Thermal dielectron measurements

in Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 14.6, 19.6$ GeV

with the STAR experiment

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Rice University

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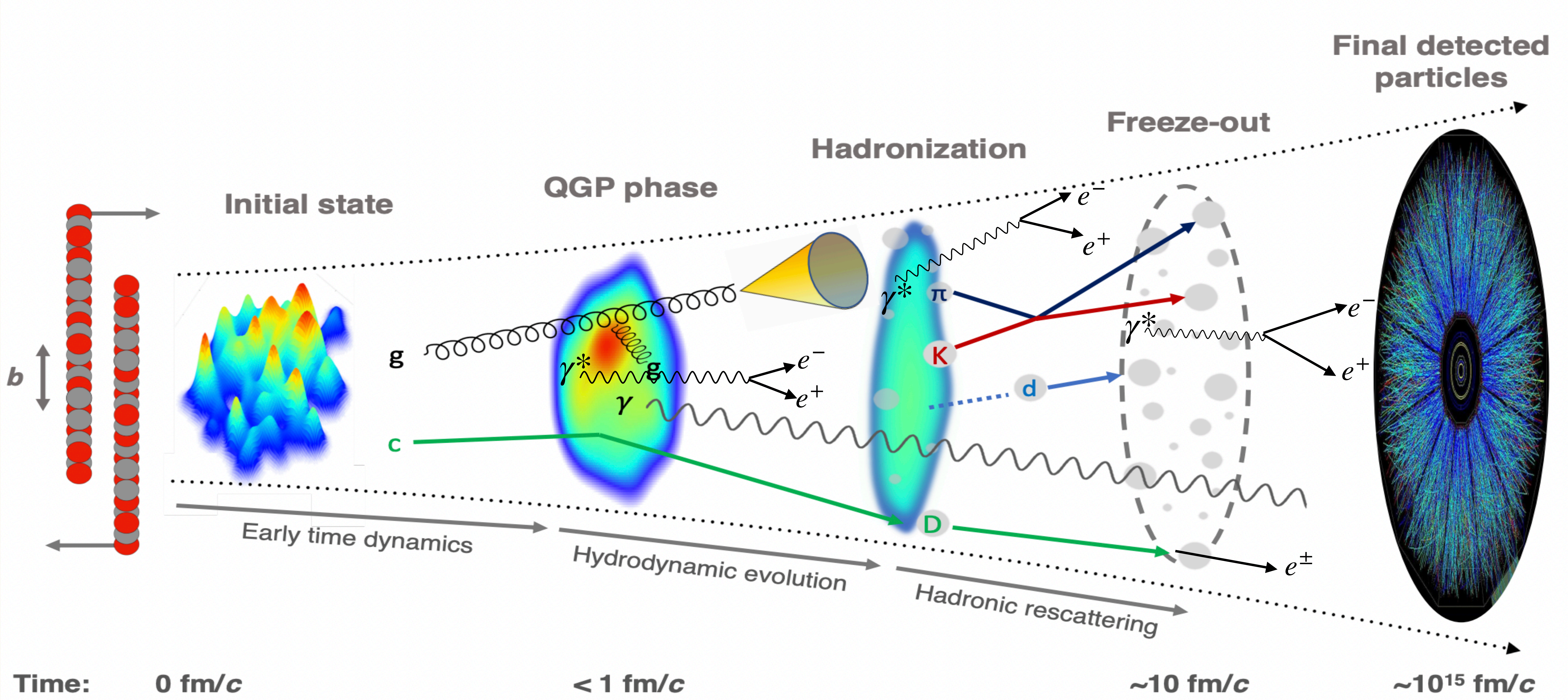
U.S. DEPARTMENT OF ENERGY
Office of Science

STAR

RICE

2023

Thermal radiation



CERN: Hot QCD White Paper (2023)

- Emitted from fireball evolution.
- Probe EM current medium interaction, fireball evolution information
- Can be detected via dilepton production

Dilepton Production

- Thermal radiation
  - Dilepton emission rate

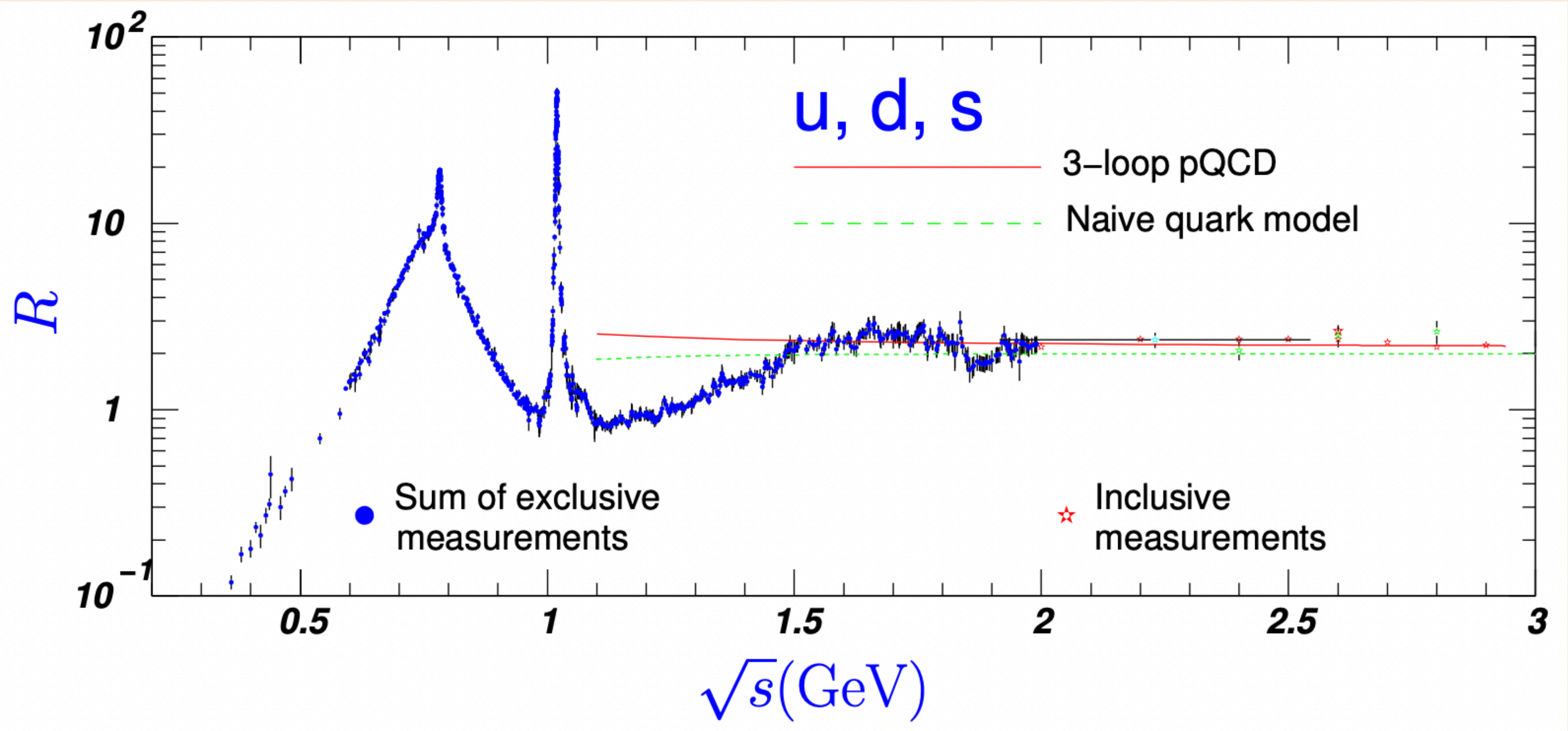
- $$\frac{dR_{l^+l^-}}{d^4x d^4q} = \frac{-\alpha_{EM}^2 L(M)}{3\pi^3 M^2} f_B(q_0, T) g_{\mu\nu} \mathrm{Im}[\Pi_{EM}^{\mu\nu}(M, q, T, \mu_B)]$$

  - $L(M)$: Lepton phase-space factor
  - $f_B(q_0; T)$: Thermal Bose–Einstein distribution
  - $\mathrm{Im}[\Pi_{EM}^{\mu\nu}(M, q; T, \mu_B)]$: EM spectral function

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

Dilepton Production

- Thermal radiation
  - Dilepton emission rate
  - EM spectral function
    - $M_{ee} \gtrsim 1.5 GeV/c^2$
      - Partonic dominance
    - $M_{ee} \lesssim 1 GeV/c^2$
      - Vector Meson dominance
      - $\text{Im}\Pi_{EM} \sim [\text{Im}D_\rho + \frac{1}{9}\text{Im}D_\omega + \frac{2}{9}\text{Im}D_\phi]$
      - ρ dominance



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

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

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

Dilepton Production

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    - $M_{ee} \gtrsim 1.5 GeV/c^2$
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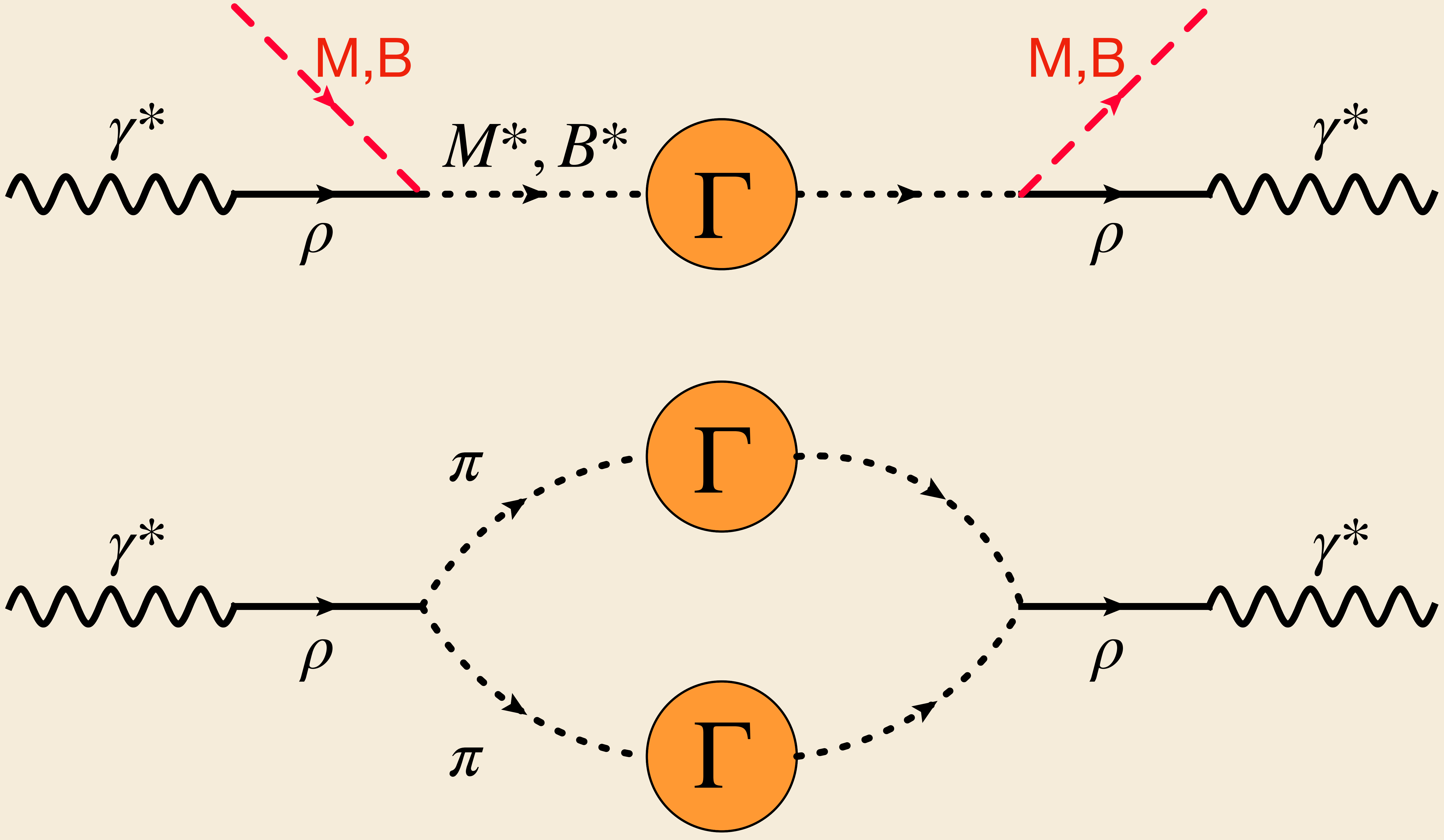
      - Vector Meson dominance
      - Sensitive to Medium interactions
        - $\rho MM^*, \rho BB^*, \rho\pi\pi$



EM current interacts with the QCD medium
$M_{ee} \lesssim 1$ GeV/c^2

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).
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).

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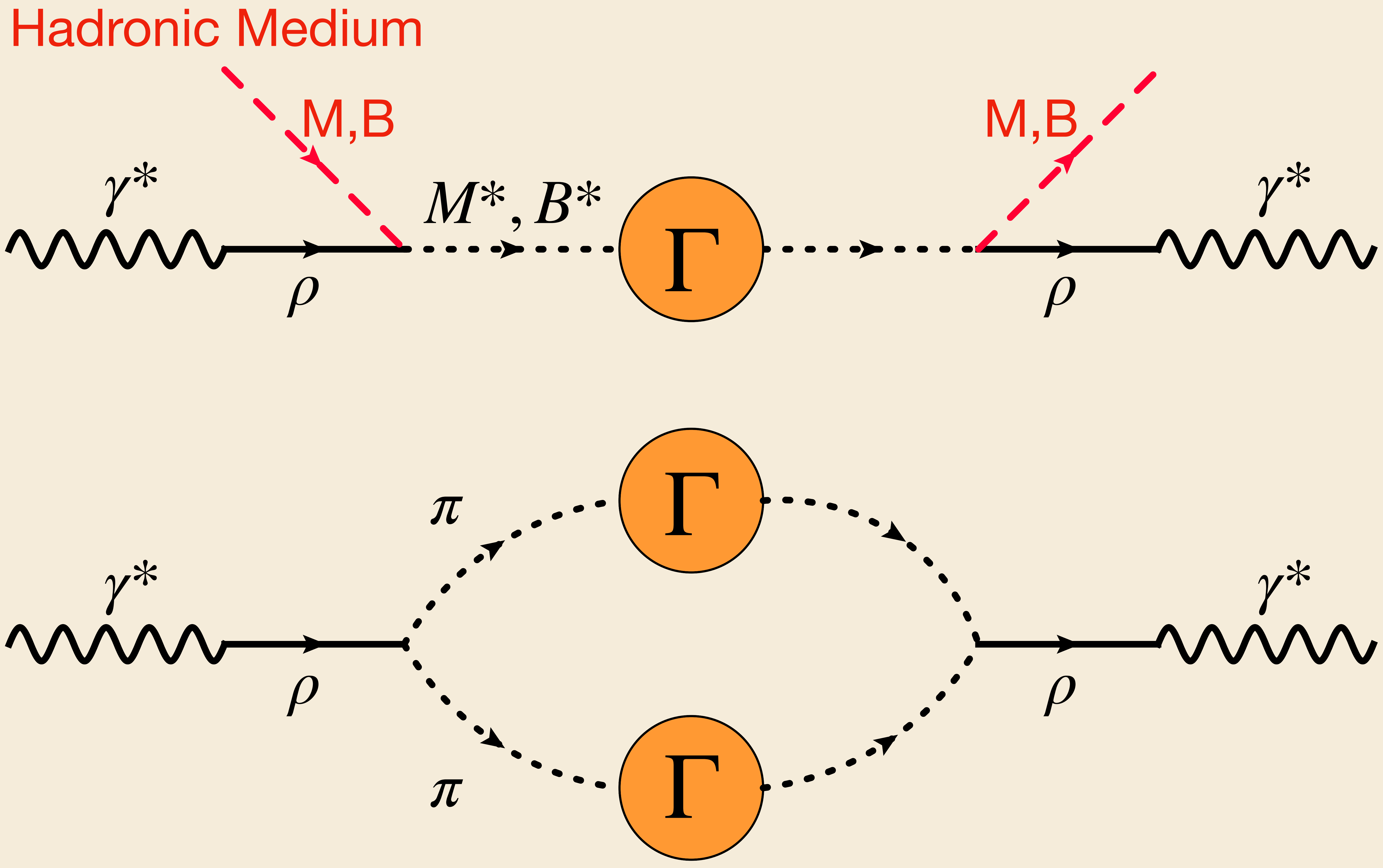


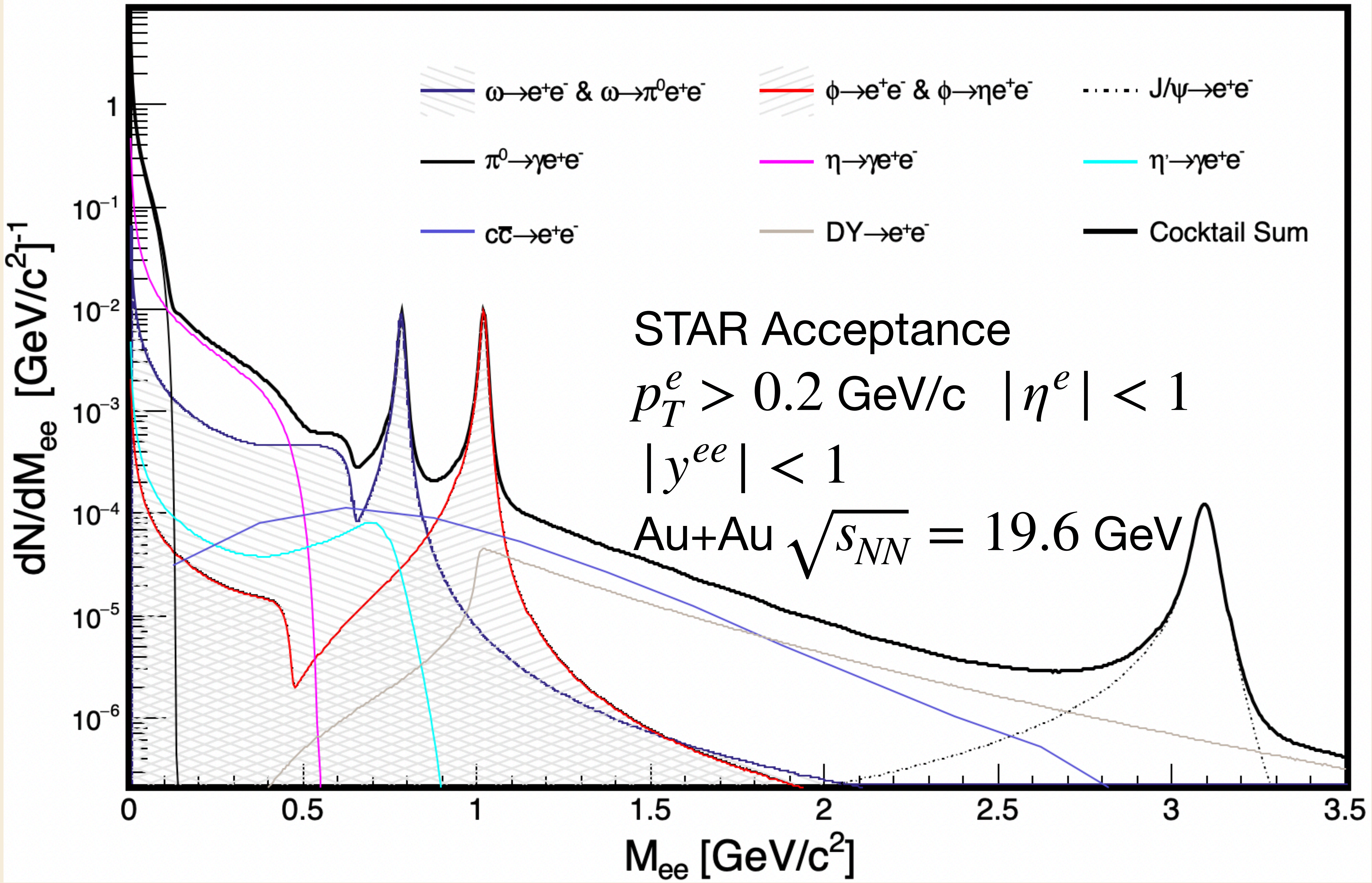
EM current interacts with the QCD medium
$M_{ee} \lesssim 1$ GeV/c^2

Depends on Temperature (T), Total Baryon Density (ρ_B), medium lifetime (τ_{fo}),

Dilepton Production

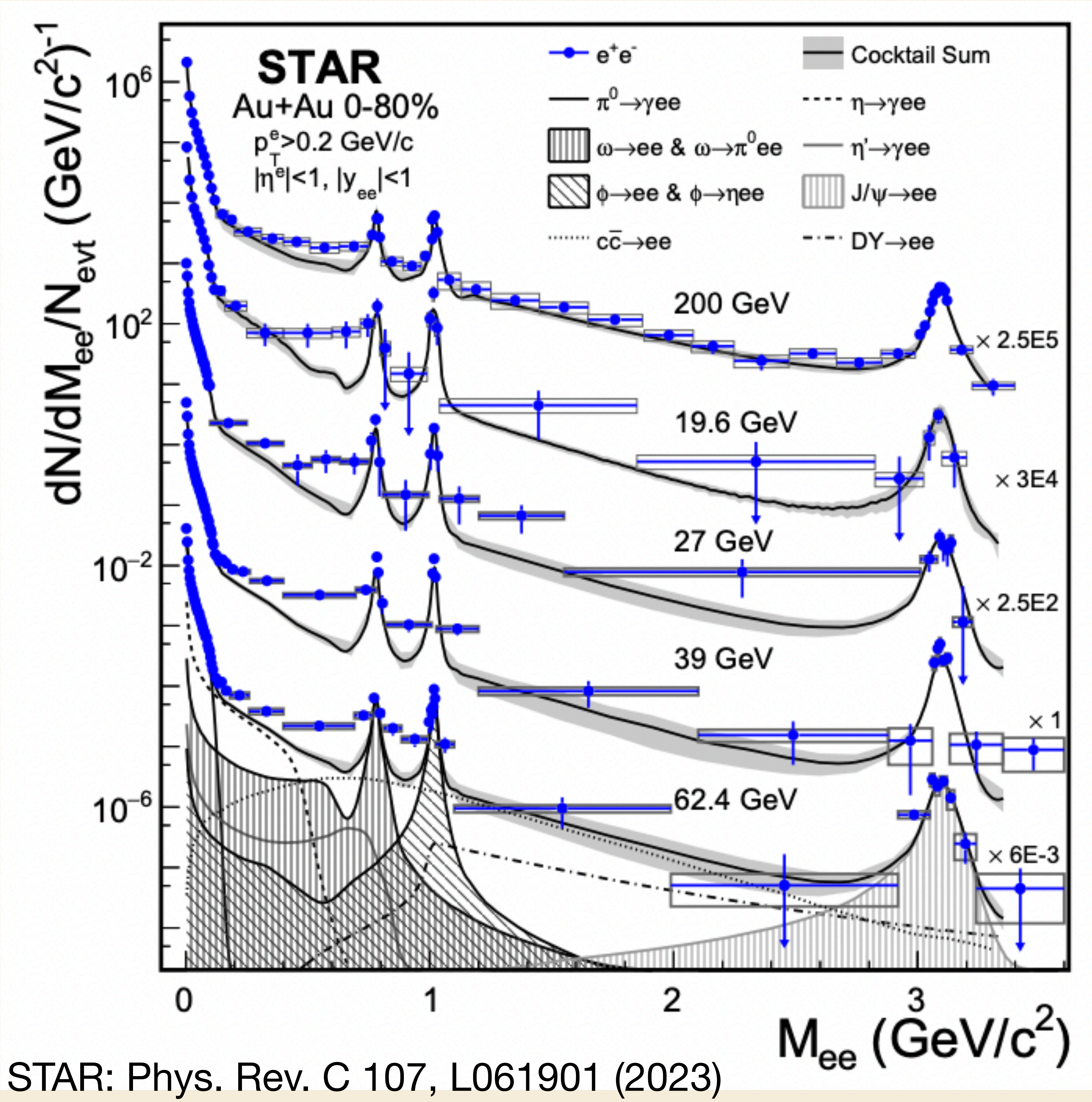
- Thermal radiation
- Physical Background
  - Drell Yan $\rightarrow e^+e^-$
  - $c\bar{c} \rightarrow e^+e^-$
  - $J/\psi \rightarrow e^+e^-$
  - $\omega \rightarrow (\pi^0)e^+e^-, \phi \rightarrow (\eta)e^+e^-$
  - $M \rightarrow \gamma e^+e^-$ ($M : \pi^0, \eta, \eta'$)

Simulated Physical Background



STAR: Phys. Rev. C 107, L061901 (2023)
STAR: PLB750 (2015) 64
STAR: PLB 771 13 (2017)
STAR: Phys. Rev. C 96, 044904 (2017)
NA50: Phys. Lett. B 499, 85 (2001)

STAR BES-I Dielectron Measurement



STAR BES-I published:

Au+Au $\sqrt{s_{NN}}$ = 19.6—200 GeV

Efficiency corrected Data = Raw Data / Eff

Eff : Pair Efficiency

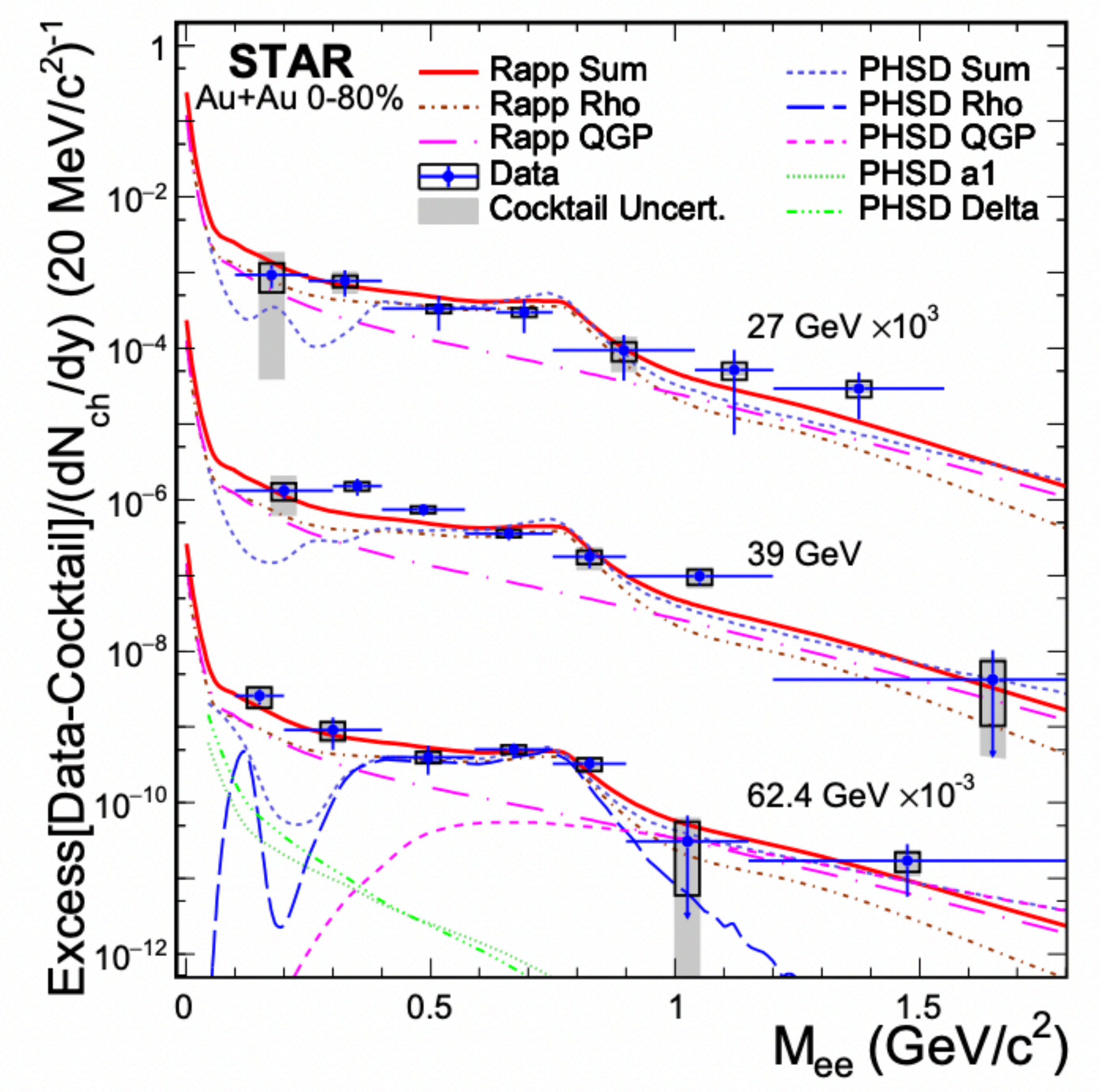
Excess yield = (Eff corrected Data- Cocktail) / Acc

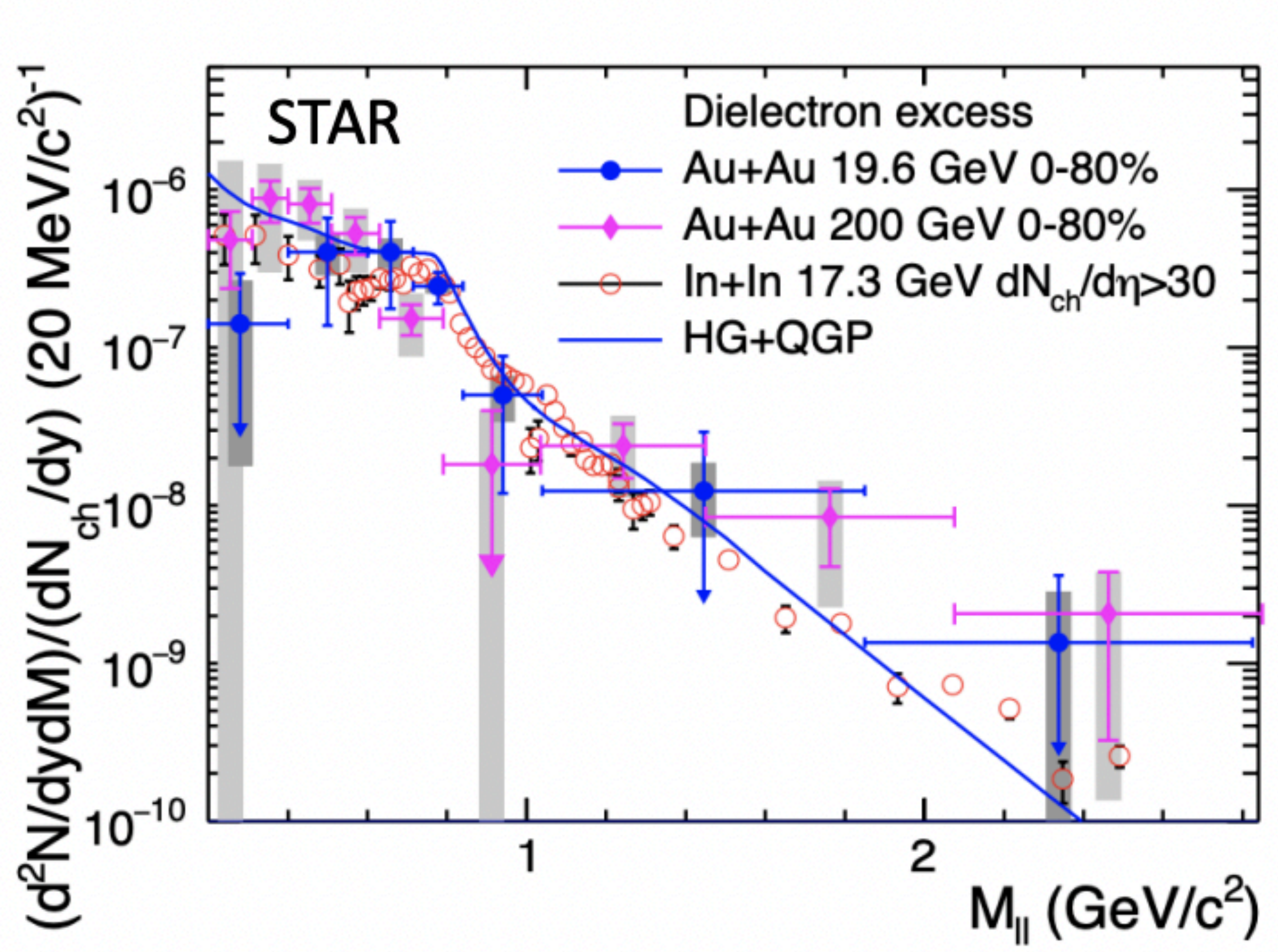
Acc: Pair Acceptance

STAR: Phys. Rev. C 107, L061901 (2023)
STAR: PLB750 (2015) 64
STAR: Phys. Rev. C 92, 024912 (2015)

STAR BES-I Dielectron Measurement

STAR BES-I dielectron measurement





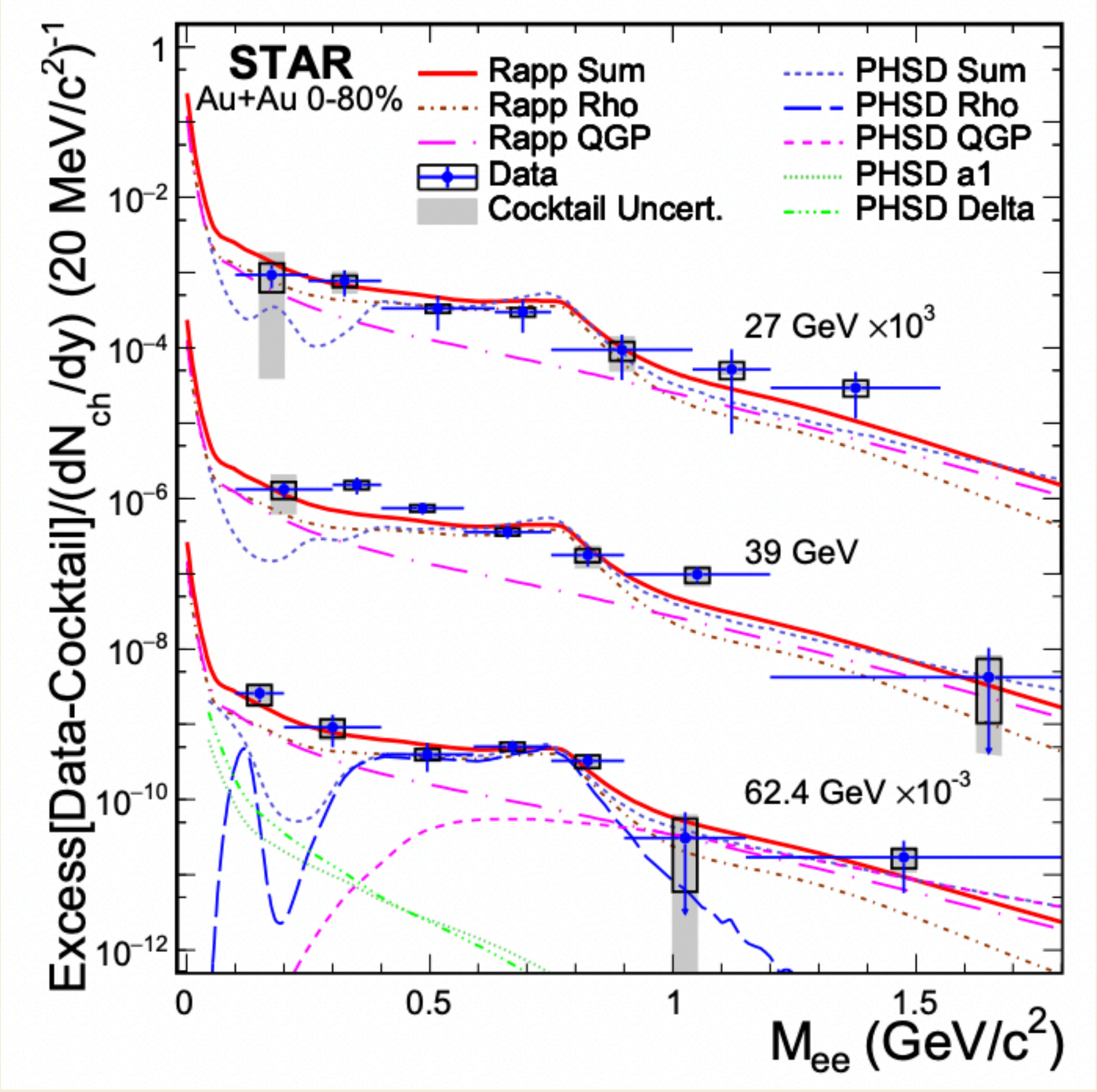
STAR: PLB750 (2015) 64, NA60: EPJ C 59 (2009) 607
Rapp: PRC 63 (2001) 054907, PRL 97, 102301 (2006) ;
PHSD: Phys. Rep. 308, 65 (1999), NPA 831, 215 (2009)
STAR: Phys. Rev. C 107, L061901 (2023)

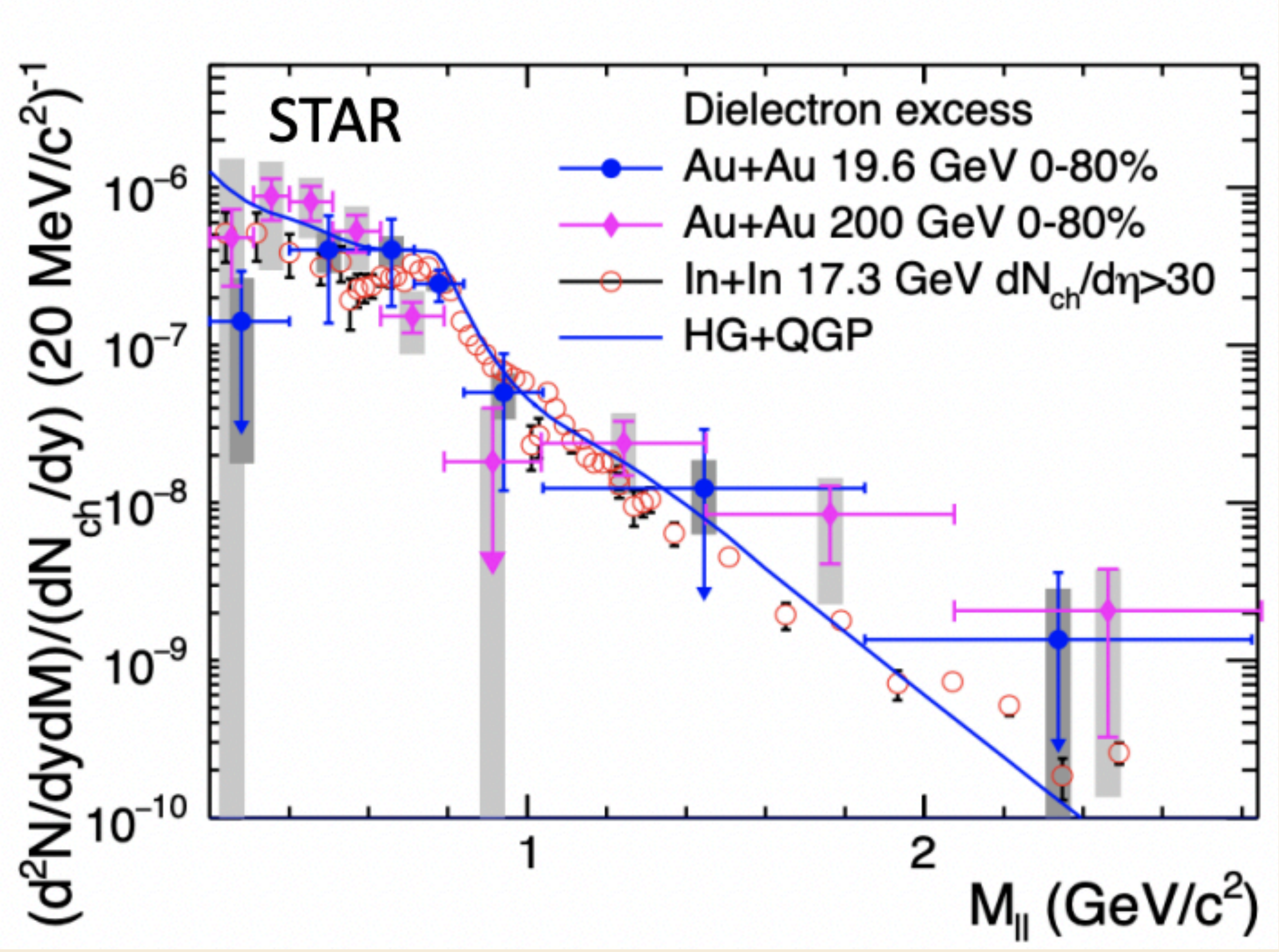
STAR BES-I:

- Excess yield is well described by the in-medium ρ + QGP emission models

STAR BES-I Dielectron Measurement

STAR BES-I dielectron measurement





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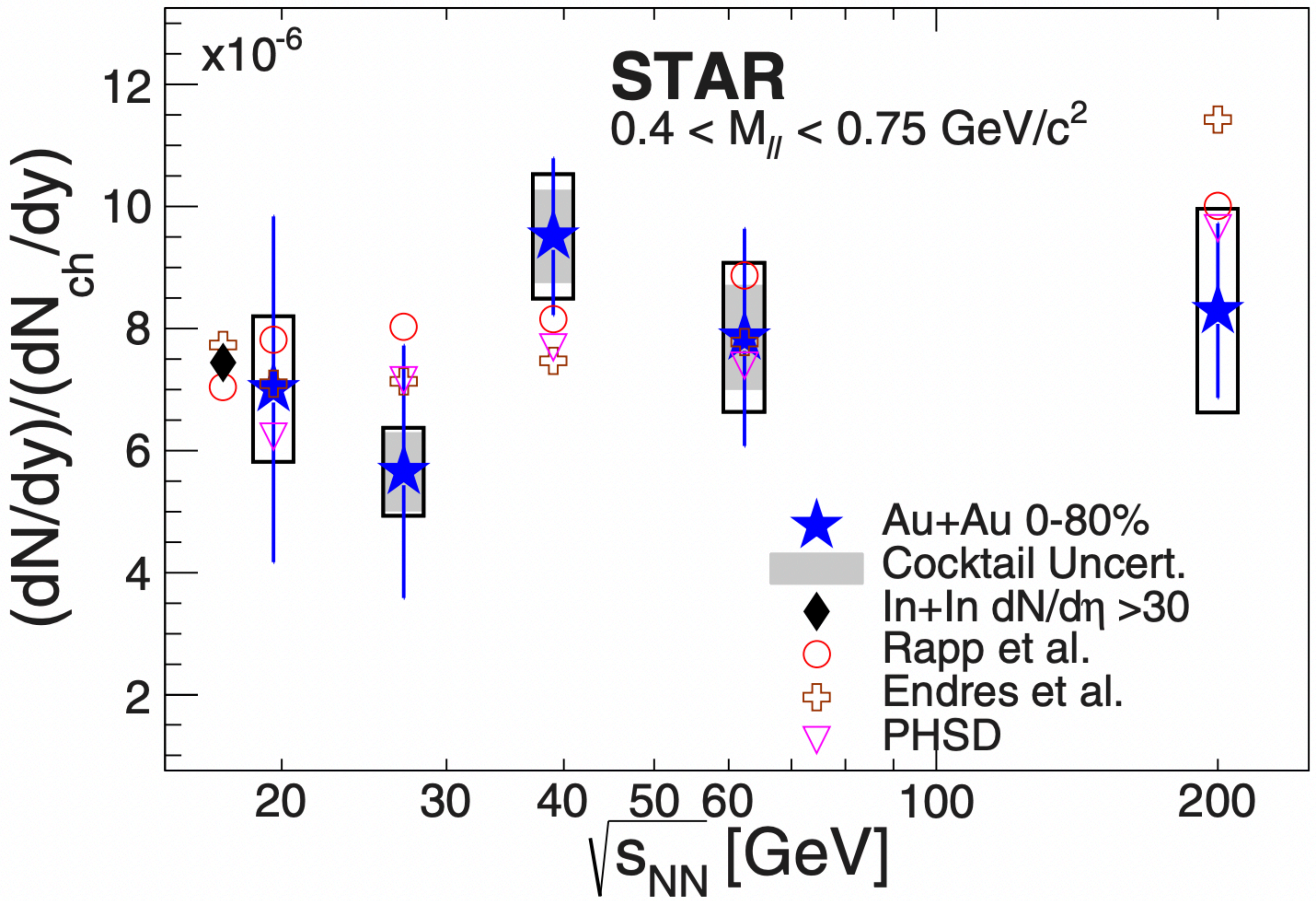
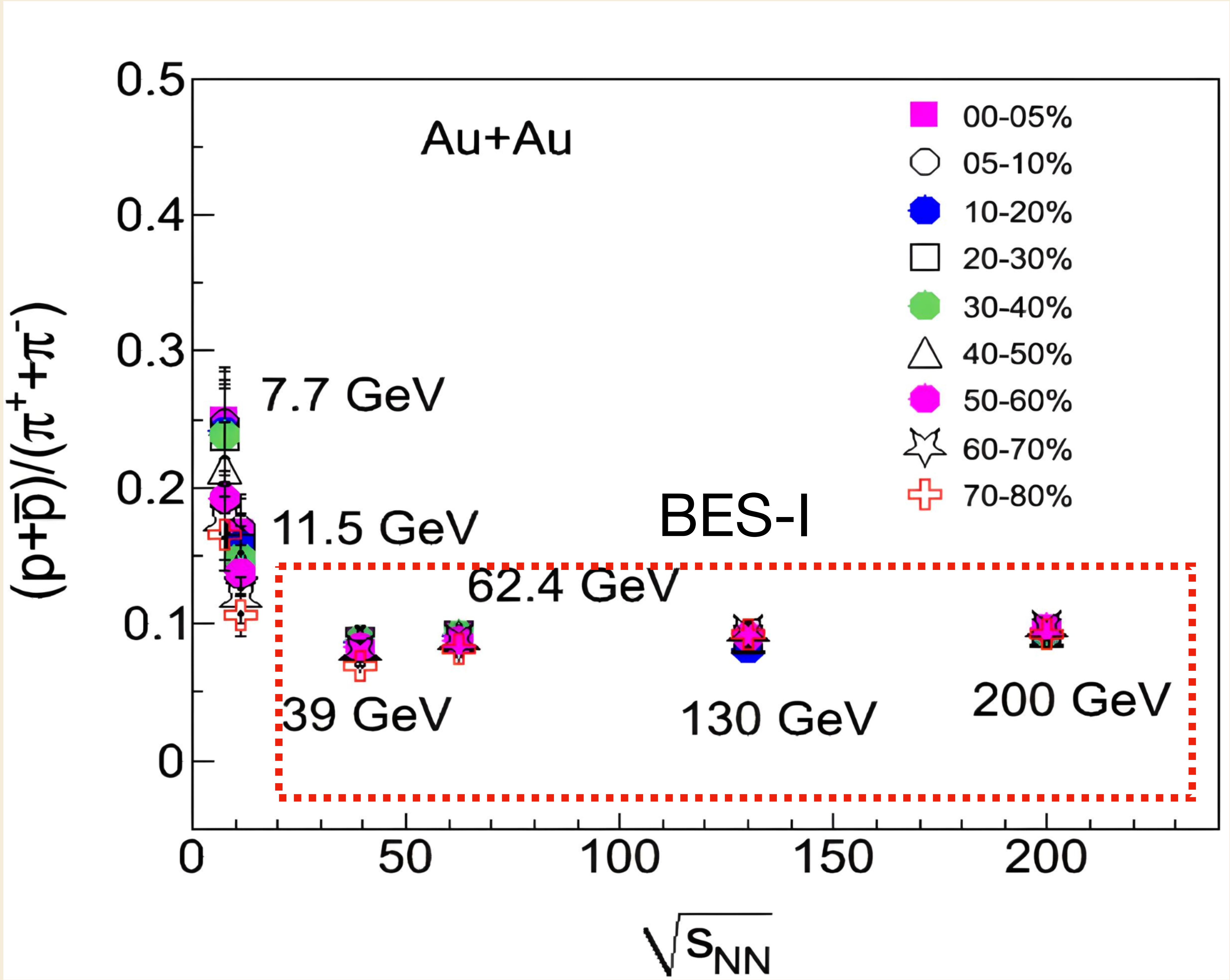


dN_{ch}/dy normalized low mass excess yield shows no clear $\sqrt{s_{NN}}$ dependence

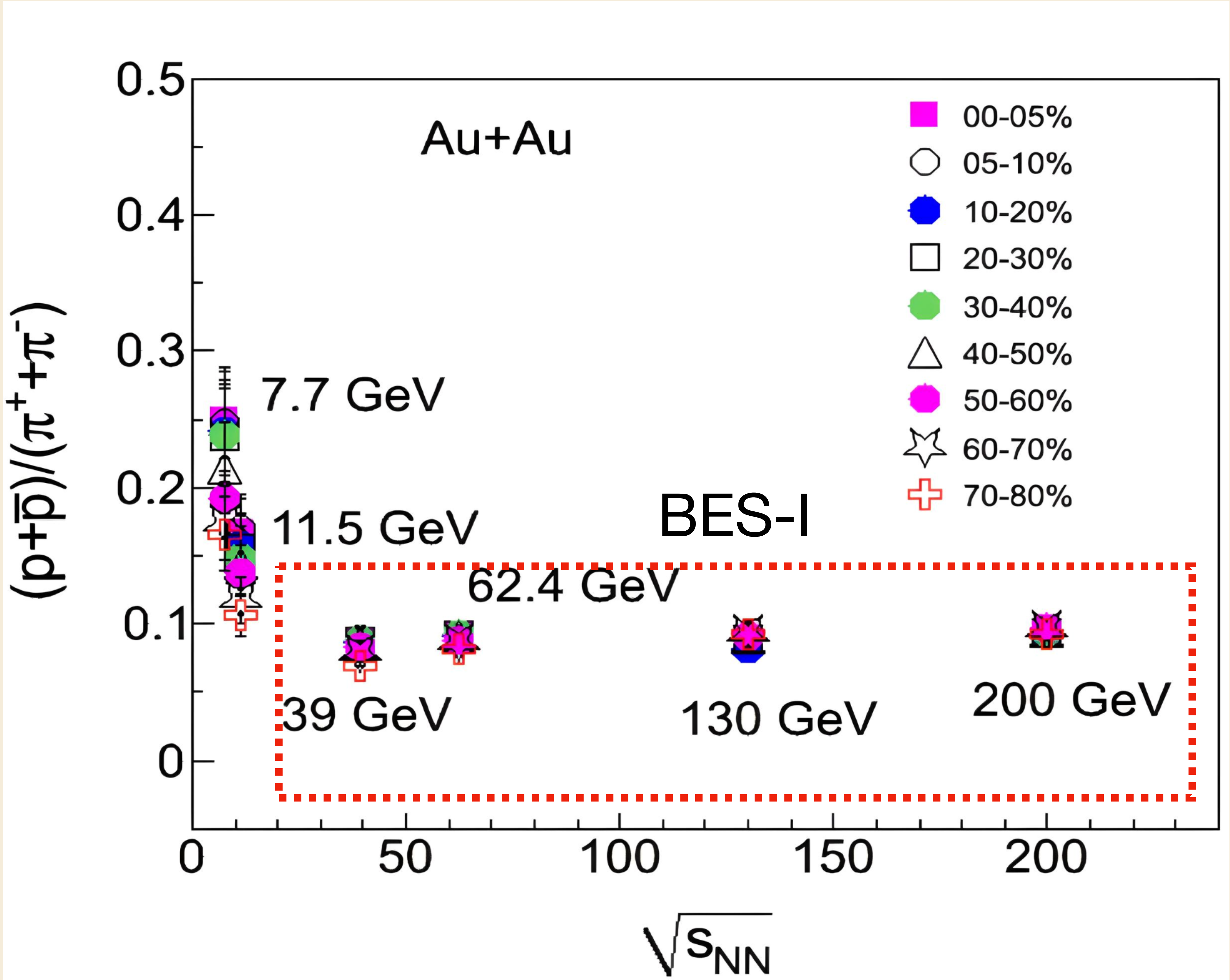
STAR BES-I medium environment

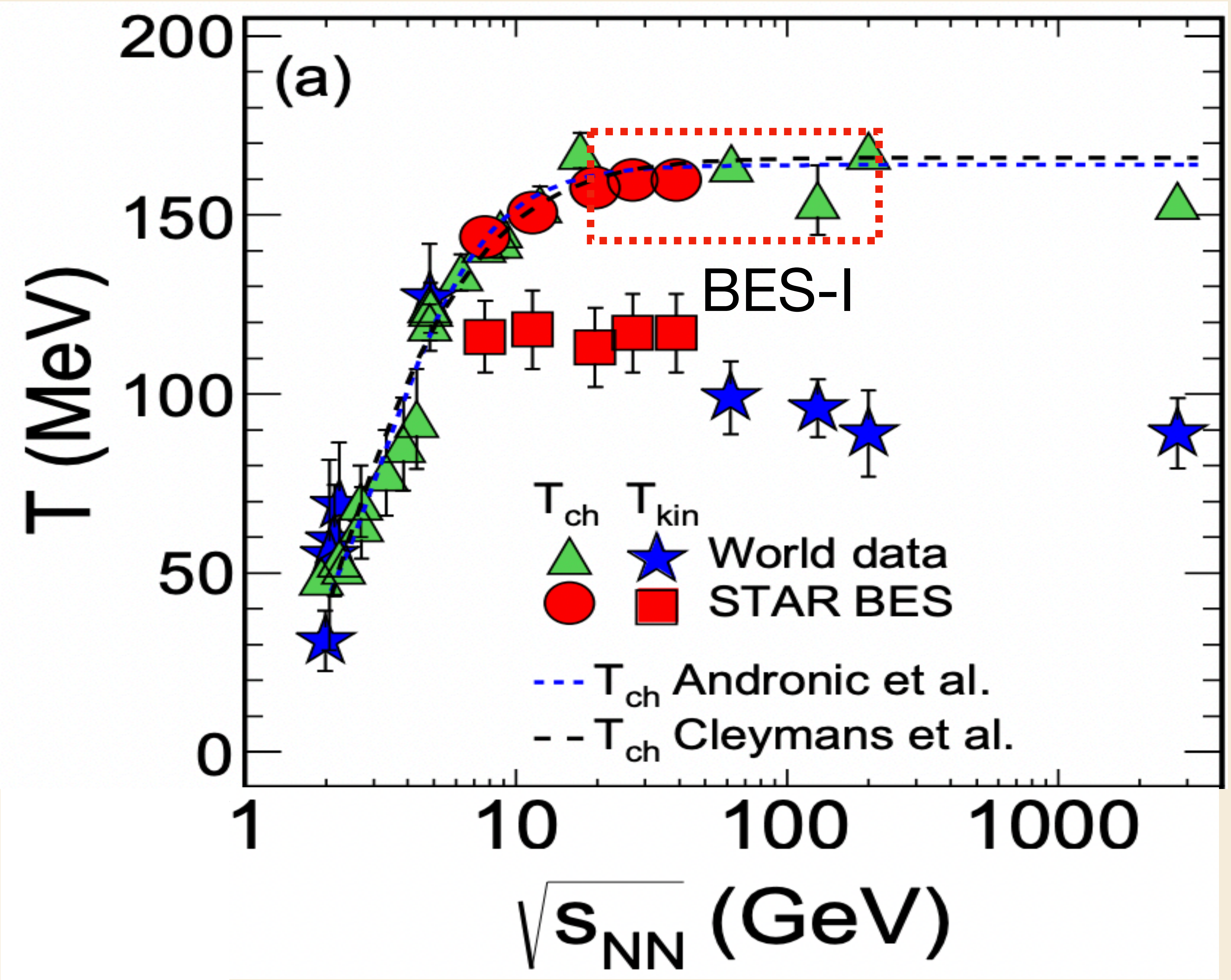


- For STAR BES-I energy range:
  - Total baryon densities are constant

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

STAR BES-I medium environment

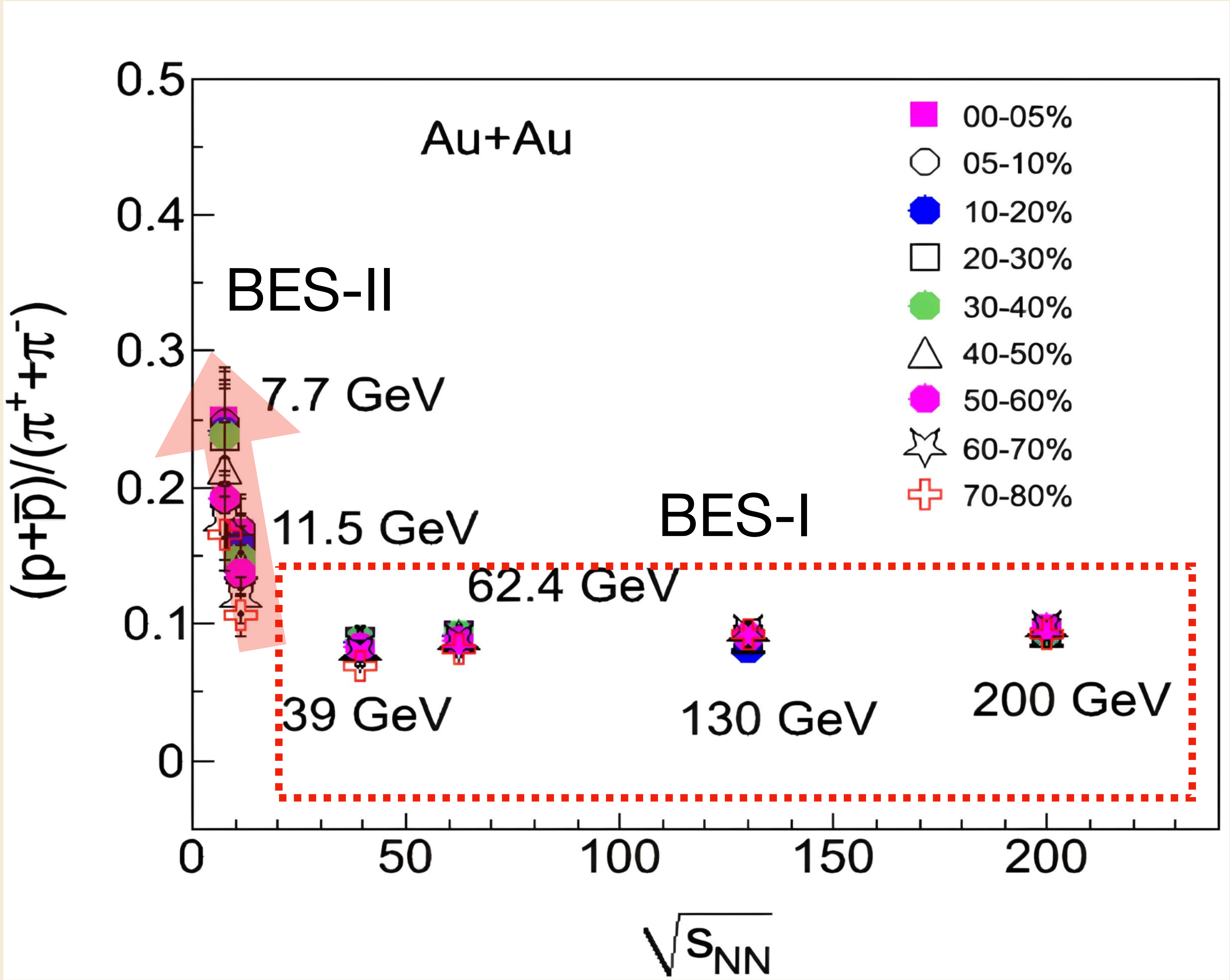


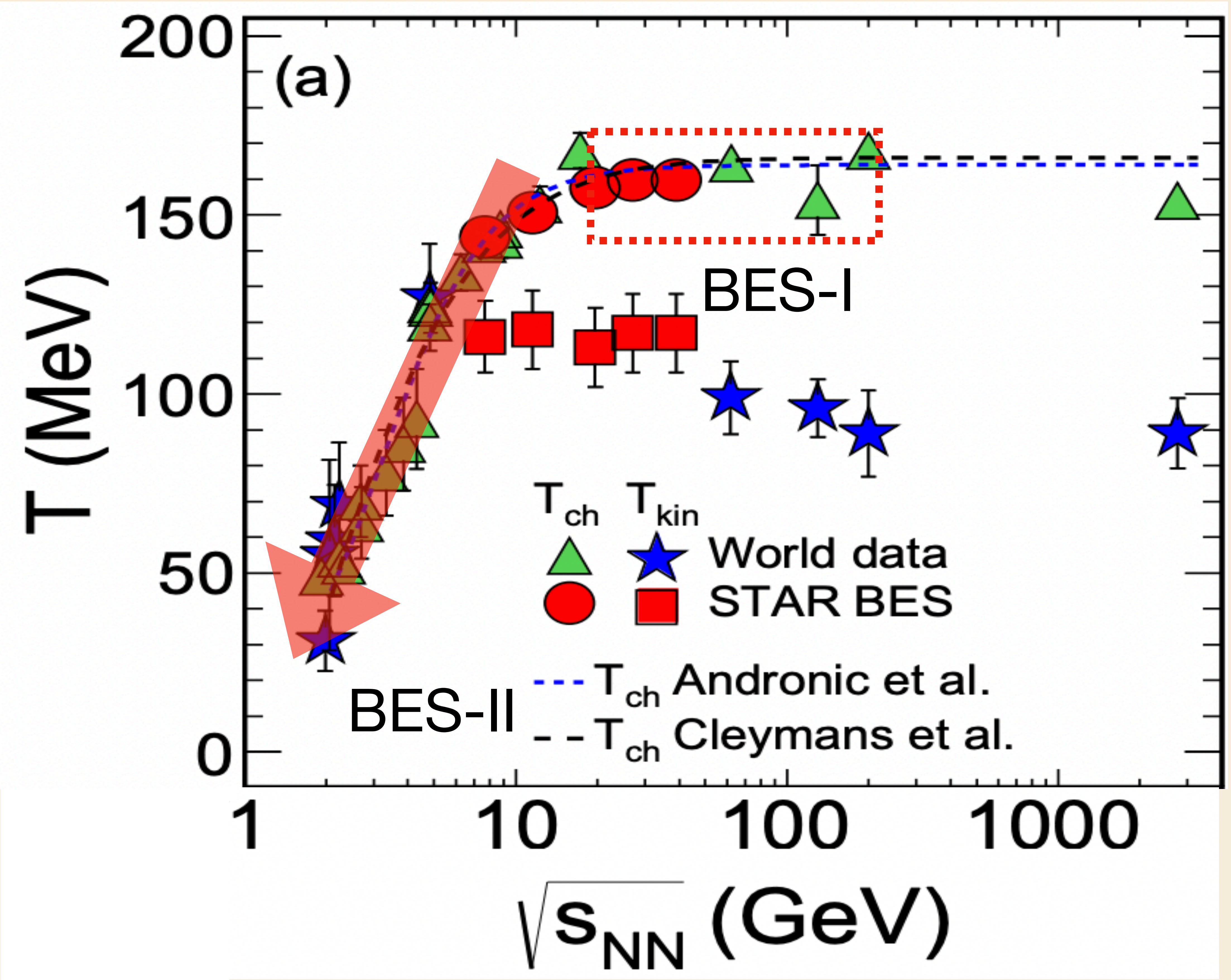


- For STAR BES-I energy range:
  - Total baryon densities are constant
- Average temperature (Hadronic Phase) are approximately constant

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

STAR BES-I medium environment

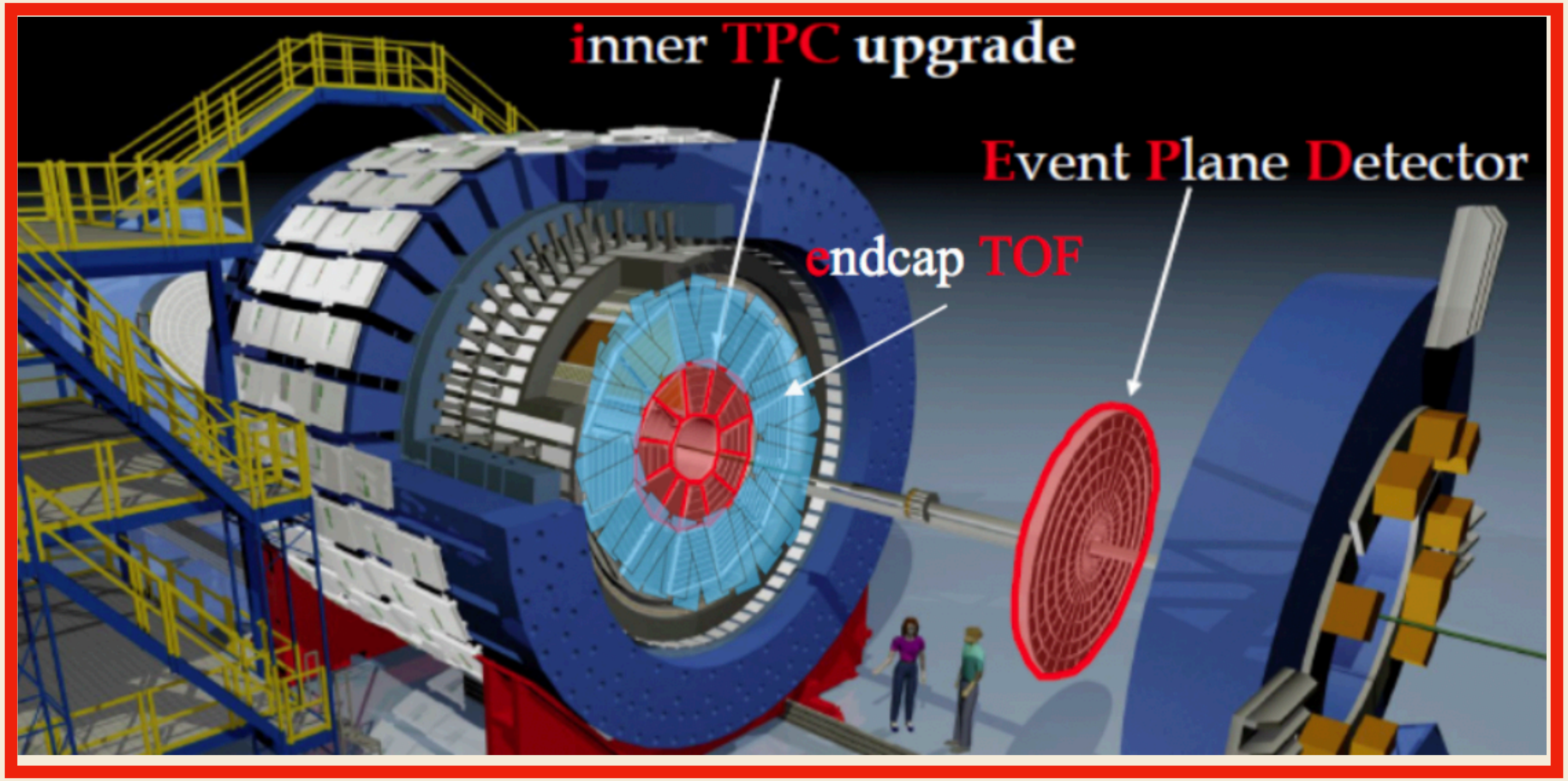




- Explore Lower $\sqrt{s_{NN}}$:
  - Probe the total baryon density and temperature effects on EM spectral function

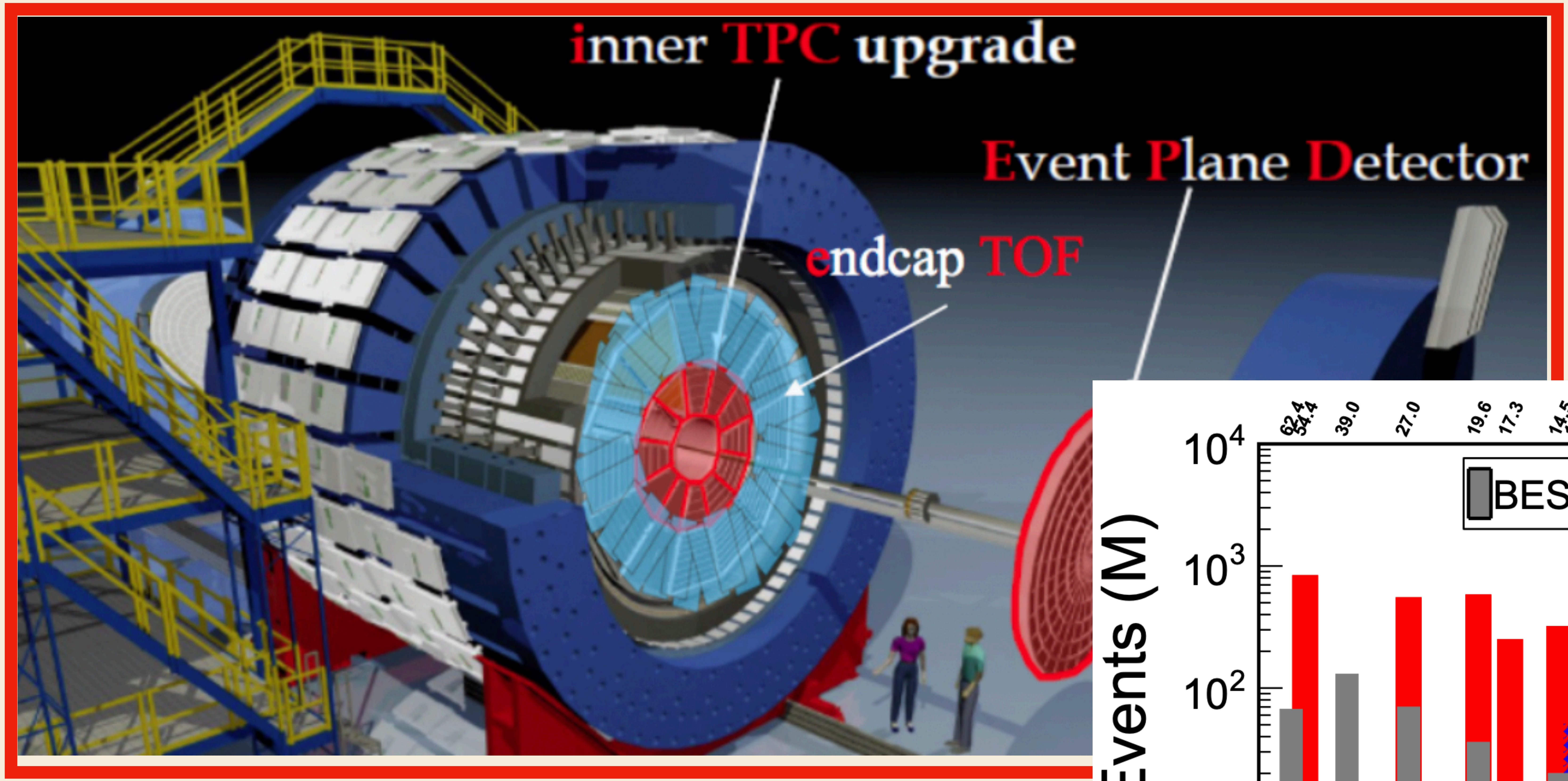
STAR: Phys. Rev. C 96, 044904 (2017)

STAR BES-II

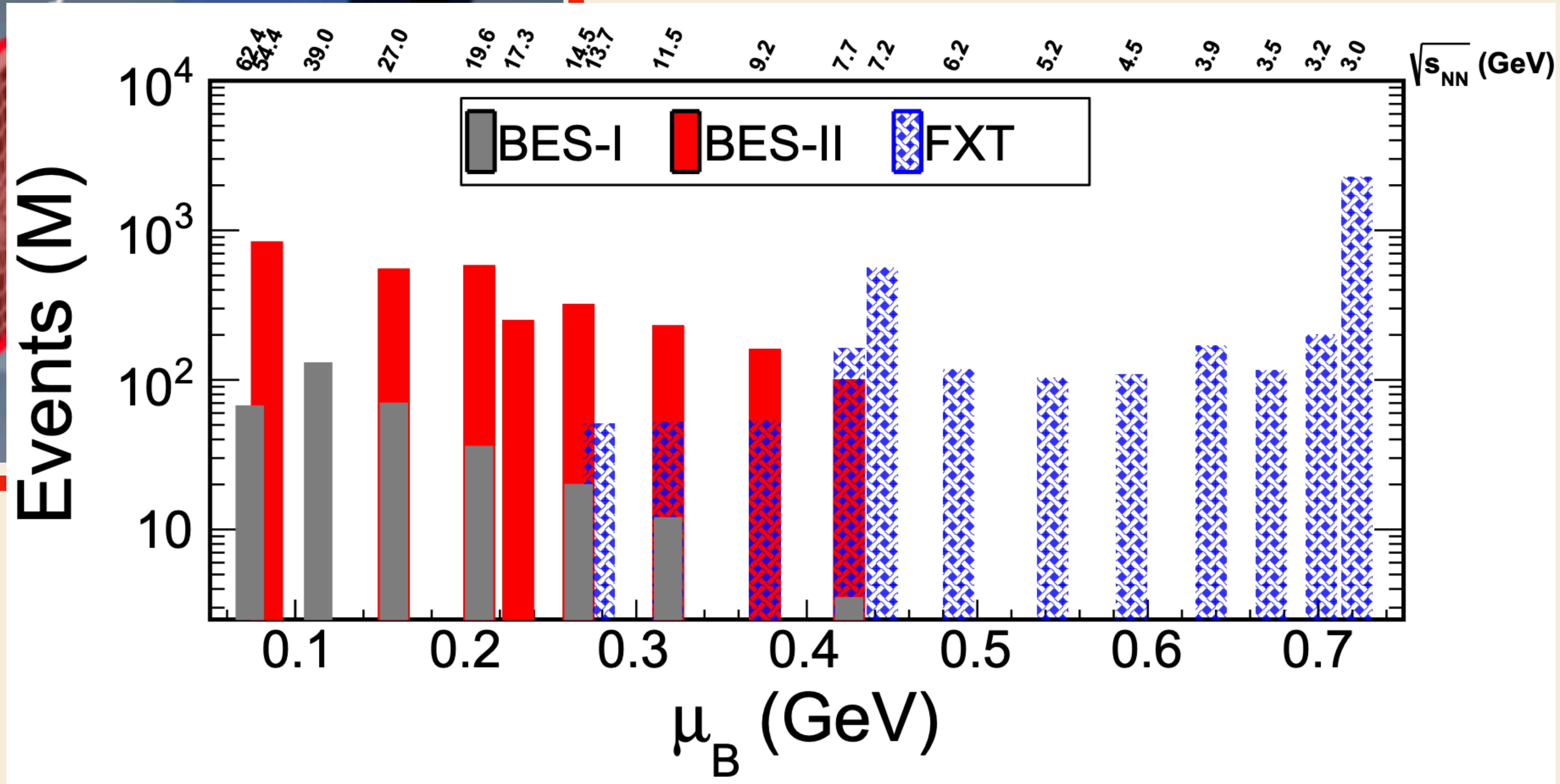


STAR Beam Use Request 2019/2020 (SN696) https://drupal.star.bnl.gov/STAR/system/files/bur2018-final_0.pdf

STAR BES-II

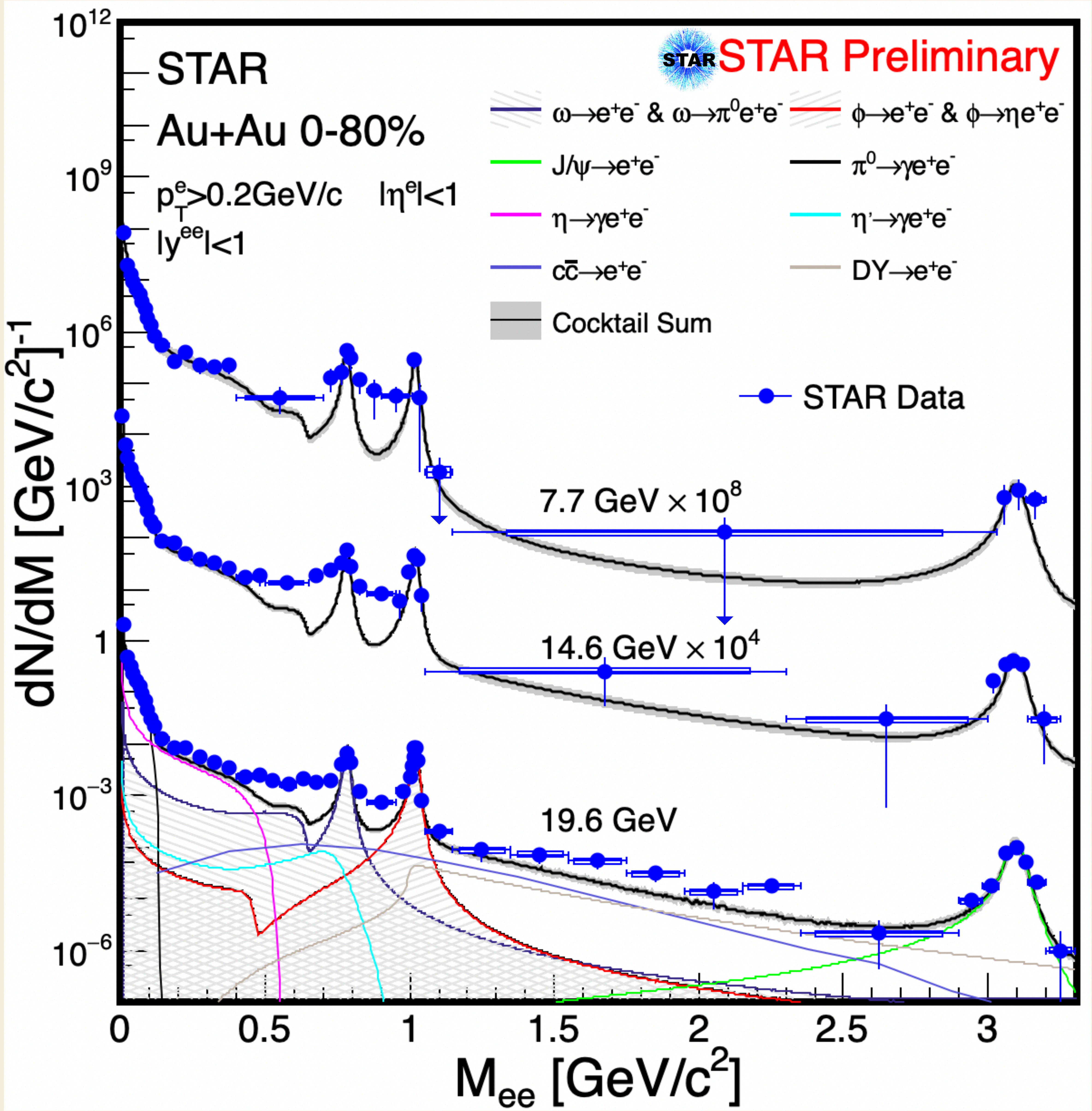


BES-II > 10 × BES-I



STAR Beam Use Request 2019/2020 (SN696) https://drupal.star.bnl.gov/STAR/system/files/bur2018-final_0.pdf

STAR BES-II Dielectron Measurement

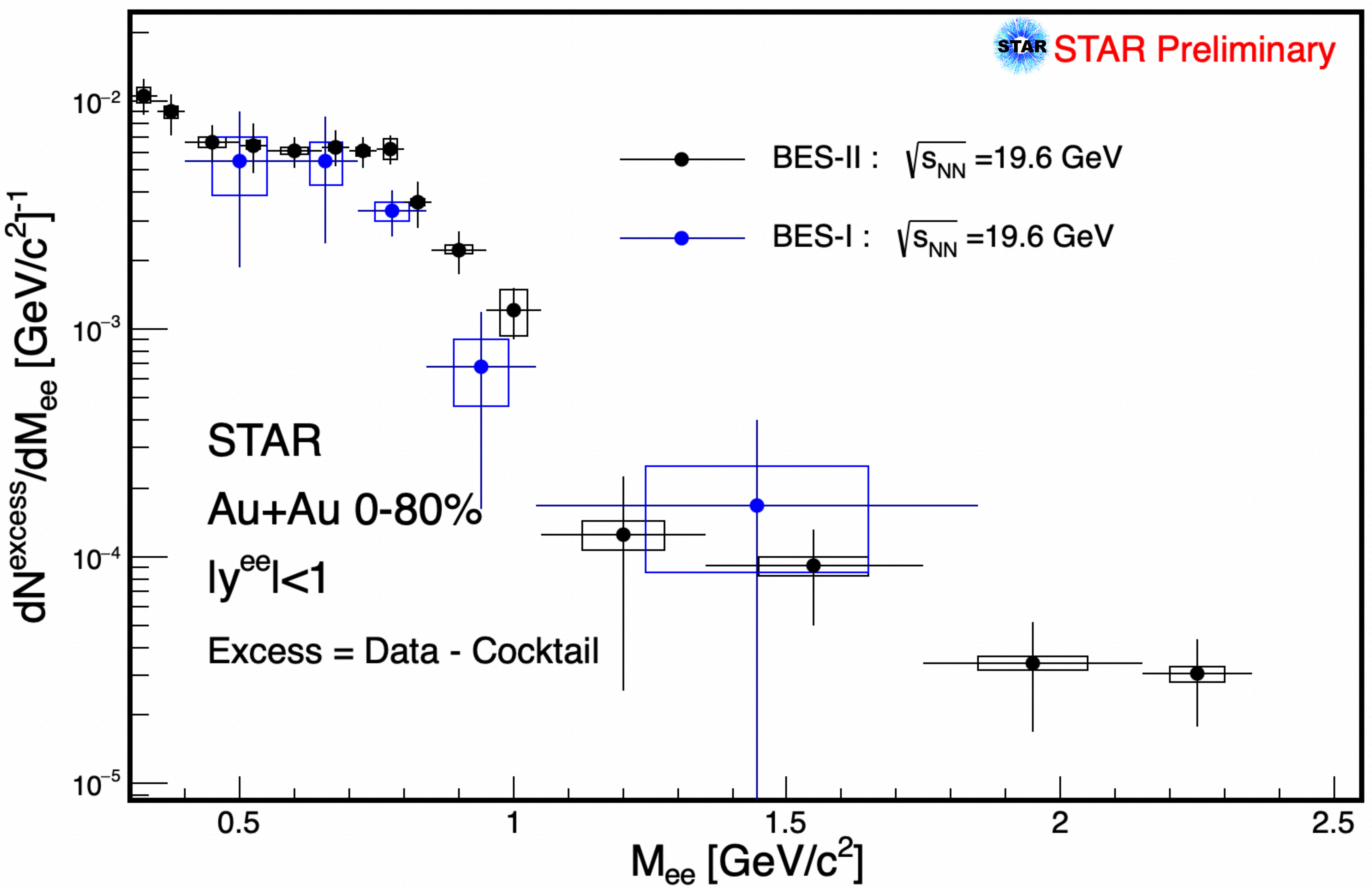


STAR BES-II COL:

Au+Au $\sqrt{s_{NN}}$ = 7.7—19.6 GeV (2019-2021)

First Dielectron Measurement for $\sqrt{s_{NN}}$ < 19.6 GeV in **collider mode.**

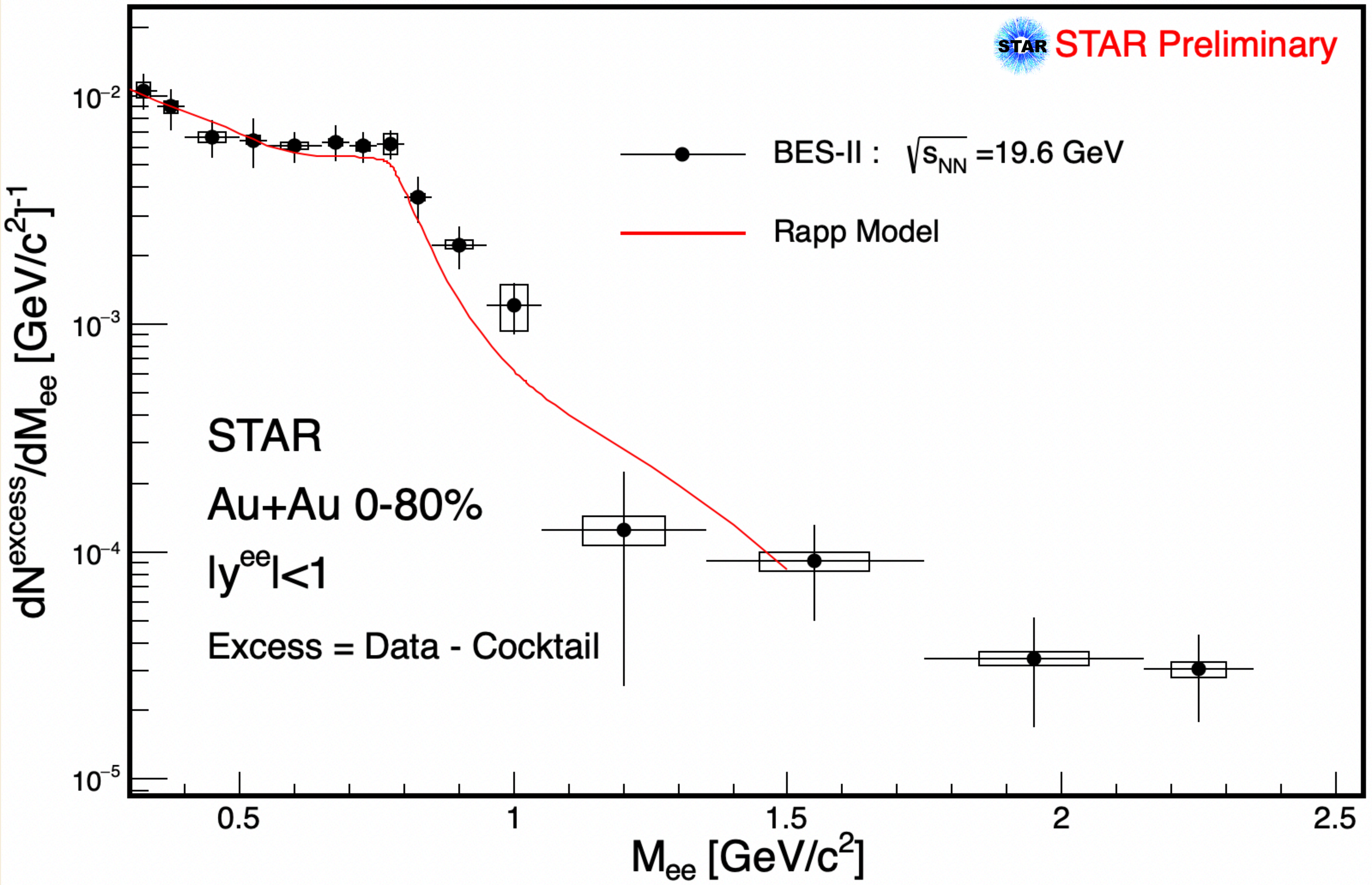
STAR BES-II Dielectron Measurement at 19.6 GeV

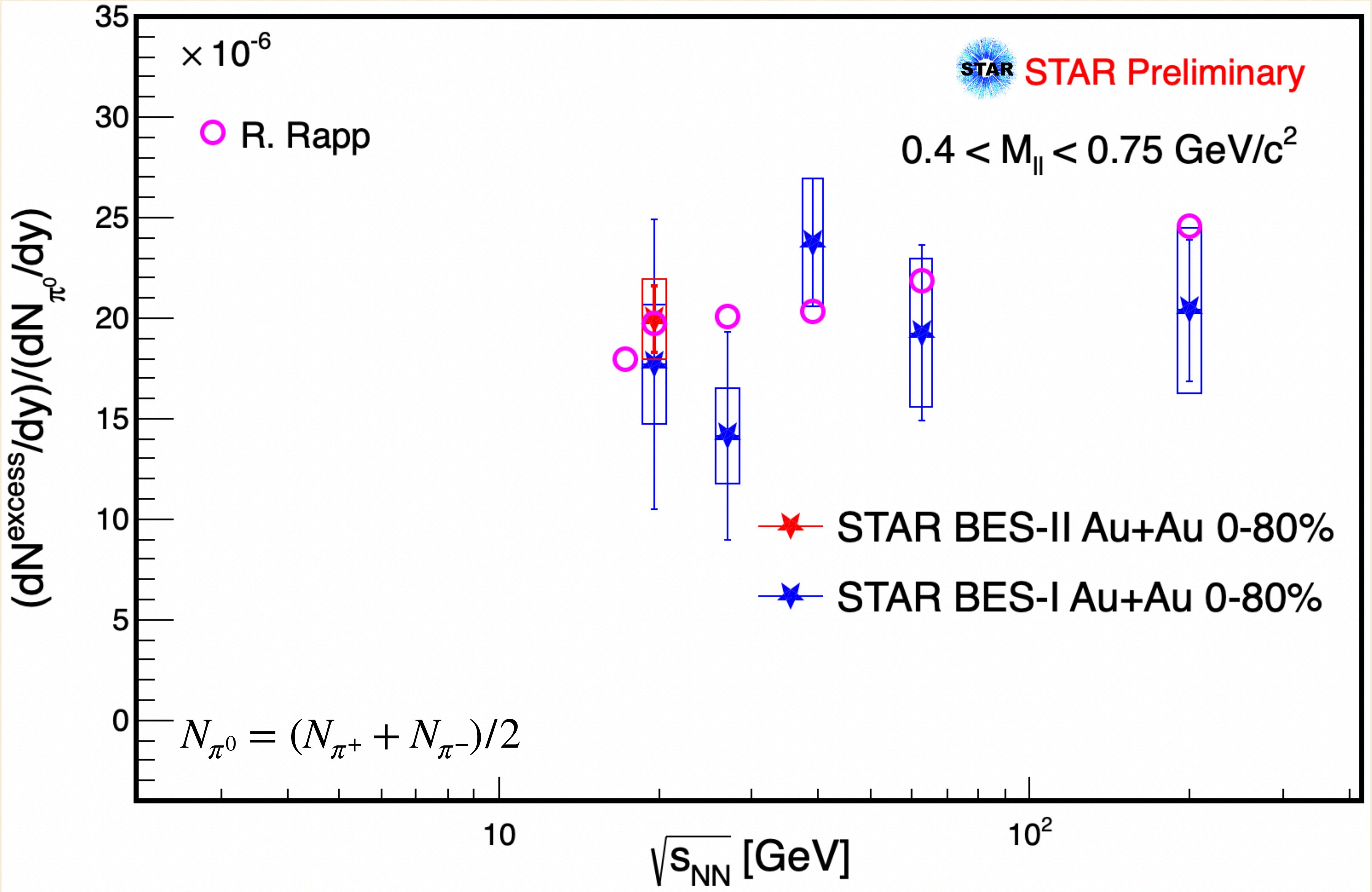


Excess yield invariant mass spectra at 19.6GeV

- Consistency between BES-I and BES-II
- Much better statistical and systematical uncertainties at BES-II than BES-I
  - Total error reduced by factor of 4

STAR BES-II Dielectron Measurement at 19.6 GeV



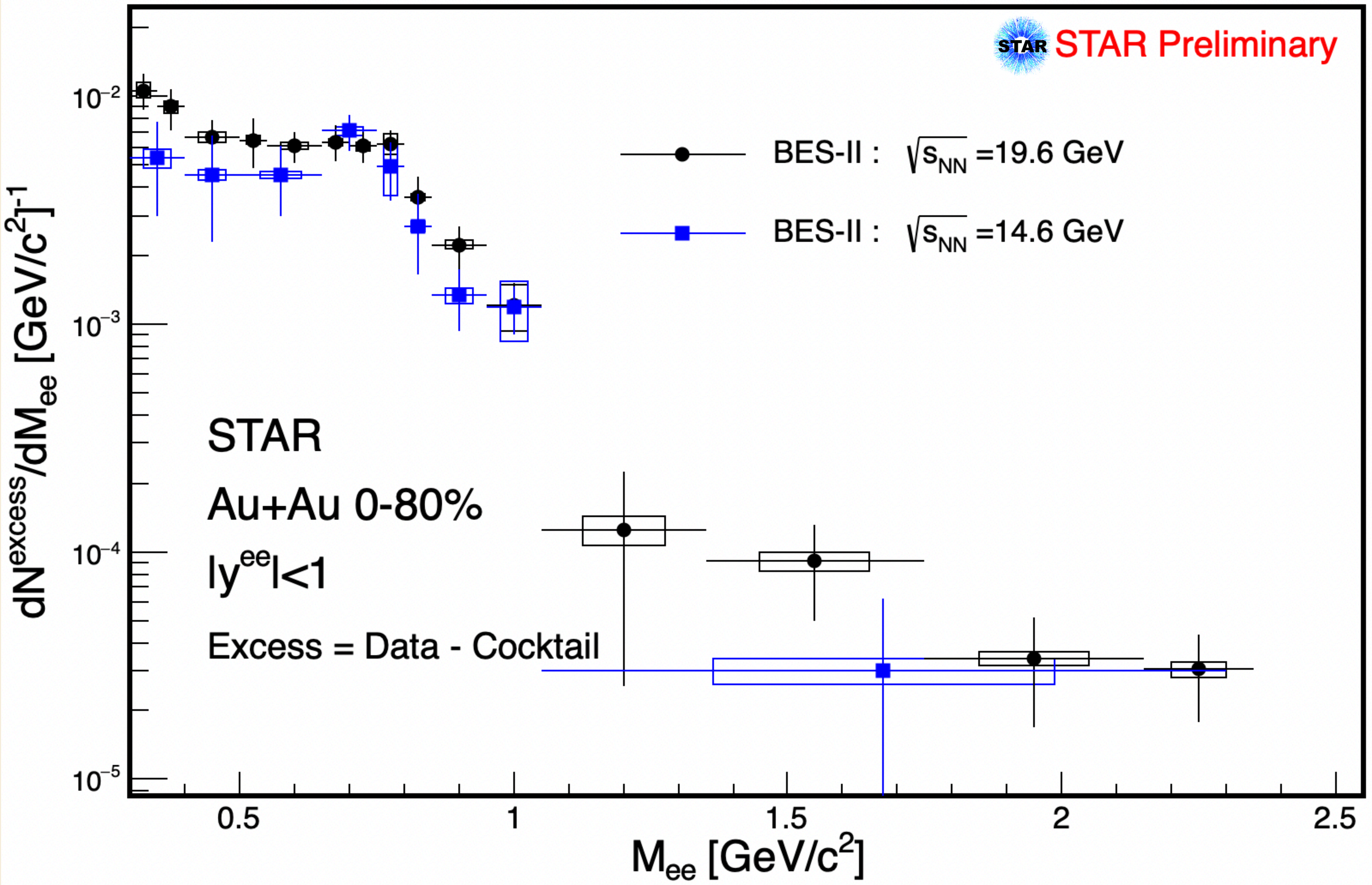


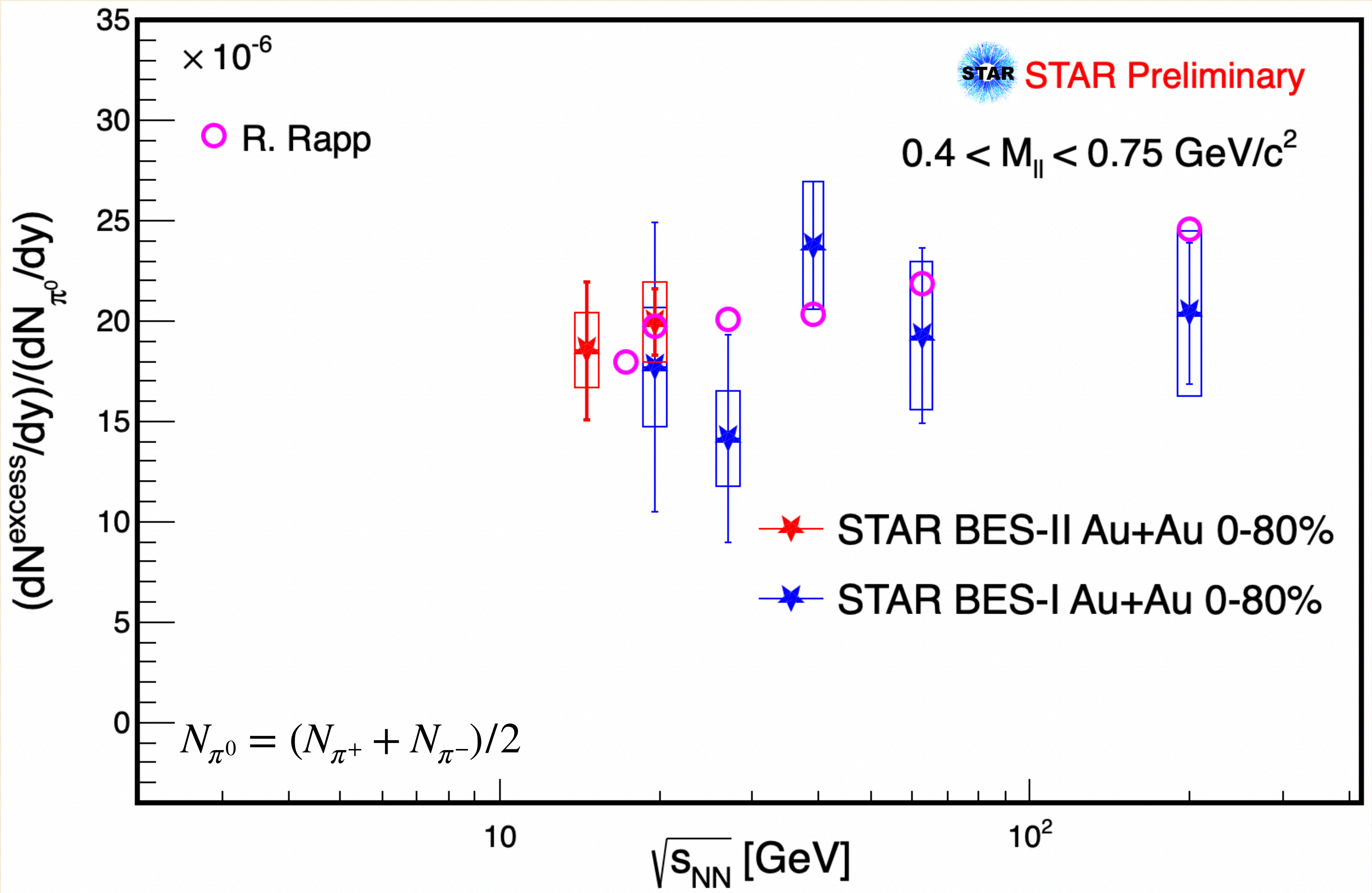
Excess yield invariant mass spectra at 19.6 GeV

- Described by R. Rapp's calculation

R. Rapp, Phys. Rev. C 63, 054907 (2001)
H. van Hees and R. Rapp, Phys. Lett. 97, 102301 (2006)
O. Linnyk, E. L. Bratkovskaya, and W. Cassing, Prog. Part. Nucl. Phys. 87, 50 (2016).

STAR BES-II Dielectron Measurement vs $\sqrt{s_{NN}}$

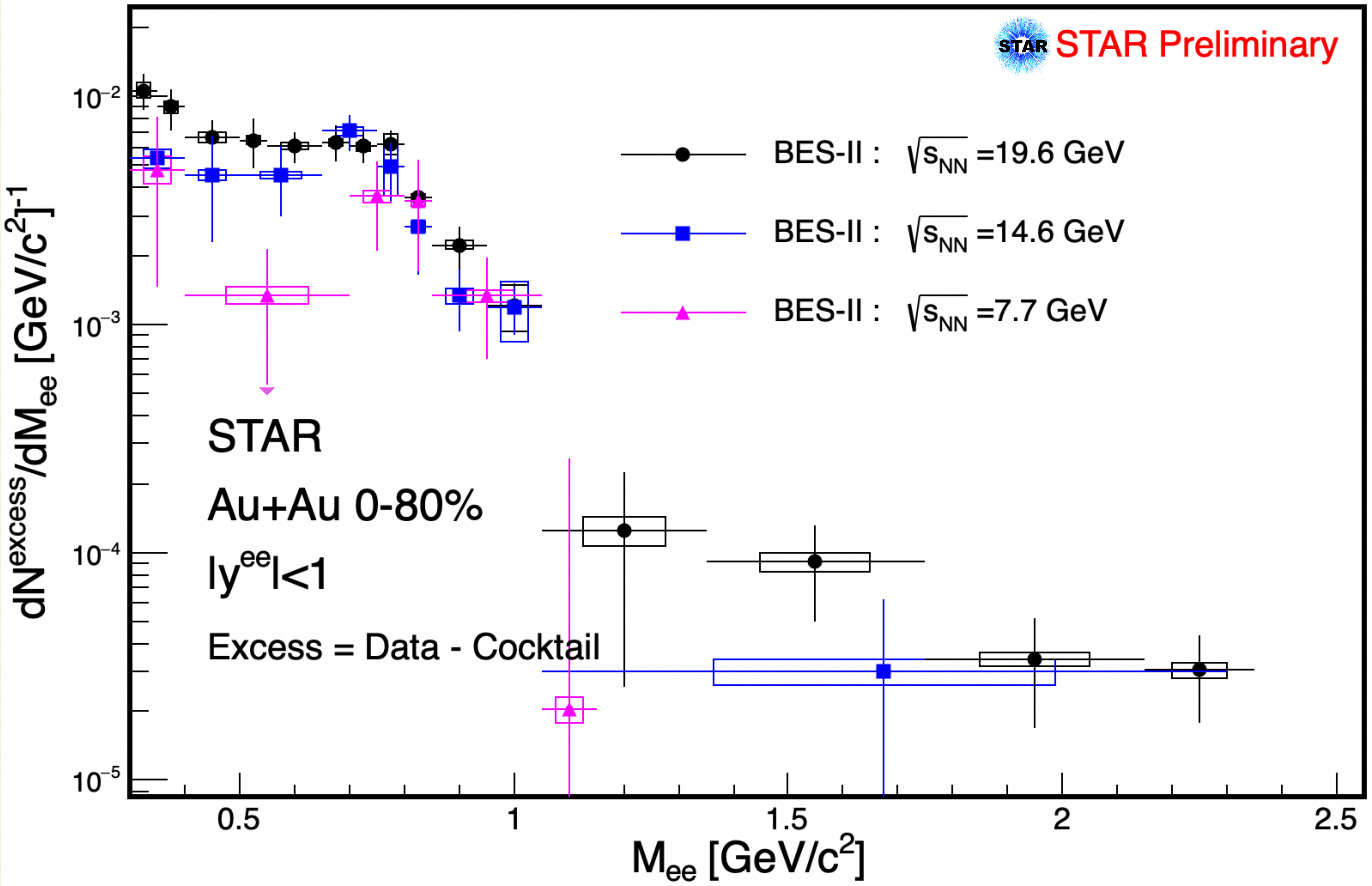


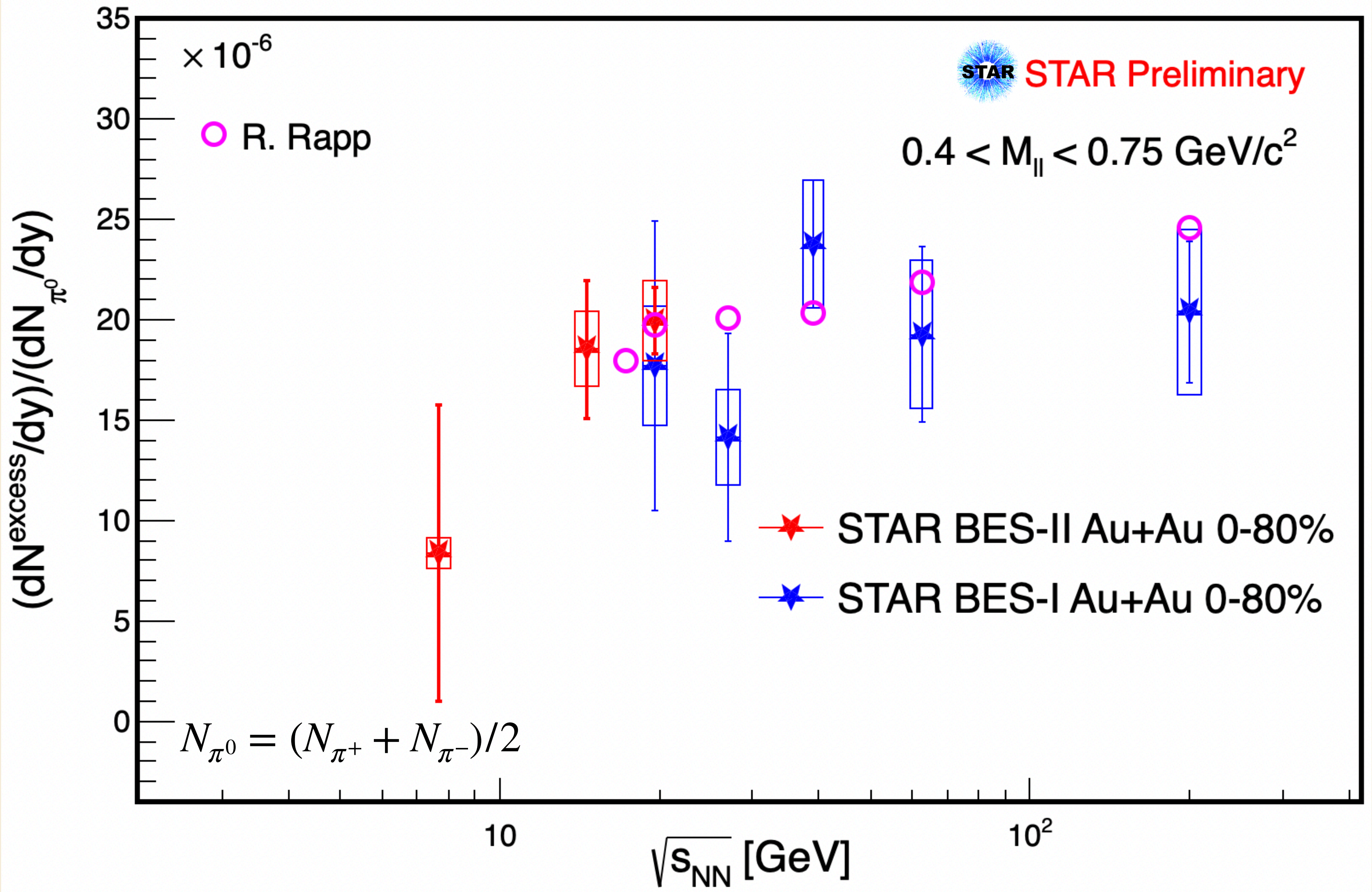


Various excess yield invariant mass spectra at different $\sqrt{s_{NN}}$

- Medium interactions in different environments
  - Total baryon density
  - Temperature

STAR BES-II Dielectron Measurement vs $\sqrt{s_{NN}}$





Various excess yield invariant mass spectra at different $\sqrt{s_{NN}}$

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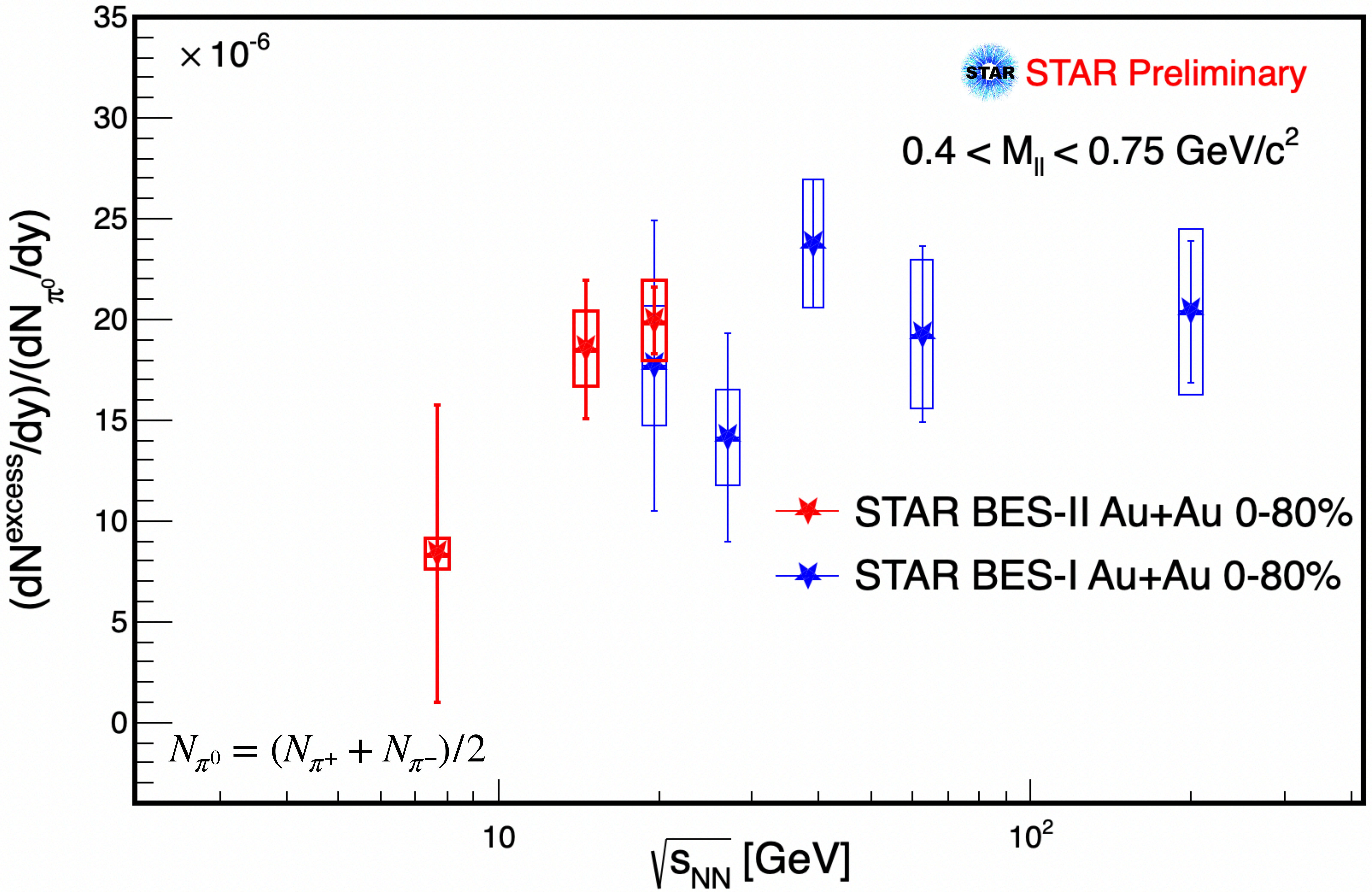
STAR BES Dielectron Measurement: Excess yield vs $\sqrt{s_{NN}}$



Integrated excess yield normalized by π^0 yield

- Hints a decreasing trend from high to low $\sqrt{s_{NN}}$

STAR: Phys. Rev. C 107, L061901 (2023)
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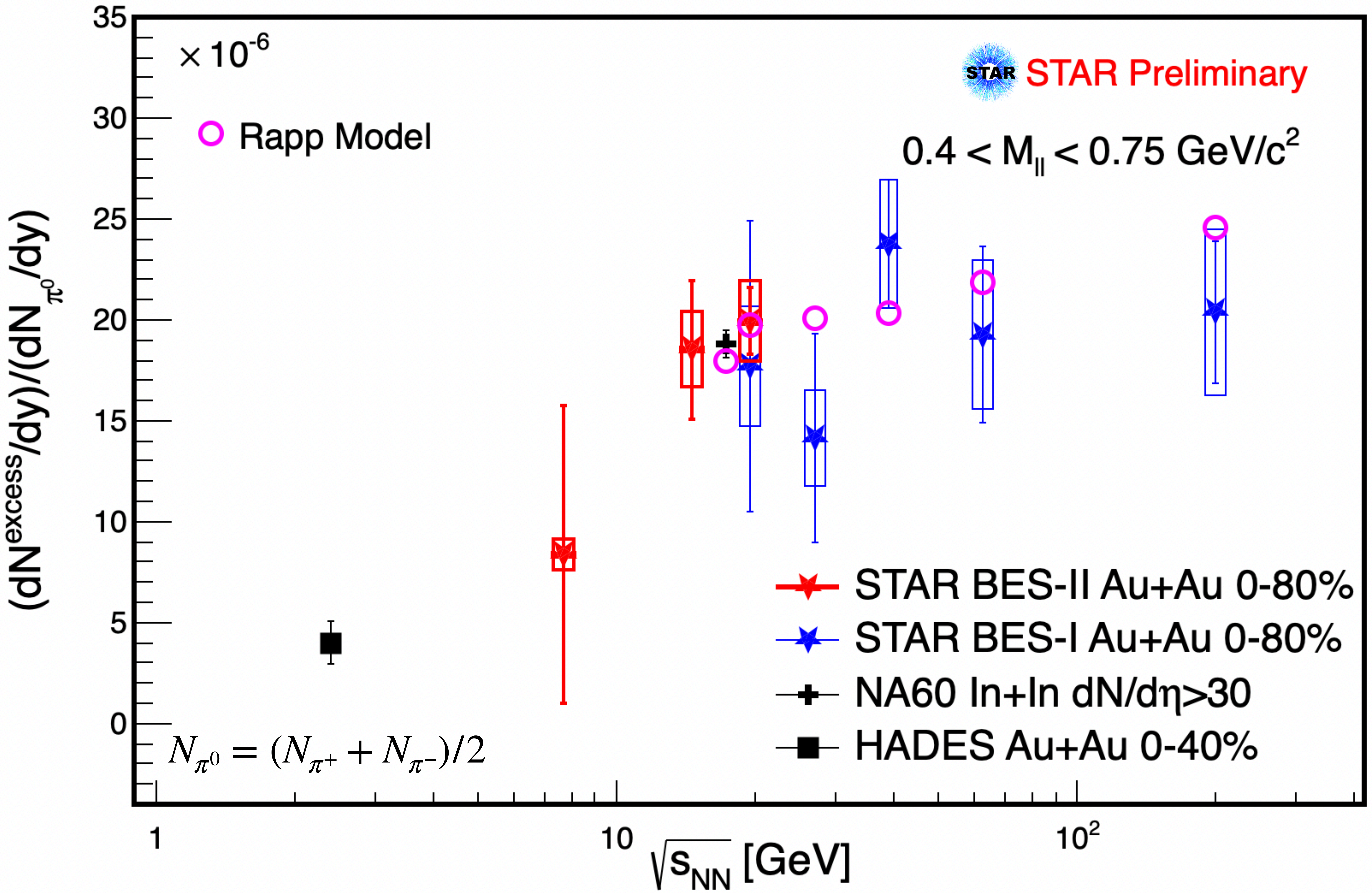

Integrated excess yield normalized by π^0 yield

- Hints a decreasing trend from high to low $\sqrt{s_{NN}}$
- Constrains the models which describe the medium interaction

STAR: Phys. Rev. C 107, L061901 (2023)
STAR: PLB750 (2015) 64
NA60: EPJ C 59 (2009) 607
HADES: *Nat. Phys.* **15**, 1040–1045 (2019)
R. Rapp, Phys. Rev. C 63, 054907 (2001)
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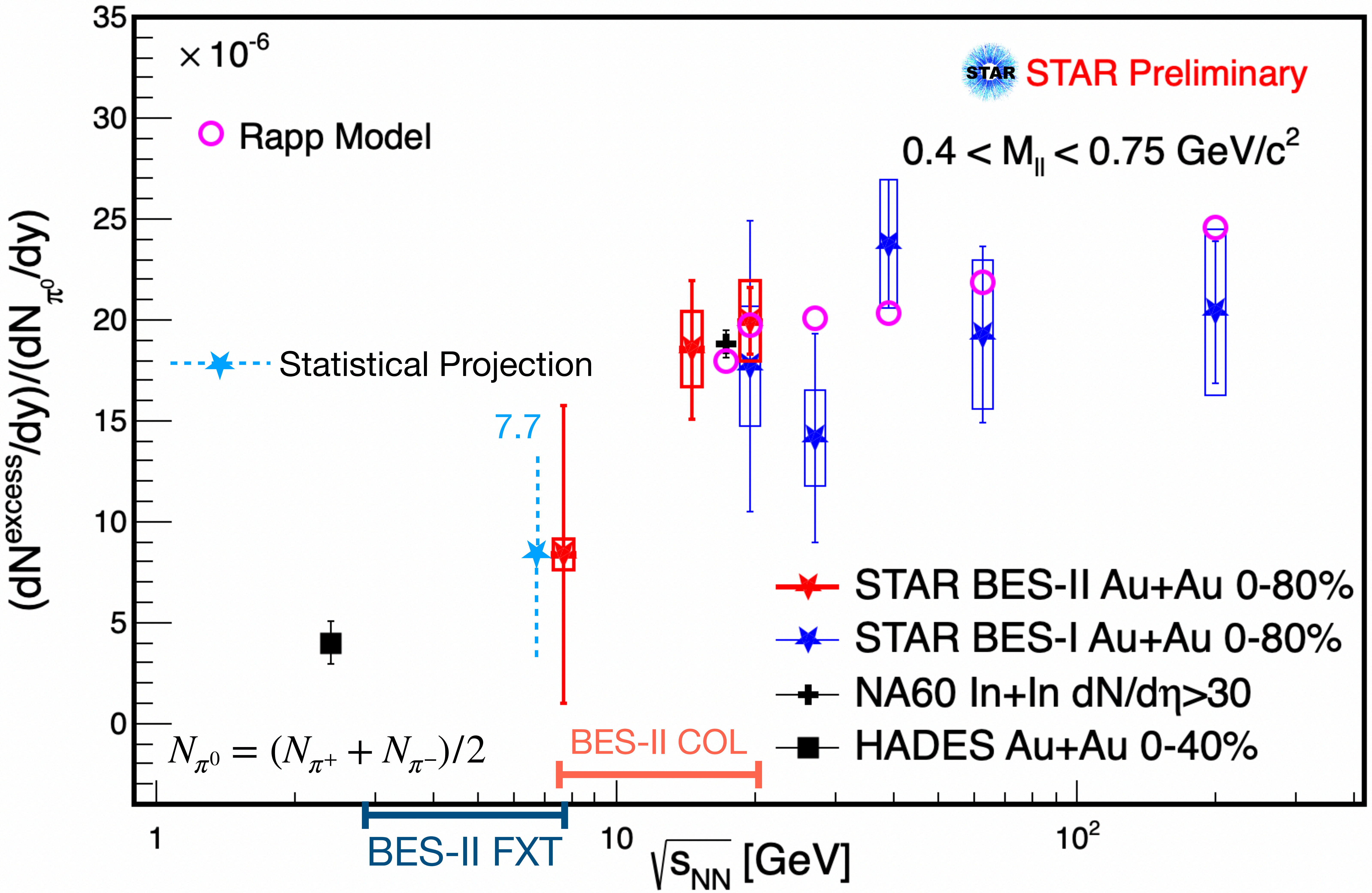
STAR BES Dielectron Measurement: Future



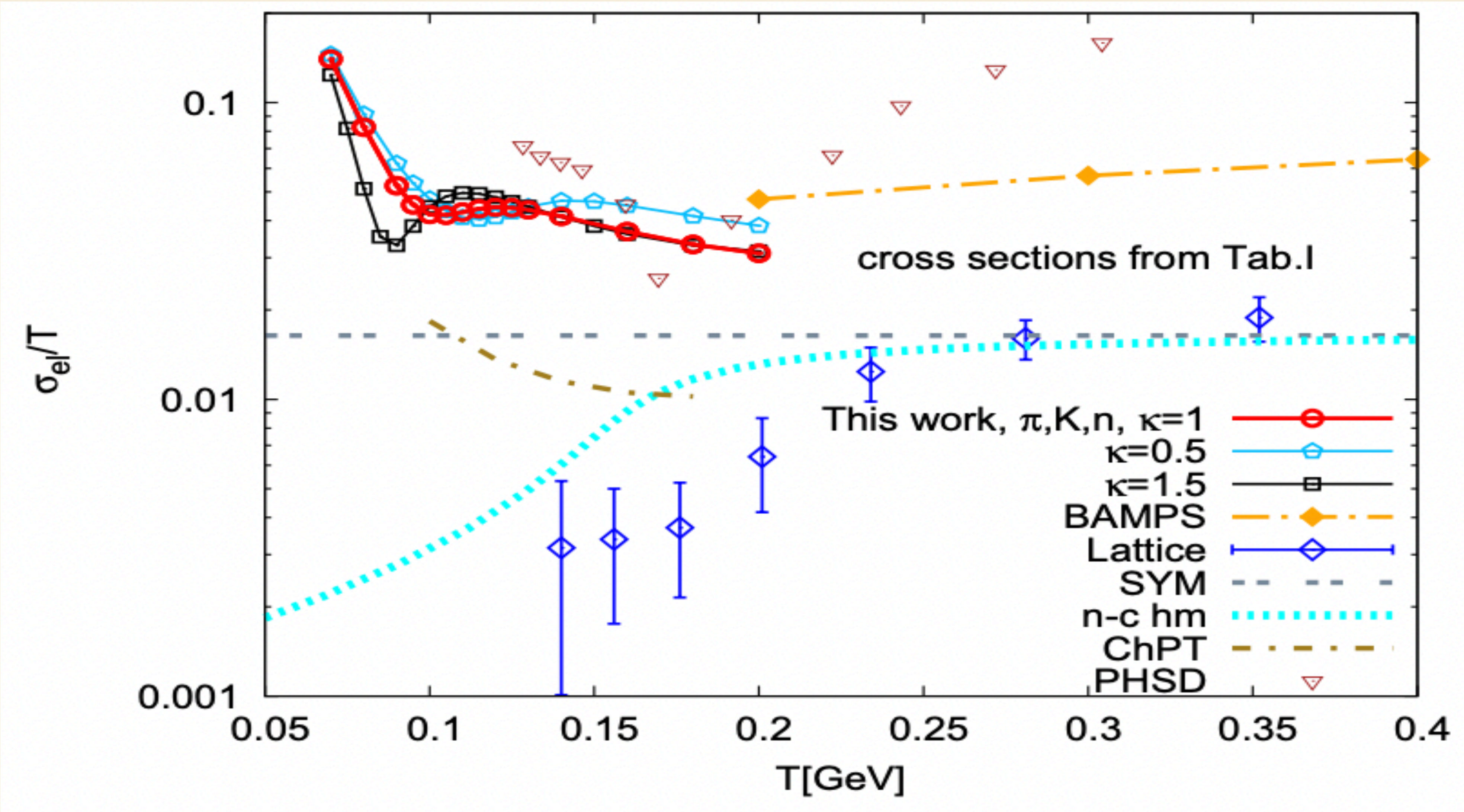
Poster id:186, Chenliang Jin

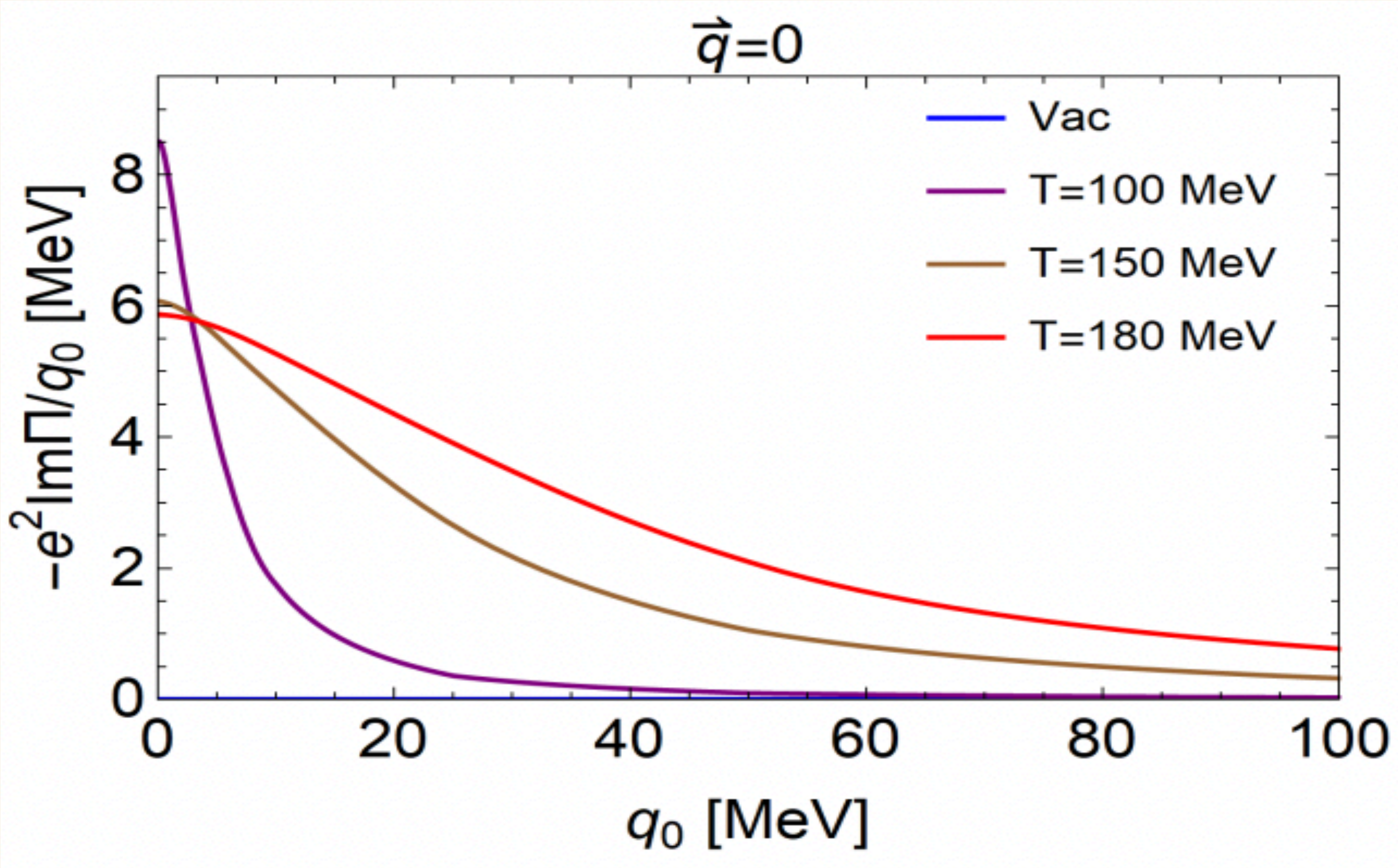
Reducing photonic conversion background from material

- Neural Network approach
- Expect to reduce > 30% statistical uncertainty
- Relevant for STAR further BES-II, FXT dielectron analysis
  - BES-II COL 11.5, 9.2 GeV
  - BES-II FXT 3-7.2 GeV

STAR BES Dielectron Measurement: Future

M. Greif, etc. Phys. Rev. D 93, 096012 (2016)





J. Atchison and R. Rapp, Nucl. Phys. A 1037, 122704 (2023).

Electrical conductivity: Moore & Robert arXiv:hep-ph/0607172

$$\sigma_{el} = \frac{\langle eJ_i \rangle}{E_i} = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} Im[\Pi_{EM}(q_0, q=0, T)]$$

At low energy limit, EM spectral function is related to electrical conductivity

- Lower p_T threshold (from 135 MeV/c to 60 MeV/c) by STAR iTPC upgrade
- An opportunity to probe the EM spectral function low mass peak
- Potential extraction of the conductivity

Conclusion/Outlook

STAR BES dielectron measurement:

BES-I:

- Excess yield is well described by theoretical models considering in-medium ρ + QGP emissions
- $< T >$ and ρ_B are approximately constant

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New BES-II: $\sqrt{s_{NN}}$ = 7.7 ,14.6, 19.6 GeV

- High precision measurement at $\sqrt{s_{NN}}$ = 19.6 GeV
- Excess yield spectra in different environments (lower $< T >$ and higher ρ_B)
- Hints the decreasing trend in normalized integrated excess yield for Au+Au collisions as the $\sqrt{s_{NN}}$ decreases.

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Outlook:

- Efforts for reducing photonic conversion background
- An opportunity arises for electrical conductivity analysis

Backup

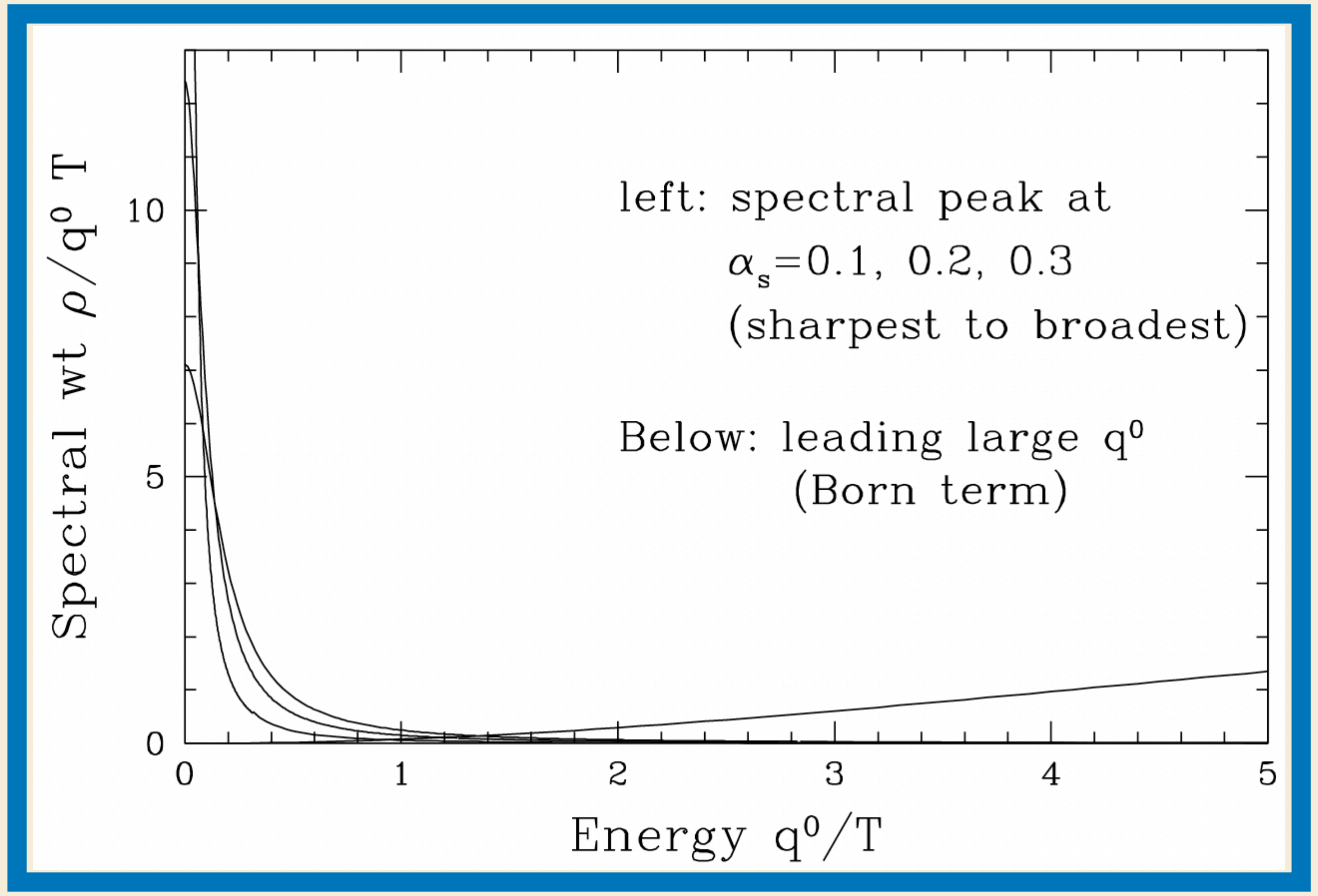
Dilepton Production

- Thermal radiation
  - Dilepton emission rate
  - EM spectral function
    - $M_{ee} > 1.5 GeV/c^2$
      - Partonic Distribution. $j^{\mu}_{EM} = \sum_{q=u,d,s} e_q \bar{q} \gamma^{\mu} q$
    - $M_{ee} < 1 GeV/c^2$
      - Vector Meson dominance Model (VDM)

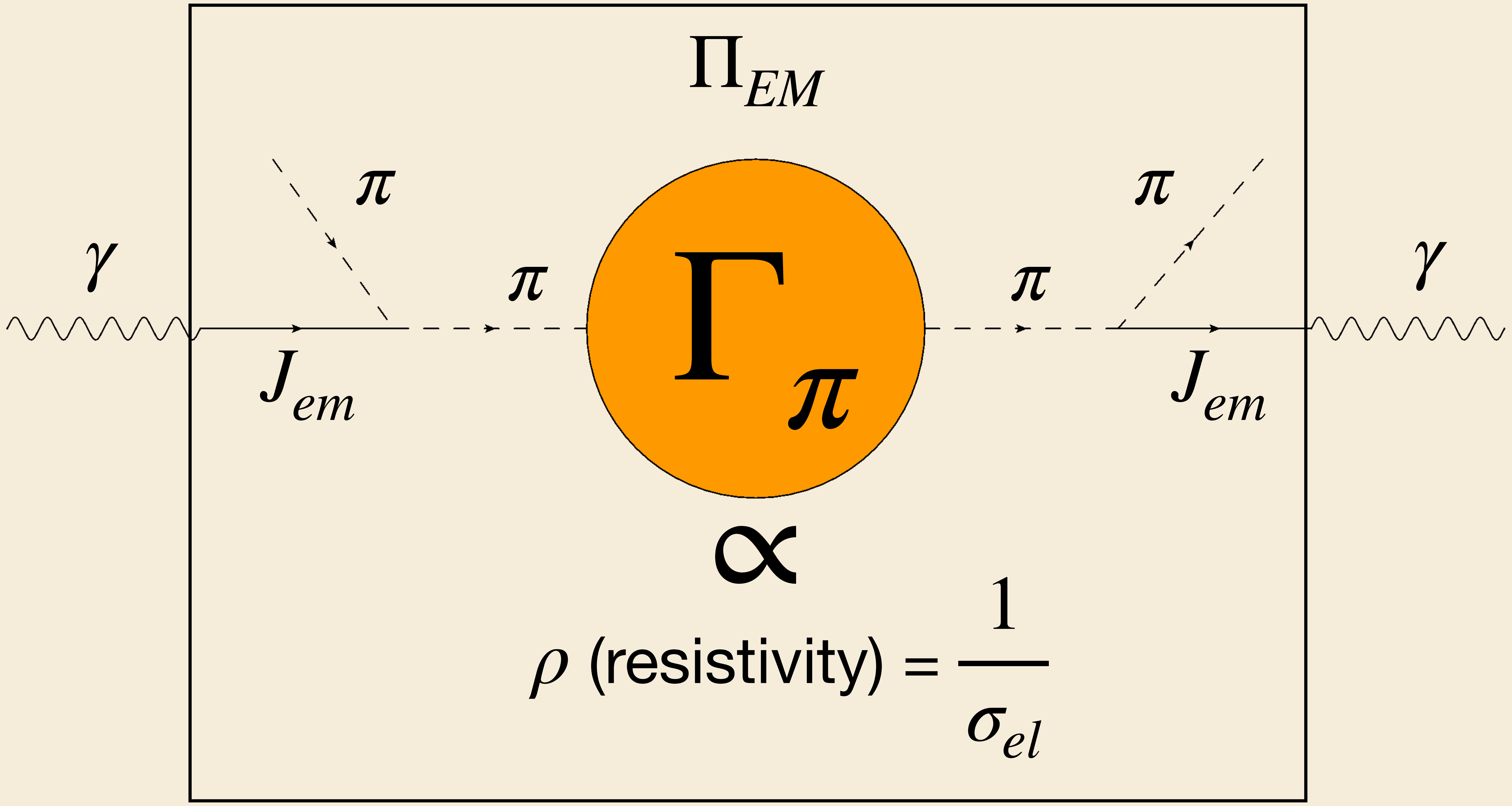
$$j^{\mu}_{EM} = \frac{1}{2}(\bar{u}\gamma^{\mu}u - \bar{d}\gamma^{\mu}d) + \frac{1}{6}(\bar{u}\gamma^{\mu}u + \bar{d}\gamma^{\mu}d) + \frac{1}{3}\bar{s}\gamma^{\mu}s$$

      - $\text{Im}\Pi_{EM} \sim [\text{Im}D_{\rho} + \frac{1}{9}\text{Im}D_{\omega} + \frac{2}{9}\text{Im}D_{\phi}]$
      - $D_{\rho,\omega,\phi}$: Vector-meson propagators

New Opportunity: Electrical Conductivity of the Medium

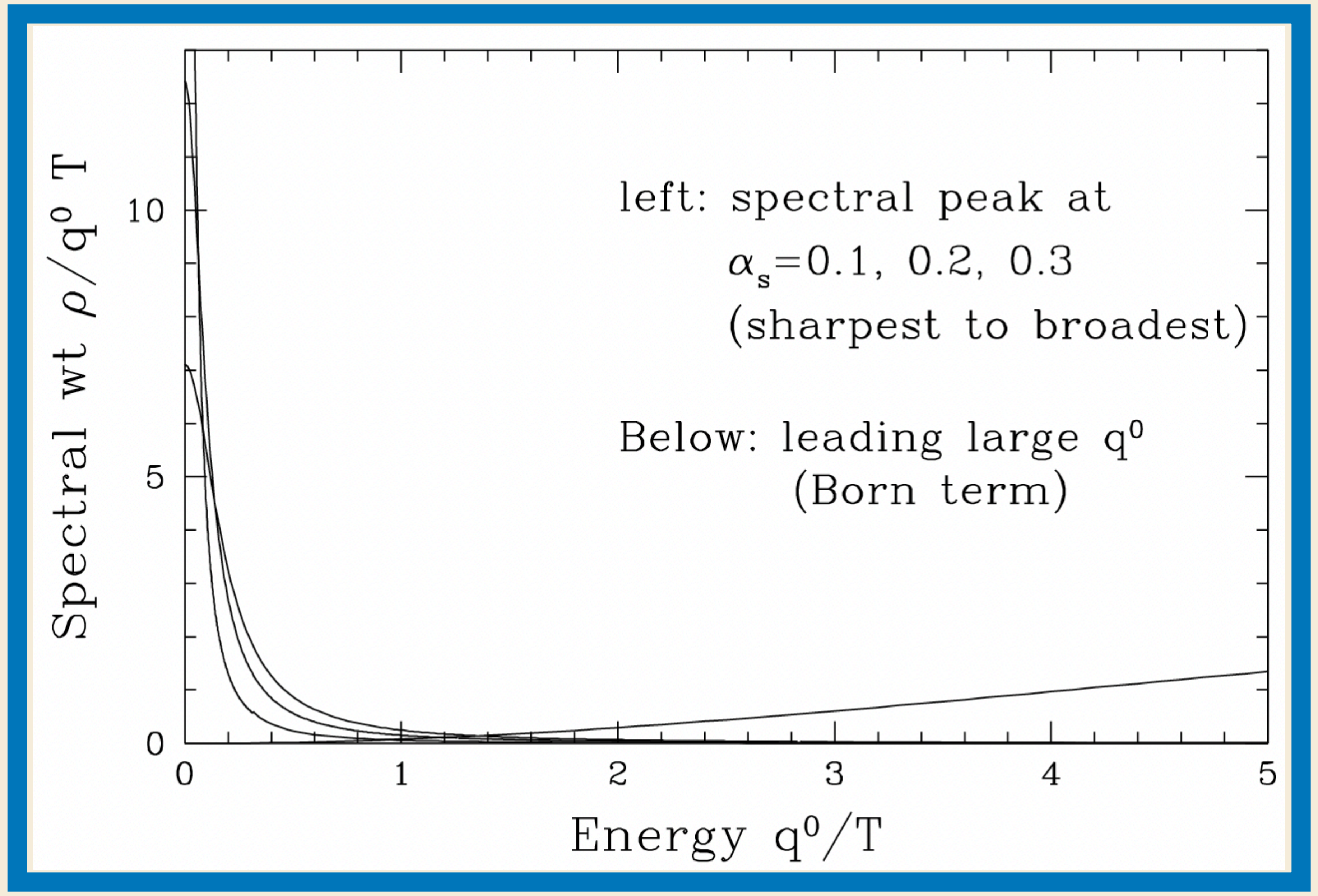


Moore & Robert arXiv:hep-ph/0607172



- Electrical conductivity: $\sigma_{el} = \frac{\langle eJ_i \rangle}{E_i} = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} Im[\Pi_{EM}(q_0, q = 0, T)]$
- Dilepton emission rate: $\frac{dR_{l^+l^-}}{d^4q} = \frac{-\alpha_{EM}^2}{3\pi^3 M^2} f_B(q_0, T) g_{\mu\nu} Im[\Pi_{EM}^{\mu\nu}(M, q, T, \mu_B)]$
- The above connection brings up an opportunity to measure the electrical conductivity through dielectron mass spectrum. **As the resistivity increases, the transport peak melts, and dielectron spectrum extends to higher mass.**

New Opportunity: Electrical Conductivity of the Medium



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Better chance to extract electrical conductivity at lower energy

⇒Detectors with lower p_T cut off limitation will benefit this measurement

- Electrical conductivity: $\sigma_{el} = \frac{\langle eJ_i \rangle}{E_i} = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} Im[\Pi_{EM}(q_0, q = 0, T)]$
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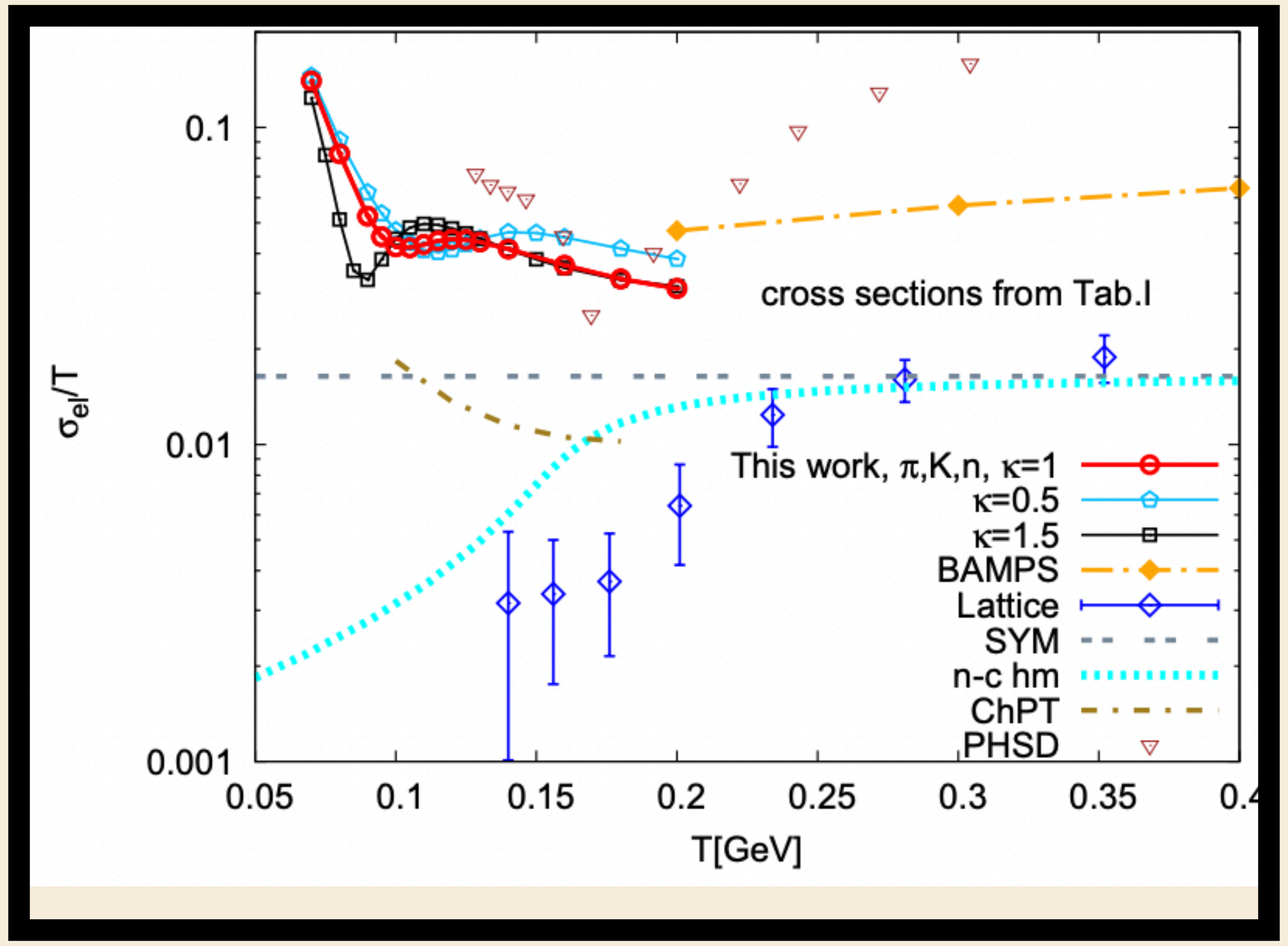

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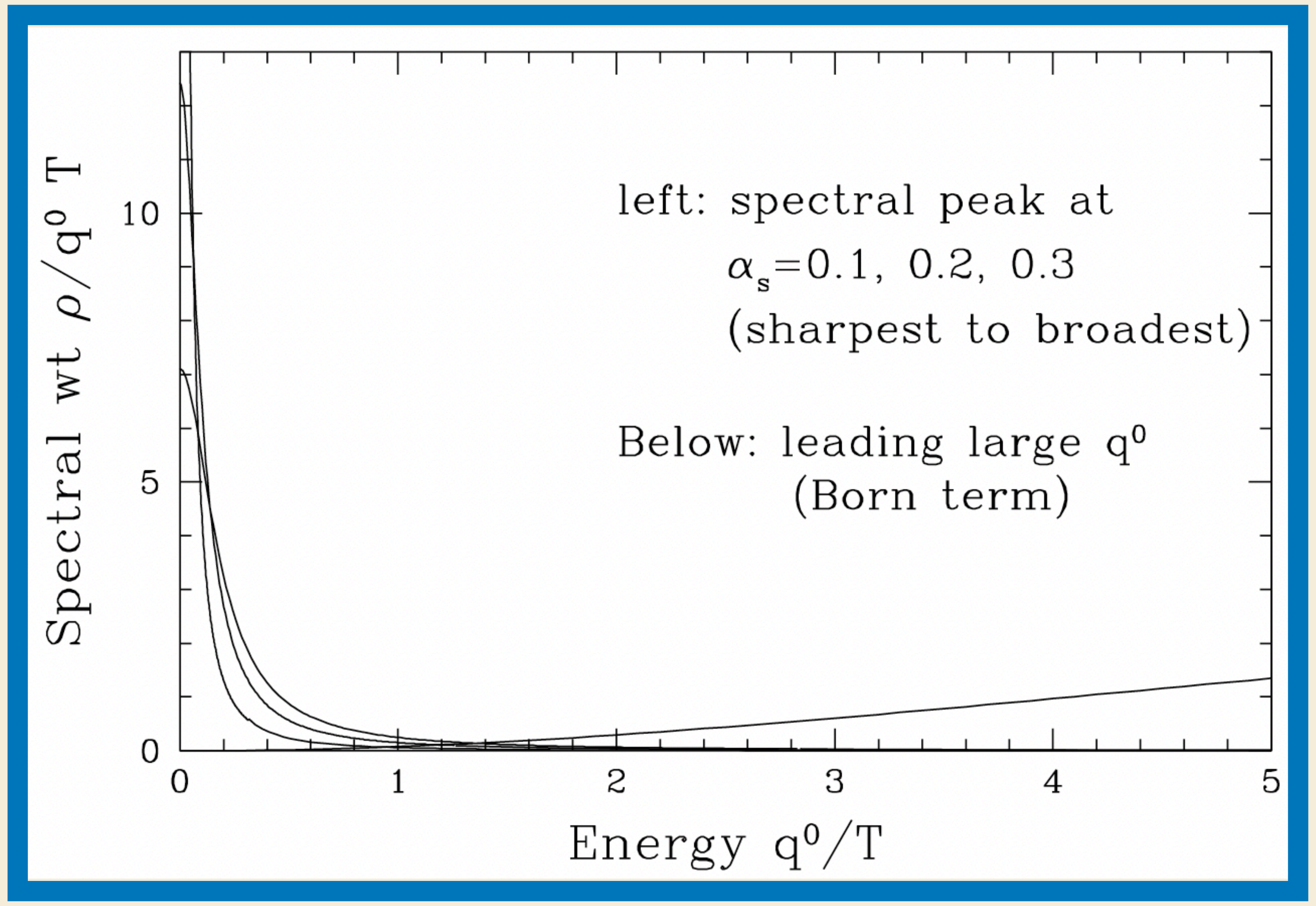

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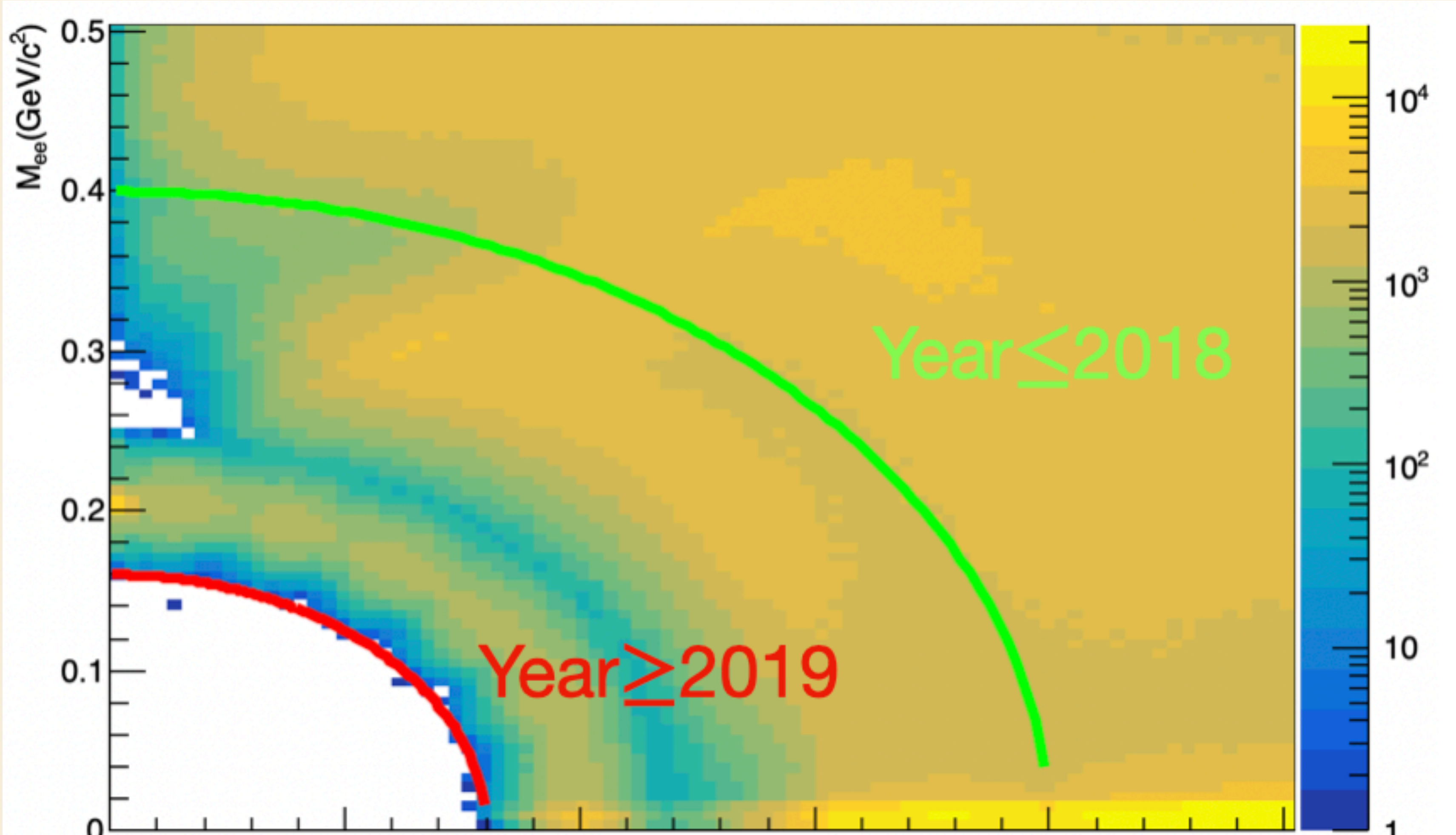
STAR Acceptance



- Extend p_T^{ee} vs M_{ee} acceptance with iTPC upgrade
  - **Lower $(M_{ee}\ ,\ p_T^{ee})$ limitation after iTPC upgrade**