New LHC Simulation Methods
How to GAN

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TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

PTFS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

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, ...

$\Rightarrow$ **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

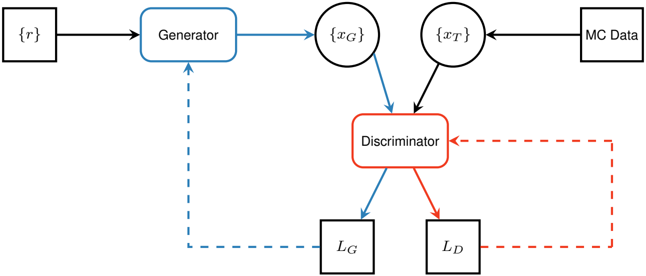
- Training data: true events $\{x_T\}$
  Output data: generated events $\{x_G\}$
- **Discriminator** distinguishes $\{x_T\}, \{x_G\}$ $[D(x_T) \to 1,\, D(x_G) \to 0]$

$$L_D = \big\langle -\log D(x) \big\rangle_{x \sim P_T} + \big\langle -\log(1 - D(x)) \big\rangle_{x \sim P_G} \xrightarrow{D(x) \to 0.5} -2 \log 0.5$$

- **Generator** fools discriminator $[D(x_G) \to 1]$

$$L_G = \big\langle -\log D(x) \big\rangle_{x \sim P_G}$$

$\Rightarrow$ **New statistically independent samples**



GANgogh

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

- Trained on 15,000 portraits
- Sold for $432,500
- **New independent potrait!**

GANs at the LHC

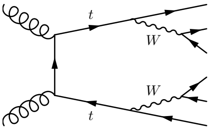
A lot of experience as community [since 2017]

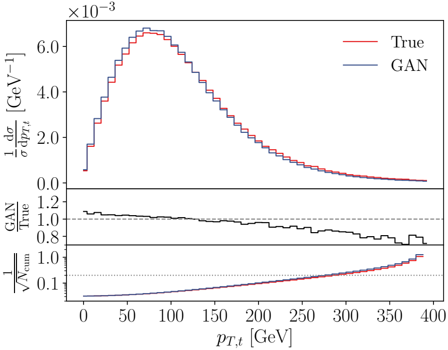
- Jet images [1701.05927, 1909.01359]
- Calorimeters [1705.02355, 1712.10321, 1805.00850, 1807.01954, ATL-SOFT-PUB-2018-001/2019-007, 2005.05334]
- Event generation [1901.00875, 1901.05282, 1903.02433, 1907.03764, 1912.02748, 2001.11103]
- Unfolding [1806.00433, 1912.0047]
- EFT models [1809.02612]
- Mass templates [1903.02556]
- Event subtraction [1912.08824]
- ...

1 - How to GAN LHC events

Idea: generate hard process

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





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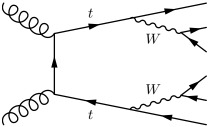

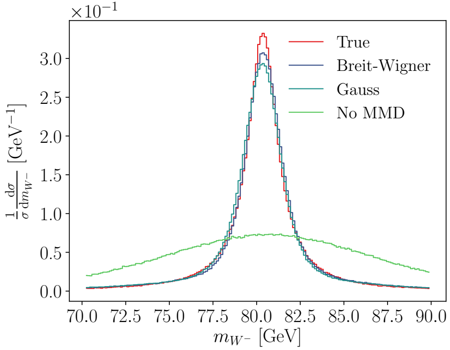

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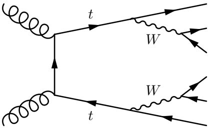
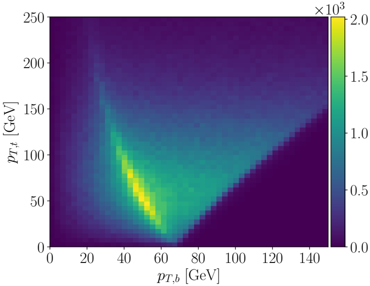
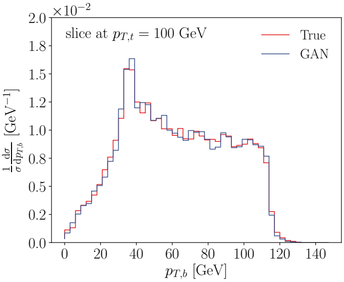
- 2D correlations ✓







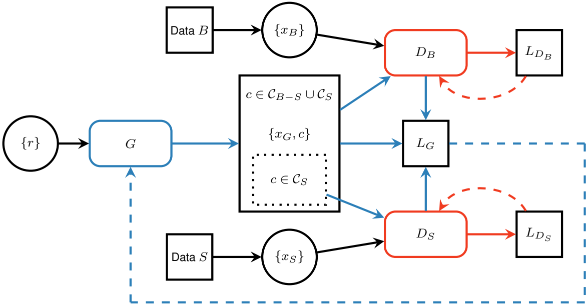
2 - How to GAN event subtraction

Idea: sample based subtraction of distributions [1912.08824]

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

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

- Many applications:
  - Soft-collinear subtraction, multi-jet merging, on-shell subtraction
  - Background subtraction [4-body decays $\longrightarrow$ preserves correlations]



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- Many applications:
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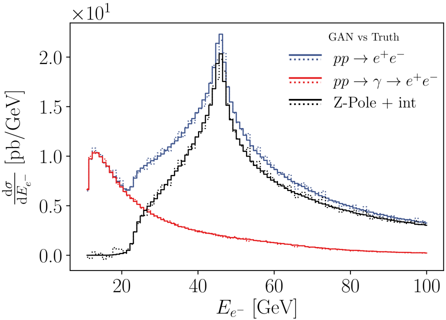
  - Background subtraction [4-body decays $\longrightarrow$ preserves correlations]
- Example: event-based background subtraction $\longrightarrow$ generate Z-Pole events [+ interference]



3 - How to GAN away detector effects

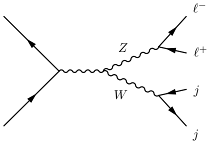
Idea: invert Markov process [1912.0047]

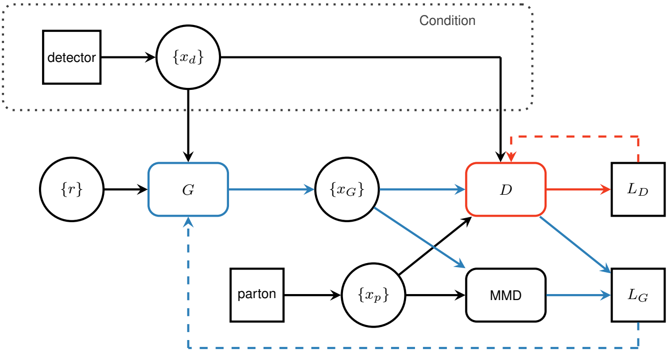
Detector simulation

- Typical Markov process
- Inversion possible, in principle

Reconstruct parton level $pp \to ZW \to (ll)(jj)$

- Use **fully conditional** GAN (FCGAN)





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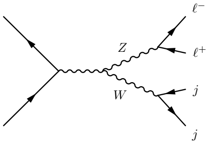
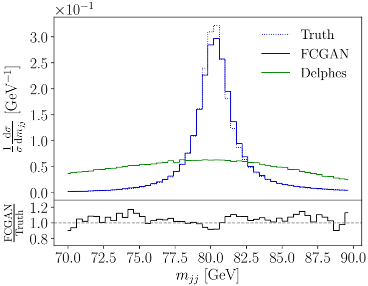
Detector simulation

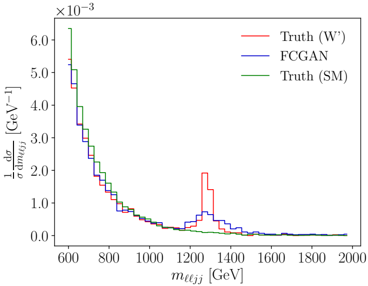
- Typical Markov process
- Inversion possible, in principle

Reconstruct parton level $pp \to ZW \to (ll)(jj)$

- Use **fully conditional** GAN (FCGAN)
- Inversion works ✓
- BSM injection ✓
  - train: SM events
  - test: 10% events with W' in s-channel







Outlook

LHC physics is big data!

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

Open questions

- Uncertainties in GANs?
- Ultimate precision?

Appendix