Dileptons at NICA: challenges and opportunities

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מכון ויצמן למדע

Outline

- Introduction – Motivation
- What did we learn from SPS and RHIC dilepton measurements
- Prospects and challenges at NICA
- Summary

Introduction

Motivation

- Dileptons (e^+e^-, $\mu^+\mu^-$) are sensitive probes of the two fundamental properties of the QGP:
  - *Deconfinement*
  - *Chiral Symmetry Restoration*

- *Thermal radiation* emitted in the form of real photons or virtual photons (dileptons) provides a direct fingerprint of the matter formed (QGP and HG) and a measurement of its temperature.

$$\text{QGP:} \quad q\bar{q} \longrightarrow \gamma^* \longrightarrow l^+l^-$$

$$\text{HG:} \quad \pi^+\pi^- \longrightarrow \rho \longrightarrow \gamma^* \longrightarrow l^+l^-$$

- Dileptons are unique probes of CSR

QCD and explicit chiral symmetry breaking

- QCD encoded in a one line Lagrangian:

$$\mathcal{L} = -\frac{1}{4}F^{\alpha}_{\mu\nu}F^{\mu\nu}_{\alpha} - \sum_n \bar{\psi}_n \gamma^{\mu}[\partial_{\mu} - igA^{\alpha}_{\mu}t_{\alpha}]\psi_n - \sum_n m_n \bar{\psi}_n \psi_n$$

Free gluon field

q interaction with gluon field

Free quarks of mass m_n at rest

- The mass term $m_n \psi_n \psi_n$ ***explicitly*** breaks the chiral symmetry of the QCD Lagrangian

Spontaneous Chiral Symmetry Breaking

- Chiral limit: $m_u = m_d = m_s = 0$
  In this idealized world, the interactions quark-gluon conserve the quark chirality.

In the chiral limit:
all states have a chiral partner with opposite parity and equal mass

m_u and m_d are so small ($m_u \approx 4$ MeV $m_d \approx 7$ MeV) that our world should be very close to the chiral limit

- In reality:
- ρ ($J^P = 1^-$) m=770 MeV chiral partner a_1 ($J^P = 1^+$) m=1250 MeV → $\Delta \approx 500$ MeV
- For the nucleons the splitting is even larger:
  N ($1/2^+$) m=940 MeV chiral partner N^* ($1/2^-$) m=1535 MeV → $\Delta \approx 600$ MeV
- The differences are too large to be explained by the small current quark masses

Chiral symmetry is spontaneously (≡ dynamically) broken in nature
Quarks have large "effective" mass $m_u \approx m_d \approx 1/3 m_N \approx 300$ MeV/c^2
Constituent quark masses

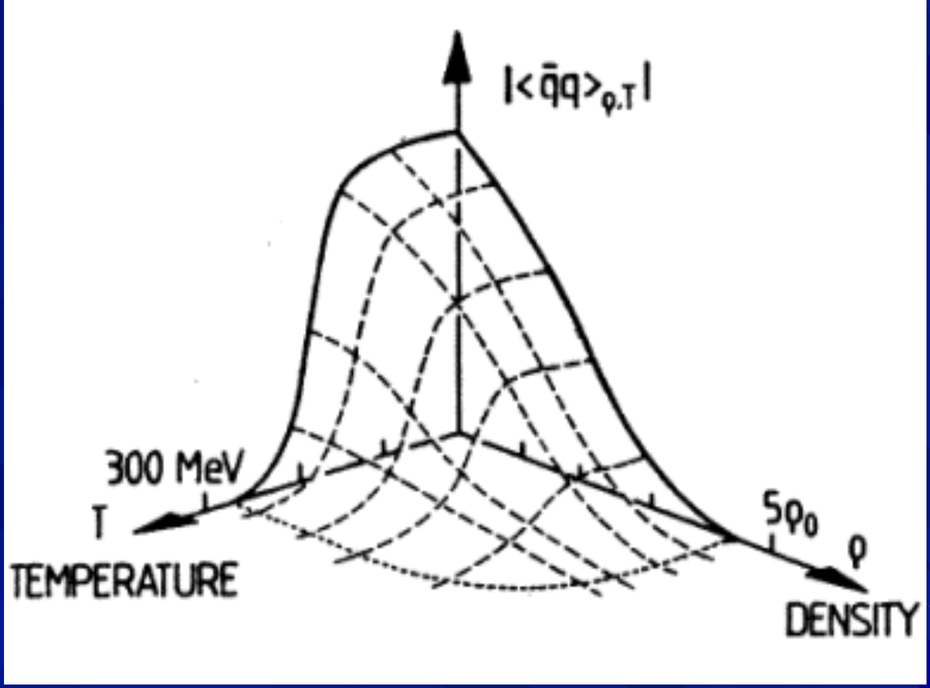
Chiral Symmetry Restoration

- The spontaneous breaking is marked by a non-zero value of an order parameter, the quark condensate:

$$<\bar{q}q> \approx 250 MeV^3$$

- Numerical calculations of QCD on the lattice show that at high T ($T>T_C$) or high baryon densities ($\rho>\rho_C$), the quark condensate vanishes:

$$\langle \bar{q}q \rangle \rightarrow 0$$



constituent mass → current mass
chiral symmetry (approximately) restored
Chiral partners (e.g. ρ and a_1) become degenerate

- How is the quark condensate linked to the hadron properties (mass and width)? How is the degeneracy of the chiral partners achieved?

$\rho - a_1$

If CS is restored the masses of the a_1 and ρ mesons should become equal.

Problem: very hard to measure the a_1 meson

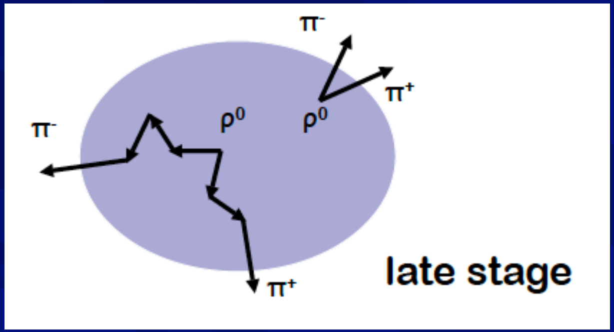
a_1(1260) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+\pi^-\pi^0$	
Γ_2	$\pi^0\pi^0\pi^0$	
Γ_3	$(\rho\pi)_{S-\text{wave}}$	seen
Γ_4	$(\rho\pi)_{D-\text{wave}}$	seen
Γ_5	$(\rho(1450)\pi)_{S-\text{wave}}$	seen
Γ_6	$(\rho(1450)\pi)_{D-\text{wave}}$	seen
Γ_7	$\sigma\pi$	seen
Γ_8	$f_0(980)\pi$	not seen
Γ_9	$f_0(1370)\pi$	seen
Γ_{10}	$f_2(1270)\pi$	seen
Γ_{11}	$K\overline{K}^*(892)+$ c.c.	seen
Γ_{12}	$\pi\gamma$	seen

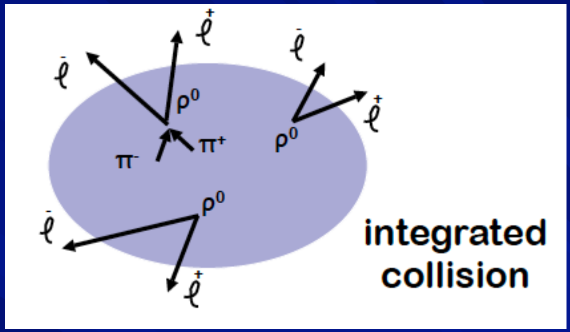
Experimental efforts focused on the ρ meson

$\rho \rightarrow e^+e^-$ decay and CSR

- $\rho \rightarrow \pi^+\pi^-$ BR ~100%



$\rho \rightarrow e^+e^-$ BR = 4.7 10^{-5}



- Low-mass dileptons are the best probes to look for CSR effects:

  * **Large mfp:** → no final state interaction

  carry information from place of creation to detectors.

	m [MeV]	Γ_{tot} *[MeV]*	τ *[fm/c]*
ρ	*770*	*150*	*1.3*
ω	*782*	*8.6*	*23*
ϕ	*1020*	*4.4*	*44*

❖ **Best candidate: the ρ-meson**

short lifetime compared to the medium lifetime ($\tau \approx 10$ fm/c)

can decay and be regenerated in the medium

Advantages and Chellenges

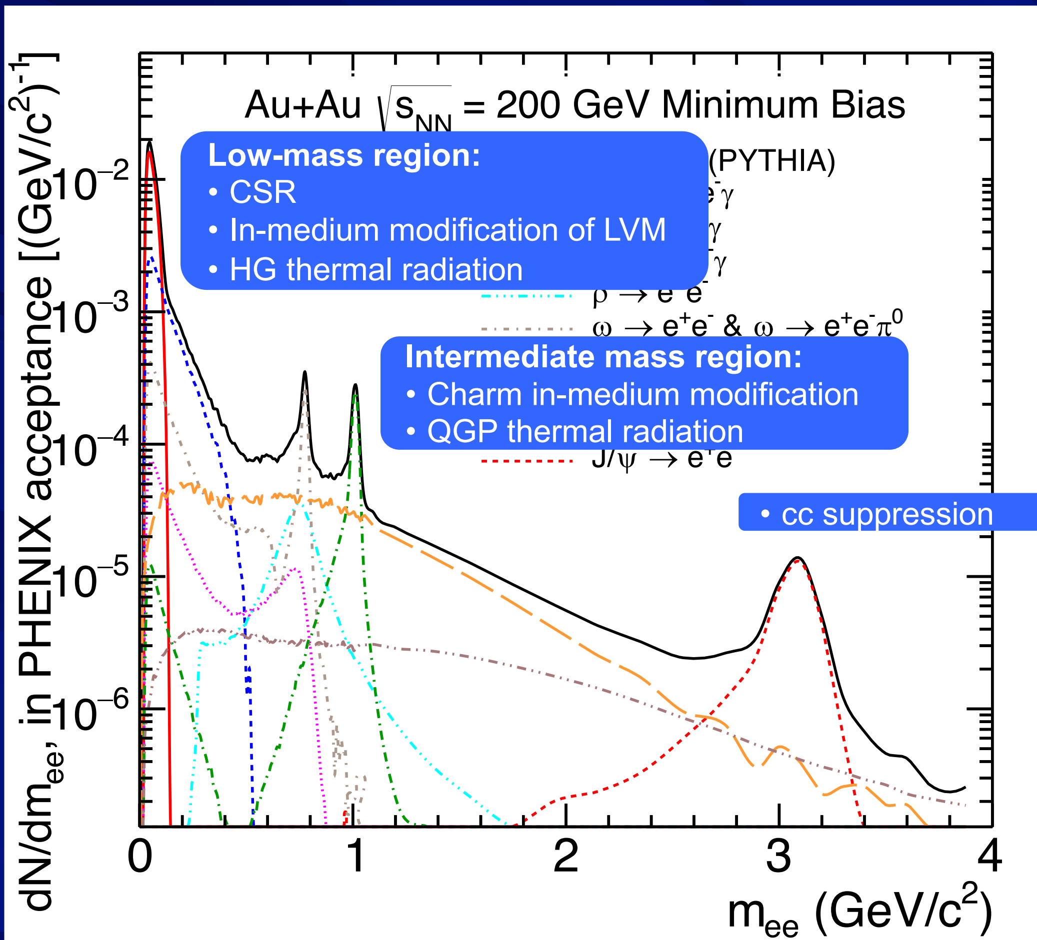
- No final state interaction: large mfp compared to the size of the system. Once produced they leave the fireball without any further interaction
  → carry direct information from place of production to detectors

- Production rate strongly increasing function of T and density
  → most abundantly produced at the early stage of the collisions

- …But very difficult measurements
  → large combinatorial background

- Emitted by a variety of sources all along the history of the collision
  → need a very good understanding of all these sources to disentangle the interesting ones.

Hadronic Cocktail and New Physics



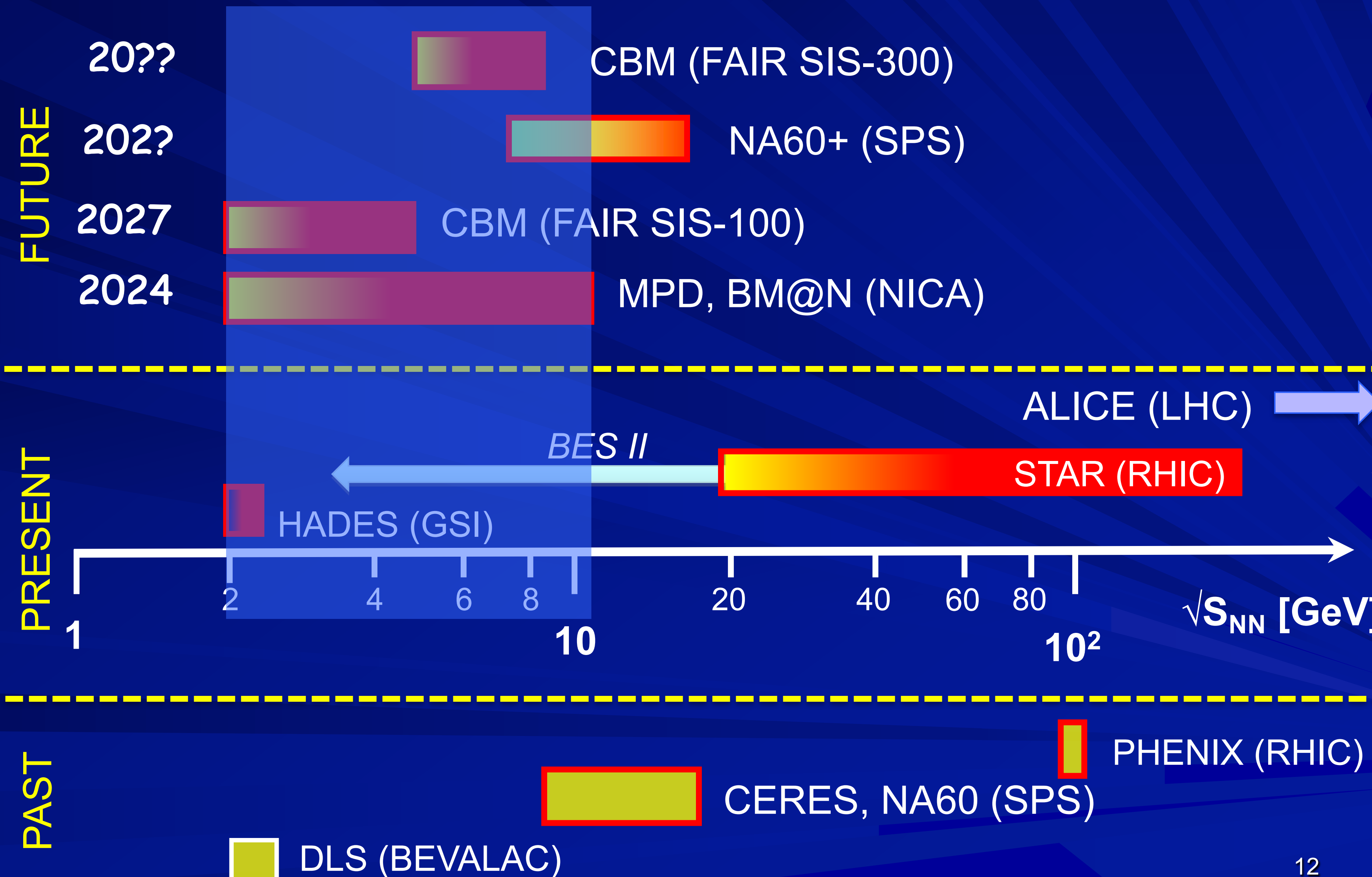
Cocktail of known sources:

- Dalitz decays:
  - $\pi^0, \eta, \eta' \longrightarrow e^+e^-\gamma$
  - $\omega \longrightarrow \pi^0 e^+e^-$
- Resonance decays:
  - $\rho, \omega, \varphi \longrightarrow e^+e^-$
- Semi-leptonic decays of HF:
  - $c\bar{c}, b\bar{b} \longrightarrow e^+e^-$

- Expected new physics in AA collisions

- Sources independently measured in AA collisions
- If not, use m_T scaling or scale from pp collisions

Dilepton experiments at low energies



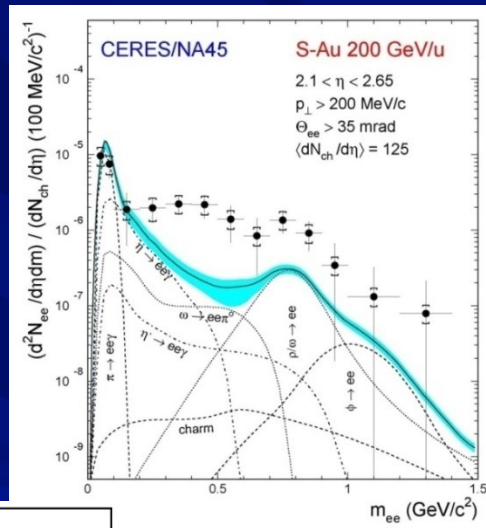
After ~30 years of dilepton measurements

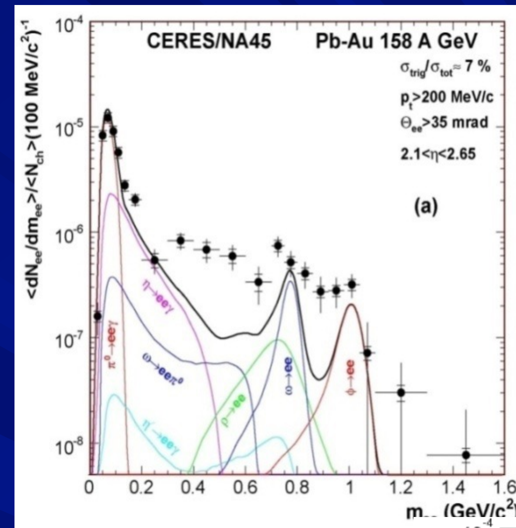
- All HI systems at all energies studied show an excess of dileptons wrt to hadronic sources

SPS: CERES Pioneering Dilepton Results

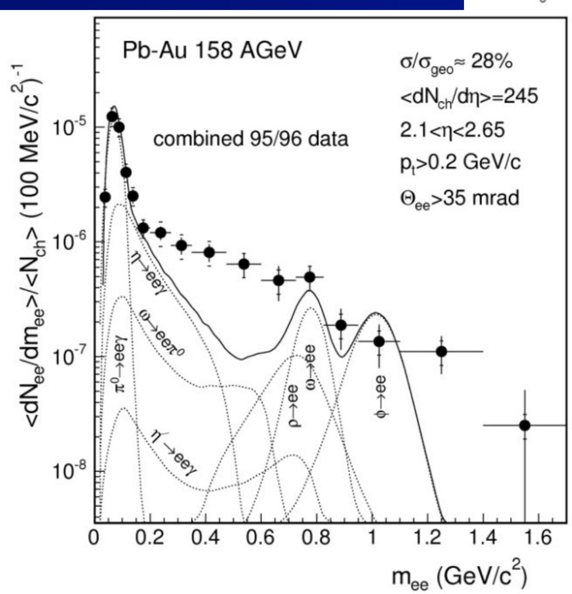
First CERES result
PRL 75, 1272 (1995)

(renowned paper: 550 citations)





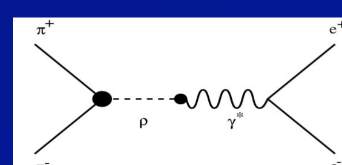
Last CERES result
PLB 666, 425 (2008)

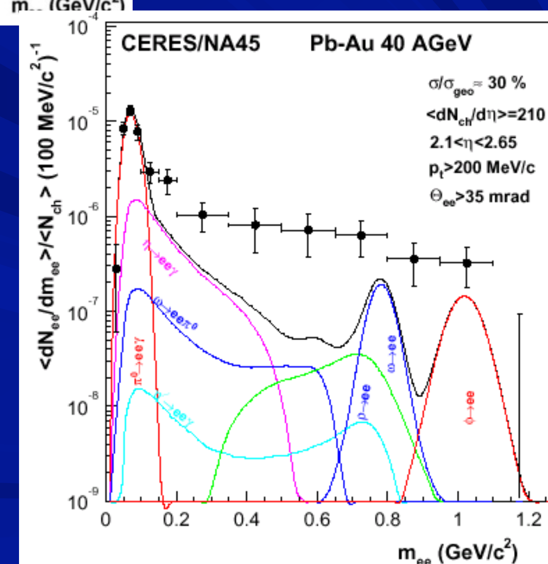


- Strong enhancement of low-mass e^+e^- pairs in all A-A systems studied

- First evidence of thermal radiation from the HG

$$\pi^+\pi^- \longrightarrow \rho \longrightarrow \gamma^* \longrightarrow e^+e^-$$



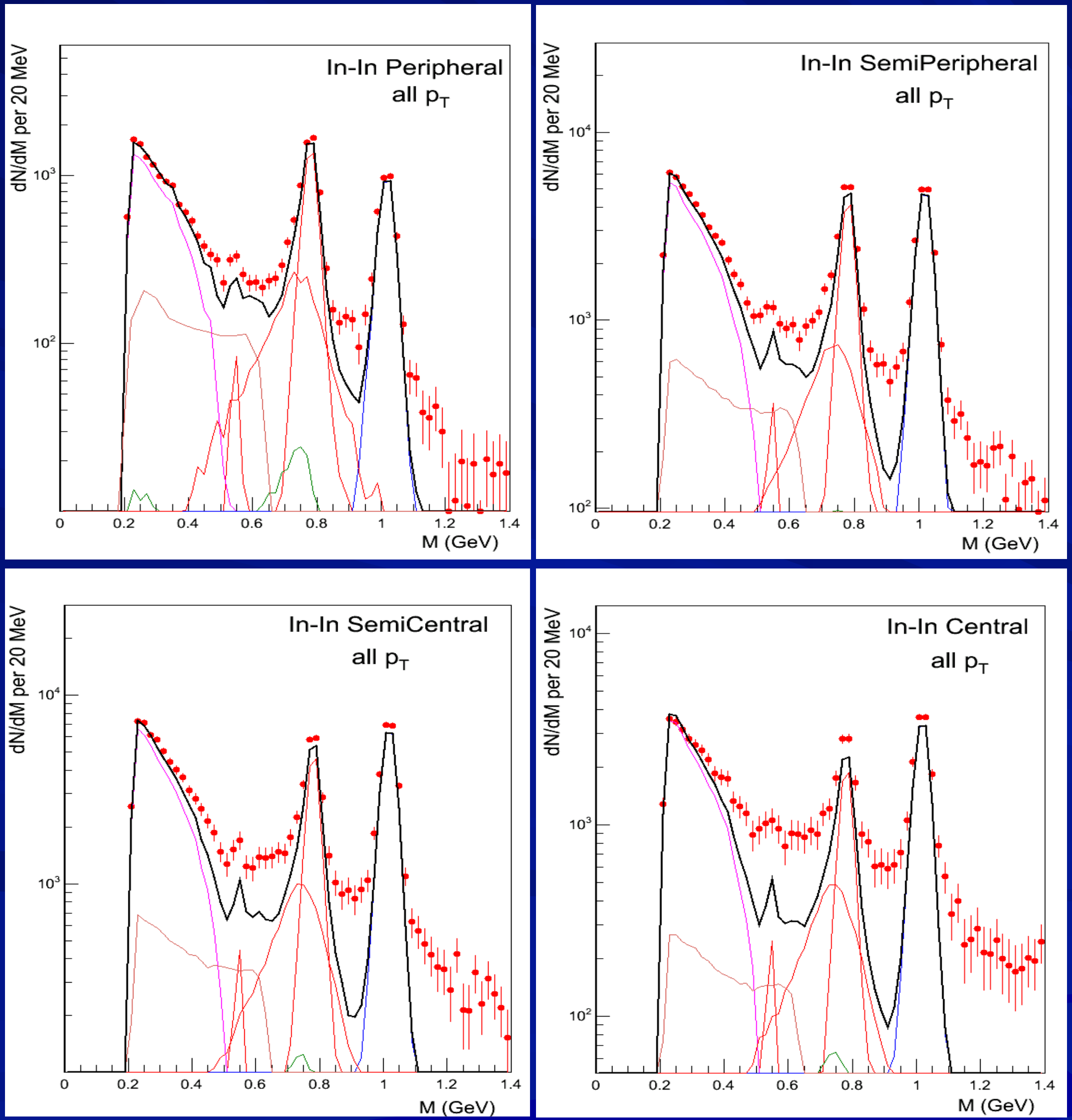


Eur. Phys J. C41, 475 (2005)

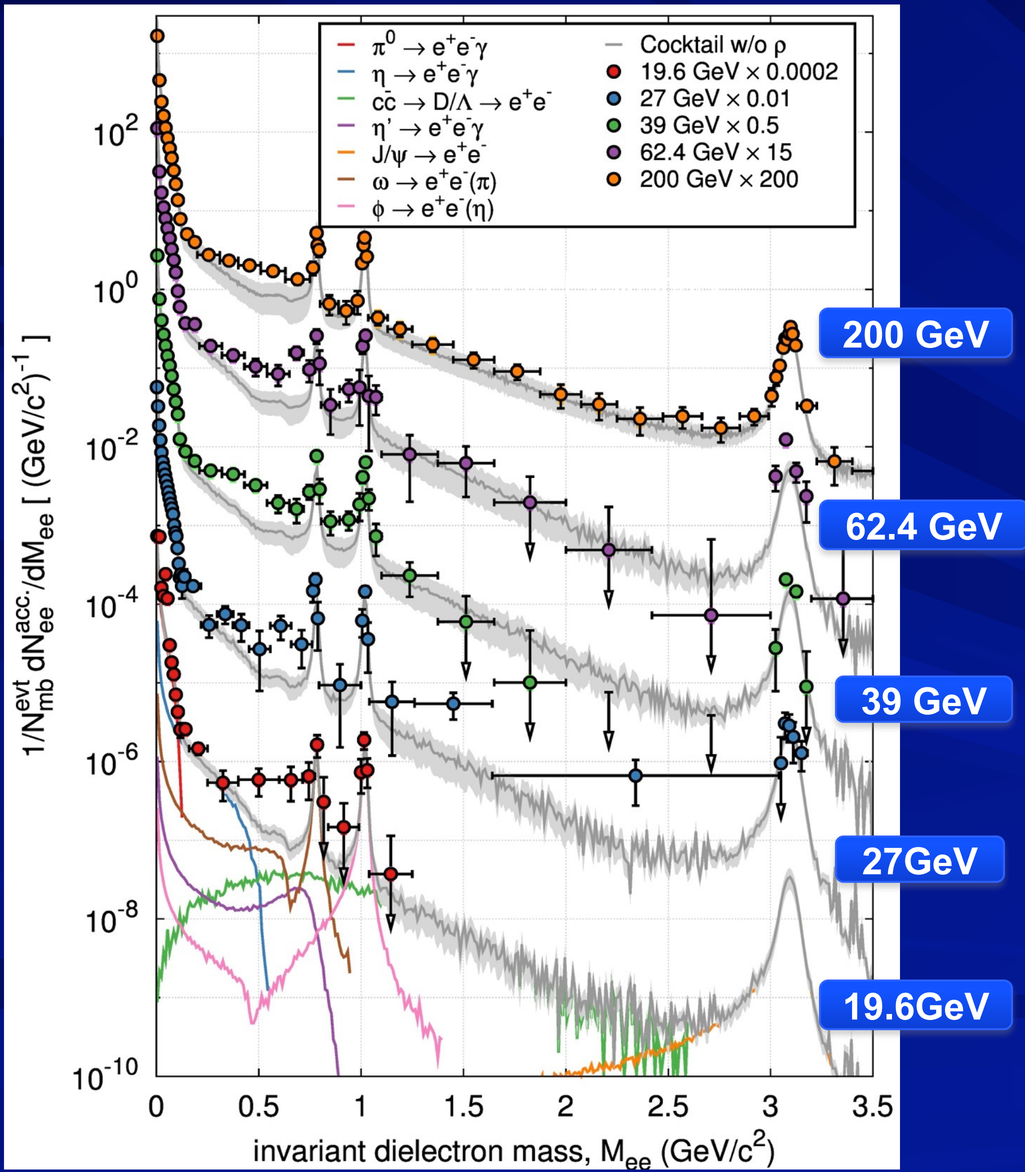
PRL 91, 042301 (2003)

SPS: NA60 dimuon results

Clear excess observed at all centralities in In+In at 158 AGeV



RHIC: STAR dileptons



- Systematic study of the dielectron continuum studied in Au+Au collisions at:

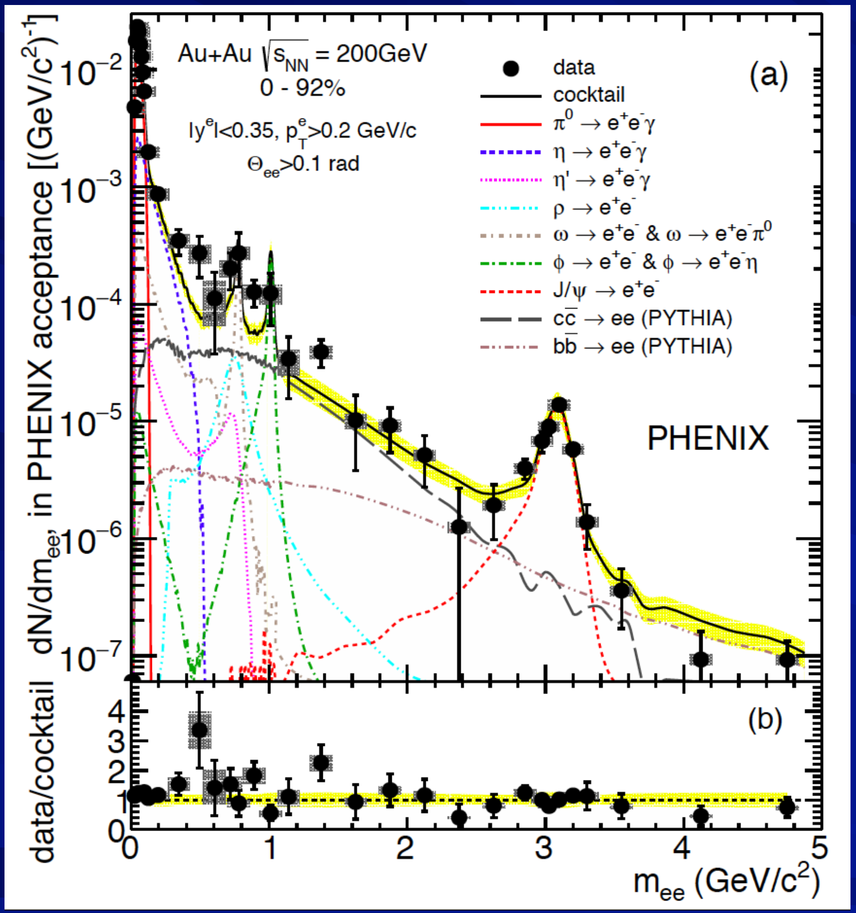
  200, 62.4, 39, 27 and 19.6 GeV

- Low mass excess observed at all energies

- Additional results expected from the BES-II

RHIC: PHENIX dileptons

PRC 93, 014904 (2016)



- ❑ HBD upgrade:
  - Improved hadron rejection: 30% → 5%
  - Improved signal sensitivity
- ❑ New improved analysis
  - Neural network for e-id
  - Flow modulation incorporated in the mixed event using an exact analytical method
  - Absolutely normalized correlated BG

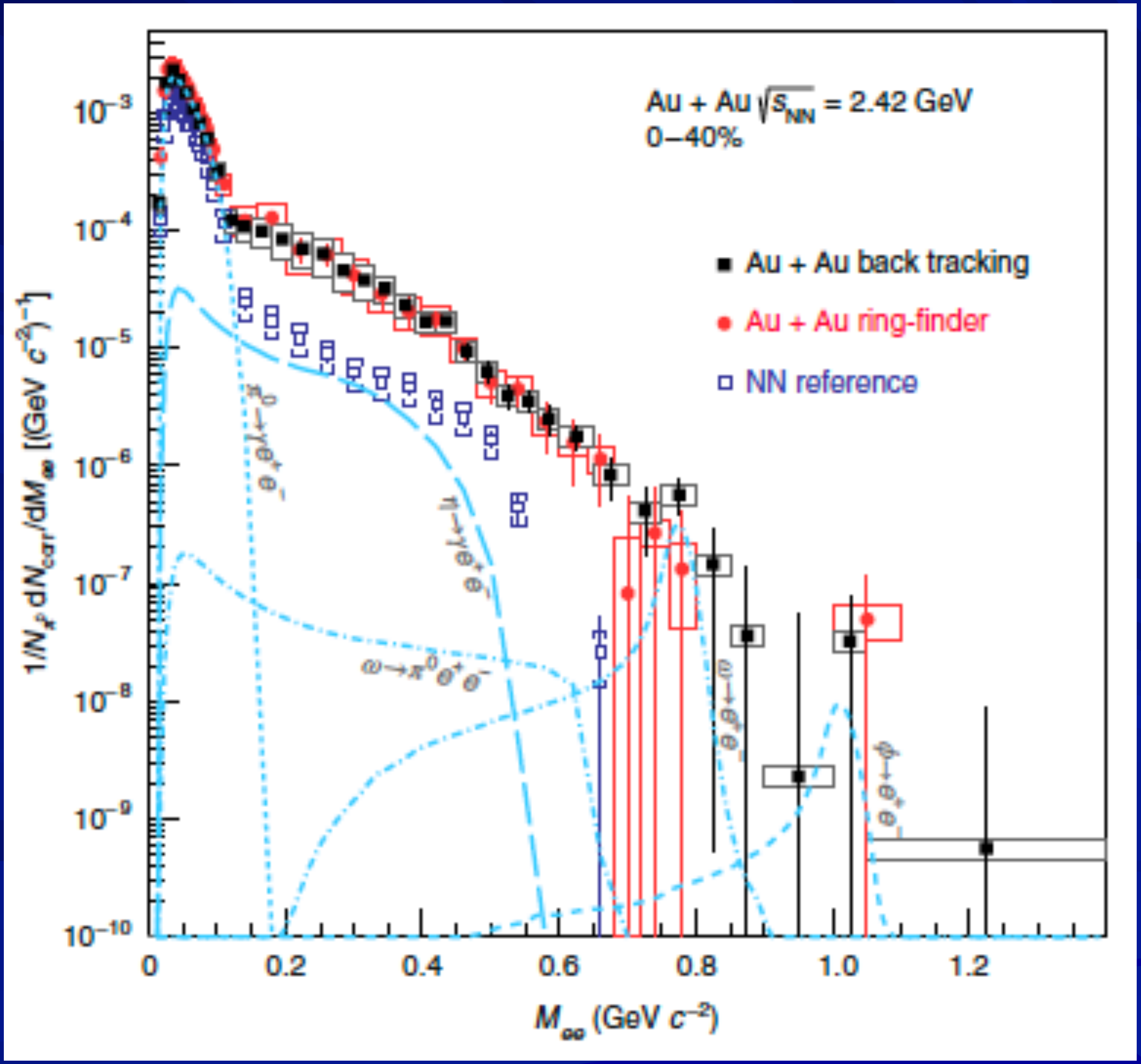
Minimum bias data/cocktail

0.3-0.76 (GeV/c²)	Data/cocktail ±stat ±syst ±model
PHENIX 2010	2.3 ± 0.4 ± 0.4 ± 0.2 (Pythia) 1.7 ± 0.3 ± 0.3 ± 0.2 (MC@NLO)
STAR	1.76 ± 0.06 ± 0.26 ± 0.29

Consistent results between PHENIX and STAR

SIS 18: HADES dileptons

Nature Physics 15, 1040 (2019)

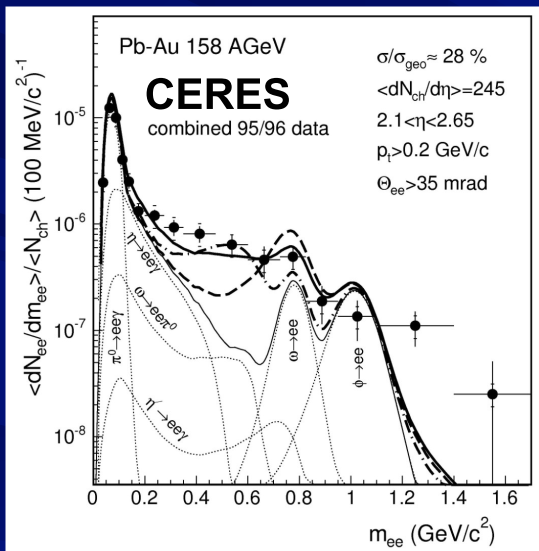


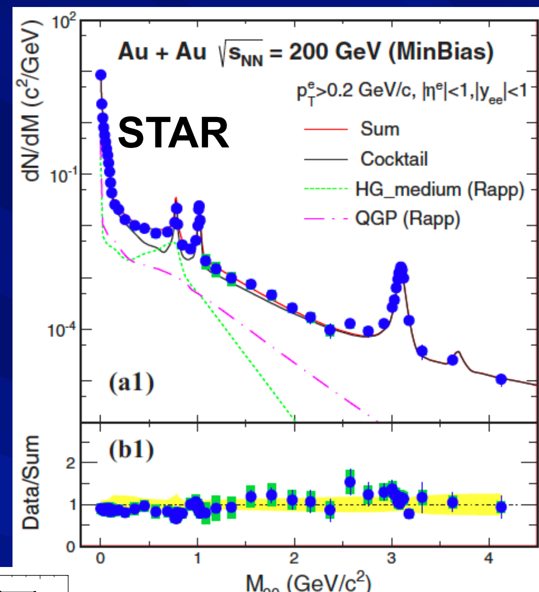
After ~30 years of dilepton measurements

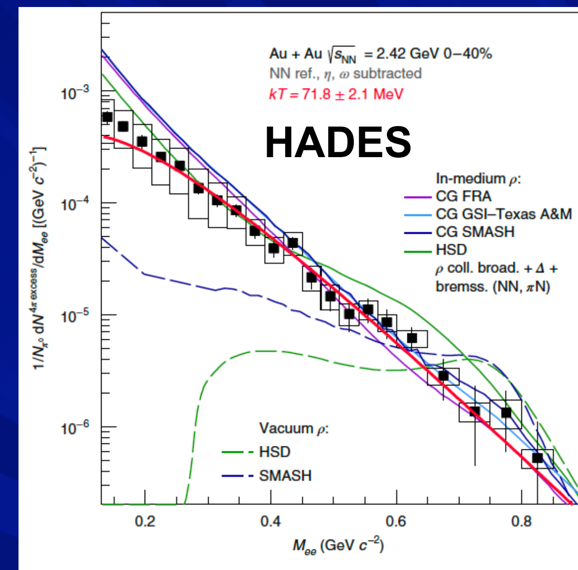
- All HI systems at all energies studied show an excess of dileptons wrt to hadronic sources
- Excess consistently reproduced by microscopic many body model (Rapp et al.)

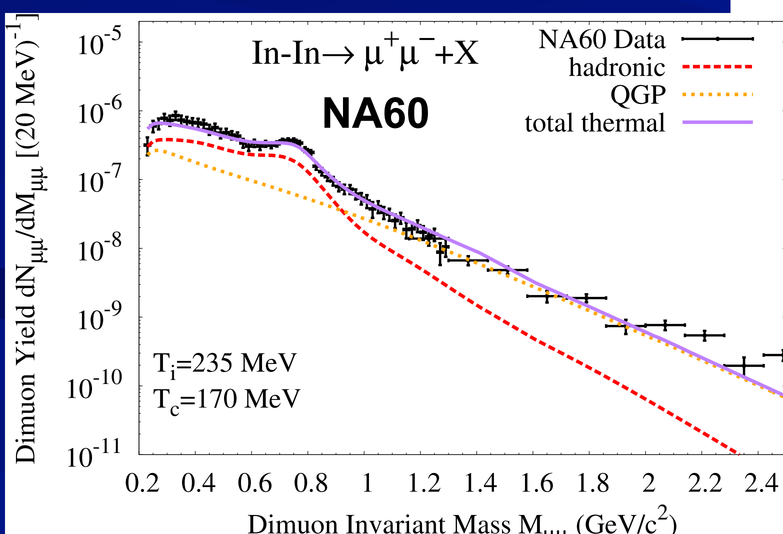
All results reproduced by one single model

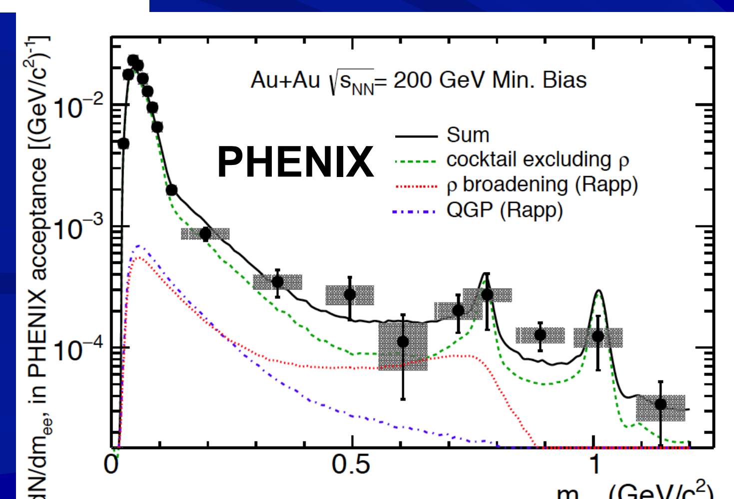
- Vacuum ρ meson fails to reproduce the data.
- Good agreement with models based on ρ meson in-medium broadening – Linked to CSR







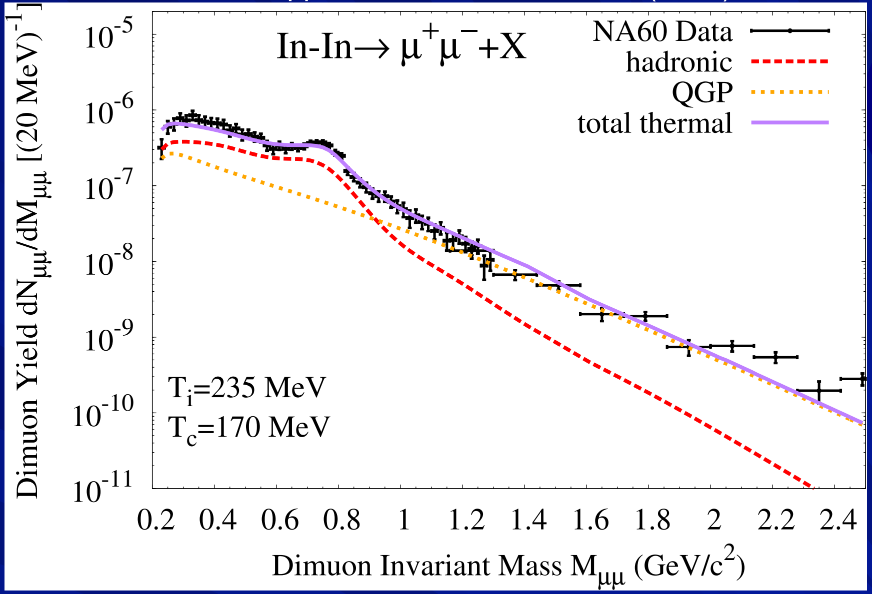




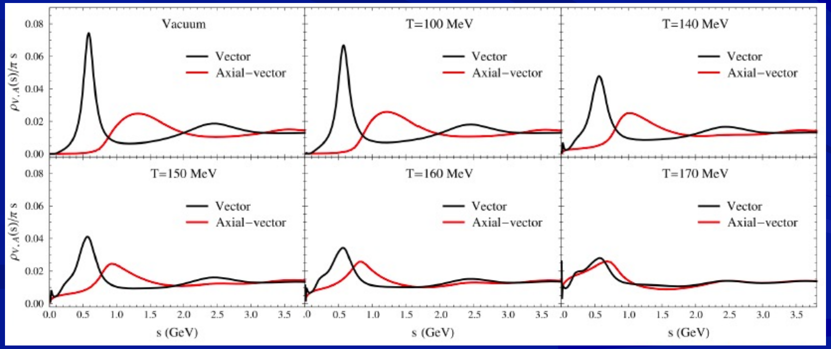
After ~30 years of dilepton measurements

- All HI systems at all energies studied show an excess of dileptons wrt to hadronic sources
- Excess consistently reproduced by microscopic many body model (Rapp et al.)
- LMR:
  - Thermal radiation from HG
    $\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$
  - Tracks the medium lifetime
- IMR:
  - Thermal radiation from QGP
    $q\bar{q} \rightarrow \mu^+\mu^-$
  - Provides a measurement of <T>
- Emerging picture for the realization of CSR: the ρ meson broadens in the medium, the a_1 mass drops and becomes degenerate with the ρ.

NA60 data: Eur. Phys. J. C61, 711 (2009)
Curves: Rapp and Hees PLB 753, 586 (2016)



Hohler and Rapp PLB 73, 103 (2014)



- One of the few effects exclusively observed in AA collisions

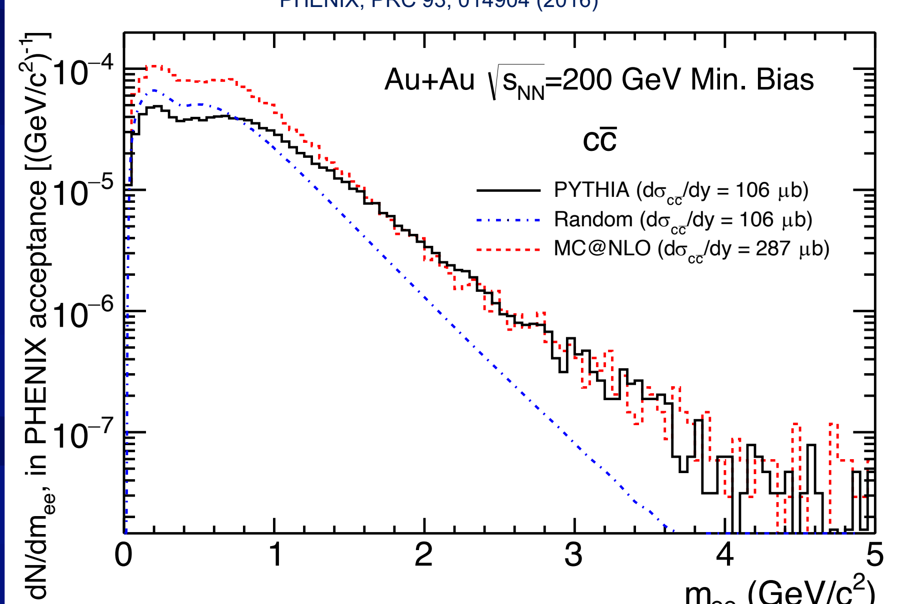
- Dileptons: quo vadis?

What is missing (I)?

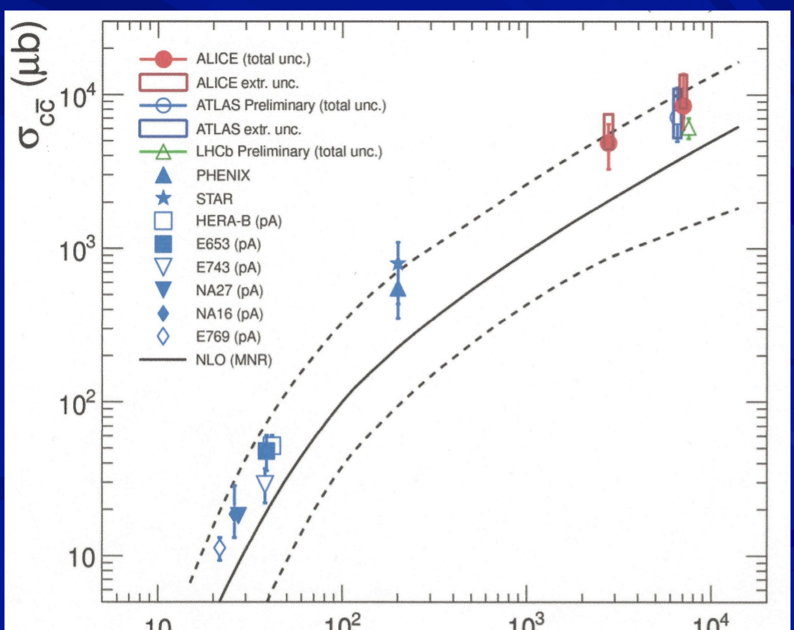
- **Confirmation of QGP thermal radiation in the IMR**.
  - IMR thermal radiation observed only at SPS by one experiment NA60
  - Difficulties in identifying the QGP thermal radiation at the top RHIC energies due to a sizable contribution from semi-leptonic decays of charmed mesons
  - Should be easier at NICA energies: charm cross section negligible

Large uncertainties in shape and magnitude both in the LMR and the IMR

PHENIX, PRC 93, 014904 (2016)



Charm cross section in pp



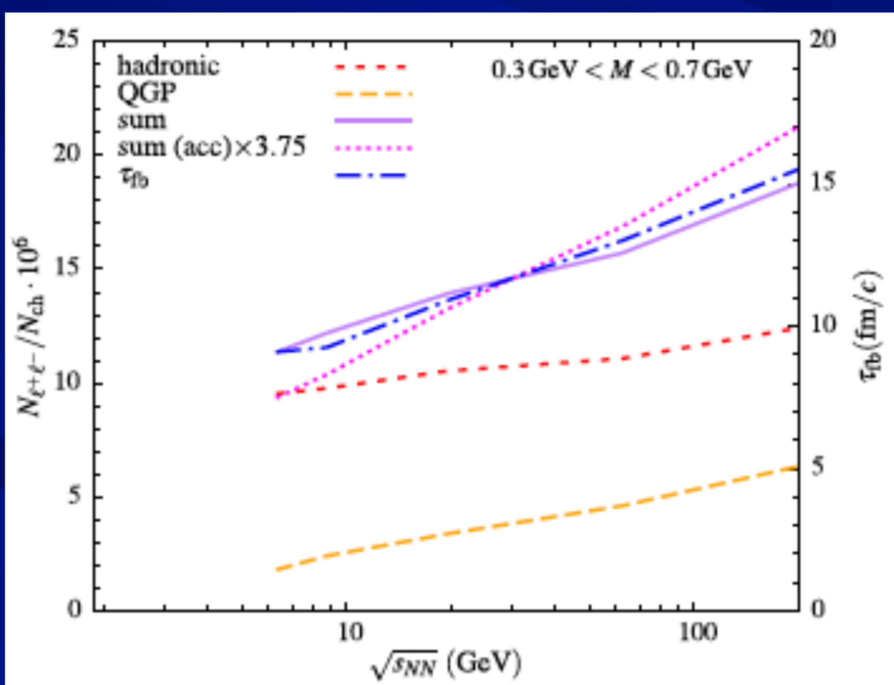
What is missing (II)?

- Onset of deconfinement? Onset of CSR? → Energy scan of dilepton exces
  - Integrated yield in the LMR tracks the fireball lifetime
  - Inverse slope of the mass spectrum in the IMR provides a measurement of <T>

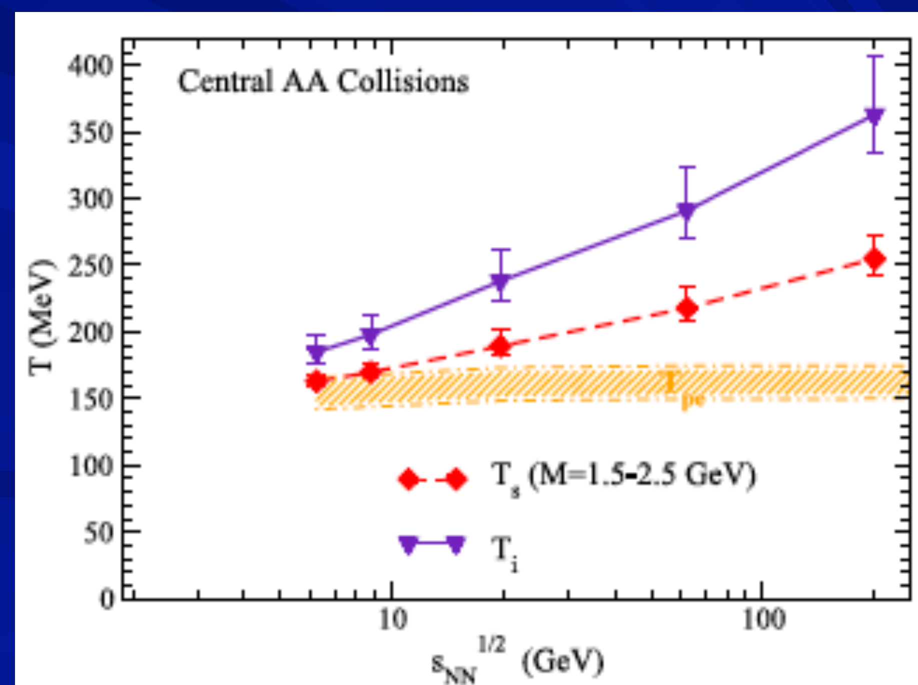
    First order phase transition?
  - Thermal radiation down to $\sqrt{s_{NN}}$ – 6 GeV ?

Rapp and Hees, PLB 753, 586 (2016)

LMR - Chronometer



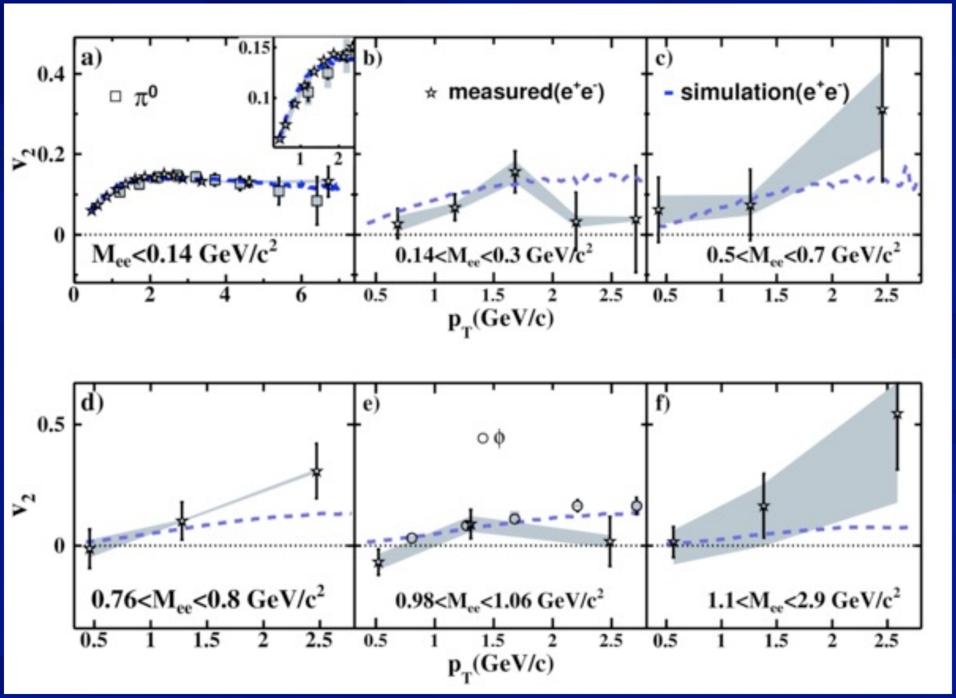
IMR - Thermometer



What is missing (III)?

- ❑ v_2 of thermal radiation
  - Very challenging measurement
  - Could provide an independent confirmation about the origin of the thermal radiation

Inclusive dielectron v_2
STAR PRC 90, 64904 (2014)

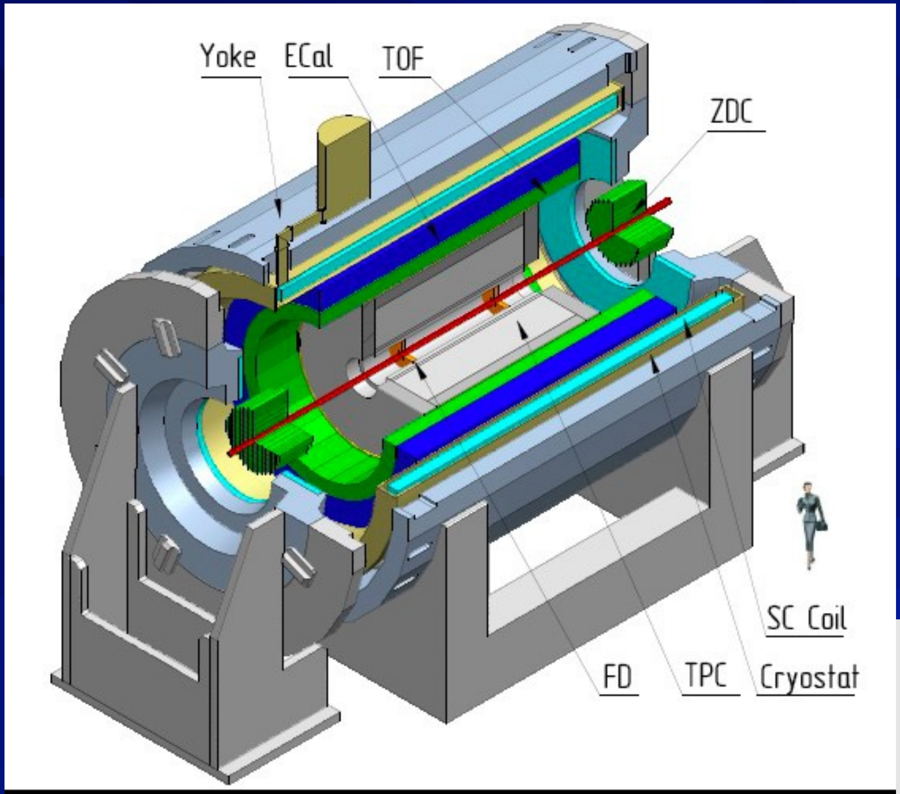


Challenge: isolate the v_2 of the excess dileptons

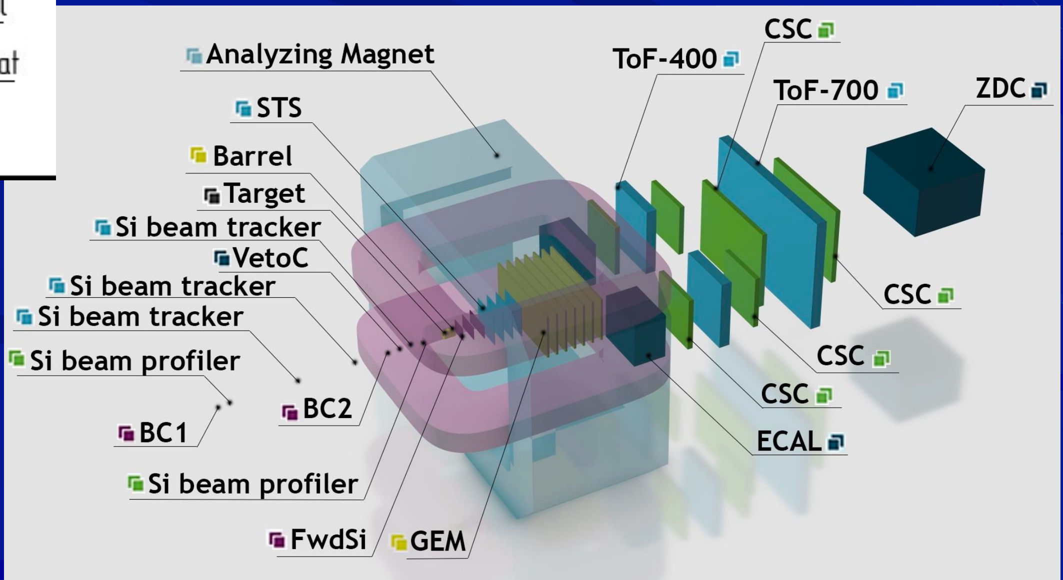
❑ NICA experiments well suited for dilepton studies

MPD and BM@N Experiments

MPD Stage I

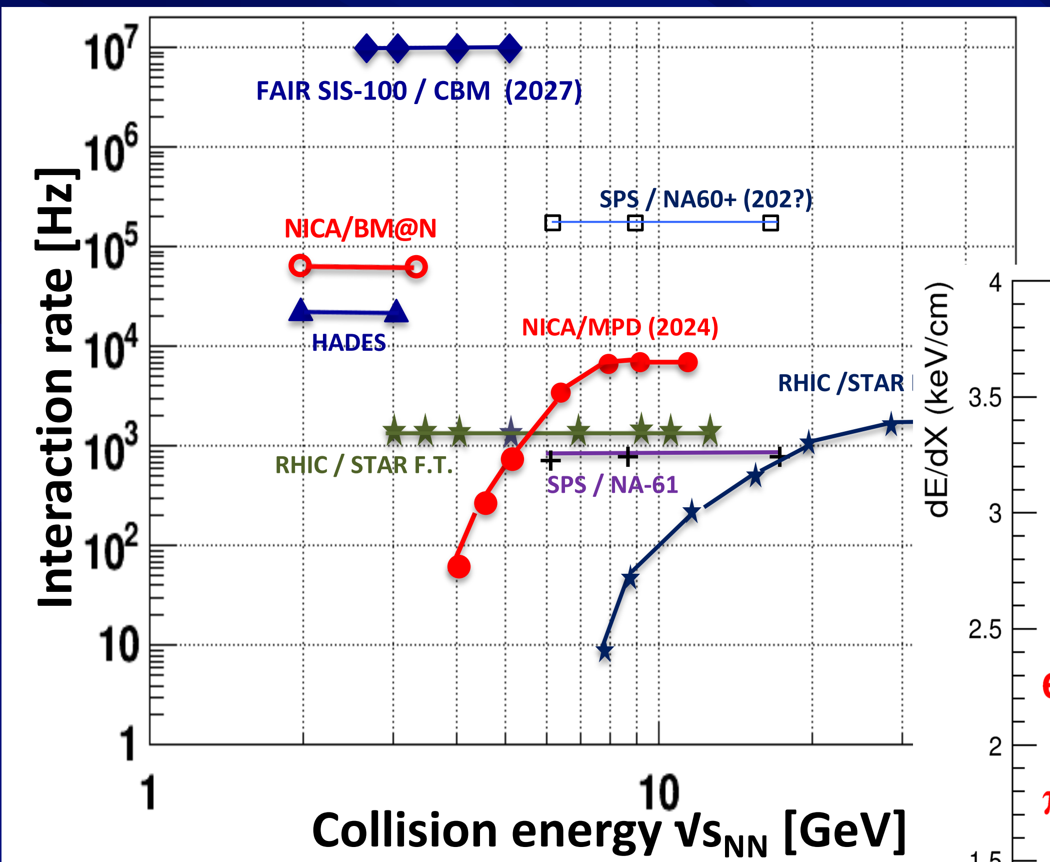


BM@N set-up for HI runs

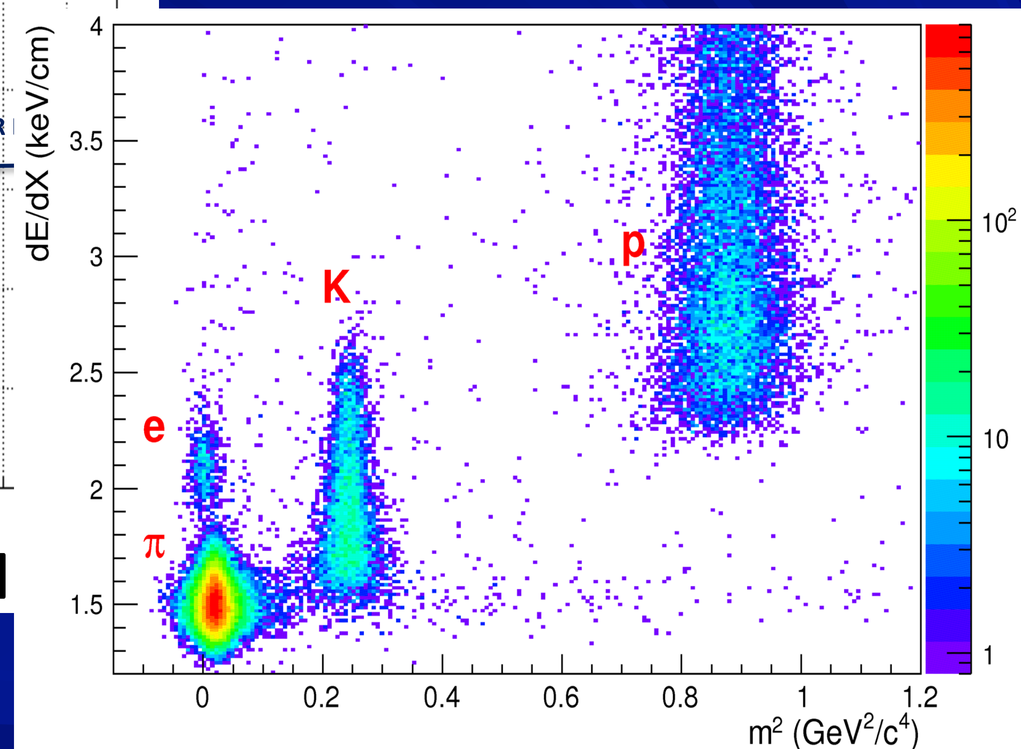


MPD Experiment

Interaction rate



Electron identification:
- TPC dE/dx
- ToF
- Ecal (E/p =1)



- ❑ Challenge: overwhelming yield of combinatorial background dileptons from π^0 Dalitz decays and γ conversions
- ❑ Efforts underway to reduce the CB.

Summary

- Exciting dilepton prospects at NICA energies
- MPD well suited for dilepton studies
- Looking forward to the start of the NICA physics program

- Thank you!