Status of 4-top experimental results in ATLAS and CMS

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on behalf of the ATLAS and CMS Collaborations

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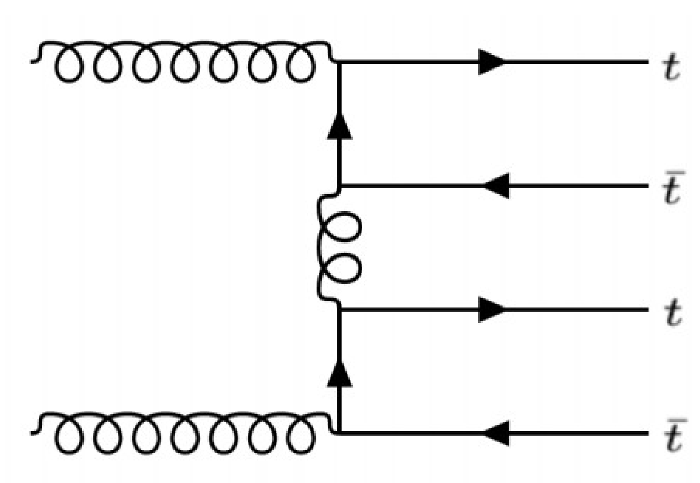
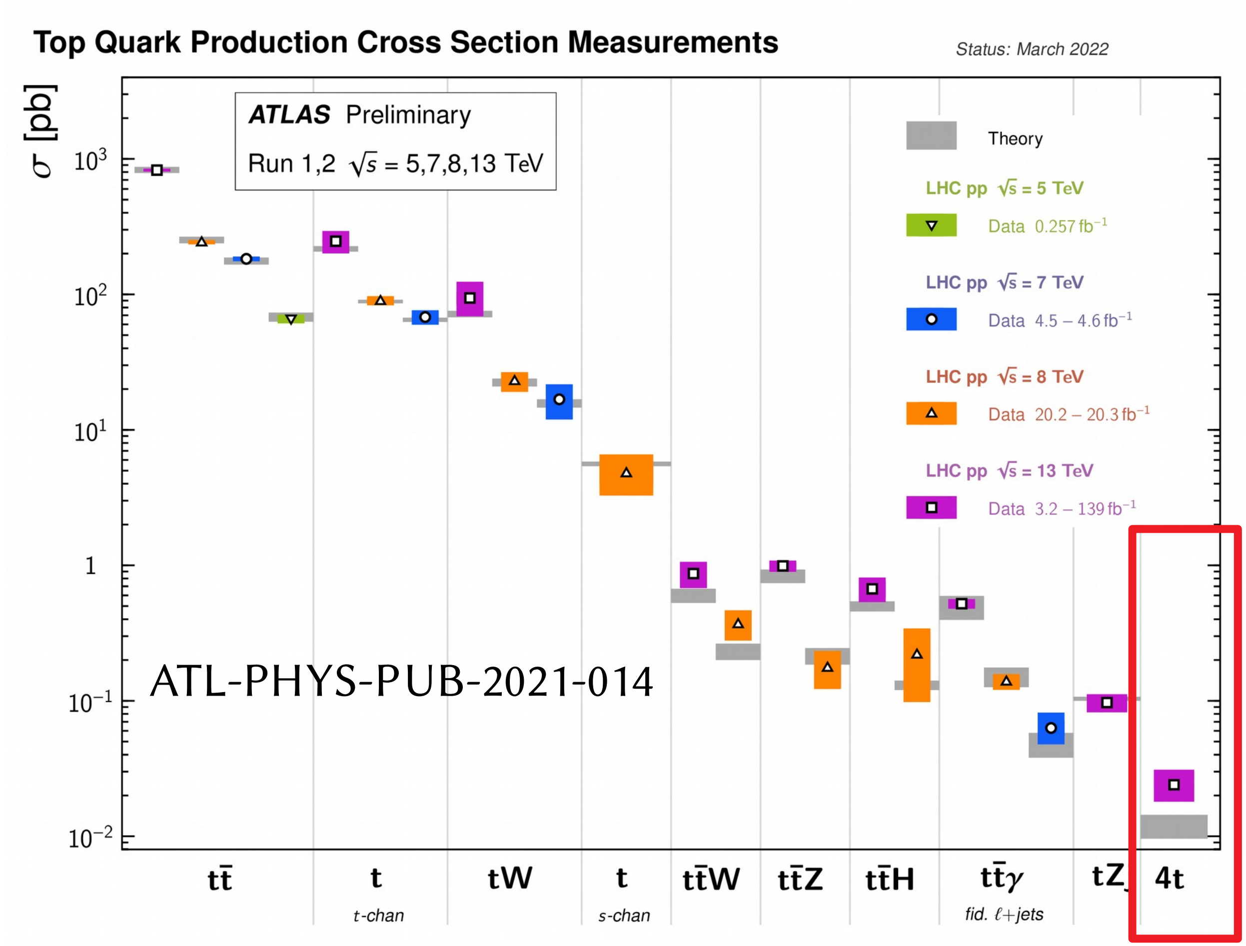
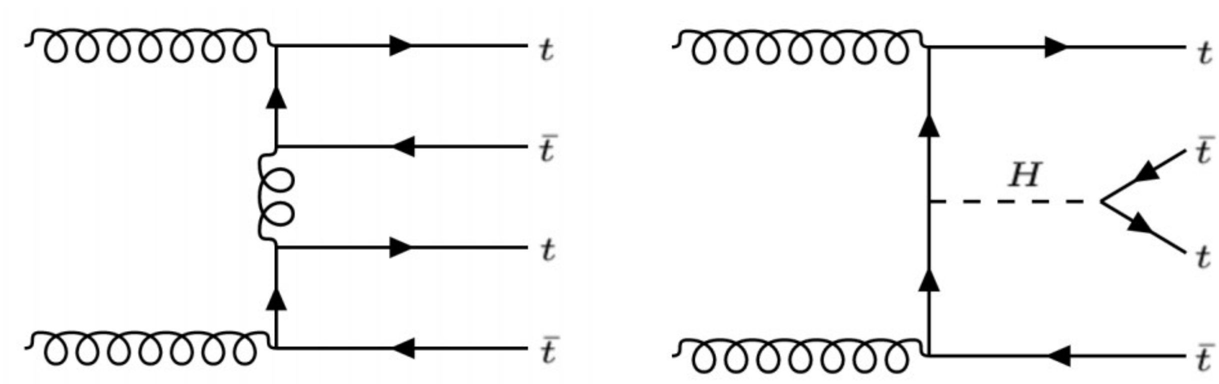
Introduction



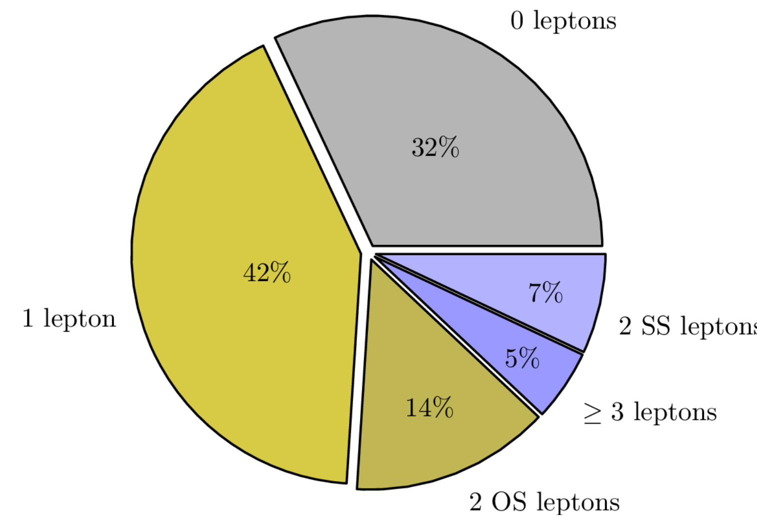


- Full Run 2 offers 139 fb^{-1} ⟶ rare top production modes
- Associated top production - massive final states
- Top quark couples to many SM and new physics particles
- ttV is important background for 4-tops

4-top quark signatures



4-top decay modes



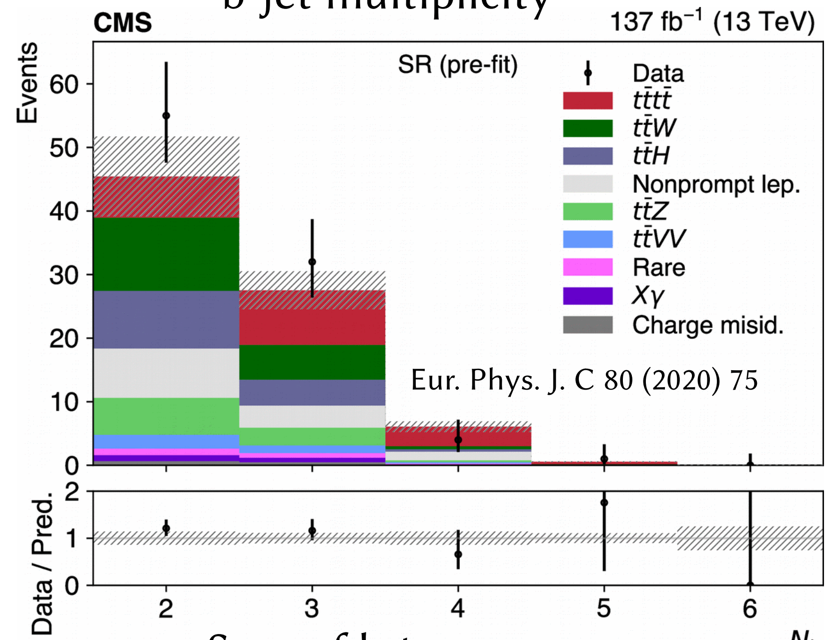
- Rare process: $\sigma(pp \rightarrow t\bar{t}t\bar{t}) = 12.0 \pm 2.4$ fb at NLO in QCD+QED JHEP 02 (2018) 031
- High jets and b-jets multiplicities
- Single lepton and two opposite sign leptons (1LOS)
  - Higher branching fraction
  - Larger irreducible background
  - ATLAS: 139 fb^{-1}, JHEP 11 (2021) 118
  - CMS: 36 fb^{-1}, JHEP 11 (2019) 082
- Same-sign di-lepton and multi-lepton (SSML)
  - Smaller branching fraction
  - Higher purity
  - ATLAS: 139 fb^{-1}, Eur. Phys. J. C 80 (2020) 1085
  - CMS: 137 fb^{-1}, Eur. Phys. J. C 80 (2020) 75

	CMS	ATLAS EXPERIMENT
SSML	137 fb^{-1}	139 fb^{-1}
1LOS	36 fb^{-1}	139 fb^{-1}
Combination		139 fb^{-1}

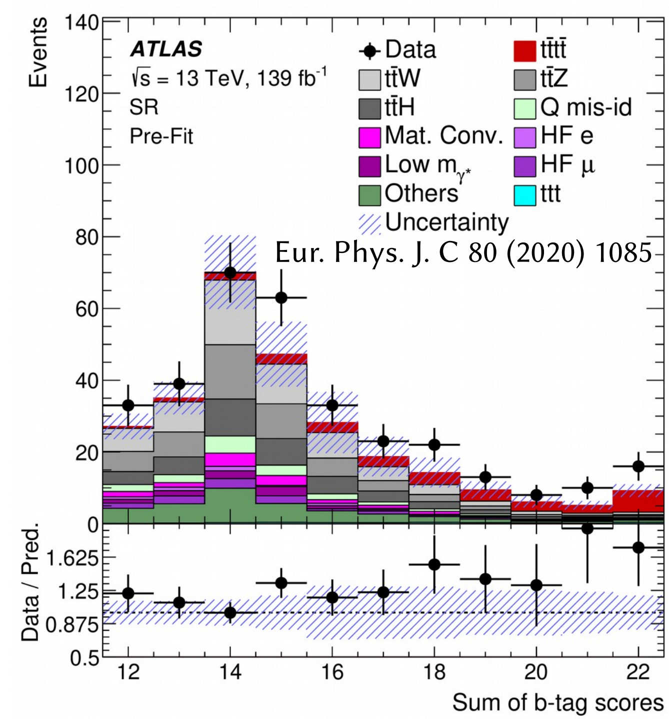
4-top SSML analysis strategy

- Likelihood fit of signal and control regions → extract signal strength and background
- Boosted Decision Tree separates tttt from background
- CMS: 19 input variables
  - Including lepton/jet multiplicity and jet flavor
  - Baseline ≥ 2 jet, ≥ 2 b-jet, H_T > 300 GeV
- ATLAS 12 input variables
  - Including sum of b-tagging scores and minimum ΔR between any pair of leptons
  - Signal region ≥ 6 jets, ≥ 2 b-jets, H_T > 500 GeV

b-jet multiplicity

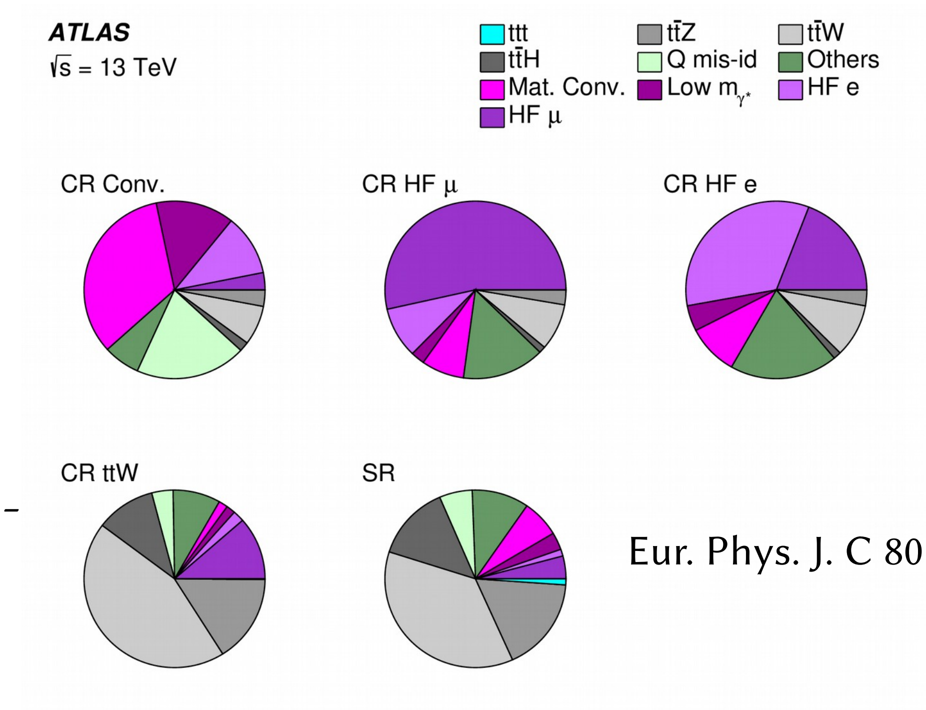


Sum of b-tag scores



4-top SSML backgrounds

- Main backgrounds:
  - ttW/ttZ/ttH
  - Events with non-prompt or charge-misidentified lepton
- Data-driven method for charge mis-identification estimation



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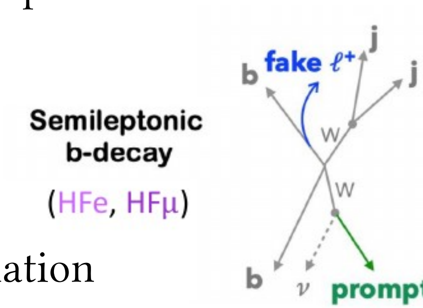
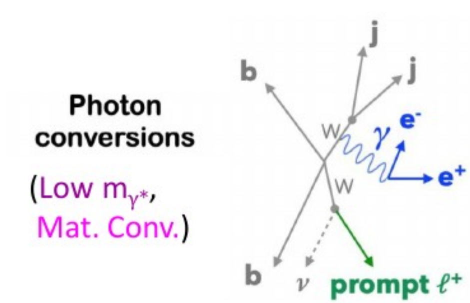
- ATLAS
  - Template fit method to estimate the non-prompt backgrounds
  - Dedicated control regions for ttW, heavy flavour leptons and conversions
    - ttW background normalization is free parameter
- CMS
  - Dedicated control region for ttZ
  - Tight-to-loose ratio method for non-prompt estimation



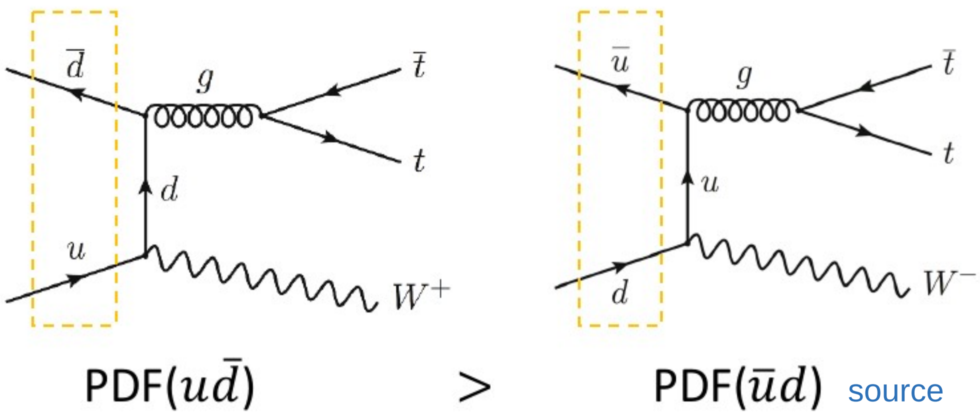


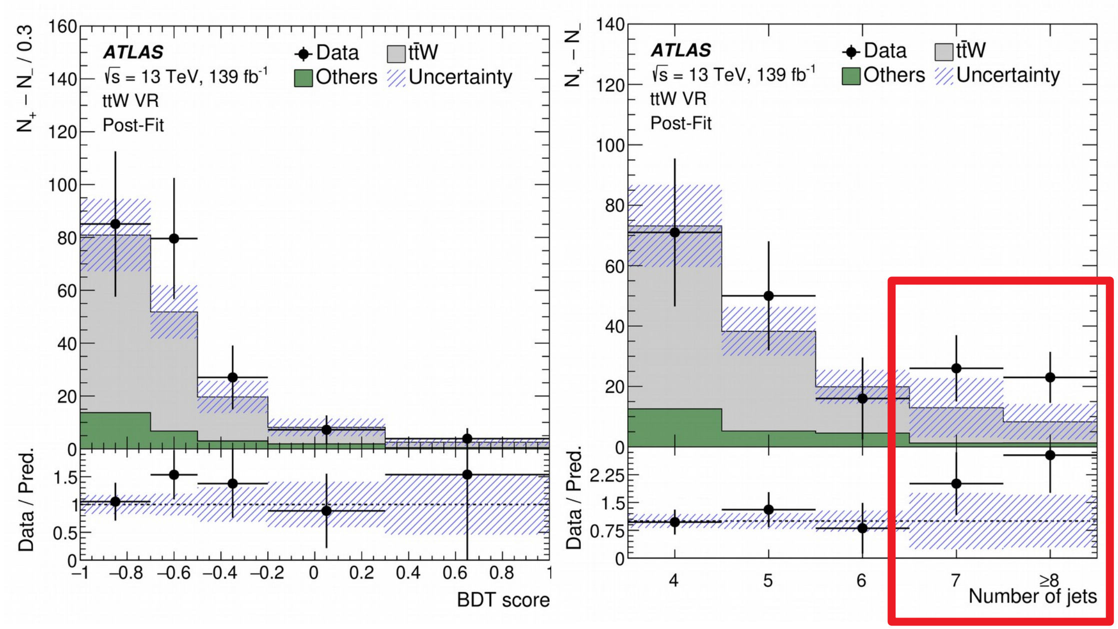
source

4-top SSML ATLAS - ttW modeling

ttW validation region

- $n_j \geq 4$, $n_b \geq 2$
- Plot $N_+ - N_-$
  - Charge asymmetry of leptons
    - $\sigma(t\bar{t}W^+) : \sigma(t\bar{t}W^-) \sim 2:1$
  - Removes charge symmetric processes
- Large uncertainty from 7j, ≥8j bins





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4-top SSML uncertainties

ATLAS

Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross section	+0.56	−0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	−0.09
Background modelling		
$t\bar{t}W$+jets modelling	+0.26	−0.27
$t\bar{t}t$ modelling	+0.10	−0.07
Non-prompt leptons modelling	+0.05	−0.04
$t\bar{t}H$+jets modelling	+0.04	−0.01
$t\bar{t}Z$+jets modelling	+0.02	−0.04
Other background modelling	+0.03	−0.02
Charge misassignment	+0.01	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.08
Jet flavour tagging (light-flavour jets)	+0.11	−0.06
Simulation sample size	+0.06	−0.06
Luminosity	+0.05	−0.03
Jet flavour tagging (b-jets)	+0.04	−0.02
Jet flavour tagging (c-jets)	+0.03	−0.01
Other experimental uncertainties	+0.03	−0.01
Total systematic uncertainty	+0.70	−0.44
Statistical	+0.42	−0.39
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	+0.05	−0.04
$t\bar{t}W$ normalisation	+0.04	−0.04
Total uncertainty	+0.83	−0.60

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CMS

Source	Uncertainty (%)	Impact on $\sigma(t\bar{t}t\bar{t})$ (%)
Integrated luminosity	2.3–2.5	2
Pileup	0–5	1
Trigger efficiency	2–7	2
Lepton selection	2–10	2
Jet energy scale	1–15	9
Jet energy resolution	1–10	6
b tagging	1–15	6
Size of simulated sample	1–25	<1
Scale and PDF variations †	10–15	2
ISR/FSR (signal) †	5–15	2
$t\bar{t}H$ (normalization) †	25	5
Rare, Xγ, $t\bar{t}VV$ (norm.) †	11–20	<1
$t\bar{t}Z$, $t\bar{t}W$ (norm.) †	40	3–4
Charge misidentification †	20	<1
Nonprompt leptons †	30–60	3
$N_{\text{jets}}^{\text{ISR/FSR}}$	1–30	2
$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ †	35	11

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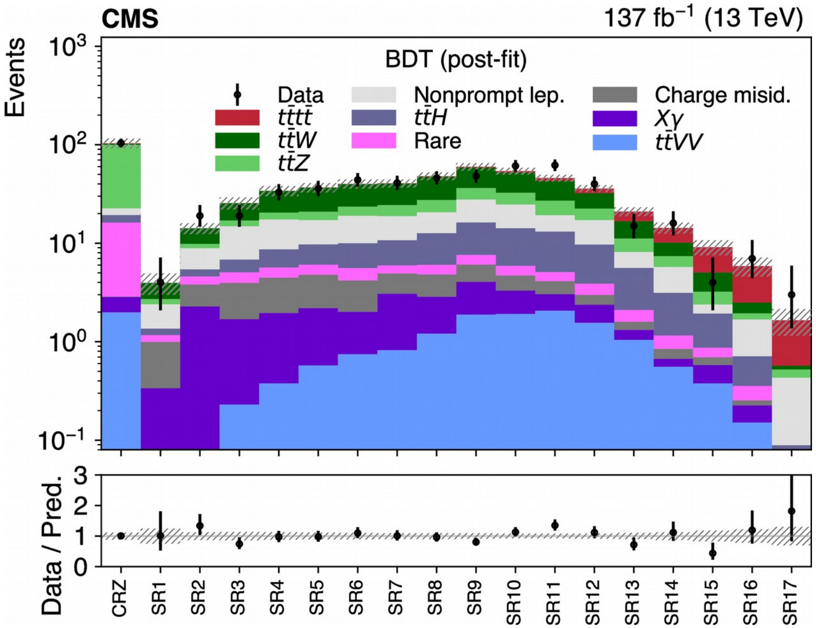
- Similar contribution from statistical and systematic uncertainty
- ATLAS: ttW modelling is largest background uncertainty

4-top SSML results

Signal and control regions



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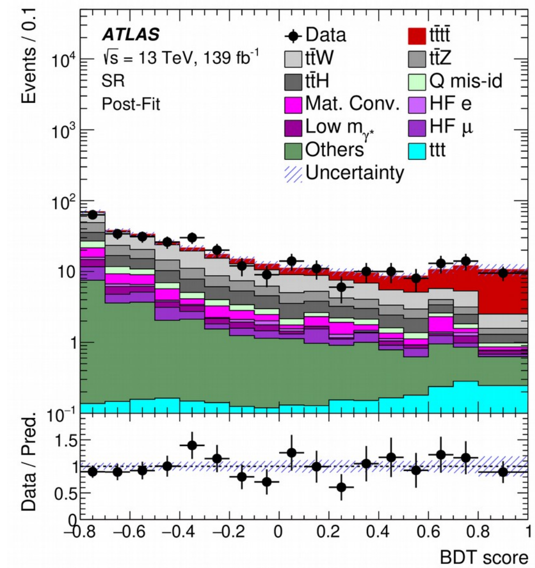
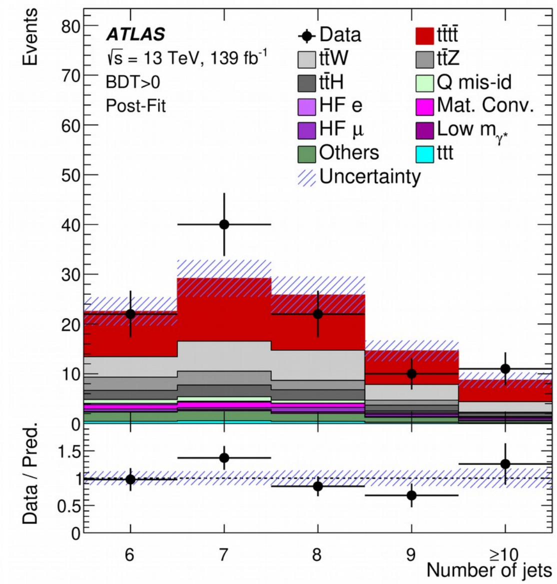
BDT score



Jet multiplicity



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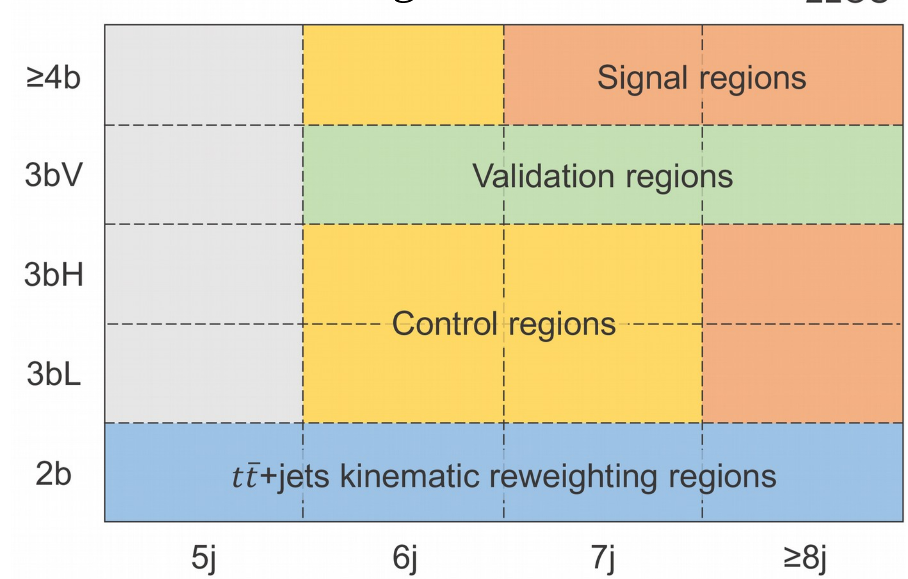
- Agreement between post-fit prediction and data
- Less than 2 σ away from SM prediction (ATLAS)

	CMS	ATLAS
σ(tttt)	$12.6^{+5.8}_{-5.2}$ fb	24^{+7}_{-6} fb
Significance	2.6 (2.7) σ	4.3 (2.4) σ

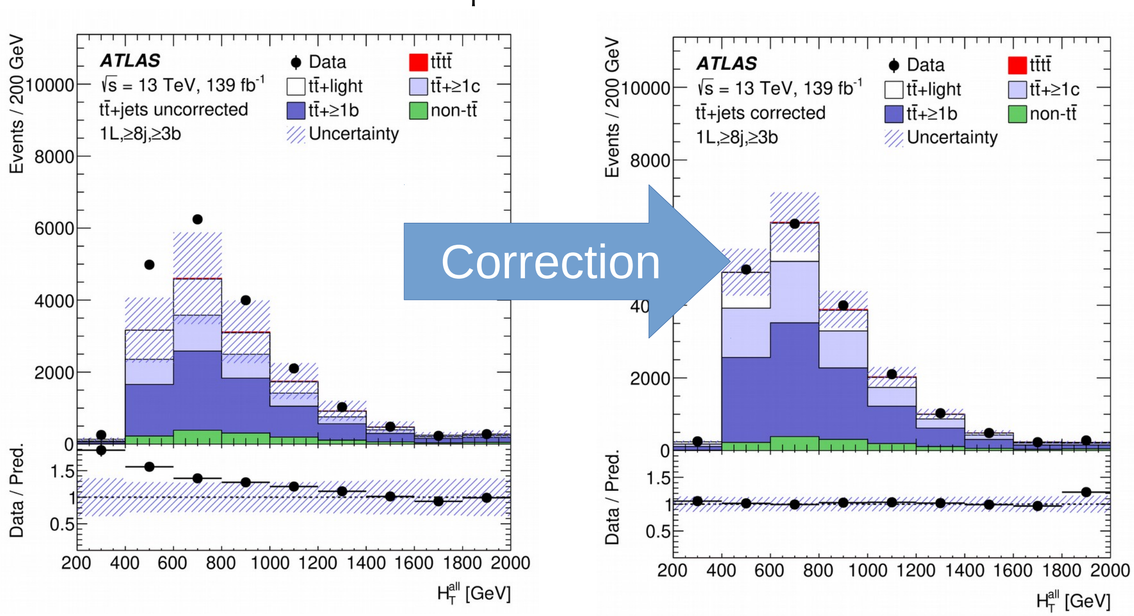
4-top 1LOS ATLAS JHEP 11 (2021) 118

- Event categorization based on jet multiplicity and b-tagging requirements (3b L/H/V)
- Balance: 4top sensitivity – tt+jets estimation
- Data-driven tt+jets corrections
- Simultaneous profile likelihood fit
  - BDT discriminant used in signal region

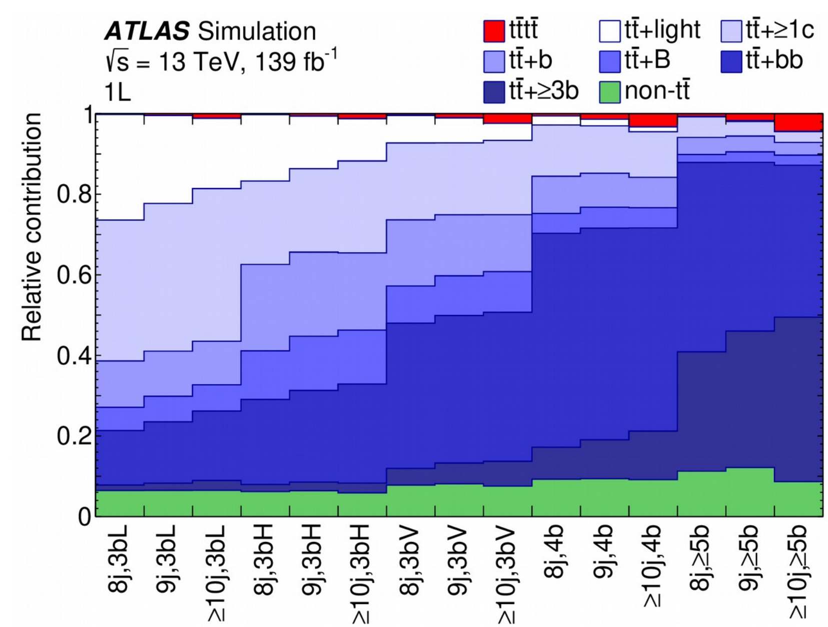
Regions



H_T^{all} distribution

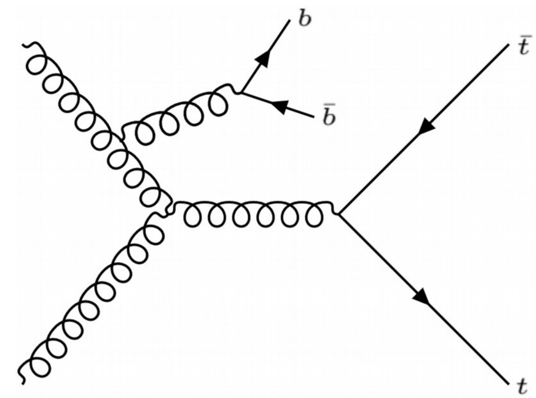


Relative contribution

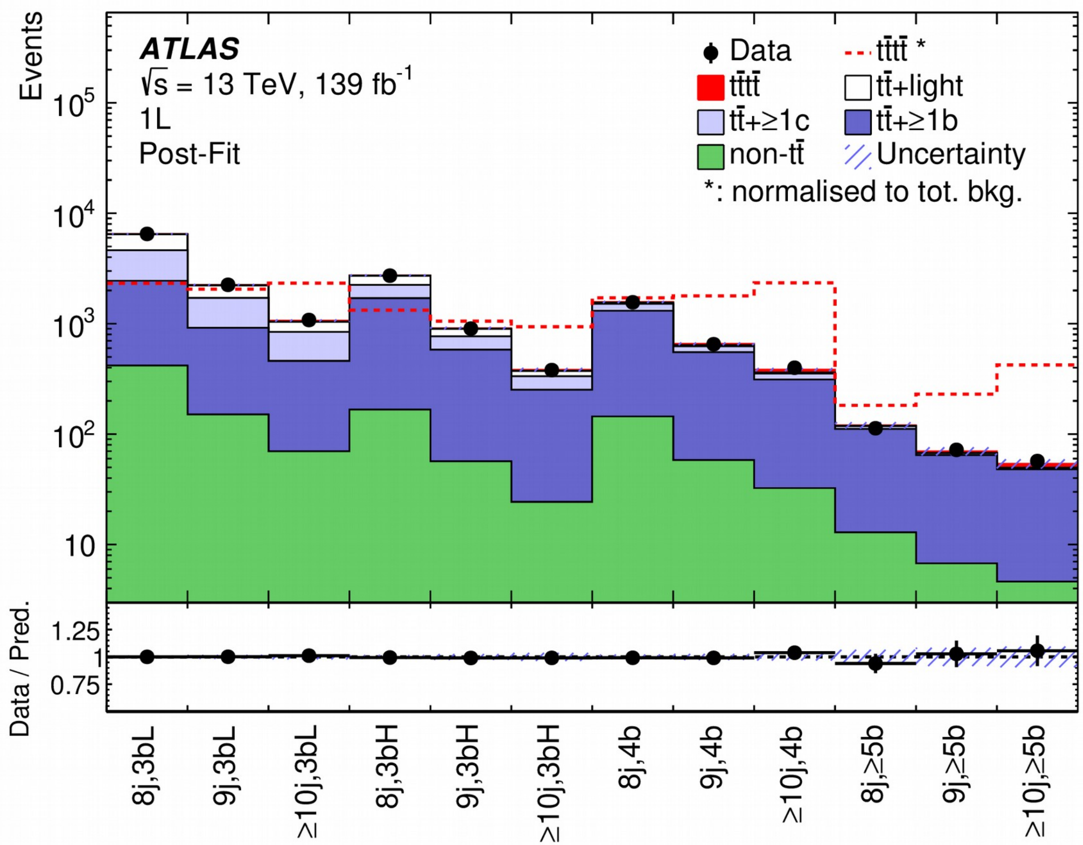


4-top 1LOS uncertainties JHEP 11 (2021) 118

- Dominated by tt + heavy flavour modelling uncertainties
- Limited by systematic uncertainties



Post-fit yields

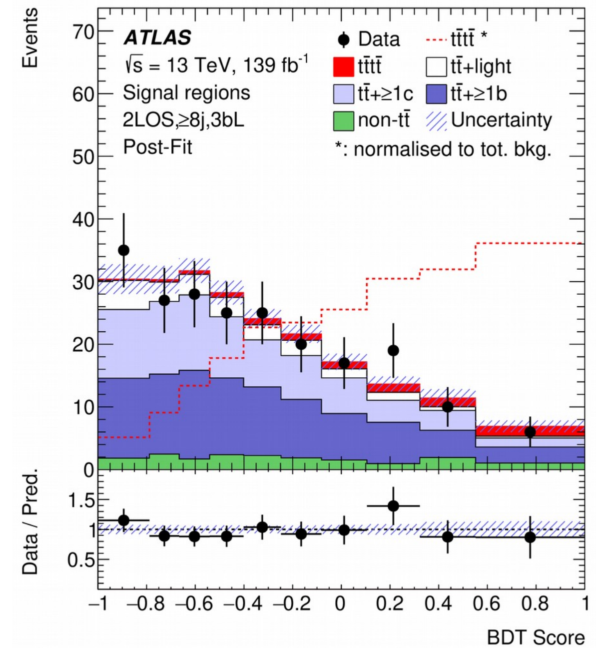


Uncertainty source	$\Delta\sigma_{t\bar{t}t\bar{t}}$ [fb]	
Signal Modelling		
$t\bar{t}t\bar{t}$ modelling	+8	−3
Background Modelling		
$t\bar{t}+\geq 1b$ modelling	+8	−7
$t\bar{t}+\geq 1c$ modelling	+5	−4
$t\bar{t}$+jets reweighting	+4	−3
Other background modelling	+4	−3
$t\bar{t}$+light modelling	+2	−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

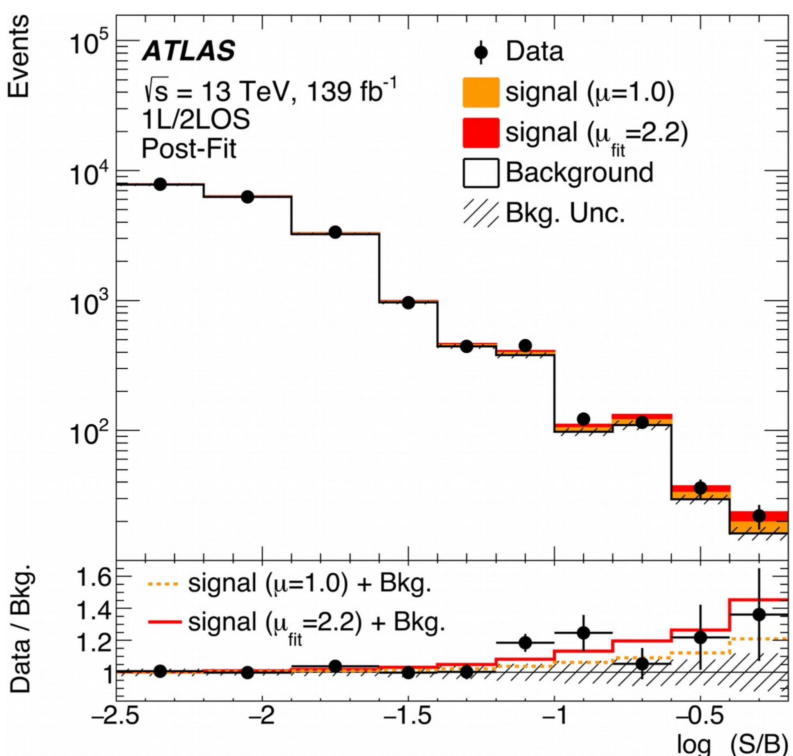
4-top 1LOS results and combination

- 1LOS measured σ(tttt) = 26^{+17}_{-15} fb and 1.9 (1.0) σ observed (expected) significance
- Different uncertainties dominate SSML and 1LOS
- Combination improves observed (expected) significance to 4.7 σ (2.6 σ)
- Combination 2 σ away from SM expectation 12.0 ± 2.4 fb

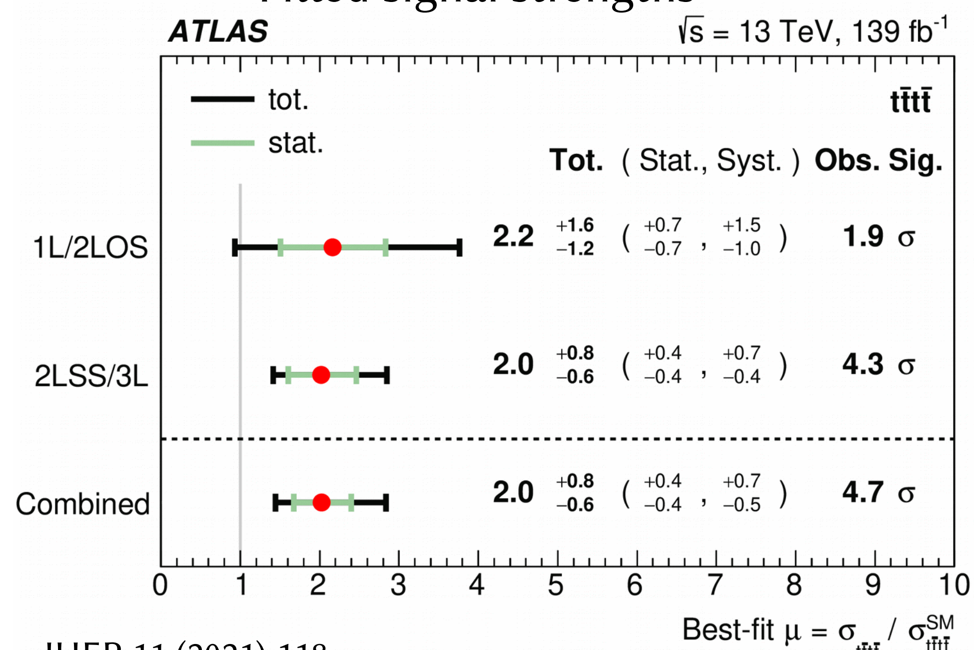
Post-fit BDT Score



$\log_{10}(S/B)$



Fitted signal strengths



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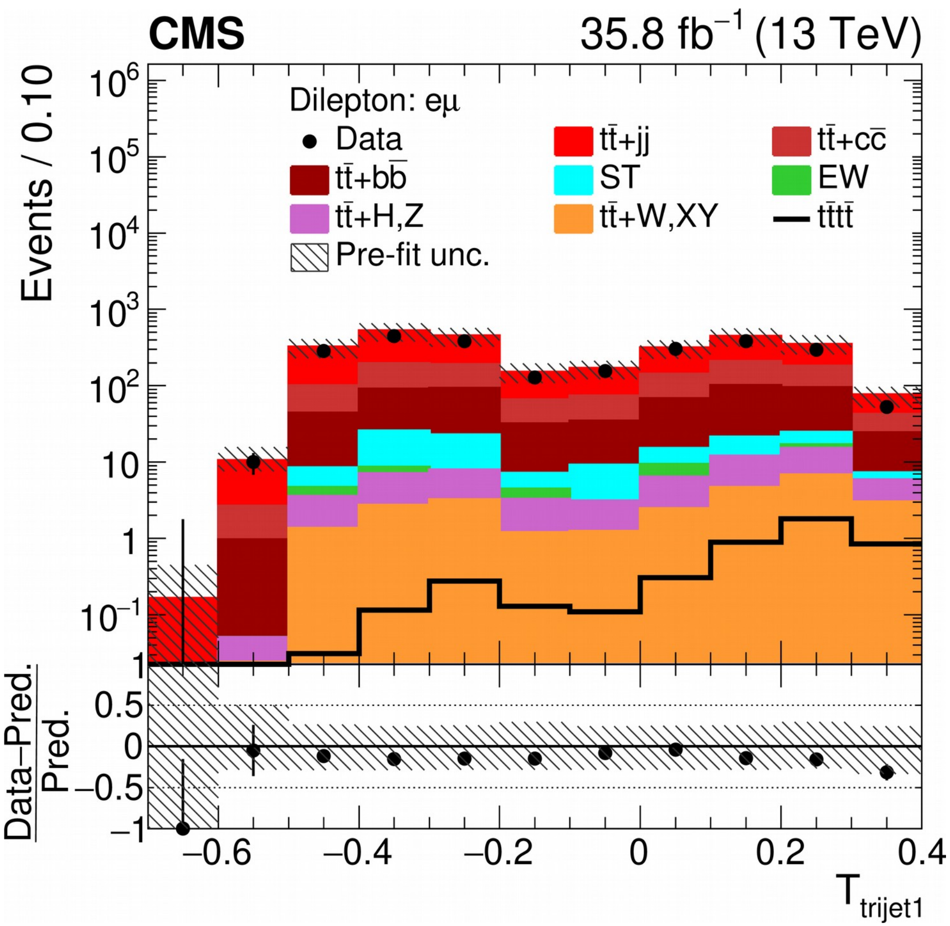
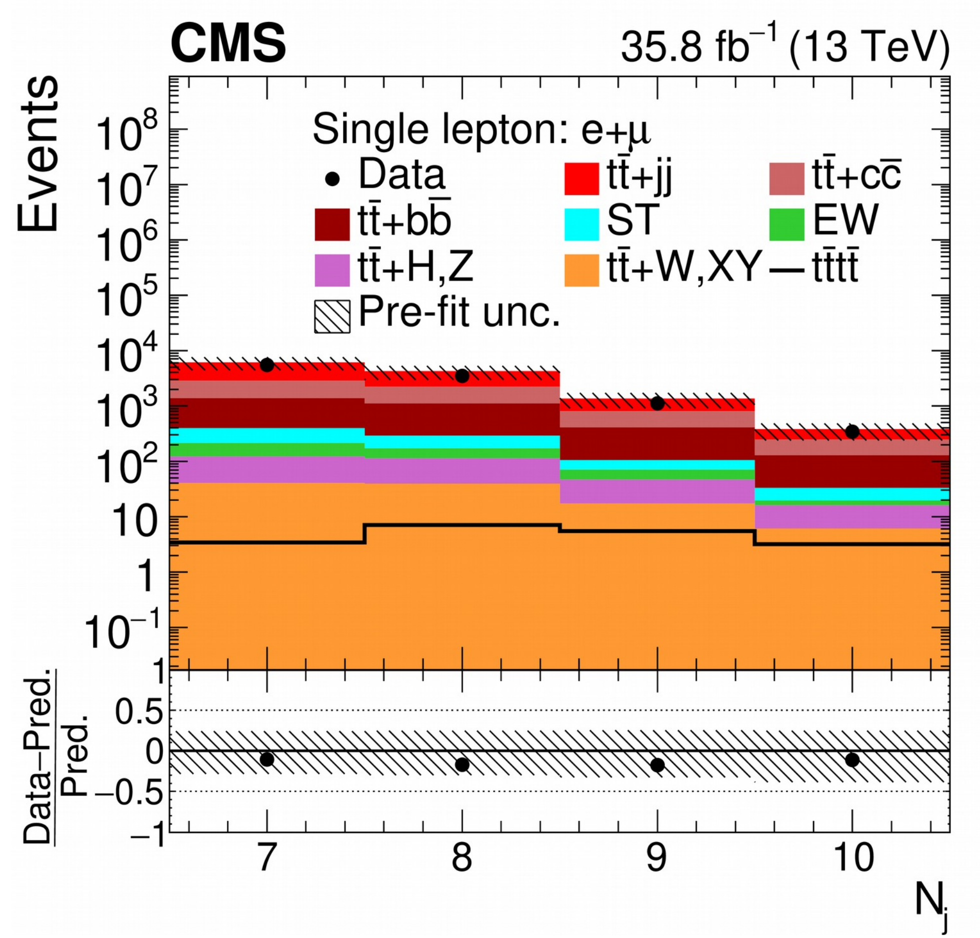
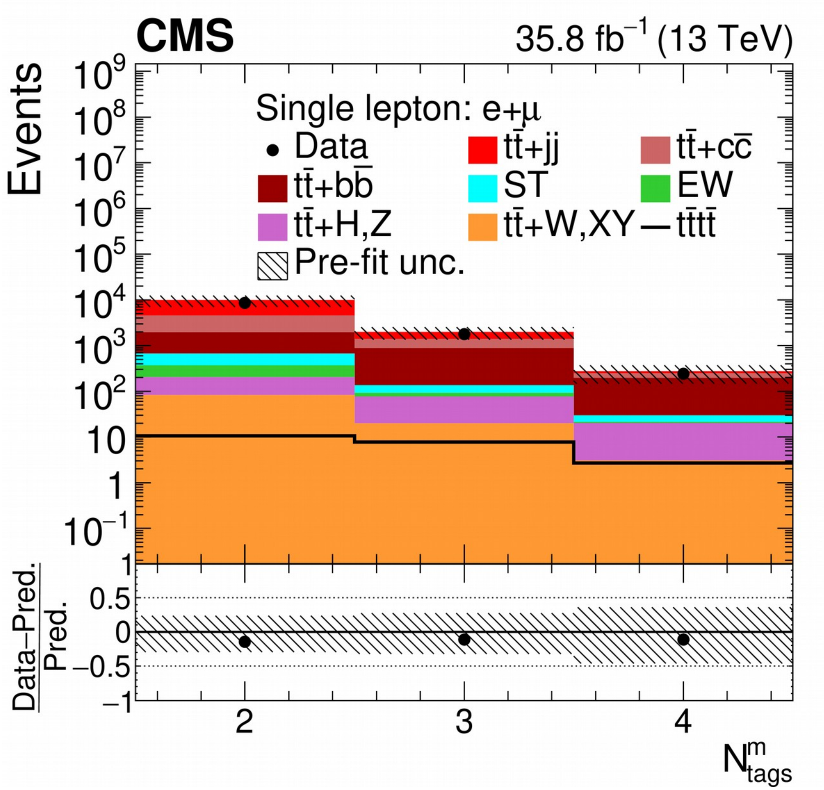
4-top 1LOS CMS JHEP 11 (2019) 082

- BDT to separate signal from background in each category
  - Jet and b-jet multiplicities, jet properties, kinematic variables
- Dedicated BDT for top quark identification (trijets from hadronic top quarks)
  - Dijet and trijet masses, b-tagging information, angles between jets





1LOS CMS background and uncertainties

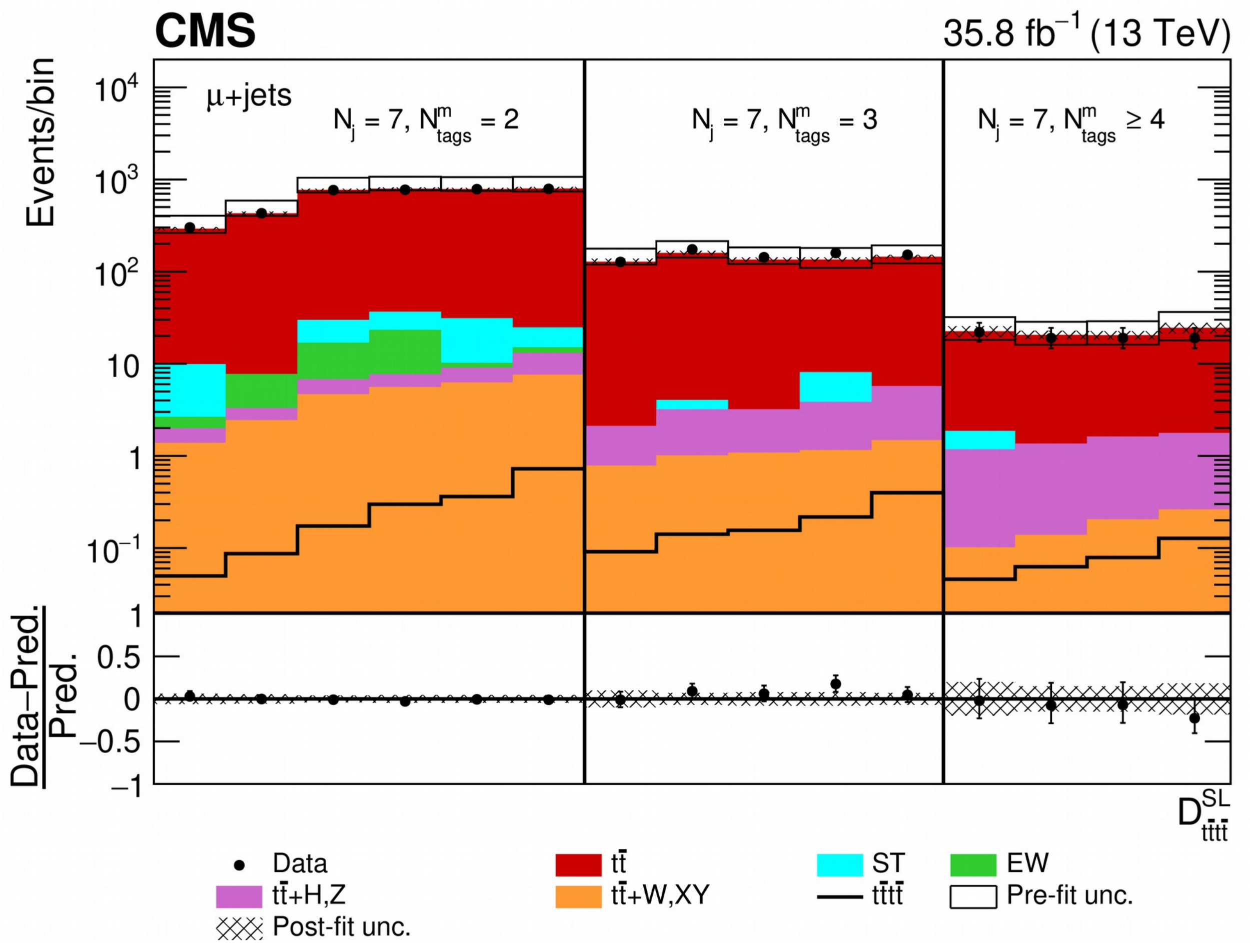


JHEP 11 (2019) 082

Systematic uncertainty	Normalization	Shape
Integrated luminosity	X	
Pileup modeling	X	X
Lepton reconstruction and identification	X	
Jet energy corrections	X	X
b tagging	X	X
Ren. and fact. scales	X	X
PS scales	X	
ME-PS matching	X	
UE	X	
Jet multiplicity correction	X	
Parton distribution functions	X	X
Top quark p_T reweighting		X
Heavy-flavor reweighting	X	X
Rare process	X	

- tt+ jets is dominant background
- Reweighting of tt + jets events
- Equally affected by statistical and systematic uncertainties
- Main uncertainties: tt+heavy-flavor reweighting, jet multiplicity correction, PS and UE modeling in tt simulation

4-top 1LOS results JHEP 11 (2019) 082



- Categories based on jet and b-jet multiplicities

- Observed (expected) significance 0.0σ (0.4σ)
- σ(tttt) = 0^{+20} fb

4-top interpretations - CMS

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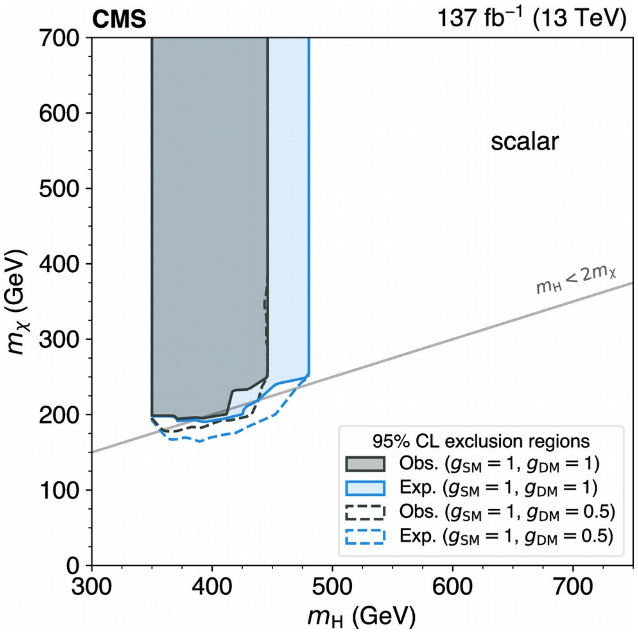
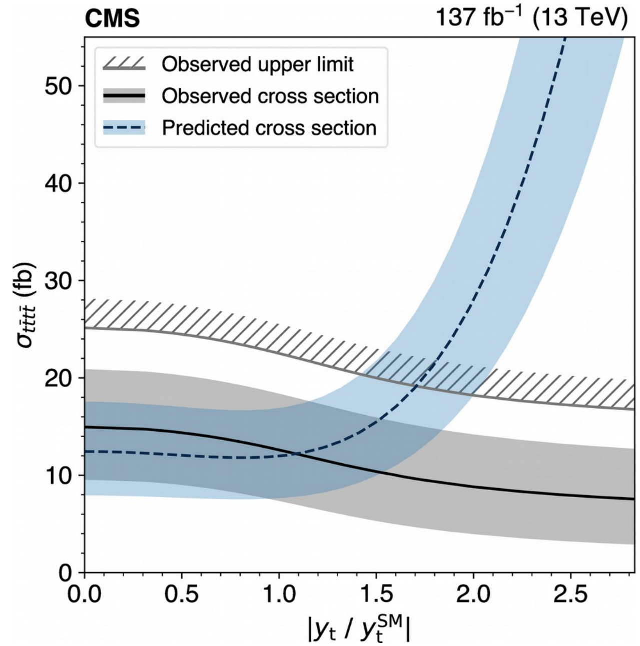
Dark matter model SSML



Top Yukawa coupling SSML



- Top Yukawa coupling $|y_t/y_t^{SM}| < 1.7$
- Higgs oblique parameter < 0.12 at 95% CL
- Limits on new particles
  - Type-II two-Higgs-doublet models
  - Simplified dark matter models

4-top EFT parameters – CMS 1LOS

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$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)}\mathcal{O}_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)}\mathcal{O}_k^{(6)} + \ldots,$$

$$\mathcal{O}_{\mathrm{tt}}^{1} = (\bar{\mathrm{t}}_{\mathrm{R}}\gamma^{\mu}\mathrm{t}_{\mathrm{R}})\left(\bar{\mathrm{t}}_{\mathrm{R}}\gamma_{\mu}\mathrm{t}_{\mathrm{R}}\right),$$

$$\mathcal{O}_{\mathrm{QQ}}^{1} = (\overline{\mathrm{Q}}_{\mathrm{L}}\gamma^{\mu}\mathrm{Q}_{\mathrm{L}})\left(\overline{\mathrm{Q}}_{\mathrm{L}}\gamma_{\mu}\mathrm{Q}_{\mathrm{L}}\right),$$

$$\mathcal{O}_{\mathrm{Qt}}^{1} = (\overline{\mathrm{Q}}_{\mathrm{L}}\gamma^{\mu}\mathrm{Q}_{\mathrm{L}})\left(\bar{\mathrm{t}}_{\mathrm{R}}\gamma_{\mu}\mathrm{t}_{\mathrm{R}}\right),$$

$$\mathcal{O}_{\mathrm{Qt}}^{8} = \left(\overline{\mathrm{Q}}_{\mathrm{L}}\gamma^{\mu}T^{\mathrm{A}}\mathrm{Q}_{\mathrm{L}}\right)\left(\bar{\mathrm{t}}_{\mathrm{R}}\gamma_{\mu}T^{\mathrm{A}}\mathrm{t}_{\mathrm{R}}\right),$$

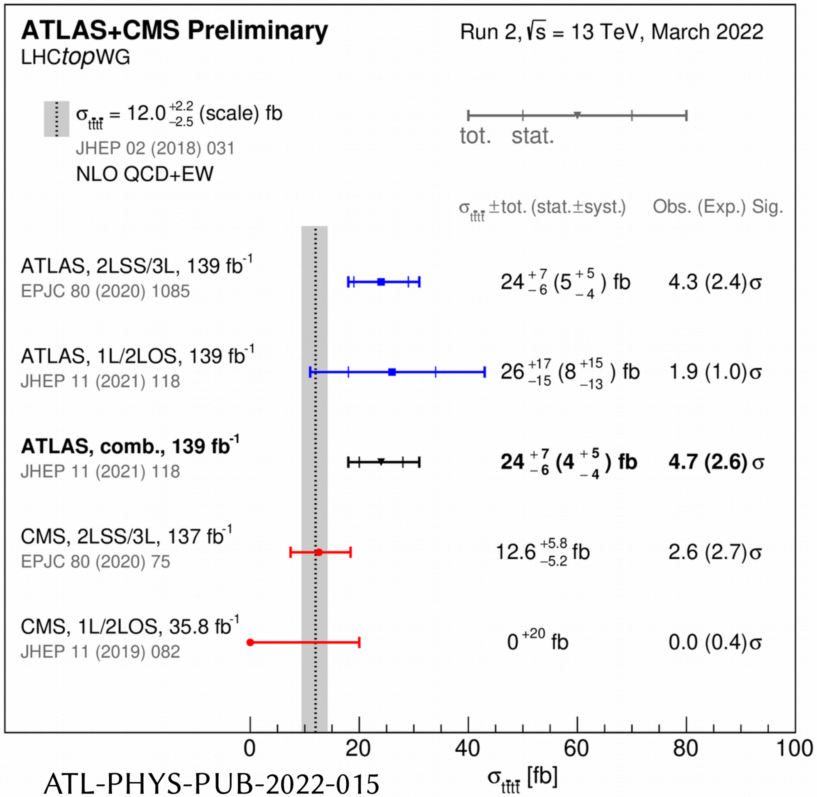
4-top EFT parameters 1LOS (36 fb^{-1})

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

- Using 4 linear independent operators
- Constraints based on rates

Summary

4-top cross-section



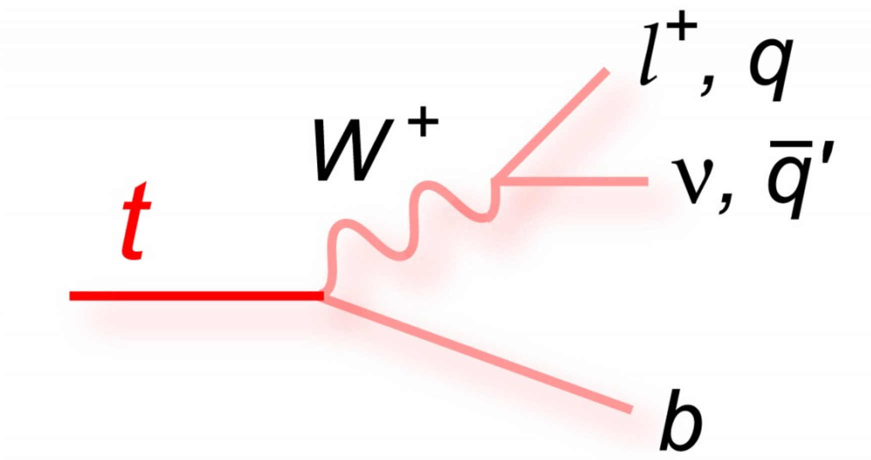
ATL-PHYS-PUB-2022-015

- Many 4-top signatures are studied in CMS and ATLAS
- First evidence for SM 4-top in ATAS SSML analysis
- ATLAS SSML and 1LOS combination improves significance
- CMS analyses constrain various BSM models

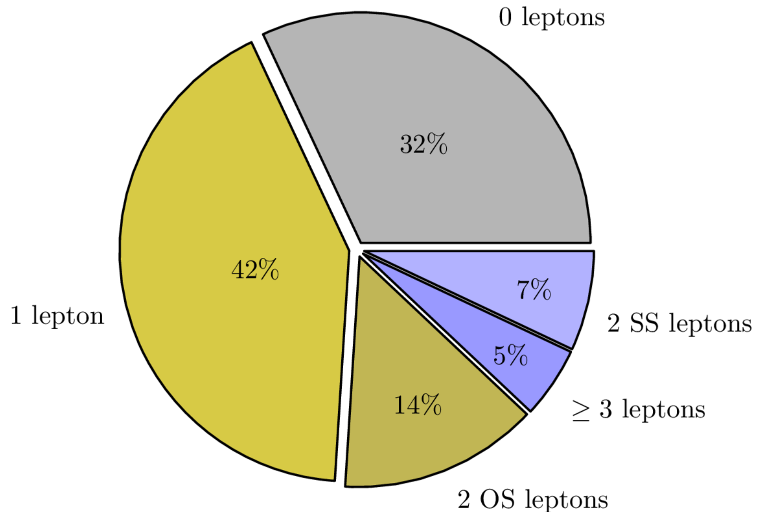
Backup

Introduction

Top quark decay

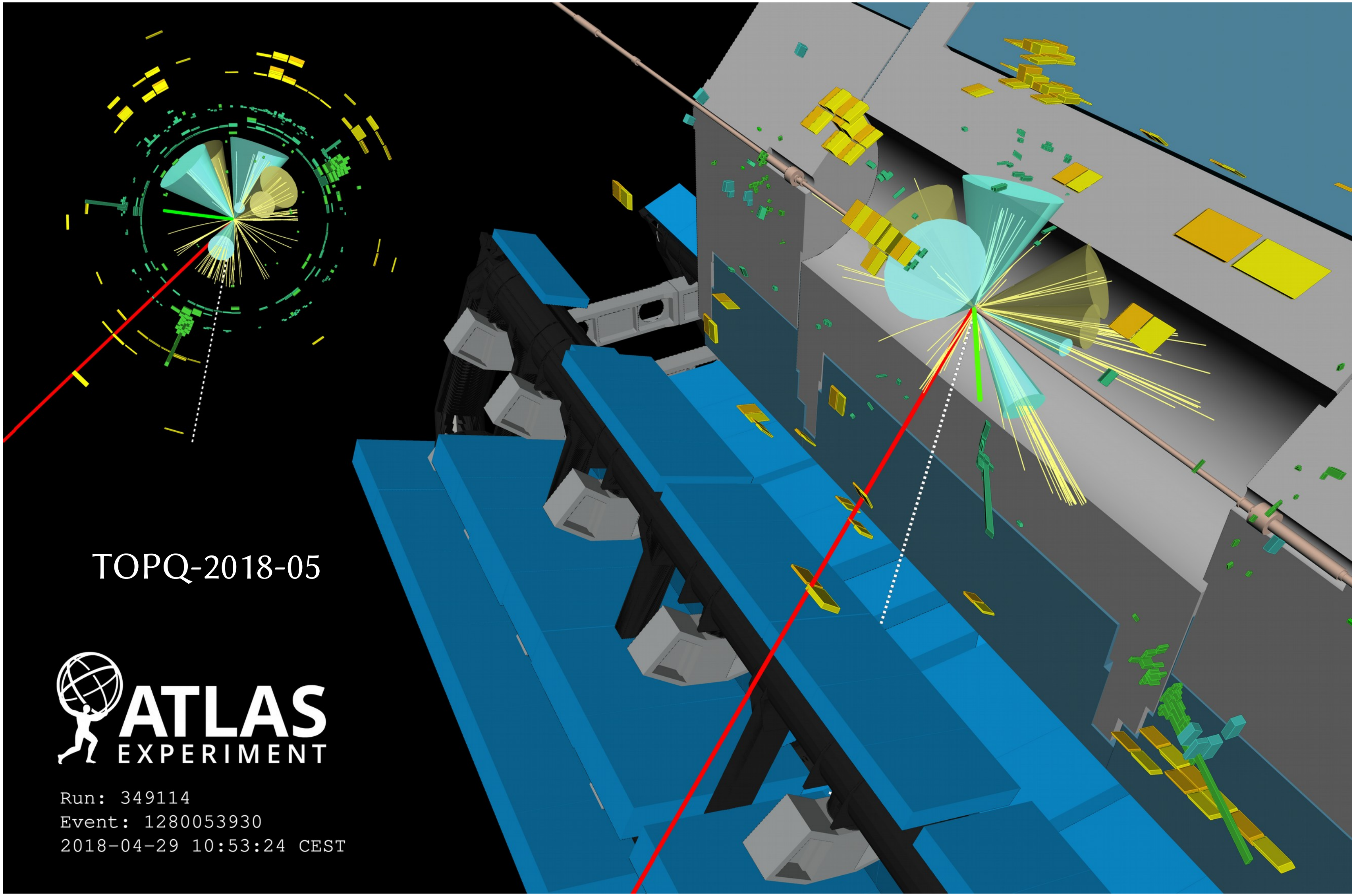


4-top decay modes



- Top quark is heaviest fundamental particle
- Decays before hadronization
- Almost uniquely decays to W boson and bottom quark
- Focus on tttt

4-top event display



4top SSML

- Control and signal region definitions

ATLAS

Region	Channel	N_j	N_b	Other requirements	Fitted variable
SR	2LSS/3L	≥ 6	≥ 2	$H_T > 500$	BDT
CR Conv.	$e^\pm e^\pm \| \| e^\pm \mu^\pm$	$4 \leq N_j < 6$	≥ 1	$m_{ee}^{CV} \in [0, 0.1$ GeV$]$ $200 < H_T < 500$ GeV	m_{ee}^{PV}
CR HF e	$eee \| \| ee\mu$	-	$= 1$	$100 < H_T < 250$ GeV	counting
CR HF μ	$e\mu\mu \| \| \mu\mu\mu$	-	$= 1$	$100 < H_T < 250$ GeV	counting
CR ttW	$e^\pm \mu^\pm \| \| \mu^\pm \mu^\pm$	≥ 4	≥ 2	$m_{ee}^{CV} \notin [0, 0.1$ GeV$]$, $\|\eta(e)\| < 1.5$ for $N_b = 2$, $H_T < 500$ GeV or $N_j < 6$ for $N_b \geq 3$, $H_T < 500$ GeV	Σp_T^ℓ

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CMS

N_ℓ	N_b	N_{jets}	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
		≥ 8	SR3
	3	5	SR4
		6	SR5
		7	SR6
		≥ 8	SR7
	≥ 4	≥ 5	SR8
≥ 3	2	5	SR9
		6	SR10
		≥ 7	SR11
	≥ 3	4	SR12
		5	SR13
		≥ 6	SR14
Inverted resonance veto			CRZ

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4-top 1LOS - regions

Name	$N_b^{60\%}$	$N_b^{70\%}$	$N_b^{85\%}$
2b	-	$= 2$	-
3bL	≤ 2	$= 3$	-
3bH	$= 3$	$= 3$	$= 3$
3bV	$= 3$	$= 3$	≥ 4
≥4b (2LOS)	-	≥ 4	-
4b (1L)	-	$= 4$	-
≥5b (1L)	-	≥ 5	-

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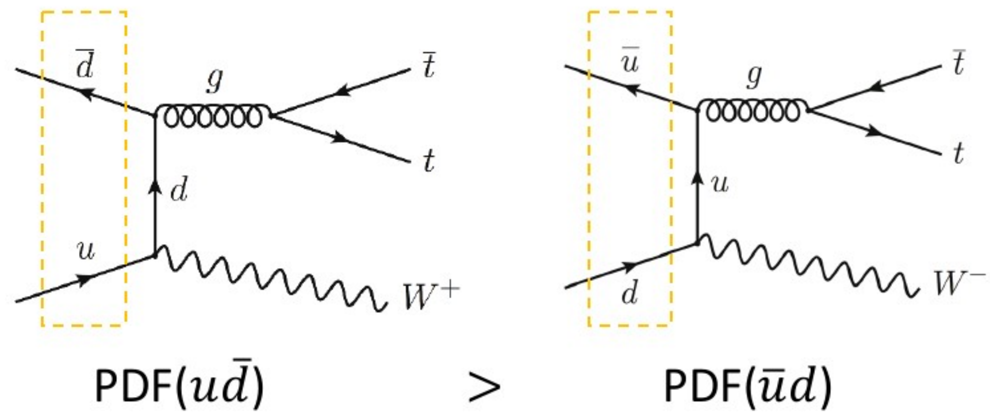
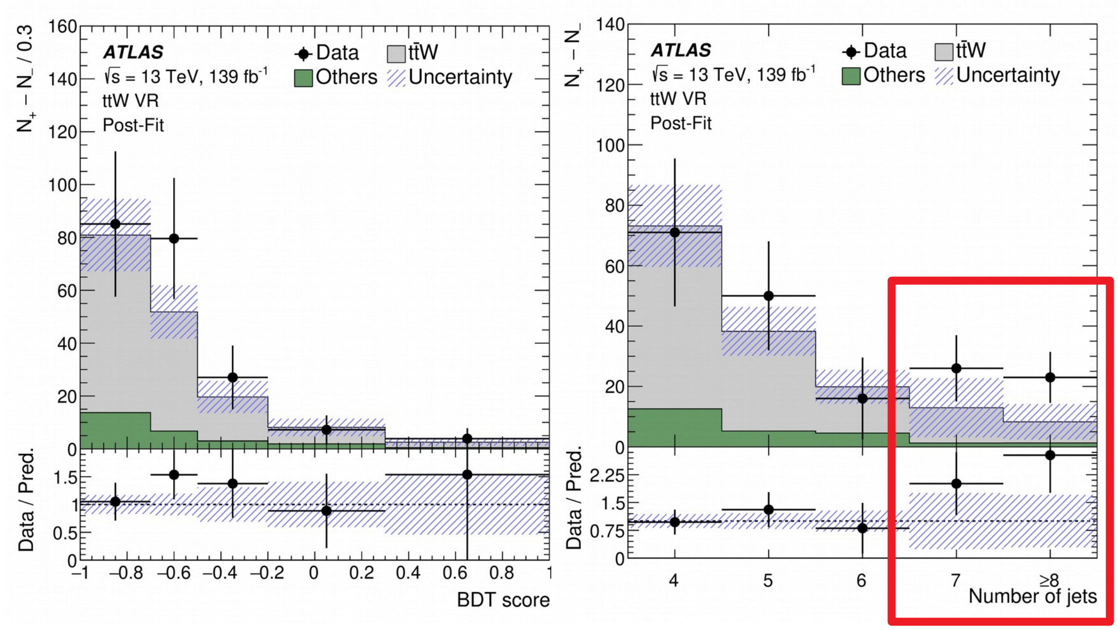
ttW modeling

ttW validation region

- Nj ≥ 4, Nb ≥ 2
- Plot $N_+ - N_-$
  - Charge asymmetry of leptons
    - $\sigma(t\bar{t}W^+) : \sigma(t\bar{t}W^-) \sim 2:1$
  - Removes charge symmetric processes
- Large uncertainty from 7j, ≥8j bins





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Data-driven ttW Eur. Phys. J. C 81 (2021) 1023

- Method to model tt̄W background used in SUSY RPV analysis
- Motivation: large uncertainties in MC jet multiplicity modeling
- SUSY RPV analysis:
  - ttV+ttbar background with parameterized model
  - Simultaneous likelihood fit in jet and b-jet multiplicity regions
    - 54-110 bins depending on jet p_T threshold
  - Same central value with completely different background estimation method, reduced reliance on MC and no MVA

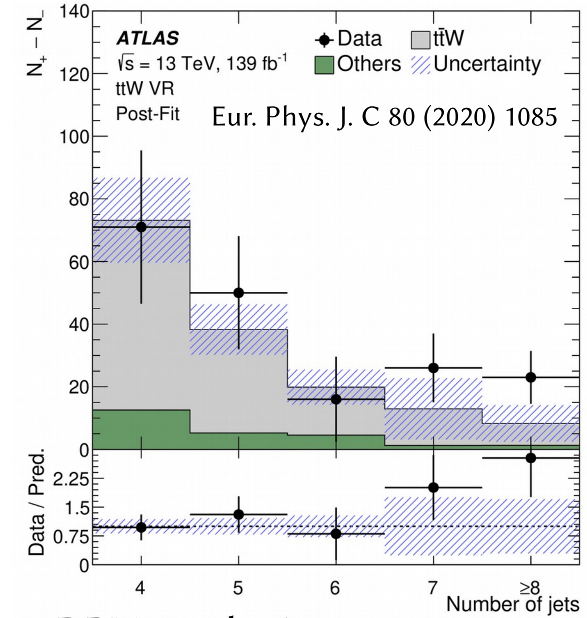
RPV analysis - Eur. Phys. J. C 81 (2021) 1023

$$\mu_{tttt} = 2.0^{+0.9}_{-0.7}$$

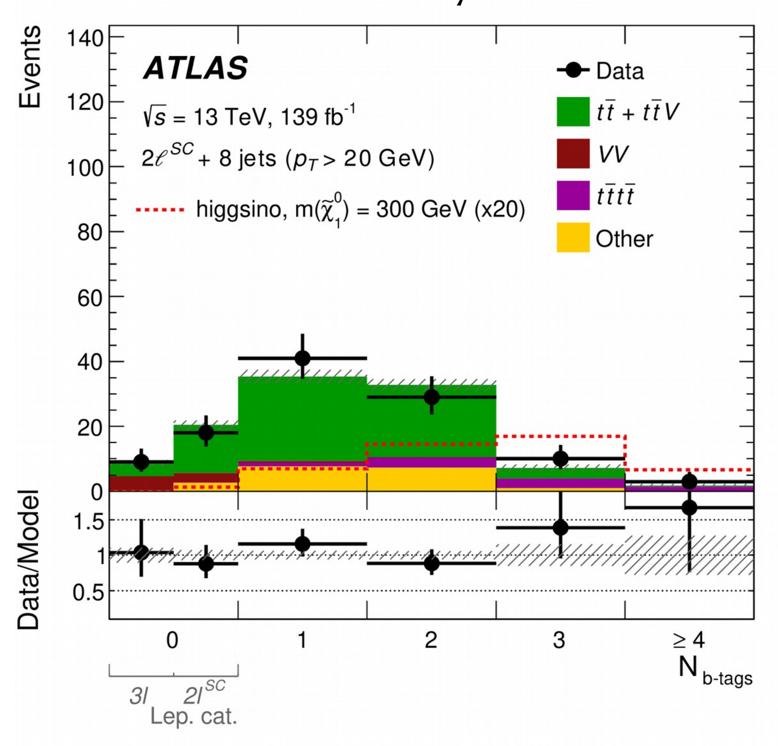
SM 4-top analysis - Eur. Phys. J. C 80 (2020) 1085

$$\mu_{tttt} = 2.0^{+0.8}_{-0.6}$$

SM 4-top analysis



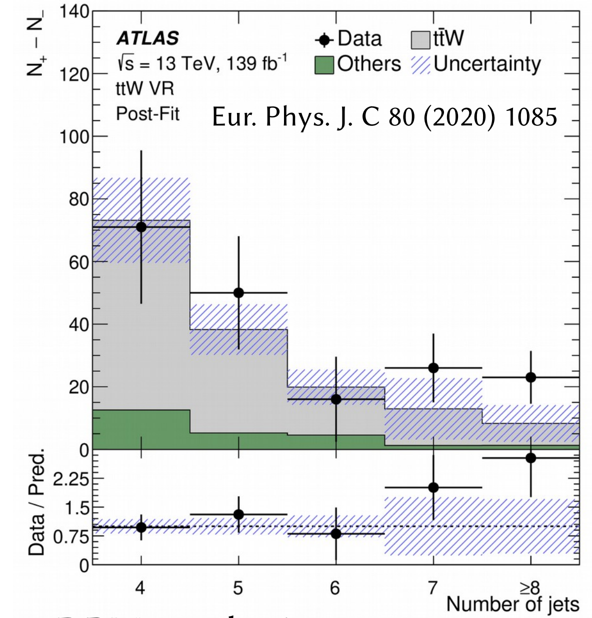
RPV analysis



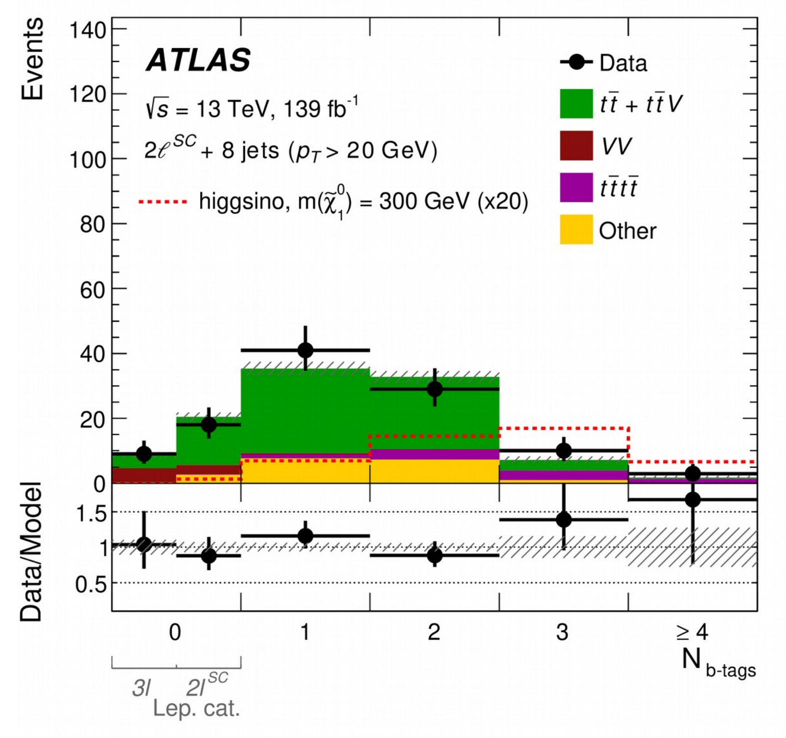
Data-driven $t\bar{t}W$ Eur. Phys. J. C 81 (2021) 1023

- Method to model $t\bar{t}W$ background used in SUSY RPV analysis
- Motivation: large uncertainties in MC jet multiplicity modeling
- Data-driven background model
  - N_{b-jet} distribution: obtained with $N_{j,b} = f_{j,b} \times N_j$
  - N_{jet} distribution: parameterized using scaling

SM 4-top analysis



RPV analysis



Jet scaling Eur. Phys. J. C 81 (2021) 1023

$$N_j = N_4 \cdot \prod_{j'=4}^{j'=j-1} r(j')$$

- N_{jet} distribution: parameterized using scaling
  - $r(j) = N_{j+1} / N_j$
  - $r(j) = c_0$ for very high jet multiplicities (staircase)
  - $r(j) = c_1 / (j+1)$ for low jet multiplicities (Poisson)
- Ratio $r(j) \equiv N_{j+1} / N_j = c_0 + c_1 / (c_2 + j)$
  - c2, introduced to account for the ambiguity counting extra jets in tt events
  - Fit one normalization (N_4) and two/three parameters (c0, c1, c2) per background

RPV analysis Data and MC