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Encoding off-shell effects in top pair production in direct diffusion networks

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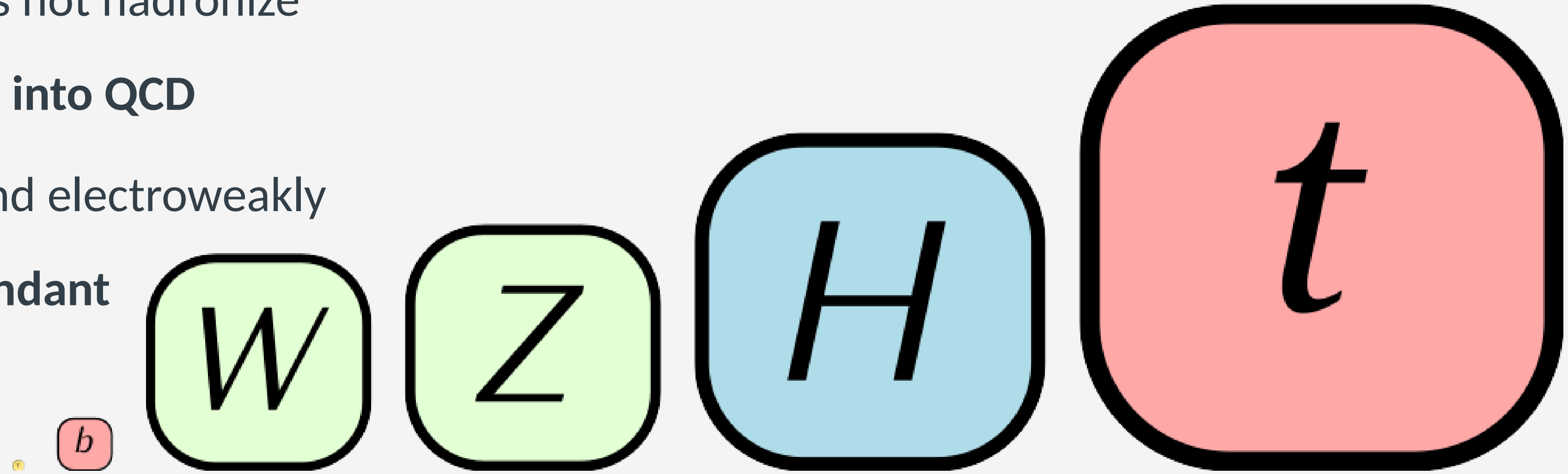
The top quark

- Heaviest fundamental particle
  - **Couples the strongest to the Higgs boson**
- Only coloured particle that does not hadronize
  - **May give us greater insight into QCD**
- Produced at the LHC strongly and electroweakly
  - **i.e. is everywhere and abundant**



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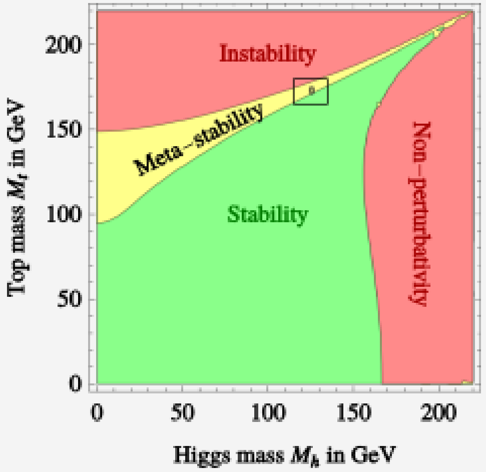
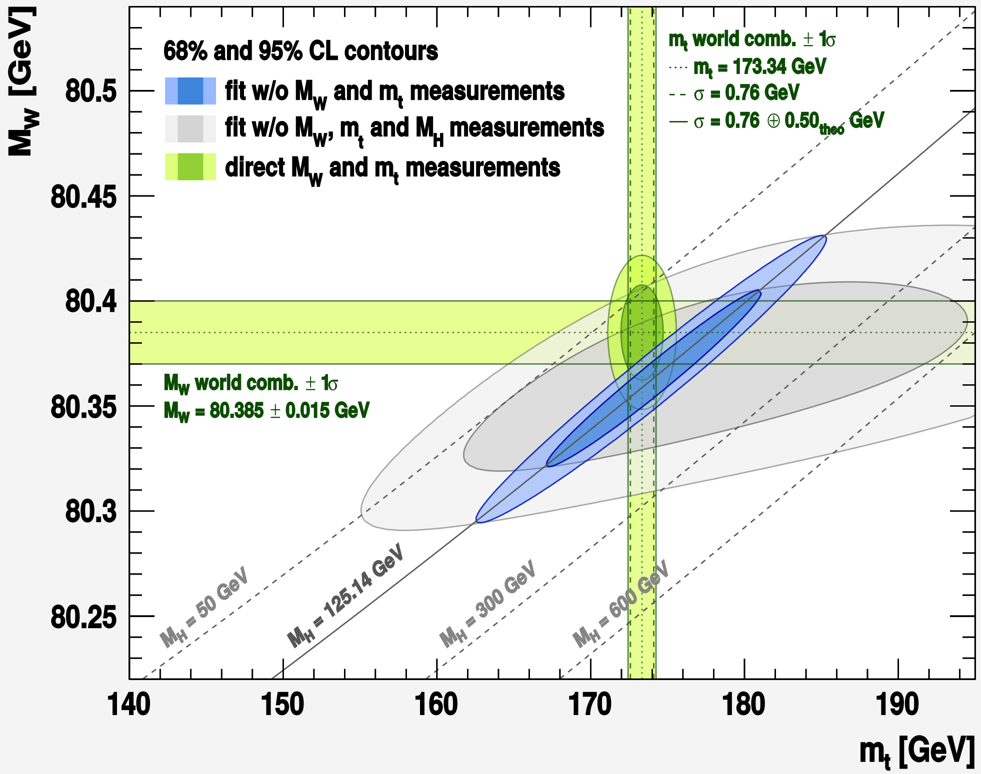
Importance of the top quark mass

- Test of the Standard Model
- Hints towards BSM physics
- Stability of the universe

[arXiv:1205.6497]



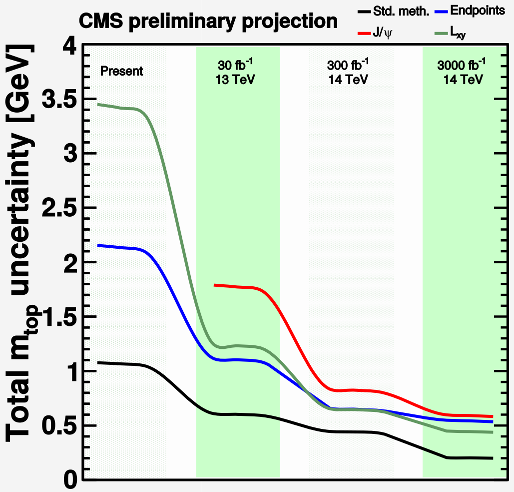
[arXiv:1407.3792]



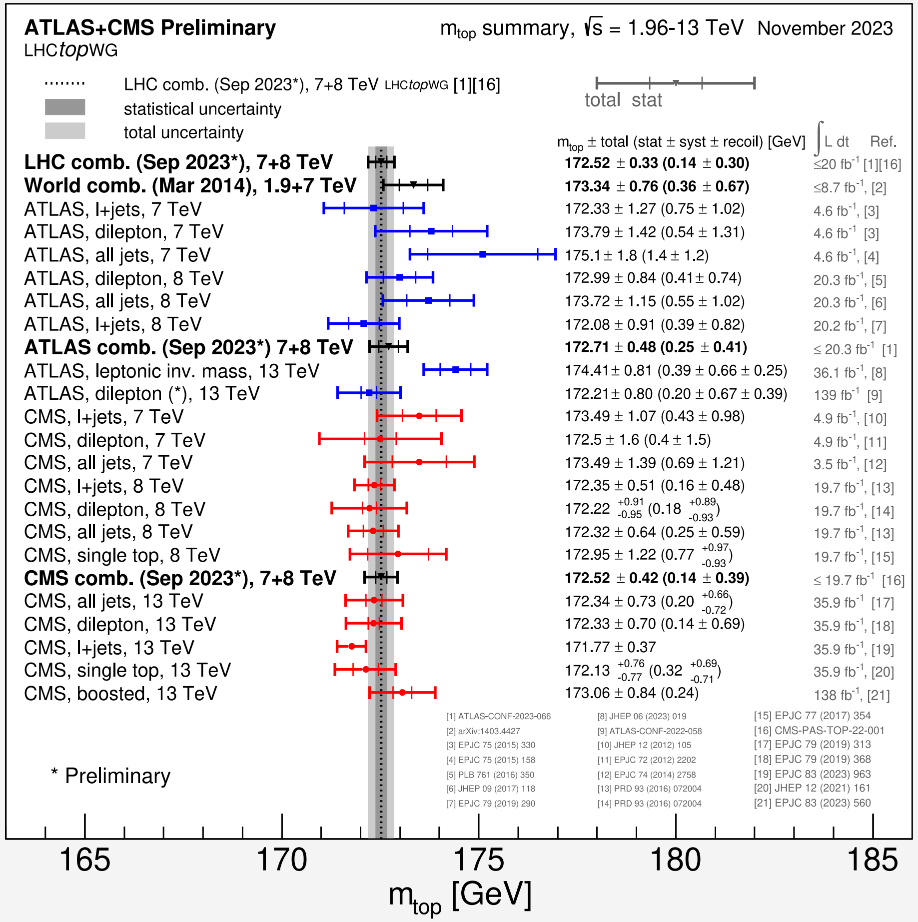
Precision of top quark mass measurement

- Experimental predictions increase in accuracy
  - **Currently: Error of 0.4-0.5 GeV at LHC experiments**
  - **Future: Error of ca. 0.2 GeV**

[arXiv:1404.1013]



[ATL-PHYS-PUB-2023-036]

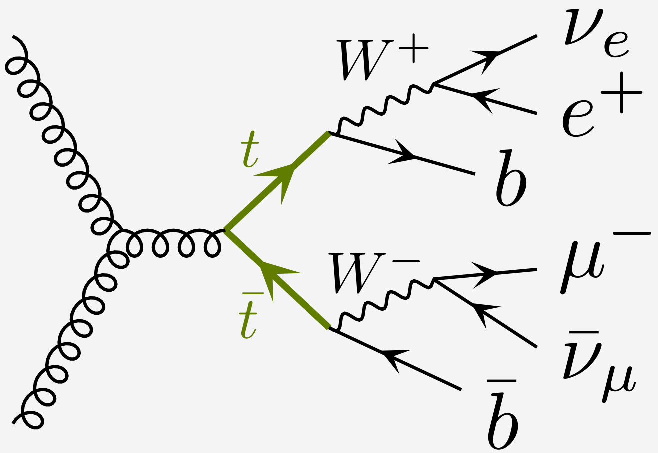


Motivation

- Basis of every LHC analysis: Fast and precise predictions of event kinematics from first principles
- Two main challenges:
  - **Conceptual problems to overcome: e.g. dealing with loop diagrams with many scales**
  - **Technical problems: increased precision comes with higher computational cost**
- In this talk (and the corresponding paper) we focus on off-shell effects
  - **Given the precision targets of the upcoming LHC runs, approximate decay modelling is not justified**
  - **High computational cost of exact calculation**
  - **Can a neural network encode the exact calculation of full off-shellness with the purpose to make it easier to use, more efficient, to store and publish results etc.**

Off-shell effects in MC event generation

- Proof of concept: top pair production and dileptonic decay (LO in QCD)



- Generated data for training a transformation of “on-shell” to off-shell events:
  - **hvq data includes only approx. off-shell effects using finite top width**

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Off-shell effects in MC event generation

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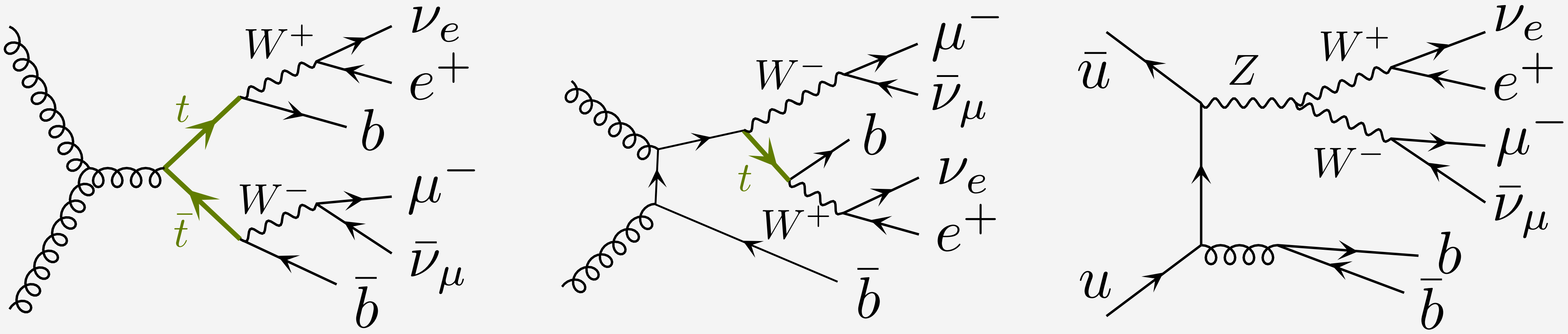
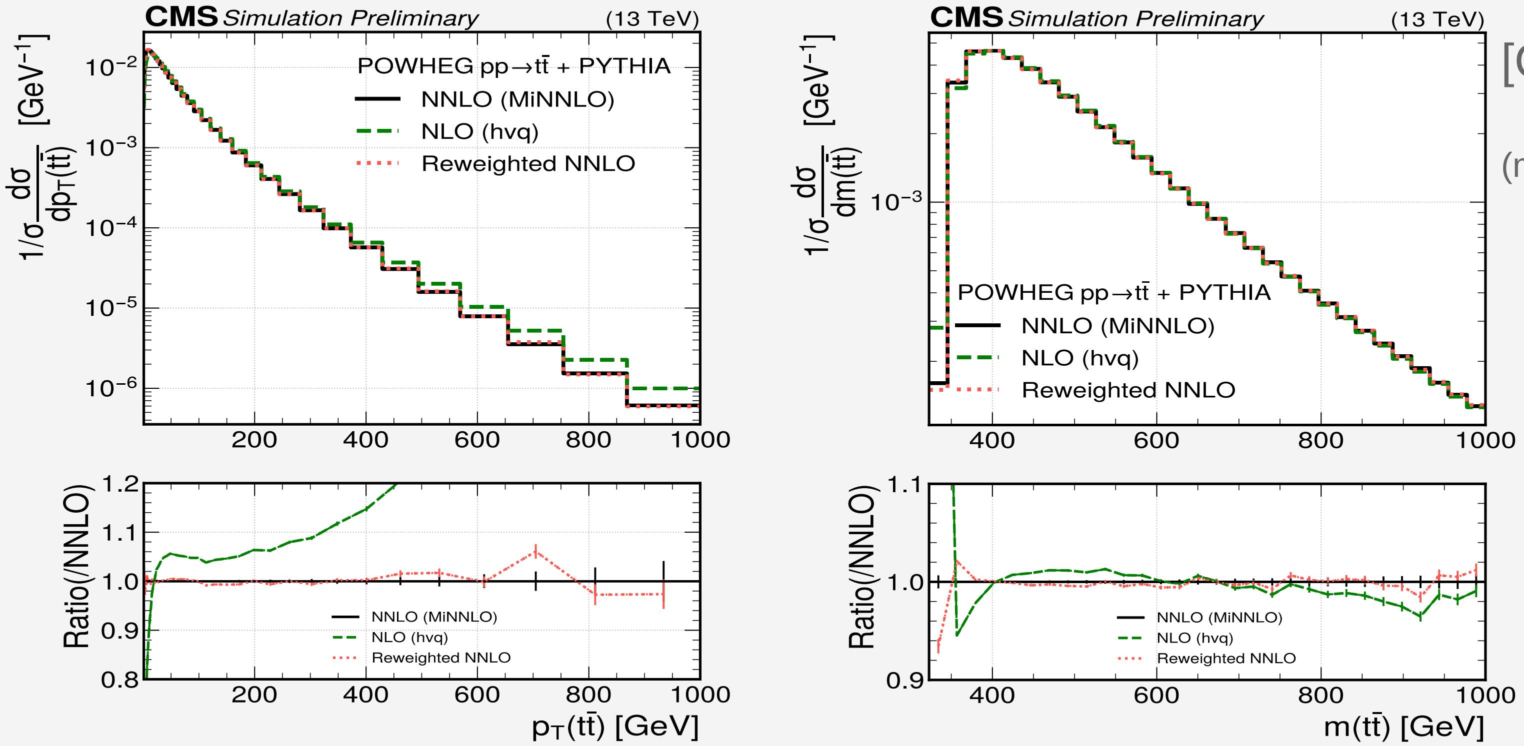


- Generated data for training a transformation of “on-shell” to off-shell events:
  - **hvq data includes only approx. off-shell effects using finite top width**
  - **bb4l data includes full off-shell effects (including e.g non-resonant effects)**

What's on the market?

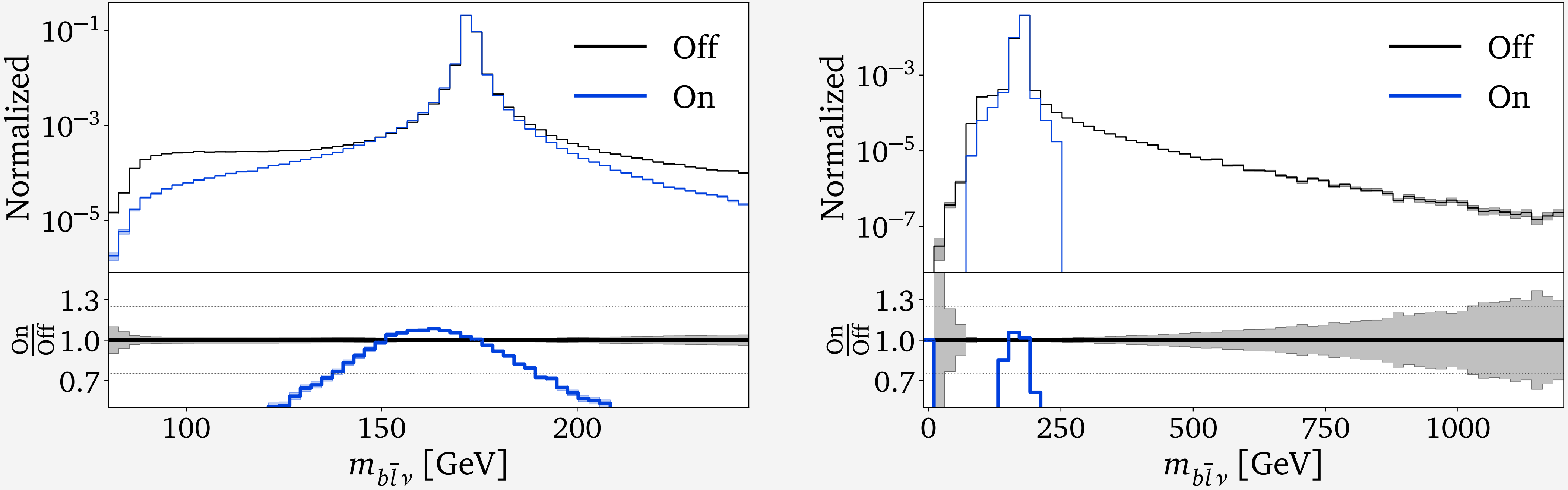


[CMS-PAS-MLG-24-001]

(more details M. Komm, Top 2024)

- Example of Reweighting NLO to NNLO
- Also unfolding: Reweighting detector-level-MC to particle-level-MC

The deviation between approx. and full off-shell calculation



- Huge chunks of the phase space are not populated by on-shell events
  - Cannot be reweighted to match off-shell event distribution

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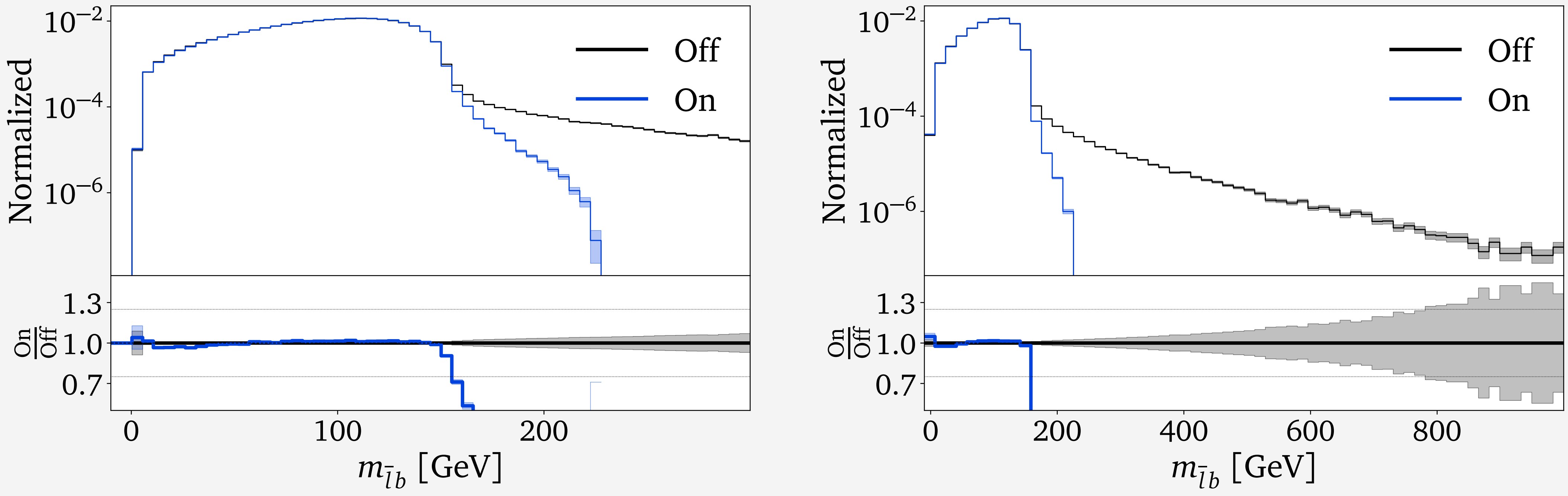

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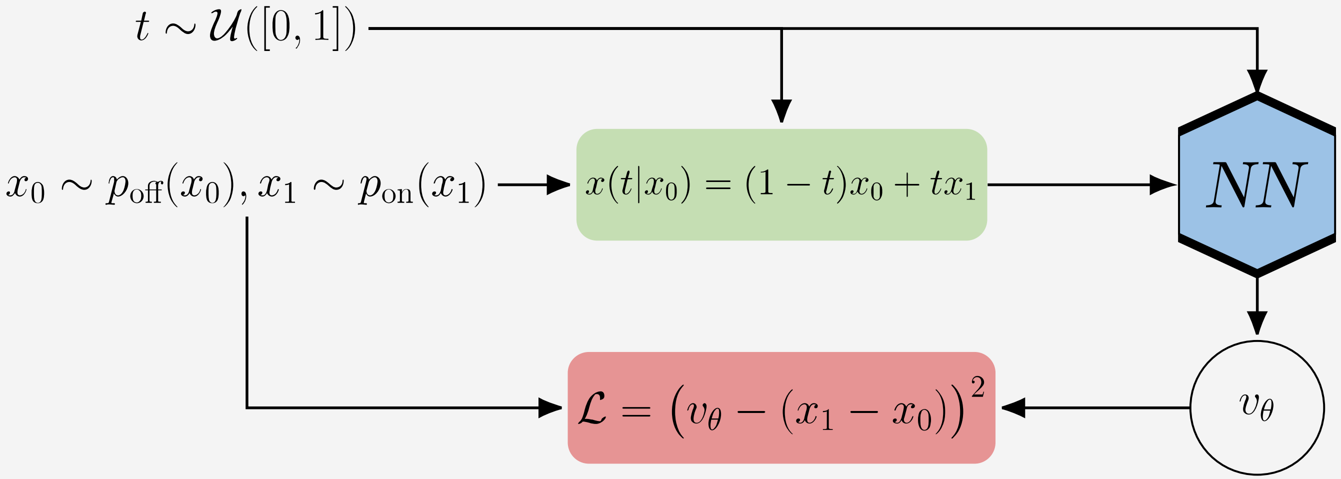
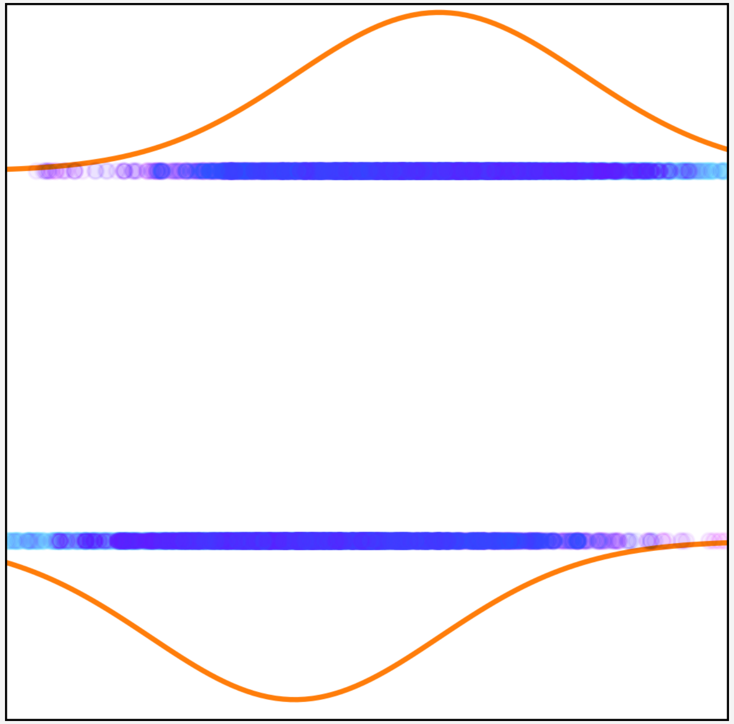
The Direct Diffusion network

- Off-Shell event $x_{off}(t=0)=x_0$, on-shell events $x_{on}(t=1)=x_1$ respectively





[arXiv:2209.15571, arXiv:2210.02747, arXiv:2209.03003, arXiv:2305.10475v2]

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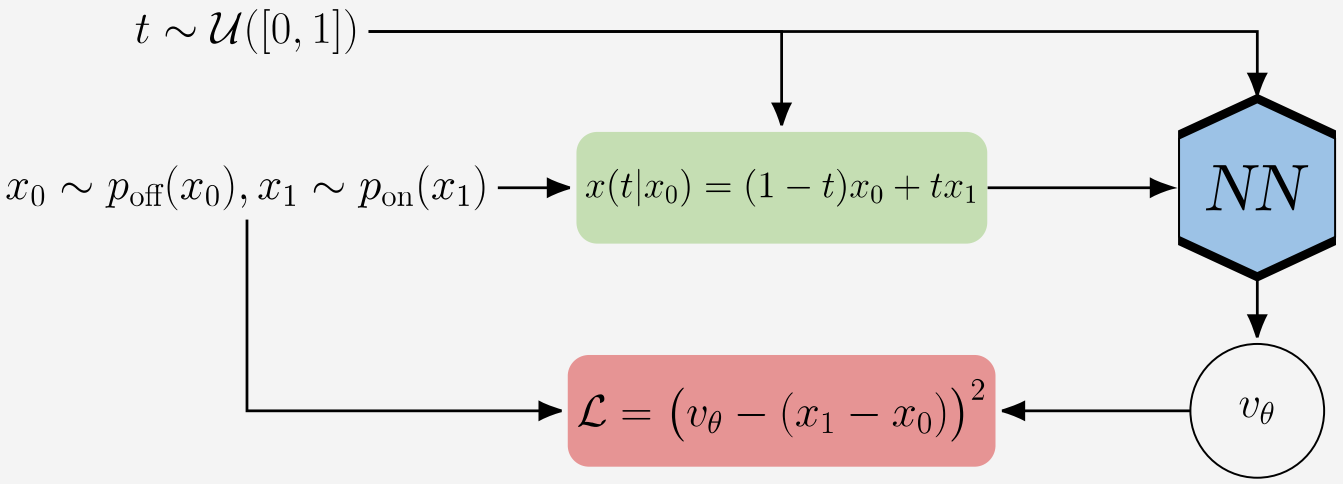

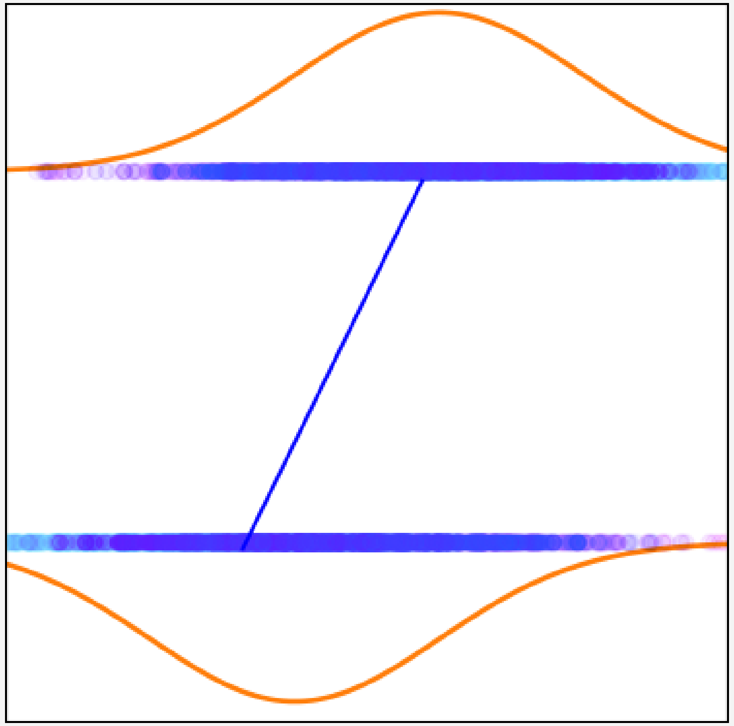

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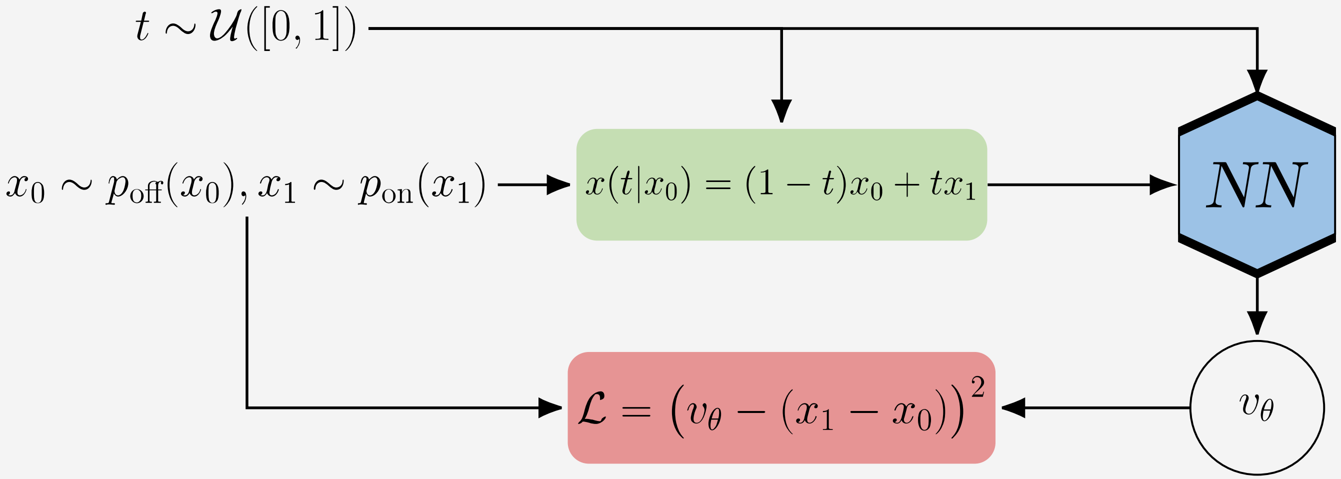

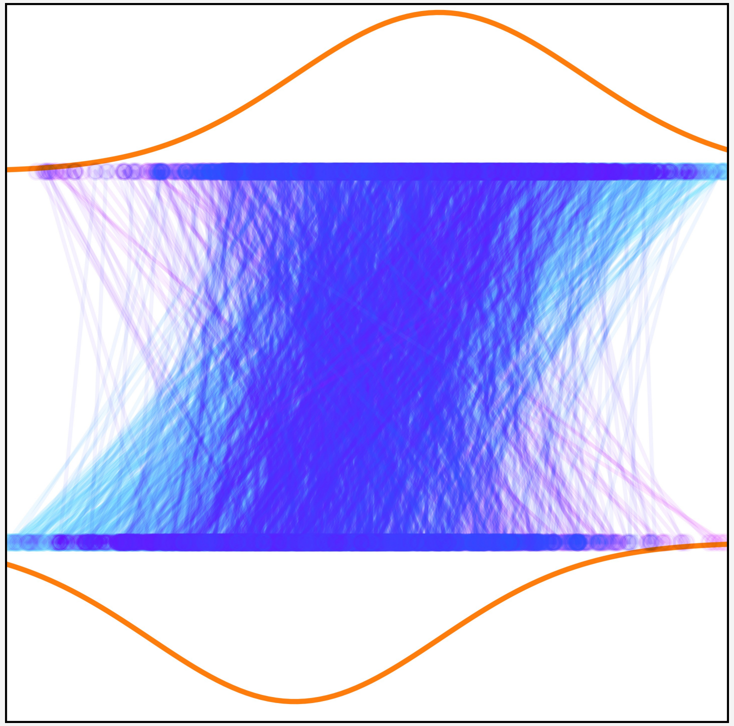

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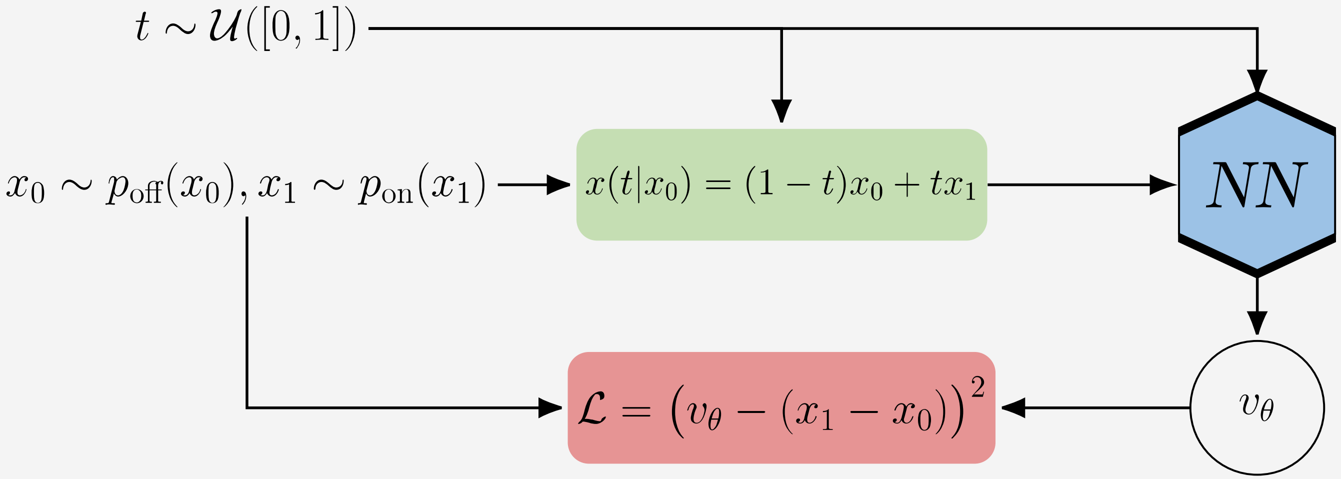

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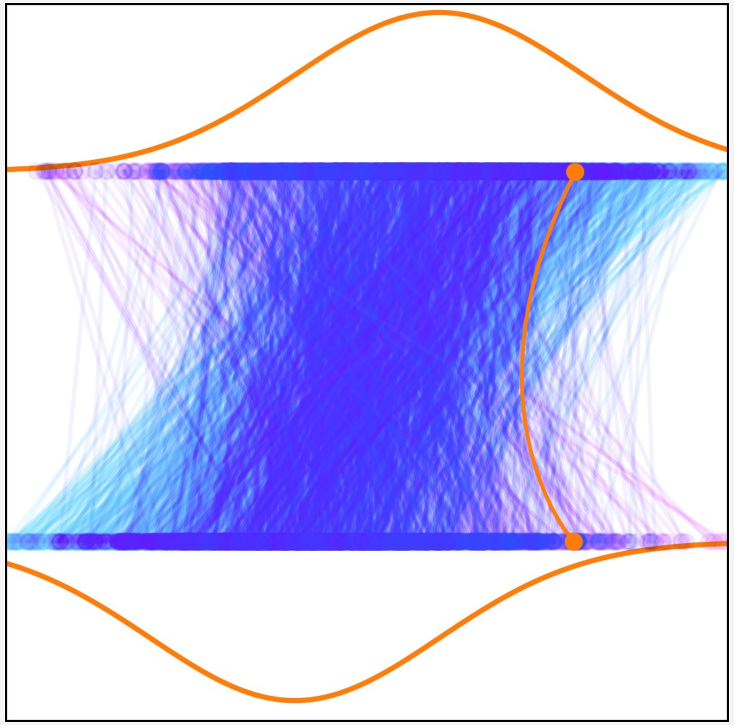
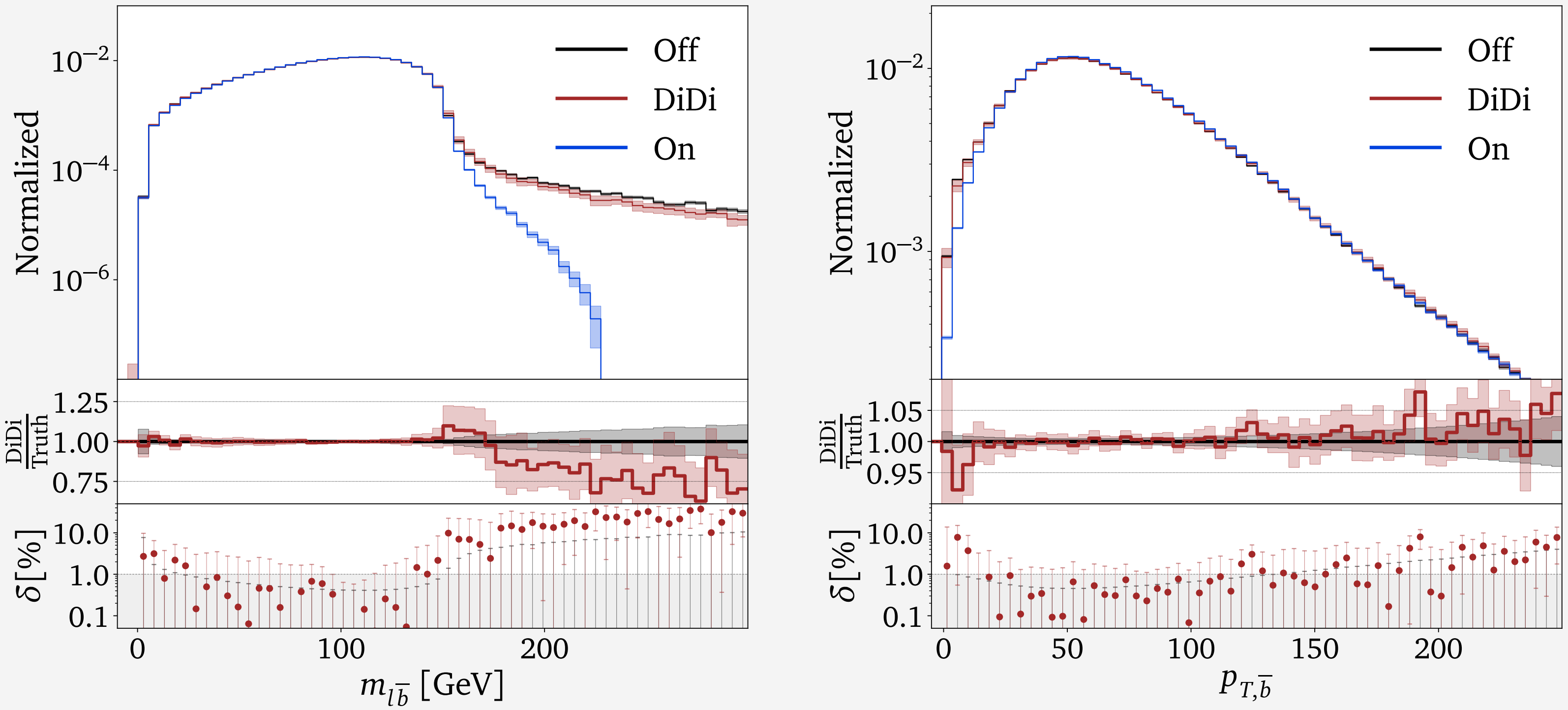


Results of the Direct Diffusion network



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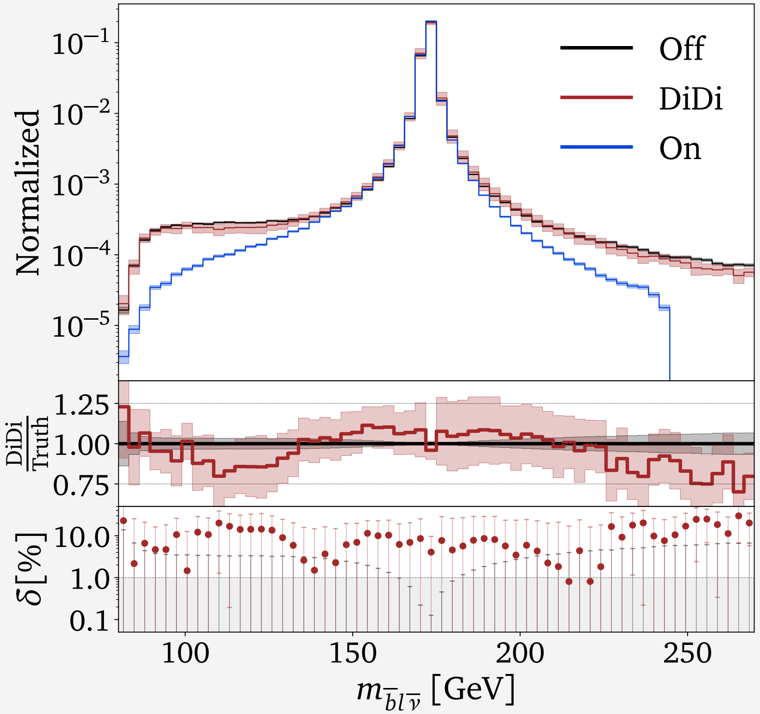

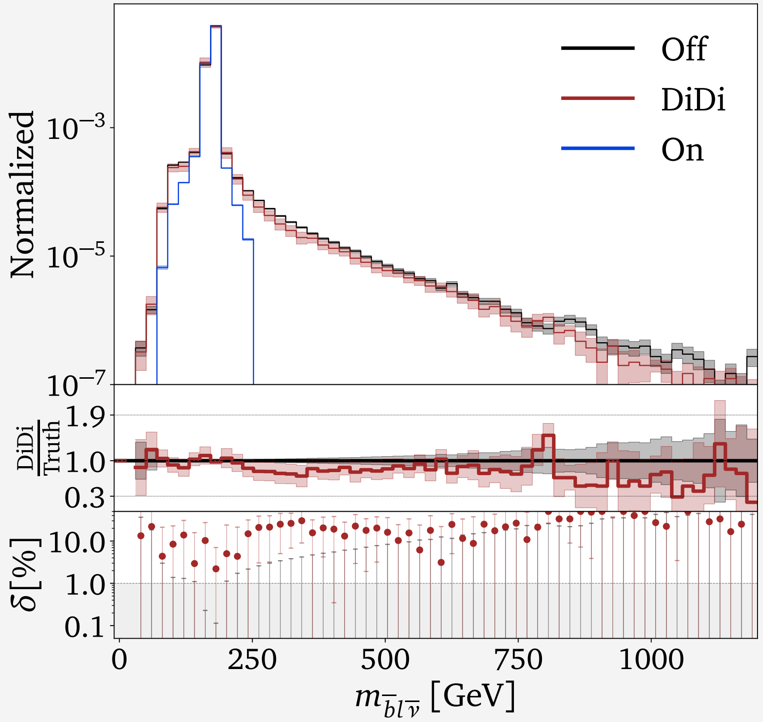

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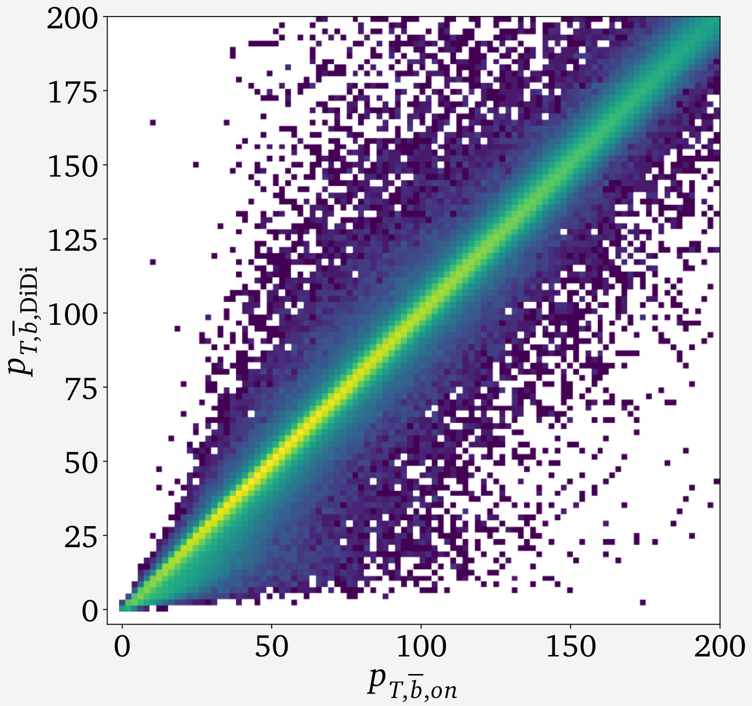

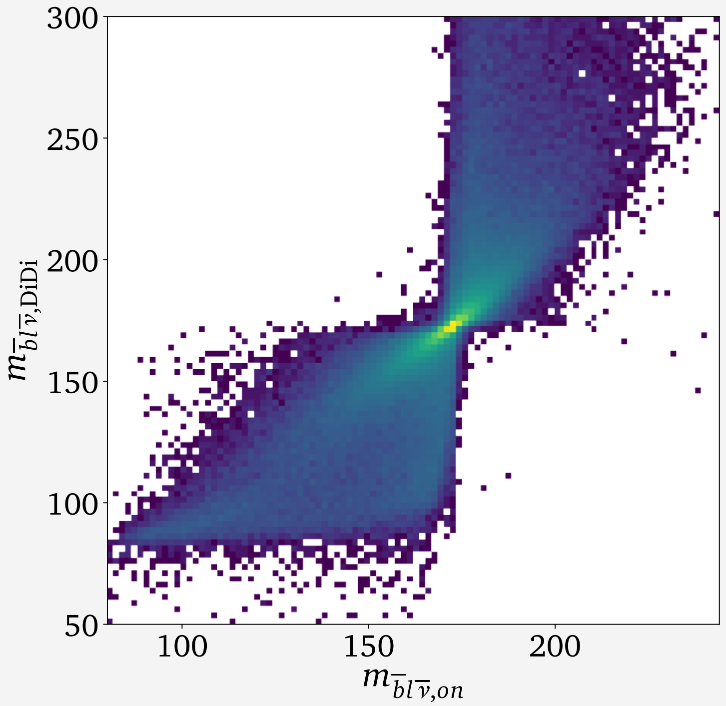

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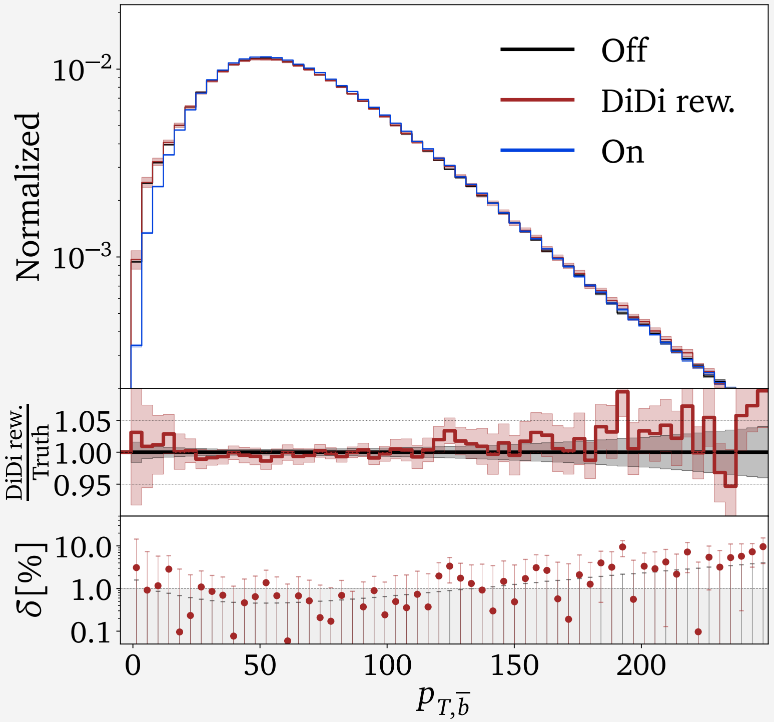
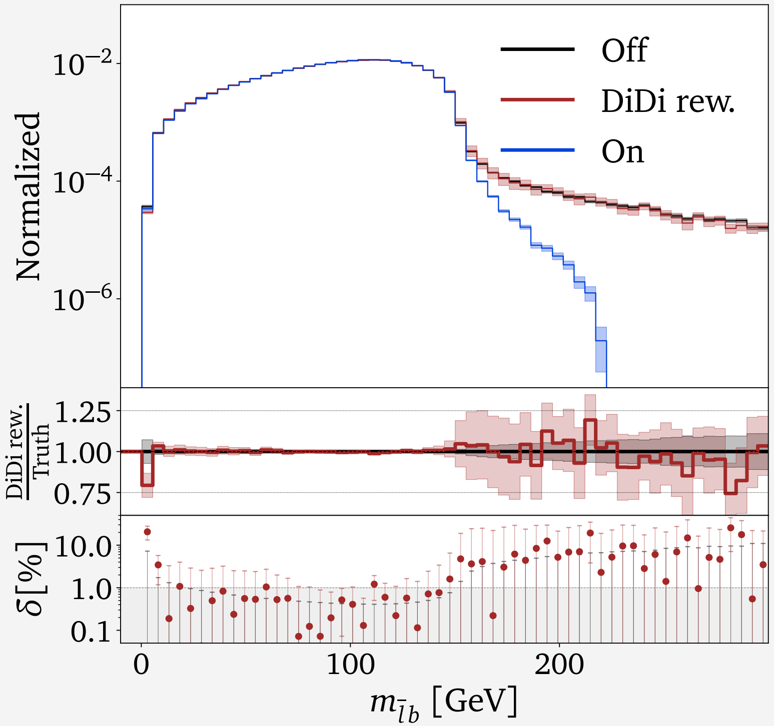
Results after an additional Reweighting





$$C(x) = \frac{p_{\mathrm{off,data}}(x)}{p_{\mathrm{off,data}}(x) + p_{\mathrm{off,model}}(x)}$$

$$w(x) = \frac{p_{\mathrm{off,data}}(x)}{p_{\mathrm{off,model}}(x)} = \frac{C(x)}{1 - C(x)}$$

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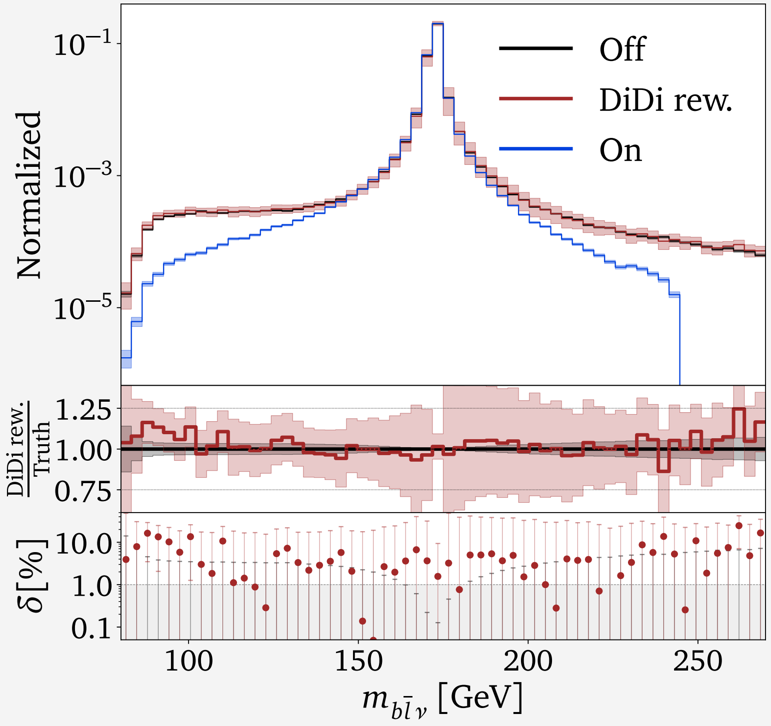

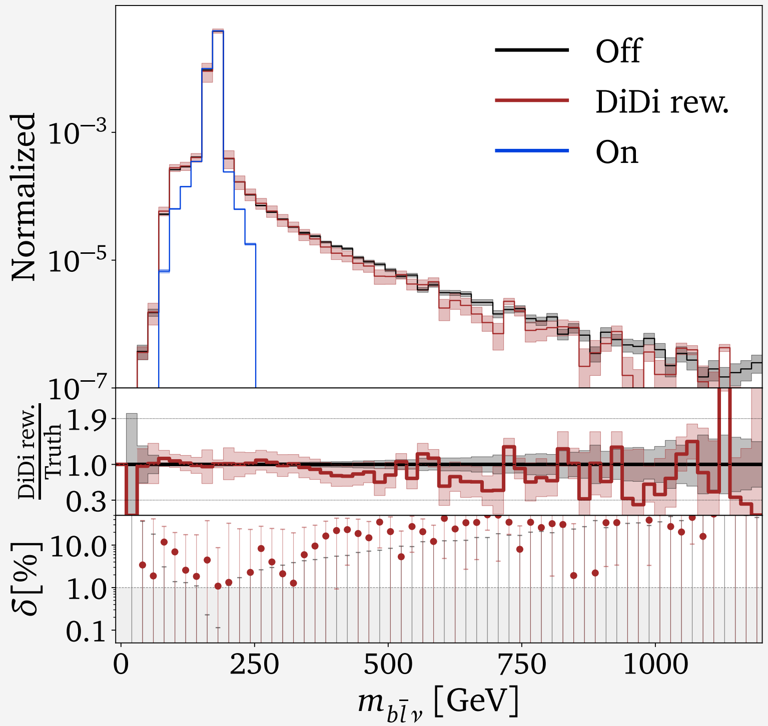

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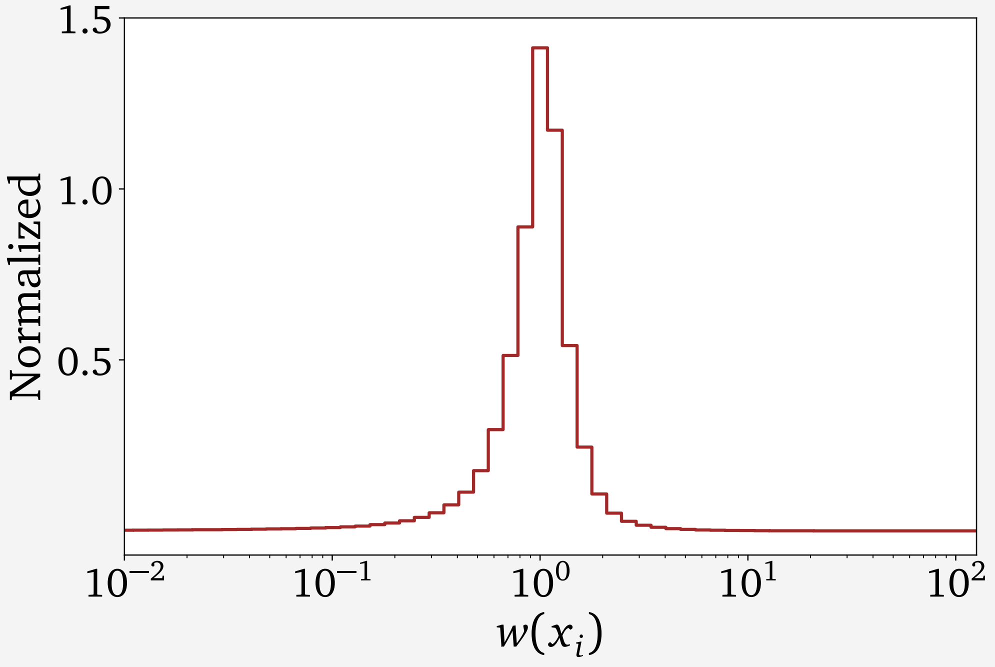

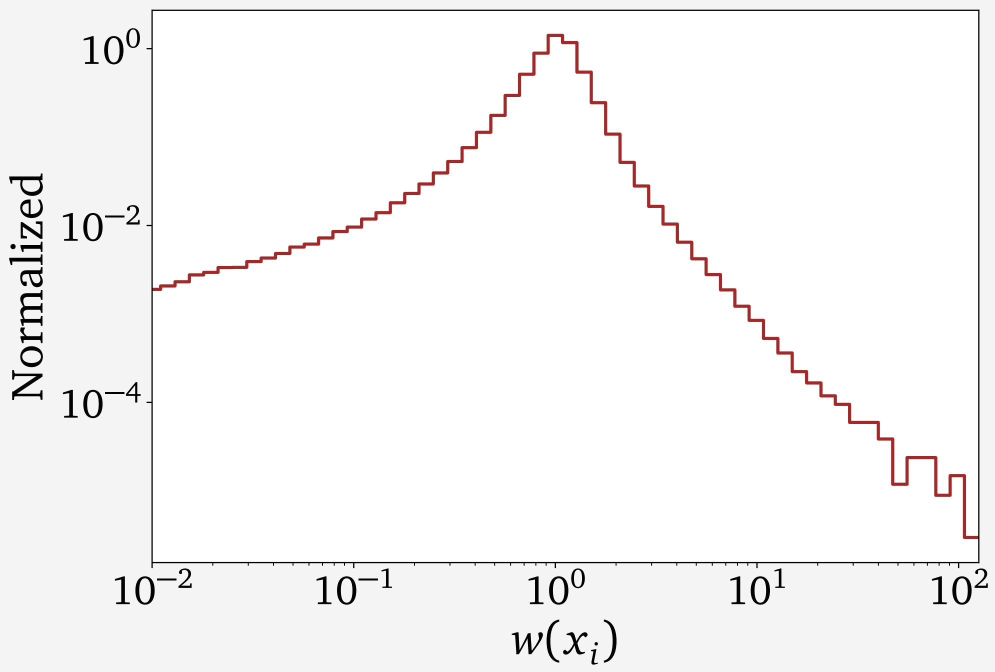

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Conclusion

- Small network with limited training effort can reproduce the target off-shell kinematics at the 10% level or better with only 5 million events
- Classifier reweighting improves its precision to the level of few percent even in challenging kinematic distributions
- Paper: Kicking it Off(-shell) with Direct Diffusion [arXiv:2311.17175]

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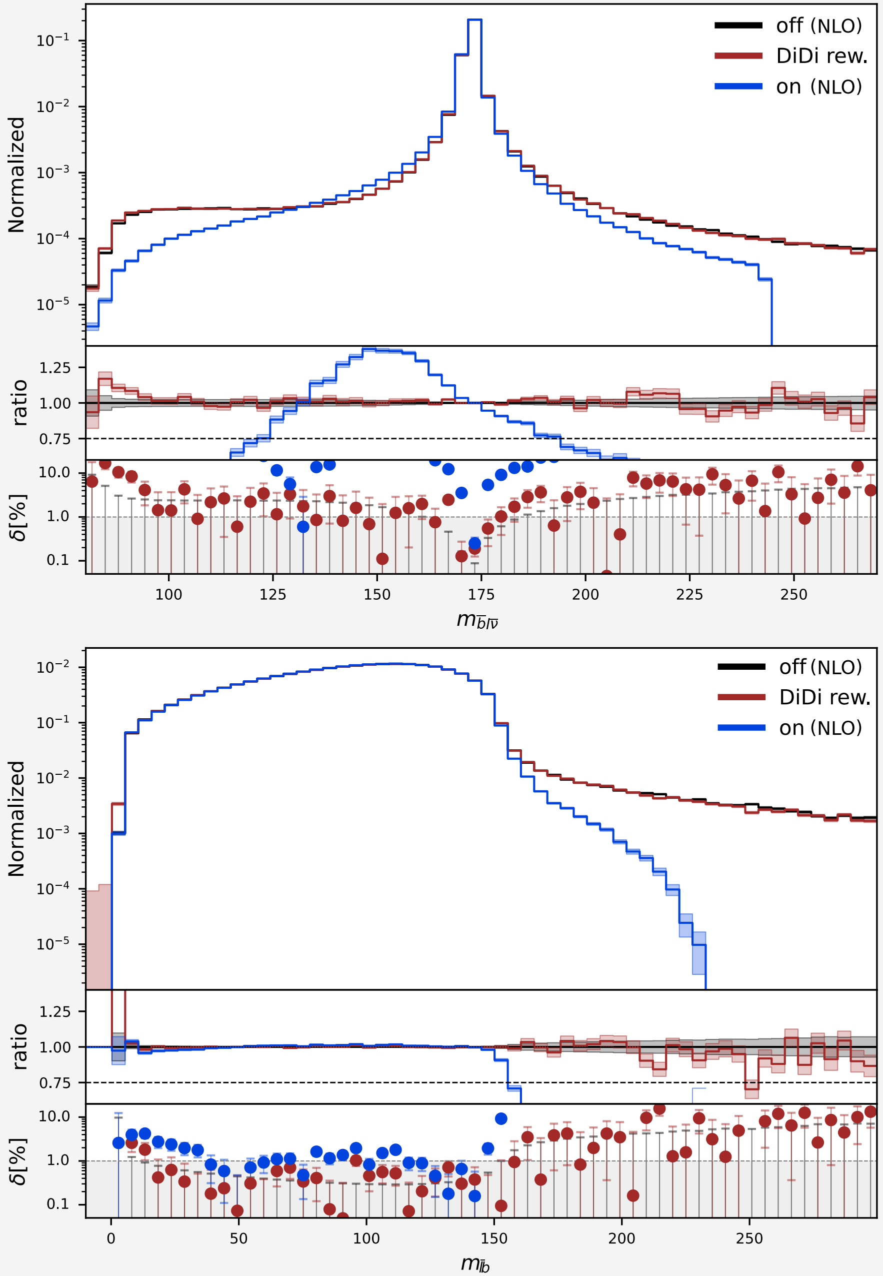
Outlook

- Advance to higher orders (paper in the making)
  - Increased dimensionality (DiDi scales well)
- Study impact of a dedicated NN for single top contributions
- Analyze impact on showering
- Train networks for a wide range of parameters to make it usable for template fits



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