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RICE

Dilepton Physics in BES

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Rice University

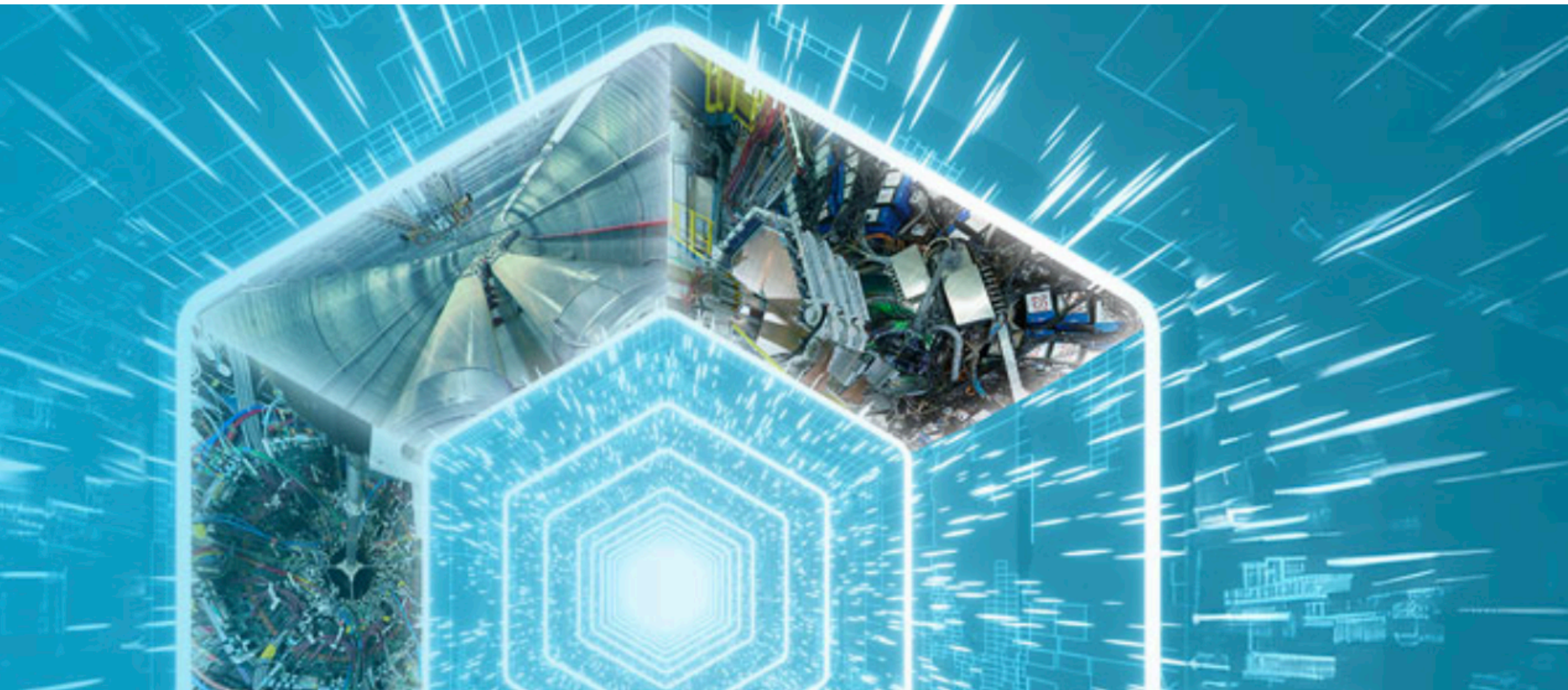
2024 RHIC/AGS ANNUAL USERS' MEETING

A New Era of Discovery

Guided by the New Long Range Plan for Nuclear Science

June 11–14, 2024

Brookhaven National Laboratory



Outline

- QCD Matter Phase Diagram
- Dileptons as probe with theoretical consideration
- Experimental challenge
- Dilepton in BES
  - Spectrometer, Thermometer, Chronometer
- Dilepton physics in the future

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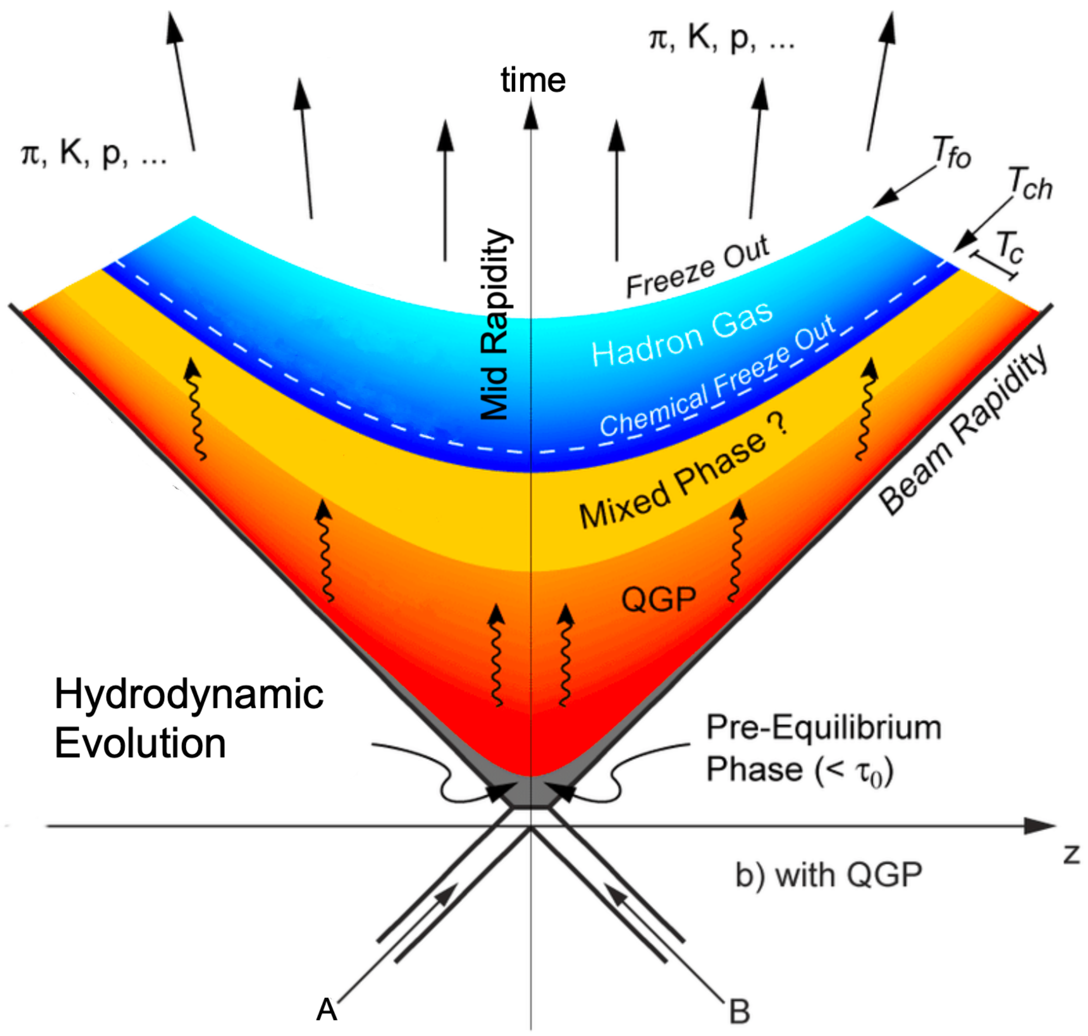
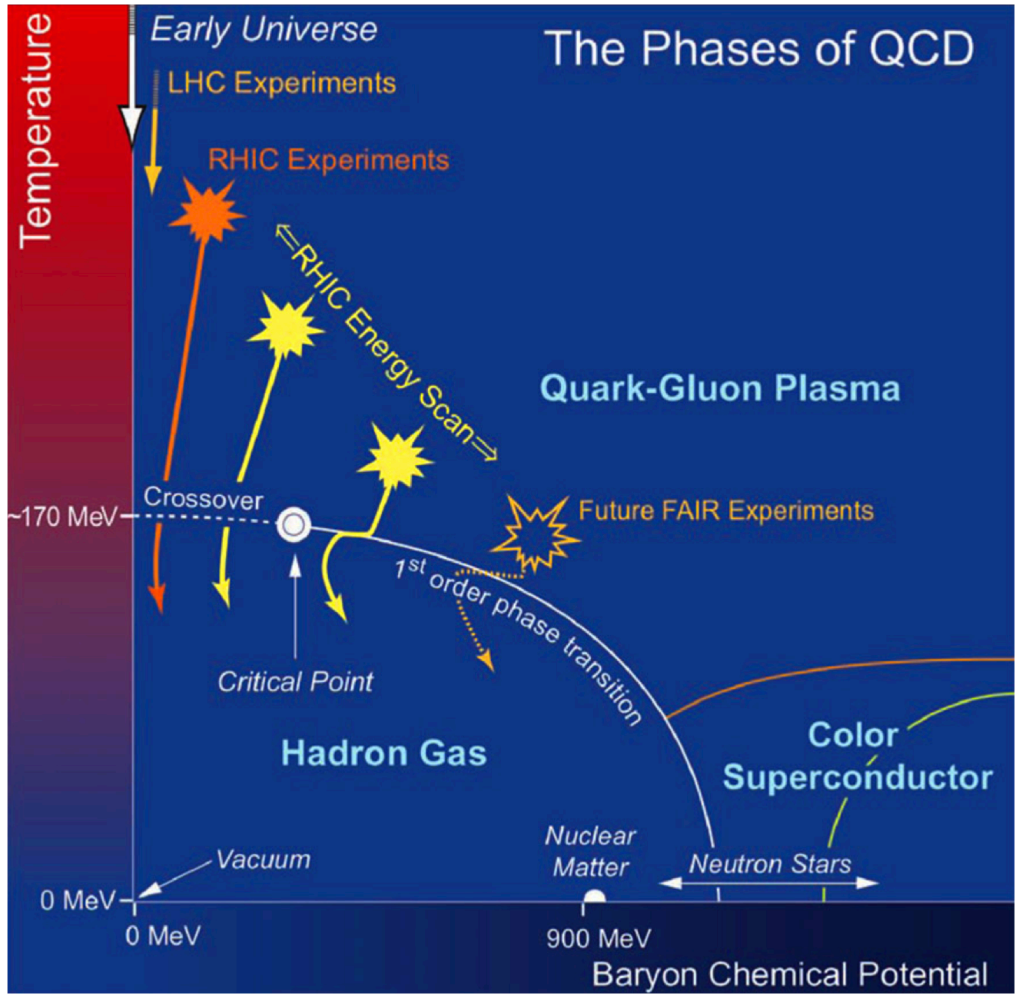
QCD Phase Diagram

- Quark-Gluon Plasma (QGP) phase
  - Deconfined quark and gluon
  - Local thermal equilibrium
- Hadronization: Phase transition to the Hadron Gas phase
- First-order phase transition and Crossover
- Critical point
  - divergence of the correlation length: non-monotonic behavior of higher moments of conserved quantities

Relativistic Heavy-Ion Collision Evolution

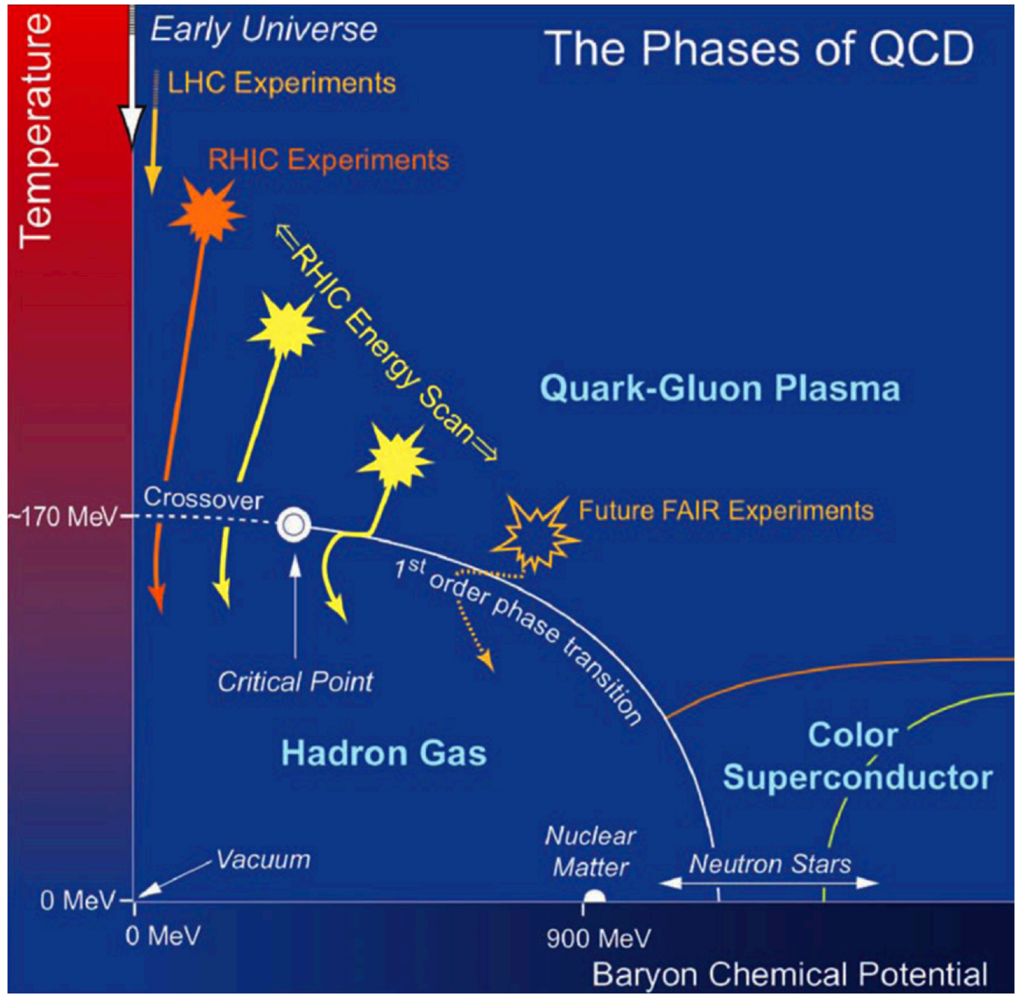




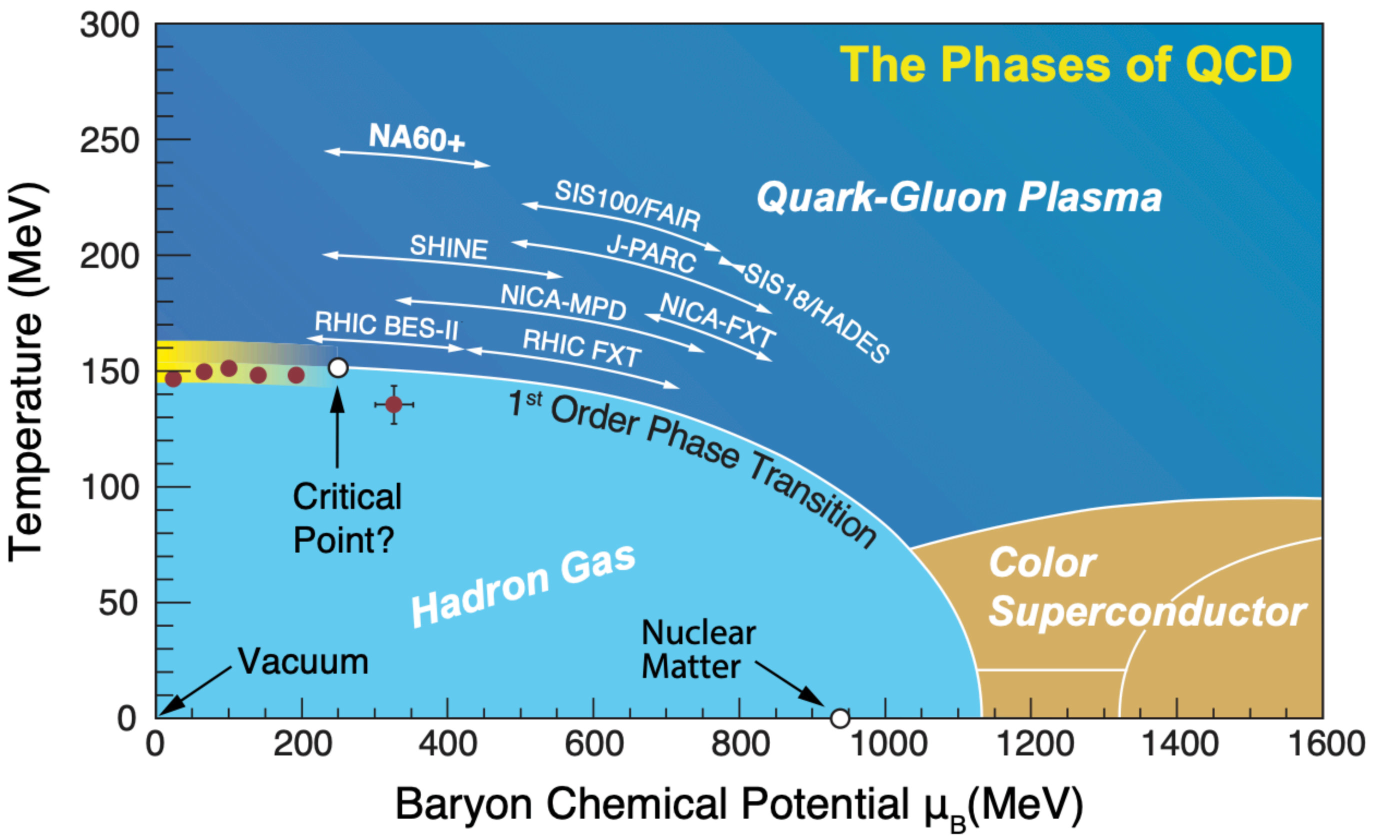
STAR Collaboration, Studying the Phase Diagram of QCD Matter at RHIC, 2014

Charting QCD Phase Diagram

- Experimentally, one can access different regions of phase diagram by varying centre-of-mass energy.
  - Current experiment data already cover around 4 orders of magnitude.
- Low μ_B region: LHC, RHIC, FAIR
- Higher μ_B region: large discovery potential with possible 1st order PT and a conjectured CP.
  - HADES, RHIC beam energy scan (BES)
  - CBM, NA60+ in the future



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



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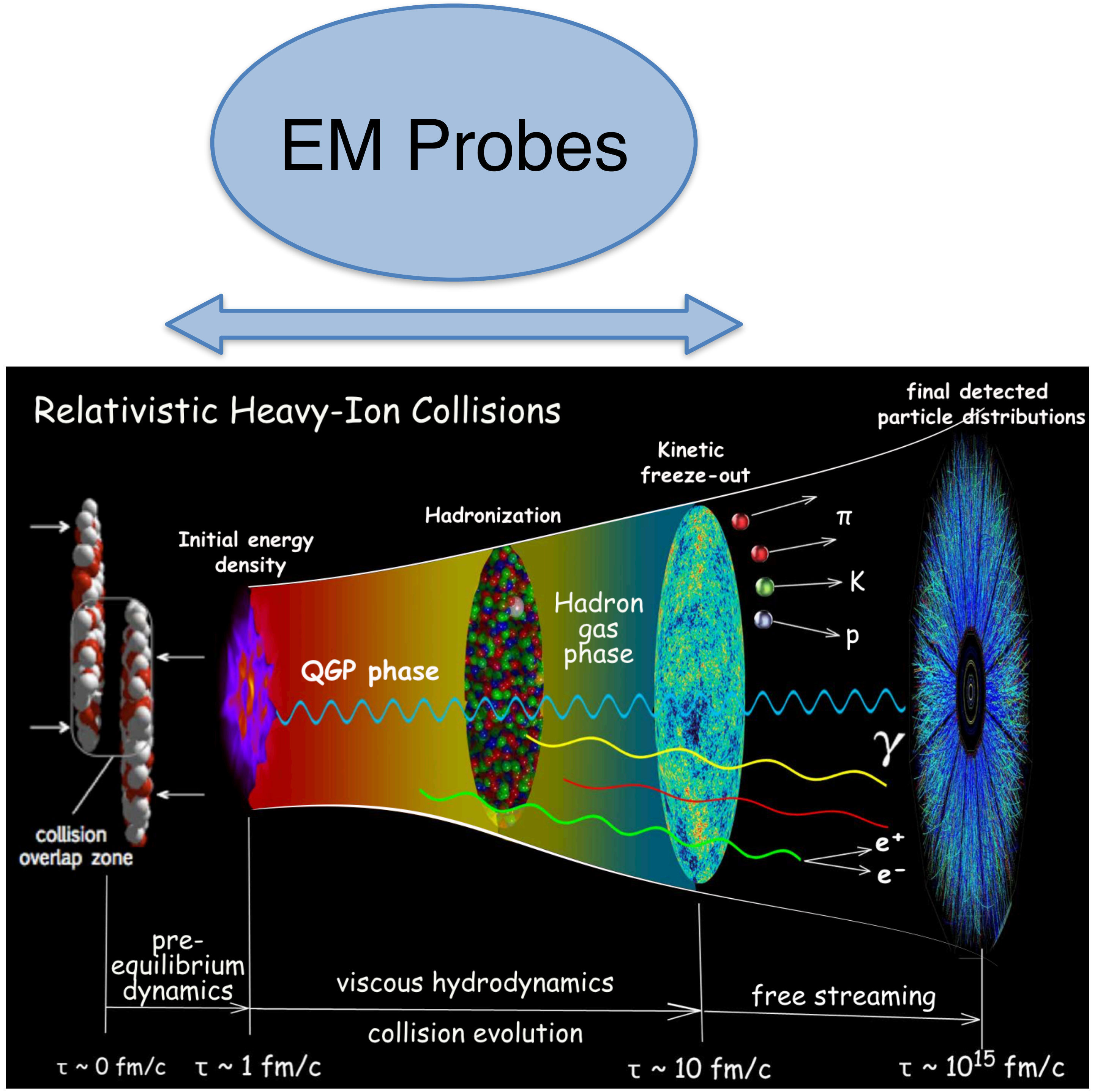
Why Dileptons?

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

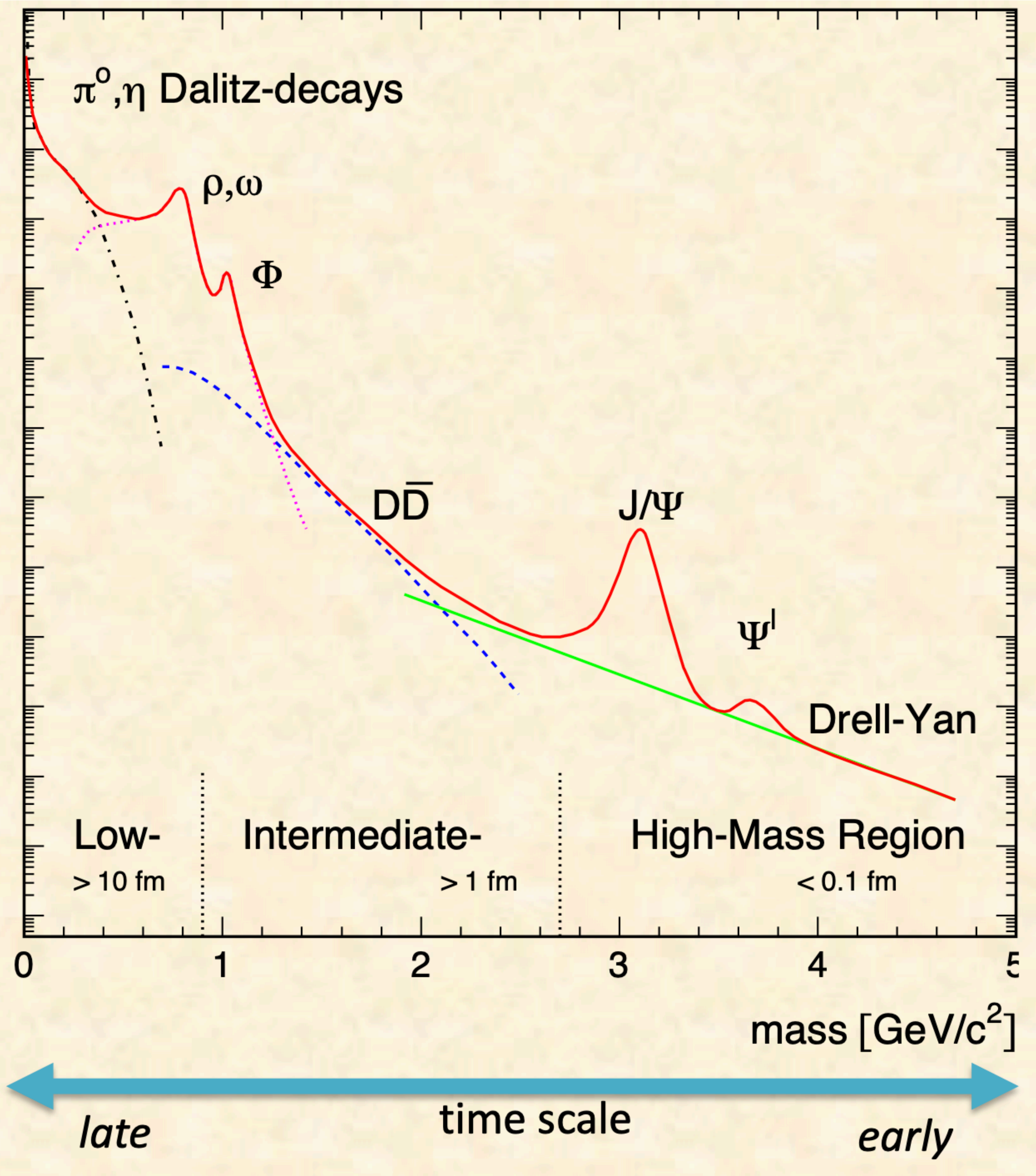
- Dileptons vs. direct photon:
  - Encode additional information: invariant mass.
  - No blue-shift effect.



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

Dilepton invariant mass spectrum

- High Mass Range (HMR: $M_{ee} > 3$ GeV/c^2)
  - Primordial emission (Drell-Yan): $NN \rightarrow e^+e^-X$
  - Heavy quarkonia: J/ψ and ϒ.
- Intermediate Mass Range (IMR: $1 < M_{ee} < 3$ GeV/c^2)
  - QGP thermal radiation: $q\bar{q} \rightarrow e^+e^-$
  - Semi-leptonic decay of correlated charm: $c\bar{c} \rightarrow e^+e^-$
- Low Mass Range (LMR: $M_{ee} < 1$ GeV/c^2)
  - In-medium vector mesons.
  - Decay of other light mesons.
  - 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

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

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

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

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

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

$\Theta(x_0)$: 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

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

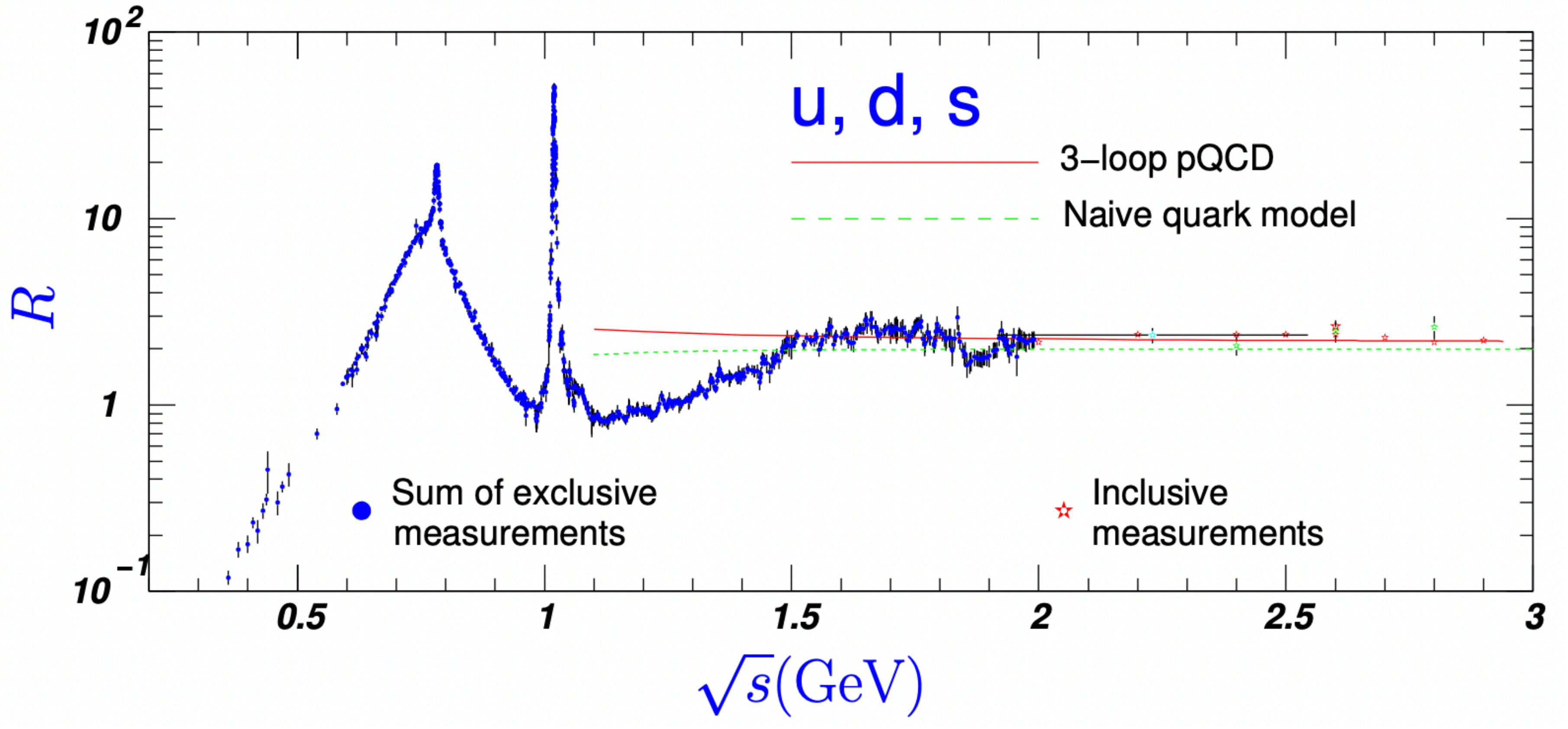
- M_{ee} < 1.1 GeV/c²: Vector Meson dominance (VDM)

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

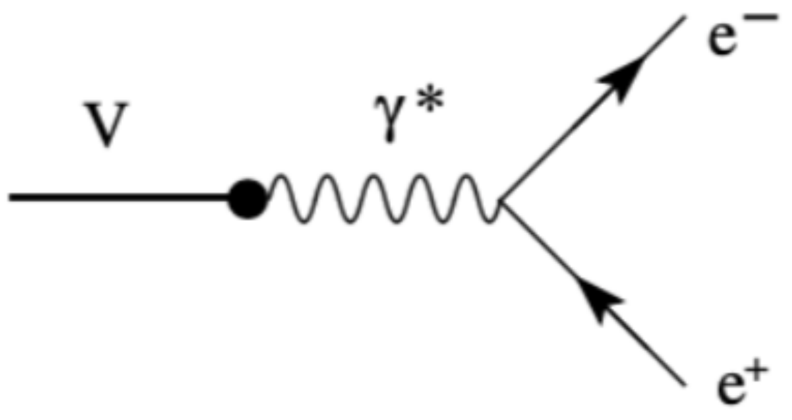
- ρ dominance $\quad \mathrm{Im}\Pi_{EM} \sim [\mathrm{Im}D_{\rho} + \frac{1}{9}\mathrm{Im}D_{\omega} + \frac{2}{9}\mathrm{Im}D_{\phi}]$

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

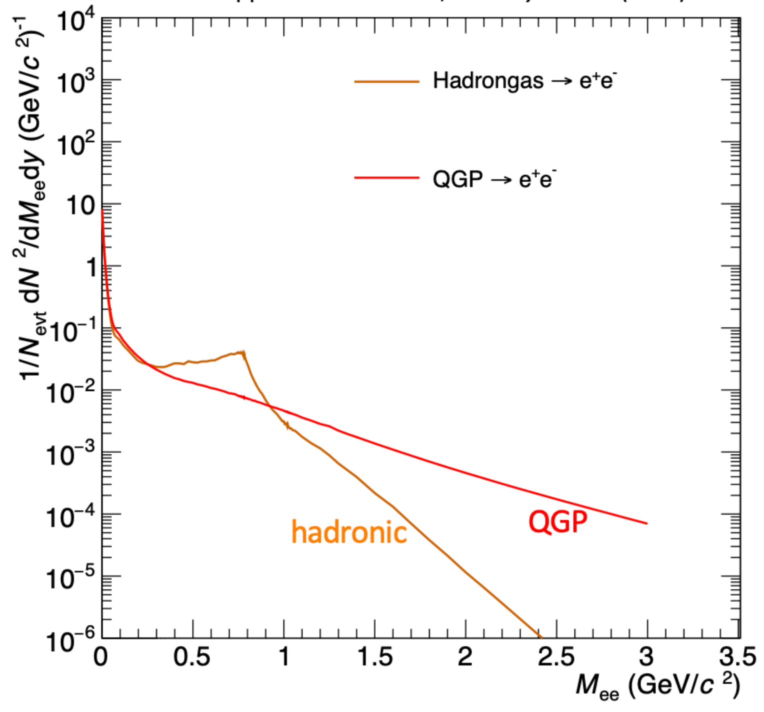
R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)



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



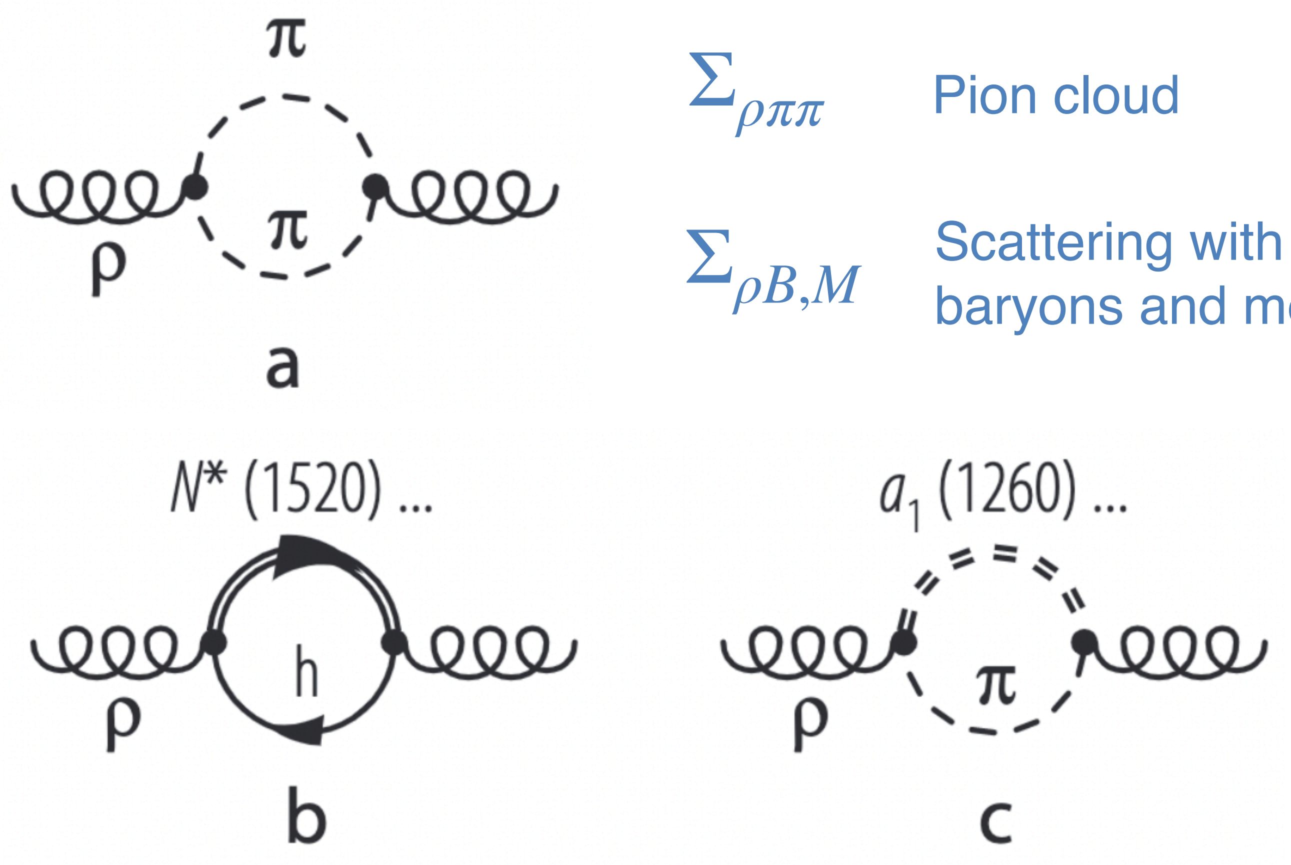
R. Rapp and J. Wambach, *Eur. Phys. J. A* 6 (1999)



In-medium Hardonic many body approach

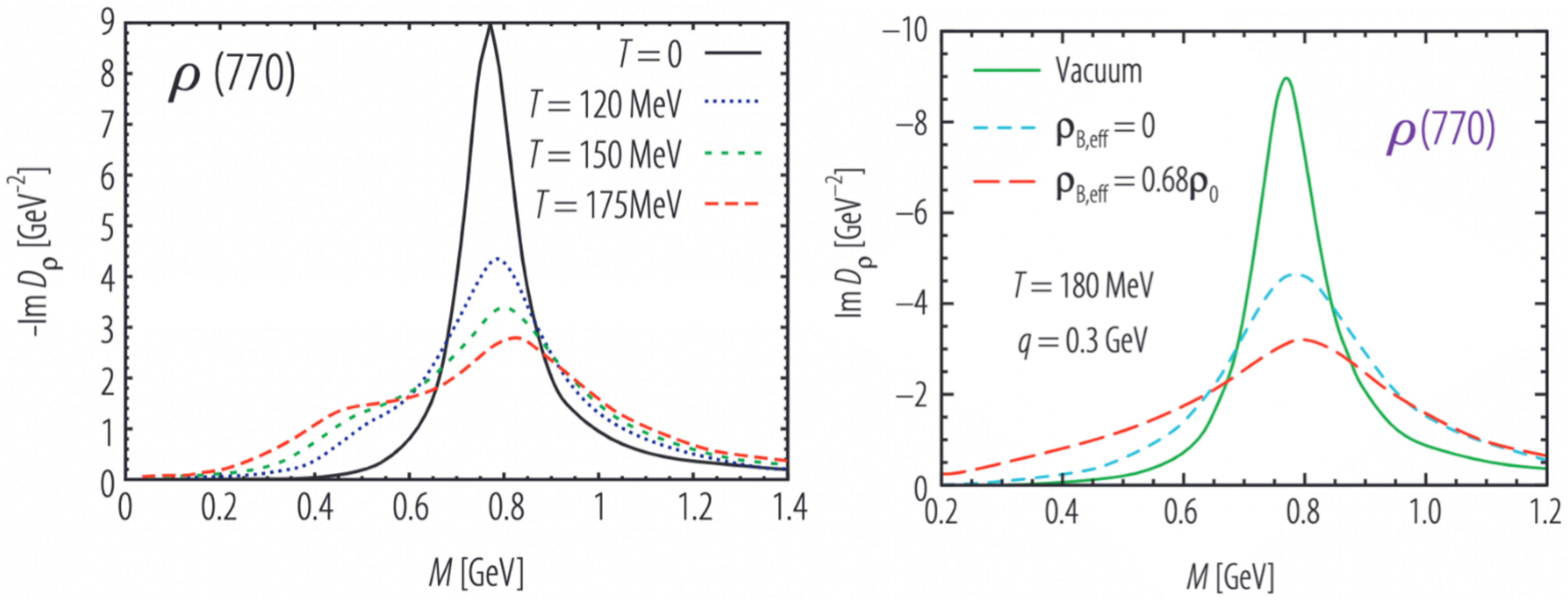
ρ meson propagator in the hot and dense hadronic matter

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



$\Sigma_{\rho\pi\pi}$ 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.

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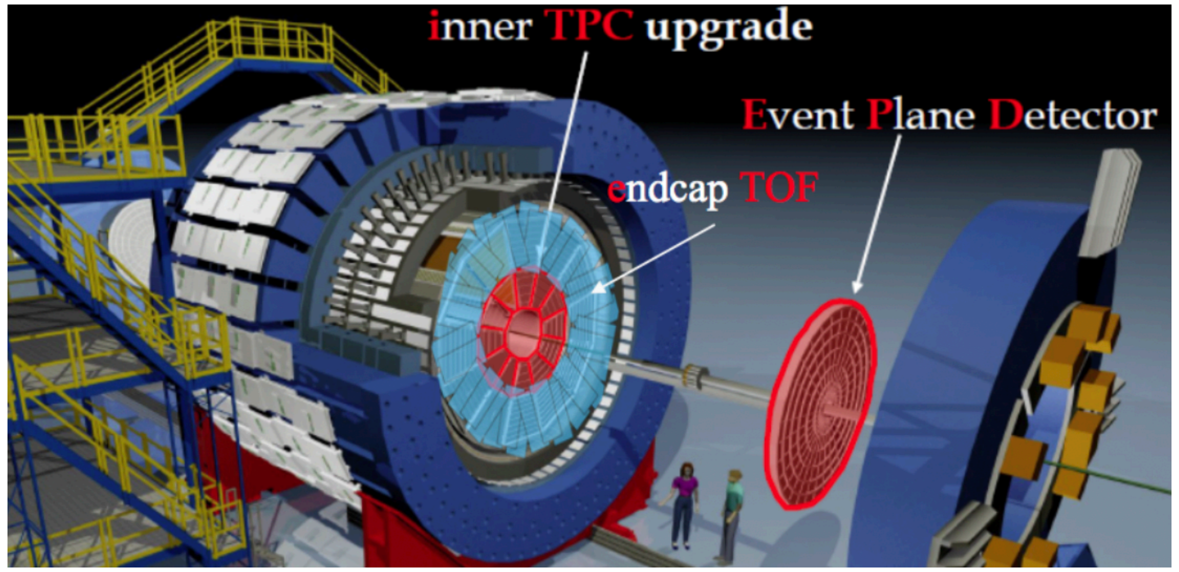
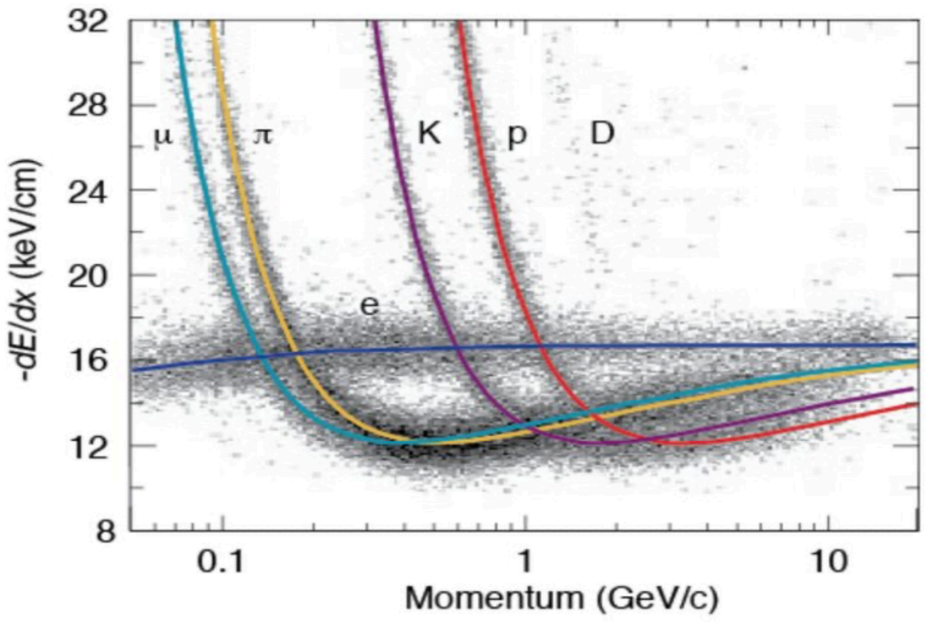
The experimental challenge

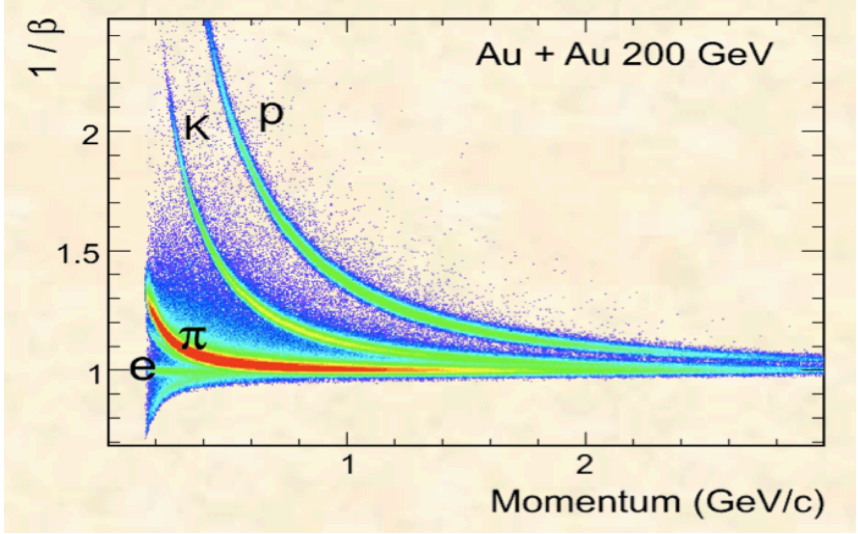
- Dileptons need large acceptance + high purity PID.
- Dilepton emission rate is highly suppressed.
- Physics background for electron:
  - Photon conversion from material or target.
  - Dalitz decay from light mesons.
  - Modification of charm.
- Combinatorial background can overwhelm the physical signal by large factors.
  - Signal/background can be as low as 1%.

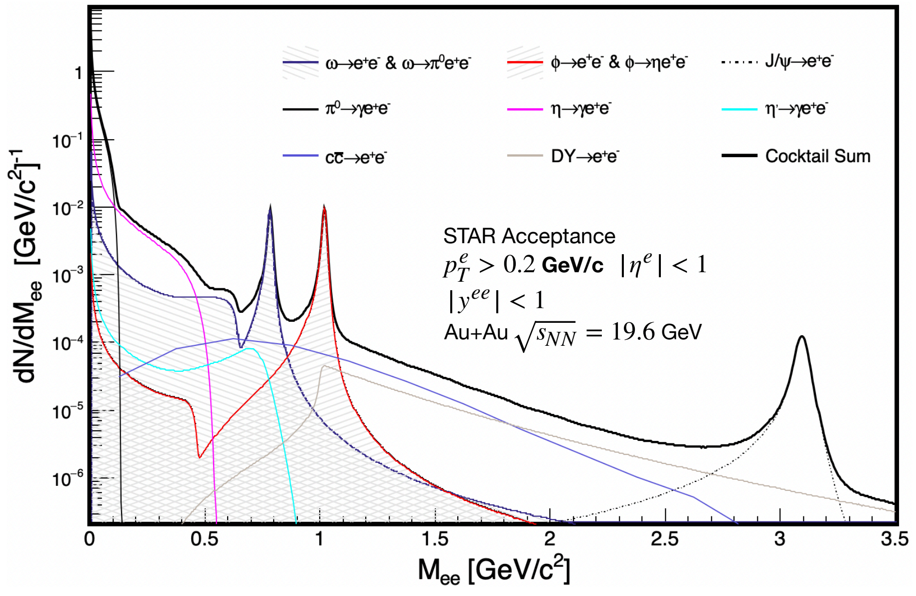
Abed Abud, (2022). A Gaseous Argon-Based Near Detector to Enhance the Physics Capabilities of DUNE.

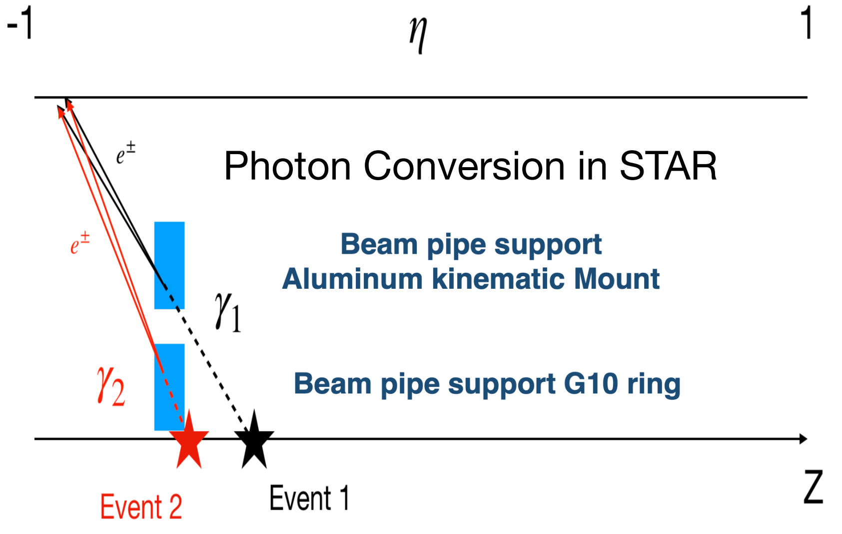


STAR Beam Use Request 2019/2020 (SN696)









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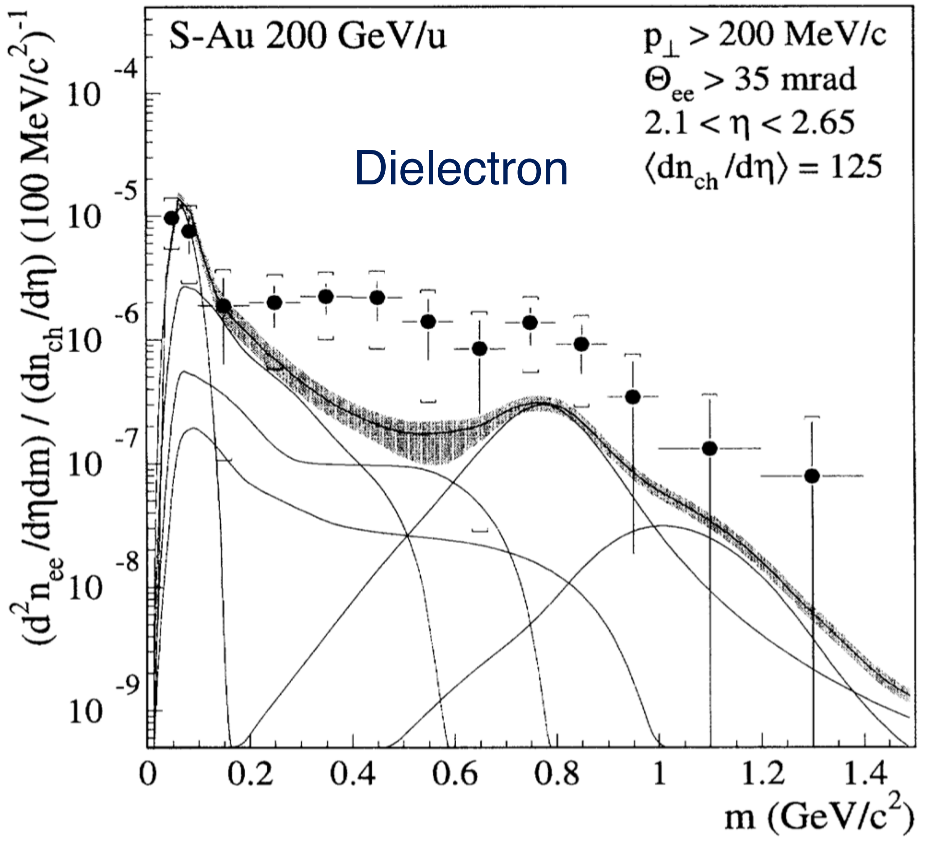
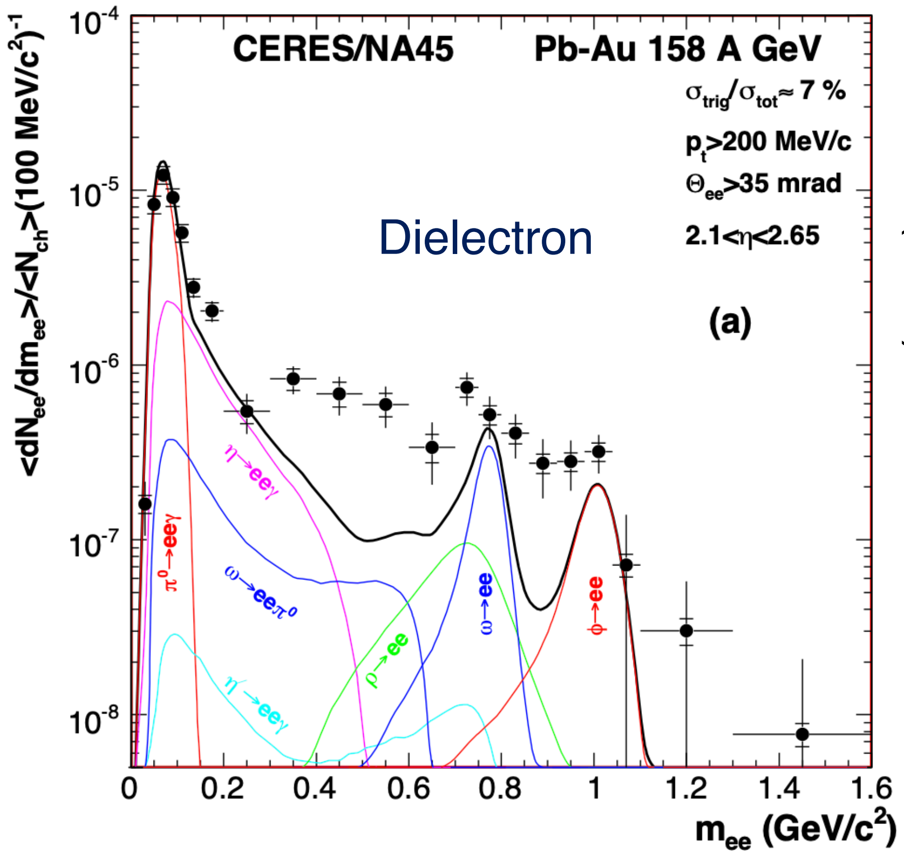
SPS dileptons spectra (CERES and NA60)

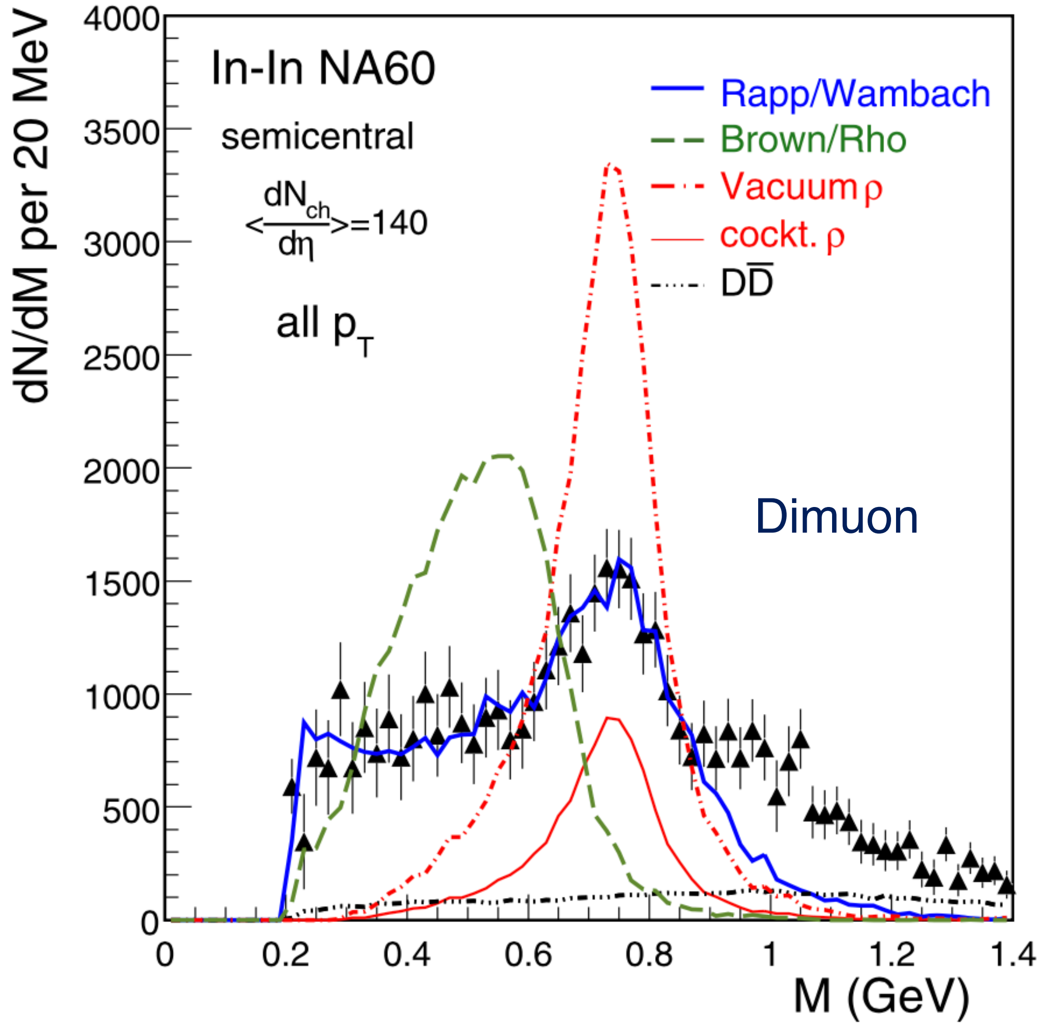
First observation of a significant LMR enhancement – PRL 75 (1995) 1272



PRL 75 (1995) 1272



PLB 666 (2008) 425



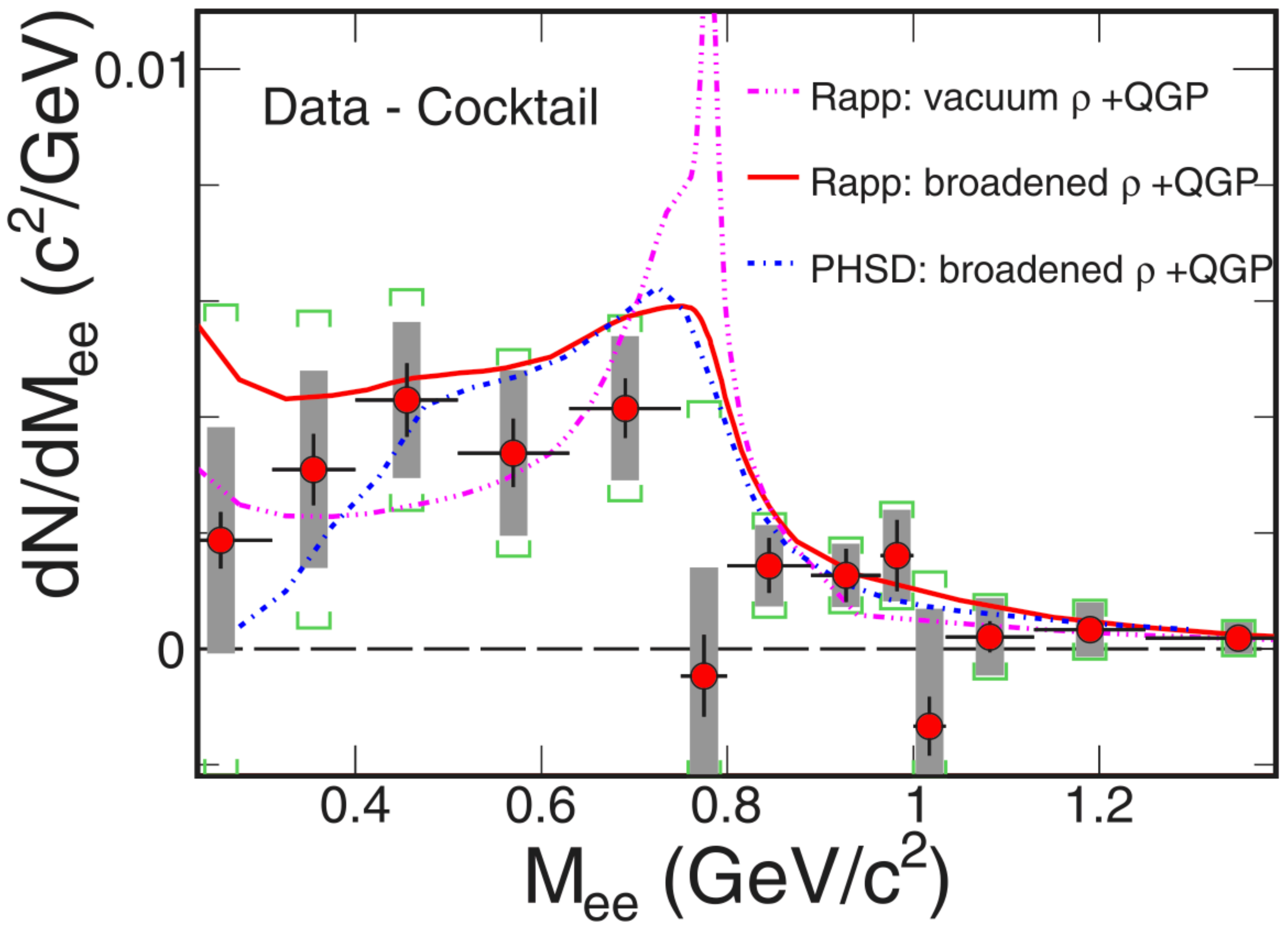
EPJ C61 (2009) 711

- Vacuum ρ can't describe strong enhancement.
- Dropping mass scenario (Brown-Rho):
  - mass expected to scale with q-qbar condensate.
- Broadening of ρ spectral function (Rapp-Wambach).

Rules out dropping mass scenario.
Agreement with width broadening in LMR.

R. Rapp and J. Wambach, Eur. Phys. J. A6 (1999)

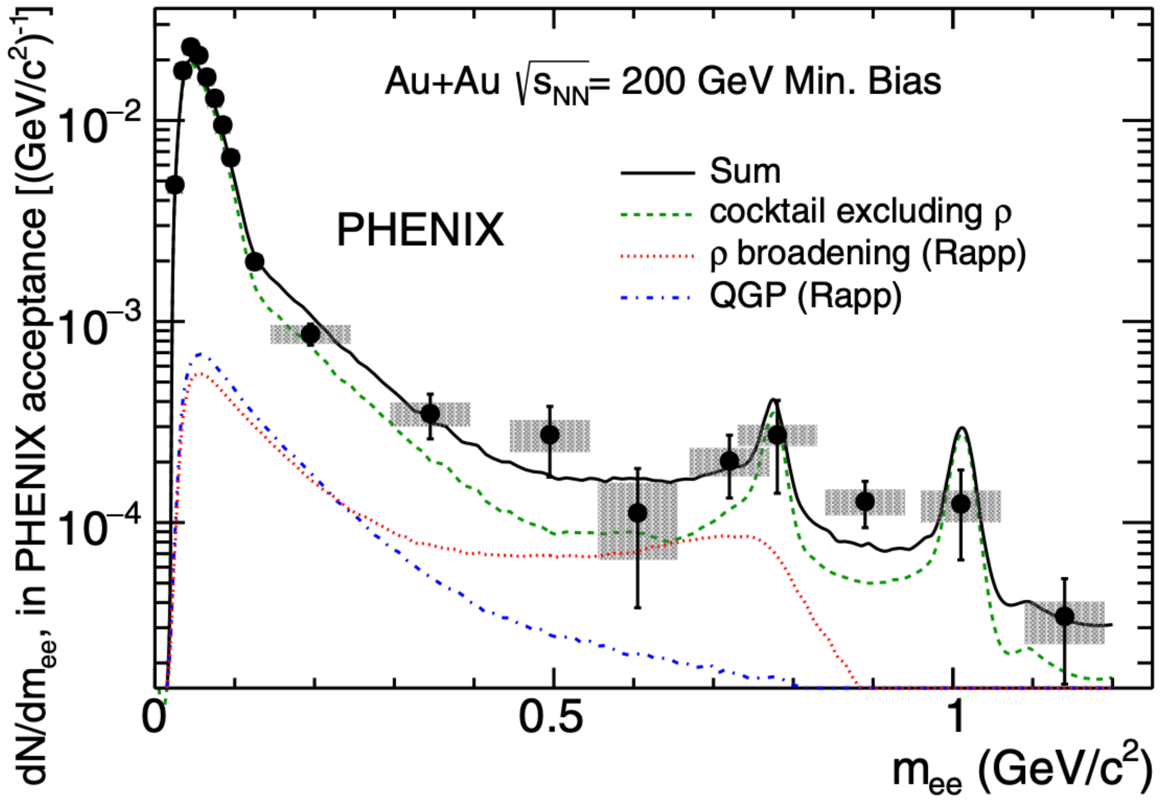
RHIC dielectron spectra at 200GeV (STAR and PHENIX)



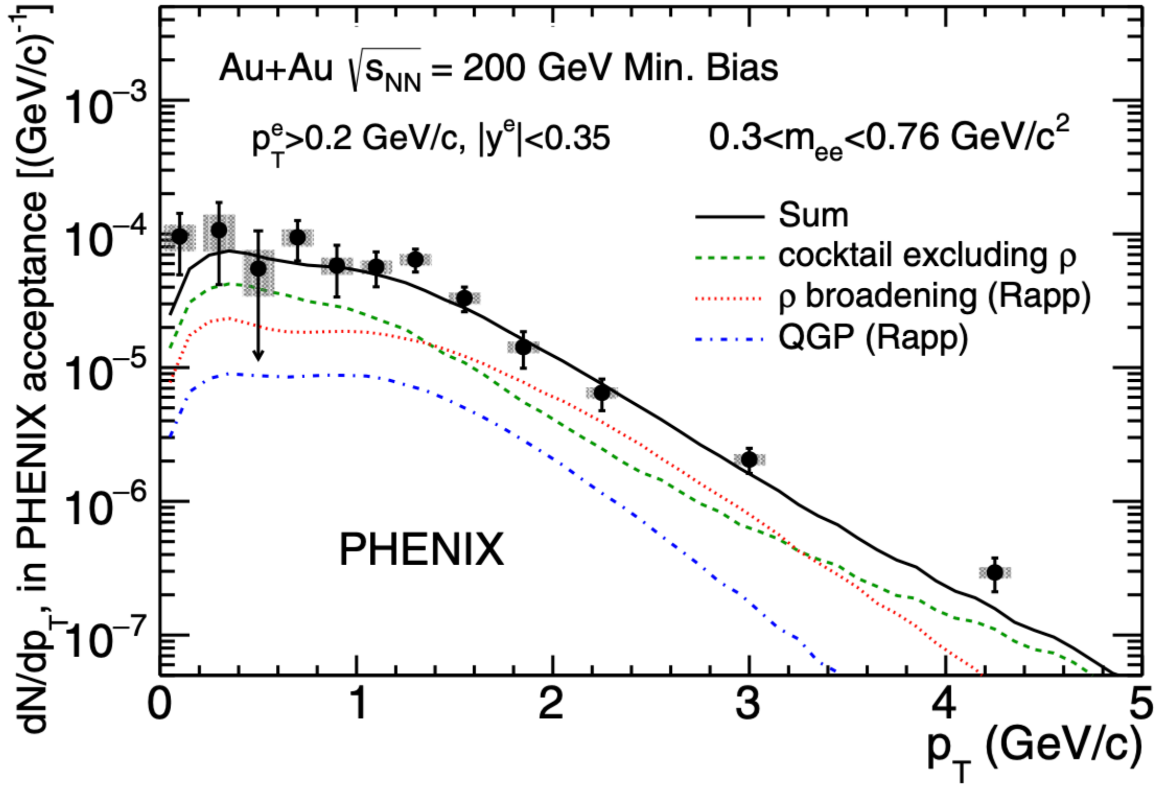
PRC 92 (2015) 024912

R. Rapp,PRC 63 (2001) 054907
O. Linnyk et al., PRC 85 024910 (2012)

higher initial T



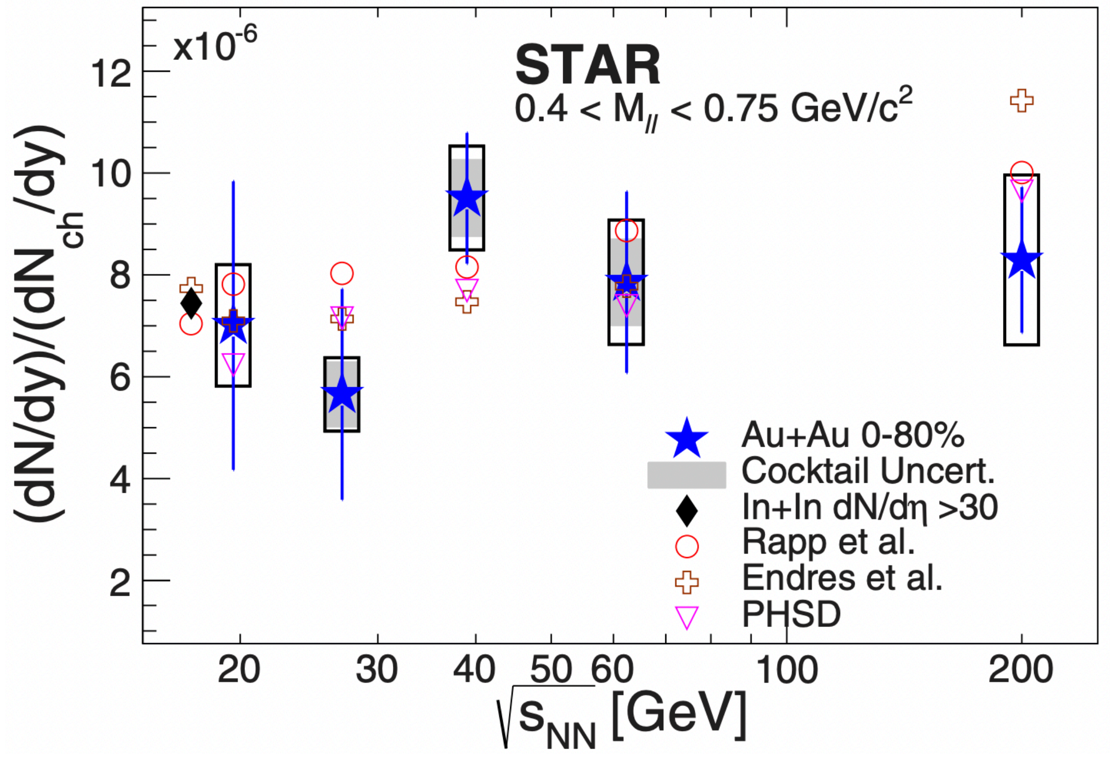
PRC 93 (2016) 014904

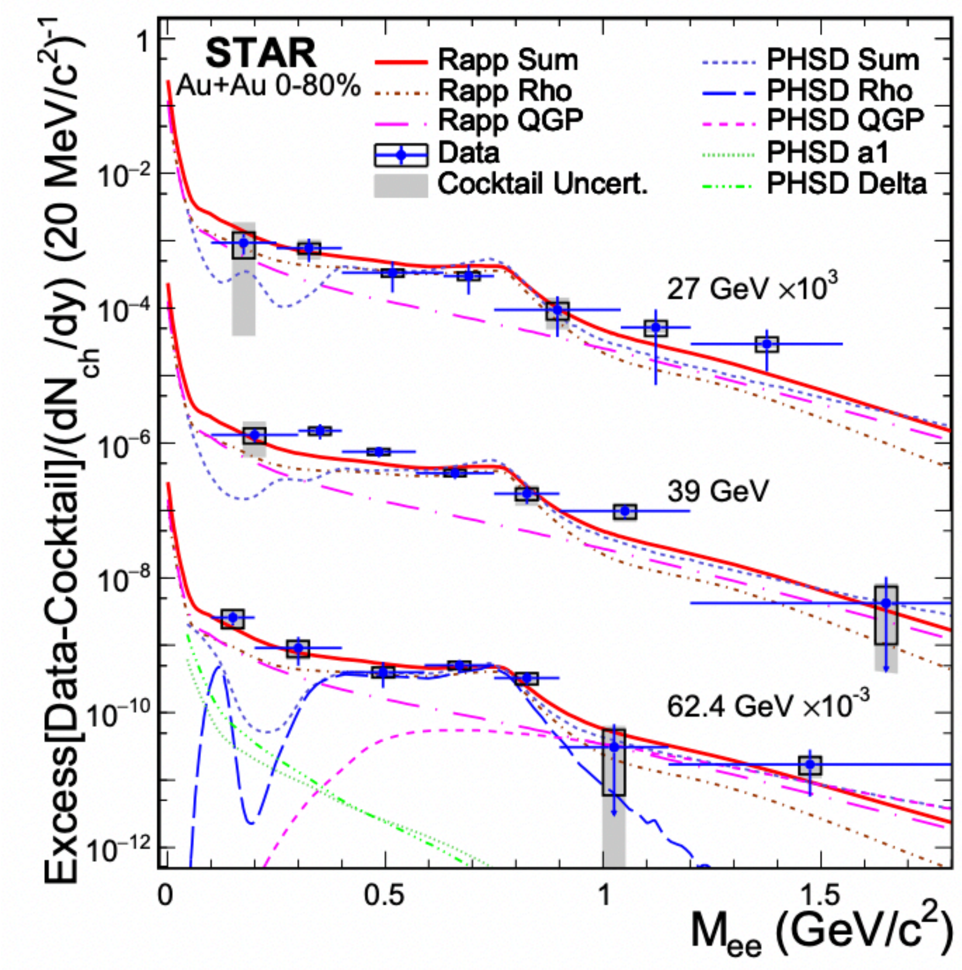


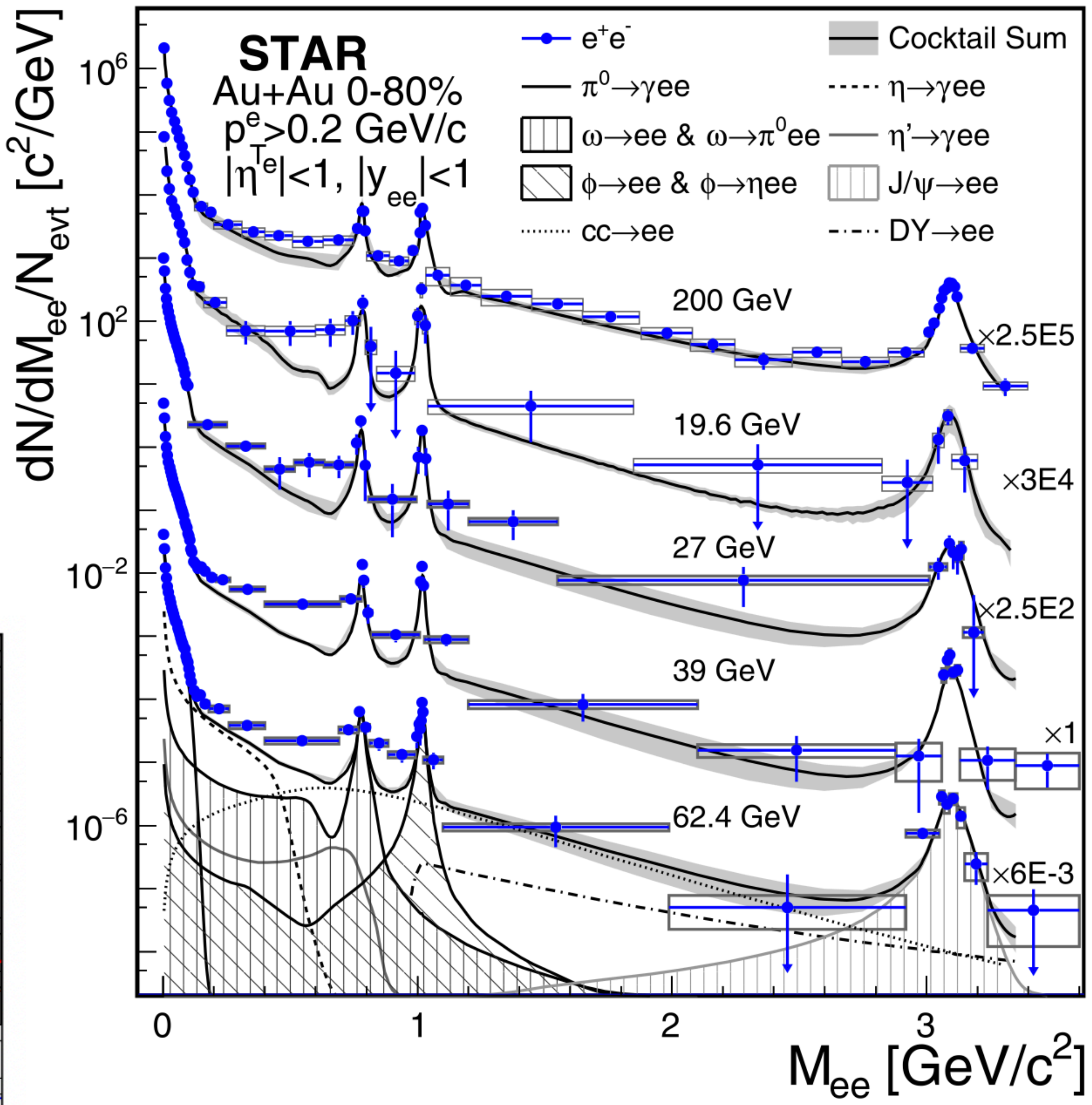
- Data can’t support vacuum ρ.
- Within uncertainties agreement between experiment and theory.

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 in low collision energy.





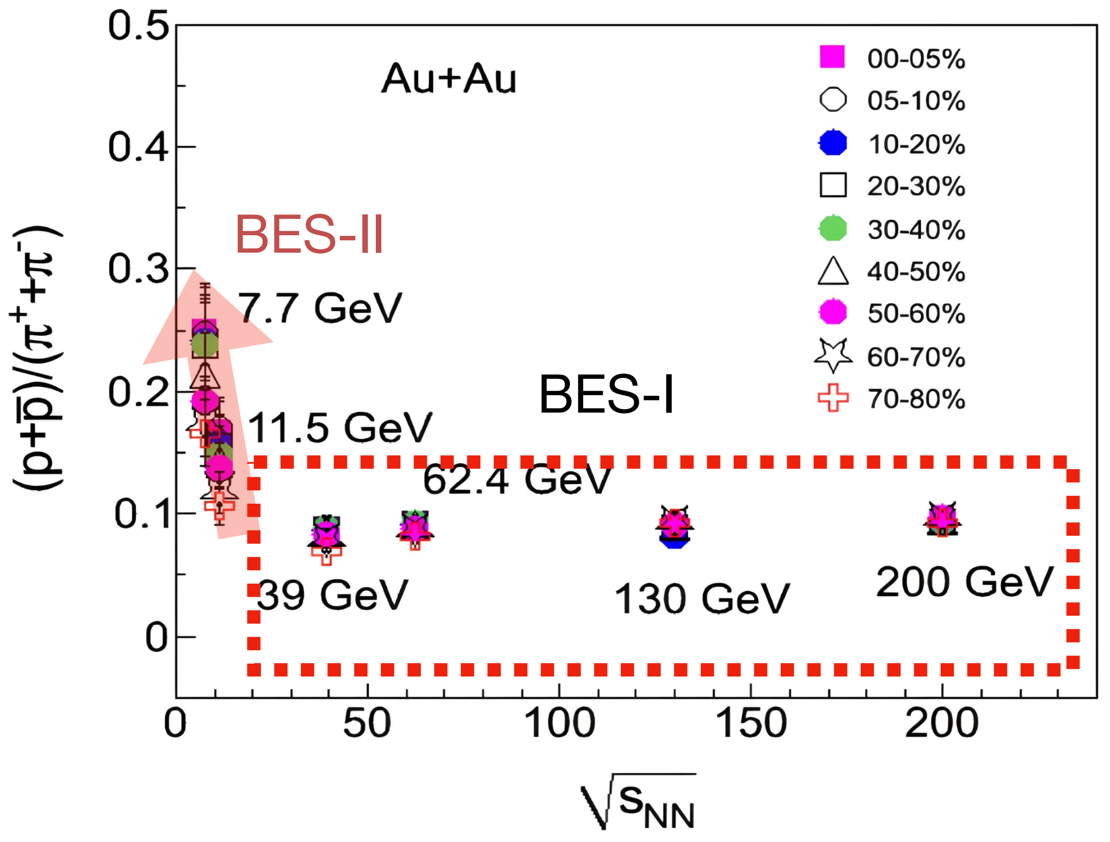


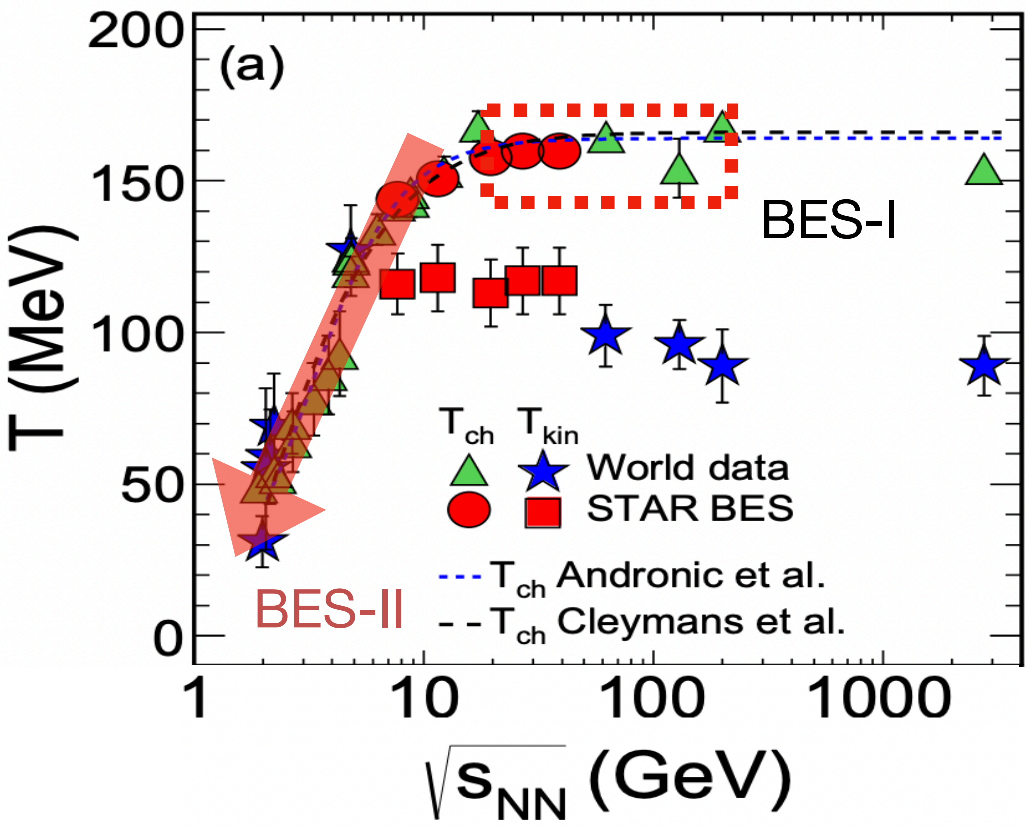
STAR: Phys. Rev. C 107, L061901 (2023)
STAR: PLB750 (2015) 64
STAR: Phys. Rev. C 92, 024912 (2015)

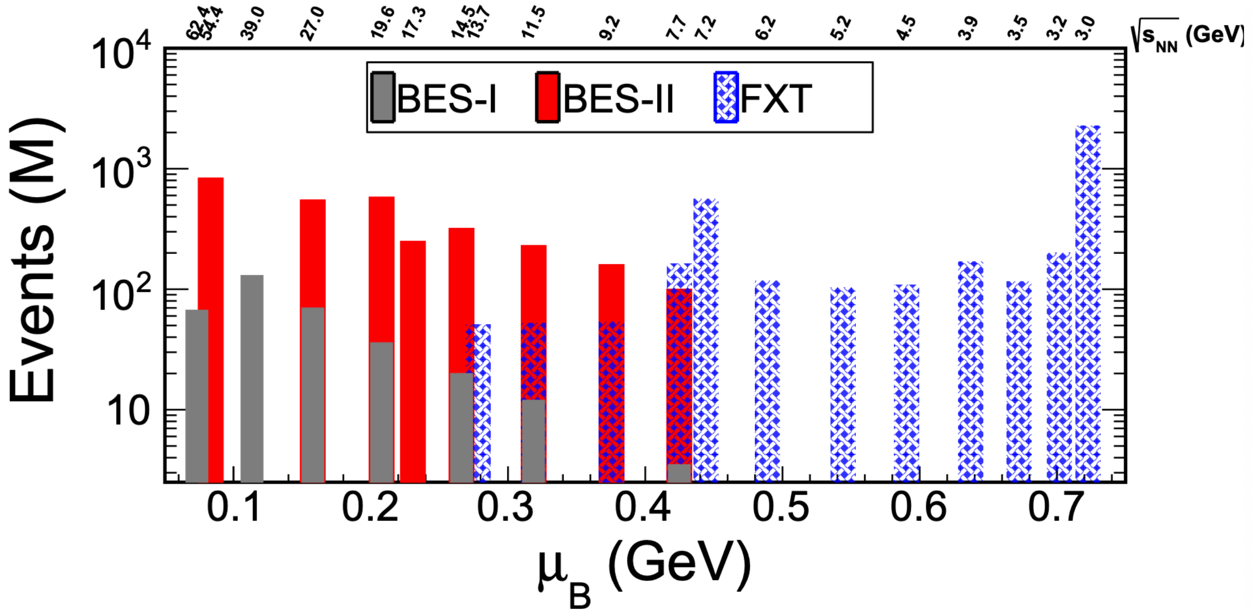
From BES-I to BES-II

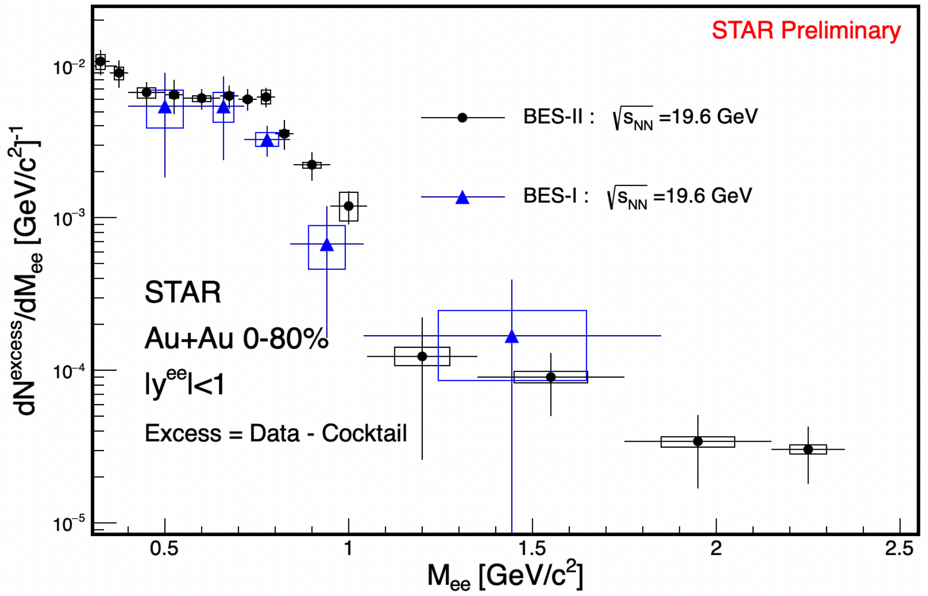
- RHIC BES-I results:
  - Total baryon densities are constant.
  - Average temperature (Hadronic Phase) are approximately constant.
- RHIC BES-II:
  - Probe the total baryon density and temperature effects on EM spectral function with changing properties.
  - BES-II has 10 times more statistics than BES-I with consistent result.

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



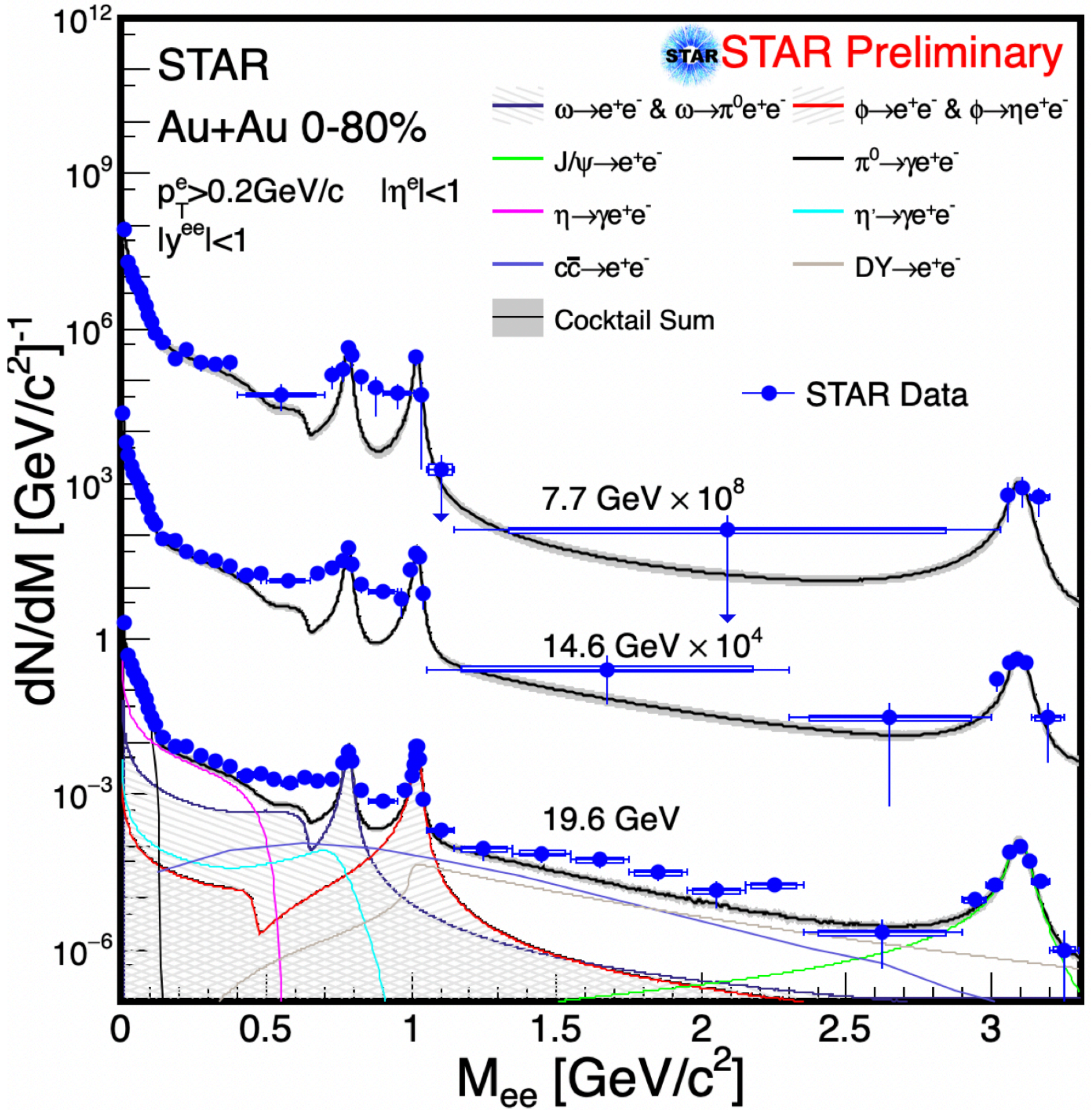


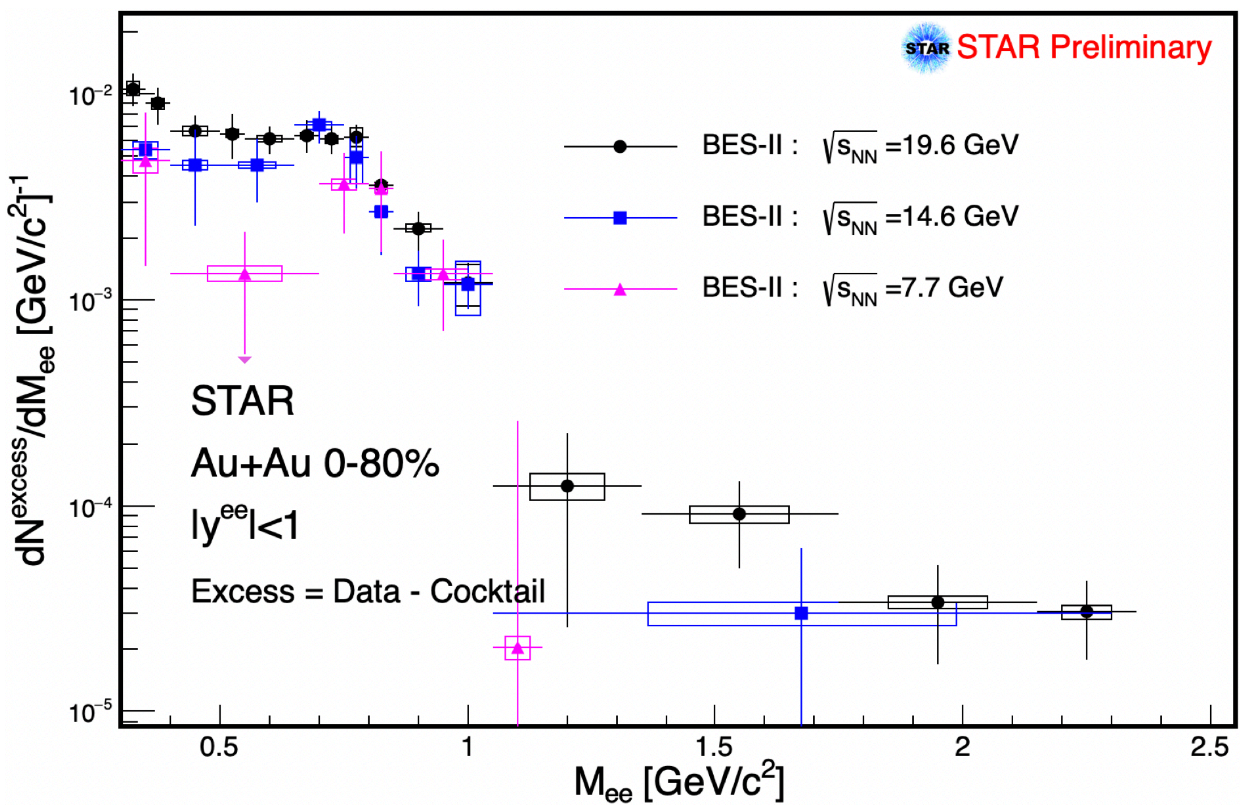


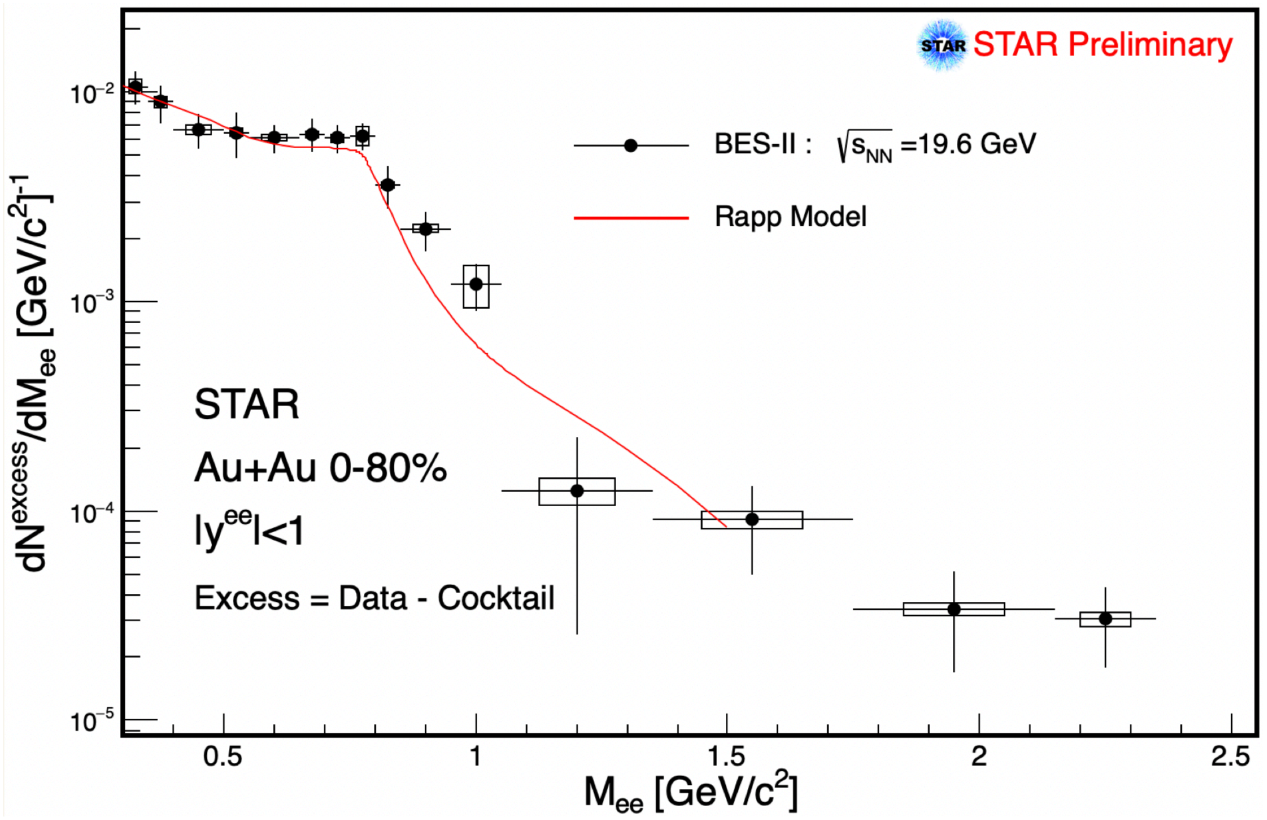


Z. Ye, STAR, Quark Matter (2022)
Y. Han, STAR, Quark Matter (2023)

BES-II dielectron production



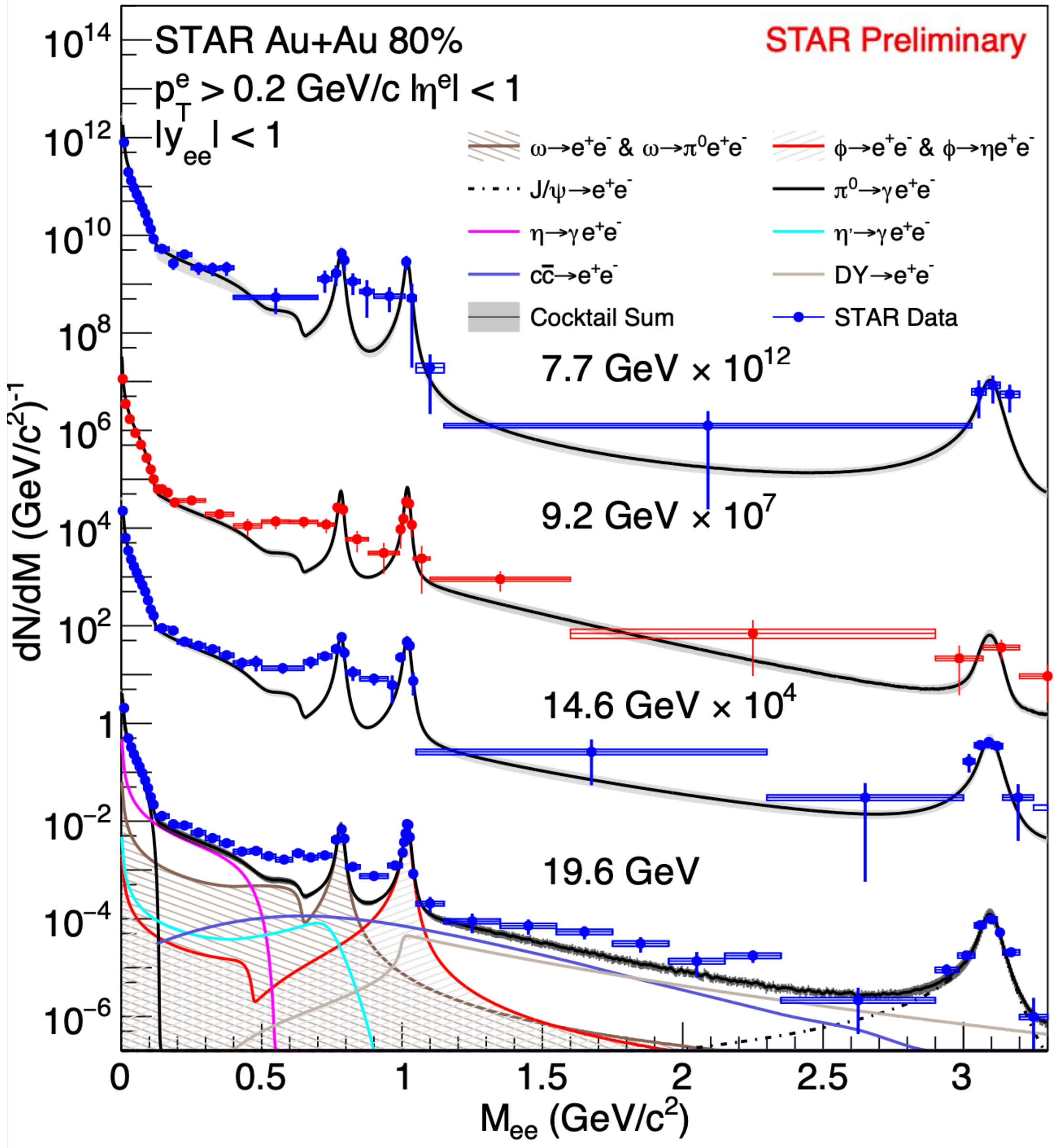


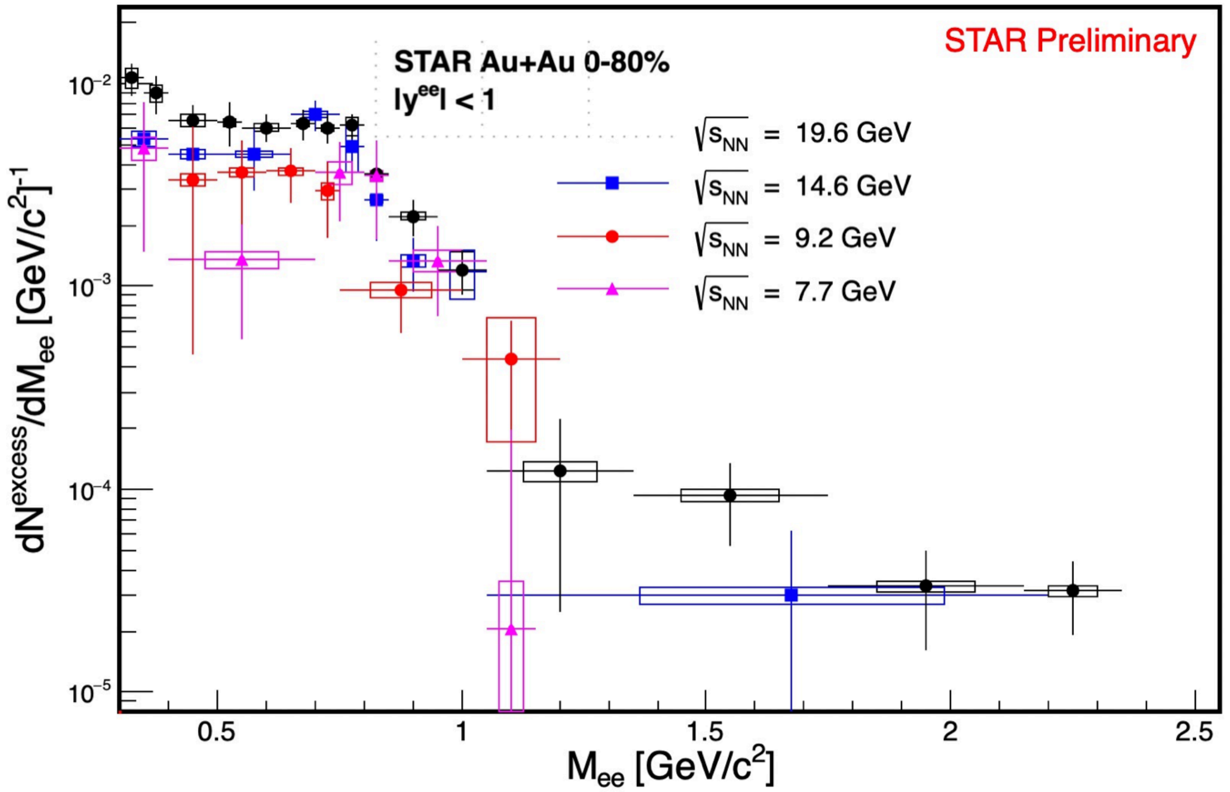


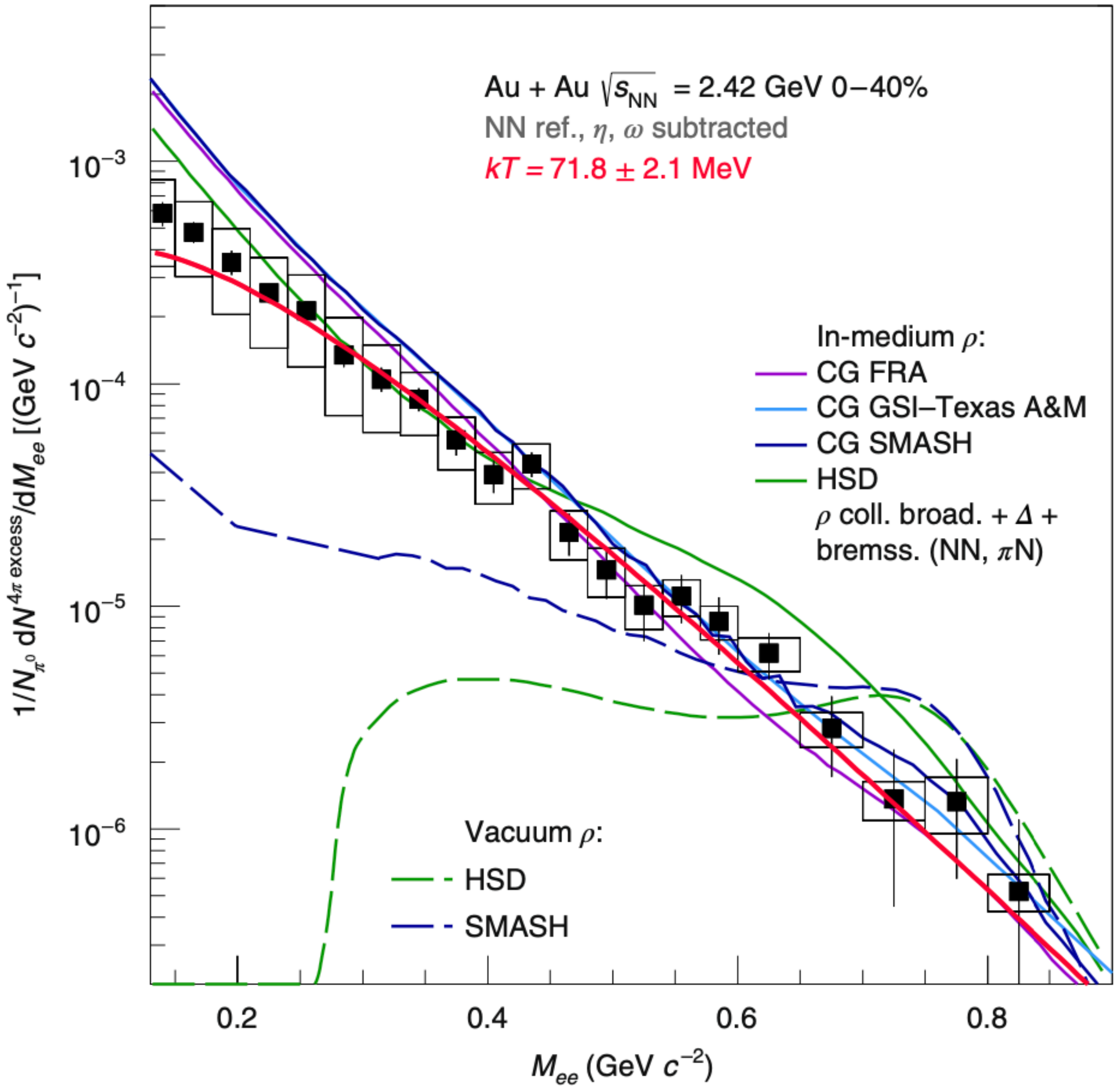
Excess yield invariant mass spectra at 19.6 GeV can be described by R. Rapp's calculation.

Y. Han, STAR, Quark Matter, Houston (2023)
R. Rapp: PRC 63 (2001) 054907, PRL 97, 102301 (2006) ;

BES-II and experiment with higher μ_B





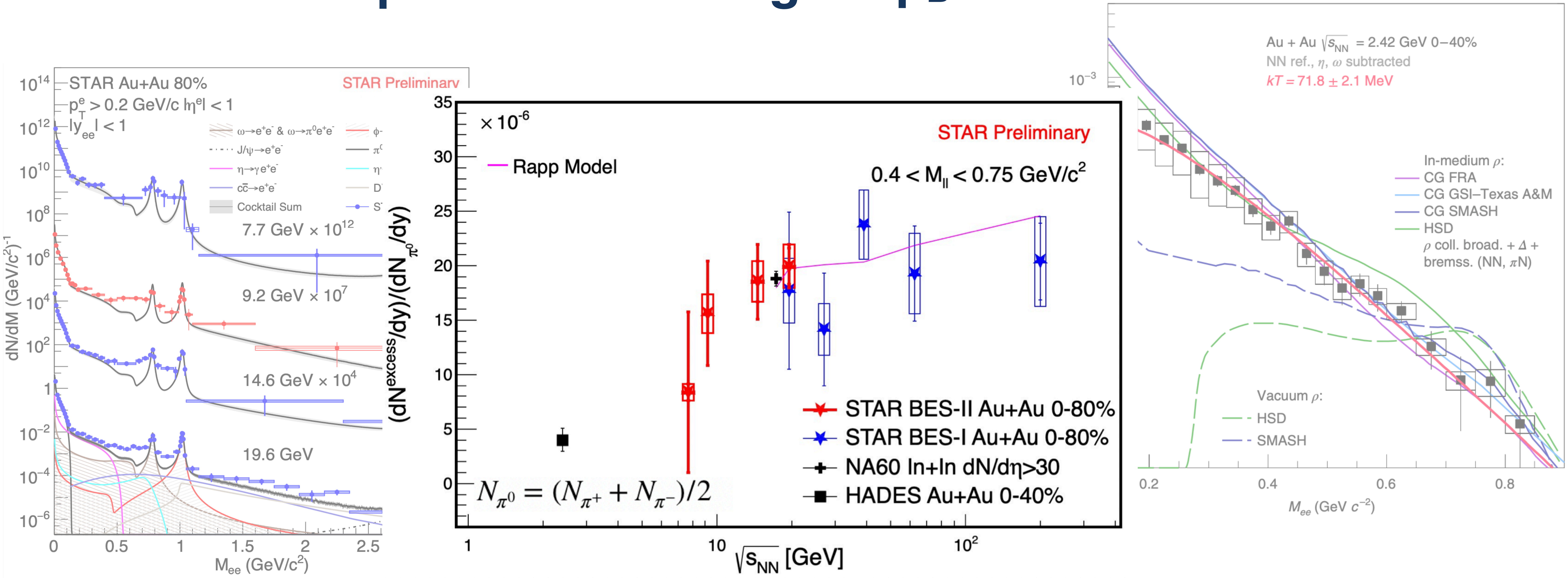


Excess yield invariant mass spectra at BES-II and HADES

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

Y. Han, STAR, Quark Matter, Houston (2023)
Z. Wang, STAR, SQM, Strasbourg (2024)
HADES Collab., Nature Physics 15 (2019) 1040

BES-II and experiment with higher μ_B



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

Y. Han, STAR, Quark Matter, Houston (2023)
Z. Wang, STAR, SQM, Strasbourg (2024)
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)

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Dileptons as thermometer at NA60

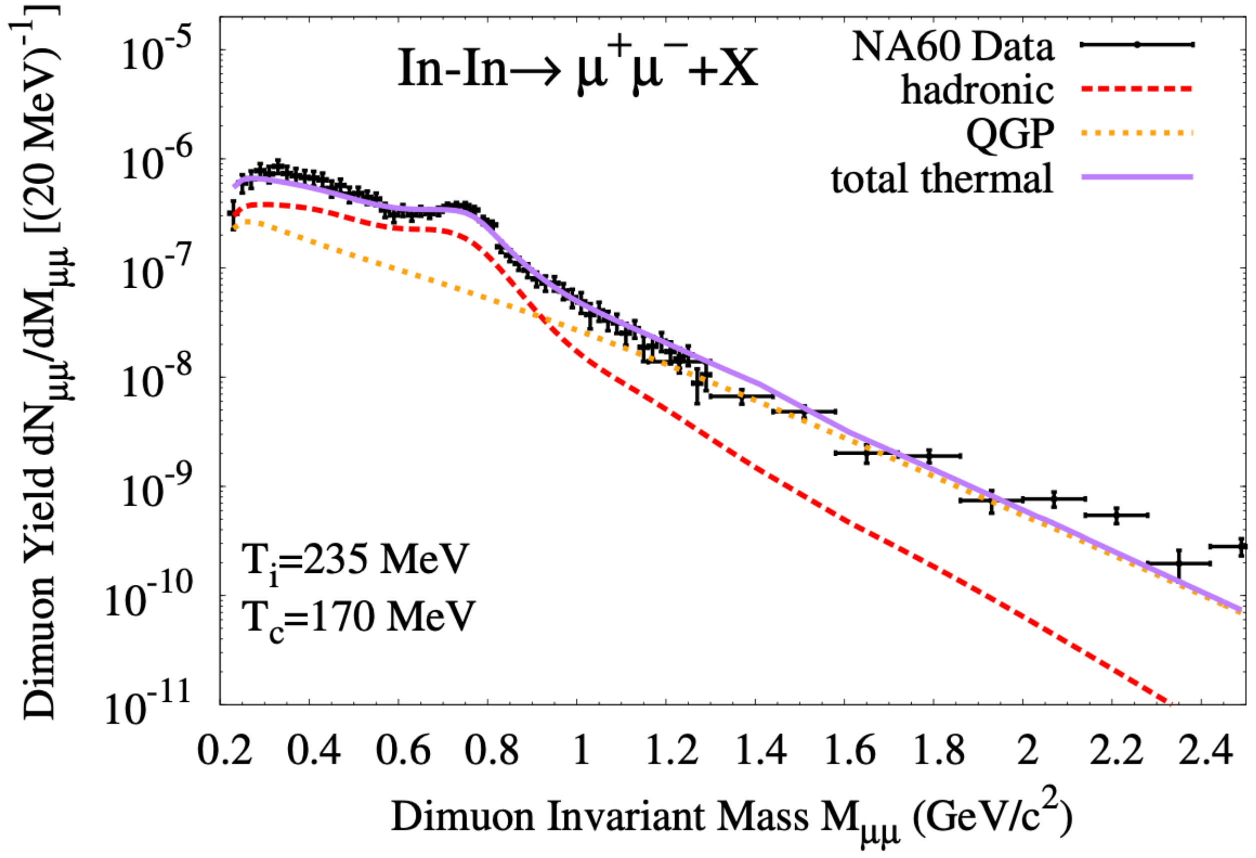
- Recall thermal dilepton radiation:
  - IMR - partonic dominnance.
  - LMR - vector meson dominnance.

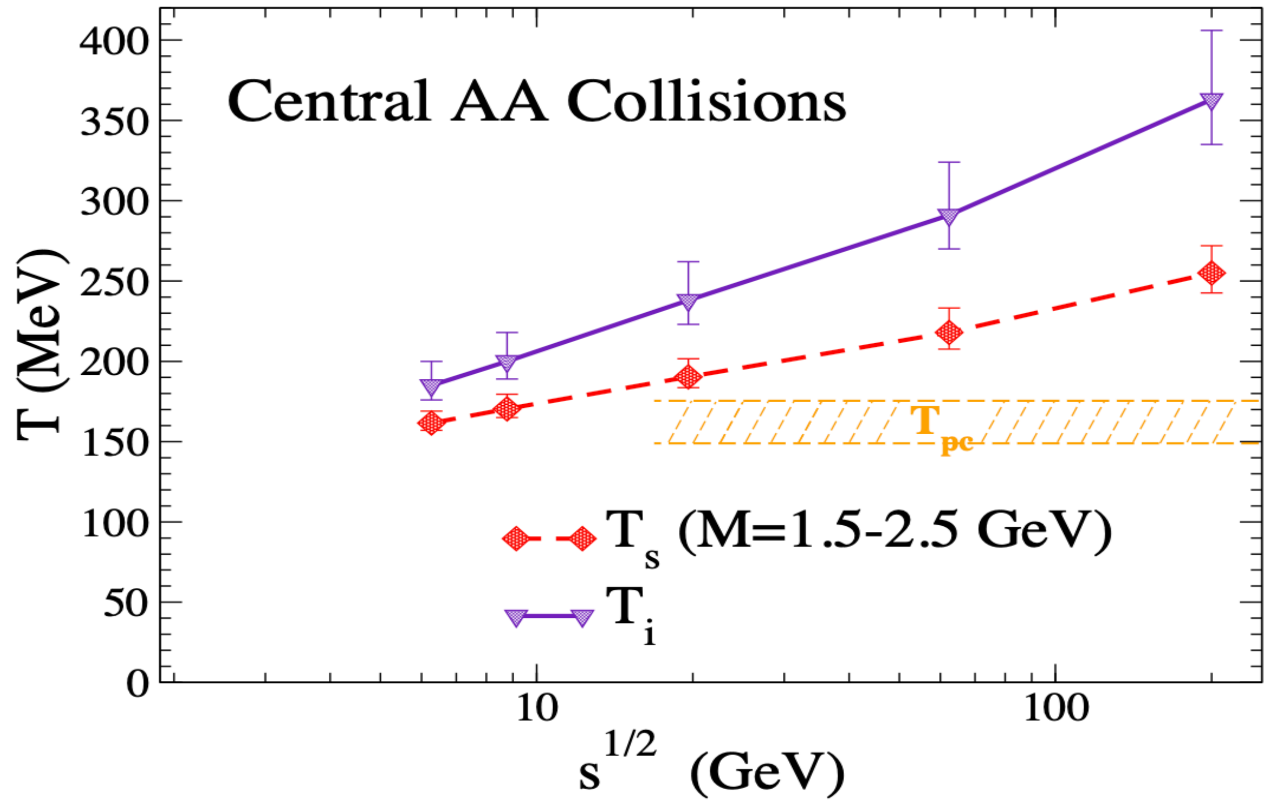
- NA60: IMR dilepton rate in non-relativistic approximation:

$$\frac{dR_{ll}}{dM} \propto (MT)^{\frac{3}{2}} exp(-M/T) \longrightarrow \langle T \rangle = 205 \pm 12 MeV$$

range 1.2 < M_{ll} < 2.0 GeV/c^2

- Independent of flow: no blue shift effects.
- Exceeding the pseudo-critical temperature computed in thermal lattice-QCD.





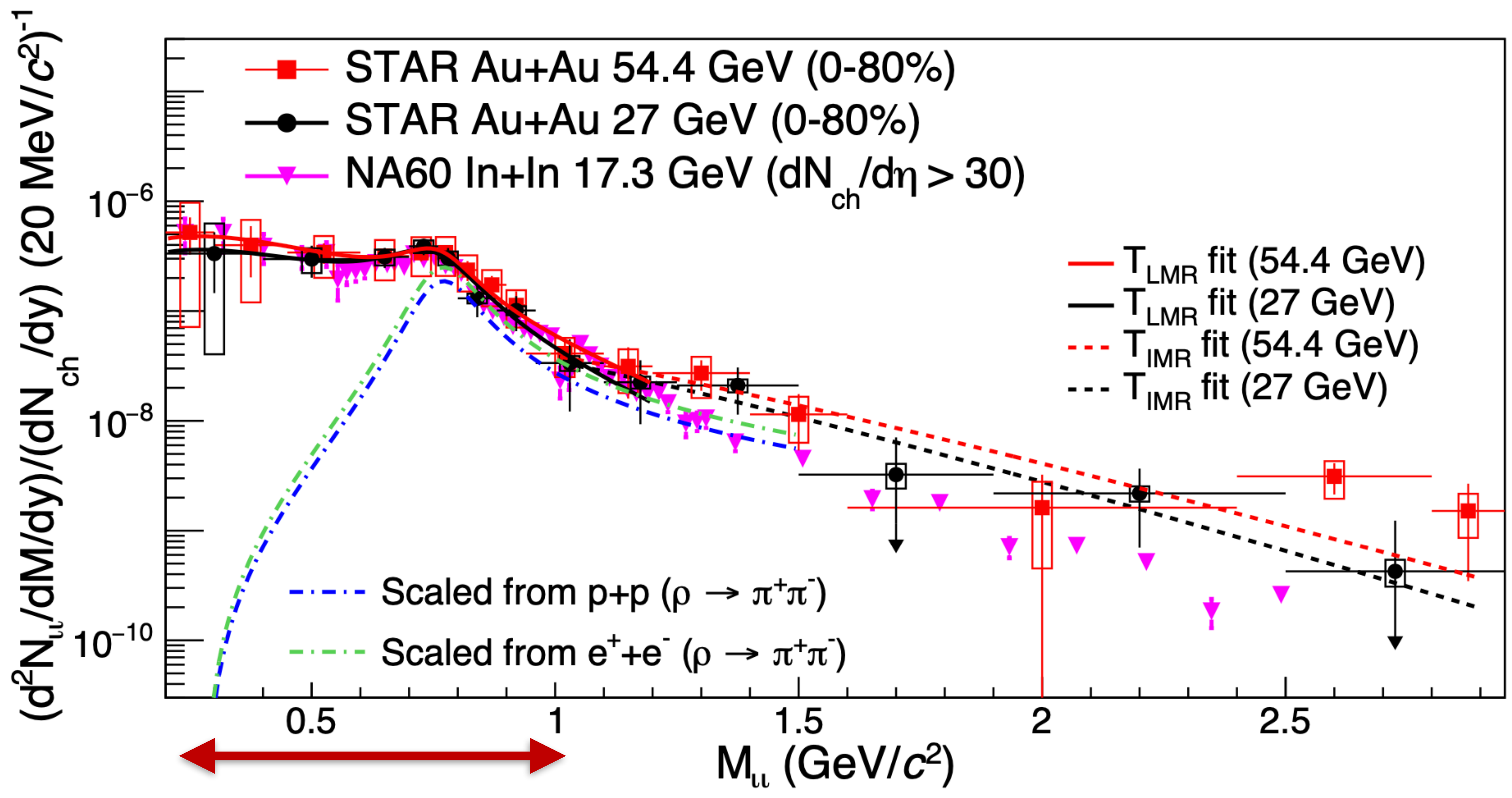
R. Arnaldi et al. (NA60), EPJC 61(2009) 711
NA60, AIP Conf.Proc. 1322 (2010) 1
Rapp, van Hees, PLB 753 (2016) 586

Dilepton temperature measurement in RHIC

STAR: arXiv: 2402.01998
T_{PC}: HotQCD, Phys.Lett.B 795 (2019) 15-21;
NA60: EPJC (2009) 59 607-623
Z. Ye, STAR, Quark Matter, Kraków (2022)
Z. Wang, STAR, SQM, Strasbourg (2024)

STAR results at $\sqrt{s_{NN}}$ = 27 and 54 GeV.

- Low mass range:
  - include ρ Breit-Wigner term in temperature fit.
  - T_{LMR} around the pseudo critical temperature T_{pc} (156 MeV).



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

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

Dilepton temperature measurement in RHIC

STAR: arXiv: 2402.01998
T_{PC}: HotQCD, Phys.Lett.B 795 (2019) 15-21;
NA60: EPJC (2009) 59 607-623
Z. Ye, STAR, Quark Matter, Kraków (2022)
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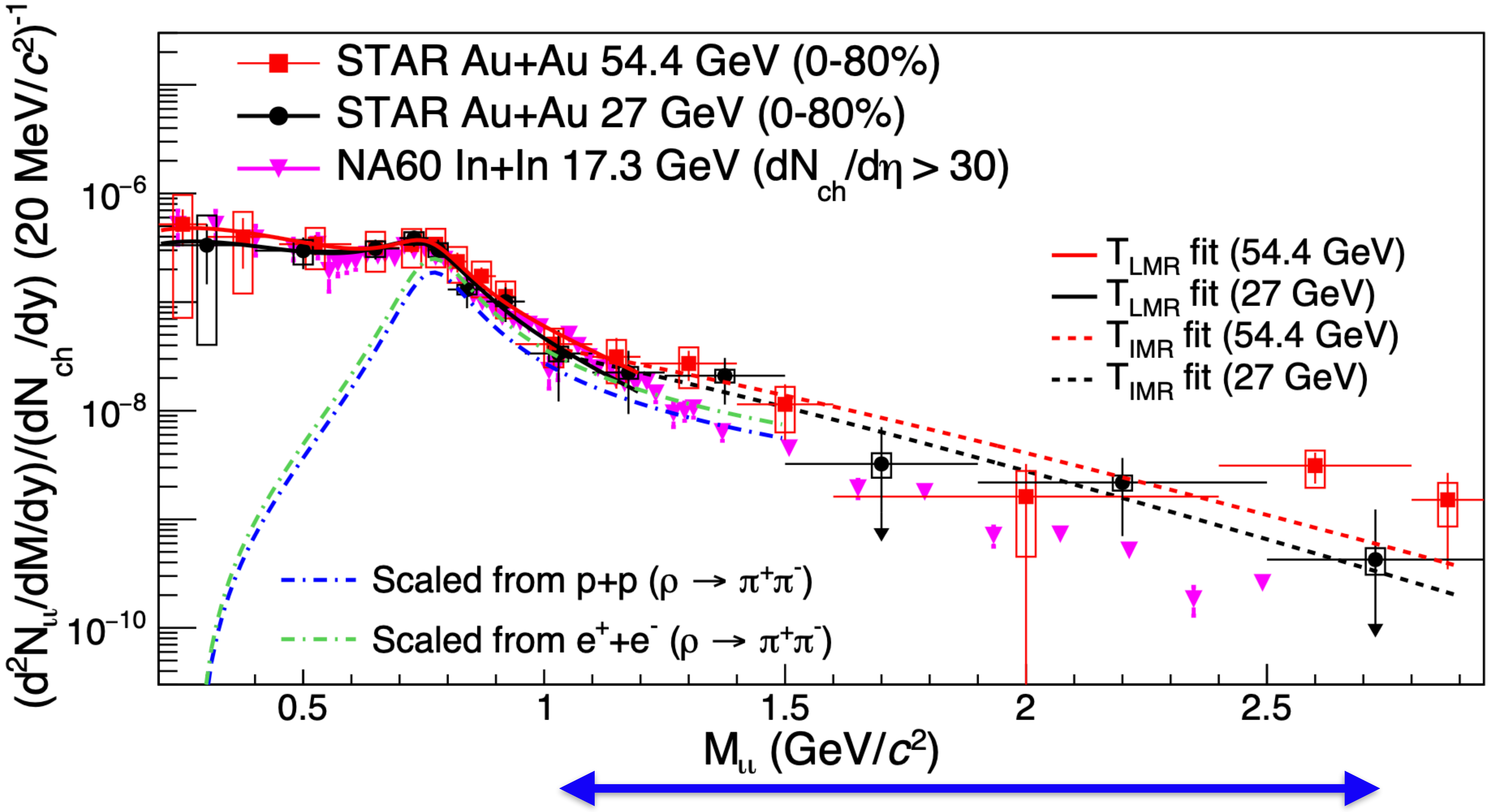
STAR results at $\sqrt{s_{NN}}$ = 27 and 54 GeV.

- Low mass range:
  - include ρ Breit-Wigner term in temperature fit.
  - T_{LMR} around the pseudo critical temperature T_{pc} (156 MeV).
- Intermediate mass range:
  - QGP thermal radiation is dominant source.
  - T_{IMR} is higher than the pseudo critical temperature T_{pc} (156 MeV).



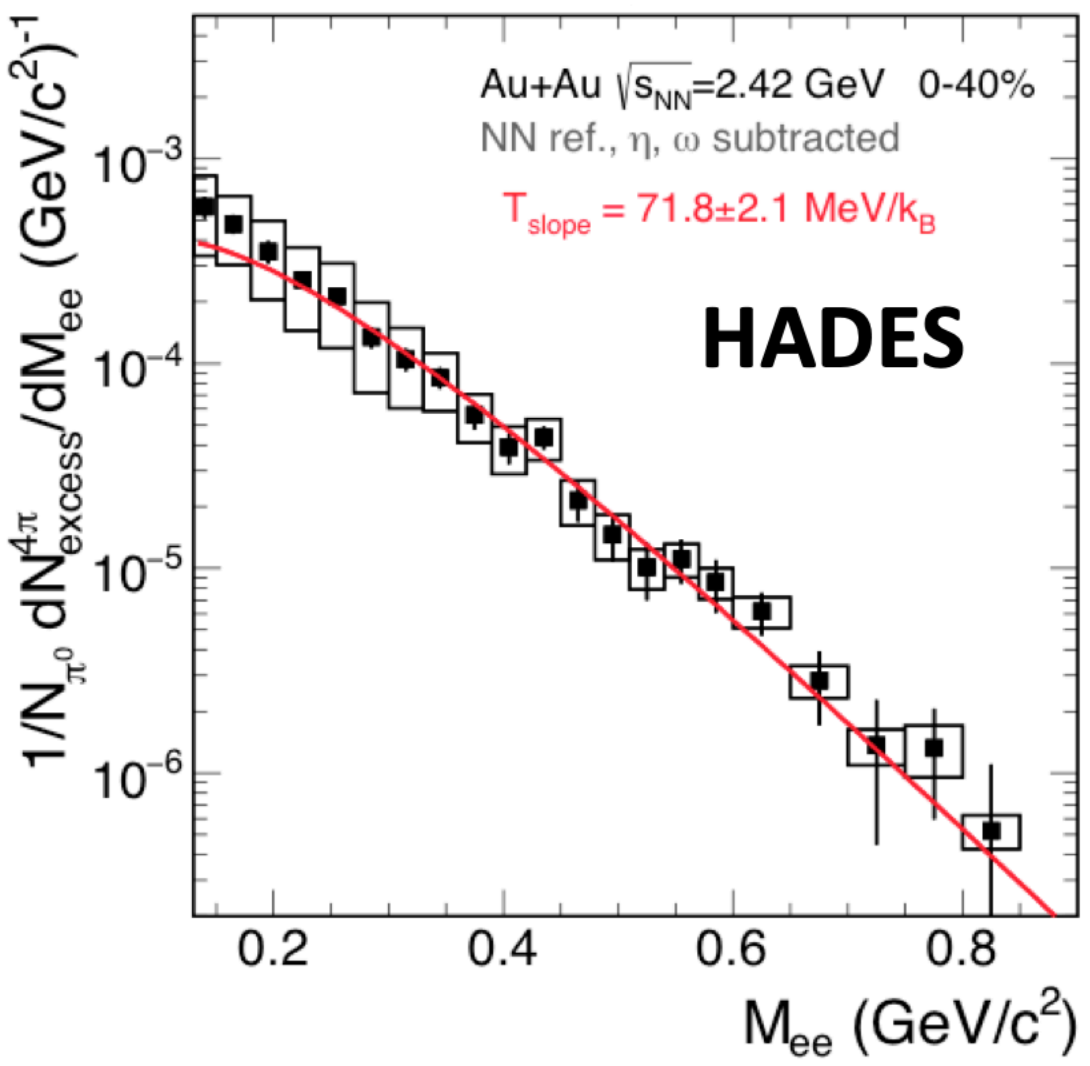
$$T_{IMR}^{54.4\ GeV} = 303 \pm 59(stat.) \pm 28(sys.)\ MeV$$

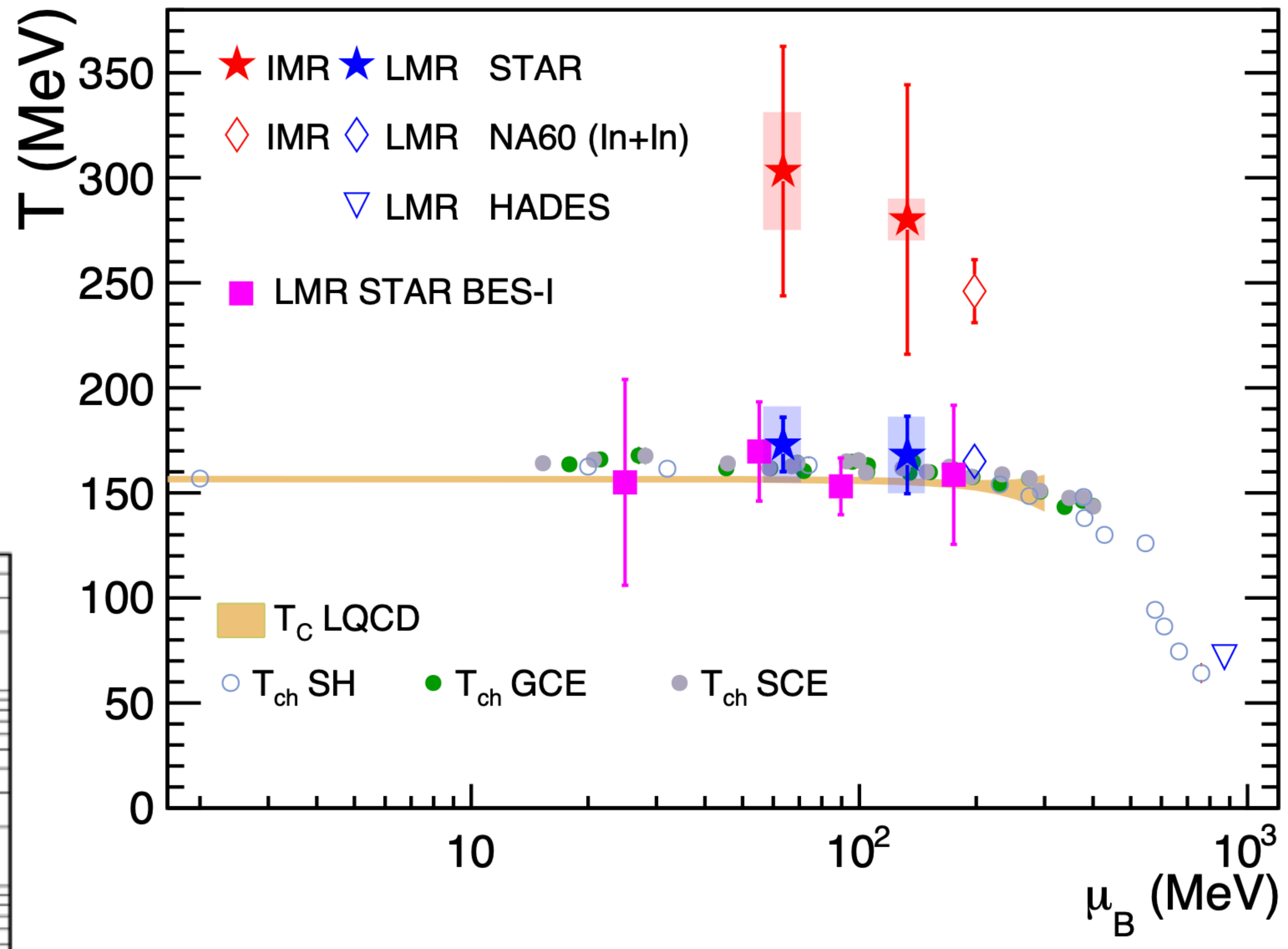
$$T_{IMR}^{27\ GeV} = 280 \pm 64(stat.) \pm 10(sys.)\ MeV$$

Summary of temperatures with other experiments

- LMR:
  - T is close to both T_{ch} and T_{pc}.
  - Results indicate the thermal radiation from hadronic gas is mainly produced around the phase transition.

- IMR:
  - T is higher than both T_{ch} and T_{pc}.
  - Thermal dileptons mainly emitted from QGP phase.





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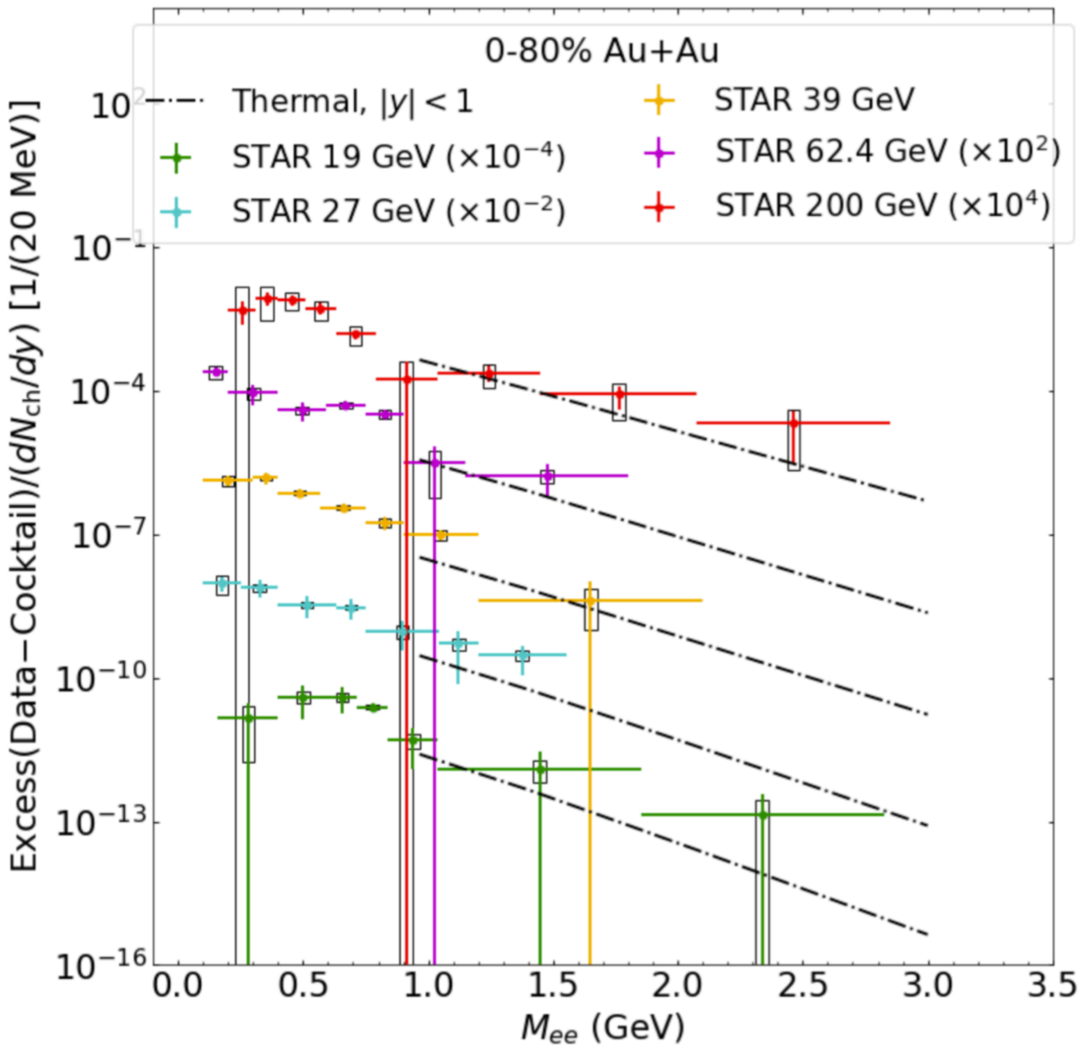
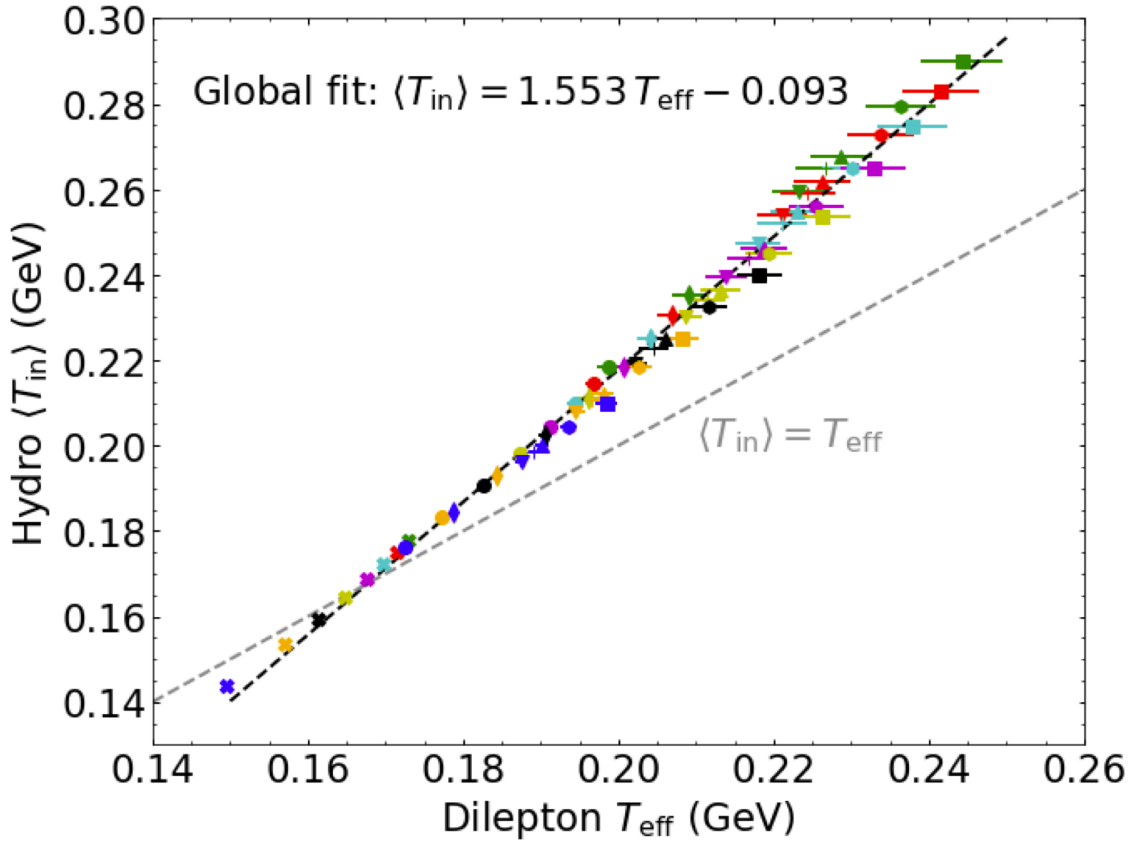
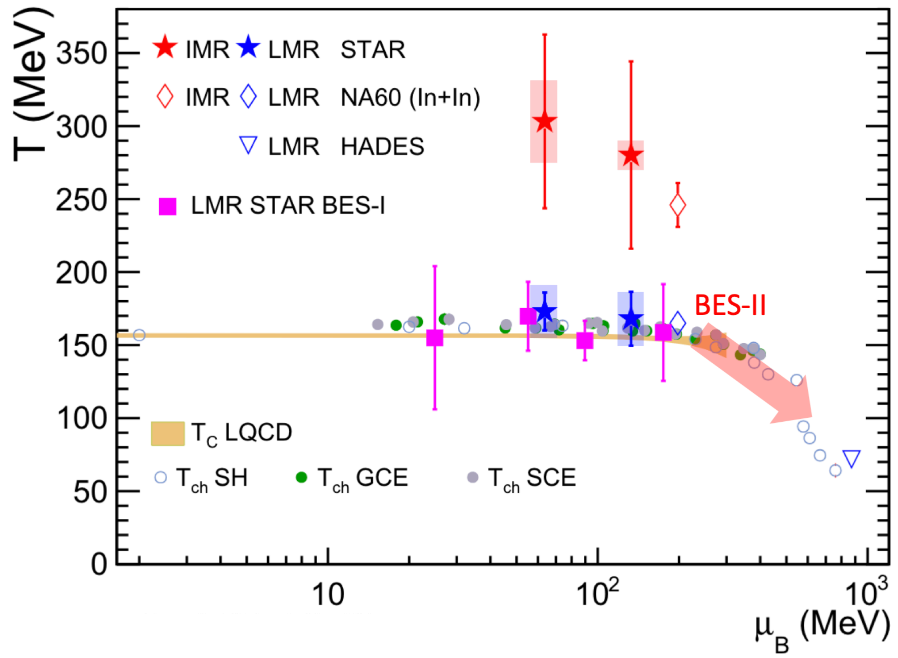
HADES: Nature Physics 15, 1040-1045 (2019)
T. G.: JPS Conf.Proc. 32 (2020) 010079
T_{ch} SH: P. Braun-Munzinger et al. Nature 561, 321-330 (2018)
T_{ch} GCE/SCE: STAR PRC 96, 044904 (2017)

The future of temperature measurement

- First estimate of NLO QGP dilepton emission with finite μB, using hydrodynamics.
- Theory and measurements agree within uncertainties using STAR IMR data.
- Potential correlation between the effective temperature extracted from IMR and the initial temperature in the fluid dynamical model.
- Development of theory and experiment are equally important to connect measured T to other physics observables.







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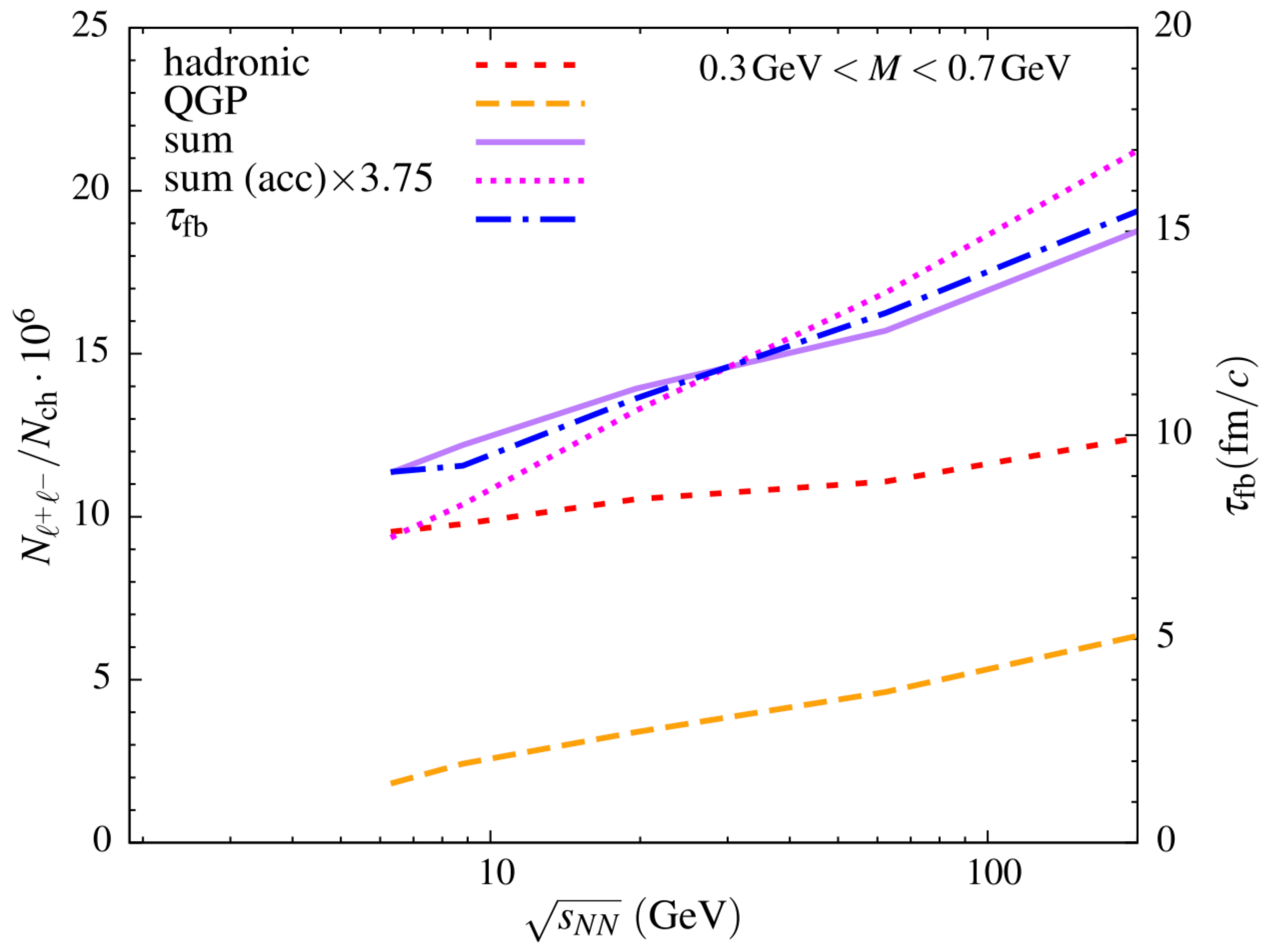
Outline

- QCD Matter Phase Diagram
- Dileptons as probe with theoretical consideration
- Experimental challenge
- **Dilepton in BES**
  - Spectrometer, Thermometer, **Chronometer**
- Dilepton physics in the future

Dileptons as chronometer

- Normalized excess yields in LMR has potential to track medium lifetime.
- The hadronic medium effects are essential: the proportionality of the excess yield to the lifetime might be compromised.
- High statistics measurements needed.



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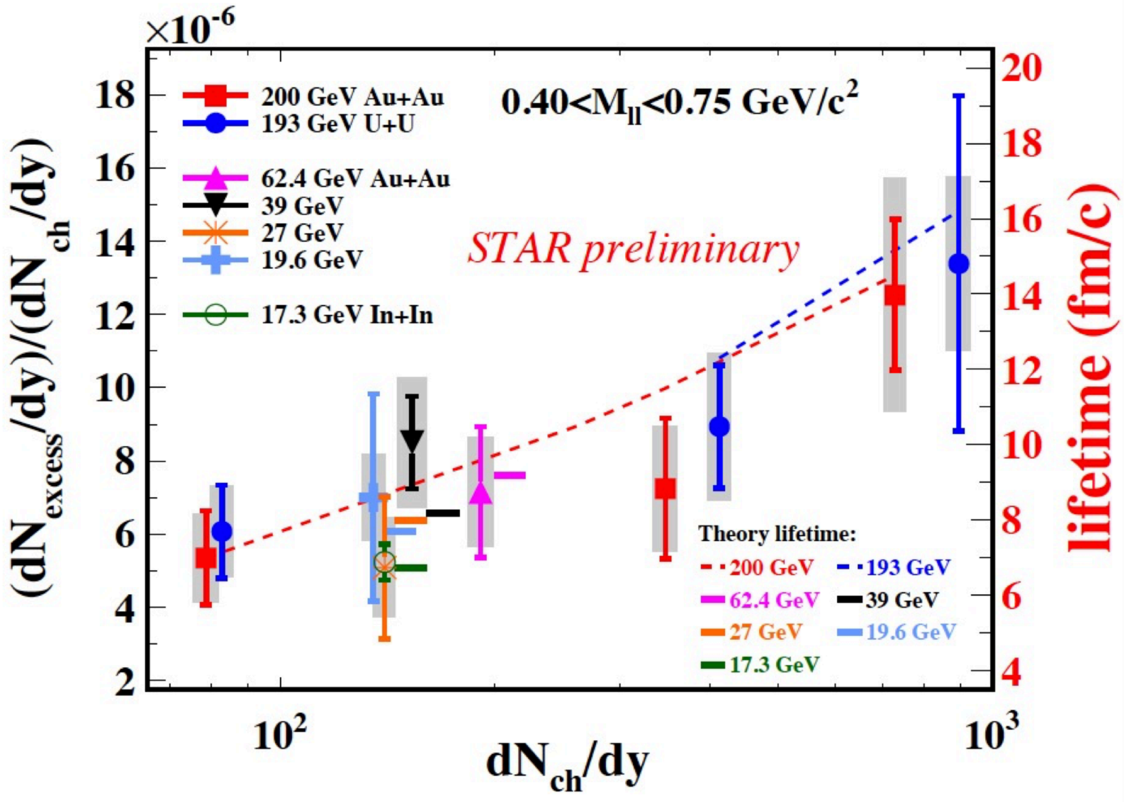

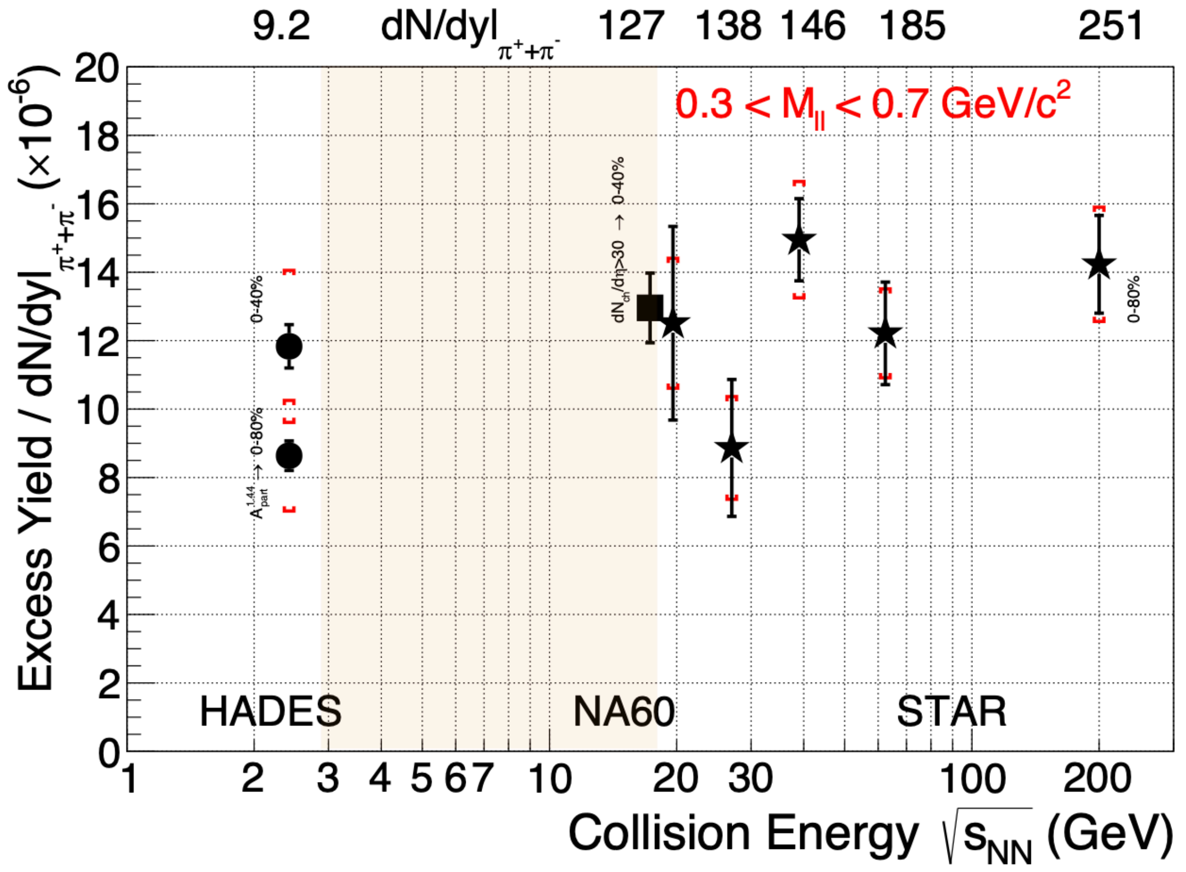

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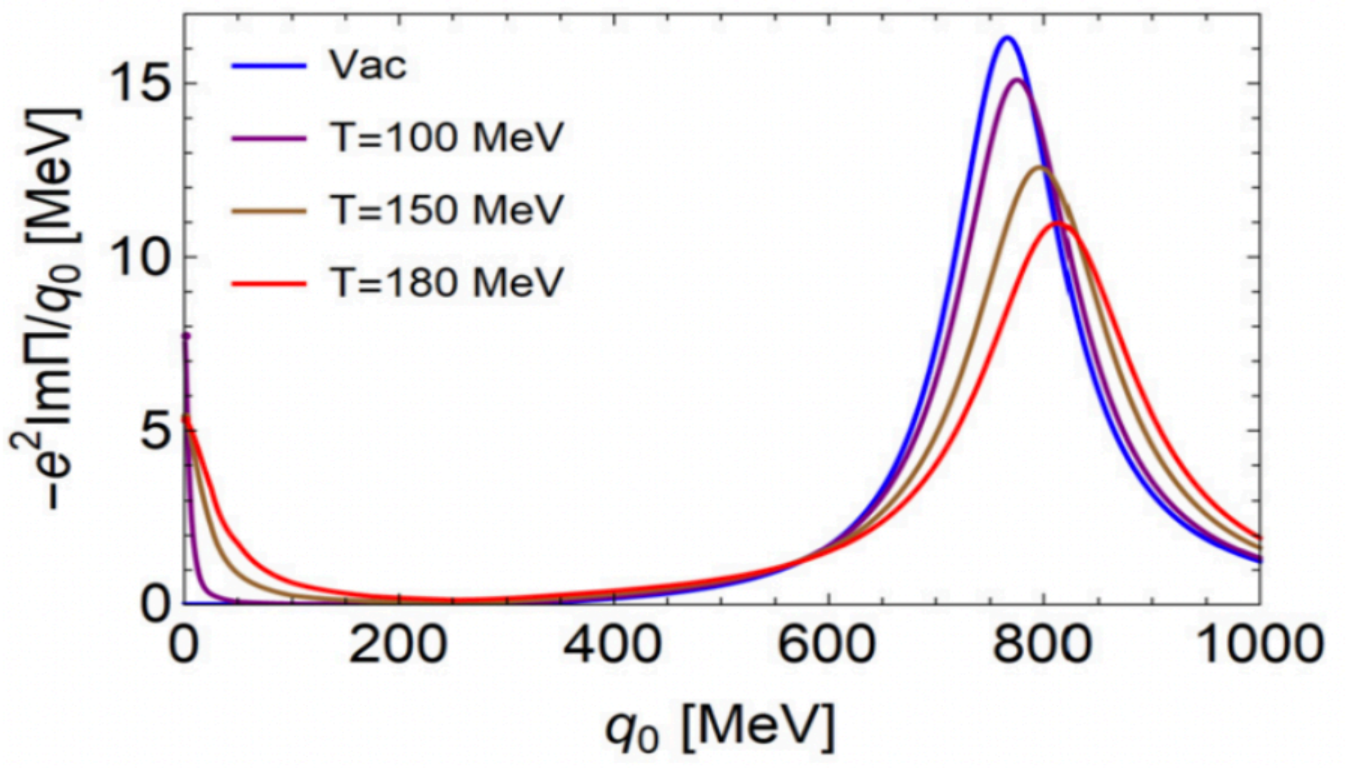
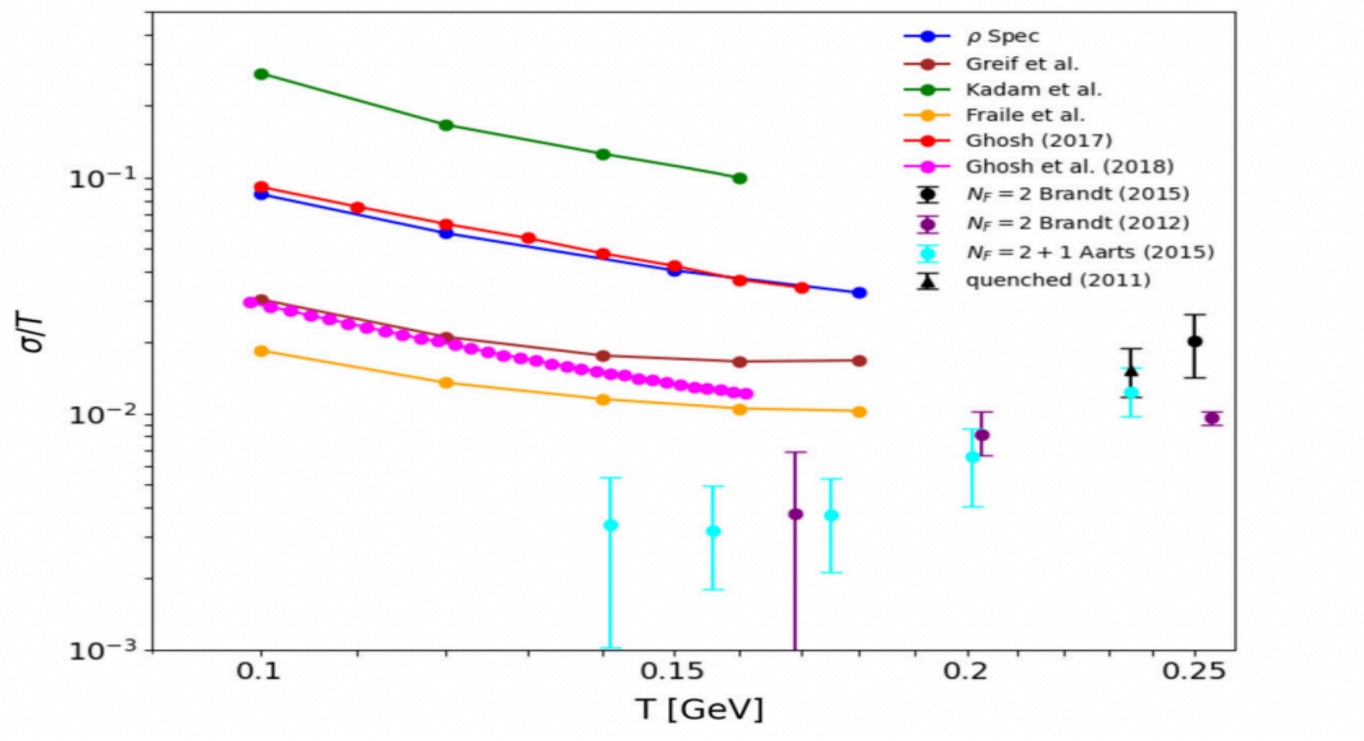
Dileptons as conductivity meter





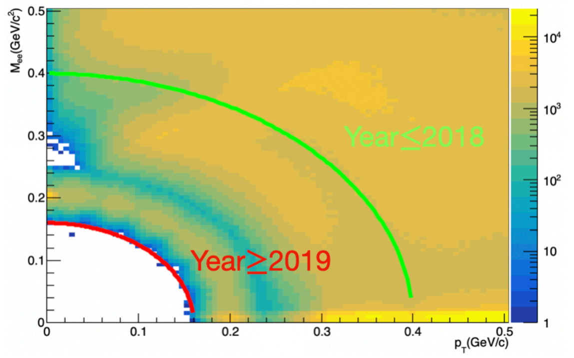
In the zero-momentum, low energy limitation, Electrical Conductivity:

Moore & Robert arXiv:hep-ph/0607172

$$\sigma_{el} = -\frac{e^2}{3} \lim_{q_0 \to 0} \frac{1}{q_0} \mathrm{IM}[\Pi_{EM}(q_0, q = 0, T)]$$

- At low energy limit, EM spectral function is related to electrical conductivity.
- Various theoretical estimations should be constrained via precise experimental measurements.
- Experimental challenge:
  - low invariant mass and p_T limit.
  - precise result on hadron contribution.

STAR Dielectron Acceptance



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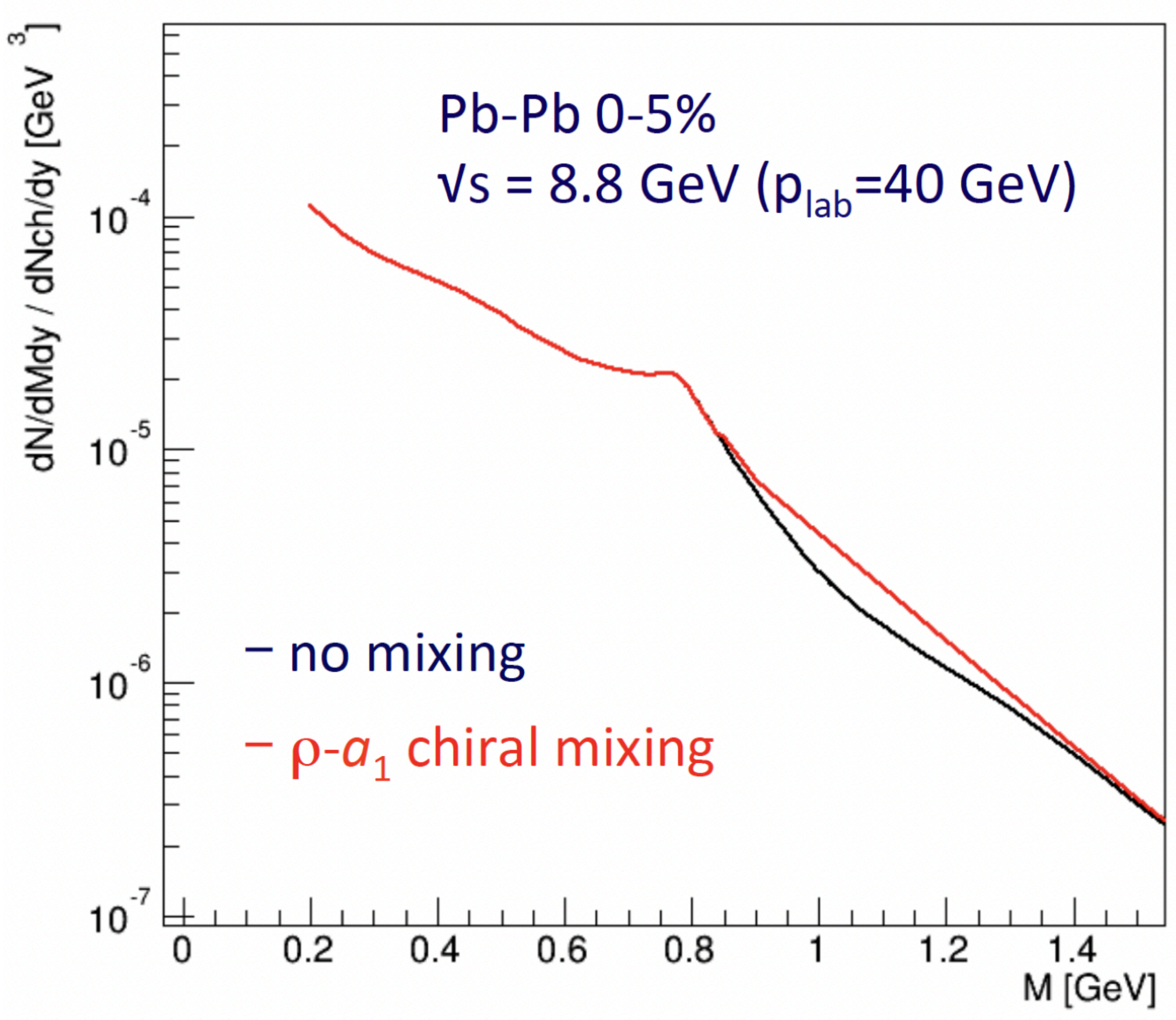
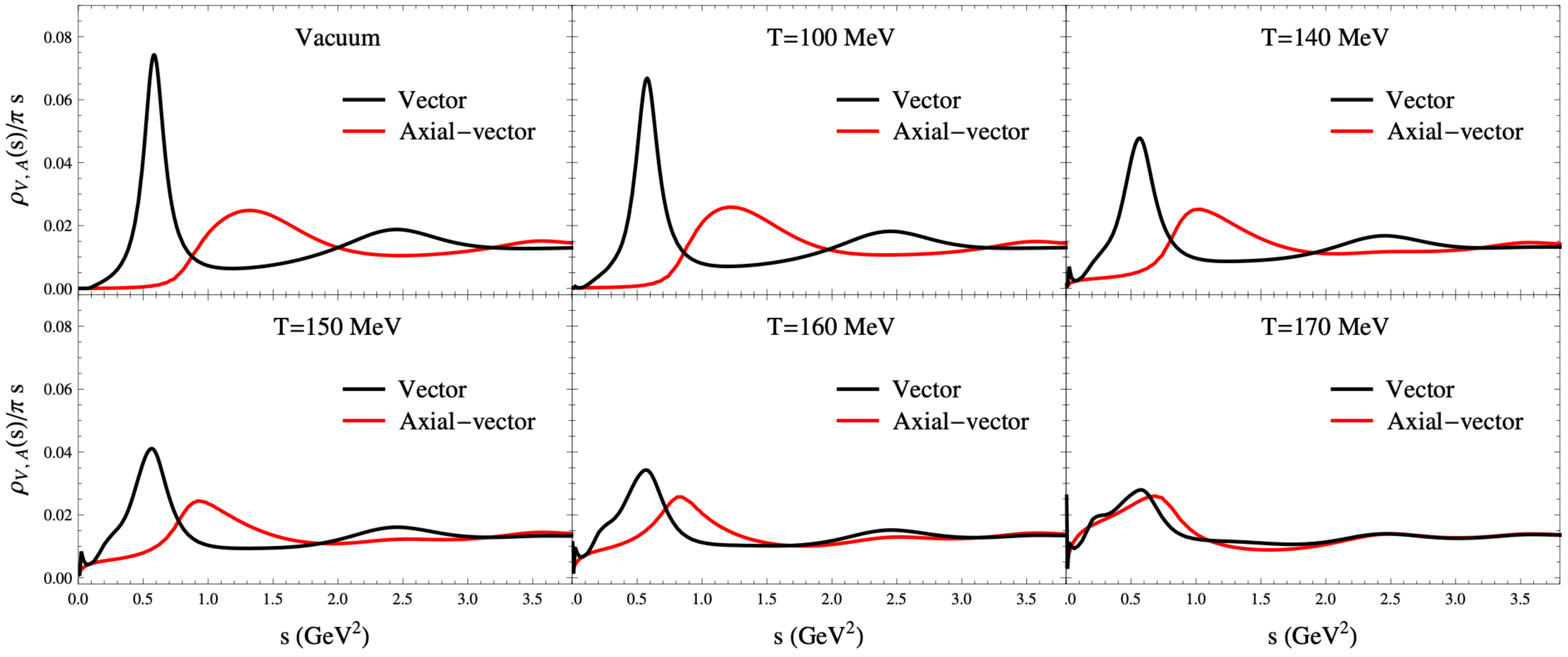
ρ - a_1 mixing

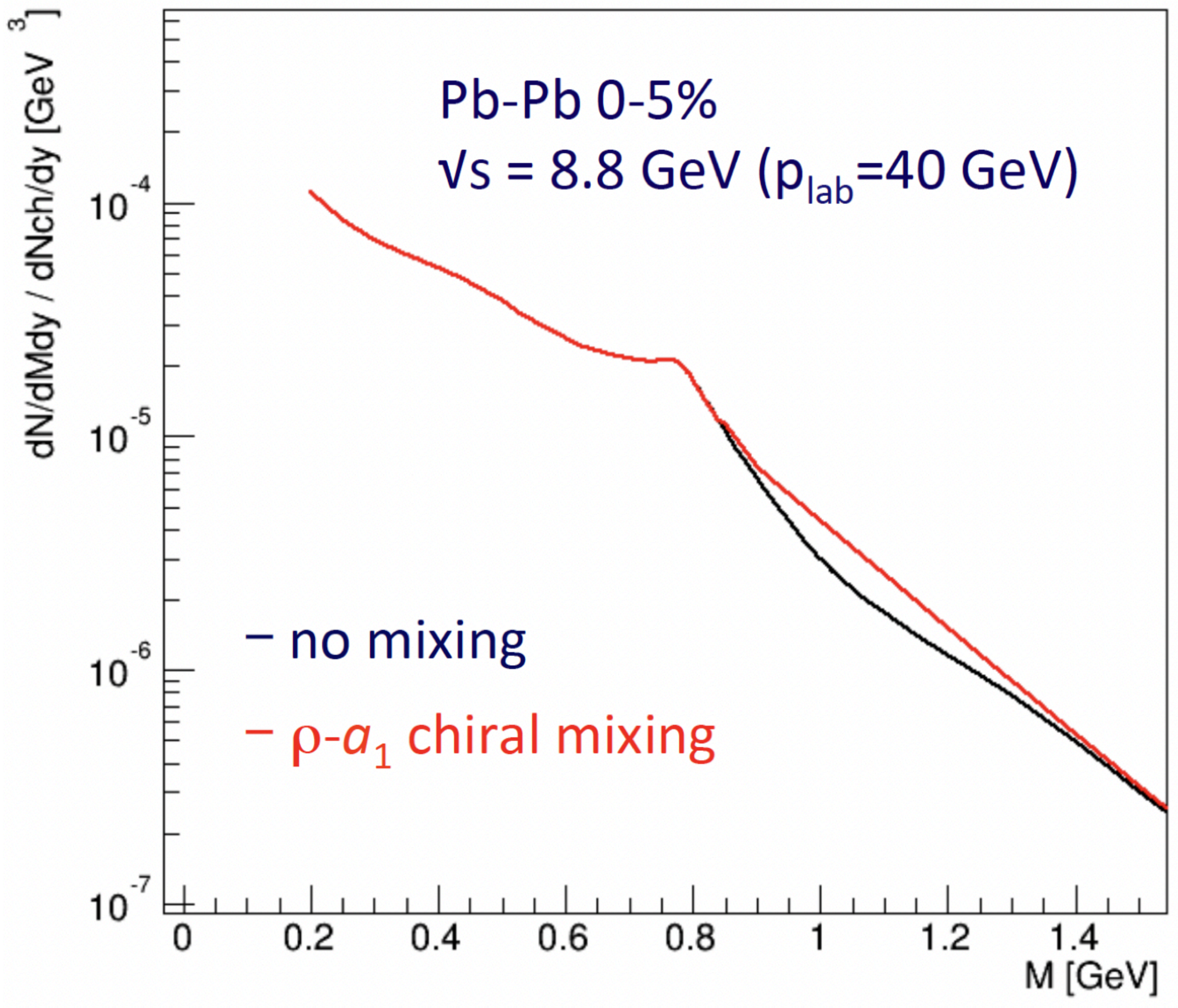
- ρ - a_1 mixing: $\pi a_1 \rightarrow \rho' \rightarrow l^+ l^-$
- At a high temperature, the axial vector spectral function degenerates with the vector channel through a strong broadening accompanied by a mass drop of the *a_1* meson toward the ρ meson.
- Potential signature of Chiral Symmetry Restoration.



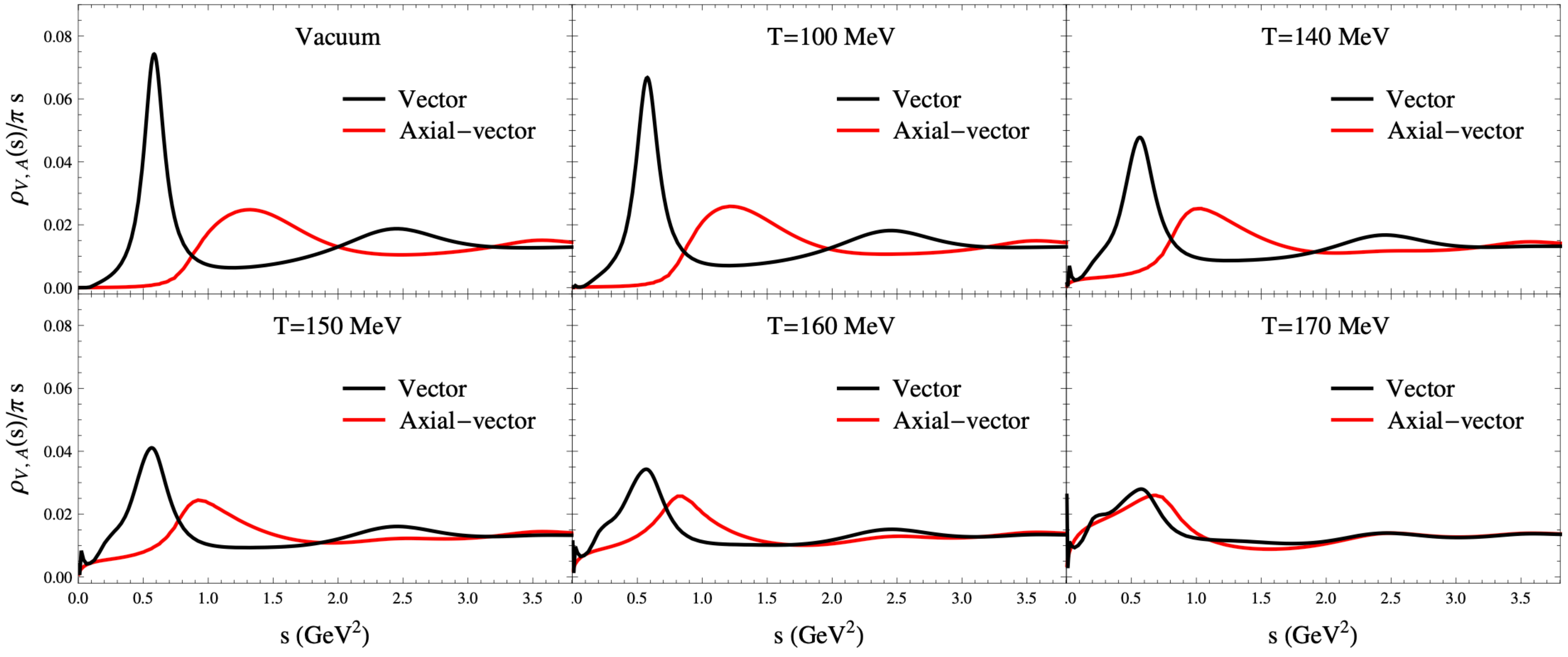


P. M. Hohler and R. Rapp, *Phys. Lett.* B731 (2014) 103
H. van Hees and R. Rapp, *Nucl. Phys.* A806 (2008) 339
Letter of Intent NA60+ (2022)

ρ - a₁ mixing: Experiment



- Indicating enhancement M_{ll} = 0.9 - 1.5 GeV.
- QGP radiation should become suppressed and possibly negligible (low collision energy).
- Need precise measurement both in signal and physics background. (Future in NA60+)



P. M. Hohler and R. Rapp, *Phys. Lett.* B731 (2014) 103
H. van Hees and R. Rapp, *Nucl. Phys.* A806 (2008) 339
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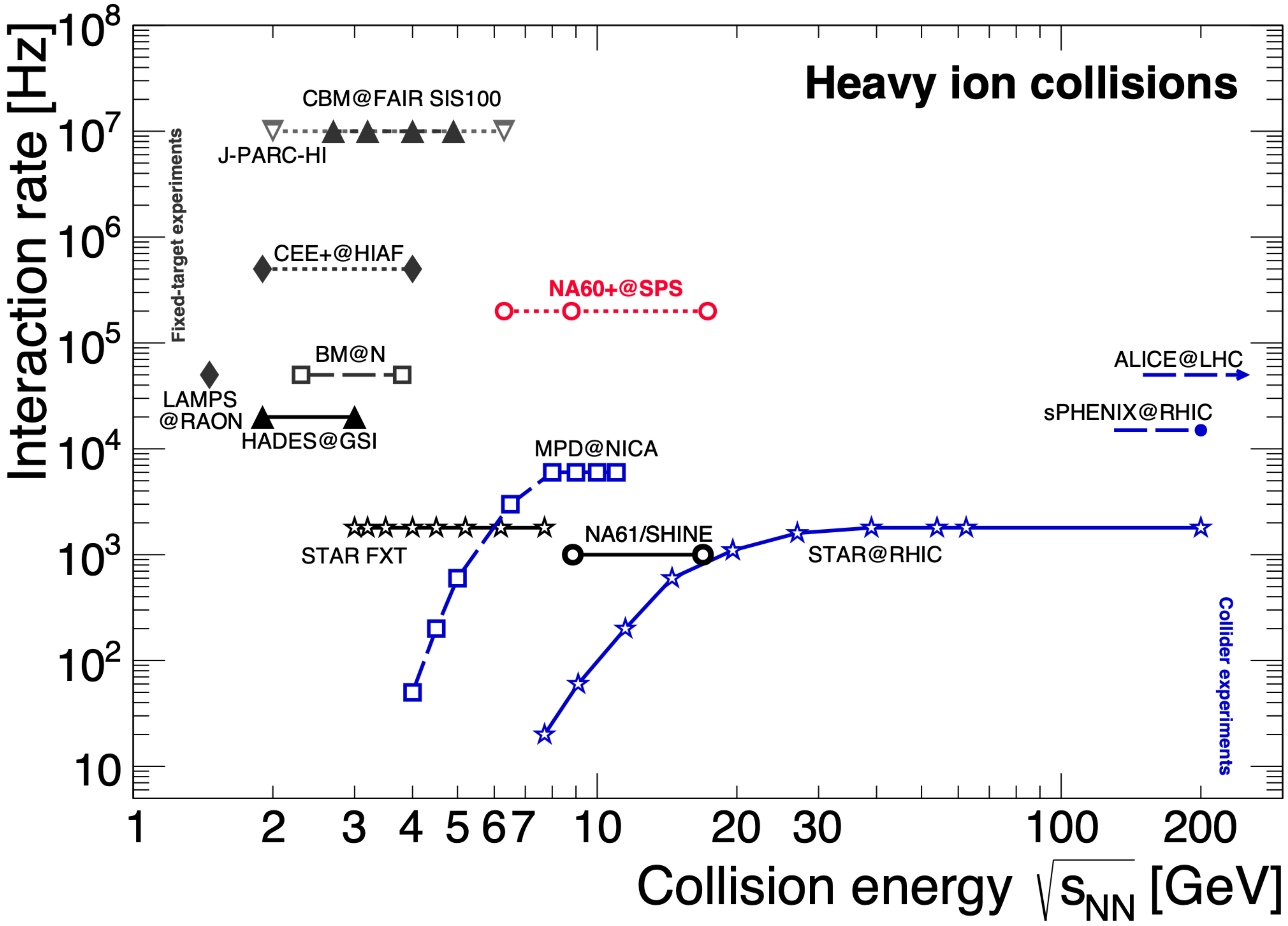
Future Prospects

Letter of Intent NA60+ (2022)



High-Statistics Data

- High statistics
  - high interaction rates
  - large acceptance
- Precise reference
  - cocktail (meson, DY et. al)
  - detector with multipurpose
- Better background control
  - photon conversion from material
  - purity from PID

Summary

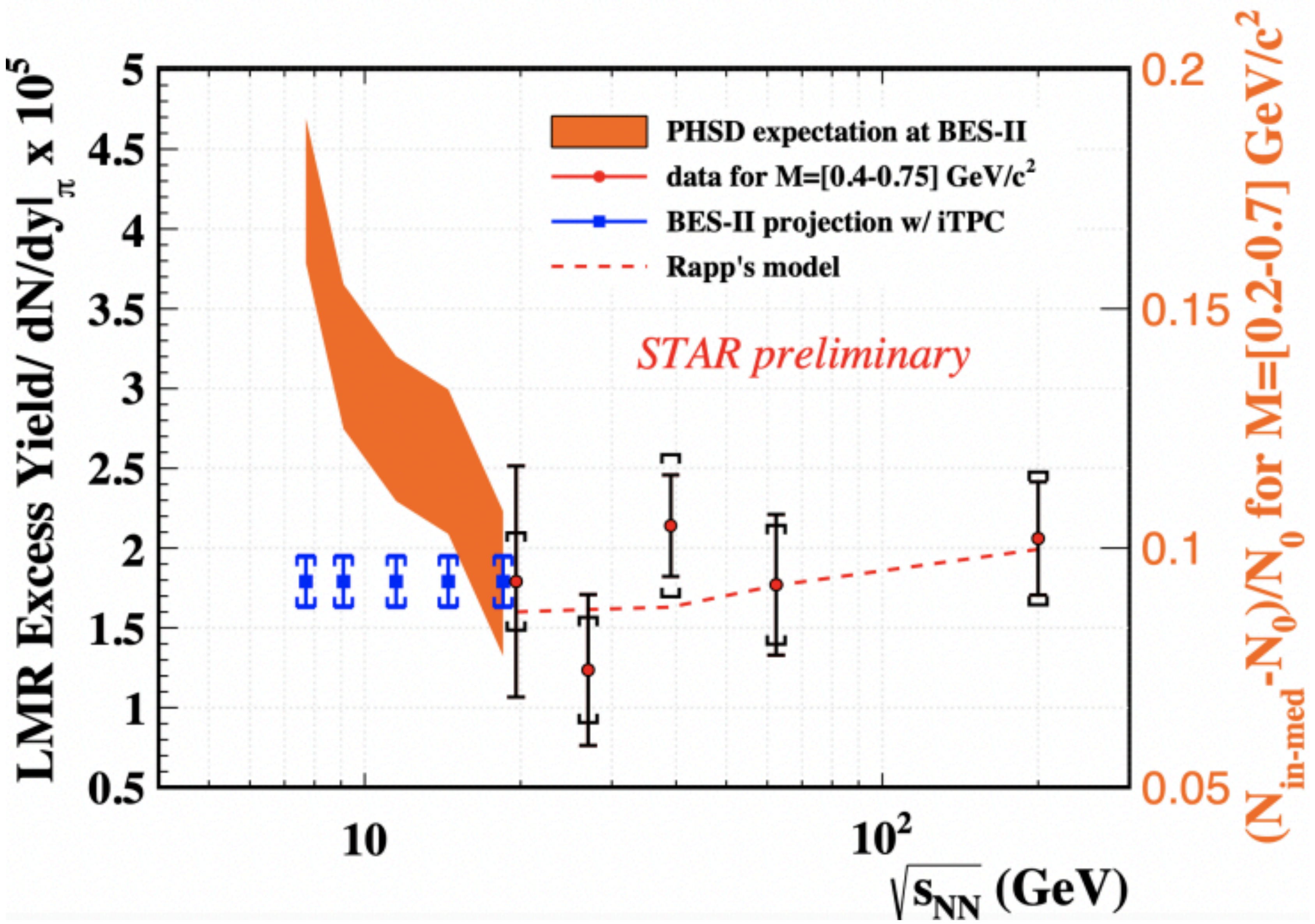
- Dileptons can provide access to various physics observables.
  - vector meson spectral function, medium properties, chiral symmetry restoration.
- Potential of accurate dilepton measurements combined with new theoretical developments.
  - NA60+, ALICE, CBM et al.
- High-statistics data is the key to the future dilepton experimental progress.

Thank you for your attention

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.



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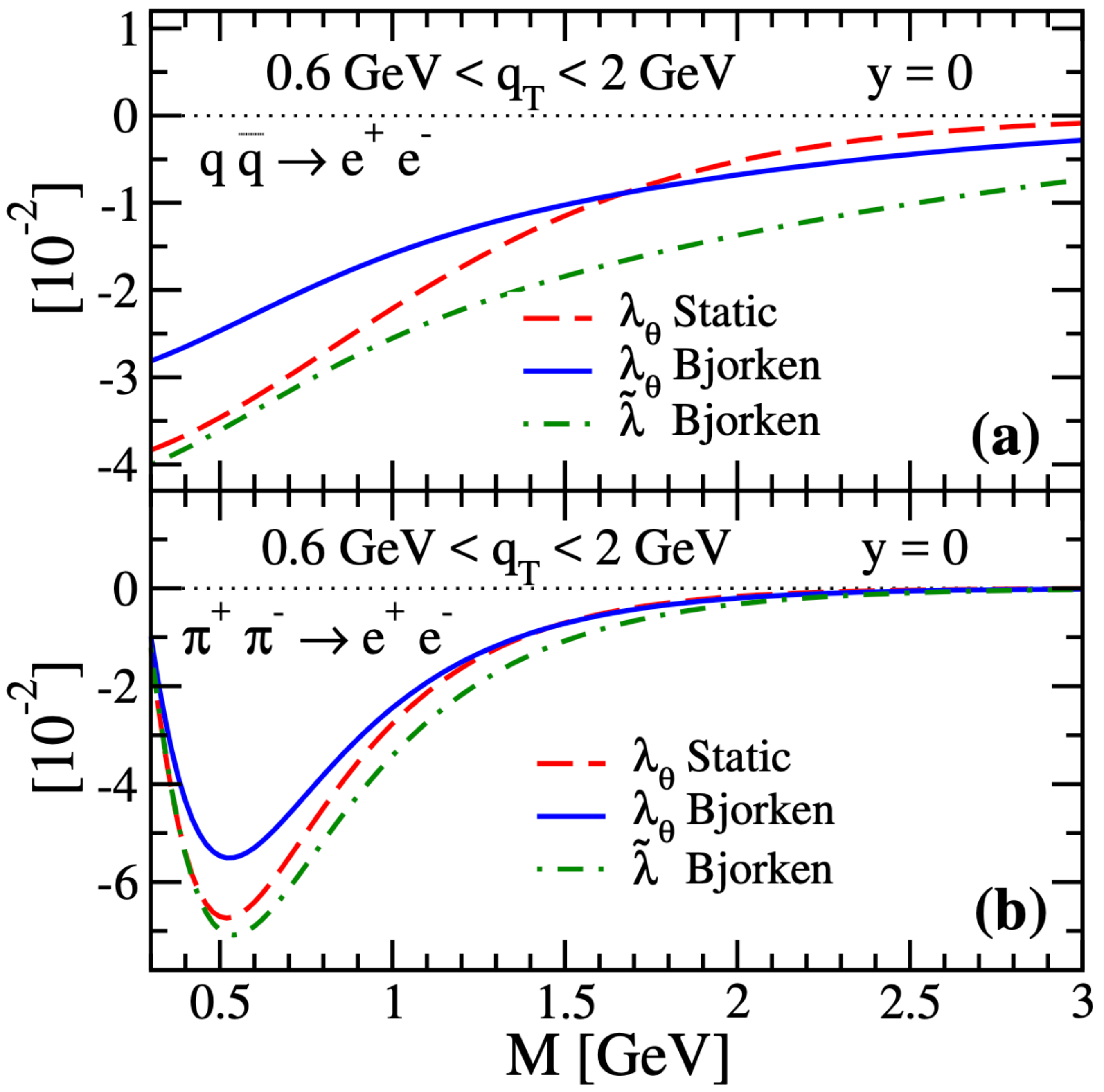
L. Adamczyk et al., Phys. Rev. C, 2017.
H. v. Hees, R. Rapp. Phys.Rev.Lett. 97 (2006) 102301

Dileptons as polarimeter

Angular distribution of dilepton rate in the photon rest frame:

$$\frac{d\Gamma}{d^4q d\Omega_\ell} = \mathcal{N}\Big(1 + \lambda_\theta \cos^2\theta_\ell + \lambda_\phi \sin^2\theta_\ell \cos 2\phi_\ell + \lambda_{\theta\phi} \sin 2\theta_\ell \cos\phi_\ell + \lambda_\phi^\perp \sin^2\theta_\ell \sin 2\phi_\ell + \lambda_{\theta\phi}^\perp \sin 2\theta_\ell \sin\phi_\ell\Big)$$

- Anisotropy coefficients λ:
  - give info on γ* polarization.
  - relate to production mechanisms.
- Virtual photons from (unpolarized) thermal sources are polarized.
- Expect small but finite polarization.
  - need high-statistics future experiments.



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