



東京大学
素粒子物理国際研究センター
International Center for Elementary Particle Physics
The University of Tokyo



Beyond AI

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)



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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

2022 / 7 / 8

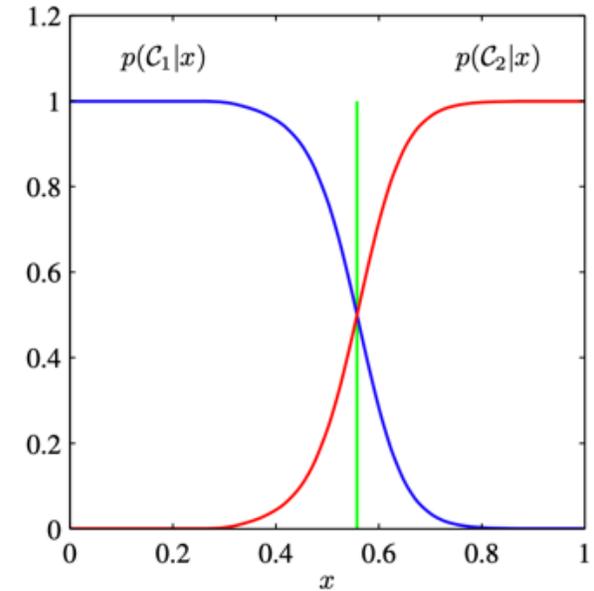
ML@HEP

齊藤 真彦 (ICEPP, Beyond AI)

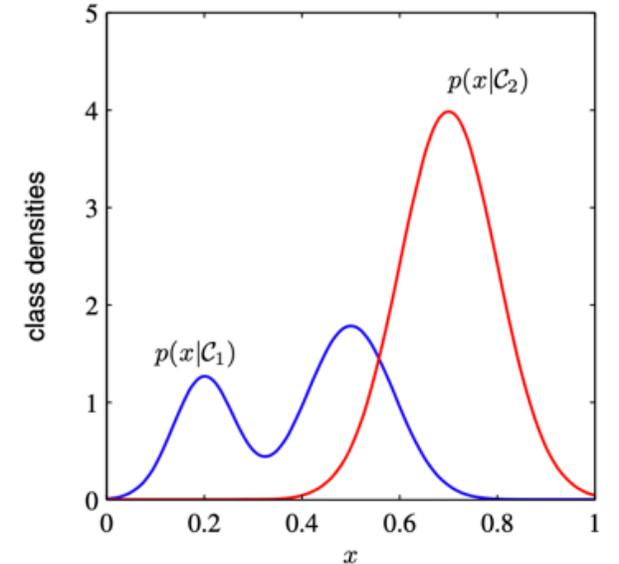
生成モデル (Generative model) と異常検知 (anomaly detection)

- 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**

クラス確率($p(C|x)$)をモデリング



確率($p(x)$)をモデリング

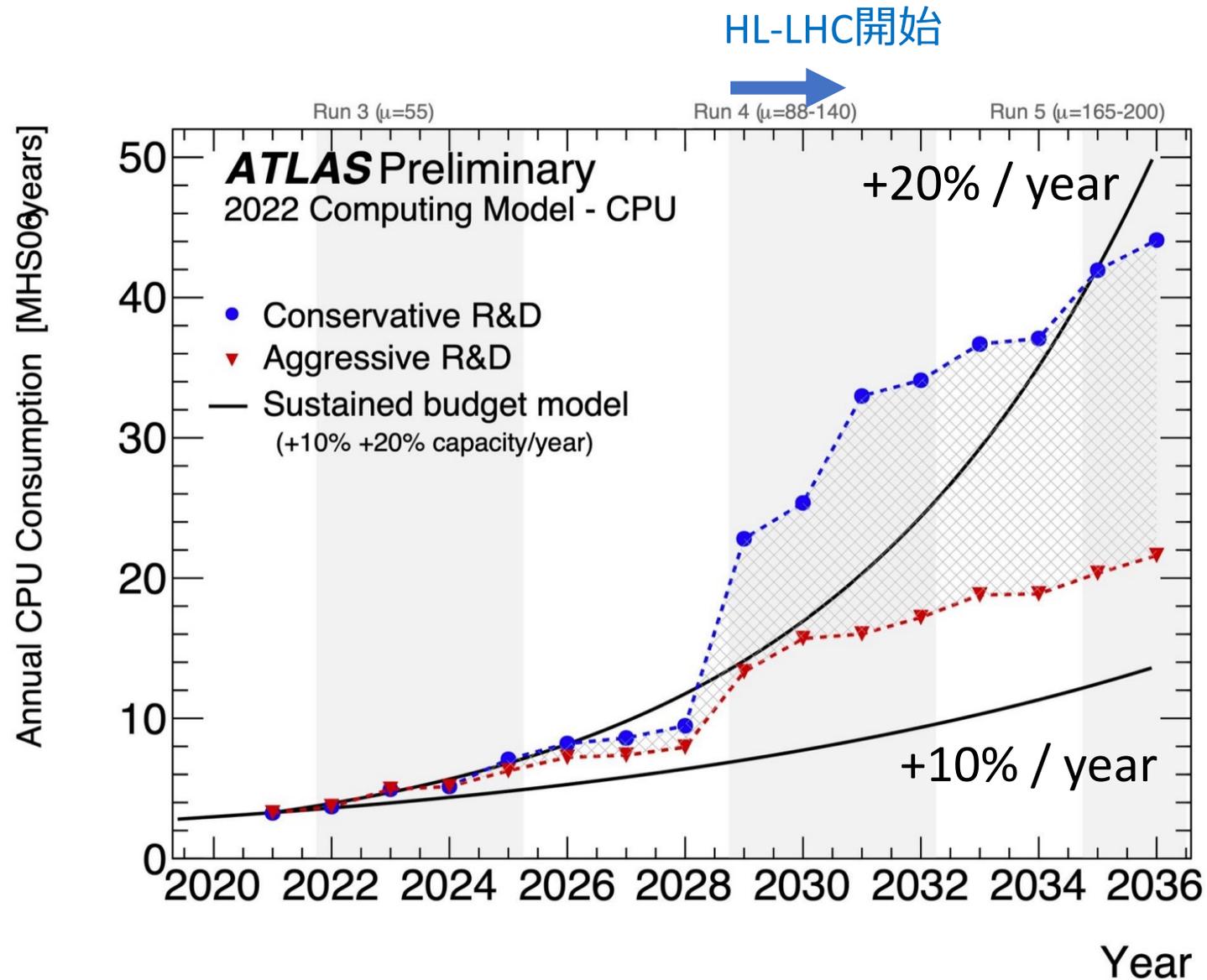


生成モデル

Generative model

for calorimeter shower simulation

HL-LHC (2029-) における計算機資源 予測

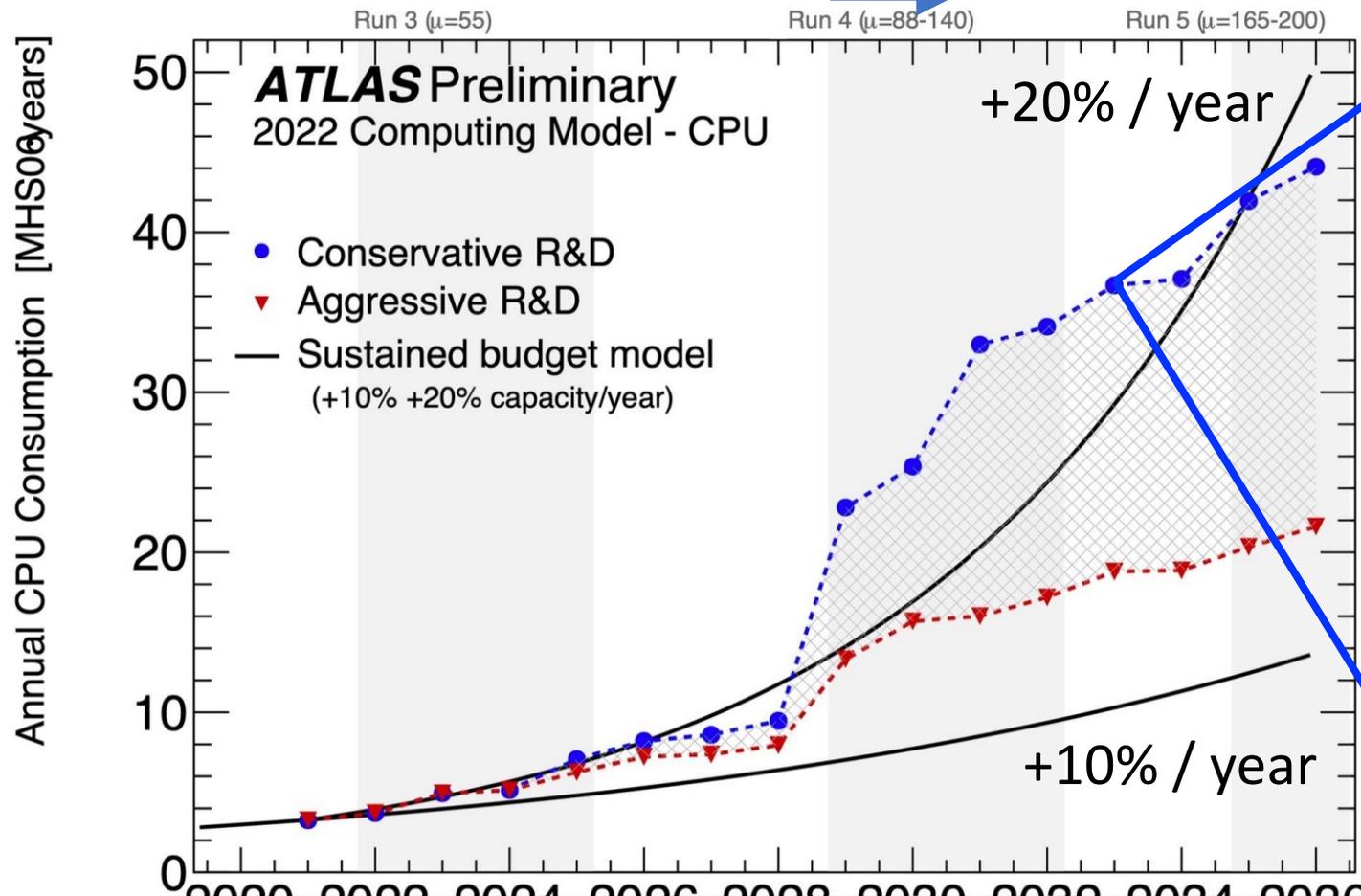


現状のFTE維持を仮定

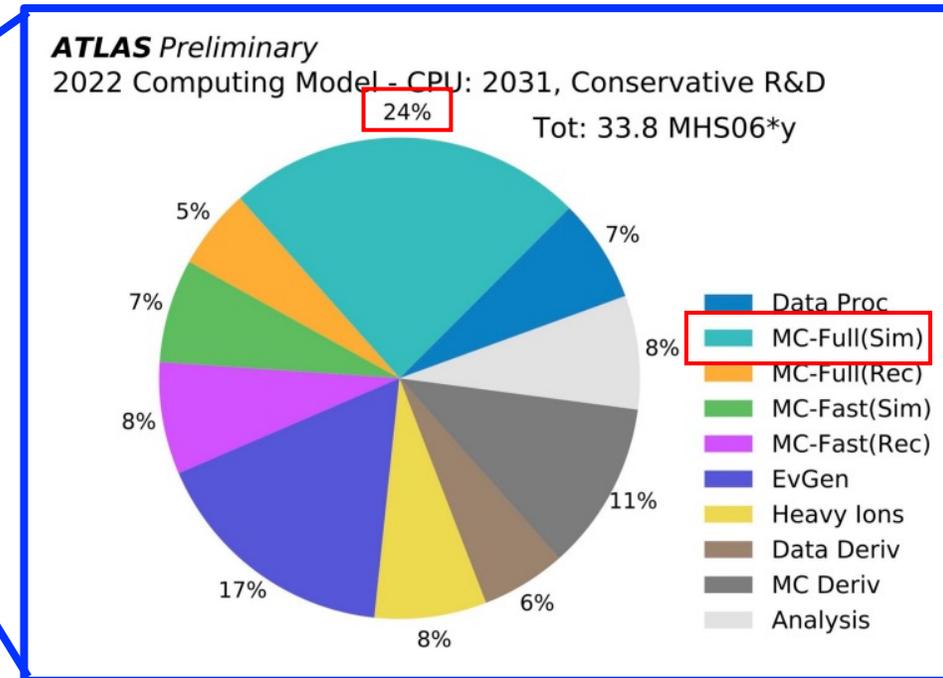
FTEの増加を仮定

HL-LHC (2029-) における計算機資源 予測

HL-LHC開始



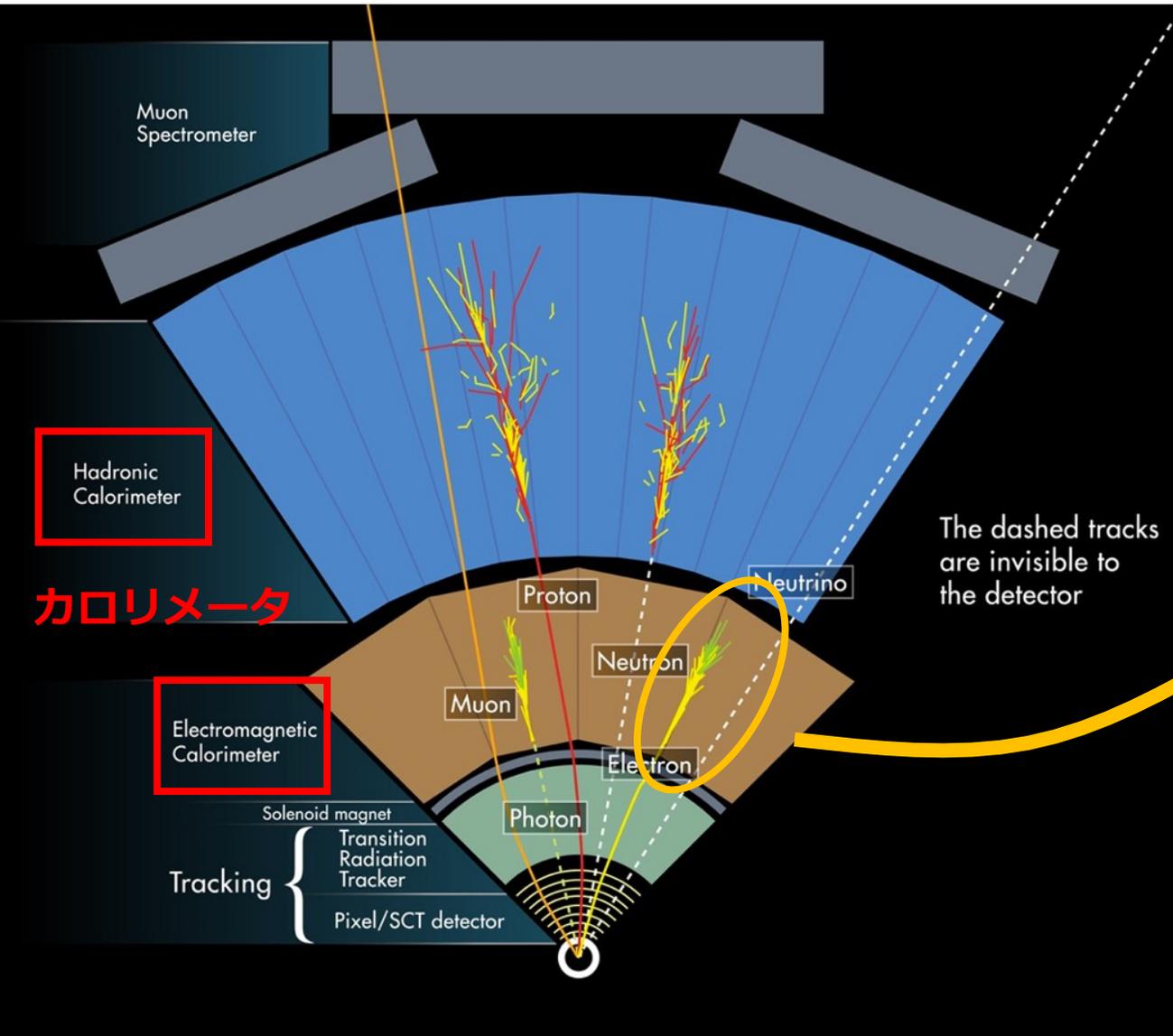
内訳



Geant4シミュレーションの割合が大きい

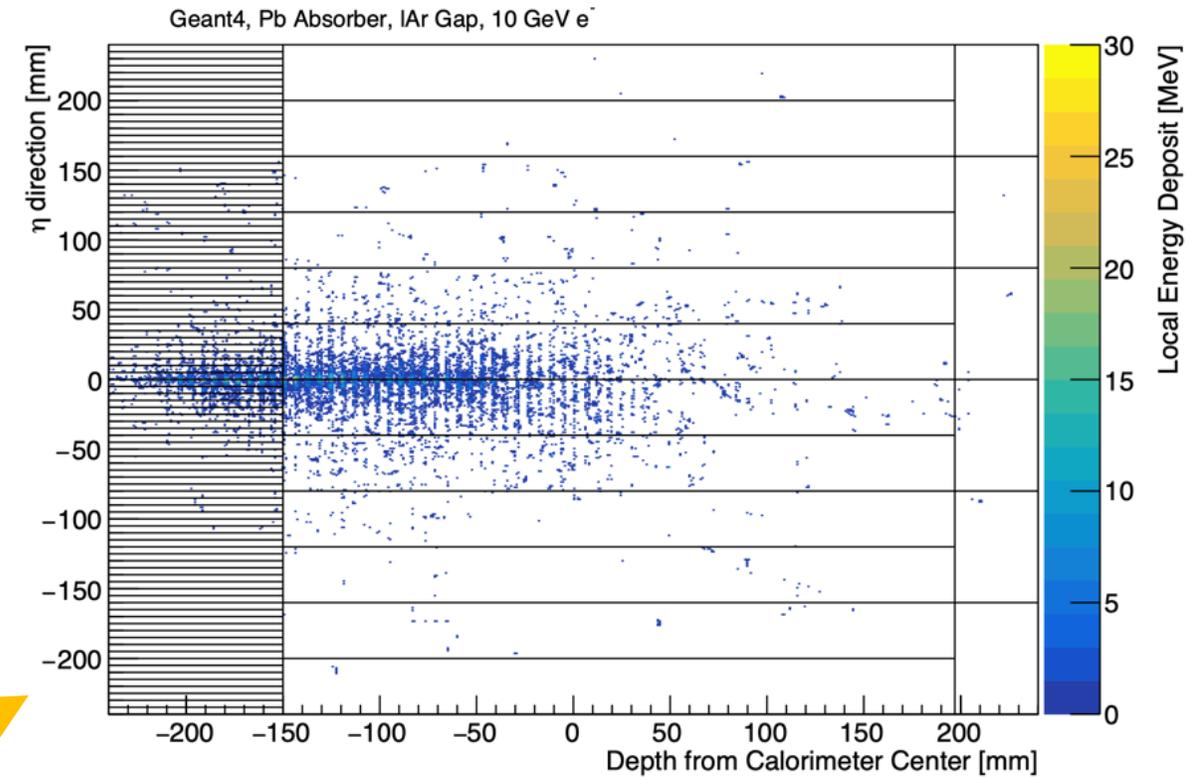
- Geant4を使わない高速なシミュレーション(Fast Simulation)が必要
- 深層学習を使った**生成モデル**で高精度+高速化を実現

検出器

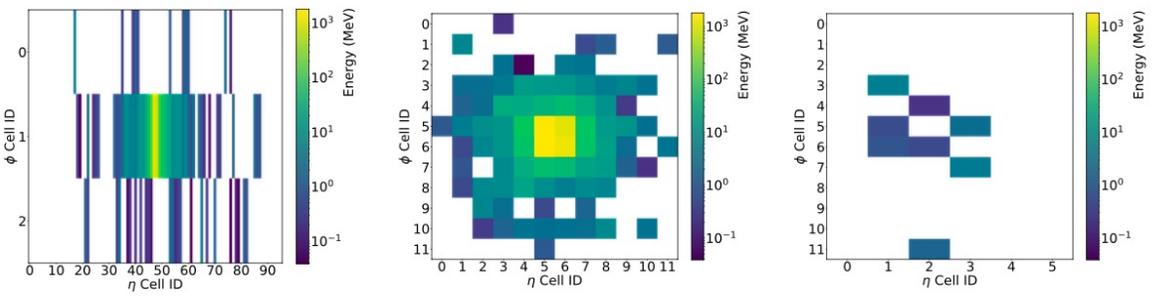
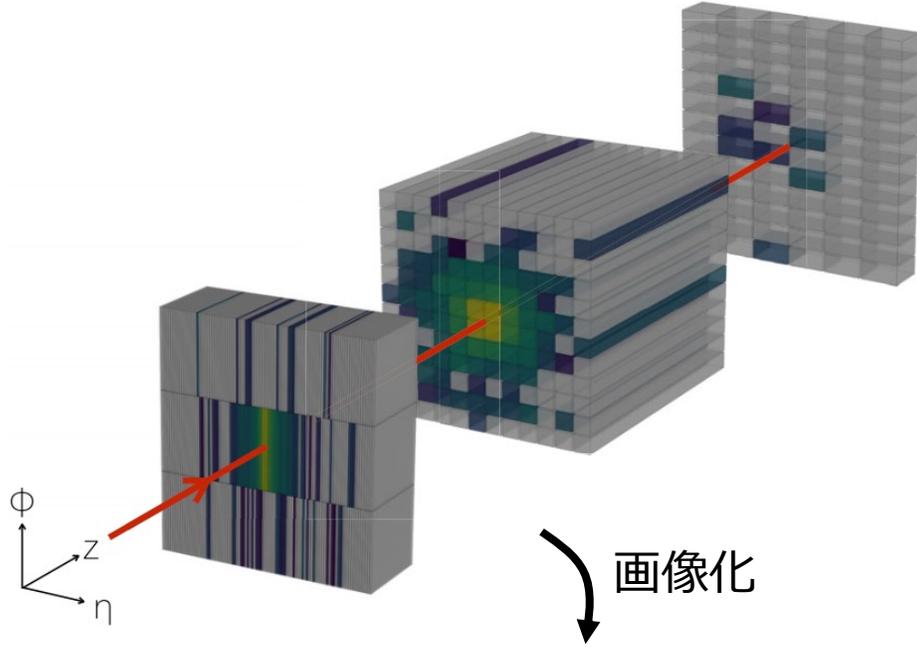


カロリメータ

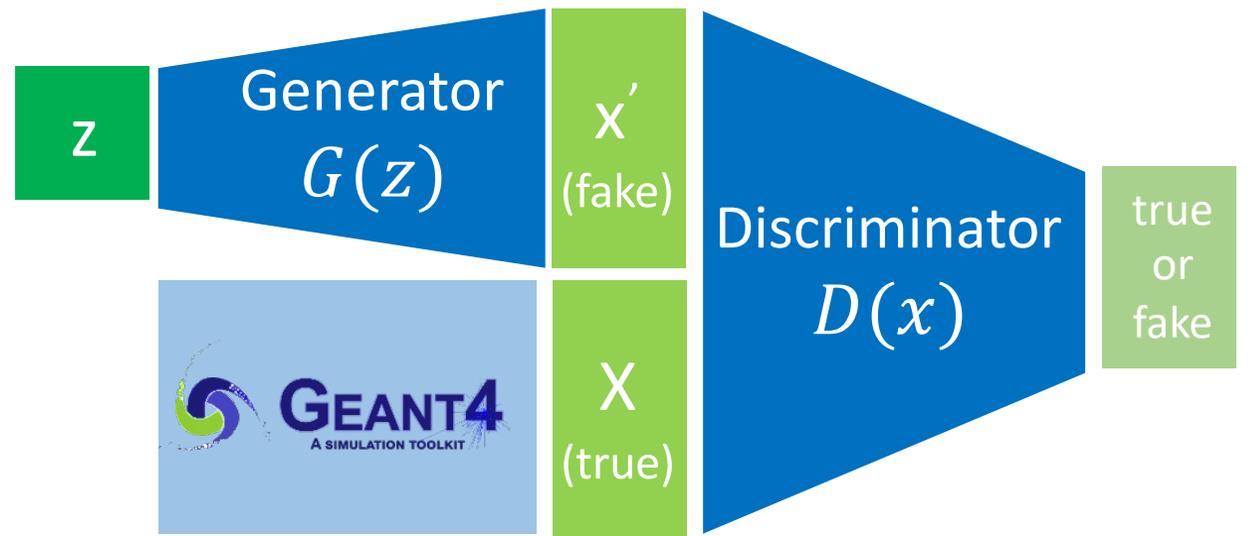
粒子のシャワー



- カロリメータで粒子を止めてエネルギーを測定
 - 入射粒子が多数の粒子に崩壊：シャワー
- カロリメータ中のエネルギー分布をシミュレート
 - Geant4 では一つ一つの粒子を追うため高コスト



Generative Adversarial Network (GAN)

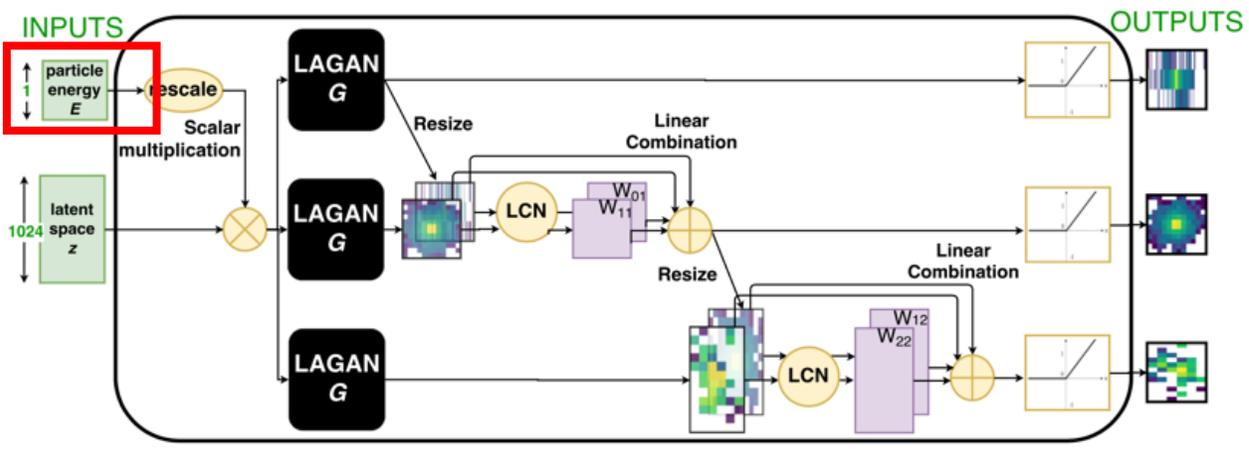


$$\mathcal{L}_{\text{adv}} = \mathbb{E}_{z \sim p(z)} [\log (1 - D(G(z)))] + \mathbb{E}_{x \sim p_{\text{Geant4}}} [\log D(x)]$$

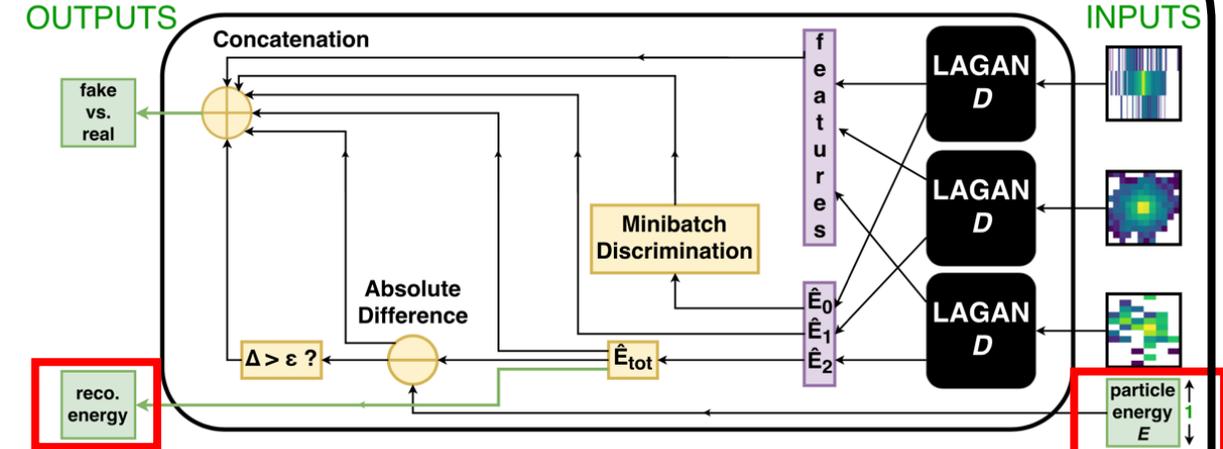
- カロリメータセルごとのエネルギー量 → 画像
- GANで3層の電磁カロリメータ(画像)を生成

モデルアーキテクチャ

Generator



Discriminator



深層畳み込みGANをベースに改良したもの (複雑...)

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^\pm)に**別々のGAN**をトレーニング
- 粒子の**エネルギー**で条件つけたGAN ($p(x|E)$)
- **総エネルギー量**についての制約をロスに追加

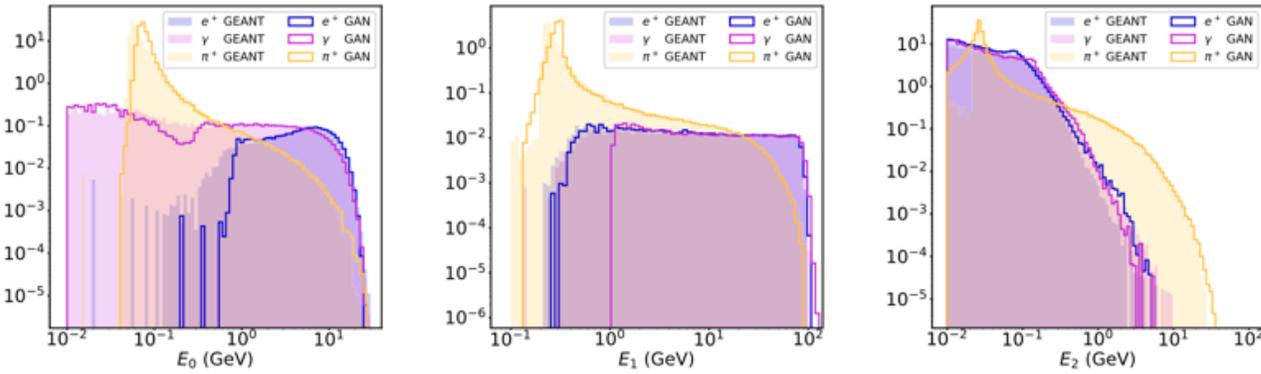
$$\mathcal{L}_{\text{generator}} = \lambda_E \mathcal{L}_E - \mathcal{L}_{\text{adv}}$$

$$\mathcal{L}_{\text{discriminator}} = \lambda_E \mathcal{L}_E + \mathcal{L}_{\text{adv}}$$

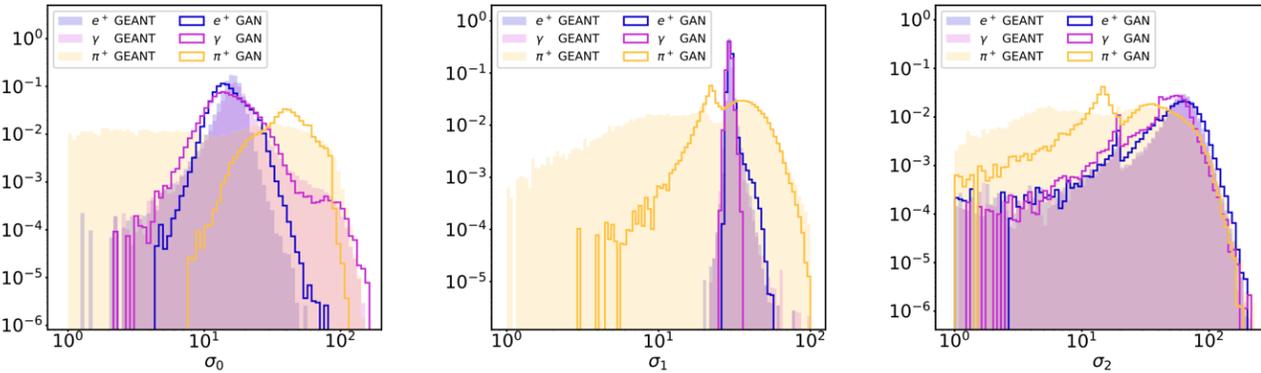
エネルギーへの制約 通常のGANのloss



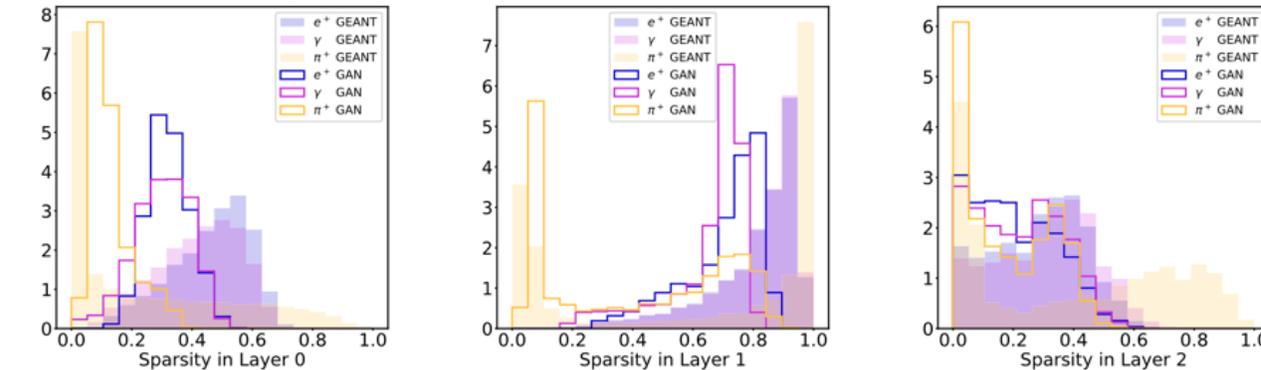
レイヤー毎のエネルギー



レイヤーごとのシャワーの横方向の幅



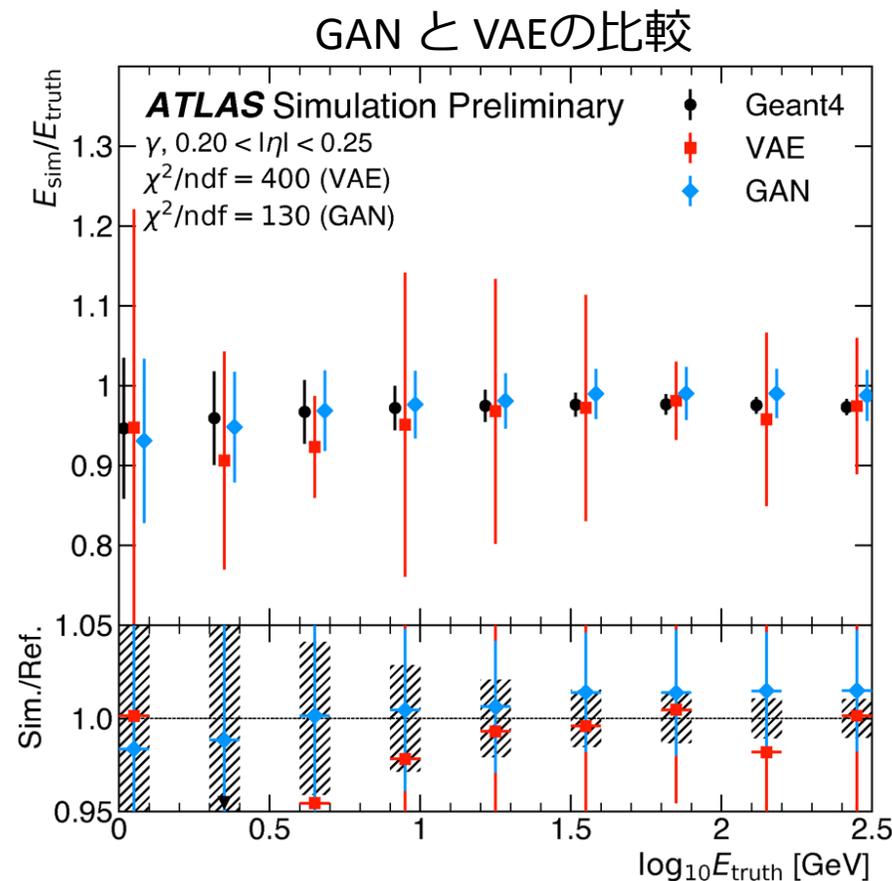
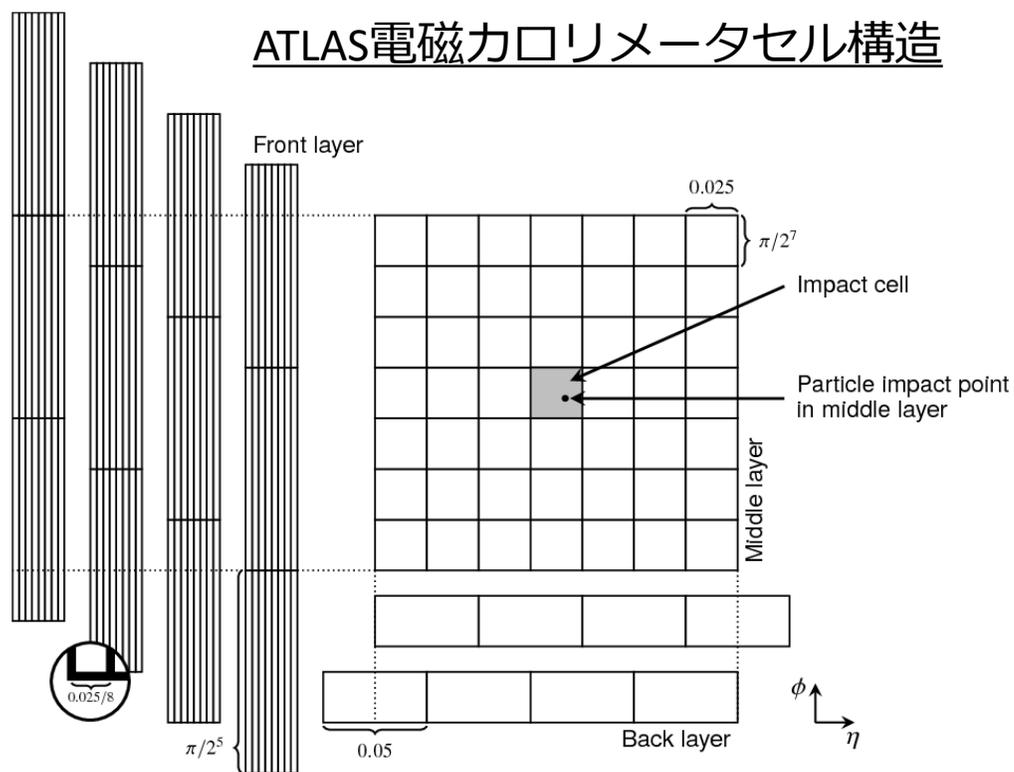
レイヤーごとのsparsity



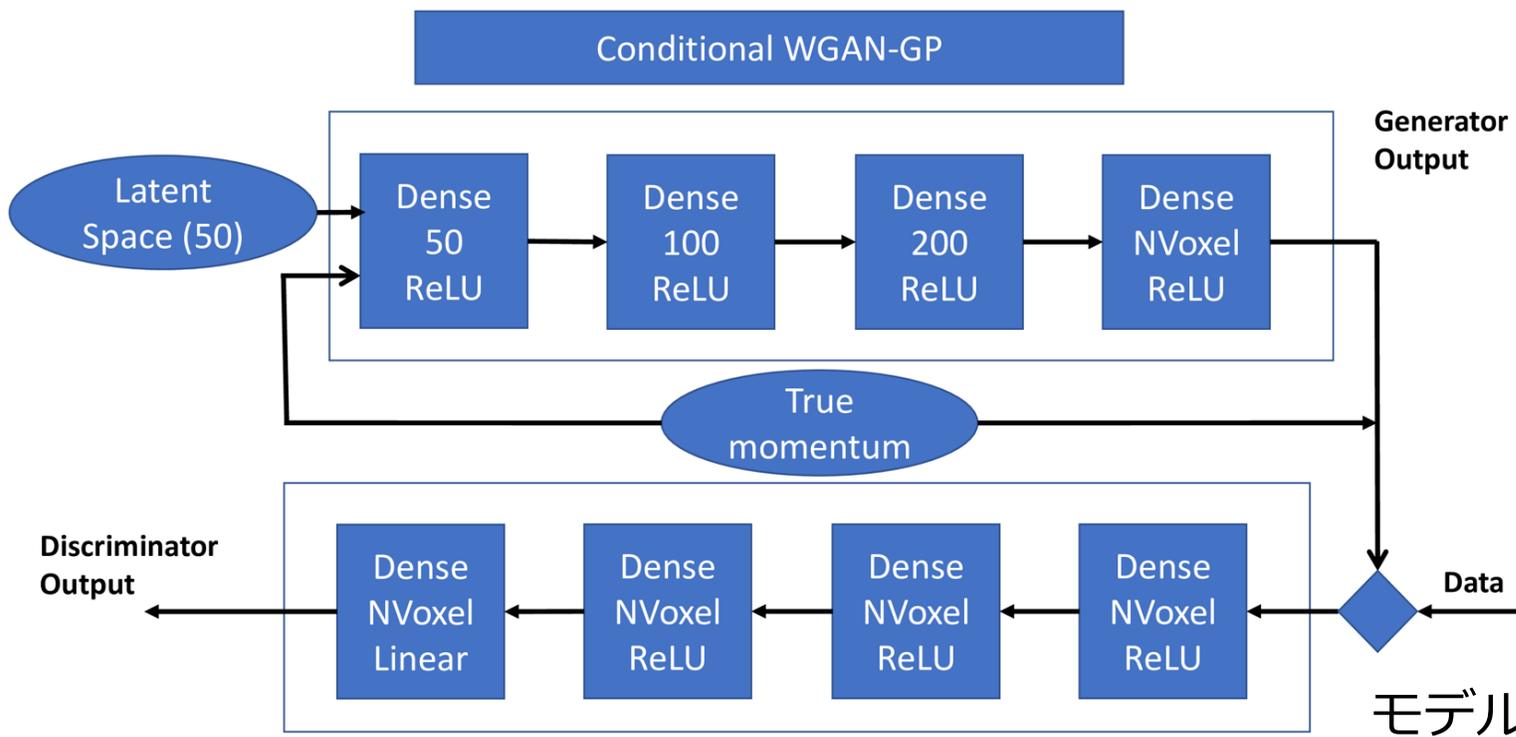
Simulator	Hardware	Batch size	ms/shower
GEANT4	CPU	N/A	1772
		1	13.1
		10	5.11
		128	2.19
		1024	2.03
CALOGAN	GPU	1	14.5
		4	3.68
		128	0.021
		512	0.014
		1024	0.012

- 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

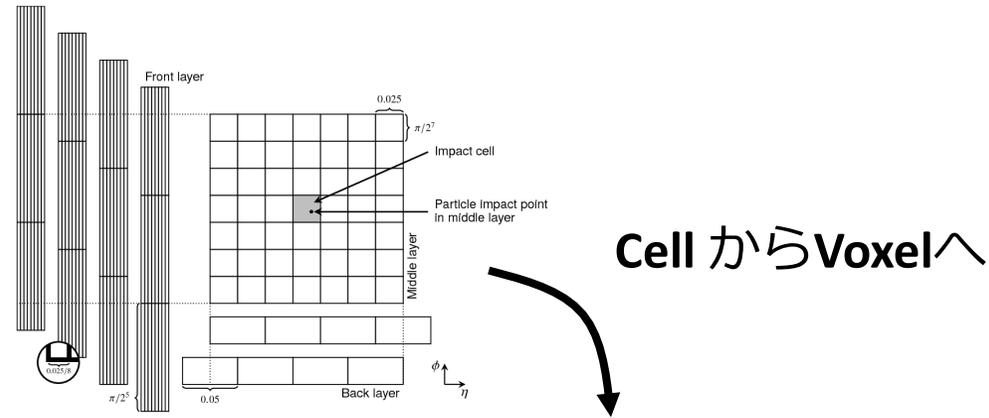
- ATLAS検出器の電磁カロリメータのジオメトリを想定した生成モデルの研究
- 画像ではなく、266次元(セルの個数)の1次元のベクトルを生成
- **限られた範囲**の入射粒子だけに着目 ($|\eta|: 0.20 \sim 0.25$)
- **GANとVAE**の両方を試して比較



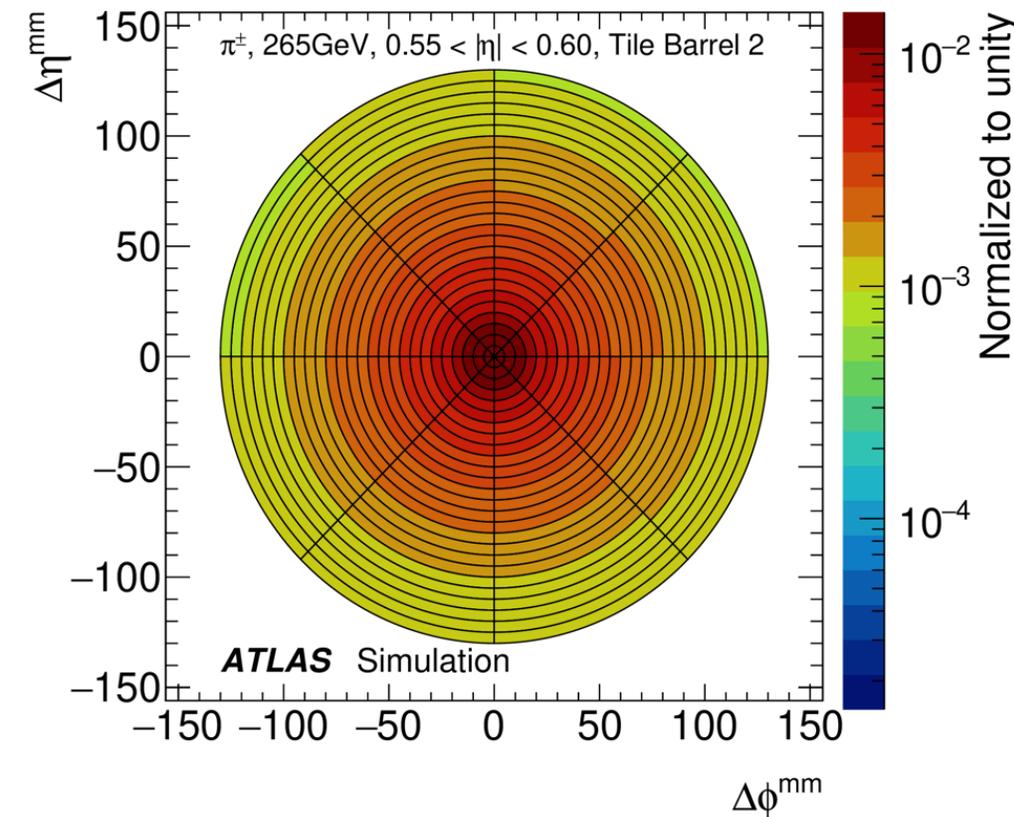
- GANの方が性能が良かった
- 現在のATLASのFast simulationではGANが採用



- **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 ($-5 < \eta < 5$)
- 粒子ごと(e, γ, π)、 η sliceごと(100 slice) にGANを作成 (計**300 GANs**)

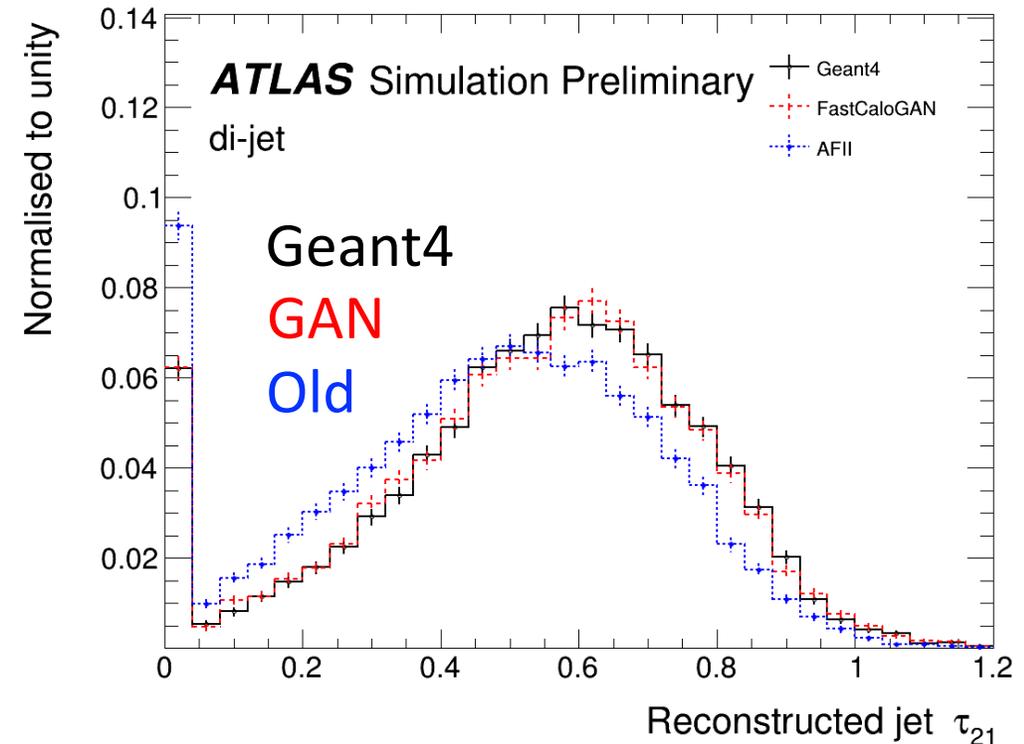
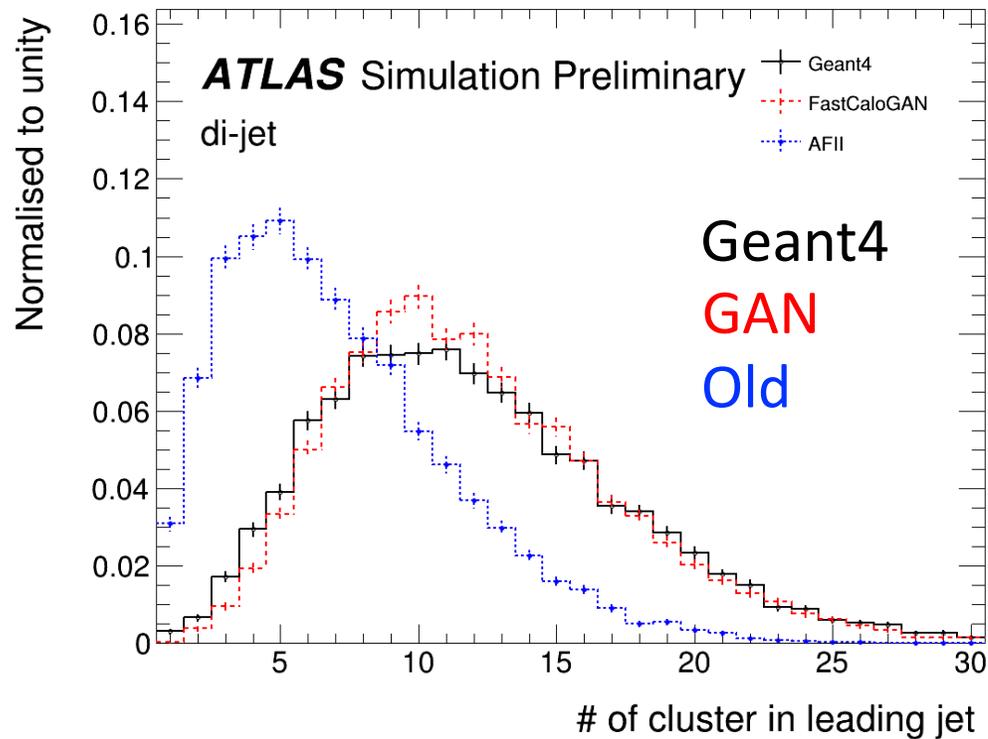


- セルベースな手法では粒子の入射位置に影響を受ける
- 入射粒子を中心とした座標系で考える
 - 生成粒子周りで円筒状のグリッド (Voxel)
 - Voxelはcellよりも細かい。予測後に各cellにエネルギーを割り当てる
- 粒子タイプ・ η ごとにグリッドの切り方を最適化



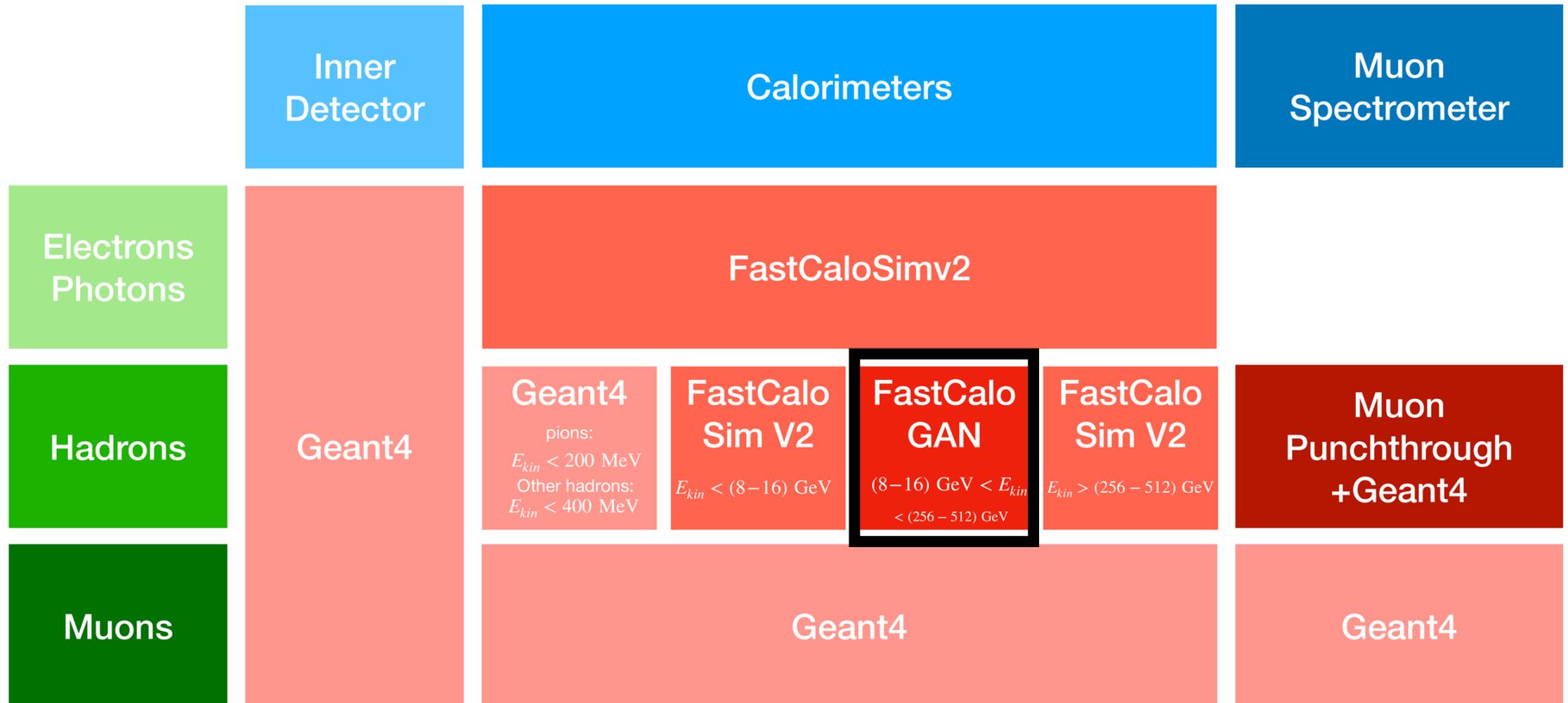
Voxelの切り方の一例

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, ... 100, 130, 160, 200, 250 ... 400, 1000, 2000	10
TileBar1	10, 20, 30, ... 100, 130, 160, 200, 250, ... 400, 600, 1000, 2000	10
TileBar2	0, 50, 100, ... 300, 400, 600, 1000, 2000	1



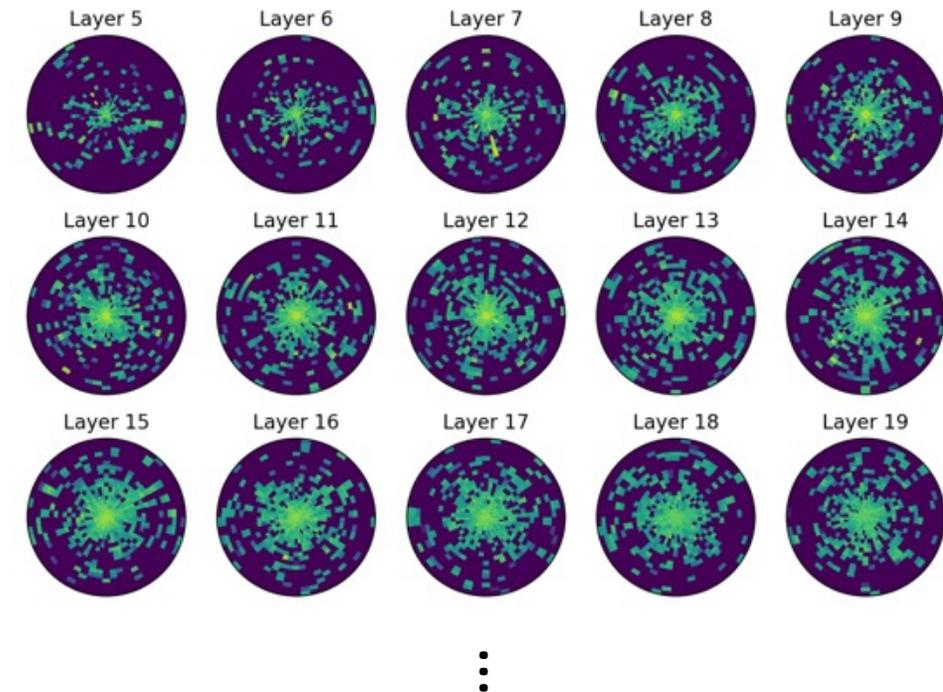
- Jet substructure variableで大きく改善
- 速度も高速
 - Geant4: 6 秒 (65 GeV pion)
162 秒 (2 TeV pion)
 - GAN : **0.07 秒** (pion, エネルギー依存性なし)

- 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**



- [ML4Jets 2022](#)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
 - サンプルング時間、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 SUSY Searches* - 95% CL Lower Limits

March 2022

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	\tilde{q} [1x, 8x Degen.] 1.0 \tilde{q} [8x Degen.] 0.9	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV	2010.14293 2102.10874	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e, μ 2-6 jets	\tilde{g} 2.3 Forbidden 1.15-1.95	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{g}) = 1000$ GeV	2010.14293 2010.14293	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 e, μ 2-6 jets	\tilde{g} 2.2	$m(\tilde{\chi}_1^0) < 600$ GeV	2101.01629	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$ 2 jets	\tilde{g} 2.2	$m(\tilde{\chi}_1^0) < 700$ GeV	CERN-EP-2022-014	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 e, μ 7-11 jets	\tilde{g} 1.97	$m(\tilde{\chi}_1^0) < 600$ GeV	2008.06032	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	SS e, μ 6 jets	\tilde{g} 1.15	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV	1909.08457	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ 3 b	\tilde{g} 2.25	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2018-041	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	SS e, μ 6 jets	\tilde{g} 1.25	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV	1909.08457	
	3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e, μ 2 b	\tilde{b}_1 1.255 \tilde{b}_1 0.68	$m(\tilde{\chi}_1^0) < 400$ GeV 10 GeV $< \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV	2101.12527 2101.12527
		$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b h\tilde{\chi}_1^0$	0 e, μ 2 b	\tilde{b}_1 0.23-1.35 \tilde{b}_1 0.13-0.85	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ 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	\tilde{t}_1 1.25	$m(\tilde{\chi}_1^0) = 1$ 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	\tilde{t}_1 0.65	$m(\tilde{\chi}_1^0) = 500$ GeV	2012.03799	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$		1-2 τ 2 jets/1 b	\tilde{t}_1 1.4	$m(\tilde{\tau}_1) = 800$ GeV	2108.07665	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$		0 e, μ 2 c	\tilde{t}_1 0.85	$m(\tilde{\chi}_1^0) = 0$ GeV	1805.01649	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$		0 e, μ mono-jet	\tilde{t}_1 0.55	$m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV	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, μ 1-4 b	\tilde{t}_1 0.067-1.18	$m(\tilde{\chi}_2^0) = 500$ GeV	2006.05880	
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$		3 e, μ 1 b	\tilde{t}_2 0.86	$m(\tilde{\chi}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40$ GeV	2006.05880	
EW direct		$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets $ee, \mu\mu$	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.96 $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.205	$m(\tilde{\chi}_1^0) = 0$, 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	$\tilde{\chi}_1^{\pm}$ 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	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 1.06	$m(\tilde{\chi}_1^0) = 70$ GeV, wino-bino	2004.10894, 2108.07586	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ	$\tilde{\chi}_1^{\pm}$ 1.0	$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^{\pm}) + m(\tilde{\chi}_1^0))$	1908.08215	
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 τ	$\tilde{\tau}$ [F _L , F _{R,L}] 0.16-0.3, 0.12-0.39	$m(\tilde{\chi}_1^0) = 0$	1911.06660	
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ 0 jets	$\tilde{\ell}$ 0.7	$m(\tilde{\chi}_1^0) = 0$	1908.08215	
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	$ee, \mu\mu$ ≥ 1 jet	$\tilde{\ell}$ 0.256	$m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10$ GeV	1911.12606	
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ ≥ 3 b	\tilde{H} 0.13-0.23	$BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$	1806.04030	
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	4 e, μ 0 jets	\tilde{H} 0.55	$BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$	2103.11684	
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ ≥ 2 large jets	\tilde{H} 0.45-0.93	$BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$	2108.07586	
Long-lived particles	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk 1 jet	$\tilde{\chi}_1^{\pm}$ 0.66 $\tilde{\chi}_1^{\pm}$ 0.21	Pure Wino Pure higgsino	2201.02472 2201.02472	
	Stable \tilde{g} R-hadron	pixel dE/dx	\tilde{g} 2.05		CERN-EP-2022-029	
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq\tilde{\chi}_1^0$	pixel dE/dx	\tilde{g} [$\tau(\tilde{g}) = 10$ ns]	$m(\tilde{\chi}_1^0) = 100$ GeV	CERN-EP-2022-029	
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	Displ. lep	$\tilde{\ell}$ 0.7	$\tau(\tilde{\ell}) = 0.1$ ns	2011.07812	
RPV	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm} \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 e, μ	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_1^0$ [BR(Z τ)=1, BR(Z e)=1] 0.625, 1.05	Pure Wino	2011.10543	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0 \rightarrow WWZ\ell\ell\ell\nu\nu$	4 e, μ 0 jets	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ [$A_{33} \neq 0, A_{124} \neq 0$] 0.95, 1.55	$m(\tilde{\chi}_1^0) = 200$ GeV	2103.11684	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{\chi}_1^0$	4-5 large jets	\tilde{g} [$m(\tilde{\chi}_1^0) = 200$ GeV, 1100 GeV] 1.3, 1.9	Large \mathcal{A}_{112}	1804.03568	
	$\tilde{u}, \tilde{t} \rightarrow b\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple	\tilde{u} [$\mathcal{A}_{335} = 2e-4, 1e-2$] 0.55, 1.05	$m(\tilde{\chi}_1^0) = 200$ GeV, bino-like	ATLAS-CONF-2018-003	
	$\tilde{u}, \tilde{t} \rightarrow b\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow bbs$	$\geq 4b$	\tilde{u} 0.95	$m(\tilde{\chi}_1^0) = 500$ GeV	2010.01015	
	$\tilde{u}\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 b	\tilde{u} [qq, bs] 0.42, 0.61		1710.07171	
	$\tilde{u}\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 e, μ 2 b	\tilde{u} 0.4-1.45	$BR(\tilde{u}_1 \rightarrow b\ell/h\nu) > 20\%$	1710.05544	
	$\tilde{u}\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	1 μ DV	\tilde{u} 1.0, 1.6	$BR(\tilde{u}_1 \rightarrow q\mu) = 100\%$, $\cos\theta = 1$	2003.11956	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs, \tilde{\chi}_1^0 \rightarrow bbs$	1-2 e, μ ≥ 6 jets	$\tilde{\chi}_1^0$ 0.2-0.32	Pure higgsino	2106.09609	

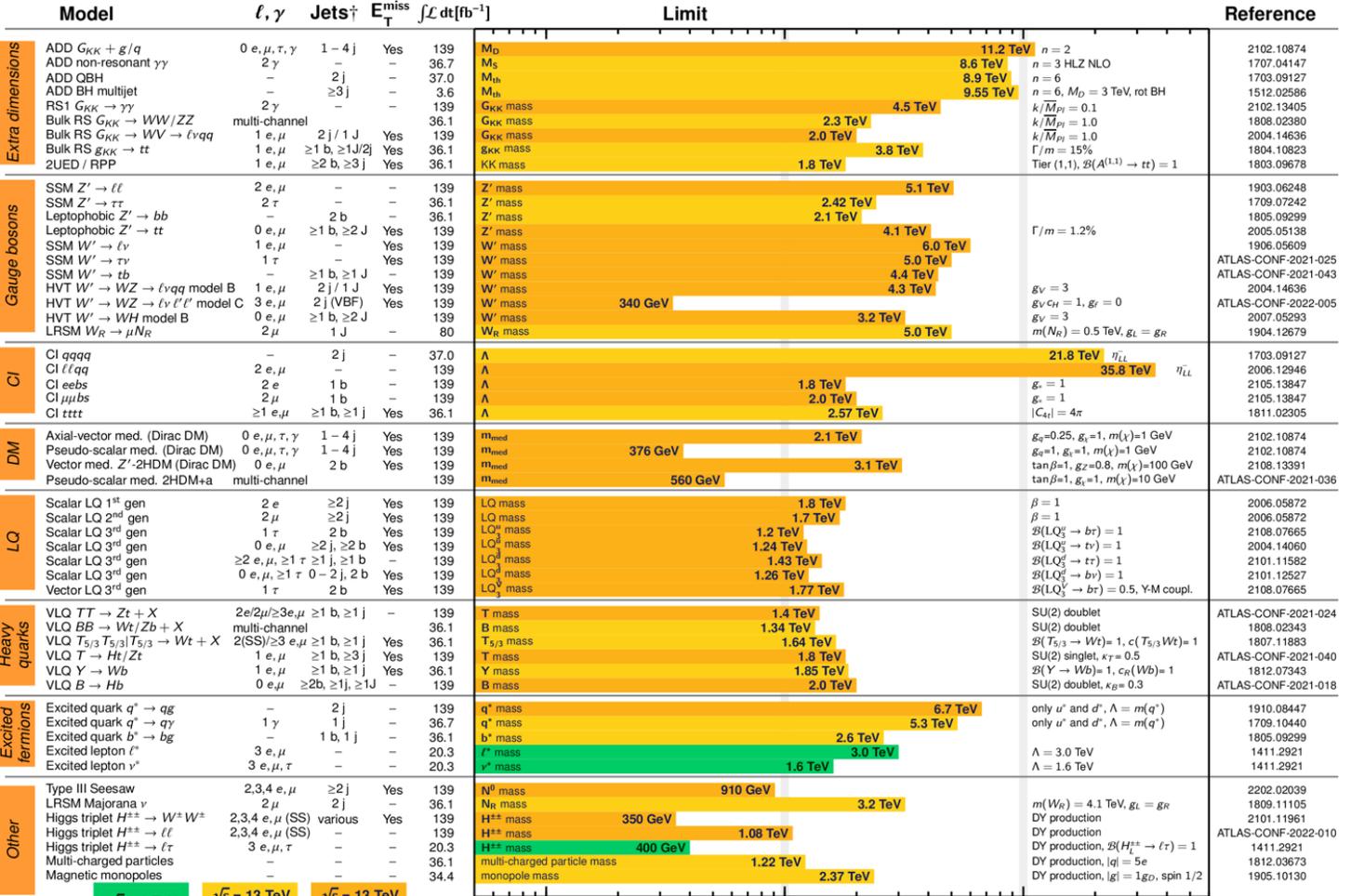
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10⁻¹ 1 Mass scale [TeV]

ATLAS SUSY Searches* - 95% CL Lower Limit:

March 2022

Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 e, μ mono-jet	139
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e, μ 2-6 jets	139
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 e, μ 2 jets	139
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	0 e, μ 2 jets	139
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0 e, μ 7-11 jets	139
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ SS e, μ	79.8 139
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e, μ 2 b	139
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$	0 e, μ 2 τ	139 139
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 e, μ ≥ 1 jet	139
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 e, μ 3 jets/1 b	139
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$	1-2 τ 2 jets/1 b	139
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ 2 c mono-jet	36.1 139
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets ≥ 1 jet	139 139
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	2 e, μ Multiple ℓ/jets	139 139
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	2 e, μ Multiple ℓ/jets	139 139
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ 2 τ	139 139
	$\tilde{\tau}_1, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 e, μ 0 jets	139 139
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \tilde{\chi}_1^0$	2 e, μ Multiple ℓ/jets	139 139
Long-lived particles	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk 1 jet	139
	Stable \tilde{g} R-hadron	pixel dE/dx	139
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	pixel dE/dx	139
RPV	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0/\tilde{\chi}_2^0 \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 e, μ 0 jets	139
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0 \rightarrow WWZZ\ell\ell\nu\nu$	4 e, μ 0 jets	139
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$	Multiple $\geq 4b$	36.1 139
	$\tilde{u}, \tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple $\geq 4b$	36.1 139
	$\tilde{u}, \tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0 \rightarrow bbs$	Multiple $\geq 4b$	36.1 139
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	2 e, μ 2 b	36.7 136
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{\ell}$	1 μ DV	136	
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0/\tilde{\chi}_1^0/\tilde{\chi}_2^0 \rightarrow tbs, \tilde{\chi}_1^{\pm} \rightarrow bbs$	1-2 e, μ ≥ 6 jets	139	



*Only a selection of the available mass limits on new states or phenomena is shown.

† Small-radius (large-radius) jets are denoted by the letter (j) (J).

Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1-4 j	Yes	139	M_0 11.2 TeV $n=2$
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_S 8.6 TeV $n=3$ HLZ NLO
	ADD QBH	-	2 j	-	37.0	M_{th} 8.9 TeV $n=6$
	ADD BH multijet	-	$\geq 3j$	-	3.6	M_{th} 9.55 TeV $n=6, M_D = 3 \text{ TeV, rot BH}$
Gauge bosons	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	139	G_{KK} mass 4.5 TeV $k/\tilde{M}_{Pl} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV $k/\tilde{M}_{Pl} = 1.0$
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu q\bar{q}$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV $k/\tilde{M}_{Pl} = 1.0$
	Bulk RS $G_{KK} \rightarrow t\bar{t}$	1 e, μ	$\geq 1 b, \geq 1J/2J$	Yes	36.1	G_{KK} mass 3.8 TeV $\Gamma/m = 15\%$
	2UED / RPP	1 e, μ	$\geq 2 b, \geq 3j$	Yes	36.1	G_{KK} mass 1.8 TeV Tier (1,1), $2\mathcal{A}(A^{(1,1)} \rightarrow t\bar{t}) = 1$
	CI	Cl $qqqq$	-	2 j	-	37.0
Cl $\ell\ell q\bar{q}$		2 e, μ	-	-	139	A 35.8 TeV η_{LL}
Cl $e\bar{e}bs$		2 e	1 b	-	139	A 1.8 TeV $g_s = 1$
Cl $\mu\mu bs$		2 μ	1 b	-	139	A 2.0 TeV $g_s = 1$
Cl $t\bar{t}tt$		$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	A 2.57 TeV $ C_{4l} = 4\pi$
DM		Axial-vector med. (Dirac DM)	0 e, μ, τ, γ	1-4 j	Yes	139
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1-4 j	Yes	139	\tilde{m}_{med} 376 GeV $g_a = 1, g_s = 1, m(\chi) = 1 \text{ GeV}$
	Vector med. Z'-2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	\tilde{m}_{med} 3.1 TeV $\tan\beta = 1, g_Z = 0.8, m(\chi) = 100 \text{ GeV}$
	Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	\tilde{m}_{med} 560 GeV $\tan\beta = 1, g_s = 1, m(\chi) = 10 \text{ GeV}$
LQ	Scalar LQ 1 st gen	2 e	$\geq 2j$	Yes	139	LQ mass 1.8 TeV $\beta = 1$
	Scalar LQ 2 nd gen	2 μ	$\geq 2j$	Yes	139	LQ mass 1.7 TeV $\beta = 1$
	Scalar LQ 3 rd gen	1 τ	2 b	Yes	139	LQ mass 1.2 TeV $\mathcal{B}(LQ_s^{\pm} \rightarrow b\tau) = 1$
	Scalar LQ 3 rd gen	0 e, μ	$\geq 2j, \geq 2 b$	Yes	139	LQ mass 1.24 TeV $\mathcal{B}(LQ_s^{\pm} \rightarrow \tau\nu) = 1$
	Scalar LQ 3 rd gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 j, \geq 1 b$	$\geq 2 b$	Yes	139	LQ mass 1.43 TeV $\mathcal{B}(LQ_s^{\pm} \rightarrow \tau\tau) = 1$
	Vector LQ 3 rd gen	0 $e, \mu, \geq 1 \tau, 0-2 j, 2 b$	Yes	139	LQ mass 1.26 TeV $\mathcal{B}(LQ_s^{\pm} \rightarrow b\nu) = 1$	
Heavy quarks	VLQ $TT \rightarrow Zt + X$	2e/2 μ / $\geq 3e, \mu$	$\geq 1 b, \geq 1 j$	-	139	T mass 1.4 TeV SU(2) doublet
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV SU(2) doublet
	VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	2(SS)/ $\geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$
	VLQ $T \rightarrow Ht/Zt$	1 e, μ	$\geq 1 b, \geq 3j$	Yes	139	T mass 1.8 TeV SU(2) singlet, $\kappa_T = 0.5$
	VLQ $Y \rightarrow Wb$	1 e, μ	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_Y(Wb) = 1$
	VLQ $B \rightarrow Hb$	0 e, μ	$\geq 2b, \geq 1j, \geq 1J$	-	139	B mass 2.0 TeV SU(2) doublet, $\kappa_B = 0.3$
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2 j	-	139	q^* mass 6.7 TeV only u^* and $d^*, \Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	-	36.7	q^* mass 5.3 TeV only u^* and $d^*, \Lambda = m(q^*)$
	Excited quark $b^* \rightarrow bg$	-	1 b, 1 j	-	36.1	b^* mass 2.6 TeV $\Lambda = 3.0 \text{ TeV}$
	Excited lepton ℓ^*	3 e, μ	-	-	20.3	ℓ^* mass 3.0 TeV $\Lambda = 1.6 \text{ TeV}$
Other	Excited lepton ν^*	3 e, μ, τ	-	-	20.3	ν^* mass 1.6 TeV $\Lambda = 1.6 \text{ TeV}$
	Type III Seesaw	2,3,4 e, μ	$\geq 2j$	Yes	139	N^0 mass 910 GeV $m(W_R) = 4.1 \text{ TeV, } g_L = g_R$
	LRSM Majorana ν	2 μ	2 j	-	36.1	N_R mass 3.2 TeV DY production
	Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV DY production
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV DY production
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau) = 1$
RPV	Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV DY production, $ q = 5e$
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV DY production, $ g = 1g_D, \text{spin } 1/2$
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_1^0$ [BR(Z τ)=1, ...]	-	-	-	0.95	$m(\tilde{\chi}_1^{\pm}) = 500 \text{ GeV}$
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ [$\beta_{\text{mix}} \neq 0, A_0$]	-	-	-	1.0	$m(\tilde{\chi}_1^{\pm}) = 500 \text{ GeV}$

*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.

ATLAS SUSY Searches* - 95% CL Lower Limit

March 2022

Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference		
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 e, μ mono-jet	E_T^{miss}	139	\tilde{q} [1x, 8x Degen.] \tilde{q} [8x Degen.]	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e, μ	E_T^{miss}	139	\tilde{g}	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 e, μ	2-6 jets	E_T^{miss}	139	\tilde{g}
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	E_T^{miss}	139	\tilde{g}
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0 e, μ	7-11 jets	E_T^{miss}	139	\tilde{g}
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	SS e, μ	6 jets	E_T^{miss}	139	\tilde{g}
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e, μ	2 b	E_T^{miss}	139	\tilde{b}_1
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b\tilde{h}\tilde{\chi}_1^0$	0 e, μ	6 b	E_T^{miss}	139	\tilde{b}_1
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0 e, μ	≥ 1 jet	E_T^{miss}	139	\tilde{t}_1
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 e, μ	3 jets/1 b	E_T^{miss}	139	\tilde{t}_1
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	139	\tilde{t}_1
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ	2 c mono-jet	E_T^{miss}	36.1	\tilde{t}_1
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets	≥ 1 jet	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	2 e, μ		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	Multiple ℓ/jets		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ Forbidden
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$
	$\tilde{\tau}_1, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	139	$\tilde{\tau}$ [F.L.R.]
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \tilde{\chi}_1^0$	2 e, μ $ee, \mu\mu$	0 jets ≥ 1 jet	E_T^{miss} E_T^{miss}	139	$\tilde{\ell}$
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	≥ 3 b 0 jets ≥ 2 large jets	E_T^{miss} E_T^{miss} E_T^{miss}	36.1 139 139	\tilde{H} 0.13
	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$
	Stable \tilde{g} R-hadron	pixel dE/dx		E_T^{miss}	139	\tilde{g}
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	pixel dE/dx		E_T^{miss}	139	\tilde{g} [$\tau(\tilde{g})=10$ ns]
RPV	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm} \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 e, μ		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_1^0$ [BR(Z τ)=1]
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0 \rightarrow WWZZ\ell\ell\nu\nu$	4 e, μ	0 jets	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ [$\mu_{\alpha\beta} \neq 0$]
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$	Multiple	4-5 large jets	E_T^{miss}	36.1	\tilde{g} [$m(\tilde{\chi}_1^0)=200$ GeV]
	$\tilde{u}, \tilde{t} \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t\tilde{b}\tilde{s}$	Multiple	$\geq 4b$	E_T^{miss}	36.1	\tilde{u} [$\mu_{33}^u=2\theta-4, 1\theta-2$]

Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1-4 j	Yes	139	M_D 11.2 TeV $n=2$
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_S 8.6 TeV $n=3$ HLZ NLO
	ADD QBH	-	2 j	-	37.0	M_{th} 8.9 TeV $n=6$
	ADD BH multijet	-	$\geq 3j$	-	3.6	M_{th} 9.55 TeV $n=6, M_D=3$ TeV, rot BH
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	139	G_{KK} mass 4.5 TeV $k/M_{Pl}=0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV $k/M_{Pl}=1.0$
	Bulk RS $G_{KK} \rightarrow W\nu \rightarrow \ell\nu q\bar{q}$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV $k/M_{Pl}=1.0$
	Bulk RS $G_{KK} \rightarrow t\bar{t}$	1 e, μ	$\geq 1 b, \geq 1J/2J$	Yes	36.1	G_{KK} mass 3.8 TeV $\Gamma/m=15\%$
	2UED / RPP	1 e, μ	$\geq 2 b, \geq 3j$	Yes	36.1	KK mass 1.8 TeV Tier (1,1), $2\mathcal{A}^{(1,1)} \rightarrow t\bar{t}$ = 1
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	139
SSM $Z' \rightarrow \tau\tau$		2 τ	-	-	36.1	Z' mass 2.42 TeV
Leptophobic $Z' \rightarrow b\bar{b}$		-	2 b	-	36.1	Z' mass 2.1 TeV
Leptophobic $Z' \rightarrow t\bar{t}$		0 e, μ	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass 4.1 TeV $\Gamma/m=1.2\%$
SSM $W' \rightarrow \ell\nu$		1 e, μ	-	Yes	139	W' mass 6.0 TeV
SSM $W' \rightarrow \tau\nu$		1 τ	-	Yes	139	W' mass 5.0 TeV
SSM $W' \rightarrow t\bar{b}$		-	$\geq 1 b, \geq 1 J$	-	139	W' mass 4.4 TeV
HVT $W' \rightarrow WZ \rightarrow \ell\nu q\bar{q}$ model B		1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV
HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell' \ell'$ model C		3 e, μ	2j (VBF)	Yes	139	W' mass 340 GeV
HVT $W' \rightarrow WH$ model B		0 e, μ	$\geq 1 b, \geq 2 J$	Yes	139	W' mass 3.2 TeV
LRSM $W_R \rightarrow \mu N_R$	2 μ	1 J	-	80	W_R mass 5.0 TeV	
CI	CI $qqqq$	-	2 j	-	37.0	A 21.8 TeV η_{LL}
	CI $\ell\ell q\bar{q}$	2 e, μ	-	-	139	A 35.8 TeV η_{LL}
	CI $e\bar{e}b\bar{b}$	2 e	1 b	-	139	A 1.8 TeV $g_s=1$
	CI $\mu\bar{\mu}b\bar{b}$	2 μ	1 b	-	139	A 2.0 TeV $g_s=1$
DM	CI $t\bar{t}t\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	A 2.57 TeV $ C_{41} =4\pi$
	Axial-vector med. (Dirac DM)	0 e, μ, τ, γ	1-4 j	Yes	139	θ^{med} 2.1 TeV $g_{\sigma}=0.25, g_{\tau}=1, m(\chi)=1$ GeV
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1-4 j	Yes	139	θ^{med} 376 GeV $g_{\sigma}=1, g_{\tau}=1, m(\chi)=1$ GeV
	Vector med. Z' -2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	θ^{med} 3.1 TeV $\tan\beta=1, g_Z=0.8, m(\chi)=100$ GeV
LQ	Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	θ^{med} 560 GeV $\tan\beta=1, g_{\tau}=1, m(\chi)=10$ GeV
	Scalar LQ 1 st gen	2 e	$\geq 2j$	Yes	139	LQ mass 1.8 TeV $\beta=1$
	Scalar LQ 2 nd gen	2 μ	$\geq 2j$	Yes	139	LQ mass 1.7 TeV $\beta=1$
	Scalar LQ 3 rd gen	1 τ	2 b	Yes	139	LQ mass 1.2 TeV $\mathcal{B}(LQ_{\tau}^{\pm} \rightarrow b\tau)=1$
	Scalar LQ 3 rd gen	0 e, μ	$\geq 2j, \geq 2 b$	Yes	139	LQ mass 1.24 TeV $\mathcal{B}(LQ_{\tau}^{\pm} \rightarrow \tau\nu)=1$
	Scalar LQ 3 rd gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 b$	$\geq 2j, \geq 2 b$	Yes	139	LQ mass 1.43 TeV $\mathcal{B}(LQ_{\tau}^{\pm} \rightarrow \tau\tau)=1$
Heavy quarks	Vector LQ 3 rd gen	0 $e, \mu, \geq 1 \tau, 0-2j, 2 b$	Yes	139	LQ mass 1.26 TeV $\mathcal{B}(LQ_{\tau}^{\pm} \rightarrow b\nu)=1$	
	Vector LQ 3 rd gen	1 τ	2 b	Yes	139	LQ mass 1.77 TeV $\mathcal{B}(LQ_{\tau}^{\pm} \rightarrow b\nu)=0.5, Y-M$ coupl.
	VLO $TT \rightarrow Zt + X$	2e/2 μ / $\geq 3e, \mu$	$\geq 1 b, \geq 1 j$	-	139	T mass 1.4 TeV SU(2) doublet
	VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV SU(2) doublet
	VLO $T_{5/3}T_{5/3}/T_{5/3} \rightarrow Wt + X$	2(SS)/ $\geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt)=1, c(T_{5/3}Wt)=1$
	VLO $T \rightarrow Ht/Zt$	1 e, μ	$\geq 1 b, \geq 3j$	Yes	139	T mass 1.8 TeV SU(2) singlet, $\kappa_T=0.5$
Excited fermions	VLO $Y \rightarrow Wb$	1 e, μ	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV $\mathcal{B}(Y \rightarrow Wb)=1, c_Y(Wb)=1$
	VLO $B \rightarrow Hb$	0 e, μ	$\geq 2b, \geq 1j, \geq 1J$	-	139	B mass 2.0 TeV SU(2) doublet, $\kappa_B=0.3$
	Excited quark $q^* \rightarrow qg$	-	2 j	-	139	q^* mass 6.7 TeV only u^* and $d^*, \Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	-	36.7	q^* mass 5.3 TeV only u^* and $d^*, \Lambda = m(q^*)$
	Excited quark $b^* \rightarrow bg$	-	1 $b, 1 j$	-	36.1	b^* mass 2.6 TeV
	Excited lepton ℓ^*	3 e, μ	-	-	20.3	ℓ^* mass 3.0 TeV $\Lambda = 3.0$ TeV
Other	Excited lepton ν^*	3 e, μ, τ	-	-	20.3	ν^* mass 1.6 TeV $\Lambda = 1.6$ TeV
	Type III Seesaw	2,3,4 e, μ	$\geq 2j$	Yes	139	N^0 mass 910 GeV
	LRSM Majorana ν	2 μ	2 j	-	36.1	N_R mass 3.2 TeV $m(W_R)=4.1$ TeV, $g_L = g_R$
	Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV DY production
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV DY production
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau)=1$
Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV DY production, $ q =5e$	
Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV DY production, $ g =1g_D, \text{spin } 1/2$	

*Only a selection of the available mass limits on new states or phenomena is shown.

† Small-radius (large-radius) jets are denoted by the letter J (j).

広い領域を探索してきたが未だ兆候なし...
シグナルモデルによらない探索が必要

*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.

モンテカルロ(MC)シミュレーションが使えるか？

YES

- MCシミュレーションからのズレを網羅的に探すサーチ
- バックグラウンドはMCシミュレーションを使う

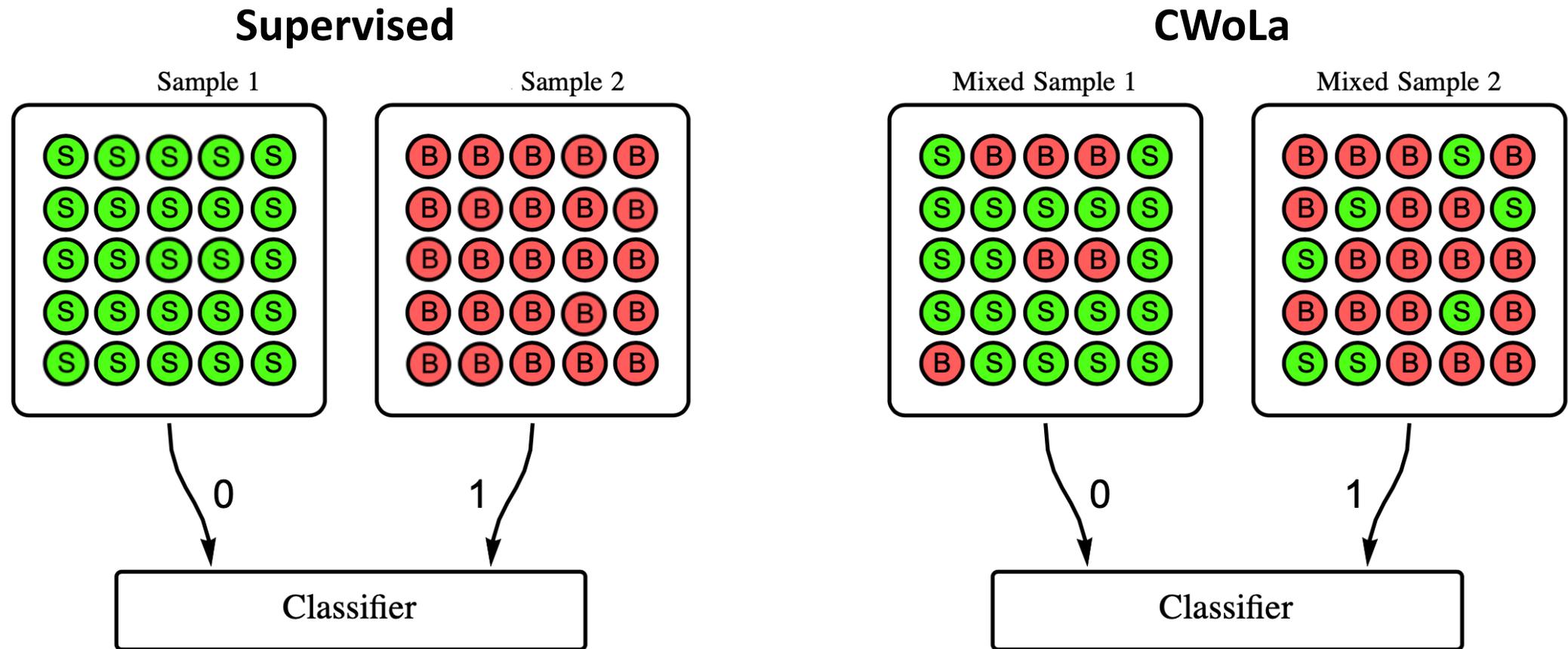
[Model Unspecific Search in CMS \(MUSiC\)](#)
[ATLAS General search](#)

NO

- データドリブンなサーチ
- バックグラウンドをデータから推定

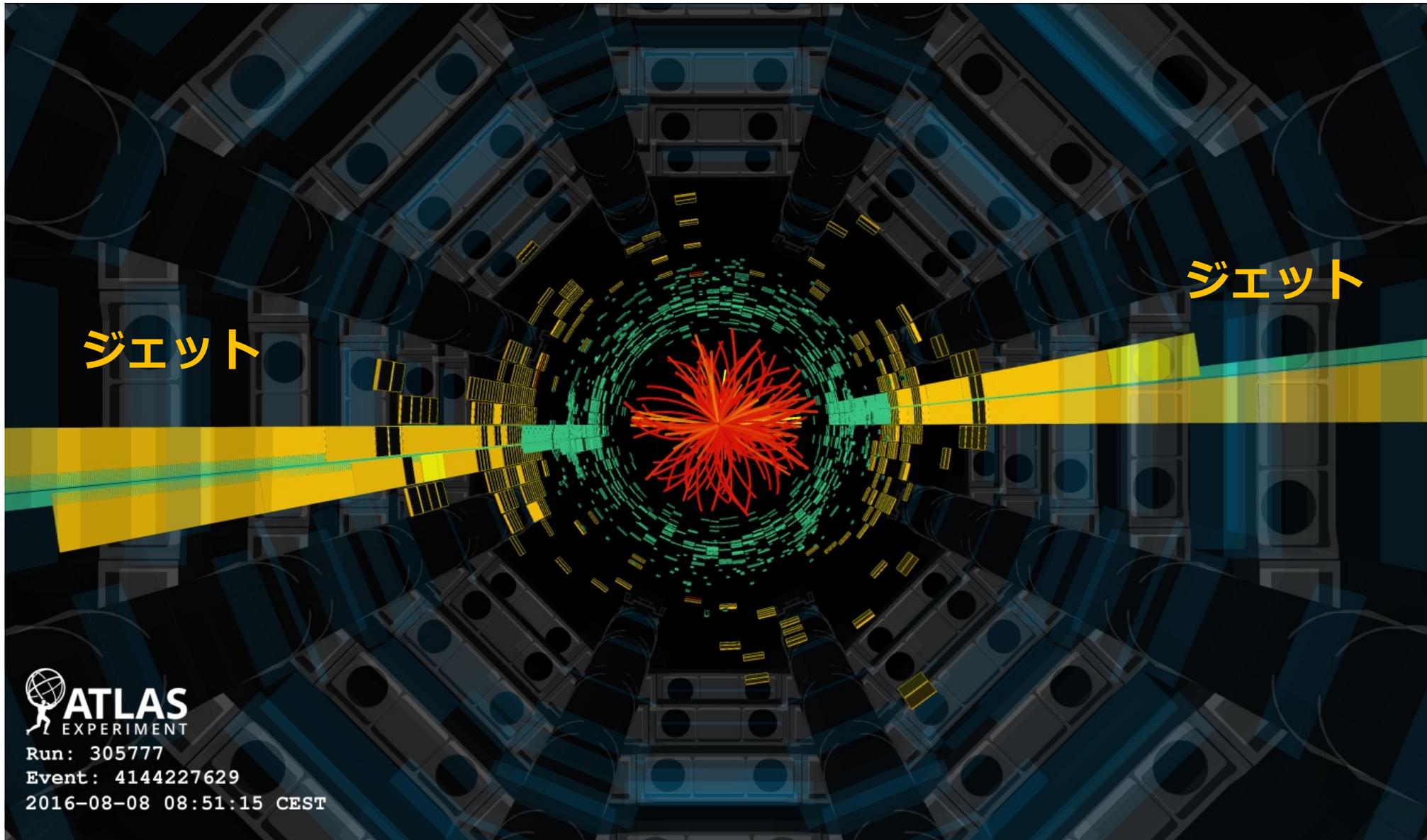
[弱教師学習を使った新粒子探索 at ATLAS](#)

今日のトピック

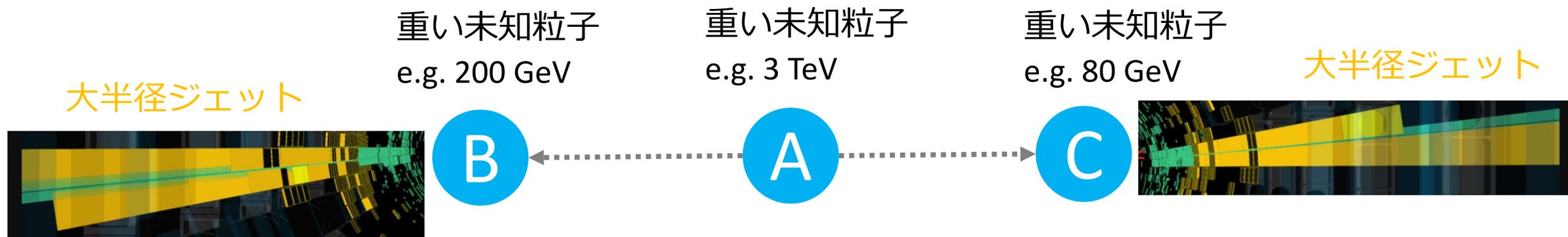


- ラベルがノイジーでも分類器はsignal/backgroundを分けるように学習される
 - ただし、統計的なふらつきの影響は受ける
- ATLAS実験で、Di-jet バンプサーチにCWoLaを適用

=> [Phys. Rev. Lett. 125, 131801 \(2020\)](#)

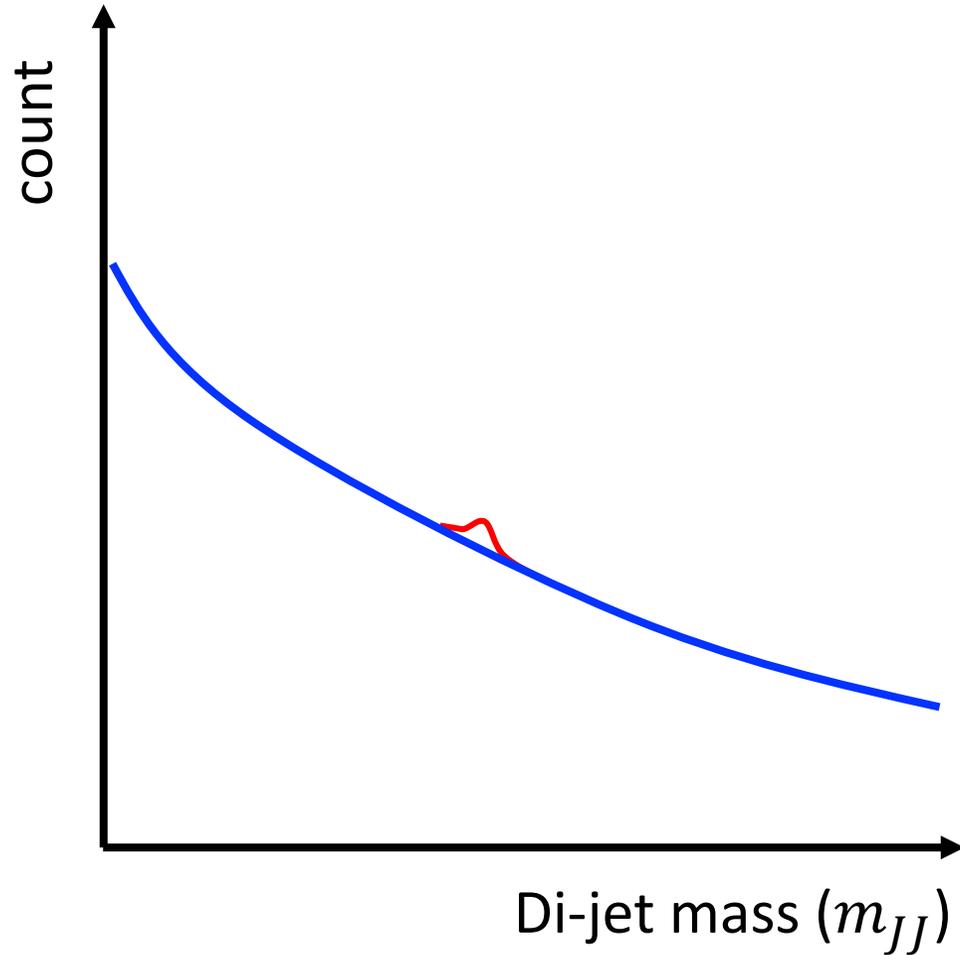
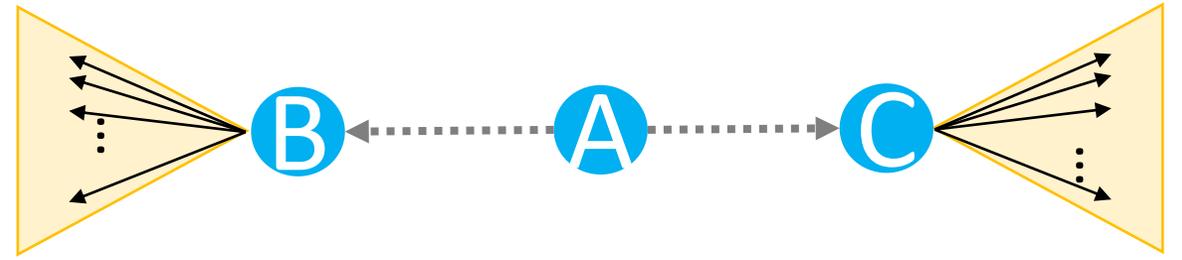


シグナルモデル

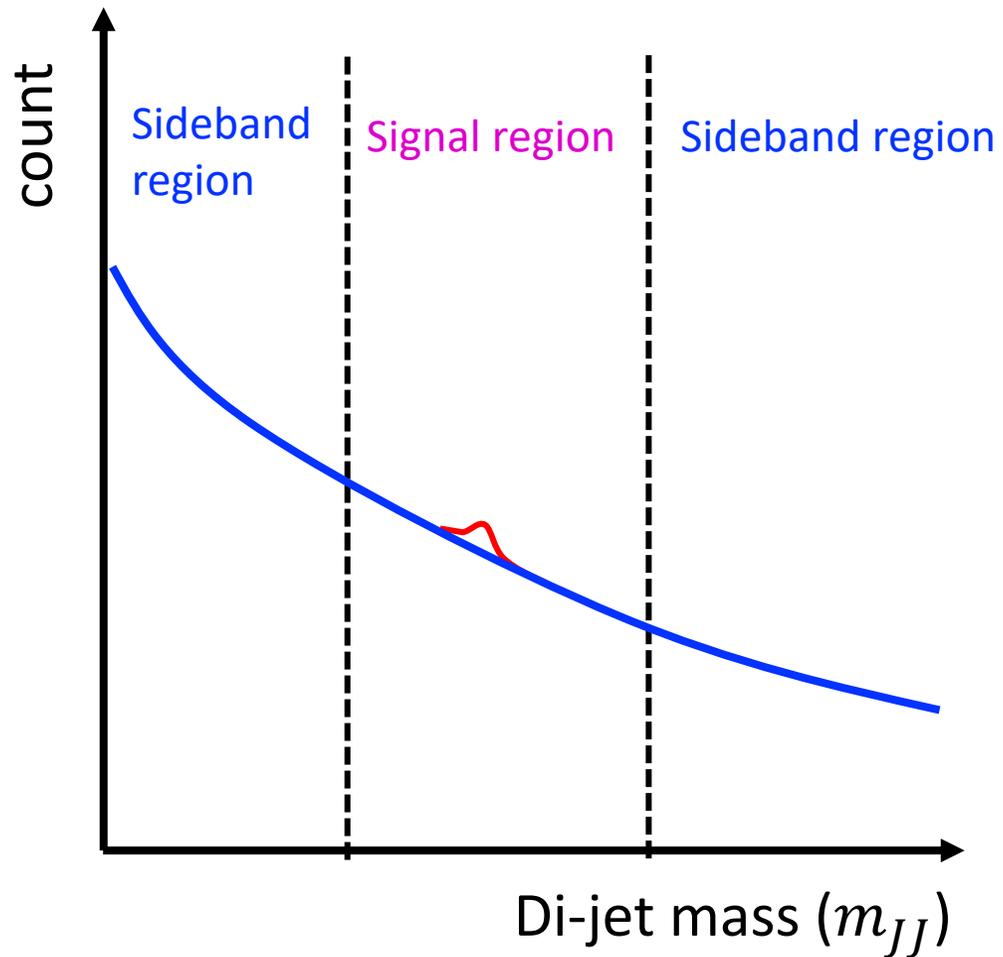


$$m_A \sim \mathcal{O}(\text{TeV})$$

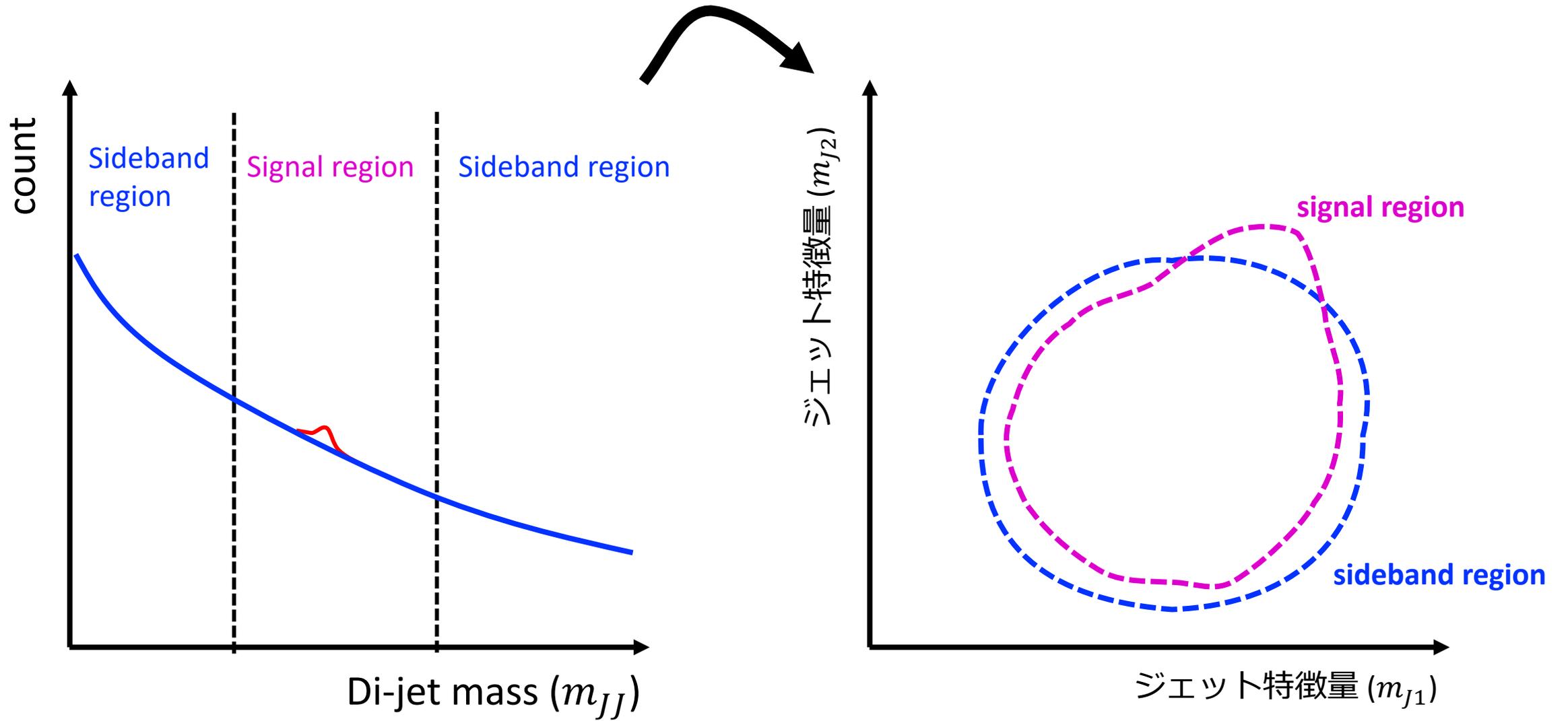
$$m_B, m_C \sim \mathcal{O}(100 \text{ GeV})$$



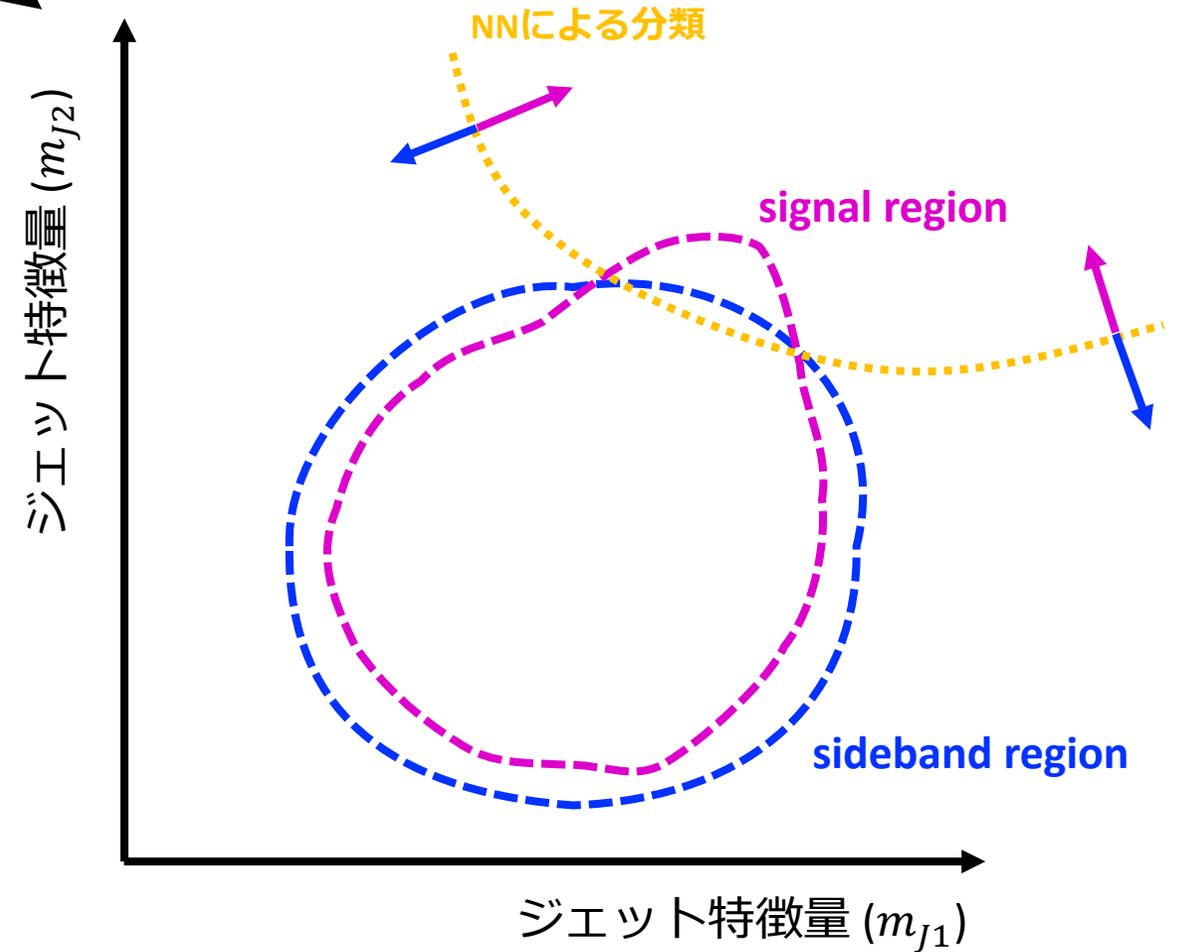
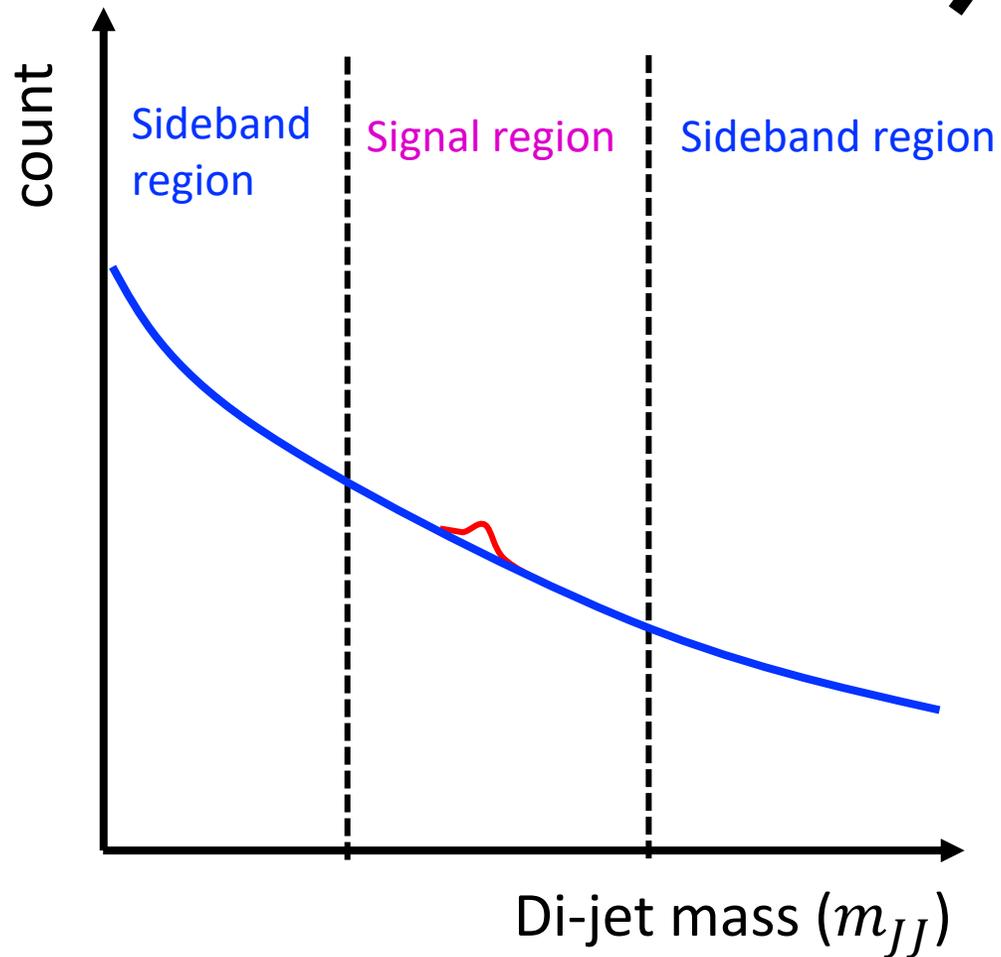
- Di-jet mass分布のバンプを探す ($m_{JJ} \sim m_A$)
- S/B 改善のためjet massでカットをかける
- 最適なカットはシグナルモデルに依存する
 - $m_J \sim m_B, m_C$
- CWoLaで**Data-driven**にカットを決める

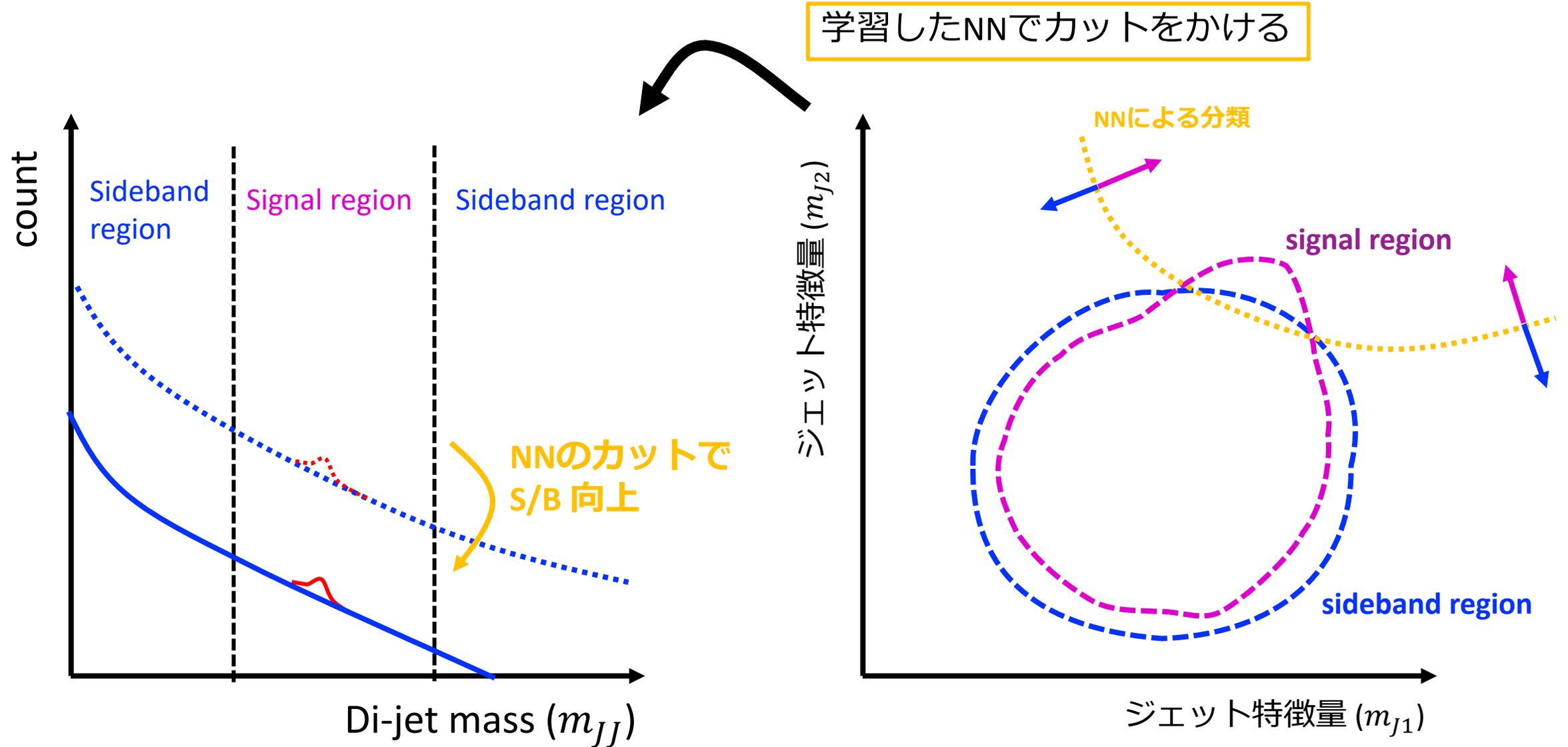


- m_{JJ} を使って
 - Signal region ($y=0$)
 - Sideband region ($y=1$)を定義



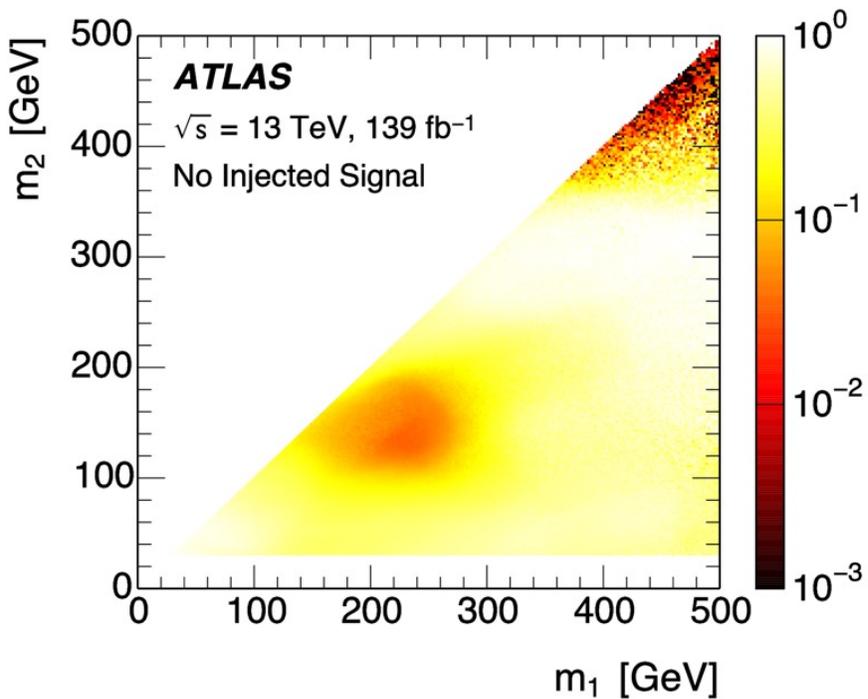
- シグナルがあると、S/Bを改善するように学習
- シグナルがないと、ランダムな分類器になる



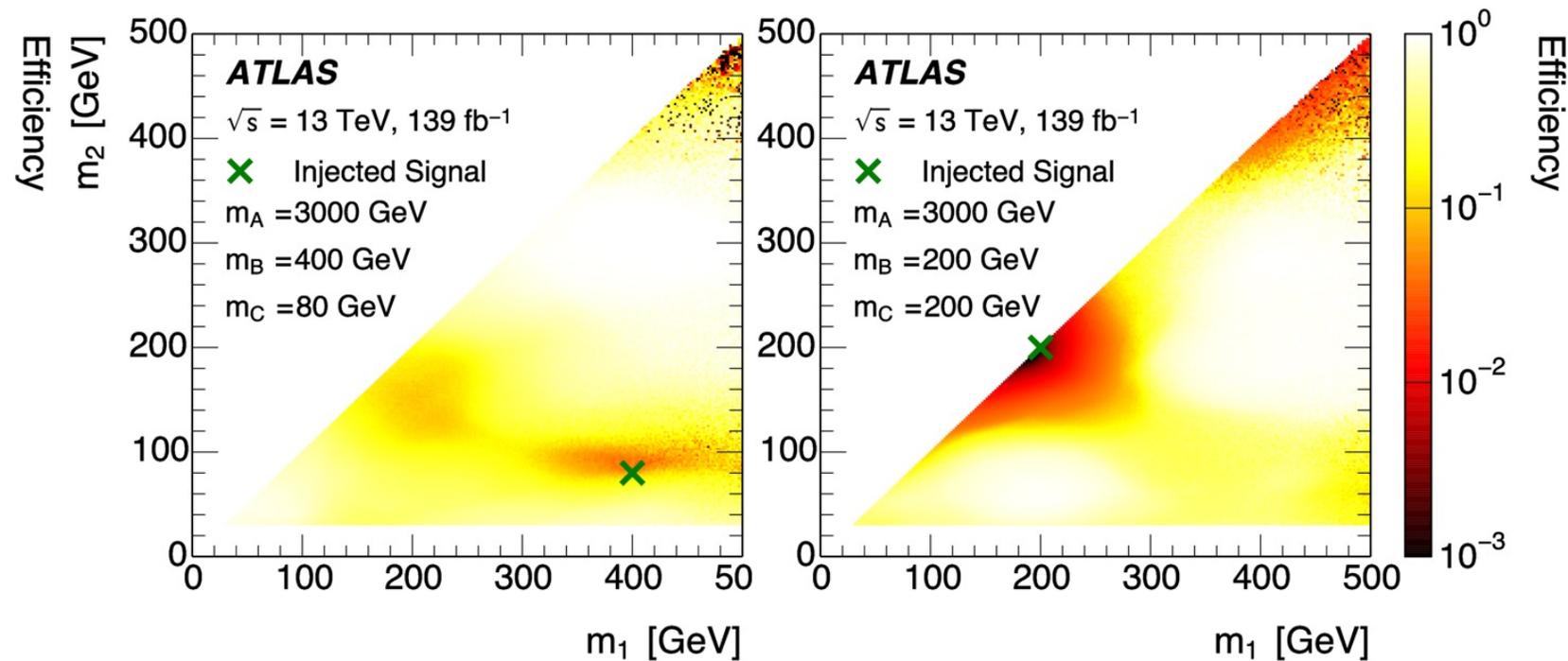


注: カット(NN)に使う変数はdi-jet massに依存しない変数
相関があると性能が悪化する

Signal injectionなし

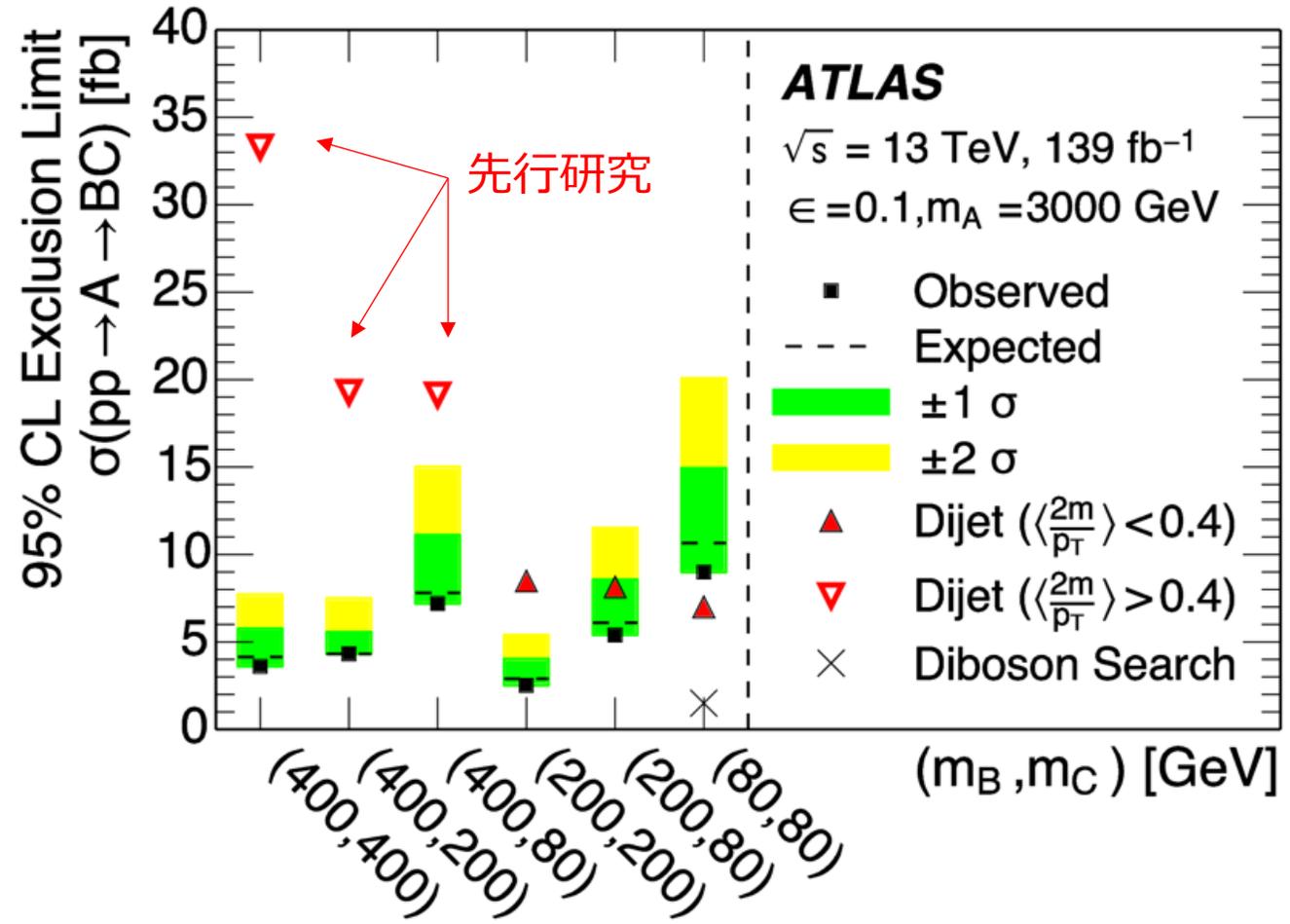
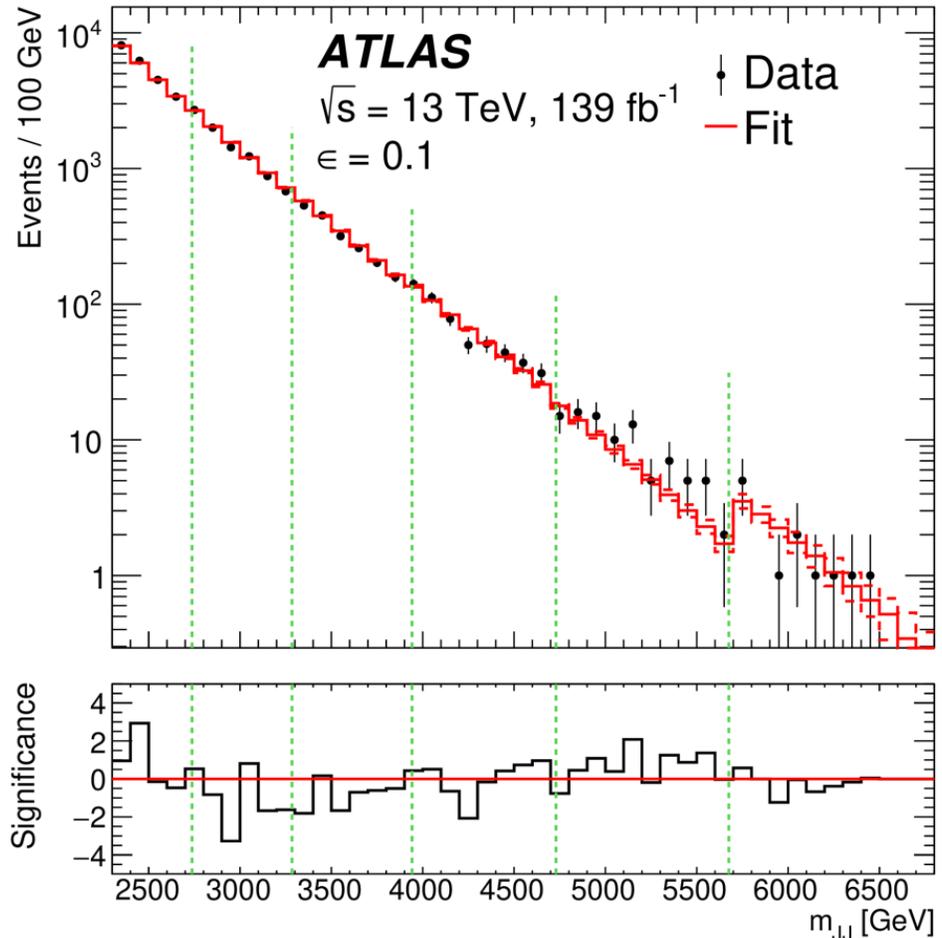


Signal injectionあり



- 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

カット後のdi-jet mass分布



- 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

- シグナルモデルパラメータによっては、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

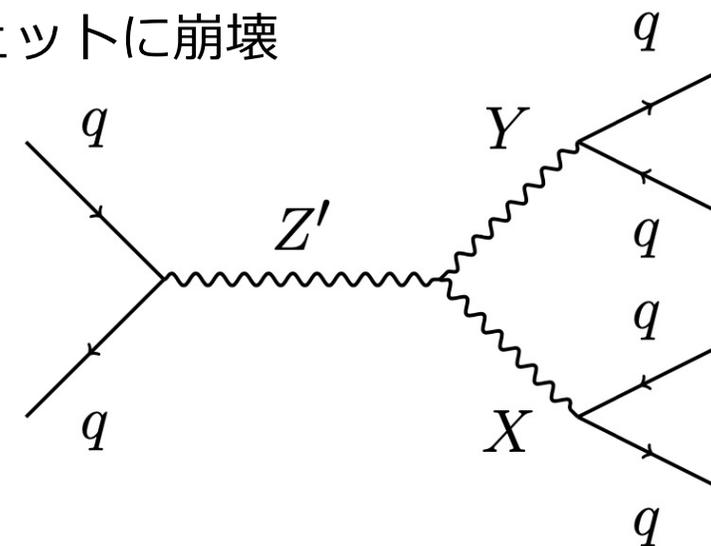
- シグナルモデルによらない物理探索の研究を推進するために開催
 - 最終的に計18の提出
 - ベンチマークデータセットはZenodoで公開されており、先行研究との比較が可能
- 問題設定はATLAS の弱教師学習を用いたDijet resonance searchとほぼ同じ
 - 重い未知粒子(Z')が軽い未知粒子(X, Y)を通して2つの大半径ジェットに崩壊

- 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



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

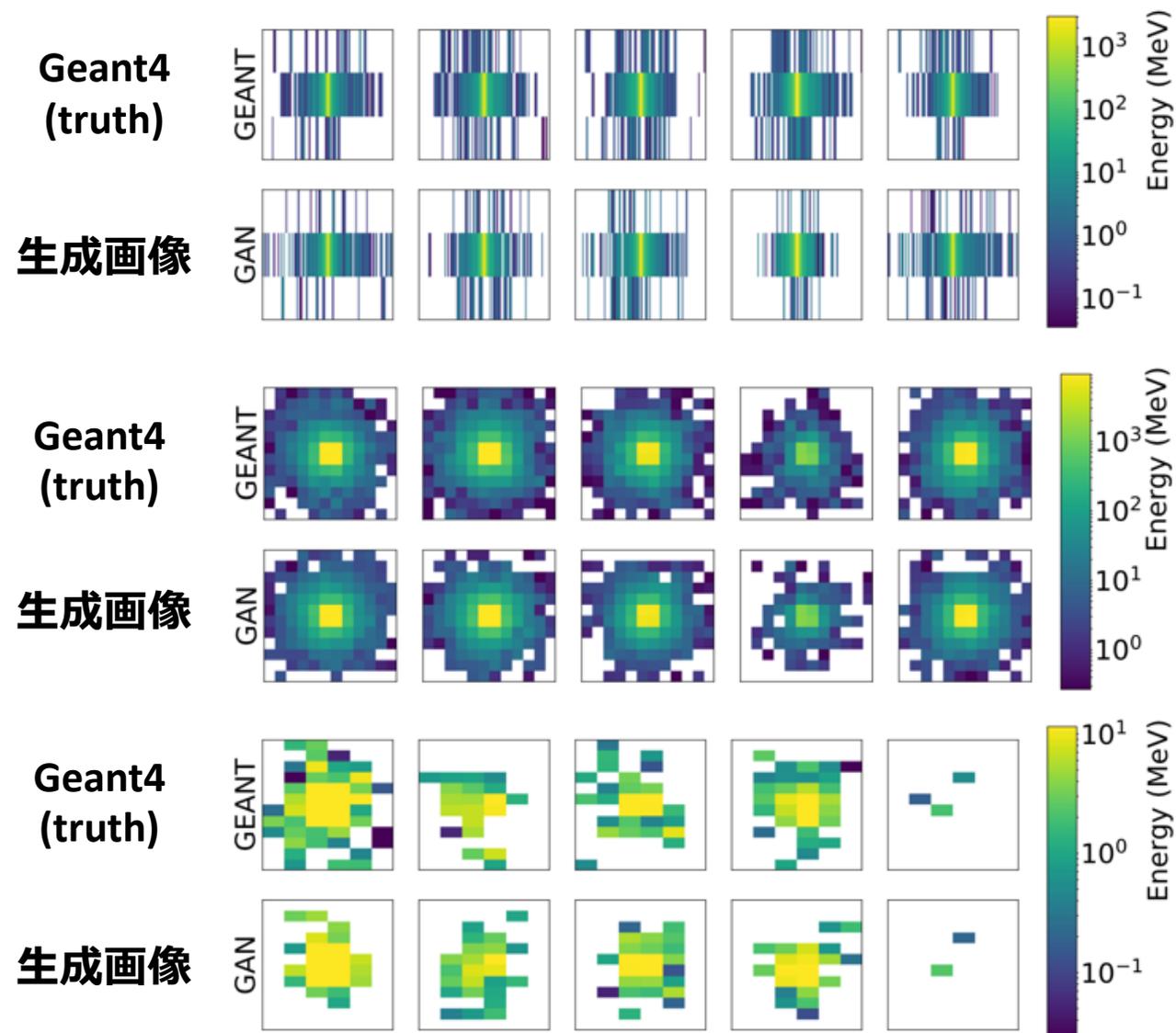
- BB2でシグナルを誤検知したチームもあった。今後の課題
- BB3は正解チームなし。トポロジーの変化に対応できる汎用的な手法はまだ難しい

サマリー

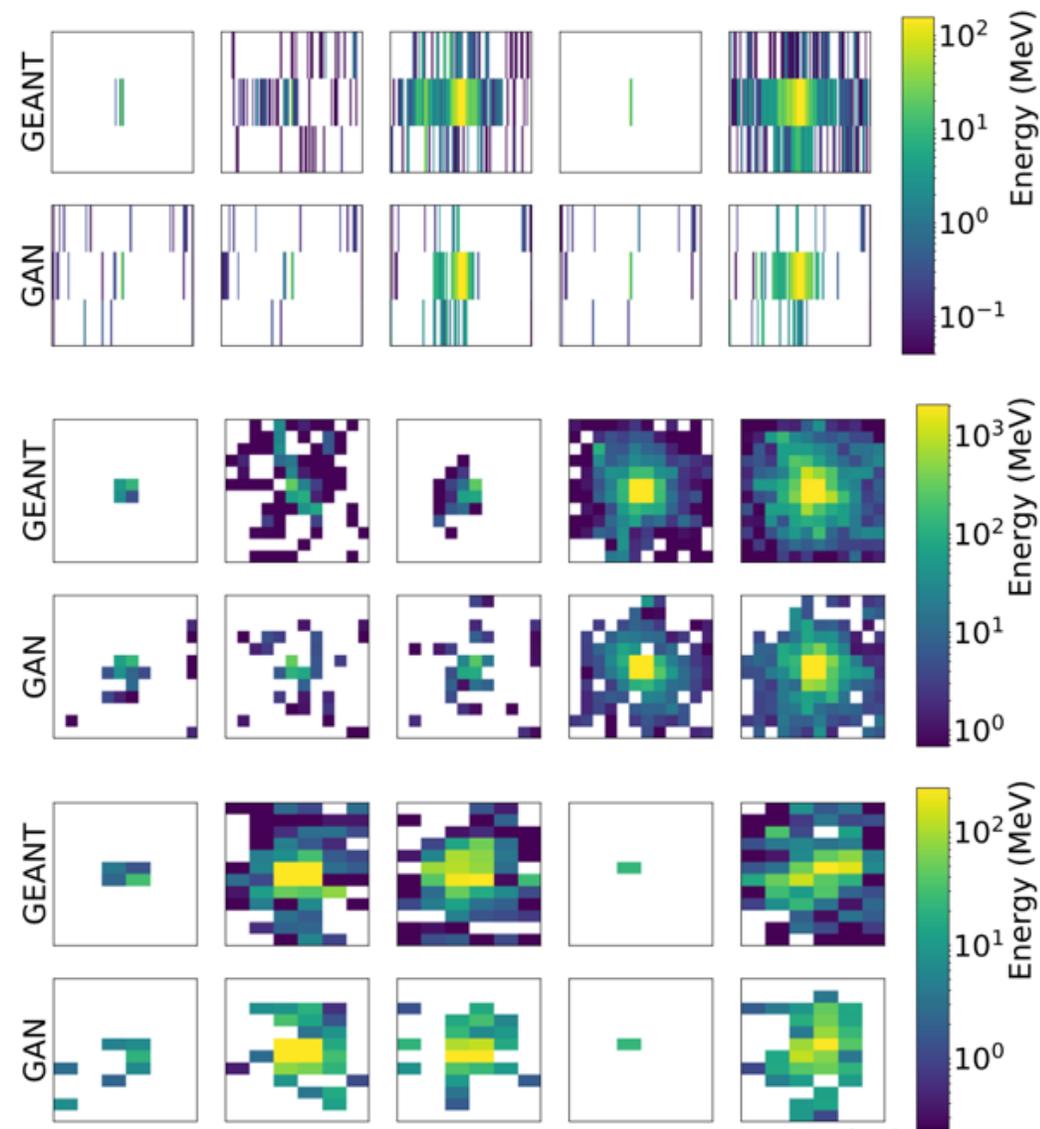
- 生成モデル・異常検知の応用例を紹介した
 - GANを用いたカロリーメータシャワーシミュレーション
 - 弱教師あり学習(CWoLa)を使ったDijet resonance search
- この分野は発展途上
 - 実験で実際に使われている例はまだ少ない
 - コンテストが開催されたり、ベンチマークデータセットが整備されるなど、R&Dがしやすい環境が整ってきている
- 今後に期待

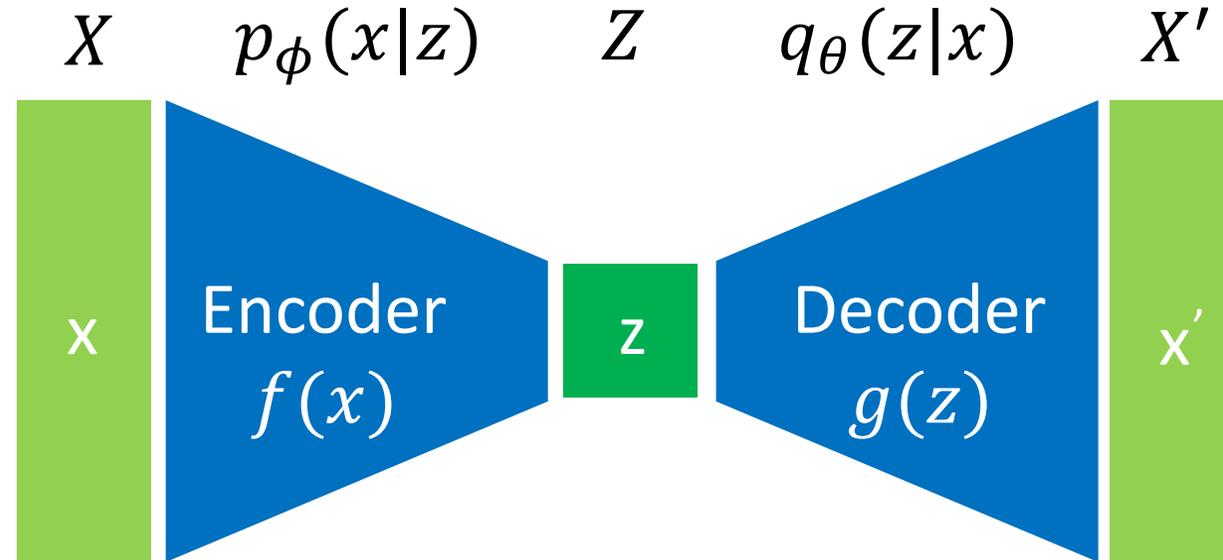
Backup

Electron



Pion



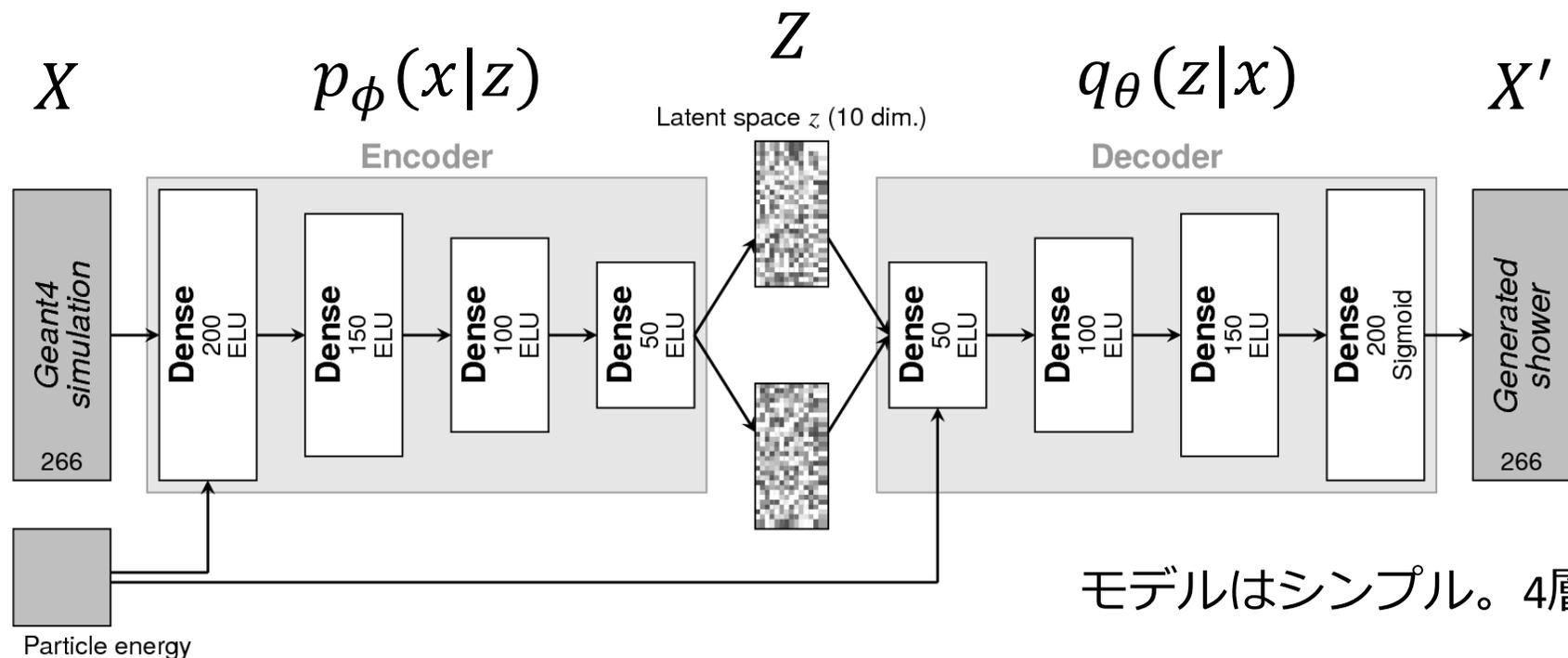
Variational autoencoder (VAE)VAE for 生成モデル

- $\|x - x'\|^2$ 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

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



VAE for 生成モデル

- $\|X - X'\|^2$ 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

ATLASでの工夫

- 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

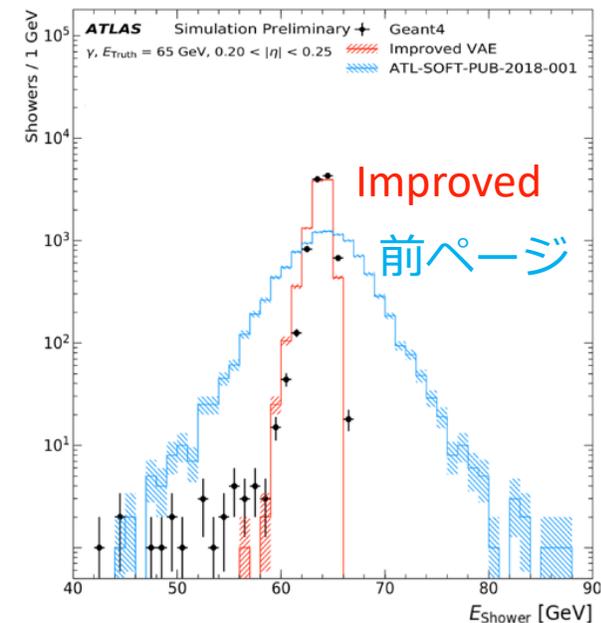
改善が続けられている

- Normalizing Flow (IAF)の導入
- ロス関数の変更

[ATL-PLOTS-SIM-2019-007](#)

ロス関数の変更

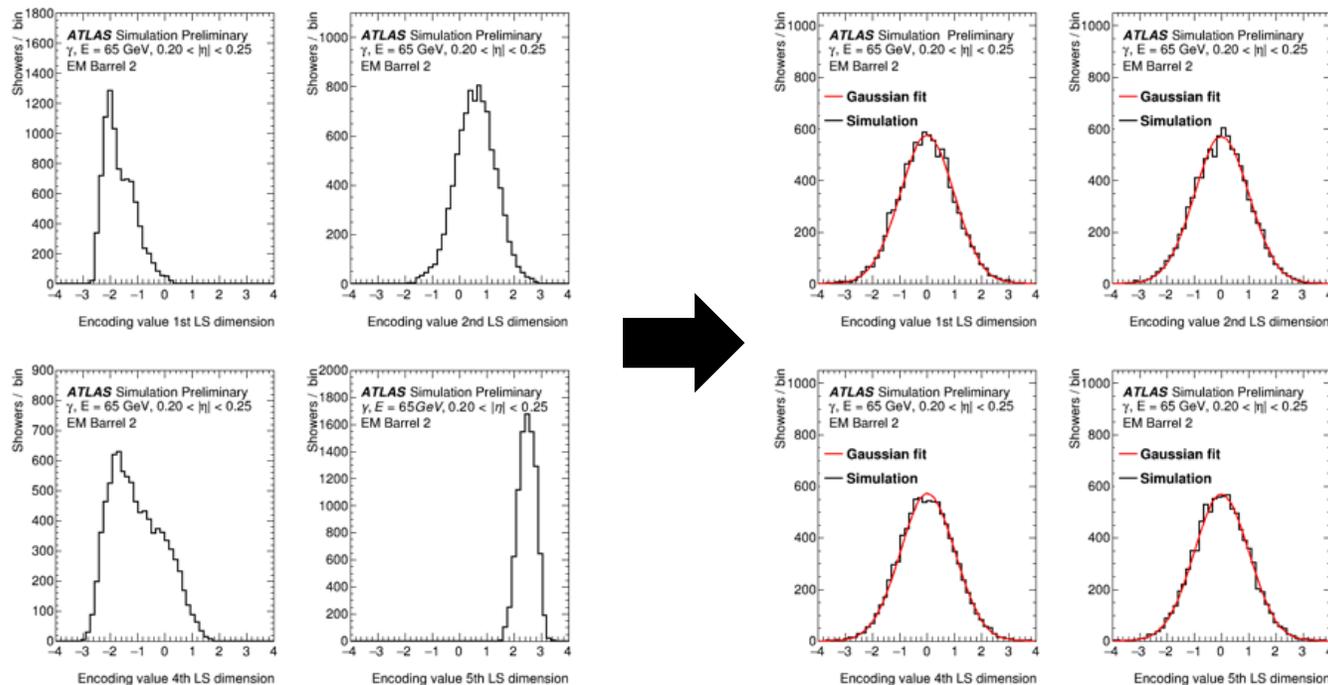
各セルのエネルギー(E_{cell})の代わりに
エネルギー比($E_{\text{total}}, E_{\text{layer}}/E_{\text{total}}, E_{\text{cell}}/E_{\text{layer}}$)
を予測



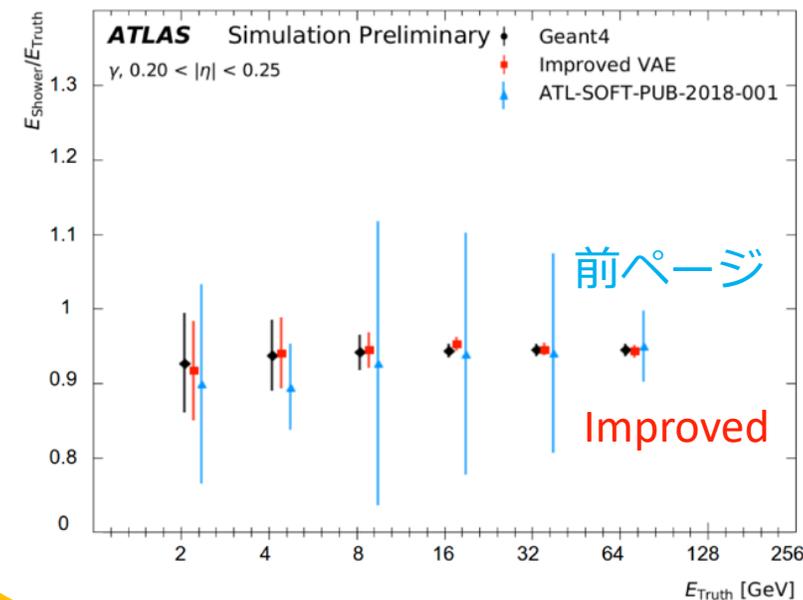
latent space(z)の分布

Original

Normalizing Flowの導入

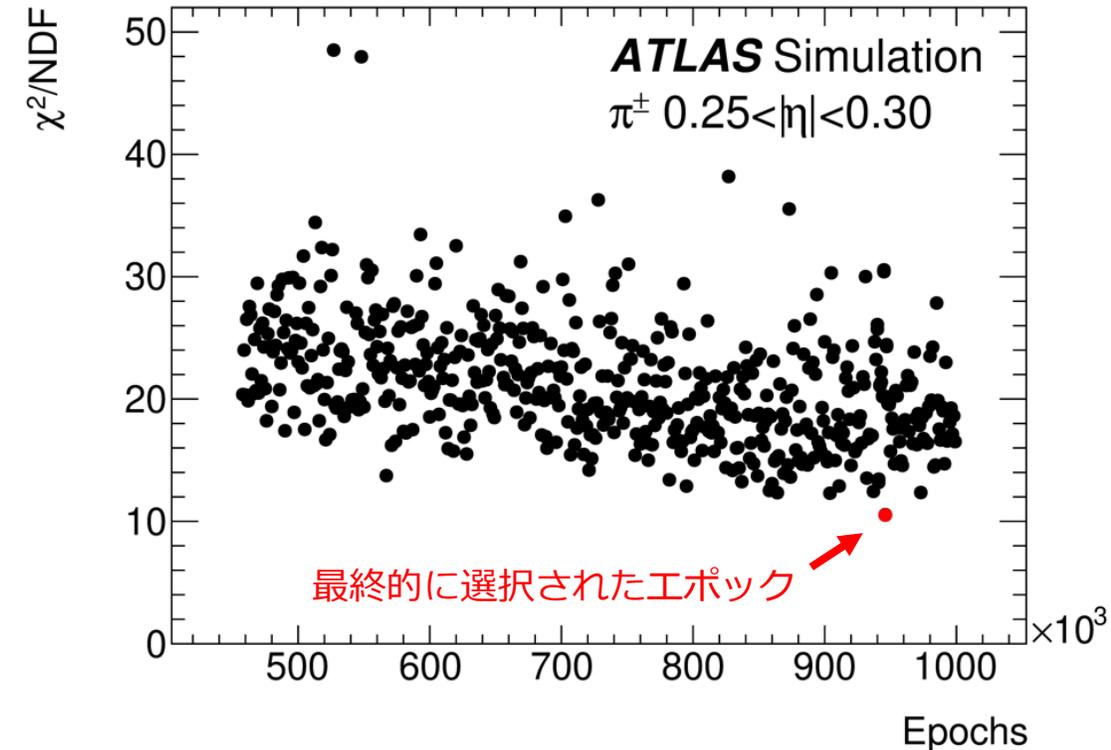


[ATL-PLOTS-SIM-2019-003](#)

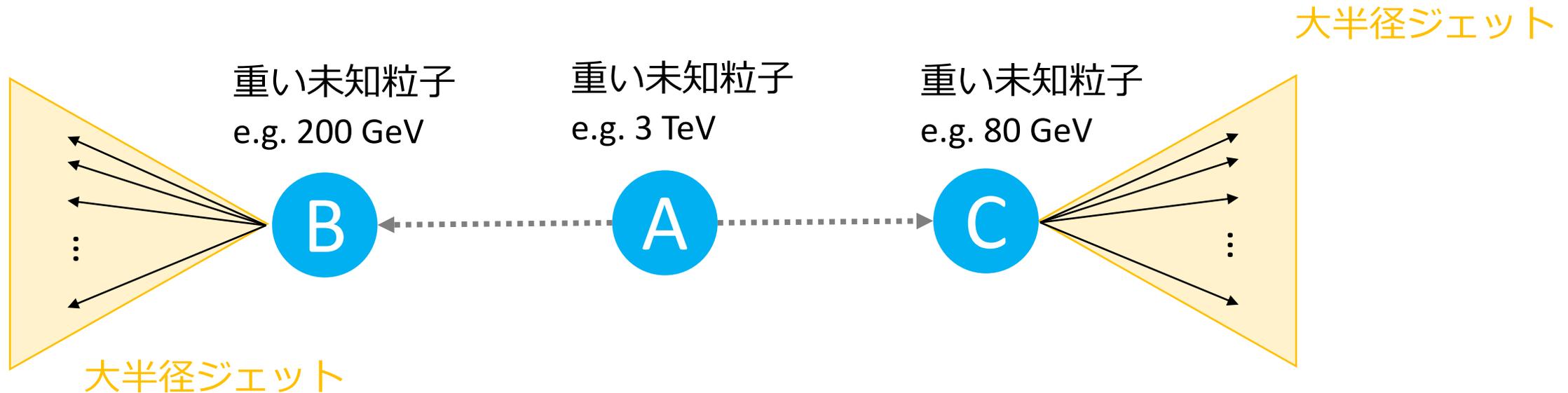


- 学習サンプルの逐次投入
 - 全エネルギー領域(256 MeV ~ 4 TeV)を一気に学習するのではなく、1つのエネルギーポイント(32 GeV)を中心に徐々に学習サンプルを拡張
 - 全サンプル追加後は全てのサンプルを使って学習
- Best エポックの選び方
 - 最後のエポックが最適とは限らない
 - 総エネルギー量の分布がGANとGeant4でどの程度あっているかを χ^2 で定義し、それを基にベストなエポックを選択
- 1つのGANモデルの学習時間は **8時間** ほど (V100使用)

学習中の χ^2 の推移

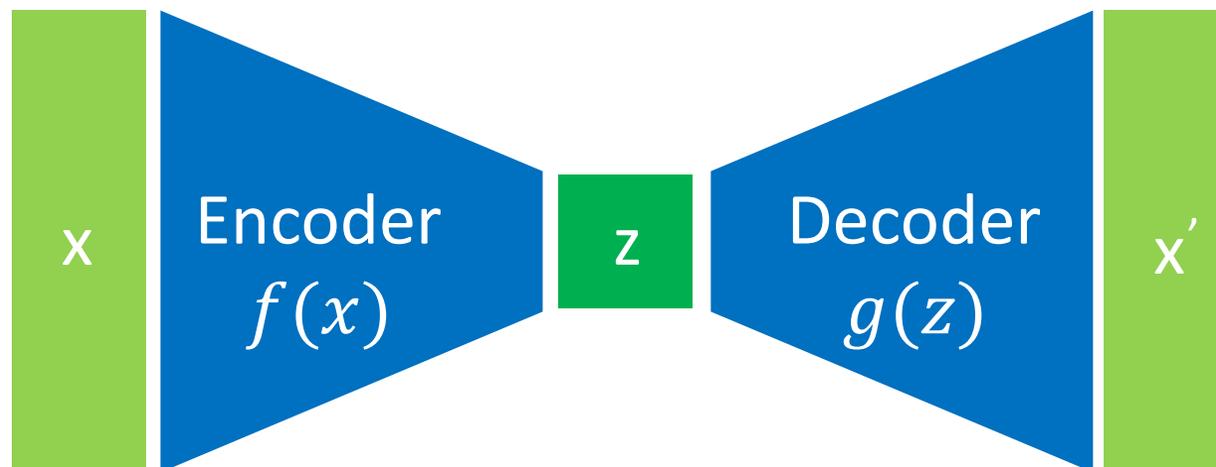


シグナルモデル



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

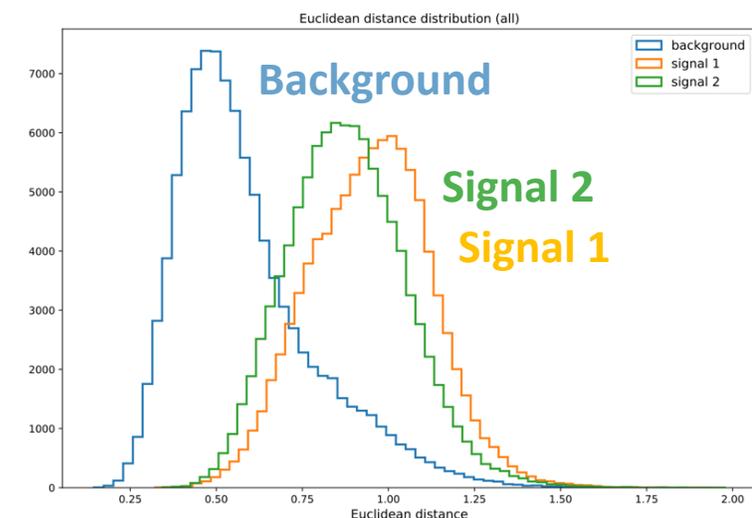
$$m_B, m_C \sim \mathcal{O}(100 \text{ GeV})$$



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

- 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

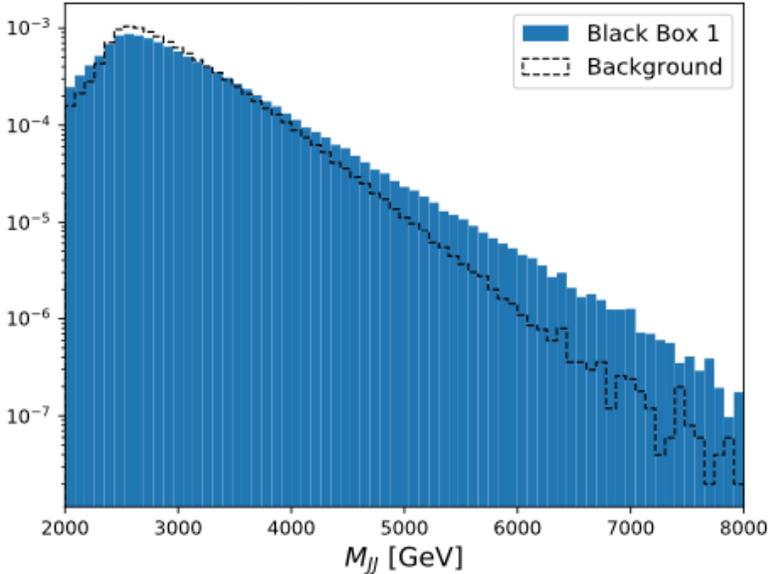
等のアノマリーとして判定できる。



再構成エラー($\|X - X'\|^2$) 42

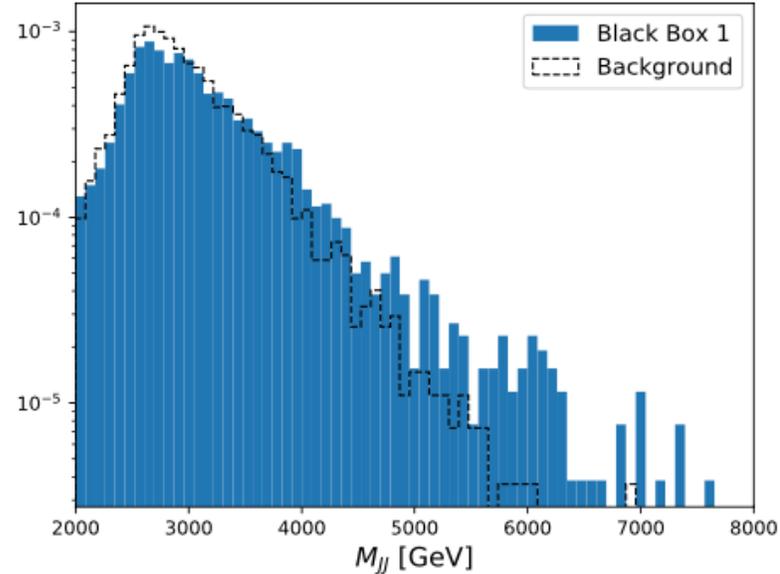
No selection

Black Box 1: Dijet Mass, No Event Score Cut

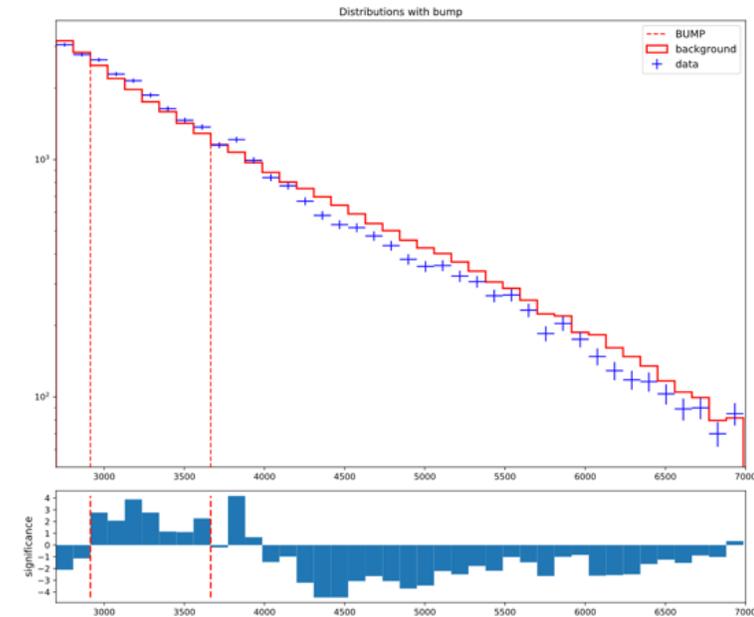


anomaly scoreでcut後

Black Box 1: Dijet Mass, EventScore > 0.75

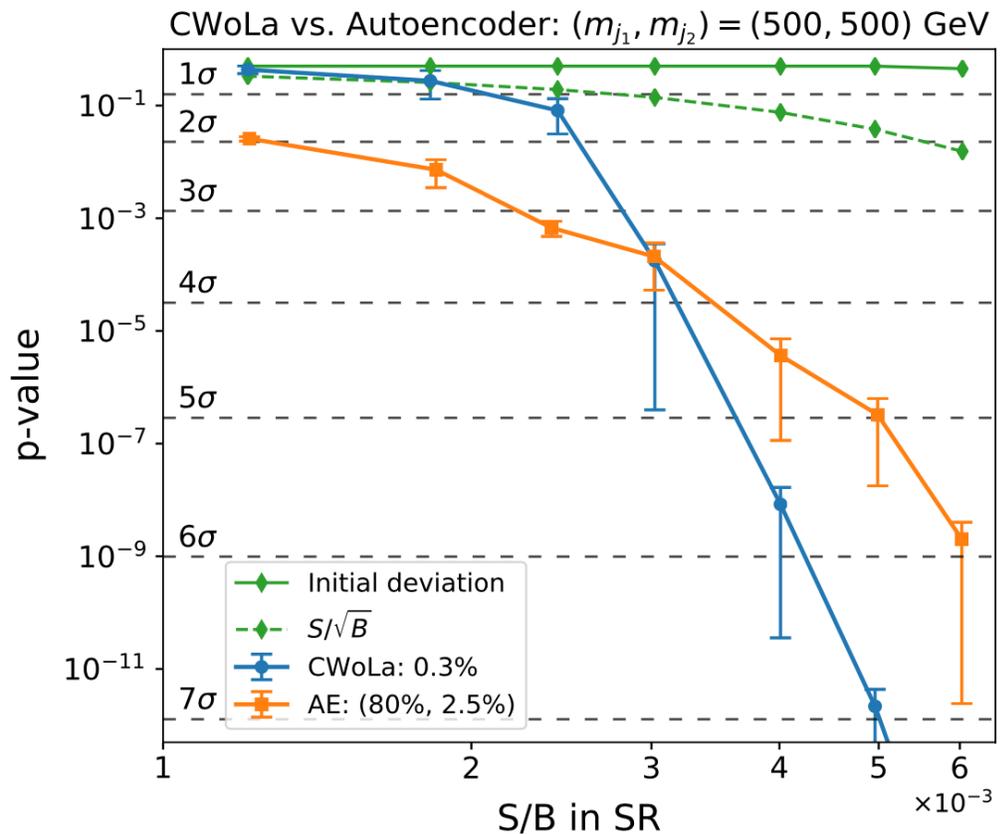
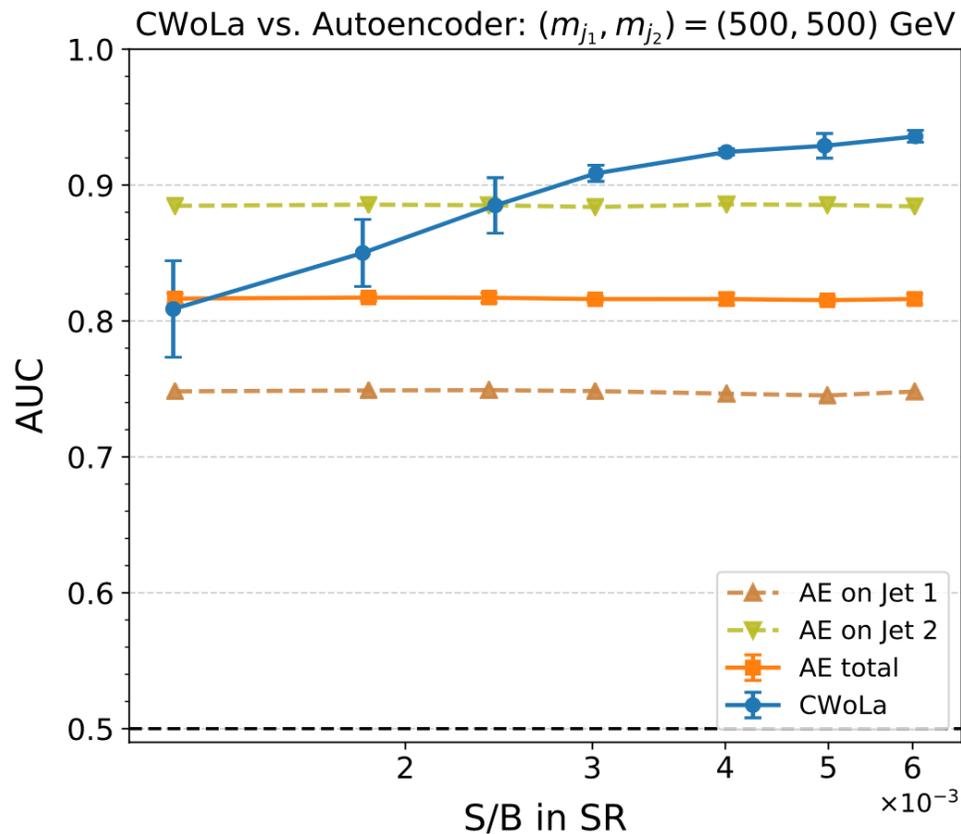


anomaly scoreでcut後

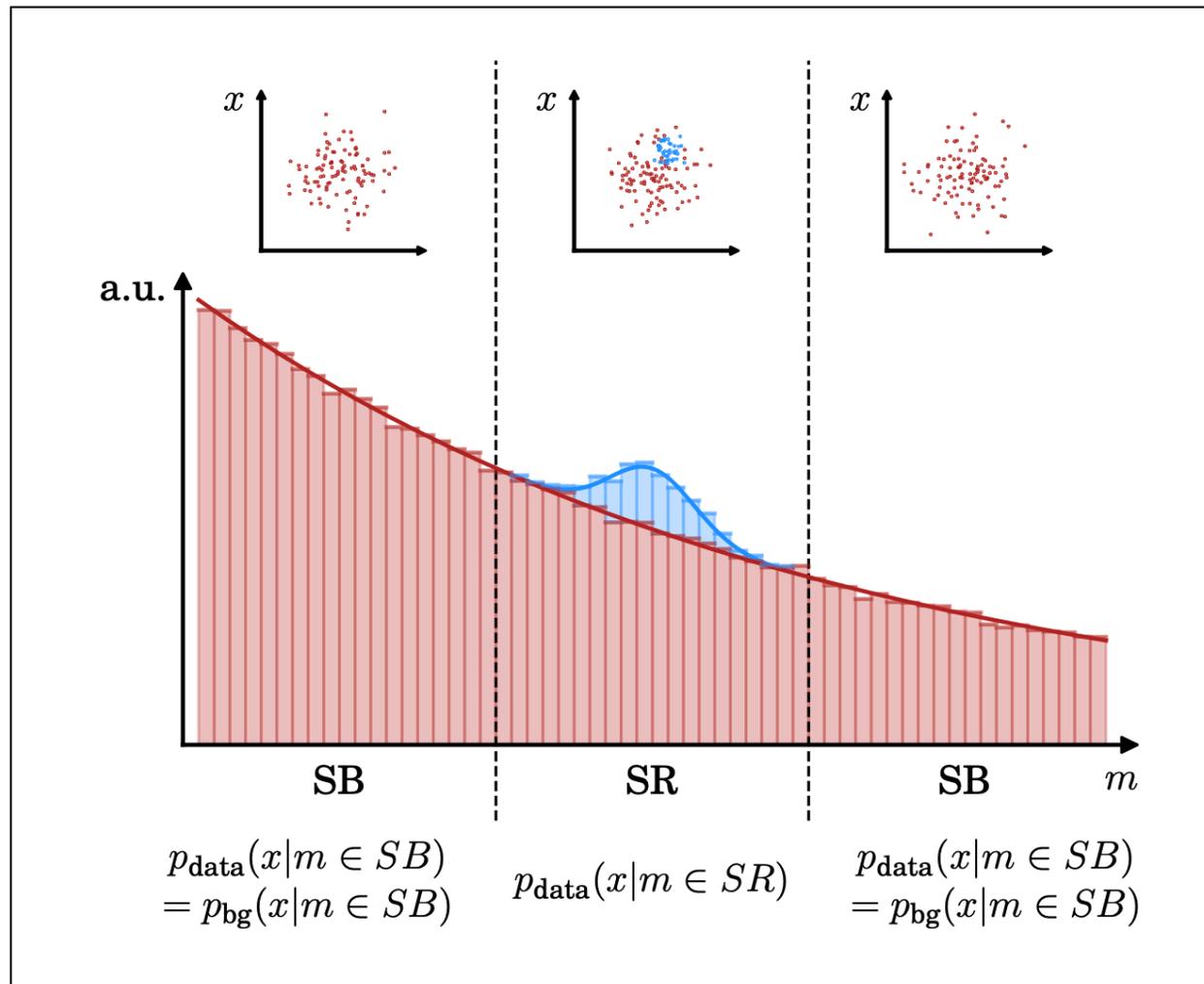


- R&DデータでVAEの学習をした例
- 学習データにバイアスがあるためうまくいかなかった

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



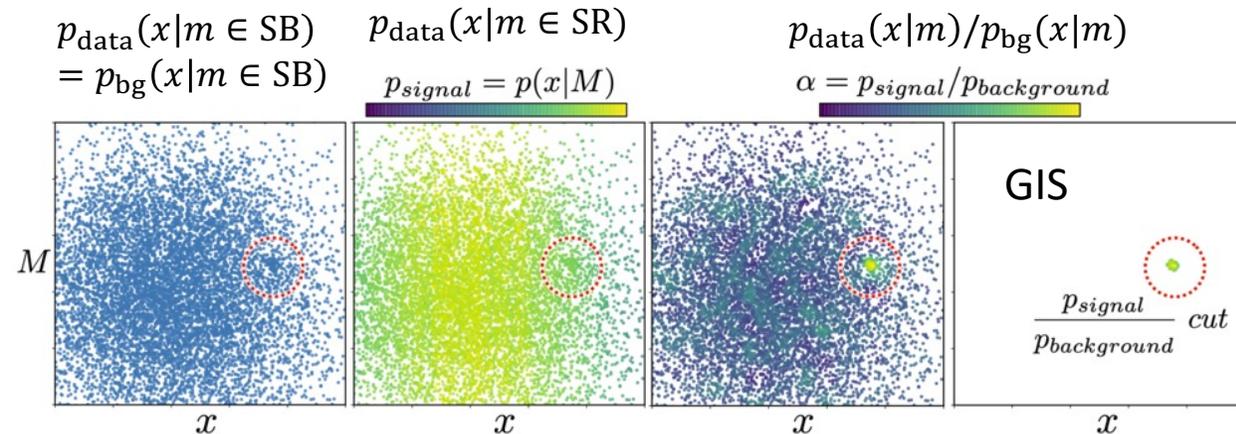
- S/Bが小さいとCWoLaは性能が悪くなる。VAEの性能はS/Bに依存しない
 - VAEは **BG分布** をモデリングする。
 - CWoLaは **Signal分布とBG分布の差** をモデリングする。



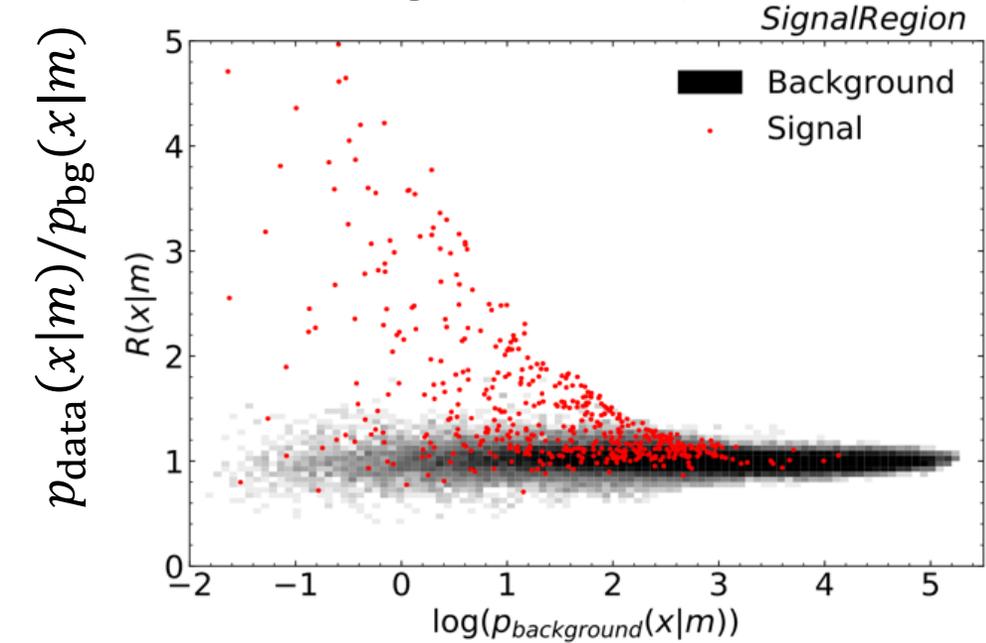
2109.00546

手法

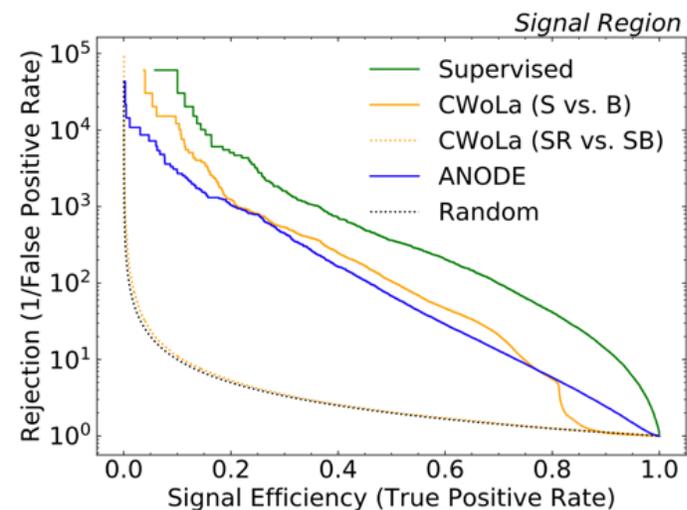
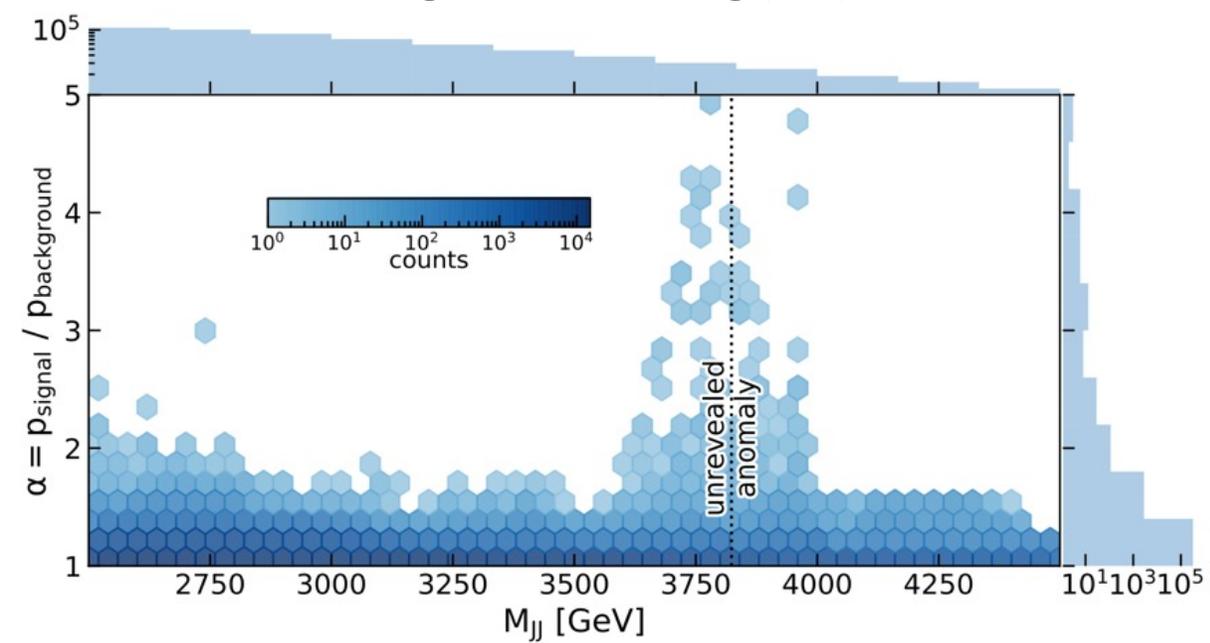
1. NNでSRの分布 $p_{\text{data}}(x|m \in SR)$ フィット
2. NNでSBの分布 $p_{\text{data}}(x|m \in SB)$ フィット
 - $p_{\text{data}}(x|m \in SB) = p_{\text{bg}}(x|m \in SB)$
3. SBで推定した分布をSRに内挿
4. $p_{\text{data}}(x|m)/p_{\text{bg}}(x|m)$ を分類器として使う



Masked Autoregressive Flow (MAF)を使った例

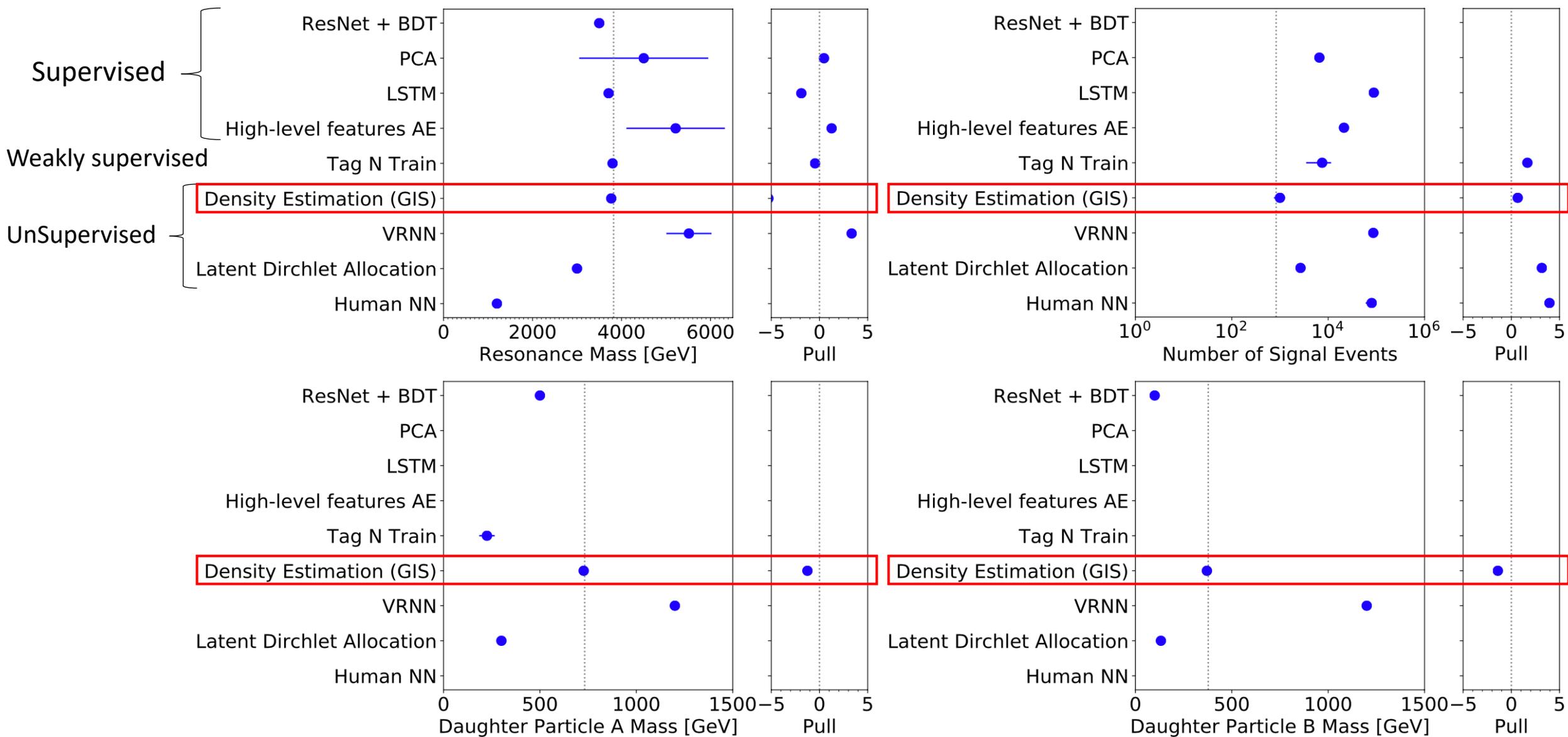


Gaussianizing Iterative Slicing (GIS)を使った例



- 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**

Section	Short Name	Method Type	Results Type
3.1	VRNN	Unsupervised	(i) (BB2,3) and (ii) (BB1)
3.2	ANODE	Unsupervised	(iii)
3.3	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	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

$$\text{Original GAN : } L(G, D) = \mathbb{E}_{\tilde{x} \sim p_{\text{gen}}} [\log (1 - D(\tilde{x}))] + \mathbb{E}_{x \sim p_{\text{Geant4}}} [\log D(x)]$$

$$\text{WGAN-GP : } L(G, D) = \mathbb{E}_{\tilde{x} \sim p_{\text{gen}}} [D(\tilde{x})] - \mathbb{E}_{x \sim p_{\text{Geant4}}} [D(x)] + \lambda \mathbb{E}_{x \sim p_{\hat{x}}} [(\|\Delta_{\hat{x}} D(\hat{x})\|_2 - 1)^2]$$

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