Dielectron measurements in Au+Au collisions at BES-II energies with the STAR experiment

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(STAR Collaboration)
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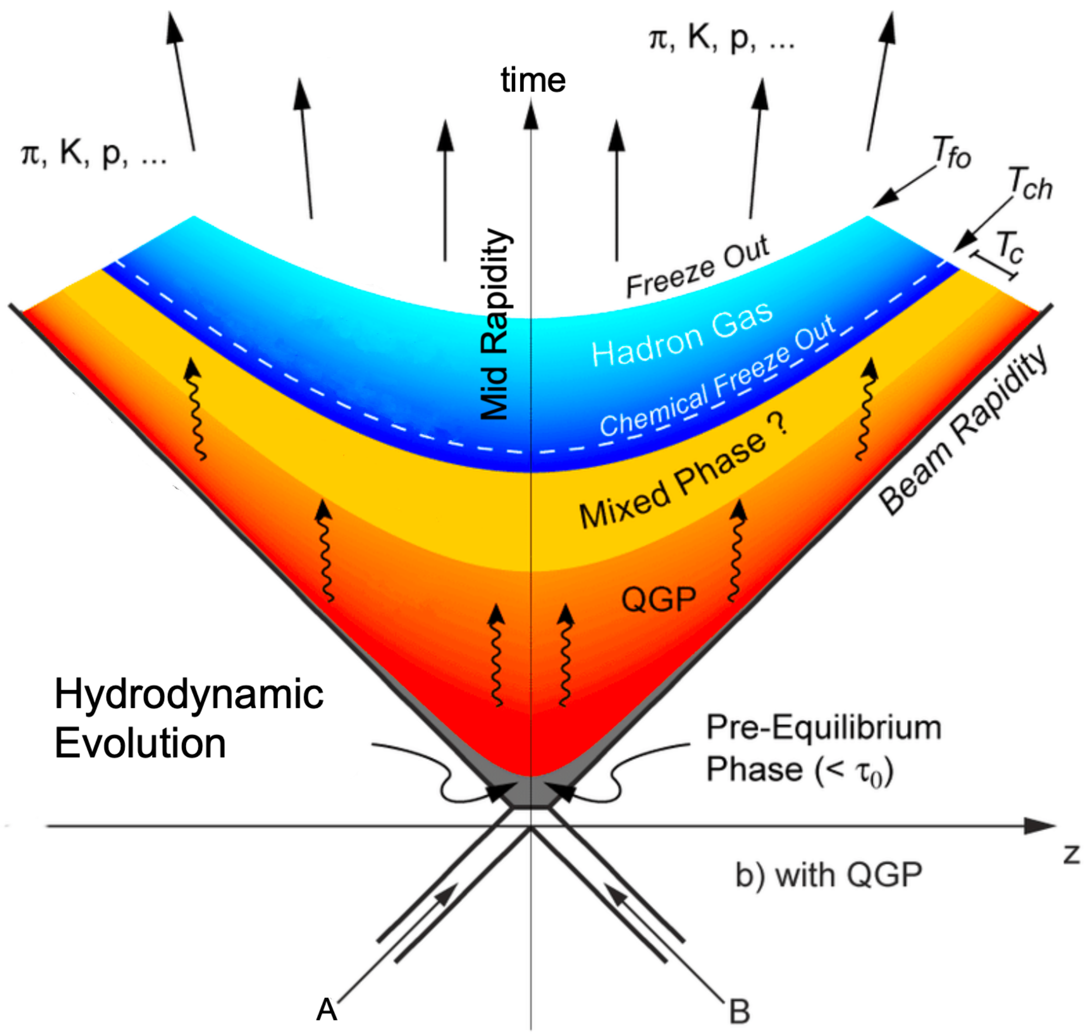
Outline

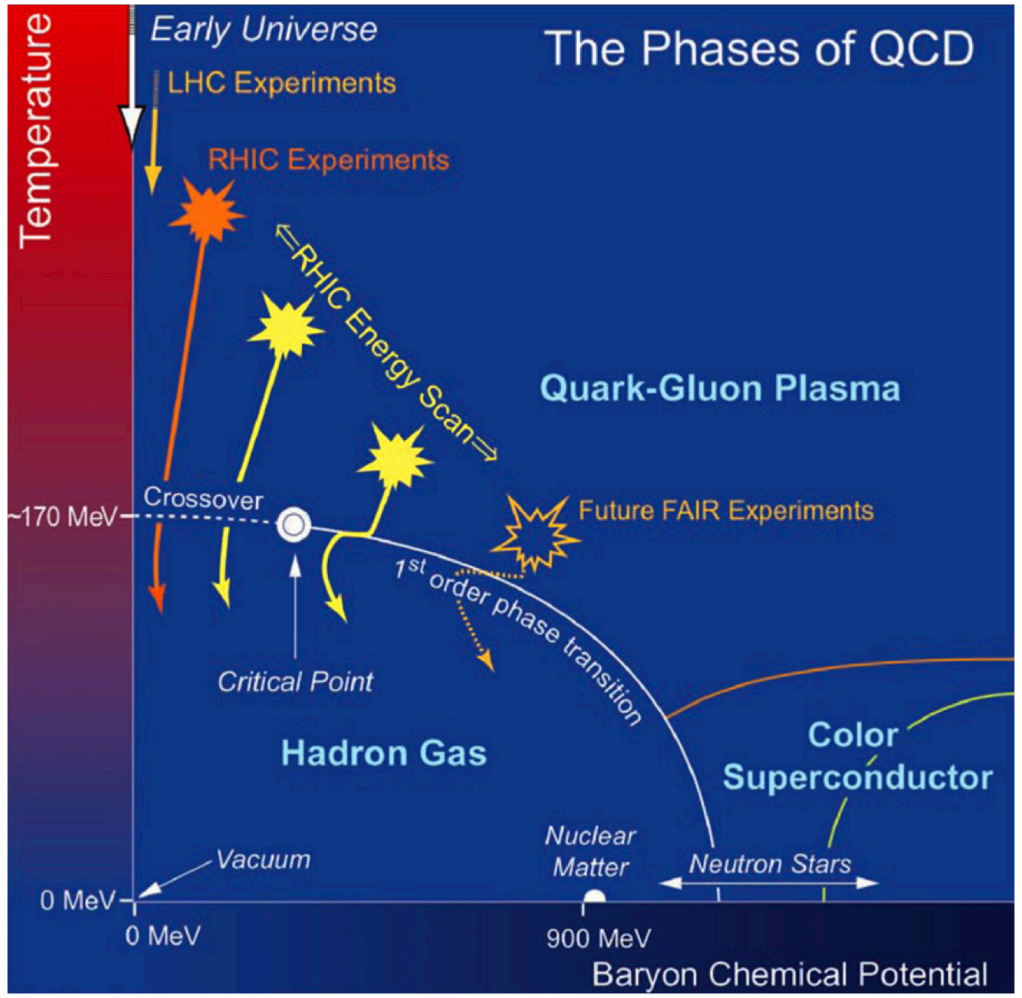
- QCD Phase Diagram and Heavy-ion collision
- Dileptons as probe with theoretical considerations
- Dielectron analysis in RHIC BES-II energies
    - Spectrometer, Thermometer
- Summary and Outlook

QCD Phase Diagram and Heavy-Ion Collision

- Quark-Gluon Plasma (QGP) phase
  - Deconfined quarks and gluons.
  - Local thermal equilibrium.
- Hadronization: Phase transition to the Hadron Gas phase.
- First/second order phase transition or Crossover?
- Experimentally, one can access different regions of phase diagram by varying centre-of-mass energy of colliding ions.
  - Current experiment data already cover around 4 orders of magnitude.

Relativistic Heavy-Ion Collision Evolution



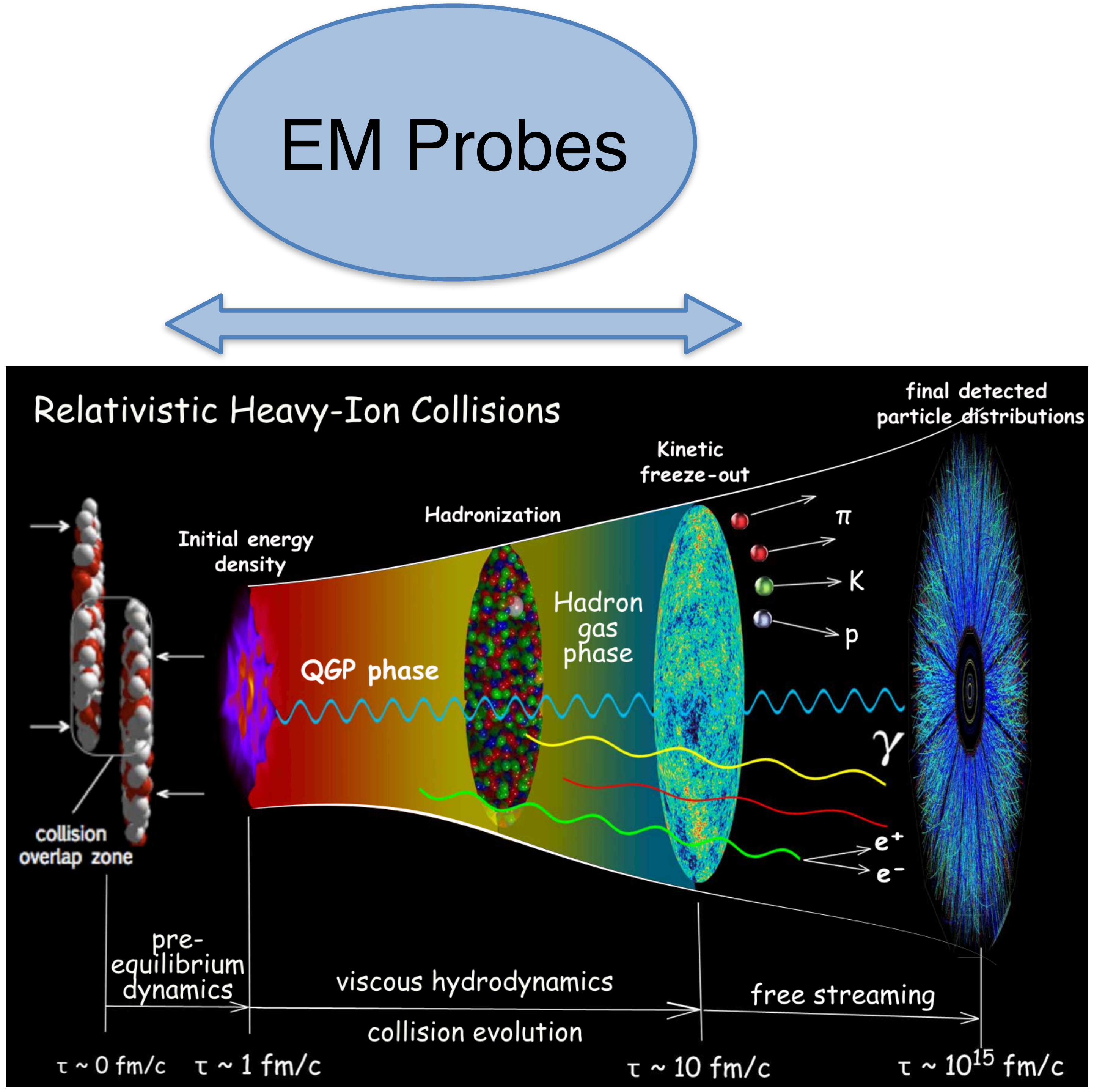


STAR Collaboration, Studying the Phase Diagram of QCD Matter at RHIC, 2014

Why Dileptons?

- EM probes are penetrating:
  - No coupling to strongly interaction matter.
  - Mean free path length » size of the fireball.
  - Reflect the whole history of a collision.

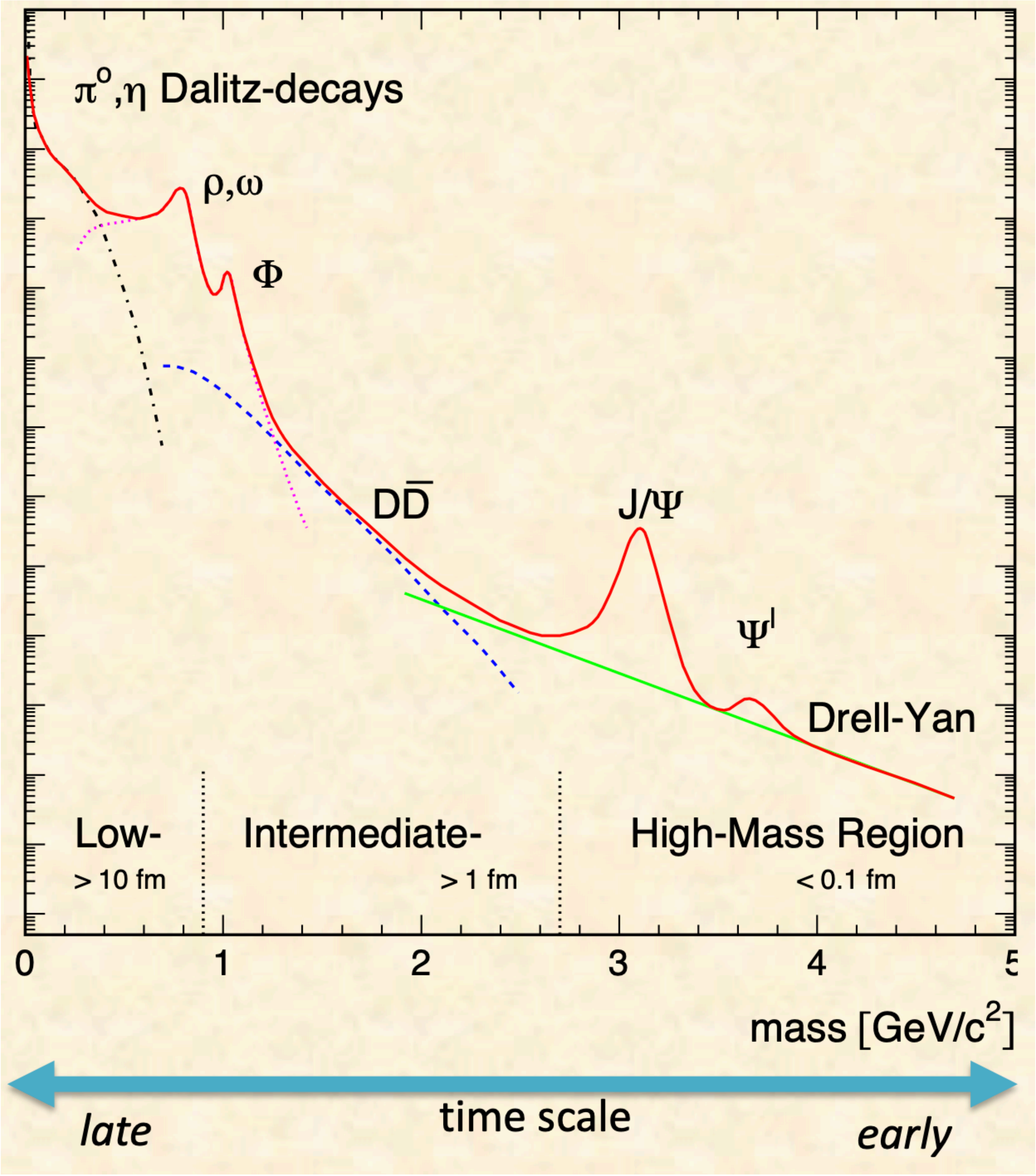
- Dileptons vs. direct photon:
  - Encode additional information: invariant mass.
  - No blue-shift effect.



Shen, C.;Heinz, U. Nucl. Phys. News 2015,25, 6–11

Dilepton invariant mass spectrum

- High Mass Range (HMR: M_{ee} > 3 GeV/c²)
  - Drell-Yan: $q\bar{q} \rightarrow \gamma^* \rightarrow e^+e^-$
  - Heavy quarkonia: J/ψ and ϒ.
- Intermediate Mass Range (IMR: 1 < M_{ee} < 3 GeV/c²)
  - QGP thermal radiation: $q\bar{q} \rightarrow e^+e^-$
  - Semi-leptonic decay of correlated charm: $c\bar{c} \rightarrow e^+e^-X$
- Low Mass Range (LMR: M_{ee} < 1 GeV/c²)
  - In-medium vector mesons.
  - Light meson decays: π, η Dalitz decays.
  - Transport coefficients (electrical conductivity).



courtesy of Axel Drees

Electromagnetic production rate

In a strongly interacting thermal equilibrium medium Dilepton emission rate in four-dimensional space and momentum

$$\frac{dR_{l^+l^-}}{d^4x d^4q} = \frac{-\alpha_{EM}^2}{3\pi^3 M^2} f_B(q_0, T) g_{\mu\nu} \mathrm{Im}[\Pi_{EM}^{\mu\nu}(M, q, T, \mu_B)]$$

$f_B(q_0; T)$: Thermal Bose–Einstein distribution

Im$[\Pi_{EM}^{\mu\nu}(M, q; T, \mu_B)]$: EM correlation function

The emission rate is connected to the imaginary part of correlation function defined via the hadronic EM current

$$\Pi_{EM}^{\mu\nu}(M, q, T, \mu_B) = -i \int d^4x e^{iq\cdot x} \Theta(x_0) \langle\langle [j_{EM}^{\mu}(x), j_{EN}^{\nu}(0)] \rangle\rangle$$

$\Theta(x_0)$: Heaviside function with time (x_0)

E. L. Feinberg, Nuovo Cim. A 34, 391 (1976).
L. D. McLerran and T. Toimela, Phys. Rev. D 31, 545 (1985).

EM spectral function and Vector Meson Dominance

EM spectral function:

- $M_{ee} > 1.5$ GeV/c²: Partonic dominance

$$j^{\mu}_{EM} = \sum_{q=u,d,s} e_q \bar{q}\gamma^{\mu} q$$

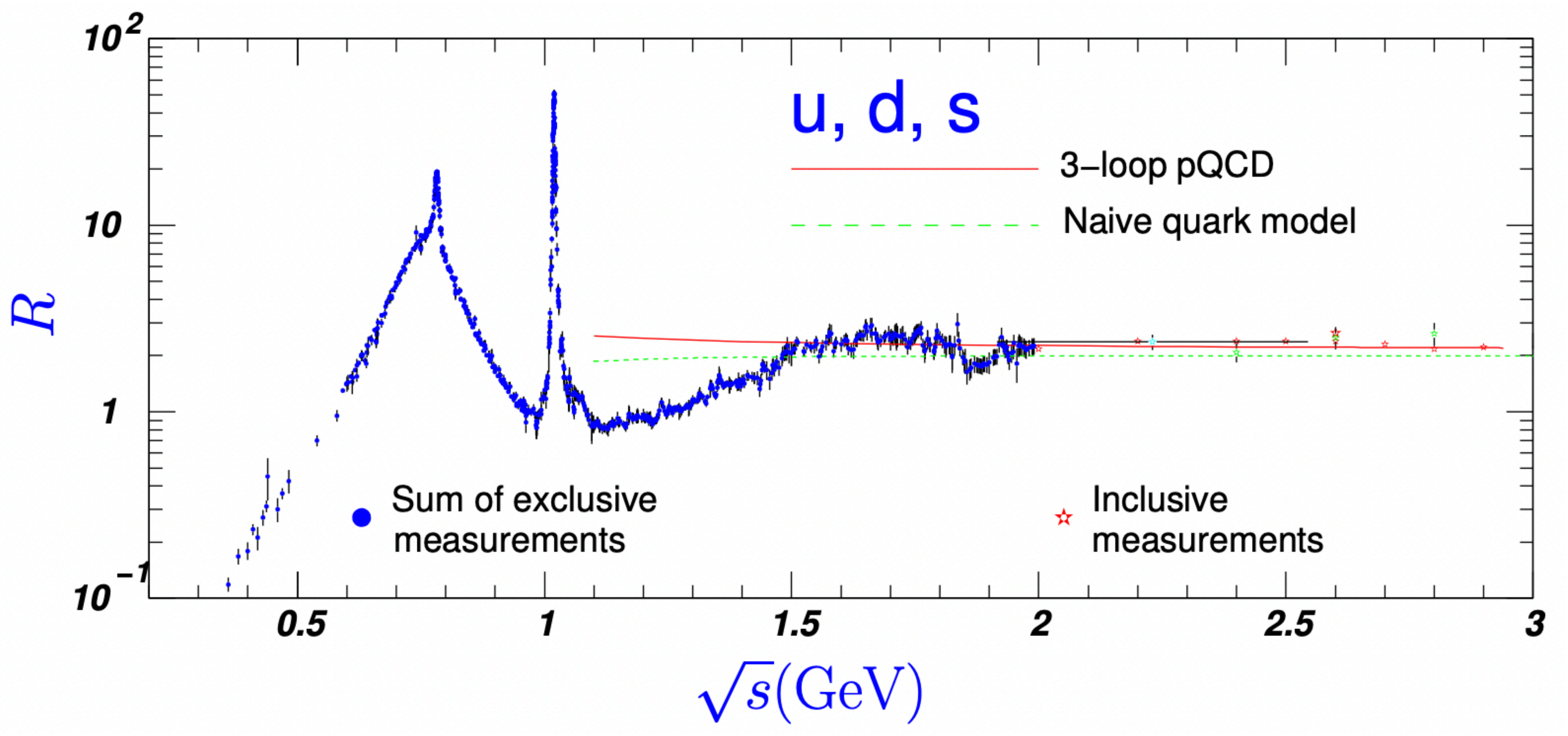
- $M_{ee} < 1.1$ GeV/c²: Vector Meson dominance (VDM)

$$j^{\mu}_{EM} = \frac{1}{2}(\bar{u}\gamma^{\mu}u - \bar{d}\gamma^{\mu}d) + \frac{1}{6}(\bar{u}\gamma^{\mu}u + \bar{d}\gamma^{\mu}d) + \frac{1}{3}\bar{s}\gamma^{\mu}s$$
$$= \frac{1}{\sqrt{2}} j^{\mu}_{\rho} + \frac{1}{3\sqrt{2}} j^{\mu}_{\omega} + \frac{1}{3} j^{\mu}_{\phi}$$

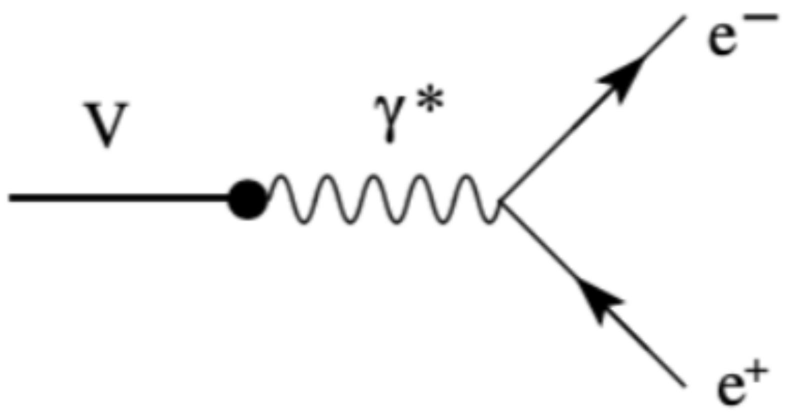
- ρ dominance $\quad \mathrm{Im}\Pi_{EM} \sim [\mathrm{Im}D_{\rho} + \frac{1}{9}\mathrm{Im}D_{\omega} + \frac{2}{9}\mathrm{Im}D_{\phi}]$

J. J. Sakurai, Currents and Mesons, University of Chicago Press, Chicago (1969).

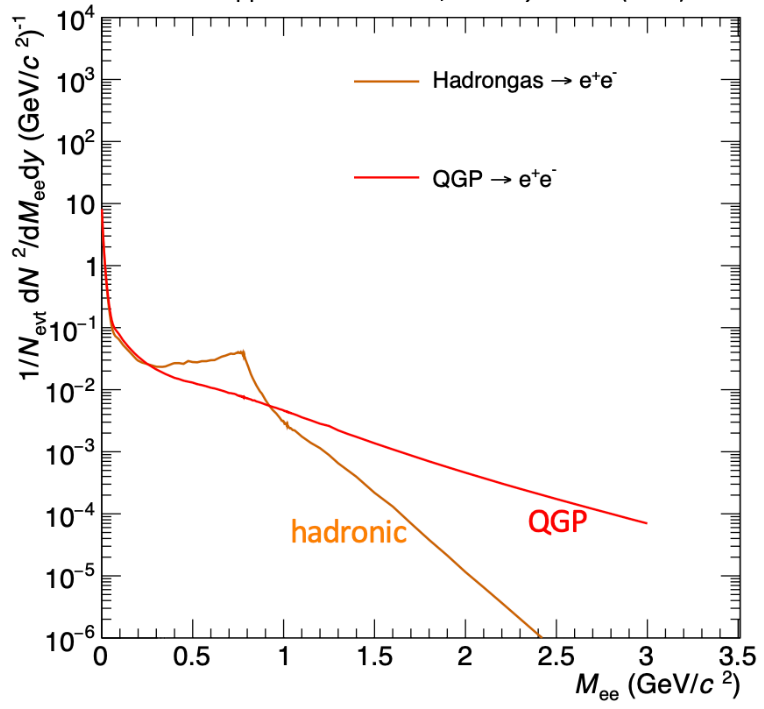
R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)



$$R = \frac{\sigma(e^-e^+ \to hadron)}{\sigma(e^-e^+ \to \mu^-\mu^+)}$$



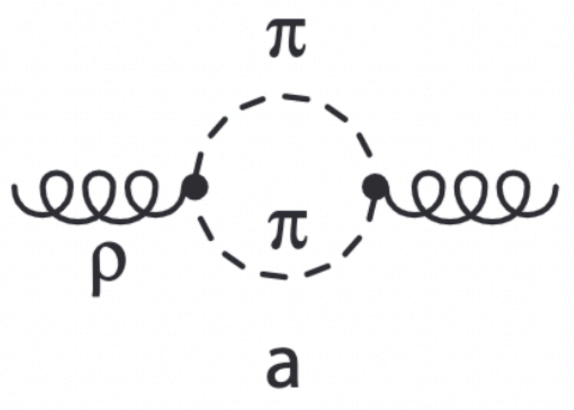
R. Rapp and J. Wambach, *Eur. Phys. J. A* 6 (1999)



In-medium Hadronic many body approach

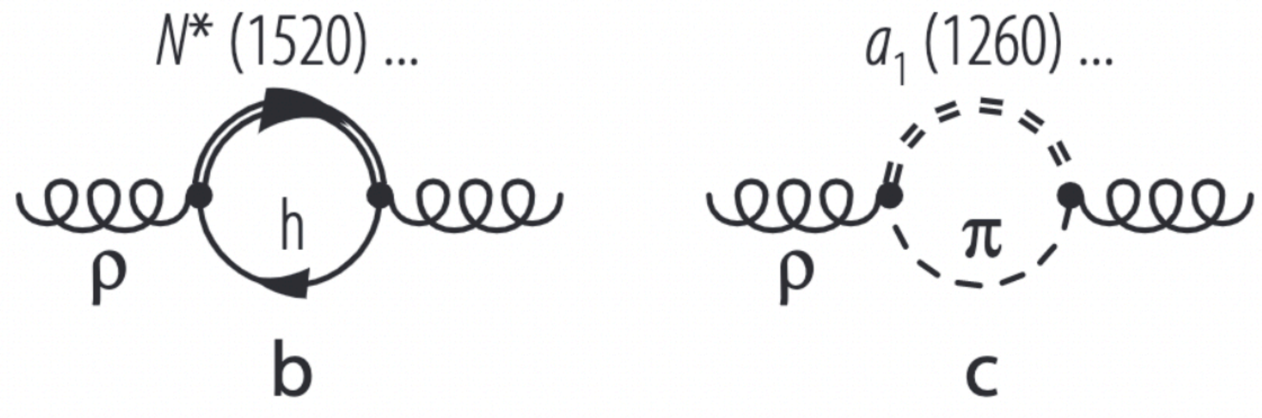
ρ meson propagator in the hot and dense hadronic matter

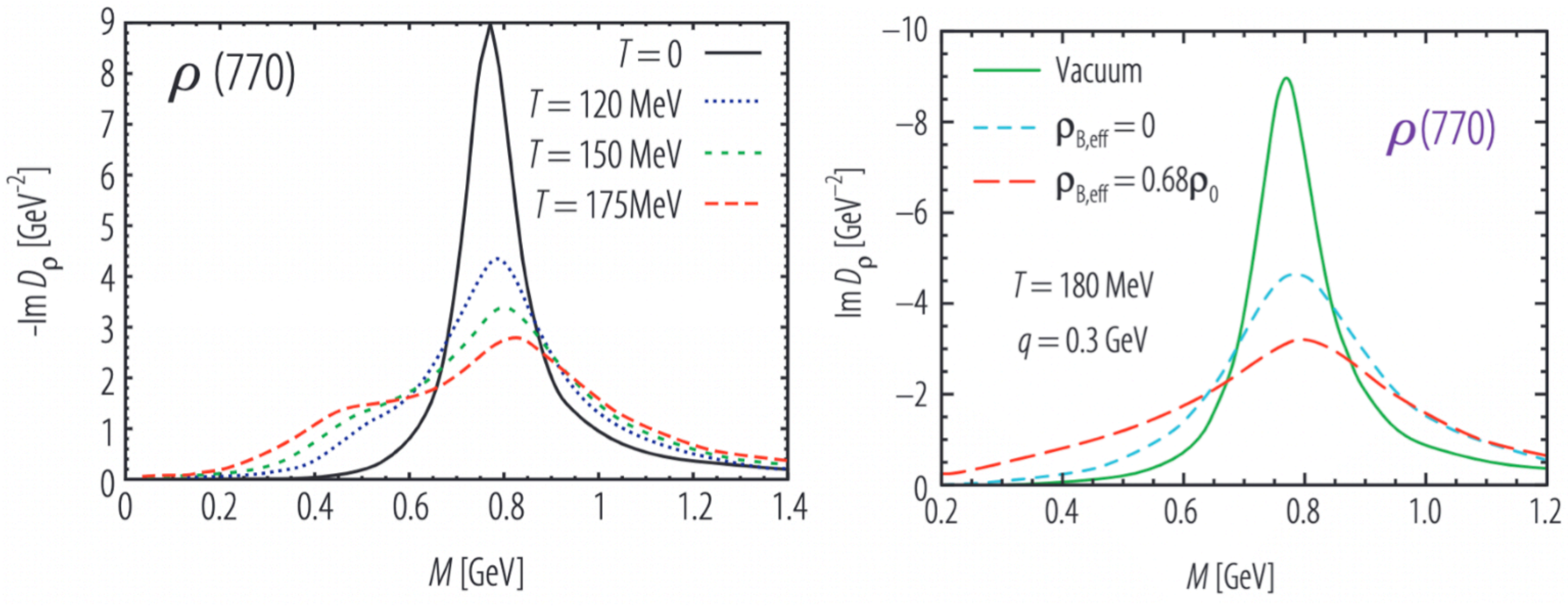
$$D_\rho(q_0, q; \mu_B, T) = \frac{1}{M^2 - (m_\rho^0)^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho M} - \Sigma_{\rho B}}$$



$\Sigma_{\rho\pi\pi}$ Pion cloud

$\Sigma_{\rho B,M}$ Scattering with baryons and mesons





Broadening depends on Temperature and Baryon Density

R. Rapp and C. Gale, Phys. Rev. C 60, 024903 (1999).
R. Rapp, G. Chanfray, and J. Wambach, Nucl. Phys. A 617, 472-495 (1997).
M. Herrman, B. L. Friman and W. Nörenberg, Nucl. Phys. A 560, 411 (1993).
R. Rapp and J. Wambach, Eur. Phys. J. A 6, 415 (1999).

M. Urban, M. Buballa, R. Rapp, and J. Wambach, Nucl. Phys. A 673, 357 (2000).
J. Atchison and R. Rapp, Nucl. Phys. A 1037, 122704 (2023).
Rapp, Acta Phys. Polon. B42 (2011) 2823.

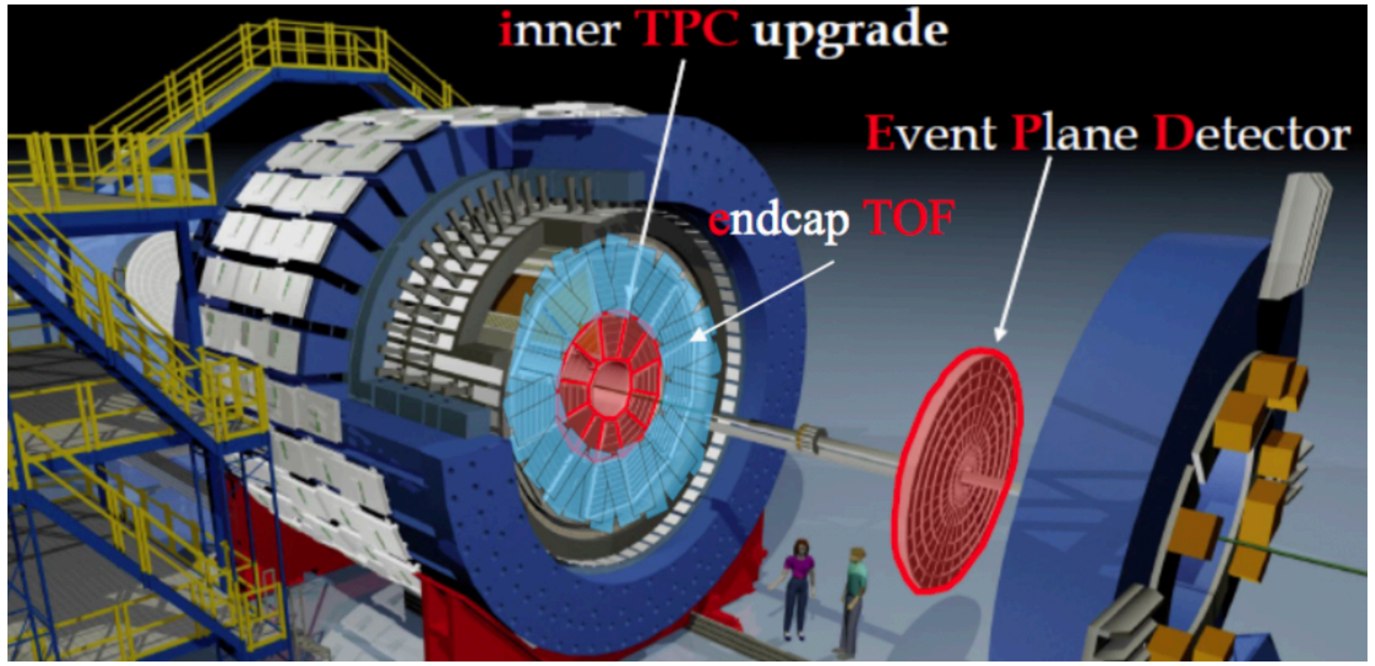
STAR experiment

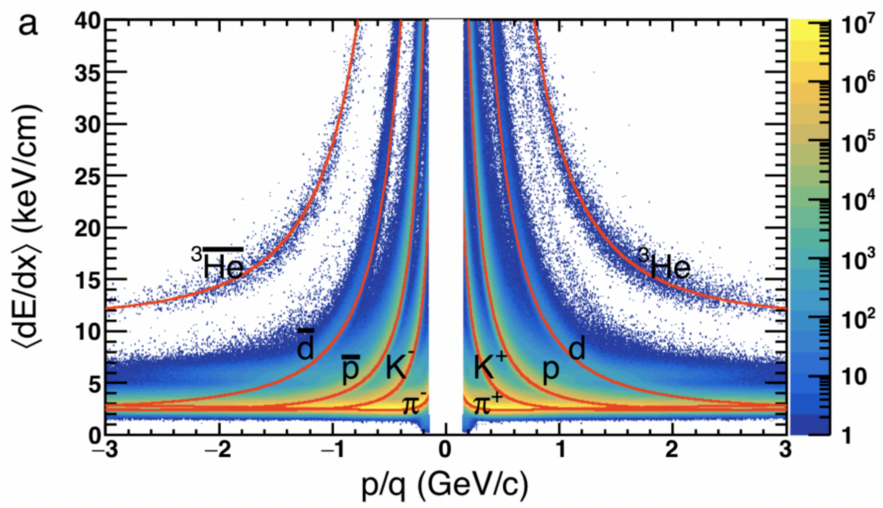
STAR Beam Use Request 2019/2020 (SN696)
STAR, Nature Physics 16, 409-412 (2020)

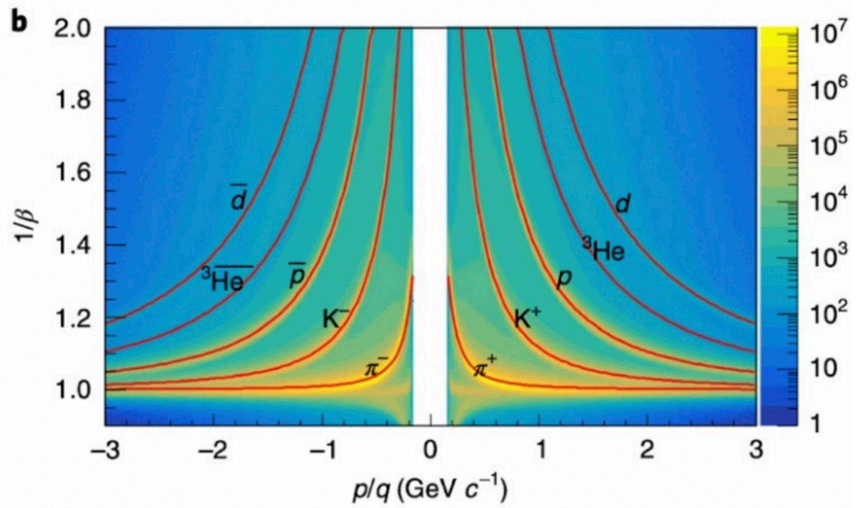
- Dielectron analysis need large acceptance + high purity PID.

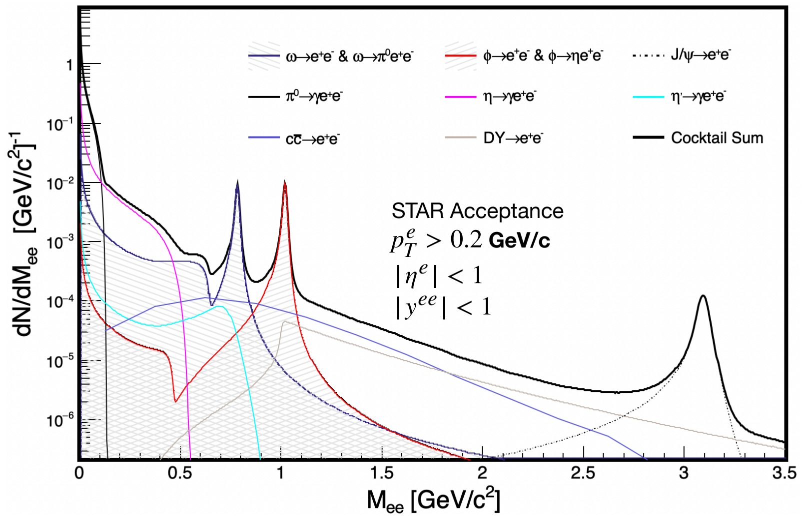
- STAR experiment PID system: Time Projection Chamber + Time of Flight detectors.
  - Momentum measurement.
  - dE/dx and velocity($1/\beta$).
  - High purity sample.

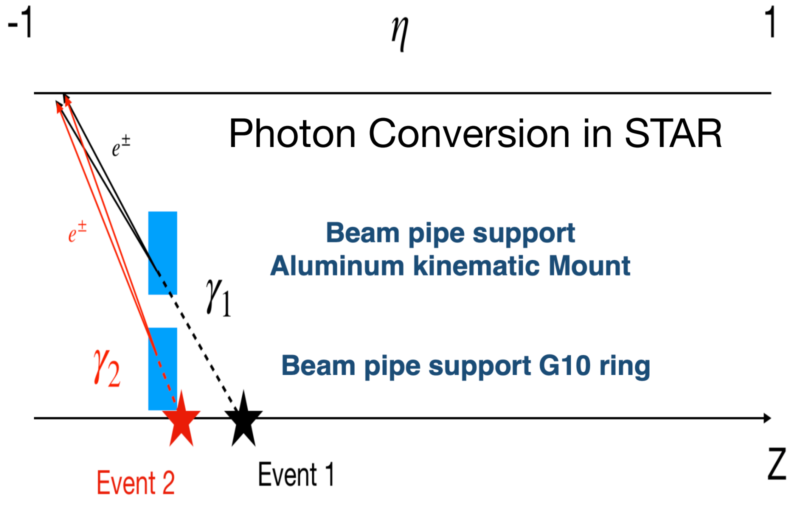
- Physics background for electron:
  - Photon conversion from material or target.
  - Dalitz decay from light mesons.
  - In-medium modification of charm.





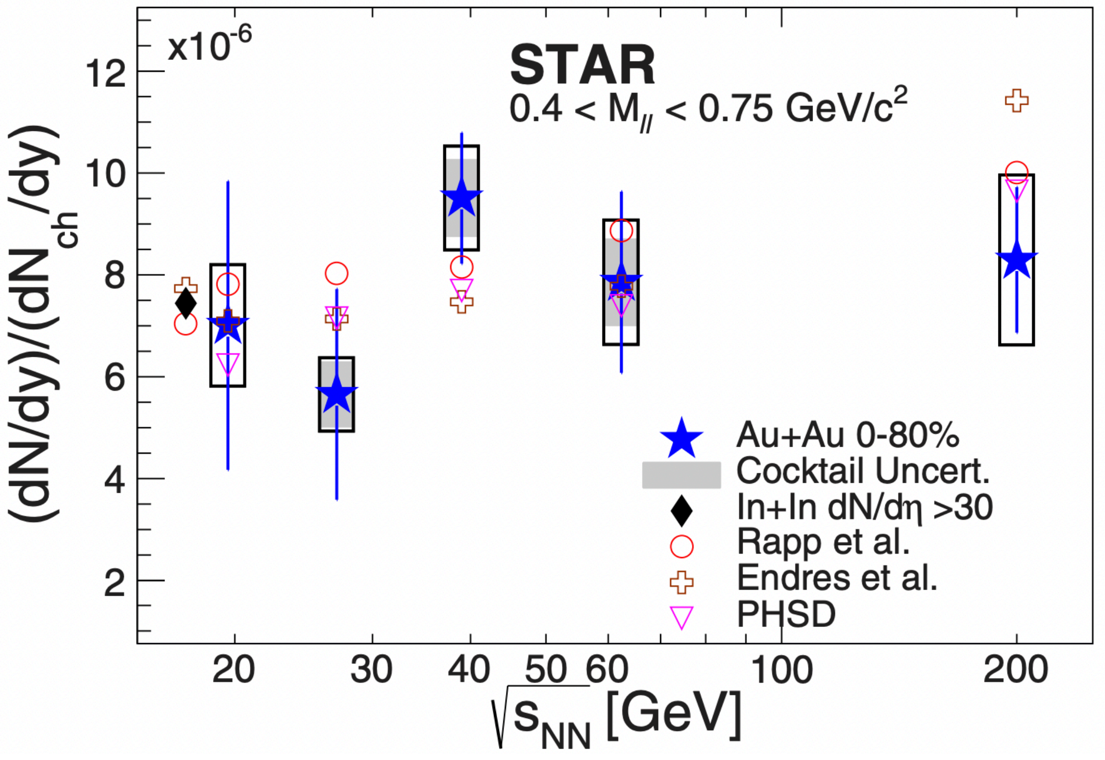


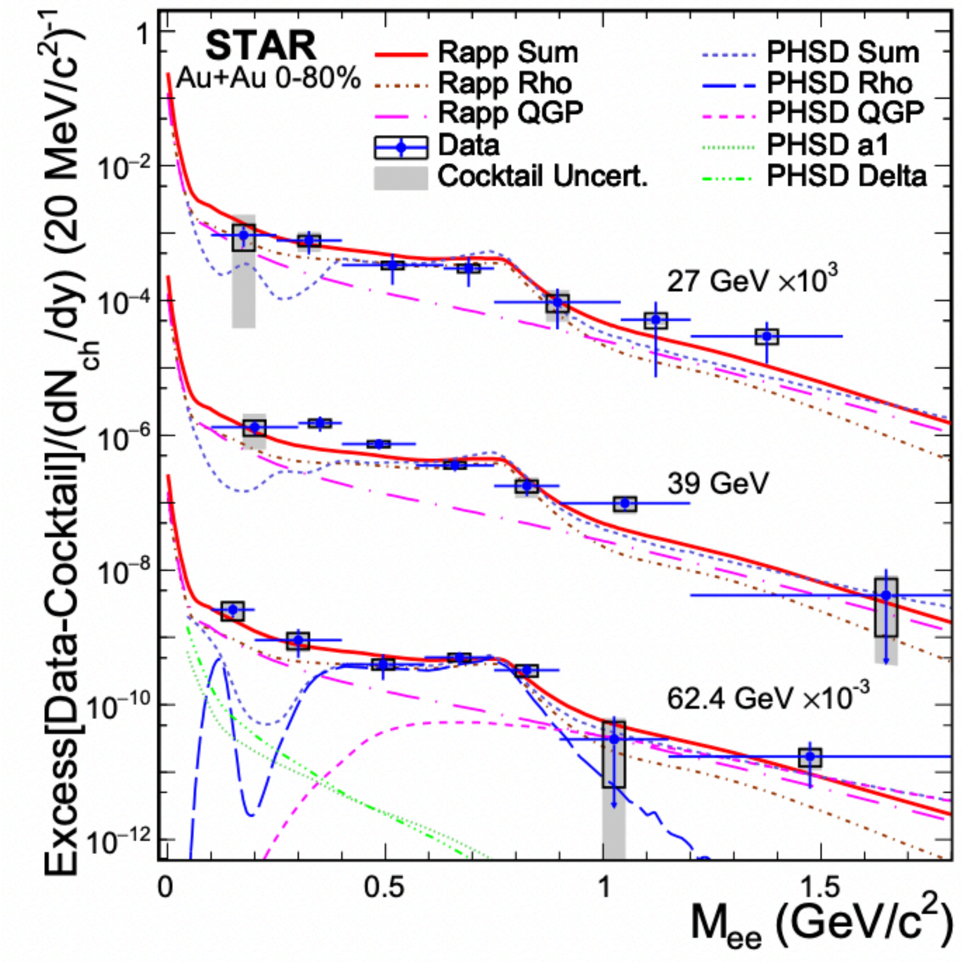


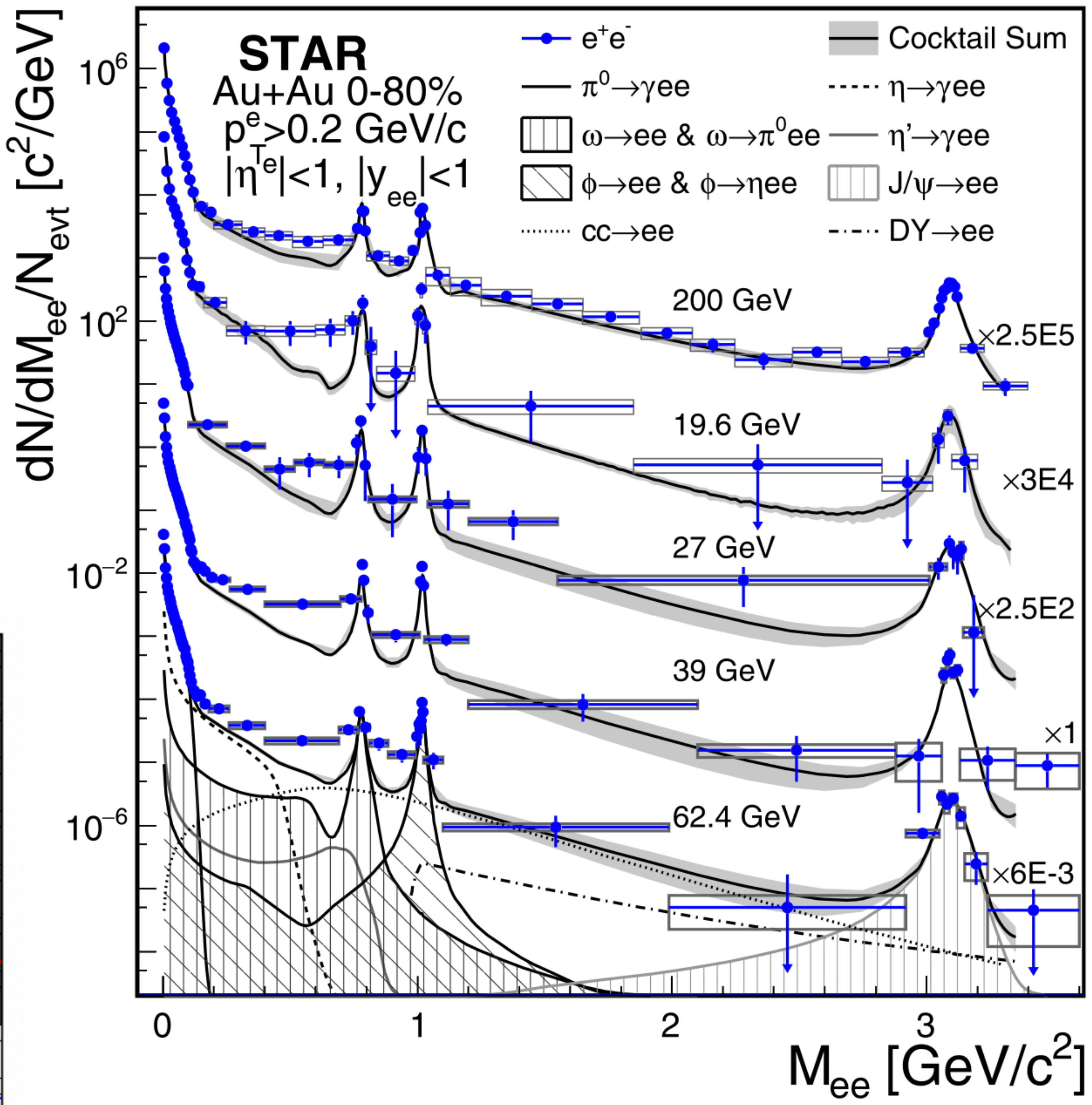


BES-I dielectron production

- Explore low-mass range down to SPS energies.
- Excess yield is well described by the in-medium ρ + QGP emission models.
- Normalized excess yield shows no significant $\sqrt{s_{NN}}$ dependence.
- Limited precision especially at low collision energies.





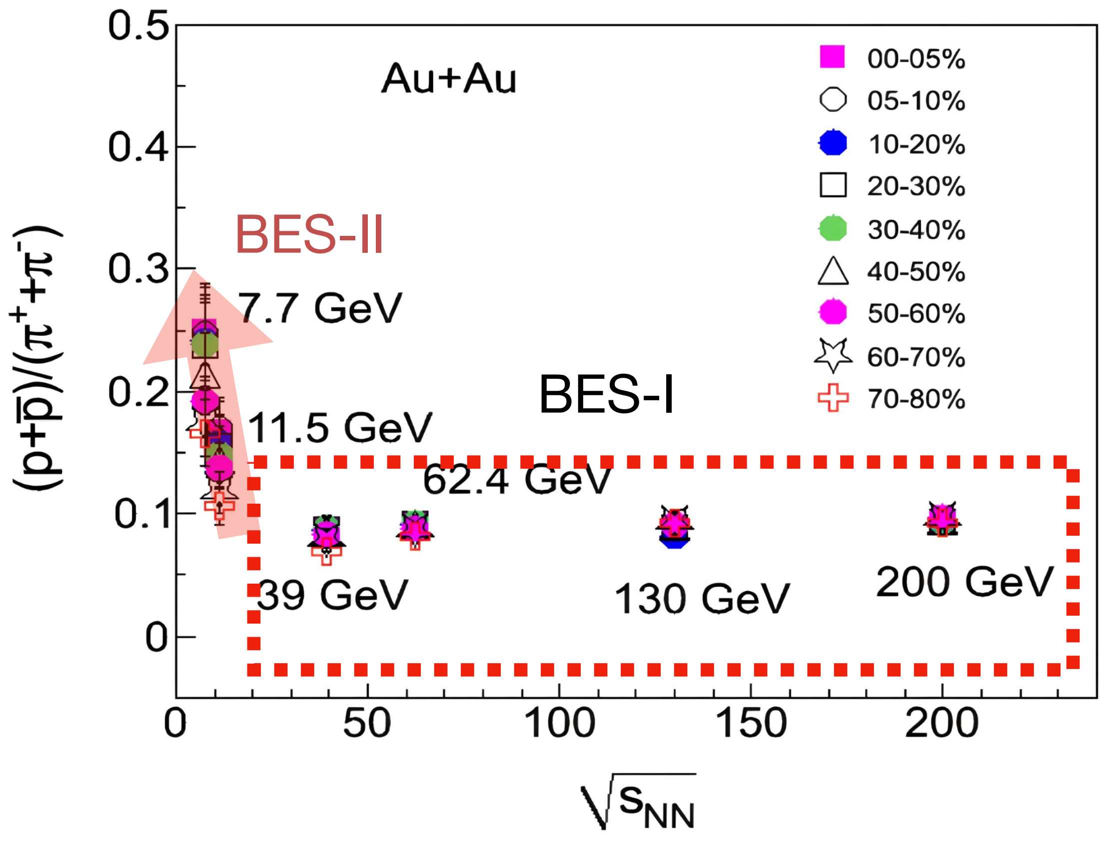


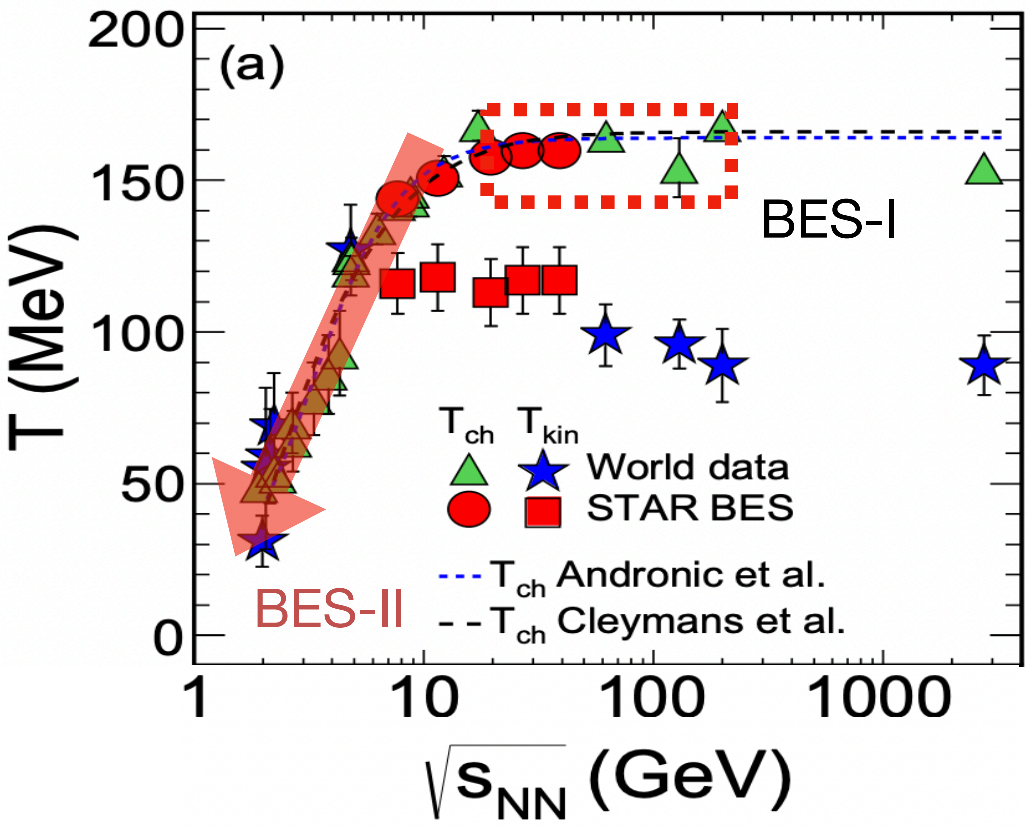
STAR: Phys. Rev. C 107, L061901 (2023)
STAR: Phys. Lett. B 750 (2015) 64
STAR: Phys. Rev. C 92, 024912 (2015)

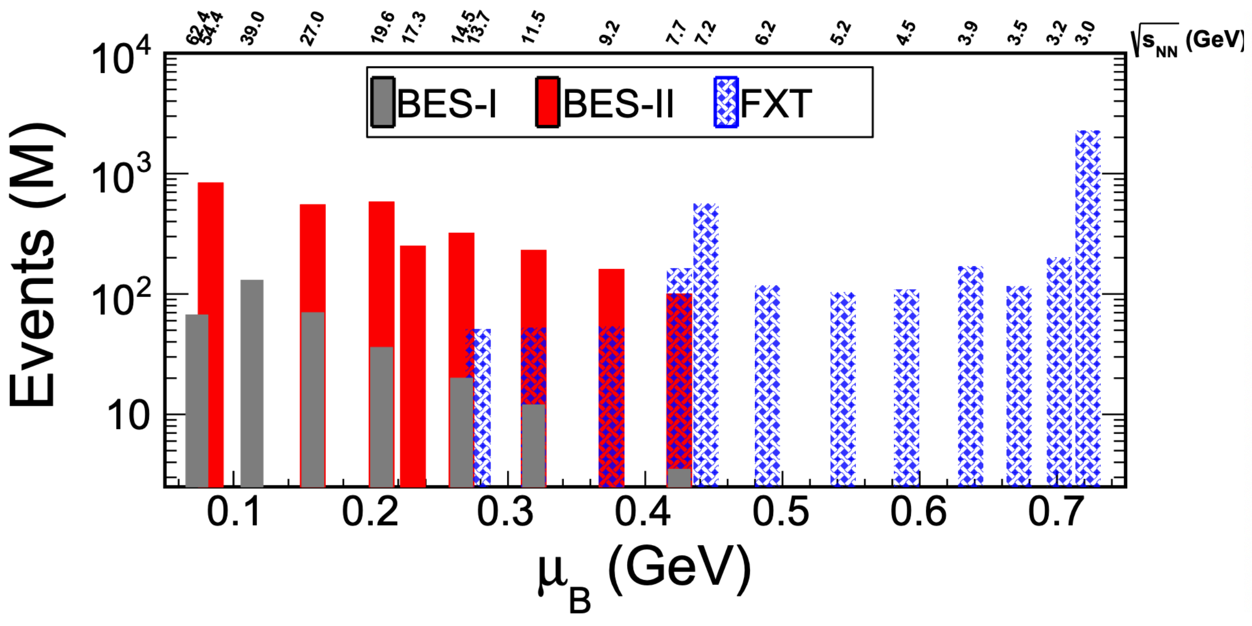
From BES-I to BES-II

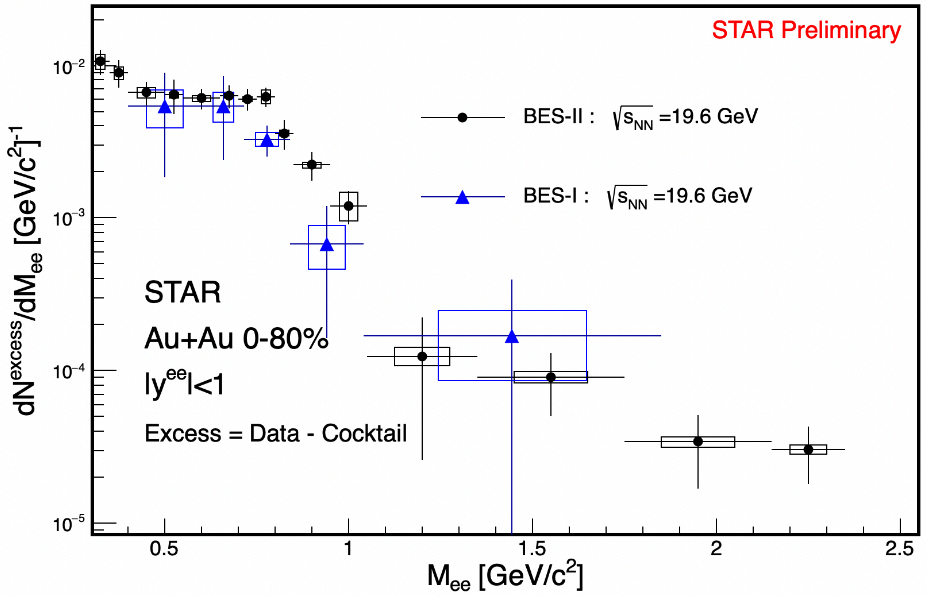
- RHIC BES-I results (19.6 - 62.4 GeV):
  - Total baryon densities are constant.
  - Kinetic and chemical freezeout temperatures are approximately constant.
- RHIC BES-II (7.7 - 19.6 GeV):
  - Probe the total baryon density and temperature effects on EM spectral function with changing properties.
  - BES-II has 10 times more statistics than BES-I. Total error reduced by factor of 4 at 19.6GeV.
  - Excess yield invariant mass spectrum results are consistent with BES-I at 19.6GeV.

STAR: Phys. Rev. C 96, 044904 (2017)

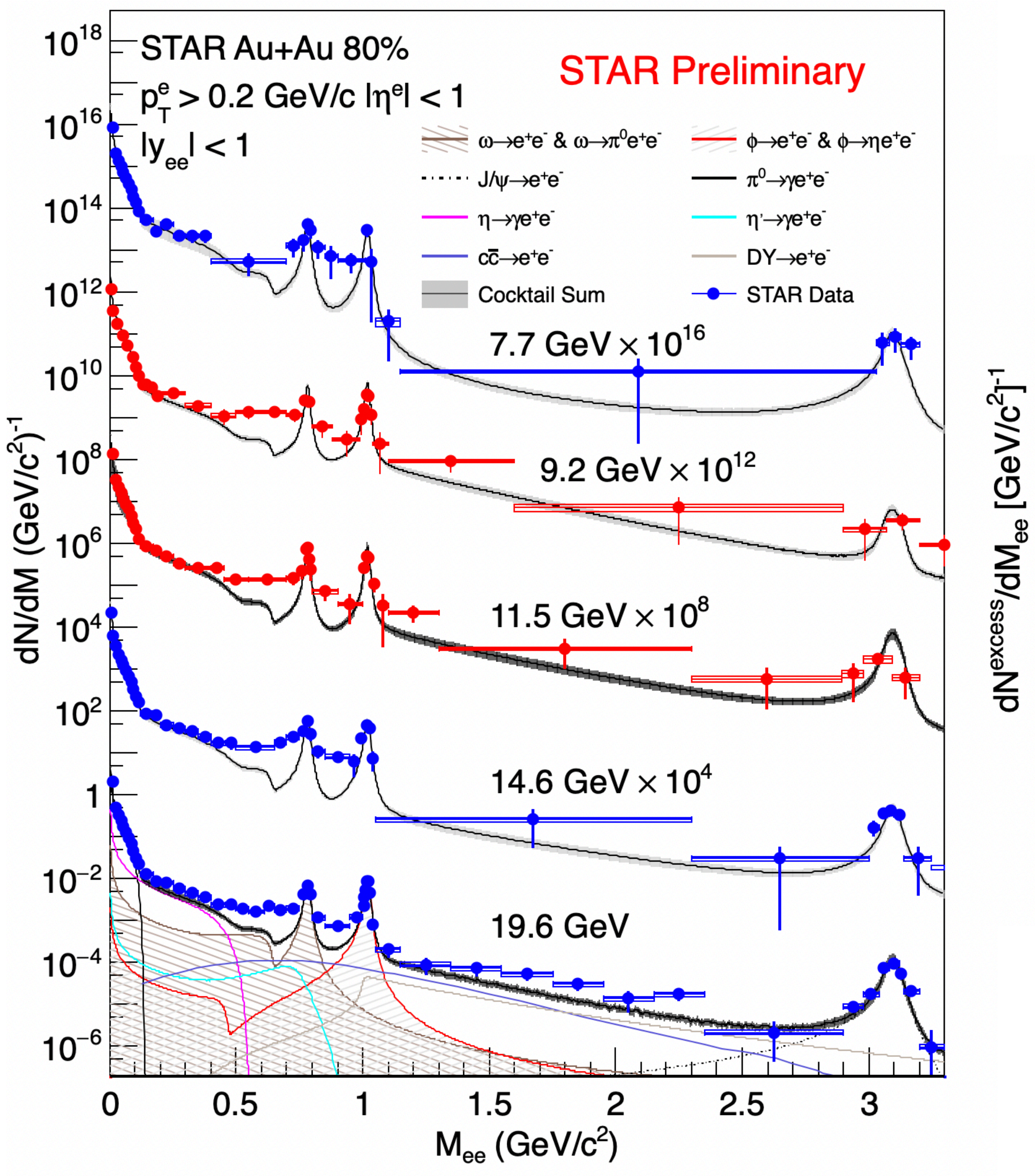






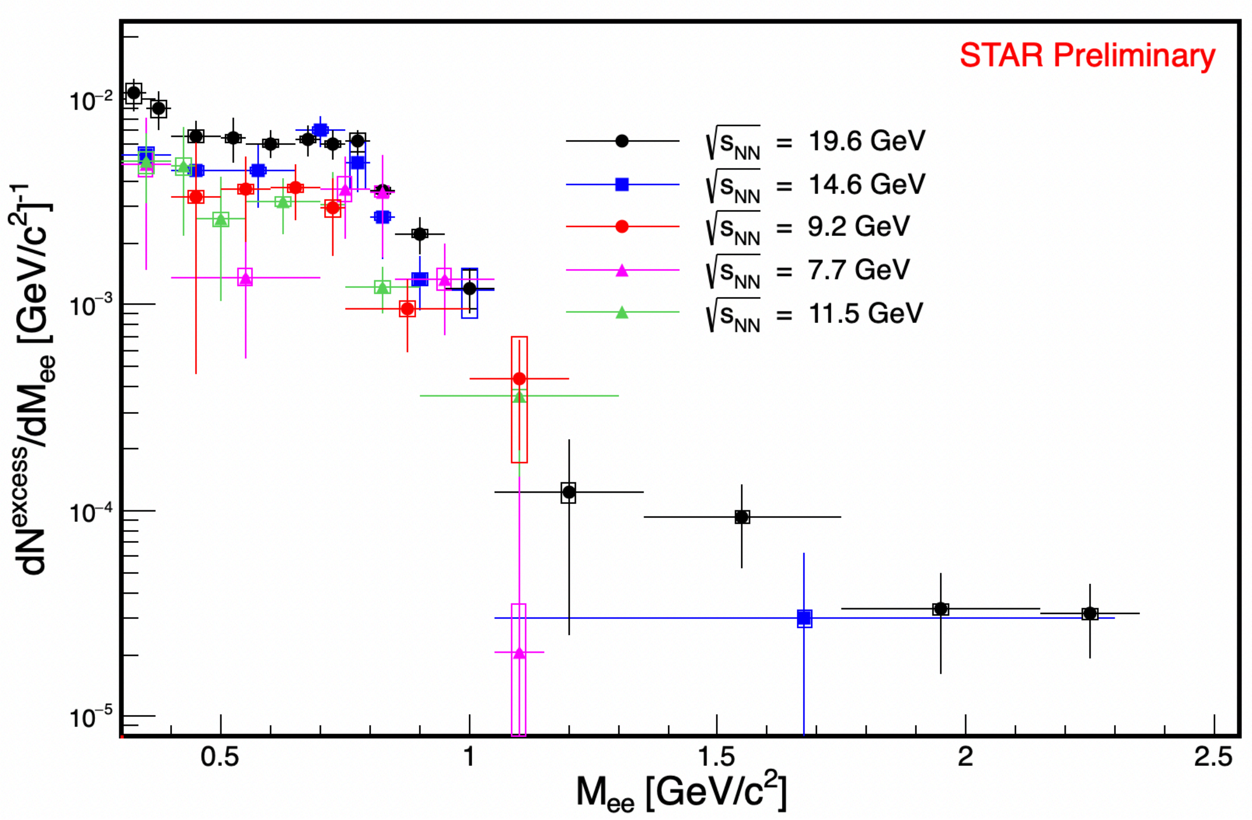


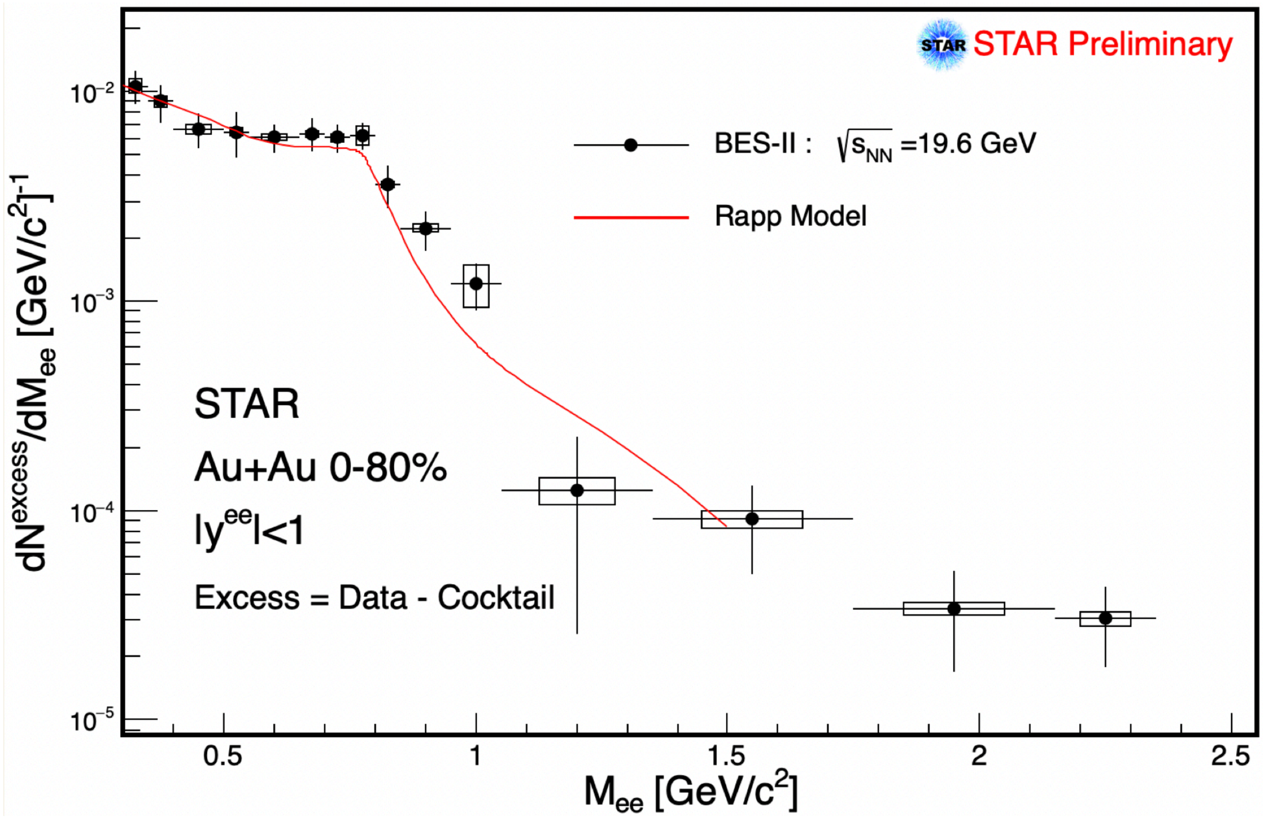
BES-II dielectron production



R. Rapp: Phys. Rev. C 63 (2001) 054907, Phys. Rev. Lett. 97, 102301 (2006) ;

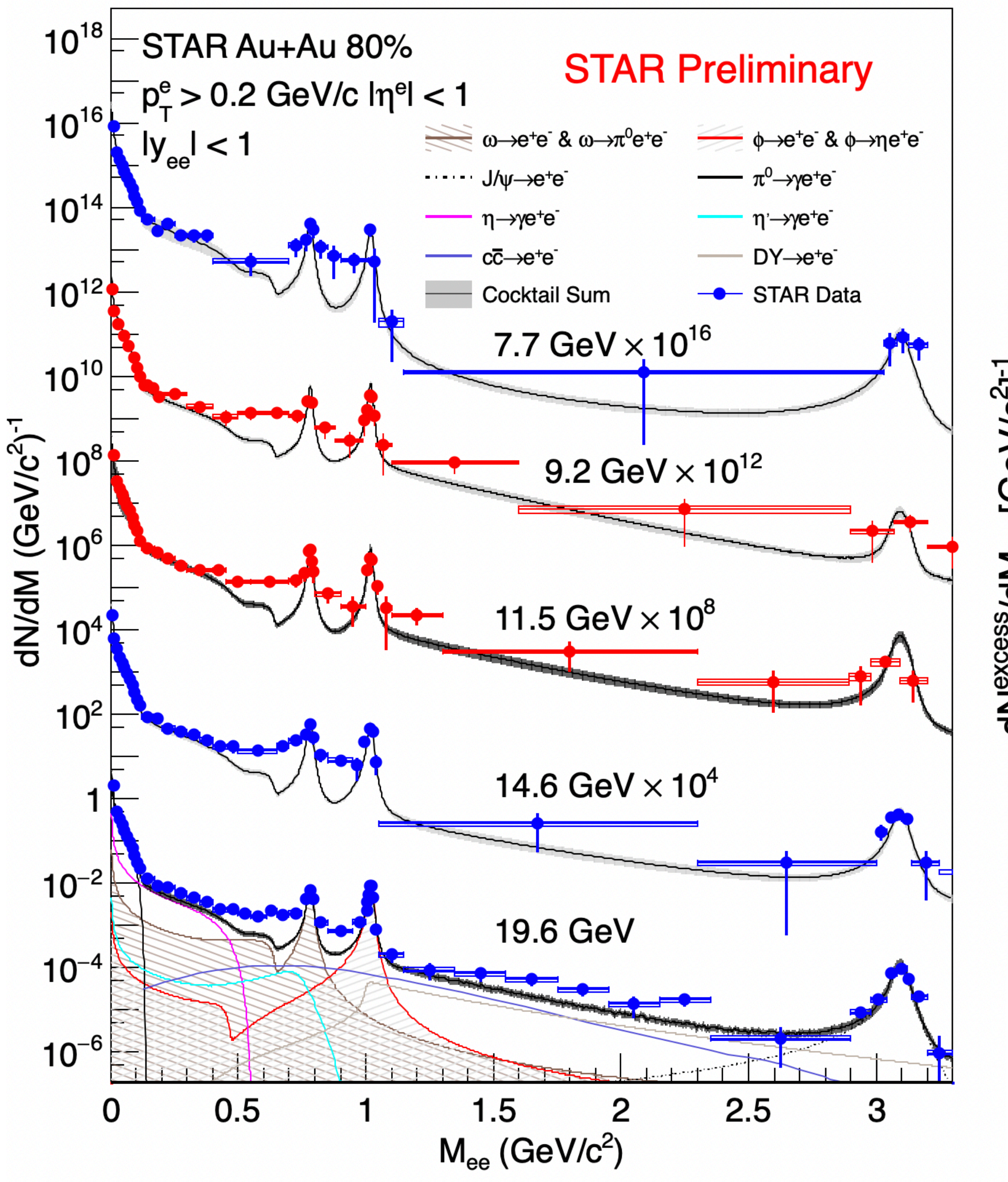
Thermal dielectron spectra with STAR BES-II

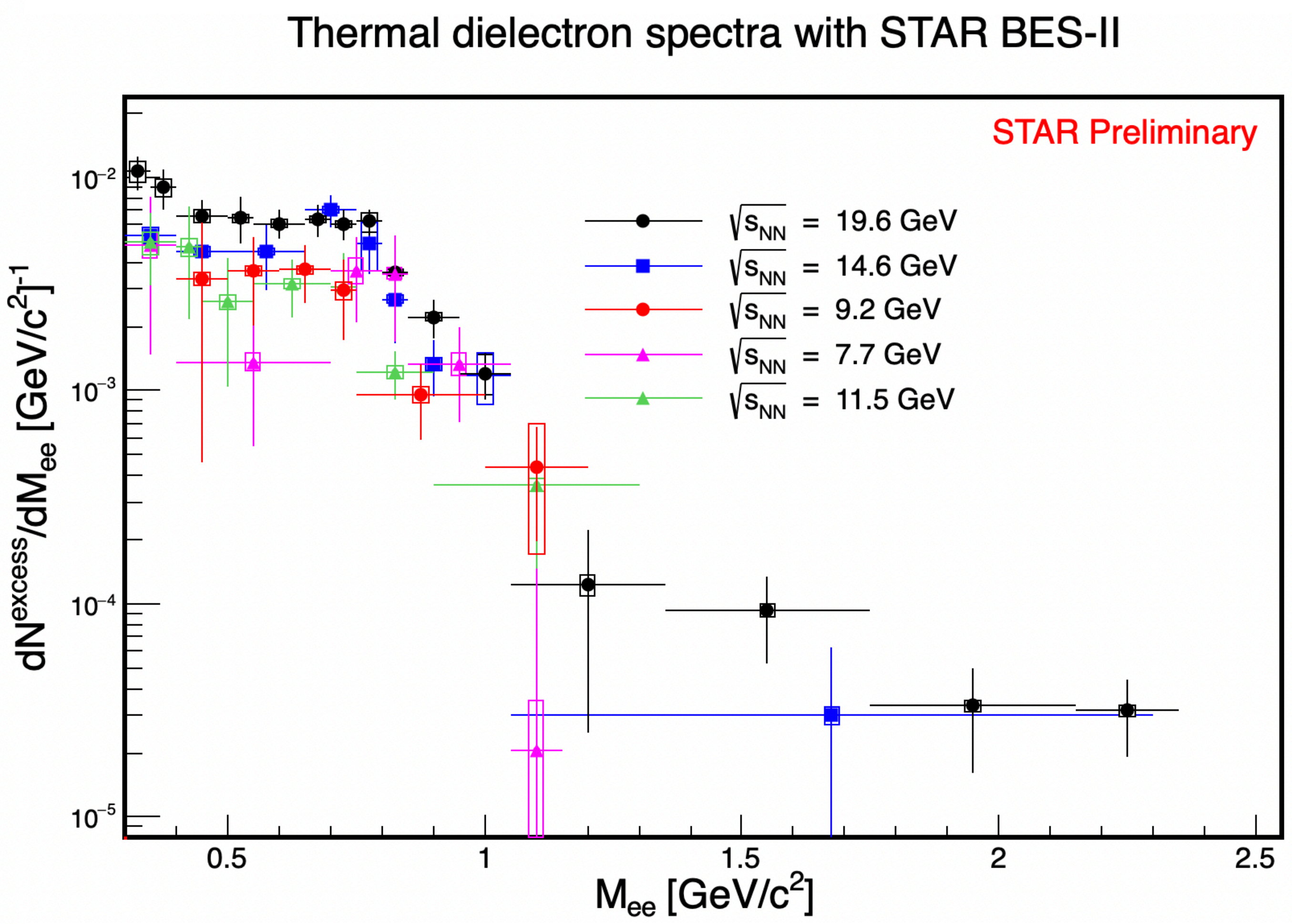


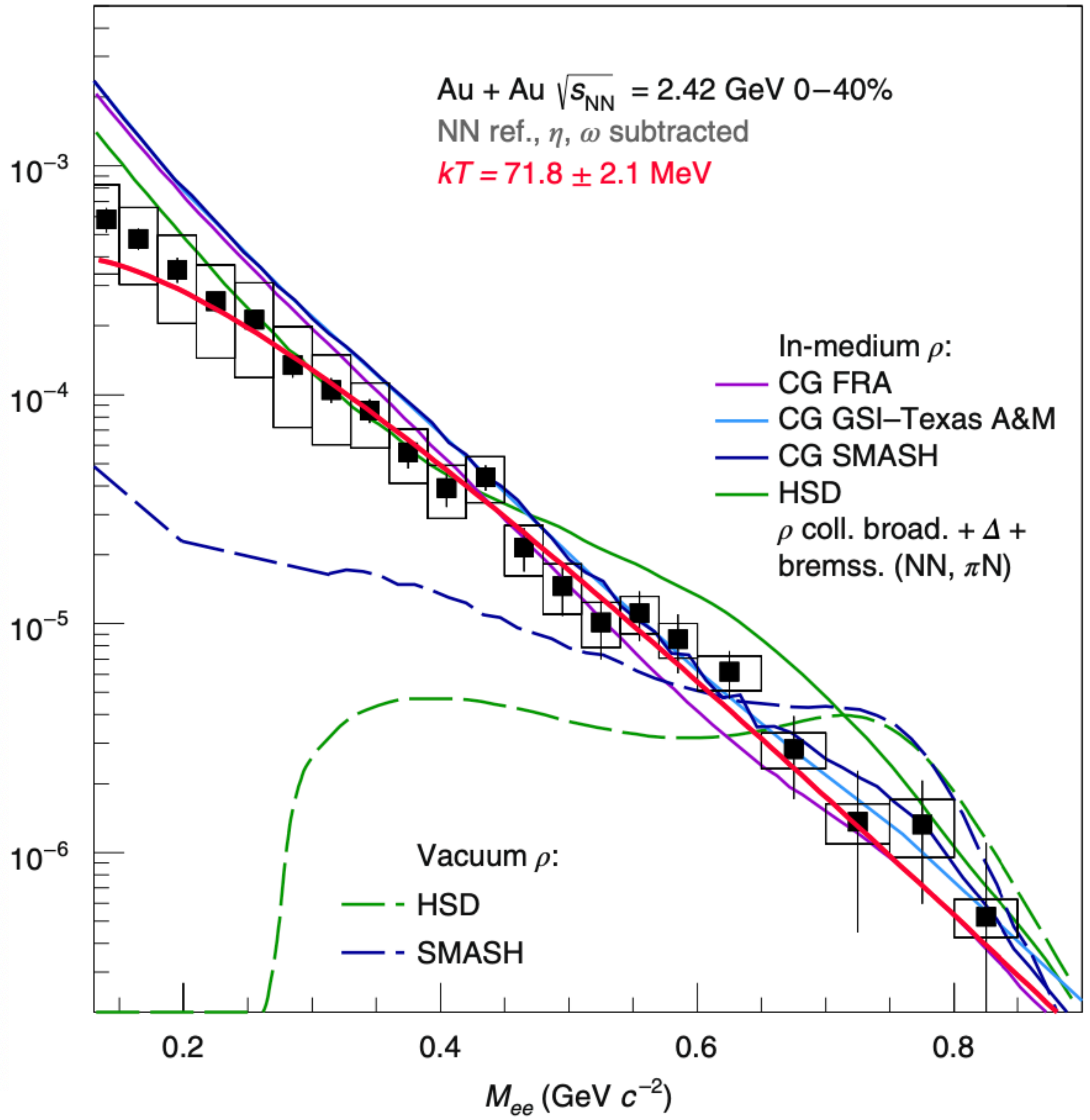


Excess yield invariant mass spectra at $\sqrt{s_{NN}}$ = 19.6 GeV can be well described by R. Rapp's calculation.

BES-II and experiment with higher μ_B





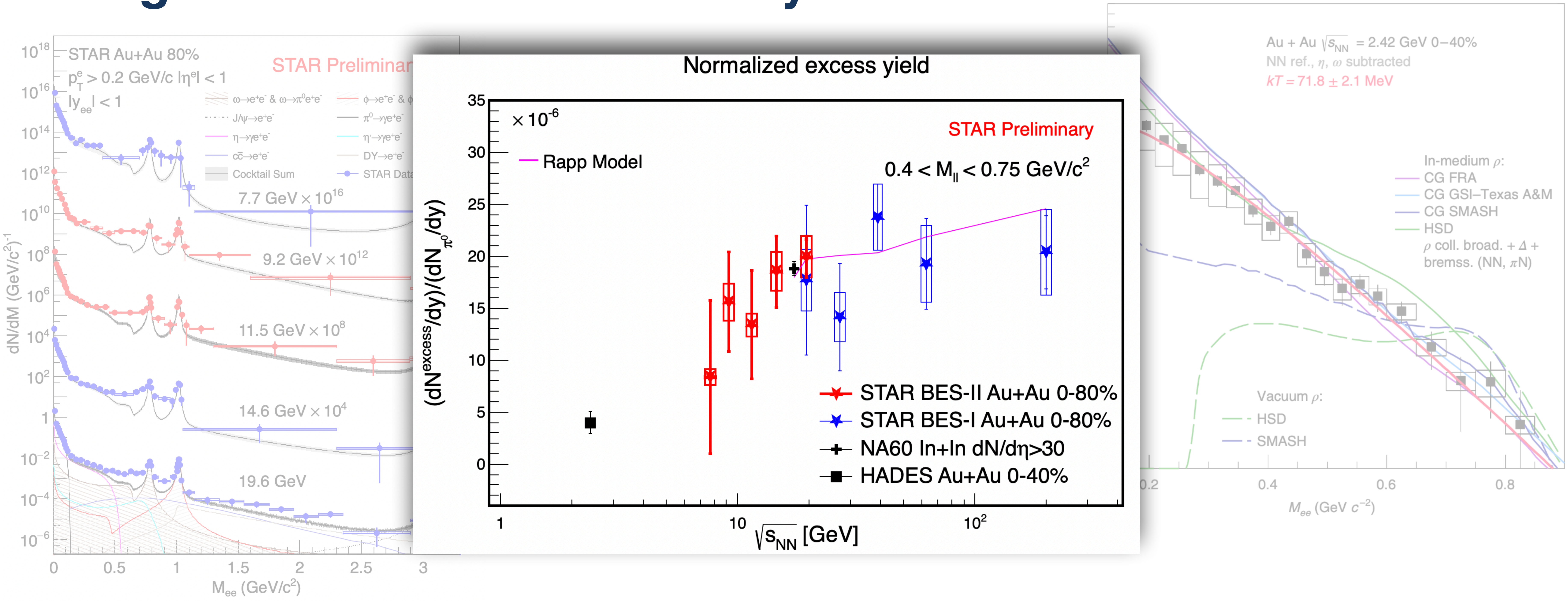


HADES Collab., Nature Physics 15 (2019) 1040

Excess yield invariant mass spectra at BES-II and HADES

- Medium interactions at diverse environment:
  - Total baryon density
  - Temperature

Integral of normalized excess yield



- Hint of a decreasing trend from high to low $\sqrt{S_{NN}}$

HADES Collab., Nature Physics 15 (2019) 1040
NA60: EPJ C 59 (2009) 607
R. Rapp, Phys. Rev. C 63, 054907 (2001)
H. van Hees and R. Rapp, Phys. Rev. Lett. 97, 102301 (2006)

Dilepton temperature measurement

STAR: arXiv: 2402.01998 submitted
Rapp, van Hees, PLB 753 (2016) 586
T_{PC}: HotQCD, Phys.Lett.B 795 (2019) 15-21;
NA60: EPJC (2009) 59 607-623

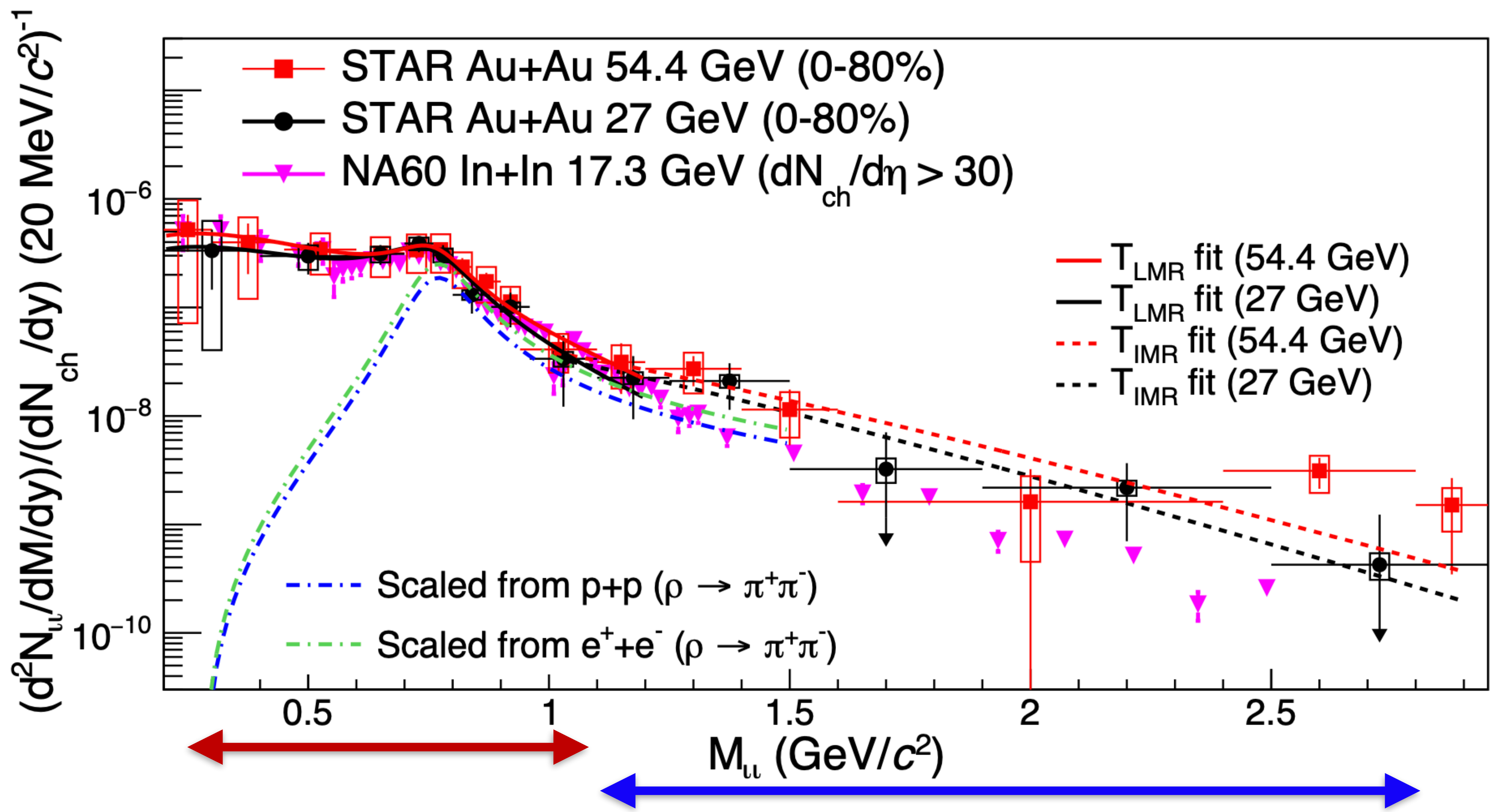
- Dielectron temperature measurement at $\sqrt{s_{NN}}$ = 27 and 54.4 GeV with STAR experiment.
- Thermal dileptons can directly access the hot QCD medium at both QGP phase and hadronic phase.
- QGP radiation: $M^{3/2} * e^{-M/T}$.
- In-medium ρ: Breit-Wigner * $e^{-M/T}$.

Low Mass Range fitting function:

$$(a * BW + b * M^{3/2}) * e^{-M/T}$$

Breit-Wigner(BW) function:

$$\frac{M M_0 \Gamma}{(M_0^2 - M^2)^2 + M_0^2 \Gamma^2}$$



$T_{LMR}^{54.4\,GeV} = 172 \pm 12(stat.) \pm 18(sys.)$ MeV

$T_{LMR}^{27\,GeV} = 167 \pm 21(stat.) \pm 18(sys.)$ MeV

$T_{IMR}^{54.4\,GeV} = 303 \pm 59(stat.) \pm 28(sys.)$ MeV

$T_{IMR}^{27\,GeV} = 280 \pm 64(stat.) \pm 10(sys.)$ MeV

M: dilepton invariant mass. M_0: rho meson pole mass. Γ: rho meson width

BES-II temperature measurement

- First temperature measurement in STAR BES-II energies.
- 19.6 and 14.6GeV LMR Temperature:
  - T is close to pseudo critical temperature.
  - Results indicate the thermal radiation from hadronic gas is mainly produced around the phase transition.

$$T_{LMR}^{19.6GeV}(0-80\%) = 168 \pm 13(stat.) \pm 15(sys.)\ MeV$$

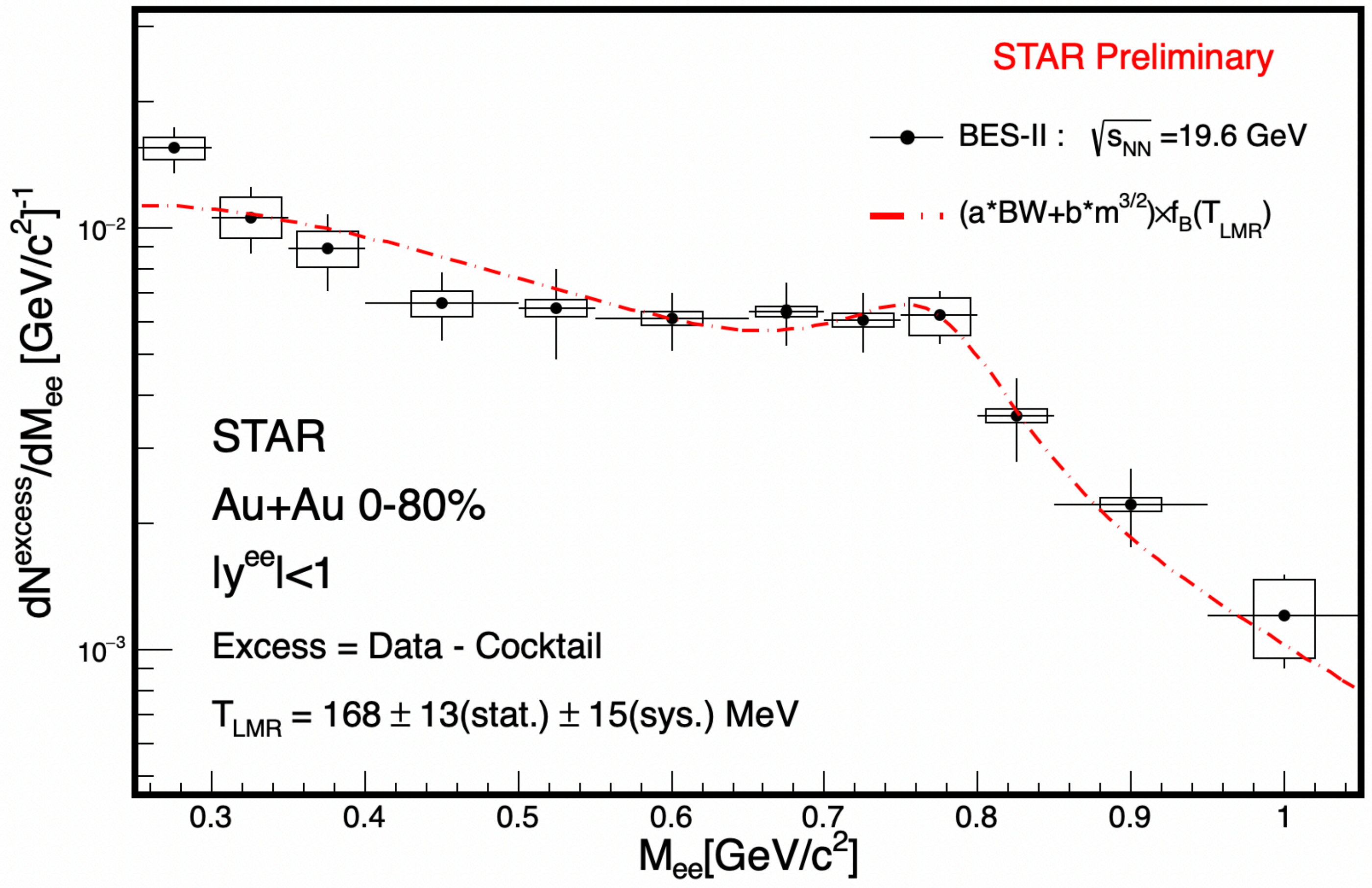
$$T_{LMR}^{14.6GeV}(0-80\%) = 183 \pm 25(stat.) \pm 21(sys.)\ MeV$$

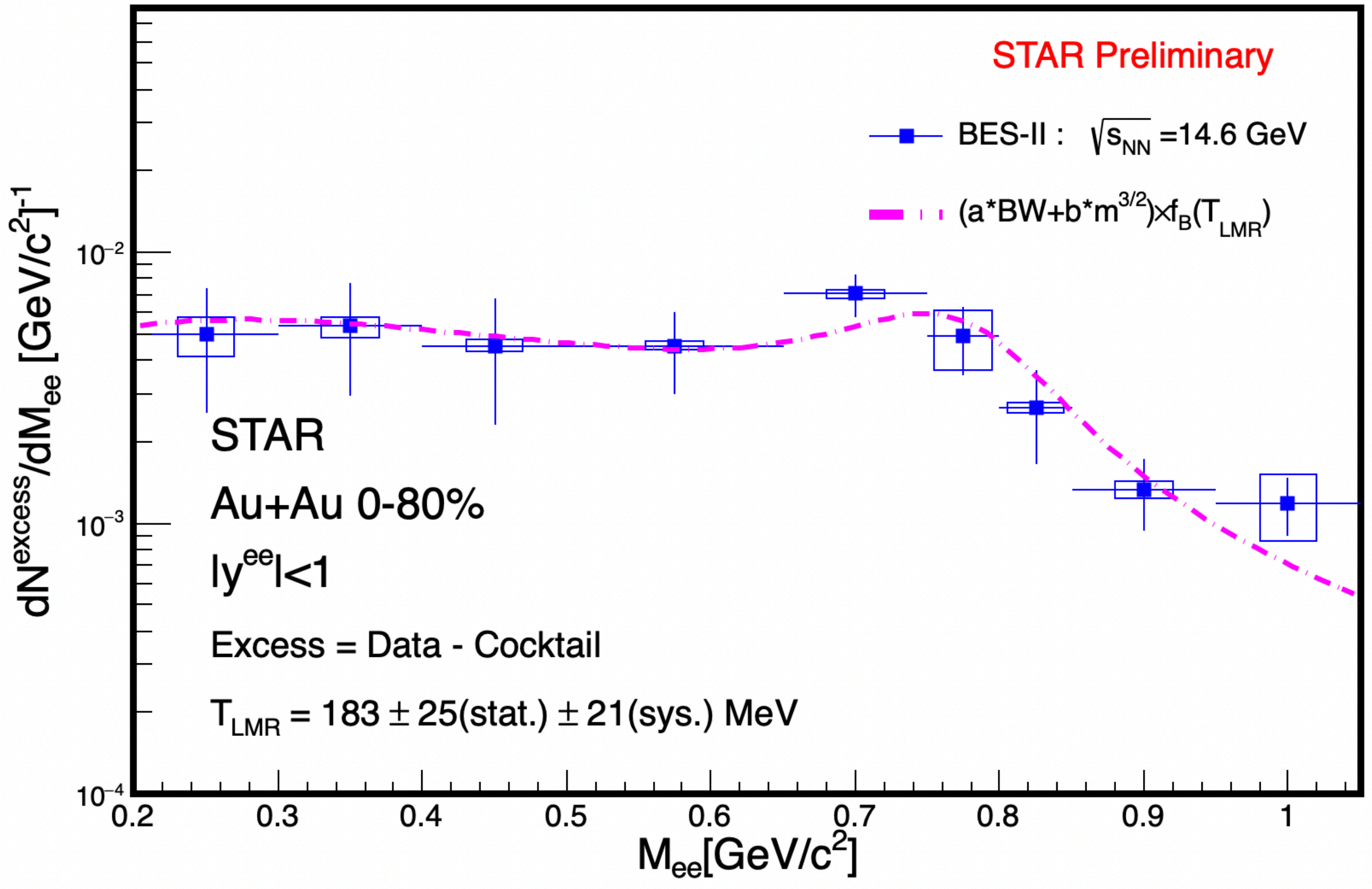
Low Mass Range fitting function:

$$(a * BW + b * M^{3/2}) * e^{-M/T}$$

Breit-Wigner(BW) function:

$$\frac{M M_0 \Gamma}{(M_0^2 - M^2)^2 + M_0^2 \Gamma^2}$$





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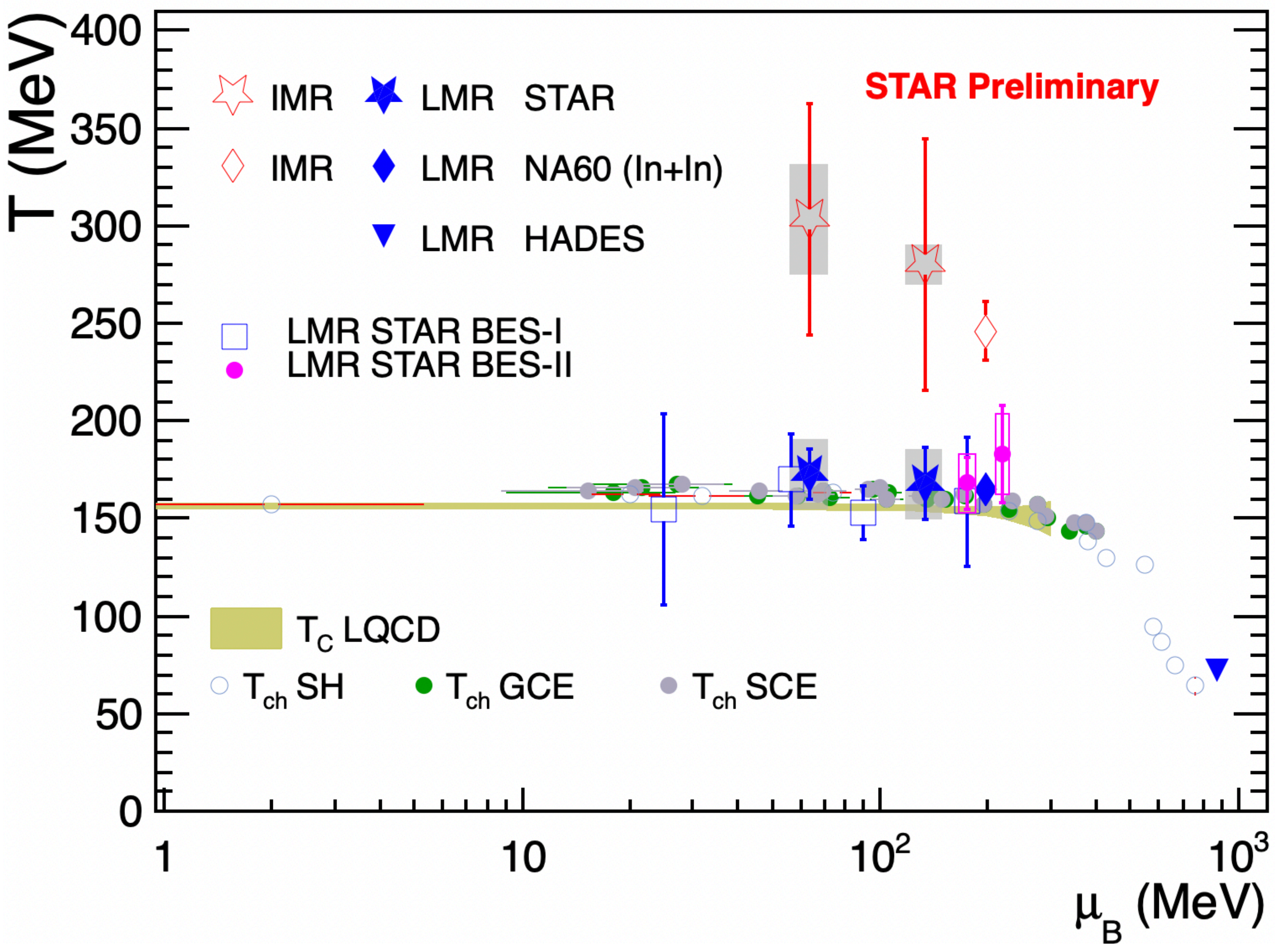
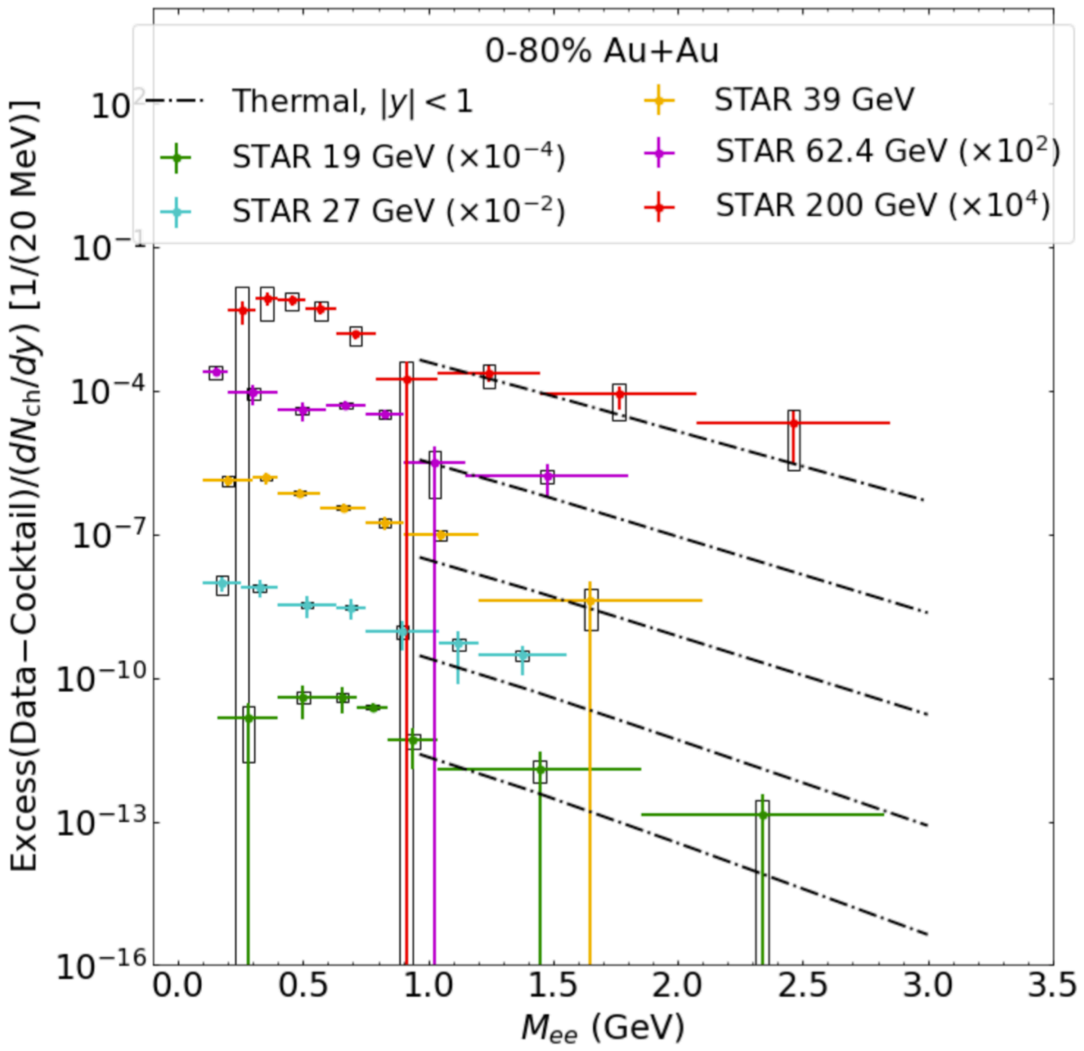


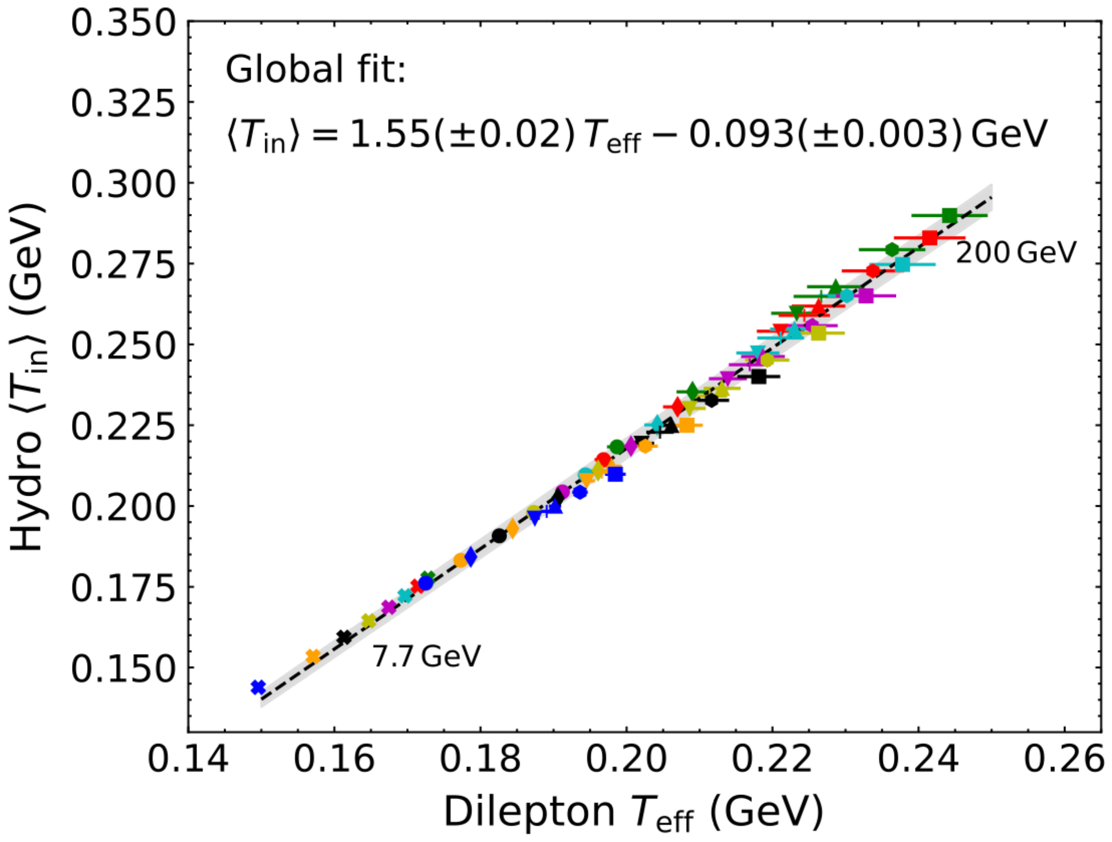
Temperature measurement in STAR isobar collisions: Jiaxuan Luo 09/24/2024 Hard Probe

STAR: arXiv: 2402.01998, Phys. Lett. B 750 (2015) 64-71
NA60: EPJC (2009) 59 607–623
HADES: Nature Physics 15, 1040-1045 (2019)
T. G.: JPS Conf.Proc. 32 (2020) 010079
T_{ch} SH: P. Braun-Munzinger et al. Nature 561, 321-330 (2018)
T_{ch} GCE/SCE: STAR Phys. Rev. C 96, 044904 (2017)

From dielectron temperature to initial temperature

- First estimate of NLO QGP dilepton emission with finite μ_B, using hydrodynamics.
- Theoretical calculations agree with STAR BES-I data in the IMR within uncertainties.
- Potential correlation between the effective temperature extracted from IMR and the initial temperature in the fluid dynamical model to reflect different stage of the collision.





C. Gale, Quark Matter, Houston (2023)
Abhdulhamid et al. (STAR), Phys. Rev. C (2023) ,Phys. Rev. Lett. **132**, 172301 (2024)
J. Churchill, L. Du, C. Gale, G. Jackson, S. Jeon (2023), 2311.06675,2311.06951
A. Elfner et al., HP (2023)
B. A. Schäfer et al., Phys. Rev. C (2022)

$\langle T_{in} \rangle$: initial temperature refers to the temperature at the beginning of QGP fireball hydrodynamic expansion.

Summary and outlook

- STAR BES-II dielectron measurement: $\sqrt{s_{NN}}$ = 7.7, 9.2, 11.5, 14.6 and 19.6 GeV
  - Excess yield invariant mass spectra in different environments.
  - Hints there is a decreasing trend in normalized integrated excess yield for Au+Au collisions as the collision energies decreases.
  - First temperature measurement at BES-II energies.

- Outlook:
  - Efforts for reducing photonic conversion background.
  - Comparison with theory calculation to constrain models and further physics interpretation.
  - Opportunity for other topics with electromagnetic probe:
    - conductivity meter, chronometer.

Thank you for your attention

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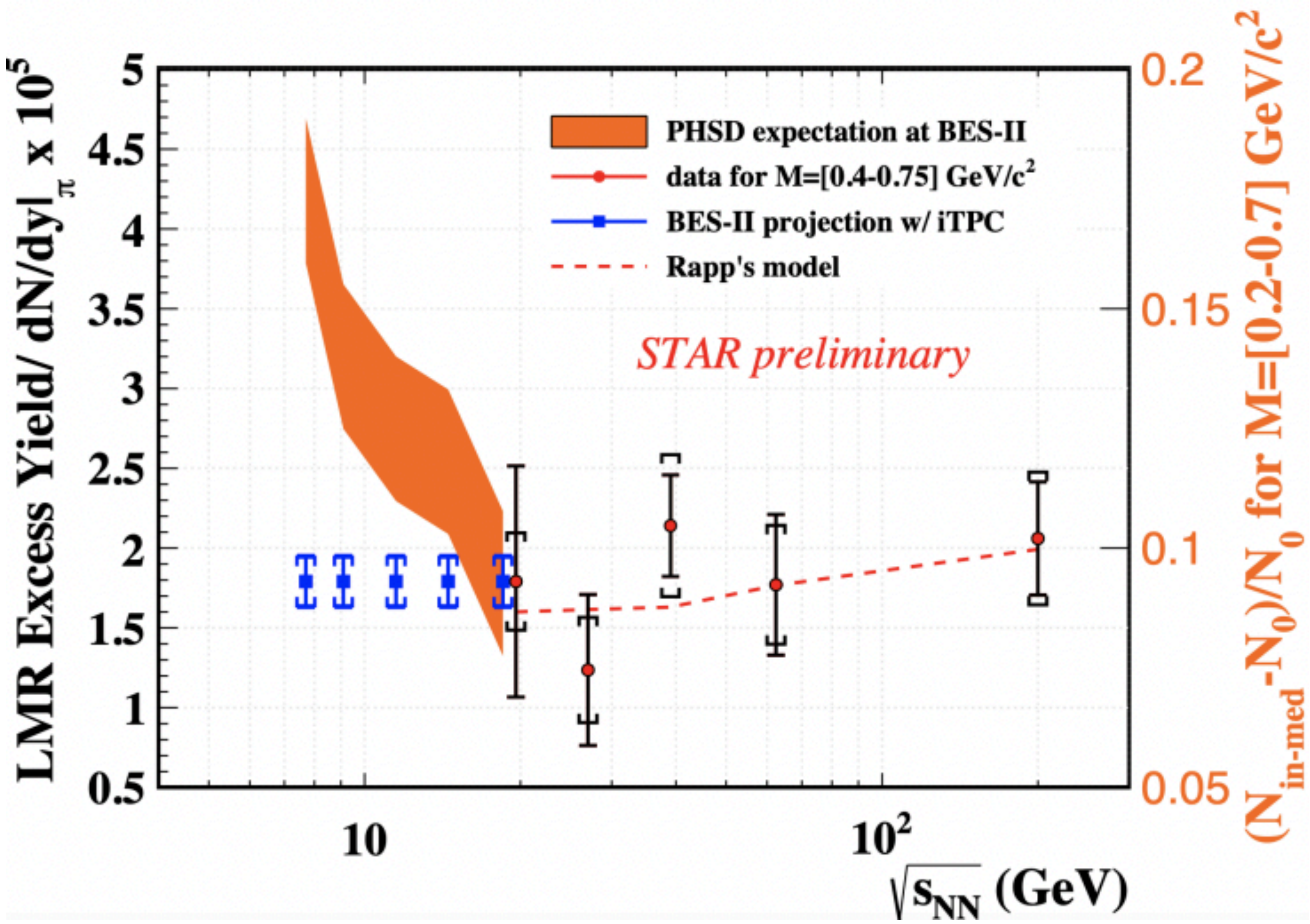
Back Up

PHSD predication on normalized LMR excess yield

- PHSD: Parton Hadron String Dynamic is a relativistic transport model.
- PHSD model predicts that normalized dielectron yield will increase at lower collision energies which have higher total nucleon density without the temperature effect.



V. Metag, arXiv:0711.4709
L. Adamczyk et al., Phys. Rev. C, 2017.
H. v. Hees, R. Rapp. Phys.Rev.Lett. 97 (2006) 102301