Thoughts on future jet observables

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Recent RHIC and LHC results and their implications
for heavy ion physics in the 2020's
MIT, Cambridge

Outline

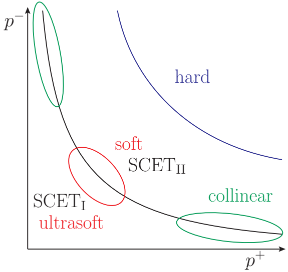
- Goals
  - examine heavy ion physics at different energy scales
  - stress-testing models
  - reliably understand and extract QGP properties
- Ideas and why
  - exclusive and correlated measurements
  - jet substructure observables
  - artificial v.s. natural jet quenching
- Some specific future jet observables
  - splitting function and subjet distribution
    - subjet kinematics probing parton splitting and bremsstrahlung
  - artificially quenched (e.g. soft drop) jet cross sections
    - simplest, soft-radiation insensitive observable
  - quark v.s. gluon, heavy v.s. light
    - soft-radiation sensitive (jet mass, jet broadening, subjettiness, ...)
    - flavor sensitive (jet charge, different rapidity, different hard process, ...)
- Discussions

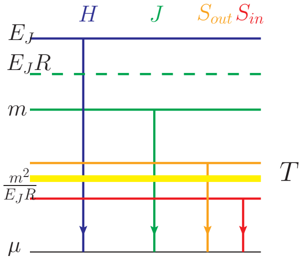
QCD modes and jet observables

- Jets are manifestation of the infrared structure of QCD at high energies: enhancement of soft/collinear radiations
- They are multi-scaled objects with rich information about the physics across the entire energy spectrum
- The scaling of modes in lightcone coordinates $(p^- = \bar{n}\cdot p, p^+ = n\cdot p, p_\perp)$ where $n = (1, \hat{n}_J)$:

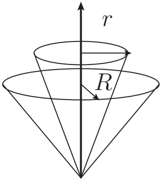
  $p_h : E_J(1,1,1)$, $p_c : E_J(1,\lambda^2,\lambda)$ and $p_s : E_s(1,R^2,R)$

  - E_J is the hard scale which is the energy of the jet
  - $E_J\lambda$ is the jet scale and λ is the angular spread of particles ($\lambda \approx p_\perp/p_\parallel \ll 1$)
  - Relevant soft modes depend on the observables, e.g. for jet mass, a lower soft, seesaw scale emerges ($E_s \approx m^2/E_JR$)
  - Medium modes interact with and respond to jets





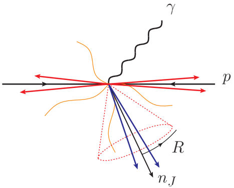
Sensitivity of jet observables to modes



$$\Psi_J(r,R) = \frac{\sum_{r_i<r} E_{T\,i}}{\sum_{r_i<R} E_{T\,i}}$$

$$\langle \Psi \rangle = \frac{1}{N_J} \sum_{J}^{N_J} \Psi_J(r,R)$$

$$\psi(r,R) = \frac{d\langle \Psi \rangle}{dr}$$



$$m^2 = \Big(\sum_{i\in J} p_i\Big)^2$$
$$= \big(p_c + p_s\big)^2$$
$$\approx p_c^2 + 2p_c \cdot p_s$$
$$\approx p_c^2 + 2E_J n_J \cdot p_s$$

- Jet shape has dominant contributions from energetic collinear radiations

$$\Psi(r) = \frac{E_c^{<r} + E_s^{<r}}{E_c^{<R} + E_s^{<R}} = \frac{E_c^{<r}}{E_c^{<R}} + \mathcal{O}(\frac{E_s}{E_c})$$

- Jet mass is sensitive to soft modes

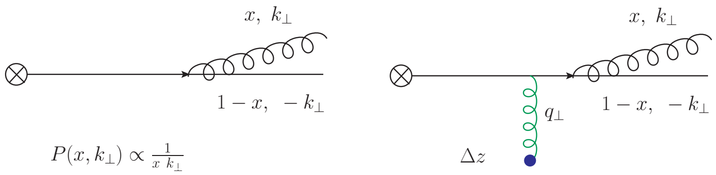
$$m^2 \approx p_c^2 + 2E_J n_J \cdot p_s, \quad \Delta m \approx E_s \frac{E_J}{m}$$

- Jet observables have different sensitivities to physics at different energy scales simply because of kinematics. In principle, through a series of jet measurements we will be able to map out the whole jet formation history

How do we isolate physics and distinguish models?

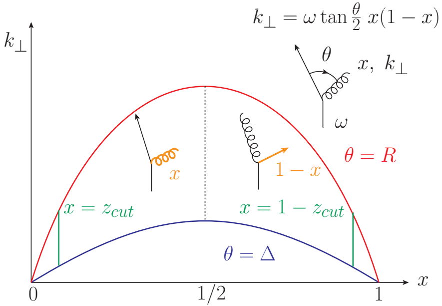
- Whether the model relies on the low scale physics corresponds to two rough pictures of jet quenching
  - Yes. Parton showers are not affected much until the later stages. The medium depletes the partons out of the jet
  - No. The medium effects open up more channels in the jet formation process, all the way from the hard process through hadronization
- Can we test the two pictures and the role of medium response?
- Thanks to Jesse's talk on the state-of-the-art jet techniques, I will put them in specific contexts that may help answering the above question
  - We are able to dissect radiations and pick out the components of interest
  - The idea: come up with an observable as insensitive to low scale physics as possible
  - The tool: grooming

Groomed momentum sharing z_g



- Soft Drop: a tree-based procedure to drop soft radiation
  - Recluster a jet using C/A algorithm
  - For each branching, consider the p_T of each branch and the angle θ
  - Drop the soft branch if $z < z_{cut}\ \theta^\beta$, where $z = \frac{\min(p_{T,1},p_{T,2})}{p_{T,1}+p_{T,2}}$
  - CMS used $\beta = 0$, $z_{cut} = 0.1$, $R = 0.4$, $\Delta R_{12} > 0.1$ and measured z_g
- z_g the momentum fraction of the soft branch. r_g: the angle between the branches
- In vacuum, the soft branch kinematics is closely related to the Altarelli-Parisi splitting function (the original motivation of z_g)
- In the medium, the bremsstrahlung component modifies the soft branch kinematics

An analysis of z_g



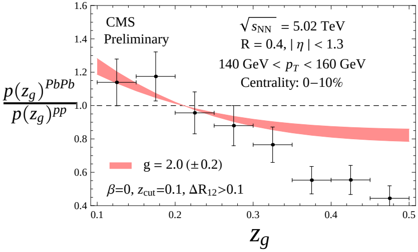
- The partonic phase space is constrained by R, Δ and z_{cut}
- At leading order, the $1 \to 2$ branching probability directly affects the subjet distribution

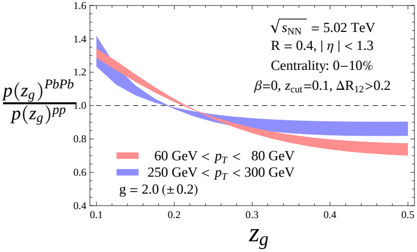
$$\mathcal{P}_{i\to jl}(x, k_\perp) = \mathcal{P}^{vac}_{i\to jl}(x, k_\perp) + \mathcal{P}^{med}_{i\to jl}(x, k_\perp)$$

- $\mathcal{P}^{med}_{i\to jl}(x, k_\perp)$ is the medium-induced contribution
- The distributions of z_g and r_g can be constructed

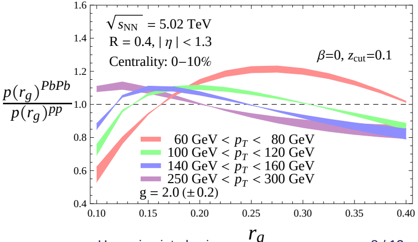
$$p_i(z_g) = \frac{\int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(z_g, k_\perp)}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x, k_\perp)}\,, \qquad p_i(r_g) = \frac{\int_{z_{cut}}^{1/2} dx\, p_T x(1-x) \overline{\mathcal{P}}_i(x, k_\perp(r_g, x))}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x, k_\perp)}$$

A theory calculation of z_g





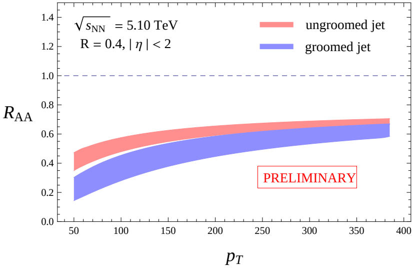
- The medium enhances the soft branches, and the effect becomes smaller for higher p_T jets. How about the angular distribution?



Thoughts on z_g and what follows

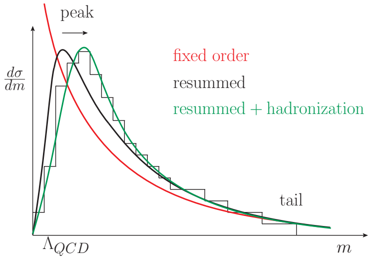
- Qualitatively expected and quantitatively surprising
- By construction, soft drop observables are made soft-radiation insensitive
- Hadronization effects and soft-correlations (absence of NGLs) are suppressed
- Difference between quark and gluon jets suppressed
  - To zeroth order, the color charges cancel
- Cutting on the angle between branches selects a special subset of the jet sample
  - Jets with a two prong structure not typical for QCD jets
  - The scale of this subjet branching is high
- Another picture: subjet energy loss and broadening
  - $q \to qg$: one quark subjet and one gluon subjet
  - $g \to gg$: two gluon subjets
- The next step is to measure the r_g distribution (which may already be happening)
- Propose:
  - 2-subjettiness ($\approx m_1^2/p_{T_1}^2 + m_2^2/p_{T_2}^2$)
  - z_g and r_g distributions with different quark/gluon jet fractions

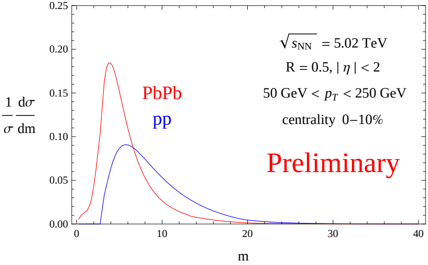
Jet grooming is actually an artificial jet quenching



- It is a controlled way to remove soft radiation
- How does a jet quenching model confront with jet grooming?
  - Do they add up or interfere?
  - Does R_{AA} go up or down?
  - Let's measure groomed jet R_{AA}
- "Can we turn off the recoil contribution?"
  - Yeah, I think we can.

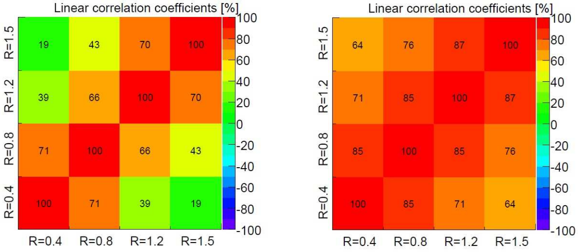
Eventually we want to probe the soft physics





- A consensus of measuring jet mass was formed at Hard Probes
  - Precision jet substructure calculation involves all-order resummation
  - Hadronization affects the position of the peak at small m
  - medium response dramatically shifts the distribution to the right
  - Let's measure jet mass and groomed jet mass

Telescoping jets and observable correlations



- Correlation matrix of jet observables
  - Distinguishing $h \to b\bar{b}$ and $g \to b\bar{b}$
  - Scanning radiations around dominate energy flows dramatically improves the extracting of information in the radiation pattern
  - Lesson: there is huge information hidden in the correlation among jet observables
  - Measuring the modification of the correlation pattern

Discussion

- Radius dependence of R_{AA}
- Tension for the need of medium response
- Flavor dependence of jet quenching and the role of quark/gluon fraction
- The interplay between jet grooming and jet quenching