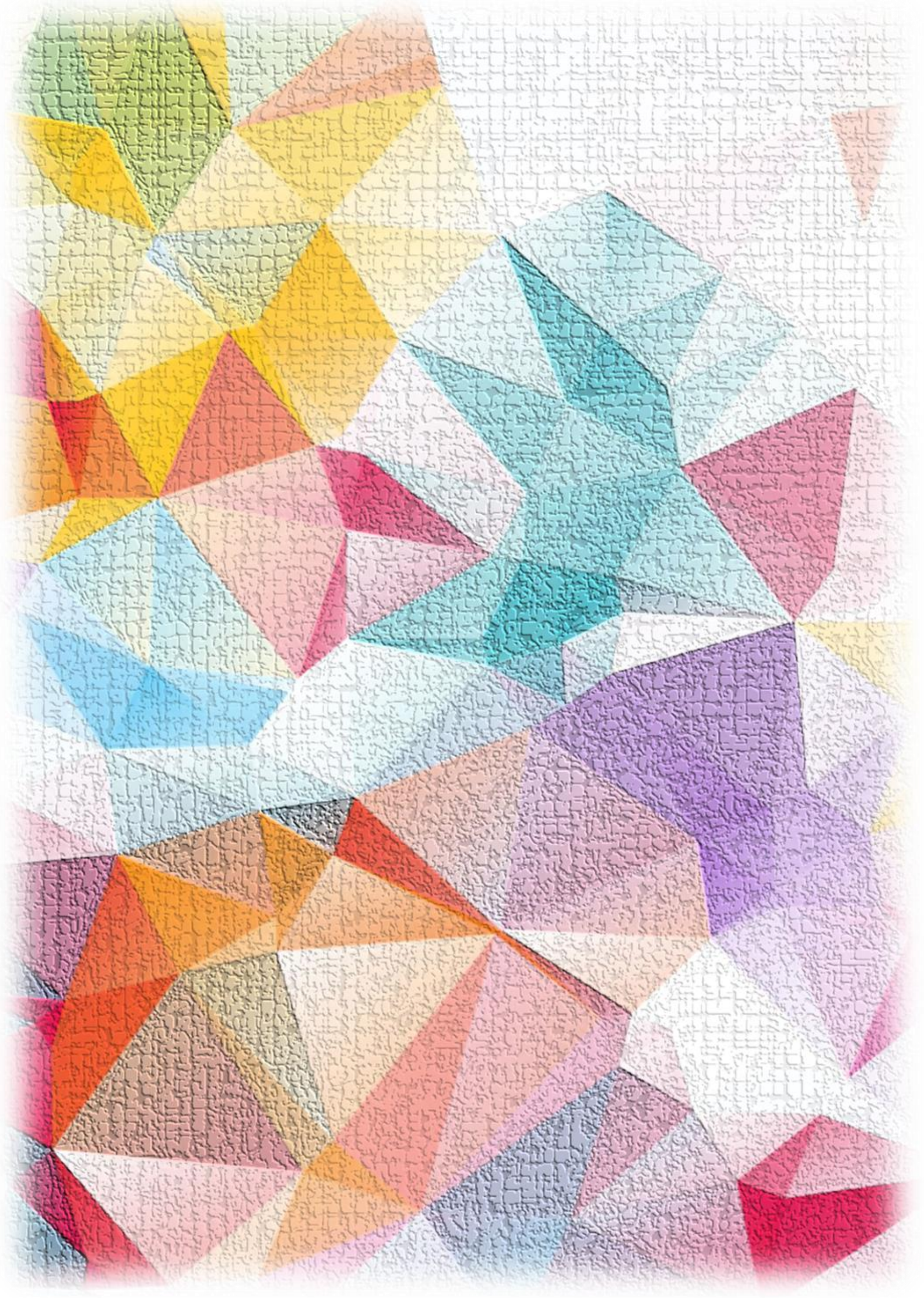


Tracing early time dynamics through high energy probes

Souvik Priyam Adhya

Institute of Physics of the Czech Academy of Sciences, Prague

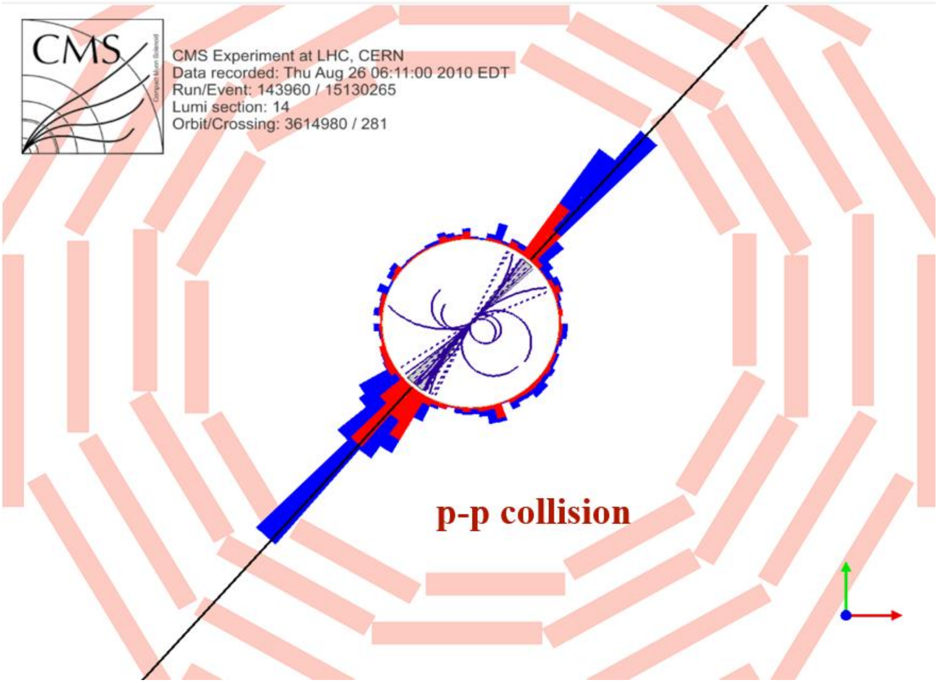
PHYSICS
FOR
FUTURE
FZU

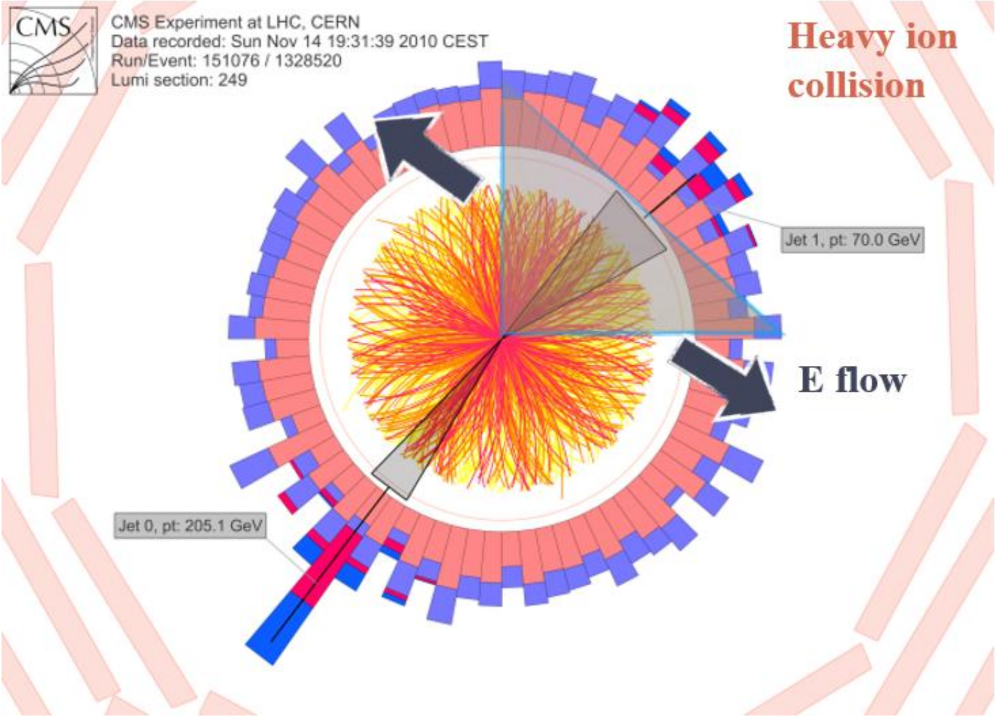
Initial Stages, Taipei, Taiwan, 2025

Co-funded
by the European Union

The “jet” definition

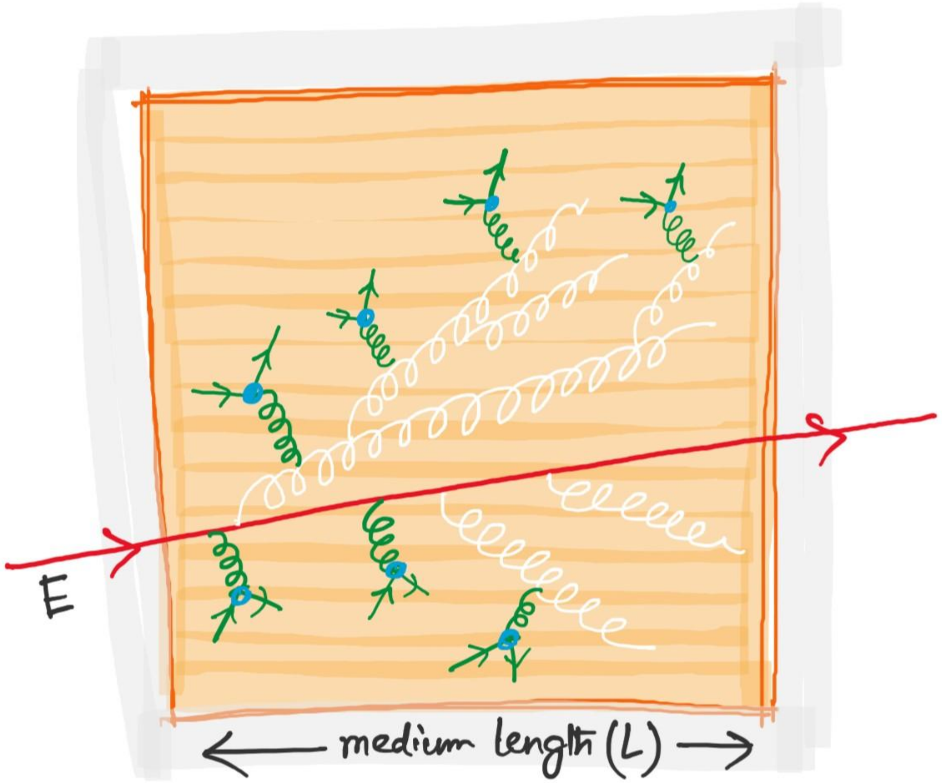
- Collision of high-energy particles produces jets of elementary particles.
- Formation of hot & dense medium comparable to the conditions in early Universe.
- Jets *interact with medium*, leading to reduction of their energy *called "jet quenching"*.

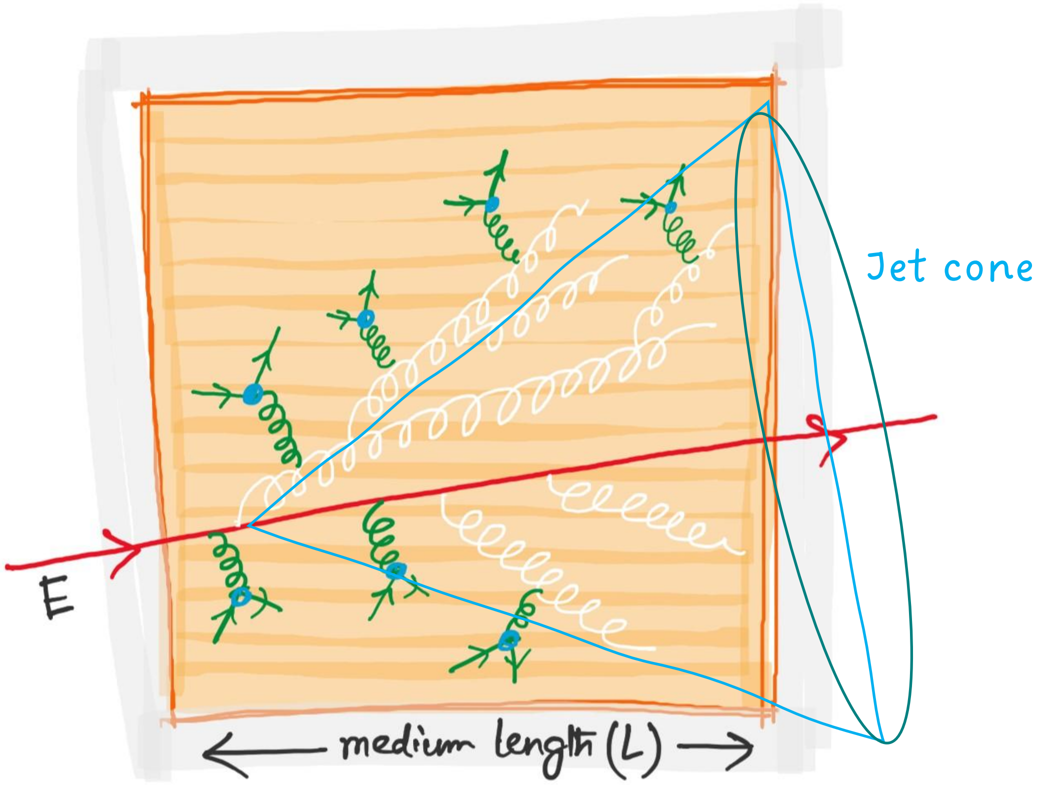




energy is lost in soft particles at large angles

Parton propagation: the picture





- Propagation of fast parton (q and g) inside medium ➔ Branching + Scattering
  - *Dynamical picture*
  - Information on "soft" and hard gluons in angular space (through jet cone).

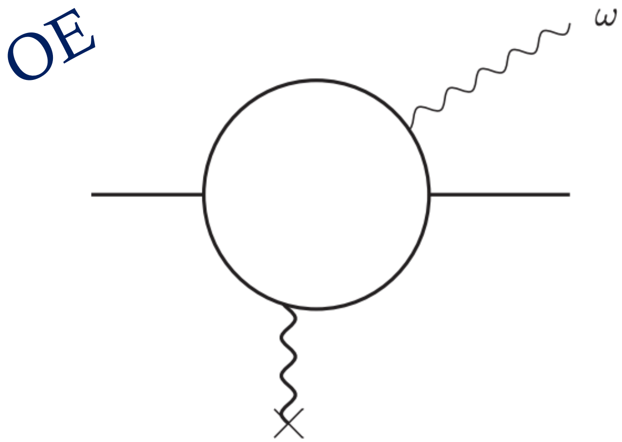
Our field has explored … and wants more …

- QUESTION: *Are we sensitive to the initial stage dynamics through jet observables ?*
  - *Jets sensitive to medium dynamics at early stages* [**SPA**, KT : 2409.04295]
  - *Gamma-jet spectra are sensitive to the initial state PDFs* [**SPA**, MR, KK, WP, KT : EPJC 85 343 (2025)]
- *ADVANTAGE for parton shower models ?*
  - Crucial for understanding medium effects on observables, like jet substructure.
  - Simple form for spectra and rate to better understand relevant scales governing modifications.
- *Finite medium size effects :*
  - realistic medium (**expanding**); relevant for phenomenological parton shower models.
  - validity of soft multiple and hard scattering as function of energy as well as initial medium quenching time.

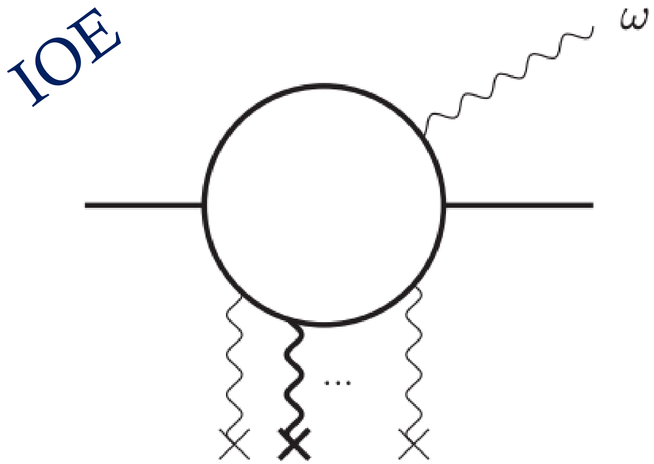
Earlier works on expanding scenarios : SPA, Kutak, Placzek, Rohrmoser, Tywoniuk, EPJC, 2022, EPJC 2025
SPA, Salgado, Spousta, Tywoniuk, EPJC, 2022**; SPA**, Salgado, Spousta, Tywoniuk, JHEP, 2020.

Jet quenching in dynamic medium

Our tool : Improved Opacity Expansion (IOE)



In medium Single scattering



One hard scattering (thick wavy line)
+
Multiple soft scattering

OE : Wiedemann (2000), Gyulassy, Levai, Vitev (2001)

IOE : Mehatr-Tani, Tywoniuk (2019), Barata, Takacs, Soto-Ontoso, Isaksen (2020 - 22)

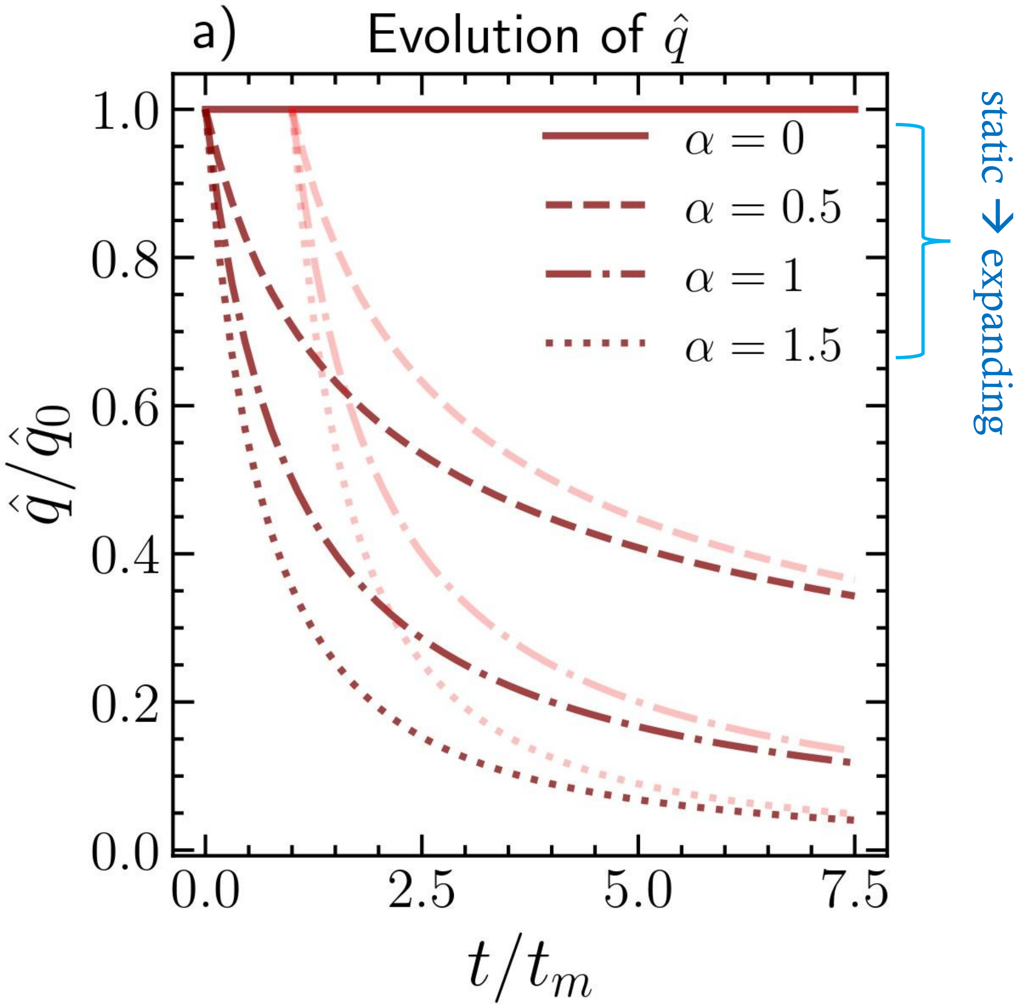
Medium expansion models

- Two toy models for the evolution of quenching parameter $\hat{q}$:
  - model (i) : initially *over-occupied system*.
    (mimics a bottom-up thermalisation scenario, fluid dynamics after t_m ; Glasma like IC)
  - model (ii) : initially *under-occupied system*.
    (effective for Kinetic theory calculations)

$$\hat{q}_0(t) = \begin{cases} \hat{q}_0 \left(\frac{t_m}{t+t_m}\right)^{\alpha} & \text{for model } \texttt{(i)}\,, \quad \text{[dark line]} \\ \hat{q}_0 \Theta(t-t_m) \left(\frac{t_m}{t}\right)^{\alpha} & \text{for model } \texttt{(ii)} \quad \text{[light line]} \end{cases}$$

t_m = "hydrodynamization time"; α = expansion parameter

- Sensitivity of the jets to expanding model scenarios on quenching observables [Andres 2022, Caucal 2021, **SPA** 2020-24].



SPA, Tywoniuk :arXiv:2409.04295

Why shall we calculate the rate?

- *The in-medium emission rate* is local and hence feels the local property of medium unlike the spectra.

- ***$\hat{q}$ is now $\hat{q}(t)$*** : First time we do *IOE for time dependent problem.*

$$\Gamma(\omega, t) = \frac{dI^{med}}{d\omega dt} = \frac{4\alpha_s C_R}{\omega^2} \int_0^t \mathrm{d}t_0 \int_{\boldsymbol{p},\boldsymbol{p}_0} \underbrace{\Sigma(\boldsymbol{p}^2, t)} \frac{\boldsymbol{p}\cdot\boldsymbol{p}_0}{\boldsymbol{p}^2} \underbrace{\tilde{\mathcal{K}}(\boldsymbol{p}, t; \boldsymbol{p}_0, t_0)}$$

- Three-point correlator $\widetilde{K}(p, p_0)$: transverse momentum broadening experienced by gluon during its formation time (Green's function).

- Expansion of potential in elastic medium scatterings $\underbrace{v(\boldsymbol{z}, t)} = v_{\mathrm{HO}}(\boldsymbol{z}, t) + \delta v(\boldsymbol{z}, t)$

and for IOE : $\mathcal{K}(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1) = \mathcal{K}_{\mathrm{HO}}(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1) - \int_{\boldsymbol{z}} \int_{t_1}^{t_2} \mathrm{d}s\, \mathcal{K}_{\mathrm{HO}}(\boldsymbol{x}, t_2; \boldsymbol{z}, s)\delta v(\boldsymbol{z}, s)\mathcal{K}(\boldsymbol{z}, s; \boldsymbol{y}, t_1)$

$$\Sigma(\boldsymbol{k}^2, t) = \frac{\hat{q}_0(t)}{\boldsymbol{k}^2 + \mu^2}$$

Why shall we calculate the rate?

- The time-dependent medium potential $v(x,t)$ is related to the elastic scattering cross-section :

$$v(\boldsymbol{x},t) = \int_{\boldsymbol{q}} \sigma(\boldsymbol{q},t)\left(1 - \mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right)$$

where

$$\Sigma(\boldsymbol{p}^2,t) = \int_{\boldsymbol{q}} \Theta(\boldsymbol{q}^2 - \boldsymbol{p}^2)\sigma(\boldsymbol{q},t) \quad \left\{ \begin{array}{ll} \Sigma(\boldsymbol{k}^2,t) = \dfrac{\hat{q}_0(t)}{\boldsymbol{k}^2 + \mu^2} & \text{“G-W model”} \\ \Sigma(\boldsymbol{k}^2,t) = \dfrac{\hat{q}_0(t)}{m_D^2} \ln\left(\dfrac{\boldsymbol{k}^2 + m_D^2}{\boldsymbol{k}^2}\right) & \text{“HTL model”} \end{array} \right.$$

Note, MFP is now time dependent, $\Sigma(0,t) \equiv \lambda^{-1}(t)$

Potential re-written sum of: $v_{HO}(\boldsymbol{x},t) = \hat{q}(t)\boldsymbol{x}^2/4$ and $\delta v(\boldsymbol{x},t) = \hat{q}_0(t)\ln(1/(\boldsymbol{x}^2Q^2))\boldsymbol{x}^2/4$

Separation scale : Q^2

Improved opacity expansion rate

- We have *re-calculated for expanding medium* the first two orders that encompass multiple-soft (IR) and single hard (UV) scattering regimes.

The rate reads as :

$$\Gamma^{(0)}_{\mathrm{IOE}}(\omega,t) = \frac{\bar{\alpha}\hat{q}(t)}{\omega^2}(-\mathrm{Im})\mathrm{Tan}(t)\,,$$

$$\Gamma^{(1)}_{\mathrm{IOE}}(\omega,t) = \frac{\bar{\alpha}\hat{q}_0(t)}{\omega^2}(-\mathrm{Im})\mathrm{Tan}(t)\ln\left[\frac{\omega\,\mathrm{Cot}(t)}{2i e^{-\gamma_E}Q^2}\right]$$

where,

$$\mathrm{Tan}(t) = 1/\mathrm{Cot}(t) \equiv \underbrace{\frac{S(t,0)}{C(0,t)}}$$

S and *C* satisfy harmonic eqn. with boundary conditions

In soft limit:

$$\lim_{\omega\to 0}\Gamma^{(0)}_{\mathrm{IOE}}(\omega,t) = \bar{\alpha}\sqrt{\frac{\hat{q}(t)}{\omega^3}}\,,$$

$$\lim_{\omega\to 0}\Gamma^{(1)}_{\mathrm{IOE}}(\omega,t) = \bar{\alpha}\frac{\hat{q}_0(t)}{\sqrt{\hat{q}(t)\omega^3}} \times\left[\ln\frac{\sqrt{\hat{q}(t)\omega}}{Q^2} + \gamma_E - \frac{3}{2}\ln 2 + \frac{\pi}{4}\right]$$

In high energy limit, the HO term strongly suppressed:

$$\lim_{\omega\to\infty}\Gamma^{(1)}_{\mathrm{IOE}}(\omega,t) = \bar{\alpha}\frac{\pi}{2}\frac{\hat{q}_0(t)t}{\omega^2}$$

identical to the hard limit of the opacity expansion.

Dressed transport coeff. : $\hat{q}(t) = \hat{q}_0(t)\ln Q^2/\mu^2$

Medium rates : novel kinematical conditions

- Ratio of radiative spectrum to NLO in expansion around LO gives matching scale Q.

$$\left.\frac{\Gamma^{(1)}_{\rm IOE}}{\Gamma^{(0)}_{\rm IOE}}\right|_{\omega\ll\omega_c(t)} = \frac{\hat{q}_0}{\hat{q}}\left[\gamma_E + \frac{\pi}{4} - \frac{3}{2}\ln 2 + \boxed{\ln\frac{\sqrt{\hat{q}(t)\omega}}{Q^2}}\right]$$

  - Need to scale fixing of correction : Log term should disappear

SPA, Tywoniuk :arXiv:2409.04295

Medium rates : novel kinematical conditions

- Ratio of radiative spectrum to NLO in expansion around LO gives matching scale Q.

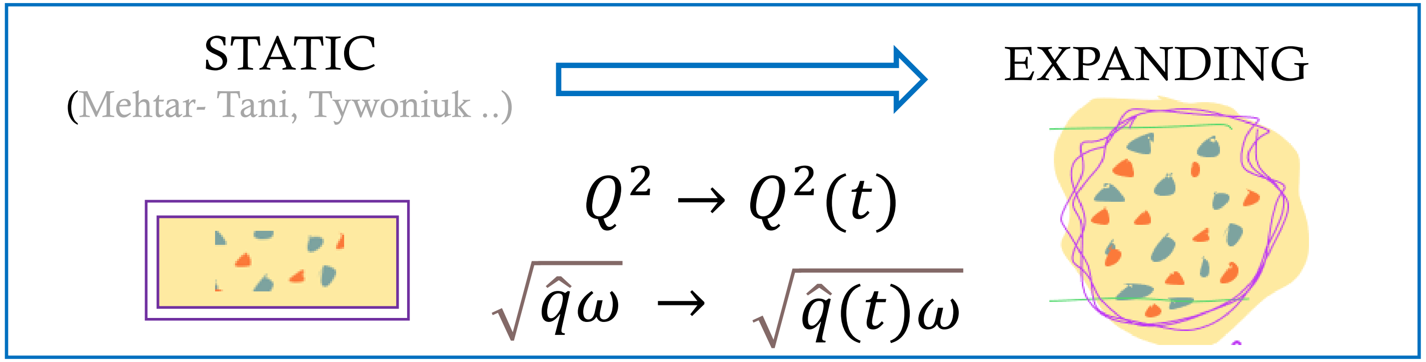
$$\frac{\Gamma^{(1)}_{\mathrm{IOE}}}{\Gamma^{(0)}_{\mathrm{IOE}}}\bigg|_{\omega \ll \omega_c(t)} = \frac{\hat{q}_0}{\hat{q}}\left[\gamma_E + \frac{\pi}{4} - \frac{3}{2}\ln 2 + \boxed{\ln\frac{\sqrt{\hat{q}(t)\omega}}{Q^2}}\right]$$

$$\omega_c(t) = \hat{q}(t)t^2/2$$

$$\bar{\omega_c}(t) = \mu(t)^2 t/2$$

$$\omega_{BH}(t) = \mu^2\lambda(t)/2$$

- Need to scale fixing of correction : Log term should disappear



STATIC

(Mehtar- Tani, Tywoniuk ..)

EXPANDING

$$Q^2 \rightarrow Q^2(t)$$

$$\sqrt{\hat{q}\omega} \rightarrow \sqrt{\hat{q}(t)\omega}$$

Birth of a new kinematical condition

$$\boxed{1 \ll \frac{t}{\lambda_0}\left(\frac{t_m}{t}\right)^{\alpha}}$$

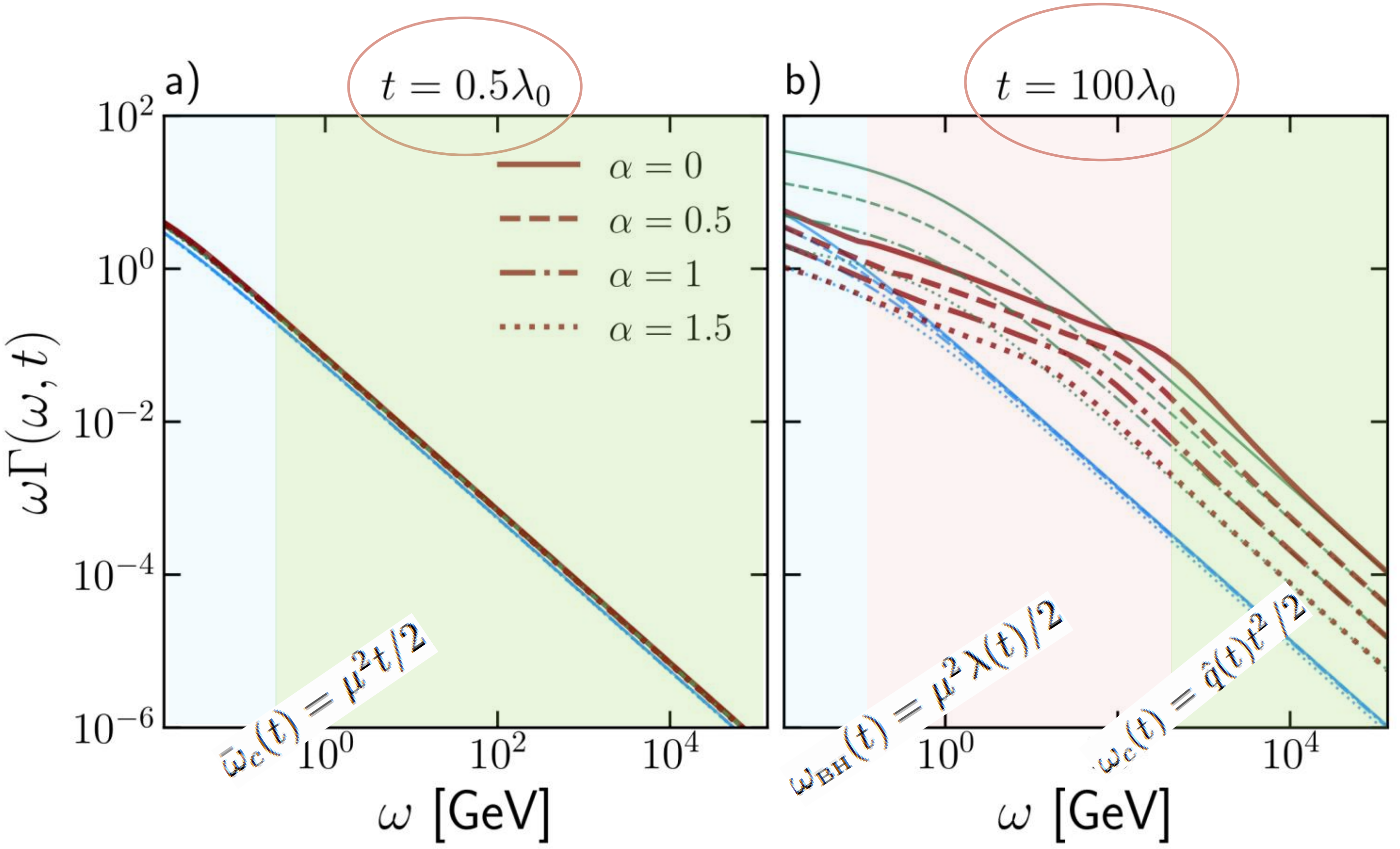
for $\omega_C(t) >> \omega_{BH}(t)$

- Interestingly, *such simple form for local dynamic matching valid for rate only and not spectra* !

SPA, Tywoniuk :arXiv:2409.04295

Medium rates : completely analytical

- Re-summation schemes , covering the whole emission phase space :
  - Opacity expansion (N = 1)
  - Improved opacity expansion (IOE)
- (fig. a) : Rate in *dilute regime;* not reached 1 MFP in medium, *not expanded* yet.
- (fig. b) : *Considerable expansion*, all phases showing up.



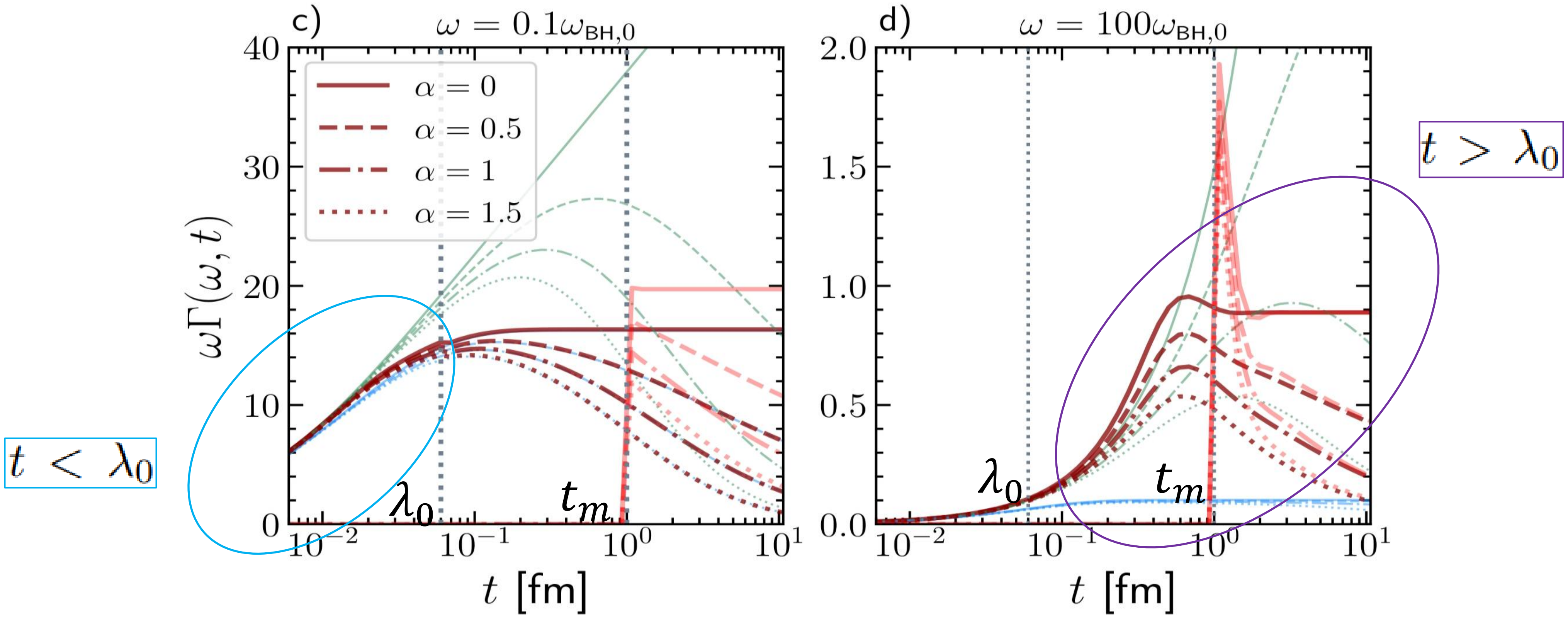
Insensitive to medium expansion

Sensitive to medium expansion

Assumptions : For limit ω << 1 GeV, thermal masses and non-perturbative effects not included.

SPA, Tywoniuk :arXiv:2409.04295

Medium rates : completely analytical



- (Left) Medium expansion has no effect *[early emissions in dilute media]*, OE rates valid.
- (Right) Medium expansion has effect on both quenching models *across all resummation schemes*.
- The re-summation schemes matched through time dependent kinematic scales.

SPA, Tywoniuk :arXiv:2409.04295

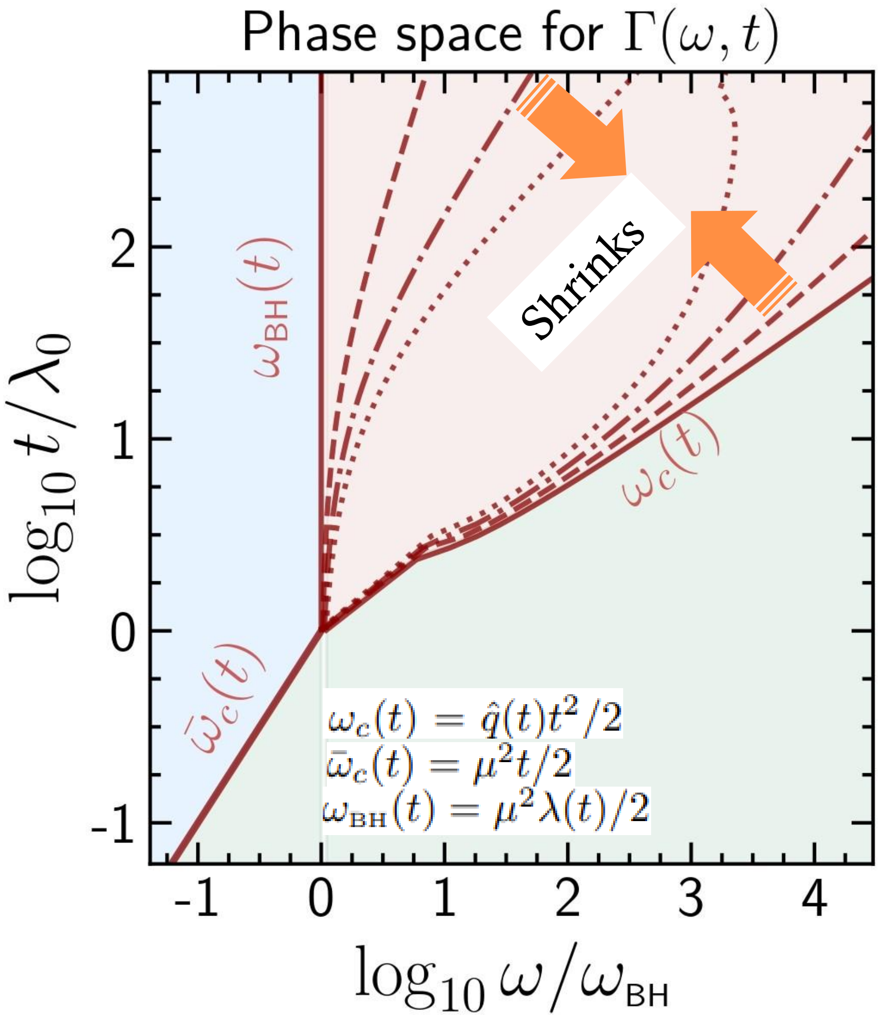
Medium rates : novel kinematical conditions

Medium "hydrodynamization" time should be much bigger than the mean-free-path $t_m \gg \lambda_0$ in order to get contributions from multiple scattering regime
(example: check Bjorken expansion)

$$\boxed{1 \ll \frac{t}{\lambda_0}\left(\frac{t_m}{t}\right)^{\alpha}}$$

Check the shrinking phase space for expanding profiles !

Rethink : *Decreased multiple scattering regime for radiative in-medium parton showers !*

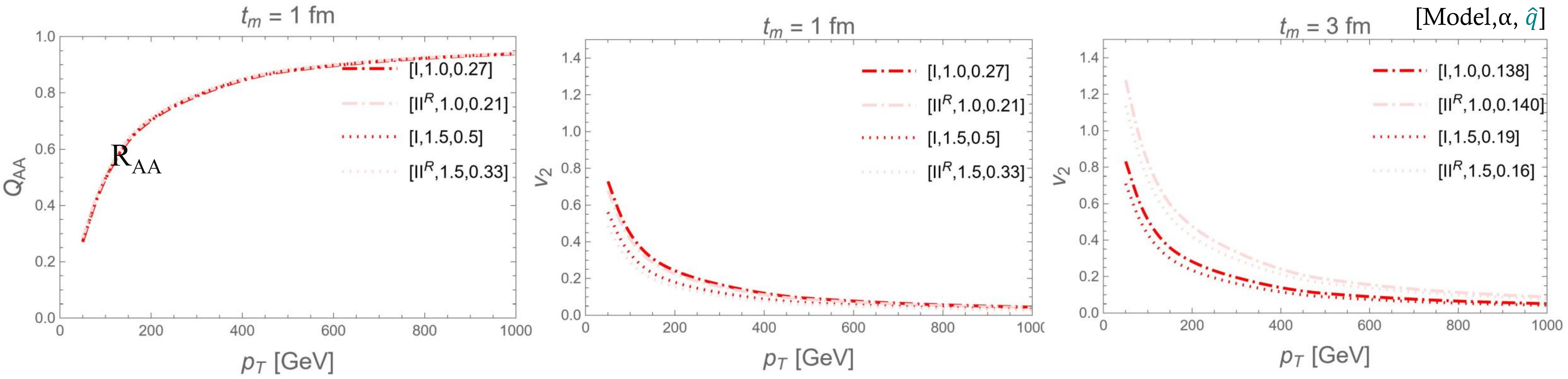


SPA, Tywoniuk :arXiv:2409.04295

Phenomenological consequence : R_{AA} and v_2

- Q_{AA} is not sensitive to the expansion models I and II.
- v_2 coefficient is marginally more sensitive :
  - Model I : No sensitivity to t_m
  - Model II : Sensitivity (enhancement) to t_m

- Assumptions : fully coherent jets, energy loss proceeds as off a single parton.



[Model,α, $\hat{q}$]

Phenomenological consequence : R_{AA} and v_2

What about other initial effects ?

Can we disentangle saturation effects via TMDs and medium induced broadening ?

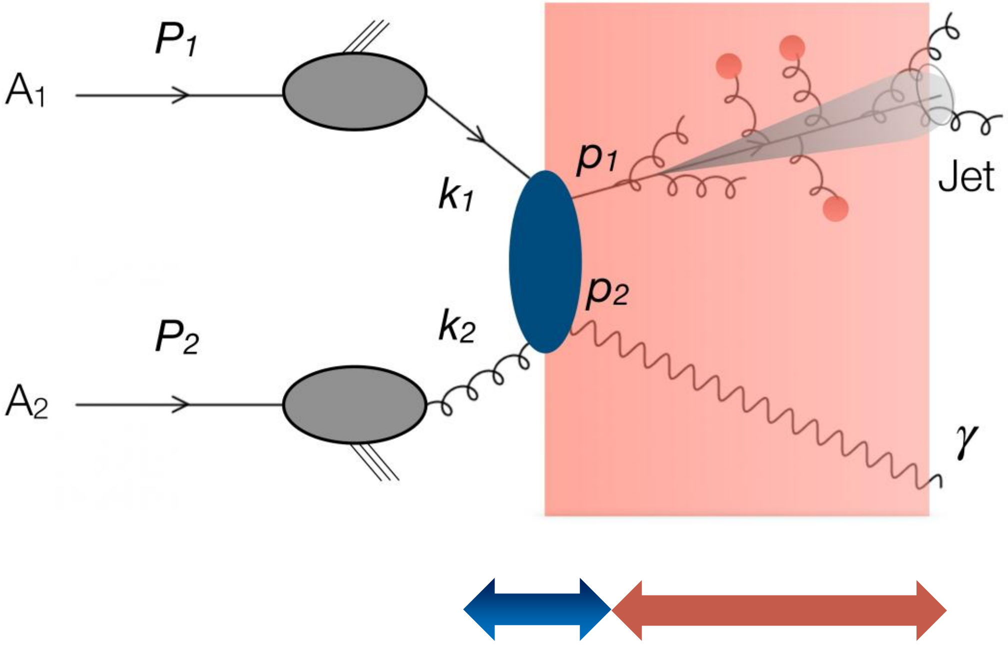
γ-jet at forward rapidity (FoCaL, ALICE)

- Currently, no LHC experiments explicitly studies saturation physics, to be observed in processes where longitudinal momentum of target probed at $x < 1E\text{-}5$.
- In the LHC jet kinematics, this corresponds to particle production in a forward rapidity region : $x \propto exp(-y)$.
- Forthcoming FoCal, ALICE shall measure jets and photons at $3.4 < \eta < 5.8$.

In pPb collisions, strong saturation effects. True for A-A collisions in spite of medium modifications (VLE + BDIM) ?

TMDICE MC : Rohrmoser 2022
KATIE : van Hameren 2018

$A_1 + A_2 \rightarrow \gamma + \text{jet} + X$



KATIE MC
+
Gluon TMDs

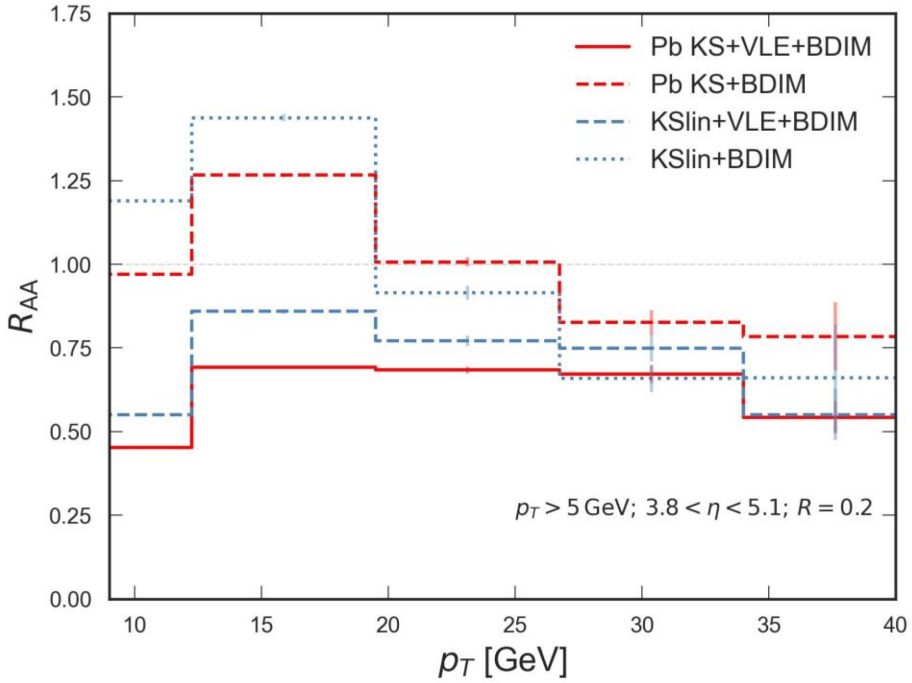
TMDICE MC
+
Fastjet

---

x : momentum fraction of the nucleon carried by struck parton
Wang & Huang (1997)

γ-jet at forward rapidity (FoCaL, ALICE)

- Currently, no LHC experiments explicitly studies saturation physics, to be observed in processes where longitudinal momentum of target probed at $x < 1E\text{-}5$.
- In the LHC jet kinematics, this corresponds to particle production in a forward rapidity region : $x \propto exp(-y)$.
- Forthcoming FoCal, ALICE shall measure jets and photons at $3.4 < \eta < 5.8$.



- Gluon Transverse Momentum Distributions (TMD) configurations :
  - KSlin: No gluon saturation effects, solution of BFKL equation, DGLAP splitting functions.
  - Pb KS : *Gluon saturation*, gluon density solution of BK equation, Sudakov effects, DGLAP splitting functions.

- *Takeaway : Considerable saturation effects (with medium effects) at forward rapidity.*
- *Baton passed to experimentalists (ALICE) with their upcoming FOCAL detector.*

SPA, Kutak, Placzek, Rohrmoser, Tywoniuk: EPJC (2025)

Summary and future challenges

- Incorporation of re-summation techniques for medium induced gluon emissions in *expanding medium*:
  - Finite size realistic medium effects.[1]
  - Analytical results : Effective designing of existing Parton shower MCs (**faster, precise**).
  - *Rates are generic*, can be applied to **small collision systems**.
- Future predictions for ALICE : Description of photon-jet events in forward direction (FOCAL-range) via Monte-Carlo algorithms (saturation + quenching) [2].

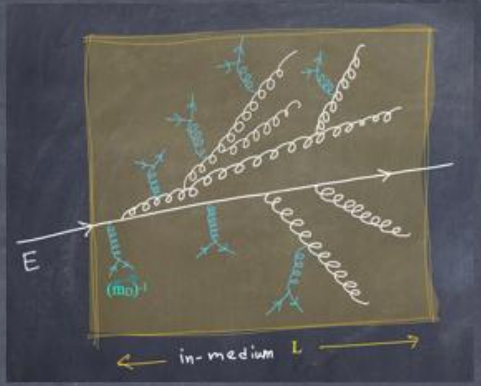
Looking forward to views, suggestions and criticisms !

---

[1] SPA, Tywoniuk :arXiv:2409.04295

[2] SPA, Kutak, Placzek. Rohrmoser, Tywoniuk, EPJC 85 343 (2025)

In- medium gluon evolution equations



The gluon evolution inside a medium is described by the BDIM equation :

$$\frac{\partial}{\partial t}D(x,k,t) = \frac{1}{t^*}\int_0^1 dz\,\boxed{\tilde{\mathcal{K}}(z,t)}\Big[\underbrace{\frac{1}{z^2}\sqrt{\frac{z}{x}}D\Big(\frac{x}{z},\frac{k}{z},t\Big)}_{\text{gain term}}\theta(z-x) - \underbrace{\frac{z}{\sqrt{x}}D(x,k,t)\Big]}_{\text{loss term}} + \int \underbrace{\frac{d^2l}{(2\pi)^2}C(l,t)D(x,k-l,t)}_{\text{elastic collision term}}$$

Medium evolved gluon spectra

Splitting Kernel.

$$D \equiv \omega\frac{dN}{d\omega}$$

$$C(l,t) = \frac{4\pi\hat{q}}{l^2(l^2+m_D^2)}$$

$m_D \sim gT$ (Debye mass)

$$\frac{1}{t^*} = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\hat{q}}{E}} \longrightarrow \text{“Quenching parameter”.}$$

Integration over all 'k' drops off the collision term.

k = transverse momentum

x = energy fraction ; $0 \leq x \leq 1$

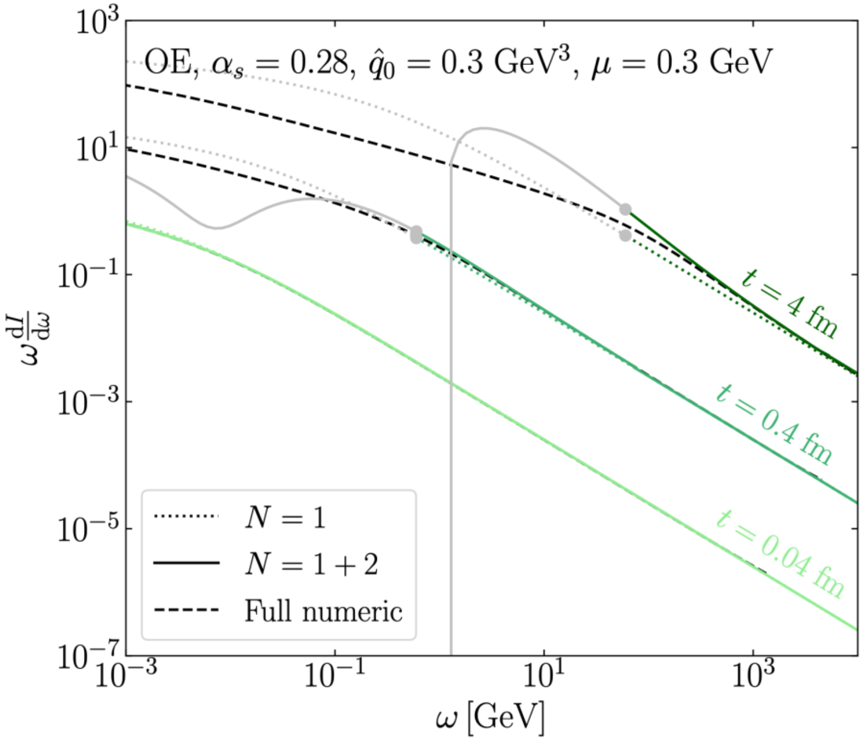
t = evolution length.

BACKUP

Blaizot, Dominguez, Iancu, Mehtar-Tani, 2014.

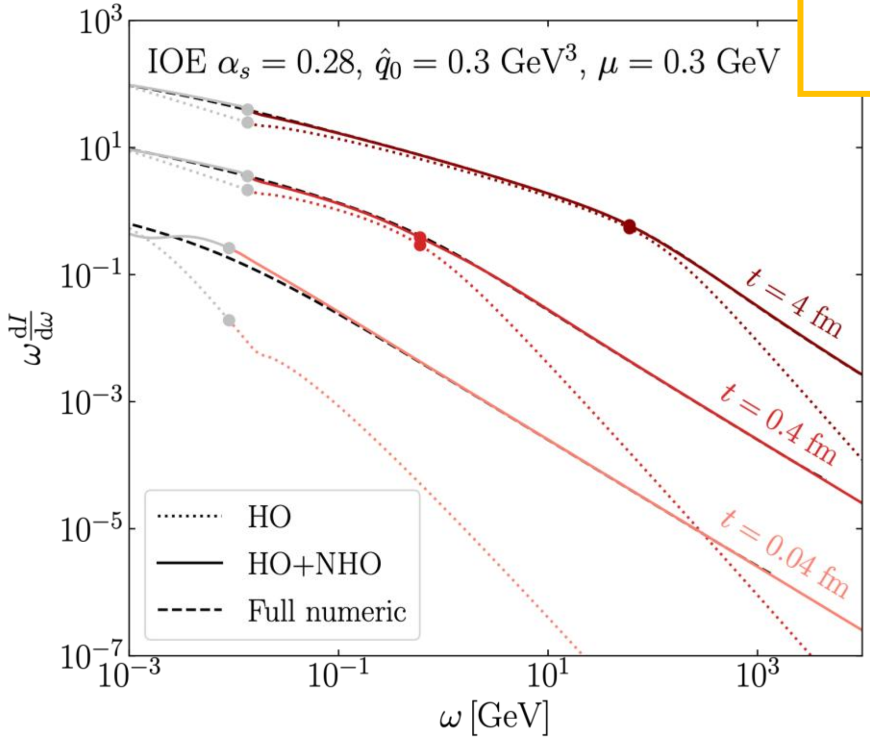
Recent : features of in-medium spectra

BACKUP



Opacity expansion spectra:

Direct expansion around vacuum in terms of L/λ (opacity), truncated at order 1 (N=1). Converges in dilute medium & hard regime.



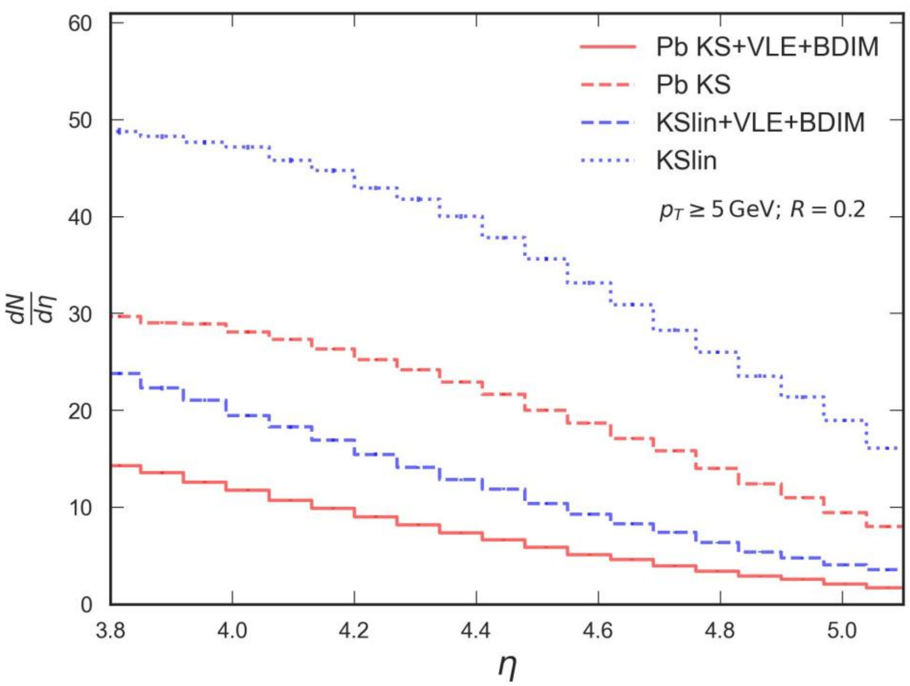
Improved opacity expansion spectra:

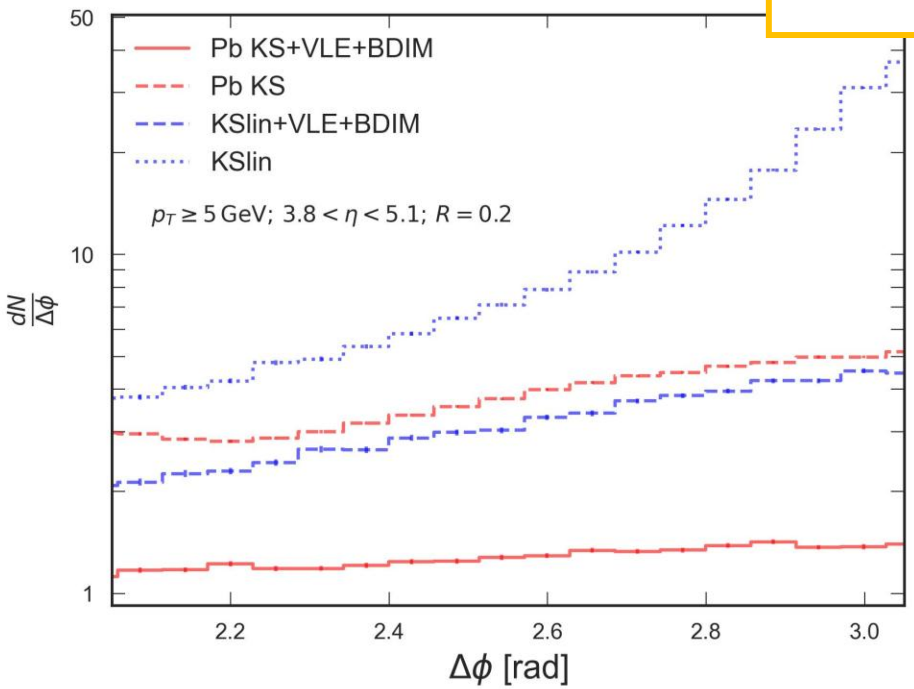
Expansion of rare, hard scattering on top of HO solution. Scale dependent quenching parameter. Converges in dense media above Bethe-Hietler energy.

Plots : [STATIC medium] Isaksen, Takacs, Tywoniuk (2023)

γ-jet rapidity and azimuthal correlations

BACKUP





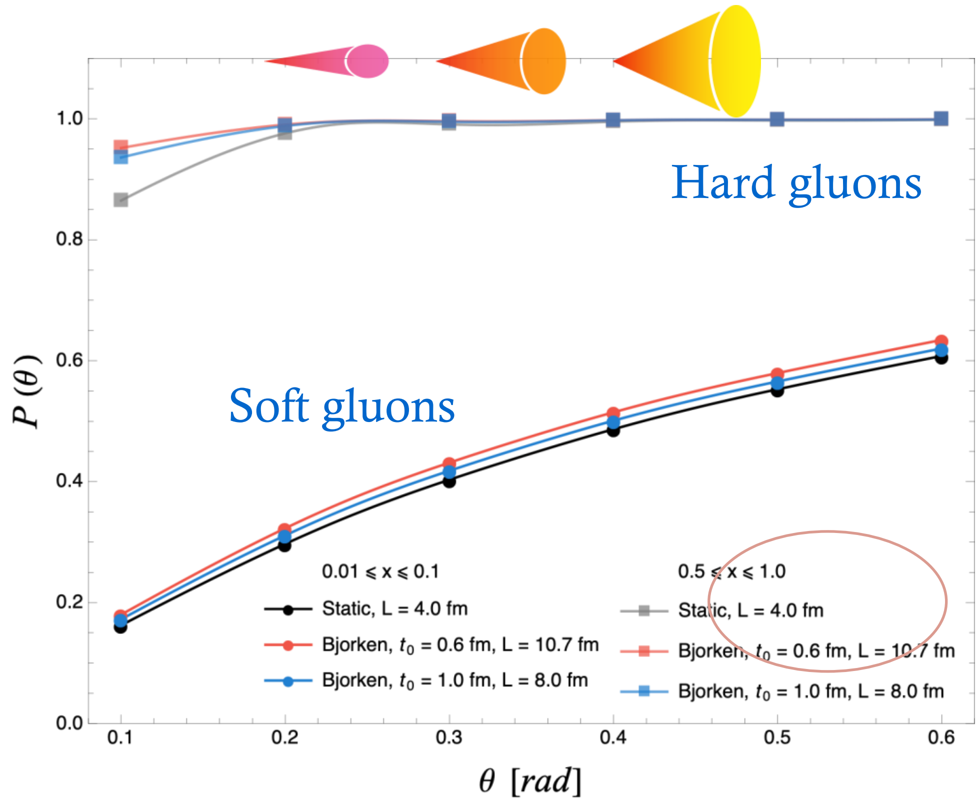
- Gluon Transverse Momentum Distributions (TMD) configurations :
  - KSlin: No gluon saturation effects, solution of BFKL equation, DGLAP splitting functions.
  - Pb KS : *Gluon saturation*, gluon density is a solution of the BK equation, Sudakov effects, DGLAP splitting functions.

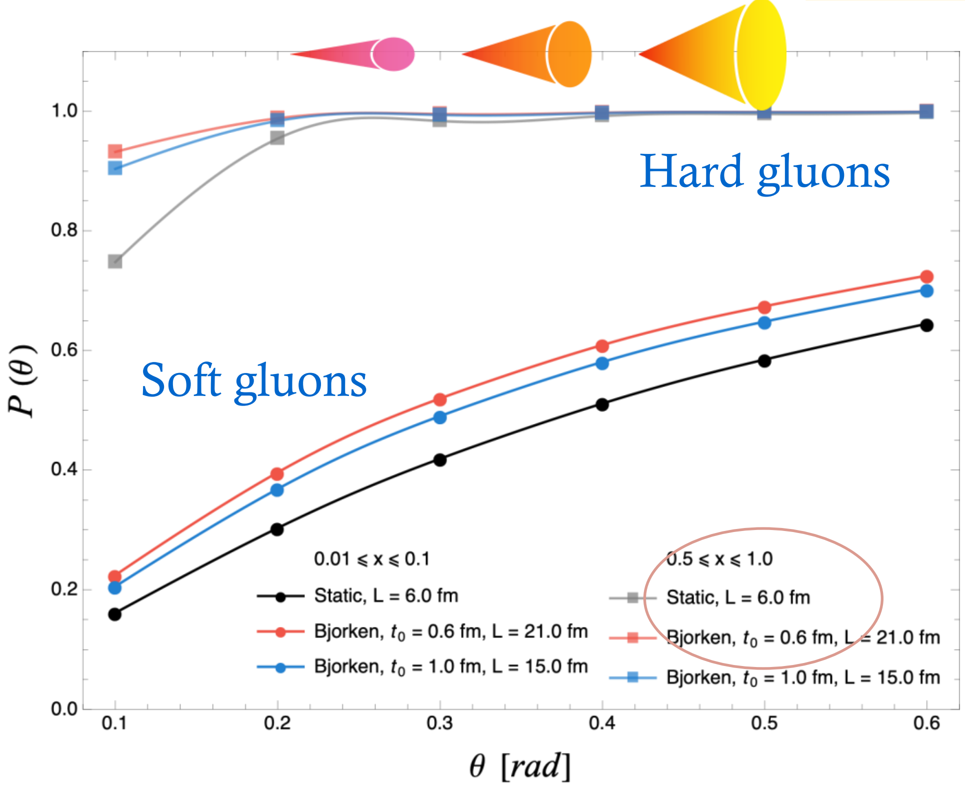
SPA, Kutak, Placzek, Rohrmoser, Tywoniuk: EPJC (2025)

Recap : phenomenological R_{AA} and v_2

BACKUP

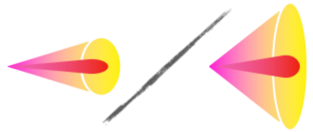
- Calculated with medium modified splitting rates.





- Significant differences in $q^\wedge$ for early and late Bjorken dynamics.

$$P(\theta, t; \{x_{\min}, x_{\max}\}) = \frac{\int_{x_{min}}^{x_{max}} \mathrm{d}x \int_0^{\theta} \mathrm{d}\theta' \, \bar{D}(x, \theta', t)}{\int_{x_{min}}^{x_{max}} \mathrm{d}x \int_0^{\pi} \mathrm{d}\theta' \, \bar{D}(x, \theta', t)} =$$



SPA, Kutak, Placzek, Rohrmoser, Tywoniuk, EPJC, 2022

SPA, Salgado, Spousta, Tywoniuk, EPJC, 2022; SPA, Salgado, Spousta, Tywoniuk, JHEP, 2020.