What is a quenched jet ?

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I. what is a jet

jet definition [in elementary collisions]

:: a jet is ***defined*** *by a set of rules and parameters [a jet algorithm] specifying how to combine constituents and when to stop ::*

jet definition [in elementary collisions]

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e.g., generalized k_T family of sequential recombination jet algorithms

1. compute all distances d_{ij} and d_{iB}
2. find the minimum of the d_{ij} and d_{iB}
3. if it is a d_{ij}, recombine i and j into a single new particle and return to 1
4. otherwise, if it is a d_{iB}, declare i to be a jet, and remove it from the list of particles. return to 1
5. stop when no particles left

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2,$$

$$d_{iB} = p_{ti}^{2p},$$

p = 1 :: k_T algorithm

p = 0 :: Cambridge/Aachen algorithm

p = -1 :: anti-k_T algorithm

jet definition [in elementary collisions]

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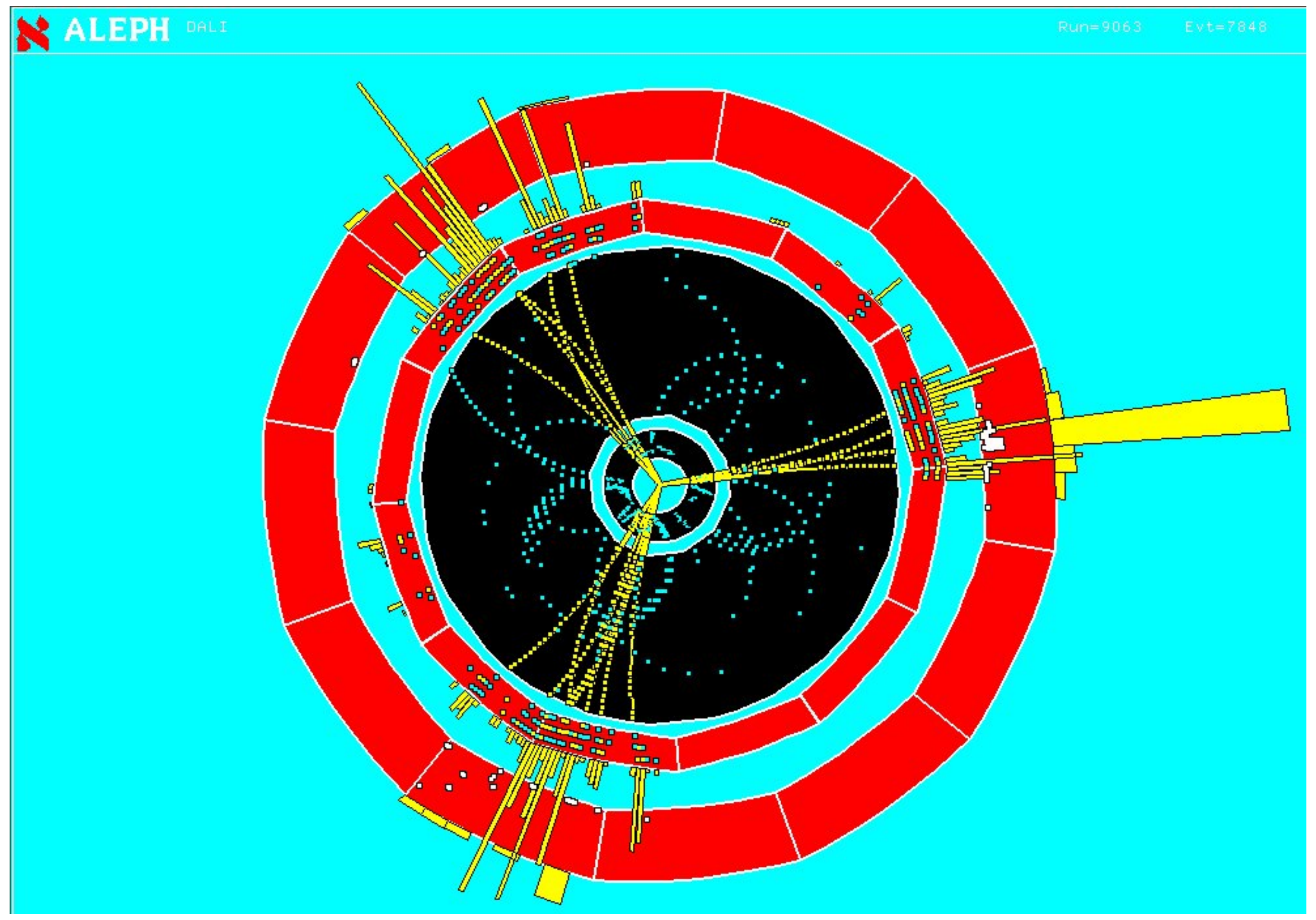
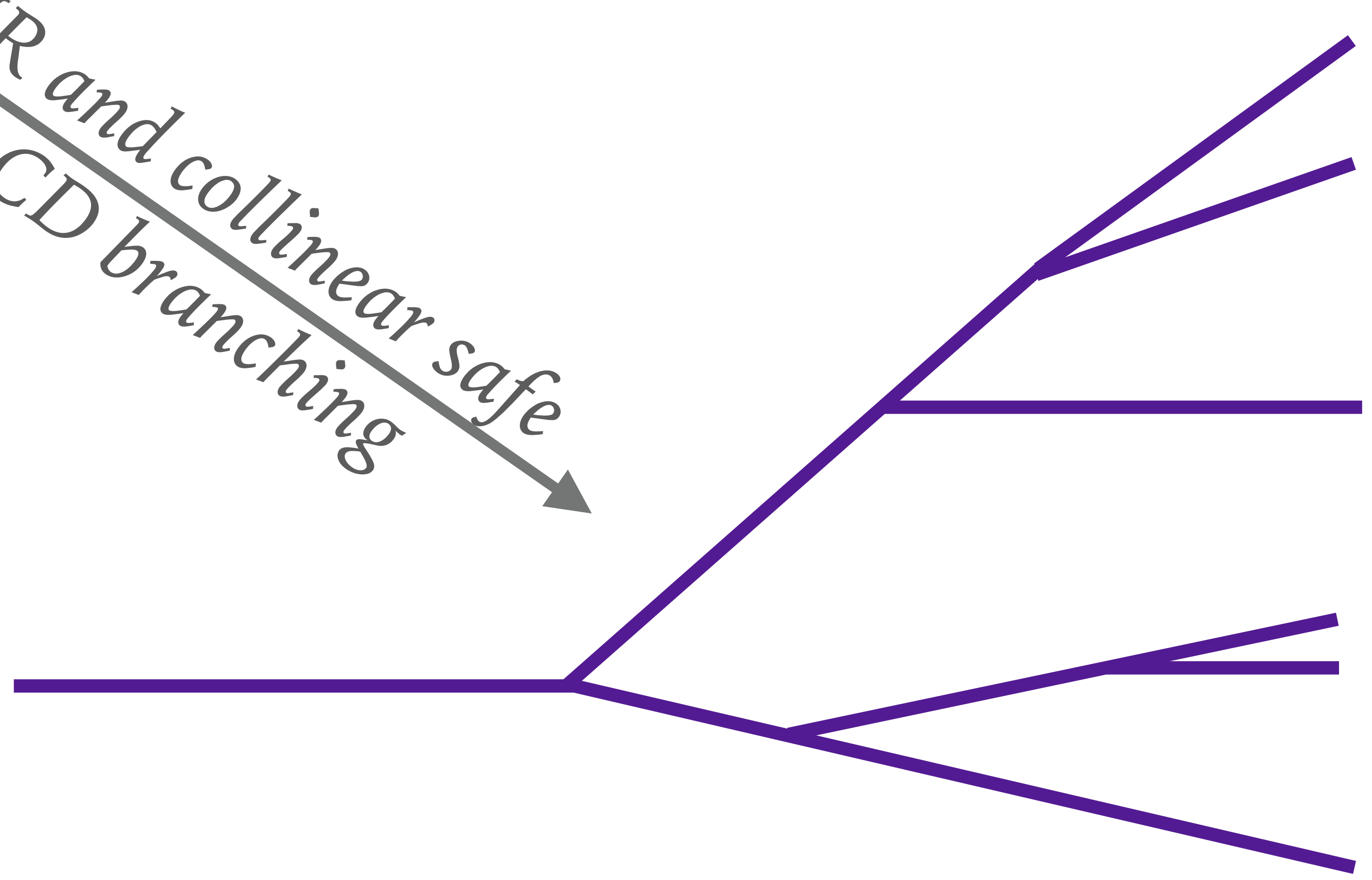
jet algorithm

robust and efficient
IR and collinear safe

IR and collinear safe
QCD branching



experimentally measurable
collimated spray of hadrons



theoretically calculable
fragmentation of energetic parton

jet definition [in elementary collisions]

*:: a **jet** is **defined** by a set of rules and parameters [a jet algorithm] specifying how to combine constituents and when to stop ::*

theory jet

experimental jet

jet algorithm

robust and efficient
IR and collinear safe

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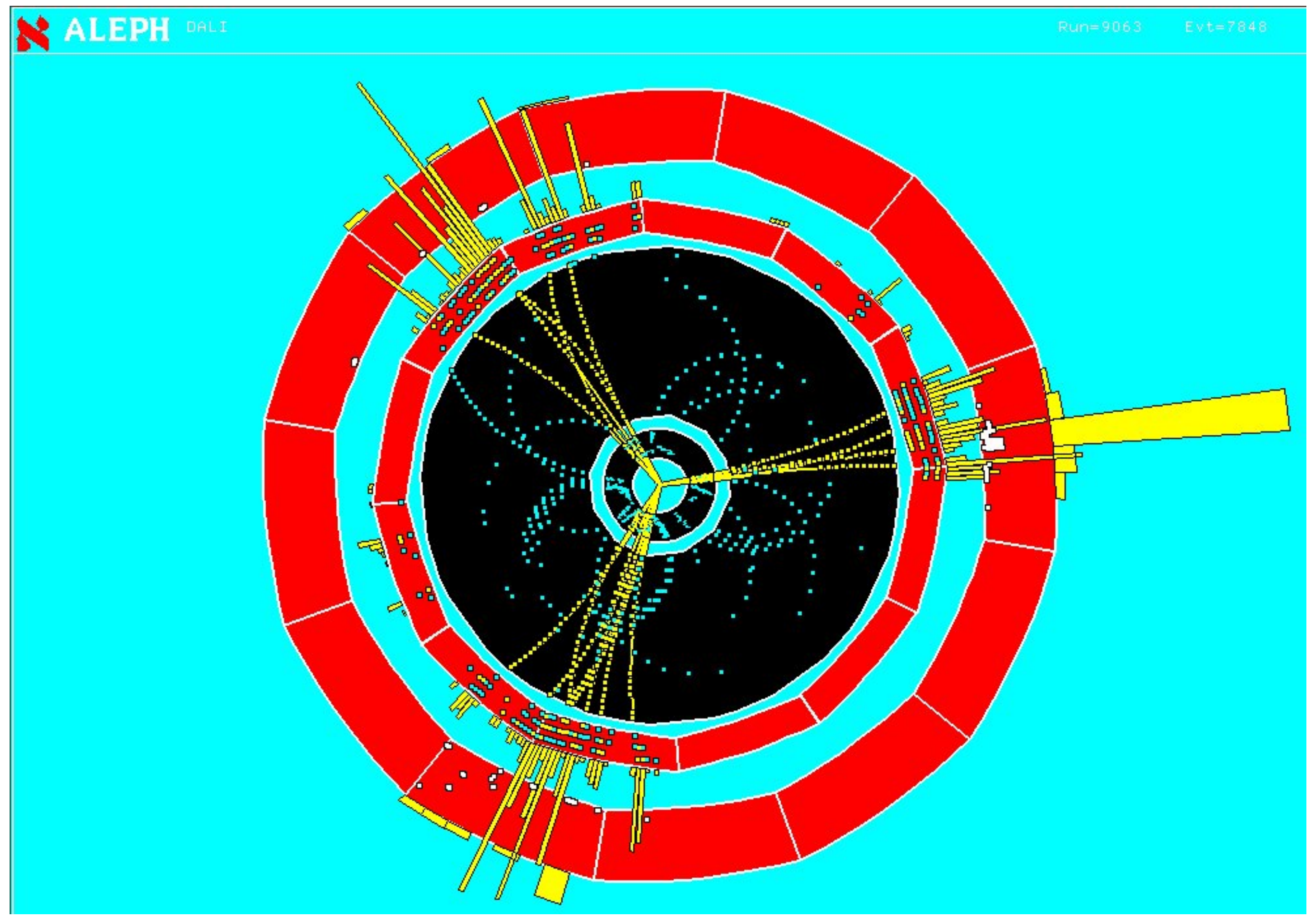
QCD branching



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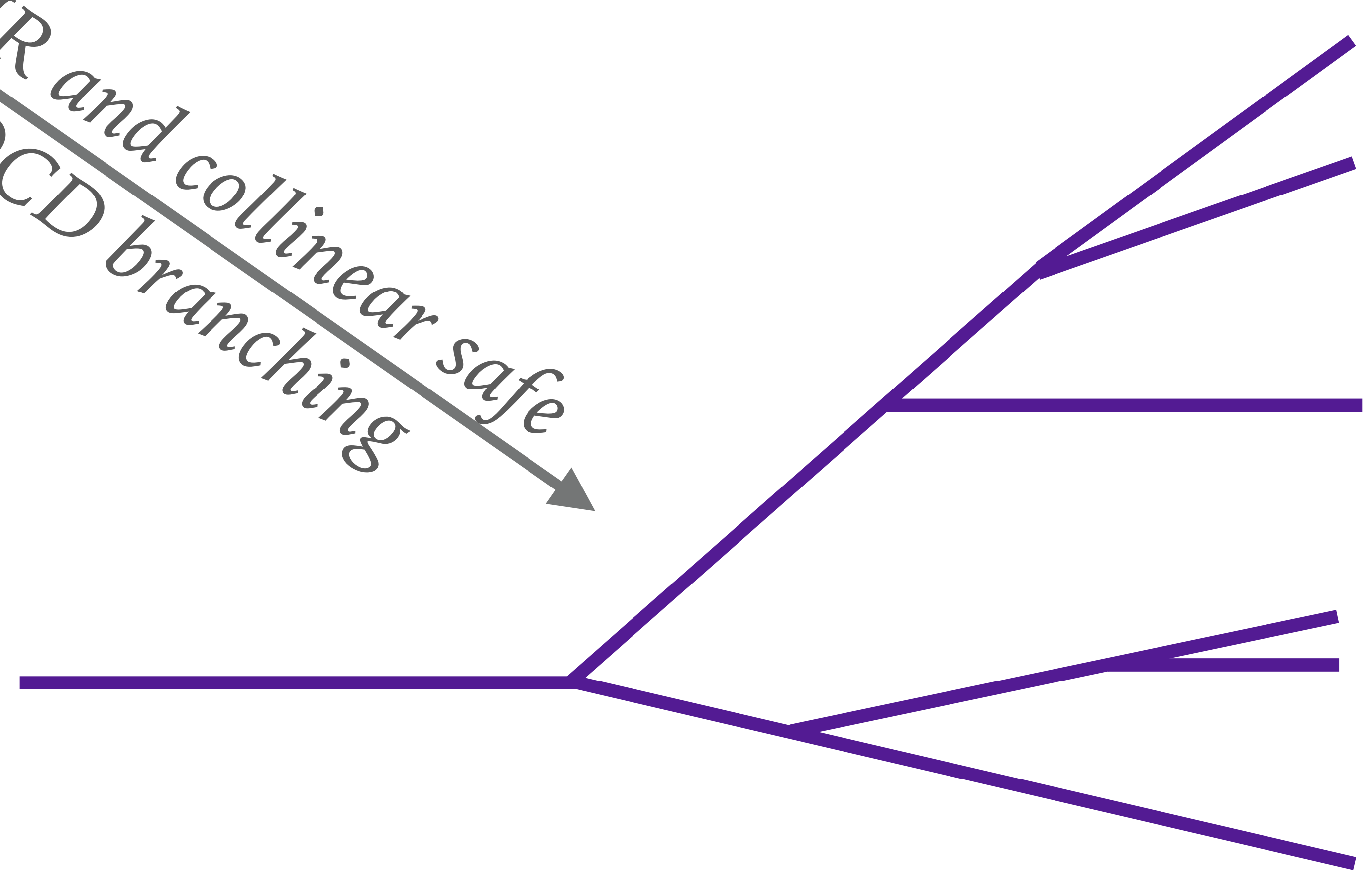
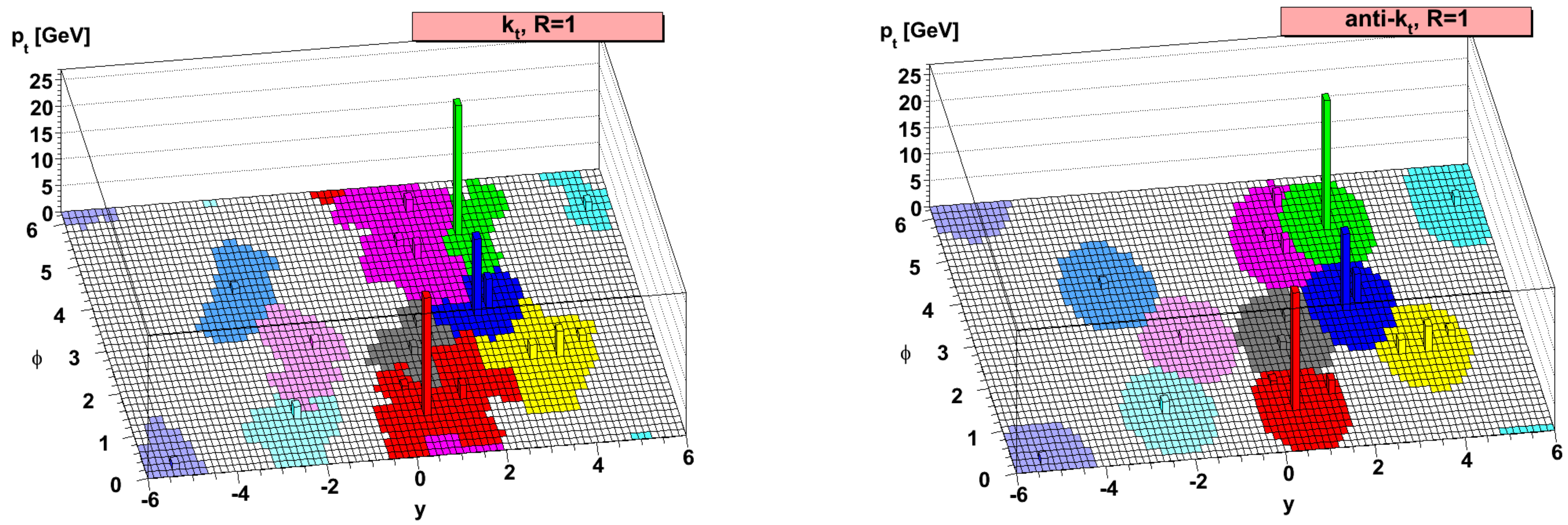


theoretically calculable
fragmentation of energetic parton

a jet is a jet is a jet is a jet

jet diversity

- k_T R=0.4 jets are **different** from anti-k_T R=0.4,

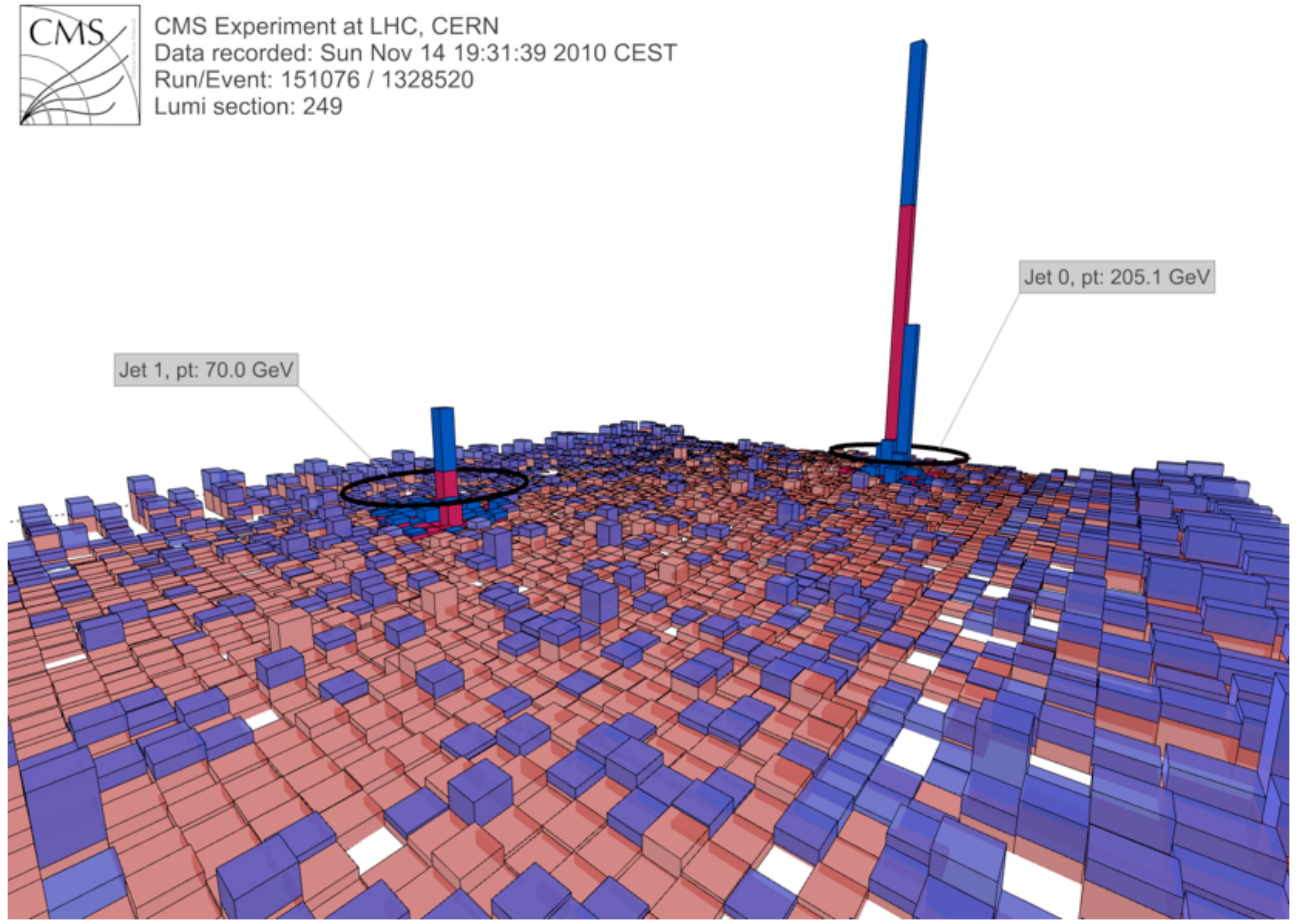


Cacciari, Salam, Soyez 0802.1189

- also, anti-k_T R=0.2 are **not** the inner R=0.2 core of anti-k_T R=0.4 jets, etc.
- jets reconstructed with a given algorithm can be reinterpreted [**reclustered**] with a different algorithm to benefit simultaneously from experimental robustness and direct theoretical interpretation
    - however, C/A reclustering of anti-kt R=0.4 jet is not C/A R=0.4 jet
- **jet diversity is a tool** rather than a hindrance :: grooming/substructure methods

jets in heavy ion collisions

- defined by same jet algorithm[s] as in elementary collisions with essential background subtraction



jet algorithm
+
background subtraction

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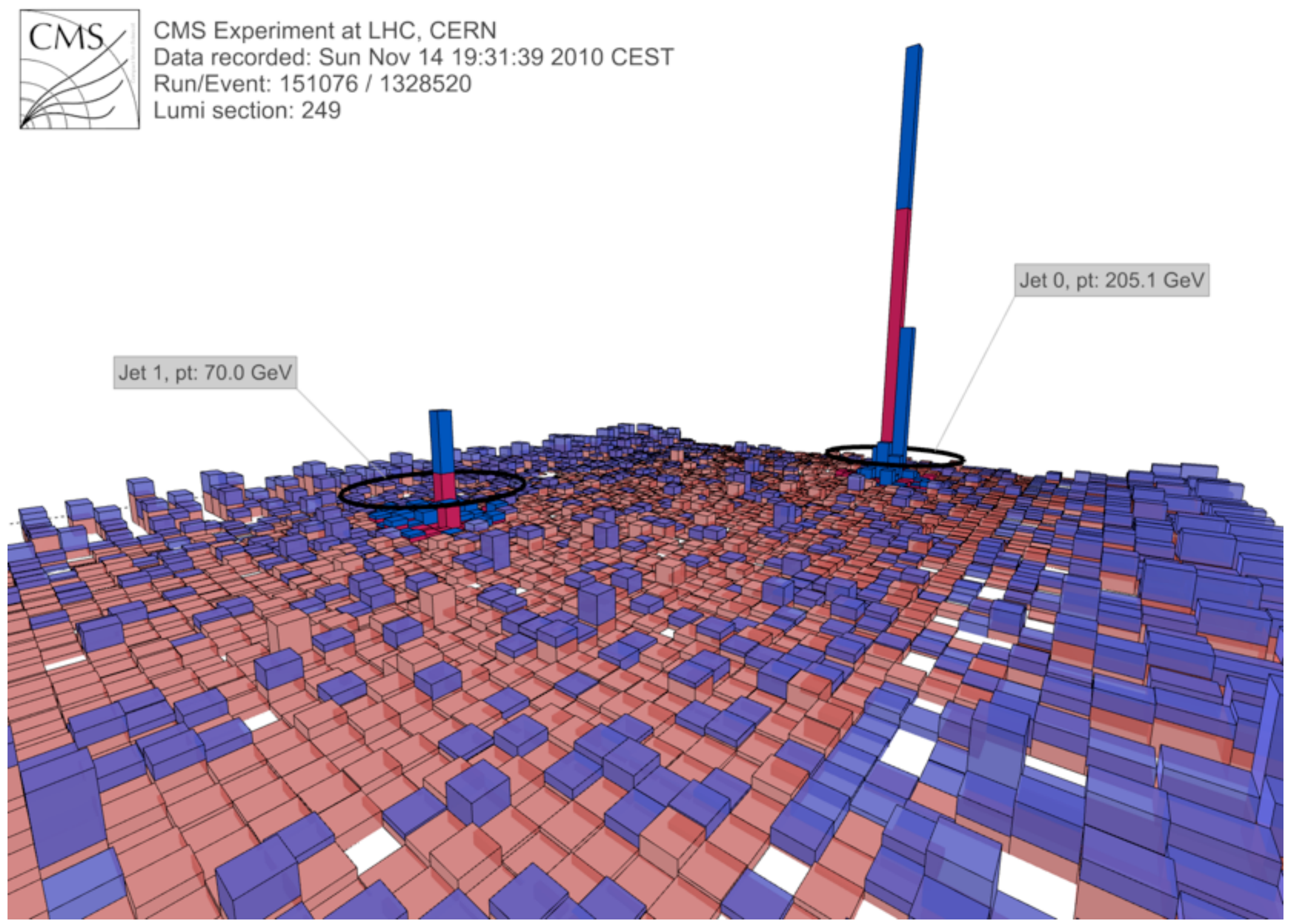
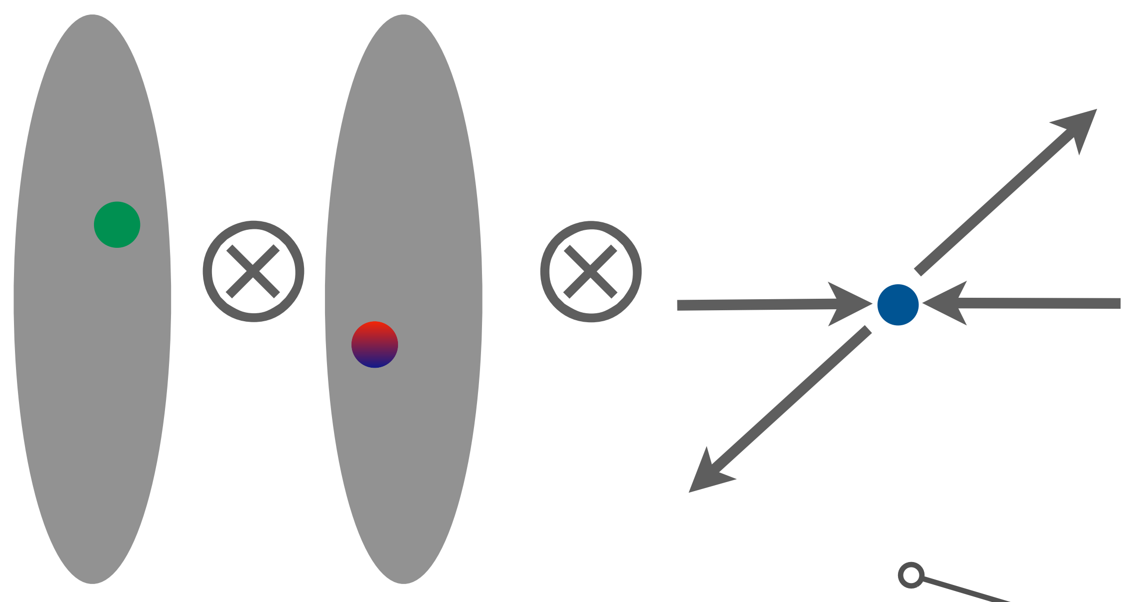


jet algorithm
+
background subtraction

what has to be calculated?

II. what is a jet in heavy ion collisions

A JET IN QGP :: HARD PRODUCTION



hard scattering localized on point like scale
oblivious to surrounding matter
[calculable to arbitrary pQCD order]

nuclear structure sufficiently
constrained in relevant
kinematical domain

all will be easy [denial]

A JET IN QGP :: PARTON SHOWER

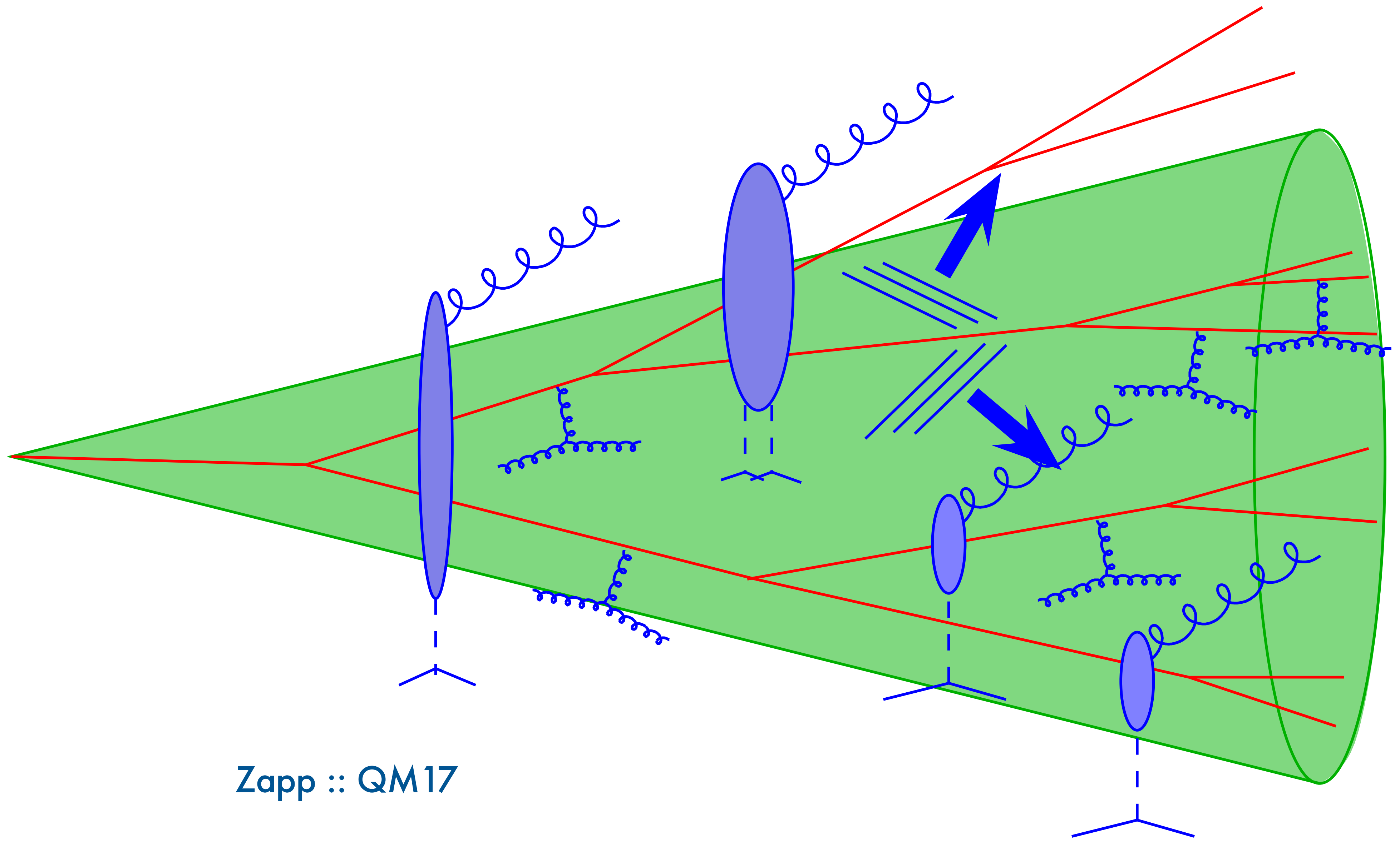
shower constituents exchange [soft] 4-momentum and colour with QGP :: shower modified into interleaved vacuum+induced shower :: modified coherence properties :: single parton intuition and results do not carry through trivially :: multi-scale problem :: some shower constituents de-correlate :: some QGP becomes correlated

Mehtar-Tani, Milhano, Tywoniuk :: Int.J.Mod.Phys. A28 (2013)

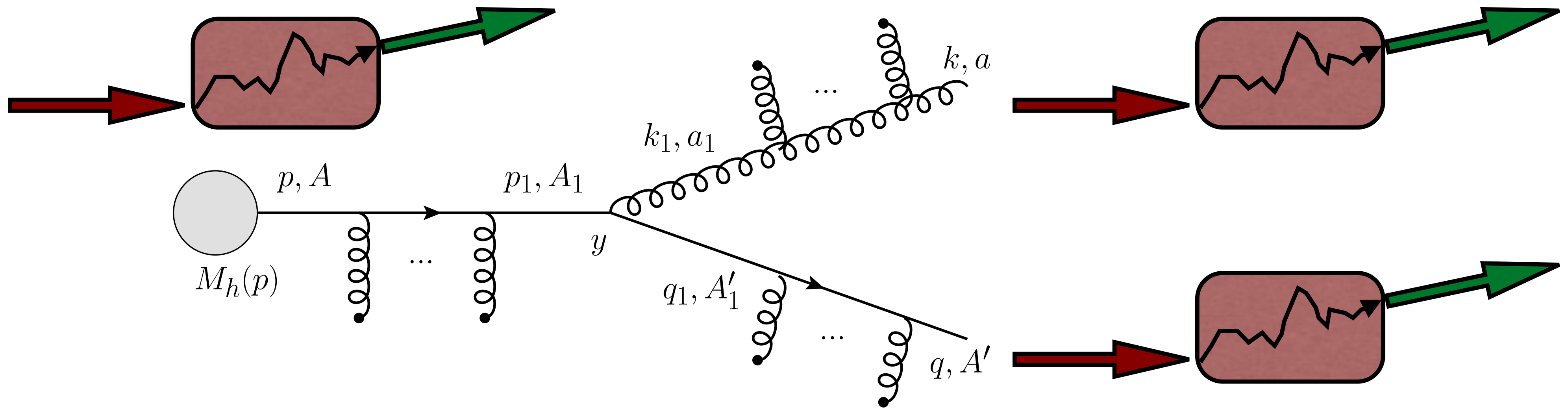
Mehtar-Tani, Tywoniuk, Salgado :: many

Blaizot, Dominguez, Iancu, Mehtar-Tani :: JHEP 1406 (2014)

Apolinário, Armesto, Milhano, Salgado :: JHEP 1502 (2015)



Zapp :: QM17

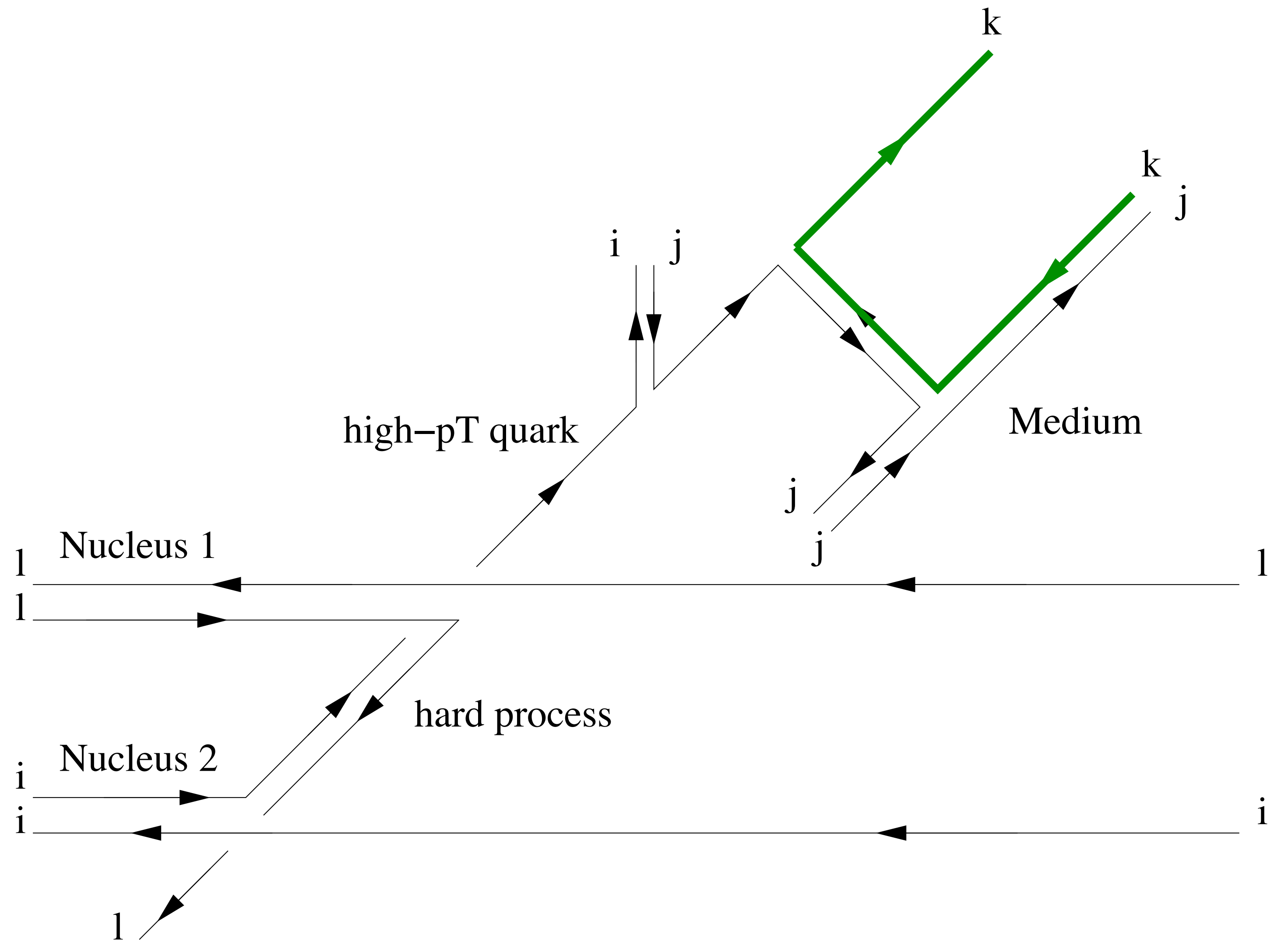


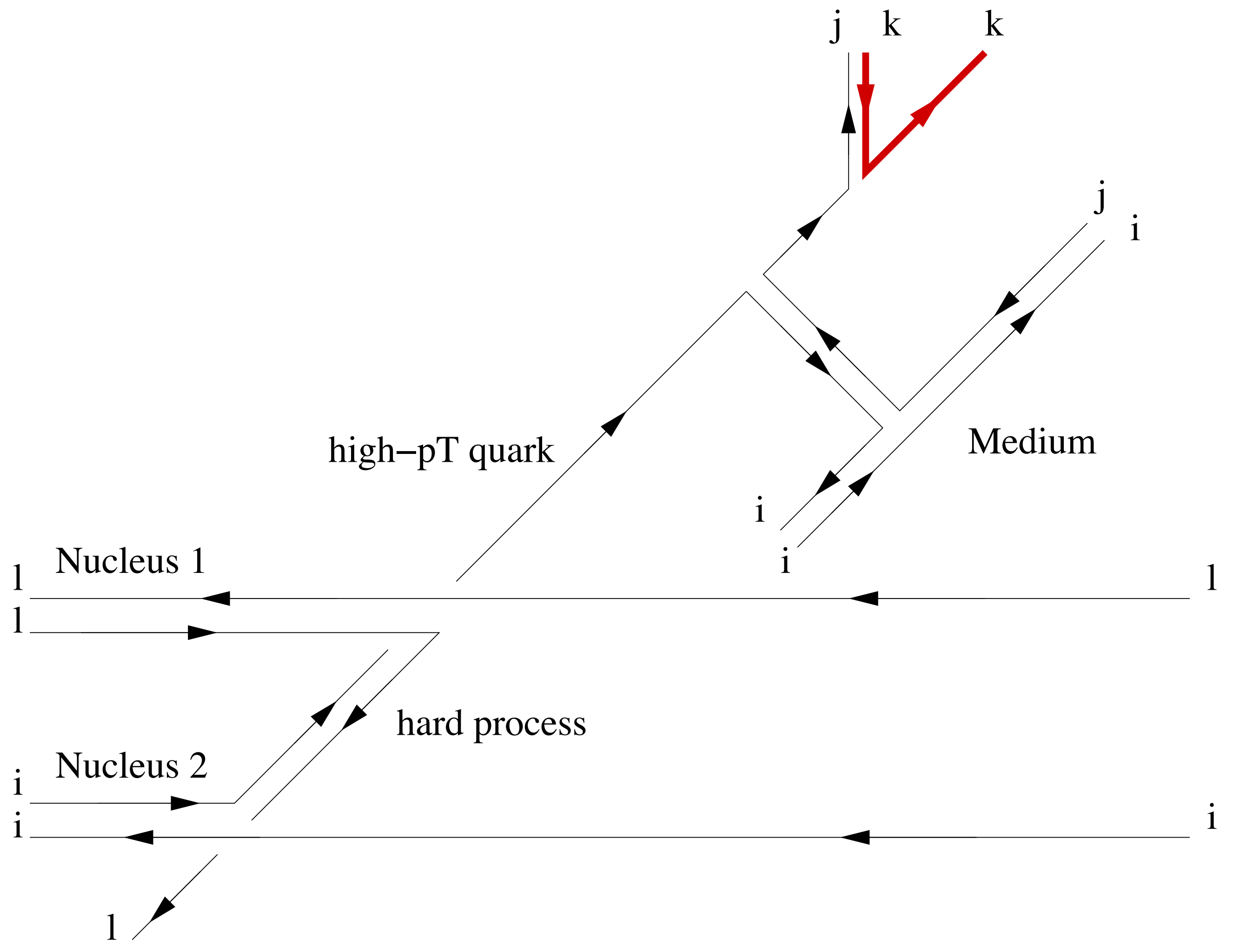
this is tough [anger]

A JET IN QGP :: HADRONIZATION

Beraudo, Milhano, Wiedemann :: JHEP 1207 (2012)

very little known about QGP induced modifications of already ill-understood hadronization in vacuum



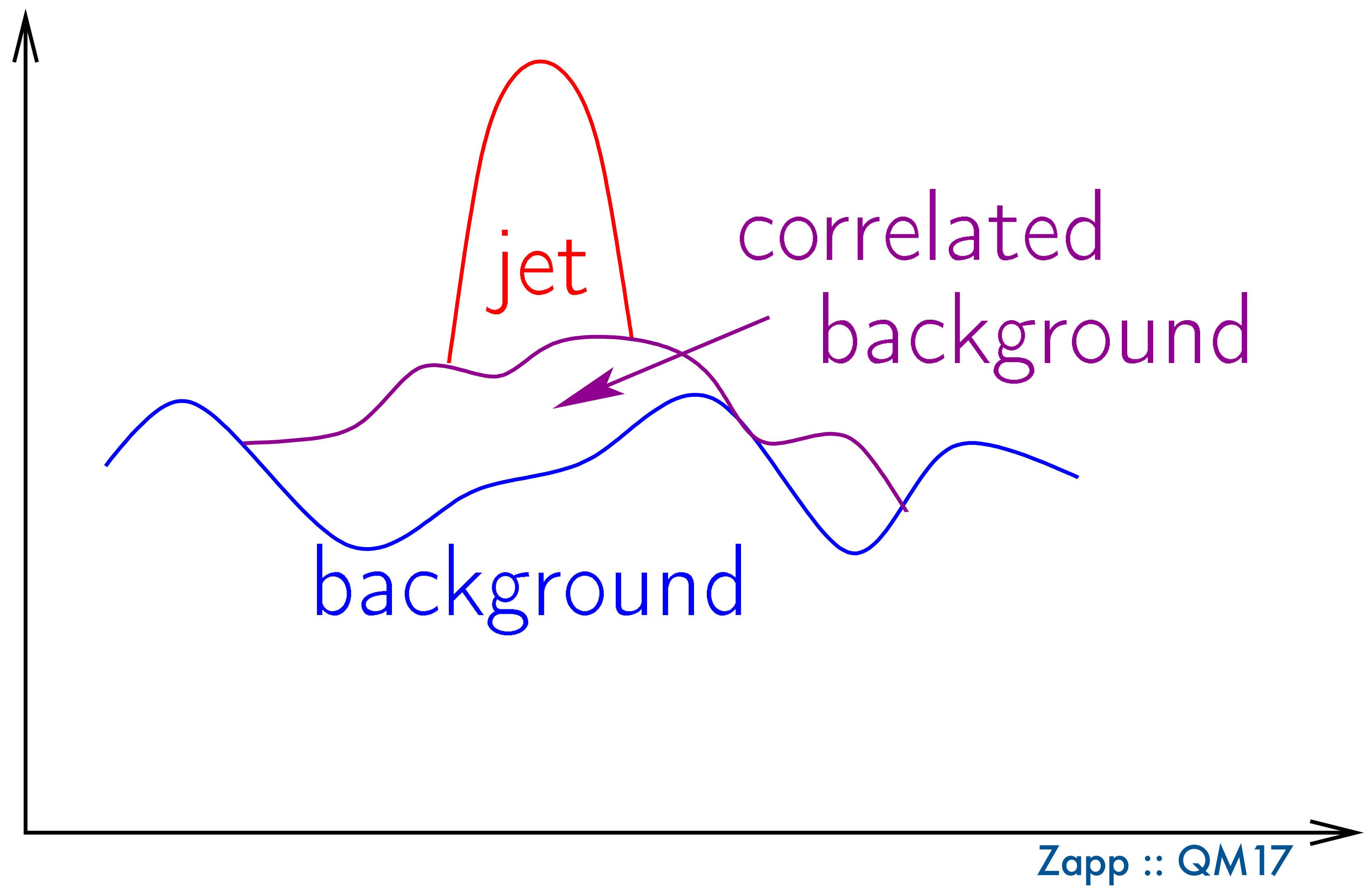


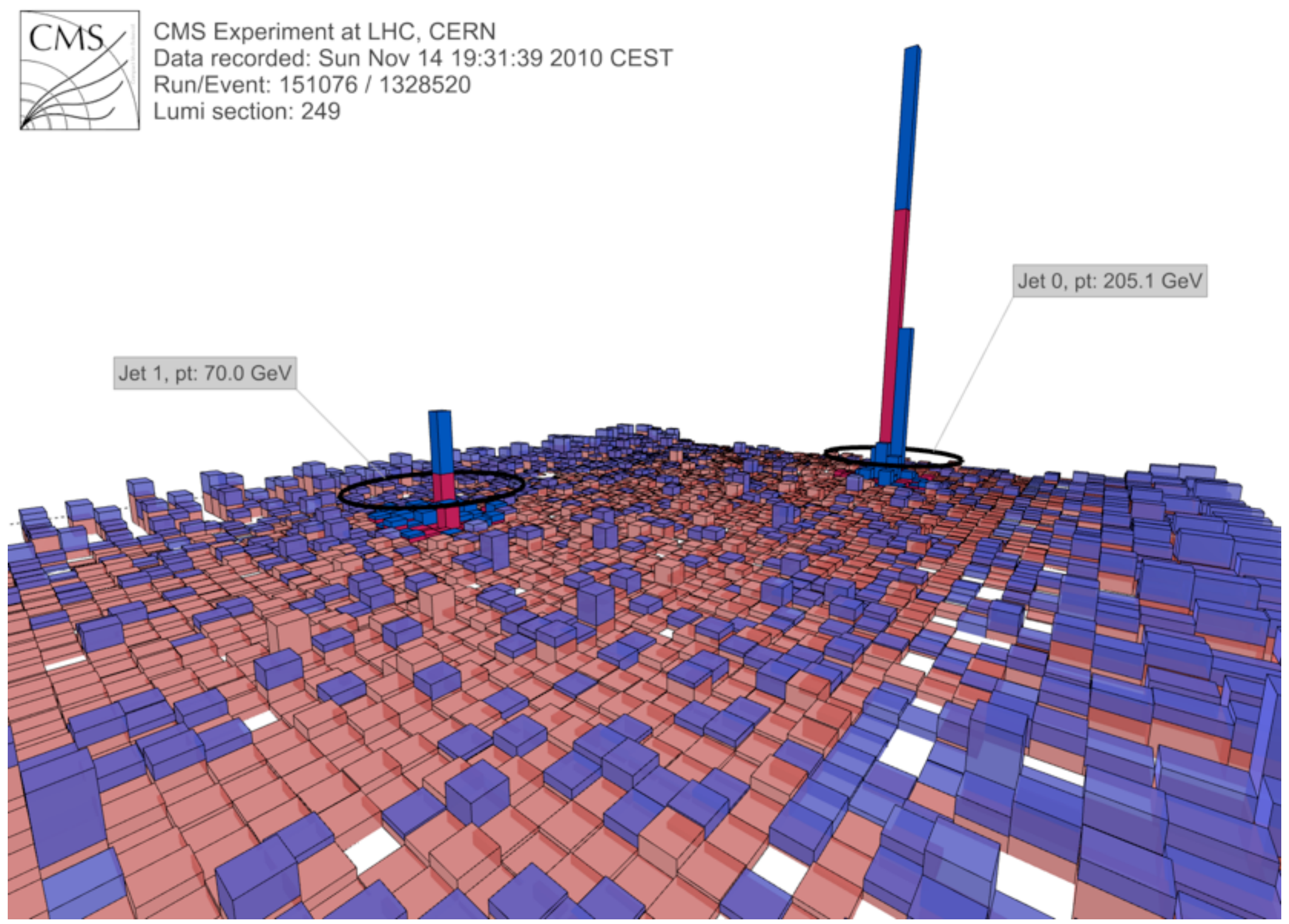
jet-QGP interaction modifies color connections in the jet and thus hadronization pattern
[in any reasonable effective model]
can learn about hadronization modifications at an EIC

if you let me do away with this, I will produce some results [bargaining]

A JET IN QGP :: JET RECONSTRUCTION

uncorrelated QGP background needs to be subtracted :: jet-correlated QGP should not :: do experimental and phenomenological procedures do the same [and the right] thing? :: how can I know?





this is probably hopeless [depression]

A JET IN QGP :: OBSERVABLES

keeping in mind all the caveats compute something that has been/you want to be measured and understand what it might be sensitive to and how it can help removing the caveats

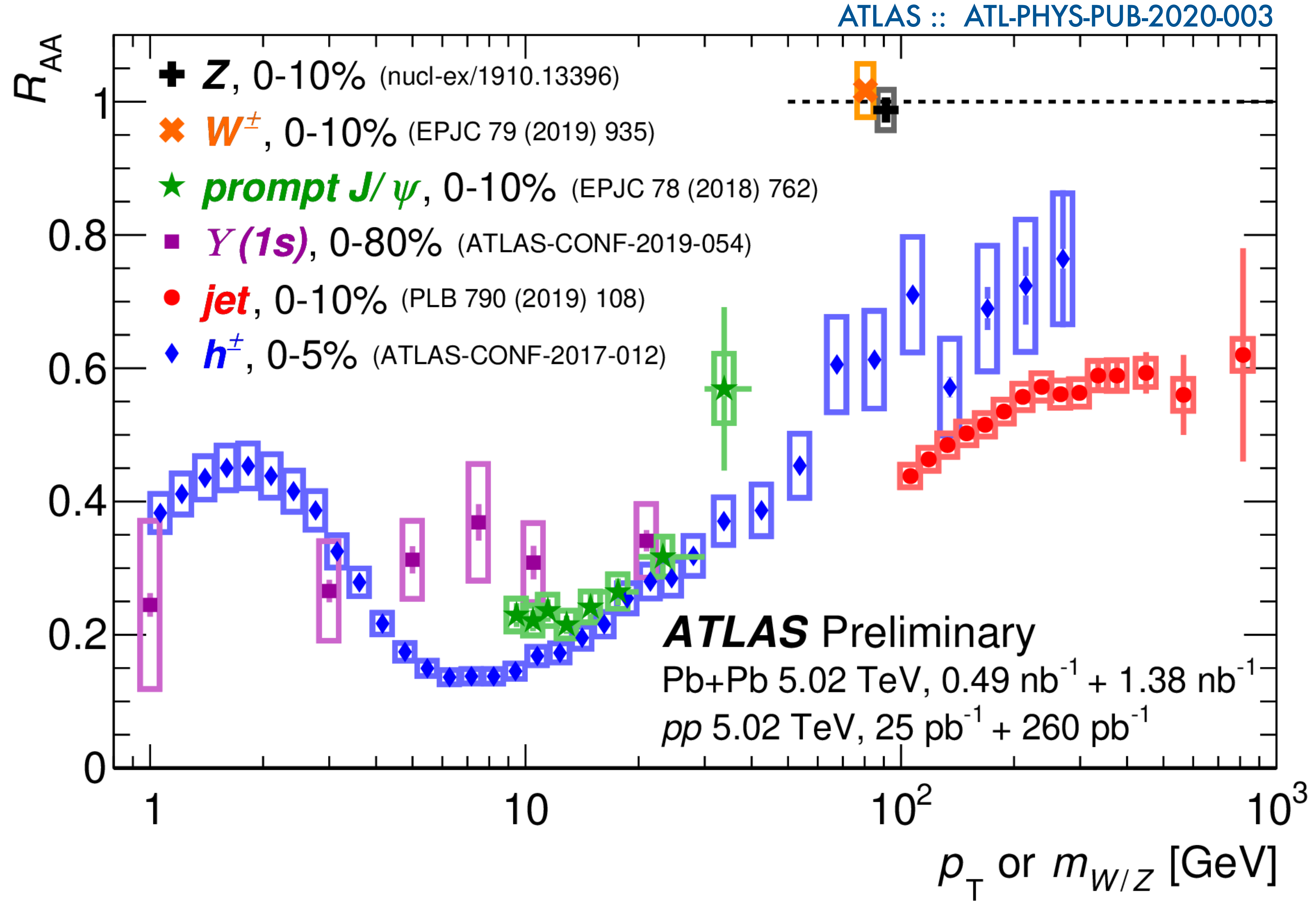
work with what you have to eventually have more [acceptance]

THE FIVE STAGES OF HEAVY ION JET PHENOMENOLOGY

denial :: anger :: bargaining :: depression :: acceptance

III. a few of the things we have learnt about jets in QGP

JETS AND HADRONS LOSE ENERGY WHEN TRAVERSING QGP



$$R_{AA} = \left.\frac{\sigma^{\text{eff}}_{\text{AA}}}{\sigma^{\text{eff}}_{\text{pp}}}\right|_{p_T}$$

$$\sigma^{\text{eff}}_{\text{pp}} = \sigma_{\text{pp}}$$

$$\sigma^{\text{eff}}_{\text{AA}} = \sigma_{\text{AA}}/\langle N_{\text{coll}}\rangle$$

essentially measures fraction of jets that lost little or no energy

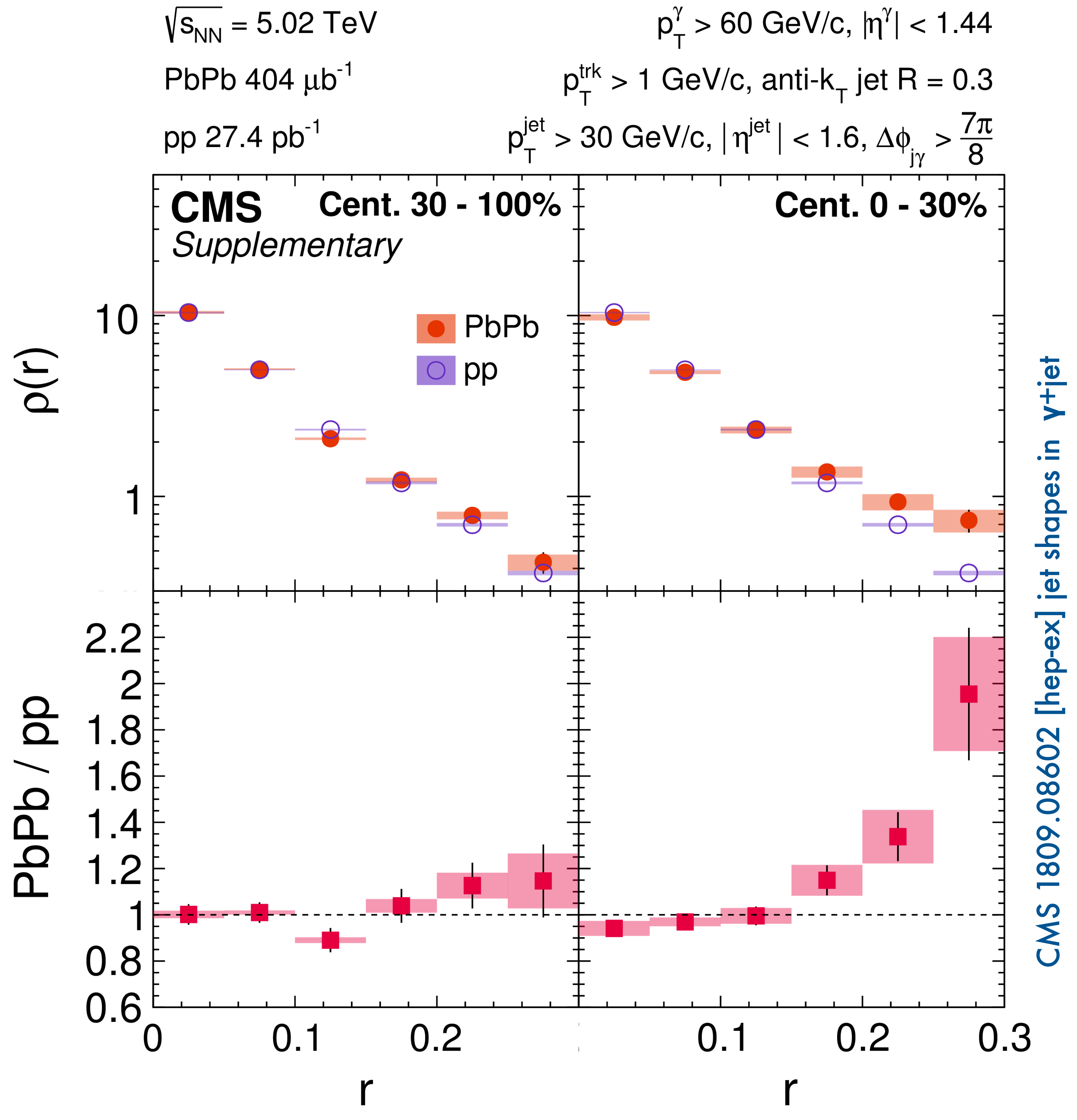
- in steeply falling spectrum large energy losses translate into very small effects
- R_{AA} provides quantitative handle on energy loss only within some model framework
- it compares jets [hadrons] that were detected with same p_T, not born alike

- R_{AA} only measures suppression :: it does not quantify energy loss in a model independent way
- both jets and hadrons (which belong to jets) are suppressed, but differently

SUPPRESSION IS NOT THE SAME AS ENERGY LOSS

- the standard approach to assess QGP effects on jets [quenching] compares a given observable in AA and pp collisions for jets with the same reconstructed p_t
  - e.g., a jet shape

$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{r_a<r<r_b} (p_T^{\text{trk}} / p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{0<r<r_f} (p_T^{\text{trk}} / p_T^{\text{jet}})},$$



comparison between AA and pp at same reconstructed jet p_t confounds QGP-induced shape modification with bin-migration effects

- here the comparison is between jets that were born different
- again, some model framework that must be invoked for assessment of what was modified in a jet

BETTER CAN DE DONE

Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]

- divide jet samples sorted in p_t [from highest] in quantiles of equal probability
- compare the p_t of jets in AA and pp in *the same quantile*

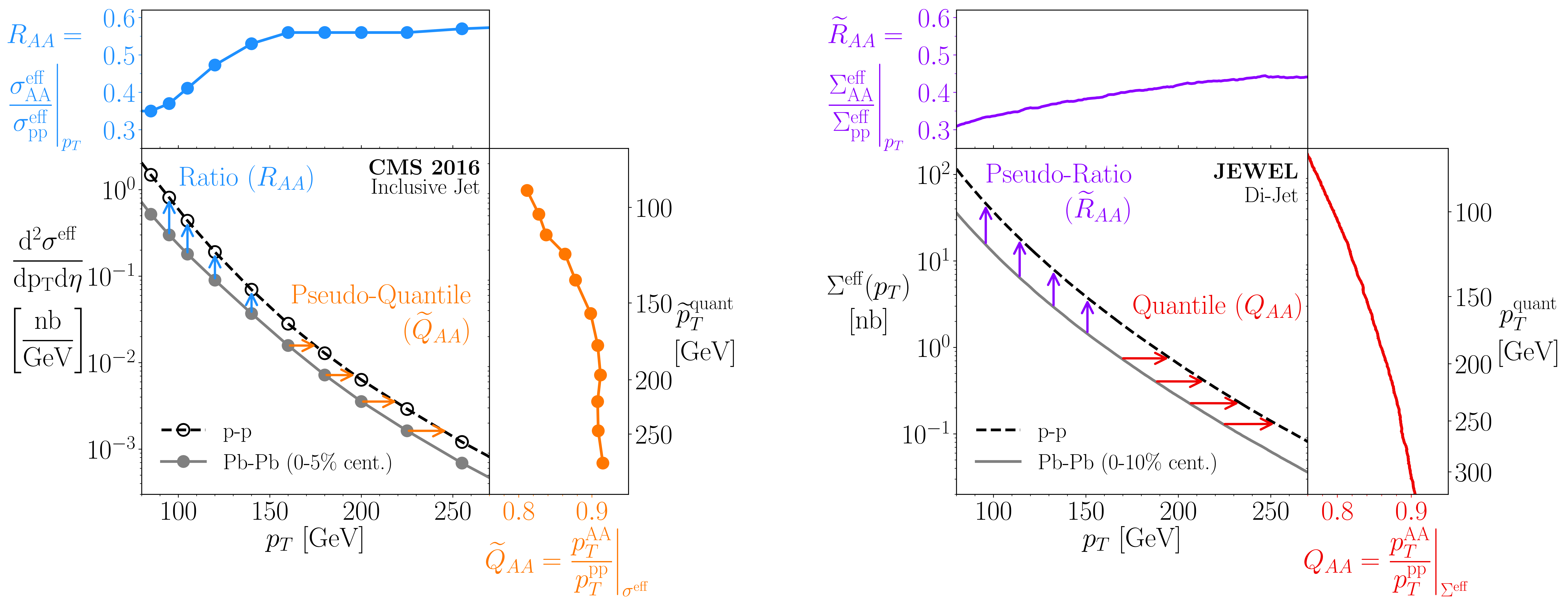
$$Q_{AA} = \left. \frac{p_T^{\rm AA}}{p_T^{\rm pp}} \right|_{\Sigma^{\rm eff}}$$

$$\Sigma^{\rm eff}(p_T^{\rm min}) = \int_{p_T^{\rm min}}^{\infty} {\rm d}p_T \, \frac{{\rm d}\sigma^{\rm eff}}{{\rm d}p_T}$$

(1-QAA) is a proxy for the average energy loss :: would be exact if energy loss was strictly monotonic

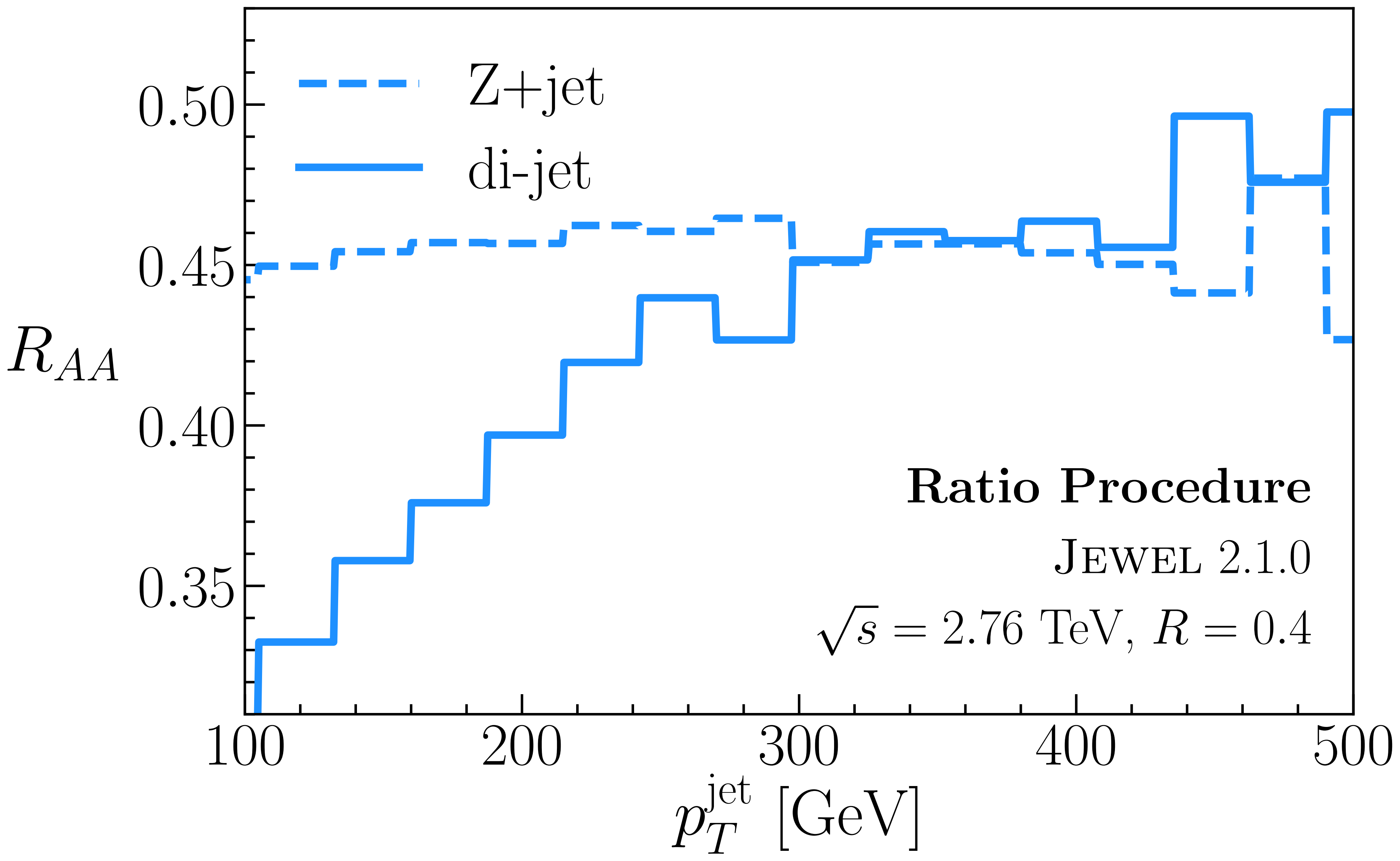
QUANTILE PROCEDURE

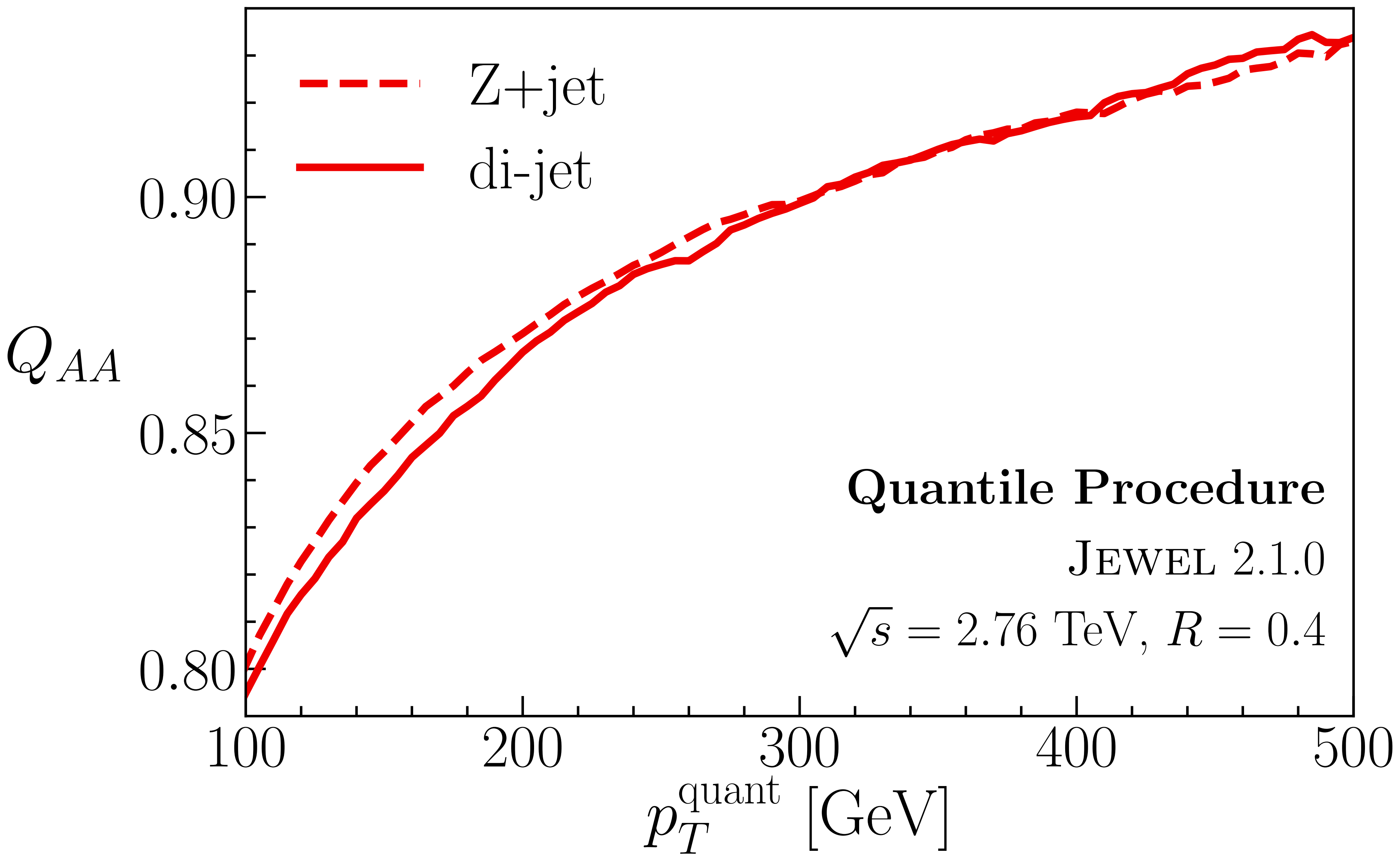
Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]



COMPLEMENTARY INFORMATION

Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]

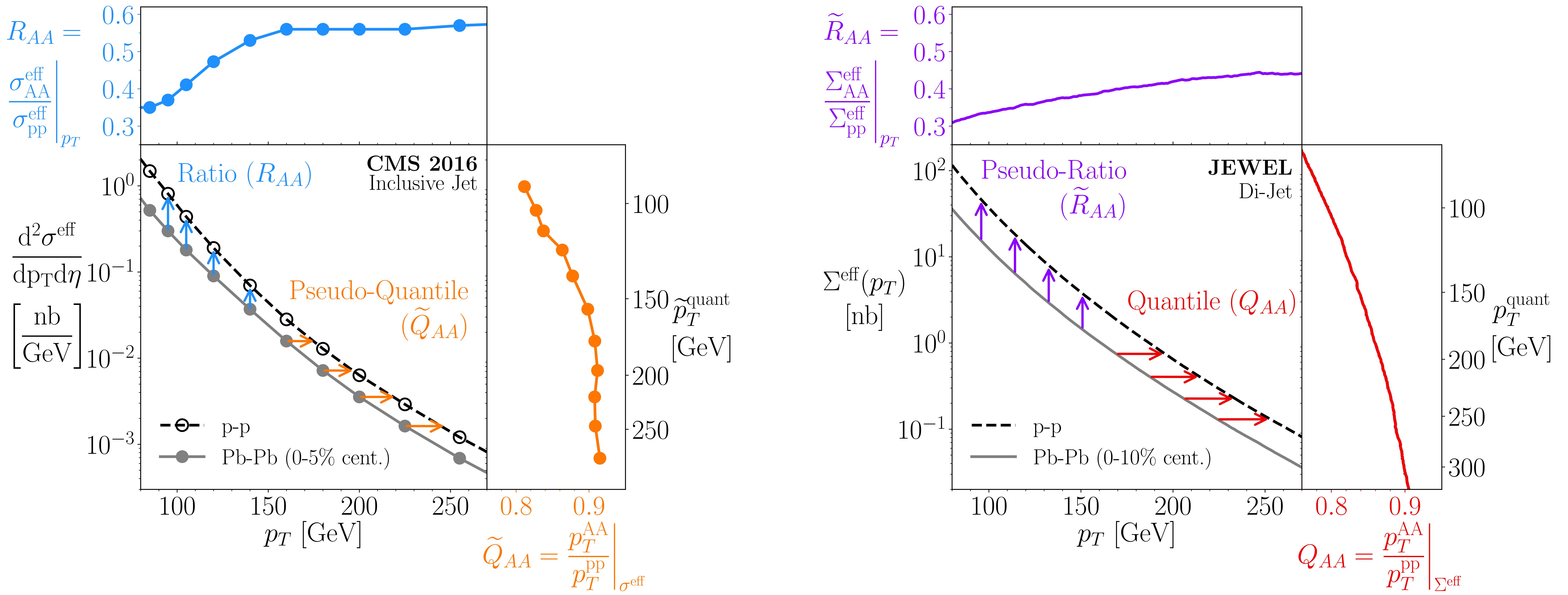




- Q_{AA} and R_{AA} provide very different information
  - R_{AA} depends on different spectral shape for quark and gluon initiated jets :: Q_{AA} does not

QUANTILE PROCEDURE AS PROXY FOR INITIAL ENERGY

Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]

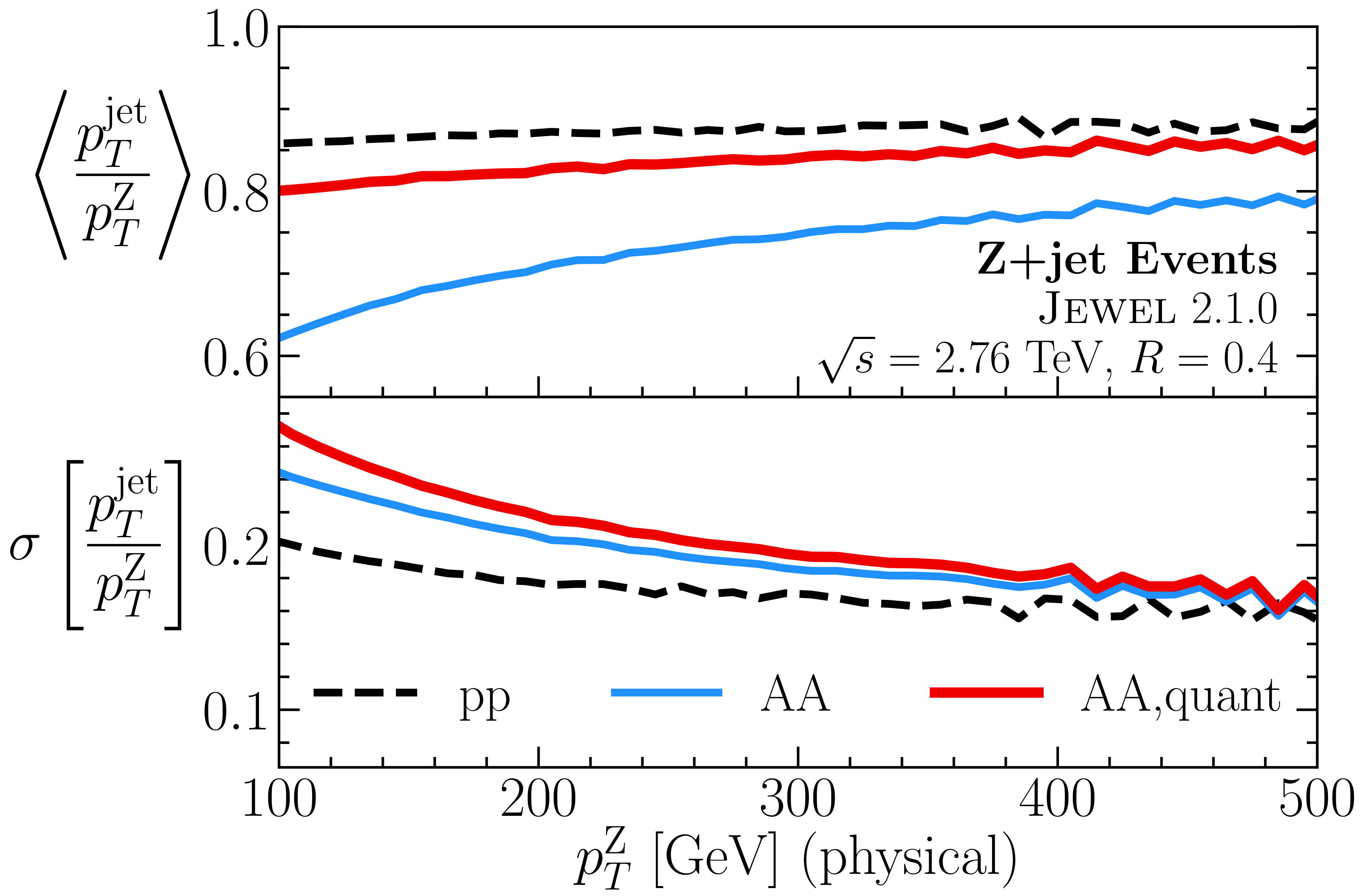


- provides a proxy for the initial p_t of a quenched [prior to QGP-induced energy loss]

$$\Sigma^{\rm eff}_{\rm pp}(p_T^{\rm quant}) \equiv \Sigma^{\rm eff}_{\rm AA}(p_T^{\rm AA})$$

VALIDATION IN Z+JET

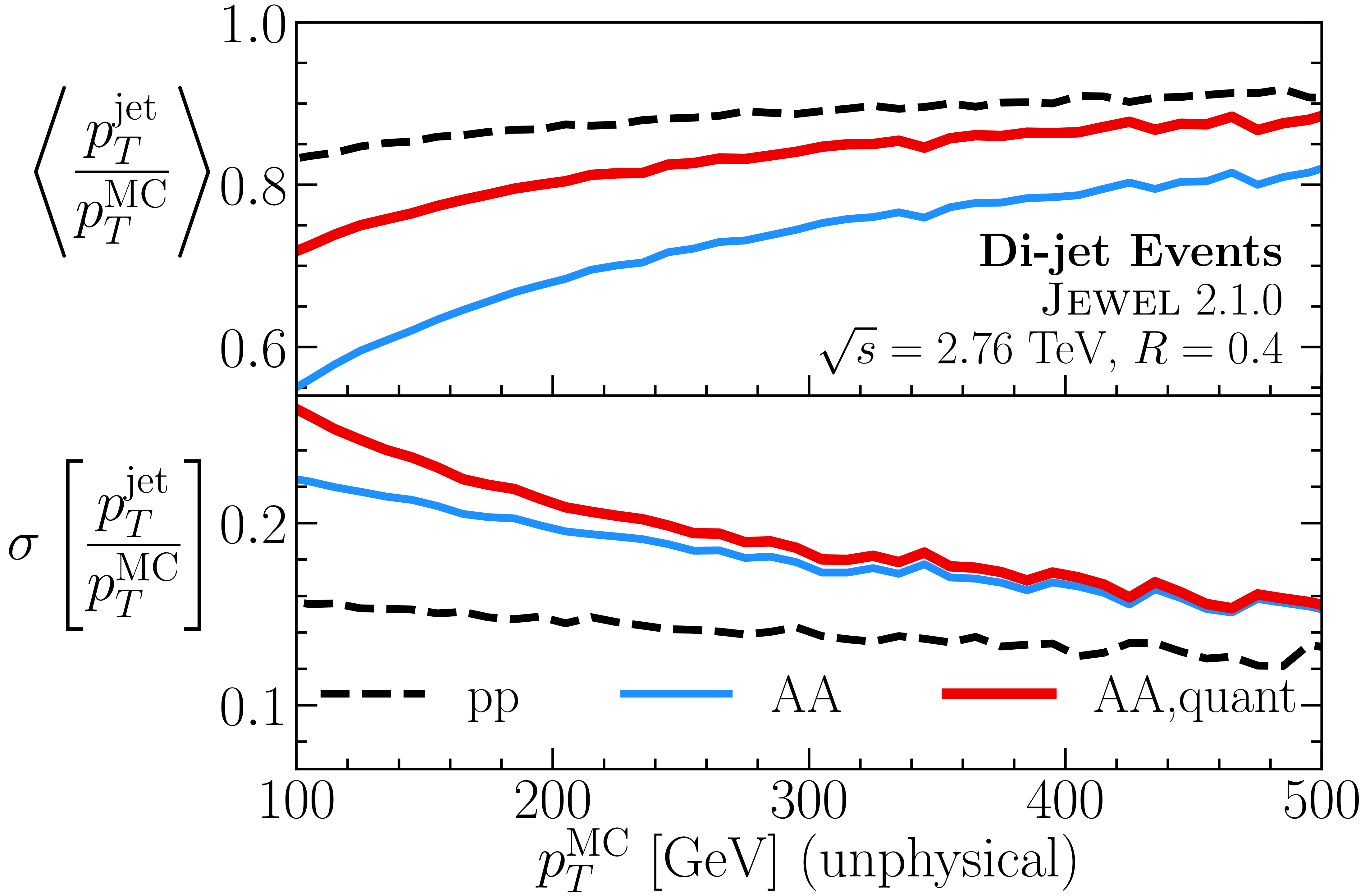
Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]



- quantile procedure closely reconstructs unquenched [initial] p_t :: in this case measurable
- quantile procedure cannot [yet] undo fluctuations

PERFORMANCE IN DI-JET EVENTS

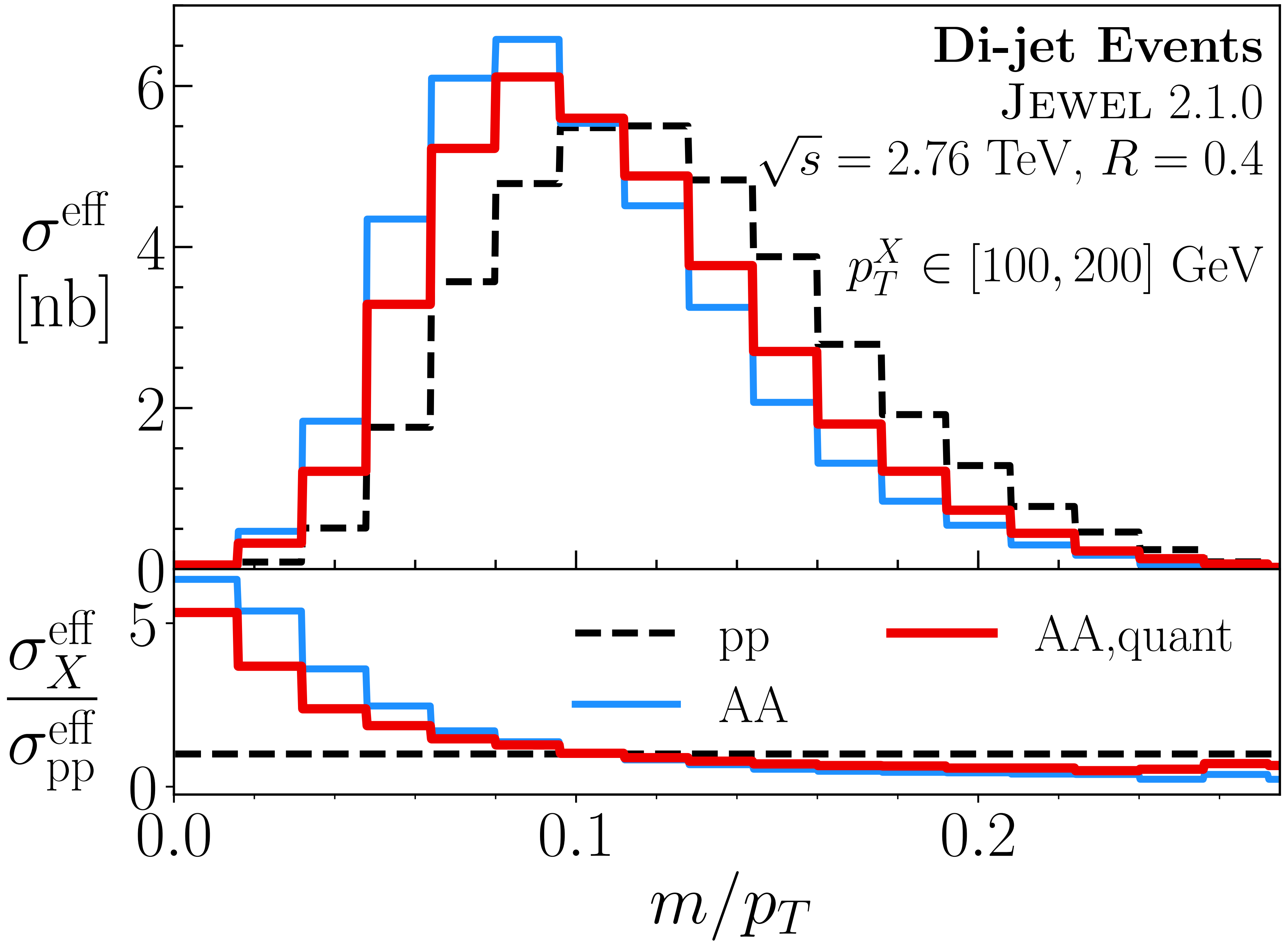
Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]



- similar performance to Z+jet
- access to unmeasurable quantity :: allows for comparison of large statistics samples of jets that were born fairly equal

MITIGATION OF MIGRATION EFFECTS :: AN EXAMPLE

Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]

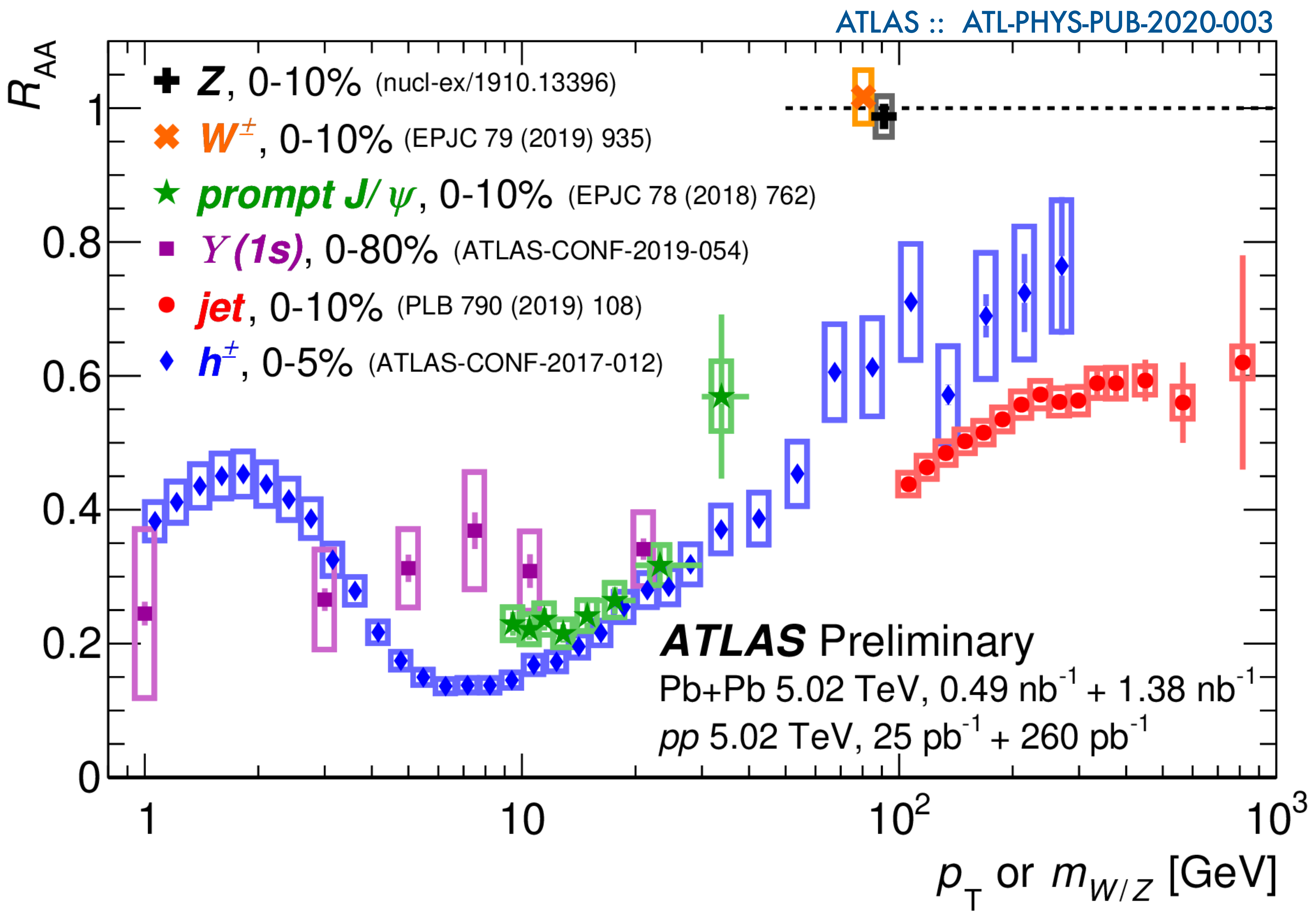


$p_T^{\text{AA}} \in [80, 173]$ GeV

$p_T^{\text{quant}} \in [100, 200]$ GeV

- part of observable modification due to bin migration [comparison of jets with different initial energy]
- quantile procedure isolates 'true' modification

JETS AND HADRONS LOSE ENERGY WHEN TRAVERSING QGP



$$R_{AA} = \left.\frac{\sigma^{\rm eff}_{\rm AA}}{\sigma^{\rm eff}_{\rm pp}}\right|_{p_T}$$

$$\sigma^{\rm eff}_{\rm pp} = \sigma_{\rm pp}$$

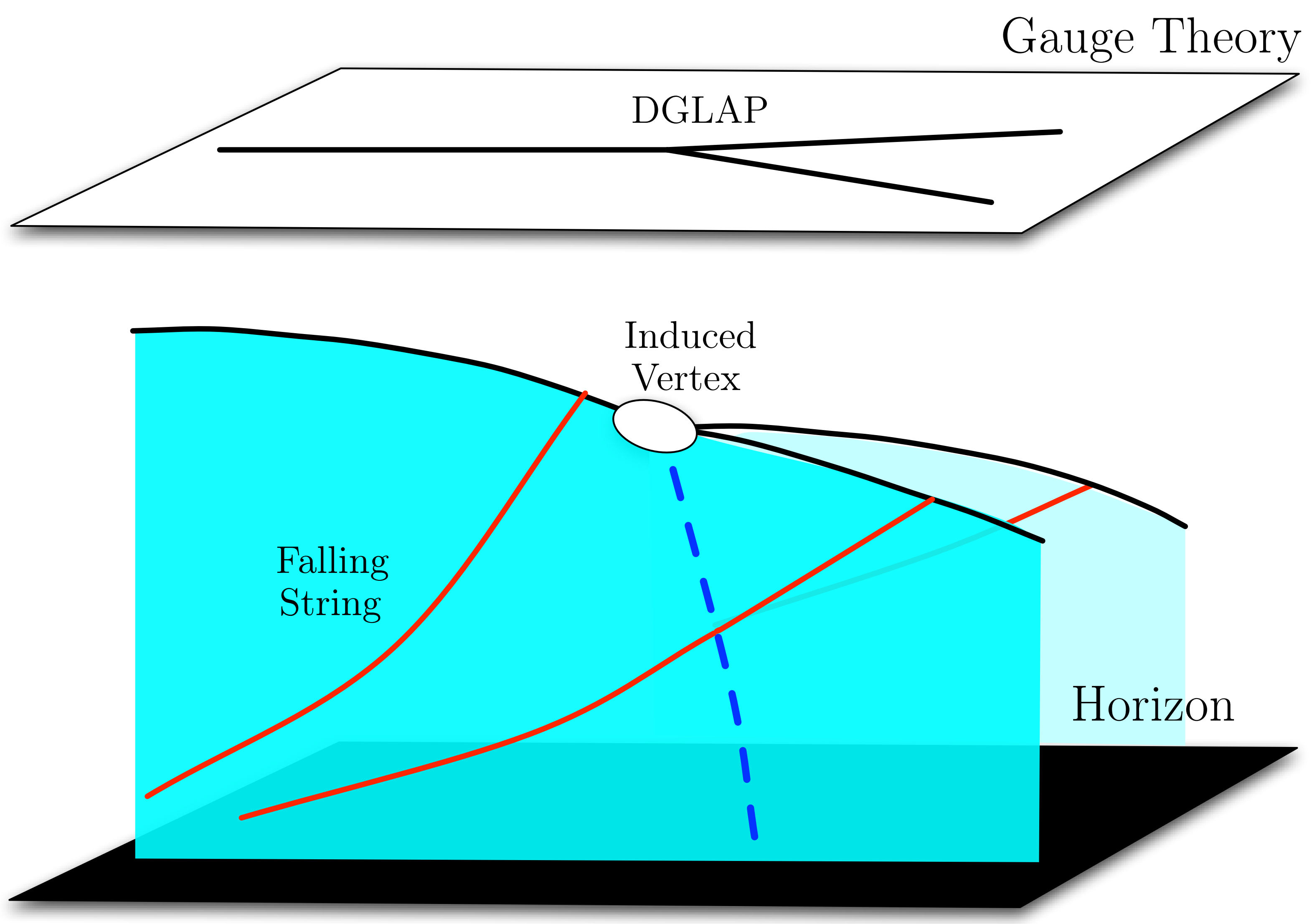
$$\sigma^{\rm eff}_{\rm AA} = \sigma_{\rm AA}/\langle N_{\rm coll}\rangle$$

- both jets and hadrons (which belong to jets) are suppressed, but differently
  - can the difference be understood? is it important?

UNDERSTANDING DIFFERENT SUPPRESSION OF JETS AND HADRONS

- essential to describe both within same theoretical framework
  - here in the strong/weak coupling hybrid model [conclusions are general]

[Can Gulan, Hulcher, Yao], Casalderrey, Milhano, Pablos, Rajagopal :: since 2014



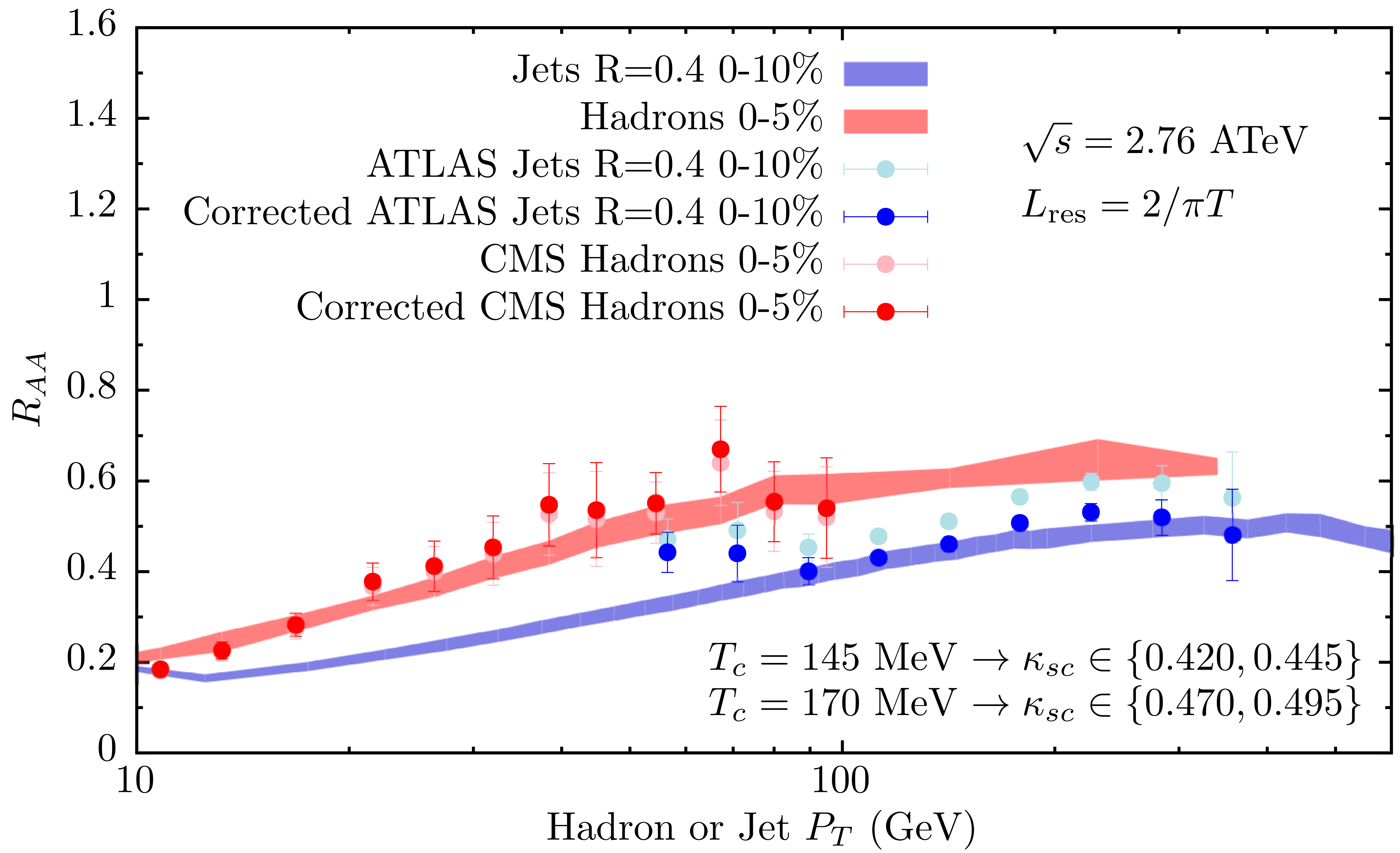
- physics at different scales merit different treatments
  - vacuum jets where each parton loses energy non-perturbatively [as given by a holographic AdS-CFT calculation]
- lost energy becomes a wake [QGP response], part of which will belong to the jet

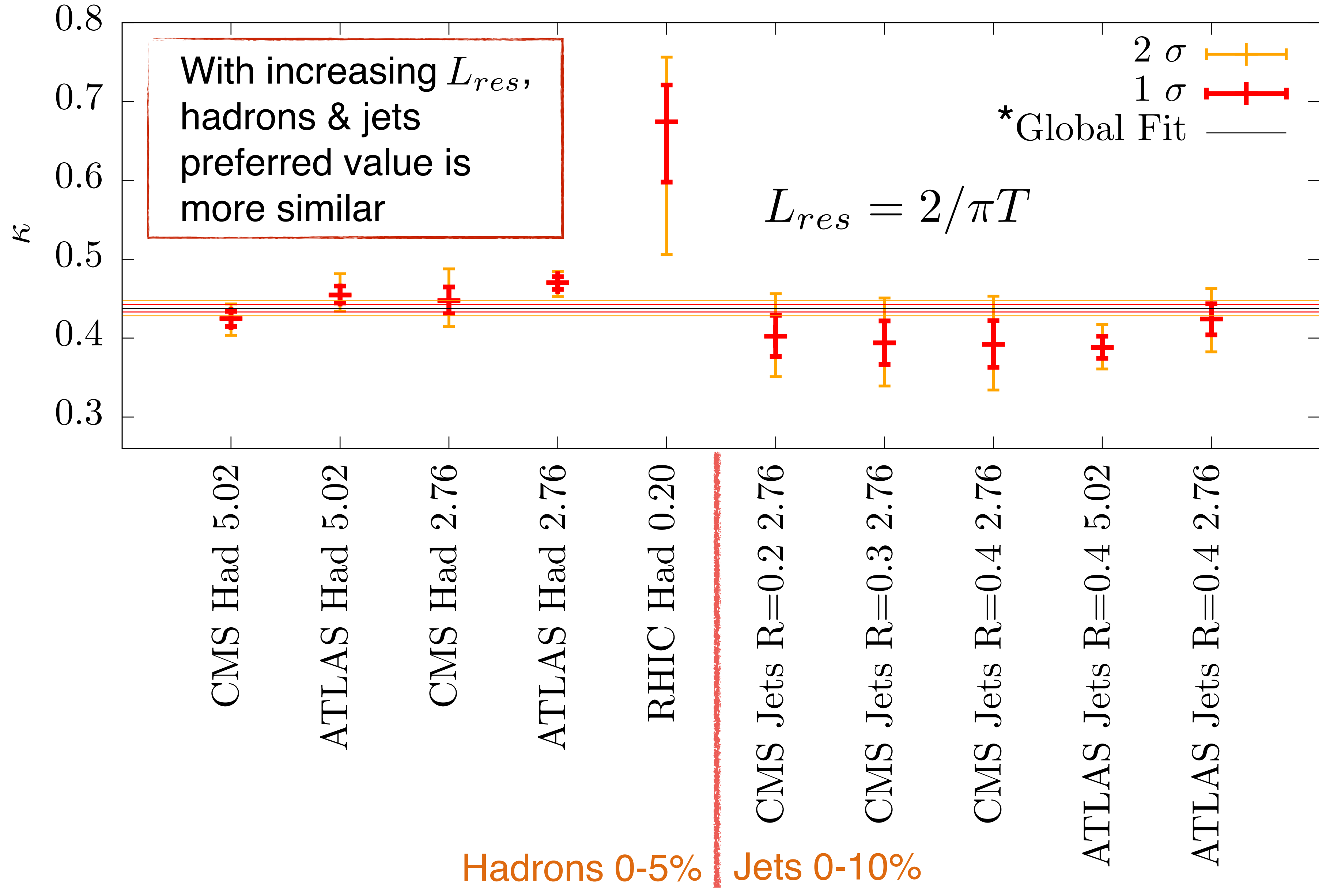
$$\left.\frac{dE}{dx}\right|_{\text{strongly coupled}} = -\frac{4}{\pi} E_{\text{in}} \frac{x^2}{x_{\text{stop}}^2} \frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}} , \qquad x_{\text{stop}} = \frac{1}{2\kappa_{\text{sc}}} \frac{E_{\text{in}}^{1/3}}{T^{4/3}}$$

single free parameter
[accounts for QCD/N=4 SYM differences]

wide and narrow jets :: jet and hadron R_{AA}

Casalderrey, Hulcher, Milhano, Pablos, Rajagopal :: 1808.07386 [hep-ph]

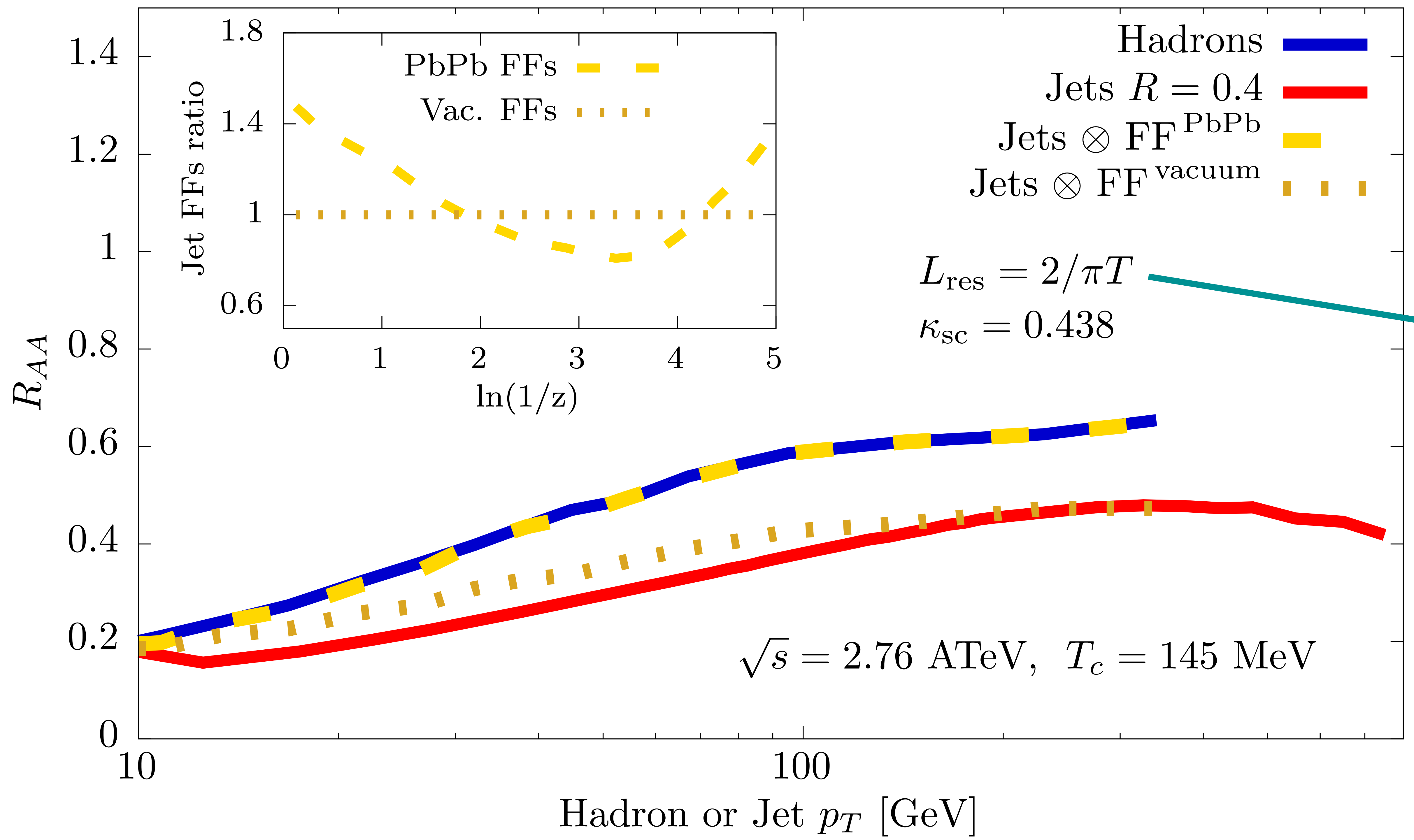




- excellent global fit for LHC data :: tension with RHIC data
- high p_T hadrons originate from narrow jets [fragmented less] which are less suppressed than inclusive jets
- simultaneous description of jet and hadron R_{AA} natural feature of any approach that treats jets as such [ie, objects with internal structure]

wide and narrow jets :: jet and hadron R_{AA}

Casalderrey, Hulcher, Milhano, Pablos, Rajagopal :: 1808.07386 [hep-ph]



the QGP resolution power

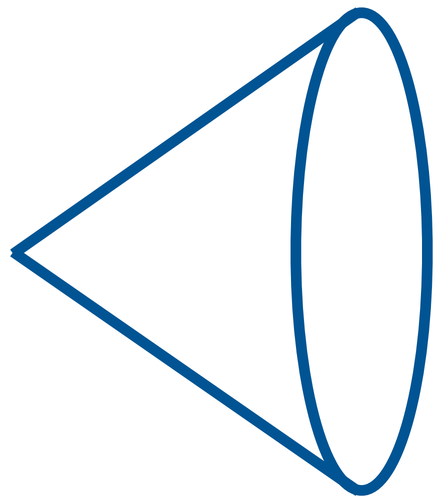
- modification of FF is essential for joint description :: jets change
- QGP resolves the internal partonic structure of a jet

VERY IMPORTANT LESSONS

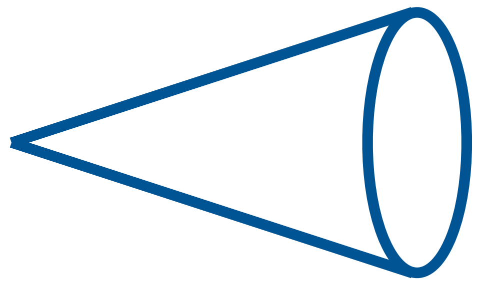
- the QGP resolves the partonic structure of an evolving branching sequence
    - this is a highly non-trivial statement
        - quark and gluons [partons] are NOT asymptotic states [an infinite resolution spacetime detector/tracker CANNOT see partons] :: the QGP allows us to 'see' them
        - evolving branching sequence resolves the QGP
            - explore sub-structure to see spatio-temporal dynamics of QGP [a lot of ongoing work]
- jet quenching depends strongly on branching 'width'
    - branching 'width' is dictated [because QCD is angular ordered] by first branching step
    - first branching step occurs before QGP forms :: it is vacuum physics
    - vacuum physics drives jet quenching

the importance of vacuum-like parton branching in QGP

- parton branching in vacuum driven by initial mass [p^2] and species [quark or gluon], and angular ordered
- scale of first splitting defines jet envelope



large m^2 :: wide jet :: more constituents



small m^2 :: narrow jet :: fewer constituents

- vacuum-like evolution at play, and dominant, within QGP :: jets are modified not re-invented
  - first splitting in QGP always vacuum-like [very short formation time]
  - number of constituents largely determined by vacuum-like physics

a reasonable question:

can quenched jets be distinguished

from unquenched

[vacuum or those that escaped QGP without significant modification]

on a jet-by-jet basis ?

IV. can a machine learn to tell them apart?

CLASSIFICATION OF QUENCHED JETS

Apolinário, Castro, Crispim Romão, Milhano, Pedro, Peres, :: *JHEP* 11 (2021) 219

- jet representations [for JEWEL+PYTHIA jets in Z+jet] with varying theoretical input for different ML/DL architectures
  - jet images :: 2-channel [p_T and multiplicity] calorimetric images in a grid centred on jet axis :: Convolutional Neural Network (CNN) :: channels both normalized and unnormalized
  - Lund plane coordinates :: (kT, ΔR) for primary branch of C/A [angular ordered] declustering of jet :: Recurrent Neural Network (RNN)
  - Tabular data :: global (pT and multiplicity) for each jet :: Dense Neural Network (DNN)
    - benchmark case with minimal information

JET IMAGES :: CNN

Apolinário, Castro, Crispim Romão, Milhano, Pedro, Peres, :: *JHEP* 11 (2021) 219

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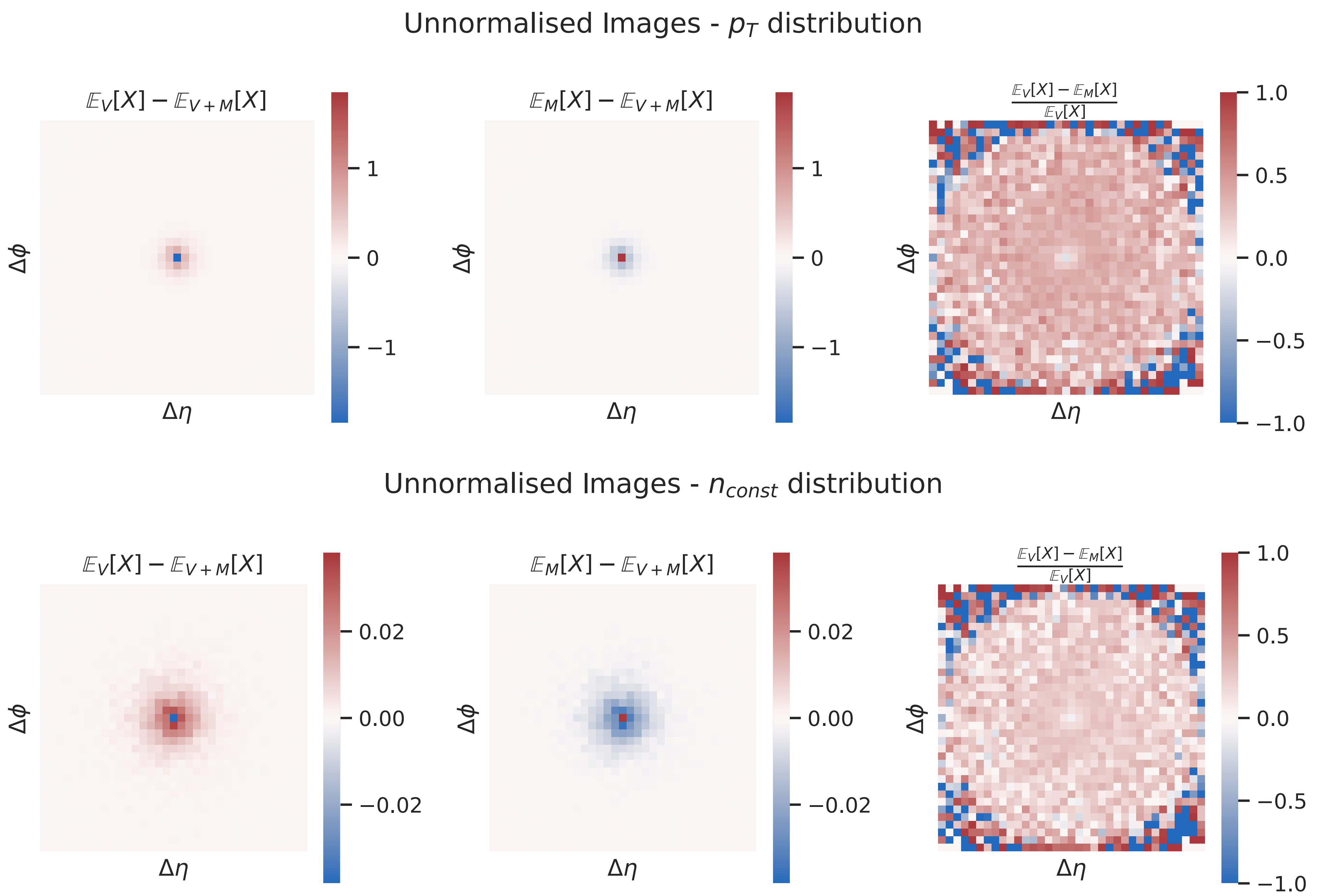
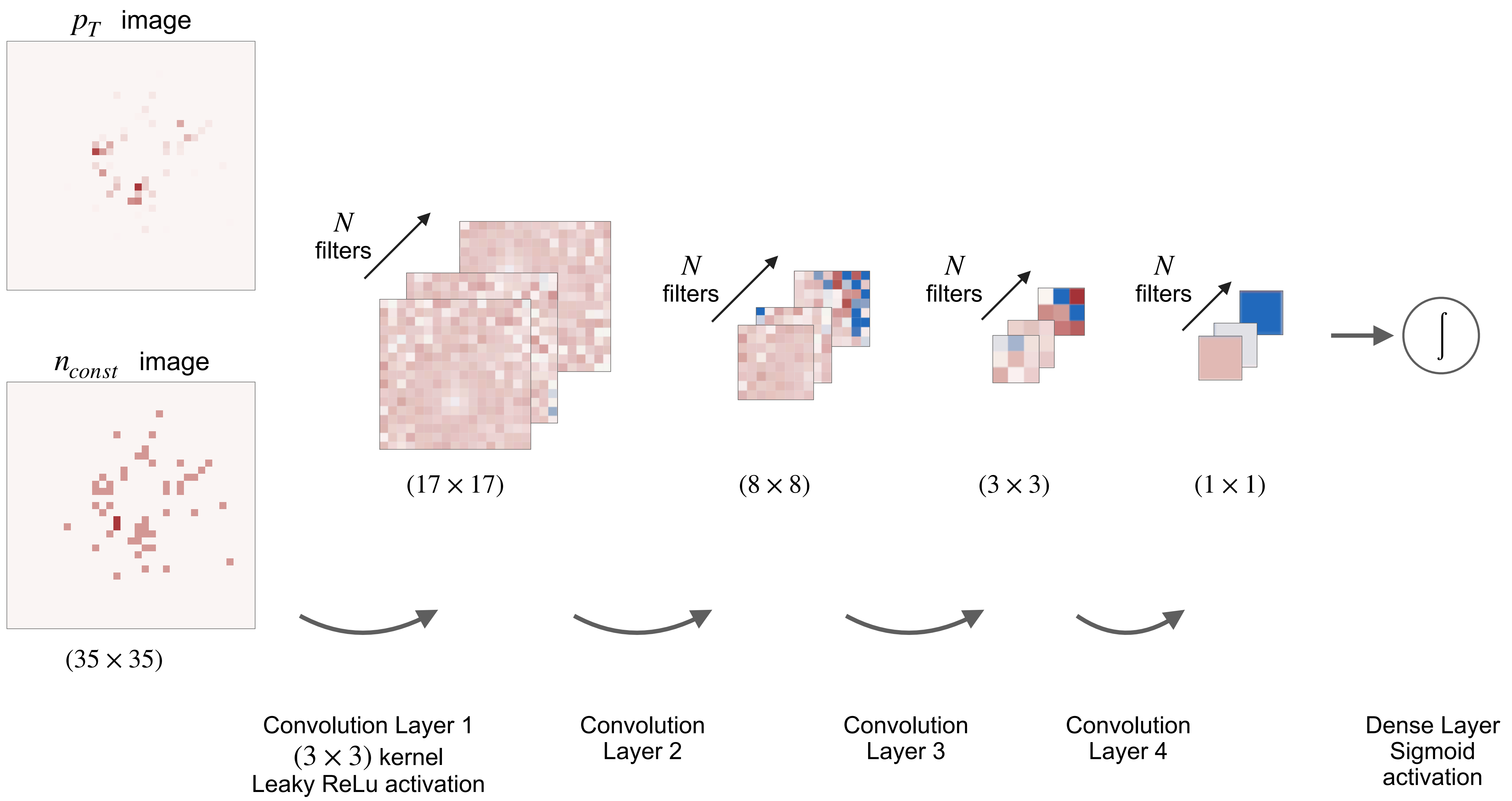


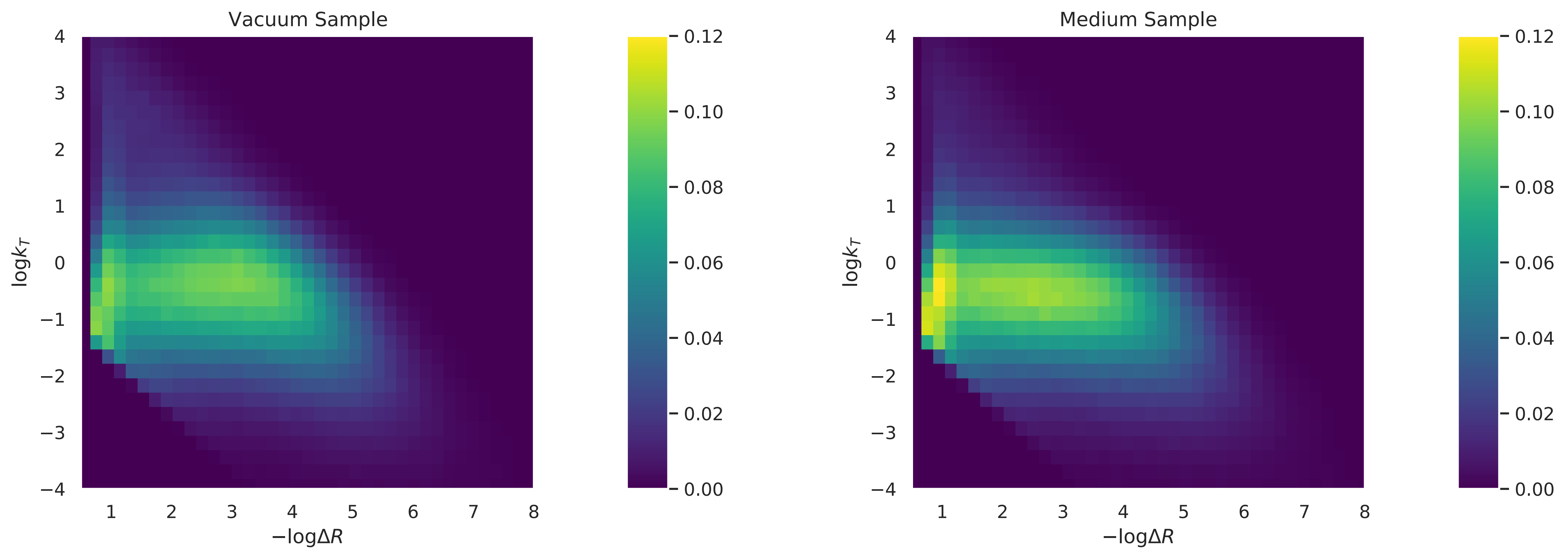
$$\mathbb{E}_{V+M}[X] = \frac{1}{2}(\mathbb{E}_V[X] + \mathbb{E}_M[X])$$



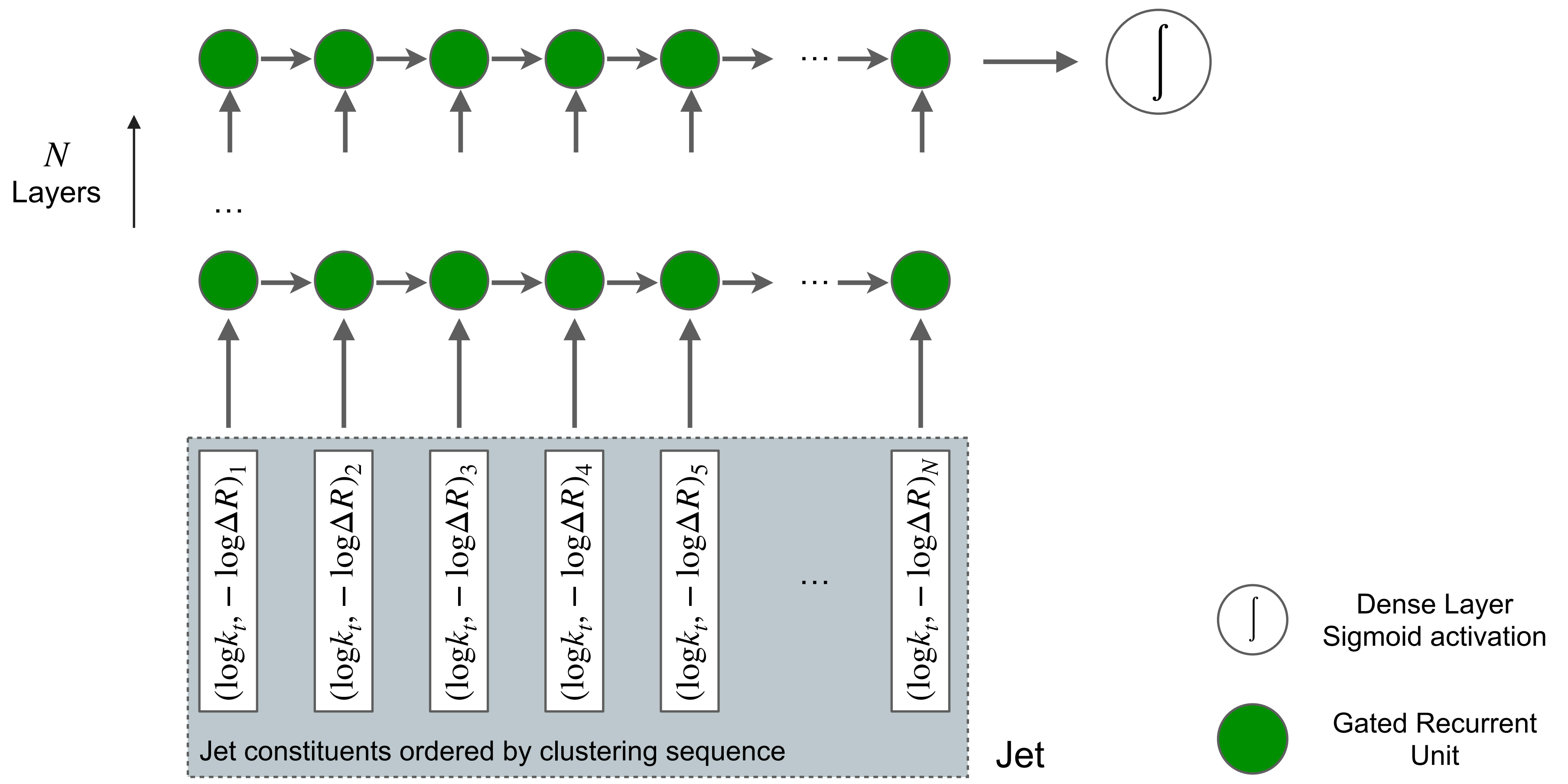
CLASSIFICATION OF QUENCHED JETS

Apolinário, Castro, Crispim Romão, Milhano, Pedro, Peres, :: *JHEP* 11 (2021) 219

- Lund plane coordinates :: Recurrent Neural Network (RNN) :: sensitive to sequence of inputs



- decluster jet according to C/A distance [angular distance]
- record (kT, ΔR) for branching
- follow hardest branch and repeat



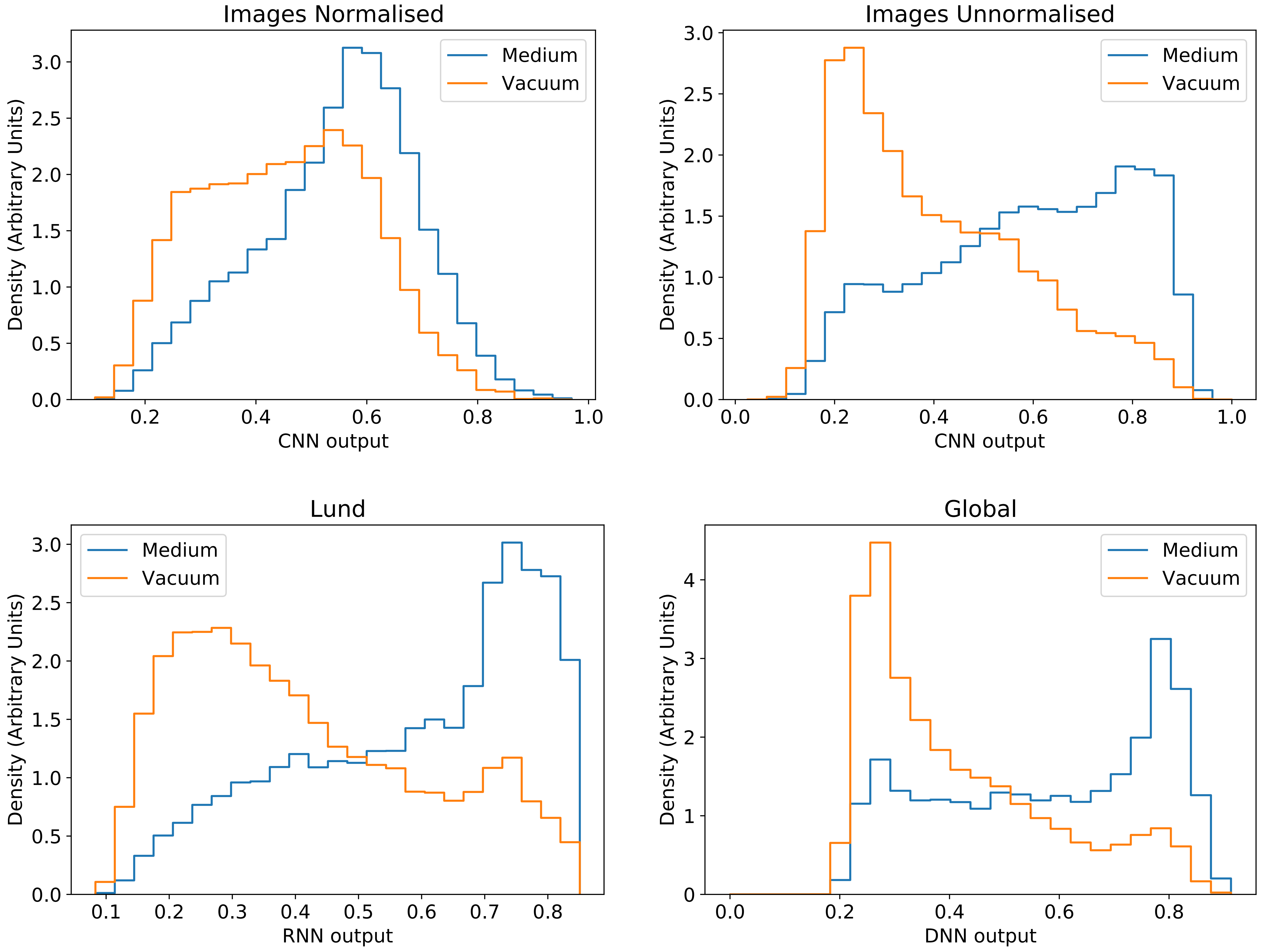
CLASSIFICATION OF QUENCHED JETS

Apolinário, Castro, Crispim Romão, Milhano, Pedro, Peres, :: *JHEP* 11 (2021) 219

- Tabular data :: global jet properties (pT and multiplicity) for each jet :: Dense Neural Network (DNN)
    - benchmark case with no sub-structure information

NETWORK OUTPUTS :: DISCRIMINANTS

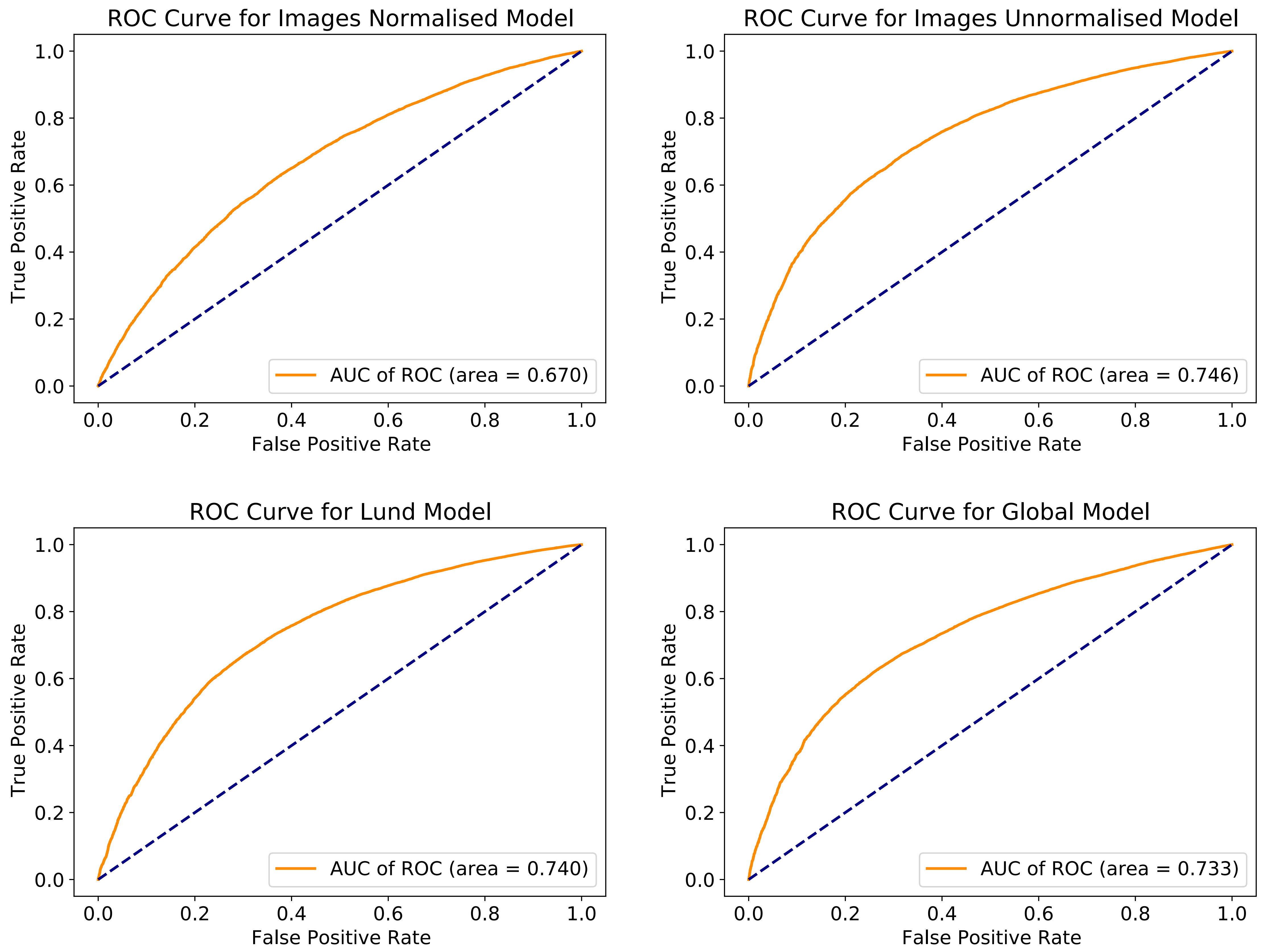
Apolinário, Castro, Crispim Romão, Milhano, Pedro, Peres, :: *JHEP* 11 (2021) 219



- all inputs/architectures yield reasonable discriminants
- normalized [pT indep] images appear somehow inferior

PERFORMANCE

Apolinário, Castro, Crispim Romão, Milhano, Pedro, Peres, :: *JHEP* 11 (2021) 219

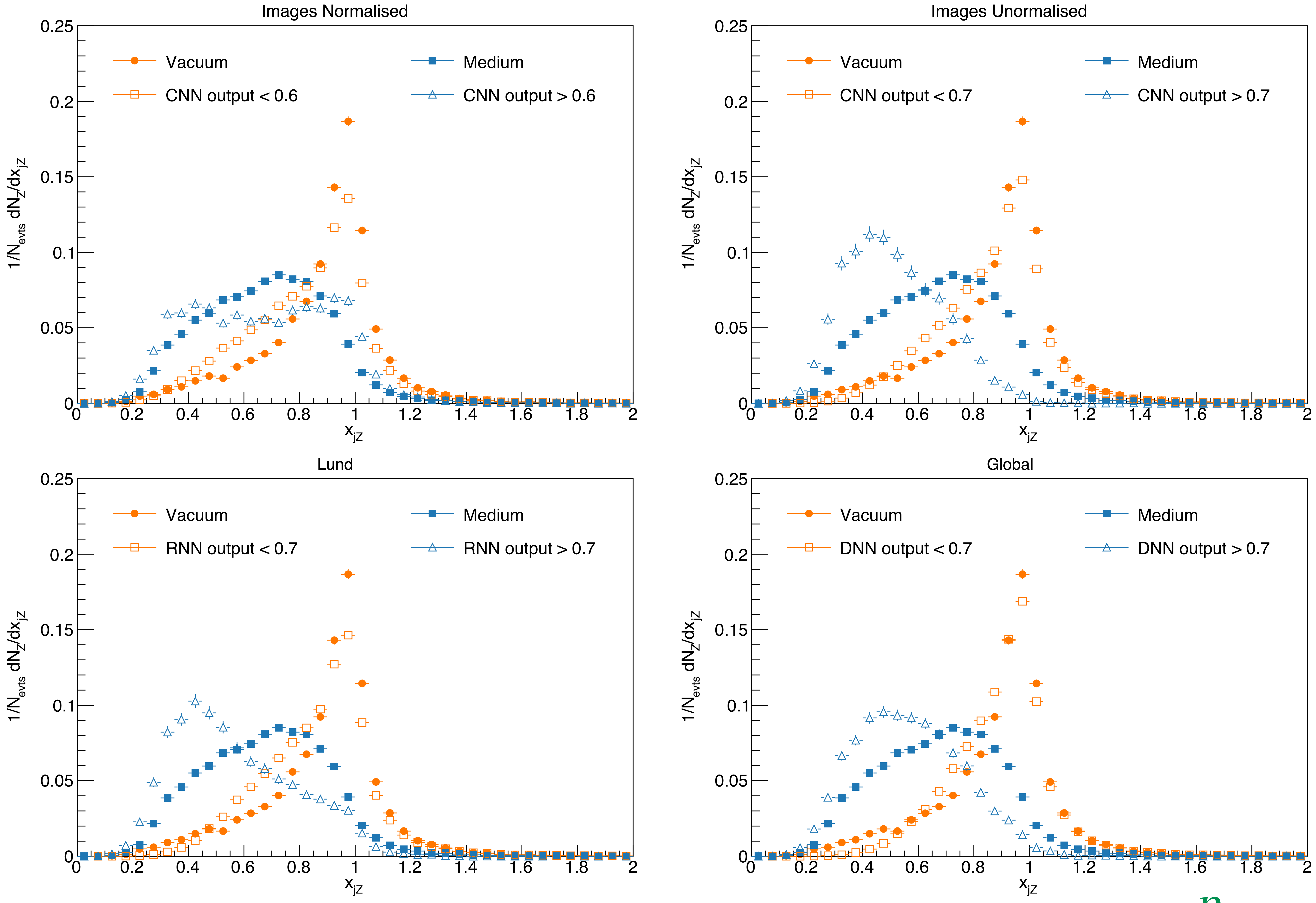


Model	$p_{T,jet}$ >30 GeV	$p_{T,jet}$ >125 GeV
Normalised jet images CNN	0.67	0.65
Unnormalised jet images CNN	0.75	0.68
Lund sequences RNN	0.74	0.69
Global DNN	0.73	0.64

- less discrimination with normalized images BUT more robust across different pT

IS THE MACHINE TELLING QUENCHED AND UNQUENCHED APART ?

Apolinário, Castro, Crispim Romão, Milhano, Pedro, Peres, :: *JHEP* 11 (2021) 219



- vacuum jets consistently identified as unquenched
- medium jets a mixture of quenched and unquenched
- quenched sample more modified that all-medium

momentum imbalance

$$x_{jZ} = \frac{p_{T,j}}{p_{T,Z}}$$

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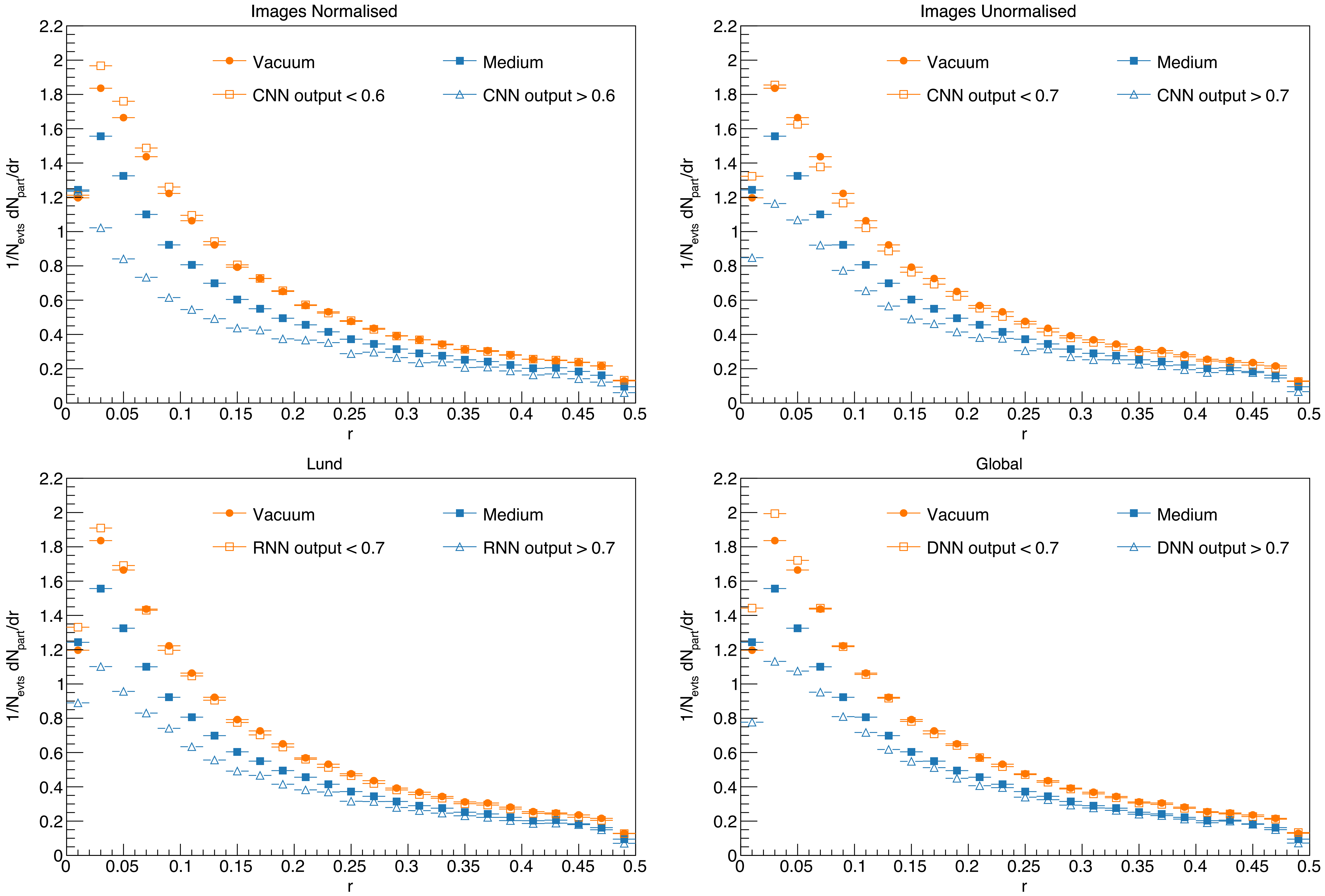

jet profile

- vacuum jets consistently identified as unquenched
- medium jets a mixture of quenched and unquenched
- quenched sample more modified that all-medium
- consistent picture across all observables

CORRELATION OF OUTPUTS

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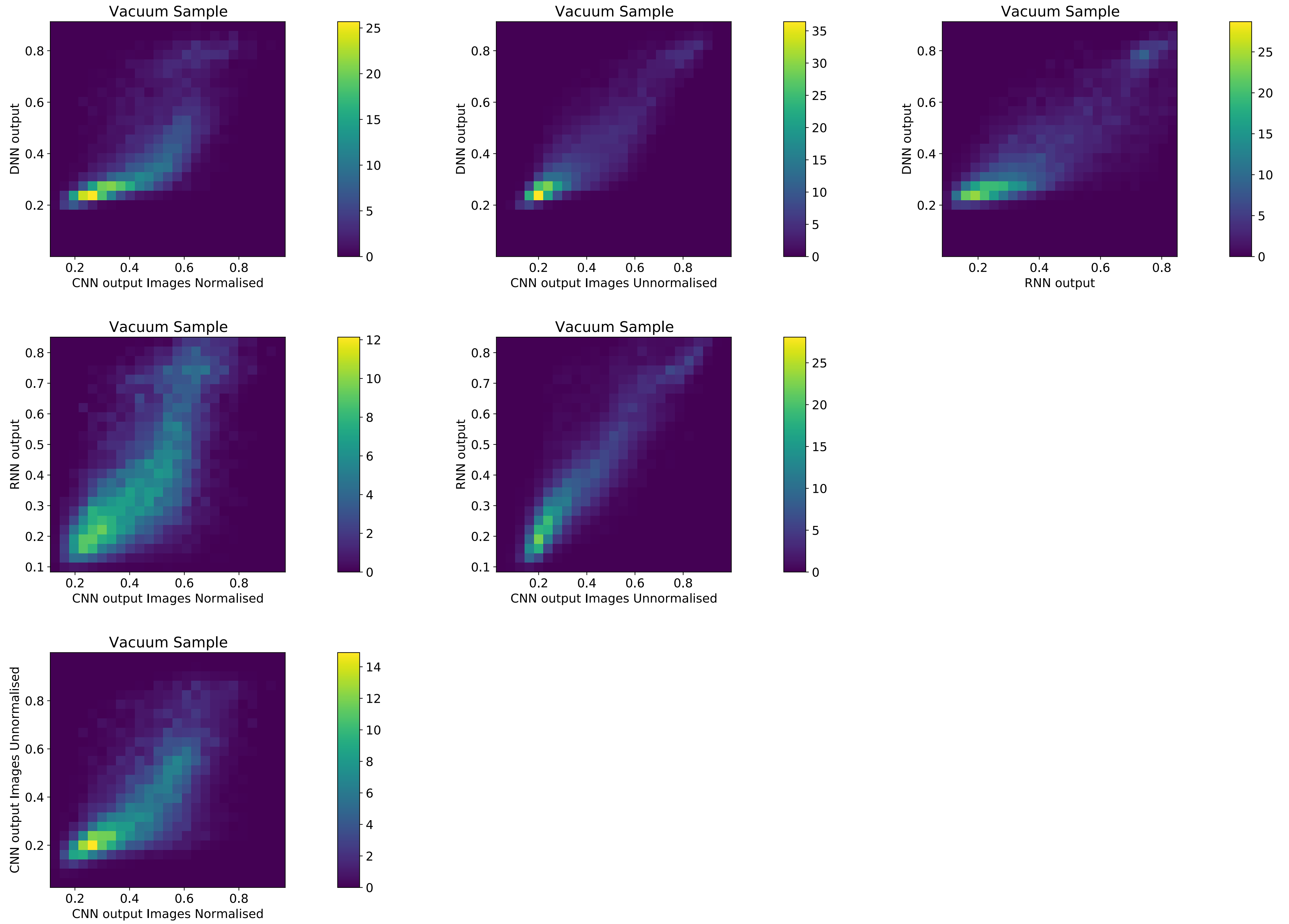
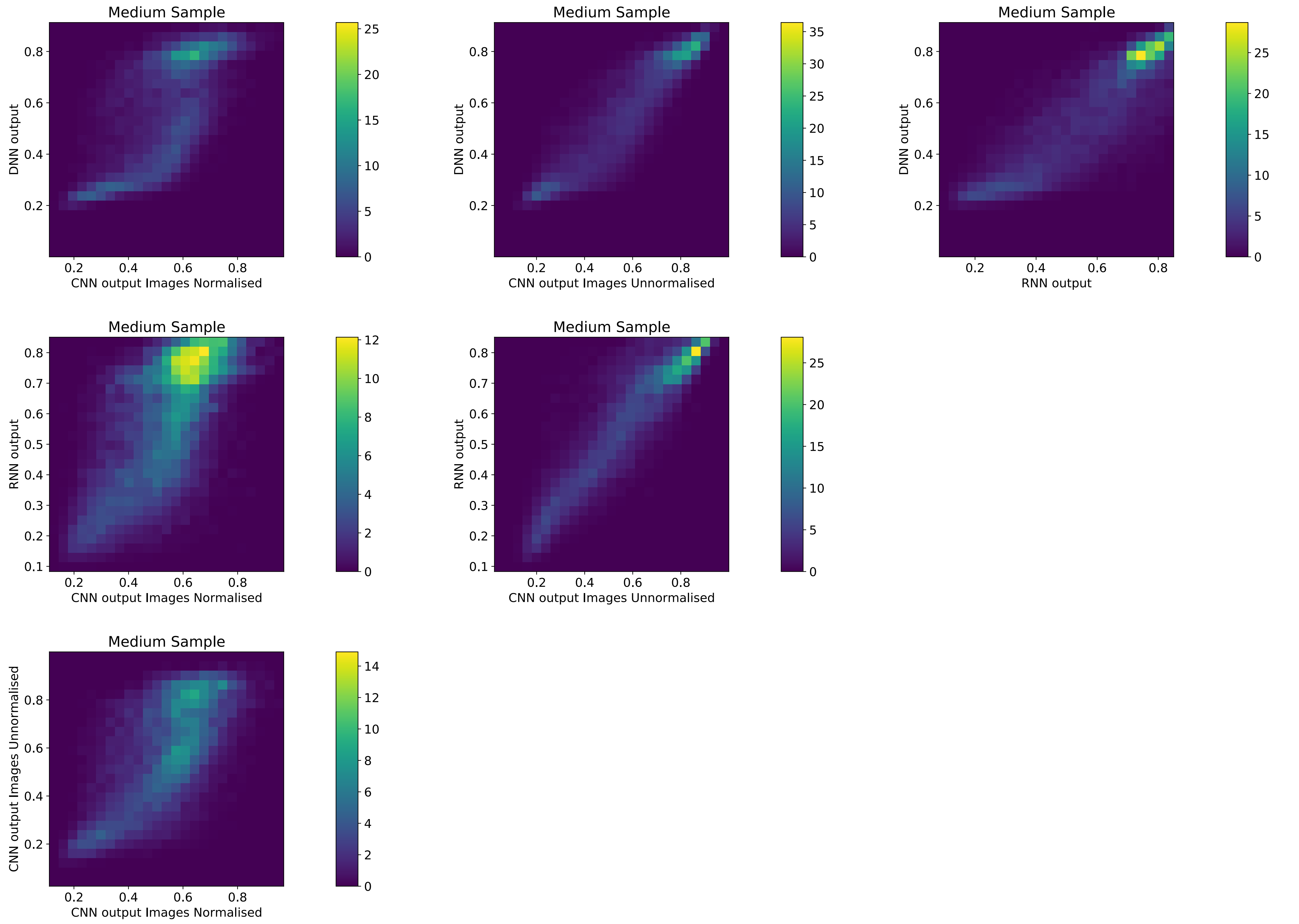




linear correlation between outputs of different indicates that same information is being learnt

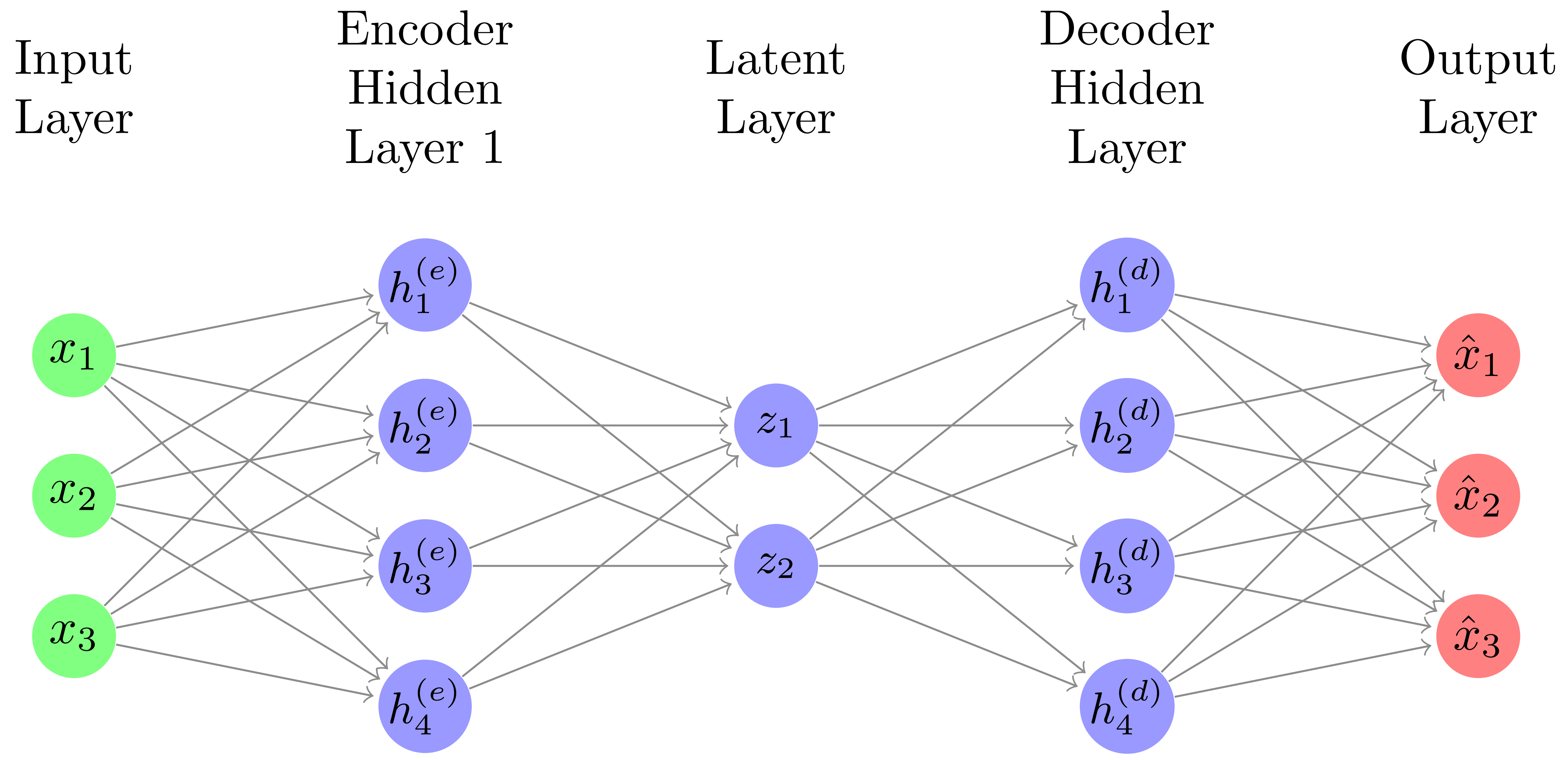
lesser correlation with normalized images indicates importance of correlation between pT and n_{const} for other netwroks

IV. how much is enough

PAIR WISE CORRELATIONS OF OBSERVABLES

Crispim Romão, Milhano, van Leeuwen, :: *in preparation*

- take large set of jet observables [observables that give a number per jet]
- look at pairwise correlations
    - principal component analysis [not shown] :: only linear correlations
    - auto-encoder :: captures non-linear relations between observables
- conclusions very similar for both studies

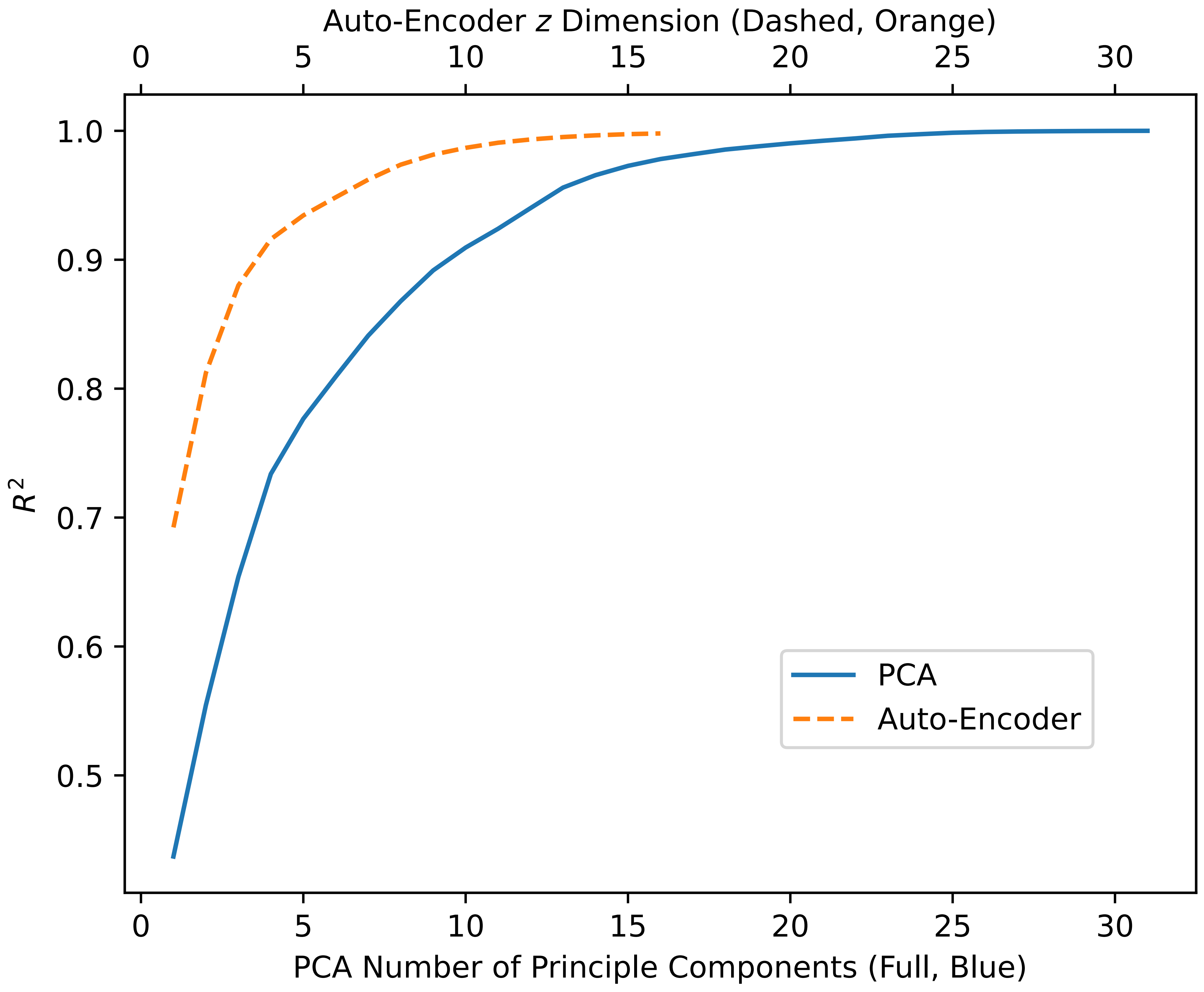


autoencoder :: reduces information content of inputs to minimum [latent space] capable of reconstructing it fully

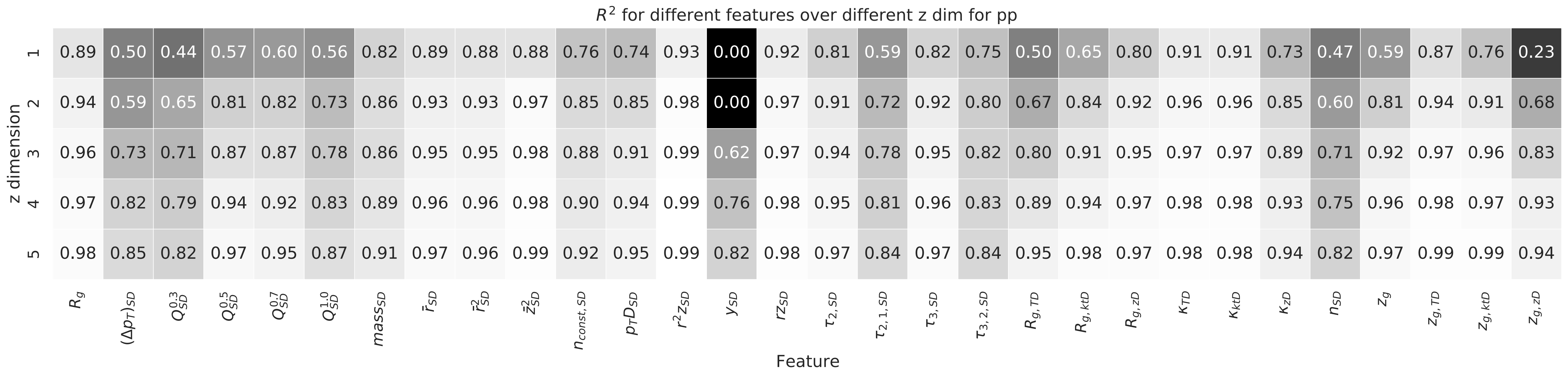
HOW MUCH IS ENOUGH

Crispim Romão, Milhano, van Leeuwen, :: *in preparation*

- dimensionality of latent space [or number of relevant principal components] is not large



R^2 measures quality of reconstruction



excellent reconstruction with latent space dimension 5

WHAT IS SENSITIVE TO QUENCHING

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- use auto-encoder trained only with vacuum jets to predict quenched sample

R^2 differences from Unquenched to Quenched

z dimension	R_g	$(\Delta p_T)_{SD}$	$Q_{SD}^{0.3}$	$Q_{SD}^{0.5}$	$Q_{SD}^{0.7}$	$Q_{SD}^{1.0}$	$mass_{SD}$	$\bar{r}_{SD}$	$\bar{r}^2_{SD}$	$\bar{z}^2_{SD}$	$n_{const,SD}$	p_TD_{SD}	r^2z_{SD}	y_{SD}	rz_{SD}
1	0.03	0.17	-0.03	-0.02	-0.01	-0.01	0.00	0.04	0.01	-0.01	-0.02	-0.03	-0.00	0.00	0.02
2	0.02	0.15	-0.01	0.00	-0.02	-0.04	-0.01	0.03	0.01	-0.01	-0.02	-0.03	0.00	0.00	0.02
3	0.02	0.09	-0.02	-0.01	-0.03	-0.05	-0.01	0.02	0.01	-0.00	-0.02	-0.01	0.00	0.03	0.02
4	0.01	0.05	-0.01	0.00	-0.02	-0.05	-0.00	0.01	0.00	-0.00	-0.02	-0.01	0.00	-0.01	0.01
5	0.01	0.03	-0.01	0.01	-0.02	-0.04	0.01	0.01	0.00	-0.00	-0.01	-0.01	0.00	-0.00	0.01

z dimension	$\tau_{2,SD}$	$\tau_{2,1,SD}$	$\tau_{3,SD}$	$\tau_{3,2,SD}$	$R_{g,TD}$	$R_{g,ktD}$	$R_{g,zD}$	κ_{TD}	κ_{ktD}	κ_{zD}	n_{SD}	z_g	$z_{g,TD}$	$z_{g,ktD}$	$z_{g,zD}$
1	0.02	-0.10	0.02	-0.08	0.17	0.18	0.05	0.03	0.03	0.12	-0.11	0.14	0.01	0.09	0.05
2	0.01	-0.09	0.01	-0.07	0.15	0.09	0.05	0.02	0.03	0.07	-0.11	0.06	0.02	0.01	0.05
3	0.01	-0.07	0.00	-0.07	0.07	0.06	0.03	0.02	0.03	0.06	-0.07	0.05	0.02	0.01	0.04
4	0.00	-0.05	0.00	-0.07	0.03	0.03	0.02	0.02	0.02	0.04	-0.06	0.04	0.01	0.02	0.01
5	0.01	-0.04	0.00	-0.07	0.02	0.01	0.01	0.01	0.02	0.03	-0.02	0.03	0.01	0.00	0.00

Feature

inability to reconstruct quenched information indicates sensitivity to quenching

almost perfect reconstruction with z=5 does not mean that quenched and unquenched jets identical

it means that correlations are analogous

BUT

mean values can change

WHAT IS SENSITIVE TO QUENCHING

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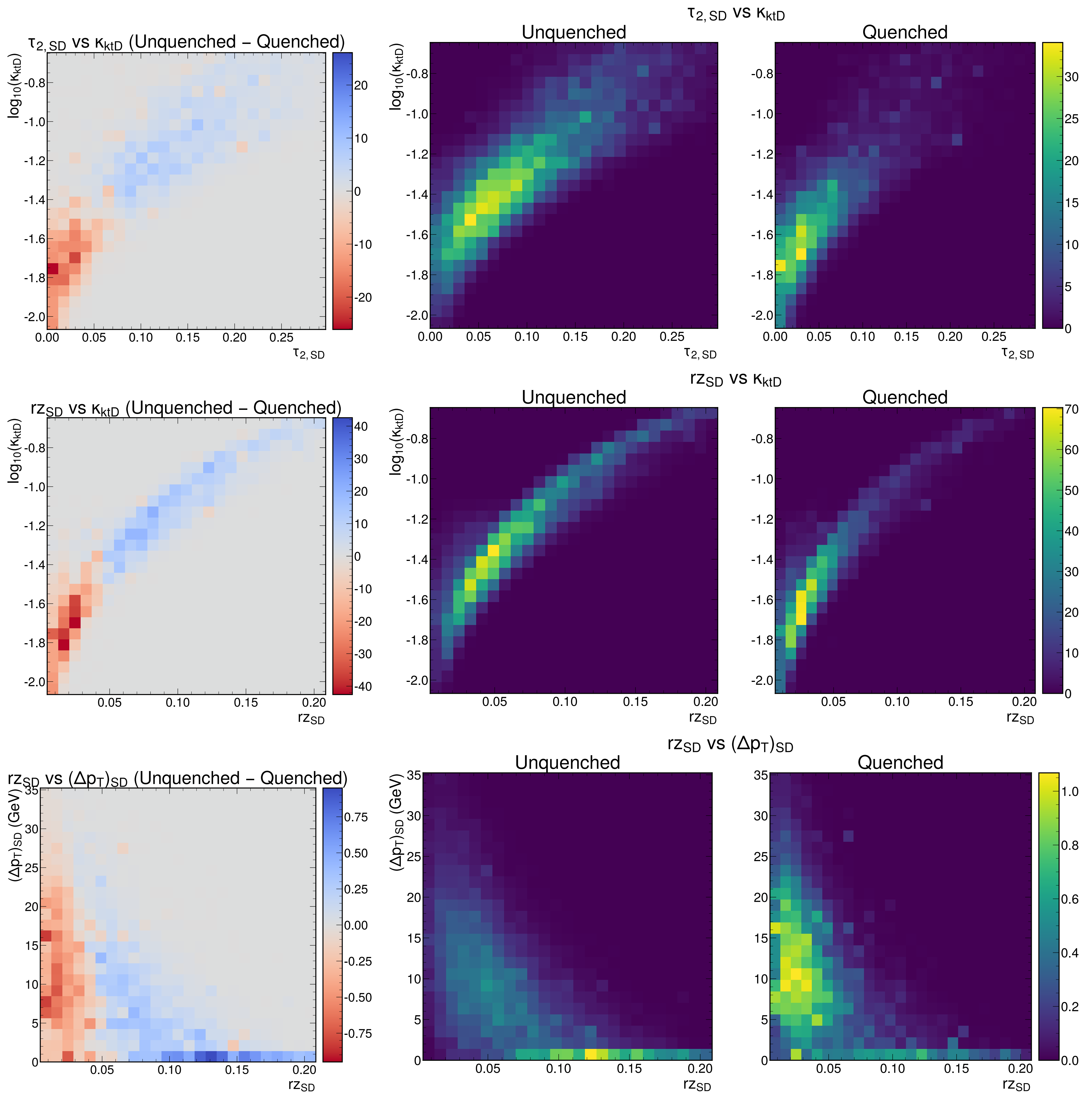
- shape of correlation barely changed [thus predictable by AE] but populations migrate



detailed study [measurement] of correlations
encodes a wealth of information
for discrimination of
quenched and unquenched jets