Tracing early time dynamics through high energy probes

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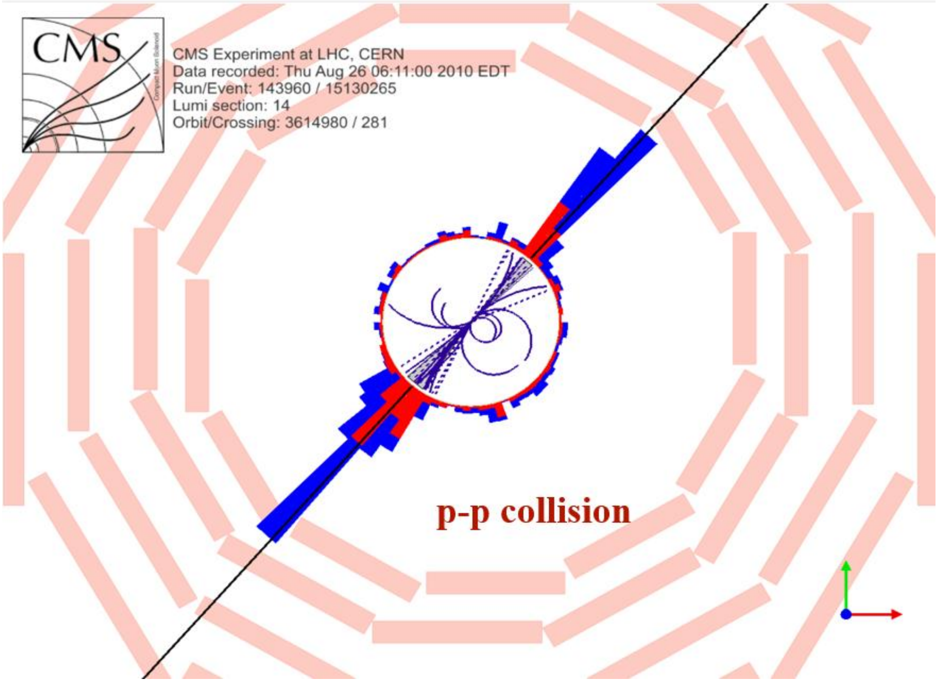
MARIE CURIE ACTIONS

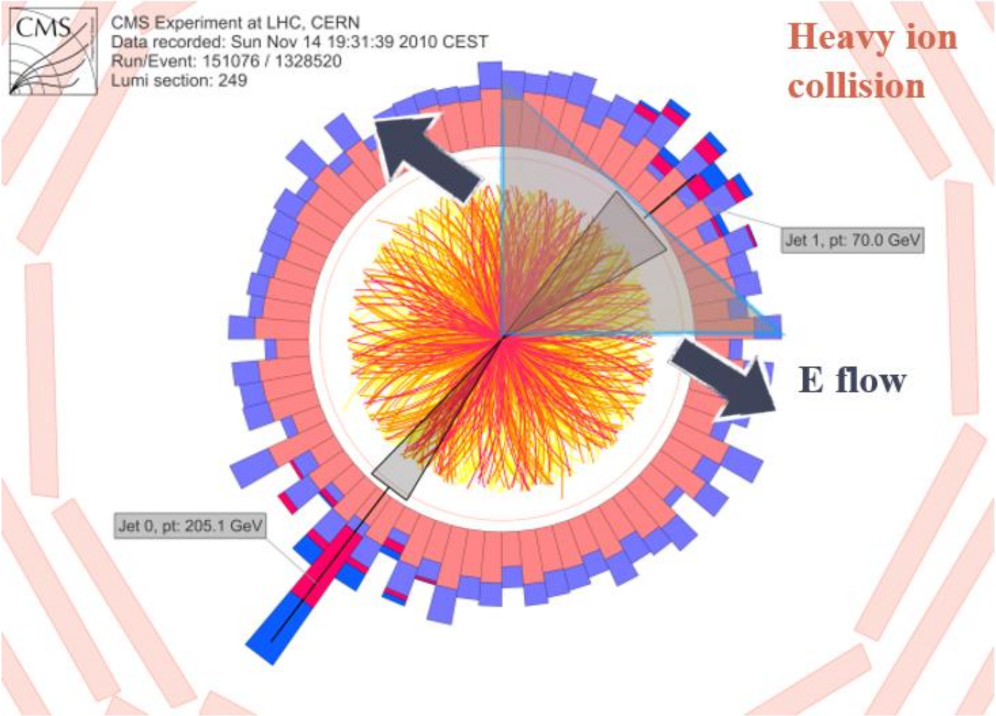
FZU

PHYSICS FOR FUTURE

The "jet" definition

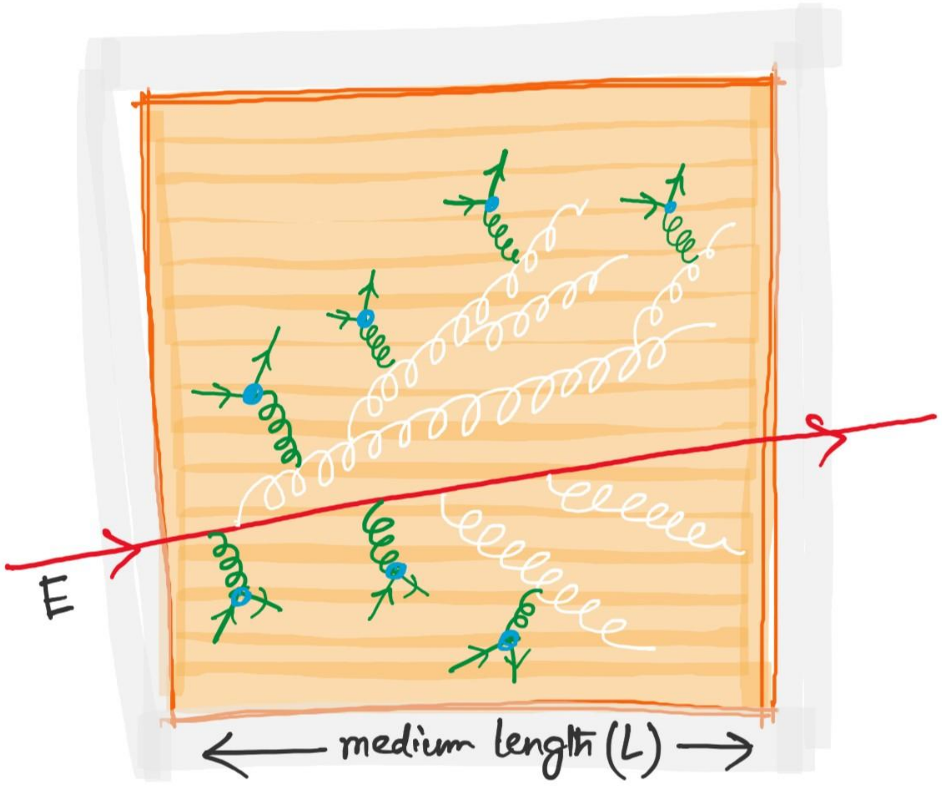
- Collision of high-energy particles produces jets of elementary particles.
- Formation of hot & dense medium comparable to the conditions in early Universe.
- Jets *interact with medium*, leading to reduction of their energy *called "jet quenching"*.

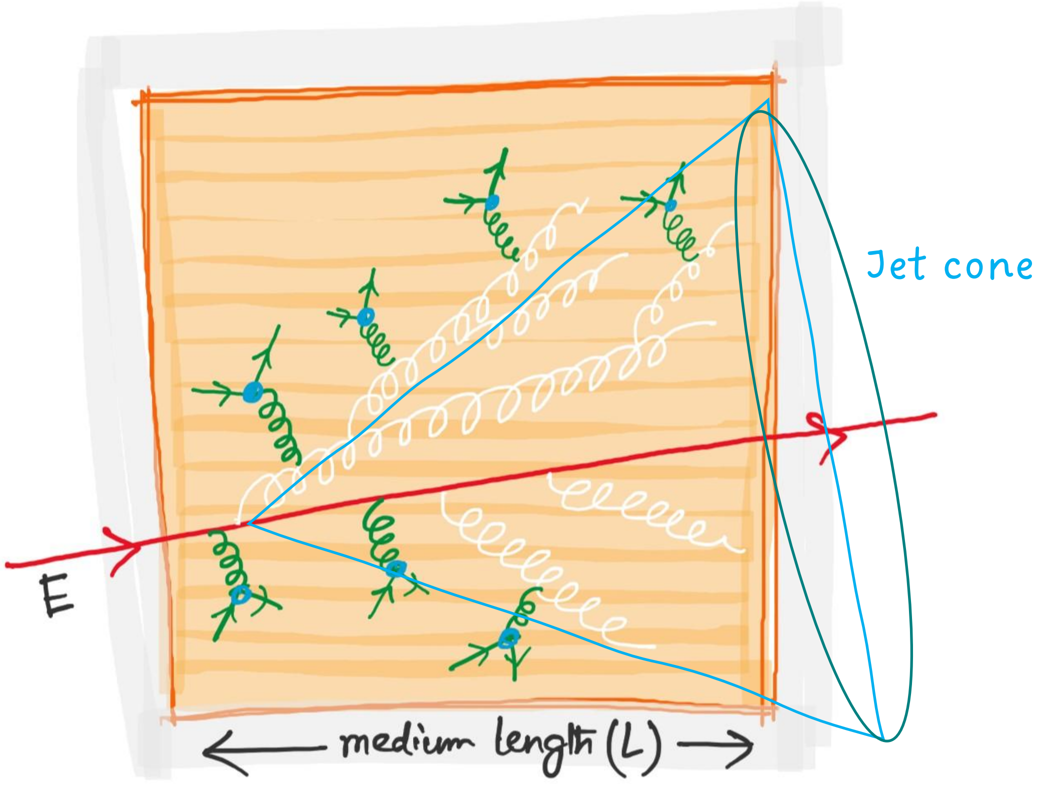




energy is lost in soft particles at large angles

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.

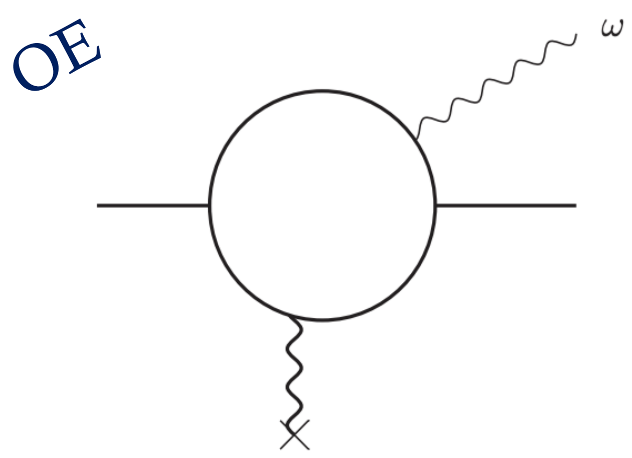
- *Finite medium size effects :*

    - 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.

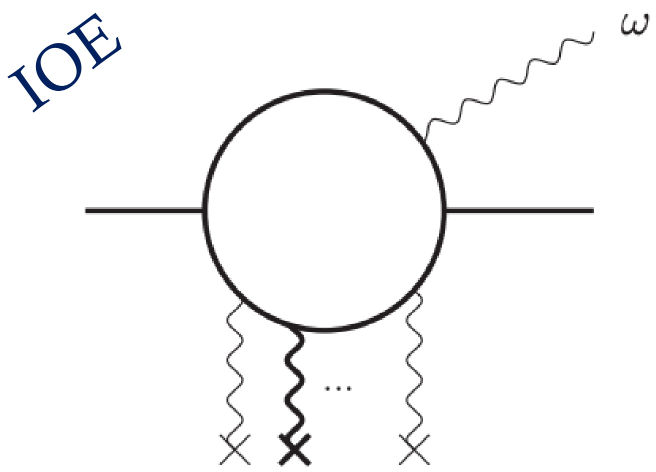
Earlier works on expanding scenarios : SPA, Kutak, Placzek, Rohrmoser, Tywoniuk, EPJC, 2022, EPJC 2025
SPA, Salgado, Spousta, Tywoniuk, EPJC, 2022**;** SPA, Salgado, Spousta, Tywoniuk, JHEP, 2020.

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)

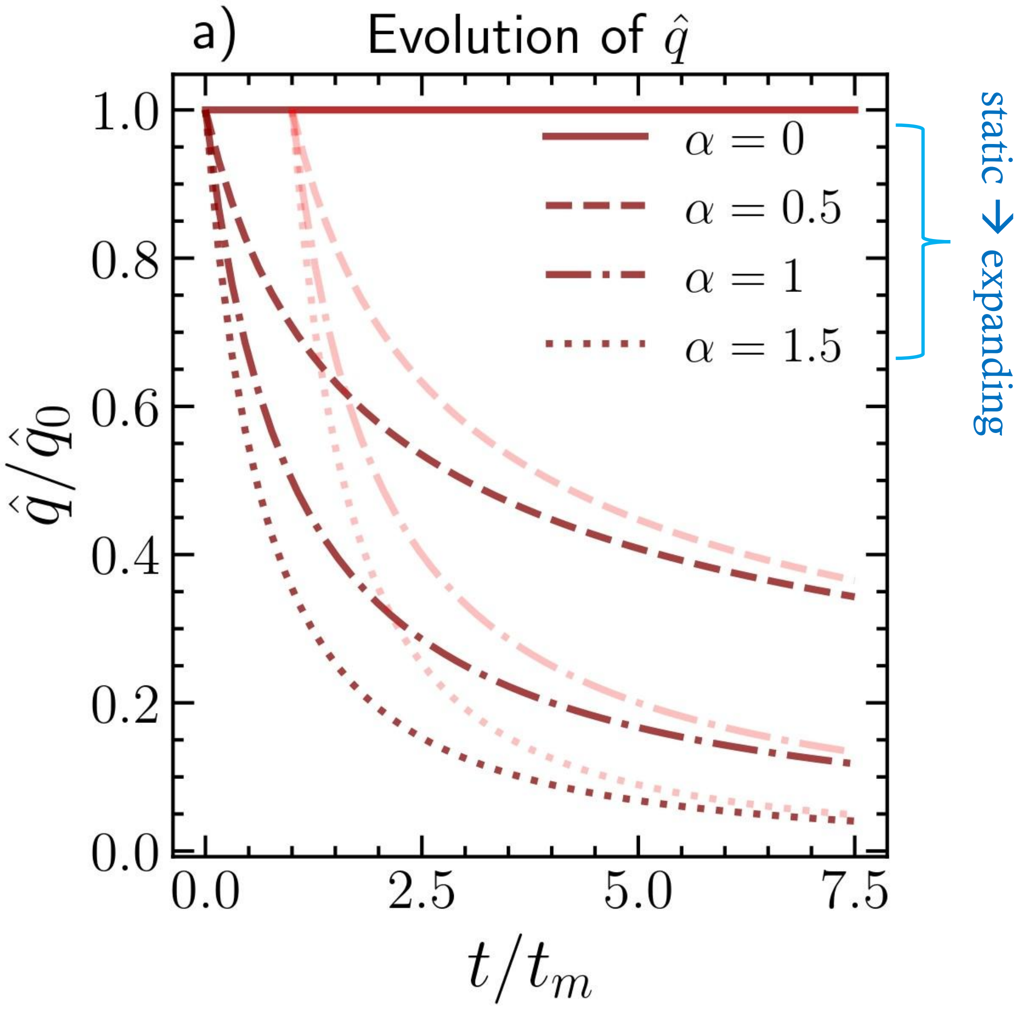
Medium expansion models

- 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)

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

t_m = "hydrodynamization time"; α = expansion parameter

- Previous works have explored the sensitivity of the jets to such expanding model scenarios on the quenching observables [Andres 2022, Caucal 2021, **SPA** 2020-24].



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

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

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 :

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

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

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

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

In soft limit:

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

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

In high energy limit, the HO term strongly suppressed:

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

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

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

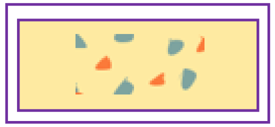
$$\bar{\omega_c}(t) = \mu(t)^2 t/2$$

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

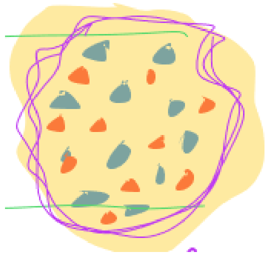
- Need to scale fixing of correction : Log term should disappear

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

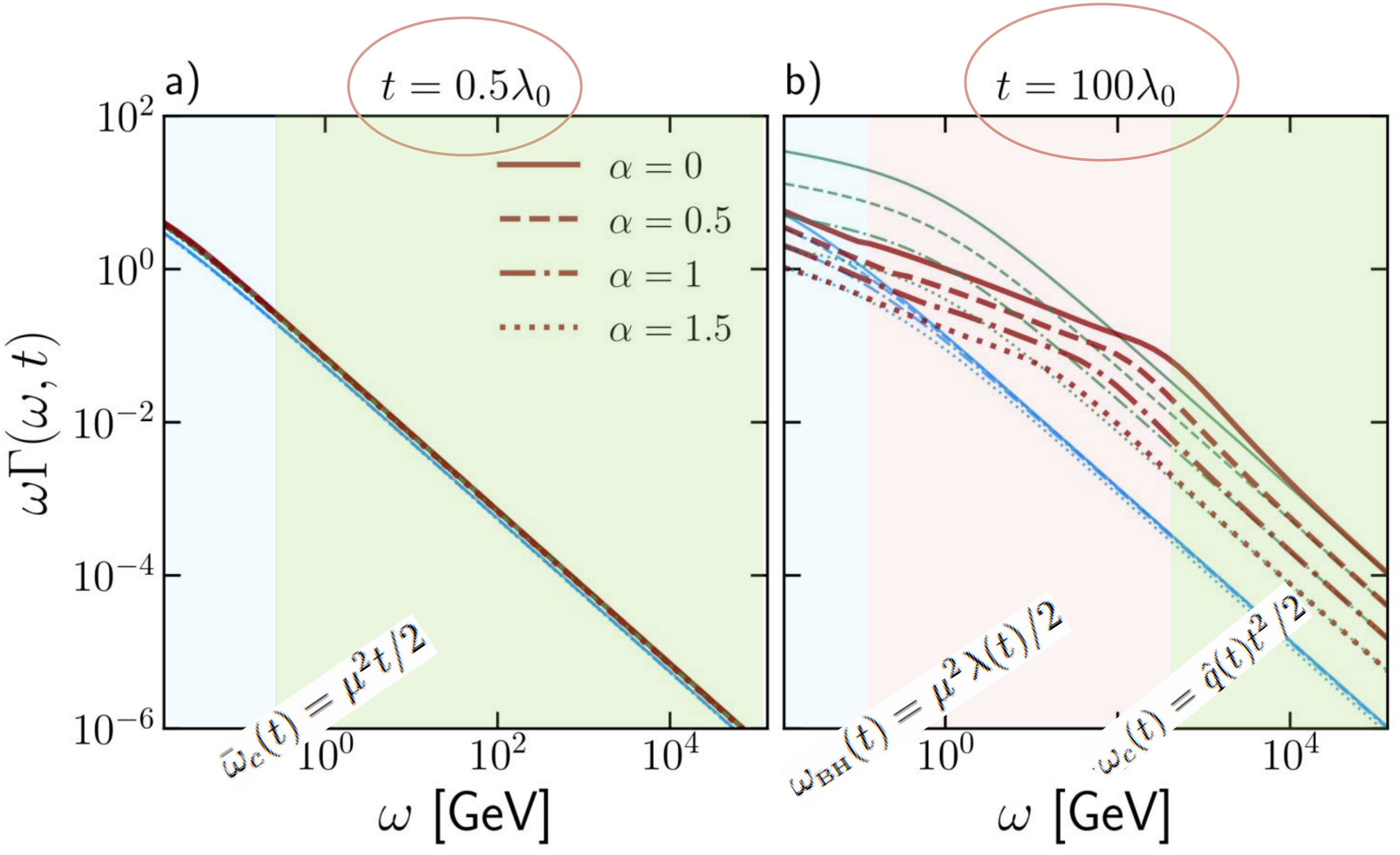
$$\boxed{1 \ll \frac{t}{\lambda_0}\left(\frac{t_m}{t}\right)^{\alpha}}$$

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

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

Medium rates : completely analytical

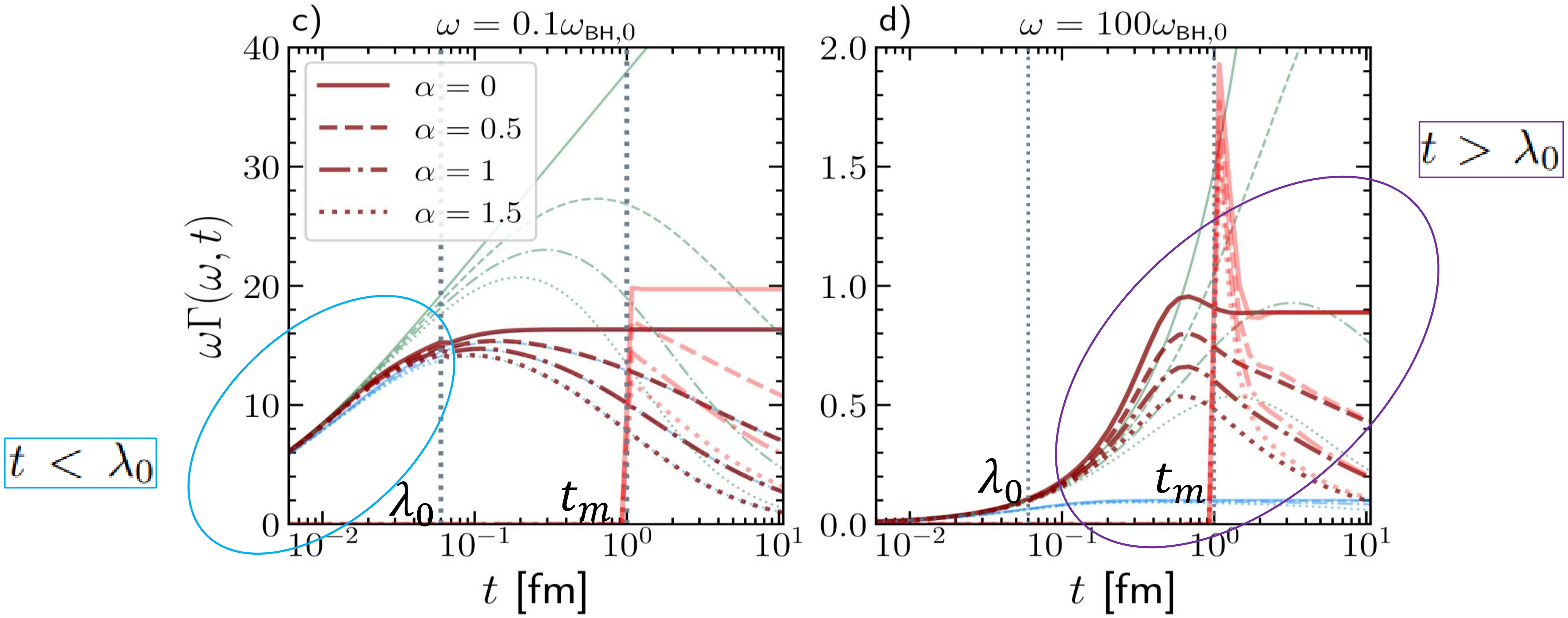
- Re-summation schemes , covering the whole emission phase space :
  - Opacity expansion (N = 1)
  - Improved opacity expansion (IOE)
- (fig. a) : Rate in *dilute regime;* not reached 1 MFP in medium, *not expanded* yet.
- (fig. b) : *Considerable expansion*, all phases showing up.



Insensitive to medium expansion Sensitive to medium expansion

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

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.

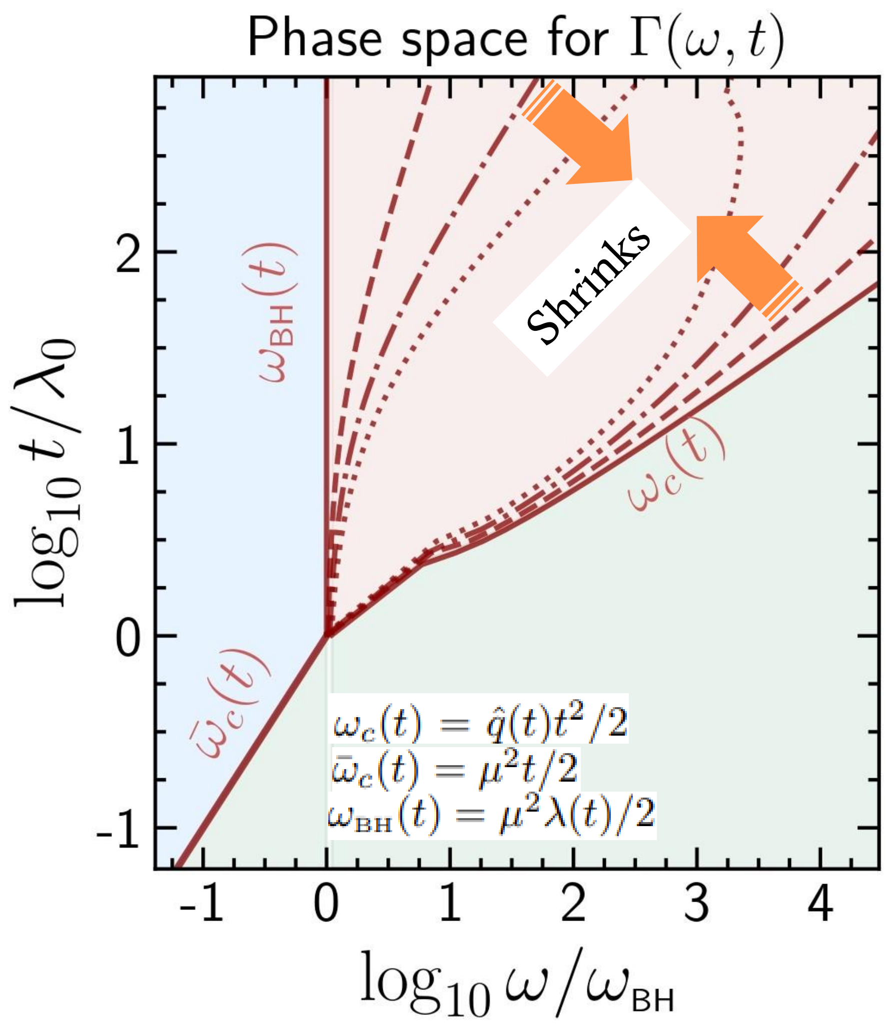
Medium rates : novel kinematical conditions

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)

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

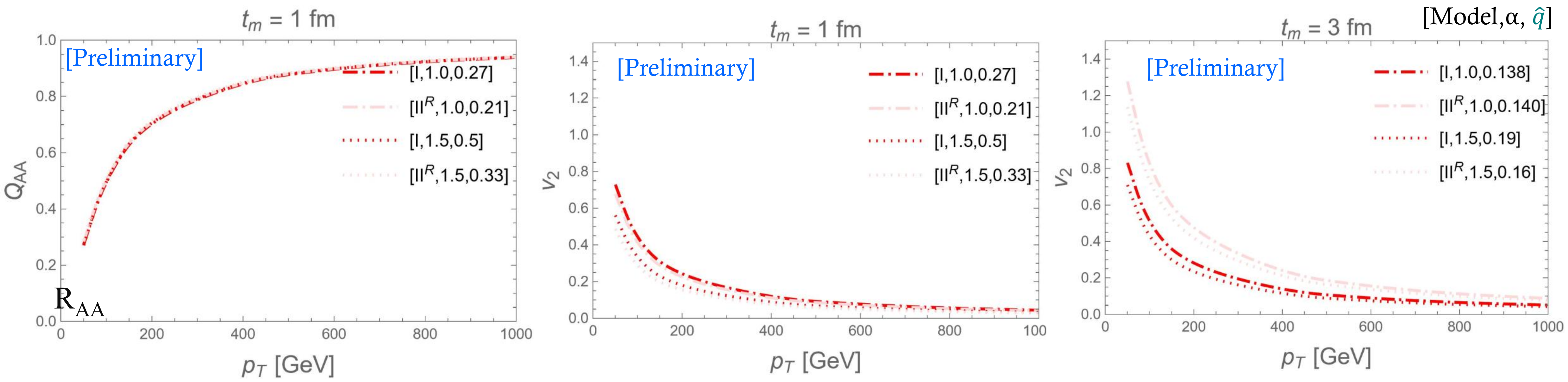
Check the shrinking phase space for expanding profiles !

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



Phenomenological consequence : R_{AA} and v_2

- R_{AA} sensitive to the accumulation of emissions along the entire in-medium path length L.
- v_2 coefficient is directly sensitive to the rate at late times for expanding profiles.
- Assumptions : fully coherent jets, energy loss proceeds as off a single parton.



We demonstrate analytically that a medium evolution, which initially has a small coupling to jets, typically leads to a stronger jet azimuthal asymmetry at the same jet suppression factor.

Phenomenological consequence : R_{AA} and v_2

What about other initial effects ?

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

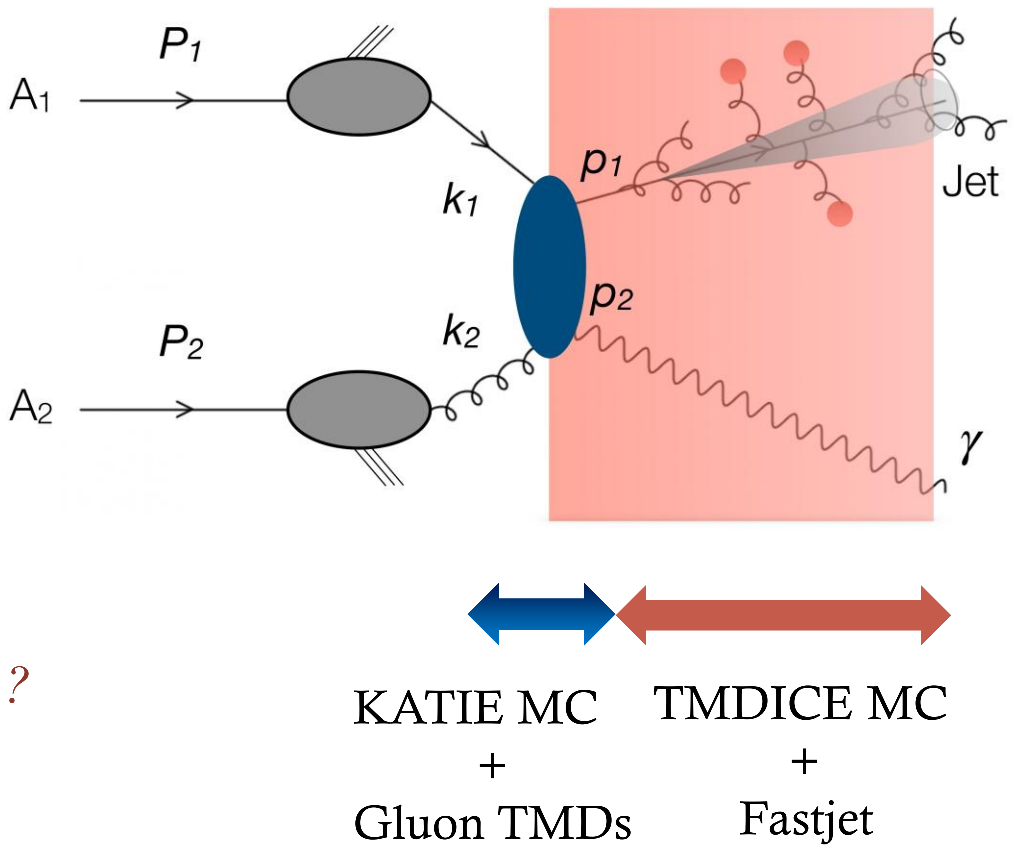
γ-jet at forward rapidity (FoCaL, ALICE)

- 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

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



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

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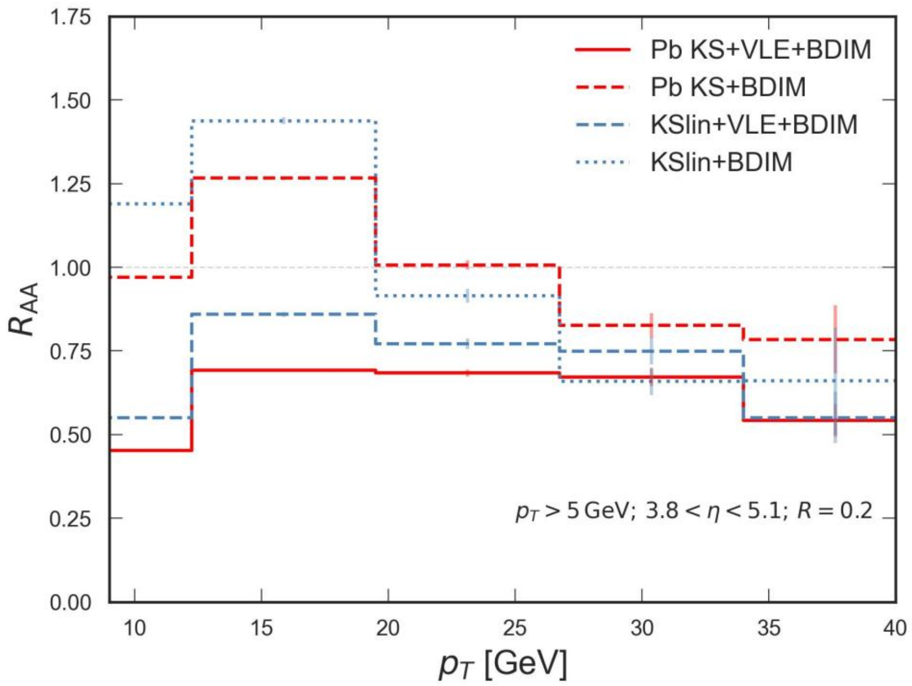

- Gluon Transverse Momentum Distributions (TMD) configurations :
  - KSlin: No gluon saturation effects, solution of BFKL equation, DGLAP splitting functions.
  - Pb KS : *Gluon saturation*, gluon density solution of BK equation, Sudakov effects, DGLAP splitting functions.

- *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

- Novel 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**).
  - New feature for HIC jet community : *Range of validity of multiple soft scatterings for parton showers ?*

- Future predictions for ALICE : Description of photon-jet events in forward direction (FOCAL-range) via Monte-Carlo algorithms (saturation + quenching) . Di-jets coming soon.[2]

- Utilisation of theoretical developments for upcoming O-O runs (small collision systems) in 2025.

Looking forward to views, suggestions and criticisms !

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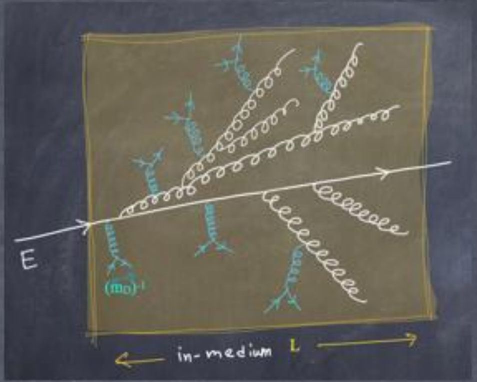
[1] SPA, Tywoniuk :arXiv:2409.04295

[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 :

$$\frac{\partial}{\partial t}D(x,k,t) = \frac{1}{t^*}\int_0^1 dz\,\tilde{\mathcal{K}}(z,t)\left[\frac{1}{z^2}\sqrt{\frac{z}{x}}\,D\left(\frac{x}{z},\frac{k}{z},t\right)\theta(z-x) - \frac{z}{\sqrt{x}}D(x,k,t)\right] + \int \frac{d^2l}{(2\pi)^2}C(l,t)D(x,k-l,t)$$

Medium evolved gluon spectra

Splitting Kernel.

gain term

loss term

elastic collision term

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

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

$m_D \sim gT$ (Debye mass)

$$\frac{1}{t^*} = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\hat{q}}{E}}$$ → "Quenching parameter".

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

t = evolution length.

k = transverse momentum

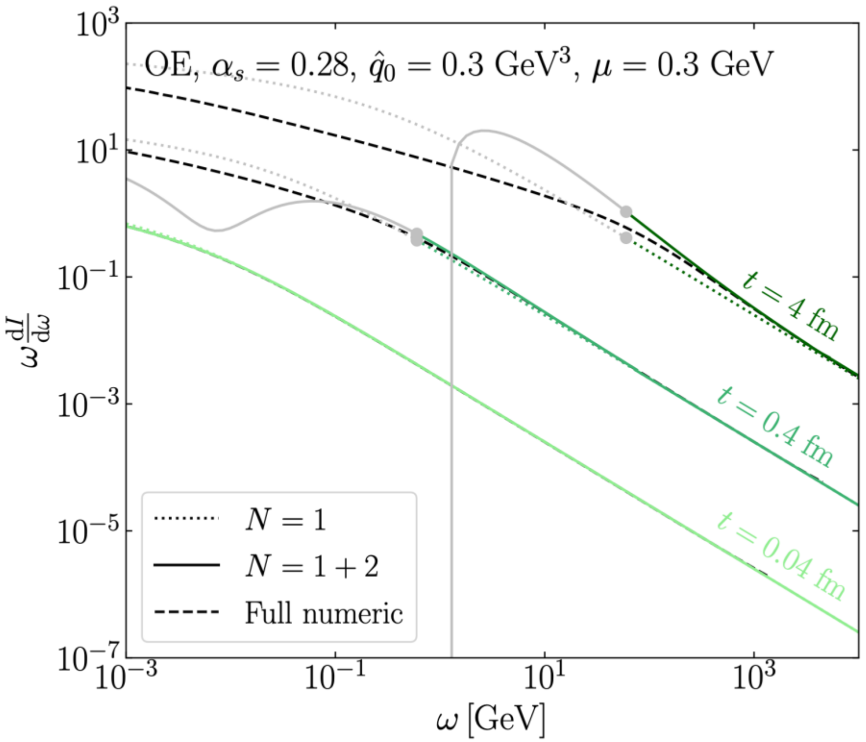
x = energy fraction ; $0 \le x \le 1$

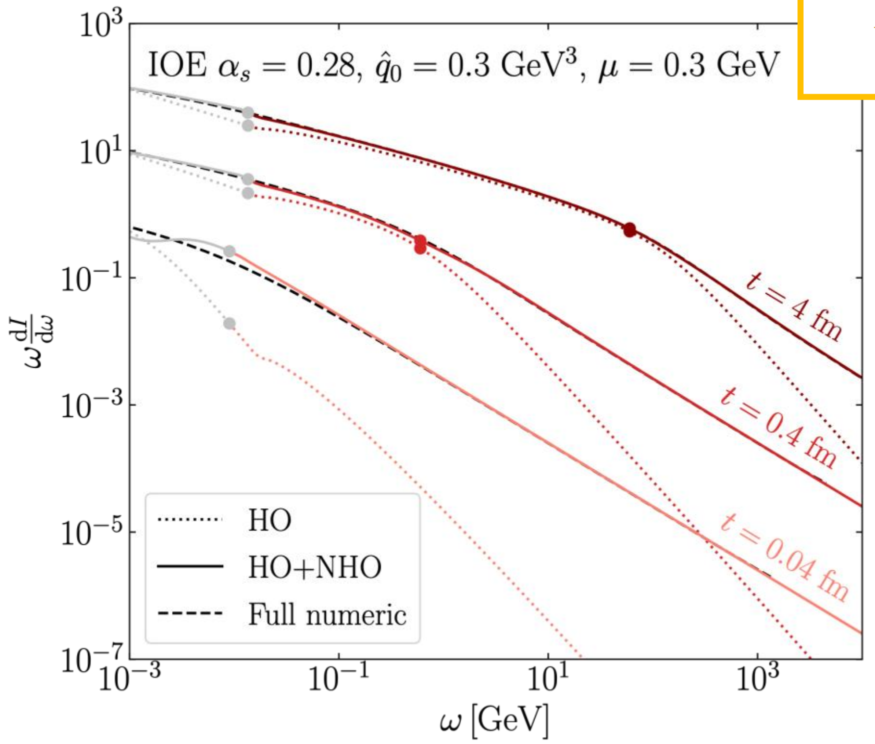
BACKUP

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.

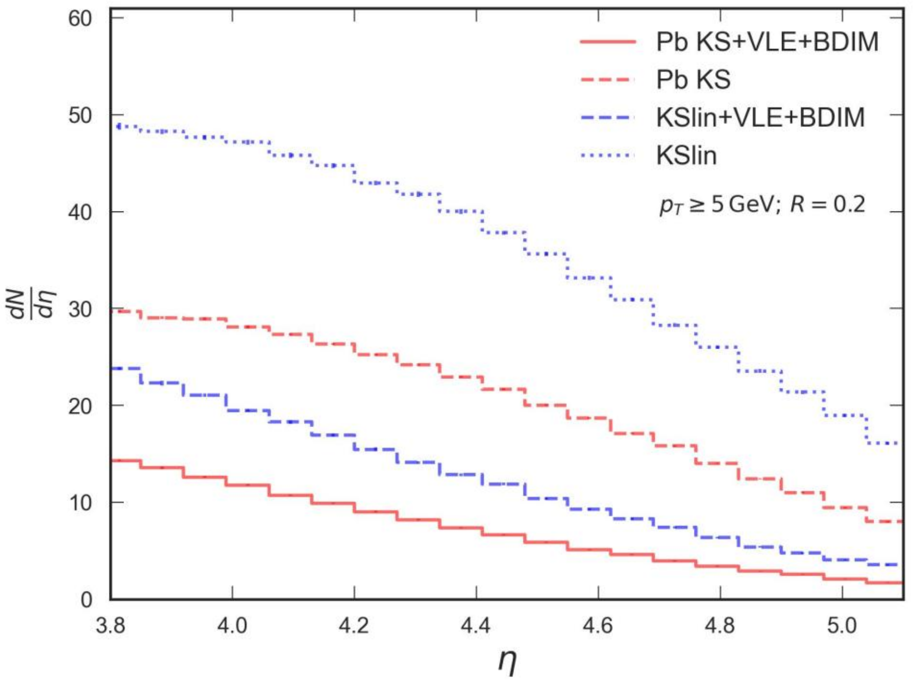
Improved opacity expansion spectra:

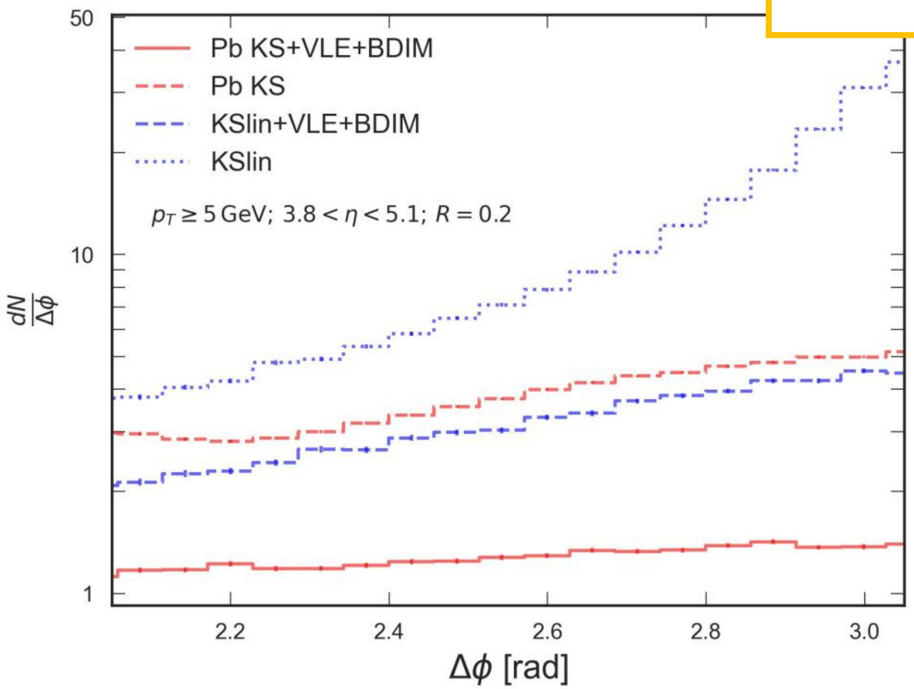
Expansion of rare, hard scattering on top of HO solution. Scale dependent quenching parameter. Converges in dense media above Bethe-Hietler energy.

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

γ-jet rapidity and azimuthal correlations

BACKUP





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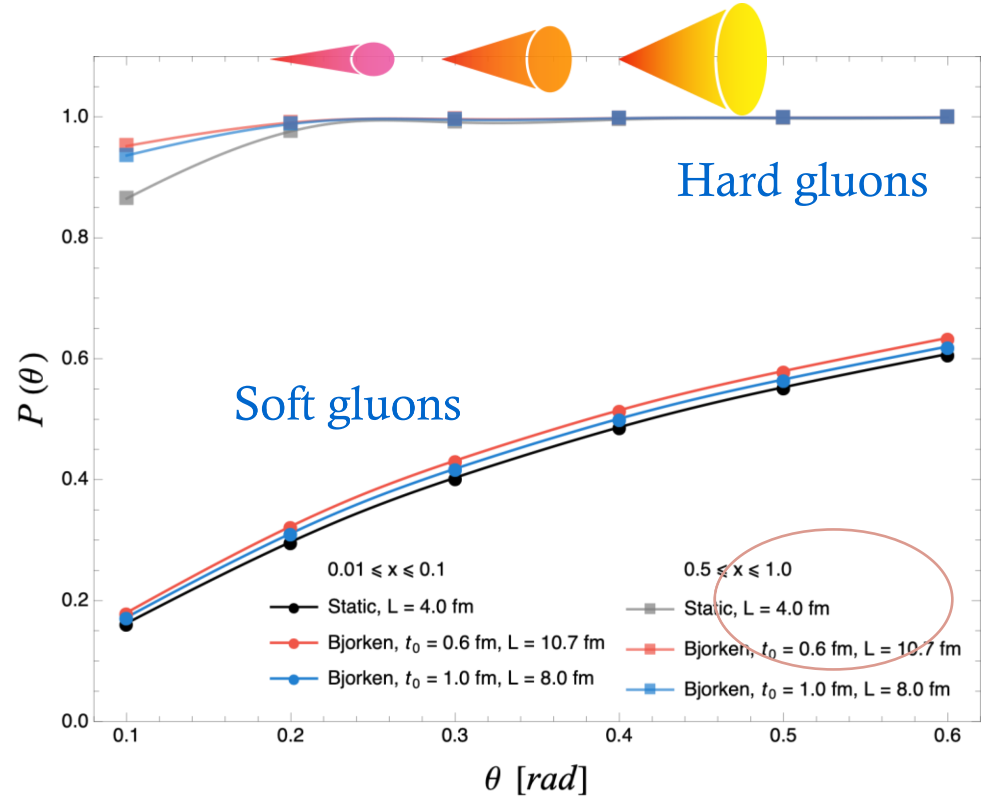
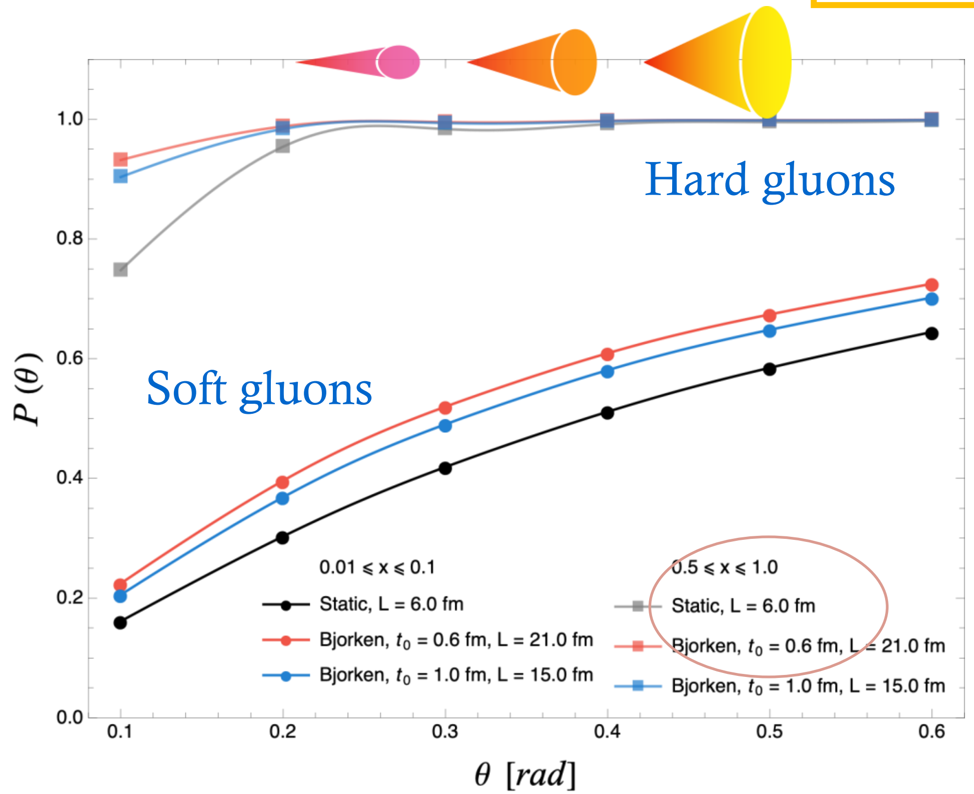
SPA, Kutak, Placzek. Rohrmoser, Tywoniuk :arXiv:2409.06675

Recap : phenomenological R_{AA} and v_2

BACKUP

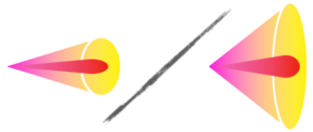
- Calculated with medium modified splitting rates.





- Significant differences in $q\hat{}$ 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.