Fantastic Jet Substructures and Where to Find Them

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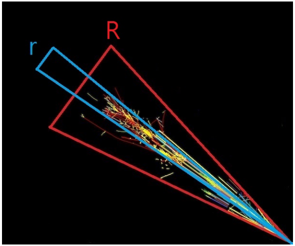
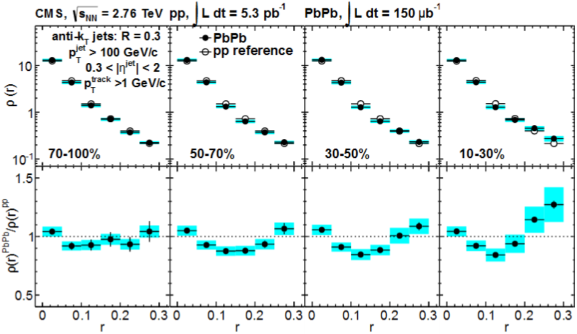
Outline

- "How we can get quantitative information about the QGP from jet measurements"
  - examine heavy ion physics from high to low energy scales
  - stress-testing jet quenching models
  - reliably understand and extract QGP properties
- Tools
  - Jet substructure
  - Jet grooming
  - Hadrons and heavy flavors (not covered in this talk)
- Splitting function
- Bonus: groomed jet mass and telescoping deconstruction
- Conclusions

"Jet spectroscopy" of the QGP





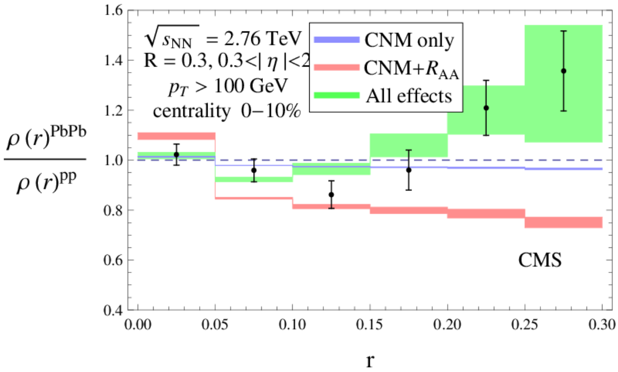
$$\Psi_J(r) = \frac{\sum_{r_i<r} E_{T\,i}}{\sum_{r_i<R} E_{T\,i}}$$

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

$$\rho(r) = \frac{d\langle\Psi\rangle}{dr}$$

- Jets have become essential tools to probe the medium dynamics
- We evaluate the observable modification by the ratio $\frac{\mathcal{O}^{AA}}{\mathcal{O}^{pp}}$
- With detailed understanding of jets and their structures we can relate their modifications to the medium properties: **the need of precise jet substructure studies**

First quantitative understanding of jet shape modification



- Cold nuclear matter (CNM) effect is negligible in jet substructure observables
- Jet quenching increases the quark jet fraction and quark jets are narrower
- Jet-by-jet the shape is broadened
- The same picture holds in jet fragmentation functions

"The devil is in the detail"

- Jets are multi-scaled objects with rich information about the physics across the entire energy spectrum
- Jet observables have different sensitivities to physics at different energy scales
- Through a series of jet measurements we can map out the whole jet formation history
    - Jet substructures are being used to constrain and tune parton shower Monte Carlos

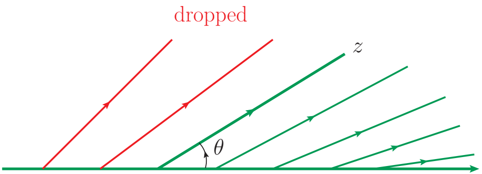
How do we isolate physics and distinguish jet quenching model**s**?

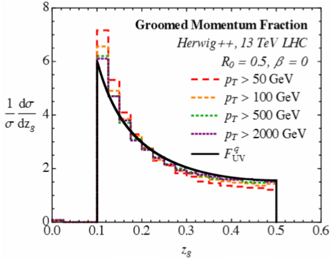
- Whether the model relies on the low scale physics corresponds to two rough pictures of jet quenching
  - Yes. Parton showers are not affected much until the later stages. The medium depletes the partons out of the jet
  - No. The medium effects open up more channels in the jet formation process, all the way from the hard process through hadronization
- Can we test the two pictures and the role of medium response?
  - 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: jet grooming

Jet grooming is actually an artificial jet quenching

- It is a controlled way to remove soft radiation
  - The original motivation is to mitigate radiation contaminations
- How does a jet quenching model confront with jet grooming?
  - Do they add up or interfere?

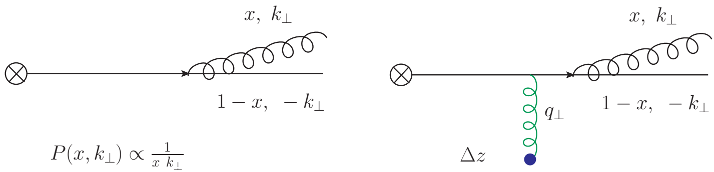
Groomed momentum sharing z_g





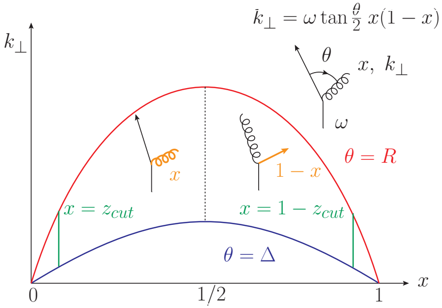
- Soft Drop: a tree-based procedure to drop soft radiation
  - Recluster a jet using C/A algorithm: angular ordered
  - For each branching, consider the p_T of each branch and the angle θ
  - Drop the soft branch if $z < z_{cut}\,\theta^\beta$, where $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}}$
  - CMS used $\beta = 0$, $z_{cut} = 0.1$, $R = 0.4$, $\Delta R_{12} > \Delta = 0.1$ and measured z_g
  - STAR does without the ΔR_{12} cut
- z_g: the momentum fraction of the soft branch. r_g: the angle between the branches

z_g and splitting functions



- In vacuum, the soft branch kinematics is closely related to the Altarelli-Parisi splitting function
- In the medium, the bremsstrahlung component modifies the soft branch kinematics

Analysis of z_g



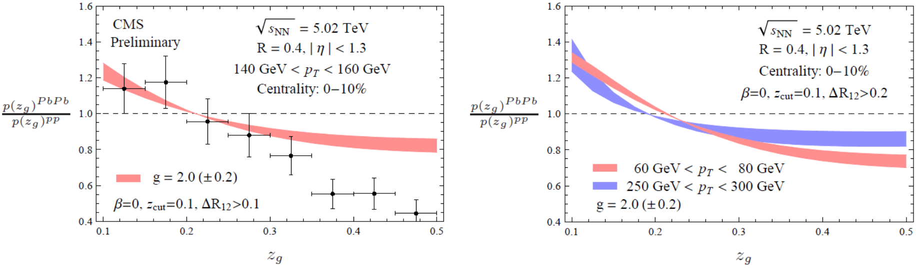
- The partonic phase space is constrained by R, Δ and z_{cut}
- At leading order, the $1 \to 2$ branching probability directly affects the subjet distribution

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

- $\mathcal{P}^{med}_{i\to jl}(x, k_\perp)$ is the medium-induced contribution
- The distributions of z_g and r_g can be constructed where $\overline{\mathcal{P}}(x) = \mathcal{P}(x) + \mathcal{P}(1-x)$

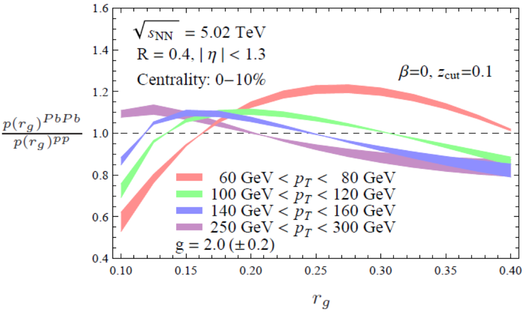
$$p_i(z_g) = \frac{\int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(z_g, k_\perp)}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x, k_\perp)}\,, \qquad p_i(r_g) = \frac{\int_{z_{cut}}^{1/2} dx\, p_T x(1-x) \overline{\mathcal{P}}_i(x, k_\perp(r_g, x))}{\int_{z_{cut}}^{1/2}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

Theory calculation of z_g



- The medium enhances the soft branches, and the effect becomes smaller for higher p_T jets
- Qualitatively expected and quantitatively surprising
- 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
- Calculation for the STAR measurement in progress
  - Jets with lower energies suffer more from non-perturbative effects

Theory prediction for r_g

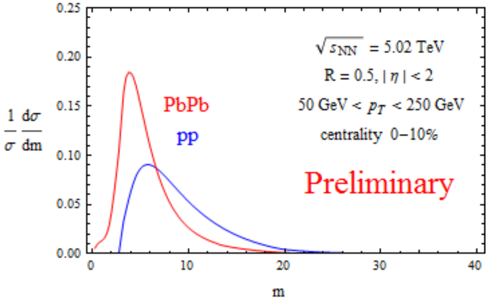


- The subjet angular distribution will reveal the nature of bremsstrahlung with characteristic angular distribution
- It will be a direct probe of the medium scale

Thoughts on z_g and what follows

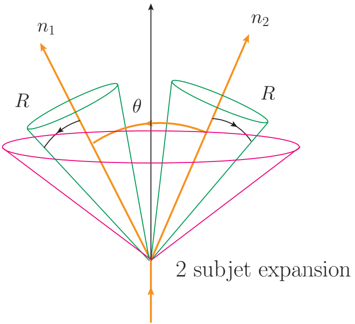
- By construction, soft drop observables are less soft-radiation sensitive
  - Hadronization and non-perturbative effects are suppressed
  - Perturbative tools can hopefully give valuable insights
- Difference between quark and gluon jets suppressed
  - To zeroth order, the color charges cancel!
- Cutting 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
- More considerations: subjet energy loss and broadening
  - $q \to qg$: one quark subjet and one gluon subjet
  - $g \to gg$: two gluon subjets
  - Subjet substructure will reveal subjet flavor difference
  - z_g and r_g distributions with different quark/gluon jet fractions

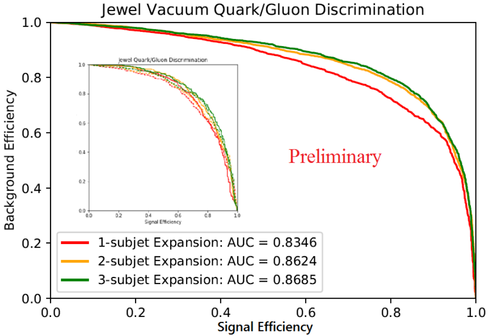
Bonus 1: groomed jet mass distribution



- Jet mass is the classic jet substructure observable
  - Precision jet substructure calculation involves all-order resummation
  - Medium response can dramatically increase the jet mass
  - Groomed jet mass probes soft physics in a controlled way
- Work in progress with Ivan Vitev

Bonus 2: Telescoping deconstruction: a subjet expansion





- Extract the complete information of jets from correlation among jet substructures
  - Telescoping: scanning radiations around dominate energy flows
  - Subjet expansion provides an efficient and complete basis of jet
  - Deep learning techniques are applied to scrutinize heavy ion simulations
- Studying quark/gluon discrimination in JEWEL as a first example (work in progress with Patrick Komiske and Eric Metodiev)

Conclusions

- What we have learned: flavor dependence of jet quenching and the role of quark/gluon jet fraction in jet substructures
- z_g and r_g provides an opportunity to test the modification of hard splitting within jets
- Groomed jet mass allows us to constrain the contributions from medium responses
- Telescoping deconstruction can be a powerful technique in jet quenching studies
- Although not covered in this talk, heavy flavors and hadrons continue to be important probes of the QGP. More correlated measurements welcome.
- The era of precision jet quenching studies has begun!