Jet grooming through reinforcement learning

based on PRD 100, 014014, arXiv:1903.09644

Stefano Carrazza and Frédéric Dreyer

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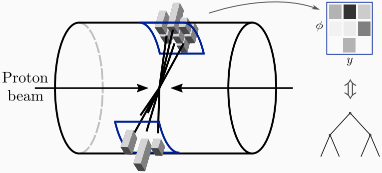
Introduction

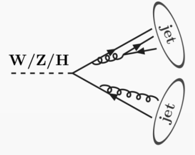
Boosted jets at the LHC

High energy collisions at the LHC $\Rightarrow$ **boosted objects**:

- particles such as W, Z, H, $t, \ldots$ are produced with $p_T^{\text{jet}} \gg m_{\text{jet}}$,
- hadronic collimated decays often reconstructed into single jets.



$p_T^{\text{jet}} \leq m_{\text{jet}}$



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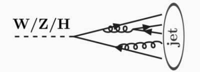

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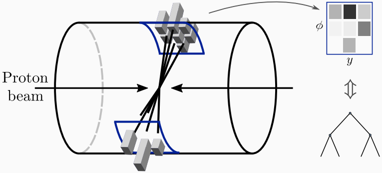

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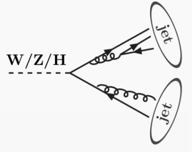

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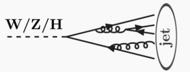
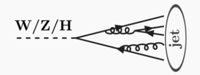


Problem: identify **hard structure** of a jet from **radiation patterns**.

(Jet from W, Z, H, t or QCD?)

$p_T^{\text{jet}} \gg m_{\text{jet}}$



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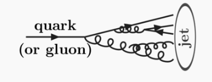

Jet drawings by G. Soyez

Jet grooming techniques

How to identify hard structure of a jet?

- Look at the mass of the jet.
- Remove distortion due to QCD radiation and pileup.

Grooming goal $\Rightarrow$ remove unassociated soft wide-angle radiation.

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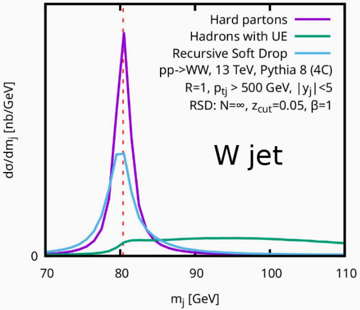
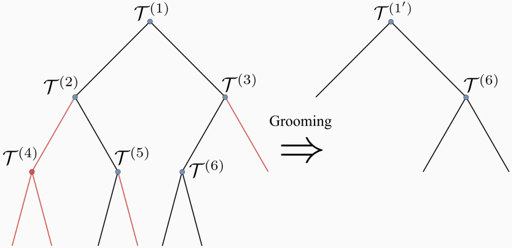
Jet grooming algorithms:

- modified MassDrop Tagger
  Dasgupta *et al.*, arXiv:1307.0007
- Soft Drop (SD)
  Larkoski *et al.*, arXiv:1402.2657
- Recursive Soft Drop (RSD)
  Dreyer *et al.*, arXiv:1804.03657



(Recursive) Soft Drop algorithm



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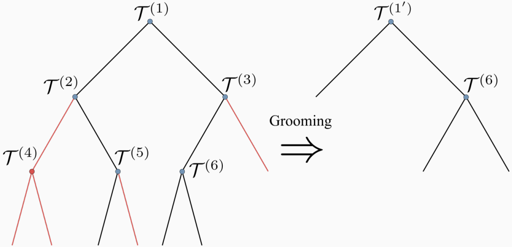

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2. Define state of each node as $s_t = \{z, \Delta_{ab}\}$ where

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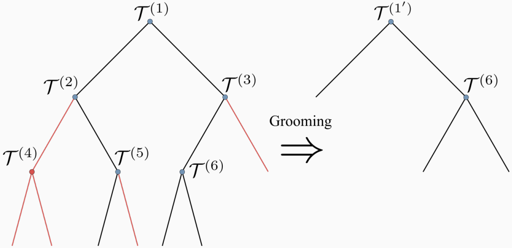

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3. Evaluate policy (β, z_{cut} and R_0 are free parameters):

$$\pi_{\mathrm{RSD}}(s_t) = \begin{cases} 0 & \text{if} \quad z > z_{\mathrm{cut}} \left(\frac{\Delta_{ab}}{R_0}\right)^{\beta} \\ 1 & \text{else} \end{cases}$$

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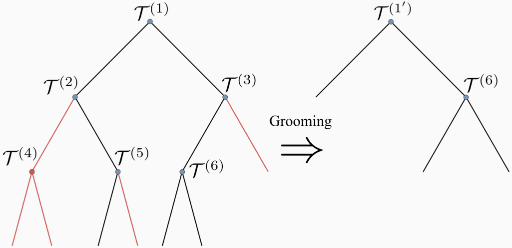

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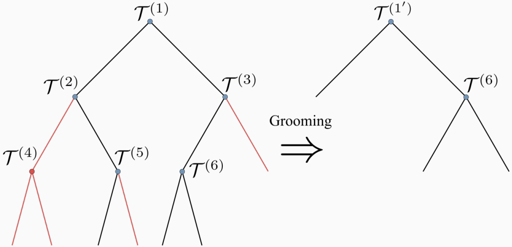

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4. If $\pi_{\rm RSD}(s_t) = 1 \to$ remove softer branch and update jet tree,
5. If $\pi_{\rm RSD}(s_t) = 0 \to$ stop recursion.

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How?

- using Deep Reinforcement Learning (DRL) techniques.

A deep learning approach

Grooming a jet tree with DRL

Input data:

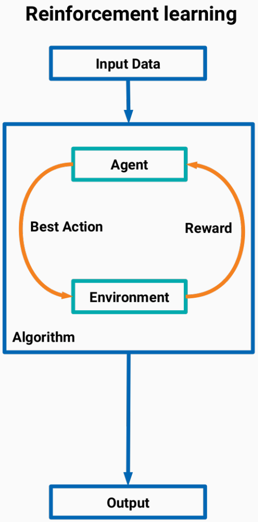
Generate jet events with Monte Carlo. Define a set of possible **states** in a five dimensional box:

$$s_t = \{z, \Delta_{ab}, \phi, m, k_t\}$$

Methodology:

Jet grooming is characterized by a policy and a sequential set of actions/cuts, so:

- Train a reinforcement learning agent which learns how to decide which action to take.
- Define an environment reward which motivates the agent to groom efficiently.



Choosing an DRL agent

Which agent?

Deep Q-Network $\rightarrow$ off-policy and discrete action space.

A deep neural network maximizes the action-value quality function:

$$Q^*(s,a) = \max_{\pi} \mathbb{E}\left[r_t + \gamma r_{t+1} + \gamma^2 r_{t+2} + \cdots | s_t = s, a_t = a, \pi\right]$$

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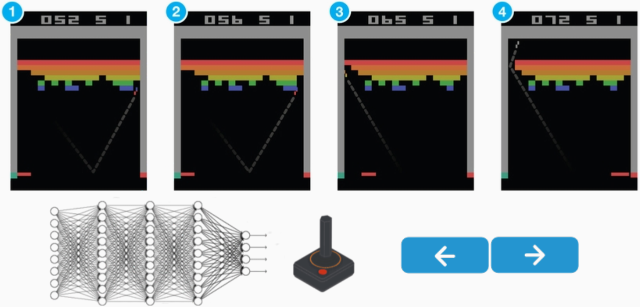
A simple example:

Playing ATARI games with DRL from Minh *et al.*, arXiv:1312.5602, Nature'15:



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- Hyperparameter tune?
  obtain the best model for our specific problem

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In practice we implement the DRL framework using:

- Python $\in$ (`Keras-RL`, `TensorFlow`, `OpenAI Gym`, `hyperopt`)
- Public code available at `https://github.com/JetsGame`

Environment

Defining a jet grooming game:

Game score $\Rightarrow$ reward function *(next slides)*

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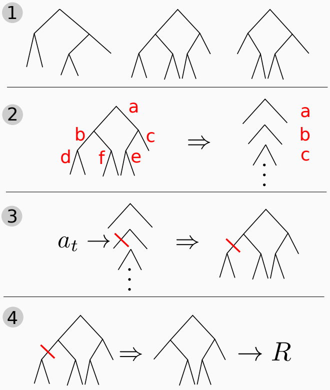
Game environment:

1. Initialize list of all trees for training.
2. Each episode starts by randomly selecting a tree and adding its root to a priority queue (ordered in Δ_{ab}).
3. Each step removes first node from priority queue, then takes action on removal of soft branch based on s_t.
4. After action, update kinematics of parent nodes, add current children to priority queue, and evaluate reward.
5. Episode terminates once priority queue is empty.



Reward function

We construct a reward function based on two components:

$$R(m, a_t, \Delta, z) = R_M(m) + \frac{1}{N_{\mathrm{SD}}} R_{\mathrm{SD}}(a_t, \Delta, z)$$

so the DQN agent is motivated to:

- improve jet mass resolution $\Rightarrow$ increase R_M,
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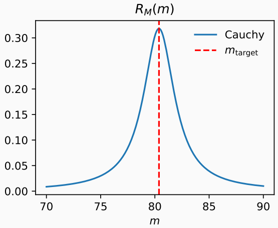
The mass reward is defined using a Cauchy distribution:

$$R_M(m) = \frac{\Gamma^2}{\pi\left(|m - m_{\mathrm{target}}|^2 + \Gamma^2\right)}$$



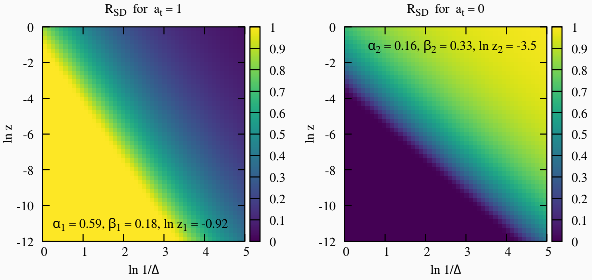
Reward function

The Soft-Drop reward is defined as

$$R_{\mathrm{SD}}(a_t, \Delta, z) = a_t \min\left(1, e^{-\alpha_1 \ln(1/\Delta) + \beta_1 \ln(z_1/z)}\right) \\ + (1 + a_t) \max\left(0, 1 - e^{-\alpha_2 \ln(1/\Delta) + \beta_2 \ln(z_2/z)}\right),$$

so the DQN agent is motivated to:

- remove wide-angle soft radiation
- keep hard-collinear emissions



Adding a multi-level approach

What about background events?

Potential mass bias for background events ⇒ use multi-level training:

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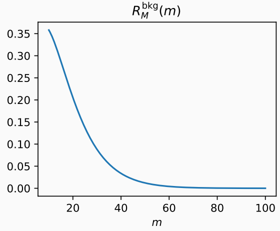
In the background case, the mass reward term is changed to:

$$R_M^{\mathrm{bkg}}(m) = \frac{m}{\Gamma_{\mathrm{bkg}}} \exp\left(-\frac{m}{\Gamma_{\mathrm{bkg}}}\right)$$



Hyperparameter tune

Free parameters to be determined:

- DQN architecture $\Rightarrow$ *(layers, nodes, activations, ...)*
- Reward parameters $\Rightarrow$ $(\alpha_{1,2},\, \beta_{1,2},\, z_{1,2},\, \Gamma)$
- Learning parameters $\Rightarrow$ *(optimizer, learning rate, ...)*

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Use distributed asynchronous hyperparameter optimization $\Rightarrow$ `hyperopt`.

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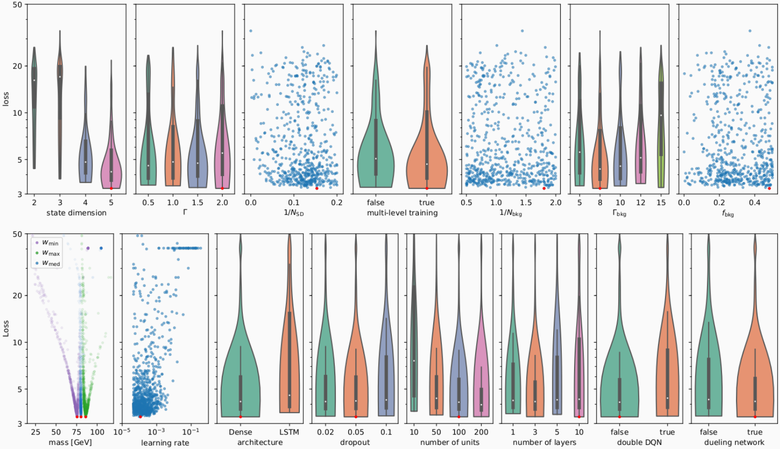
   - the median w_{med} in that interval.
3. Define f_{bkg} the fraction of groomed background sample $(w_{\min}, w_{\max})$:

$$\mathcal{L} = \frac{1}{5}|w_{\max} - w_{\min}| + |m_{\text{target}} - w_{\text{med}}| + 20 f_{\text{fkg}}$$

Hyperparameter tune

Validation loss for 2000 models



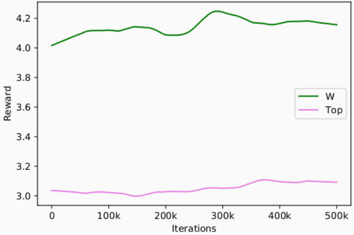
Results

Optimal GroomRL model for W and top jets

Reward evolution during the training of the GroomRL for W bosons and top quarks:

- improvement during the first 300k epochs,
- stability after 300k epochs.

$$R(m, a_t, \Delta, z)$$

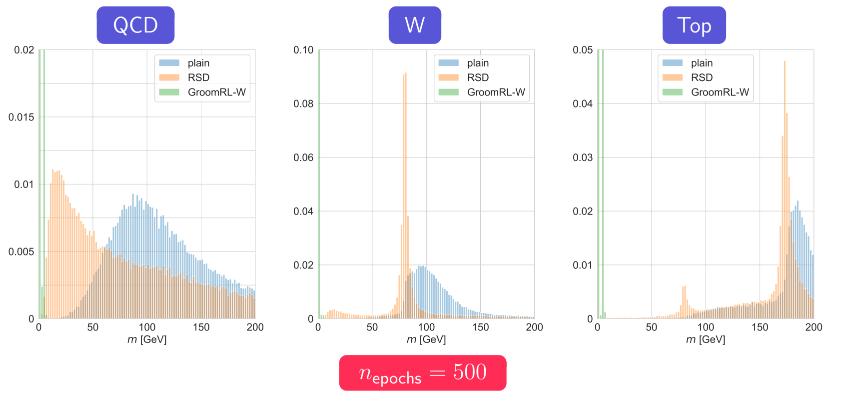


Parameters	Value
m_{target}	80.385 GeV or 173.2 GeV
s_t dimension	5
reward	Cauchy
Γ	2 GeV
$(\alpha_1, \beta_1, \ln z_1)$	$(0.59, 0.18, -0.92)$
$(\alpha_2, \beta_2, \ln z_2)$	$(0.65, 0.33, -3.53)$
$1/N_{\text{SD}}$	0.15
multi-level training	Yes
Γ_{bkg}	8 GeV
$1/N_{\text{bkg}}$	1.8 or 1.0
p_{bkg}	0.48 or 0.2
learning rate	10^{-4}
Dueling NN	Yes
Double DQN	No
Policy	Boltzmann
$N_{\text{epochs}}^{\text{max}}$	500K
Architecture	Dense
Dropout	0.05
Layers	10
Nodes	100
Optimizer	Adam

TABLE I: Final parameters for GroomRL, with the two values of m_{target} corresponding to the W and top mass.

DRL training animation

GroomRL-W predictions vs n_{epochs}



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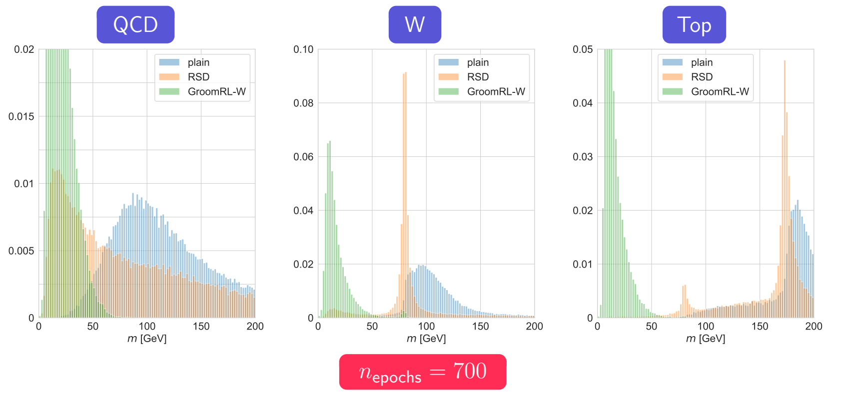
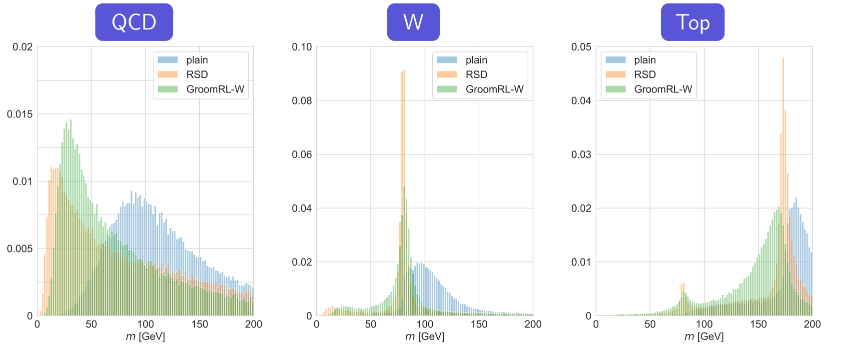


DRL training animation

`GroomRL-W` predictions vs n_{epochs}



$n_{\text{epochs}} = 1k$

DRL training animation

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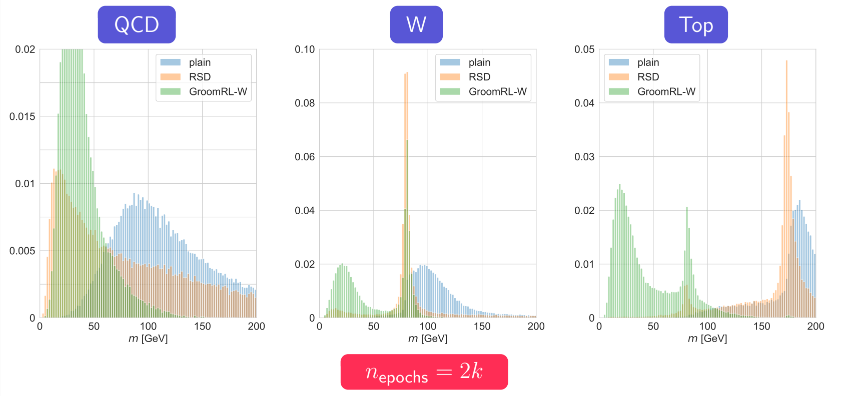

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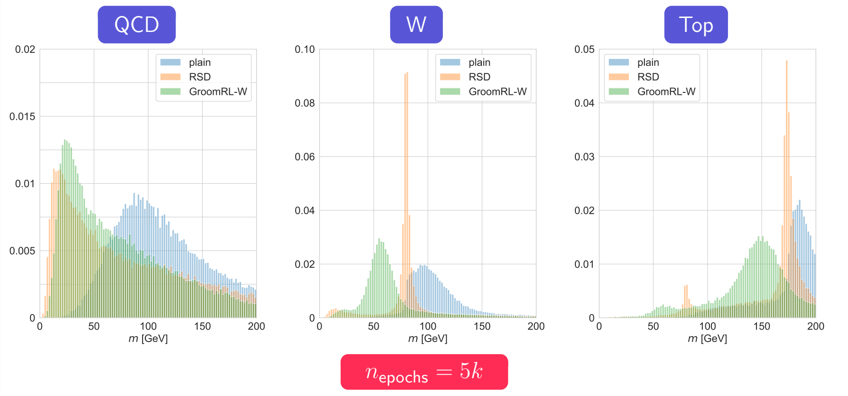

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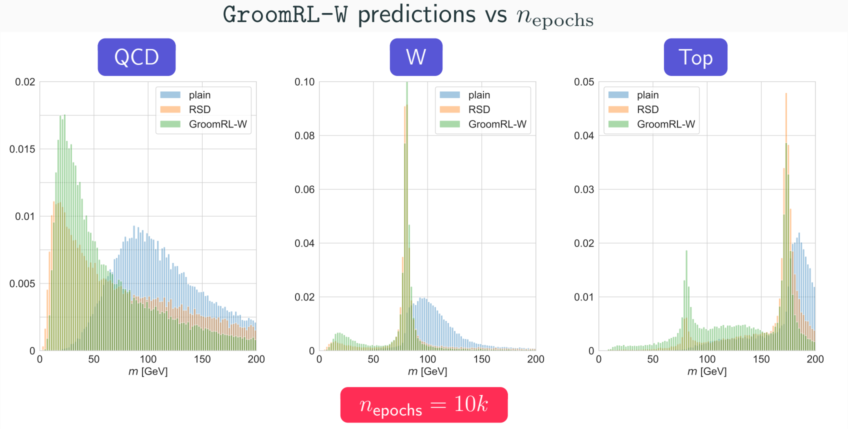

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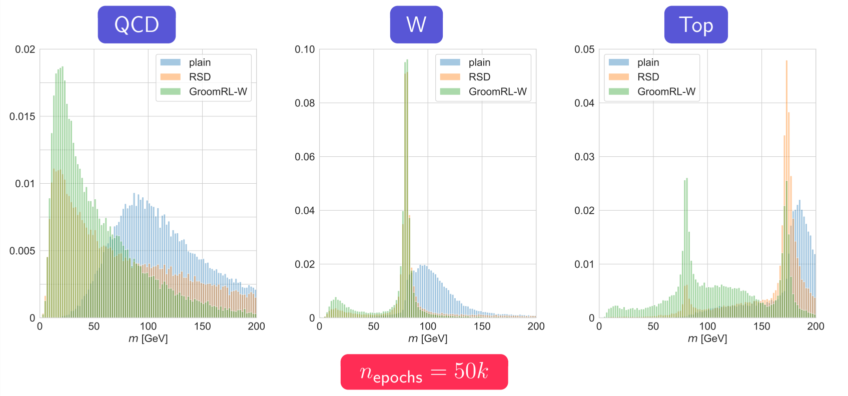

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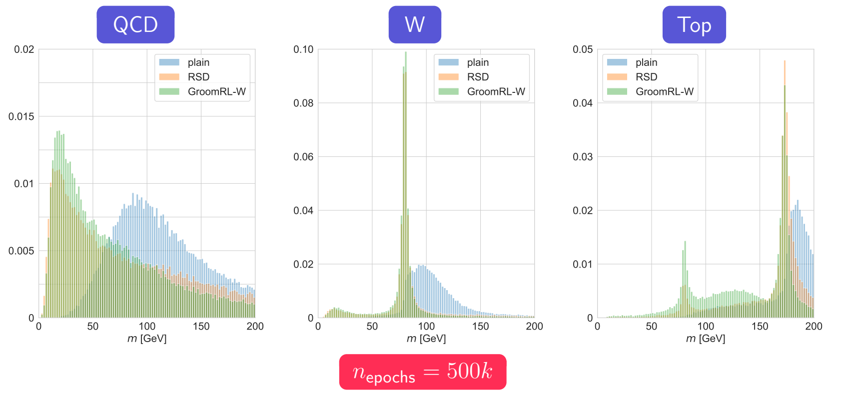
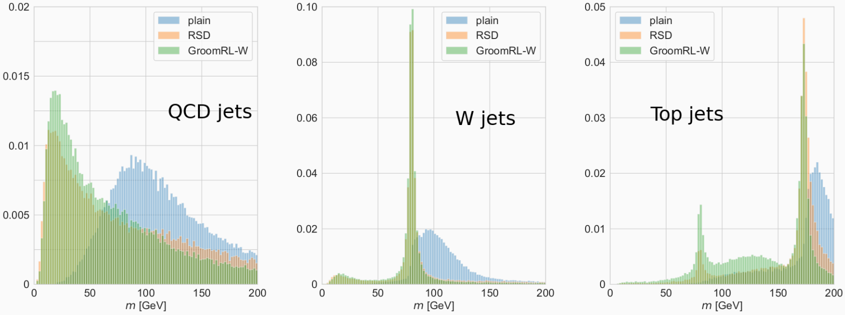


Optimal GroomRL model for W jets

GroomRL-W tested on QCD, W and Top jet data

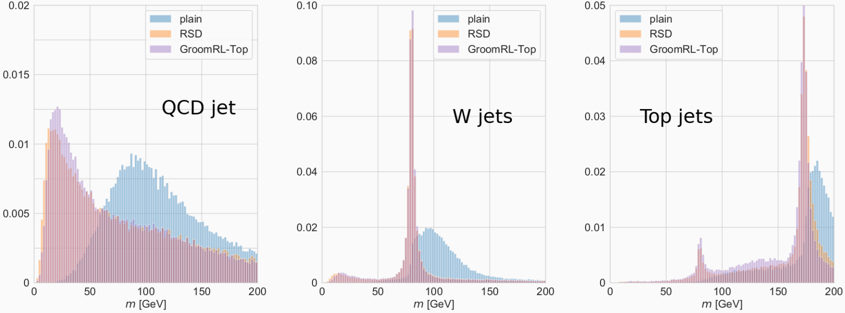


	$w_{\max} - w_{\min}$ [GeV]	w_{med} [GeV]
plain	44.65	104.64
GroomRL-W	10.70	80.09
GroomRL-Top	13.88	80.46
RSD	16.96	80.46

TABLE II: Size of the window containing 60% of the W mass spectrum, and median value on that interval.

Optimal GroomRL model for W jets

GroomRL-Top tested on QCD, W and Top jet data

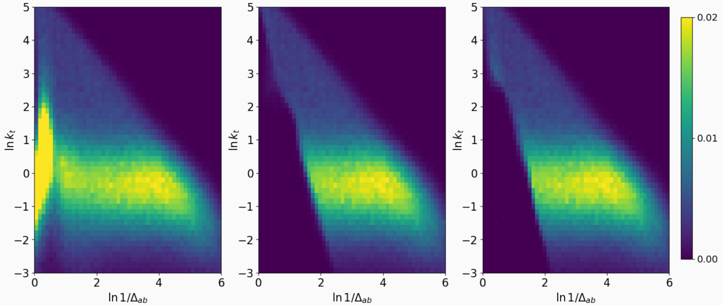


	$w_{\max} - w_{\min}$ [GeV]	w_{med} [GeV]
plain	44.65	104.64
GroomRL-W	10.70	80.09
GroomRL-Top	13.88	80.46
RSD	16.96	80.46

TABLE II: Size of the window containing 60% of the W mass spectrum, and median value on that interval.

Lund jet plane density

Lund jet plane before and after applying GroomRL



(a) Plain (b) GroomRL-W (c) GroomRL-Top

Inspecting $(\ln 1/\Delta_{ab}, \ln k_t) \Rightarrow$ soft and wide-angle radiation removed.

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- GroomRL complete python framework available at:
  https://github.com/JetsGame/GroomRL
  (contains pre-trained W and top jet DQN models)
- libGroomRL a C++ library for jet grooming models inference:
  https://github.com/JetsGame/libGroomRL
- Datasets for top, W and QCD jets at:
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Conclusions

- Reinforcement learning can be applied to jet grooming successfully.
- Results are quantitatively similar to RSD with moderate improvement in mass resolution.
- Remarkable model generalization when changing underlying process without retraining.

Thank you!