Monte Carlos in heavy ions collisions

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LHCP 2022
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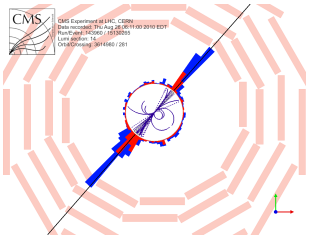
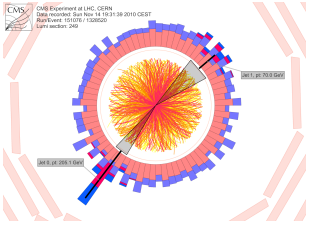
Jets in *pp* vs jets in heavy-ions collisions





parton shower

$\log(Q)$

$Q_{\rm NP} \sim 1{\rm GeV}$

$p_T R \geq 100$ GeV

hadronization, MPI, UE

hydro, medium-response...

parton shower

$\log(Q)$

T

$Q_{\rm NP} \sim 1{\rm GeV}$ $\omega_c \sim \hat{q}L^2_{\sim 30 \div 60{\rm GeV}}$

$p_T R \geq 100$ GeV

medium-induced emissions

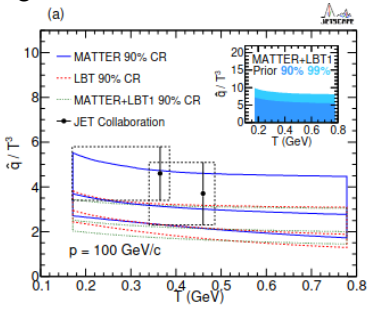
Jets as hard probes of the quark-gluon plasma

Jets are sensitive to a broad range of scales and thus to many medium-induced mechanisms.

Advantages and drawbacks of multipurpose event generators in AA

- ✓ Include collision geometry, the evolution of the bulk, etc
- ✓ Understand the data using few effective parameters for the jet-medium interactions
  - Ex: $\hat{q} \equiv \langle k_\perp^2 \rangle / L$, T, $\alpha_{\rm med}$.
  - Allow for "global fit" strategies.

JETSCAPE collab., 2102.11337
$\hat{q}$ determined from Bayesian inference using hadron suppression data at RHIC and the LHC.
(see talk by J-F. Paquet on Wednesday)



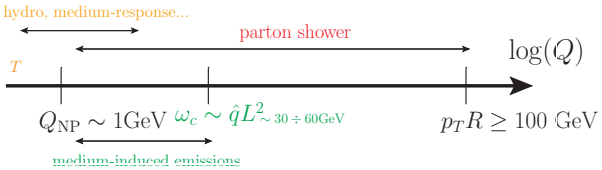
- × But: temptation of doing only "modeling".
- × What are the systematic errors in a MCs? $\Longrightarrow$ rely on **pQCD** as much as possible.

Outlook

This talk

My very biased perspective on some recent developments in MC in heavy-ion collisions.

- Vacuum-like shower in the high virtuality regime.
- Medium-induced cascades.



Things that I won't discuss

- In-medium hadronization, hydro evolution, ...

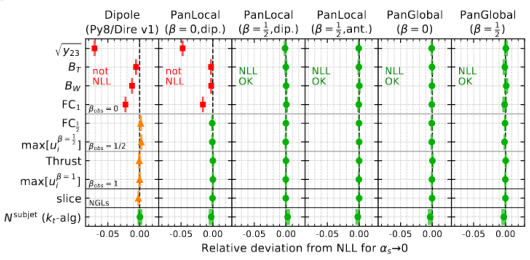
Insights from the *pp* community

- Many event generators: Pythia, Herwig, Sherpa, etc. but at least leading log agreement.

Why?

pQCD provides a common framework to compare parton showers: **logarithmic accuracy**!

Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez, 2002.11114
van Beekveld, Ferrario Ravasio, Salam, Soto-Ontoso, Soyez, Verheyen, 2205.02237



Long term goal in AA

Towards precision: need a pQCD control on the in-medium high virtuality parton shower.

Status of high virtuality shower in (some) AA event generators

MATTER

Cao,Majumder, 1301.5323, 1712.10055

- Medium modified DGLAP splitting functions down to a medium virtuality scale treated as a parameter:

$$P(z, Q^2) = P_{\text{vac}}(z) + \underbrace{P_{\text{med}}(z, Q^2)}_{\propto \hat{q}}$$

Hybrid model

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, 1609.05842

- Same vacuum-like shower as Pythia.
- Strong coupling energy loss.

JEWEL

Zapp, Krauss, Wiedemann, 1212.1519, 1311.0048

- No sharp transition between vacuum-like and medium-induced processes.
- The interplay between competing radiative processes is governed by the formation times of the emissions.

pQCD perspective

- Different modeling $\Longrightarrow$ what is the corresponding logarithmic accuracy?
- Is there a well-defined perturbative limit which enables to compare these MC?

The most simple pQCD limit: the double logarithmic approximation

Main messages

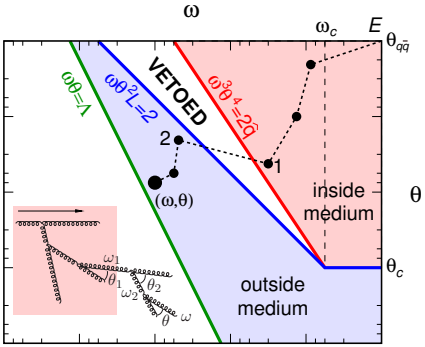
- Vacuum-like shower in dense QCD media admits a robust pQCD double logarithmic limit.
- Convergence of event generators: they should reproduce this limit under the same assumptions.

Main assumptions:

- Strong ordering in both angles and energies of successive splittings in the parton shower.
- Dense medium: allows for multiple soft scatterings.

The vacuum-like cascade at DLA

- The evolution of a jet **factorizes** into three steps:
  (1) An **angular ordered** *vacuum-like shower* inside the medium ,
  (2) *medium-induced emissions* triggered by previous sources,
  (3) finally, a *vacuum-like shower* outside the medium.
- Re-opening of the phase space for the first emission outside the medium.



- $\omega_c = \frac{1}{2}\hat{q}L^2$
- $\theta_c = \frac{2}{\sqrt{\hat{q}L^3}}$

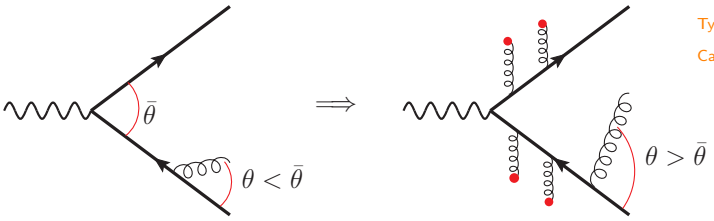
PC, Iancu, Mueller, Soyez, 1801.09703

- Recently extended for longitudinally expanding media!

PC, Iancu, Soyez, 2012.01457

Physics of color (de)coherence

- In vacuum: antenna radiation pattern $\Longrightarrow$ suppression of soft large angle gluon emissions, angular ordered showers.
- In medium: multiple soft scatterings break color coherence, over a time scale $t_d = (\hat{q}\bar{\theta}^2)^{-1/3} \Rightarrow t_d = L \Leftrightarrow \bar{\theta}^2 = \theta_c^2 \equiv 1/(\hat{q}L^3)$.



Mehtar-Tani, Salgado, Tywoniuk, 2011 - Casalderrey-Solana, Iancu, 2011

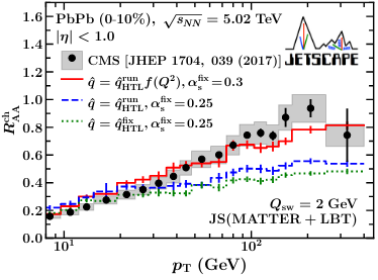
Two consequences

- Additional soft gluons radiations from in-medium dipoles with $\theta \geq \theta_c$.
- Antenna with $\theta \leq \theta_c$ are not "resolved" by the medium and do not radiate MIEs.

"Concept" of color coherence in Monte-Carlos

(1) JETSCAPE

- Recent developments in MATTER: virtuality dependent $\hat{q}$ to mimic coherence effects. Kumar, Majumder, Chen, 1909.03178
- "Essential to describe the p_T dependence of the RAA of charged particles". JETSCAPE collab. 2204.01163



(2) Hybrid model

(3) JetMed (shower based on the factorized picture)

"Concept" of color coherence in Monte-Carlos

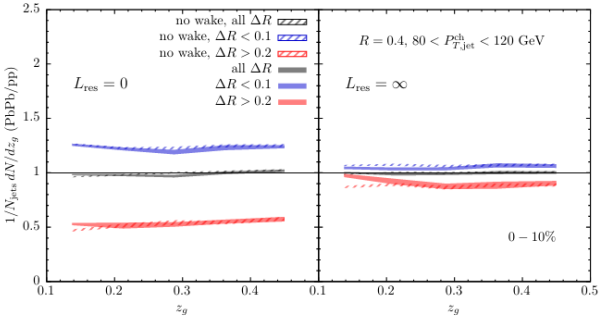
(1) JETSCAPE

(2) Hybrid model

- introduction of a plasma resolution length computed at strong coupling,
- splitting with transverse size smaller $L_{\rm res}$ are quenched like single prong,
- successful to understand qualitatively substructure data.

Hulcher, Pablos, Rajagopal, 1707.05245

Casalderrey-Solana, Milhano, Pablos, Rajagopal, 1907.11248



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"Concept" of color coherence in Monte-Carlos

(1) JETSCAPE
(2) Hybrid model
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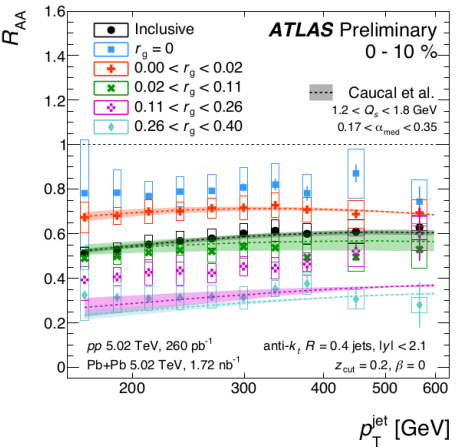


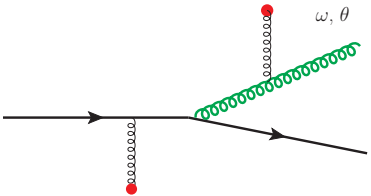
- Weak coupling picture.
- Coherence implemented by the **angular scale** θ_c
- Predictions for R_{AA} binned in θ_g as measured by ATLAS.

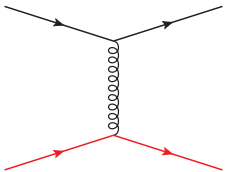
PC, Iancu, Soyez, 2012.01457

See talk by M. Rybar on Monday and Y. Mao on Tuesday

Medium-induced showers

- Recent developments on the theory side: analytic/semi-analytic expressions for LO inelastic processes. See talk by A. Soto-Ontoso on Monday





- Also many Monte-Carlo formulations of medium-induced cascades:
  - **LBT model**: linear boltzmann transport with higher twist splitting rates,
  - **MARTINI**: Fokker-Planck like equation with AMY inelastic and elastic rates,
  - **JetMed**: kinetic equation including inelastic rate and Gaussian broadening between splittings.

Recent developments in MC implementation of medium-induced cascades

- **MINCAS**: new MC framework to solve medium induced cascades including
  - Full LO collision kernel and broadening during branching

    Blanco, Kutak, Placzek, Rohrmoser, Straka, 2009.03876
  - Flavor dependence

    Blanco, Kutak, Placzek, Rohrmoser, Tywoniuk, 2109.05918

$$\frac{\partial}{\partial t} D(x,\mathbf{k},t) = \alpha_s \int_0^1 dz \int \frac{d^2q}{(2\pi)^2} \left[2\mathcal{K}(\mathbf{Q},z,\frac{x}{z}p_0^+) D\left(\frac{x}{z},\mathbf{q},t\right) - \mathcal{K}(\mathbf{q},z,xp_0^+)\, D(x,\mathbf{k},t) \right] + \int \frac{d^2\mathbf{l}}{(2\pi)^2}\, C(\mathbf{l})\, D(x,\mathbf{k}-\mathbf{l},t).$$

See also non-MC studies like Schlichting, Soudi, 2008.04928, Dai, Paquet, Teaney, Bass, 2012.03441

- but misses medium expansion, NLO corrections to $\hat{q}$ and collision kernel, elastic scatterings, ...

Recent developments in MC implementation of medium-induced cascades

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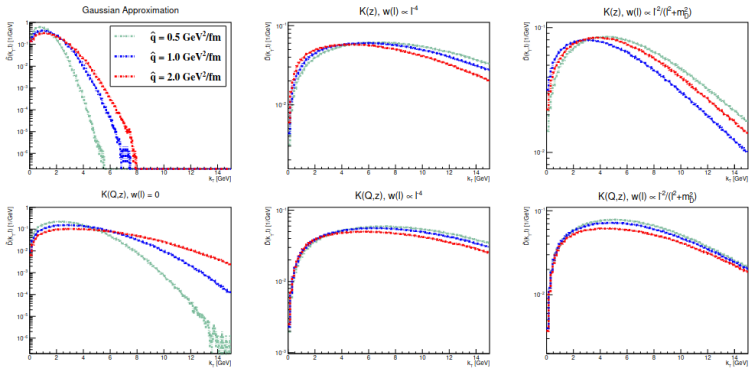
Blanco, Kutak, Placzek, Rohrmoser, Straka, 2009.03876



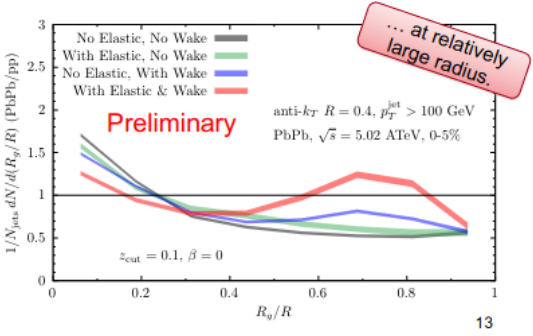
- Next step: integrate these refinements in the full jet evolution, and study effect of hard scatterings in phenomenology. Barata, PC, Soto-Ontoso, Takacs, Tywoniuk in preparation

Similar developments in the Hybrid model

- Moliere scattering in QGP recently included.

  Pablos, Hulcher, Rajagopal, see Zach's talk at QM2022

- In jet observables, hard scattering show up as modified wake effects.



Summary

- A pQCD picture for jet evolution including color coherence effects, easy to implement in MC.
  $\Rightarrow$ robust starting point to include more refined physical ingredients.

- More generally, we should aim at controlling our theoretical uncertainties, especially in the perturbative regime, and MCs should agree in perturbative limits.

- On-going efforts to include most recent theoretical developments in MCs, like color coherence or Moliere-type scatterings, and confront with new jet observables.