Theory and phenomenology of electromagnetic probes

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Wayne State University

Quark Matter 2022

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Natural Sciences and Engineering Research Council of Canada
Conseil de recherches en sciences naturelles et en génie du Canada

Direct probes of the QCD medium

- Why study electromagnetic probes of the QGP?
  - Emitted at all stages of a collision (w/ negligible re-scattering) ⇒ precise information about the QGP
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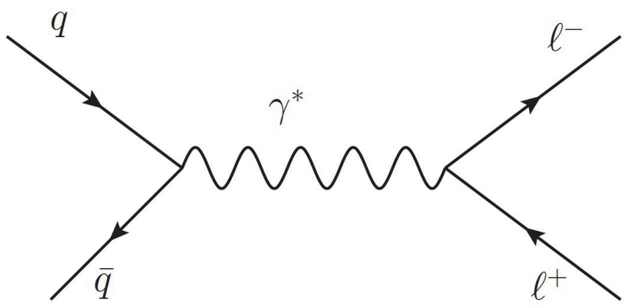

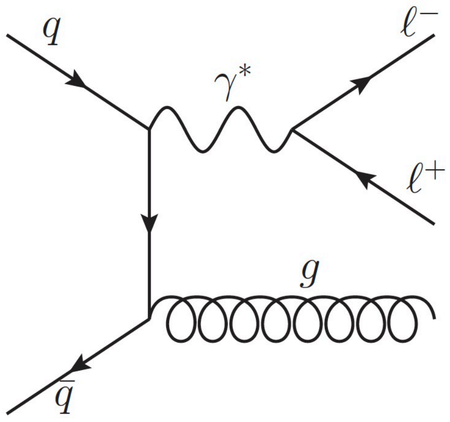

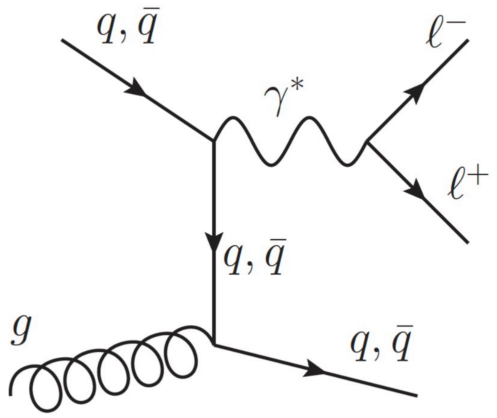

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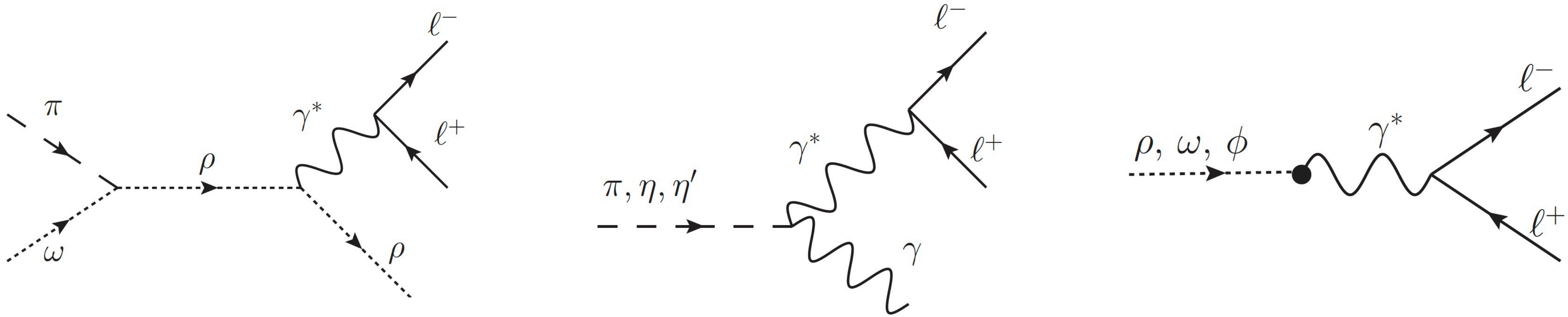

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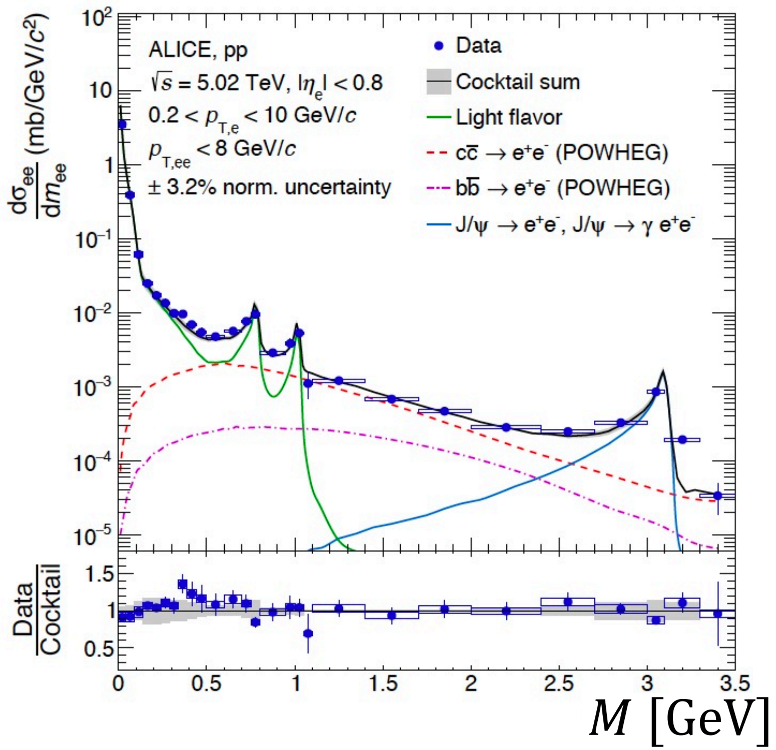
[ALICE, Phys. Rev. C 102, 055204 (2020)]



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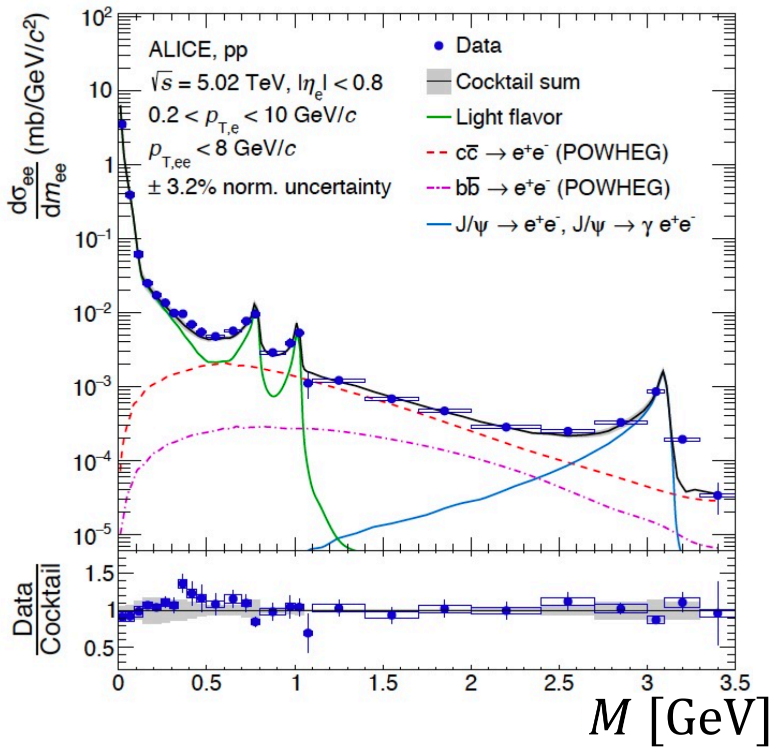

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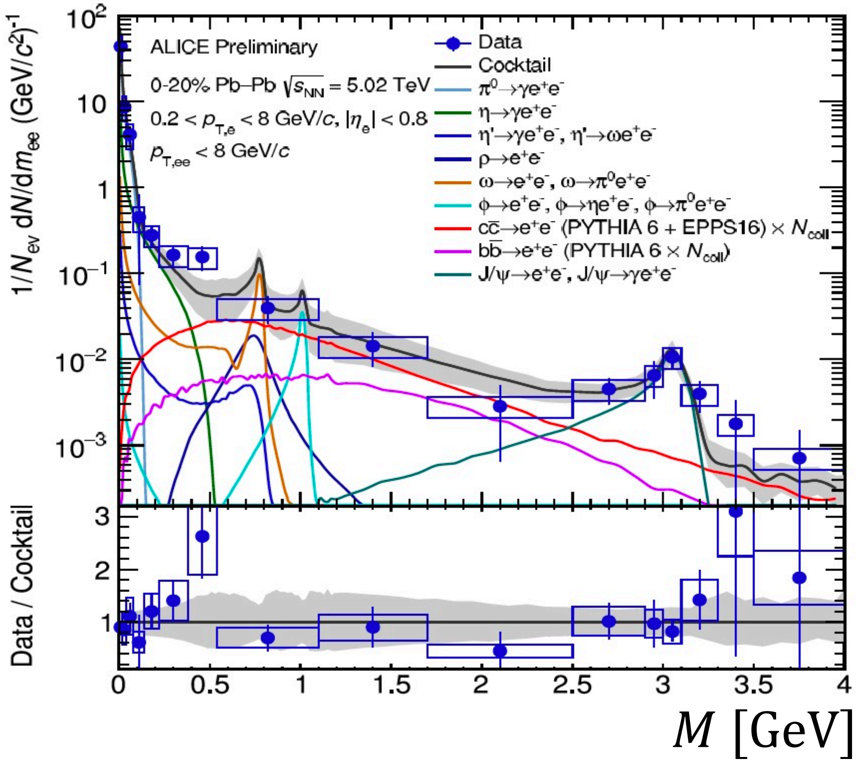

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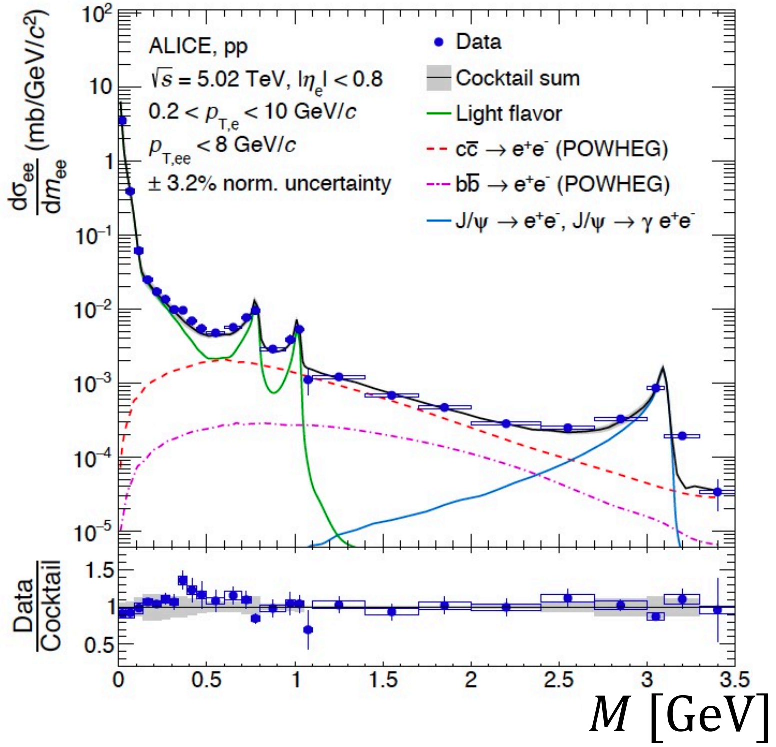

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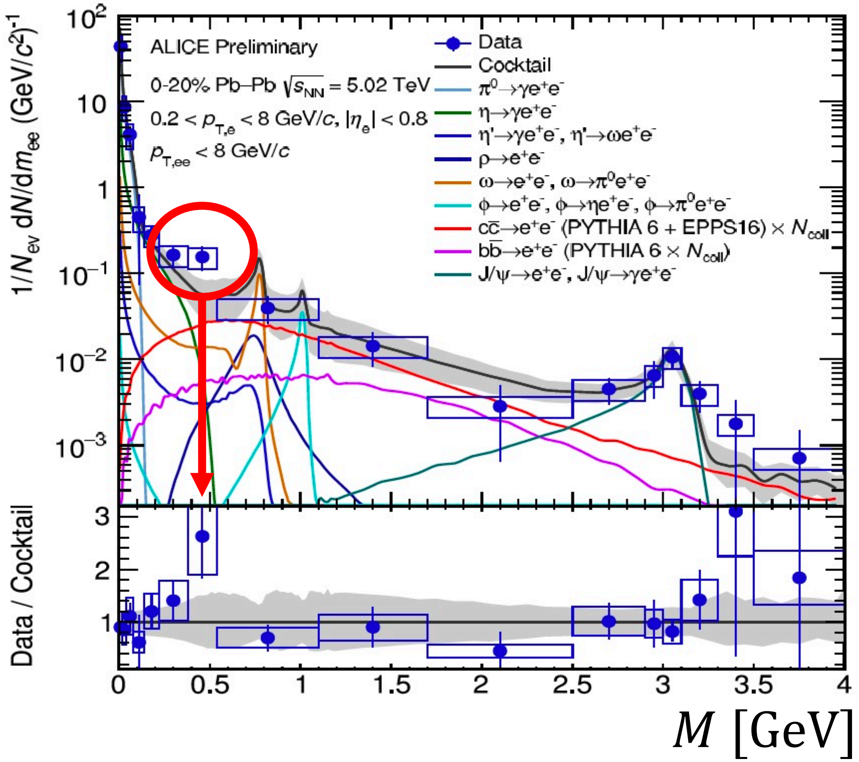

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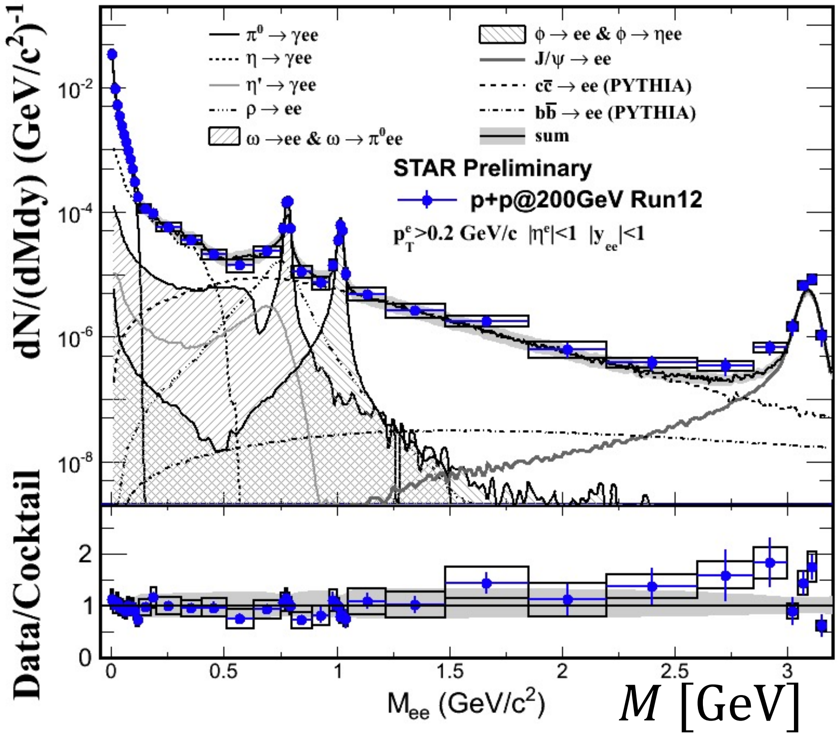

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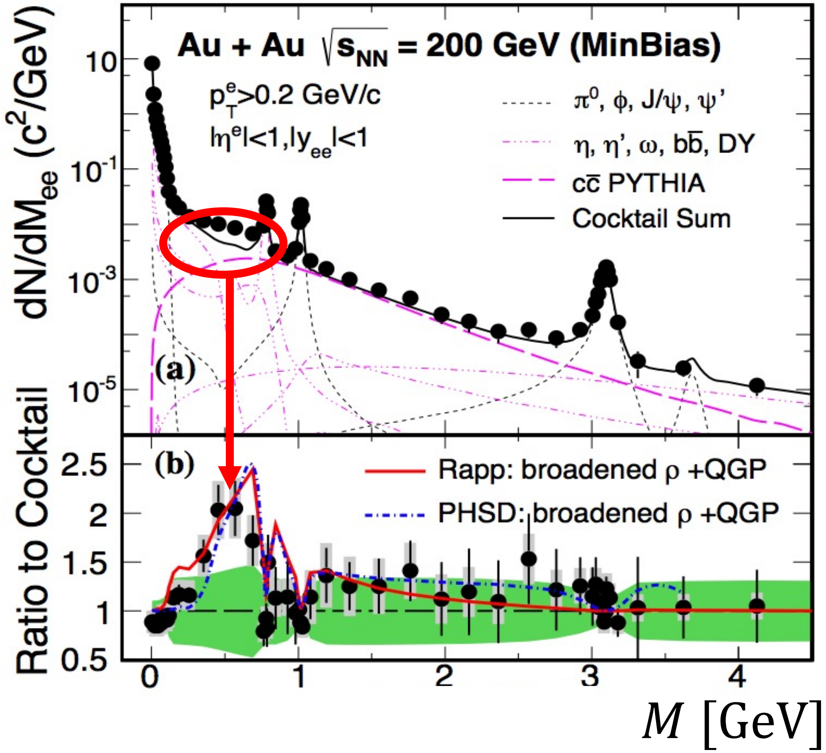

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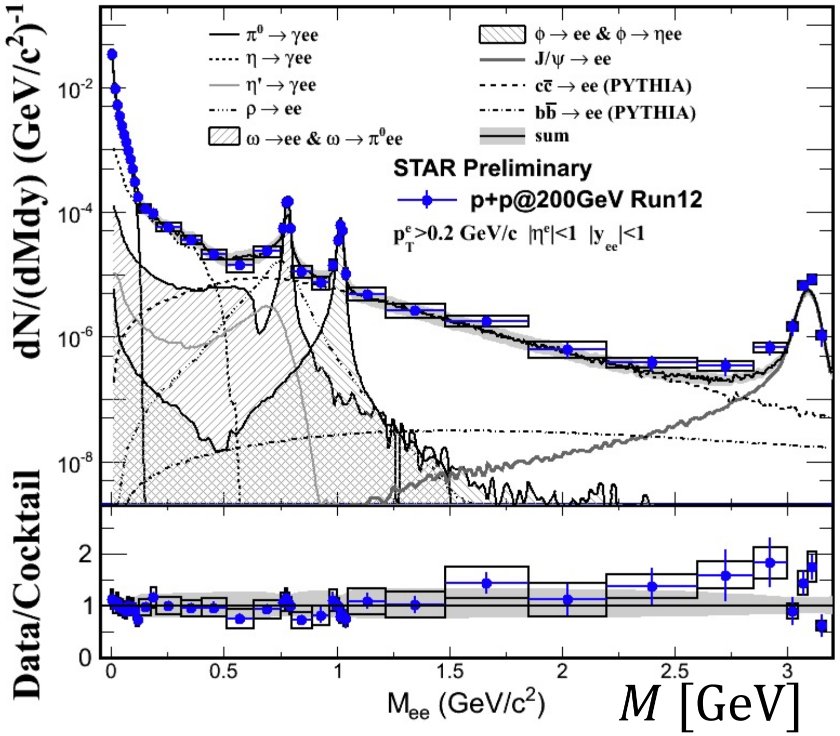

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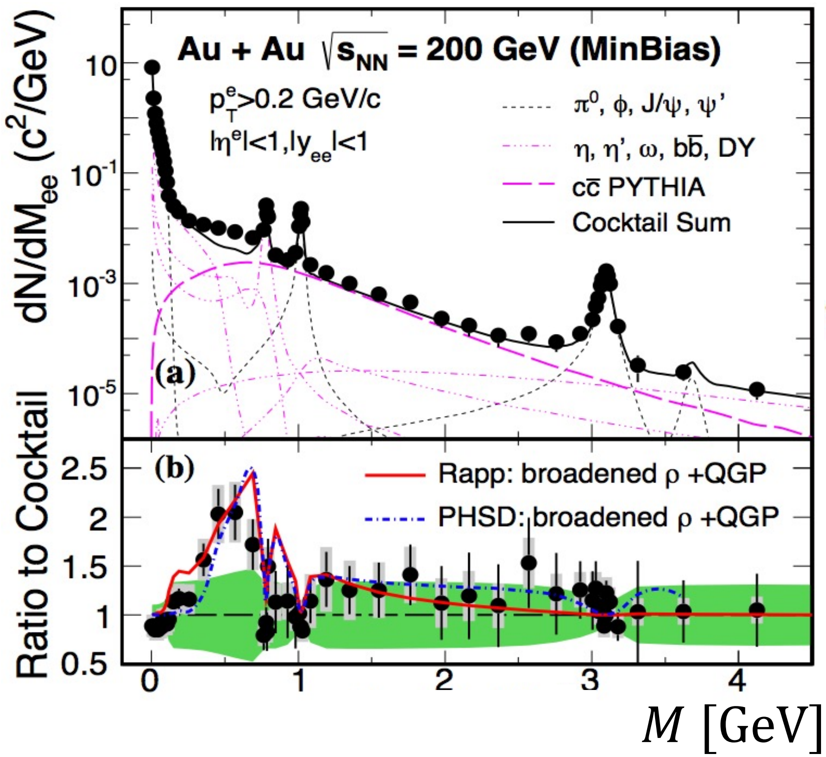
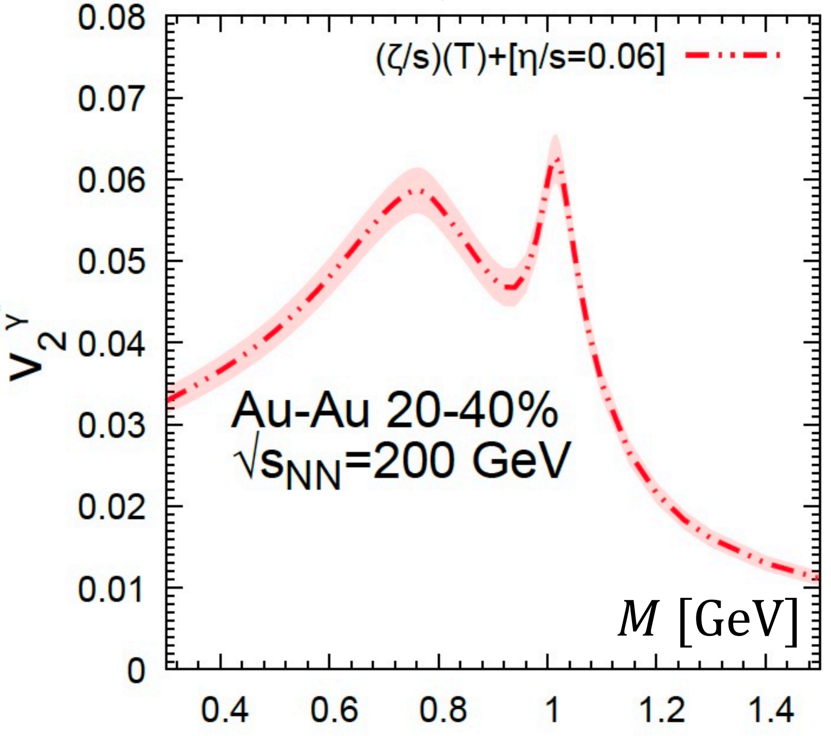


[G.V. et al., Phys. Rev. C 101, 044904 (2020)]

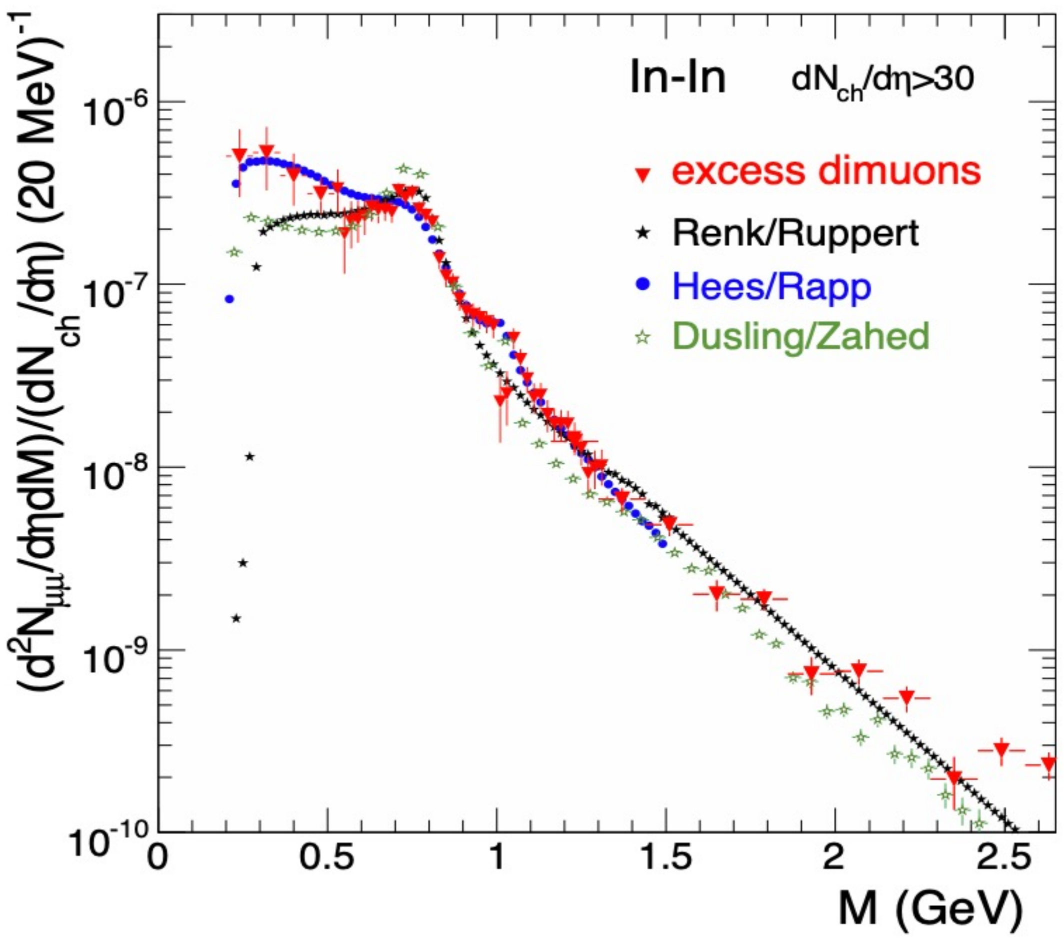


- Detailed study of QGP: measure dN/dM and $v_2(M)$, especially M $\gtrsim$ 1 GeV!

Direct probes of the QCD medium

- A high precision measurement of dileptons: NA60 dimuon experiment

[NA60, Prog. Part. Nucl. Phys. 62, 486 (2009)]



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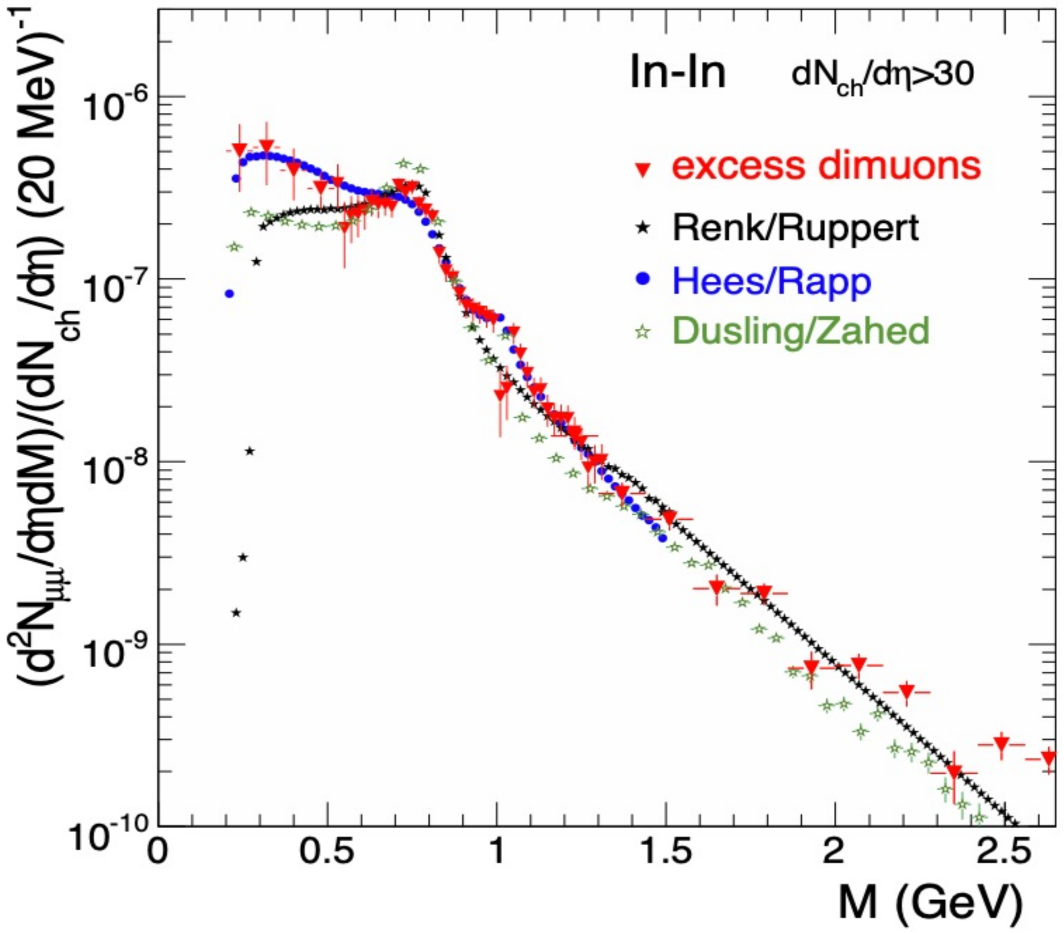

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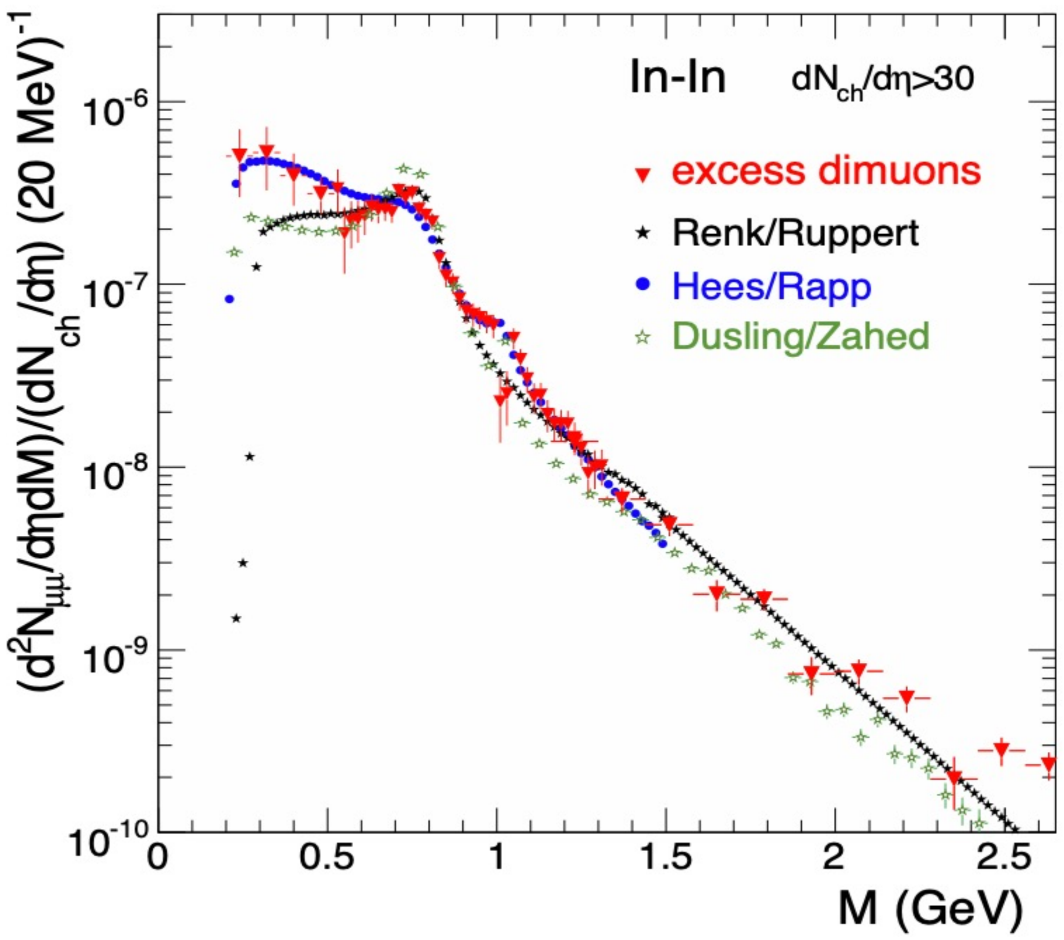

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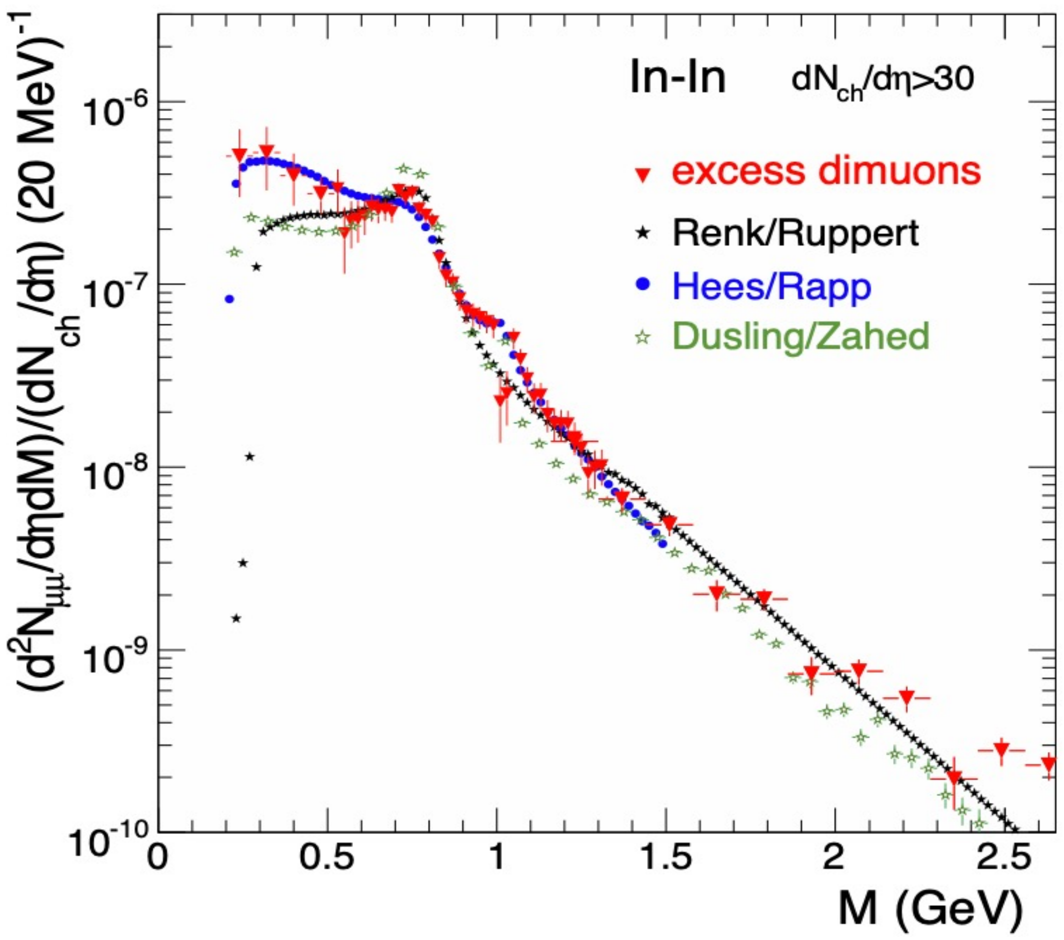

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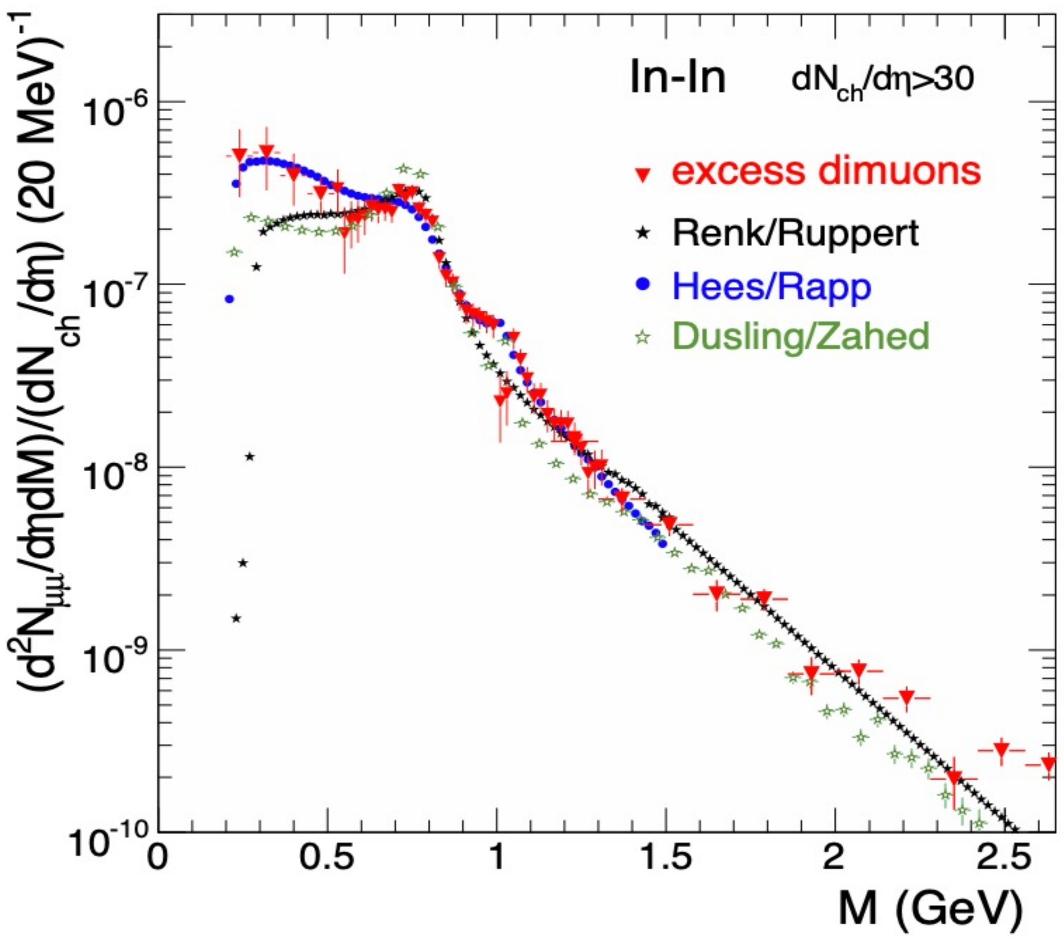

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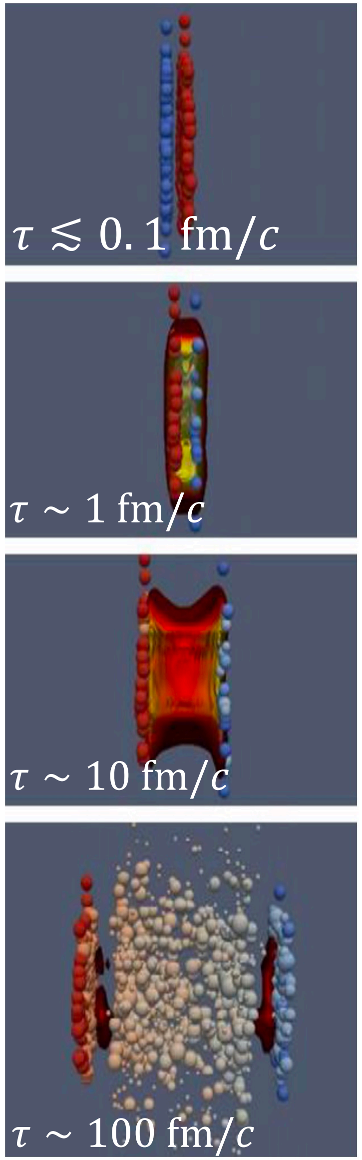
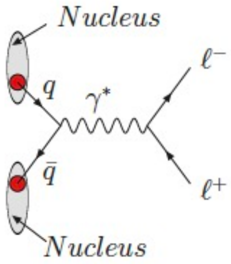
    e.g. shear viscosity (η)?
- Measurement of dilepton $v_2(M)$
  - HADES: Quark Matter 2022 [N. Schild, Wed 19:18]
  - upcoming from ALICE and NA60+
- Exploring sources of EM radiation

Sources of EM probes

Figure ref. J. Bernhard, H. Elfner (Petersen), MADAI Collaboration

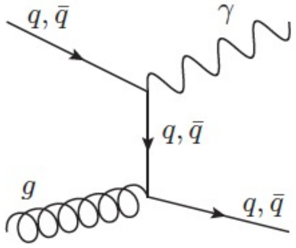


- Onset of collisions:
  - Prompt photons [C. Sirimanna, Wed 18:42; R. Modarresi-Yazdi, Thu 18:10]
  - Drell-Yan dileptons [M. Coquet, Wed 19:06]
  - Heavy Quarkonia
  - Open Heavy Flavor



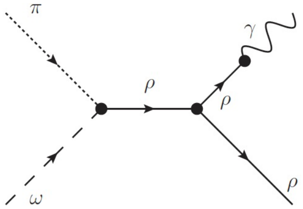
- Pre-hydrodynamical evolution/jet-medium interaction
  - EM production coming from various partonic processes
    [J.-F. Paquet, Wed 18:34; C. Sirimanna, Wed 18:42; S. Park, Thu 16:00; R. Modarresi-Yazdi, Thu 18:10]
- Hydrodynamical evolution
  - EM production coming from partonic and hadronic processes

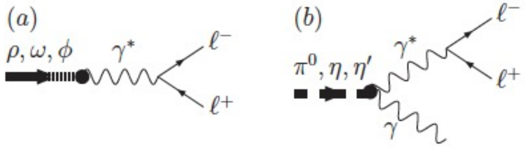
    [J.-F. Paquet, Wed 18:34; G. Jackson, Wed 18:46; T. Nishimura Wed 19:02; S. Floerchinger, Wed 19:18; P. Dasgupta, Wed 19:26; C. Nonaka, Thu 18:30]



- Transport evolution
  - EM production from hadronic interactions

  [O. Garcia-Montero, Wed 18:58; R. Hirayama, Wed 19:10; M. Wiest, Wed 19:14]





EM probes and the QGP

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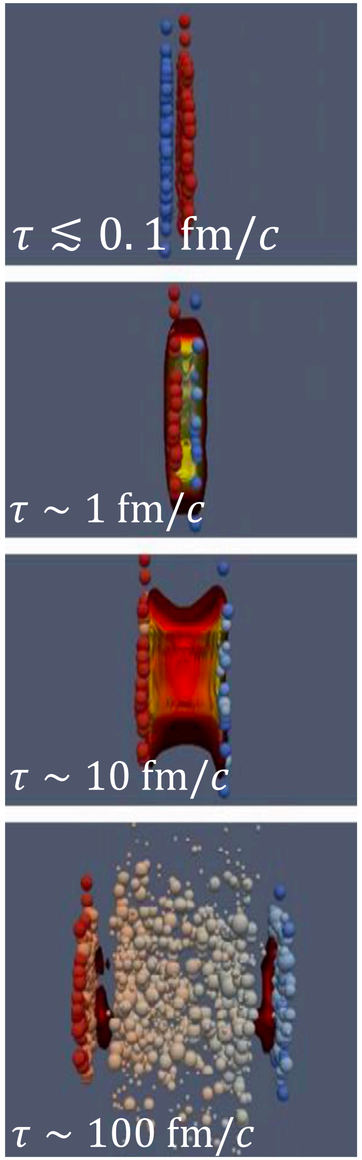

- Bayesian analysis simulating various stages for soft hadronic observables are starting to inform us about transport coefficients.

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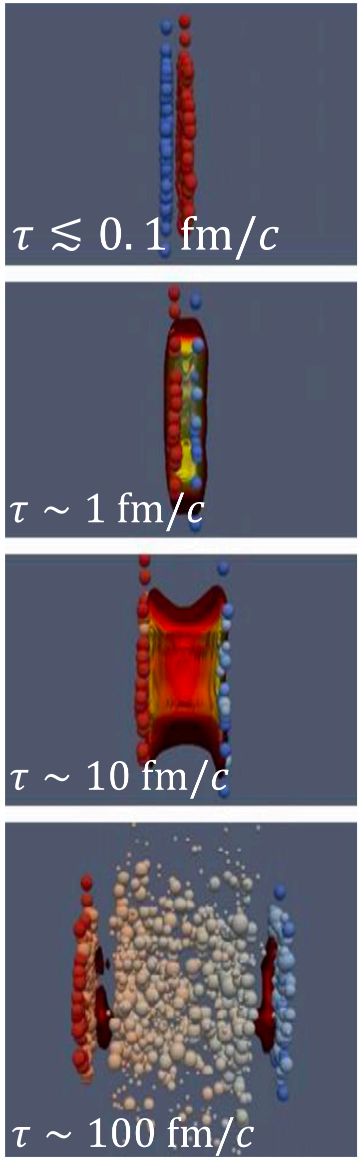

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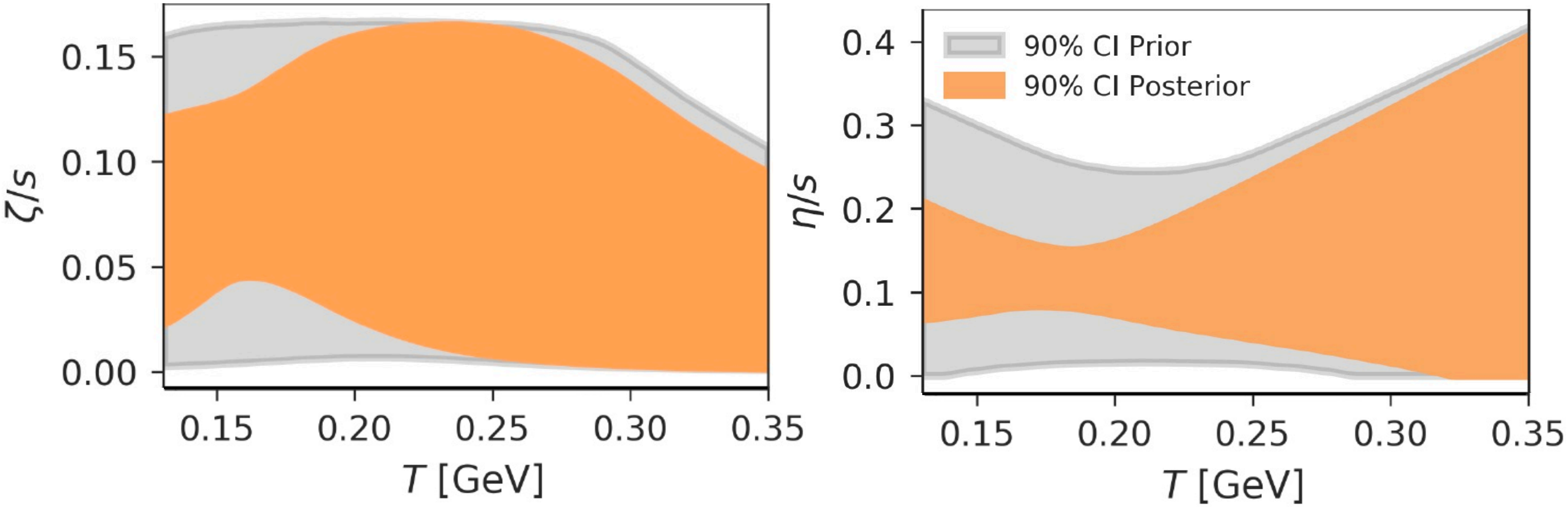
[D. Everett et al., Phys. Rev. Lett. 126, 242301 (2021)]



Bayesian Analysis by the JETSCAPE Simulations Group

EM probes and the QGP

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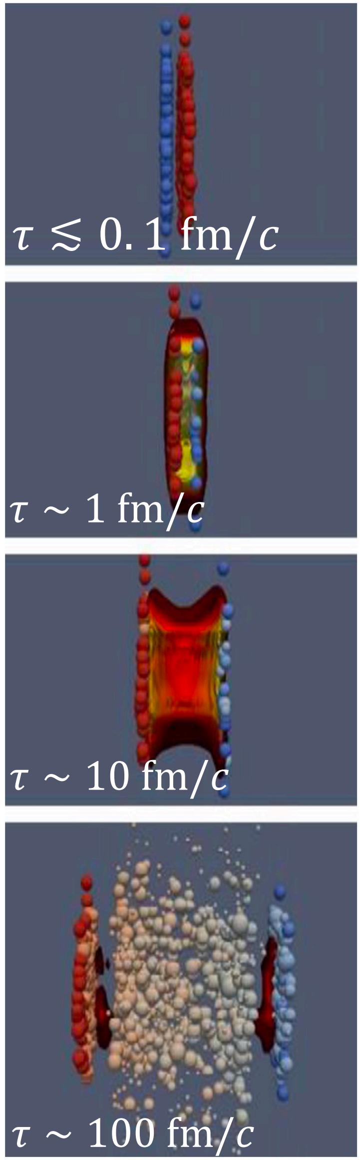

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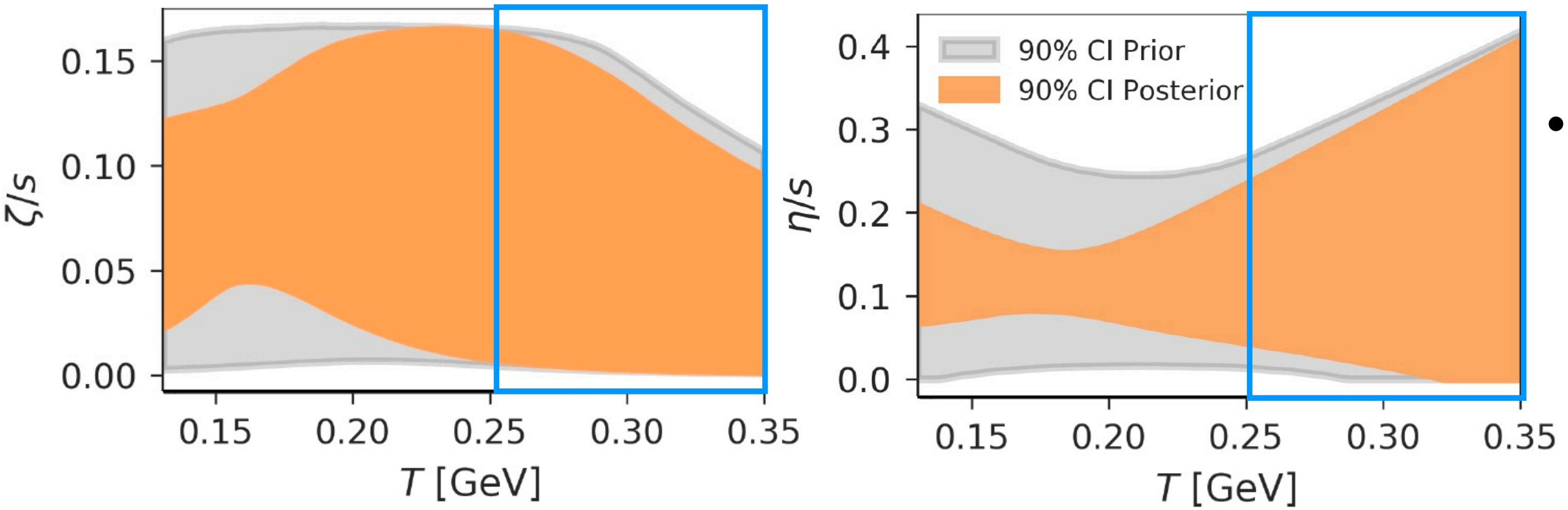

- Soft hadron observables give a better description at low T.

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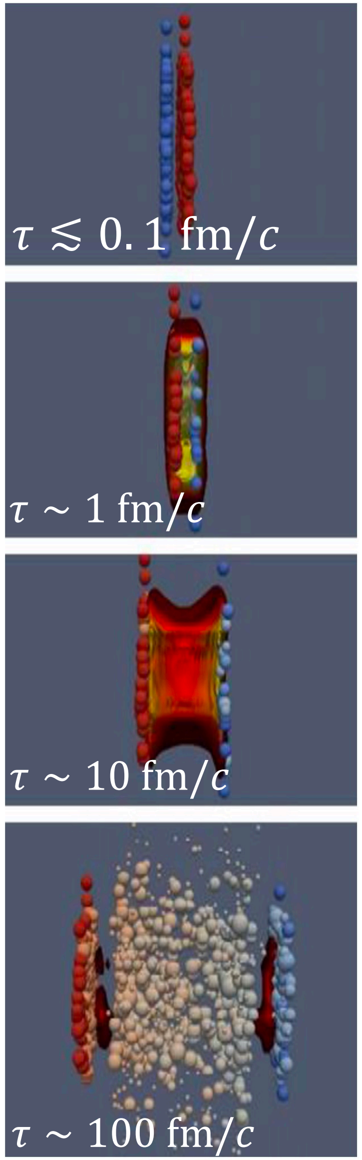

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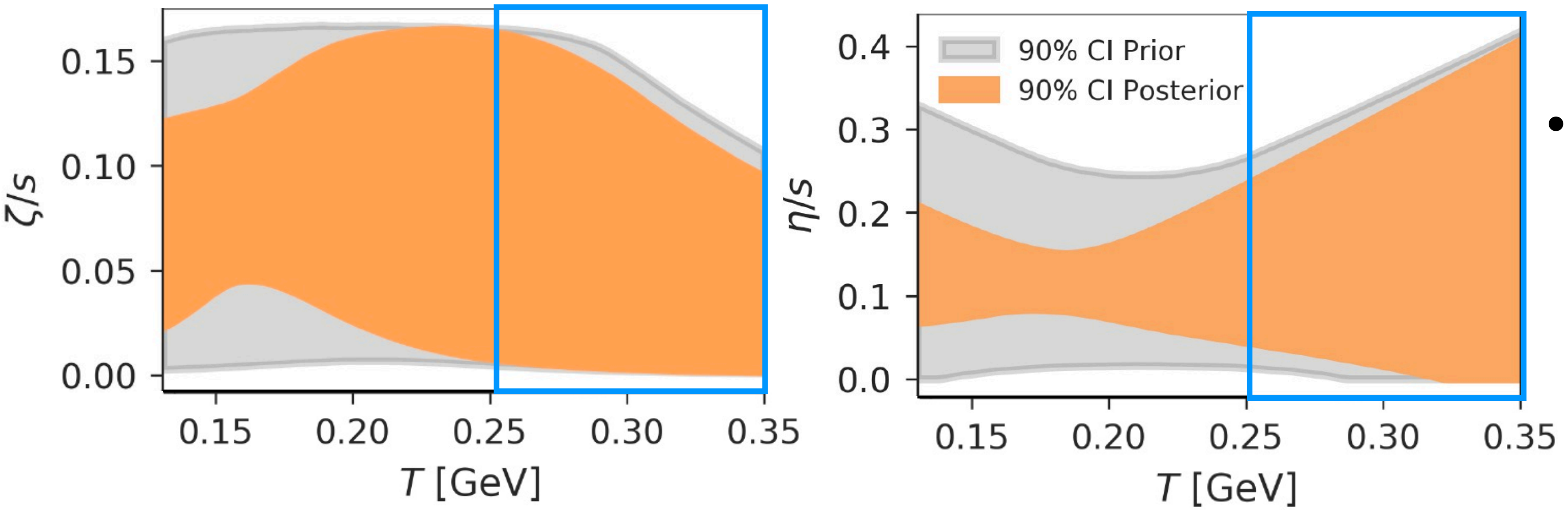


- Soft hadron observables: not enough?

Bayesian Analysis by the JETSCAPE Simulations Group

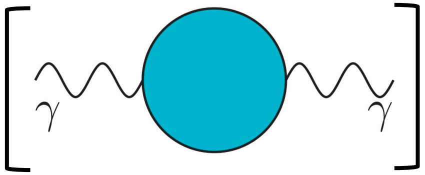
- v_n of EM probes ⇒ directly probe microscopic d.o.f. of nuclear matter and can better constrain $\frac{\eta}{s}, \frac{\zeta}{s}$

Dilepton emission

Electromagnetic radiation from QCD medium

- Finite Temperature Field Theory
  - Dilepton production rate

$$\frac{d^4R}{d^4k} \propto -\alpha_{EM}^2 Im$$



$k^2 = M^2 \geq 0$

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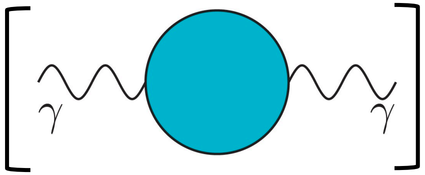

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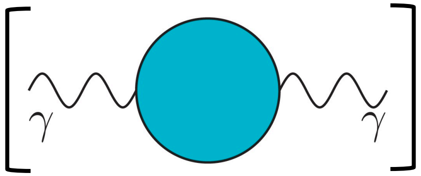

= EM Spectral Function

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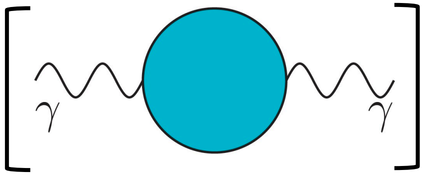

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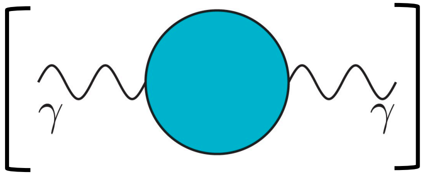

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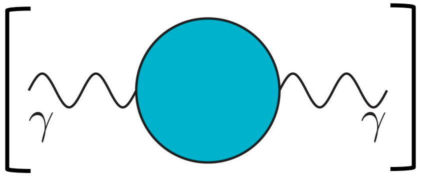
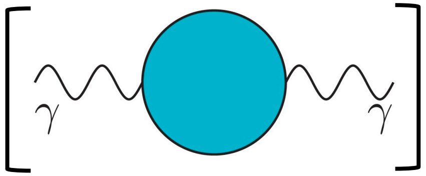


= EM Spectral Function

- EM spectral function in pQCD or on the Lattice

$$G_V(\tau) = \int \frac{dk^0}{\pi} K(k^0,\tau)\, Im$$



;

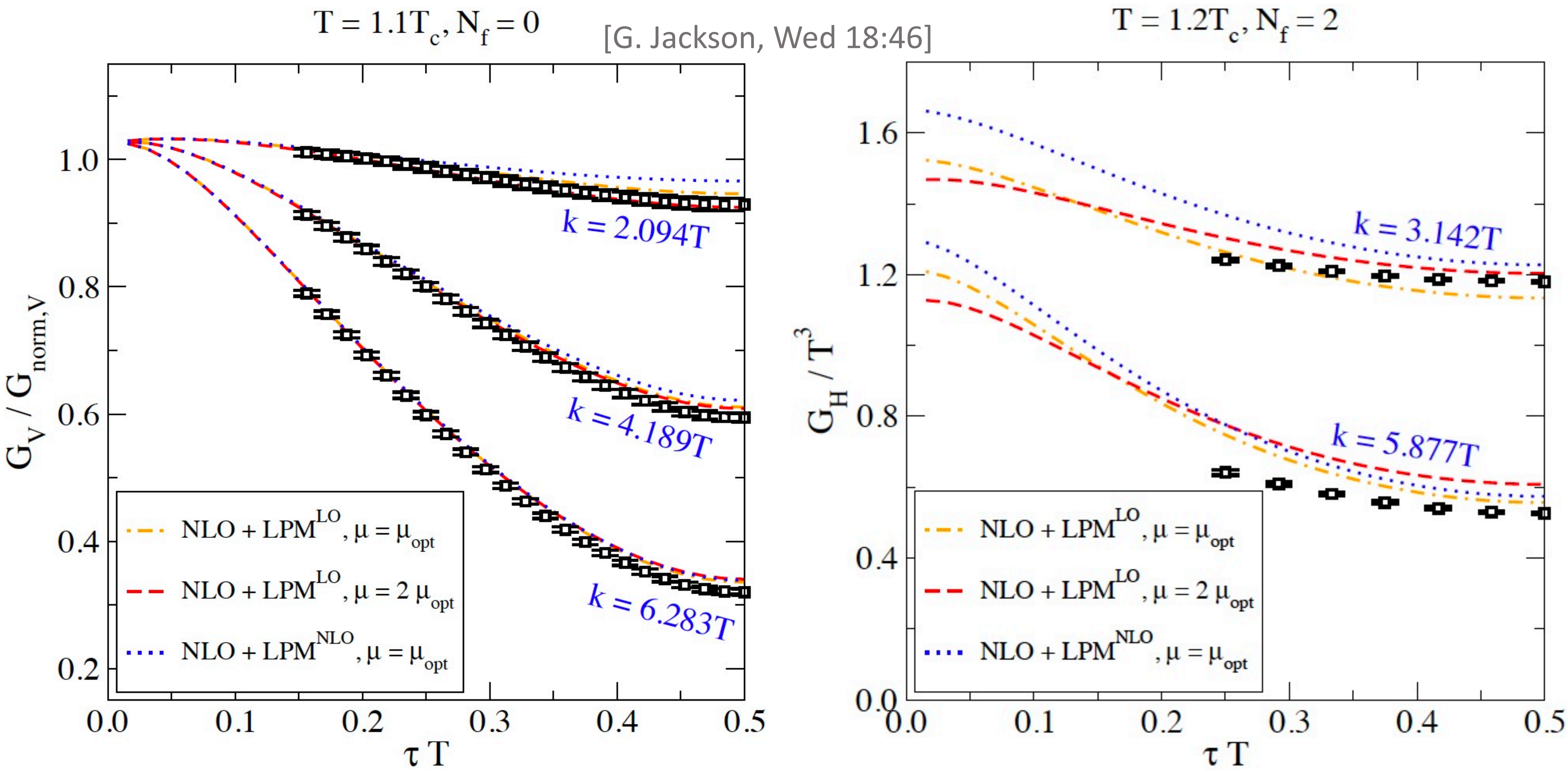
$$K(k^0,\tau) = \frac{\cosh\{k^0[1/(2T) - \tau]\}}{\sinh(k^0/2T)}$$

- Hadronic sector, sensitive to chiral symmetry breaking

Dilepton production from pQCD & lattice QCD ✓

- Quite good agreement between pQCD and lattice QCD in the (un-)quenched.

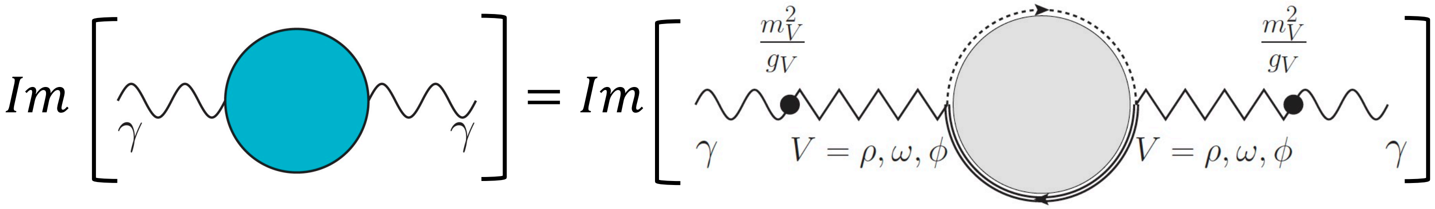
[G. Jackson, Wed 18:46]



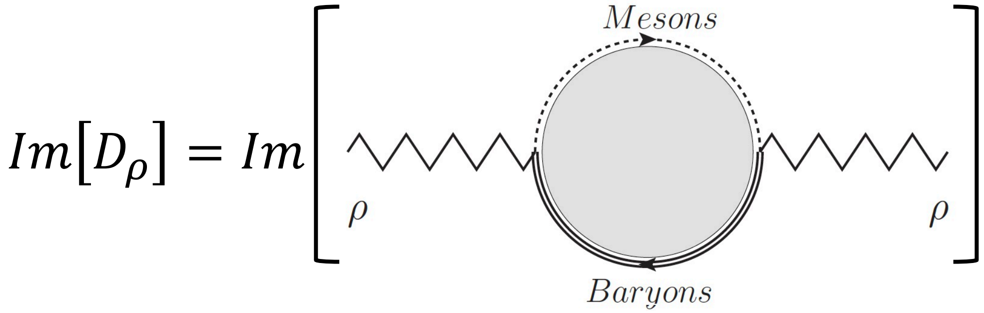
- Entering the era for precision calculations of EM spectral functions; with extension to $\boldsymbol{\mu_B > 0}$.

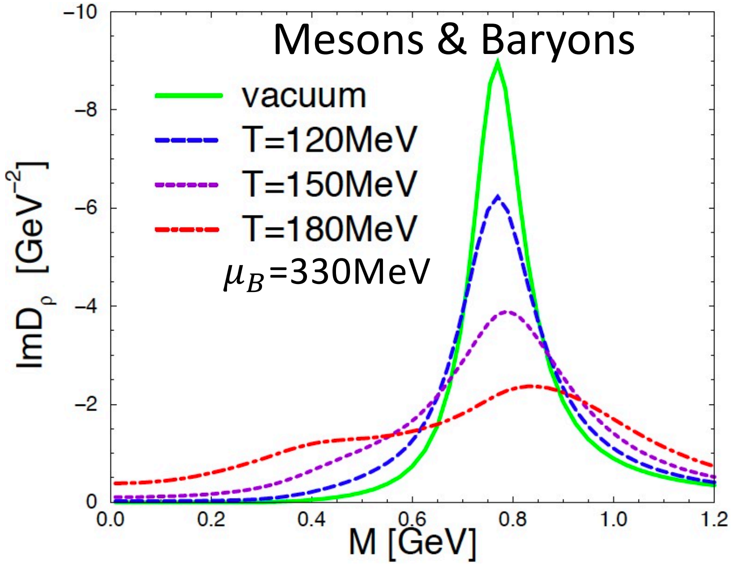
Dilepton production from hadronic interactions

- EM spectral function via vector mesons

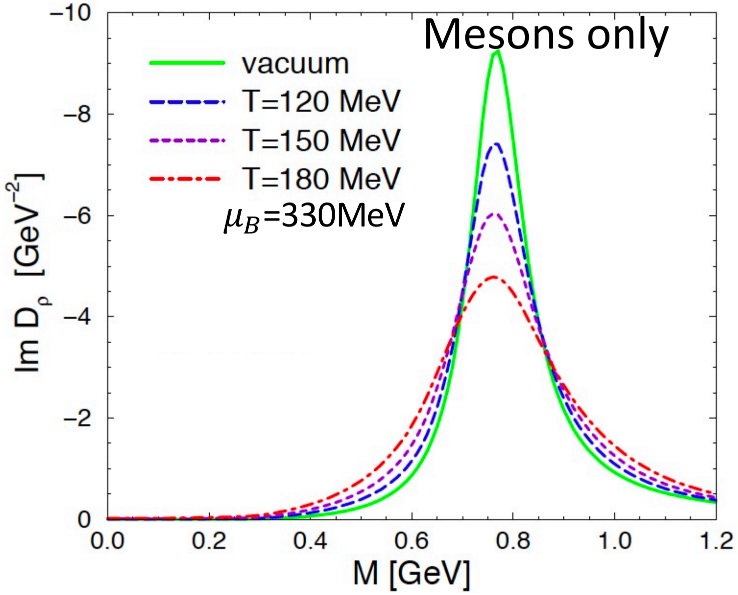


- Many-body effective Lagrangians





[R. Rapp, Acta Phys. Polon. B 42, 2823 (2011)]



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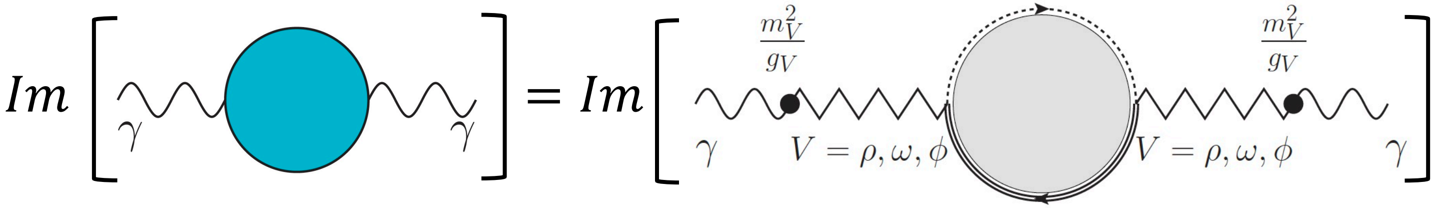

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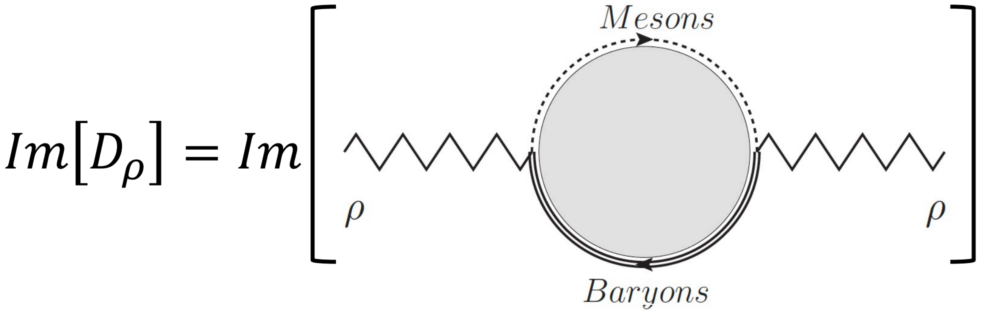
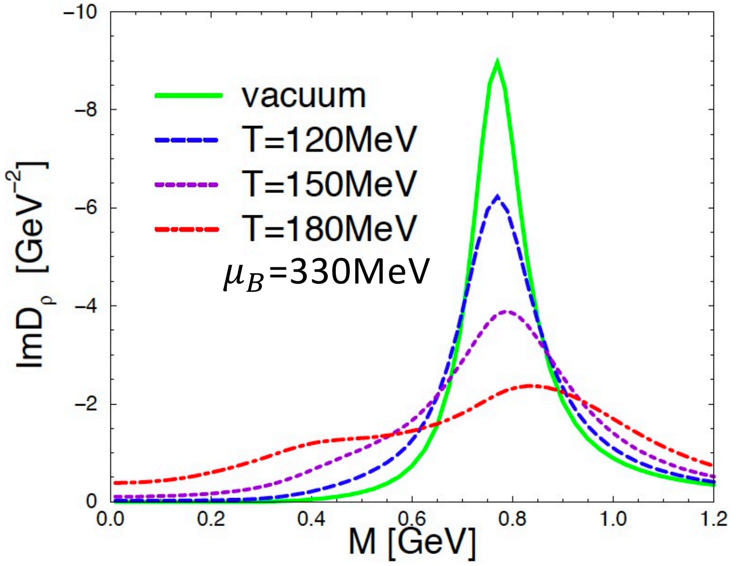
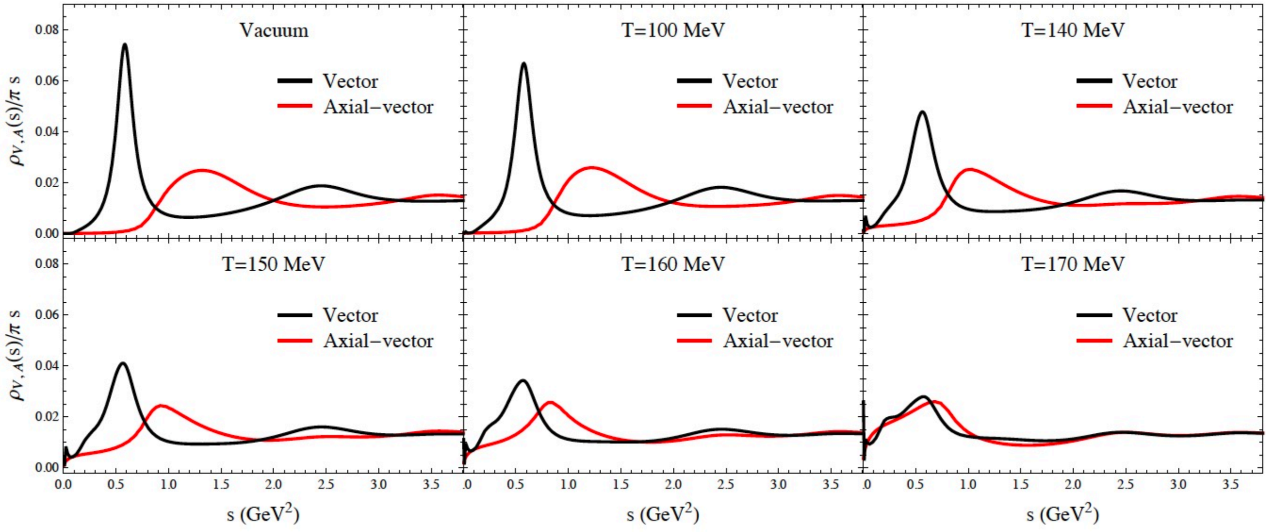




[R. Rapp, Acta Phys. Polon. B 42, 2823 (2011)]

- Many-body effective Lagrangians now include the chiral partner of ρ, the a_1
  - ρ & a_1 agree at high T ⇒ encouraging for understanding chiral symmetry restoration from a hadronic perspective.



[P.M. Hohler & R. Rapp, Phys. Lett. B 731, 103 (2014)]

Dilepton production in a viscous medium ✓

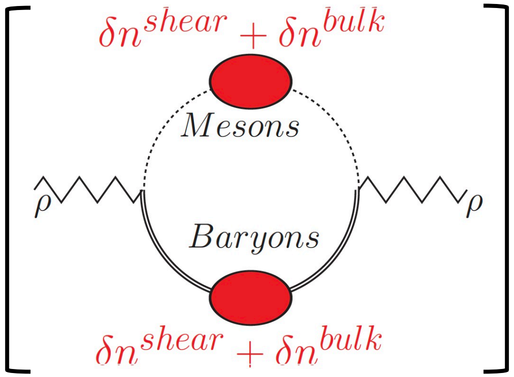
- Theory ⇒ Experimental observables

$$\frac{d^4N}{d^4k} = \int d^4x\, \frac{d^4R}{d^4k}\left[u^\mu(x), T(x), \pi^{\mu\nu}(x), \Pi(x)\right]$$

$$T^{\mu\nu}_{eq.} + \pi^{\mu\nu} - \Pi\Delta^{\mu\nu} = \int \frac{d^3k}{(2\pi)^3 k^0} k^\mu k^\nu \left[n^{eq.} + \delta n^{shear} + \delta n^{bulk}\right]$$

- Dileptons from (hadronic) scattering theory

$$\frac{d^4R}{d^4k} \propto Im$$



[Eletsky et al., Phys. Rev. C 64, 035202 (2001)]
[G.V. et al., Phys. Rev. C 101, 044904 (2020)]

- Dileptons from LO pQCD

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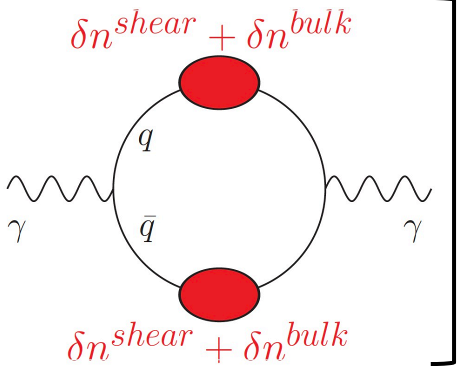

[G.V. et al., Phys. Rev. C 98, 014902 (2018)]
[G.V. et al., Phys. Rev. C 101, 044904 (2020)]

Dileptons as "timer", thermometer & viscometer

- Size of $\int \frac{dN}{dM} \in 0.3 < M < 0.7$ GeV [R. Rapp, H. van Hees, Phys. Lett. B 753, 586-590 (2016)]
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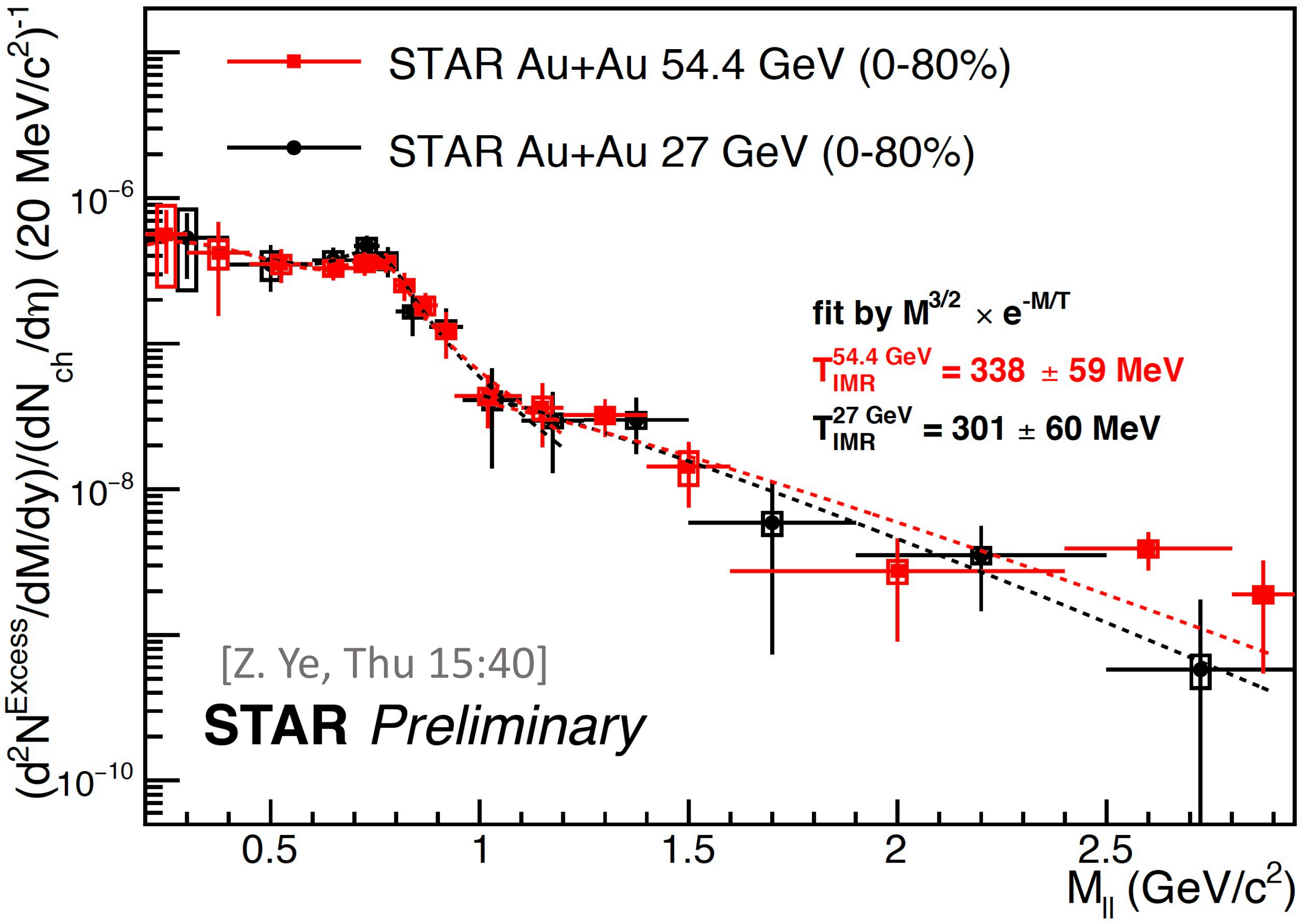

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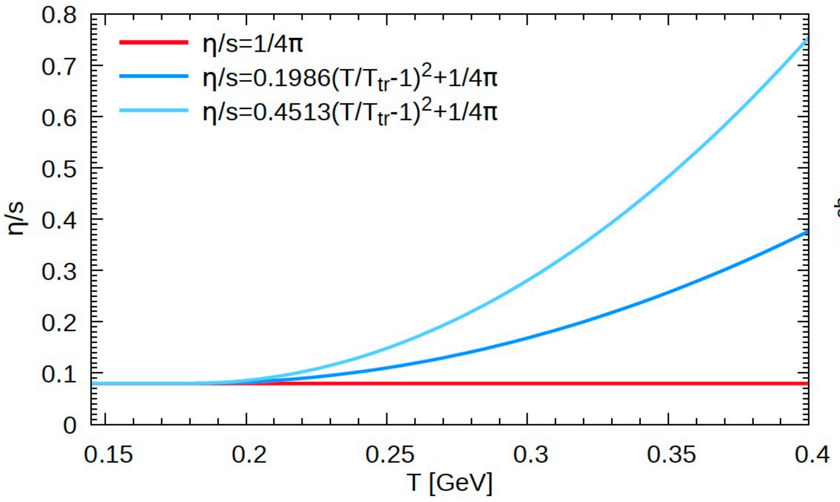

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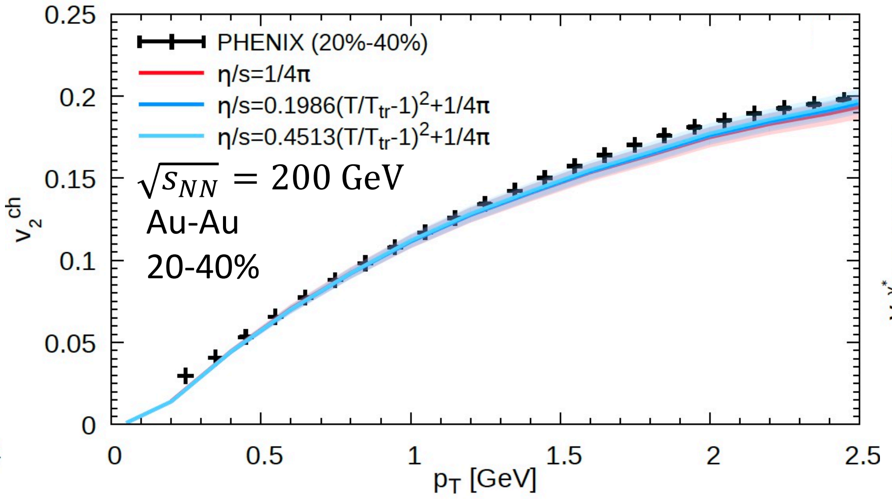

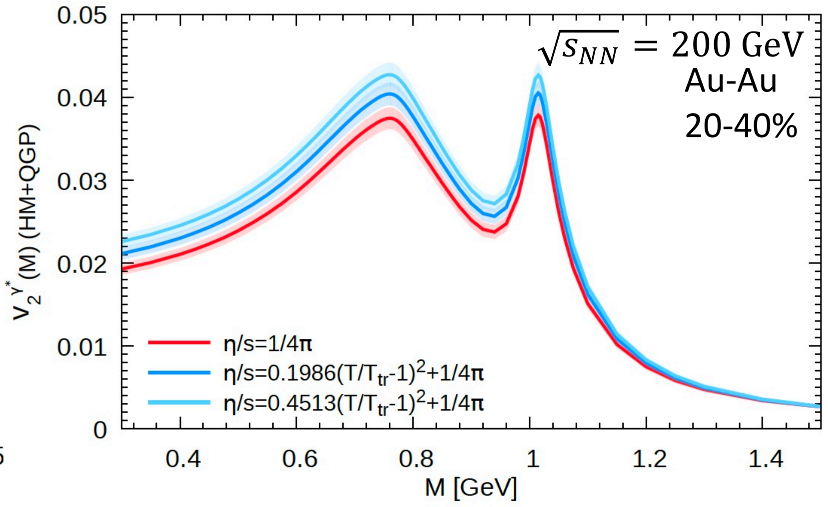

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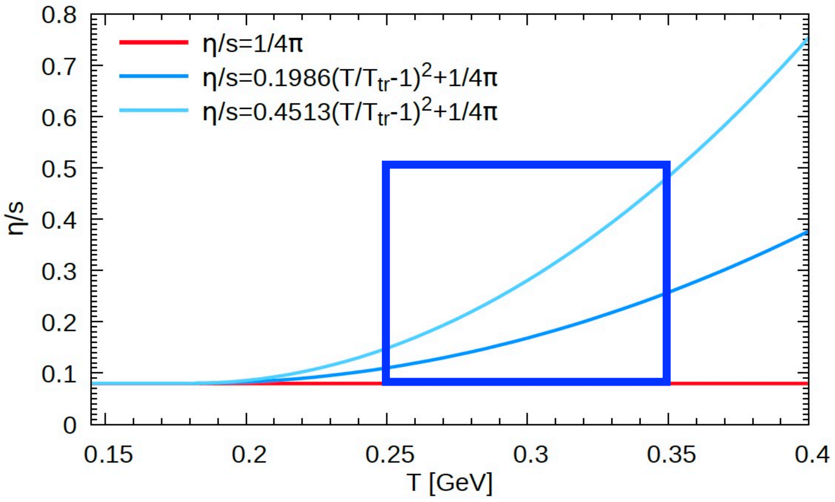

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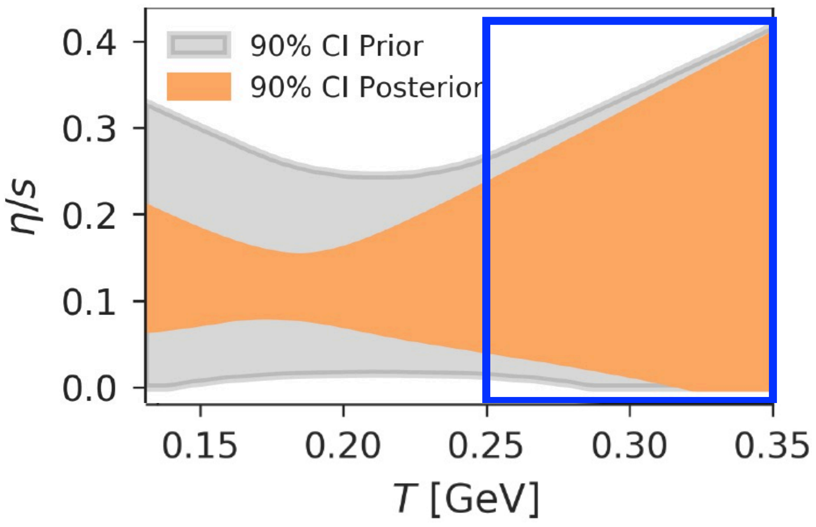
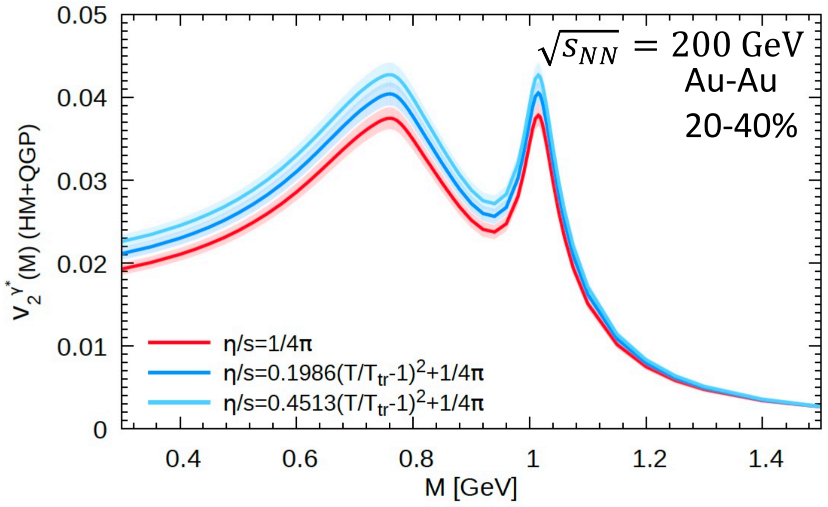


[D. Everett et al., Phys. Rev. Lett. 126, 242301 (2021)]



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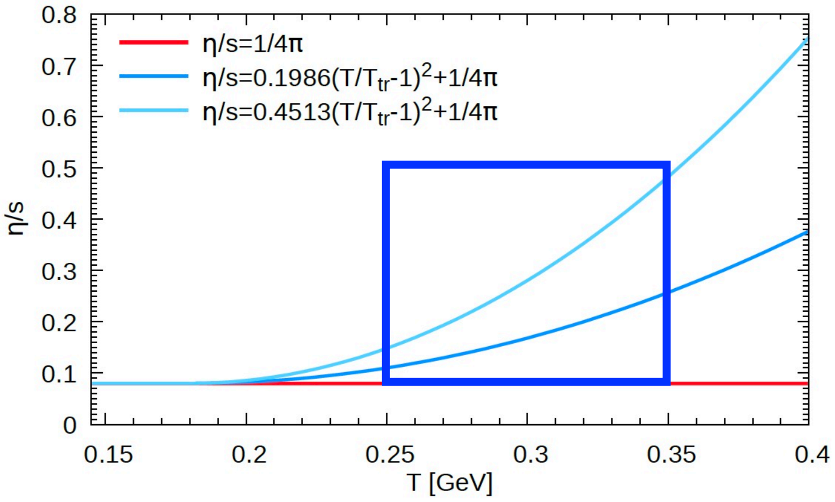

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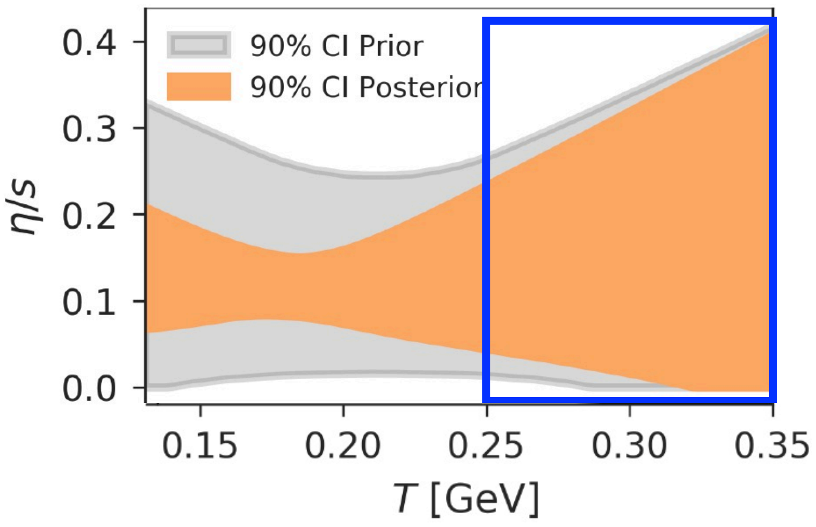

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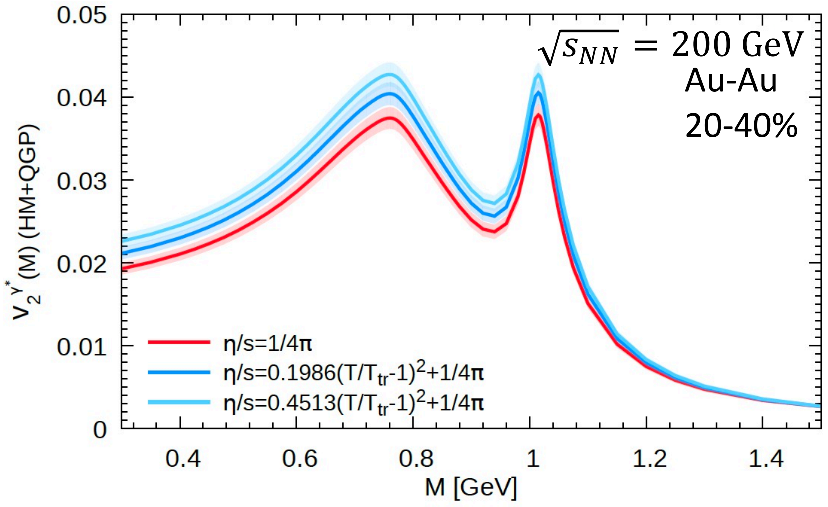

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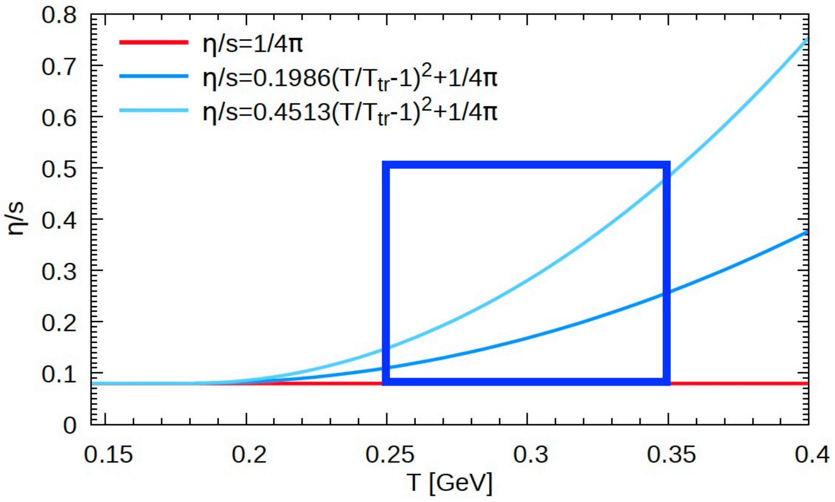

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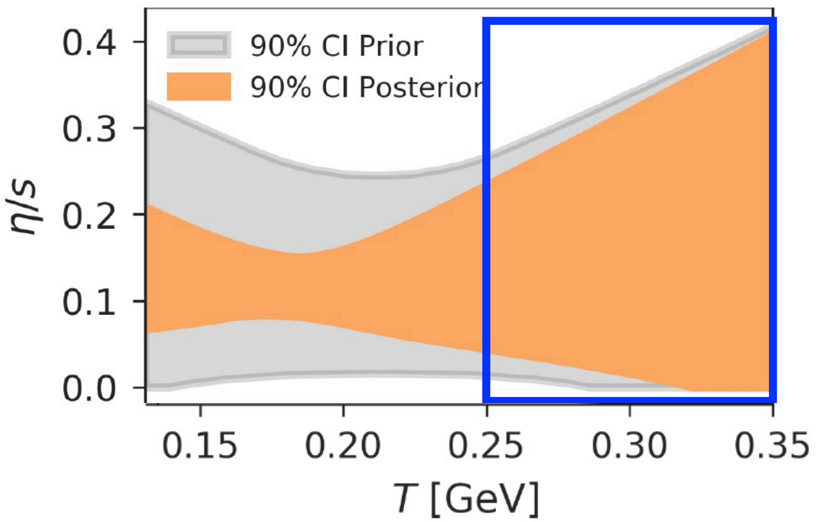

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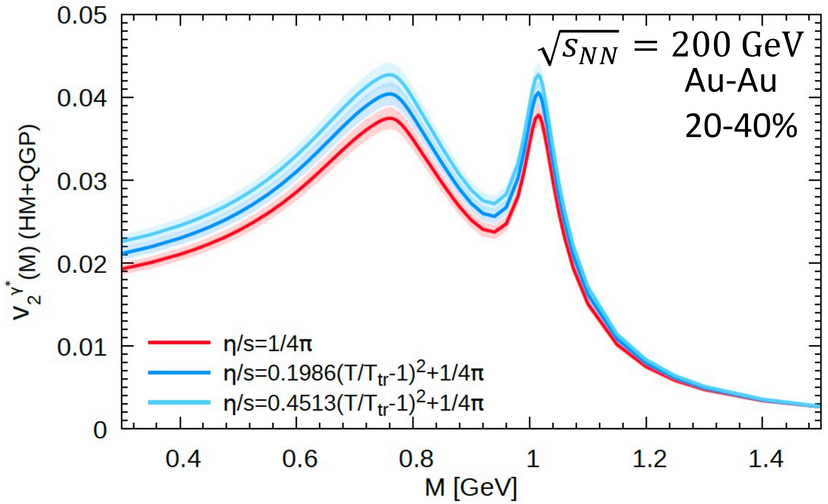


[G.V. et al., Phys. Rev. C 98, 014902 (2018)]

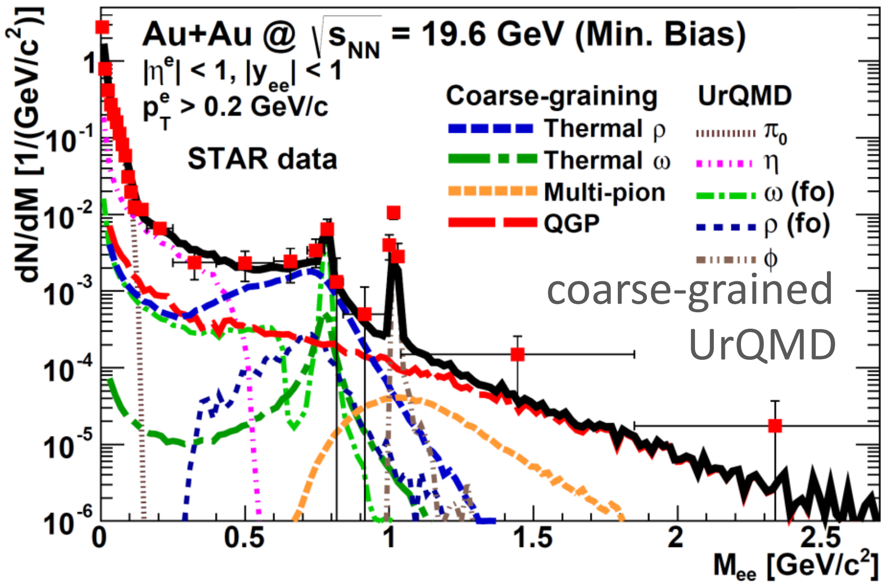
- A joint Bayesian analysis (dileptons & hadrons) to help constrain on $(\eta/s)(T)$.
- An accurate measurement of dilepton v_2 is needed at high $\sqrt{s} \Rightarrow$ possible following ALICE upgrade

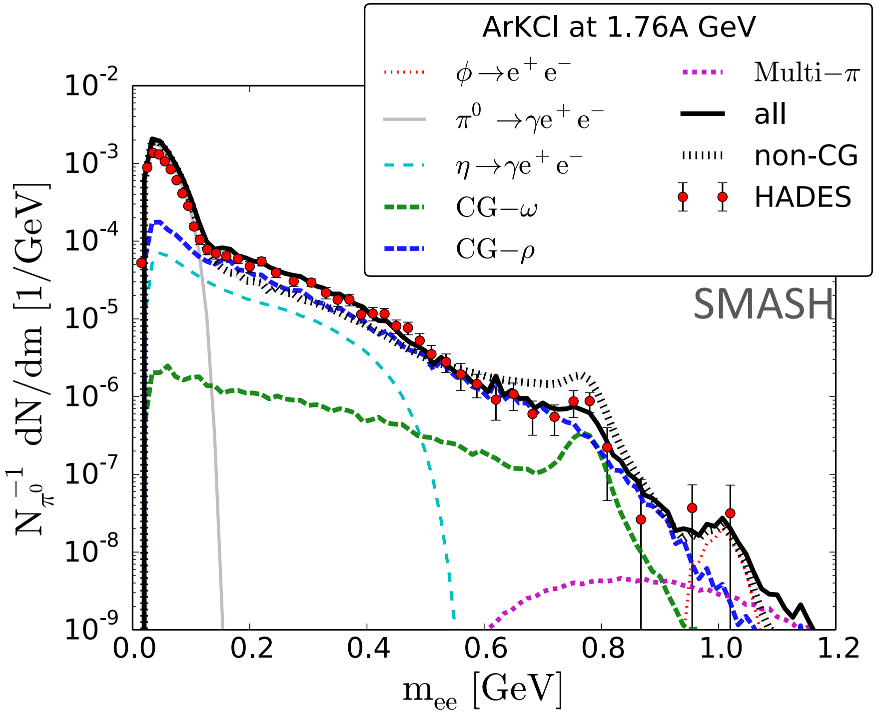
[CERN Yellow Rep. Monogr. 7, 1159 (2019)]

Dileptons from transport

- At lower $\sqrt{s_{NN}}$, more dileptons from transport

[S. Endres al., Phys. Rev. C 94, 024912 (2016)]





[R. Hirayama, Wed 19:10]

Dileptons from transport & hydrodynamics

- At lower $\sqrt{s_{NN}}$, more dileptons from transport & hydrodynamics at $\mu_B > 0$ with 1st order PT EoS

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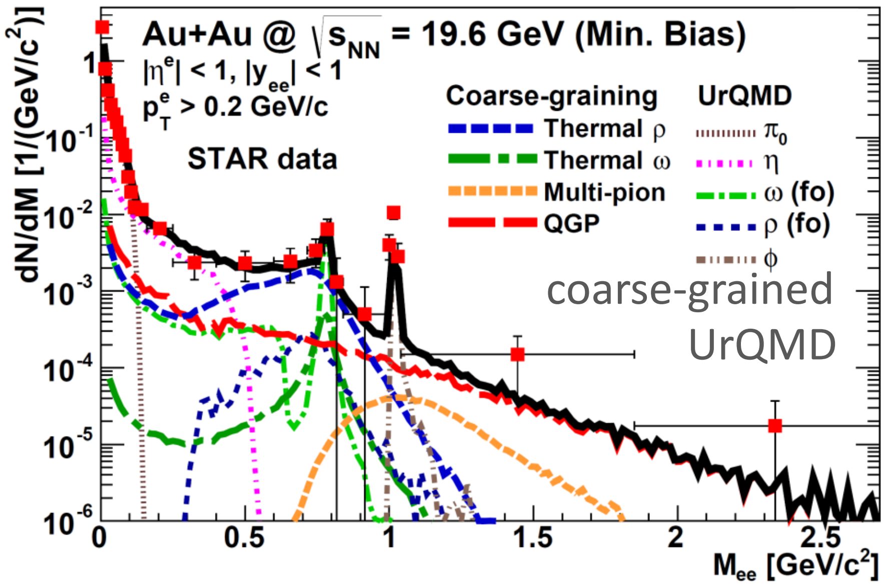

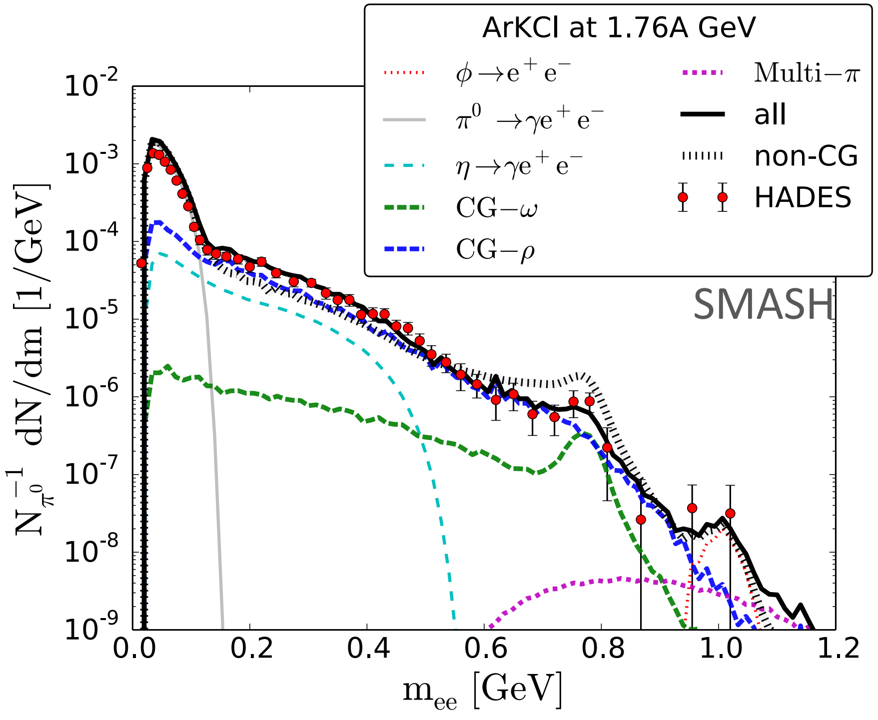

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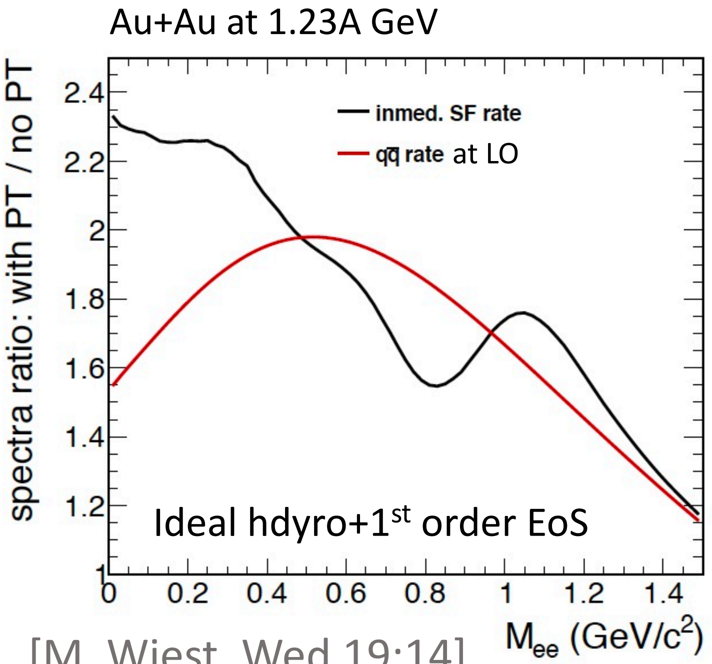

[M. Wiest, Wed 19:14]

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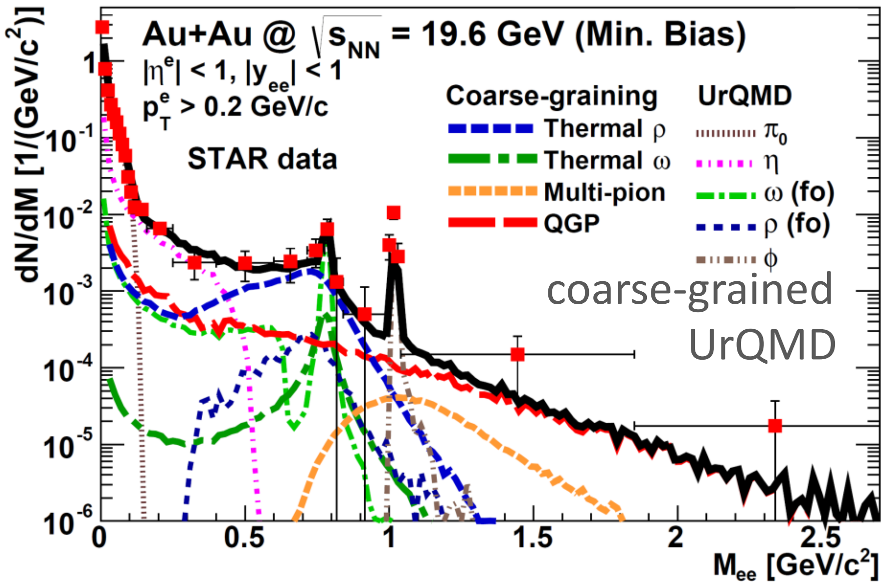

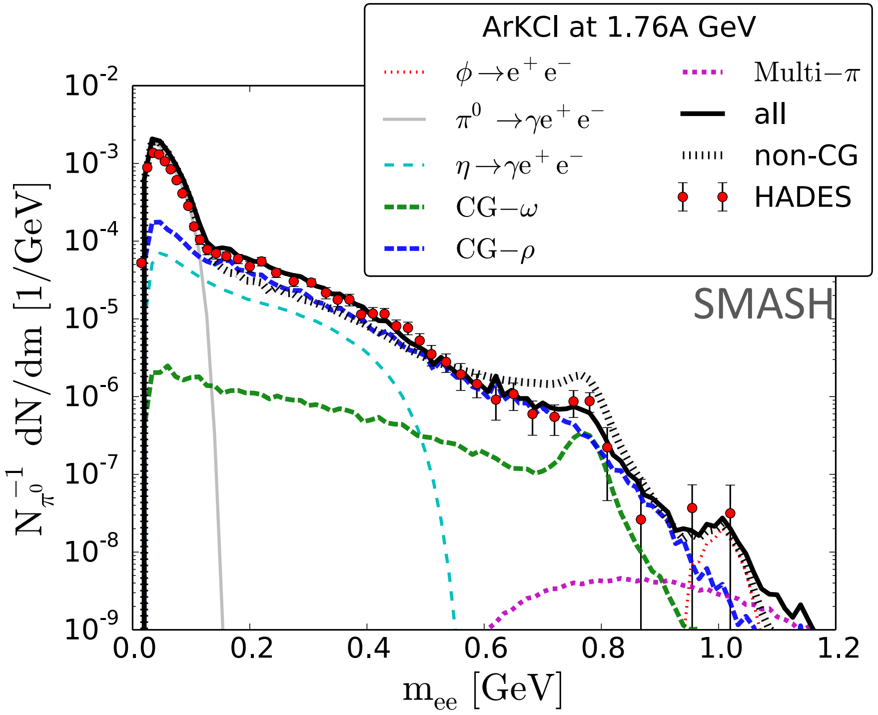

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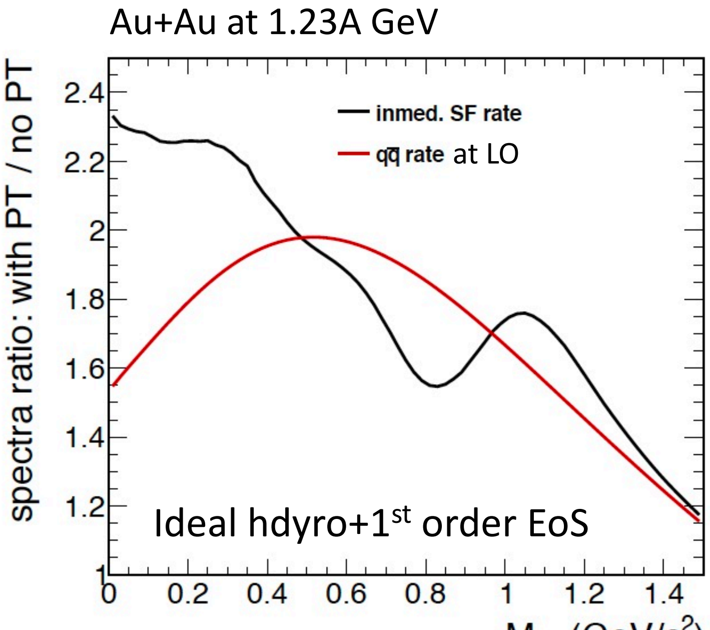

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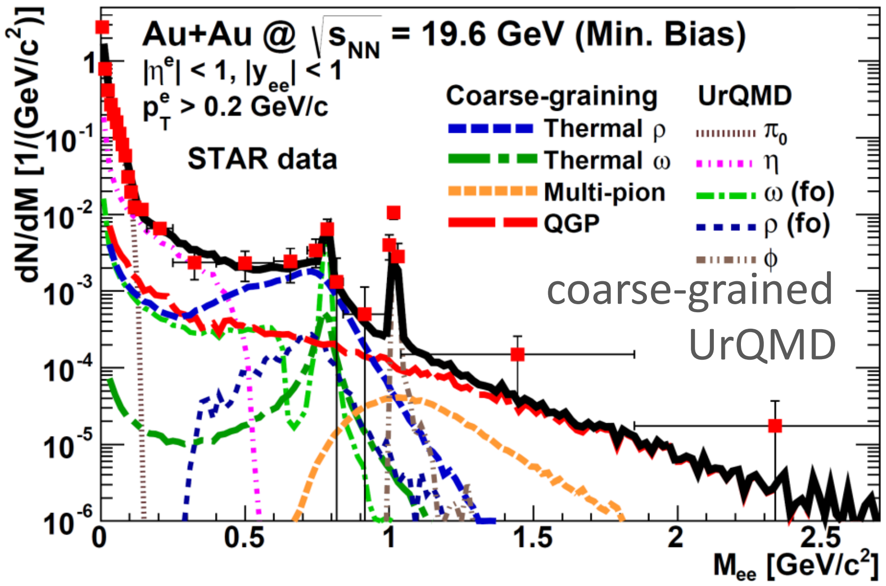

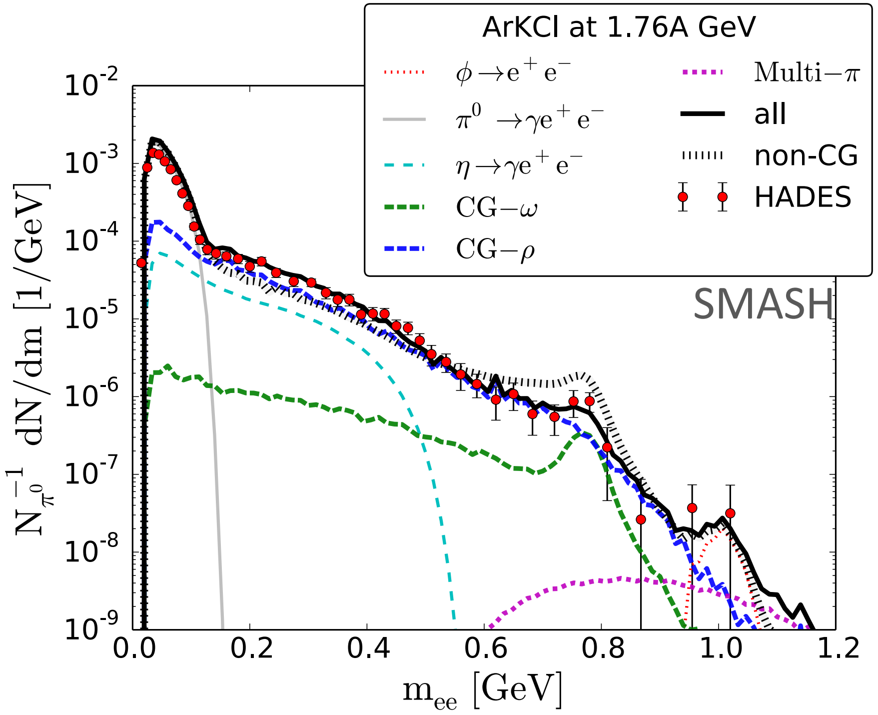

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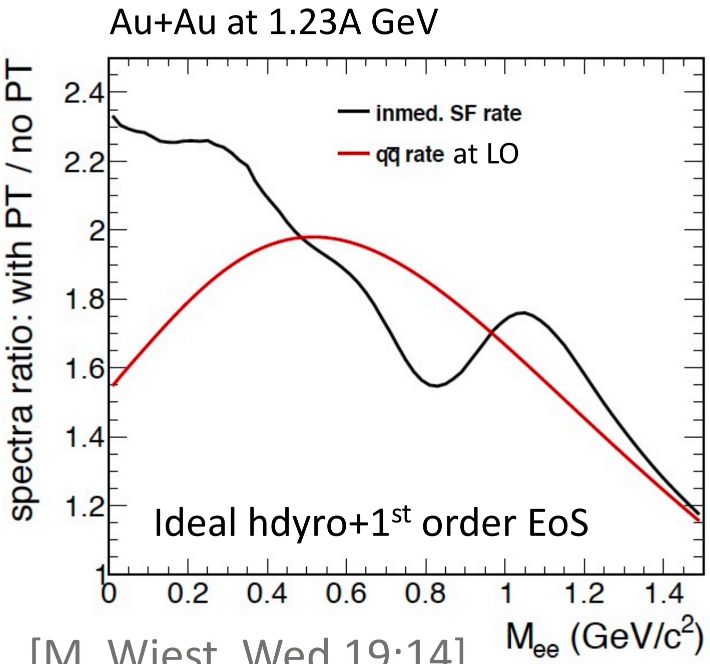

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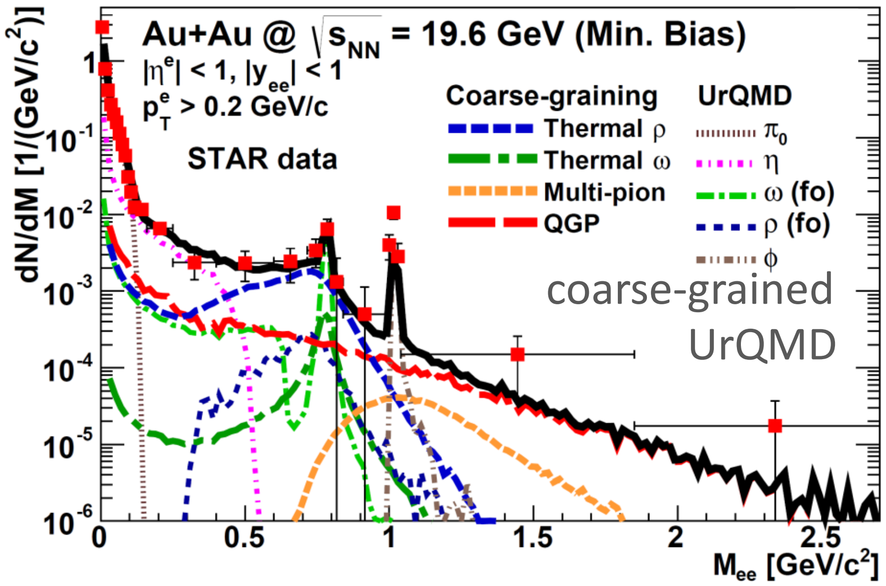

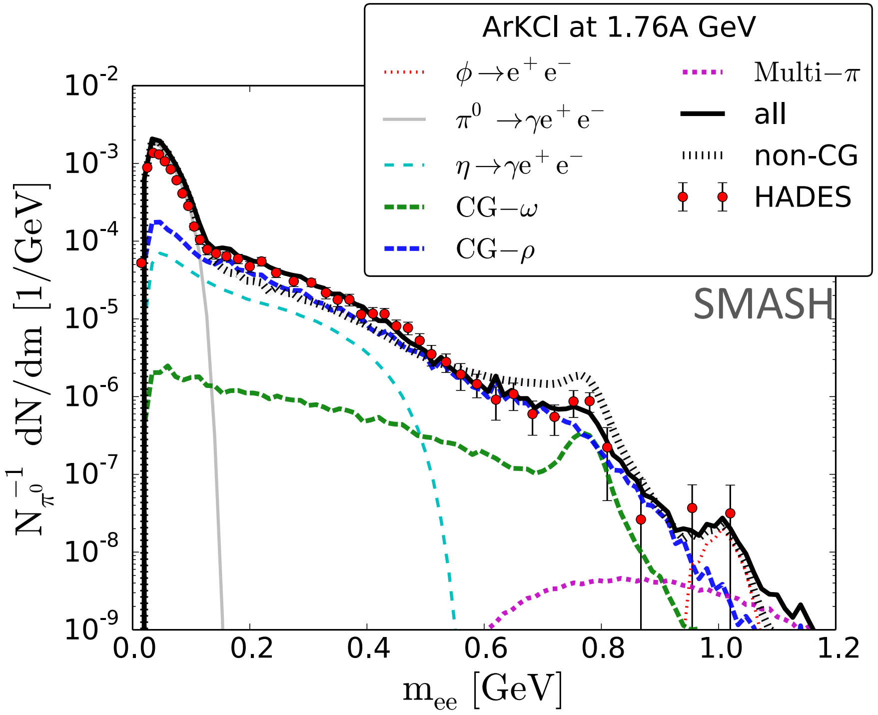

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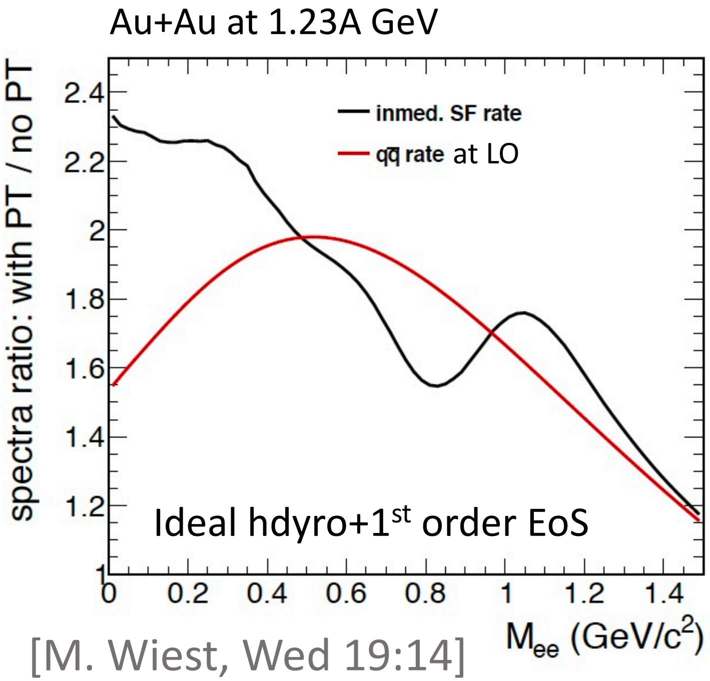
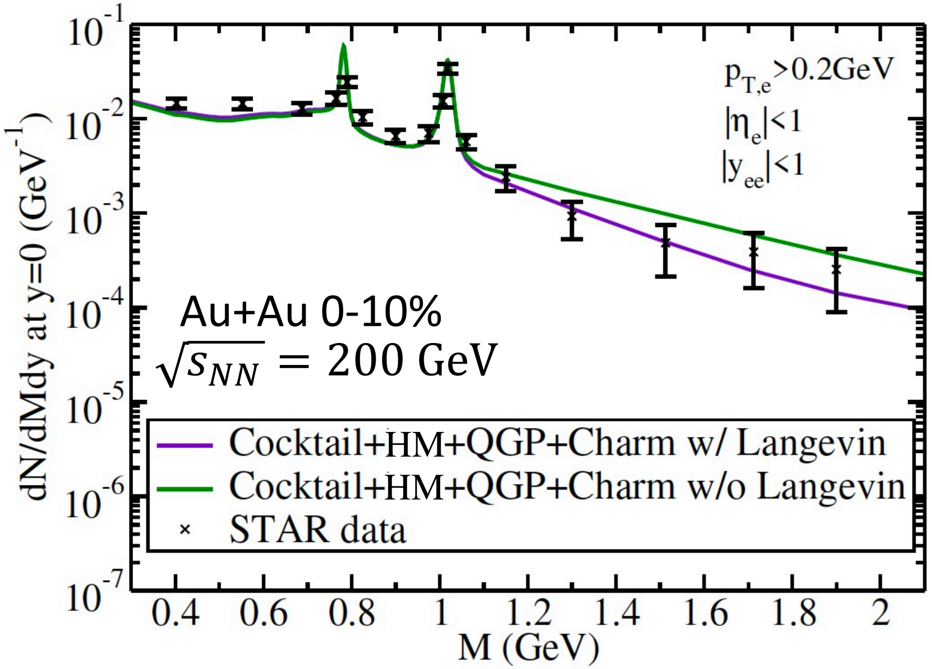


[M. Wiest, Wed 19:14]

- Consistent description at all beam energies ⇒ combining transport & hydrodynamical calculations.
- No more jets at lower $\sqrt{s_{NN}}$: only penetrating probes sensitive to QCD dofs are EM.
- Bayesian comparisons of dileptons at various $\sqrt{s_{NN}}$ ⇒ learn more dilepton production mechanisms
  - Exclude rates w/o chiral symmetry restoration by comparison with data?
  - Determine uncertainties of calculations & accurate measurements

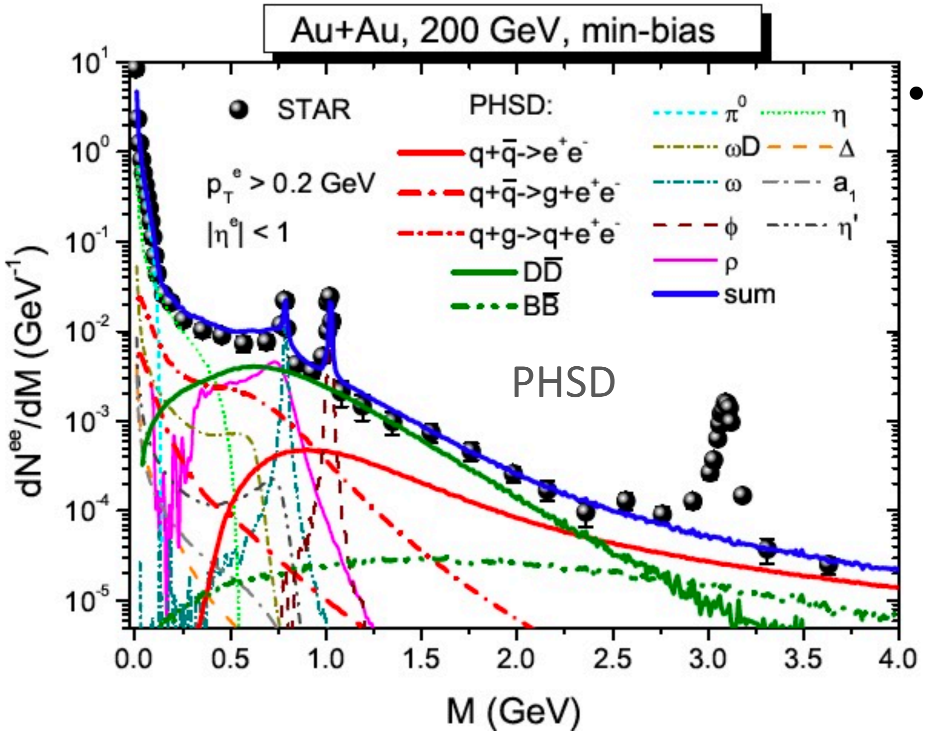
Dilepton calculations compared to data

- Comparison with data



[G.V. et al., Phys. Rev. C 89, 034904 (2014)]

[T. Song et al., Phys. Rev. C 97, 064907 (2018)]



- RHIC data is better described if charm exchanges energy & momentum w/ QGP

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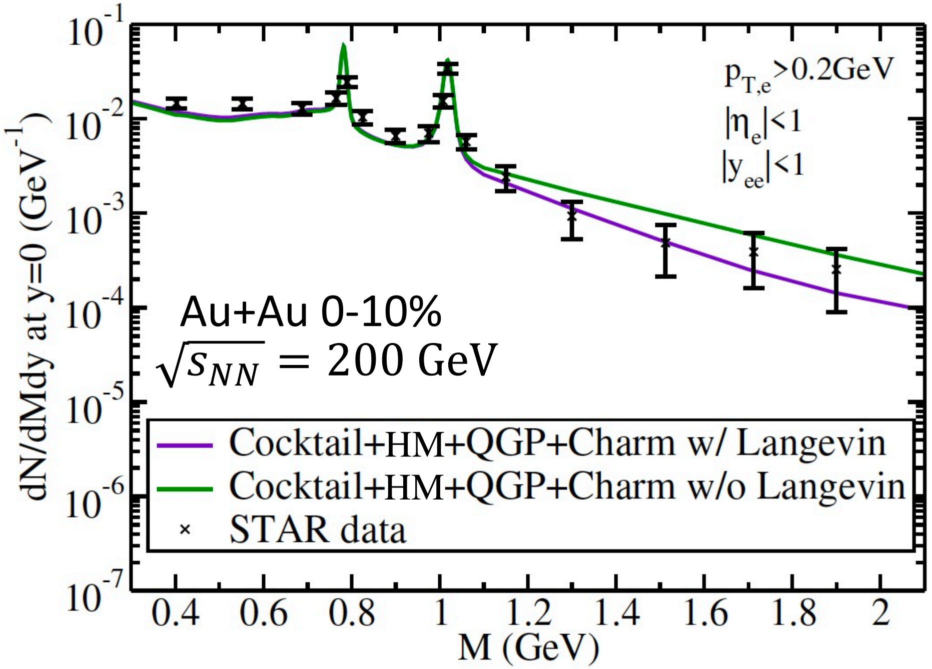
- Comparison with data



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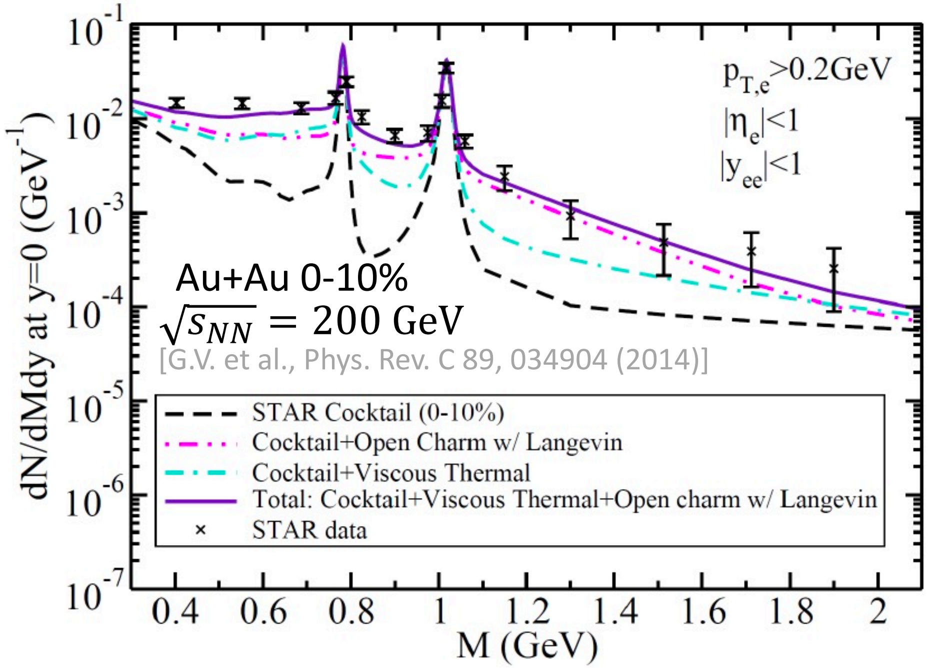

Cocktail+Thermal nor Cocktail+Charm w/ Lagenvin are not enough to explain data

⇒ all three are sources needed, in fact…

Dilepton calculations compared to data

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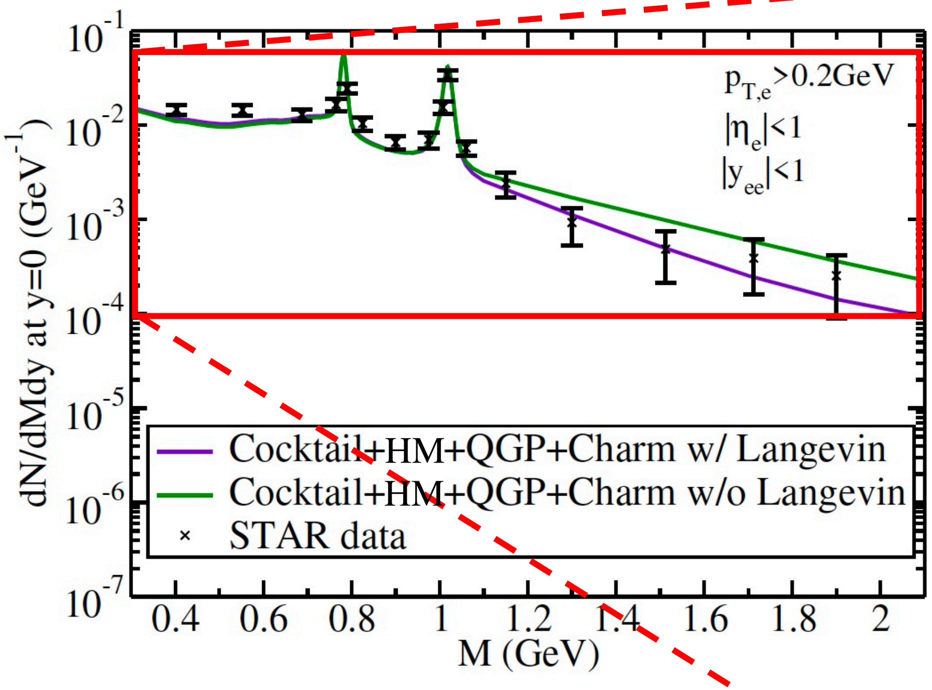

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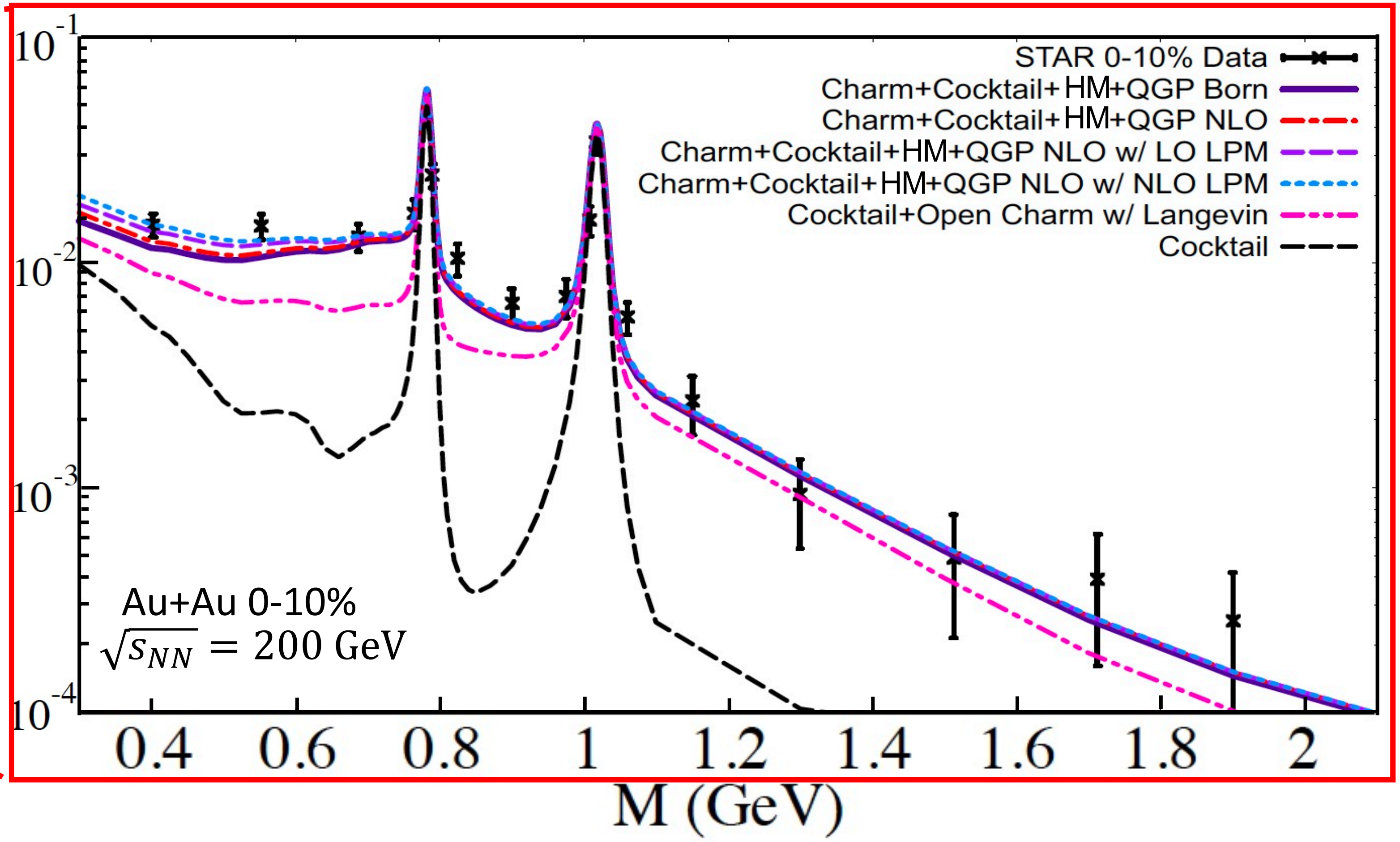
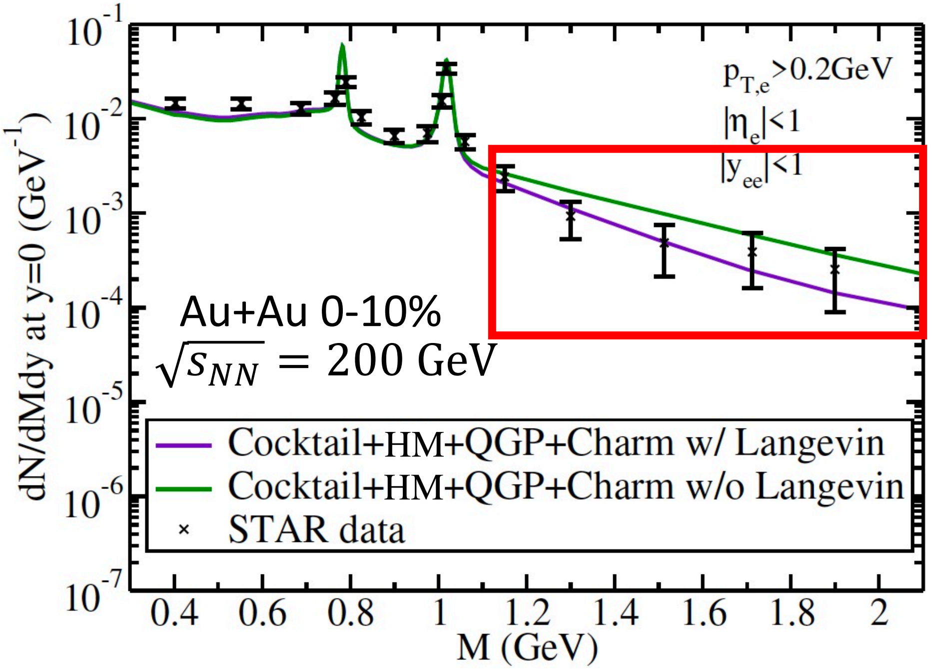
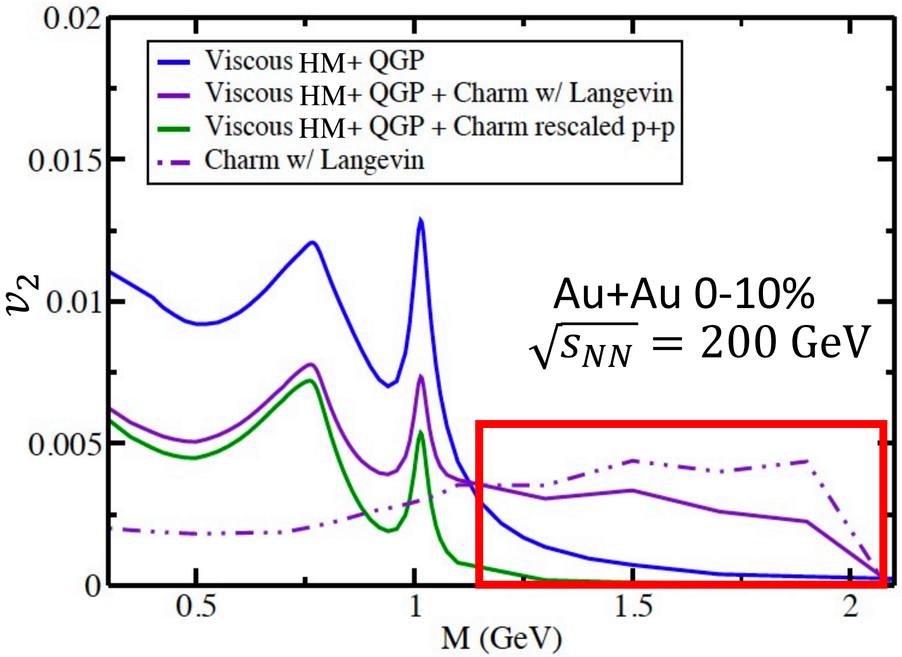


NLO pQCD dilepton rates are needed to explain the data.

Dilepton yield and v_2 at intermediate M

- Comparison with data





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- Charm's interaction w/ QGP generates dilepton v_2.

[G.V. et al., Phys. Rev. C 89, 034904 (2014)]

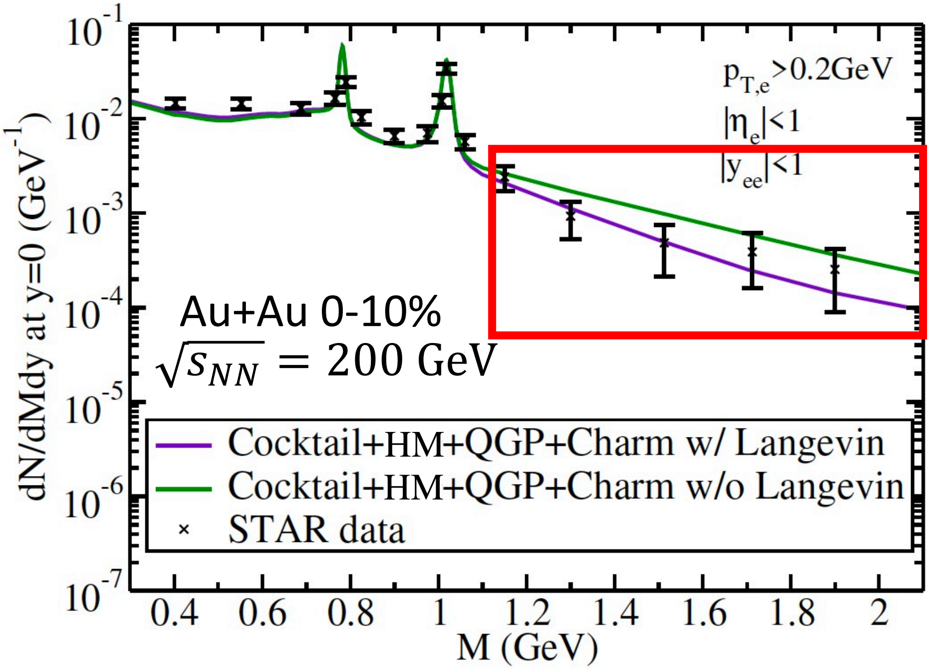
- $\frac{dN}{dM}$ and v_2 in $1 < M < 3$ GeV must be consistent with heavy flavor R_{AA} and v_2.

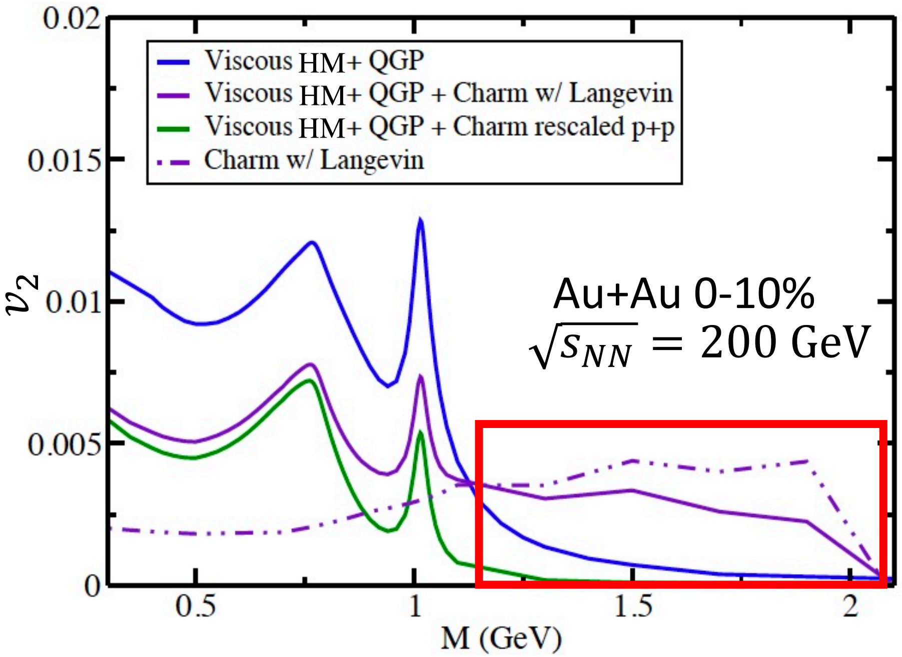
  This is *non-trivial* as dileptons follow the HF ***pair*** traversing the QGP.

- Another handle on heavy flavor transport coefficients (e.g. $\hat{q}_{QCD}$).

Dilepton yield and v_2 at intermediate M

- Comparison with data





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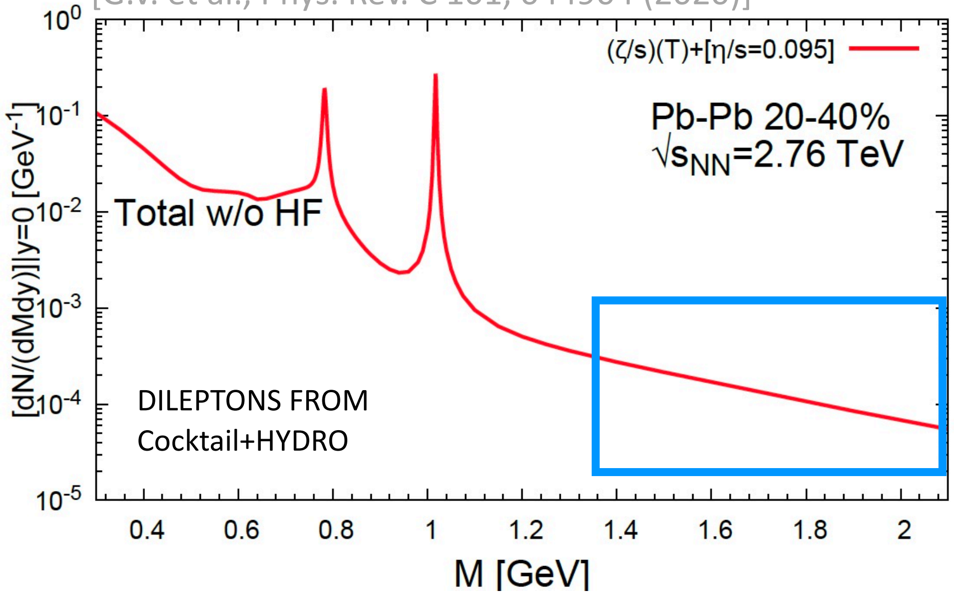
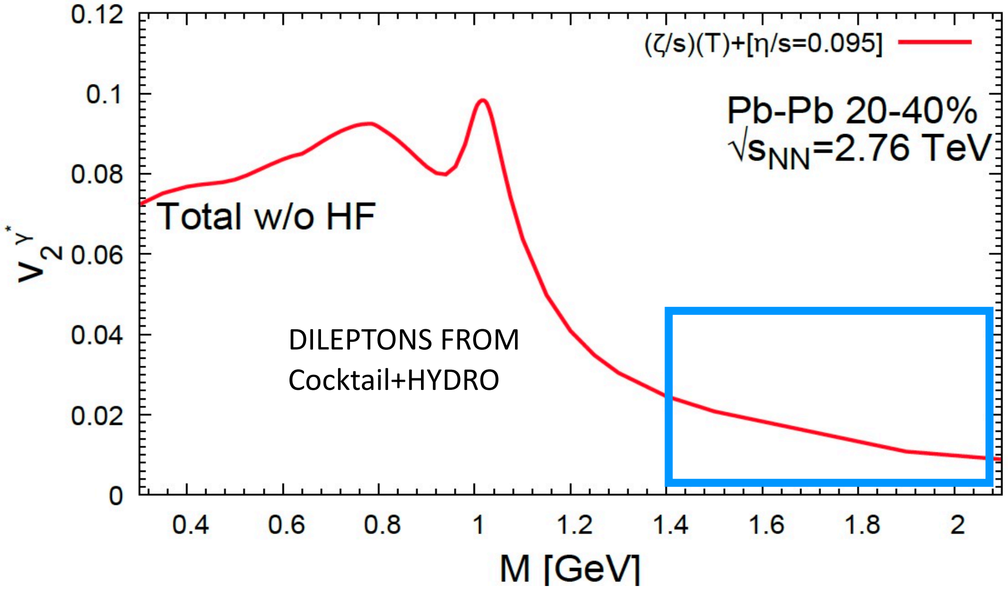
- Another handle on heavy flavor transport coefficients (e.g. $\hat{q}_{QCD}$).
- Dilepton v_2 is simultaneously sensitive to $\boldsymbol{\hat{q}_{QCD}}$ and **viscosities**!

Dilepton flow at $M \gtrsim 1$ GeV as probe of QGP

- A heavy flavor tracker can reduce/remove HF signal exposing direct QGP radiation ($M \gtrsim 1$ GeV)
  - Need to measure $\frac{dN}{dM}$ and v_2! [B. S. Kasmaei, M. Strickland, Phys. Rev. D 99, 034015 (2019)]

[G.V. et al., Phys. Rev. C 101, 044904 (2020)]

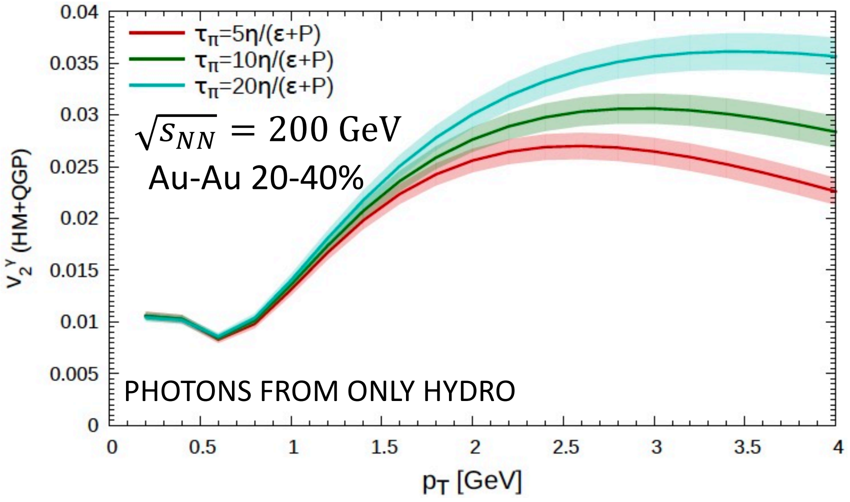


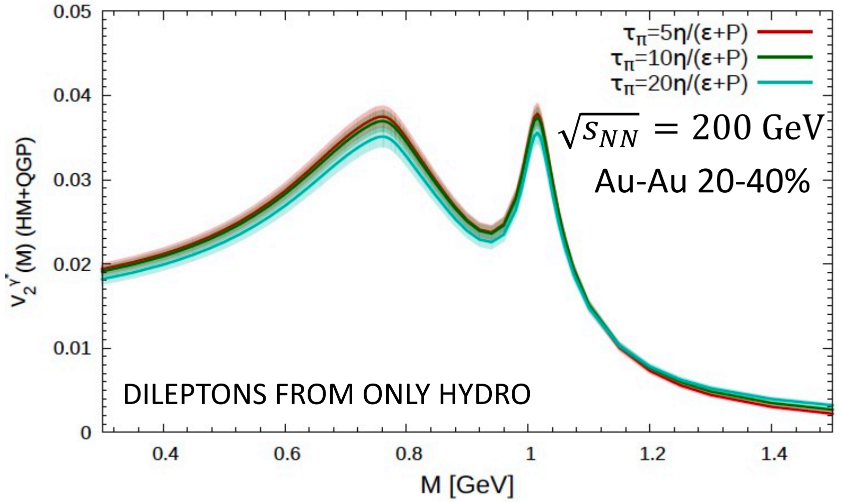


EM probes sensitivity to transport coefficients

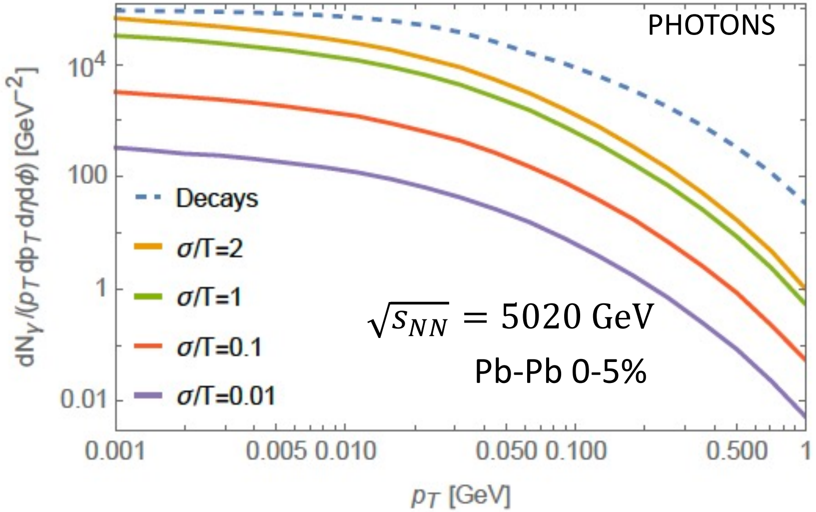
- Understanding (non-)hydrodynamical signal: better sensitivity to transport coefficients
  - Sensitivity to $\tau_\pi = b_\pi \eta/(\varepsilon + P)$

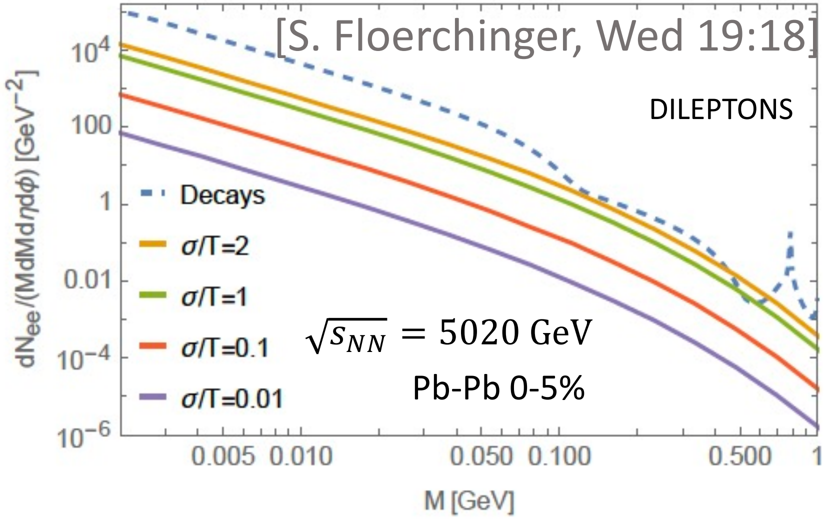
[G.V. et al., Phys. Rev. C 94, 014904 (2016)]





- Sensitivity to electrical conductivity using spectral function from EM current in hydro





[S. Floerchinger, Wed 19:18]

Photon emission

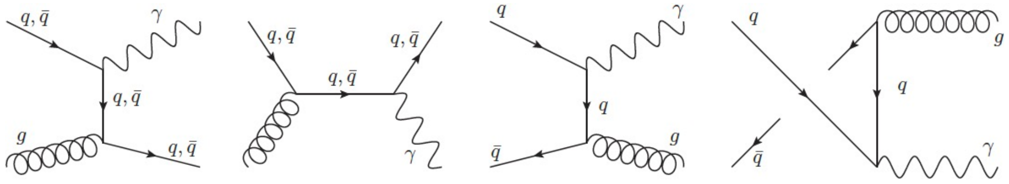
Photon sources

- Photons probing early dynamics:
  - Primodial photons / Jet-medium photons [C. Sirimanna, Wed 18:42; R. Modarresi-Yazdi, Thu 18:10]

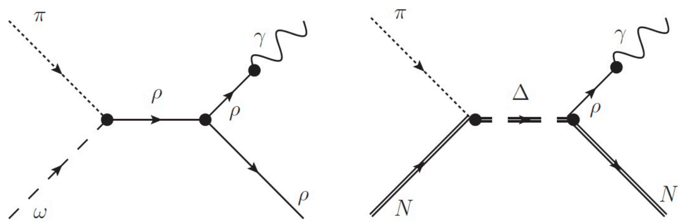
$$k^0 \frac{d^3\sigma_{A+A\to\gamma+X}}{d^3k} = \sum_{a,b,c} f_{a/A}(x_a, Q^2_{fact}) \otimes f_{b/A}(x_{\bar{q}}, Q^2_{fact}) \otimes k^0 \frac{d^3\hat{\sigma}_{a+b\to c+\gamma}(Q^2_{ren})}{d^3k} + \sum_{a,b,d} f_{a/A}(x_a, Q^2_{fact}) \otimes f_{b/A}(x_{\bar{q}}, Q^2_{fact}) \otimes k^0 \frac{d^3\hat{\sigma}_{a+b\to c+d}(Q^2_{ren})}{d^3k} \otimes D_{\gamma/c}(Q^2_{frag})$$

  - Photons from pre-hydrodynamics [J.-F. Paquet, Wed 18:34]
  - Photons as probes of charge stopping [S. Park, Thu 16:00]

- Photons emitted during hydrodynamics
  - Photons from hadronization [C. Nonaka, Thu 18:30]

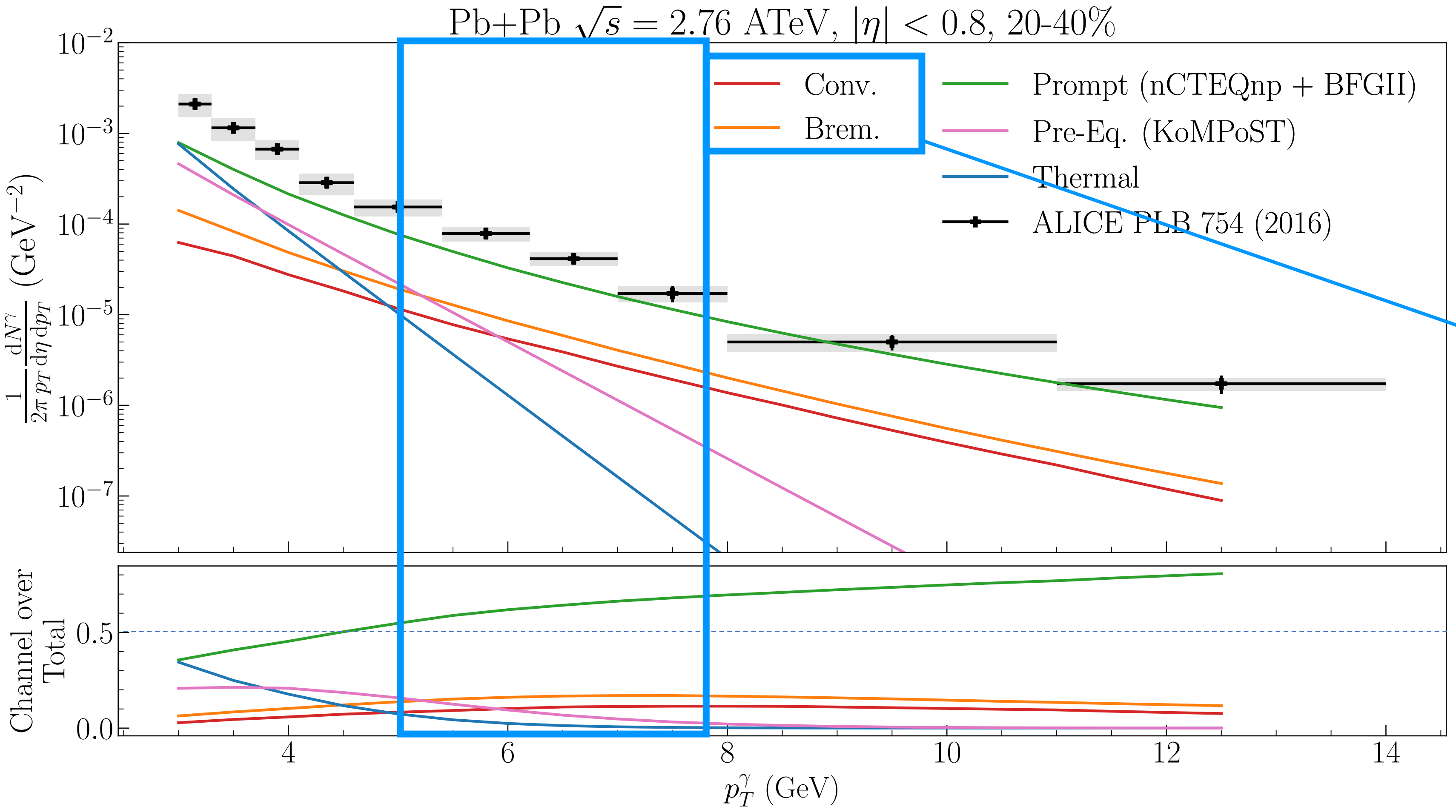


- Photons from hadronic transport
  - Same photon matrix elements as in hydrodynamical calculations [O. Garcia-Montero, Wed 18:58]



Photon production at intermediate p_T ✓

- Conversion and bremsstrahlung photons contribute significantly at intermediate p_T
  [R. Modarresi-Yazdi, Thu 18:10]



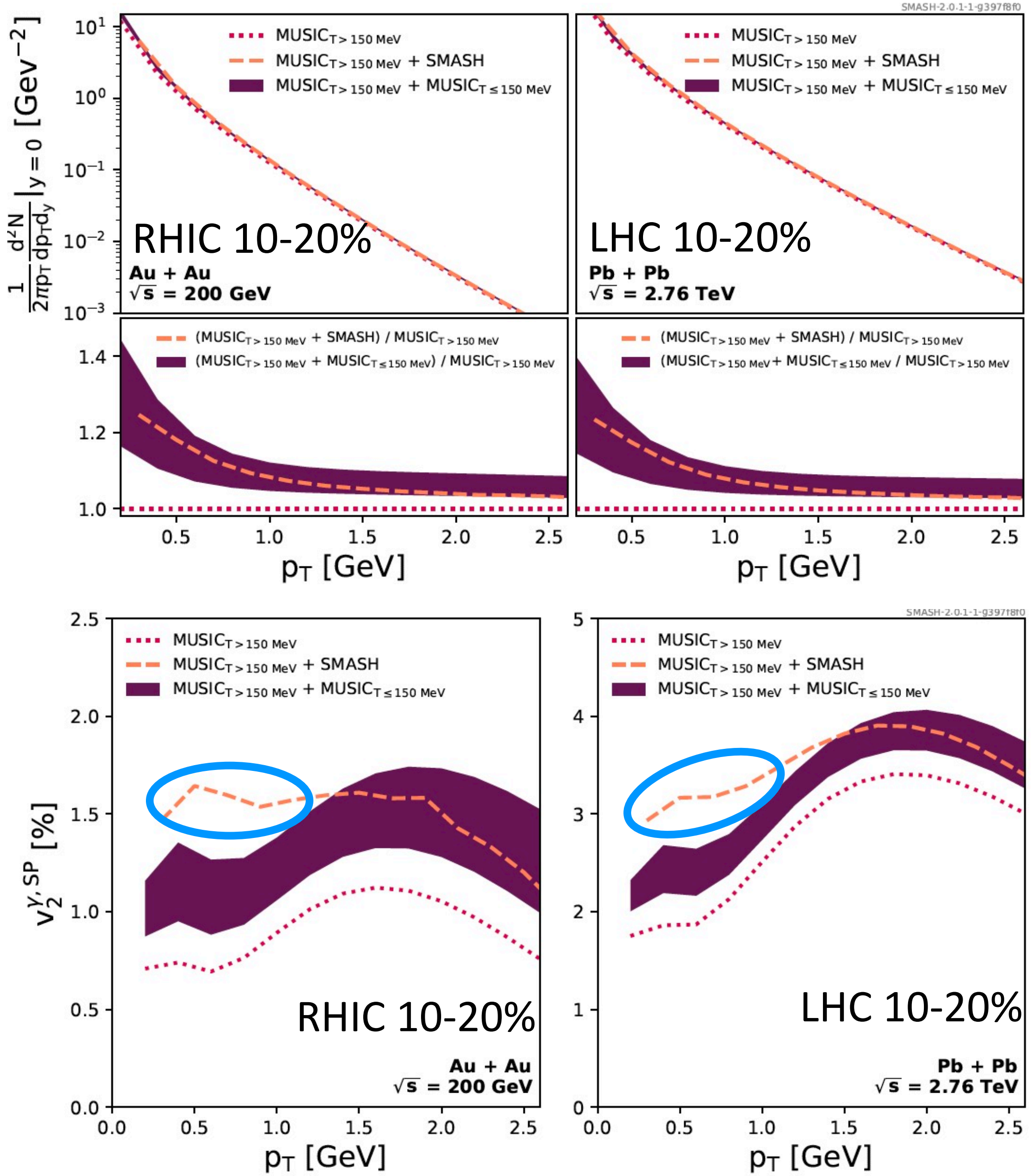
Photons $5 < p_T < 8$ GeV:

- Total yield dominated by prompt photons
- Significant contribution from jet-medium ≈ 30 %
  - Conversion ≈ 12 %
  - Bremsstrahlung ≈ 18 %

- Jet-medium photons are directly sensitive to $\hat{q}_{QCD}$, **avoiding** hadronization effects.

Photon production from hadronic reactions ✓

- Photons from SMASH



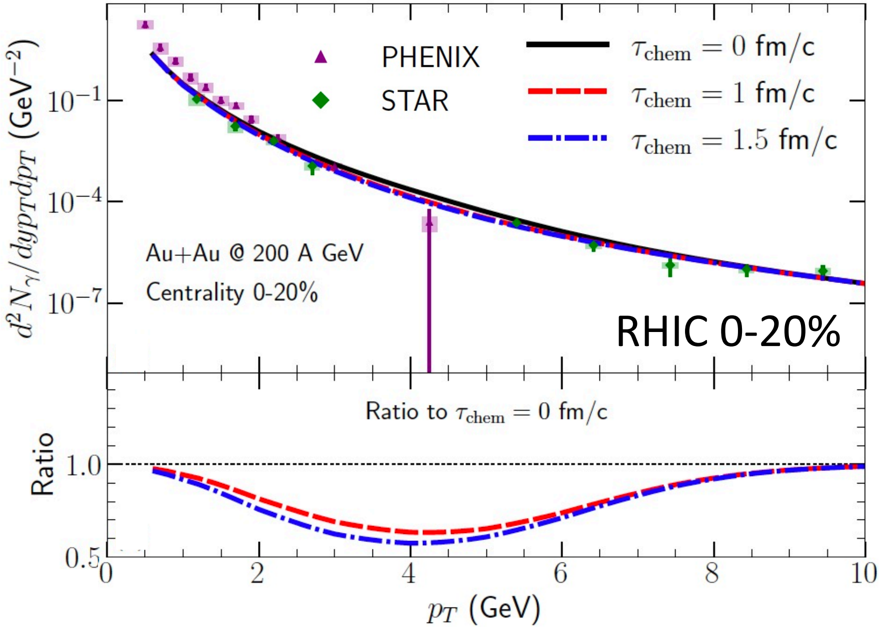
- Total photon yield from (Hydro+SMASH) is comparable to that obtained from hydro running to lower temperature (T=120 MeV).

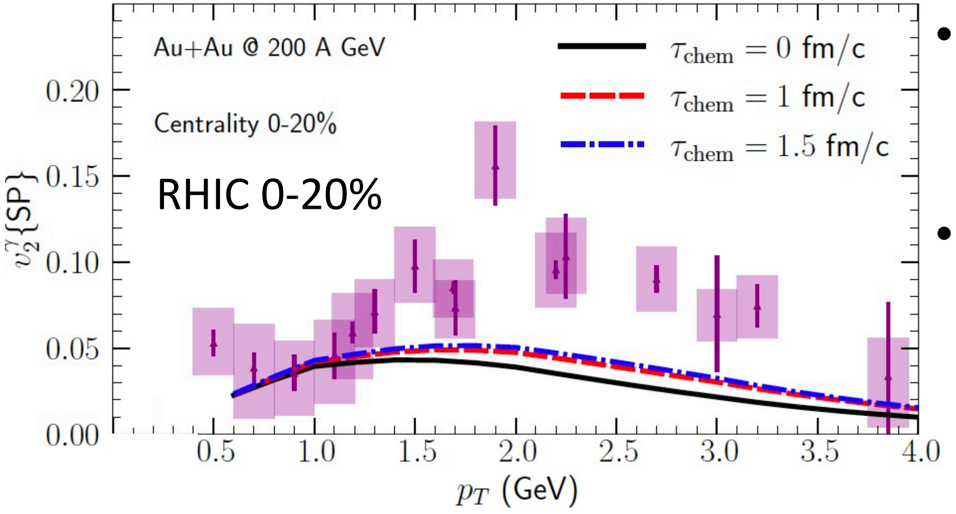
[O. Garcia-Montero, Wed 18:58]

- Non-equilibrium dynamics increase $v_2(p_T)$ **at low p_T** ⇒ better comparison with photon data, once a more complete calculation is obtained.

Photon calculations vs data & Bayesian analysis

- Match $T^{\mu\nu}$(IP-Glasma) ⇒ $T^{\mu\nu}$ (K∅MP∅ST) ⇒ $T^{\mu\nu}$ (Hydro)





[J.-F. Paquet, Wed 18:34]

- Photons are sensitive dynamics of quarks production CGC → hydrodynamics
- Different sources are continuously being included, need to include theoretical uncertainties

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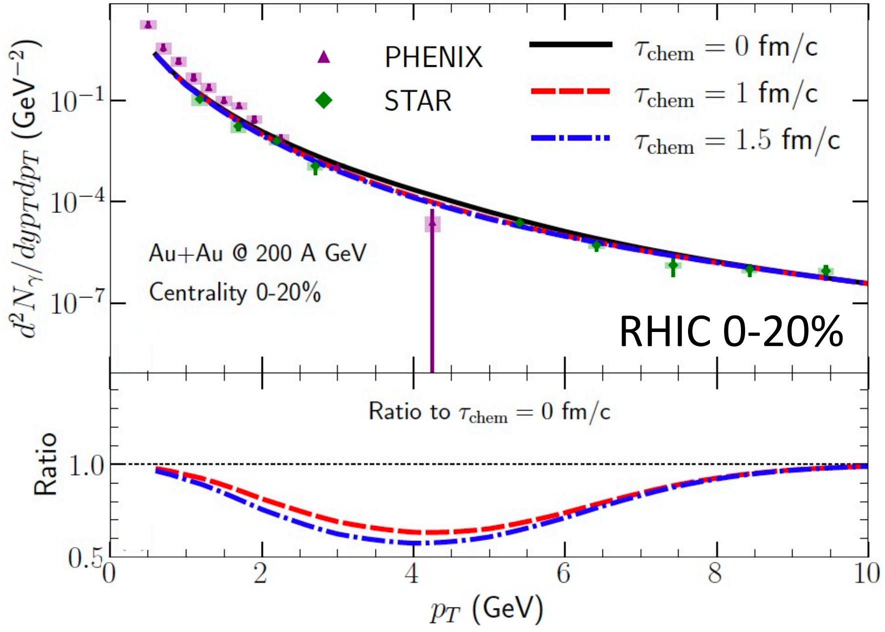

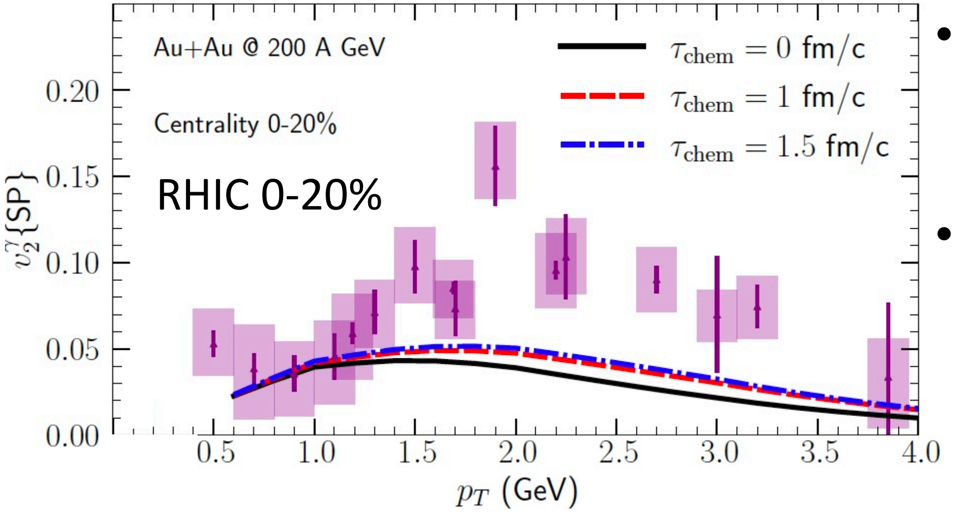

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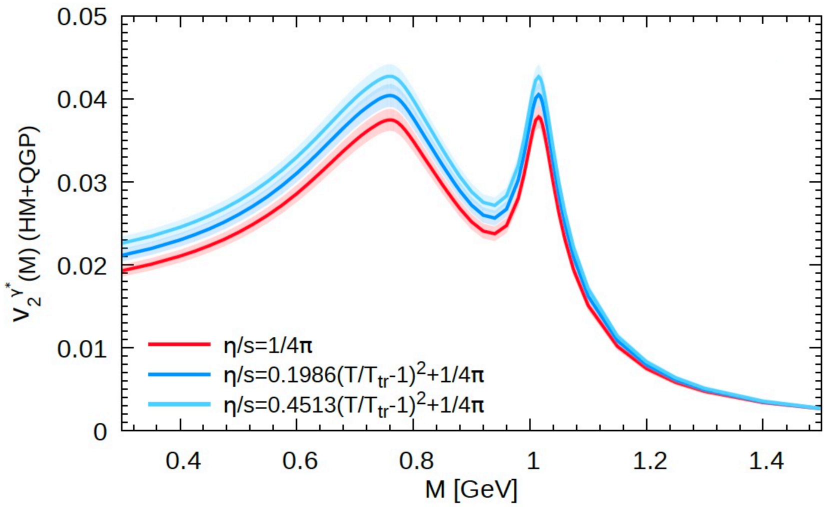
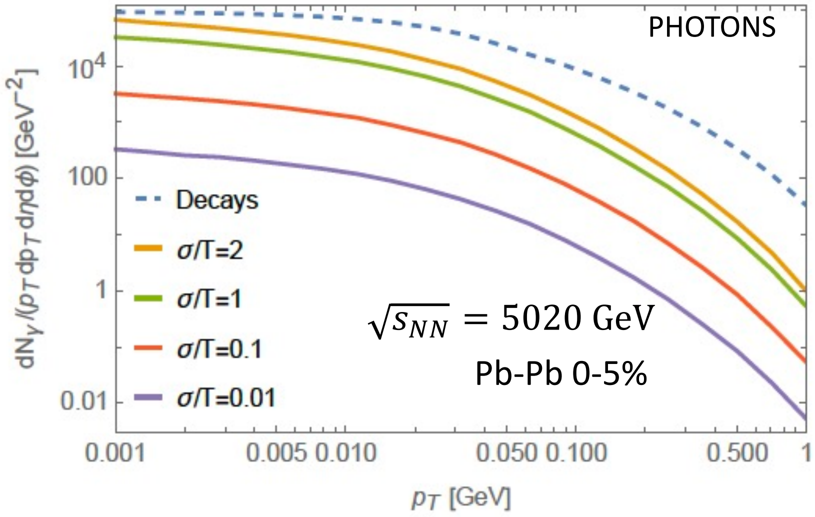


[G.V. et al., Phys. Rev. C 98, 014902 (2018)]



[S. Floerchinger, Wed 19:18]

- Bayesian Analysis using EM & hadron probes can hopefully constrain better the transport coefficients of QCD

Summary & Outlook

✓ What was/can be done

- Dynamics of quark generation can be explored via EM probes
- EM probes possess simultaneous sensitivity to hydrodynamical transport coefficients (e.g. η, σ_{EM}) and jet-related transport coefficient $\hat{q}_{QCD}$ (via jet-medium photons and open heavy flavor dileptons)

✓ Improved rates

- NLO pQCD comparable with lattice QCD; hadronic rates agree with pQCD at high T
- Hadronic rates are now including chiral symmetry restoration effects

✓ Better medium simulations

- Pre-hydrodynamical production of photons (dileptons to come…)
- Hydrodynamic production of EM probes include off-equilibrium dynamics (i.e. viscous effects)
- Off-equilibrium photon radiation from hadronic transport (improves v_2 at $p_T < 1.5$ GeV)

➢ Future directions

- Determine uncertainties of EM probes calculations (e.g. viscous corrections) for better estimation of transport coefficients such as viscosities
- Bayesian analysis using hadron & EM probes with more precise data
- More measurements of dilepton v_2 needed, and removal of HF signal in dileptons

Thank you

Questions?