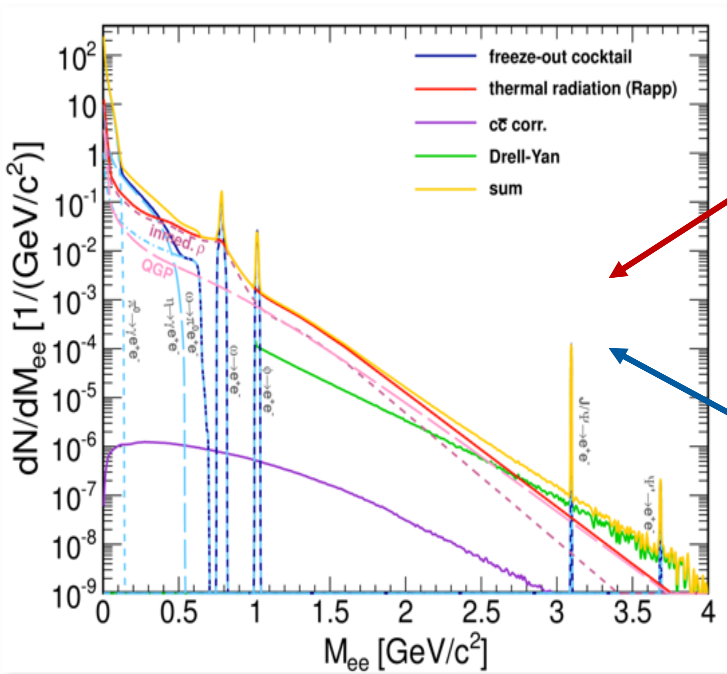




THERMAL RADIATION

Theoretical approaches to medium radiation

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



F. Seck, MSc 2015

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

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

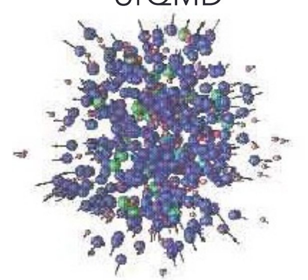
shining

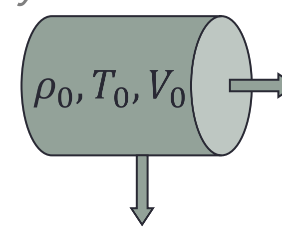
coarse graining

or

isentropic expansion, hydro

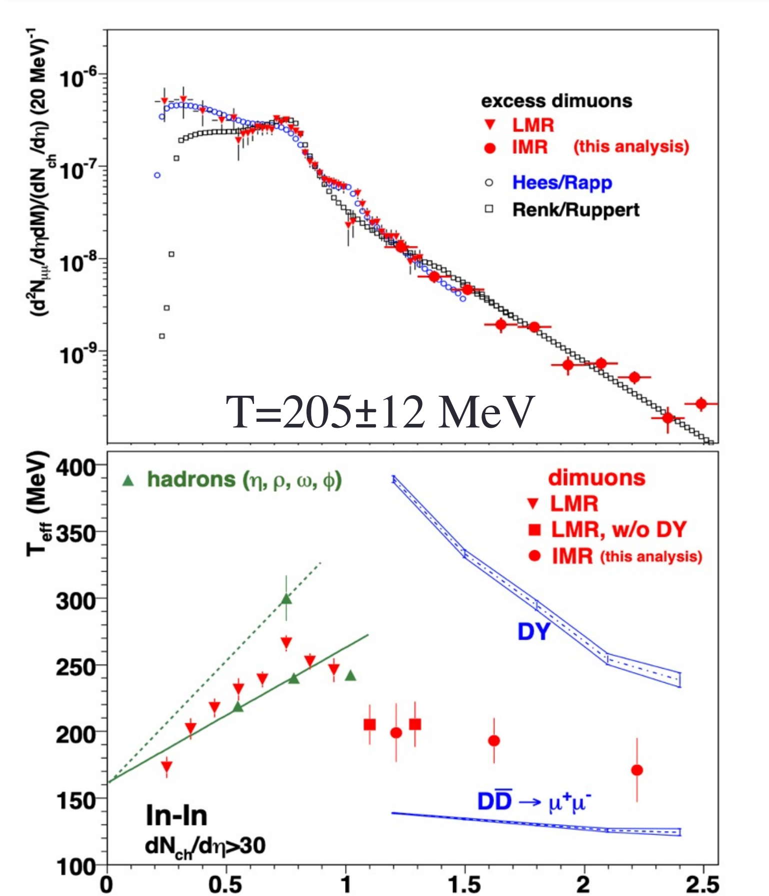
UrQMD





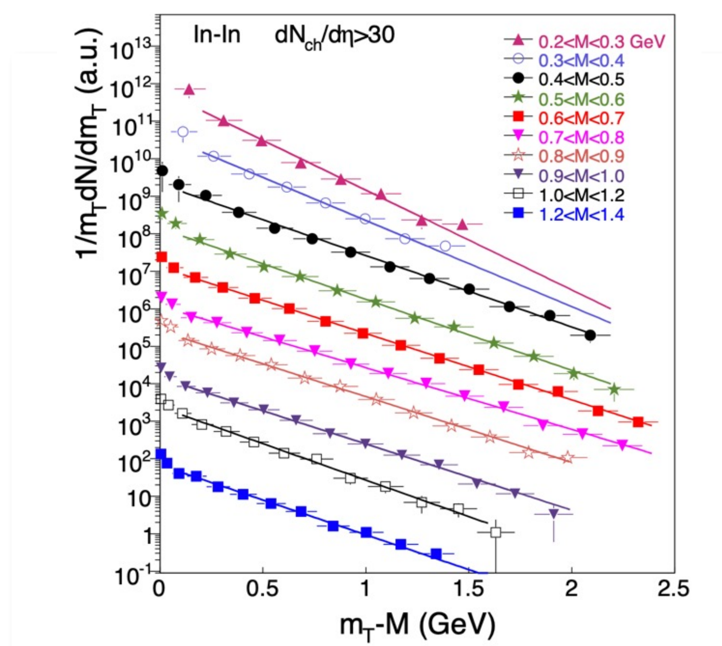
Dilepton emission from *Microscopic Transport.*

Double-differential analysis of the NA60 data



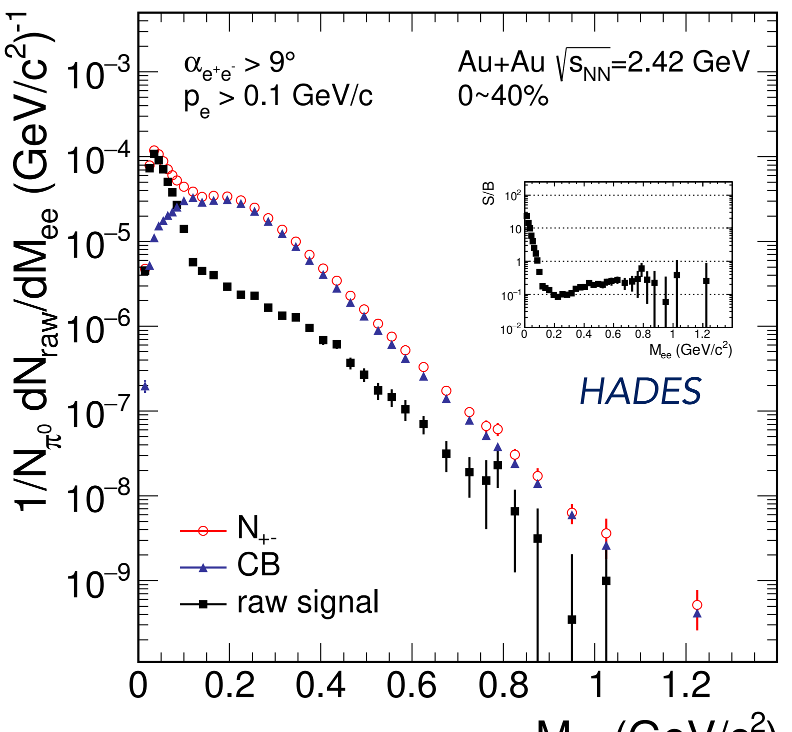
NA60, *EPJC* 59 (2009) 607-623

- Temperature, pressure, lifetime, microscopic structure (and more) – all from one observable
- Open-charm subtracted throughout

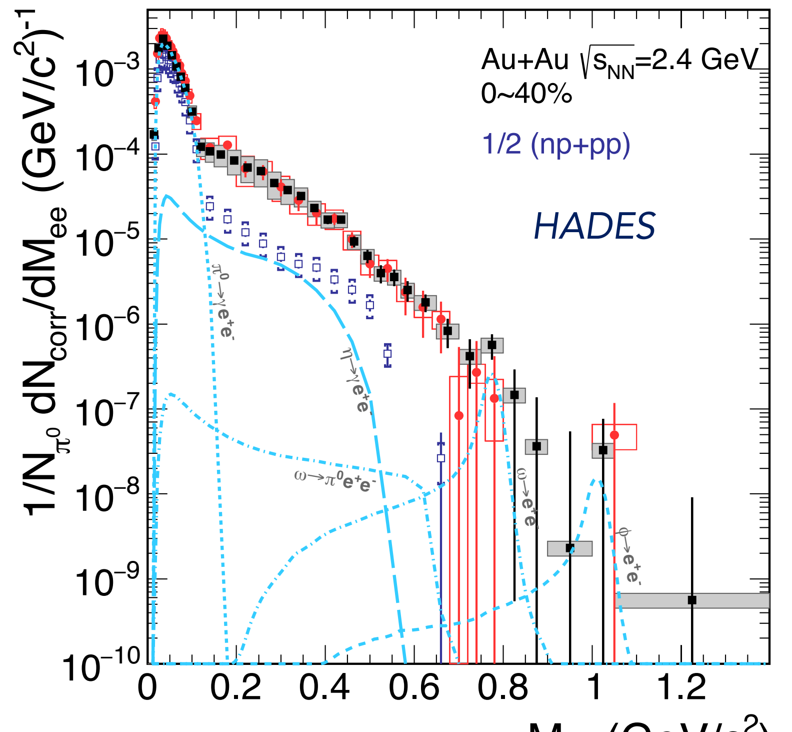


NA60, *EPJC* 59 (2009) 607-623, H. Specht Valencia 2010

Inclusive dielectron yields from Au+Au ($\sqrt{s} = 2.4\,A$ GeV)

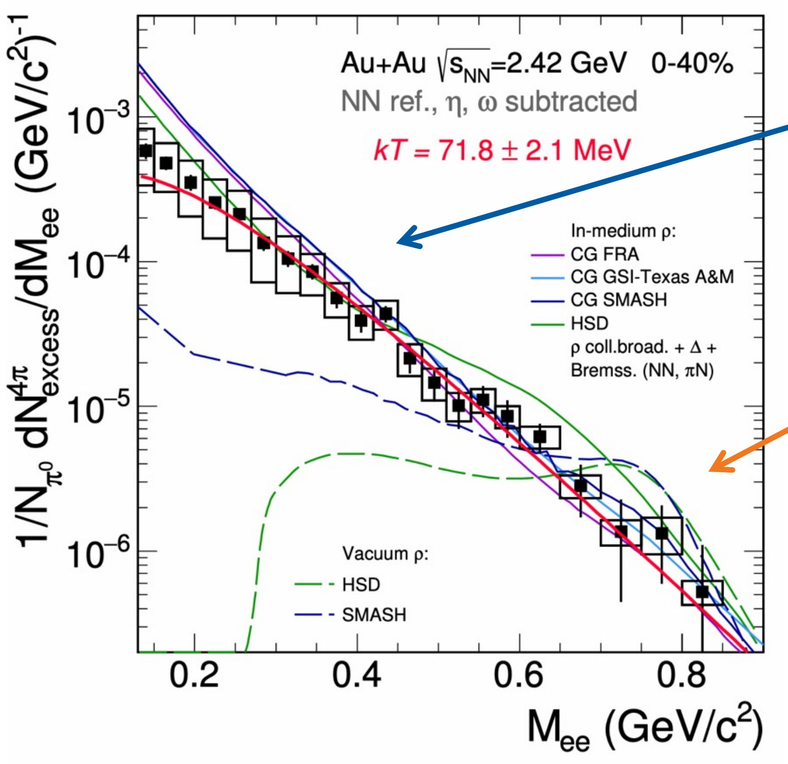


HADES, Nat. Phys. 15(2019) 1040



HADES, Nat. Phys. 15(2019) 1040

Thermal dileptons Au+Au 1.23*A* GeV (HADES)



HADES, Nat. Phys. 15(2019) 1040

0.3 < M < 0.7 GeV:
- In-medium spect. funct.
- fireball life-time
- fireball temperature(1)

M > 1 GeV/c^2:
- ρ – a1 chiral mixing
- dominated by contribution from the hottest and densest region

- 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

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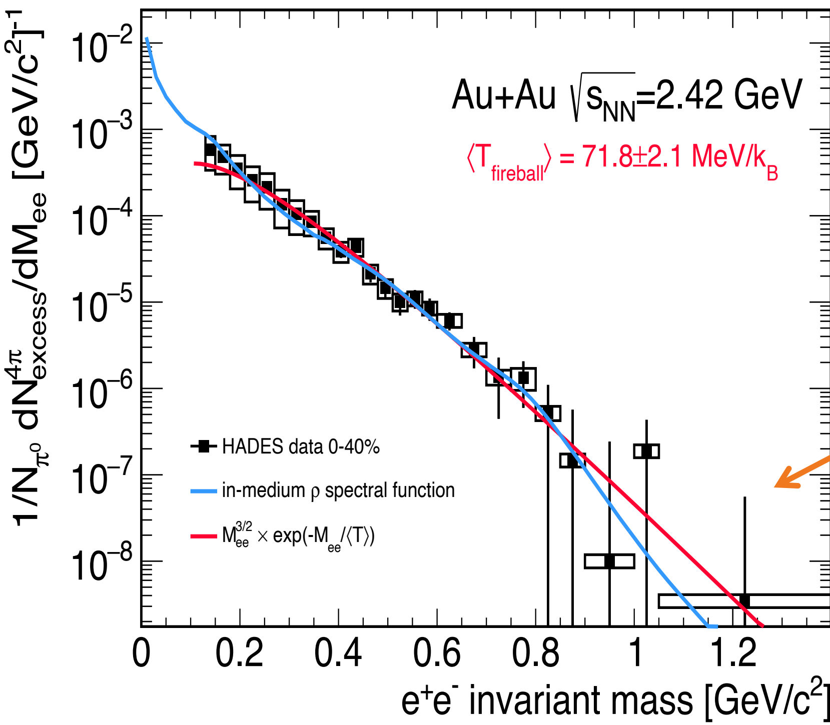

Full spectrum, "calculated" low-mass, low-momentum emissivities.
More statistics in Ag+Ag 1.56 A GeV -> SQM2021

0.3 < M < 0.7 GeV:
- In-medium spect. funct.
- fireball life-time
- fireball temperature(1)

M > 1 GeV/c^2:
- ρ – a1 chiral mixing
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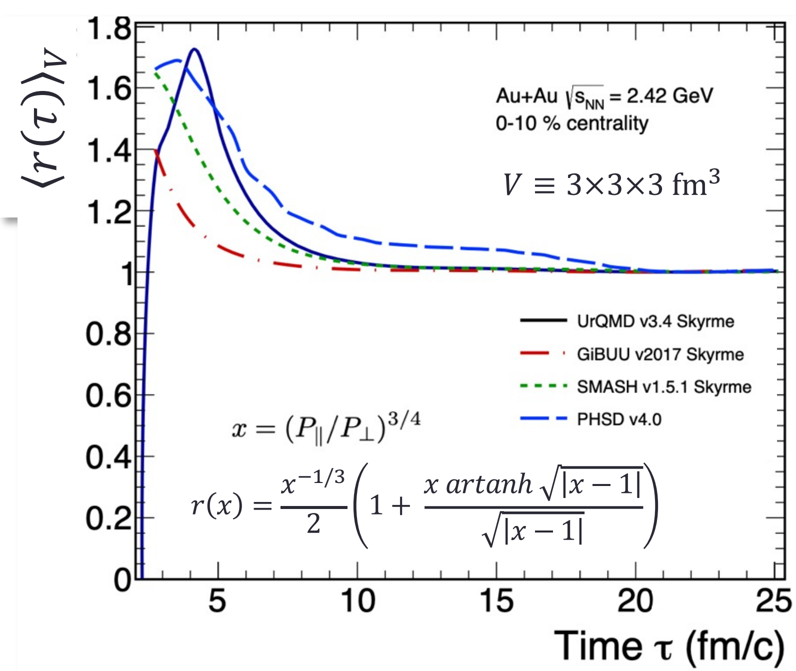
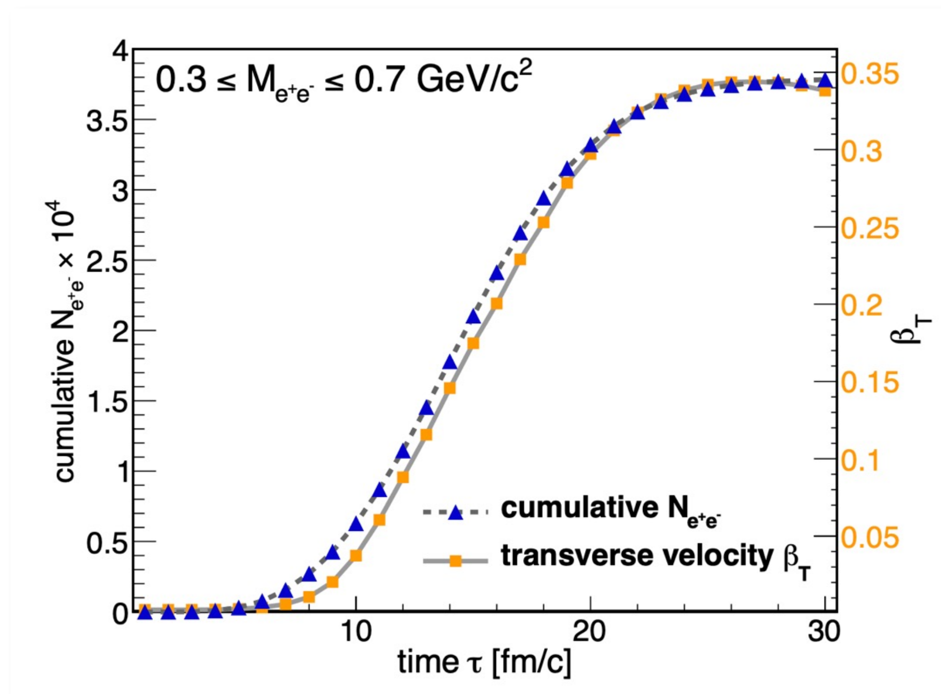
CG GSI-TAMU; Galatyuk, Seck, et al. arXiv:1512.08688
(4) Rapp, Wambach, van Hees; arXiv:0901.3289
(5) Rapp, Hohler; arXiv:1311.2921v

The "quest" for (non-)thermalization at SIS18

- pre-equillibrium state approximated by scaled reference measurement pp a nd npp_{spec}



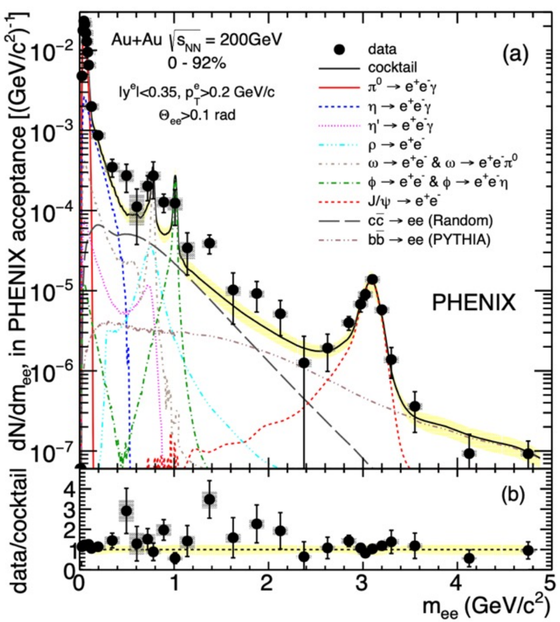


F. Seck et al.; arXiv-1512-08688

Dilepton spectra from colliders

PHENIX

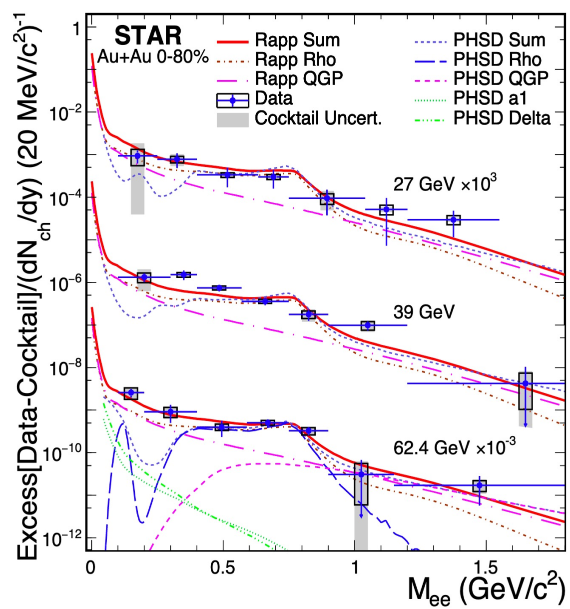
Excess established at RHIC



PHENIX, PRC 81 (2010) 034911
PHENIX, PRC 93 (2016) 1

STAR

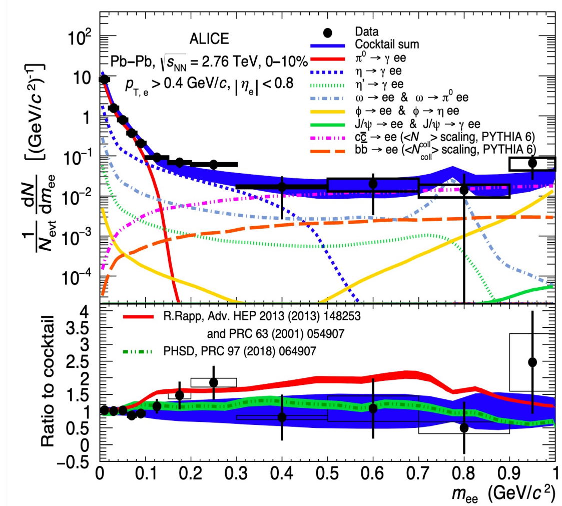
First excitation function for thermal radiation



STAR, PRL 113 (2014) 2, 022301
STAR, arXiv:1810.10159

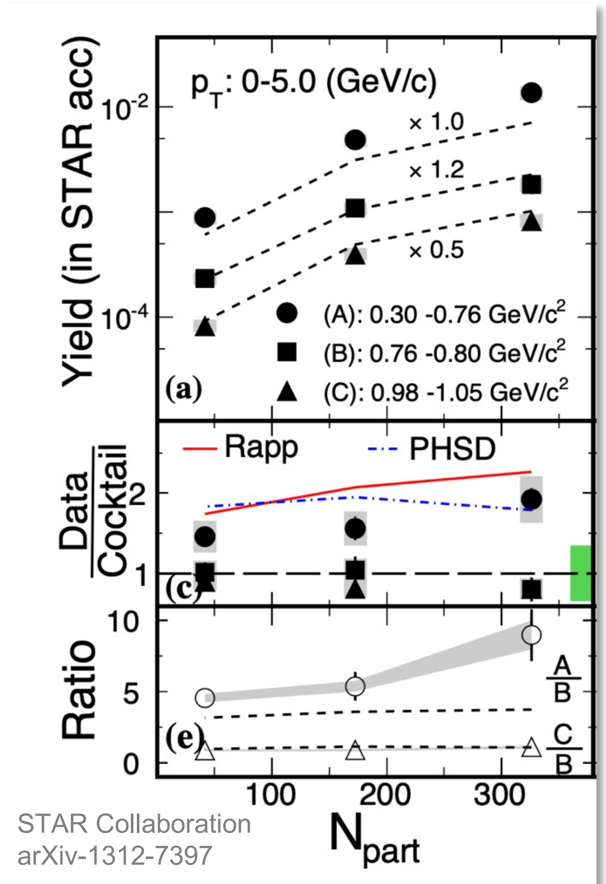
ALICE

Most difficult S/B
Excellent opportunities in RUN3

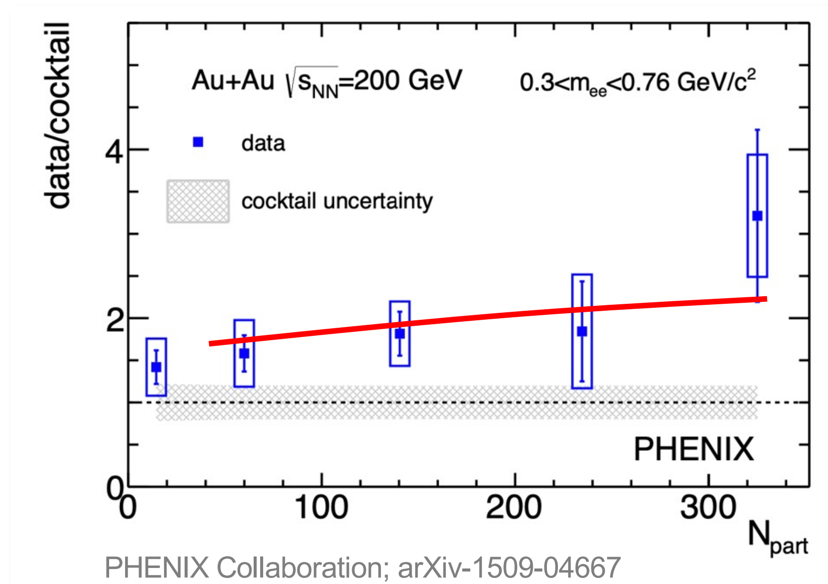


ALICE, PRC 99 (2019) 2, 024002

Centrality dependence – top RHIC energy



- Centrality dependence of excess yield in qualitative accordance with thermal radiation
- High statistics alone is not sufficient, systematic uncertainties have to decrease as well



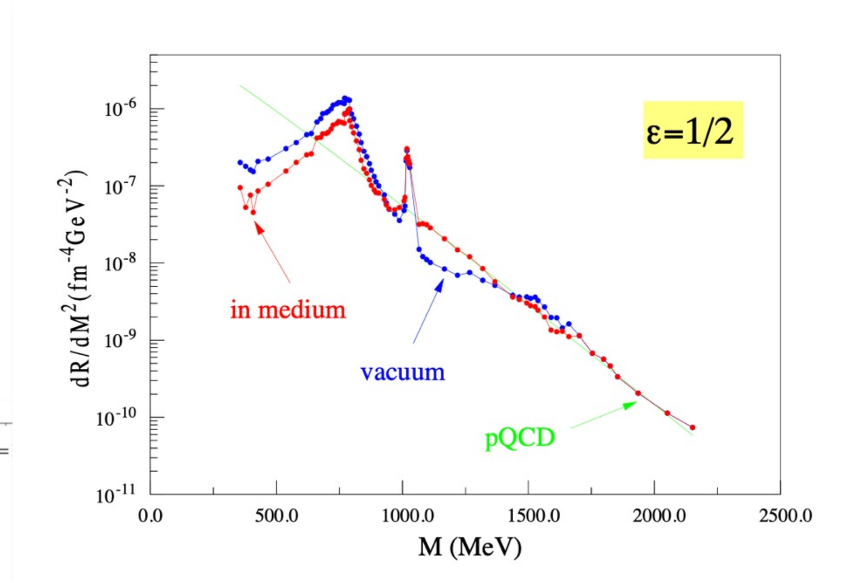
Thermal radiation and chiral symmetry restoration

- Weinberg (QCD) sum-rules:

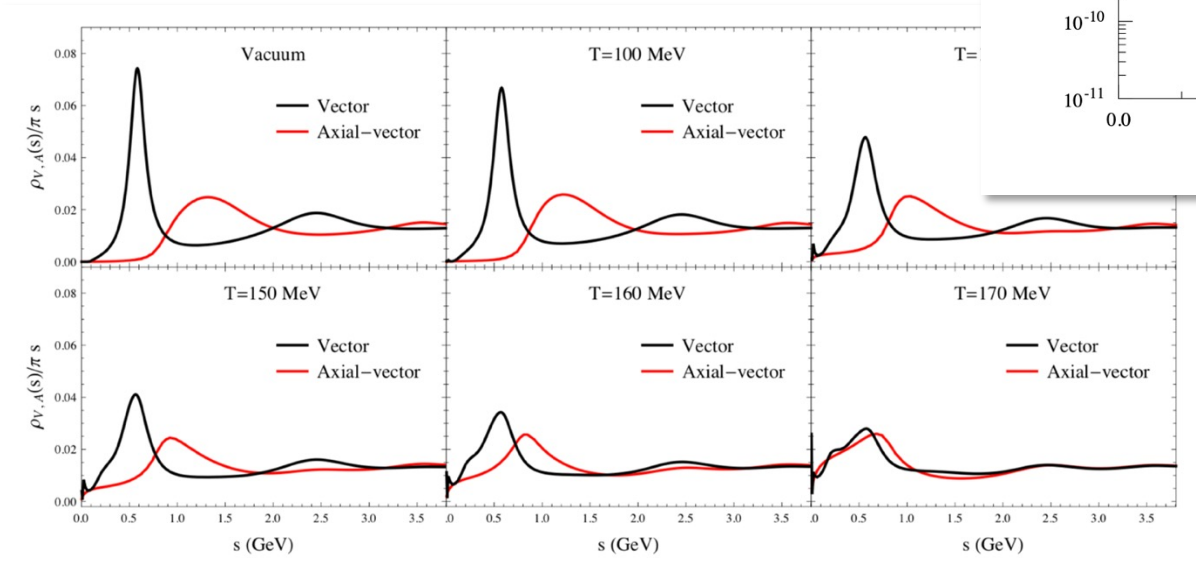
$$\int ds\,\left(D^V(s) - D^A(s)\right) \;=\; f_\pi^2 m_q = -2m_q\,\langle\bar{q}q\rangle$$

overlapping spectral distributions signal restoration

- Possibility to assess through $\rho - a_1$ mixing ($0.8 < M_{\ell\ell}/\mathrm{MeV} < 1.3$)



R.Rapp, J. Wambach, Adv.Nucl.Phys. 25 (2000)



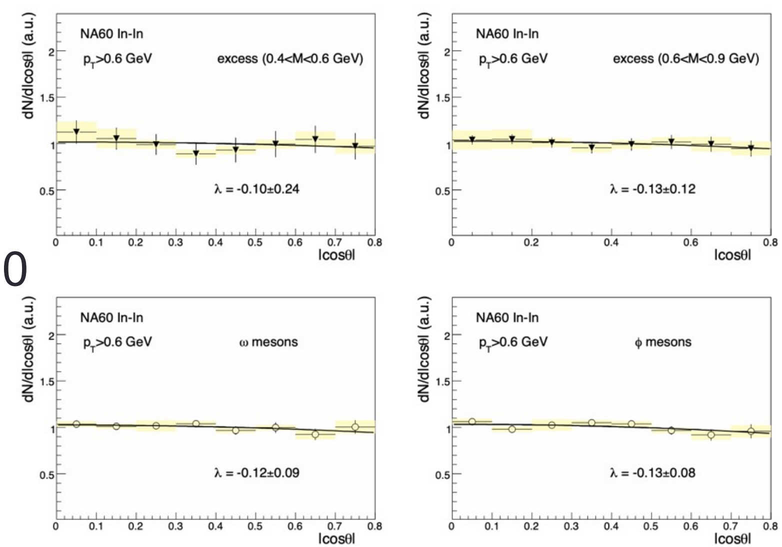
P. Hohler, R. Rapp; arXiv-:311.2921

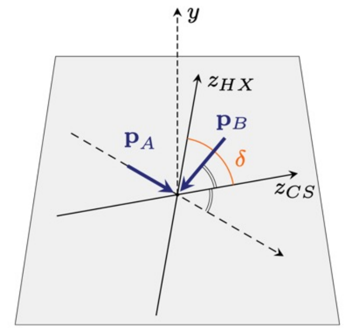
POLARIZATION, FLOW, ELECTRICAL CONDUCTIVITY

Polarization measurements

- HADES mostly Δ Dalitz-like (Ar+KCl)
  (Au+Au less pronounced)
- NA60: no evidence for polarization
- Theory: small but finite polarization in a thermal hadronic medium due to quantum statistics effects

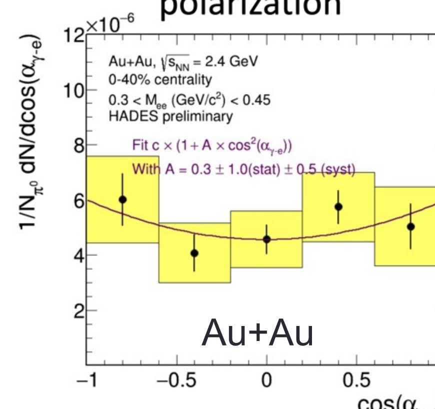
NA60



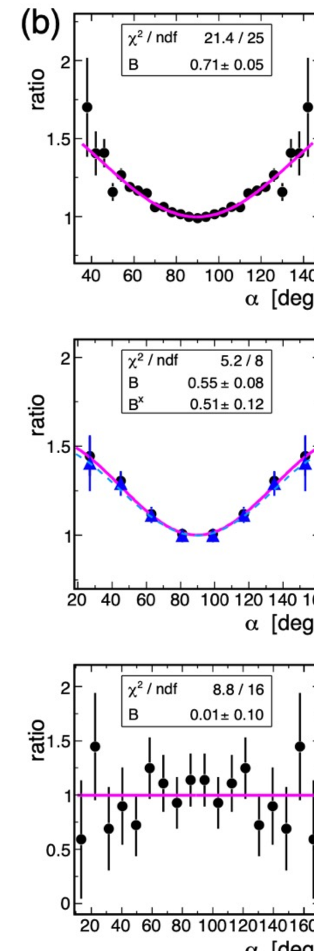


HADES

polarization



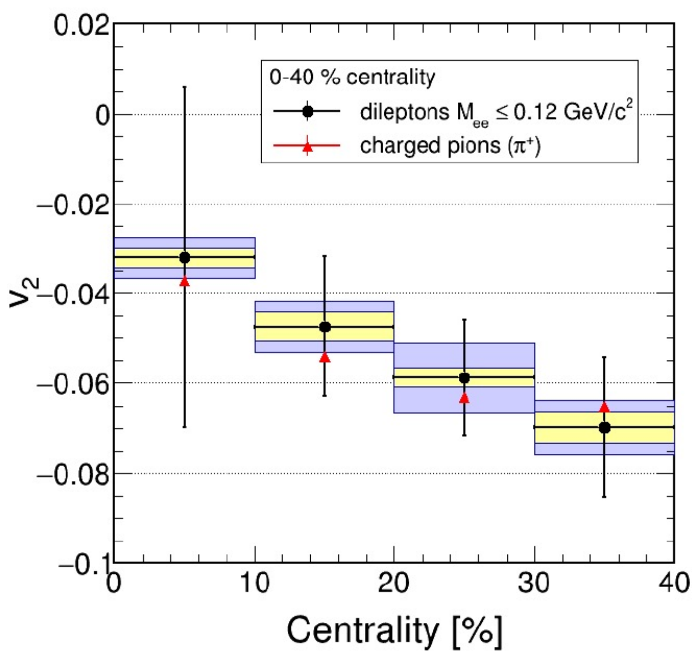
Ar+KCl

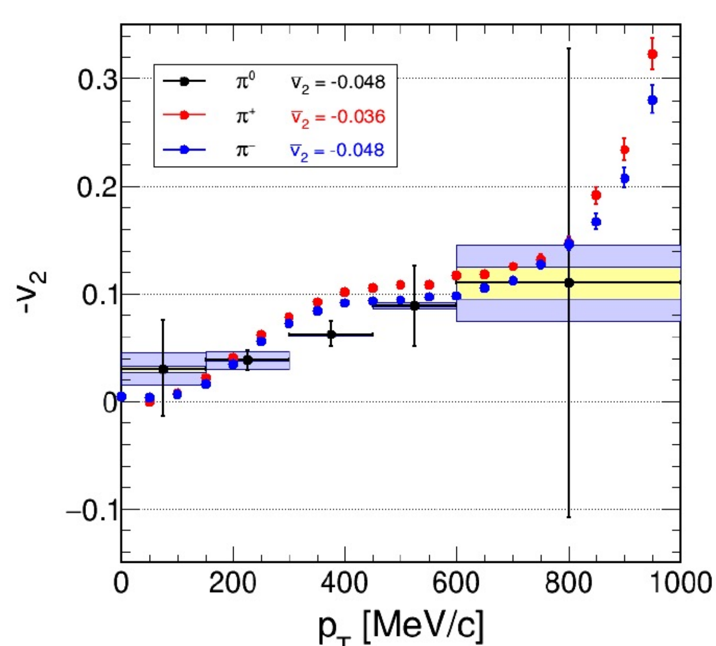


HADES Collaboration, Phys. Rev. C 84, 014902 (2011)
NA60 Collaboration, Phys. Rev. Lett. 102 (2009) 222301
E. Speranza, A. Jaiswal, B. Friman; Phys.Lett.B 782 (2018) 395-400

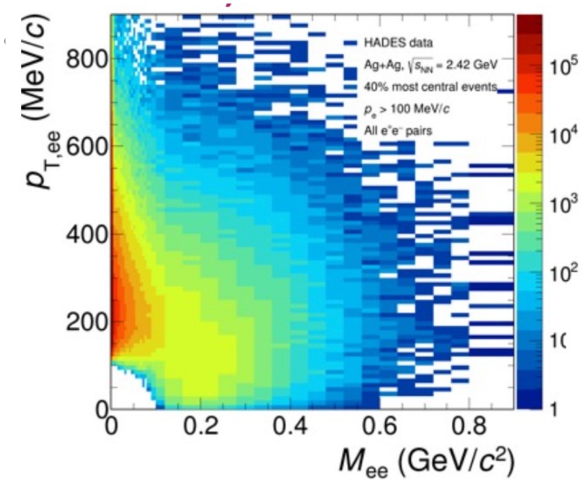
Elliptic flow at SIS18 energies

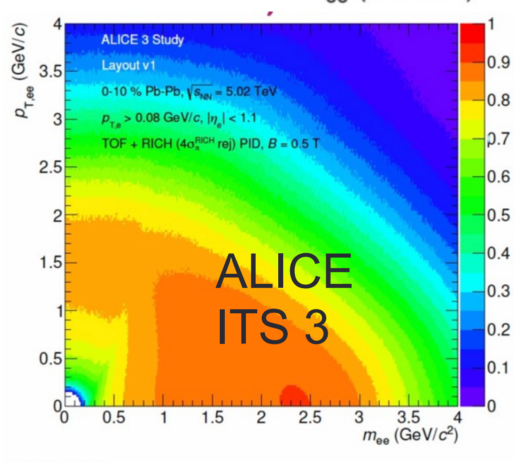
- Elliptic flow at SIS18 energies influenced by shadowing effects due to the the projectile traget spectaots.
- Dilepton are expected to be less affected (penetrating probe)
- High statistics needed to enable flow measurements at higher invariant masses



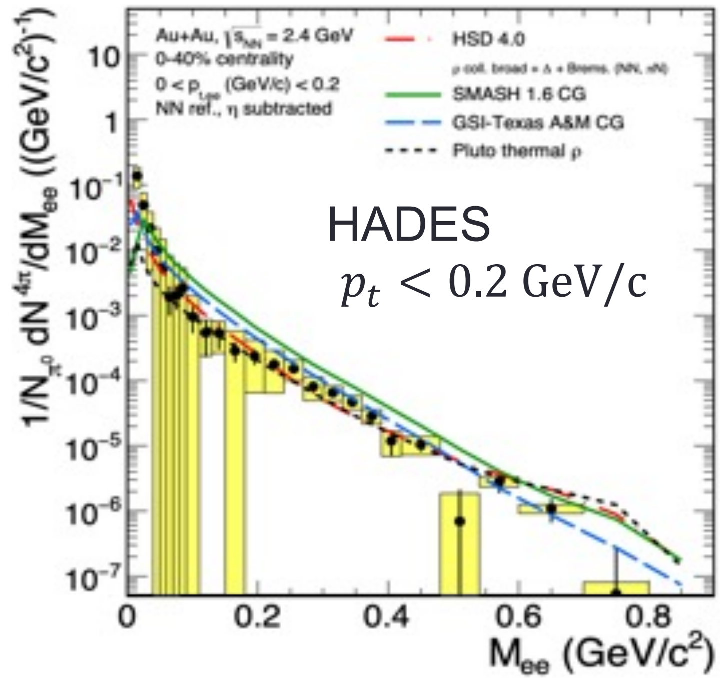


Electrical conductivity





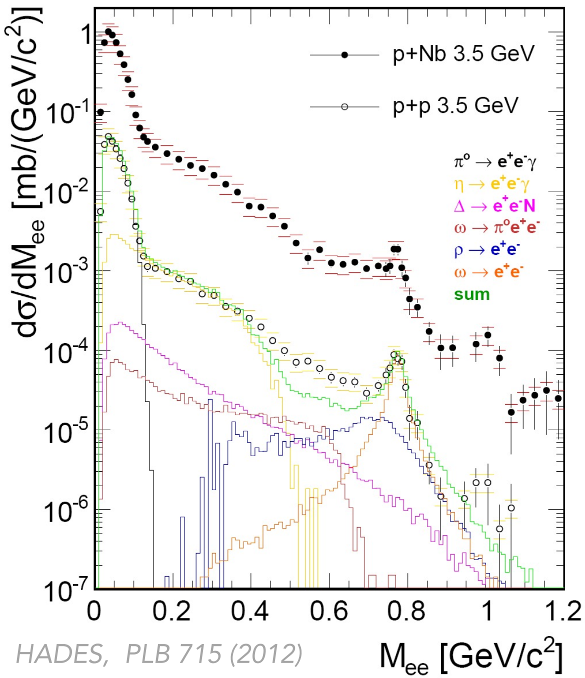
The challenge of low-mass and low p_t



COLD MATTER

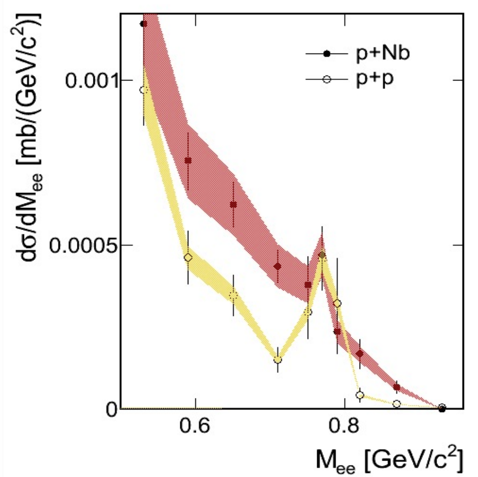
Vector mesons in cold matter

- Ideal probe to monitor possible mass shifts
- Low relative momentum to medium needed to increase sensitivity
- Broadening and/or mass shift?
- New experiment at JPARC starting up!

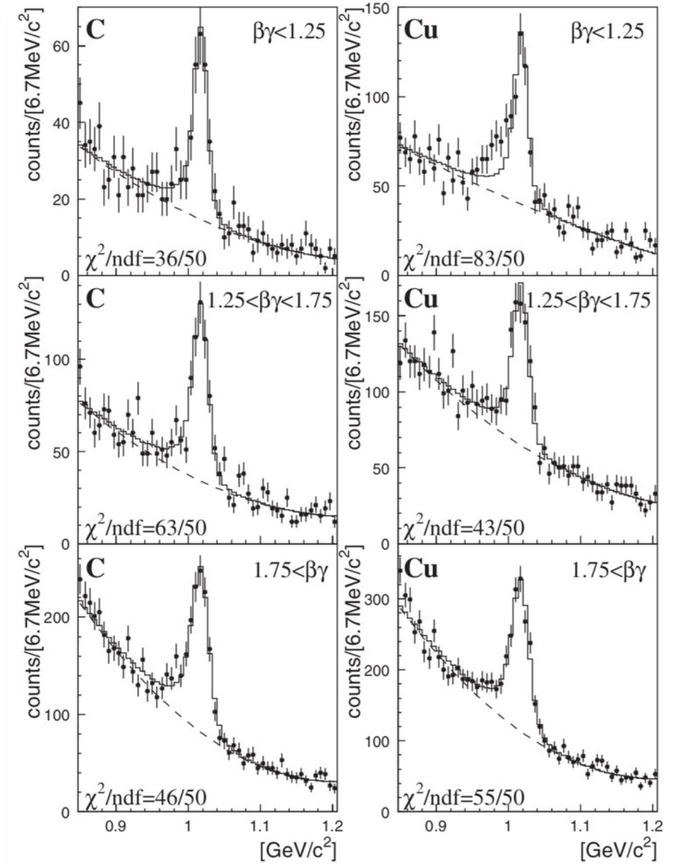


HADES, PLB 715 (2012)

HADES (ω)



KEK-PS E325 (ϕ)

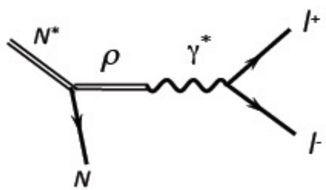


KEK-PS E325, PRL 98, 042501 (2007)

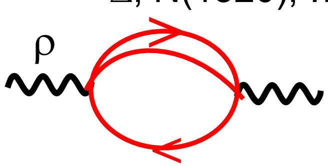
“VACUUM”

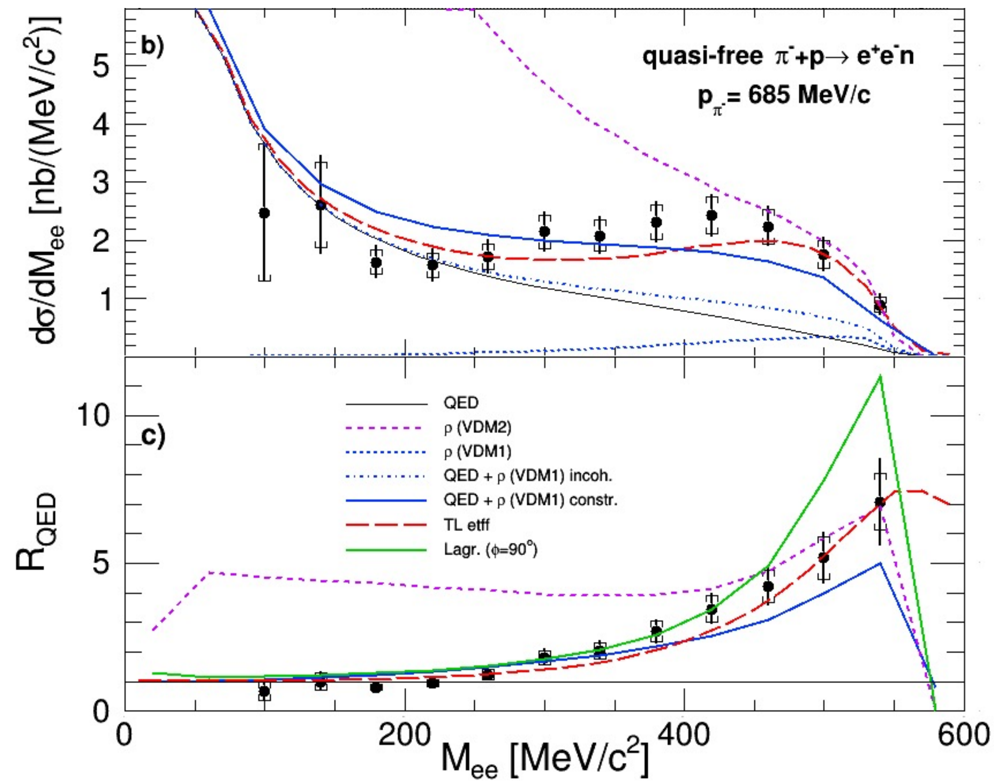
$\pi^- + p \rightarrow e^+e^- + n$

- Effective transition form factor (time-like) extracted by subtracting QED expectation.
- Δ, N^*-Dalitz decay:



- Baryonic contribution to in-mediumρ selfenergy

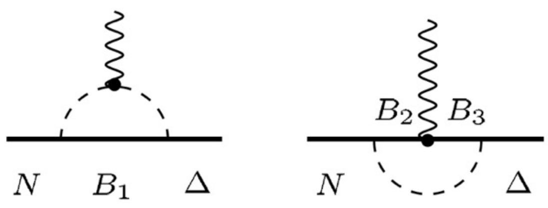




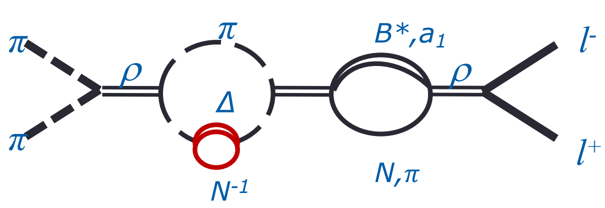
Pion cloud effect in Δ(1323)

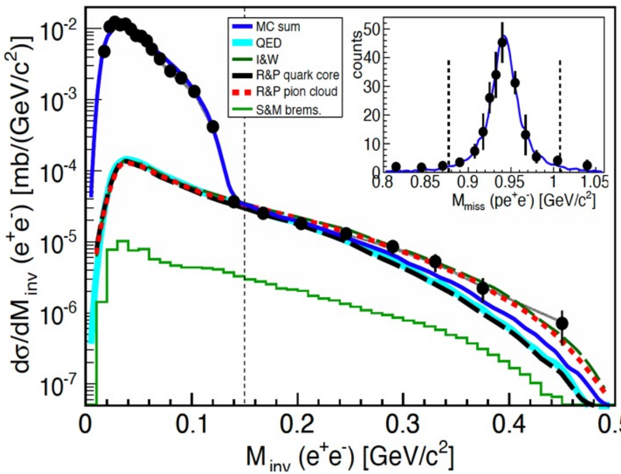
- Exclusive dielectron production in p+p collisions.
- Effect of the pion cloud observed in the time-like electromagnetic transition formafactor (off-shell ρ meson).

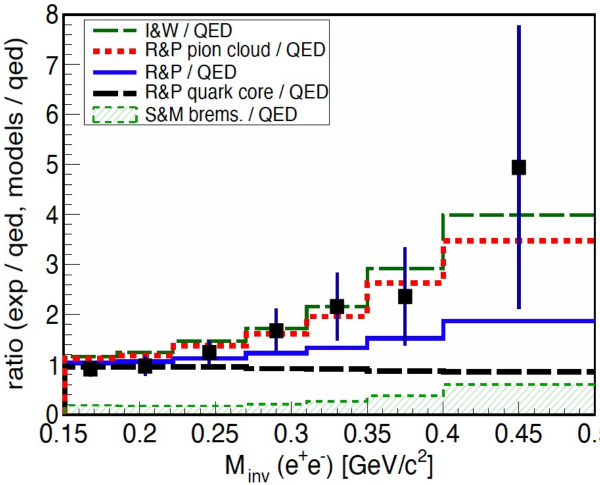
Peña, Ramalho; arXiv-1205-2575
Peña, Ramalho + GiBUU.; arXiv-1512-03764



- Moderate contribution to the in-medium propagator







HADES: arXiv:1404.2136 [nucl-th]

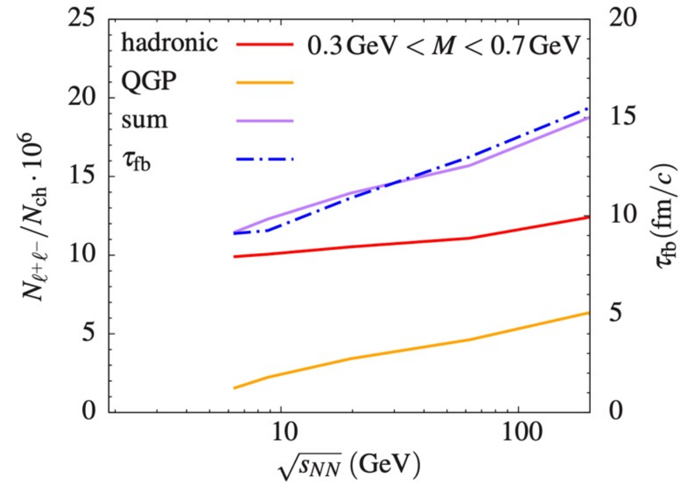
FUTURE

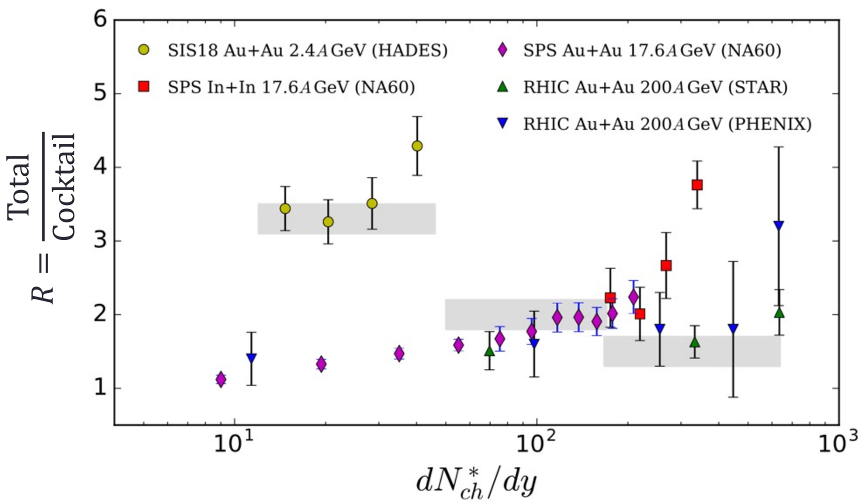
QCD landmarks at high μ_B

- **First-order deconfinement phase transition**

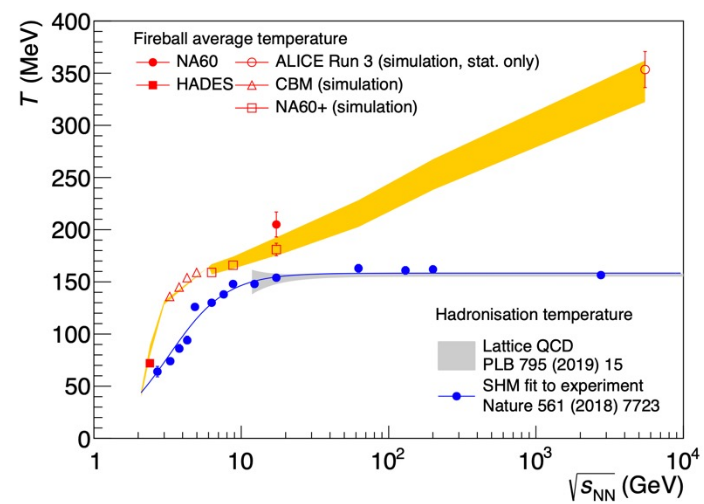
  Search for nonmonotonic excitation function of:
  - Excess yield (longer expansion due to softening of EOS)
  - Step in the temperature (latent heat)

- **χ symmetry restoration**
  - ρ broadening observed, in agreement with expectations but no proof in itself – signatures of $\rho - a_1$ mixing





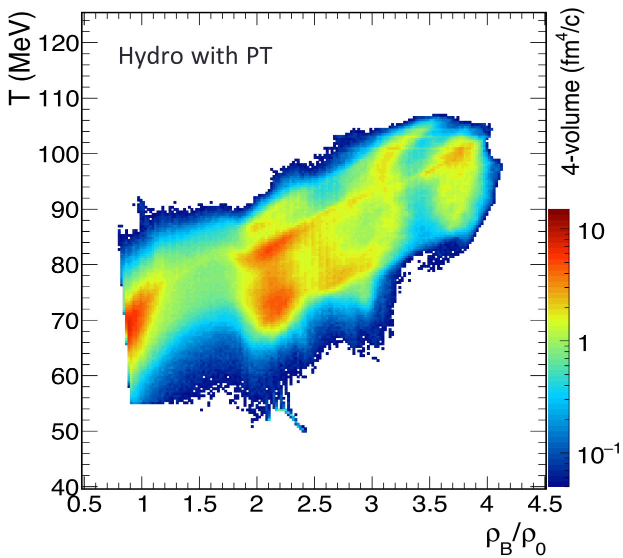
P. Salabura, J. Stroth, Prog.Part.Nucl.Sc. (arXiv:2005.14589)

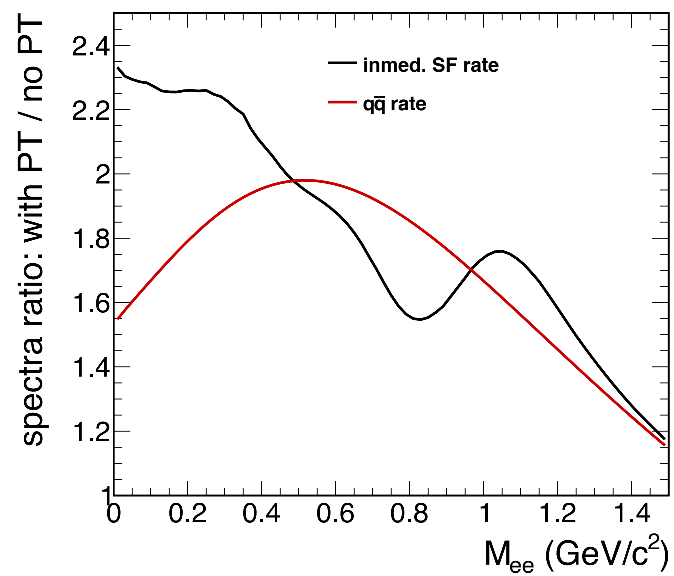


R. Rapp and H. v. Hess, PLB 753 (2016) 586
https://github.com/tgalatyuk/QCD_caloric_curve

Dilepton signature of a first-order phase transition

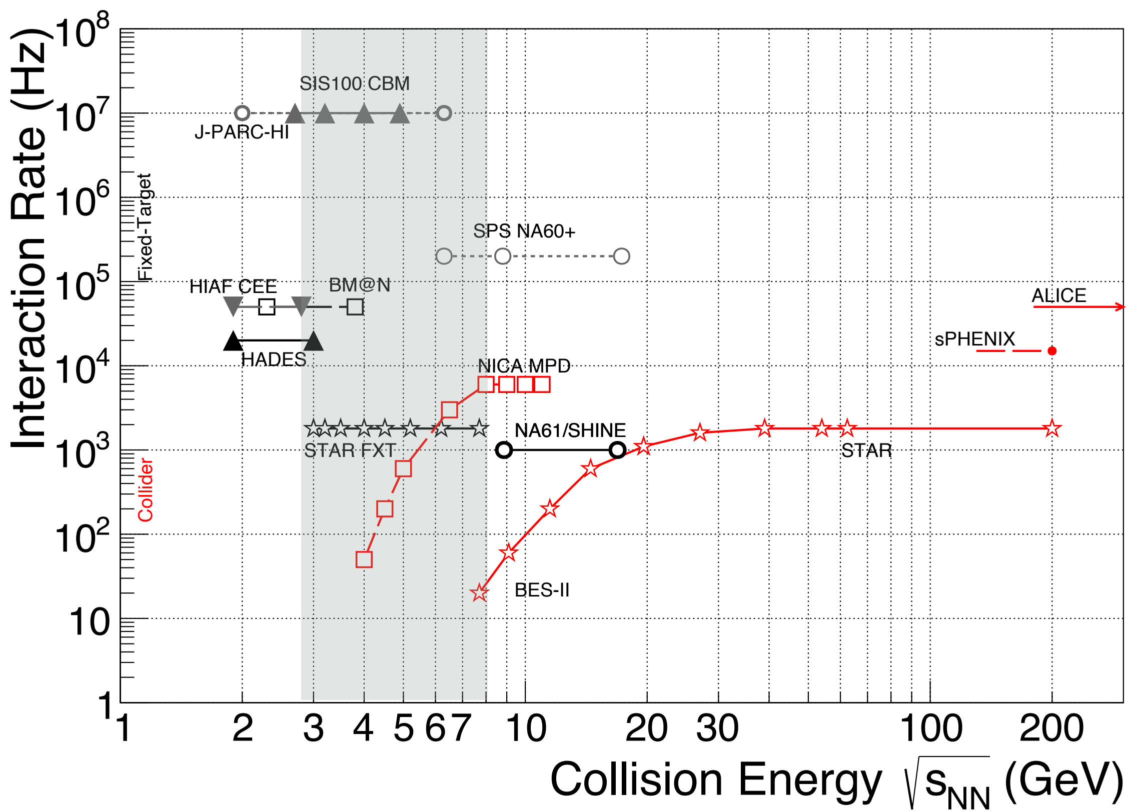
- Dilepton radiation from hydrodynamical desciption (SIS18 energies) & thermal emissivities
- Factor of ~2 extra radiation in case of hydro with PT





Seck, TG, Mukherjee, Rapp, Steinheimer, Stroth, arXiv:2010.04614 [nucl-th] (see also Li and Ko, Phys. Rev. C 95 (2017) no.5, 055203

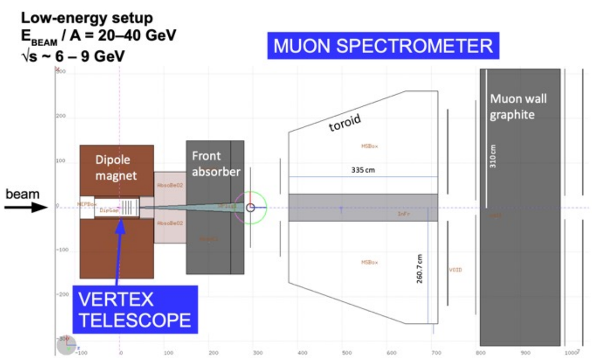
The existing and upcoming high-μ_b experiments



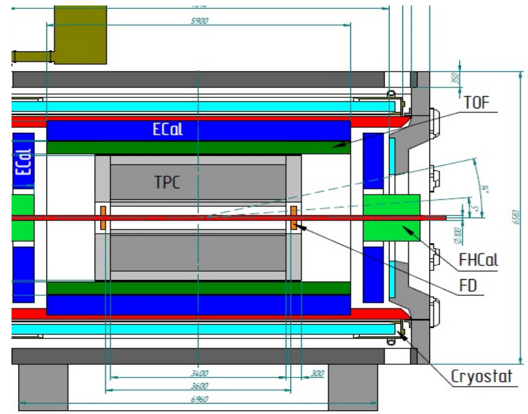
T. Galatyuk, Nucl.Phys. A982 (2019), update 2021
CBM, EPJA 53 3 (2017) 60

Future facilities for high μ_B physics

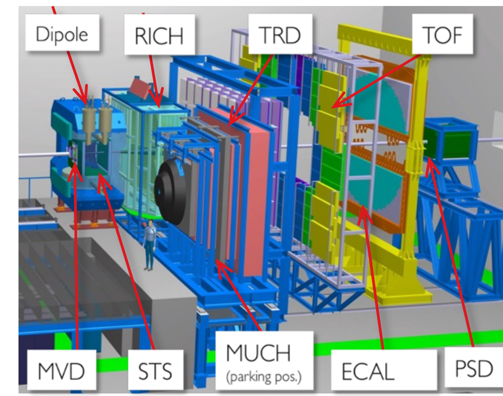
NA60⁺ – SPS



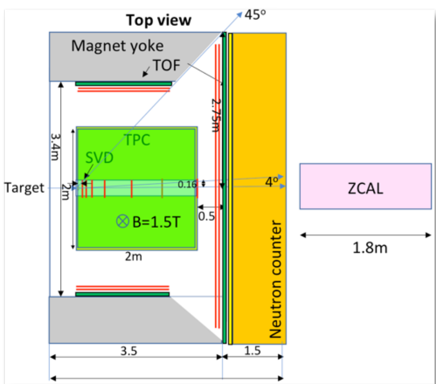
MPD – NICA



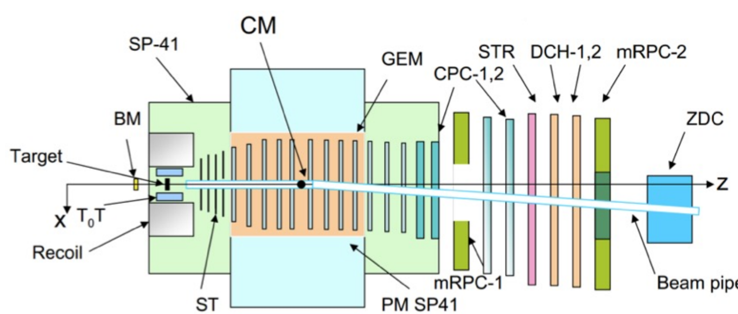
CBM– FAIR



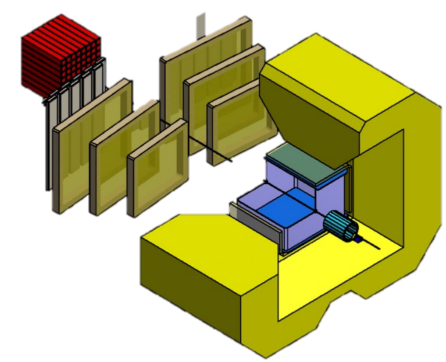
DHS – JPARC-HI



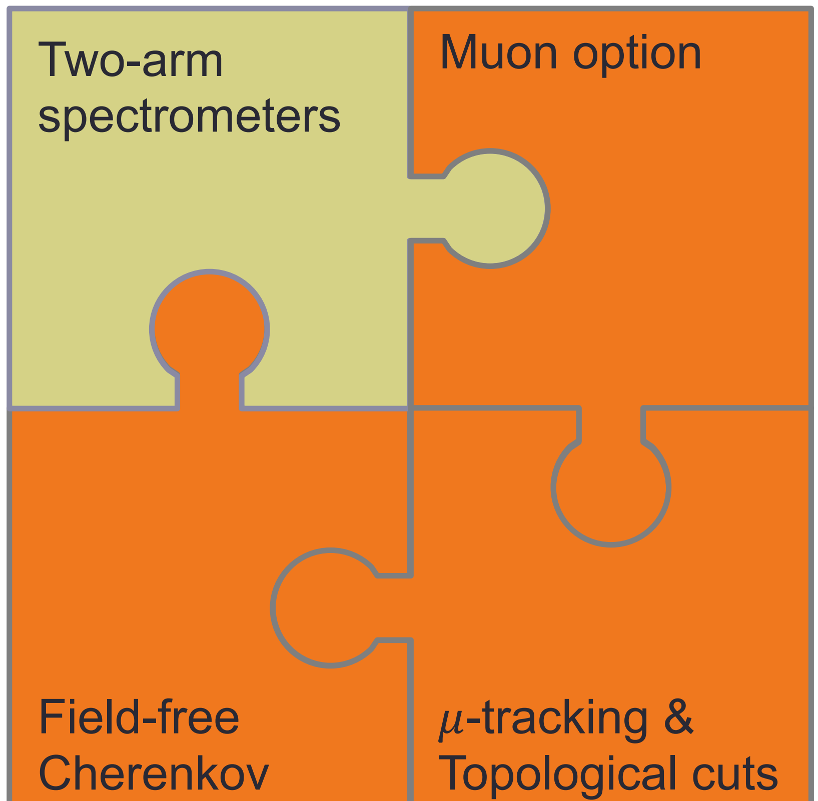
BM@N – NICA



CEE– HIAF



… and the FAIR strategy



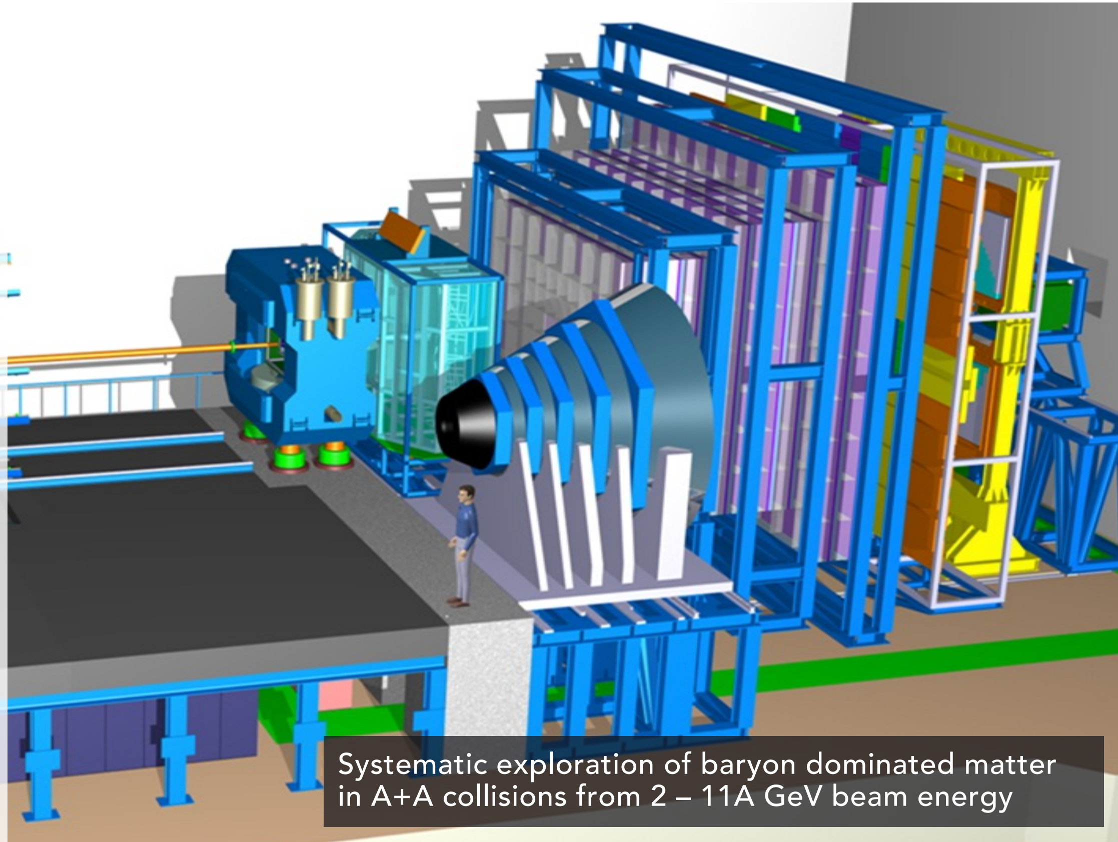
CBM-MUCH

HADES

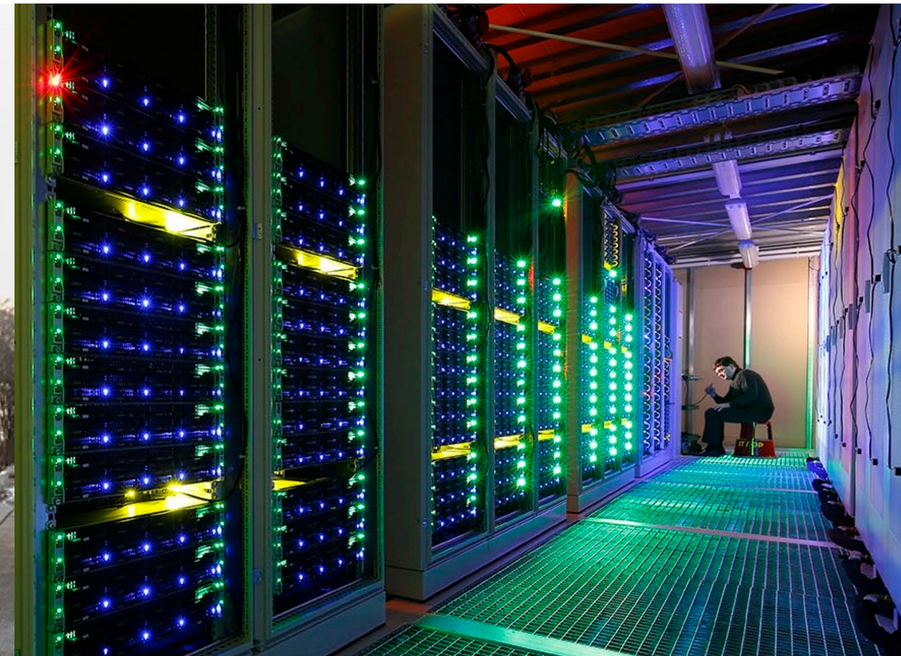
CBM

The CBM experiment

- High-rate particle detector with free streaming data acquisition on real-time event reconstruction
- Compact tracking with silicon in a 1 Tm magnetic field (dipole)
  - Double-sided silicon strip
  - MAPS based micro vertex detector
- Particle identification
  - Hadron ID: TOF
  - Photons, π^0, η: ECAL
  - Electrons: RICH, TRD
  - Muons: instrumented absorber (GEM, Straws)



Forefront Technologies (Green Cube)

- Technological advancements in high-performance & scientific computing, Big Data, Green IT
  (V. Lindenstruth, Goethe University)

The challenges for future measurements

- High statistics, i.e. > 10^{10} collisions per system
- Excitation functions
- Precise reference for pre-equillibrium and mesonic cocktail
- Good controll on combinatoric background
  - Conversion rejection – electrons
  - Weak decay (fake match) rejection – muons

- Scrutinize in-medium spectral functions (VMD)
  - Role of missing resonances
  - Chrial mixing
- Hydro description for low energies (?)
- Micro/macro transport "duality"

Summary

- Increasing effort world-wide to explore the high-μ_B region of the QCD phase diagram with state-of-the-art detectors and dileptons.
- Vector mesons valuable probe to monitor the properties of dense matter
- Strong modification of in-medium meson states due to meson-baryon coupling
- Thermal rates can be used as "standard candle" to explore phase space "trajectories"
- Possible link to chiral symmetry restoration through $a_1 - \rho$ mixing
- Further experimental progress depends on high-statistics data for cold-matter and hot & dense matter studies
- Dileptons important element of the search for QCD landmarks

THANK YOU