



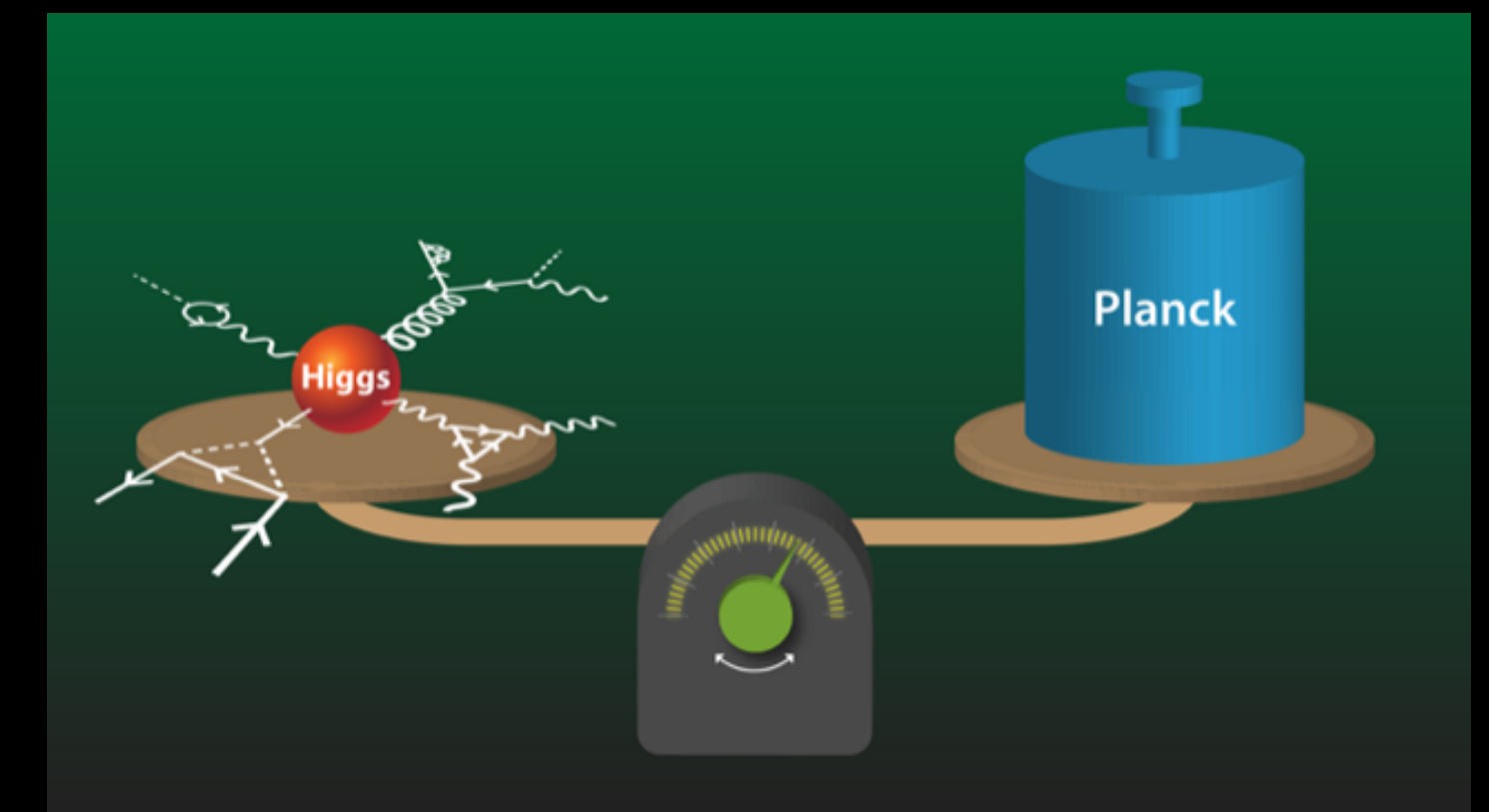
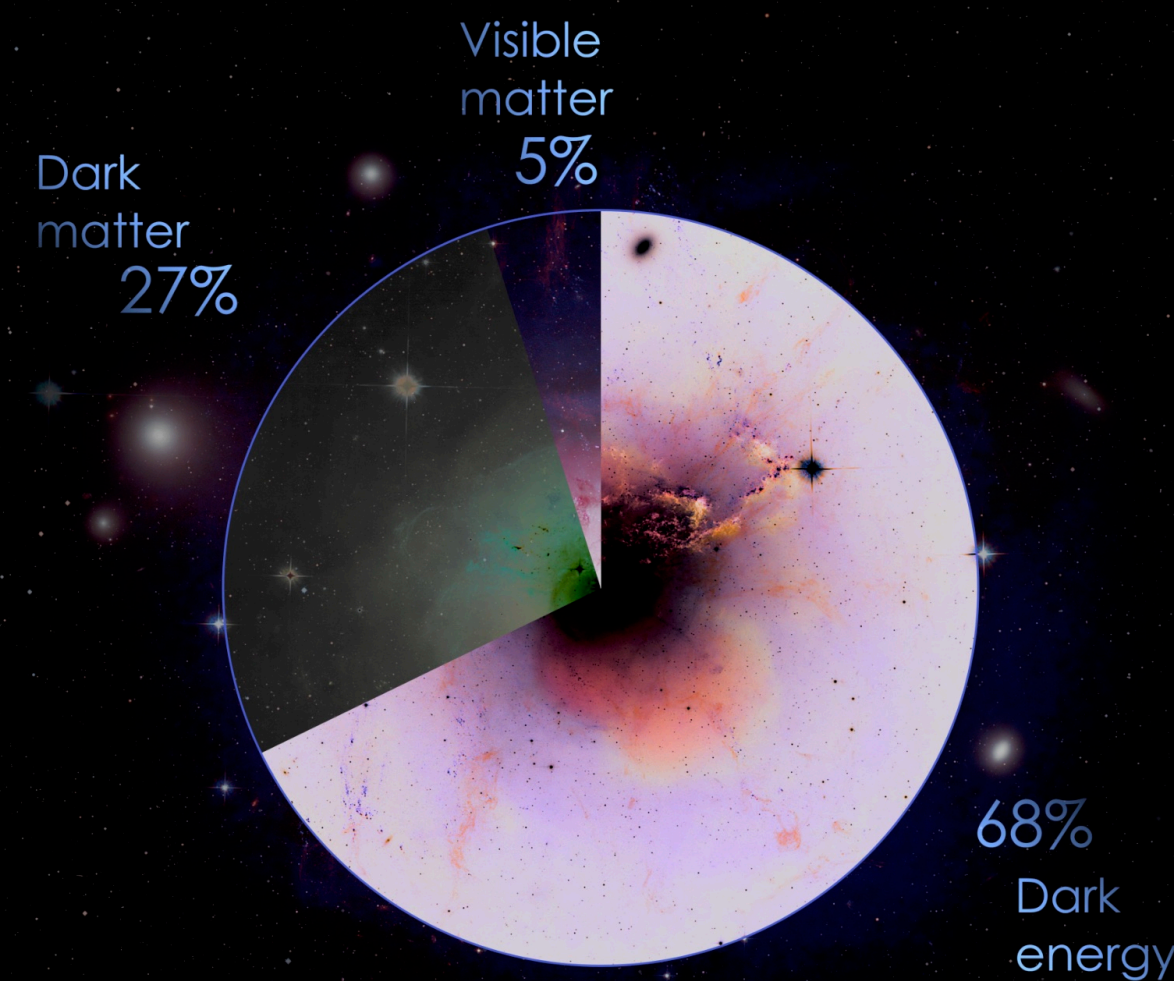
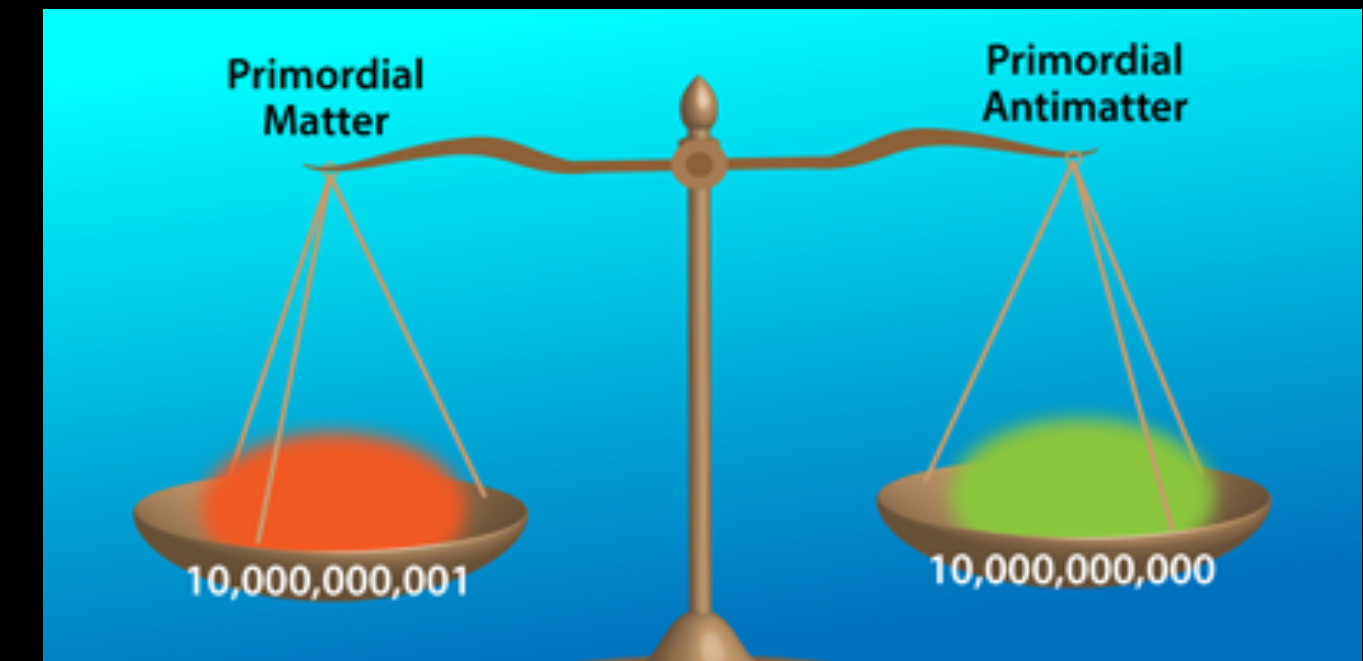
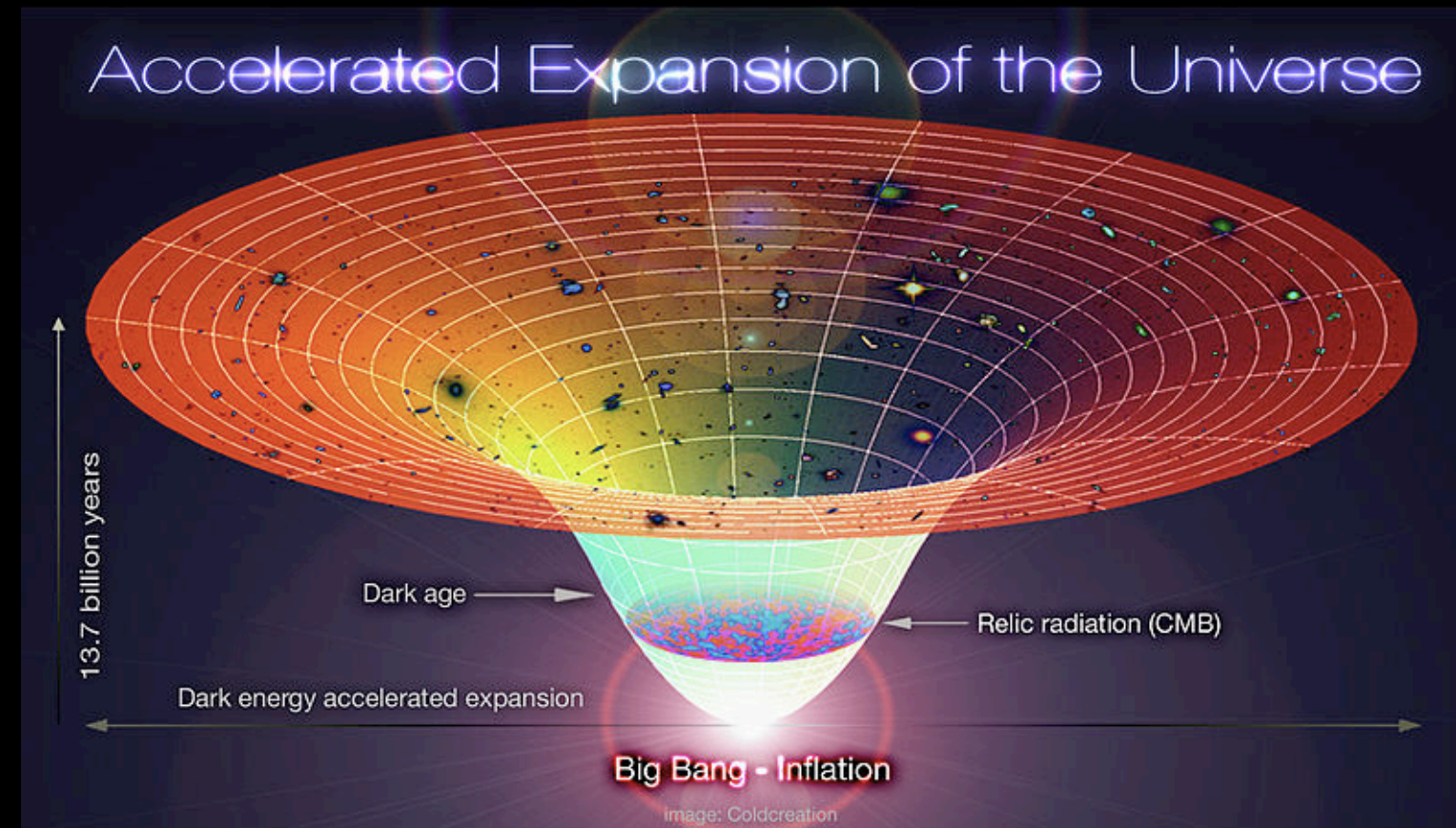
Harnessing Anomaly Detection Tools as Novel Analysis Resources for High Energy Physics

Rocky Bala Garg
Stanford University

US-LUA Annual Meeting
December 16-18, 2024

Many open questions in HEP and Cosmology

- Dark matter
- Accelerated expansion of universe → Dark Energy?
- Matter-antimatter asymmetry
- Hierarchy problem
-



ATLAS experiment has an established Physics Program

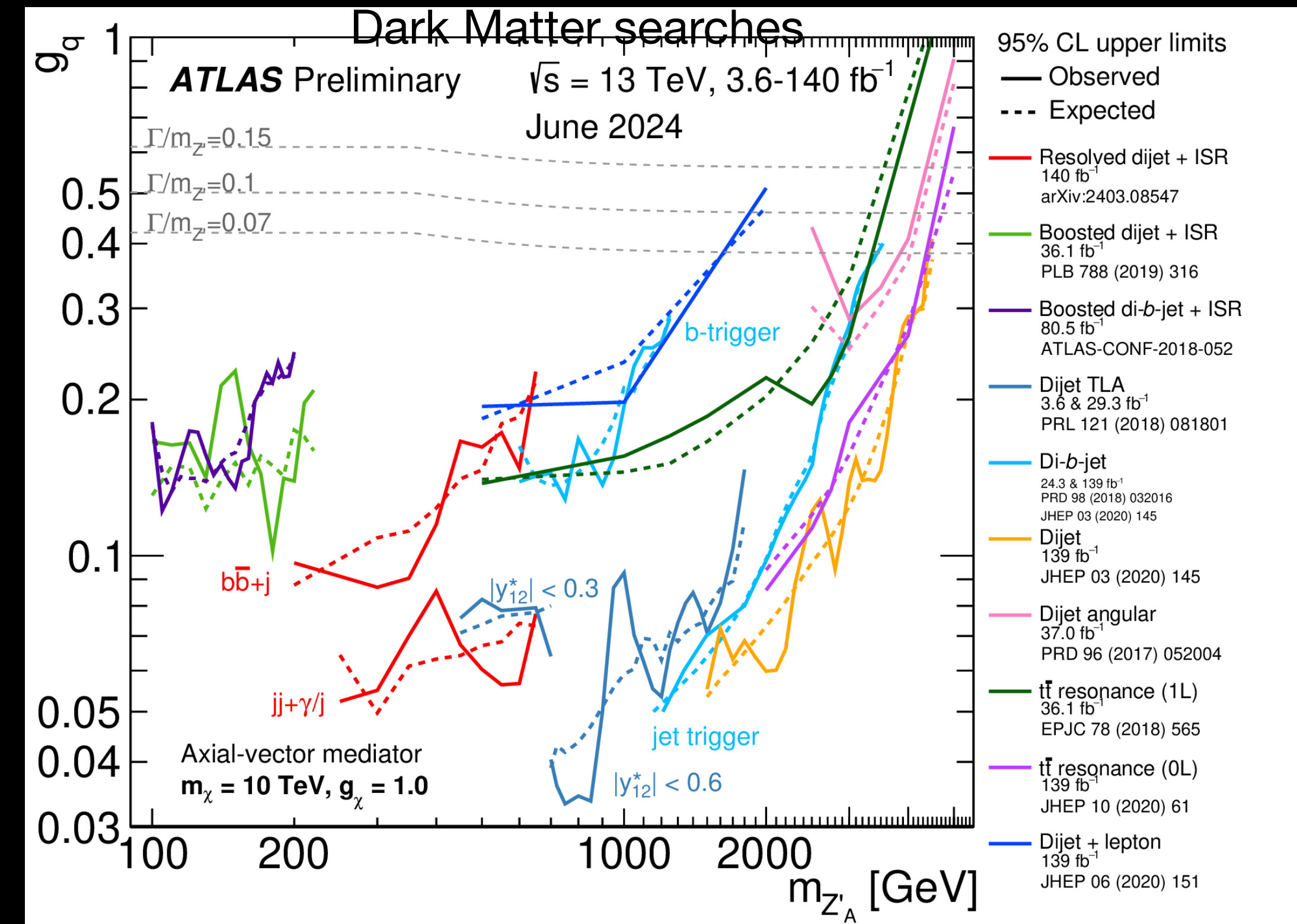
Looking into various directions
 → No signs of new physics yet

ATLAS SUSY Searches* - 95% CL Lower Limits
 July 2024

ATLAS Preliminary
 $\sqrt{s} = 13$ TeV

Model	Signature	$\int \mathcal{L} dt$ [fb ⁻¹]	Mass limit	Reference		
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 e, μ mono-jet	E_T^{miss} 140	\tilde{q} [1x, 8x Degen.] \tilde{q} [8x Degen.]	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e, μ	E_T^{miss} 140	\tilde{g} \tilde{g}	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{g}) = 1000$ GeV	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 e, μ	2-6 jets	E_T^{miss} 140	\tilde{g}	$m(\tilde{\chi}_1^0) < 600$ GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	E_T^{miss} 140	\tilde{g}	$m(\tilde{\chi}_1^0) < 700$ GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0 e, μ SS e, μ	7-11 jets 6 jets	E_T^{miss} 140	\tilde{g} \tilde{g}	$m(\tilde{\chi}_1^0) < 600$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ SS e, μ	3 b 6 jets	E_T^{miss} 140	\tilde{g} \tilde{g}	$m(\tilde{\chi}_1^0) < 500$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e, μ	E_T^{miss} 140	\tilde{b}_1	$m(\tilde{\chi}_1^0) < 400$ GeV $10 \text{ GeV} < \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$	0 e, μ 2 τ	E_T^{miss} 140	\tilde{b}_1	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 e, μ	≥ 1 jet	E_T^{miss} 140	\tilde{t}_1	$m(\tilde{\chi}_1^0) = 1$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 e, μ	3 jets/1 b	E_T^{miss} 140	\tilde{t}_1	$m(\tilde{\chi}_1^0) = 500$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss} 140	\tilde{t}_1	$m(\tilde{\tau}_1) = 800$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ 0 e, μ	2 c mono-jet	E_T^{miss} 140	\tilde{t}_1 \tilde{c}	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV
EW direct	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via WZ	Multiple ℓ /jets	E_T^{miss} 140	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	$m(\tilde{\chi}_1^0) = 0$, wino-bino $m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0) = 5$ GeV, wino-bino	
	$\tilde{\chi}_1^+ \tilde{\chi}_1^0$ via WW	2 e, μ	E_T^{miss} 140	$\tilde{\chi}_1^+$	$m(\tilde{\chi}_1^0) = 0$, wino-bino	
	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via Wh	Multiple ℓ /jets	E_T^{miss} 140	$\tilde{\chi}_1^+$	$m(\tilde{\chi}_1^0) = 70$ GeV, wino-bino	
	$\tilde{\chi}_1^+ \tilde{\chi}_1^0$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ	E_T^{miss} 140	$\tilde{\chi}_1^+$	$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^+) + m(\tilde{\chi}_1^0))$	
	$\tilde{\tau}_1\tilde{\tau}_1, \tilde{\tau}_1 \rightarrow \tau\tilde{\chi}_1^0$	2 τ	E_T^{miss} 140	$\tilde{\tau}_1$	$m(\tilde{\chi}_1^0) = 0$	
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ $ee, \mu\mu$	0 jets ≥ 1 jet	E_T^{miss} 140	$\tilde{\ell}$	$m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10$ GeV
Long-lived particles	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ 0 e, μ	E_T^{miss} 140	\tilde{H} \tilde{H} \tilde{H}	$\text{BR}(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$ $\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$ $\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$	
	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet E_T^{miss} 140	$\tilde{\chi}_1^\pm$	Pure Wino Pure higgsino	
	Stable \tilde{g} R-hadron	pixel dE/dx	E_T^{miss} 140	\tilde{g}	$m(\tilde{\chi}_1^0) = 100$ GeV	
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	pixel dE/dx	E_T^{miss} 140	\tilde{g}	$\tau(\tilde{\ell}) = 0.1$ ns $\tau(\tilde{\tau}) = 0.1$ ns $\tau(\tilde{t}) = 10$ ns	
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	Displ. lep	E_T^{miss} 140	$\tilde{\ell}, \tilde{\mu}$ $\tilde{\tau}$		
		pixel dE/dx	E_T^{miss} 140	$\tilde{\tau}$		
RPV	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet E_T^{miss} 140	$\tilde{\chi}_1^\pm$	Pure Wino Pure higgsino	
	Stable \tilde{g} R-hadron	pixel dE/dx	E_T^{miss} 140	\tilde{g}	$m(\tilde{\chi}_1^0) = 100$ GeV	
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	pixel dE/dx	E_T^{miss} 140	\tilde{g}	$\tau(\tilde{\ell}) = 0.1$ ns $\tau(\tilde{\tau}) = 0.1$ ns $\tau(\tilde{t}) = 10$ ns	
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	Displ. lep	E_T^{miss} 140	$\tilde{\ell}, \tilde{\mu}$ $\tilde{\tau}$		
		pixel dE/dx	E_T^{miss} 140	$\tilde{\tau}$		

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



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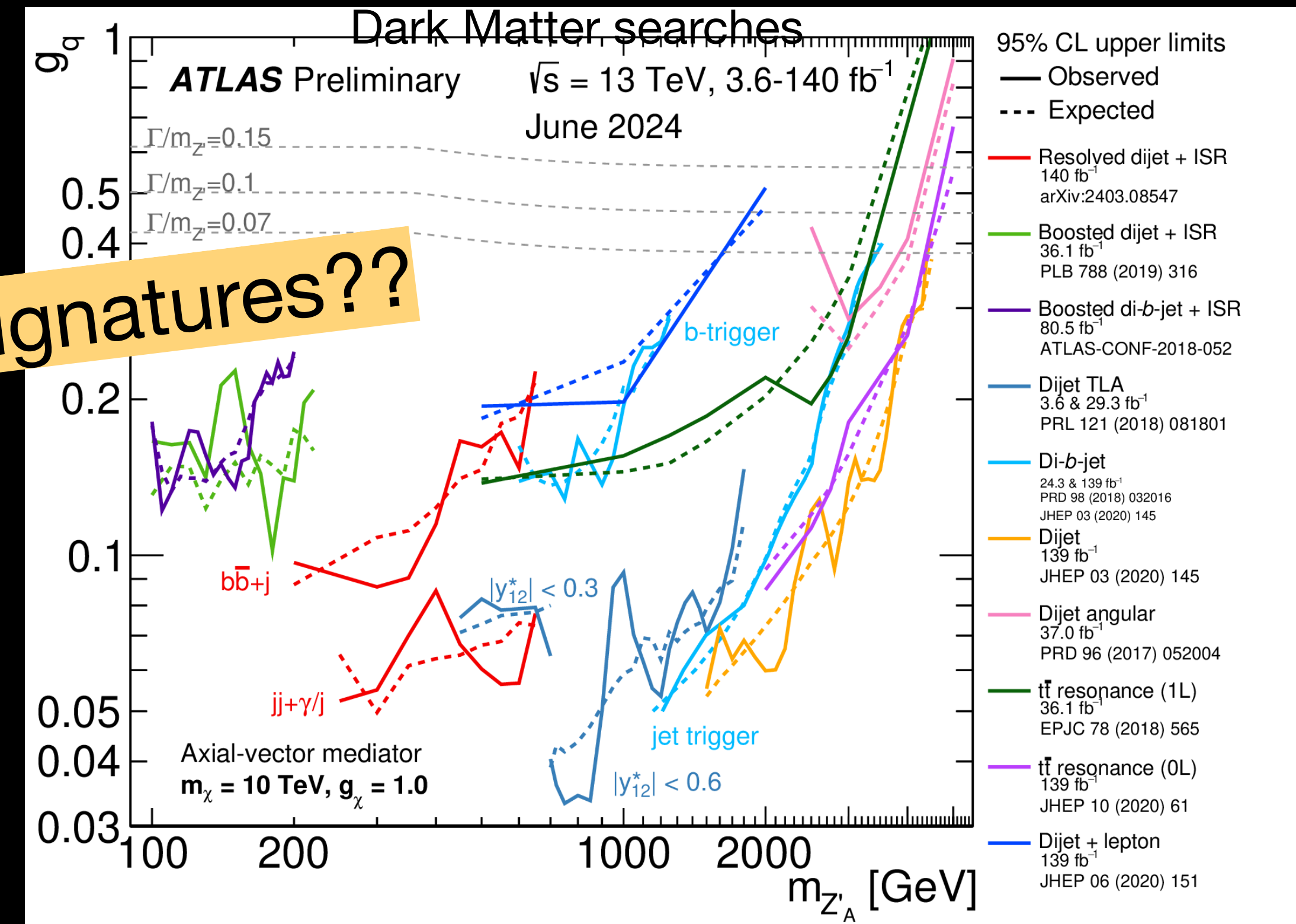
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Model	Signature	$\int \mathcal{L} dt$ [fb ⁻¹]	Mass limit	Reference			
Inclusive Searches	$q\bar{q}, \bar{q} \rightarrow q\bar{\chi}_1^0$	0 e, μ mono-jet	E_T^{miss} 140	\tilde{q} [1x, 8x Degen.] \tilde{q} [8x Degen.]	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV	2010.14293 2102.10874	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 e, μ 2-6 jets	E_T^{miss} 140	\tilde{g} \tilde{g}	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{g}) = 1000$ GeV	2010.14293 2010.14293	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$	1 e, μ 2-6 jets	E_T^{miss} 140	\tilde{g}	$m(\tilde{\chi}_1^0) < 600$ GeV	2101.01629	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	e, μ 2 jets	E_T^{miss} 140	\tilde{g}	$m(\tilde{\chi}_1^0) < 700$ GeV	2204.13072	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}WZ\tilde{\chi}_1^0$	0 e, μ SS e, μ	7-11 jets 6 jets	E_T^{miss} 140 140	\tilde{g} \tilde{g}	$m(\tilde{\chi}_1^0) < 600$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV	2008.06032 2307.01094
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ SS e, μ	3 b 6 jets	E_T^{miss} 140 140	\tilde{g} \tilde{g}	$m(\tilde{\chi}_1^0) < 500$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV	2211.08028 1909.08457
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e, μ 2 b	E_T^{miss} 140	\tilde{b}_1	$m(\tilde{\chi}_1^0) < 400$ GeV $10 \text{ GeV} < \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV	2101.12527 2101.12527	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$	0 e, μ 2 b	E_T^{miss} 140	\tilde{b}_1	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	1908.03122 2103.08189	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 e, μ ≥ 1 jet	E_T^{miss} 140	\tilde{t}_1	$m(\tilde{\chi}_1^0) = 1$ GeV	2004.14060, 2012.03799	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 e, μ 3 jets/1 b	E_T^{miss} 140	\tilde{t}_1	$m(\tilde{\chi}_1^0) = 500$ GeV	2012.03799, 2401.13430	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \bar{\tau}b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$	1-2 τ 2 jets/1 b	E_T^{miss} 140	\tilde{t}_1	$m(\tilde{\tau}_1) = 800$ GeV	2108.07665	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ 0 e, μ mono-jet	36.1 E_T^{miss} 140	\tilde{t}_1 \tilde{c} \tilde{c}	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV	2108.07665	
EW direct	$\tilde{\chi}_1^+\tilde{\chi}_2^0$ via WZ	Multiple ℓ /jets e, μ	E_T^{miss} 140	$\tilde{\chi}_1^+, \tilde{\chi}_2^0$	$m(\tilde{\chi}_1^+) = 0$, wino-bino	1911.12606	
	$\tilde{\chi}_1^+\tilde{\chi}_1^0$ via WW	2 e, μ	E_T^{miss} 140	$\tilde{\chi}_1^+, \tilde{\chi}_1^0$	$m(\tilde{\chi}_1^+) = 70$ GeV, wino-bino	1908.08215	
	$\tilde{\chi}_1^+\tilde{\chi}_2^0$ via Wh	Multiple ℓ /jets	E_T^{miss} 140	$\tilde{\chi}_1^+, \tilde{\chi}_2^0$	$m(\tilde{\chi}_1^+) = 0.5(m(\tilde{\chi}_1^+) + m(\tilde{\chi}_1^0))$	2004.10894, 2108.07586	
	$\tilde{\chi}_1^+\tilde{\chi}_1^0$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ	E_T^{miss} 140	$\tilde{\chi}_1^+, \tilde{\chi}_1^0$	$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\ell}_1^+) + m(\tilde{\chi}_1^0))$	1908.08215	
	$\tilde{\tau}_1\tilde{\tau}_1, \tilde{\tau}_1 \rightarrow \tau\tilde{\chi}_1^0$	2 τ	E_T^{miss} 140	$\tilde{\tau}_1$	$m(\tilde{\chi}_1^0) = 0$	2402.00603	
	$\tilde{\ell}_L, \tilde{\ell}_R \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ e, μ	0 jets ≥ 1 jet	E_T^{miss} 140 140	$\tilde{\ell}$ $\tilde{\ell}$	$m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10$ GeV	1908.08215 1911.12606
Long-lived particles	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ 0 jets 0 e, μ ≥ 2 large jets	E_T^{miss} 140 140 140 140	\tilde{H} \tilde{H} \tilde{H} \tilde{H}	$m(\tilde{H}) = 10$ GeV $\text{BR}(\tilde{H} \rightarrow h\tilde{G}) = 1$ $\text{BR}(\tilde{H} \rightarrow Z\tilde{G}) = 1$ $\text{BR}(\tilde{H} \rightarrow h\tilde{G}) = 1$ $\text{BR}(\tilde{H} \rightarrow Z\tilde{G}) = 1$ $\text{BR}(\tilde{H} \rightarrow h\tilde{G}) = 0.5$	2401.14922 2103.11684 2108.07586 2204.13072	
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk 1 jet	E_T^{miss} 140	$\tilde{\chi}_1^\pm$	Pure Wino Pure higgsino	2201.02472 2201.02472	
	Stable \tilde{g} R-hadron	pixel dE/dx	E_T^{miss} 140	\tilde{g}		2205.06013	
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	pixel dE/dx	E_T^{miss} 140	\tilde{g}	$m(\tilde{\chi}_1^0) = 100$ GeV	2205.06013	
	$\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	Displ. lep	E_T^{miss} 140	$\tilde{\ell}, \tilde{\mu}$ $\tilde{\tau}$	$\tau(\tilde{\ell}) = 0.1$ ns $\tau(\tilde{\ell}) = 0.1$ ns $\tau(\tilde{\ell}) = 10$ ns	ATLAS-CONF-2024-011 ATLAS-CONF-2024-011 2205.06013	
		pixel dE/dx	E_T^{miss} 140	$\tilde{\tau}$			
RPV	$\tilde{\chi}_1^+\tilde{\chi}_1^0/\tilde{\chi}_1^0/\tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow Z\ell\ell$	3 e, μ	E_T^{miss} 140	$\tilde{\chi}_1^+, \tilde{\chi}_1^0$	Pure Wino	2011.10543	
	$\tilde{\chi}_1^+\tilde{\chi}_1^0/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$	4 e, μ	E_T^{miss} 140	$\tilde{\chi}_1^+, \tilde{\chi}_2^0$	$m(\tilde{\chi}_1^0) = 200$ GeV	2103.11684	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq$	≥ 8 jets	E_T^{miss} 140	\tilde{g}	Large $A'_{1,2}$	2401.16333	
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple $\geq 4b$	36.1 140	\tilde{t}_1	$m(\tilde{\chi}_1^0) = 200$ GeV, bino-like $m(\tilde{\chi}_1^0) = 500$ GeV	ATLAS-CONF-2018-003	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bbs$	2 jets + 2 b	36.7	\tilde{t}_1		1710.07171	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e, μ 1 μ	2 b DV	E_T^{miss} 140 136	\tilde{t}_1	$\text{BR}(\tilde{t}_1 \rightarrow b\ell/b\mu) > 20\%$ $\text{BR}(\tilde{t}_1 \rightarrow q\mu) = 100\%$, $\cos\theta_{\tilde{t}} = 1$	2406.18367 2003.11956
$\tilde{\chi}_1^+\tilde{\chi}_2^0/\tilde{\chi}_1^0/\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs, \tilde{\chi}_1^+ \rightarrow bbs$	1-2 e, μ ≥ 6 jets	140	E_T^{miss} 140	$\tilde{\chi}_1^+, \tilde{\chi}_2^0$ $\tilde{\chi}_1^0$	Pure higgsino	2106.09609	

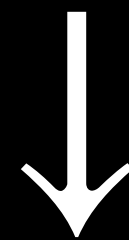
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



An alternative approach

- Instead of looking for a specific signal model, look for anomalies in data

Does this event look like BSM theory ABC?



Does this event look like Standard Model?

Anomaly detection in data

Analysis Strategy

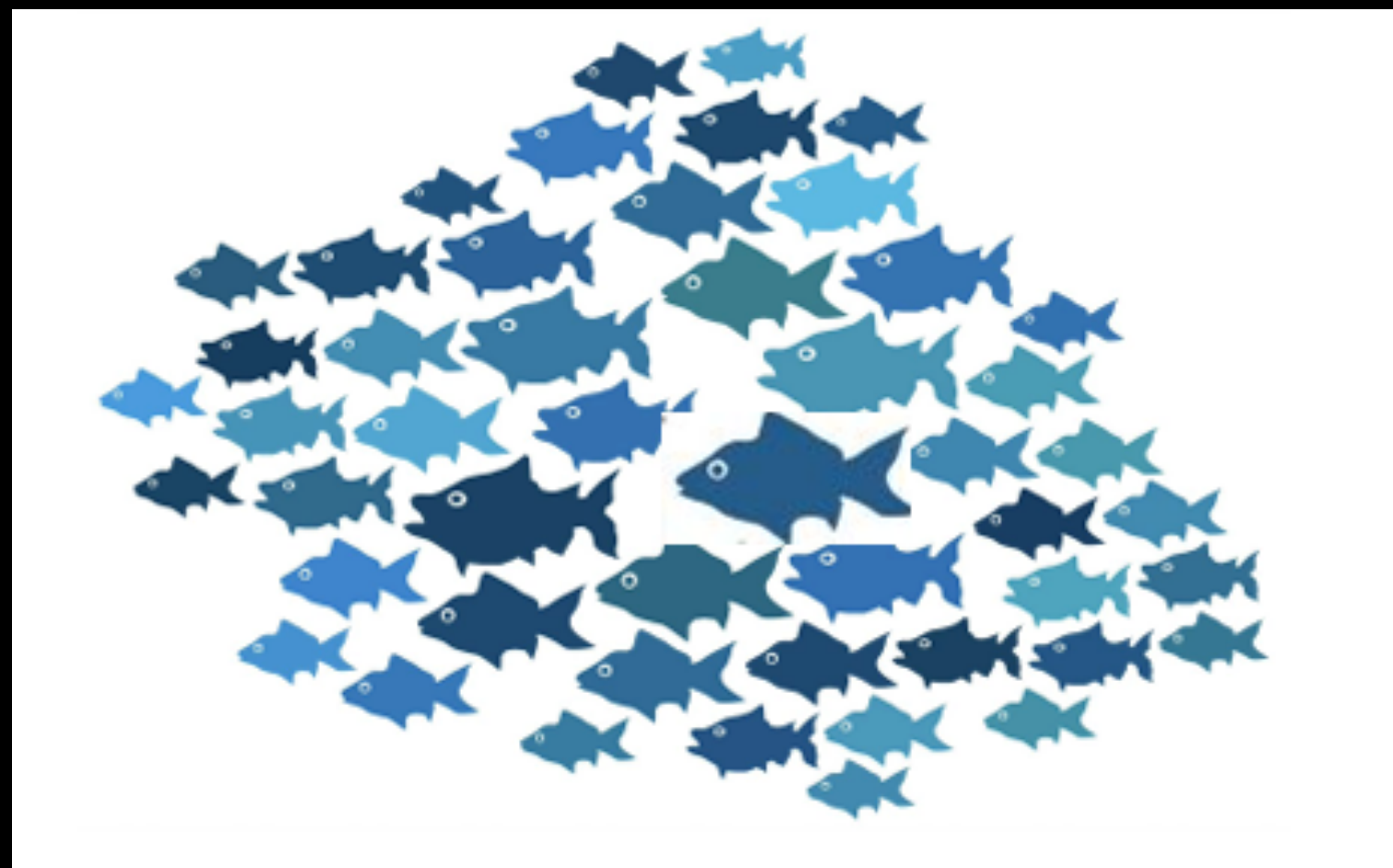


Anomaly detection in data

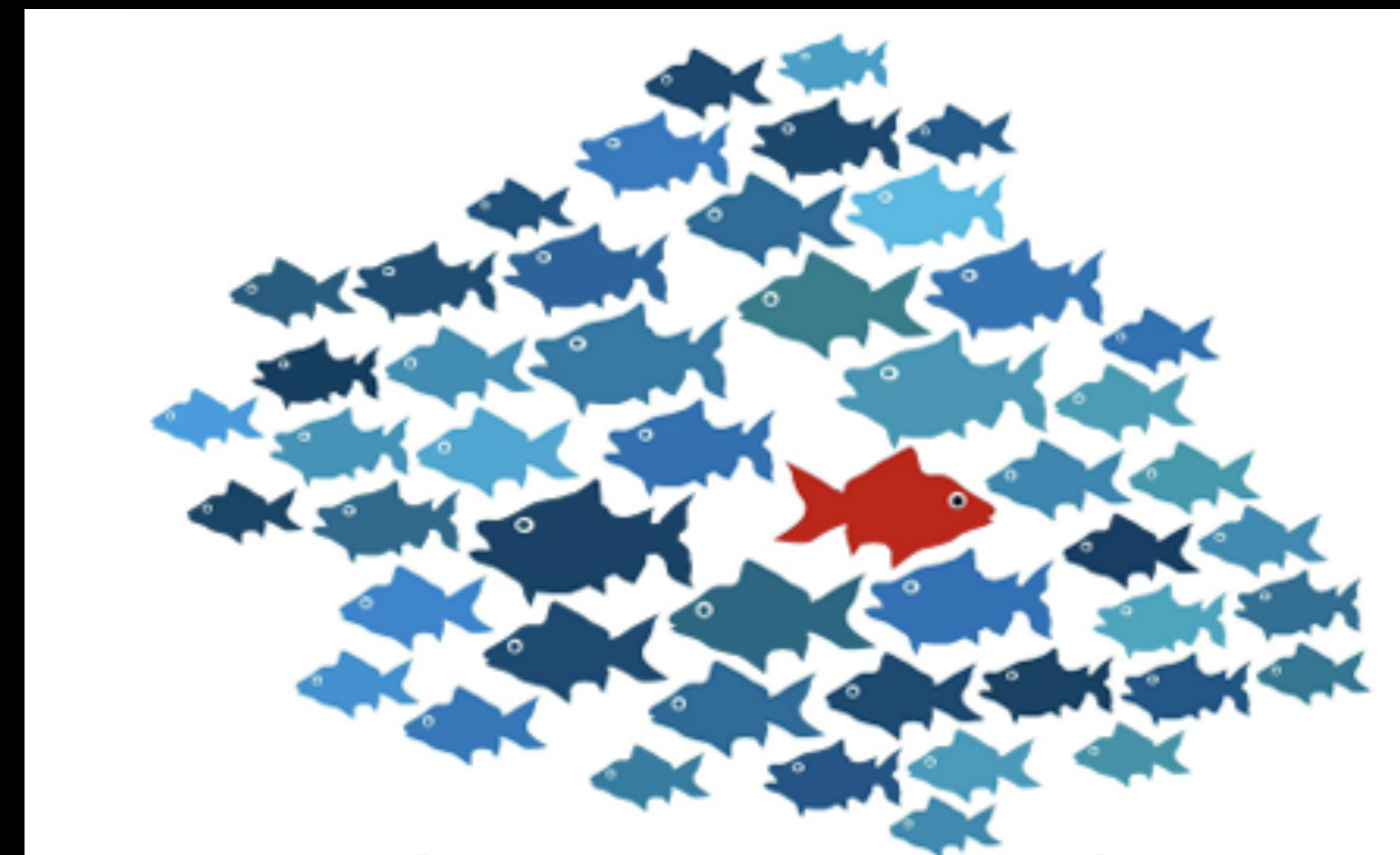
Analysis Strategy



Known training Sample (SM Physics)

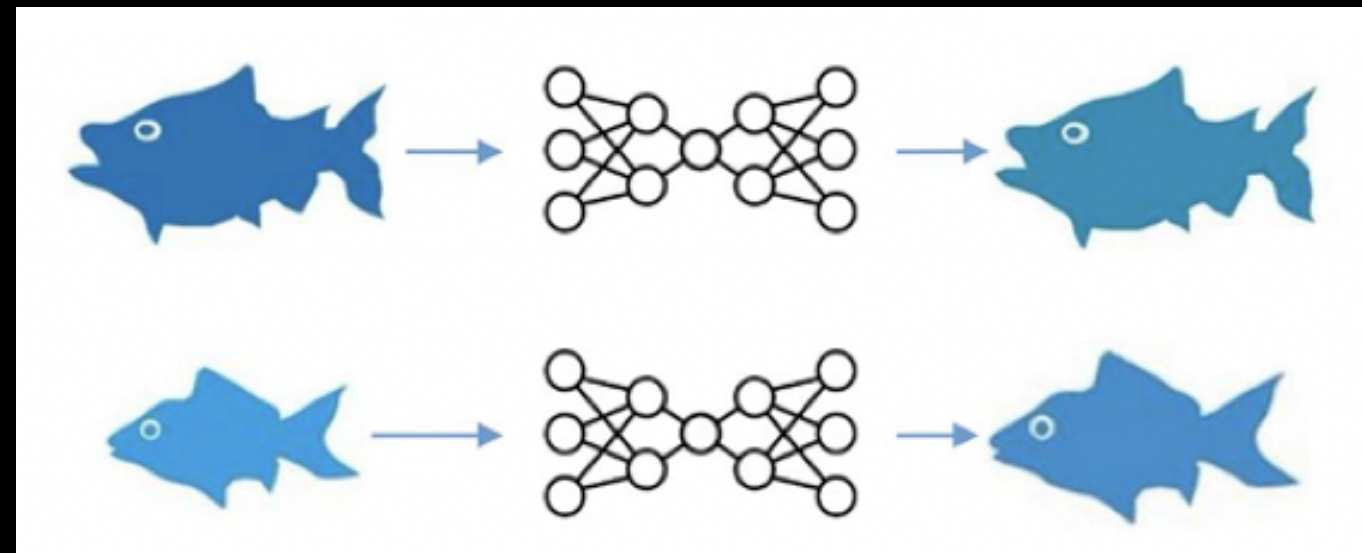


Unknown testing Sample (BSM Physics)

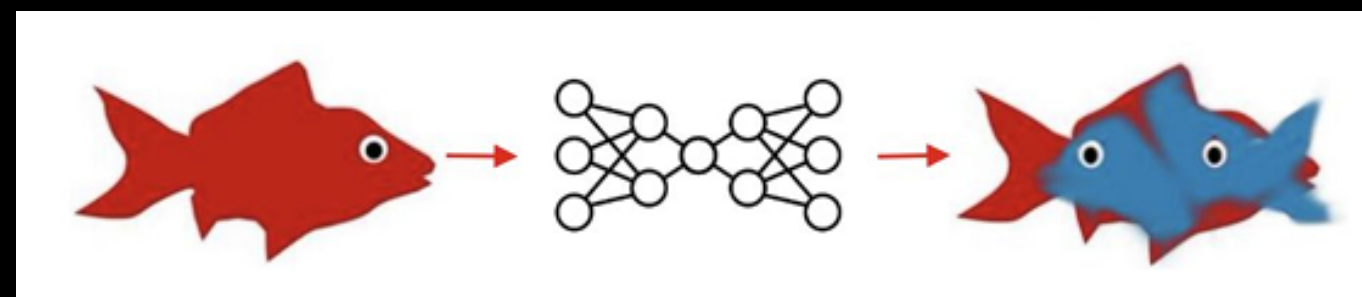


Anomaly detection in data

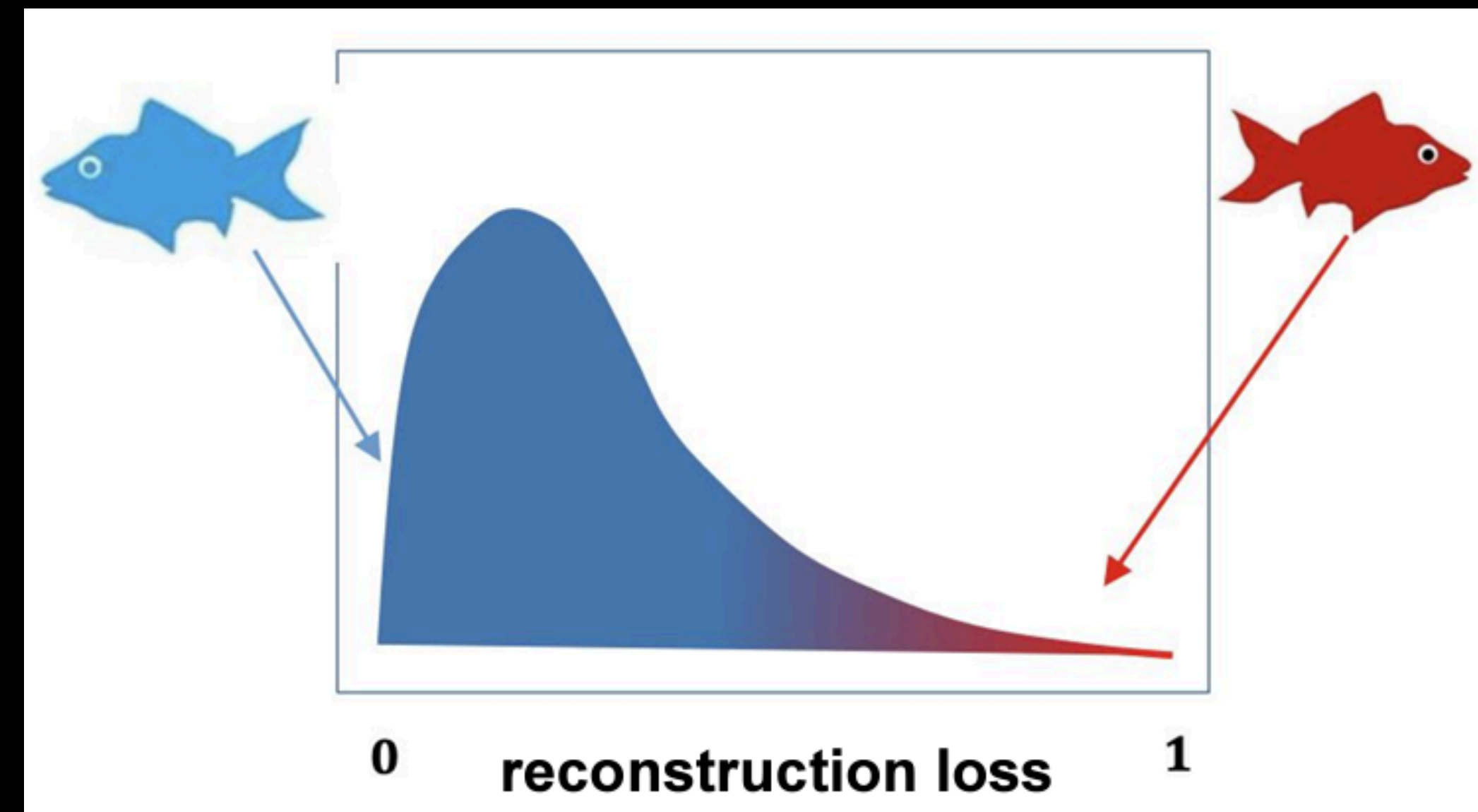
Train the model over non-anomalous samples
(known SM Background processes)



Test the model over real data to look for any anomalies

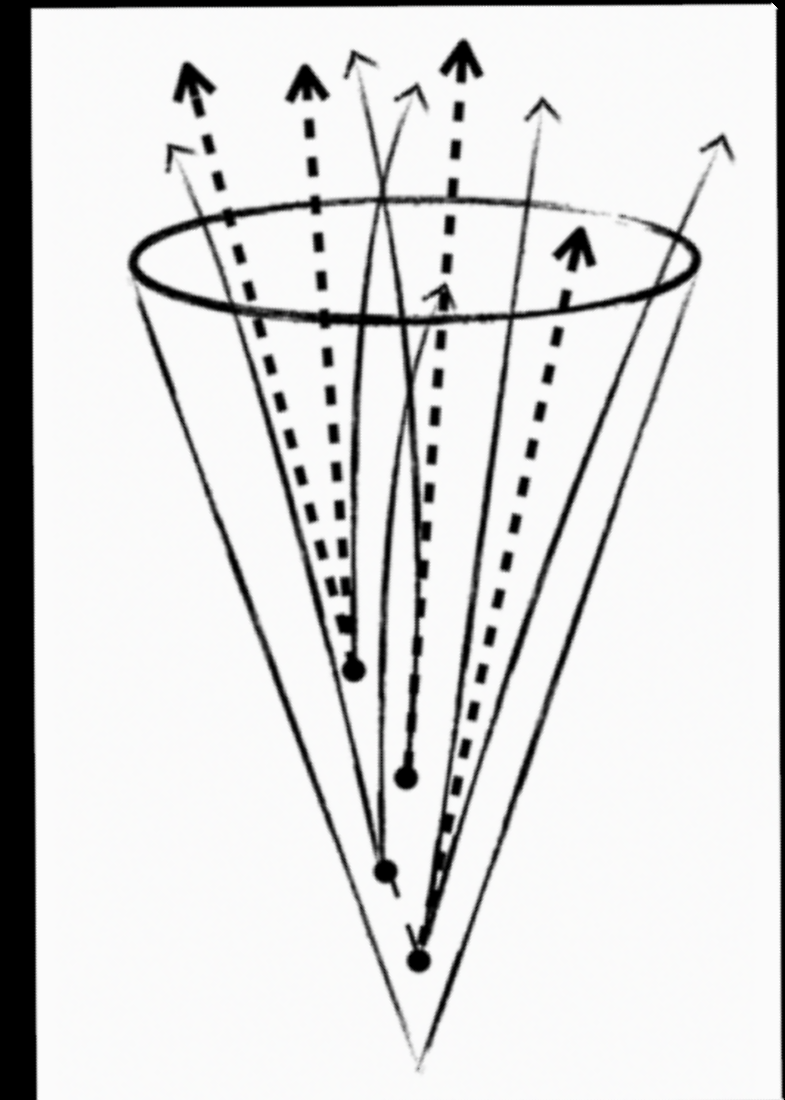


Anomaly Score

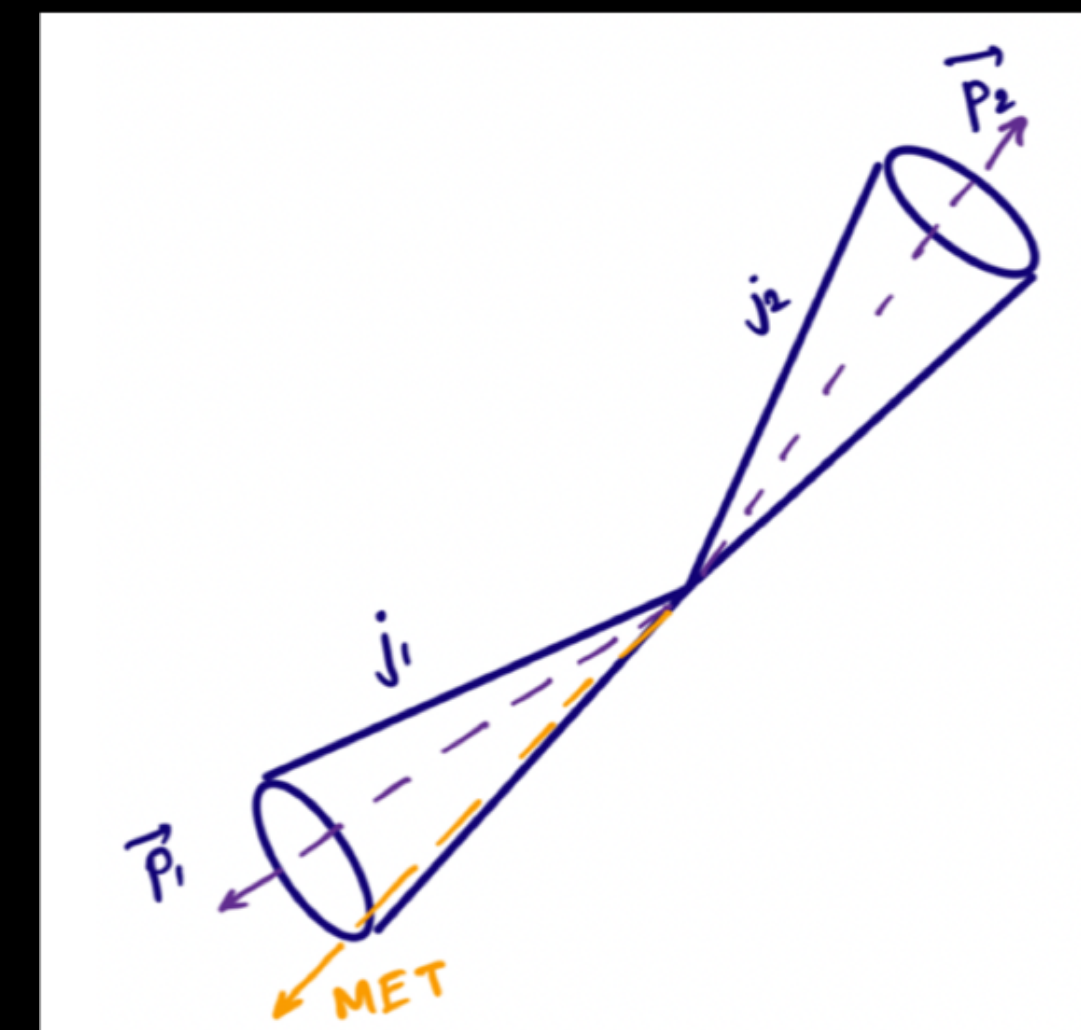
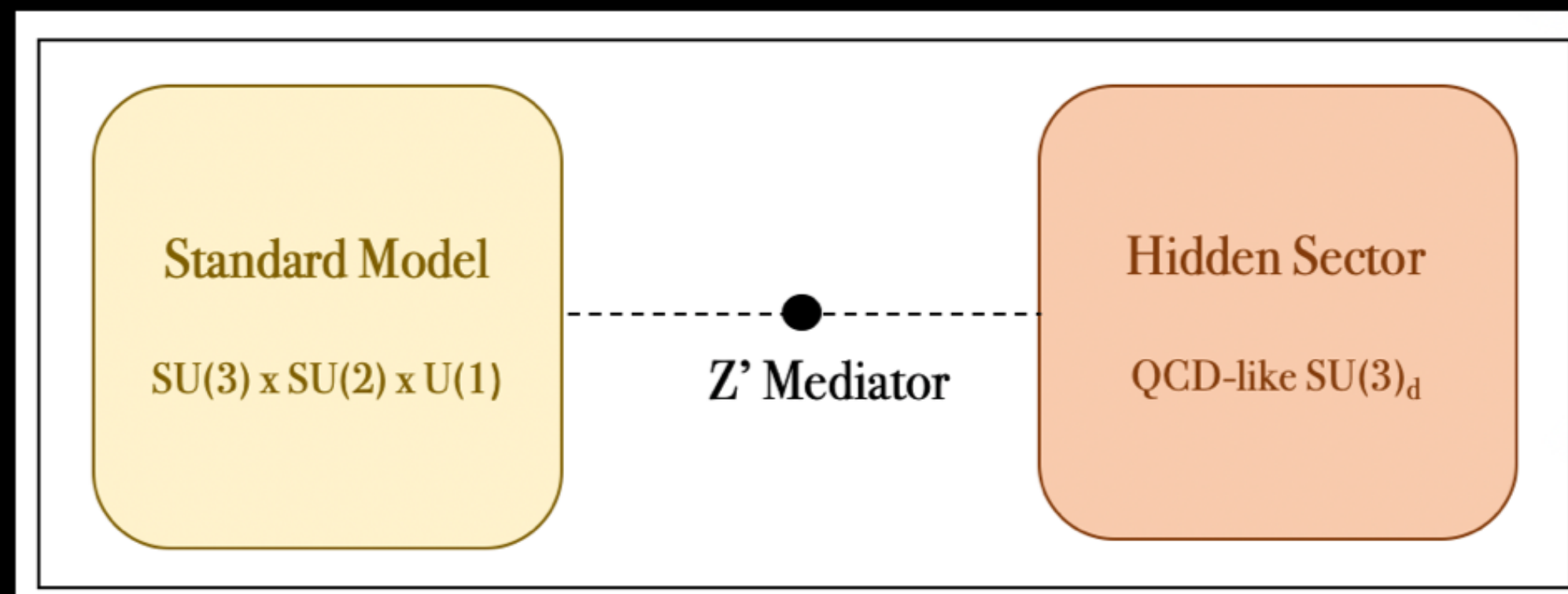


A case study: Semi-Visible Jets

- Inspired by Hidden Valley Models: Dark Matter with rich internal structure/interactions
- Unusual signature \rightarrow Two back-to-back jets with E_T^{miss} aligning with one of the jets



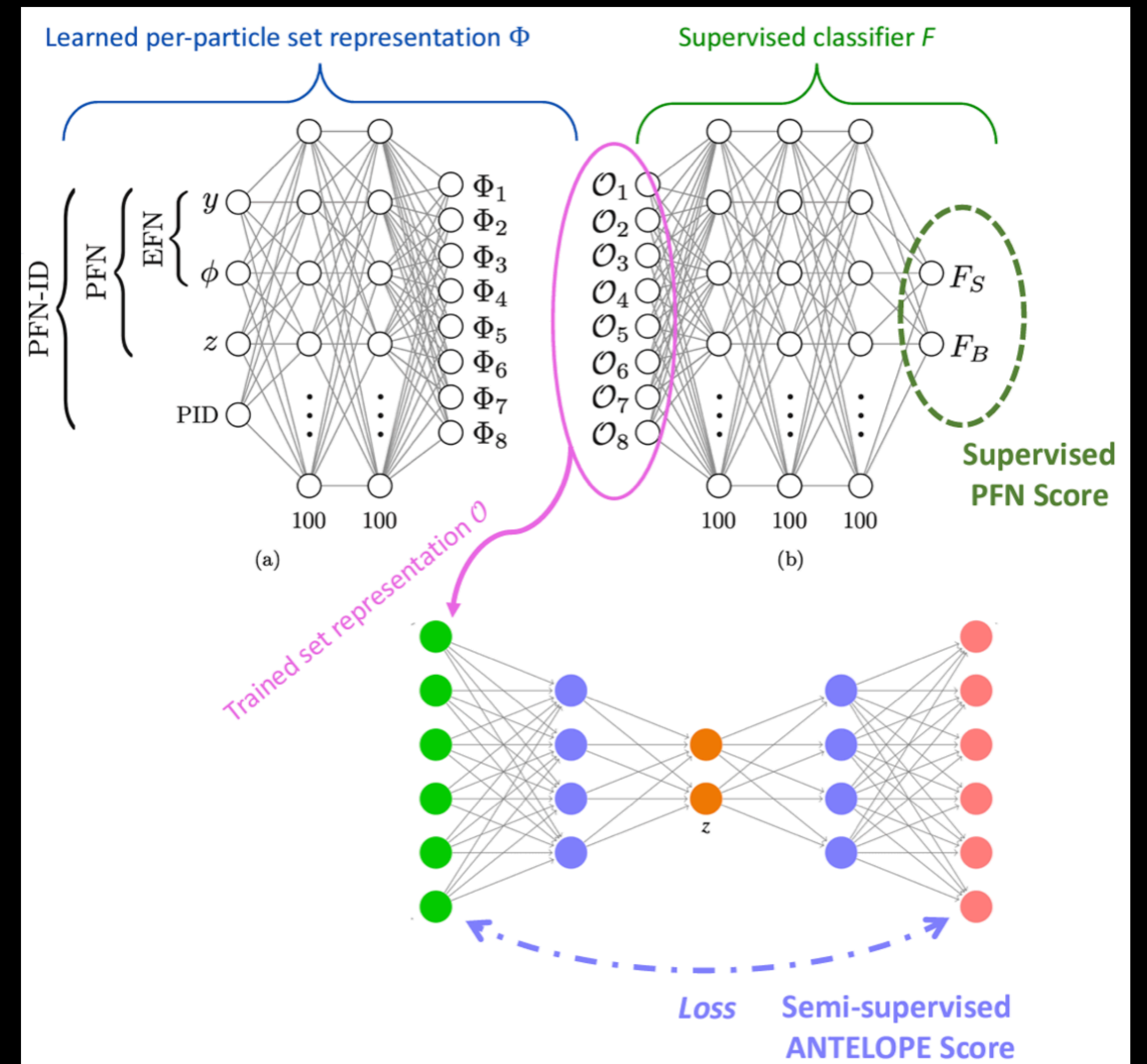
SM_{QCD} \rightarrow Dark_{QCD}? \rightarrow Dark Jets?



A case study: Semi-Visible Jets

ANomaly deTEction on particle fLOW latent sPacE

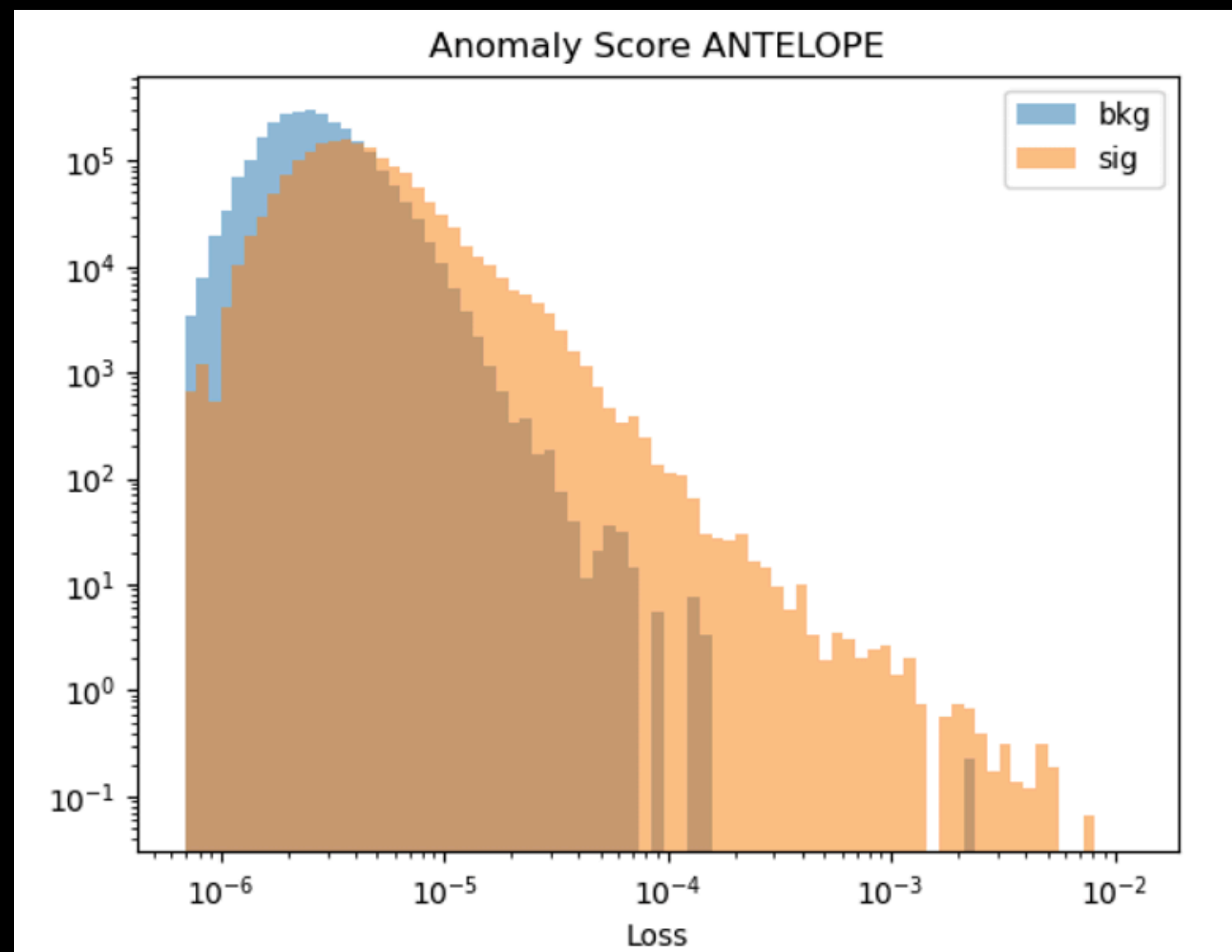
- Semi-Visible jets differ from QCD jets at sub-structure level \rightarrow information of tracks associated to jets: $p_T, \eta, \phi, E, d_0, z_0, q/p$



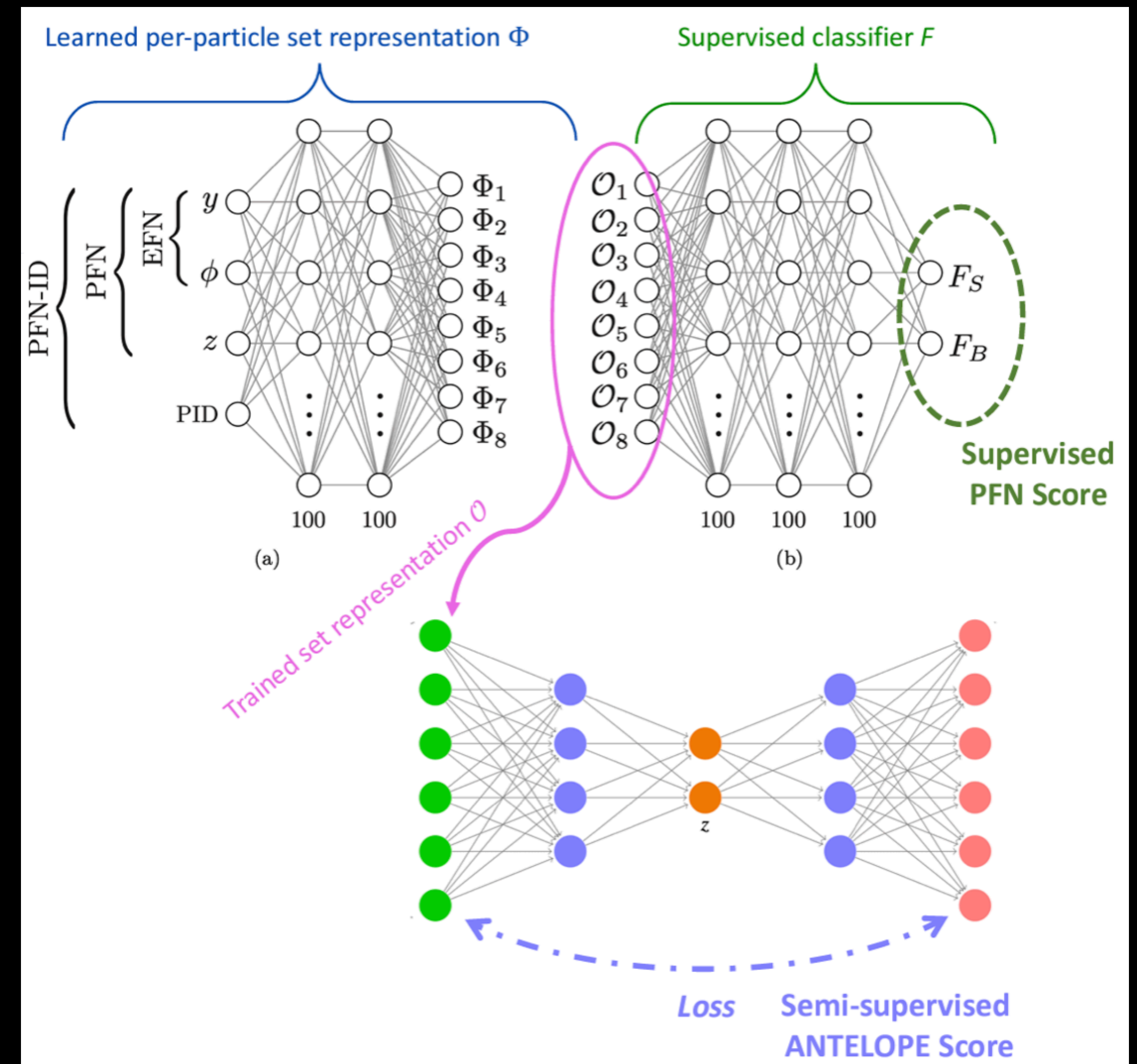
A case study: Semi-Visible Jets

- Semi-Visible jets differ from QCD jets at sub-structure level \rightarrow information of tracks associated to jets: $p_T, \eta, \phi, E, d_0, z_0, q/p$

Anomaly score for signal and background

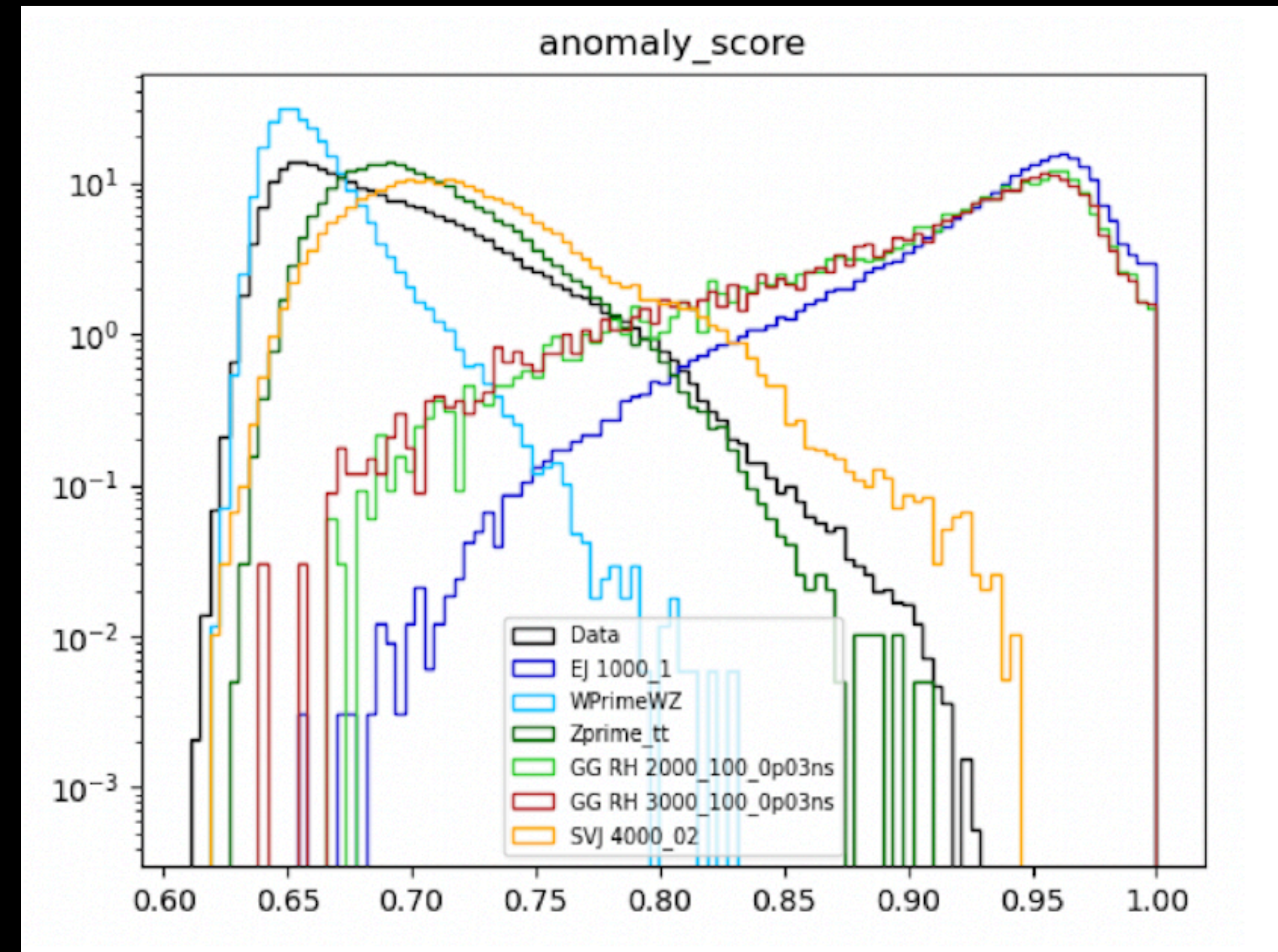


ANomaly deTEction on particle fLOW latent sPacE



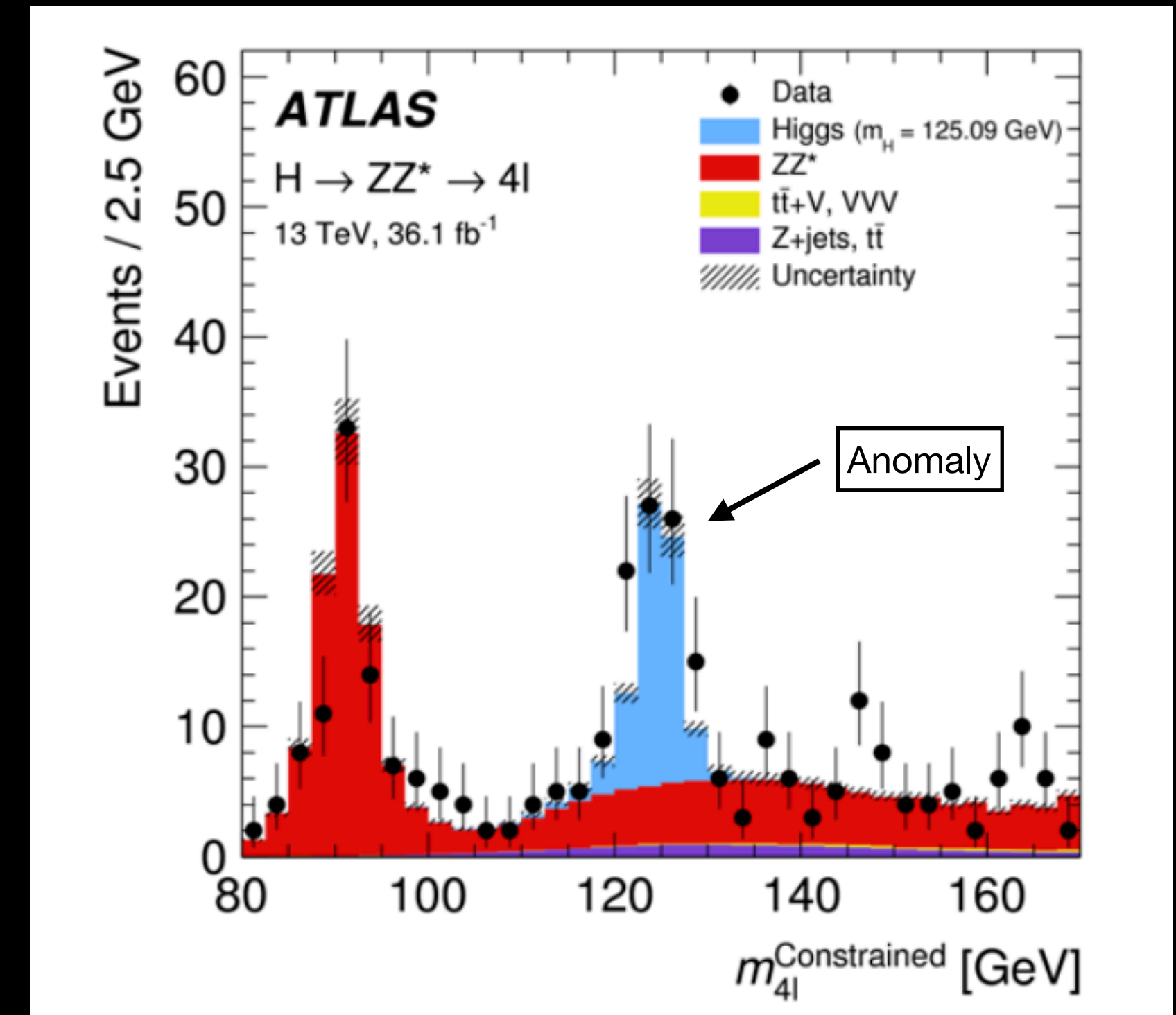
A case study: Semi-Visible Jets

- Antelope has learned model independence



Summary

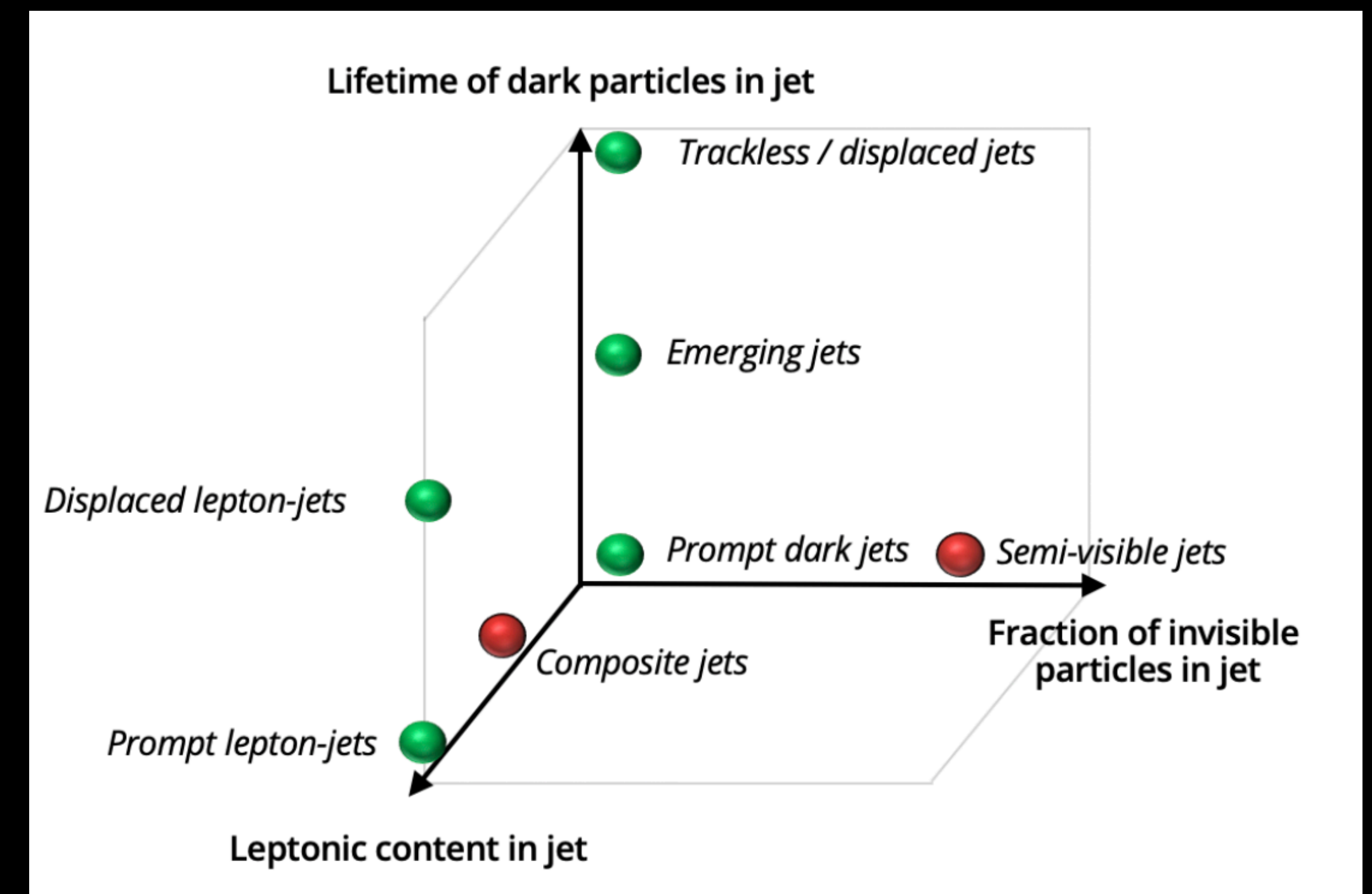
- Anomaly detection has been a fundamental aspect in the field of High Energy Physics
 - z-significance, p-value estimation in statistical methods
- ML based techniques can provide new dimensions for searching anomalies
- These techniques are still in their infancy within HEP, but an increasing number of analyses are experimenting with them
- Exciting times ahead!!!!



Back-up

Theoretical motivation behind these models

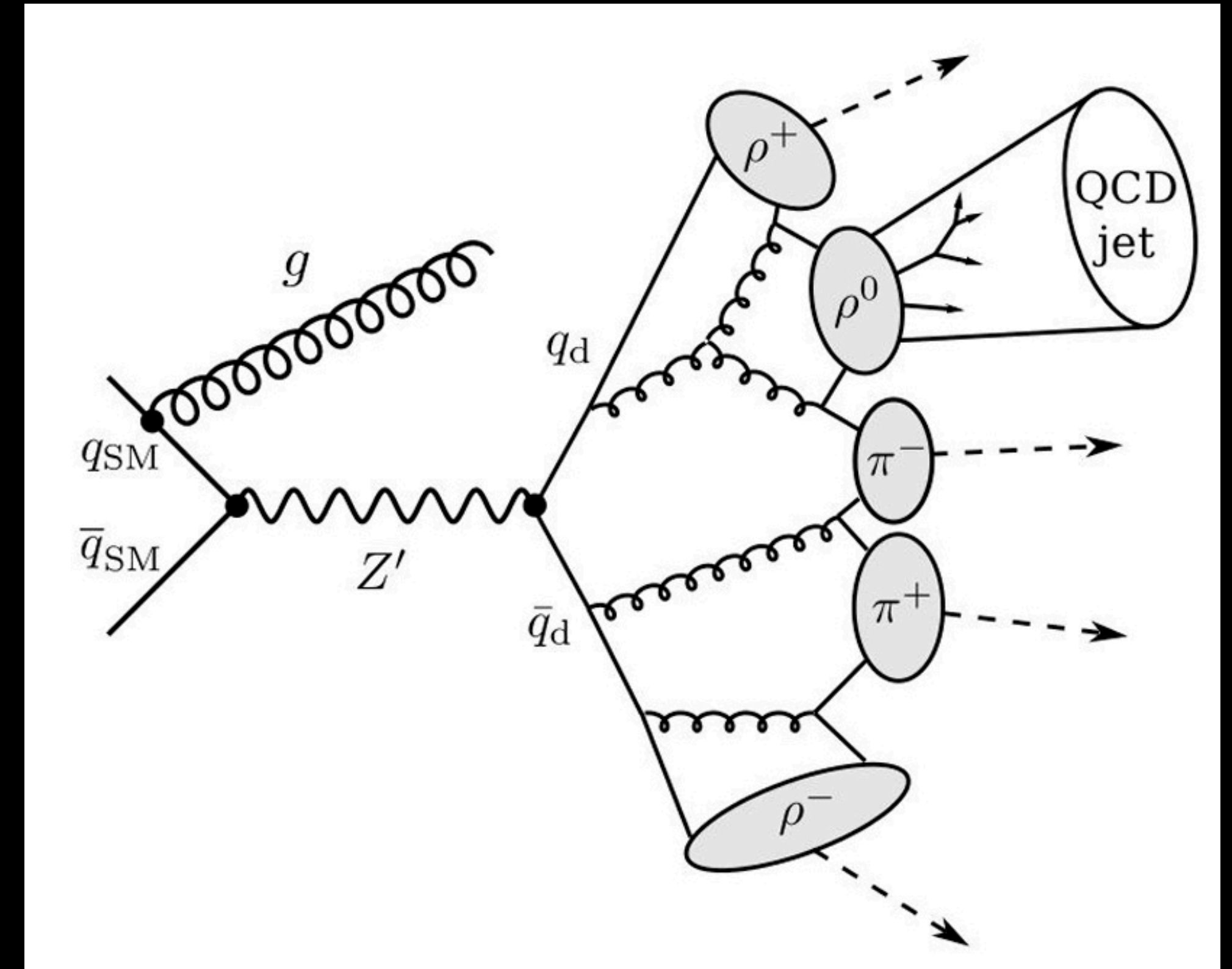
- DM may be composed of Strongly Coupled Dark Matter (SCDM) particles resembling SM QCD
- These SCDM particles can undergo QCD-like showers, generating various stable and unstable DM states
- Various possible topologies; depending upon the couplings in the dark sector
 - **Dark Jets:** Dark hadrons decaying **promptly and fully** in QCD-like fashion
 - **Semi-visible jets:** Dark hadrons decaying **promptly and partially** in QCD-like fashion
 - **Emerging Jets:** Dark hadrons undergoing **displaced decays** in QCD-like fashion



Semi-Visible Jets (SVJ)

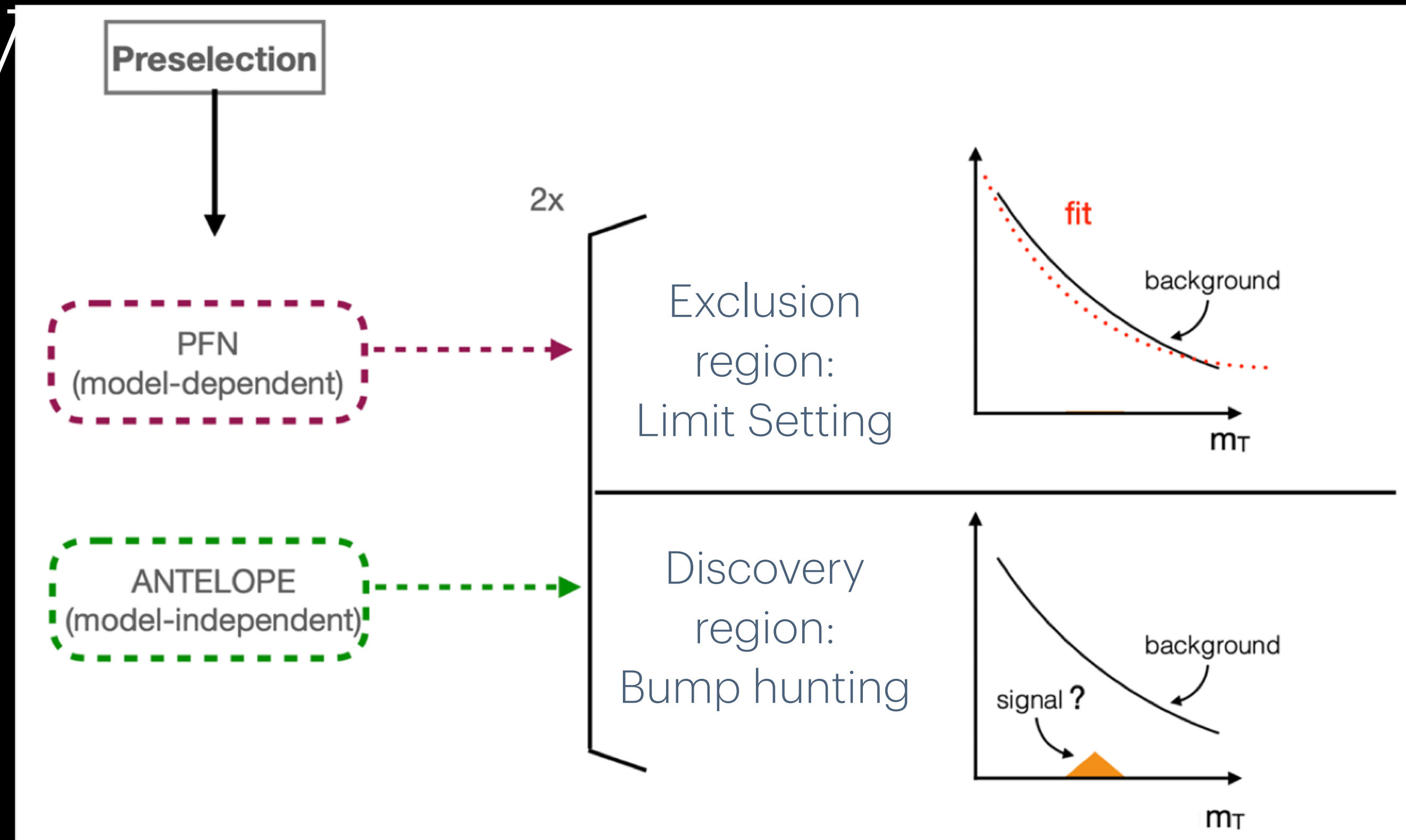
s-channel resonant production via Z' mediator

- Unusual signature \rightarrow Two back-to-back jets with E_T^{miss} aligning with one of the jets
- Wide jet with high track multiplicity and significant E_T^{miss}



Analysis Strategy

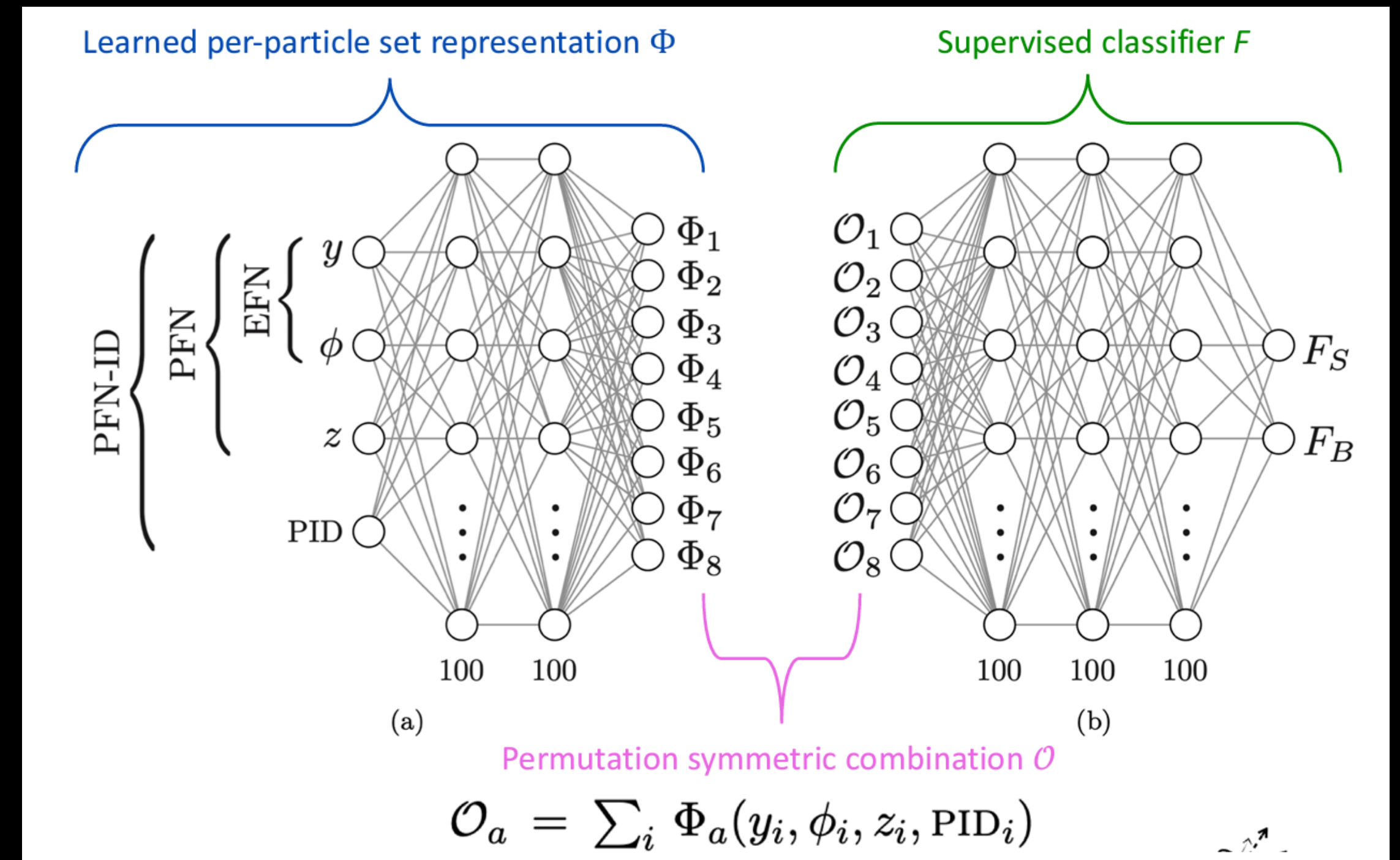
- Two back-to-back jets and E_T^{miss} in the final state
- Trigger and pre-selection
- Machine Learning Models
 - Particle Flow Network : Limit Setting
 - ANTELOPE : Bump hunting
- Construction of Control and validation regions
- Data-driven background estimation using multi-parameter function
- Systematics uncertainties and estimation of signal significance
- In the absence of significant deviation, set limits



ML tools

Particle flow networks (PFN)

- Semi-visible jets differ from QCD jets at substructure level, this property is utilized by providing low-level information of associated tracks to leading and sub-leading jets to PFN
 - Track info: $p_T, \eta, \phi, E, d_0, z_0, q/p$
- Supervised and model dependent approach: to enhance signal sensitivity



ML tools

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 - Track info: $p_T, \eta, \phi, E, d_0, z_0, q/p$
- Supervised and model dependent approach: to enhance signal sensitivity
- Trained over QCD MC and SVJ signals
- PFN is found to be performant over the complete signal grid

