Jet Substructure observables for jet quenching

presented by

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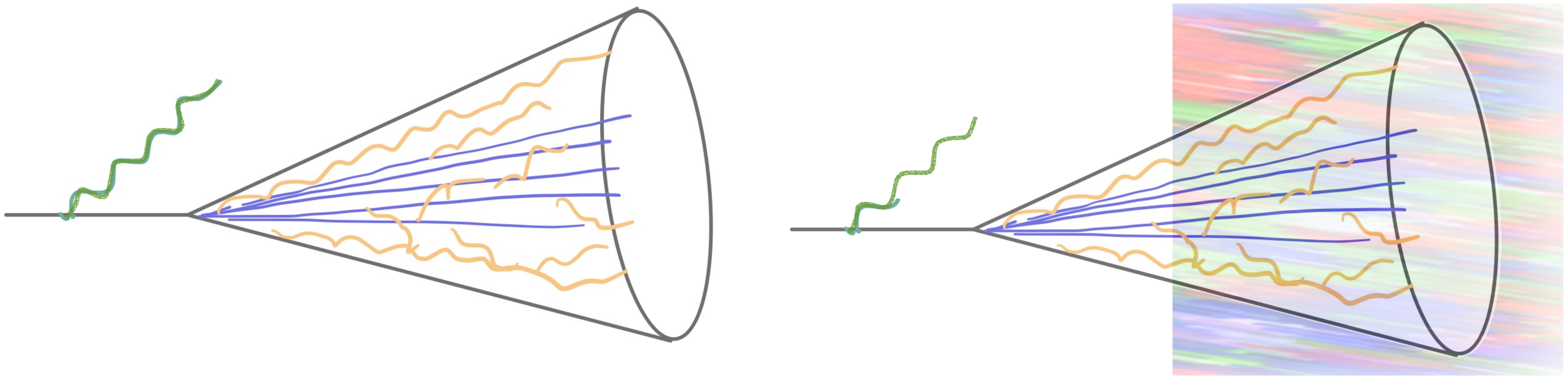
Based on: **arXiv: 2304.07196**

Jets in vacuum vs matter

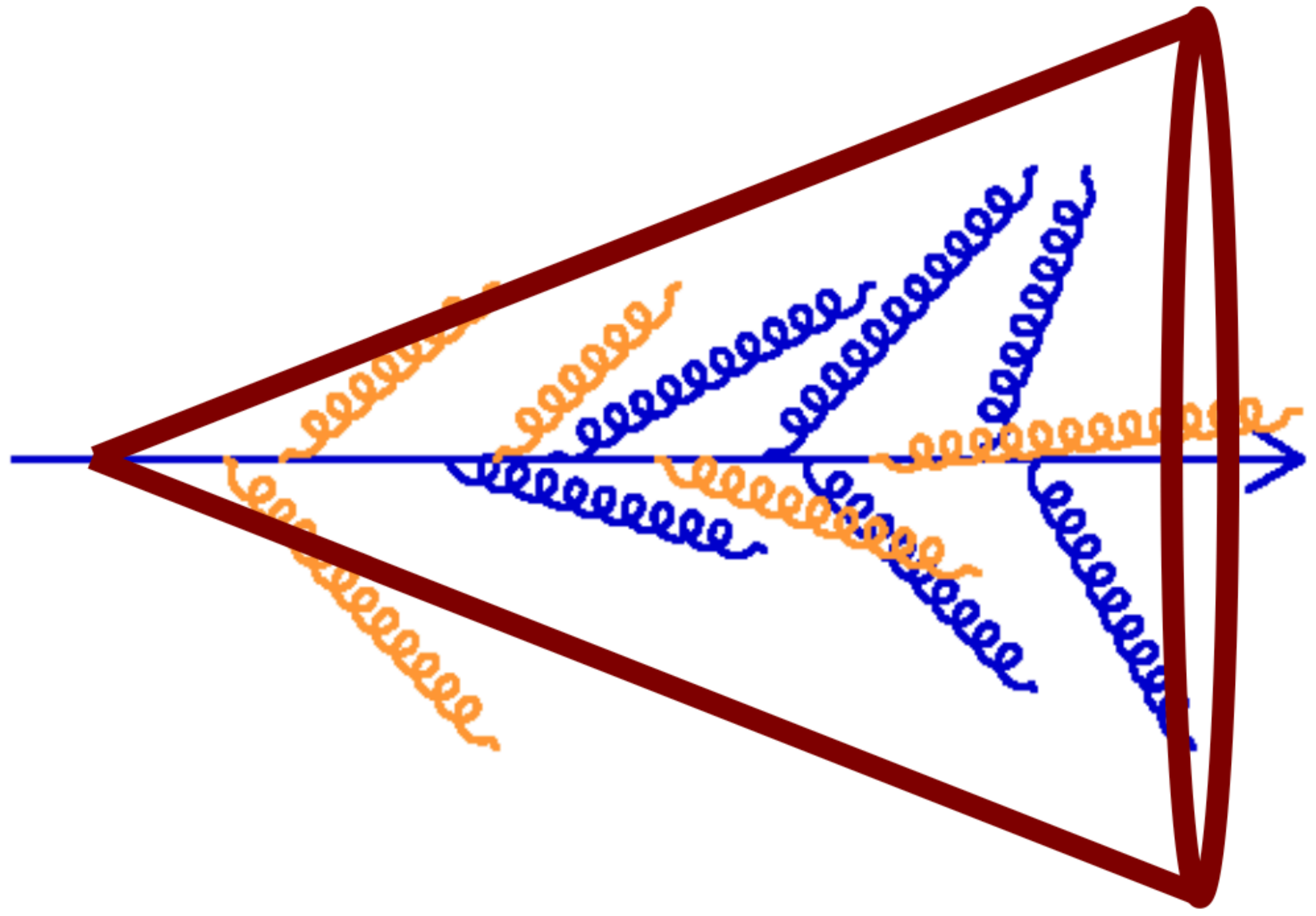


What happens when the jet passes through a hot QGP medium/ How is the parton shower being modified due to interactions with the medium patrons ?

How to use this information to decipher the properties of the medium ?

Jet Quenching

- How is the parton shower modified ?
- What are the underlying mechanisms ?
- Can this modification be related to the properties of the medium ?



Tool : Jet substructure techniques, use JEWEL+PYTHIA for event generation

main goal: survey jet observables to identify the ones most sensitive to quenching effects.

Jet Substructure Observables

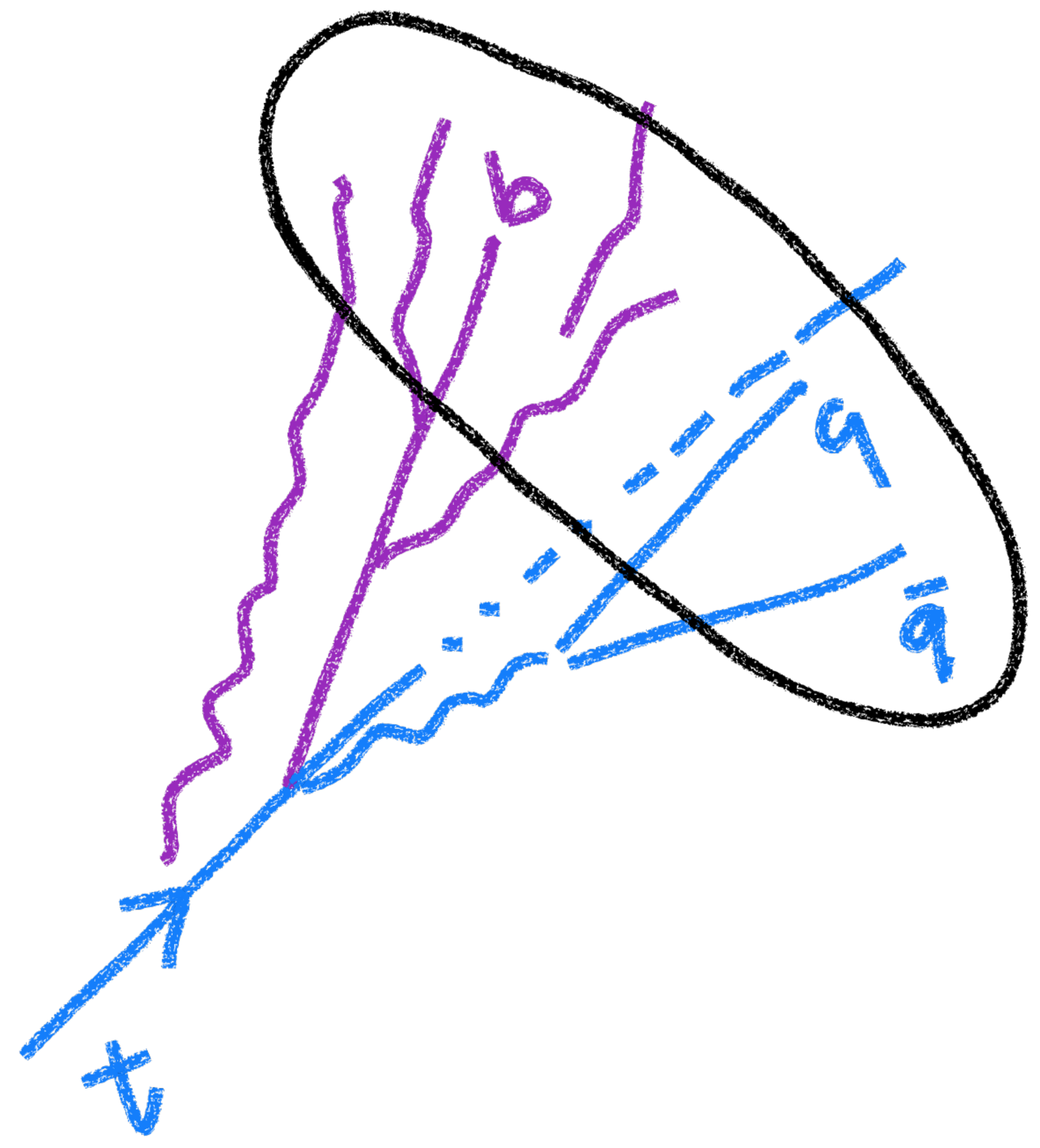
- Angularities

$$\lambda_\beta^\kappa = \sum_{i \epsilon \text{jet}} z_i^\kappa R_{i,\text{jet}}^\beta$$

  - $\kappa = 1$ for IRC safety, $\beta = 1$ (broadening) and $\beta = 2$ (thrust).
  - Allows to smoothly understand the behaviour of soft-to-collinear emission in the jet through varying exponent β.

- N-subjettiness

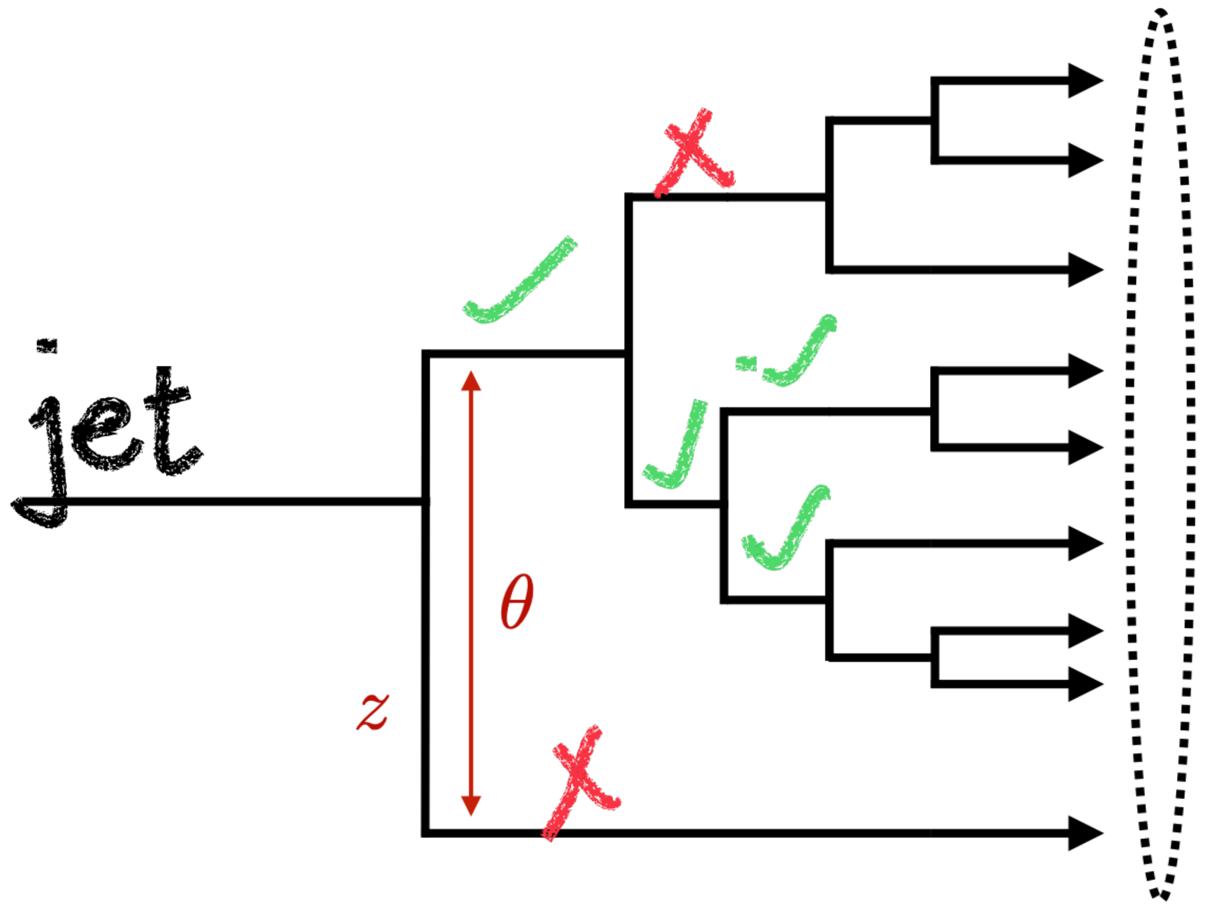
$$\tau_N = \frac{\sum_{i\,\epsilon\,\text{jet}} p_T^i \min(R_{1,i}, \ldots, R_{N,i})}{R_0\, p_{T,\text{jet}}}$$



  - Measures how similar a given jet is to an object composed of N subjets.
  - Small values of τ_N correspond to being more N-subjet like.

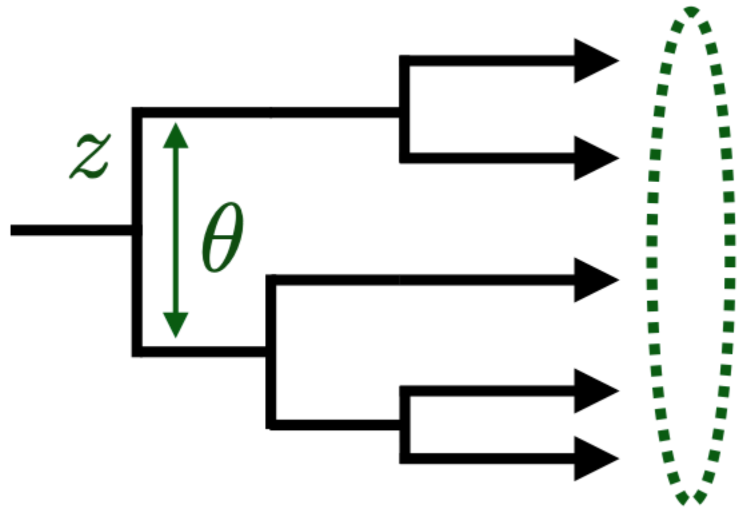
Jet Grooming Algorithms

- Soft-drop Grooming



$$z > z_{\text{cut}} \left(\frac{\theta}{R}\right)^{\beta}$$

Stop



$R_g = \theta$ of emission that passes

- Dynamical grooming

$$\kappa^{(a)} = \frac{1}{p_{T,jet}} \max_{i \,\epsilon\, \text{C/A seq}} \left| z_i(1 - z_i) p_{T,i} \left(\frac{R_{i,j}}{R_0}\right)^{a} \right|$$

TimeDrop (TD)

$t_f^{-1} \sim \kappa^{(2)} p_T$

kt-Drop (ktD)

$k_T \sim \kappa^{(1)} p_T$

z-Drop (zD)

most symmetric splitting

Observables for this talk

2304.07196

Observables	Type
$r\,z_{\rm SD} = \lambda^1_{1,\rm SD}$ $r^2\,z_{\rm SD} = \lambda^1_{2,\rm SD}$	Angularities
$\tau_{2,\rm SD}\,,\,\tau_{3,\rm SD}$	N-subjettiness
$\Delta p_{T,\rm SD} = p_{T,\rm jet} - p_{T,\rm jet_{SD}}$	Jet momenta
$R_{g\,,\,\rm TD}\;R_{g\,,\,\rm ktD}\,,\,R_{g\,,\,\rm zD}$ $\kappa_{\rm TD}\;\kappa_{\rm ktD}\,,\,\kappa_{\rm zD}$	Dynamical grooming based

- **Note** : most of/all these observables are defined over the groomed jet constituents, except for $(\Delta p_T)_{\rm SD}$ which also needs the information of the ungroomed jet transverse momentum.

Principal Component Analysis

- Identify main directions of the dataset that explain the most variance $\Rightarrow$ **Principal components**

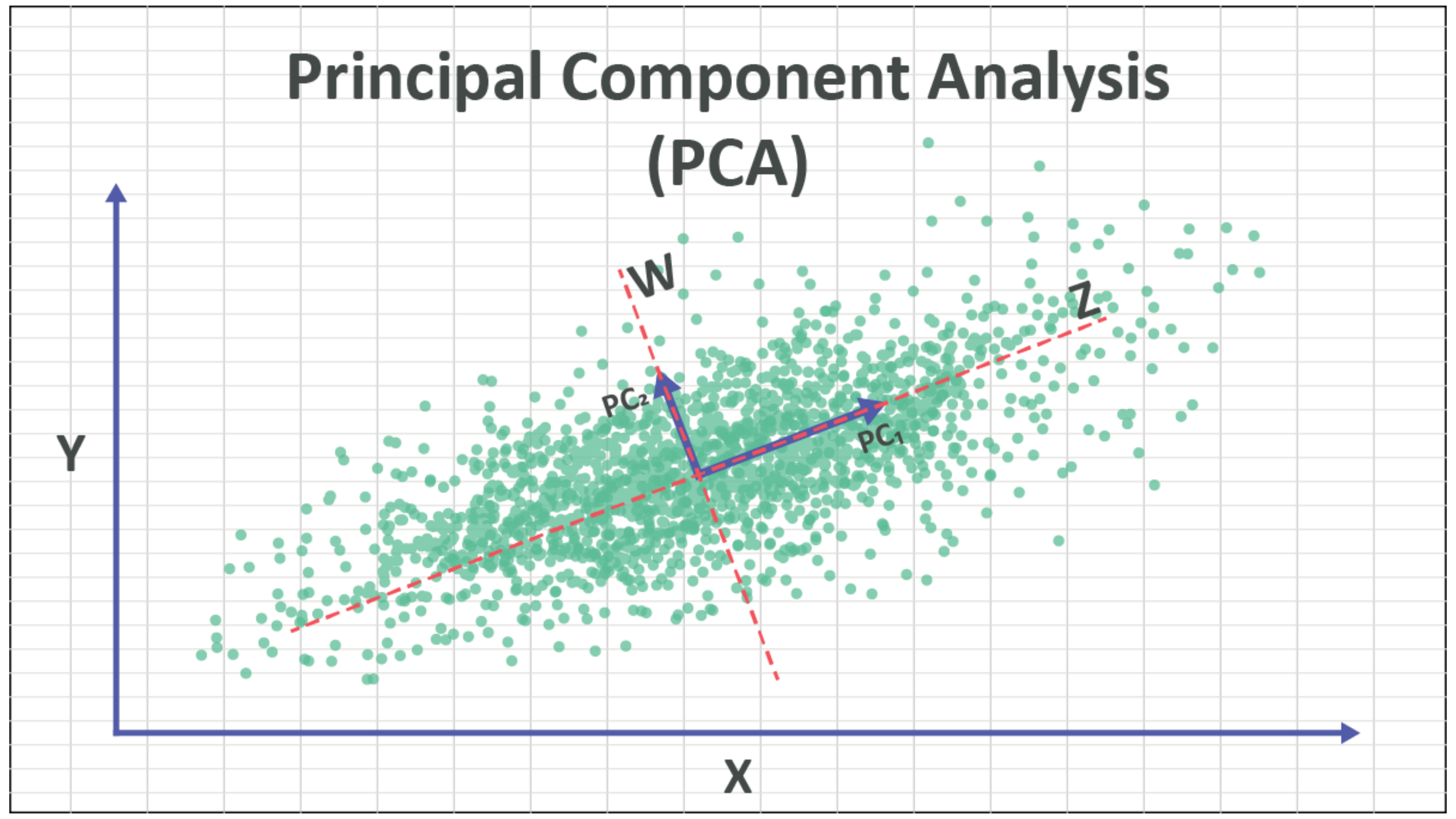
- To assess the quality of reconstruction, compute

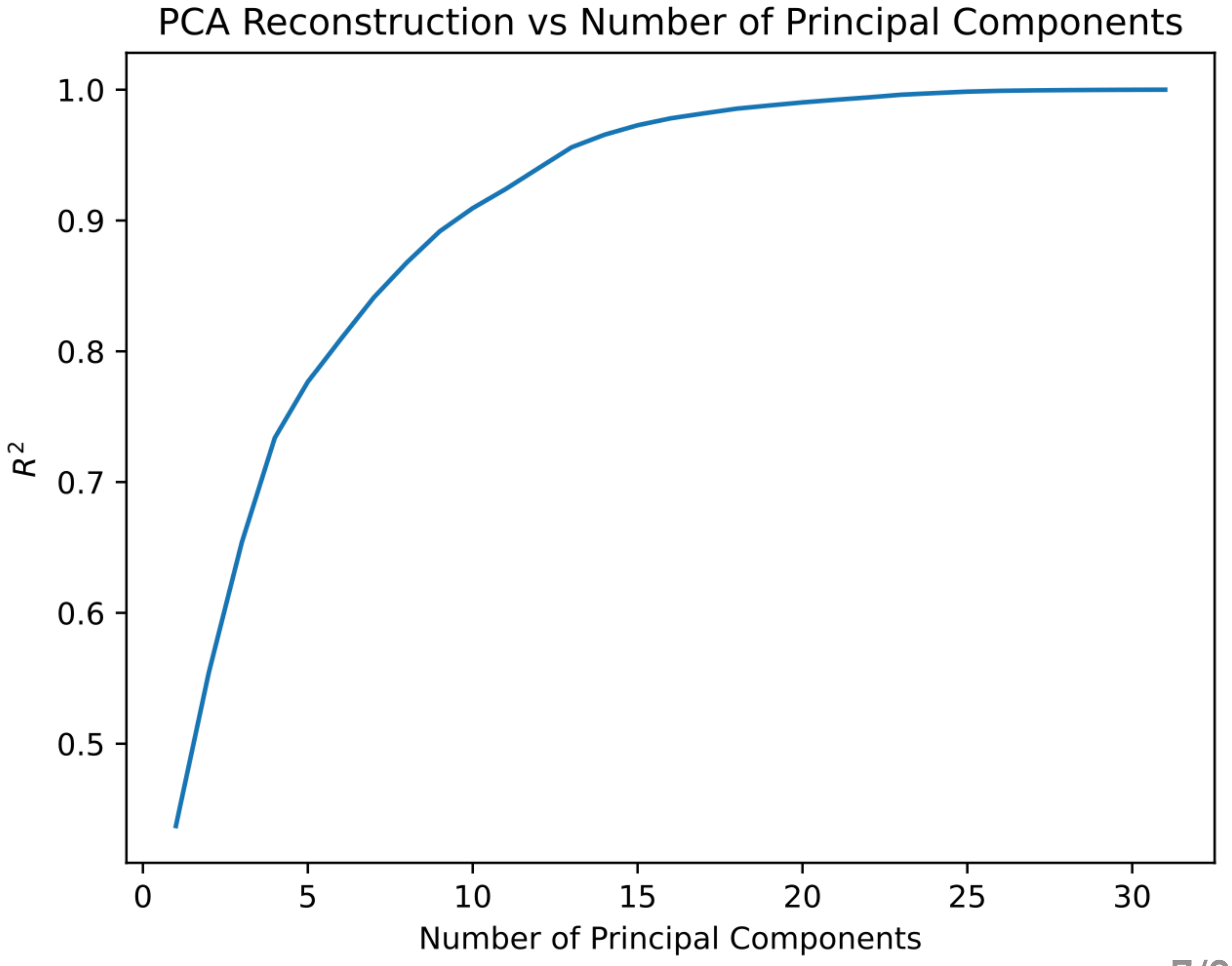
$$R^2(x, \hat{x}) = 1 - \frac{\mathbf{E}[||x - \hat{x}||^2]}{\mathbf{E}[||x - \mathbf{E}[x]||^2]}$$

x - vector of observables and $\hat{x} = \mathbf{V} \cdot \mathbf{V}^{\mathbf{T}} \cdot x$ are the reconstructed x after rotating into principal components.

- $R^2 \sim 0 \Rightarrow$ only the average value of each observable is predicted.
  $R^2 \sim 1 \Rightarrow$ a perfect reconstruction.

- Most of the relations between observables already described by the first $5 - 10$ principal components.





Unquenched Sample

Main directions of the principal components

	R_g	$(\Delta p_T)_{SD}$	$Q^{0.3}_{SD}$	$Q^{0.5}_{SD}$	$Q^{0.7}_{SD}$	$Q^{1.0}_{SD}$	$mass_{SD}$	$\bar{r}_{SD}$	$\bar{r}^2_{SD}$	$\bar{z}^2_{SD}$	$n_{const,SD}$	ϕ_{SD}	p_TD_{SD}	r^2z_{SD}	y_{SD}	rz_{SD}	$\tau_{2,SD}$	$\tau_{2,1,SD}$	$\tau_{3,SD}$	$\tau_{3,2,SD}$	$R_{g,TD}$	$R_{g,ktD}$	$R_{g,zD}$	κ_{TD}	κ_{ktD}	κ_{zD}	n_{SD}	z_g	$z_{g,TD}$	$z_{g,ktD}$	$z_{g,zD}$
1	0.25	-0.17	-0.02	-0.05	-0.07	-0.10	0.24	0.25	0.24	-0.14	0.24	0.00	-0.20	0.25	-0.00	0.26	0.25	0.04	0.25	0.17	0.05	0.13	0.24	0.23	0.25	0.18	0.16	0.06	0.19	0.13	0.02
2	-0.04	-0.01	-0.32	-0.38	-0.40	-0.39	-0.03	-0.05	-0.09	-0.23	0.06	0.00	-0.20	-0.11	0.00	-0.07	0.02	0.32	0.02	0.19	-0.09	-0.12	-0.10	-0.16	-0.13	-0.11	0.21	-0.17	-0.09	-0.05	-0.04
3	-0.10	0.02	-0.23	-0.23	-0.21	-0.17	-0.03	-0.07	-0.08	0.09	-0.08	-0.00	0.06	-0.02	0.00	0.00	-0.09	-0.31	-0.09	-0.10	-0.16	-0.18	0.00	0.00	0.07	0.34	-0.17	0.43	0.22	0.35	0.31
4	-0.09	-0.03	0.32	0.30	0.24	0.13	-0.03	-0.06	-0.13	-0.30	0.07	0.00	-0.25	-0.11	0.00	-0.03	0.02	0.23	0.03	0.25	-0.28	-0.32	-0.08	-0.18	-0.09	0.15	0.18	0.11	0.11	0.27	0.18
5	-0.08	0.38	0.11	0.05	-0.02	-0.10	-0.06	-0.09	-0.05	-0.18	-0.02	-0.01	-0.16	0.02	-0.00	-0.02	-0.01	0.10	-0.02	0.05	0.57	0.26	-0.13	0.13	0.02	0.10	0.06	0.19	-0.22	-0.06	0.46
6	-0.00	0.01	-0.00	0.00	0.00	0.00	-0.00	0.00	0.00	-0.00	-0.00	0.67	-0.00	0.00	0.74	0.00	0.00	0.00	0.00	-0.00	0.00	0.00	-0.00	0.00	0.00	-0.00	0.00	0.00	-0.00	-0.00	0.01
7	-0.00	0.01	0.00	0.00	-0.00	-0.00	0.00	-0.00	-0.00	-0.00	0.00	-0.74	-0.00	-0.00	0.67	-0.00	-0.00	-0.00	-0.00	0.00	-0.01	0.01	0.01	0.00	0.00	-0.00	0.01	0.01	0.01	-0.00	-0.02
8	0.11	-0.38	-0.06	-0.02	0.02	0.06	-0.04	0.10	0.10	0.11	-0.03	-0.02	0.10	0.04	0.01	0.04	0.16	0.17	0.11	-0.21	-0.13	0.03	-0.29	-0.07	-0.07	0.05	-0.15	-0.32	-0.01	-0.11	0.66
9	0.06	-0.37	-0.07	-0.02	0.02	0.07	-0.03	0.06	0.06	-0.05	-0.08	-0.01	0.08	0.02	0.01	0.02	-0.01	0.00	-0.02	0.06	0.53	-0.45	0.05	-0.02	-0.06	0.05	-0.13	-0.07	-0.37	0.38	-0.11
10	0.08	-0.22	-0.12	-0.03	0.05	0.11	-0.01	0.06	0.02	-0.47	-0.21	0.00	0.07	-0.10	0.00	-0.06	-0.29	-0.02	-0.26	0.43	-0.04	0.27	0.03	0.09	0.09	0.06	-0.40	-0.05	0.13	-0.13	0.02

- 1st principal component - mostly angularity type observables
- 2nd principal component - jet charges
- 3rd principal component - groomed momentum sharing $z_g^{\prime}s$
- 6th and 7th principal component - uncorrelated observables like rapidity and azimuth

Quenched Sample

- Use principal component coefficients of the unquenched sample to compute R^2 on the quenched sample. Allows to estimate the effect of quenching.

R^2 differences between Unquenched and Quenched

No. of Principal Components	$(\Delta p_T)_{SD}$	$r^2\, z_{SD}$	$r\, z_{SD}$	$\tau_{2,SD}$	$\tau_{3,SD}$	$R_{g,TD}$	$R_{g,ktD}$	$R_{g,zD}$	κ_{TD}	κ_{ktD}	κ_{zD}
1	0.14	0.12	0.04	-0.02	0.00	0.04	0.16	0.12	0.13	0.08	0.10
2	0.14	0.04	0.01	-0.01	0.01	0.04	0.14	0.05	0.05	0.02	0.11
3	0.14	0.05	0.01	0.00	0.02	0.08	0.16	0.05	0.05	0.03	0.14
4	0.14	0.02	0.00	0.01	0.03	0.15	0.15	0.04	0.06	0.03	0.07
5	0.31	0.02	0.00	0.01	0.03	0.07	0.07	0.04	0.05	0.03	0.05

- R^2 difference provides information about how well the relations are explained in the presence of quenching.

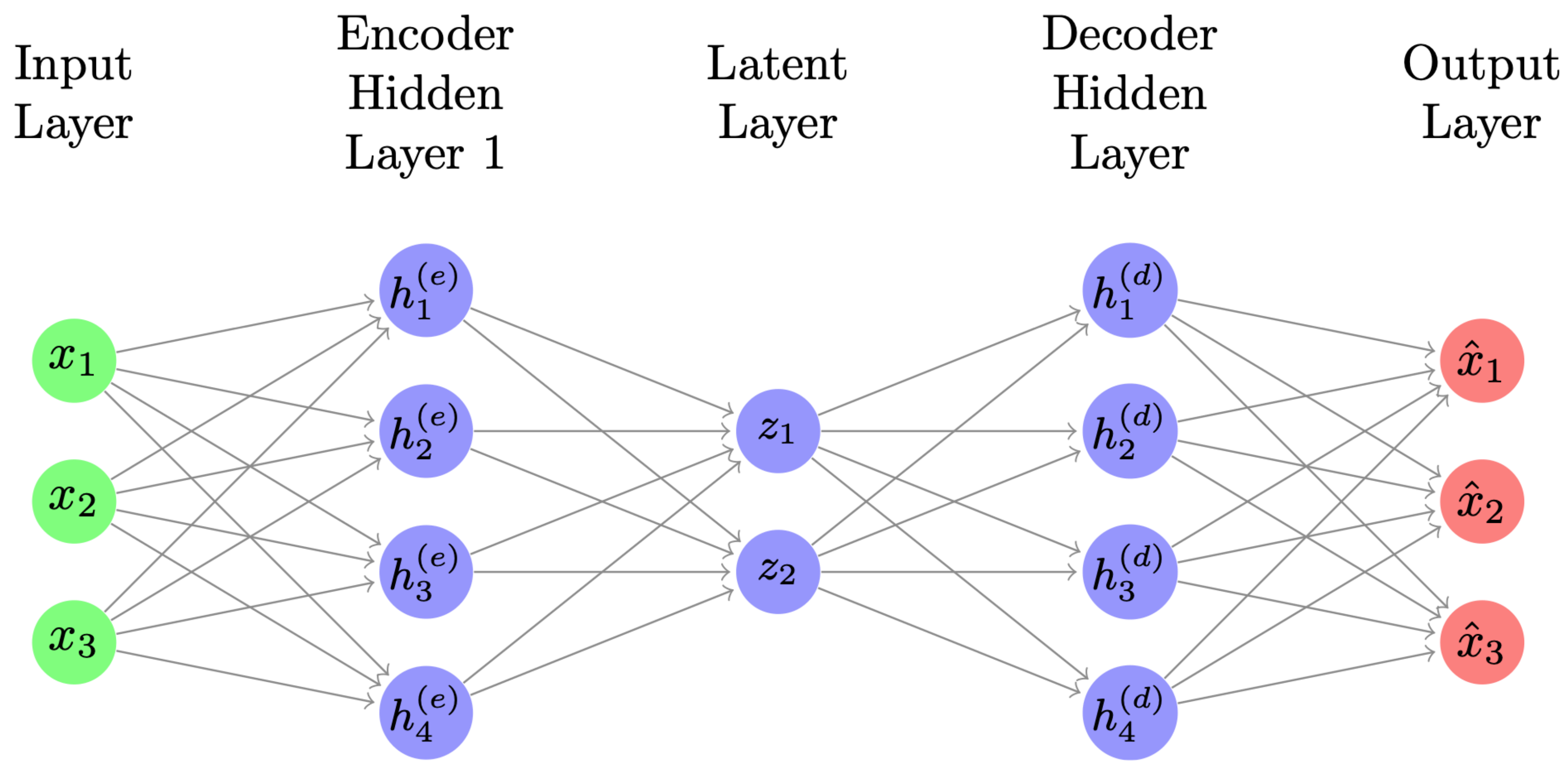
- Close to 0 being perfect reconstruction (not sensitive to quenching).

- Remarkably, this suggests that what is learnt in pp allows for very good predictions of most observables in AA.

- Large deviations for $(\Delta p_T)_{SD}$ and dynamic grooming observables.
- Also somewhat large values also for angularities.

} Potential candidates for identifying quenching effects.

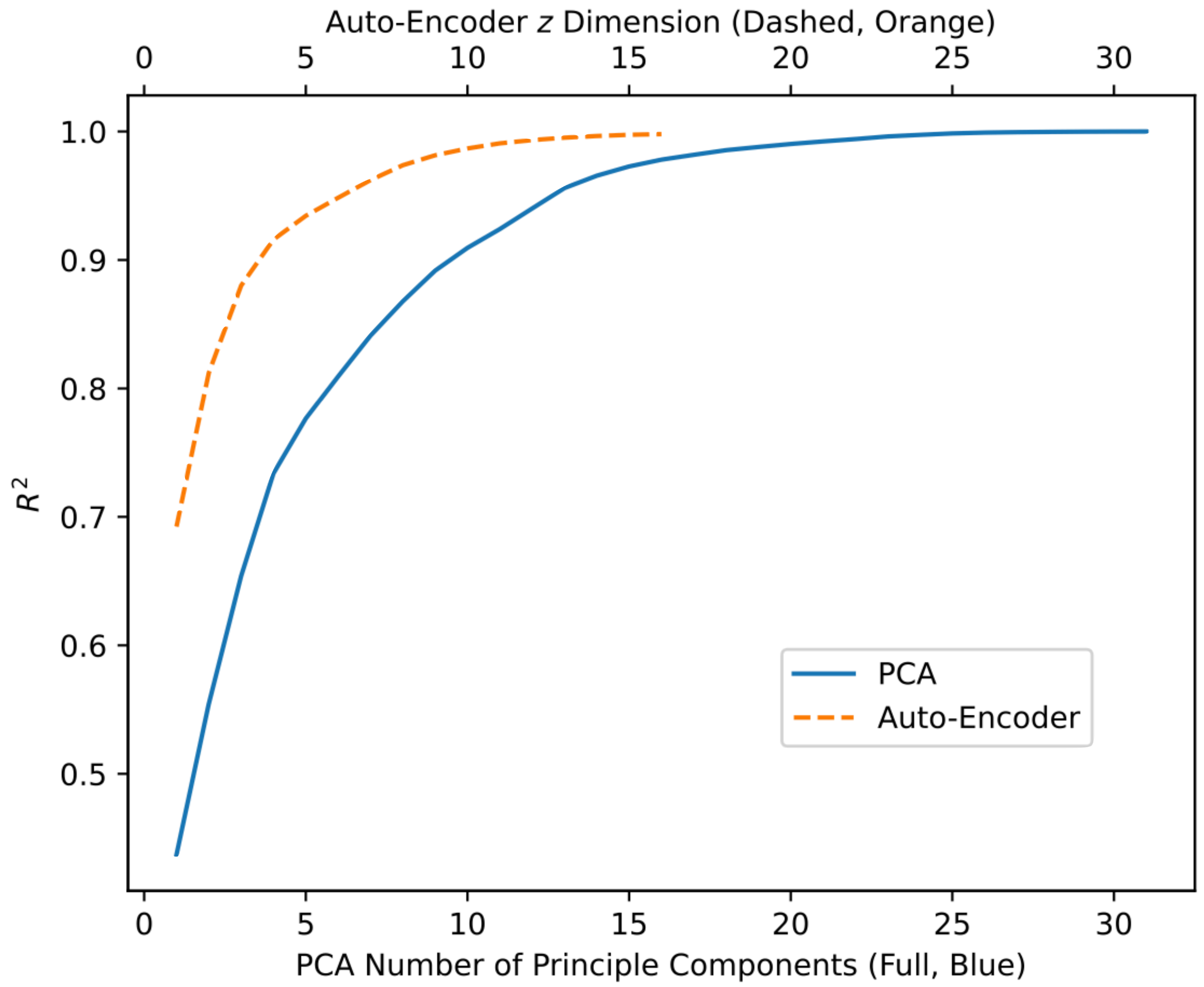
Auto-Encoder Analysis



- Optimize the non-linear maps implicit in the AE.

- R^2 increases faster, i.e. one needs fewer degrees of freedom to explains the relations between jet observables.

- With only 5 degrees of freedom, about 90 % of the relations are explained.



Quenched Sample

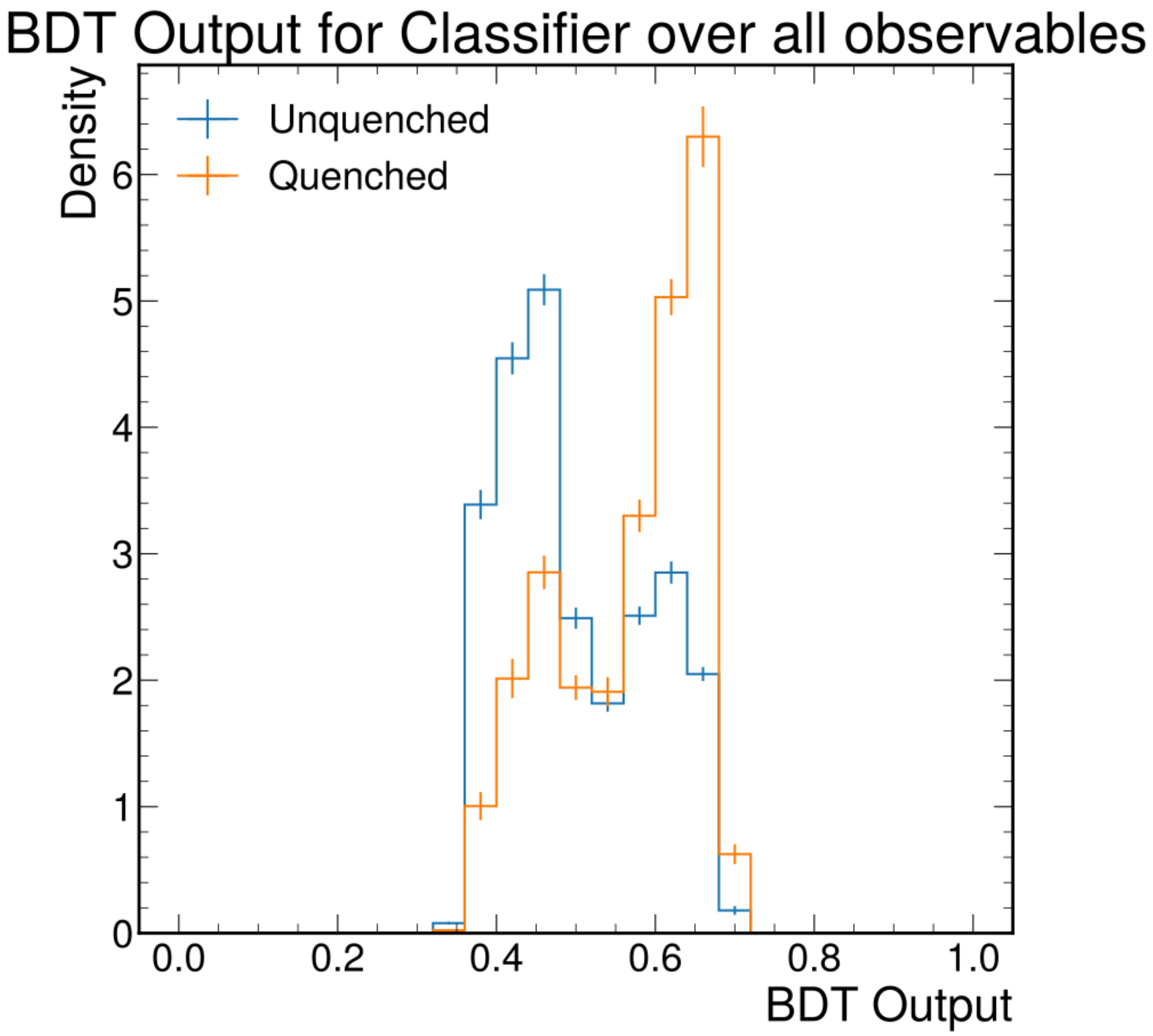
R^2 differences between Unquenched and Quenched

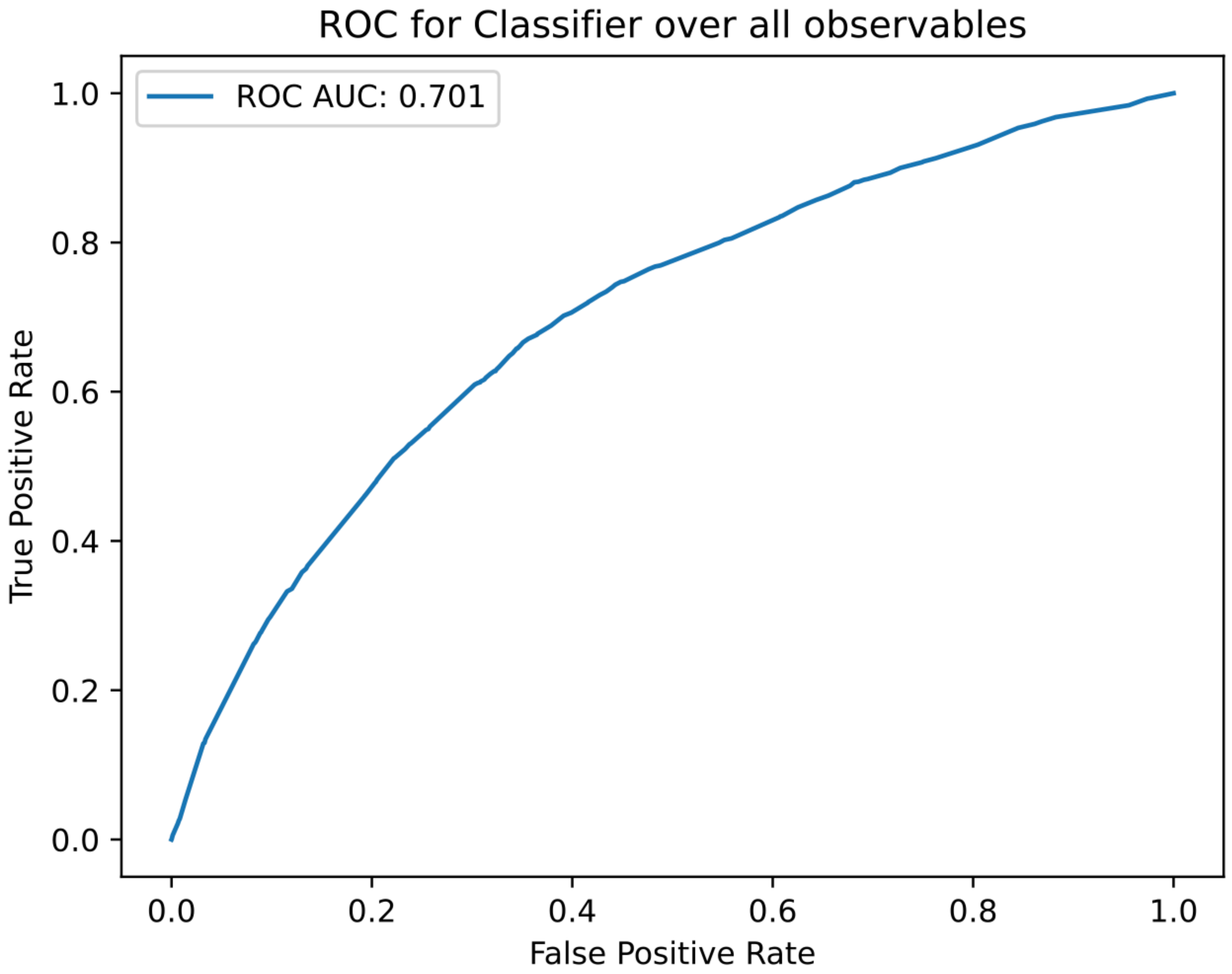
z dimensions	$(\Delta p_T)_{SD}$	$r^2 z_{SD}$	$r z_{SD}$	$\tau_{2,SD}$	$R_{g,ktD}$	$R_{g,zD}$	κ_{TD}	κ_{ktD}	κ_{zD}	$\tau_{3,SD}$	$R_{g,TD}$
1	0.17	-0.00	0.02	0.02	0.18	0.05	0.03	0.03	0.12	0.02	0.17
2	0.15	0.00	0.02	0.01	0.09	0.05	0.02	0.03	0.07	0.01	0.15
3	0.09	0.00	0.02	0.01	0.06	0.03	0.02	0.03	0.06	0.00	0.07
4	0.05	0.00	0.01	0.00	0.03	0.02	0.02	0.02	0.04	0.00	0.03
5	0.03	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.00	0.02

- Observables for R^2 changes most due to presence of medium are $R_{g,\mathrm{ktD}}$, $R_{g,\mathrm{TD}}$, $(\Delta p_T)_{\mathrm{SD}}$, κ_{zD}
- Interestingly, these differences are only sizeable for a small number of z dimensions.
- Suggests that relations between some of the observables very similar in quenched and unquenched jets, even if mean values of specific observables may change due to quenching.

Unquenched vs Quenched Discrimination

- Benchmark:
    - Train a Boosted Decision Tree (BDT) for all observables.
    - Provides the most optimal discriminant based on the considered observables..
    - Gives the area under curve (AUC) of the ROC as **0.701**





Unquenched vs Quenched Discrimination contd…

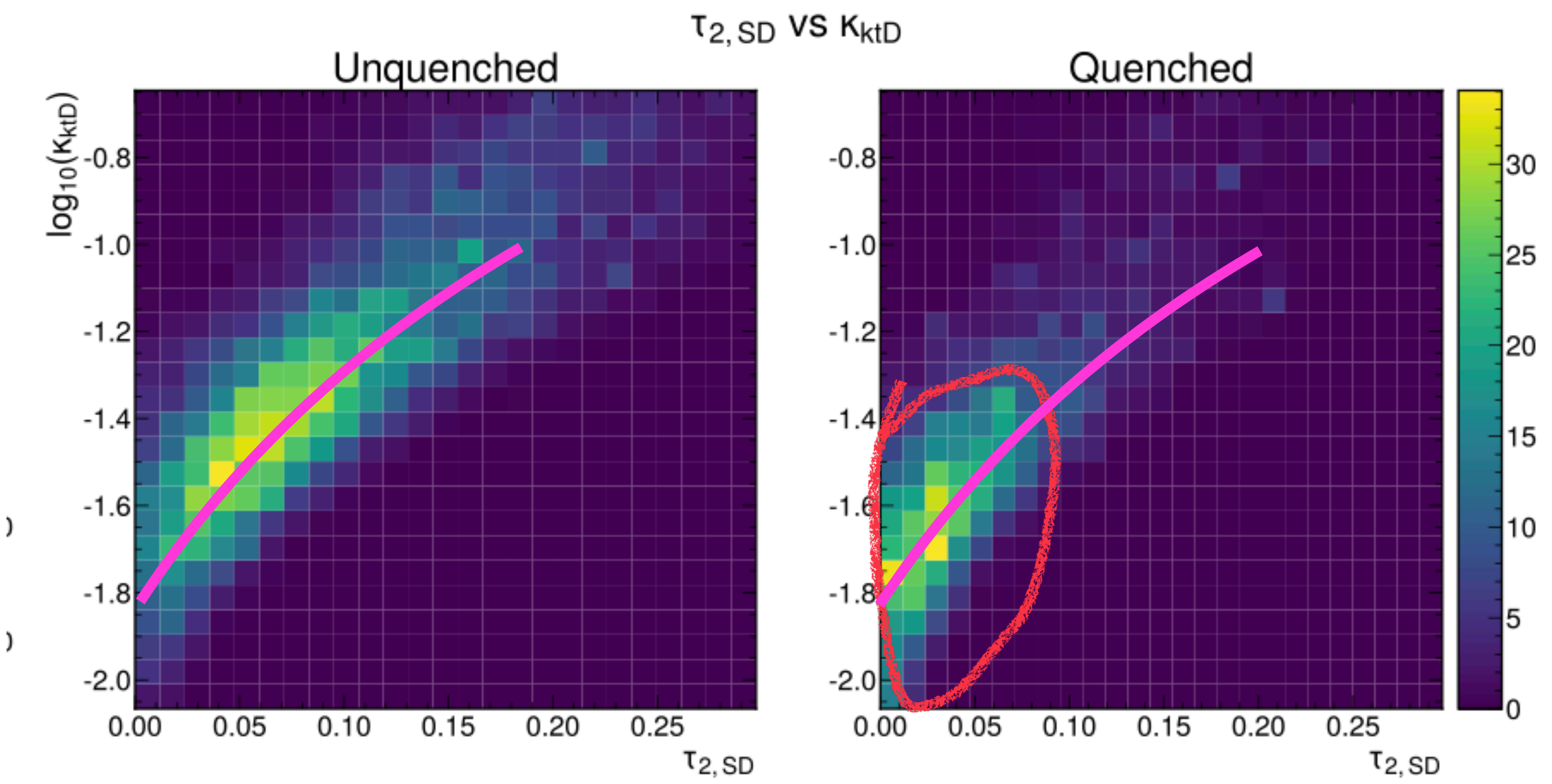
- $r\,z_{\rm SD}$, $\tau_{2,\rm SD}$ sensitive to QGP effects by themselves, accounting for around 0.99 of the discriminating ability.

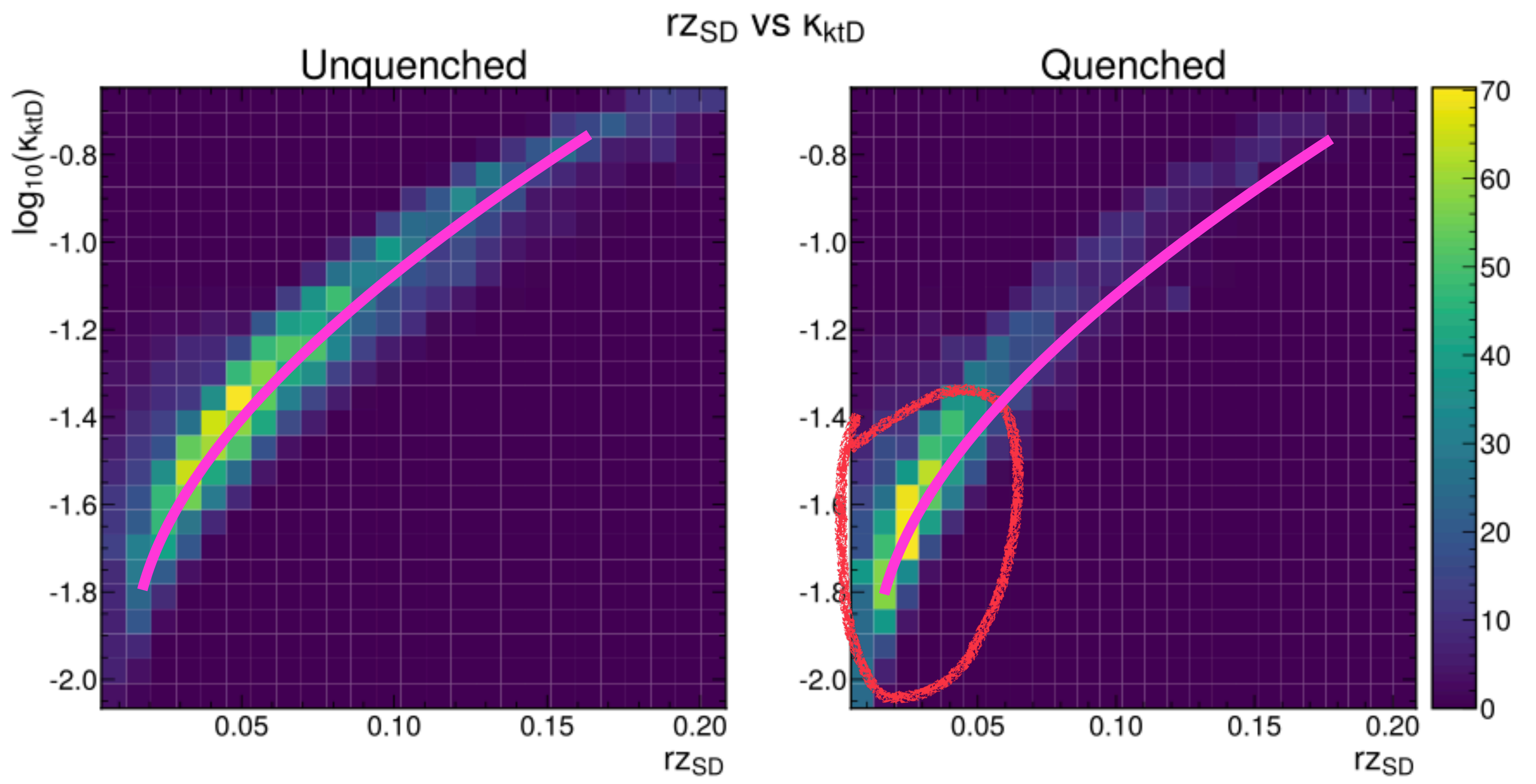
- $r^2\,z_{\rm SD}$, $\tau_{3,\rm SD}$, $\kappa_{\rm ktD}$ account for around 0.98 of the BDT discriminating ability.

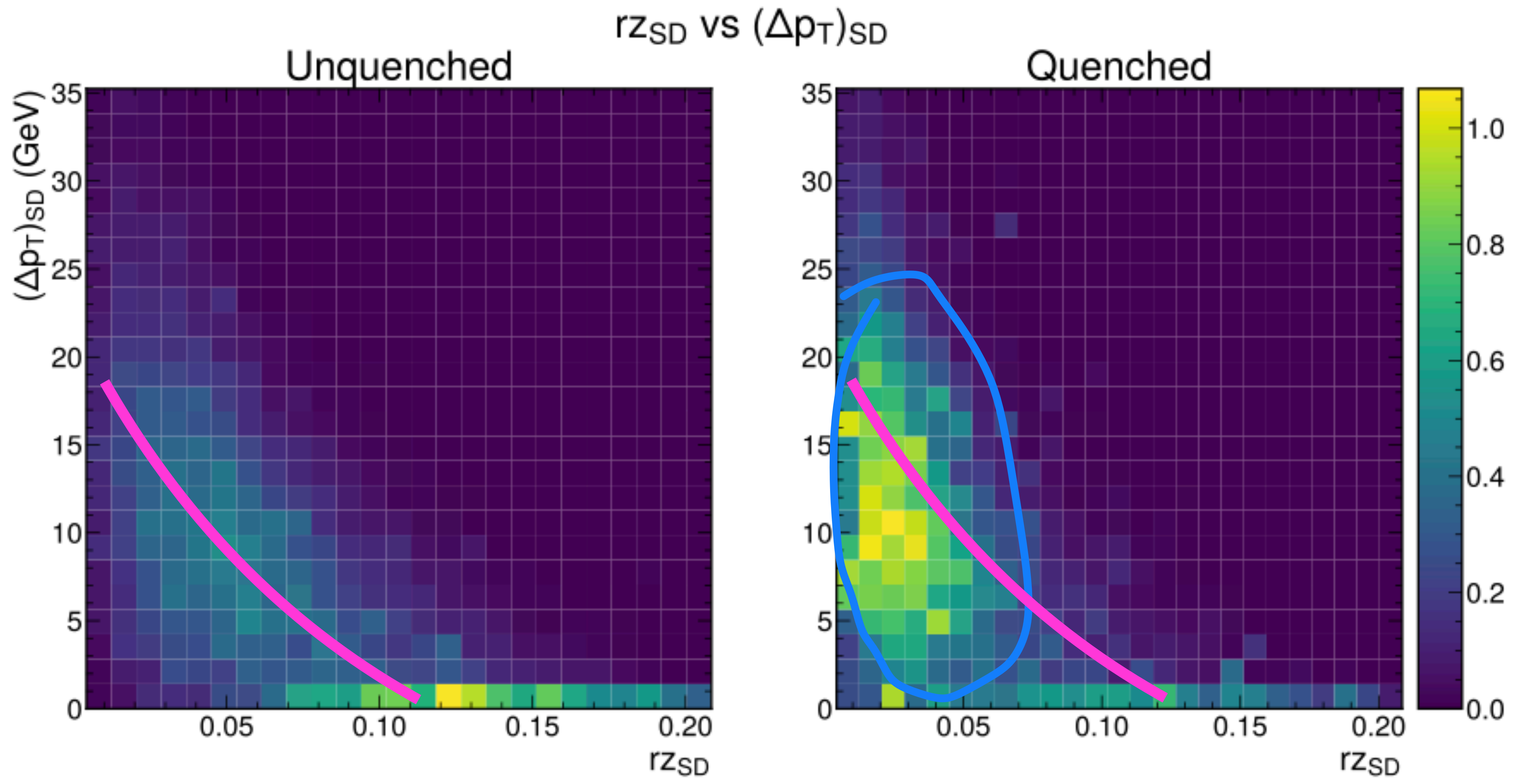
- Pairs of observables that saturate the BDT are specifically $r\,z_{\rm SD}$ with $(\Delta p_T)_{\rm SD}$, $\tau_{3,\rm SD}$, $\kappa_{\rm TD}$, $\kappa_{\rm ktD}$

	$(\Delta p_T)_{\rm SD}$	$r^2\,z_{\rm SD}$	$r\,z_{\rm SD}$	$\tau_{2,\rm SD}$	$\tau_{3,\rm SD}$	$R_{g,\rm TD}$	$R_{g,\rm ktD}$	$R_{g,\rm zD}$	$\kappa_{\rm TD}$	$\kappa_{\rm ktD}$	$\kappa_{\rm zD}$
$(\Delta p_T)_{\rm SD}$	0.81										
$r^2\,z_{\rm SD}$	0.99	0.98									
$r\,z_{\rm SD}$	1.00	0.99	0.99								
$\tau_{2,\rm SD}$	0.99	0.99	0.99	0.99							
$\tau_{3,\rm SD}$	0.99	0.99	1.00	0.98	0.98						
$R_{g,\rm TD}$	0.84	0.99	0.99	0.99	0.99	0.74					
$R_{g,\rm ktD}$	0.90	0.99	0.99	0.99	0.98	0.82	0.83				
$R_{g,\rm zD}$	0.96	0.99	0.99	0.99	0.99	0.95	0.96	0.95			
$\kappa_{\rm TD}$	0.95	0.99	1.00	1.00	0.99	0.96	0.97	0.98	0.95		
$\kappa_{\rm ktD}$	0.98	0.99	1.00	1.00	1.00	0.98	0.98	0.99	0.98	0.98	
$\kappa_{\rm zD}$	0.84	0.98	0.99	0.98	0.98	0.86	0.92	0.97	0.96	0.98	0.85

Unquenched vs Quenched Discrimination contd…





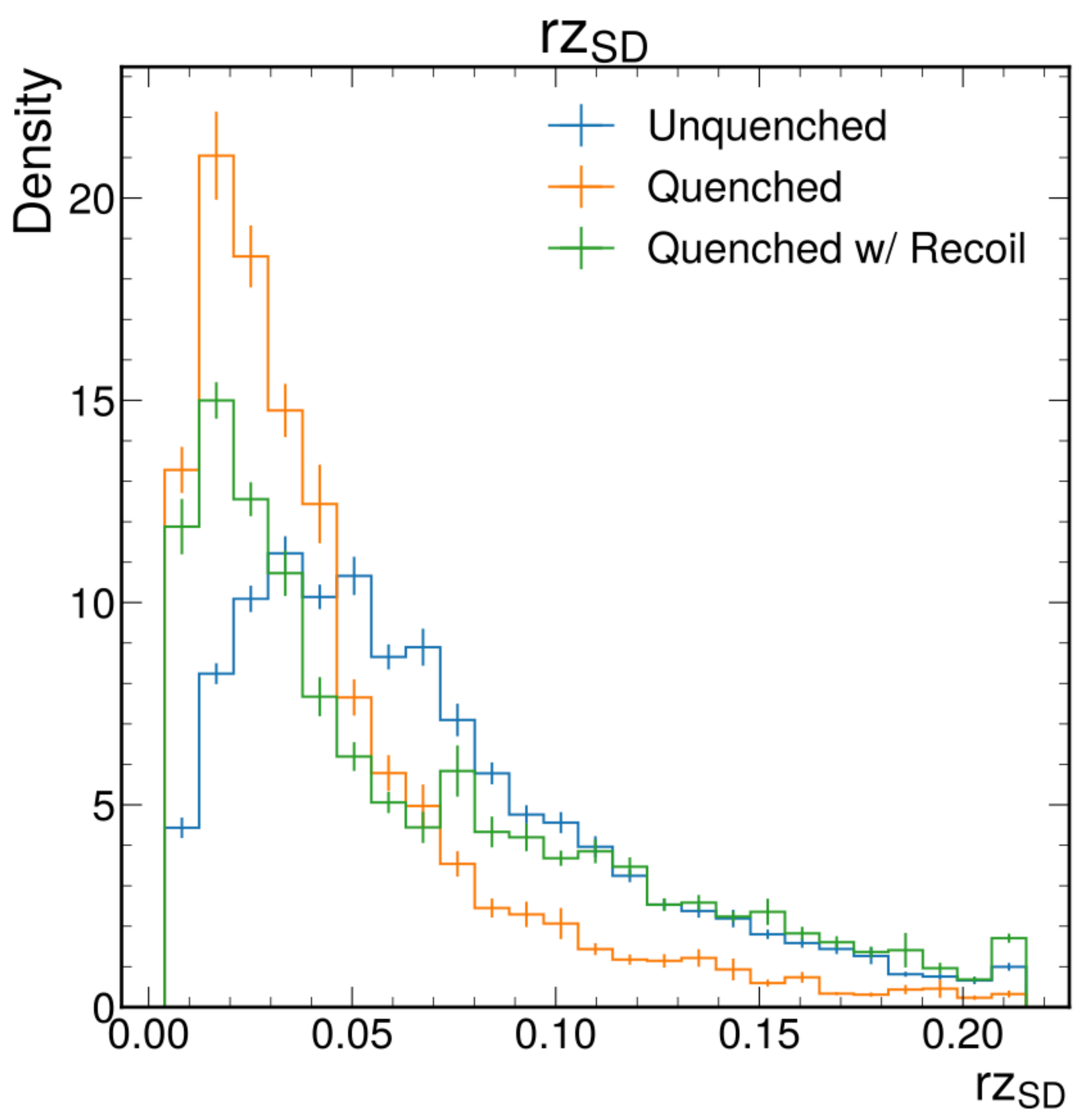


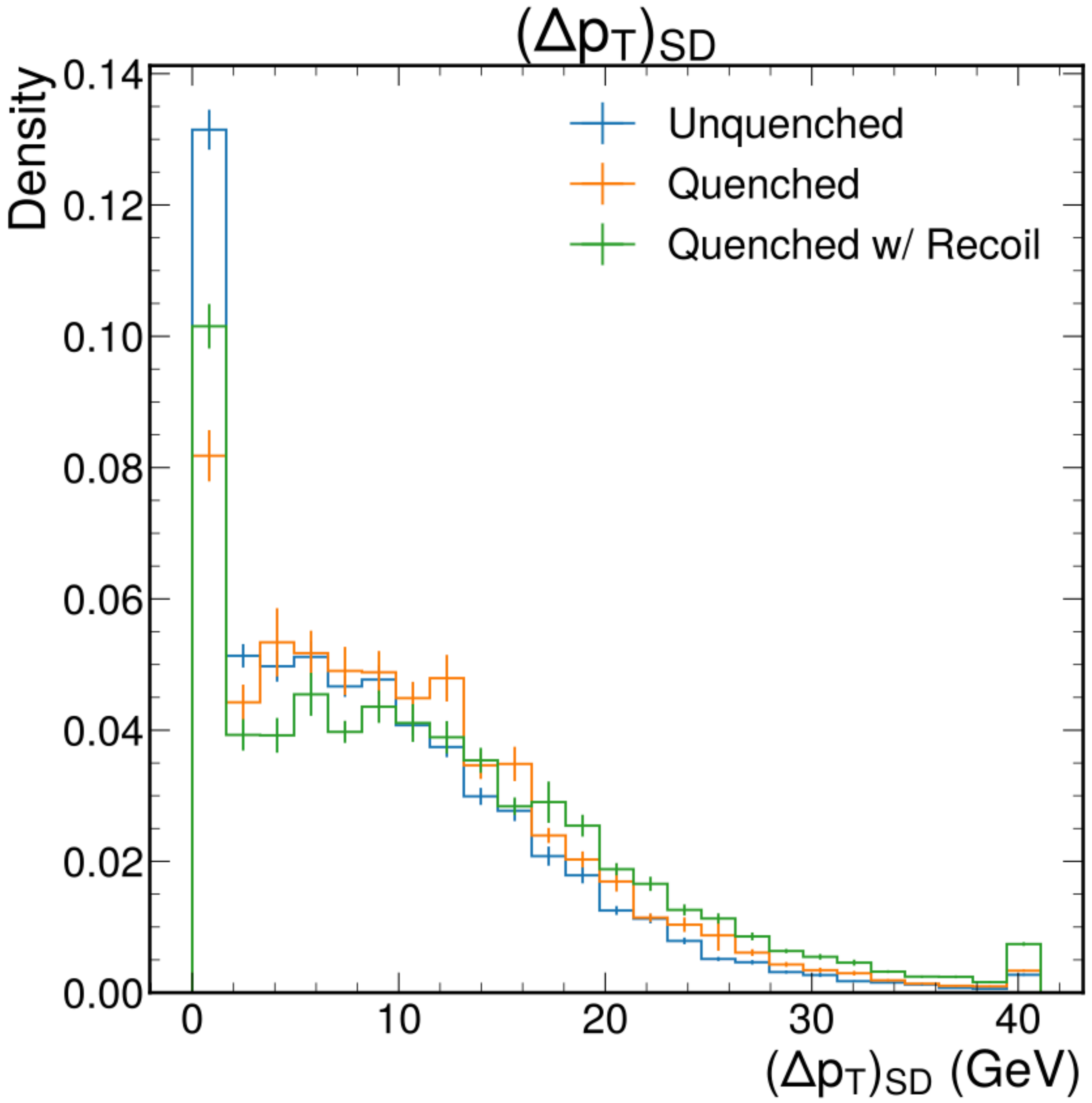
- For observables in top panel, relations between observables are quite similar for quenched and unquenched samples.

- $r\,z_{\text{SD}}$, $(\Delta p_T)_{\text{SD}}$ seem different than the other pairs $\Rightarrow$ most sensitive to quenching effects.

Impact of QGP response

- Use JEWEL with recoil to prepare quenched jet samples.

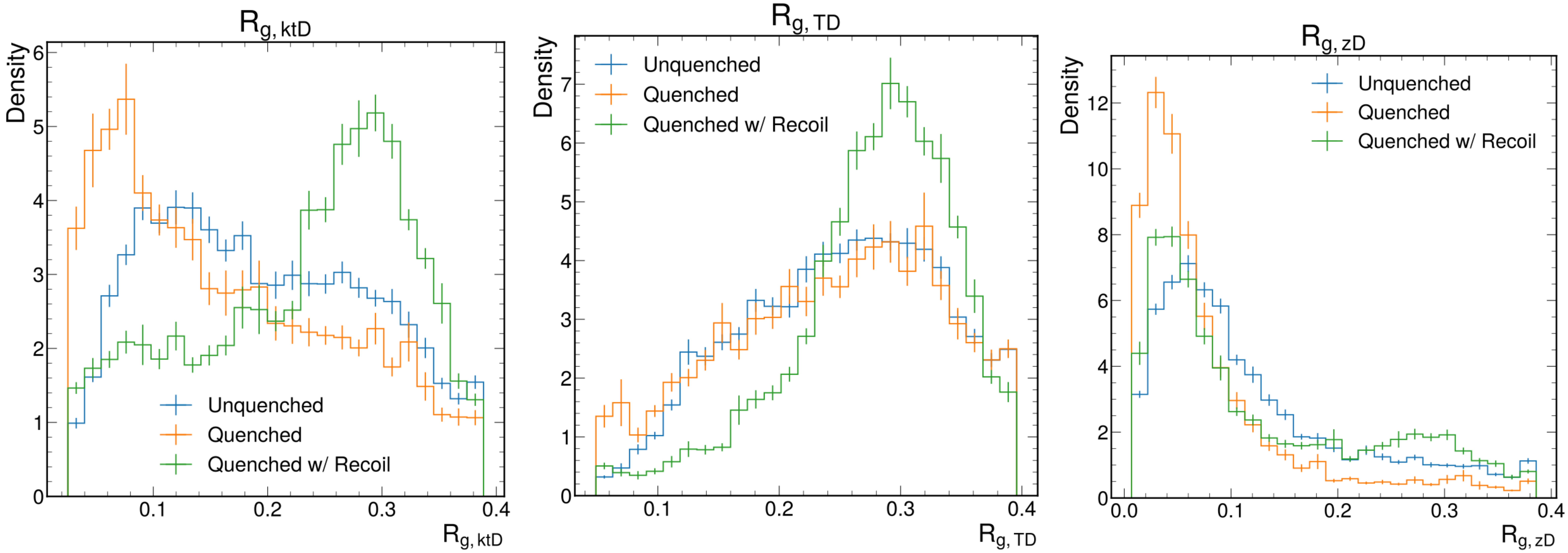




For these observables, quenching reduces the mean value while addition of recoil produces a tail.

Impact of QGP response contd…

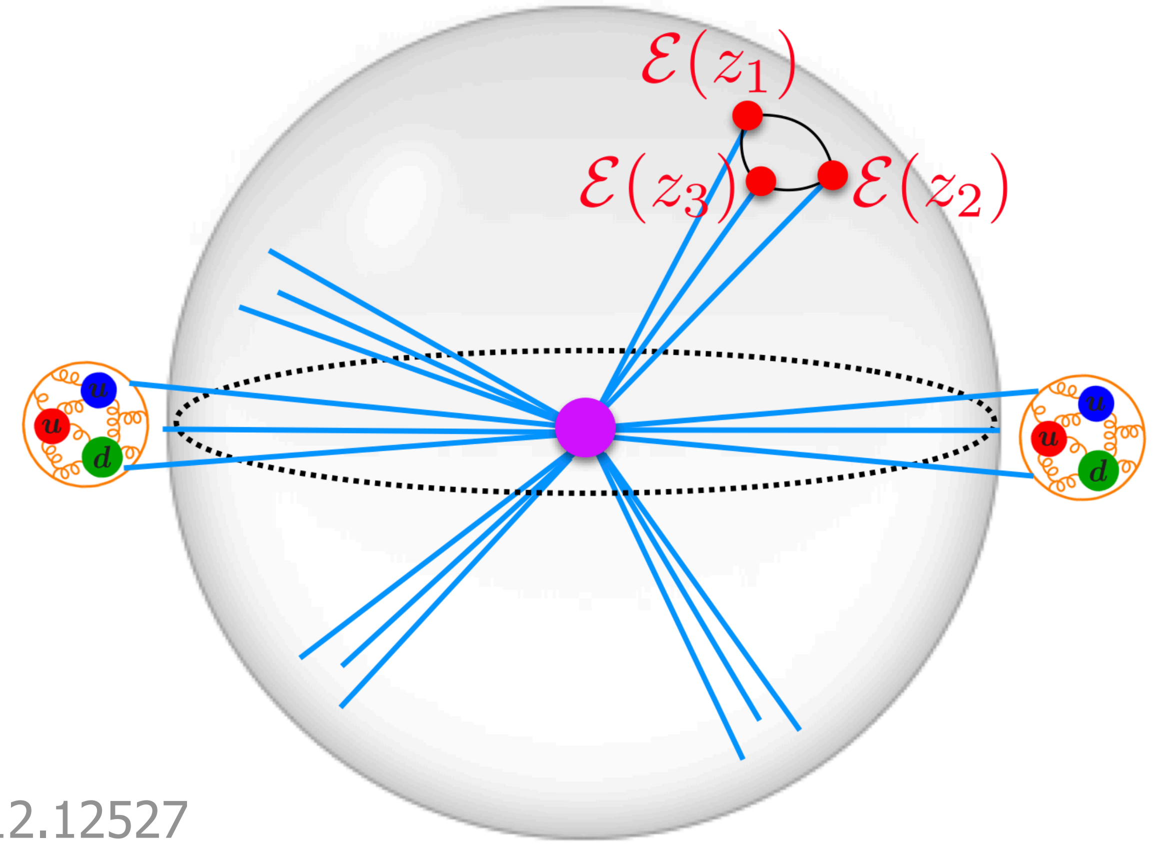
- Dynamical grooming observables are far strongly impacted.



- Effect of recoil stronger than that of quenching itself.
- Suggests that these observables are more sensitive to large-angle radiations and/or background.

Future prospects

Energy-Energy Correlators



- The observables considered so far are ones which return a single value per jet.
- A complementary class of jet observables are n-point correlators of energy flow operators that are energy weighted distributions of angular separation between pairs .
  - vacuum
  - medium

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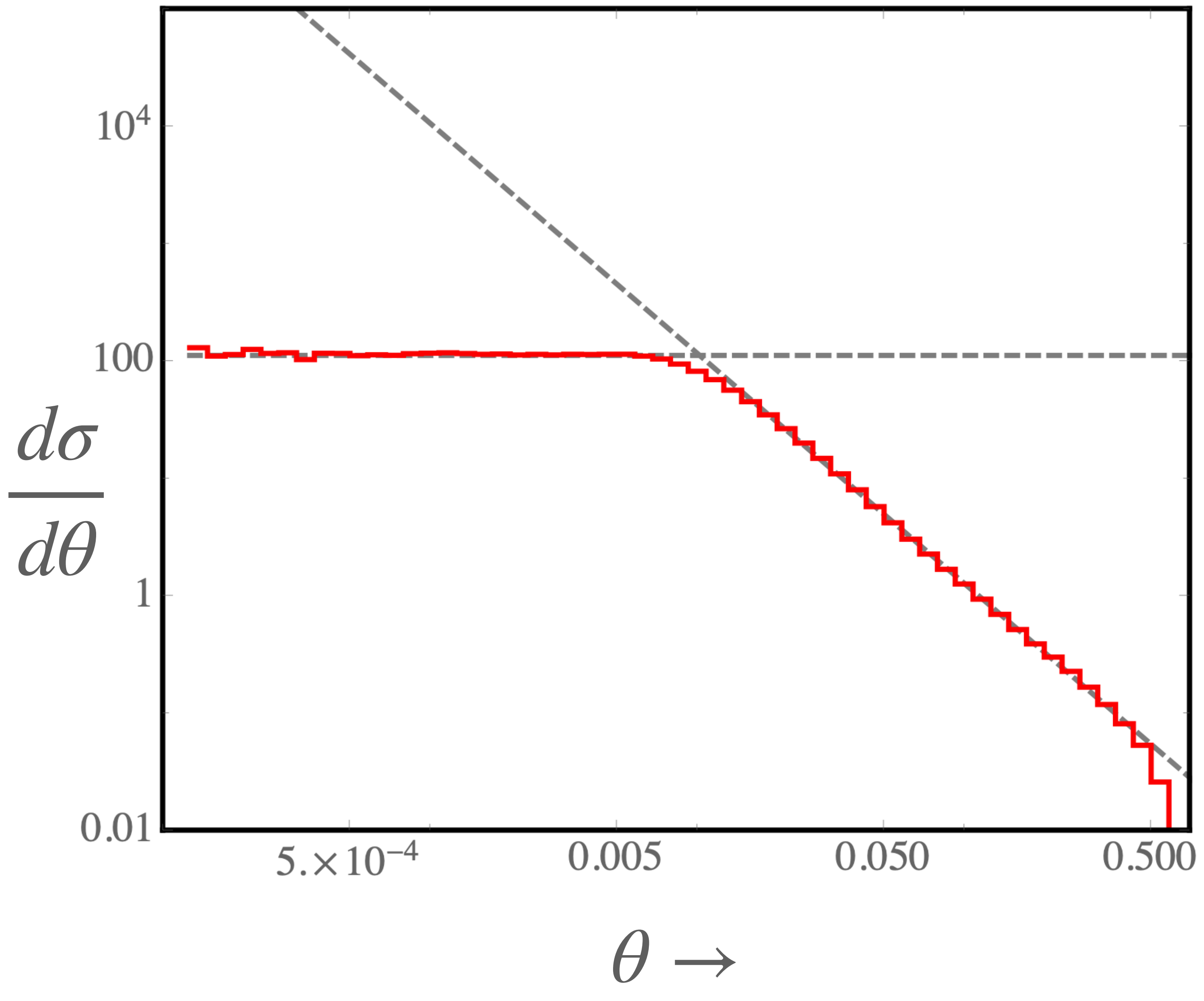
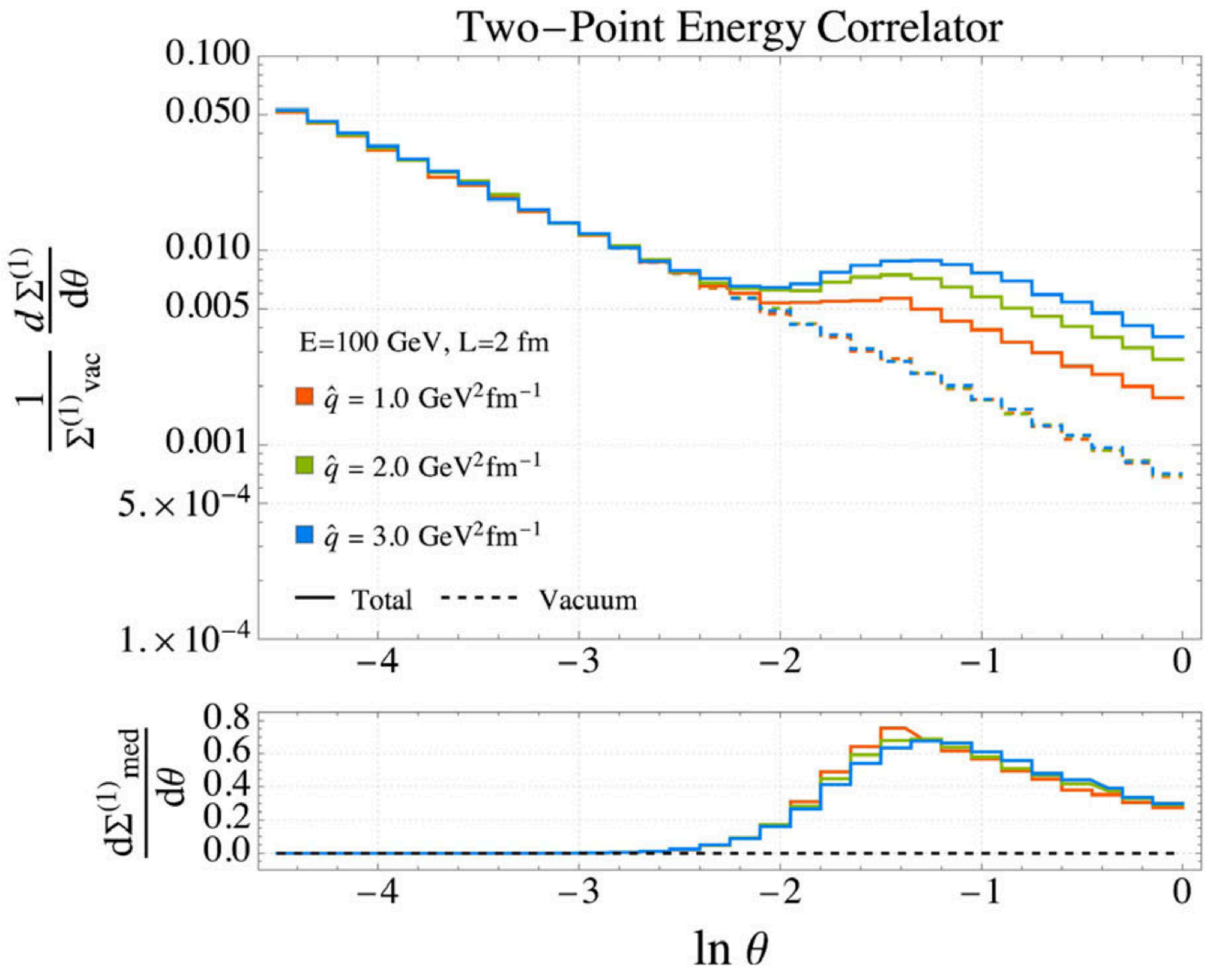


Fig. from Ian Moult's talk



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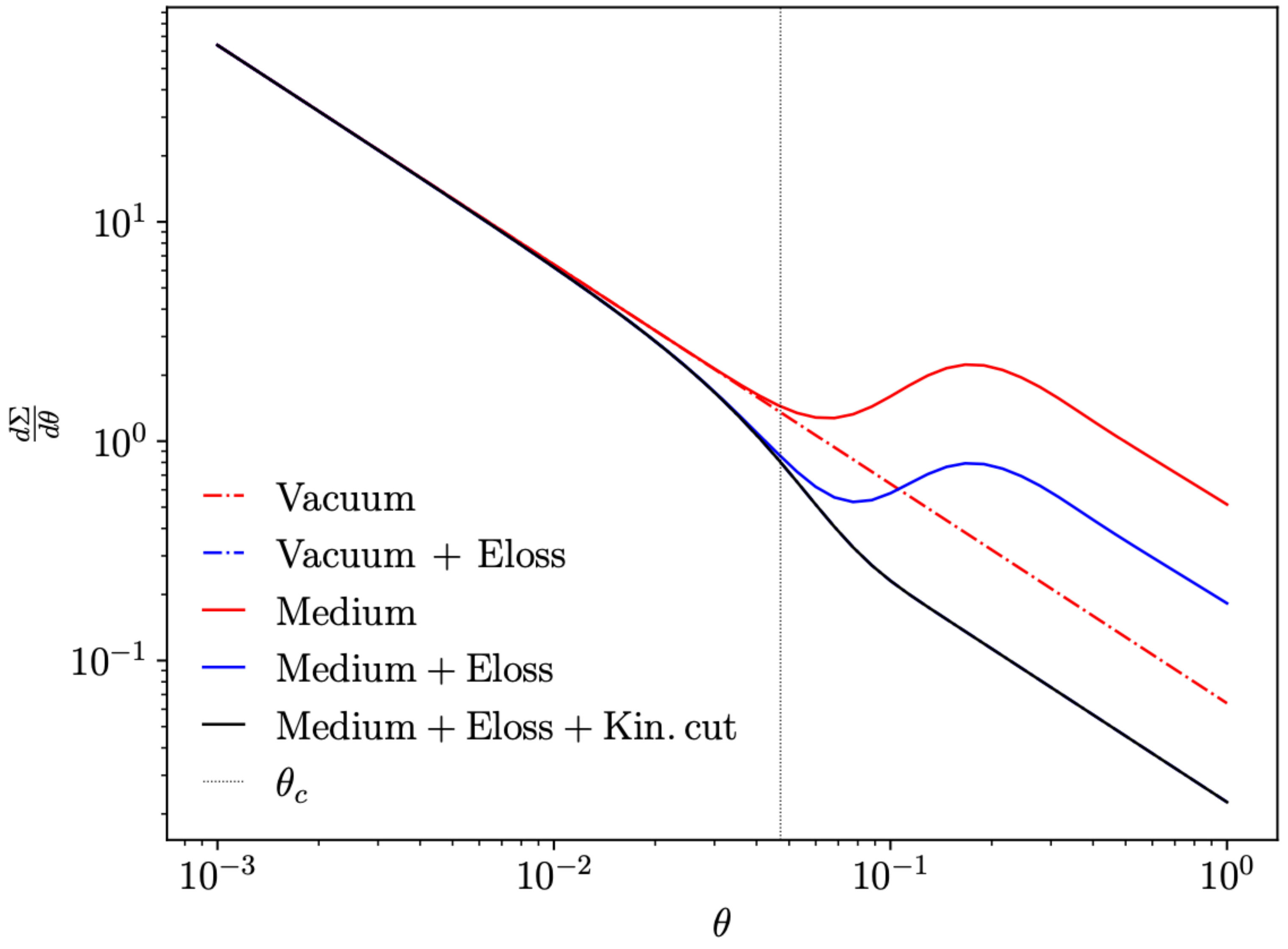

2307.08943

Modified EEC for resolving radiation in medium

- Proposal: To move beyond the standard correlators defined relative to angle and utilize the emergent medium scale, the formation time t_f of an emission.

- This make the observable collinear unsafe. Various approaches can used to regulate this for instance the use of subjet radius, Lund-based EEC.

arXiv: 2312.12527

- Goal: to see if one can obtain a clear separation between incoherent and coherent emissions in the medium.

Some options to explore :

- Correlations between two particles or correlations with the jet axis.

- Modifying the energy weightage from $E_i \to E_i^\kappa$ would work out to be better for further reducing the background or the effect is simply nominal.

Summary

- Using ML methods, a survey of 31 jet substructure observables was performed.
- In both the unquenched and quenched cases, the PCA identified clusters of observables that encode the transverse substructure of the jet to be linearly correlated.
- The information content of the entire set of observables can be described by a small number of effective degrees of freedom.
- These effective degrees of freedom do not correspond to simple observables. It is essentially a linear combination involving few or most observables in the PCA and non-linear maps of the input observables that are implicit in the AE case.
- Correlations between observables are mostly resilient to quenching effects.
- Specific observables and pairs of observables effectively determine the discriminately potential of the BDT trained on all jet observables.