



LHCにおける 生成モデル・異常検知

2022 / 7 / 8

ML@HEP

齊藤 真彦 (ICEPP, Beyond AI)





ATLAS実験における 生成モデル for カロリメータシミュレーション 異常検知 for 新粒子探索

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生成モデル (Generative model) と異常検知 (anomaly detection)

- ・ 深層学習応用の代表例は 識別モデル (教師あり)
 - 入力xが与えられたときの出力yの事後確率 p(y|x) をモデリング
- 入力xの分布 p(x)をモデリングするアプローチ(教師なし)
 - ・ 生成モデル
 - *p*(*x*) からサンプリングすることでデータを生成
 - 異常検知
 - *p*(*x*) が小さい異常データ*x*を見つける
 - ただし、いろいろなバリエーションあり
- ATLAS実験で論文化された研究を中心に手法を紹介
 - ・ GANを用いたカロリメータシャワーシミュレーション
 - 弱教師学習を用いたDijet resonance search



生成モデル Generative model for calorimeter shower simulation

HL-LHC (2029-) における計算機資源 予測



HL-LHC (2029-) における計算機資源 予測



カロリメータとシャワー

検出器

Phys. Rev. D 97, 014021 (2018)

粒子のシャワー



初期の研究例: CaloGAN

<u>Comput Softw Big Sci (2017) 1: 4</u> Phys. Rev. D 97, 014021 (2018)



Generative Adversarial Network (GAN)



$$\mathcal{L}_{adv} = \mathbb{E}_{z \sim p(z)} \left[\log \left(1 - D(G(z)) \right) \right]$$
$$+ \mathbb{E}_{x \sim p_{Geant4}} \left[\log D(x) \right]$$

- カロリメータセルごとのエネルギー量 → 画像
- GANで3層の電磁カロリメータ(画像)を生成

10-1

2 3 n Cell ID

CaloGAN: 概要



後にATLASで使われるGANにも使われているアイデア

- 粒子ごと(e, γ, π[±])に**別々のGAN**をトレーニング
- 粒子のエネルギーで条件づけたGAN (p(x|E))
- ・ 総エネルギー量についての制約を口スに追加



CaloGAN: 性能評価

e⁺ GAN

10⁰

 10^{-1}

 10^{-2}

 10^{-3}

GEANT4 GAN

e + GEANT

γ GEANT

100

10¹

 σ_2

0.6

Sparsity in Layer 2

e+ GAN

🔲 γ GAN

π* GEANT ______ π* GAN

101

102

10²

e + GEANT

γ GEANT

🗖 e+ GAN

🖂 γ GAN Π π⁺ GAN

0.8

1.0

π⁺ GEANT

Phys. Rev. D 97, 014021 (2018)

Simulator	Hardware	Batch size	ms/shower
Geant4	CPU	N/A	1772
	CPU	1 10 128 1024	13.1 5.11 2.19 2.03
CALOGAN	GPU	1 4 128 512 1024	14.5 3.68 0.021 0.014 0.012

- ・シャワー形状を"おおよそ"再現
- ・**高速化**を実現
 - Geant4より 2桁 速い



Sparsity in Layer 1

e + GEANT

γ GEANT

e⁺ GAN

🔲 γ GAN

π* GEANT _____ π* GAN

10¹

10⁰

 10^{-1}

10-2

レイヤー毎のエネルギー

🦳 γ GEANT 🗔 γ GAN

π* GEANT ______ π* GAN

e⁺ GEANT

10¹

10⁰

 10^{-1}

10-2

10-3

 10^{-4}

10-5

10⁰

 10^{-1}

 10^{-2}

10-3

 10^{-4}

 10^{-5}

10-6

100

0.0

Sparsity in Layer 0

10-2

ATLASでの初期の研究: VAE と GAN

- ・ATLAS検出器の電磁カロリメータのジオメトリを想定した生成モデルの研究
- ・ 画像ではなく、266次元(セルの個数)の1次元のベクトルを生成
- ・ 限られた範囲の入射粒子だけに着目 (|η|: 0.20~0.25)
- GANとVAEの両方を試して比較





- GANの方が性能が良かった
- 現在のATLASのFast simulationではGANが採用

GAN for Fast Simulation at ATLAS: 概要



- **WGAN-GP** (Wasserstein GAN with a gradient penalty)
 - オリジナルのGANよりも学習が安定化し、モード崩壊も起こしづらい
- 粒子のエネルギーで条件付けをする (256 MeV ~ 4 TeV)
- ・ 全 η 領域をカバー (-5 < η < 5)

- 粒子ごと(e, γ, π)、η sliceごと(100 slice) にGANを作成 (計300 GANs)

GAN for Fast Simulation at ATLAS: Voxelization



- セルベースな手法では粒子の入射位置に影響を受ける
- 入射粒子を中心とした座標系で考える
 - ・ 生成粒子周りで円筒状のグリッド (Voxel)
 - Voxelはcellよりも細かい。予測後に各cellに

エネルギーを割り当てる

粒子タイプ・ηごとにグリッドの切り方を最適化

Voxelの切り方の-	-例
-------------	----

U U			
Ζ	Layer	Bin boundaries in ΔR^{mm} [mm]	Number of bins in ϕ
	PreSamplerB	5, 10, 30, 50, 100, 200, 400, 600	1
	EMB1	1, 4, 7, 10, 15, 30, 50, 90, 150, 200	10
	EMB2	5, 10, 20, 30, 50, 80, 130, 200, 300, 400	10
	EMB3	50, 100, 200, 400, 600	1
	TileBar0	$10, 20, 30, \cdots 100, 130, 160, 200, 250 \cdots 400, 1000, 2000$	10
	TileBar1	$10, 20, 30, \cdots 100, 130, 160, 200, 250, \cdots 400, 600, 1000, 2000$	10
	TileBar2	0, 50, 100, · · · 300, 400, 600, 1000, 2000	1

GAN for Fast Simulation at ATLAS: 結果

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- Jet substructure variableで大きく改善
- 速度も高速
 - Geant4: 6秒 (65 GeV pion) 162 秒 (2 TeV pion)
 - GAN : 0.07 秒 (pion, エネルギー依存性なし)

GAN for Fast Simulation at ATLAS: GANの位置づけ

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- ・ 公式のソフトウェア(AtlFast3)にproductionとして導入
- ・ただし、使われているのは**ハドロン&中程度のエネルギー部分のみ**
 - まだまだ改善できる余地あり



Calo Challenge 2022

- <u>ML4Jets 2022</u>をターゲットにコンテストを開催
- ・ データセット
 - 難易度の異なる3つのデータセット
 - Easy : Voxel数 O(100) (= ATLAS fast simulationのvoxel)
 - Medium : Voxel数 O(1000)
 - Hard : Voxel数 O(10000)
- 評価指標
 - 単一のものではなく多種多様な指標を使う予定
 - ・ サンプリング時間、メモリ使用量
 - ・ シャワー形状変数分布
 - 入射エネルギーに対する内挿がうまくできているか
 - Geant4と生成サンプルを区別するclassifier
- 今後はこのベンチマークを使って手法・モデルの比較が容易に
 - 今後の手法の発展に期待大

Hard datasetの入力



異常検知

Anomaly detection for new particle search

ATLASでの 新粒子探索

ATLAS SUSY Searches* - 95% CL Lower Limits March 2022

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

	Model	Signatu	re ∫ <i>L dt</i> [f	b ⁻¹]	Mass lim	it				Reference
Se	$\tilde{q}\tilde{q},\tilde{q}{\rightarrow}q\tilde{\chi}^0_1$	0 e, µ 2-6 jets mono-jet 1-3 jets	$\begin{array}{cc} E_T^{ m miss} & 139 \ E_T^{ m miss} & 139 \end{array}$	\tilde{q} [1×, 8× Degen \tilde{q} [8× Degen.]	.]	1. 0.9	0	1.85	$m(\tilde{\chi}_{1}^{0}) \le 400 \text{ GeV}$ $m(\tilde{q})-m(\tilde{\chi}_{1}^{0}) = 5 \text{ GeV}$	2010.14293 2102.10874
arche	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \bar{q} \tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i> 2-6 jets	$E_T^{\rm miss}$ 139	ğ ğ		Forbidde	n 1	2.3 .15-1.95	m(𝒱₁)=0 GeV m(𝒱₁)=1000 GeV	2010.14293 2010.14293
Se	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_{1}^{0}$	1 e, µ 2-6 jets	139	Ĩ				2.2	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	2101.01629
Ve Ve	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	ee, μμ 2 jets	E_T^{miss} 139	ĝ				2.2	$m(\tilde{\chi}_1^0) < 700 \text{ GeV}$	CERN-EP-2022-014
clusi	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	$\begin{array}{ccc} 0 \ e, \mu & 7-11 \ \text{jets} \\ \text{SS} \ e, \mu & 6 \ \text{jets} \end{array}$	$E_T^{\text{miss}} = 139$ 139	ĝ ĝ			1.15	1.97	m(𝑋̃_1^0) <600 GeV m(𝔅)-m(𝑋̃_1)=200 GeV	2008.06032 1909.08457
LI LI	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\chi}_1^0$	$\begin{array}{ccc} \text{0-1 } e, \mu & \text{ 3 } b \\ \text{SS } e, \mu & \text{ 6 jets} \end{array}$	E _T ^{miss} 79.8 139	Ĩġ Ĩġ			1.25	2.25	m(𝔅 ⁰)<200 GeV m(𝔅)-m(𝔅 ⁰)=300 GeV	ATLAS-CONF-2018-041 1909.08457
	$\tilde{b}_1 \tilde{b}_1$	0 <i>e</i> , <i>µ</i> 2 <i>b</i>	$E_T^{\rm miss}$ 139	${ar b_1\ ar b_1}$		0.68	1.255		m($\tilde{\chi}_1^0$)<400 GeV 10 GeV<Δm($\tilde{b}_1, \tilde{\chi}_1^0$)<20 GeV	2101.12527 2101.12527
arks tion	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	$\begin{array}{ccc} 0 \ e, \mu & 6 \ b \\ 2 \ \tau & 2 \ b \end{array}$	$\begin{array}{cc} E_T^{ m miss} & 139 \ E_T^{ m miss} & 139 \end{array}$	$egin{array}{ccc} & & & & & For \ & & & & & \\ & & & & & & & \\ & & & & &$	bidden	0.13-0.85	0.23-1.35	$\Delta m(\tilde{\chi}_2^0)$ $\Delta m(\tilde{\chi}_2^0)$	$(\tilde{\chi}_{1}^{0})=130 \text{ GeV}, m(\tilde{\chi}_{1}^{0})=100 \text{ GeV}$ $(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0})=130 \text{ GeV}, m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$	1908.03122 2103.08189
onp	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	0-1 $e, \mu \ge 1$ jet	E_T^{miss} 139	\tilde{t}_1			1.25		m($\tilde{\chi}_{1}^{0}$)=1 GeV	2004.14060,2012.03799
n. s pro	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$	1 e, µ 3 jets/1 b	E_T^{miss} 139	\tilde{t}_1	Forb	dden 0.65			m($\tilde{\chi}_{1}^{0}$)=500 GeV	2012.03799
ge	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b \nu, \tilde{\tau}_1 \rightarrow \tau \bar{G}$	1-2 τ 2 jets/1 b	E_T^{miss} 139	Ĩ1		Forbidden	1.4		m(tti)=800 GeV	2108.07665
3 rd dire	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \chi_1^\circ / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \chi_1^\circ$	0 e,μ 2 c 0 e,μ mono-jet	$E_T^{\text{miss}} = 36.1$ $E_T^{\text{miss}} = 139$	\tilde{t}_1		0.85			$m(\tilde{t}_1)=0 \text{ GeV}$ $m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1)=5 \text{ GeV}$	1805.01649 2102.10874
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	$1-2 e, \mu$ $1-4 b$	E_T^{miss} 139	Ĩ1		0.06	7-1.18	~0	$m(\tilde{\chi}_2^0)=500 \text{ GeV}$	2006.05880
	$t_2 t_2, t_2 \rightarrow t_1 + Z$	$3 e, \mu$ $1 b$	E_T^{mass} 139	12	Forbi	iden 0.86		$m(\mathcal{X}_1) =$	$360 \text{ GeV}, m(\tilde{t}_1) - m(\tilde{t}_1') = 40 \text{ GeV}$	2006.05880
	$ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via WZ	$\begin{array}{ll} \text{Multiple } \ell/\text{jets} \\ ee, \mu\mu & \geq 1 \text{ jet} \end{array}$	E_T^{miss} 139 E_T^{miss} 139	$ \begin{array}{c} \tilde{\chi}_1^{\pm} / \tilde{\chi}_2^0 \\ \tilde{\chi}_1^{\pm} / \tilde{\chi}_2^0 \end{array} $ 0.2	205	0.96			$m(\tilde{\chi}_1^0)=0$, wino-bino $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606
	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}$ via WW	2 e, µ	E_T^{miss} 139	$\tilde{\chi}_{1}^{\pm}$	0.42				$m(\tilde{\chi}_1^0)=0$, wino-bino	1908.08215
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via Wh	Multiple ℓ/jets	E_T^{miss} 139	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}$ Forbidde	ən	1	06		$m(\tilde{\chi}_1^0)=70$ GeV, wino-bino	2004.10894, 2108.07586
sct ≥	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{+}$ via $\tilde{\ell}_{L}/\tilde{\nu}$	$2 e, \mu$	E_T^{miss} 139	$\tilde{\chi}_1^{\pm}$		1.	D		$m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$	1908.08215
Шi	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau \chi_1'$	2τ	E_T^{miss} 139	τ [τ_L , $\tau_{R,L}$]	0.16-0.3 0.12-0.3	9			$m(\chi_1^0)=0$	1911.06660
Ŭ	$\ell_{\mathrm{L,R}}\ell_{\mathrm{L,R}}, \ell {\rightarrow} \ell \chi_1^{\circ}$	$2 e, \mu$ 0 jets $ee, \mu\mu$ ≥ 1 jet	E_T^{mass} 139 E_T^{miss} 139	l l	0.256	0.7			$m(\tilde{\ell}_1)=0$ $m(\tilde{\ell})\cdot m(\tilde{\chi}_1^0)=10 \text{ GeV}$	1908.08215 1911.12606
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	$0 e, \mu \ge 3 b$	E_T^{miss} 36.1	<u>Ĥ</u> 0.1	13-0.23	0.29-0.88			$BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G})=1$	1806.04030
		$0 e, \mu \ge 2$ large je	ets E_T^{miss} 139	H Ĥ		0.55			$BH(\chi_1 \rightarrow ZG)=1$ $BR(\chi_1^0 \rightarrow ZG)=1$	2103.11684 2108.07586
									,	
D (1	Direct $\tilde{\chi}_1^* \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk 1 jet	E_T^{miss} 139		0.21	0.66			Pure Wino Pure higgsino	2201.02472 2201.02472
live Slee	Stable g R-hadron	pixel dE/dx	E_T^{miss} 139	\tilde{g}				2.05		CERN-EP-2022-029
-g-	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$	pixel dE/dx	E_T^{miss} 139	\tilde{g} [$\tau(\tilde{g}) = 10 \text{ ns}$]				2.2	m($\tilde{\chi}_{1}^{0}$)=100 GeV	CERN-EP-2022-029
pa	$\ell\ell, \ell \rightarrow \ell G$	Displ. lep	E_T^{miss} 139	$\tilde{e}, \tilde{\mu}$ $\tilde{\tau}$	0.34	0.7			$\tau(\ell) = 0.1 \text{ ns}$ $\tau(\ell) = 0.1 \text{ ns}$	2011.07812
		pixel dE/dx	$E_T^{\rm miss}$ 139	Ť	0.34				$\tau(\tilde{\ell}) = 0.1 \text{ ms}$ $\tau(\tilde{\ell}) = 10 \text{ ns}$	CERN-EP-2022-029
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_1^0, \tilde{\chi}_1^{\pm} \rightarrow Z \ell \rightarrow \ell \ell \ell$	3 e, µ	139	$\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{1}^{0}$ [BR($Z\tau$)=	1, BR(Ze)=1]	0.625 1.	05		Pure Wino	2011.10543
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \rightarrow W W / Z \ell \ell \ell \ell \nu \nu$	4 e, µ 0 jets	E_T^{miss} 139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0 [\lambda_{i33} \neq 0, \lambda_{i33} \neq 0, \lambda_{i33$	$\lambda_{12k} \neq 0$]	0.95	1.5	5	m($\tilde{\chi}_{1}^{0}$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$	4-5 large je	ets 36.1	\tilde{g} [m($\tilde{\chi}_1^0$)=200 Ge	eV, 1100 GeV]		1.3	1.9	Large \mathcal{X}_{112}''	1804.03568
>	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$	Multiple	36.1	$t = [\mathcal{A}_{323}'' = 2e-4, 1e-3]$	2]	0.55 1.	05		$m(\tilde{\chi}_1^0)=200 \text{ GeV}, \text{ bino-like}$	ATLAS-CONF-2018-003
R	$t\bar{t}, t \rightarrow b\chi_1, \chi_1 \rightarrow bbs$	$\geq 4b$	139	î Î	Forb	dden 0.95			m(X1)=500 GeV	2010.01015
	$i_1i_1, i_1 \rightarrow bs$ $\tilde{i}_1\tilde{i}_1, \tilde{i}_1 \rightarrow a\ell$	2 jets + 2	v 36./	$\tilde{i}_1 [qq, bs]$	0.42	0.61	0.4-1.45		$BB(\tilde{t}, \rightarrow he/hu) > 20\%$	1710.05544
	1111, 11-790	$1 \mu DV$	136	\tilde{t}_1 [1e-10< λ'_{23k}	<1e-8, 3e-10< X'_23k} <3e-9]	1.	0.4-1.45	1.6	$BR(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_i = 1$	2003.11956
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^+ \rightarrow bbs$	1-2 $e, \mu \ge 6$ jets	139	$\tilde{\chi}_{1}^{0}$	0.2-0.32				Pure higgsino	2106.09609
							1			
*Only	a selection of the available ma	ss limits on new state	es or	10^{-1}			1		Mass scale [TeV]	

phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

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ATLASでの 新粒子探索

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits Status: March 2022

ATLAS Preliminary $\sqrt{s} = 8, 13 \text{ TeV}$ $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$

								Model	<i>ℓ</i> ,γ	Jets† E	miss T	∫£ dt[fl	b ⁻¹]	Limit	5 -	, , , , , , , , , , , , , , , , , , ,	Reference
A	ATLAS SUSY Sea farch 2022 Model	arches'	* - 95° Signatu	% C	L L0 [™] ∫ <i>L dt</i> [fb	wer Limit:	Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell \nu qq$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP	$\begin{array}{c} 0 \ e, \mu, \tau, \gamma \\ 2 \ \gamma \\ \\ - \\ 2 \ \gamma \\ \\ multi-chann \\ 1 \ e, \mu \\ 1 \ e, \mu \\ 1 \ e, \mu \end{array}$	1 - 4j 2j $\ge 3j$ - 2j/1J $\ge 1b, \ge 1J/2j$ $\ge 2b, \ge 3j$	Yes - - Yes Yes Yes	139 36.7 37.0 3.6 139 36.1 139 36.1 36.1	Mo Ms Mth Grkk mass Grkk mass Grkk mass grkk mass grkk mass		11.2 8.6 TeV 8.9 TeV 9.55 TeV 2.3 TeV 2.0 TeV 2.0 TeV 3.8 TeV 1.8 TeV		2102.10874 1707.04147 1703.09127 1512.02586 2102.13405 1808.02380 2004.14636 1804.10823 1803.09678
Inclusive Searches	$\begin{array}{l} qq, q \rightarrow q\tilde{x}_{1} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}WZ\tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_{1}^{0} \end{array}$	$\begin{array}{c} 0 \ e, \mu \\ mono-jet \\ 0 \ e, \mu \\ 1 \ e, \mu \\ 0 \ e, \mu \\ S \ e, \mu \\ S \ e, \mu \\ S \ e, \mu \end{array}$	2-6 jets 2-6 jets 2-6 jets 2 jets 7-11 jets 6 jets 3 <i>b</i> 6 jets	E_T^{miss} E_T^{miss} E_T^{miss} E_T^{miss} E_T^{miss} E_T^{miss}	139 139 139 139 139 139 139 79.8 139	q [1X, OX Degen.] q q [8x Degen.] g g g g g g g g g g g g g g g g g g g g g g g g g g g g g g g g g g g g g	Gauge bosons	$\begin{array}{l} \text{SSM } Z' \to \ell\ell\\ \text{SSM } Z' \to \tau\tau\\ \text{Leptophobic } Z' \to bb\\ \text{Leptophobic } Z' \to bb\\ \text{SSM } W' \to \ell\nu\\ \text{SSM } W' \to \tau\nu\\ \text{SSM } W' \to tv\\ \text{HVT } W' \to WZ \to \ell\nu\ell'\ell' \text{ mod}\\ \text{HVT } W' \to WZ \to \ell\nu\ell' \mu' \text{ mod}\\ \text{HVT } W' \to WZ \to \ell\nu\ell' \mu' \text{ mod}\\ \text{HVT } W' \to WZ \to \ell\mu' \mu' \text{ mod}\\ \text{HVT } W' \to WZ \to \ell\mu' \mu' \text{ mod}\\ \text{HVT } W' \to WZ \to \ell\mu' \mu' \text{ mod}\\ \text{HVT } W' \to WZ \to \ell\mu' \mu' \text{ mod}\\ \text{HVT } W' \to WZ \to \ell\mu' \mu' \text{ mod}\\ \text{HVT } W' \to WZ \to \ell\mu' \mu' \text{ mod}\\ \text{HVT } W' \to \ell\mu' \mu' \mu$	2 e, µ 2 τ - 0 e, µ 1 e, µ 1 τ del C 3 e, µ 0 e, µ 2 μ	$\begin{array}{c} - & - & - \\ 2 b \\ \geq 1 b, \geq 2 J \\ - & - \\ 2 j / 1 J \\ 2 j / 1 J \\ 2 j (VBF) \\ \geq 1 b, \geq 2 J \\ 1 J \end{array}$	- Yes Yes Yes Yes Yes	139 36.1 36.1 139 139 139 139 139 139 139 139 80	Z' mass Z' mass Z' mass Z' mass W' mass W mass W mass	340 GeV	5.1 TeV 2.42 TeV 2.1 TeV 4.1 TeV 5.0 TeV 5.0 TeV 4.4 TeV 4.3 TeV 3.2 TeV 5.0 TeV	$\Gamma/m = 1.2\%$ $g_V = 3$ $g_V c_H = 1, g_T = 0$ $g_V = 3$ $m(N_R) = 0.5$ TeV, $g_L = g_R$	1903.06248 1709.07242 1805.09299 2005.05138 1906.05609 ATLAS-CONF-2021-02 ATLAS-CONF-2021-04 2004.14636 ATLAS-CONF-2022-00 2007.05293 1904.12679
arks ction	$\tilde{b}_1 \tilde{b}_1$ $\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	0 e,μ 0 e,μ 2 τ	2 b 6 b 2 b	$E_T^{ m miss}$ $E_T^{ m miss}$ $E_T^{ m miss}$	139 139 139		CI	Cl $qqqq$ Cl $\ell\ell qq$ Cl $eebs$ Cl $\mu\mu bs$ Cl $tttt$	2 e, μ 2 e 2 μ ≥1 e,μ	2 j - 1 b 1 b ≥1 b, ≥1 j	- - - Yes	37.0 139 139 139 36.1	Λ Λ Λ Λ Λ		1.8 TeV 2.0 TeV 2.57 TeV	$\begin{array}{c c} \textbf{21.8 TeV} & \eta_{\bar{L}L} \\ \textbf{35.8 TeV} \\ \textbf{g}_s = 1 \\ C_{4t} = 4\pi \end{array} \qquad \eta_{\bar{L}L}$	1703.09127 2006.12946 2105.13847 2105.13847 1811.02305
3 rd gen. squ direct produc	$ \begin{array}{l} \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow \tilde{t}_{1}^{0} \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow Wb\tilde{t}_{1}^{0} \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow \tilde{\tau}_{1}bv, \tilde{\tau}_{1} \rightarrow \tau \tilde{G} \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow c\tilde{t}_{1}^{0} / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{t}_{1}^{0} \end{array} $	0-1 <i>e</i> , μ 1 <i>e</i> , μ 1-2 τ 0 <i>e</i> , μ	≥ 1 jet 3 jets/1 / 2 jets/1 / 2 c mono-ie	E_T^{miss} $b E_T^{miss}$ $b E_T^{miss}$ E_T^{miss} e_T^{miss}	139 139 139 36.1 139	τ̃ ₁ τ̃ ₁ τ̃ ₁ τ̃ ₁ τ̃ ₁	MQ	Axial-vector med. (Dirac DM) Pseudo-scalar med. (Dirac DN) Vector med. Z'-2HDM (Dirac D Pseudo-scalar med. 2HDM+a	0 e, μ, τ, γ 1) 0 e, μ, τ, γ DM) 0 e, μ multi-chann	1-4j 1-4j 2b	Yes Yes Yes	139 139 139 139	m _{med} m _{med} m _{med}	376 GeV 560 GeV	2.1 TeV 3.1 TeV	$\begin{array}{l} g_q = 0.25, \ g_k = 1, \ m(\chi) = 1 \ \text{GeV} \\ g_q = 1, \ g_{\chi} = 1, \ m(\chi) = 1 \ \text{GeV} \\ \tan \beta = 1, \ g_{\chi} = 0.8, \ m(\chi) = 10 \ \text{GeV} \\ \tan \beta = 1, \ g_{\chi} = 1, \ m(\chi) = 10 \ \text{GeV} \end{array}$	2102.10874 2102.10874 2108.13391 ATLAS-CONF-2021-03
	$ \begin{split} \tilde{i}_{1}\tilde{i}_{1}, \tilde{i}_{1} \to t \tilde{\chi}_{2}^{0}, \tilde{\chi}_{2}^{0} \to Z/h \tilde{\chi}_{1}^{0} \\ \tilde{i}_{2}\tilde{i}_{2}, \tilde{i}_{2} \to \tilde{i}_{1} + Z \\ \tilde{\chi}_{1}^{\pm} \tilde{\chi}_{2}^{0} \text{ via } WZ \end{split} $	1-2 e, μ 3 e, μ Multiple ℓ/je	$1-4 b$ $1 b$ ets $\geq 1 \text{ jet}$	$ \begin{array}{c} E_T^{\text{miss}} \\ E_T^{\text{miss}} \\ E_T^{\text{miss}} \\ E_T^{\text{miss}} \\ E_T^{\text{miss}} \end{array} $	139 139 139 139 139		70	Scalar LQ 1 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen	$2 e 2 \mu 1 \tau 0 e, \mu \ge 2 e, \mu, \ge 1 0 e, \mu, \ge 1 - 1 = 1 = 1 = 1 = 1 = 1 = 1 = 1 = 1 =$	$ \begin{array}{c} \geq 2 \\ \geq 2 \\ 2 \\ \end{pmatrix} \\ \geq 2 \\ j, \geq 2 \\ \tau \geq 1 \\ j, \geq 1 \\ b \\ \tau \\ 0 - 2 \\ j, 2 \\ b \end{array} $	Yes Yes Yes - Yes	139 139 139 139 139 139	LQ mass LQ" mass LQ" mass LQ" mass LQ ³ mass LQ ³ mass	1	1.8 IeV 1.7 TeV 1.2 TeV 1.24 TeV 1.43 TeV 1.45 TeV 1.26 TeV	$p = 1$ $\beta = 1$ $\mathcal{B}(LQ_3^g \to b\tau) = 1$ $\mathcal{B}(LQ_3^g \to t\tau) = 1$ $\mathcal{B}(LQ_3^d \to t\tau) = 1$ $\mathcal{B}(LQ_3^d \to b\tau) = 1$ $\mathcal{B}(LQ_3^d \to b\tau) = 0$	2006.05872 2006.05872 2108.07665 2004.14060 2101.11582 2101.12527
EW direct	$ \begin{split} \tilde{\chi}_1^{\dagger} \tilde{\chi}_1^{\intercal} & \text{via } WW \\ \tilde{\chi}_1^{\dagger} \tilde{\chi}_2^0 & \text{via } Wh \\ \tilde{\chi}_1^{\dagger} \tilde{\chi}_1^{\intercal} & \text{via } \tilde{\ell}_L / \tilde{\nu} \\ \tilde{\tau}_{\tau}^{\dagger}, \tilde{\tau} \to \tau \tilde{\chi}_1^{\intercal} \\ \tilde{\ell}_{L,R} \tilde{\ell}_{L,R}, \tilde{\ell}_{-L,R}, \tilde{\ell} \to \ell \tilde{\chi}_1^0 \end{split} $	$\begin{array}{c} 2 \ e, \mu \\ \text{Multiple } \ell/je \\ 2 \ e, \mu \\ 2 \ \tau \\ 2 \ e, \mu \\ ee, \mu \mu \end{array}$	ets 0 jets ≥ 1 jet	E_T^{miss} E_T^{miss} E_T^{miss} E_T^{miss} E_T^{miss} E_T^{miss}	139 139 139 139 139 139	$ \vec{x}_{1}^{\pm} \\ \vec{x}_{1}^{\pm} / \vec{x}_{2}^{0} Forbidden \\ \vec{x}_{1}^{\pm} \\ \vec{\tau} [\tilde{\tau}_{L}, \tilde{\tau}_{R,L}] \\ \vec{\ell} \\ \vec{\ell} $	Heavy quarks	Vector LQ 3 ¹⁵ gen VLQ $TT \rightarrow Zt + X$ VLQ $BB \rightarrow Wt/Zb + X$ VLQ $T_{5/3}T_{5/3} T_{5/3} \rightarrow Wt + X$ VLQ $T \rightarrow Ht/Zt$ VLQ $Y \rightarrow Wb$ VLQ $B \rightarrow Hb$	1τ $2e/2\mu/\geq 3e,$ multi-chann $(2(SS))\geq 3e,$ $1 e, \mu$ $1 e, \mu$ $0 e, \mu$	$\begin{array}{c} 2 \text{ b} \\ \mu \geq 1 \text{ b}, \geq 1 \text{ j} \\ \text{iel} \\ ,\mu \geq 1 \text{ b}, \geq 1 \text{ j} \\ \geq 1 \text{ b}, \geq 3 \text{ j} \\ \geq 2 \text{ b}, \geq 1 \text{ j} \\ \geq 2 \text{ b}, \geq 1 \text{ j}, \geq 1 \text{ J} \end{array}$	- Yes Yes Yes -	139 36.1 36.1 139 36.1 139	T mass B mass T _{5/3} mass T mass Y mass B mass		1.4 TeV 1.4 TeV 1.64 TeV 1.64 TeV 1.8 TeV 2.0 TeV 2.0 TeV	$\begin{split} &\mathcal{D}(\mathrm{LQ}_{5}^{-} \rightarrow \sigma^{+}) = 0.5, \ \mathrm{t\text{-}W} \ \mathrm{Couple}, \\ &\mathrm{SU}(2) \ \mathrm{doublet} \\ &\mathcal{D}(2) \ \mathrm{doublet} \\ &\mathcal{D}(T_{5/3} \rightarrow Wt) = 1, \ c(T_{5/3}Wt) = 1 \\ &\mathrm{SU}(2) \ \mathrm{singlet}, \ \kappa_{T} = 0.5 \\ &\mathcal{D}(Y \rightarrow Wb) = 1, \ c_{K}(Wb) = 1 \\ &\mathrm{SU}(2) \ \mathrm{doublet}, \ \kappa_{B} = 0.3 \end{split}$	ATLAS-CONF-2021-02 1808.02343 1807.11883 ATLAS-CONF-2021-04 1812.07343 ATLAS-CONF-2021-01
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e,μ 4 e,μ 0 e,μ	$\geq 3 b$ 0 jets ≥ 2 large je	E_{T}^{miss} E_{T}^{miss} ets E_{T}^{miss}	36.1 139 139	<u>Й</u> 0.13- <u>Й</u> Й	Excited	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton ℓ^* Excited lepton γ^*	- 1γ 3 e,μ 3 e,μ,τ	2 j 1 j 1 b, 1 j -	-	139 36.7 36.1 20.3 20.3	q* mass q* mass b* mass /* mass y* mass		6.7 TeV 5.3 TeV 2.6 TeV 3.0 TeV 1.6 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	1910.08447 1709.10440 1805.09299 1411.2921 1411.2921
Long-lived particles	Direct $\tilde{\chi}_1^* \chi_1^-$ prod., long-lived $\tilde{\chi}_1^+$ Stable \tilde{g} R-hadron Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$ $\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell \tilde{G}$	Disapp. tr pixel dE/d pixel dE/d Displ. lep pixel dE/d	rk 1 jet ix ix ix ix	$E_T^{\rm miss}$ $E_T^{\rm miss}$ $E_T^{\rm miss}$ $E_T^{\rm miss}$ $E_T^{\rm miss}$	139 139 139 139 139	$\begin{array}{c} \tilde{X}_{1}^{\tilde{\pi}} \\ \tilde{X}_{1}^{\tilde{\pi}} \end{array} 0.2 \\ \tilde{g} \\ \tilde{g} \\ \tilde{r}, \tilde{\mu} \\ \tilde{\tau} \\ \tilde{\tau} \\ \tilde{\tau} \end{array}$	Other	Type III Seesaw LRSM Majorana v Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Multi-charged particles Magnetic monopoles	$2,3,4 e, \mu$ 2μ $2,3,4 e, \mu (S)$ $2,3,4 e, \mu (S)$ $3 e, \mu, \tau$ -	$ \sum_{i=1}^{2} 2i $ $ \sum_{i=1}^{2} 3i $ $ \sum_{i=1}^{2} 3i $ $ \sum_{i=1}^{2} 3i $	Yes - Yes - - -	139 36.1 139 20.3 36.1 34.4	N ⁰ mass N _R mass H ^{±±} mass H ^{±±} mass multi-charged particle mas monopole mass	910 G 350 GeV 400 GeV 1.0 5 1	eV 3.2 TeV 8 TeV .22 TeV 2.37 TeV	$\begin{split} m(W_R) &= 4.1 \text{ TeV}, g_L = g_R \\ \text{DY production} \\ \text{DY production} \\ \text{DY production}, \mathcal{B}(H_L^{t\pm} \to \ell \tau) = 1 \\ \text{DY production}, q = 5e \\ \text{DY production}, g = 1_{g_D}, \text{spin } 1/2 \end{split}$	2202.02039 1809.11105 2101.11961 ATLAS-CONF-2022-01 1411.2921 1812.03673 1905.10130
RPV	$\begin{split} \tilde{\chi}_{1}^{+} \tilde{\chi}_{1}^{+} / \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{+} \rightarrow \mathcal{I}\ell \rightarrow \mathcal{U}\ell \ell \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{1}^{+} / \tilde{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell v \\ \tilde{g}\tilde{g}, \tilde{g} - qq \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow qq \\ \tilde{n}, \tilde{t} \rightarrow \tilde{k}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs \\ \tilde{n}, \tilde{t} \rightarrow b\tilde{k}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow bbs \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow bs \\ \tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow dt \\ \tilde{\chi}_{1}^{+} / \tilde{\chi}_{2}^{0} / \tilde{\chi}_{1}^{0}, \tilde{\chi}_{12}^{0} \rightarrow tbs, \tilde{\chi}_{1}^{+} \rightarrow bbs \end{split}$	3 e,µ 4 e,µ 2 e,µ 1 µ 1-2 e,µ	0 jets 4-5 large ju Multiple $\geq 4b$ 2 jets + 2 2 b DV ≥ 6 jets	E ^{miss} ets 2 b	139 139 36.1 36.1 139 36.7 36.1 136 139	$ \begin{array}{c} \tilde{X}_{1}^{*} / \tilde{X}_{2}^{0} (BR(Zr)=1, 1) \\ \tilde{X}_{1}^{*} / \tilde{X}_{2}^{0} (BR(Zr)=1, 1) \\ \tilde{X}_{1}^{*} / \tilde{X}_{2}^{0} (BR(Zr)=1, 2) \\ \tilde{R} (m \tilde{X}_{2}^{0})=200 \text{ GeV}, \\ \tilde{I} (X_{23}^{*})=204 \text{ GeV}, \\ \tilde{I} $	*Or †Sr 9-8, 3e-10 0.	$\sqrt{s} = 8$ TeV hly a selection of the availat mall-radius (large-radius) je Forbidden 0.42 0.61 $< l_{214}^{2} < 3e-9$ 2-0.32	ys = 13 TeV partial data ble mass lin ts are denou 0.95 0.4 1.0	Vs = 13 Tr full data its on new si ted by the let +1.45 1.6	ev states tter j (or phei J). BF	10^{-1} nomena is shown. $m(\tilde{t}_1^+)=500 \text{ GeV}$ $BR(\tilde{t}_1 \rightarrow bc/b\mu)>20\%$ $R(\tilde{t}_1 \rightarrow q\mu)=100\%, \cos\theta_{\theta}=1$ Pure higgsino	2010.010 1710.075 2003.119 2106.096	1 1 1 1 1 1 5 7 1 44 4 5 6 09	¹⁰ Mass scale [TeV]	
*Only phen simp	a selection of the available ma nomena is shown. Many of the plified models, c.f. refs. for the	ass limits on e limits are b assumption	n new stat based on is made.	tes or		10 ⁻¹			1			Ma	ss scale [TeV]				10

19

ATLASでの 新粒子探索

Inclusive Searches

squarks oduction

gen.

EW

Long-lived

RPV

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits Status: March 2022

 $\int f dt = (3.6 - 139) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$

								$\int \mathcal{L} dt = 0$	1.0 – 1.03) 10	$y_3 = 0, 10 10 v$
		Model	ℓ,γ Je	ets† E _T ^{miss}	່∫£dt[fb	1]	Limit			Reference
ATLAS SUSY Sea	rches* - 95% CL Lower Lim	$\begin{array}{c} \textbf{S} \\ \textbf{S} \\ \textbf{S} \\ \textbf{S} \\ \textbf{S} \\ \textbf{A} \\ \textbf{D} \\ \textbf{D} \\ \textbf{C} \\ $	$ \begin{array}{cccc} 0 & e, \mu, \tau, \gamma & 1 \\ 2 & \gamma & - \\ & - & 2 \\ 2 & \gamma & - & 2 \end{array} $	-4j Yes 2j - ≥3j -	139 36.7 37.0 3.6 139	M _D M _S M _{th} M _{th} G _{KK} mass		11.2 Te 8.6 TeV 8.9 TeV 9.55 TeV 4.5 TeV	n = 2 n = 3 HLZ NLO n = 6 $n = 6, M_D = 3 \text{ TeV, rot BH}$ $k/\overline{M}_{Pl} = 0.1$	2102.10874 1707.04147 1703.09127 1512.02586 2102.13405
Model	Signature ∫£ dt [f	Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell v q q$	multi-channel 1 e, μ 2 j	j/1J Yes	36.1 139	G _{KK} mass G _{KK} mass		2.3 TeV 2.0 TeV	$\frac{k}{M_{Pl}} = 1.0$ $\frac{k}{M_{Pl}} = 1.0$	1808.02380 2004.14636
$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_1^0$	$0 e, \mu$ 2-6 jets $E_{T_{\text{pine}}}^{\text{miss}}$ 139 \tilde{q} [1×, 8× Dege	$\widehat{\mathbf{u}} \qquad $	1 <i>e</i> ,μ ≥1b 1 <i>e</i> ,μ ≥2	b, ≥3 j Yes	36.1 36.1	KK mass		3.8 TeV	1/m = 15% Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1804.10823 1803.09678
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	mono-jet1-3 jets E_T^{mins} 139 \bar{q} [BX Degen.] $0 e, \mu$ 2-6 jets E_T^{mins} 139 \bar{g} $1 e, \mu$ 2-6 jets139 \bar{g}	$\begin{array}{c} \text{SSM } Z' \to \ell\ell\\ \text{SSM } Z' \to \tau\tau\\ \text{Leptophobic } Z' \to bb\\ \text{Leptophobic } Z' \to tt\\ \text{SSM } W' \to \ell\nu \end{array}$	2 e, μ 2 τ - 0 e, μ ≥1 i 1 e, μ	– – 2 b – b, ≥2 J Yes – Yes	139 36.1 36.1 139 139	Z' mass Z' mass Z' mass Z' mass W' mass		5.1 TeV 2.42 TeV 2.1 TeV 4.1 TeV 6.0 TeV	Γ/ <i>m</i> = 1.2%	1903.06248 1709.07242 1805.09299 2005.05138 1906.05609
$\begin{array}{c} \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_{1}^{\prime} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow tt\tilde{\chi}_{1}^{0} \end{array}$	$ee, \mu\mu$ 2 lets E_{μ}^{mins} 139 \ddot{g} $0, e, \mu$ 7-11 lets E_{T}^{mins} 139 \ddot{g} SS e, μ 6 lets 139 \ddot{g} $0-1, e, \mu$ 3 b E_{T}^{mins} 79.8 \ddot{g} SS e, μ 6 lets 7 139 \ddot{g}	0. SSM $W' \rightarrow \tau \gamma$ SSM $W' \rightarrow tb$ HVT $W' \rightarrow WZ \rightarrow \ell \nu q mode$ HVT $W' \rightarrow WZ \rightarrow \ell \nu \ell' \ell' mode$ HVT $W' \rightarrow WZ \rightarrow \ell \nu \ell' \ell' mode$ HVT $W' \rightarrow WH model$ B	$\begin{array}{cccc} & 1 \tau & & \\ & - & \geq 1 t \\ \text{el B} & 1 e, \mu & 2 j \\ \text{del C} & 3 e, \mu & 2 j \\ & 0 e, \mu & \geq 1 t \\ & 2 u \end{array}$	- Yes b, ≥1 J - j/1 J Yes (VBF) Yes b, ≥2 J	139 139 139 139 139	W' mass W' mass W' mass W' mass W' mass	340 GeV	5.0 TeV 4.4 TeV 4.3 TeV 3.2 TeV	$g_V = 3$ $g_V c_H = 1, g_f = 0$ $g_V = 3$ $g_V (f_H) = 0$ (f $T_{V} (f_H) = 0$	ATLAS-CONF-2021-025 ATLAS-CONF-2021-043 2004.14636 ATLAS-CONF-2022-005 2007.05293
	$0e,\mu$ 2 b E_T^{miss} 139 \tilde{b}_1	Cl qqqq	2 μ -	2j –	37.0	۸ N N N N N N N N N N N N N N N N N N N		5.0 TeV	$m(N_R) = 0.5 \text{ lev}, g_L = g_R$ 21.8 TeV η_{LL}^-	1703.09127
$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	rt Cl eebs Cl eebs Cl µµbs Cl tttt	2 e, µ 2 e 2 µ ≥1 e,µ ≥1	 1 b - 1 b - b, ≥1 j Yes	139 139 139 36.1	Λ Λ Λ		1.8 TeV 2.0 TeV 2.57 TeV	$\begin{array}{c} 35.8 \text{ TeV} \\ g_* = 1 \\ g_* = 1 \\ C_{4t} = 4\pi \end{array} \eta_{LL}$	2006.12946 2105.13847 2105.13847 1811.02305
$\begin{array}{c} \tilde{I}_{1}\tilde{I}_{1}, \tilde{I}_{1} \rightarrow t\tilde{X}_{1}^{\prime} \\ \tilde{I}_{1}\tilde{I}_{1}, \tilde{I}_{1} \rightarrow Wb\tilde{\chi}_{1}^{0} \\ \tilde{I}_{1}\tilde{I}_{1}, \tilde{I}_{1} \rightarrow \tilde{\tau}_{1}bv, \tilde{\tau}_{1} \rightarrow \tau\tilde{G} \\ \tilde{I}_{1}\tilde{I}_{1}, \tilde{I}_{1} \rightarrow \tilde{\tau}_{1}^{0}/\tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_{1}^{0} \end{array}$	$\begin{array}{llllllllllllllllllllllllllllllllllll$	Axial-vector med. (Dirac DM) Pseudo-scalar med. (Dirac DM) Vector med. Z'-2HDM (Dirac D Pseudo-scalar med. 2HDM+a	$\begin{array}{cccc} 0 \ e, \mu, \tau, \gamma & 1 \\ 1) & 0 \ e, \mu, \tau, \gamma & 1 \\ DM) & 0 \ e, \mu & \\ multi-channel \end{array}$	-4j Yes -4j Yes 2b Yes	139 139 139 139	m _{med} m _{med} m _{med}	376 GeV 560 GeV	2.1 TeV 3.1 TeV	$\begin{array}{l} g_q = 0.25, \ g_{\chi} = 1, \ m(\chi) = 1 \ {\rm GeV} \\ g_q = 1, \ g_{\chi} = 1, \ m(\chi) = 1 \ {\rm GeV} \\ {\rm tan} \beta = 1, \ g_{\chi} = 0.8, \ m(\chi) = 100 \ {\rm GeV} \\ {\rm tan} \beta = 1, \ g_{\chi} = 1, \ m(\chi) = 10 \ {\rm GeV} \end{array}$	2102.10874 2102.10874 2108.13391 ATLAS-CONF-2021-036
$\tilde{i}_{1}\tilde{i}_{1}, \tilde{i}_{1} \rightarrow t\tilde{\chi}_{2}^{0}, \tilde{\chi}_{2}^{0} \rightarrow Z/h\tilde{\chi}_{1}^{0}$ $\tilde{i}_{2}\tilde{i}_{2}, \tilde{i}_{2} \rightarrow \tilde{i}_{1} + Z$ $\tilde{\chi}^{\pm}\tilde{\chi}^{0}, ijo WZ$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Scalar LQ 1 st gen Scalar LQ 2 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen Scalar LQ 3 rd gen	$2 e$ 2μ 1τ $0 e, \mu \geq 2$ $\geq 2 e, \mu, \geq 1 \tau \geq 1$	≥2j Yes ≥2j Yes 2b Yes j, ≥2b Yes j, ≥1b –	139 139 139 139 139 139	LQ mass LQ mass LQ ^u mass LQ ^d mass LQ ^d mass	1.2 Te 1.2 Te 1.24 Te 1.43	1.8 TeV 1.7 TeV V TeV	$\begin{array}{l} \beta = 1 \\ \beta = 1 \\ \mathcal{B}(LQ_3^u \to b\tau) = 1 \\ \mathcal{B}(LQ_3^u \to t\tau) = 1 \\ \mathcal{B}(LQ_3^d \to t\tau) = 1 \end{array}$	2006.05872 2006.05872 2108.07665 2004.14060 2101.11582
$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ via WW $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^{0}$ via Wh	$\begin{array}{llllllllllllllllllllllllllllllllllll$	2 Scalar LQ 3 rd gen Vector LQ 3 rd gen VLQ $TT \rightarrow Zt + X$ VLQ $BB \rightarrow Wt/Zb + X$	$\begin{array}{c} 0 \ e, \mu, \geq 1 \ \tau \ 0 - 2 \\ 1 \ \tau \end{array}$ $\begin{array}{c} 2e/2\mu/\geq 3e, \mu \ \geq 1 \\ multi-channel \end{array}$	2 j, 2 b Yes 2 b Yes b, ≥1 j –	139 139 139 36.1	LQ ^V mass LQ ^V mass T mass B mass	1.26 Te 1 1.4 ⁻ 1.34 T	V .77 TeV TeV eV	$\begin{array}{l} \mathcal{B}(\mathrm{LQ}_3^{\sigma} \rightarrow b\nu) = 1 \\ \mathcal{B}(\mathrm{LQ}_3^{V} \rightarrow b\tau) = 0.5, \mbox{ Y-M coupl.} \\ \end{array}$ SU(2) doublet SU(2) doublet	2101.12527 2108.07665 ATLAS-CONF-2021-024 1808.02343
$ \begin{array}{c} \widetilde{\chi}_{1}^{\tau}\widetilde{\chi}_{1}^{\tau} \operatorname{via} \widetilde{\ell}_{L}/\widetilde{v} \\ \widetilde{\tau}_{\tau}^{\tau}, \widetilde{\tau} \rightarrow \tau \widetilde{\chi}_{1}^{0} \\ \widetilde{\ell}_{L,R} \widetilde{\ell}_{L,R}, \widetilde{\ell} \rightarrow \ell \widetilde{\chi}_{1}^{0} \end{array} $	$\begin{array}{cccc} 2 e, \mu & E_{pins}^{mins} & 139 & \tilde{x}_{1}^{*} \\ 2 \tau & E_{pins}^{mins} & 139 & \tilde{\tau} & [\tilde{\tau}_{L}, \tilde{\tau}_{R,L}] \\ 2 e, \mu & 0 \text{ jets} & E_{pins}^{mins} & 139 & \tilde{t} \\ ee, \mu\mu & \geq 1 \text{ jet} & E_{T}^{mins} & 139 & \tilde{t} \end{array}$	$\begin{array}{c} \overbrace{\textbf{U}} \\ \overbrace{\textbf{U}} I \atop \overbrace{\textbf{U}} I \atop\overbrace{\textbf{U} } \atop\overbrace{\textbf{U} } \overbrace{\textbf{U}} \atop\overbrace{\textbf{U}} I \atop\overbrace{\textbf{U}} I \atop\overbrace{\textbf{U} } \overbrace{\textbf{U} } \overbrace{\textbf{U} } \overbrace{\textbf{U}} I \overbrace{\textbf{U}} \overbrace{\textbf{U}} I \atop\overbrace{\textbf{U}} I \atop\overbrace{\textbf{U}} $	$\begin{array}{ccc} 2(\text{SS})/\geq 3 \; e, \mu \geq 1 \\ 1 \; e, \mu & \geq 1 \\ 1 \; e, \mu & \geq 1 \\ 0 \; e, \mu & \geq 2b, \end{array}$	b, ≥1 j Yes b, ≥3 j Yes b, ≥1 j Yes ≥1 j, ≥1J –	36.1 139 36.1 139	T _{5/3} mass T mass Y mass B mass	1.6	64 TeV 1.8 TeV 1.85 TeV 2.0 TeV	$\begin{array}{l} \mathcal{B}(T_{5/3} \rightarrow Wt) = 1, \ c(T_{5/3}Wt) = 1 \\ \mathrm{SU}(2) \ \text{singlet}, \ \kappa_T = 0.5 \\ \mathcal{B}(Y \rightarrow Wb) = 1, \ c_R(Wb) = 1 \\ \mathrm{SU}(2) \ \text{doublet}, \ \kappa_B = 0.3 \end{array}$	1807.11883 ATLAS-CONF-2021-040 1812.07343 ATLAS-CONF-2021-018
ĤĤ, Ĥ→hĜ/ZĜ	$\begin{array}{c c} 0 \ e, \mu &\geq 3 \ b & E^{\rm miss} & 36.1 \\ 4 \ e, \mu & 0 \ {\rm jets} & E^{\rm miss}_{\rm miss} & 139 \\ 0 \ e, \mu &\geq 2 \ {\rm large \ jets} & E^{\rm miss}_{\rm T} & 139 \\ \end{array}$	1: Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton t^*	- 1γ - 1 3 e,μ 3 e,μ	2j – 1j – b,1j – – –	139 36.7 36.1 20.3 20.3	q* mass q* mass b* mass (* mass * mass	1	6.7 TeV 5.3 TeV 2.6 TeV 3.0 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	1910.08447 1709.10440 1805.09299 1411.2921 1411.2921
Direct $\tilde{\chi}_1^* \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^*$ Stable \tilde{g} R-hadron Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$ $\tilde{\ell}\ell$, $\tilde{\ell} \rightarrow \ell G$	Disapp. trk1 jet E_T^{miss} 139 $\tilde{\chi}_1^*$ pixel dE/dx E_T^{miss} 139 \tilde{g} pixel dE/dx E_T^{miss} 139 \tilde{g} pixel dE/dx E_T^{miss} 139 \tilde{g} pixel dE/dx E_T^{miss} 139 \tilde{r} pixel dE/dx E_T^{miss} 139 \tilde{r}	0 Type III Seesaw LRSM Majorana ν Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Multi-charged particles Magnetic monopoles	$\begin{array}{c} 2,3,4 e, \mu \\ 2\mu \\ 2,3,4 e, \mu (SS) \\ 3,3,4 e, \mu (SS) \\ 3 e, \mu, \tau \\ - \\ - \\ - \\ - \\ - \\ - \\ - \\ - \\ - \\$	≥2j Yes 2j – arious Yes – – – –	139 36.1 139 139 20.3 36.1 34.4	N ⁰ mass N _R mass H ^{±±} mass H ^{±±} mass multi-charged particle mass monopole mass	910 GeV 350 GeV 400 GeV 1.08 TeV 1.22 Te	3.2 TeV 2.37 TeV	$\begin{split} m(W_R) &= 4.1 \text{TeV}, g_L = g_R \\ DY \text{production} \\ DY \text{production} \\ DY \text{production}, \mathcal{B}(H_l^{zz} \to \ell\tau) = 1 \\ DY \text{production}, g_l = 5e \\ DY \text{production}, g_l = 1g_D, \text{spin } 1/2 \end{split}$	2202.02039 1809.11105 2101.11961 ATLAS-CONF-2022-010 1411.2921 1812.03673 1905.10130
$\begin{array}{c} \tilde{\chi}_{1}^{+} \tilde{\chi}_{1}^{T} / \tilde{\chi}_{1}^{0} , \tilde{\chi}_{1}^{+} \rightarrow \mathcal{Z}\ell \rightarrow \ell\ell\ell \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{1}^{T} / \tilde{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell \ell_{YY} \\ \tilde{g}, \tilde{g}, \tilde{g} \rightarrow q \tilde{\chi}_{1}^{0} , \tilde{\chi}_{1}^{0} \rightarrow q q q \\ \tilde{u}, \tilde{t} \rightarrow \tilde{u} \tilde{\chi}_{1}^{0} , \tilde{\chi}_{1}^{0} \rightarrow t b s \end{array}$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	vs = 8 TeV vs = 8 TeV only a selection or the availation of Small-radius (large-radius) je	bartial data	full data full data in new state by the letter j	s or prien j (J).	10 ⁻¹ omena is shown.	1	10	Mass scale [TeV]	
$\begin{array}{c} tt, \bar{t} \rightarrow b X_1^-, X_1^- \rightarrow b b s \\ \bar{t}_1 \bar{t}_1, \bar{t}_1 \rightarrow b s \\ \bar{t}_1 \bar{t}_1, \bar{t}_1 \rightarrow d t \\ \bar{\chi}_1^\pm / \bar{\chi}_2^0 / \bar{\chi}_1^0, \bar{\chi}_{1,2}^0 \rightarrow t b s, \bar{\chi}_1^+ \rightarrow b b s \end{array}$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	ない領域	を招	家			たがラ	トだ兆候	なし	
nly a selection of the available ma nenomena is shown. Many of the	ass limits on new states or 10^{-1} limits are based on	シグナル	モテ	ール	に	よら	ない掛	探索 が必	要	20

*Only a phénomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

ATLAS Preliminary

シグナルモデルを仮定しない新粒子探索



Classification Without Labels (CWoLa)

<u>JHEP 10 (2017) 174</u>



- ラベルがノイジーでも分類器はsignal/backgroundを分けるように学習される
 - ただし、統計的なふらつきの影響は受ける
- ATLAS実験で、Di-jet バンプサーチにCWoLaを適用

Dijet resonance search using CWoLa: Di-jet event

ATLAS-PHOTO-2019-017



Dijet resonance search using CWoLa: ターゲットモデル Phys. Rev. Lett. 125, 131801 (2020)

シグナルモデル

$$m_A \sim \mathcal{O}(\text{TeV})$$

 $m_B, m_C \sim \mathcal{O}(100 \text{ GeV})$

Dijet resonance search using CWoLa: アルゴリズム



- Di-jet mass分布のバンプを探す(m_{JJ} ~ *m_A*)
- S/B 改善のためjet massでカットをかける
- 最適なカットはシグナルモデルに依存する
 - $m_J \sim m_B, m_C$
- CWoLaで**Data-driven**にカットを決める



Dijet resonance search using CWoLa: アルゴリズム



- m_{JJ}を使って
 - Signal region (y=0)
 - Sideband region (y=1)

を定義

Dijet resonance search using CWoLa: アルゴリズム



Dijet resonance search using CWoLa: アルゴリズム



Dijet resonance search using CWoLa: アルゴリズム





- 入力変数(m_{J1}, m_{J2})に対するNNの出力
- ・シグナルをインジェクトした領域をエンハンスするNN出力が得られている

Dijet resonance search using CWoLa: 結果



- 6つの Signal region (SR)
- ・ シグナルがSRに少ない(or いない) ために、カットもなめらか

は、先行研究よりも良い結果 モデルへの仮定が少ないことの恩恵 31

LHC Olympics 2020: 概要

- ・ シグナルモデルによらない物理探索の研究を推進するために開催
 - 最終的に計18の提出
 - ベンチマークデータセットはZenodoで公開されており、

先行研究との比較が可能

- 問題設定はATLASの弱教師学習を用いたDijet resonance searchとほぼ同じ
 - 重い未知粒子(Z')が軽い未知粒子(X,Y)を通して2つの大半径ジェットに崩壊
- ・ シグナルの質量が不明なブラックボックスサンプルから

 (1) シグナルイベント数 + uncertainty
 (2) シグナルの質量(Z', X, Y)
 等を推定



2101.08320

LHC Olympics 2020: データセット

2101.08320

Dataset	Signal	Background
R&D	$Z' \to XY \to qqqq$	QCD di-jets
(ラベルあり)	(<i>Z</i> ′, <i>X</i> , <i>Y</i>) = (3500 GeV, 500 GeV, 100 GeV)	
Black Box 1	$Z' \to XY \to qqqq$	QCD di-jets
	(<i>Z</i> ′, <i>X</i> , <i>Y</i>) = (3823 GeV, 732 GeV, 378 GeV)	(simulatorのconfigを変更)
Black Box 2	No signal	QCD di-jets
	(誤検知のチェック)	(simulatorそのものを変更)
Black Box 3	$G \rightarrow gg$ and $G \rightarrow Rg \rightarrow ggg$	QCD di-jets
	(<i>G</i> , <i>R</i>) = (4.2 TeV, 2.2 TeV)	(simulatorのconfigを変更)

- BB2でシグナルを誤検知したチームもあった。今後の課題
- BB3は正解チームなし。トポロジーの変化に対応できる汎用的な手法はまだ難しい

サマリー

- 生成モデル・異常検知の応用例を紹介した
 - GANを用いたカロリメータシャワーシミュレーション
 - 弱教師あり学習(CWoLa)を使ったDijet resonance search

- この分野は発展途上
 - 実験で実際に使われている例はまだ少ない
 - コンテストが開催されたり、ベンチマークデータセットが整備されるなど、 R&Dがしやすい環境が整ってきている

・ 今後に期待

Backup

CaloGAN: 生成画像

Phys. Rev. D 97, 014021 (2018)



ATLASでの初期の研究: VAE

Variational autoencoder (VAE)



<u>VAE for 生成モデル</u>

 $\mathcal{L} = \|x - g(f(x))\|^2 + D_{KL}(q(z|x), p(z))$

- ||X X'||² が小さくなるように
- Zが正規分布に従うように

エンコーダ・デコーダを学習する

学習したデコーダを生成モデルとして使用する



<u>VAE for 生成モデル</u>

- ||X X'||² が小さくなるように
- Zが正規分布に従うように

エンコーダ・デコーダを学習する

学習したデコーダを生成モデルとして使用する

<u>ATLASでの工夫</u>

- ・ 全エネルギー
- 各レイヤーでのエネルギーの割合

もロス関数に加えることで、より詳細にコントロール

ATLASでのVAEの発展

改善が続けられている

Normalizing Flow (IAF)の導入 •

ロス関数の変更 •

ATL-PLOTS-SIM-2019-007

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ロス関数の変更

各セルのエネルギー(Ecell)の代わりに

エネルギー比(E_{total}, E_{laver}/E_{total}, E_{cell}/E_{laver})

を予測







前ページ

Improved

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GAN for Fast Simulation at ATLAS: 学習時の工夫

Comput Softw Big Sci 6 (2022) 7

- 学習サンプルの逐次投入
 - 全エネルギー領域(256 MeV ~ 4 TeV)を一気に学習するのではなく、
 - 1つのエネルギーポイント(32 GeV)を中心に徐々に学習サンプルを拡張
 - 全サンプル追加後は全てのサンプルを使って学習
- Best エポックの選び方
 - 最後のエポックが最適とは限らない
 - 総エネルギー量の分布がGANとGeant4で どの程度あっているかをχ²で定義し、 それを基にベストなエポックを選択
- 1つのGANモデルの学習時間は8時間ほど(V100使用)



Dijet resonance search using CWoLa: ターゲットモデル Phys. Rev. Lett. 125, 131801 (2020)

シグナルモデル



 $m_A \sim \mathcal{O}(\text{TeV})$ $m_B, m_C \sim \mathcal{O}(100 \text{ GeV})$

LHC Olympics 2020: VAEを使った異常検知



 $\mathcal{L} = \|x - g(f(x))\|^2 + D_{KL}(q(z|x), p(z))$

- バックグラウンドデータ分布をVAEで学習する
- シグナルが入力されると、
 - 再構成エラー(||X X'||²)が大きい
 - Zの値(||*Z*||²)が大きい

等のアノマリーとして判定できる。



LHC Olympics 2020: VAEを使った異常検知

2101.08320



- R&DデータでVAEの学習をした例
- 学習データにバイアスがあるためうまくいかなかった

LHC Olympics 2020: VAEを使った異常検知

<u>2101.08320</u>

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BBデータを直接使った例。S/Bが小さいためシグナルの影響が無視できた



- S/Bが小さいとCWoLaは性能が悪くなる。VAEの性能はS/Bに依存しない
 - VAE は **BG分布** をモデリングする。
 - CWoLaは Signal分布とBG分布の差 をモデリングする。

LHC Olympics 2020: 密度推定を使った異常検知

2101.08320



手法

- 1. NNでSRの分布 $p_{data}(x | m \in SR)$ フィット
- 2. NNでSBの分布 $p_{data}(x | m \in SB)$ フィット
 - $p_{\text{data}}(x|m \in \text{SB}) = p_{\text{bg}}(x|m \in \text{SB})$
- 3. SBで推定した分布をSRに内挿
- 4. $p_{data}(x|m)/p_{bg}(x|m)$ を分類器として使う



LHC Olympics 2020: 密度推定を使った異常検知

2101.08320





- Normalizing Flowで密度推定
- CWoLaより少し結果が悪い
 - CWoLaは比(p_S/p_B)を直接モデリングしているが、
 - 密度推定では2つの分布を独立にモデリング
- CWoLaと異なり、massへの相関にロバスト 46

LHC Olympics 2020

(i): blind datasetでの結果 (ii): unblind後の結果 (iii): R&D のみ

Section	Short Name	Method Type	Results Type		
3.1	VRNN	Unsupervised	(i) (BB2,3) and (ii) (BB1)		
3.2	ANODE	Unsupervised	(iii)		
3.3	$\operatorname{BuHuLaSpa}$	Unsupervised	(i) (BB2,3) and (ii) (BB1)		
3.4	GAN-AE	Unsupervised	(i) (BB2-3) and (ii) (BB1)		
3.5	GIS	Unsupervised	(i) (BB1)		
3.6	LDA	Unsupervised	(i) (BB1-3)		
3.7	\mathbf{PGA}	Unsupervised	(ii) (BB1-2)		
3.8	Reg. Likelihoods	Unsupervised	(iii)		
3.9	UCluster	Unsupervised	(i) (BB2-3)		
4.1	CWoLa	Weakly Supervised	(ii) (BB1-2)		
4.2	CWoLa AE Compare	Weakly/Unsupervised	(iii)		
4.3	Tag N' Train	Weakly Supervised	(i) (BB1-3)		
4.4	SALAD	Weakly Supervised	(iii)		
4.5	SA-CWoLa	Weakly Supervised	(iii)		
5.1	Deep Ensemble	Semisupervised	(i) (BB1)		
5.2	Factorized Topics	Semisupervised	(iii)		
5.3	QUAK	Semisupervised	(i) (BB2,3) and (ii) (BB1)		
5.4	LSTM	Semisupervised	(i) (BB1-3)		



WGAN-GP

Original GAN : $L(G, D) = \mathbb{E}_{\tilde{x} \sim p_{\text{gen}}} \left[\log \left(1 - D(\tilde{x}) \right) \right] + \mathbb{E}_{x \sim p_{\text{Geant4}}} \left[\log D(x) \right]$ WGAN-GP : $L(G, D) = \mathbb{E}_{\tilde{x} \sim p_{\text{gen}}} \left[D(\tilde{x}) \right] - \mathbb{E}_{x \sim p_{\text{Geant4}}} \left[D(x) \right] + \lambda \mathbb{E}_{x \sim p_{\hat{x}}} \left[\left(\| \Delta_{\hat{x}} D(\hat{x}) \|_{2} - 1 \right)^{2} \right]$

Original GAN ではJSD(Jensen-Shannon divergence)を最小化する WGANではWasserstein distanceを最小化する