

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

(b

- i.e. is everywhere and abundant



Importance of the top quark mass

200

150

100

50

0

0

Top mass Mt in GeV

Instability

Stability

100

Higgs mass M_k in GeV

150

Non-perturbativity

200

Meta-stability

50

- Test of the Standard Model ۲
- Hints towards BSM physics ۲
- Stability of the universe ۲





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



[ATL-PHYS-PUB-2023-036]

ATLAS+CMS Preliminary m _{top} summary, \sqrt{s} = 1.96-13 TeV November 2023 LHC <i>top</i> WG			
LHC comb. (Sep 2023*), 7+8 TeV LHCtop	wg [1][16]		4
statistical uncertainty		total stat	
total uncertainty		m. + total (stat + syst + rec	
LHC comb. (Sep 2023*), 7+8 TeV		172.52 ± 0.33 (0.14 ± 0.30) $\leq 20 \text{ fb}^{-1} [1][16]$
World comb. (Mar 2014), 1.9+7 TeV	-	173.34 ± 0.76 (0.36 ± 0.67) ≤8.7 fb ⁻¹ , [2]
ATLAS, I+iets, 7 TeV		172.33 ± 1.27 (0.75 ± 1.02)	4.6 fb ⁻¹ , [3]
ATLAS, dilepton, 7 TeV		173.79 ± 1.42 (0.54 ± 1.31)	4.6 fb ⁻¹ [3]
ATLAS, all jets, 7 TeV		175.1±1.8 (1.4±1.2)	4.6 fb ⁻¹ , [4]
ATLAS, dilepton, 8 TeV	ł	$172.99 \pm 0.84 (0.41 \pm 0.74)$	20.3 fb ⁻¹ , [5]
ATLAS, all jets, 8 TeV		$173.72 \pm 1.15 \; (0.55 \pm 1.02)$	20.3 fb ⁻¹ , [6]
ATLAS, I+jets, 8 TeV		$172.08 \pm 0.91 \; (0.39 \pm 0.82)$	20.2 fb ⁻¹ , [7]
ATLAS comb. (Sep 2023*) 7+8 TeV		172.71 \pm 0.48 (0.25 \pm 0.41)	$\leq 20.3 \; \text{fb}^{-1}$ [1]
ATLAS, Ieptonic inv. mass, 13 TeV	+ = + - 1	$174.41 \pm 0.81 \ (0.39 \pm 0.66 \pm 0.66)$	± 0.25) 36.1 fb ⁻¹ , [8]
ATLAS, dilepton (*), 13 TeV		$172.21 \pm 0.80 \; (0.20 \pm 0.67 \pm 0.67)$	± 0.39) 139 fb ⁻¹ [9]
CMS, I+jets, 7 TeV	+1	173.49 ± 1.07 (0.43 ± 0.98)	4.9 fb ⁻¹ , [10]
CMS, dilepton, 7 TeV	-	$172.5 \pm 1.6 \; (0.4 \pm 1.5)$	4.9 fb ⁻¹ , [11]
CMS, all jets, 7 TeV		173.49 ± 1.39 (0.69 ± 1.21)	3.5 fb ⁻¹ , [12]
CMS, I+jets, 8 TeV		172.35 ± 0.51 (0.16 ± 0.48)	19.7 fb ⁻¹ , [13]
CMS, dilepton, 8 TeV		172.22 0.95 (0.18 0.93)	19.7 fb ⁻¹ , [14]
CMS, all jets, 8 TeV		$172.32 \pm 0.64 \ (0.25 \pm 0.59)$	19.7 fb ⁻¹ , [13]
CMS, single top, 8 TeV	-1	$172.95 \pm 1.22 (0.77 + 0.93)$	19.7 fb ⁻¹ , [15]
CMS comb (Sep 2023*), 7+8 TeV		$172.52 \pm 0.42 (0.14 \pm 0.39)$) ≤ 19.7 fb ⁻¹ [16]
		$172.34 \pm 0.73 (0.20 + 0.72)$	35.9 fb ⁻ ' [17]
		$1/2.33 \pm 0.70 (0.14 \pm 0.69)$	35.9 fb ⁻ ', [18]
		$1/1.//\pm 0.3/$	35.9 fb ⁻ ', [19]
CMS, single top, 13 TeV		$1/2.13_{-0.77} (0.32_{-0.71})$	35.9 fb ', [20]
		173.06 ± 0.04 (0.24)	138 fb ', [21]
	[2] arXiv:1403.4427	[9] ATLAS-CONF-2022-058	[16] CMS-PAS-TOP-22-001
	[3] EPJC 75 (2015) 330 [4] EPJC 75 (2015) 158	[10] JHEP 12 (2012) 105 [11] EPJC 72 (2012) 2202	[17] EPJC 79 (2019) 313 [18] EPJC 79 (2019) 368
* Preliminary	[5] PLB 761 (2016) 350	[12] EPJC 74 (2014) 2758	[19] EPJC 83 (2023) 963
	[7] EPJC 79 (2019) 290	[14] PRD 93 (2016) 072004 [14] PRD 93 (2016) 072004	[21] EPJC 83 (2023) 560
		.	
165 170	175	180	185
m _{ton} [GeV]			



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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 - 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?



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







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Results of the Direct Diffusion network





Results of the Direct Diffusion network





Results of the Direct Diffusion network





Results after an additional Reweighting





Results after an additional Reweighting





Results after an additional Reweighting



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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]



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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