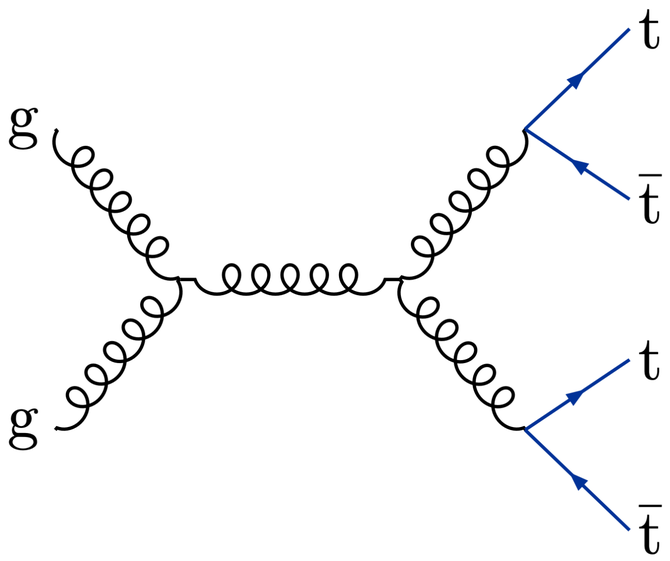
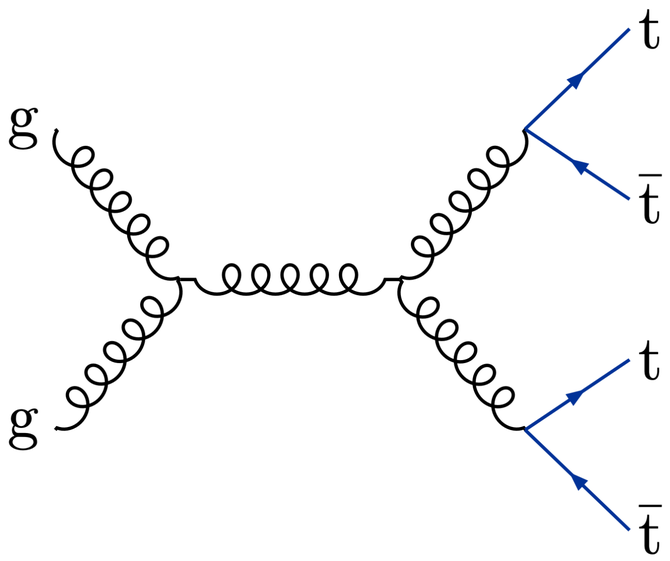


Four Top Searches and Constraints on the Top Yukawa In ATLAS and CMS

12th Large Hadron Collider Physics Conference
Boston, MA, USA
June 4, 2024



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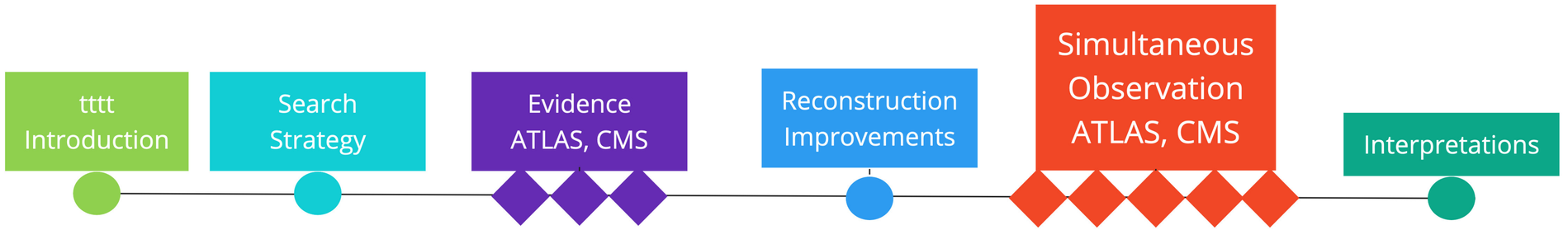
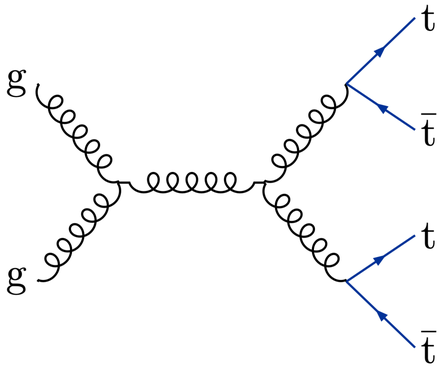
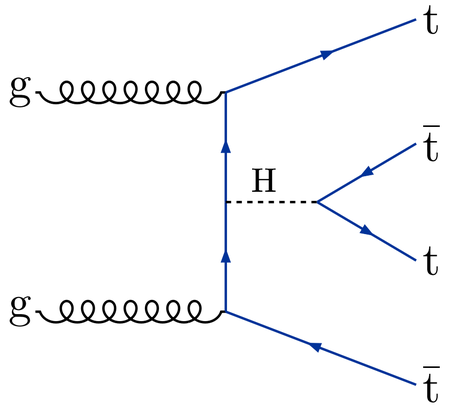
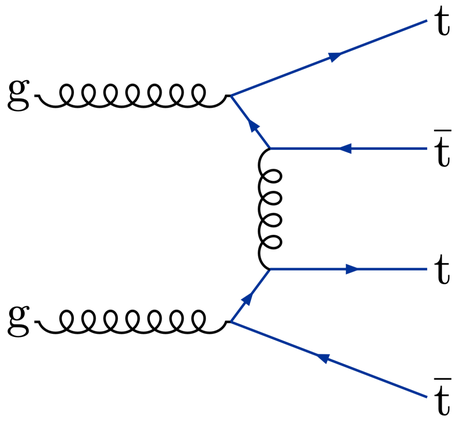


Four Top

- A very rare process in the SM
  - σ_{tttt} ~13.4fb
  - Challenges in theory and experiment
- Tests our understanding of high-mass QCD
- Multitude of decay channels
- Only recently passing the thresholds for Evidence and Observation
- A probe for Top Yukawa, EFT measurements

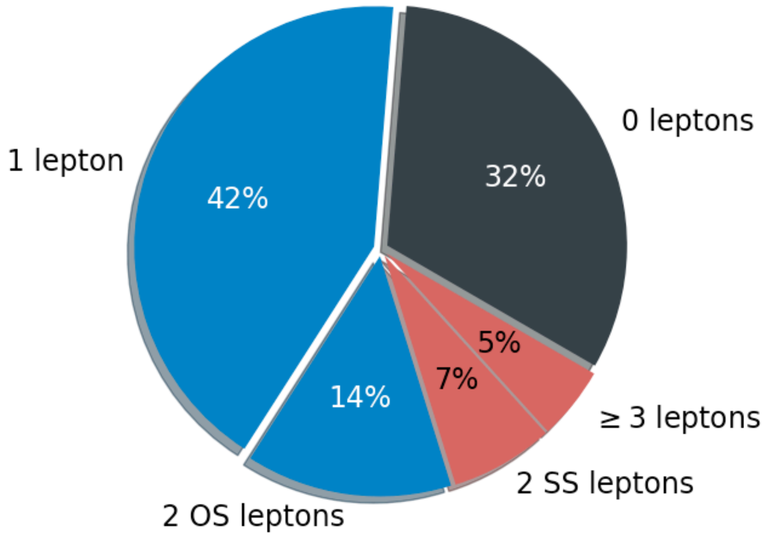






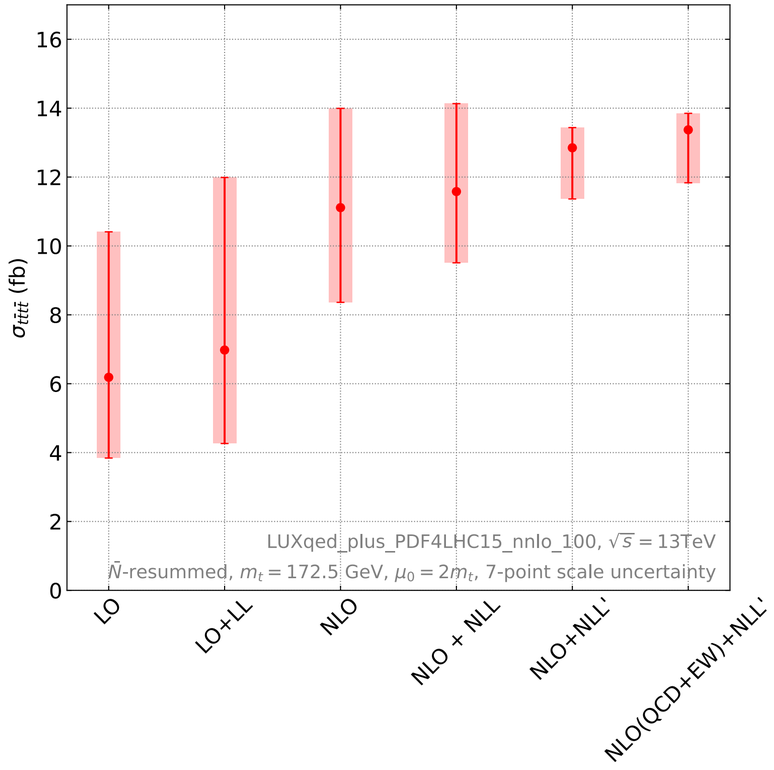
Rich Decay Landscape

- Same-Sign dilepton (SSDL) and multiplepton (3+, ML)
  - Most sensitive channels
  - Major backgrounds: ttZ, ttW, ttH
- Opposite-Sign Dilepton (OSDL), Single Lepton (SL)
  - Major backgrounds: ttbb, ttjj (non-b), ttH
- All Hadronic
  - Major backgrounds: QCD multijet, ttbb, ttjj



Link

Signal Theory Modeling



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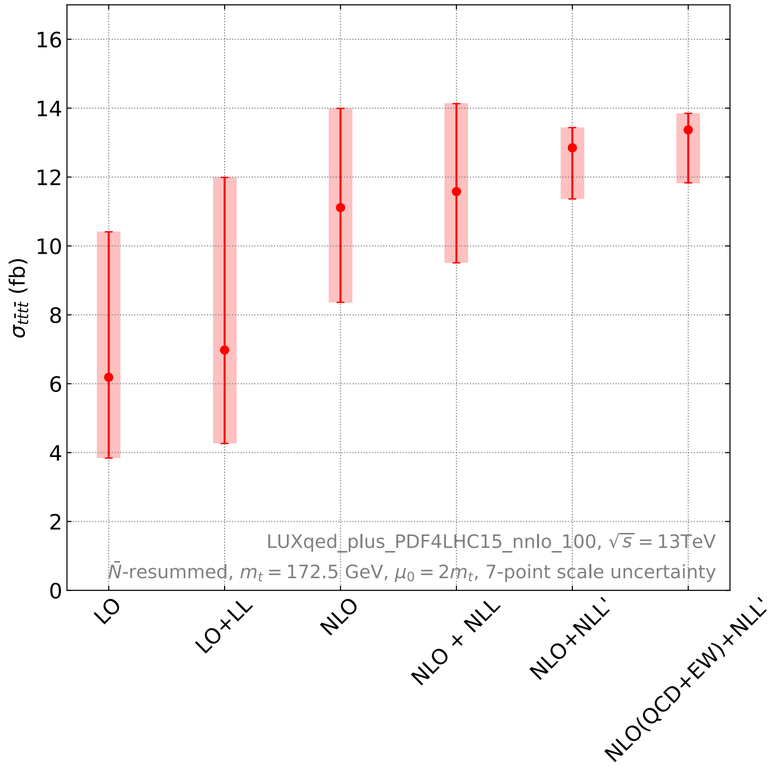
- σ_{tttt} ~ 9fb @ LO



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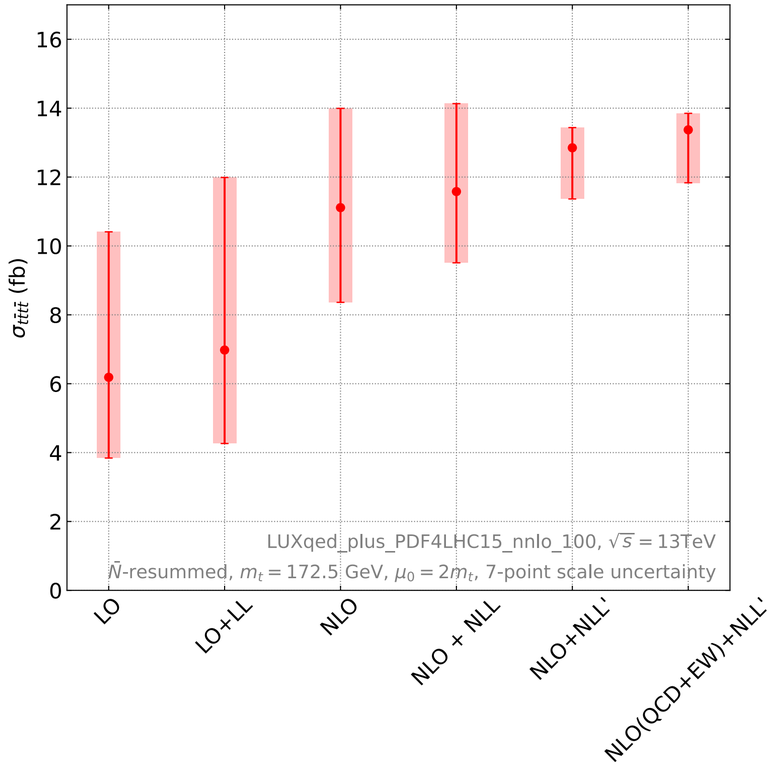

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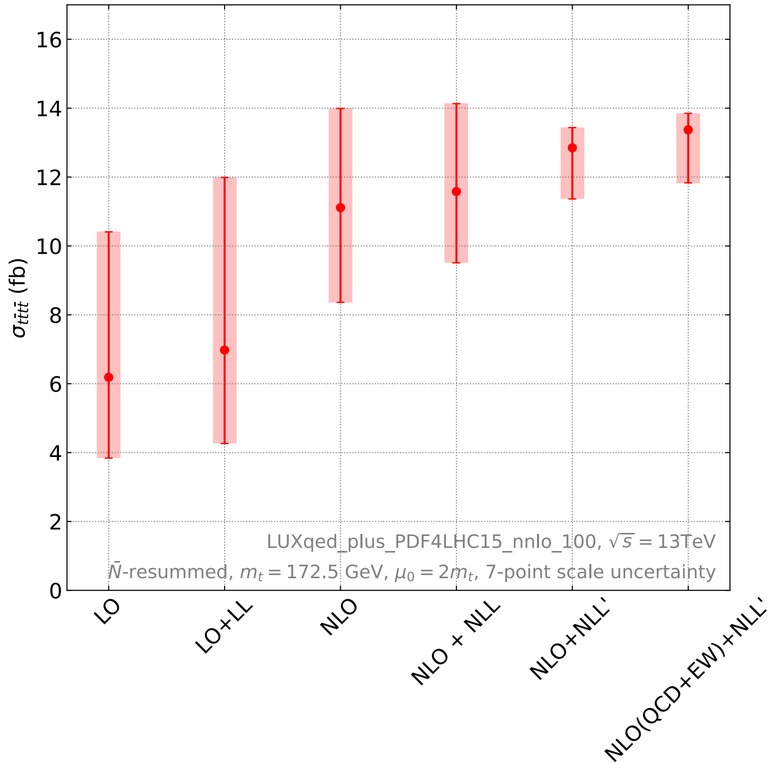

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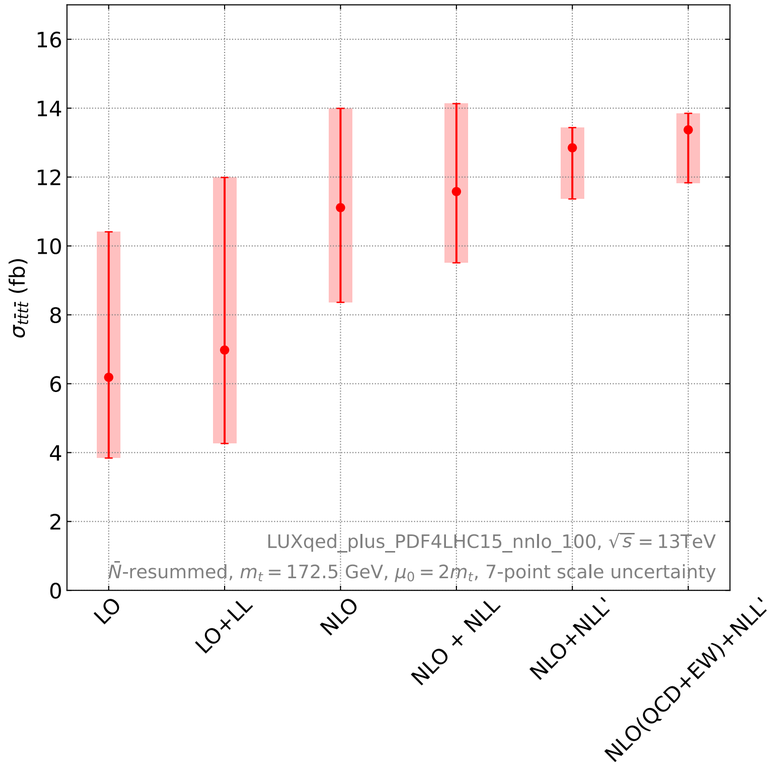
- Large modeling uncertainties in μ_F, μ_R and Parton Showering



Background Modeling and Experimental

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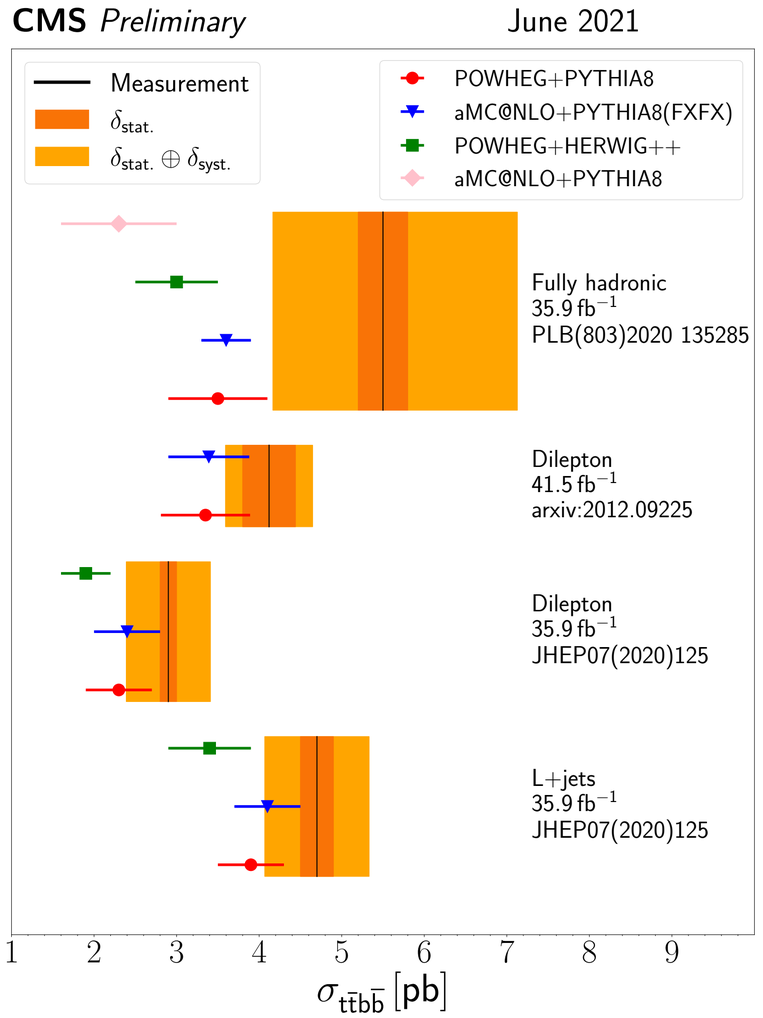

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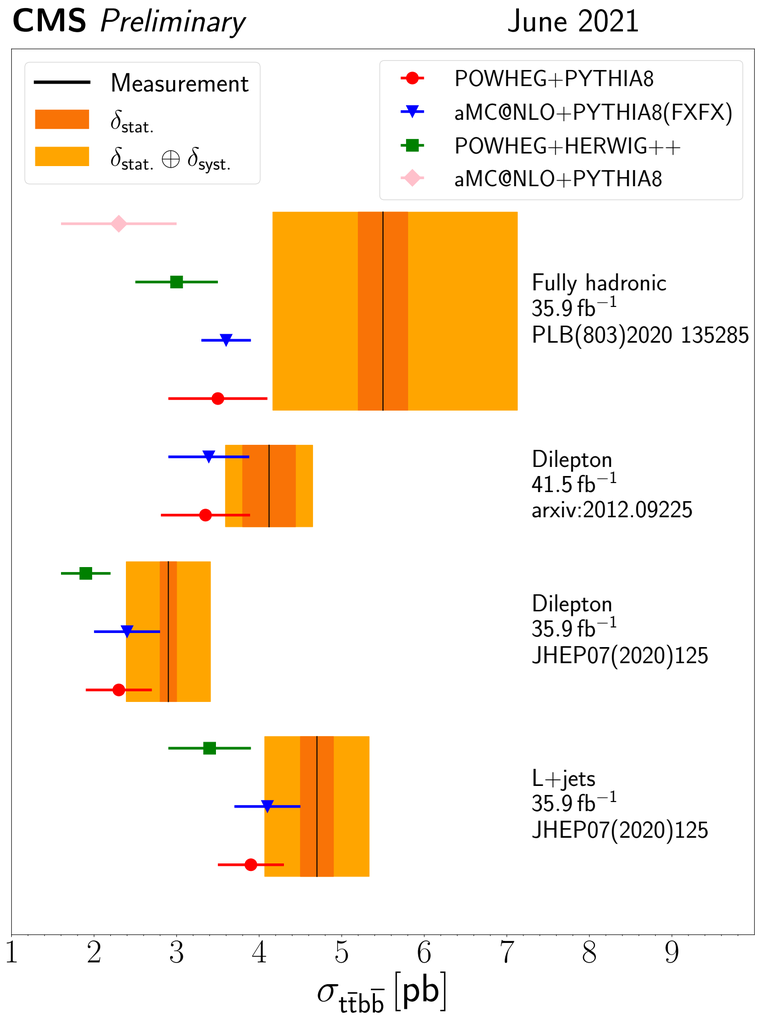

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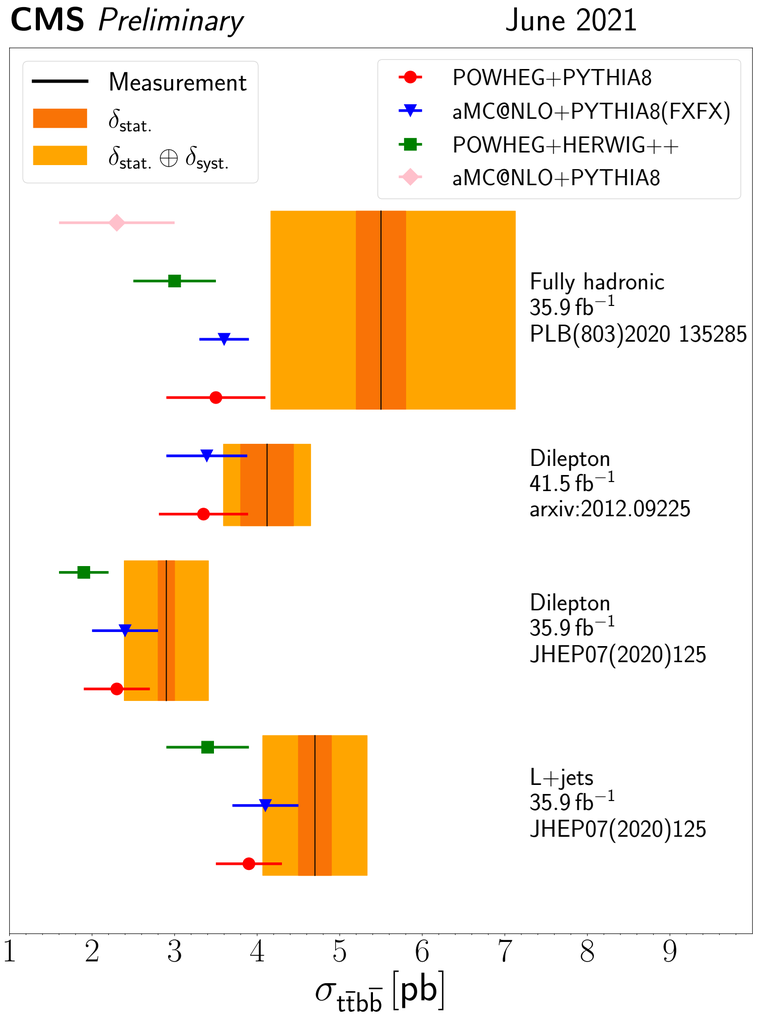

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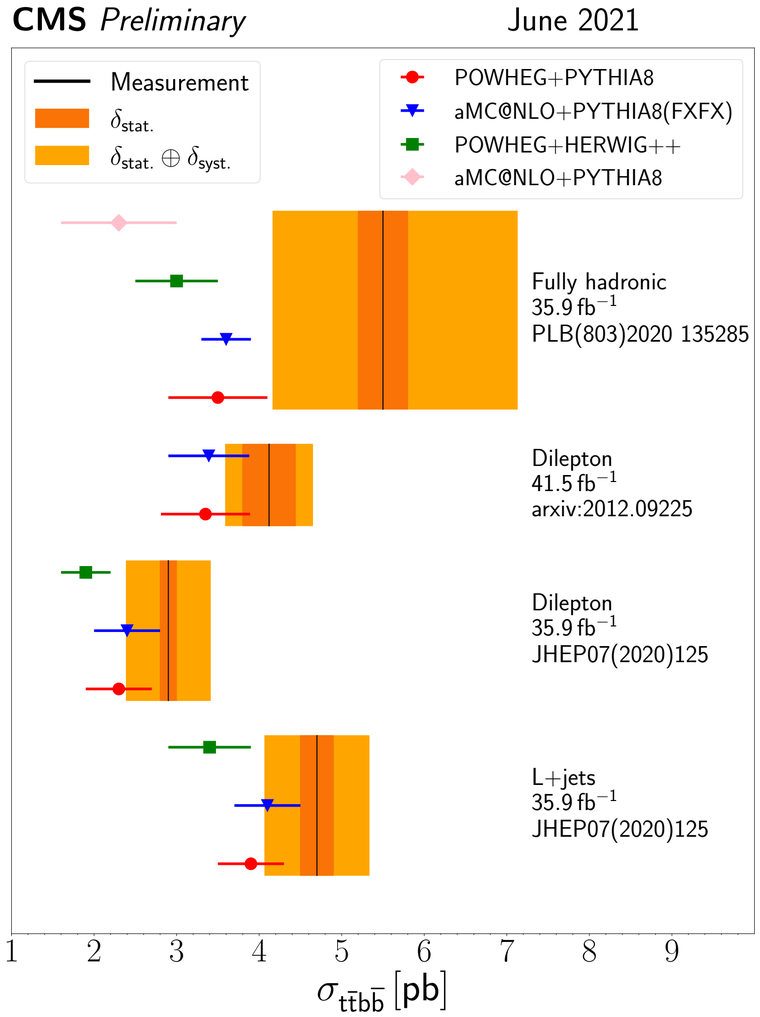

- Comparable to experimental challenges in Jet Energy Scale/Resolution and b-tagging

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- Perform simultaneous binned maximum likelihood fit of H_T or an MVA Classifier across Signal Regions (SRs) and Control Regions (CRs)

Evidence (ATLAS) - Run II (2015-18)

- SL + OSDL + SSDL + ML
- BDT Event Classifiers

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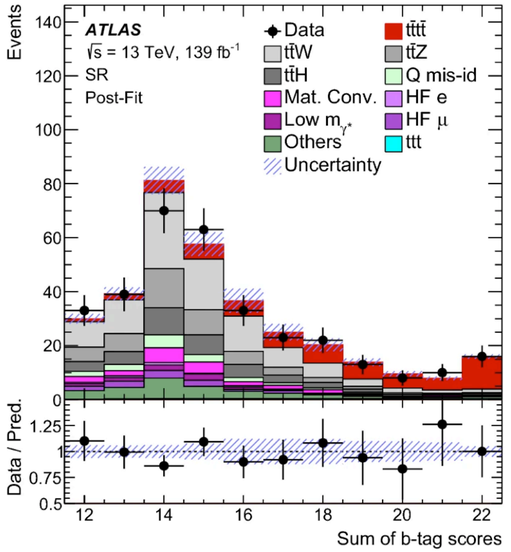

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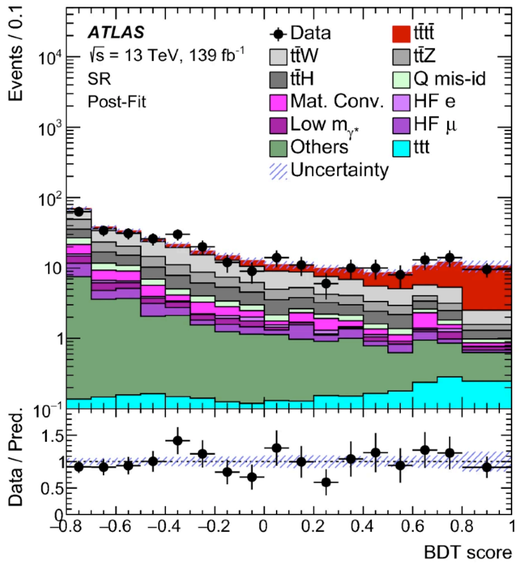

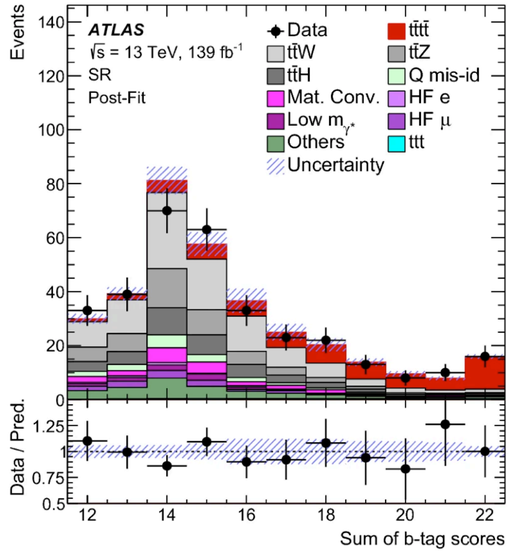

[redacted]

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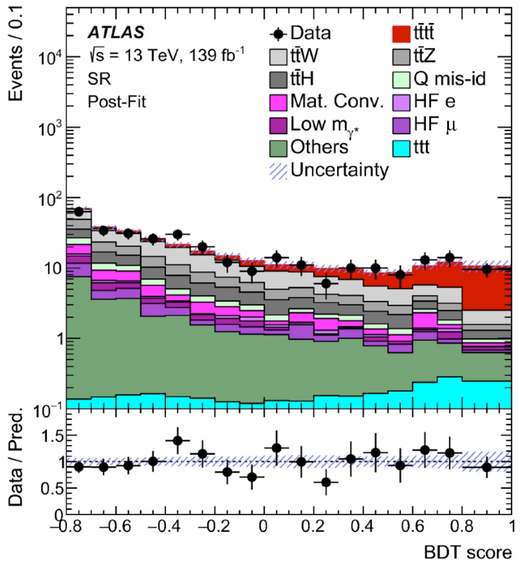
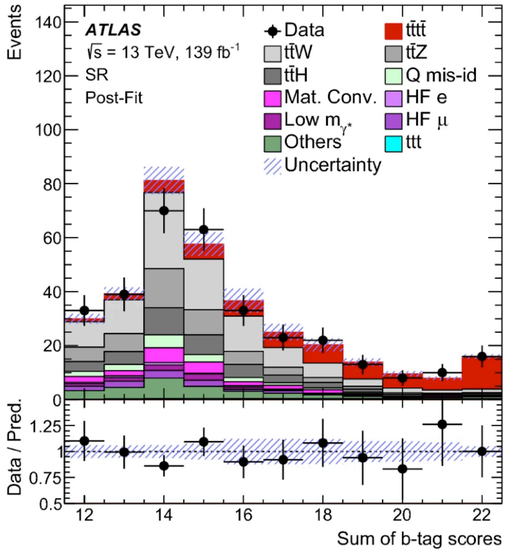
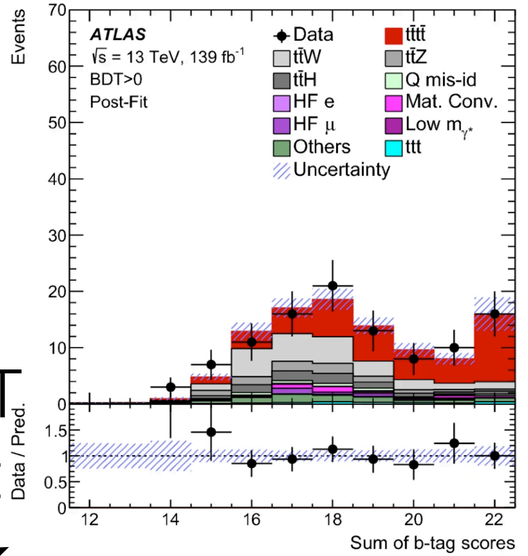
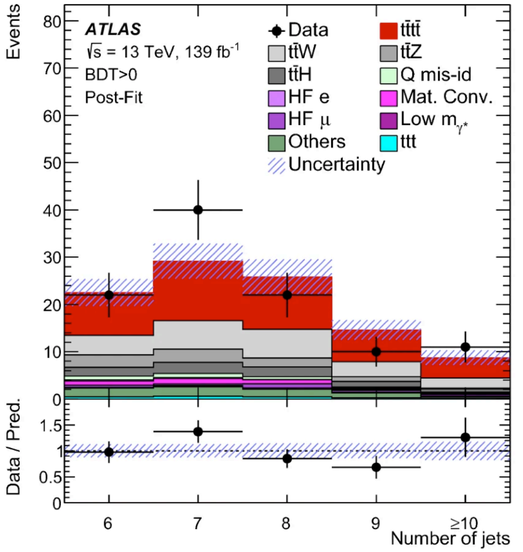




BDT cut





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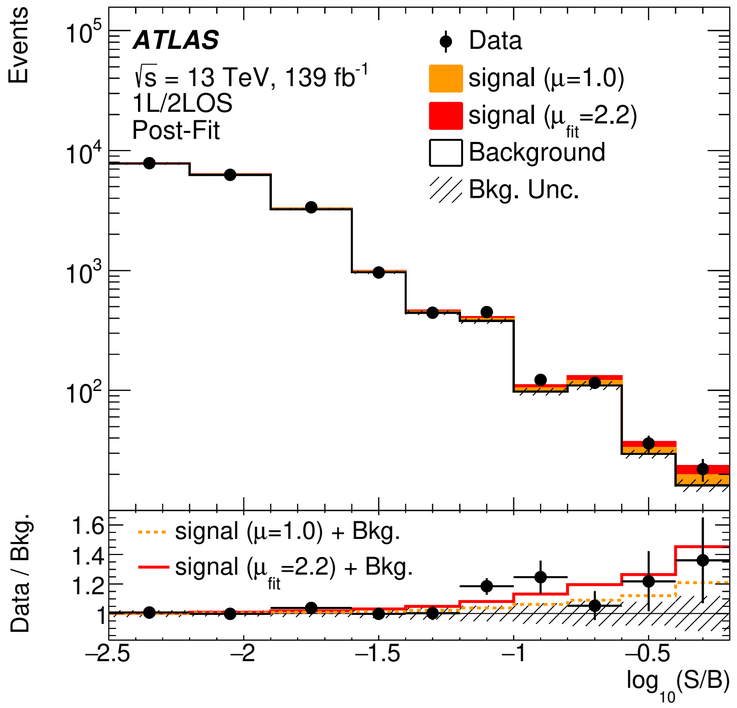

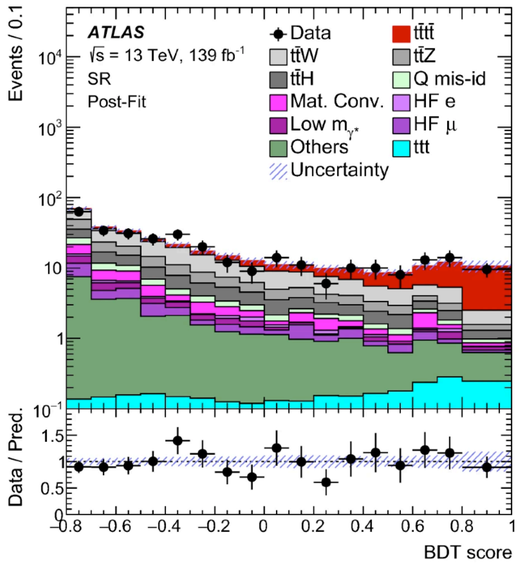

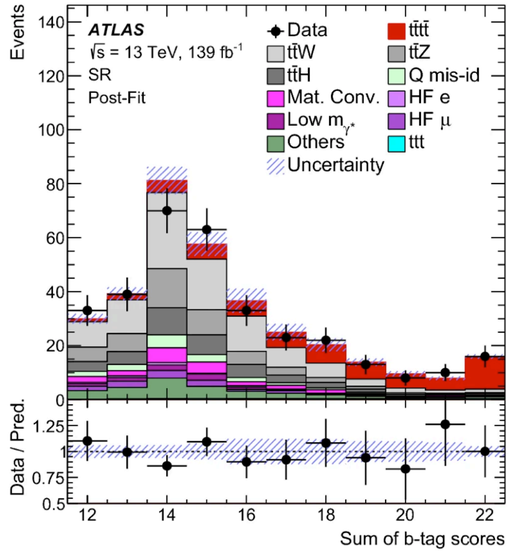

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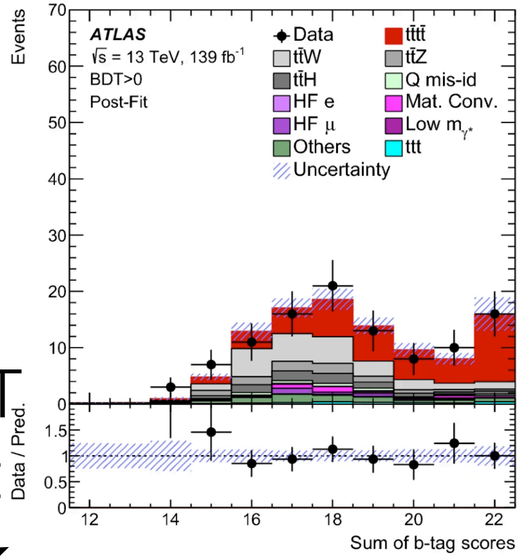

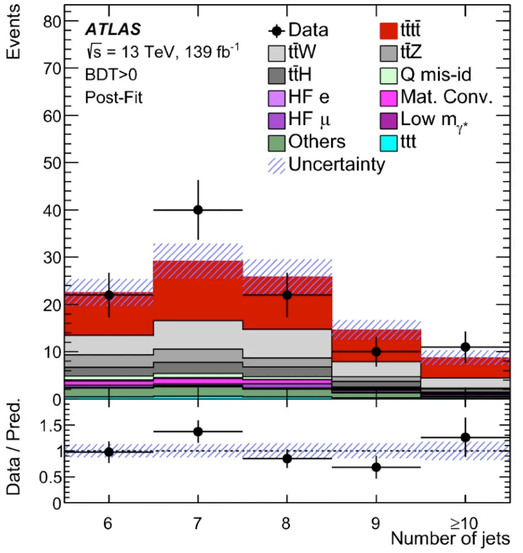

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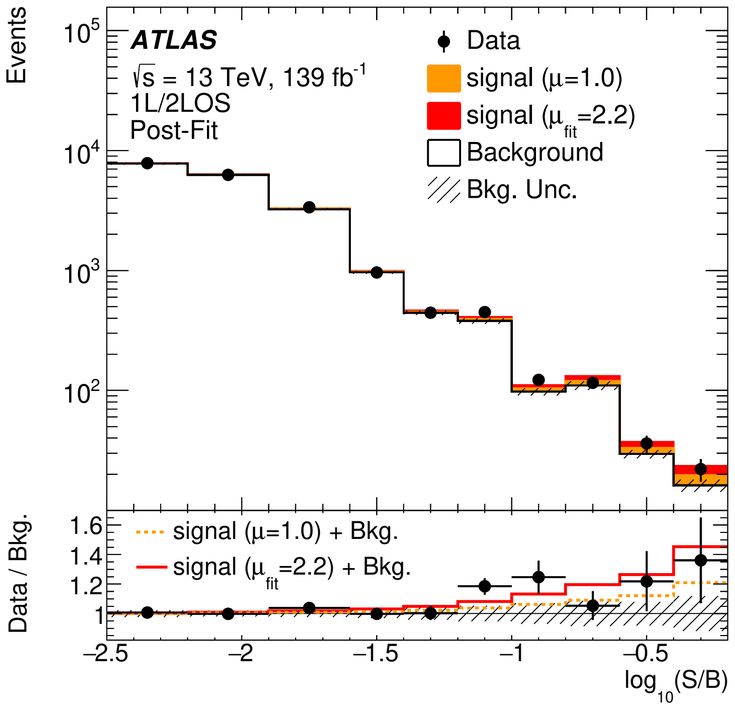

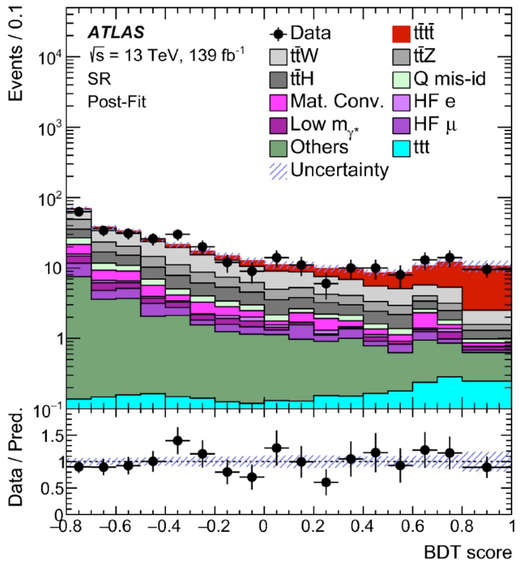

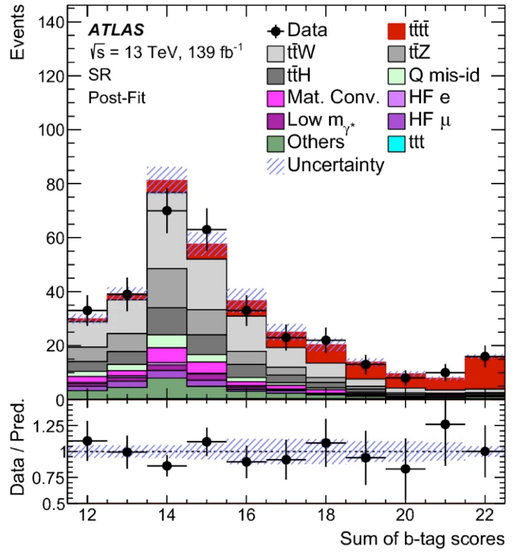

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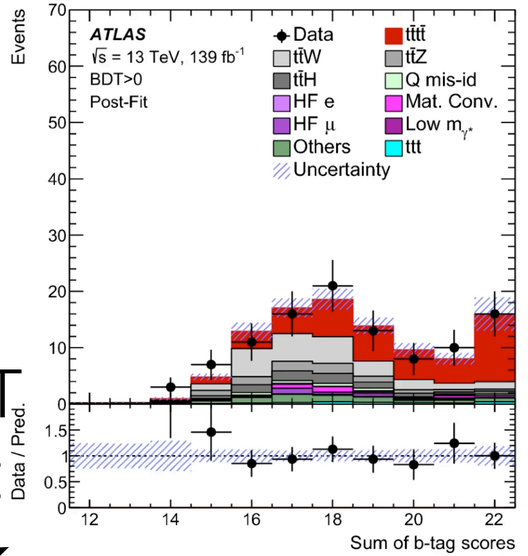

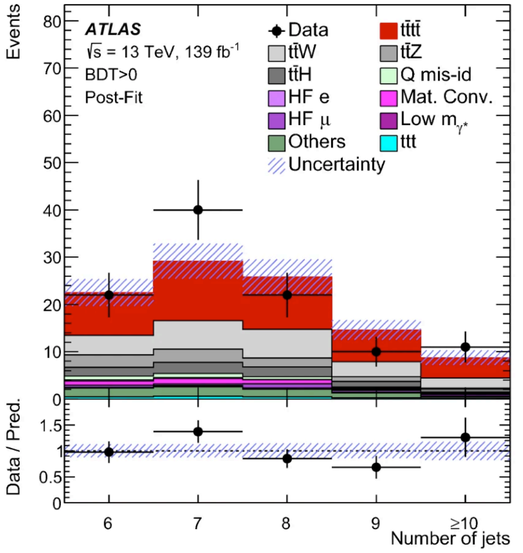

$\sigma_{t\bar{t}t\bar{t}}$ ± tot. (± stat. ± syst.) Obs. Sig.

24^{+7}_{-6} ($\pm 4^{+5}_{-4}$) fb **4.7 σ**

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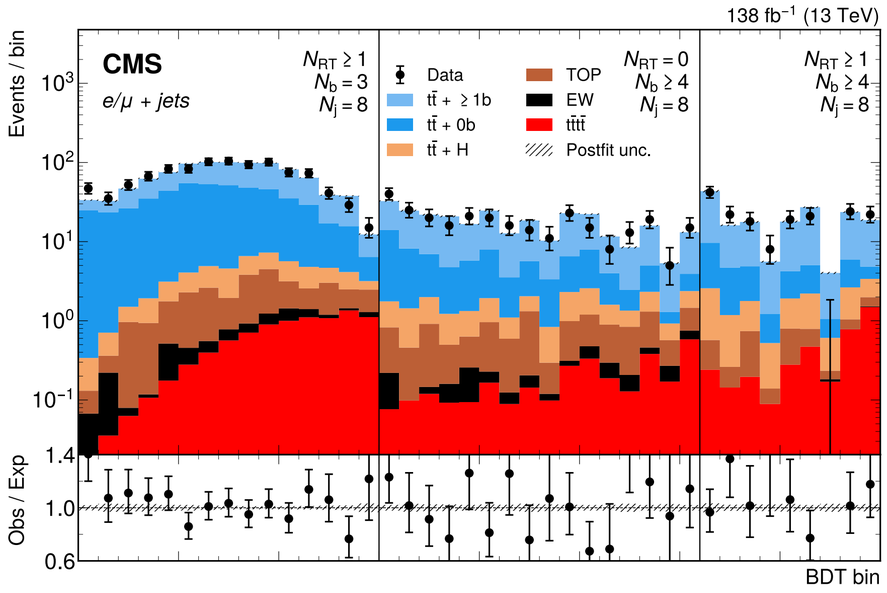
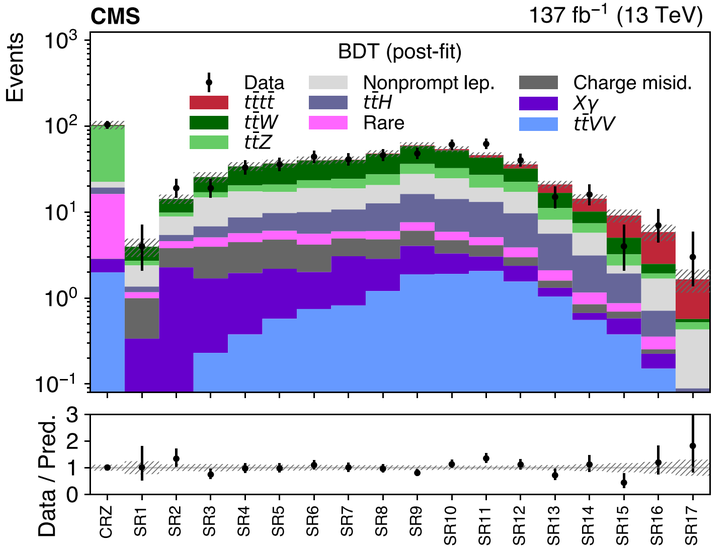
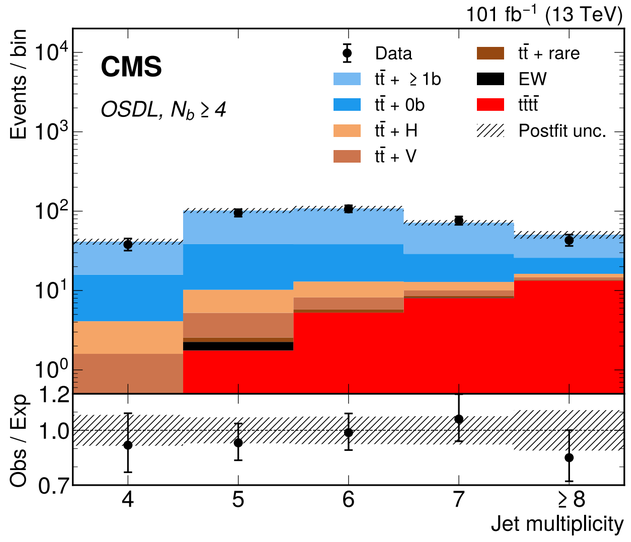
Evidence (CMS) - Run II (2016-18)







Phys. Lett. B 844 (2023) 138076

EPJC 80 (2020) 75

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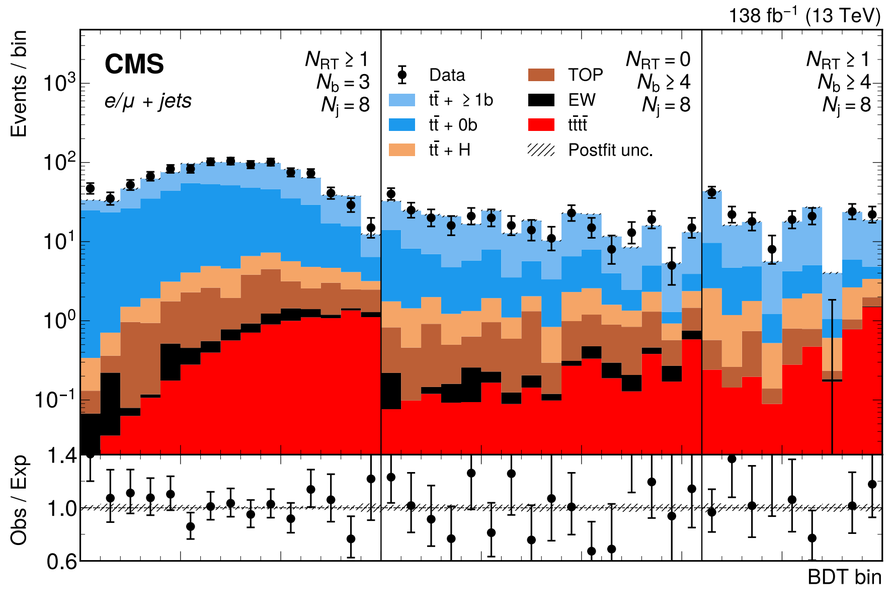

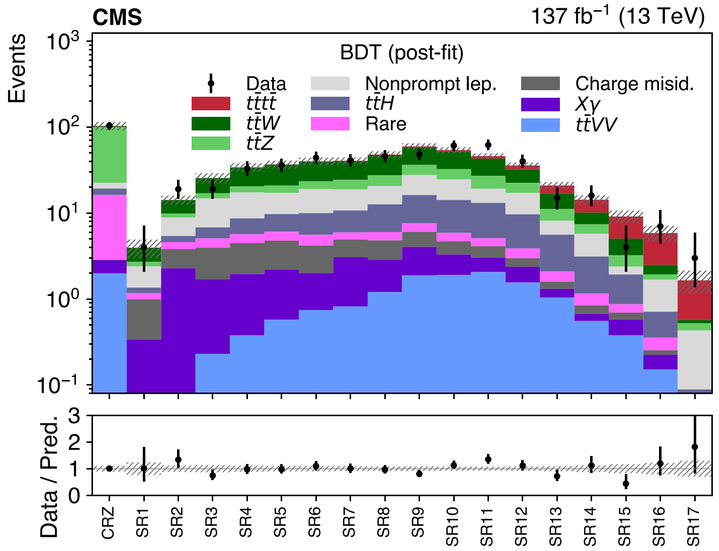

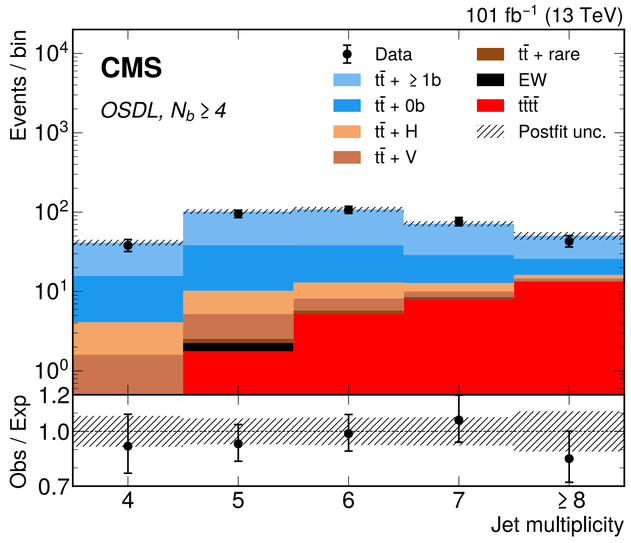

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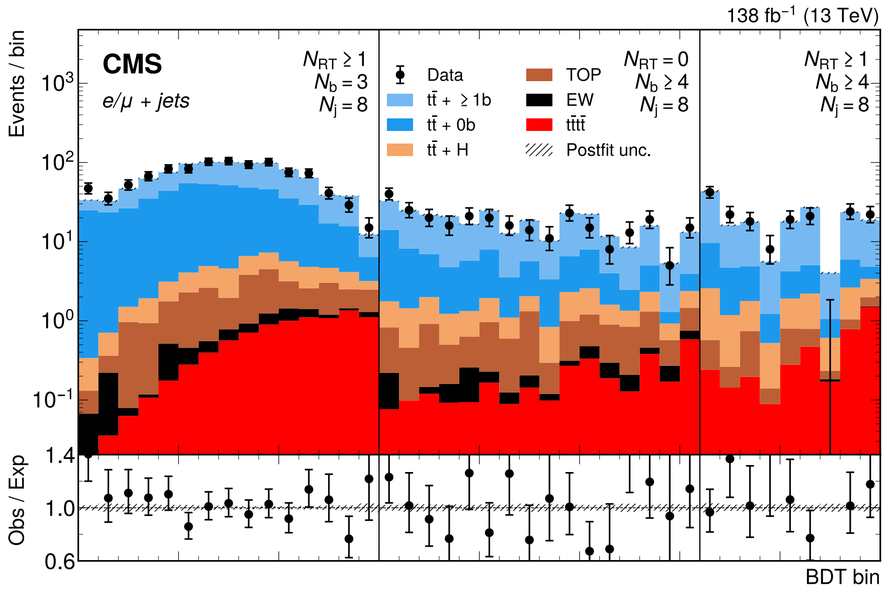

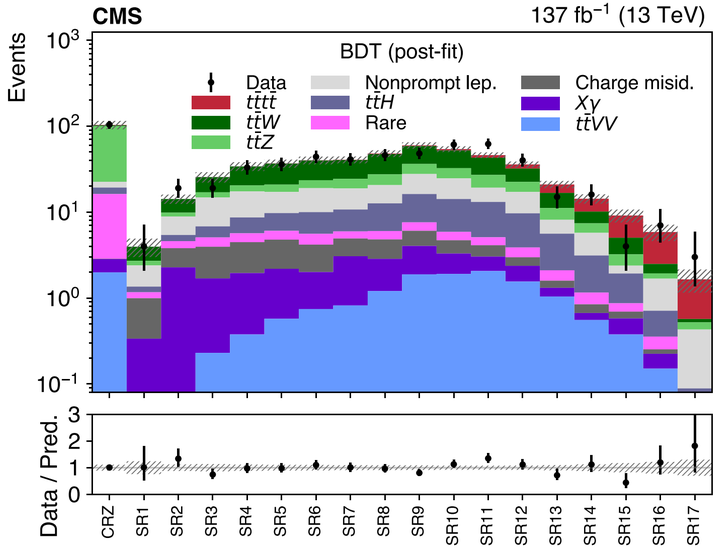

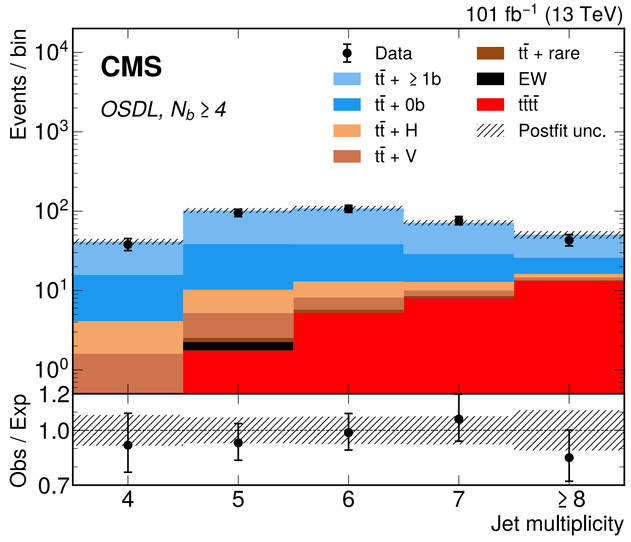

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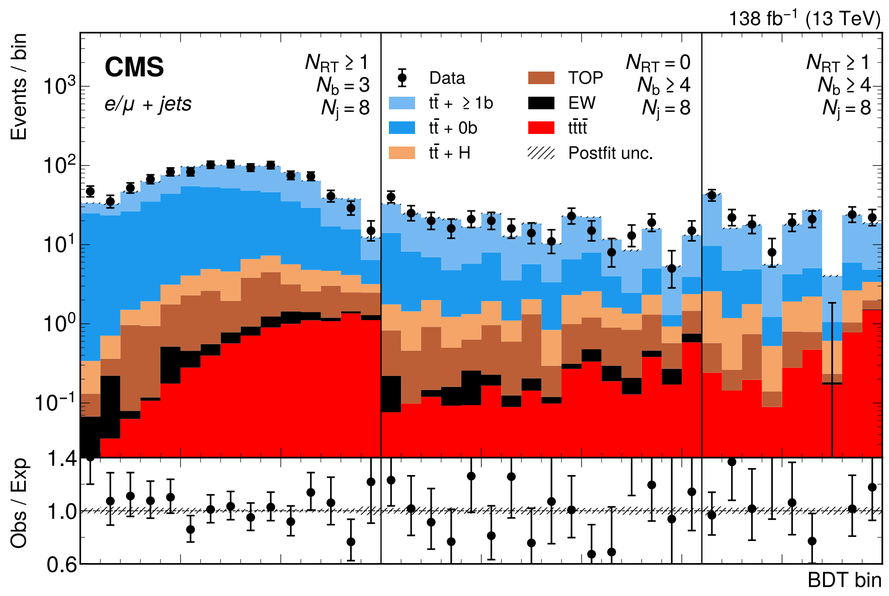

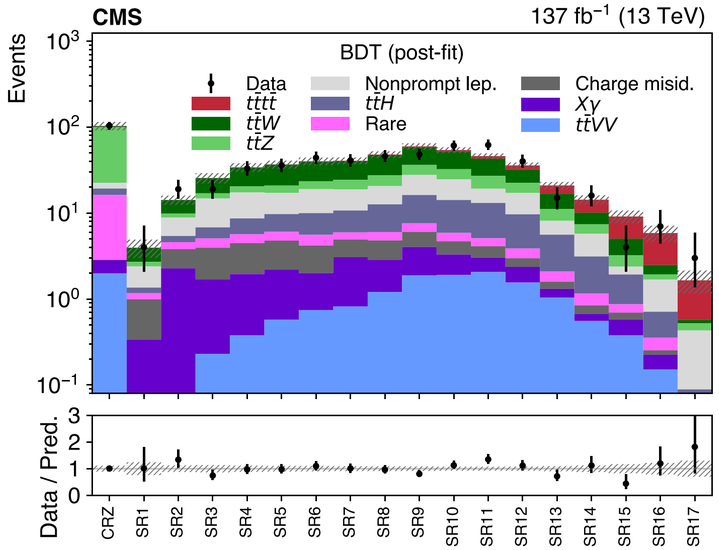

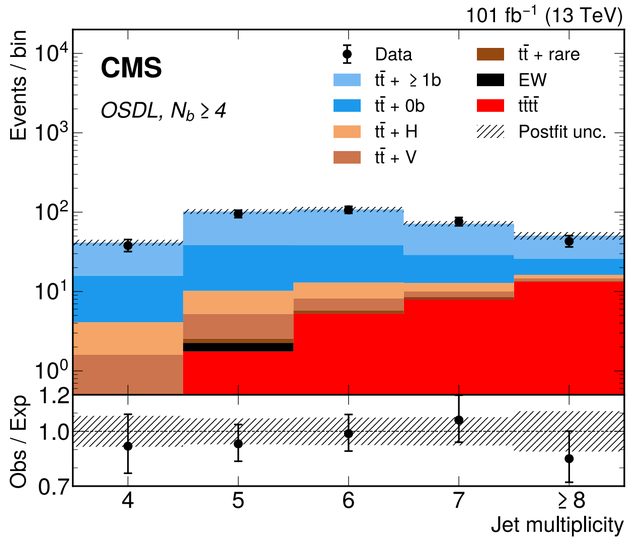

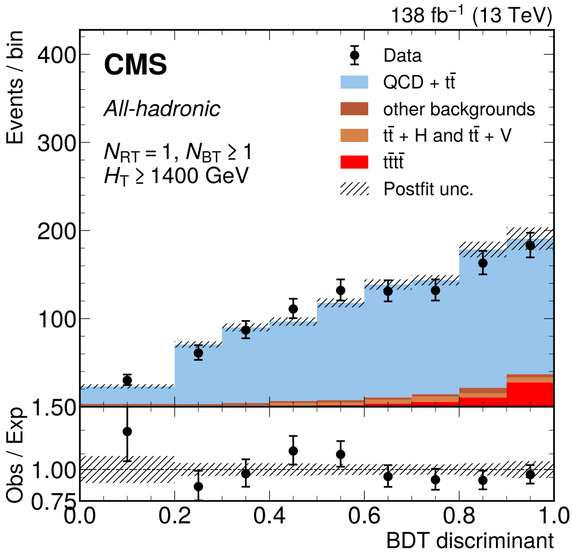

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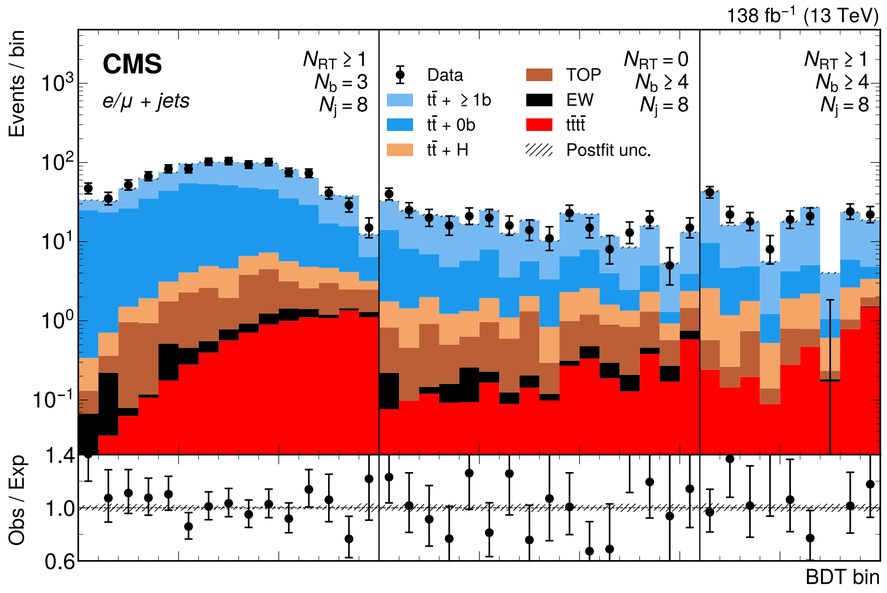

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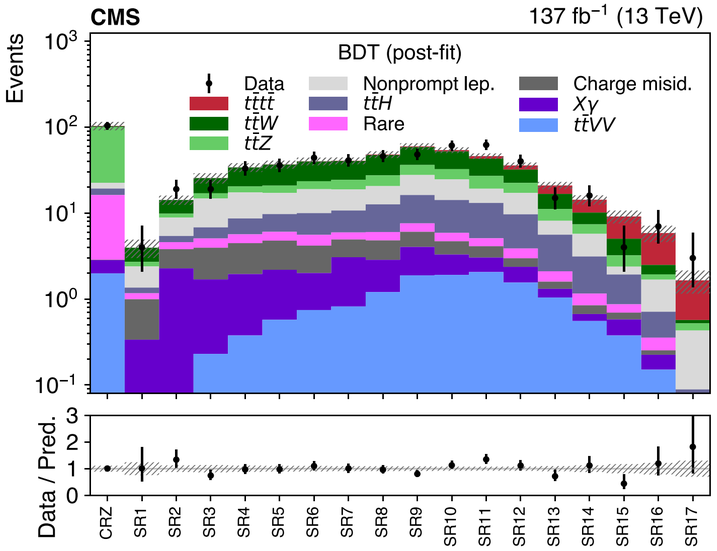
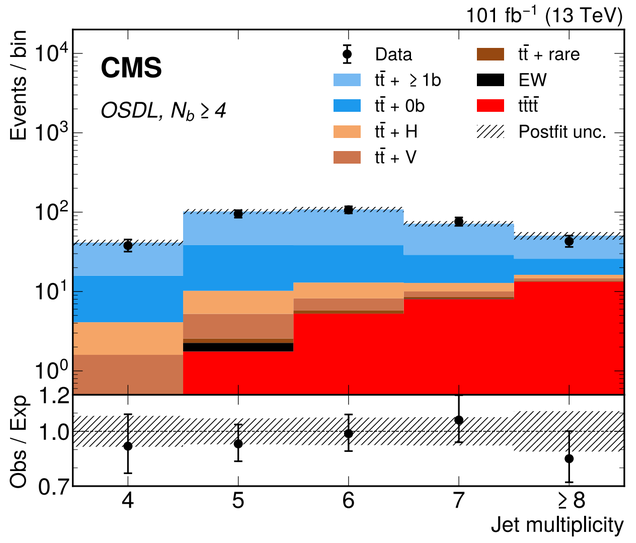
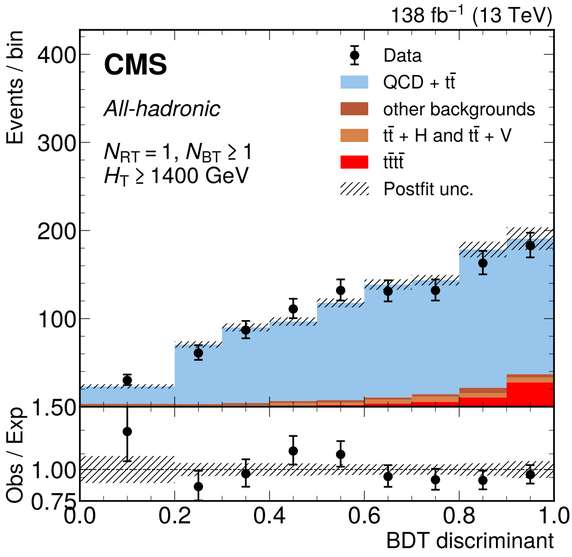
17±5 (±4 ±3) fb	**4.0 σ**







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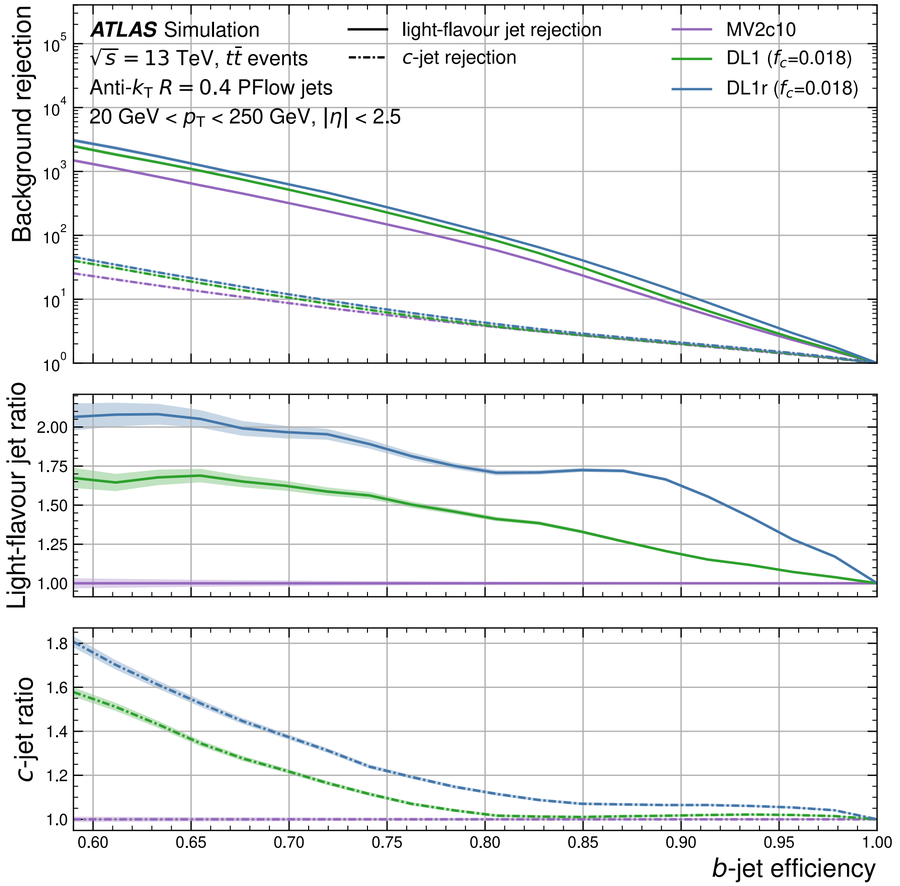
Reconstruction Improvements Key to Observation

- ATLAS MV2c10 to DL1r



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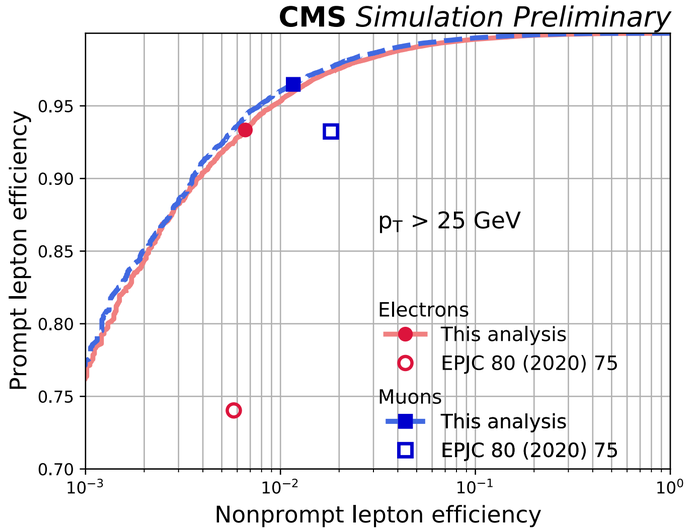
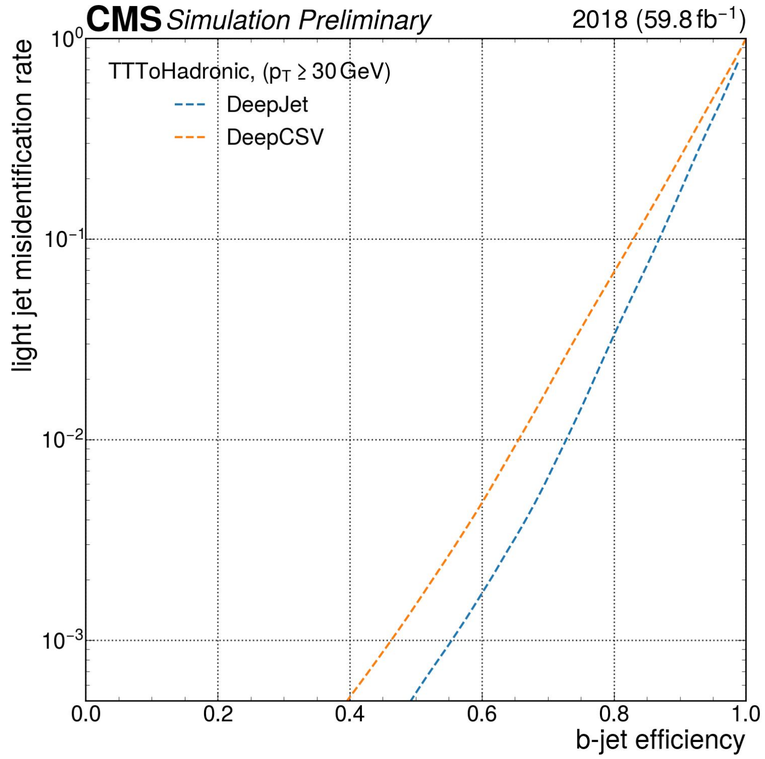
- CMS DeepCSV to DeepJet



CERN-CMS-DP-2023-005



JINST 15 (2020) P12012

Observation (CMS) - Run II (2016-18)

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Observation (CMS) - Run II (2016-18)

- SSDL + ML analysis

Phys. Lett. B 847 (2023) 138290

Observation (CMS) - Run II (2016-18)

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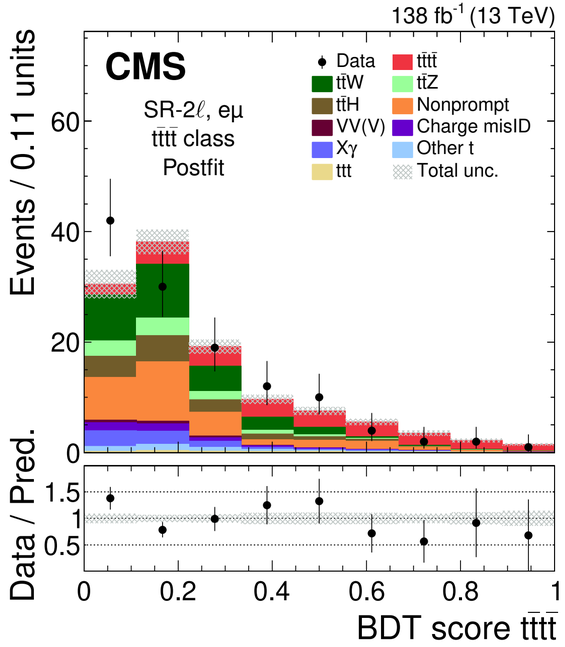

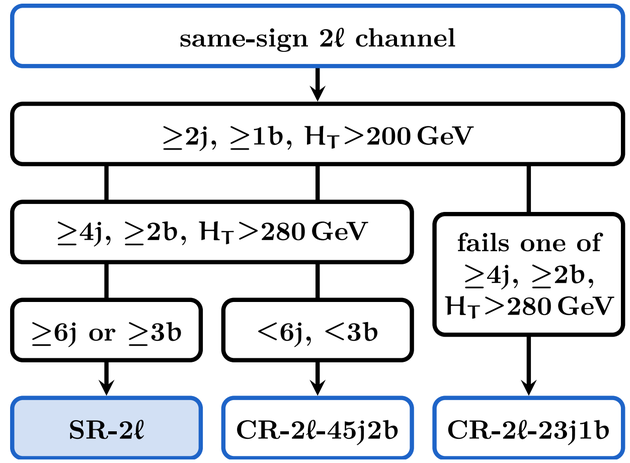

Phys. Lett. B 847 (2023) 138290

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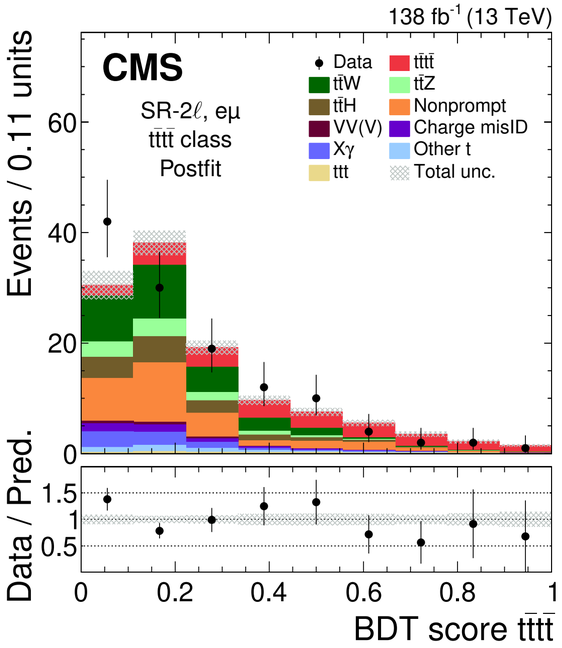

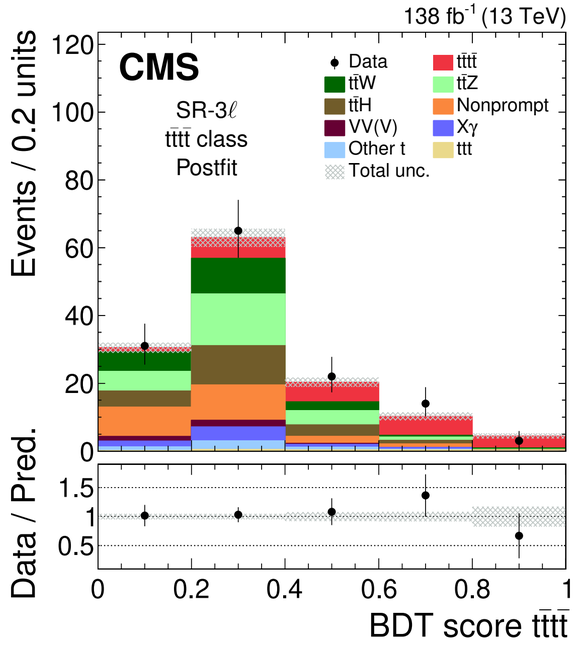

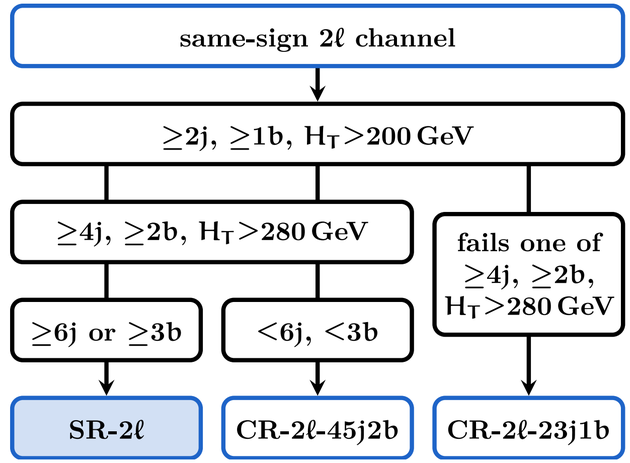

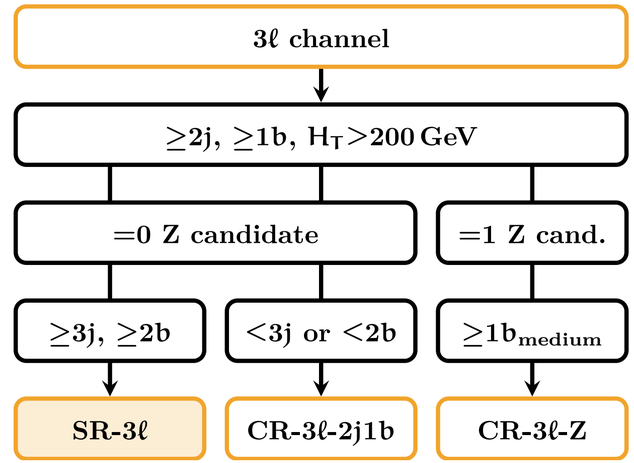

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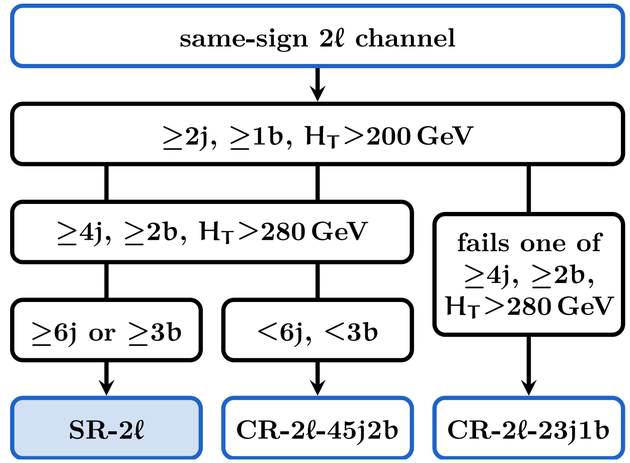
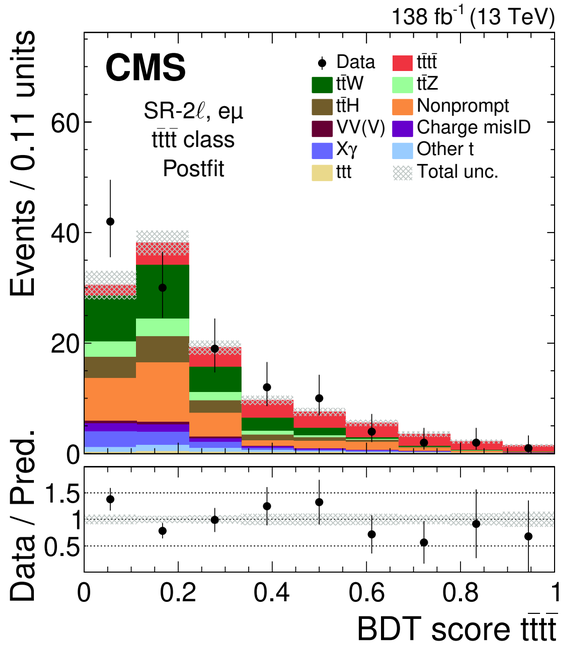
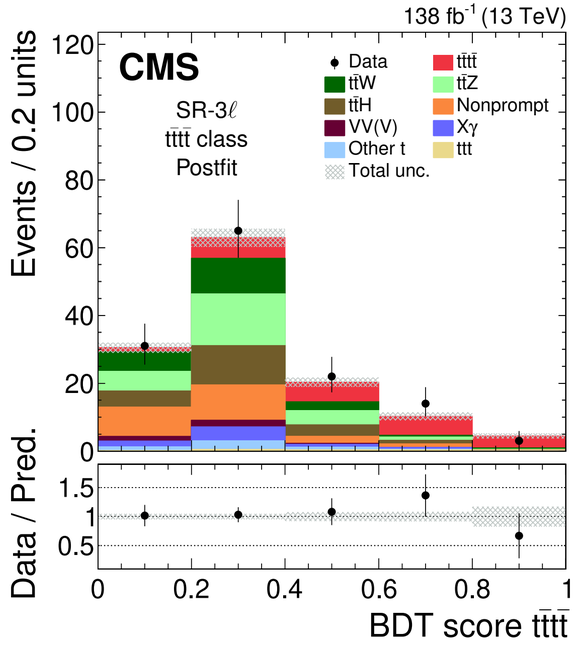
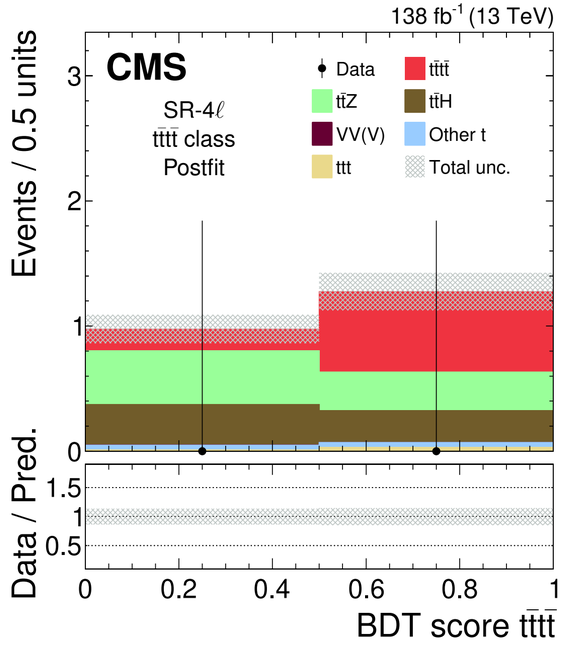
Observation (CMS) - Run II (2016-18)

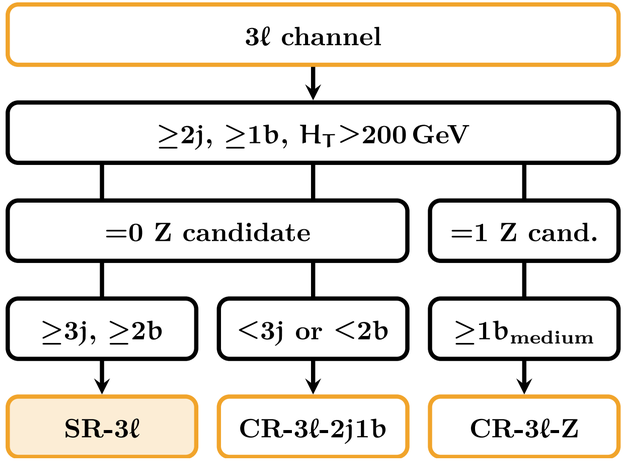
- SSDL + ML analysis
- Multiclass (tttt, ttX, tt) BDT











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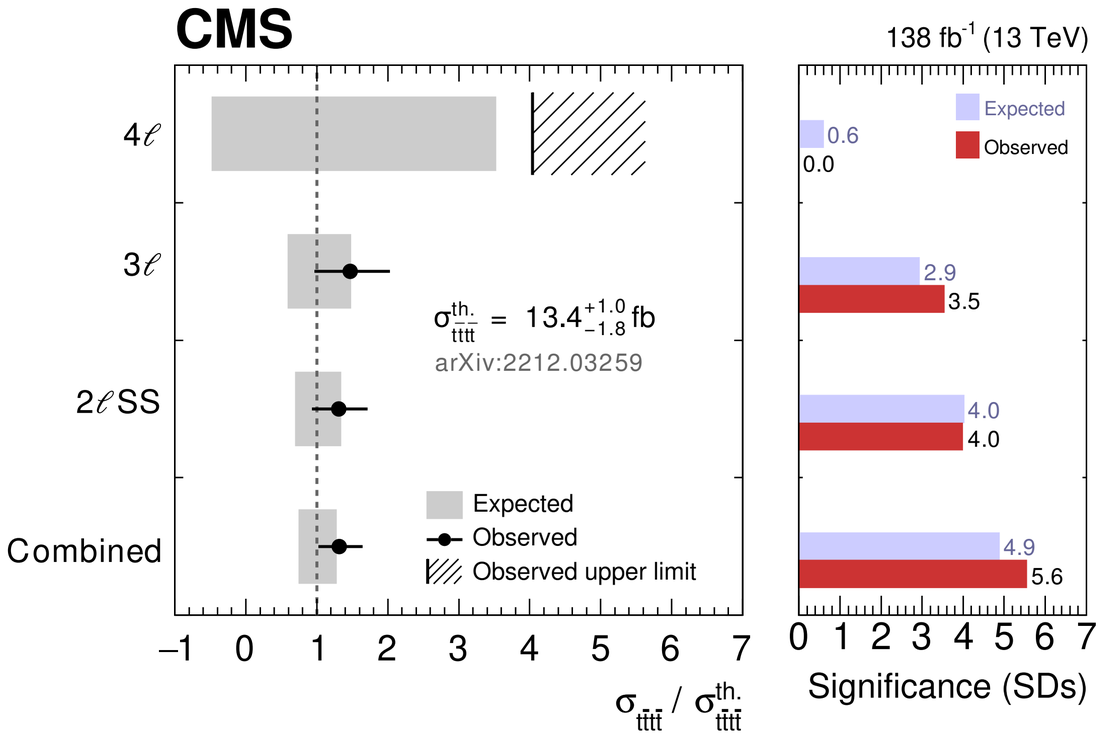
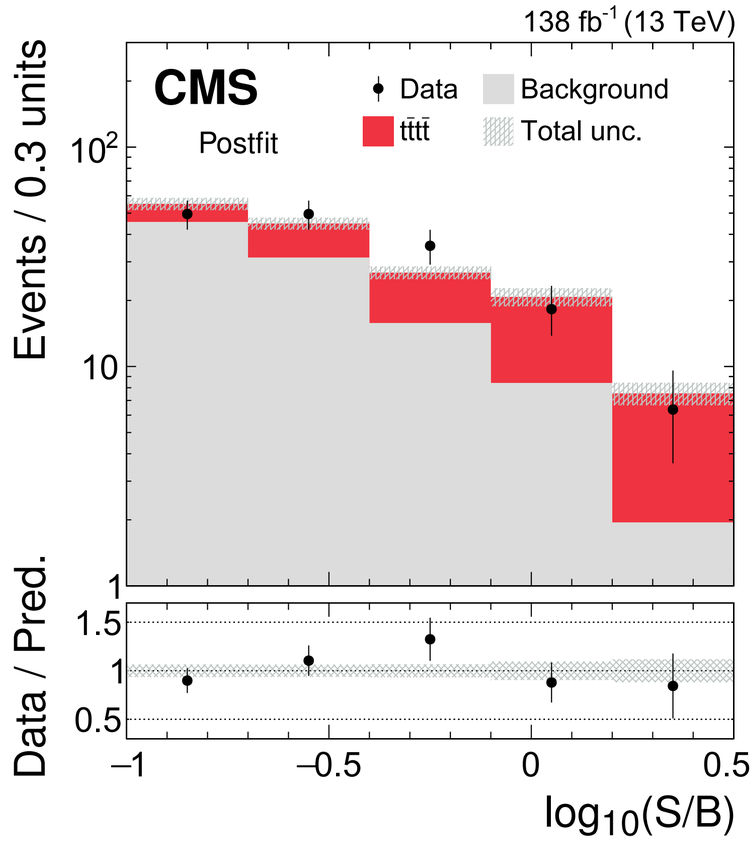
Observation (CMS) - Run II (2016-18)

$\sigma_{t\bar{t}t\bar{t}}$ ± tot. (± stat. ± syst.)	Obs. Sig.
$17.7^{+4.4}_{-4.0}$ ($^{+3.7\ +2.3}_{-3.5\ -1.9}$) fb	5.6 σ

- ttW + ttZ constrained from CRs (improved Lep ID)





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Observation (ATLAS) - Run II (2015-18)

- SSDL + ML analysis
- ttW+, ttW-, 1b, HF, QmisID CRs

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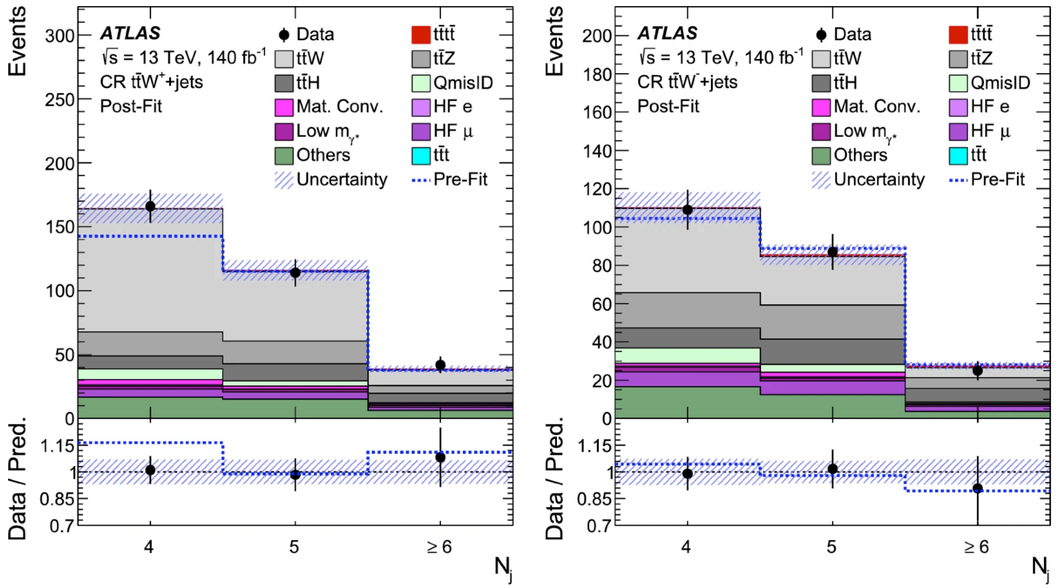
Observation (ATLAS) - Run II (2015-18)

- SSDL + ML analysis
- ttW+, ttW-, 1b, HF, QmisID CRs



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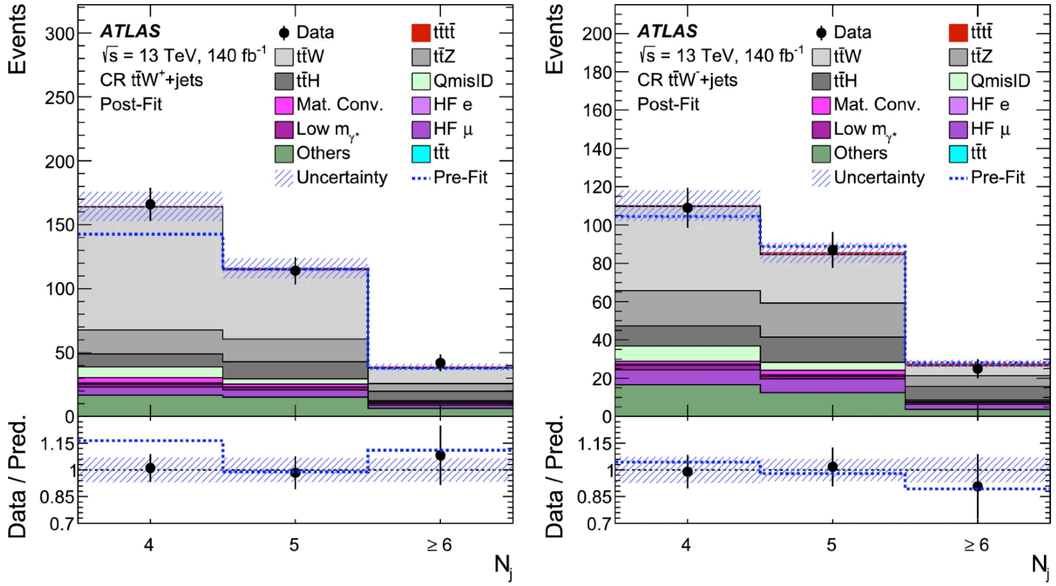
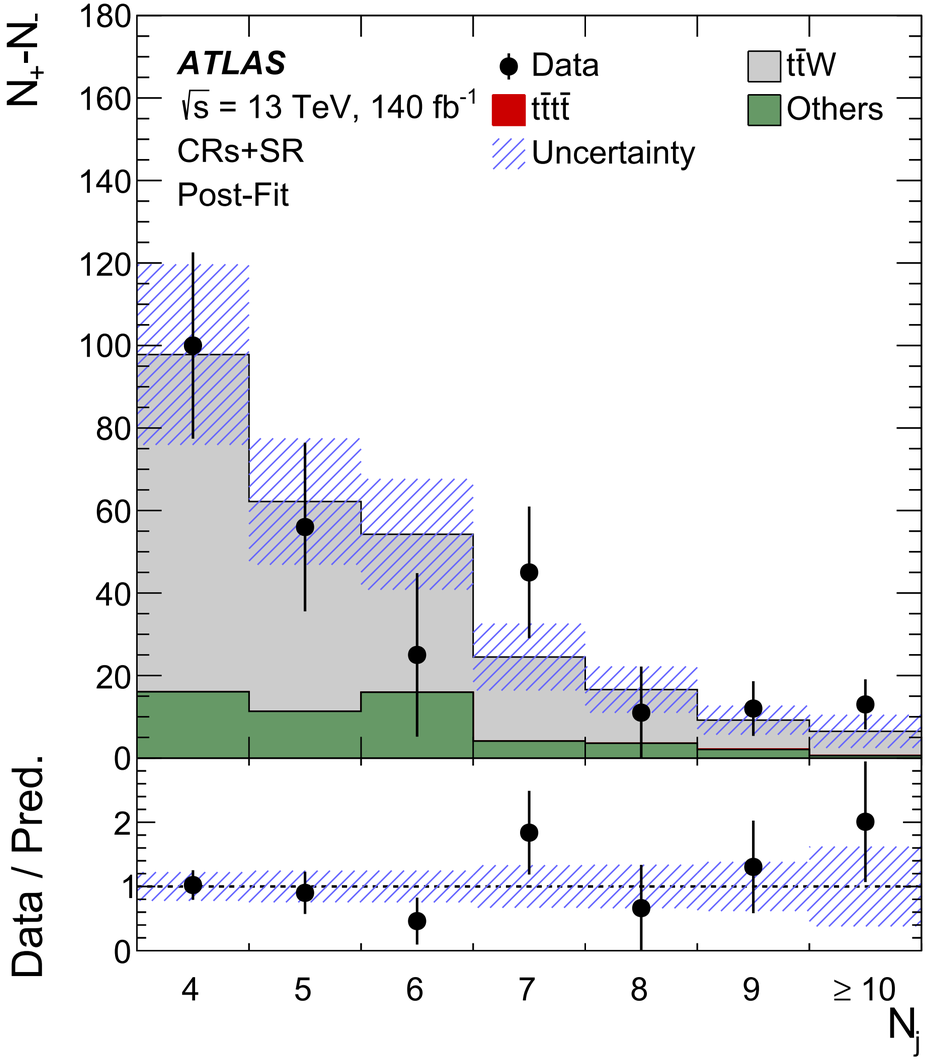
Observation (ATLAS) - Run II (2015-18)

- SSDL + ML analysis
- ttW+, ttW-, 1b, HF, QmisID CRs





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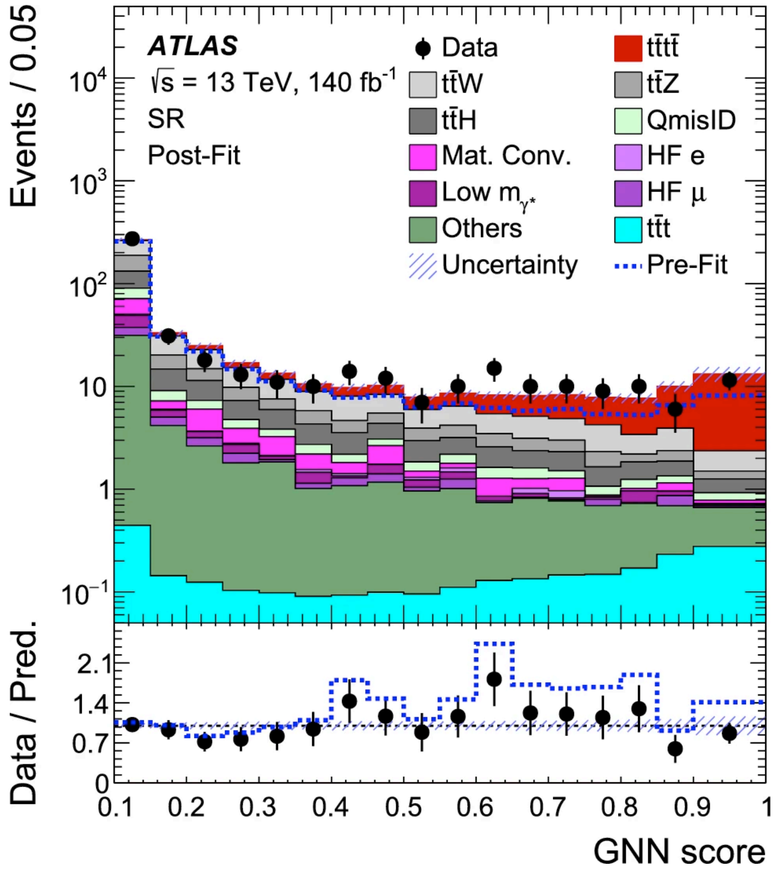
Observation (ATLAS) - Run II (2015-18)

- Event Graph Neural Net Classifier (GNN)



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Observation (ATLAS) - Run II (2015-18)

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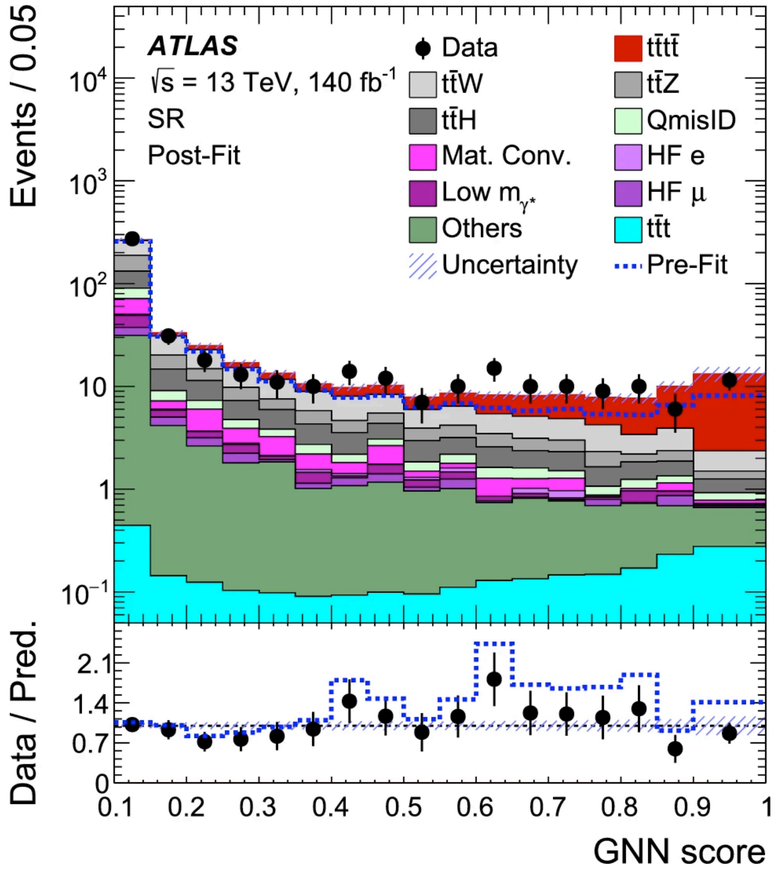

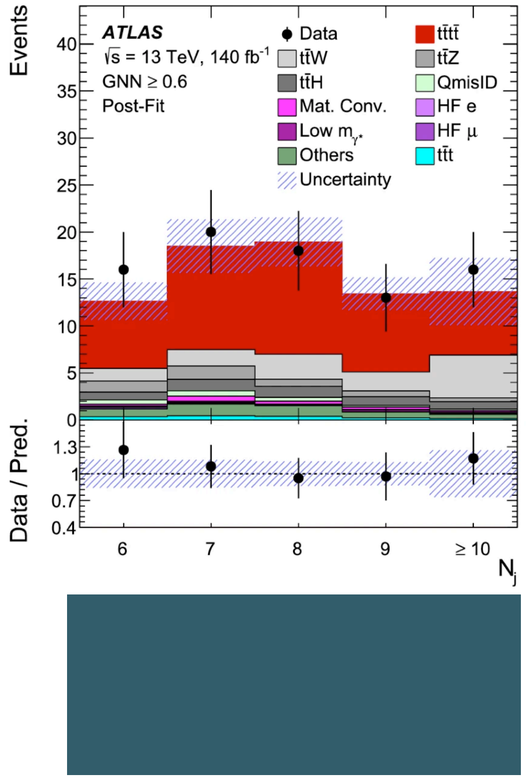

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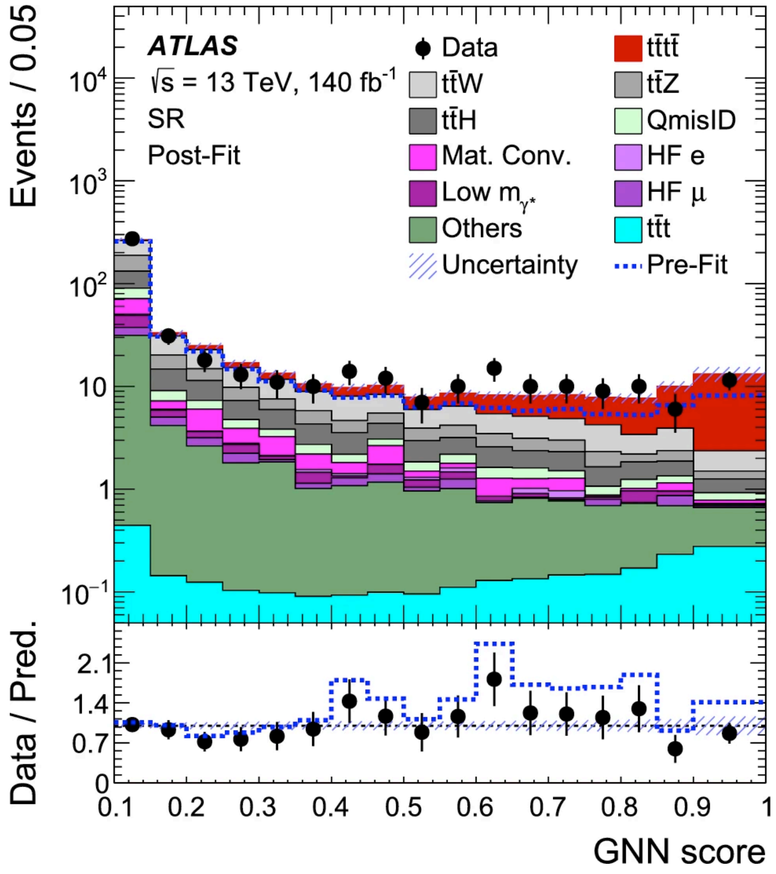
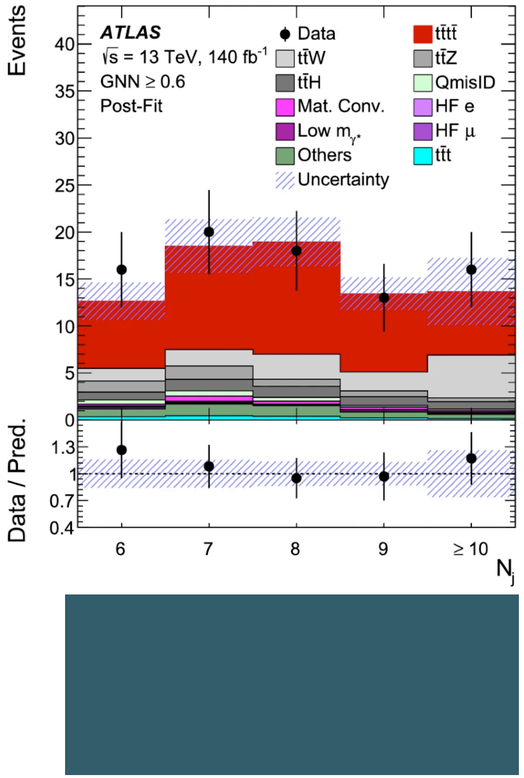
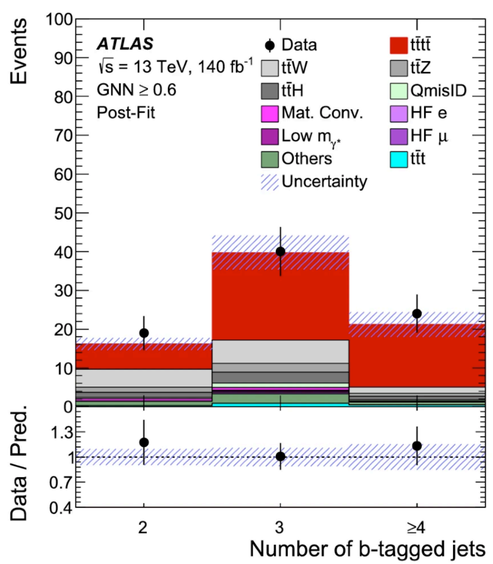
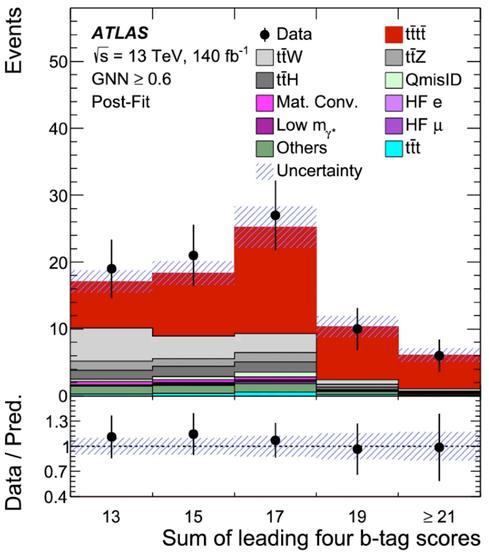
Observation (ATLAS) - Run II (2015-18)

- Event Graph Neural Net Classifier (GNN)









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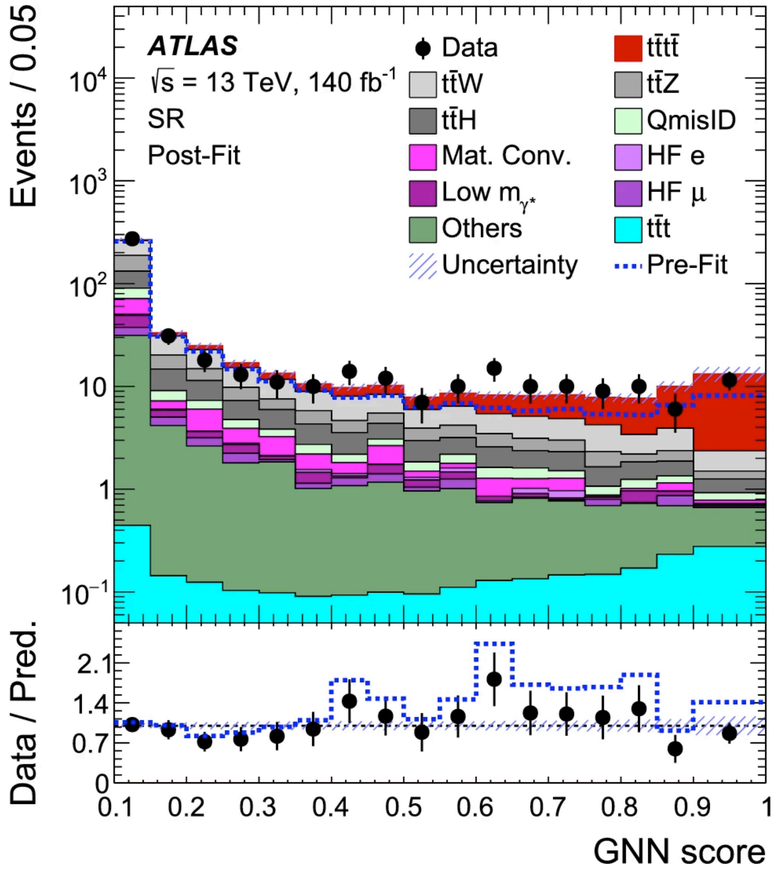

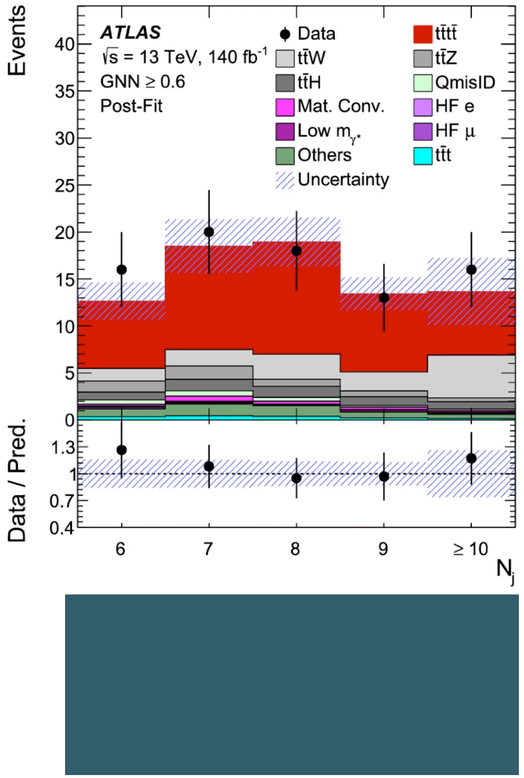

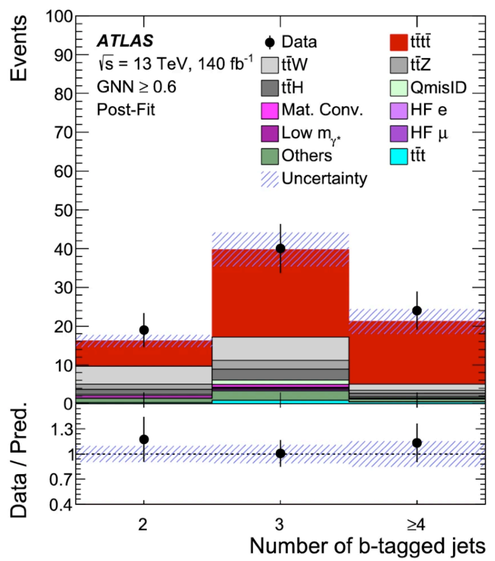

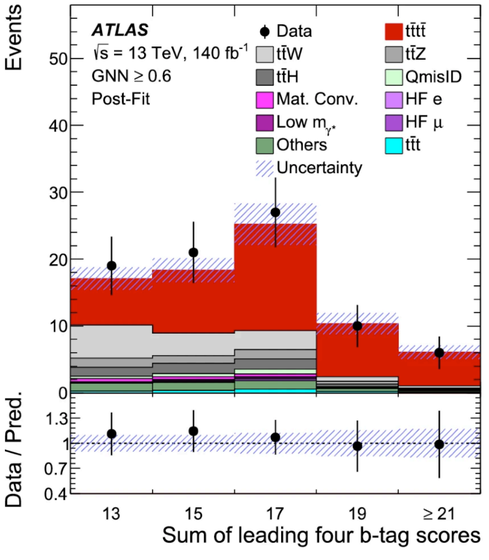

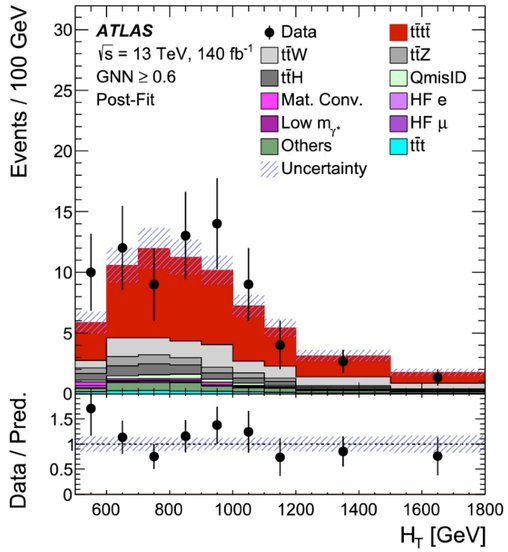

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Observation (ATLAS) - Run II (2015-18)

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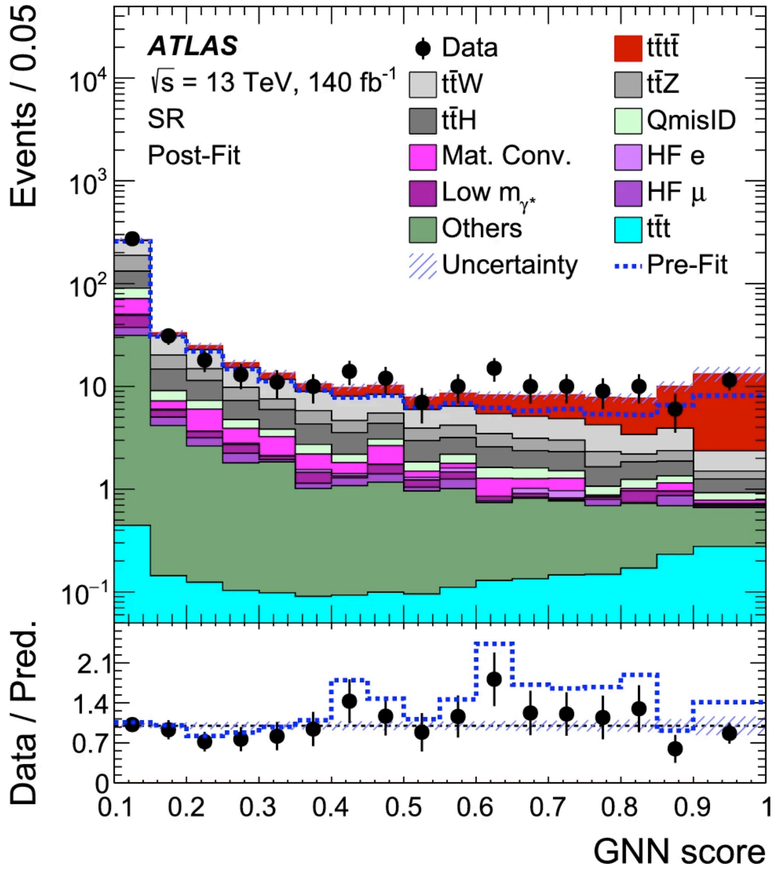
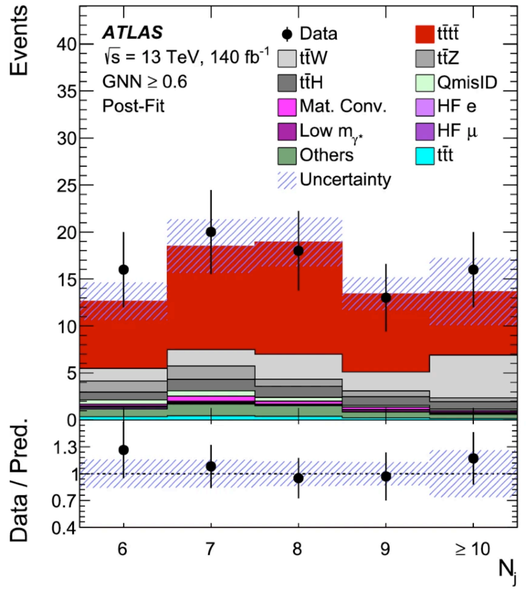
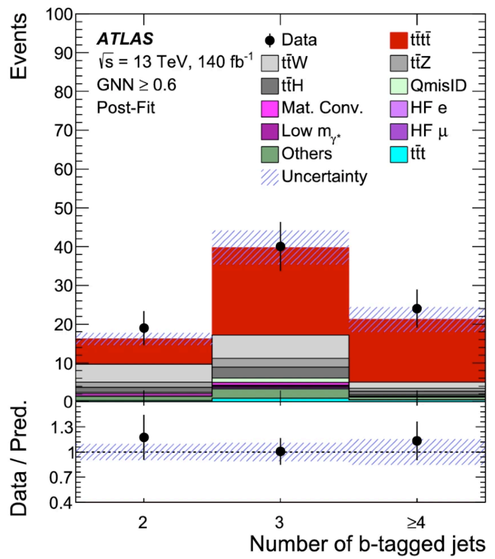
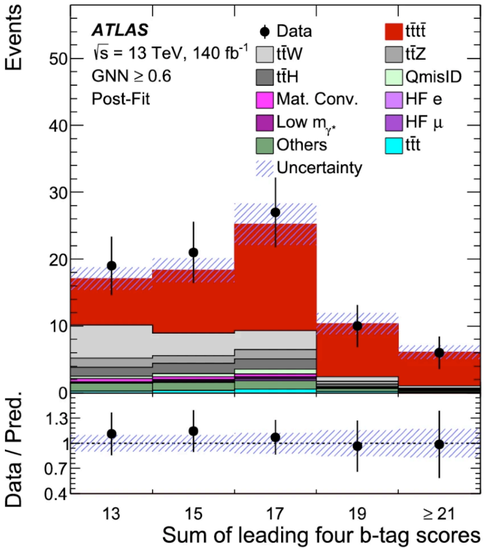
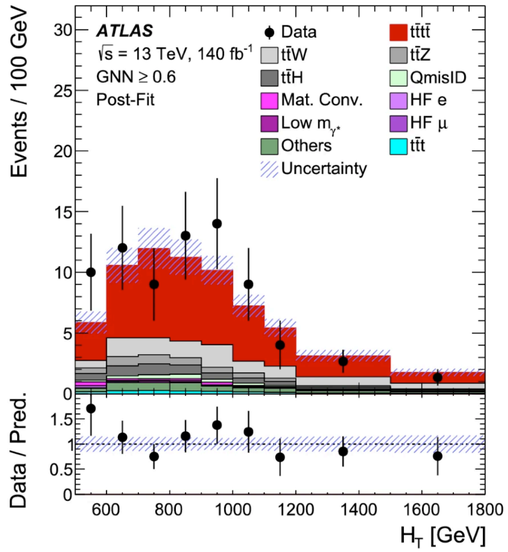




$\sigma_{t\bar{t}t\bar{t}}$ ± tot. (± stat. ± syst.)	Obs. Sig.
$22.5\ ^{+6.6}_{-5.5}\ (^{+4.7\ +4.6}_{-4.3\ -3.4})$ fb	6.1 σ







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Looking Forward

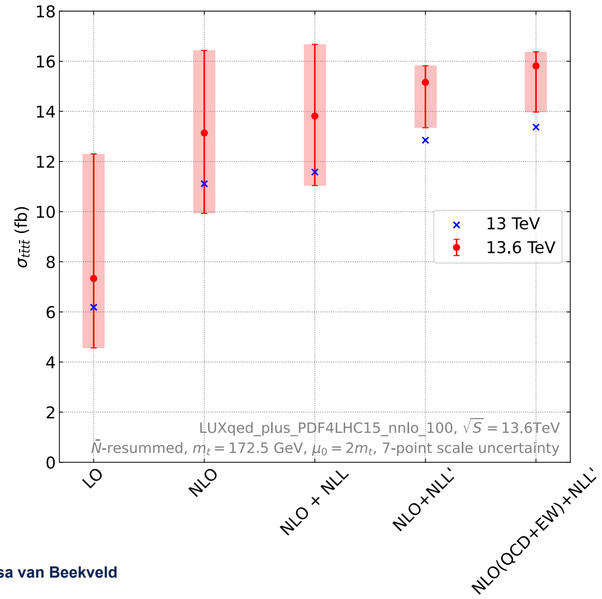
Looking Forward

- Next Four Top Searches
  - Enhanced 13.6 TeV Production (tt less)
  - Better: b-tagging, ML, BKG-estimation
  - Dedicated hadronic-tau analyses

Results for 13.6 TeV

	$\sigma_{t\bar{t}t\bar{t}}$ (fb)	K-factor
NLO	$13.14(2)^{+25.1\%}_{-24.4\%}$	
NLO+NLL	$13.81(2)^{+20.7\%}_{-20.1\%}$	1.05
NLO+NLL'	$15.16(2)^{+4.3\%}_{-11.9\%}$	1.15
NLO(QCD+EW)	$13.80(2)^{+22.9\%}_{-22.6\%}$	
NLO(QCD+EW)+NLL	$14.47(2)^{+18.4\%}_{-18.5\%}$	1.05
NLO(QCD+EW)+NLL'	$15.81(2)^{+3.6\%}_{-11.6\%}$	1.14

PDF error is 6.7 %



32 Melissa van Beekveld

Looking Forward

- Next Four Top Searches
  - Enhanced 13.6 TeV Production (tt less)
  - Better: b-tagging, ML, BKG-estimation
  - Dedicated hadronic-tau analyses
- Three tops
  - tttJ + tttW production modes
  - $\sigma_{ttt} = 2fb$
  - Expect future combination analyses to benefit

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	$\sigma_{t\bar{t}t\bar{t}}$ (fb)	K-factor
NLO	$13.14(2)^{+25.1\%}_{-24.4\%}$	
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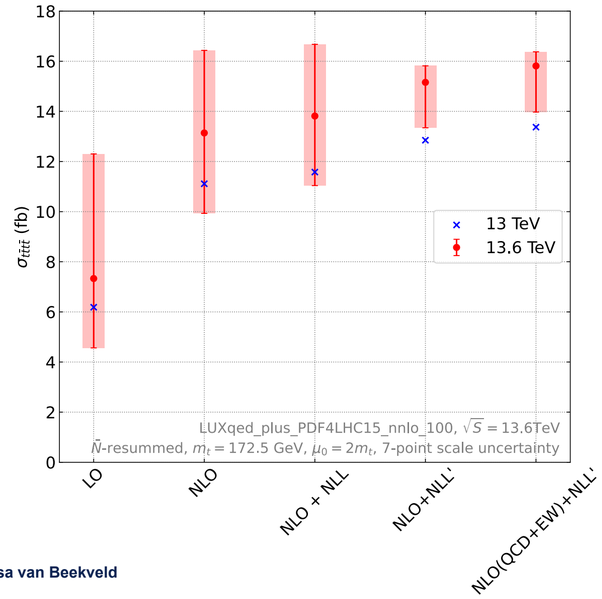

32 Melissa van Beekveld

Looking Forward

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	$\sigma_{t\bar{t}t\bar{t}}$ (fb)	*K*-factor
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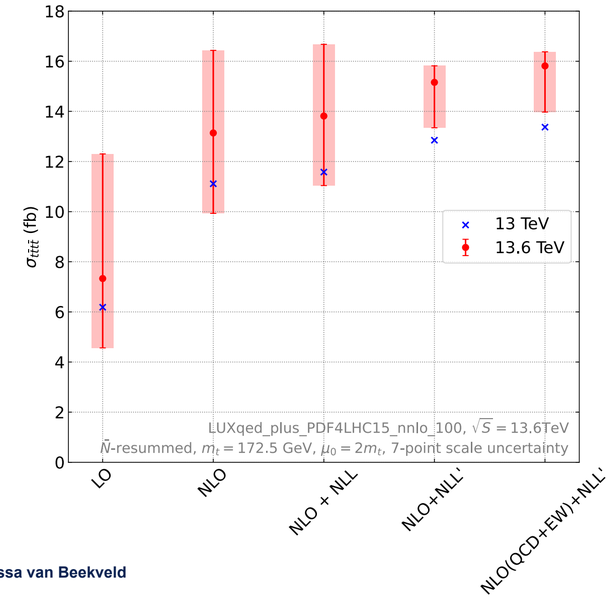
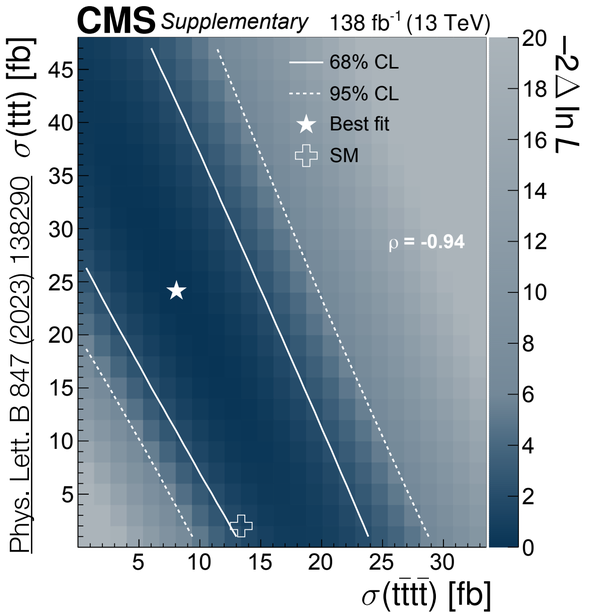
PDF error is 6.7 %



32 Melissa van Beekveld



Looking Forward

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  - Enhanced 13.6 TeV Production (tt less)
  - Better: b-tagging, ML, BKG-estimation
  - Dedicated hadronic-tau analyses
- Three tops
  - tttJ + tttW production modes
  - $\sigma_{ttt} = 2fb$
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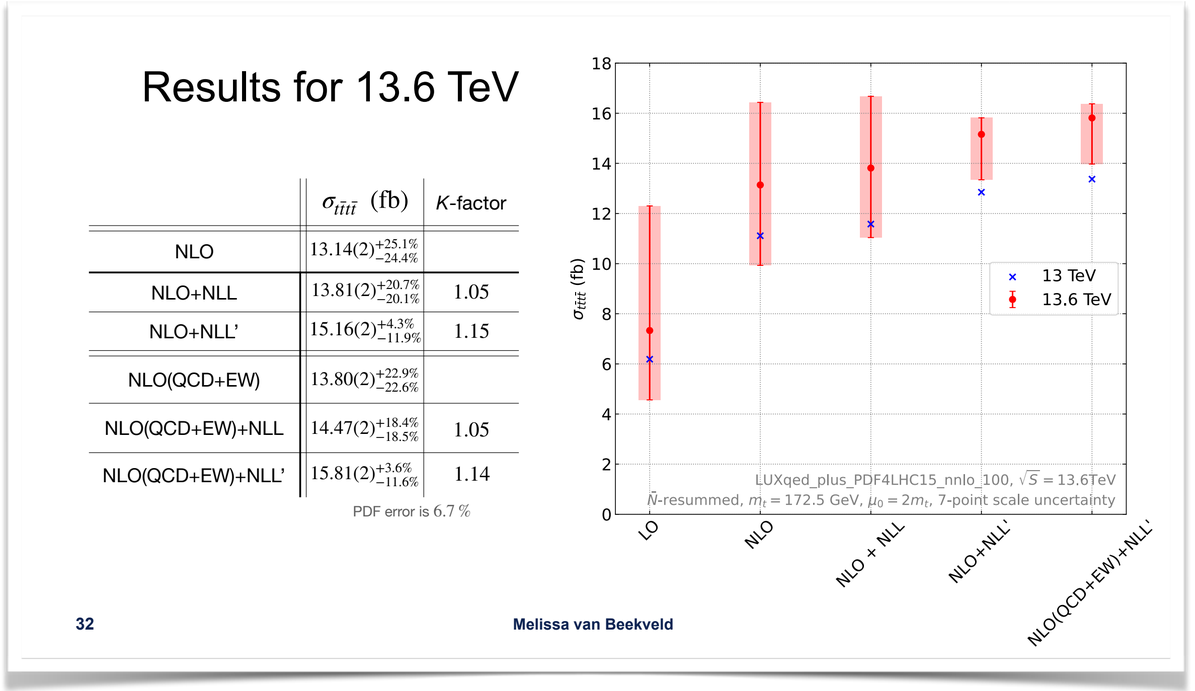
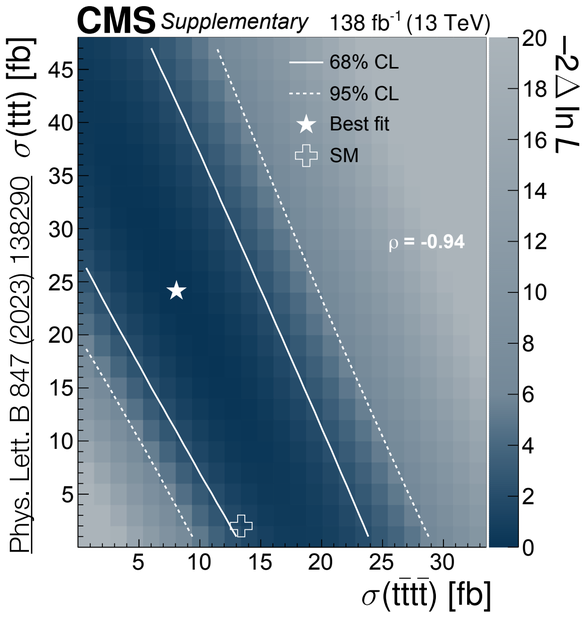
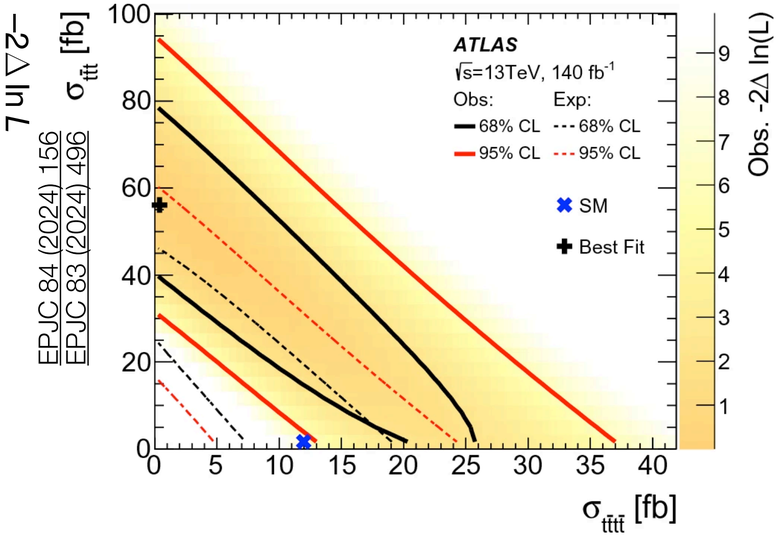
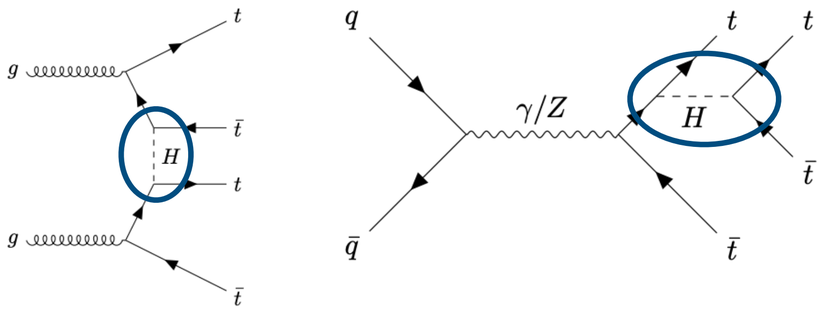




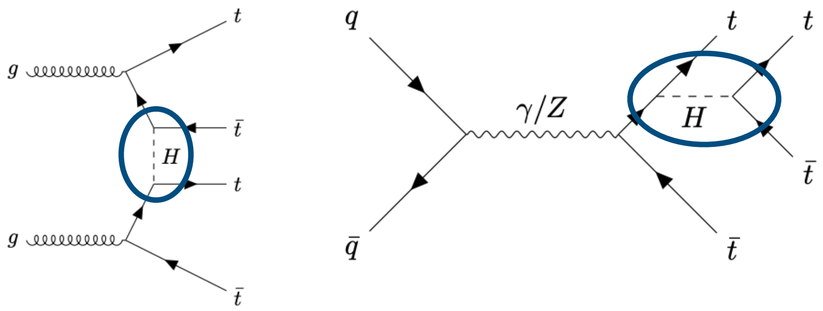


Top Yukawa



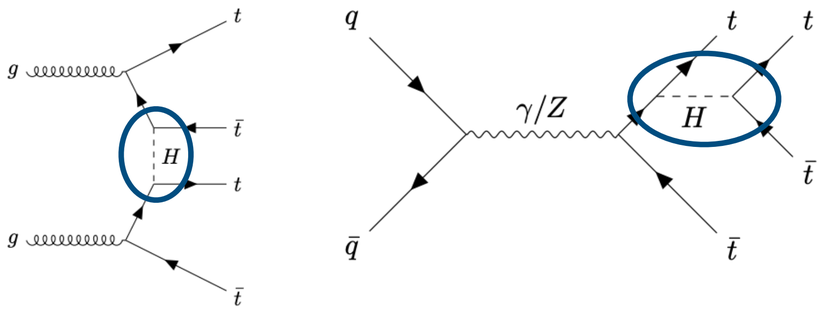
Top Yukawa

- tttt Sensitive to both coupling strength and CP properties



Top Yukawa

- tttt Sensitive to both coupling strength and CP properties
  - Complementary to extraction from ttH measurements



Top Yukawa

- tttt Sensitive to both coupling strength and CP properties
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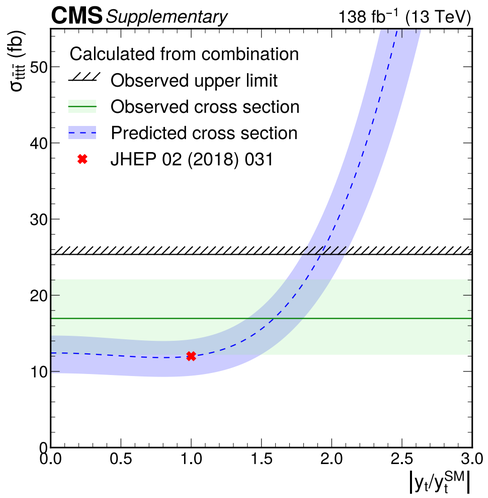
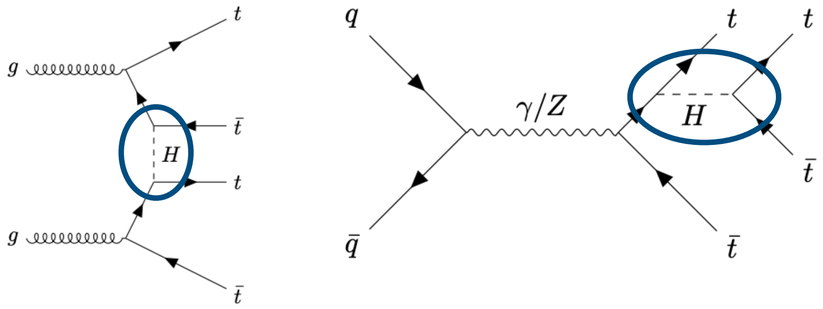
  - Upper limit of 1.9 x SM in CMS

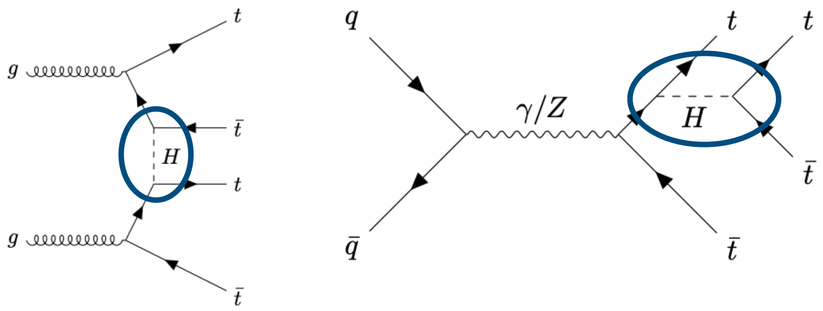


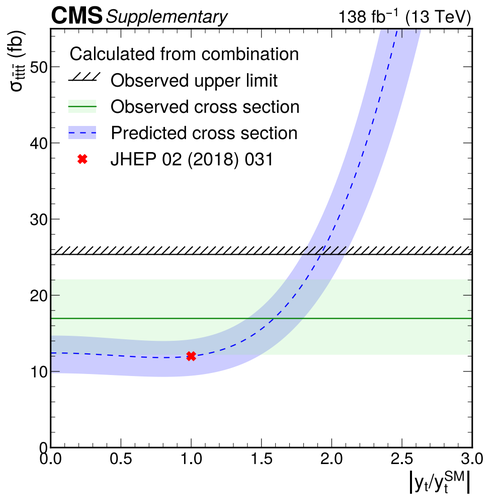
Phys. Lett. B 844 (2023) 138076



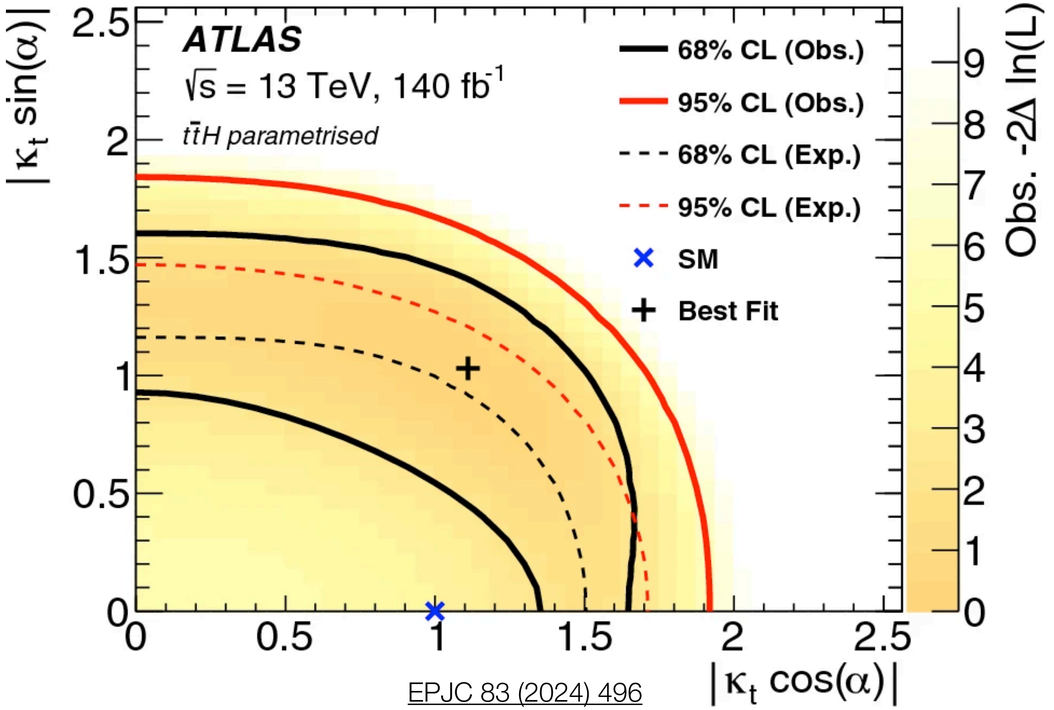
Top Yukawa

- tttt Sensitive to both coupling strength and CP properties
  - Complementary to extraction from ttH measurements
  - Upper limit of 1.9 x SM in CMS
  - Simultaneous fit of CP-odd/even in ATLAS



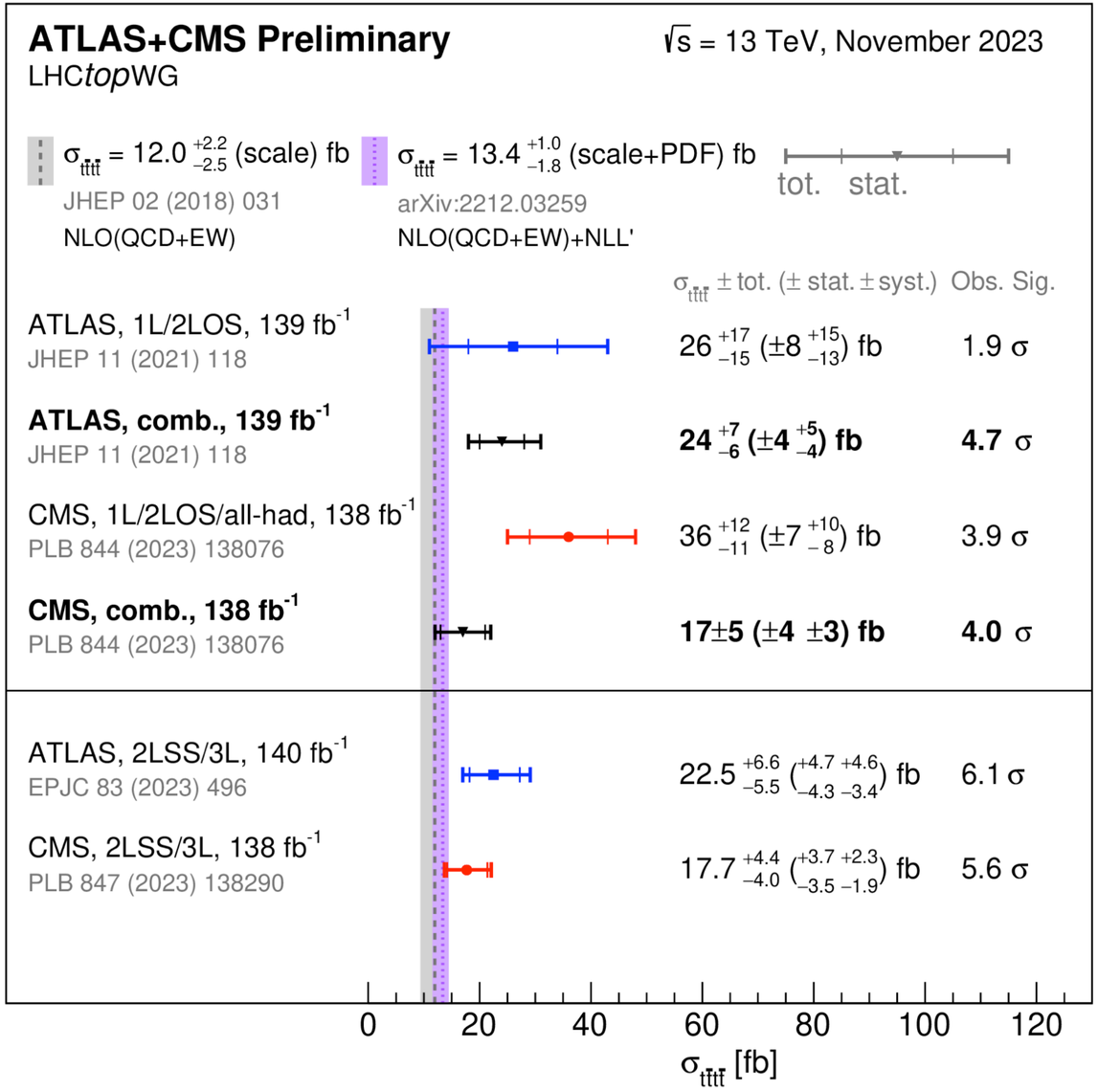


Phys. Lett. B 844 (2023) 138076



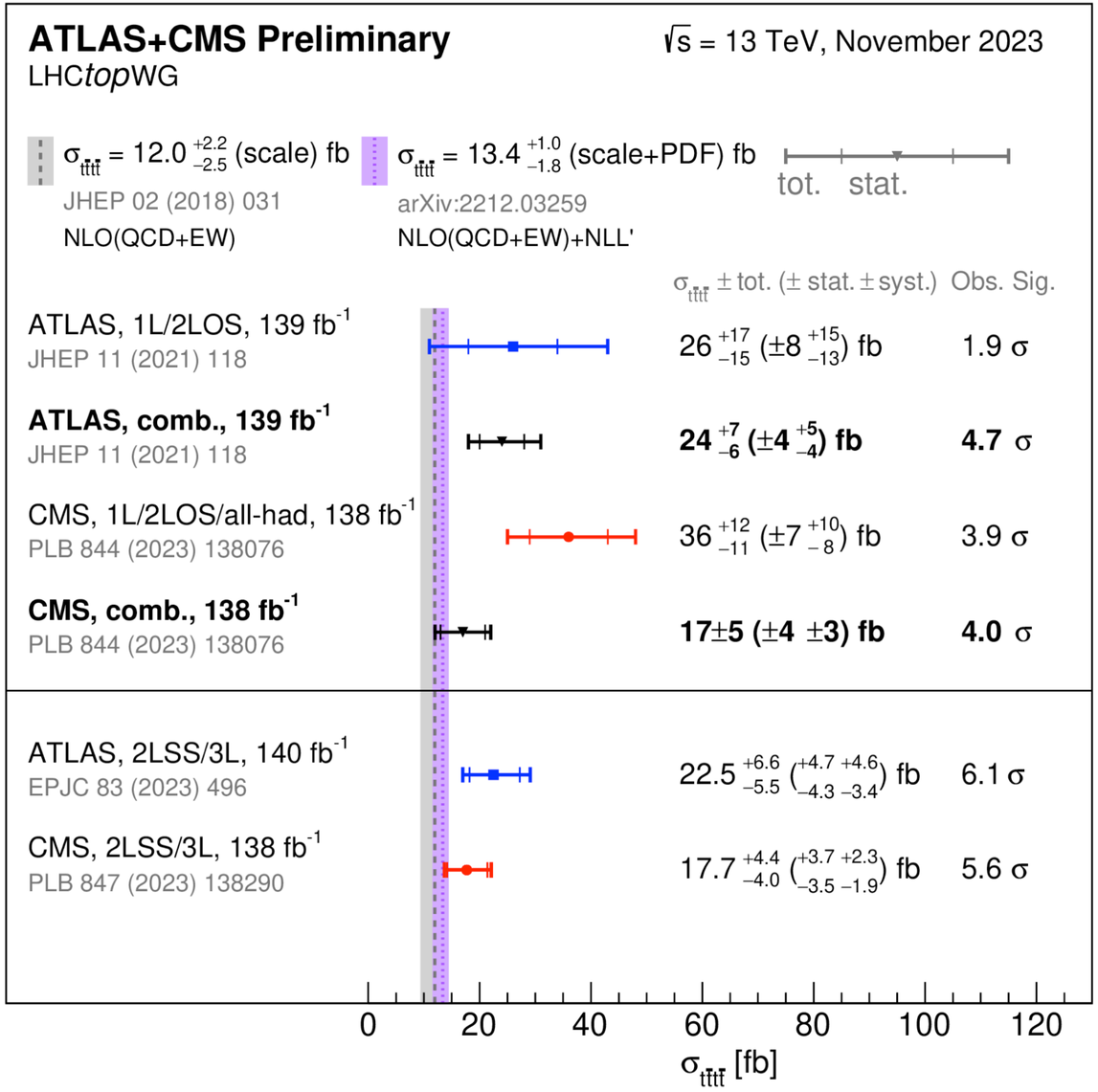
EPJC 83 (2024) 496
EPJC 84 (2024) 156

Summary


ATLAS+CMS Preliminary
LHCtopWG
√s = 13 TeV, November 2023
σ_tttt = 12.0 +2.2 −2.5 (scale) fb
JHEP 02 (2018) 031
NLO(QCD+EW)
σ_tttt = 13.4 +1.0 −1.8 (scale+PDF) fb
arXiv:2212.03259
NLO(QCD+EW)+NLL'
tot. stat.
σ_tttt ± tot. (± stat. ± syst.) Obs. Sig.
ATLAS, 1L/2LOS, 139 fb-1
JHEP 11 (2021) 118
26 +17 −15 (±8 +15 −13) fb 1.9 σ
ATLAS, comb., 139 fb-1
JHEP 11 (2021) 118
24 +7 −6 (±4 +5 −4) fb 4.7 σ
CMS, 1L/2LOS/all-had, 138 fb-1
PLB 844 (2023) 138076
36 +12 −11 (±7 +10 −8) fb 3.9 σ
CMS, comb., 138 fb-1
PLB 844 (2023) 138076
17±5 (±4 ±3) fb 4.0 σ
ATLAS, 2LSS/3L, 140 fb-1
EPJC 83 (2023) 496
22.5 +6.6 −5.5 (+4.7 +4.6 −4.3 −3.4) fb 6.1 σ
CMS, 2LSS/3L, 138 fb-1
PLB 847 (2023) 138290
17.7 +4.4 −4.0 (+3.7 +2.3 −3.5 −1.9) fb 5.6 σ
0 20 40 60 80 100 120
σ_tttt [fb]

Summary

- Four top production observed!
  - σ_{tttt} compatible with SM
  - But measured above expectation in many channels



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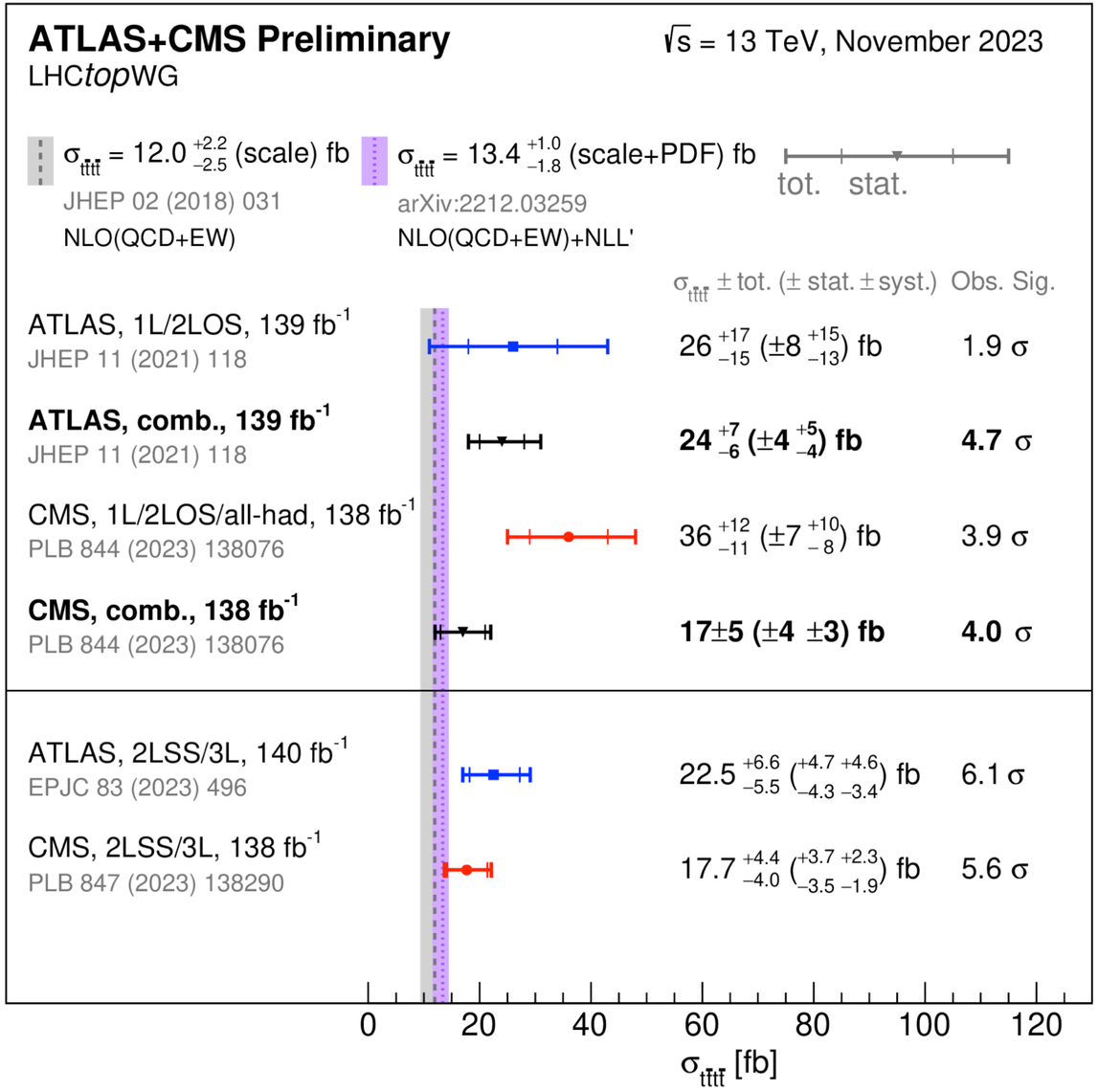
- Challenging phase space, where measurement of the major backgrounds are themselves frontier topics, and modeling is evolving
  - Exciting region for novel background-estimation techniques, ML event classifiers, simultaneous measurements, and seeing the benefit of improved reconstruction techniques
  - Overlap with ttbb, ttH, ttW, ttZ, ttt measurements/searches



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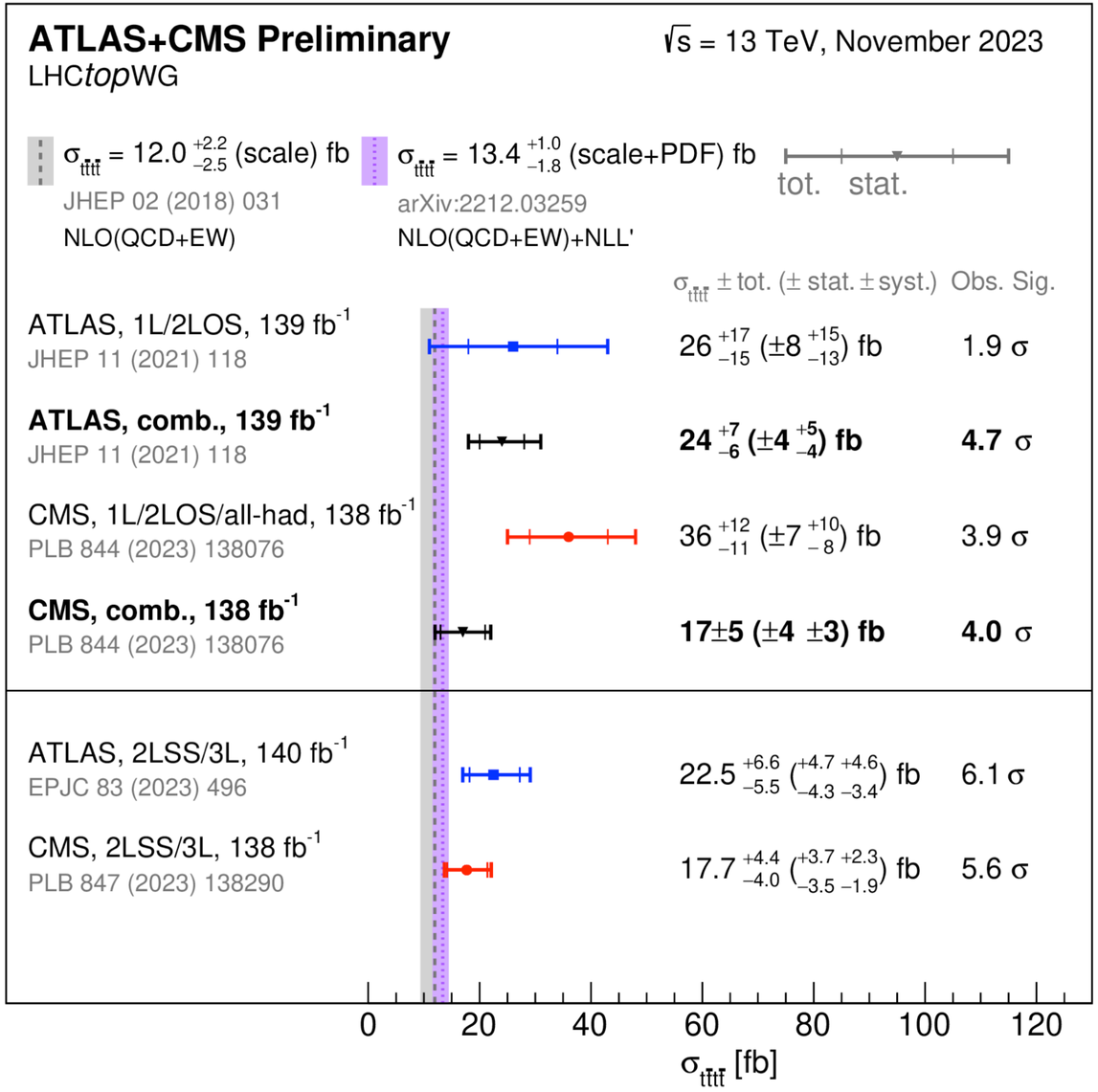
- More data coming @ 13.6 TeV



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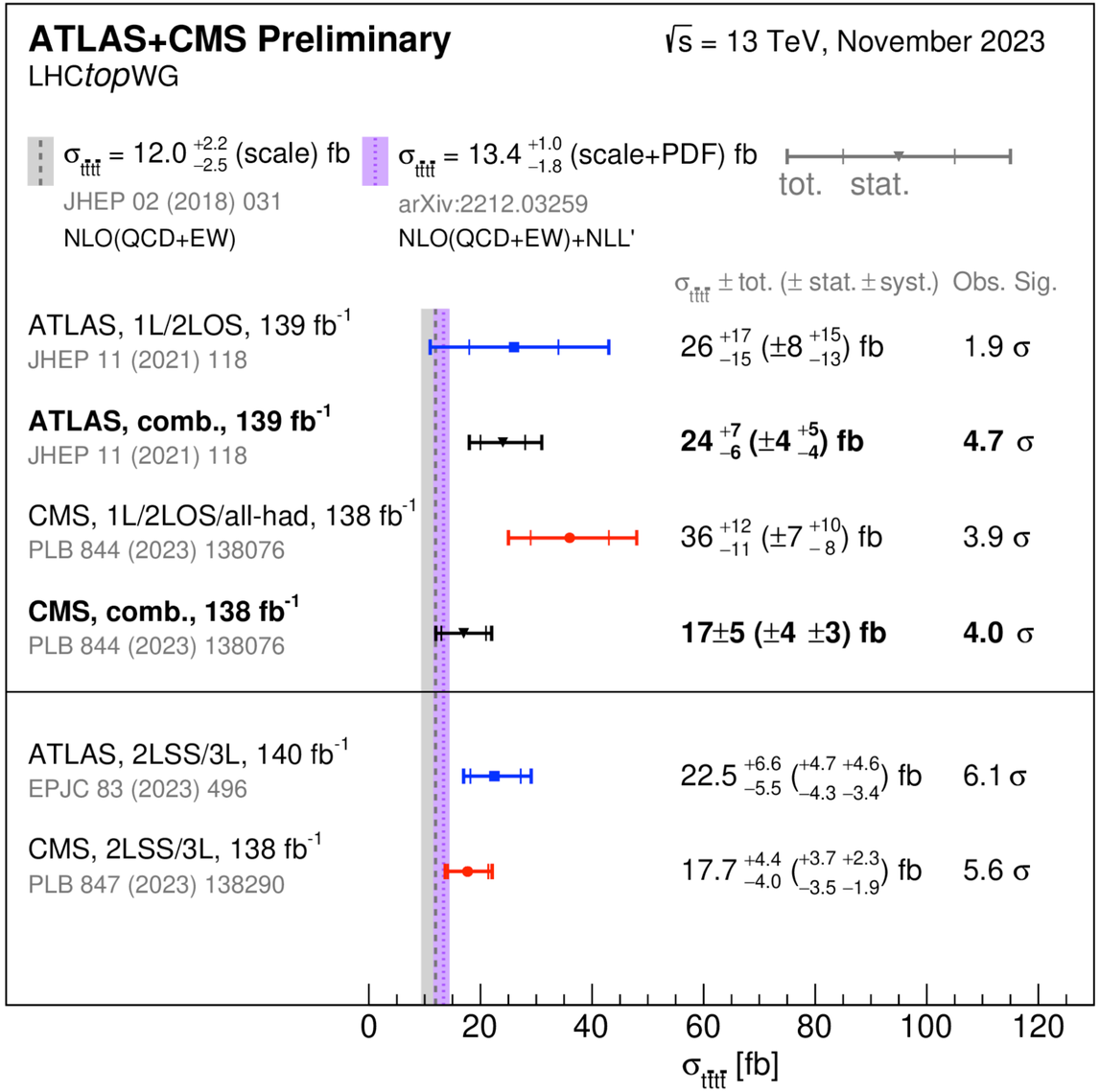
- More data coming @ 13.6 TeV
- Rich potential for Yukawa and EFT extraction
  - See Jack's talk (Thursday, 10:18, ISEC Room 140)



BACKUP

EFT

$$\sigma_{t\bar{t}t\bar{t}} = \sigma^{SM}_{t\bar{t}t\bar{t}} + \frac{1}{\Lambda^2}\sum_i C_i \sigma^{(1)}_i + \frac{1}{\Lambda^4}\sum_{i\leq j} C_i C_j \sigma^{(2)}_{i,j}$$

- tttt is sensitive to several Dim-6 contact operators in the EFT framework
- CMS tttt search (2016 OSDL + SL) recasts tttt upper limit

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{\mathrm{tt}}$	$[-2.0, 1.8]$	$[-2.1, 2.0]$
$\mathcal{O}^1_{\mathrm{QQ}}$	$[-2.0, 1.8]$	$[-2.2, 2.0]$
$\mathcal{O}^1_{\mathrm{Qt}}$	$[-3.3, 3.2]$	$[-3.5, 3.5]$
$\mathcal{O}^8_{\mathrm{Qt}}$	$[-7.3, 6.1]$	$[-7.9, 6.6]$

JHEP 11 (2019) 082

- ATLAS result parameterizes each GNN bin's tttt contribution
  - Set 95% CL upper limit on coefficients of the 4 sensitive terms individually (3 set to SM = 0 for fit)

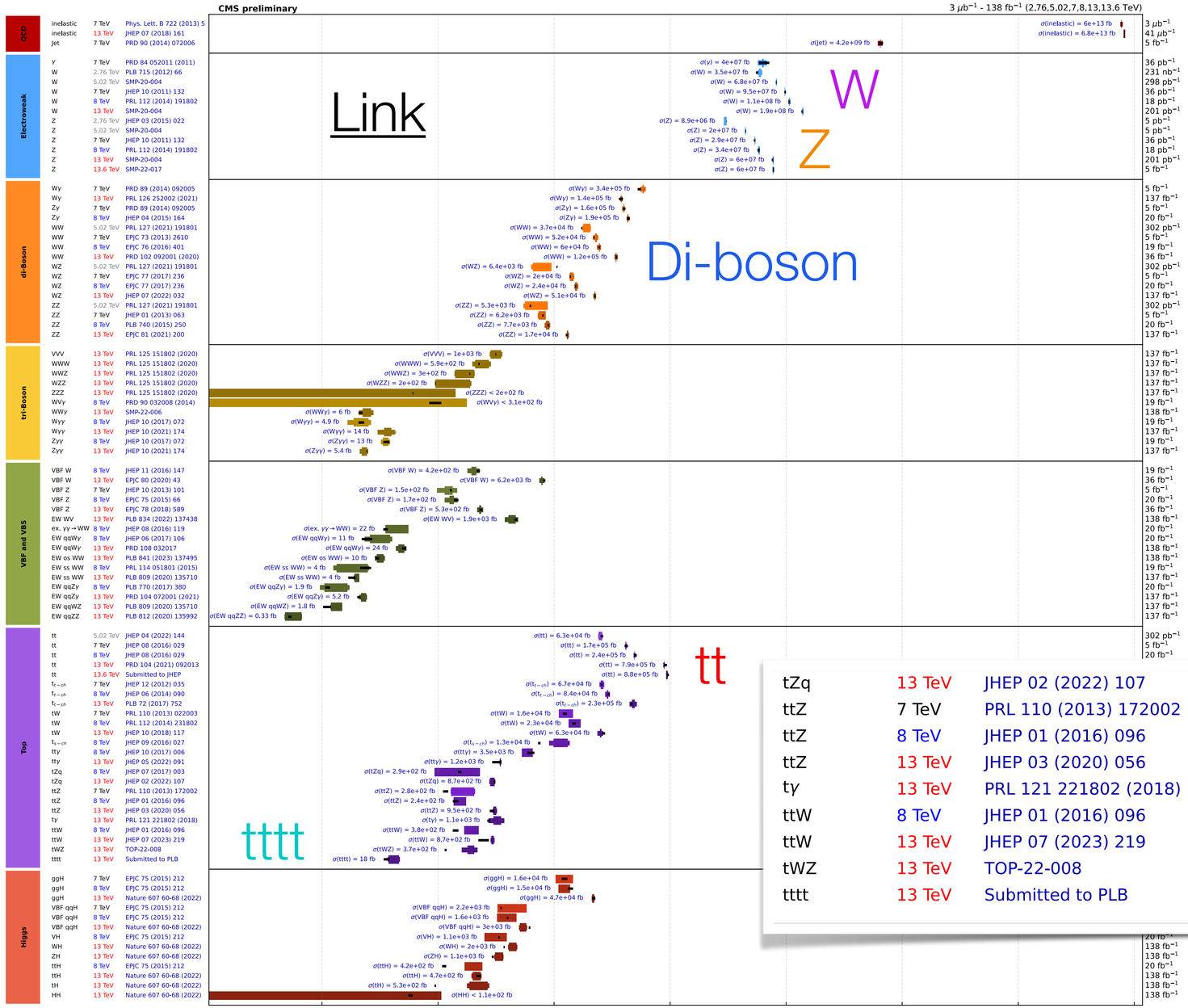
EPJC 83 (2024) 496

O^1_{QQ}	O^1_{Qt}	O^1_{tt}	O^8_{Qt}
5.3	3.3	2.4	8.8

$(TeV)^{-2}$

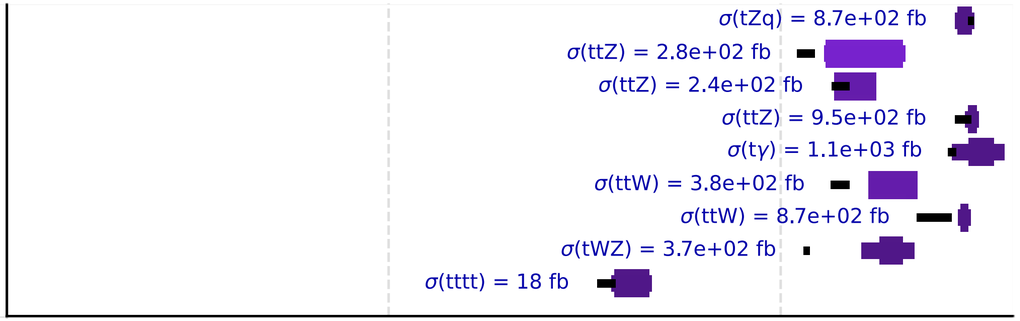
- Dedicated EFT searches contain tttt-enriched Signal Regions JHEP 12 (2023) 068

Overview of CMS cross section results



QCD	inelastic	7 TeV	Phys. Lett. B 722 (2013) 5	3 μb^{-1}
	inelastic	13 TeV	JHEP 07 (2018) 161	41 μb^{-1}
	Jet	7 TeV	PRD 90 (2014) 072006	5 fb^{-1}
Electroweak	γ	7 TeV	PRD 84 052011 (2011)	36 pb^{-1}
	W	2.76 TeV	PLB 715 (2012) 66	231 nb^{-1}
	W	5.02 TeV	SMP-20-004	298 pb^{-1}
	W	7 TeV	JHEP 10 (2011) 132	36 pb^{-1}
	W	8 TeV	PRL 112 (2014) 191802	18 pb^{-1}
	W	13 TeV	SMP-20-004	201 pb^{-1}
	Z	2.76 TeV	JHEP 03 (2015) 022	5 pb^{-1}
	Z	5.02 TeV	SMP-20-004	5 pb^{-1}
	Z	7 TeV	JHEP 10 (2011) 132	36 pb^{-1}
	Z	8 TeV	PRL 112 (2014) 191802	18 pb^{-1}
	Z	13 TeV	SMP-20-004	201 pb^{-1}
	Z	13.6 TeV	SMP-22-017	5 fb^{-1}
di-Boson	Wγ	7 TeV	PRD 89 (2014) 092005	5 fb^{-1}
	Wγ	13 TeV	PRL 126 252002 (2021)	137 fb^{-1}
	Zγ	7 TeV	PRD 89 (2014) 092005	5 fb^{-1}
	Zγ	8 TeV	JHEP 04 (2015) 164	20 fb^{-1}
	WW	5.02 TeV	PRL 127 (2021) 191801	302 pb^{-1}
	WW	7 TeV	EPJC 73 (2013) 2610	5 fb^{-1}
	WW	8 TeV	EPJC 76 (2016) 401	19 fb^{-1}
	WW	13 TeV	PRD 102 092001 (2020)	36 fb^{-1}
	WZ	5.02 TeV	PRL 127 (2021) 191801	302 pb^{-1}
	WZ	7 TeV	EPJC 77 (2017) 236	5 fb^{-1}
	WZ	8 TeV	EPJC 77 (2017) 236	20 fb^{-1}
	WZ	13 TeV	JHEP 07 (2022) 032	137 fb^{-1}
	ZZ	5.02 TeV	PRL 127 (2021) 191801	302 pb^{-1}
	ZZ	7 TeV	JHEP 01 (2013) 063	5 fb^{-1}
	ZZ	8 TeV	PLB 740 (2015) 250	20 fb^{-1}
	ZZ	13 TeV	EPJC 81 (2021) 200	137 fb^{-1}
tri-Boson	VVV	13 TeV	PRL 125 151802 (2020)	137 fb^{-1}
	WWW	13 TeV	PRL 125 151802 (2020)	137 fb^{-1}
	WWZ	13 TeV	PRL 125 151802 (2020)	137 fb^{-1}
	WZZ	13 TeV	PRL 125 151802 (2020)	137 fb^{-1}
	ZZZ	13 TeV	PRL 125 151802 (2020)	137 fb^{-1}
	WVγ	8 TeV	PRD 90 032008 (2014)	19 fb^{-1}
	WWγ	13 TeV	SMP-22-006	138 fb^{-1}
	W$\gamma\gamma$	8 TeV	JHEP 10 (2017) 072	19 fb^{-1}
	W$\gamma\gamma$	13 TeV	JHEP 10 (2021) 174	137 fb^{-1}
	Z$\gamma\gamma$	8 TeV	JHEP 10 (2017) 072	19 fb^{-1}
	Z$\gamma\gamma$	13 TeV	JHEP 10 (2021) 174	137 fb^{-1}
VBF and VBS	VBF W	8 TeV	JHEP 11 (2016) 147	19 fb^{-1}
	VBF W	13 TeV	EPJC 80 (2020) 43	36 fb^{-1}
	VBF Z	7 TeV	JHEP 10 (2013) 101	5 fb^{-1}
	VBF Z	8 TeV	EPJC 75 (2015) 66	20 fb^{-1}
	VBF Z	13 TeV	EPJC 78 (2018) 589	36 fb^{-1}
	EW WV	13 TeV	PLB 834 (2022) 137438	138 fb^{-1}
	ex. $\gamma\gamma \to$ WW	8 TeV	JHEP 08 (2016) 119	20 fb^{-1}
	EW qqWγ	8 TeV	JHEP 06 (2017) 106	20 fb^{-1}
	EW qqWγ	13 TeV	PRD 108 032017	138 fb^{-1}
	EW os WW	13 TeV	PLB 841 (2023) 137495	138 fb^{-1}
	EW ss WW	8 TeV	PRL 114 051801 (2015)	19 fb^{-1}
	EW ss WW	13 TeV	PLB 809 (2020) 135710	137 fb^{-1}
	EW qqZγ	8 TeV	PLB 770 (2017) 380	20 fb^{-1}
	EW qqZγ	13 TeV	PRD 104 072001 (2021)	137 fb^{-1}
	EW qqWZ	13 TeV	PLB 809 (2020) 135710	137 fb^{-1}
	EW qqZZ	13 TeV	PLB 812 (2020) 135992	137 fb^{-1}
Top	tt	5.02 TeV	JHEP 04 (2022) 144	302 pb^{-1}
	tt	7 TeV	JHEP 08 (2016) 029	5 fb^{-1}
	tt	8 TeV	JHEP 08 (2016) 029	20 fb^{-1}
	tt	13 TeV	PRD 104 (2021) 092013	36 fb^{-1}
	tt	13.6 TeV	Submitted to JHEP	138 fb^{-1}
	t_{t-ch}	7 TeV	JHEP 12 (2012) 035	20 fb^{-1}
	t_{t-ch}	8 TeV	JHEP 06 (2014) 090	20 fb^{-1}
	t_{t-ch}	13 TeV	PLB 72 (2017) 752	138 fb^{-1}
	tW	7 TeV	PRL 110 (2013) 022003	138 fb^{-1}
	tW	8 TeV	PRL 112 (2014) 231802	19 fb^{-1}
	tW	13 TeV	JHEP 10 (2018) 117	137 fb^{-1}
	t_{s-ch}	8 TeV	JHEP 09 (2016) 027	20 fb^{-1}
	tγ	8 TeV	JHEP 10 (2017) 006	20 fb^{-1}
	tγ	13 TeV	JHEP 05 (2022) 091	138 fb^{-1}
	tZq	8 TeV	JHEP 07 (2017) 003	138 fb^{-1}
	tZq	13 TeV	JHEP 02 (2022) 107	138 fb^{-1}
	ttZ	7 TeV	PRL 110 (2013) 172002	19 fb^{-1}
	ttZ	8 TeV	JHEP 01 (2016) 096	20 fb^{-1}
	ttZ	13 TeV	JHEP 03 (2020) 056	138 fb^{-1}
	tγ	13 TeV	PRL 121 221802 (2018)	138 fb^{-1}
	ttW	8 TeV	JHEP 01 (2016) 096	20 fb^{-1}
	ttW	13 TeV	JHEP 07 (2023) 219	138 fb^{-1}
	tWZ	13 TeV	TOP-22-008	138 fb^{-1}
	tttt	13 TeV	Submitted to PLB	138 fb^{-1}
Higgs	ggH	7 TeV	EPJC 75 (2015) 212	20 fb^{-1}
	ggH	8 TeV	EPJC 75 (2015) 212	138 fb^{-1}
	ggH	13 TeV	Nature 607 60-68 (2022)	138 fb^{-1}
	VBF qqH	7 TeV	EPJC 75 (2015) 212	20 fb^{-1}
	VBF qqH	8 TeV	EPJC 75 (2015) 212	138 fb^{-1}
	VBF qqH	13 TeV	Nature 607 60-68 (2022)	138 fb^{-1}
	VH	8 TeV	EPJC 75 (2015) 212	20 fb^{-1}
	WH	13 TeV	Nature 607 60-68 (2022)	138 fb^{-1}
	ZH	13 TeV	Nature 607 60-68 (2022)	138 fb^{-1}
	ttH	8 TeV	EPJC 75 (2015) 212	20 fb^{-1}
	ttH	13 TeV	Nature 607 60-68 (2022)	138 fb^{-1}
	tH	13 TeV	Nature 607 60-68 (2022)	138 fb^{-1}
	HH	13 TeV	Nature 607 60-68 (2022)	138 fb^{-1}

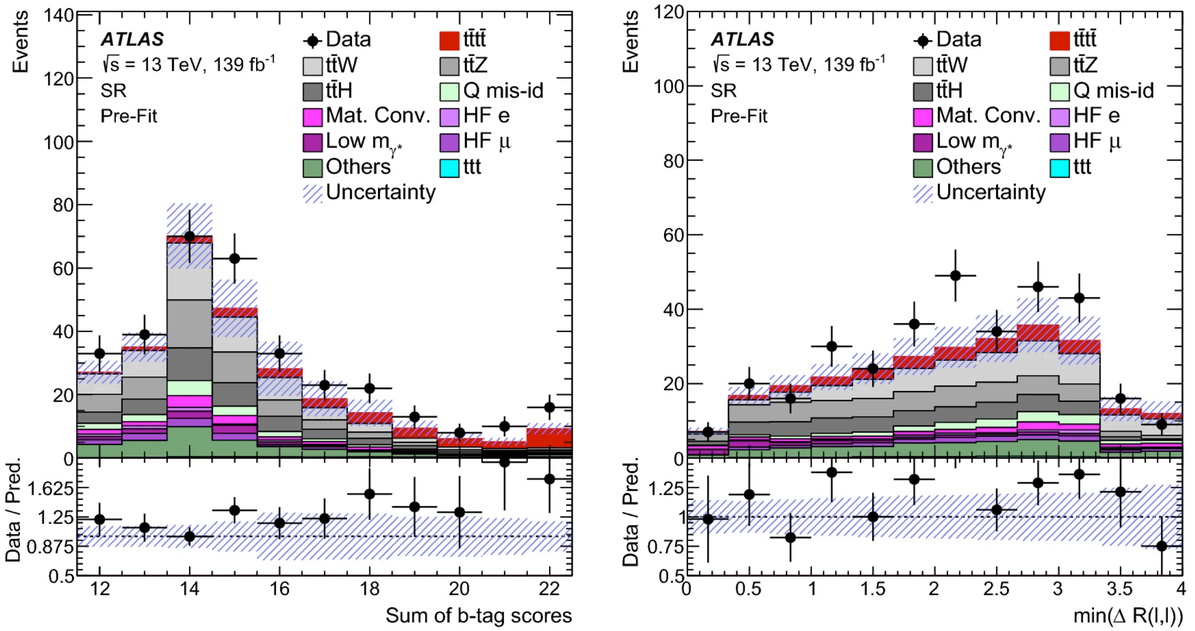
tZq	13 TeV	JHEP 02 (2022) 107
ttZ	7 TeV	PRL 110 (2013) 172002
ttZ	8 TeV	JHEP 01 (2016) 096
ttZ	13 TeV	JHEP 03 (2020) 056
tγ	13 TeV	PRL 121 221802 (2018)
ttW	8 TeV	JHEP 01 (2016) 096
ttW	13 TeV	JHEP 07 (2023) 219
tWZ	13 TeV	TOP-22-008
tttt	13 TeV	Submitted to PLB



Measured cross sections and exclusion limits at 95% C.L.
See here for all cross section summary plots

Inner colored bars statistical uncertainty, outer narrow bars statistical+systematic uncertainty
Light to Dark colored bars: 2.76, 5.02, 7, 8, 13, 13.6 TeV, Black bars: theory prediction

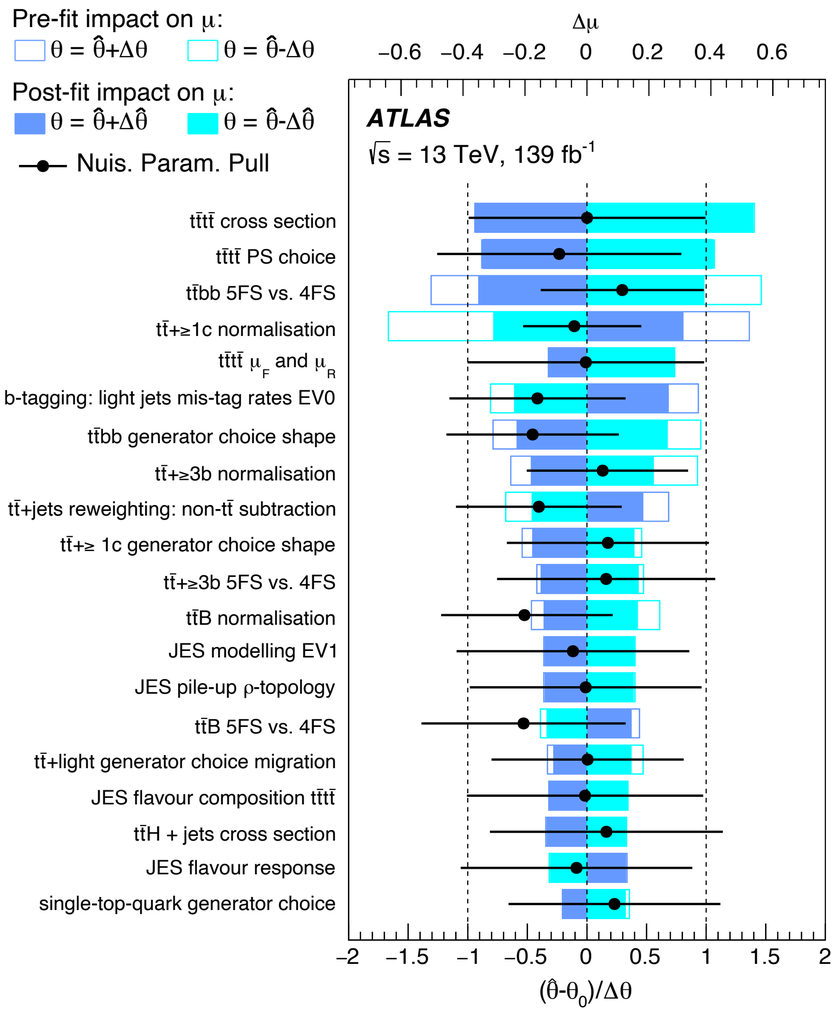
Evidence (ATLAS)



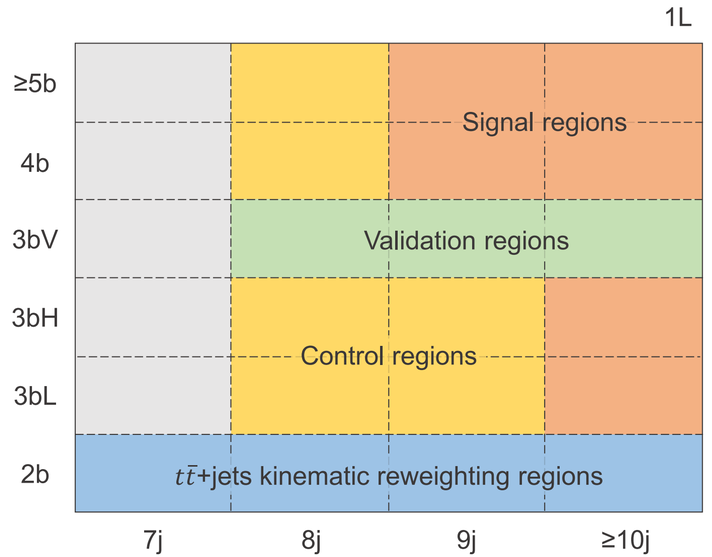
Region	Channel	N_j	N_b	Other requirements	Fitted variable
SR	2LSS/3L	≥ 6	≥ 2	$H_{\mathrm{T}} > 500$	BDT
CR Conv.	$e^{\pm}e^{\pm}\|\|e^{\pm}\mu^{\pm}$	$4 \leq N_j < 6$	≥ 1	$m_{ee}^{\mathrm{CV}} \in [0, 0.1\ \mathrm{GeV}]$	m_{ee}^{PV}
				$200 < H_{\mathrm{T}} < 500\ \mathrm{GeV}$	
CR HF e	$eee\ \|\|\ ee\mu$	–	$= 1$	$100 < H_{\mathrm{T}} < 250\ \mathrm{GeV}$	Counting
CR HF μ	$e\mu\mu\ \|\|\ \mu\mu\mu$	–	$= 1$	$100 < H_{\mathrm{T}} < 250\ \mathrm{GeV}$	Counting
CR ttW	$e^{\pm}\mu^{\pm}\|\|\mu^{\pm}\mu^{\pm}$	≥ 4	≥ 2	$m_{ee}^{\mathrm{CV}} \notin [0, 0.1\ \mathrm{GeV}], \lvert\eta(e)\rvert < 1.5$	$\Sigma p_{\mathrm{T}}^{\ell}$
				For $N_b = 2, H_{\mathrm{T}} < 500\ \mathrm{GeV}$ or $N_j < 6$	
				For $N_b \geq 3, H_{\mathrm{T}} < 500\ \mathrm{GeV}$	

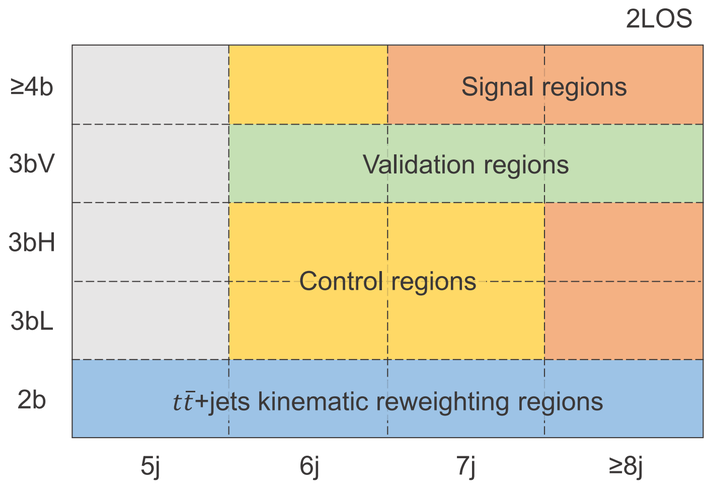
Eur. Phys. J. C 80 (2020) 1085

Evidence (ATLAS)

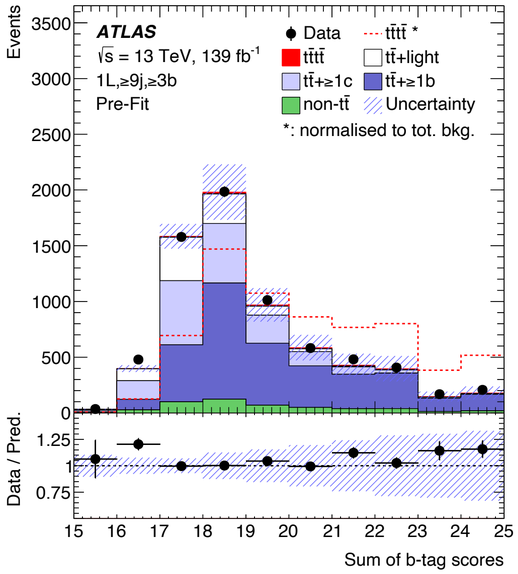


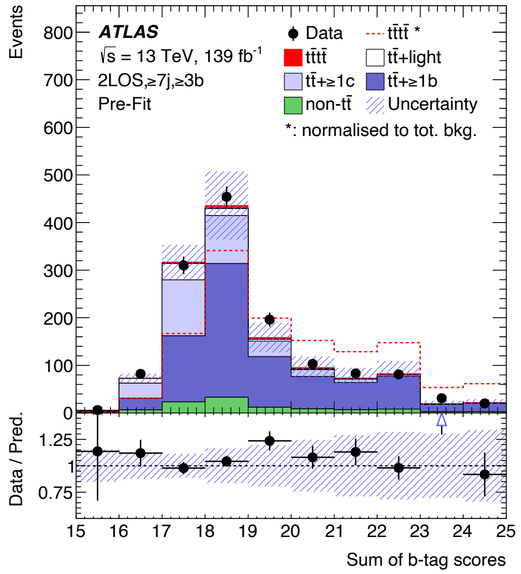
Uncertainty source	$\Delta\sigma_{t\bar{t}t\bar{t}}$ [fb]	
Signal Modelling		
$t\bar{t}t\bar{t}$ modelling	+8	−3
Background Modelling		
$t\bar{t}$+≥1b modelling	+8	−7
$t\bar{t}$+≥1c modelling	+5	−4
$t\bar{t}$+jets reweighting	+4	−3
Other background modelling	+4	−3
$t\bar{t}$+light modelling	+2	−2
Experimental		
Jet energy scale and resolution	+6	−4
b-tagging efficiency and mis-tag rates	+4	−3
MC statistical uncertainties	+2	−2
Luminosity	< 1	
Other uncertainties	< 1	
Total systematic uncertainty	+15	−12
Statistical uncertainty	+8	−8
Total uncertainty	+17	−15

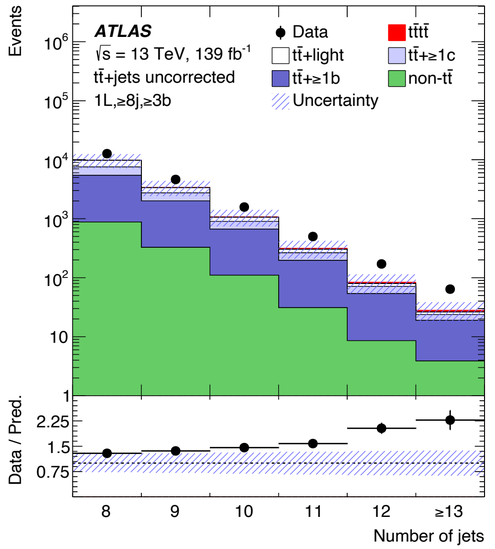


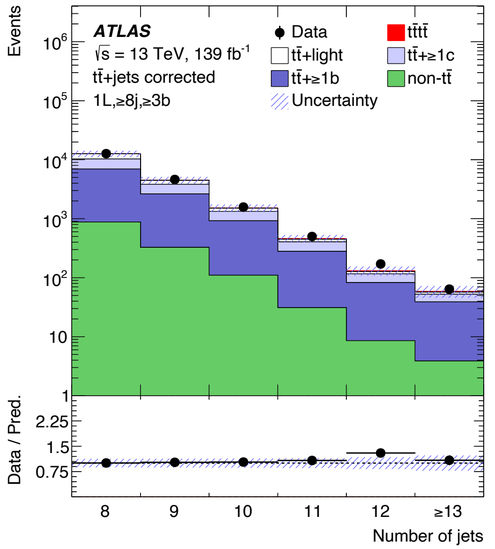


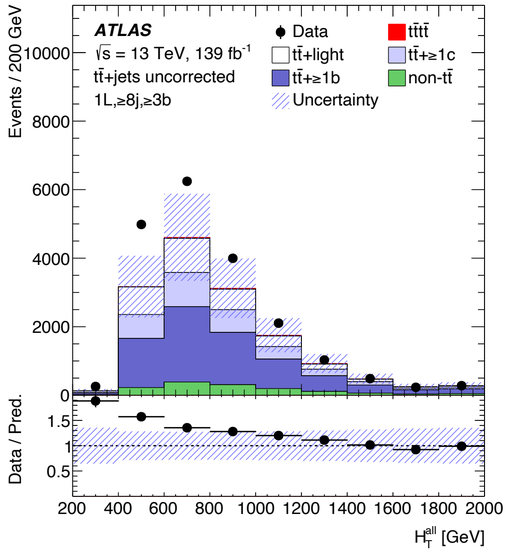
Evidence (ATLAS)

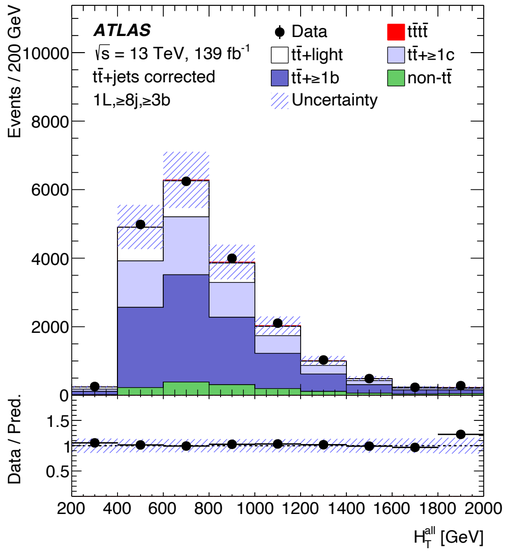






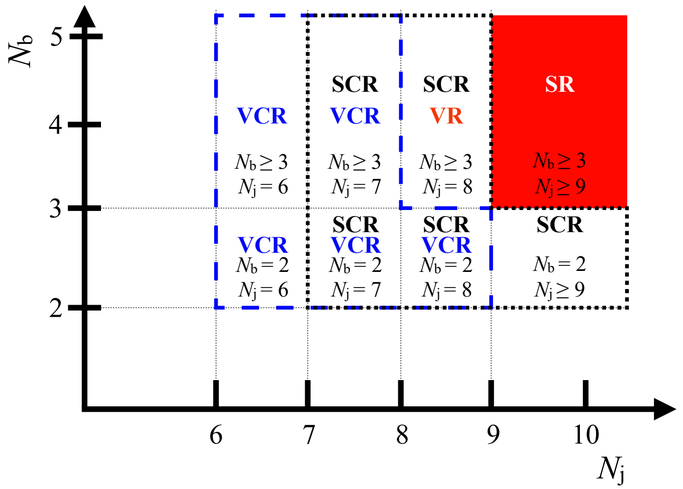


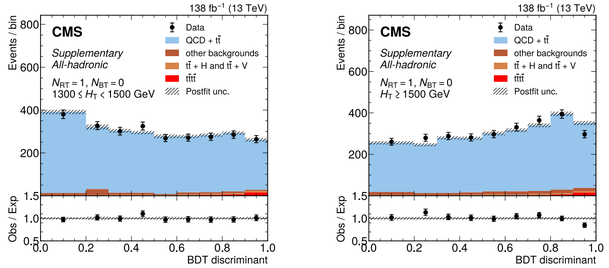


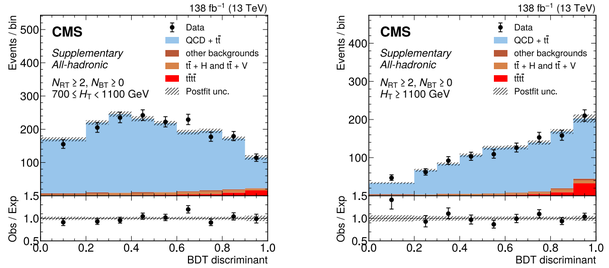


All-Hadronic Background Estimation - ABCDnn

See also:
normalising flows in ttt

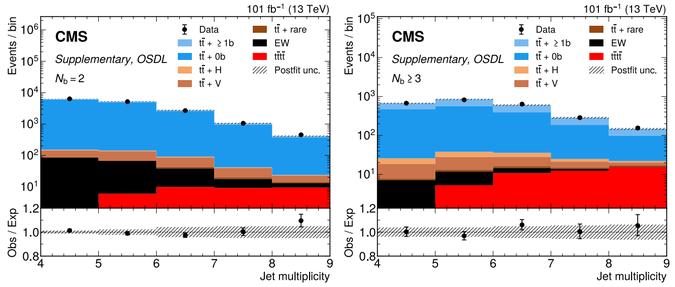


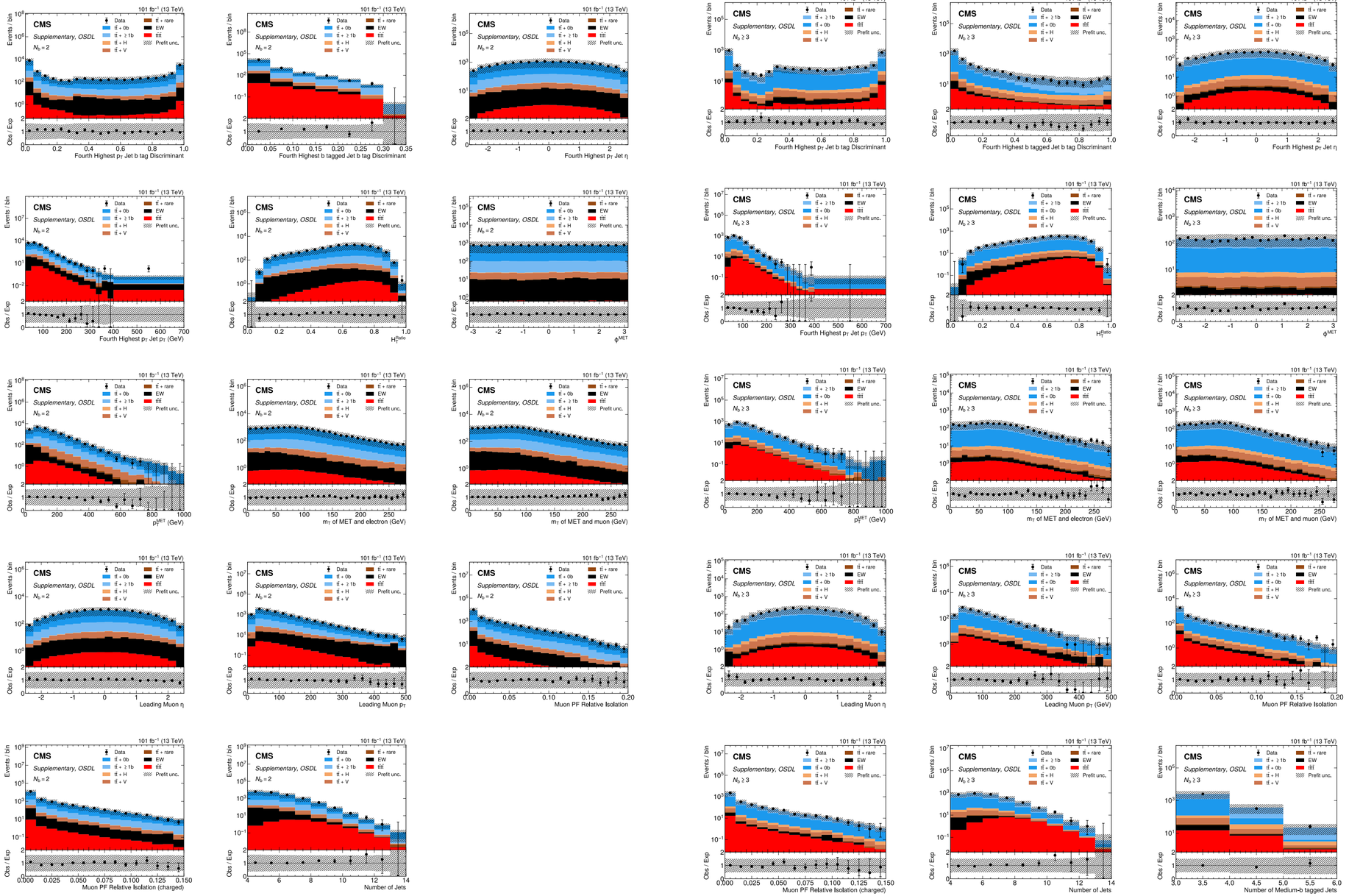




- Novel application of an Extended ABCD Method combined with Autoregressive Flows (composition of normalizing flows)
  - EPJC 81 (2021) 643, arxiv:1804.00779, arXiv:2008.03636
  - Upcoming CMS Publication (CMS-MLG-23-004)
- Neural Network learns to conditionally transform tt simulation source distribution to a target distribution
  - Trained autoregressively on the 5 control regions to map simulated tt distributions onto tt + QCD distributions using data
  - Method validated using shifted set of 5 VCRs + 1 VR
  - Simultaneously transforms multiple distributions (H_T and event BDT)

Evidence (CMS) OSDL





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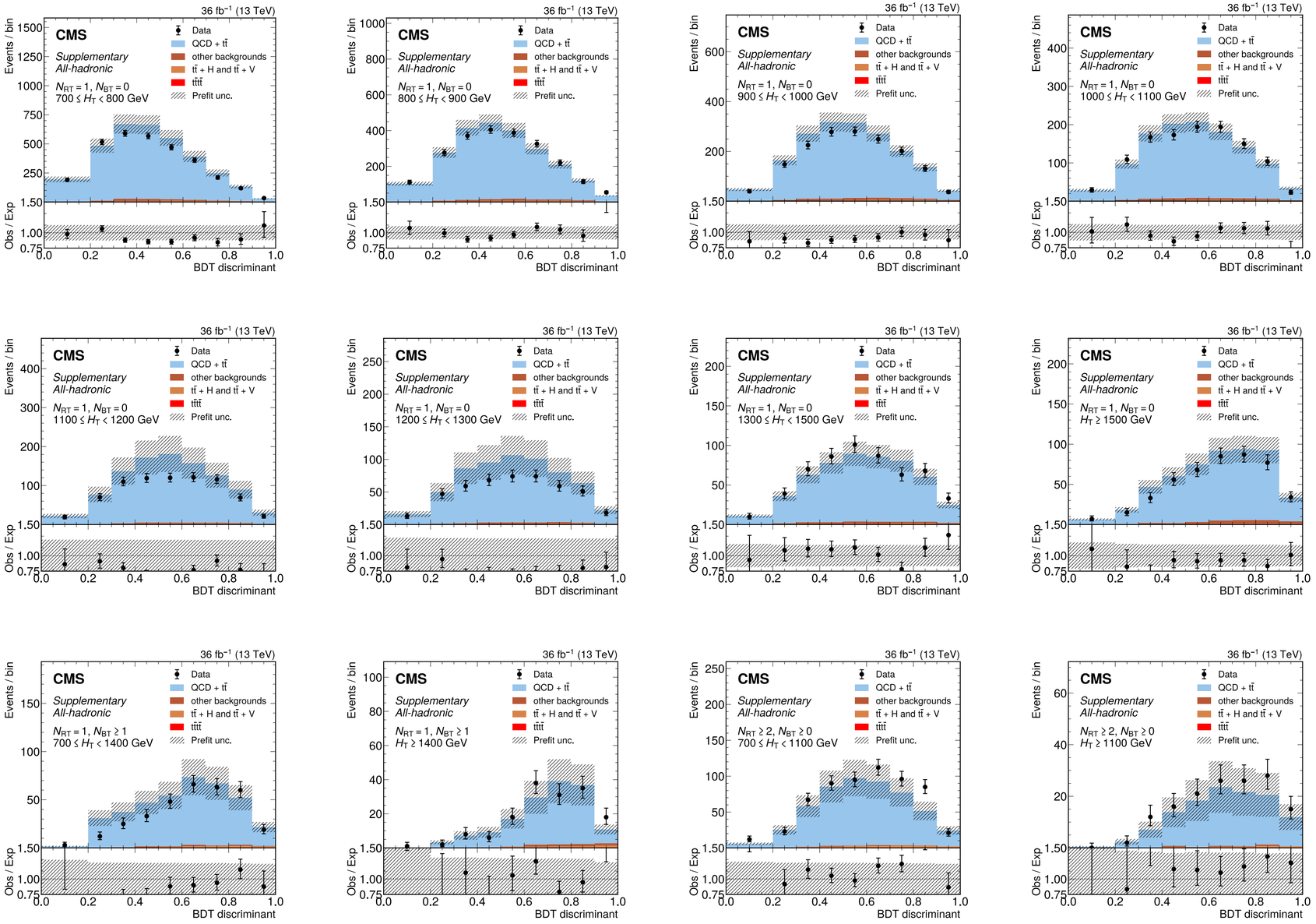
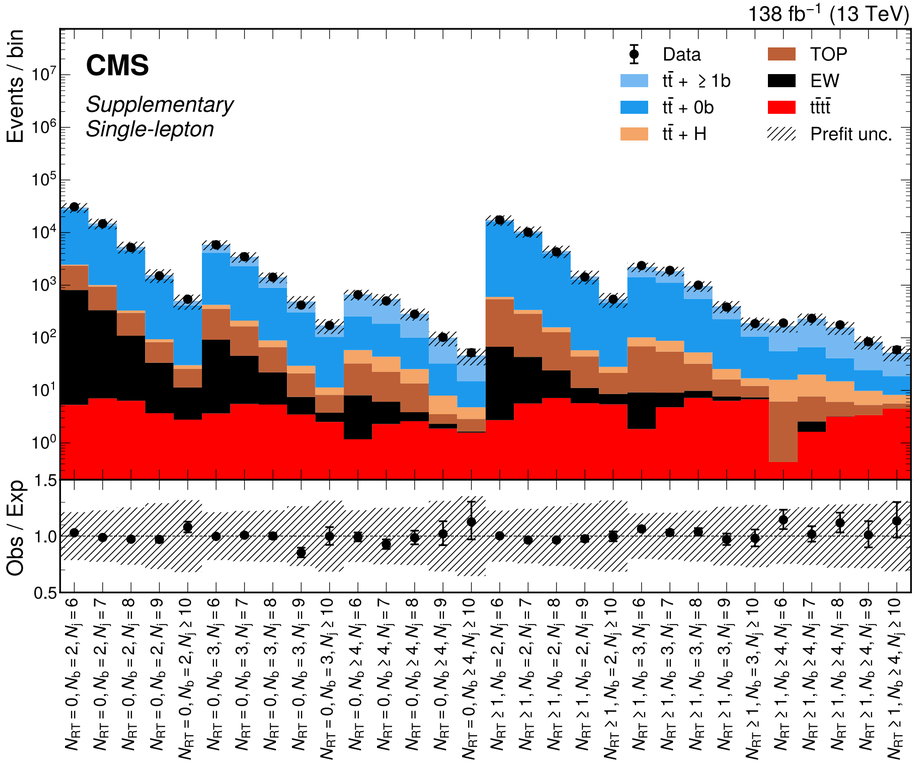
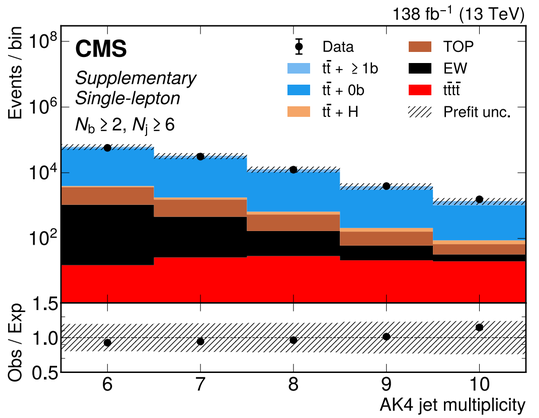
Evidence (CMS) All-Hadronic

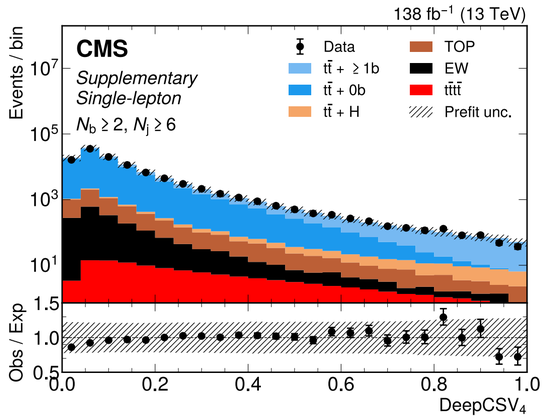
N_{RT}	N_{BT}	H_T range (GeV)
1	0	700–800
1	0	800–900
1	0	900–1000
1	0	1000–1100
1	0	1100–1200
1	0	1200–1300
1	0	1300–1500
1	0	≥1500
1	≥1	700–1400
1	≥1	≥1400
≥2	≥0	700–1100
≥2	≥0	≥1100

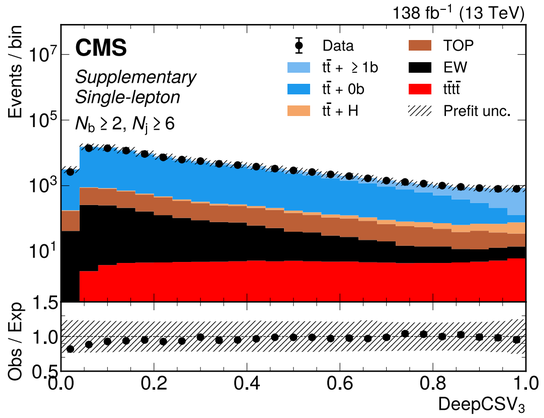


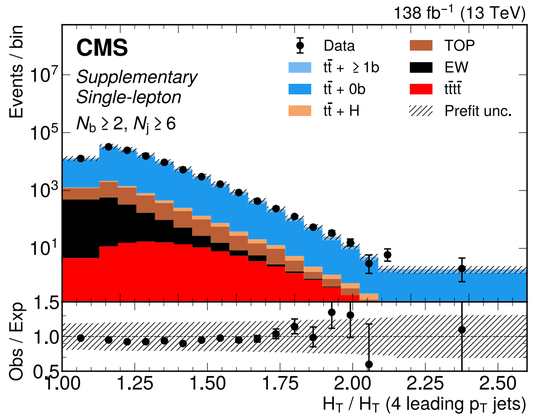
Evidence (CMS) Semi-Leptonic

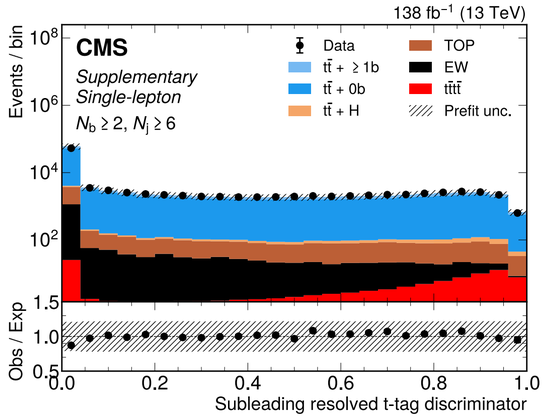


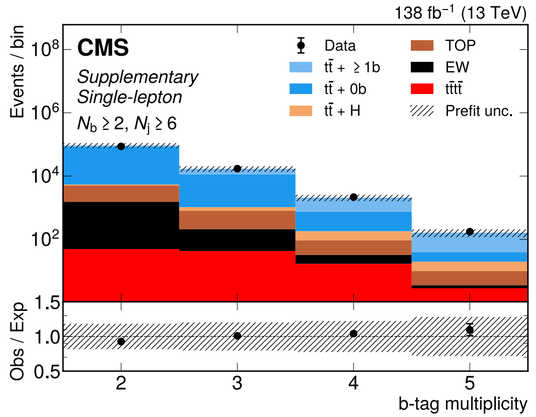




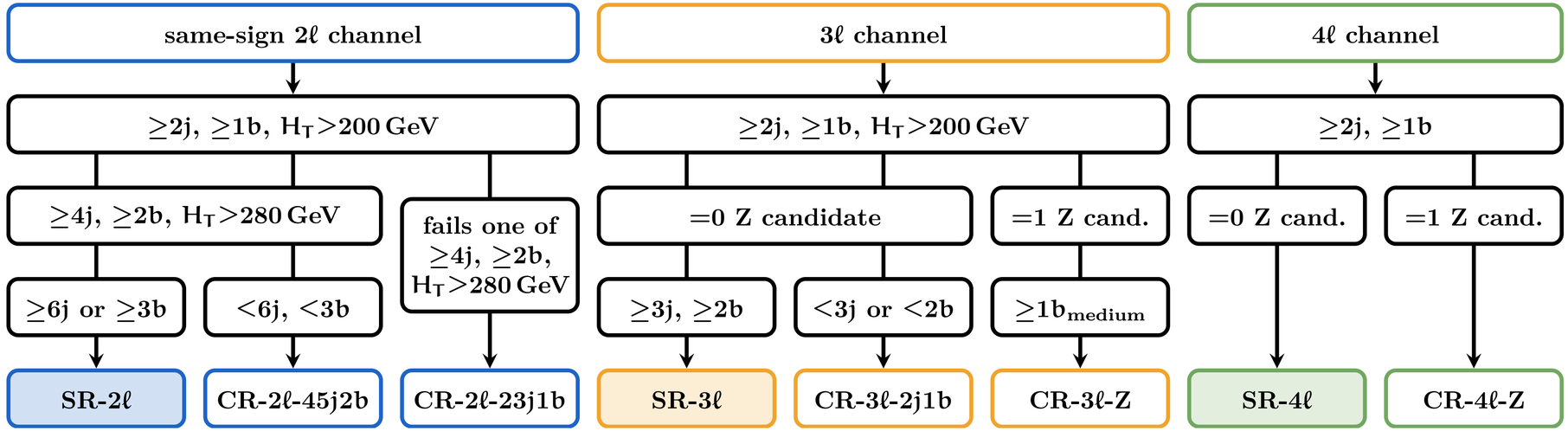


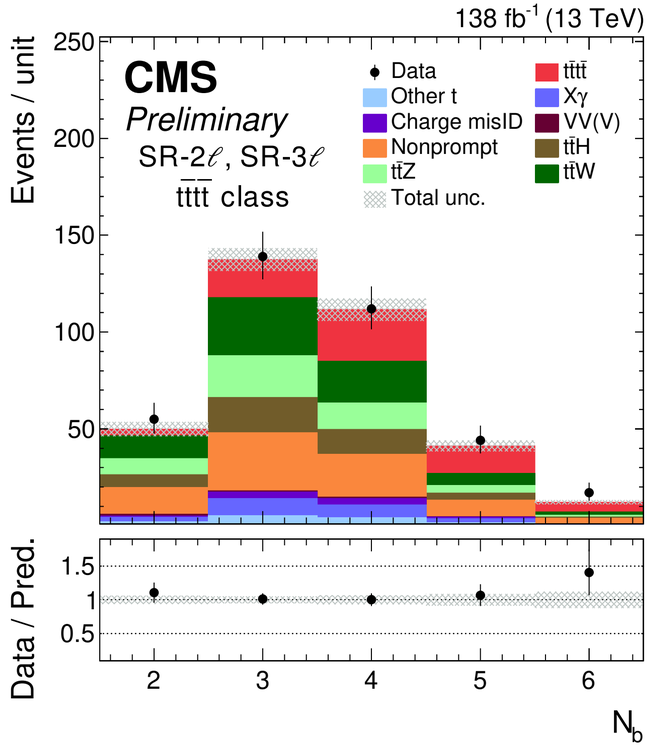






Observation (CMS)





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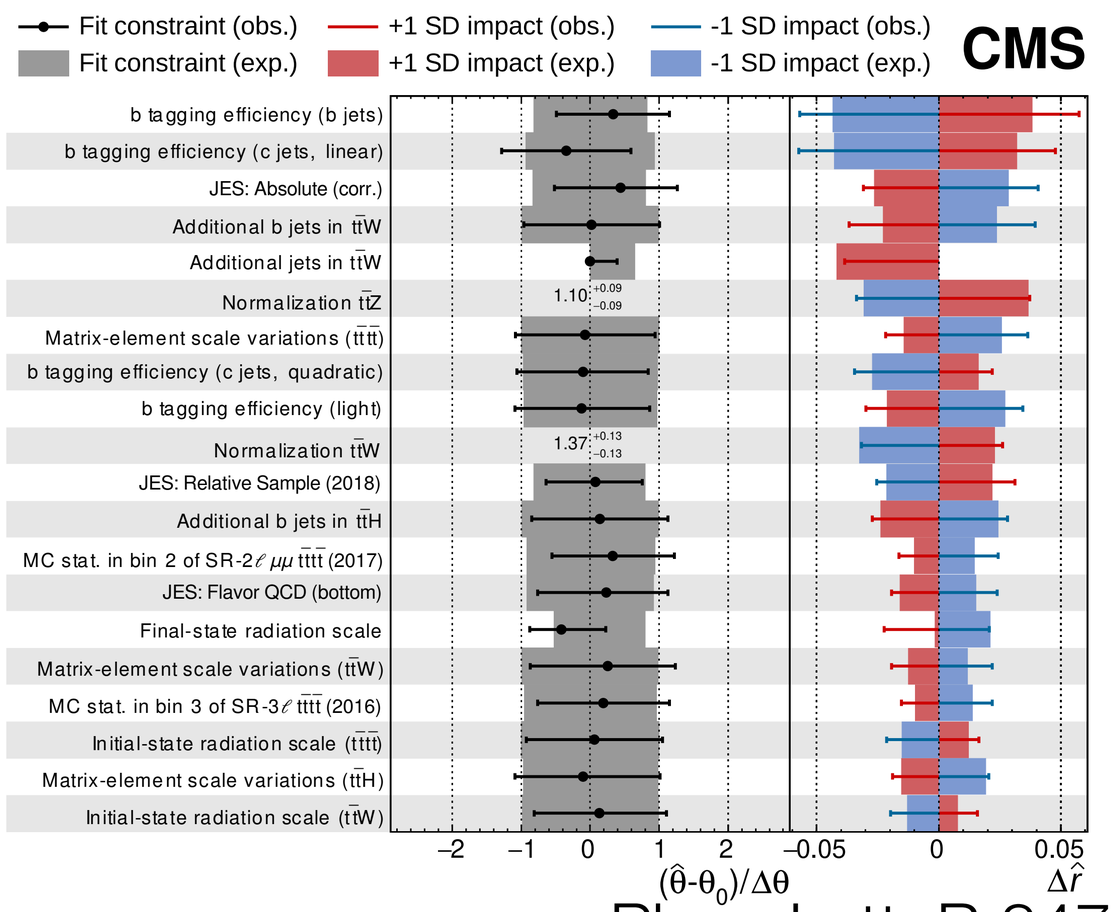
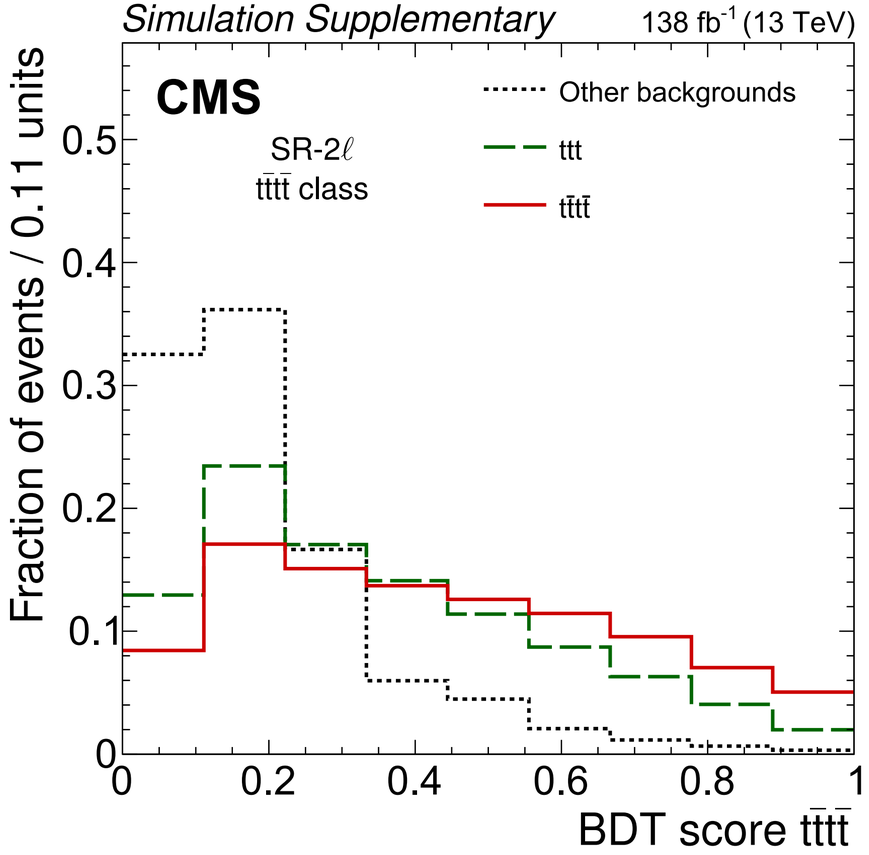
Observation (CMS)





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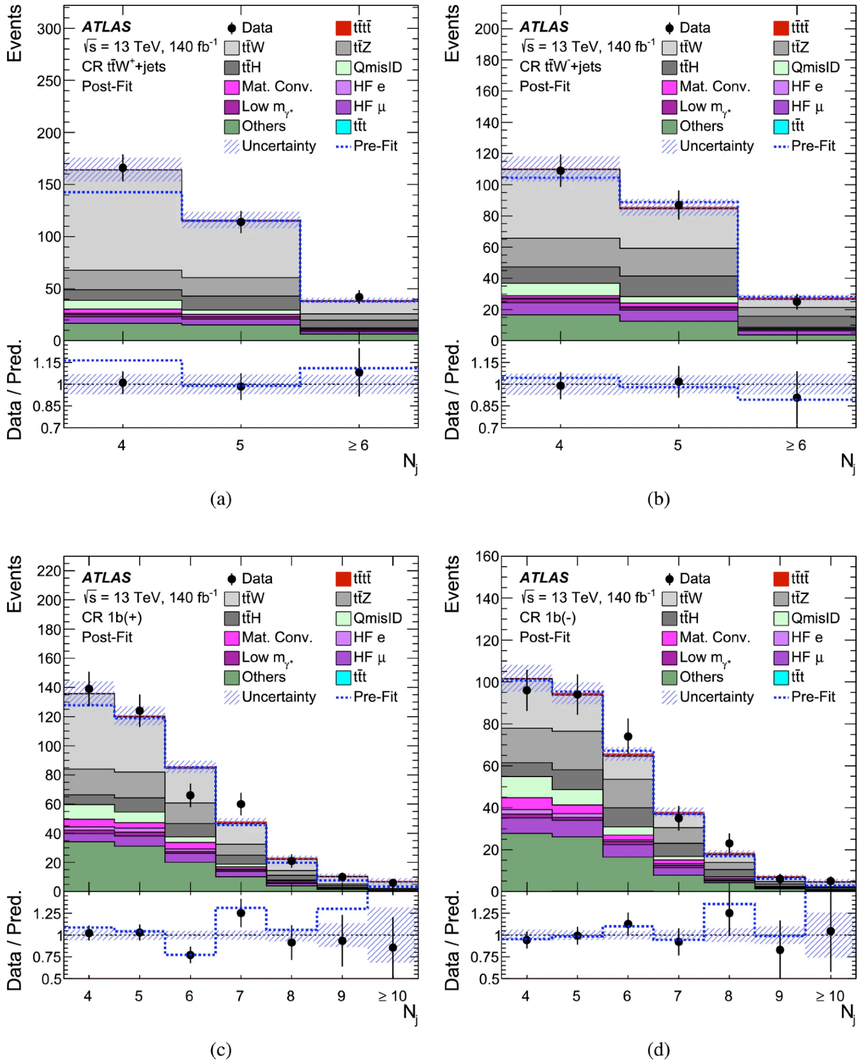
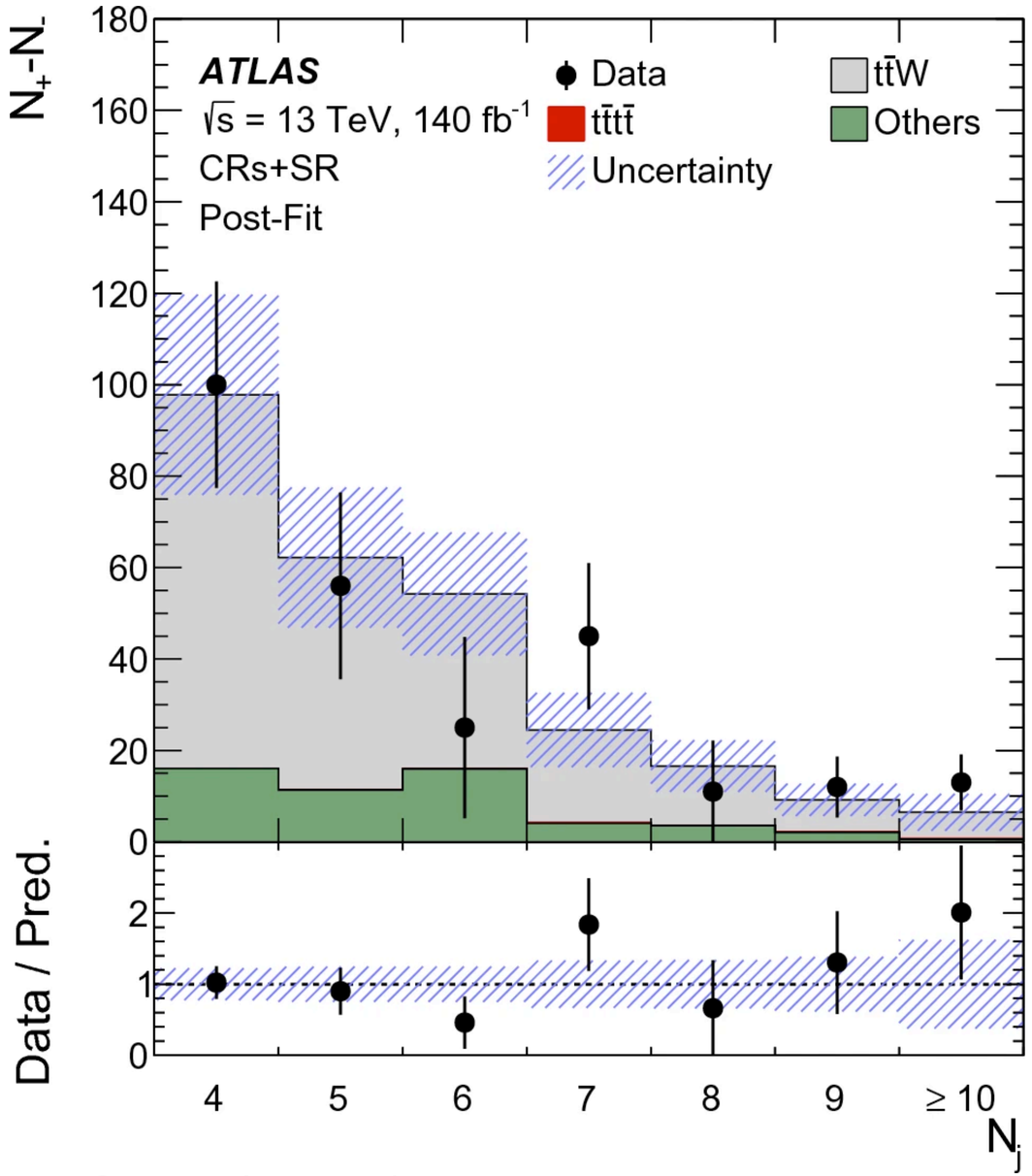
Observation (ATLAS)





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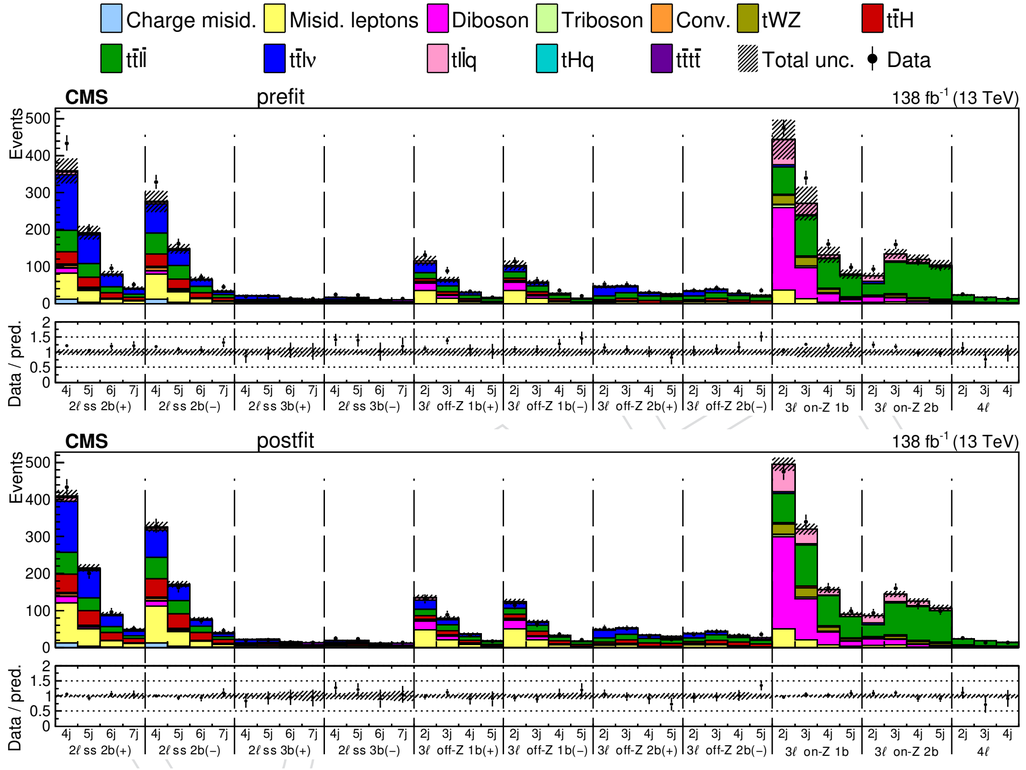
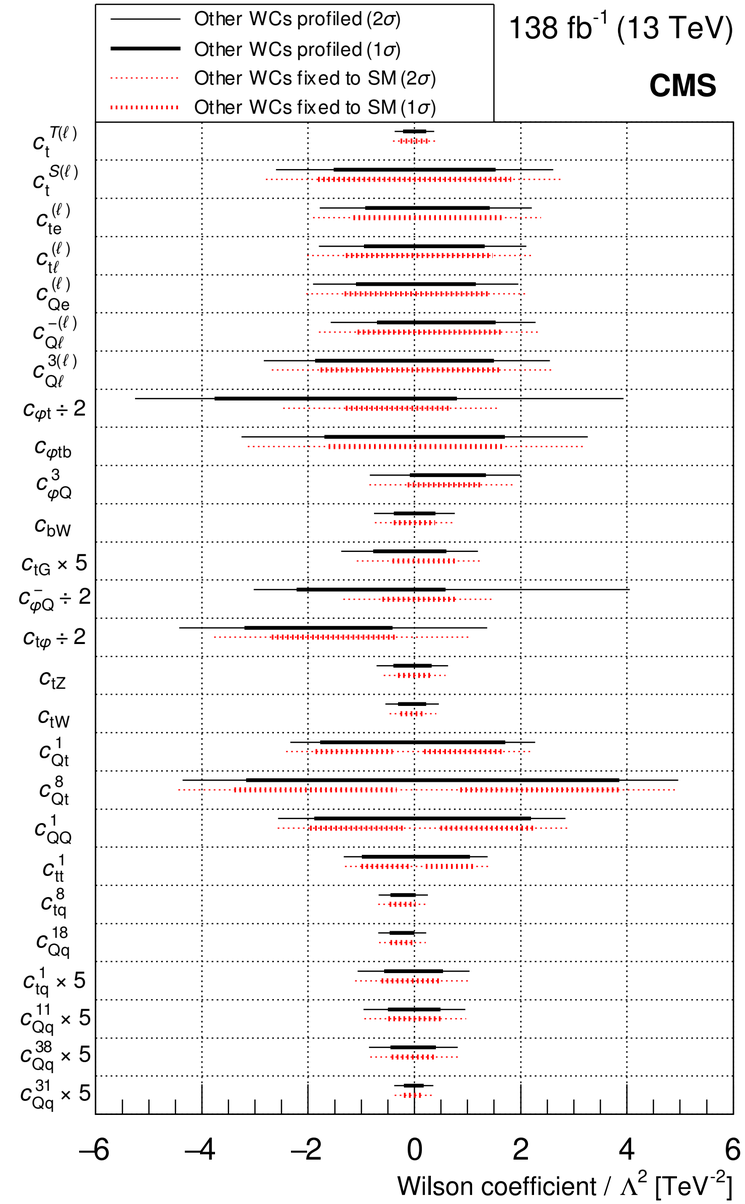
EFT

- Dedicated EFT Results contain tttt-enriched SRs
- Simultaneously fit 26 Wilson Coeffficients + NPs





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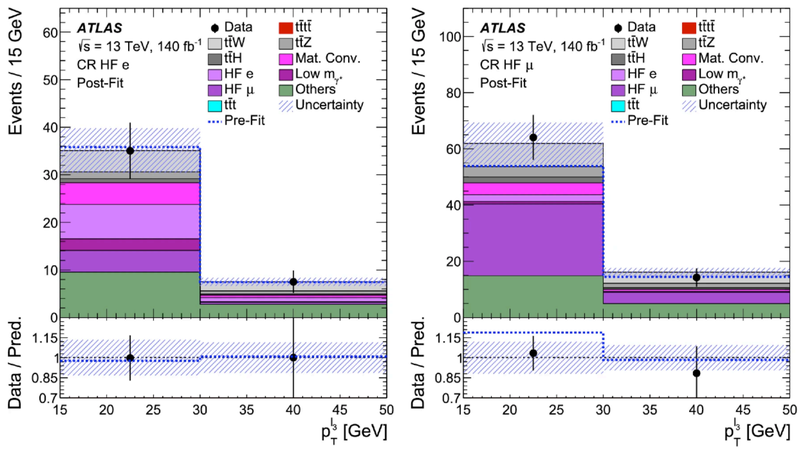
Observation (ATLAS)



Region	Channel	N_{j}	N_b	Other selection	Fitted variable
CR Low m_{γ^*}	SS, ee or eμ	$4 \leq N_{\text{j}} < 6$	≥ 1	ℓ_1 or ℓ_2 is from virtual photon (γ*) decay	Event yield
				ℓ_1 and ℓ_2 are not from photon conversion	
CR Mat. Conv.	SS, ee or eμ	$4 \leq N_{\text{j}} < 6$	≥ 1	ℓ_1 or ℓ_2 is from photon conversion	Event yield
CR HF μ	e$\mu\mu$ or $\mu\mu\mu$	≥ 1	$= 1$	$100 < H_{\text{T}} < 300$ GeV	
				$E_{\text{T}}^{\text{miss}} > 50$ GeV	
				Total charge $= \pm 1$	
CR HF e	eee or eeμ	≥ 1	$= 1$	$100 < H_{\text{T}} < 275$ GeV	$p_{\text{T}}^{\ell_3}$
				$E_{\text{T}}^{\text{miss}} > 35$ GeV	
				Total charge $= \pm 1$	
CR $t\bar{t}W^+$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$	N_{j}
				when $N_b = 2$: $H_{\text{T}} < 500$ GeV or $N_j < 6$	
				when $N_b \geq 3$: $H_{\text{T}} < 500$ GeV	
				Total charge > 0	
CR $t\bar{t}W^-$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$	N_{j}
				when $N_b = 2$: $H_{\text{T}} < 500$ GeV or $N_j < 6$	
				when $N_b \geq 3$: $H_{\text{T}} < 500$ GeV	
				Total charge < 0	
CR 1b(+)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion	N_{j}
				$H_{\text{T}} > 500$ GeV	
				Total charge > 0	
CR 1b(−)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion	N_{j}
				$H_{\text{T}} > 500$ GeV	
				Total charge < 0	
SR	2LSS+3L	≥ 6	≥ 2	$H_{\text{T}} > 500$ GeV	GNN score