PROBING INITIAL STAGE EFFECTS THROUGH QUENCHING & DIFFRACTION

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PHYSICS
FOR
FUTURE

C3NT jet-soft correlation workshop, Wuhan, 2026

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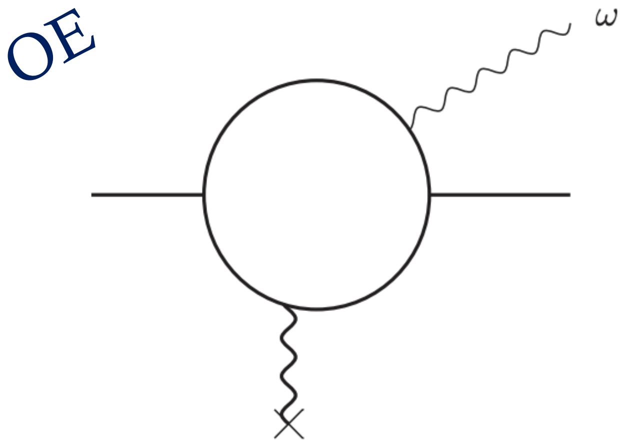
Our field has explored … and wants more …

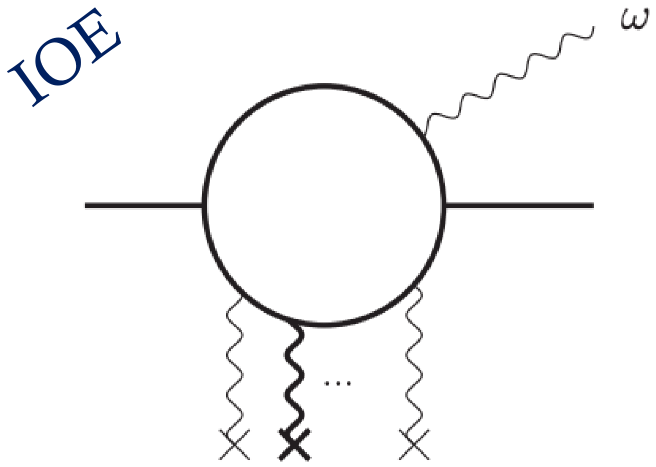
- QUESTION: *Are we sensitive to the initial stage dynamics through jet observables ?*
    - Jet quenching can be sensitive to the medium dynamics at early stages [arXiv:2409.04295]
    - Gamma-jet spectra are sensitive to the initial state PDFs [EPJC 85 343 (2025)]
- *ADVANTAGE for parton shower models ?*
    - 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, 2025
SPA, Salgado, Spousta, Tywoniuk, EPJC, 2022**;** SPA, Salgado, Spousta, Tywoniuk, JHEP, 2020.

Jet quenching in dynamic expanding medium

Tool : Improved Opacity Expansion (IOE)





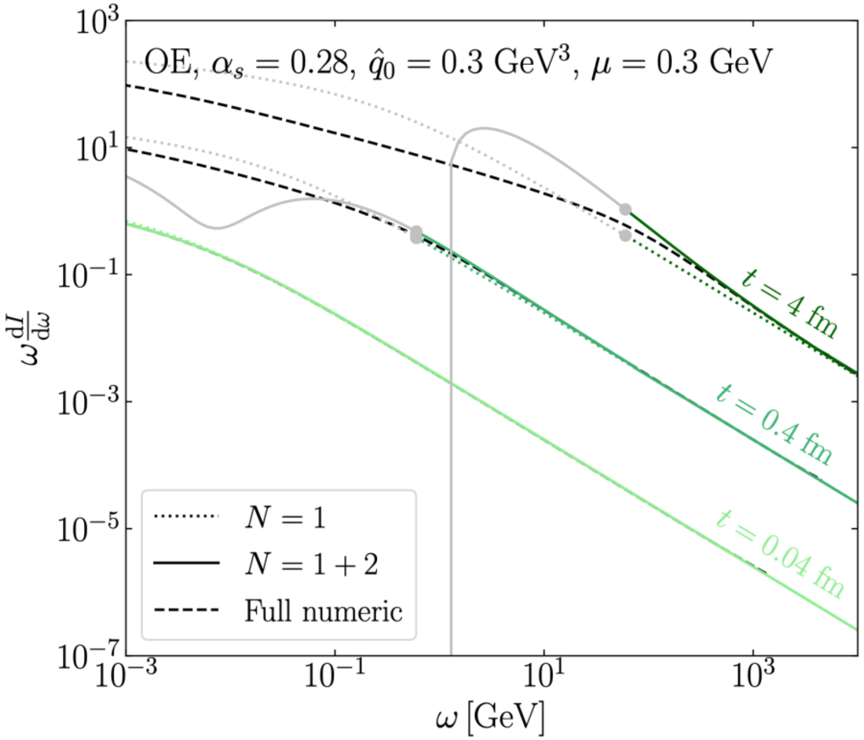
In medium Single scattering

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

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

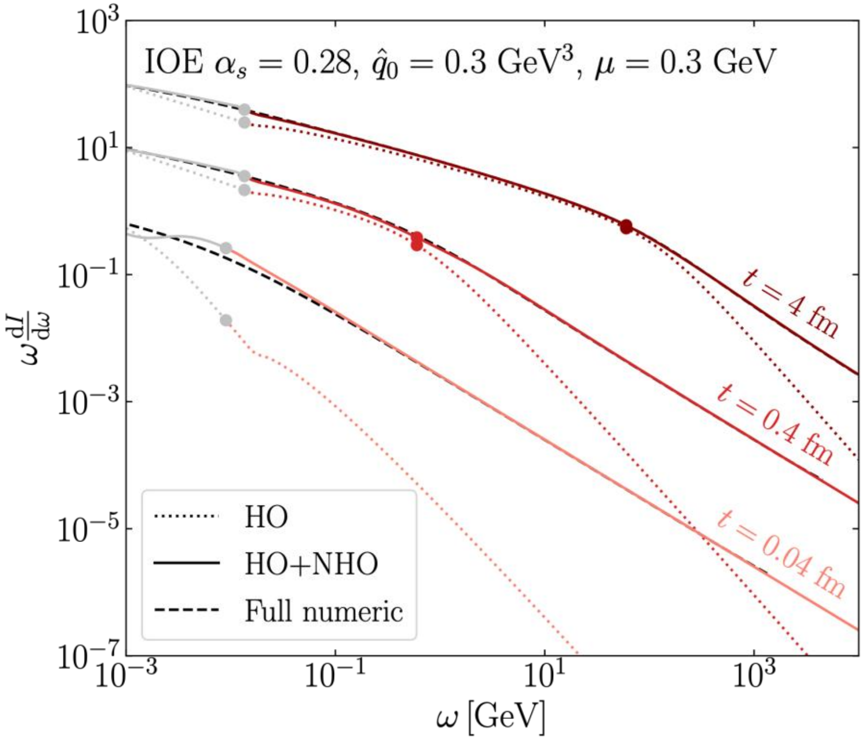
IOE : Mehatr-Tani, Tywoniuk (2019), Barata, Takacs, Soto-Ontoso, Isaksen (2020 - 22)

Recent : features of in-medium spectrum



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)

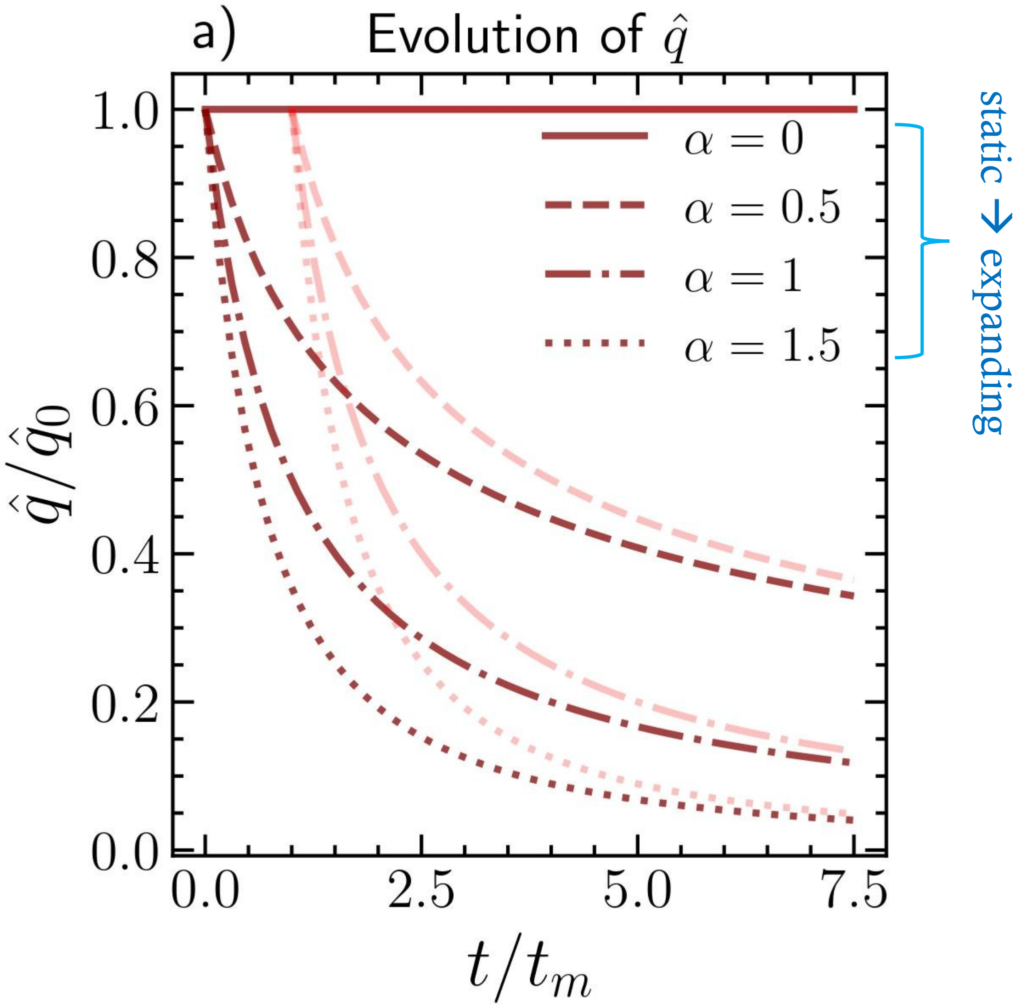
Medium expansion models

- Two toy models for the evolution of quenching parameter :
    - 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)

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

t_m = "hydrodynamization time"; α = expansion parameter

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



SPA, Tywoniuk :arXiv:2409.04295

We shall calculate rate, why?

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

- Expansion in medium scatterings (details next slide): $\underbrace{v(\boldsymbol{z},t)}_{}=v_{\mathrm{HO}}(\boldsymbol{z},t)+\delta v(\boldsymbol{z},t)$

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

We shall calculate rate, why?

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

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

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 upper scale in the calculation

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.

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

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

SPA, Tywoniuk :arXiv:2409.04295

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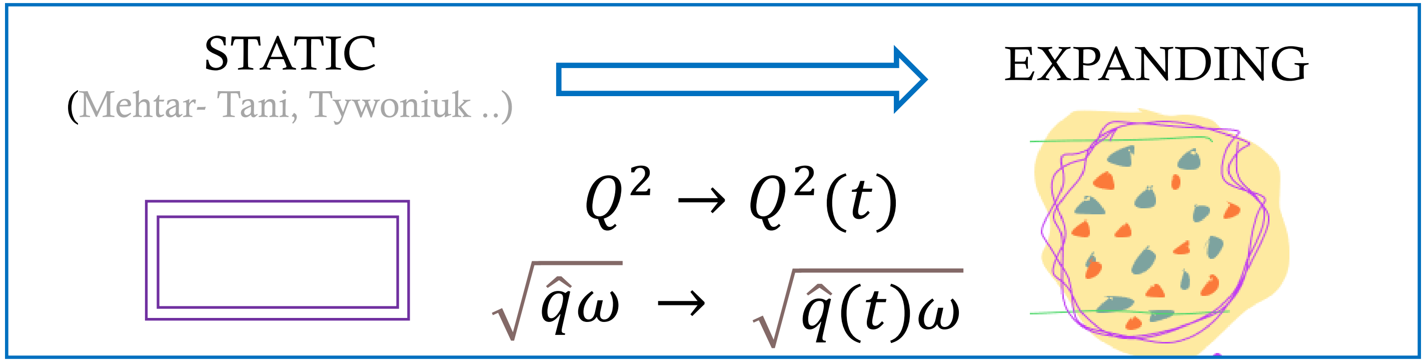

STATIC

(Mehtar- Tani, Tywoniuk ..)

EXPANDING

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

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

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

SPA, Tywoniuk :arXiv:2409.04295

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

- Calls for a re-definition of the scales of the problem : for $\omega_C(t) >> \omega_{BH}(t)$

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

Birth of a new kinematical condition

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

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

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

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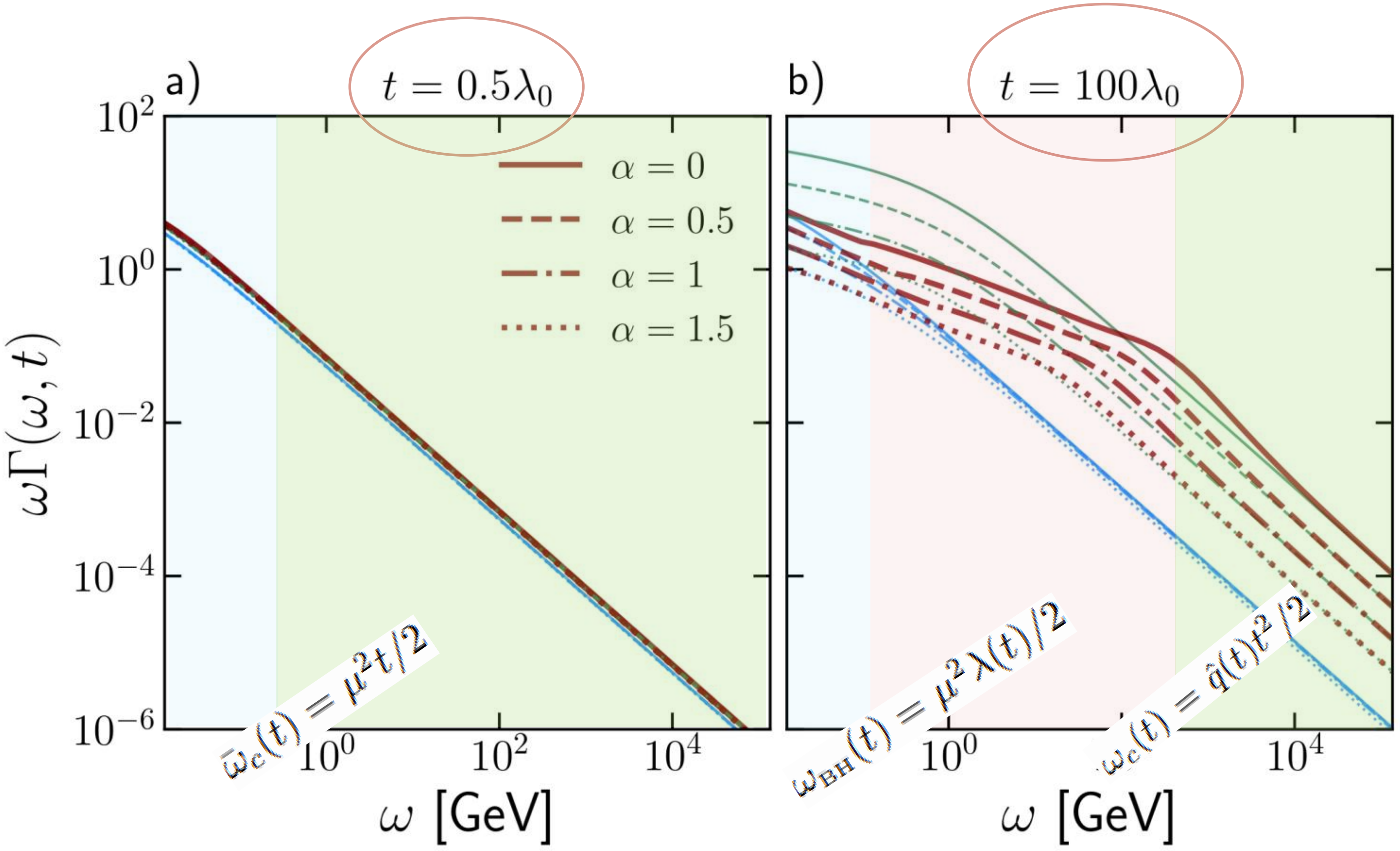
$$\boxed{1 \ll \frac{t}{\lambda_0}\left(\frac{t_m}{t}\right)^{\alpha}}$$

- $t < \lambda_0$ (early emissions), dilute condition, expansion has minimal effect; OE rates valid.
- $t > \lambda_0$, impact of expansion on both quenching models is substantial across all re-summation schemes, matched through *time dependent (dynamic)* kinematic scale.

SPA, Tywoniuk :arXiv:2409.04295

Medium rates : complete analytical rates

- 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.



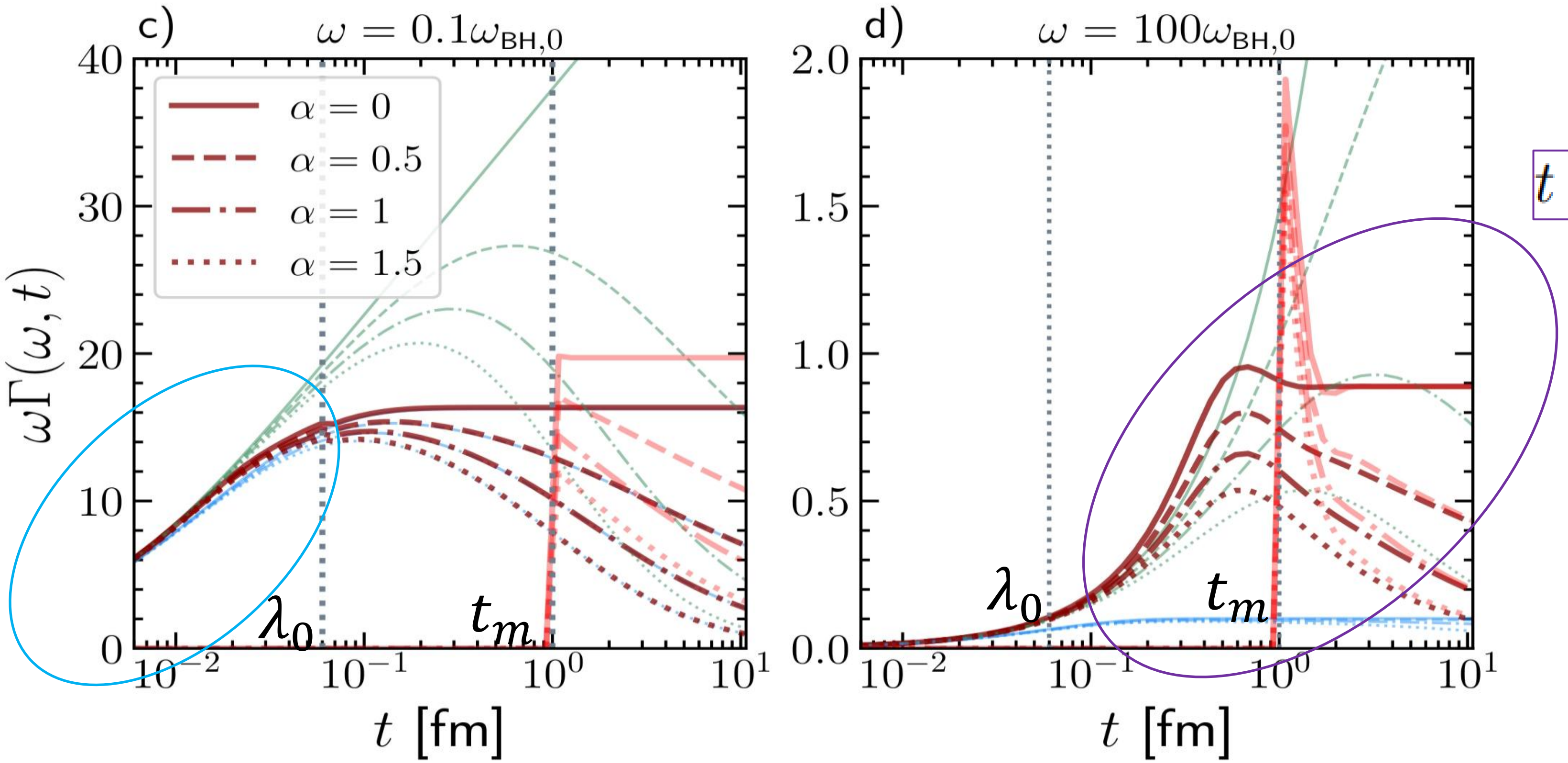
Insensitive to medium expansion

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 : complete analytical rates



$t < \lambda_0$

$t > \lambda_0$

- (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

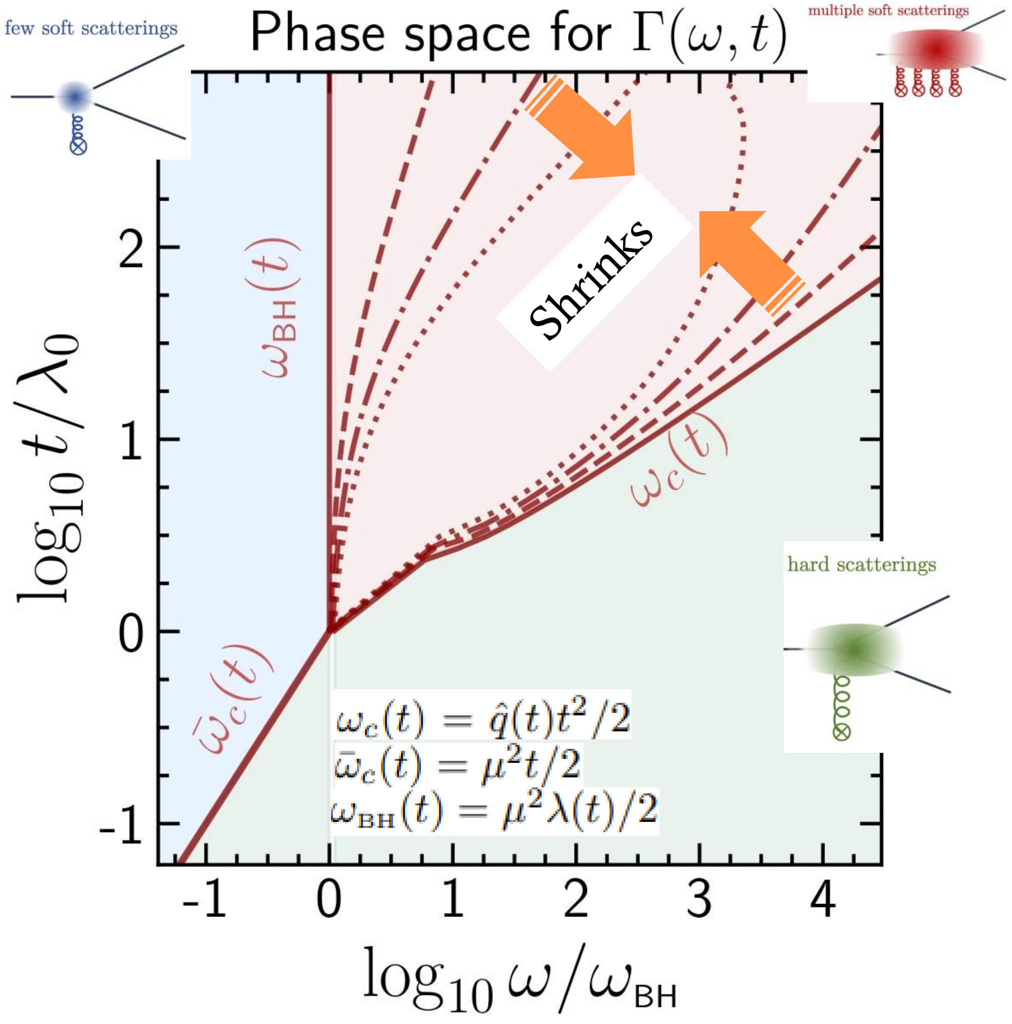
Medium rates : novel kinematical conditions

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
(eg: 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

t dependent screening/ Debye mass for completeness ?



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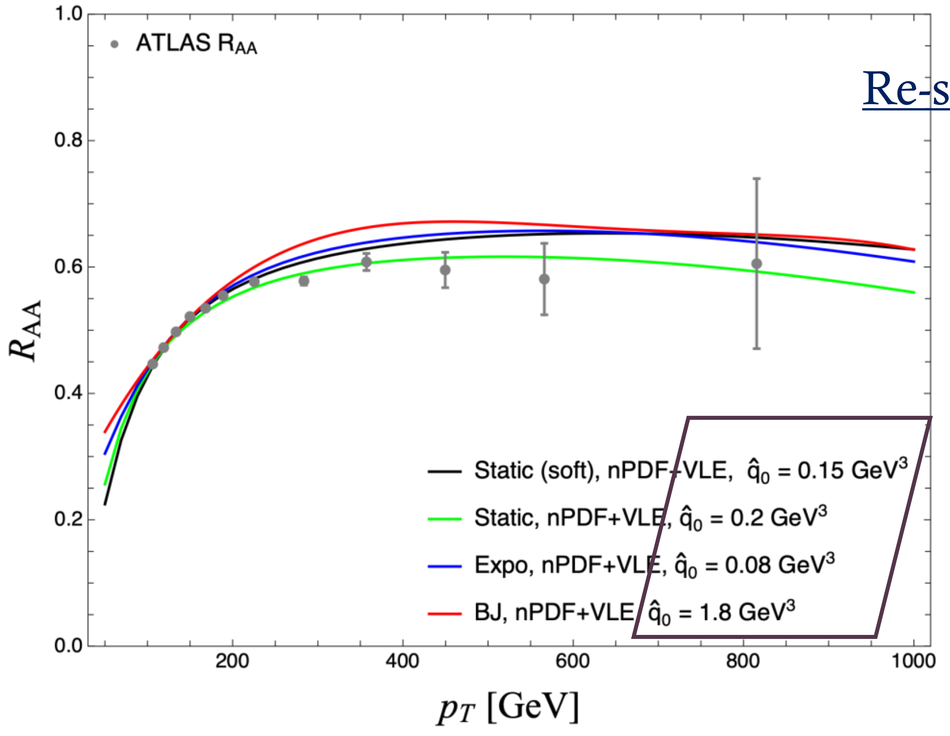
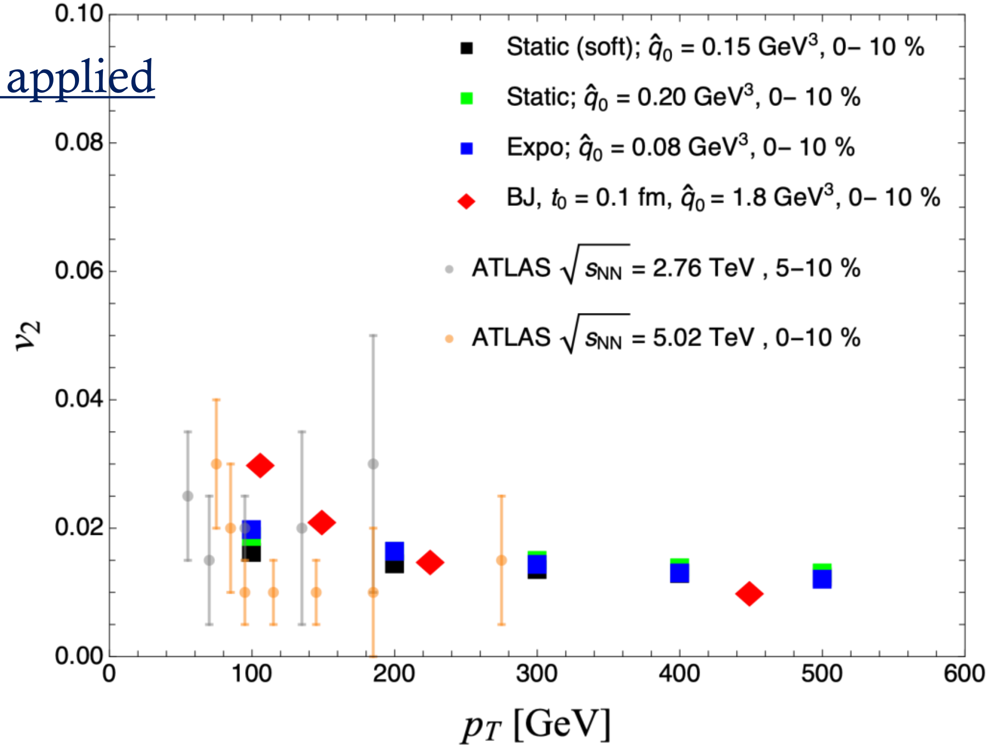
Recap : phenomenological R_{AA} and v_2

SKIP

- Calculated with medium modified splitting rates.



Re-scaling in q^ applied



- Significant differences in q^ for different medium ➔ importance of precise modelling of jet quenching phenomena.

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

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

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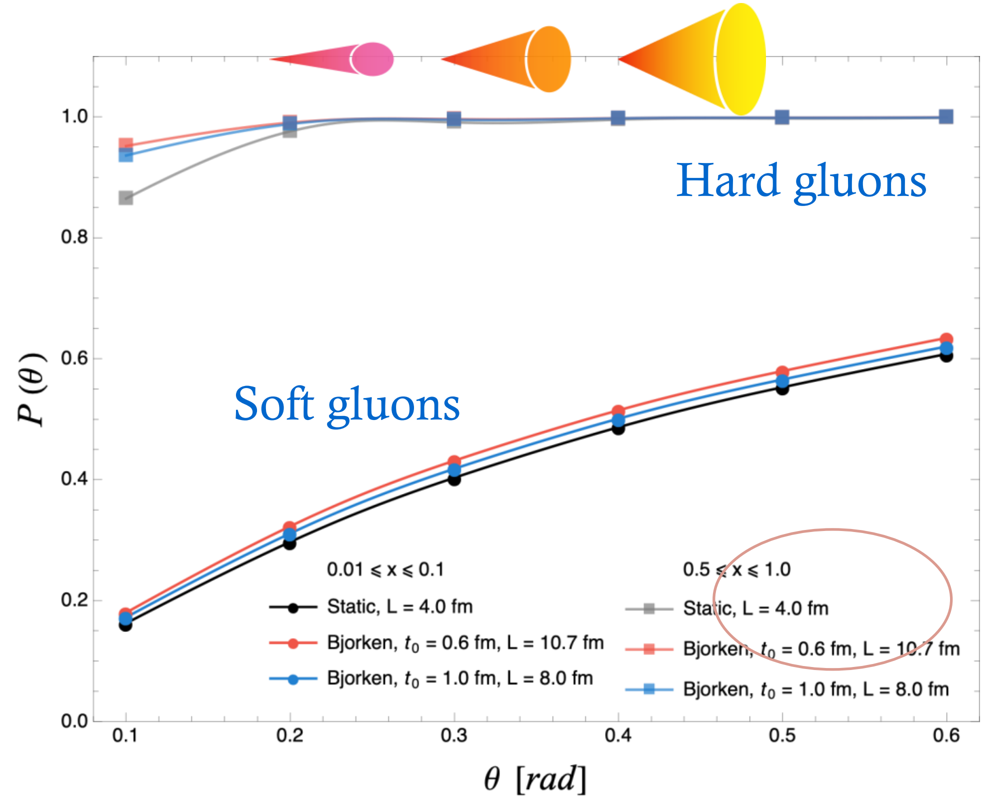
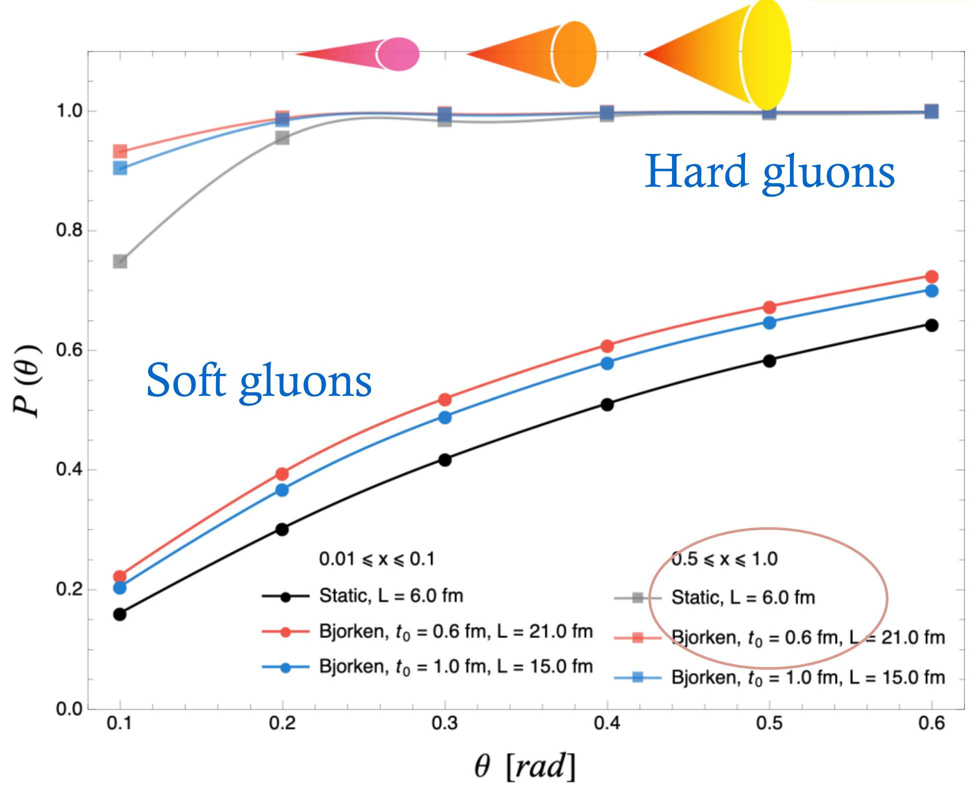
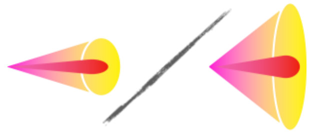




- Significant differences in q^ for early and late Bjorken dynamics.

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



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

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

Phenomenological consequence : R_{AA} and v_2

- R_{AA} (Q_{AA} as our proxy for simple power law decay form) expressed in terms of the rate,

$$-\ln \mathrm{Q_{AA}} \simeq \int_0^L t \int_{p_T/n}^{\infty} \omega\, \Gamma(\omega, t)$$

- Followed by calculation of v_2 (a more differential quantity),

$$\mathrm{v}_2/e \simeq -\tfrac{1}{2} \ln \mathrm{Q_{AA}}/ \ln L = \tfrac{1}{2} L \int_{p_T/n}^{\infty} \omega\, \Gamma(\omega, L)$$

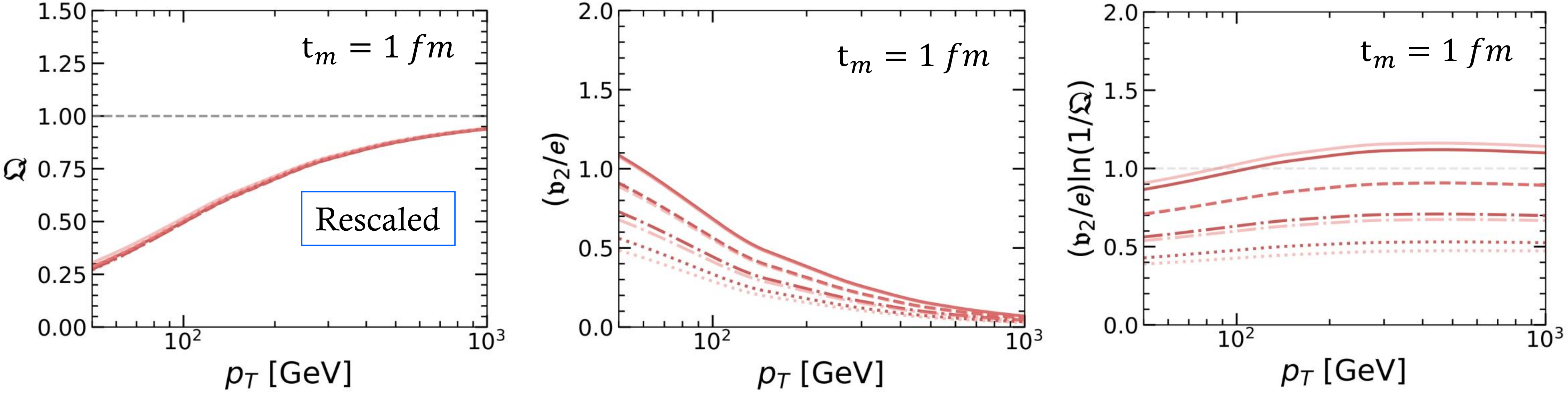
where *e* is the ellipticity of nuclear overlap.

- So, we want to examine R_{AA} and v_2 for their sensitivity on:
  - Over occupied and under occupied systems (model (i) and (ii)) (probing initial stages effect)
  - Different expansion modes (*academic exercise*)

Mehtar-Tani, Pablos, Tywoniuk, 2024
Baier, Dokshitzer, Mueller, Schif, 2001

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 , FULL gluon rates.



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

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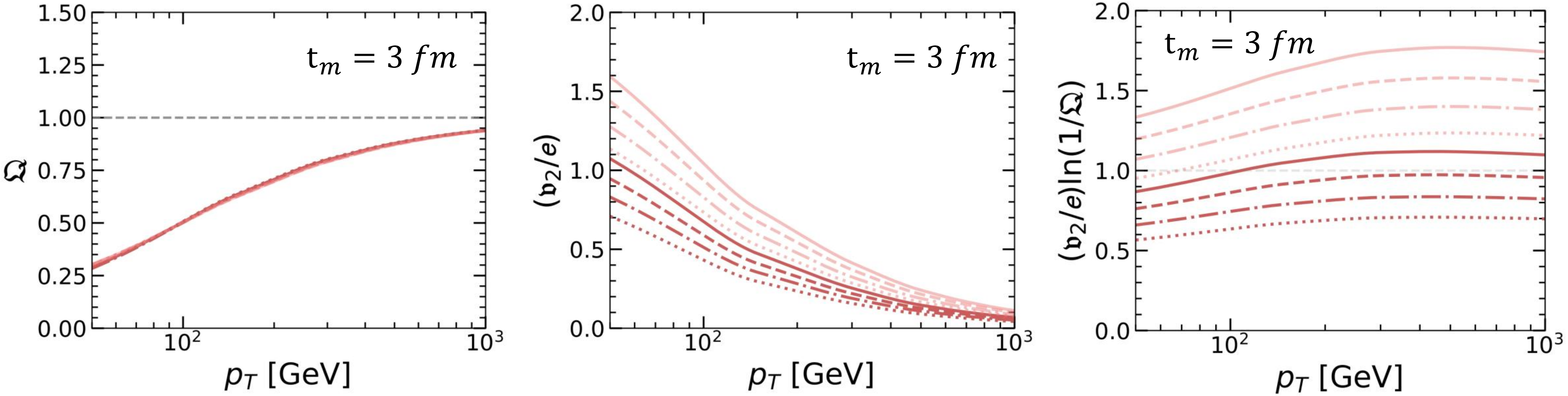


We demonstrate analytically that v_2 *is sensitive to the hydrodynamization time in medium evolution and the ratio is almost insensitive to the* p_T.

SPA, Tywoniuk :arXiv:2409.04295

What about other initial effects ?

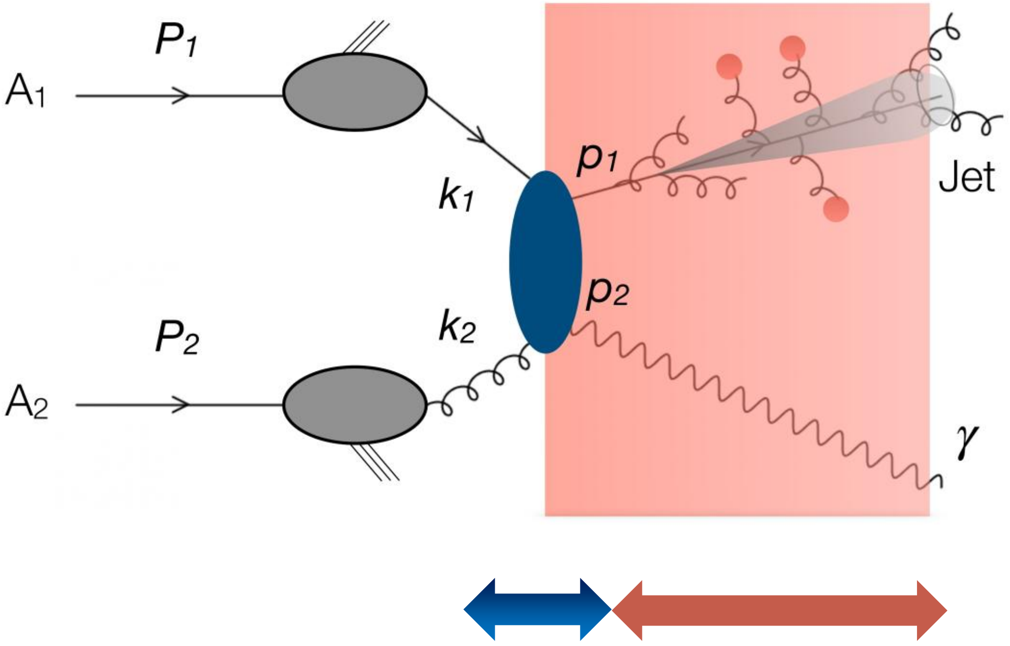
Can we disentangle saturation effects via TMDs and medium induced broadening ?

γ-jet at forward rapidity

- 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) ?

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



KATIE MC
+
Gluon TMDs

TMDICE MC
+
Fastjet

TMDICE MC : Rohrmoser 2022
KATIE : van Hameren 2018

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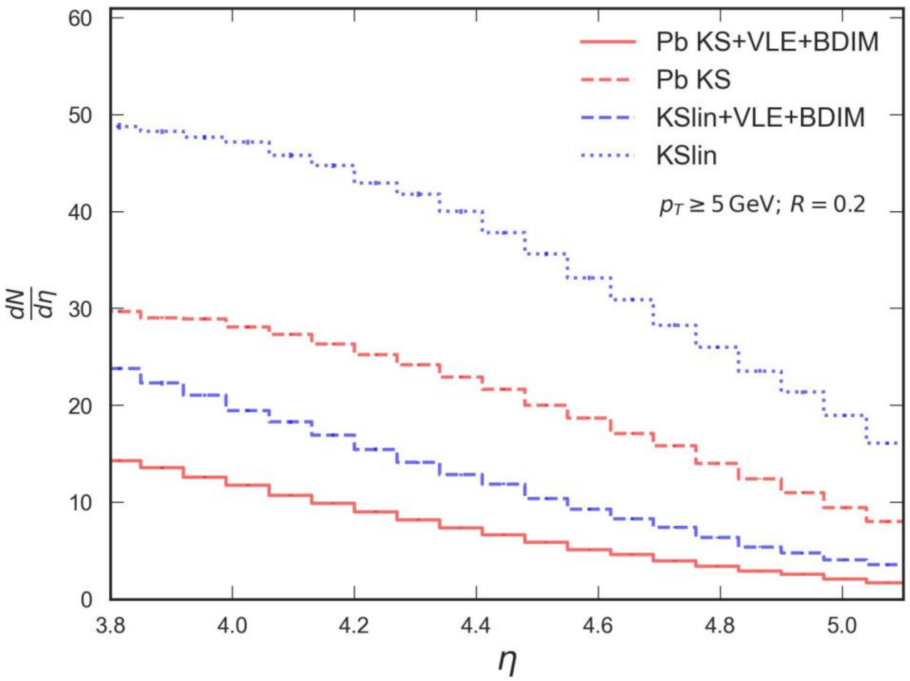
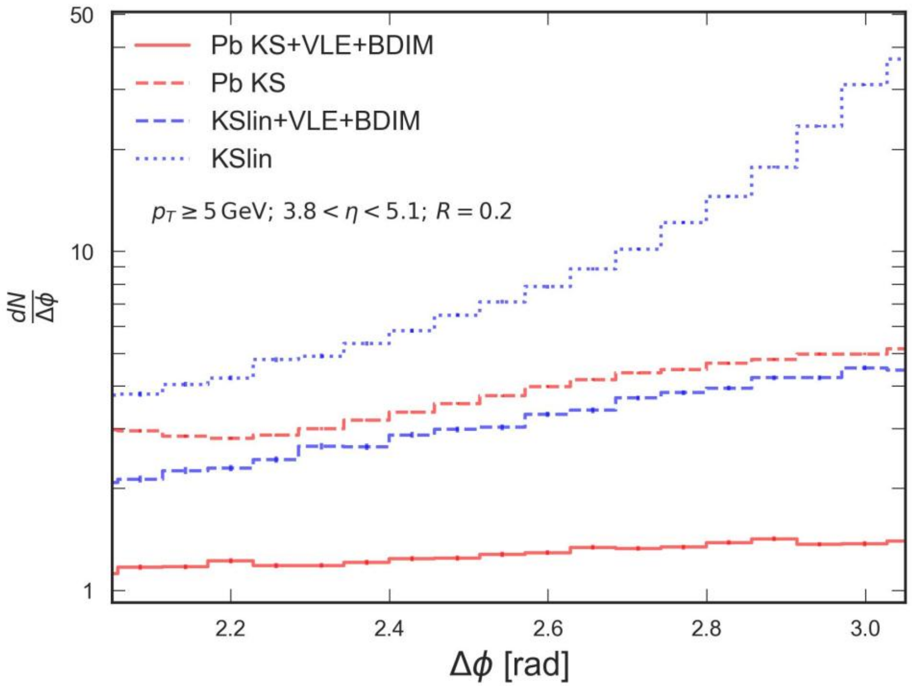
x : momentum fraction of the nucleon carried by struck parton

Wang & Huang (1997)

γ-jet rapidity and azimuthal correlations



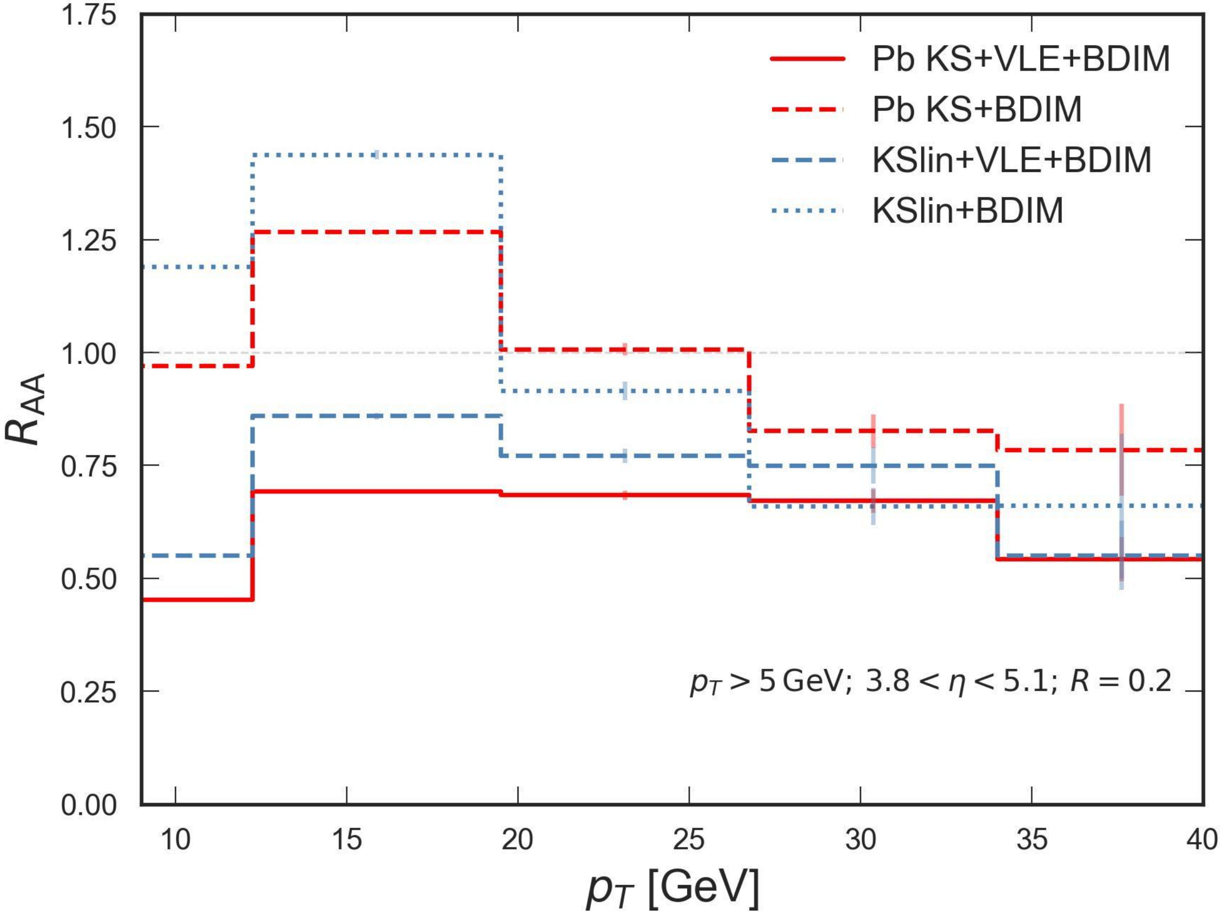


- Gluon Transverse Momentum Distributions (TMD) configurations :
  - KSlin: No gluon saturation effects, solution of BFKL equation, DGLAP splitting functions.
  - Pb KS : *Gluon saturation*, gluon density is a solution of the BK equation, Sudakov effects, DGLAP splitting functions.

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

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 ($p_T < 20$ GeV, when VLEs are not included, and $p_T < 35$ 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, EPJC 85 343 (2025)

So far ..

- 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 : *Are multiple soft scatterings important for parton showers ?*

- Utilisation of theoretical developments for *small collision systems* as our IOE rates are generic.

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[1] SPA, Tywoniuk :arXiv:2409.04295

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

What about other initial effects ?

Can we study saturation effects through UPC’s?

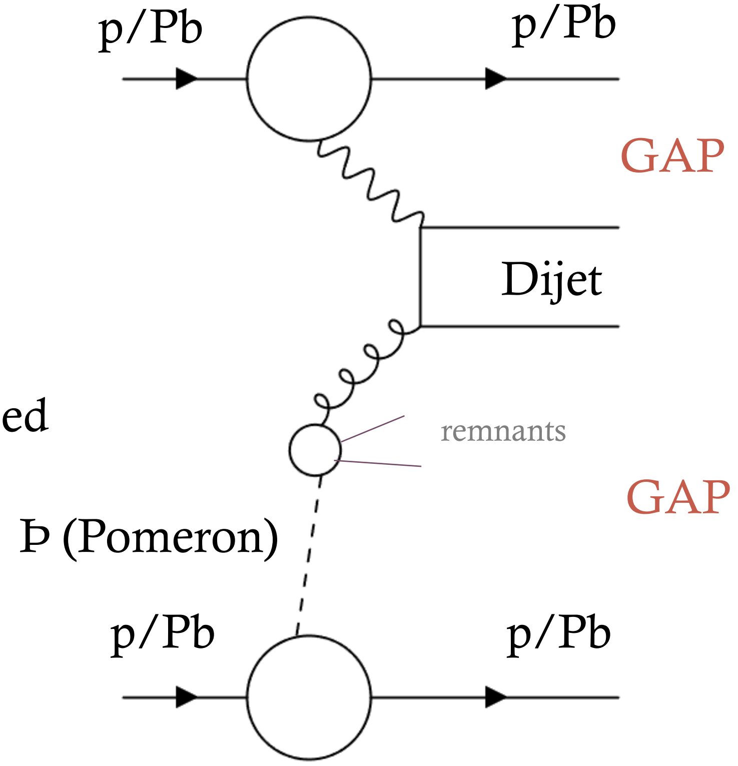
Diffractive photoproduction

- Dijets as unique probe for novel tomography imaging of the nucleon and nucleus:
  - Ideally, 2 final state jets produced in back-to-back in transverse plane with nearly balanced transverse momenta.
  - Deviations → *nonperturbative structure of the nucleon and nucleus.*

- Processes:
  - One nucleus/proton → provides photon (γ)
  - Other nucleus/proton → provides pomeron (P)

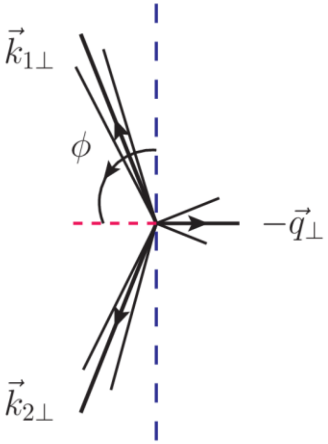
  - Diffractive refers to :
    - process in which there is a large rapidity gap between the produced jets and the nuclear target.
    - Photoproduction: $Q^2 < 1\ GeV^2$ (other limit is DIS)

  - *Diffractive photoproduction (as background) helps to understand Exclusive processes (only dijets as final state, Pomeron ladder with dijet) which gives direct access to QCD Wigner functions (parton tomography).*



Diffractive photoproduction

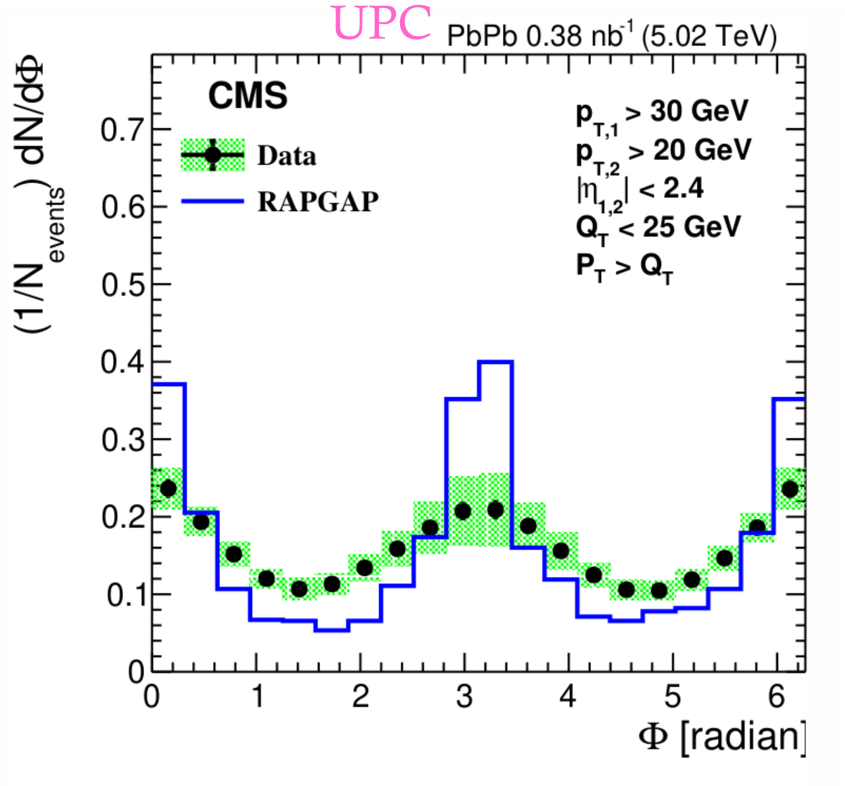
- Dijets as unique probe to the novel tomography imaging of the nucleon and nucleus →
  - Ideally, 2 final state jets produced in back-to-back in transverse plane with nearly balanced transverse momenta.
  - Deviations → *nonperturbative structure of the nucleon and nucleus.*
- Processes:
  - One nucleus/proton → emits quasi-real photon (γ)
  - Other nucleus/proton → provides pomeron (IP)



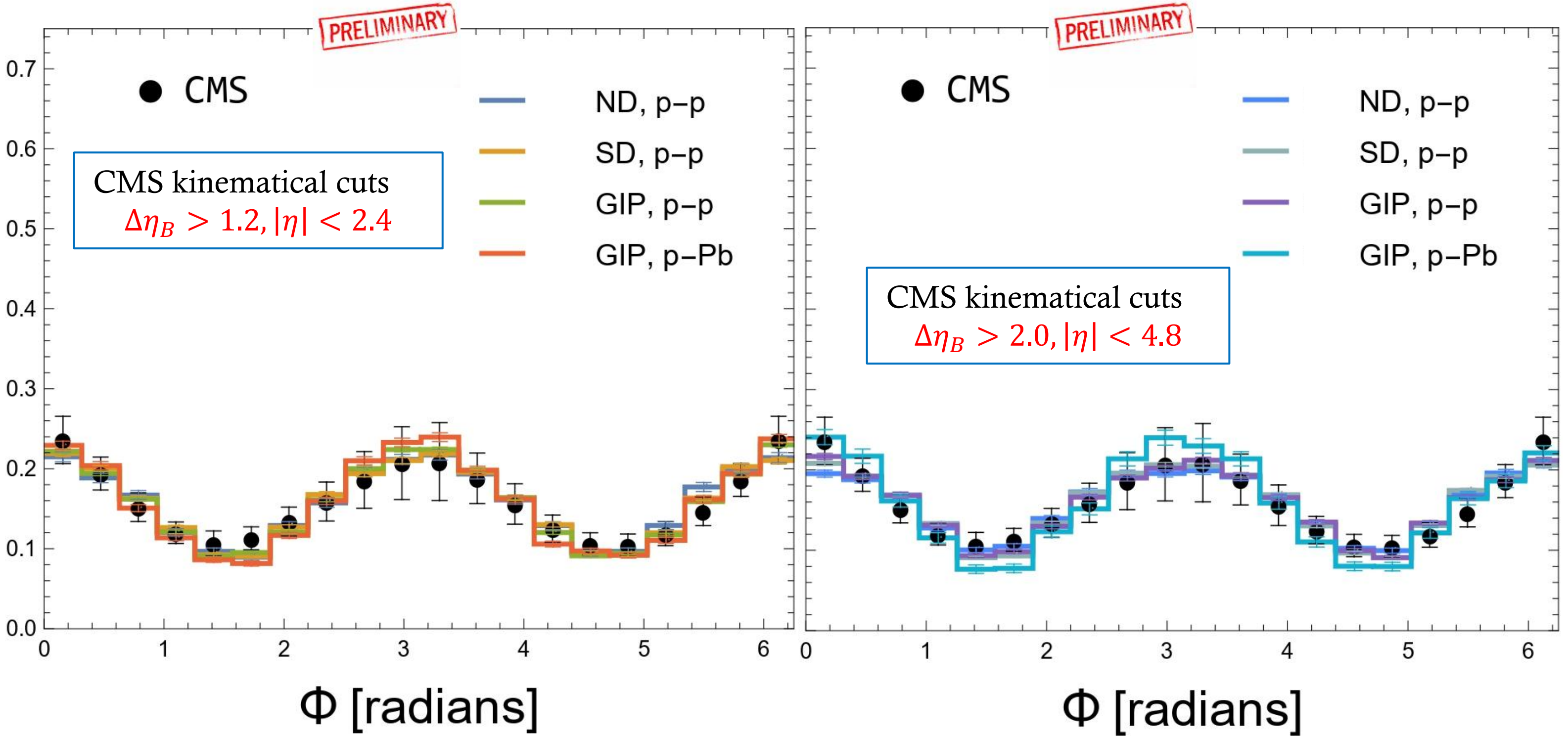
- Methodology and exclusivity cuts:
  - $\Delta\eta_F = 2.4 - \eta_{max}$; $\Delta\eta_B = 2.4 - \eta_{min}$; $\Delta\eta_B > \Delta\eta_F$; $\Delta\eta_B > 1.2$ (significant empty region)
  - Proton A → emits photon → produces jets → lots of activity (forward side)
  - Proton B → remains intact → no particles → GAP (backward side)
  - $\overrightarrow{Q_T} = \overrightarrow{p_{T,1}} + \overrightarrow{p_{T,2}}$; $\overrightarrow{P_T} = (\overrightarrow{p_{T,1}} - \overrightarrow{p_{T,2}})/2$; Φ angle between $\overrightarrow{Q_T}$ *and* $\overrightarrow{P_T}$.
- Impact :
  - Rapidity gaps isolate diffractive γ–IP interactions, enabling access to gluon dynamics through anisotropic distribution (nontrivial correlations in TMD associated with incoming hadrons).

Diffractive photoproduction

UPC



$\sigma_{ND} > \sigma_{SD} > \sigma_{GIP}$



- Pythia (8.3) studies of azimuthal correlations of dijets, *but only in events selected to have a rapidity gap*:
  - Implement CMS rapidity gap cuts (further tightened exclusivity condition) to select diffractive events.
  - Quantify the contribution of **γ-induced pomeron exchange (GIP)** to dijet production.
  - Access possible contribution from non-diffractive (ND) and single-diffractive (SD) events.

Hatta, Xiao, Yuan, Zhao; PRL 126 142001 (2021).
Jung (RAPGAP); CPC 86 147 (1995).

SPA, Goncalvez, Tasevsky; arXiv:26xx.xxxx.
CMS; PRL 131 051901 (2023).

Diffractive photoproduction

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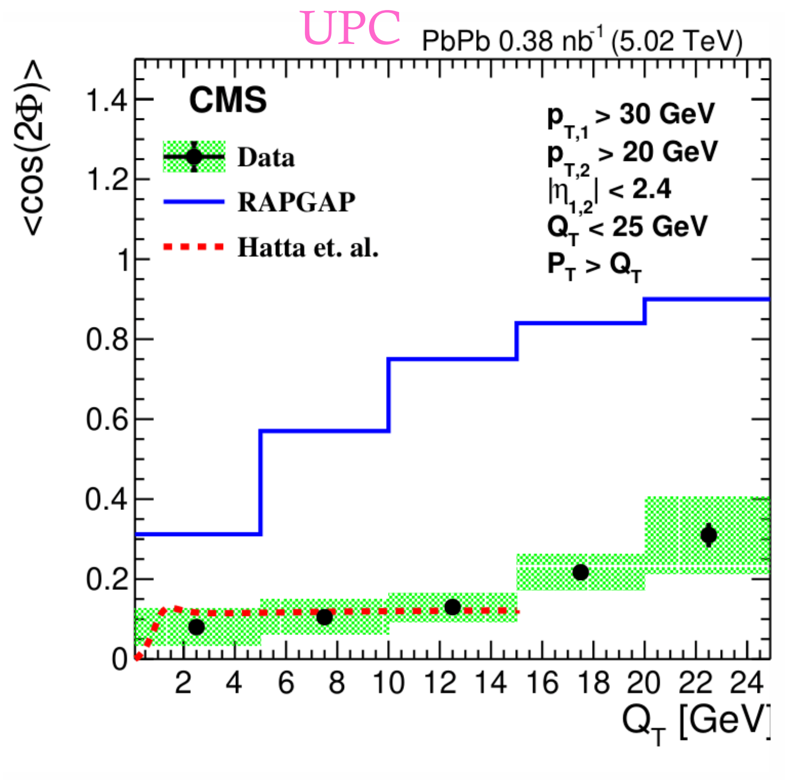

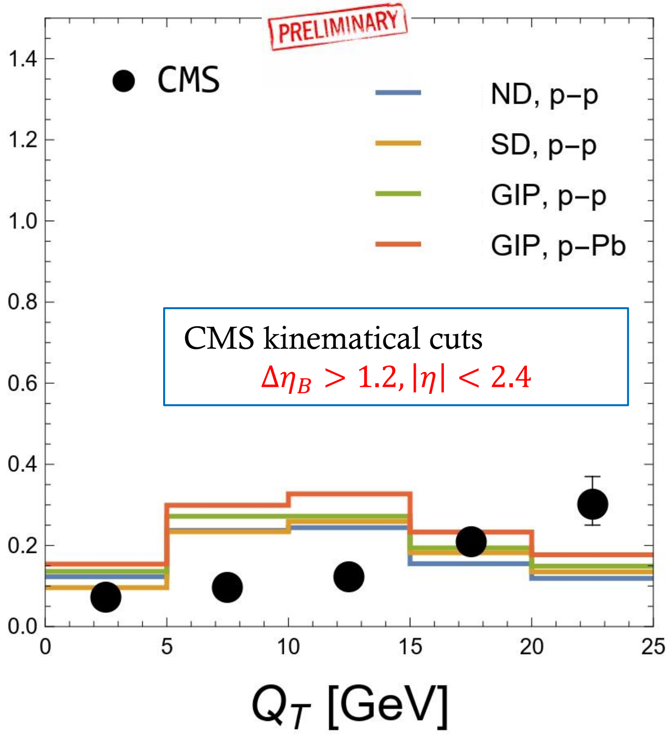

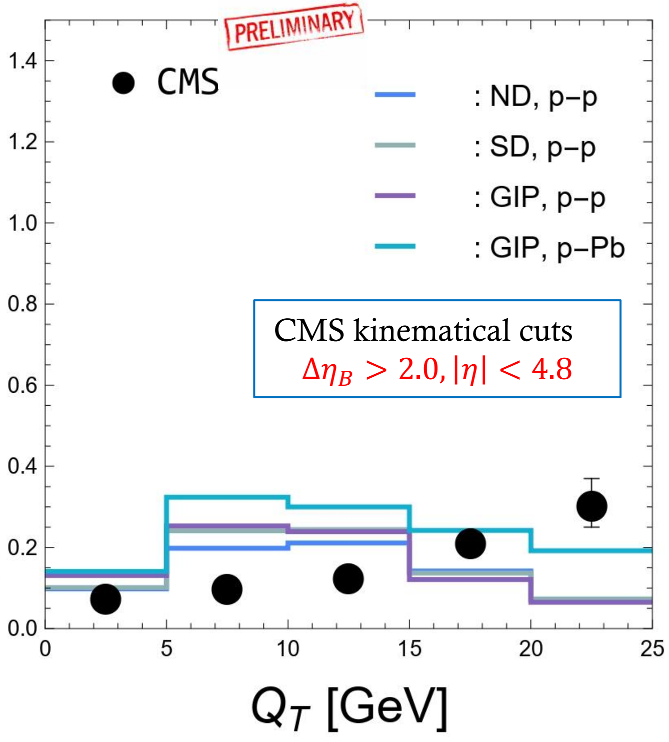

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Diffractive photoproduction

These distributions are not directly calculable in perturbative QCD, making them challenging to measure.

However, they can be accessed through exclusive diffractive dijet production in ultraperipheral collisions (UPCs) (ongoing) at the LHC and the future Electron-Ion Collider (EIC) (upcoming work).

Thank you !