Theory of Jet Substructure and EIC Potential

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Jet Observables at the EIC
BNL, virtually.
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Initial Outline

- Outline highly technical details of Jet Substructure at LHC.
- Proselytize for Soft-Collinear Effective Theory.
- Advertise for my own research.

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We will have plenty of technical talks,
Review: **[Larkoski, Moult, Nachman 1709.04464]**

Revised Outline

- What?
- Why?

What is the purpose of Jet Substructure?

Jet substructure was born in the context of the LHC.
Its (initial) Mission:

1. *Tag H/Z/W/tops decaying hadronically.*
2. *Find new physics.*

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At an EIC we will do neither.*
So why jet substructure?

*At least, "new" physics in a HEP sense.

Jet Substructure for the LHC.

QCD was not a motivation (explicitly)...
To accomplish its mission,
jet substructure *had* to understand QCD better.*

Reason:
Finding a thing in Pythia is not finding a thing in Nature.

*Until Machine Learning Happened.

EIC and jet substructure.

However, the mission of the EIC *is* to understand QCD better.

- *The obstacle is the goal.*

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This is what we should keep in mind.
Not just blindly port substructure observables.

So what were we *really* doing in jet substructure?

What we are Officially Doing

When engaging in jet substructure at the LHC, we wished to identify the progenitors of a jet:

- Quark Versus Gluon.
- QCD versus Higgs, Z, $W^{\pm}$.
- Top quarks.
- New physics versus Standard Model.

So what were we *really* doing?

1. *How do charges in a quantum field theory transport through a collision process, dominated by strongly interacting dynamics?*
2. *Can these charges constitute an asymptotically well-defined observable?*

Charges:

- Color.
- Flavor.
- Electro-weak.
- Momentum.
- Angular Momentum.

So what were we *really* doing?

1. *How do charges in a quantum field theory transport through a collision process, dominated by strongly interacting dynamics?*
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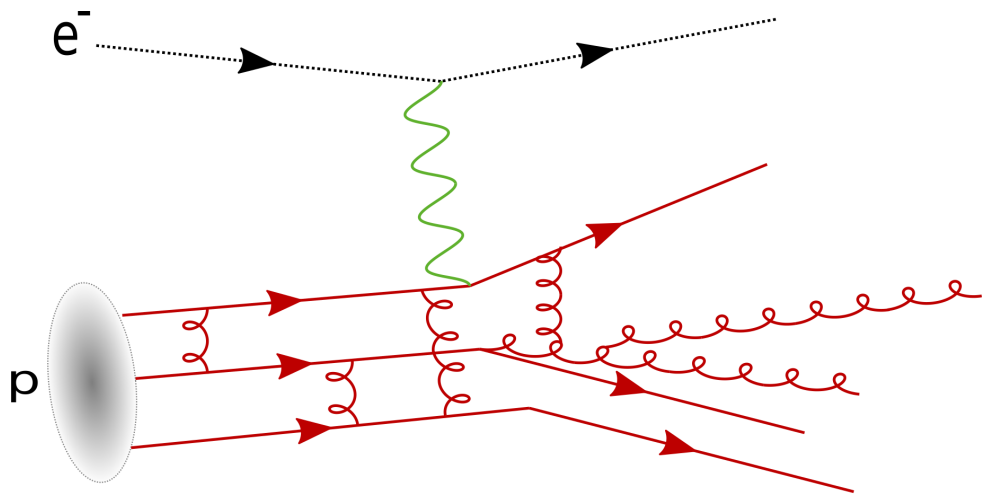
- EIC: we won't get "new" physics.*
- It is these questions that are interesting, and it is the ones we get to keep.

*Neither, apparently, will the LHC.

Advantages and Challenges

So what will be the advantages of EIC (versus LHC or RHIC)?

- Little underlying event, scattering processes can be isolated.
- Control over *initial* states:
  1. Polarization.
  2. Initial momenta.
  3. Heavy Ions.
- SIDIS:
  1. Total invariant mass of *final* states (e^+e^-).
  2. Control of *partonic* initial states



Advantages and Challenges

The challenge, we **must** confront nonperturbative physics:

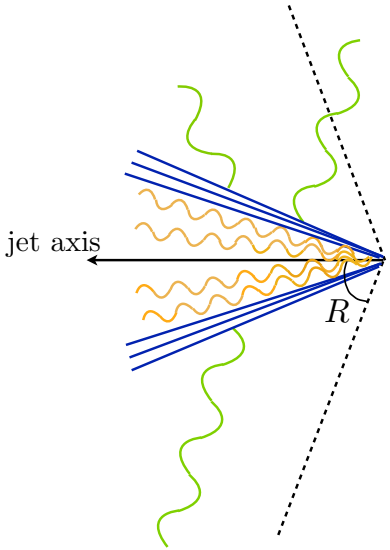
$$\text{LHC: } 1 \gg \frac{m_J}{Q_H} \gg \frac{\Lambda}{m_J}$$

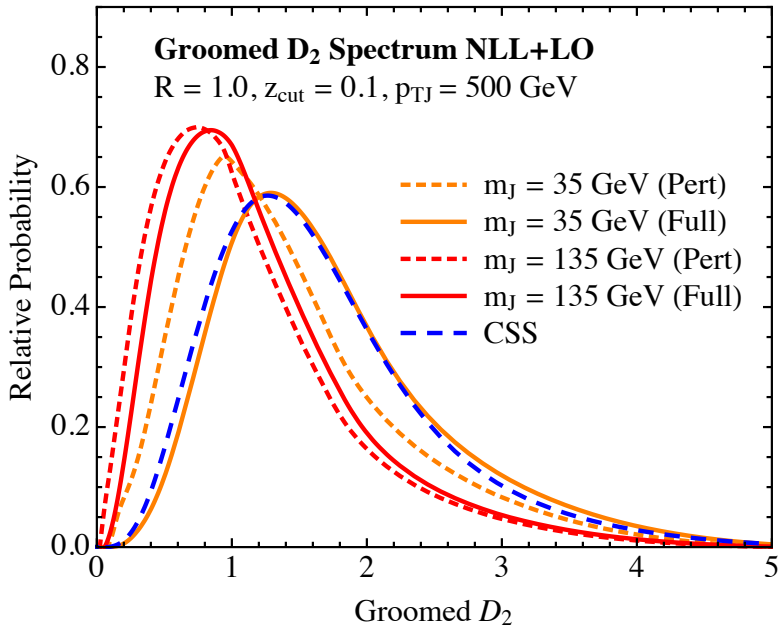
$$\text{EIC: } 1 \gg \frac{m_J}{Q_H} \geq \frac{\Lambda}{m_J}$$

Q_H hard scale, m_J jet substructure scale.

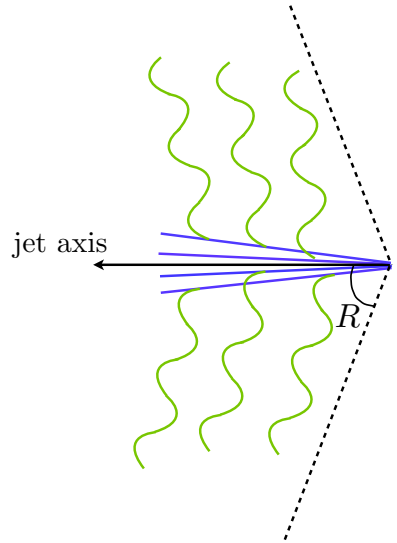
Jet Substructure at LHC

Collinear Subjets





Soft Haze

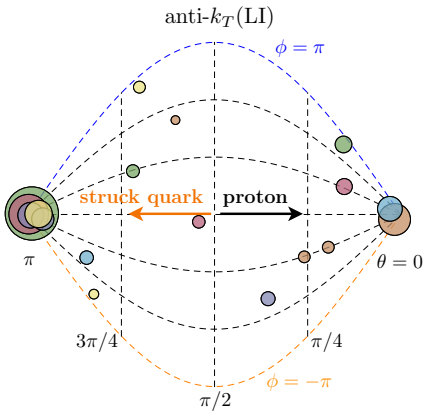


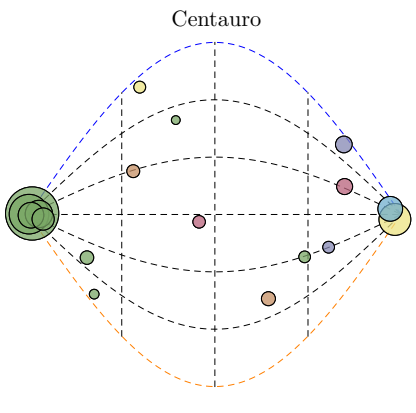
- Spectrum of 2 subjets in a jet at LHC. **[1710.06859, 1710.00014]**
- N.P. Physics: dotted $\rightarrow$ dashed
- Understanding scaling properties of N.P. sufficed.

N.P. physics a simple re-arrangement of cross-sections at LHC.*

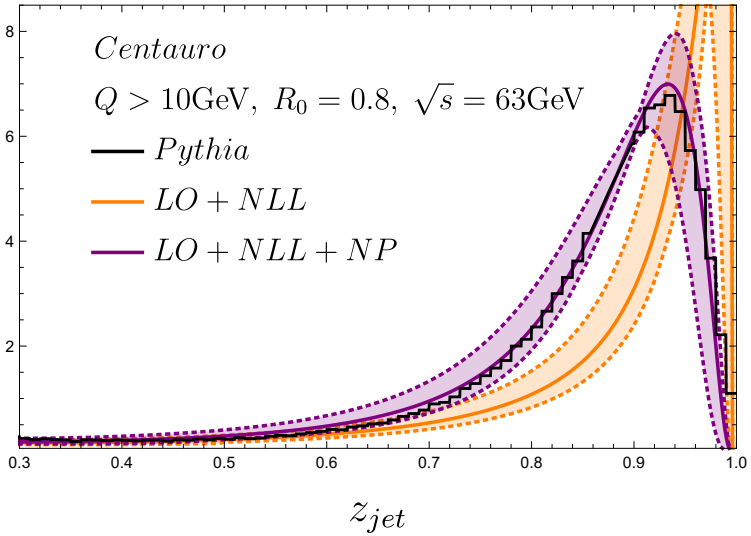
*With grooming.

Jet Structure at EIC





$$\frac{1}{\sigma}\frac{d\sigma}{dz_{jet}}$$



- Frequency of jets in SIDIS, found by Centauro, at EIC carrying momentum fraction z_{jet} of final state. **[2006.10751]**
- $R \to 0$ fragmentation.
- This is just jet *structure*.
- N.P. Physics: orange $\to$ purple

N.P. physics a dramatic re-arrangement of cross-sections at EIC.

It is not that there will be no jets,
but substructure will be non-perturbative.

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but substructure will be non-perturbative,
and this is good.

Perturbation Theory and Jets

Perturbation theory is in excellent shape.

$$\alpha_s \ln \frac{m_J}{Q_H} \sim 1$$

$$d\sigma = \alpha_s \ln^2 \frac{Q_J}{Q_H} + \alpha_s^2 \ln^4 \frac{Q_J}{Q_H} \ldots + \alpha_s \ln \frac{Q_J}{Q_H} + \ldots$$

$$= O(\alpha_s \ln^2) + O(\alpha_s \ln) + O(\alpha_s^2 \ln) + O(\alpha_s^3 \ln) + O(\alpha_s^4 \ln) + \ldots$$

Very incomplete list:

- NLL+(N)LO mandatory, and describes (LHC) data well.
- NNLL routine **[Banfi, McAslan, Monni, Zanderighi 1412.2126],[Bell, Rahn, Talbert 1812.08690,2004.08396]** .
- $\mathrm{N^3LL}$ achievable **[Moch,Vermaseren,Vogt hep-ph/0403192], [Becher, Schwartz, 0803.0342], [Li, Neill, Zhu 1604.00392, Li, Zhu 1604.00392], [Kardos,Larkoski,Trocsanyi 2002.00942].**
- $\mathrm{N^4LL}$ coming *soon* **[Moch, et al. 1707.08315, Vogt et al. 1808.08981], [Bruser, Liu, Stahlhofen 1804.09722], [Banerjee, Dhani, Ravindran 1805.02637], [Bruser, Liu, Stahlhofen 1804.09722], [Luo, Yang, Zhu, Zhu 1912.05778], [Ebert, Mistlberger, Vita 2006.03056].**

Perturbation Theory and Jets

Even at $\alpha_s(2GeV) \sim 0.3$, this is $\sim 3\%$ uncertainty!

Perturbation Theory and Jets

Why perturbation theory is in excellent shape:

1. Derive Factorization Formula (Soft Collinear Effective Field Theory or otherwise).
2. Write anomalous dimensions in terms of integrals over universal matrix elements.
3. Collaborate with a higher order loop calculation specialist, or become one.

This is not to say we are done with perturbation theory.

Non-Perturbative Theory

Ask Pythia and Herwigg...

More seriously, Non-Perturbative Theory

Some first principles:

- Understanding of scaling and universality: **[Dokshitzer,Marchesini,Webber hep-ph/9512336,hep-ph/9504219],[Lee, Sterman hep-ph/0611061].**
- Fragmentation for heavy quarks & NRQCD **[Bodwin,Braaten,Lepage hep-ph/9407339].**
- Actual N.P. calculation of anomalous dimension: **[Ji 1305.1539],[Ebert, Stewart, Zhao 1811.00026], [Shanahan, Wagman, Zhao 2003.06063].**

Non-Perturbative Theory

LHC and grooming allowed us to shuffle around this problem.

- *The Potential for the EIC is to force us to become better at understanding and predicting non-perturbative physics in dynamical processes.*

Non-Perturbative Theory: what is needed.

To really make progress for jet substructure for EIC:

- OPE for "time-like condensates."
- Lattice QCD for "time-like condensates."
- String model $\rightarrow$ Effective string theory ($N_c \gg 1$?).
- Lessons from Ads/QCD?
- Field theory constructions for parton/hadron duality.
- Entirely new EFT for hadronization?

The advantage of EIC versus LHC or RHIC will be a clean environment to engage these questions.

Non-Perturbative Theory: Observables

So which observables?

1. *How do charges in a quantum field theory transport through a collision process, dominated by strongly interacting dynamics?*
2. *Can these charges constitute an asymptotically well-defined observable,* **even non-perturbatively?**

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