LIPEI DU
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ELECTROMAGNETIC PROBES & QCD CRITICAL POINT

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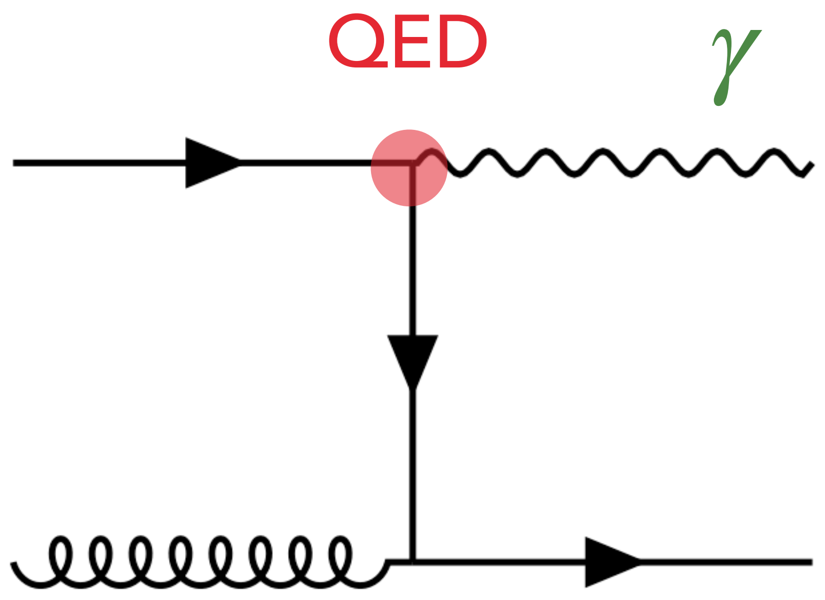
THE QCD CRITICAL POINT: ARE WE THERE YET?

INT, SEATTLE, WA

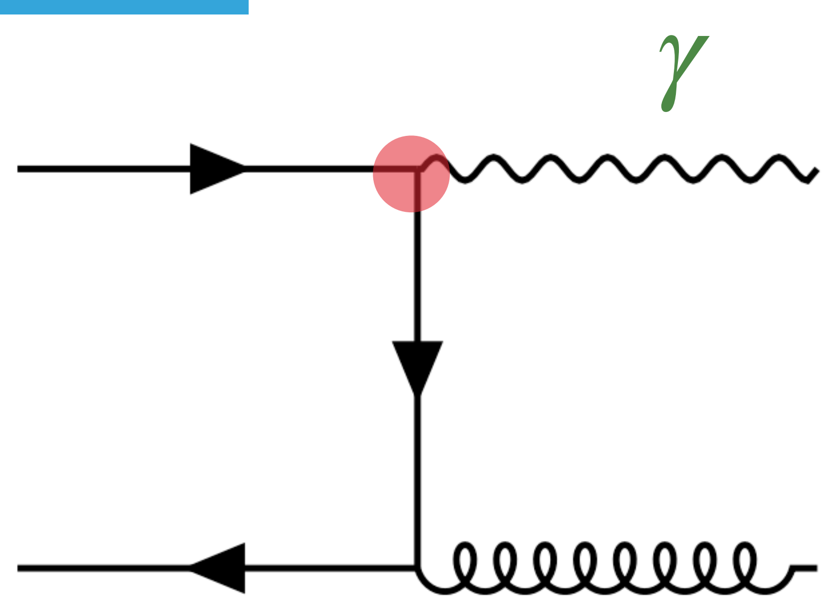
OCTOBER 28, 2025

Electromagnetic probes

real photon

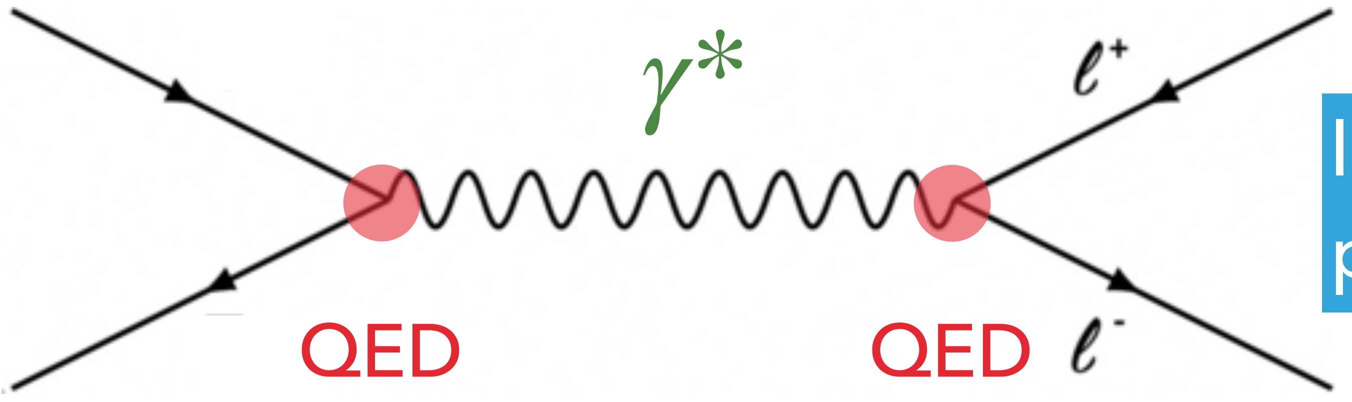


Compton scattering



quark-antiquark annihilation

virtual photon



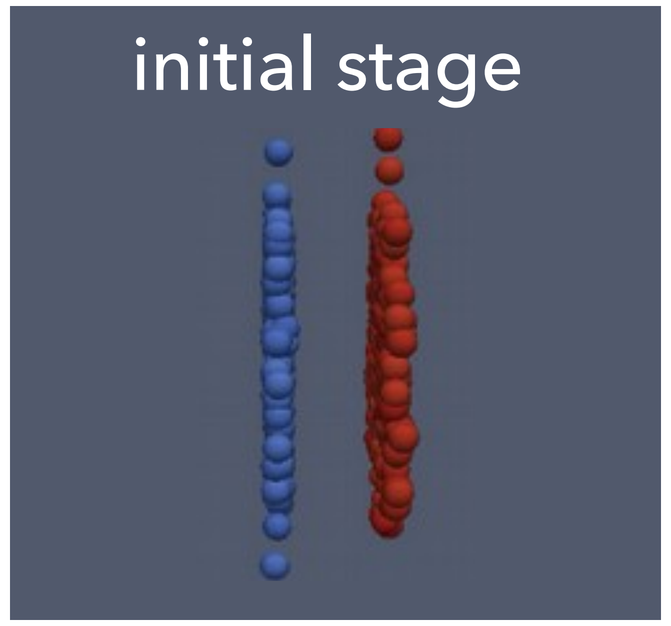
lepton–anti-lepton pair (dilepton)

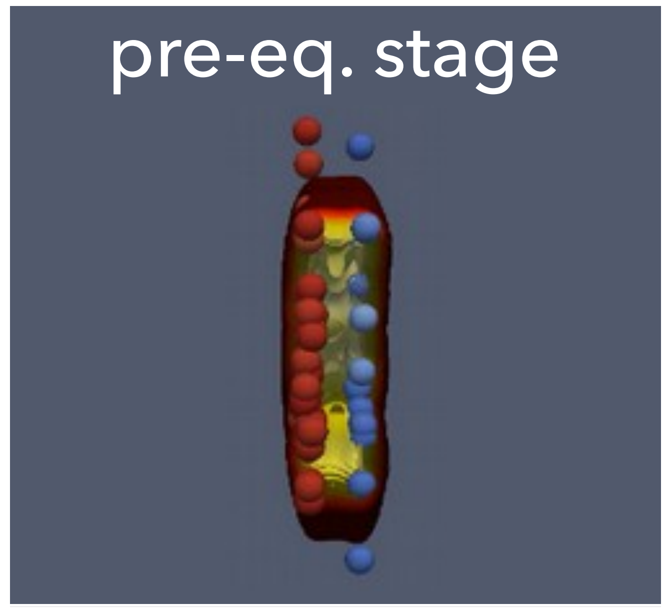
quark-antiquark annihilation

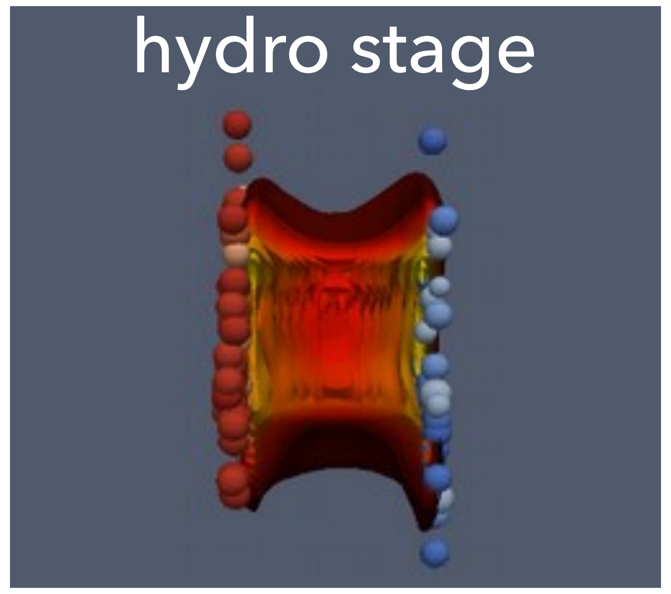
Four momentum $K^\mu = (\omega, \boldsymbol{k})$. real photon: massless, $\omega = k$; dilepton: invariant mass $M = \sqrt{\omega^2 - k^2}$

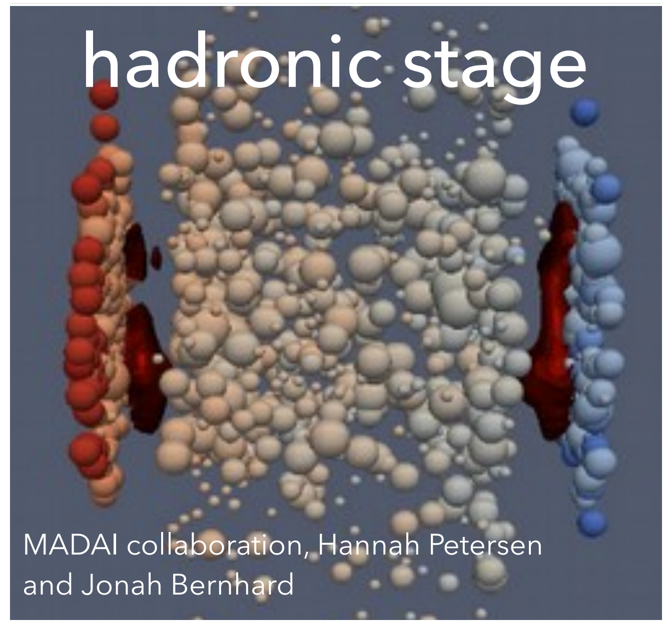
- The electromagnetic (EM) interaction is much weaker than the strong interaction; $L_{\rm mfp}^{\rm em} \gg$ system size.
- EM probes penetrate the QCD environment undisturbed, carrying information at their production points.
- Dilepton M-spectra are unaffected by the dynamics and thus not blue-shifted.

Electromagnetic radiation









photon

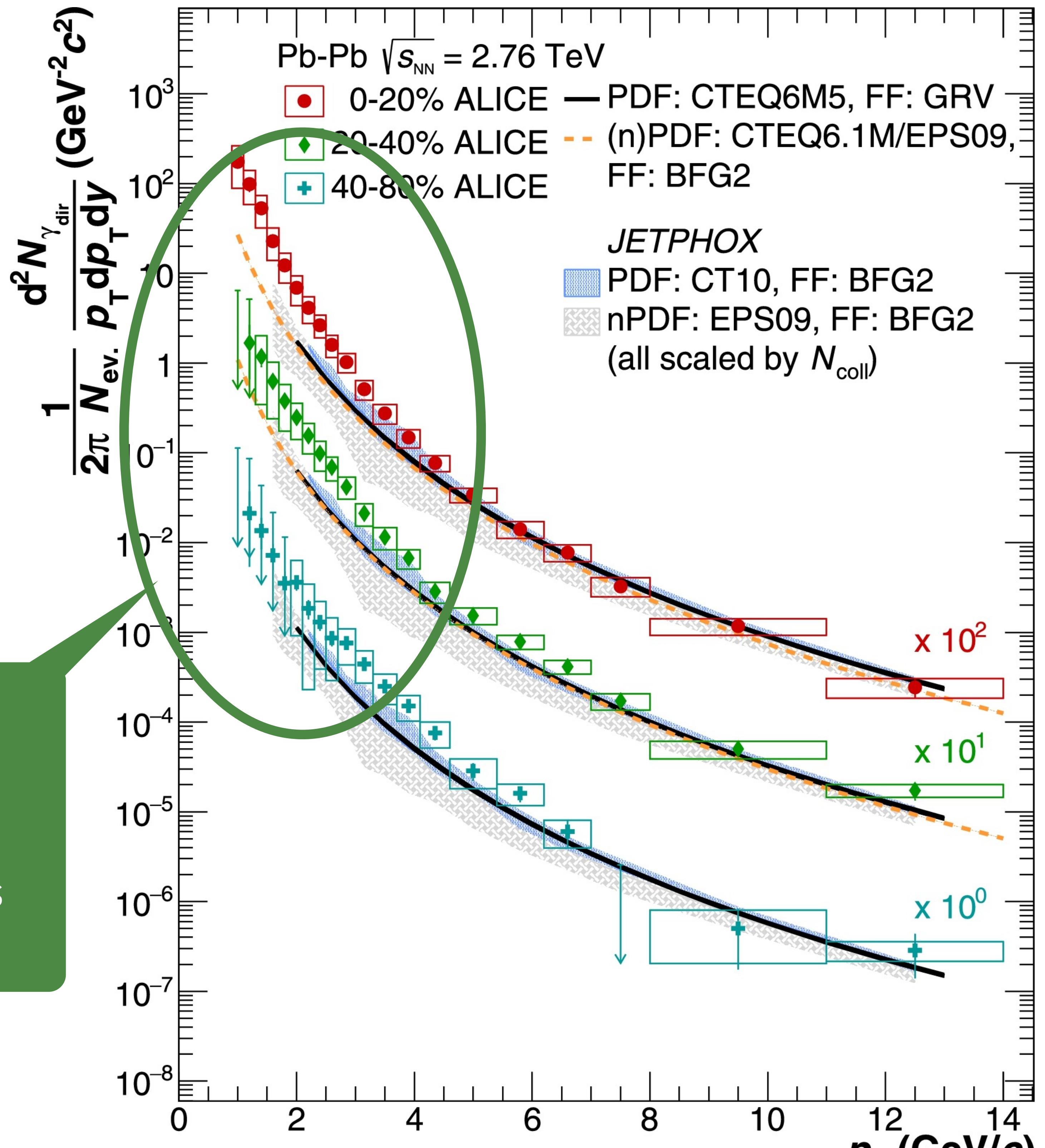
- initial hard scattering or fragmentation ('prompt' photons)
- pre-equilibrium photons
- thermal emission from QGP
- jet-medium interaction
- thermal emission from hadronic matter
- hadronic decays

dilepton

- Drell-Yan process
- pre-equilibrium dileptons
- thermal emission from QGP
- semi-leptonic decays of open heavy flavor
- thermal emission from hadronic matter
- hadronic decays

Spectra measurements in experiments

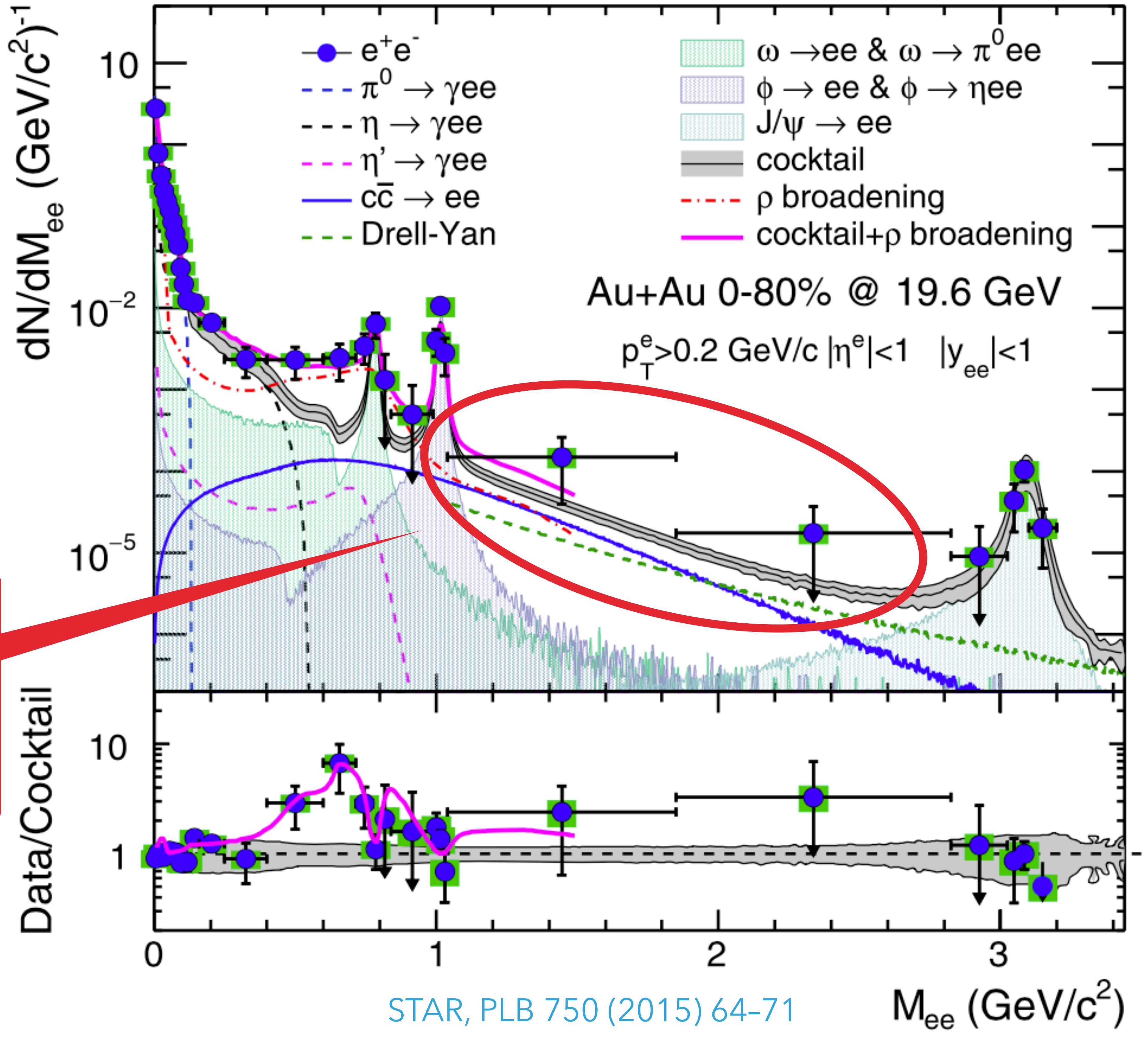
direct photons



ALICE, PLB 754 (2016) 235-248

Excess of direct photons over prompt photons

inclusive dileptons



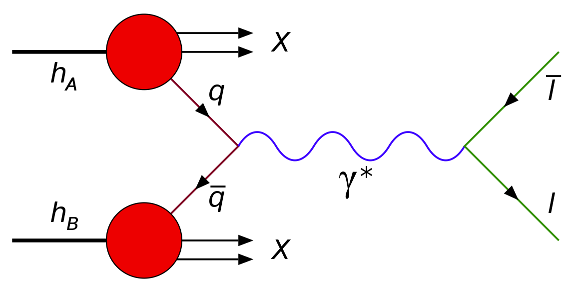
STAR, PLB 750 (2015) 64-71

Excess of inclusive dileptons over the cocktail

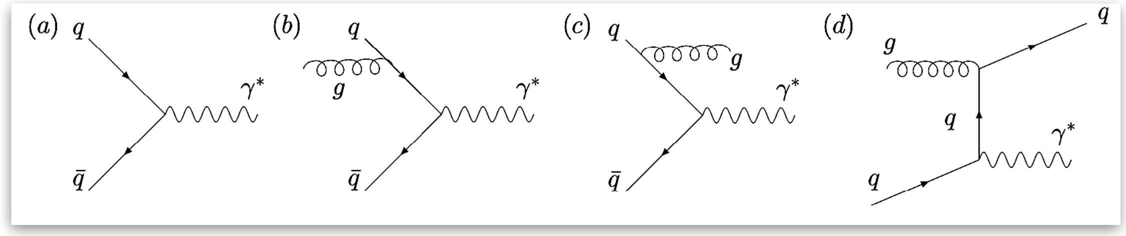
- EM are produced throughout the evolution, so isolating productions from different stages is challenging.
- However, selecting p_T or M windows can be helpful. On average, the larger p_T or M the EM probes have, the earlier they are produced.

Dilepton spectra

- High-mass region (HMR)
  - Drell-Yan process



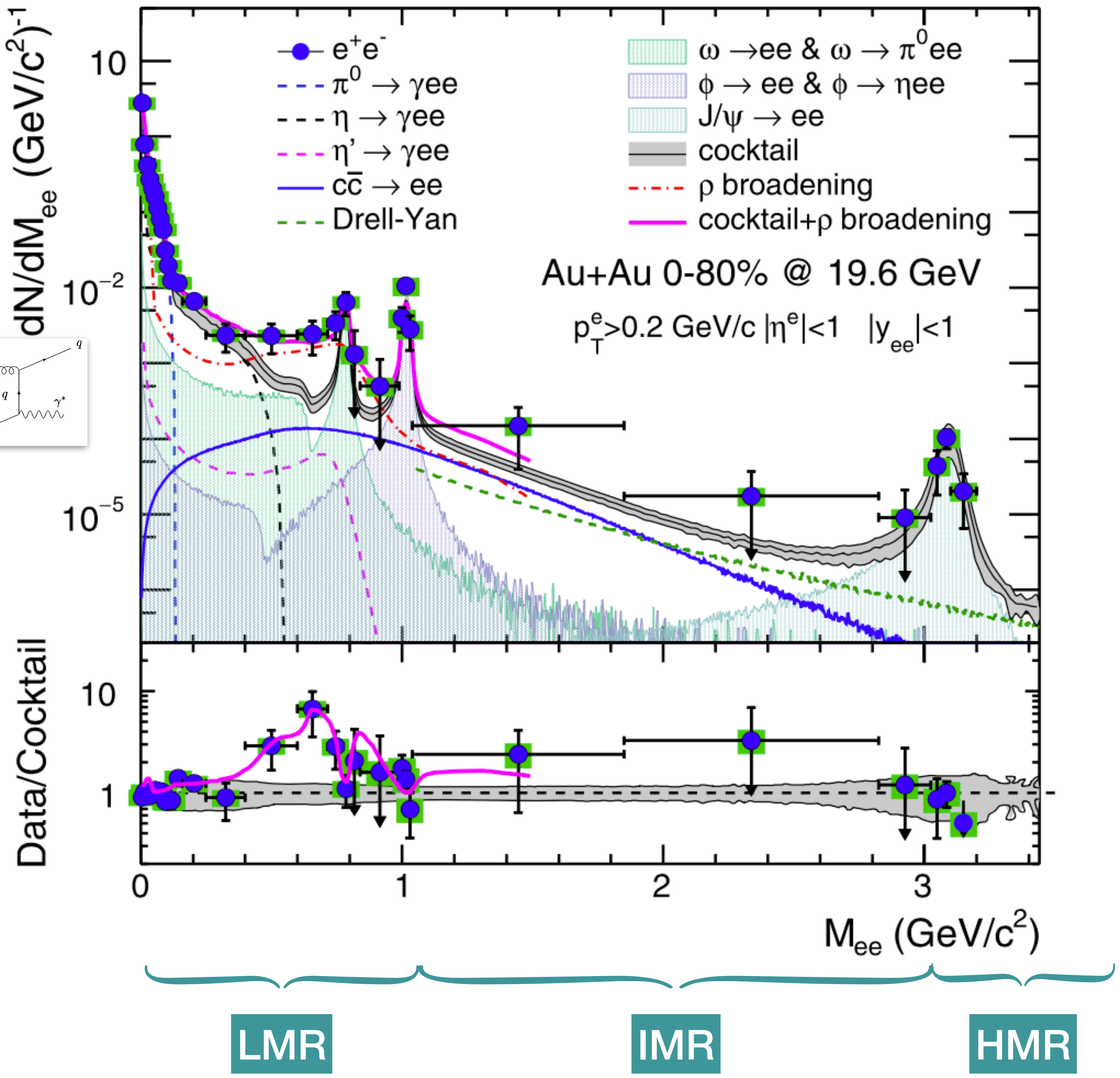
  - decays of J/ψ
- Intermediate-mass region (IMR)
  - thermal emission from QGP



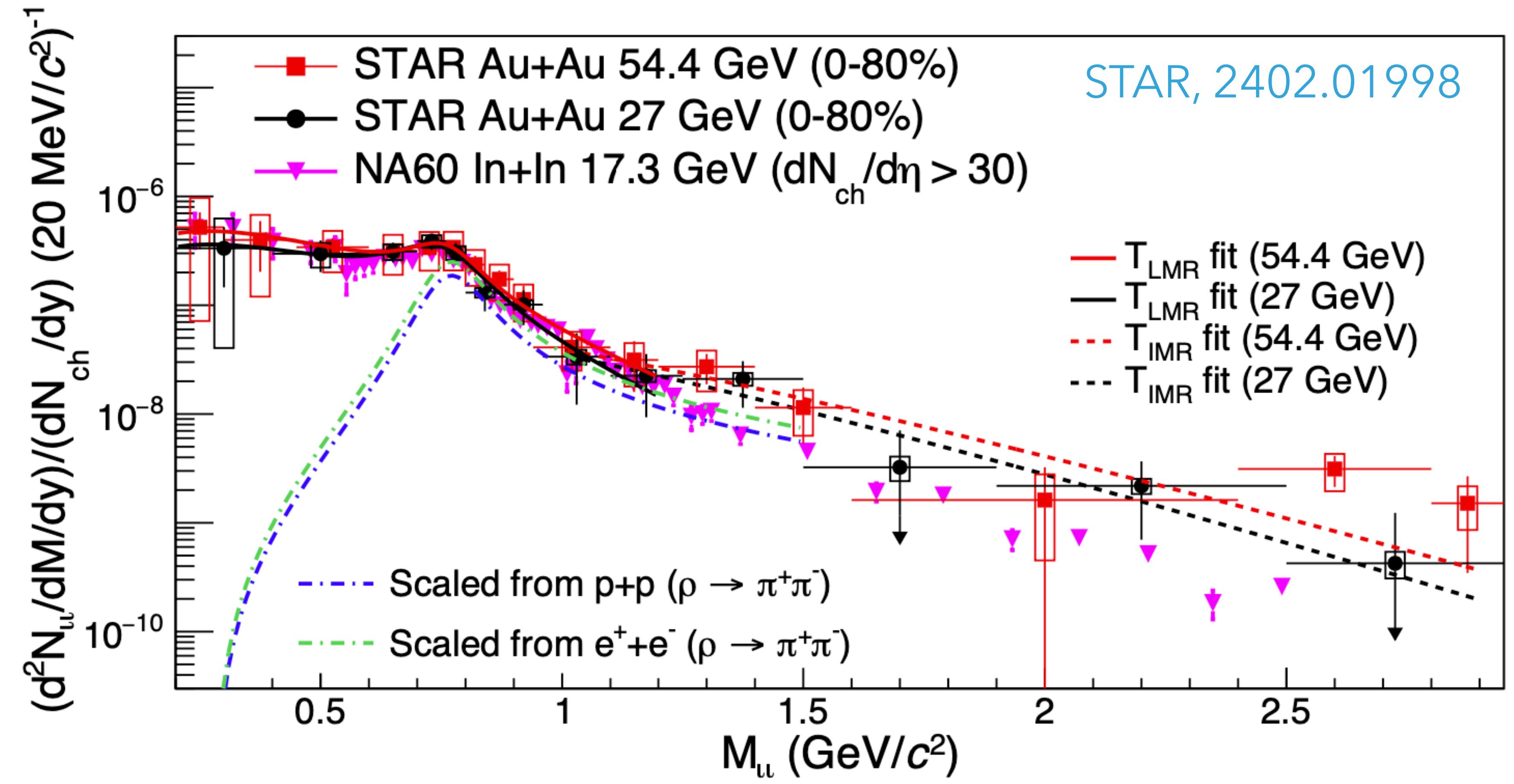
  - semileptonic decays from open heavy flavor-antiflavor pair, e.g. $D/\bar{D}$
- Low-mass region (LMR)
  - thermal emission from hadronic matter
  - direct decays of $\rho/\omega/\phi$ (ρ is short-lived)
  - Dalitz (three body) decays of $\pi^0/\eta/\eta'$

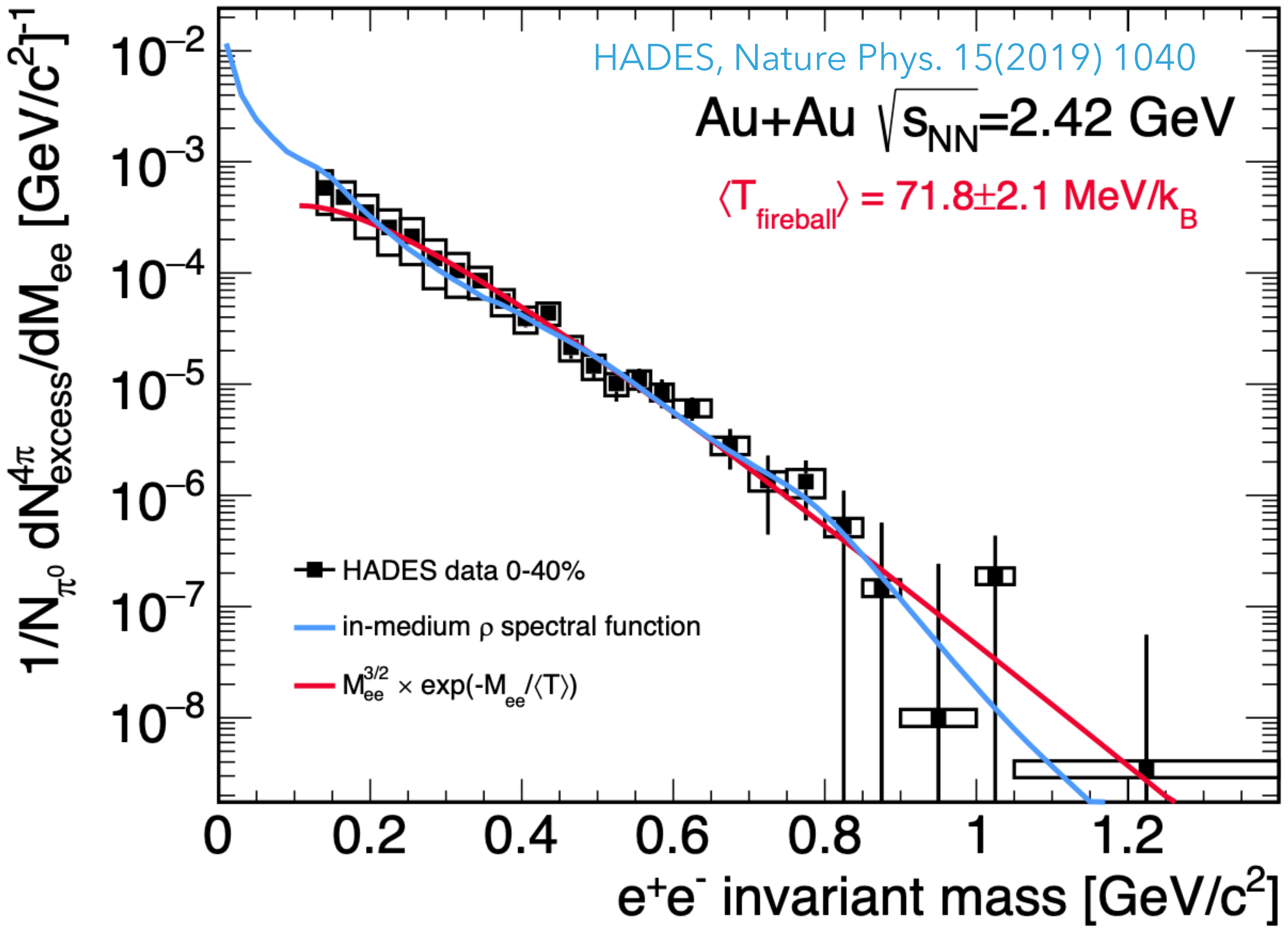
Dilepton cocktail: late decays of hadrons

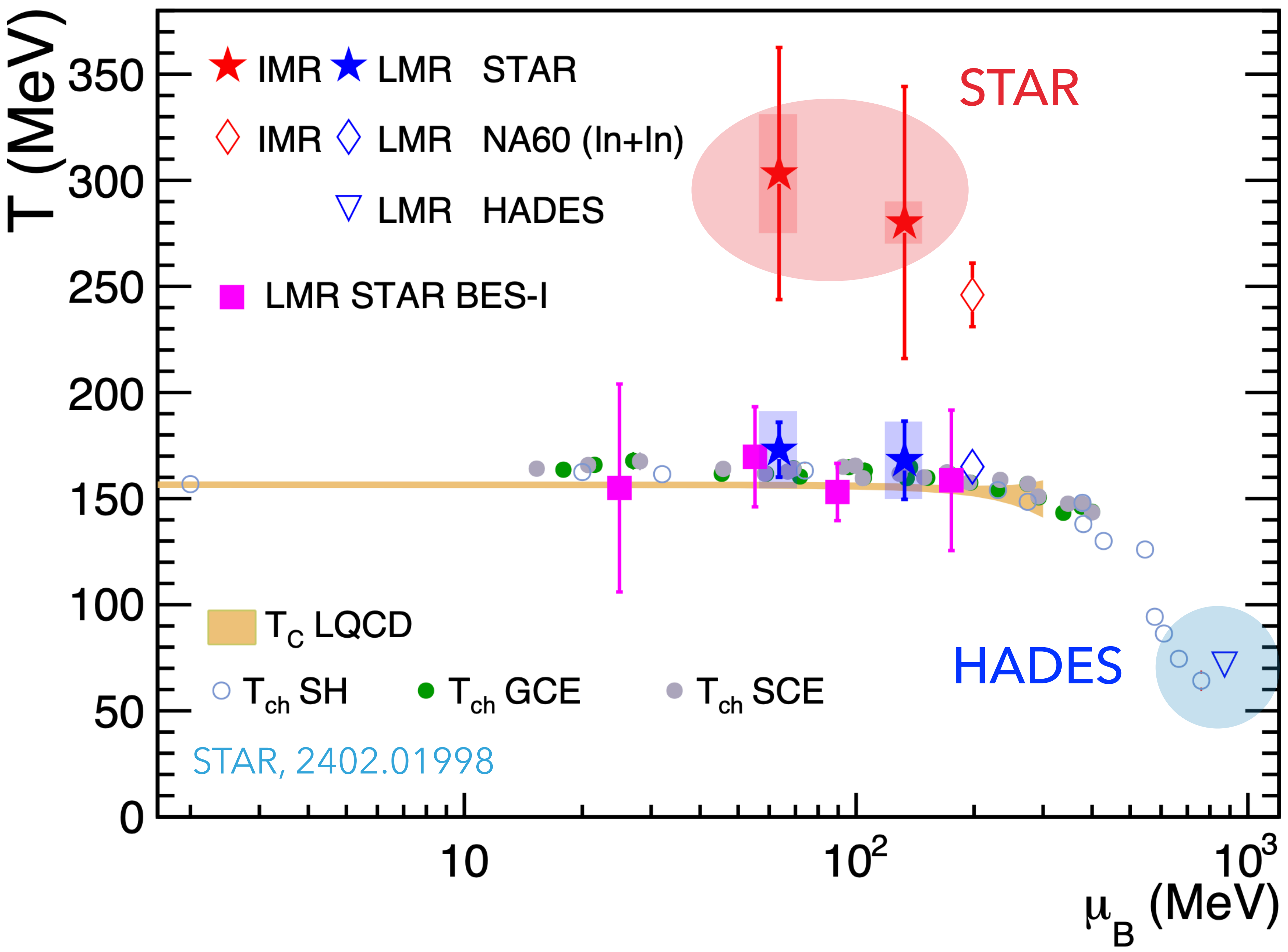
STAR, PLB 750 (2015) 64–71



QCD thermometer: experiments







nature > nature communications > articles > article

Article | Open access | Published: 14 October 2025

Temperature measurement of Quark-Gluon plasma at different stages

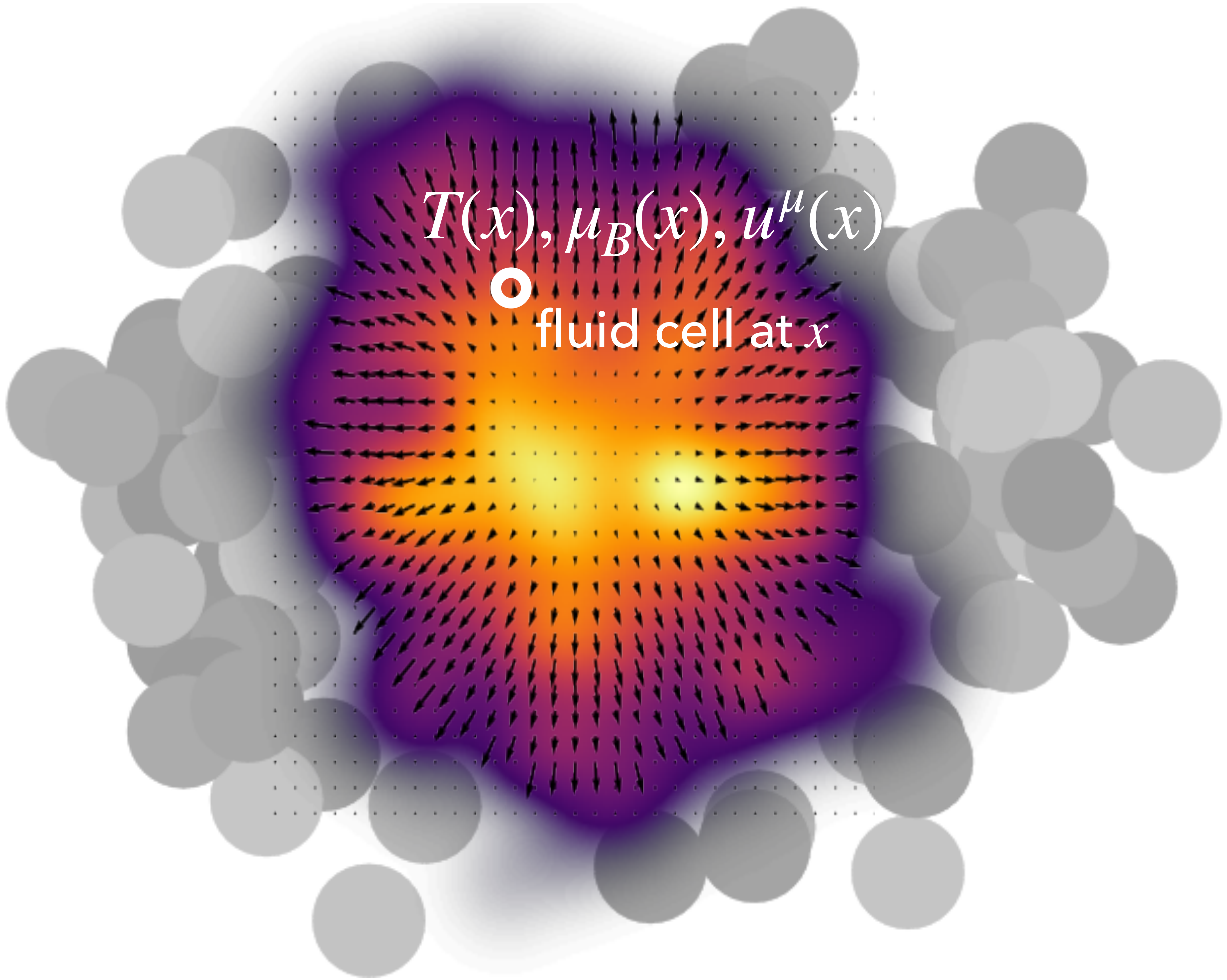
STAR Collaboration

Nature Communications **16**, Article number: 9098 (2025) | Cite this article

STAR: 7.7, 14.6, 19.6, 27, 39, 54.4, 62.4, 200 GeV

NA60, PRL 100, 022302 (2008); EPJC 59 607-623 (2009). STAR, 2402.01998. HADES, Nat. Phys.,1040–1045 (2019). Rapp and van Hees, PLB 753, 586 (2016)

Theoretical calculation of thermal spectra



- Fully differential (dilepton) production rate of a static thermal source

Bose distribution

all the QCD information

$$\frac{\mathrm{d}\Gamma_{\ell\bar{\ell}}}{\mathrm{d}\omega\,\mathrm{d}^3\boldsymbol{k}} = \frac{\mathrm{d}N_{\ell\bar{\ell}}}{\mathrm{d}t\,\mathrm{d}^3\boldsymbol{x}\,\mathrm{d}\omega\,\mathrm{d}^3\boldsymbol{k}} = \frac{2\alpha_{\mathrm{em}}^2 f_B(\omega)}{9\pi^3 M^2} B\left(\frac{m_l^2}{M^2}\right) \rho_{\mathrm{em}}(\omega, \boldsymbol{k}; T, \mu_B)$$

- Emission rate in the lab frame

Local rest frame

essential for p_T spectra, anisotropic flows v_n, and correct kinematics

Lab frame

$$\frac{\mathrm{d}\Gamma_{\ell\bar{\ell}}}{\mathrm{d}^4K'} = \left.\frac{\mathrm{d}\Gamma_{\ell\bar{\ell}}}{\mathrm{d}\omega\,\mathrm{d}^3\boldsymbol{k}}\right|_{K^\mu = \Lambda^{\mu\nu}K'_\nu}$$

Lorentz boost

- Spectra in the lab frame

$$\frac{\mathrm{d}N_{\ell\bar{\ell}}}{\mathrm{d}M\,\mathrm{d}y} = M \int_{k_{\min}}^{k_{\max}} \mathrm{d}k_\perp\, k_\perp \int_0^{2\pi} \mathrm{d}\phi \int \mathrm{d}^4x \frac{\mathrm{d}\Gamma_{\ell\bar{\ell}}}{\mathrm{d}^4K'}$$

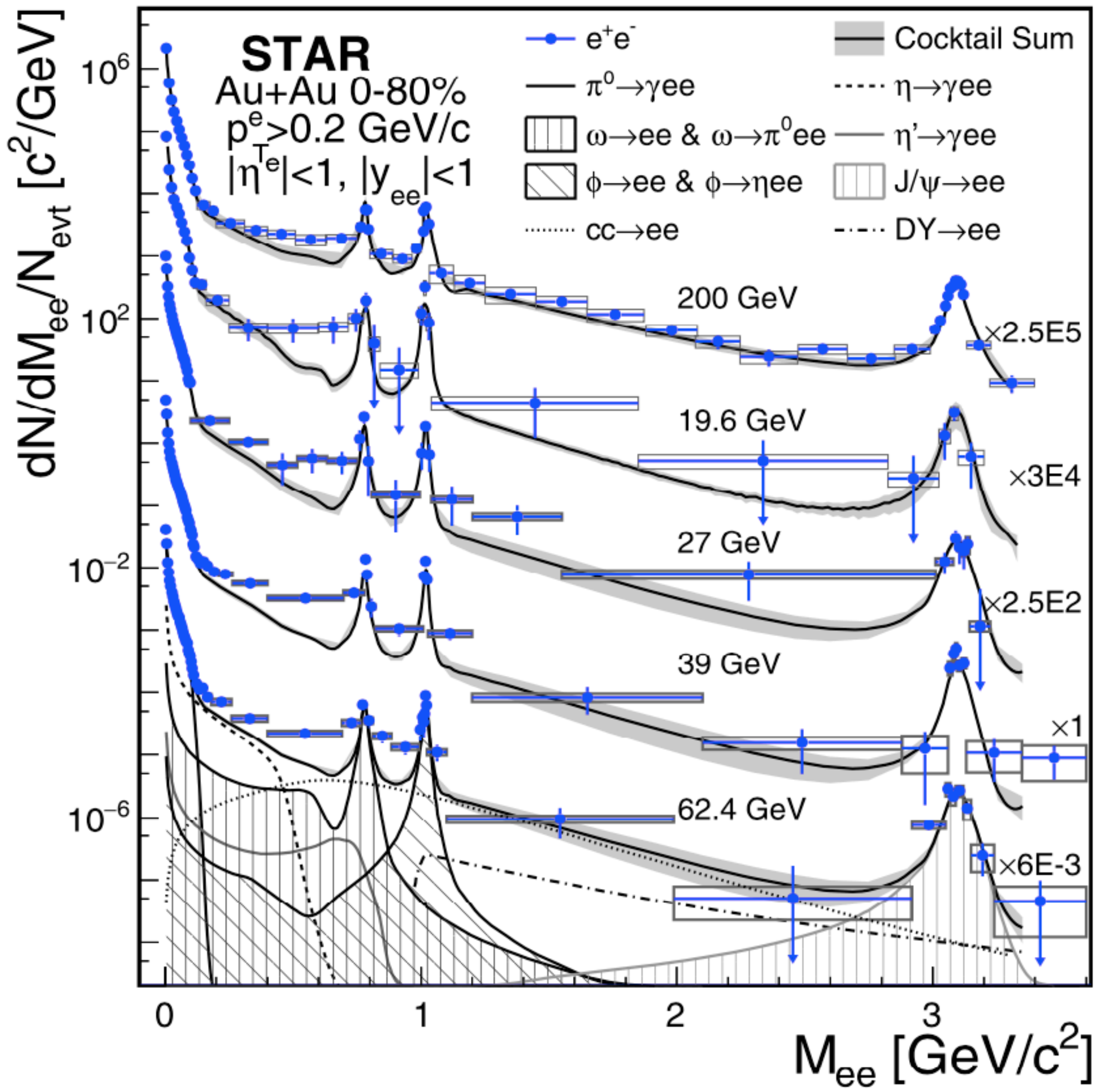
match experimental kinematic cuts

- In non-relativistic approximation ($M \gg T$), the emission rate of dileptons $\propto (MT)^{3/2}\mathrm{e}^{-M/T}$; similarly, for photons, when $p_T \gg T$, the rate $\propto \mathrm{e}^{-p_T/T}$; the exponential term is from $f_B(\omega) = 1/(\mathrm{e}^{\omega/T} - 1)$.
- Off-equilibrium corrections (such as viscous effects, B-field); …

Theoretical modeling

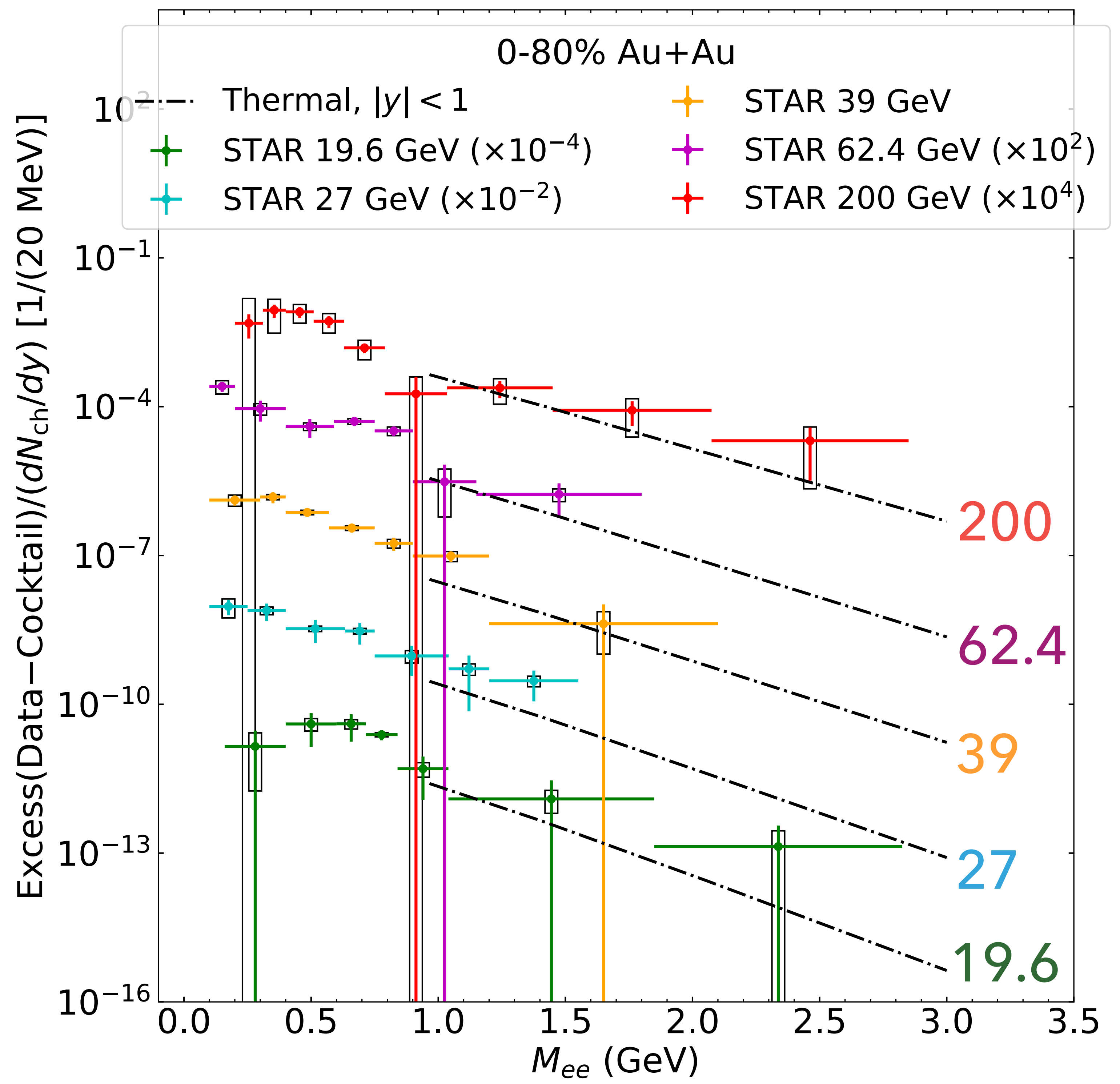
Bulk evolution (macroscopic)	**Emission rates (microscopic)**	**Unified framework**
Medium evolution through the soft region: EOS softening, latent heat, and transport anomalies near CP/FOPT. • Employ EoS families including crossover, CP, and FOPT behavior; quantify softest point and coexistence region. • Include baryon diffusion, viscosities, and relaxation times with possible critical scaling. • Treat pre-equilibrium evolution explicitly to describe early-time EM emission before hydrodynamization. • Optionally couple slow order-parameter fields (e.g., σ) to fluid dynamics (Hydro+ or chiral fluid).	Modifications of the electromagnetic spectral function near criticality. • Incorporate σ-vector mixing: enhanced low-mass dileptons from σ correlations. • Include conductivity enhancement and charge diffusion scaling with correlation length. • Track hadronic spectral broadening and $\rho/\omega/\phi$ reshaping near the transition. • Compute pre-equilibrium rates and avoid overlap with thermal emission.	Consistent integration of bulk and rate effects across stages. • Define switching criteria (pre-equilibrium $\rightarrow$ hydro $\rightarrow$ hadronic transport) with no double counting. • Ensure smooth interpolation of EM rates across QGP-HG transition in (T, μ_B). • Embed modified rates in event-by-event simulations with conserved currents. • Quantify contributions to EM yield from each stage and from critical vs. non-critical regions.

Thermal QGP dilepton production: NLO emission rates



STAR, PRL113, 022301 (2014); PRC 92, 024912 (2015); PLB 750 (2015) 64–71; PRC 107, L061901 (2023); 2402.01998.

markers: excess = inclusive – cocktail



https://github.com/LipeiDu/DileptonEmission

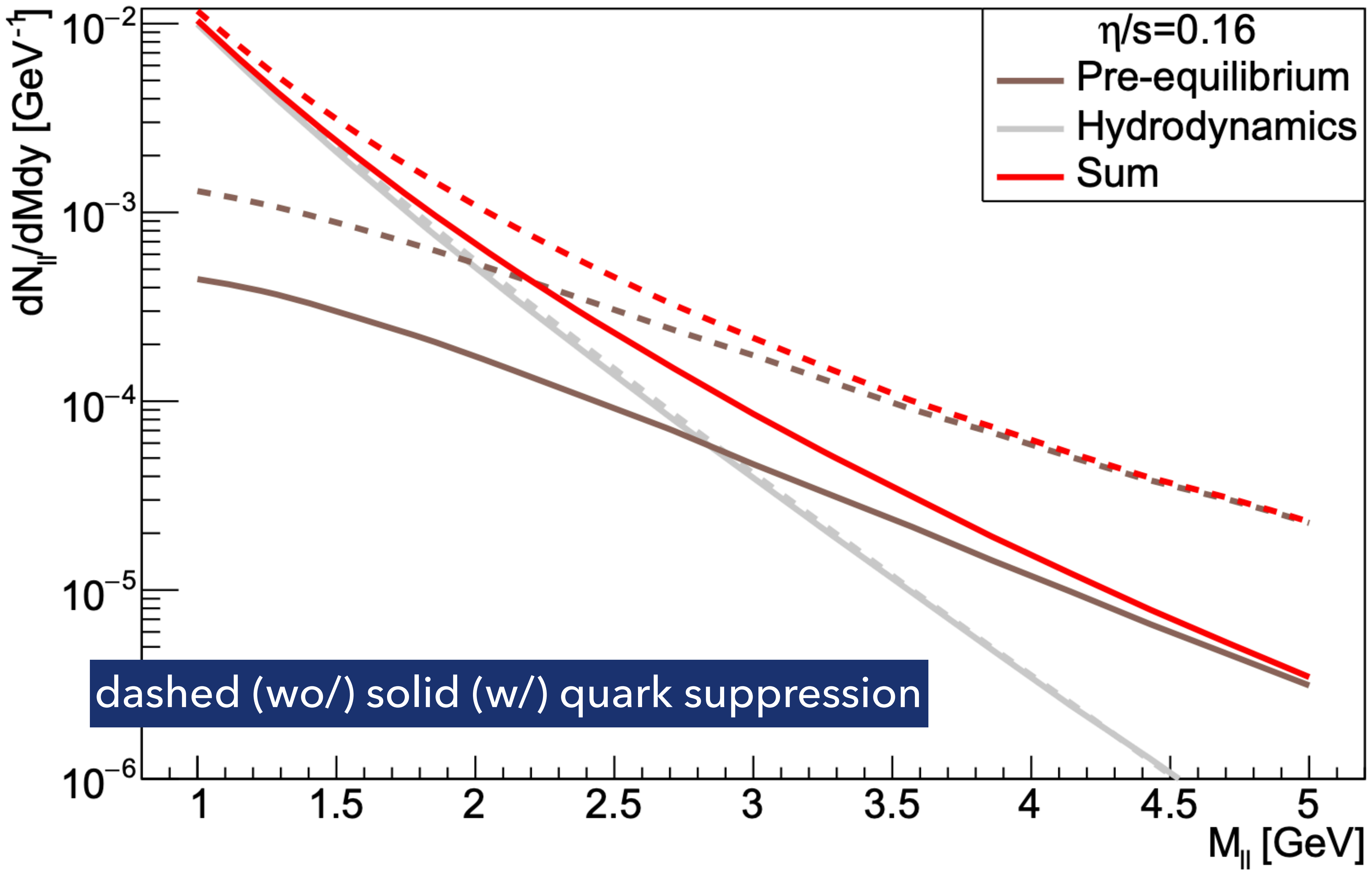
Churchill, LD, Gale, Jackson, Jeon, PRC 109, 044915 (2024), PRL 132, 172301 (2024)

- First estimate of NLO dilepton emission at nonzero μ_B with (3+1)D multistage hydrodynamic model;
- The multistage model is calibrated using rapidity-dependent hadronic observables from the Beam Energy Scan.

LD, Shen, Jeon, Gale, PRC 108 (2023) L041901; LD, Gao, Jeon, Gale, PRC 109, 014907 (2024); LD, Phys.Rev.C 110 (2024) 1, 014904

Pre-equilibrium dynamics

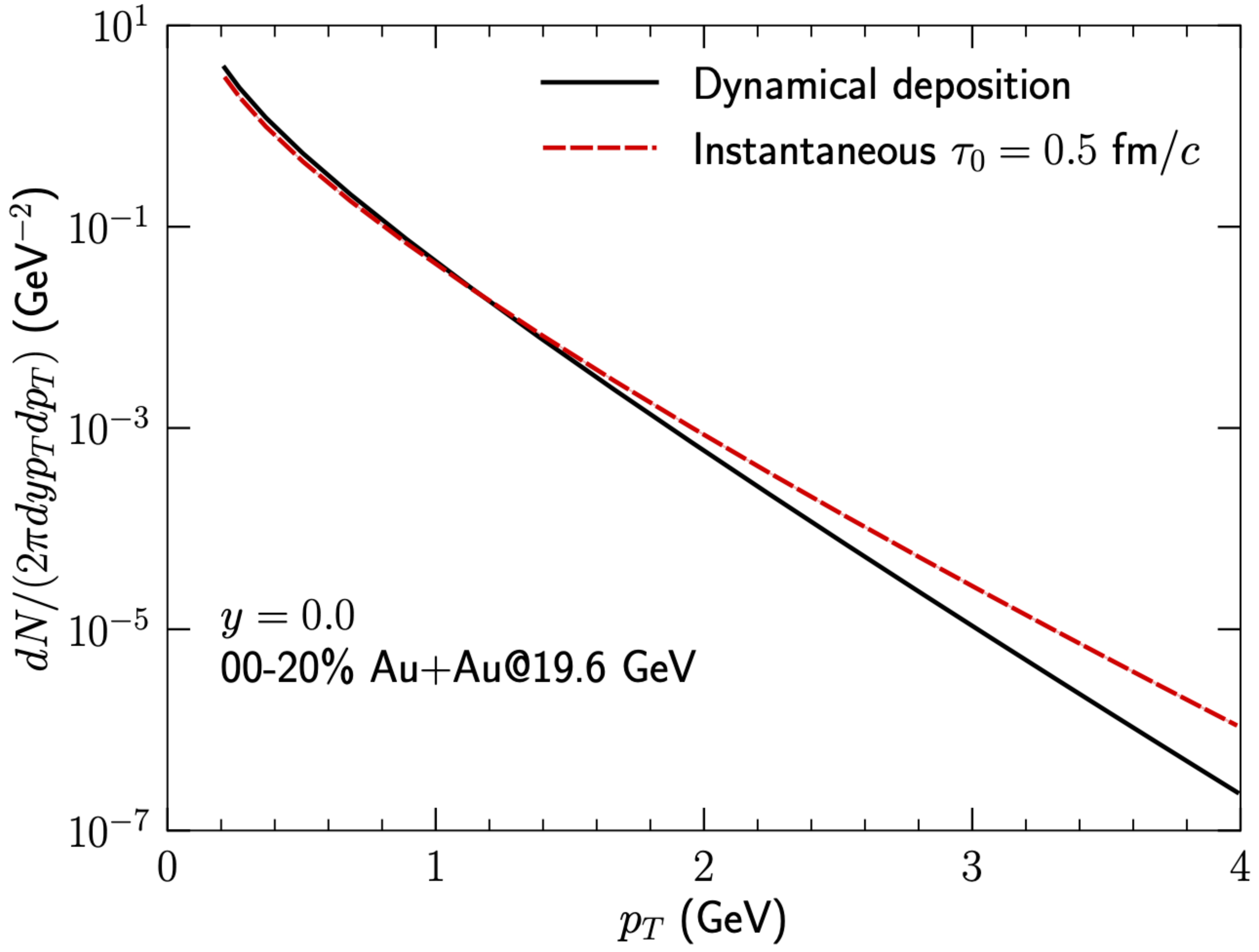
0-5% 5.02 TeV Pb+Pb dileptons



dashed (wo/) solid (w/) quark suppression

Coquet, X. Du, Ollitrault, Schlichting, Winn, Phys.Lett.B 821 (2021) 136626

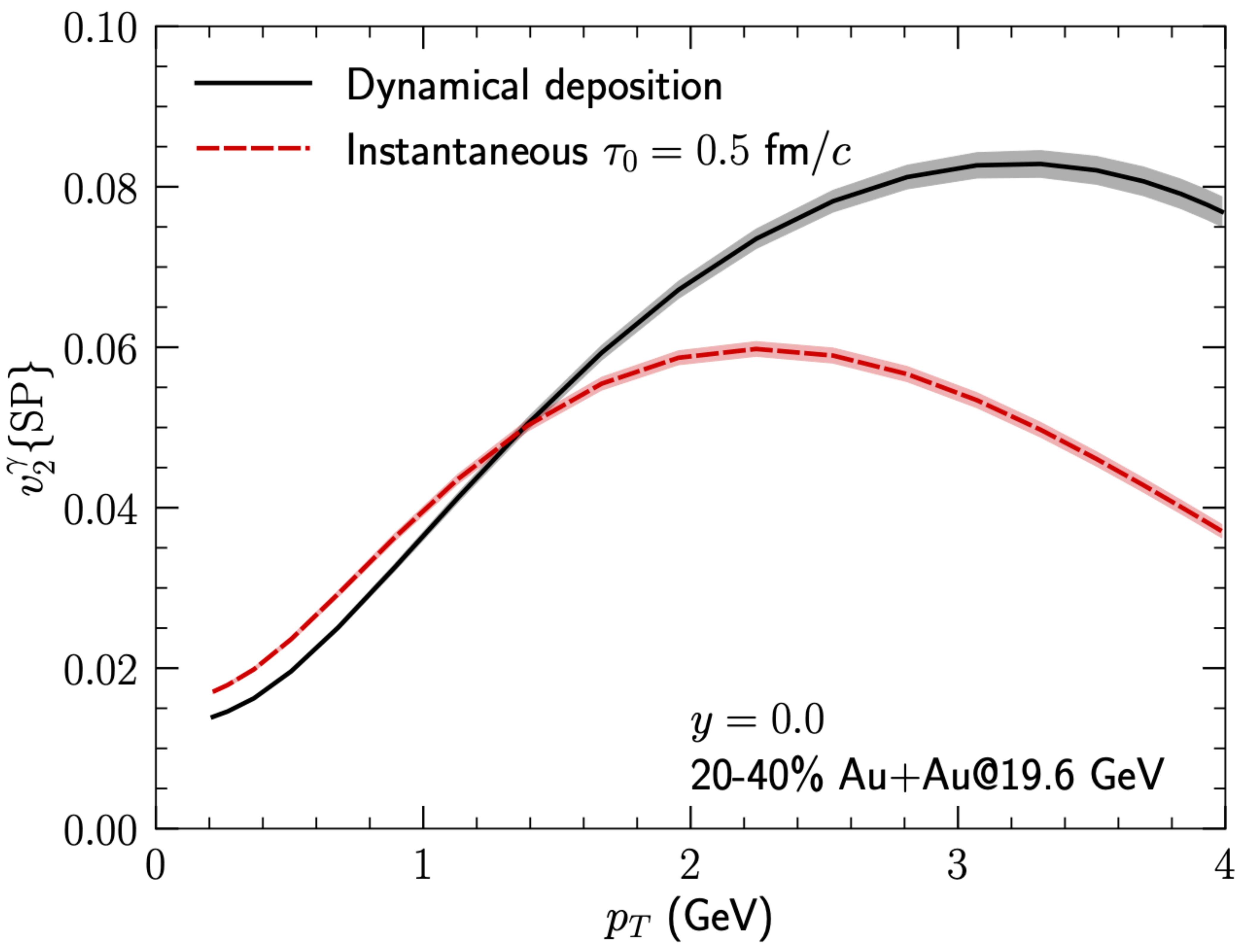
0-20% 19.6 GeV Au+Au photons

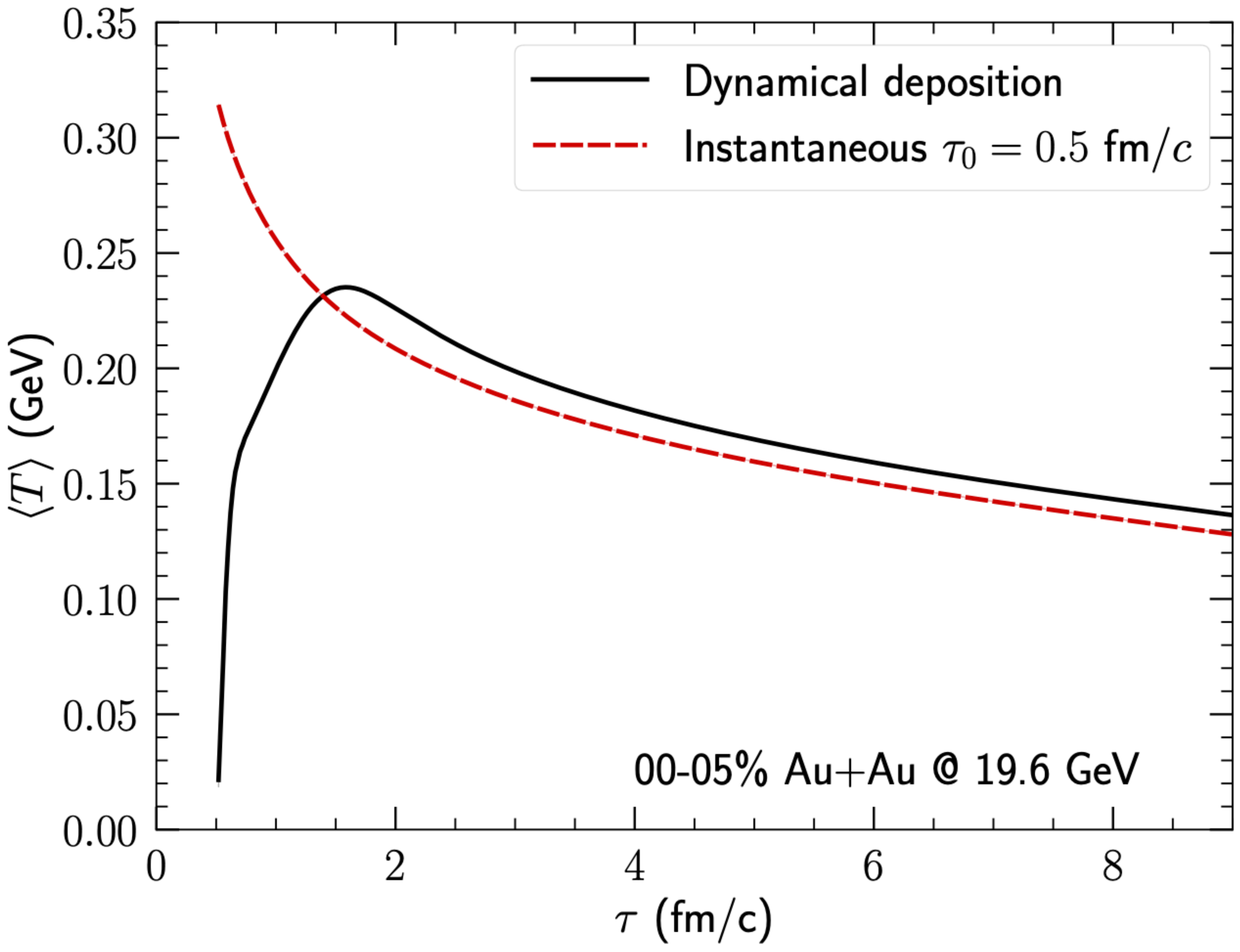


Shen, Noble, Paquet, Schenke, Gale, PoS HardProbes2023 (2024) 042

- Dynamical evolution toward chemical equilibrium studied for LHC energies
- Dynamical hydro initialization studied for BES energies

Pre-equilibrium dynamics

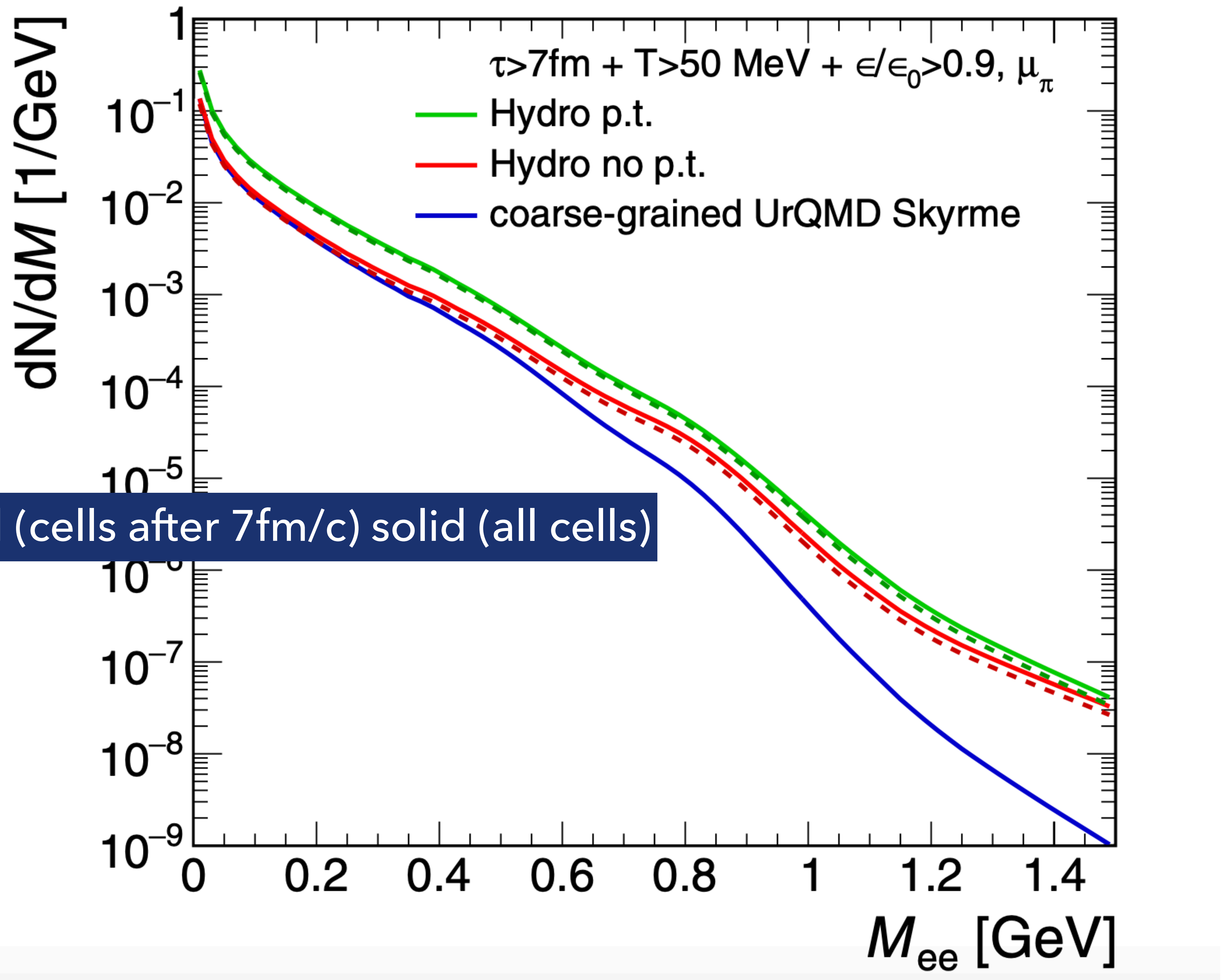




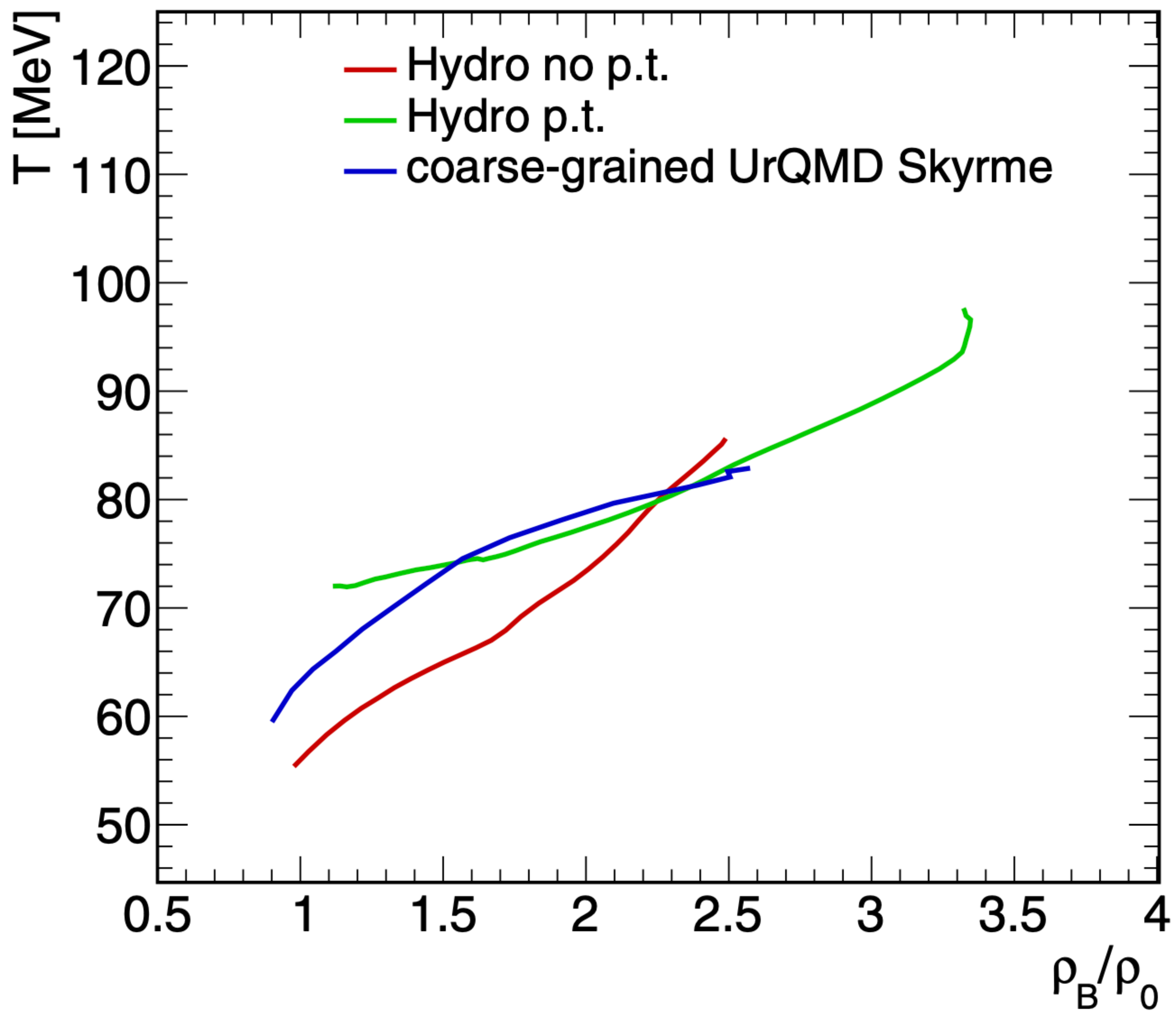
Shen, Noble, Paquet, Schenke, Gale, PoS HardProbes2023 (2024) 042

1st-order phase transition

Seck, Galatyuk, Mukherjee, Rapp, Steinheimer, Stroth, Wiest



dashed (cells after 7fm/c) solid (all cells)



- The latent heat involved in the first-order transition leads to a substantial increase in the low-mass thermal emission signal, by about a factor of two above the cross-over scenario

Criticality in the emission rates

- Enhancement of photon emission rate near the QCD critical point

  Akamatsu, Asakawa, Hongo, Stephanov, Yee, 2505.07169

- Dileptons
  - Enhancement is expected from the conductivity $\sigma \propto \xi$
  - NJL model calculation   Nishimura-Kitazawa-Kunihiro (23,24)
  - Model H calculation to obtain universal scaling form

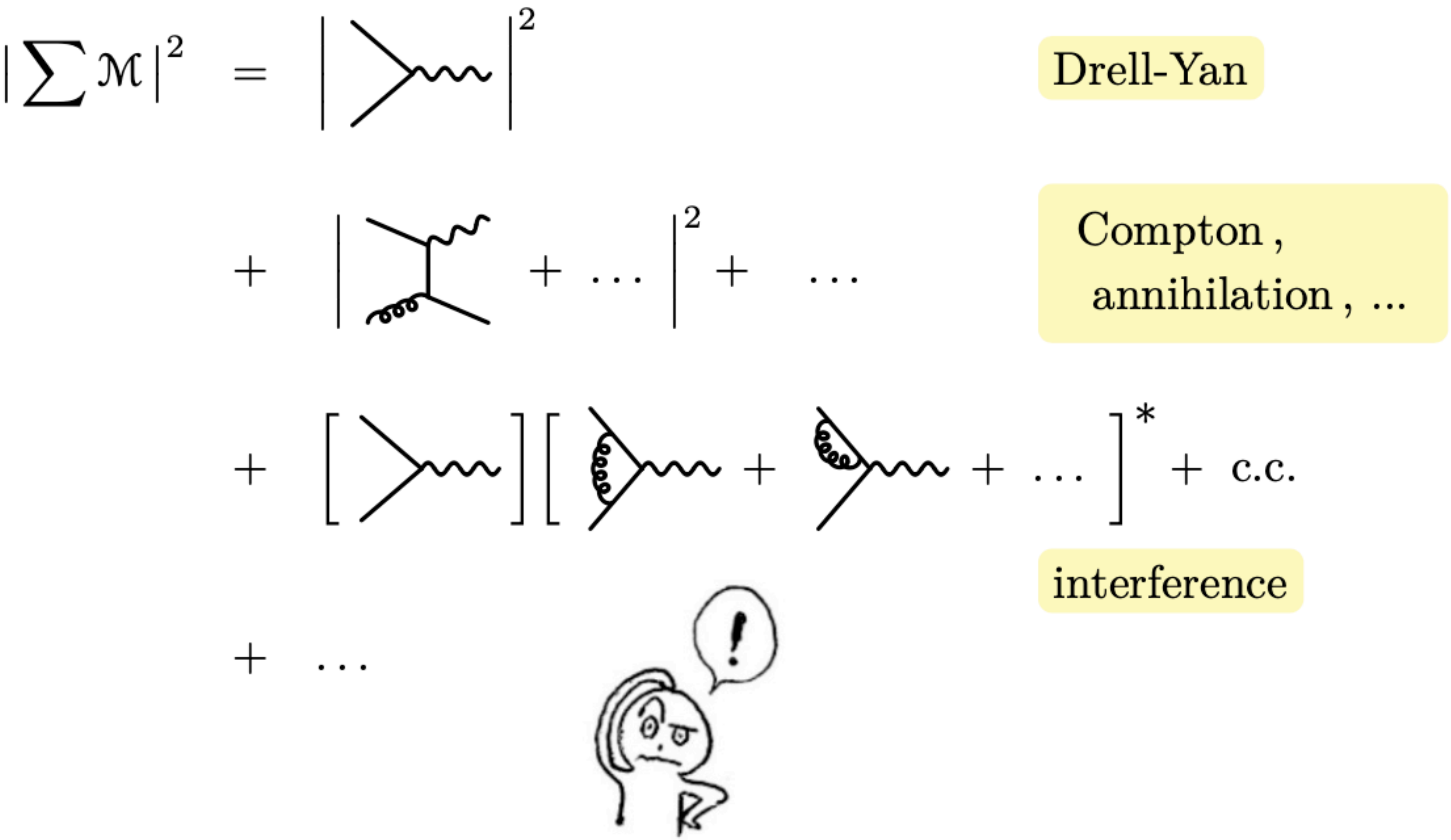
- Non-equilibrium correction to the emission rate ~ similar to Kibble-Zurek scaling

Summary

- Current BES measurements of EM probes have large uncertainties
- Quantitative calculations are quite limited
  - Bulk evolution calibrated by hadronic observables
  - Pre-equilibrium dynamics: chemical equilibration; dynamical energy deposition
  - Emission rates at NLO
- Critical point/1st-order phase transition
  - improved bulk evolution
  - dynamical evolution of a sigma mode
  - emission rates with critical effects
- Indirect search: chiral symmetry restoration/moat region?

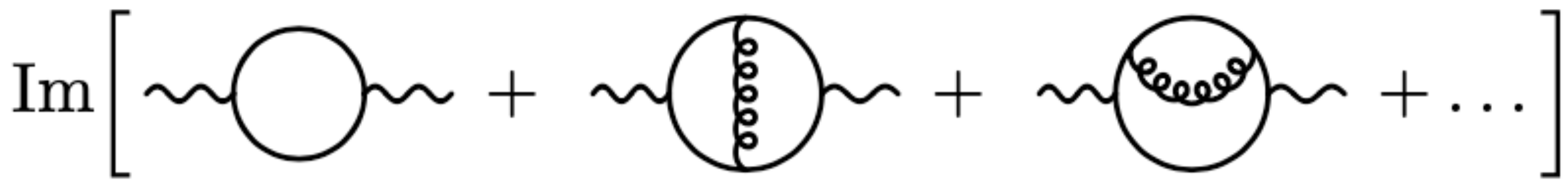
BACKUP

Application of perturbative QCD



G. Jackson

Application of perturbative QCD



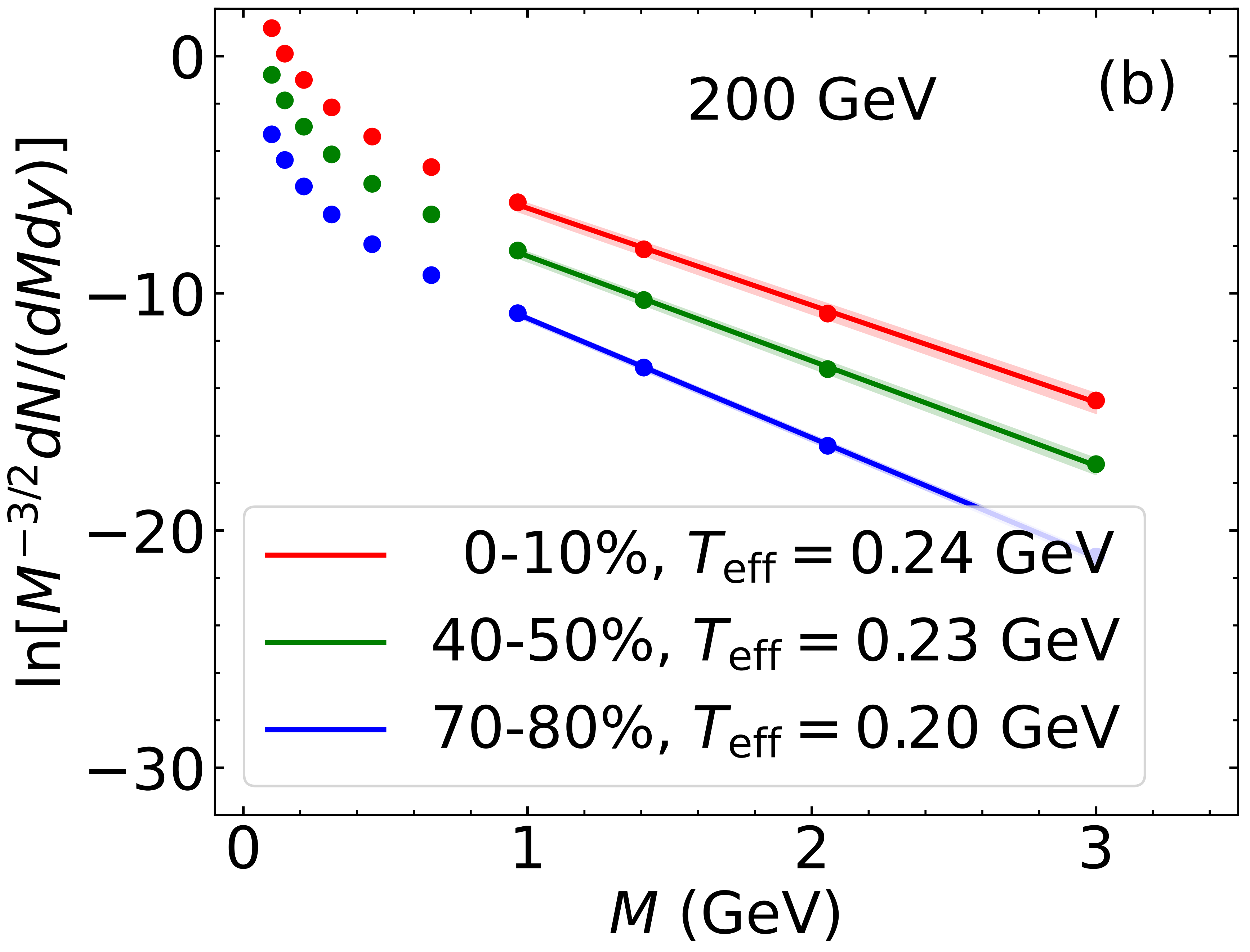
self-energy, $\Pi_{\mu\nu}$

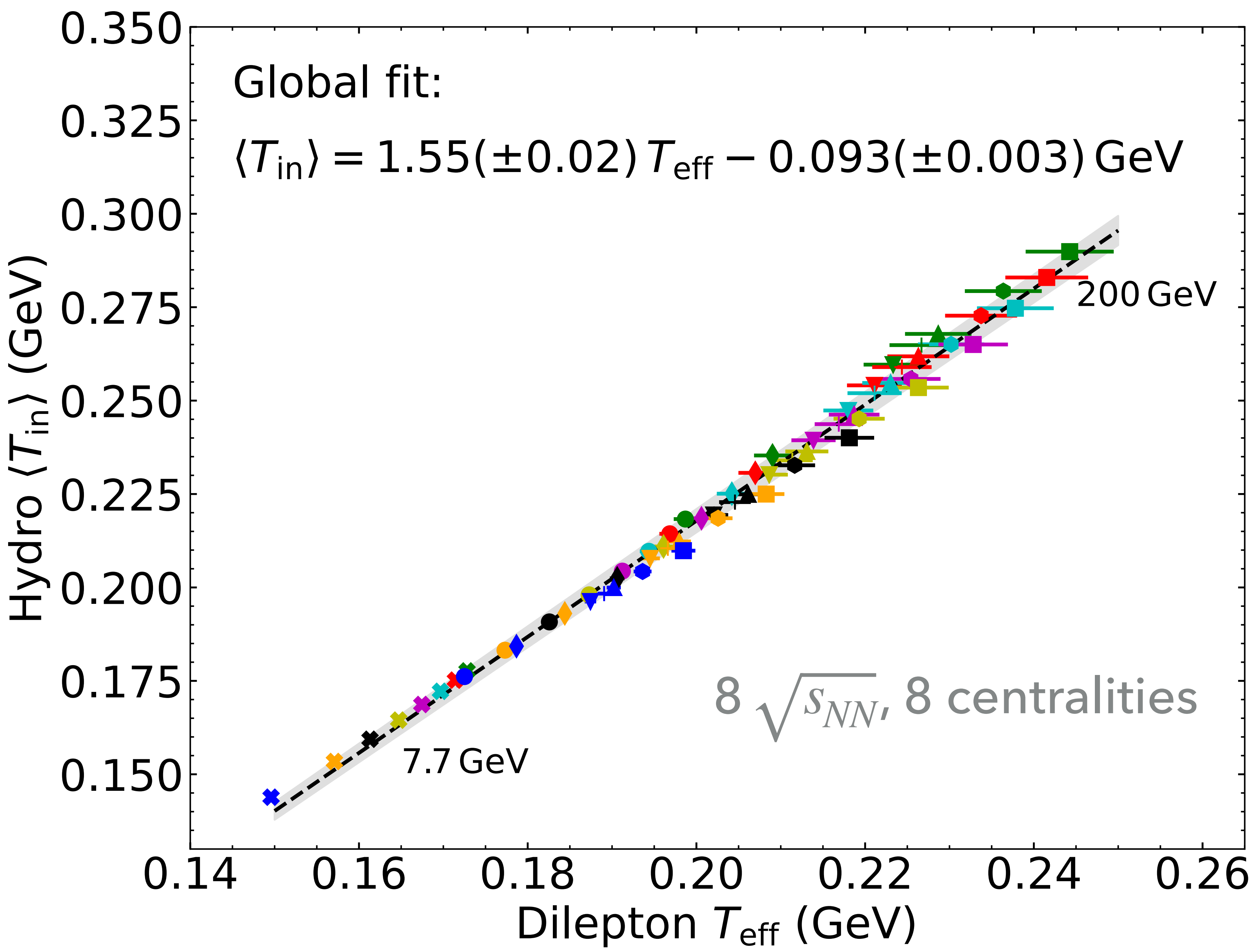
[Weldon (1990)] , [Bödeker, Sangel, Wörmann (2015)]

$$\frac{dN^{l^+l^-}}{d^4x d^4K} = \int \frac{d^3\mathbf{p}_1}{(2\pi)^3} \frac{d^3\mathbf{p}_2}{(2\pi)^3} 4N_c \sum_f f_q(x,\mathbf{p}_1) f_{\bar{q}}(x,\mathbf{p}_2) v_{q\bar{q}} \sigma_{q\bar{q}}^{l^+l^-} \delta^{(4)}(K - P_1 - P_2),$$

G. Jackson

QCD thermometer: reexamined in models

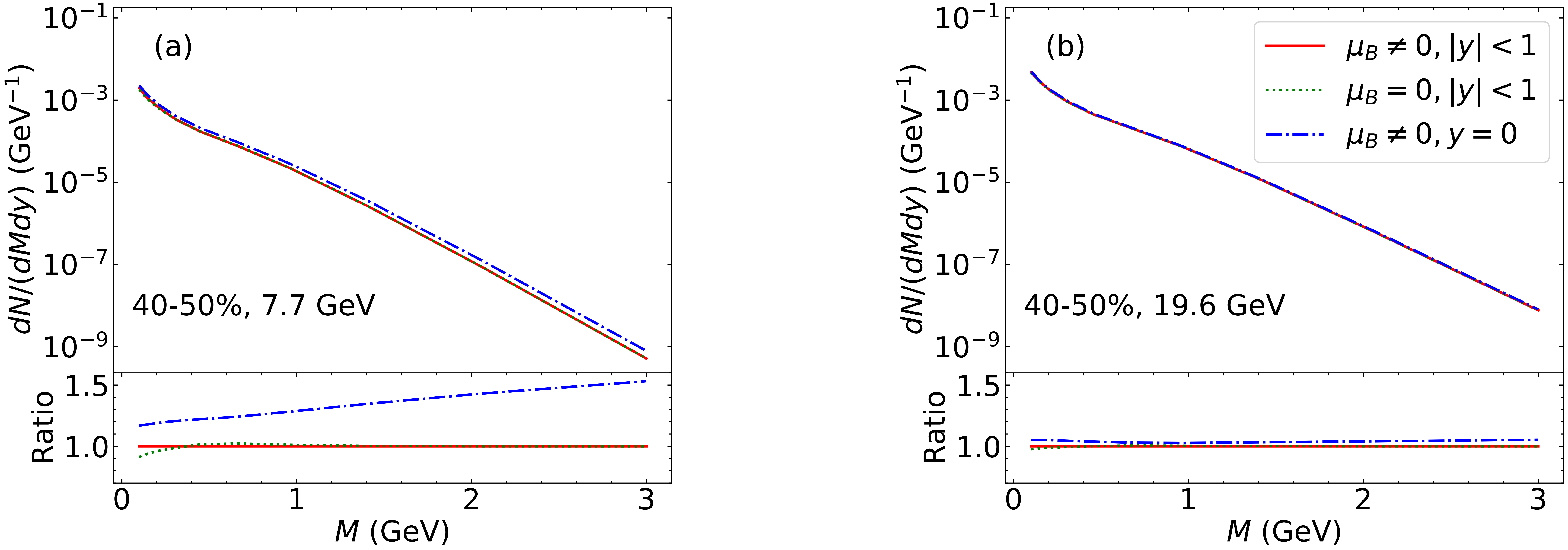




Churchill, LD, Gale, Jackson, Jeon, PRC 109, 044915 (2024), PRL 132, 172301 (2024)   https://github.com/LipeiDu/DileptonEmission

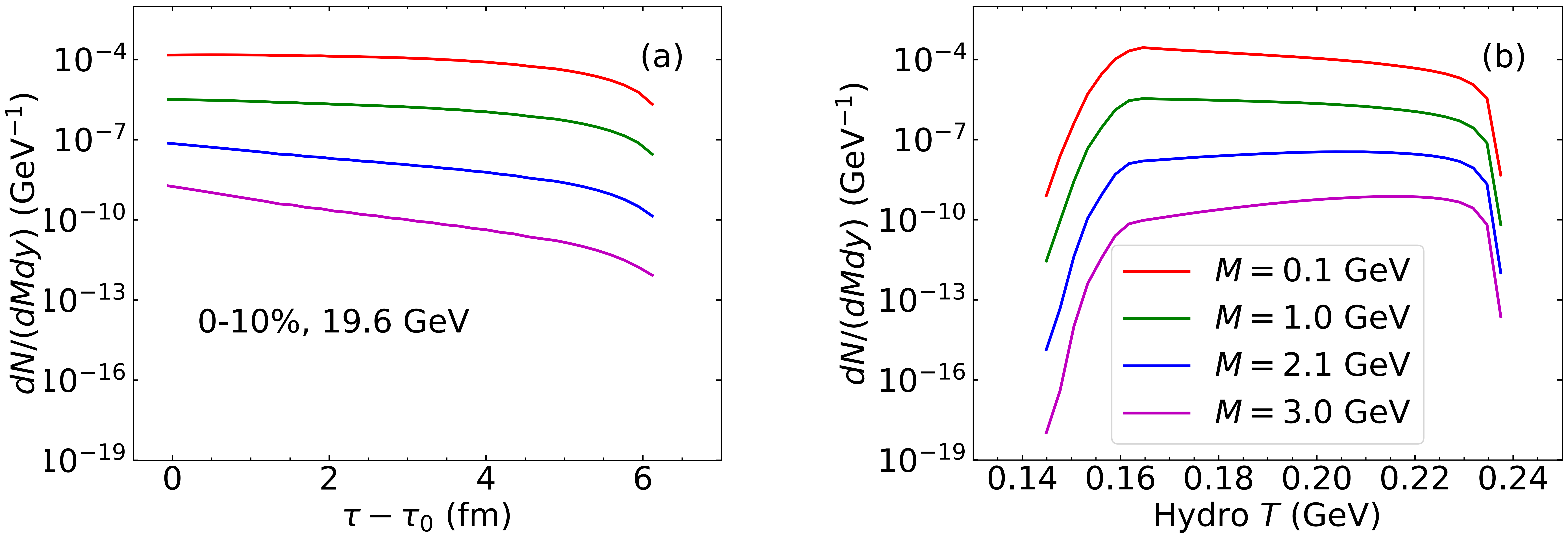
- The fit quality of the exponential ansatz is good [✅ fitting method verified!]. Uncertainties are larger at higher beam energies and in central collisions since the fireball has larger temperature variations.
- A correlation between the average temperature and the initial hydro temperature is identified [✅ interpretation of the extracted temperature found!].
- Measure the initial temperature of the evolving QCD fireball in a way that is unaffected by dynamical distortions.

RAPIDITY AND μ_B DEPENDENCE



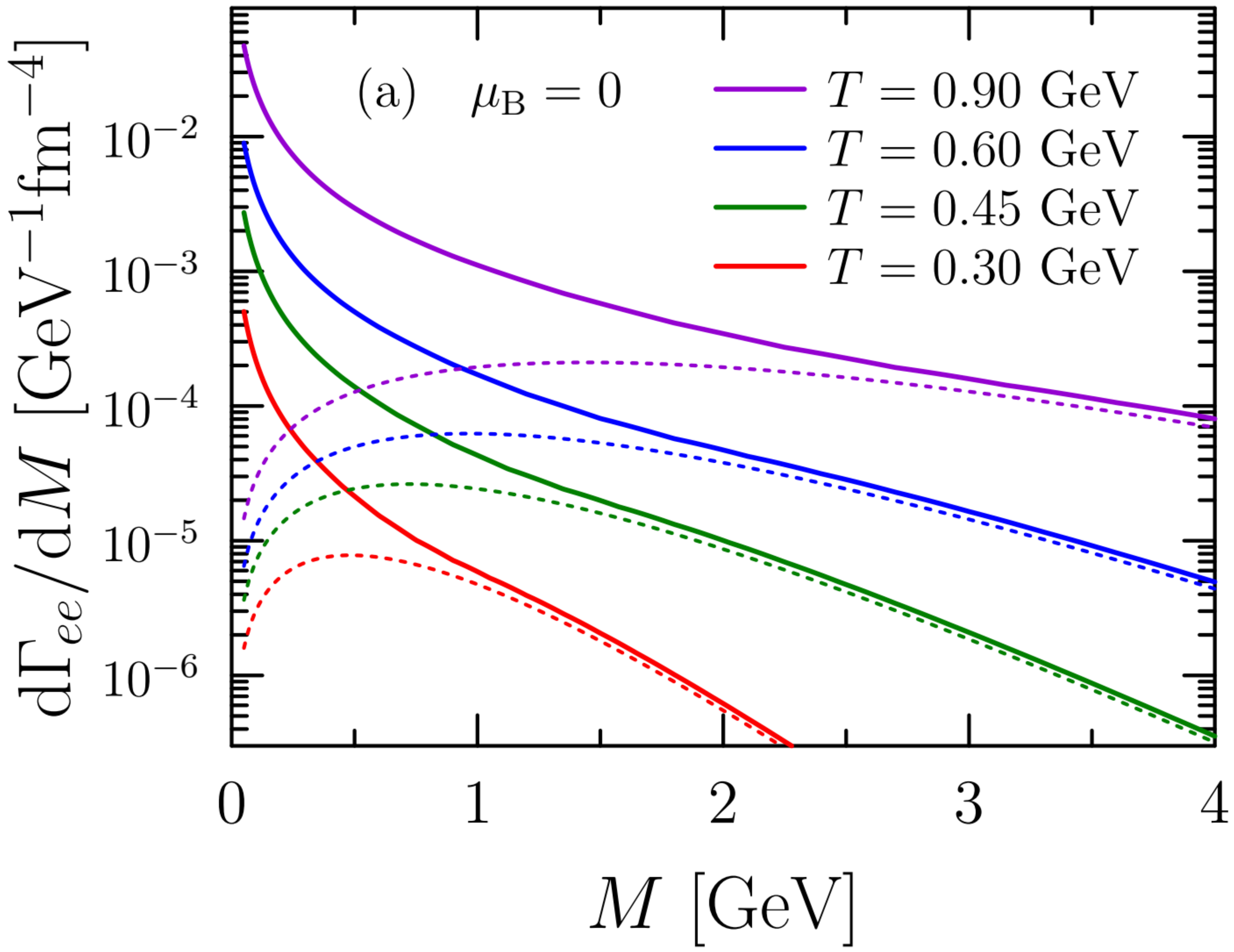
- μ_B-dependence is not significant for 7.7 GeV and higher beam energies
- At 7.7 GeV, a strong boost-non-invariant effect is observed

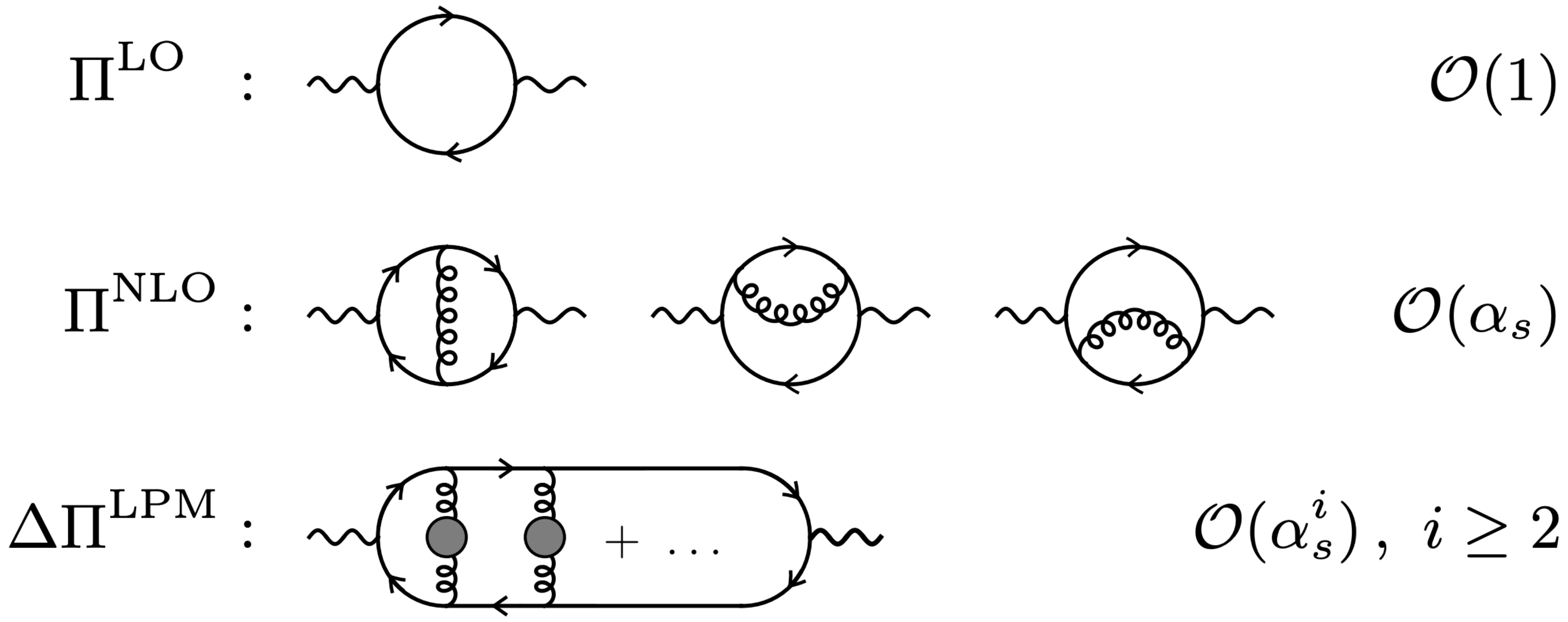
DILEPTON PRODUCTION IN T AND τ



- Two effects at play:
  - The emission rate decreases as the temperature decreases
  - The volume of the system increases with time

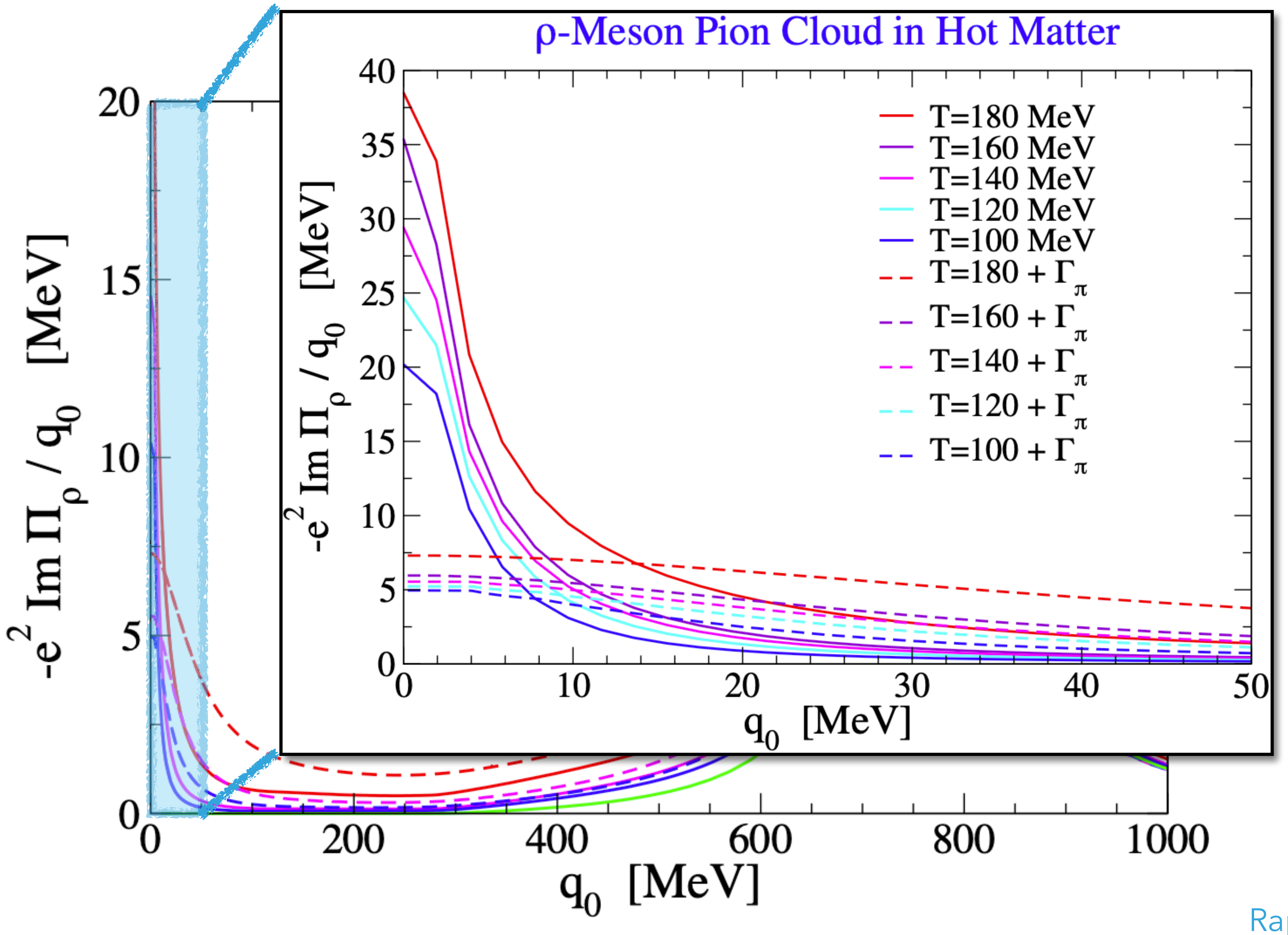
NLO emission rates

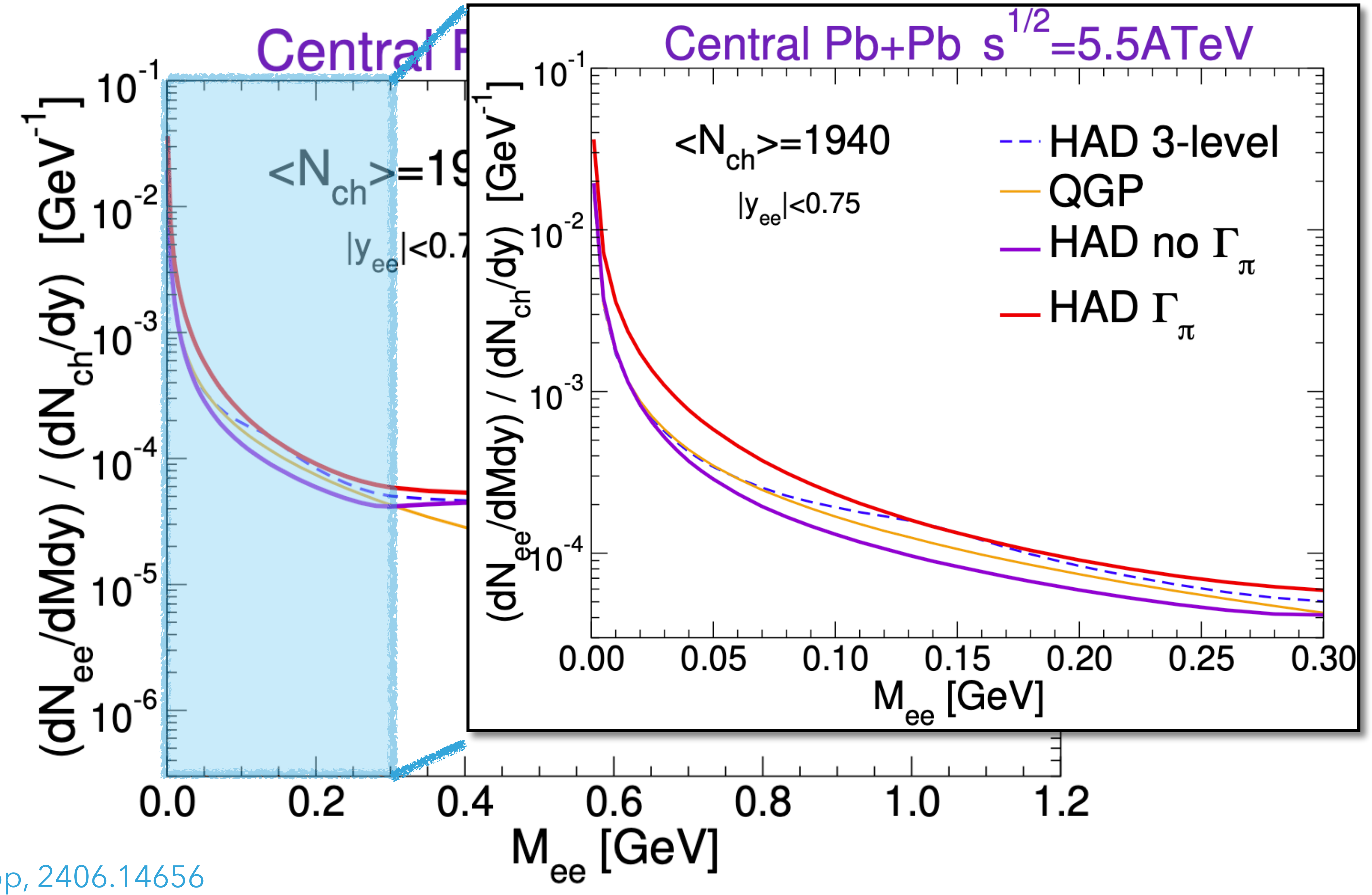




Churchill, LD, Gale, Jackson, Jeon, PRC 109, 044915 (2024), PRL 132, 172301 (2024)

Extraction of electric conductivity σ_{el}





Rapp, 2406.14656

- Electric conductivity σ_{el} manifests in low-mass thermal dilepton spectra: $\sigma_{\text{el}}(T) = \dfrac{e^2}{2} \lim_{q_0 \to 0} \rho_{\text{em}}(q_0, q = 0)/q_0$
- The inclusion of thermal pion widths significantly broadens the conductivity peak near zero energy.
- A key signature of a small conductivity is the enhanced dilepton yields in the very-low-mass region.

Floerchinger, Gebhardt, Reygers, PLB 837 (2023) 137647; Rapp, 2406.14656; Atchison, Han, Geurts, 2408.1017