# Building and observing jets in and out the medium

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CERN — Joint Heavy-Ion theory & QCD

# 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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**I have mixed feelings about the very existence of this talk**

- After all, heavy-ion collisions are QCD collisions!
  What bridges are we building then?
- Conversely, HI collisions are substantially more complex
  $\Rightarrow$ more "modelling" & qualitative arguments

# From LEP/RHIC/Tevatron to the LHC (quite obvious)

1. Higher energy

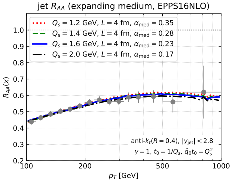
   Main consequence: large pQCD phase-space

   ✓ precision physics
   ✓ th. uncertainties

2. Higher luminosity

   ✓ more observables
   ✓ higher precision
   ✓ more differential

PC,EI,GS,2012.01457

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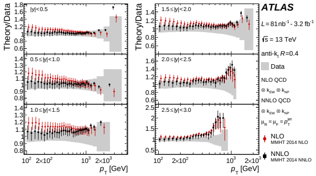


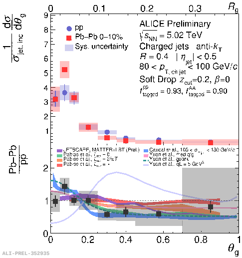


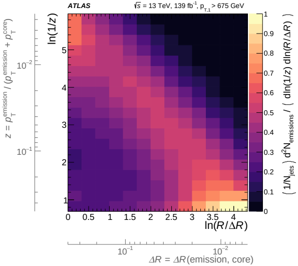


ALI-PREL-352935 ATLAS,2004.03540

# Different physics at different scales: *pp*

LHC probes physics across many scales

$Q \equiv$ 100 GeV or higher

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

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*pp*

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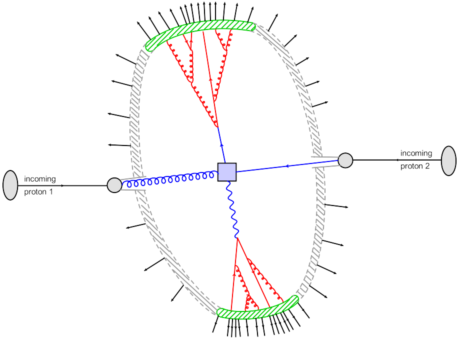
Hard process,

Parton shower

$\mu_{NP} \sim$ 1 GeV

Hadronisation MPI/UE



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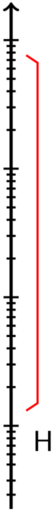

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Parton shower

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Hadronisation MPI/UE

A lot of work in past 20 years:

- amplitudes (NLO, NNLO)
- NLO availability: MadGraph, aMC@NLO, POWHEG, MCFM, ...
- matching/merging: MLM, CKKW Mi(N)NLO, UNNLOPS, Geneva, ...

- $N^{k\geq2}$LL resummations
- Historical showers: Pythia,Herwig,Sherpa
- More recent work: Dire, Vincia, Deductor, PanScales

Nonperturbative modelling

$\propto (\mu_{NP}/Q)^{\#}$

if IRC-safe

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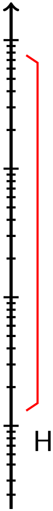

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some still need to make it to HI

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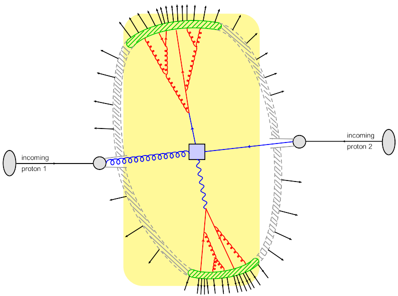
# Different physics at different scales: HI

Jets scatter off the QGP




## $k_t$ broadening

Transverse "kicks":

$$\hat{q} \equiv \langle k_\perp^2 \rangle \text{ per unit length.}$$

Relevant scale: $Q_s = \sqrt{\hat{q}L}$

## Medium-induced emissions

$\sim$ QCD colour coherence broken

$\Rightarrow$ extra emissions (mostly large-angle)

2 relevant scales:

- $\hat{q}L^2$: hard (rare) emissions
- $\alpha_s^2 \hat{q}L^2$: multiple emissions

## effects on the QGP itself

No real separation between the jet and the medium

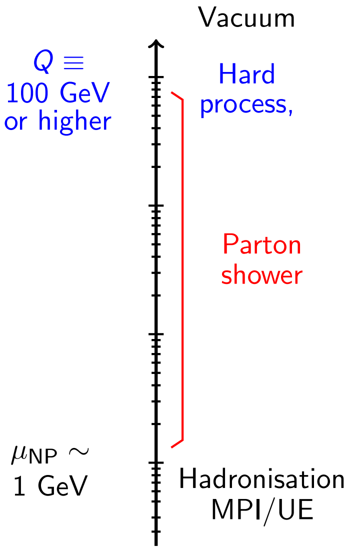
$\Rightarrow$ correlated behaviour

back-reaction, medium recoil, ...

Relevant scale $\sim T$

# Different physics at different scales: HI

LHC probes physics across many scales



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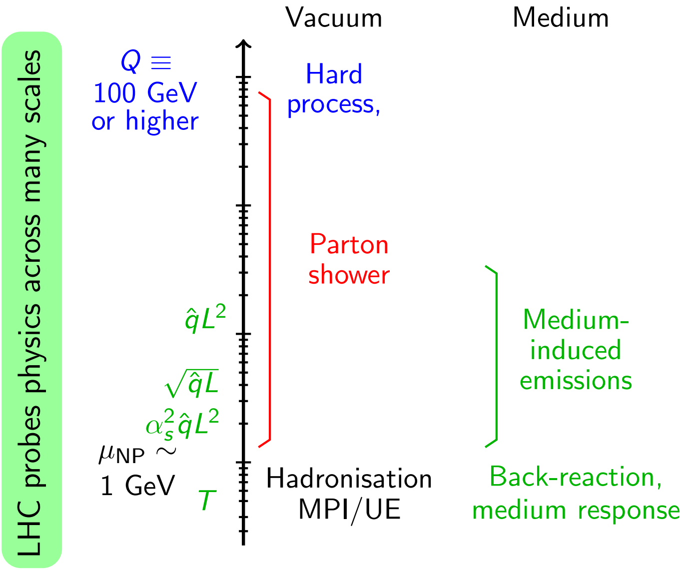

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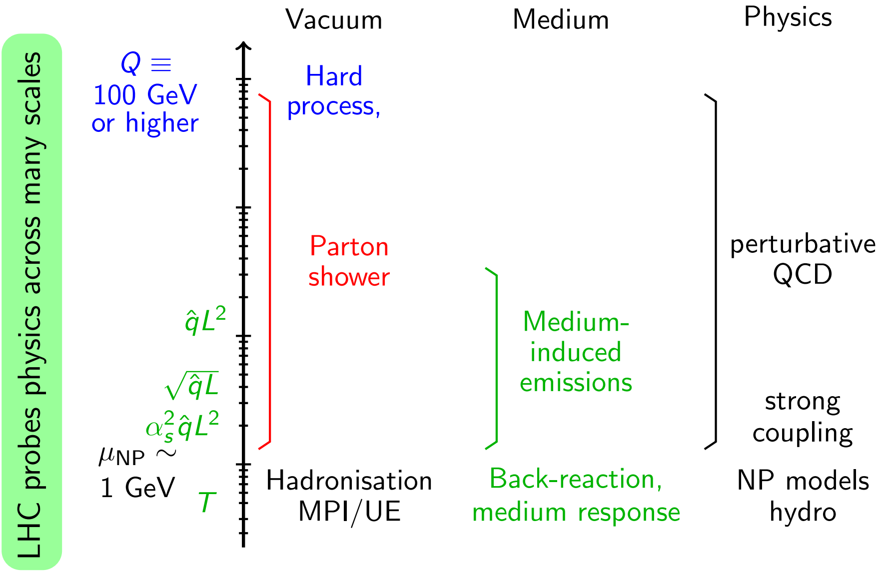

LHC probes physics across many scales

| Scale | Vacuum | Medium | Physics |
|---|---|---|---|
| $Q \equiv$ 100 GeV or higher | Hard process, | | perturbative QCD |
| | Parton shower | **Produces sources for quenching** | |
| $\hat{q}L^2$, $\sqrt{\hat{q}L}$, $\alpha_s^2\hat{q}L^2$ | | Medium-induced emissions | strong coupling |
| $\mu_{NP} \sim$ 1 GeV, $T$ | Hadronisation MPI/UE | Back-reaction, medium response | NP models hydro |

# Substructure opens (almost) endless options

**Large phase-space where perturbative QCD can genuinely be applied both in *pp* and in HI**

implies correlated effort on (at least) 2 fronts

Understand the development of parton cascades

Calls for several improvements:

- fixed-order (*pp*)
- resummations (*pp*)
- quenching description (HI)
- parton-shower MC (both)

develop observables sensitive to the QCD dynamics

Jet substructure has proven a powerful tool for about 10 years

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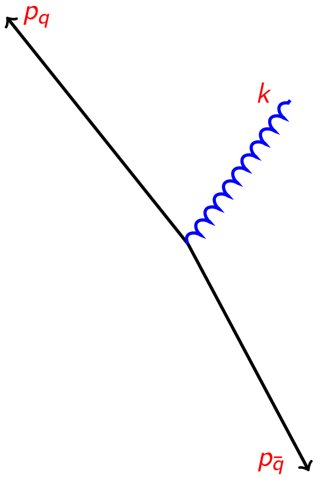
Jet substructure has proven a powerful tool for about 10 years

I will focus on these 2 topics with deep connections between *pp* and HI

## Interlude
## Representing radiation in the Lund plane

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

Take a gluon emission from a $(q\bar{q})$ dipole




Emission:

$$k^\mu \equiv z_q p_q^\mu + z_{\bar{q}} p_{\bar{q}}^\mu + k_\perp^\mu$$

3 degrees of freedom:

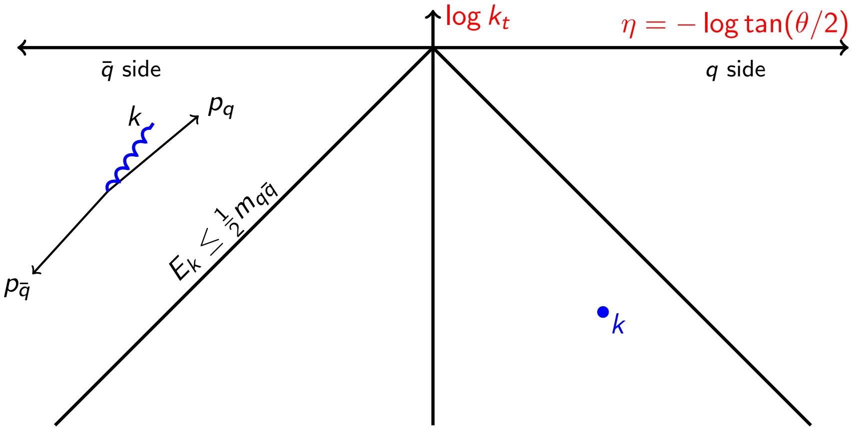
- Rapidity: $\eta = \frac{1}{2} \log \frac{z_q}{z_{\bar{q}}}$
- Transverse momentum: $k_\perp$
- Azimuth: $\phi$

In the soft-collinear approximation

$$d\mathcal{P} = \frac{\alpha_s(k_\perp) C_F}{\pi^2} \, d\eta \, \frac{dk_\perp}{k_\perp} \, d\phi$$

# Basic features of QCD radiations: the Lund plane

Lund plane: natural representation uses the 2 "log" variables $\eta$ and $\log k_\perp$



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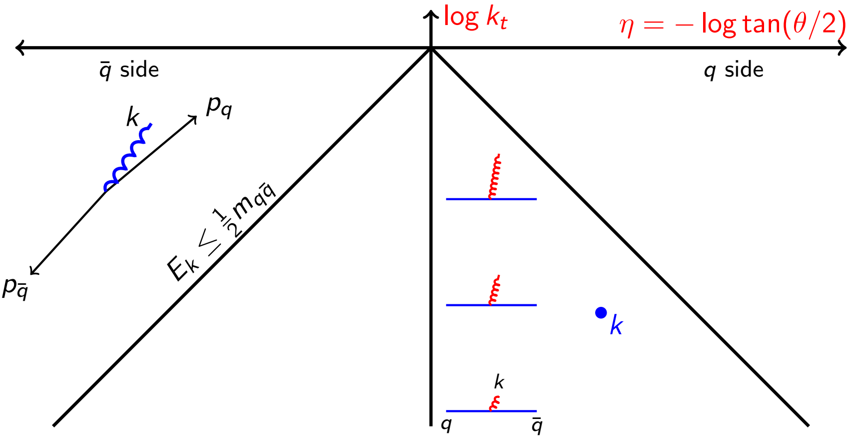

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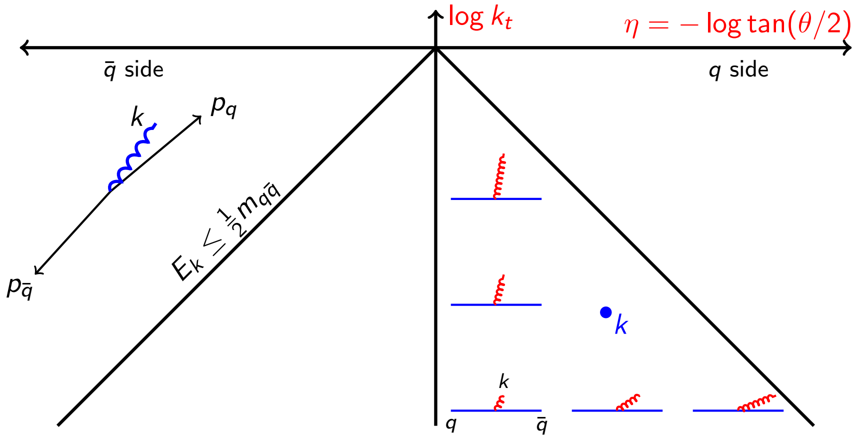

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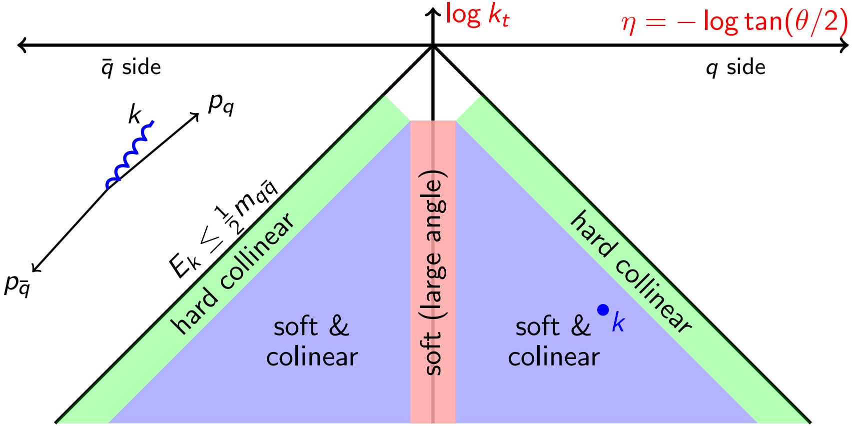

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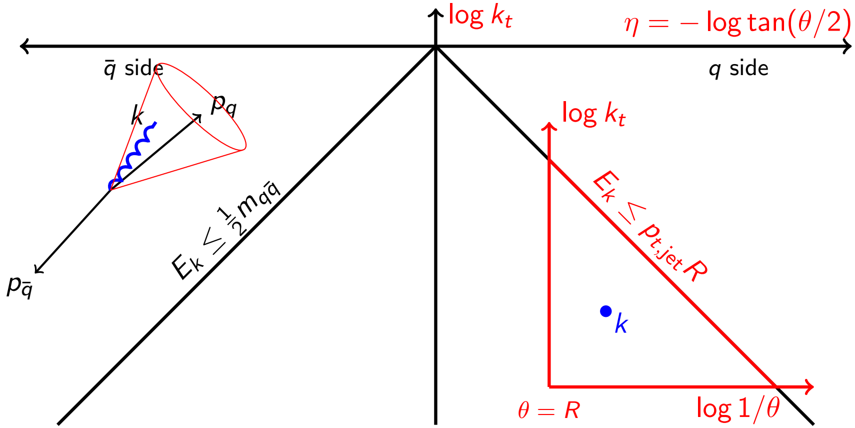
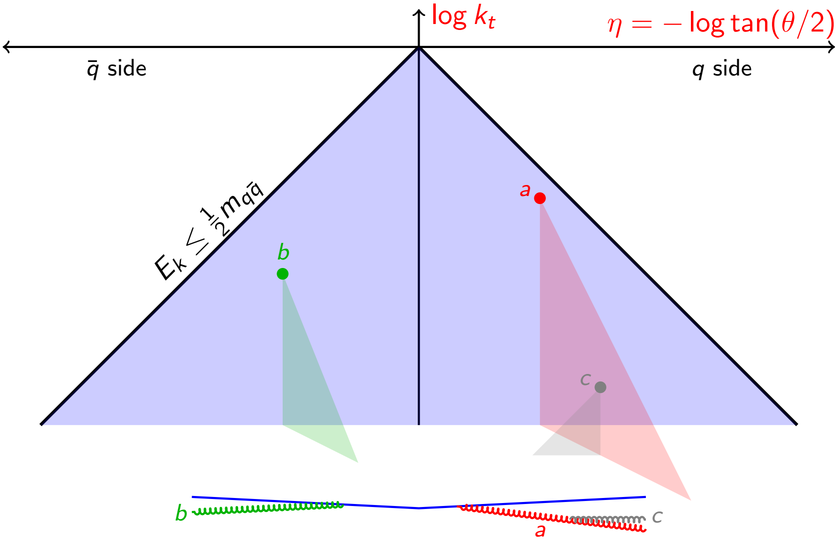



For a jet: $\eta = -\log\tan\theta/2 \approx \log 1/\theta$, $\theta < R$

# Multiple emissions in the Lund plane



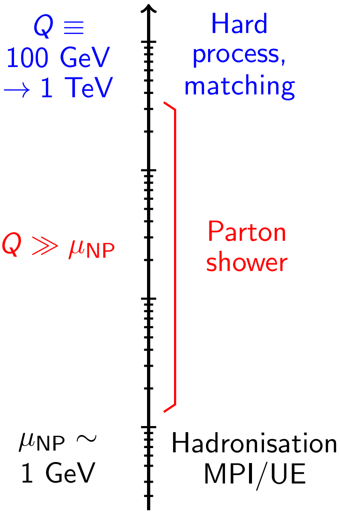
# Parton showers

# Parton shower in *pp*: big picture

Lots of progress over the past decade:

- $1 \to 3$ splitting functions: ingredients towards NLO DGLAP (e.g. Dire)
  See e.g. [Jadach *et al*,16] [Li,Skands,16] [Höche,Krauss,Prestel,17] [Höche,Prestel,17]
- Beyond leading colour: most showers (except herwig) use dipoles and are leading $N_c$ (even at leading log)
  - Amplitude-level showers (instead of ME$^2$)
    see e.g. [Forshaw,Holguin,Plätzer,19]
  - Beyond leading-$N_c$/full colour
    see e.g. [Nagy,Soper,12] [Gieseke,Kirchgaesser,Plätzer,Siodmock,18] [Höche,Reichelt,20] [Forshaw,Holguin,Plätzer,20]
- Electroweak showers: include $W/Z/\gamma$ in showers
  involved splitting functions, explicit dependence on chirality/spin$^{(*)}$
  see e.g. [Kleiss,Verheyen,20] [Bauer,Ferland,Webber,17-18] [Bauer,DeJong,Nachman,Provasoli,19]

$^{(*)}$ Technically, this is also the case for QCD showers




"Standard" perturbative expansion

$$\alpha_s(Q) f_1(v) + \alpha_s^2(Q) f_2(v) + \alpha_s^3(Q) f_3(v) + \ldots$$

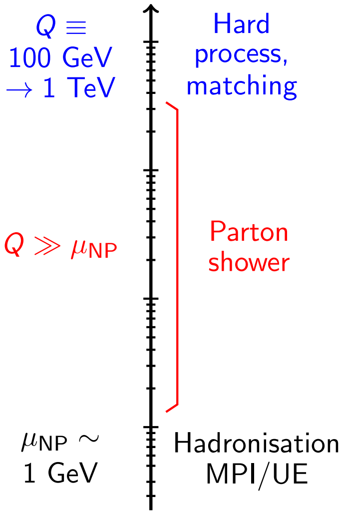
LO NLO NNLO

expect logs between disparate scales

$$\alpha_s \log^2 Q/\mu_{\rm NP},\ \alpha_s \log Q/\mu_{\rm NP}$$

(double, single,...) logs to resum

# What does shower accuracy mean?

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$\alpha_s \log^2 Q/\mu_{NP}$, $\alpha_s \log Q/\mu_{NP}$

(double, single,...) logs to resum

**PS accuracy means logarithmic accuracy: LL, NLL, N$^2$LL, ...**

**well-defined**
**+ systematically improvable**

# Target NLL accuracy

**NLL accuracy for a range of observables**

- global event shapes
  - thrust
  - jet rates
  - angularities
  - broadening
  - ...
- non-global observables

  e.g. energy in slice
- multiplicity

  (NLL is $\alpha_s^n L^{2n-1}$)

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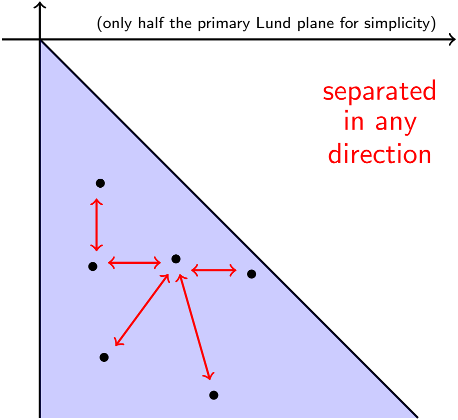
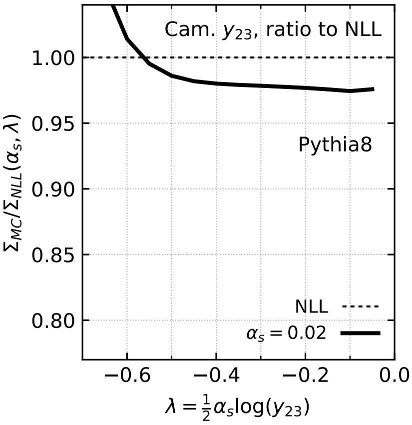
**Correct matrix elements for $N$ well separated emissions in the Lund plane**



# Target NLL accuracy

(Cumulative) distributions can (often) be written as

$$P(v < e^{-L}) = \exp\left[\underbrace{g_1(\alpha_s L)L}_{\text{leading log}(LL)} + \underbrace{g_2(\alpha_s L)}_{\text{next-to-leading log}(NLL)} + \underbrace{g_3(\alpha_s L)\alpha_s}_{NNLL} + \dots\right]$$




Idea for testing:

$$\frac{\Sigma_{MC(\lambda=\alpha_s L,\alpha_s)}}{\Sigma_{NLL(\lambda=\alpha_s L,\alpha_s)}} \quad \text{v.} \quad 1$$

with $\lambda = \alpha_s L$

NLL deviations

or

subleading effects?

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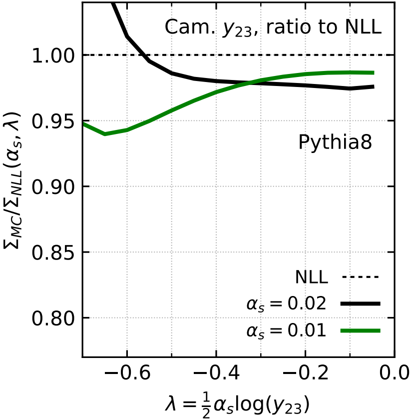


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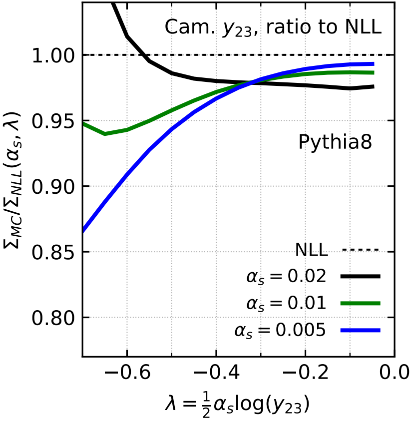


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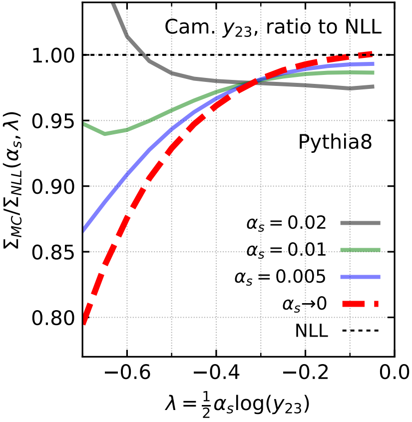


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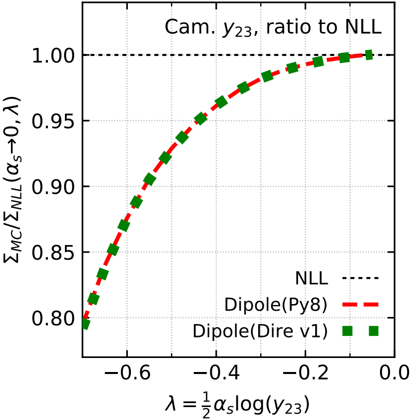


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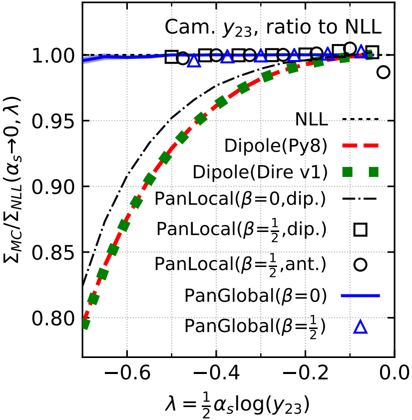


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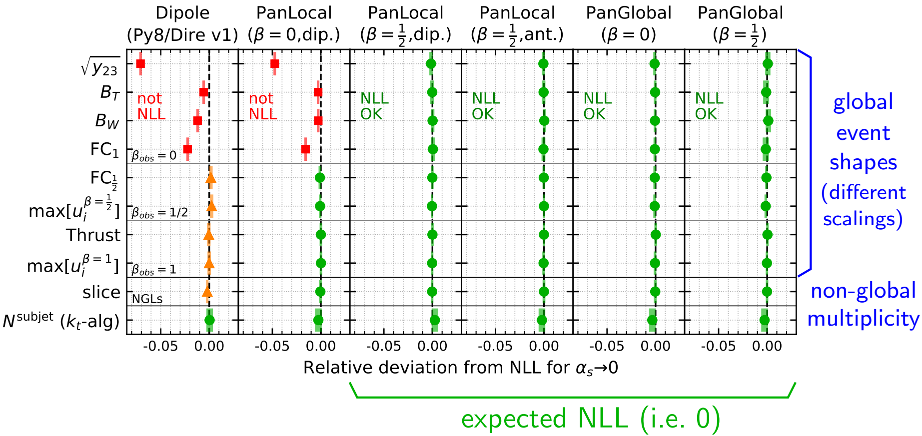
- × Pythia8 deviates from NLL
- × Dire(v1) same as Pythia8
- ✓ PanLocal($0 < \beta < 1$) OK
- ✓ PanGlobal($0 \leq \beta < 1$) OK

[M.Dasgupta,F.Dreyer,K.Hamilton, P.Monni,G.Salam,GS,20]

# More extensive tests

[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,20]




(green: OK at NLL; orange: issues at fixed order; red issues at fixed and all orders)

Recently: prescription beyond leading $N_c$ [K.Hamilton,R.Medves,G.Salam,L.Scyboz,GS,20]

# Parton shower in HI: big picture

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

Significantly improved picture of jet quenching over the past few years

- More precise calculations of medium-induced emissions
  (longitudinal and transverse spectra)
- Accumulate evidence for more fine-tuned effects
  (decoherence, back-reaction, medium response, ...)

see e.g. [Mehtar-Tani,Tywomiuk,19] [Barata,Mehtar-Tani,Soto-Ontoso,Tywomiuk,20] [Mehtar-Tani,Pablos,Tywomiuk,21] [Barata,Dominguez,Salgado,Vila,21]

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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, ...)
- More implementations in dedicated HI Monte Carlo generators
- Benefit from work in generators in *pp* collisions

# Parton shower in HI: double-logarithmic limit

How to combine (angular-ordered) “vacuum” splittings with (not-angular-ordered) medium-induced emissions?

Idea: compare the transverse momenta over the formation time: $t_f = \frac{2}{\omega\theta^2}$

$$k_{\perp,\text{vac}}^2 = \omega^2\theta^2$$
$$k_{\perp,\text{med}}^2 = \hat{q}t_f = \frac{2\hat{q}}{\omega\theta^2}$$

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$$k^2_{\perp,\text{med}} = \hat{q}t_f = \frac{2\hat{q}}{\omega\theta^2}$$

At leading log, 2 possible cases:

- $k^2_{\perp,\text{vac}} \gg k^2_{\perp,\text{med}}$: standard vacuum emissions (angular-ordered)$^{(*)}$
- $k^2_{\perp,\text{vac}} \ll k^2_{\perp,\text{med}}$: medium-induced emission

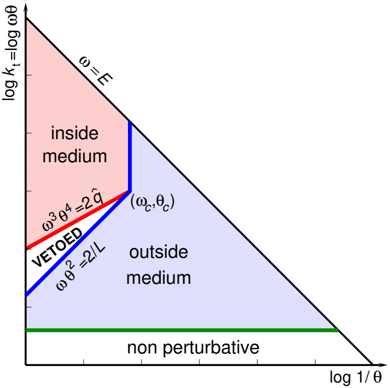
transition at $k^2_{\perp,\text{med}} = k^2_{\perp,\text{vac}}$ i.e. $\omega^3\theta^4 = 2\hat{q}$

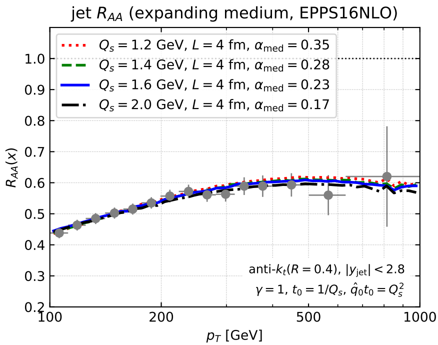
[P.Caucal,E.Iancu,A.H.Mueller,GS,17] ($^{(*)}$ includes details about colour coherence)

# Factorised physical picture

## 3-stage picture (at double-log):

1. in-medium angular-ordered vacuum emissions
2. each parton sources MIEs propagating through the medium
3. out-medium VLEs with first emission at any angle




includes nuclear PDFs and expanding medium

# Open questions

A few ideas to keep in sight for future developments

- Helpful to thing in terms of ordered scales

$$Q \gg \sqrt{\hat{q}L} \gg T$$

  to factorise different effects in a systematic way

- Can one devise accuracy tests similar to the ones discussed for *pp*?

# Jet substructure

# 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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## Main interest

Offers a differential view of a jet's radiation pattern

## What existing techniques are good for

Study the dynamics of the QCD branchings in many differnet ways

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

# Substructure example: radiation in the Lund plane

Myriads of tools available. I will focus on a visually simple one

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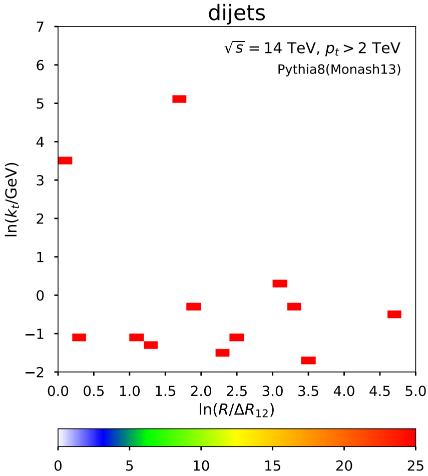
## The (primary) Lund jet plane

- Cluster the jet with Cambridge/Aachen
  (i.e. orderd in angles)
- Iteratively undo last clustering
  (following hardest subjet)
- measure $k_t$ and $\Delta R$ of branching



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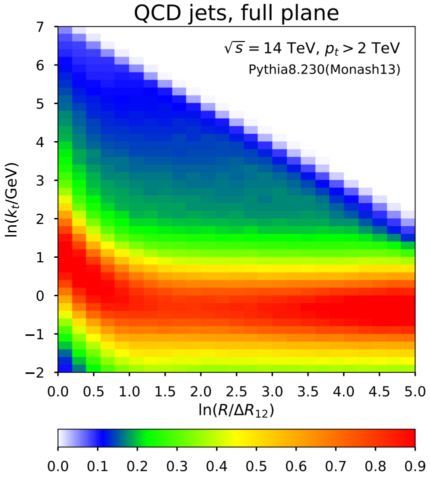
One (of many) nice properties:
separate different physical regions



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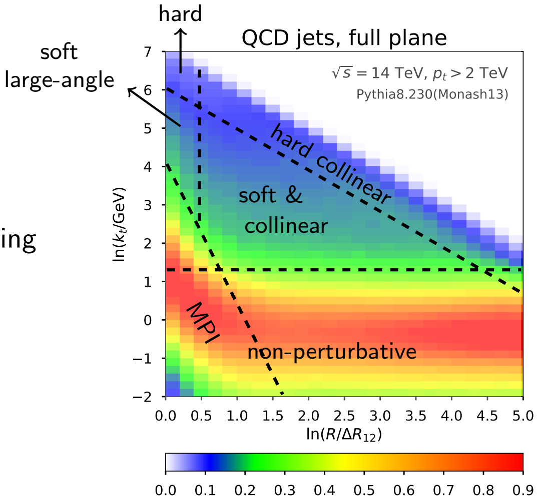
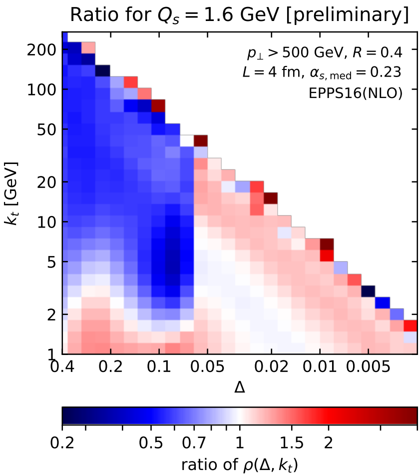


Lund plane potentially interesting in heavy-ion collisions

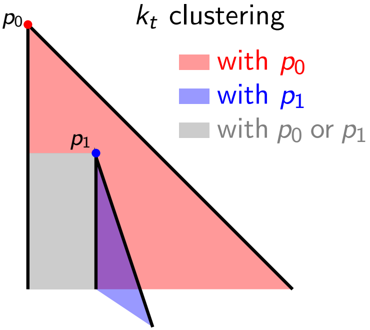
- picture not 100% clear
- some effects
  - quark v. gluon $E_{\rm loss}$
  - decoherence
  - in/out interface
  - medium induced
- beyond primary plane?
- correlations?

ratio $\rho_{\rm PbPb}/\rho_{pp}$

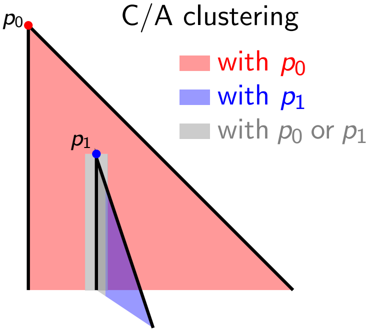


In $pp$, C/A is natural since it respects (strong) angular ordering

Imagine a leading parton $p_0$ + a largest-$k_t$ emission $p_1$




"wrong" clustering can happen
at double-logaccuracy

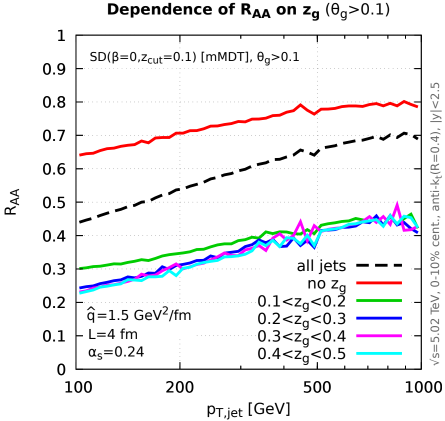



clustering as expected
except in "single-log" region

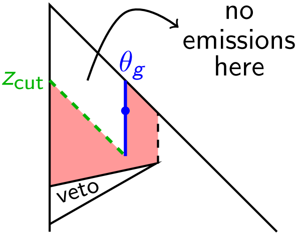
## What are the appropriate substructure tools in HI?

- Large part of the phase-space dominated by vacuum
  - Can be an advantage: *use substructure to select the vacum configuration that propagates through the mediun*
  - C/A still appears as a natural choice (for clustering-based tools)
- Different ordering can be probed
  - C/A declusterings gives an ordered list of declusterings (or a full tree); *these can be ordered as we please* (cf. e.g. dynamical grooming)
  - the first clustering is unaffected $\Rightarrow$ different algorithms can be used

**Idea: correlate jet quenching with substructure variables**




This is just an example...




$R_{AA}$ in different bins of $\theta_g$

- smaller $\theta_g \Rightarrow$ less sources
  $\Rightarrow$ less $E_{\text{loss}}$
- transition at $\theta_g \sim \theta_c$
  (decoherence angle)

# Final words

**genuine connections between *pp* and HI collisions**

## Where HI could think *pp*

- large phase-space for "*pp* physics"
- be quantitative
  - assess accuracy
  - inlcude uncertainties

## Where *pp* could think HI

- rich QCD pheno of QGP interactions
- interesting challenges to think about e.g. using substructure