SENSITIVITY OF JETS TO INITIAL STAGES

Based on: arXiv:2409.04295 and arXiv:2409.06675

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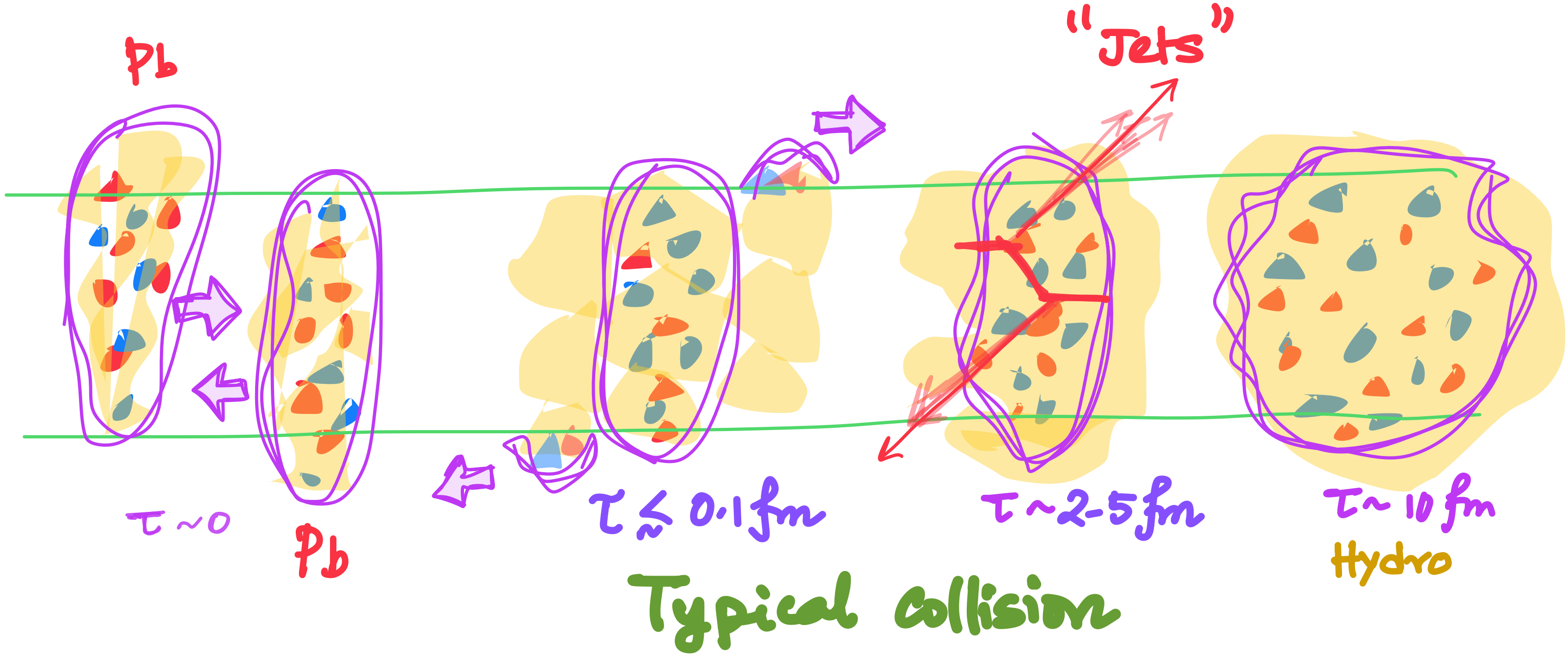
Jet quenching : quick words



Refer to Introductory slides of N. R. Sahoo, V. Vaidya and S. Oh (Tuesday)

Our field has explored … and lacked …

- QUESTION : Range of applicability of the hard vs the soft scattering for jet quenching models.

- A universal splitting rate across all gluon frequencies ?

- Finite medium size effects :

  - include realistic medium scenarios (**expanding medium**) relevant for inclusion in phenomenological in-medium parton shower models.
  - validity of the soft multiple and hard scattering not only as a function of energy but also as a function of the initial quenching time of the medium.

  - Rethink : *Are multiple scatterings important for radiative in-medium parton showers !*

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

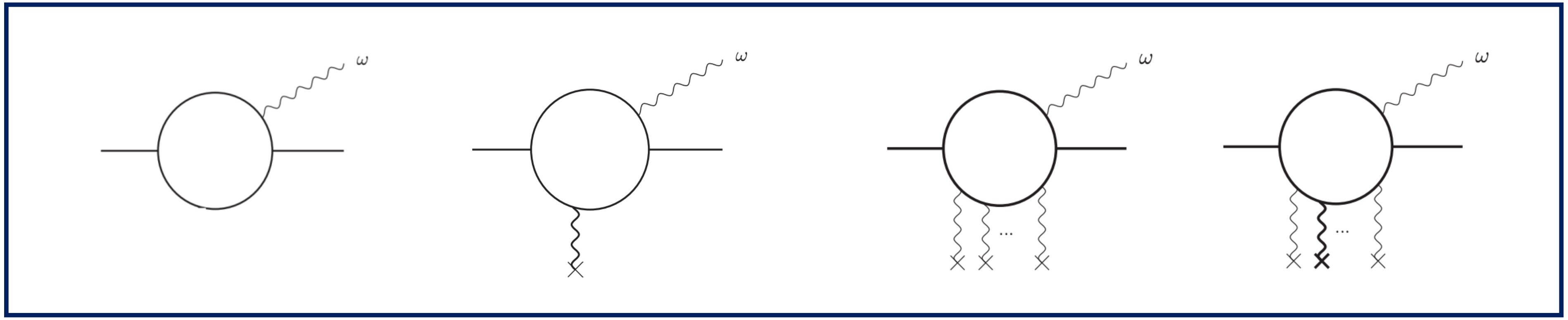
SPA, Salgado, Spousta, Tywoniuk, EPJC, 2022**;** **SPA**, Salgado, Spousta, Tywoniuk, JHEP, 2020.

Regimes of phase space emissions

- Various MC in-medium parton showers use two analytical approaches :
  - DILUTE medium: Single-hard scattering approximation (Opacity expansion).
  - DENSE medium: multiple-soft scattering. Harmonic oscillator (HO) approach [1]
- Full numerical solutions [2]

Opacity $\chi \equiv L/\lambda$ => denseness of the medium.

- ($L << \lambda$) : Medium DILUTE, or weakly interacting and ($L >> \lambda$) : Medium DENSE, or strongly interacting



NLO : One hard scattering included (thick wavy line)

+

Multiple soft scattering re-summed to all orders

LO (N=0): vacuum radiation

NLO (N=1): In medium Single scattering

LO (HO): Multiple soft scatterings (wavy vertical lines)

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[1] BDMPS-Z (1996), Salgado, Weidemann (2006), Tywoniuk, Mehtar-Tani, **SPA** (2022) …].

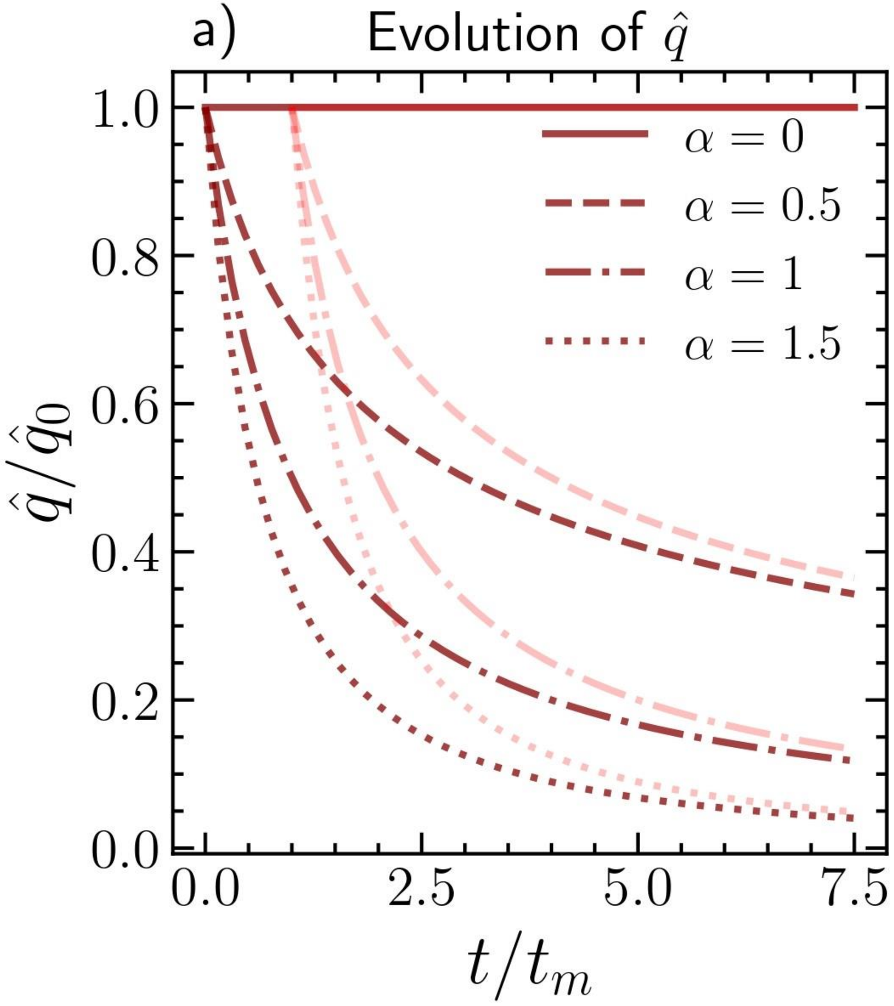
[2] Caron-Huot and Gale (2010), Ke , Xu, Bass (2018) , Andres (2022)…]

Improved opacity expansion

- Two models for the evolution of quenching parameter qhat :
  - model (i) : initially over-occupied system.
  - model (ii) : initially under-occupied system.

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

- Previous works have explored the sensitivity of the jets to such expanding model scenarios on the nuclear modification factor and the elliptic flow [Andres 2022, Caucal 2021, **SPA** 2020-24].



SPA, Tywoniuk :arXiv:2409.04295

Medium rates : complete analytical rates

- We first derive analytical in-medium emission rates to calculate energy loss that are valid for any medium expansion scenario.

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

- Three-point correlator *K* (p; p_0) describes the transverse momentum broadening experienced by the gluon during its formation time.

- We use widely used Gyulassy-Wang (GW) model for medium interaction, with screening mass μ .

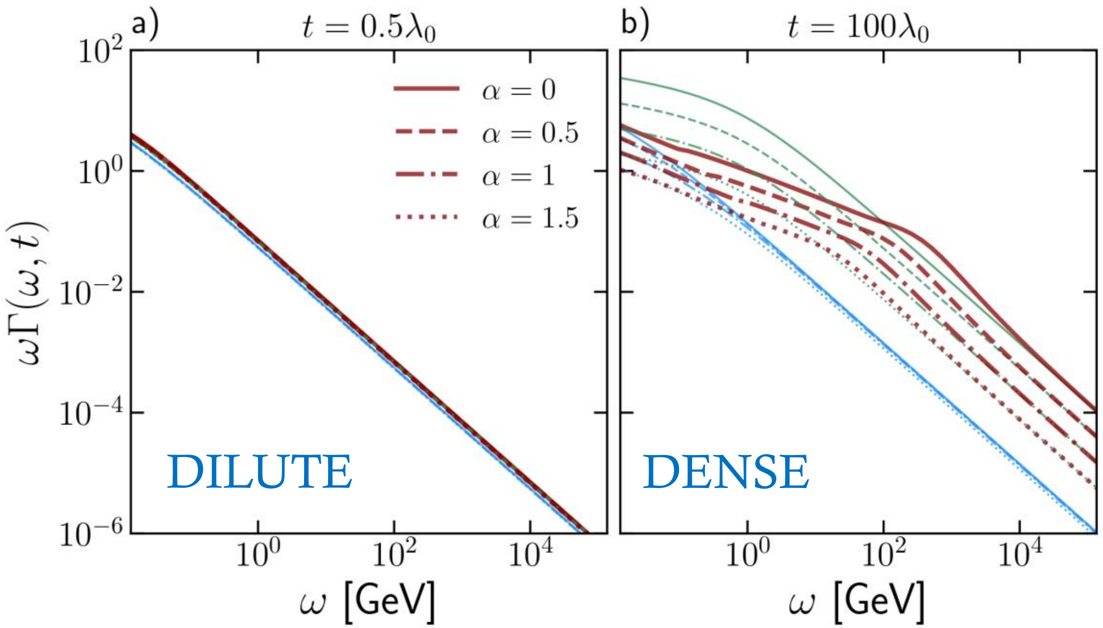
$$\Sigma(\boldsymbol{k}^2, t) = \frac{\hat{q}_0(t)}{\boldsymbol{k}^2 + \mu^2}$$

SPA, Tywoniuk :arXiv:2409.04295

Medium rates : complete analytical rates

We will employ three resummation schemes that, in total, cover the whole emission phase space :

- Opacity expansion (N = 1)/GLV
- Improved opacity expansion (IOE)
- Resummed opacity expansion



- IOE : Leading-log potential split into HO and remainder:

$$v^{\rm LT}(\boldsymbol{x}) \equiv v^{\rm HO}(\boldsymbol{x}) + \delta v(\boldsymbol{x}) = \frac{1}{4}\hat{q}_0\boldsymbol{x}^2 \log\frac{Q^2}{\mu_\star^2} + \frac{1}{4}\hat{q}_0\boldsymbol{x}^2 \log\frac{1}{Q^2\boldsymbol{x}^2}$$

Q is a separation scale and ensures that the first term dominates.

- Expanding around the harmonic oscillator

$$\mathcal{K}(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1) = \mathcal{K}_{\rm HO}(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1) \quad - \int_{\boldsymbol{z}}\int_{t_1}^{t_2} ds\, \mathcal{K}_{\rm HO}(\boldsymbol{x}, t_2; \boldsymbol{z}, s)\delta v(\boldsymbol{z}, s)\mathcal{K}(\boldsymbol{z}, s; \boldsymbol{y}, t_1)$$

- Redefinition: “dressed” transport coefficient

$$\hat{q} = \frac{\langle k_\perp^2\rangle_{\rm typ}}{L} = \hat{q}_0 \log\frac{aQ_s^2}{\mu_*^2}$$

SPA, Tywoniuk :arXiv:2409.04295

Medium rates : novel kinematical conditions

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

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

- Re-definition of the scales of the problem ($\omega_c >> \omega_{BH}$) :

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

- **Scattering regimes :**
  - For sufficiently dilute or small media, the probability of **one scattering** dominates.
  - For large or dense media, **multiple scattering** on the background medium
    - An interplay between copious, soft (LPM) interactions and rare, hard momentum exchanges.
    - Establish whether this regime is relevant for expanding media where the density rapidly decays with proper time ?

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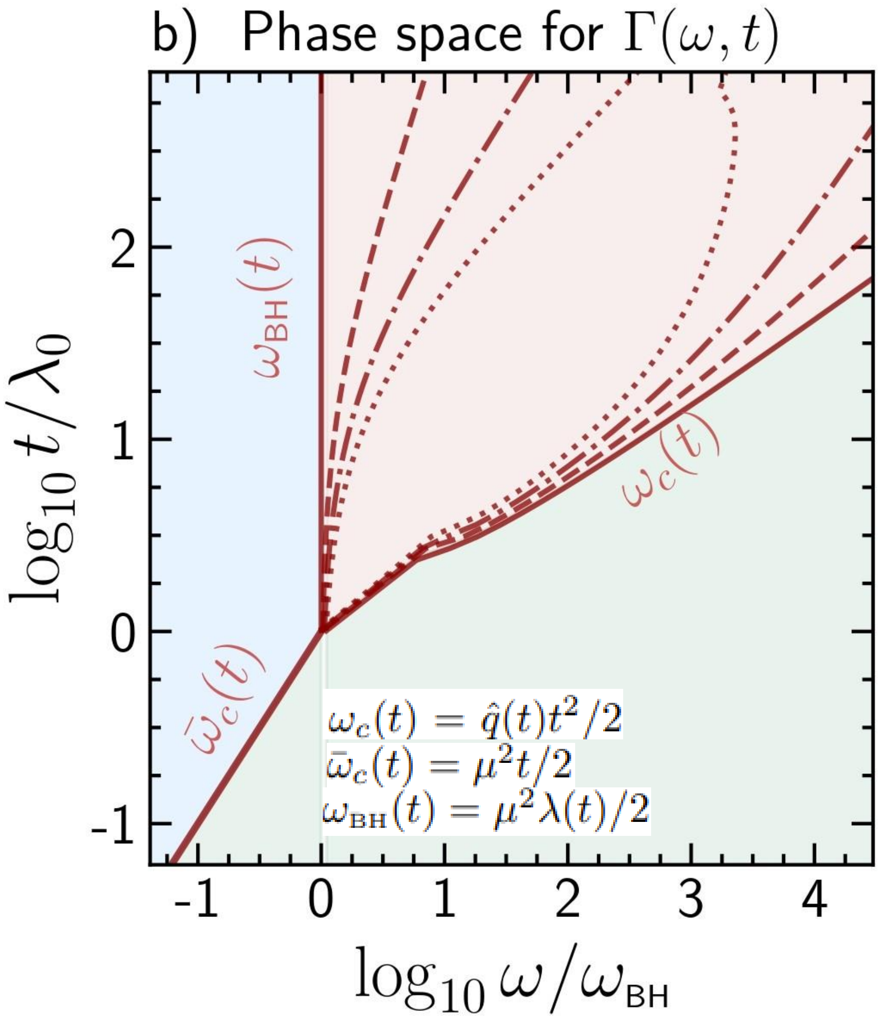
- Re-definition of the scales of the problem ($\omega_c >> \omega_{BH}$) :

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

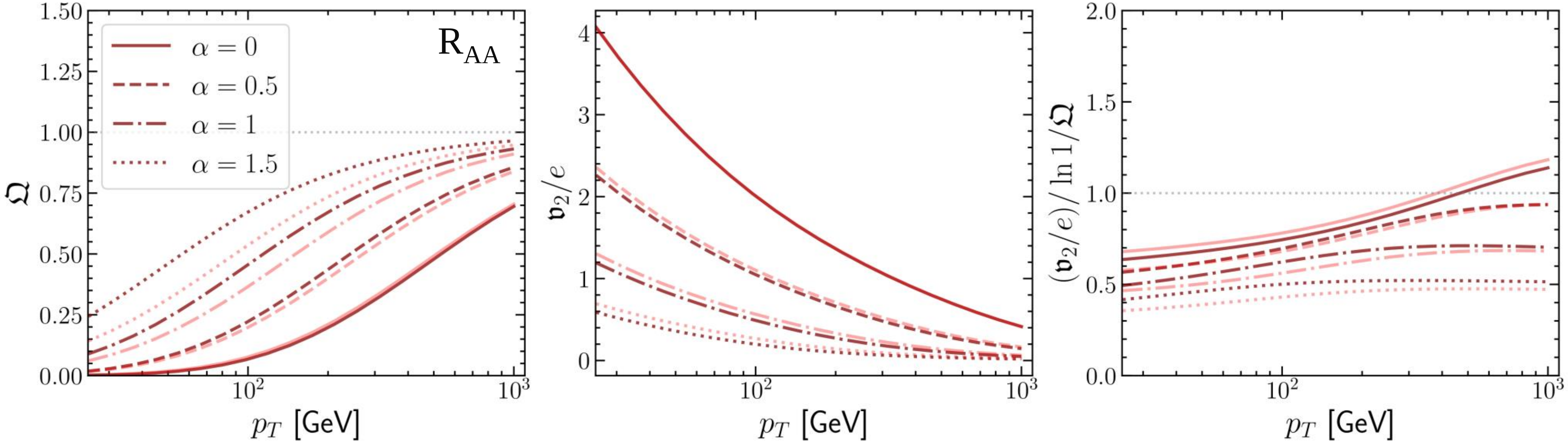
- **Implies :** *Medium “hydrodynamization” time should be much bigger than the mean-free-path* $t_m \gg \lambda_0$ *in order to get contributions from this regime (eg: check Bjorken expansion)*



SPA, Tywoniuk :arXiv:2409.04295

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.



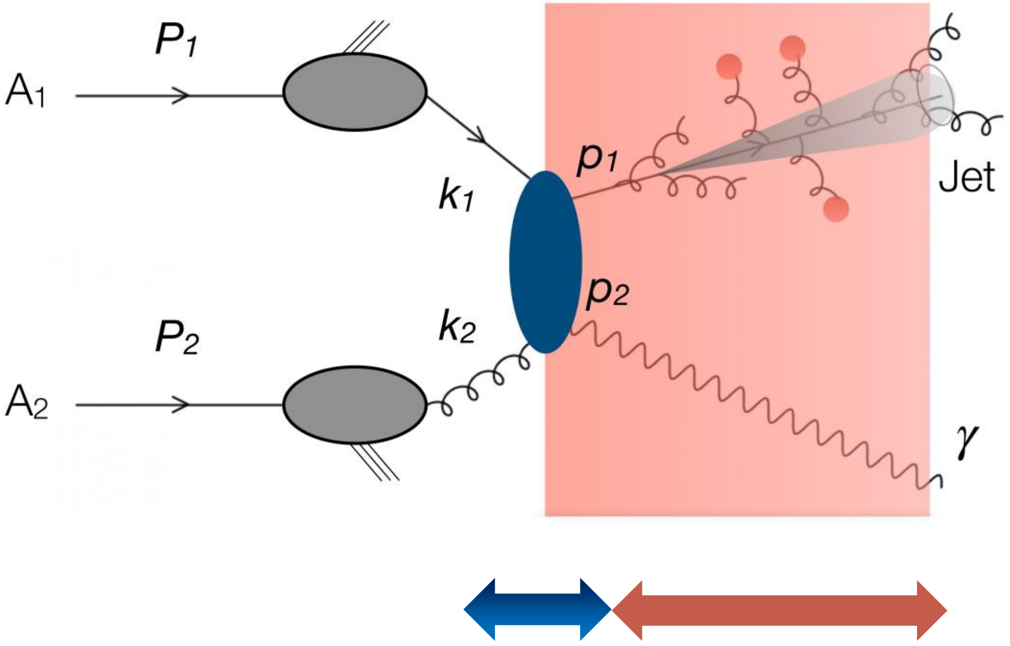
We demonstrate analytically that a medium evolution, which initially has a small coupling to jets, typically leads to a stronger jet azimuthal asymmetry at the same jet suppression factor.

SPA, Tywoniuk :arXiv:2409.04295

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-5.
- In the LHC jet kinematics, this corresponds to particle production in a forward rapidity region.
- Forthcoming FoCal, ALICE shall measure jets and photons at 3.4 < η < 5.8.

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

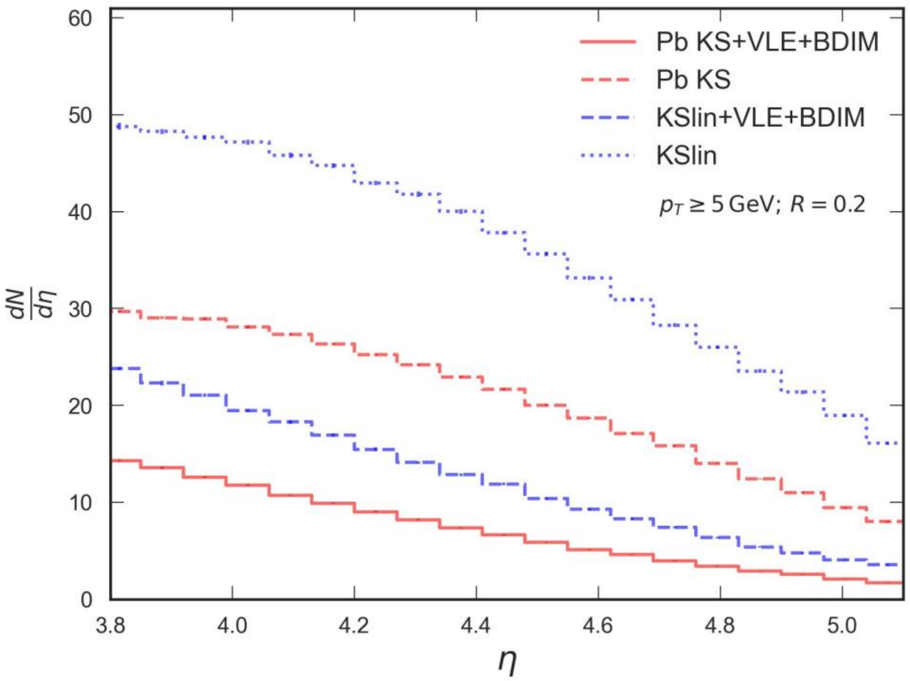


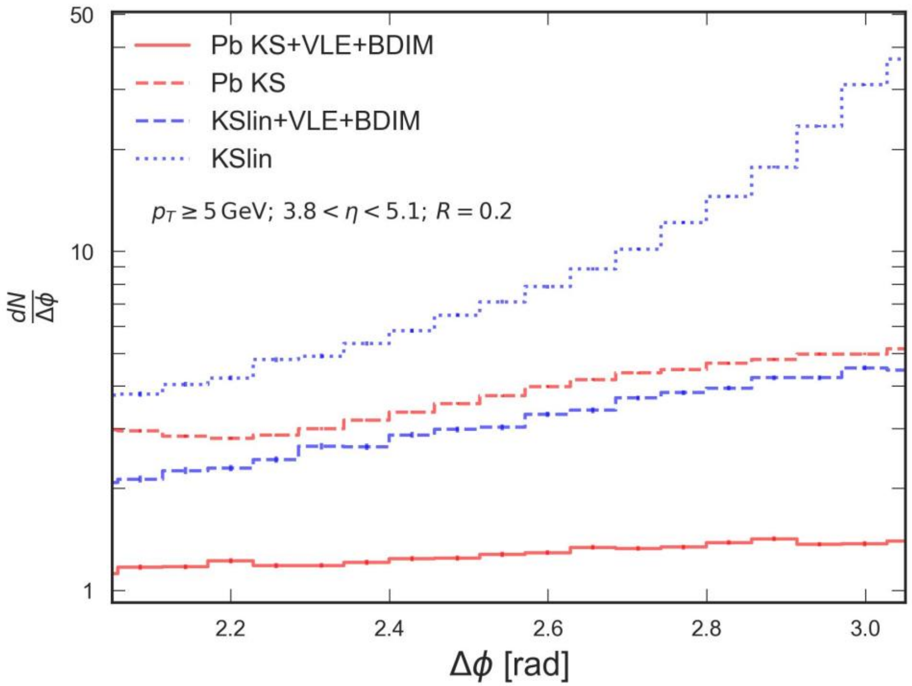
KATIE MC
+
Gluon TMDs

TMDICE MC
+
Fastjet

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

γ-jet rapidity and azimuthal correlations



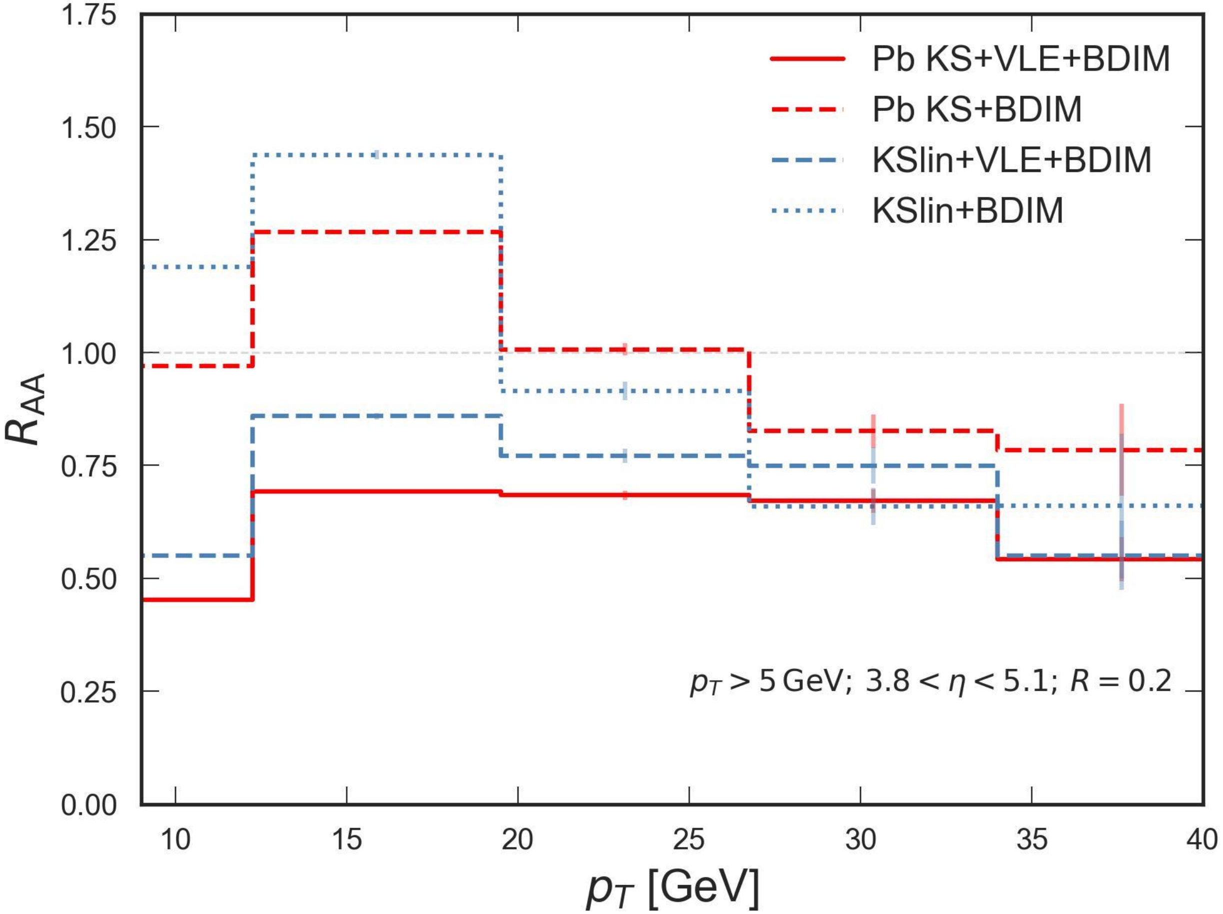


- Gluon TMD configurations :
  - KSlin: No gluon saturation effects, solution of BFKL equation, DGLAP splitting functions.
  - Pb KS : Gluon saturation, gluon density is a solution of the BK equation, Sudakov effects, DGLAP splitting functions.

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

γ-jet suppression factor

- Inclusion of VLEs strongly increases the jet-suppression at the low-p_T values by an approximate factor of 2 for $p_T \leq 20$ GeV.
- At low enough values of p_T (below $p_T = 20$ GeV, when VLEs are not included, and below $p_T = 35$ GeV, when they are included), a stronger suppression can be observed for the cases with the saturation.
- At high p_T , when VLEs are included, the case with the saturation shows a smaller suppression than the case without it.



VLE = Vacuum like emissions

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

Future challenges

- Novel incorporation of re-summation techniques for medium induced gluon emissions :

  - Finite size realistic medium effects
  - Analytical results : Effective designing of existing Parton shower MCs (faster, precise).
  - New feature for HIC jet community : Are multiple scattering important for parton showers ?

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

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

Non linear effects in asymmetric 3-jet (2+1) jet configurations
(**SPA**, Iancu, Tasevsky (in preparation)).

But this is a story (EIC) for another day !

Bayesian analysis: **R. Roy**, S. Sarkar, **SPA** :Wed, 17:21