



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

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Many open questions in HEP and Cosmology

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





Visible matter **5%**

Dark

matter

27%







al er

ATLAS experiment has an established Physics Program

ATLAS SUSY Searches* - 95% CL Lower Limits

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	Model	Si	ignatur	e ∫	` <i>L d t</i> [fb [−]	¹] Mass limit					
Inclusive Searches	$ ilde q ilde q, ilde q ightarrow q ilde \chi_1^0$	0 <i>e</i> , µ mono-jet	2-6 jets 1-3 jets	$E_T^{ m miss} \ E_T^{ m miss}$	140 140	\tilde{q} [1x, 8x Degen.] 1.0 1.85 $m(\tilde{\chi}_1^0) \leq 400 \text{ GeV}$ \tilde{q} [8x Degen.] 0.9 $m(\tilde{\chi}_1^0) = 5 \text{ GeV}$					
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \bar{q} \tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i>	2-6 jets	$E_T^{\rm miss}$	140	\tilde{g} 2.3 $m(\tilde{\chi}_1^0)=0 \text{ GeV}$ \tilde{g} Forbidden 1.15-1.95 $m(\tilde{\chi}_1^0)=1000 \text{ GeV}$					
	$\widetilde{g}\widetilde{g}, \ \widetilde{g} ightarrow q \overline{q} W \widetilde{\chi}_1^0 \ \widetilde{g}\widetilde{g}, \ \widetilde{g} ightarrow q \overline{q}(\ell \ell) \widetilde{\chi}_1^0$	1 e,μ ee,μμ	2-6 jets 2 jets	$E_T^{\rm miss}$	140 140	$\begin{array}{c} \tilde{g} & & \\ \tilde{g} & & \\ \tilde{g} & & \\ \end{array} & & \\ m(\tilde{\chi}_1^0) < 600 \text{GeV} \\ m(\tilde{\chi}_1^0) < 700 \text{GeV} \end{array}$					
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 e,μ SS e,μ	7-11 jets 6 jets	E_T^{miss}	140 140	$ \begin{array}{cccc} \tilde{g} & & & 1.97 & & & m(\tilde{\chi}_1^0) < 600 \text{GeV} \\ \tilde{g} & & & 1.15 & & & & \\ m(\tilde{g}) \cdot m(\tilde{\chi}_1^0) = 200 \text{GeV} \end{array} $					
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\chi}_1^0$	0-1 <i>e</i> ,μ SS <i>e</i> ,μ	3 <i>b</i> 6 jets	$E_T^{\rm miss}$	140 140	$\begin{array}{cccccccccccccccccccccccccccccccccccc$					
3 rd gen. squarks direct production	$ ilde{b}_1 ilde{b}_1$	0 <i>e</i> , <i>µ</i>	2 <i>b</i>	$E_T^{ m miss}$	140	$ \begin{array}{c c} \tilde{b}_1 & & \\ \tilde{b}_1 & & \\ \tilde{b}_1 & & \\ \hline{b}_1 & & \\ \hline{b}_1 & & \\ \hline{b}_1 & & \\ \hline{c}_1 & & \\ \hline{c}_2 & & \\ \hline{c}_1 & & \\ \hline{c}_2 & & \\ \hline{c}_1 & & \\ \hline{c}_1 & & \\ \hline{c}_1 & & \\ \hline{c}_1 & & \\ \hline{c}_2 & & \\ \hline{c}_1 & & \\ \hline\\ \hline\\ \hline{c}_1 & & \\ \hline\hline\\ \hline\\ $					
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	0 <i>e</i> ,μ 2 τ	6 <i>b</i> 2 <i>b</i>	$E_T^{ m miss} \ E_T^{ m miss}$	140 140	$ \begin{array}{c c} \tilde{\pmb{b}}_1 & \textbf{C}_1 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 \\ \tilde{\pmb{b}}_1 & \textbf{C}_2 & $					
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W h \tilde{\chi}_1^0$	0-1 <i>e</i> ,μ 1 <i>e</i> ,μ	≥ 1 jet 3 jets/1 b	$E_T^{ m miss}$ $E_T^{ m miss}$	140 140	\tilde{t}_1 1.25 $m(\tilde{x}_1^0)=1 \text{ GeV}$ \tilde{t}_1 Forbidden 1.05 $m(\tilde{x}_1^0)=500 \text{ GeV}$					
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 bv, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	140	\tilde{t}_1 Forbidden 1.4 $m(\tilde{\tau}_1)$ =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 <i>e</i> ,μ 0 <i>e</i> ,μ	2 c mono-jet	E_T^{miss} E_T^{miss}	36.1 140	$ \begin{array}{c} \tilde{c} & & & & & \\ \tilde{t}_1 & & & & \\ \end{array} \\ \begin{array}{c} m(\tilde{t}_1^0) = 0 \text{ GeV} \\ m(\tilde{t}_1, \tilde{c}) - m(\tilde{t}_1^0) = 5 \text{ GeV} \end{array} $					
	$ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h \tilde{\chi}_1^0 \tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z $	1-2 <i>e</i> ,μ 3 <i>e</i> ,μ	1-4 <i>b</i> 1 <i>b</i>	E_T^{miss} E_T^{miss}	140 140	\tilde{t}_1 0.067-1.18 m($\tilde{\chi}_2^0$)=500 GeV \tilde{t}_2 Forbidden 0.86 m($\tilde{\chi}_1^0$)=360 GeV, m(\tilde{t}_1)-m($\tilde{\chi}_1^0$)= 40 GeV					
EW direct	$ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via WZ	Multiple ℓ /jets $ee, \mu\mu$	≥ 1 jet	$E_T^{ m miss}$ $E_T^{ m miss}$	140 140	$\begin{array}{ccc} \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} & \textbf{0.96} \\ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} & \textbf{0.205} \end{array} \\ \end{array} \\ \begin{array}{ccc} m(\tilde{\chi}_{1}^{0})=0, \text{ wino-bino} \\ m(\tilde{\chi}_{1}^{0})=\text{for even of } m(\tilde{\chi}_{1}^{0})=0, \text{ wino-bino} \\ m(\tilde{\chi}_{1}^{0})=0, win$					
	$ ilde{\chi}_1^{\pm} ilde{\chi}_1^{\mp}$ via WW	$2 e, \mu$		E_T^{miss}	140	$\tilde{\chi}_{1}^{\pm}$ 0.42 $m(\tilde{\chi}_{1}^{0})=0$, wino-bino					
	$\chi_1^+ \chi_2^\circ$ via Wh $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$ via $\tilde{\ell}_2$ / $\tilde{\pi}$	Multiple ℓ /jets	6	E_T^{miss}	140 140	$\begin{array}{c} \chi_1^*/\chi_2^* \text{Forbidden} \\ \tilde{\chi}^{\pm} \\ \tilde{\chi}^{\pm}$					
	$\chi_1\chi_1$ via t_L/v $\tilde{\tau}\tilde{\tau}$ $\tilde{\tau} \to \tau \tilde{\chi}^0_1$	2τ		E_T^{miss}	140	$\tilde{\tau}_{1}$ $\tilde{\tau}_{R}\tilde{\tau}_{R}$ 0.35 0.5 $\tilde{\tau}_{L}$ $\tilde{\tau}_{R}\tilde{\tau}_{R}$ $\tilde{\tau}_{R}\tilde{\tau}_{R}\tilde{\tau}_{R}$ $\tilde{\tau}_{R}\tilde{\tau}_{R}$ $\tilde{\tau}_{R}$ $$					
	$\tilde{\ell}_{\mathrm{L,R}} \tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell} \! \rightarrow \! \ell \tilde{\chi}_1^0$	2 e,μ ee,μμ	0 jets ≥ 1 jet	E_T^{miss} E_T^{miss}	140 140	$ \tilde{\ell} = 0.7 $ $\tilde{\ell} = 0.26 $ $m(\tilde{\ell}_1^0)=0$ $m(\tilde{\ell}_1^0)=10 \text{ GeV} $					
	$\tilde{H}\tilde{H},\tilde{H}{ ightarrow}h\tilde{G}/Z\tilde{G}$	0 e,μ 4 e,μ	$\geq 3 b$ 0 jets	E_T^{miss} E_T^{miss}	140 140	$\begin{array}{c} \tilde{H} \\ \tilde{H} \\ \tilde{L} \\ 0.55 \end{array} \qquad \qquad$					
		$0 e, \mu \ge$	≥ 2 large jet	E_T^{fmiss}	140	\ddot{H} 0.45-0.93 BR($\chi_1^0 \to Z\tilde{G}$)=1					
		2 <i>e</i> ,µ	≥ 2 jets	E _T ^{miss}	140	$\tilde{H} \qquad \qquad 0.77 \qquad \qquad BR(\tilde{\chi}_1^0 \to Z\tilde{G}) = BR(\tilde{\chi}_1^0 \to h\tilde{G}) = 0.5$					
pe s	Direct $\tilde{\chi}_1^* \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	E_T^{miss}	140	$ \begin{array}{c} \tilde{\chi}_{1}^{*} & 0.66 \\ \tilde{\chi}_{1}^{\pm} & 0.21 \end{array} $					
-live	Stable \tilde{g} R-hadron	pixel dE/dx		E_T^{miss}	140	\tilde{g} 2.05					
Long- parti	Metastable g R-hadron, $g \rightarrow qq\chi_1$ $\tilde{\ell}\tilde{\ell} \tilde{\ell} \rightarrow \ell\tilde{G}$	Displ. lep		E_T E^{miss}	140 140	\tilde{g} $[\tau(g) = 10 \text{ hs}]$ 2.2 $m(\chi_1) = 100 \text{ GeV}$ \tilde{e}, \tilde{u} 0.74 $\tau(\tilde{\ell}) = 0.1 \text{ ns}$					
		pixel dE/dx		E_T^{miss}	140	$\tilde{\tau}$ 0.36 $\tau(\tilde{\ell}) = 0.1 \text{ ns}$ $\tilde{\tau}$ 0.36 $\tau(\tilde{\ell}) = 10 \text{ ns}$					
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm} \rightarrow Z \ell \rightarrow \ell \ell \ell$	3 <i>e</i> , <i>µ</i>			140	$\tilde{\chi}_{1}^{+}/\tilde{\chi}_{1}^{0}$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05 Pure Wino					
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 <i>e</i> , <i>µ</i>	0 jets	$E_T^{\rm miss}$	140	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$] 0.95 1.55 m($\tilde{\chi}_{1}^{0}$)=200 GeV					
	$\tilde{g}\tilde{g}, \tilde{g} \to qq\chi_1^0, \chi_1^0 \to qqq$		≥8 jets Multiple		140	$\tilde{g} = [m(\chi_1^*)=50 \text{ GeV}, 1250 \text{ GeV}]$ $\tilde{t} = [\chi_1^* - 2e_1 4 + 1e_2]$ $\tilde{t} = [\chi_1^* - 2e_2 4 + 1e_2]$ $\tilde{t} = [\chi_1^* - 2e_2]$ \tilde					
P	$\begin{array}{ccc} II, I \to \mathcal{U}_1, \mathcal{X}_1 \to IDS \\ \tilde{II} & \tilde{I} \to b \tilde{X}_1^{\pm} & \tilde{X}_1^{\pm} \to bbs \end{array}$		> 4b		140	\tilde{t} Forbidden 0.95 $\pi(\tilde{x}_{1}) = 200 \text{ GeV}, \text{ bito-like}$					
Ä	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$		2 jets + 2 b	,	36.7	$\tilde{t}_1 \ [qq, bs]$ 0.42 0.61					
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 {\rightarrow} q\ell$	2 <i>e</i> ,μ 1 μ	2 <i>b</i> DV		140 136	$ \begin{array}{c c} \tilde{t}_1 & 0.4-1.85 \\ \tilde{t}_1 & [1e-10 < \lambda'_{23k} < 1e-8, 3e-10 < \lambda'_{23k} < 3e-9] \end{array} \begin{array}{c} 0.4-1.85 & BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\% \\ BR(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_i = 1 \end{array} $					
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^+ \rightarrow bbs$	1-2 <i>e</i> , <i>µ</i>	≥6 jets		140	$\tilde{\chi}_1^0$ 0.2-0.32 Pure higgsino					
*Only a selection of the available mass limits on new states or 10^{-1} 1 Mass coole (To)/1											

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

Mass scale [TeV]





ATLAS experiment has an established Physics Program

ATLAS SUSY Searches* - 95% CL Lower Limits

Julv 2024

Model		Sig	nature	$\int \mathcal{L} dt [\mathbf{f}\mathbf{b}^{-1}]$	Mass limit		
Inclusive Searches	$\tilde{q}\tilde{q},\tilde{q}{ ightarrow}q\tilde{\chi}_1^0$	0 <i>e</i> , μ 2	2-6 jets $E_T^{\rm m}$	^{iss} 140	ř [1×, 8× Degen.]	1.0 1.85	m($ ilde{\chi}^0_1){< \over < 0}$ 400 GeV
	$\tilde{a}\tilde{a} \tilde{a} \rightarrow a \bar{a} \tilde{\chi}_{1}^{0}$	mono-jet 1 0 e, μ 2	1-3 jets $E_T^{\rm m}$ 2-6 jets $E_T^{\rm m}$	^{iss} 140 ^{iss} 140	i [8x Degen.]	2.3	$m(\tilde{q})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$ $m(\tilde{\chi}_1^0)=0 \text{ GeV}$
	~0				F	orbidden 1.15-1.95	$m(\tilde{\chi}_1^0)=1000 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\chi_1^\circ$	$1 e, \mu \geq 2$	2-b JEIS	140 iss 140		2.2	$m(\chi_1^{\circ}) < 600 \text{ GeV}$
	$gg, g \to qq(\mathcal{U})\chi_1$ $\tilde{a}\tilde{a} \tilde{a} \to agWZ\tilde{\chi}^0$	0 e. u 7	E_T = 11 iets E_T	^{iss} 140		1 97	$m(\tilde{x}_1) < 700 \text{ GeV}$ $m(\tilde{x}_1^0) < 600 \text{ GeV}$
	$gg, g \rightarrow qq \approx 2\lambda_1$	SS e, μ	6 jets	140		1.15	$m(\tilde{g})-m(\tilde{\chi}_1^0)=200 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\chi}_1^0$	0-1 <i>e</i> , μ SS <i>e</i> ,μ	$\begin{array}{ccc} 3 \ b & E_T^{\rm m} \\ 6 \ {\rm jets} & \end{array}$	¹⁵⁵ 140 140		2.45	$m(\tilde{\chi}_{1}^{0}) < 500 \text{ GeV} \ m(\tilde{g}) - m(\tilde{\chi}_{1}^{0}) = 300 \text{ GeV}$
uarks Iction	$ ilde{b}_1 ilde{b}_1$	0 <i>e</i> , <i>µ</i>	$2 b E_T^m$	^{iss} 140	0.68	1.255	$m(ilde{\chi}_1^0){<}400GeV$ 10 GeV ${\leq} m(ilde{b}_1, ilde{\chi}_1^0){<}20GeV$
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	0 <i>e</i> ,μ	$\begin{array}{ccc} 6 \ b & E_T^{\mathrm{m}} \\ 2 \ b & E_T^{\mathrm{m}} \end{array}$	iss 140	Forbidden	0.23-1.35 ∆m(i	$(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}$
	~ ~ ~ ~ ~0	2τ	$\geq D$ L_T	140 iss 140	0.13-0	J.85	$n(\chi_2,\chi_1) = 130 \text{ GeV}, m(\chi_1) = 0 \text{ GeV}$
bs.	$t_1 t_1, t_1 \rightarrow t \chi_1^{\circ}$	$1 e \mu$	≥ 1 jet E_T^{m}	iss 140	1 Earbidden	1.25	$m(\chi_1)=1 \text{ GeV}$ $m(\tilde{\chi}^0)=500 \text{ GeV}$
en. t pr	$ \begin{array}{c} l_1 l_1, \ l_1 \rightarrow W \partial \chi_1 \\ \tilde{l}_1 \tilde{l}_1, \ \tilde{l}_1 \rightarrow \tilde{\tau}_1 b \gamma, \ \tilde{\tau}_1 \rightarrow \tau \tilde{G} \end{array} $	$1-2\tau$ 2	jets/1 $b = E_T$ jets/1 $b = E_T^{\text{m}}$	^{iss} 140	Forbidden	en 1.4	$m(\tilde{\tau}_1)=800 \text{ GeV}$ $m(\tilde{\tau}_1)=800 \text{ GeV}$
^d ge	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 <i>e</i> ,μ	$2c$ E_T^m	^{iss} 36.1		0.85	$m(\tilde{\chi}_{1}^{0})=0$ GeV
d 3		$0 e, \mu$ m	nono-jet E_T^{fr}	^{iss} 140	0.55		$\mathbf{m}(\tilde{t}_1,\tilde{c})-\mathbf{m}(\tilde{\chi}_1^0)=5$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	1-2 <i>e</i> , μ	1-4 <i>b</i> E_T^{m}	^{iss} 140	1	0.067-1.18	•
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 <i>e</i> , µ	$1 b E_T^{\text{ff}}$	¹⁵⁵ 140	2 Forbidden	0.86	
	$ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via WZ	Multiple ℓ /jets $ee, \mu\mu$	≥ 1 jet E_T^m	^{iss} 140 ^{iss} 140	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}$	Inokin	
	$ ilde{\chi}_1^{\pm} ilde{\chi}_1^{\mp}$ via WW	2 <i>e</i> , <i>µ</i>	$E_T^{\rm m}$	^{iss} 140			(1)=0, wino-bino
	$ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via Wh	Multiple ℓ /jets	E_T^{rr}	^{iss} 140	$\chi_1^{\pm}/\tilde{\chi}_2^0$ Forbidd		m($\tilde{\chi}_1^0$)=70 GeV, wino-bino
EW direct	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{+}$ via $\tilde{\ell}_L / \tilde{\nu}$	2 <i>e</i> , µ	$E_T^{\rm m}$	¹⁸⁵ 140		1.0	$m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau \chi_1^0$	2τ	$E_T^{\rm m}$	¹⁵⁵ 140	$[\tau_R \tau_R]$ 0.5		$m(\mathcal{X}_1^0)=0$
	$\ell_{\mathrm{L,R}}\ell_{\mathrm{L,R}}, \ell \to \ell \chi_1$	2 e,μ ee,μμ	≥ 1 jet E_T^{m}	^{iss} 140	0.26		$m(\tilde{\ell})-m(\tilde{\chi}_1^0)=10 \text{ GeV}$
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 <i>e</i> , <i>µ</i>	$\geq 3 b \qquad E_T^{\text{ff}}$	^{iss} 140	Ă	0.94	$BR(\tilde{\chi}_1^0 \to h\tilde{G}) = 1$
		$4 e, \mu$	0 jets E_T^{fr}	^{iss} 140	й 0.55	5.0.00	$BR(\tilde{\chi}_1^0 \to Z\tilde{G}) = 1$
		$0 e, \mu \geq 2$	> 2 jets E_T^m	iss 140	4 0.4 7 0.7	-5-0.93 7	$BR(\mathcal{X}_1 \to ZG) = 1$
		ε ε,μ <u>ε</u>		140	1 0.7	-	$DR(\mathcal{X}_1 \to \mathcal{ZG}) = DR(\mathcal{X}_1 \to \mathcal{HG}) = 0.5$
ıg-lived rticles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet E_T^m	^{iss} 140	24 0.21 0.66		Pure Wino Pure higgsino
	Stable \tilde{g} R-hadron	pixel dE/dx	$E_T^{ m m}$	^{iss} 140		2.05	
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$	pixel dE/dx	E_T^{m}	^{iss} 140	$\check{g} = [\tau(\tilde{g}) = 10 \text{ ns}]$	2.2	$m(\tilde{\chi}_1^0)$ =100 GeV
pa	$\hat{\ell}\hat{\ell},\hat{\ell}{\rightarrow}\ell\hat{G}$	Displ. lep	$E_T^{\rm rr}$	¹⁵⁵ 140	0.74 0.36	1	$\tau(\tilde{\ell}) = 0.1 \text{ ns}$ $\tau(\tilde{\ell}) = 0.1 \text{ ns}$
		pixel dE/dx	E_T^{m}	^{iss} 140			$\tau(\tilde{\ell}) = 0.1 \text{ Hz}$ $\tau(\tilde{\ell}) = 10 \text{ ns}$
	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{\pm} \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 <i>e</i> , µ		140	$\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{1}^{0}$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625	1.05	Pure Wino
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \rightarrow WW / Z\ell\ell\ell\ell\nu\nu$	4 e, μ	0 jets E_T^m	^{iss} 140	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} = [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0]$	0.95 1.55	$m(\tilde{\chi}_1^0)=200 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\chi_1^{\vee}, \tilde{\chi}_1^{\vee} \rightarrow qqq$	2	≥ŏ jets Aultiple	140	[m(X ₁)=50 GeV, 1250 GeV]	1.6 2.34	Large $\lambda_{112}^{\prime\prime}$
	$tt, t \to t X_1, X_1 \to tbs$	N	> 4b	36.1	[A ₃₂₃ =20-4, [0-2] 0.55	1.05	$m(\chi_1^*)=200 \text{ GeV}, \text{ bino-like}$
Η	$u, \iota \to \upsilon \lambda_1, \lambda_1 \to \upsilon \upsilon s$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \to b s$	2 i	ets + 2 b	36 7	[1 [<i>aa</i> , <i>bs</i>] 0.42 0.61	0.30	m(x1)=500 Gev
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 <i>e</i> ,μ	2 <i>b</i>	140		0.4-1.85	$BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$
		1 μ	DV	136	$1 [1e-10 < \lambda'_{23k} < 1e-8, 3e-10 < \lambda'_{23k} < 3e-9]$	1.0 1.6	BR($\tilde{t}_1 \rightarrow q\mu$)=100%, cos θ_t =1
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^+ \rightarrow bbs$	1-2 <i>e</i> , μ	≥6 jets	140	⁰ 0.2-0.32		Pure higgsino
					1	<u> </u>	
*Only a	a selection of the available ma	iss limits on nev	w states or	· 1(-1	1	Mass scale [TeV]

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

Mass scale [TeV]





An alternative approach

Does this event look like Standard Model?

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



Anomaly detection in data

Analysis Strategy



Anomaly detection in data

Analysis Strategy



Known training Sample (SM Physics)



Unknown testing Sample (BSM Physics)



Illustrations by A. Kahn



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





- 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

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







Link: <u>Glance, Int. Note</u> <u>Theory paper</u>



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 deTEction on particle fLOw latent sPacE





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

Anomaly score for signal and background



ANomaly deTEction on particle fLOw latent sPacE





• 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 \bullet 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^\prime 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 ightarrow
 - Particle Flow Network : Limit Setting
 - ANTELOPE : Bump hunting
- Construction of Control and validation regions
- Data-driven background estimation using multi-parameter function ullet
- Systematics uncertainties and estimation of signal significance
- In the absence of significant deviation, set limits

Full Run-2 dataset: 140 fb^{-1}





MI 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

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
- Trained over QCD MC and SVJ signals
- PFN is found to be performant over the complete signal grid









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