Jets in heavy ions: lessons from the past the and perspectives for the future

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Disclaimers

I do not consider myself a heavy-ion physicist

- My background is more on (jets from) the "vacuum" side of high-energy collisions
- The pure "heavy-ion" part of this talk is most likely biased towards my own work with Paul Caucal and Edmond Iancu

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Main idea

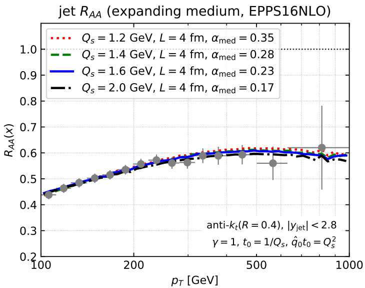
try to build a picture from history/lessons in *pp* collisions

From RHIC to the LHC (stating the obvious)

1. Higher energy

   Main consequence: ability to do genuine jet physics

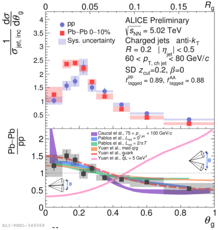
   In particular: explore jets at high p_t opening phase-space for physics studies

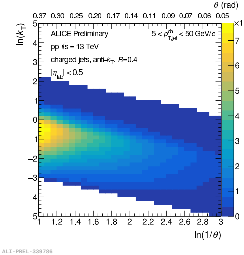


2. Higher luminosity

   Main consequence: more observables measurable and with higher precision

   In particular: explore the jet phase-space differentially





The net benefit

A picture of jet quenching starts to emerge:

- Jet energy loss: many observations, several theoretical approaches (pQCD/hybrid/...)
- Several complex effects can be discussed
  - enhancement of large-angle emissions
  - decoherence effects
  - back-reaction
  - medium response

  Many qualitatively understood from first principles
- Several Monte-Carlo implementations In particular the large-scale JETSCAPE effort

What I would like to see

The goal to keep in mind

Aim towards a quest for precision

1. Make Heavy-Ion studies quantitative (instead of qualitative)
2. Think about long(er)-term impact

Challenges

- Effort from both theorists and experimentalists
- [exp] Work on unfolded measurements with controlled systematics (e.g. background subtraction)
- [exp] Data useful in the long term (when theory will improve)
- [th] Provide a first-principles **theory of** jet quenching (not a "model")
- [th+exp] Think of designed observables to target specific quenching effects

Lessons from *pp*: looking back 30 years ago

[1990 Snowmass accord on "Toward a standardization of jet definitions"]

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

Ultimately, this led (∼2008!) to the current LHC setup (e.g. anti-k_t).

This has allowed for the LHC to be a **precision** machine

A few selected examples/topics/thoughts

(mostly on the theory side)

Background subtraction and long-term data usefulness

The background (Underlying Event) is coupled to the "hard" event
(unlike "pileup" which can be viewed as independent)

- "background subtraction" can be viewed as part of the analysis/observable's definition
- Long-term goal for a faithful (apple-to-apple) comparison: a full theory simulation (including hard+underlying event) should be able to apply the same procedure as the experiments do.

Increasingly important since:

1. Full simulations (Hard+hydro) start to appear
2. We are discussing correlated effects (typically medium response)

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Practical remarks:

- To what extend are we able to discuss fine-grained effects (details of large-angle radiation patterns, details of medium response, details of hydro) without a controlled subtraction method across theory and experiment?
- Several methods available as "simple" starting points (area–median, ConstituentSubtractor, SoftKiller, "grooming")

Different physics at different scales

LHC probes physics across many scales

$Q \equiv$ 100 GeV or higher

$\mu_{\text{NP}} \sim$ 1 GeV

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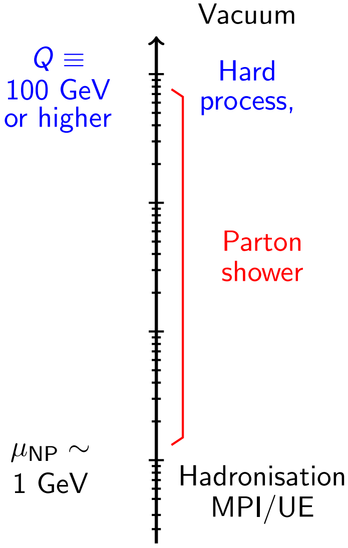

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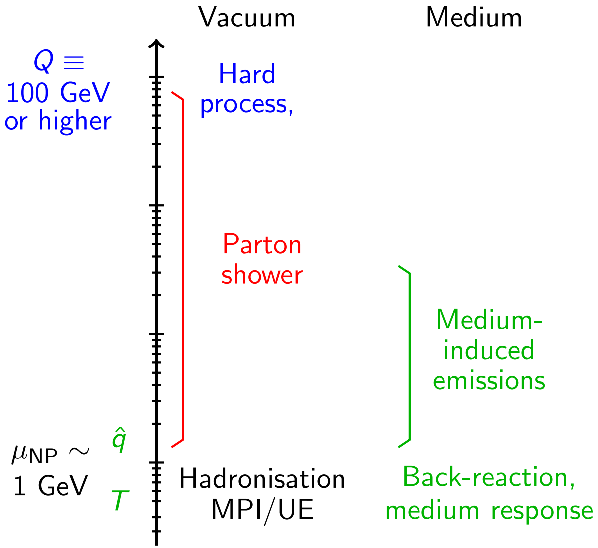
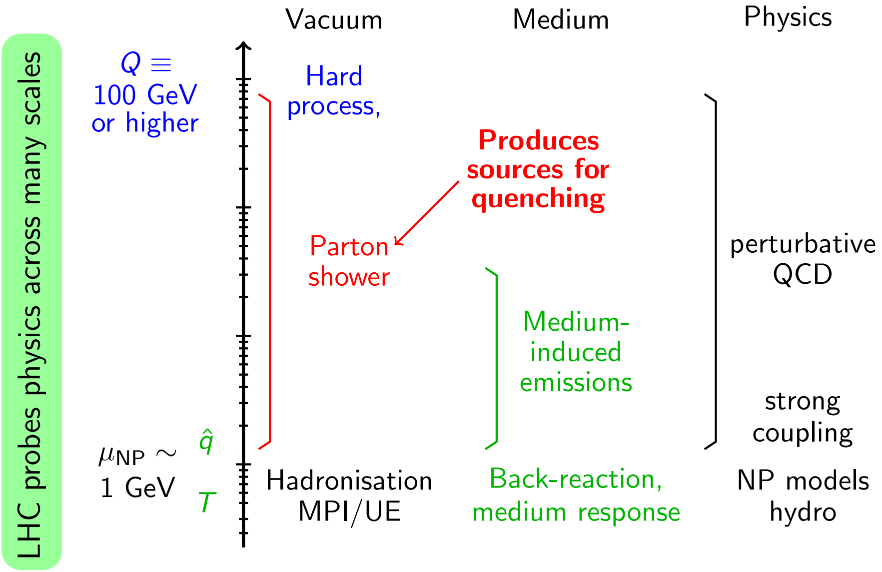


LHC probes physics across many scales

Scale	Vacuum	Medium	Physics
$Q \equiv$ 100 GeV or higher	Hard process,		perturbative QCD
	Parton shower	Medium-induced emissions	strong coupling
$\mu_{\mathrm{NP}} \sim$ 1 GeV, $\hat{q}$, T	Hadronisation MPI/UE	Back-reaction, medium response	NP models hydro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Hadronisation MPI/UE
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NP models hydro

Theory progress

Complex but a good fraction is accessible from first-principles QCD

Lots of progress over the past few years

- Improved picture of jet quenching (for jets rather than hadrons)
- More precise calculations of medium-induced emissions (longitudinal and transverse spectra)
- Accumulate evidence for more fine-tuned effects

What to look forwards to?

- Still a lot to do "analytically"
  - going beyond simplifying assumptions $\rightarrow$ higher accuracy/precision
  - more realistic medium description (expansion, geometry, ...)
- Implementation in dedicated HI Monte Carlo generators
- Benefit from work in generators in *pp* collisions
- Put uncertainty bands [question: what target accuracy for the future?]

Substructure opens (almost) endless options

Brief history

1980	Birth
2008	Re-birth (BDRS)
2008-13	Main techniques
2013	First analytics
2013-	New techniques
2018	Deep-learning
2018	Heavy-ions

Main interest

Offers a differential view of a jet's radiation pattern

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What existing techniques are good for

Select specific "vacuum" configurations as initial conditions for jet quenching

Caveat: substructure tools affect quenching effects in non-trivial ways

Where existing techniques are limited

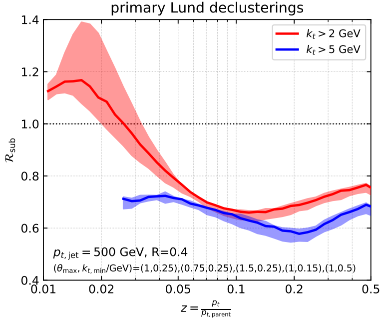
Jet quenching effects are different from *pp* parton shower: angular-ordering violations, different phase-space, ...

Caveat: delicate to find observables which isolate a given quenching effect

Possible first steps

1. Get a set of (unfolded) measurements and theory calculations
   - Explore sensitivity to different scales/ordering (e.g. different angularities, shapes)
   - Explore different phase-space regions (e.g. different grooming; SoftDrop v. DynGrm v. DynGrm+SD, ...)
   - if possible: large p_t, dijets and γ/Z+jet ($\neq q/g$)

Example 1: subjet fragmentation function



Perturbatively more robust & calculable

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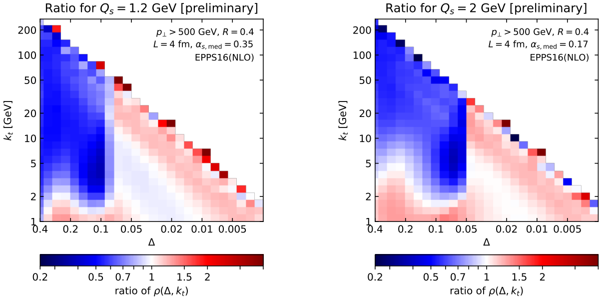
Example 2: Lund jet plane



Rich pattern sensitive to medium details

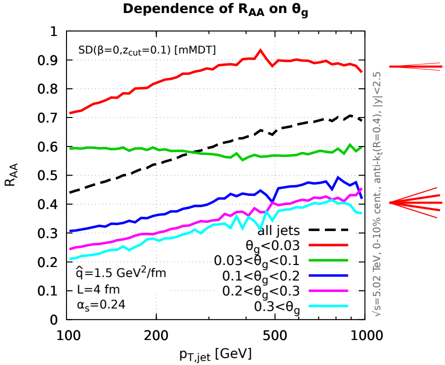
Watch out: subleading corrections and non-pert effects tend to smear quenching effects

Possible first steps

1. Get a set of (unfolded) measurements and theory calculations
2. Study fundamental observables differential in substructure variables

   Idea: use substructure to select a jet sample with desired properties

   Example 3: energy loss v. θ_g



Idea:

smaller θ_g

- $\Rightarrow$ more collimated
- $\Rightarrow$ less vacuum emissions
- $\Rightarrow$ less sources for med-ind. em.
- $\Rightarrow$ smaller E_{loss}

Same basic mechanism for the θ_g distrib

Longer term objectives

Design observables specifically targetting quenching effects

Notes:

- The previous steps are probably necessary to first set up a solid base
- Beyond a set of powerful tools, 20 years of substructure gained a lot of insight on how to think about these questions
  $\Rightarrow$ keep close ties with the substructure community

Outlook

New opportunities opened at the LHC to study jet physics
We are only beginning to explore vast possibilities

Main perspectives from my point of view:

1. Think about long term impact
2. Work on precision and uncertainty bands (as for *pp* collisions)
   Question: what accuracy can/should one target? (5-10%?)
3. Incorporate theory developments into MC generators
4. Make use of jet substructure
   - Jet characterisation using existing techniques
   - Use substructure to tweak the jet sample
   - Build dedicated observables

Backup

Substructure examples