Dileptons at NICA: challenges and opportunities

Seminar celebrating the 75th Anniversary of Professor Vladimir Kekelidze

October 21, 2022

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Outline

- NICA facility
  - Motivation and physics mission
  - A niche in the energy landscape
- Dileptons:
  - What did we learn from SPS and RHIC dilepton measurements
  - Prospects and challenges
- Summary

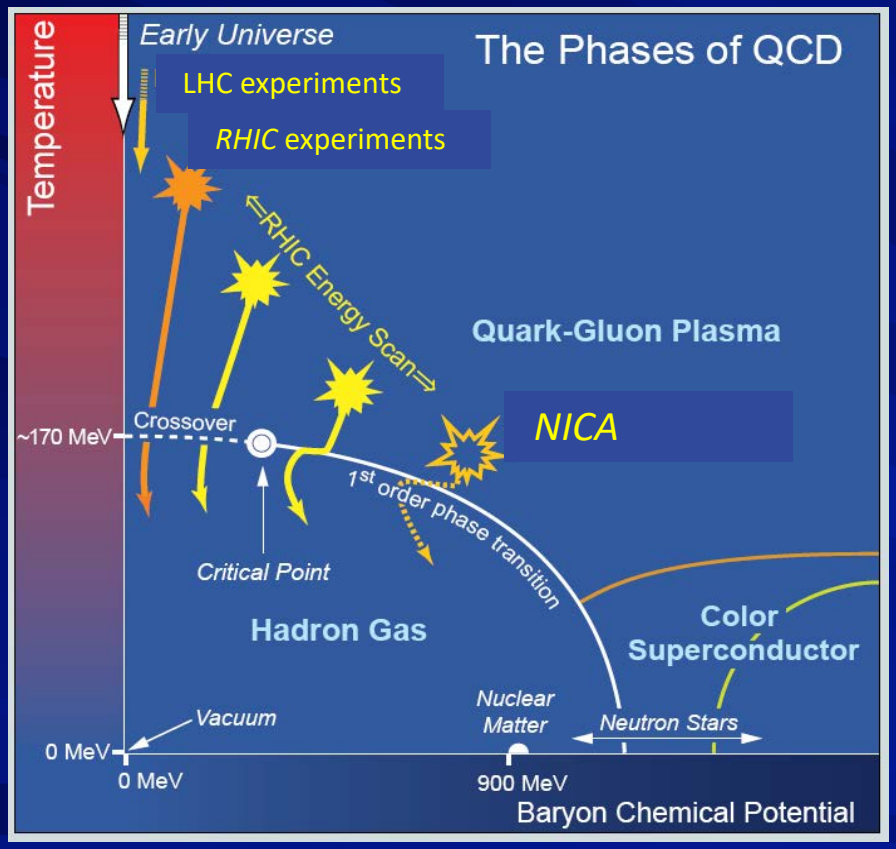
NICA

- Dedicated heavy ion facility
- Shall provide high intensity beams:

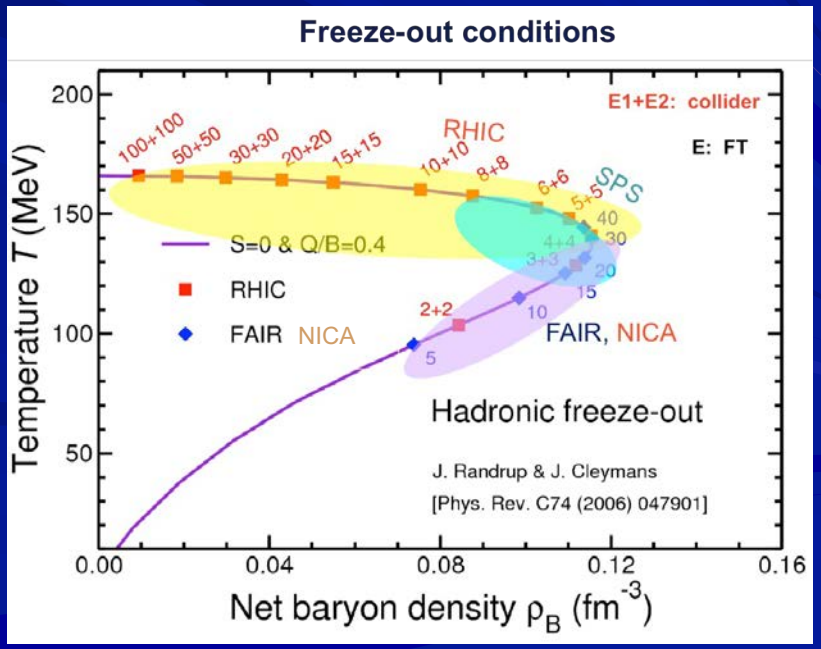
  heavy ions: Au^{79+} $\sqrt{s_{NN}}$ = 2 - 11 GeV, **L ~ 10^{27}** cm^{-2} s^{-1}

  polarized p and d: $\sqrt{s}$ up to 27 GeV, L ~ **10^{32}** cm^{-2} s^{-1}

Nuclear Matter Equation of State

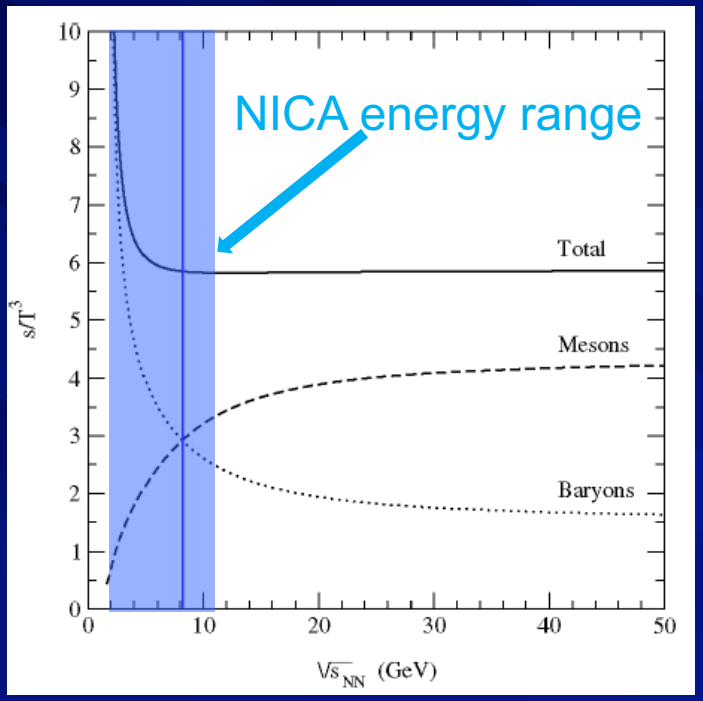


- Explore the QCD phase diagram in the region of high μ_B (baryon dominated) matter
- Search for the conjectured critical point and first order phase transition
- NICA's energy range brackets expected onset of deconfinement and chiral symmetry restoration phase transition(s)



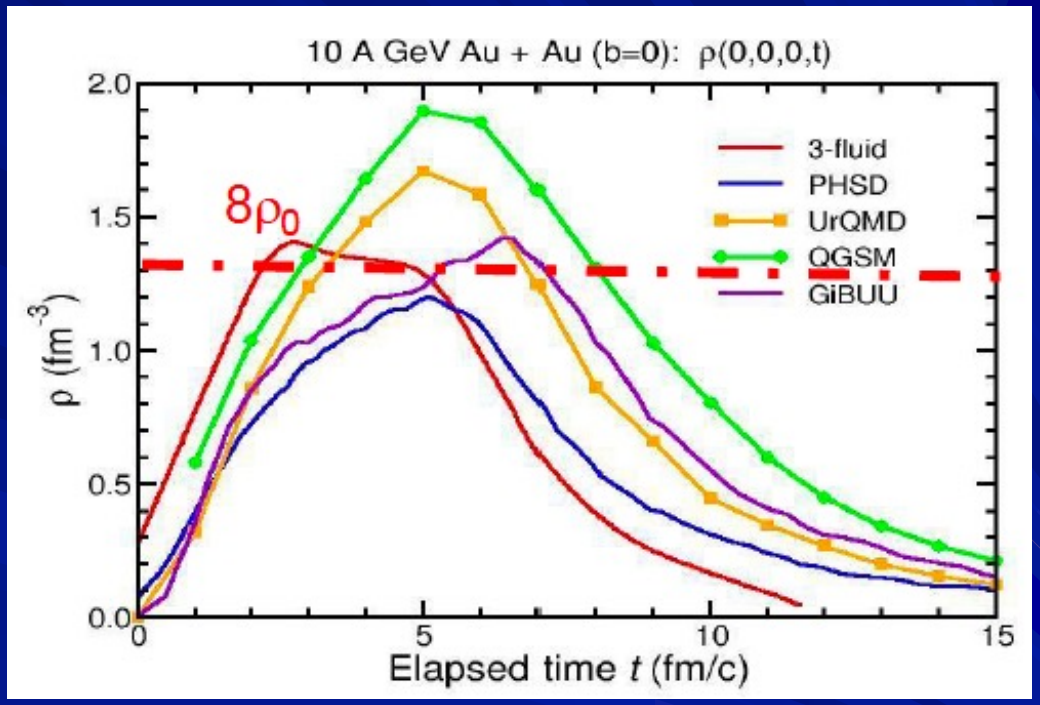
QCD matter at NICA energies

J. Cleymans et al., PLB 615, 50 (2005)



- NICA energy range brackets the transition from baryon to meson dominated matter

PRC 75, 034902 (2007)



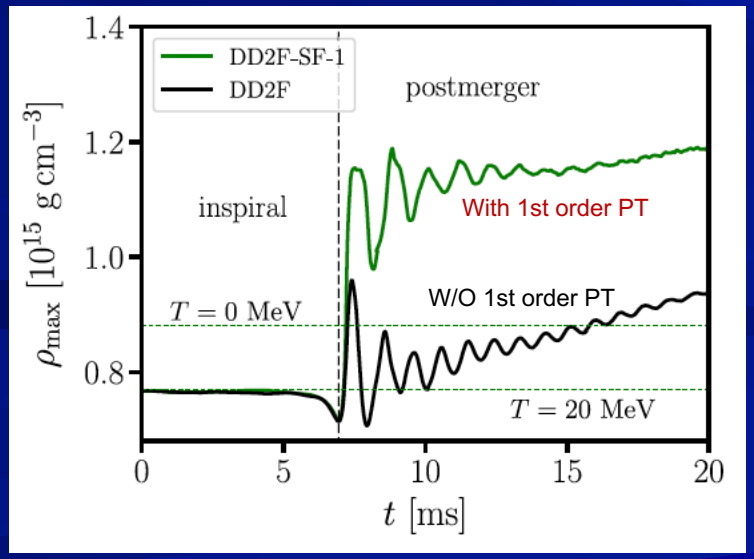
- Sizable densities up to $O(10\rho_0)$
- Long lifetime

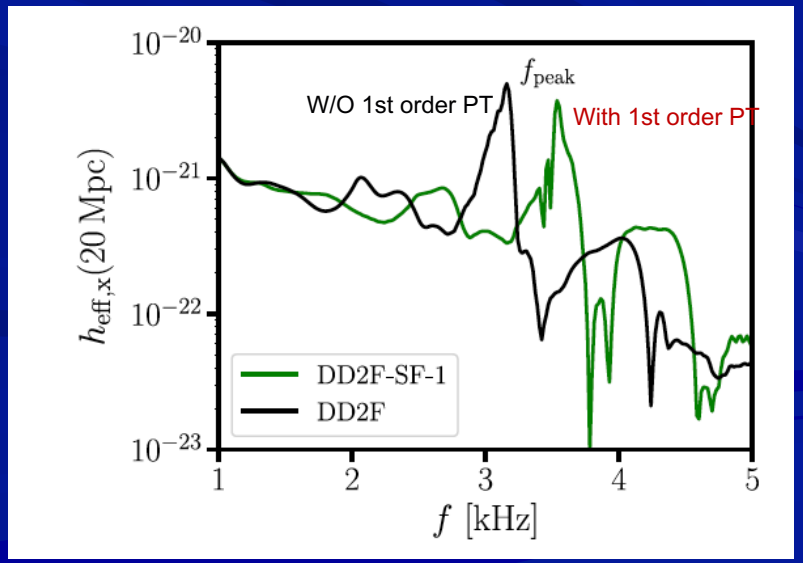
Synergy with Multi-Messanger Astronomy

- Model calculations show that in heavy-ion collisions in the NICA energy range, nuclear matter reaches densities and temperatures similar to those occurring in a neutron star merger .
- Heavy-ion collisions at NICA and neutron star mergers probe similar regions of the QCD phase diagram.

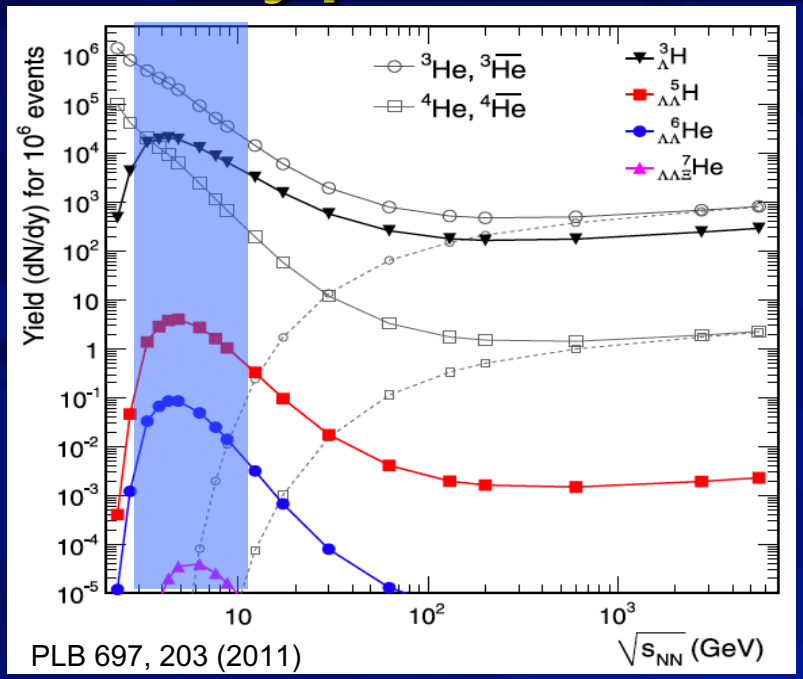
- Simulations, shows that the GW signal could provide clear signature of a first order quark-hadron phase transition. Such finding would necessarily imply the existence of a CEP in the QCD phase diagram.

PRL, 122, 061102 (2019)



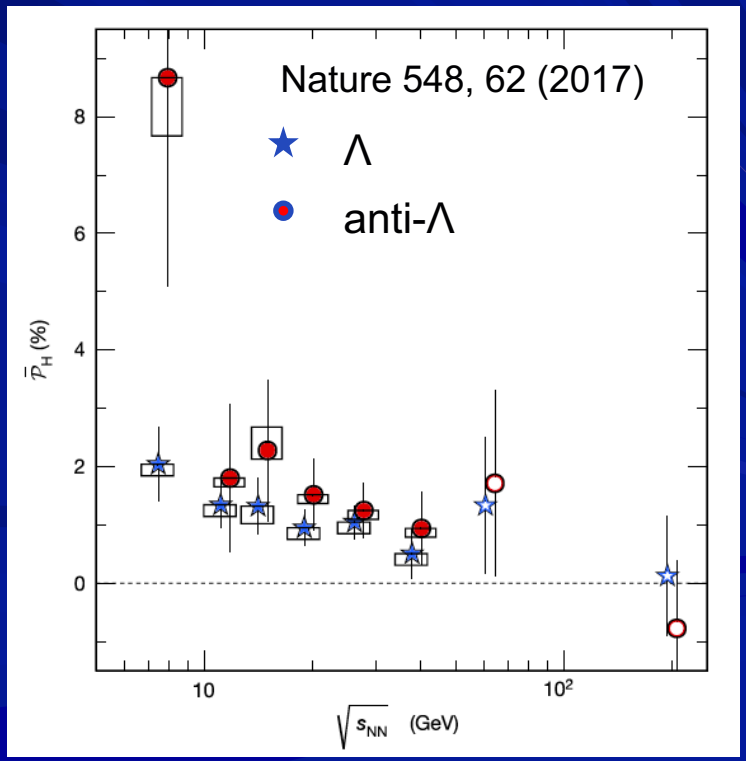


Hypernuclei and Strangeness



PLB 697, 203 (2011)

- Access the hyperon-nucleon interaction.
- Valuable insight into what the cores of neutron stars could be like.
- Maximum production of hypernuclei in the NICA energy range.



- Global polarization of Λ and anti-Λ
  - Insights into initial conditions and dynamics of QGP
  - Expected to be high at the NICA energies
- Sub-threshold production of multistrange (anti-)hyperons via sequential collisions.

MPD Physics Programme

Organized and developed in 5 Physics Working Groups

Global observables

- Total event multiplicity
- Total event energy
- Centrality determination
- Total cross-section
- Event plane measurement at all rapidities
- Spectator measurement

Spectra of light flavor and hypernuclei

- Light flavor spectra
- Hyperons and hypernuclei
- Particle yields and yield ratios
- Kinematic and chemical freeze-out
- QCD Phase Diagram

Correlations and Fluctuations

- Collective flow
- Vorticity, Λ polarization
- E-by-E fluctuation of multiplicity, momentum and conserved quantities
- Femtoscopy
- Forward-Backward corr.

Electromagnetic probes

- Dilepton spectra in low and intermediate mass regions:
  - * In-medium modification of resonances
  - * Onset of deconfinement
  - * Onset of Chiral Symmetry restoration
- Photons in ECAL and central barrel

Heavy flavor

- Open charm production
- Charmonium with ECAL and central barrel
- Charmed meson through secondary vertices in ITS and HF electrons
- Threshold charm production

Dileptons: quo vadis?

Motivation

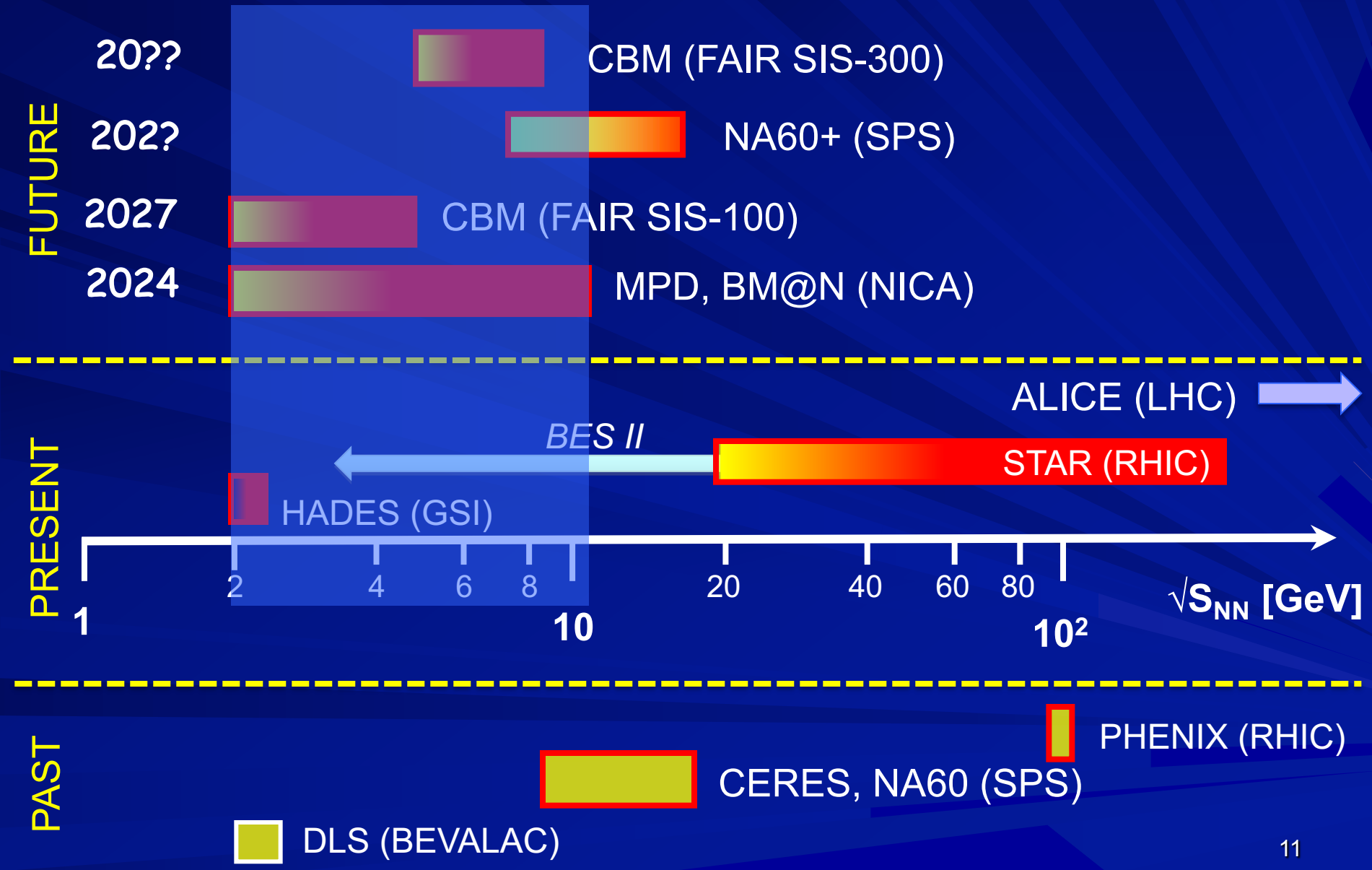
- Dileptons (e^+e^-, $\mu^+\mu^-$) are sensitive probes of the two fundamental properties of the QGP:
  - *Deconfinement*
  - *Chiral Symmetry Restoration*

- *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.

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

HG: $\pi^+\pi^- \longrightarrow \rho \longrightarrow \gamma^* \longrightarrow l^+l^-$

Dilepton experiments at low energies



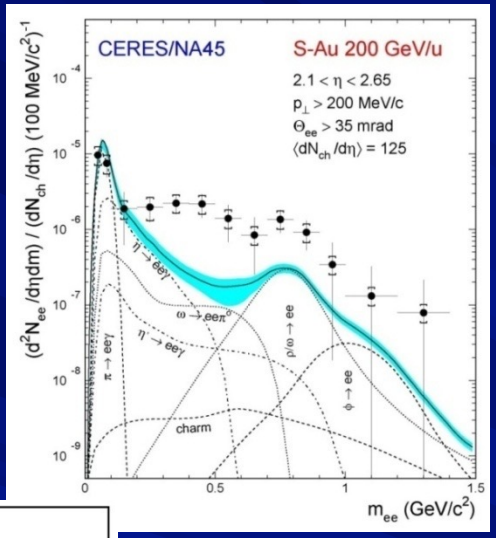
After ~25 years of dilepton measurements

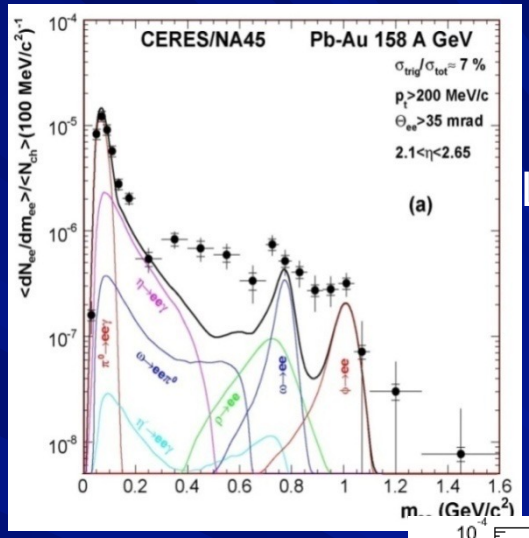
- All HI systems at all energies studied show an excess of dileptons wrt to hadronic sources

SPS: CERES Pioneering Dilepton Results

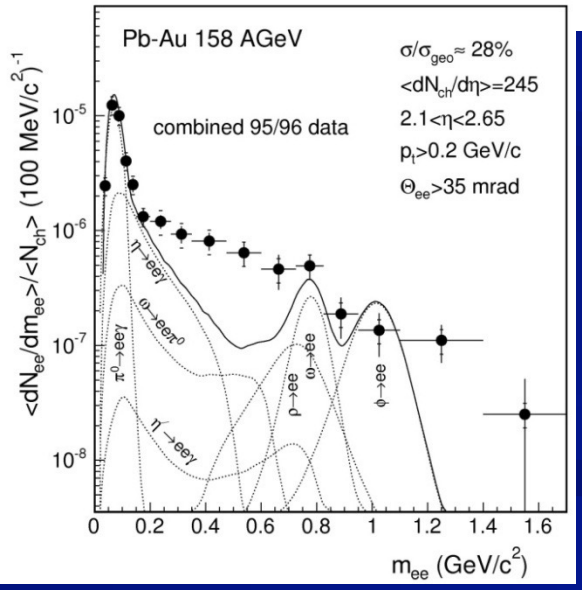
First CERES result
PRL 75, 1272 (1995)

(renowned paper: 550 citations)





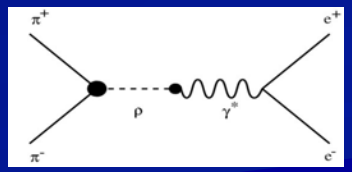
Last CERES result
PLB 666, 425 (2008)

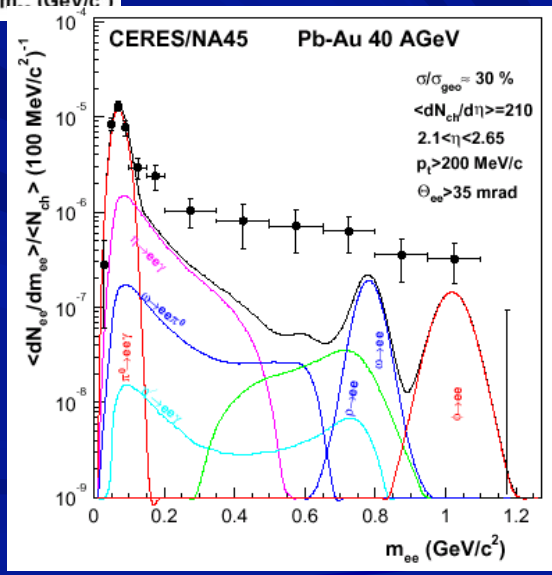


Eur. Phys J. C41, 475 (2005)

- Strong enhancement of low-mass e^+e^- pairs in all A-A systems studied
- First evidence of thermal radiation from the HG

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

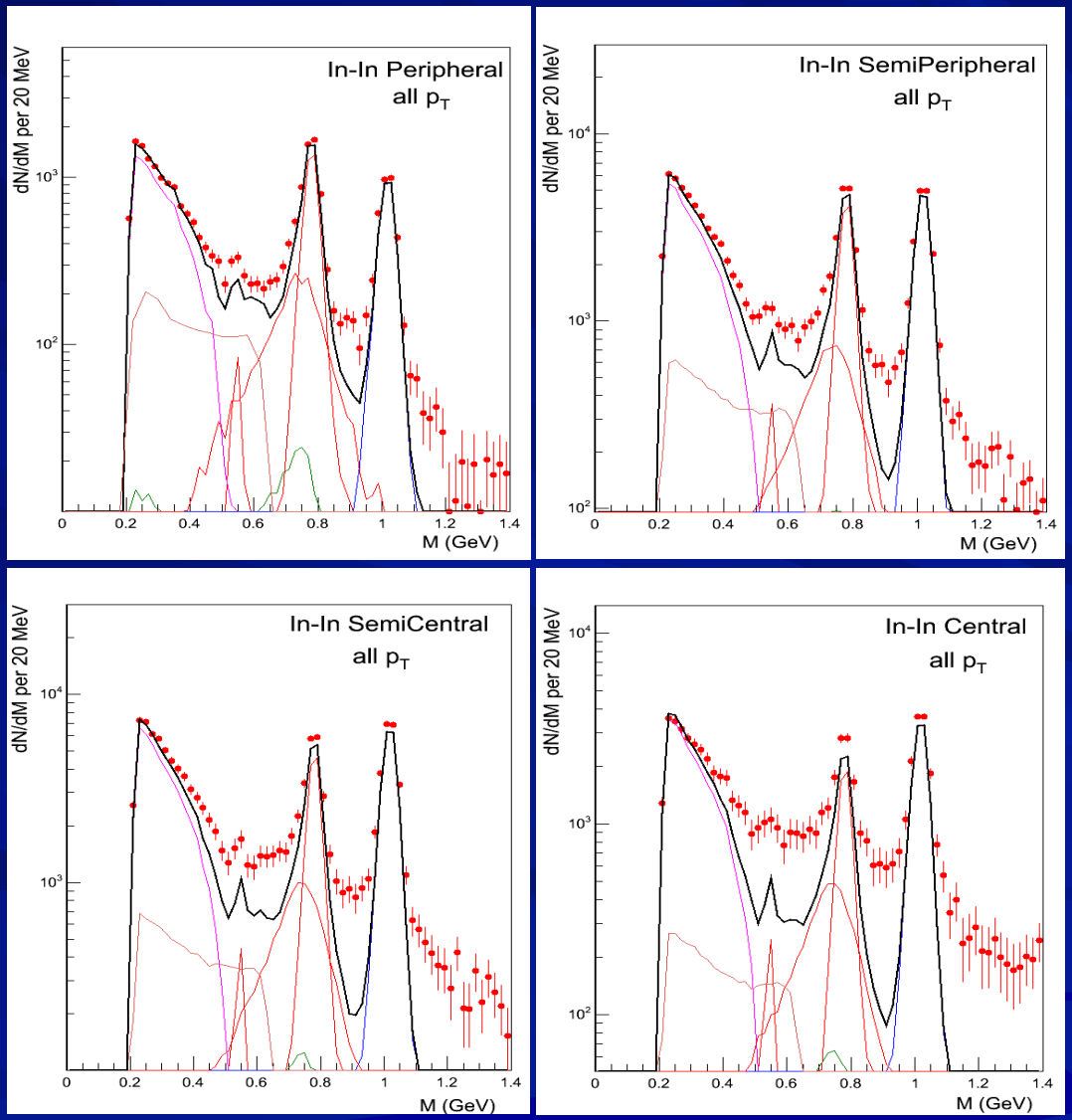




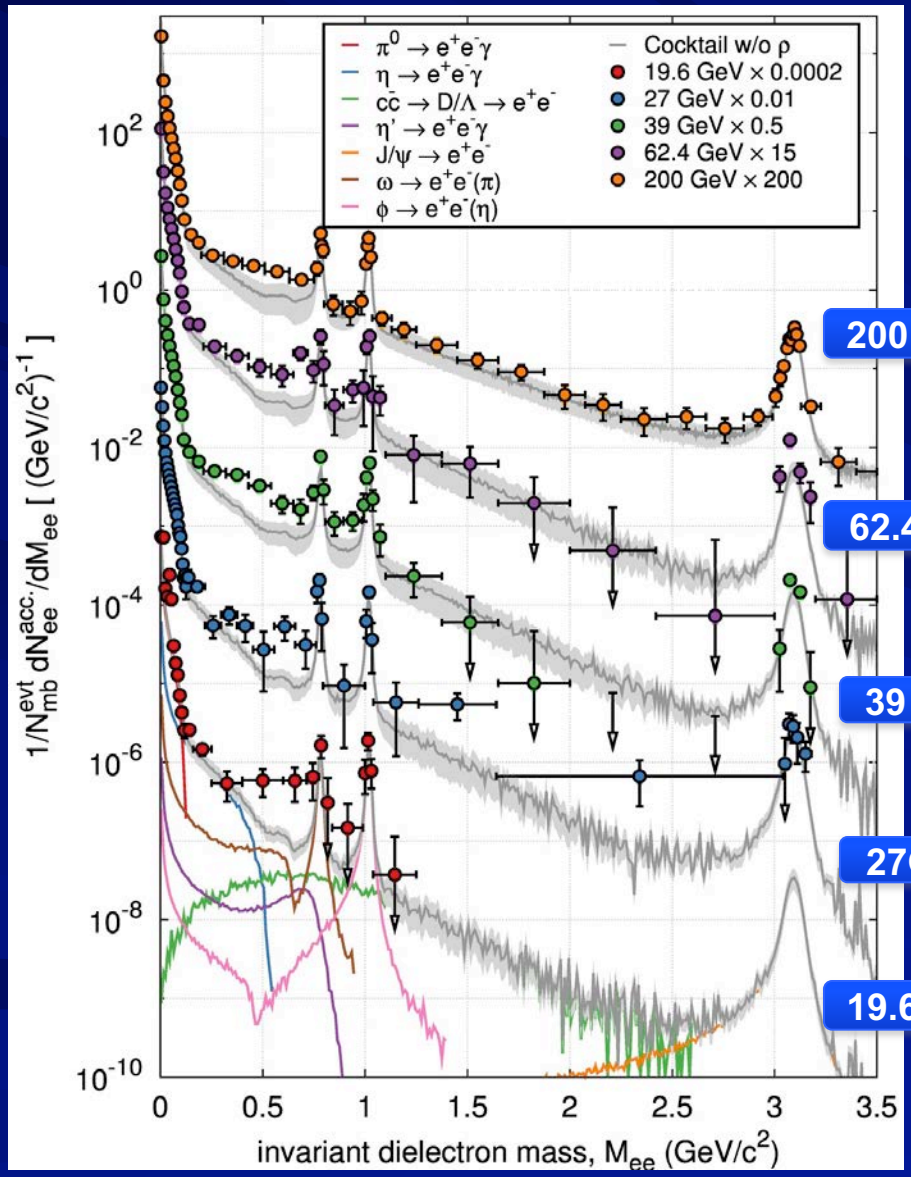
PRL 91, 042301 (2003)

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:

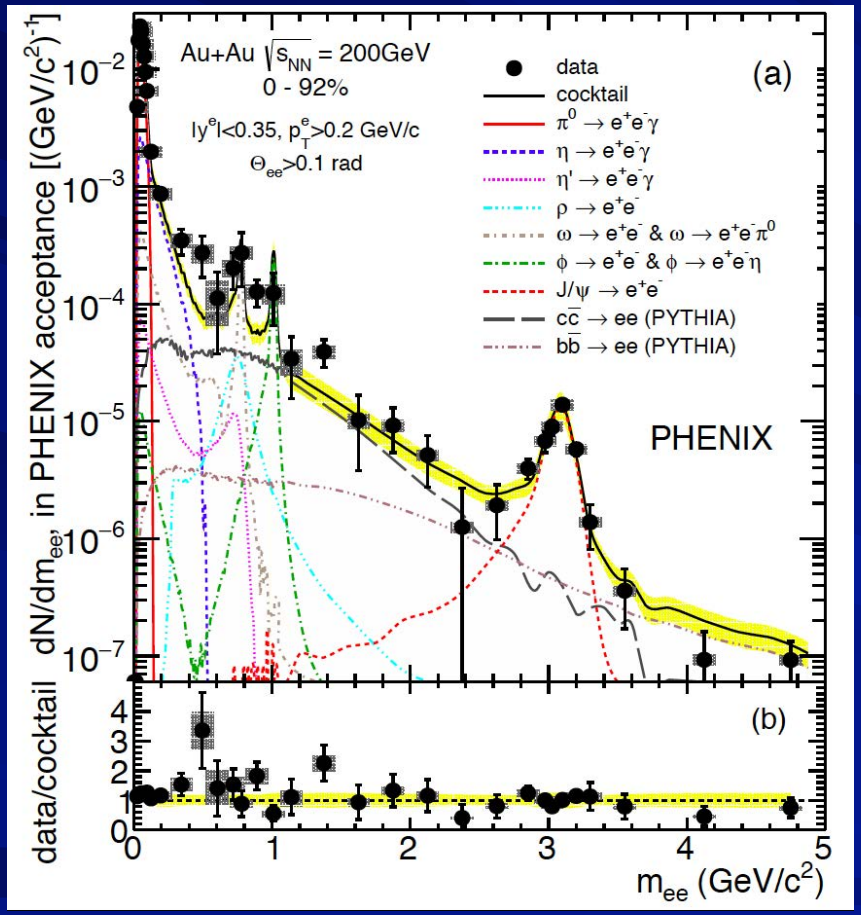
  200, 62.4, 39, 27 and 19.6 GeV

- 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

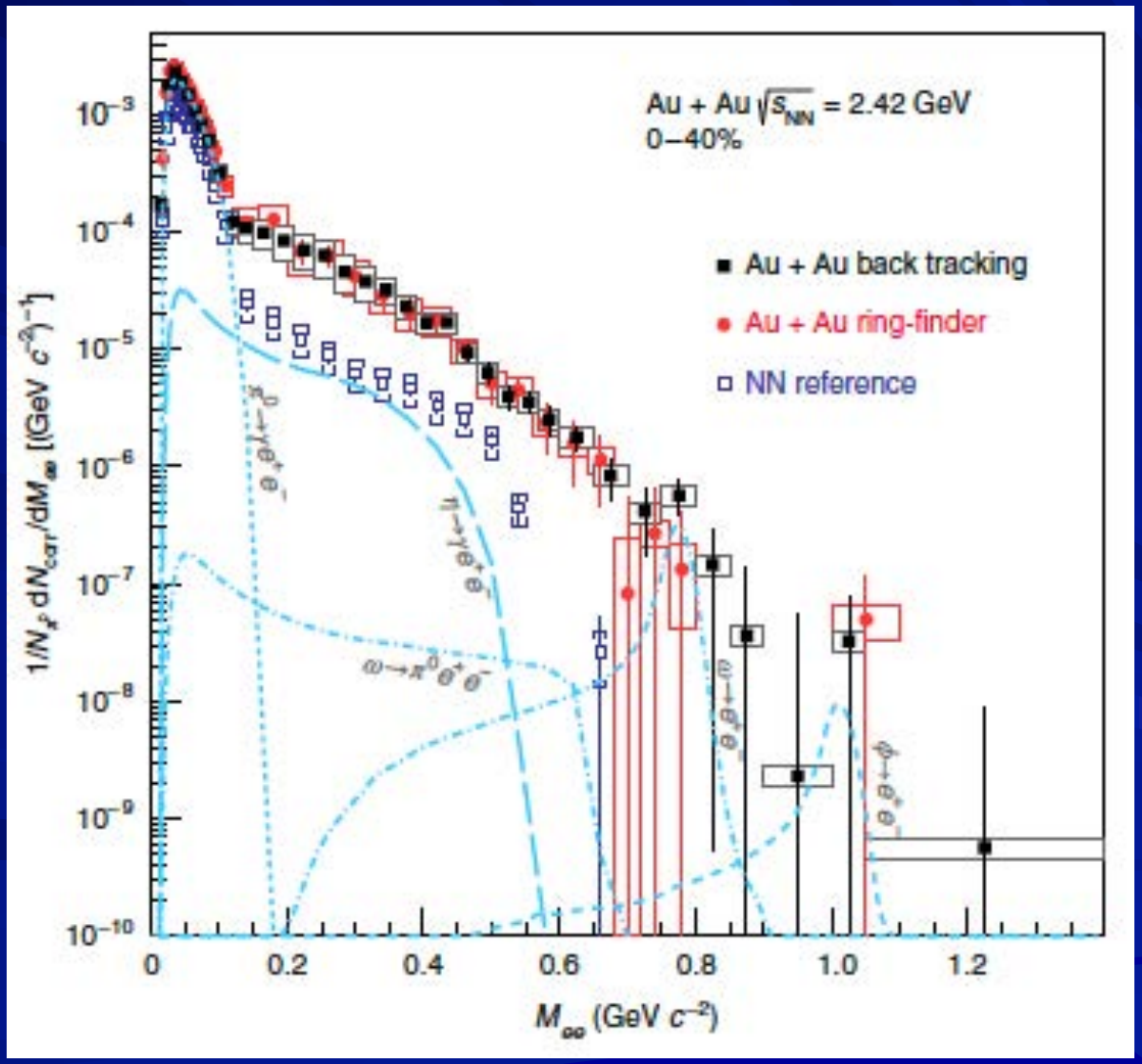
Minimum bias data/cocktail

0.3-0.76 (GeV/c^2)	Data/cocktail $\pm$stat $\pm$syst $\pm$model
PHENIX 2010	$2.3 \pm 0.4 \pm 0.4 \pm 0.2$ (Pythia) $1.7 \pm 0.3 \pm 0.3 \pm 0.2$ (MC@NLO)
STAR	$1.76 \pm 0.06 \pm 0.26 \pm 0.29$

Consistent results between PHENIX and STAR

SIS 18: HADES dileptons

Nature Physics 15, 1040 (2019)

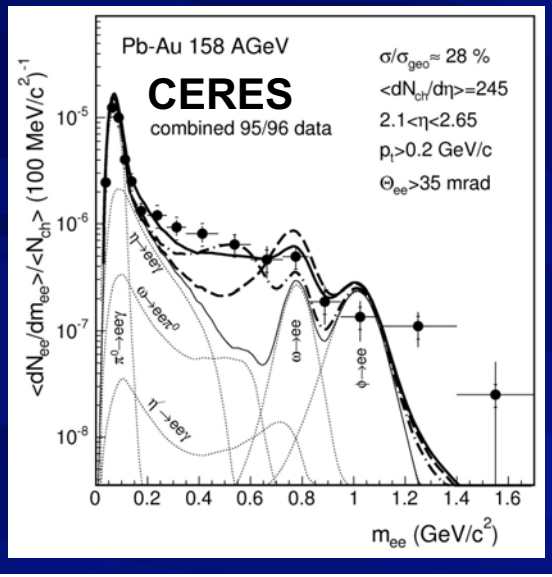


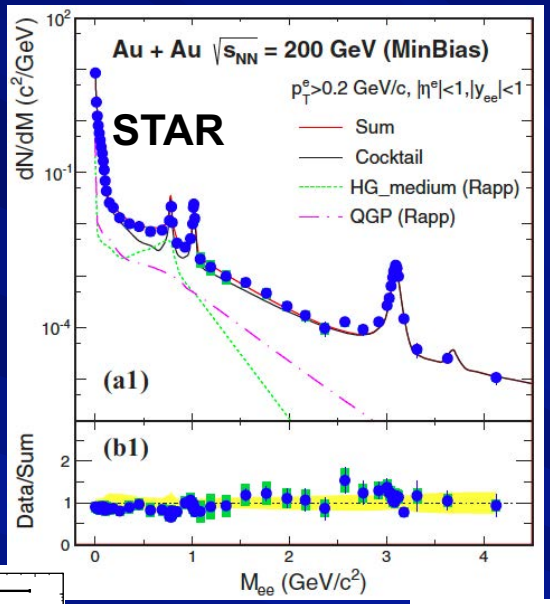
After ~25 years of dilepton measurements

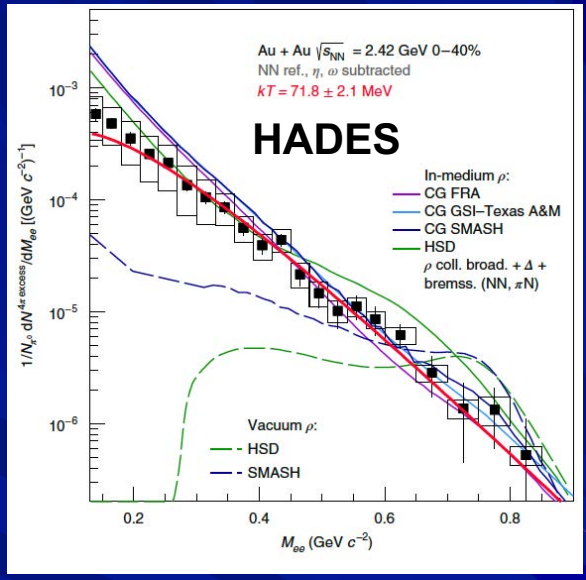
- All HI systems at all energies studied show an excess of dileptons wrt to hadronic sources
- Excess consistently reproduced by microscopic many body model (Rapp et al.)

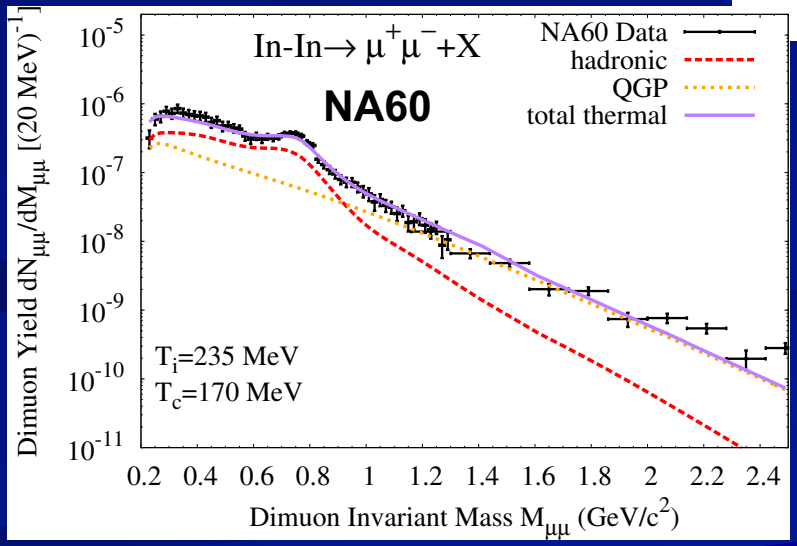
All results reproduced by one single model

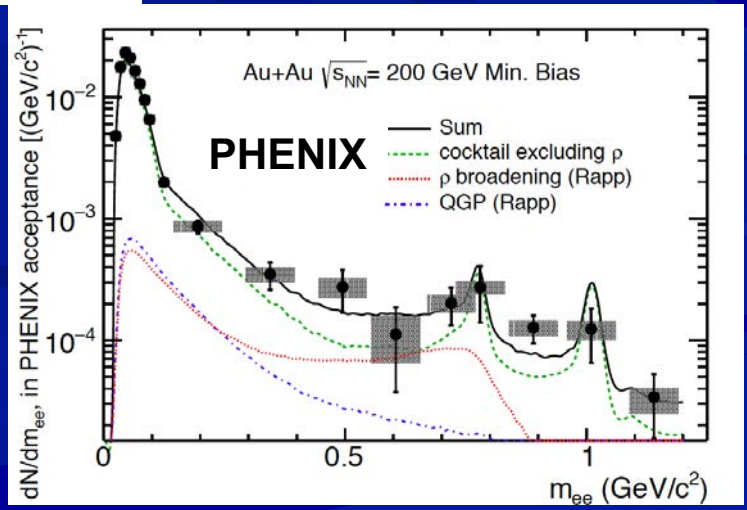
- Vacuum ρ meson fails to reproduce the data.
- Good agreement with models based on ρ meson in-medium broadening – Linked to CSR







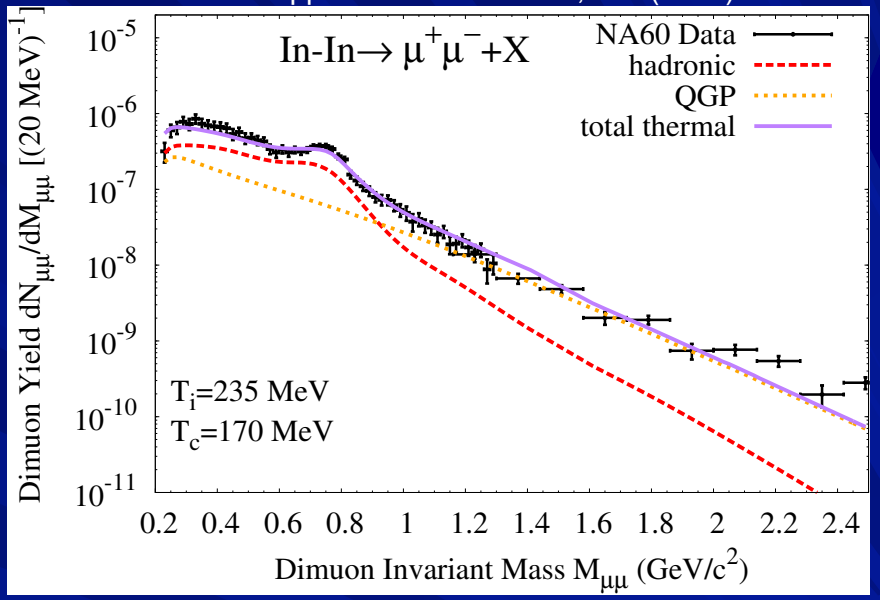




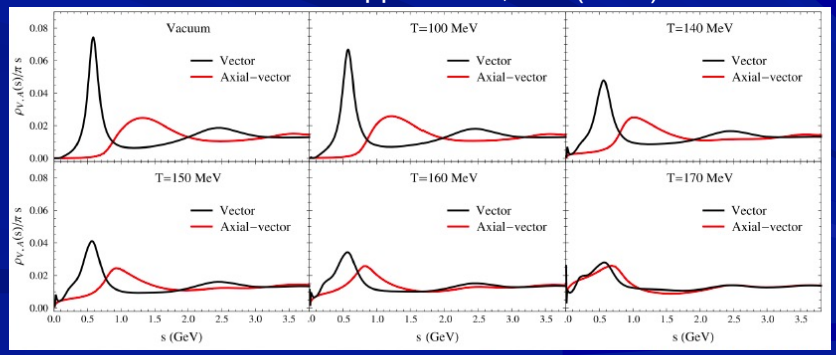
After ~25 years of dilepton measurements

- 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)

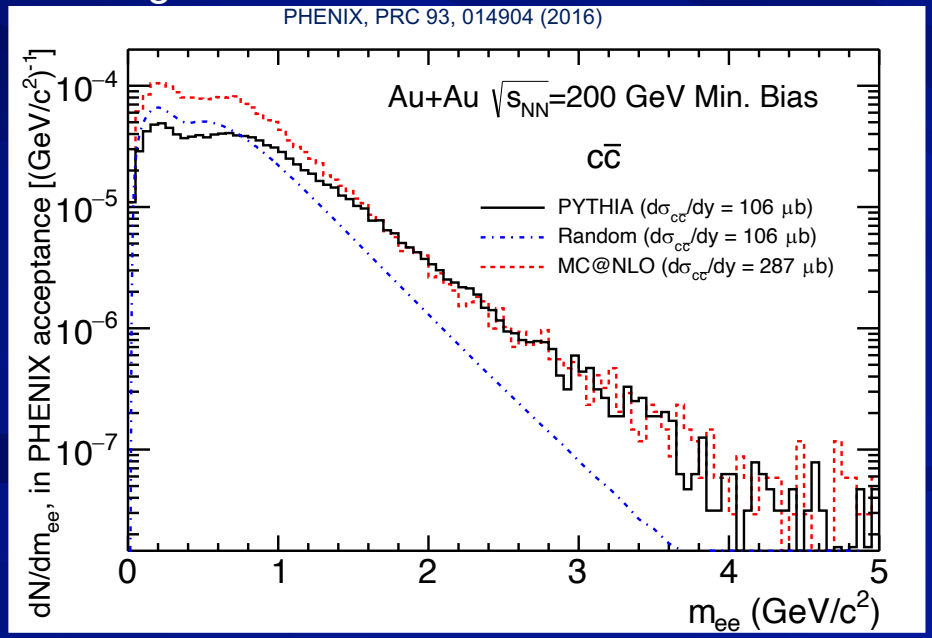


- One of the few effects exclusively observed in AA collisions

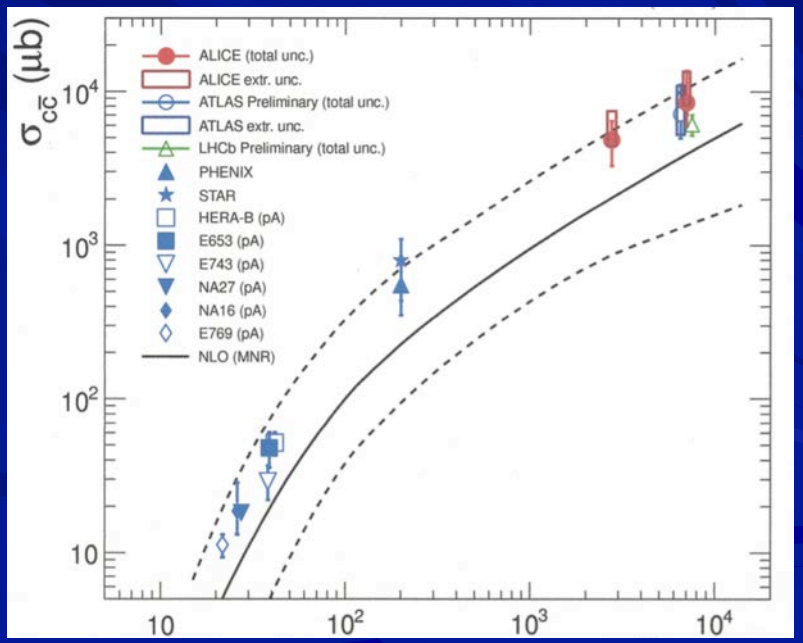
What is missing (I)?

- 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 higher 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



Charm cross section in pp

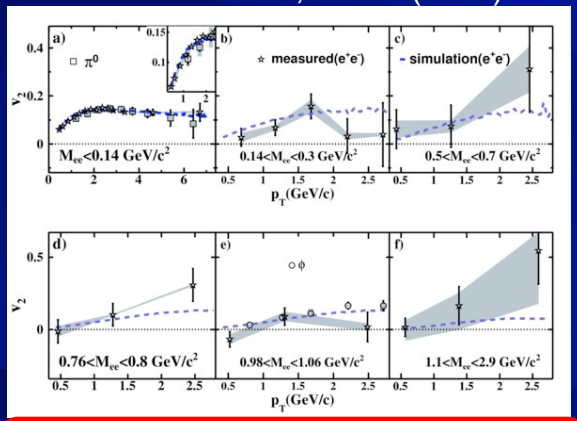


What is missing (II)?

- 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>

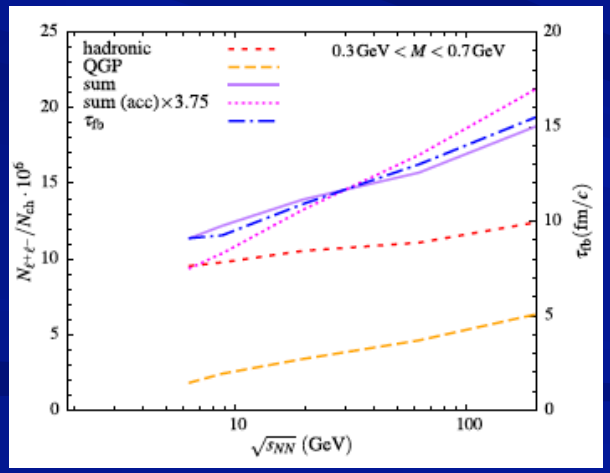
    First order phase transition?
  - Thermal radiation down to $\sqrt{s_{NN}}$ – 6 GeV ?
- v_2 of thermal radiation
  - Very challenging measurement
  - Could provide an independent confirmation about the origin of the thermal radiation

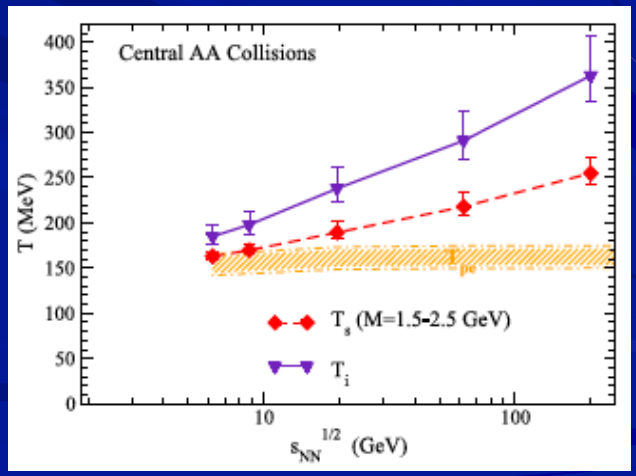
Inclusive dielectron v_2
STAR PRC 90, 64904 (2014)



Challenge: isolate the v_2 of the excess dileptons

Rapp and Hees, PLB 753, 586 (2016)

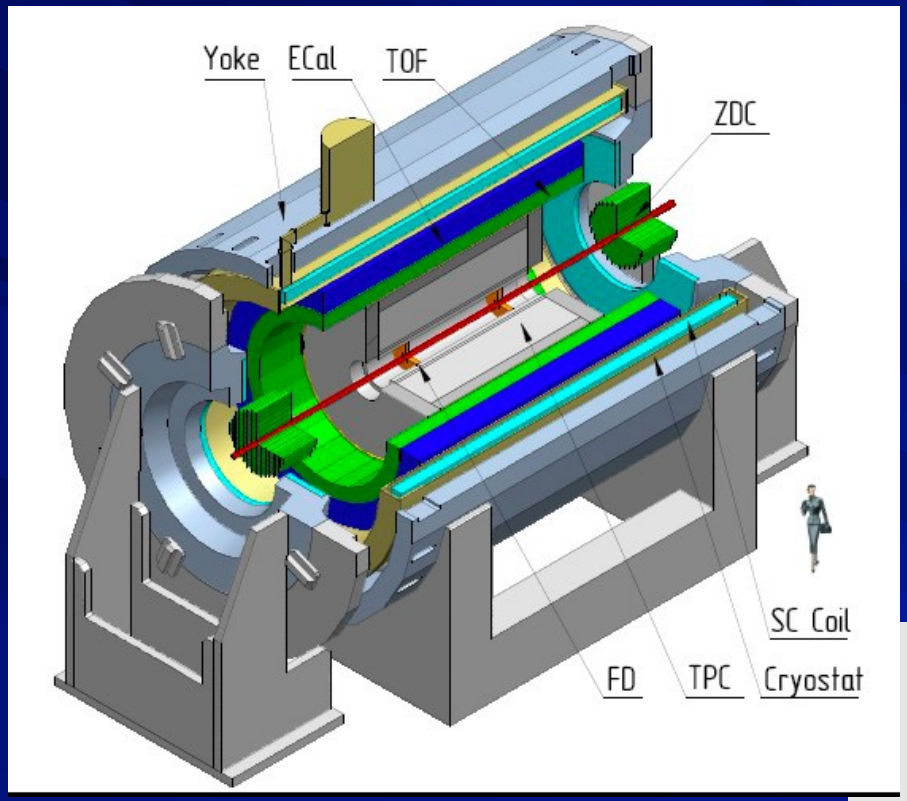




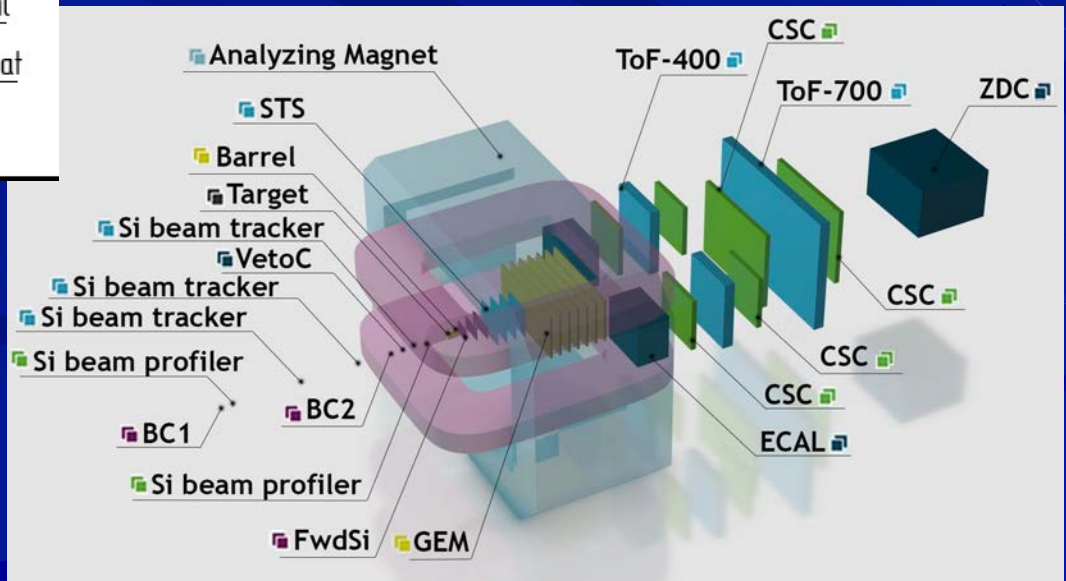
❑ NICA experiments well suited for dilepton studies

MPD and BM@N Experiments

MPD Stage I

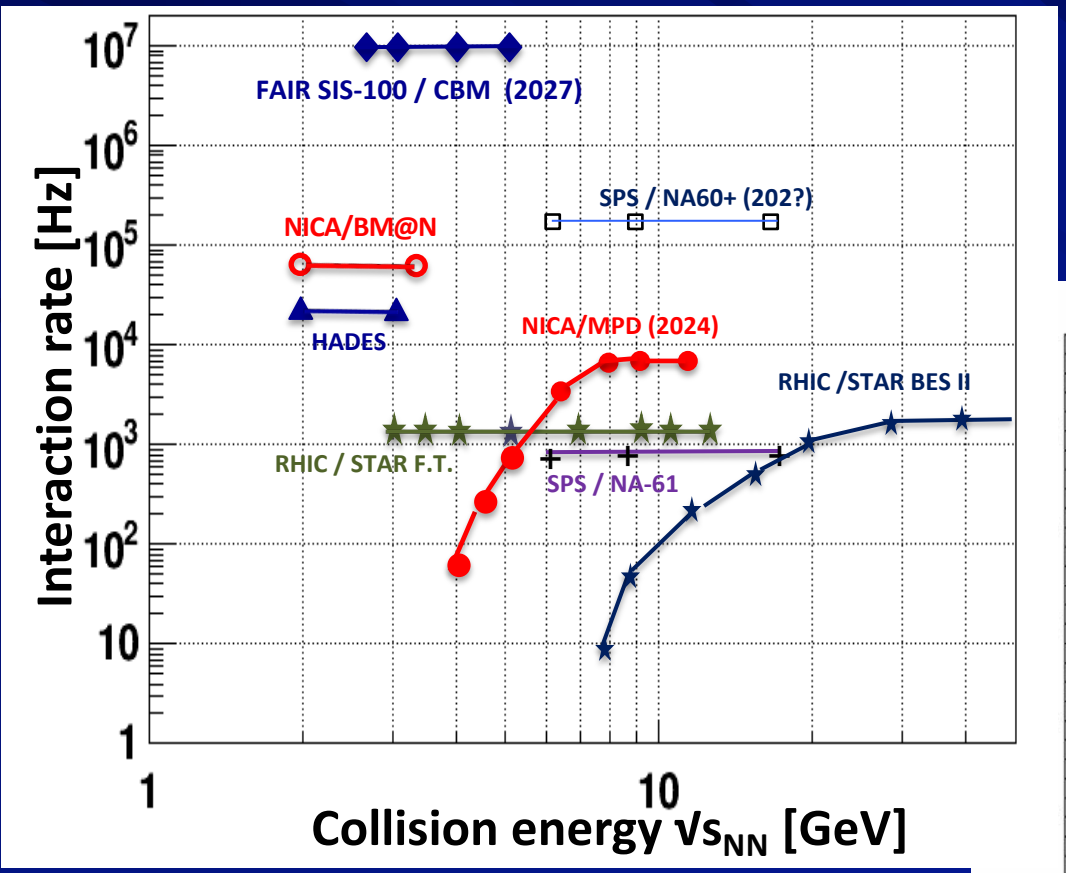


BM@N set-up for HI runs

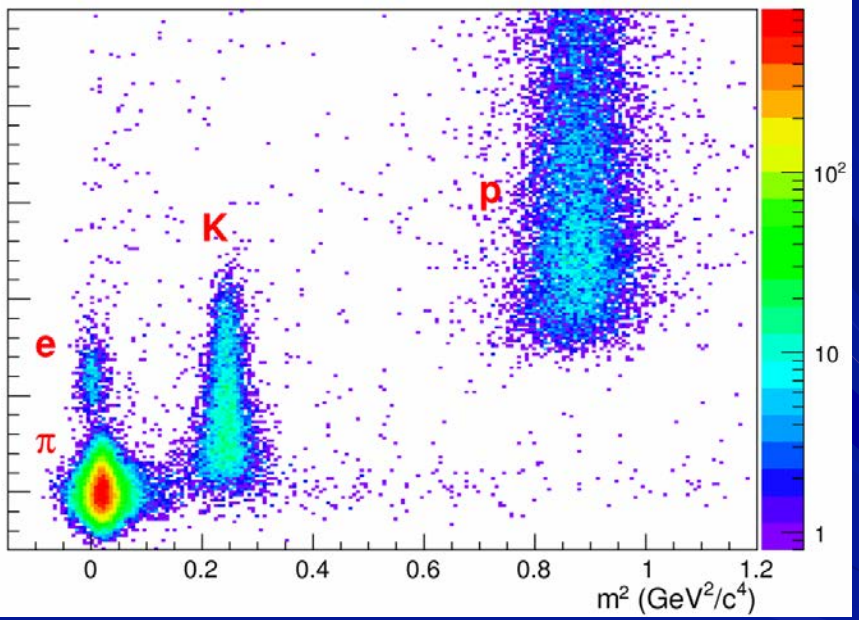


MPD Experiment

Interaction rate



Particle identification



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

Summary

- NICA dedicated HI facility for comprehensive exploration of high μ_B matter with potential of discoveries
- Exciting dilepton prospects at NICA energies - MPD well suited for dilepton studies
- Looking forward to the start of the NICA physics program


Happy Birthday !