EXPERIMENTAL OVERVIEW ON DILEPTONS

Joachim Stroth, Goethe University Frankfurt / GSI / HFHF

CBM Students Day @ 46th CBM Collaboration Meeting

IMP, Lanzhou, Chinese Academy of Science

October 19, 2025

General remarks

Phenomenology

Non-equilibrium radiation

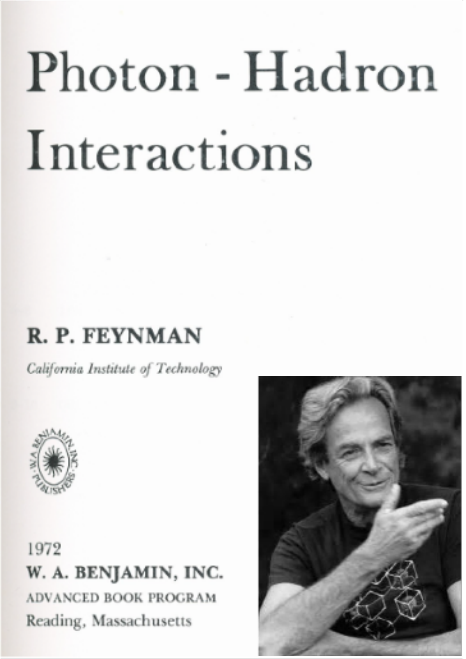
Excess radiation

The future

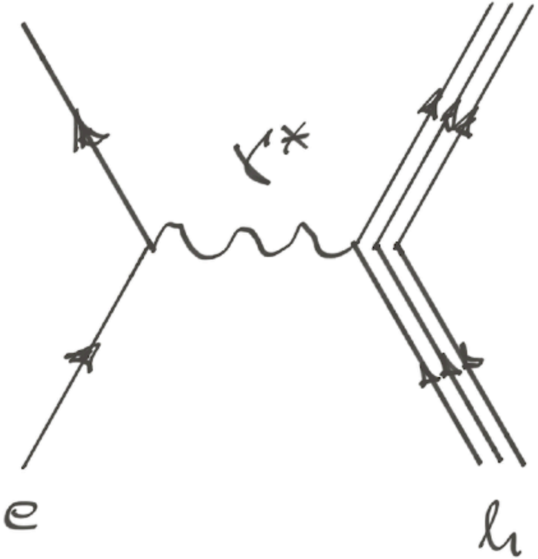
---

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

The subtle probe for strong interaction

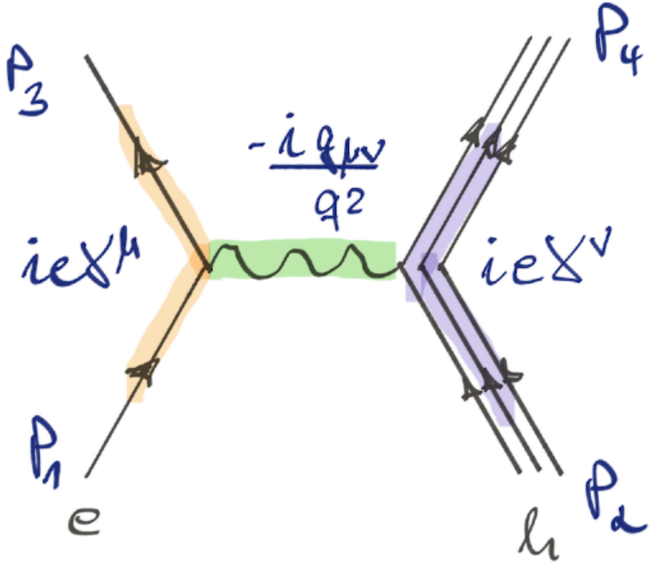


"If you want to study a hadronic system, better use a calibrated probe!"



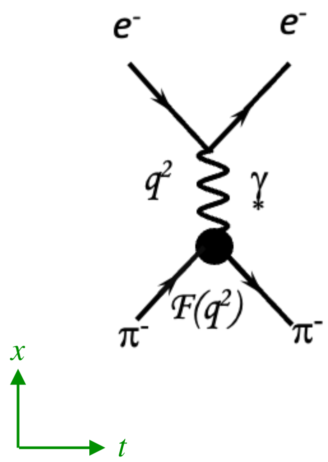
Electron hadron scattering

$$-iM = \left[\bar{u}_e(p_3) ie\gamma^\mu u_e(p_1)\right] \frac{-ig_{\mu\nu}}{q^2} \left[\bar{u}_h(p_4) ie\gamma^\nu u_h(p_2)\right] \quad \rightarrow \quad M = \frac{e^2}{q^2} g_{\mu\nu} j_e^\mu j_h^\nu$$

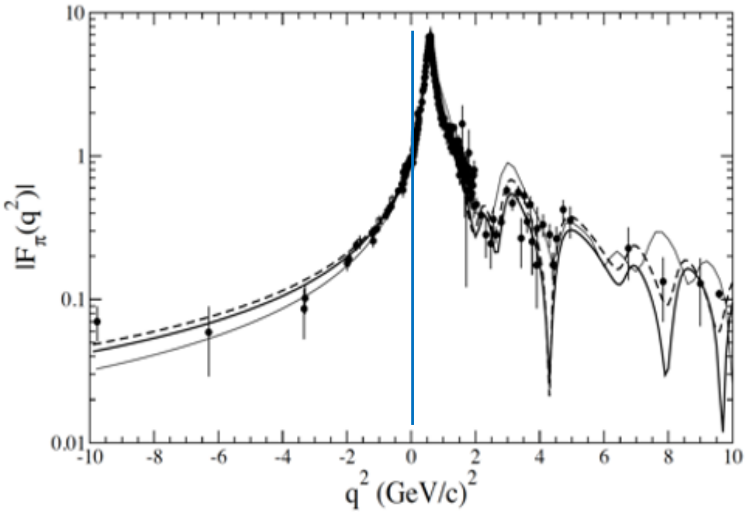


Space and time-like virtual photons

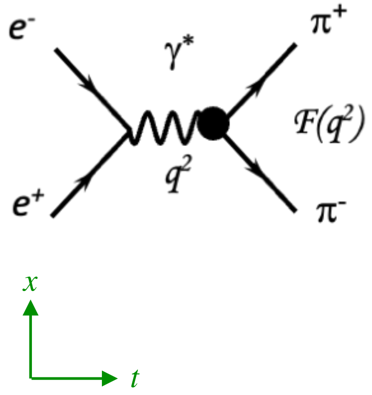
space-like



pion electromagnetic form factor



time-like



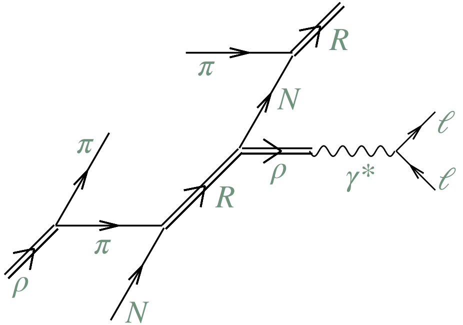
$$q^2 = q^\mu q_\mu = E^2 - |\vec{q}\,|^2$$

$$q = (E, \vec{q}\,)$$

Thermal radiation from hadronic/partonic source

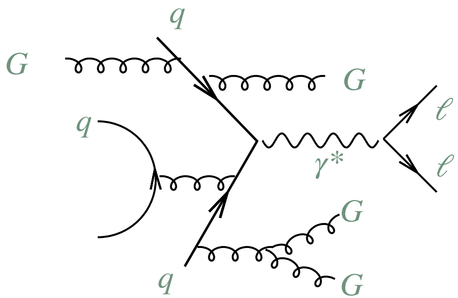
Photons couple to the electric charge carried by hadrons or quarks. Acceleration of these charges due to collisions or annihilation can produce (virtual) photons (generalised bremsstrahlung). The rate can be calculated from the product of the leptonic (*L*) and hadronic (*W*) tensor.

$$\frac{d^8N}{d4xd4q} \equiv L^{\mu\nu}(q)\frac{1}{q^4}W_{\mu\nu}(q) \simeq -\frac{\alpha^2}{\pi^3 M^2} f_B(q_0,T)\frac{1}{3}g_{\mu\nu}\,\mathrm{Im}\,\Pi^{\mu\nu}_{em}$$



The EM spectral function derives from a Fourier transform of the hadronic current-current correlation function (thermal average):

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



E. Feinberg: Nuovo: Cim.A 34 (1976) 391
L. McLerran, K. Toimela Phys. Rev. D31 (1985)
See also: Ralf Rapp: arXiv-1110-4345

Emission from a hadronic system

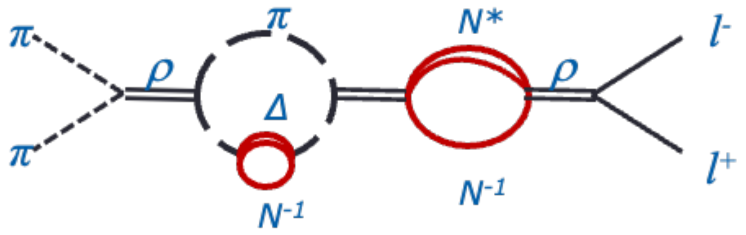
Mapping the partonic current to that of a pion gas: (Gounaris-Sakurai formula)

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

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

C. Gale, J. Kapusta: Nucl. Phys. B357 (1991)

$$\mathrm{Im}\,\Pi^{\mathrm{med}}_{\mathrm{EM}}(M) = \frac{m_{\rho}^4}{g_{\rho}^2}D(M) \rightarrow \quad D_{\rho}(M,\vec{q};T,\mu_B) = \frac{1}{M^2 - m_{\rho}^2 - \Sigma^2_{\rho\pi\pi} - \Sigma^2_{\rho M} - \Sigma^2_{\rho B}}$$

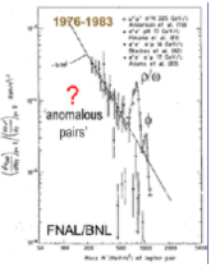


R. Rapp, J. Wambach: Adv. Nucl. Phys. 25 (2000) 1
B. Friman, Nucl. Phys. A610 (1996) 358c;
B. Friman and H.J. Pirner, Nucl. Phys. A617 (1997) 496

The historical view

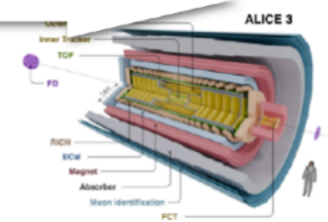
"**Drell-Yan root**" (CERN, FNAL/BNL) – Medium modified parton distribution functions and anomalous yield

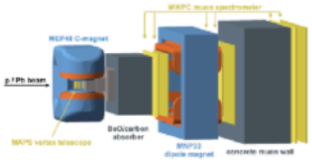
protons (1970) SPS S (1987) SPS Pb (1994) LHC Pb (2010) (2030) (2035)



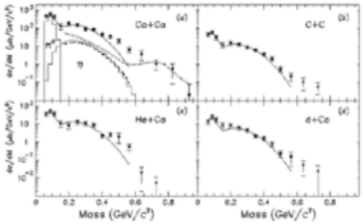
CERN: NA34, NA38 · NA45 (CERES), NA50 · NA60 · ALICE · LHCb · NA60+/DiCE · ALICE-3

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

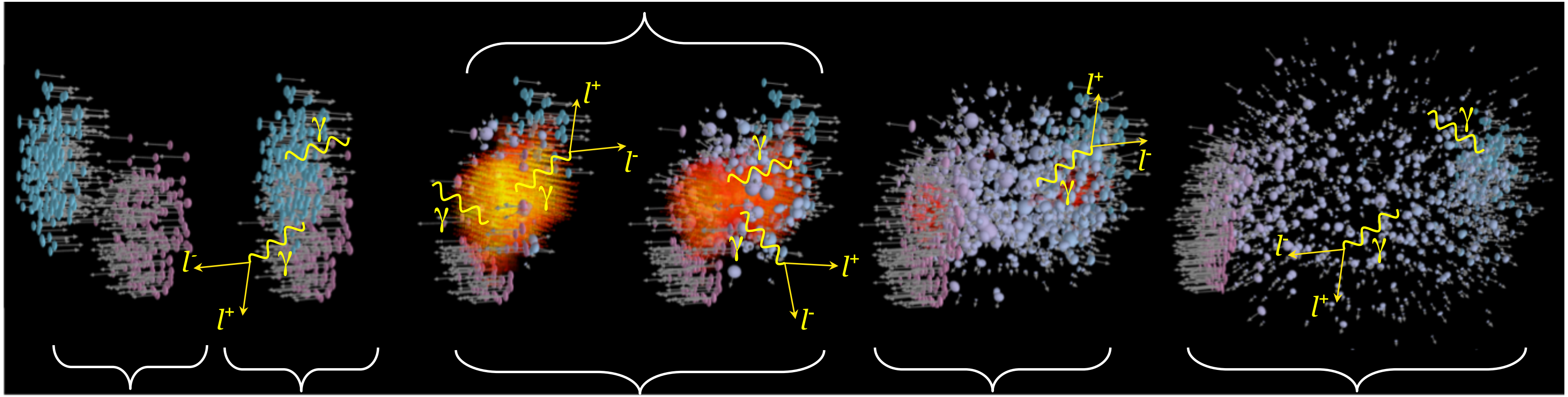
LBNL: DLS

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

NICA/MPD

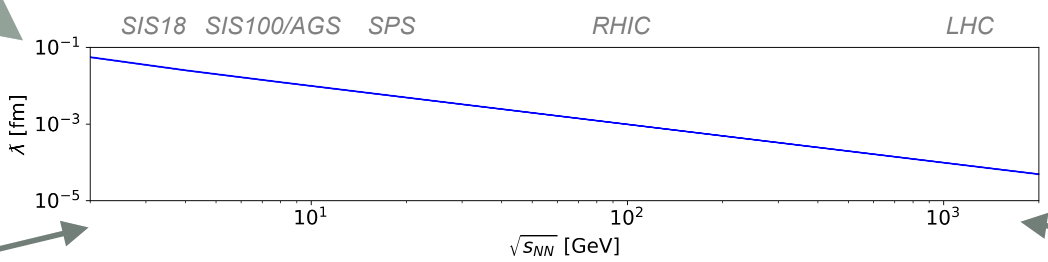
The (U)RHIC "Standard Model"

„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



nearly complete baryon stopping
one-boson exchange

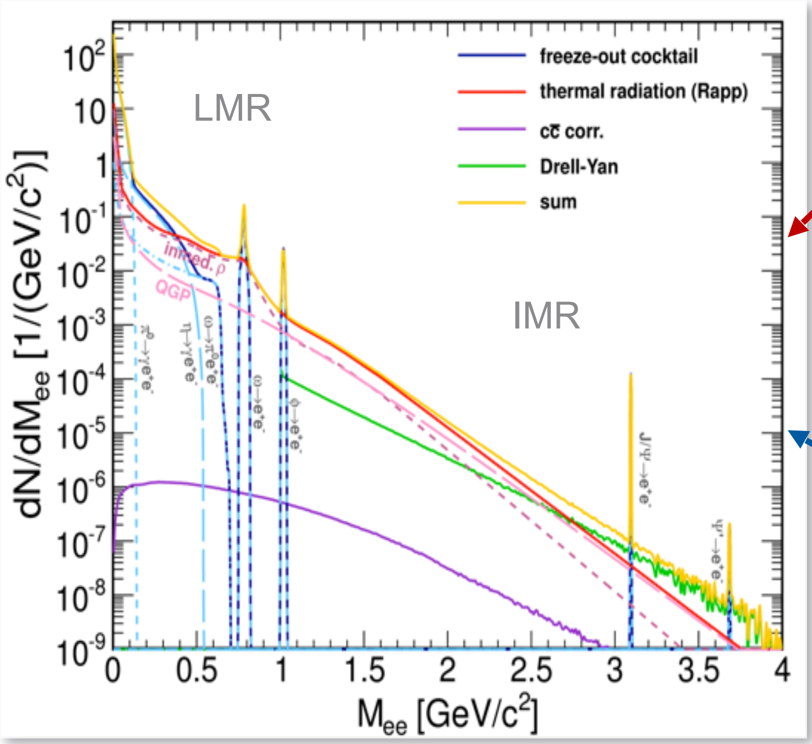
net-baryon free collision zone perturbative scattering & PDFs

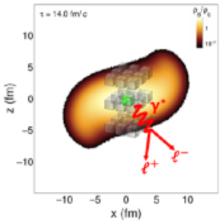
Excess Radiation as "Standard Candle" for (U)RHIC

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

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

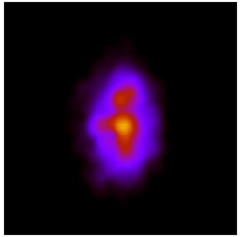
$$\equiv \int \frac{d^4\epsilon}{d\boldsymbol{q}}\left[T(\boldsymbol{x}),\mu_B(\boldsymbol{x}),\vec{v}(\boldsymbol{x})\right] d\boldsymbol{x}$$





or

hydro

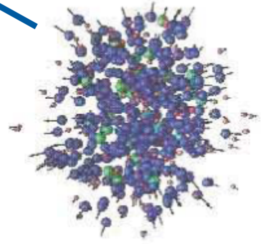


coarse graining

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

shining

UrQMD



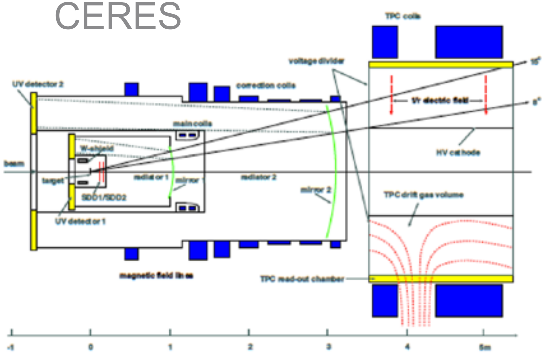
Dilepton emission from *Microscopic Transport.*

Dielectrons

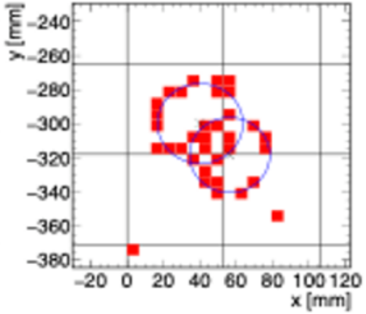
"Fast" lepton, make use of radiative effects → Cherenkov (β) [and Transition (γ)] radiation

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

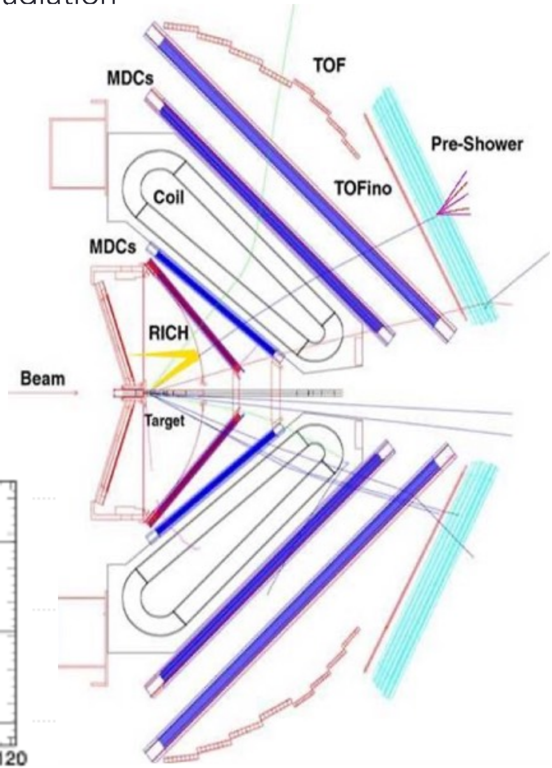
CERES



HADES RICH



HADES

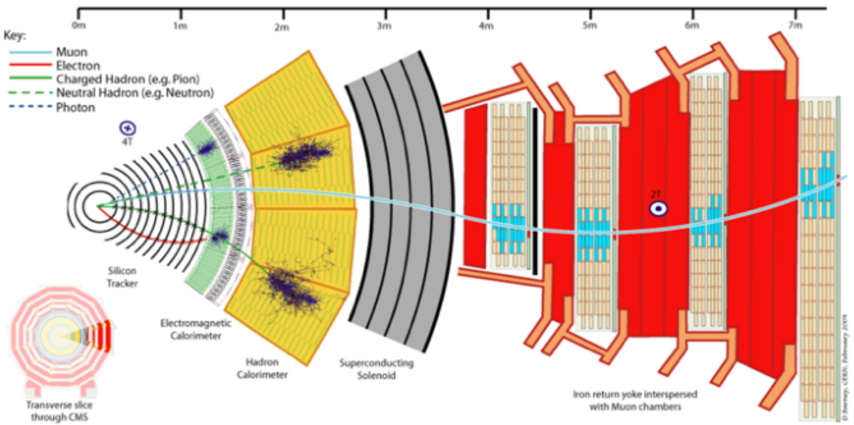


Dimuons

"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 is 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 $M_{\text{inv}} > 2m_\mu$

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

Background rejection strategies

1 High purity (good efficiency)

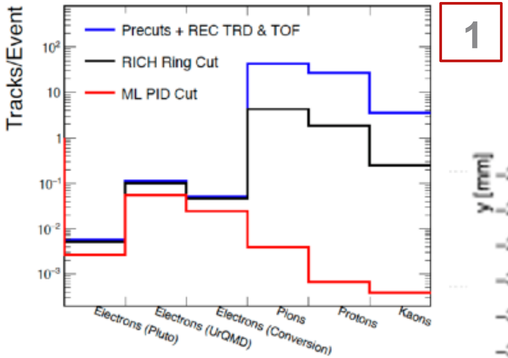
- fake (mis-identified) leptons add to the combinatorics
- can also be correlated (e.g. K^0 decay)

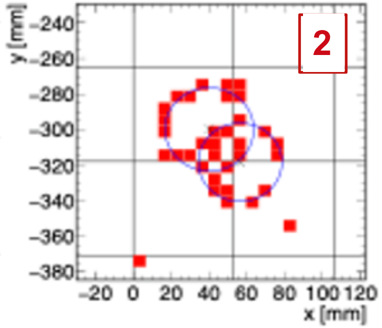
○ Dielectrons (close pair rejection)

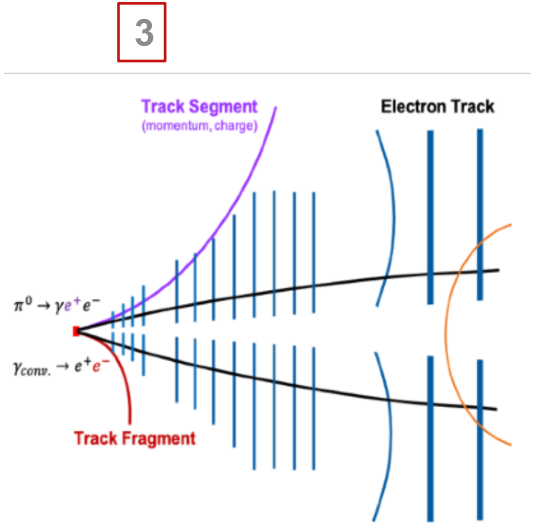
- RICH in field-free region
  - 2 Identify double rings with good significance
- Track topology
  - 3 Search for close-by track segments
- global p_T cuts

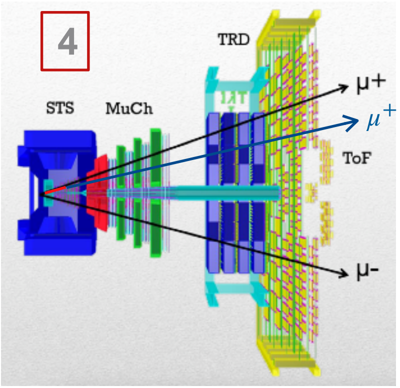
○ Dimuons (weak decay muon rejection)

4 Excellent tracking to identify kink



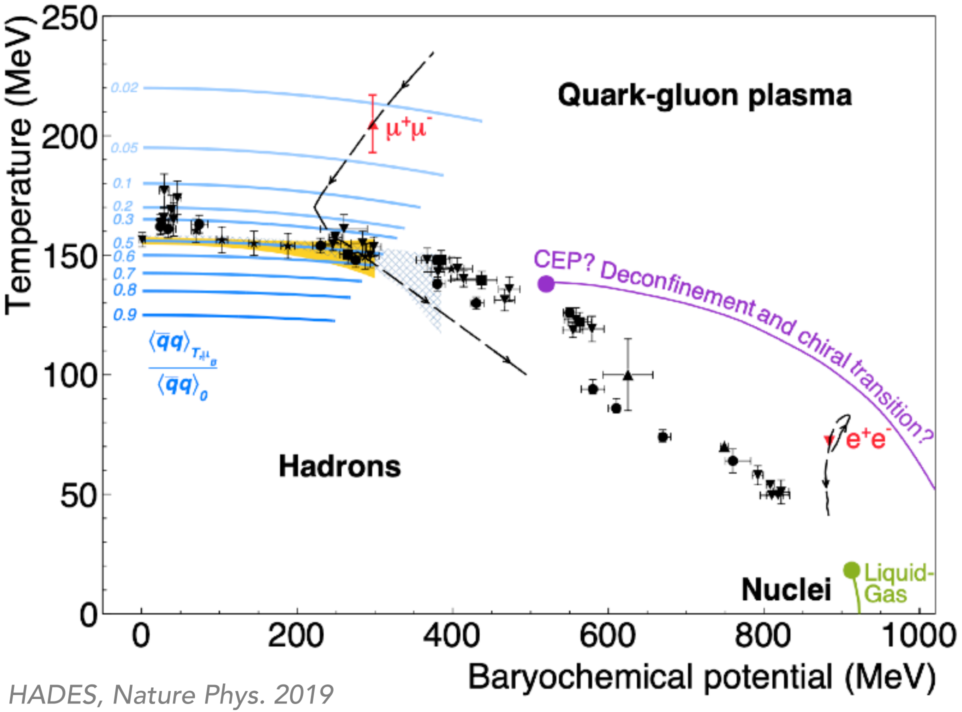






Exploration of the QCD Phase Diagram @ high-μ_B

From medium-effects to novel phases of QCD matter

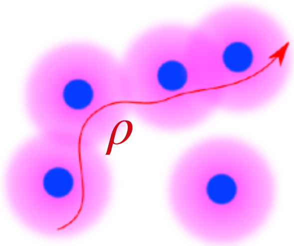


HADES, Nature Phys. 2019

Conjectures for

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

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

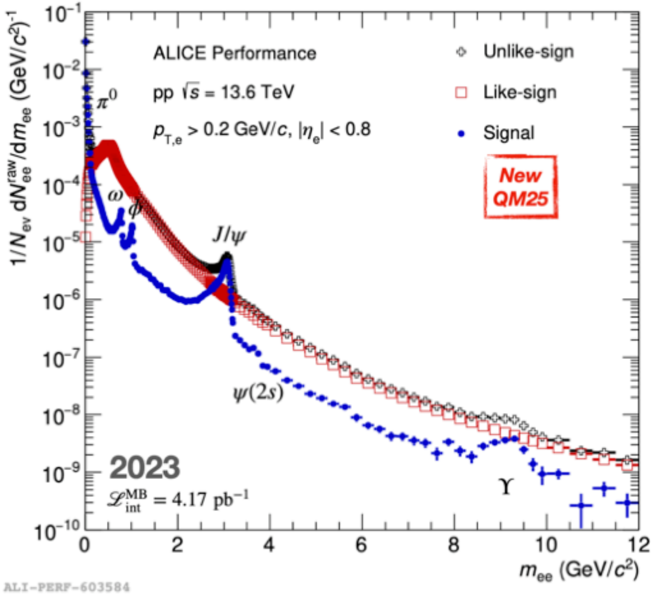


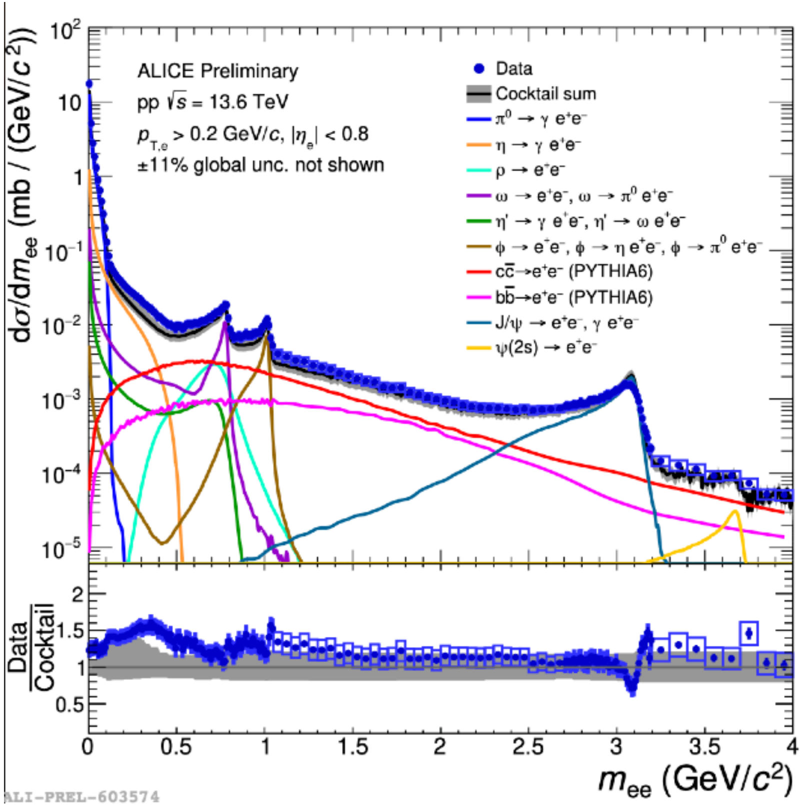
ALICE p+p $\sqrt{s_{NN}} = 13.6$ TeV (after RUN3 upgrade)

Reference for IMR open charm contribution

- Already substantial combinatorial background in p+p
- Heavy flavour decomposition using ITS-2

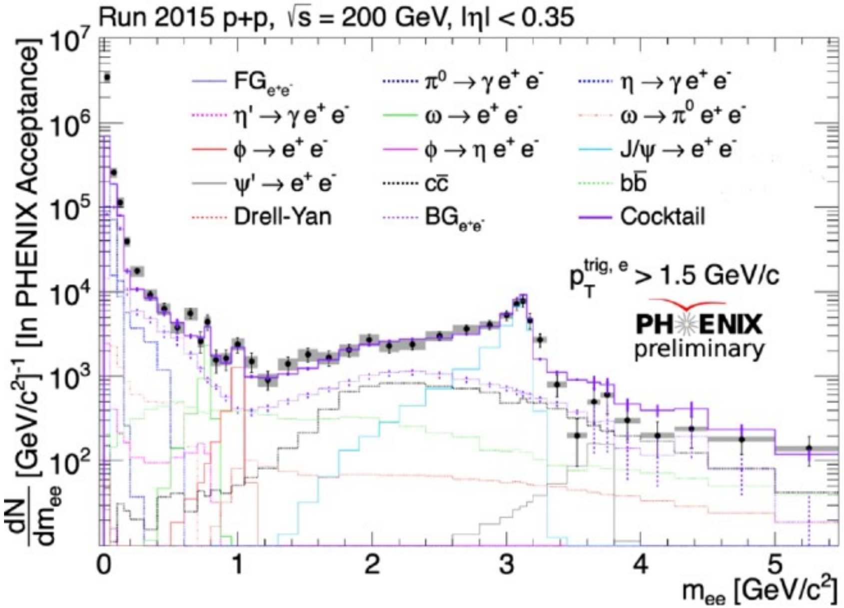
ALICE (F. Eisenhut): QM2025





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

- Similar quality from updated PHENIX measurement - see Axel's talk
- Precision measurements at SPS and SIS100 and theoretical guidance needed

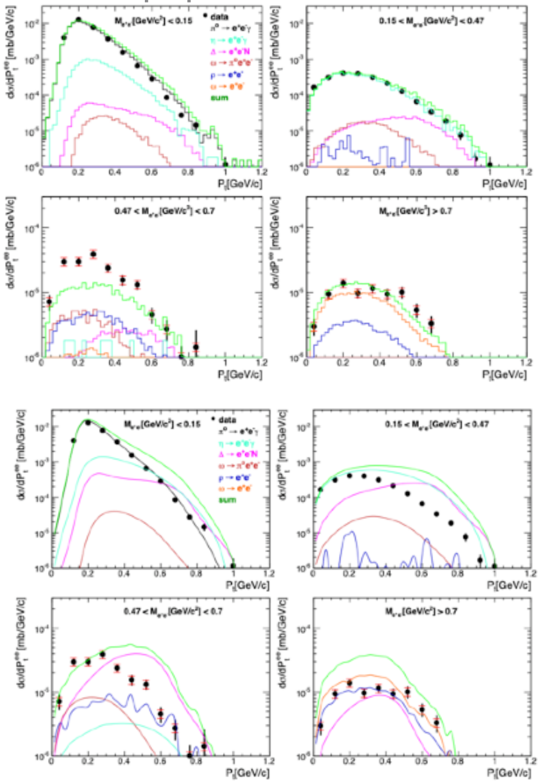


Gabor QM2025

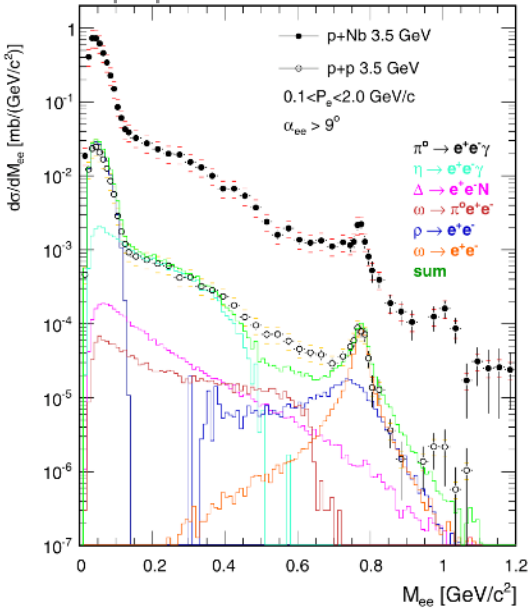
HADES - SIS18 energies

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

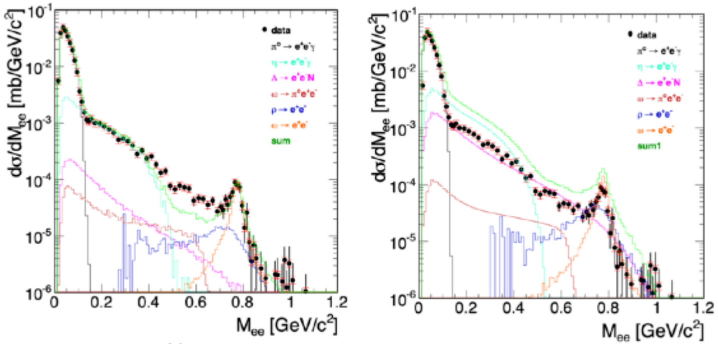
p+p 3.5 GeV/c



p+p / Nb 3.5 GeV/c



p+p 3.5 GeV/c

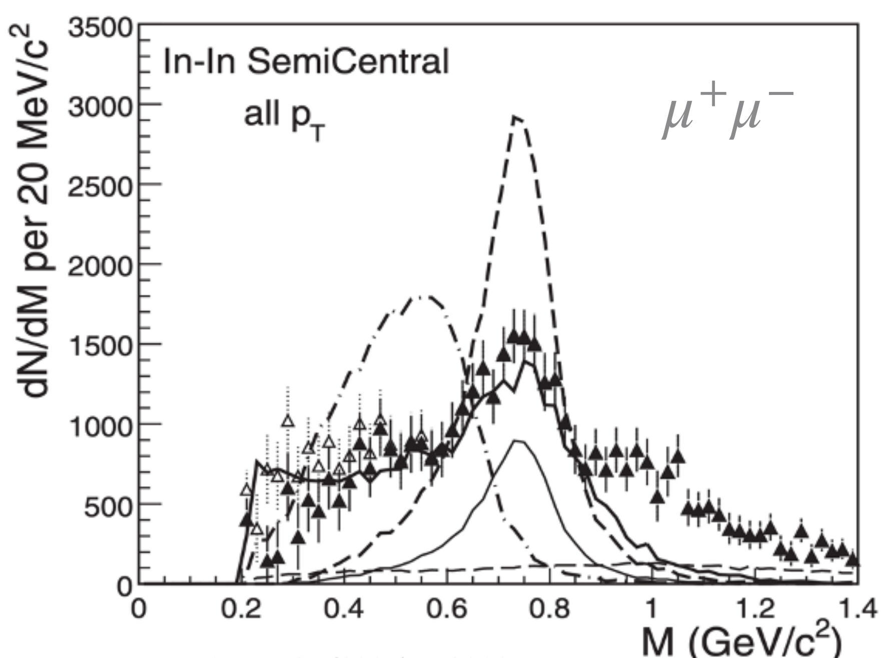


HADES: PLB 715 (2012) 304–309

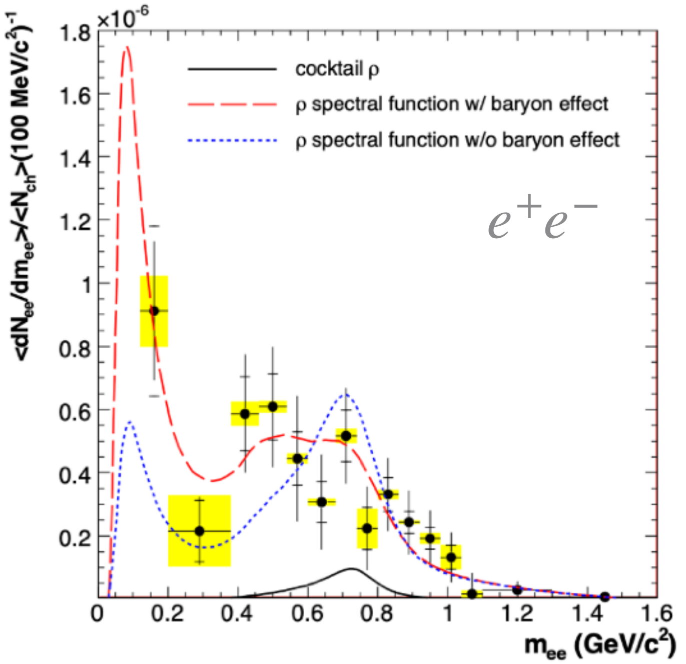
HADES: PLB 715 (2012) 304–309

General remarks
Phenomenology
Non-equilibrium radiation
Excess radiation
The future

Baryon driven ρ meting observed at SPS



NA60, PRL 96 (2006) 162302

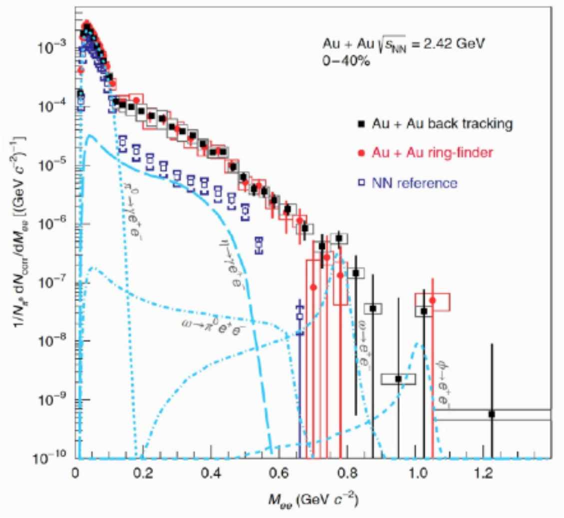


CERES, PLB 666 (2008) 425-429

Dilepton spectra measured by HADES

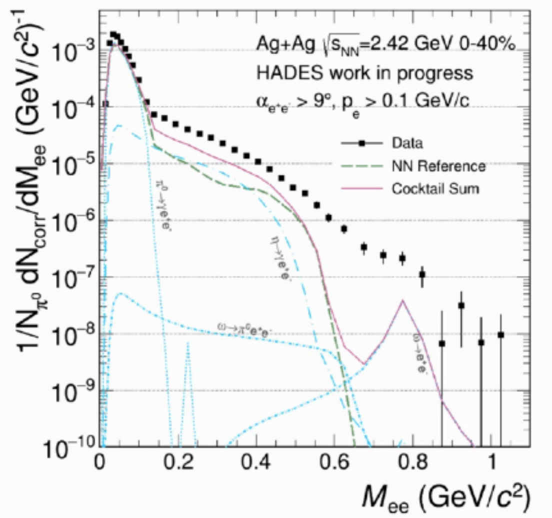
- **Significant excess radiation** above contributions from initial state (from NN reference) and freeze-out (meson cocktail) visible
- Excess radiation drops by four orders of magnitude for inv. mass of 0.2 down to 1 GeV

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

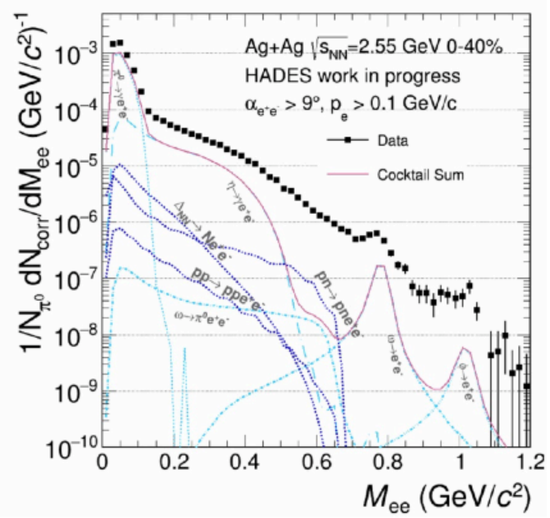


HADES, Nature Phys. 2019

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



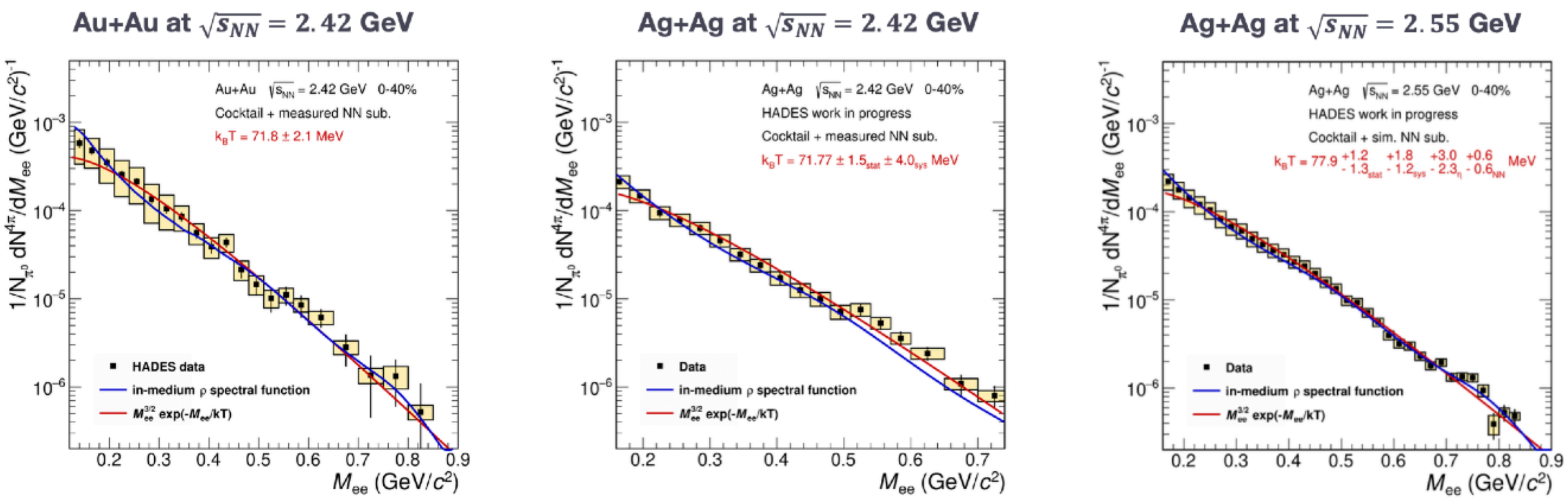
Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV



Excess radiation measured by HADES

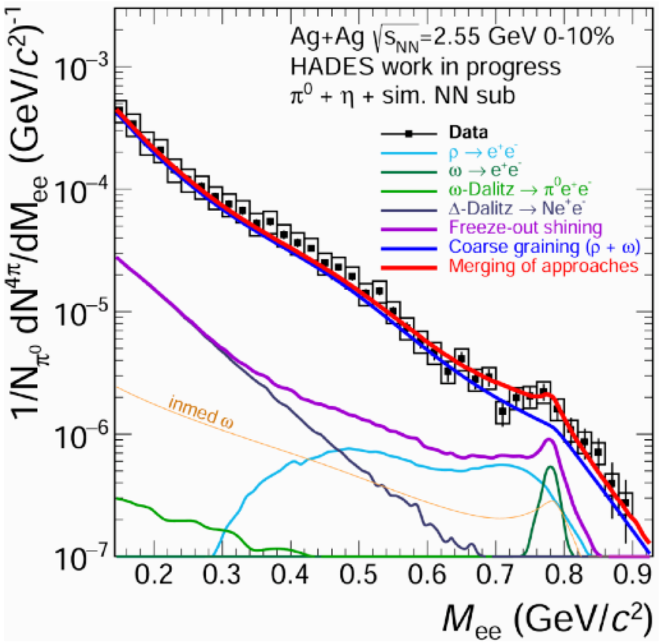
- Spectral distribution reproduced by a fit assuming thermal radiation
- Significantly higher temperature at higher collision energy
- No indication of a ρ bump at the lower beam energy energy → strong melting

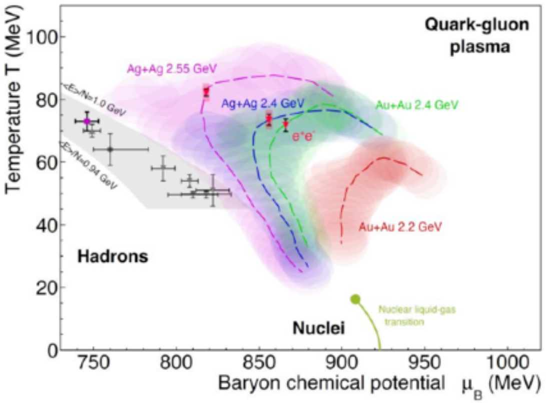
N. Holt, R. Rapp: Eur. Phys. J. A 56 (2020) 11, 292
P.Hohler, R. Rapp: Phys.Lett.B 731 (2014) 103-109

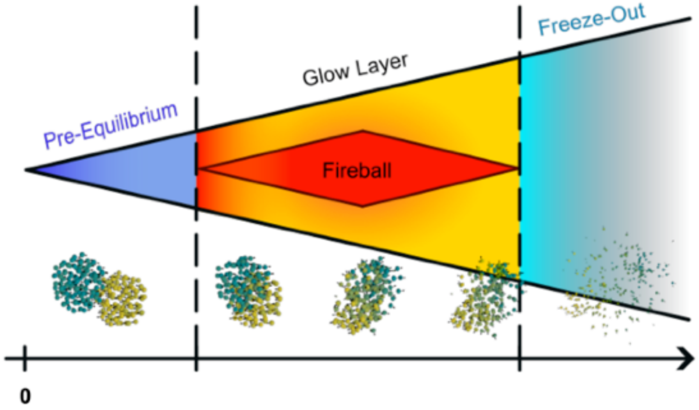


Refined coarse-graining for low energies

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



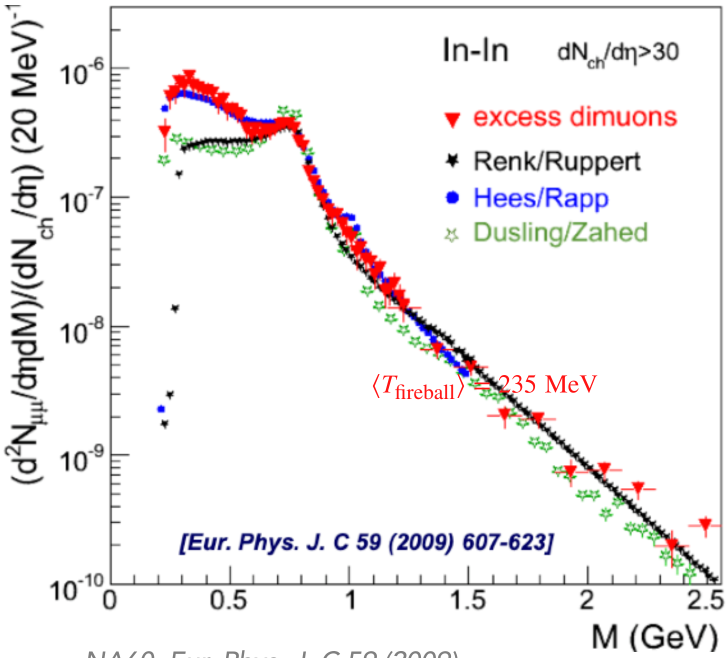




pictures from Jessica Vogel and Florian Seck (HADES)

Excess radiation in the IMR at SPS and SIS100

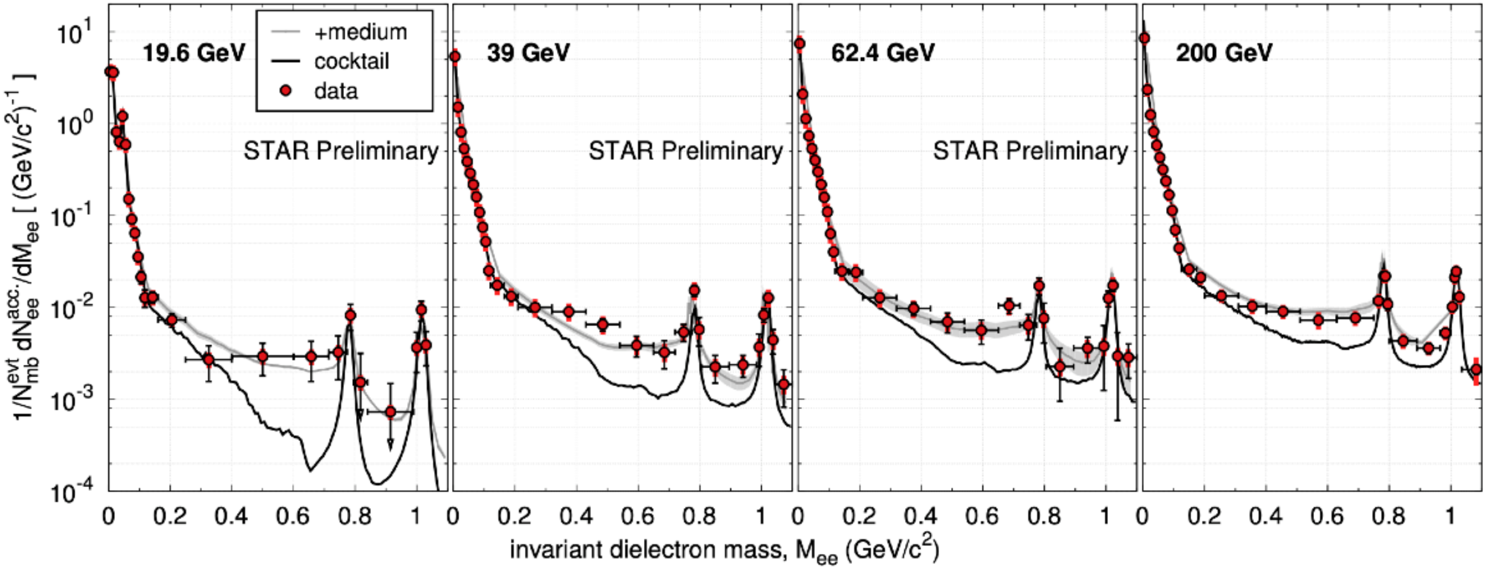
- Model independent extraction of temperature if $\frac{1}{M^2}\mathrm{Im}\Pi_{\mathrm{em}}\left(M,\vec{q},T,\mu_i\right) \simeq \mathrm{const}$.
- At SPS precise knowledge of open charm contributions needed
- Role of Drell-Yan like contributions at SIS100 energies?
  - EU project PRODY



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

STAR BES-1: LMR di-electrons

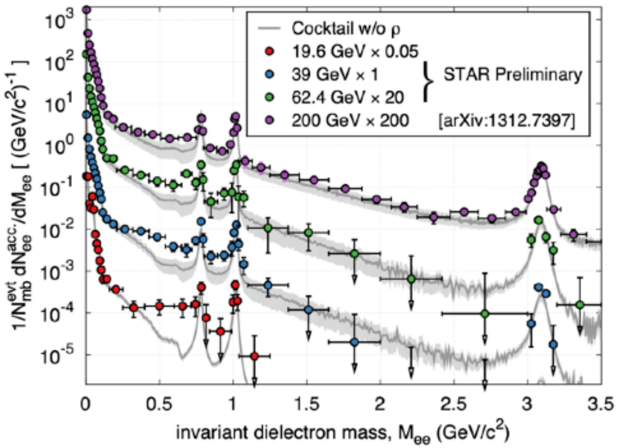
- No significant deviation from the "standard model" of dilepton production



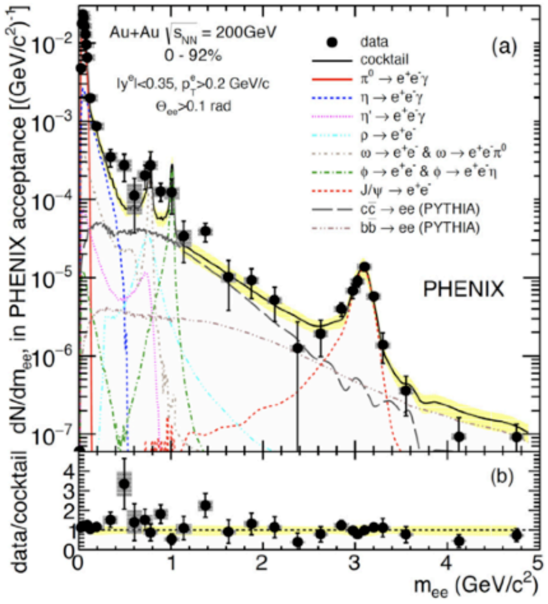
STAR: Phys. Let
392

STAR and PHENIX: IMR di-electrons

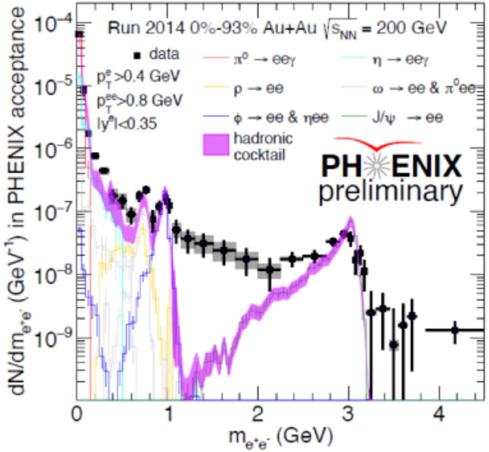
- Uncertainties from semi-leptonic open charm decays (no STAR di-electrons from run with HFT)
- Extraction of temperature in the IMR not possible



STAR, White Paper June 2014



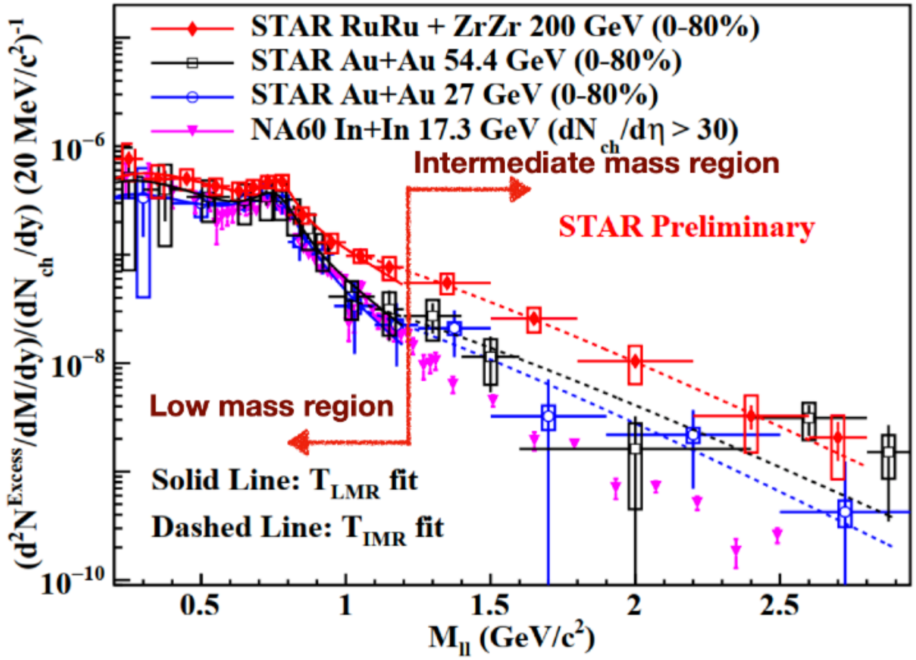
PHENIX, Phys.Rev. C93 (1) (2016) 014904



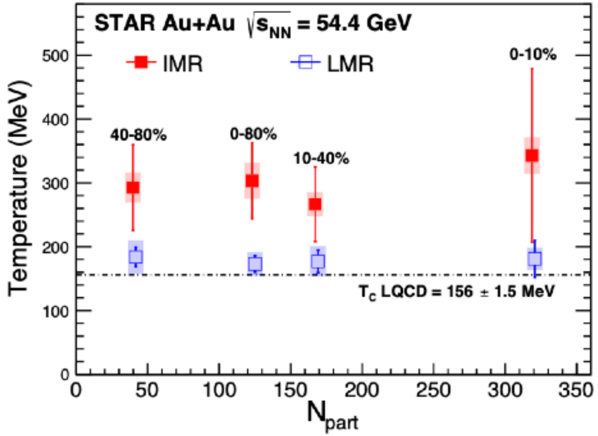
PHENIX (D. Gabor), QM2025

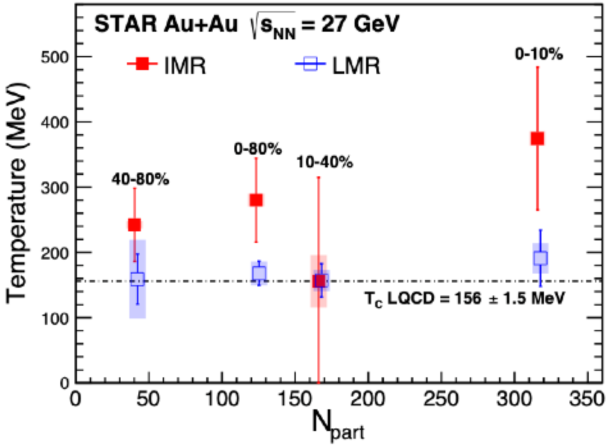
STAR new data/analysis

- Attempt to extract temperature from LMR and IMR



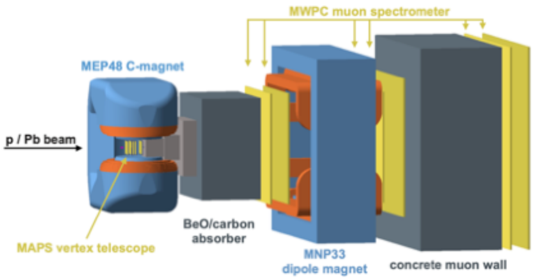
STAR: arXiv: 2402.01998, unp.



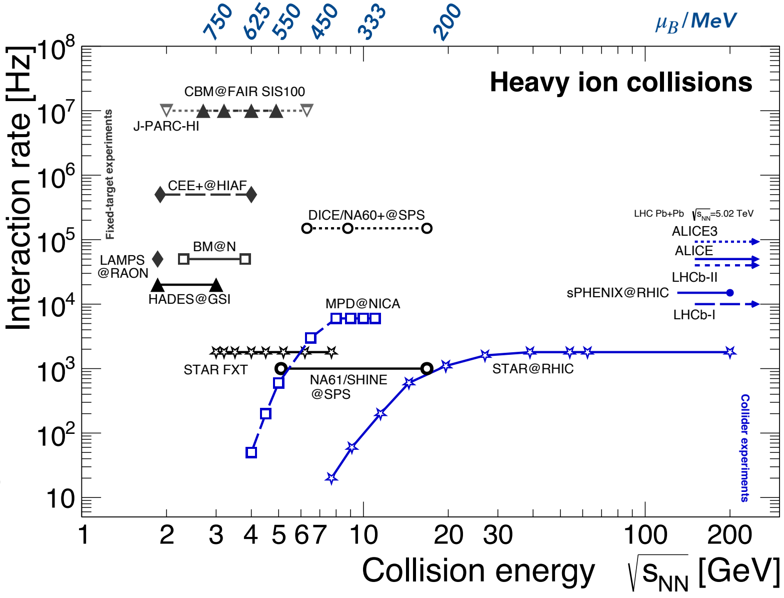


General remarks
Phenomenology
Non-equilibrium radiation
Excess radiation
The future

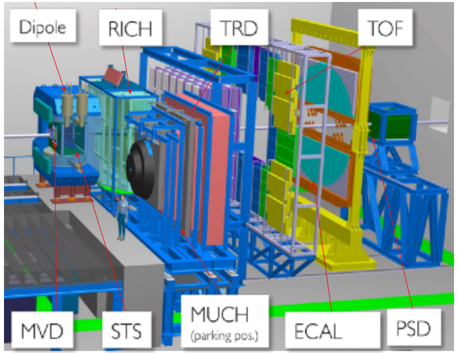
Future facilities for high μ_B physics



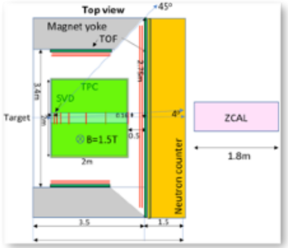
T. Galatyuk, Nucl. Phys. A982 (2019), https://github.com/tgalatyuk/QCD_caloric_curve

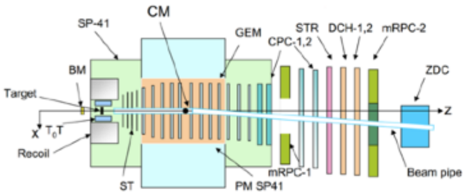


CBM– FAIR

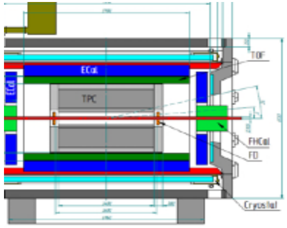


DHS – JPARC-HI



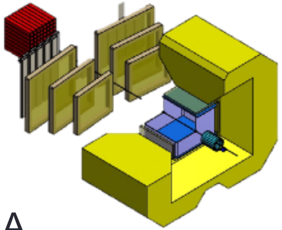


BM@N – NICA



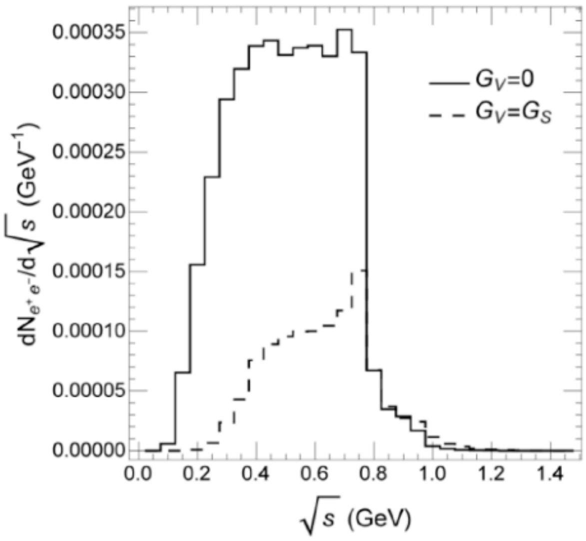
MPD – NICA

CEE– HIAF

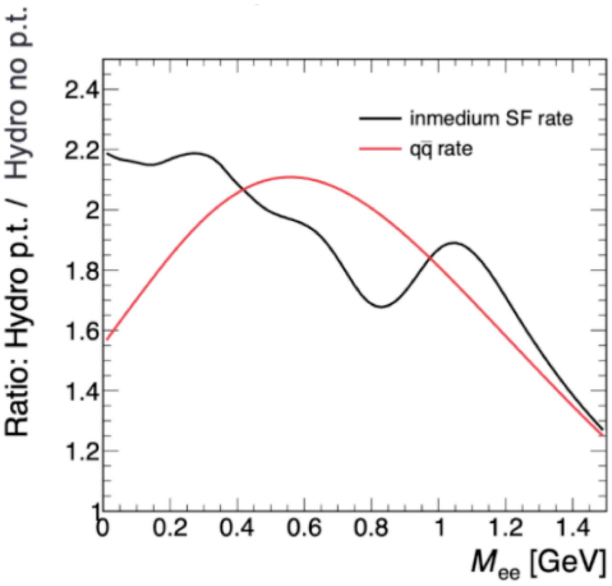


Possible dilepton signal of a first-order phase transition

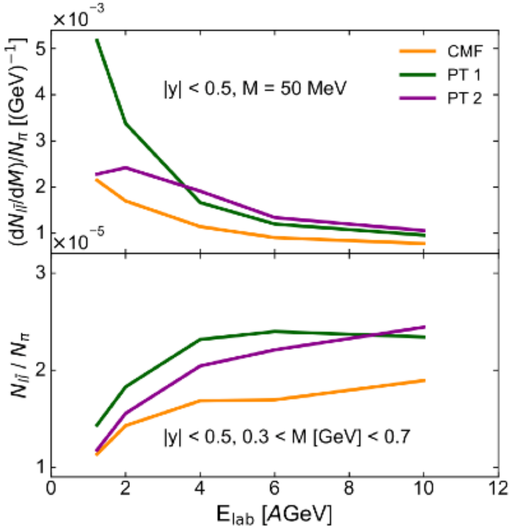
- Modification of the expansion trajectory in the phase diagram
- Changes of the in-medium photon propagator



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



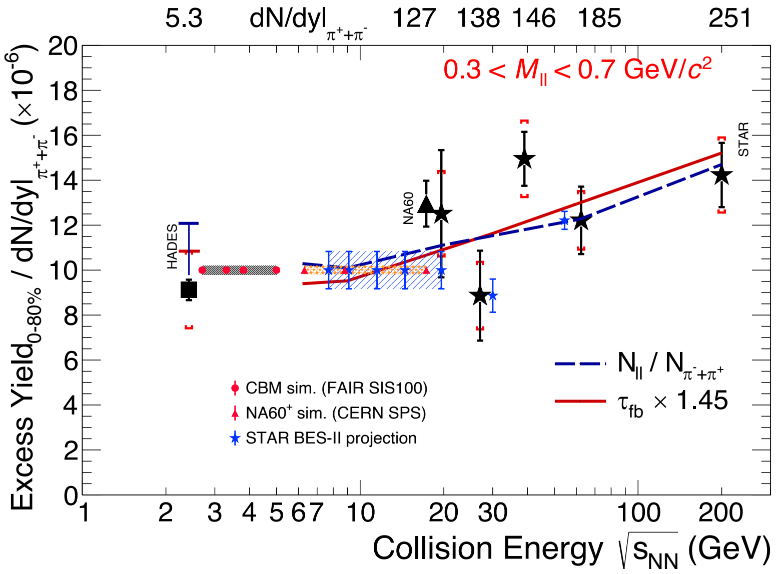
F. Seck et al., PRC 106, 014904 (2022)

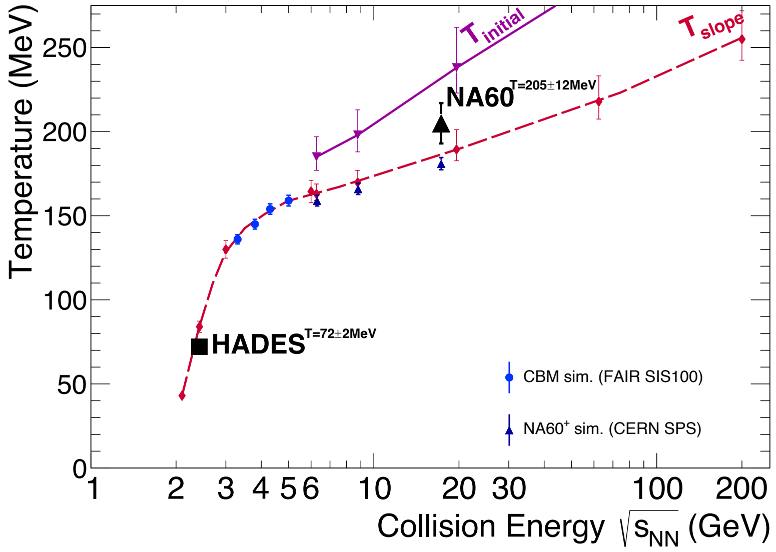


O. Savchuk et al. J.Phys.G 50 (2023) 12, 125104

The quest for the full excitation energy

- Discussed already is some detail on Monday

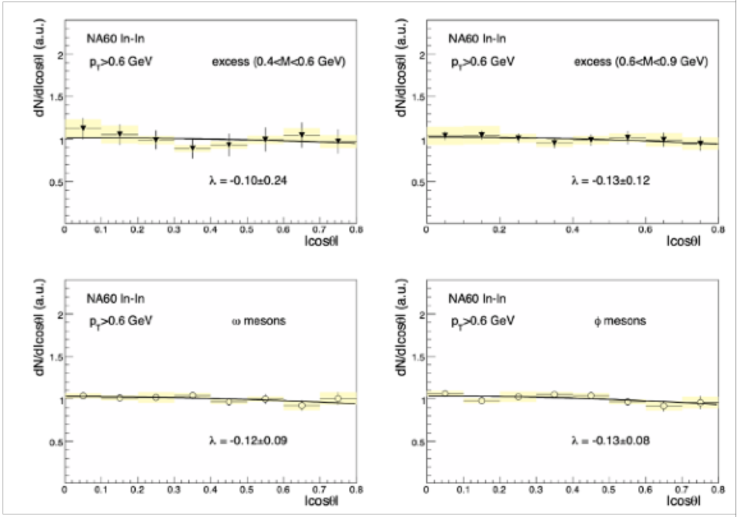




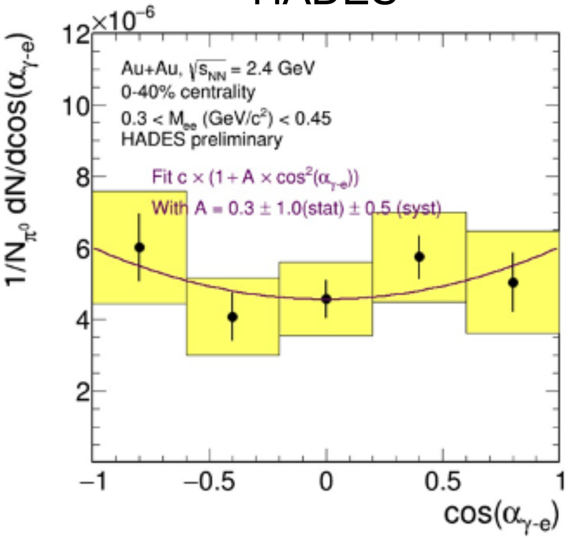
Polarisation & electrical conductivity

- Will be covered in Florian's talk
- 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

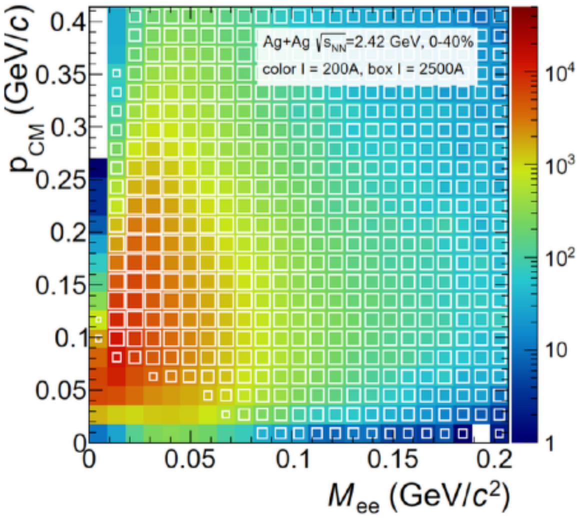
NA60



HADES



Low-field measurement by HADES to study sensitivity



Challenges for the interpretation of high-μ_B dilepton measurements

- Can we constrain the non-equilibrium radiation by reference measurements supported by model calculation sufficiently precise?
- Can SHM provide yields for cases, where neutral meson yields are not determined experimentally?
- What is the in-medium photon propagator in the presence of exotic phases?

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