Electromagnetic probes of the QCD Plasma

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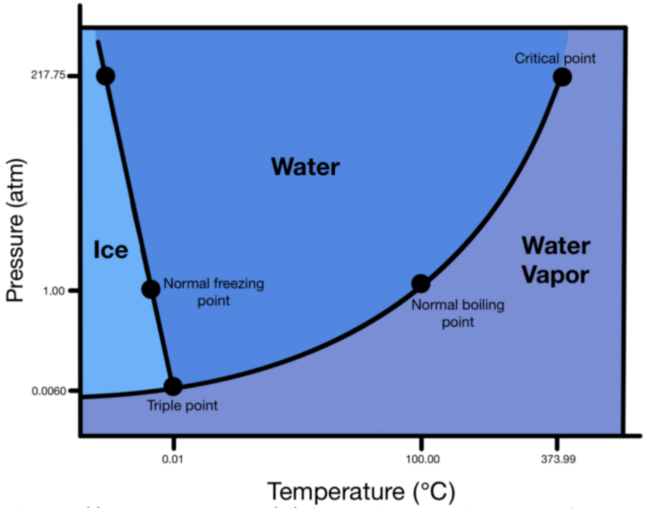
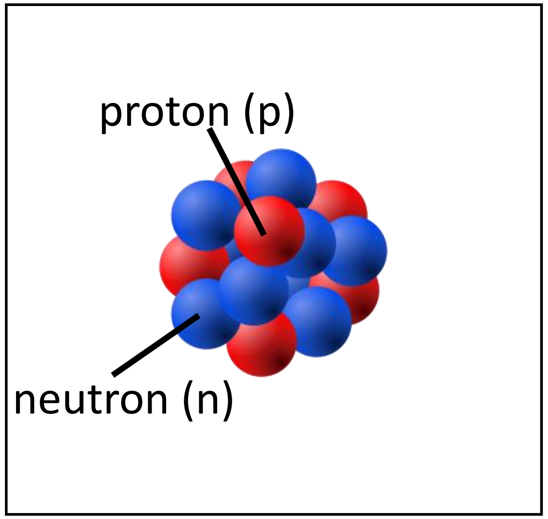
High energy nuclear collisions & nuclear equation of state

$T \uparrow$



Ref.: https://www.expii.com/t/phase-change-diagram-of-water-overview-importance-8031

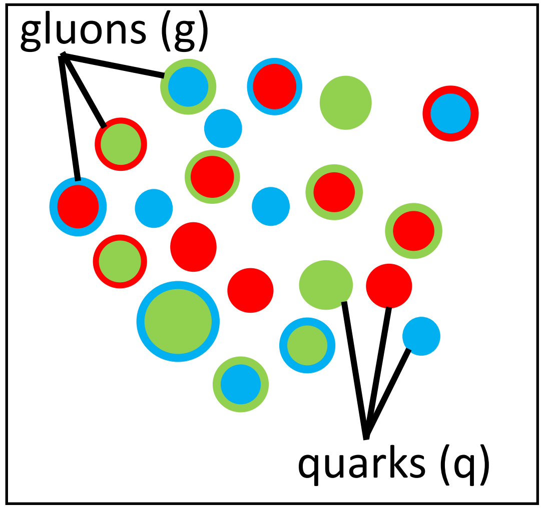
Ref.: https://en.wikipedia.org/wiki/Atomic_nucleus



$T \sim 10^2\ Kelvin\ (10^{-2}\ eV)$

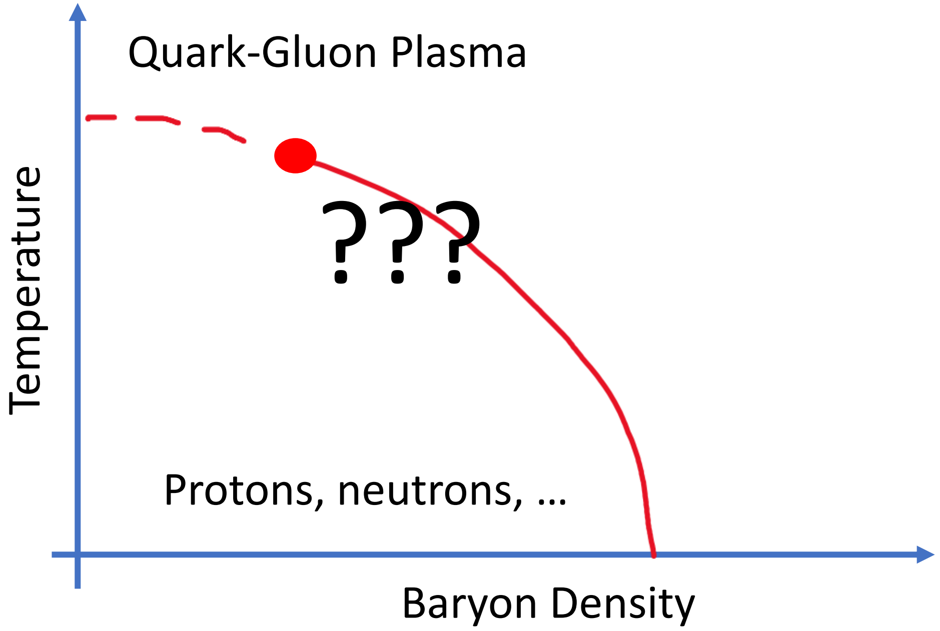
nucleus

$T \uparrow$

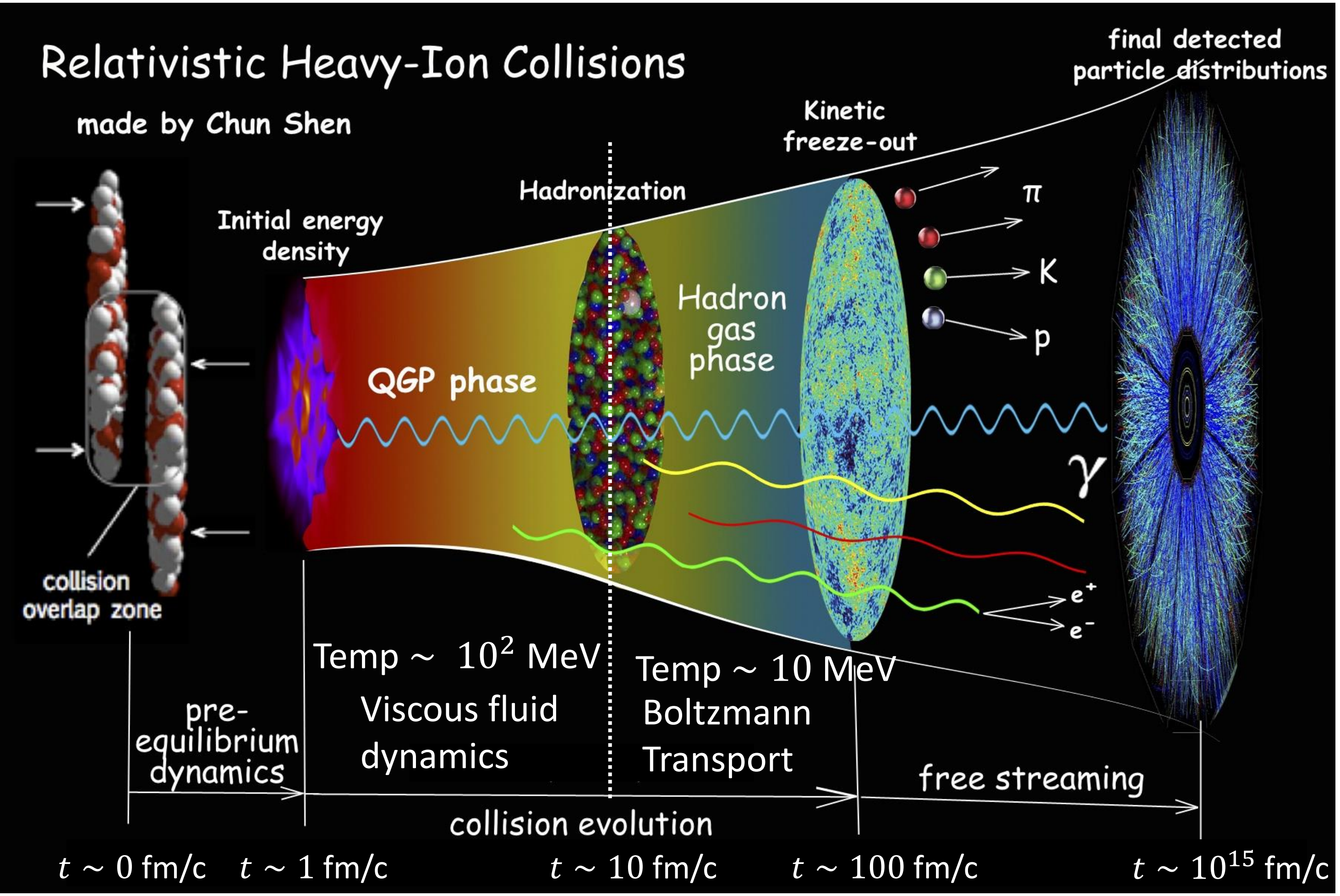


$T \sim 10^{12}\ Kelvin\ (\sim 10^8\ eV)$

Quark Gluon Plasma



Evolution of the nuclear medium



- The nuclear fluid is created during pre-equilibrium dynamics stage, where most of the collision's $T^{\mu\nu}$ will be in the fluid.
- Hydrodynamical stage (Temp $\sim 10^2$ MeV): Strongly coupled quark gluon plasma (QGP)
  - Equation of State (EoS) computed via Lattice QCD
- Molecular dynamics stage (Temp ~ 10 MeV): $\lambda_{micro} \sim L_{hydro}$, simulation switches to Boltzmann transport
- Following free-streaming, soft hadrons ($p_T \lesssim$ 3 GeV/c) carry most of the medium's $T^{\mu\nu}$ to detectors.

EM sources in the QCD plasma

- Why study electromagnetic probes of the QGP?
  - Emitted at all stages of a collision (w/ negligible re-scattering) ⇒ precise information about the QGP
  - Virtual photons/dileptons are particularly interesting because of their invariant mass M

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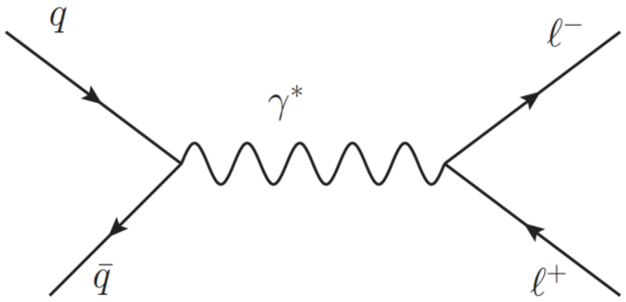

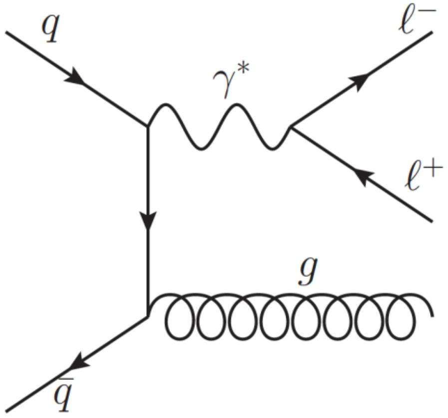

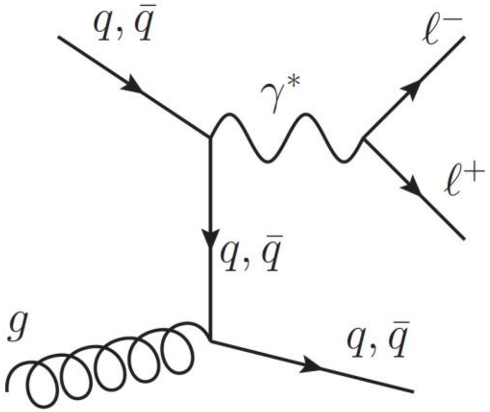

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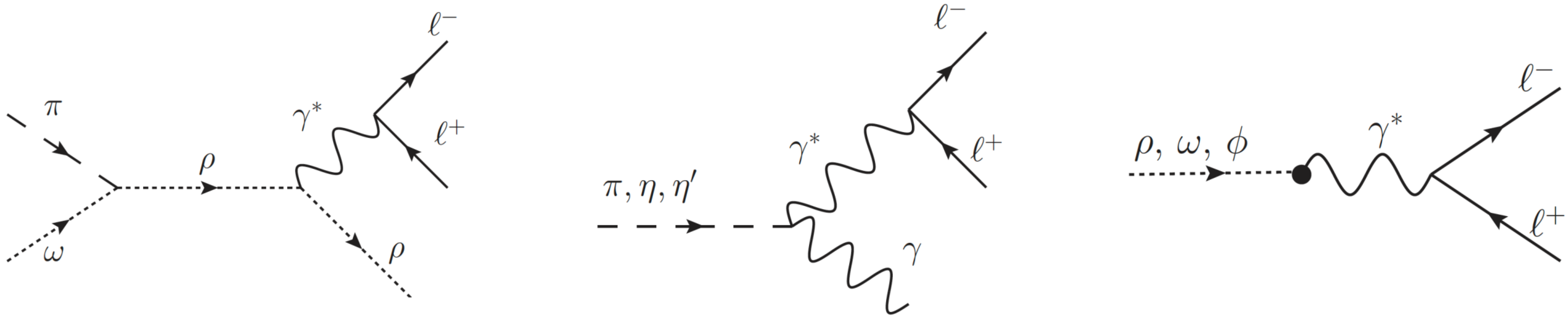

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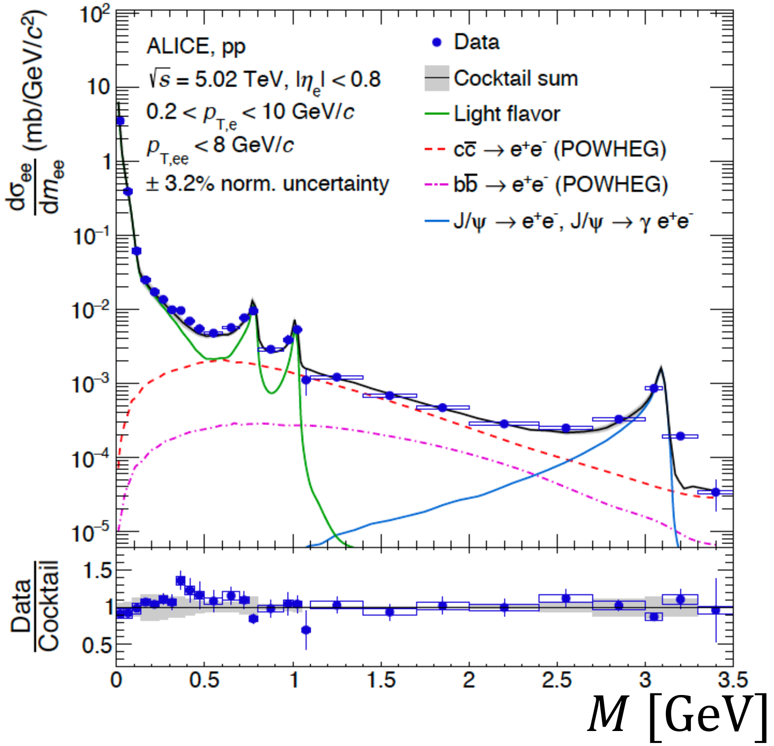
[ALICE, Phys. Rev. C 102, 055204 (2020)]



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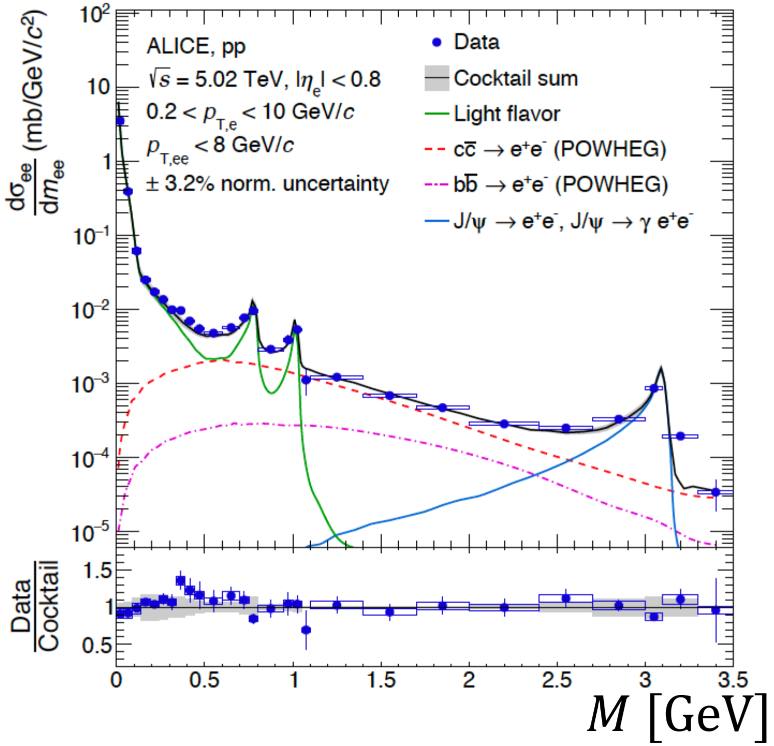

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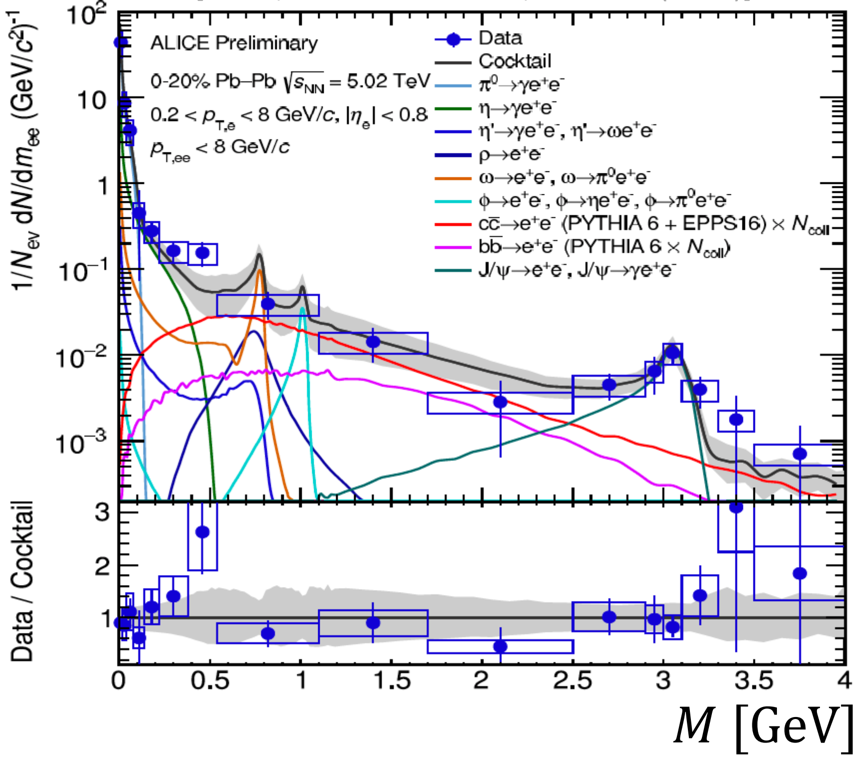

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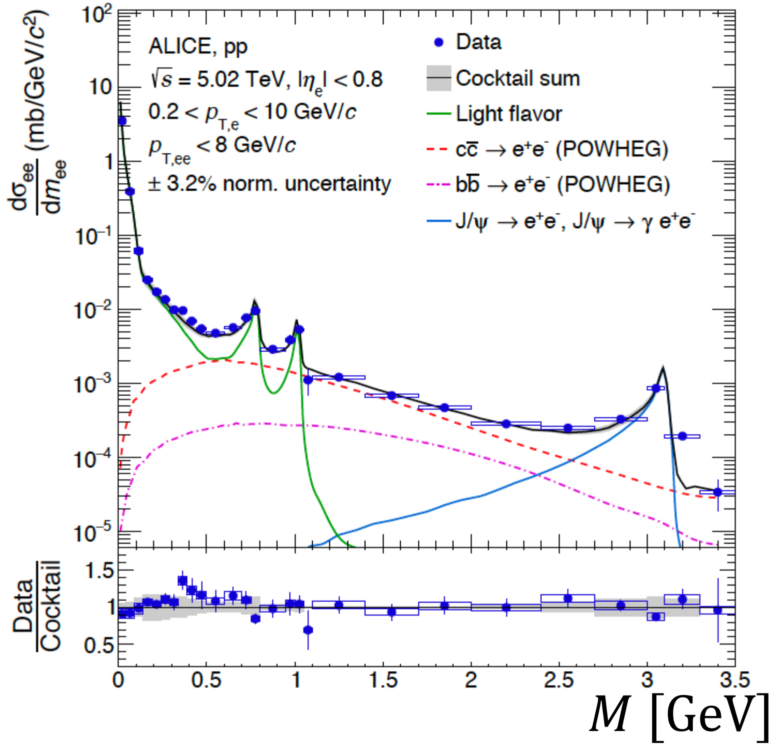

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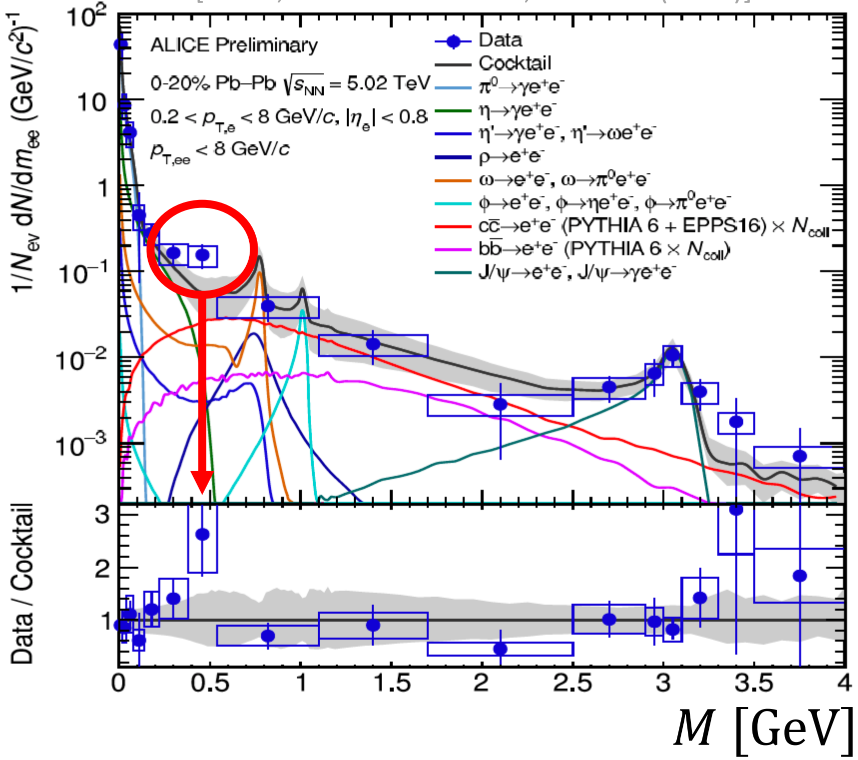

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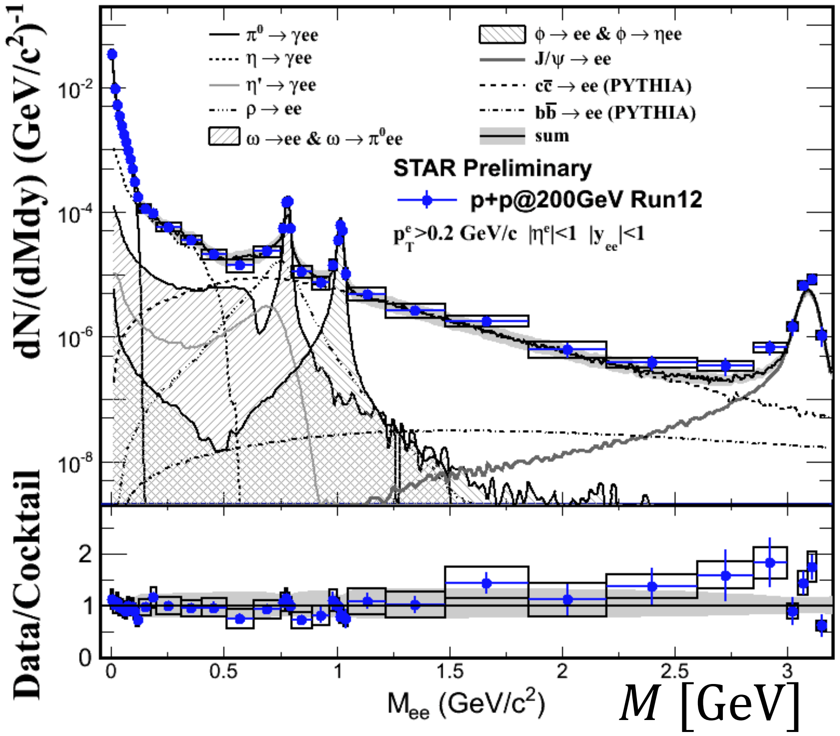

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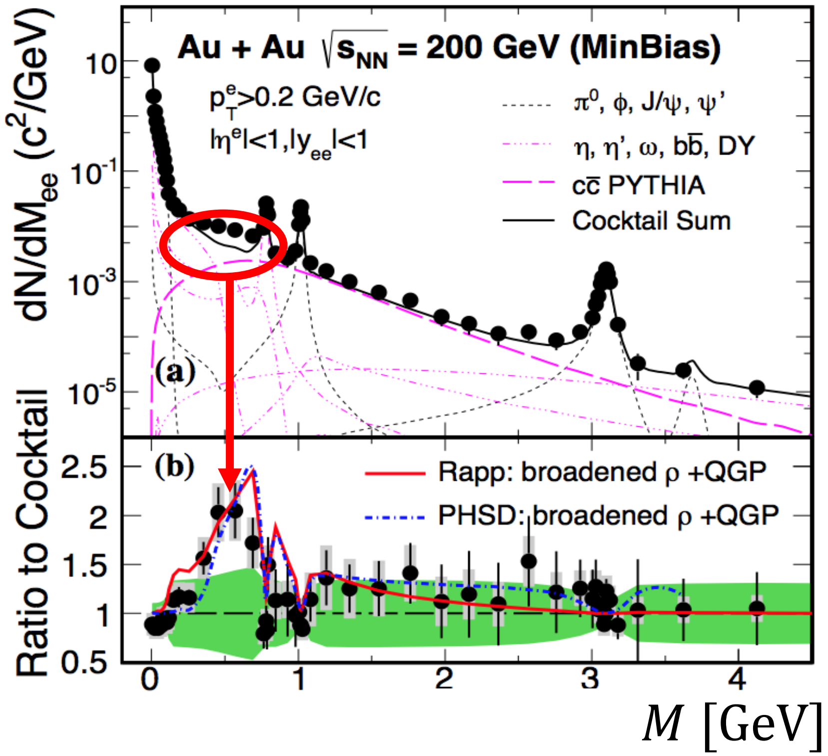

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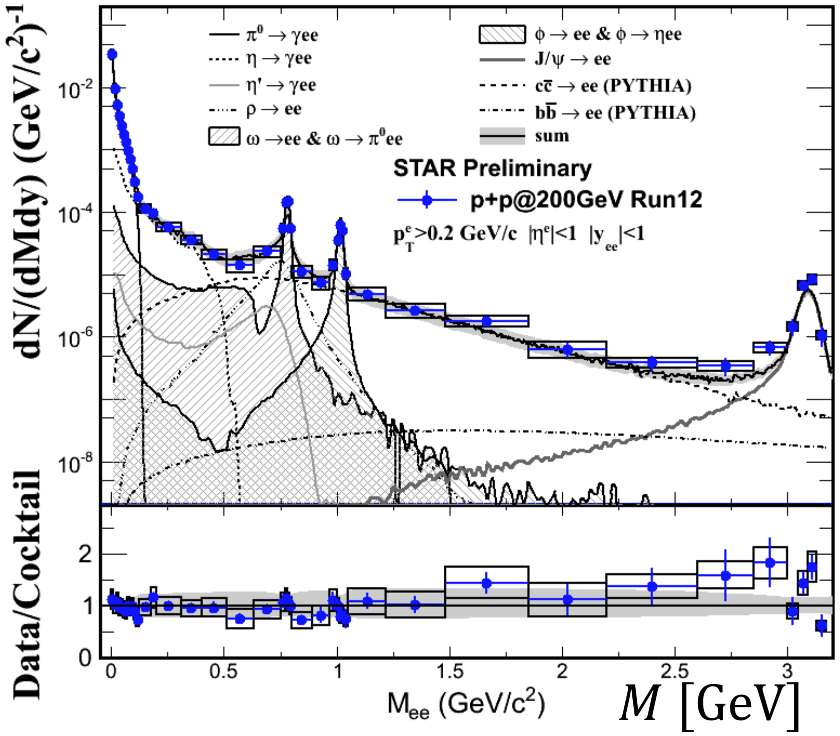

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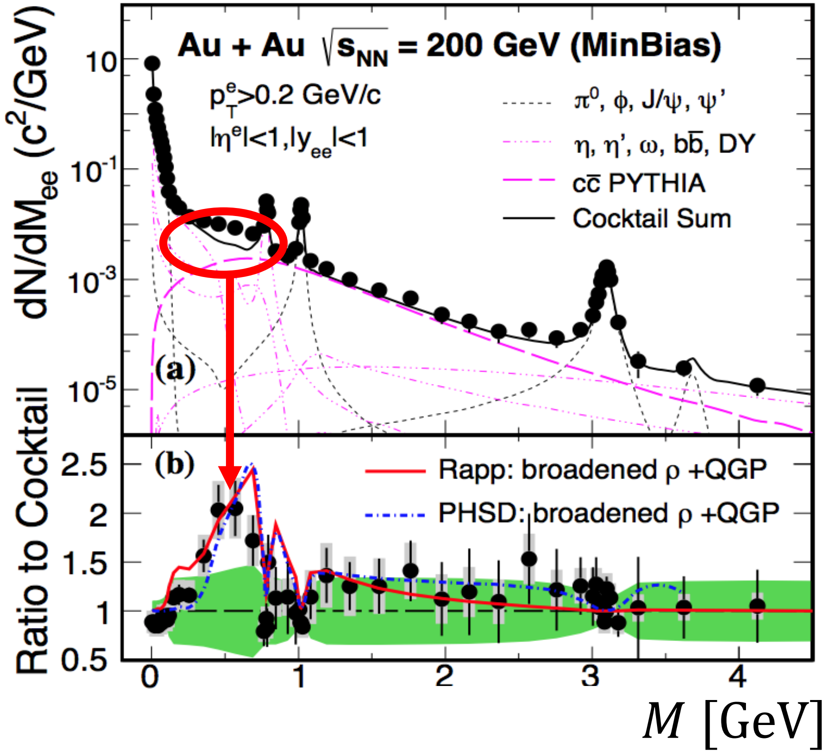

$$\frac{dN}{dM p_T dp_T d\phi dy} = \frac{1}{2\pi}\frac{dN}{dM p_T dp_T dy}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi - n\Psi_n)\right]$$

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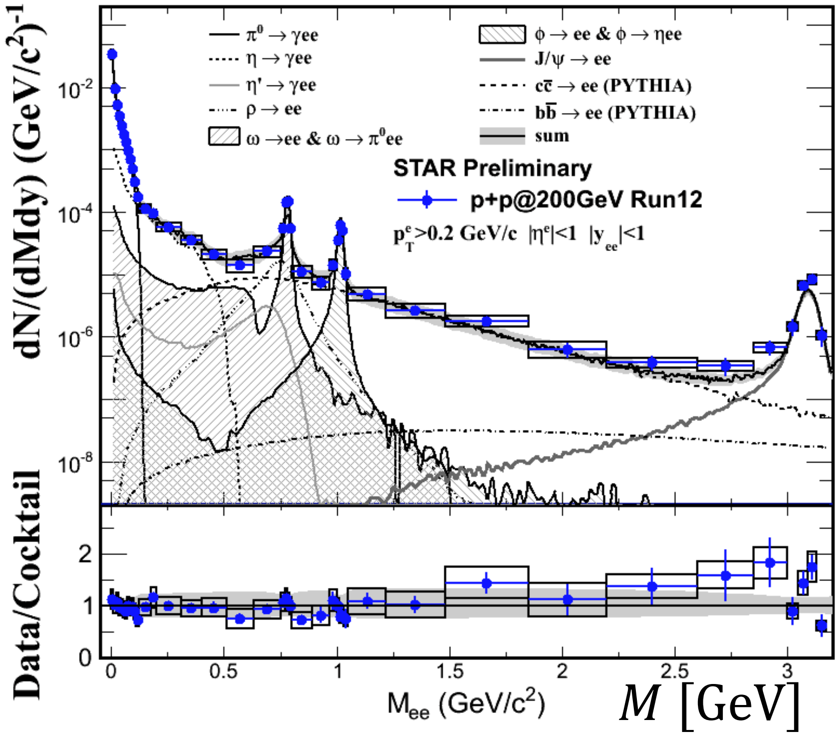

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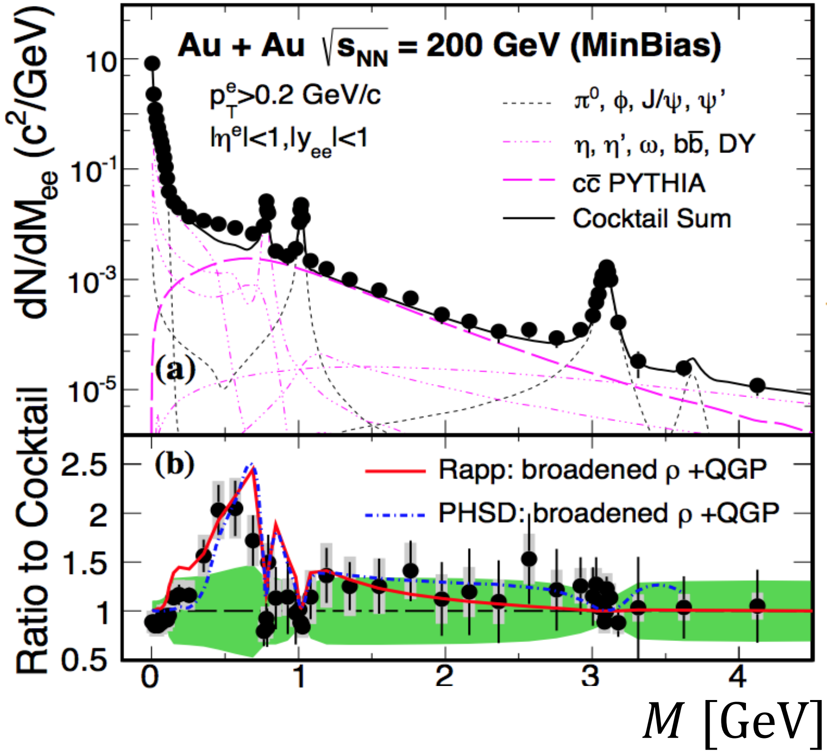
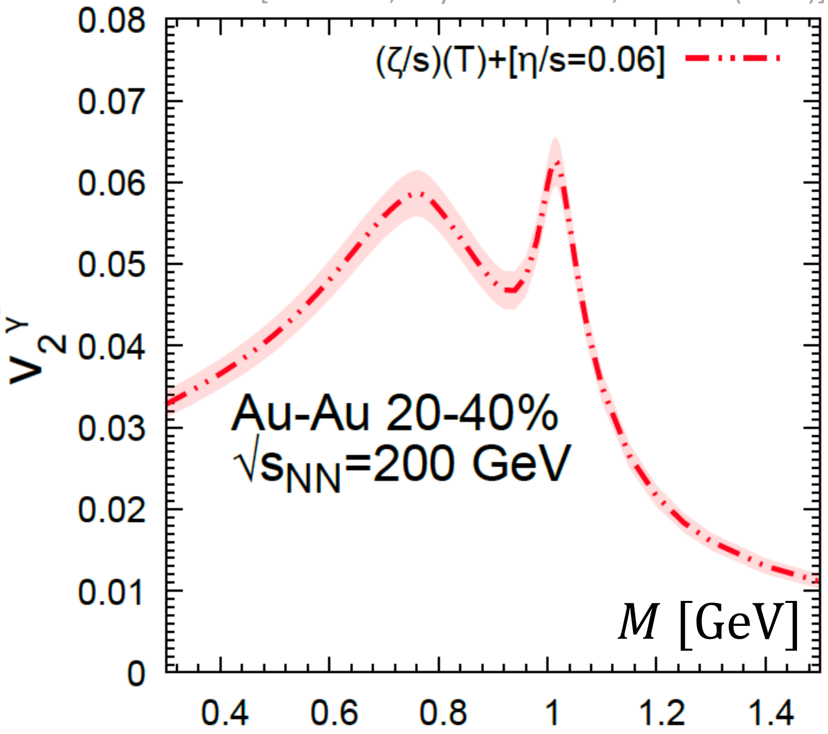


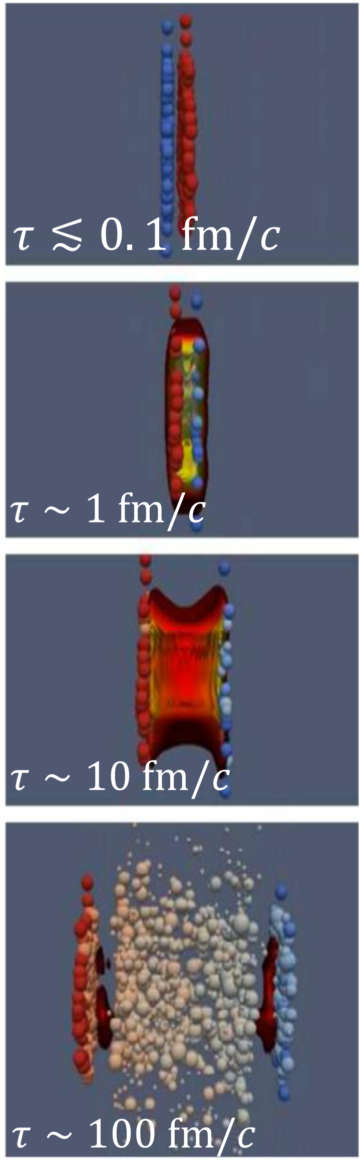
[G.V. et al., Phys. Rev. C 101, 044904 (2020)]



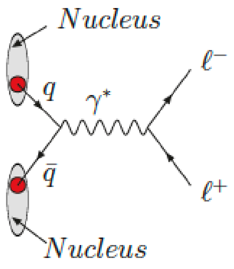
- Detailed study of QGP: measure dN/dM and $v_2(M)$, especially M $\gtrsim 1$ GeV!

Sources of EM probes

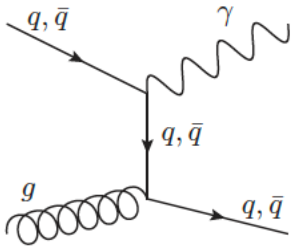
Figure ref. J. Bernhard, H. Elfner (Petersen), MADAI Collaboration



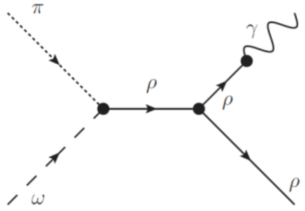
- Onset of collisions:
  - Prompt photons
  - Drell-Yan dileptons
  - Heavy Quarkonia
  - Open Heavy Flavor, …

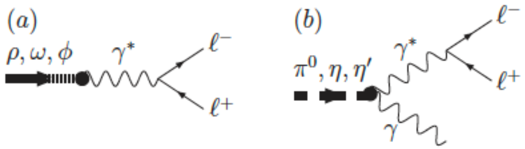


- Pre-hydrodynamical evolution/jet-medium interaction
  - EM production coming from various partonic processes
- Hydrodynamical evolution
  - EM production coming from partonic and hadronic processes



- Transport evolution
  - EM production from hadronic interactions





EM probes and the QGP

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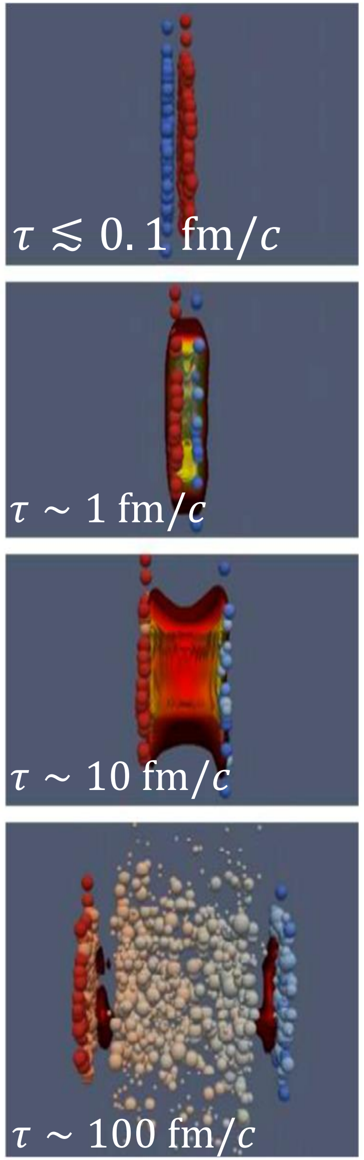

- Bayesian analysis simulating various stages for soft hadronic observables are starting to inform us about transport coefficients.

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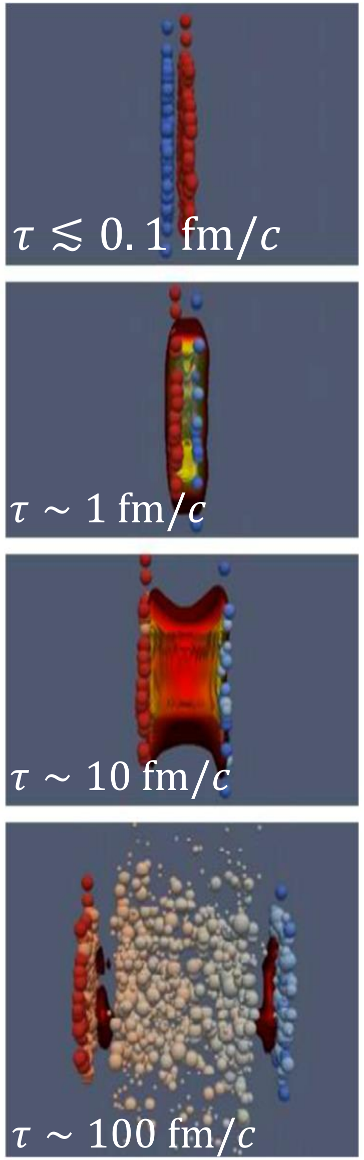

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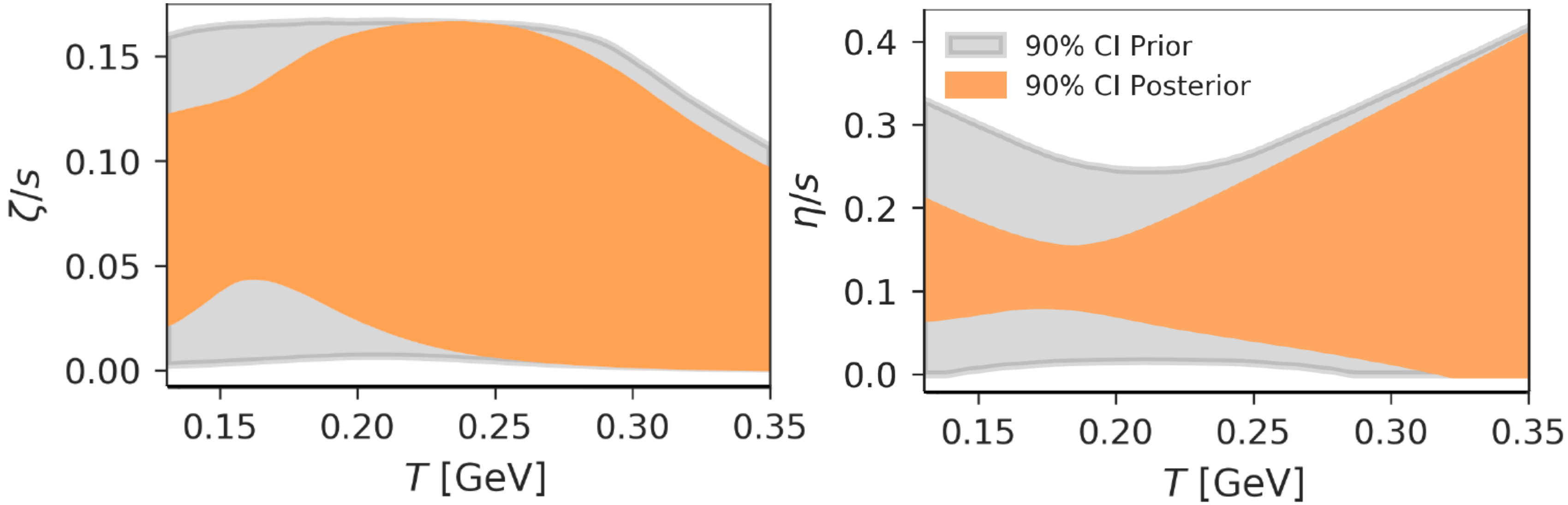
[D. Everett et al., Phys. Rev. Lett. 126, 242301 (2021)]



Bayesian Analysis by the JETSCAPE Simulations Group

EM probes and the QGP

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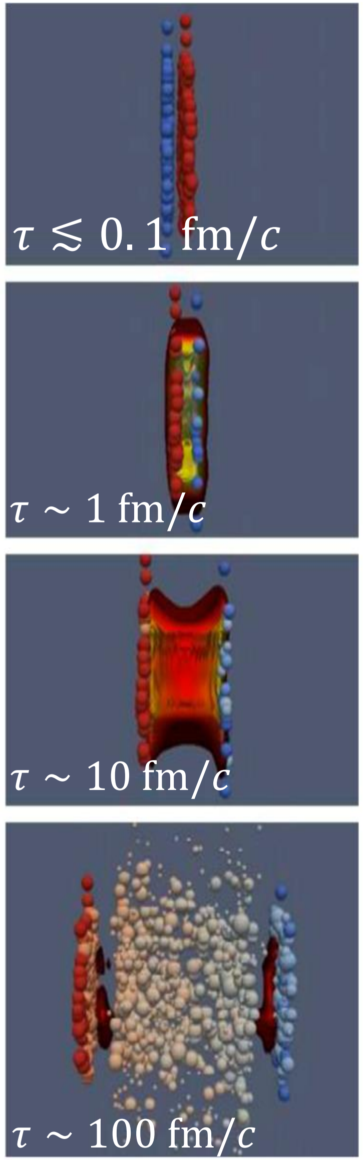

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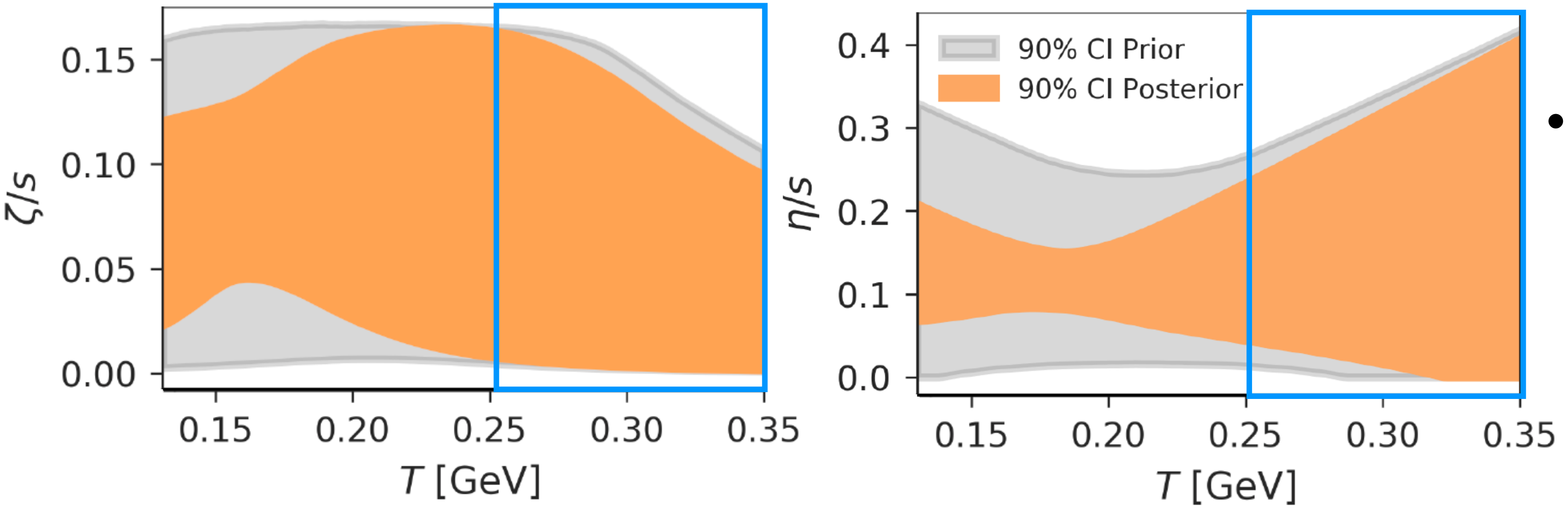

- Soft hadron observables give a better description at low T.

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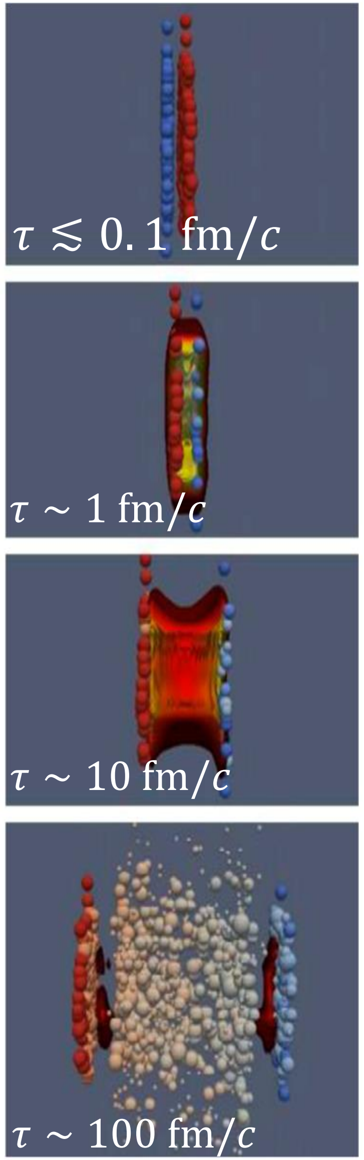

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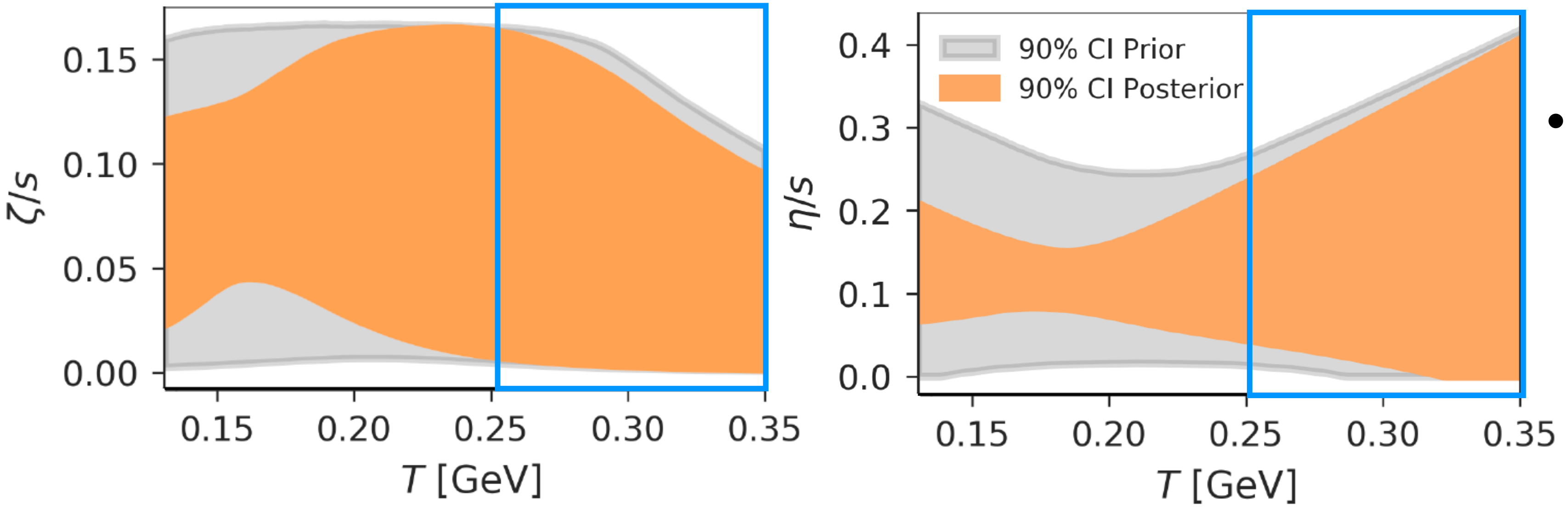


- Soft hadron observables: not enough?

Bayesian Analysis by the JETSCAPE Simulations Group

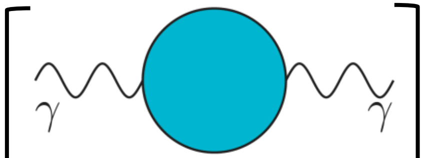
- v_n of EM probes ⇒ directly probe microscopic d.o.f. of nuclear matter and can better constrain $\frac{\eta}{s}, \frac{\zeta}{s}$

EM Rates and Simulations

Electromagnetic radiation from QCD medium

- Finite Temperature Field Theory
  - Dilepton production rate

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



$k^2 = M^2 > 0$

  - Photon production rate

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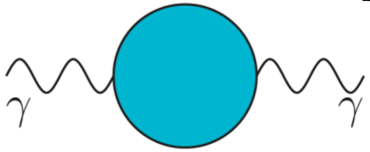
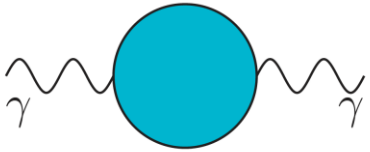


$k^2 = M^2 = 0$

$Im \left[\right]$



= EM Spectral Function

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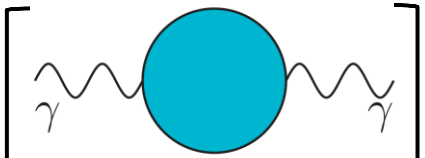

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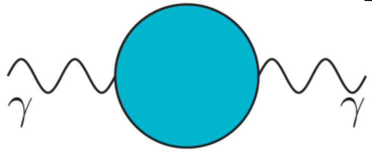

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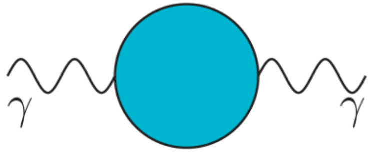
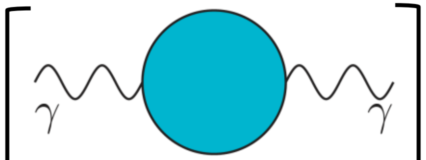


$$\left. \right]$$ = EM Spectral Function

- High Temperature EM spectral function: in pQCD and on the Lattice QCD

$$G(\tau) = \int \frac{dk^0}{\pi} K(k^0,\tau)\, Im \left[\right.$$


$$\left. \right];$$

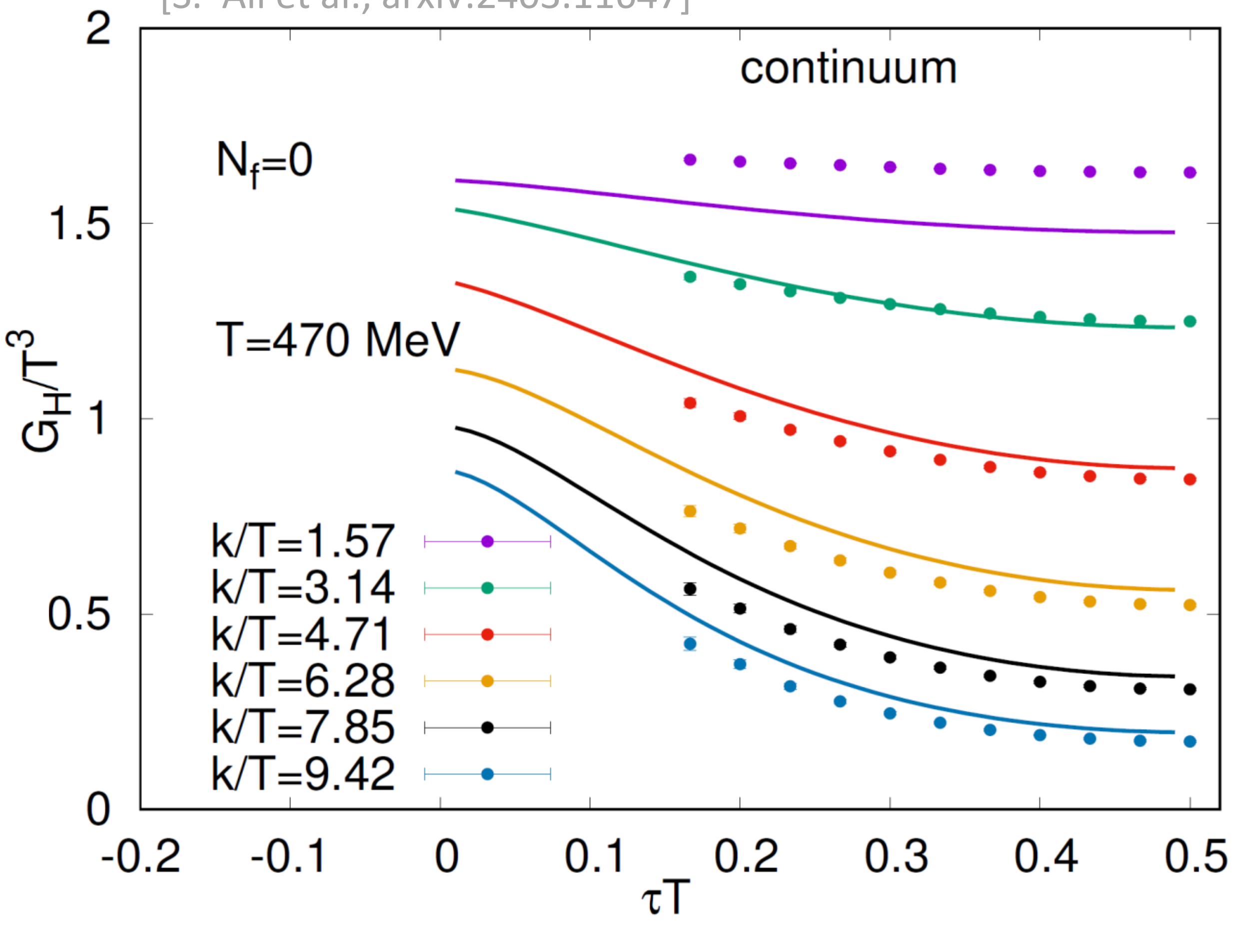
$$K(k^0,\tau) = \frac{\cosh\{k^0[1/(2T) - \tau]\}}{\sinh(k^0/2T)}$$

- Low Temperature EM spectral function: hadronic effective Lagrangians
  - sensitive to chiral symmetry breaking/restoration

Dilepton production from pQCD & lattice QCD ✓

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

[S. Ali et al., arxiv:2403.11647]



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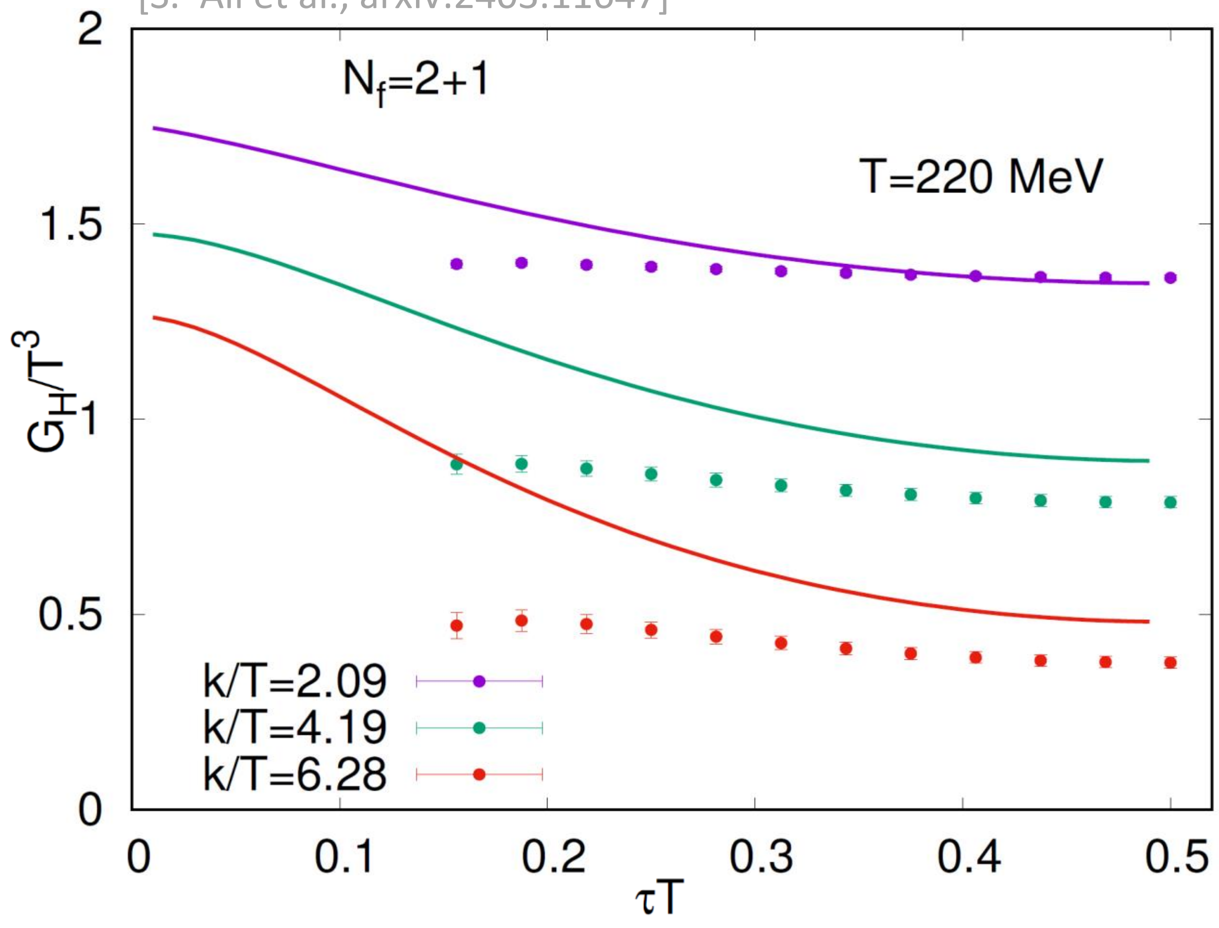
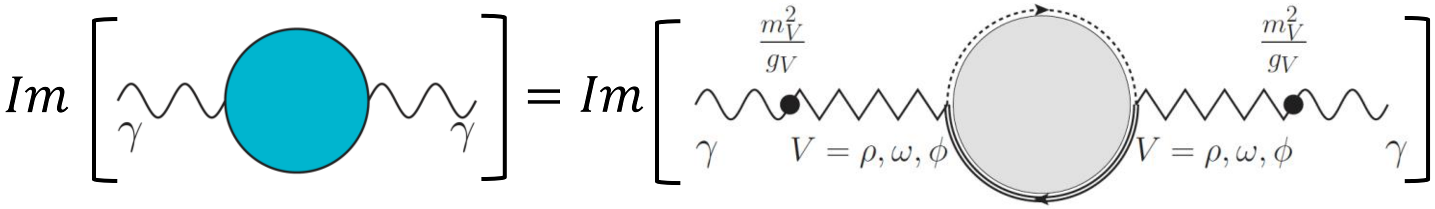


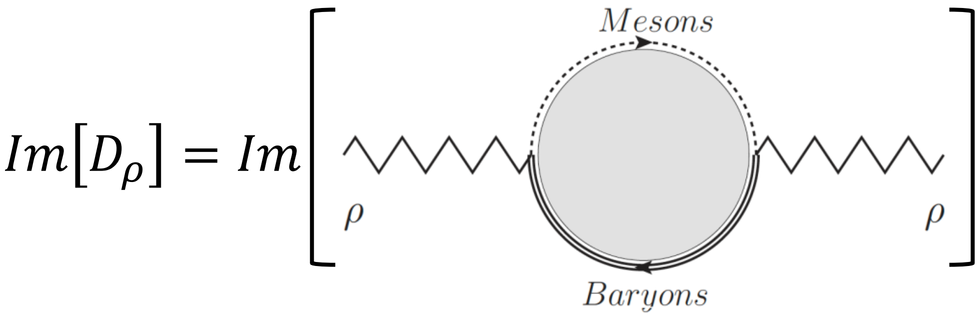
- Entering the era for precision calculations of EM spectral functions; with extension to $\mu_B > 0$.

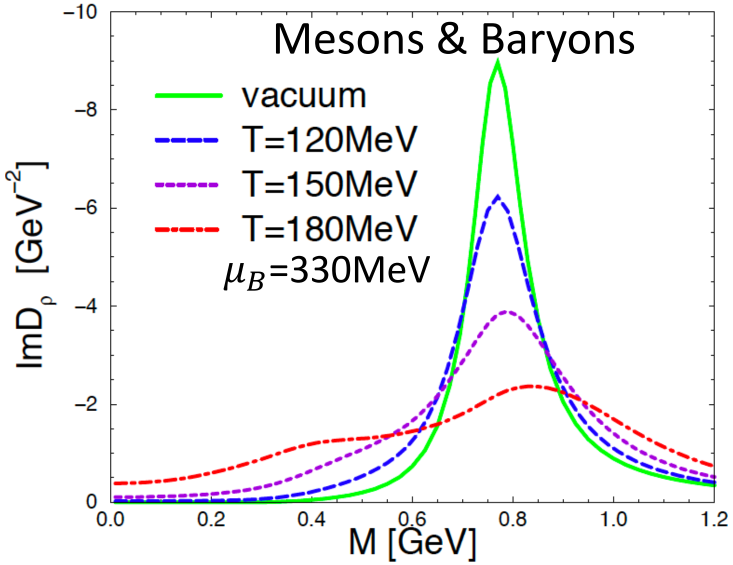
Dilepton production from hadronic interactions

- EM spectral function via vector mesons

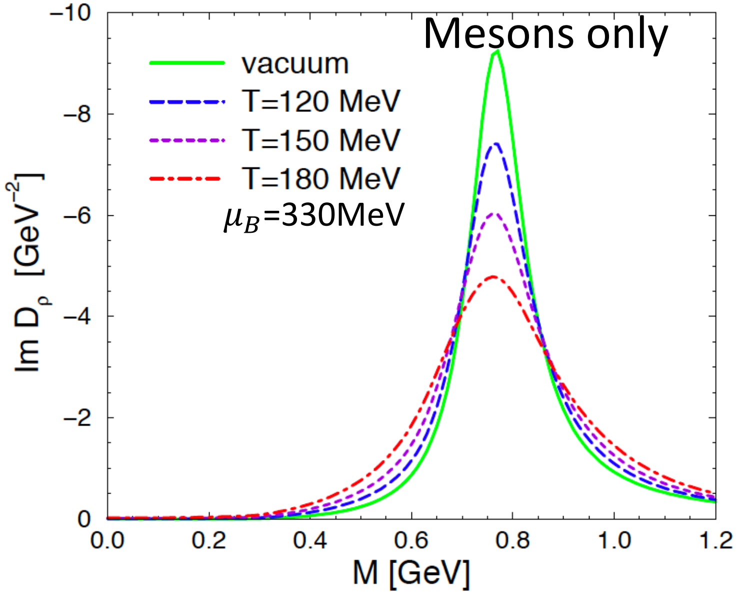


- Many-body effective Lagrangians





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



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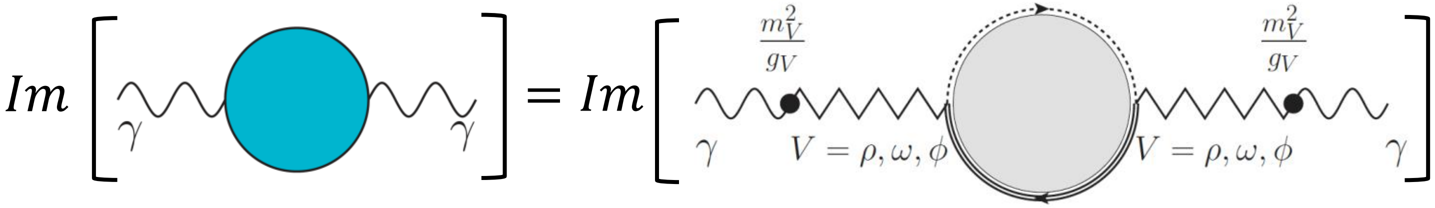

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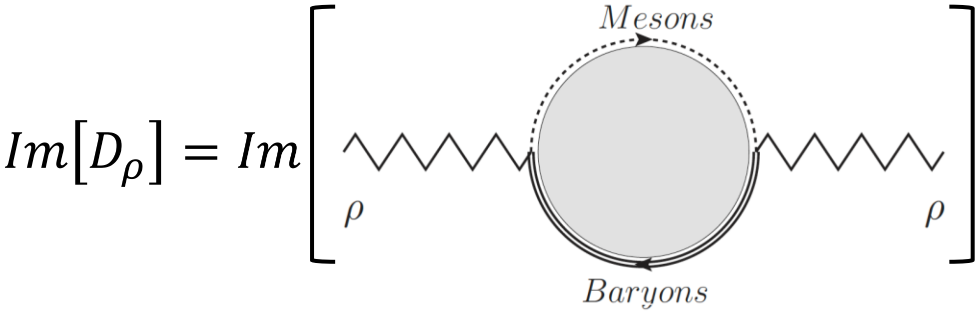
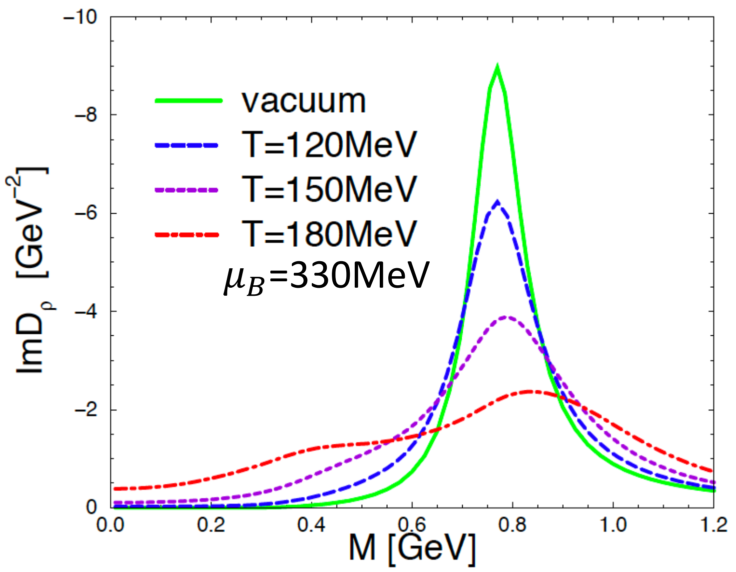


- Many-body effective Lagrangians now include the chiral partner of ρ, the a_1
  - ρ & a_1 agree at high T ⇒ encouraging for understanding chiral symmetry restoration from a hadronic perspective.



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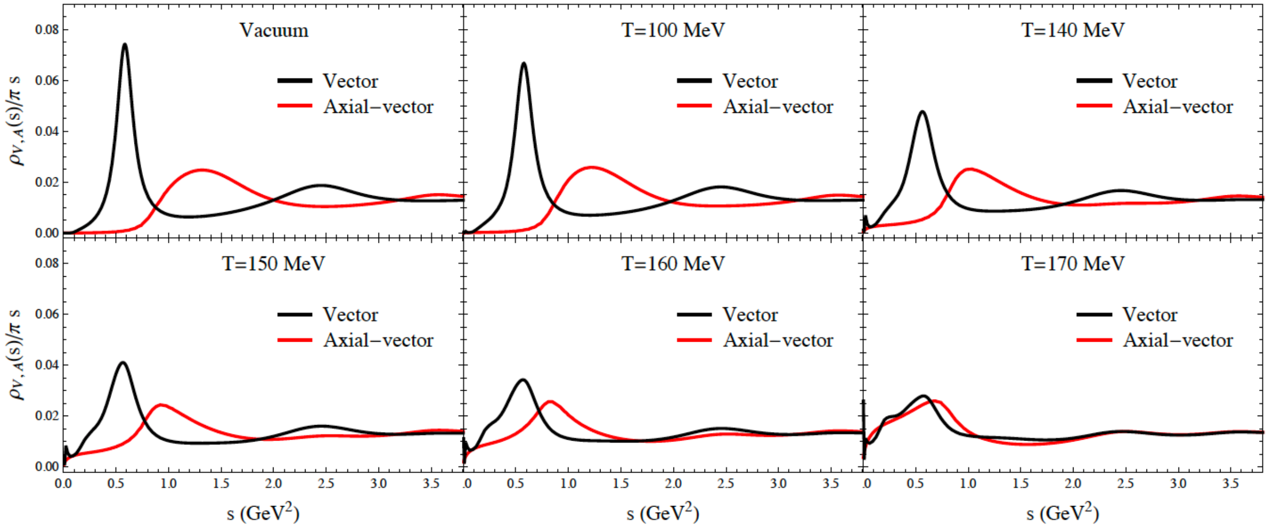


[P.M. Hohler & R. Rapp, Phys. Lett. B 731, 103 (2014)]

Dilepton production in a viscous medium ✓

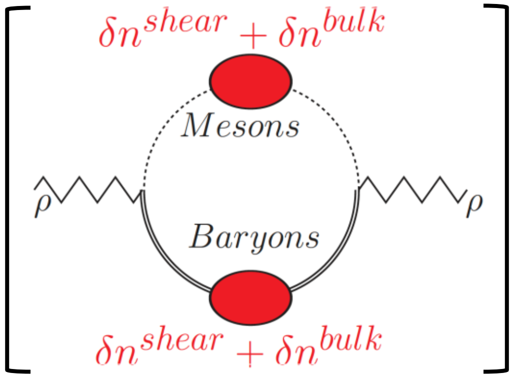
- Theory ⇒ Experimental observables

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

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

- Dileptons from (hadronic) scattering theory

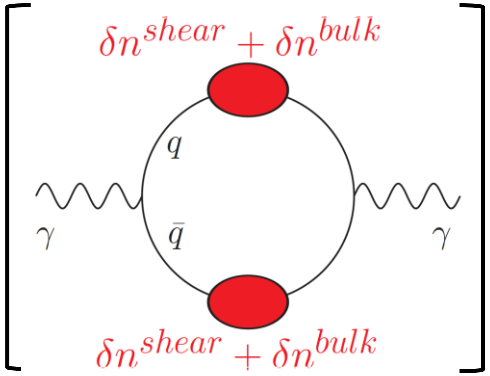
$$\frac{d^4R}{d^4k} \propto Im$$



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

- Dileptons from LO pQCD

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



[G.V. et al., Phys. Rev. C 98, 014902 (2018)]
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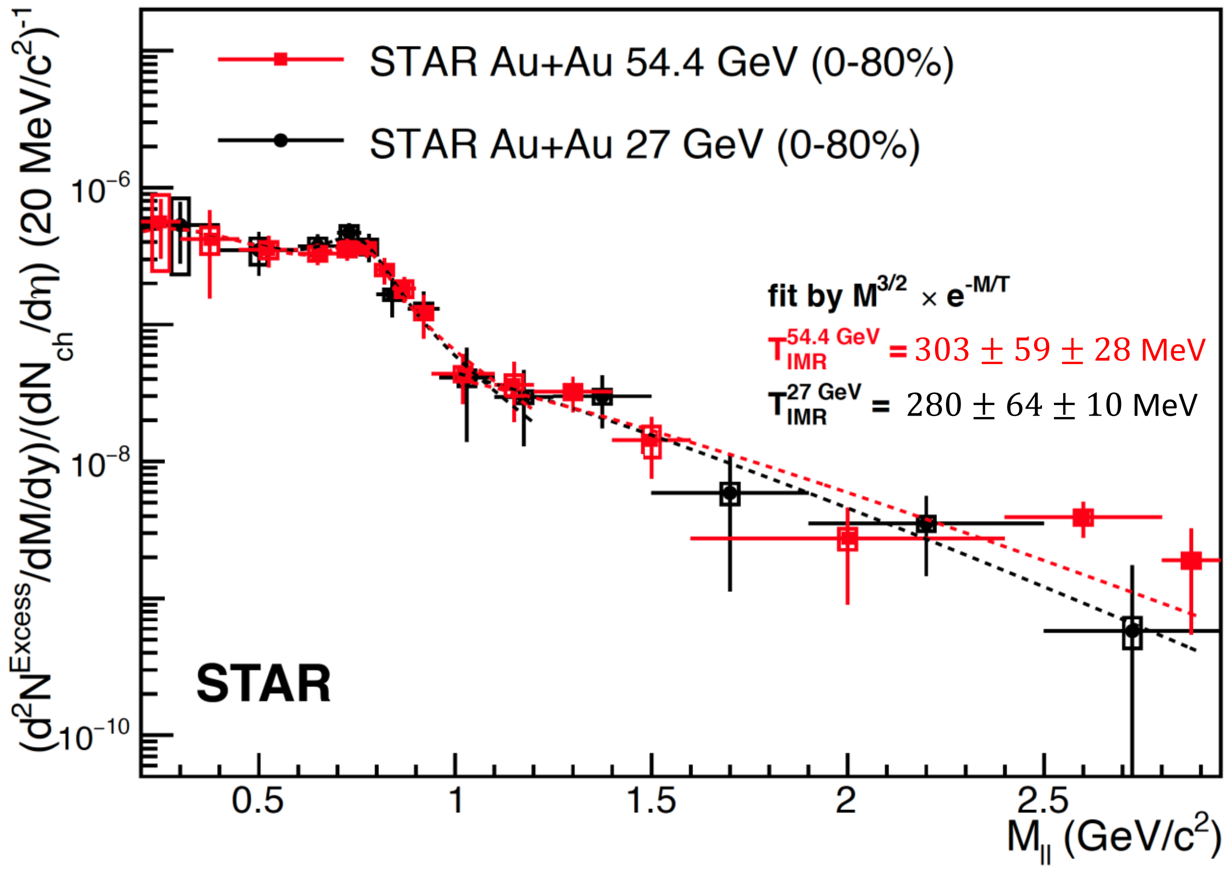
Dileptons as "timer", thermometer & viscometer

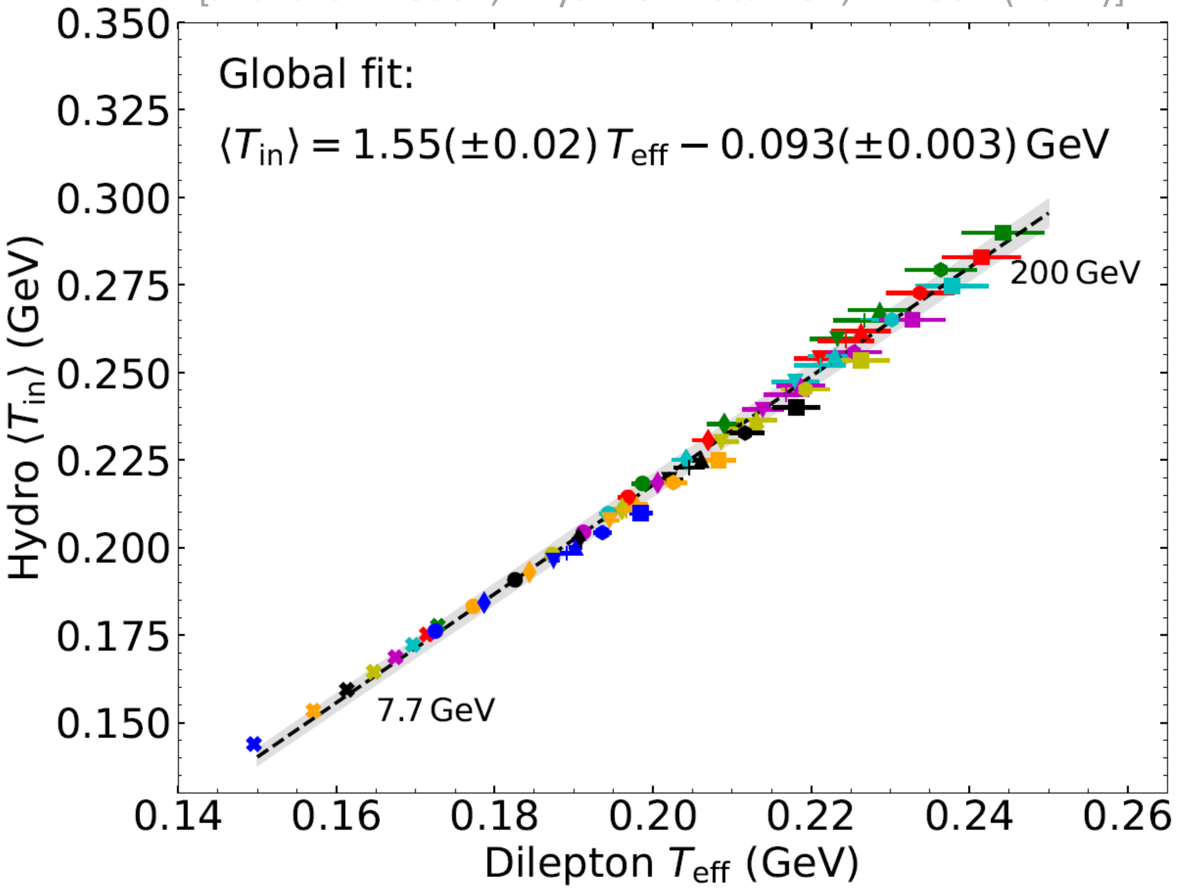
- Size of $\int \frac{dN}{dM} \in 0.3 < M < 0.7$ GeV
- Slope of $\frac{dN}{dM} \in 1.5 < M < 2.5$ GeV

[R. Rapp, H. van Hees, Phys. Lett. B 753, 586-590 (2016)]

[STAR, arxiv:2402.01998]



[J. Churchill et al., Phys. Rev. Lett. 132, 172301 (2024)]



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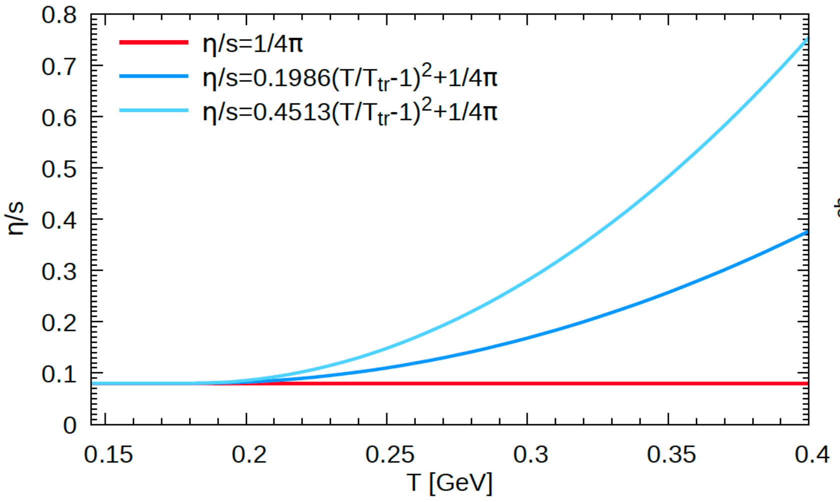

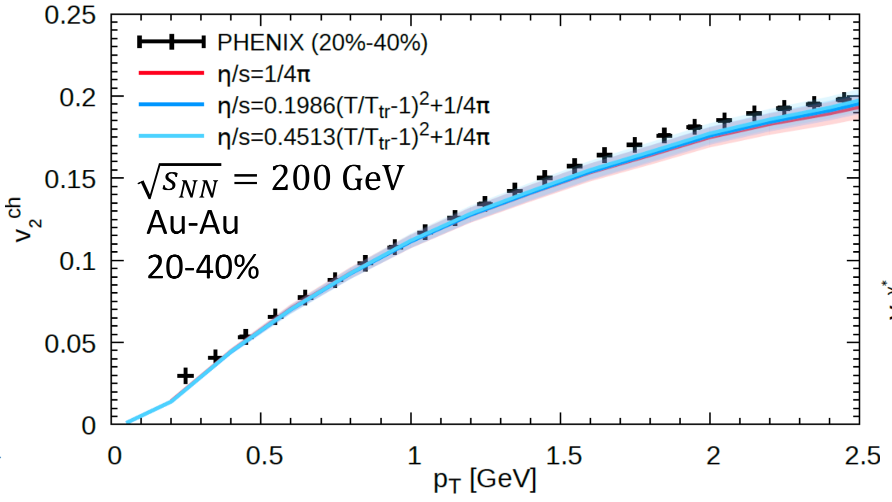

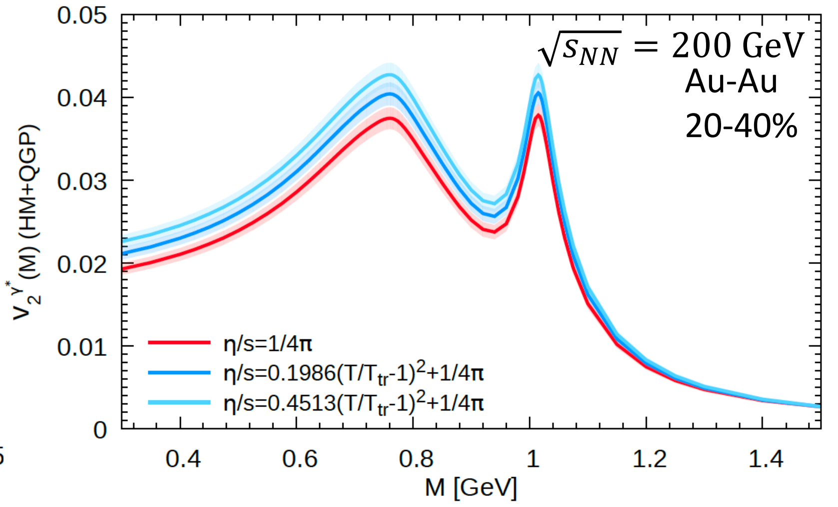

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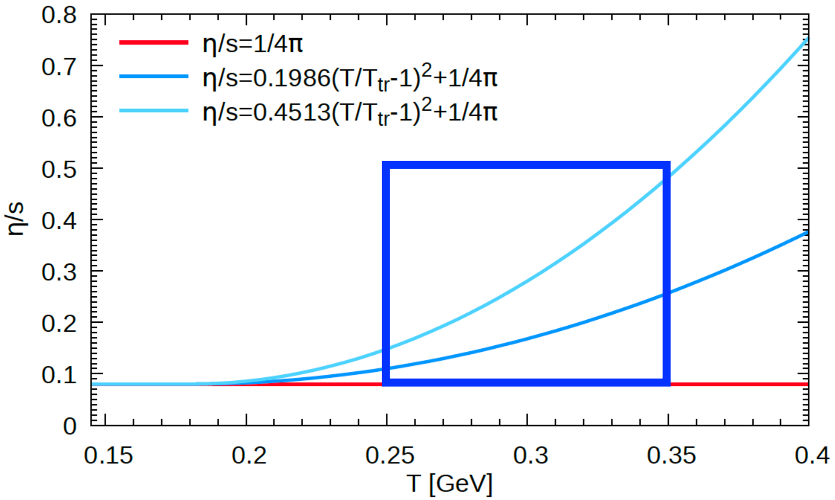

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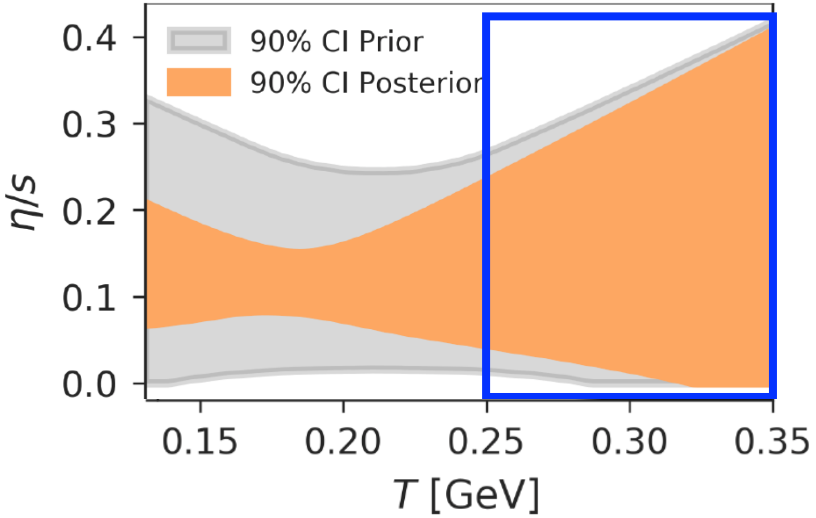
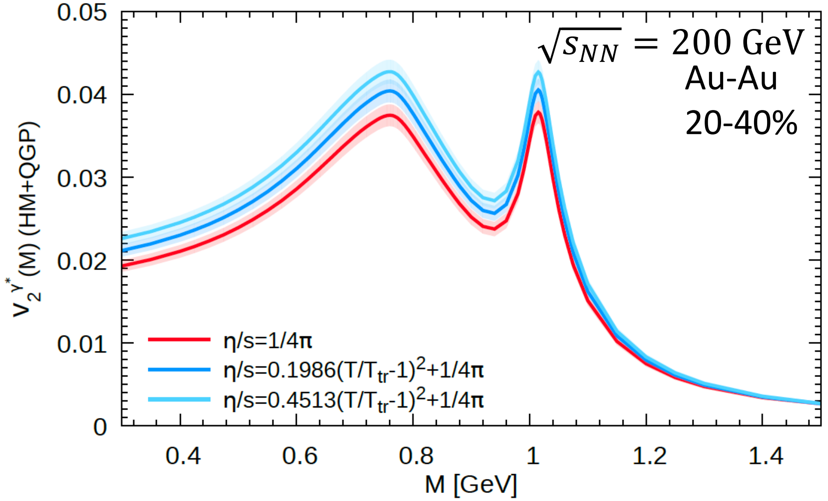


[D. Everett et al., Phys. Rev. Lett. 126, 242301 (2021)]



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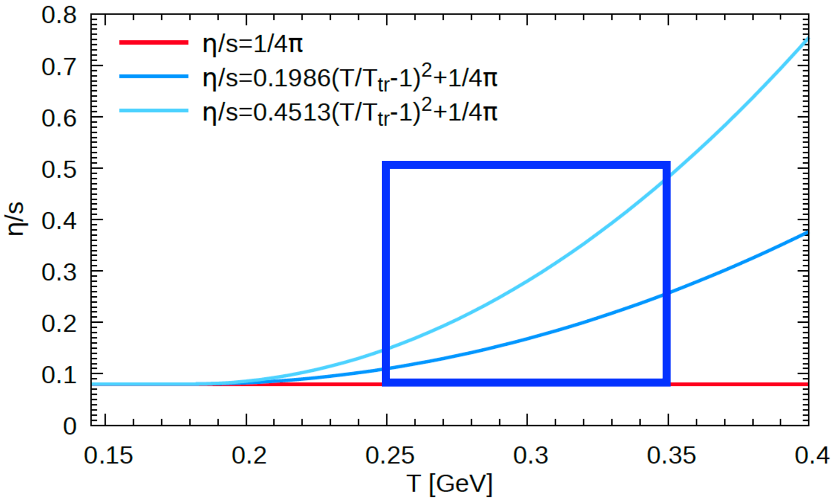

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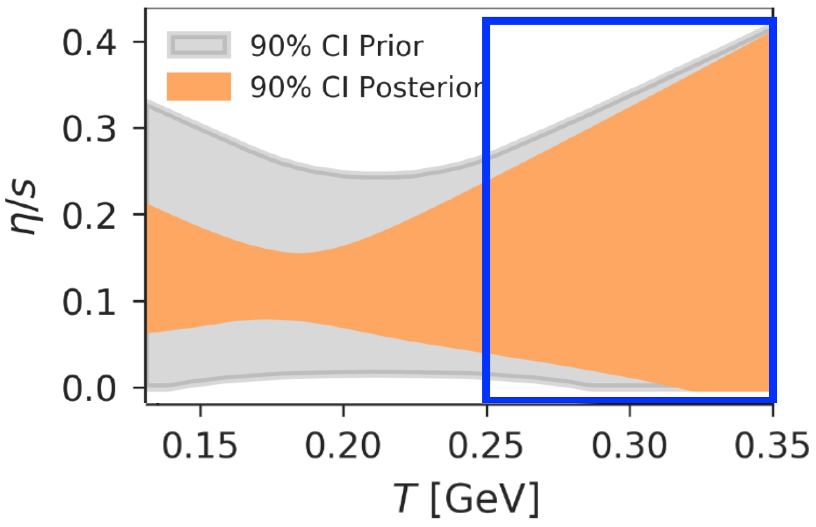

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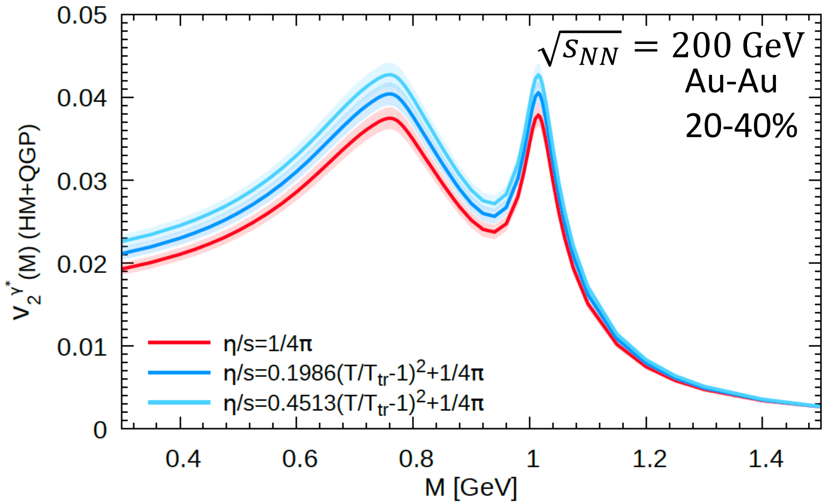

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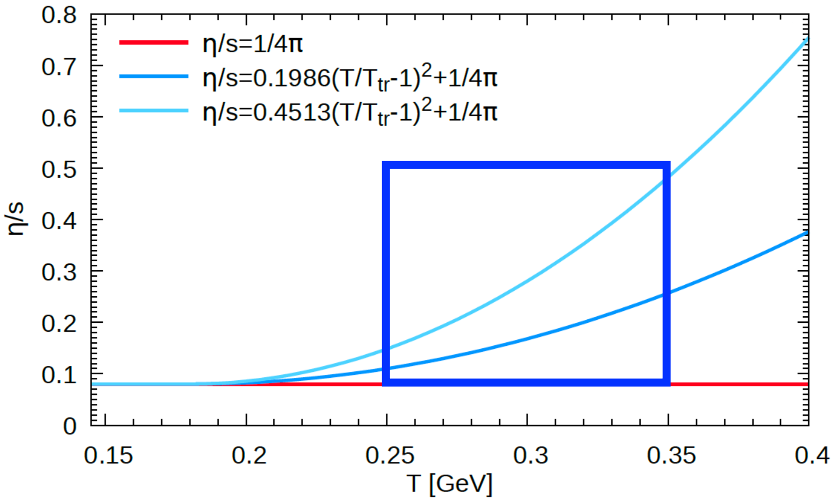

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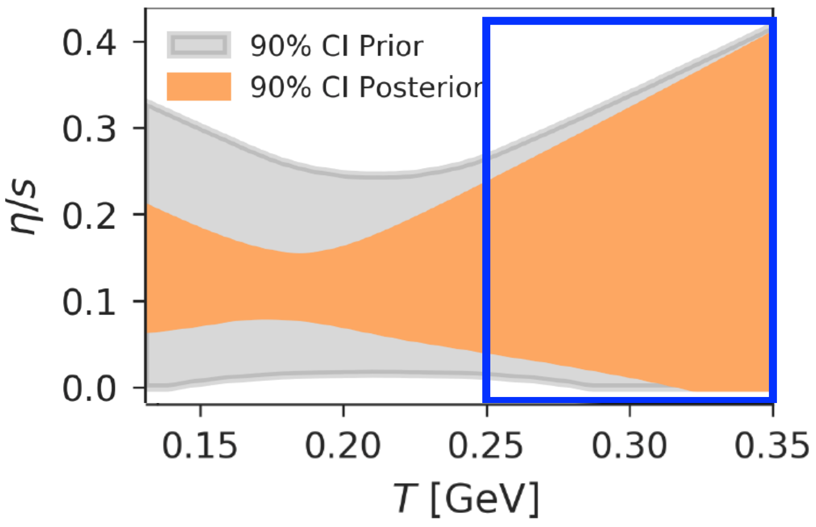

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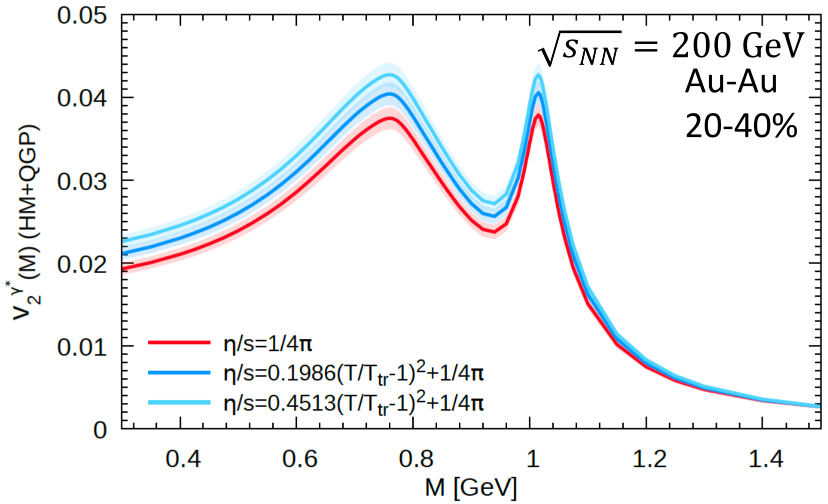

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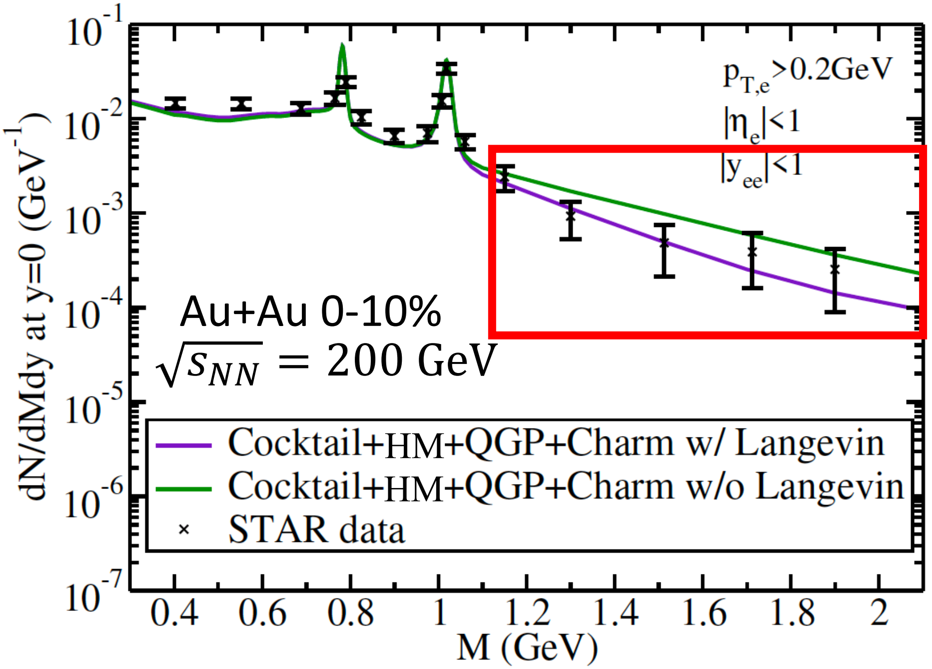
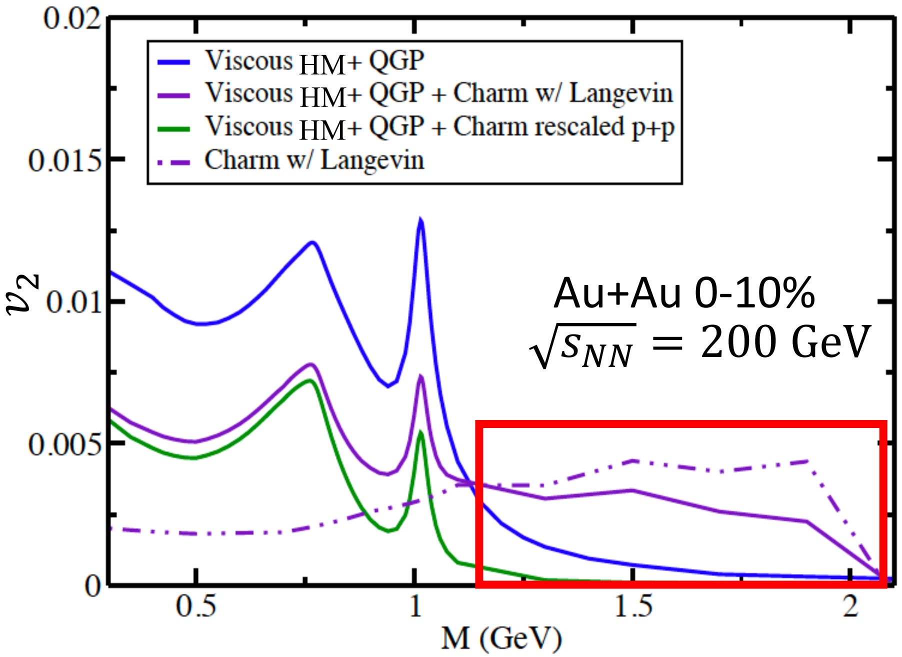
- A joint Bayesian analysis (dileptons & hadrons) to help constrain on $(\eta/s)(T)$.
- An accurate measurement of dilepton v_2 is needed at high $\sqrt{s}$ ⇒ possible following ALICE upgrade

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

Dilepton yield and v_2 at intermediate M

- Importance of semi-leptonic decays of open heavy flavor to explaining the data





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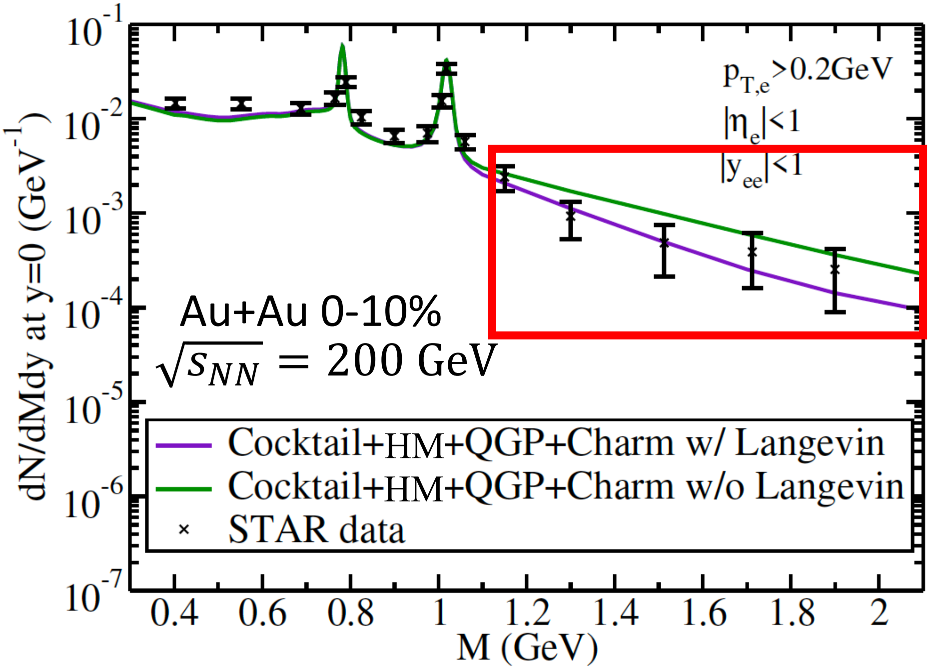

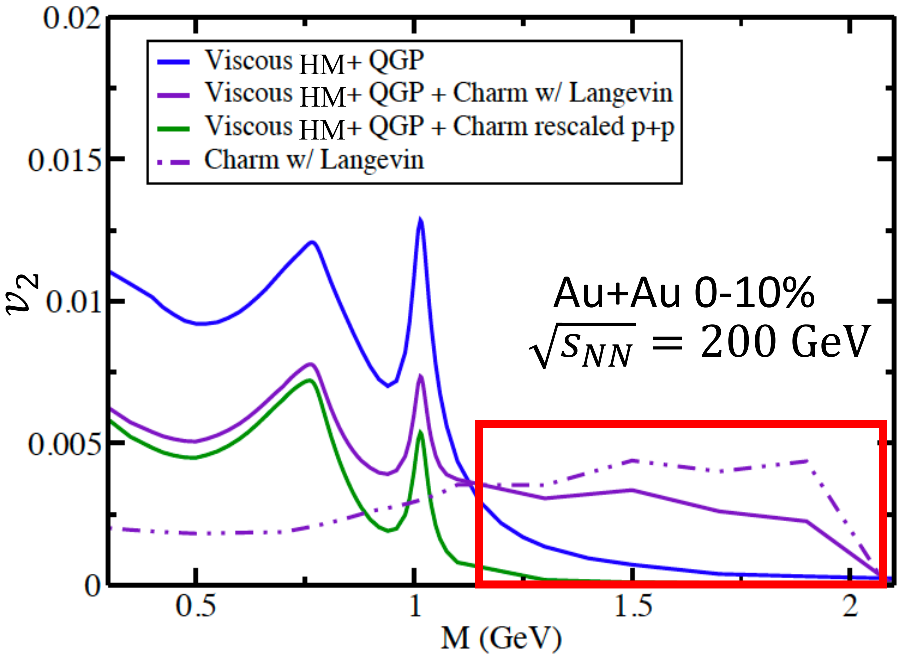

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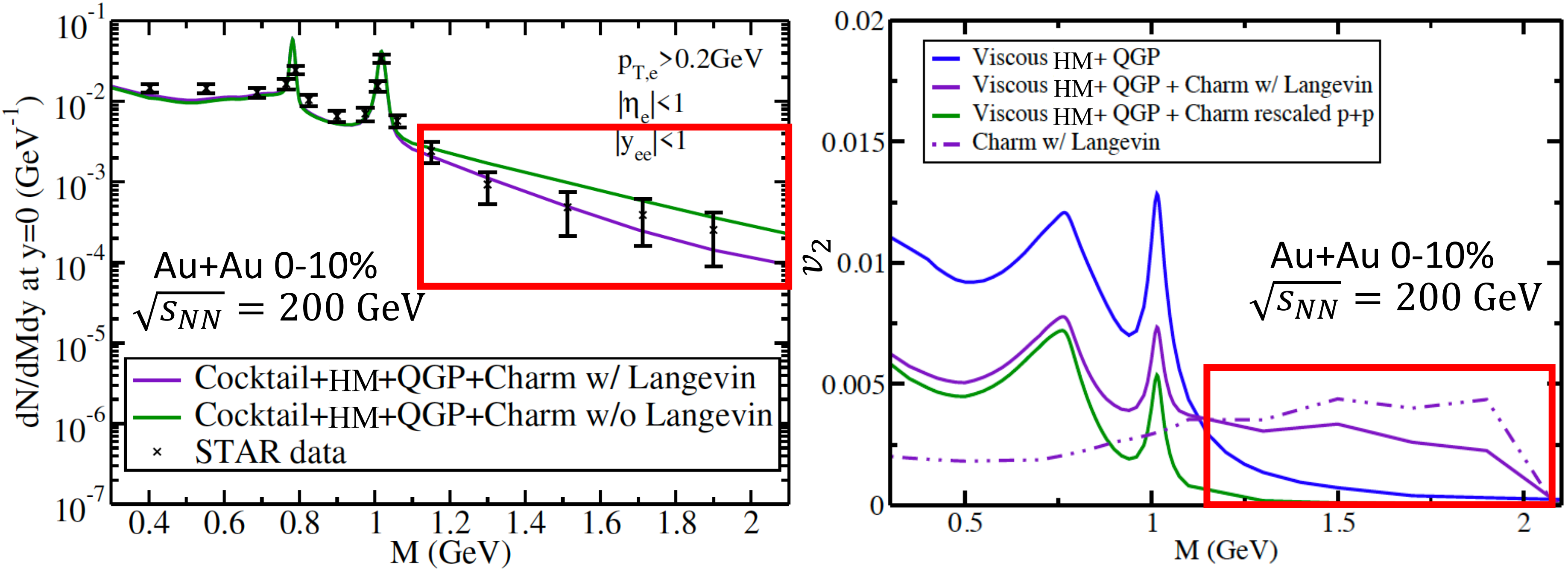

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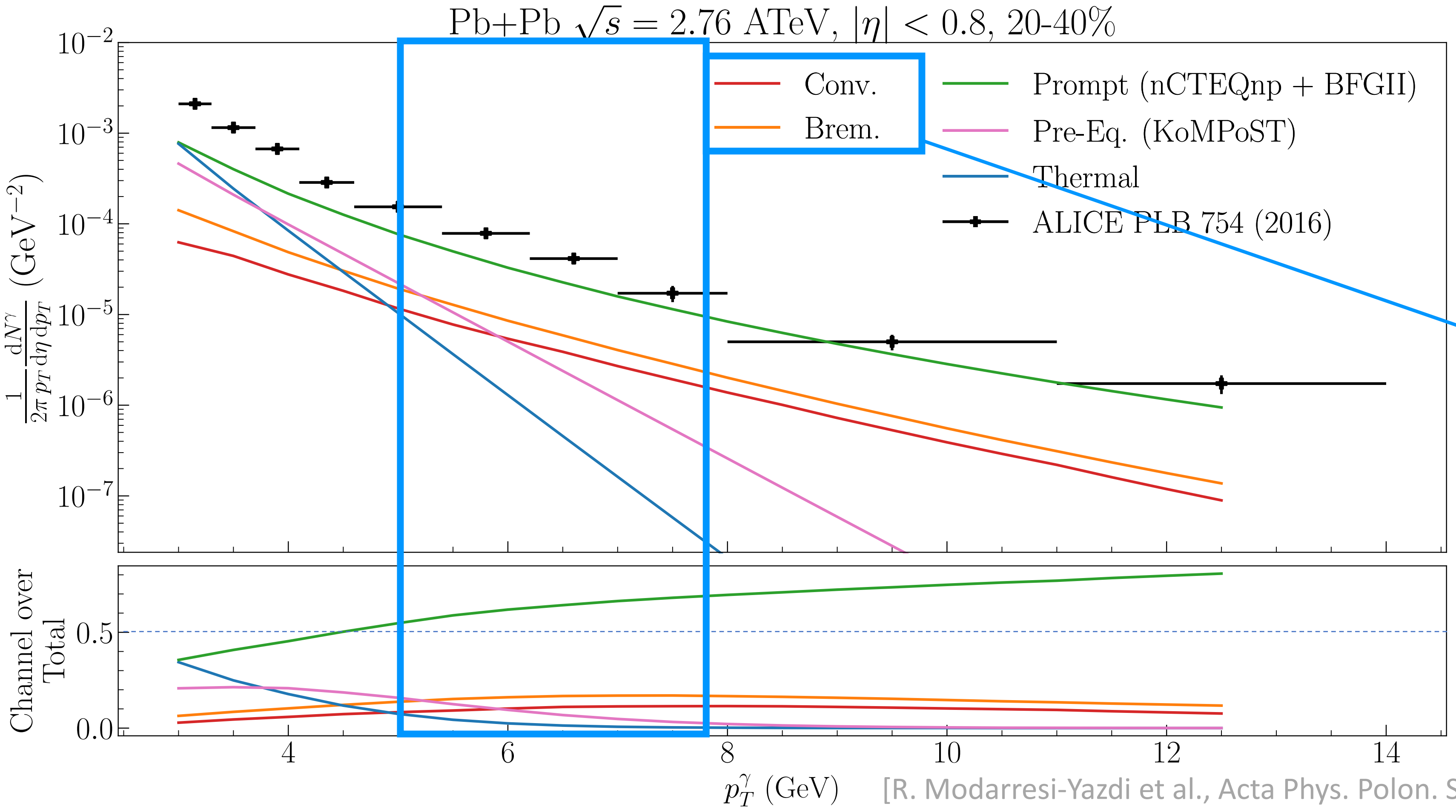
- Dilepton v_2 is simultaneously sensitive to $\boldsymbol{\hat{q}_{QCD}}$ and **viscosities**!

Photon production at intermediate p_T

- Jet-medium EM production is directly sensitive to $\hat{q}_{QCD}$, **avoiding** hadronization effects
- Jet-medium photons are composed of: conversion and bremsstrahlung.



[R. Modarresi-Yazdi et al., Acta Phys. Polon. Supp. 16, A129 (2023)]

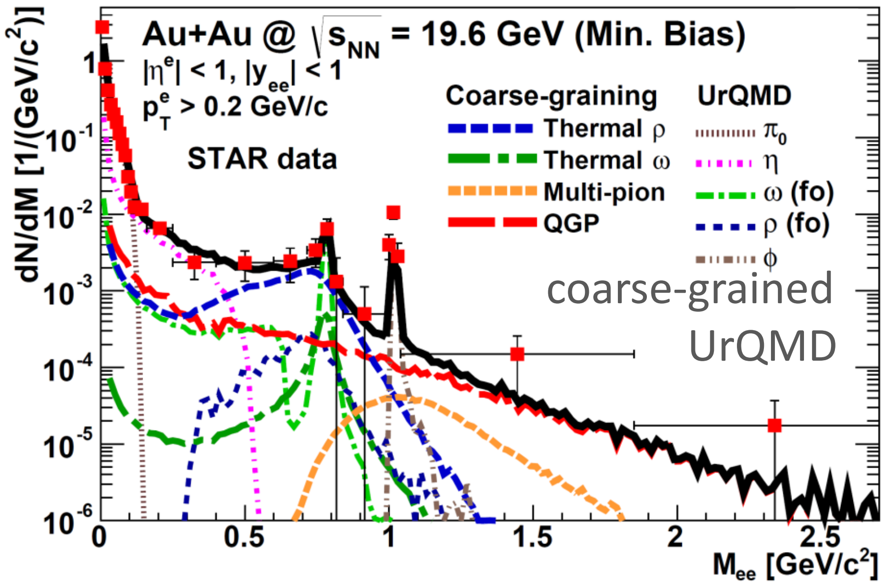
Photons $5 < p_T < 8$ GeV:

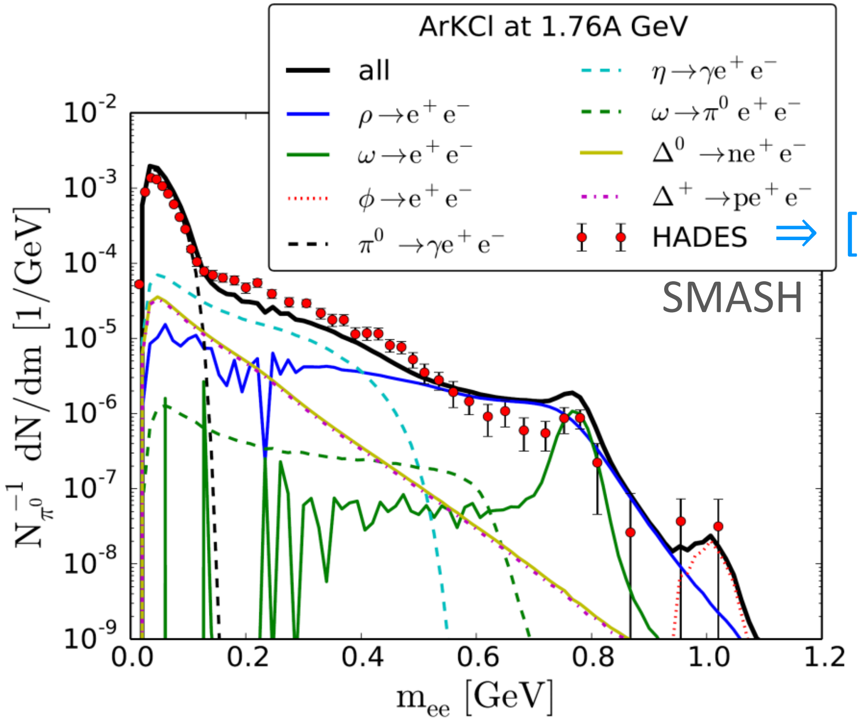
- Total yield dominated by prompt photons
- Significant contribution from jet-medium ≈ 30 %
  - Conversion ≈ 12 %
  - Bremsstrahlung ≈ 18 %

Dileptons from transport

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

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





⇒ [N. Schild, Mon, 5:05PM]

[J. Staundenmaier, Phys. Rev. C 98, 054908 (2018)]

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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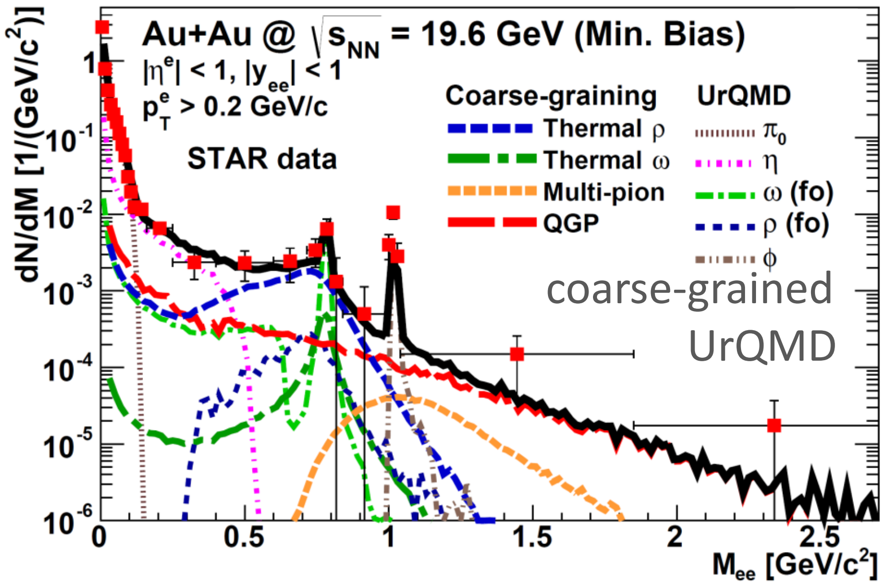

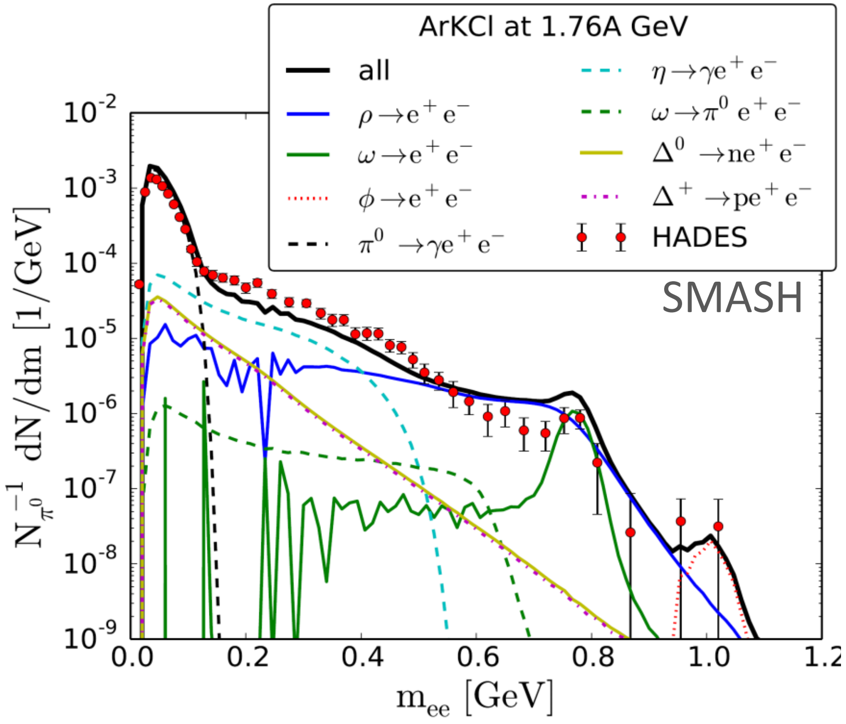

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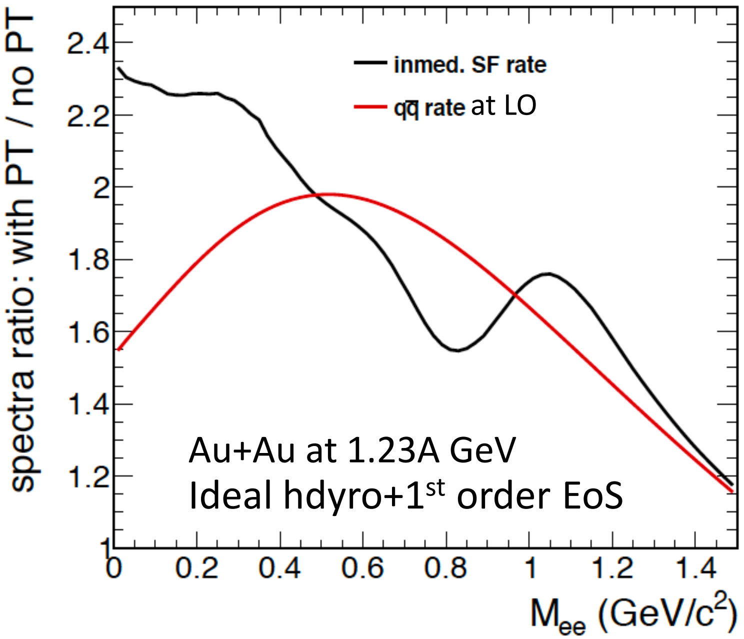

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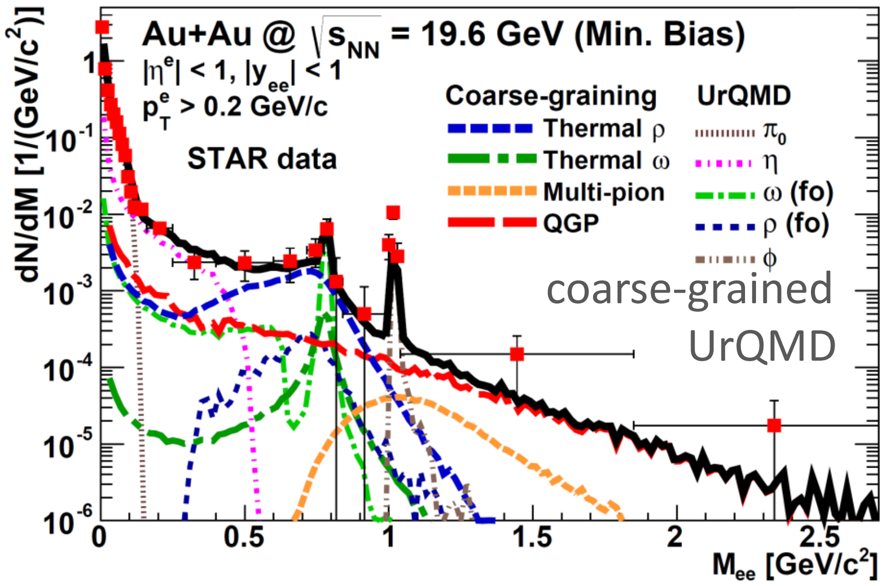

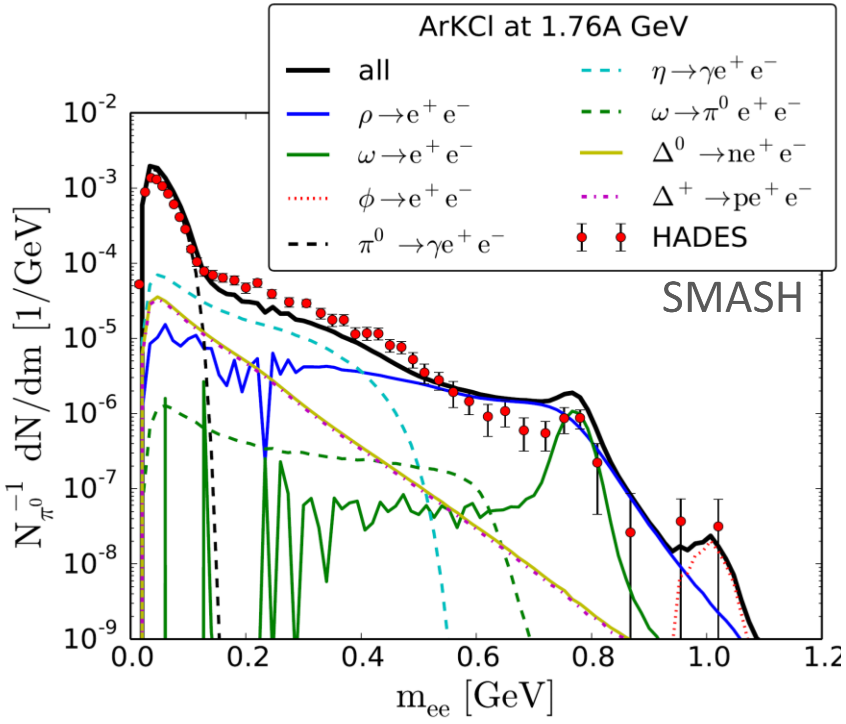

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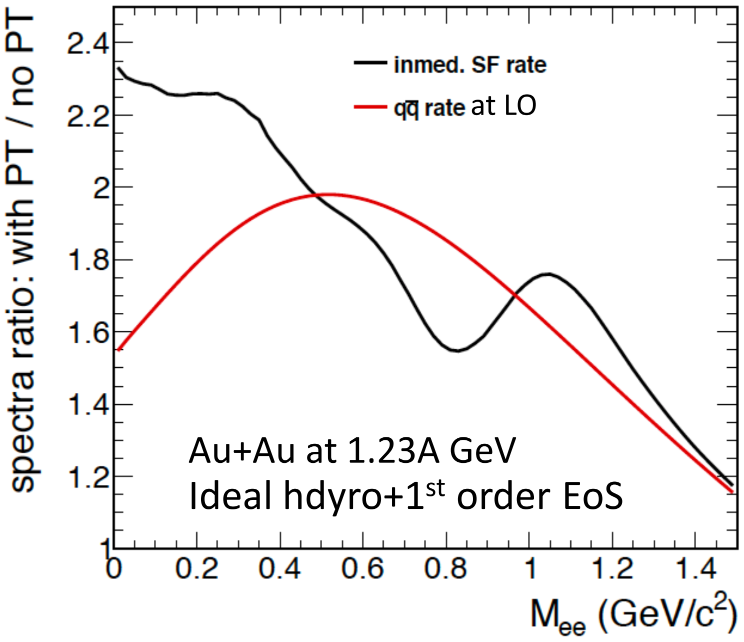

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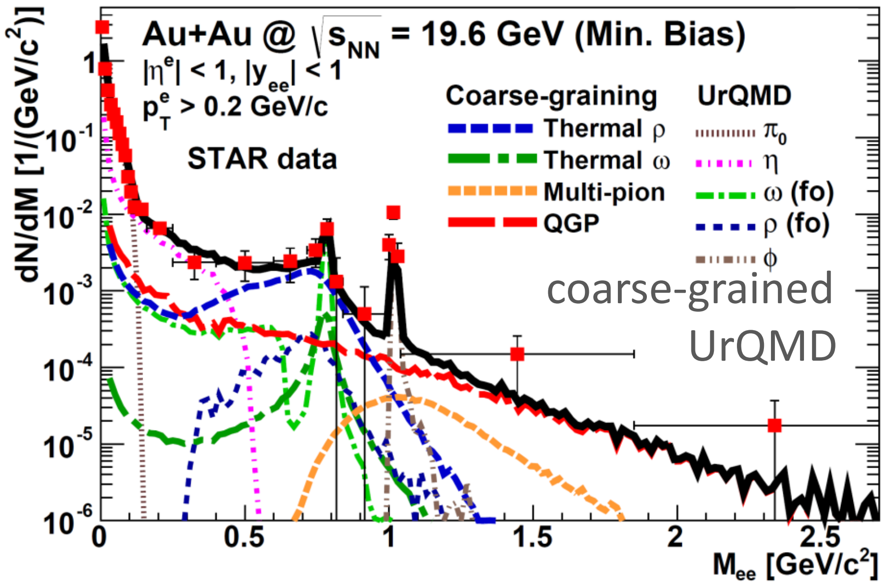

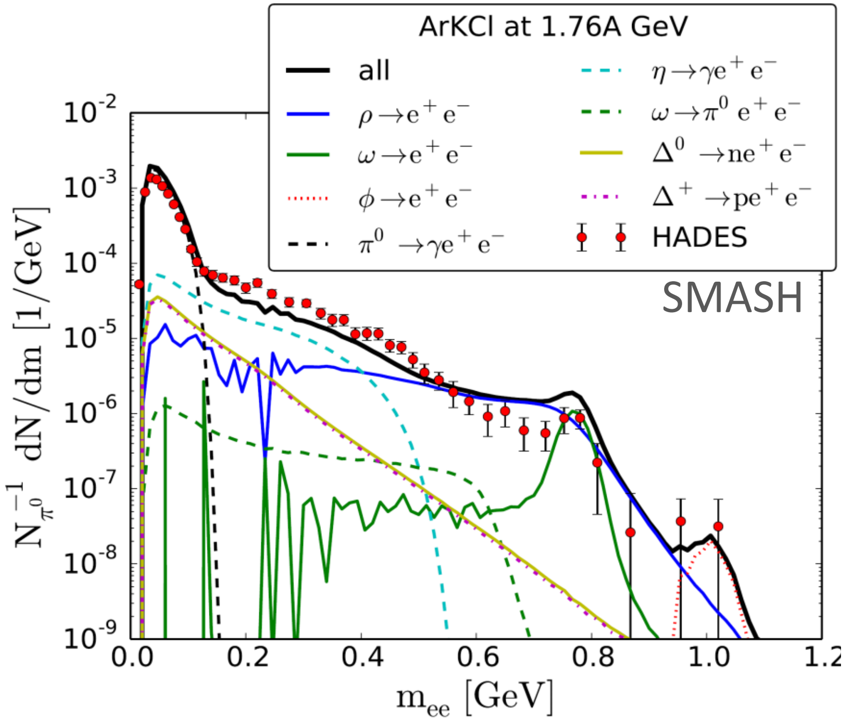

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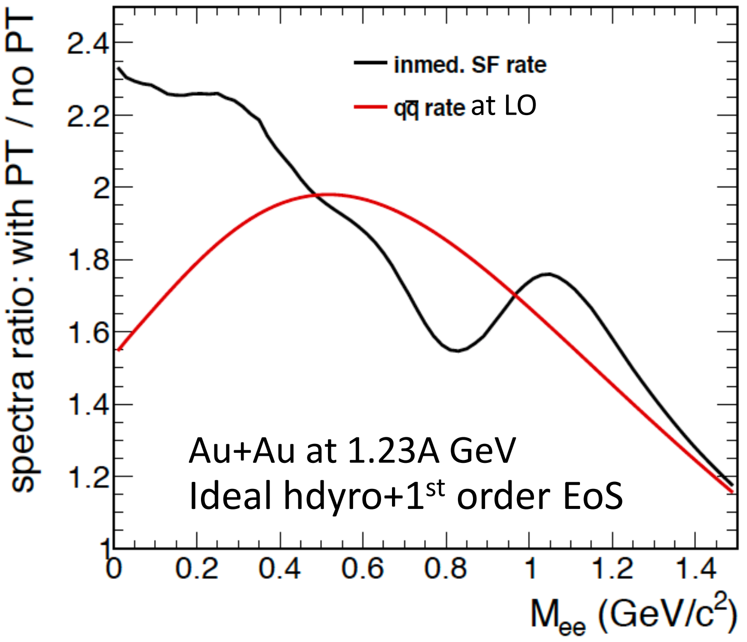

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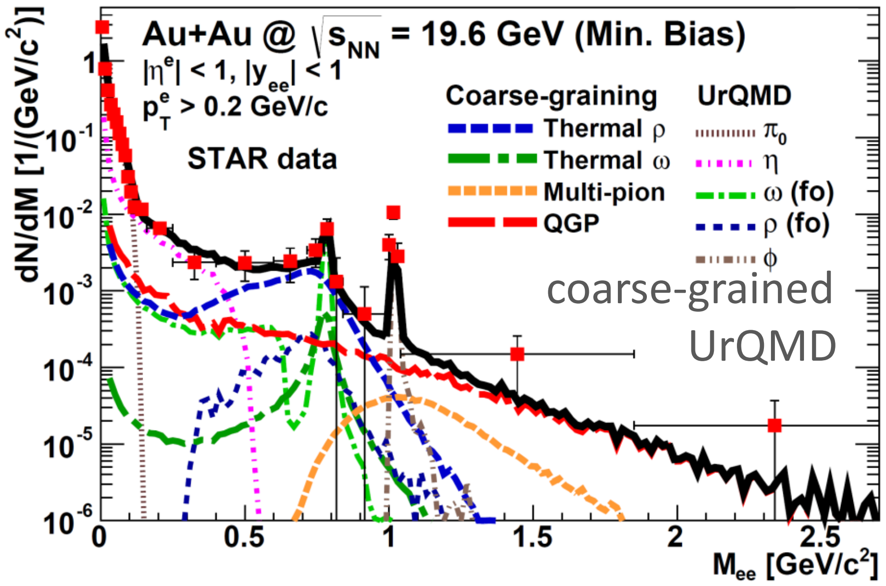

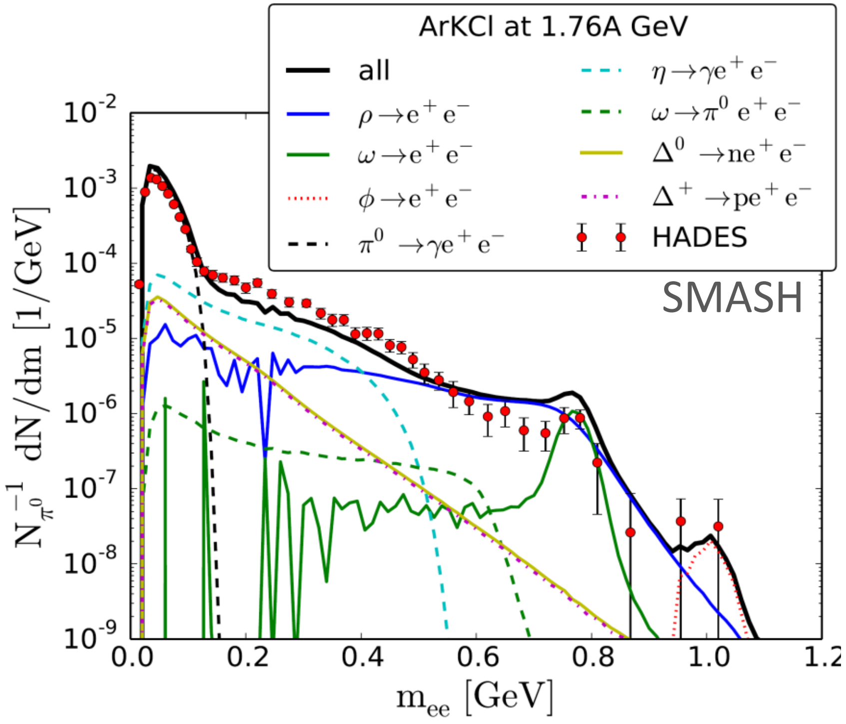

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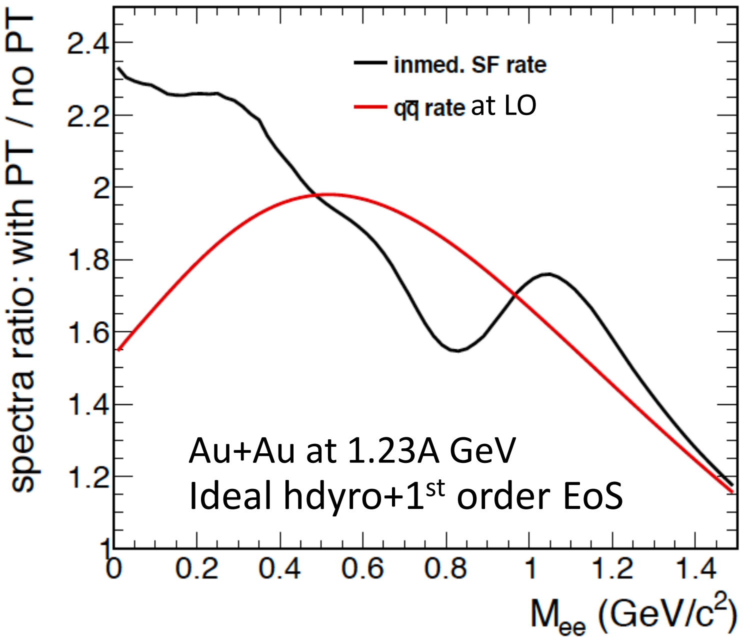

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- No more jets at lower $\sqrt{s_{NN}}$: **only** penetrating probes sensitive to QCD dofs are EM.
- Bayesian comparisons of dileptons at various $\sqrt{s_{NN}}$ ⇒ learn more dilepton production mechanisms
  - Exclude rates w/o chiral symmetry restoration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

Summary & Outlook

✓Improved rates

- NLO pQCD comparable with lattice QCD
- Hadronic rates are now including chiral symmetry restoration effects

✓Better medium simulations

- Hydrodynamic production of EM probes include off-equilibrium dynamics (i.e., viscous effects) and many different sources of EM production are included.

✓What was/can be done

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

➢Future directions

- Determine uncertainties of EM probes calculations (e.g. viscous corrections) for better estimation of transport coefficients be it first order (e.g., $\zeta, \eta, \hat{q}$ ...).
- Bayesian analysis using hadron & EM probes with more precise data
- More measurements of dilepton v_2 needed

Thank you

Questions?

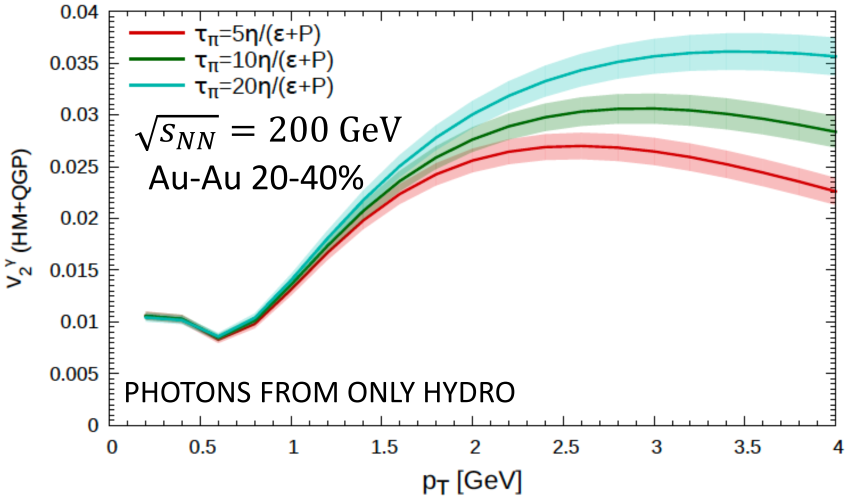
Backup

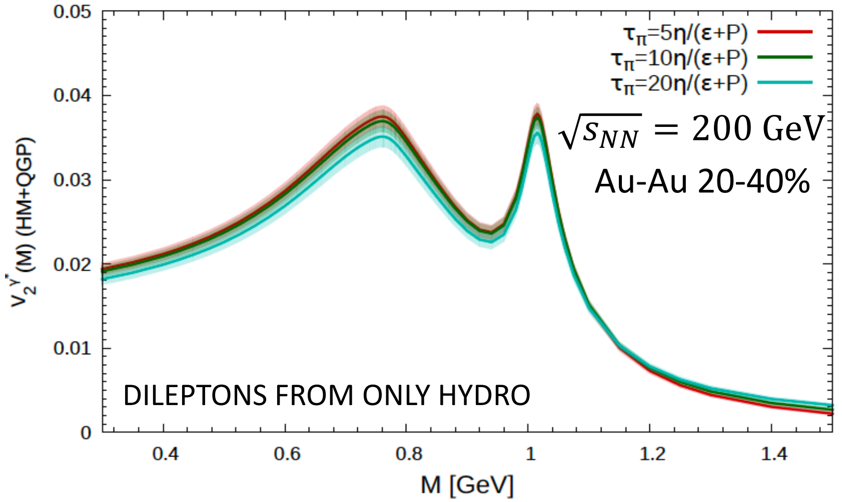
EM probes sensitivity to other transport coefficients

- Sensitivity to second order transport coefficient

$$\tau_\pi = b_\pi \eta/(\varepsilon + P)$$

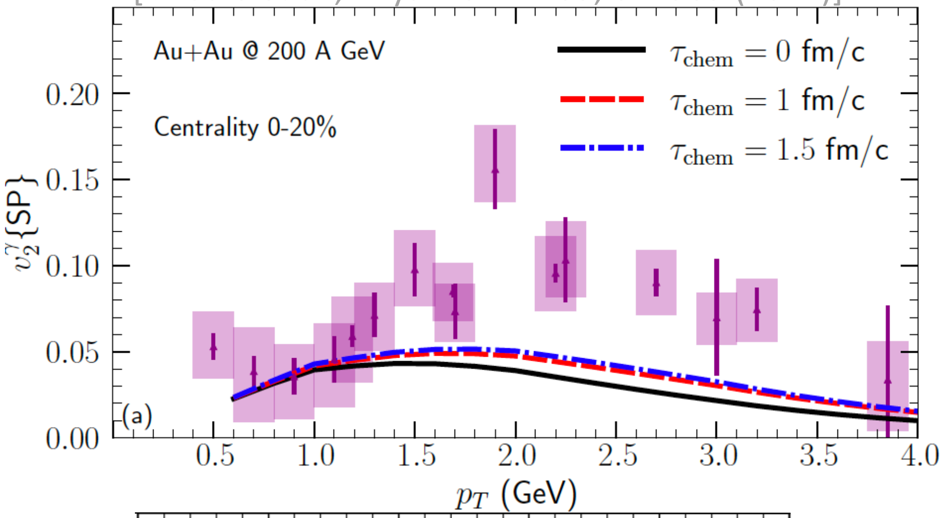
[G.V. et al., Phys. Rev. C 94, 014904 (2016)]



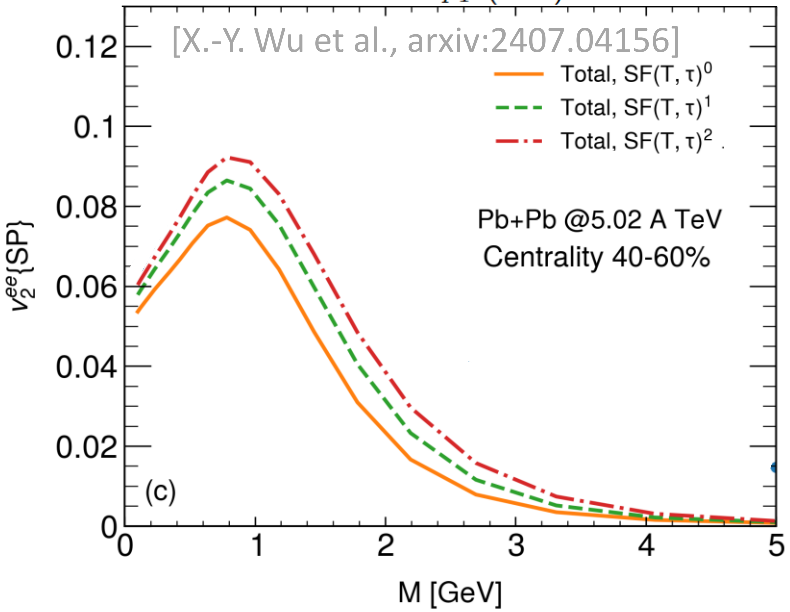


- Sensitivity to chemical equilibration

[C. Gale et al., Phys. Rev. C 105, 014909 (2022)]



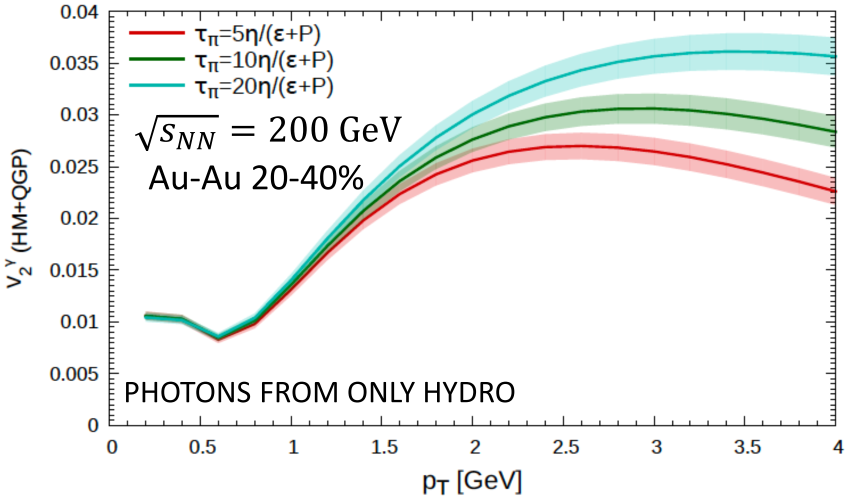
[X.-Y. Wu et al., arxiv:2407.04156]

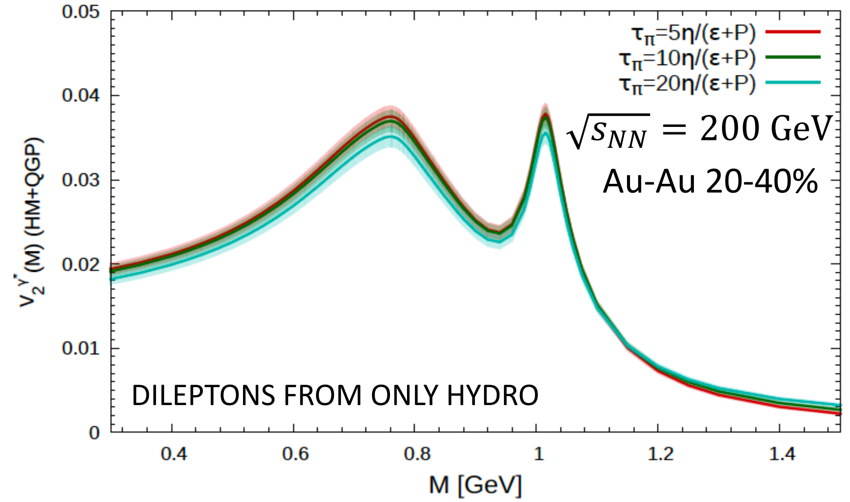


EM probes sensitivity to transport coefficients

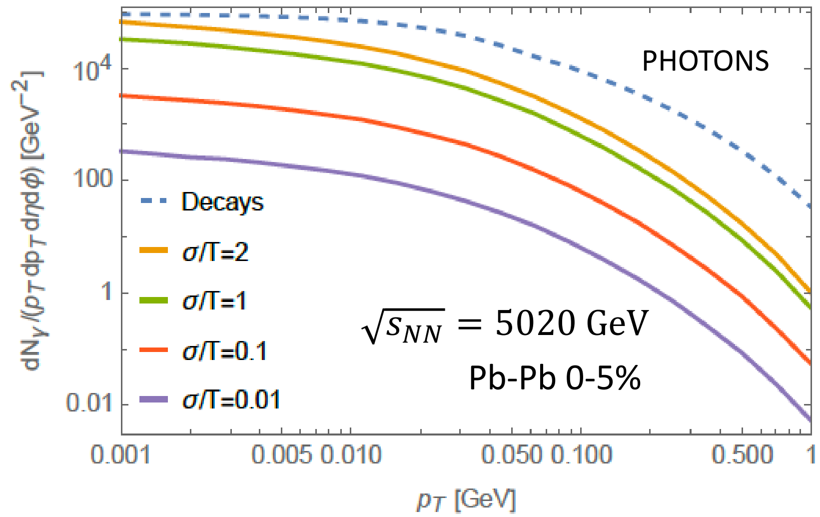
- Sensitivity to second order transport coefficient $\tau_\pi = b_\pi \eta/(\varepsilon + P)$

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

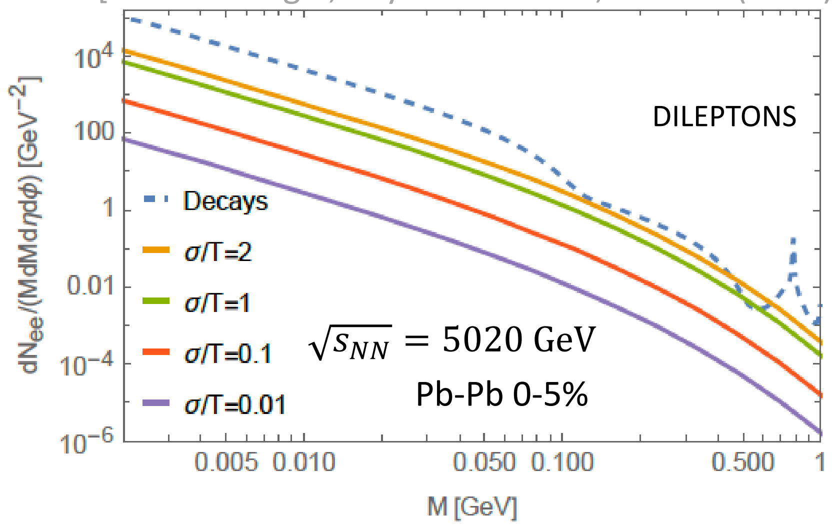




- Sensitivity to electrical conductivity using spectral function from EM current in hydro



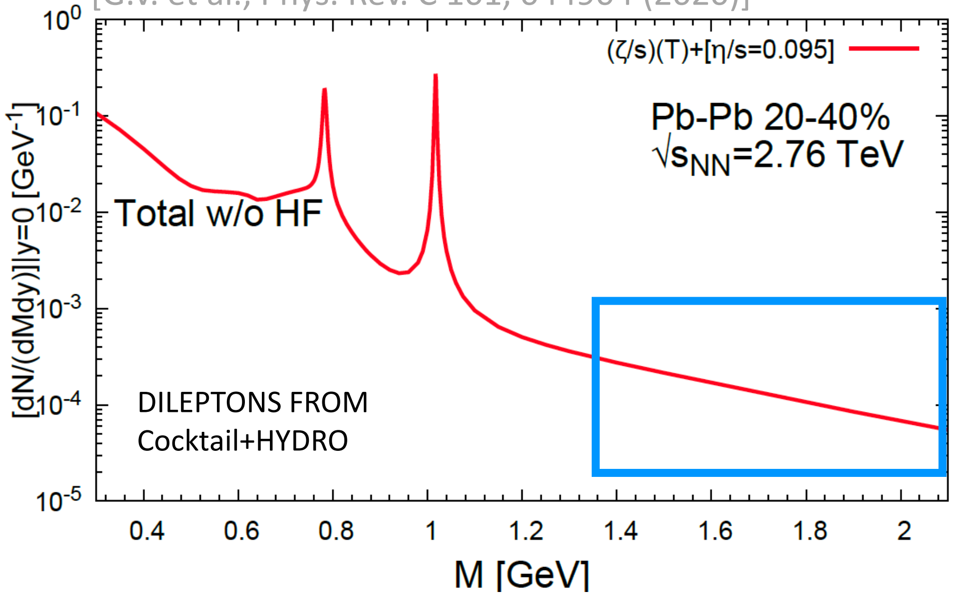
[S. Floerchinger, Phys. Lett. B 837, 137647 (2023)]

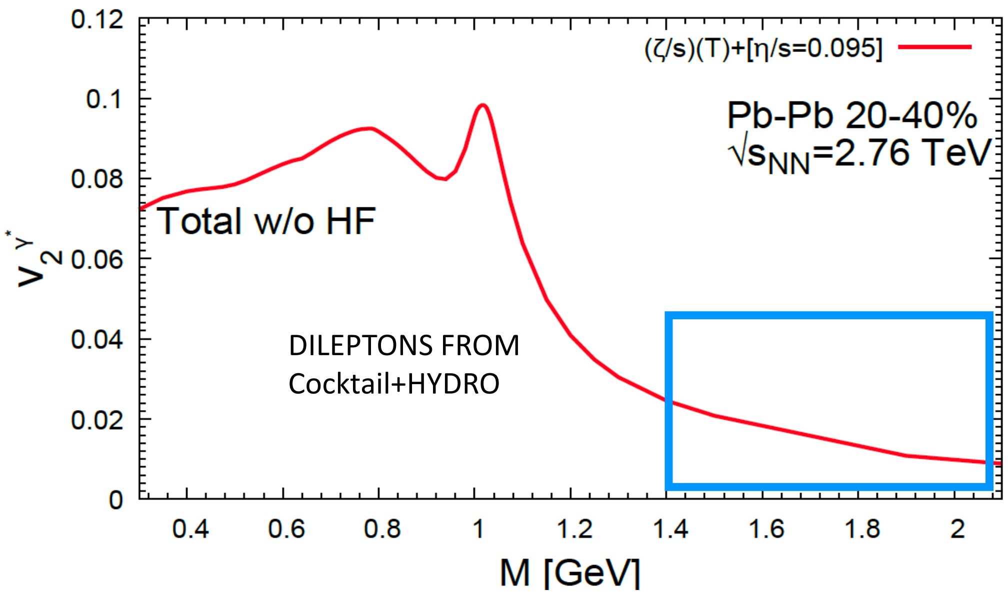


Dilepton flow at $M \gtrsim 1$ GeV as probe of QGP

- 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! [also, c.f. B. S. Kasmaei, M. Strickland, Phys. Rev. D 99, 034015 (2019)]

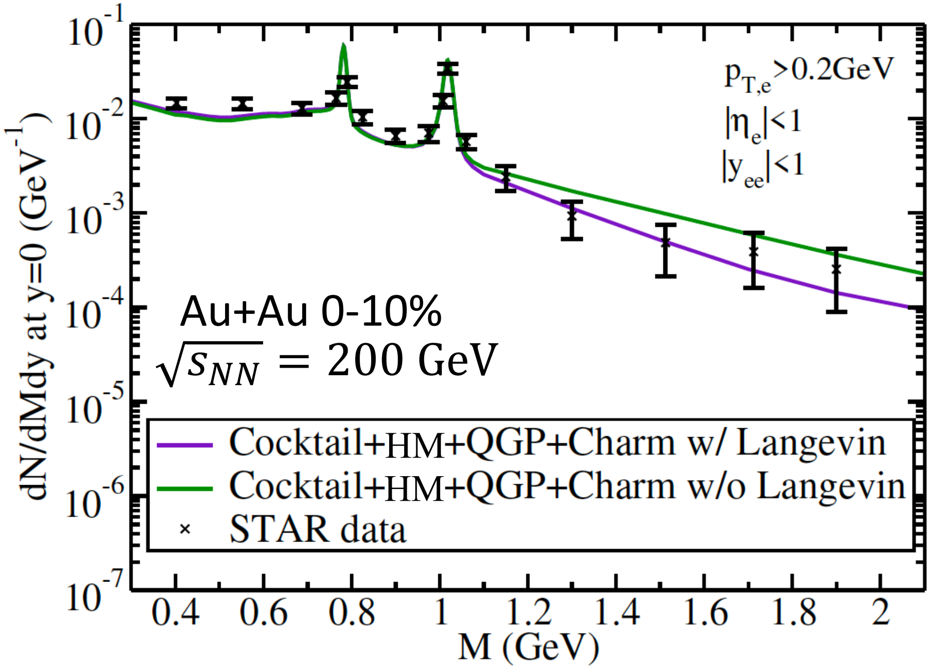
[G.V. et al., Phys. Rev. C 101, 044904 (2020)]



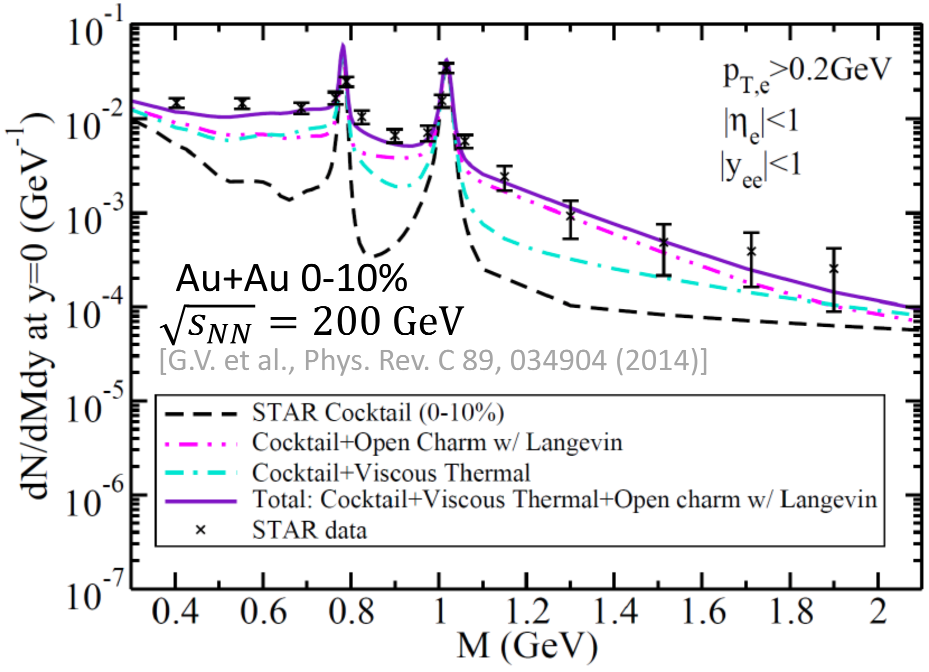


Dilepton calculations compared to data

- Comparison with data



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



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

⇒ all three are sources needed, in fact…

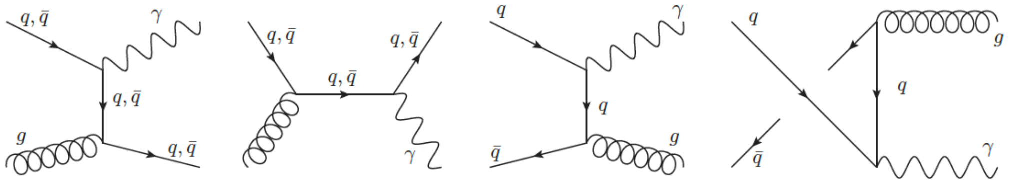
Photon sources

- Photons probing early dynamics:
  - Primodial photons / Jet-medium photons

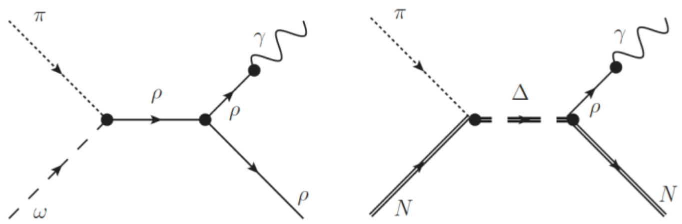
$$k^0 \frac{d^3\sigma_{A+A\to\gamma+X}}{d^3k} = \sum_{a,b,c} f_{a/A}\left(x_a, Q^2_{fact}\right) \otimes f_{b/A}\left(x_{\bar{q}}, Q^2_{fact}\right) \otimes k^0 \frac{d^3\hat{\sigma}_{a+b\to c+\gamma}\left(Q^2_{ren}\right)}{d^3k}$$
$$+ \sum_{a,b,d} f_{a/A}\left(x_a, Q^2_{fact}\right) \otimes f_{b/A}\left(x_{\bar{q}},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

  - Photons from jet-medium interaction

- Photons emitted during hydrodynamics
  - Photons from hadronization

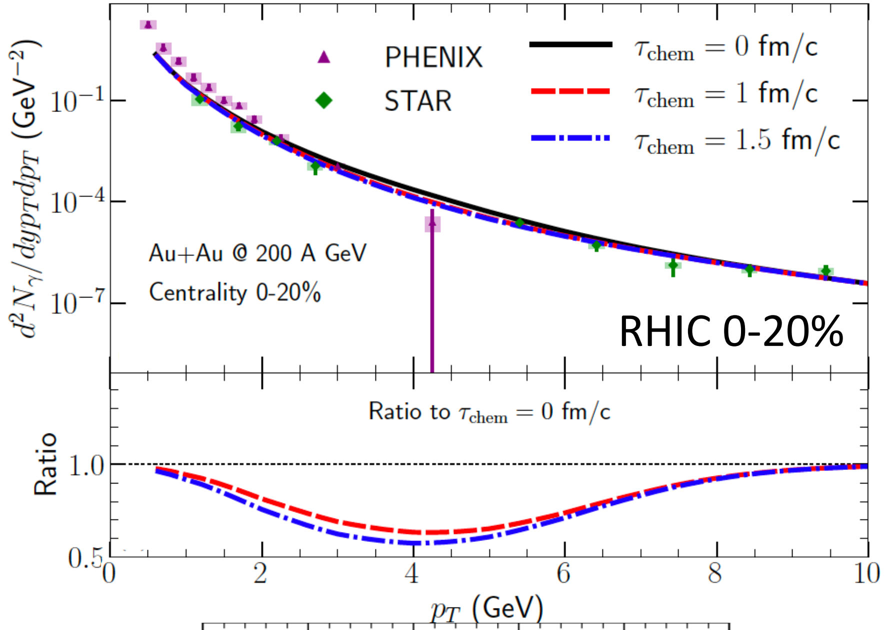


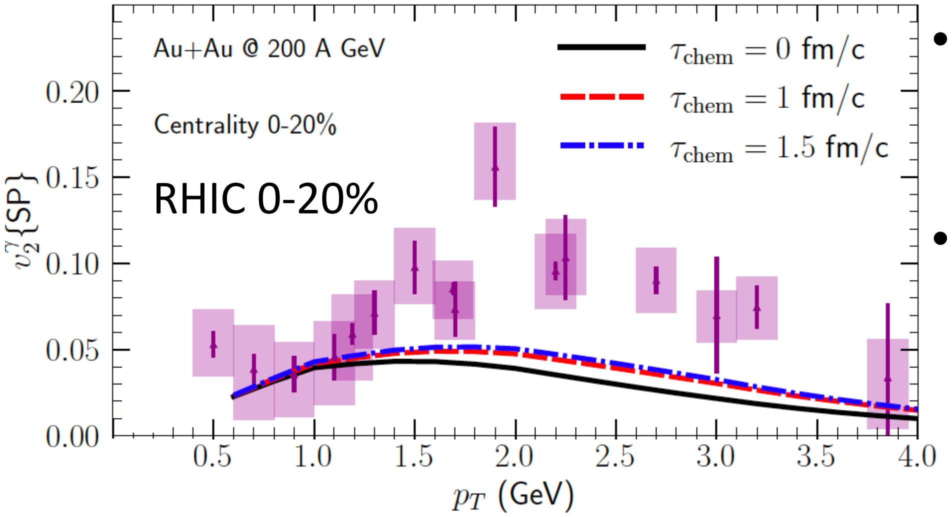
- Photons from hadronic transport
  - Same photon matrix elements as in hydrodynamical calculations



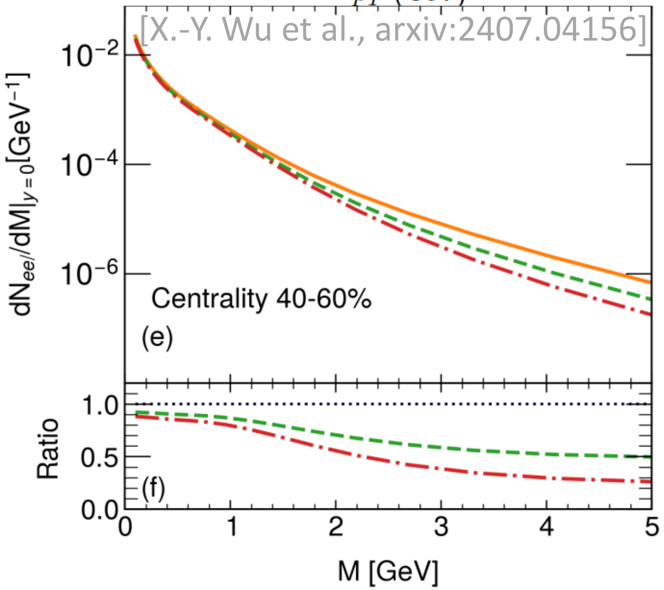
Photon/Dilepton calculations vs data & Bayesian analysis

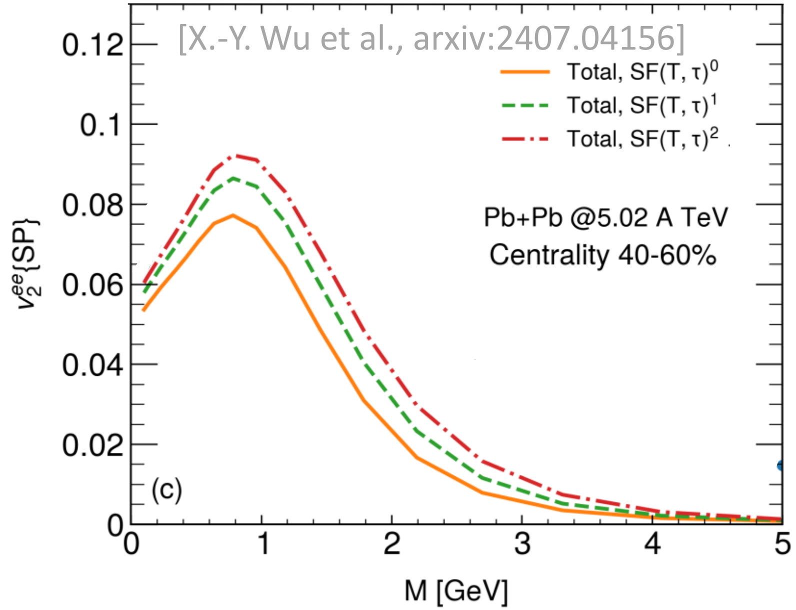
- Match $T^{\mu\nu}$(IP-Glasma) ⇒ $T^{\mu\nu}$ (KØMPØST) ⇒ $T^{\mu\nu}$ (Hydro)





[C. Gale et al., Phys. Rev. C 105, 014909 (2022)]





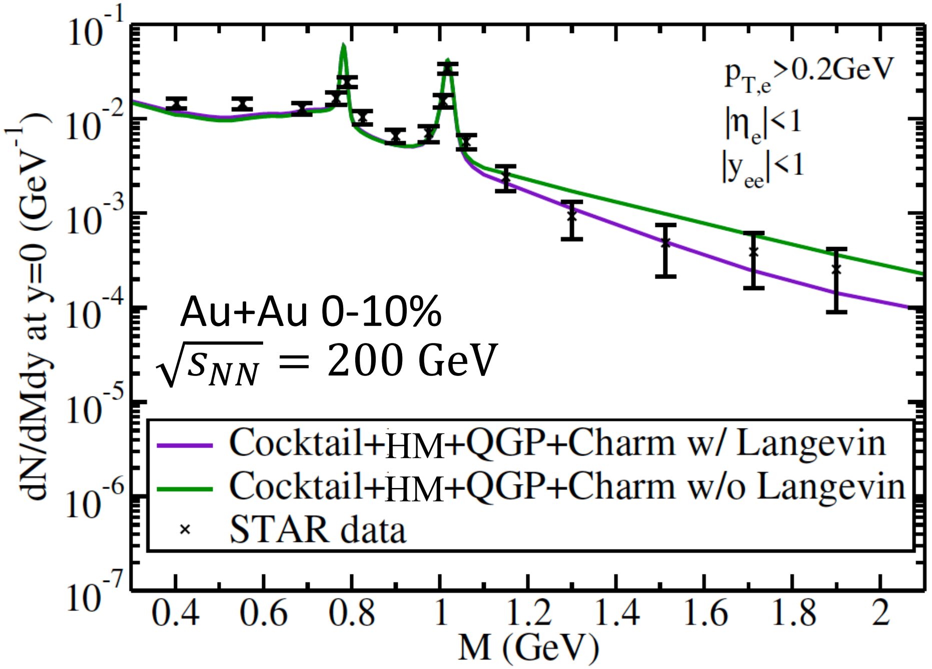
- Photons are sensitive dynamics of quarks production CGC → hydrodynamics
- Different sources are continuously being included, need to include theoretical uncertainties

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

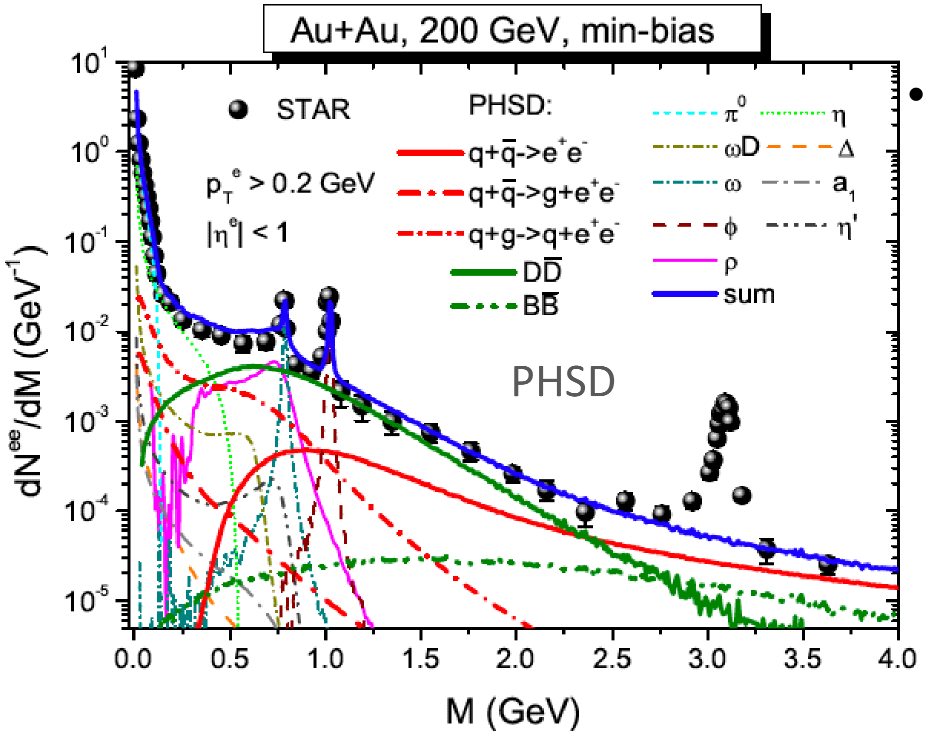
Dilepton calculations compared to data

- Comparison with data

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



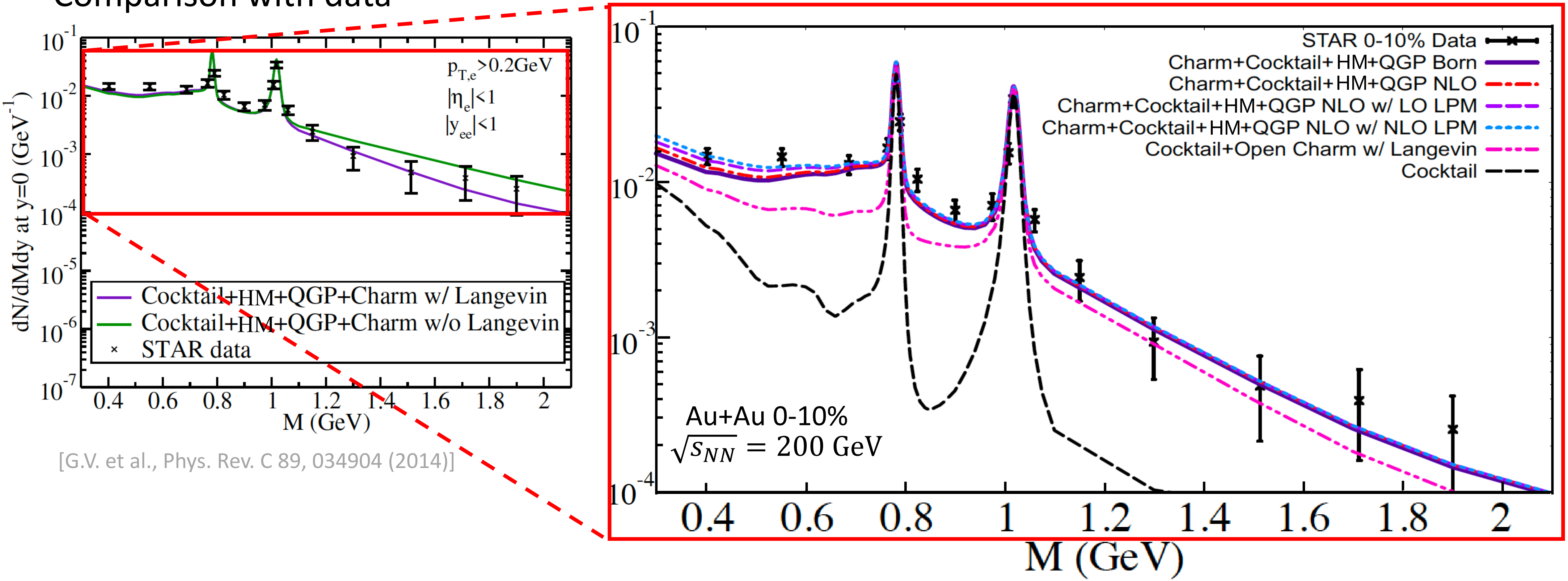
[G.V. et al., Phys. Rev. C 89, 034904 (2014)]



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

Dilepton calculations compared to data

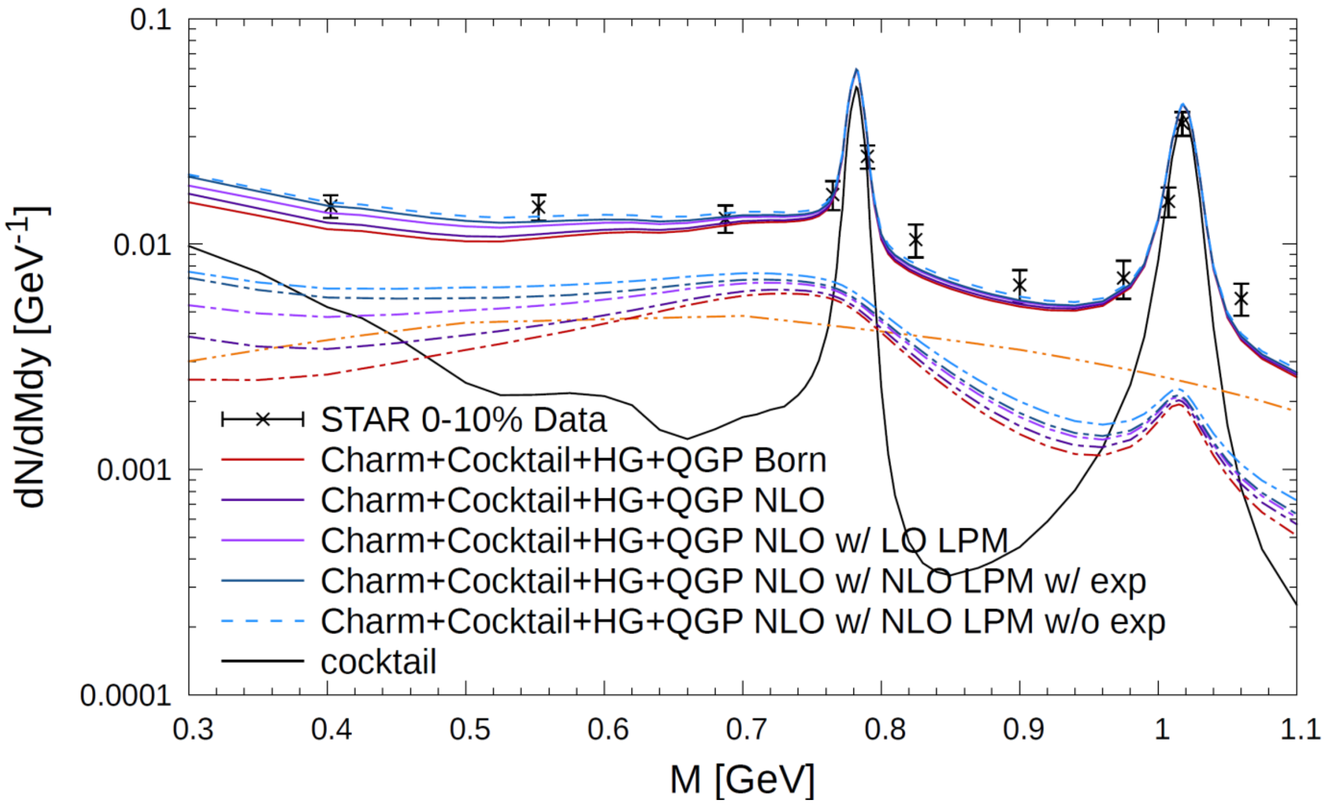
- Comparison with data

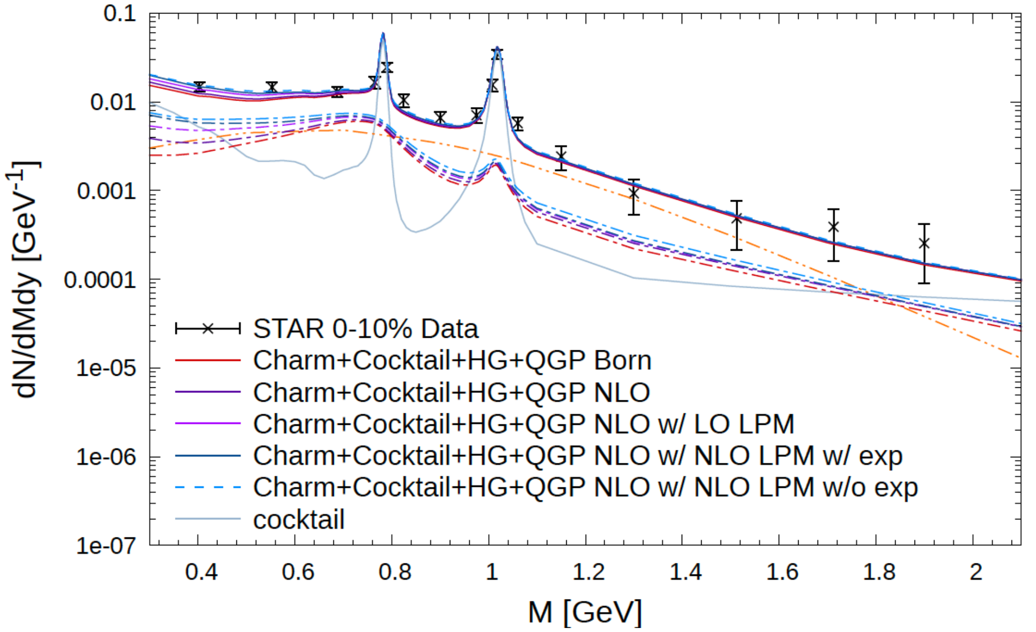


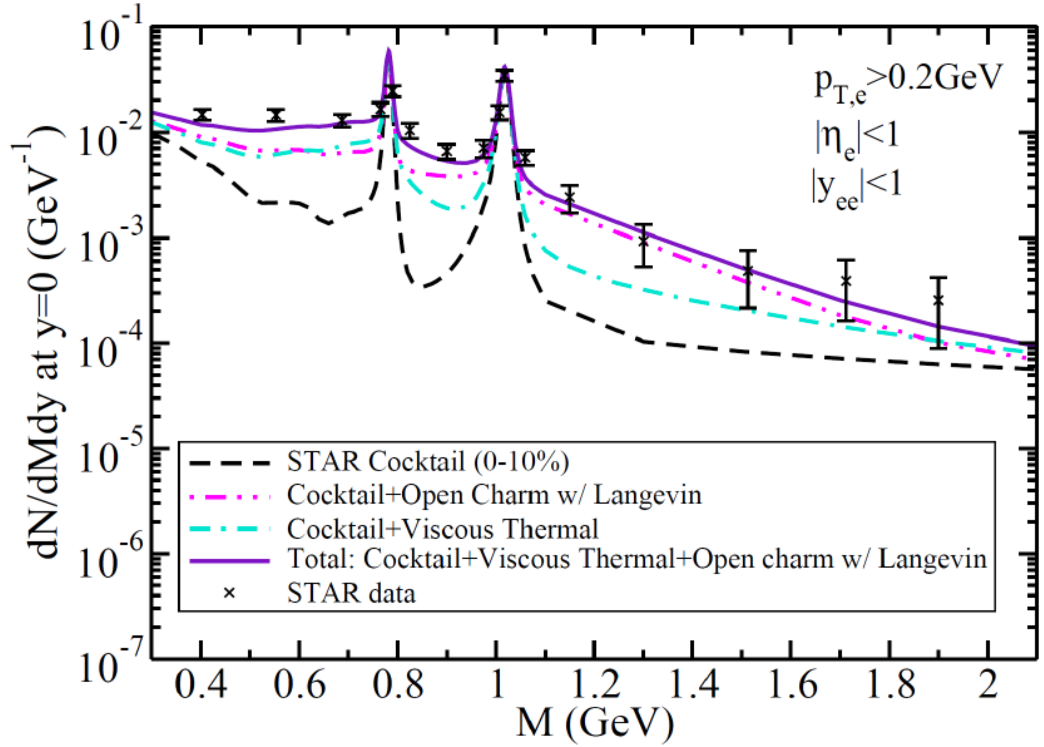
[G.V. et al., Phys. Rev. C 89, 034904 (2014)]

NLO pQCD dilepton rates are needed to explain the data.

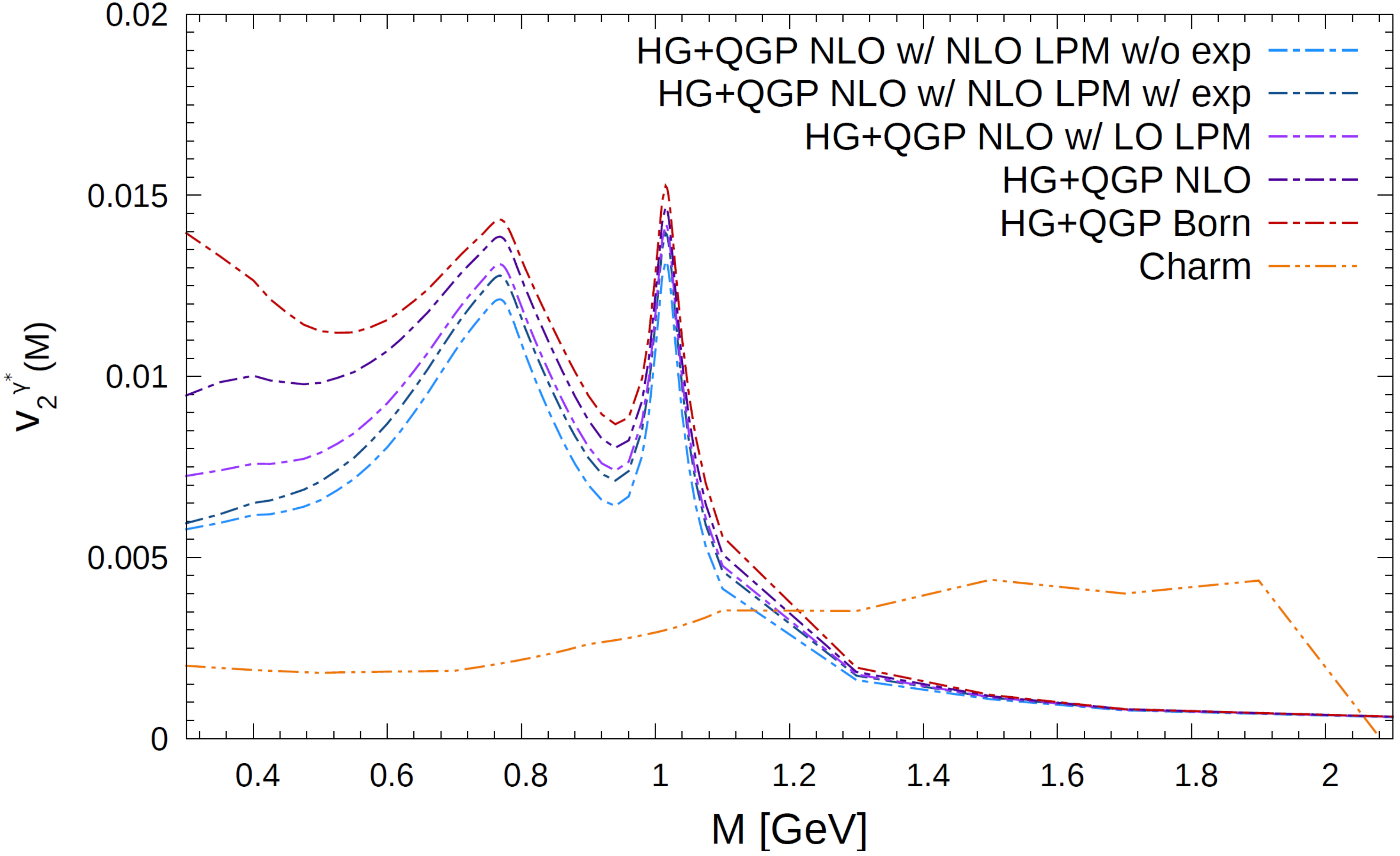
NLO dilepton calculations



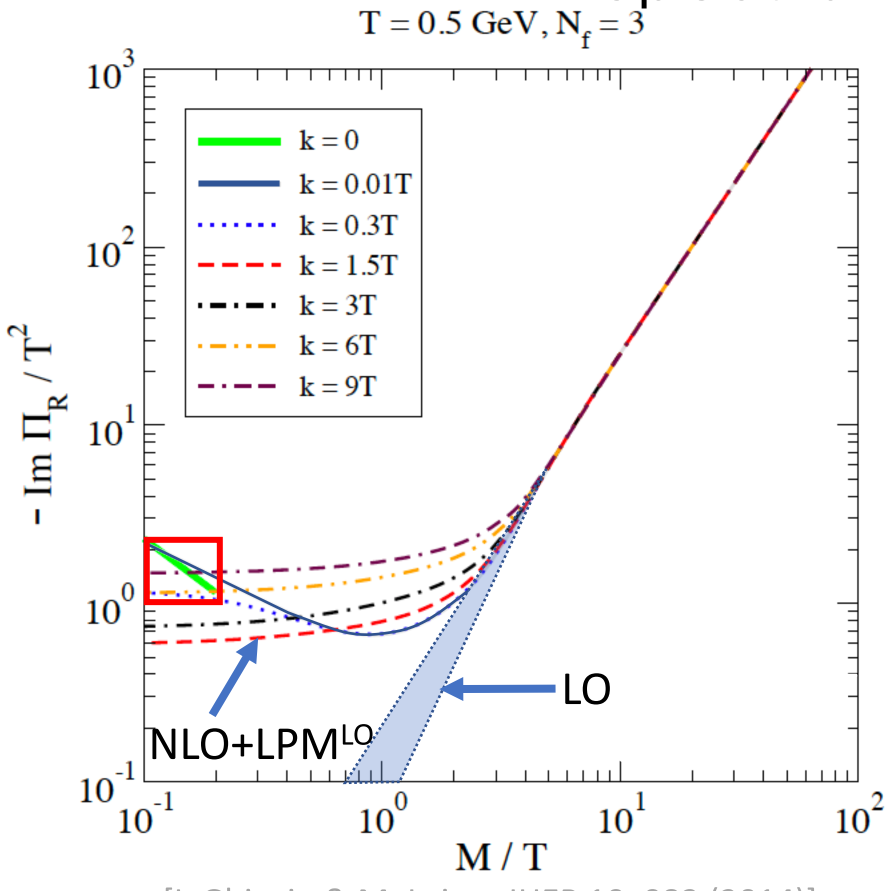




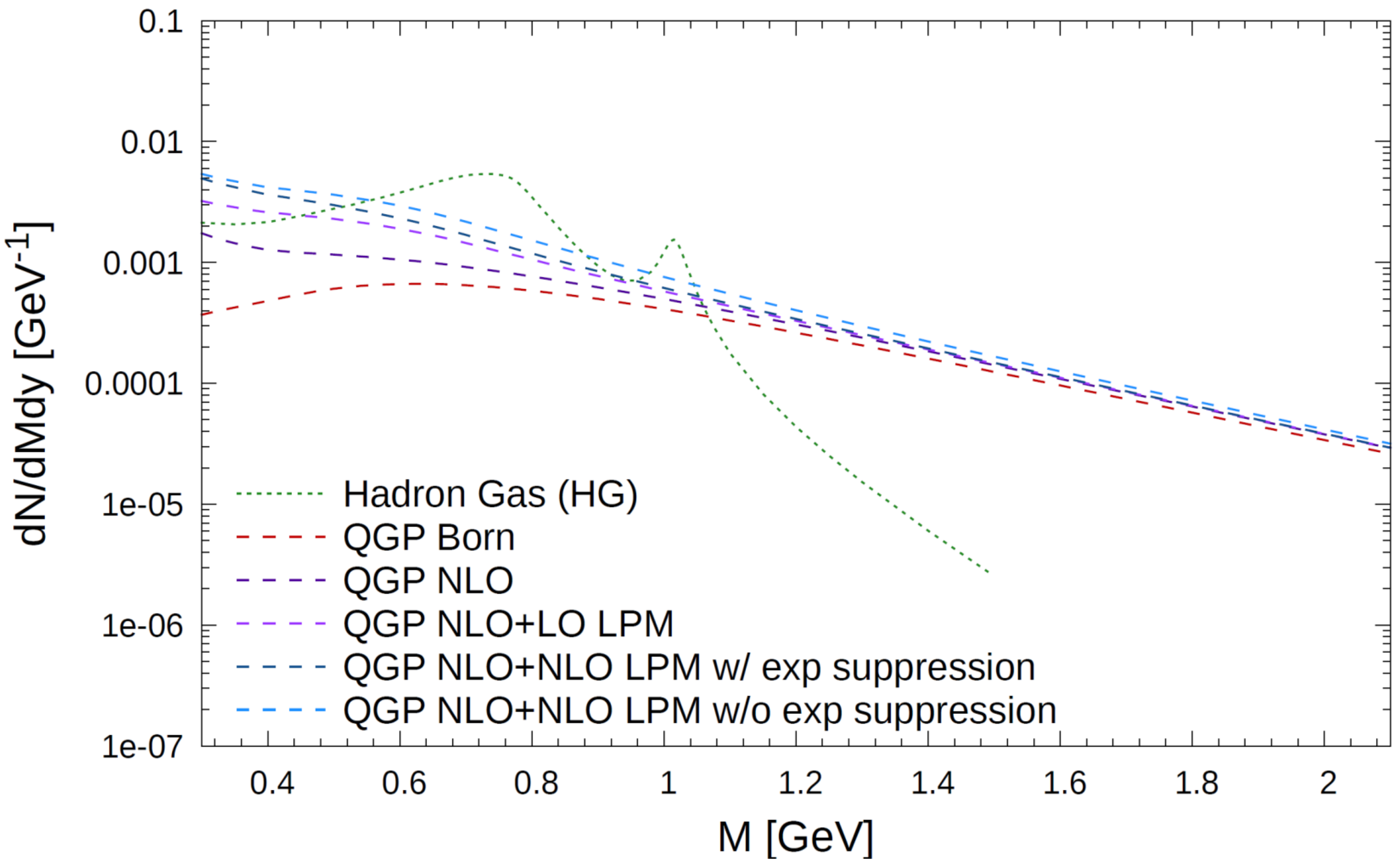
NLO effects on v_2



EM spectral function from pQCD & lattice QCD

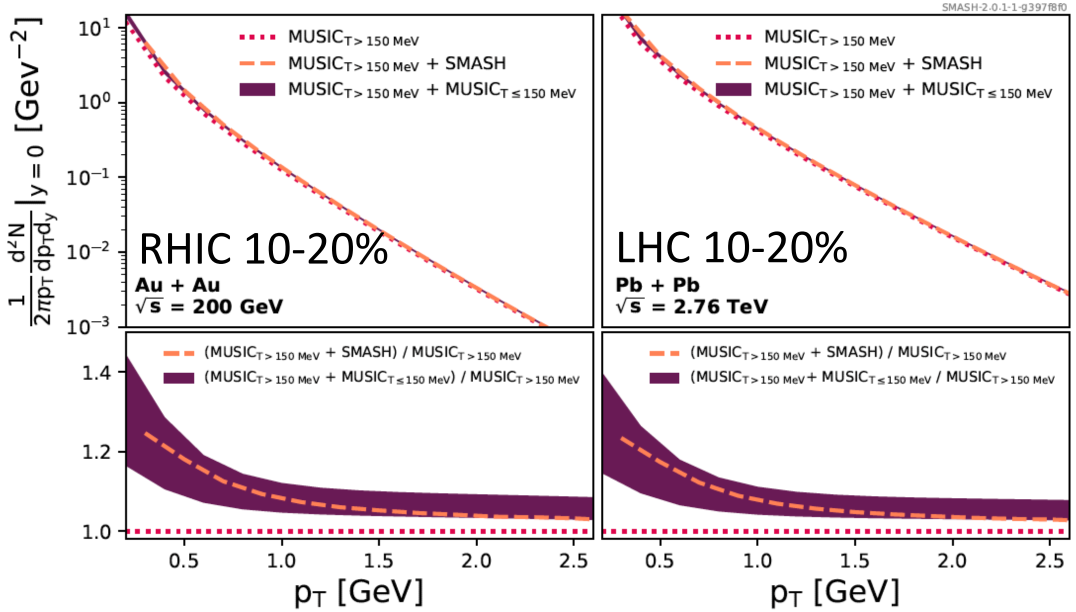


[I. Ghisoiu & M. Laine; JHEP 10, 083 (2014)]



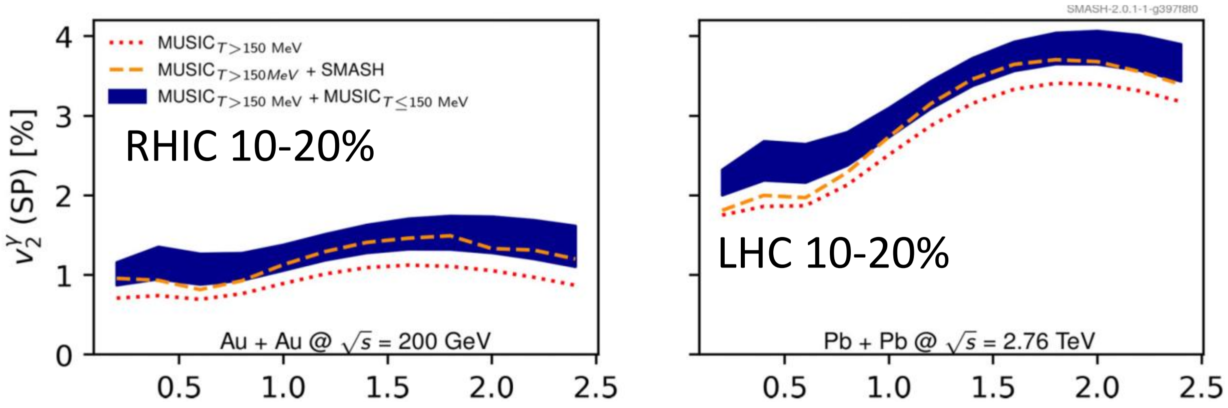
Photon production from hadronic reactions ✓

- Photons from SMASH



[A. Schäfer, Phys. Rev. C 105, 044910 (2022)]

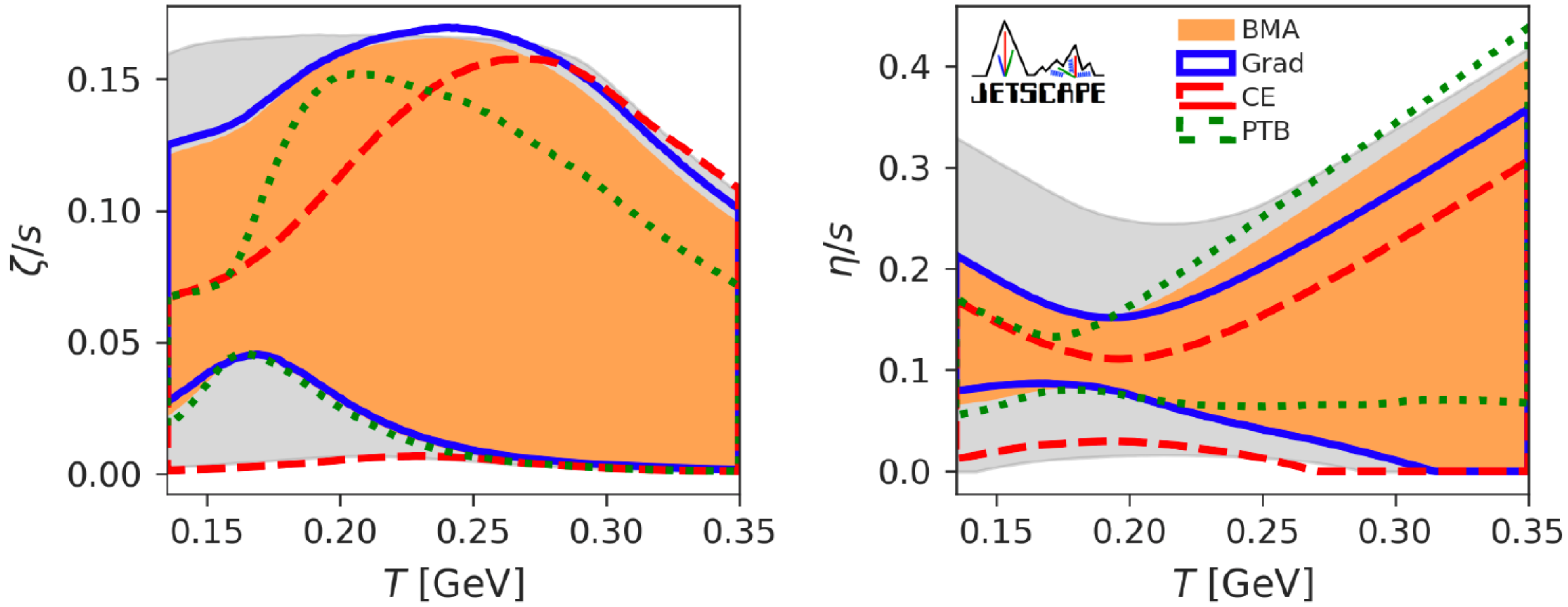
- Total photon yield from Hydro+SMASH is comparable to that obtained from hydro running to lower temperature (T=120 MeV).



[N. Götz, Phys. Rev. C 109, 049901(E) (2024)]

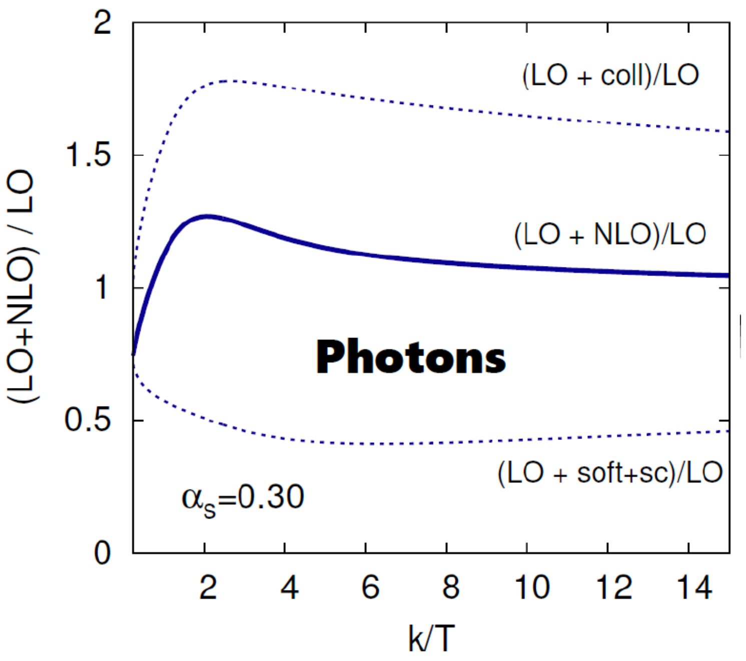
- Photon $v_2(p_T)$ from Hydro+SMASH is comparable to that obtained from hydro running to lower temperature (T=120 MeV)

Uncertainty from viscous corrections

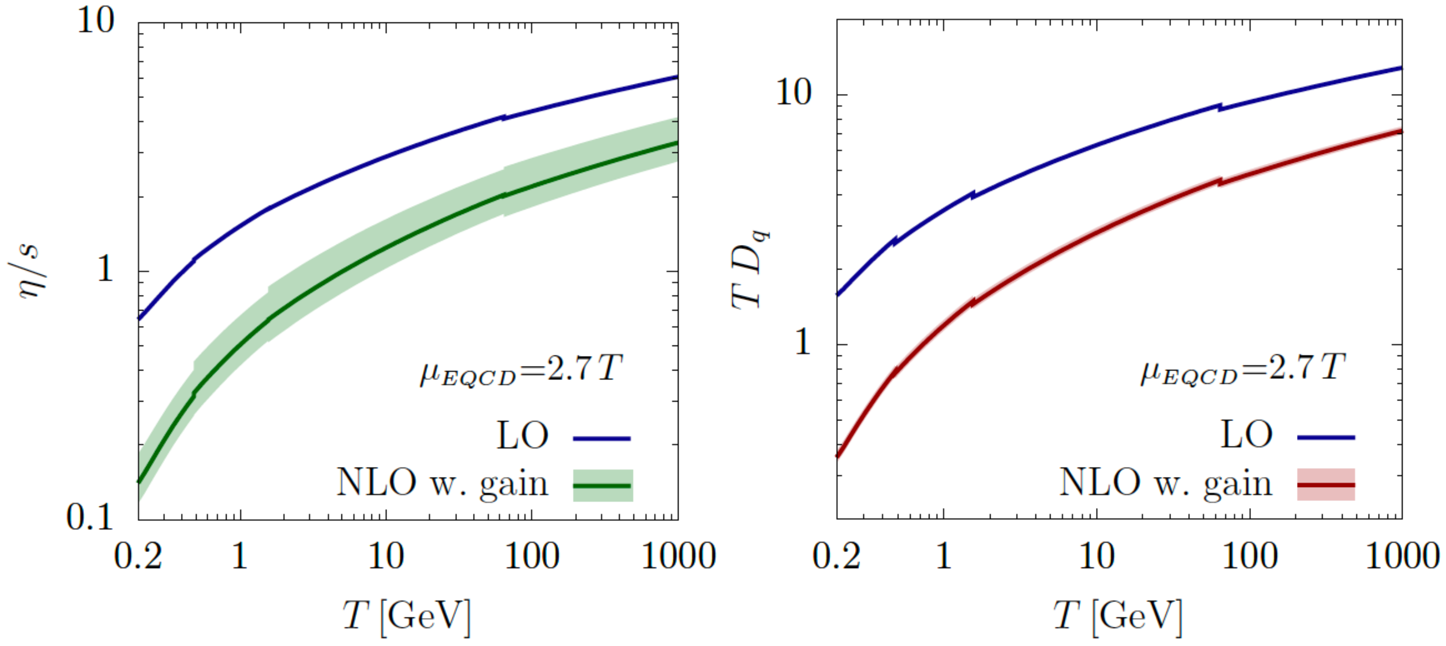


[D. Everett et al., Phys. Rev. Lett. 126, 242301 (2021)]

NLO calculations



[J. Ghiglieri et al., JHEP 1305, 010 (2013)]



[J. Ghiglieri et al., JHEP 1803, 179 (2018)]

- Sizeable cancellations in photon rates between the collinear (coll) contribution and soft+semi-collinear (sc) contributions

- Large corrections to shear viscosity (η/s) and baryon number diffusion (D_q) at NLO

[S. Caron-Hot et al., PRL 100, 052301 (2008)]

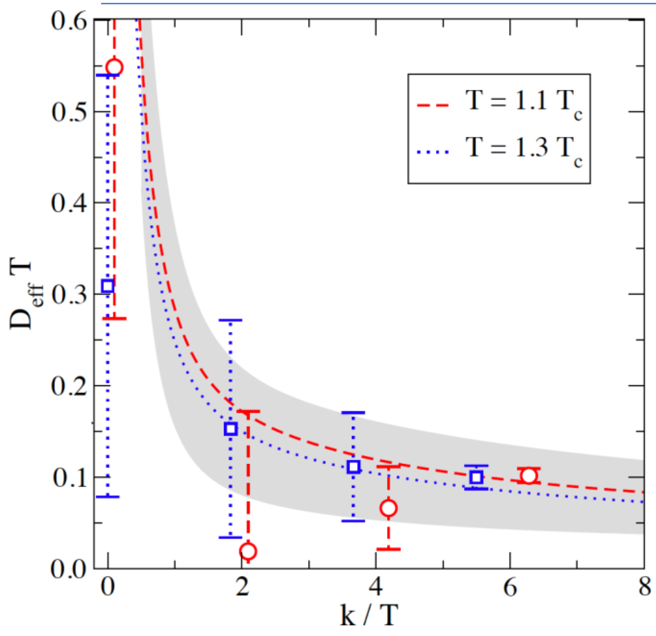
- Heavy-quark diffusion coefficient acquires large corrections at NLO

Photon production from pQCD and lattice QCD

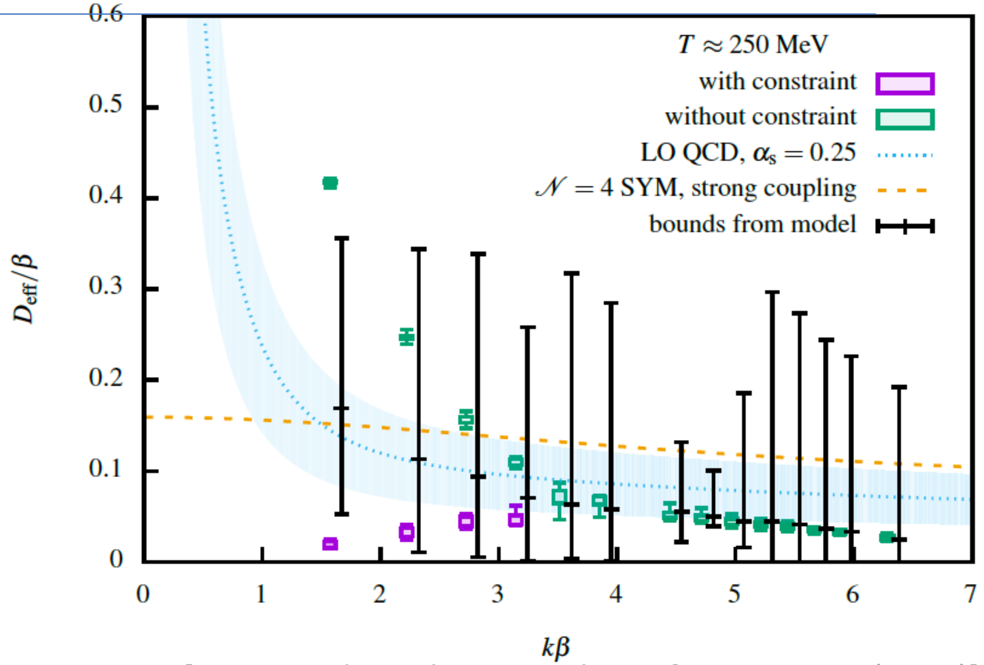
- Quenched and non-quenched lattice calculations consistent are consistent pQCD calculations, though uncertainties are large.

$$\frac{d^3R}{d^3k} = \frac{2\alpha_{EM}\chi_q}{3\pi^2}\frac{D_{eff}(k)}{\exp(k/T)-1}$$

$$D_{eff}(k) = \frac{Im[\Pi^R_{EM}]}{2\chi_q k}$$



[J. Ghiglieri et al., Phys. Rev. D 94, 016005 (2016)]

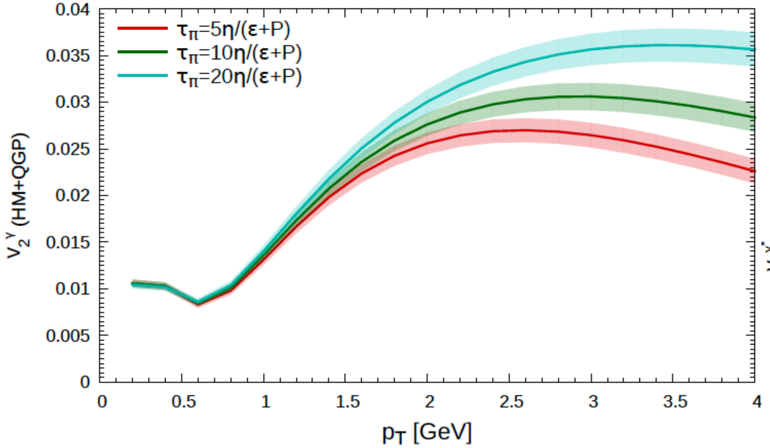


[B.B. Brandt et al., EPJ Web Conf. 175, 07044 (2018)]

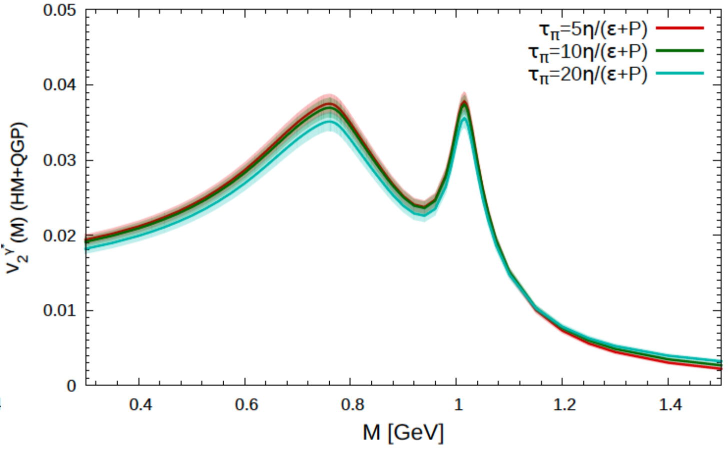
Sensitivity of EM probes to transport coefficients

$\tau_\pi = b_\pi \eta/(\varepsilon + P)$

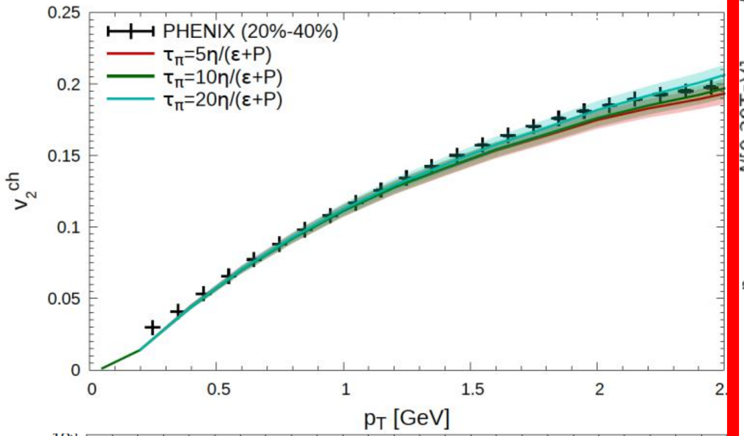
Photon & $\tau_\pi = b_\pi \eta/(\varepsilon + P)$

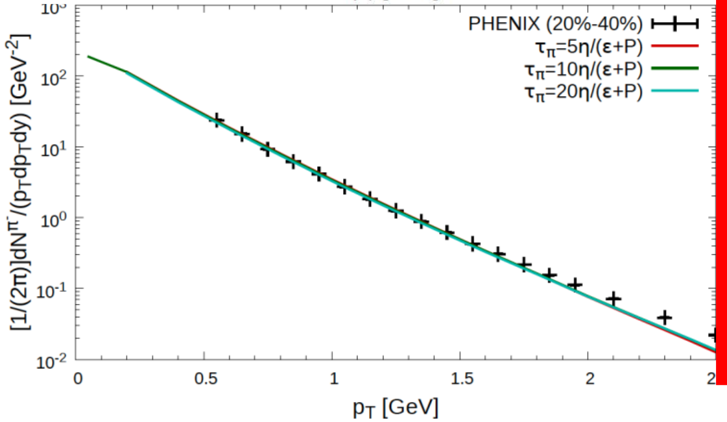


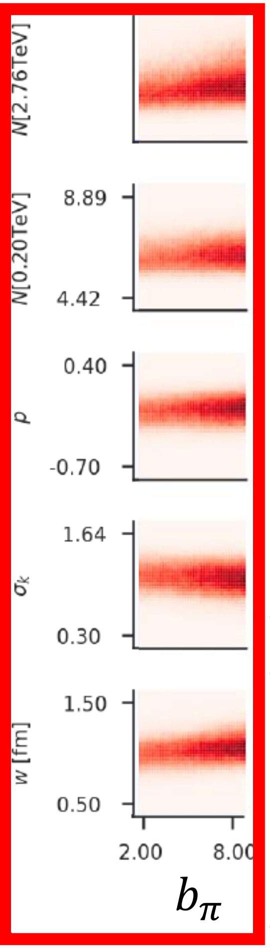
Dileptons & $\tau_\pi = b_\pi \eta/(\varepsilon + P)$



Hadrons & $\tau_\pi = b_\pi \eta/(\varepsilon + P)$

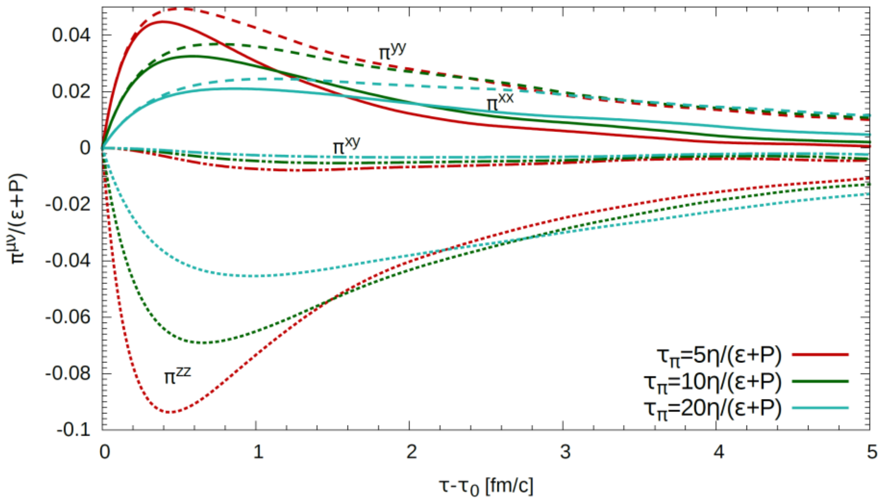






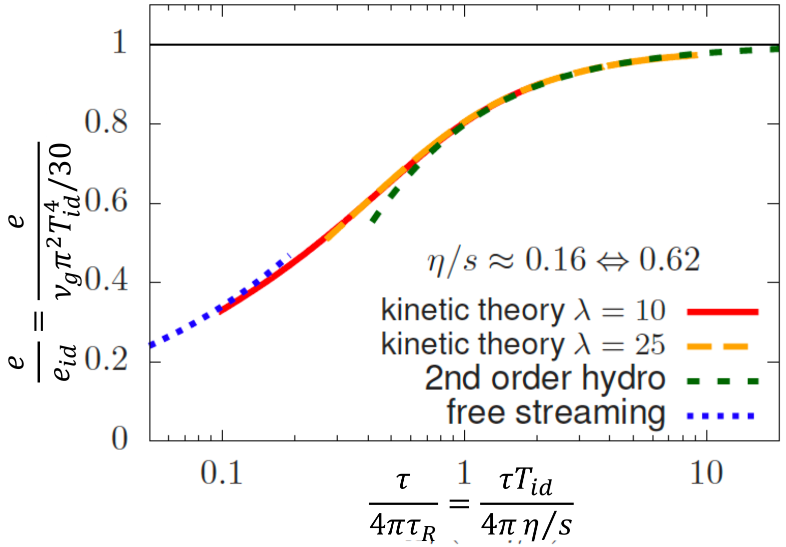
Preliminary results by JETSCAPE SIMULATIONS GROUP

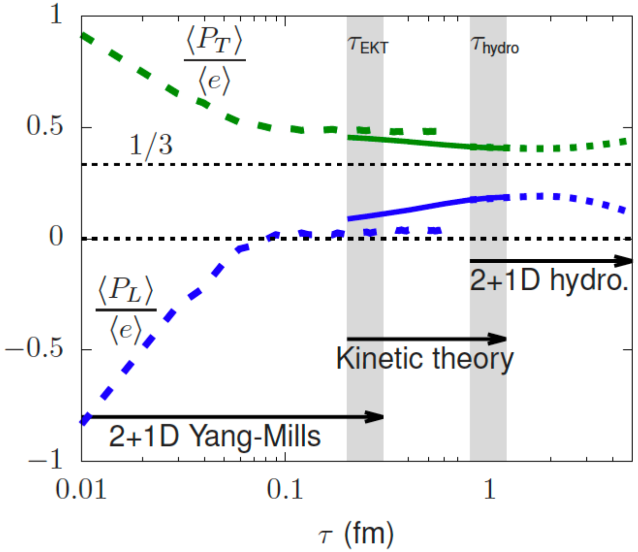
[G.V., J.-F. Paquet et al., Phys. Rev. C 91, 024908 (2015)]



Pre-hydrodynamic photon production

- KøMPøST: Solving the Boltzmann equation in the linear response approximation.

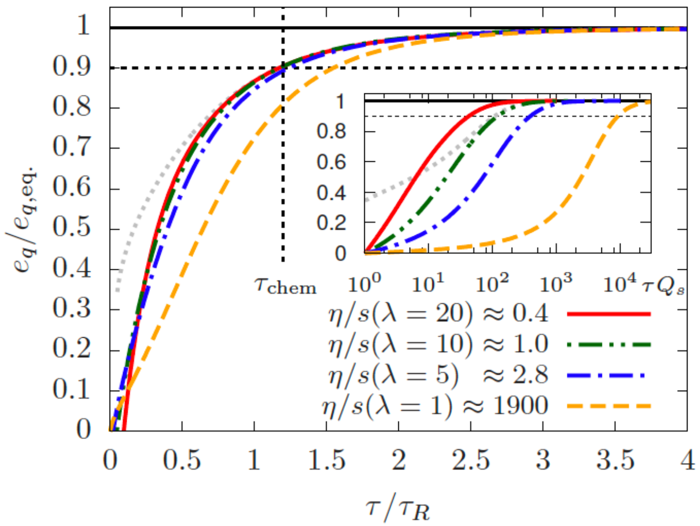




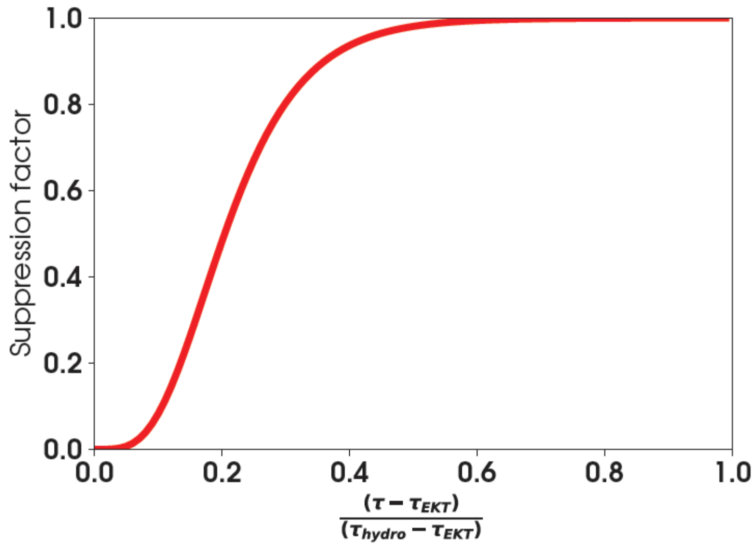
- Bridges the gap between the asymptotic behavior of IP-Glasma → free-streaming and hydrodymamics → thermalization

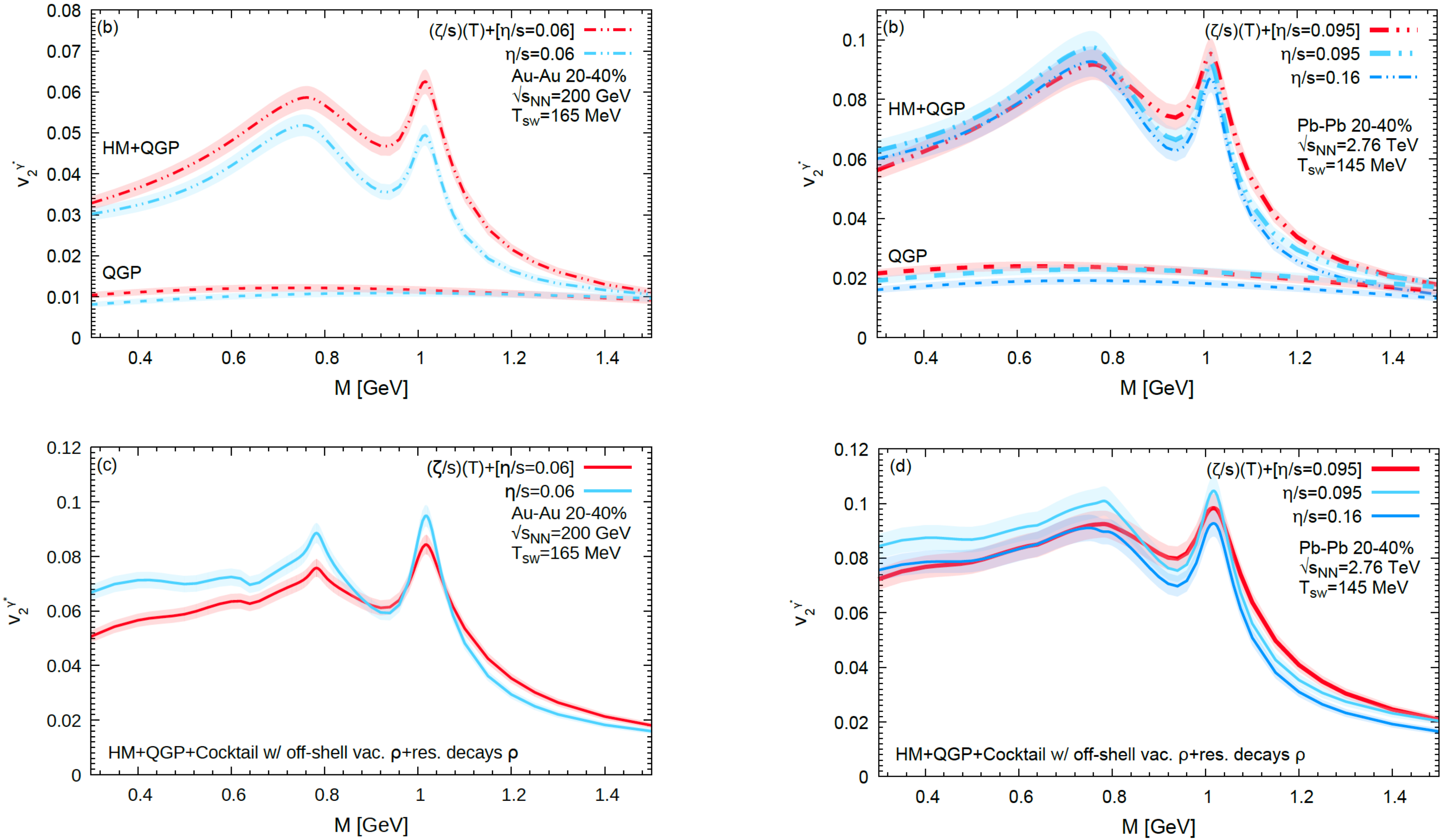
[A. Kurkela et al., Phys. Rev. Lett. 122, 122302 (2019)]

- Match $T^{\mu\nu}$(IP-Glasma) ⇒ $T^{\mu\nu}$ (KøMPøST) ⇒ $T^{\mu\nu}$ (Hydro)



⇒





(b)
(ζ/s)(T)+[η/s=0.06]
η/s=0.06
Au-Au 20-40%
√sNN=200 GeV
Tsw=165 MeV
HM+QGP
QGP
M [GeV]
(b)
(ζ/s)(T)+[η/s=0.095]
η/s=0.095
η/s=0.16
HM+QGP
Pb-Pb 20-40%
√sNN=2.76 TeV
Tsw=145 MeV
QGP
M [GeV]
(c)
(ζ/s)(T)+[η/s=0.06]
η/s=0.06
Au-Au 20-40%
√sNN=200 GeV
Tsw=165 MeV
HM+QGP+Cocktail w/ off-shell vac. ρ+res. decays ρ
M [GeV]
(d)
(ζ/s)(T)+[η/s=0.095]
η/s=0.095
η/s=0.16
Pb-Pb 20-40%
√sNN=2.76 TeV
Tsw=145 MeV
HM+QGP+Cocktail w/ off-shell vac. ρ+res. decays ρ
M [GeV]