EXPERIMENTAL OVERVIEW ON DILEPTON SPECTROSCOPY

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International School on Nuclear Physics, 46th course

Ettore Majorana Foundation and Center of Scientific Culture, Erice, Italy

September 17 – 21, 2025

General remarks

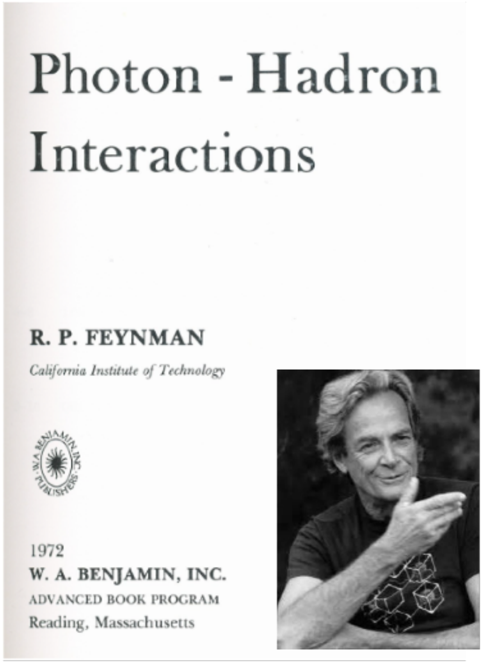
Heavy-ion phenomenology

Radiation from proton/pion induced reactions

Excess radiation

The future

Electromagnetic Probes of Extreme States of QCD



Original motivation for dilepton spectroscopy in HI collisions two-fold:

- direct temperature measurement to find $T > T_c$
- search for chiral symmetry restoration via modification of vector meson spectral function

Thermal emission rate (multi-differential) is connected to the (retarded) hadronic/partonic electromagnetic current-current correlator

$$\frac{dR_{ee}}{d^4p\,d^4x} = -\frac{\alpha^2}{\pi^3}\frac{L(M)}{M^2} f^B(q_0;T)\,\mathrm{Im}\Pi^{\mu}_{\mathrm{em}\,\mu}\left(q_0,\vec{q};\mu_i,T\right)$$

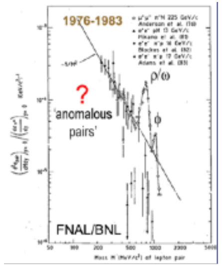
Spectrometer integrates over four-volume, but virtual photon provides access to invariant mass and polarisation (M_{inv}, y, p_T, ϕ, α)

See also. P. Salabura, JS, Prog.Part.Nucl.Phys. 120 (2021)

The historical view

“**Drell-Yan root**” (CERN, FNAL/BNL) – Medium modified parton distribution functions and anomalous yield

protons (1970) SPS S (1987) SPS Pb (1994) RHIC Au (2000) LHC Pb (2010) (2030) (2035)



CERN

NA34, NA38

NA45 (CERES)
NA50

NA60

ALICE LHCb

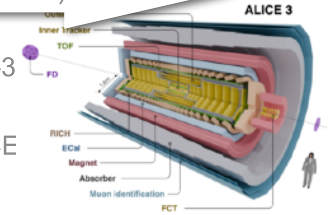
ALICE-3

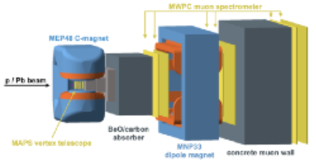
NA60+/DiCE

BNL (FNAL)

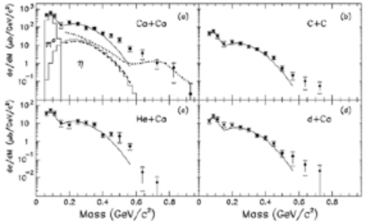
E-537
E-605
E-771

PHENIX
STAR





“**Fireball root**” (LBNL, GSI) – Brown-Rho / Hatsuda-Lee scaling and the DLS puzzle



GSI

HADES

CBM

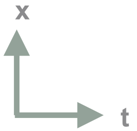
LBNL

DLS

BEVALAC Ca (1987-93) SIS18 C (2002), Au (2012) SIS100 (2028)

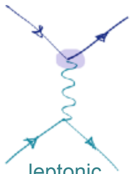
NICA/MPD

Probing QCD with virtual photons



Electron scattering

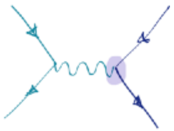
hadronic/partonic



leptonic

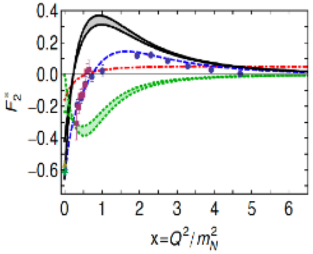
lepton beam

e^+e^- annihilation

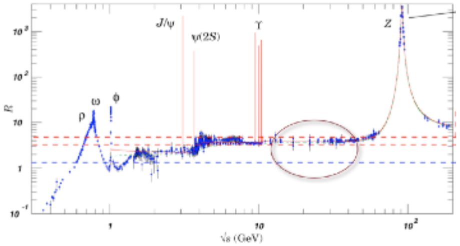


form factors (ff)
transition ff
generalised PDFs

QCD excitation spectrum
CP violation in HF states

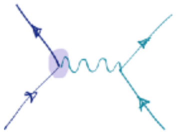


JLAB/CLAS
Hera
EIC



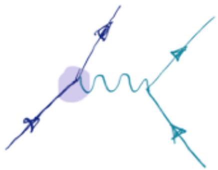
SLAC, DESY
BES, Belle

Drell Yan,
hadron/quark annihilation



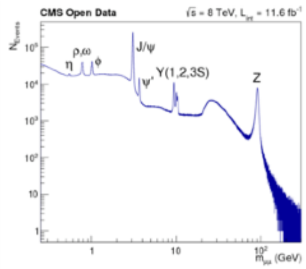
hadron beam

Dalitz decays

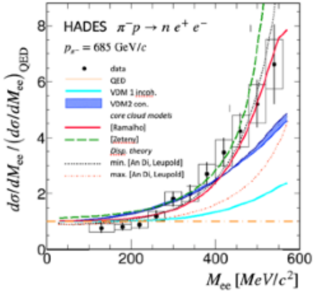


Parton distribution functions
CP violation in HF states

transition from factors
VMD tests



Proton synchrotrons (AGS/SPS)
Hadron colliders



SPS/CERES/NA60
SIS18/HADES

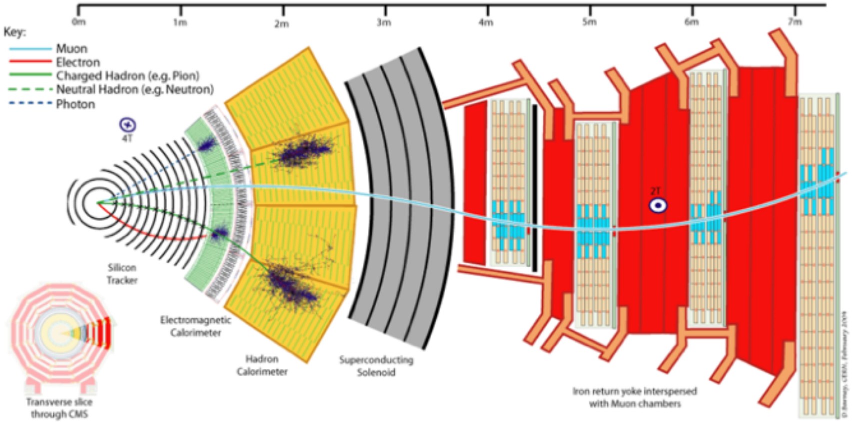
➡ Dilepton signal is suppressed (α^2) – High purity needed in particle identification (PID)

Dimuons

"Massive" leptons, make use of absence of strong interaction → hadron absorber

- Challenge:
  - Match track identified in the muon "arm" with the track measured in the spectrometer (before absorber)
  - Track in first section needed to provide DCA resolution!
    (DCA = closest distance of reconstructed track w.r.t. interaction vertex)
  - Background from weak pion and kaon decay before absorber.

CMS



- Advantage:
  - Easy to trigger muon pairs: two tracks behind absorber stack.
- Disadvantage
  - Invariant mass limited to $M_{\mathrm{inv}} > 2m_\mu$

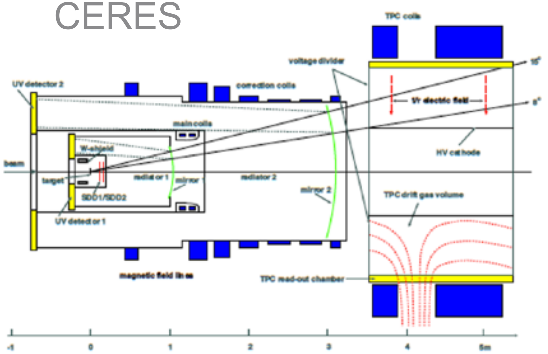
Works better for larger lab momenta: fixed target experiments (NA60+, CBM), forward rapidity coverage (ALICE)

Dielectrons

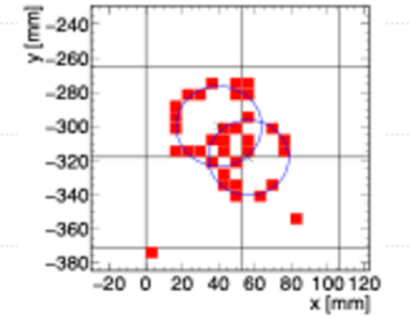
"Fast" lepton, make use of radiative effects → Cherenkov (β) [and Transition (γ)] radiation

- Challenge:
  - Field free region for RICH, ideally before magnetic field, hadron blind detector for charged hadrons with $\beta < \beta_{\mathrm{thr.}} = 1/n$
  - Excellent track – ring-center matching
- Advantage: – Effectively no invariant mass threshold
- Disadvantage: – Abundant pairs from π^0 Dalitz decay and conversion

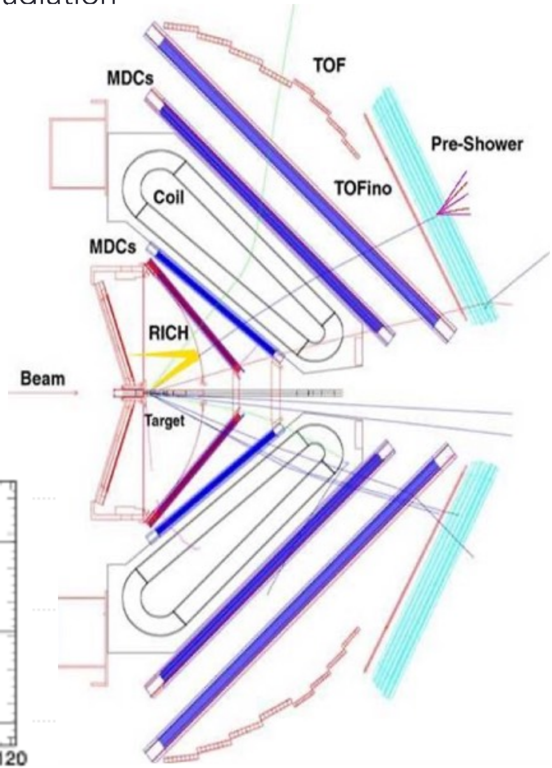
CERES



HADES RICH



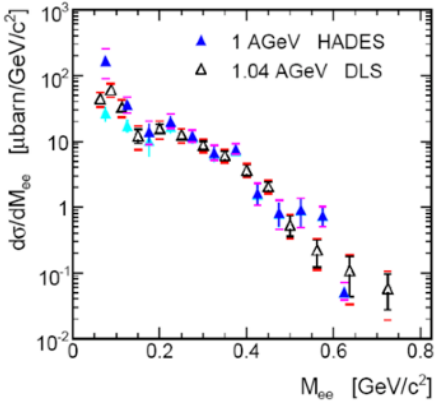
HADES



“Know your reference”

DLS puzzle

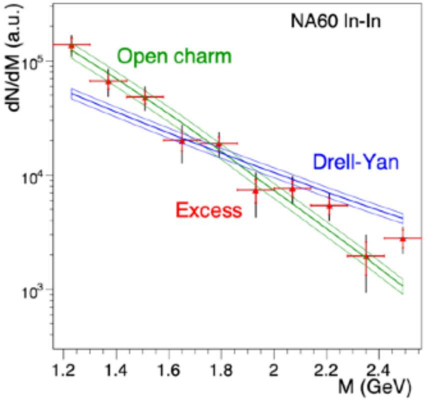
HADES confirmed measurement and demonstrated strong iso-spin dependence of bremsstrahlung



HADES PLB 690 (2010) 118

IMR temperature

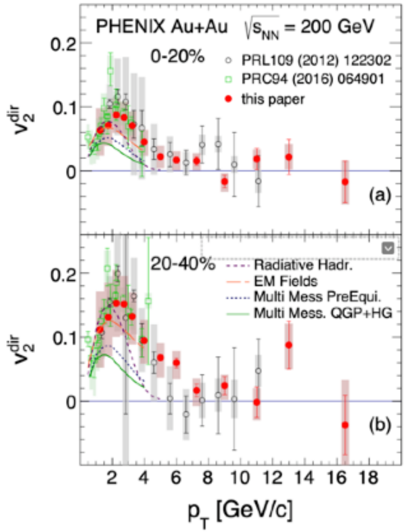
Precise determination of contributions from heavy-flavour correlated semi-leptonic decay



NA60 EPJ C61 2008

Direct photon puzzle

v_2 signal and STAR/PHENIX discrepancy.
Different treatment of η contribution?



PHENIX arXiv:2504.02955

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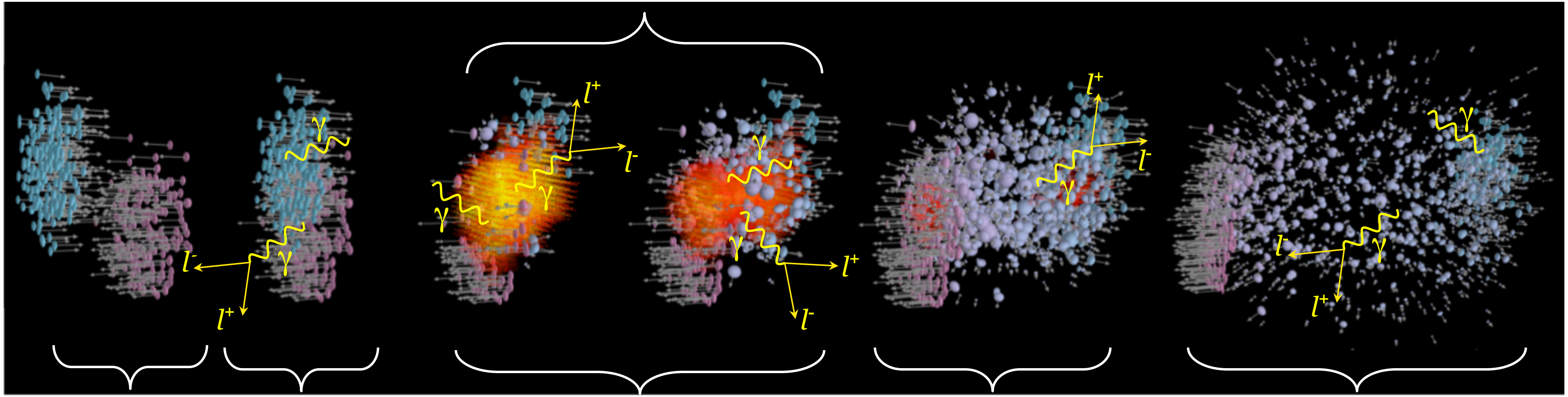
The (U)RHIC "Standard Model"

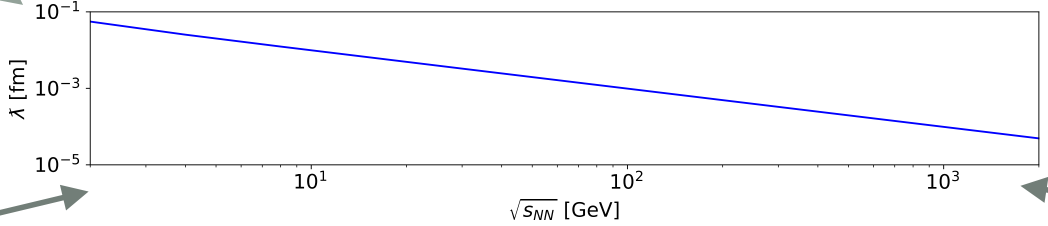
„First chance" *„Pre-equillibrium"* *Fireball* *Freeze-out* *Late stage hadrons seen in detectors*



kinetic theory *hydro or coarse-grained transport* *resonance decay* *hadronic cocktail*

Very different from vanishing to high μ_B

SIS18 *SIS100/AGS* *SPS* *RHIC* *LHC*



nucleons

partons

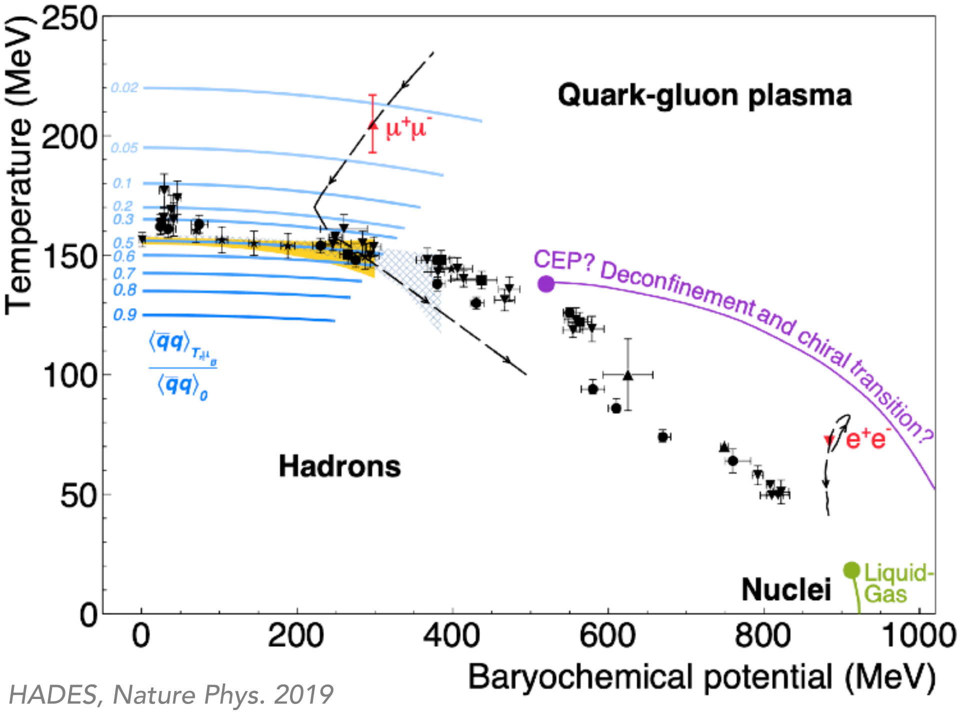
"softest" gluons

nearly complete baryon stopping
one-boson exchange

net-baryon free collision zone
perturbative scattering & PDFs

Exploration of the QCD Phase Diagram @ high-μ_B

From medium-effects to novel phases of QCD matter

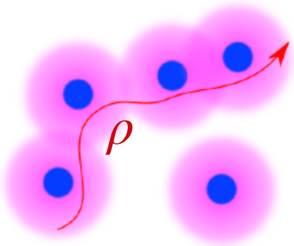


HADES, Nature Phys. 2019

Conjectures for

$$T \gtrsim 25\,\mathrm{MeV},\ \mu_B \gtrsim 500\,\mathrm{MeV}:$$

- First order transition (CEP, mixed phase)?
  - Chiral
  - Deconfinement
- What phases?
  - Hadron resonance "gas"
  - Soft deconfinement
  - Quarkyonic
  - Moat regime
- Equilibration driven by entangled pion cloud?

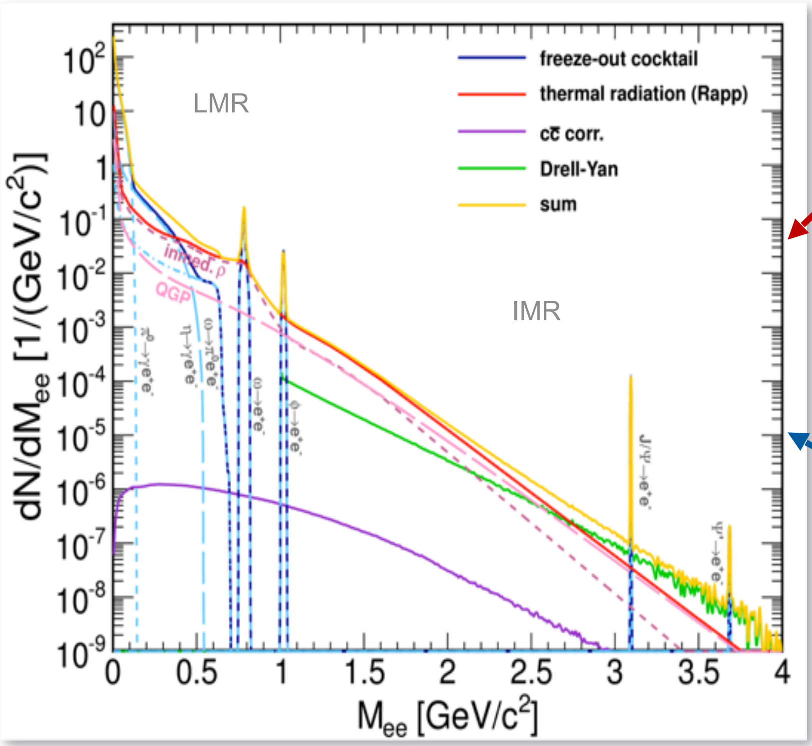


Excess Radiation as “Standard Candle” for (U)RHIC

Medium radiation from ***Thermal Emission Rates*** (ϵ):

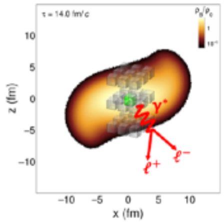
$$\frac{dR_{\mathrm{ee}}}{dM\,dy\,dp_T\,d\alpha} = \int -\frac{\alpha^2}{\pi^3}\frac{L(M)}{M^2} f^B(q_0;T)\,\mathrm{Im}\Pi^{\mu}_{\mathrm{em}\,\mu}\left(q_0,\vec{q},\mu_i,T\right) dV dt$$

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



or

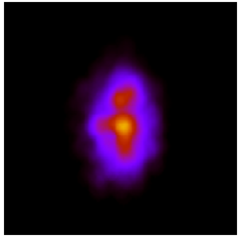
hydro



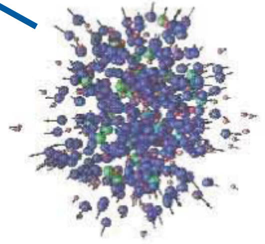
coarse graining

T: Galatyuk, JS, et al., EPJA 52 (2016) 5

shining



UrQMD



Dilepton emission from ***Microscopic Transport.***

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

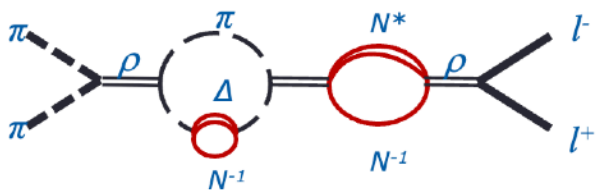
Extension of the Gounaris-Sakurai formula to a thermal pion gas: C. Gale, J. Kapusta: Nucl. Phys. B357 (1991) 65

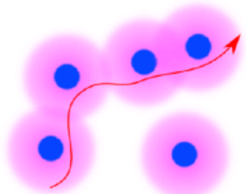
$$j^{\mu}_{EM} = \frac{1}{2}(\bar{u}\gamma^{\mu}u - \bar{d}\gamma^{\mu}d) + \frac{1}{6}(\bar{u}\gamma^{\mu}u + \bar{d}\gamma^{\mu}d) - \frac{1}{3}\bar{s}\gamma^{\mu}s \;\Longrightarrow\; \mathrm{Im}\Pi_{EM} \sim \mathrm{Im}\,\mathrm{D}_{\rho} + \frac{1}{9}\mathrm{Im}\,\mathrm{D}_{\omega} + \frac{2}{9}\mathrm{Im}\,\mathrm{D}_{\phi}$$

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





General remarks

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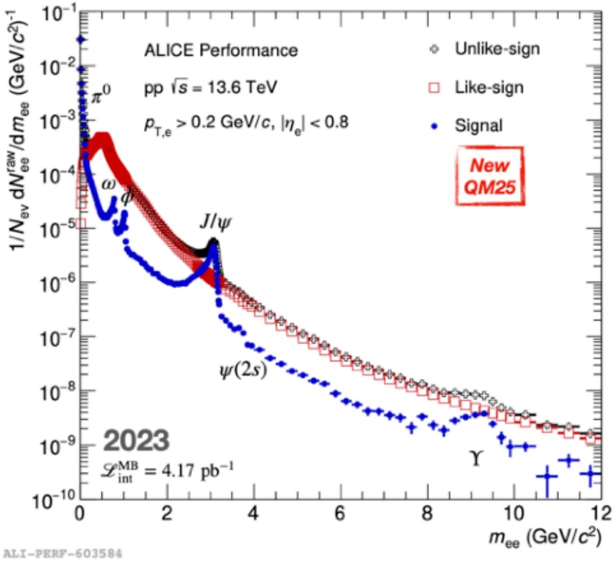
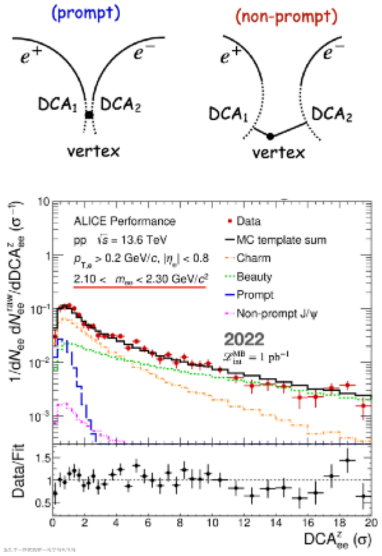
ALICE p+p $\sqrt{s_{NN}} = 13.6$ TeV (after RUN3 upgrade)

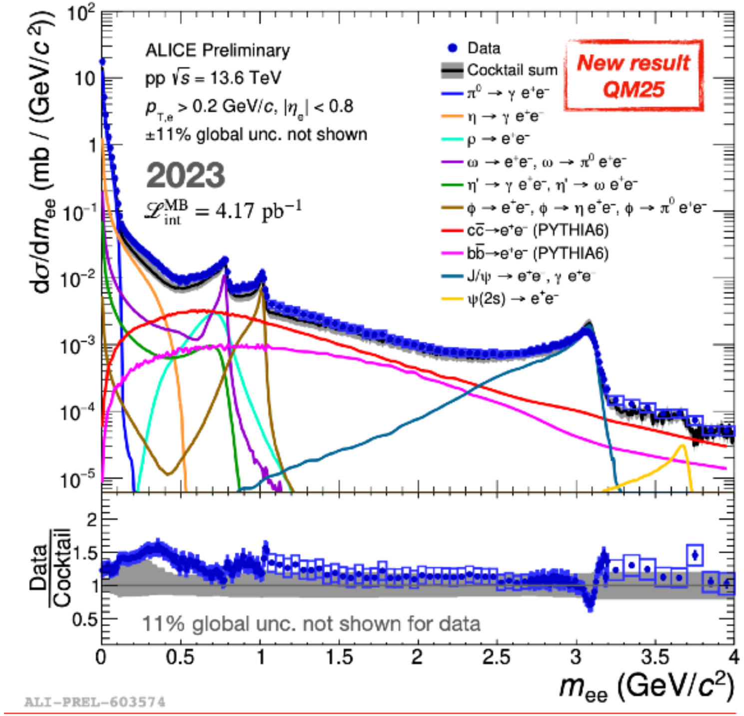
Reference for IMR open charm contribution

ALICE (F. Eisenhut): QM2025

- Already substantial combinatorial background in p+p (S/B ~ 0.1 in IMR)
- Heavy flavour decomposition using ITS-2
- Overall good agreement with cocktail



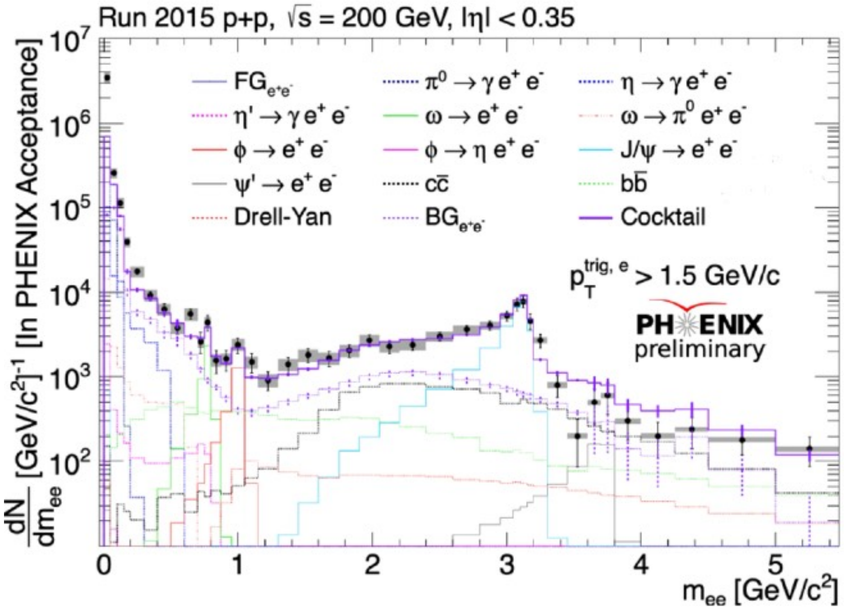




PHENIX: p+p $\sqrt{s_{NN}} = 200$ GeV reference

- Similar quality like ALICE from updated PHENIX measurement
- Precision measurements at SPS and SIS100 and theoretical guidance needed

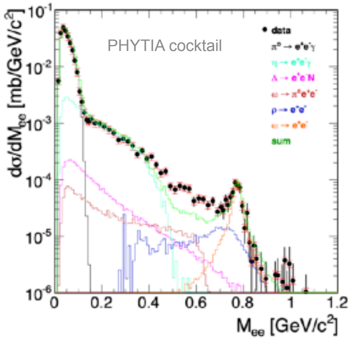
PHENIX (D. Gabor) QM2025

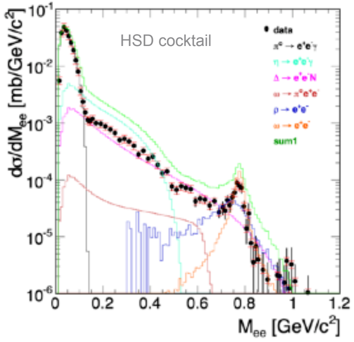


HADES - p+p SIS18 energies

- Good description by models (PYTHIA, HSD, GiBUU, …) only after tuning
- HADES uses A_{part} scaled reference measurement
  $(\, p + p; n_{\mathrm{tagged}} + p \,)$
  as proxy of early stage radiation

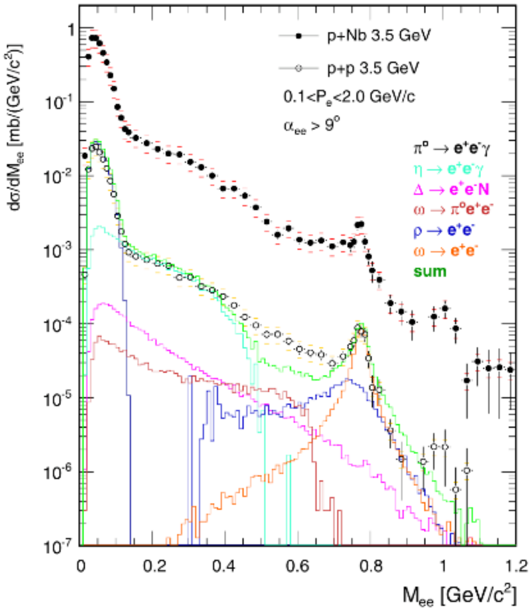
p+p 3.5 GeV/c





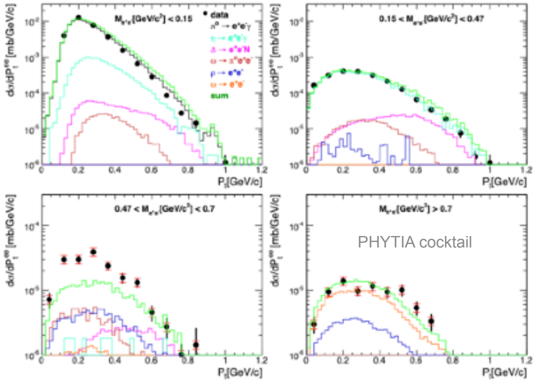
HADES: PLB 715 (2012) 304–309

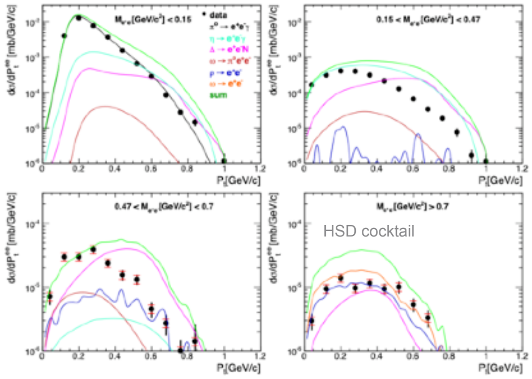
p+p / Nb 3.5 GeV/c



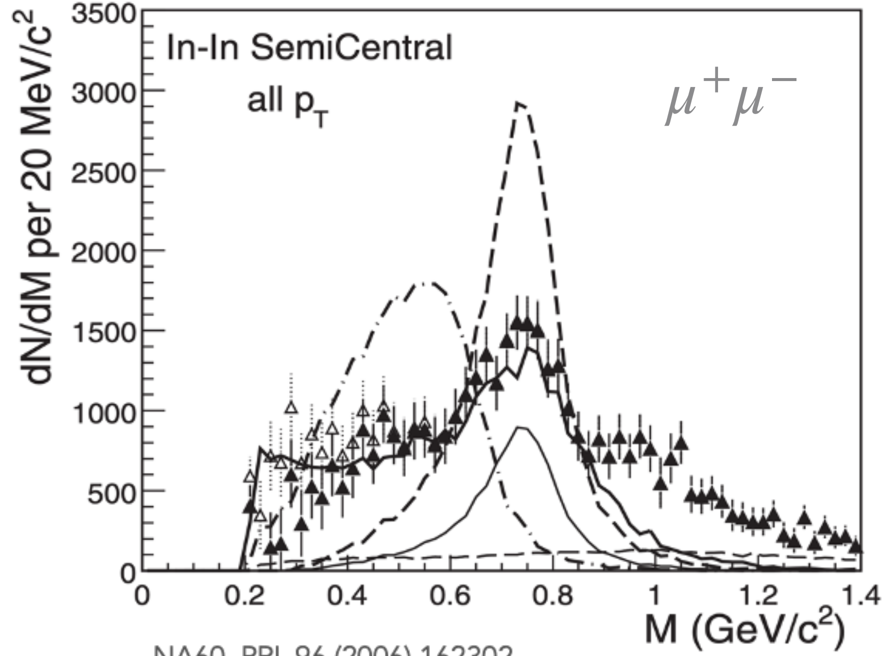
HADES: PLB 715 (2012) 304–309

p+p 3.5 GeV/c

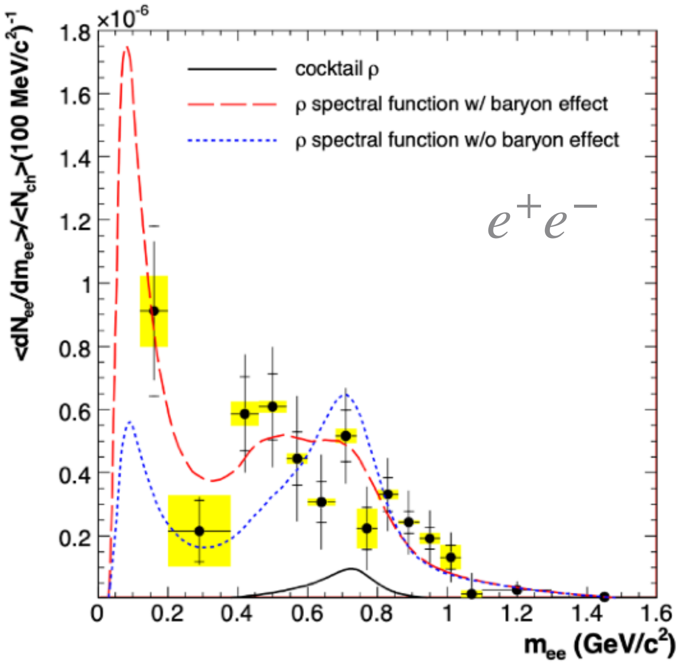




Baryon driven ρ meting observed at SPS



NA60, PRL 96 (2006) 162302

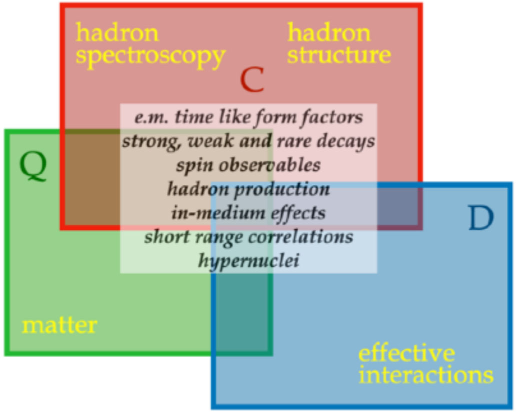


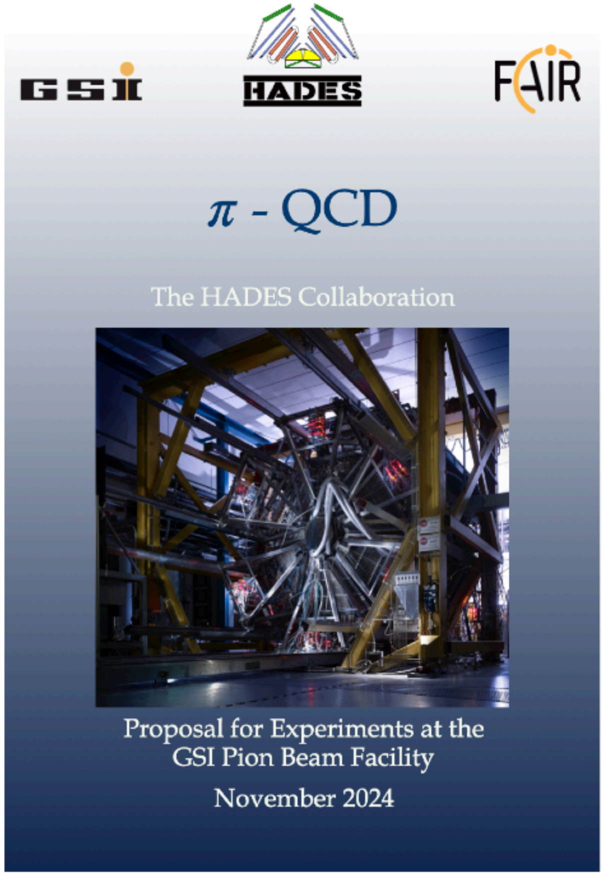
CERES, PLB 666 (2008) 425-429

The HADES Proposal for 2026 – 2028

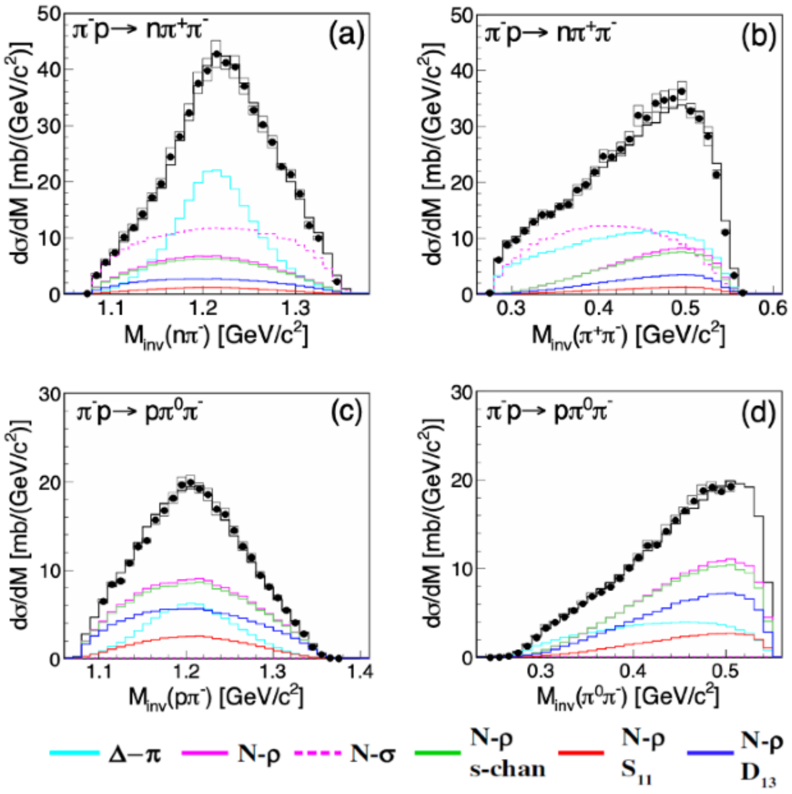
"Boosting the understanding of non-perturbative QCD
by combining pion beams with HADES
and involving three pillars"

π - QCD





Extraction of partial waves from two-pion channel

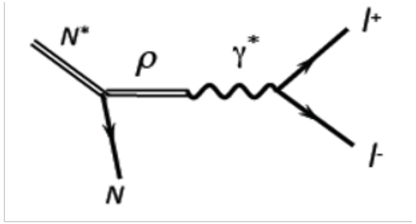


- $p_\pi = [0.66, 0.69, 0.75, 0.8]$ GeV
- $\pi^- + p \to \pi^- + \pi^+ + n$
  - Hadronic final states used in PWA (Bonn/ Gatchina code)
  - Use invariant masses, and angular distribution (not shown here)
- $\pi^- + p \to e^- + e^+ + n$
  - Prediction for dilepton invariant mass assuming strict VMD
  - Comparison to two-component model by Pena & Ramalho

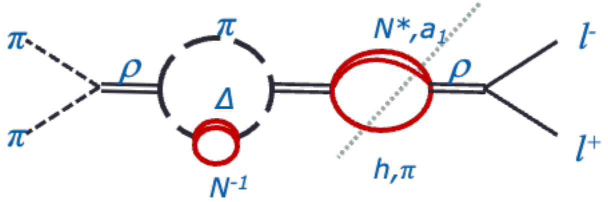
HADES arXiv:2309.13357; arXiv:2205.15914; Phys. Rev. C 102 (2020) 2, 024001

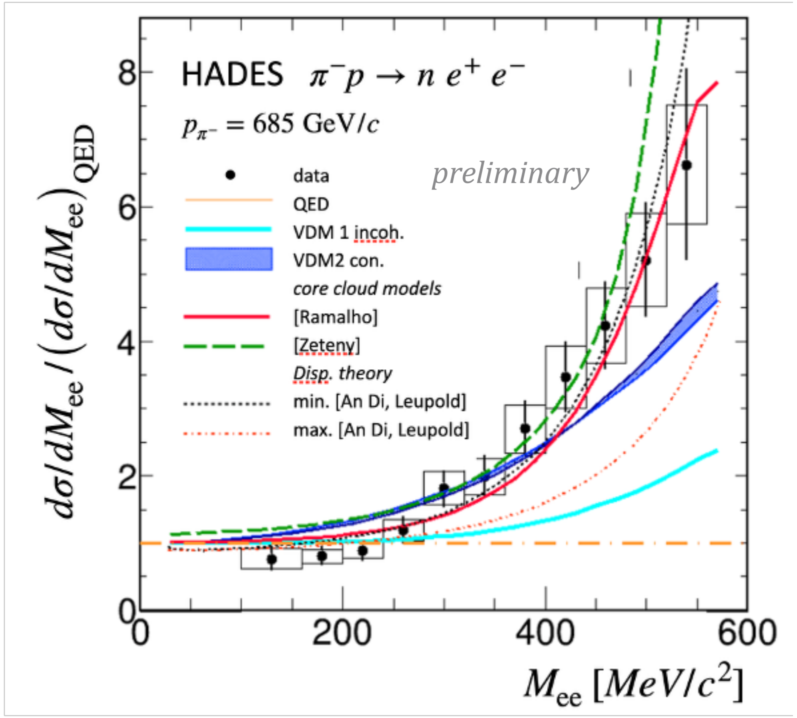
$\pi^- + p \rightarrow e^- + e^+ + n$

Resonance-Dalitz decay (a la VMD) …



… is analogous to baryonic contribution to in-medium ρ self-energy (emissivity)





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

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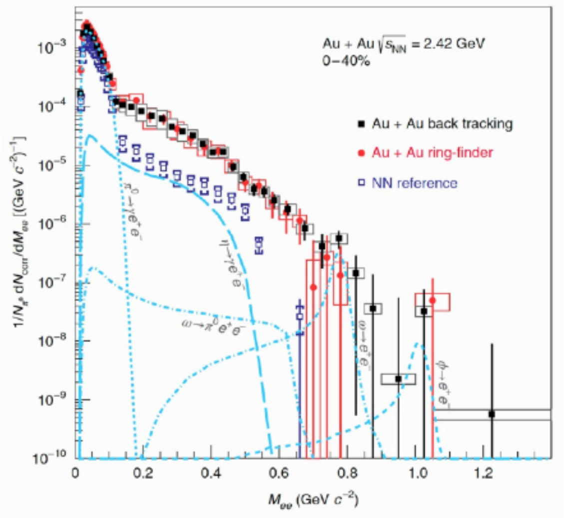
Dilepton spectra measured by HADES

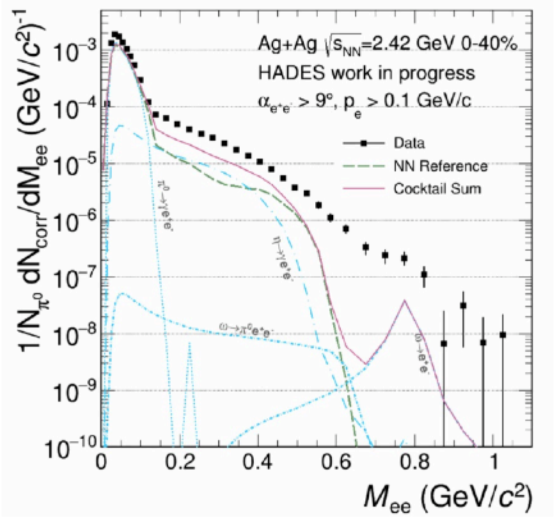
- **Significant excess radiation** above contributions from initial state (from NN reference) and freeze-out (meson cocktail) visible
- Excess radiation drops by four orders of magnitude for inv. mass of 0.2 down to 1 GeV

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

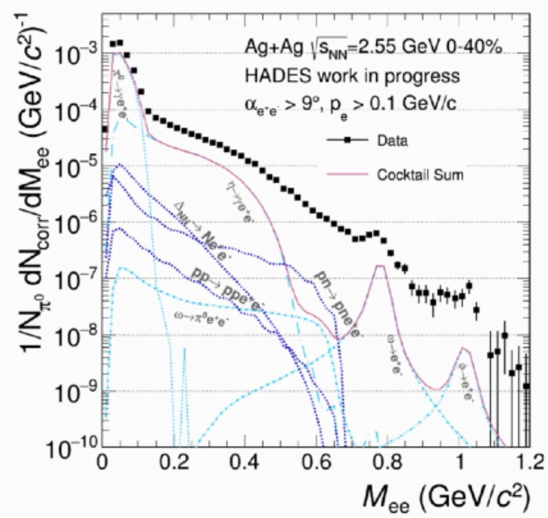


HADES, Nature Phys. 2019

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



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

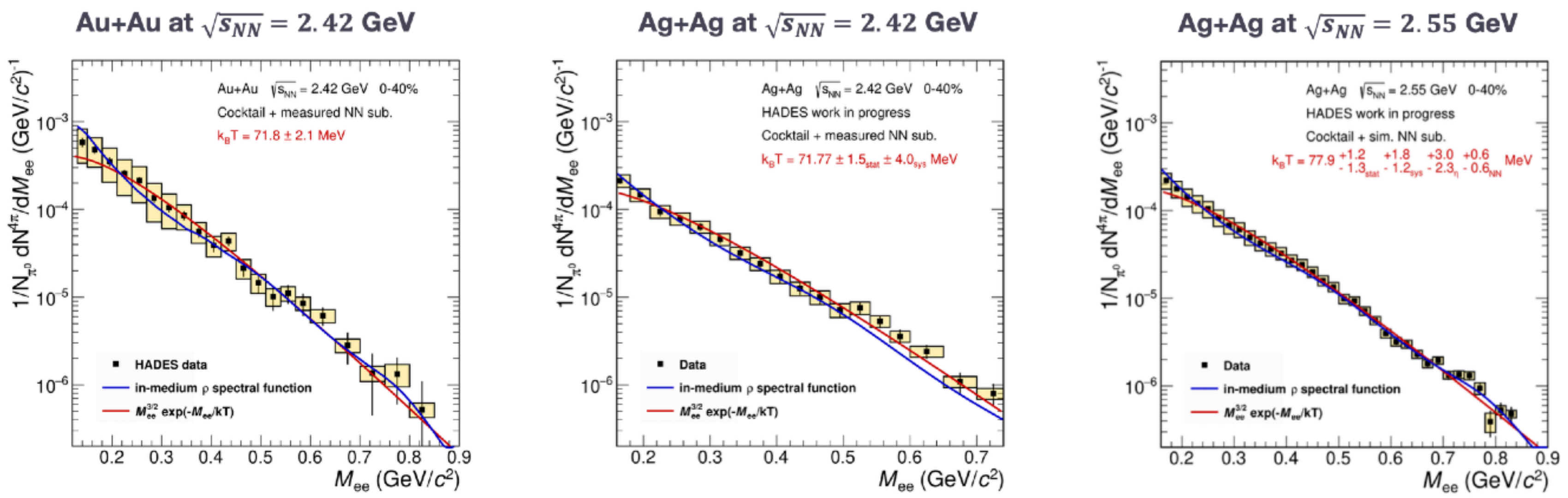


Excess radiation measured by HADES

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

N. Holt, R. Rapp: Eur. Phys. J. A 56 (2020) 11, 292

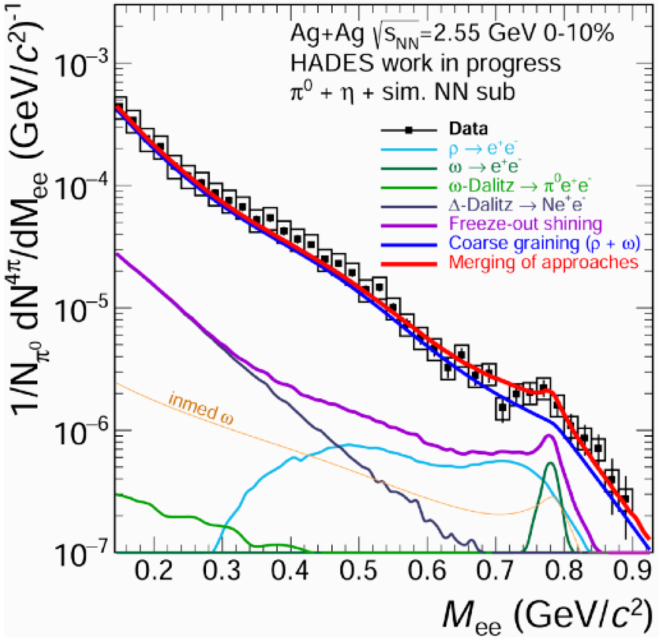
P.Hohler, R. Rapp: Phys.Lett.B 731 (2014) 103-109

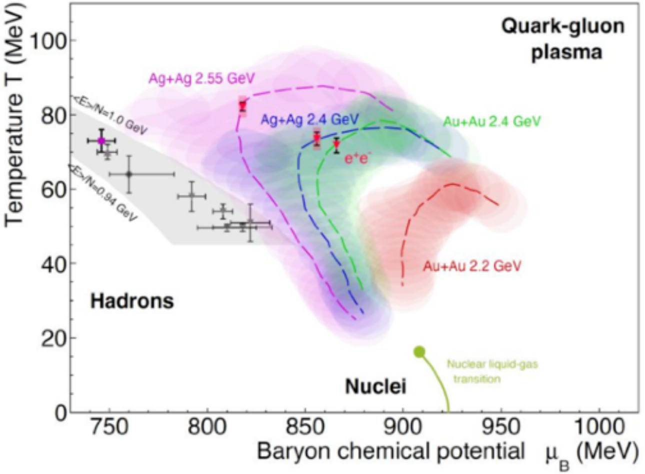


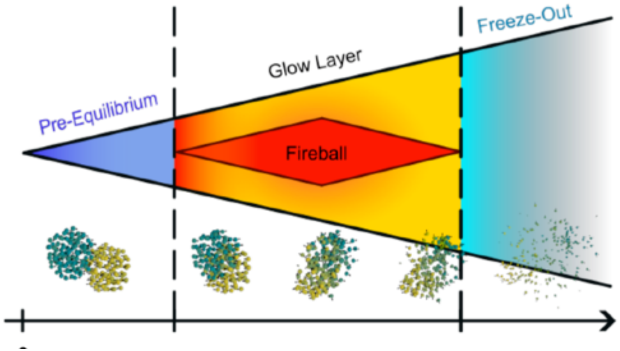
cf Niklas Schild, this school

Refined coarse-graining for HADES

- Treat the "corona" of the fireball separately
- Explains bump around vector mesons ρ, ω



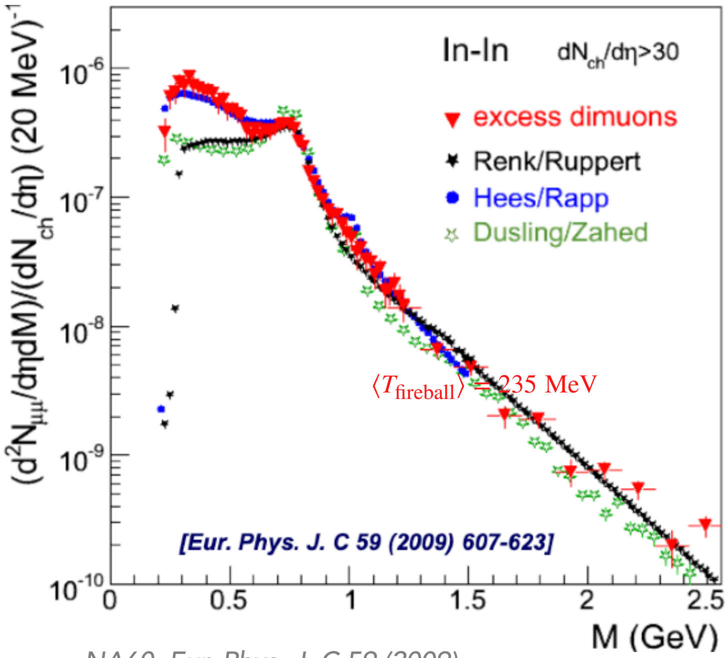




pictures from Jessica Vogel and Florian Seck (HADES)

Excess radiation in the IMR at SPS and SIS100

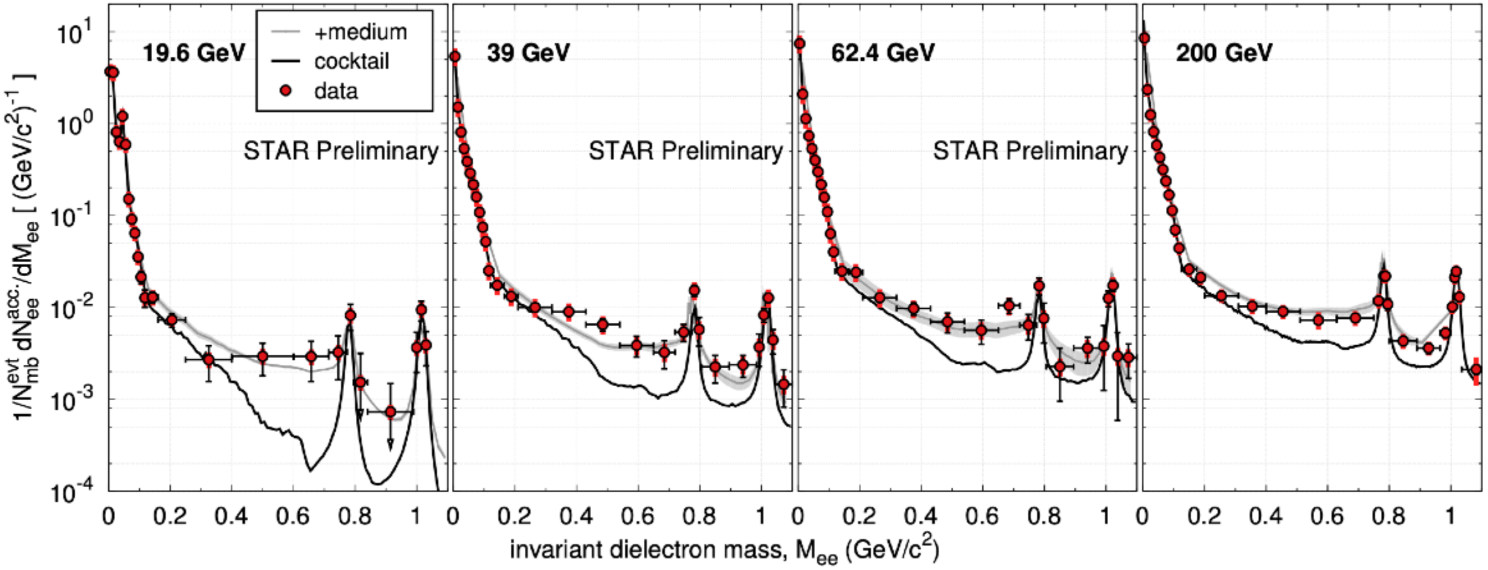
- Model independent extraction of temperature if $\frac{1}{M^2}\mathrm{Im}\Pi_{\mathrm{em}}\left(M,\vec{q},T,\mu_i\right) \simeq \mathrm{const}\,.$
- At SPS precise knowledge of open charm contributions needed
- Role of Drell-Yan like contributions at SIS100 energies?
  - EU project PRODY



NA60, Eur. Phys. J. C 59 (2009)

STAR BES-1: LMR dielectrons

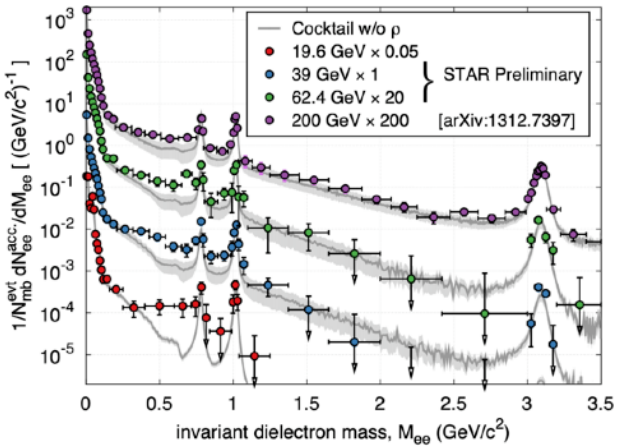
- No significant deviation from the “standard model”of dilepton production



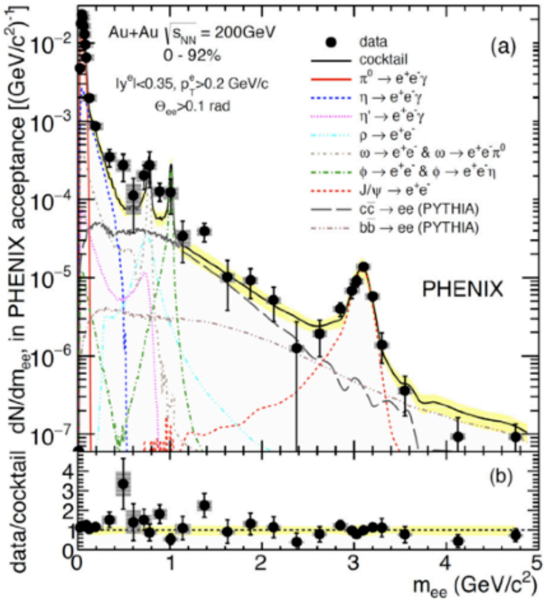
STAR: Phys. Lett. B 20

STAR and PHENIX: IMR dielectrons

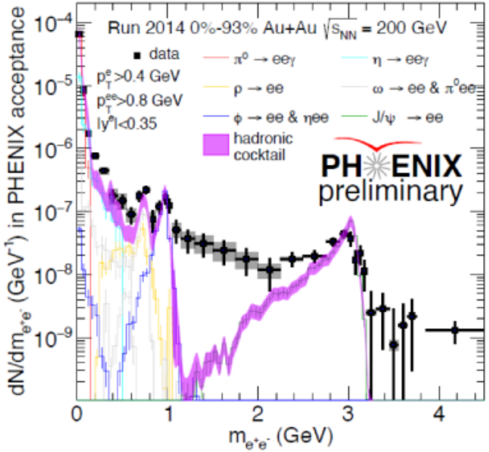
- Uncertainties from semi-leptonic open charm decays (no STAR di-electrons from run with HFT)
- Extraction of temperature in the IMR not possible



STAR, White Paper June 2014



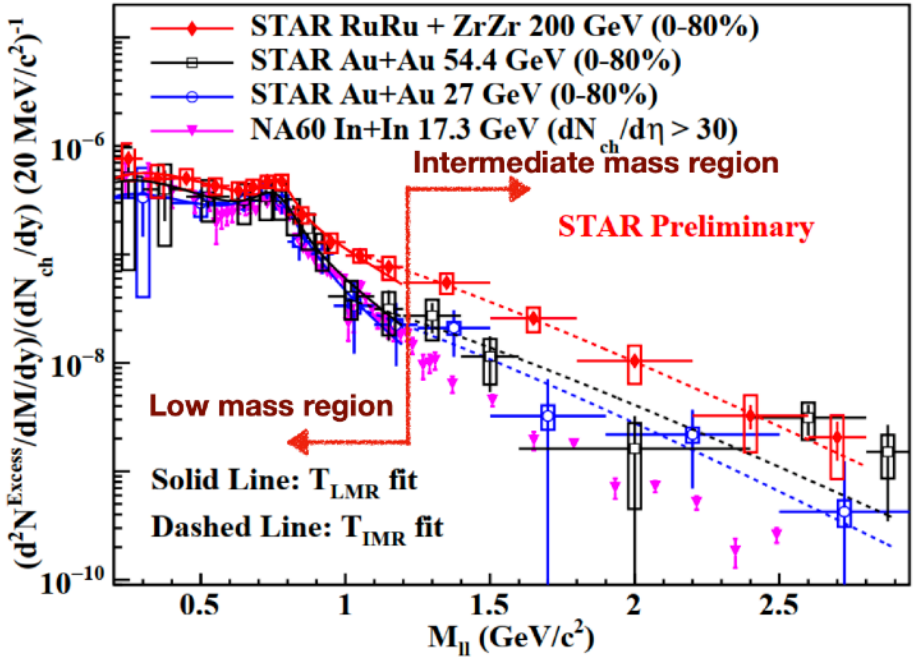
PHENIX, Phys.Rev. C93 (1) (2016) 014904



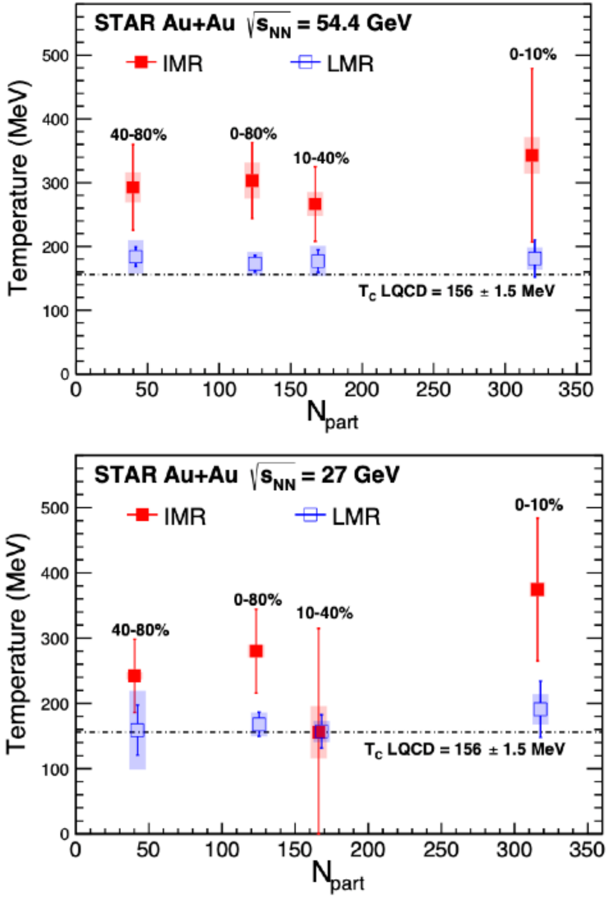
PHENIX (D. Gabor), QM2025

STAR new data/analysis

- Attempt to extract temperature from LMR and IMR



STAR: arXiv: 2402.01998, unp.



General remarks

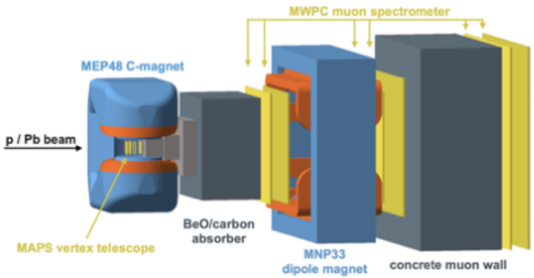
Heavy-ion Phenomenology

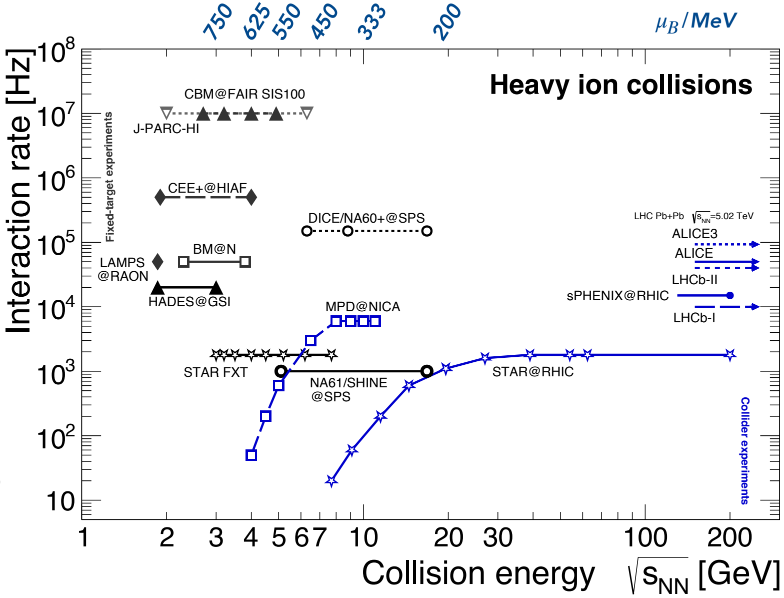
Radiation from proton induced reactions

Excess radiation

The future

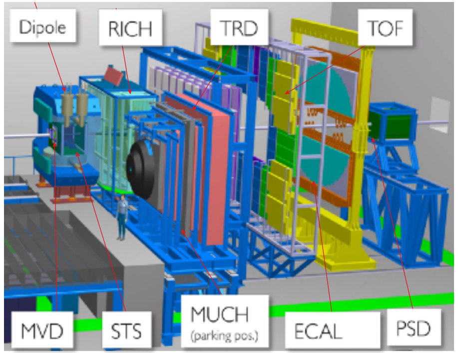
Future facilities for high μ_B physics



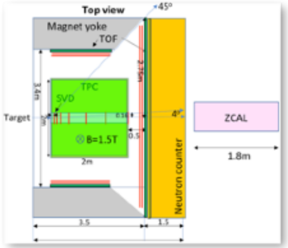


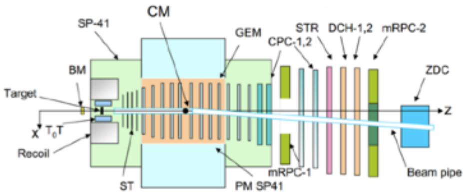
T. Galatyuk, Nucl. Phys. A982 (2019),
https://github.com/tgalatyuk/QCD_caloric_curve

CBM– FAIR

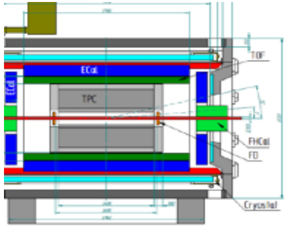


DHS – JPARC-HI



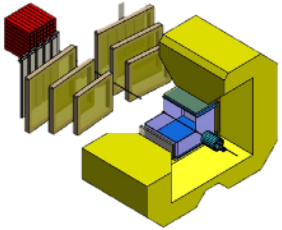


BM@N – NICA



MPD – NICA

CEE– HIAF



FAIR – Cosmic Matter in the Laboratory

APPA

- Atomic processes in highly ionised isotopes

NUSTAR

- Experiments with rare (neutron-rich) isotopes

CBM

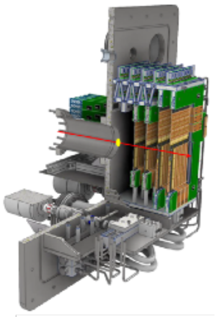
- Investigation of compressed baryonic matter

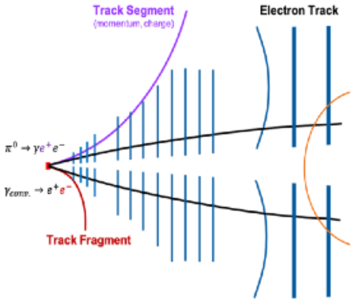
Compressed Baryonic Matter at FAIR

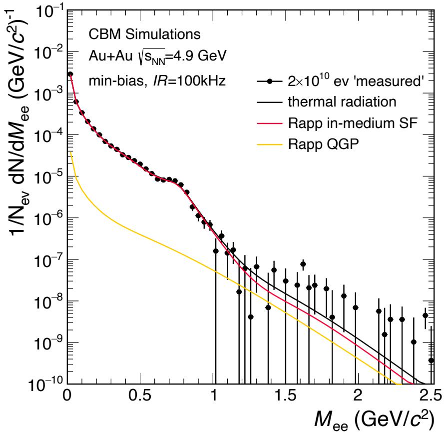
CBM dielectron performance (first year, 5 days/energy)

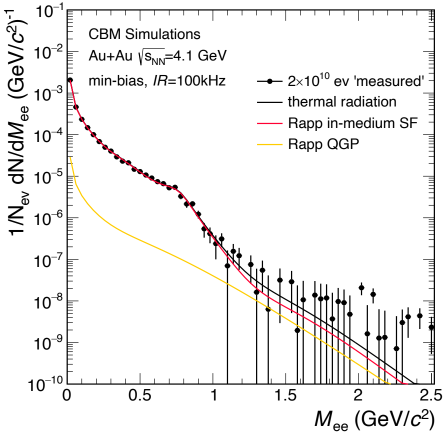
- Background rejection using topological cuts *(T. Galatyuk, PhD thesis GU Frankfurt 2009)*
- Micro vertex tracker augments low-momentum tracking
- Identify background pairs (small opening angle) by combining identified electron/positrons with track segments/fragments

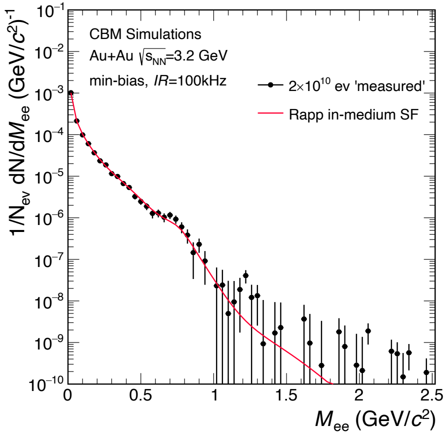
see also CBM: PhD thesis A. Meyer-Ahrens, Münster

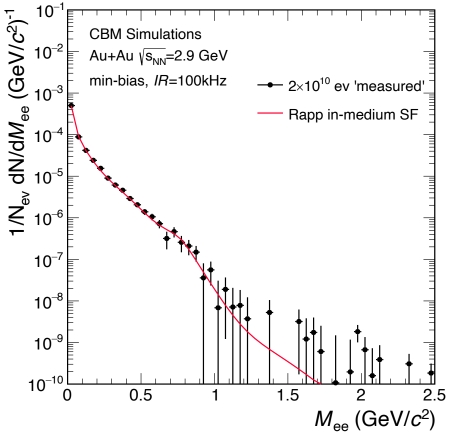






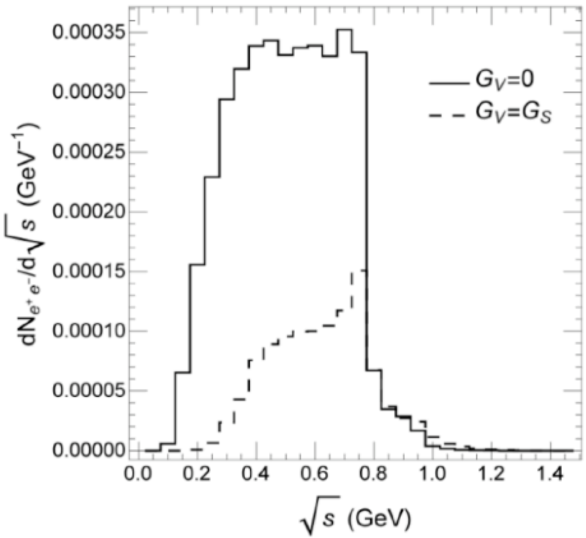




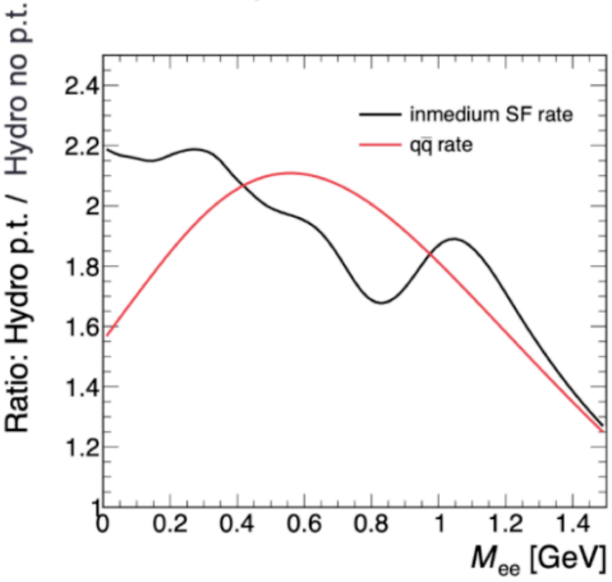


Possible dilepton signal of a first-order phase transition

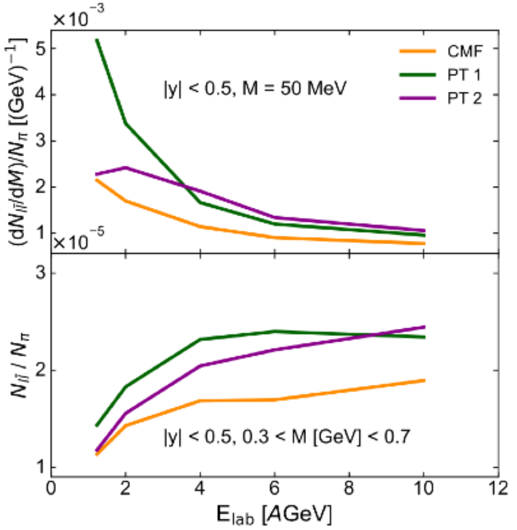
- Modification of the expansion trajectory in the phase diagram
- Changes of the in-medium photon propagator



F. Li and C.M. Ko PRC 95 (2017) 5, 055203



F. Seck, JS, et al., PRC 106, 014904 (2022)

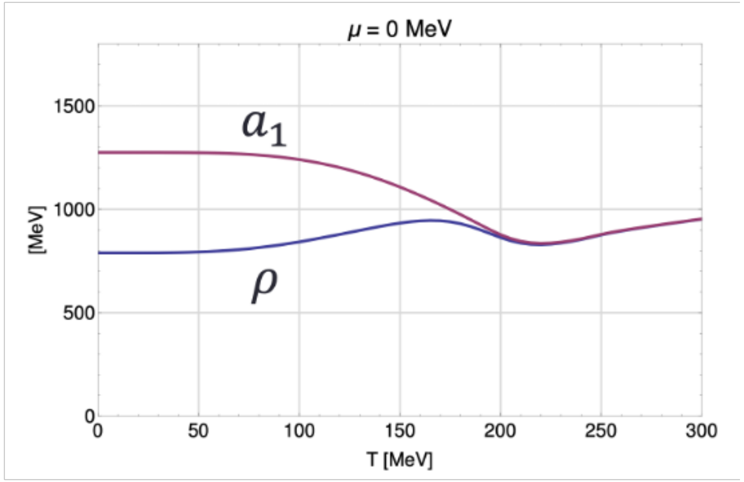


O. Savchuk et al. J.Phys.G 50 (2023) 12, 125104

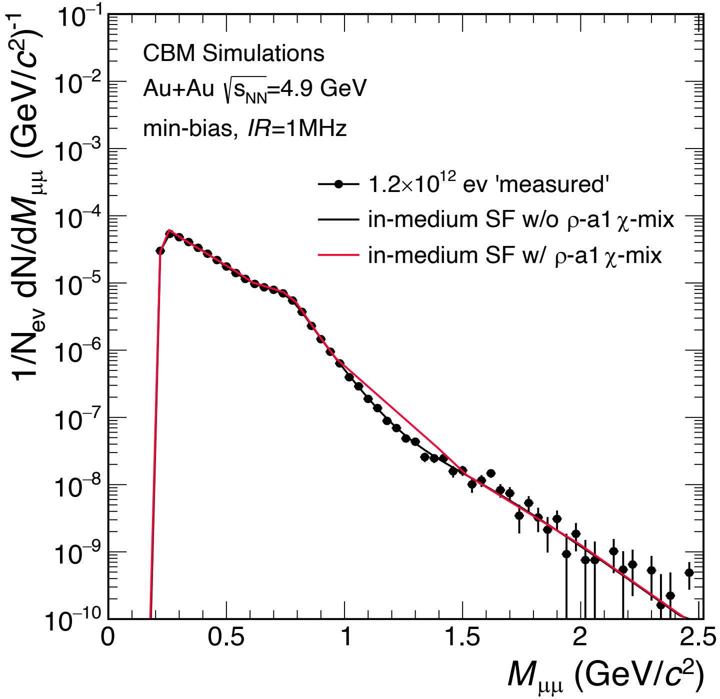
CBM dilepton performance

- Search for signs of (partial) χ-symmetry restoration ($\langle \bar{q}q \rangle \to 0$)
- Degeneracy of chiral partners:

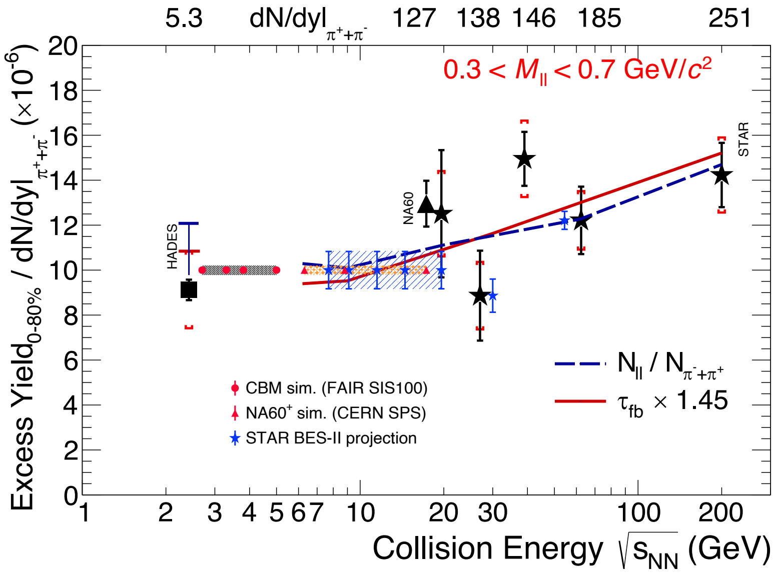
$$\int_0^\infty \frac{ds}{\pi}[\mathrm{Im}\Pi_V(s) - \mathrm{Im}\Pi_A(s)] = -2m\langle \bar{q}q \rangle$$

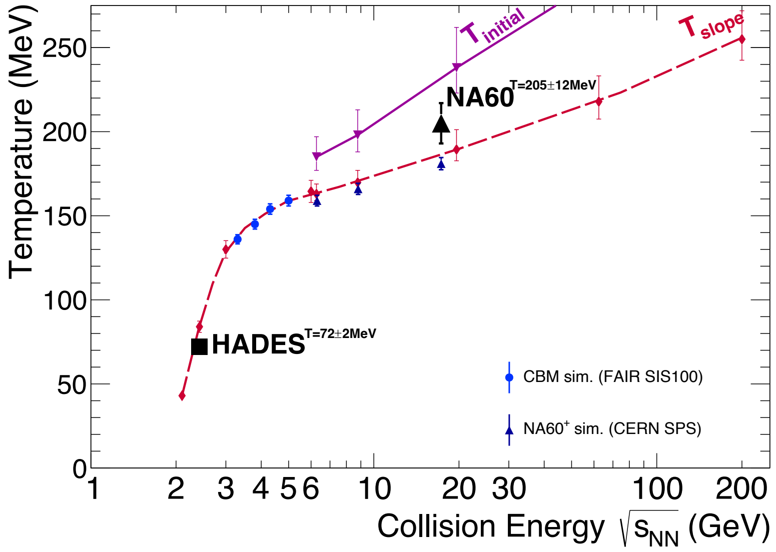


Jung et al., PRD 95, 036020 (2017)
Hohler and Rapp, PLB 731 (2014)



The quest for the full excitation energy





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

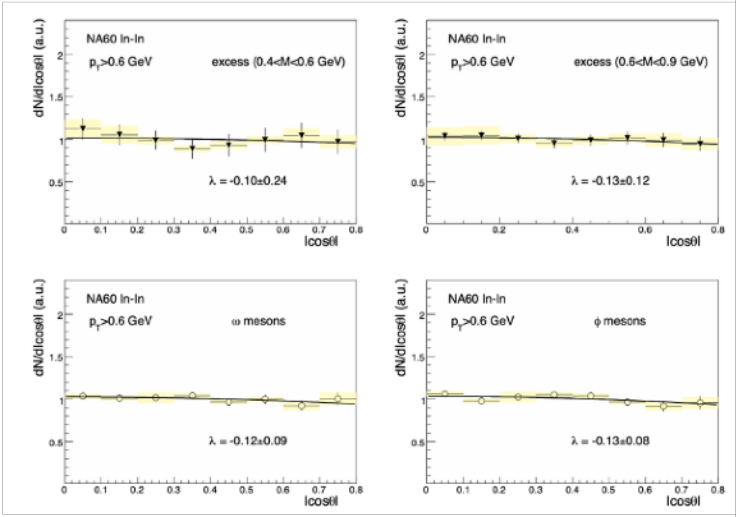
Polarisation & electrical conductivity

- Polarisation sensitive to the difference of longitudinal and transverse components of the spectral function
- Conductivity accessible via the *zero-energy limit* of the spectral function

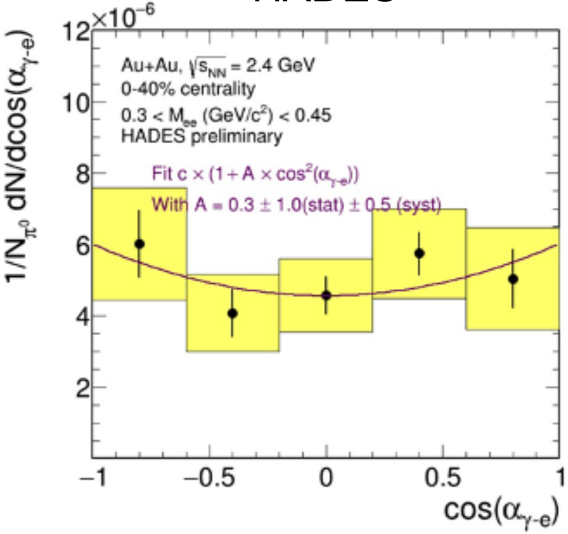
R. Rapp, H. van Hees, Phys. Lett. B 753, 586 (2016)
G. Baym et al., Phys. Rev. C 95, 044907 (2017)
E. Speranza et al., Phys. Lett. B 782, 395 (2018)

R. Rapp; Phys. Rev. C 110 (2024) 5, 054909
J. Atchison et al.; Phys. Lett. B 858 (2024) 139024

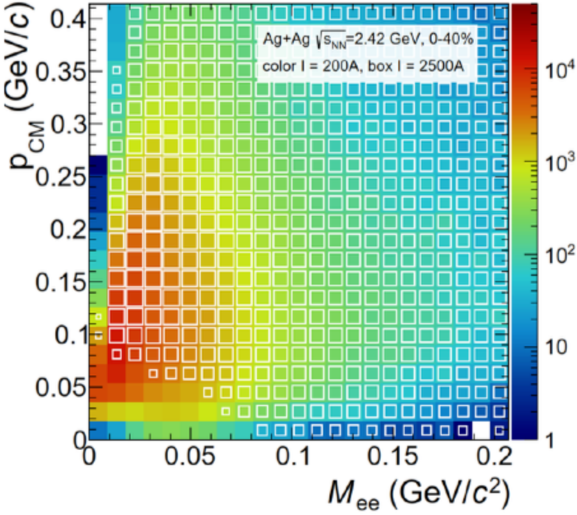
NA60



HADES



Low-field measurement by HADES to study sensitivity



Summary

- Dileptons are an excellent tool to explore the QCD phase diagram in the region of high μ_B
- Excess radiation is well described by thermal emission rates – standard candle established?!
- To fully exploit this observable, measurement at unprecedented precision and statistics are needed
- Additional insight from polarisation measurements and from very-low mass (momentum) dilepton (electrical conductivity)
- Promising perspectives to establish the full excitation function up to the exclusion region for CEP

Thank you for your attention