Canadian Institute of Nuclear Physics
Institut canadien de physique nucléaire

Dilepton emission in heavy ion collisions and equilibrium of QCD matter

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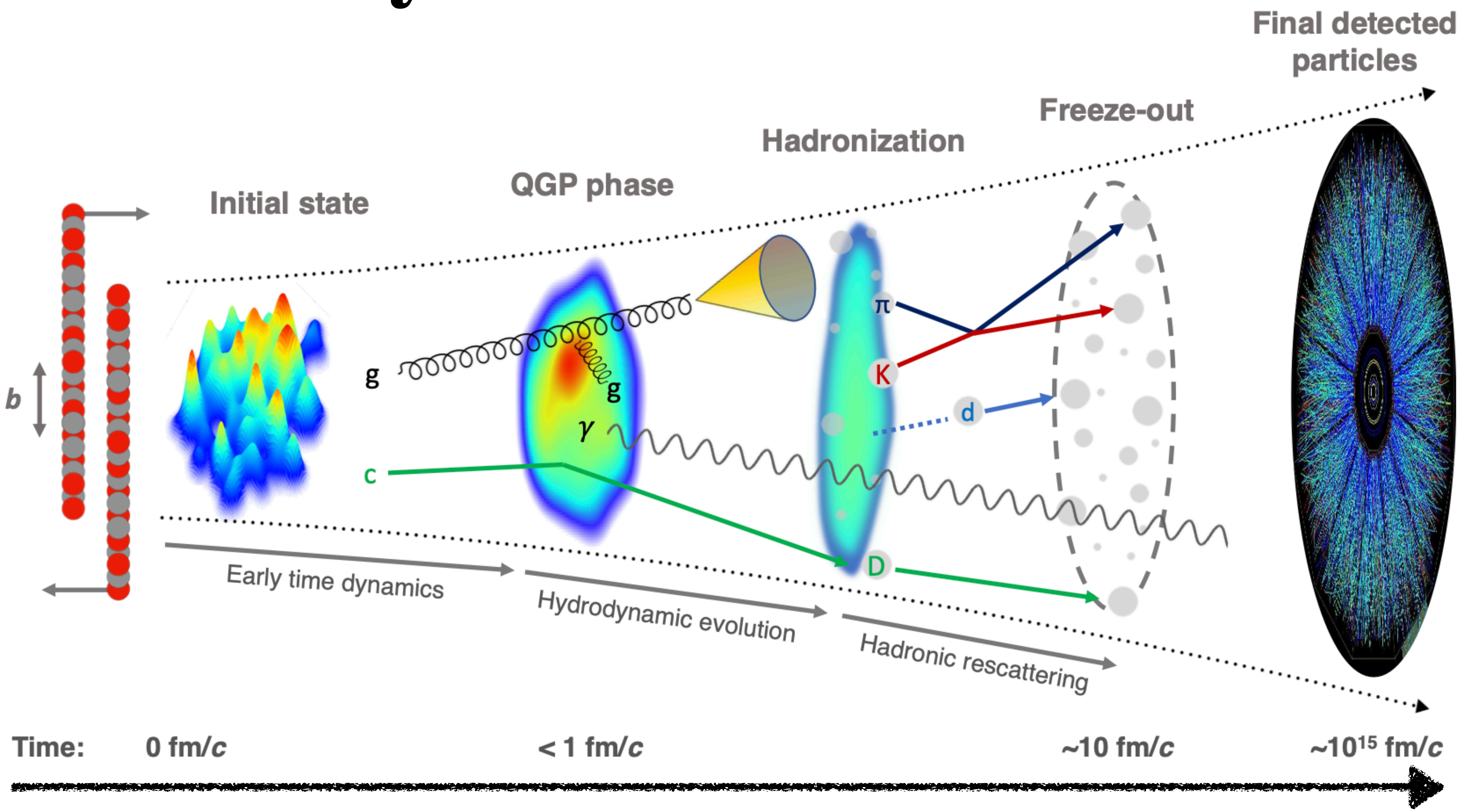
In collaboration with Lipei Du, Charles Gale and Sangyong Jeon

McGill University

Based on e-Print: 2407.04156 [nucl-th]

Hard Probe 2024, Nagasaki, Japan
September 24, 2024

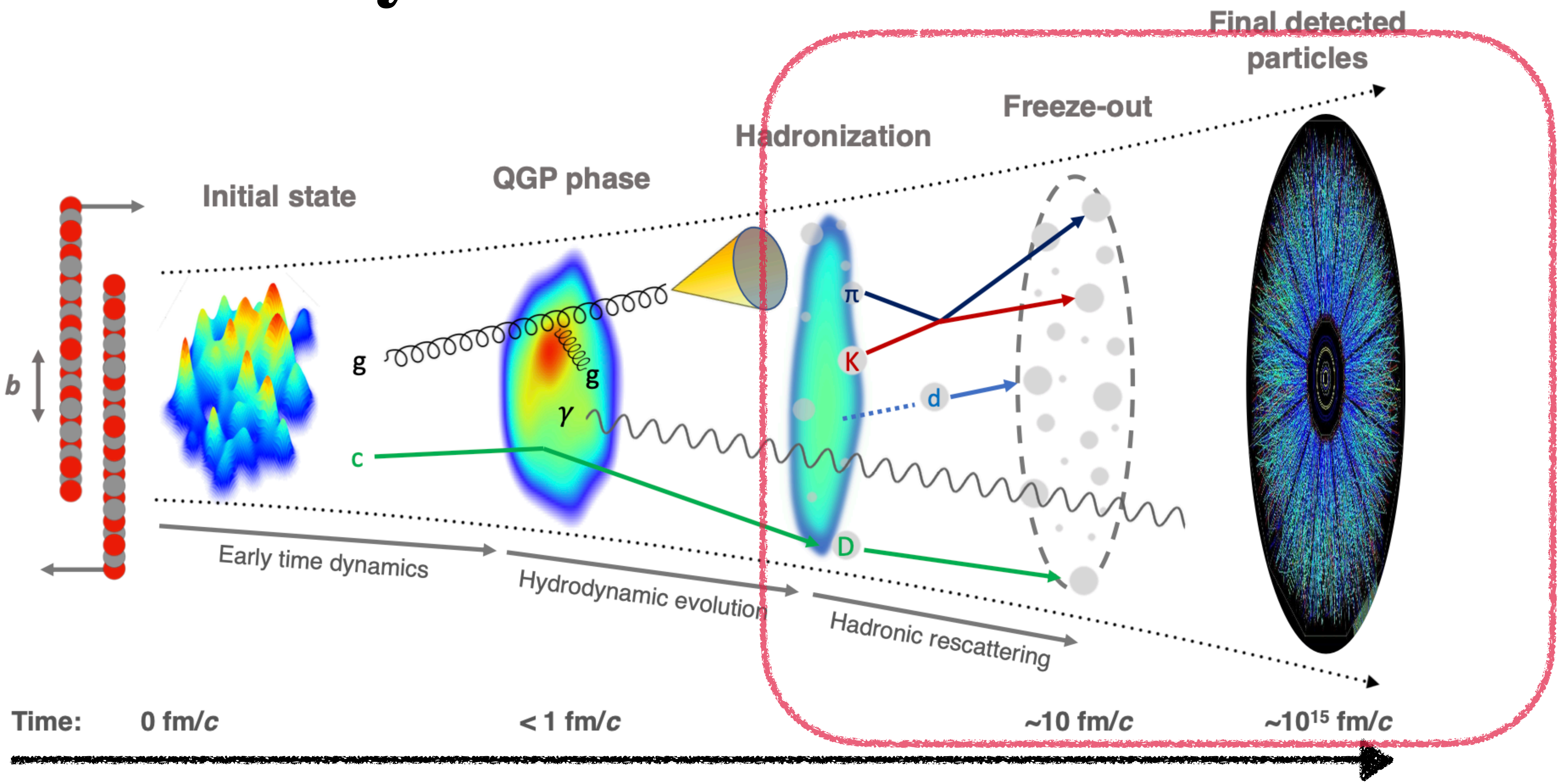
Relativistic Heavy Ion Collision



Goal: explore and study the properties of QGP.

[ALICE, Eur.Phys.J.C 84 (2024) 8, 813]

Relativistic Heavy Ion Collision



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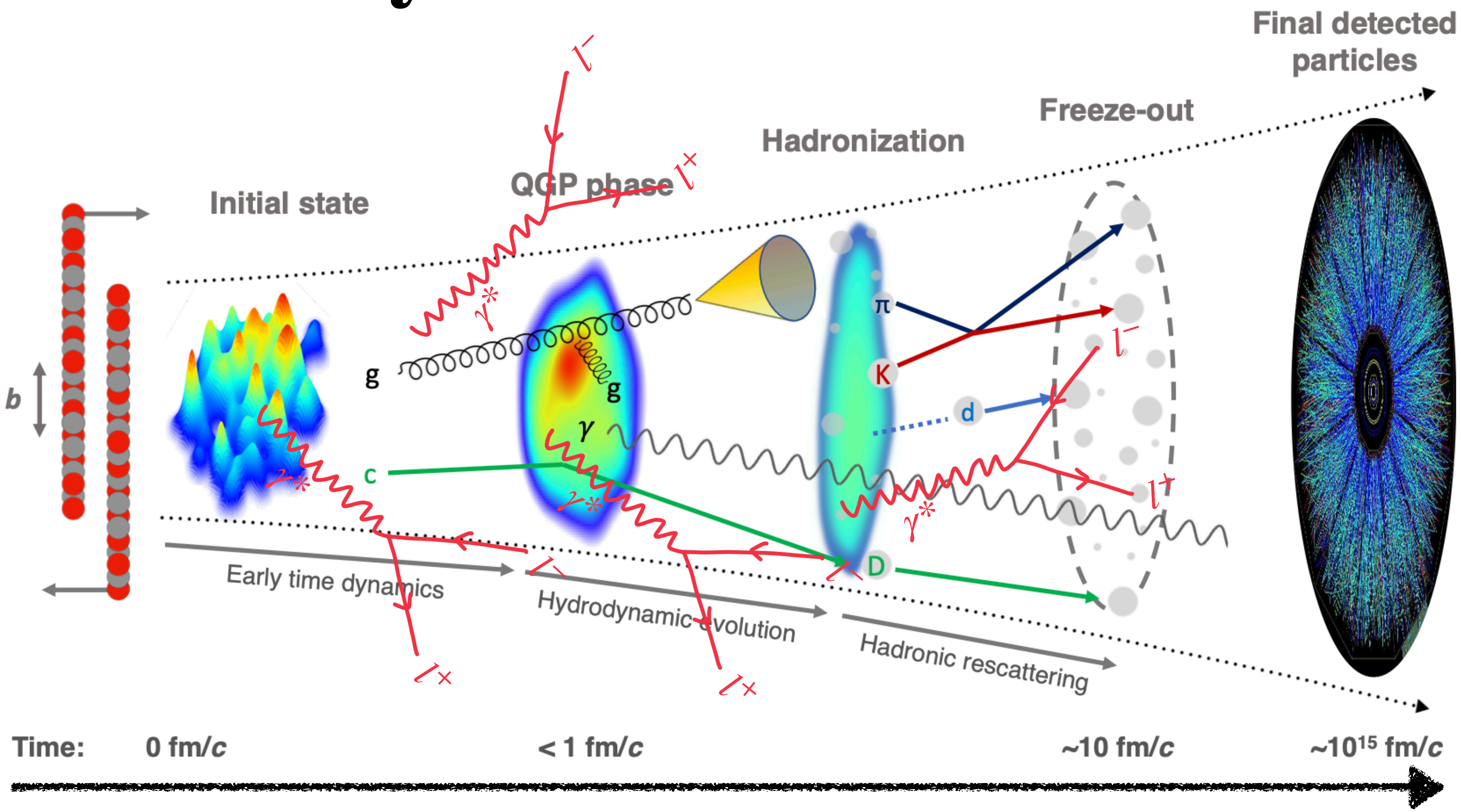
Probes:

- Soft hadrons: $T < T_{\mathrm{frz}}$, indirect probe.

Relativistic Heavy Ion Collision



Goal: explore and study the properties of QGP.

[ALICE, Eur.Phys.J.C 84 (2024) 8, 813]

Probes:

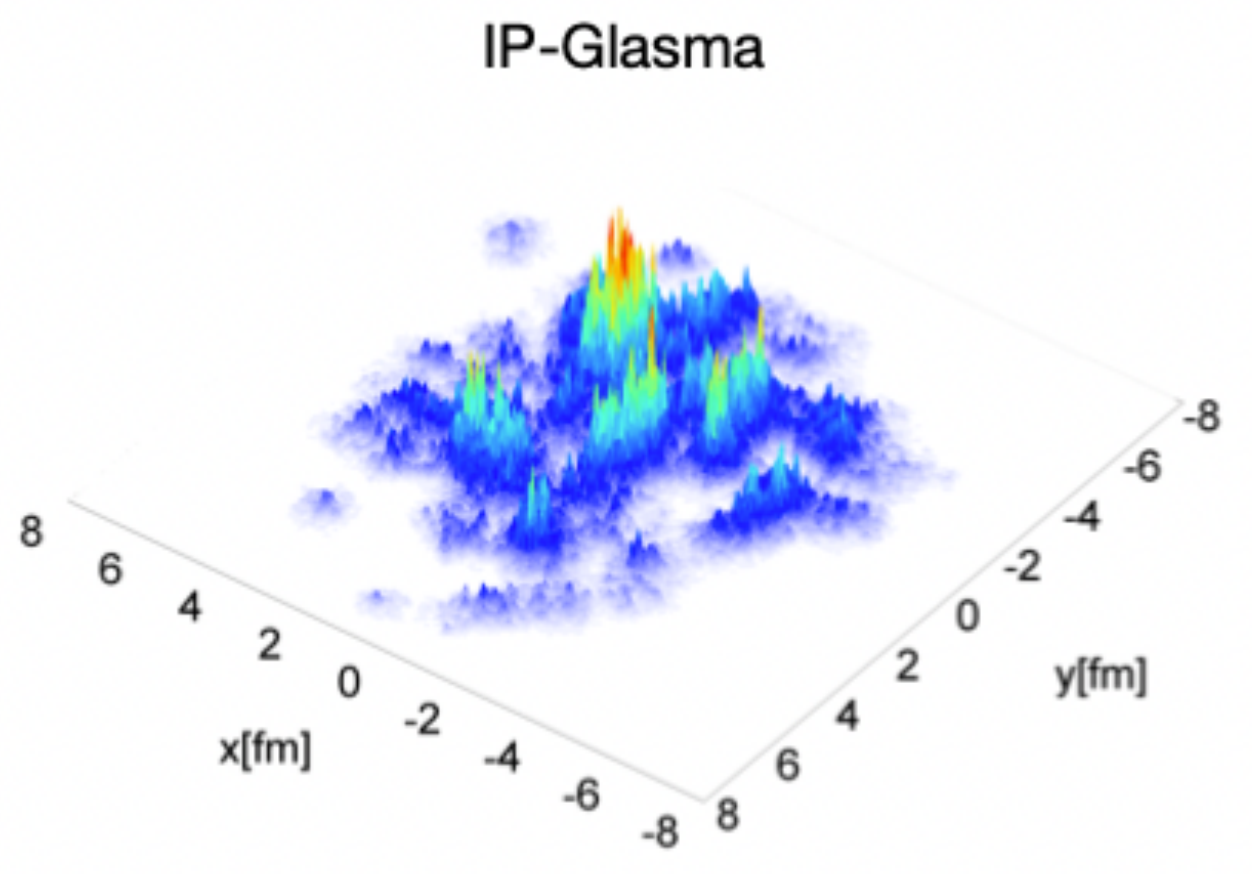
- Soft hadrons: $T < T_{\mathrm{frz}}$, indirect probe.
- EM probes ($\gamma/l\bar{l}$): $T > T_{\mathrm{frz}}$, direct probe.

iEBE-MUSIC Framework

$\tau = 0^+$ fm

Initial condition: IP-Glasma

- Color glass condensates.
- Evolved by Yang-Mills equations.



[Schenke, Tribedy & Venugopalan, PRL 108, 252301 (2012)]
[Schenke, Tribedy & Venugopalan, PRC 86, 034908 (2012)]

iEBE-MUSIC Framework

$\tau = 0^{+}$ fm

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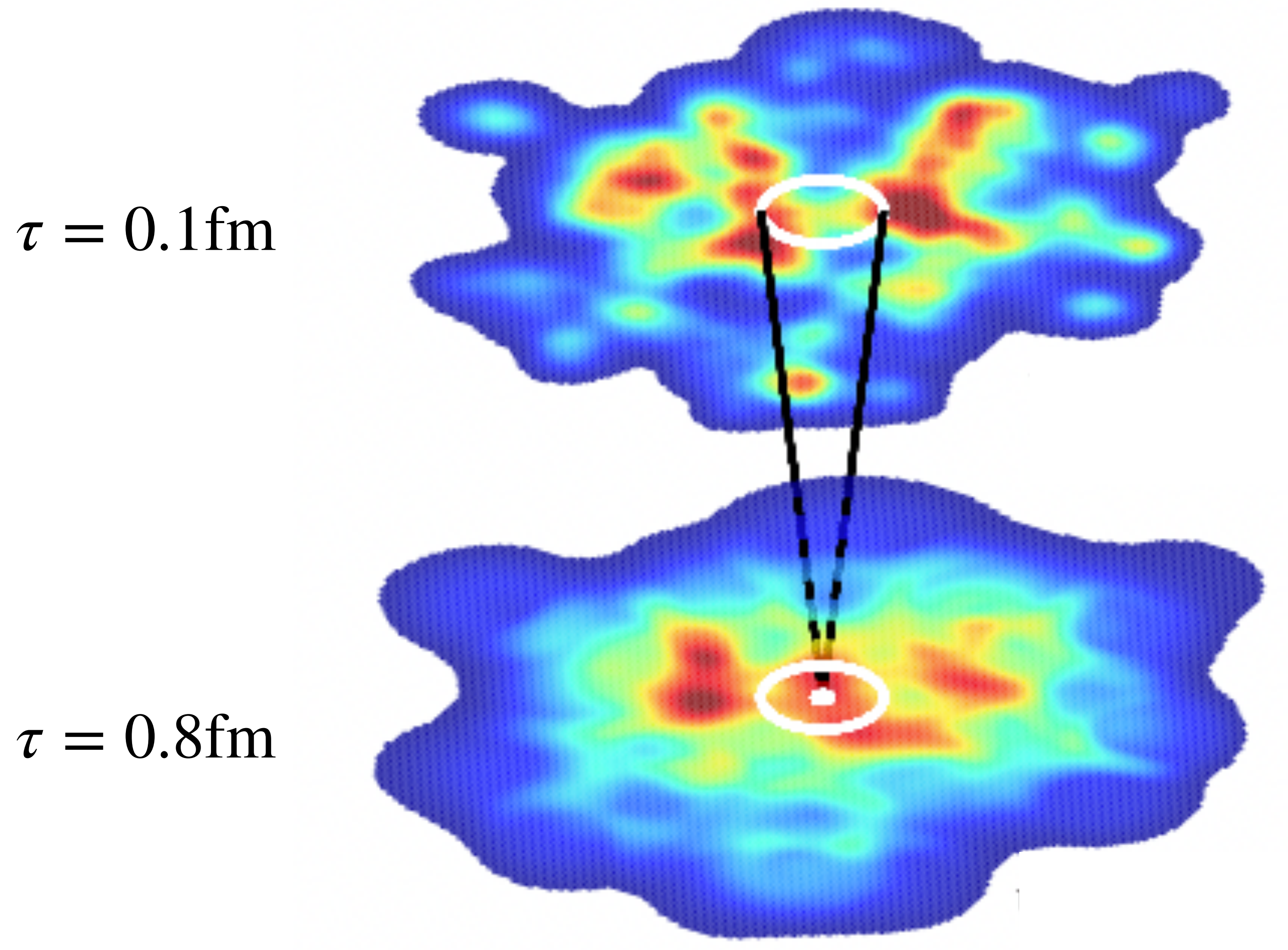
$\tau = 0.1$ fm

Pre-equilibrium stage: KøMPøST

$$T^{\mu\nu}(\tau, \mathbf{x}) = \bar{T}^{\mu\nu}(\tau, \mathbf{x}) + \delta T^{\mu\nu}(\tau, \mathbf{x})$$

- Background and perturbation.
- Kinetic theory scaling curve and linear response.



[Kurkela, Mazeliauskas, Paquet, Schlichting & Teaney, PRC 99, 034910 (2019)]
[Kurkela, Mazeliauskas, Paquet, Schlichting & Teaney, PRL122, 122302 (2019)]

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$\tau = 0.1$ fm

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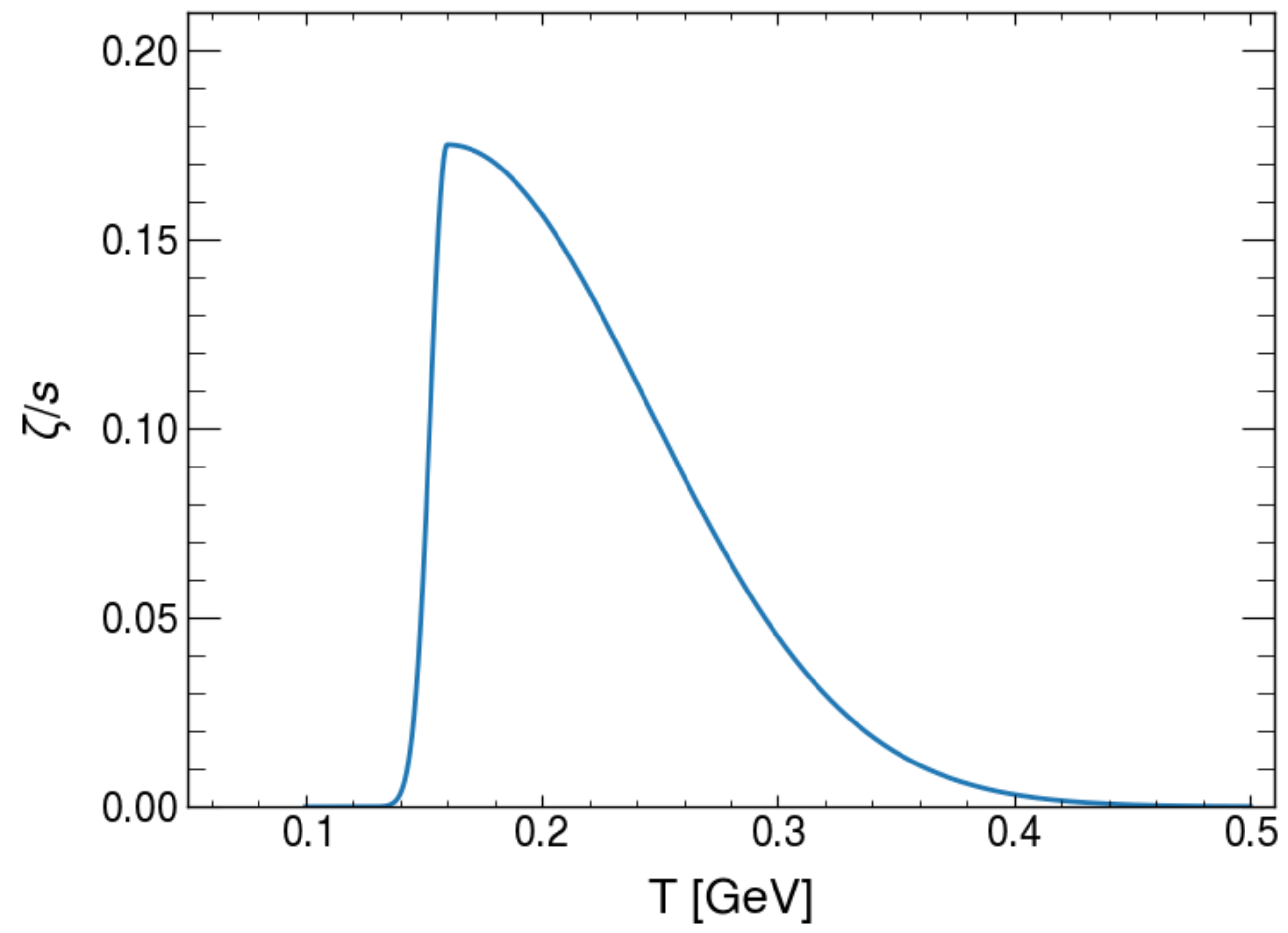
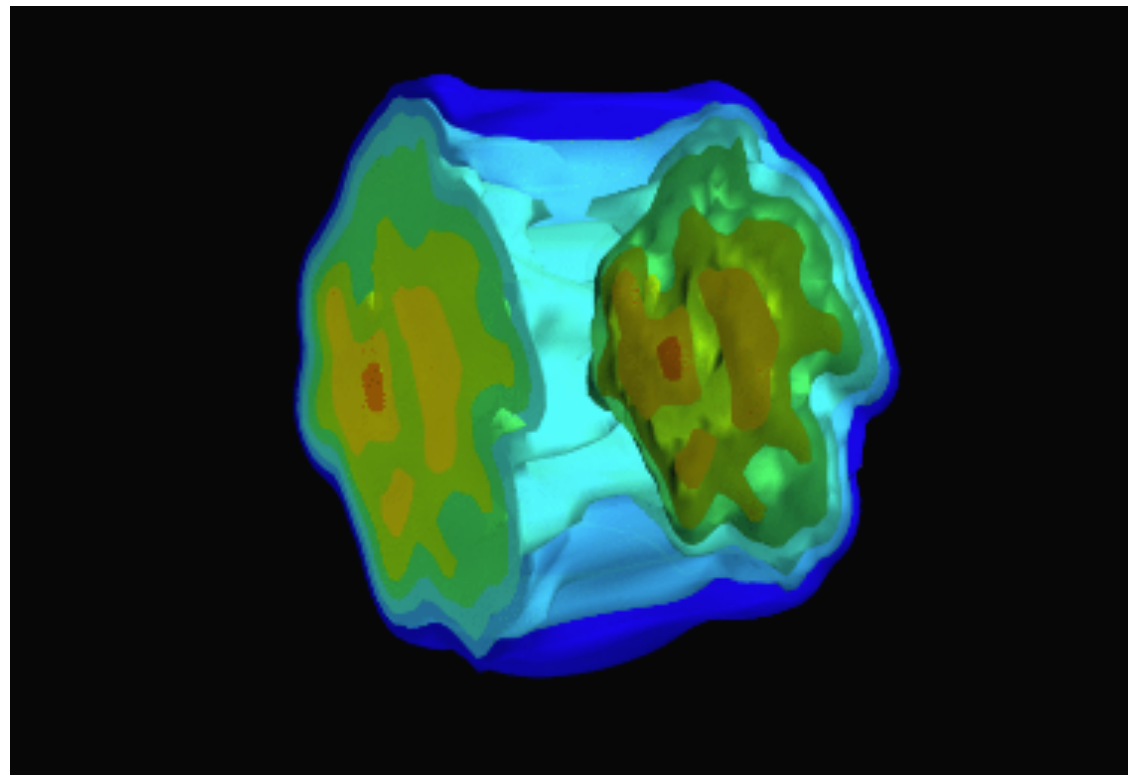
$\tau = 0.8$ fm

Hydrodynamic evolution: MUSIC

- (2+1)-D event-by-event 2^{nd} viscous hydrodynamics model.
- Shear viscosity $\eta/s = 0.12$ and bulk viscosity $\zeta/s(T)$.
- HotQCD+hadron gas equation of states.

$\tau \approx 10$ fm





[Paquet, Shen, Denicol, Luzum, Schenke, Jeon & Gale, PRC 93, 044906 (2016)]
[Schenke, Jeon & Gale, PRC 82, 014903 (2010)]
[Schenke, Jeon & Gale, PRL 106, 042301 (2011)]
[Gale, Paquet, Schenke & Shen, PRC 105, 014909 (2022)]

iEBE-MUSIC Framework

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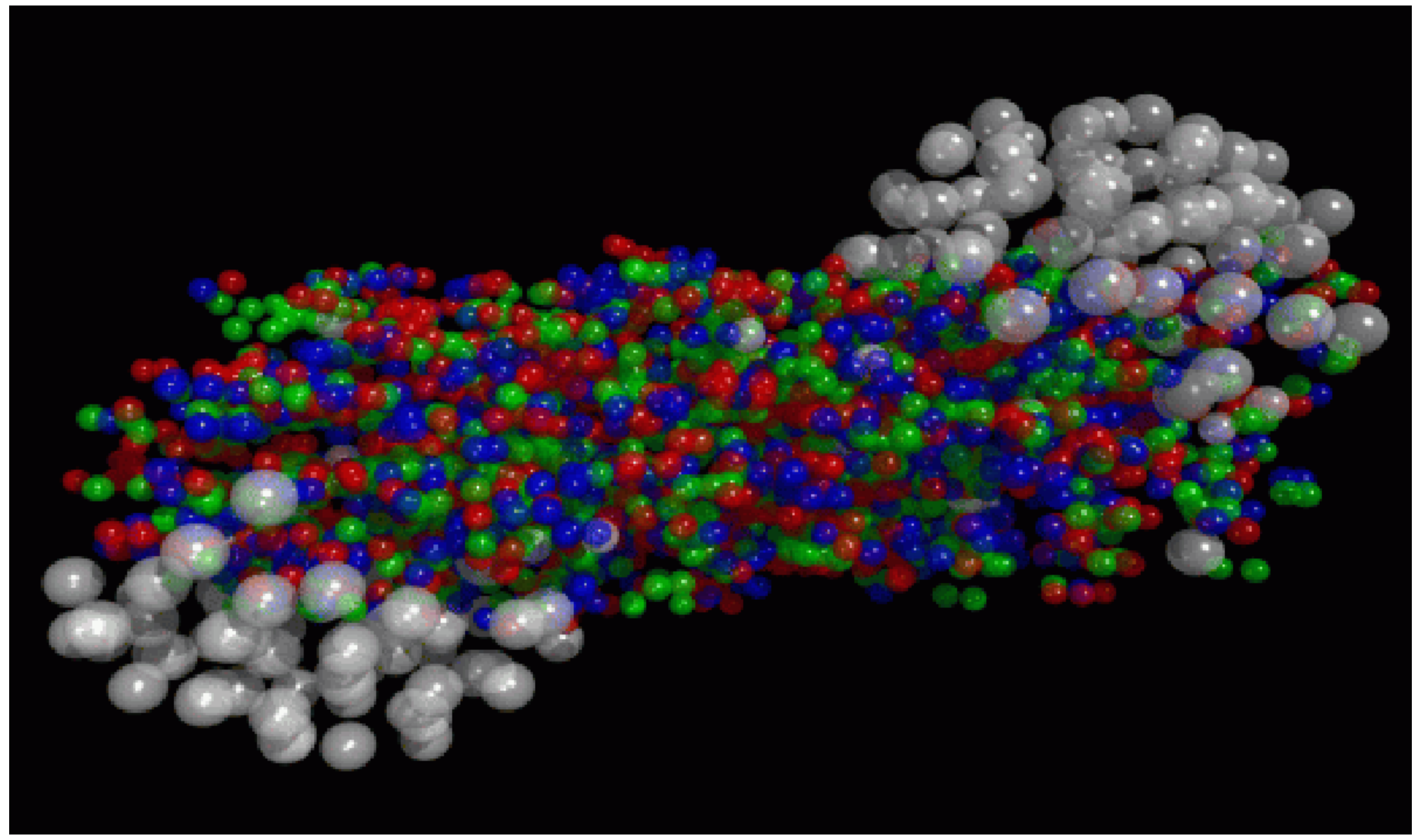
$\tau \approx 10$ fm

Hadronic cascade: URQMD

- Elastic collisions.
- Resonance formation and decays.



[S. A. Bass et al, Prog. Part. Nucl. Phys. 41, 255–369 (1998)]

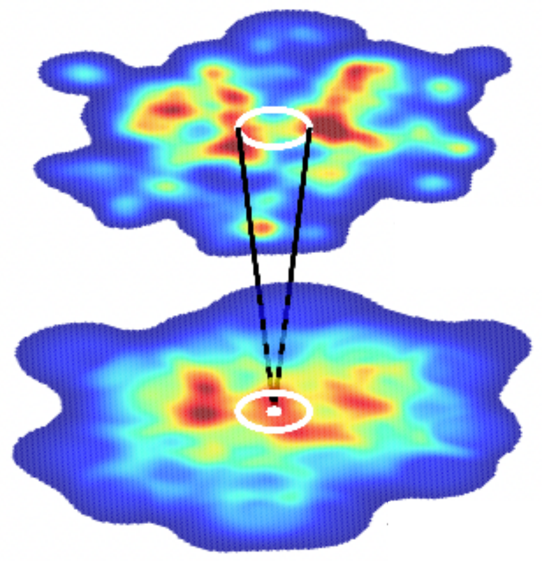
Model Calibration

- Hydrodynamic results agree well with hadron multiplicity in all centrality bins.
- Small discrepancy in mean transverse momentum $\langle p_T \rangle$ and anisotropic flow $v_n\{2\}$ originates from vanishing bulk viscosity in IP-Glasma and KøMPøST.
- The discrepancy increases in peripheral collision due to shorter lifetime in hydrodynamic phase.

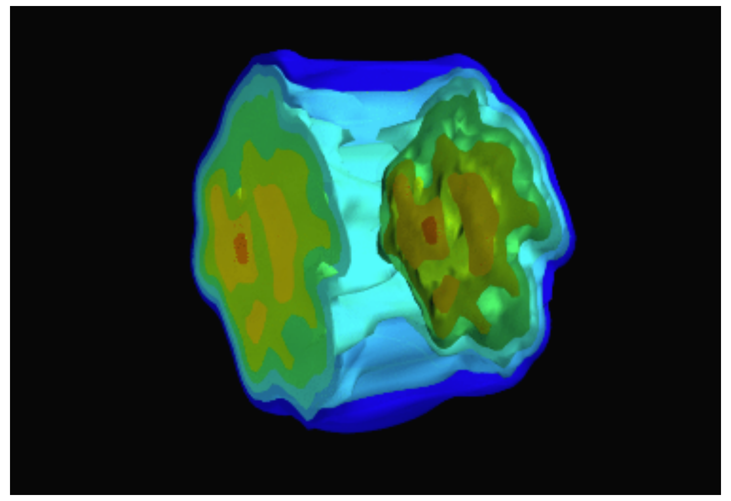
Dilepton Production

$\tau = 0^{+}$ fm — Initial condition: IP-Glasma

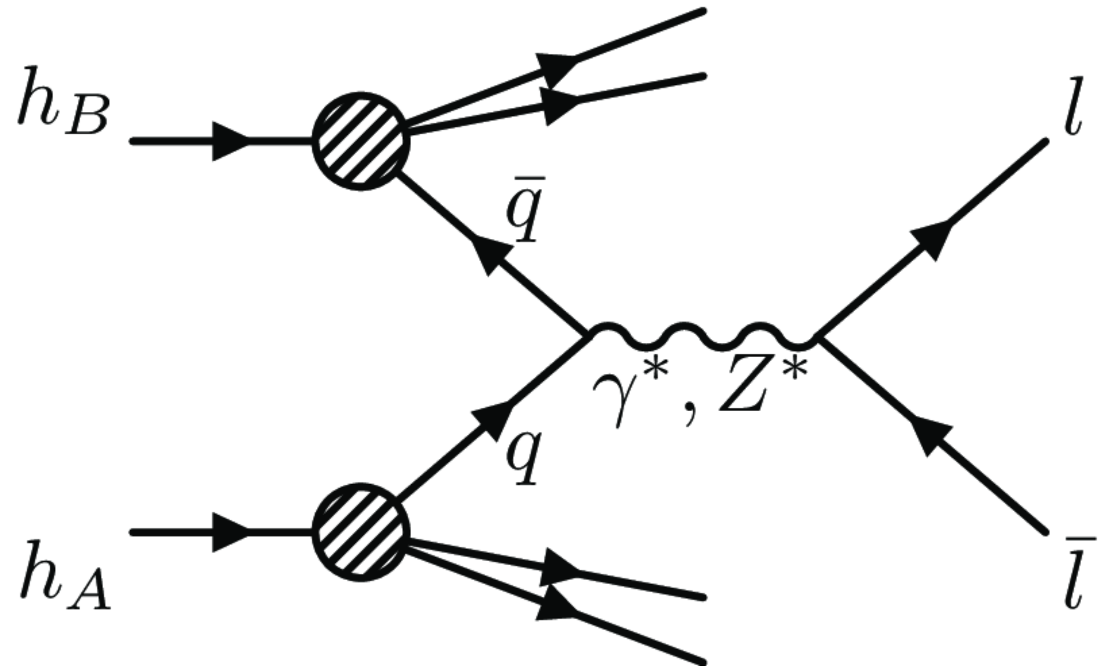
$\tau = 0.1$ fm — Pre-equilibrium stage: KøMPøST



$\tau = 0.8$ fm — Hydrodynamic evolution: MUSIC



$\tau \approx 10$ fm — Hadronic cascade: URQMD



Drell-Yan dilepton

DYTurbo package: NLO order in p+p collision.

In A+A collisions

$$\frac{dN_{ee}^{DY}}{dMdy} = \frac{d\sigma_{ee}^{DY;pp}}{dMdy} \cdot \frac{N_{coll}}{\sigma_{in}^{pp}}$$

nPDF: EPPS16nlo-CT14nlo-Pb208.

Thickness function: MC-Glauber.

[Camarda et al., EPJC 80, 251 (2020)]
[Eskola, Paakkinen, Paukkunen & Salgado, EPJC 77, 163 (2017)]
[Loizides, Kamin & Enterria, PRC 97, 054910 (2018)]

Dilepton Production

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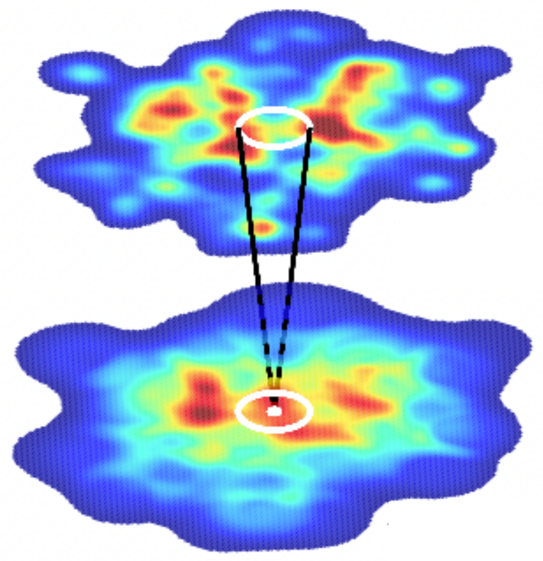
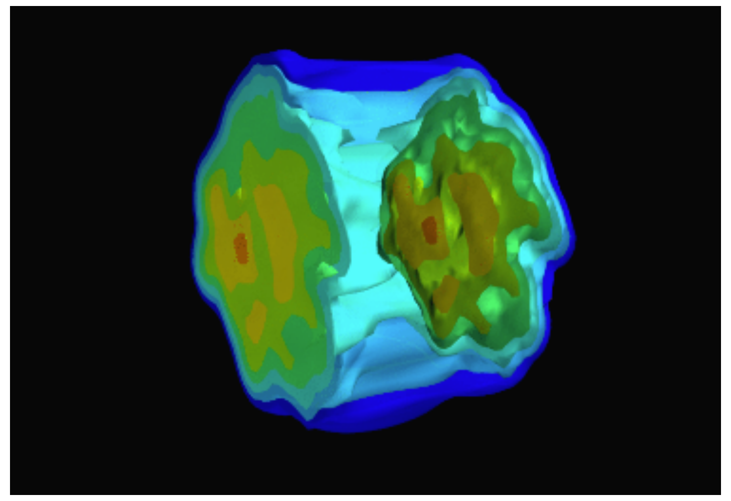
$\tau = 0.1$ fm — Pre-equilibrium stage: KøMPøST



$T(x), U^\mu(x)$

$\tau = 0.8$ fm — Hydrodynamic evolution: MUSIC

$T(x), U^\mu(x)$



$\tau \approx 10$ fm — Hadronic cascade: URQMD

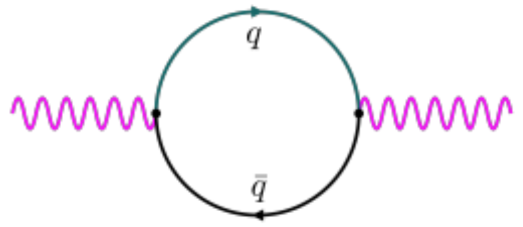
Drell-Yan dilepton

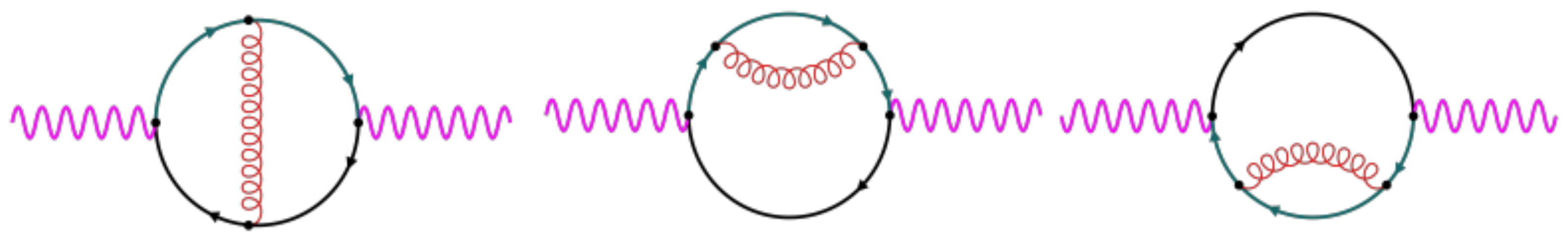
Thermal dilepton

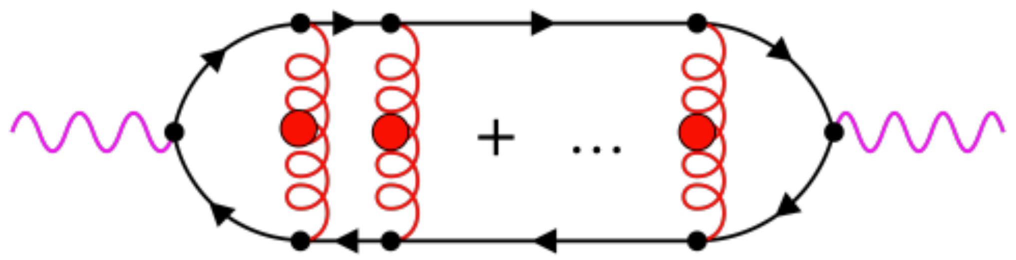
$$\frac{dN_{l\bar{l}}}{MdMdy'} = \int d^4x p'_T dp'_T d\phi' \frac{d\Gamma_{l\bar{l}}}{d^4P}\Bigg|_{P^\mu=\Lambda^\nu_\mu(U(X))P'^\nu}$$

$$\frac{dN_{l\bar{l}}}{p'_T dp'_T dy'} = \int d^4x MdMd\phi' \frac{d\Gamma_{l\bar{l}}}{d^4P}\Bigg|_{P^\mu=\Lambda^\nu_\mu(U(X))P''}$$

$\frac{d\Gamma_{l\bar{l}}}{d^4P}$: the differential dileption emission rate at NLO with finite μ_B.

LO  $\mathcal{O}(1)$

NLO  $\mathcal{O}(\alpha_s)$

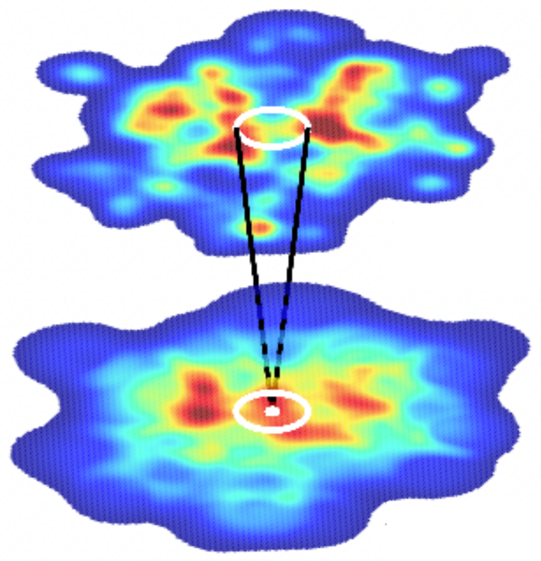
LPM  $\mathcal{O}(\alpha_s^i), \quad i \geq 2$

[Churchill, Du, Gale, Jackson & Jeon, PRC 109, 044915 (2024), PRL 132, 172301 (2024)]

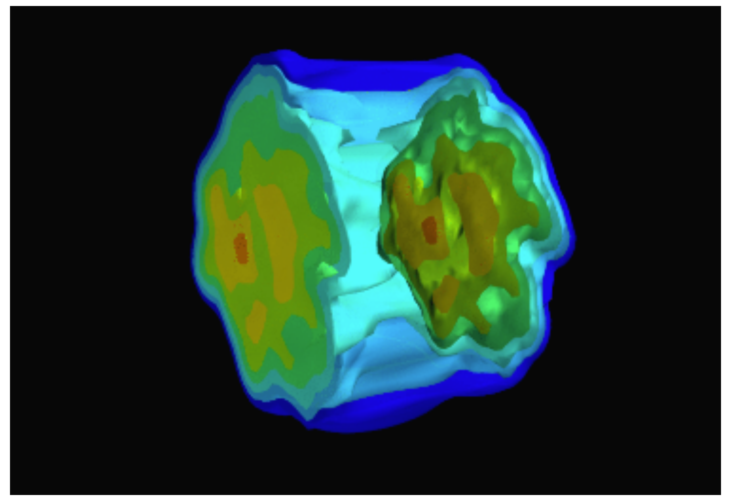
Dilepton Production

$\tau = 0^+$ fm — Initial condition: IP-Glasma

$\tau = 0.1$ fm — Pre-equilibrium stage: KøMPøST



$\tau = 0.8$ fm — Hydrodynamic evolution: MUSIC



$\tau \approx 10$ fm — Hadronic cascade: URQMD

$T(x)$, $U^\mu(x)$

$T(x)$, $U^\mu(x)$

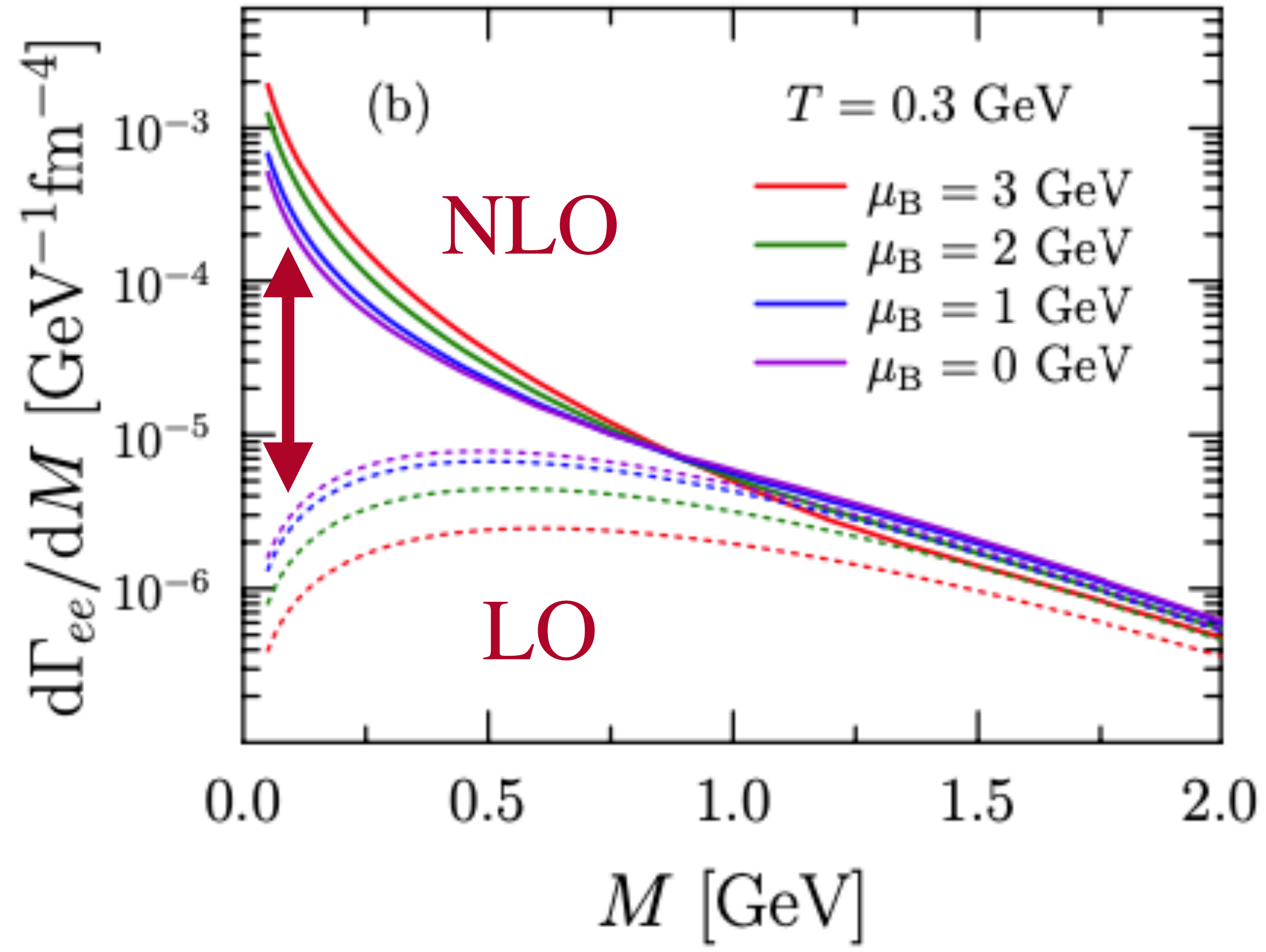
Drell-Yan dilepton

Thermal dilepton

$$\frac{dN_{l\bar{l}}}{MdMdy'} = \int d^4x p'_T dp'_T d\phi' \frac{d\Gamma_{l\bar{l}}}{d^4P}\bigg|_{P^\mu = \Lambda^\nu_\mu(U(X))P'^\nu}$$

$$\frac{dN_{l\bar{l}}}{p'_T dp'_T dy'} = \int d^4x MdMd\phi' \frac{d\Gamma_{l\bar{l}}}{d^4P}\bigg|_{P^\mu = \Lambda^\nu_\mu(U(X))P''}$$

$\frac{d\Gamma_{l\bar{l}}}{d^4P}$: the differential dileption emission rate at NLO with finite μ_B.

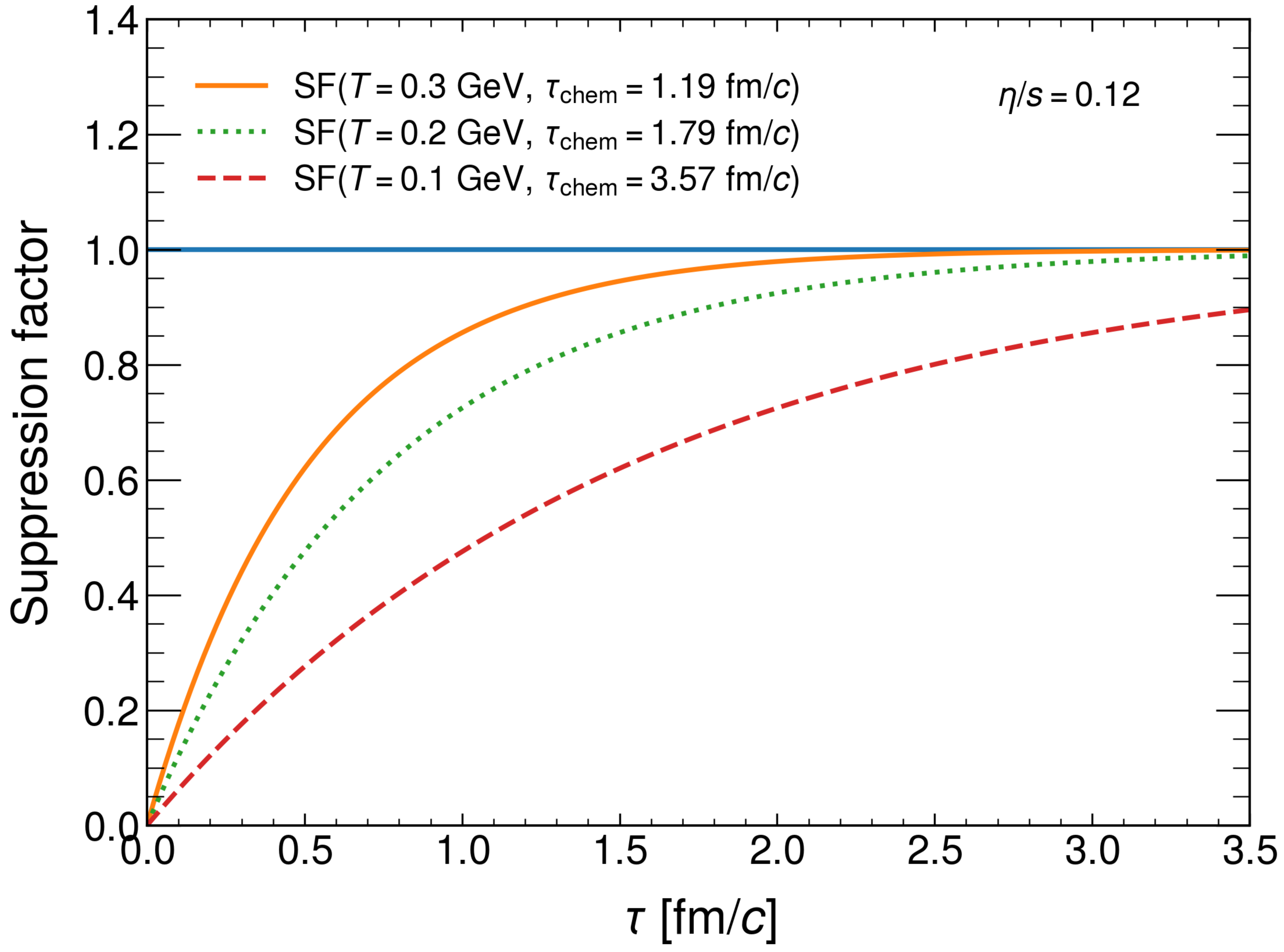


[Churchill, Du, Gale, Jackson & Jeon, PRC 109, 044915 (2024), PRL 132, 172301 (2024)]

[Kurkela & Mazeliauskas, PRL 122, 142301 (2019), PRD 99, 054018 (2019)]

Chemical Equilibrium

- The gluon fields dominate in the early stage.
- Quarks and anti-quarks are produced via $gg \to q\bar{q}$ and $g \to q\bar{q}$.
- The effective suppression factor $\mathrm{SF}(T, \tau)$ is introduced in relation to chemical relaxation time $\tau_R = 4\pi\eta/Ts$.

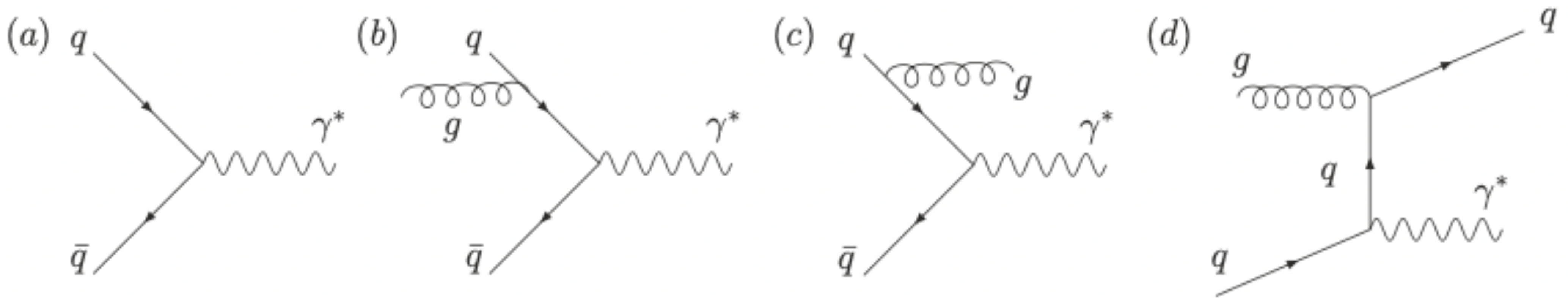


Systems with higher temperatures reach chemical equilibrium faster than those at lower temperatures.

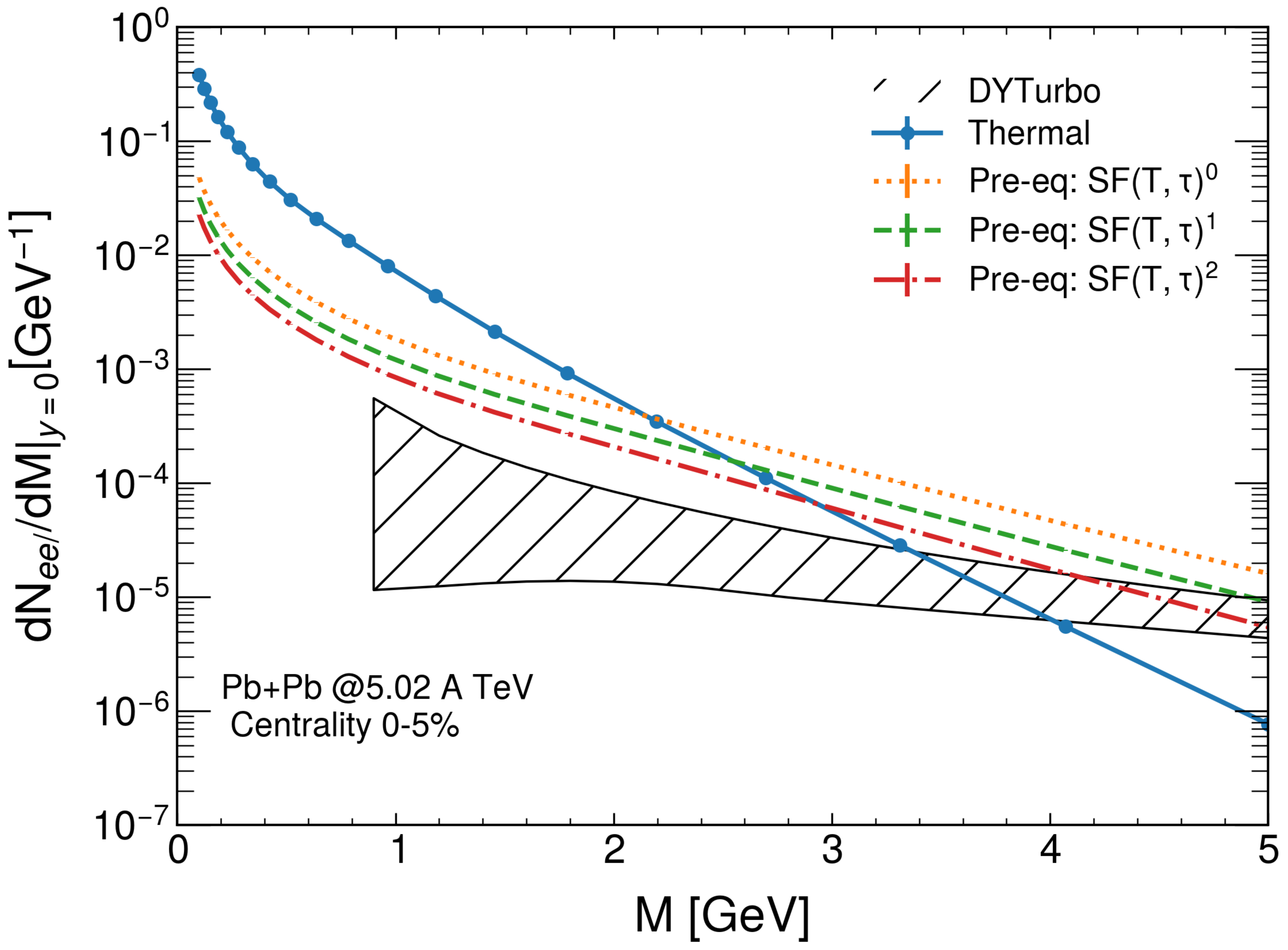
$$\frac{dN_{l\bar{l}}}{MdMdy'} = \int dV\, \mathrm{SF}(T,\tau)^n \frac{d\Gamma_{l\bar{l}}}{d^4P}\bigg|_{P^\mu = \Lambda^\nu_\mu(U(X))P'^\nu} p'_T dp'_T d\phi'$$

$$\frac{dN_{l\bar{l}}}{p'_T dp'_T dy'} = \int dV\, \mathrm{SF}(T,\tau)^n \frac{d\Gamma_{l\bar{l}}}{d^4P}\bigg|_{P^\mu = \Lambda^\nu_\mu(U(X))P''} MdMd\phi'$$

Here $n = 0,1,2$.



Dilepton M spectrum

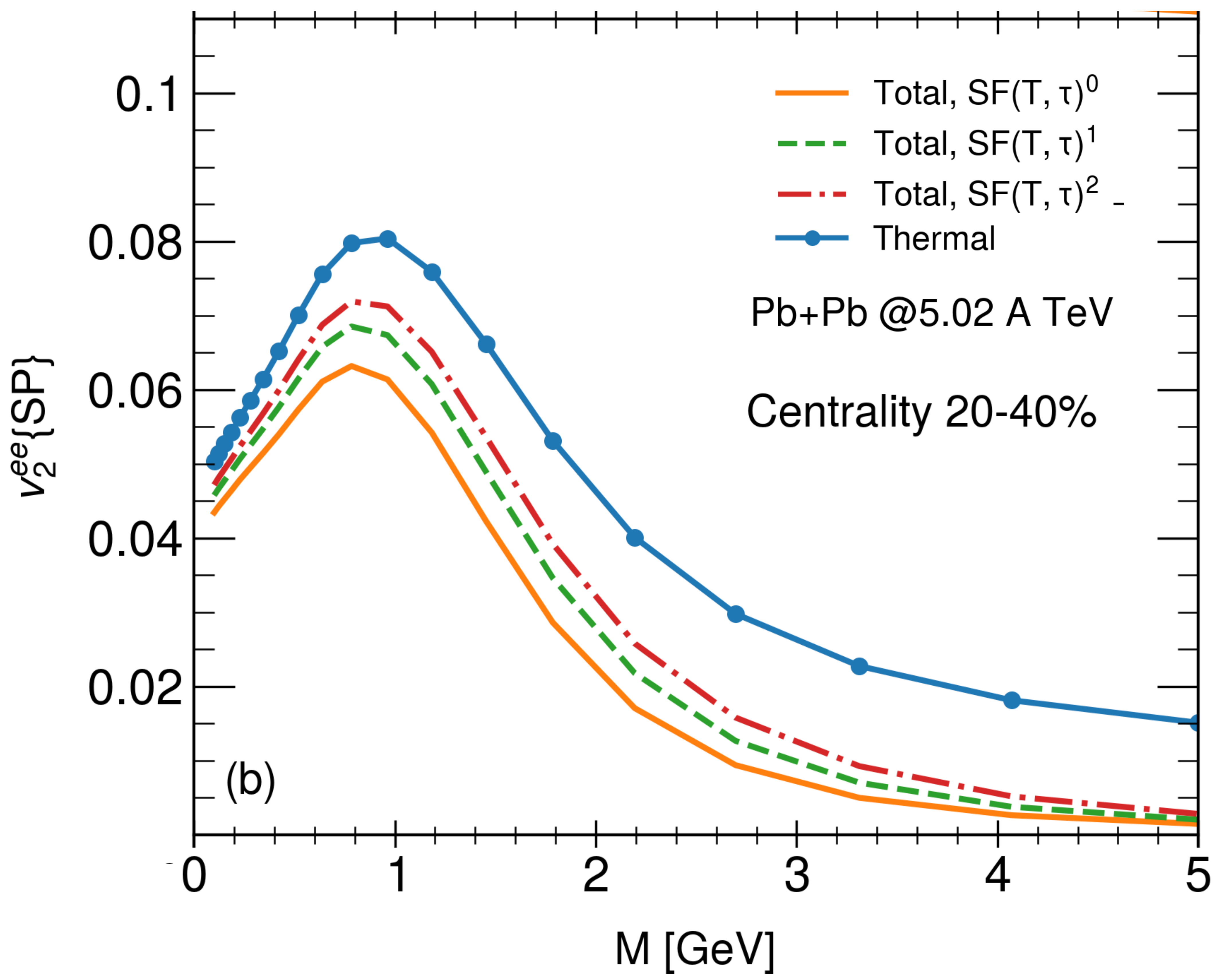


- Thermal dilepton production dominates in the low-mass region (LMR).
- The pre-equilibrium dileptons are the dominant source over thermal dileptons in the intermediate mass region (IMR).
- Drell-Yan dileptons are consistently smaller than the pre-equilibrium contribution until the high-mass region (HMR).
- Dilepton production during the pre-equilibrium phase will be sensitive to the power of suppression factor for chemical equilibrium.

Oscar's Talk@Tue 9:00AM.

[Oscar Garcia-Montero, Philip Plaschke, Sören Schlichting, e-Print: 2403.04846 [hep-ph]]

Dilepton $v_n^{ee}\{SP\}(M)$



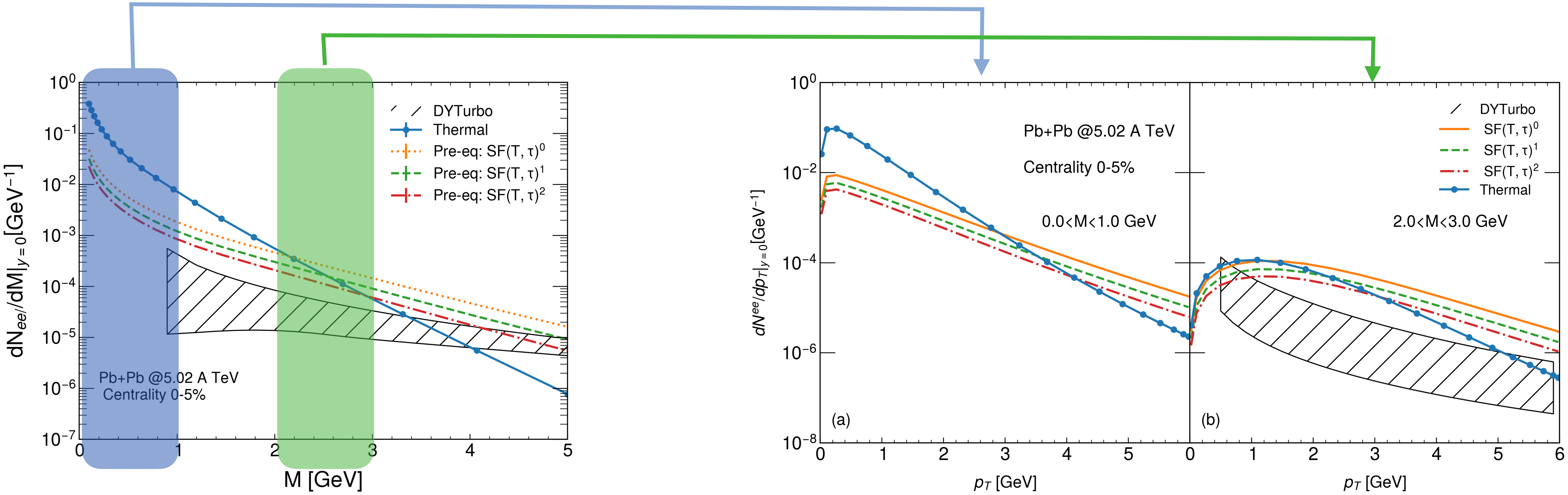
- The scalar-product (SP) method:

$$v_n^{l\bar{l}}\{\mathrm{SP}\}(X) = \frac{\left\langle v_n^{l\bar{l}}(X) v_n^h \cos\left\{ n\left[\Psi_n^{l\bar{l}}(X) - \Psi_n^h\right]\right\}\right\rangle}{\sqrt{\left\langle \left(v_n^h\right)^2\right\rangle}}$$

- The total $v_2^{ee}(M)$ will be suppressed due to the almost zero momentum anisotropy in the pre-equilibrium stage.

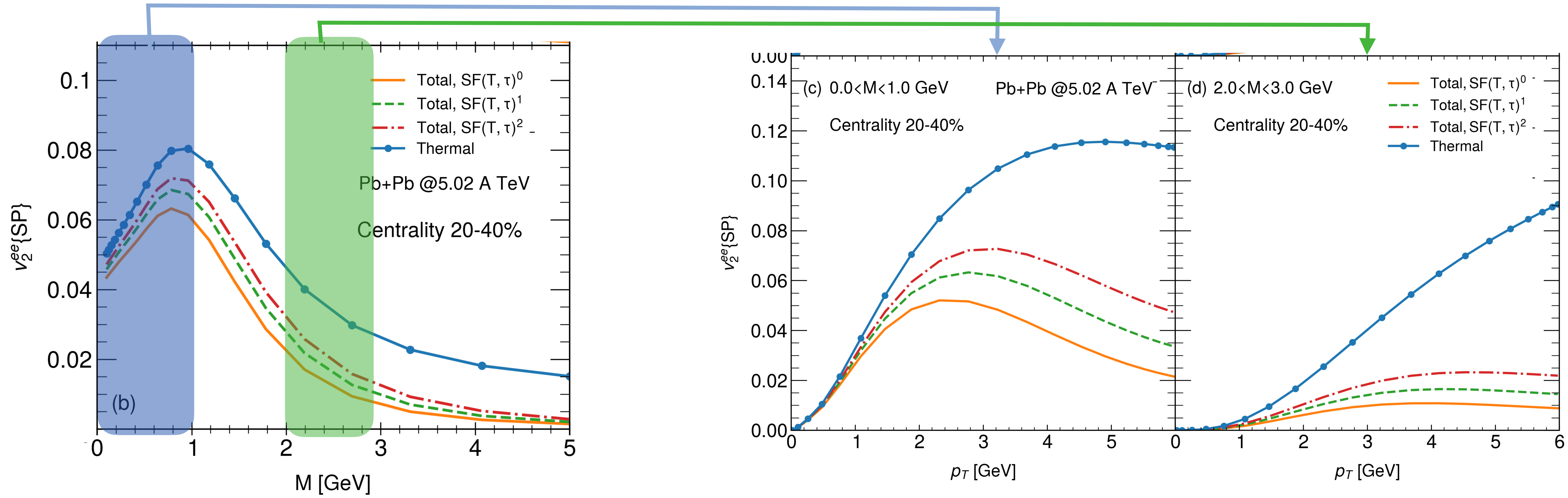
- For the higher order of the suppression factor, the total dilepton flow $v_2^{ee}(M)$ moves closer to that of thermal dileptons.

Dilepton p_T spectra



- By carefully selecting the invariant mass window, it is possible to reveal the pre-equilibrium stage.
- $0 < M < 1$ GeV:
  - the thermal dilepton production dominates at low p_T region.
  - dilepton from the pre-equilibrium stage becomes dominant from intermediate p_T region.
- $2 < M < 3$ GeV:
  - the pre-equilibrium dilepton is comparable to thermal dilepton production in the low p_T region.
  - the pre-equilibrium dilepton consistently exceeds both thermal dilepton and Drell-Yan dilepton production.

Dilepton $v_n^{ee}\{SP\}(p_T)$



- Total elliptic flow $v_2^{ee}(p_T)$ is highly sensitive to the effects of chemical equilibrium.
- $0 < M < 1$ GeV:
  - after considering the pre-equilibrium stage, the total dilepton flow $v_2^{ee}(p_T)$ is significantly suppressed.
- $2 < M < 3$ GeV:
  - the total dilepton elliptic flow $v_2^{ee}(p_T)$ shows a noticeable reduction compared to that in the IMR.

Summary

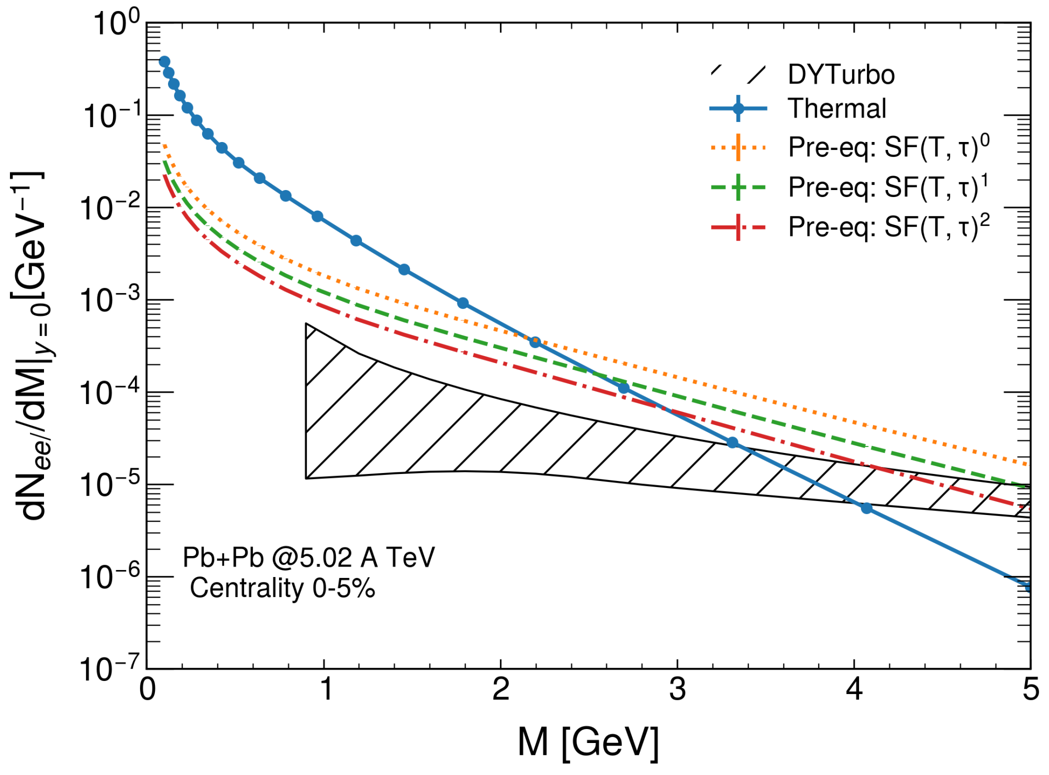
- Dilepton observables offer an opportunity to explore quark production of the pre-equilibrium stage.

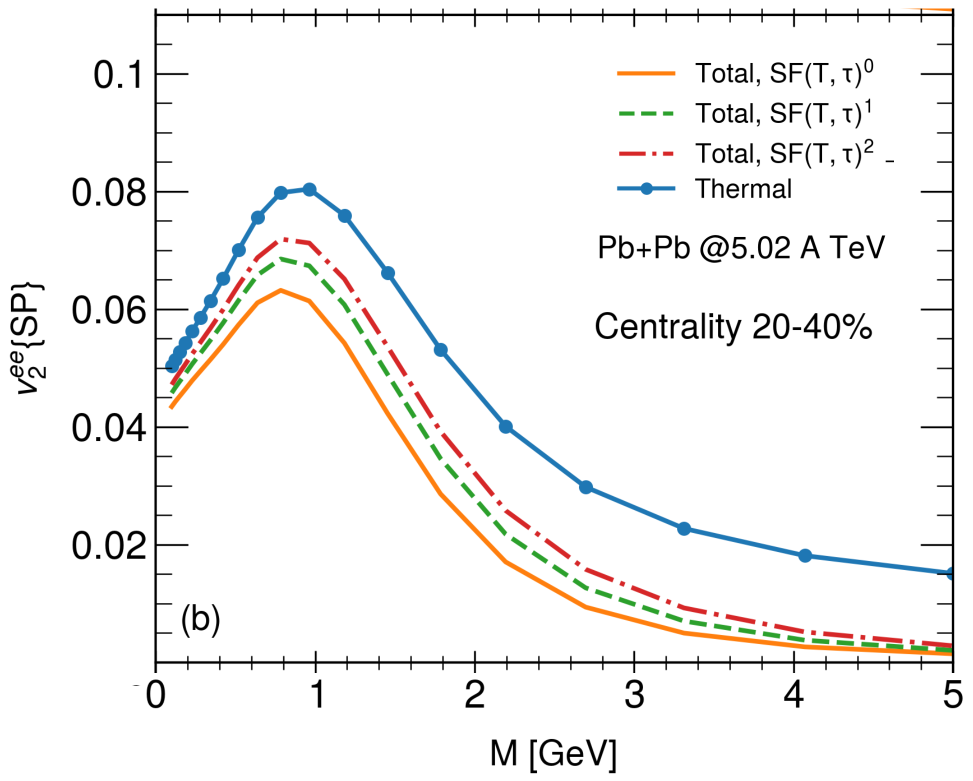
- Dilepton flow could help constrain the effects of chemical equilibrium during the pre-equilibrium stage in the future.

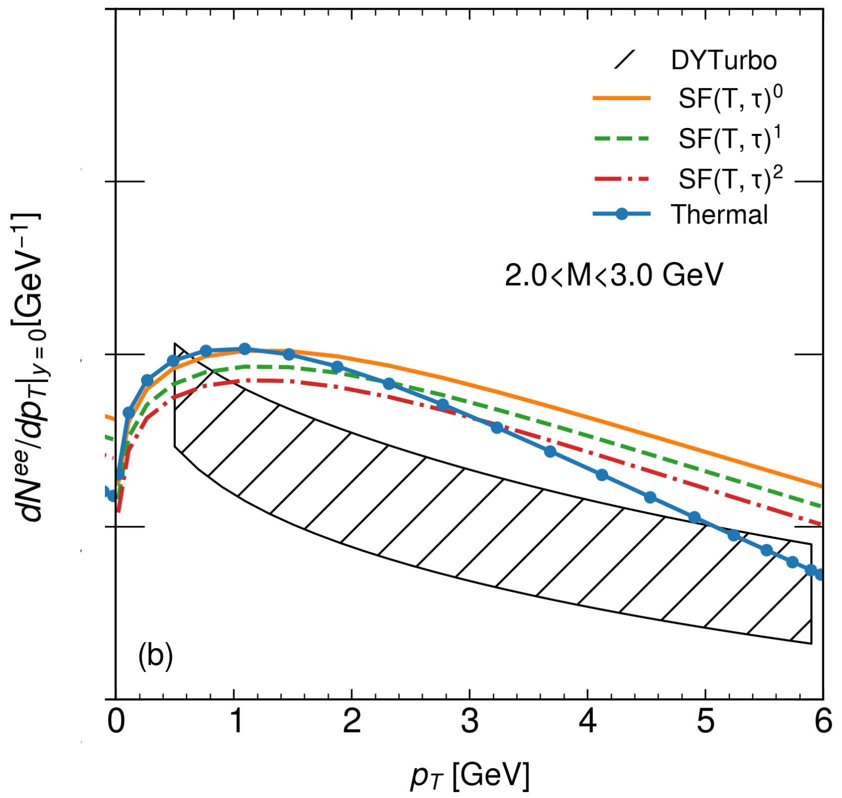
- An analysis of thermal dilepton production and anisotropic flow based on NLO order emission rate is performed in Pb+Pb collisions at a LHC collision energy of $\sqrt{s_{NN}} = 5.02$ TeV.

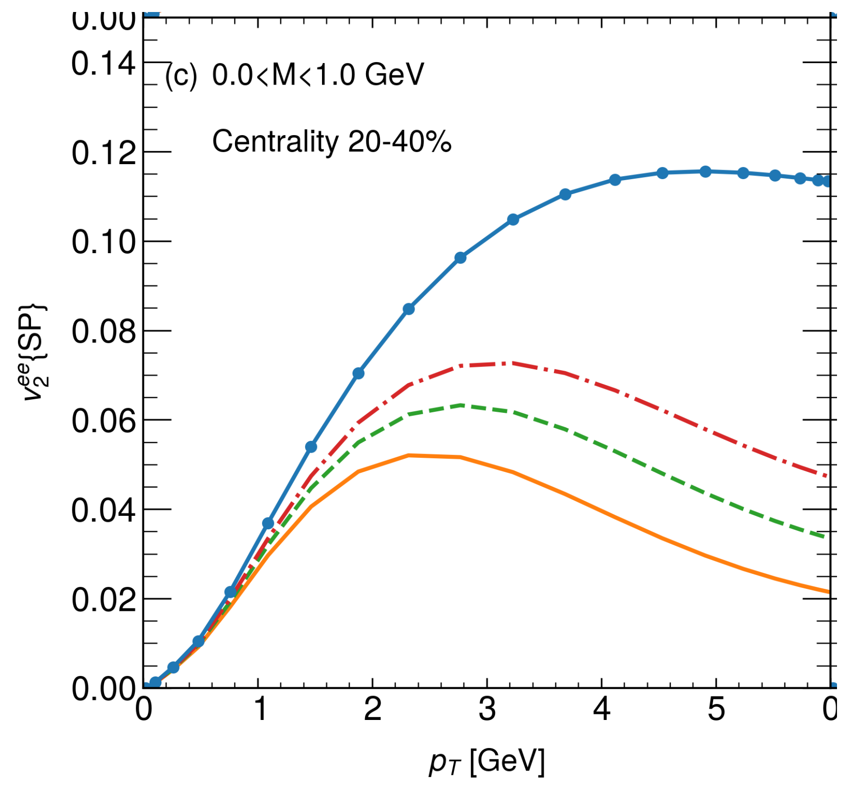
- The pre-equilibrium dilepton contribution dominates in the IMR, exceeding both Drell-Yan and thermal dilepton production.

- Dilepton production is slightly affected by chemical equilibrium.



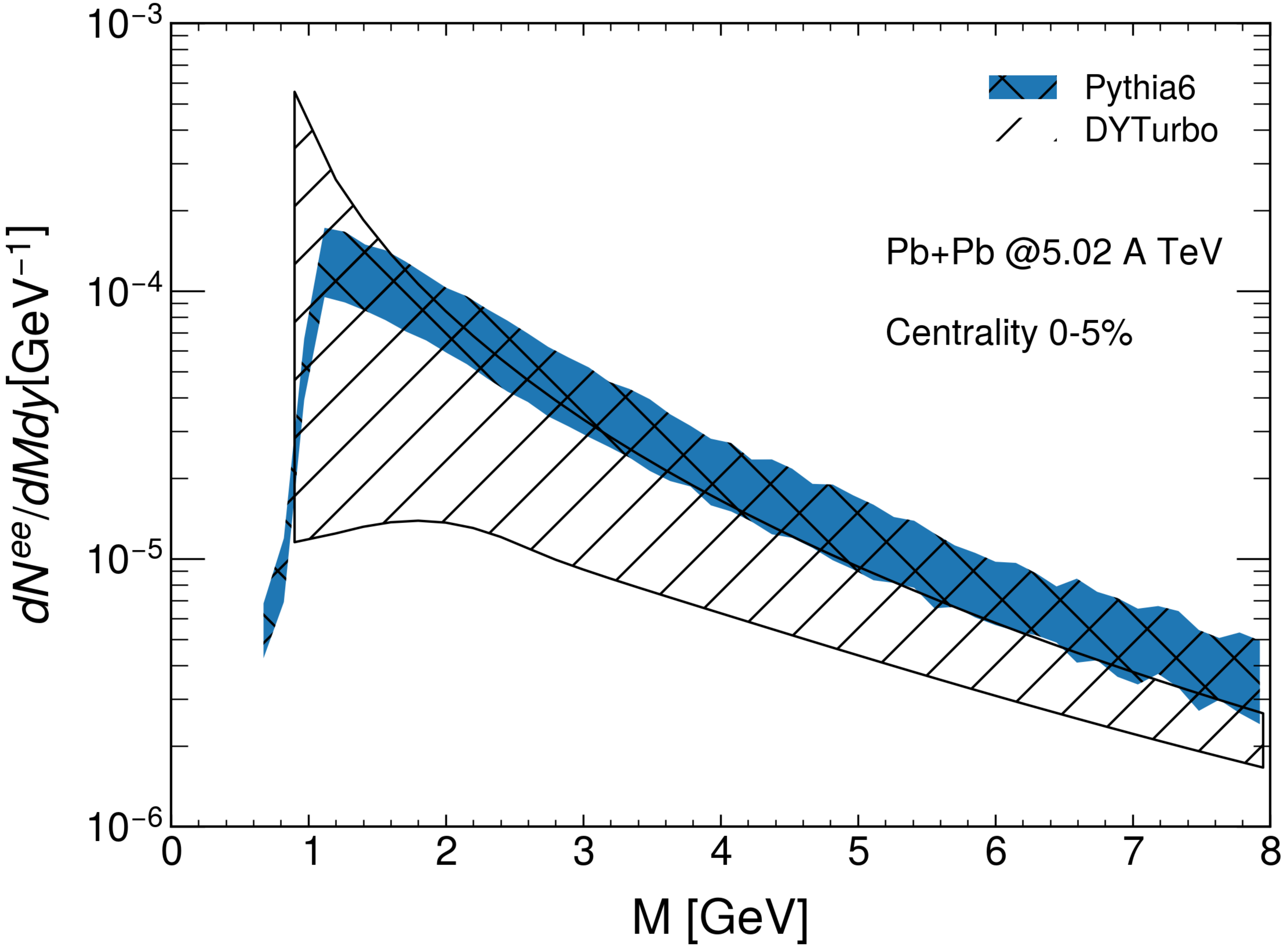






Backup

DYTurbo vs Pythia 6



Pythia 6:

PDF CTEQ5L

Bands: K factor, effectively account for higher order corrections.

DYTurbo:

Bands:

NLO, factorization and renormalization scales.

Upper limits: $2m_{ll}$, lower limit: $0.5m_{ll}$.

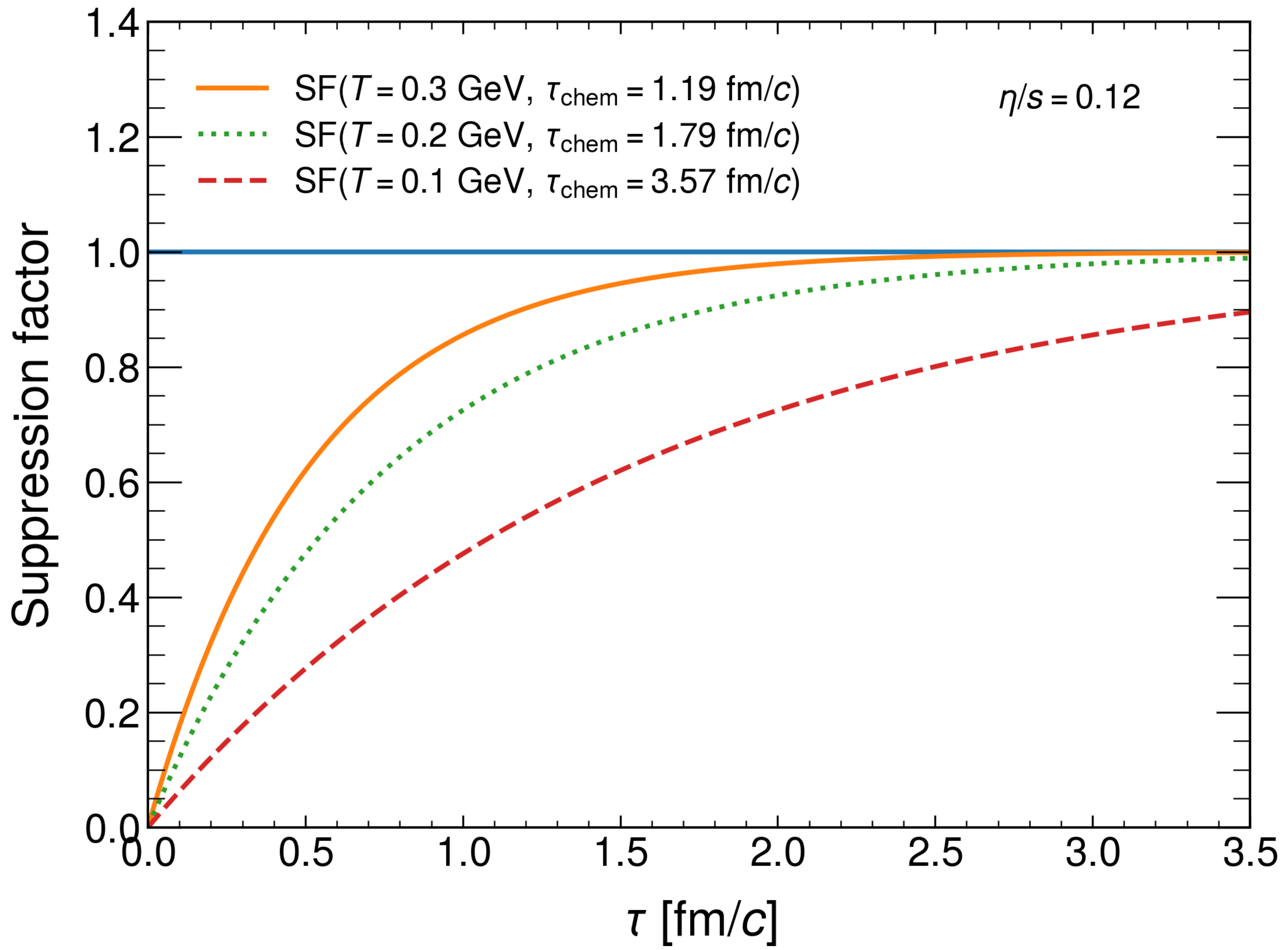
Parton distribution functions and fragmentation functions limits scale $Q \sim 1\mathrm{GeV}$.

Chemical Equilibrium

Introduce an effective suppression factor (SF) to include the process of the establishment of chemical equilibrium

$$\mathrm{SF}(T,\tau) = 1 - e^{-A\frac{\tau}{\tau_R(T)}}$$

with chemical relaxation time $\tau_R = 4\pi\eta/Ts$

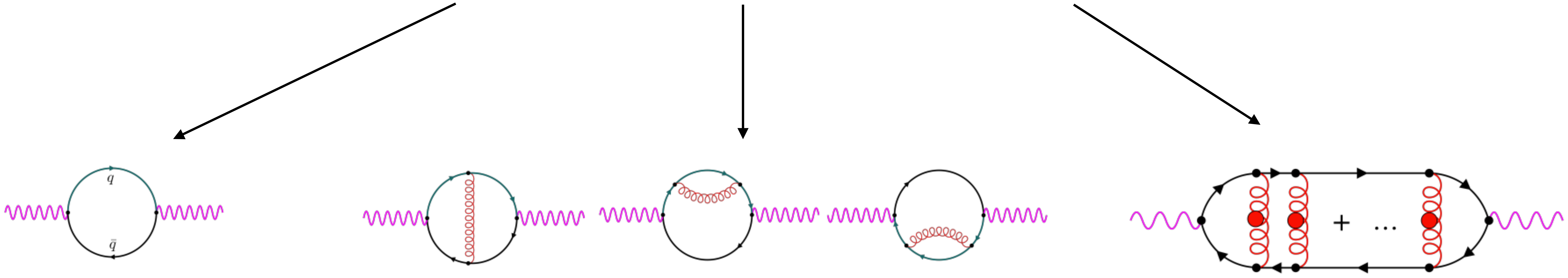


The chemical equilibrium is found to be $\tau_{\mathrm{chem}} = 1.2\tau_R$. The constant A can bedetermined by requiring $\mathrm{SF}\left(\tau_{\mathrm{chem}}\right) = 0.9$.

[Kurkela & Mazeliauskas, PRL 122, 142301 (2019), PRD 99, 054018 (2019)]

How to combine NLO and LPM

$$\rho_i\Big|^{\text{resummed}}_{\text{NLO}} \equiv \rho_i\Big|^{\text{strict}}_{1-\text{ loop}} + \rho_i\Big|^{\text{strict}}_{2-\text{ loop}} + \left(\rho_i\Big|^{\text{full}}_{\text{LPM}} - \rho_i\Big|^{\text{expanded}}_{\text{LPM}}\right)$$



LO

$\mathcal{O}(1)$

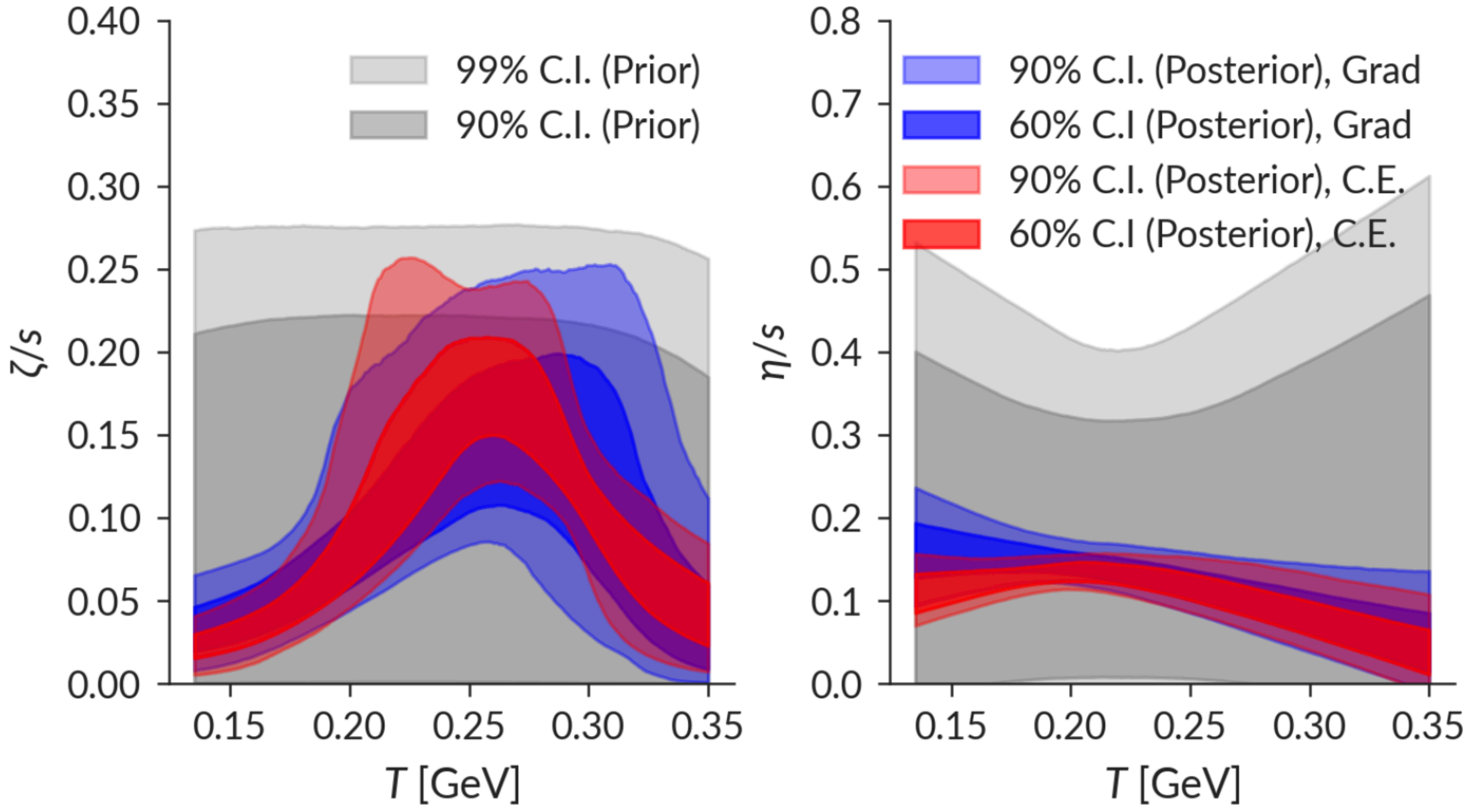
NLO

$\mathcal{O}\left(\alpha_s\right)$

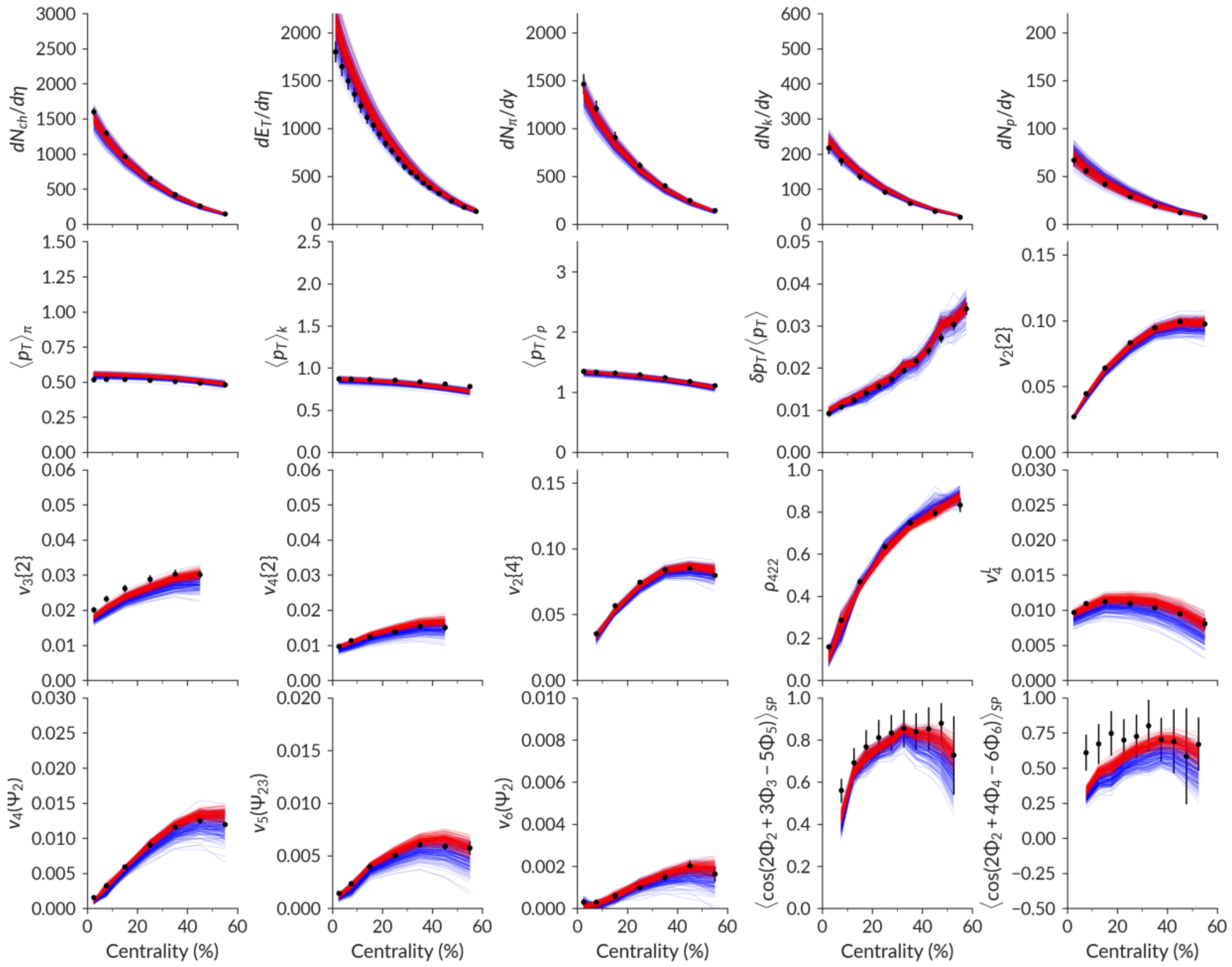
LPM

$\mathcal{O}\left(\alpha_s^i\right), \quad i \geq 2$

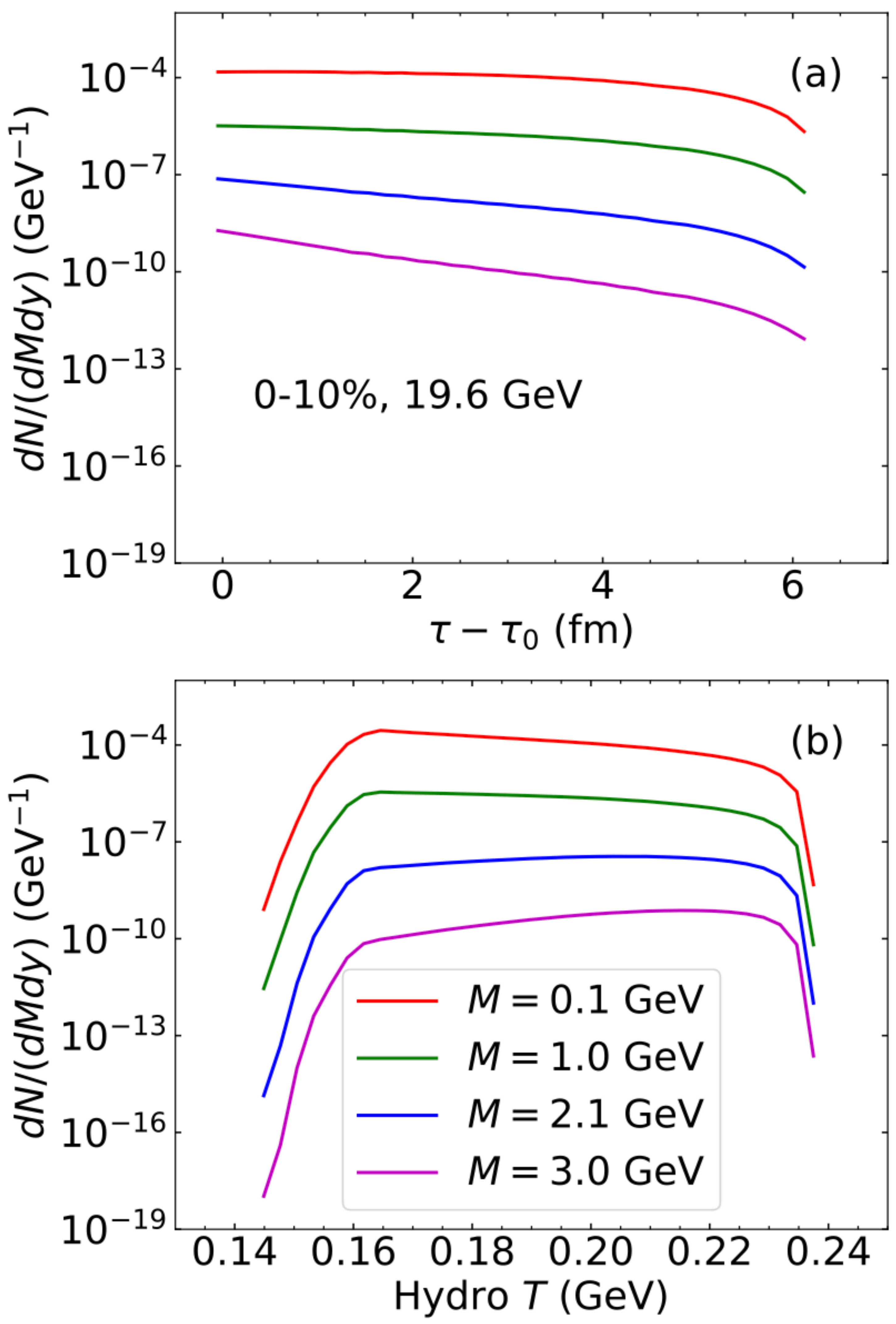
Model



99% C.I. (Prior)
90% C.I. (Prior)
90% C.I. (Posterior), Grad
60% C.I (Posterior), Grad
90% C.I. (Posterior), C.E.
60% C.I (Posterior), C.E.
ζ/s
η/s
T [GeV]

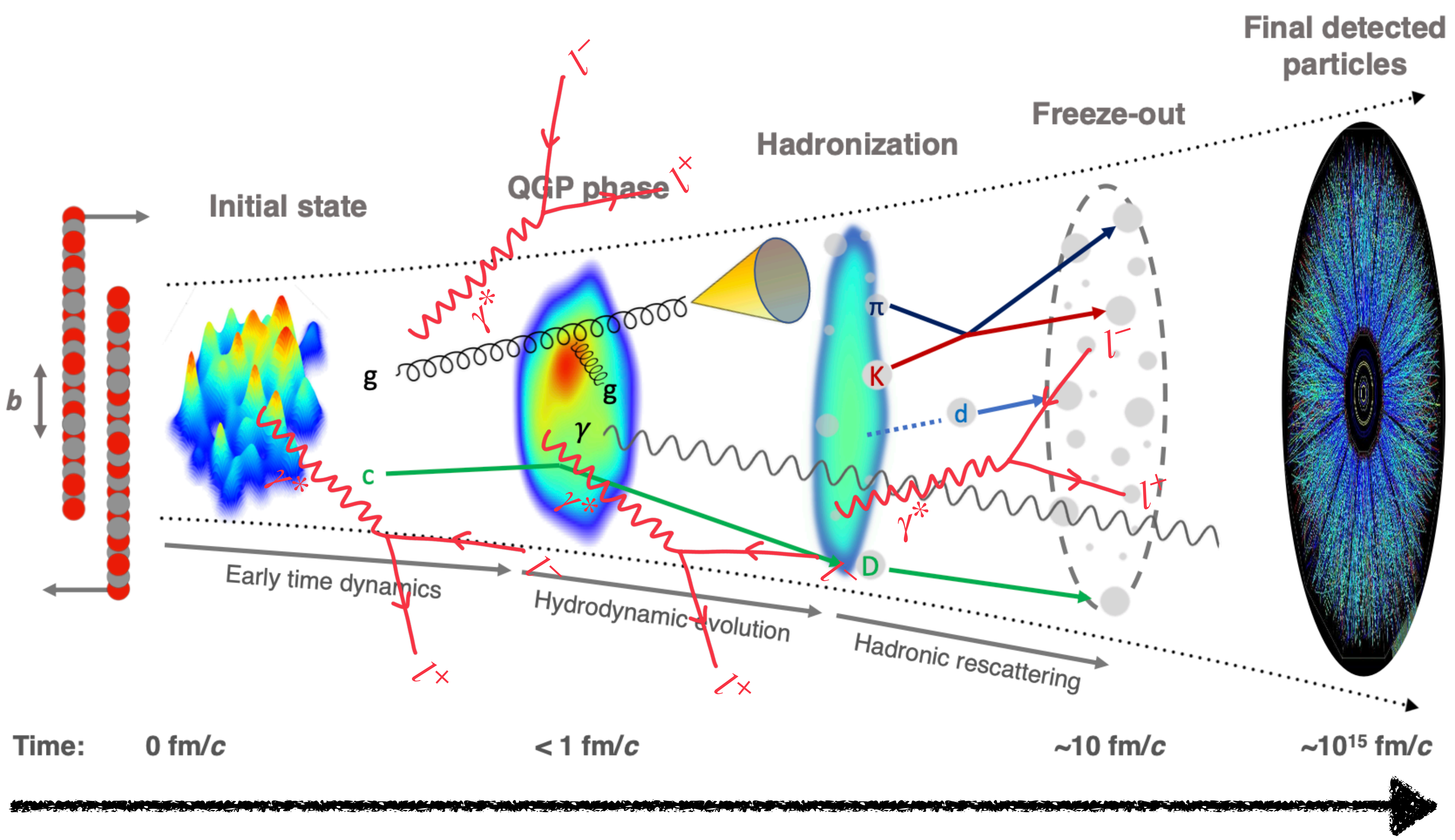


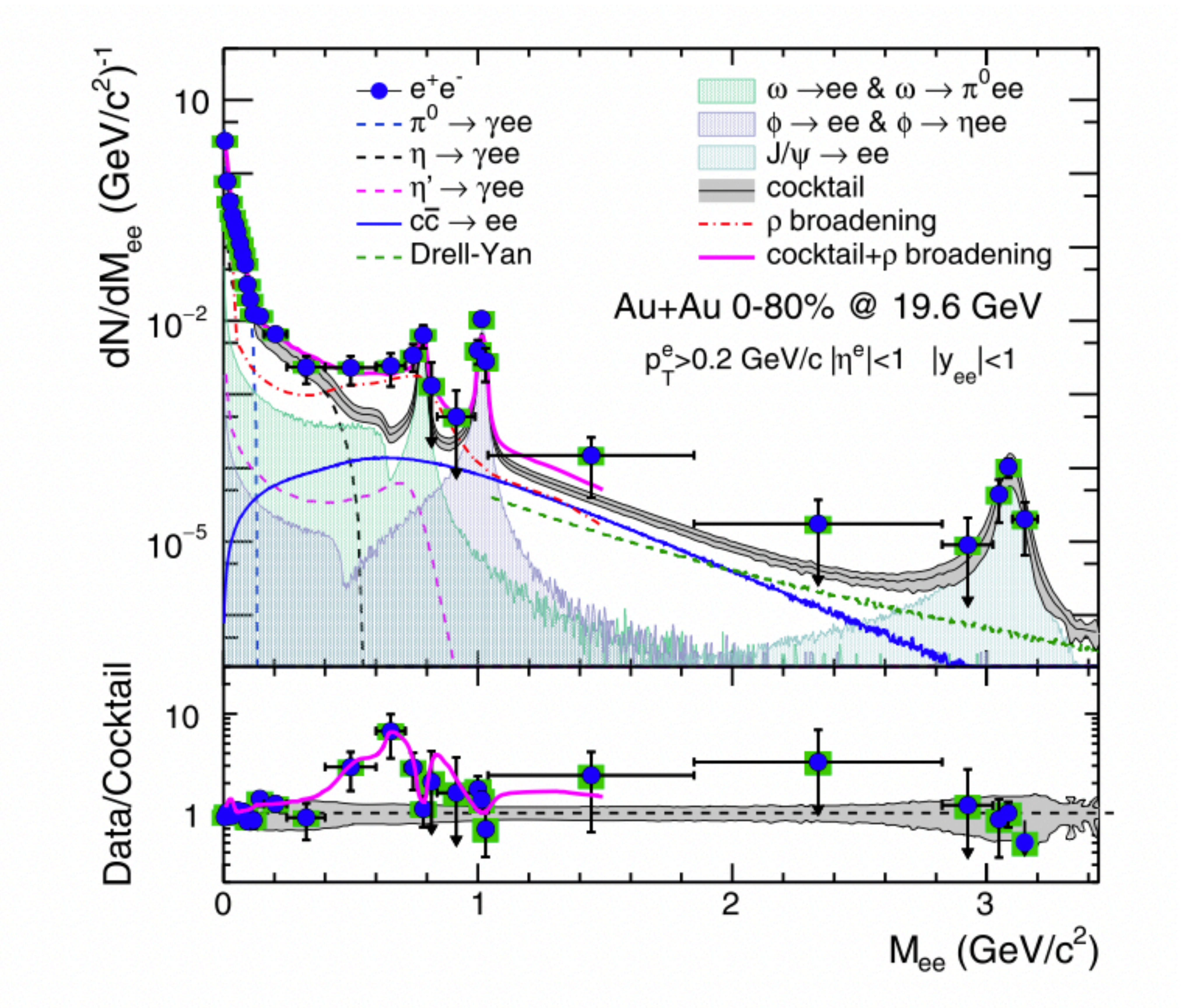
Centrality (%)



(a)
0-10%, 19.6 GeV
$dN/(dMdy)$ (GeV^{-1})
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
0
2
4
6
$\tau - \tau_0$ (fm)
(b)
$M = 0.1$ GeV
$M = 1.0$ GeV
$M = 2.1$ GeV
$M = 3.0$ GeV
0.14
0.16
0.18
0.20
0.22
0.24
Hydro T (GeV)

A blessing and a curse

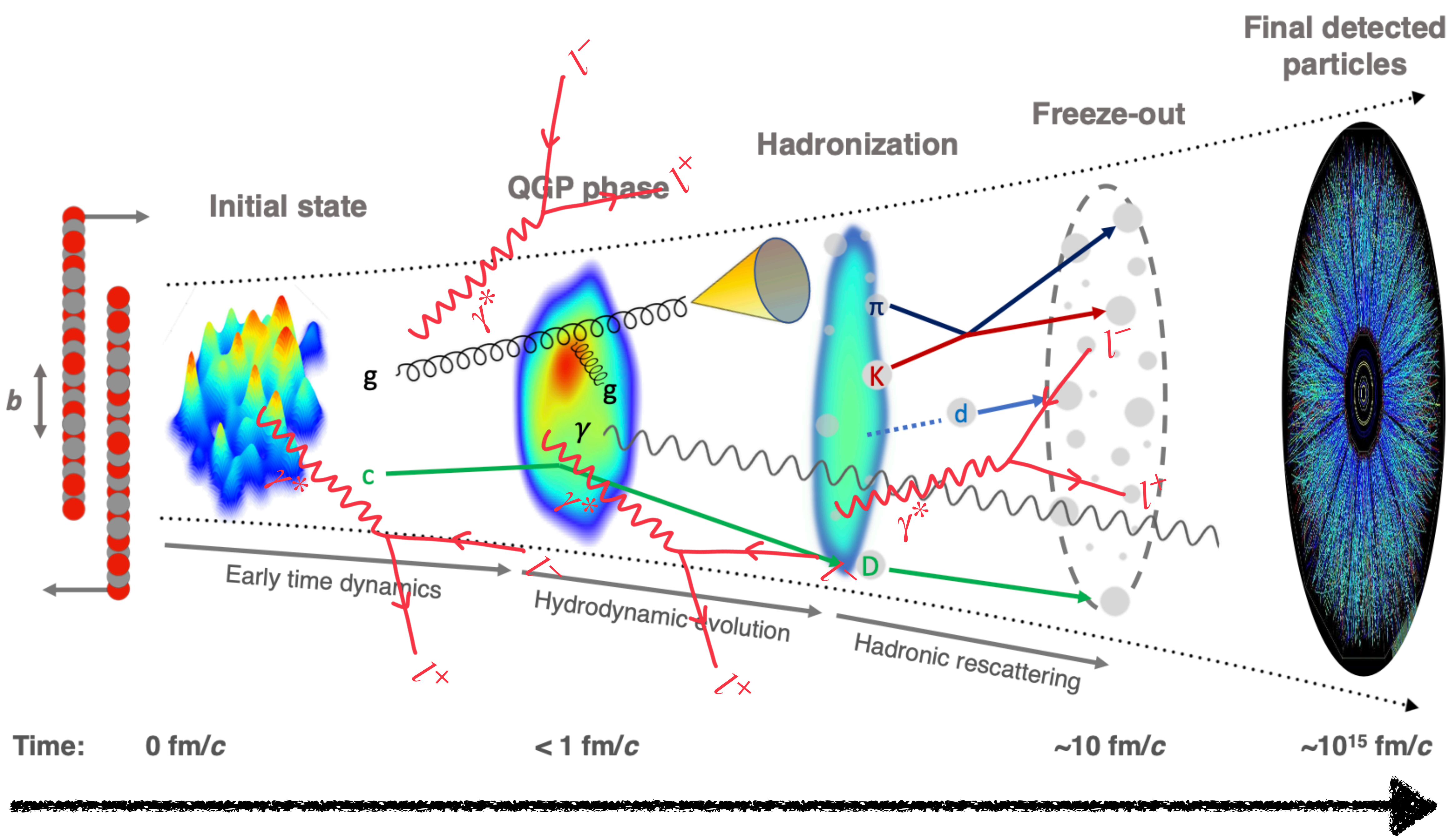


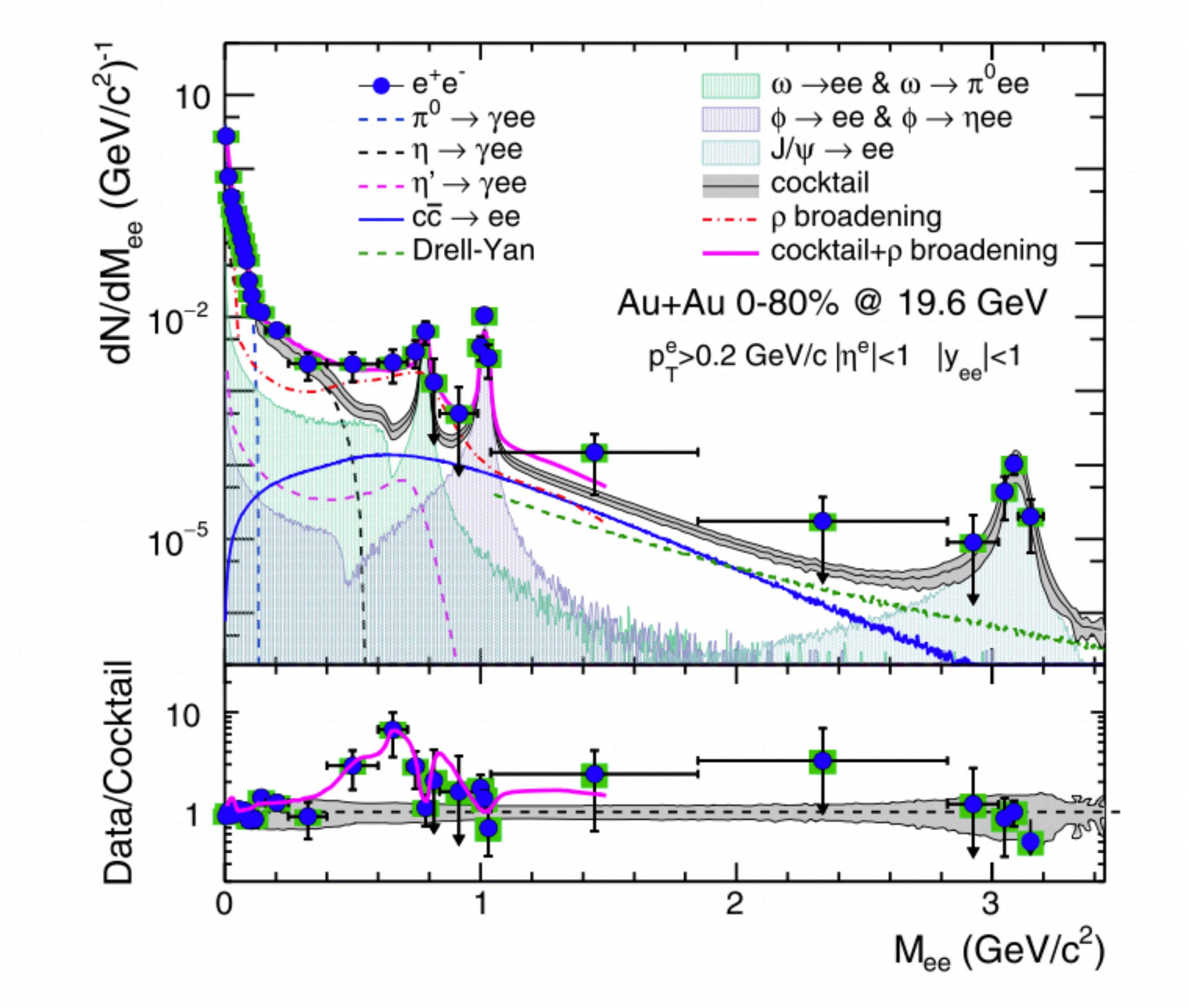


Dilepton from different stages are a blend together from experimental side.

- The low-mass region (LMR, 0< M < 1.1 GeV): the decays of light mesons.
- The intermediate mass region (IMR, 1.1< M < 3 GeV): thermal dilepton and decays of open heavy flavor.
- The high-mass region (HMR, M > 3 GeV): Drell-Yan process and quarkonium decays.

A blessing and a curse





Dilepton from different stages are a blend together from experimental side.