Telescoping **D**econstruction and **C**ollinear **D**rop

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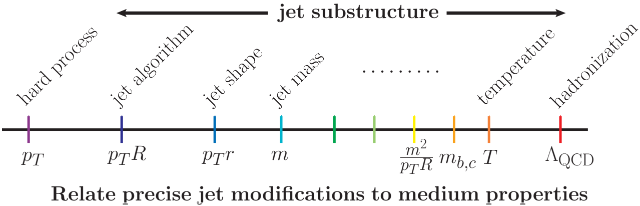
In collaboration with A. Emerman, S.-C. Hsu, S. Meehan, Z. Montague (arXiv:1711.11041)
R. Elayavalli (arXiv:1803.03589), and I. Stewart (to appear soon)

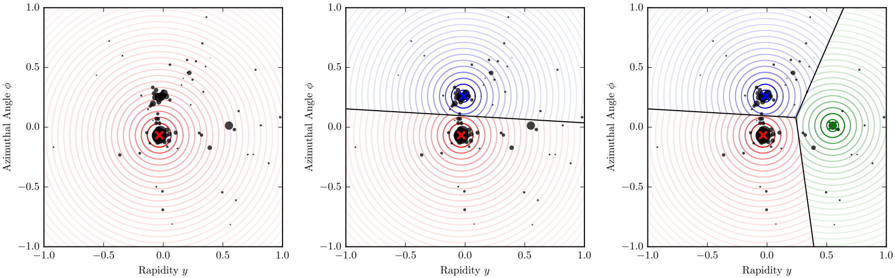
The goals of jet substructure studies



- Heavy ion jet physics: jet physics in $X+Y$ collisions, $X, Y \in \{e, p, A\}$
- The ultimate arena for jet and QCD/SM studies
- Precision is the key

Goals	**TD**	**CD**
Jet grooming	yes	included
Jet-initiating particle tagging	yes	yes
Test the accuracy of the description of soft radiation in MC	yes, →	yes
Test methods of predicting hadronization corrections	yes, →	yes
Illuminate the inner working of Quark-Gluon Plasma	hopefully	hopefully
Goal in the world cup	no	no

Telescoping Deconstruction: a complete subjet fragmentation basis



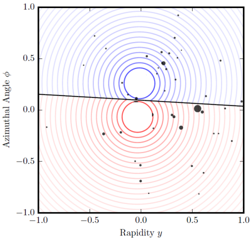
- A fixed-order N subjet expansion with subjet kinematics (p_T, y, ϕ, m)
    - identify dominant energy flow directions using N soft recoil-free axes
    - reconstruct subjets around the axes with multiple subjet radii R_T
    - TD obervables represent *subjet topology* and *subjet substructure*
- Closely related to perturbative expansion and parton shower picture

arXiv:1803.03589, thanks to P. Komiske and E. Metodiev for early stage collaboration

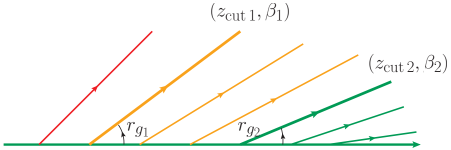
Collinear Drop: veto energetic, collinear particles

- Understanding soft QCD is the goal
- Monte Carlo accuracy limited by soft radiation and hadronization modeling
- Heavy ion medium scale is low
- Want to *directly* probe soft physics by disentangling hard components of jets
- Implementation examples: (i)TD, (ii)soft drop and (iii)flattened angularity

(i) TD



(ii) Two soft-drop settings $z_{\text{cut1}} < z_{\text{cut2}}, \beta_1 \geq \beta_2$



(iii) Flattened angularity

$$\tau_\omega = \sum_{i \in \text{jet}} z_i \, \omega(\theta_i)$$

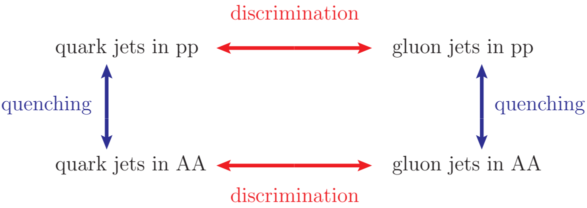
Suppress collinear and wide-angle radiation

$$\omega(\theta) \to 0 \,, \quad \theta \to 0, R$$

With I. Stewart, to appear soon

Use quark and gluon jets to probe heavy ion collisions

Challenge: figure out the air composition and number of tourists at Eiffel tower from this photo.



discrimination

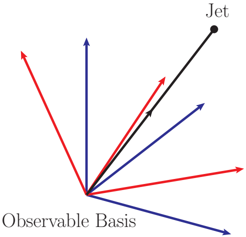
quark jets in pp ⟷ gluon jets in pp

quenching ↕ quenching

quark jets in AA ⟷ gluon jets in AA

discrimination

- Classify quark jets and gluon jets in pp and AA
- Different multivariate techniques suit different jet representations
  - list of physics-motivated observables
  - unbiased and raw input
  - complete basis and expansion
- Modern computation power and deep learning tools help benchmark jet feature identification

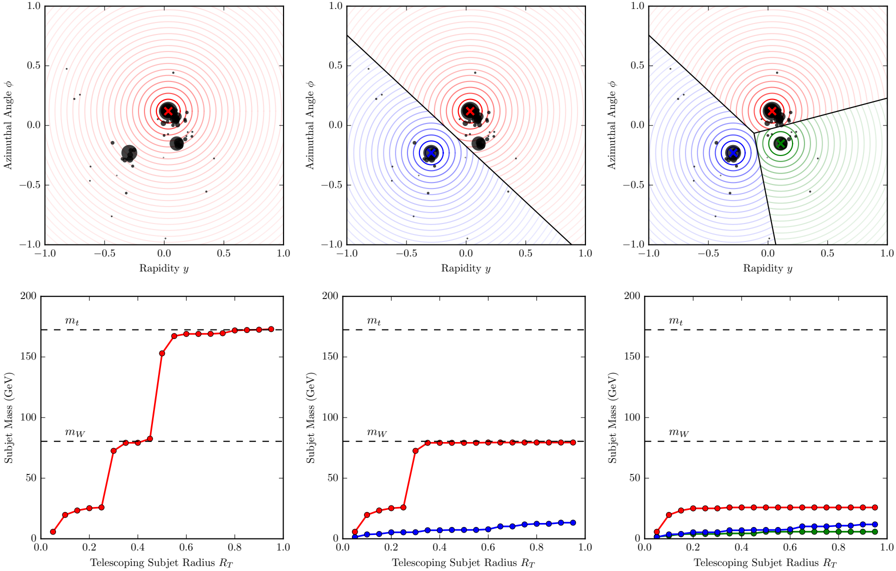


Outline

- Telescoping deconstruction
  - boosted W, top, quark v.s. gluon tagging
  - collinear QCD splitting
  - heavy ion jet modification
- Collinear drop
  - designed for soft physics studies
  - color singlet jet isolation
- Conclusions

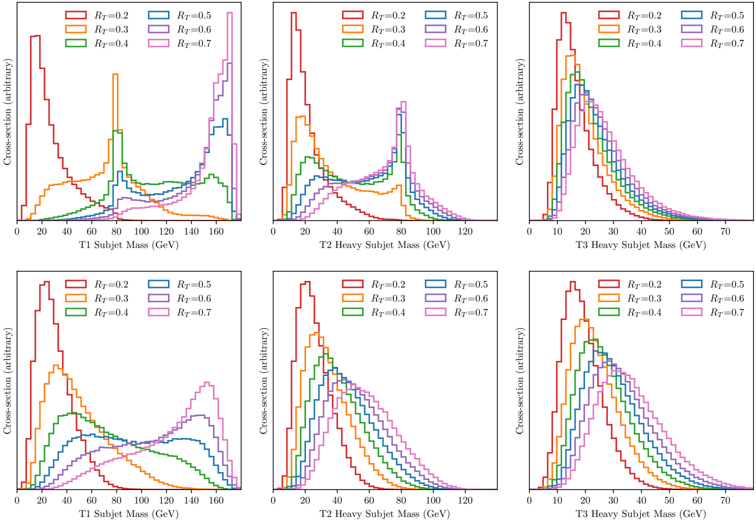
Subjet masses of a top jet, resonance finder

arXiv:1803.03589

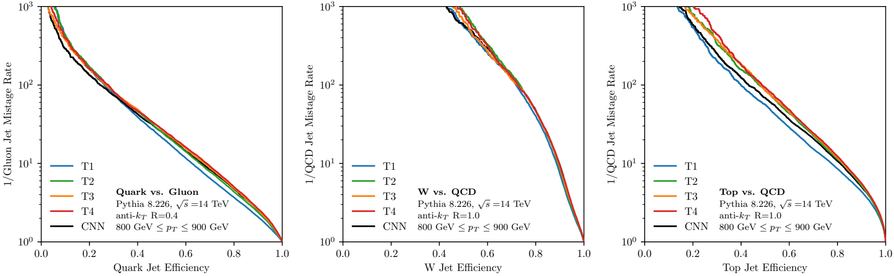


Heavy subjet mass distribution

- Top (top row) v.s. QCD (bottom row)

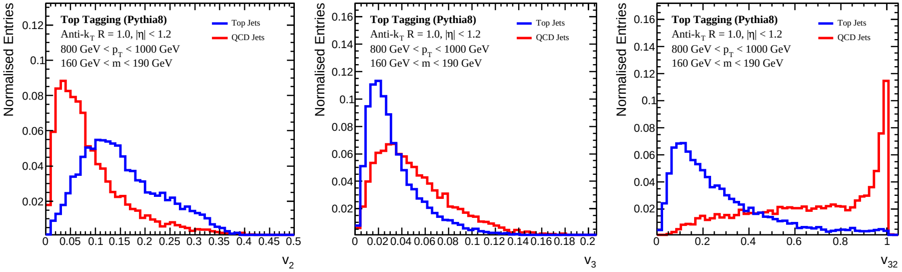


Good performances in multivariate analysis



- TN performances converge quickly to optimal performance
- TD faithfully represents jet information

Variability



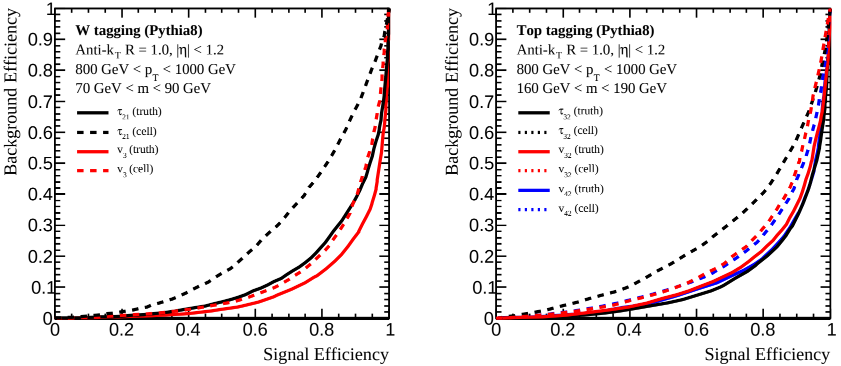
- The variation of the invariant masses $m_N(R_T)$ of the sum of N subjets can be quantified by the *variability*, motivated by the Qjet volatility (Ellis et al).

$$v_N = \frac{\sigma(\{m_N(R_T)\})}{\langle\{m_N(R_T)\}\rangle}$$

- In the case of top tagging, we also consider $v_{N2} = v_N/v_2$ for $N = 3, 4$ to optimize the variability performance, motivated by the N-subjettiness (Thaler et al) and energy correlation function (Larkoski et al) ratios.

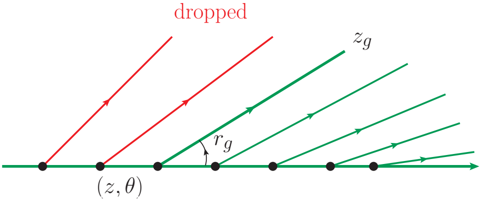
BOOST2015 and arXiv:1711.11041

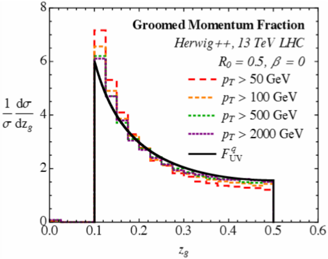
Variability in *W* and top tagging



- v_3 and v_{42} have good performance and are robust against substructure smearing, which is meant to destroy the N-prong structure
- Manifestation of W jet isolation due to its color-singlet nature
    - A dominant feature over the two-prong structure
    - Net color charge: leading-order contribution in multipole expansion

QCD subjet distribution in soft drop





- Tree-based procedure to drop soft radiation (Larkoski et al)
    - 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 $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}}$
- z_g: the momentum fraction of the soft branch. r_g: the angle between the branches

Telescoping subjet topology (z, θ)

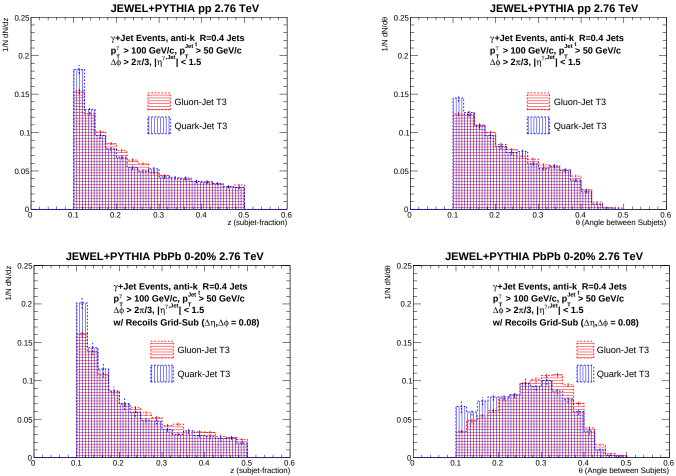
arXiv:1803.03589

- Enhancement of soft, wide angle radiation in AA (simulated with Jewel (Zapp et al))

z θ

pp

AA

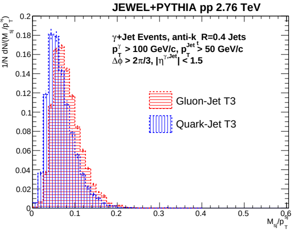


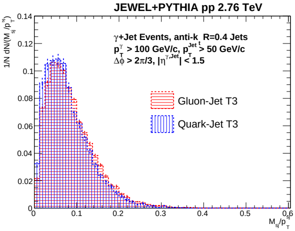
Telescoping subjet substructure m

- Reveal subjet flavor dependence in first splitting $q \to qg$ and $g \to gg$ using $m^{\mathrm{sub}}/p_T^{\mathrm{sub}}$

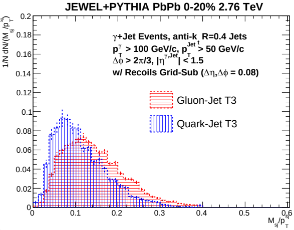
Hard Subjet

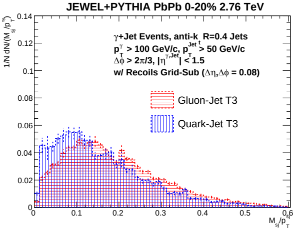
Soft Subjet





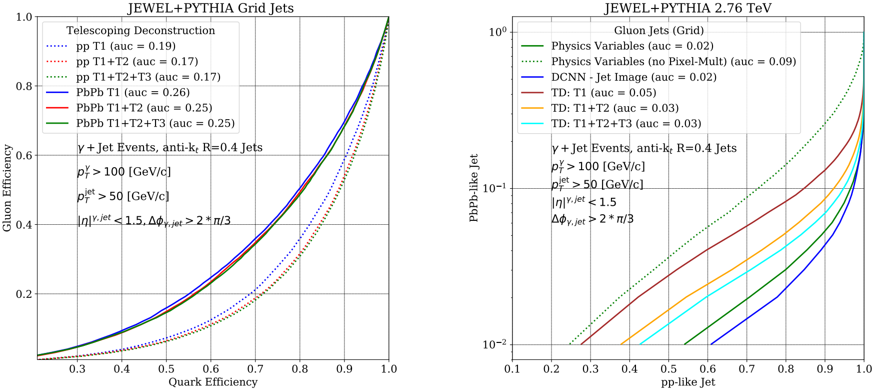
pp





AA

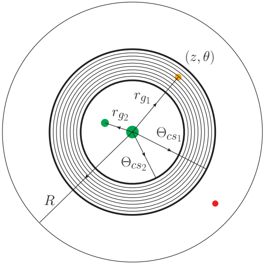
Quark gluon jet classification in pp and AA

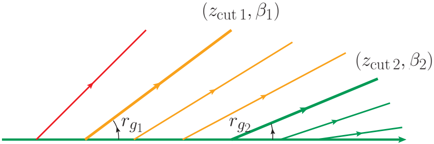


- Quark/gluon discrimination performance drops in JEWEL-simulated AA collisions
- Information contained in subleading subjets is washed out
- Pixel multiplicity is the dominant feature distinguishing pp and AA jets

Collinear drop

One example of a CD observable can be constructed using a Soft Drop + an Anti Soft Drop





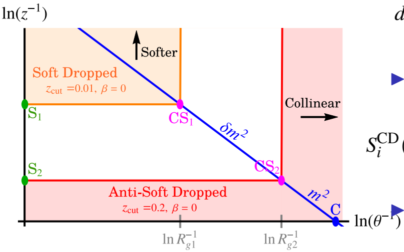
- Consider $\delta m^2 = m^2_{\text{SD}_1} - m^2_{\text{SD}_2}$ to quantify the radiation distribution within the “ring"
  - TD version: $\delta m^2 = m^2(r_2) - m^2(r_1)$ where $r_2 > r_1$ (BOOST2015)
  - Difference of angularities, event shapes are not CD observables
- Contributions from collinear radiation to soft-drop jet mass cancel

$$m^2_{\text{SD}_\text{i}} \sim p_c^2 + 2E_J n\cdot p_{cs_i}\ , \qquad \delta m^2 \sim 2E_J n\cdot (p_{cs_1} - p_{cs_2})$$

- Phase space constraints on the kinematics of soft emissions,

$$z\theta^2 \approx \frac{\Delta m^2}{E_J^2}\ , \qquad z_{\text{cut}\,1}\left(\frac{\theta}{R_0}\right)^{\beta_1} \lesssim z \lesssim z_{\text{cut}\,2}\left(\frac{\theta}{R_0}\right)^{\beta_2}$$

Factorization and resummation of δm^2 using SCET

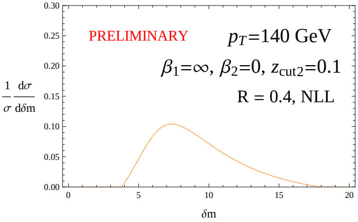


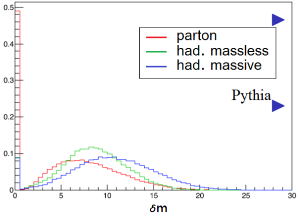
$$\frac{d\sigma}{d\delta m^2} = \sum_{i=q,g} N_i(\mu) J^{\rm SD}_{{\rm un},i}(z_{{\rm cut}\,2},\beta_2,\mu) S_i^{\rm CD}(\delta m^2, z_{{\rm cut}\,i},\beta_i,\mu)$$

- If two soft-drop conditions are hierarchically separated, collinear-soft sector can be further factorized

$$S_i^{\rm CD}(\delta m^2,\mu) = \int dk_i \overline{S_{C_2,i}}(k_2,\mu) S_{C_1,i}(k_1,\mu)\delta(\delta m^2 - 2E_J(k_1+k_2))$$

- Using SCET renormalization group techniques we can resum δm^2





- Massless hadrons are constructed using the p-scheme
- Significant hadronization correction is seen. Addressed in future work.

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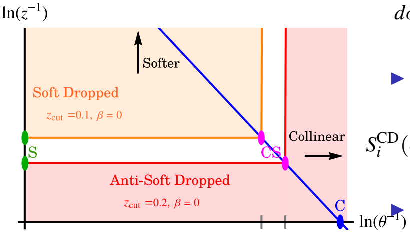

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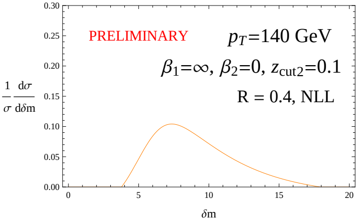

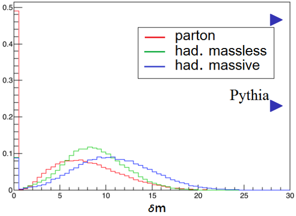

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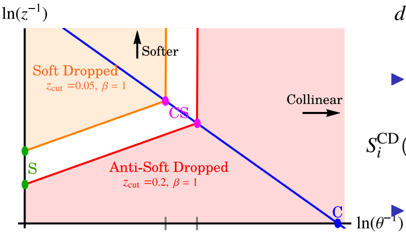

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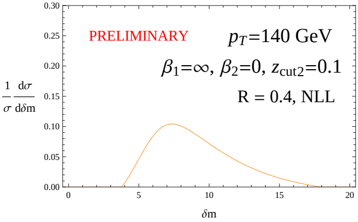

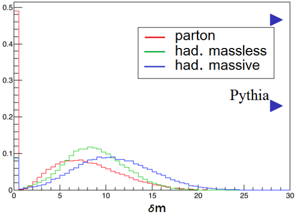

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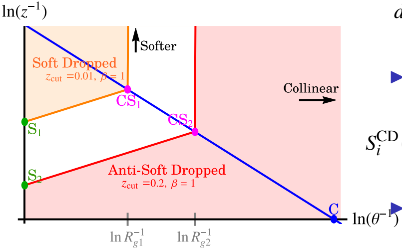

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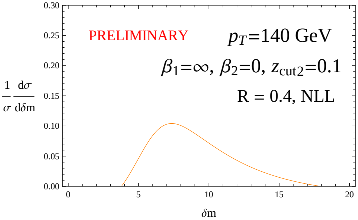

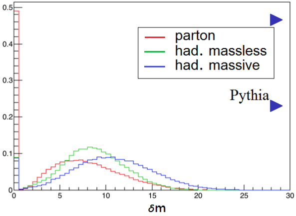

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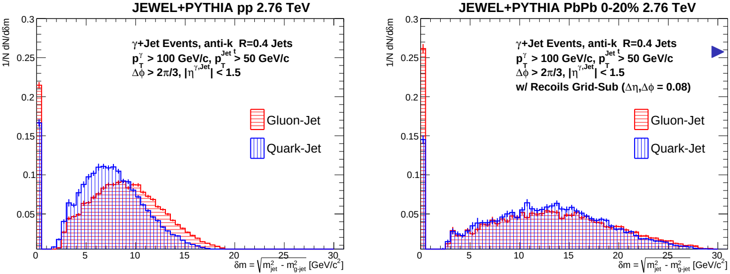
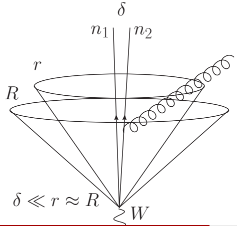
Collinear-drop in heavy ion and *W* jet isolation



- Quark/gluon jet difference disappearing in JEWEL-simulated AA collisions



- In the boosted regime, $\delta \approx m_W/p_T \ll 1$
- At $\mathcal{O}(\alpha_s)$,

$$\frac{d\sigma}{d\delta m^2} = \delta^2 \frac{\alpha_s C_F}{\pi \delta m^2} \frac{R^2 - r^2}{R^2 r^2}\ , \text{ power suppressed by } \delta^2$$

- Key difference between *W* and QCD jets: net color charge (also seen in Jet Lund plane (F. Dreyer))

Conclusions

- Telescoping deconstruction is a systematic framework for jet studies
    - Can be easily extended to event-level studies
- Collinear-drop class of observables allows one to directly probe soft physics in Jets
    - studying hadronization in Jets and testing MC
    - studying the effect of the jet on the soft medium in heavy ion
    - discrimination studies
- Heavy ion jet modification can be comprehensively studied as a classification problem
- W jet isolation is identified as a dominant feature of boosted W jets