# Spectral Analysis of Jet Substructure with Neural Network: Boosted Higgs Case

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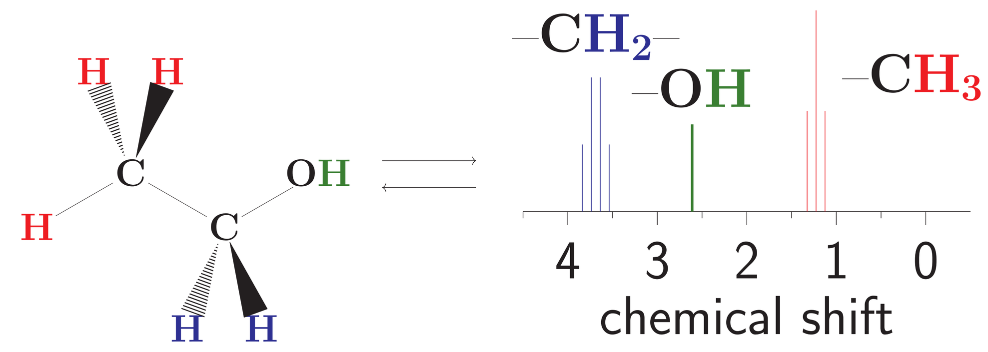
## Analogy of Jet Substructures and Organic Molecules

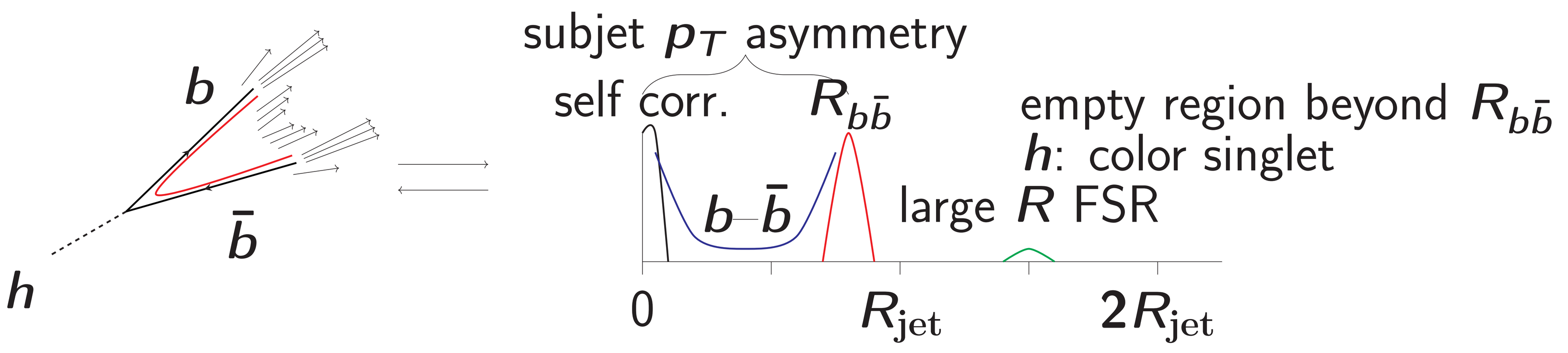
- $^1$H-NMR is a successful example of spectral analysis of molecular substructures.




- The perturbative description of jets is analogous to organic molecules.

| Spectral analysis | $^1$H-NMR spectroscopy $\longrightarrow$ ?? |
|---|---|
| Primary geometry | Carbon skeleton $\longrightarrow$ partons from the decay |
| Observables | Hydrogen $\longrightarrow$ hadronized particles |

- Can we build a similar analysis framework of jet substructures?




## Definition of a Spectral Function

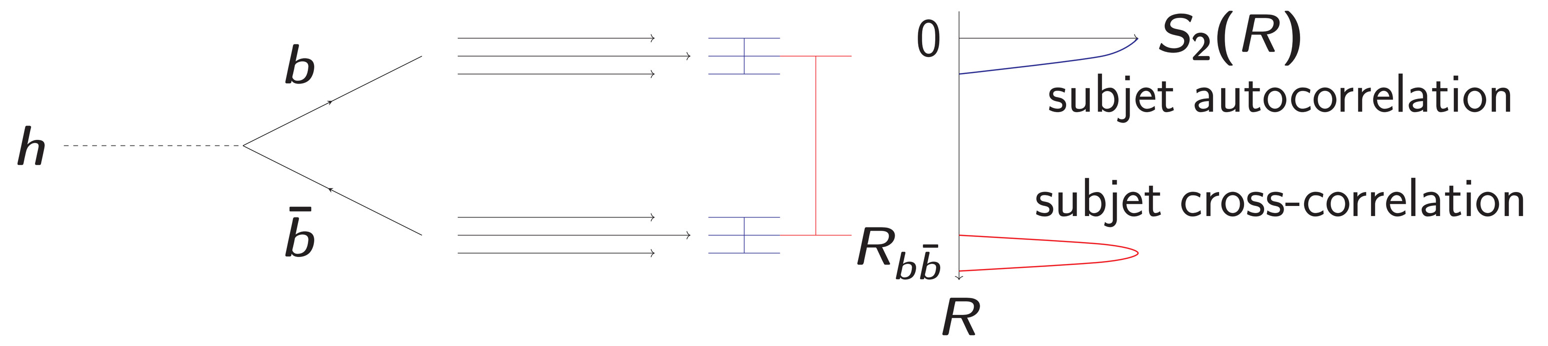
- We define an IRC safe binned spectral function,

$$S_2(R;\Delta R) = \frac{1}{\Delta R} \sum_{\substack{i,j \in \mathrm{jet} \\ R_{ij} \in [R, R+\Delta R)}} p_{T,i} p_{T,j}.$$

- In a continuum limit, where the bin width $\Delta R \to 0$, $S_2(R;\Delta R)$ turns into

$$S_2(R) = \int_{\vec{R}_i,\vec{R}_j \in \mathrm{jet}} d\vec{R}_i d\vec{R}_j \; P_T(\vec{R}_i) P_T(\vec{R}_j) \cdot \delta(R - R_{ij}).$$

- This spectral function observes two-point correlations in a jet at an angular scale $R$.

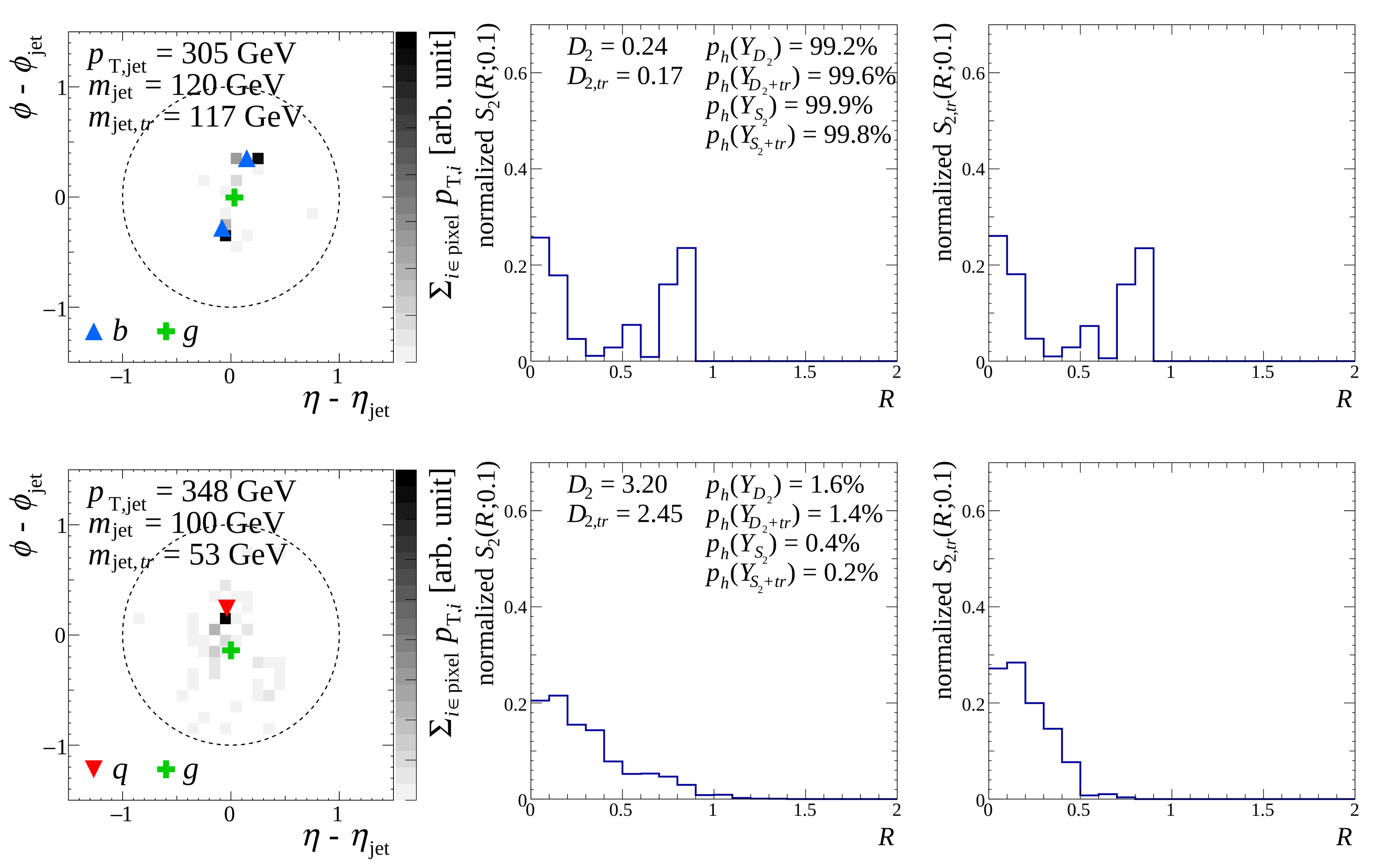



- The $S_2(R)$ spectrum is IRC safe because soft or collinear radiation does not introduce additional angular scale.
- The $S_2(R)$ spectrum is constrained by kinematics.

$$\int_0^\infty dR\, S_2(R) = \left(\sum_{i \in \mathrm{jet}} p_{T,i}\right)^2, \quad \int_0^\infty dR\, R^2 S_2(R) = \sum_{i,j \in \mathrm{jet}} p_{T,i} p_{T,j} R_{ij}^2.$$

- $S_2(R)$ measures contribution to $p_{T,\mathrm{jet}}^2$ from pairs of jet constituents at a particular relative angle $R$.
- $R^2 S_2(R)$ measures contribution to $m_{\mathrm{jet}}^2$ from the pairs at the angle $R$.

## Example: a Typical Higgs Jet and a Typical QCD Jet

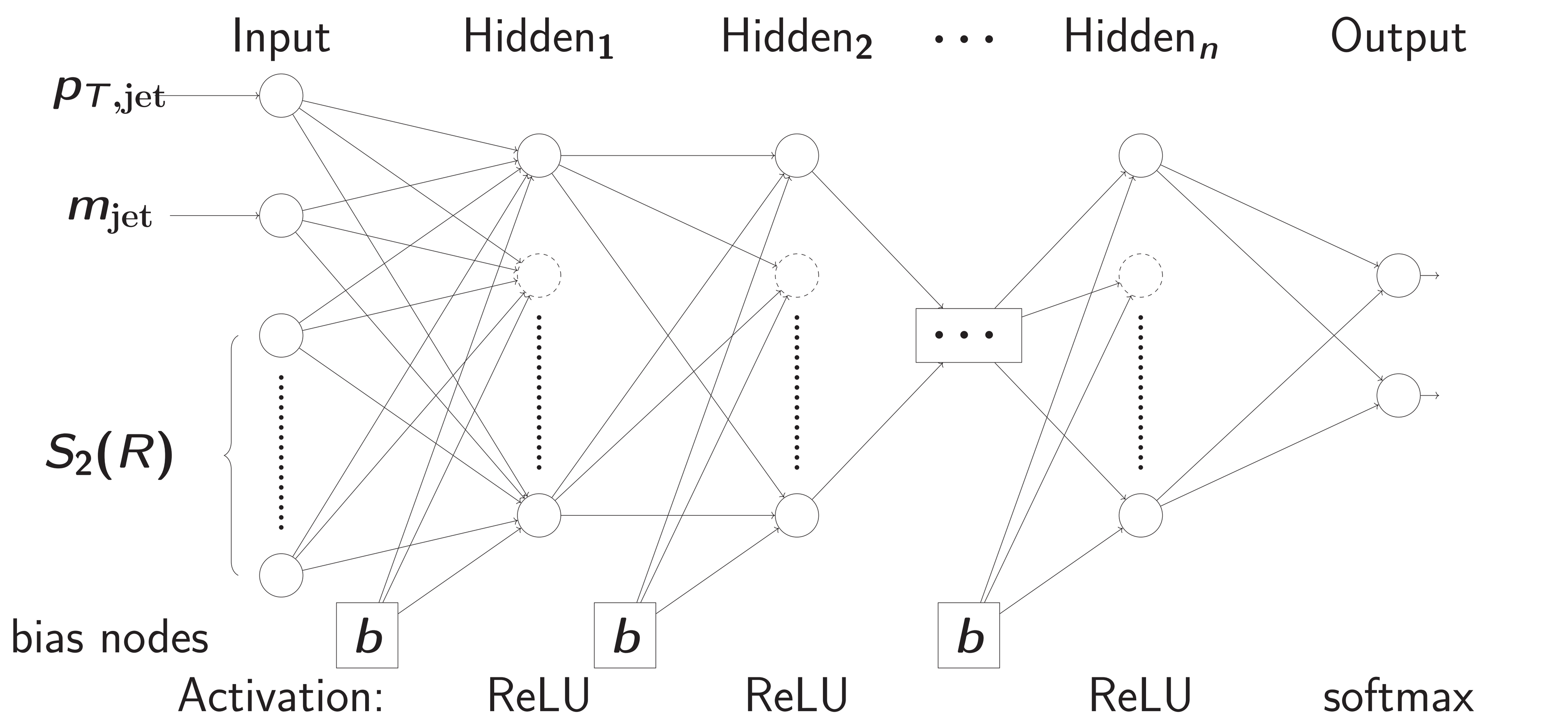



- Higgs jets are two-prong jets with angular scale $R_{b\bar{b}}$. Hence, $S_2(R)$ has two peaks at $R = 0$ and $R = R_{b\bar{b}}$,

$$S_2(R) = (p_{T,b}^2 + p_{T,\bar{b}}^2)\delta(R) + 2 p_{T,b} p_{T,\bar{b}} \delta(R - R_{b\bar{b}}).$$

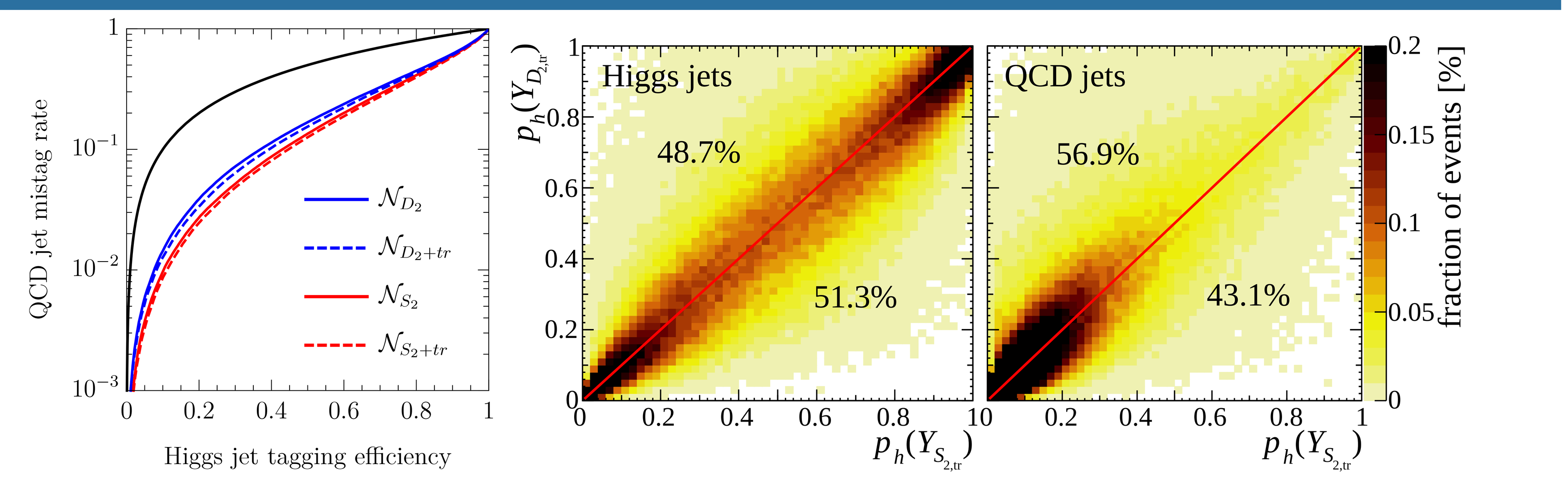
- Jet trimming helps differentiating hard and soft jet substructures.

## Spectral Analysis with an Artificial Neural Network



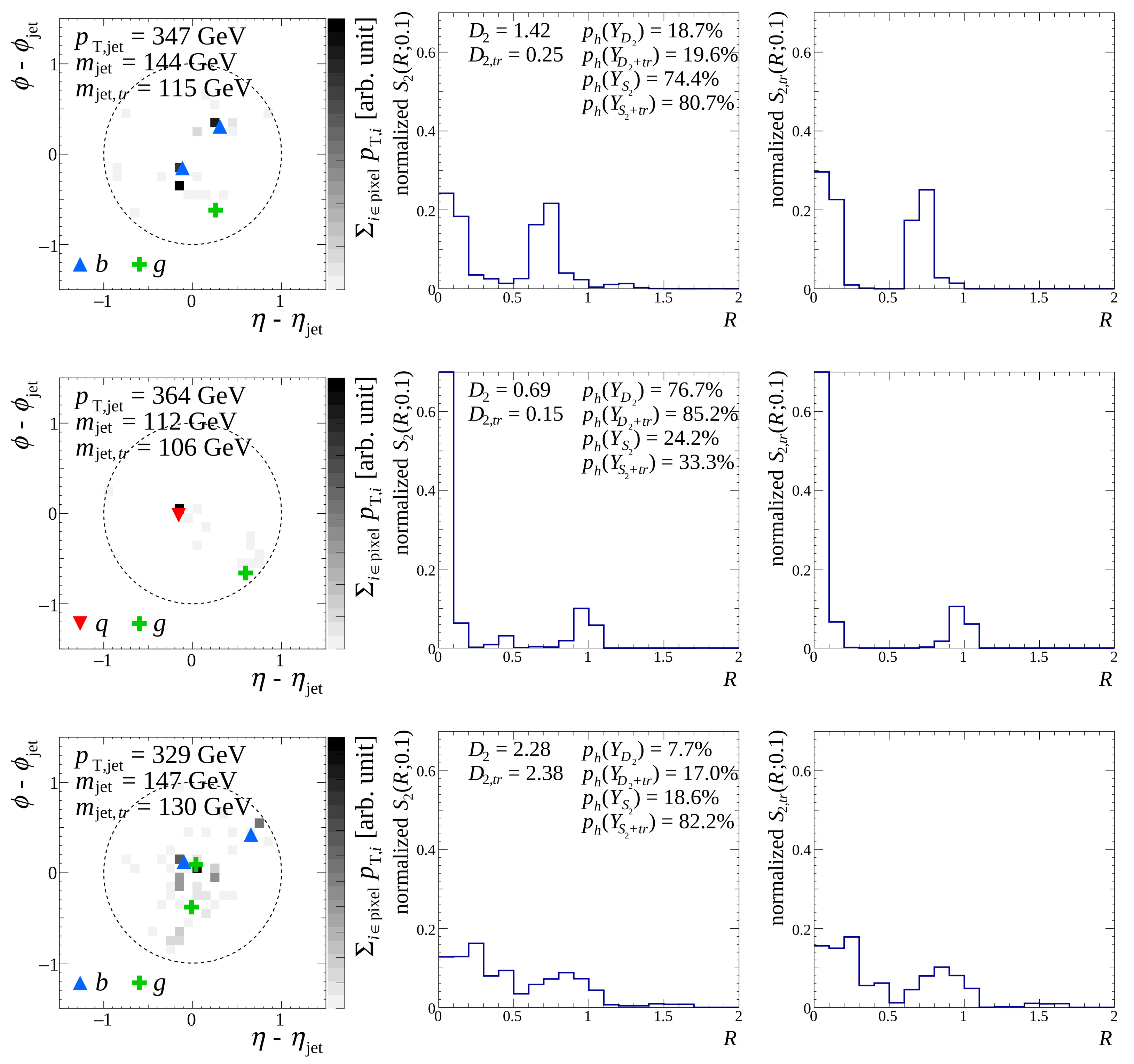

- Inputs for $S_2(R)$ analysis
  - $\mathcal{N}_{S_2}$ : $\{x_i\}_{S_2} = \{p_{T,\mathrm{jet}}, m_{\mathrm{jet}}, S_2(0;0.1), \cdots, S_2(1.9;0.1)\}$
  - $\mathcal{N}_{S_2+tr}$ : $\{x_i\}_{S_2+tr}$ $= \{x_i\}_{S_2} \cup \{p_{T,\mathrm{jet},tr}, m_{\mathrm{jet},tr}, S_{2,tr}(0;0.1), \cdots, S_{2,tr}(1.9;0.1)\}$
- Inputs for $D_2$ analysis
  - $\mathcal{N}_{D_2}$ : $\{x_i\}_{D_2} = \{p_{T,\mathrm{jet}}, m_{\mathrm{jet}}, D_2^{\beta=2}\}$
  - $\mathcal{N}_{D_2+tr}$ : $\{x_i\}_{D_2+tr} = \{x_i\}_{D_2} \cup \{p_{T,\mathrm{jet},tr}, m_{\mathrm{jet},tr}, D_{2,tr}^{\beta=2}\}$

## ROC curve and Correlation between the Taggers




- $\mathcal{N}_{S_2+tr}$ improves signal and background ratio $S/B$ from $\mathcal{N}_{D_2+tr}$.

## More Examples




## Conclusion

- $\mathcal{N}_{S_2}$ and $\mathcal{N}_{S_2+tr}$ can learn non-local correlations in jets from the spectrum.
- $\mathcal{N}_{S_2}$ discriminates between boosted Higgs jets and QCD jets with better performance compared to $\mathcal{N}_{D_2}$.
- Introducing trimming to $S_2(R)$ further helps to separate hard and soft substructures, and the ANN with trimmed observable outperforms the ANN without trimming.
- The $S_2(R)$ has information on multi-point correlations and is easily applicable to other jet substructures.

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