Jet quenching and parton showers: some of the latest theoretical developments in heavy-ion collisions

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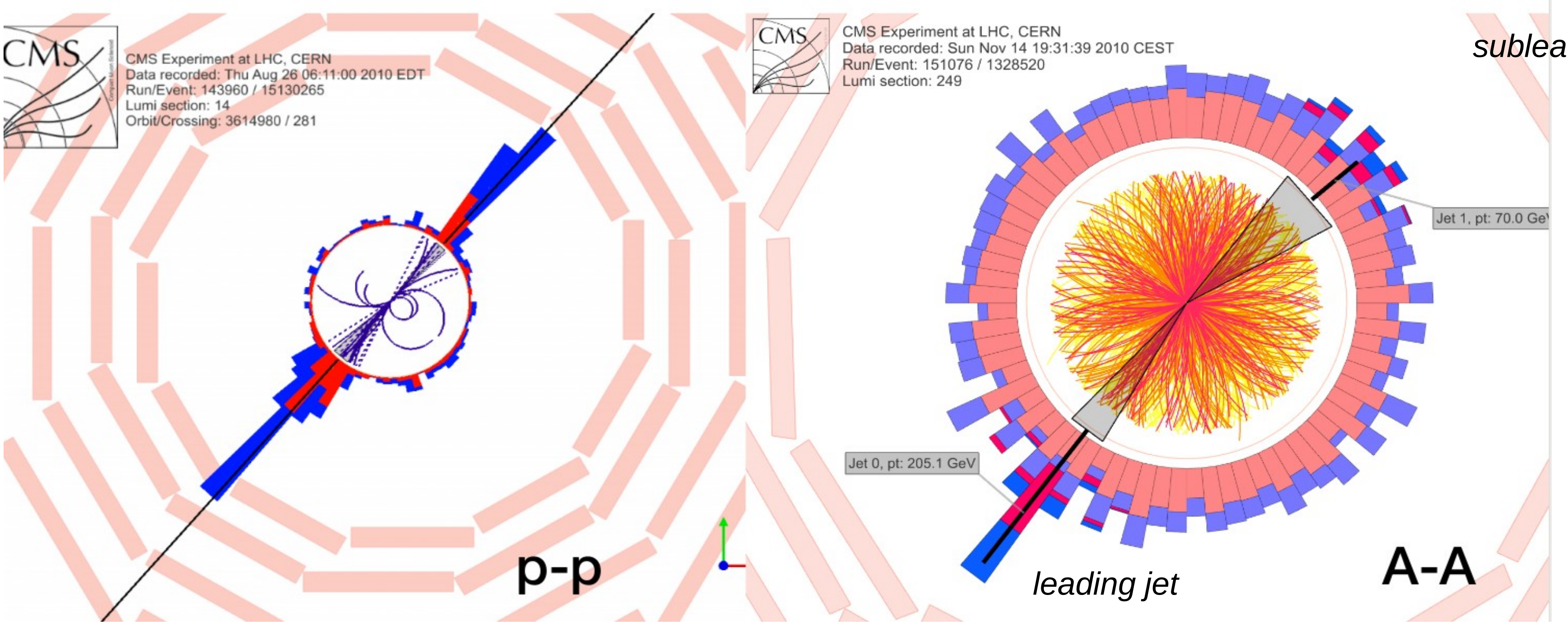
PASIFIC

Jet quenching

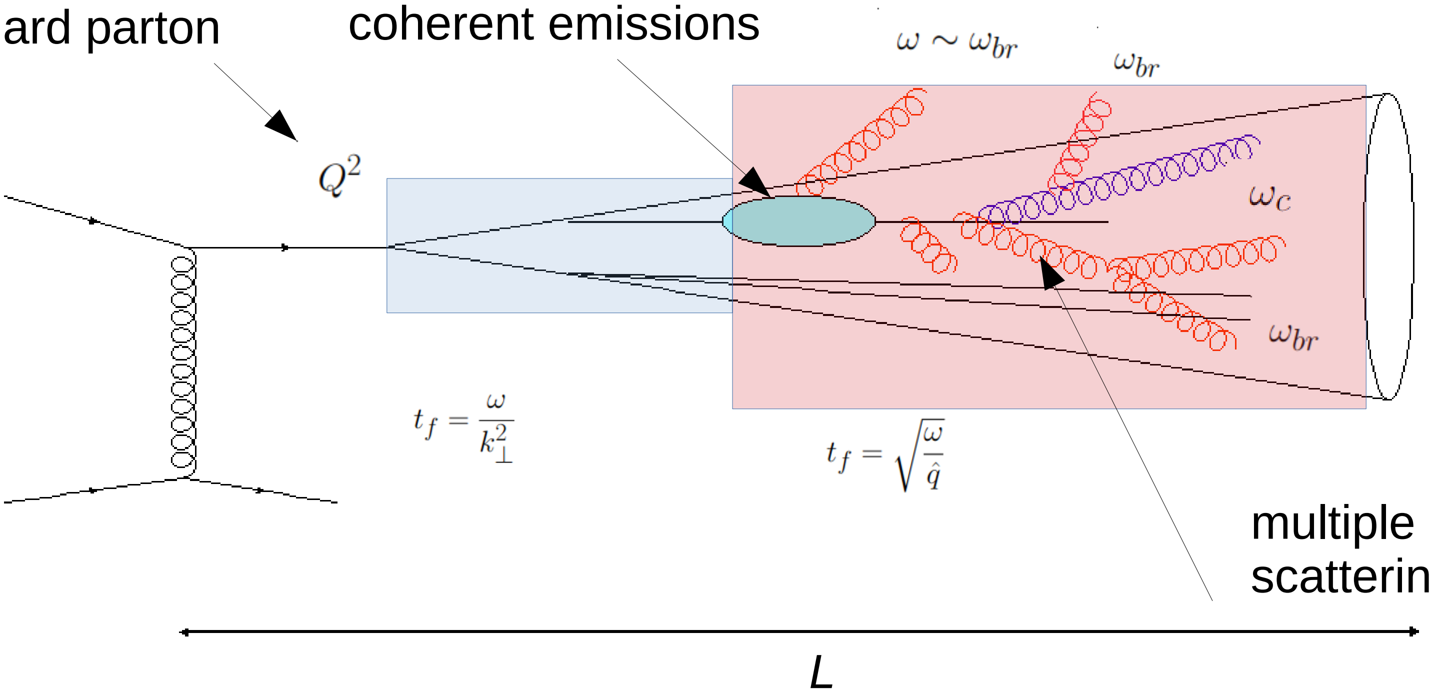


subleading jet

leading jet

virtuality of hard parton

coherent emissions



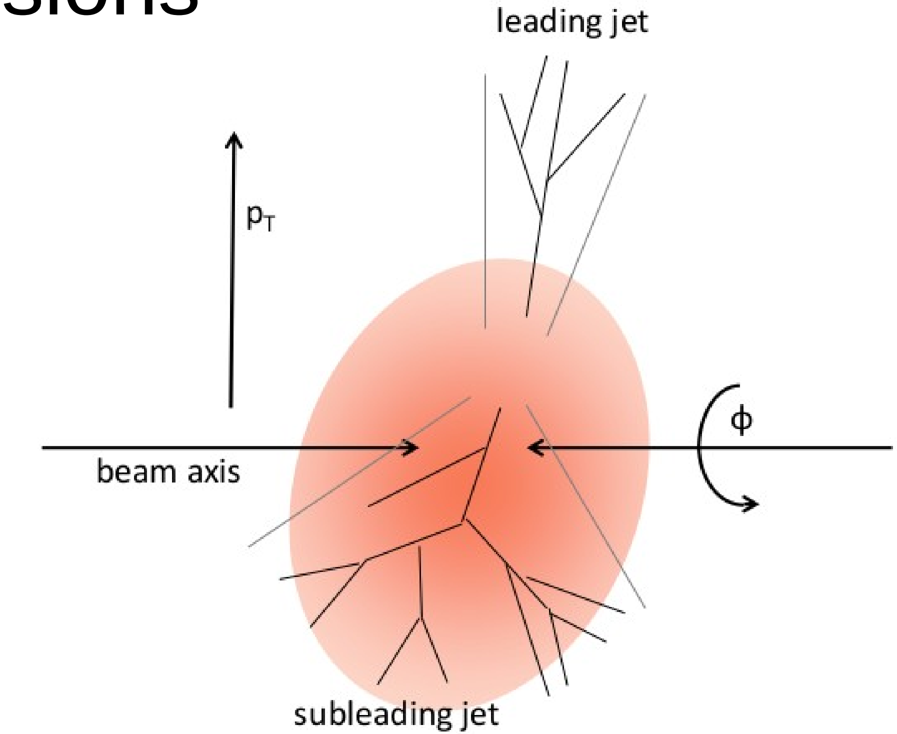
multiple soft
scatterings

Jet propagation through QGP
is a complicated multiscale problem

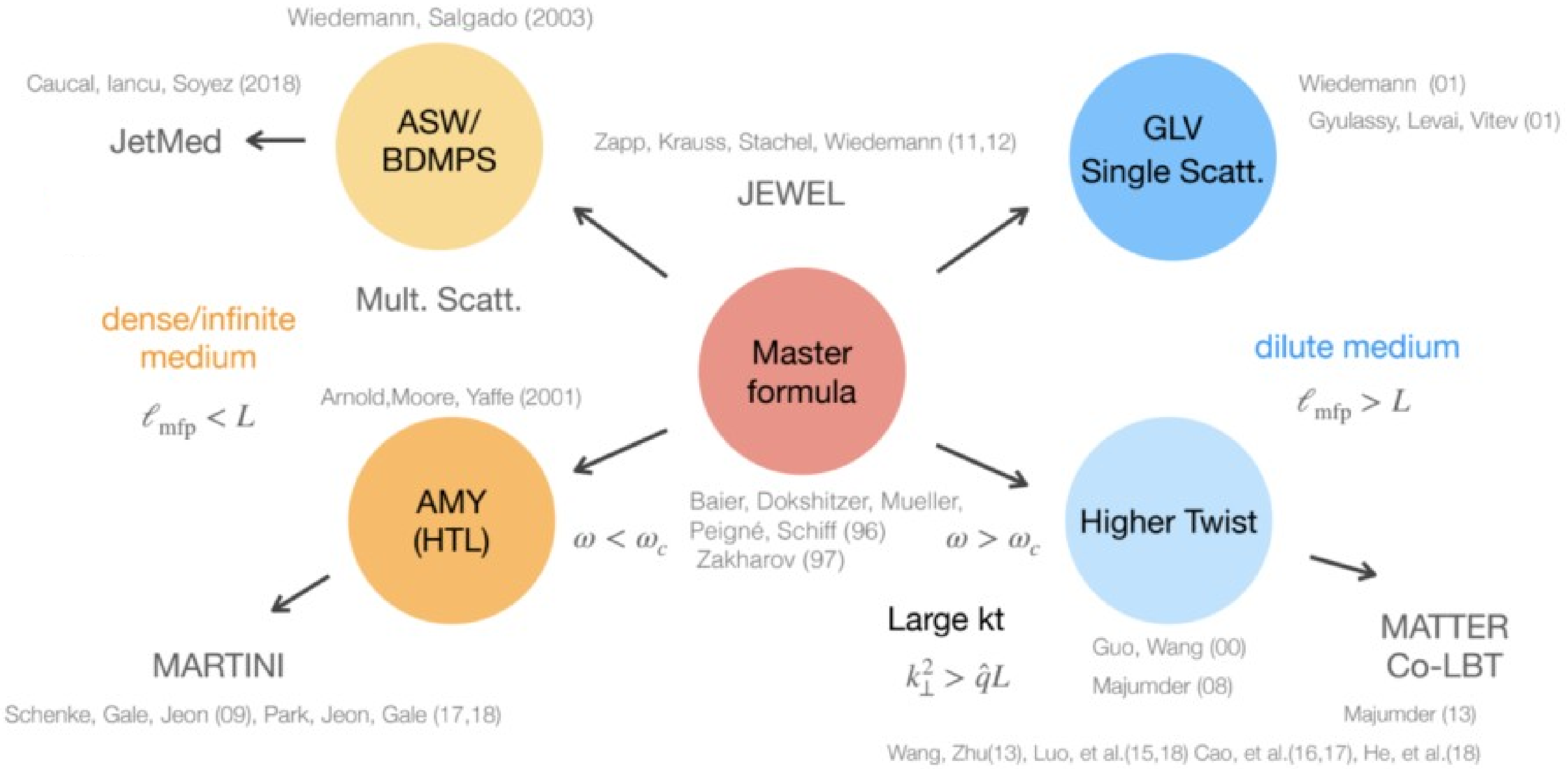
Jets in heavy ion collisions

Three types of emissions

- Vacuum like emissions in medium
- Medium induced emissions
- Vacuum like emissions outside of medium



Jet quenching frameworks and tools



Wiedemann, Salgado (2003)

Caucal, Iancu, Soyez (2018)

JetMed ⟵

ASW/ BDMPS

Mult. Scatt.

Zapp, Krauss, Stachel, Wiedemann (11,12)

JEWEL

GLV Single Scatt.

Wiedemann (01)

Gyulassy, Levai, Vitev (01)

dense/infinite medium

$\ell_{\mathrm{mfp}} < L$

Master formula

dilute medium

$\ell_{\mathrm{mfp}} > L$

Arnold,Moore, Yaffe (2001)

AMY (HTL)

$\omega < \omega_c$

Baier, Dokshitzer, Mueller, Peigné, Schiff (96)
Zakharov (97)

$\omega > \omega_c$

Higher Twist

MARTINI

Schenke, Gale, Jeon (09), Park, Jeon, Gale (17,18)

Large kt

$k_{\perp}^{2} > \hat{q}L$

Guo, Wang (00)

Majumder (08)

MATTER
Co-LBT

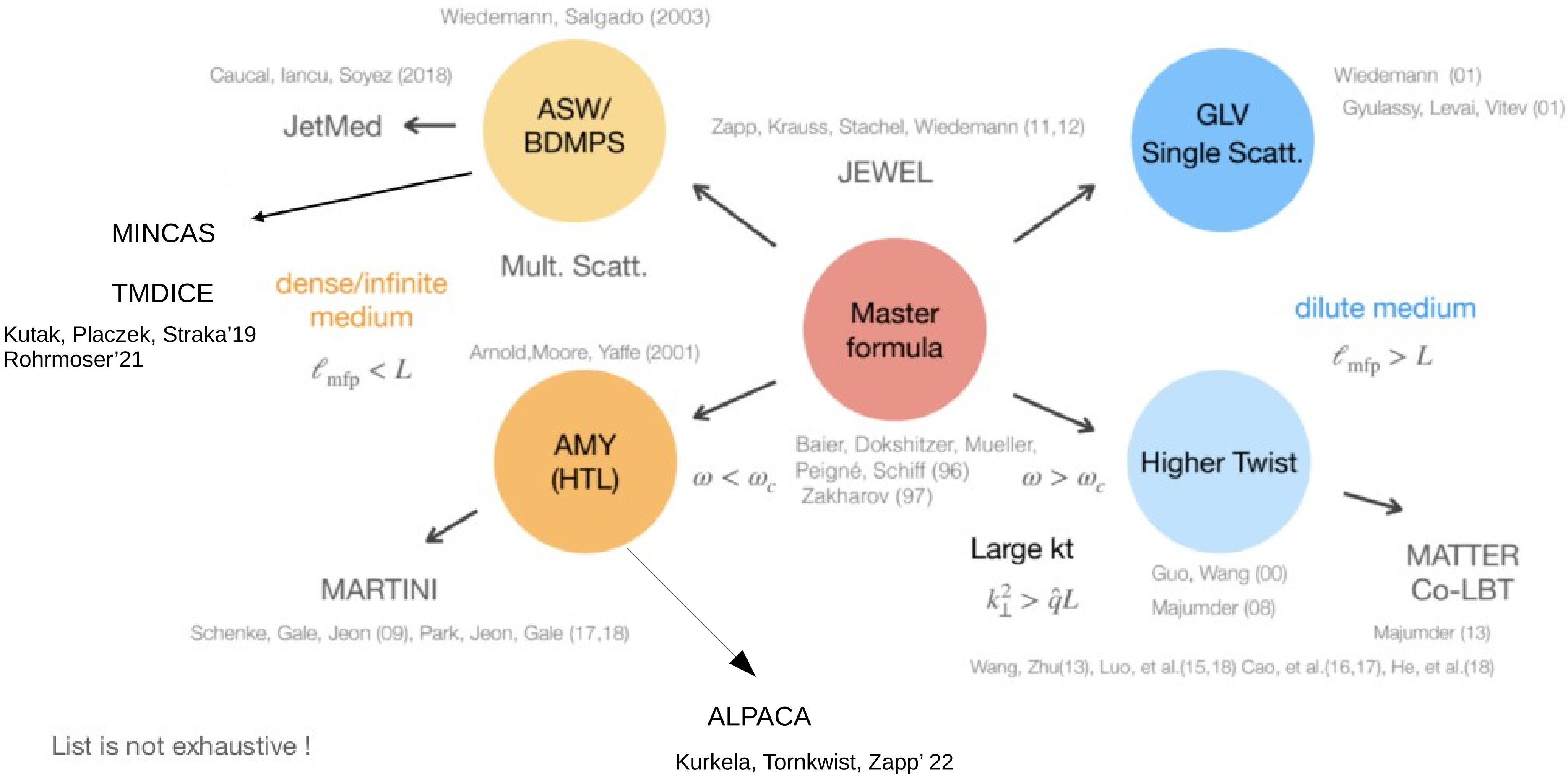
Majumder (13)

Wang, Zhu(13), Luo, et al.(15,18) Cao, et al.(16,17), He, et al.(18)

List is not exhaustive !

From Methar-Tani HTE seminar

Jet quenching frameworks and tools



Wiedemann, Salgado (2003)

Caucal, Iancu, Soyez (2018)

JetMed ←

ASW/
BDMPS

MINCAS

TMDICE

Kutak, Placzek, Straka'19
Rohrmoser'21

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ALPACA

Kurkela, Tornkwist, Zapp' 22

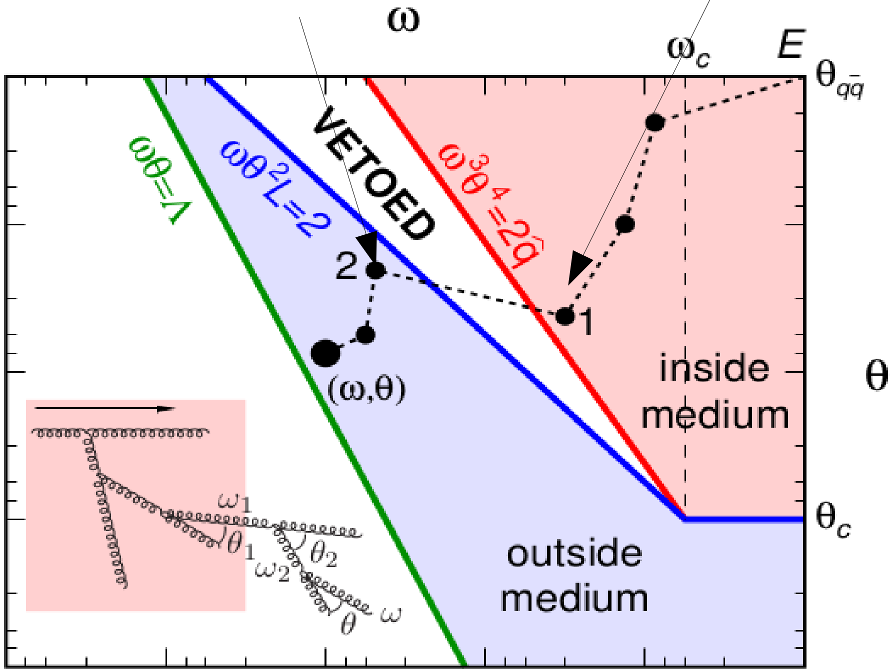
List is not exhaustive !

Jets in heavy ion collisions

Color antena propagating hrough QGP

Three types of emissions

- Vacuum like emissions in medium
- Medium induced emissions
- Vacuum like emissions outside of medium

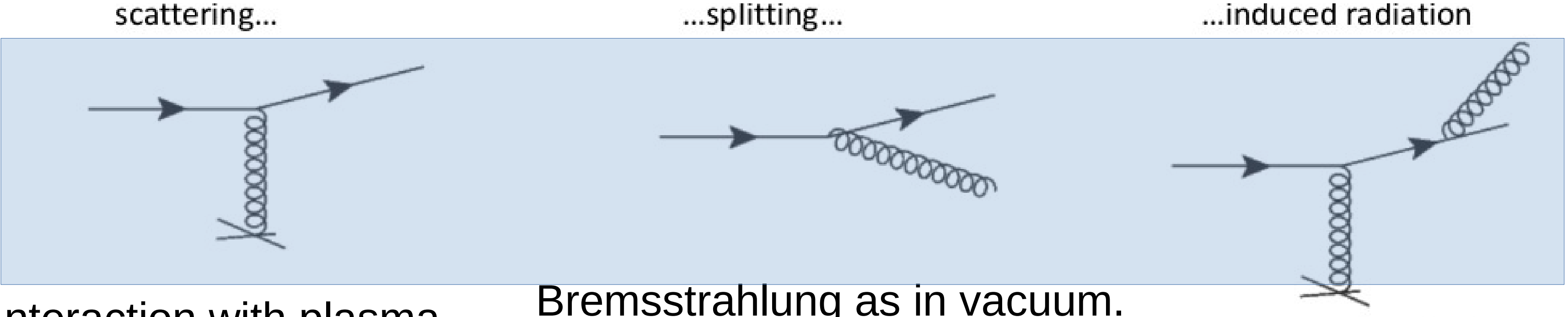


Last emission inside the medium

First emission outside

Iancu, Mueller, Soyez,Phys. Rev. Lett. 120, 232001 (2018)

Processes in the medium 1



Interaction with plasma
quasi-particles

Bremsstrahlung as in vacuum.
Angular ordering preserved.
Reduced phase space
Driven by the virtuality
of hard parton produced in
the medium short formation
times t_f

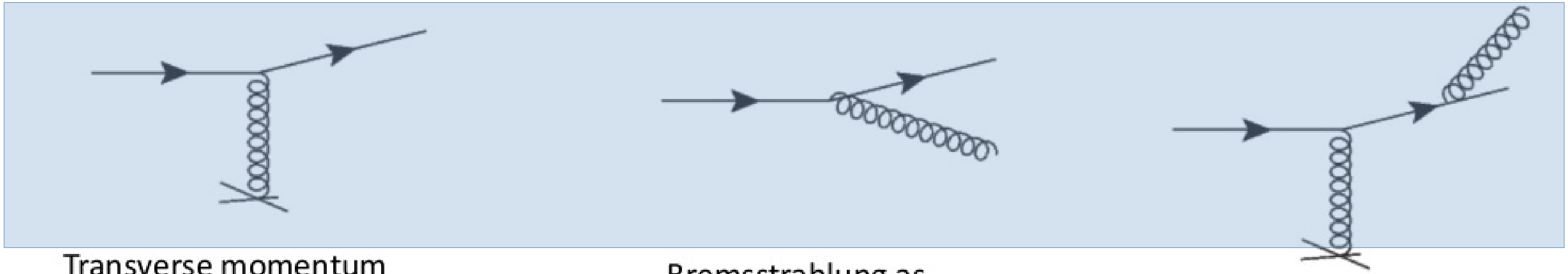
After formation, the partons
produced via VLEs propagate
through the medium and
act as sources for the next
stage, medium-induced
radiation. Driven by collisions
in th emedium

Processes in the medium 2

scattering…

…splitting…

…induced radiation



Transverse momentum transfer!

$p \rightarrow p + k_T$

Scattering Kernel: $C(k_T)$

Average transfer: $\hat{q}$

Bremsstrahlung as in vacuum.

Momentum distribution:

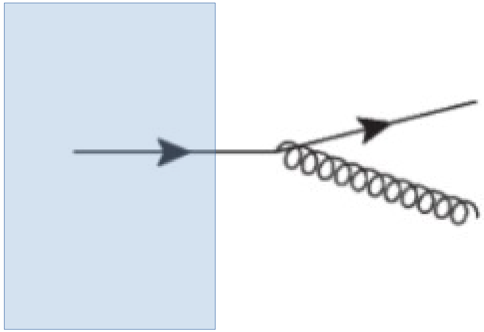
$p \rightarrow zp$

+Momentum transfer:

$p \rightarrow zp + k_T$

Kernel: $\mathcal{K}(z, k_T)$

Outside of the medium



Follow the standard vacuum angular-ordered pattern, but the very first emission outside the medium can occur at any angle.

Medium decoheres rescatterings so they can be seen as independent. Angular phase-space is opened beyond what would normally happen in a vacuum parton cascade.

Coherent emissions BDMPS-Z

$$t_{br} \sim \sqrt{\frac{2\omega}{\hat{q}}}$$

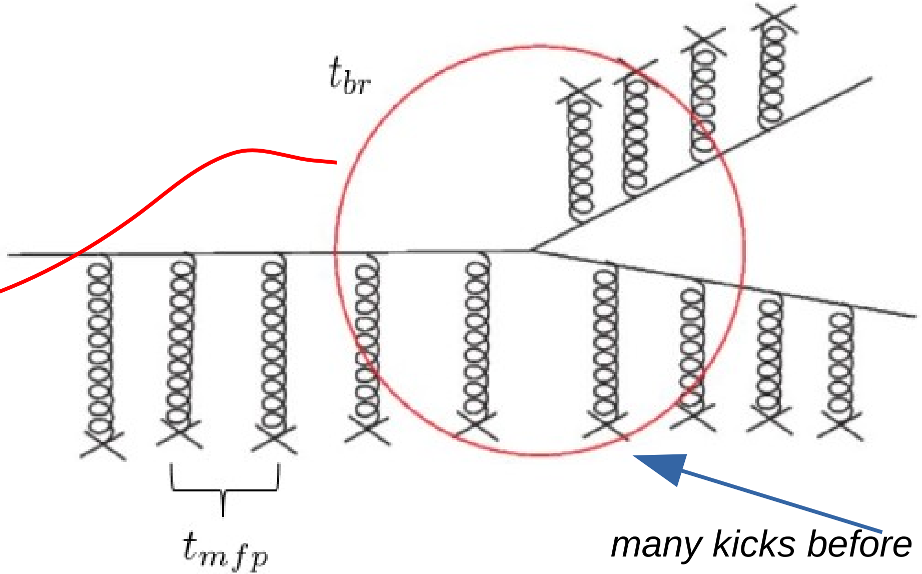
$t_{br} \sim t_{mfp}$: one scattering + radiation
...Bethe-Heitler spectrum

$t_{br} \gg t_{mfp}$: coherent radiation

$$\omega \frac{dI}{d\omega} \sim \alpha_s \frac{L}{t_{br}} = \alpha_s \sqrt{\frac{\omega_c}{\omega}}$$

Energy of observed gluon

maximal energy that can
be taken by single gluon



many kicks before radiation;
many centers
act as a single source

Look at range: $\omega_{BH} < \omega < \omega_c$

need effective kernel: $\mathcal{K}(z, k_T)$

The BDIM equation for gluons

Blaizot, Dominguez, Iancu, Methar-Tani’13

$$\frac{\partial}{\partial t} D_g(x,\boldsymbol{k},t) = \int_0^1 \mathrm{d}z \int \frac{\mathrm{d}^2\boldsymbol{q}}{(2\pi)^2}\alpha_s \left[2\mathcal{K}_{gg}\left(\boldsymbol{Q}, z, \frac{x}{z}p_0^+\right) D_g\left(\frac{x}{z},\boldsymbol{q},t\right) - \mathcal{K}_{gg}(\boldsymbol{q}, z, xp_0^+)\, D_g(x,\boldsymbol{k},t)\right] + \int \frac{\mathrm{d}^2\boldsymbol{l}}{(2\pi)^2} C_g(\boldsymbol{l})\, D_g(x,\boldsymbol{k}-\boldsymbol{l},t)\,,$$

virtual term

BDMPS scattering kernel

accounts for jet medium interaction

Shower equation

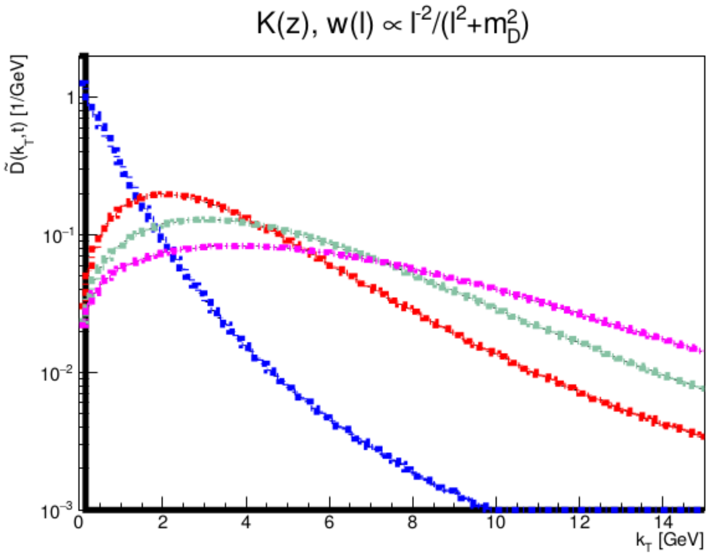
$$D(x,\mathbf{k},\tau) = e^{-\Psi(x)(\tau-\tau_0)} D(x,\mathbf{k},\tau_0) + \int_{\tau_0}^{\tau} d\tau' \int_0^1 dz \int_0^1 dy \int d^2\mathbf{k}' \int d^2\mathbf{q}\, \mathcal{G}(z,\mathbf{q}) \times \delta(x - zy)\,\delta(\mathbf{k}-\mathbf{q}-z\mathbf{k}')\, e^{-\Psi(x)(\tau-\tau')} D(y,\mathbf{k}',\tau')$$

Equation describes interplay of rescatterings and branching. This particular equation has kt independent kernel. This is an approximation. The whole broadening comes from rescattering. Energy of emitted gluon is much larger than its transverse momentum

Kutak, Placzek, Straka ’19

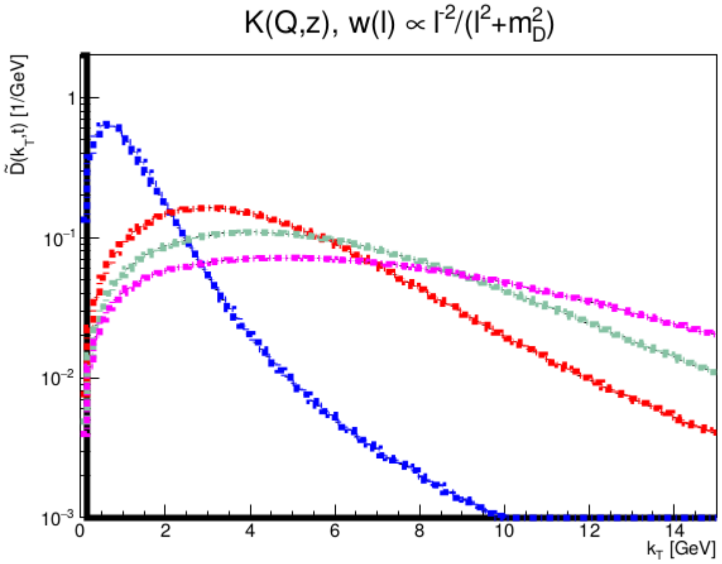
BDIM and various scenarios for the emission kernels

E. Blanco, K.Kutak, W. Płaczek, M. Rohrmoser, R.Straka, JHEP 04 (2021) 014



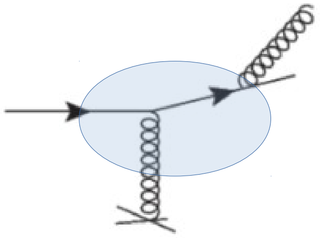
$K(z),\ w(l) \propto l^{-2}/(l^2+m_D^2)$

Momentum transfer during the formation time of the splittings neglected



$K(Q,z),\ w(l) \propto l^{-2}/(l^2+m_D^2)$

Momentum transfer during the formation time of the splittings accounted for. Clearly the distributions are wider



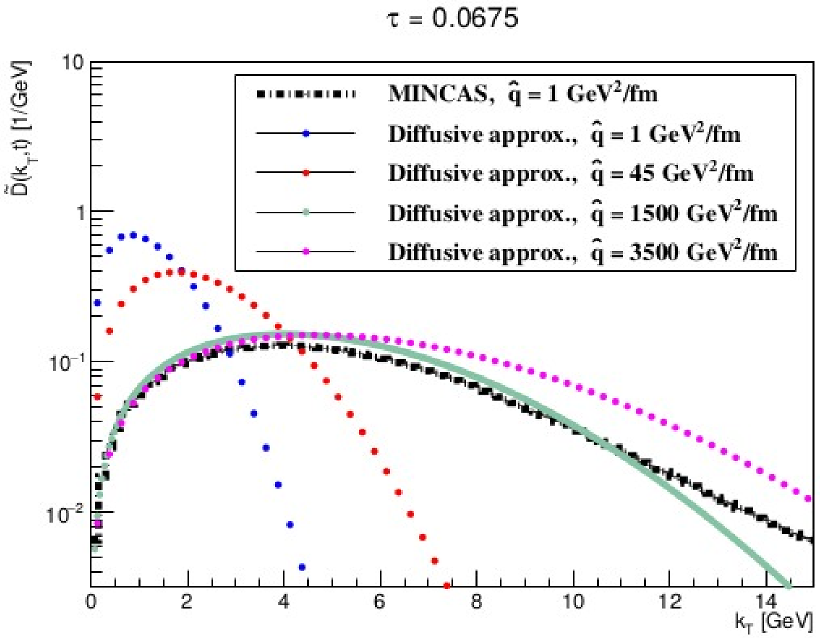
BDIM and diffusion

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

$$\frac{\partial}{\partial t}D(x,\mathbf{k},t)=\frac{1}{t^*}\int_0^1 dz\,\mathcal{K}(z)\left[\frac{1}{z^2}\sqrt{\frac{z}{x}}\,D\left(\frac{x}{z},\frac{\mathbf{k}}{z},t\right)\theta(z-x)-\frac{z}{\sqrt{x}}D(x,\mathbf{k},t)\right]$$
$$+\frac{1}{4}\hat{q}\nabla_k^2\Big[D(x,\mathbf{k},t)\Big]$$

$$C(\mathbf{l})=w(\mathbf{l})-\delta(\mathbf{l})\int d^2\mathbf{l}'\,w(\mathbf{l}')$$

$$w(\mathbf{l})=\frac{g^2m_D^2T}{\mathbf{l}^2(\mathbf{l}^2+m_D^2)}$$



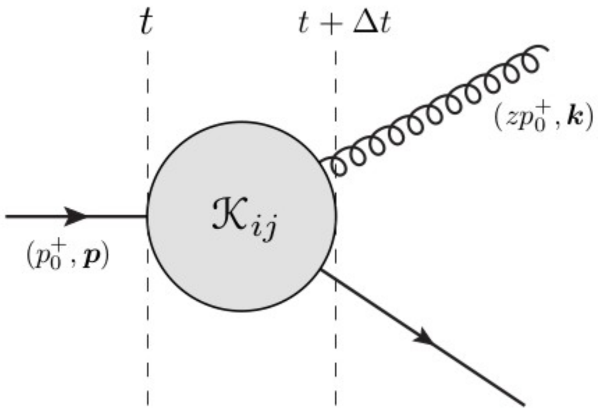
Hard kicks from the medium correspond to strong diffusion

E. Blanco, K.Kutak, W. Płaczek, M. Rohrmoser, R.Straka, JHEP 04 (2021) 014

BDIM equation for quark and gluons

$$
\begin{aligned}
\frac{\partial}{\partial t} D_g(x,\boldsymbol{k},t) = & \int_0^1 \mathrm{d}z \int \frac{\mathrm{d}^2\boldsymbol{q}}{(2\pi)^2} \alpha_s \Big\{ 2\mathcal{K}_{gg}\left(\boldsymbol{Q}, z, \frac{x}{z}p_0^+\right) D_g\left(\frac{x}{z}, \boldsymbol{q}, t\right) + \mathcal{K}_{gq}\left(\boldsymbol{Q}, z, \frac{x}{z}p_0^+\right) \sum_i D_{q_i}\left(\frac{x}{z}, \boldsymbol{q}, t\right) \\
& - \left[\mathcal{K}_{gg}(\boldsymbol{q}, z, xp_0^+) + \mathcal{K}_{qg}(\boldsymbol{q}, z, xp_0^+)\right] D_g(x,\boldsymbol{k},t) \Big\} + \int \frac{\mathrm{d}^2\boldsymbol{l}}{(2\pi)^2} C_g(\boldsymbol{l}) \, D_g(x, \boldsymbol{k}-\boldsymbol{l}, t), \\
\frac{\partial}{\partial t} D_{q_i}(x,\boldsymbol{k},t) = & \int_0^1 \mathrm{d}z \int \frac{\mathrm{d}^2\boldsymbol{q}}{(2\pi)^2} \alpha_s \Big\{ \mathcal{K}_{qq}\left(\boldsymbol{Q}, z, \frac{x}{z}p_0^+\right) D_{q_i}\left(\frac{x}{z}, \boldsymbol{q}, t\right) + \frac{1}{N_F} \mathcal{K}_{qg}\left(\boldsymbol{Q}, z, \frac{x}{z}p_0^+\right) D_g\left(\frac{x}{z}, \boldsymbol{q}, t\right) \\
& - \mathcal{K}_{qq}(\boldsymbol{q}, z, xp_0^+) \, D_{q_i}(x,\boldsymbol{k},t) \Big\} + \int \frac{\mathrm{d}^2\boldsymbol{l}}{(2\pi)^2} C_q(\boldsymbol{l}) \, D_{q_i}(x, \boldsymbol{k}-\boldsymbol{l}, t)\,,
\end{aligned}
$$

Equation implemented in Monte Carlo shower TMDICE and MC Monte Carlo MINCAS



exampe of proces with initial quark

Blanco, Kutak, Placzek, Rohrmoser, Tywoniuk’21

BDIM equation for quark and gluons

$$\frac{\partial}{\partial t} D_g(x,\boldsymbol{k},t) = \int_0^1 \mathrm{d}z \int \frac{\mathrm{d}^2\boldsymbol{q}}{(2\pi)^2}\alpha_s \Big\{ 2\mathcal{K}_{gg}\left(\boldsymbol{Q}, z, \frac{x}{z}p_0^+\right) D_g\left(\frac{x}{z},\boldsymbol{q},t\right) + \mathcal{K}_{gq}\left(\boldsymbol{Q},z,\frac{x}{z}p_0^+\right)\sum_i D_{q_i}\left(\frac{x}{z},\boldsymbol{q},t\right)$$

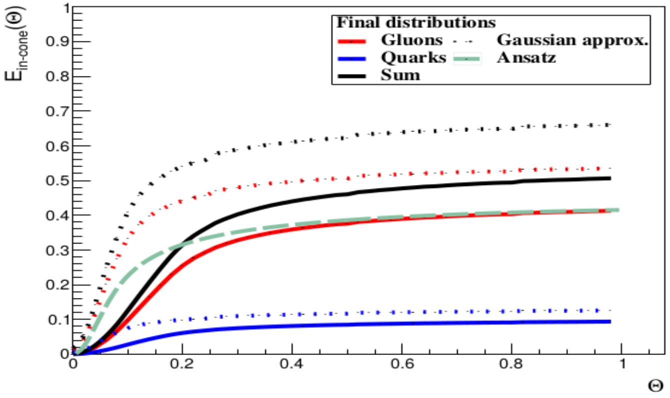
$$- \left[\mathcal{K}_{gg}(\boldsymbol{q},z,xp_0^+) + \mathcal{K}_{qg}(\boldsymbol{q},z,xp_0^+)\right] D_g(x,\boldsymbol{k},t)\Big\} + \int \frac{\mathrm{d}^2\boldsymbol{l}}{(2\pi)^2}\, C_g(\boldsymbol{l})\, D_g(x,\boldsymbol{k}-\boldsymbol{l},t),$$

$$\frac{\partial}{\partial t} D_{q_i}(x,\boldsymbol{k},t) = \int_0^1 \mathrm{d}z \int \frac{\mathrm{d}^2\boldsymbol{q}}{(2\pi)^2}\alpha_s \Big\{ \mathcal{K}_{qq}\left(\boldsymbol{Q}, z, \frac{x}{z}p_0^+\right) D_{q_i}\left(\frac{x}{z},\boldsymbol{q},t\right) + \frac{1}{N_F}\mathcal{K}_{qg}\left(\boldsymbol{Q},z,\frac{x}{z}p_0^+\right) D_g\left(\frac{x}{z},\boldsymbol{q},t\right)$$

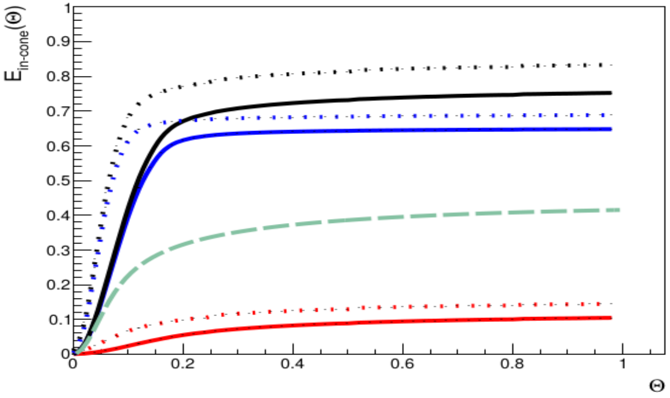
$$- \mathcal{K}_{qq}(\boldsymbol{q},z,xp_0^+)\, D_{q_i}(x,\boldsymbol{k},t)\Big\} + \int \frac{\mathrm{d}^2\boldsymbol{l}}{(2\pi)^2}\, C_q(\boldsymbol{l})\, D_{q_i}(x,\boldsymbol{k}-\boldsymbol{l},t)\,,$$

Equation implemented in Monte Carlo shower TMDICE and MC Monte Carlo MINCAS

Initial gluon

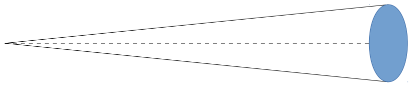


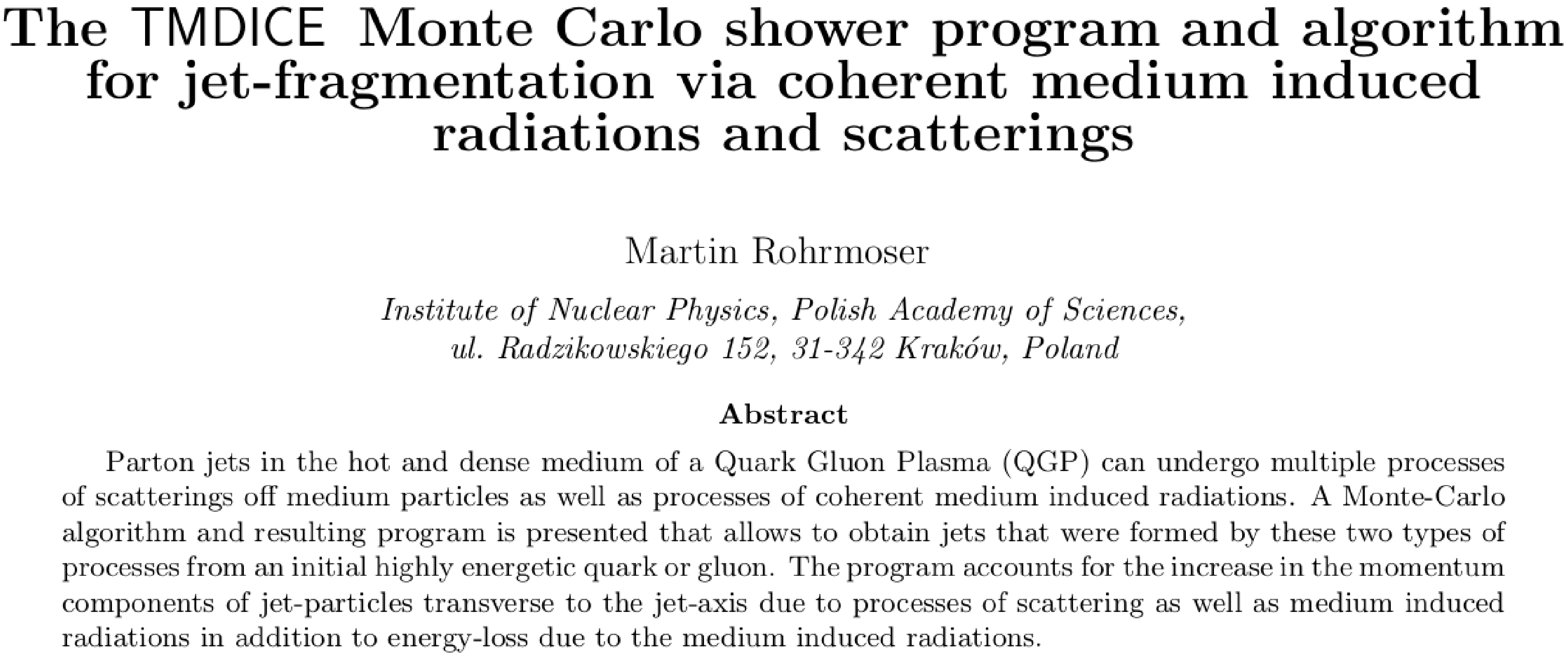
Initial quark



Quark jets appear to be wider than gluon jets

$$E_{\text{in-cone}}(\Theta) = \int_0^1 \mathrm{d}x \int_0^{xE\sin\Theta} \mathrm{d}k_T\, \tilde{D}(x,k_T,t)$$





The TMDICE Monte Carlo shower program and algorithm for jet-fragmentation via coherent medium induced radiations and scatterings

Martin Rohrmoser

Institute of Nuclear Physics, Polish Academy of Sciences,
ul. Radzikowskiego 152, 31-342 Kraków, Poland

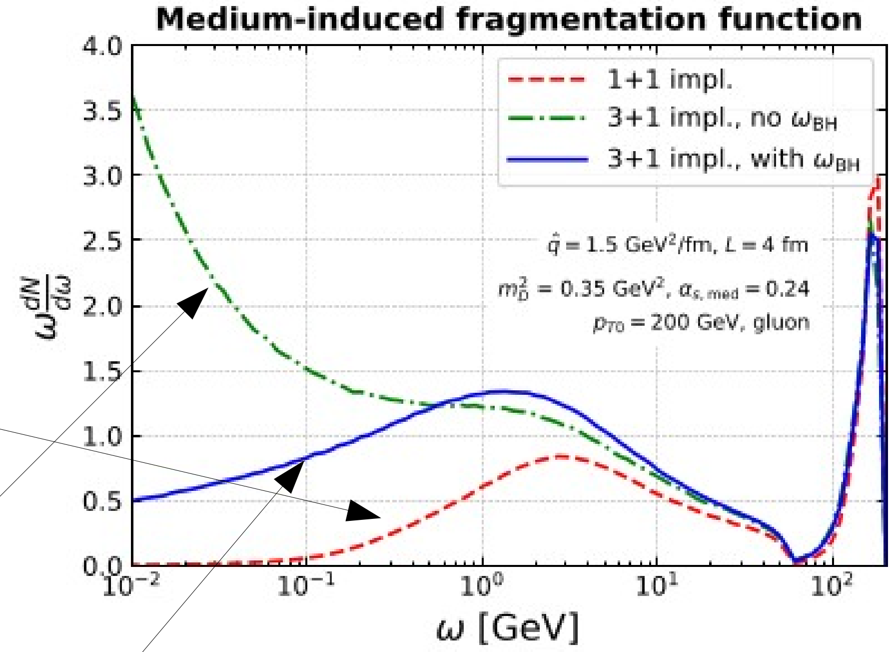
Abstract

Parton jets in the hot and dense medium of a Quark Gluon Plasma (QGP) can undergo multiple processes of scatterings off medium particles as well as processes of coherent medium induced radiations. A Monte-Carlo algorithm and resulting program is presented that allows to obtain jets that were formed by these two types of processes from an initial highly energetic quark or gluon. The program accounts for the increase in the momentum components of jet-particles transverse to the jet-axis due to processes of scattering as well as medium induced radiations in addition to energy-loss due to the medium induced radiations.

Rohrmoser, Comput.Phys.Commun. 276 (2022) 108343

Bethe-Heitler regime: single soft scattering

BDMPSZ breaks down already when
when $\omega \sim \omega_{BH}$



From E. Iancu, HP 2023

Decrease of gluon energy in cone because of deflection coming from interaction with medium in Gaussian model

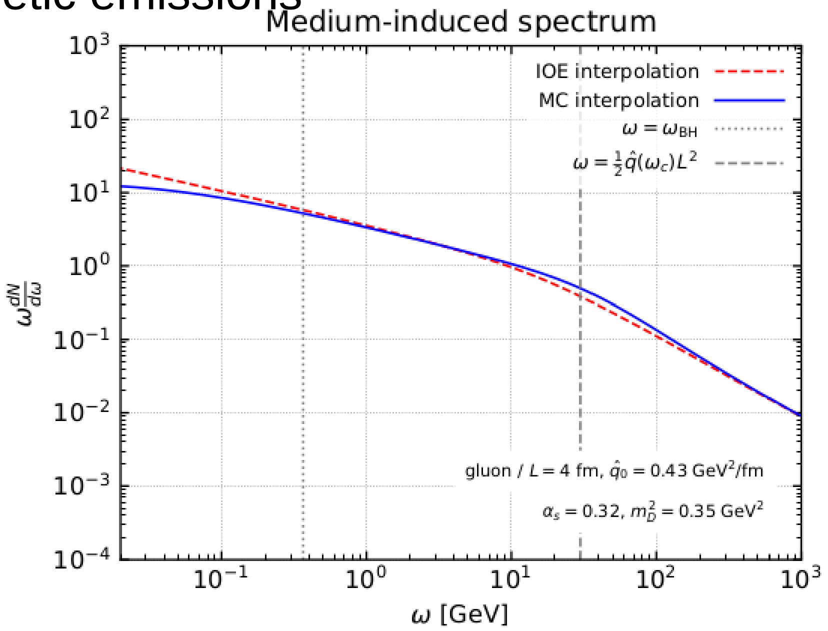
Acconting for non Gaussian broadening

Accounting for non Gaussian broadening and single soft scattering

Accounting for more energetic emissions: GLV

Change in the spectrum for very energetic emissions

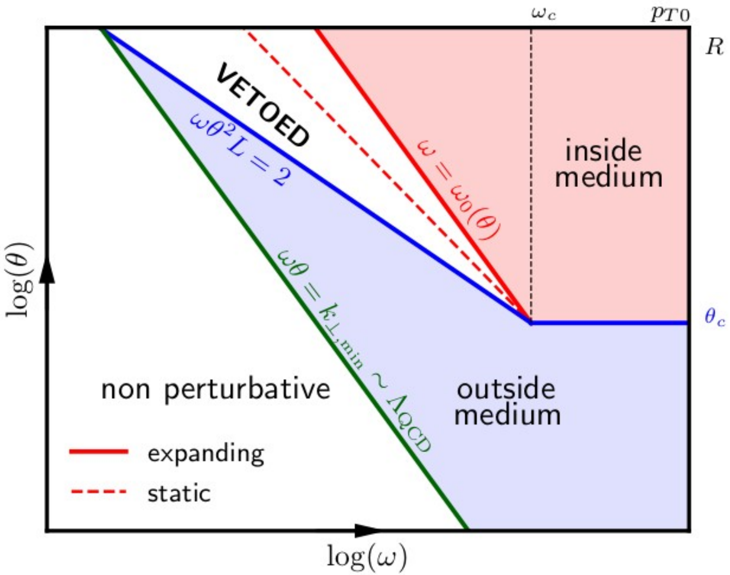
$$\omega\frac{dN}{d\omega} \simeq \alpha_s \begin{cases} \frac{L}{\lambda} & \omega \lesssim \omega_{BH} \\ \sqrt{\frac{\hat{q}(\omega_c)L^2}{\omega}} & \omega_{BH} << \omega << \omega_s \\ \boxed{\left[\frac{\hat{q}L^2}{\omega}\right]^2 \qquad \omega \gtrsim \omega_c} & \\ \frac{q_0 L^2}{\omega} & \omega >> \omega_c \end{cases}$$

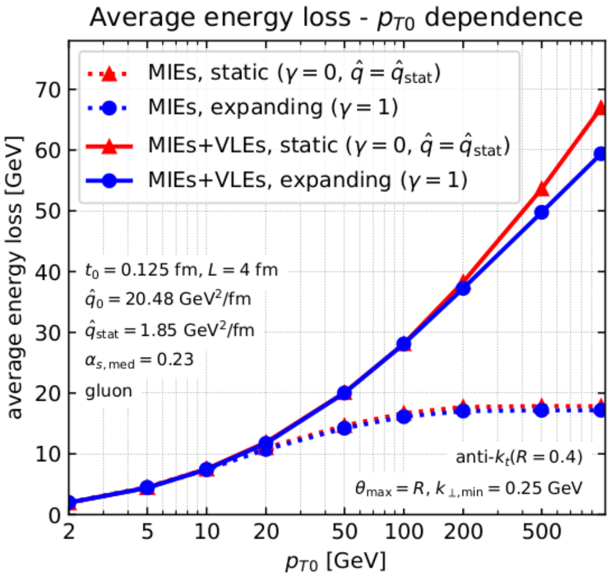


The full spectrum has been computed numerically
Caron-Huot and Gale, 2010; Feal, Vazquez, 2018; Andres et al, 2020-21 ...
Analytic interpolations (Improved Opacity Expansion)
Mehtar-Tani and Tywoniuk, 2019; Barata et al, 2022; Isaksen et al, 2022 ...

From E. Iancu
HP 2023

Jets in heavy ion collisions – accounting for expansion





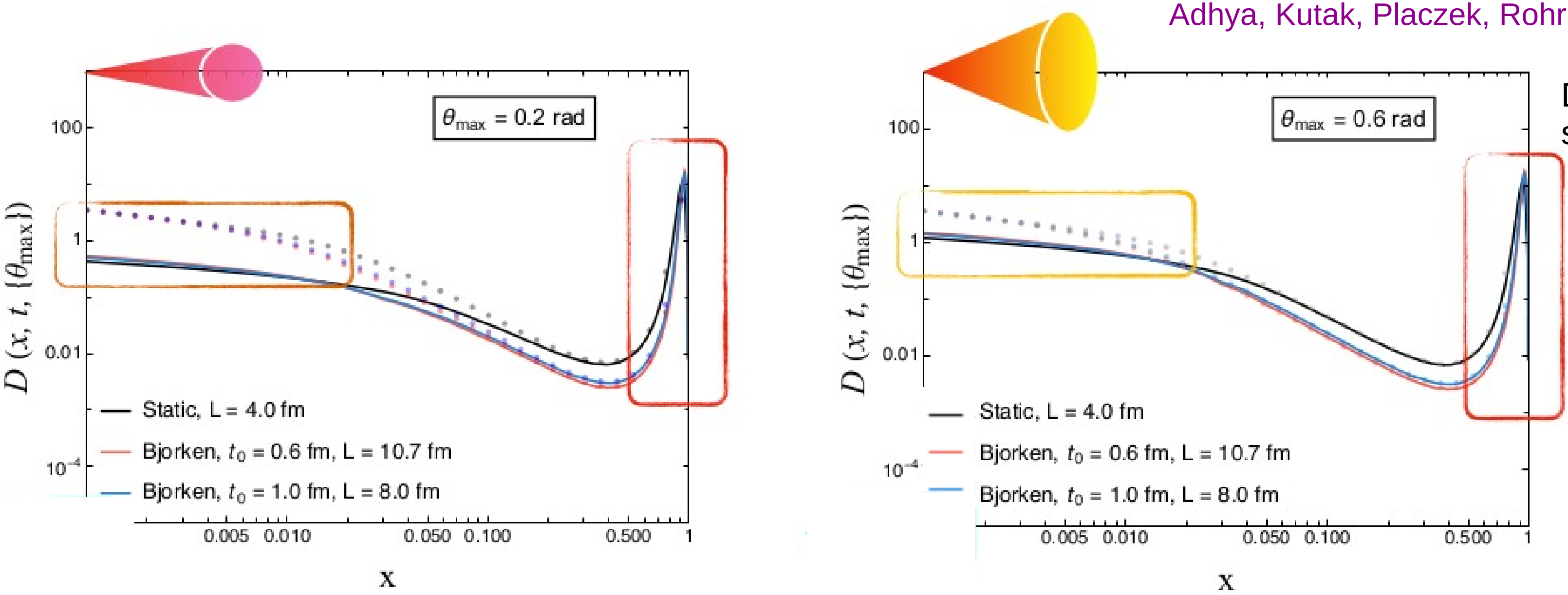
Less quenching as compared to static medium

energy loss is slightly smaller for an expanding medium

Caucal, Iancu, Soyez’ 20

Soft gluons and medium expansion

Adhya, Kutak, Placzek, Rohrmoser, Tywoniuk ‘22



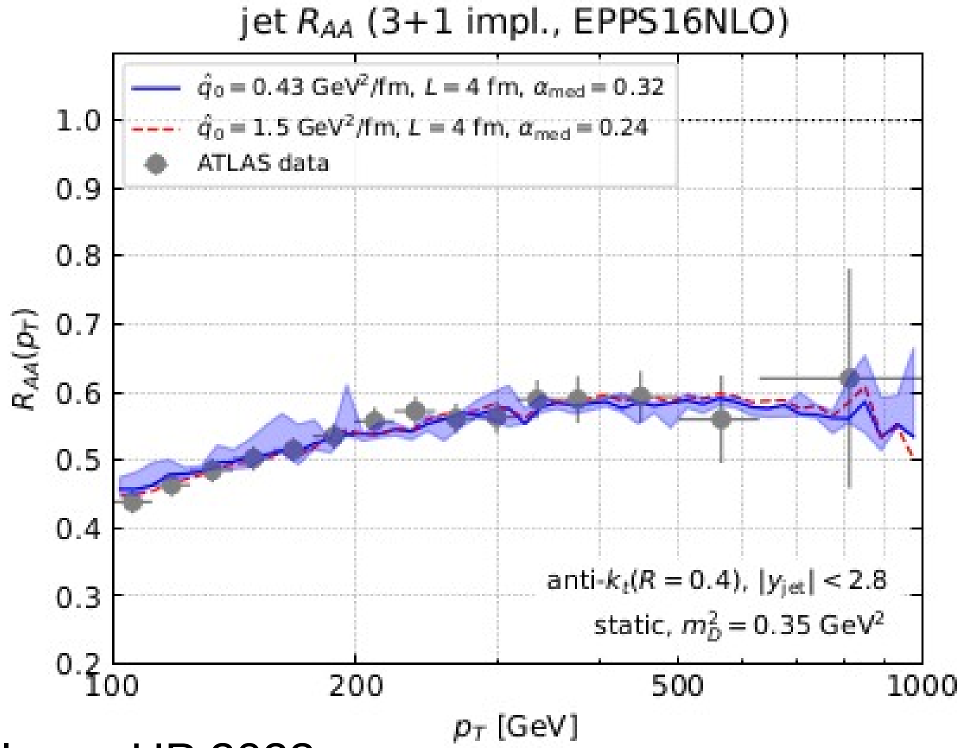
Dotted line (..) is spectra for full angular region.

$$D(x,t;\{\theta_{\max}\}) = \int_0^{\theta_{\max}} \mathrm{d}\theta\, \bar{D}(x,\theta,t)$$

As one opens up the angle one recoversmore softer gluons
No change of harder gluons as they primarily remain collimated
Hard jet fragments are sensitive to medium expansion, softer once are not

See also
Adhya, Salgado, Spousta, Tywoniuk ‘20

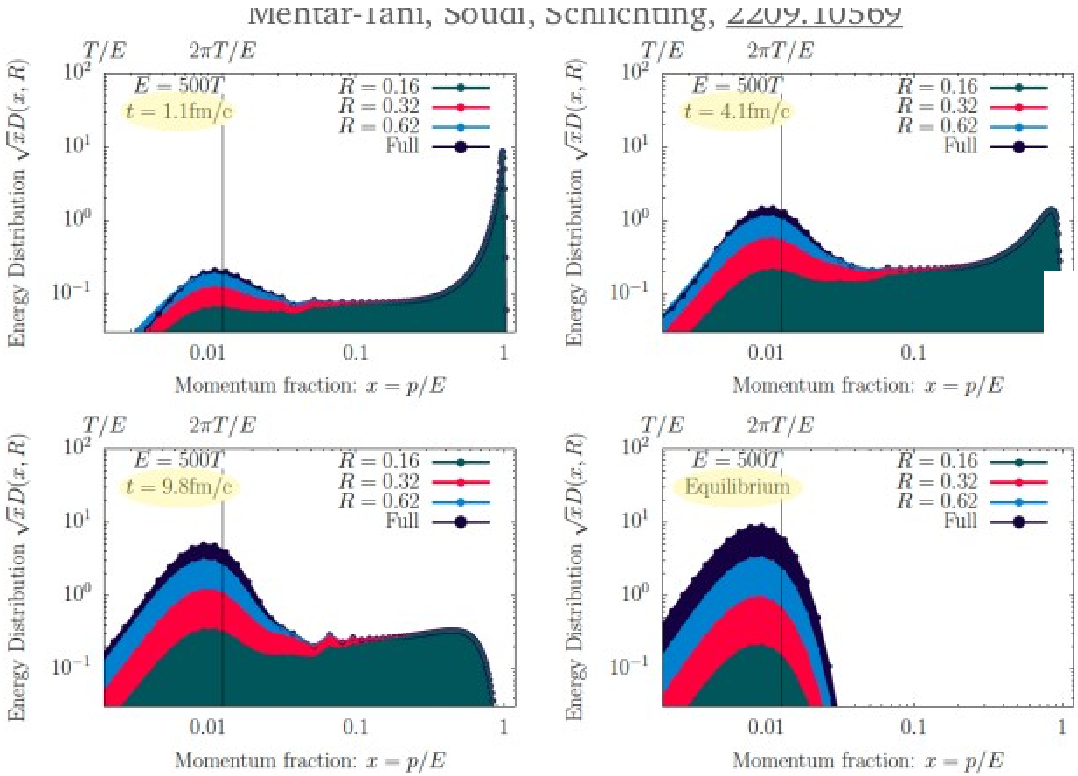
Results for nuclear modification ratio



A lot more observables to look at: jet shapes,..

JetMed From E. Iancu HP 2023

Termalization and out cone emissions – non MC



Mehtar-Tani, Soudi, Schlichting'22

$$\left(\partial_t + \frac{\boldsymbol{p}}{|\boldsymbol{p}|}\cdot\nabla_x\right) f_a(\boldsymbol{p},\mathbf{x},t) = -C_a^{2\leftrightarrow 2}[\{f_i\}] - C_a^{1\leftrightarrow 2}[\{f_i\}]$$

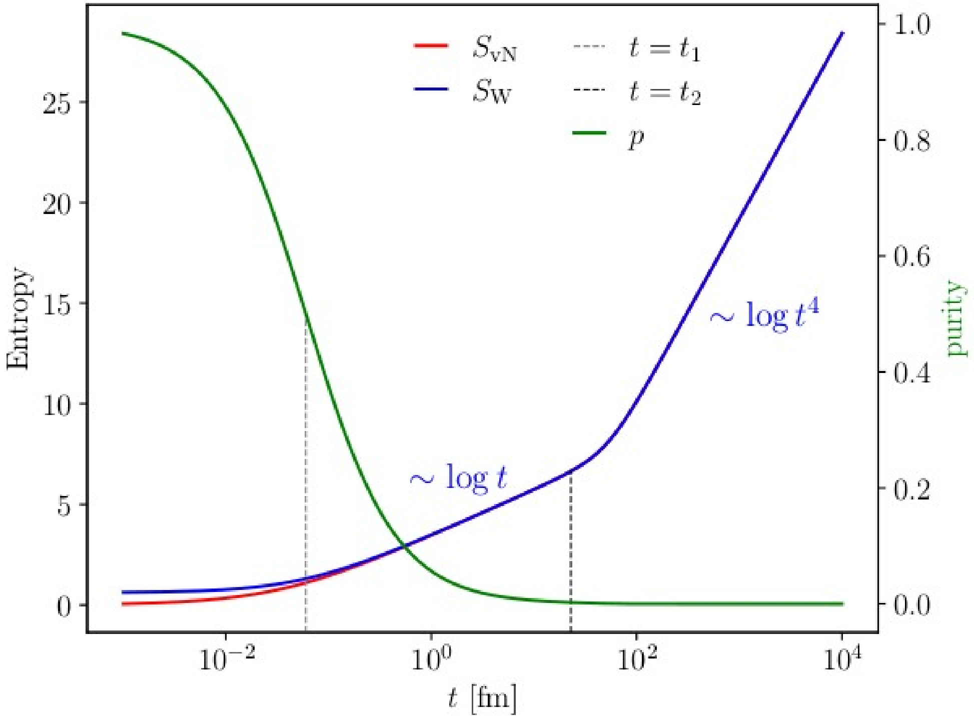
$$D_{a/\mathrm{jet}}(x,\theta,t) \equiv x\frac{\mathrm{d}N_a}{\mathrm{d}x\,\mathrm{d}\cos\theta}$$

$$= \nu_a \int d^3\mathbf{x} \int \frac{d^3p}{(2\pi)^3}\,\frac{|\boldsymbol{p}|}{E}\,\delta\Big(\frac{|\boldsymbol{p}|}{E} - x\Big)\delta\Big(\frac{\boldsymbol{p}\cdot\hat{e}_z}{xE} - \cos\theta\Big)\delta f_a(\boldsymbol{p},\mathbf{x},t)$$

non – Monte Carlo

Out-of-cone energy loss via medium-induced radiation, followed by elastic scatterings of soft fragments pushing the distribution to large angles and thermalization

Von Neumann entropy of jet in QGP



Barata, Blaizot, Methar-Tani ‘23

Quick classicalization of density matrix.
At early times the density matrix has diagonal and off diagonal components.
As evolution progresses the density matrix becomes classical,

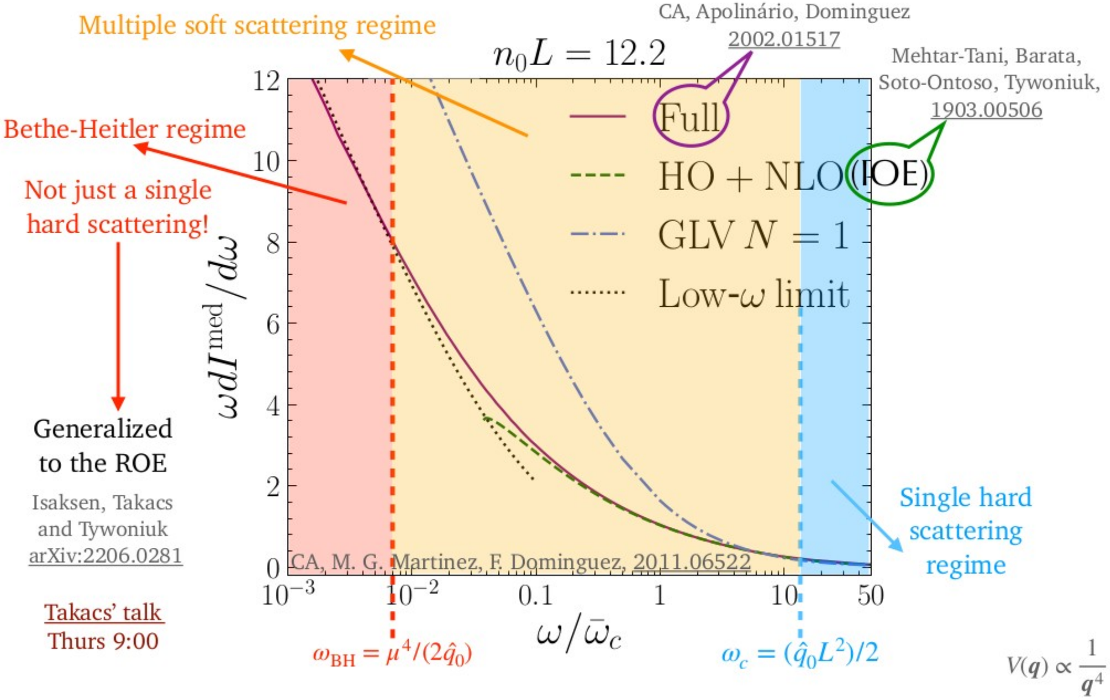
Conclusions

- Many developments in recent years: intensive studies of out cone emissions, new Monte Carlo tools

- Quantified relevance of momentum transfer during branching

- Better understanding of interplay of
- VLE and mediuminduced emissions

- Entropic measure of how
- quantum is evolution of jet



Multiple soft scattering regime

CA, Apolinário, Dominguez 2002.01517

Mehtar-Tani, Barata, Soto-Ontoso, Tywoniuk, 1903.00506

Bethe-Heitler regime

Not just a single hard scattering!

Generalized to the ROE

Isaksen, Takacs and Tywoniuk arXiv:2206.0281

Takacs' talk Thurs 9:00

CA, M. G. Martinez, F. Dominguez, 2011.06522

Single hard scattering regime

$\omega_{\rm BH} = \mu^4/(2\hat{q}_0)$

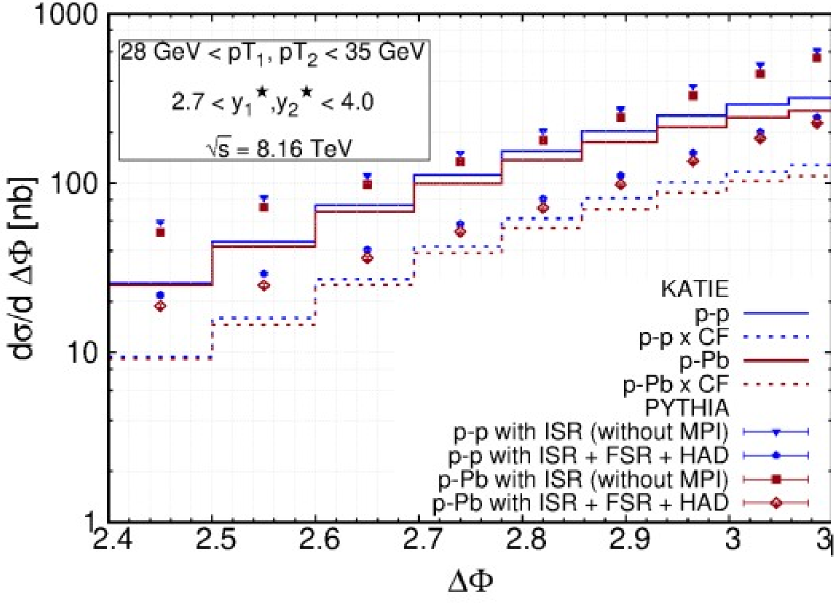
$\omega_c = (\hat{q}_0 L^2)/2$

$V(\boldsymbol{q}) \propto \frac{1}{\boldsymbol{q}^4}$

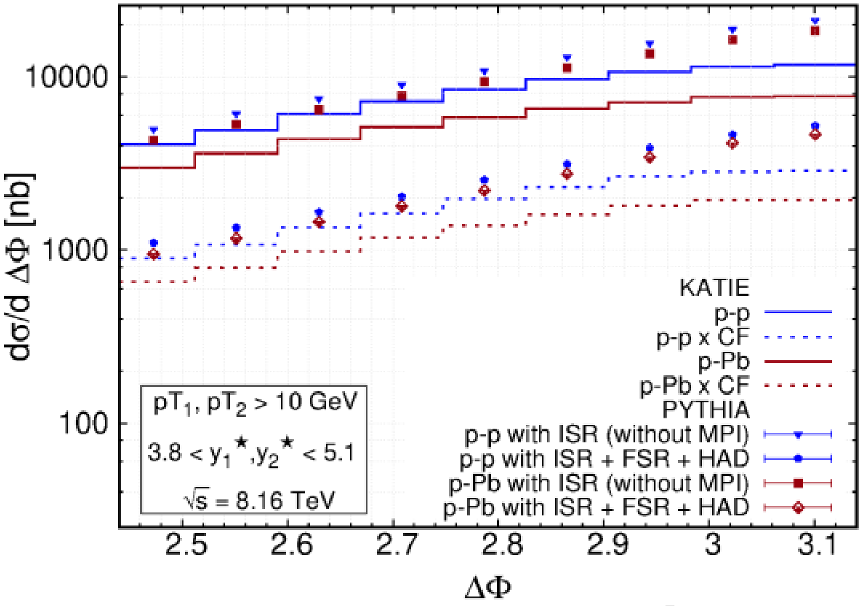
From C. Anders, HP 2023

p – Pb as preparation for Pb-Pb

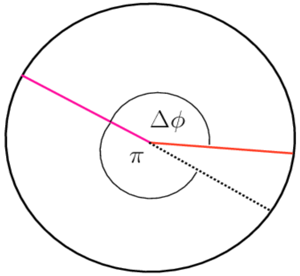
Kakad, Kotko, Kutak, Sapeta, van Mechelen,
van Hameren, van Mechelen ’23



ATLAS

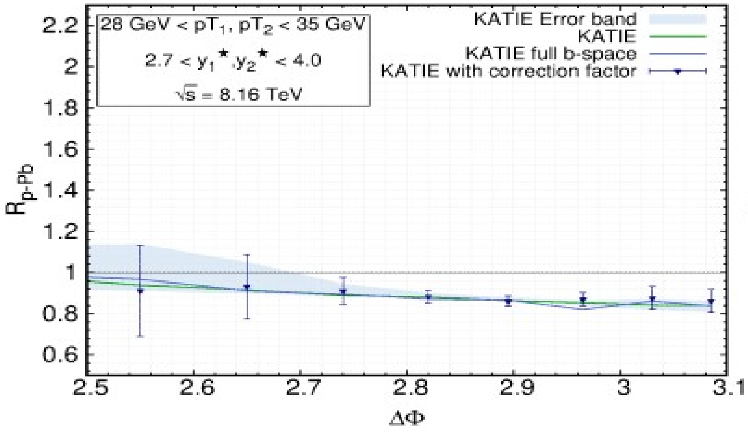


ALICE

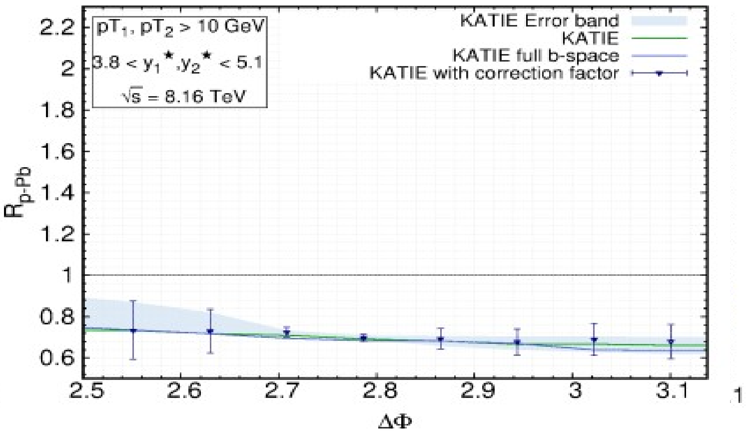


Cross-section for dijets in the forward rapidity region.
Saturation effects are accounted for within ITMD factorization

Nuclear modification ratio p-Pb



ATLAS



FoCal

$$R_{\mathrm{p-Pb}} = \frac{\frac{d\sigma^{p+Pb}}{d\mathcal{O}}}{A\frac{d\sigma^{p+p}}{d\mathcal{O}}}$$

Visible suppression in both ATLAS and ALICE kinematical setup.
Correction factor effectively cancels. Strong saturation signal.

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