
Pre-Equilibrium Photon and Dilepton Production

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Photon and Dilepton Production in Heavy-Ion Collisions

- ▶ Electromagnetic probes escape plasma without re-interaction \Rightarrow provide important information on the various stages
- ▶ State-of-the-art calculations typically take into account emissions from hydrodynamic QGP and hadronic phase
- ▶ Compute production rates during pre-equilibrium phase in QCD kinetic theory
- ▶ Central result: **Universal scaling functions** for pre-eq. photon and dilepton production

$$\mathcal{N}_\gamma \left(\tilde{w}, \sqrt{\eta/s} p_T / \left(T \tau^{1/3} \right)_\infty^{3/2} \right)$$

$$\mathcal{N}_{ll} \left(\tilde{w}, \sqrt{\eta/s} M / \left(T \tau^{1/3} \right)_\infty^{3/2} \right)$$

Scaling function - Why and how?

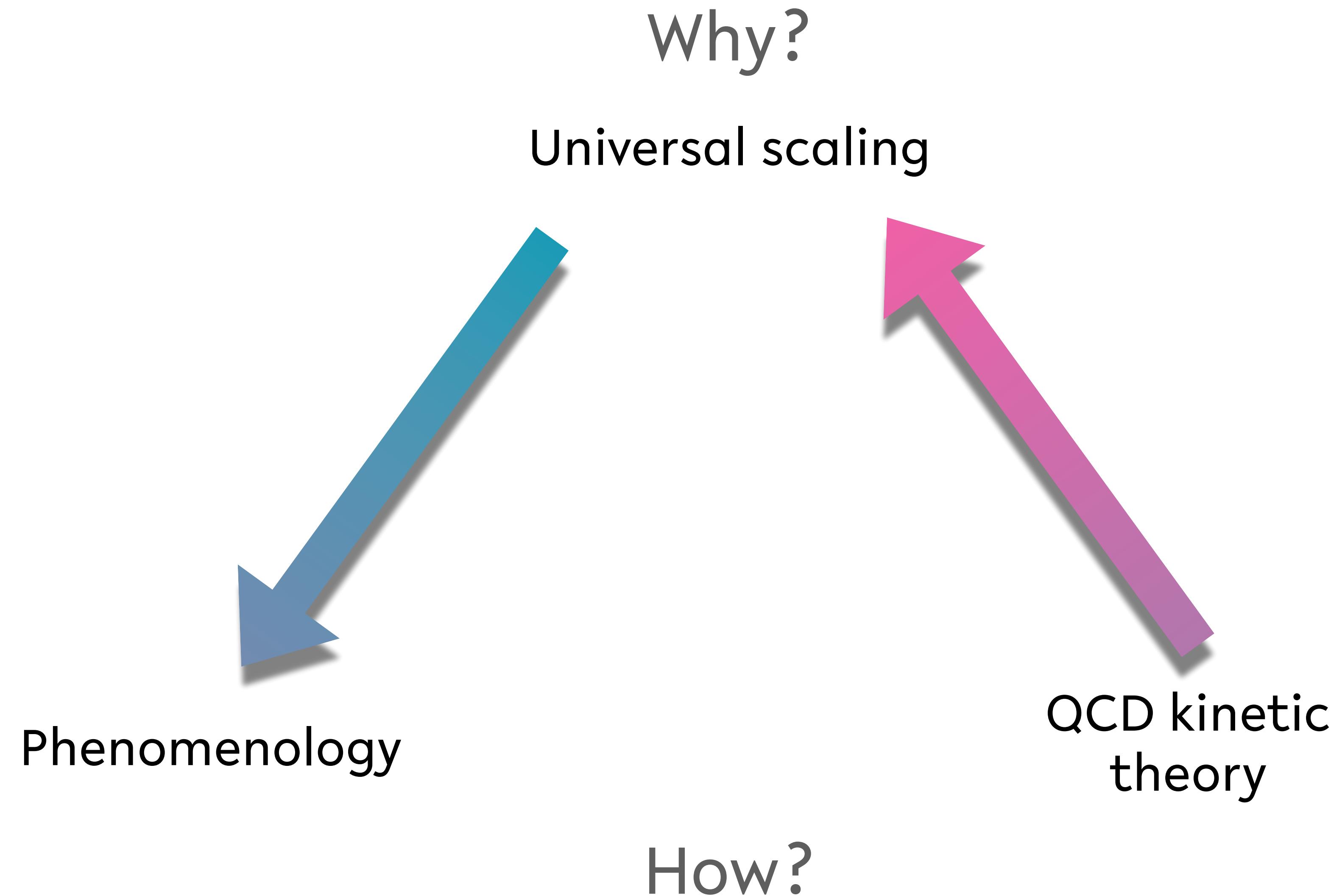
Why?

Universal scaling



Phenomenology

Scaling function - Why and how?



Pre-equilibrium dynamics of the QGP

- ▶ Early time dynamics described by QCD kinetic theory

Elastic $2 \leftrightarrow 2$
scattering screened
by Debye mass

$$p^\mu \partial_\mu f(x, p) = C_{2 \leftrightarrow 2}[f] + C_{1 \leftrightarrow 2}[f]$$

Boltzmann equation

[Arnold et al., JHEP 0301 (2003)]

Collinear $1 \leftrightarrow 2$ including
Landau-Pomeranchuk-
Migdal (LPM) effect via
effective vertex resummation

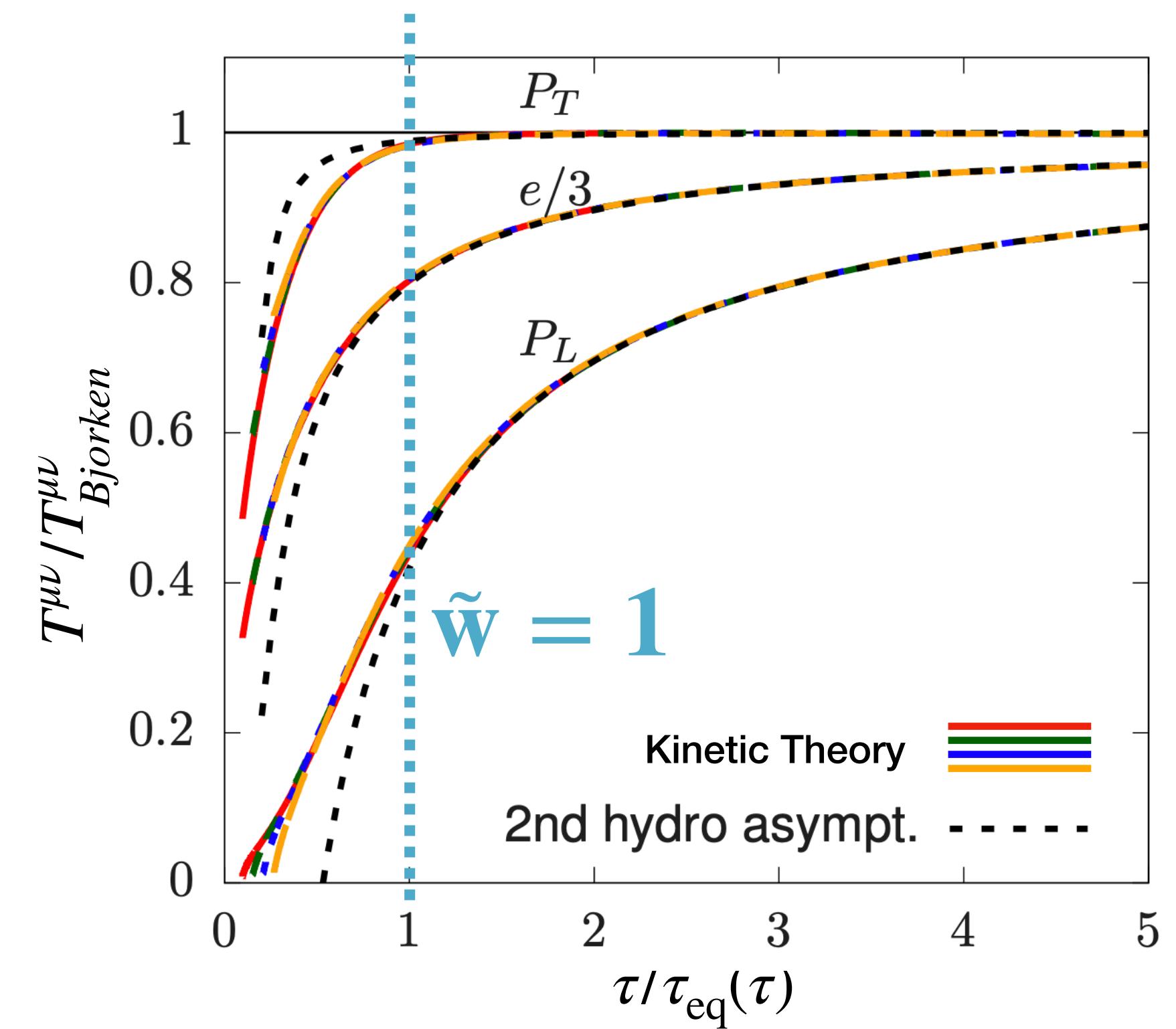
- ▶ Equilibration controlled by single relaxation rate

$$\tau_{\text{eq}}(\tau) = 4\pi(\eta/s)/T_{\text{eff}}(\tau)$$

- ▶ Evolution time:

$$\tilde{w} = \frac{\tau}{\tau_{\text{eq}}(\tau)} = \frac{\tau T_{\text{eff}}(\tau)}{4\pi\eta/s}$$

- ⇒ Hydrodynamics applicable on timescales of the order of unity in rescaled time



[Kurkela et al., Phys.Rev.C 99 (2019)]

Pre-equilibrium dynamics of the QGP

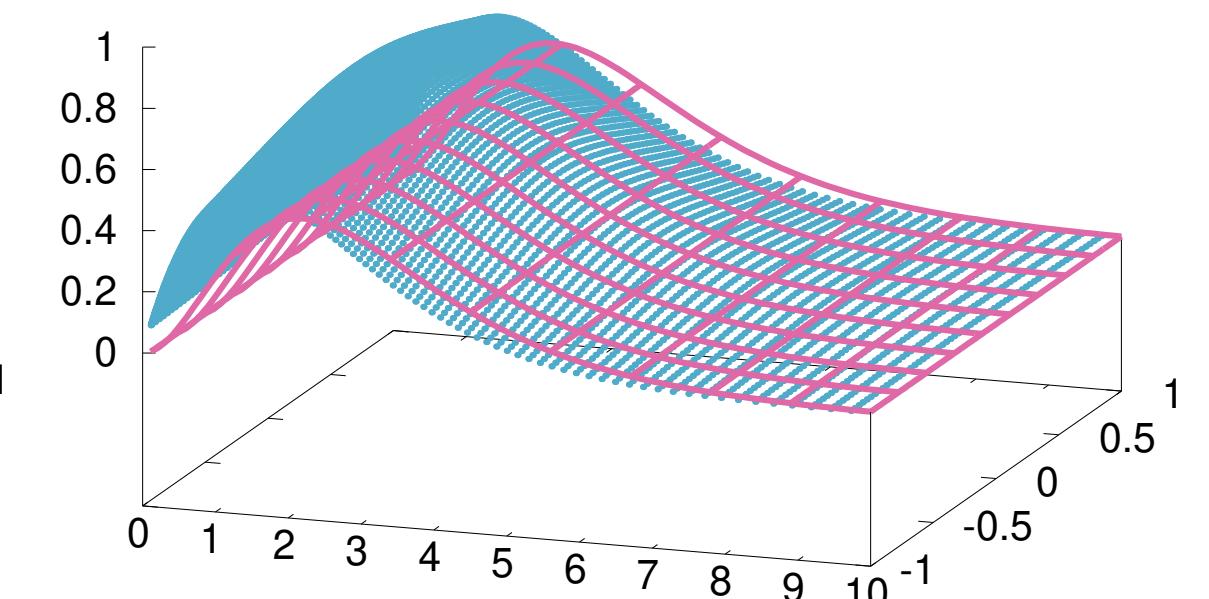
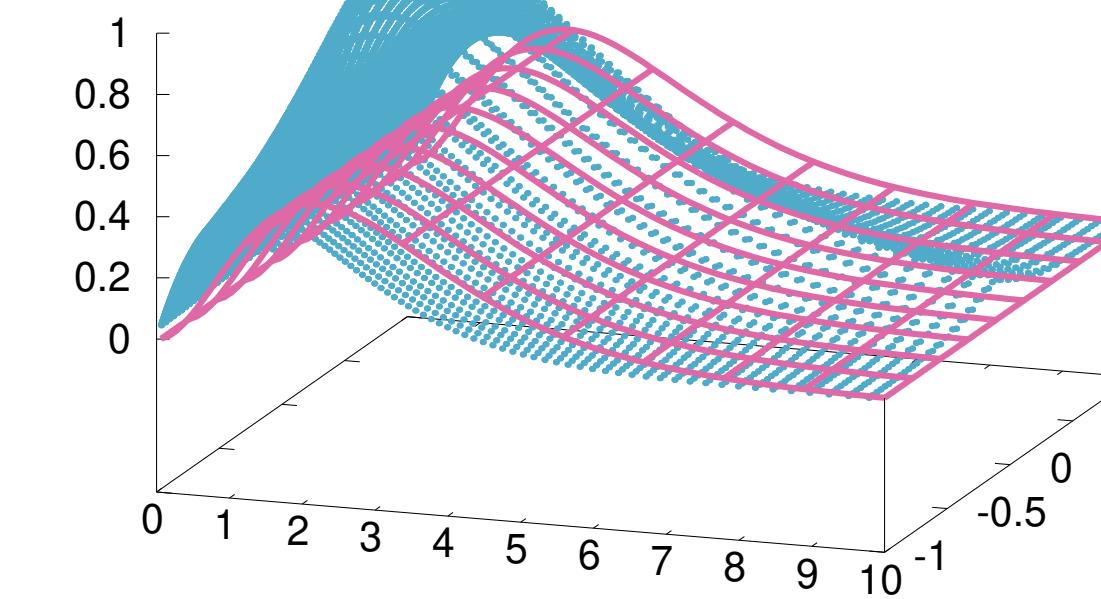
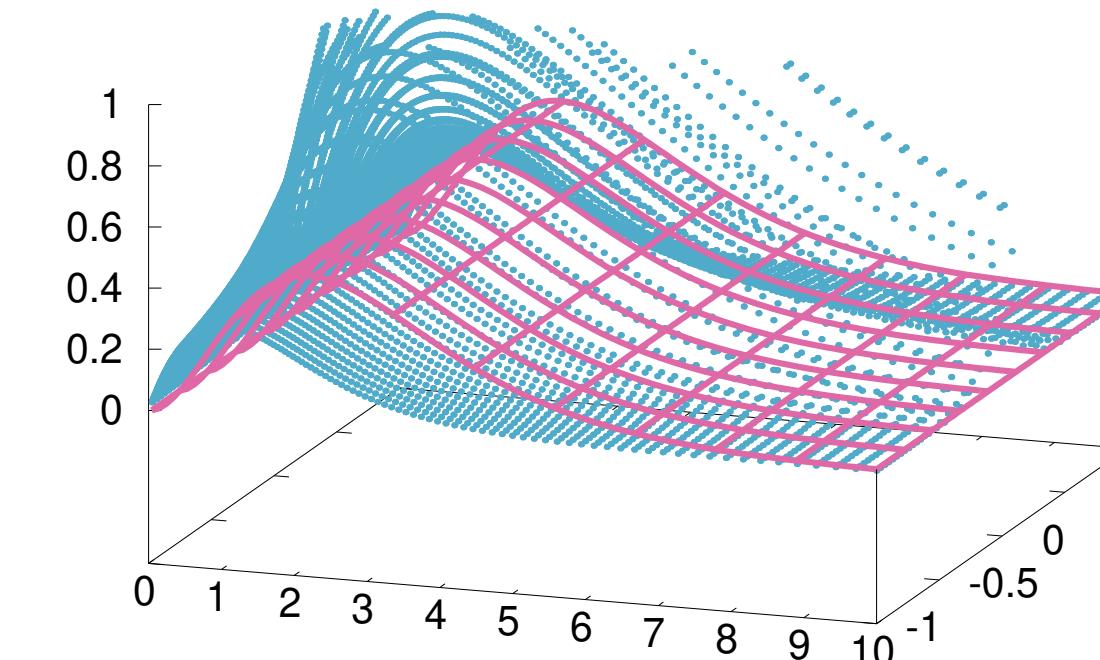
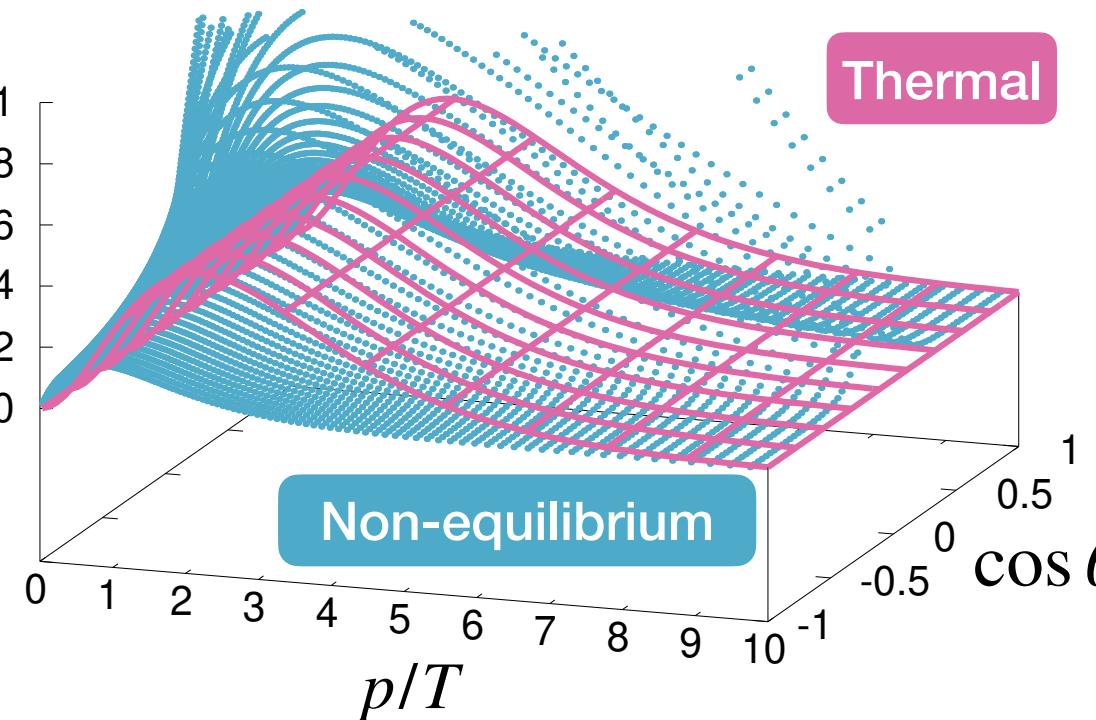
► Gluon dominated initial state

► Quarks produced dynamically

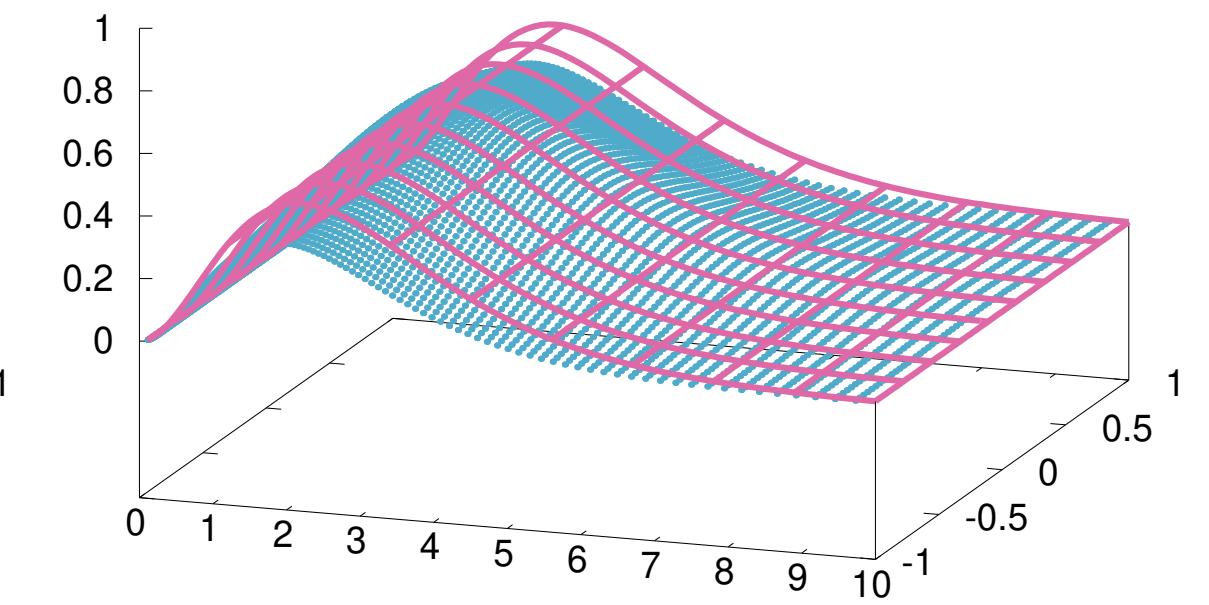
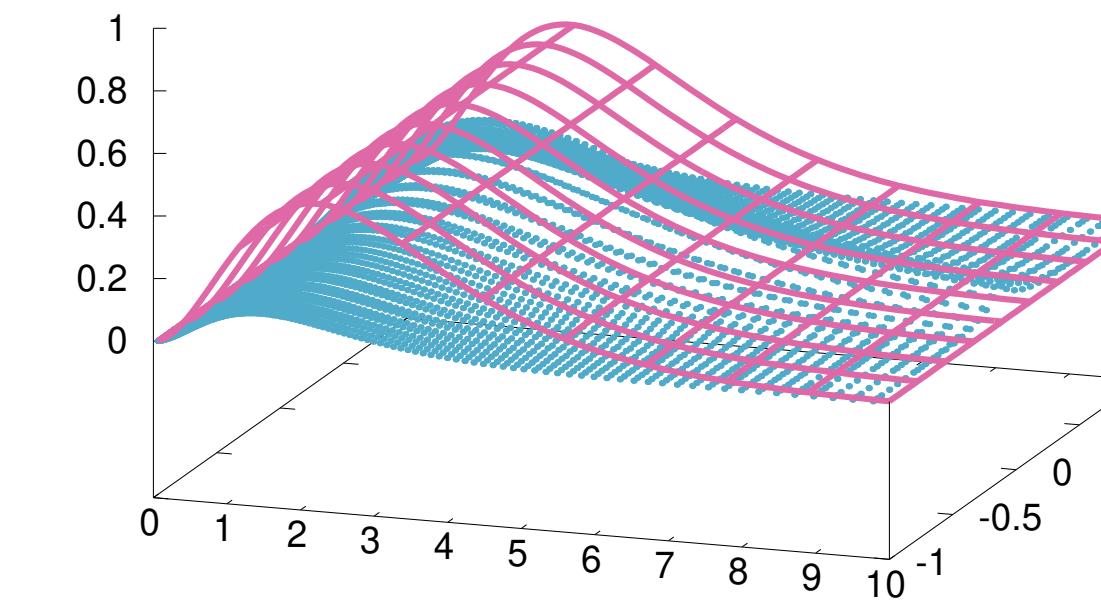
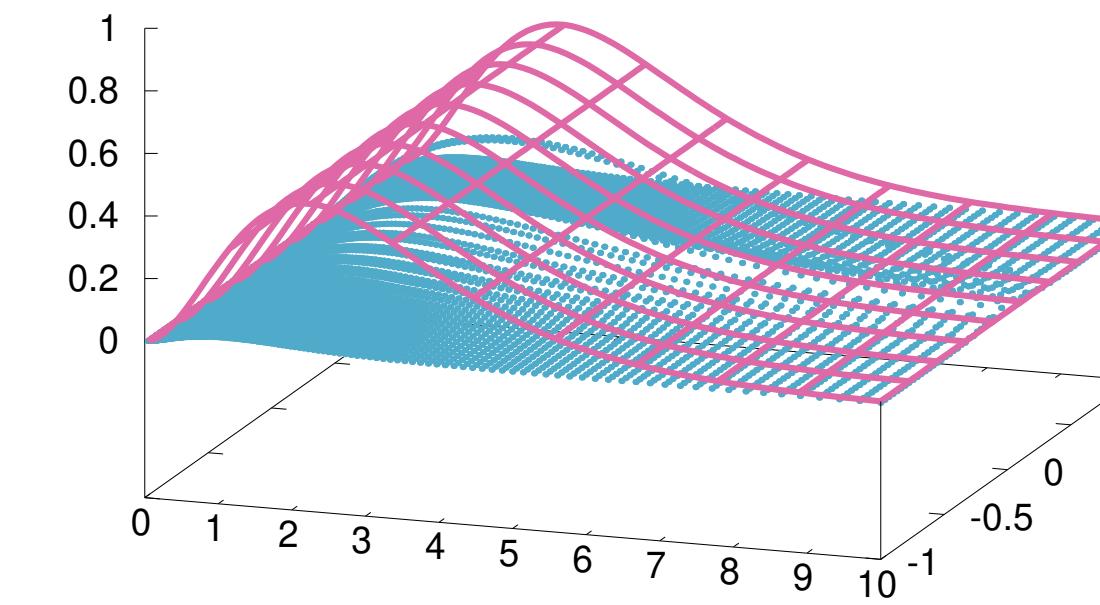
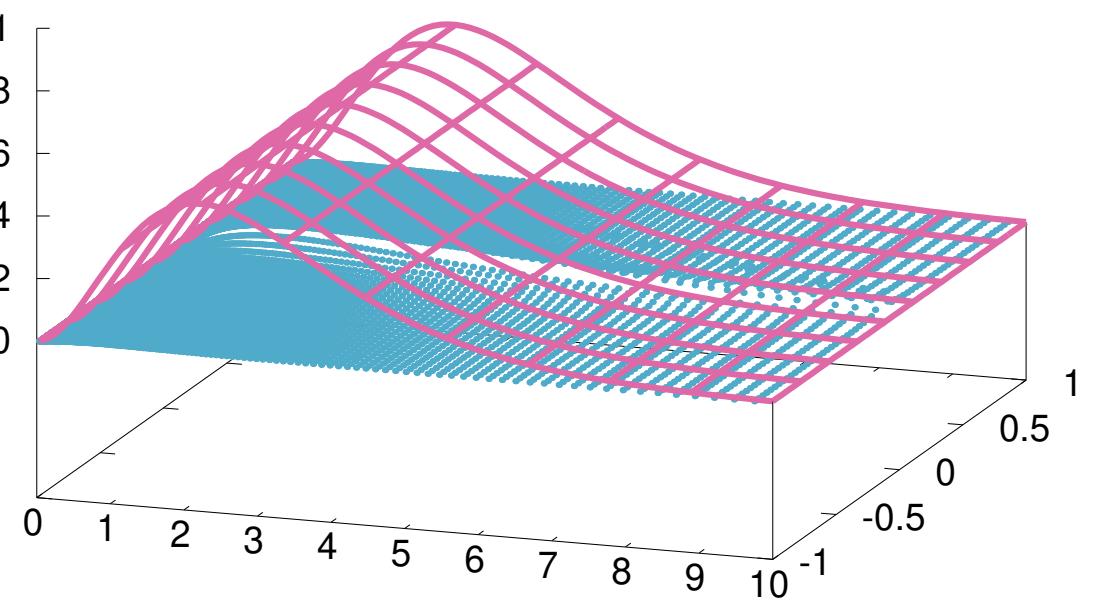
► System initially highly anisotropic
→ peak at $\cos \theta \approx 0$
represents $p_L \ll p_T$

$$\lambda = 10, \alpha_S = 0.26$$

GLUONS



QUARKS



$$\tilde{w} = 0.08$$

$$\tilde{w} = 0.2$$

$$\tilde{w} = 0.5$$

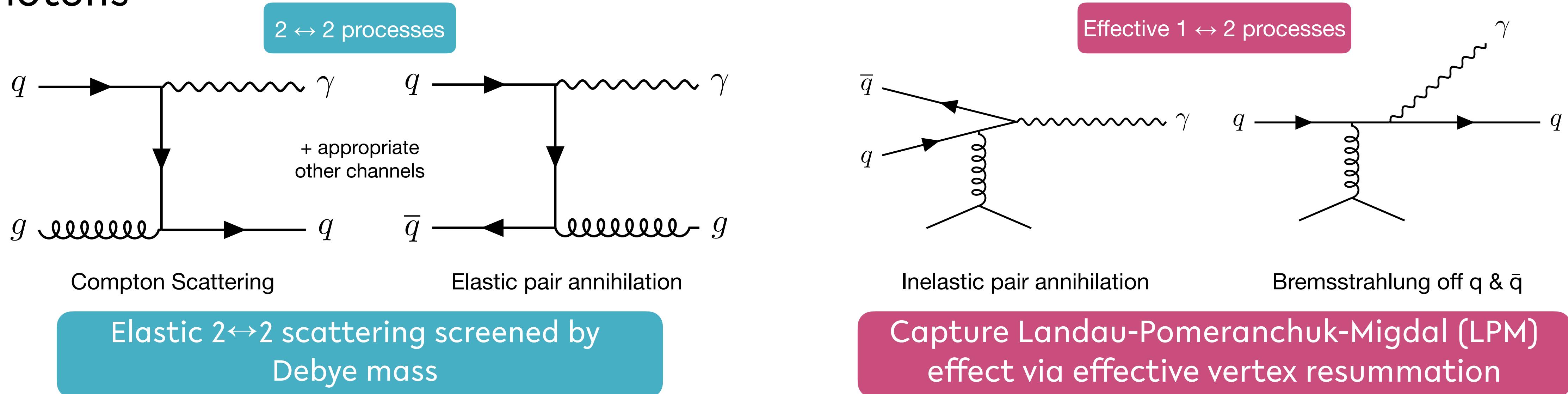
$$\tilde{w} = 2.0$$

Relevant Processes at Leading Order

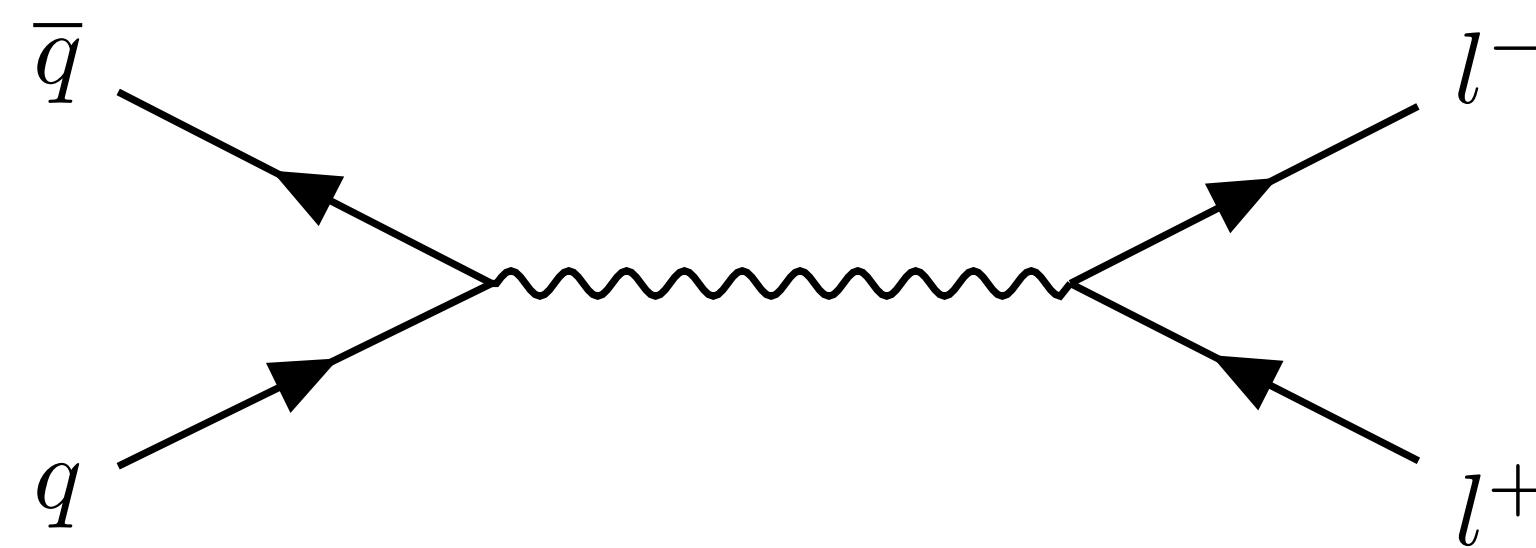
- ▶ Leading order production rates can be derived from effective kinetic theory

[Arnold et al., JHEP, (2001)]

- ▶ Photons



- ▶ Dileptons



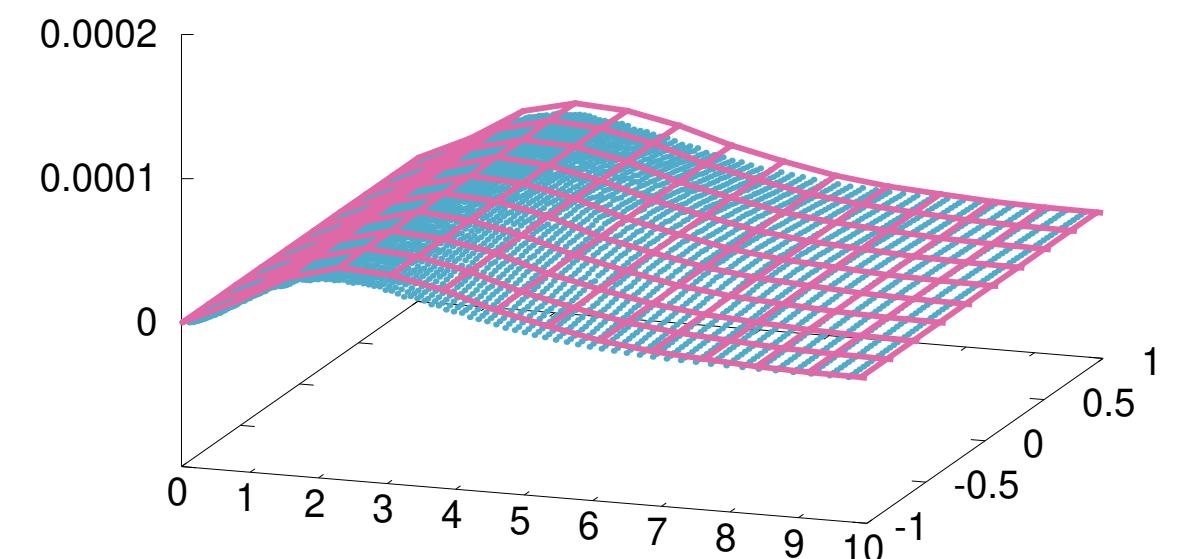
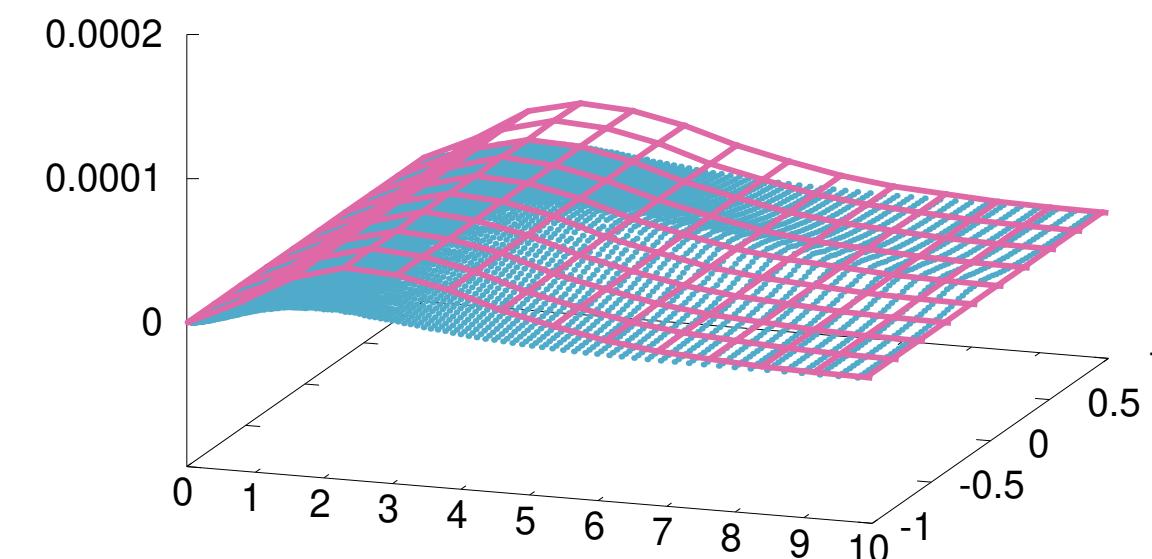
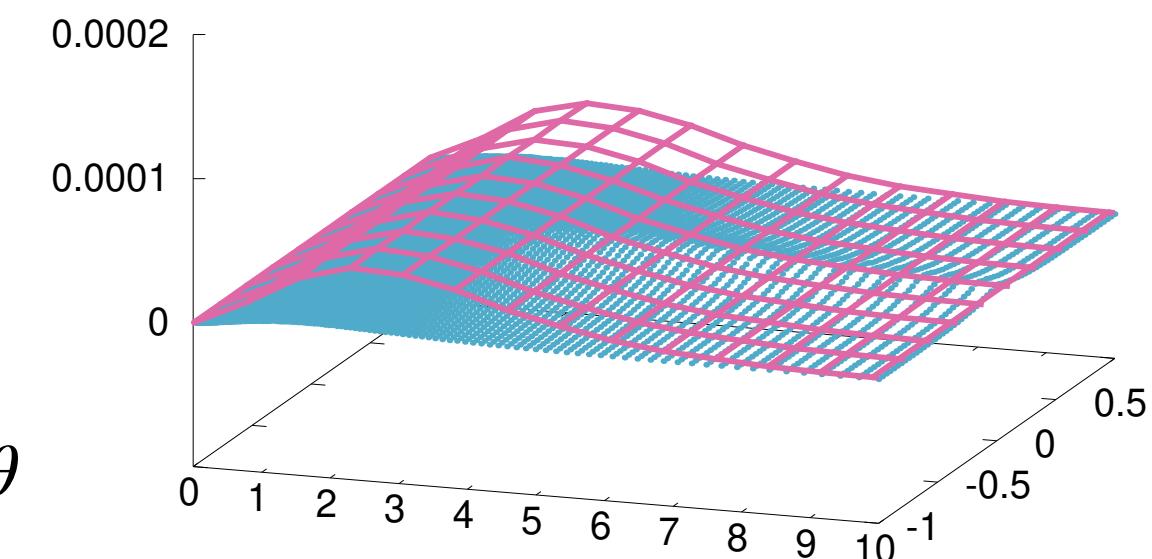
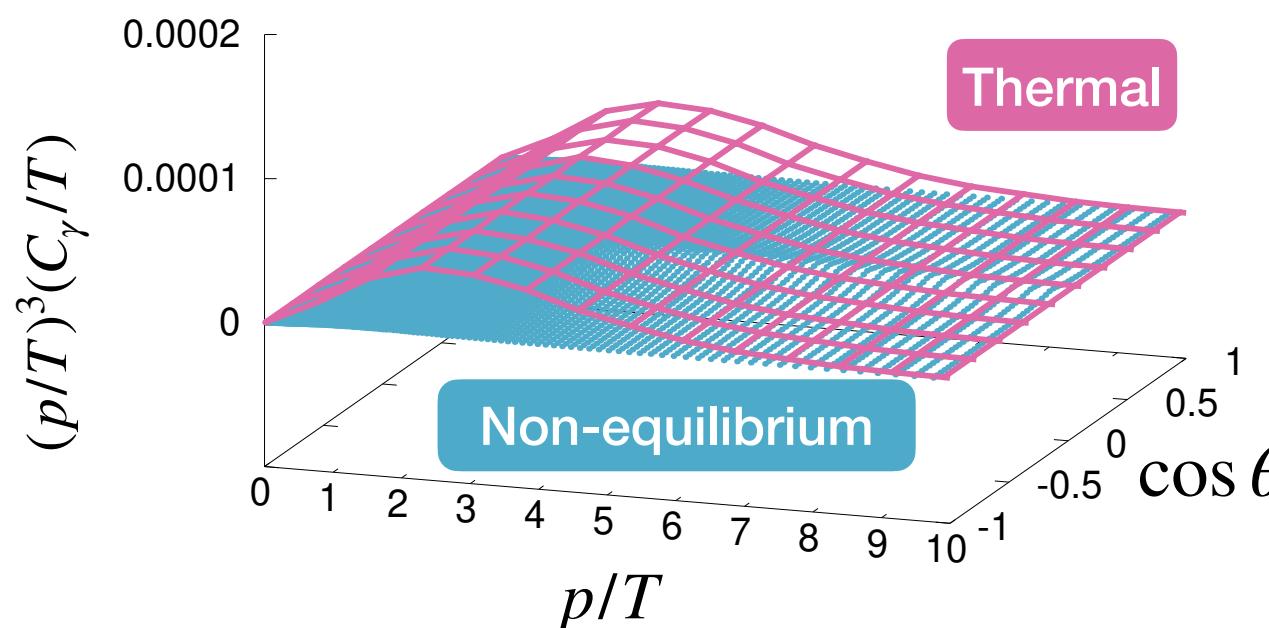
Photon - Time differential spectrum

- ▶ At early times: no quarks \rightarrow non-eq. rate small
- ▶ Peak at $\cos \theta \approx 0$: Gluon distribution highly anisotropic at early times
- ▶ As quarks get created \rightarrow non-eq. rate approaches thermal production rate

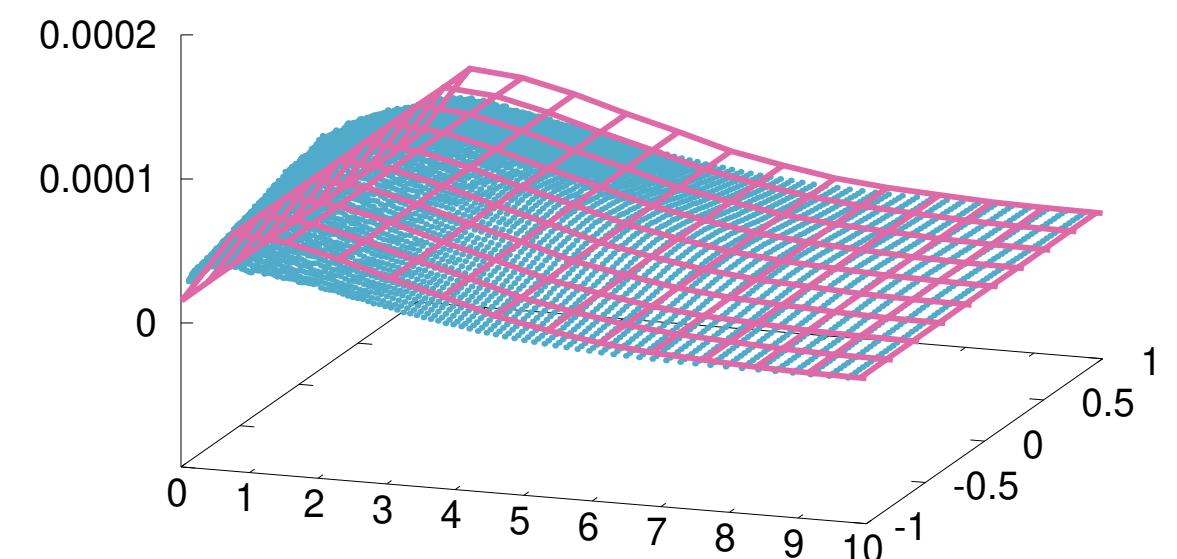
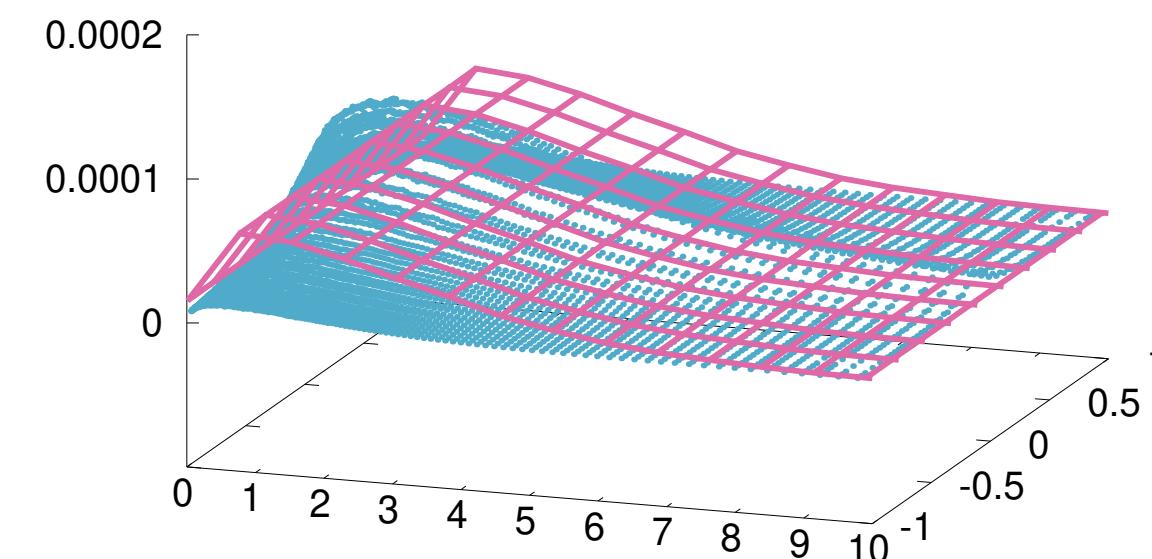
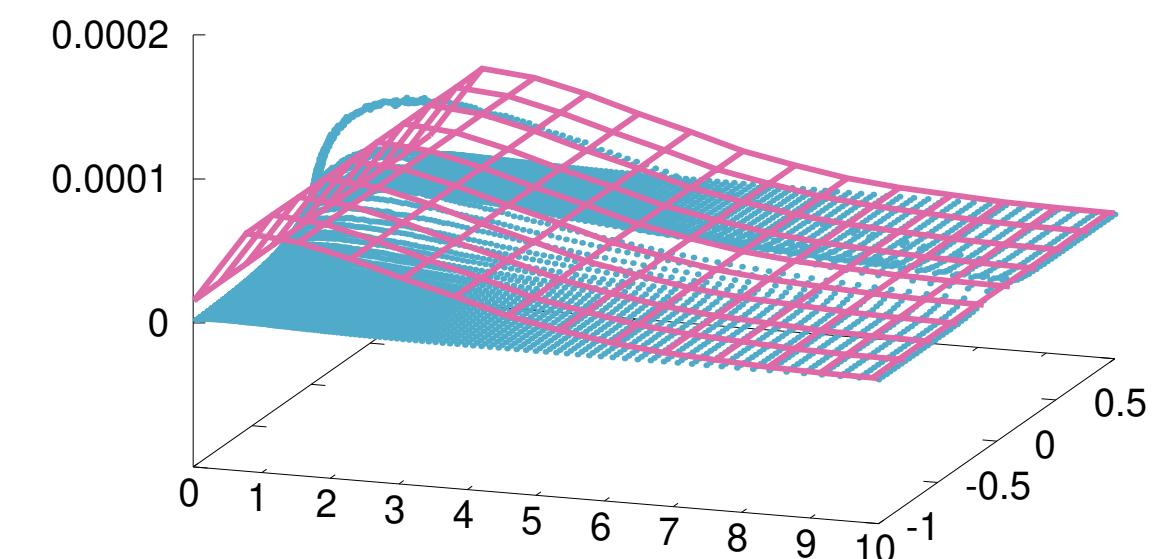
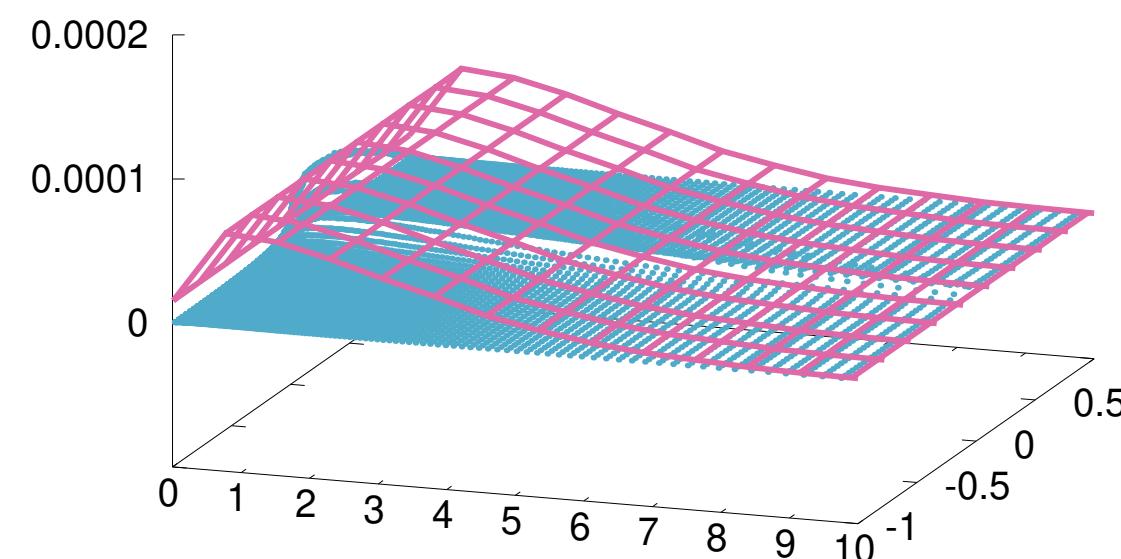
$$C_\gamma = \frac{dN}{\tau d\tau d^3p d^2x_T}$$

$\lambda = 10, \alpha_S = 0.26$

ELASTIC



INELASTIC



$\tilde{w} = 0.08$

$\tilde{w} = 0.2$

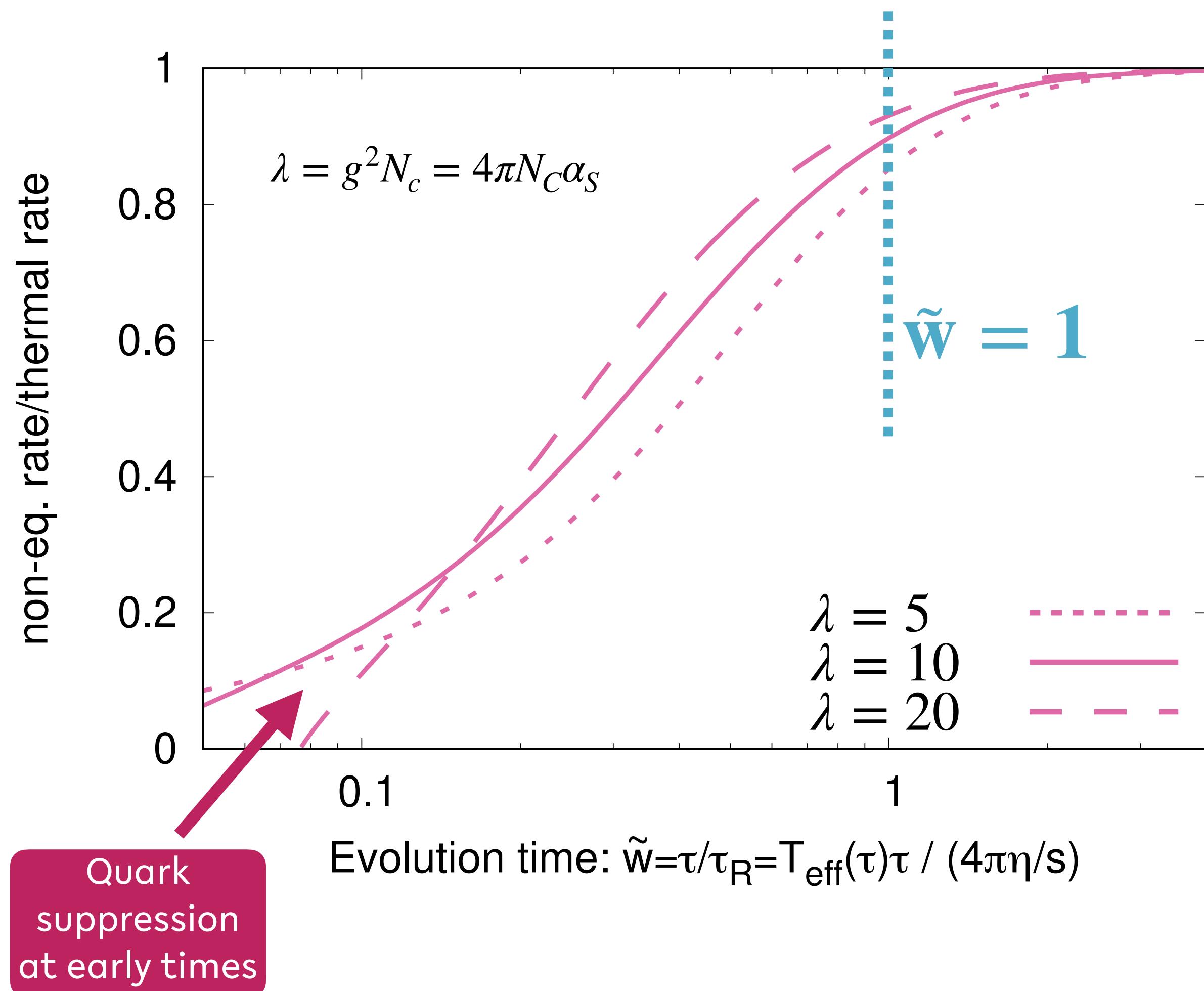
$\tilde{w} = 0.5$

$\tilde{w} = 2.0$

T I M E

Photon Energy Loss Rate

- ▶ Non-equilibrium energy loss rate due to photons compared to thermal energy rate



Energy rate:

$$\partial_\tau e_\gamma(\tau) = \int \frac{d^3 p}{(2\pi)^3} p C_\gamma(\tau, \vec{p})$$

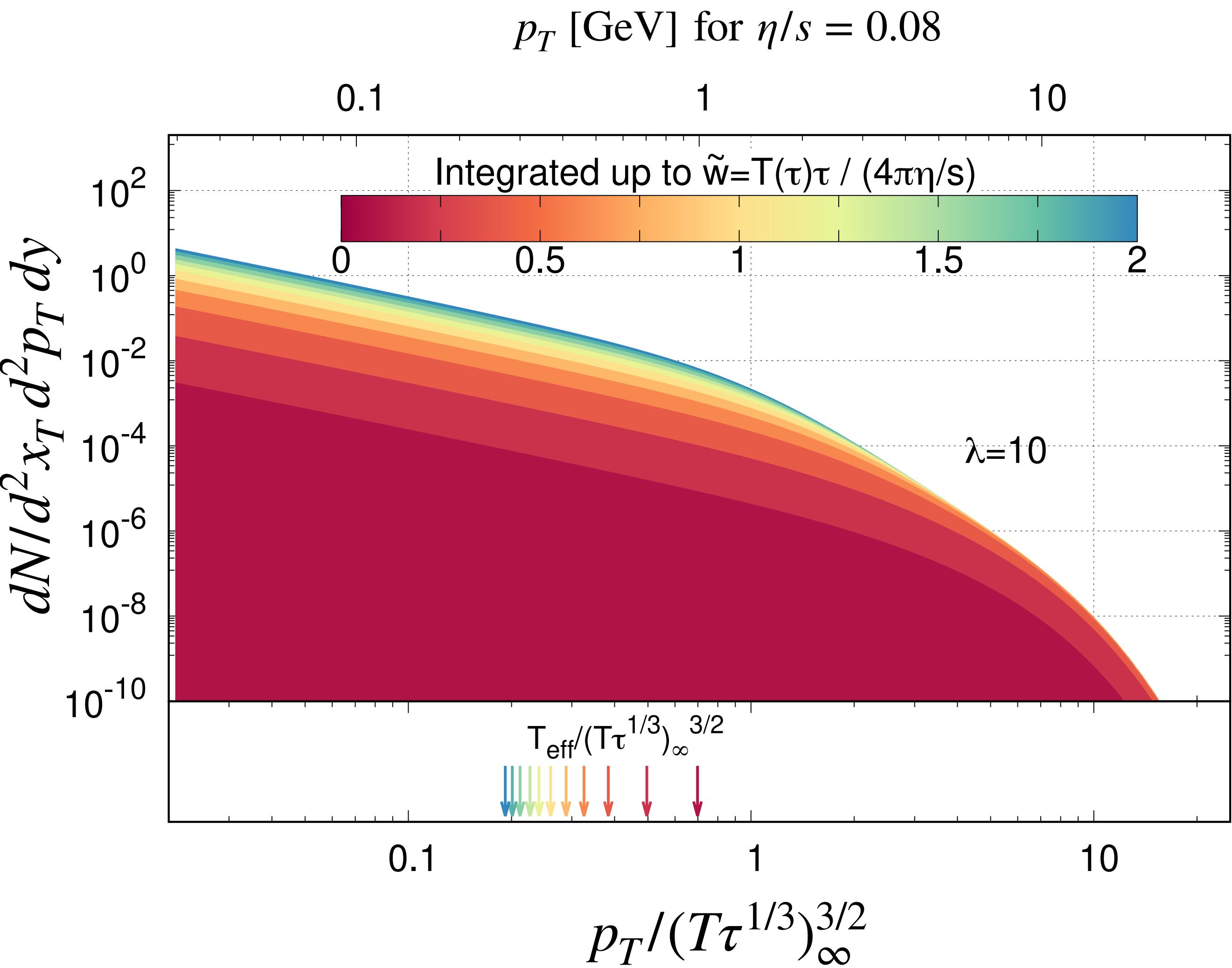
where:

$$C_\gamma = \frac{dN}{\tau d\tau d^3 p d^2 x_T}$$

Recover thermal energy rate on timescales
when hydrodynamics
becomes applicable

Photon - p_T -Spectrum

- ▶ Const. entropy at late times →
 $(\tau s)_\infty^{1/3} \sim (T\tau^{1/3})_\infty$ fixed
- ▶ High p_T -regime produced at early times
- ▶ Early time production ($\tilde{w} \lesssim 0.5$) suppressed due to absence of quarks
- ▶ Competition between increase of non-eq. photon production rate relative to thermal rate and rapid cooling of pre-eq. QGP



Photon - Universal Scaling

- ▶ Only two scales in the system: τ_{eq} , T_{eq}
- ▶ Const. entropy at late times fixes scale $(\tau s)_\infty^{1/3} \sim (T_{\text{eq}} \tau_{\text{eq}}^{1/3})$
- ▶ Equilibration on timescales of the order of unity $\tau_{\text{eq}} T_{\text{eq}} \sim \eta/s$

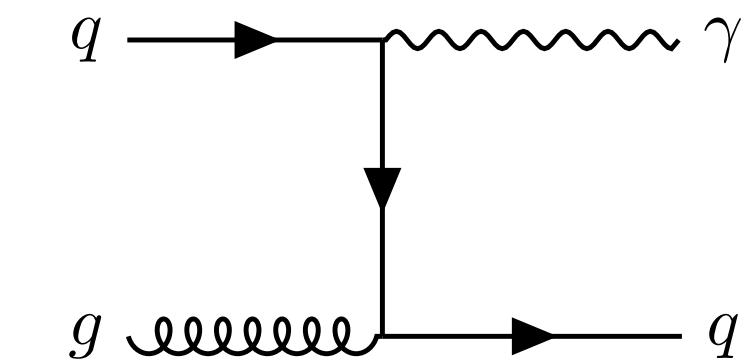
$$\rightarrow \tau_{\text{eq}} \sim (\eta/s)^{3/2}, \quad T_{\text{eq}} \sim (\eta/s)^{-1/2}$$

Photon - Universal Scaling

$$\tau_{\text{eq}} \sim (\eta/s)^{3/2}, \quad T_{\text{eq}} \sim (\eta/s)^{-1/2}$$

- ▶ Scaling of momentum → results universal when expressed in $p_T/T_{\text{eq}} \sim \sqrt{\eta/s}$ $p_T/(T\tau^{1/3})_\infty^{3/2}$
- ▶ Additional factors contained in photon spectrum

$$\frac{dN}{d^2x_T d^2p_T dy} \sim \int d\tau \tau E_p T \sim (\tau_{\text{eq}}^2 T_{\text{eq}})^{-2} \sim (\eta/s)^2$$

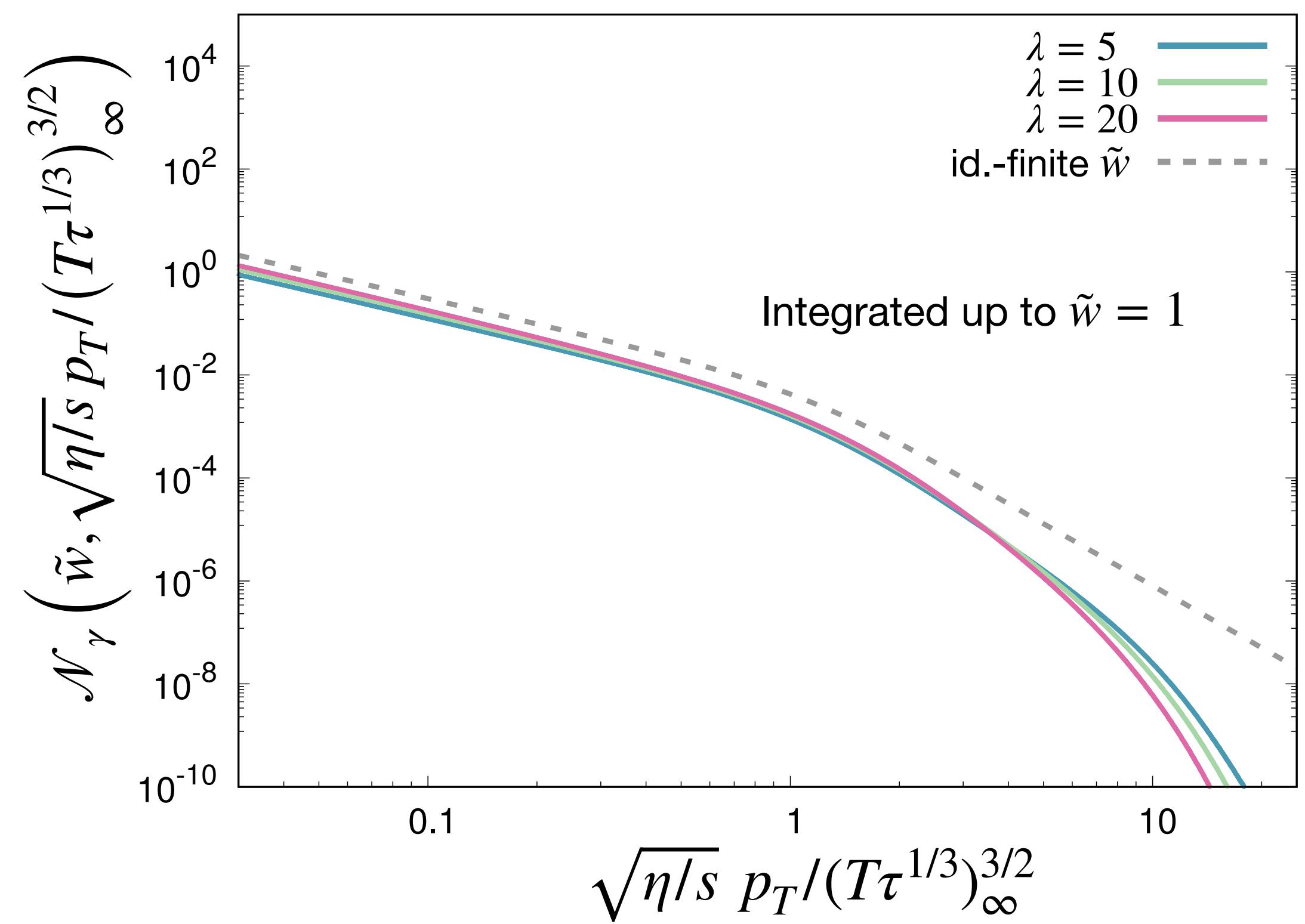
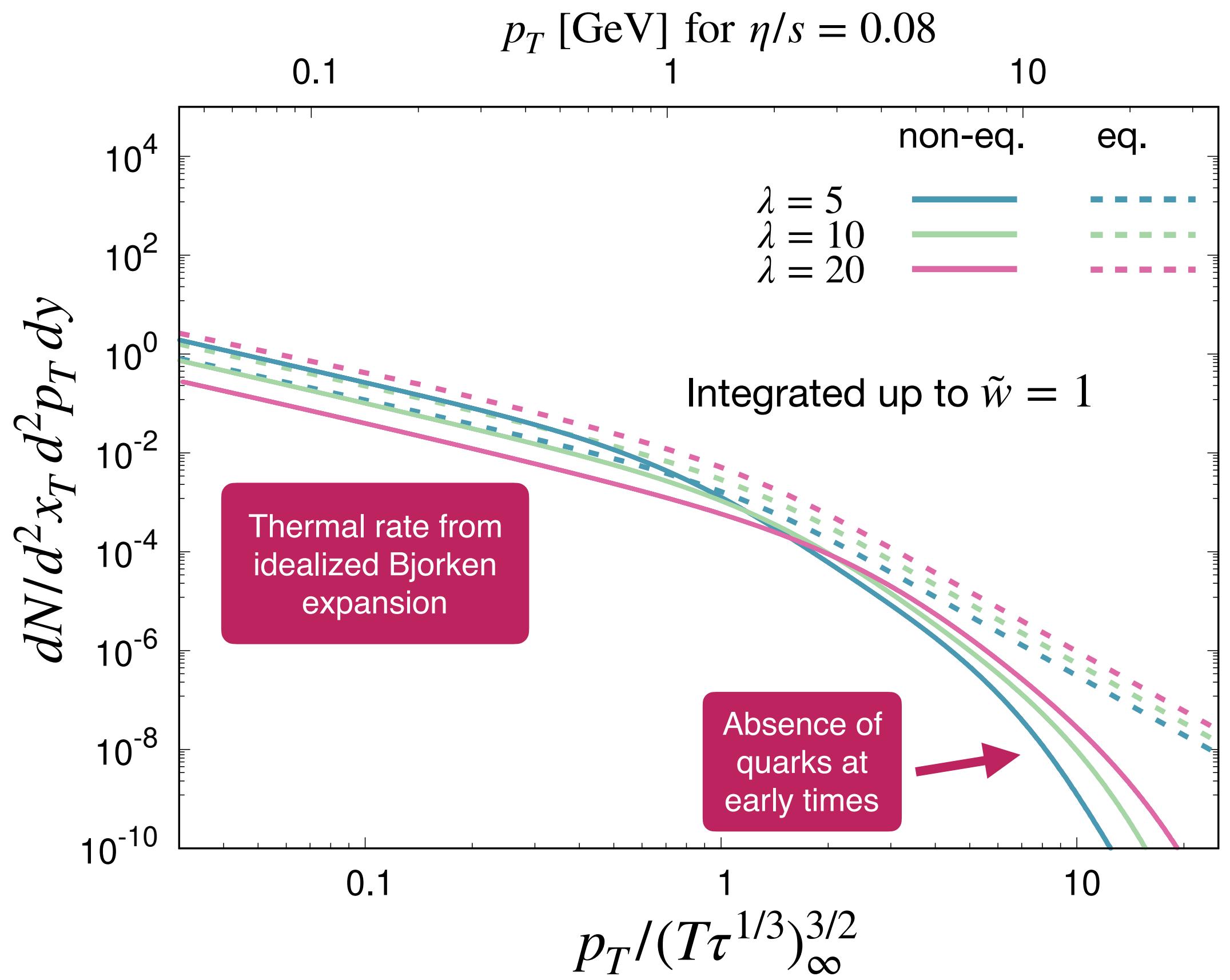


- ▶ α_S contained in collision integrals → scale spectrum by moment $\tilde{C}_\gamma^{\text{ideal}}$ of eq. rate
- ▶ Universal scaling function \mathcal{N}_γ :

$$\mathcal{N}_\gamma \left(\tilde{w}, \sqrt{\eta/s} \ p_T / (T\tau^{1/3})_\infty^{3/2} \right) = \frac{1}{(\eta/s)^2 \ \tilde{C}_\gamma^{\text{ideal}}} \ \frac{dN}{d^2x_T d^2p_T dy}$$

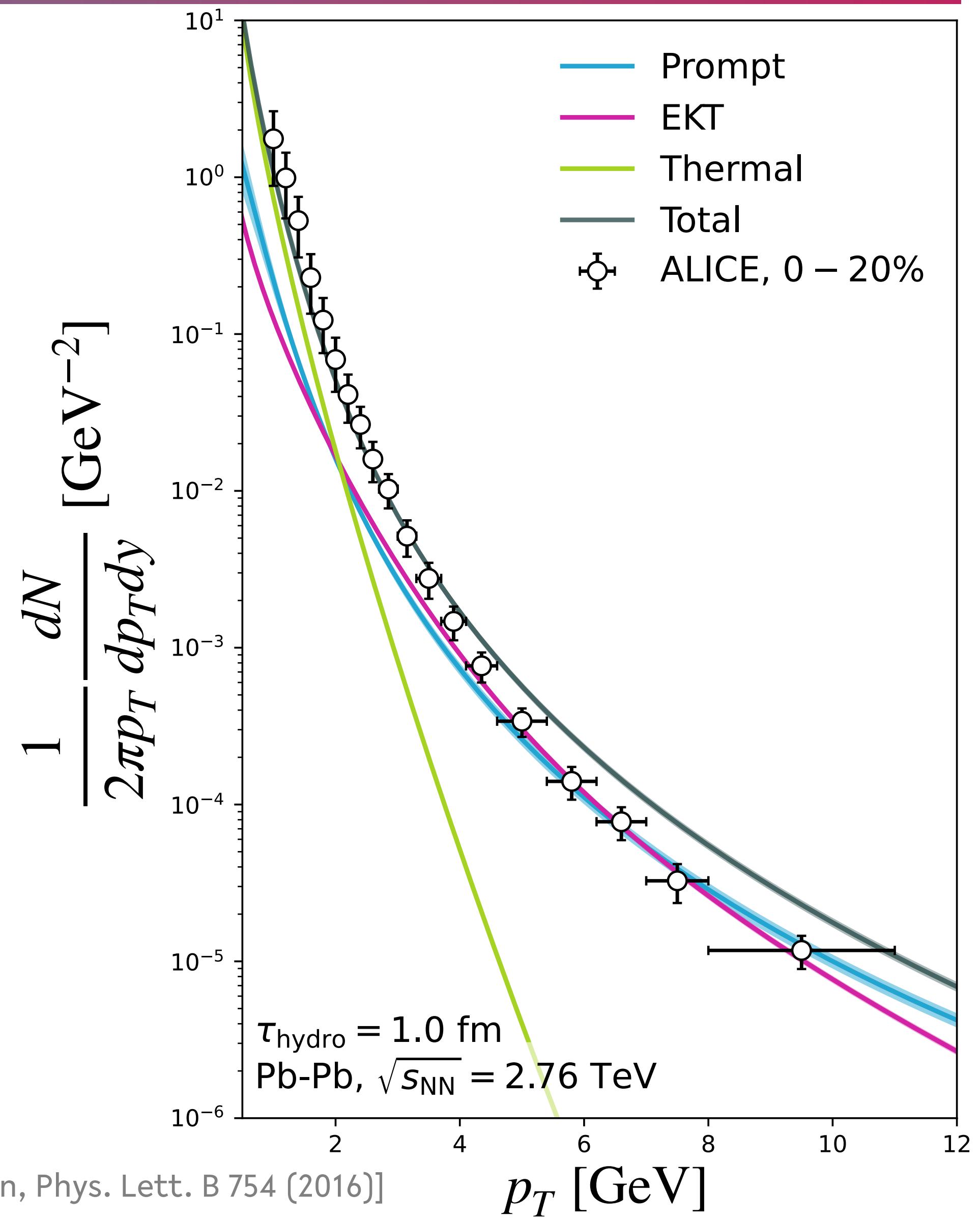
Photon - p_T -Spectrum

$$\mathcal{N}_\gamma \left(\tilde{w}, \sqrt{\eta/s} p_T / \left(T \tau^{1/3} \right)_\infty^{3/2} \right) = \frac{1}{(\eta/s)^2 \tilde{C}_\gamma^{ideal}} \frac{dN}{d^2x_T d^2p_T dy}$$



Photons - Phenomenology

- ▶ Calculate pre-eq. photon production by matching scaling function to **event-by-event** energy density profiles
- ▶ Background evolution obtained from VISHNU 2+1 hydro with $\eta/s=0.08$ tuned to 0-20% PbPb collisions at 2.76TeV [Garcia-Montero et al., Phys.Rev.C, (2020)]
- ▶ Pre-eq. contribution of the order of prompt yield
- ▶ Total in-medium (EKT+thermal) yield independent of switching time



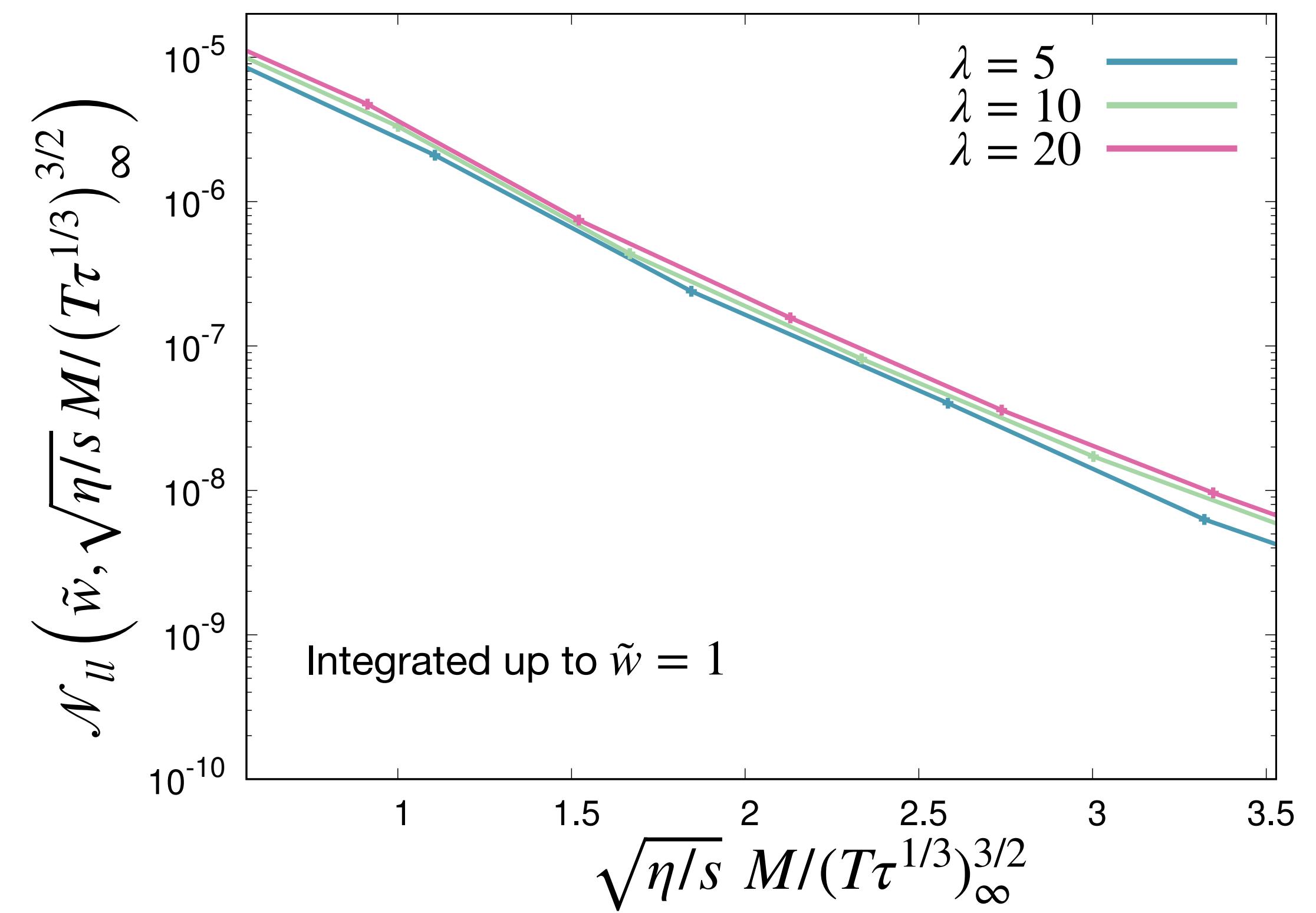
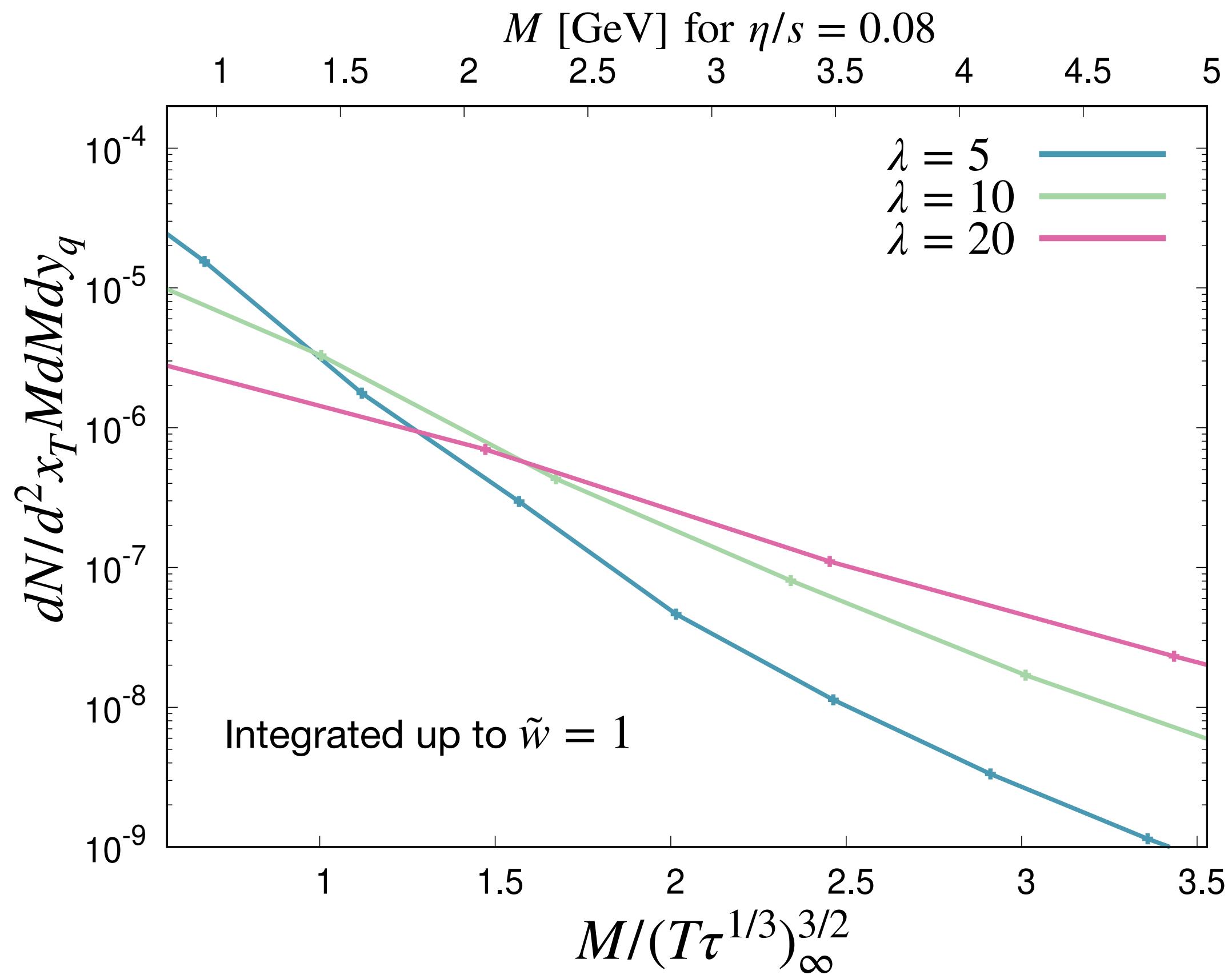
[ALICE Collaboration, Phys. Lett. B 754 (2016)]

Dilepton - M -Spectrum

- Dileptons scale similarly but without equilibrium rate

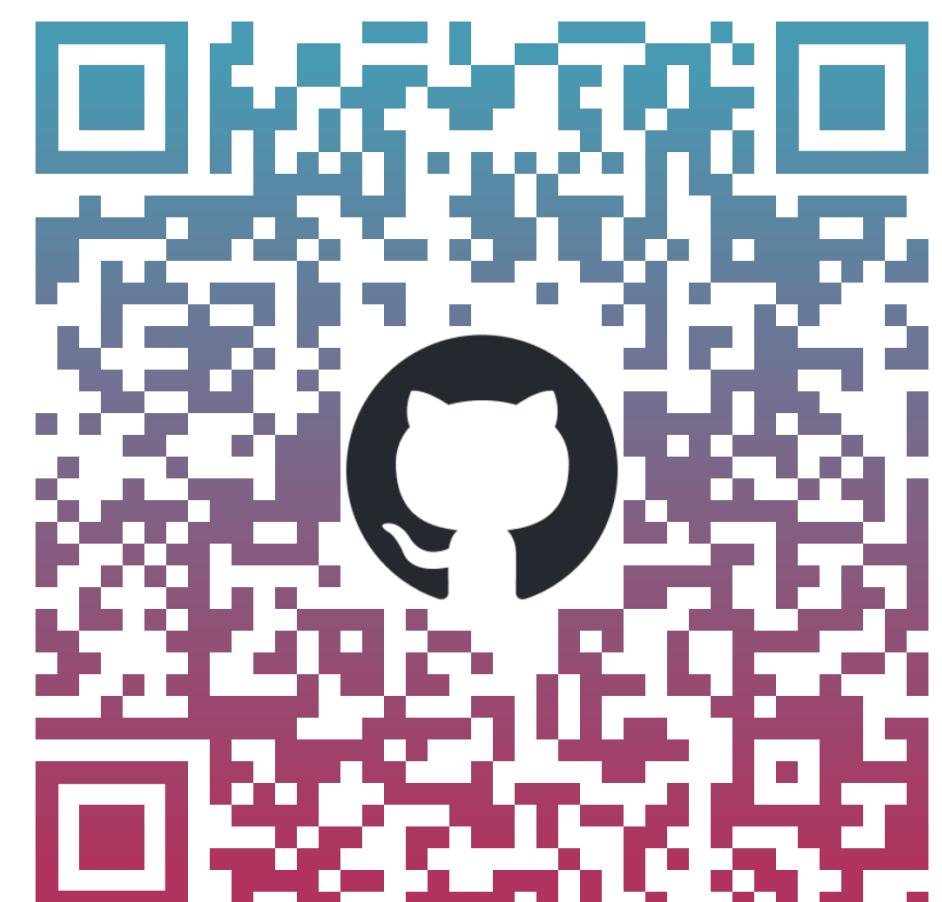
$$\mathcal{N}_{ll} \left(\tilde{w}, \sqrt{\eta/s} M / \left(T \tau^{1/3} \right)_{\infty}^{3/2} \right) = \frac{1}{(\eta/s)^2} \frac{dN}{d^2x_T M dM dy}$$

Also applicable to Romatschke-Strickland parameterization
 [Coquet et al., Phys. Lett. B 821 (2021)]



Conclusion and Outlook

- ▶ Presented pre-equilibrium photon and dilepton production rate computed from QCD kinetic theory
- ▶ Universal scaling functions allow for event-by-event calculations for pre-equilibrium spectrum of photons and dileptons
- ▶ Photons already included into KøMPøST → available now
 - ▶ Dileptons will be included to allow for event-by-event calculations



[Download ShinyKøMPøST!](#)

Backup

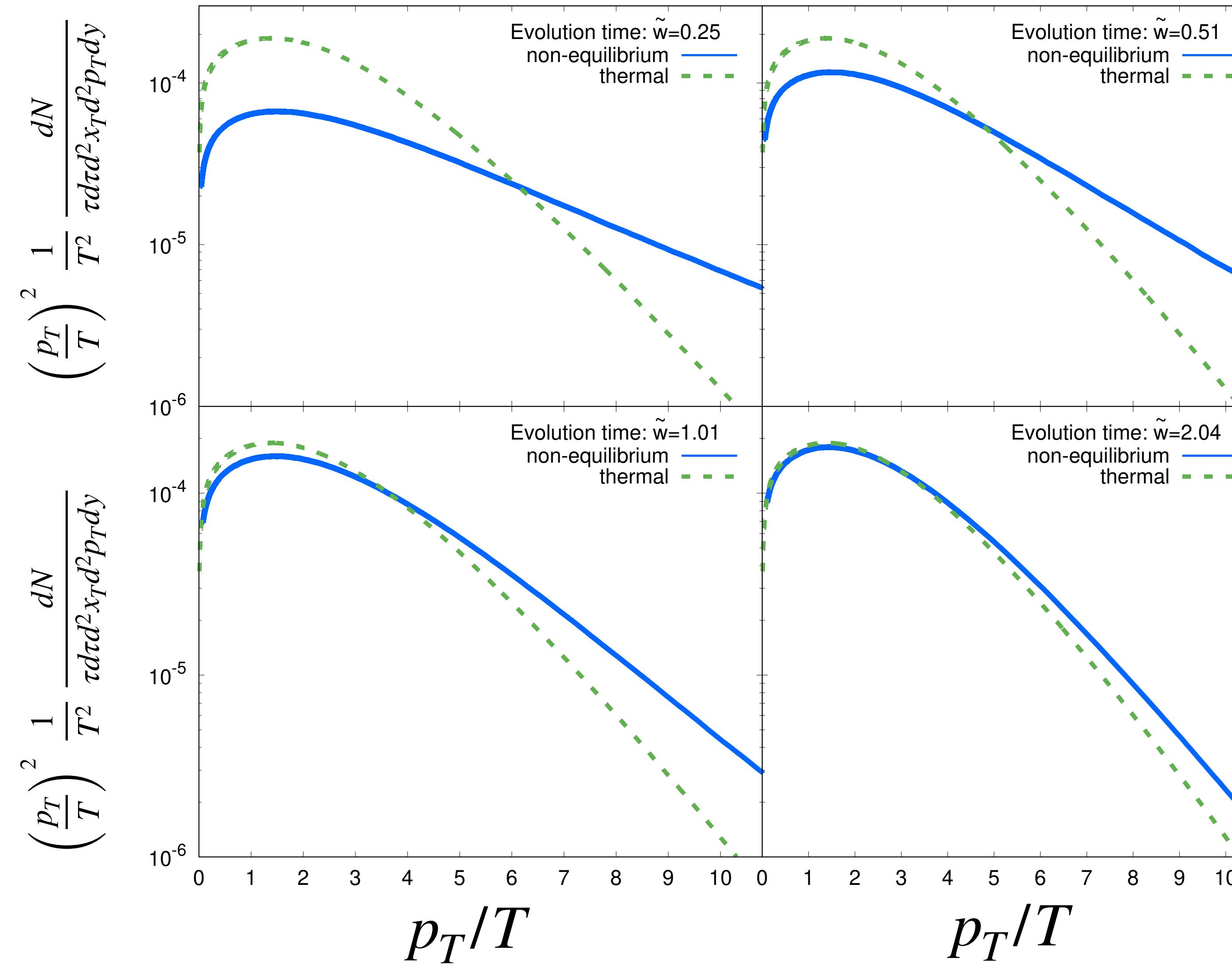
Backup - Momentum scale

$$(\tau T^3)_\infty = 4.173 \text{ fm}^{-2} \left(\frac{dN_{\text{ch}}/d\zeta}{1600} \right) \left(\frac{S/N_{\text{ch}}}{7.5} \right) \left(\frac{A_\perp}{138 \text{ fm}^2} \right)^{-1} \left(\frac{\nu_{\text{eff}}}{\nu_g + 2N_f \frac{7}{8} \nu_q} \right)^{-1}$$

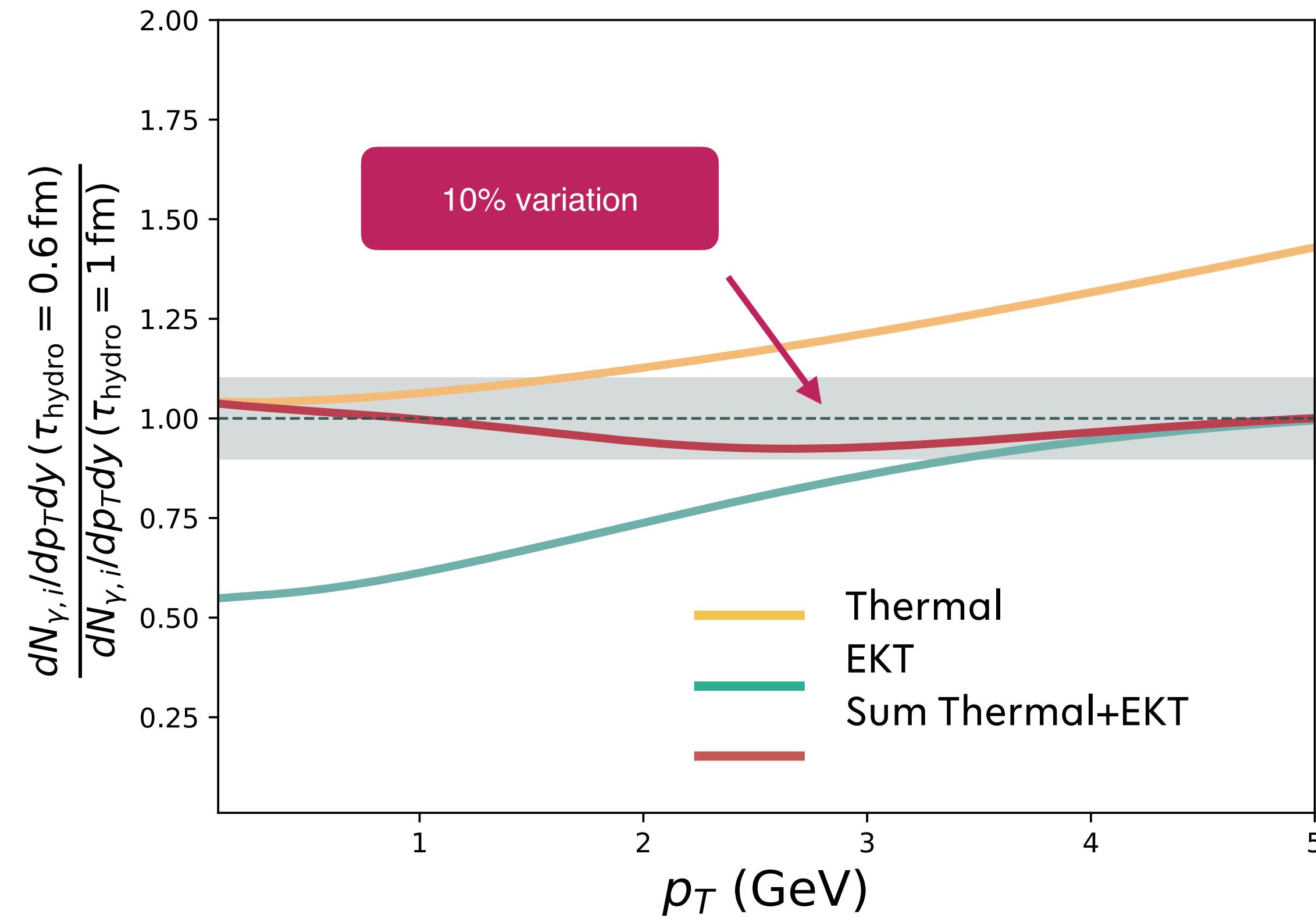
Match

$$\sqrt{\eta/s} \left. \frac{p_T}{(\tau^{1/3}T)_\infty^{3/2}} \right|_{\text{sim}} = \sqrt{\eta/s} \left. \frac{p_T}{(\tau^{1/3}T)_\infty^{3/2}} \right|_{\text{phys}}$$

Backup - Time differential p_T -spectrum



Backup - Switching time



Total in-medium yield independent of switching time!

Backup - $\tilde{C}_\gamma^{\text{ideal}}$

- ▶ Starting point:

$$\frac{dN}{d^2x_T d^2p_T dy} = \frac{\nu_\gamma}{(2\pi)^3} \int d\zeta \int d\tau \tau E_p C_\gamma(\tau, \vec{p}) \quad \text{with} \quad C_\gamma = \frac{dN}{d^4x d^3p}$$

- ▶ Dimensionless collision integral:

$$C_\gamma^{\text{eq}}(\tau, \vec{p}) = T(\tau) \bar{C}_\gamma^{\text{eq}} \left(\frac{\tau}{\tau_{\text{eq}}}, \frac{\vec{p}}{T(\tau)} \right)$$

- ▶ Rewrite time integral into temperature integral via $T(\tau) = (\tau^{1/3} T)_\infty / \tau^{1/3}$ and perform rapidity integral to get

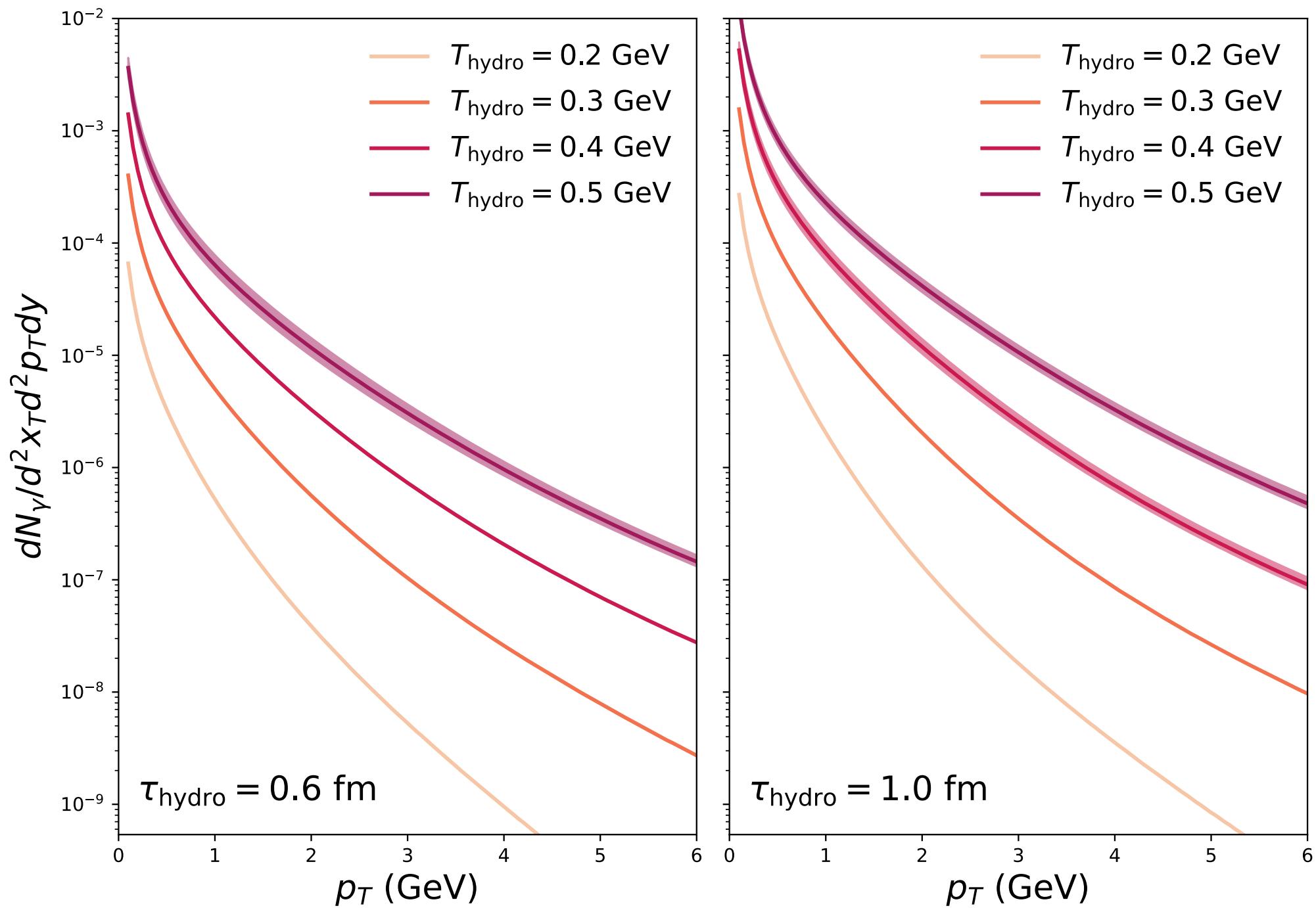
$$\frac{dN}{d^2x_T d^2p_T dy} = \frac{\nu_\gamma}{(2\pi)^3} \frac{(\tau^{1/3} T)_\infty^6}{p_T^4} 4 \int d\left(\frac{p}{T}\right) \left(\frac{p}{T}\right)^4 \bar{C}_\gamma^{\text{eq}}\left(\frac{p}{T}\right)$$

where

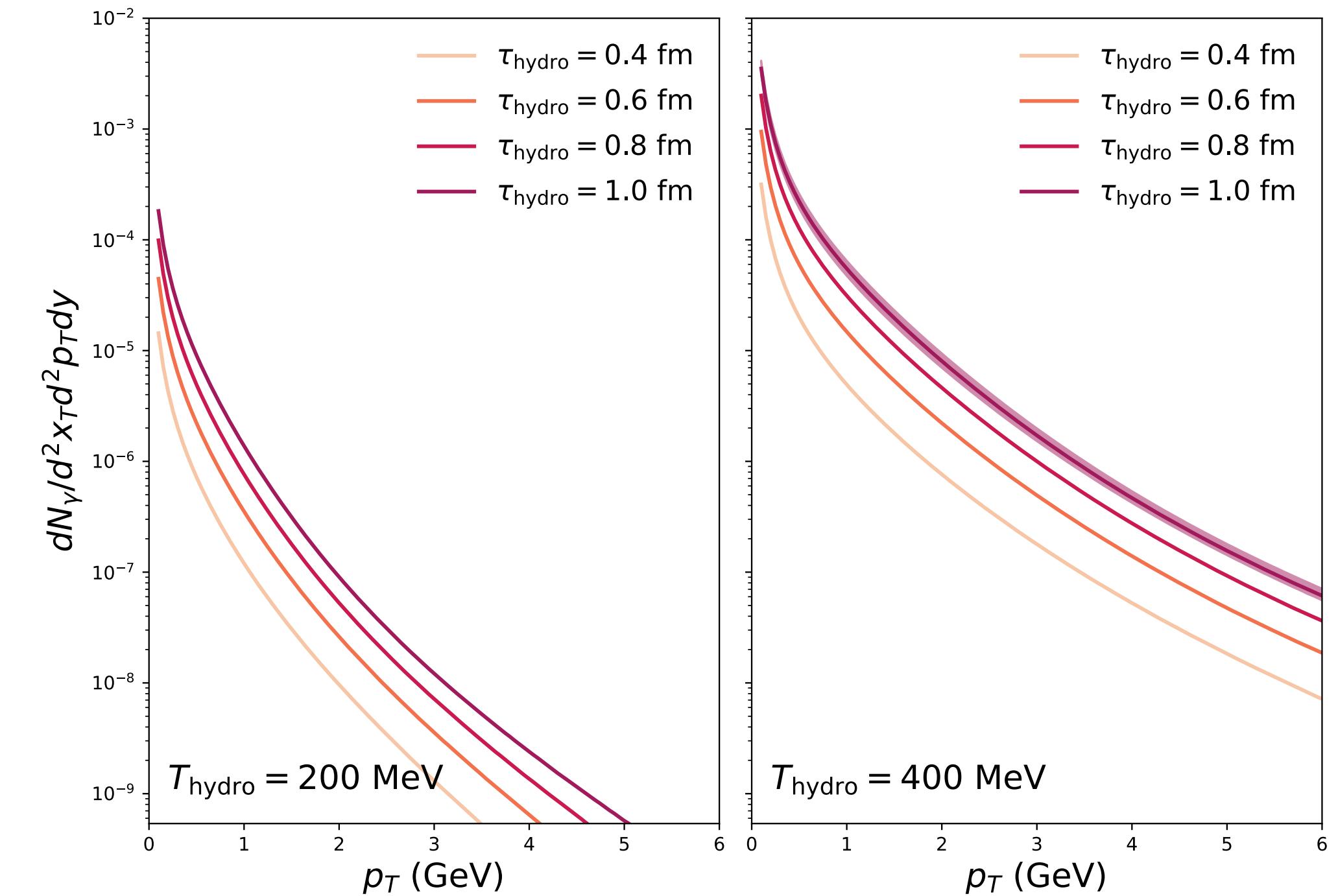
$$\tilde{C}_\gamma^{\text{ideal}} = 4 \int d\left(\frac{p}{T}\right) \left(\frac{p}{T}\right)^4 \bar{C}_\gamma^{\text{eq}}\left(\frac{p}{T}\right)$$

Backup - Spectrum η/s -dependence

Fixed temperature



Fixed switching time



Variations of η/s from 0.08 to 0.16
for $\tilde{C}_\gamma^{\text{ideal}} = 1.019$ (from EKT simulations)

Backup - Dilepton comparison EKT & RS

