SUBA-Jet – New developments

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2404.14579 [hep-ph]

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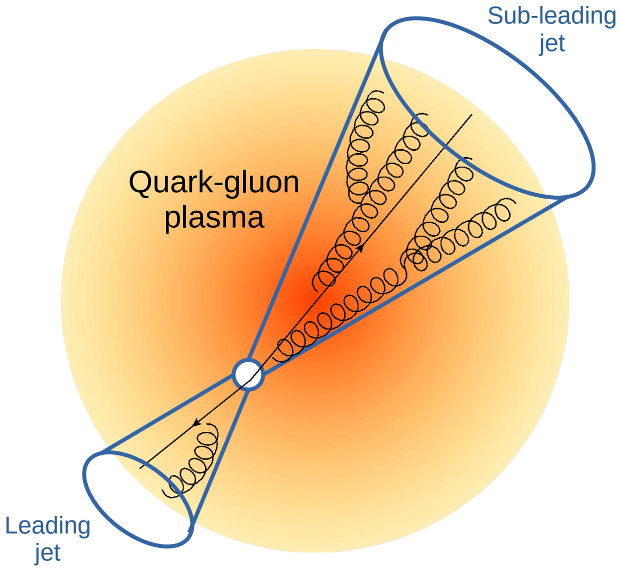
Jets in heavy ion collisions



Interactions between jet partons and the QGP medium leads to modifications of jet properties

$\Rightarrow$ **Jet energy loss / quenching**

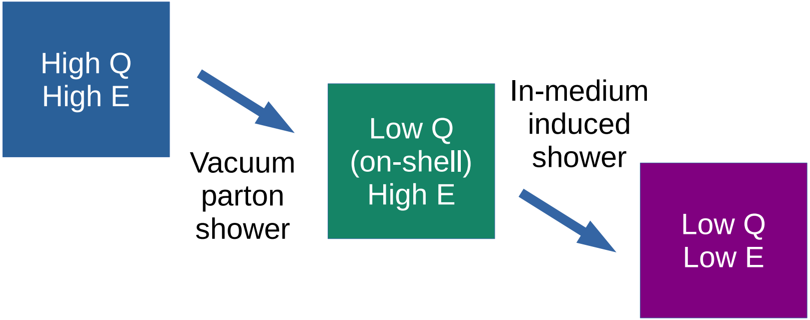
SUBA-Jet:

Monte Carlo for jet energy loss in heavy ion collisions

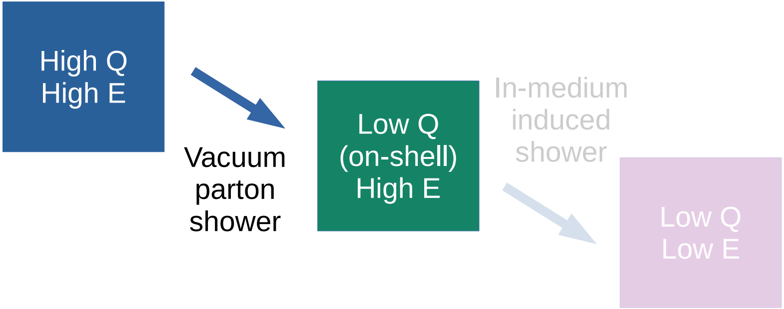
Outline

- Description of **SUBA-Jet**
- Replication of theoretical expectations for medium-induced emissions
- Implementation in Monte Carlo frameworks (Pythia 8 and EPOS4)
- Preliminary results for pp data
- Work towards AA simulation
- Newer theoretical developments

Two virtuality-ordered regimes

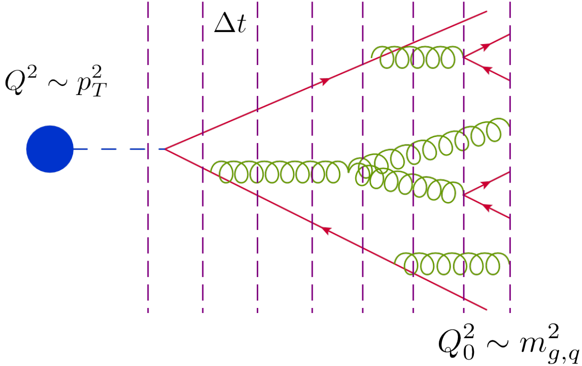


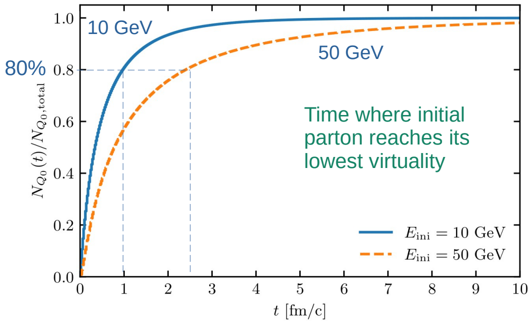
High-virtuality regime



Vacuum-like parton shower

- Monte Carlo of a vacuum parton shower originally developed by Martin Rohrmoser
- Evolution according to the DGLAP equations from high virtuality $Q_{max} \sim p_T$ to low virtuality Q_0
- Time evolution split into time steps, mean life time $\Delta t = \tau = \frac{E}{Q^2}$

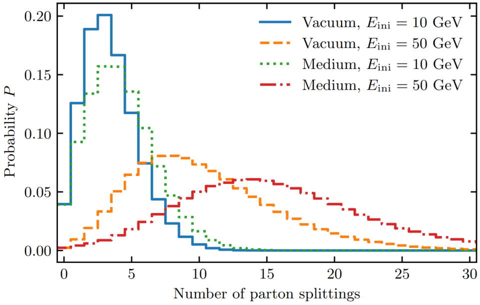


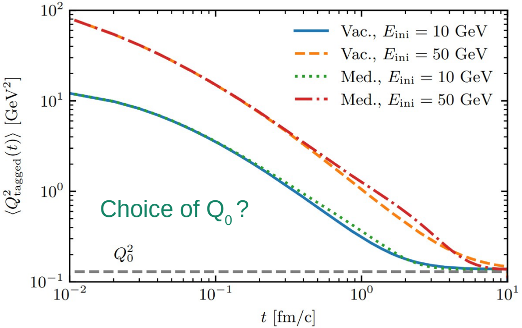


Vacuum-like parton shower with medium modifications

- Medium interactions for high Q regime resulting in virtuality increase, similar to YaJEM (T. Renk, 2008)

$$\frac{\mathrm{d}Q^2}{\mathrm{d}t} = \hat{q}(T)$$





Criteria for stopping the high-virtuality regime

The high-virtuality regime ends when a parton becomes 'on-shell'

In vacuum: $Q_0 \sim 2\,\Lambda_{\mathrm{QCD}}$ or proton mass ($1\ \mathrm{GeV}$)

In medium: More complicated – We need to compare formation times

$$t_f \sim \frac{E}{Q^2} \qquad (k_\perp^{\mathrm{vac.}})^2 \sim zQ^2$$

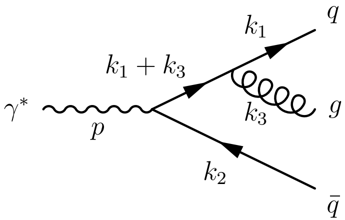
$$(k_\perp^{\mathrm{med.}})^2 \sim \int_0^{t_f} \mathrm{d}t\,\hat{q}(t) \sim \hat{q}\,t_f$$

$$k_\perp^{\mathrm{med.}} < k_\perp^{\mathrm{vac.}} \quad \Rightarrow \quad \frac{zQ^4}{E} \lesssim \hat{q}$$

Integral is performed as sum over Δt with frozen-in-time medium

Four-momentum of suddenly on-shell parton modified keeping E const.

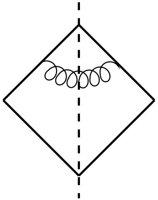
Angular-ordering



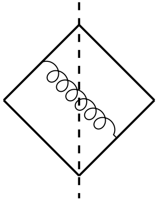
Radiation from a $q\bar{q}$ antenna

$$|\mathcal{M}|^2 = |\mathcal{M}_q + \mathcal{M}_{\bar{q}}|^2 = |\mathcal{M}_q|^2 + |\mathcal{M}_{\bar{q}}|^2 + 2\,\mathrm{Re}\left(\mathcal{M}_q^* \mathcal{M}_{\bar{q}}\right)$$

Destructive interference term



$$\sim \frac{m_q^2}{(p \cdot k)^2} \to 0$$



$$\sim \frac{2\,p_1 \cdot k}{(p_1 \cdot k)(p_2 \cdot k)} \sim \frac{1 - \cos\theta_{q\bar{q}}}{(1 - \cos\theta_{qg})(1 - \cos\theta_{\bar{q}g})}$$

Rate of soft, collinear gluon emission

$$\mathrm{d}\sigma_{n+1} \simeq \mathrm{d}\sigma_n \sum_i \left[C_i \frac{\alpha_s}{\pi} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}\theta_i^2}{\theta_{ik}^2}\, \Theta(\theta_{\mathrm{max}} - \theta_i) \right]$$

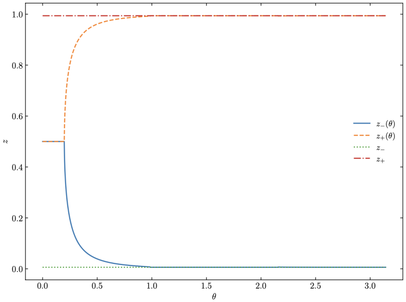
Enforcement of angular-ordering

Veto algorithm:

Parton branching $a \to b + c$ decided from t_f

1. Sample z
2. Sample Q_b, Q_c where $Q_b^2 + Q_c^2 \leq Q_a^2$
3. Calculate $k_\perp^2 \sim z(1-z)Q_a^2$
4. Calculate θ
5. Require $k_\perp^2 \geq 0$ and $\theta < \theta_0$

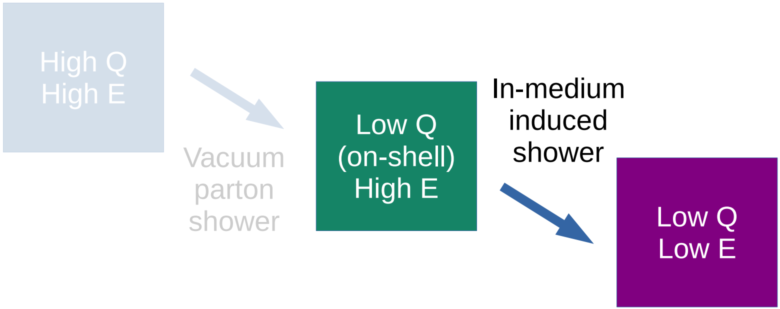
Then sample kinematics



$$\cos(\theta) = \frac{Q_b^2 + Q_c^2 + 2z(1-z)E_a^2 - Q_a^2}{2\sqrt{(zE_a)^2 - Q_b^2}\sqrt{((1-z)E_a)^2 - Q_c^2}} \quad \Rightarrow \quad \theta \sim \frac{Q_a}{E_a\sqrt{z(1-z)}}$$

$$z_\pm = \frac{1}{2}\left(1 \pm \sqrt{\left(1 - \frac{4Q_0^2}{Q_a^2}\right)\left(1 - \frac{2Q_a^2}{E_a^2(1-\cos\theta_0)}\right)}\right)$$

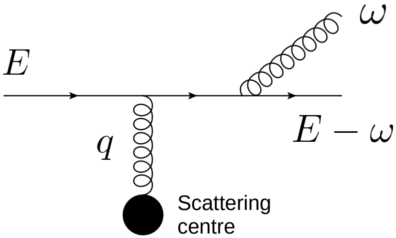
Low-virtuality regime



Medium-induced single radiation

- **Inelastic collision:**
  Single gluon emission from
  single medium scattering

- Original result from Gunion-Bertsch (1982)
  Generalised to massive case by
  Aichelin, Gossiaux, Gousset (2014)



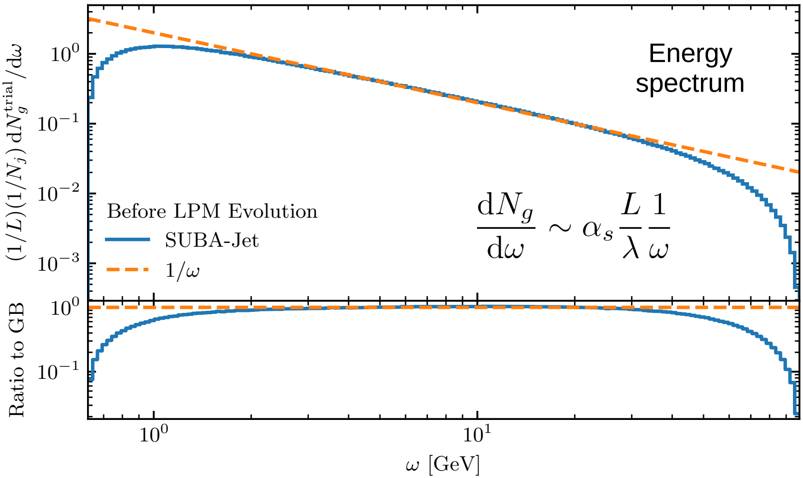
- Initial Gunion-Bertsch seed: i.e. radiation of a **preformed gluon** from a single scattering
  (Each parton can generate a number of preformed gluons)

- Gunion-Bertsch cross-section from scalar QCD

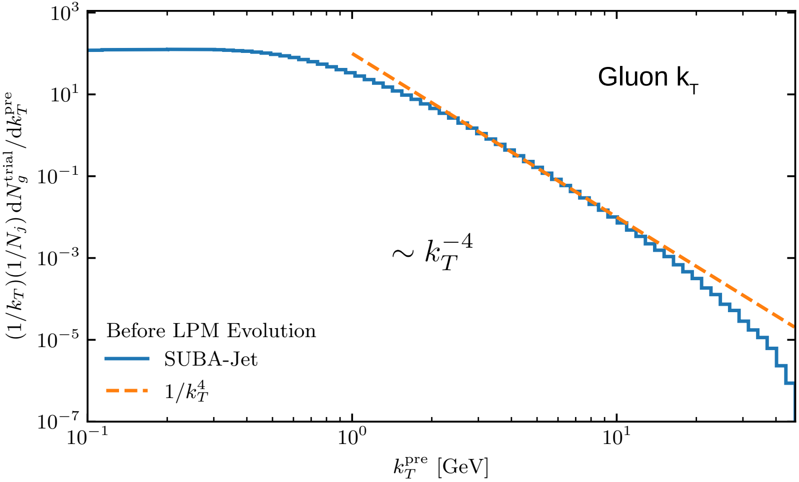
$$\frac{\mathrm{d}\sigma^{Qq\to Qqg}}{\mathrm{d}x\,\mathrm{d}^2k_T\,\mathrm{d}^2l_t} = \frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}^2l_t} P_g(x, k_T, l_T)\theta(\Delta)$$

$$\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}^2l_t} \sim \frac{8\alpha_s^2}{9(l_T^2+\mu^2)^2}$$

Medium-induced single radiation



Medium-induced single radiation



Coherency and the LPM effect

- The formation of the radiated gluon is a quantum mechanical process

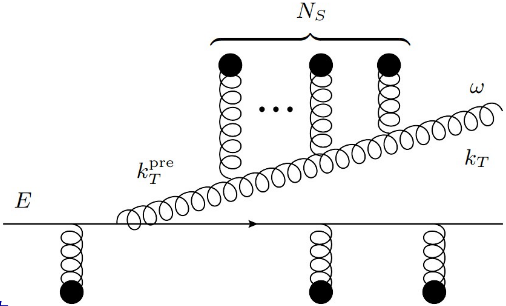
  Formation time: $t_f \sim \sqrt{\frac{\omega}{\hat{q}}}$

- Coherence effects:
  Landau-Pomeranchuk-Migdal (LPM) effect

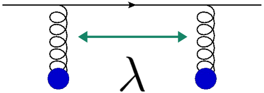
- Have to take into account multiple scatterings with the medium during the formation time

$\omega =$ gluon energy

$\hat{q} =$ medium modifications



$$N_s = \frac{t_f}{\lambda}$$



$$\lambda \simeq \frac{\hbar c}{\alpha_s T}$$

$L =$ path length of medium

Implementation of the LPM effect

- At each timestep:
  - Elastic scattering with prob. $\Gamma_{\rm el}\Delta t$

$$\Gamma^q_{\rm el} = \left(1 + \frac{N_f}{N}\right)\frac{(N^2-1)T^3}{\pi\hbar c}\frac{4\alpha_s^2}{\mu^2}$$

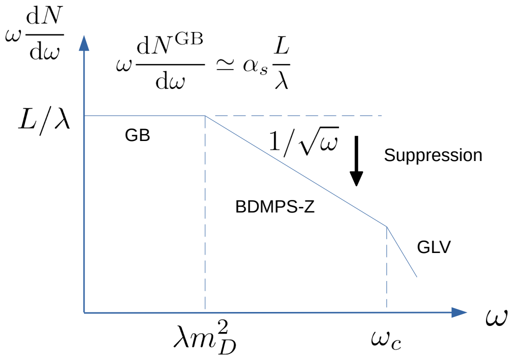
  - Radiation of preformed gluon with prob. $\Gamma_{\rm inel}\Delta t$

- BDMPS-Z spectrum at intermediate energies achieved by suppressing GB seed by

$$1/N_s$$

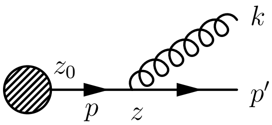
Like in Zapp, Stachel, Wiedemann, JHEP 07 (2011), 118

Radiation energy spectrum:



$$\omega\frac{\mathrm{d}N^{\rm BDMPS\text{-}Z}}{\mathrm{d}\omega} \simeq \alpha_s\sqrt{\frac{\hat{q}L^2}{\omega}}$$

Phase of the emitted gluon



$$\mathcal{M} = \bar{u}(p')\left[g_s t^a \gamma^\mu\right] \varepsilon^*_\mu(k) \frac{\not{p} + m_q}{p^2 - m_q^2} J(p) e^{-ip\cdot(z-z_0)}$$

Gluon phase

$$\Phi = p \cdot (z - z_0) \simeq \frac{1}{2} p^- (z - z_0)^+ \simeq \frac{p^2}{2p^+} t_f$$

Gluon formation time

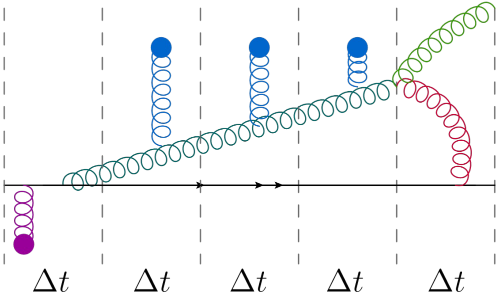
$$t_f \simeq \frac{2p^+}{p^2} \sim \frac{E}{Q^2} \simeq \frac{\omega}{k_\perp^2}$$

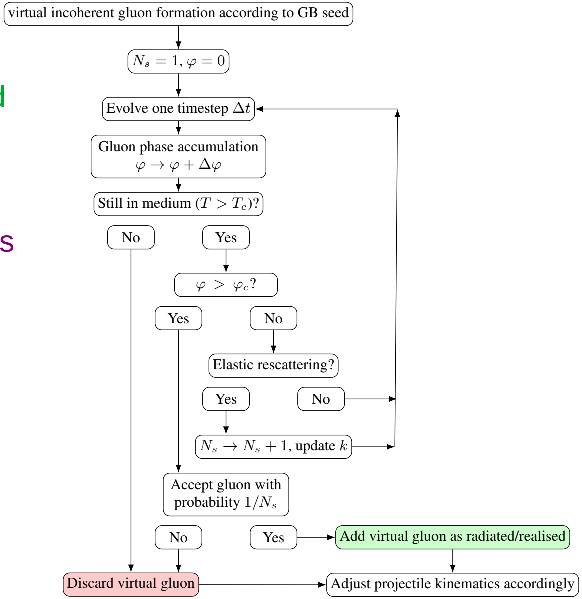
The low-virtuality algorithm

Flow diagram:

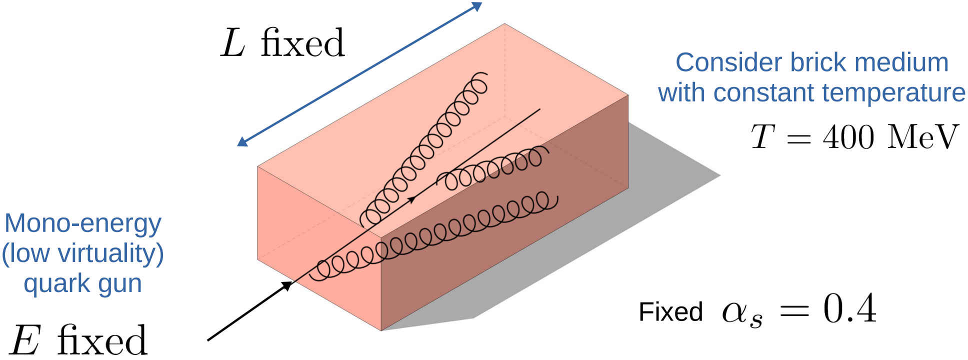
Algorithm for the coherent medium-induced gluon radiation in our model

Various parameters and settings can be changed and tuned to compare distributions



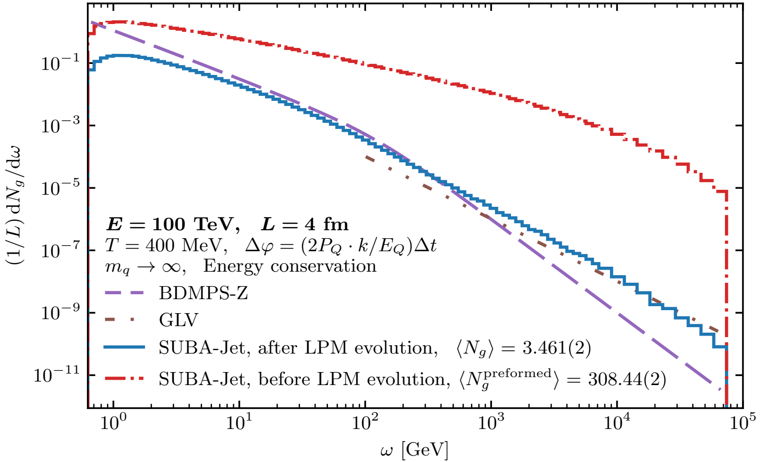


Replication of theoretical expectations



We want to reproduce theoretical expectations

Reproduction of the LPM and GLV regimes

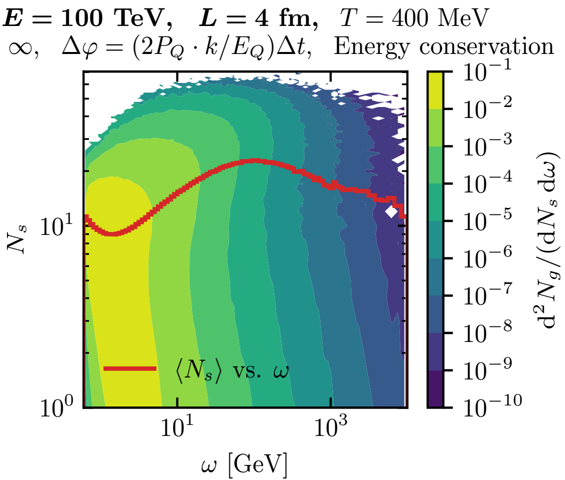


Gluon energy ω spectrum

$$\frac{\mathrm{d}N^{\mathrm{LPM}}}{\mathrm{d}\omega} \sim \frac{1}{\omega^{3/2}}$$

$$\frac{\mathrm{d}N^{\mathrm{GLV}}}{\mathrm{d}\omega} \sim \frac{1}{\omega^{2}}$$

Reproduction of the LPM and GLV regimes



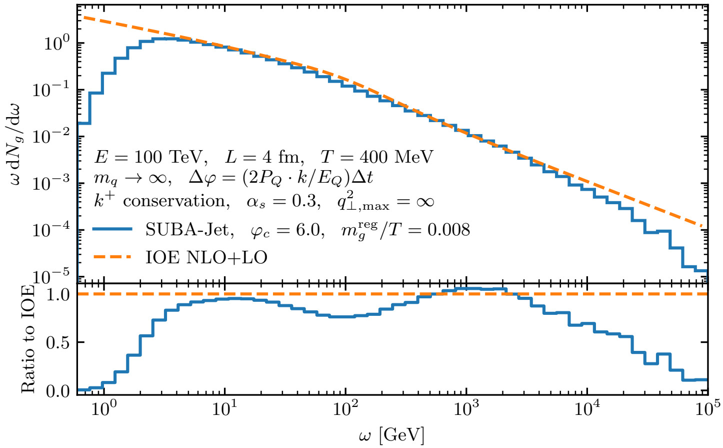
Double differential plot in N_s and ω

Red line: ‹N_s› vs. ω

$$N_S \sim t_f \sim \sqrt{\omega}$$

Convolution of different distributions

Reproduction of the improved opacity expansion result



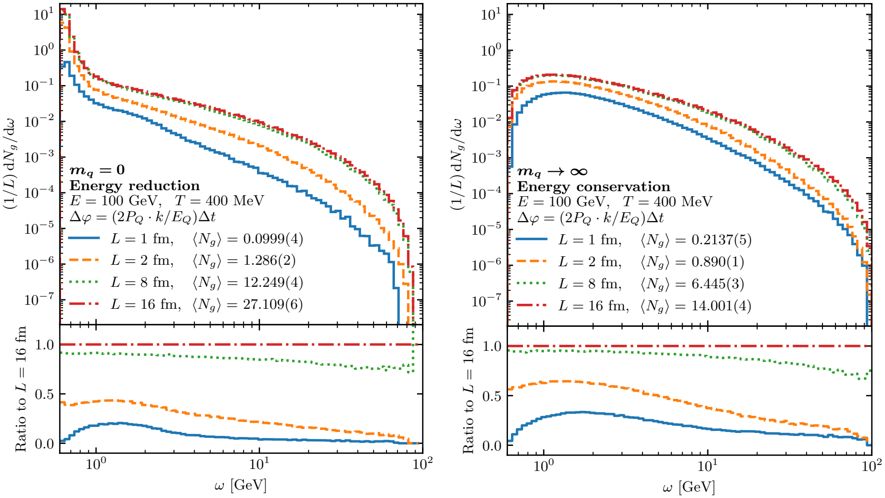
Improved Opacity Expansion

arXiv:1910.02032 [hep-ph]

$$\frac{dN^{\rm IOE}}{d\omega} = \frac{dN^{\rm IOE}_{\rm LO}}{d\omega} + \frac{dN^{\rm IOE}_{\rm NLO}}{d\omega}$$

$$\omega\frac{dN^{\rm IOE}_{\rm NLO}}{d\omega} \simeq \frac{1}{2}\frac{\alpha_s C_R}{\pi}\hat{q}_0\,{\rm Re}\int_0^L ds\,\frac{1}{k^2(s)}\left[\ln\frac{k^2(s)}{Q^2} + \gamma_E\right]$$

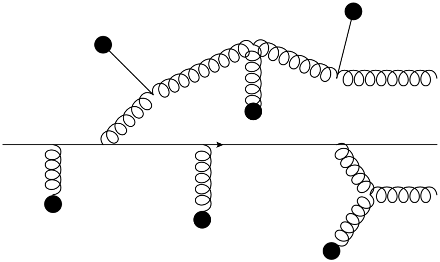
Effects of path length (system size)



$$\frac{\mathrm{d}N}{\mathrm{d}\omega} \overset{L\to\infty}{\approx} L$$

Effects of the gluon phase accumulation

Choice of phase accumulation of the preformed (trial) gluons:



- **More general formula:**

$$\Delta\varphi = \frac{2P_Q \cdot k}{E_Q}\Delta t$$

- **What is used in JEWEL:**

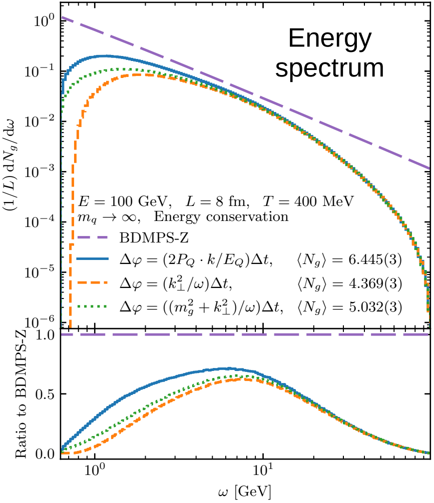
$$\Delta\varphi = \frac{k_T^2}{\omega}\Delta t$$

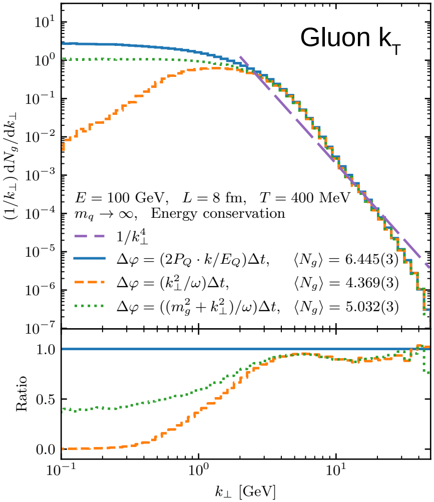
- **Including thermal gluon mass:**

$$\Delta\varphi = \frac{m_g^2 + k_T^2}{\omega}\Delta t$$

Effects of the gluon phase accumulation

Effects at low energy & low k_T

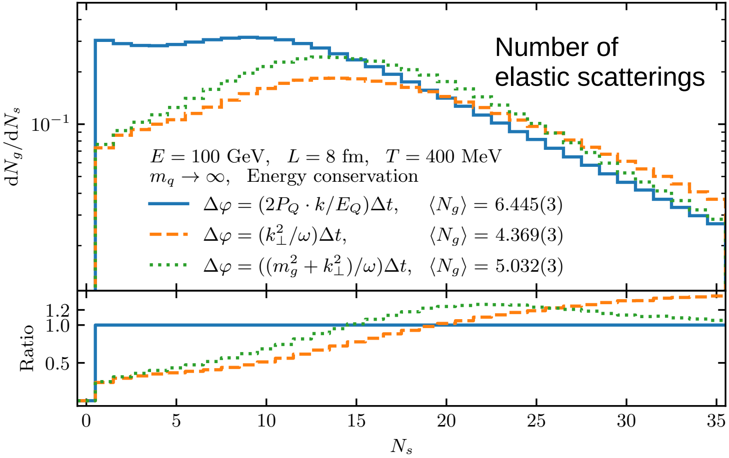




Number of radiated gluons per jet ~ 5 -- 6

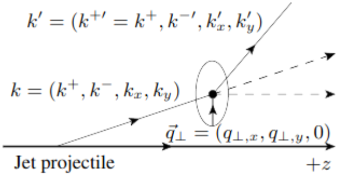
Effects of the gluon phase accumulation

Effects at low Ns

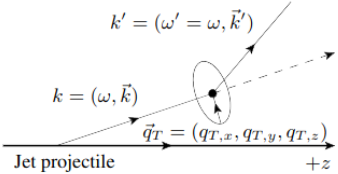


When neglecting the gluon mass in the phase accumulation, a larger path length is required to have a comparable overall number off radiations

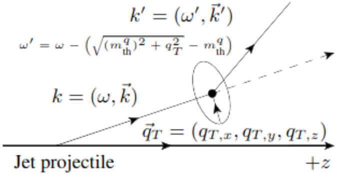
Choice of prescription in elastic scatterings:



k+ conservation

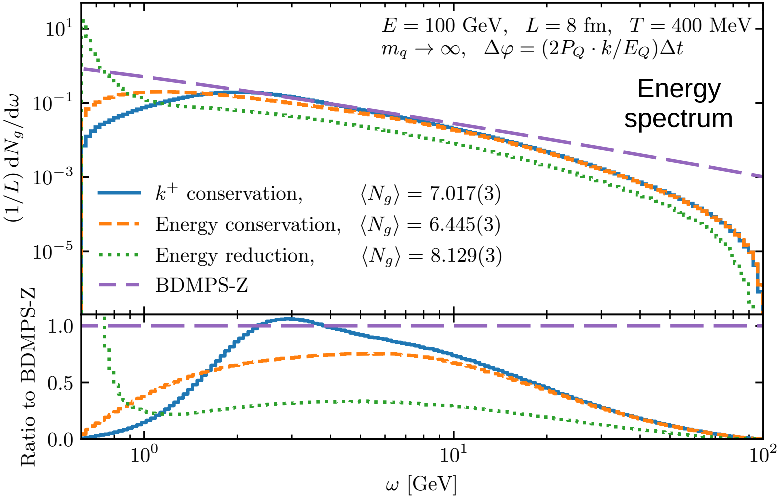


Energy conservation



Energy reduction

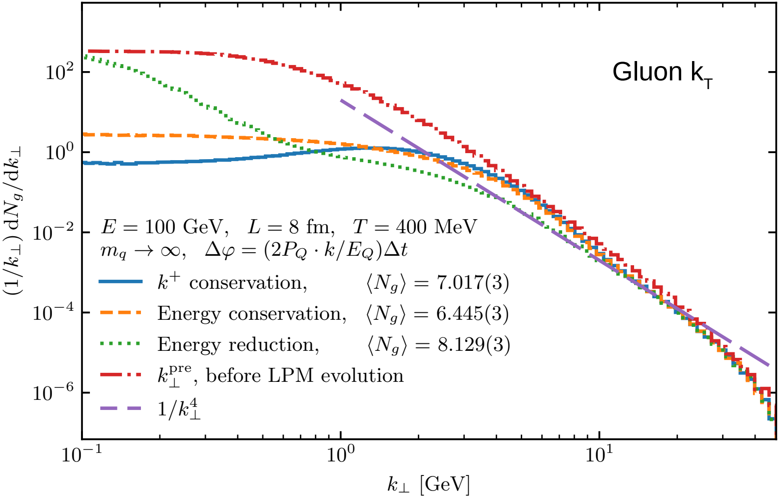
Effects of the elastic scatterings



Same BDMS behaviour at intermediate energies

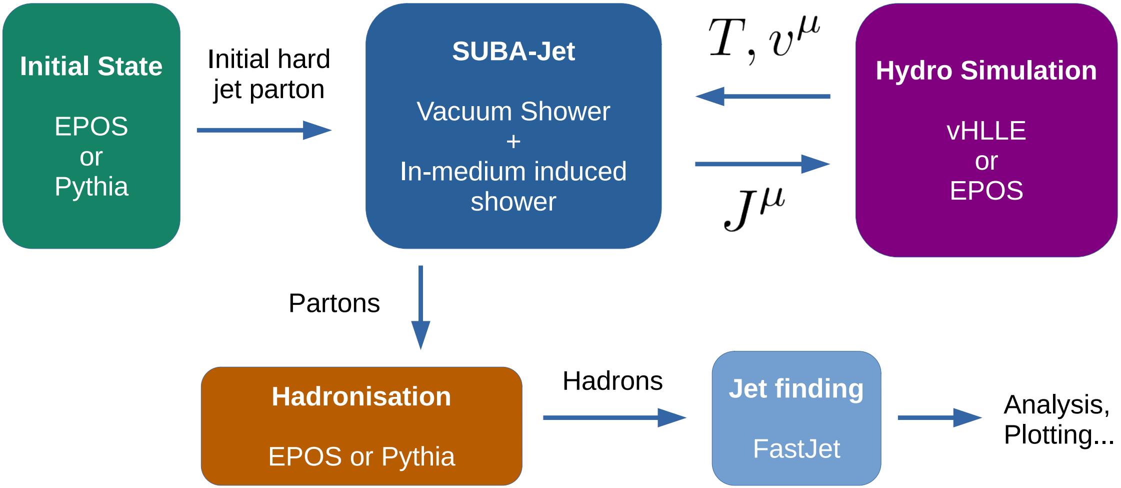
Difference at small energies

Effects of the elastic scatterings



Large difference at small k_T

General picture of Monte Carlo implementation

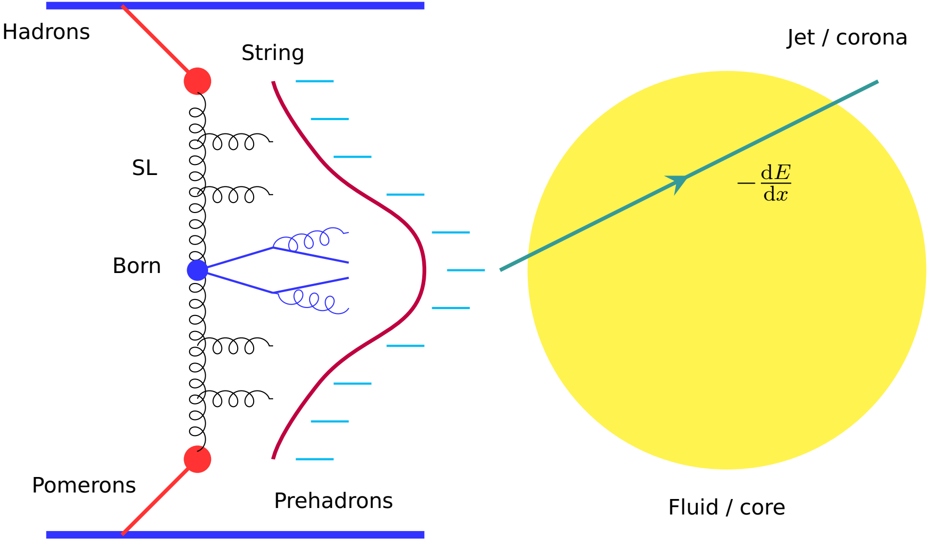


Implementation in Monte Carlo frameworks

SUBA-Jet is implemented in two different Monte Carlo frameworks, with vastly different physics models:

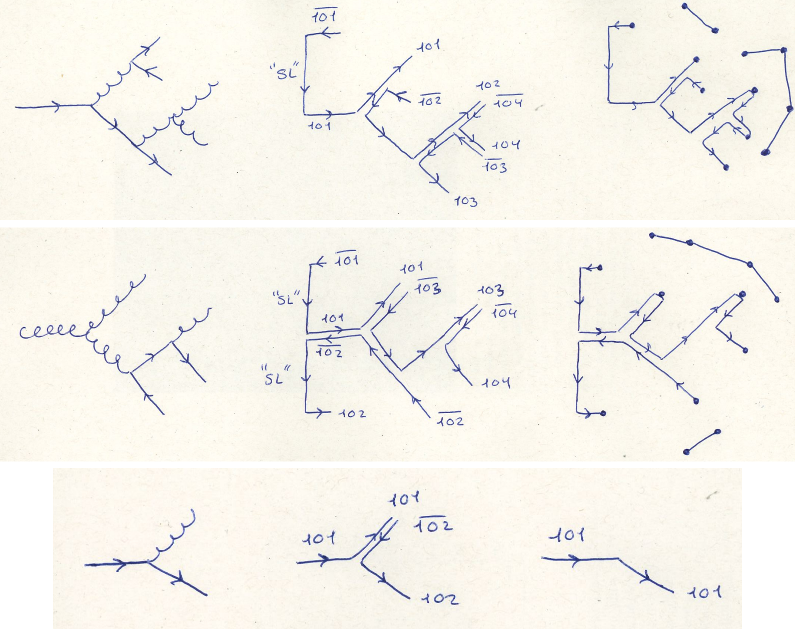
- SUBA-Jet + Pythia 8
  - Angantyr initial state
  - Rope shoving
  - String hadronisation
- SUBA-Jet + EPOS4
  - Parton-based Gribov-Regge theory
  - vHLLE hydro simulation
  - String hadronisation (albeit different)

EPOS4 event



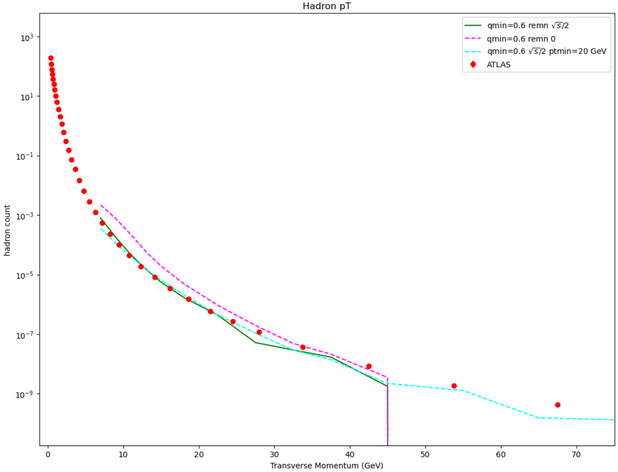
Hadrons
String
Jet / corona
SL
$-\frac{\mathrm{d}E}{\mathrm{d}x}$
Born
Pomerons
Prehadrons
Fluid / core

Hadronisation

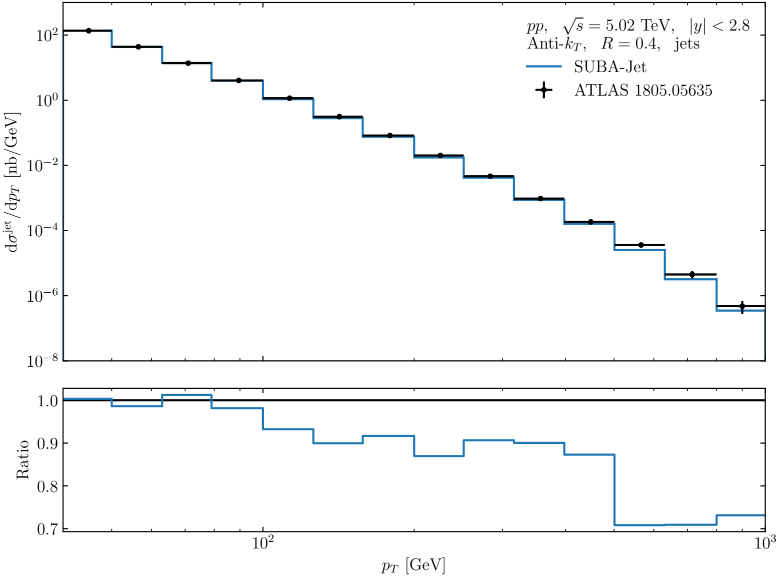


Colour reconnections

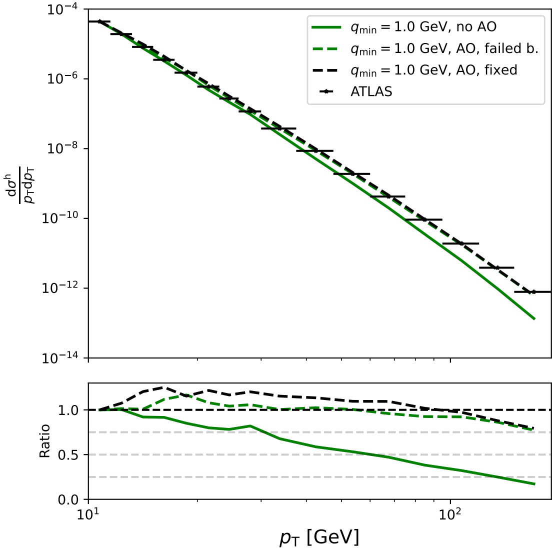
Which partons in a hadron-hadron event should be included in the colour strings?

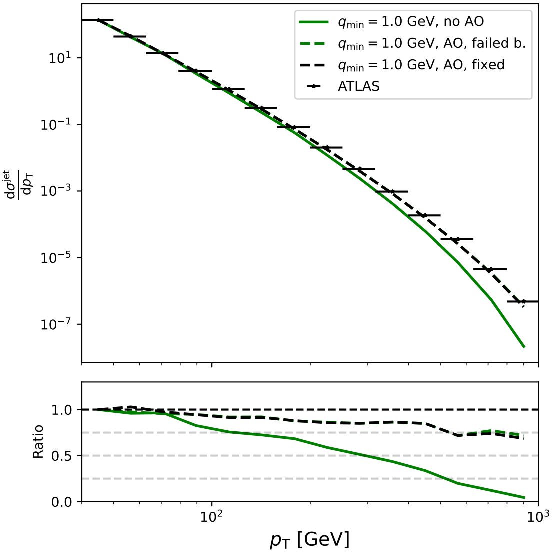


Preliminary pp results with SUBA-Jet + Pythia 8

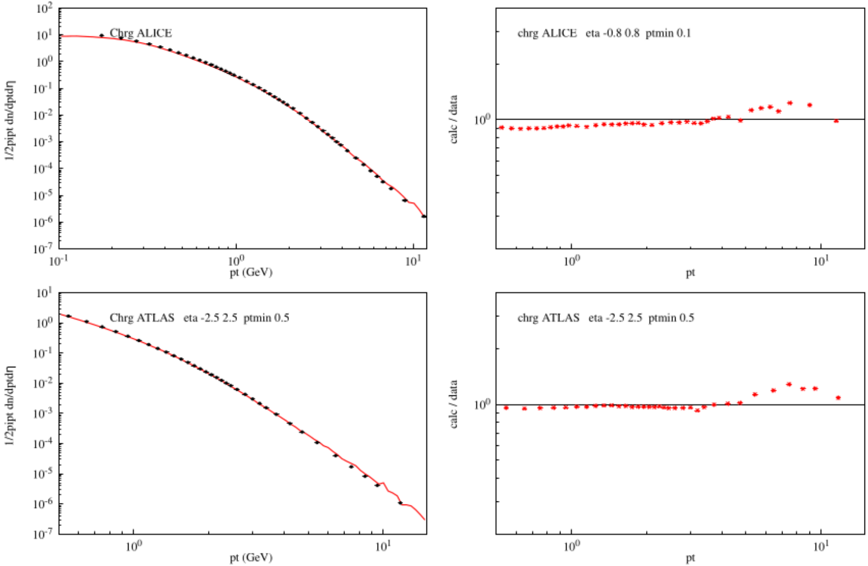


Preliminary pp results with SUBA-Jet + Pythia 8

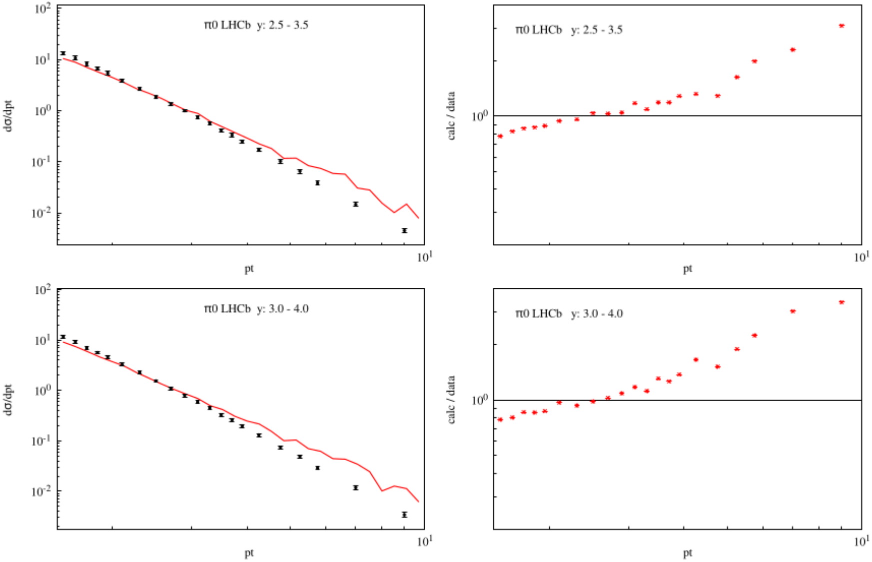




Preliminary pp results with SUBA-Jet + EPOS4



Preliminary pp results with SUBA-Jet + EPOS4



The road to simulating AA collisions

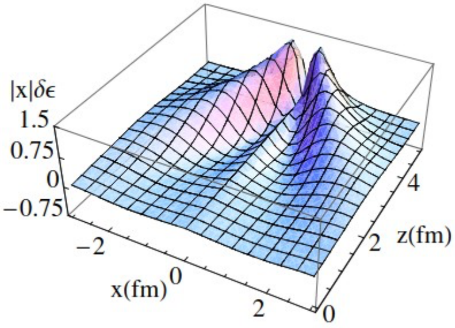
We have reasonable agreement with pp data

Additional challenges for AA collisions:

- Handling of pre-equilibrium stage
- Interface to hydro simulation (vHLLE)
- Hadronic phase

Effect of jets on medium

The jet also affects the medium

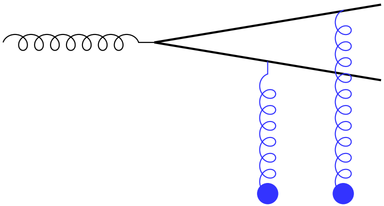


G.-Y. Qin, A. Majumder, H. Song, U. Heinz
0903.2255 [nucl-th]

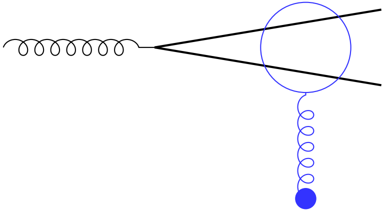
‘Wake wave’
in the medium
due to the jet

Coherence effects

How does the medium 'see' a (collinear) $q\bar{q}$ antenna?



As individual colour charges?



Or as a single colour charge?

Coherence effects

Survival probability of a colour-singlet $q\bar{q}$ antenna

$$P_s \simeq \exp\left(-\int_0^L dt\,\hat{q}(t)\,r^2(t)\right)$$

Decoherence probability

$$P_{\text{coherence}} \simeq \exp\left(-\frac{\theta_{q\bar{q}}^2}{\theta_c^2}\right)$$

Critical angle

$$\theta_c \simeq \left(\int dt\,t^2\,\hat{q}(t)\right)^{-1/2} \simeq \frac{1}{\sqrt{\hat{q}L^3}}$$

(Mehtar-Tani, Tywoniuk, arXiv:1105.1346 [hep-ph]. Reproduced with open quantum systems, see Pietro Benzoni's talk at AG GDR QCD 2025)

Anti-angular ordering

Soft gluon emission spectrum

$$\mathrm{d}N_g^{\mathrm{tot}} = \mathrm{d}N_g^{\mathrm{vac.}} + \mathrm{d}N_g^{\mathrm{med.}}$$

Vacuum contribution

$$\mathrm{d}N_g^{\mathrm{vac.}} \simeq C_R \frac{\alpha_s}{\pi} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}\theta^2}{\theta^2} \Theta(\theta_{\max} - \theta)$$

Medium-induced contribution

$$\mathrm{d}N_g^{\mathrm{med.}} \simeq C_R \frac{\alpha_s}{\pi} A_{\mathrm{med.}} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}\theta^2}{\theta^2} \Theta(\theta - \theta_{\max})$$

(Mehtar-Tani, Salgado, Tywoniuk, arXiv:1009.2965 [hep-ph])

Summary

- Jets serves as hard probes of the QGP
- A lot of interesting physics at the interface of perturbative and non-perturbative QCD
- We present a new Monte Carlo for jet quenching – **SUBA-Jet**
- We reproduce theoretical expectations for medium-induced emissions
- We reproduce pp data
- Work towards R_{AA}
- Presentation of work towards state-of-the-art algorithm