Dileptons at low energies: Prospects and challenges

CPOD 2017
Stony Brook University, August 7-11, 2017

Itzhak Tserruya

WEIZMANN INSTITUTE OF SCIENCE

Outline

- Motivation
- What did we learn from almost 25 years of dilepton measurements at SPS and RHIC
- Prospects and challenges at low energies
- Summary

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.

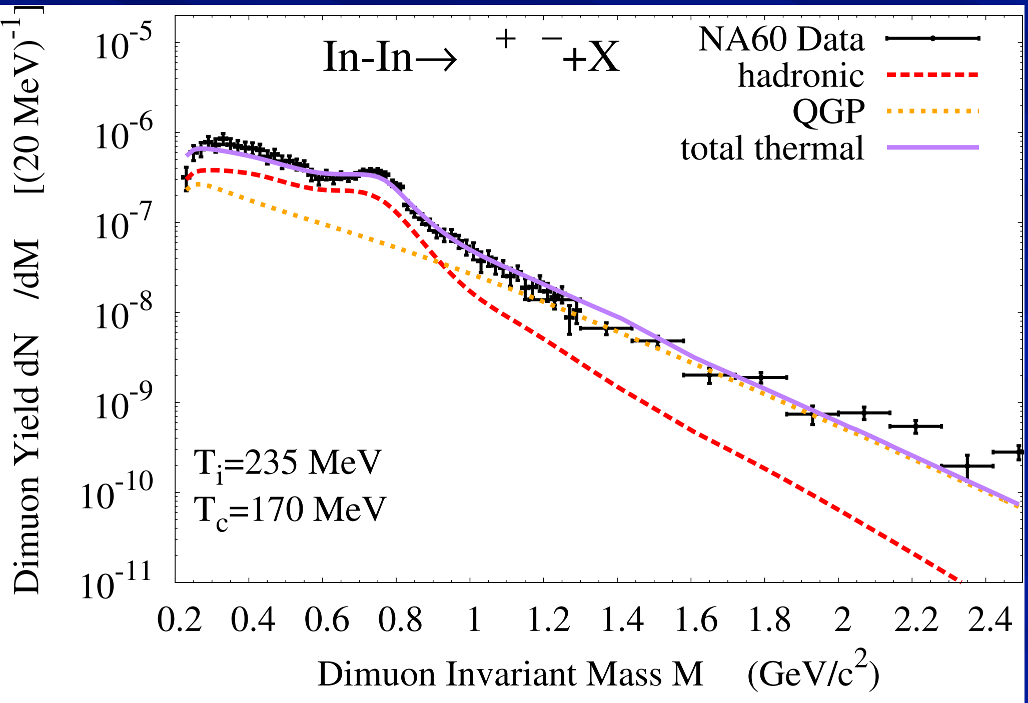
$$\text{QGP:} \quad q\bar{q} \longrightarrow \gamma^* \longrightarrow l^+l^-$$

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

NA60 Acceptance corrected invariant mass spectrum

NA60 dimuon excess corrected for acceptance in m - p_T

Rapp and Hees PLB 753, 586 (2016)
NA60 data: Eur. Phys. J. C 59 (2009) 607



- LMR:
  - Thermal radiation from HG
    $\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$
  - Resonances melt as the system approaches CSR
- IMR:
  - Thermal radiation from QGP
    $q\bar{q} \rightarrow \mu^+\mu^-$

- Low masses (m < 1 GeV/c^2)

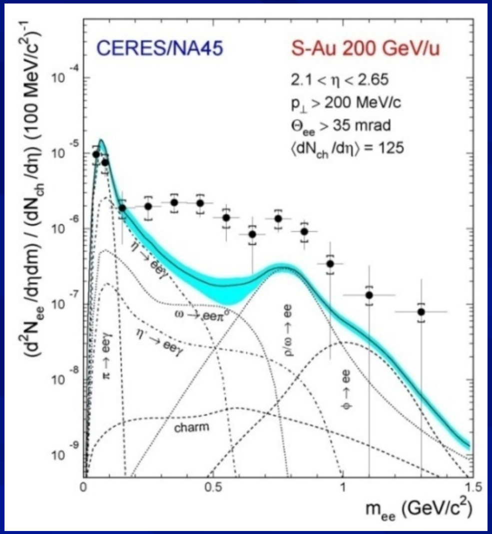
SPS: CERES, NA60

RHIC: PHENIX, STAR

CERES Pioneering Dilepton Results

First CERES result
PRL 75, 1272 (1995)

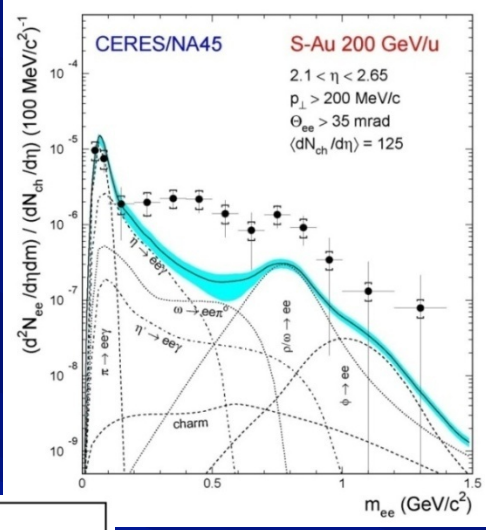
(renowned paper: 579 citations)

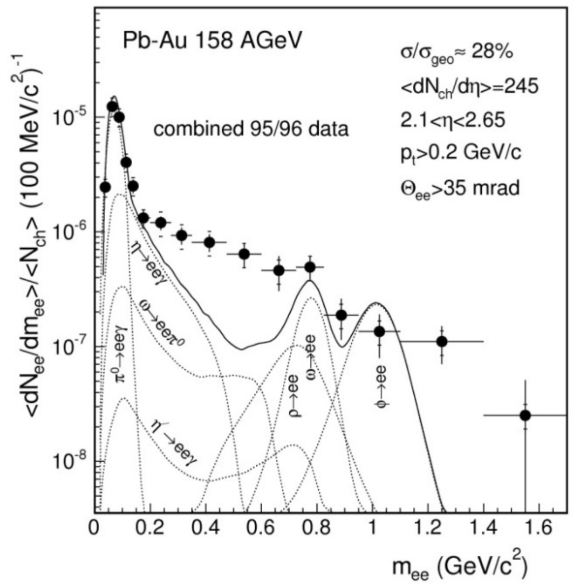


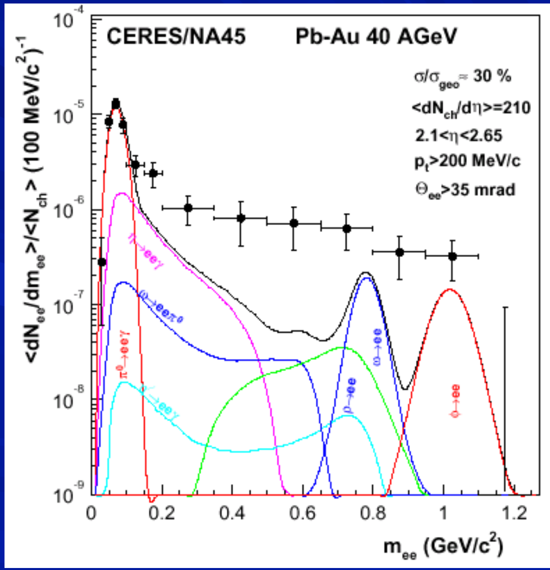
CERES Pioneering Dilepton Results

First CERES result
PRL 75, 1272 (1995)

(renowned paper: 579 citations)







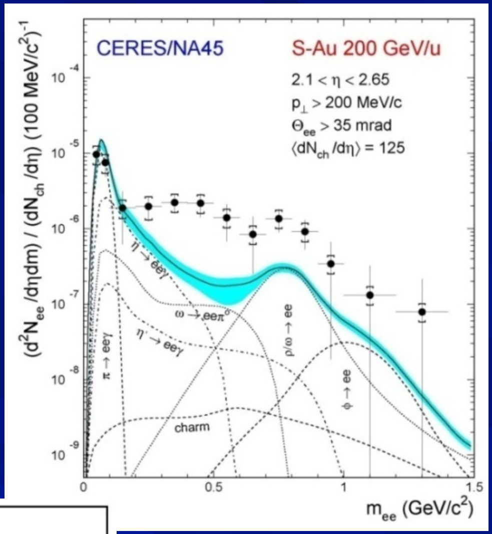
Eur. Phys J. C41, 475 (2005)

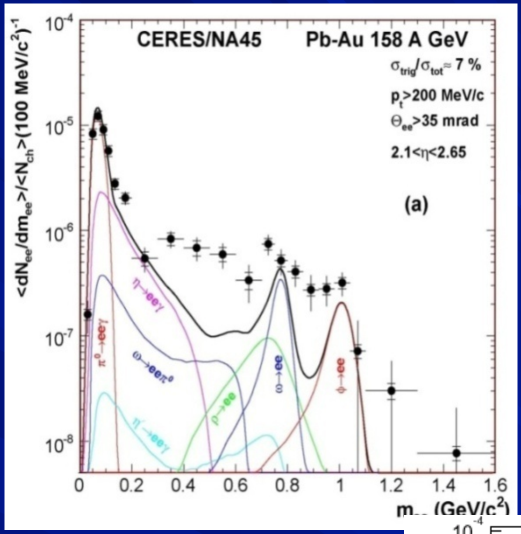
PRL 91, 042301 (2003)

CERES Pioneering Dilepton Results

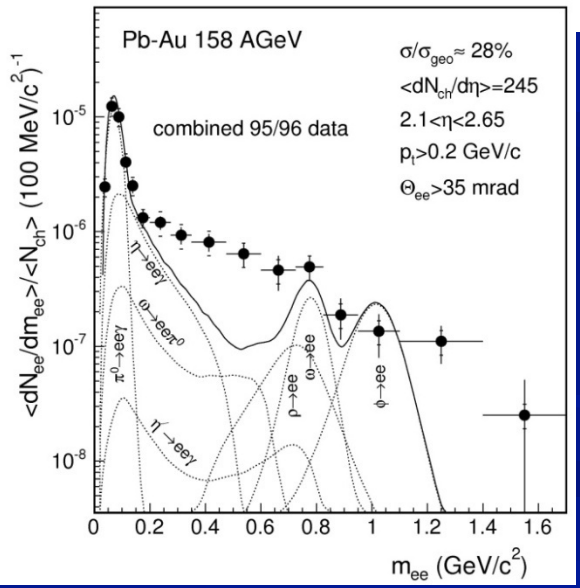
First CERES result
PRL 75, 1272 (1995)

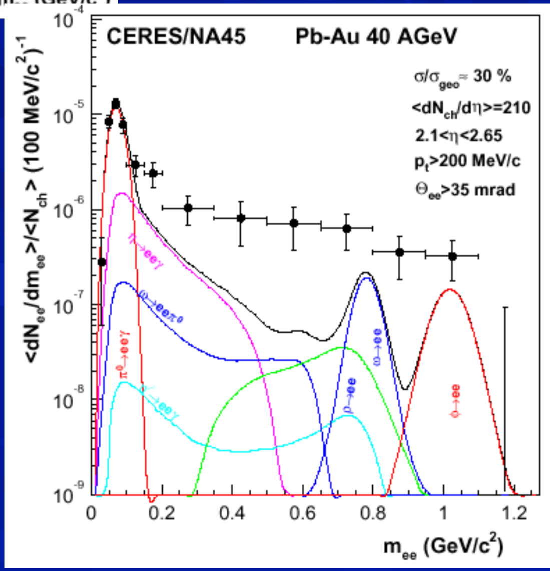
(renowned paper: 579 citations)





Last CERES result
PLB 666, 425 (2008)





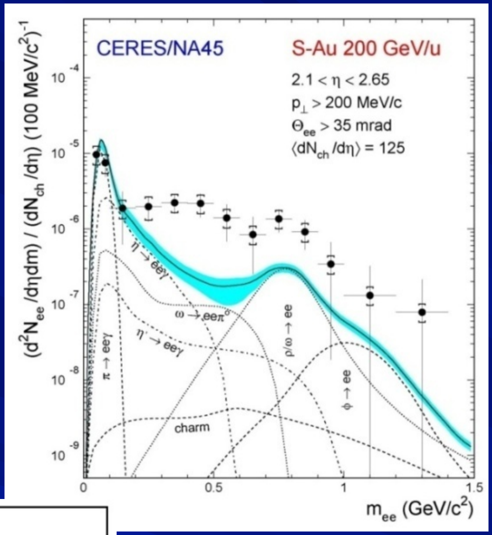
Eur. Phys J. C41, 475 (2005)

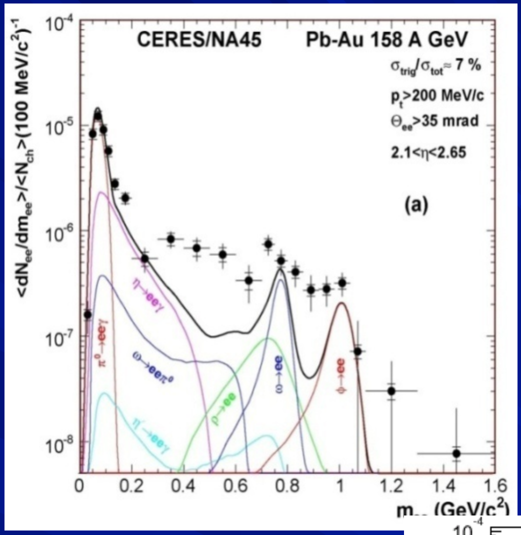
PRL 91, 042301 (2003)

CERES Pioneering Dilepton Results

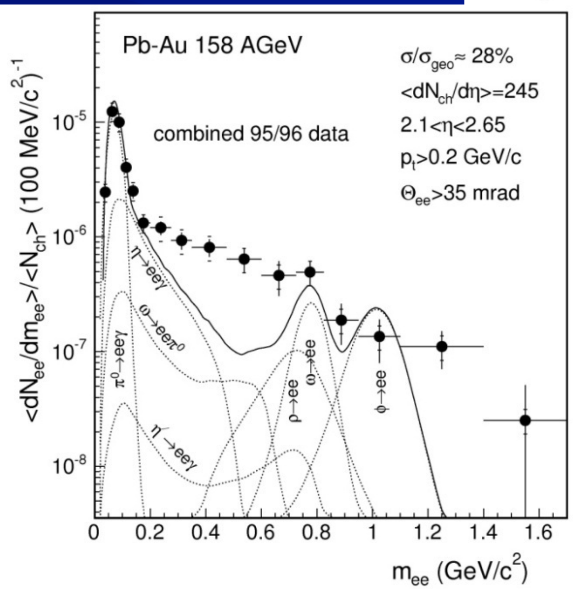
First CERES result
PRL 75, 1272 (1995)

(renowned paper: 579 citations)



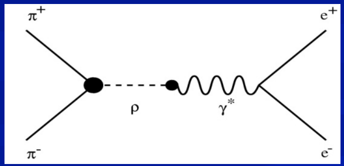


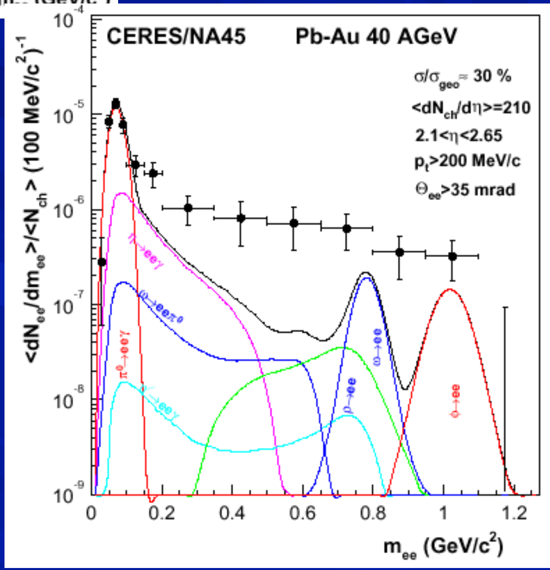
Last CERES result
PLB 666, 425 (2008)



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

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



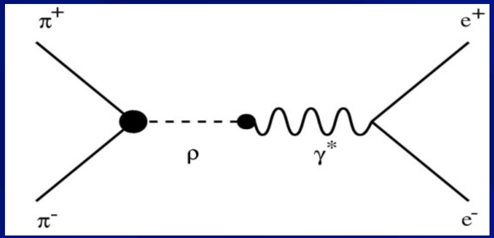


Eur. Phys J. C41, 475 (2005)

PRL 91, 042301 (2003)

Dropping Mass or Broadening (I) ?

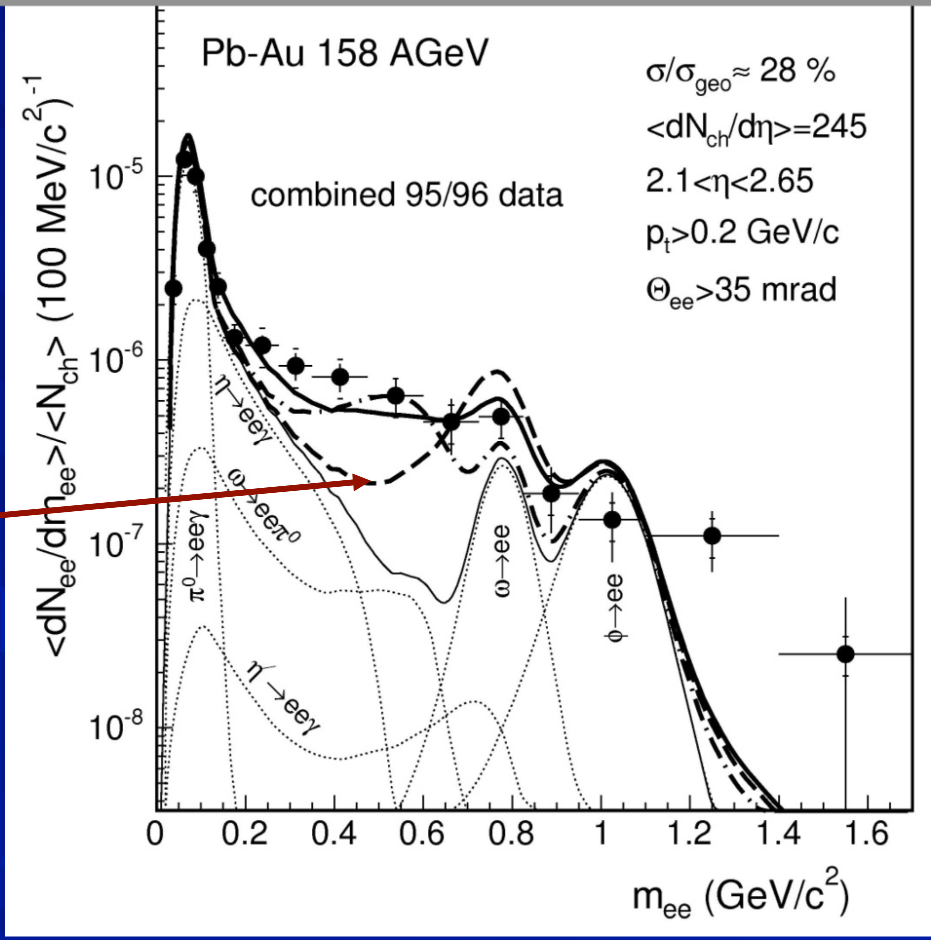
* Interpretations invoke:
$\pi^+\pi^- \rightarrow \rho \rightarrow \gamma^* \rightarrow e^+e^-$



thermal radiation from HG

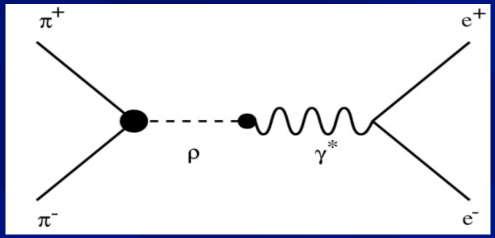
* vacuum ρ not enough to reproduce data

CERES Pb-Au 158 A GeV 95/96 data



Dropping Mass or Broadening (I) ?

* Interpretations invoke:
$\pi^+\pi^- \rightarrow \rho \rightarrow \gamma^* \rightarrow e^+e^-$



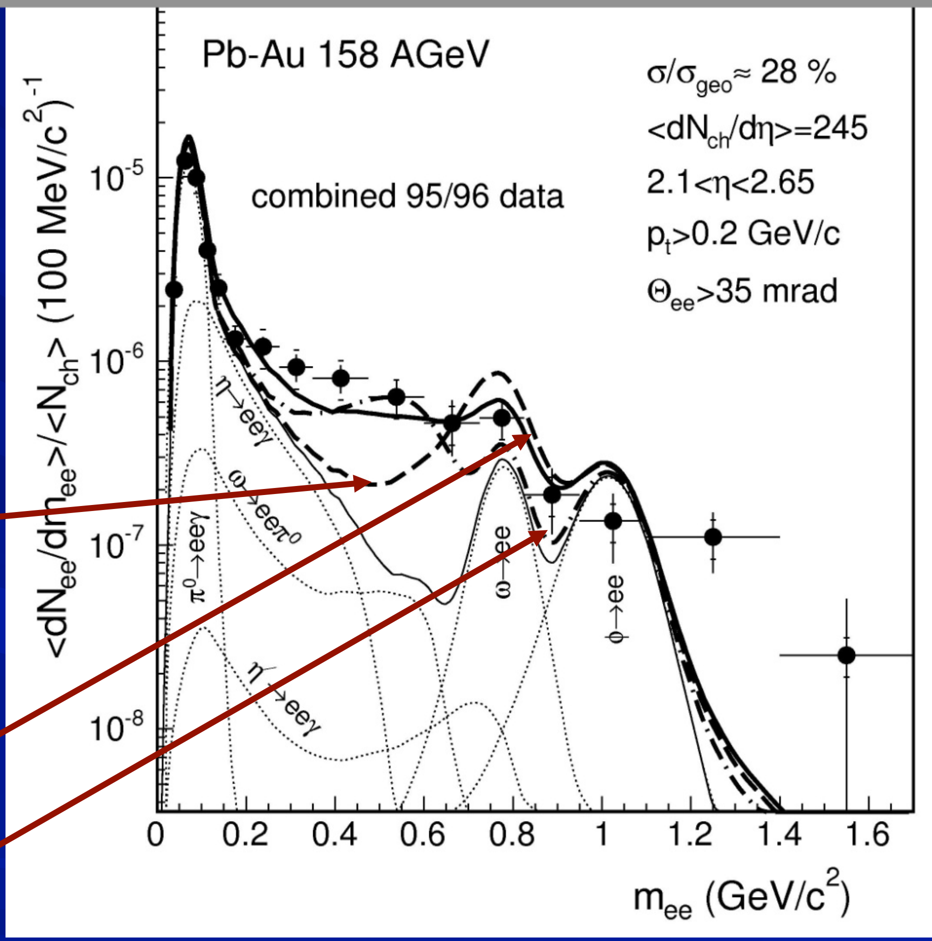
thermal radiation from HG

* vacuum ρ not enough to reproduce data

* in-medium modifications of ρ:

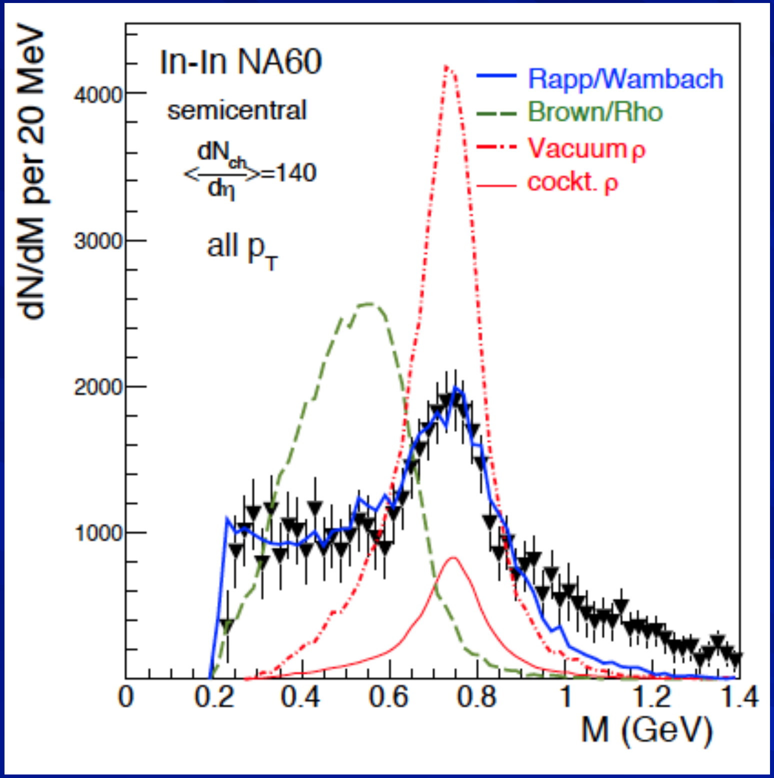
- broadening ρ spectral shape (Rapp and Wambach)
- dropping ρ meson mass (Brown et al)

CERES Pb-Au 158 A GeV 95/96 data



Low-mass dileptons and in-medium ρ

NA60, PRL 96, 162302 (2006)



- ❑ **Excess shape in agreement with broadening of the ρ mainly due to the scattering of ρ off baryons (Rapp-Wambach)**
- ❑ **Dropping mass of the ρ (Brown-Rho) ruled out**
- ❑ **Confirmed by CERES results** (PLB 666, (2008) 425)
- ❑ **Melting of the ρ**

Low-mass e^+e^- Pairs: Prospects at RHIC

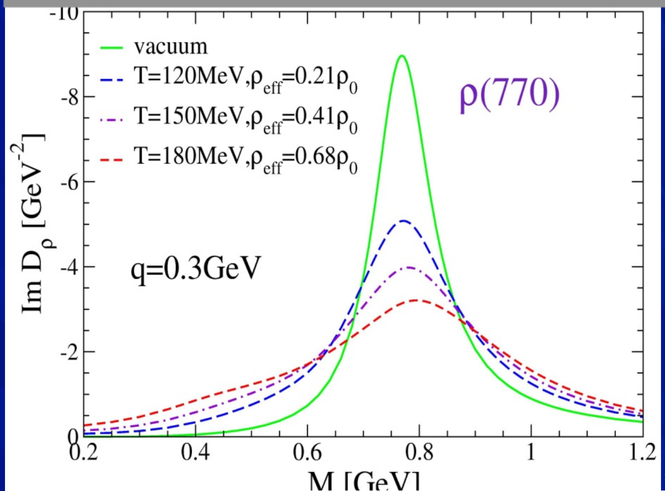
- At SPS energies, the ρ-meson broadening, that explains both the CERES and NA60 data, relies on the high baryon density.
- What was expected at RHIC?

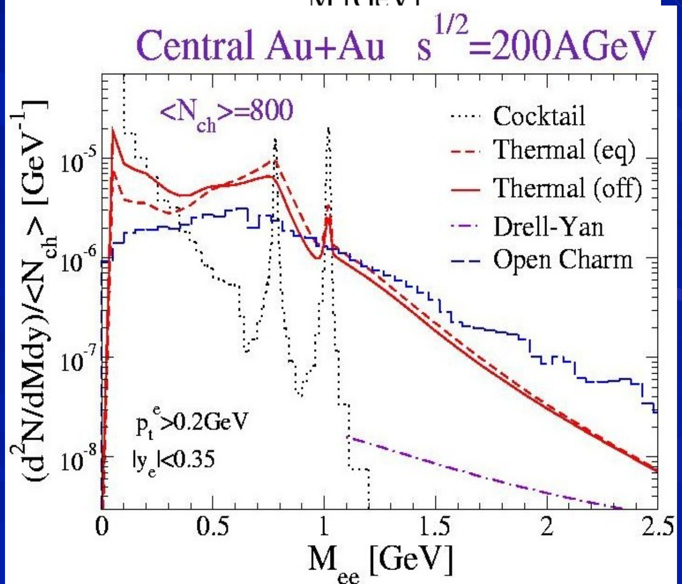
	SPS (Pb-Pb)	RHIC (Au-Au)
dN($\bar{p}$) / dy Produced baryons ($\bar{p}$, p, $\bar{n}$, n)	6.2 24.8	20.1 80.4
p – $\bar{p}$ Participants nucleons ($\bar{p}$ – p)A/Z	33.5 85	8.6 21.4
Total baryon density	110	102

- Baryon density is almost the same at RHIC and SPS (the decrease in the participating nucleons transported to mid-rapidity is compensated by the copious production of nucleon-antinucleon pairs)

Strong enhancement of low-mass pairs predicted to persist at RHIC

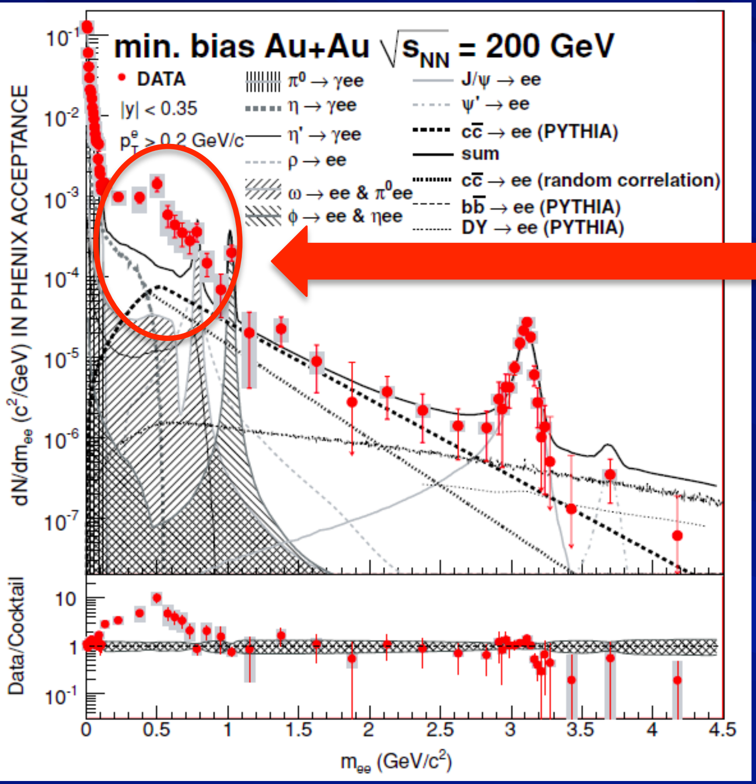
R. Rapp nucl-th/0204003



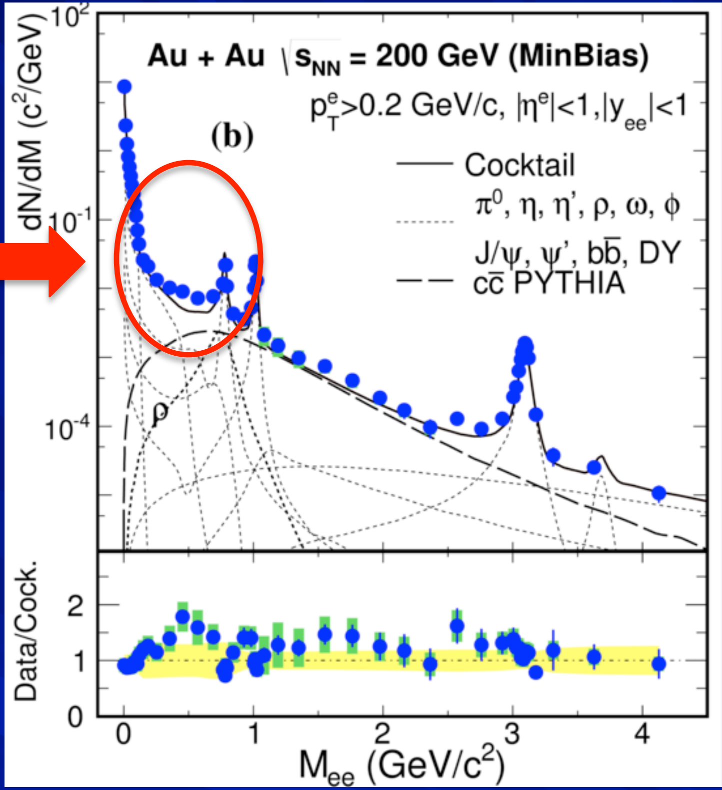


PHENIX vs. STAR

PHENIX PRC 81, 034911 (2010)



STAR PRL 113, 22301 (2014)



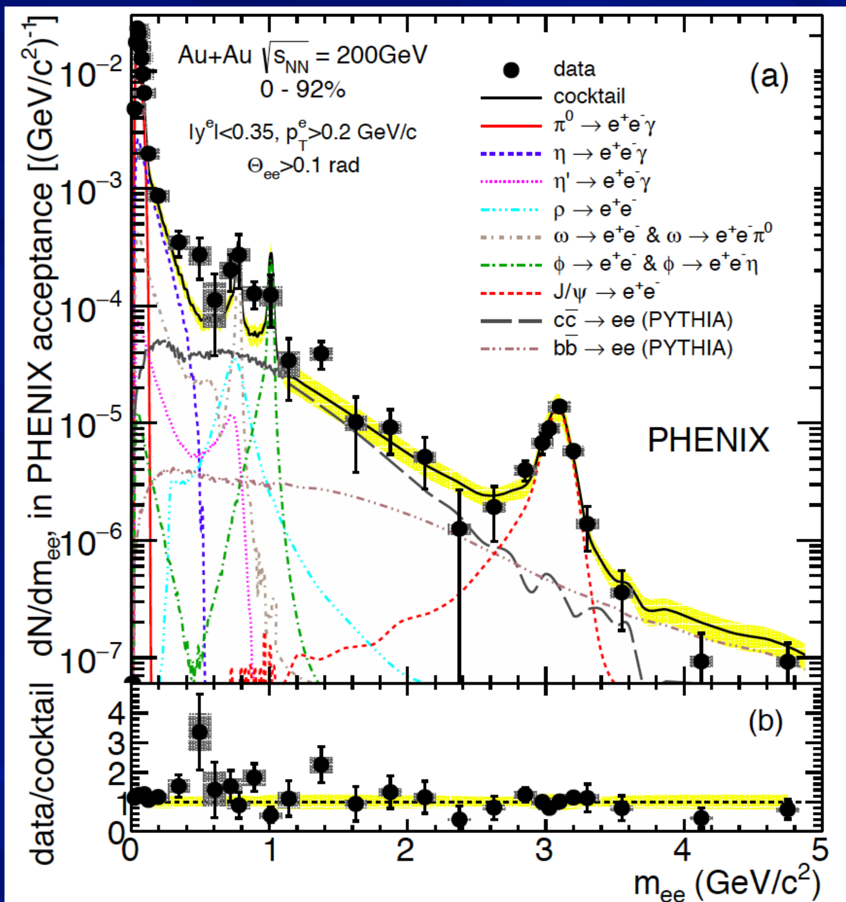
Enhancement factor in $0.15<M_{ee}<0.75$ Gev/c^2

	Minimum Bias	Central collisions
PHENIX	4.7 ± 0.4 ± 1.5	7.6 ± 0.5 ± 1.3
STAR	1.40 ± 0.06 ± 0.38	1.54 ± 0.09 ± 0.45

Large quantitative differences

Last PHENIX results

PRC 93, 014904 (2016)



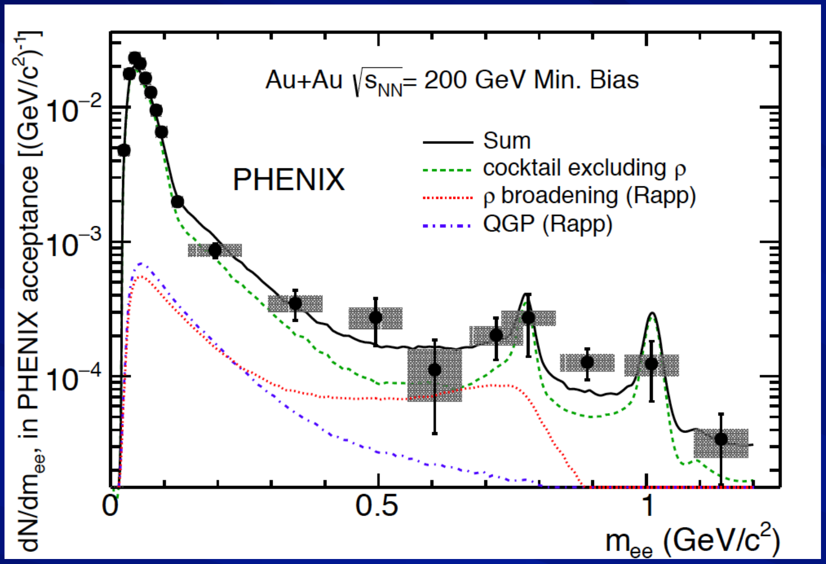
- HBD upgrade:
  - Improved hadron rejection: 30% → 5%
  - Improved signal sensitivity
- New improved analysis
  - Neural network for e-id
  - Flow modulation incorporated in the mixed event using an exact analytical method
  - Absolutely normalized correlated BG

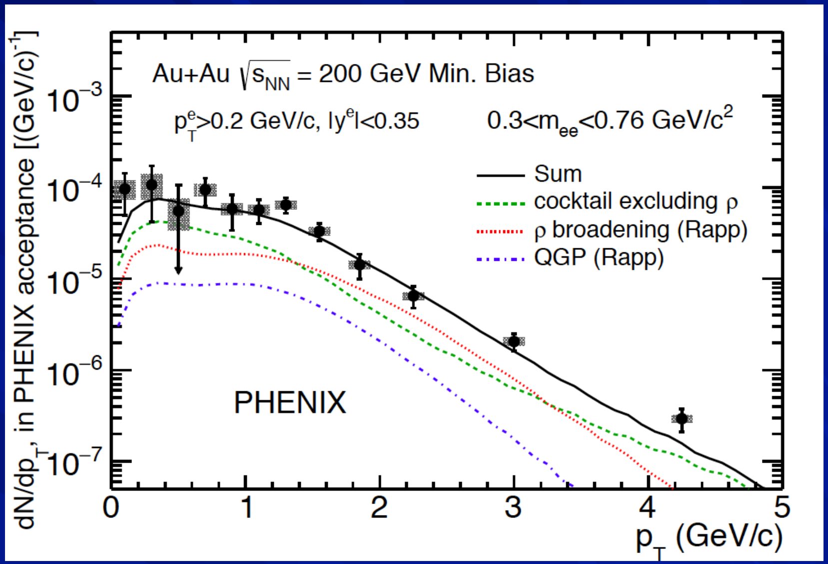
Minimum bias data/cocktail

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

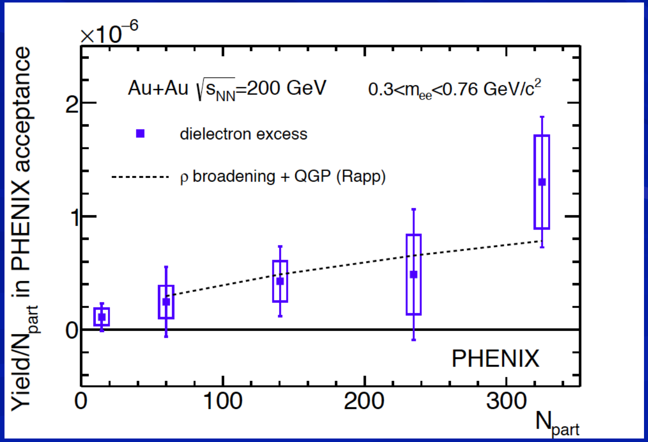
Comparison to Rapp's model



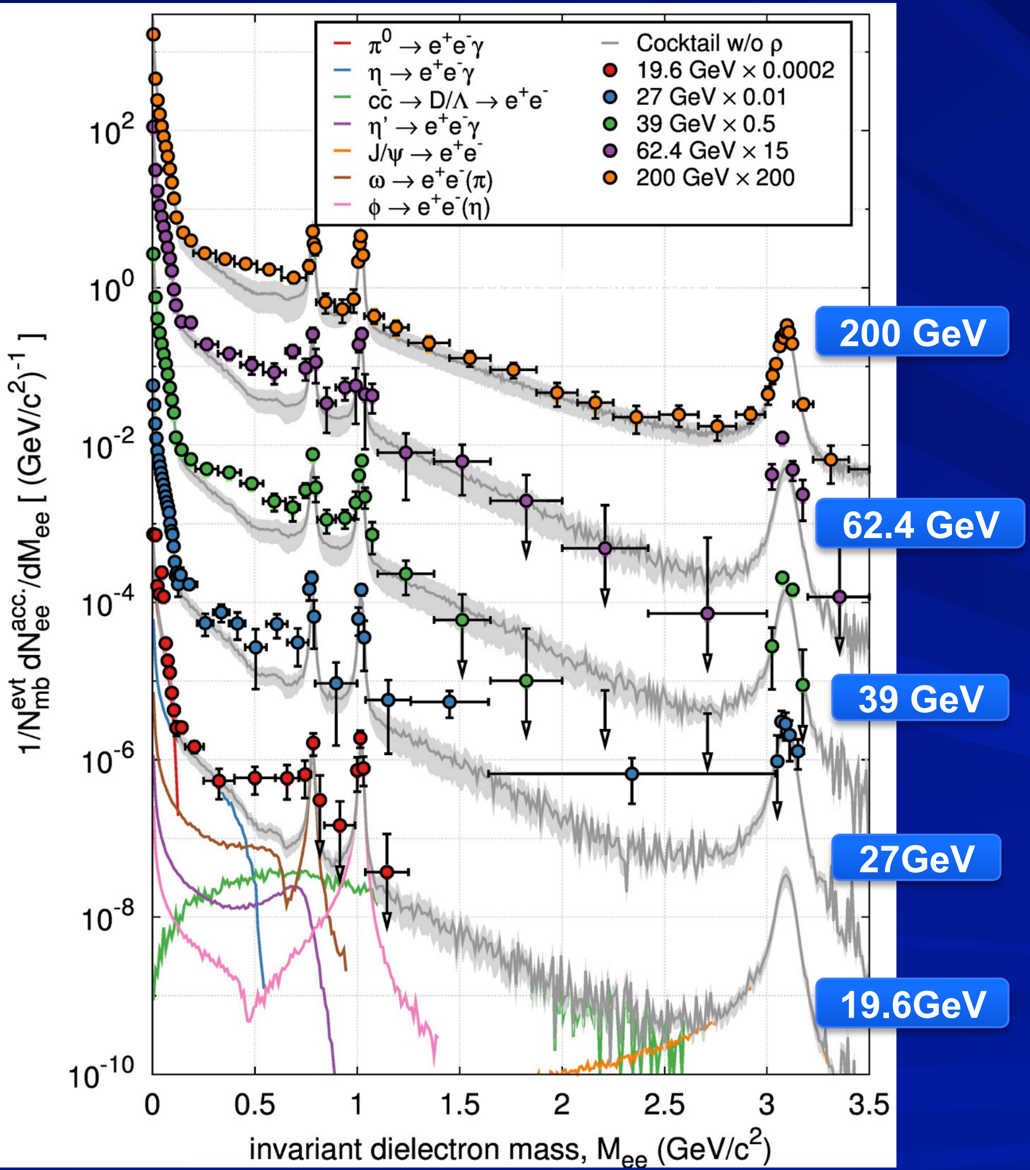


- Mass and p_T dependencies of excess well reproduced by Rapp's model
- In-medium ρ broadening due to the scattering of the ρ off baryons in the HG
- Significant contribution from the QGP at low masses

Centrality dependence consistent with $N_{part}^{1.45}$ as predicted by model.



STAR beam energy scan

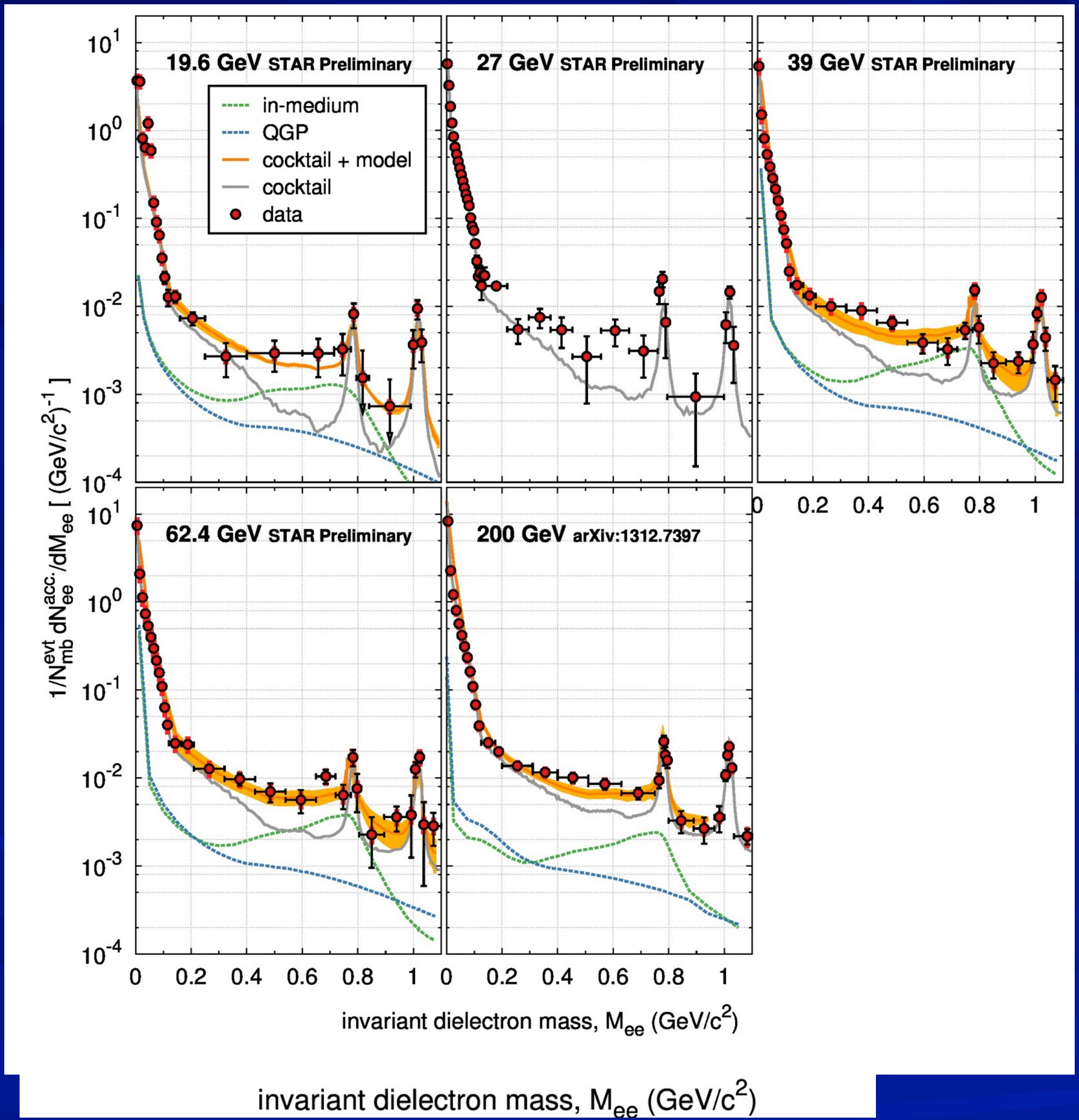


- Systematic study of the dielectron continuum at:

200, 62.4, 39, 27 and 19.6 GeV

- Low mass excess observed at all energies

STAR beam energy scan



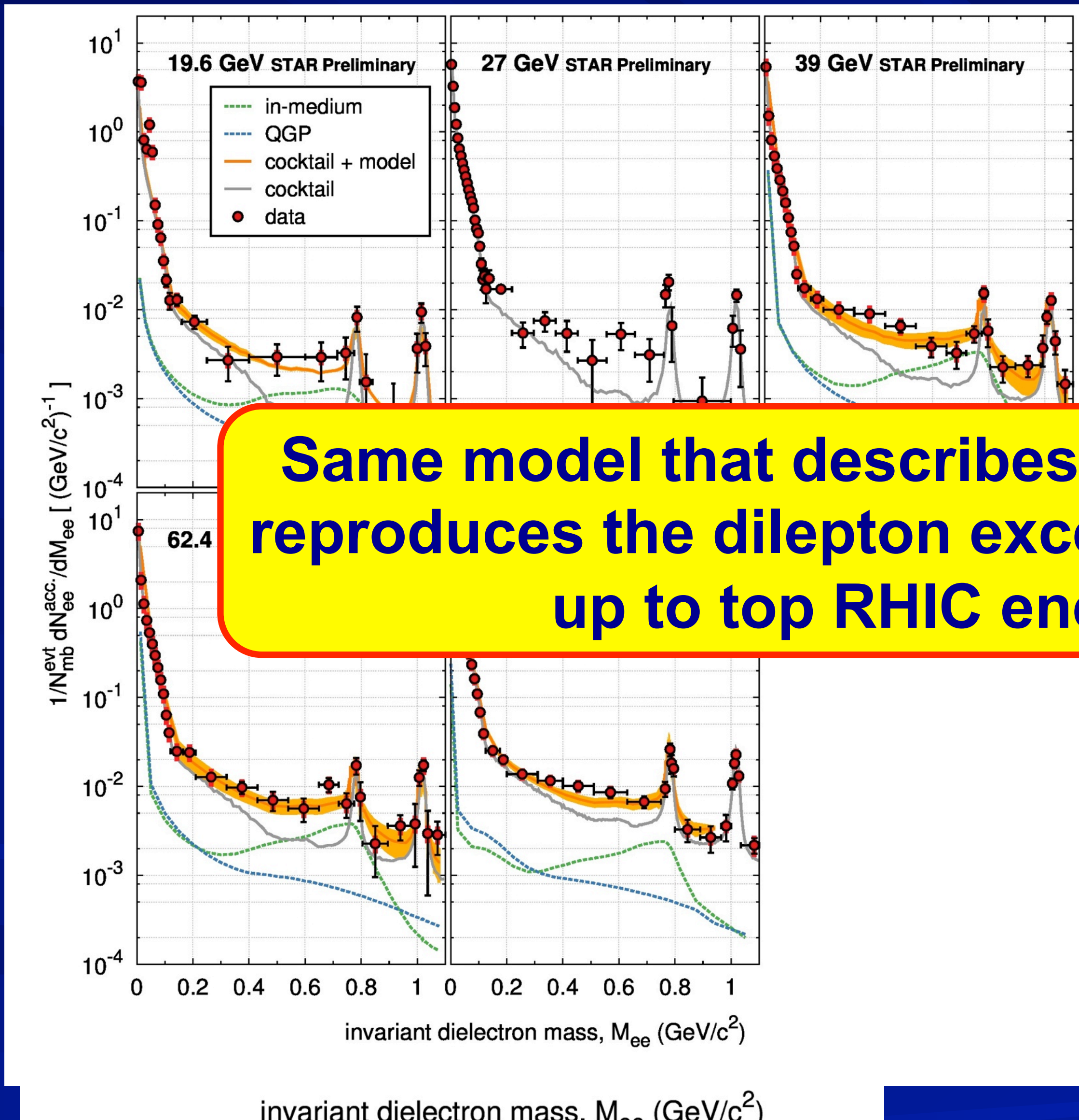
- Systematic study of the dielectron continuum at:

  200, 62.4, 39, 27 and 19.6 GeV

- Low mass excess observed at all energies

- Rapp's model reproduces the excess at all energies.

STAR beam energy scan



Same model that describes the SPS data reproduces the dilepton excess all the way up to top RHIC energy

- Systematic study of the dielectron continuum at:

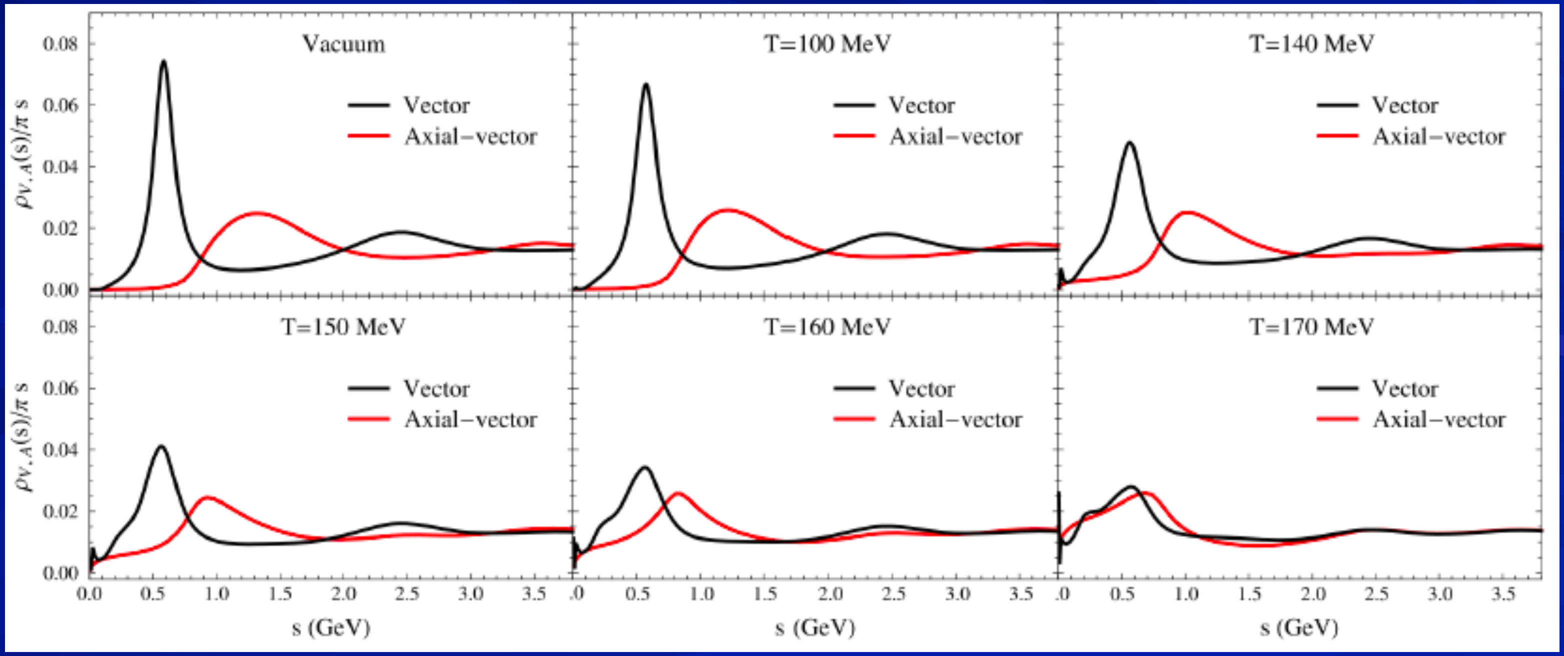
  200, 62.4, 39, 27 and 19.6 GeV

ess
ergies

- Rapp's model reproduces the excess at all energies.

Connection with CSR?

- In-medium broadening of the ρ meson (mainly by scattering off baryons) explains the dilepton excess in the LMR – The ρ meson *"melts"* in the high density medium.
- Is this connected to CSR? The measurement of the chiral partner a_1 is very difficult
- Recent calculations by Hohler and Rapp (PLB 731 (2014) 103) show that ρ and a_1 become degenerate at high temperatures: the ρ broadens as T increases, whereas a_1 mass drops and the spectral shapes of ρ and a_1 coincide at high T.



Intermediate masses

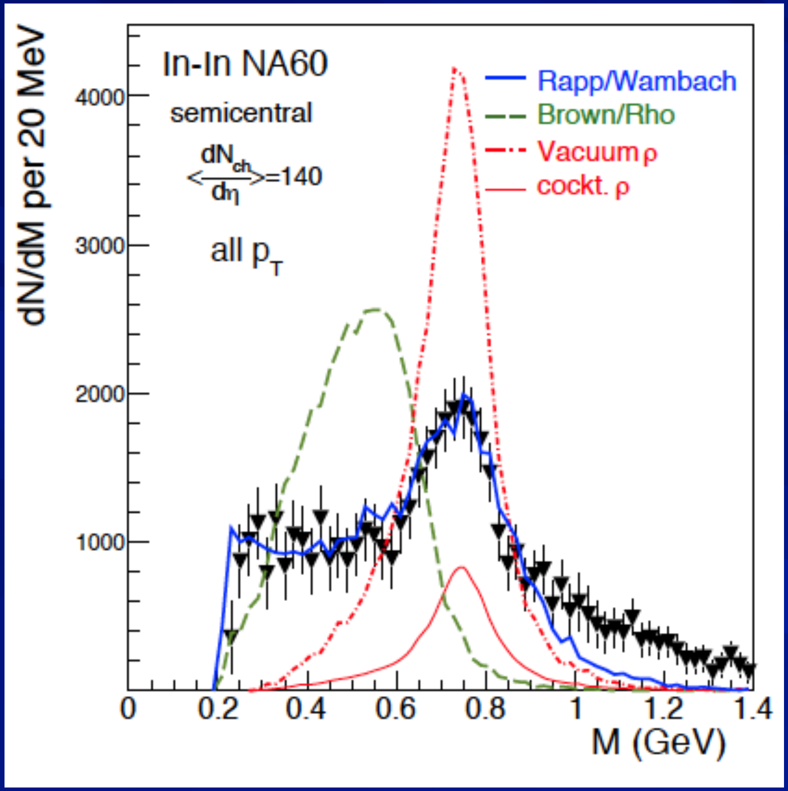
(m = 1-3 GeV/c^2)

SPS: NA60

RHIC: PHENIX and STAR

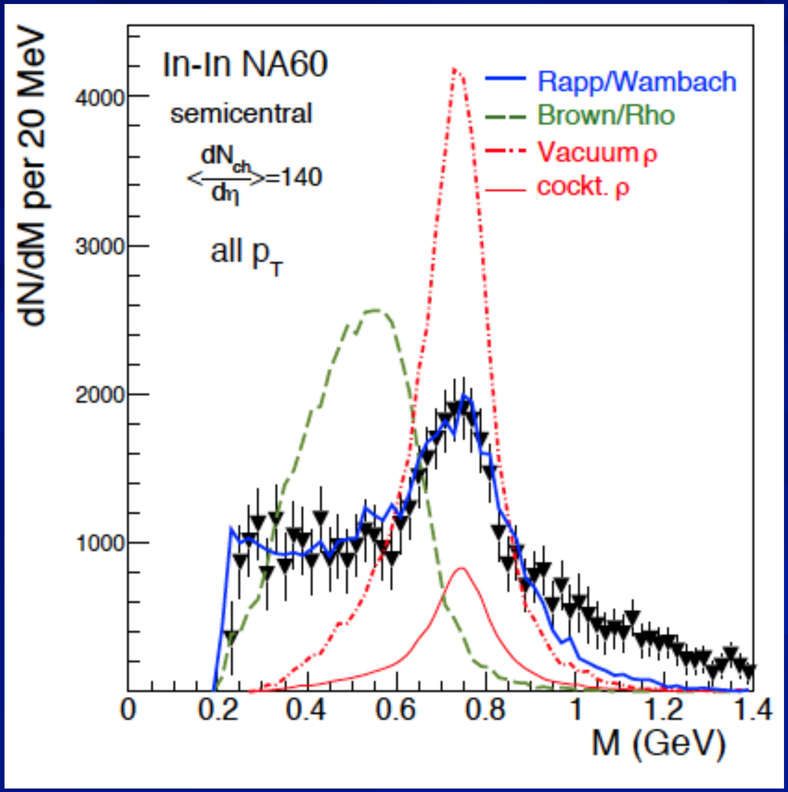
Origin of the IMR Excess

NA60, PRL 96, 162302 (2006)

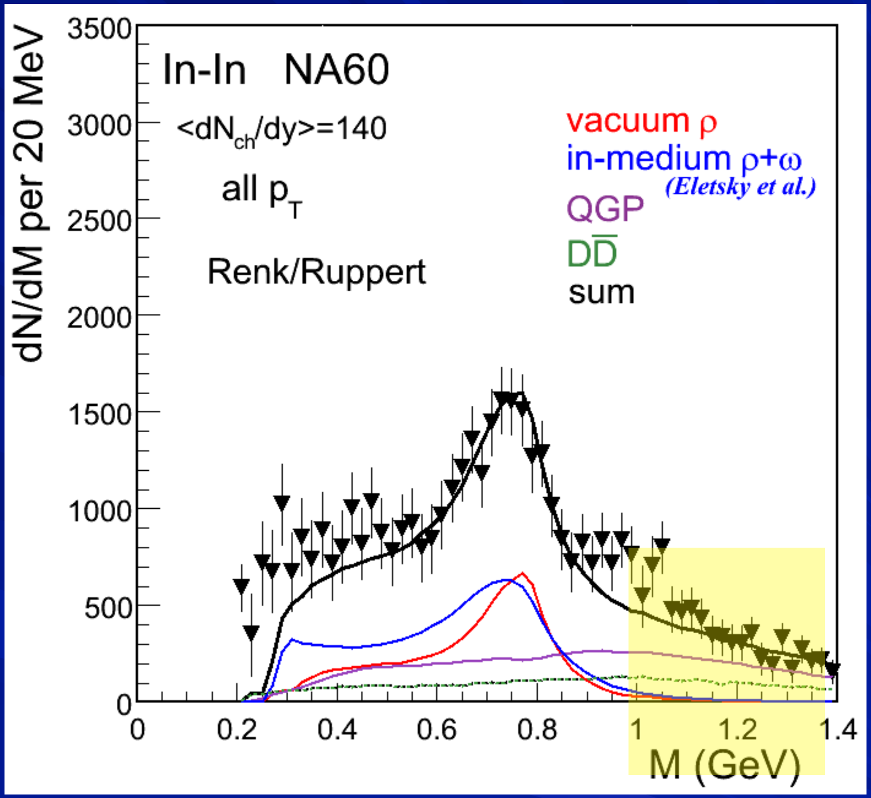


Origin of the IMR Excess

NA60, PRL 96, 162302 (2006)



Renk/Ruppert, PRL 100,162301 (2008)

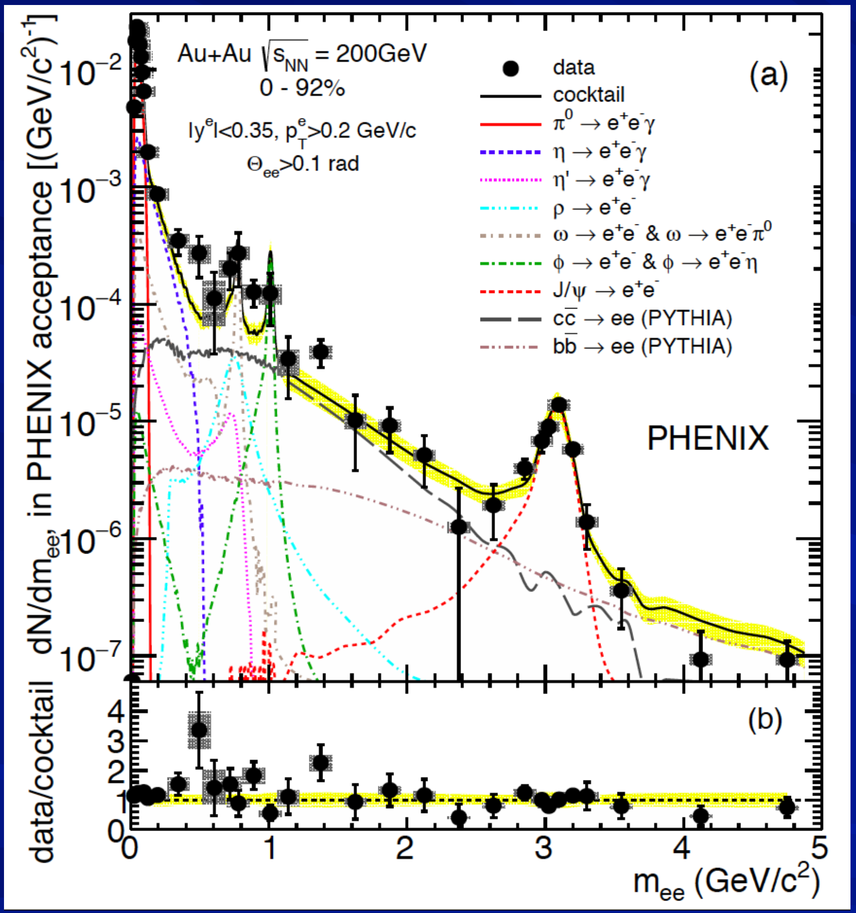


Dominant process in mass region m > 1 GeV/c^2:

$q\bar{q}$ annihilation − thermal radiation from the QGP

Last PHENIX results

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

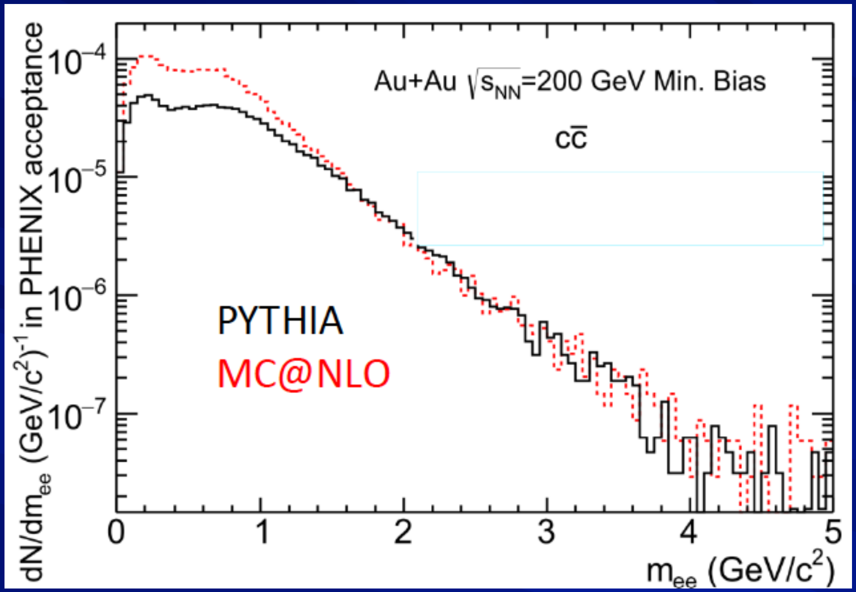
Minimum bias data/cocktail

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

PHENIX and STAR results are now consistent

$c\bar{c}$ in cocktail

PHENIX, PRC 93, 014904 (2016)



- Cross section derived using IMR in d+Au collisions and extrapolating to m~0
  → uncertainty in cross section

PHENIX, PRC 91, 014907 (2015)

	$d\sigma_{c\bar{c}}^{pp}/dy$ (μb)
PYTHIA	$106 \pm 9^{stat} \pm 33^{syst}$
MC@NLO	$287 \pm 29^{stat} \pm 100^{syst}$

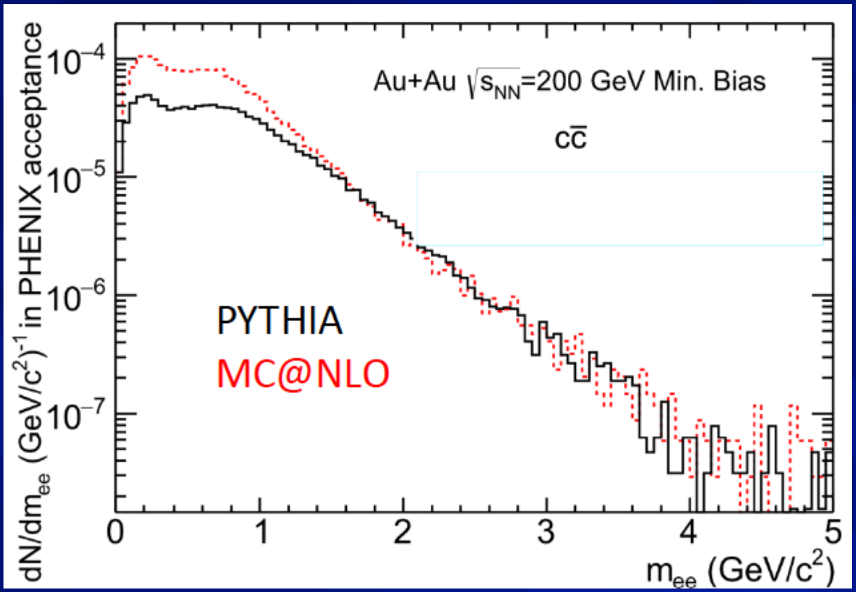
- Hadronic decays of D mesons

STAR, PRL 113, 22301 (2014)

dσ/dy = 171 ± 26 μb (PYTHIA)

$c\bar{c}$ in cocktail

PHENIX, PRC 93, 014904 (2016)

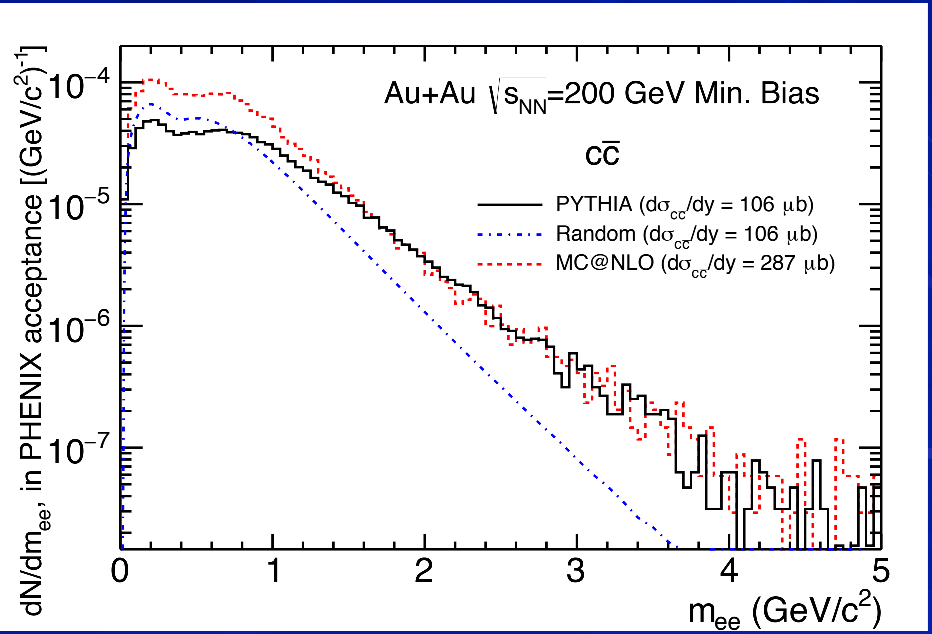


- c quarks suffer energy loss in the medium → effect on the $c\bar{c}$ correlation?
- Lack of appropriate modeling of $c\bar{c}$ correlation
  → uncertainty in shape

- Cross section derived using IMR in d+Au collisions and extrapolating to m~0
  → uncertainty in cross section

PHENIX, PRC 91, 014907 (2015)

	$d\sigma^{pp}_{c\bar{c}}/dy$ (μb)
PYTHIA	$106 \pm 9^{stat} \pm 33^{syst}$
MC@NLO	$287 \pm 29^{stat} \pm 100^{syst}$



- Hadronic decays of D mesons

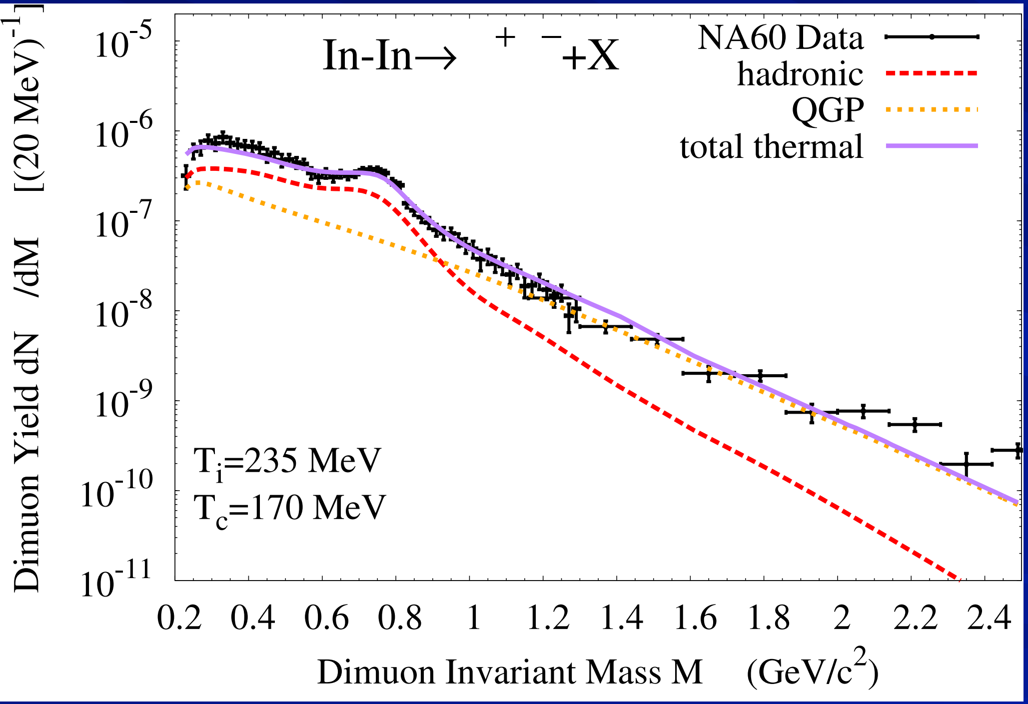
STAR, PRL 113, 22301 (2014)

dσ/dy = 171 ± 26 μb (PYTHIA)

NA60 Acceptance corrected invariant mass spectrum

NA60 dimuon excess corrected for acceptance in m - p_T

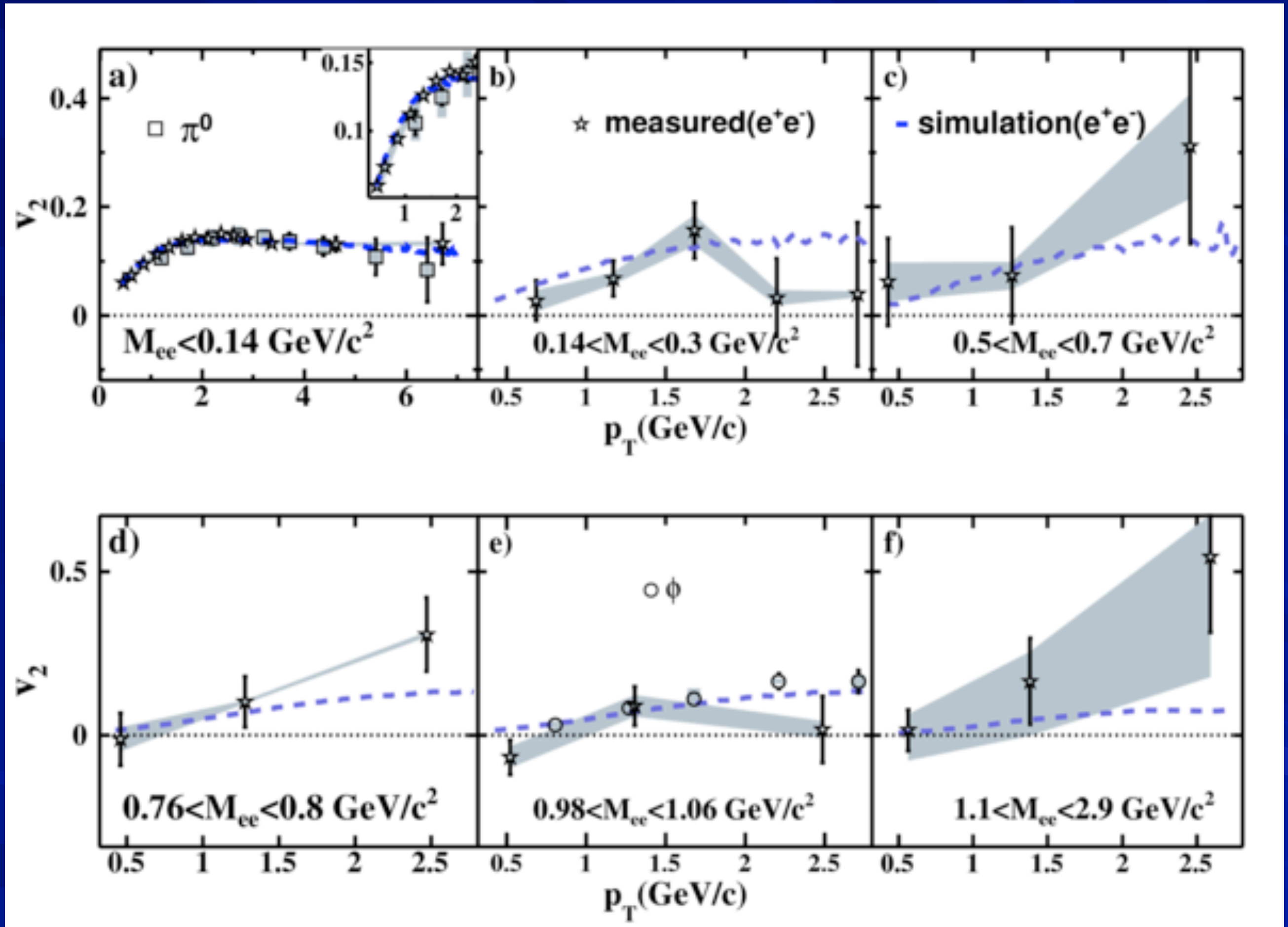
Rapp and Hees PLB 753, 586 (2016)
NA60 data: Eur. Phys. J. C 59 (2009) 607



- LMR:
  - Thermal radiation from HG
    $\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$
  - Resonances melt as the system approaches CSR
- IMR:
  - Thermal radiation from QGP
    $q\bar{q} \rightarrow \mu^+\mu^-$

Dielectron v_2

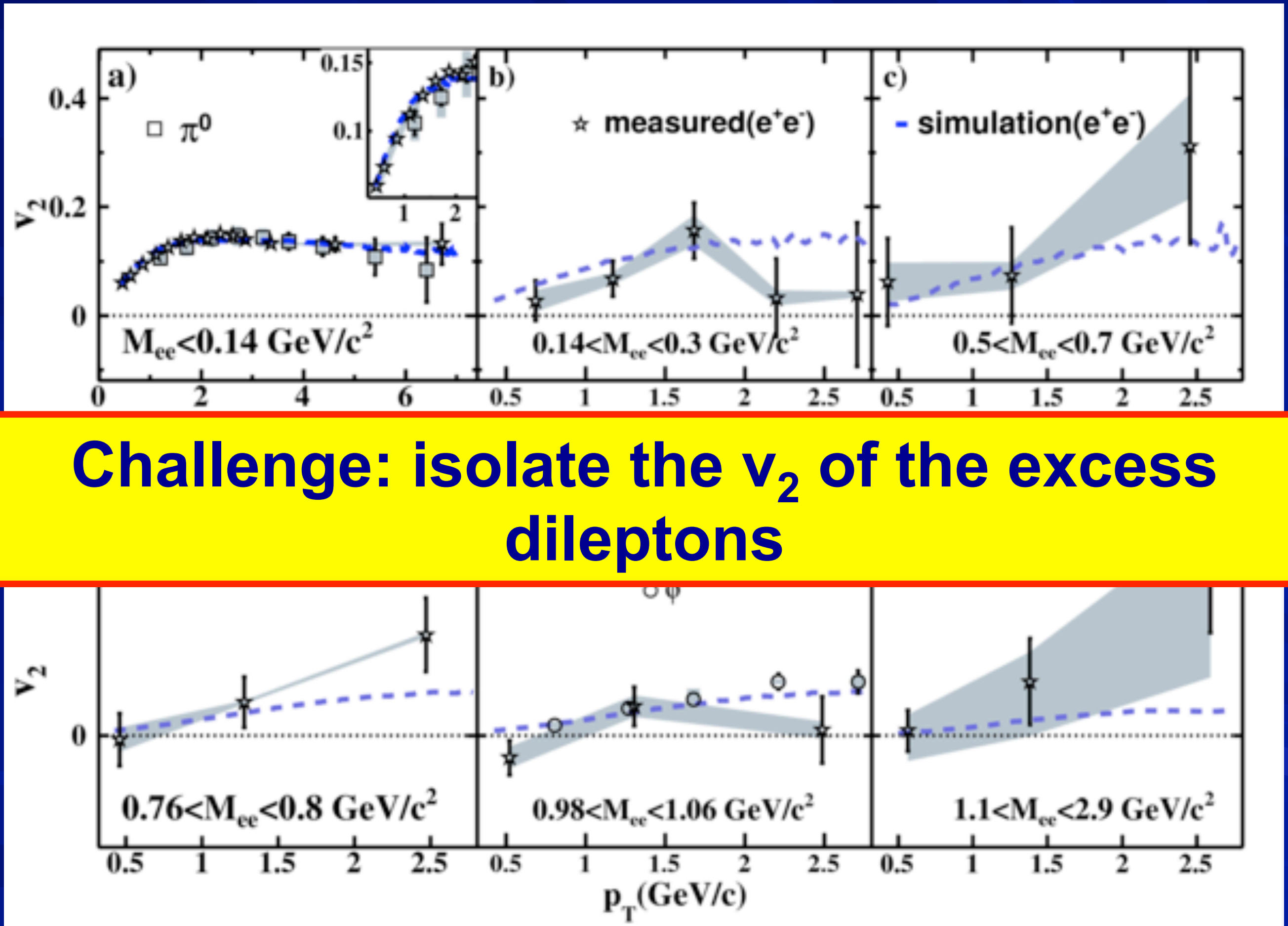
STAR PRC 90, 64904 (2014)



Inclusive dielectron v_2 consistent with simulated v_2 from cocktail sources

Dielectron v_2

STAR PRC 90, 64904 (2014)



Challenge: isolate the v_2 of the excess dileptons

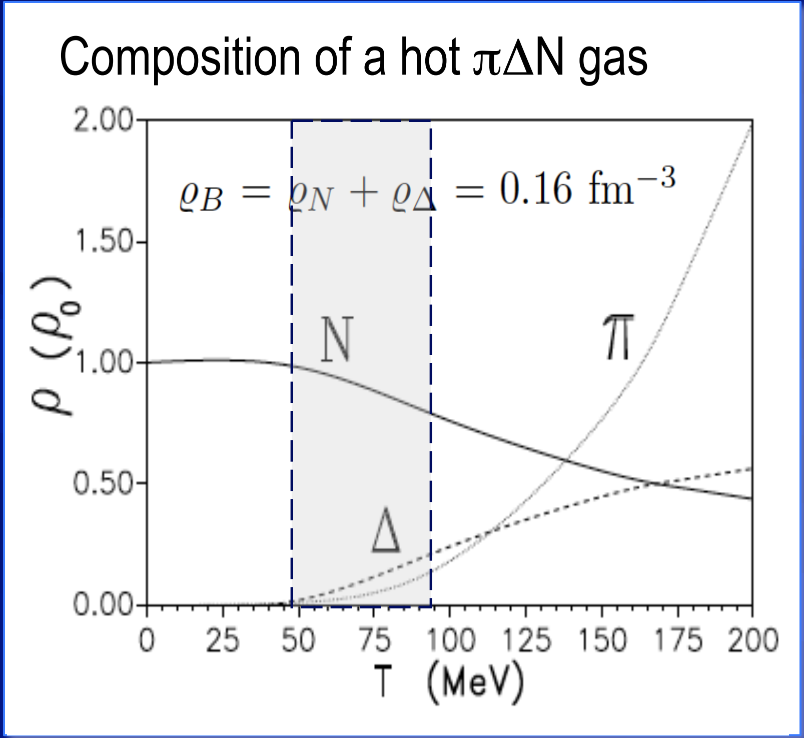
Inclusive dielectron v_2 consistent with simulated v_2 from cocktail sources

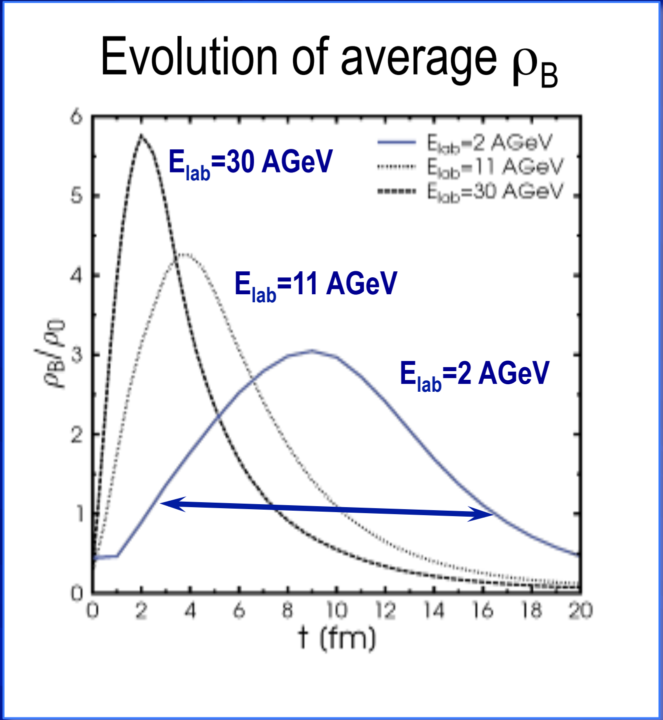
Lower – energies:

BM@N at Nuclotron
CBM at FAIR
HADES at GSI
MPD at NICA
NA60+ at SPS ?
STAR – BES-II at RHIC

Matter at low energy collisions

Rapp, Wambach, Adv.Nucl.Phys. 25, 1 (2000)



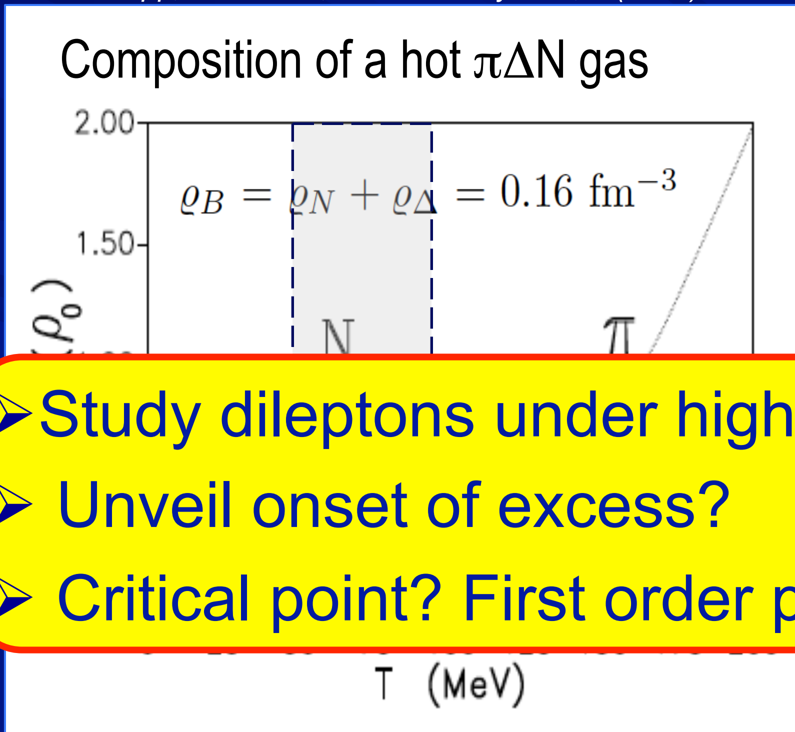


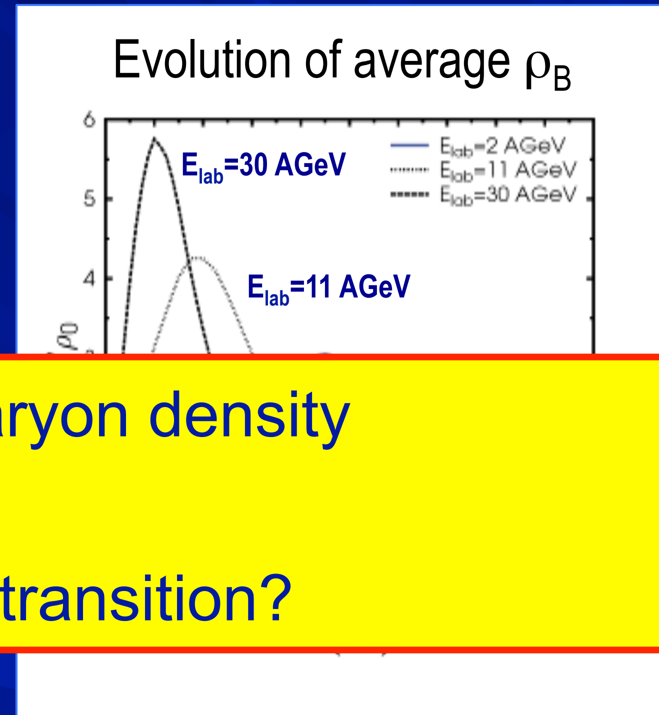
- Baryon dominated matter
- Very low pion density

- Sizable densities 3-6 ρ_0
- Long lifetime

Matter at low energy collisions

Rapp, Wambach, Adv.Nucl.Phys. 25, 1 (2000)





- ➢ Study dileptons under highest baryon density
- ➢ Unveil onset of excess?
- ➢ Critical point? First order phase transition?

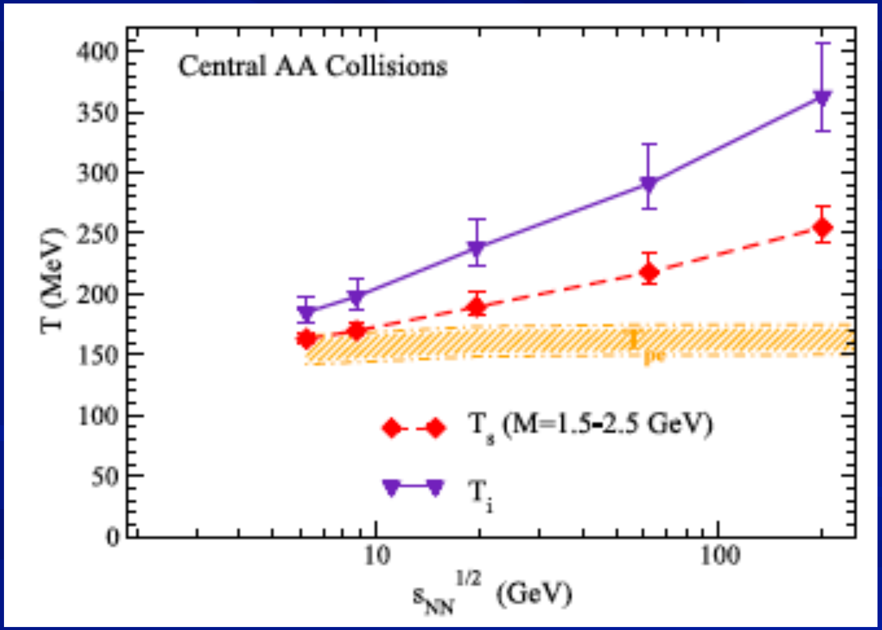
- ❑ Baryon dominated matter
- ❑ Very low pion density

- ❑ Sizable densities 3-6 ρ_0
- ❑ Long lifetime

IMR as thermometer

Rapp and Hees, PLB 753, 586 (2016)

T given by inverse slope of the acceptance corrected mass spectrum in the IMR.

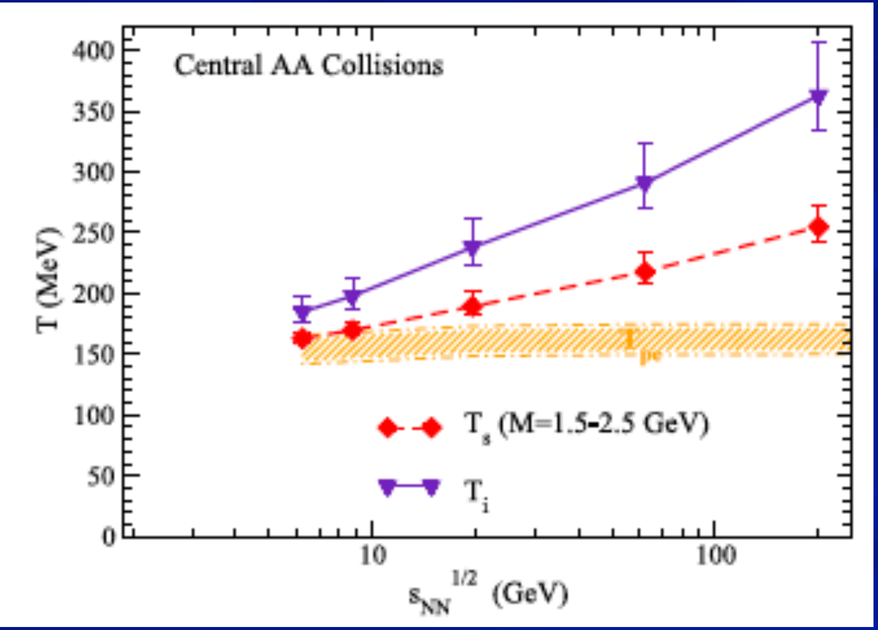


IMR as thermometer

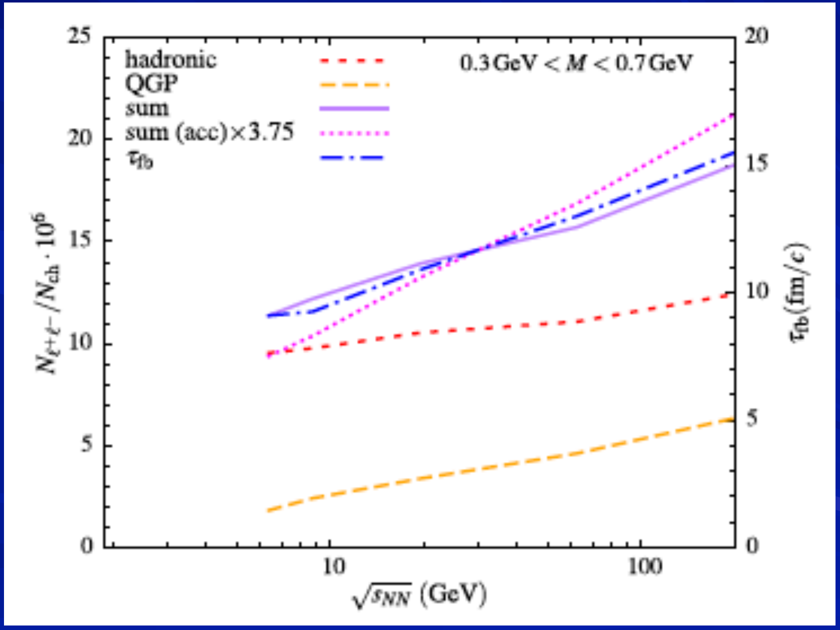
and LMR as chronometer

Rapp and Hees, PLB 753, 586 (2016)

T given by inverse slope of the acceptance corrected mass spectrum in the IMR.

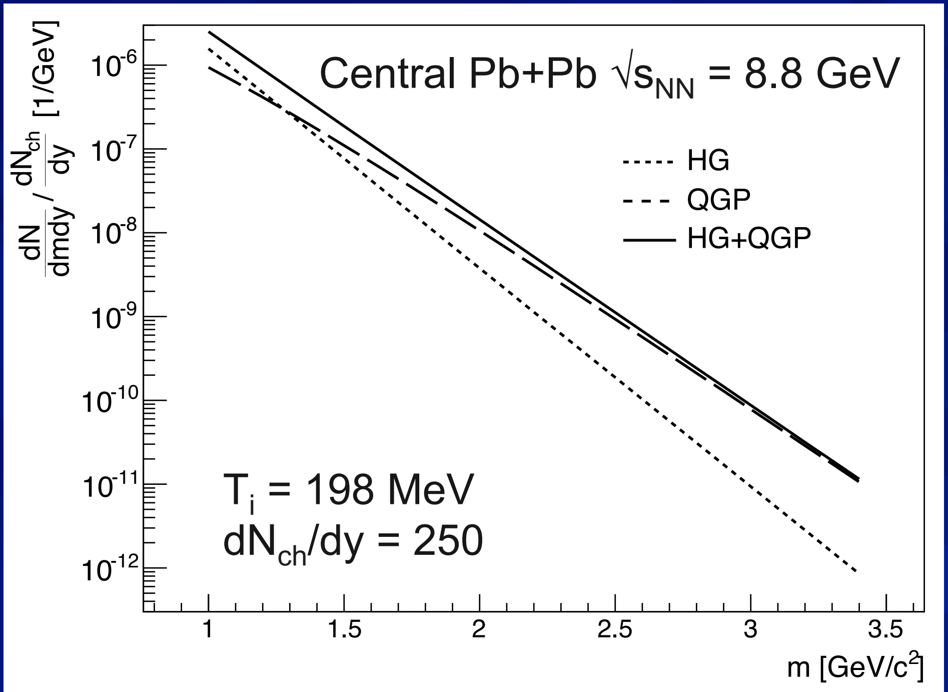


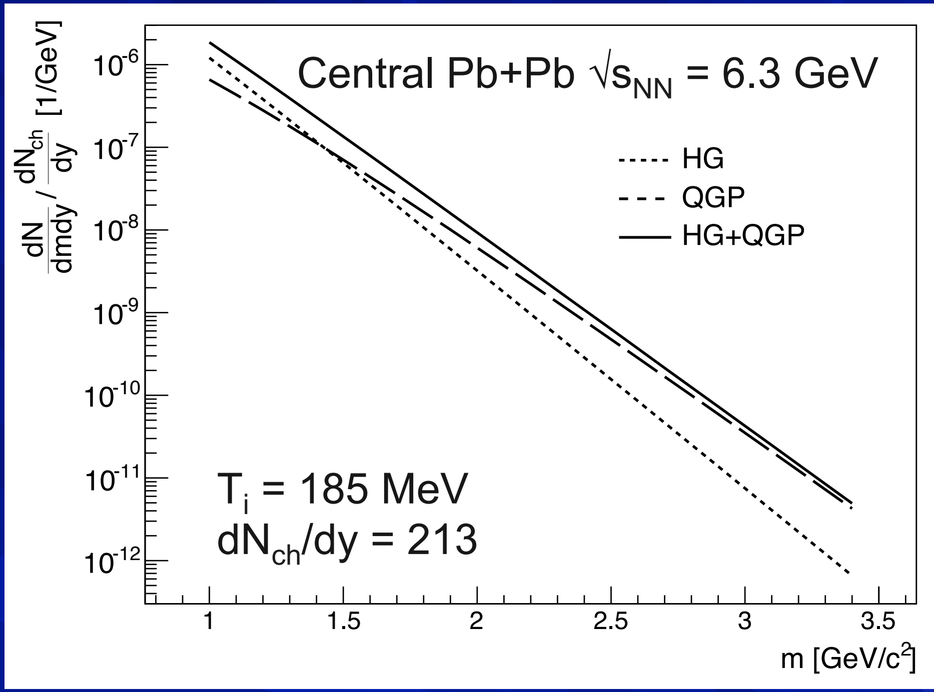
The thermal radiation integrated in the LMR m = 0.3 – 0.7 GeV/c^2 tracks the fireball lifetime quite well



Thermal yields at low energies

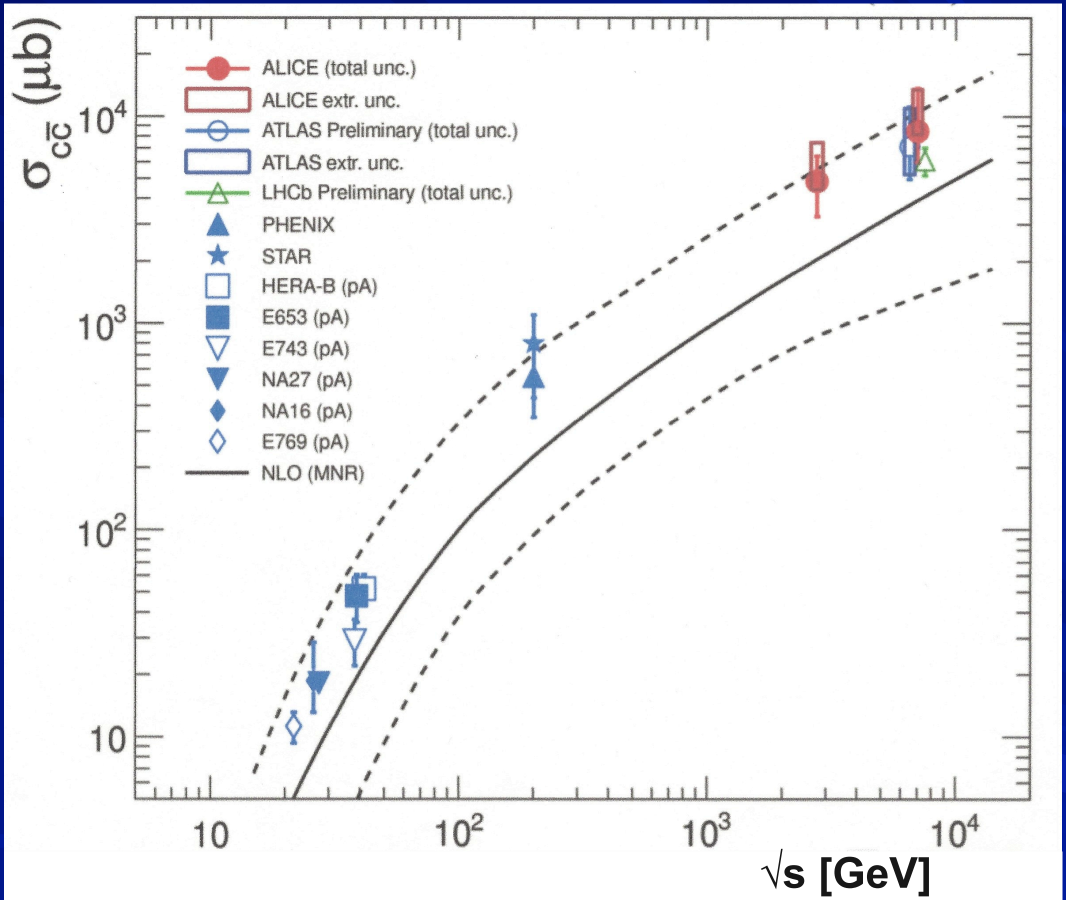
R. Rapp – private communication





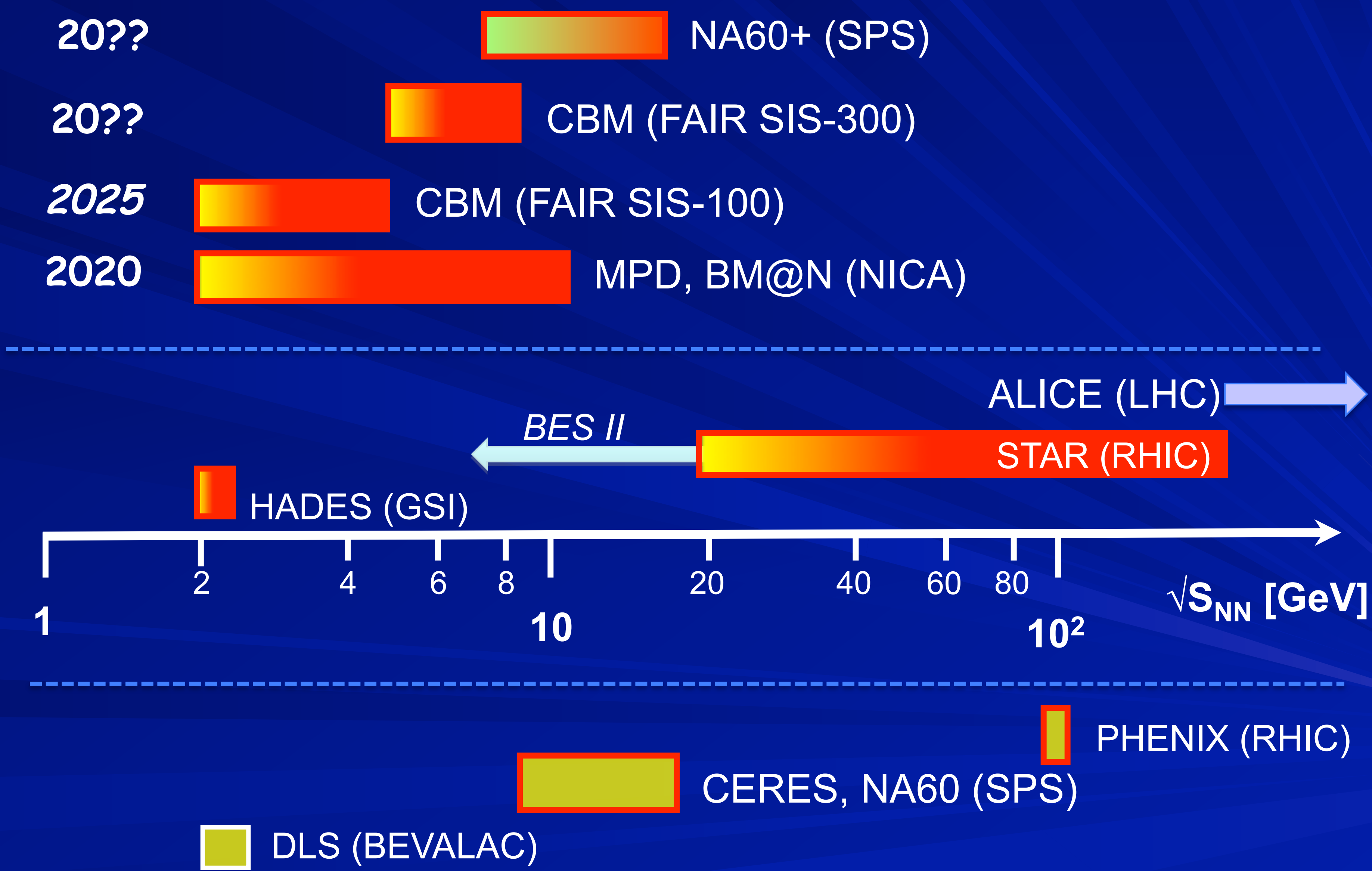
- Cross sections decrease by almost two orders of magnitude between central Au+Au at 200 GeV and central Pb+Pb at 6.3 GeV at m=2 GeV/c^2
- Challenging measurements

Charm cross section in pp

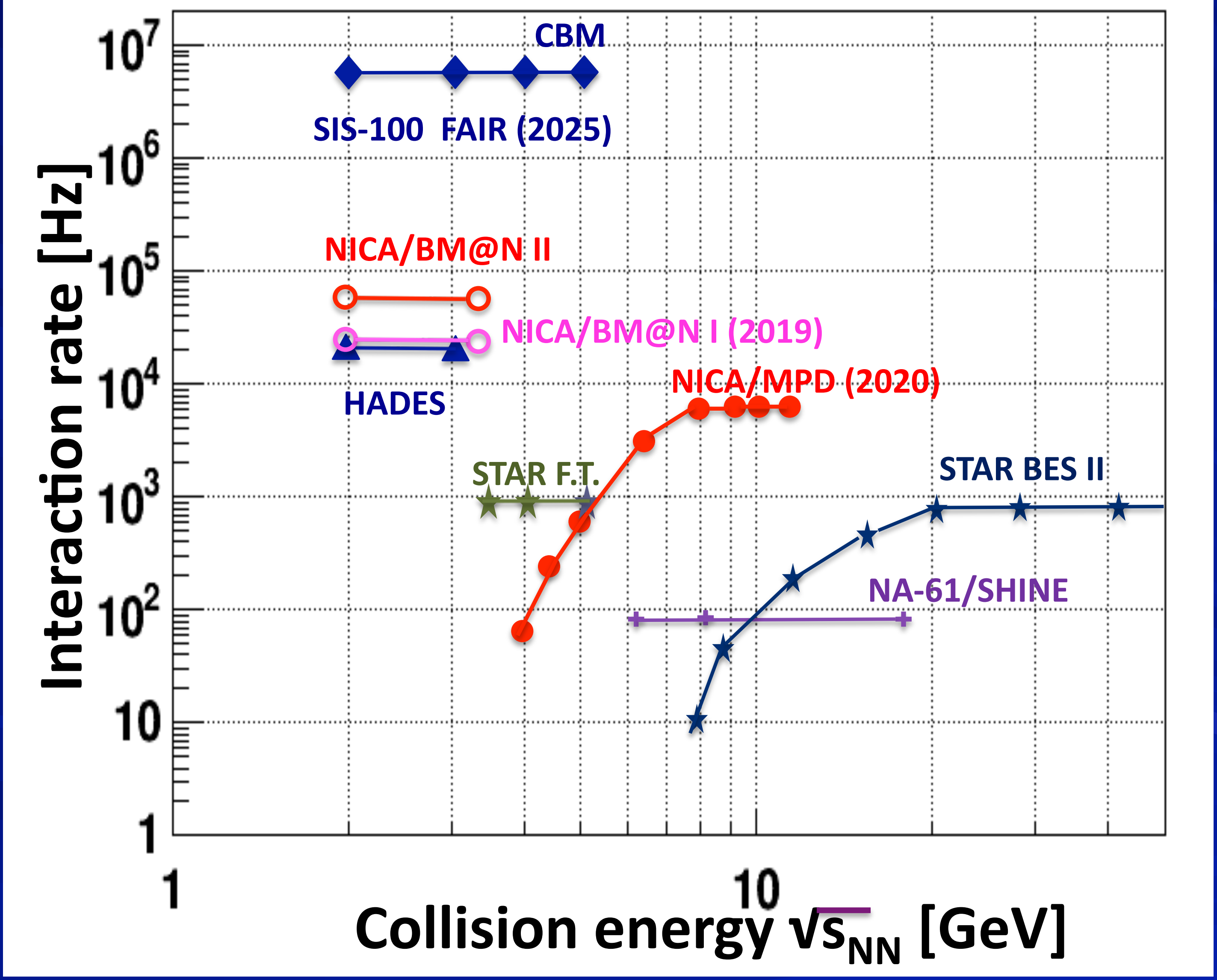


Cross sections down by ~3 orders of magnitude
between RHIC and NICA energies.

Dilepton experiments – energy map

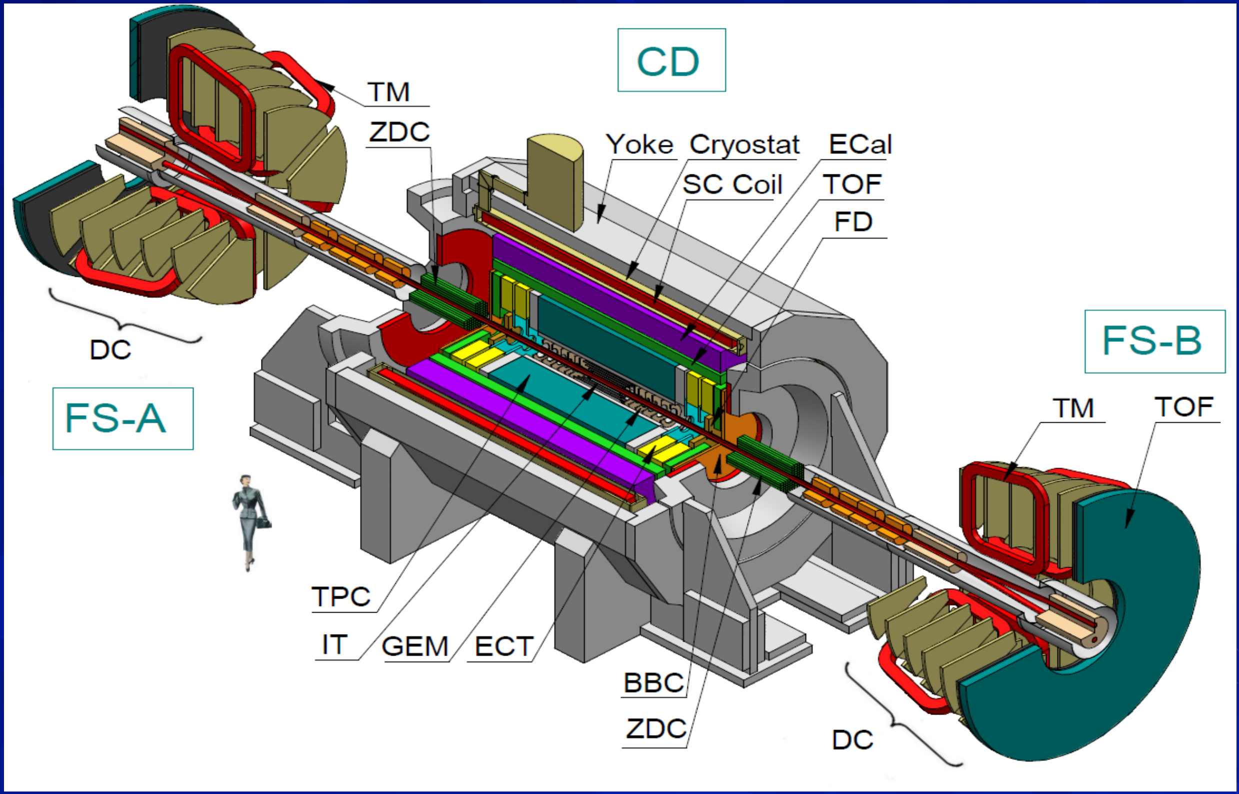


Comparison to other facilities



MPD detector at NICA

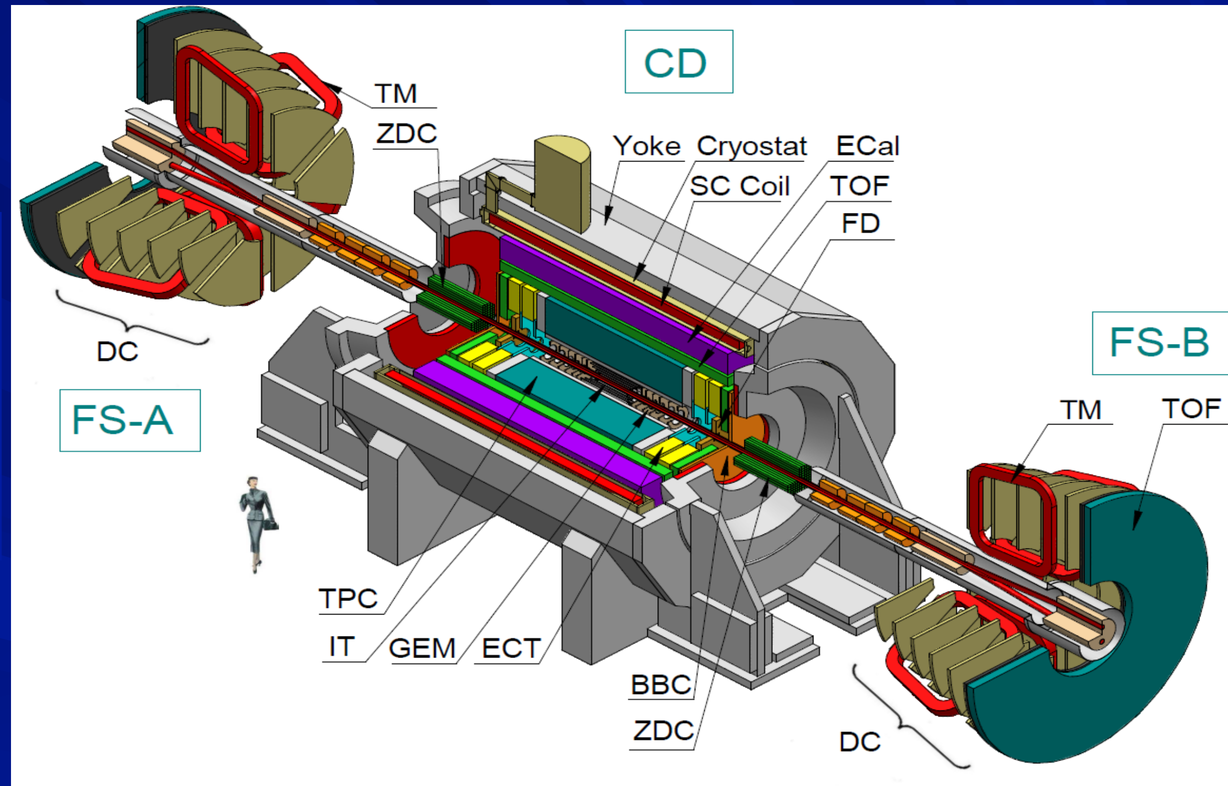
- 9 m long 6 m diameter
- Low material budget
- Tracking (TPC):
  up to $|\eta|<2$, 2π in azimuth
- PID (TOF, TPC, ECAL):
  hadrons, e, γ



BM@N

MPD detector at NICA

- **9 m long 6 m diameter**
- **Low material budget**
- **Tracking (TPC):**
  up to |η|<2, 2π in azimuth
- **PID (TOF, TPC, ECAL):**
  hadrons, e, γ



Estimate of dilepton yield in central Au+Au at m = 2 - 2.5 GeV/c^2

$\sqrt{s_{NN}}$ = 8 GeV	410 pairs/10 d
$\sqrt{s_{NN}}$ = 6.3 GeV	54 pairs/10 d

BM@N

Summary

- All systems at all energies studied show an enhancement of dileptons.
- A single model consistently reproduces the observed enhancement.
- The thermal radiation from the QGP dominates the dilepton excess in the IMR. Provides a measurement of the average temperature of the medium in the QGP phase.
- The thermal radiation from the HG dominates the dilepton excess in the LMR. Seems to track the medium lifetime.
- 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.
- Missing:
  - precise measurements of IMR at RHIC energies.
  - v_2 measurements of the excess dileptons.
- Clear predictions and strong experimental program to study dileptons at low energies.