EXPERIMENTAL OVERVIEW ON DILEPTONS

Joachim Stroth, Goethe University Frankfurt / GSI / HFHF

Penetrating Probes of Hot High-μ_B Matter: Theory meets Experiment

ECT*, Trento, Italy

July 21 – 25, 2025

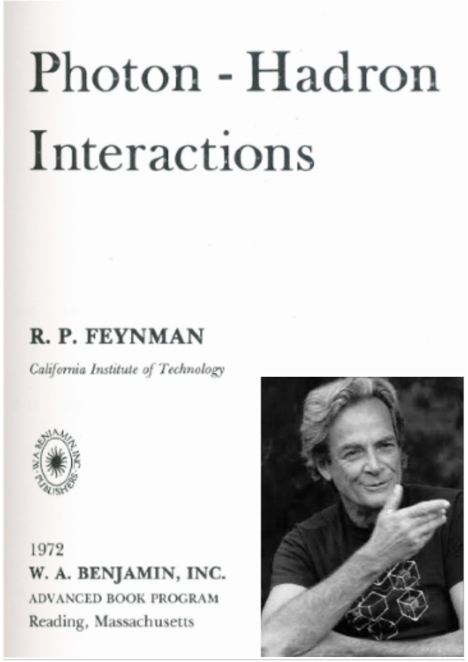
This presentation is dedicated to the late Hans Specht

For his contribution to the strength of our field in general, for his invaluable contribution to ECT*, and in particular for helping HADES and CBM collaborators to become passionate “Dileptoniker”

All the long way from contaminations in radiator gases to the role of ρ mesons in baryon the Dalitz decays!

General remarks
Phenomenology
Non-equilibrium radiation
Excess radiation
The future

Motivation - penetrating and “controlled” probe



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

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

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

From photons to virtual photons

Pro: 8 observables, 3 fixed from collinearity in the γ^* rest frame

Typically $M_{inv}, y, p_T, \phi, \alpha$

Contra: Another alpha and combinatorics

Detector: Low-mass tracking and excellent lepton PID (high purity)

Backg. sources:

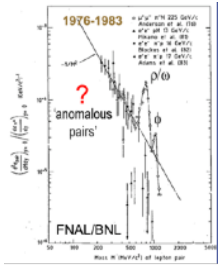
Muons: Weak decay muons from $\pi^{\pm}, K^{\pm}$

Electrons: External pair conversion, π-Dalitz

The historical view

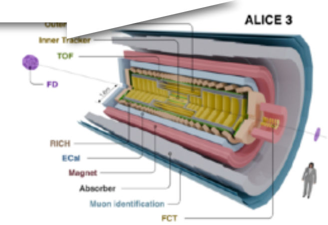
"**Drell-Yan root**" (CERN, FNAL/BNL) – Medium modified parton distribution functions and anomalous yield

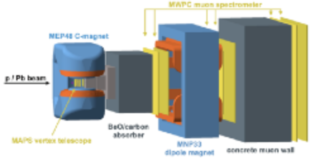
protons (1970) SPS S (1987) SPS Pb (1994) LHC Pb (2010) (2030) (2035)



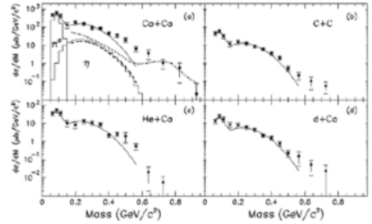
CERN: NA34, NA38 · NA45 (CERES), NA50 · NA60 · ALICE · LHCb · NA60+/DiCE · ALICE-3

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

Background rejection strategies

1 High purity (good efficiency)

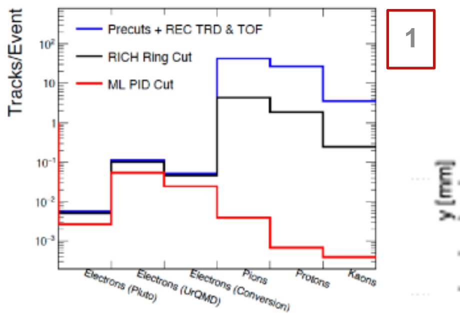
- fake (mis-identified) leptons add to the combinatorics
- can also be correlated (e.g. K^0 decay)

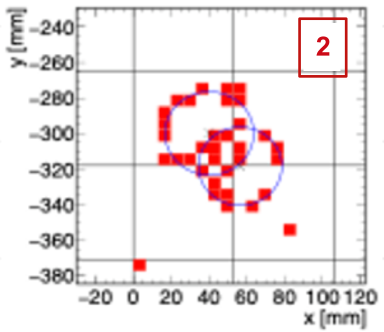
○ Di-electrons (close pair rejection)

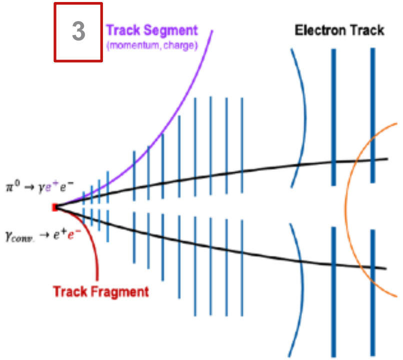
- RICH in field-free region
  - 2 Identify double rings with good significance
- Track topology
  - 3 Search for close-by track segments
- global p_T cuts

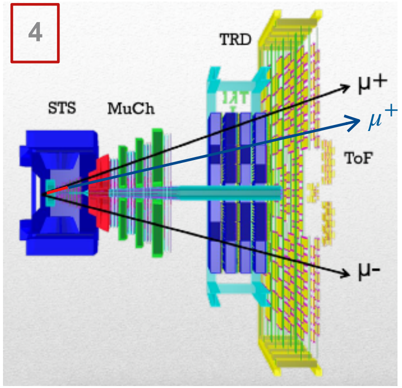
○ Dimuons (weak decay muon rejection)

4 Excellent tracking to identify kink





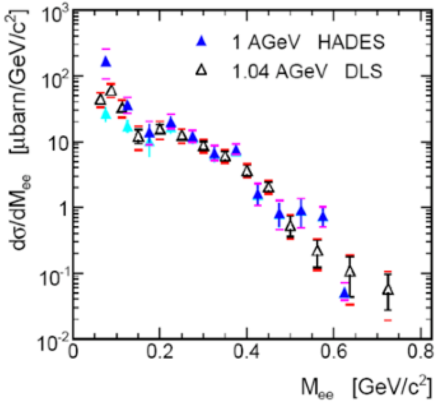




"Know your reference"

DLS puzzle

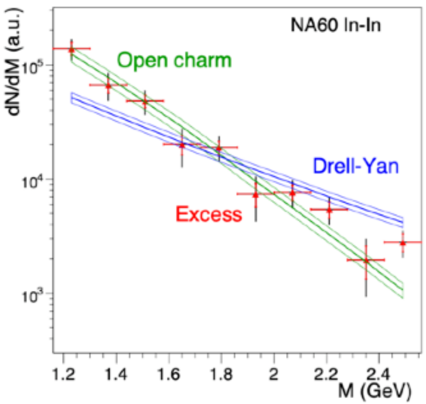
HADES confirmed measurement and demonstrated strong iso-spin dependence of bremsstrahlung



HADES PLB 690 (2010) 118

IMR temperature

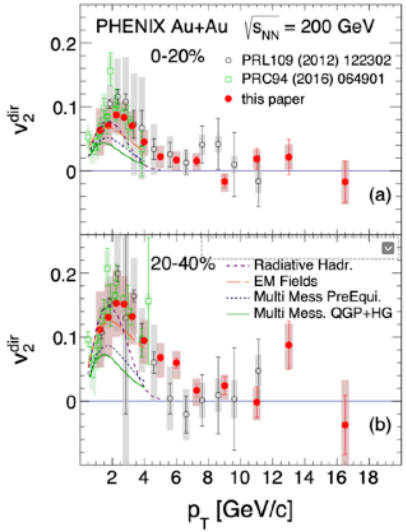
Precise determination of contributions from heavy-flavour correlated semi-leptonic decay



NA60 EPJ C61 2008

Direct photon puzzle

Unexplained v_2 signal and STAR/PHENIX discrepancy. Need for "new" sources"?

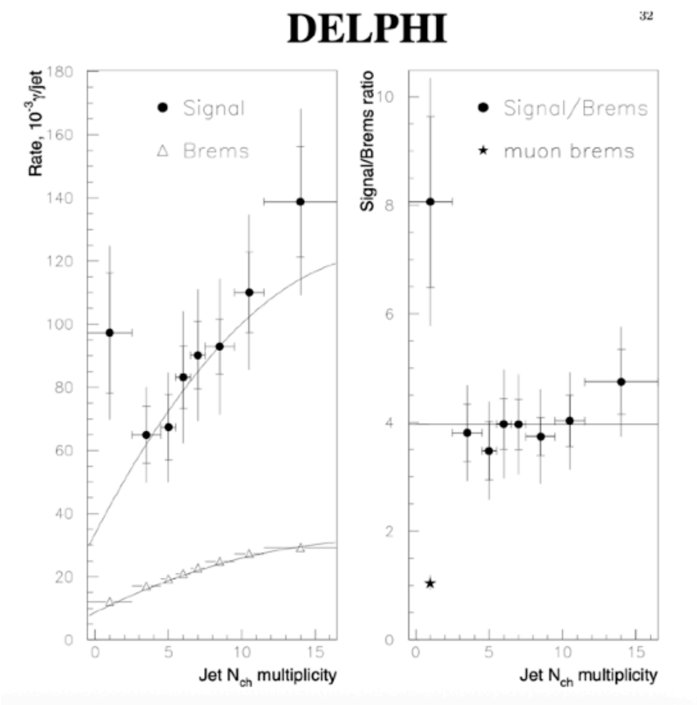


PHENIX arXiv:2504.02955

Soft photons and the Low Theorem

- EMMI RRTFs GSI-2022 and Heidelberg-2025

R.Bailhache Phys.Rep.1097 (2024) 1–40
G. Sterman et al. PRL 132.091902
Ma, Sherman, Venkata; arXiv:2311.06912v1



- Co-moving quarks can only be treated as charge-neutral (like in a neutron) if the photon fulfils the condition $\omega > 1/\tau_{\text{min}}$, where τ i the time scale the charges truly travel differently.
- From this it is clear that for true "soft photons" the condition $\omega < 1/\tau_{\text{min}}$ must be fulfilled.
- DELPHI tested Low using the channel $e^+e^- \to Z_0 \to \mu^+\mu^-\gamma$ and found perfect agreement
- Quarks: $m_{\text{u,d}} \ll k_T \ll m_\pi$ fermion loops vanish like $(k_T/m)^2$
- "For $k_T \gg m_{u,d}$ we do expect radiation from virtual quark loops"
-

General remarks

Phenomenology

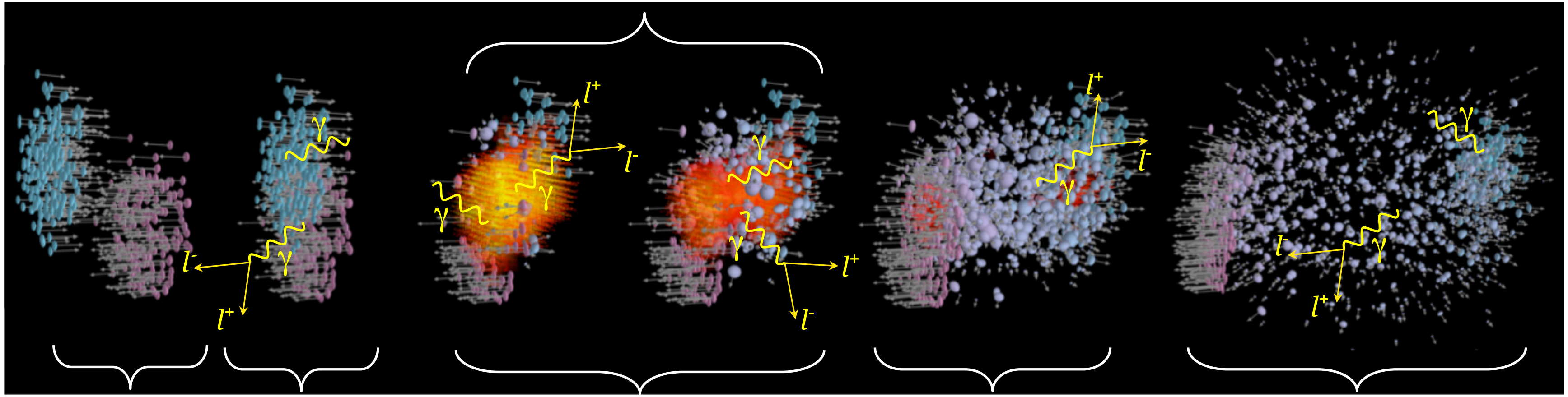
Non-equilibrium radiation

Excess radiation

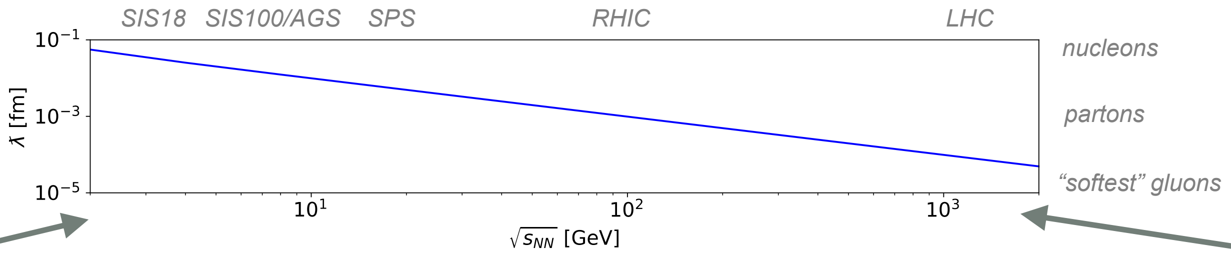
The future

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

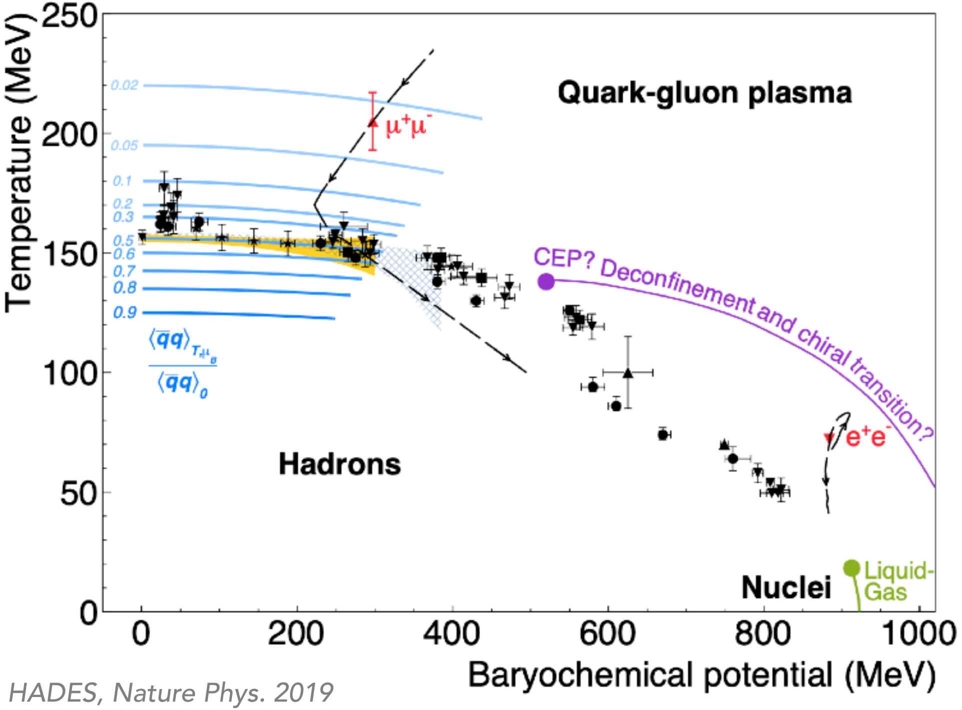


nearly complete baryon stopping
one-boson exchange

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

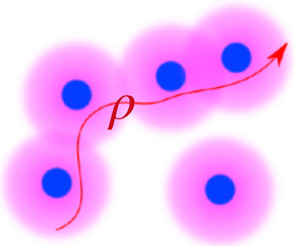


HADES, Nature Phys. 2019

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



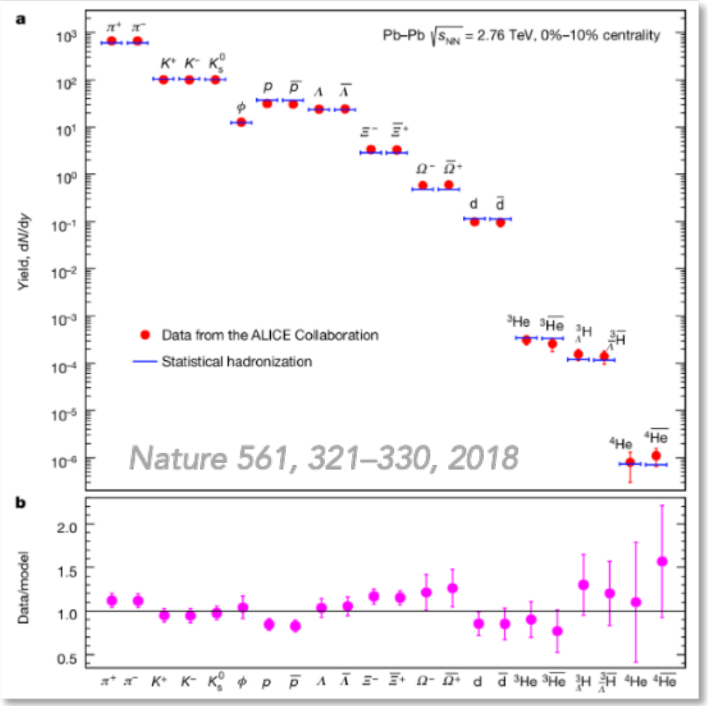
Particle Yields & Statistical Hadronization

ALICE ($\sqrt{s_{NN}} = 2.76$ TeV): $T_{ch} = 156.5\ (1.5); \mu_B = 0.7\ (3.6)$

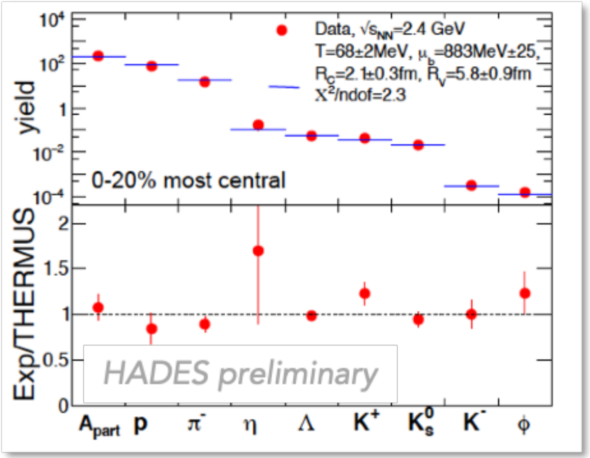
HADES ($\sqrt{s_{NN}} = 2.4$ GeV): $T_{ch} = 68.2\ (2.5); \mu_B = 883\ (25)$

➡ Factor 1000 in beam energy / factor ~2 in temperature

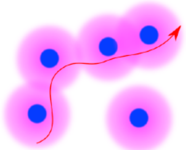
- Strangeness canonical treatment at low beam energies!
- Calculation carried out with vacuum masses!



1 ppm



1 ppm



Fast thermalization via entangled pion cloud?

General remarks

Phenomenology

Non-equilibrium radiation

Excess radiation

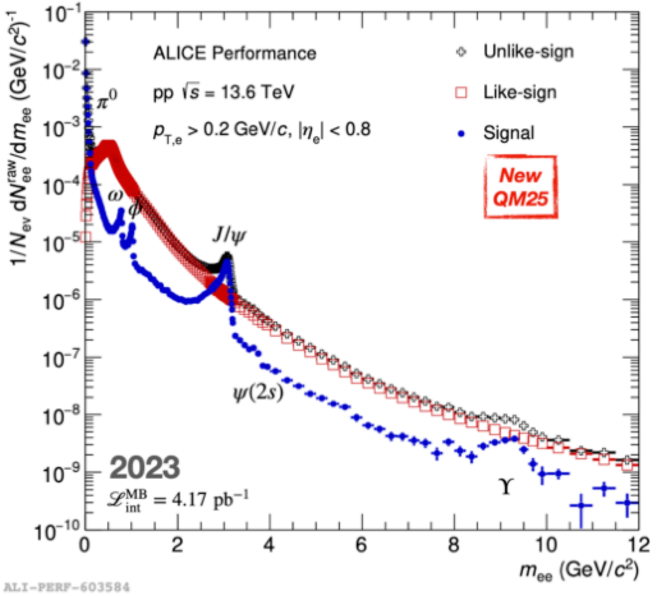
The future

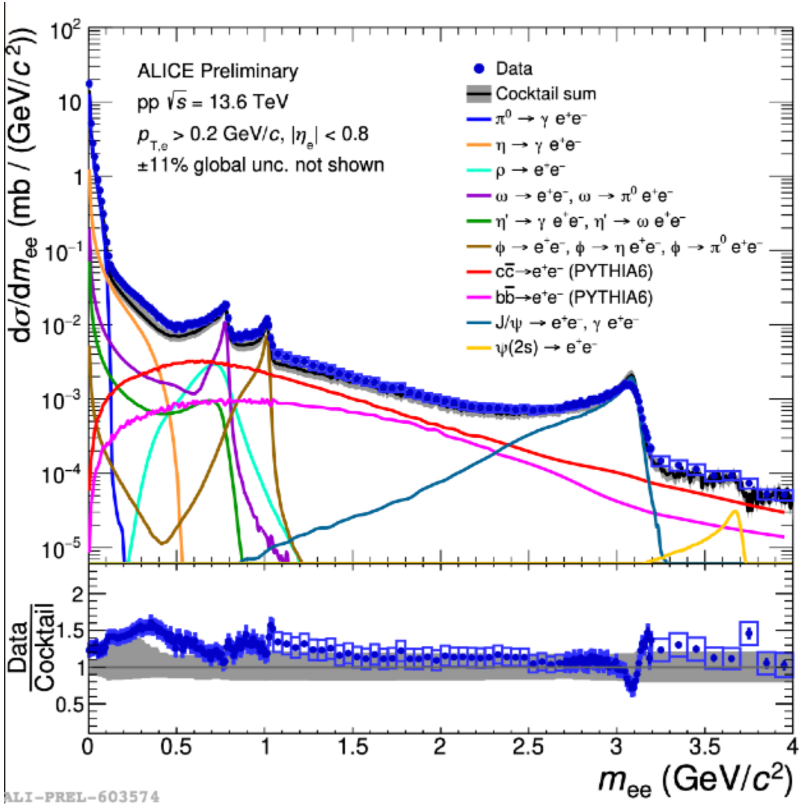
ALICE p+p $\sqrt{s_{NN}} = 13.6$ TeV (after RUN3 upgrade)

Reference for IMR open charm contribution

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

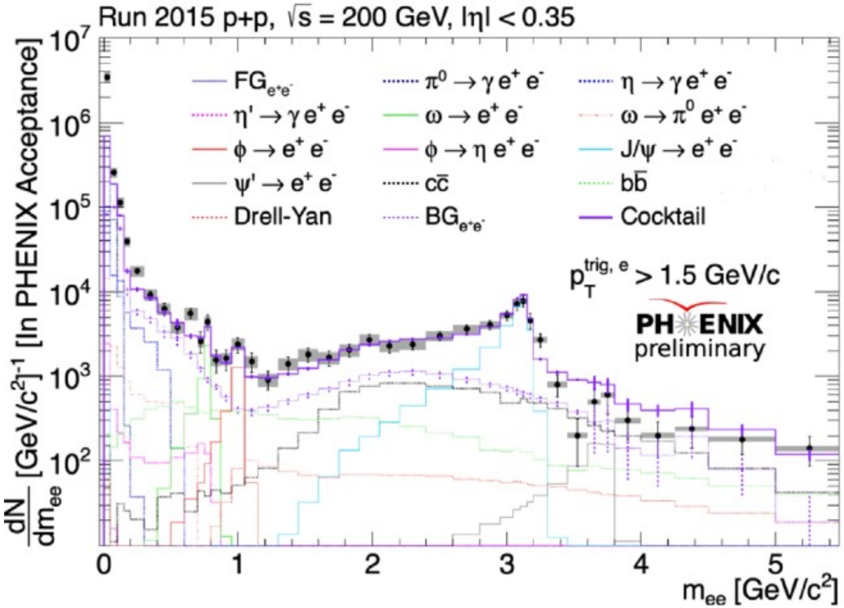
ALICE (F. Eisenhut): QM2025





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

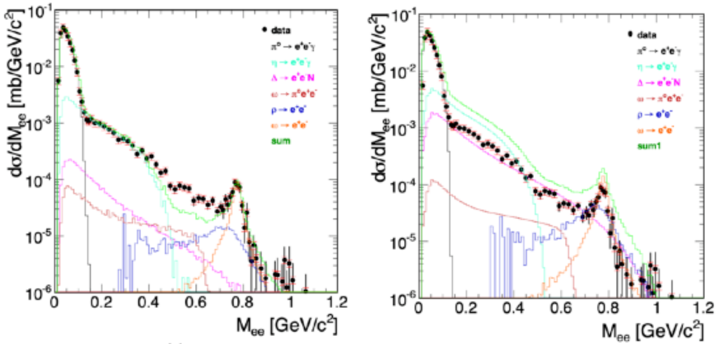


Gabor QM2025

HADES - SIS18 energies

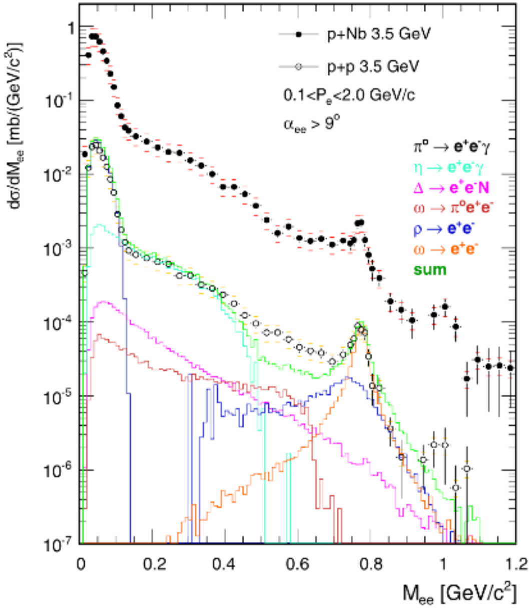
- Good description by models (PYTHIA, HSD, GiBUU, … after tuning
- HADES uses A_{part} scaled reference measurement
  $$(\, p + p; (p)n + p \,)$$
  as proxy of early stage radiation

p+p 3.5 GeV/c



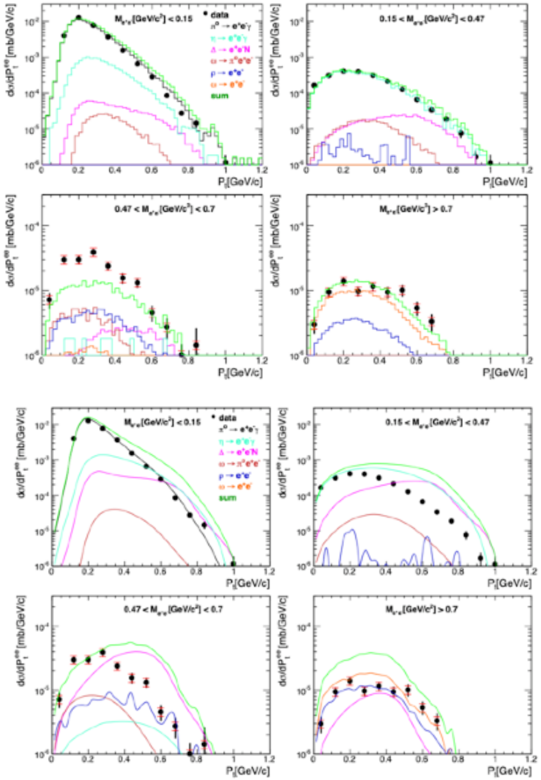
HADES: PLB 715 (2012) 304–309

p+Nb / Nb 3.5 GeV/c



HADES: PLB 715 (2012) 304–309

p+p 3.5 GeV/c



Direct photon puzzle

Refined analysis PHENIX (new data at high p_T)

- No centrality dependence of the effective temperatures → freeze-out temperature

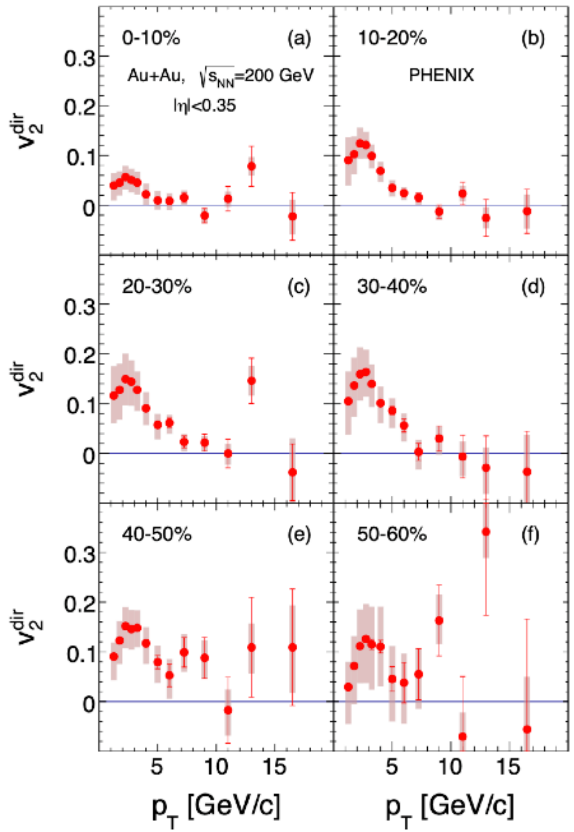
- Yield shows low-p_T enhancement above (most) theoretical descriptions and in contrast to STAR and ALICE
  (*cf. Charles' talk and arXiv:2502.13938*)

- Flow signal below $p_T \lesssim 5\ \mathrm{GeV}/c$
  - Is there evidence for "extra" radiation due to hadronization?
  - Fair agreement with data after upscaling emission around the transition region (*R. Rapp, H. v. Hees; Nucl. Phys. A 931 (2014) 696-700*)
  - Makes up for v_2, but with enhanced emissivity far from being explained based on diagrammatic approaches

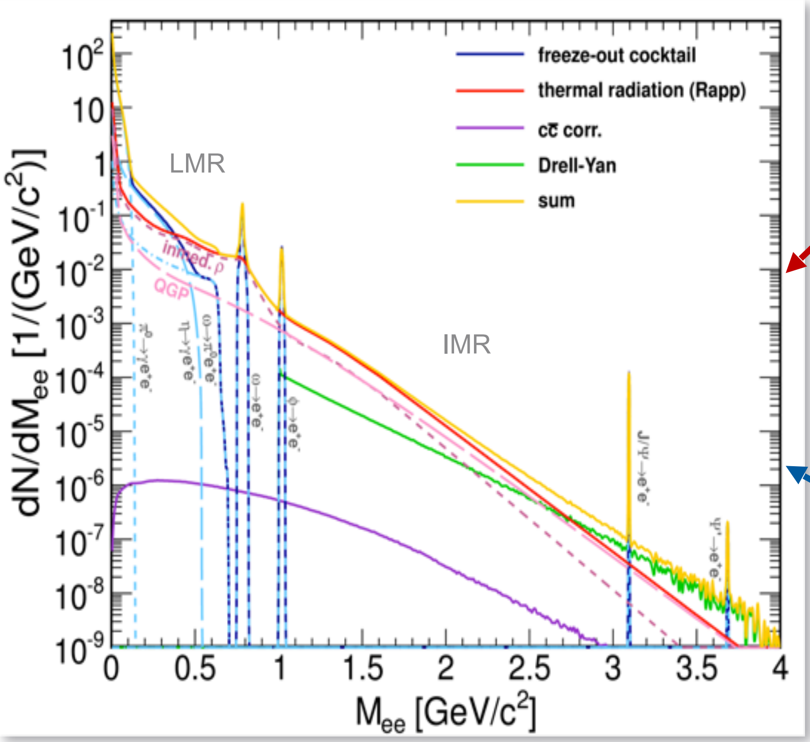
- PHENIX vs. STAR
  - dN_{ch}/dy scaling
  - Yield

Wait for Axel's talk

PHENIX ,arXiv:2504.02955



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

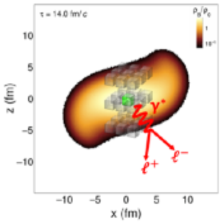


Medium radiation from *Thermal Emission Rates* (ϵ):

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

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

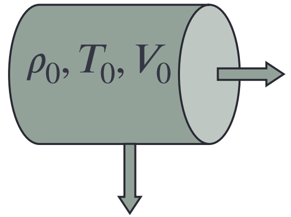
shining

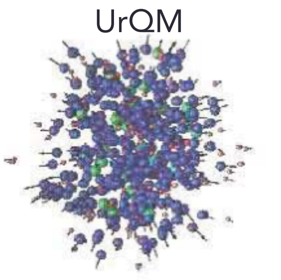


coarse graining

or

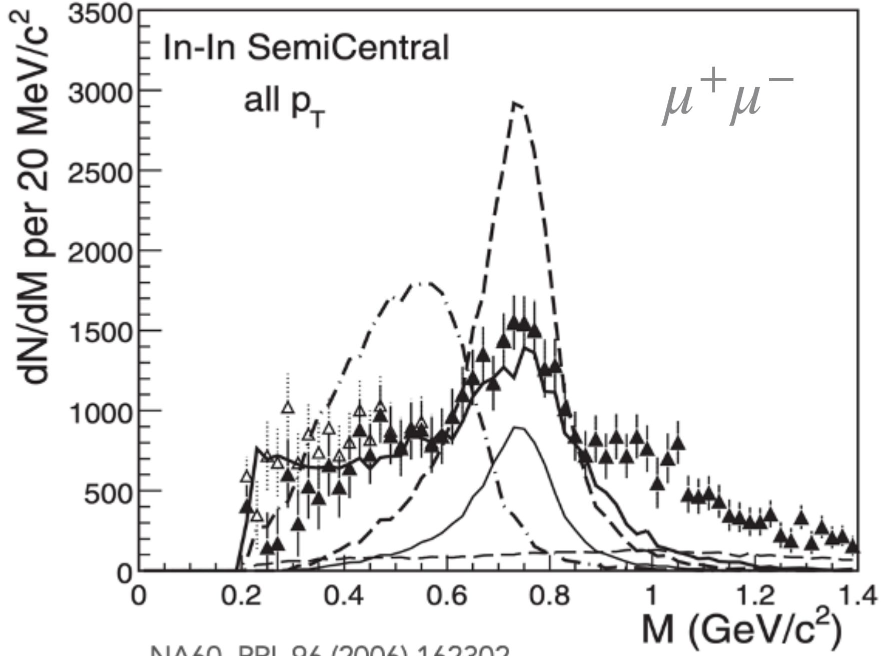
isentropic expansion



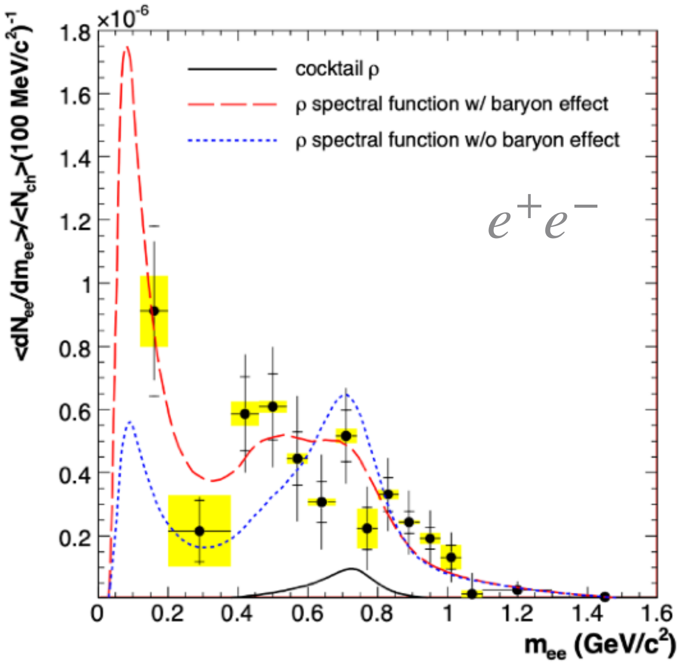


Dilepton emission from *Microscopic Transport.*

Baryon driven ρ meting observed at SPS



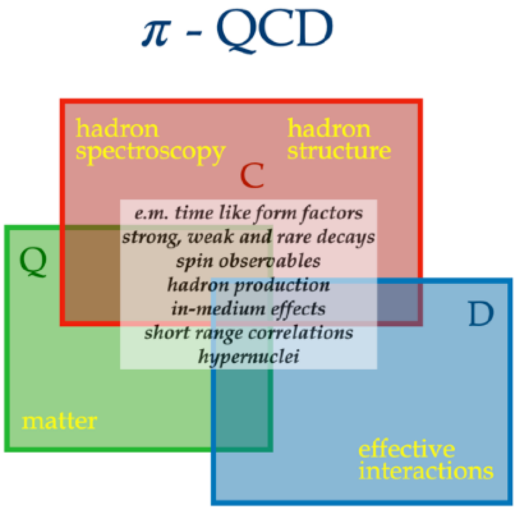
NA60, PRL 96 (2006) 162302

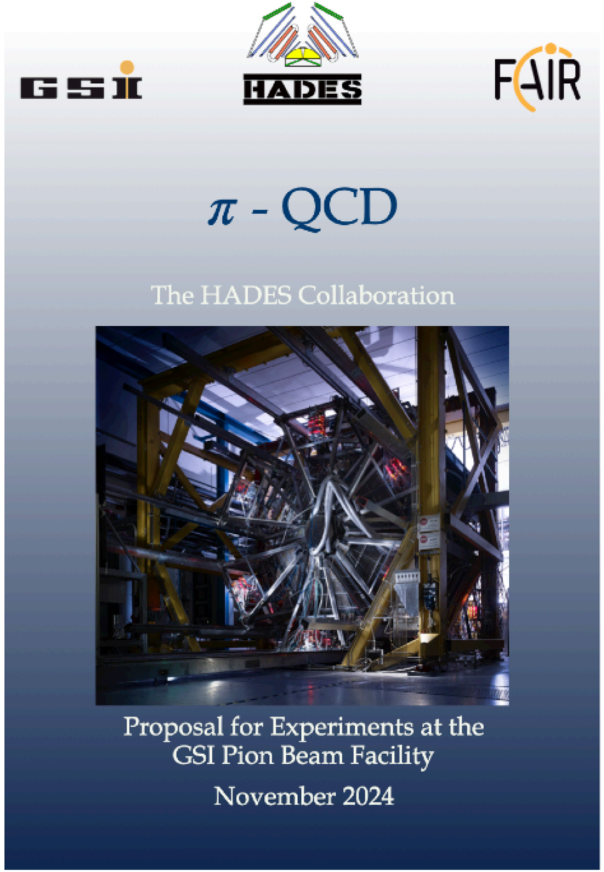


CERES, PLB 666 (2008) 425-429

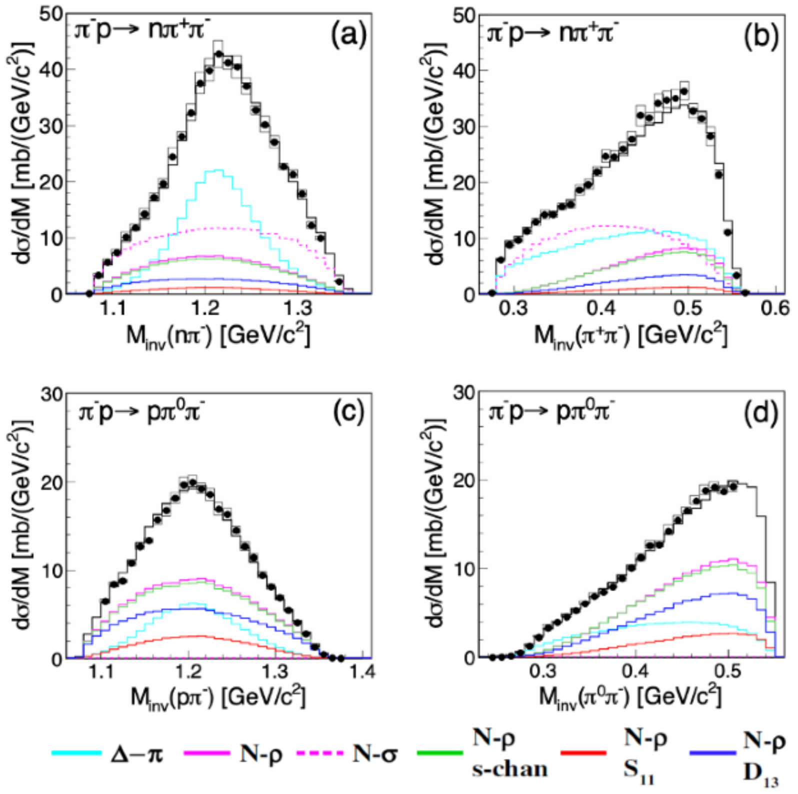
The HADES Proposal for 2026 — 2028

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





Extraction of partial waves from two-pion channel

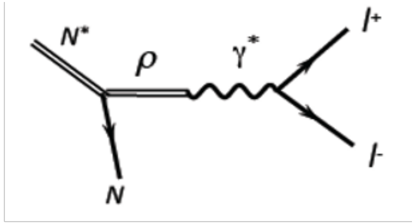


- $p_\pi = [0.66, 0.69, 0.75, 0.8]$ GeV
- $\pi^- + p \rightarrow \pi^- + \pi^+ + n$
  - Hadronic final states used in PWA (Bonn/ Gatchina code)
  - Use invariant masses, and angular distribution (not shown here)
- $\pi^- + p \rightarrow e^- + e^+ + n$
  - Prediction for dilepton invariant mass assuming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

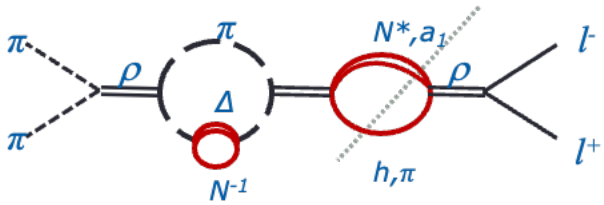
HADES arXiv:2309.13357; arXiv:2205.15914; Phys. Rev. C 102 (2020) 2, 024001

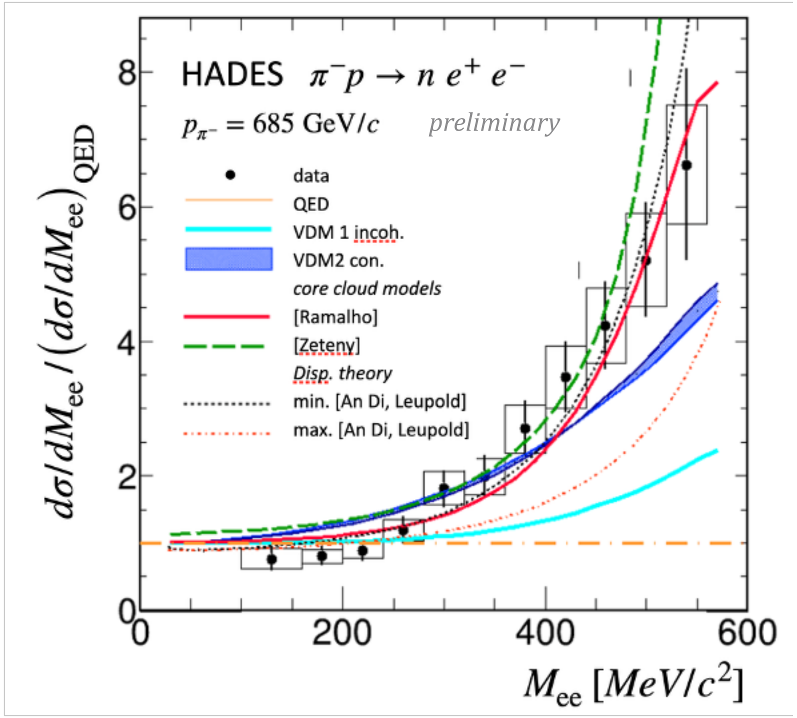
$\pi^- + p \rightarrow e^- + e^+ + n$

Resonance-Dalitz decay (a la VMD) …



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



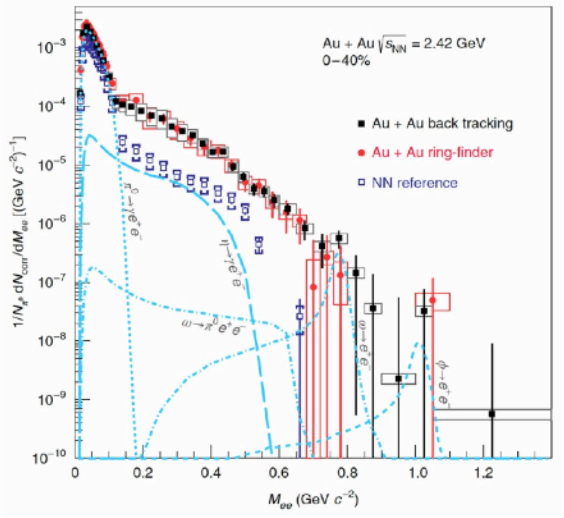


Transition form factor (time-like) extracted by subtracting QED expectation from exclusive invariant mass distribution.

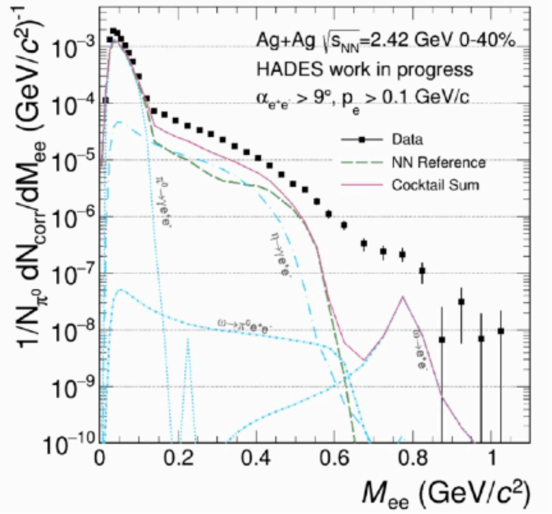
Dilepton spectra measured by HADES

- **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

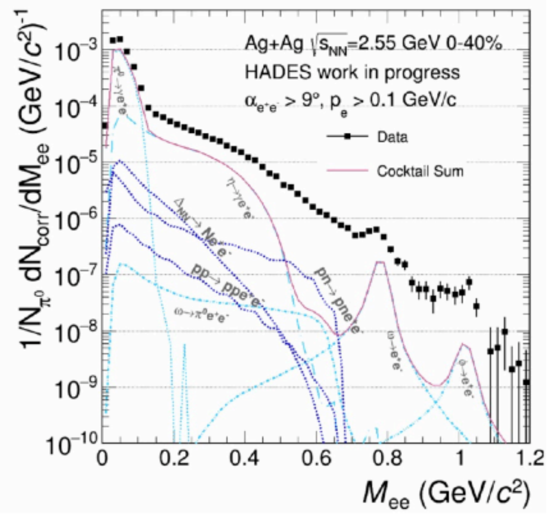
Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



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



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

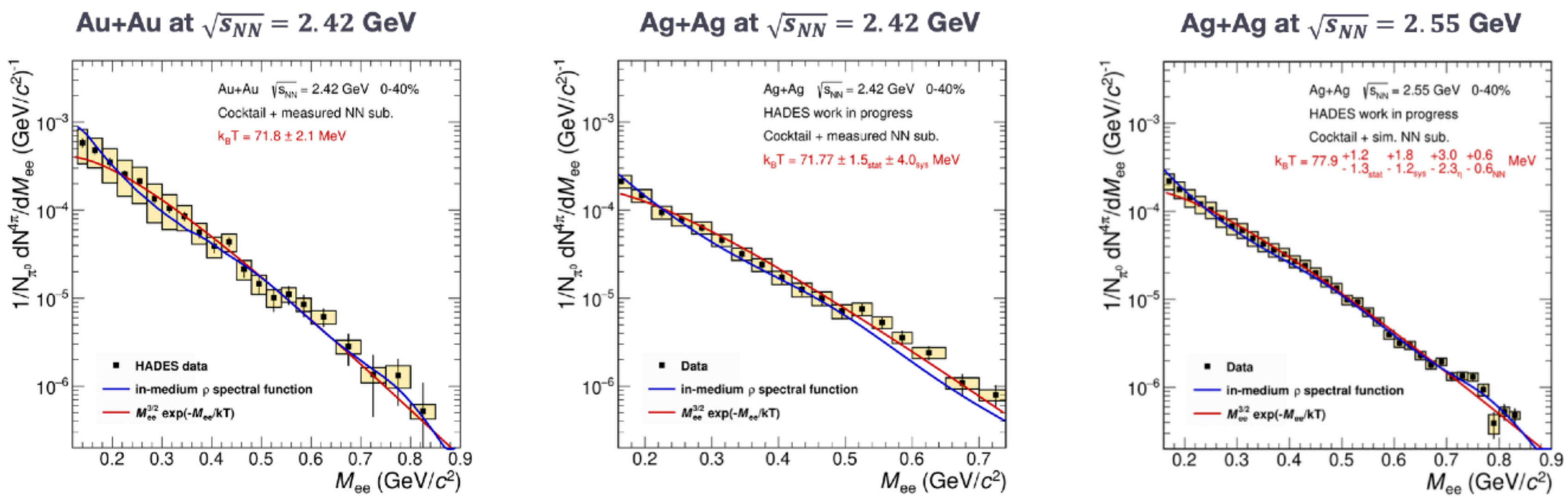


HADES, Nature Phys. 2019

Excess radiation measured by HADES

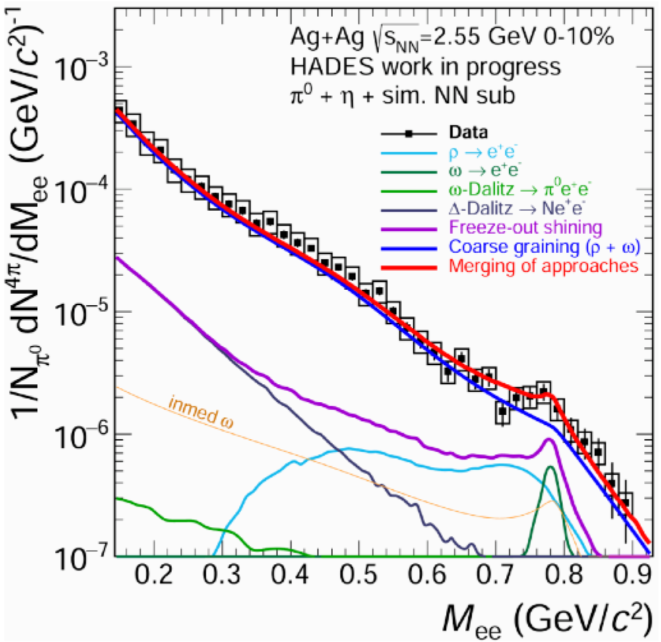
- Spectral distribution reproduced by a fit assuming thermal radiation
- Significantly higher temperature at higher collision energy
- No indication of a ρ bump at the lower beam energy energy → strong melting
-

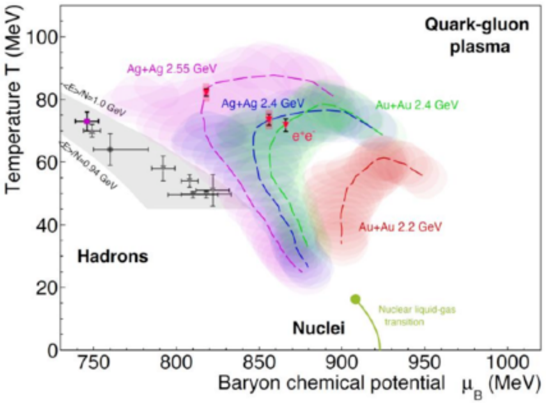
N. Holt, R. Rapp: Eur. Phys. J. A 56 (2020) 11, 292
P.Hohler, R. Rapp: Phys.Lett.B 731 (2014) 103-109

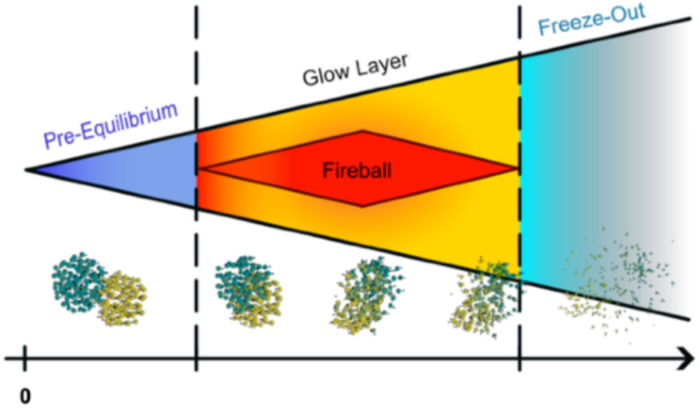


Refined coarse-graining for low energies

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



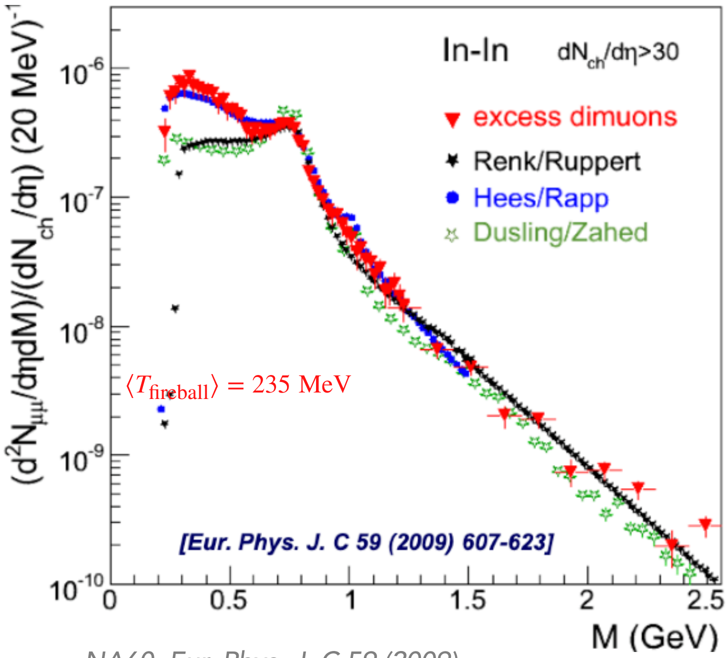




pictures from Jessica Vogel and Florian Seck (HADES)

Excess radiation in the IMR at SPS and SIS100

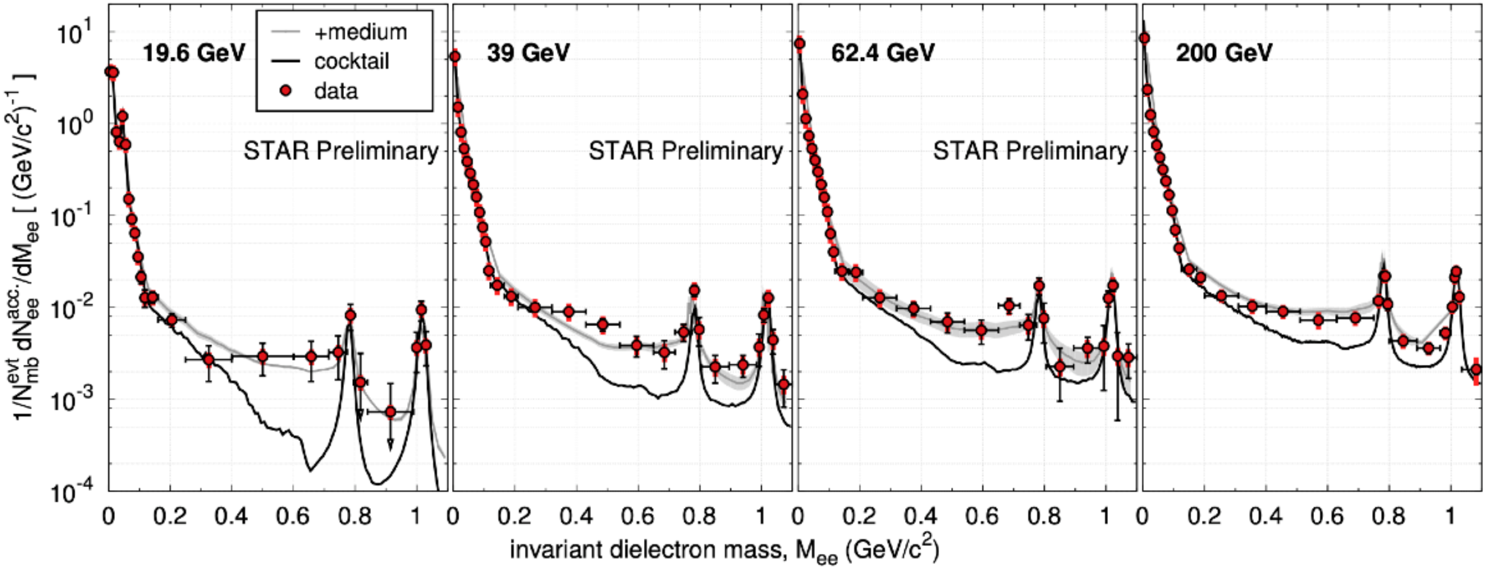
- Model independent extraction of temperature if $\frac{1}{M^2}\mathrm{Im}\Pi_{\mathrm{em}}\left(M,\vec{q},T,\mu_i\right) \simeq \mathrm{const}\,.$
- At SPS precise knowledge of open charm contributions needed
- Role of Drell-Yan like contributions at SIS100 energies?
  - EU project PRODY



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

STAR BES-1: LMR di-electrons

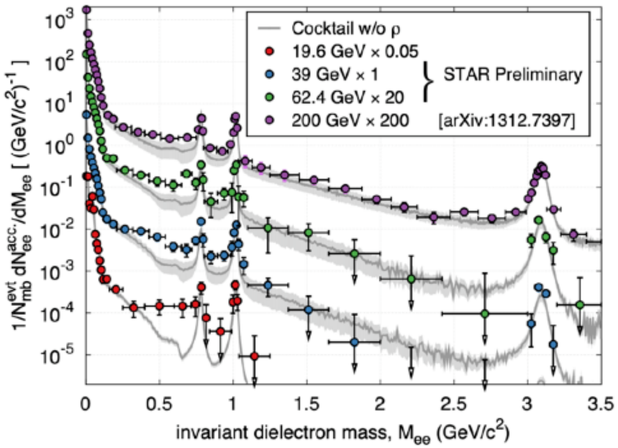
- No significant deviation from the "standard model"of dilepton production



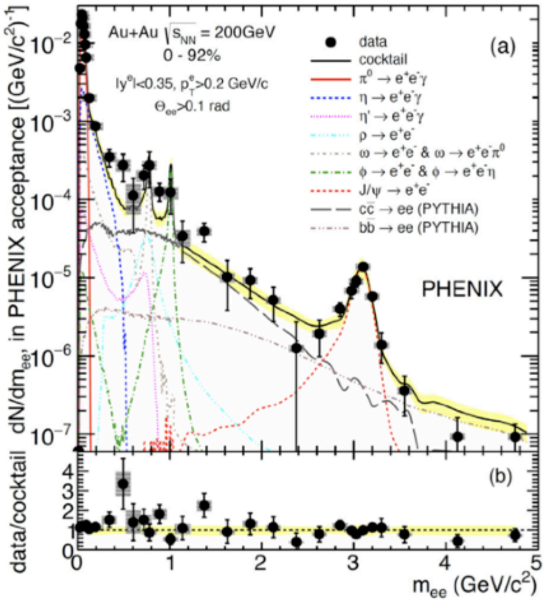
STAR: Phys. Lett. B 2015, 750, 64–71, arXiv:nucl-ex/1810.10159 unp.; X. Dong et al.: *Symmetry* 15 (2023) 2, 392

STAR and PHENIX: IMR di-electrons

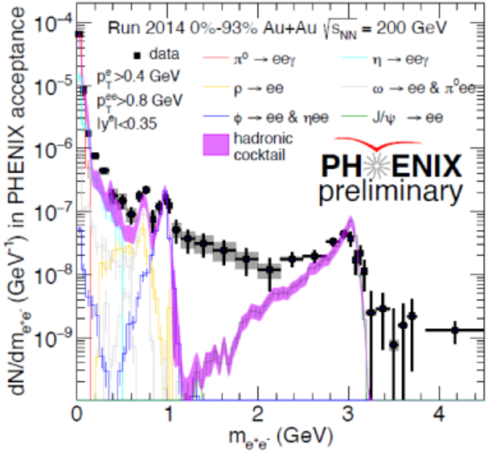
- Uncertainties from semi-leptonic open charm decays (no STAR di-electrons from run with HFT)
- Extraction of temperature in the IMR not possible



STAR, White Paper June 2014



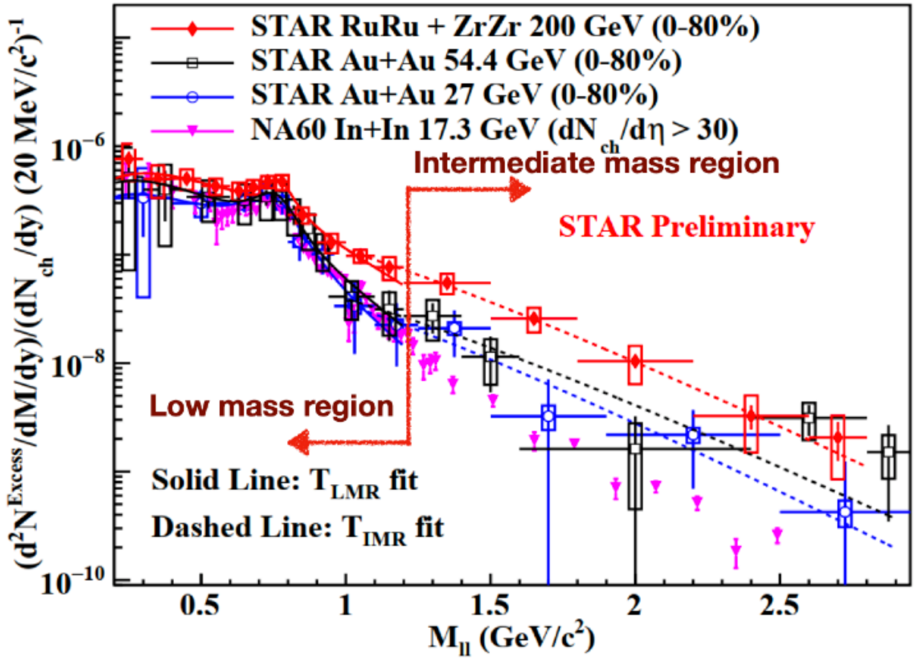
PHENIX, Phys.Rev. C93 (1) (2016) 014904



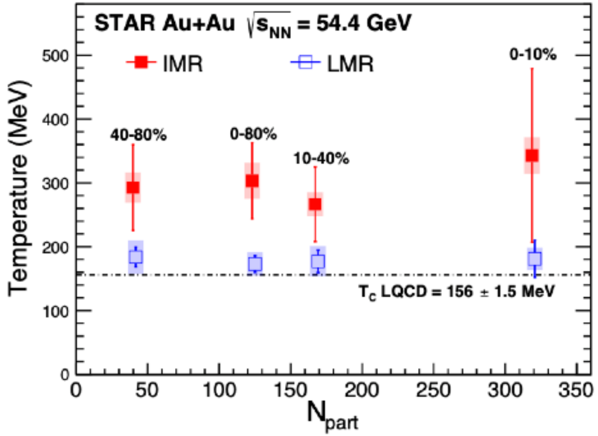
PHENIX (D. Gabor), QM2025

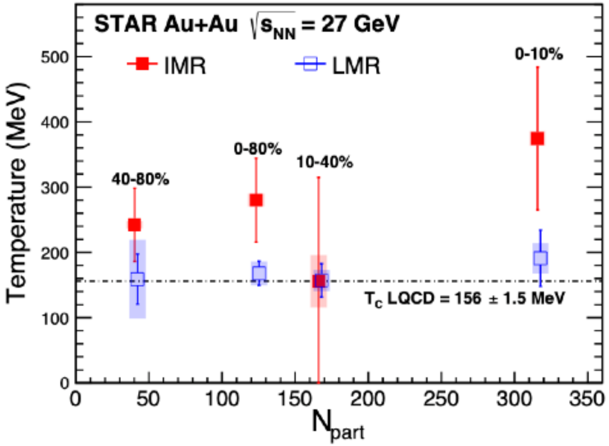
STAR new data/analysis

- Attempt to extract temperature from LMR and IMR



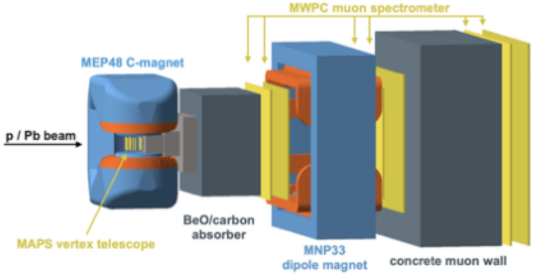
STAR: arXiv: 2402.01998, unp.

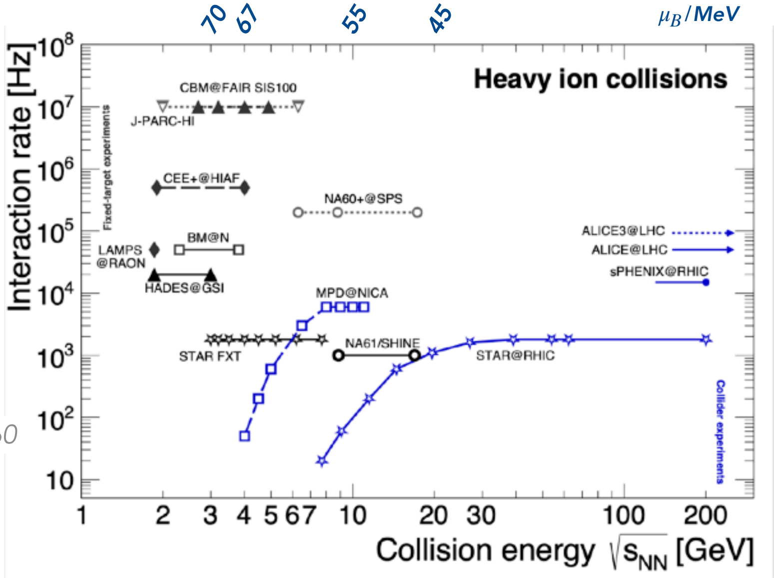




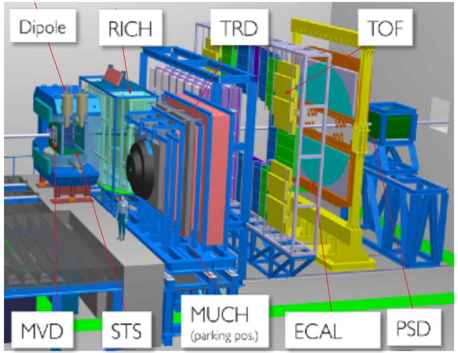
The future

Future facilities for high μ_B physics



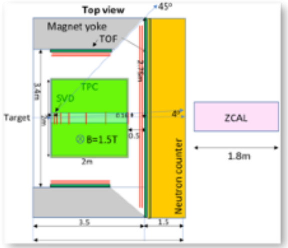


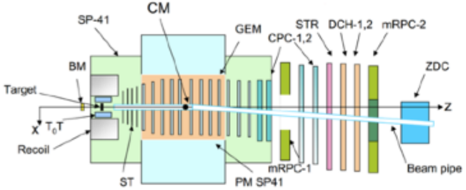
CBM– FAIR



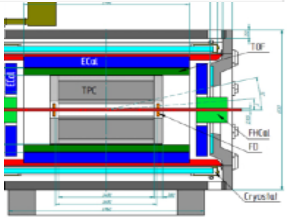
T. Galatyuk, Nucl. Phys. A982 (2019), update 2021 and CBM, EPJA 53 3 (2017) 60

DHS – JPARC-HI



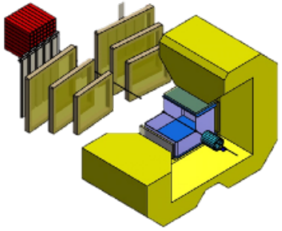


BM@N – NICA



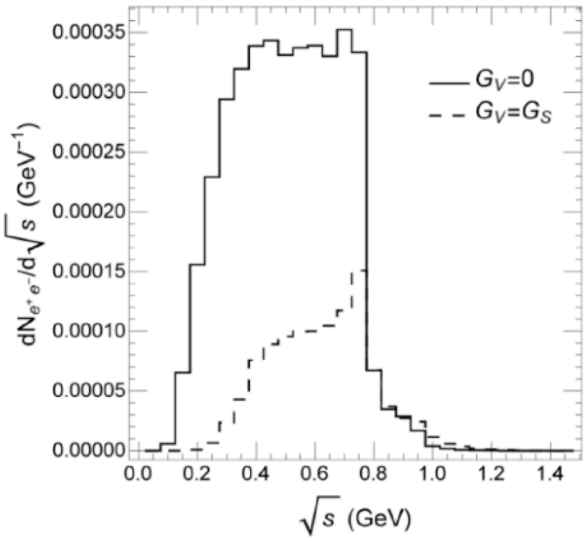
MPD – NICA

CEE– HIAF

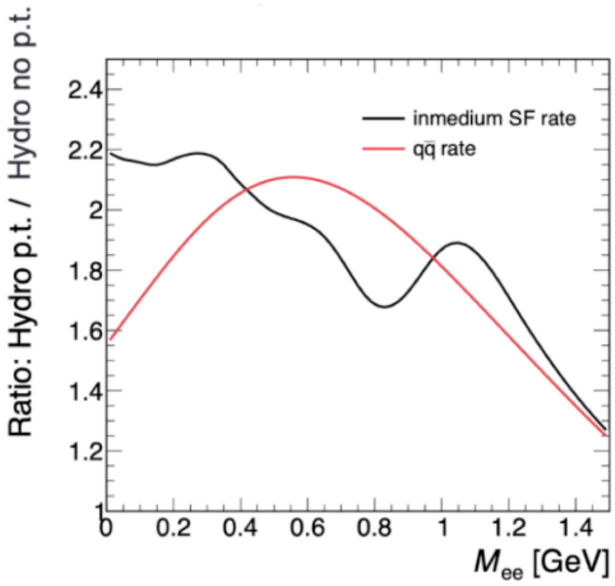


Possible dilepton signal of a first-order phase transition

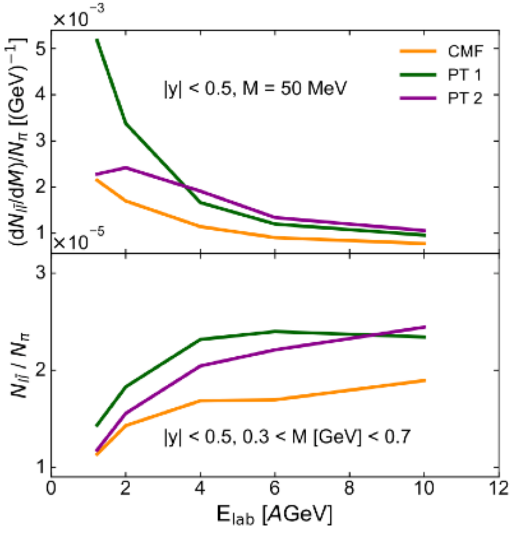
- Modification of the expansion trajectory in the phase diagram
- Changes of the in-medium photon propagator



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



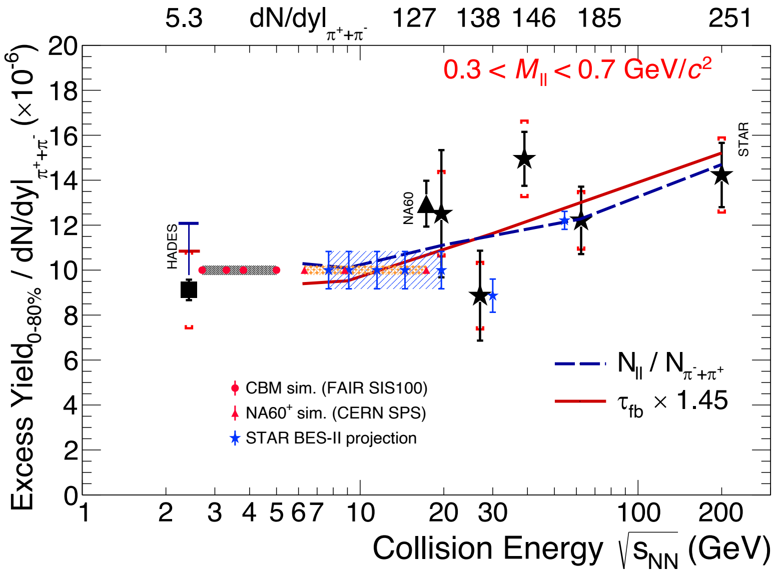
F. Seck et al., PRC 106, 014904 (2022)

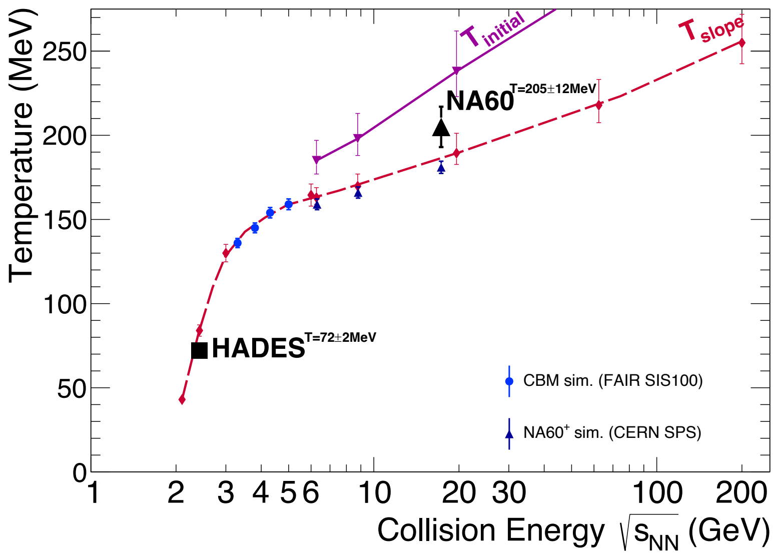


O. Savchuk et al. J.Phys.G 50 (2023) 12, 125104

The quest for the full excitation energy

- Discussed already is some detail on Monday

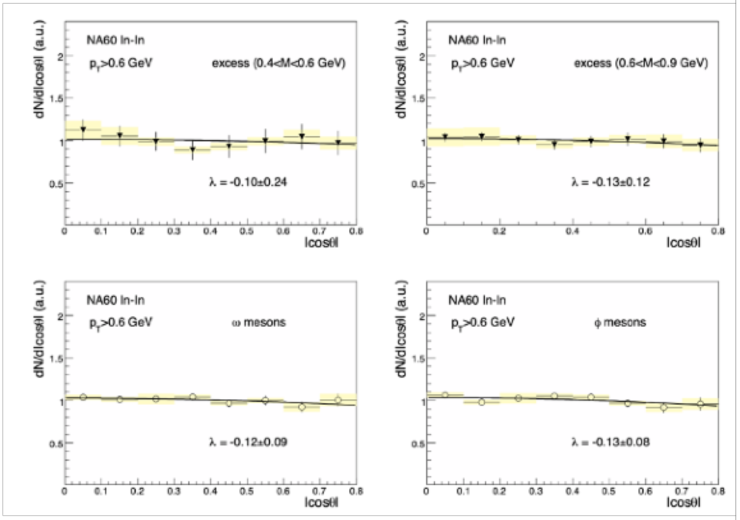




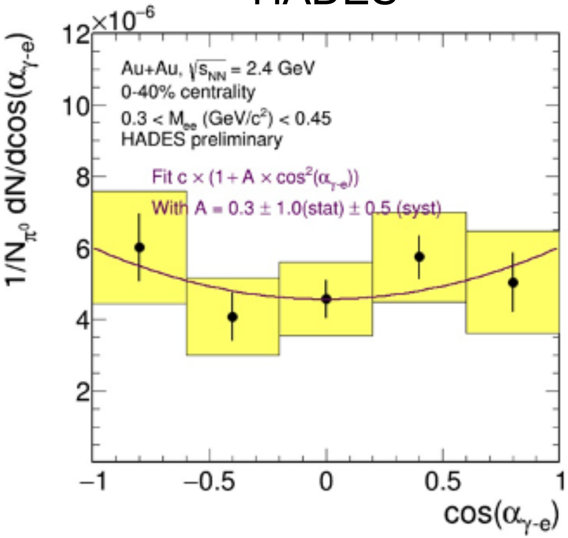
Polarisation & electrical conductivity

- 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

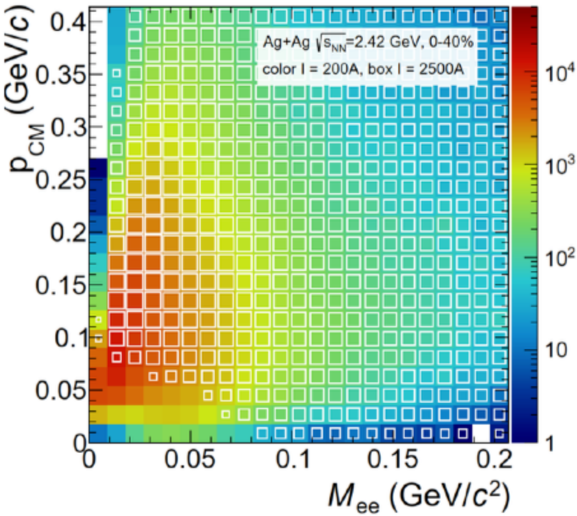
NA60



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

Conference Chairs for ECT's Dilepton Workshop 2005*

Dinner photo during ECT's Dilepton Workshop 2005*

Thank you for your attention