Hunting the unseen: Deep Learning Analysis for Semi Visible Jet Tagging

Speaker: Miguel Ángel Avendaño Bernal

In collaboration with

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arXiv:
2609.11692

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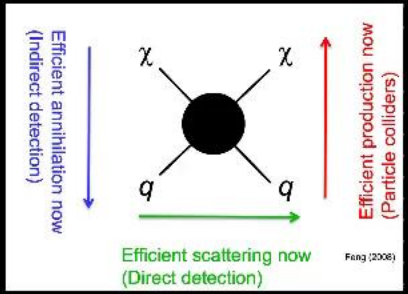

Motivation:

1. Dark-sector particles are (quasi-)stable viable DM candidates.
2. Detections lead to non-standard decays with atypical signatures (jets)
3. Current searches led by the DarkShowers LHC Taskforce

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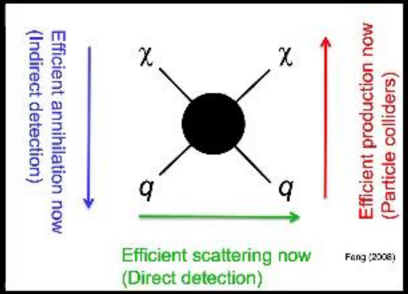

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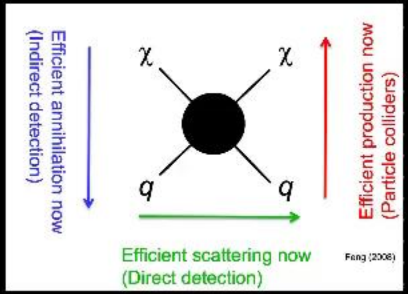

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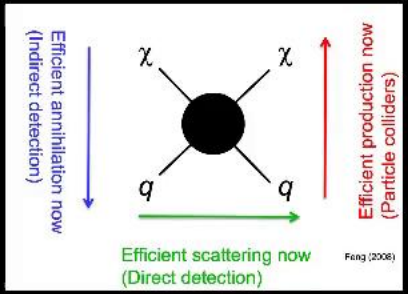

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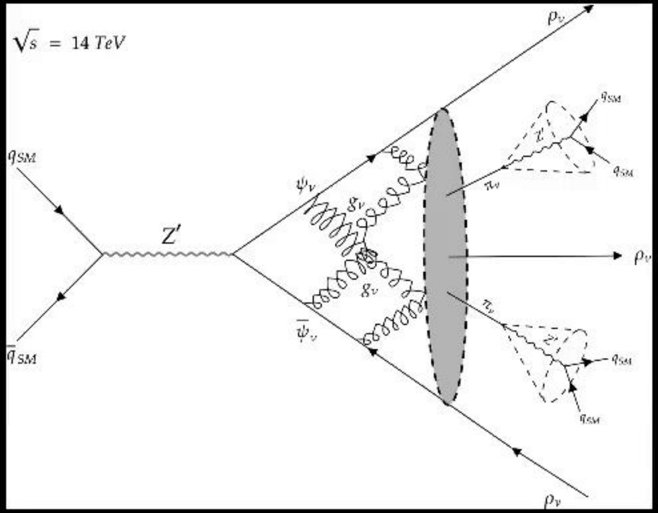

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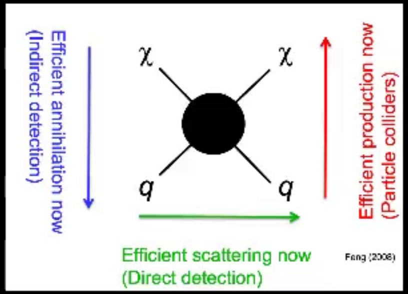

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SM Sector — Portals — Hidden Sector

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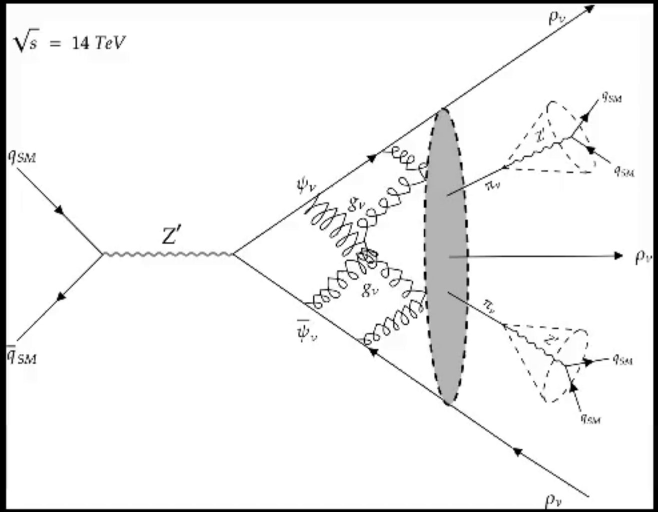

- Production mode through a resonance (Higgs, Z', etc)
- Dark Shower and Dark hadronisation (Complex part)
- Decay into visible observables, via the invisible fraction:

$$r_{\text{inv}} \equiv \left\langle \frac{n_{\text{dark;hadrons;stable}}}{n_{\text{dark;hadrons;total}}} \right\rangle$$

MONTE CARLO EVENT GENERATORS

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Hidden valley processes in Pythia8

Recovered from: Bierlich, C (2022)

1. Dark QCD sector pre-computed on the hidden valley module
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Herwig Dark showers package: H7

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- Anti-k_{T} jet clustering algorithm
- Jet radius = 0.8 (Looking at Fatjets)
- Current applied cuts in table 1.
- 18 BPs generated, compared to QCD bck.
- Plus 3 more for testing.

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

Cut	Requirement
Large-R jets multiplicity	≥ 2 jets
Large-R jet pT (Leading Jet, m0=2.5 TeV)	pT > 1.0 TeV
Large-R jet pT (Leading Jet, m0=4.5 TeV)	pT > 1.25 TeV
Missing transverse energy	MET > 200 GeV

PREPARED DATASETS FOR QCD BCK AND SVJ SIGNALS

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Dataset	m_{ψ_v} [GeV]	Λ_{dark} [GeV]	r_{inv} [%]
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SVJs_BP_02_mzp_2.5TeV	50	12.50	40
SVJs_BP_03_mzp_2.5TeV	100	25.0	40
SVJs_BP_04_mzp_4.5TeV	10	2.50	40
SVJs_BP_05_mzp_4.5TeV	50	12.50	40
SVJs_BP_06_mzp_4.5TeV	100	25.0	40
SVJs_BP_07_mzp_2.5TeV	50	20.0	30
SVJs_BP_08_mzp_2.5TeV	50	20.0	20
SVJs_BP_09_mzp_2.5TeV	50	20.0	50
SVJs_BP_10_mzp_4.5TeV	50	20.0	30
SVJs_BP_11_mzp_4.5TeV	50	20.0	20
SVJs_BP_12_mzp_4.5TeV	50	20.0	50
SVJs_BP_13_mzp_2.5TeV	50	4.0	40
SVJs_BP_14_mzp_2.5TeV	50	10.0	40
SVJs_BP_15_mzp_2.5TeV	50	30.0	40
SVJs_BP_16_mzp_4.5TeV	50	4.0	40
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SVJs_BP_05_mzp_4.5TeV	50	12.50	40
SVJs_BP_06_mzp_4.5TeV	100	25.0	40
SVJs_BP_07_mzp_2.5TeV	50	20.0	30
SVJs_BP_08_mzp_2.5TeV	50	20.0	20
SVJs_BP_09_mzp_2.5TeV	50	20.0	50
SVJs_BP_10_mzp_4.5TeV	50	20.0	30
SVJs_BP_11_mzp_4.5TeV	50	20.0	20
SVJs_BP_12_mzp_4.5TeV	50	20.0	50
SVJs_BP_13_mzp_2.5TeV	50	4.0	40
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Performing a parameter scan over three key physical quantities:

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

Dark Quarks masses : m_{ψ_D}

Dark hadronisation cte : Λ_D

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Changes are pointed in red

With the following BPs used as testing for the DL analysis

Dataset	m_{ψ_v} [GeV]	Λ_{dark} [GeV]	r_{SM} [%]
SVJs_BP_19_mzp_3.5TeV	75	2.50	60
SVJs_BP_20_mzp_3.5TeV	50	12.50	65
SVJs_BP_21_mzp_3.5TeV	50	20.0	40

SVJ Jet-Level observables: Basic Kinematics

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DID OUR CUTS MATCHES WHAT DO WE EXPECT FROM THEM?

SVJ Jet-Level observables: Basic Kinematics

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We implemented some cuts but are they being properly applied in our current analysis? and will they be able to reconstruct the invariant and transverse mass? We should extract:

- Di-jet Energy: $E_{1,2}$
- Di-jet three-momentum: $\vec{p}_{1,2}$
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and see if we can get an approximation to the Z' mass

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Transverse mass

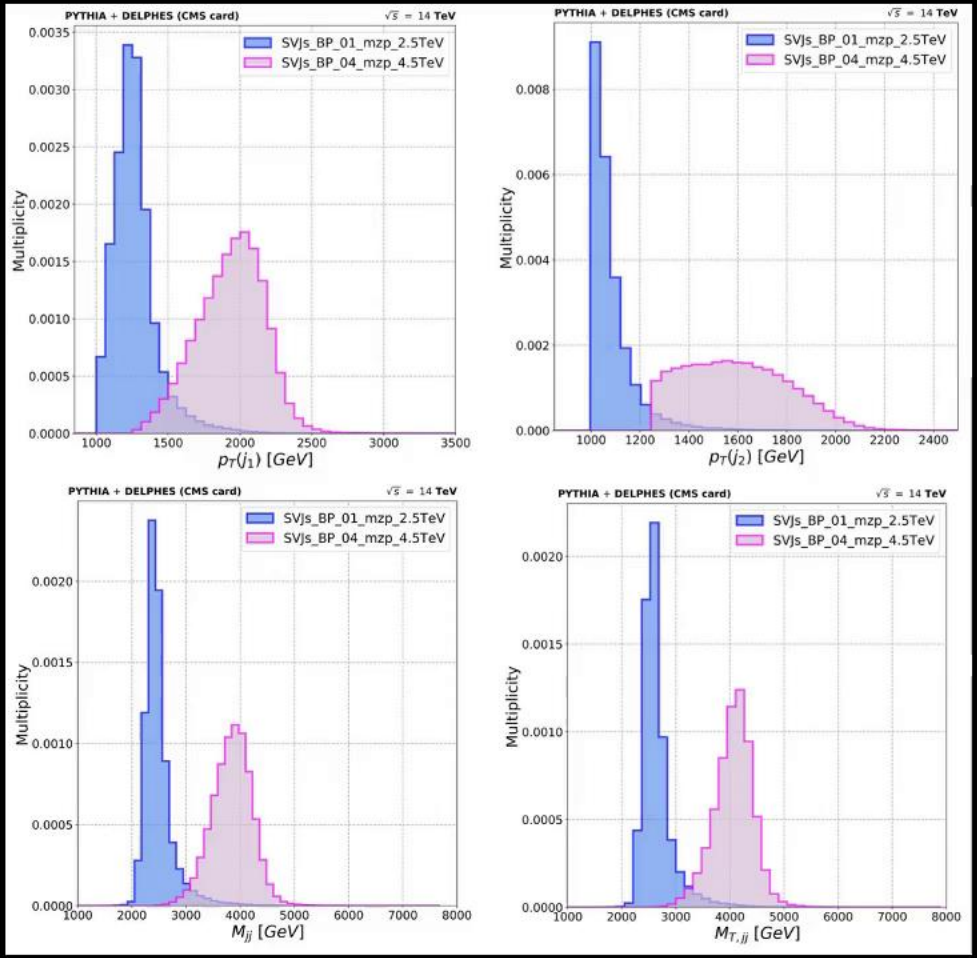
$$m_T^2 = M_{jj}^2 + 2\left(|E_T^{miss}|\sqrt{M_{jj}^2 + |\vec{p}_{T,jj}|^2} - E_T^{miss} \cdot \vec{p}_{T,jj}\right),$$

Recovered from: (Asadi, P., et al. (2026))

RESULTS

DO WE SATISFY OUR EXPECTATIONS?

RESULTS



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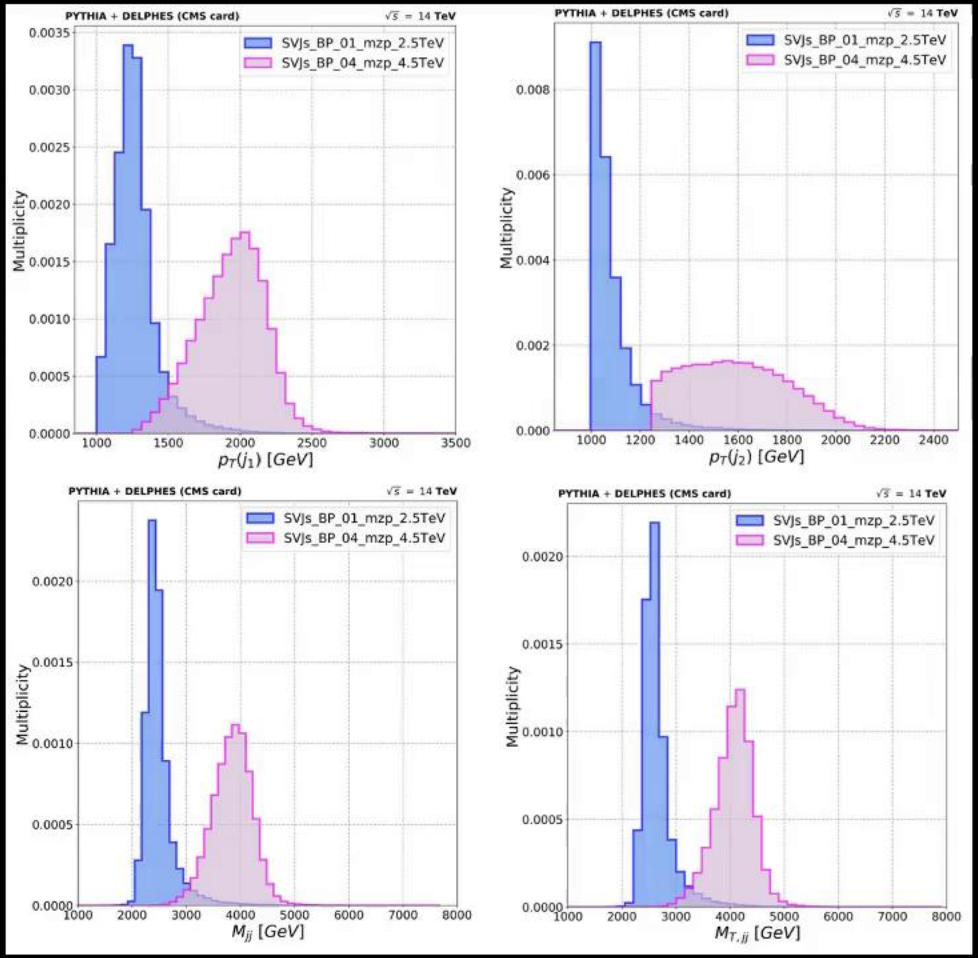

DO WE SATISFY OUR EXPECTATIONS?

All the cuts were satisfied!

The cut for the transverse momentum in both jets is correctly applied, and if we do measure the transverse and invariant mass we observed that

1. The invariant mass is lower that the transverse mass.
2. The invisible constituents from the stable dark hadrons contribute to the total Z' mass reconstruction.

Global MET and Difference on the Azimuthal

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THEORY BEHIND IT AND APPLICATION OF DELPHES COLLIDER ANALYSIS

Global MET and Difference on the Azimuthal

2 *THEORY BEHIND IT AND APPLICATION OF DELPHES COLLIDER ANALYSIS*

DELPHES allows us to compute the MET from the "tree" file which already takes into account:

- Detector dimensions
- Particle isolation
- Particle smearing

this includes the invisible particles (both neutrinos and BSM), within the detector.
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Difference on the azimuthal

$$\Delta\phi = \phi_{MET_{Global}} - \phi_{jet_{lead}}$$

Recovered from: (Franceschini, R., et al 2023)

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Plots from the difference on the azimuthal are on the backup.

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WHAT CAN WE LEARN FROM IT?

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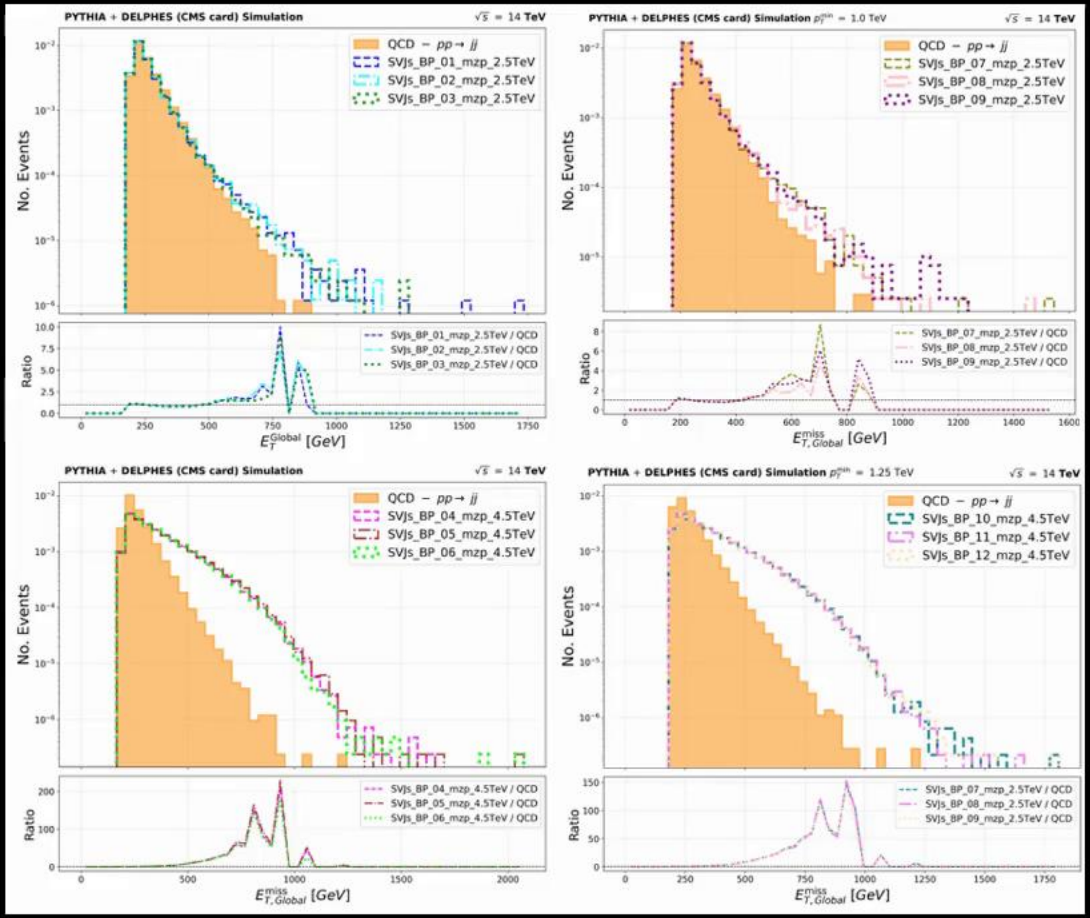

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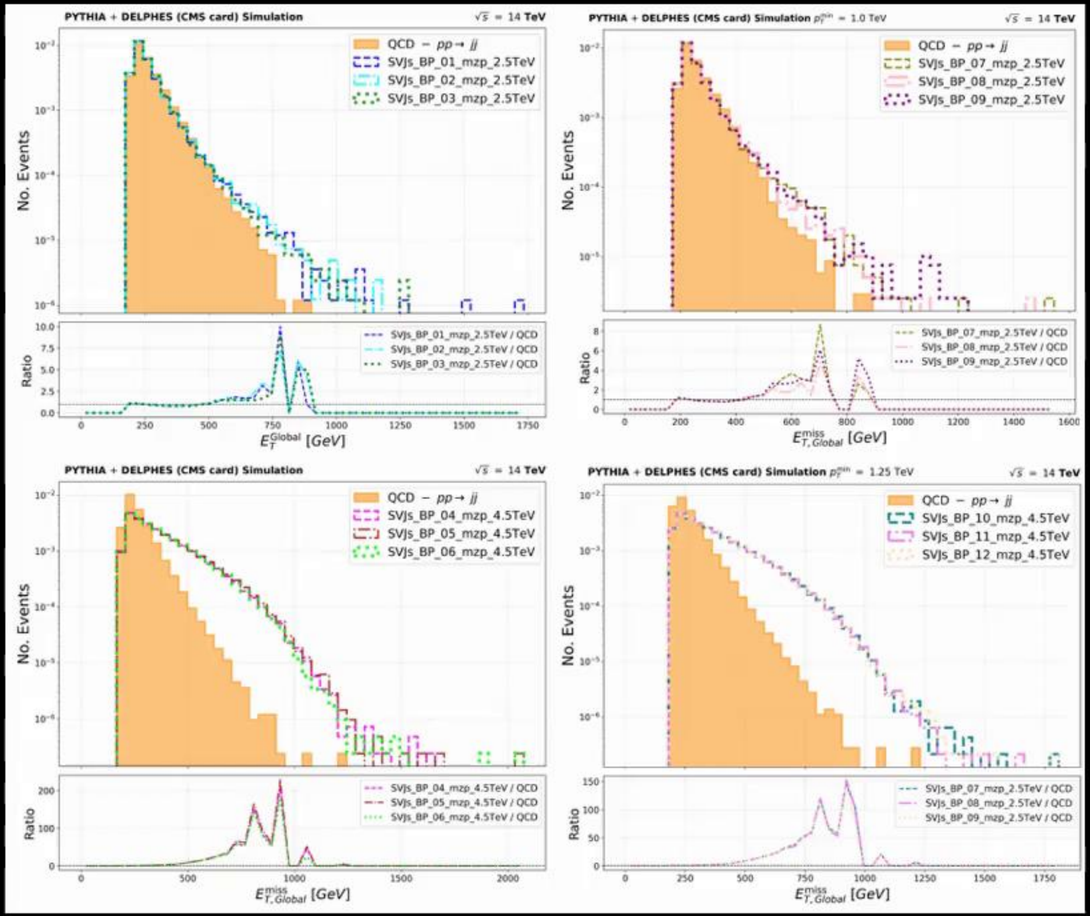

WHAT CAN WE LEARN FROM IT?

Main differences:

1. The HV parameters dependence is visible, where the dark hadrons mass and the invisible fraction produces the largest changes in the MET distribution
2. Increasing the mediator mass yields to a harder energy spectrum and higher MET values
3. SVJ BPs can overlap but all of the distributions exhibit differences.

The Lund-plane (Delphes-Level)

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1 *THEORY BEHIND IT*

The Lund-plane (Delphes-Level)

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THEORY BEHIND IT

2D Representation of jet visible constituents:

1. Charged hadrons (in particular mesons: Neutral Kaons and negative/positive pions)
2. Photons.

WHERE:

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WHERE:

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

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

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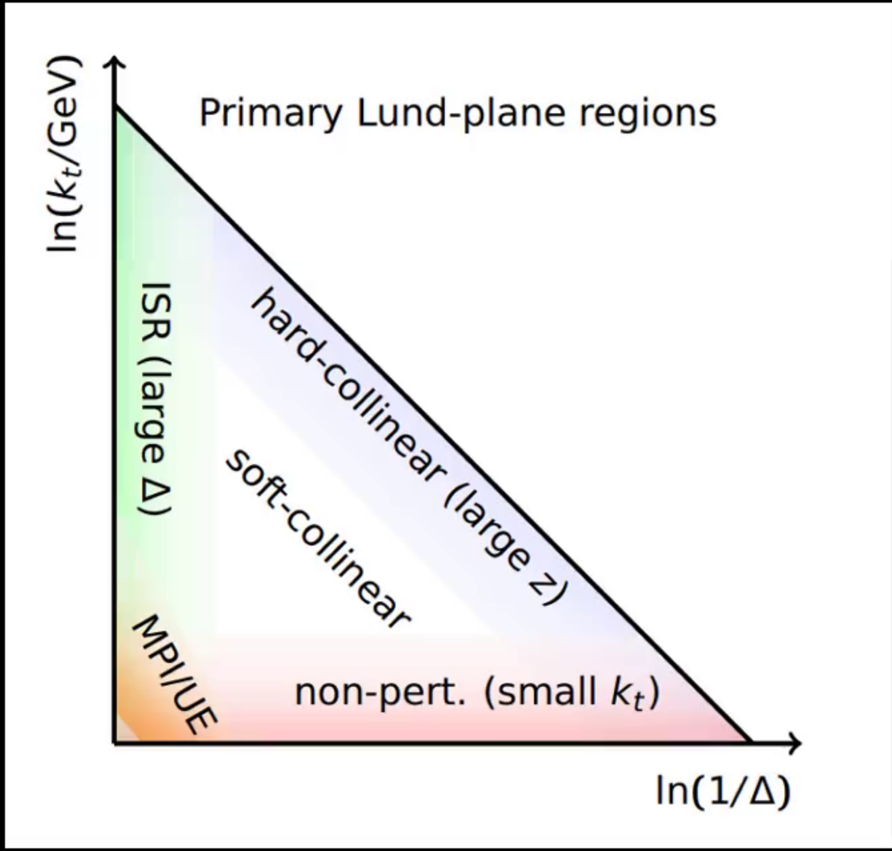

Recovered from: (Dreyer, F.A., et al, 2018)

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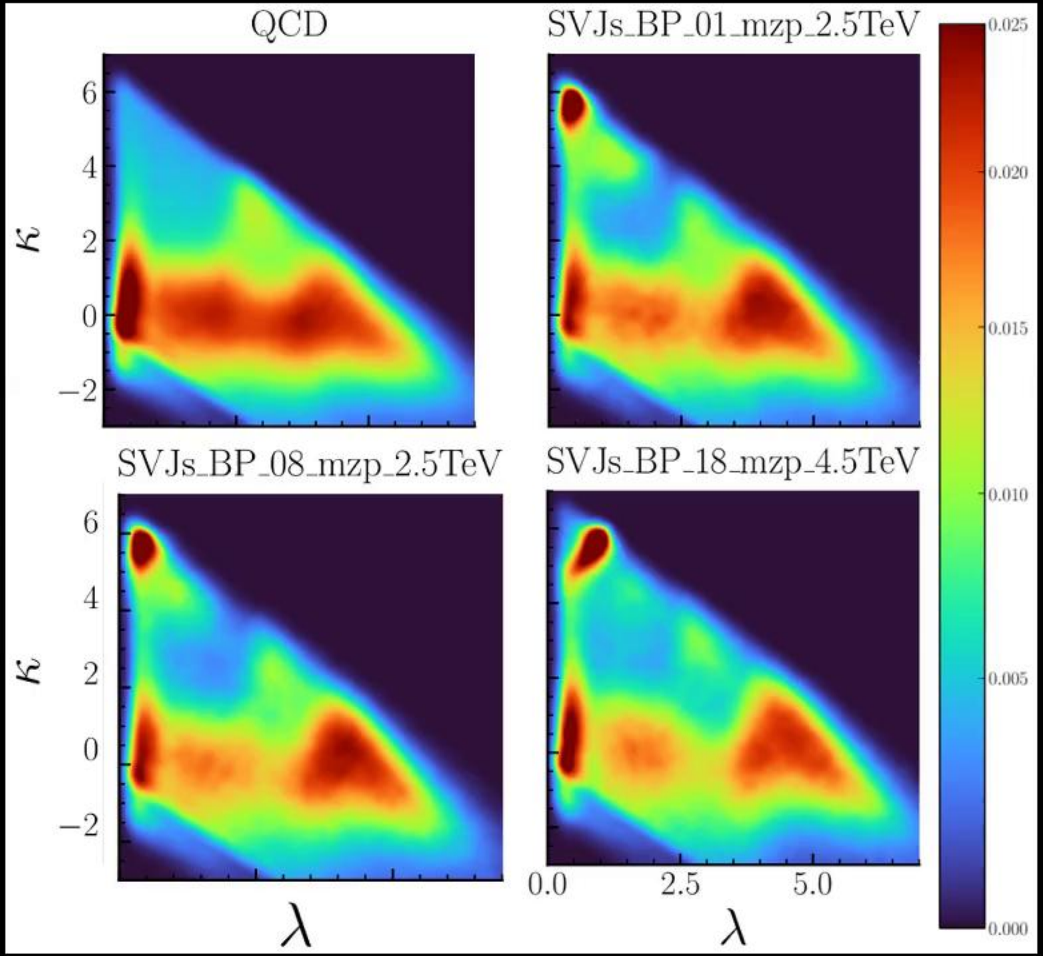

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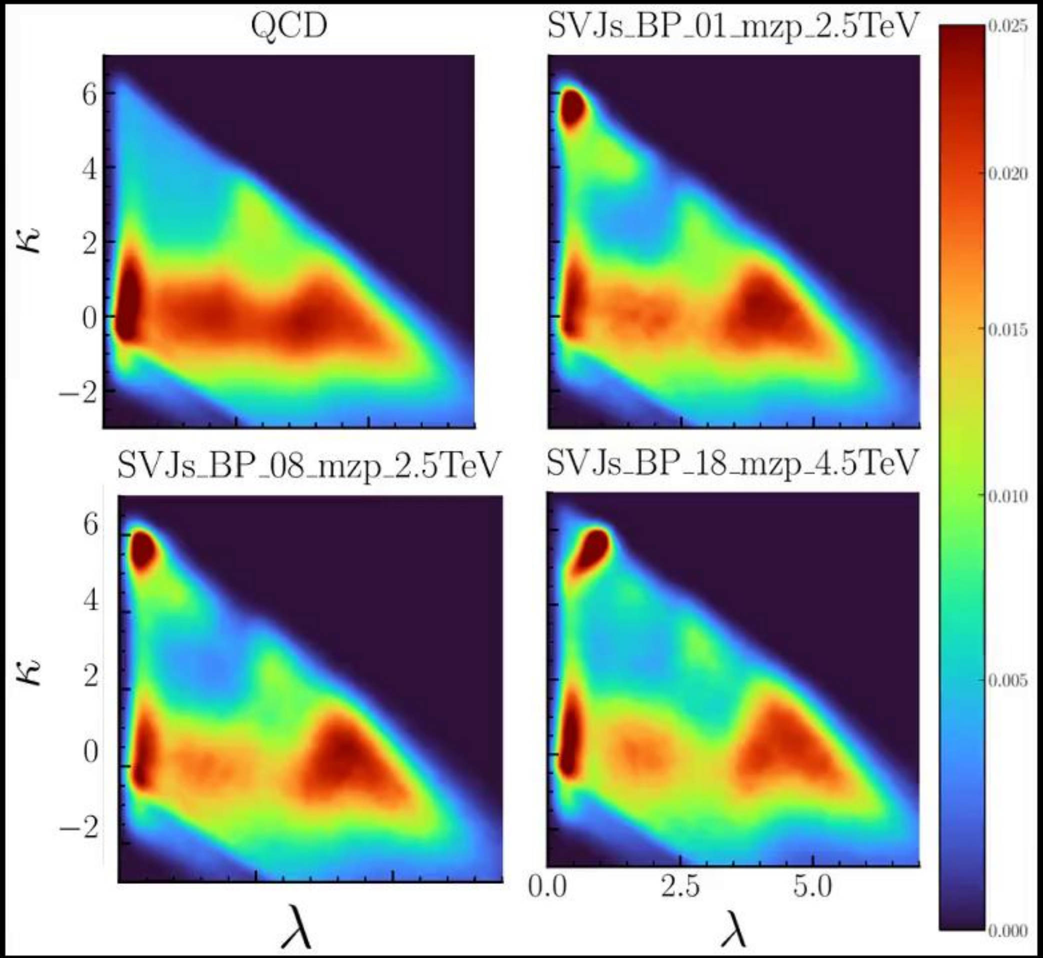

WHAT CAN WE LEARN FROM IT?

Visual differences from QCD/SVJ signals.

1. Dark quarks masses affect the boost of decay hadrons causing larger MPI emissions.(For $\ln(k_T)$)
2. The invisible fraction modifies the ISR and hard-collinear radiation
3. Dark hadronisation impacts the non-perturbative and soft collinear regions(For small k_T)

ML ANALYSIS IDEA

FUSION NETWORK

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We want to know how much discrimination power we have using 5 NNs:

1. Vision Transformer (ViT) for the LJP images
2. JetLOV using the Lund variables from Lund tree
3. MLP for all the kinematical information
4. Fusion network between the ViT and the MLP
5. Fusion network between the JetLOV and the MLP

All trained on a common balanced dataset.

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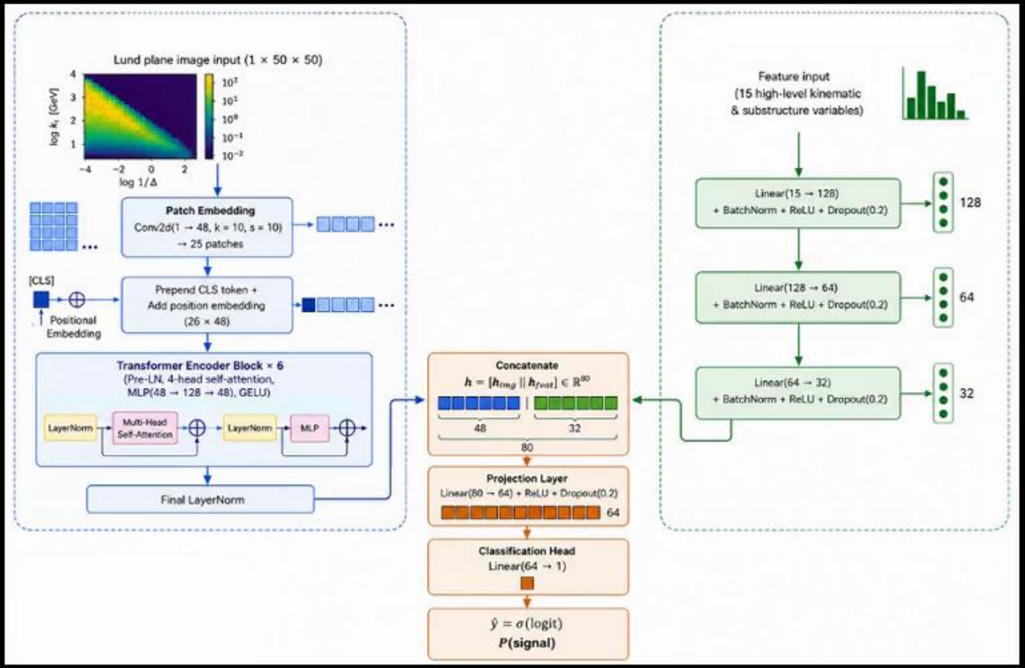

ML ANALYSIS IDEA

We want to know how much discrimination power we have using 5 NNs:

1. Vision Transformer (ViT) for the LJP images
2. JetLOV using the Lund variables from Lund tree
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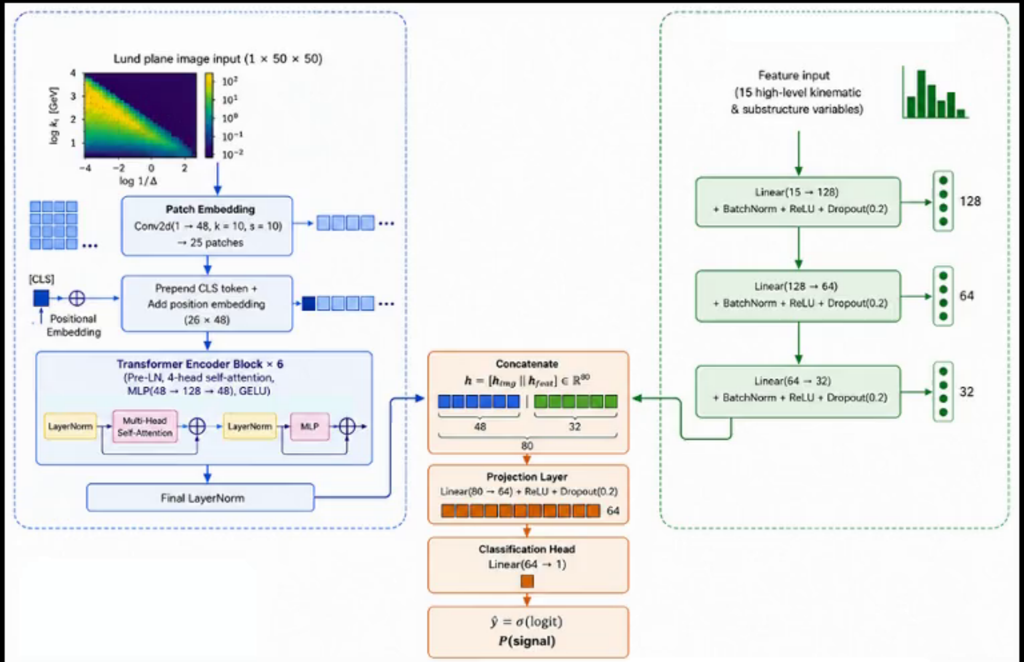

OBSERVABLES DISTRIBUTION

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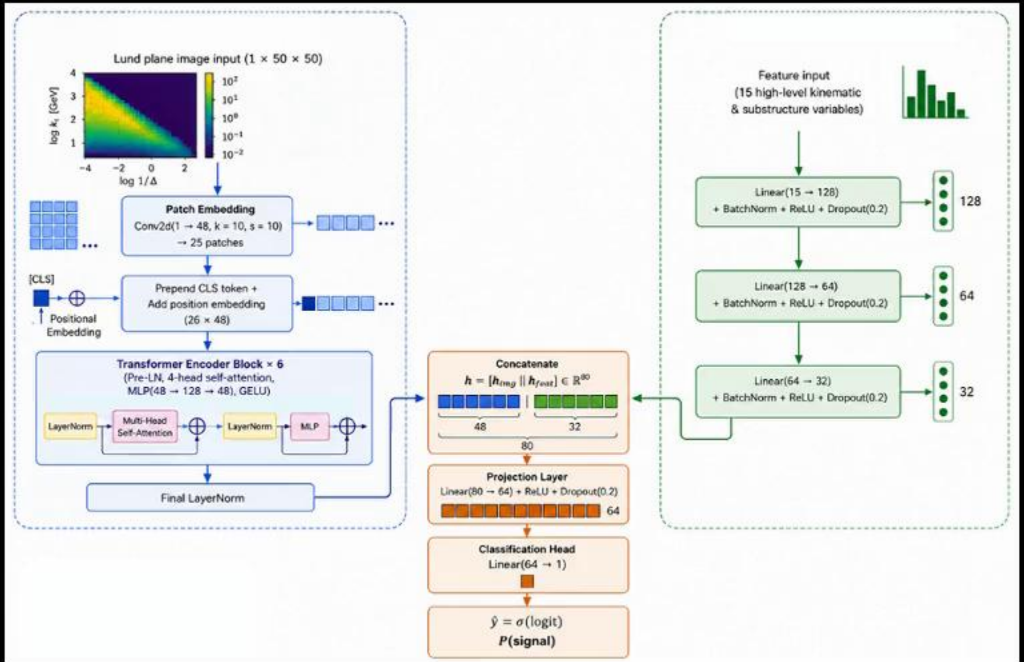

OBSERVABLES DISTRIBUTION

The Lund Jet Plane (LJP) for:

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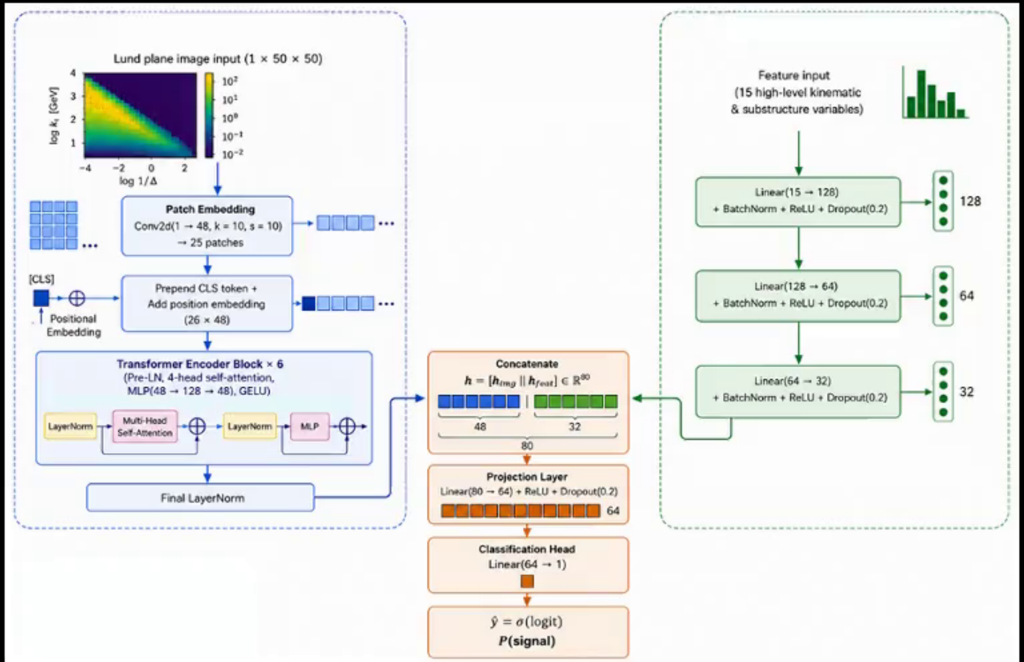

OBSERVABLES DISTRIBUTION

The Lund Jet Plane (LJP) for:

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2. JetLOV

The MLP for:

Global	Local (Jet-Level)	
	Final-state	Sub-structure
MET	$p_T(j_1)$, $p_T(j_2)$	$\tau(0.1)$
$\Delta\phi(MET, j_{\text{lead}})$	$\phi(j_1)$, $\phi(j_2)$	$\tau(0.8)$
	$\eta(j_1)$, $\eta(j_2)$	$\tau(1.5)$
	m_{jj}	e_2-EEC
	$\Delta\phi(j_1, j_2)$	
	Hadron multiplicity	

CLASSIFICATION RESULTS

CONFUSION MATRICES

ARE WE ABLE TO DISTINGUISH QCD AND SVJ?

CLASSIFICATION RESULTS

Model	Accuracy	ROC AUC
ViT	0.8629	0.9293
JetLOV	0.9003	0.9572
MLP (All)	0.9054	0.9653
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ARE WE ABLE TO DISTINGUISH QCD AND SVJ?

From the previous tables we can say that:

- One observable such as the LJP won't provide enough discrimination rather than merging it with other observables.
- Merging 2 different networks allow us to reconstruct and retain the dominant jet information.
- The fusion model achieves the highest discrimination power between SVJ or QCD, and the best performance for identify true SVJ or QCD signals.

SUMMARY

FURTHER WORK

SUMMARY

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Can jet sub-structure observables help us to detect DS signatures for future CMS searches?

Short answer: **Yes!**, dark showers and SVJ searches allow us to distinguish them from a well-known QCD bck, and understand their kinematical parameters:

- Jet-substructure observables reveals which parameters have the strongest impact on the kinematics
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More detail in the backup!

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Thanks!

ANY QUESTIONS?

:)

BACKUP

Speaker: Miguel Ángel Avendaño Bernal

In collaboration with:

Srinandan Dasmahapatra, Ahmed Hammad, Stefano Moretti, Mihoko Nojiri, Michael H. Seymour and Claire Shepherd-Themistocleous

Based on the work published on arXiv:

arXiv: 2609.11692

What is a jet? The theoretical perspective

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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:

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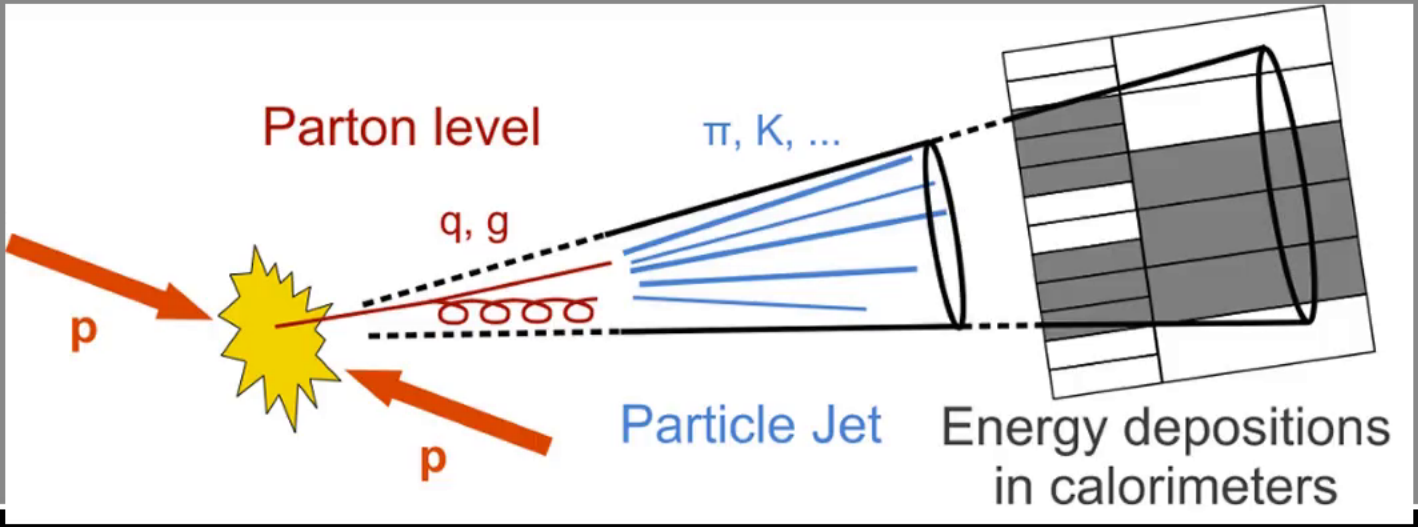
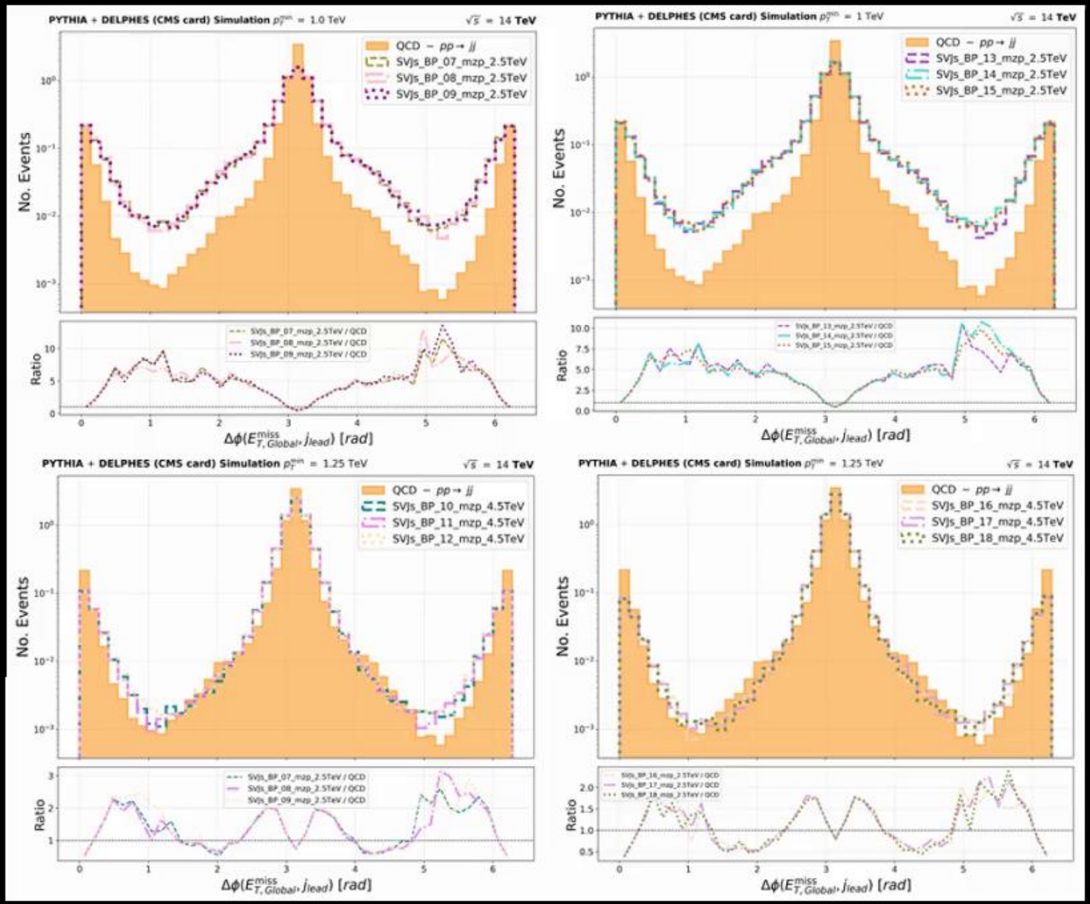


RESULTS

WHAT CAN WE LEARN FROM IT?

RESULTS



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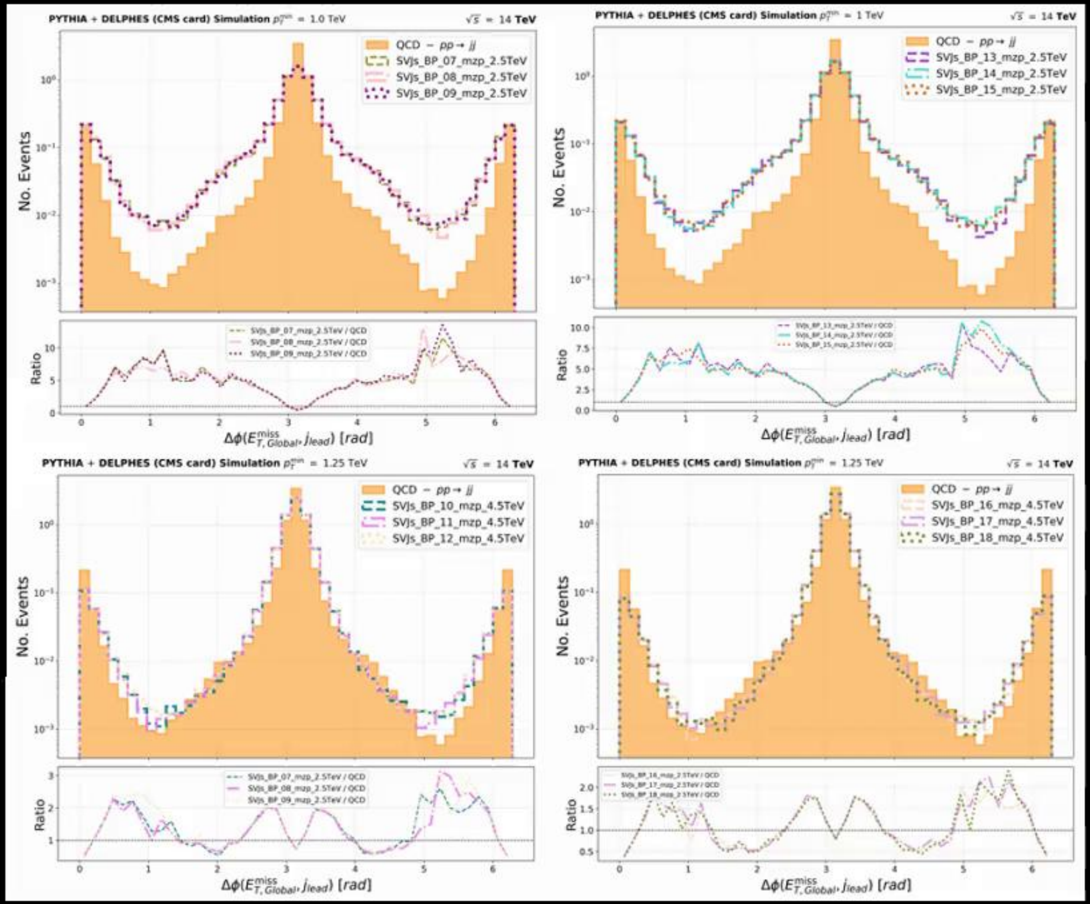

WHAT CAN WE LEARN FROM IT?

Now the dependence on the HV parameters is mainly driven for:

- The mediator mass
- The dark hadron mass
- The invisible fraction

Physics reveal:

- Mediator mass will control the available energy scale of the event, leading jet kinematics and the amount of energy from the dark sector and the phase space for DS evolution.

Angularity Function (Delphes Level)

Angularity Function (Delphes Level)

2

THEORY BEHIND IT

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THEORY BEHIND IT

Numerical computation between constituents to quantify the p_T weighted angular separation between the constituents and the selected jet, with:

1. θ_i^α is the angle from the particle within the jet.
2. E_i is the energy from the constituent
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$\beta = 1$ $\alpha \geq 0;$ $\alpha \in [0.1, 2]$

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

RESULTS

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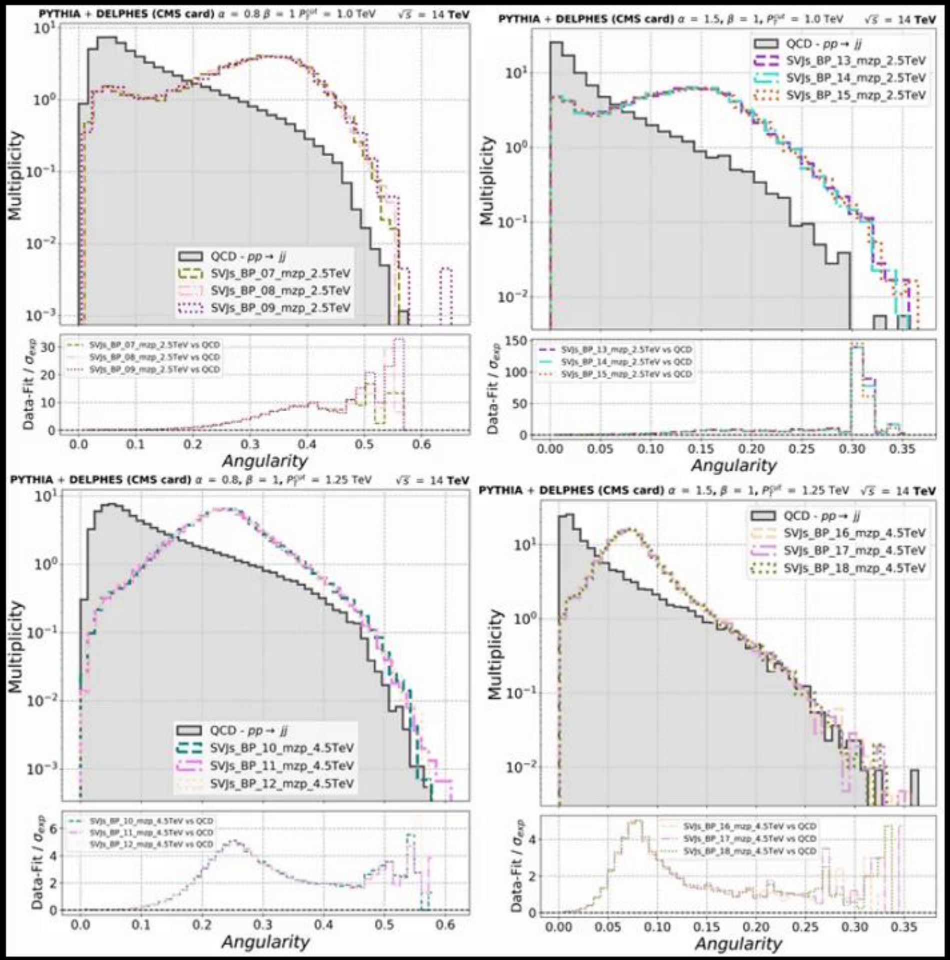

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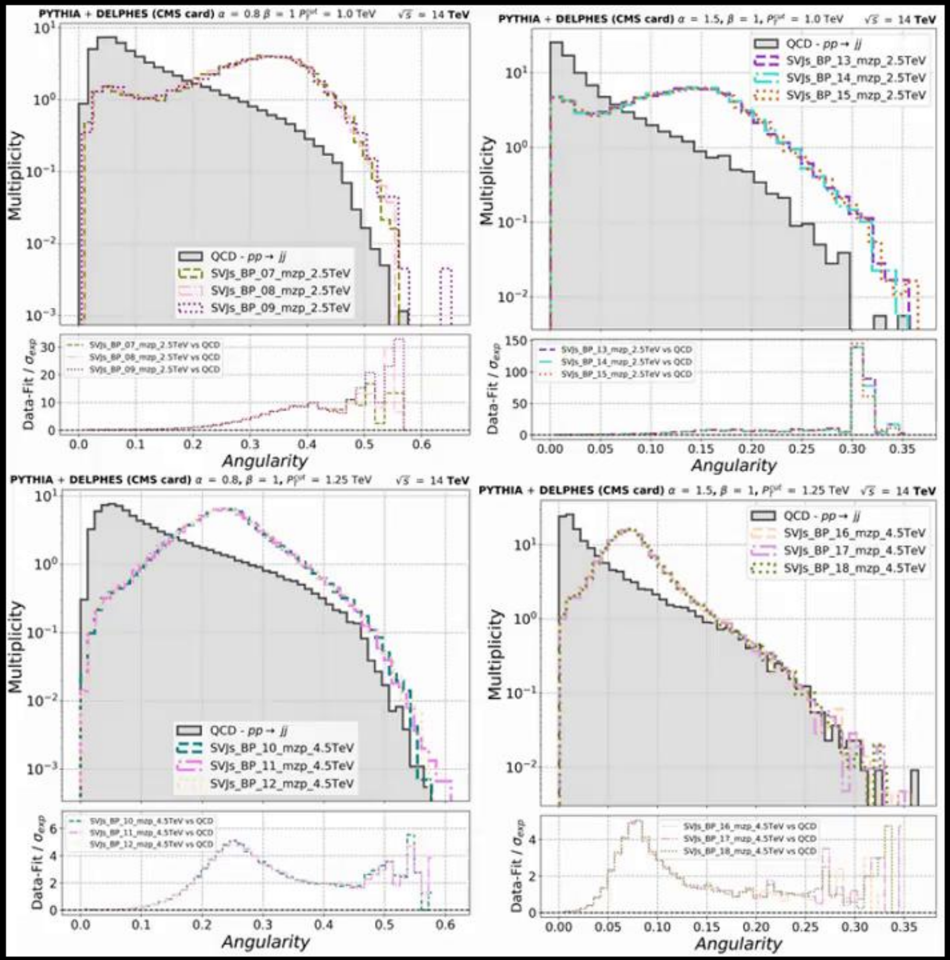

WHAT CAN WE LEARN FROM IT?

Physical changes:

- Varying α will change the relative sensitivity of the observable at the perturbative and non-perturbative emission level.
- Increasing α will enhance the radiation close to the jet axis with more collinear configurations
- For small α, emissions will be more alike to large angular separations, more sensitive to the broad radiation pattern of the jet.
- At α = 0.8 the observable will be more balanced between collinear and wide-angle emissions.

Training hyperparameters

Training hyperparameters

Hyperparameter	ViT	MLP	JetLOV	ViT+MLP	JetLOV+MLP
Optimizer	Adam	Adam	Adam	Adam	Adam
Learning rate	7x10^-4	1x10^-3	1x10^-3	5x10^-4	5x10^-4
Adam (b1,b2)	0.9, 0.999	0.9, 0.999	0.9, 0.999	0.9, 0.999	0.9, 0.999
Batch size	128	256	256	128	128
Dropout	0.1	0.2	0.1	0.1 / 0.2	0.1 / 0.2
Weight decay	0	0	0	0	0
Max epochs	60	100	60	15	60
Early-stop patience	5 epochs	5 epochs	5 epochs	5 epochs	5 epochs
Early-stop min. delta	1x10^-4	1x10^-4	1x10^-4	1x10^-4	1x10^-4
Random seed	42	42	42	42	42
Epochs trained (max)	35 (60)	11 (100)	15 (20)	48 (60)	18 (69)
Best epoch	30	8	7	43	13
Best val. loss	0.3361	0.2356	0.2518	0.1567	0.1504
Avg. epoch time	75.2 s	5.3 s	516.7 s	63.8 s	335 s
Total train time	43.8 min	1.0 min	1.01 hrs	51.0 min	1.68 hrs