Dileptons at low energies: prospects and challenges

Workshop “Exploring the QGP through soft and hard probes”

Serbian Academy of Science and Arts, Belgrade, May 29-31, 2023

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Outline

- Introduction – Motivation
  - General motivation for dileptons
  - General motivation for low energy HIC
- What did we learn from ~30 years of dilepton measurements
- Opportunities of dileptons at low energies.
- When and where? Prospects and challenges at NICA
- Summary

Motivation - Why dileptons

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

- Dileptons are sensitive 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

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

- 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 equal mass and opposite parity

- 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

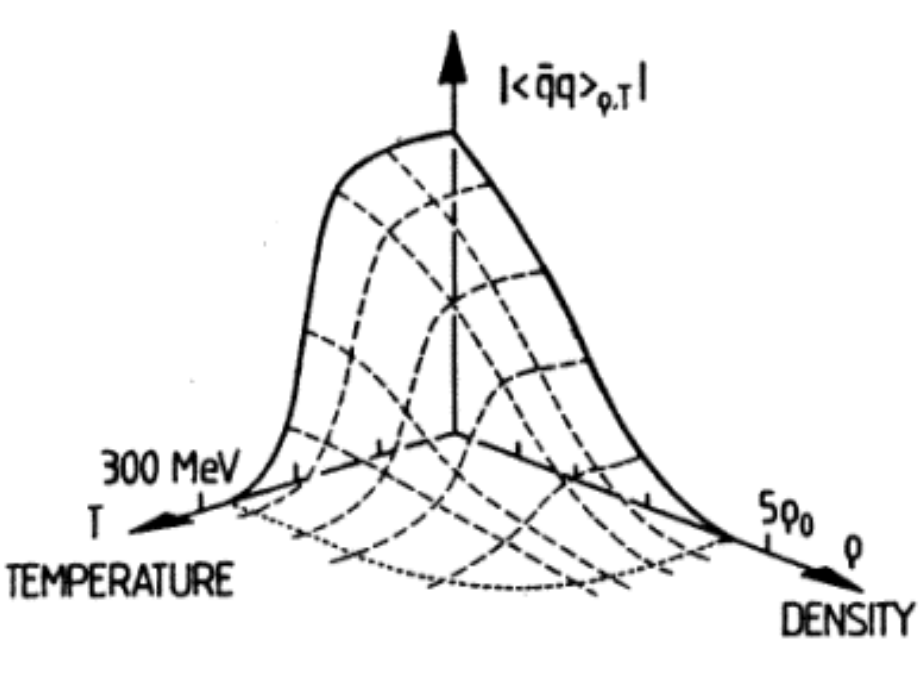
Chiral Symmetry Restoration

- 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:

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



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

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

$\rho - a_1$

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

PDG 2022

$a_1(1260)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	T
1230 ±40 OUR ESTIMATE			

$a_1(1260)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID
250 to 600 OUR ESTIMATE		
420 ± 35 OUR AVERAGE		

$a_1(1260)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	3π	seen
Γ_2	$(\rho\pi)_{S-\text{wave}},\ \rho \to \pi\pi$	seen
Γ_3	$(\rho\pi)_{D-\text{wave}},\ \rho \to \pi\pi$	seen
Γ_4	$(\rho(1450)\pi)_{S-\text{wave}},\ \rho \to \pi\pi$	seen
Γ_5	$(\rho(1450)\pi)_{D-\text{wave}},\ \rho \to \pi\pi$	seen
Γ_6	$f_0(500)\pi,\ f_0 \to \pi\pi$	seen
Γ_7	$f_0(980)\pi,\ f_0 \to \pi\pi$	not seen
Γ_8	$f_0(1370)\pi,\ f_0 \to \pi\pi$	seen
Γ_9	$f_2(1270)\pi,\ f_2 \to \pi\pi$	seen
Γ_{10}	$\pi^+\pi^-\pi^0$	seen
Γ_{11}	$\pi^0\pi^0\pi^0$	not seen
Γ_{12}	$KK\pi$	seen
Γ_{13}	$K^*(892)K$	seen
Γ_{14}	$\pi\gamma$	seen

Experimental efforts focused on the ρ meson. Best candidate for CSR studies

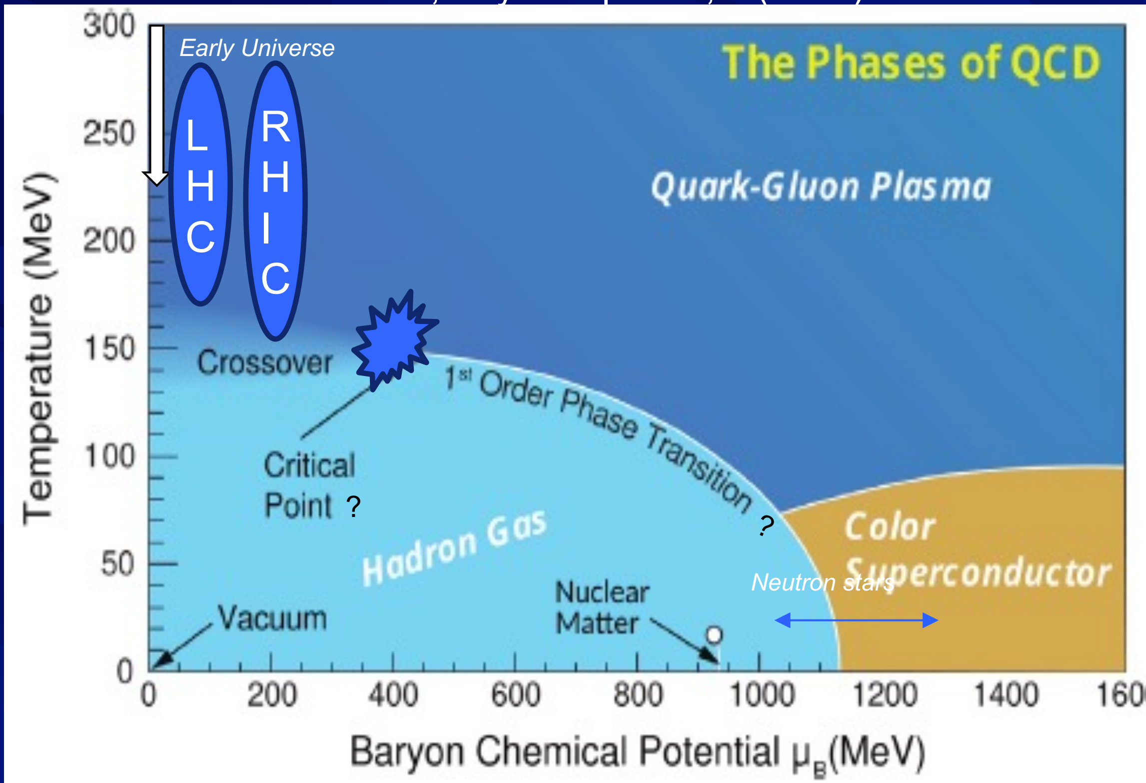
	m [MeV]	Γ_{tot} *[MeV]*	τ *[fm/c]*
ρ	*770*	*150*	*1.3*
ω	*782*	*8.6*	*23*
ϕ	*1020*	*4.4*	*44*

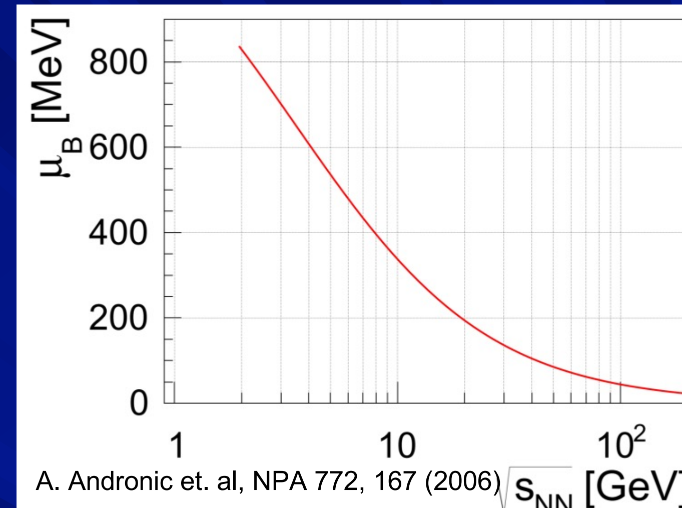
Short lifetime compared to the medium lifetime ($\tau \approx 10$ fm/c)
can decay and be regenerated in the medium

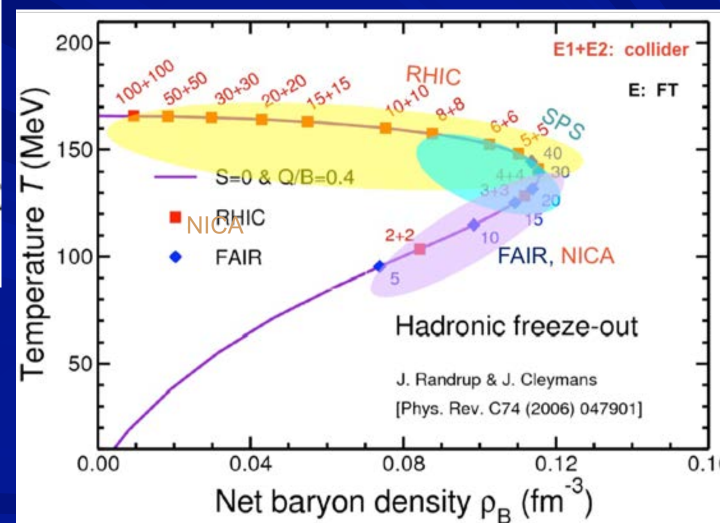
- Motivation – Why low-energy HIC

QCD Phase Diagram

A. Bzdak et al., Phys. Rep. 853, 1 (2020)





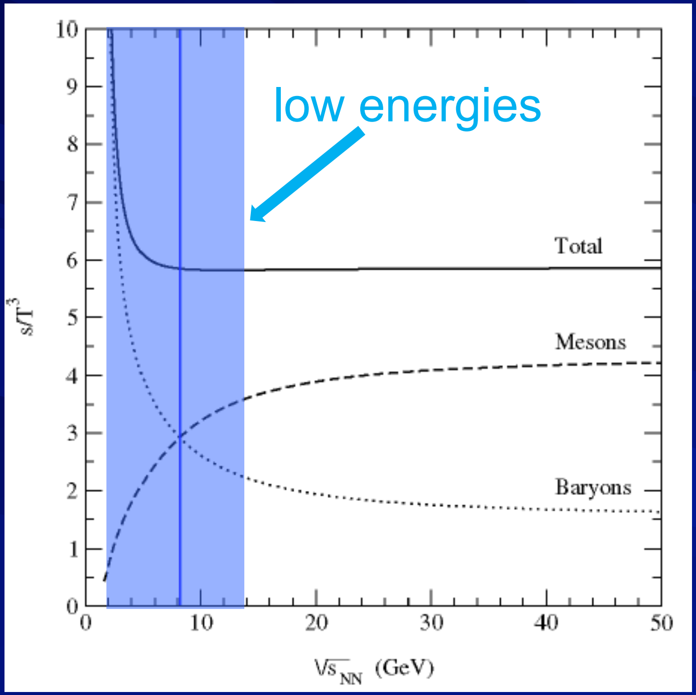


Lattice QCD: Crossover in the low μ_B region
QCD effective theories predict 1st order phase transition and critical point at large μ_B

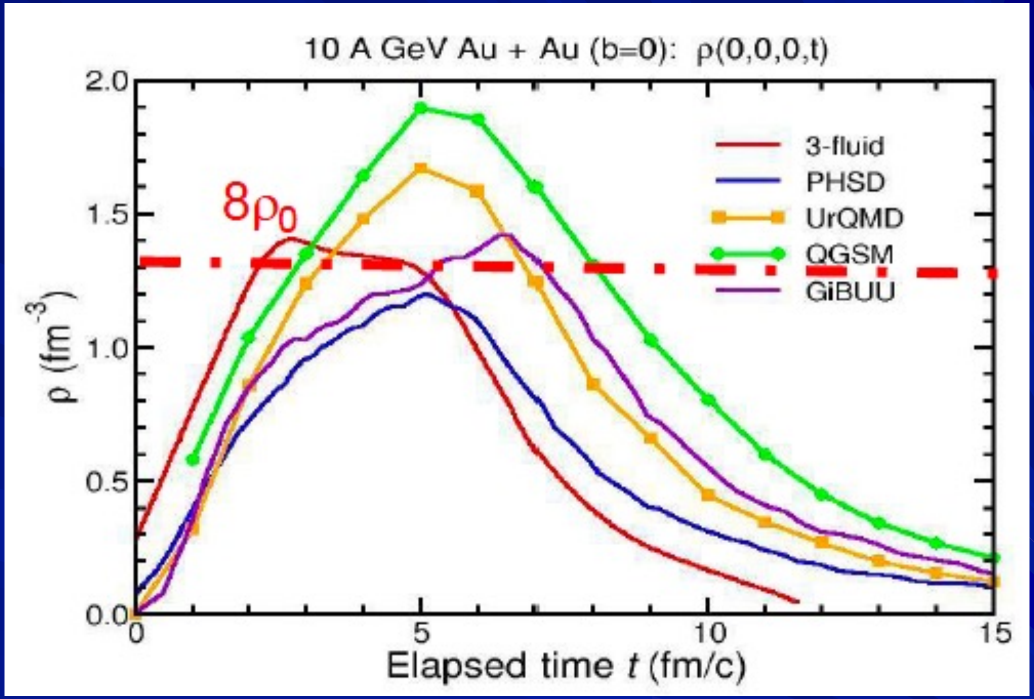
- Explore the QCD phase diagram in the region of high baryon chemical potential μ_B, also the highest net baryon density matter
- Search for the conjectured critical point and first order phase transition

QCD matter at low energies $\sqrt{s_{NN}} \lesssim 14$ GeV

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



PRC 75, 034902 (2007)



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

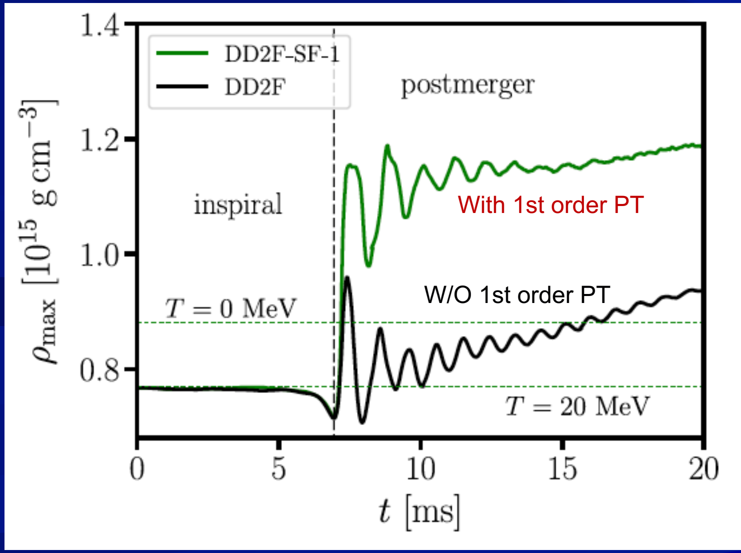
- Sizable densities up to O($10\rho_0$)
- Long lifetime

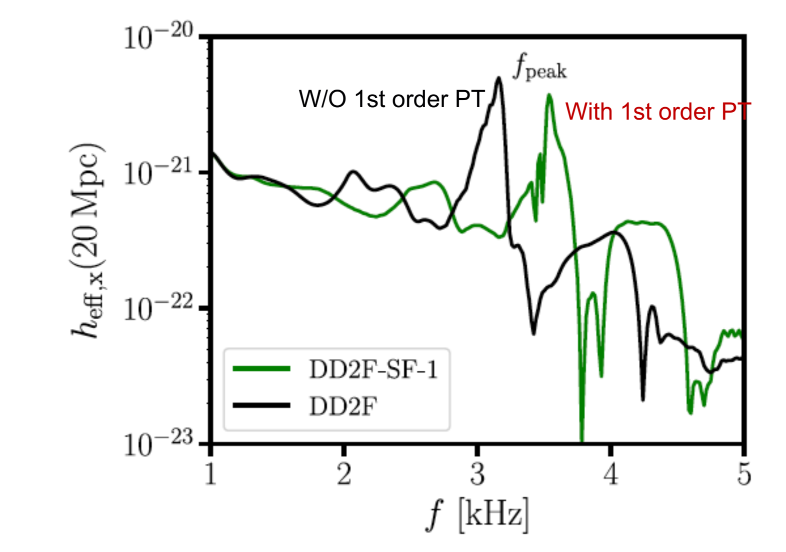
Synergy with Multi-Messanger Astronomy

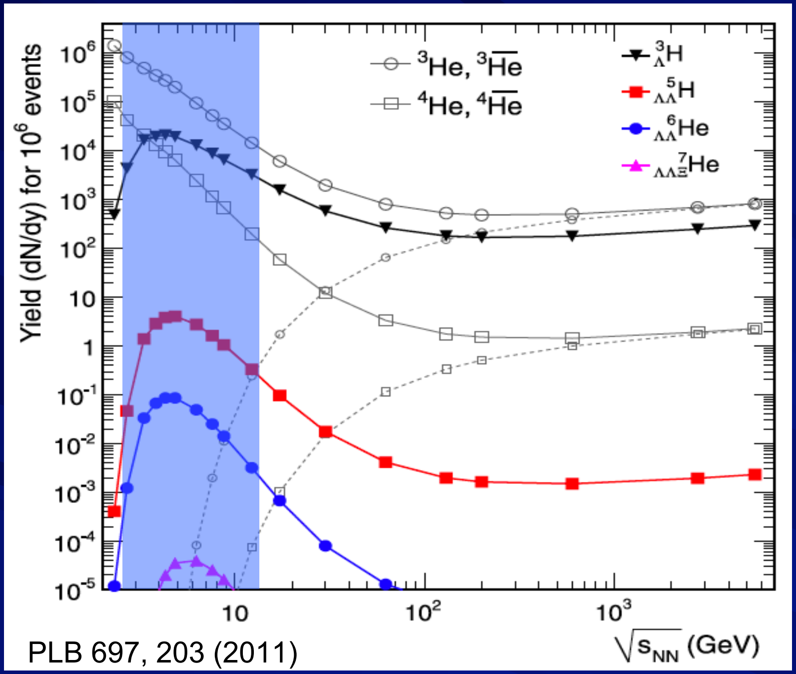
- Model calculations show that in heavy-ion collisions in the low energy range, nuclear matter reaches densities and temperatures similar to those occurring in a neutron star merger .
- Heavy-ion collisions at low-energies and neutron star mergers probe similar regions of the QCD phase diagram.

- 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)

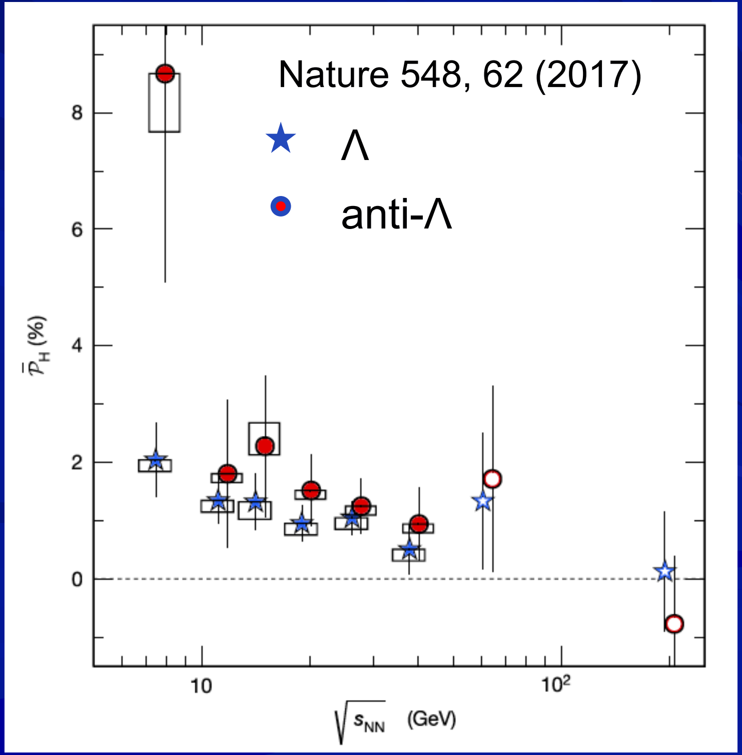






Hypernuclei

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



Global polarization

- Global polarization of Λ and anti-Λ
  - Insights into initial conditions and dynamics of QGP
  - Expected to be high at the NICA energies

Strangeness

- Sub-threshold production of multistrange (anti-)hyperons via sequential collisions.

- What did we learn from ~30 years of dileptons measurements?

After ~30 years of dilepton measurements

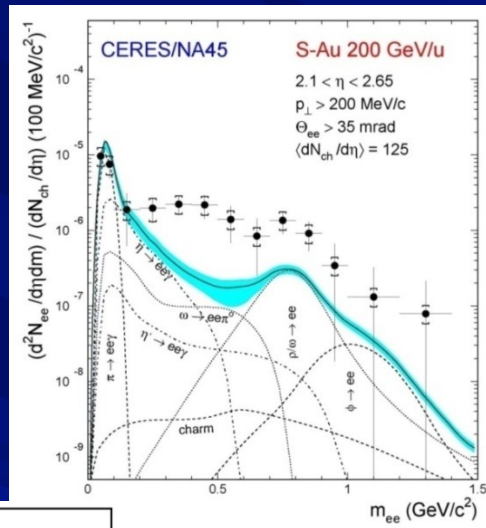
- All HI systems at all energies studied show an excess of dileptons wrt to hadronic sources

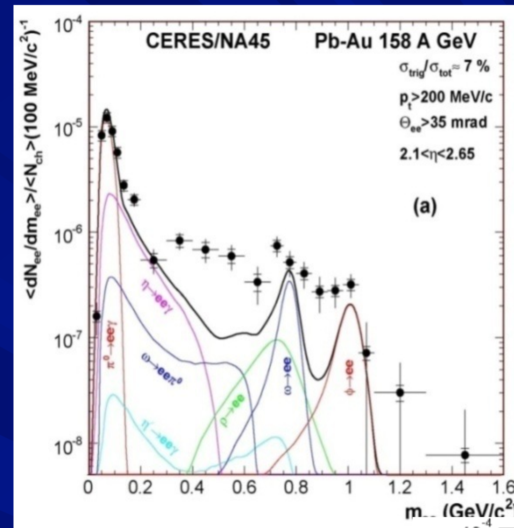
  CERES and NA60 at SPS
  PHENIX and STAR at RHIC
  HADES at SIS18

SPS: CERES Pioneering Dilepton Results

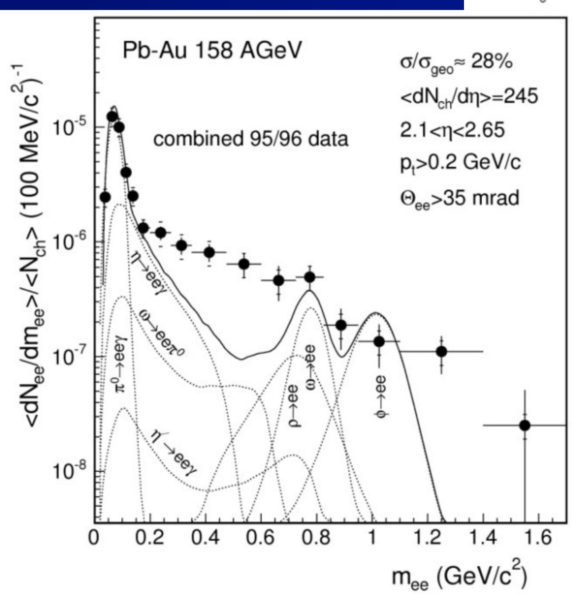
First CERES result
PRL 75, 1272 (1995)

(renowned paper: 550 citations)



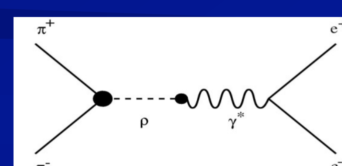


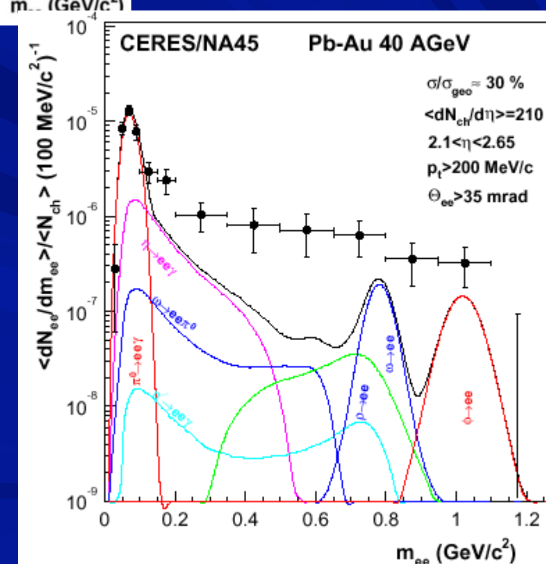
Last CERES result
PLB 666, 425 (2008)



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

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





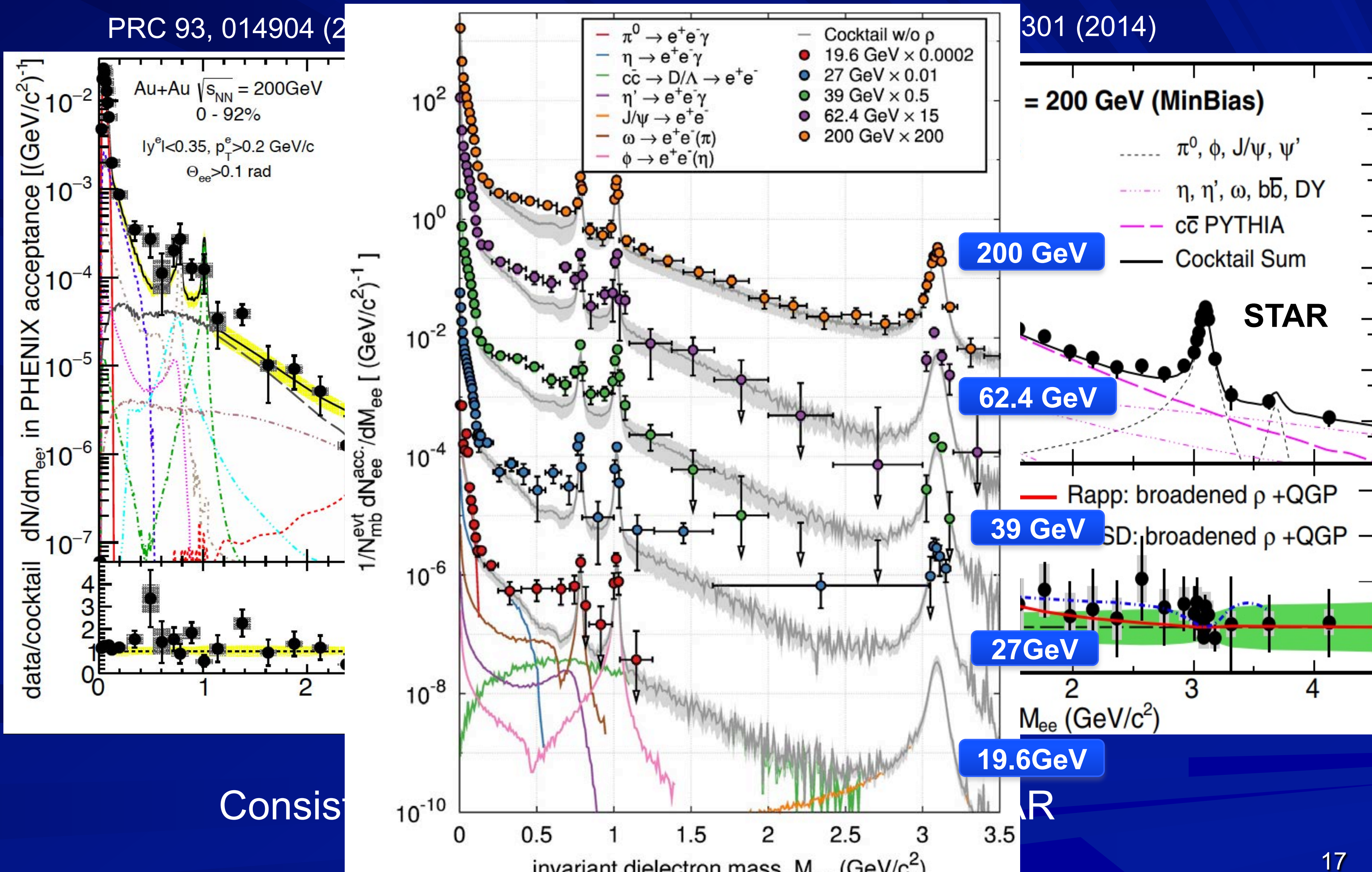
Eur. Phys J. C41, 475 (2005)

PRL 91, 042301 (2003)

RHIC: PHENIX and STAR

RHIC – BES-I

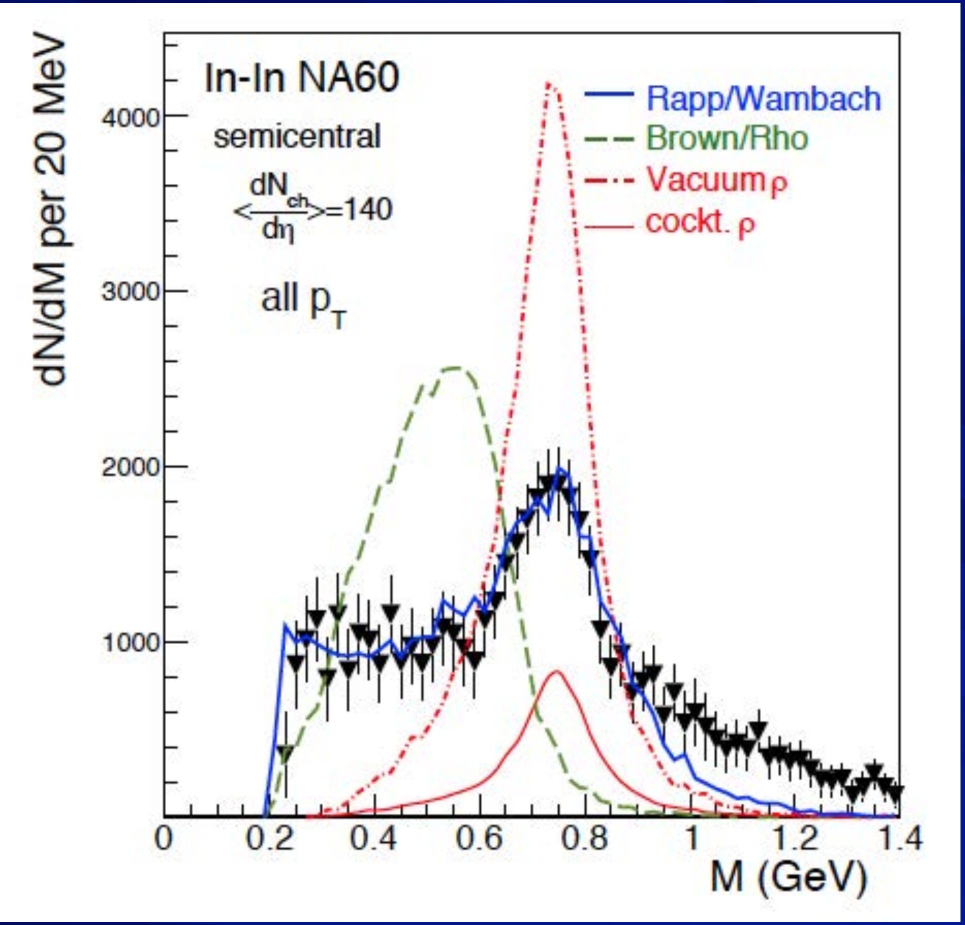
PRC 93, 014904 (2 … 301 (2014)



Consis… AR

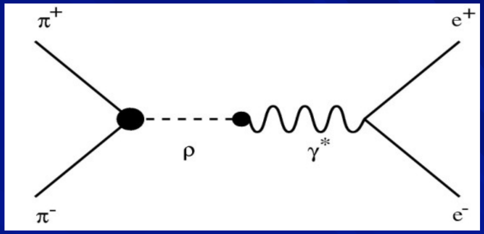
In-medium ρ modification

PRL 96, 162302 (2006)



- Evidence of thermal radiation from the HG

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



- **Dropping mass of ρ ruled out**

Brown-Rho scaling (PRL 66, (1991) 2720)

$$\frac{m_\rho^*}{m_\rho} \approx \frac{m_\omega^*}{m_\omega} \approx \left(\frac{<\bar{q}q>_{\rho^*}}{<\bar{q}q>_0} \right)^{1/3} = 1 - 0.26\frac{\rho^*}{\rho_0}$$

- **Low-mass dilepton excess isolated by subtracting the cocktail (w/o the ρ) from the data**

- **Excess shape consistent with broadening of the ρ (Rapp-Wambach)**

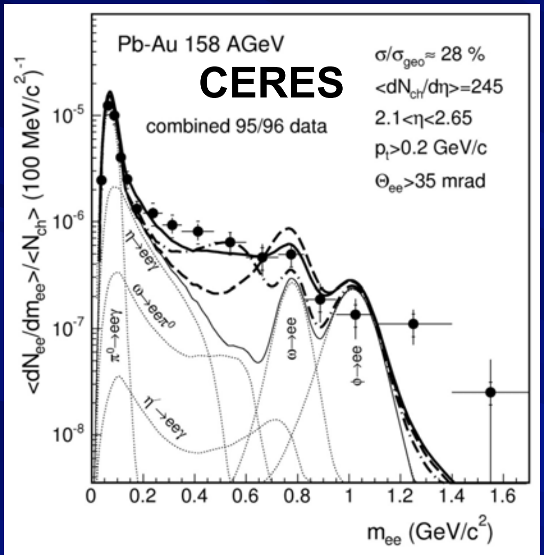
After ~30 years of dilepton measurements

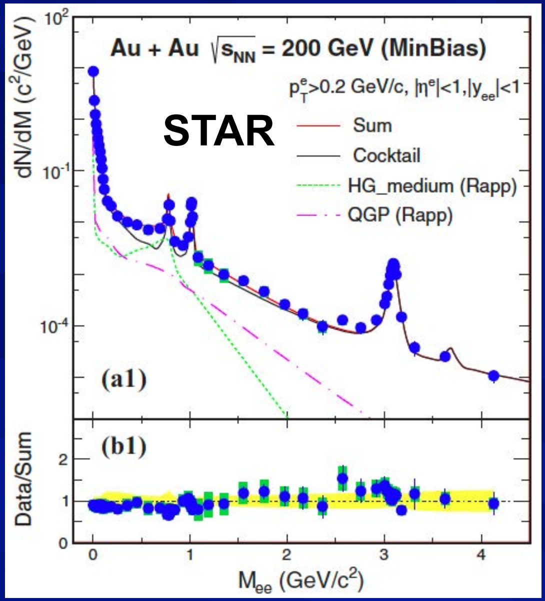
- All HI systems at all energies studied show an excess of dileptons wrt to hadronic sources
- Excess consistently reproduced by microscopic many body model (Rapp et al.)

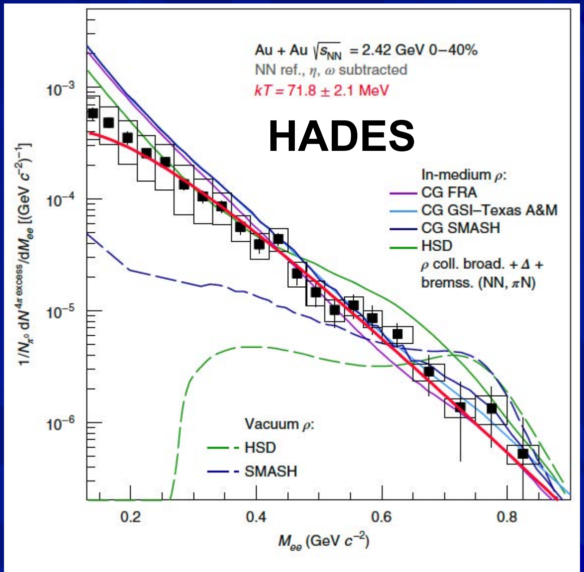
  CERES and NA60 at SPS
  PHENIX and STAR at RHIC
  HADES at SIS18

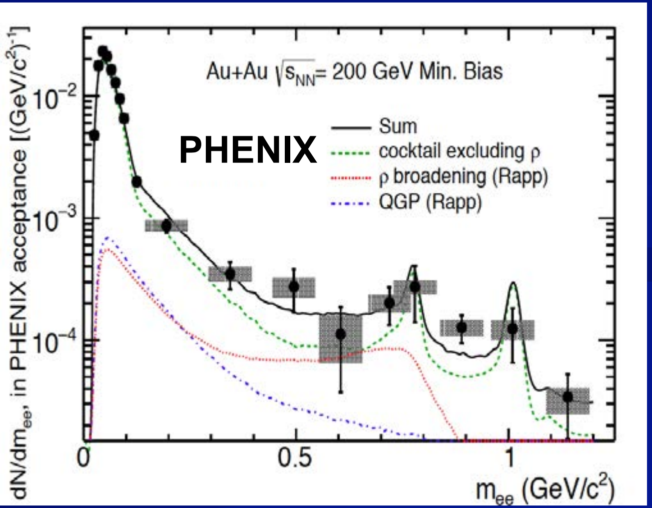
All results reproduced by one single model

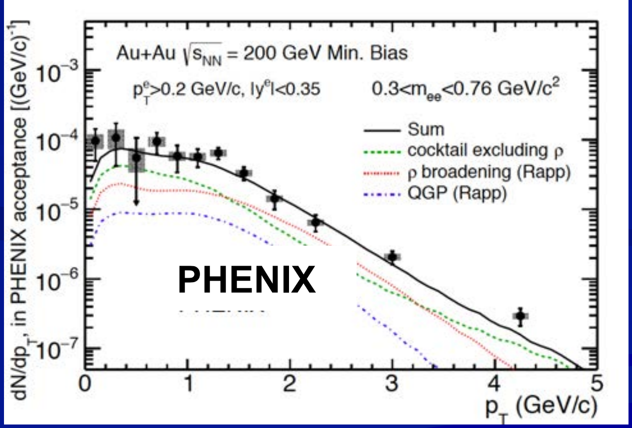
- Vacuum ρ meson fails to reproduce the data.
- Good agreement with models based on ρ meson in-medium broadening – Linked to CSR

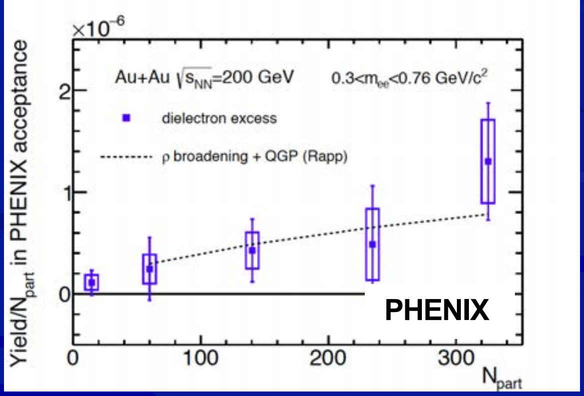








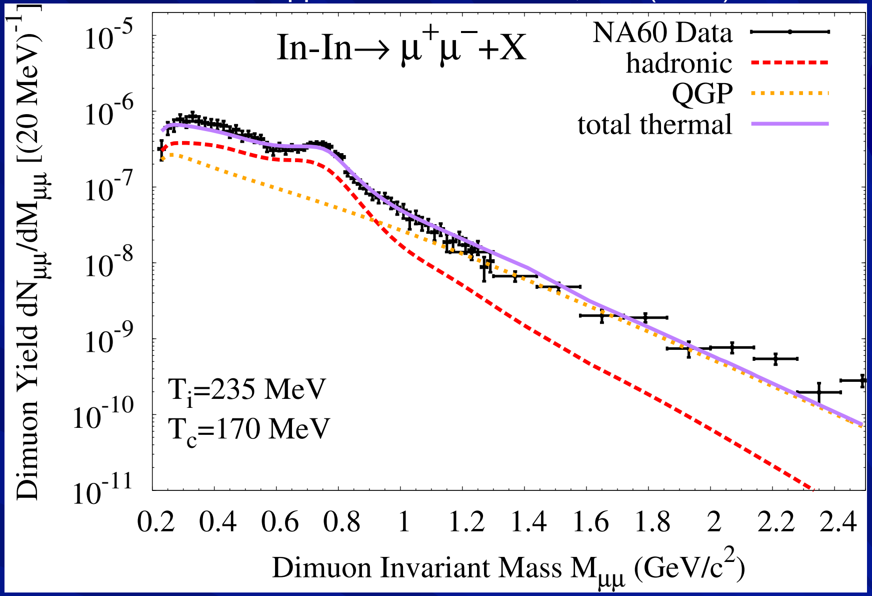




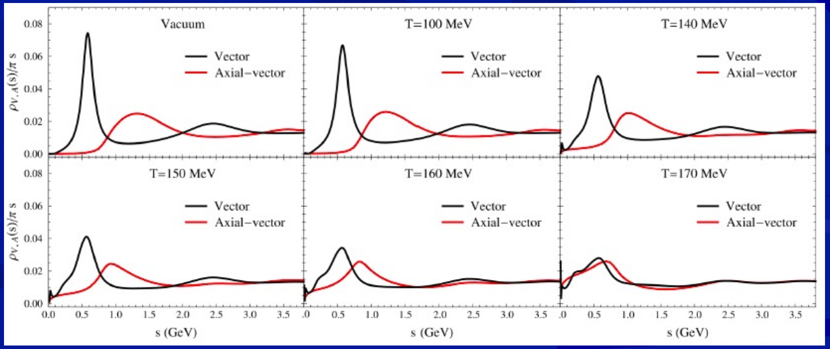
After ~30 years of dilepton measurements

- 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)



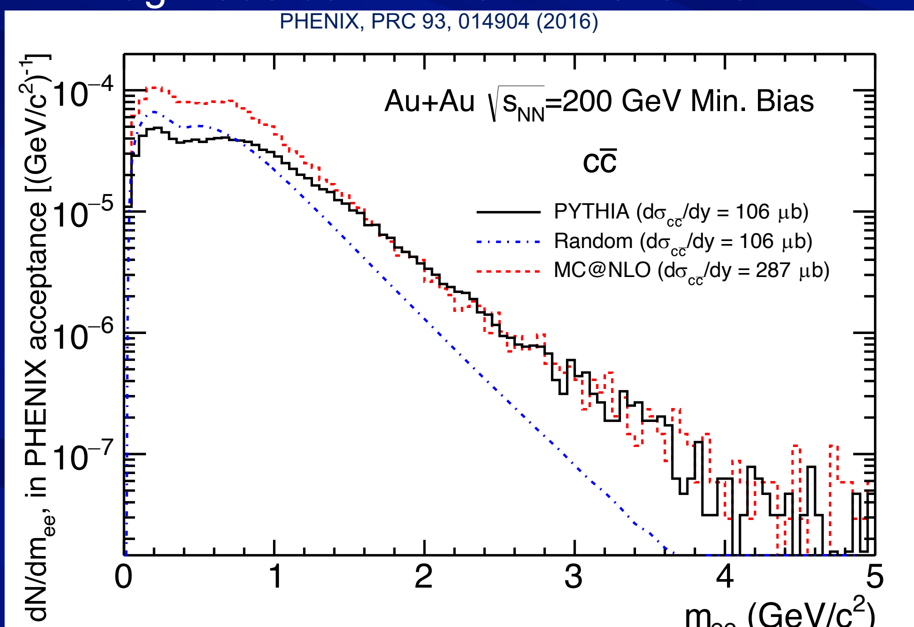
- One of the few effects exclusively observed in AA collisions

- Dileptons at low energies

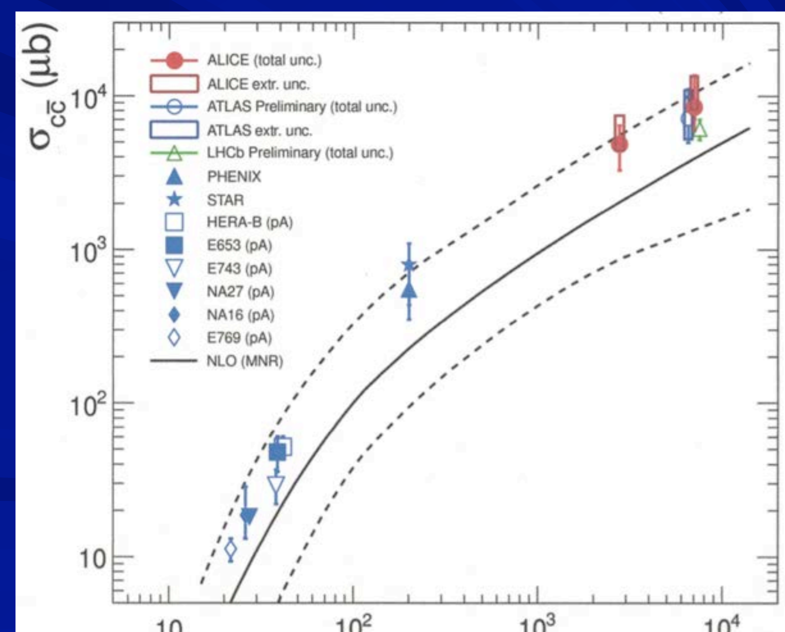
QGP thermal radiation in the IMR.

- **Confirmation of QGP thermal radiation in the IMR.**
  - The QGP thermal radiation observed in the IMR only at SPS energies by mainly 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 low energies: charm cross section negligible

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



Charm cross section in pp



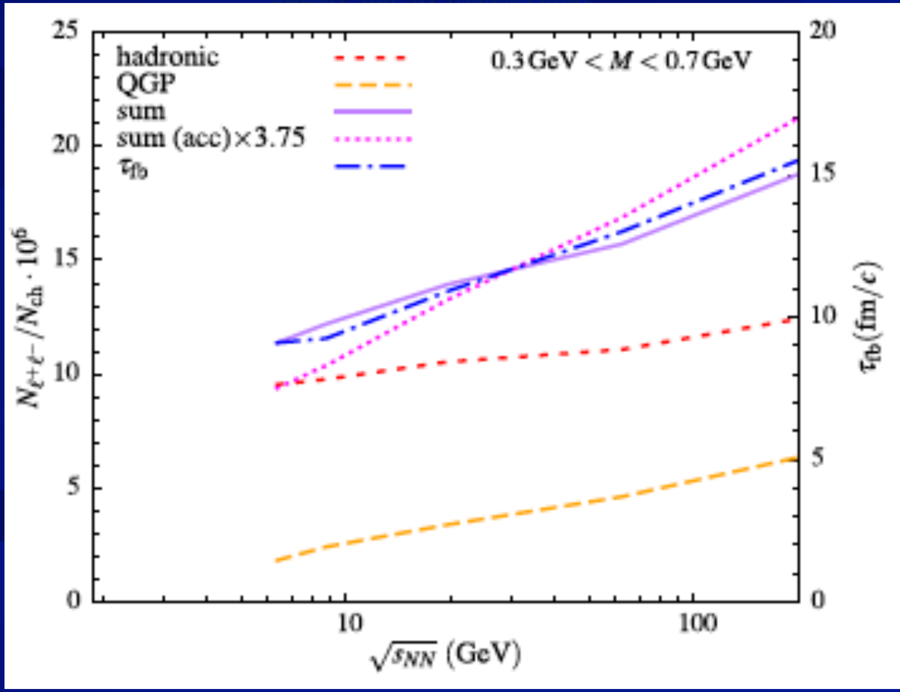
Onset of deconfinement? Onset of CSR?

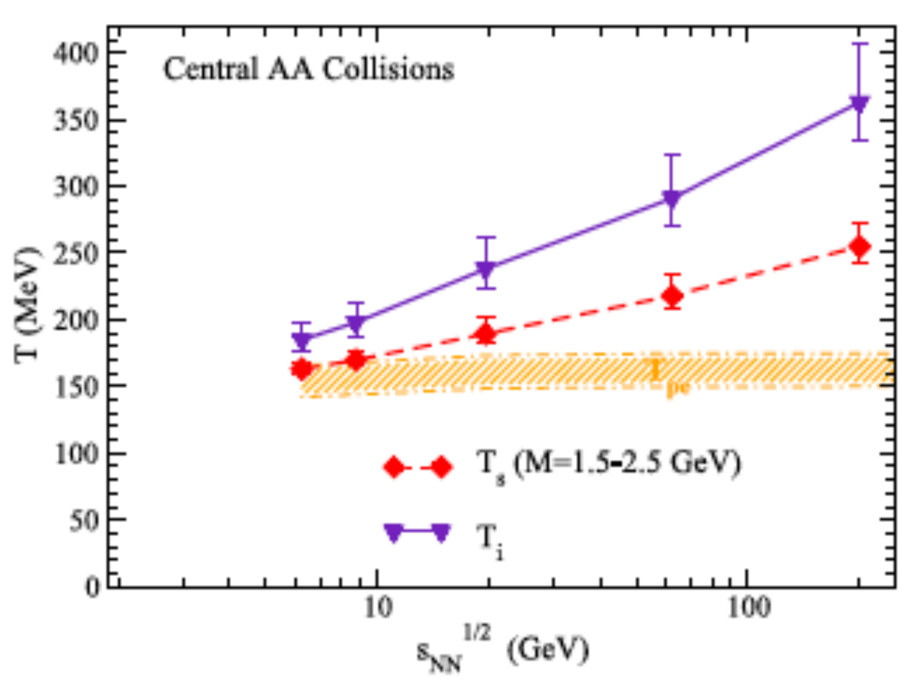
- Energy scan of dilepton excess
  - Integrated yield in the LMR tracks the fireball lifetime
  - Inverse slope of the mass spectrum in the IMR provides a measurement of <T>
  - First order phase transition?
  - Thermal radiation down to $\sqrt{s_{NN}}$ – 6 GeV ?

LMR - Chronometer

IMR - Thermometer

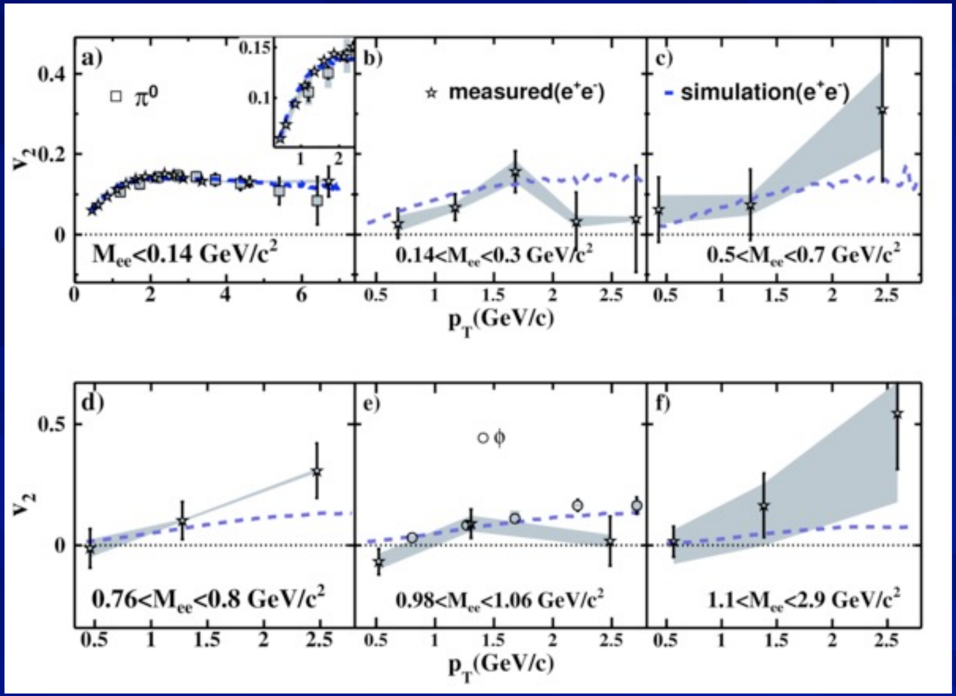
Rapp and Hees, PLB 753, 586 (2016)





Missing: elliptic flow of thermal dileptons

Inclusive dielectron v_2
STAR PRC 90, 64904 (2014)



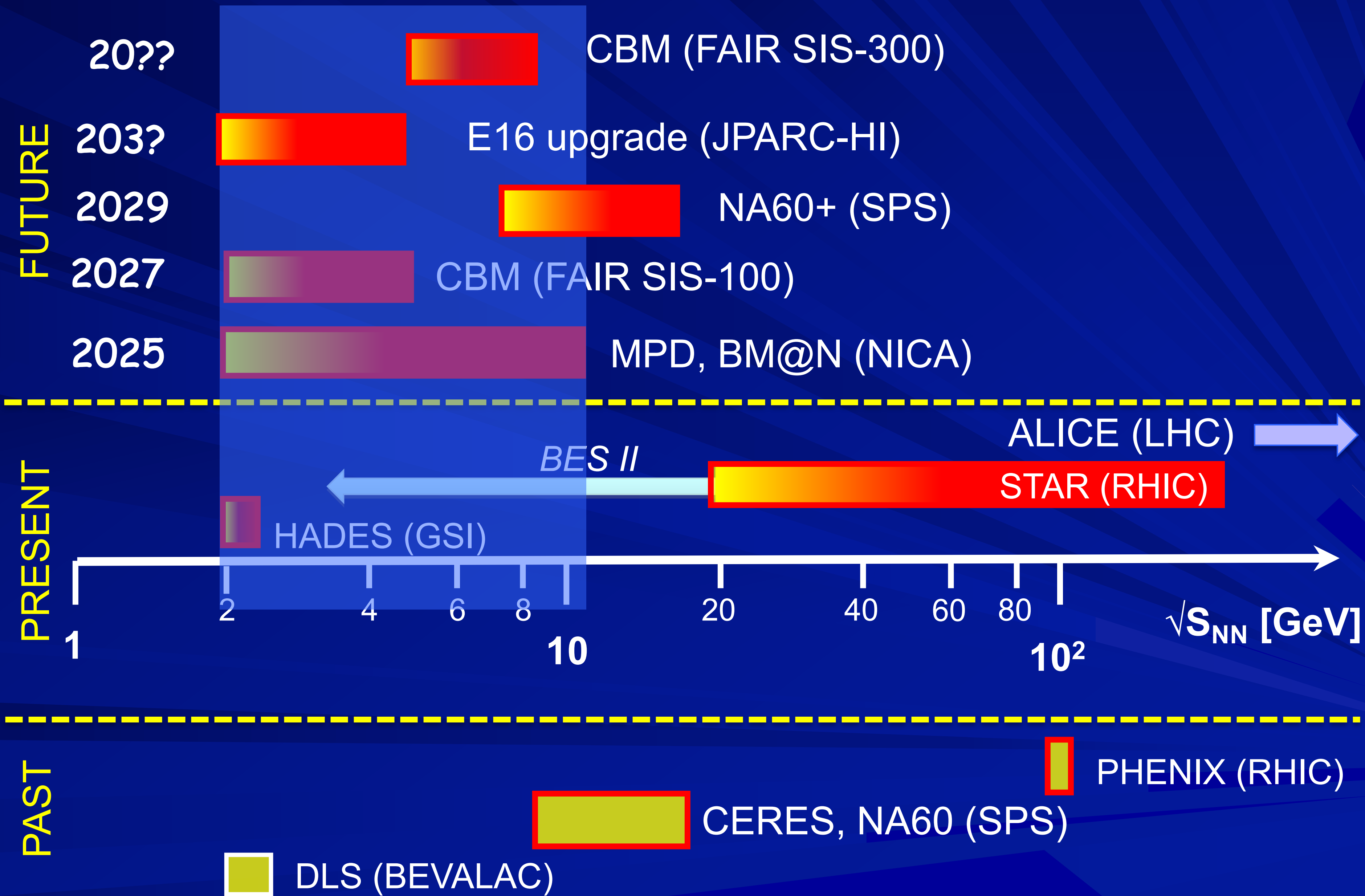
- v_2 of the excess dileptons:
  - Very challenging measurement
  - Could provide an independent confirmation about the origin of the thermal radiation:

    LMR dominated by HG → expect large v_2

    IMR dominated by QGP → expect small v_2

- Dileptons at low-energies: where and when?

Dilepton experiments at low energies



NICA and Nuclotron beams

NICA collider beams:

- Heavy ion collisions up to $^{197}Au^{79+}$ + $^{197}Au^{79+}$ at:

  $\sqrt{s_{NN}}$ = 4 - 11 GeV , $L_{average}$= 10^{27} $cm^{-2}s^{-1}$

  same or higher $L_{average}$ for lighter ions

- Polarized proton and deuteron collisions:

  $p\uparrow p\uparrow$ $\sqrt{s_{pp}}$ = 12 - 26 GeV L_{max} ≈ 10^{32} $cm^{-2}s^{-1}$

  $d\uparrow d\uparrow$ $\sqrt{s_{NN}}$ = 4 - 13.8 GeV

Nuclotron extracted beams (for fixed target experiments):

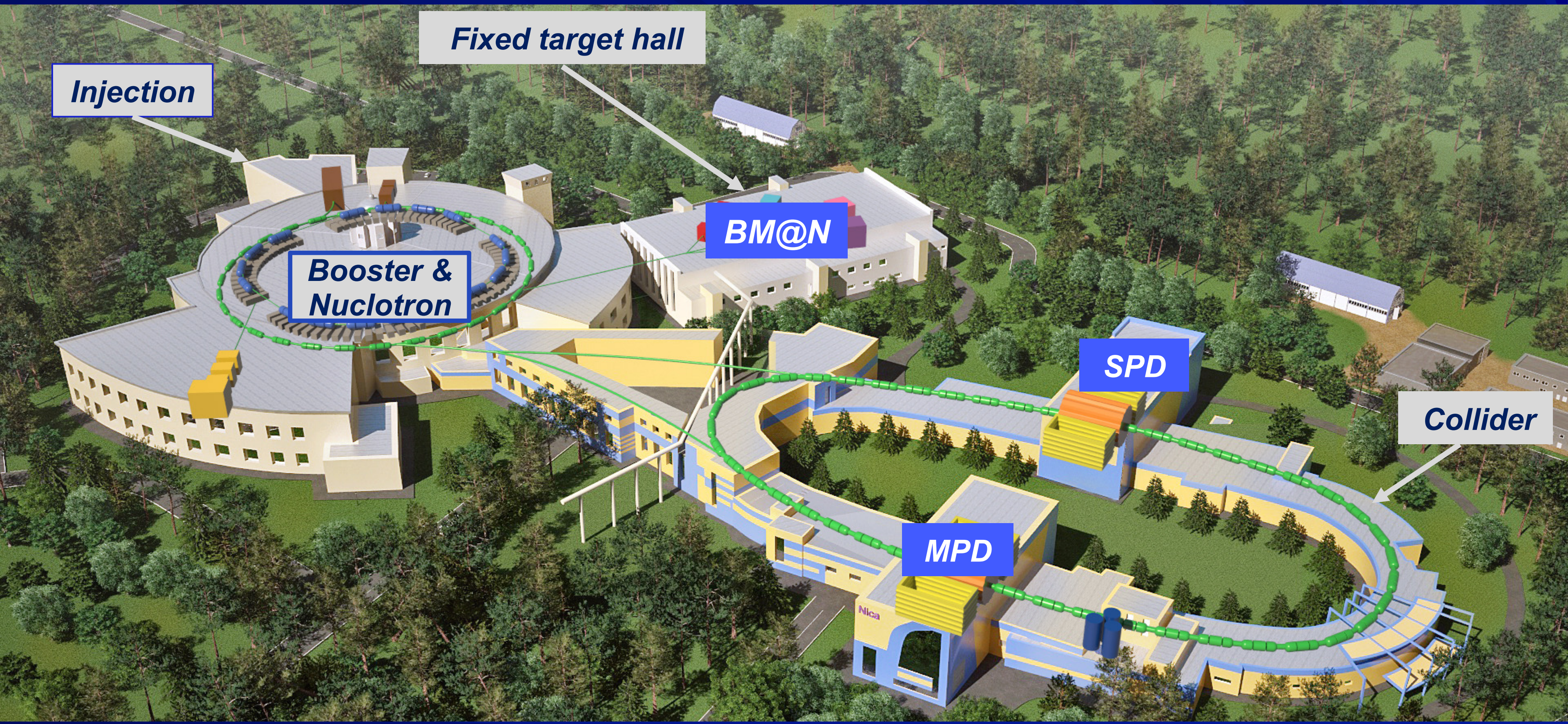
- Ions and polarized beams of p and d:

  Li - Au = 1 - 4.5 GeV/u

  $p\uparrow$ = 5 - 12.6 GeV

  $d\uparrow$ = 2 - 5.9 GeV/u

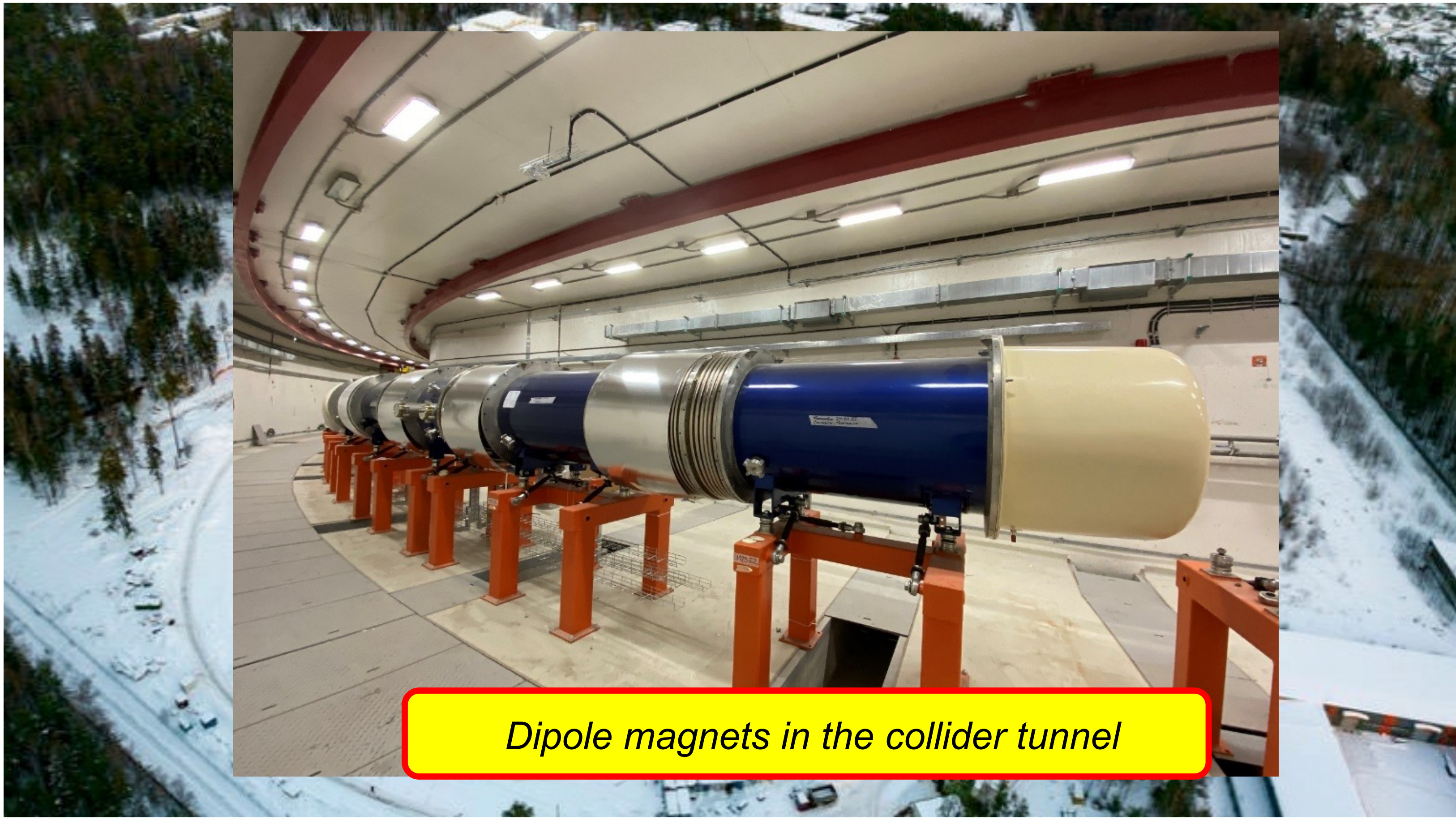
NICA complex



NICA accelerator complex

- Civil construction completed.
- Infrastructure to be completed by July 2023
- Most accelerator components have been produced and tested

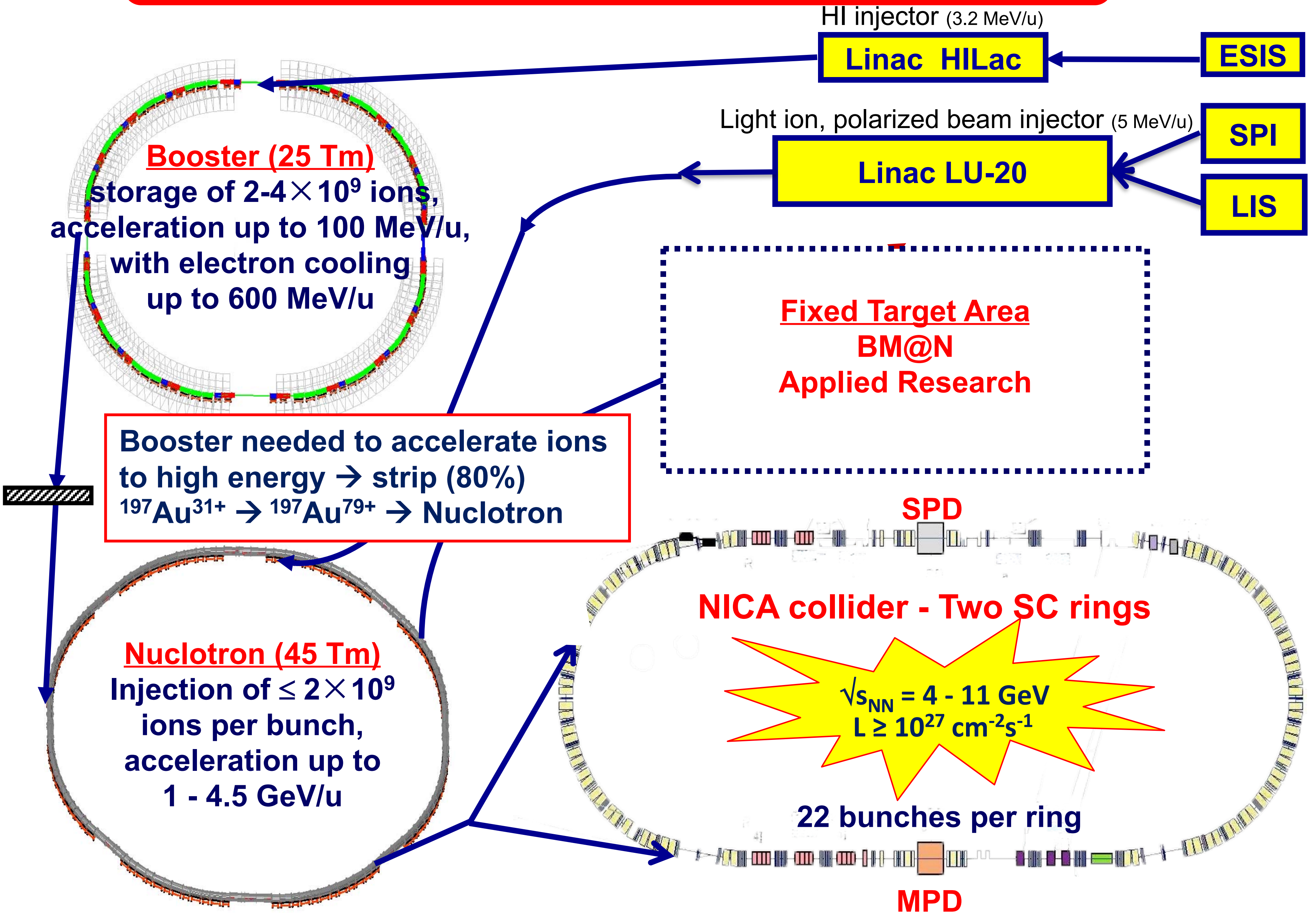
NICA accelerator complex



Dipole magnets in the collider tunnel

- Civil construction completed.
- Infrastructure to be completed by July 2023
- Most accelerator components have been produced and tested
- All dipole magnets have been installed
- Machine commissioning foreseen in 2024

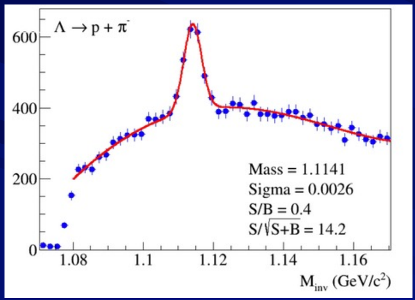
NICA acceleration schemes



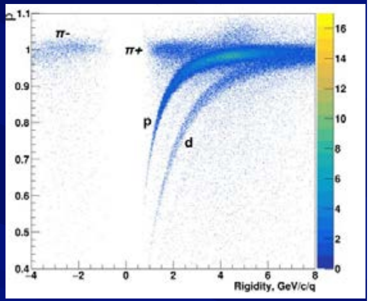
First physics BM@N run

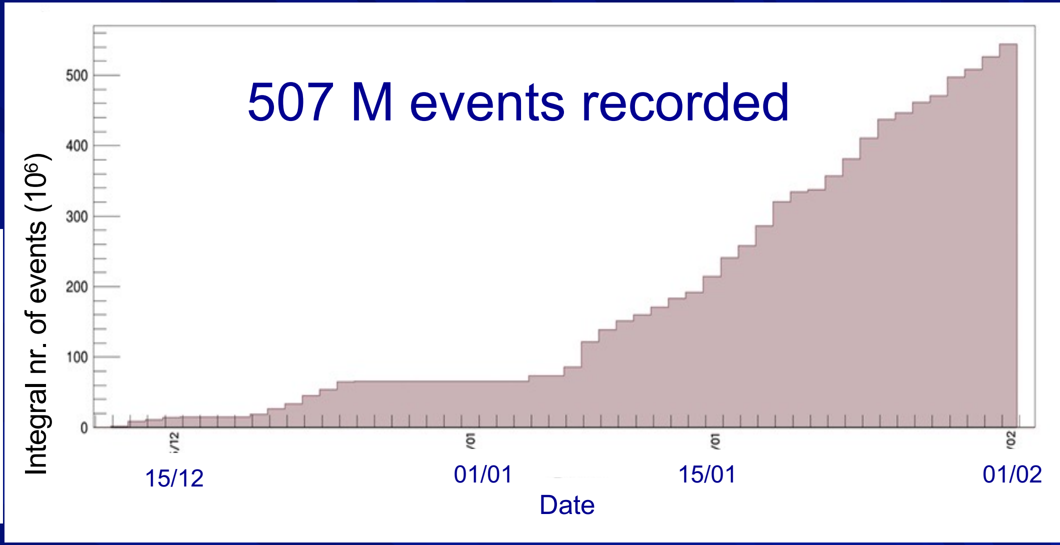
Dec. 10, 2022 – Feb. 1, 2023
3.6 AGeV Xe beam on a CsI target

Online Λ reconstruction
500K events



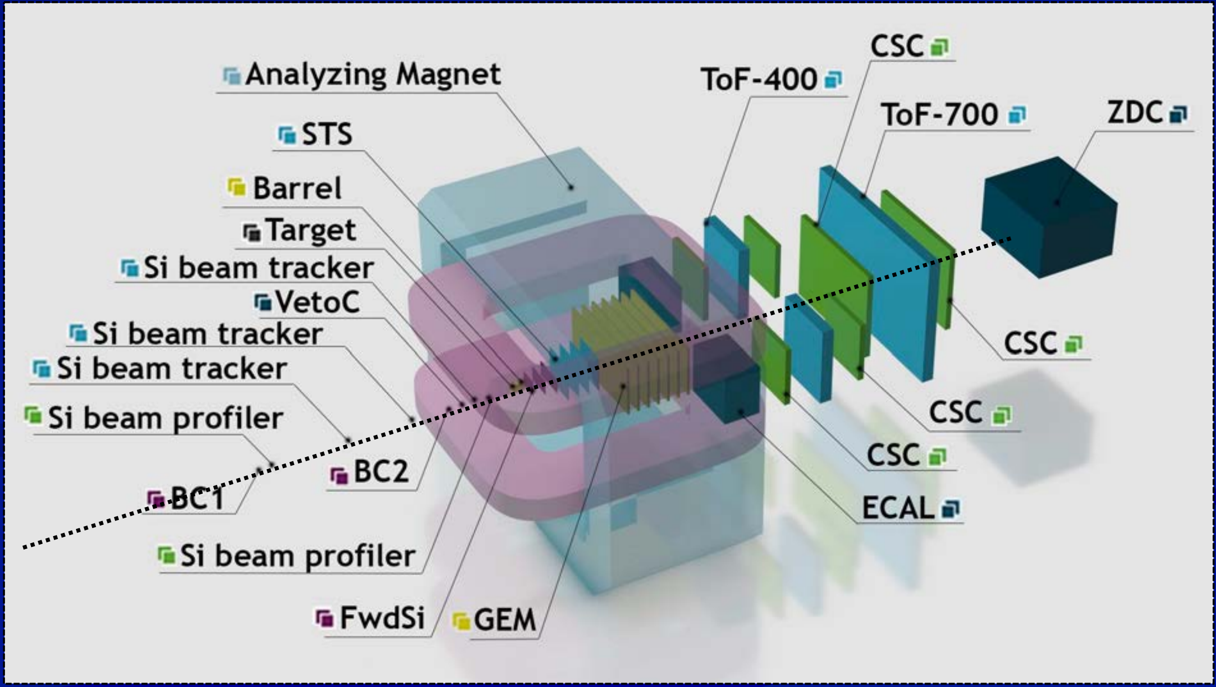
Online TOF-700 data





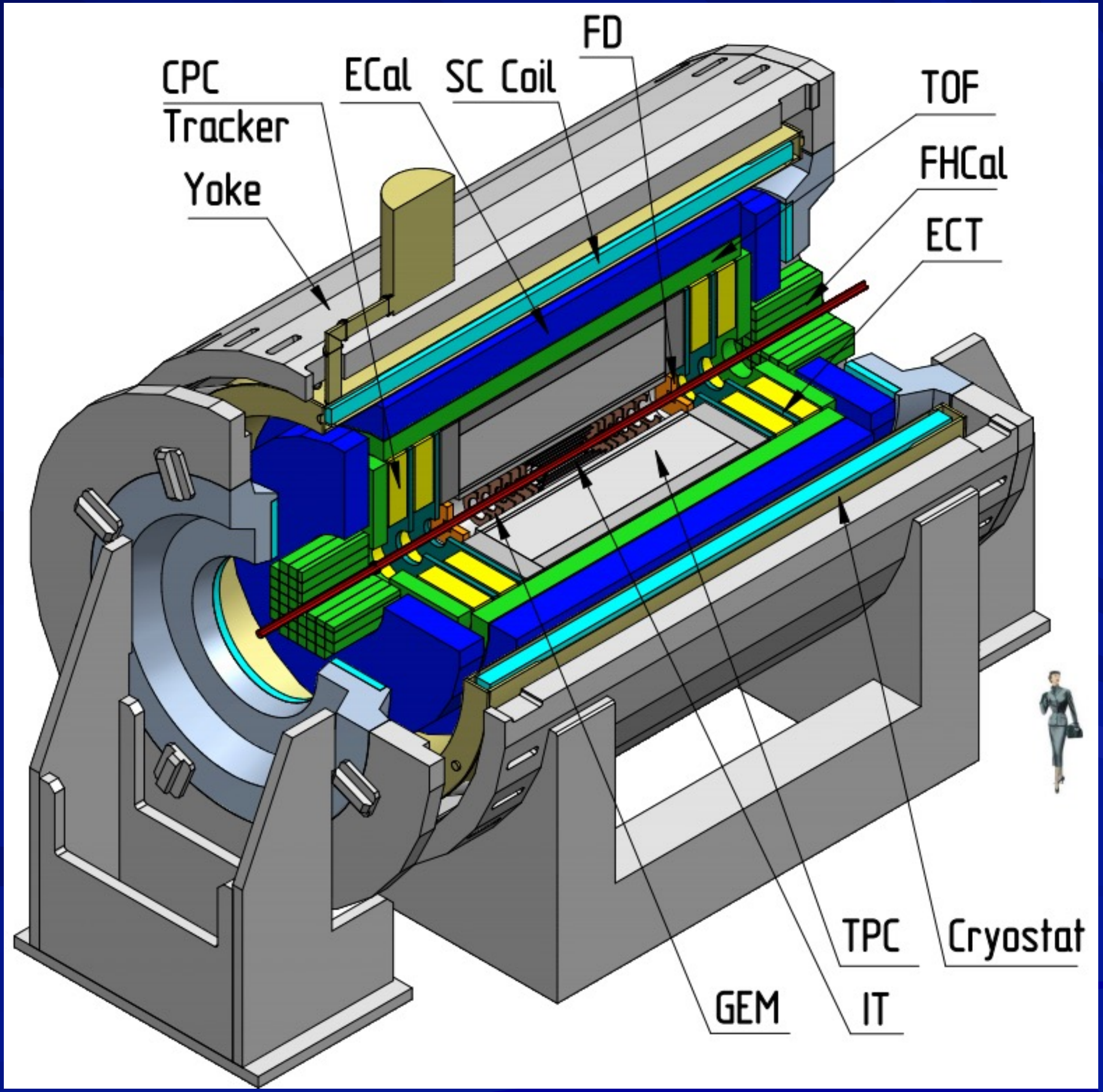
BM@N set-up:

- ❑ Central tracker:
3 Si + 7 GEM
- ❑ Outer tracker:
4 CSC
- ❑ Particle id:
ToF-400, ToF-700, ECal
- ❑ Beam tracker and ZDC
- ❑ Dipole magnet:
2.1 Tm, 1.05 m gap



Multi-Purpose Detector (MPD)

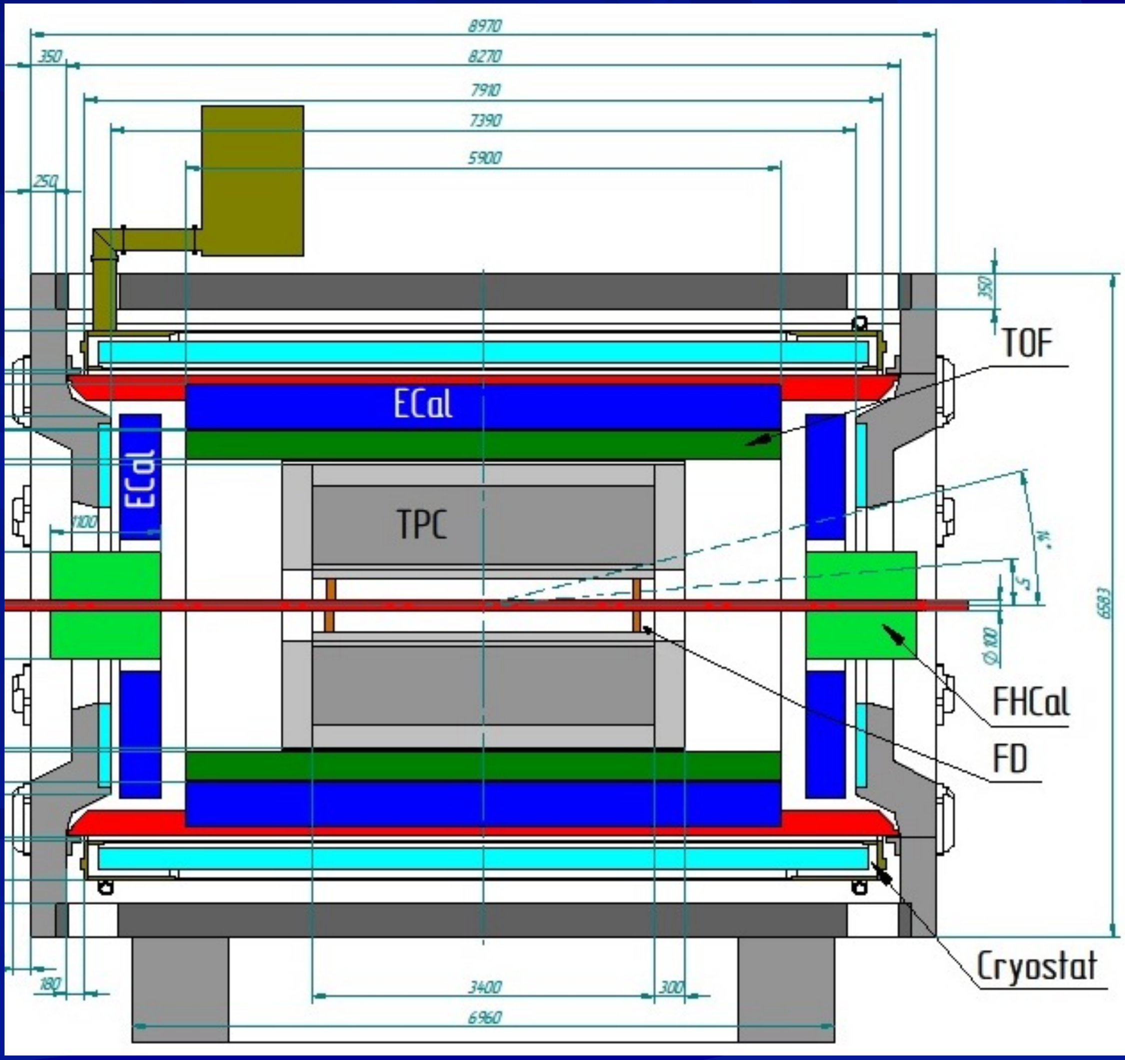
Study heavy-ion collisions at $\sqrt{s_{NN}}$ = 4−11 GeV



MPD (Multi-Purpose Detector)

Stage 1: TPC, TOF, ECAL, FHCAL, FD

- 9 m long, 6m diameter
- Low material budget
- Good tracking and pid



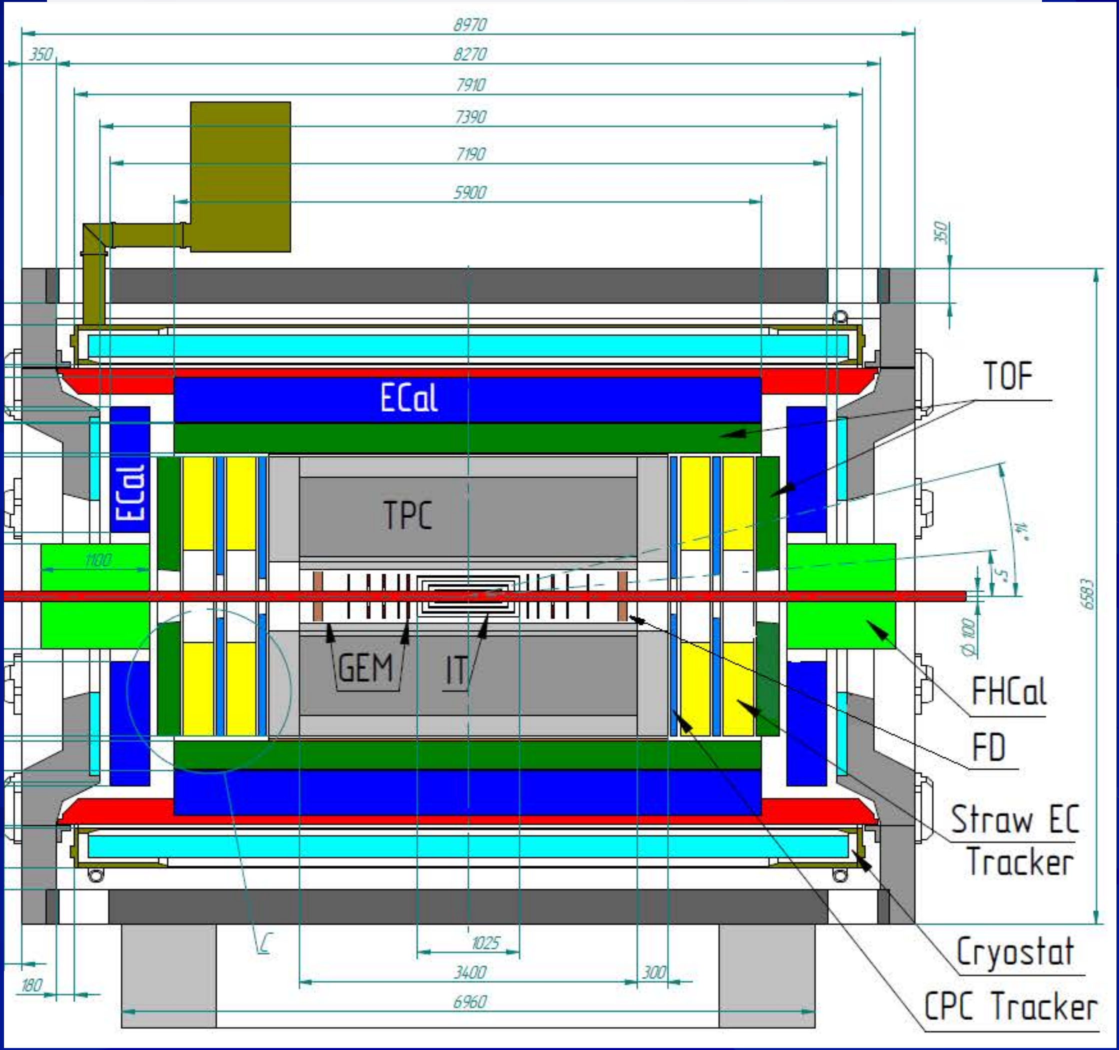
- Tracking (TPC):
  up to |η|<1.6, 2π in azimuth
- PID (TOF, TPC, ECAL):
  hadrons, e, γ
- Event characterization (FHCAL):
  centrality & event plane
- Start time (FD)

MPD (Multi-Purpose Detector)

Stage 1: TPC, TOF, ECAL, FHCAL, FD

Stage 2: IT + Endcaps (tracker, TOF, ECAL)

- 9 m long, 6m diameter
- Low material budget
- Good tracking and pid



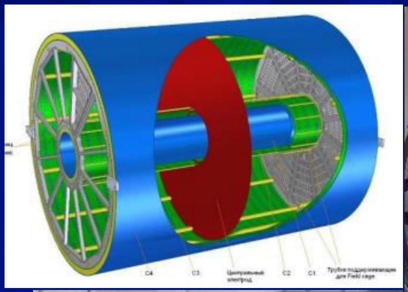
- Tracking (TPC): up to $|\eta|<1.6$, 2π in azimuth
- PID (TOF, TPC, ECAL): hadrons, e, γ
- Event characterization (FHCAL): centrality & event plane
- Start time (FD)

MPD subsystems status

SC solenoid and iron yoke

Pending: crygenic test,
Magnetic field mapping

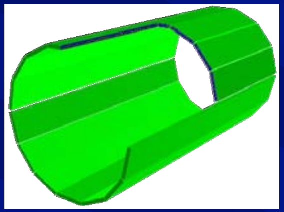
TPC



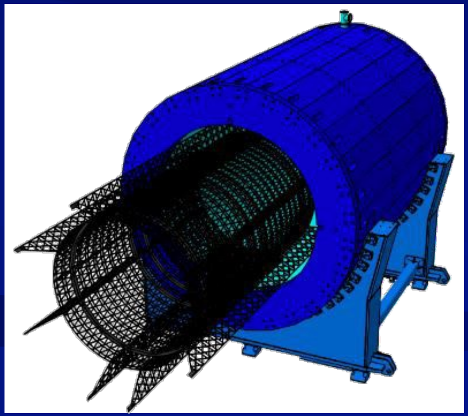
Assembly to be completed 10/23
ROC: 24 MWPC –110,000 channels
produced and tested

ToF

280 MRPC
13,440 channels
50 ps



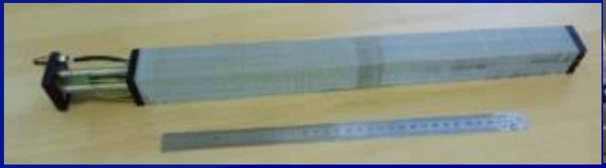
Support Structure

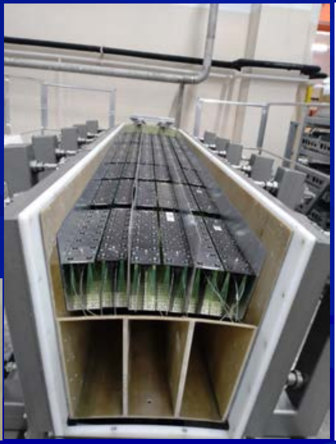


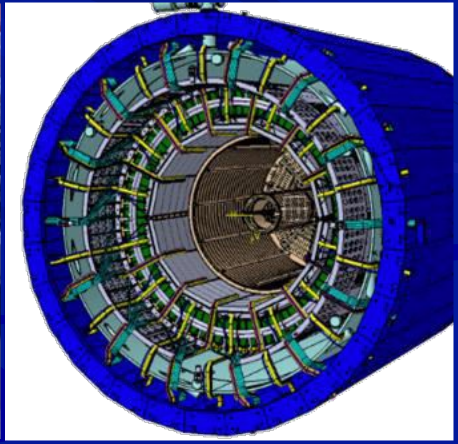
Support structure of C fiber
ECal ~100T
Sagitta 5 mm
$0.13X/X_0$

ECal

Pb-Sc shashlik – Projective geom.
38,400 towers –
50 half-sectors x 48 modules x 16 towers
At least 83% ready on day one

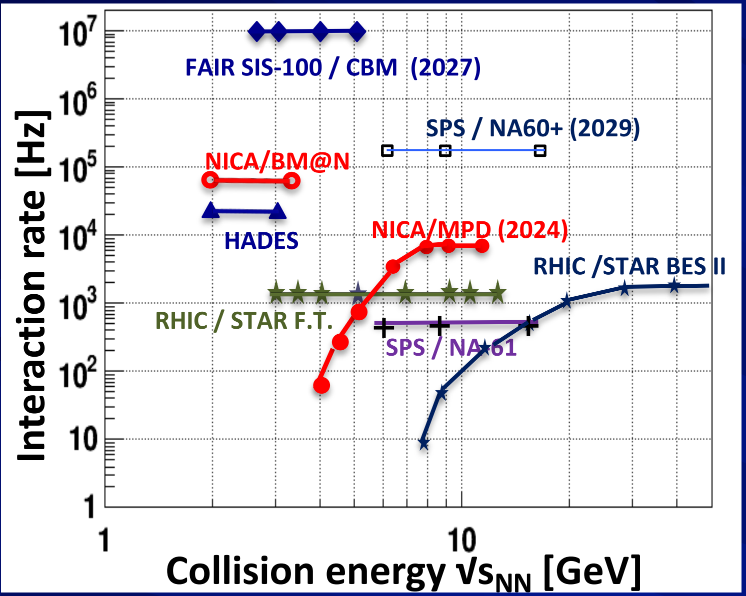




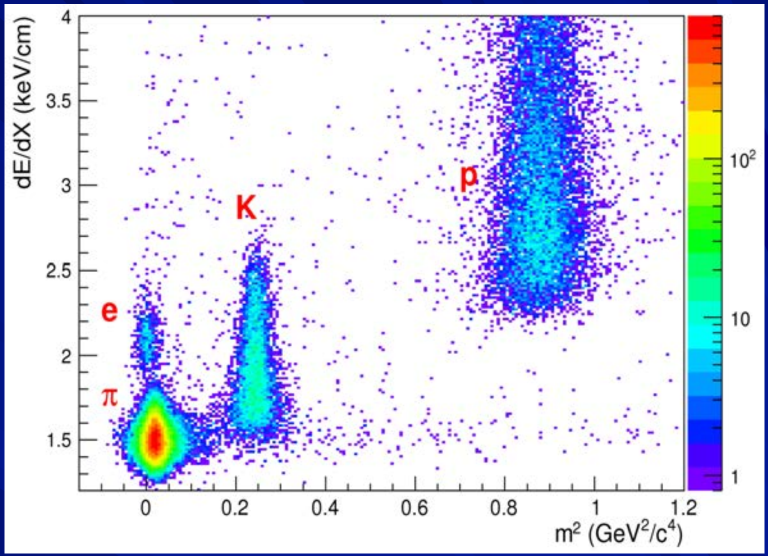


MPD Experiment

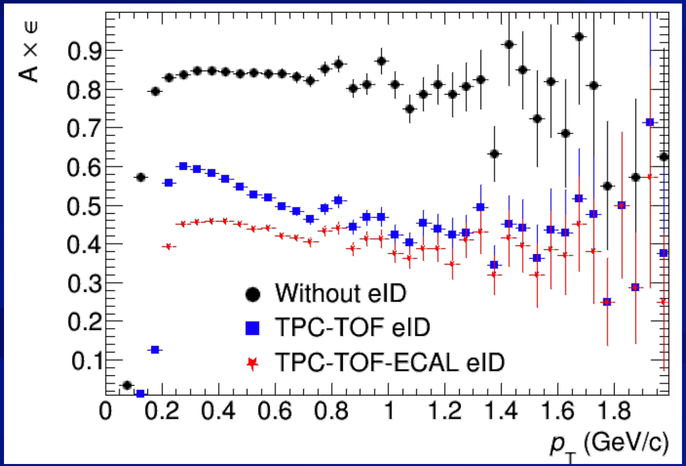
Interaction rate



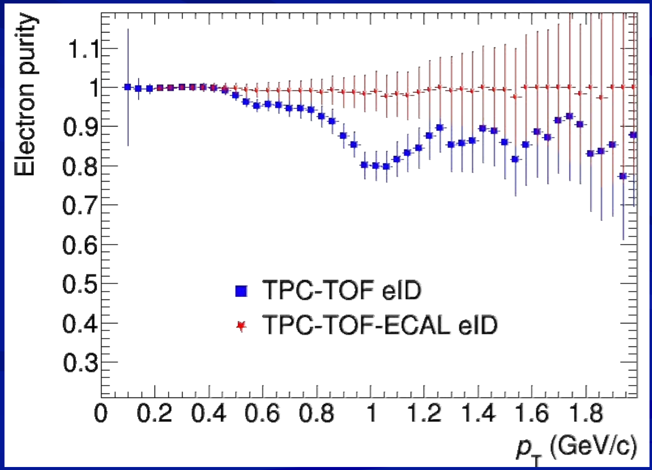
Electron ID:
- TPC dE/dx
- ToF
- Ecal (E/p =1)



Electron efficiency



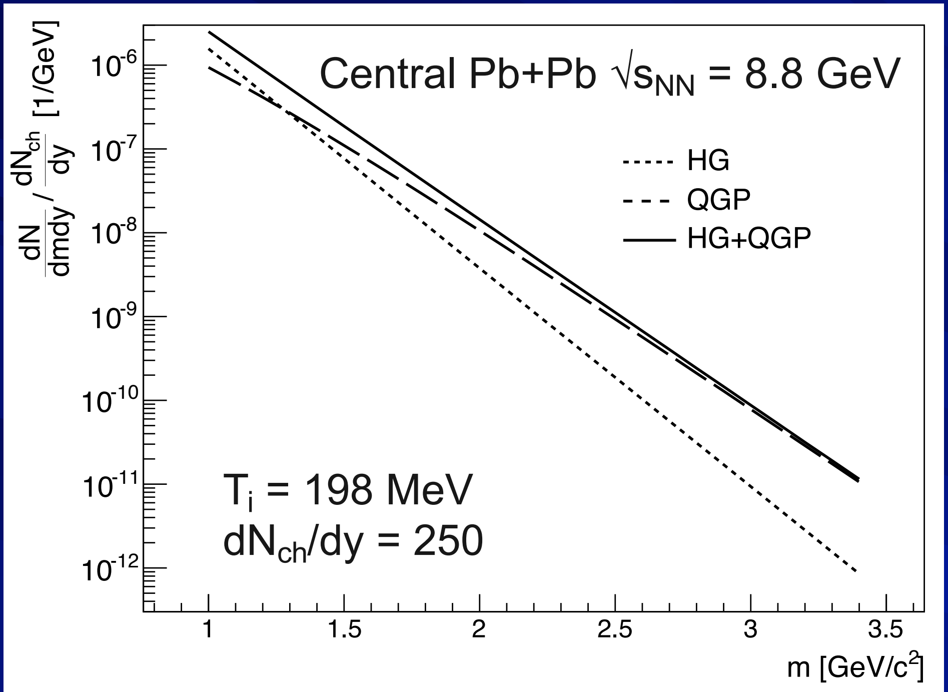
Electron purity

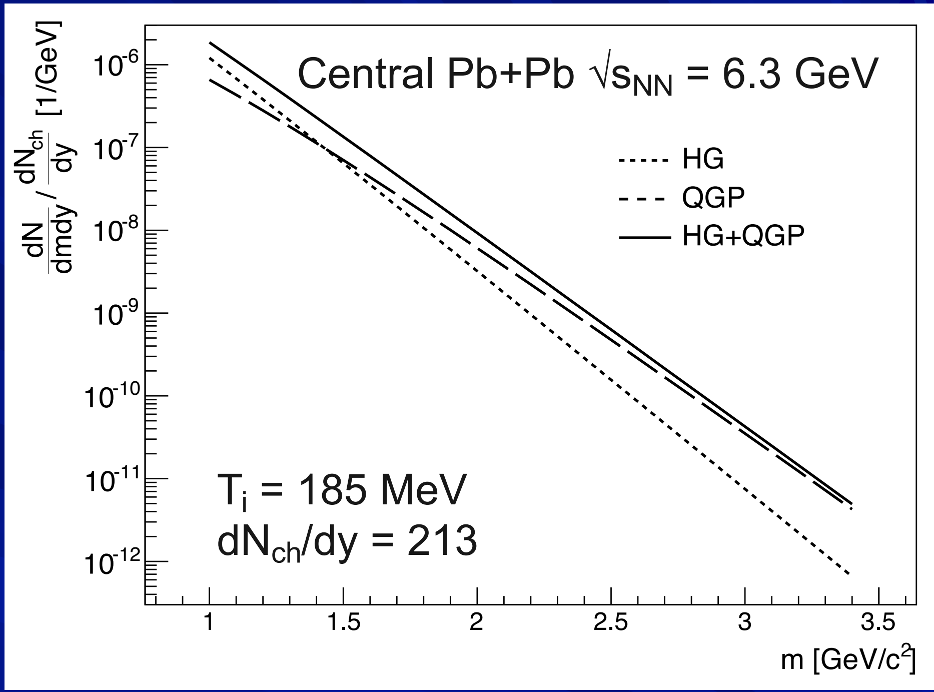


- ❑ Challenge: combinatorial background
- ❑ Efforts underway (ML) to increase efficiency and reduce CB

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
- MPD well suited for dilepton measurements

Summary

- Exciting dilepton prospects at low energies
- Measurements performed by STAR in RHIC BES-II
- Dedicated facilities under construction: NICA, FAIR, JPARC-HI
- Looking forward to the results from STAR and the new facilities

- Thank you!