

ARE DARK SHOWERS OBSERVABLES VISIBLE FOR US? A DARK SECTOR PARAMETER SCAN STUDY FROM THE JET CONSTITUENTS TO UNDERSTAND DARK MATTER

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In collaboration with:

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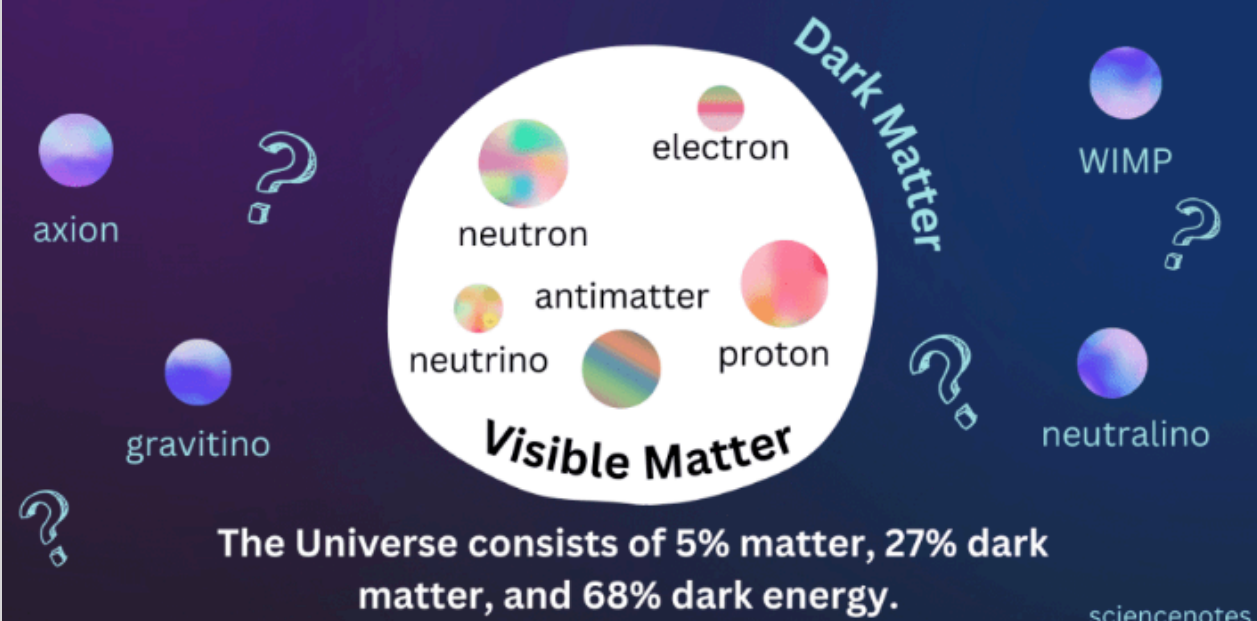
Contents:

1. Context about Dark Matter and theoretical decay channel with current approach.
2. MC event generators description
3. Datasets preparation
4. Jet-substructure metrics:
 - Lund Jet plane
 - Angularity
 - Two-point EEC function
5. Further work: Comparison between MC event generators and Machine Learning (ML) approach.
6. Conclusions and summary
7. References

WHAT IT'S HAPPENING WITH DARK MATTER?

What Is Dark Matter?

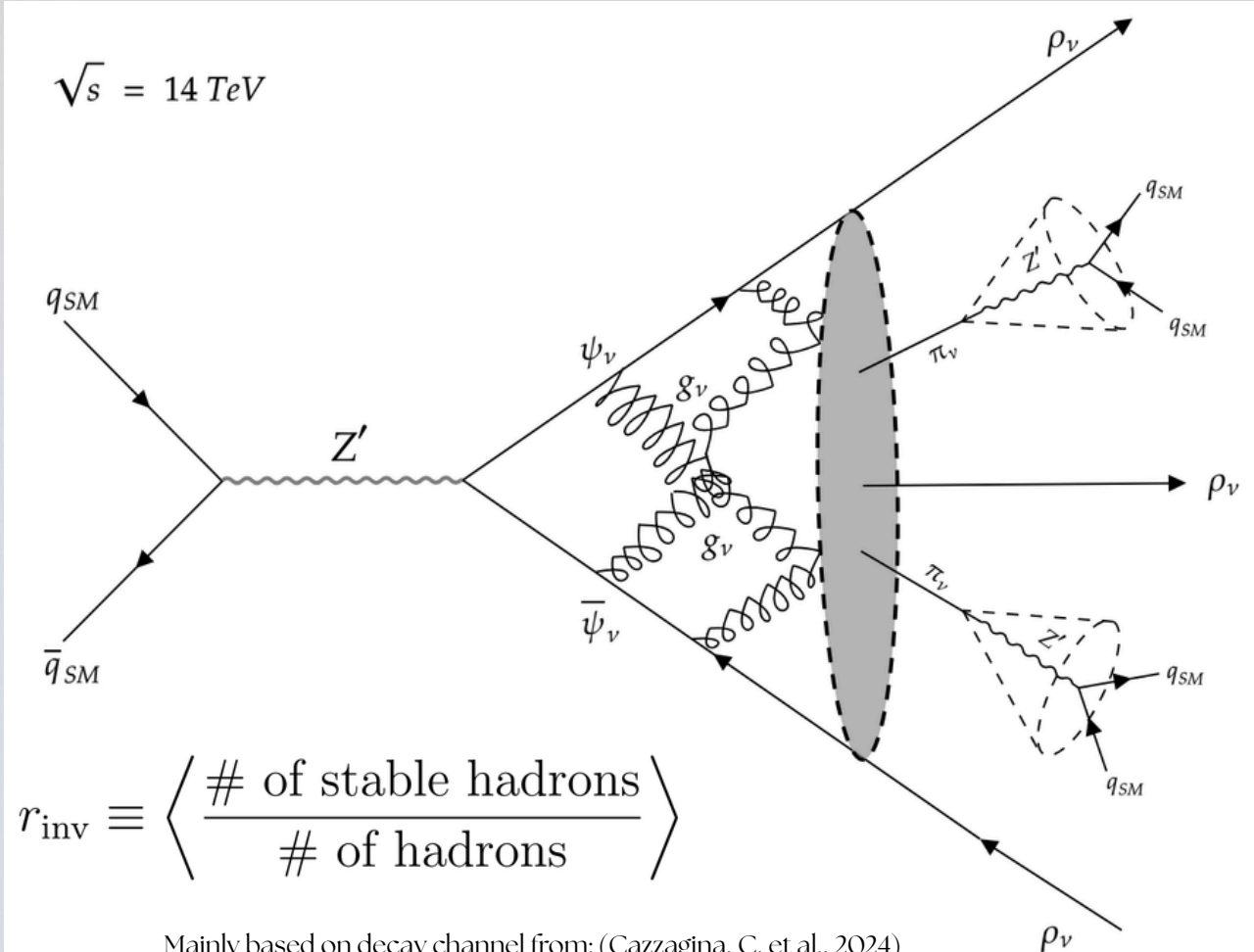
Dark matter is a hypothetical form of invisible matter that exerts gravitational effects on light and ordinary matter.



Recovered from:
(Helmenstine y
Helmenstine,
2025)

sciencenotes.

OUR THEORETICAL DECAY CHANNEL



Mainly based on decay channel from: (Cazzagina, C. et al., 2024)

Our model have mainly 40% of stable dark hadrons measured by the invisible fraction

THE NEED FOR BSM AND DM CANDIDATES

What can we do to solve this problem? We need to expand our current best approach to understand the universe (SM), and seek for other candidates that can explain this mystery. Some of them:

- M.A.CH.O.S
- WIMPs
- SUSY
- Extra dimensions
- Sterile Neutrinos
- Ours: Dark showers, specifically the signature called Semi-Visible Jets from proton-proton collisions with current approaches using:
 1. Global kinematical properties of the leading jet: p_T, E
 2. Energy-Energy correlators (Kulkarni, S., et al., 2024)
 3. Transverse mass m_T (CMS collaboration., 2022)

MONTE CARLO EVENT GENERATORS

Hidden valley processes in Pythia8

Recovered from: Bierlich, C (2022)



- Hidden QCD sector pre-computed on the Hidden Valley module
- Dark parton shower and dark hadronization (String Hadronisation model).
- Abelian and non-abelian HV gauge groups for both production processes (e.g. Z')
- Extraction of final-state data in a clearer way with 4-vectors of $(E, \mathbf{p}_{x,y,z})$

Herwig Dark showers package:

Recovered from: (Kulkarni, S., et al., 2024)



- Novel pre-computed library for studies on the Dark Sector with Herwig7
- Dark parton shower and dark hadronisation (Cluster hadronisation model)
- Studies around the $e+e^-$ collision with jet kinematical studies relying on cluster masses, meson momentums and angularity

Detector analysis

Recovered from: (De Favereau, J., et al., 2014)



DELPHES
fast simulation

- Computation of final-state particles of SM and BSM stable hadrons on a .hepmc file
- Pre-computed ATLAS and CMS card for generation of root file
- CMS card used in this sample from HEPMC3 analysis
- Realistic extraction of MET

JET CLUSTERING ANALYSIS

- Anti- k_T jet algorithm
- Jet radius = 1.0
- Leading jet (highest p_T)
- p_T - cuts at jet level of [1.0,1.25]TeV for Z' masses of [2.5,4.5]TeV
- Extraction of global kinematics: Transverse momentum energy, rapidity, etc.

JET CONSTITUENTS FOR JET SUBSTRUCTURE



Recovered from: (Cacciari, M., et al., 2012)

- Visible decays from electromagnetic-charged final-state particles: Hadrons/photons
- Extraction of Energy (E), 4-momentum $(\mathbf{p}_{x,y,z})$ per each jet at hadronisation level
- CMS card modified for jet Radius $R = 1.0$ for Collider analysis

PREPARED DATASETS FOR QCD BCK AND SVJS SIGNALS

Dataset	$m_{Z'}$ [TeV]	m_{ψ_v} [GeV]	p_T^{\min} [TeV]	a	b	Λ_v [GeV]	r_{SM} [%]	r_{BSM} [%]
pythia_set_QCD_bck			1.0				100	0
pythia_set_109.v1	2.5	10	1.0	0.3	0.7	25.0	60	40
pythia_set_109.v2	2.5	50	1.0	0.3	0.7	25.0	60	40
pythia_set_109.v3	2.5	100	1.0	0.3	0.7	25.0	60	40
pythia_set_309.v1	4.5	10	1.25	0.3	0.7	25.0	60	40
pythia_set_309.v2	4.5	50	1.25	0.3	0.7	25.0	60	40
pythia_set_309.v3	4.5	100	1.25	0.3	0.7	25.0	60	40
pythia_set_409.v1	2.5	50	1.0	0.3	0.7	25.0	70	30
pythia_set_409.v2	2.5	50	1.0	0.3	0.7	25.0	80	20
pythia_set_409.v3	2.5	50	1.0	0.3	0.7	25.0	50	50
pythia_set_509.v1	4.5	50	1.25	0.3	0.7	25.0	70	30
pythia_set_509.v2	4.5	50	1.25	0.3	0.7	25.0	80	20
pythia_set_509.v3	4.5	50	1.25	0.3	0.7	25.0	50	50
pythia_set_609.v1	2.5	50	1.0	0.3	0.7	4.0	60	40
pythia_set_609.v2	2.5	50	1.0	0.3	0.7	10.0	60	40
pythia_set_609.v3	2.5	50	1.0	0.3	0.7	30.0	60	40
pythia_set_709.v1	4.5	50	1.25	0.3	0.7	4.0	60	40
pythia_set_709.v2	4.5	50	1.25	0.3	0.7	10.0	60	40
pythia_set_709.v3	4.5	50	1.25	0.3	0.7	30.0	60	40

Taking a parameter scans over the following physical quantities:

Inv. Fraction : $r_{BSM} = r_{inv}$

Dark Quarks masses : m_{ψ_D}

Dark hadronisation cte : Λ_D

And changing the whole kinematical behaviour through the Z' mass and check how much will differ.

Changes are pointed in red

The Lund-plane (PYTHIA-Level)

1

THEORY BEHIND IT

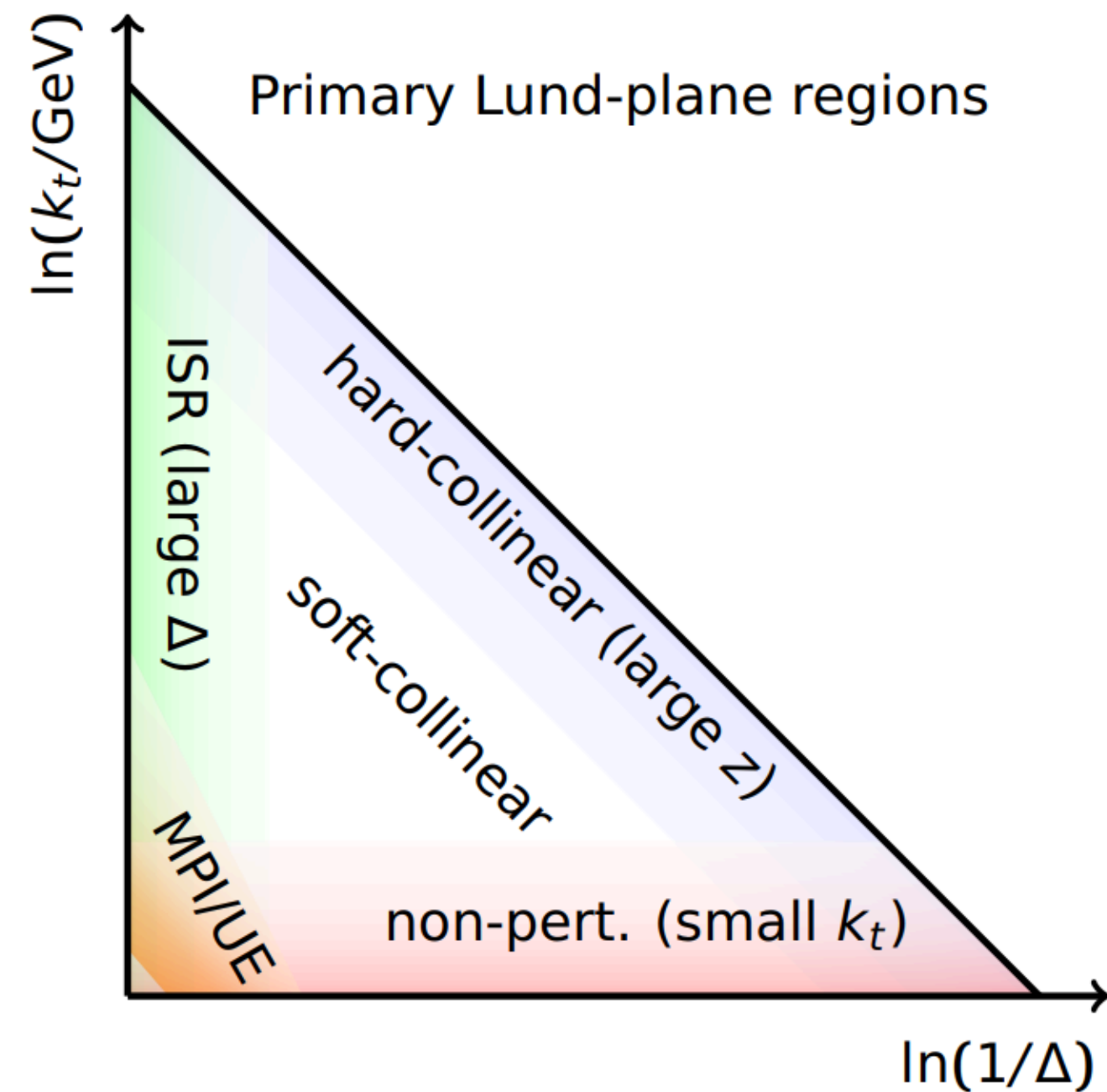
2D REPRESENTATION OF JET
VISIBLE CONSTITUENTS:

- CHARGED HADRONS (IN PARTICULAR MESONS: NEUTRAL KAONS AND NEGATIVE/POSITIVE PIONS)
- PHOTONS.

WHERE:

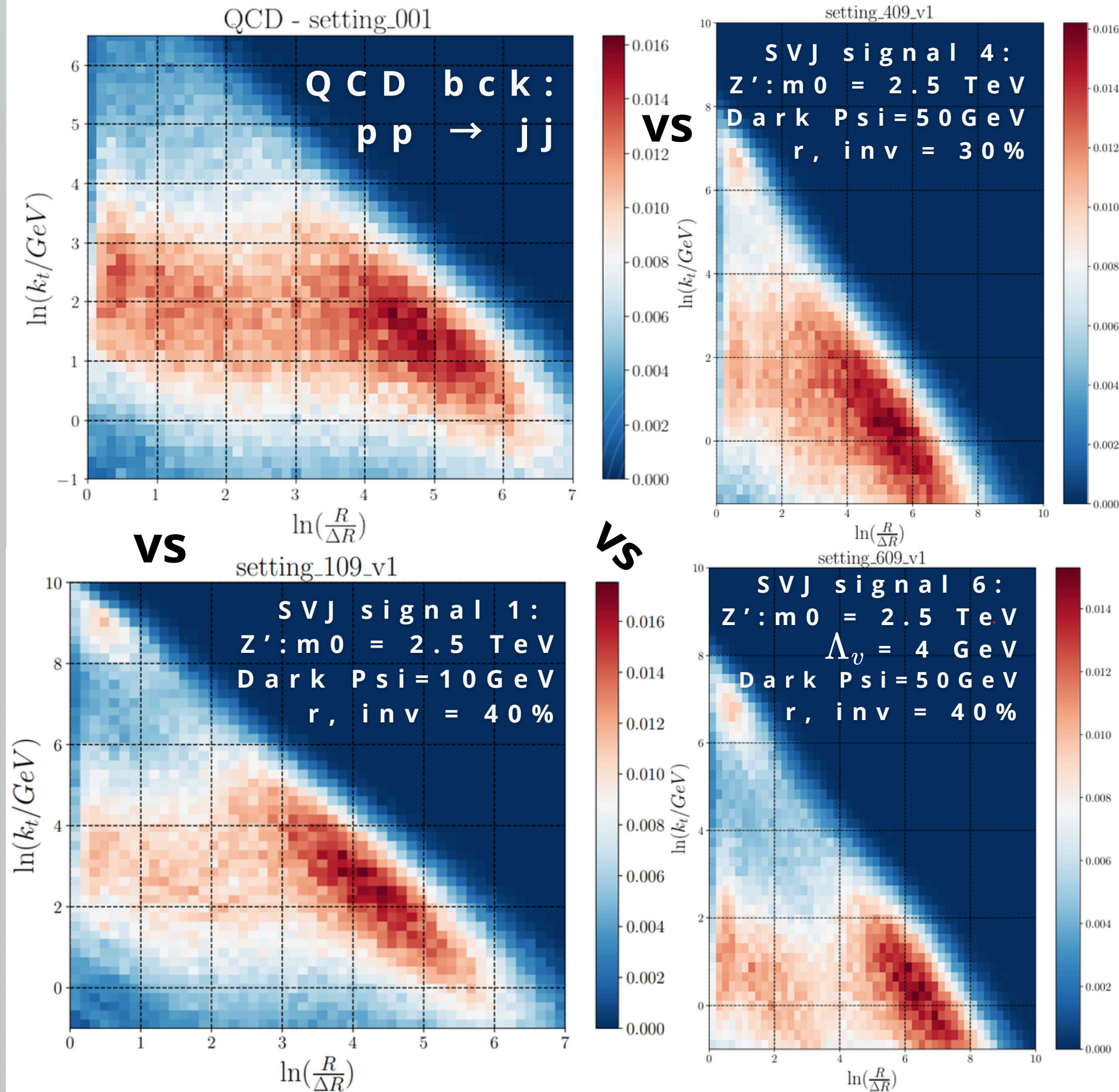
$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$\Delta \equiv \Delta_{ab}, \quad k_t \equiv p_{tb} \Delta_{ab}$$



Recovered from: (Dreyer, F.A., et al., 2018)

RESULTS



WHAT WE CAN LEARN FROM IT?

Visual differences from QCD bck and SVJs signals.

- Dark quarks masses affect decay hadrons boost rate. Larger $\ln(k_T)$.
- The invisible fraction affects the hard-collinear (not happening in QCD)
- Dark Hadronisation mainly affects the non-perturbative region (for small k_T)
- Soft collinear region is lower in SVJs signals rather than for QCD

Angularity Function (PYTHIA Level)

2

THEORY BEHIND IT

- Numerical computation between constituents to quantify the p_T weighted angular separation between the constituents and the selected jet.
- θ_i^α is the angle from the particle within the jet, E_i it's the energy from the constituent, E_{Tot} represent the total energy (For hadronic case it's the p_T)

$$\begin{aligned} \tau_{\alpha,\beta} &= \sum_{\text{jet} \in \text{jets}} \sum_{i \in \text{jet}} \left(2\sqrt{1 - \cos\theta_i} \right)^\alpha \left(\frac{E_i}{E_{Tot}} \right)^\beta \\ &\approx \sum_{\text{jet} \in \text{jets}} \sum_{i \in \text{jet}} \theta_i^\alpha \left(\frac{E_i}{E_{Tot}} \right)^\beta, \end{aligned} \quad (4.0.2)$$

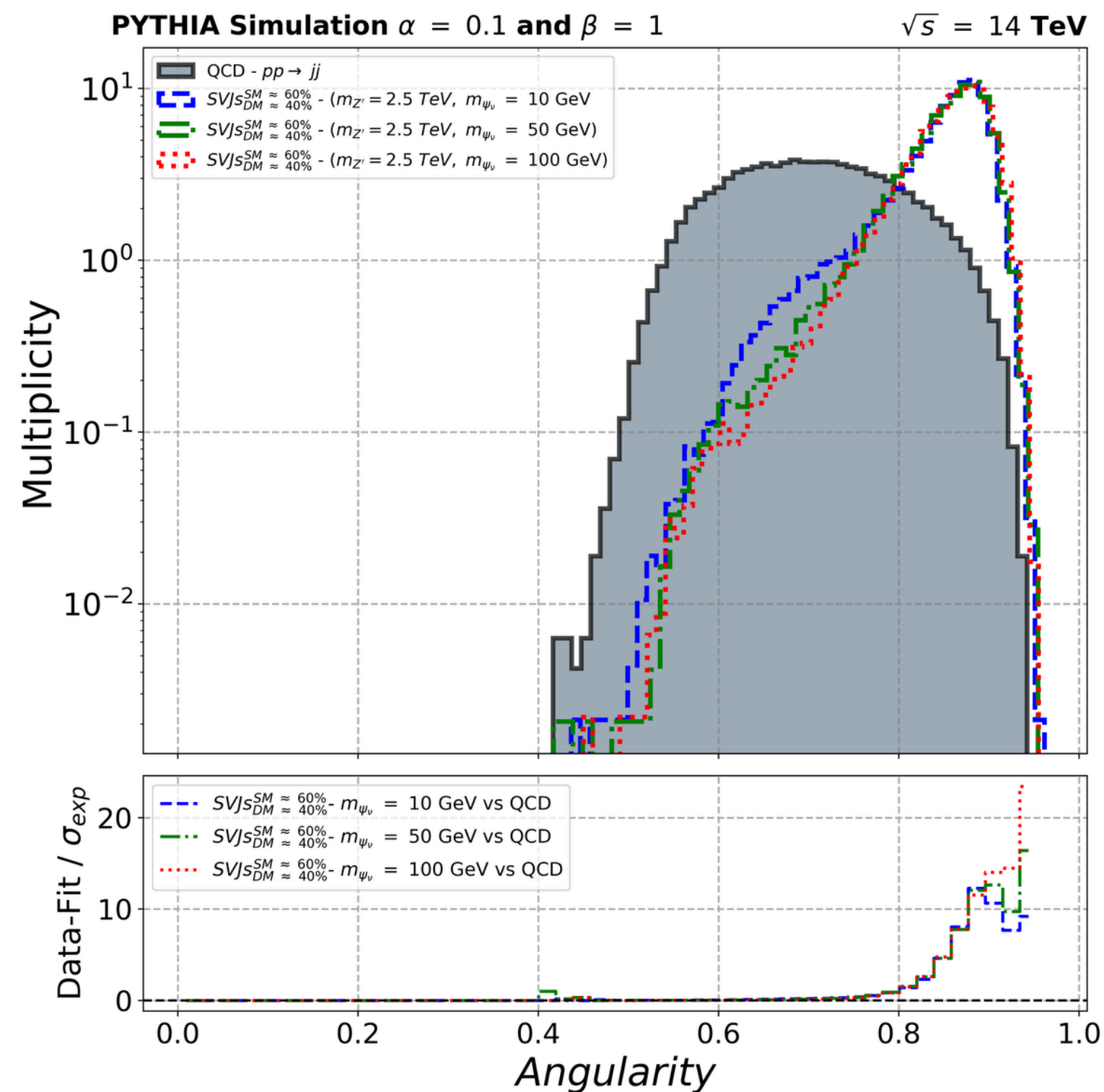
Recovered from: (Kulkarni, S., et al., 2024)

$$\beta = 1$$

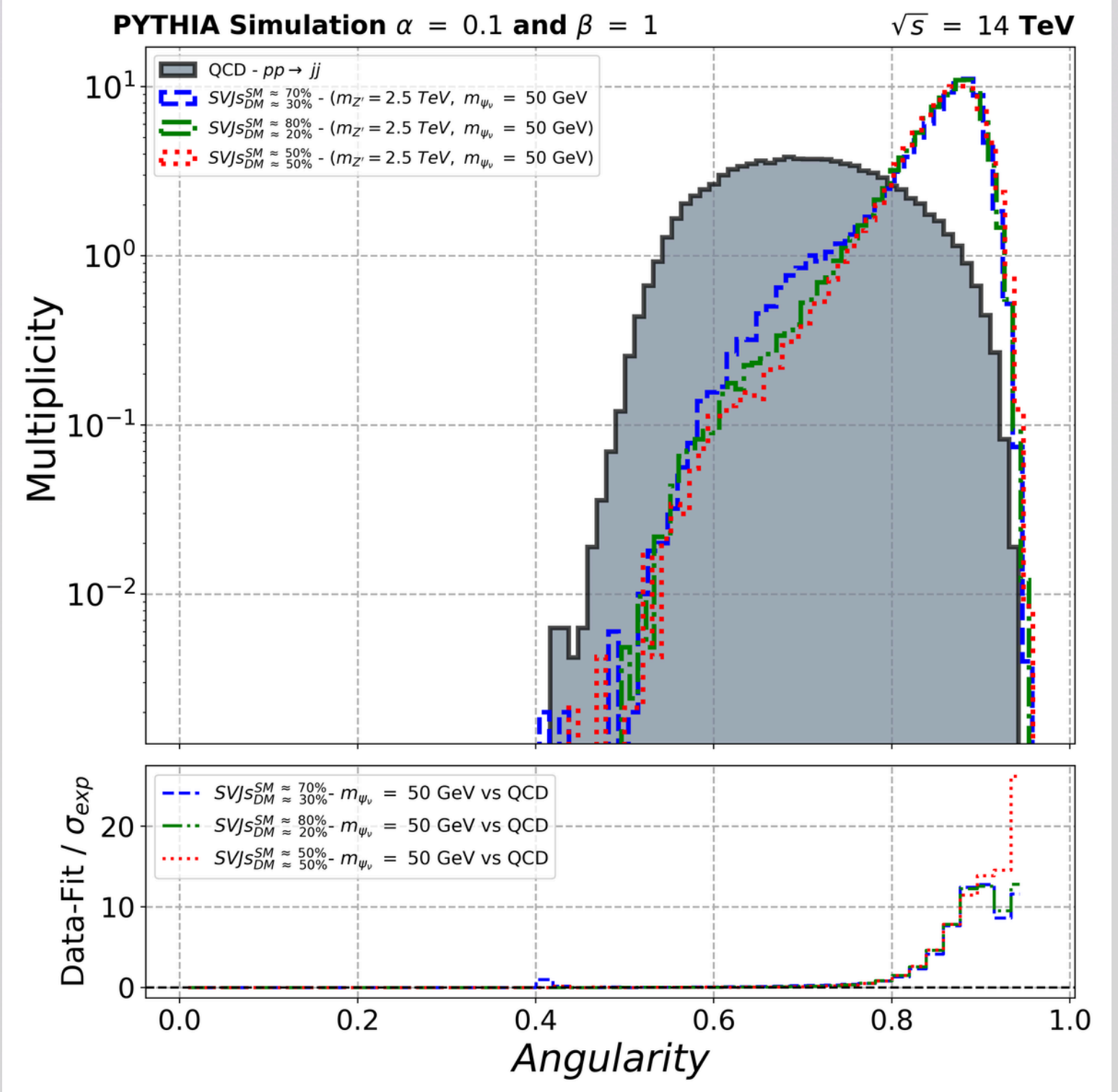
$$\alpha \geq 0;$$

$$\alpha \in [0.1, 2]$$

Angularity Function with $\alpha = 0.1$



VS



1. Dark quark masses are different from signal to signal and they could be a good candidate for characterisation
 Main changes: 2. Invisible fraction also makes a better performance for characterisation between the signals
 3. Both of them differ from QCD background!

Two-Point EEC Function (PYTHIA Level)

2

THEORY BEHIND IT

Here instead of computing one of the angularities, now it's a product between two angularities that are weighted angular separation, for hadron analysis (e.g. LHC) we define:

Generalised momentum $z_i \equiv p_{T_i}/p_{T_{Jet}}$

Angular separation $\theta_{ij} \equiv R_{ij}/R_0$

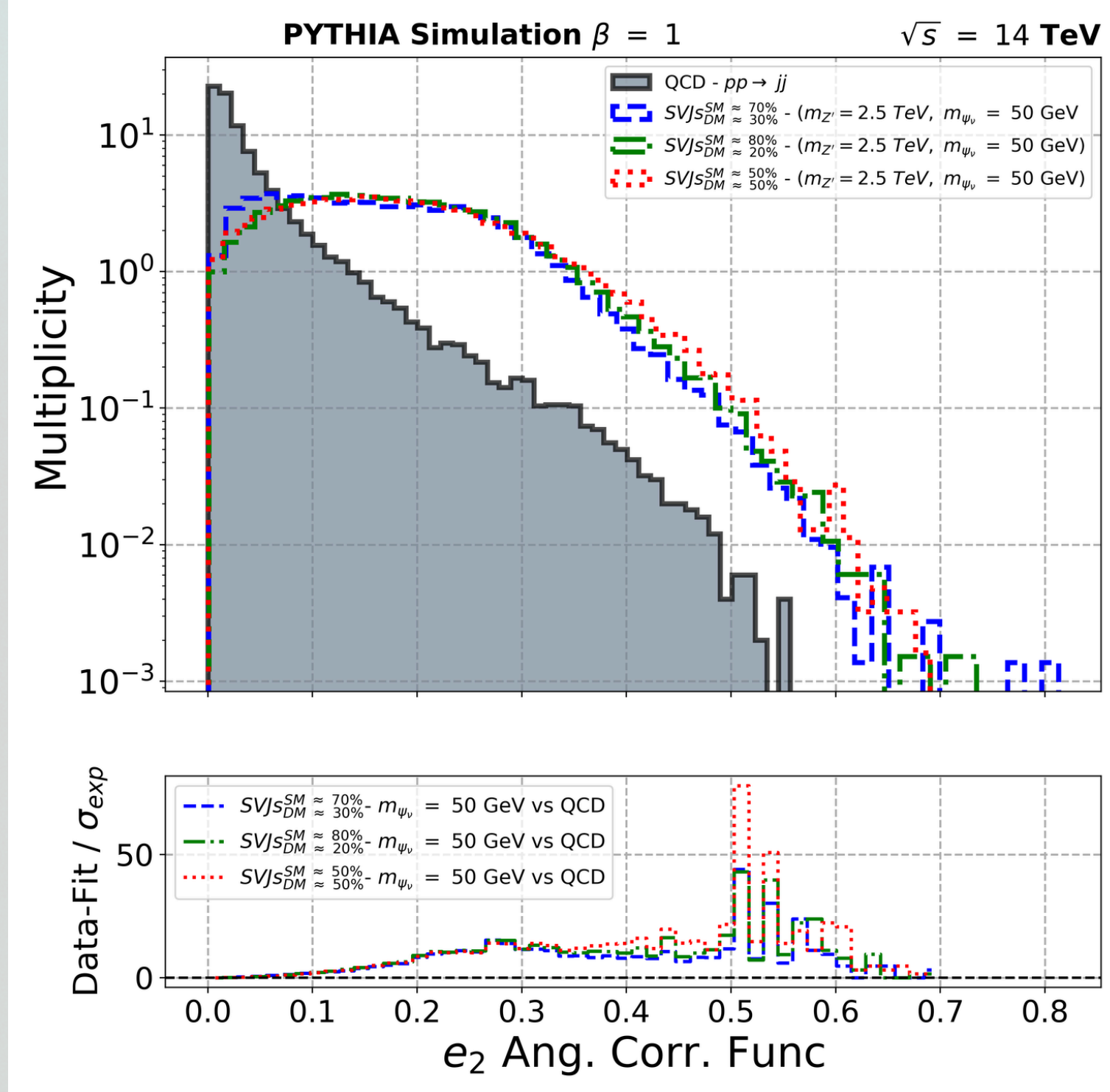
$p_{T_{Jet}}$ it's the transverse momentum of the jet, R_{ij} it's the Euclidean distance between different partons.

$$e_2^{(\beta)} = \sum_{i < j \in J} z_i z_j (\theta_{ij})^\beta,$$

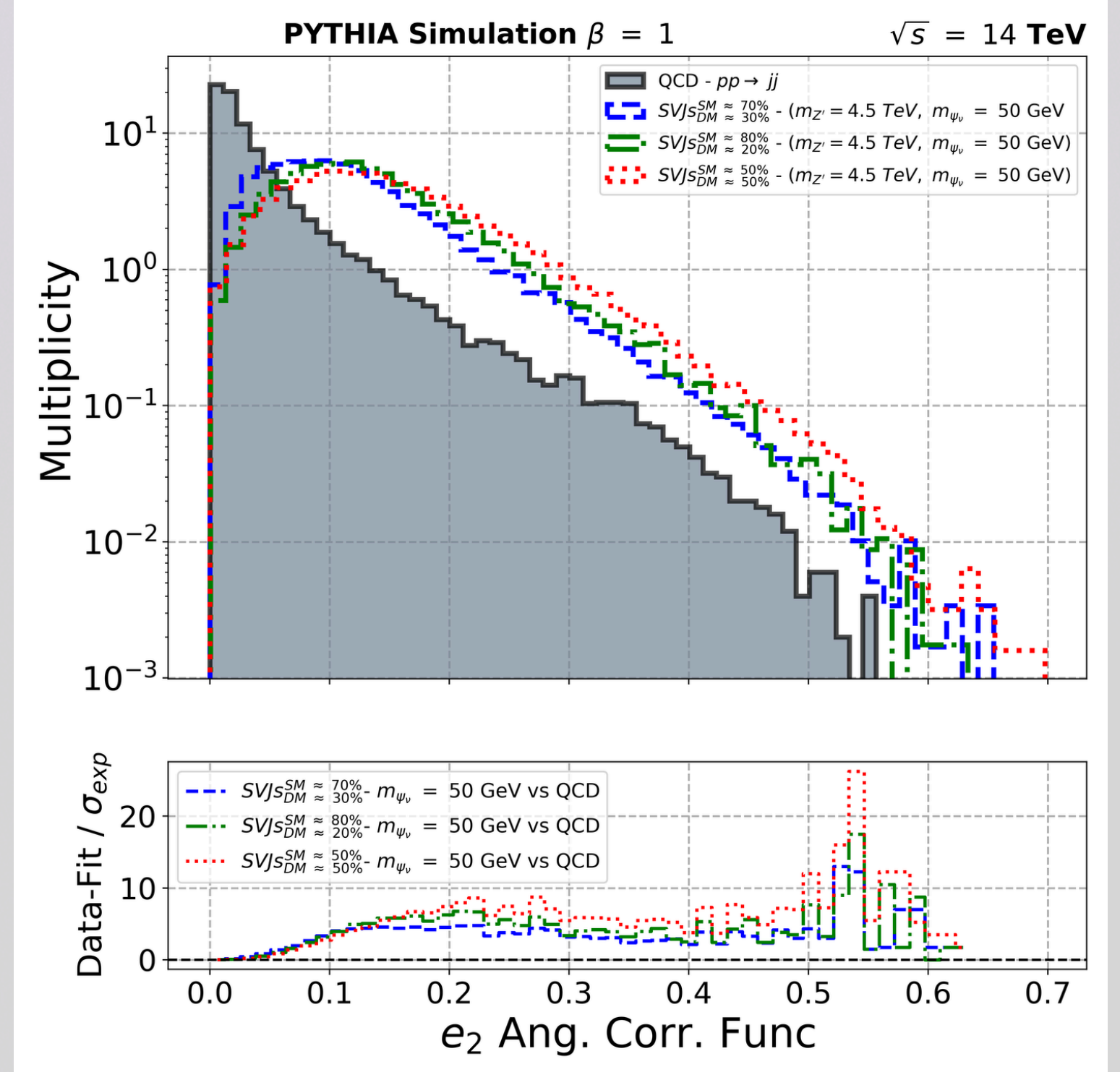
Recovered from: (Cohen, T., et al. 2020)

$$\beta = 1$$

e2-point EEC function $\beta = 1.0$



VS

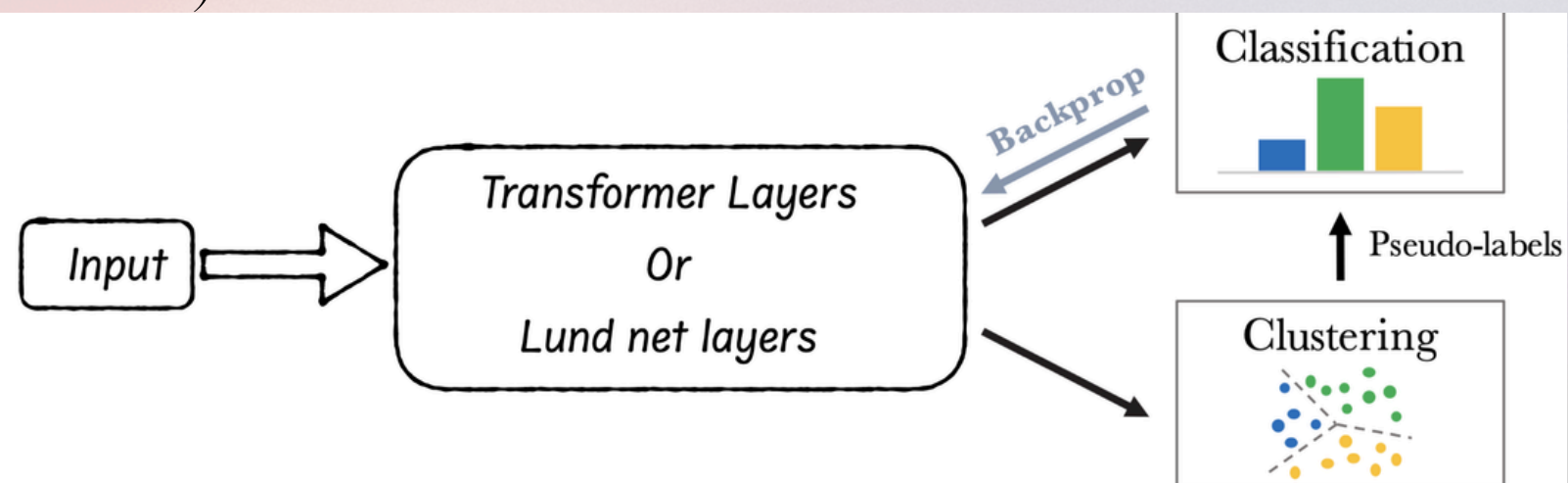


1. Compared to the angularity function the curve it's slightly more smooth; if you also change the Z' mass will be more alike as QCD bck

Main changes: 2. Both of the kinematical metrics wouldn't be that useful for characterisation purposes but good for classification tasks

FUTURE WORK: ML ANALYSIS

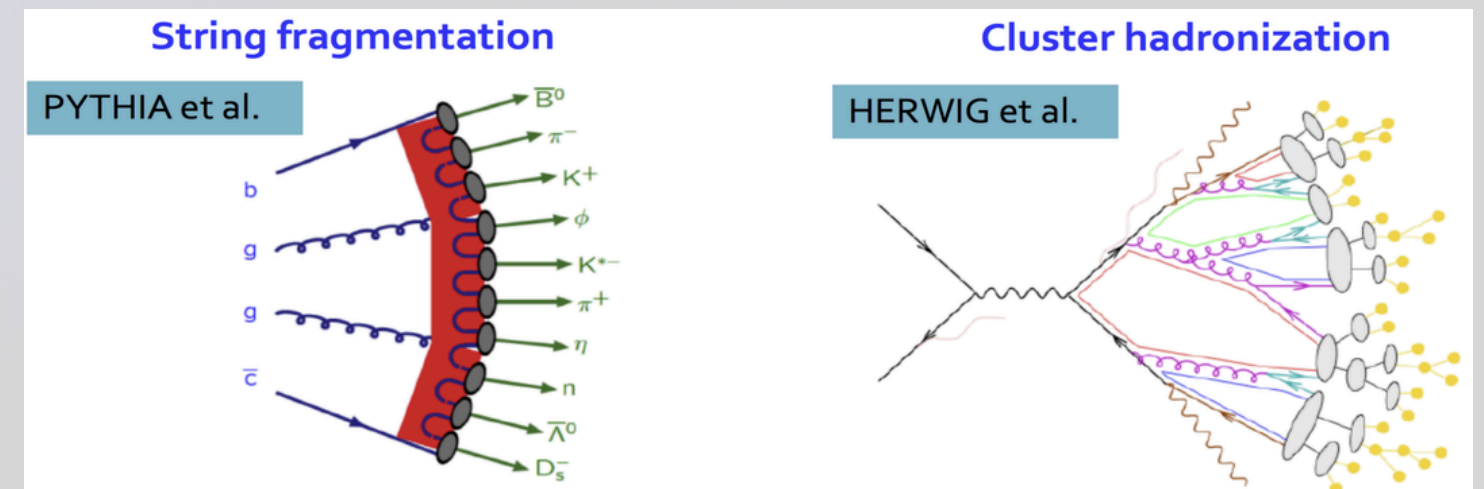
- Objective: Develop a transformer-based Neural Network (NN), for distinguish between SVJs and QCD regardless the HV parameters.
- Latent-space clustering architecture: Cluster between visible and invisible jet components. Perfect for classification of QCD/SVJs jets across varying theoretical parameters.
- Expected output: We would like to predict the MET and dark quark masses from the latent space
- Current Limitations: Few events sample (we need at least 800 k +)



Main idea recovered from: (Park, S.E., Harris, P. and Ostdiek, B., 2023)

FUTURE WORK: HERWIG VS PYTHIA COMPARISON

- Task: We would like to compared our PYTHIA/Delphes & PYTHIA kinematical analysis with the alternative dark showers library.
- Hadronisation clustering model: Since they have 2 different clustering models, we would like to explore how much the dark hadronisation will change our kinematical features
- Expected output: Different patters on all the previous kinematical results
- Current limitations: PYTHIA haven't showed us too much difference between the dark hadronisation confinement scale.



Summary

Then, Are Dark Showers observables visible for us?

Short answer: Yes!, we can extract realistic information from the hadronisation level via analysing the jet-substructure level which will allow us to have a deeper understanding of kinematical parameters:

- Jet-substructure let us see clearer which of these parameters have most effect in each of the kinematics
- With these kinematics we can perform both classification and characterisation task for ML approach.

Further work

- Add MET studies
- Create the rest of DELPHES collider datasets
- Comparison with Herwig output data
- Larger event generation for ML approach
- Transformer based neural network creation
- Complement the analysis with other decay channel dataset?

Thanks!

Any questions?

:)

References:

1. Helmenstine, A., & Helmenstine, A. (2025, 12 noviembre). What is dark matter? Science Notes And Projects. <https://sciencenotes.org/what-is-dark-matter/>
2. Cohen, T., Lisanti, M., Lou, H.K. and Mishra-Sharma, S., 2017. LHC searches for dark sector showers. *Journal of High Energy Physics*, 2017(11), pp.1-32.
3. Cazzaniga, C., Russo, A., Sitti, E. and de Cosa, A., 2024. Phenomenology of photons-enriched semi-visible jets. *The European Physical Journal C*, 84(11), p.1223.
4. Carloni, L., Rathsman, J. and Sjöstrand, T., 2011. Discerning secluded sector gauge structures. *Journal of High Energy Physics*, 2011(4), pp.1-42.
5. Kulkarni, S., Masouminia, M.R., Plätzer, S. and Stafford, D., 2024. Dark sector showers and hadronisation in Herwig 7. *The European Physical Journal C*, 84(11), p.1210.
6. De Favereau, J., Delaere, C., Demin, P., Giammanco, A., Lemaitre, V., Mertens, A. and Selvaggi, M., 2014. DELPHES 3: a modular framework for fast simulation of a generic collider experiment. *Journal of High Energy Physics*, 2014(2), pp.1-26.
7. Cacciari, M., Salam, G.P. and Soyez, G., 2012. FastJet user manual: (for version 3.0. 2). *The European Physical Journal C*, 72(3), p.1896.
8. Komiske, P.T., Metodiev, E.M. and Thaler, J., 2018. Energy flow polynomials: A complete linear basis for jet substructure. *Journal of High Energy Physics*, 2018(4), pp.1-54.
9. Tumasyan, A., Adam, W., Andrejkovic, J.W., Bergauer, T., Chatterjee, S., Damanakis, K., Dragicevic, M., Escalante Del Valle, A., Fruehwirth, R., Jeitler, M. and Krammer, N., 2022. Search for resonant production of strongly coupled dark matter in proton-proton collisions at 13 TeV. *Journal of High Energy Physics*, 2022(6).
10. Dreyer, F.A., Salam, G.P. and Soyez, G., 2018. The Lund jet plane. *Journal of High Energy Physics*, 2018(12), pp.1-42.
11. Larkoski, A.J., Salam, G.P. and Thaler, J., 2013. Energy correlation functions for jet substructure. *Journal of High Energy Physics*, 2013(6), pp.1-43.
12. Park, S.E., Harris, P. and Ostdiek, B., 2023. Neural embedding: learning the embedding of the manifold of physics data. *Journal of High Energy Physics*, 2023(7), pp.1-38.
13. Cohen, T., Doss, J., & Freytsis, M. (2020). Jet substructure from dark sector showers. *Journal of High Energy Physics*, 2020(9), 118.
14. Bierlich, C., Chakraborty, S., Desai, N., Gellersen, L., Helenius, I., Ilten, P., ... & Verheyen, R. (2022). A comprehensive guide to the physics and usage of PYTchIA 8.3. *SciPost Physics Codebases*, 008.
15. Komiske, P. T., Metodiev, E. M., y Thaler, J. (2018). Energy flow polynomials: A complete linear basis for jet substructure. *Journal of High Energy Physics*, 2018(4), Artículo 13. [https://doi.org/10.1007/JHEP04\(2018\)013](https://doi.org/10.1007/JHEP04(2018)013)
16. [Franceschini, R., Kim, D., Kong, K., Matchev, K. T., Park, M., & Shyamsundar, P. Kinematic Variables and Feature Engineering for Particle Phenomenology. 2022. arXiv preprint arXiv:2206.13431.](#)
17. [Jets at CMS and the determination of their energy scale | CMS Experiment. \(n.d.\). https://cms.cern/news/jets-cms-and-determination-their-energy-scale](#)

BACKUP

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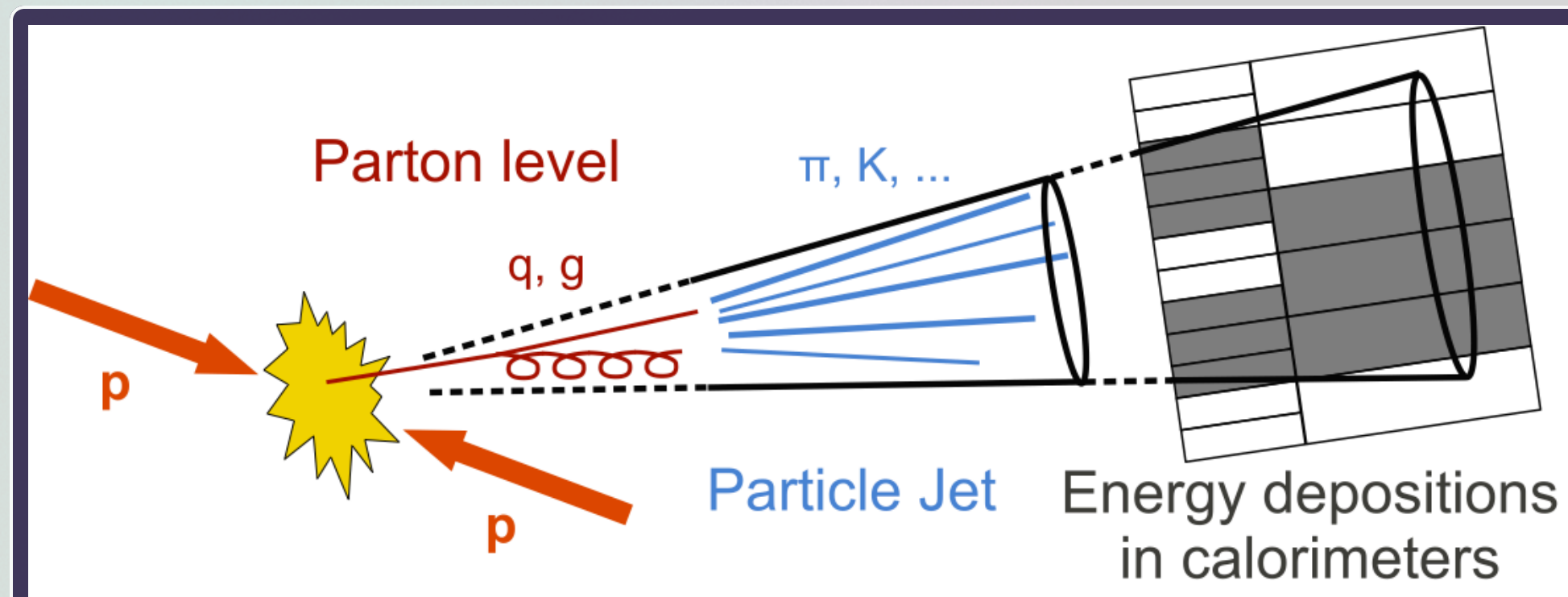
What it's a jet? The theoretical perspective

Jets are a reconstructed observable, normally described as a collimated spray of hadrons, partons and invisible particles that are being detected directly at the detector calorimeters as deposited clusters of energy after passing the hadronisation stage. For jet clustering the 3 most used jet algorithms are:

Anti-kT jet algorithm

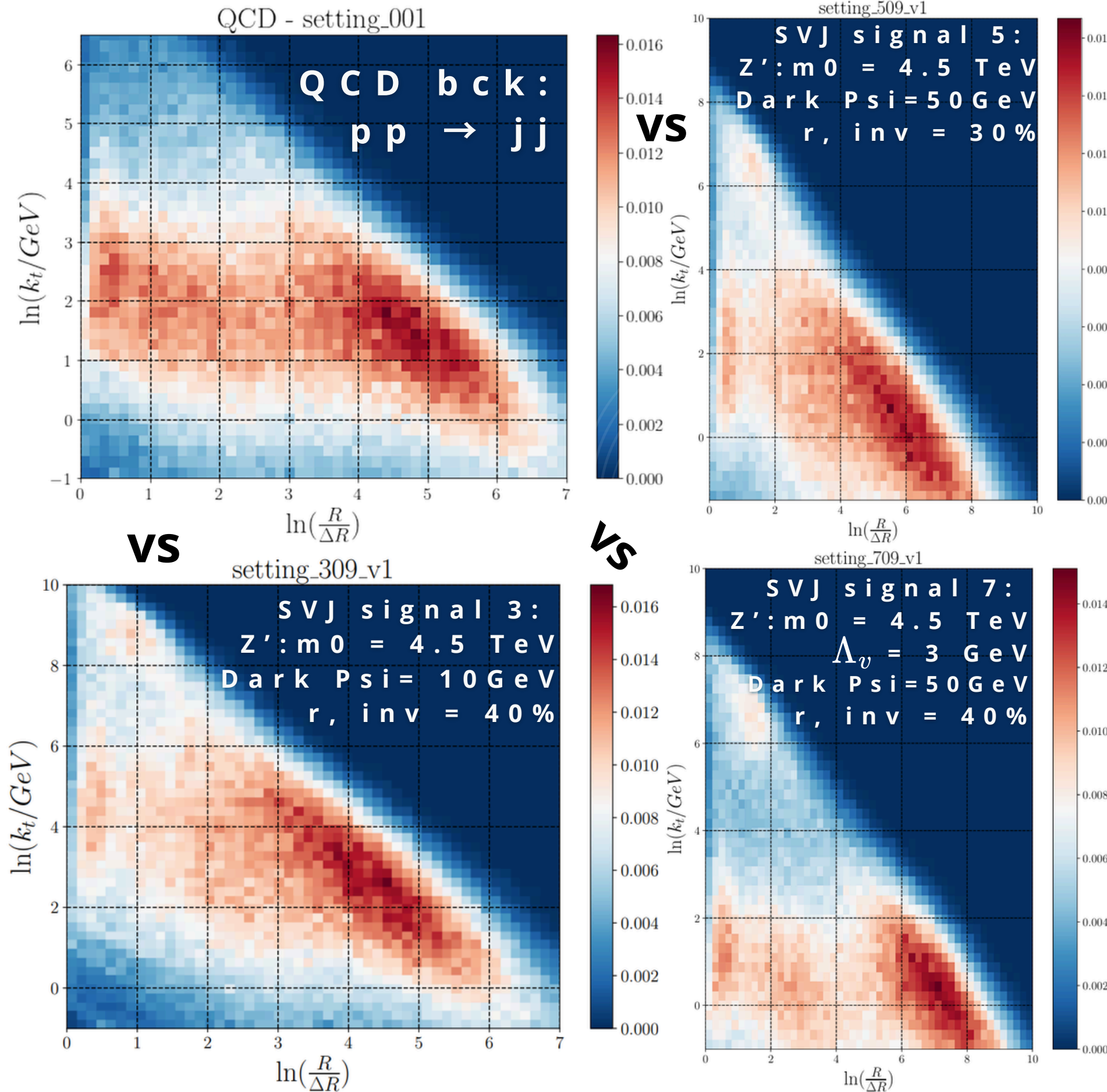
Cambridge/Aachen jet algorithm

KT jet algorithm



Recovered from:
(Jets at CMS and the
Determination of Their
Energy Scale | CMS
Experiment, n.d.)

RESULTS

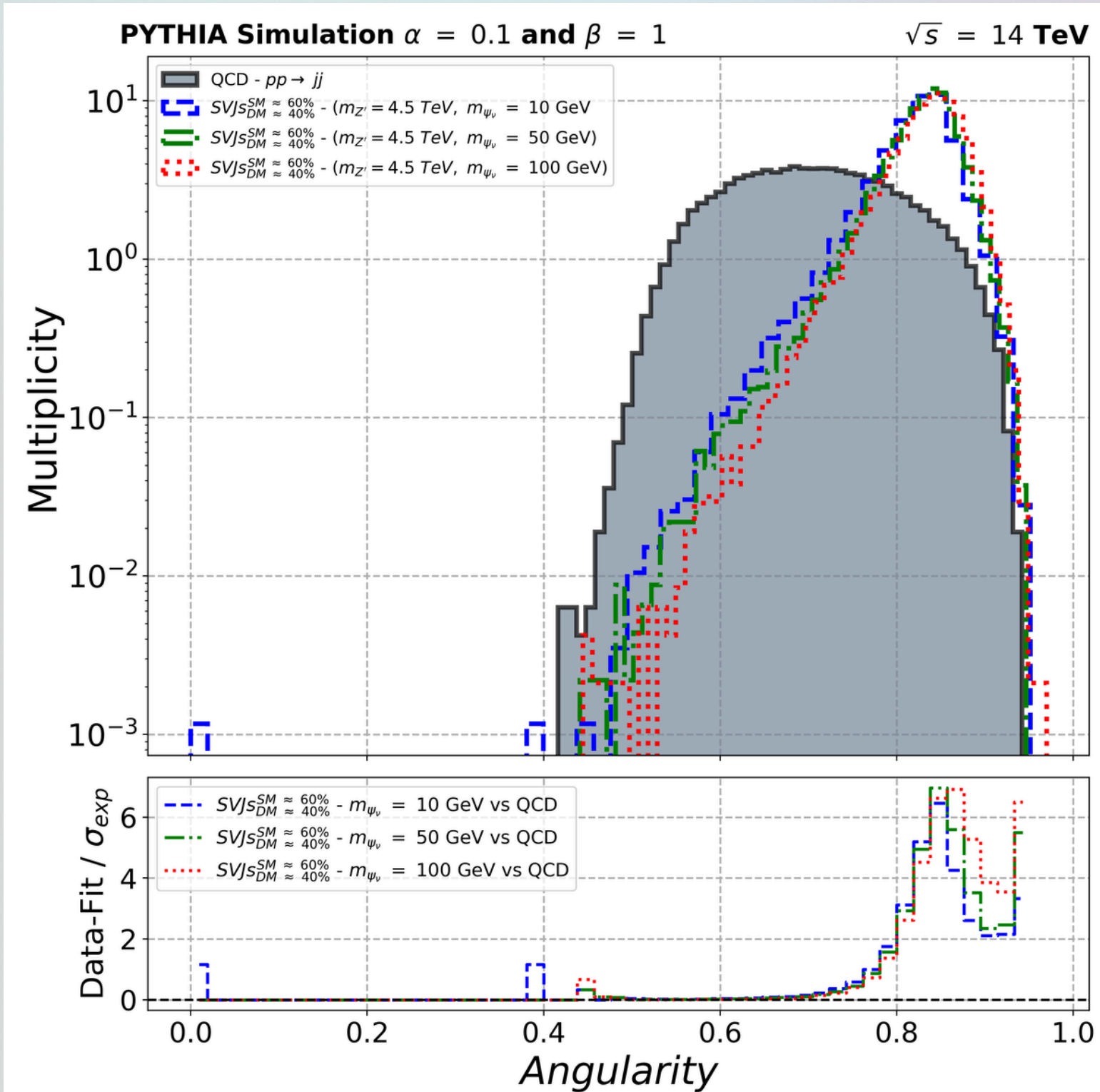


WHAT WE CAN LEARN FROM IT?

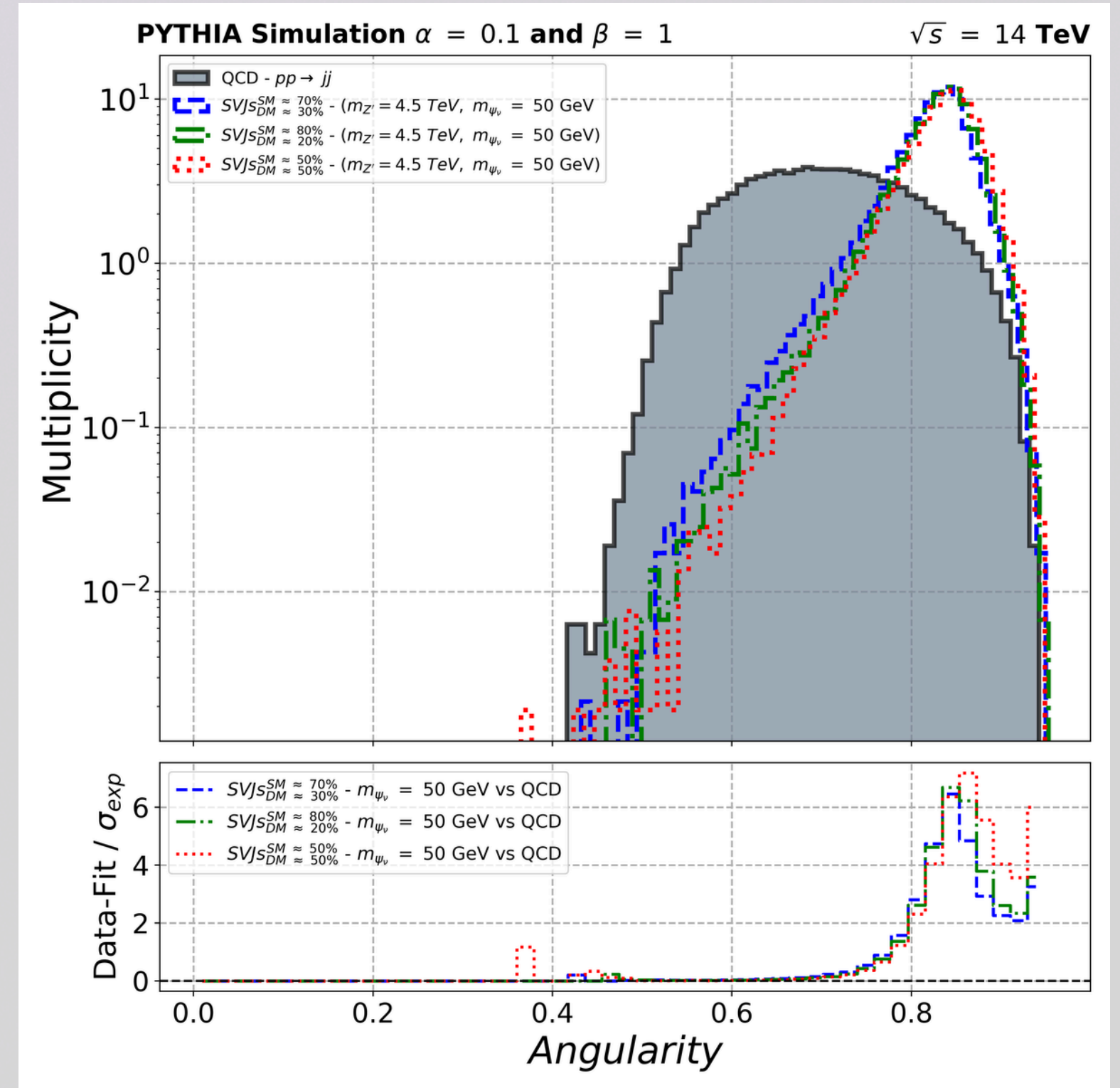
If you change the mass of the Z' portal, the whole kinematical environment change by:

- Dark quarks masses again affect decay hadrons boost rate but also have more ISR and soft-collinear emissions.
- The invisible fraction affects the hard-collinear with less ISR and more hard-collinear emissions
- Dark Hadronisation seems to behave similar as before.
- Soft collinear region increase for more of the SVJs signals

Angularity Function with $\alpha = 0.1$

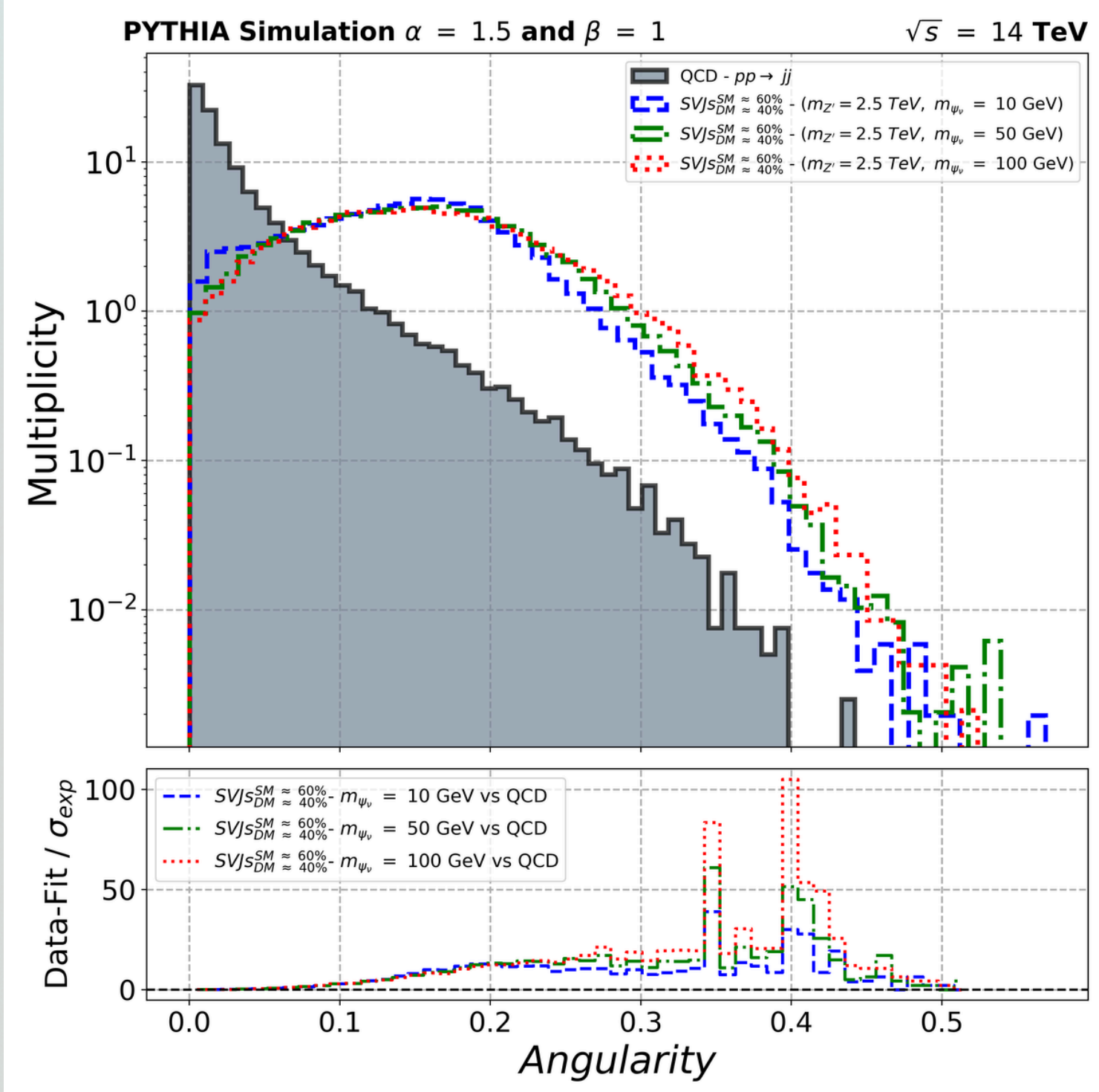


VS

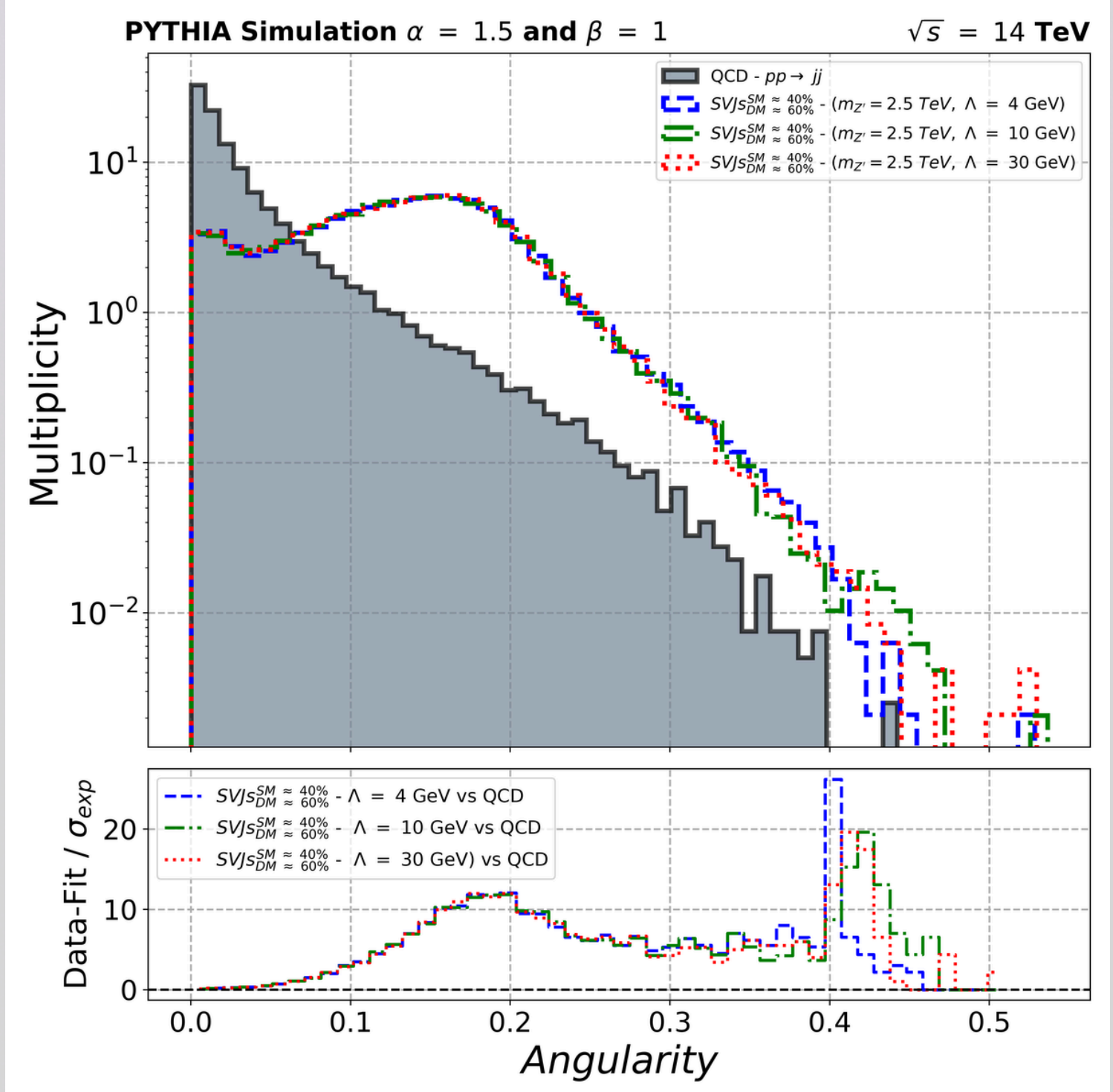


1. Changing the Z' mass again won't make much difference between previous values.
 Main changes: 2. Both of the kinematical analysis performing not as good as before
 3. Again, both of them will differ from QCD bck, good for classification.

Angularity Function with $\alpha = 1.5$

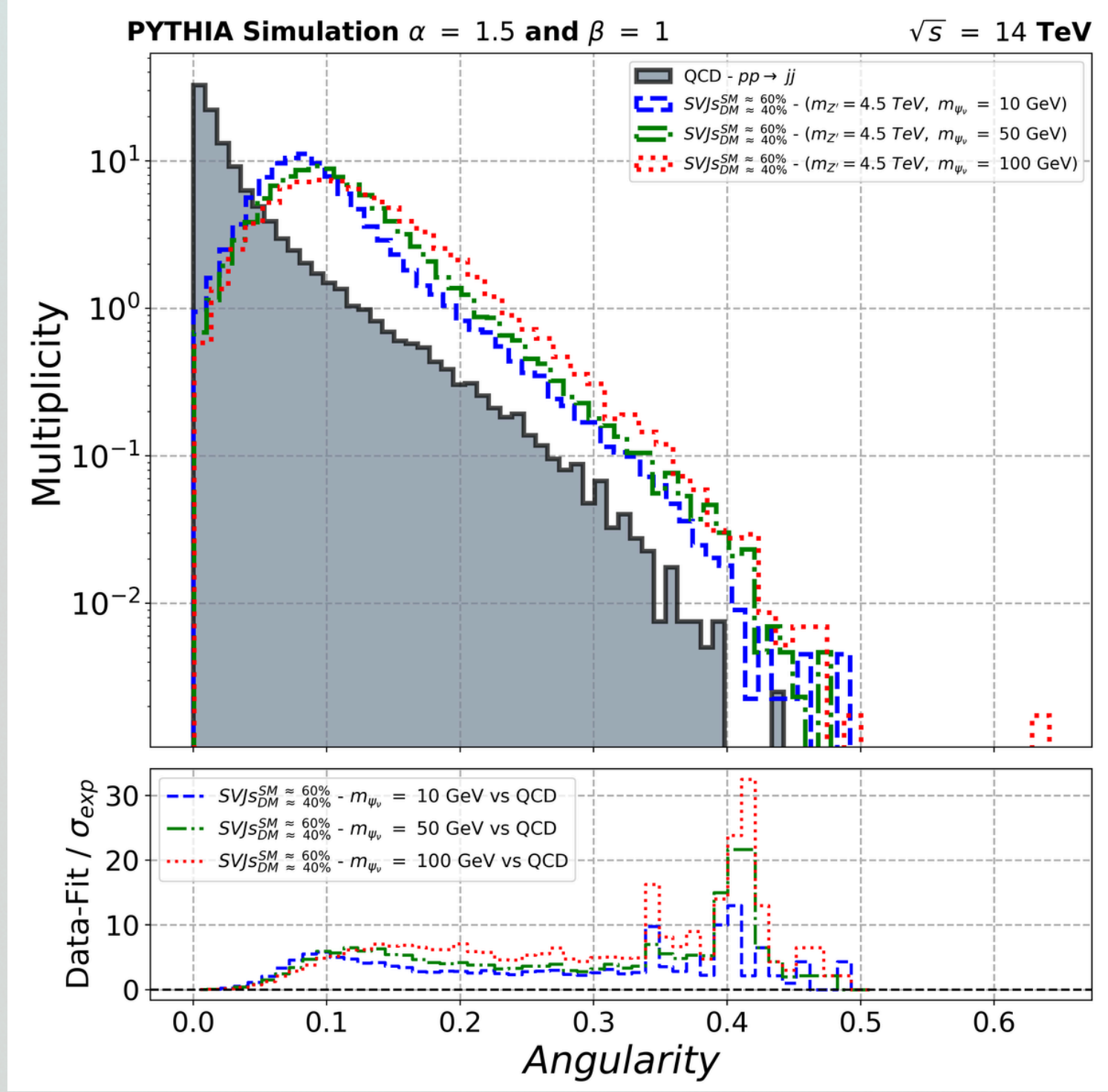


VS

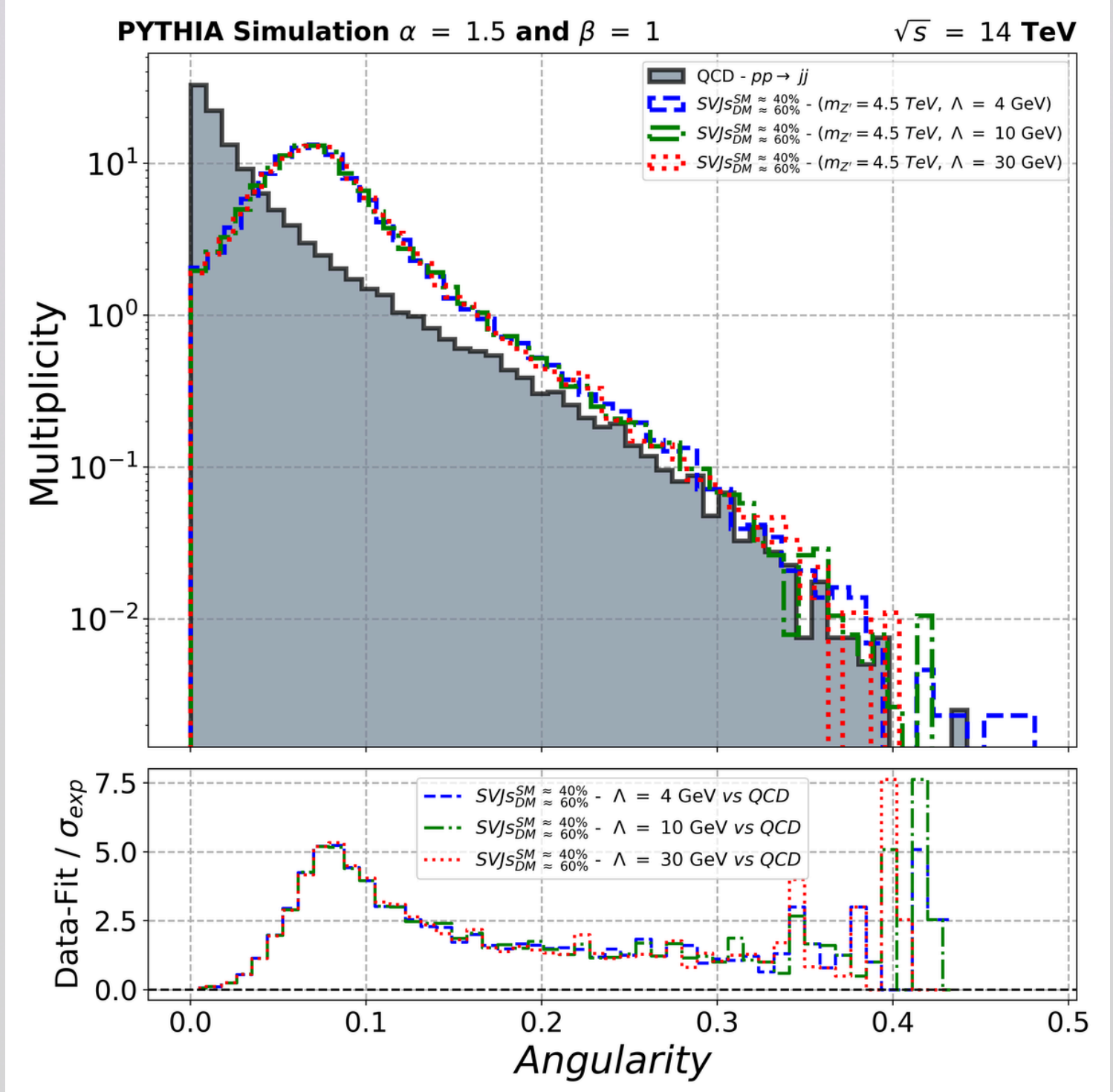


- Main changes:
1. If do we change the α parameter our distribution will change for both of the kinematical features.
 2. Dark quark masses again will give us a good candidate for characterisation.
 3. The dark hadronisation scale perform slightly better than dark hadron masses
 4. Both of them differ from QCD bck.

Angularity Function with $\alpha = 1.5$



VS



- Main changes:
1. Changing the Z' mass will make the kinematical features more alike QCD.
 2. Dark quark masses will have a better performance at the whole set of values but the dark hadronisation have major differences at greater angularity values
 3. Both of them differ from QCD bck, useful for classification tasks

Earth Moving Distance function

2

THEORY BEHIND IT

EMD it's a comparison between two jets/events to compute how much different it's one from the other by taking the total work and rearrange the radiation pattern from one jet/event to another.

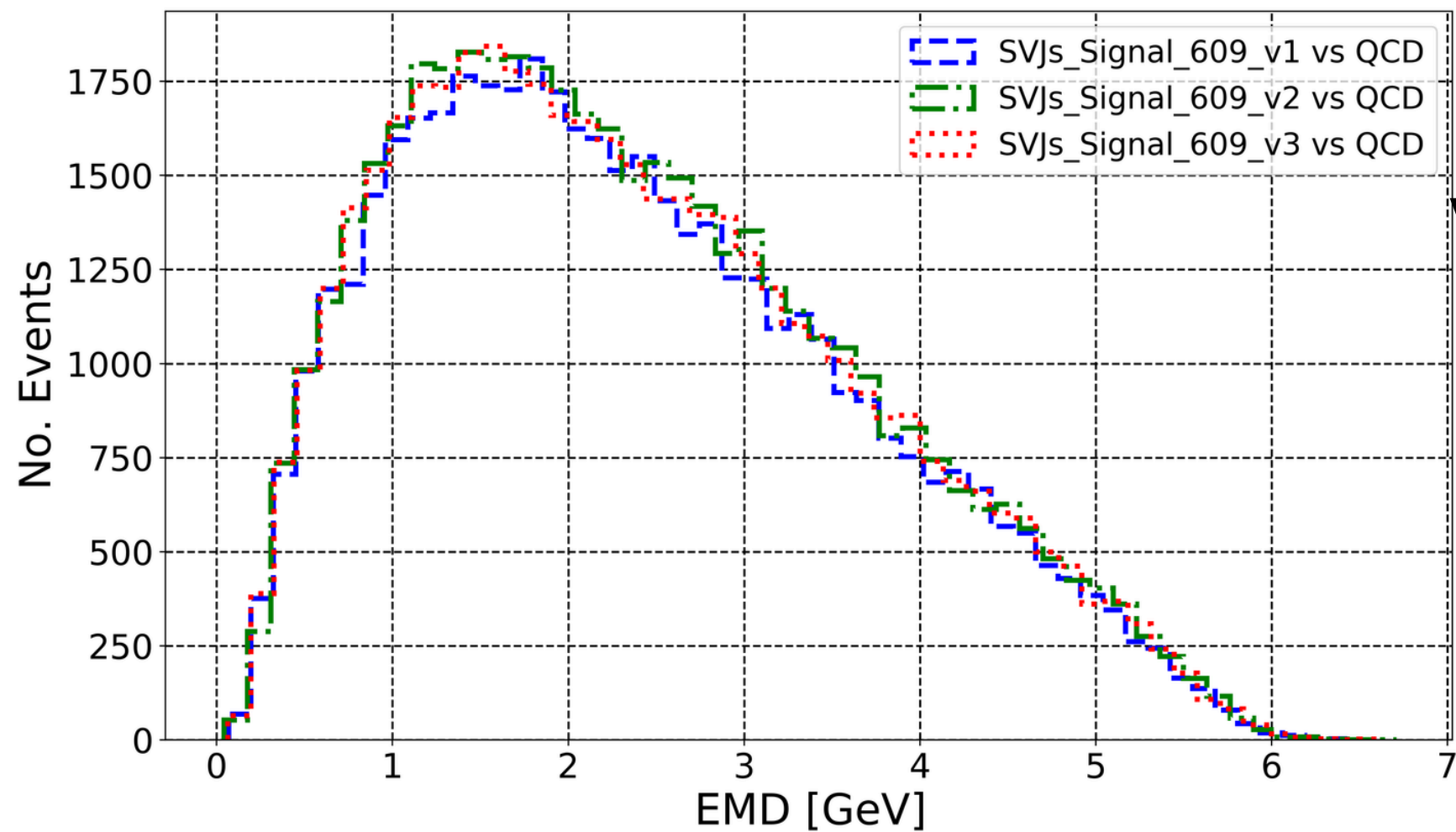
The total energy for the hadronic case can be taken as the total transverse momentum, where E_i , E'_j are the constituents energies for 2 events, and f_{ij} are the movements of energy.

The metric was already obtained using DELPHES

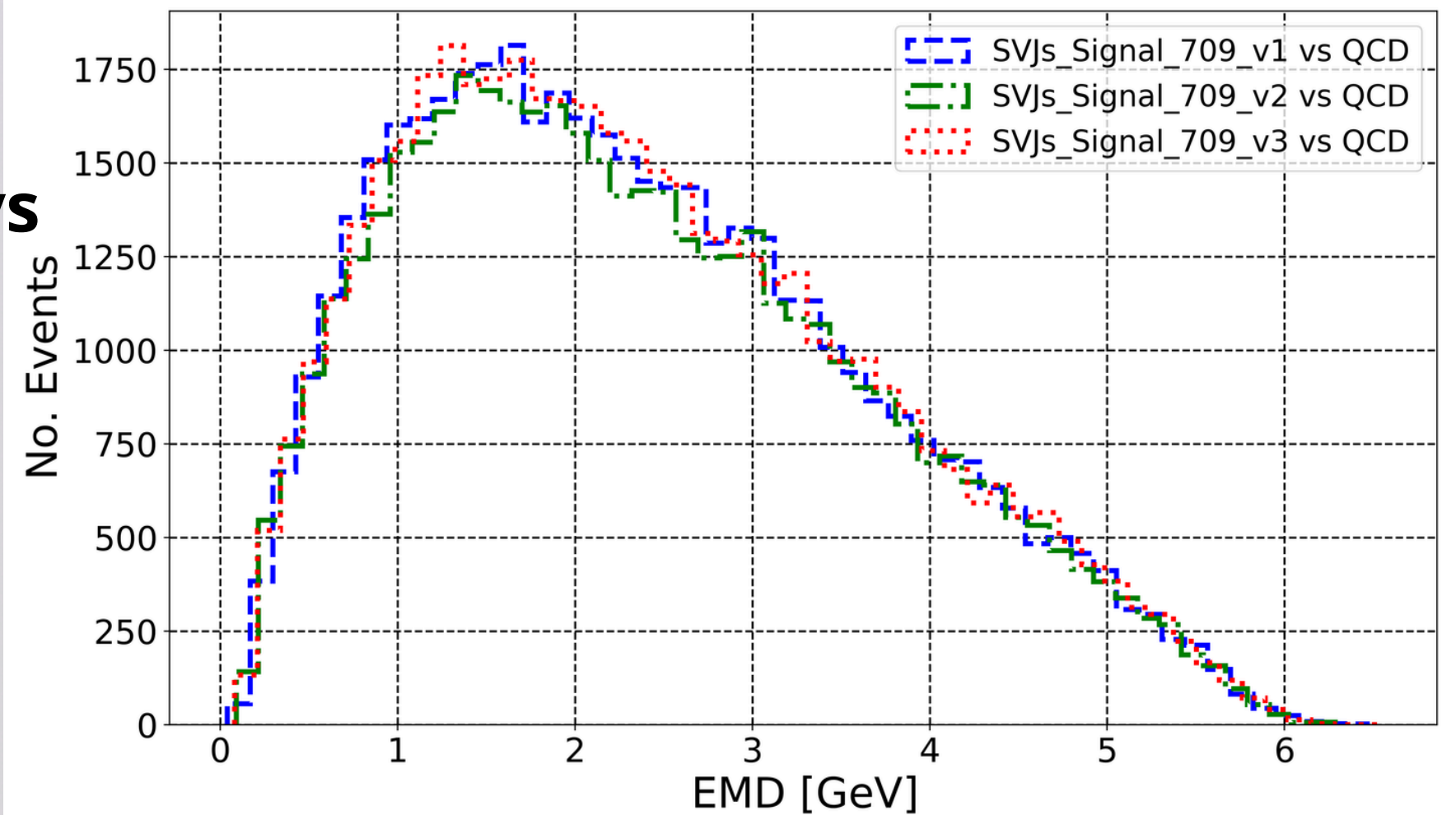
$$\text{EMD}_{\beta,R}(\mathcal{E}, \mathcal{E}') = \min_{\{f_{ij} \geq 0\}} \sum_{i=1}^M \sum_{j=1}^{M'} f_{ij} \left(\frac{\theta_{ij}}{R} \right)^\beta + \left| \sum_{i=1}^M E_i - \sum_{j=1}^{M'} E'_j \right|,$$

$$\sum_{j=1}^{M'} f_{ij} \leq E_i, \quad \sum_{i=1}^M f_{ij} \leq E'_j, \quad \sum_{i=1}^M \sum_{j=1}^{M'} f_{ij} = E_{\min}, \quad E_{\min} = \min \left(\sum_{i=1}^M E_i, \sum_{j=1}^{M'} E'_j \right)$$

EMD (Delphes Level)



VS



Main changes:

1. Having a lower Z' mass will require more rearranging of the distance between partons.
2. In this kinematical feature the dark hadronisation scale doesn't seem to be good for characterisation tasks.