New LHC Simulation Methods
How to GAN

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based on 1907.03764, 1912.0047 and 1912.08824
with Marco Bellagente, Anja Butter, Gregor Kasieczka and Tilman Plehn
The HEP trinity

Theory
- Fundamental Lagrangian
  - Perturbative QFT
- Standard Model vs. new physics
  - Matrix elements, loop integrals

Experiment
- Complex detector
  - ATLAS, CMS, LHCb, ...
- Reconstruction of individual events
  - Big data: jet images, tracks, ...

Precision simulations
- First-principle Monte Carlo generators
  - Simulation of parton/particle-level events
    - HERWIG, PYTHIA, SHERPA, MADGRAPH, ...
- Detector simulation
  - Geant4, PGS, Delphes, ...

⇒ Unweighted event samples
Neural networks for precision simulations

Problems in MC simulations

- High-dimensional phase space
- Low unweighting efficiency
- Slow detector simulations

Solution with neural networks

- Flexible parametrisation
- Automatic adaption
- Fast evaluation
- Great interpolation properties
Generative Adversarial Networks

GAN algorithm

- **Training data:** true events \( \{x_T\} \)
  - **Output data:** generated events \( \{x_G\} \)
- **Discriminator** distinguishes \( \{x_T\}, \{x_G\} \)
  \[ D(x_T) \rightarrow 1, \quad D(x_G) \rightarrow 0 \]
  \[ L_D = \langle - \log D(x) \rangle_{x \sim P_T} + \langle - \log(1 - D(x)) \rangle_{x \sim P_G} \xrightarrow{D(x) \rightarrow 0.5} -2 \log 0.5 \]
- **Generator** fools discriminator
  \[ D(x_G) \rightarrow 1 \]
  \[ L_G = \langle - \log D(x) \rangle_{x \sim P_G} \]

\( \Rightarrow \) **New statistically independent samples**

![Diagram of GAN algorithm](image-url)
GANgogh

Edmond de Belamy [Caselles-Dupre, Fautrel, Vernier, 2018]

- Trained on 15,000 portraits
- Sold for $432,500
- New independent portrait!
GANs at the LHC

A lot of experience as community [since 2017]

- **Jet images** [1701.05927, 1909.01359]
- **Event generation** [1901.00875, 1901.05282, 1903.02433, 1907.03764, 1912.02748, 2001.11103]
- **Unfolding** [1806.00433, 1912.0047]
- **EFT models** [1809.02612]
- **Mass templates** [1903.02556]
- **Event subtraction** [1912.08824]
- ...

Young Scientists Forum Ramon Winterhalder
1 - How to GAN LHC events

Idea: generate hard process

- Realistic LHC final state $t\bar{t} \rightarrow 6$ jets \[1907.03764\]
- Flat observables flat ✓
- Systematic undershoot in tails [10-20% deviation]
1 - How to GAN LHC events

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- Sharp phase-space structures ✓ [additional Loss $\rightarrow$ encodes physics]
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- Sharp phase-space structures ✓ [additional Loss $\rightarrow$ encodes physics]
- 2D correlations ✓
2 - How to GAN event subtraction

Idea: sample based subtraction of distributions [1912.08824]

• Beat bin-induced statistical uncertainty [interpolation of distributions]

\[
\Delta_{B-S} = \sqrt{n_B^2N_B + n_S^2N_S} > \max(\Delta_B, \Delta_S)
\]

• Many applications:
  - Soft-collinear subtraction, multi-jet merging, on-shell subtraction
  - Background subtraction [4-body decays → preserves correlations]
2 - How to GAN event subtraction

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• Many applications:
  - Soft-collinear subtraction, multi-jet merging, on-shell subtraction
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• Example: event-based background subtraction $\rightarrow$ generate Z-Pole events [+ interference]
### 3 - How to GAN away detector effects

**Idea: invert Markov process** [1912.0047]

**Detector simulation**
- Typical Markov process
- Inversion possible, in principle

**Reconstruct parton level** $pp \rightarrow ZW \rightarrow (ll)(jj)$
- Use **fully conditional** GAN (FCGAN)

![Diagram of the GAN model](image)

- $\ell^-$
- $\ell^+$
- $W$
- $j$
- $j$
- $\ell^+$
- $\ell^-$

- $L_D$
- $L_G$
- $\{x_P\}$
- $\{x_G\}$
- $\{x_d\}$
- $G$
- $D$
- $\{r\}$
- detector
- parton
- MMD
- Condition

You can use this template to create your own diagrams and visualizations.
3 - How to GAN away detector effects

Idea: invert Markov process [1912.0047]

Detector simulation
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Reconstruct parton level $pp \rightarrow ZW \rightarrow (ll)(jj)$
- Use fully conditional GAN (FCGAN)
- Inversion works ✓
- BSM injection ✓
  - train: SM events
  - test: 10% events with $W'$ in s-channel

![Diagram showing parton level reconstruction](image)

Truth (SM)
FCGAN
Delphes

Truth (W')
FCGAN

$\frac{d\sigma}{d m_{jj}}$ [GeV$^{-1}$]
$\sigma$ [GeV$^{-1}$]

$70.0, 72.5, 75.0, 77.5, 80.0, 82.5, 85.0, 87.5, 90.0$

$600, 800, 1000, 1200, 1400, 1600, 1800, 2000$

$0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0$

$0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0$

$\times 10^{-1}$
$\times 10^{-3}$
Outlook

LHC physics is big data!

- Directly training on MC/data
  → GAN reproduces full phase-space structure
- Smooth interpolations
  → Sample based subtraction methods
- Latent/phase space structures
  → Locality preserving unfolding (FCGAN)

Open questions

- Uncertainties in GANs?
- Ultimate precision?
Appendix