Evidence for Four-Top Quark Production at the LHC

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for the CMS Collaboration

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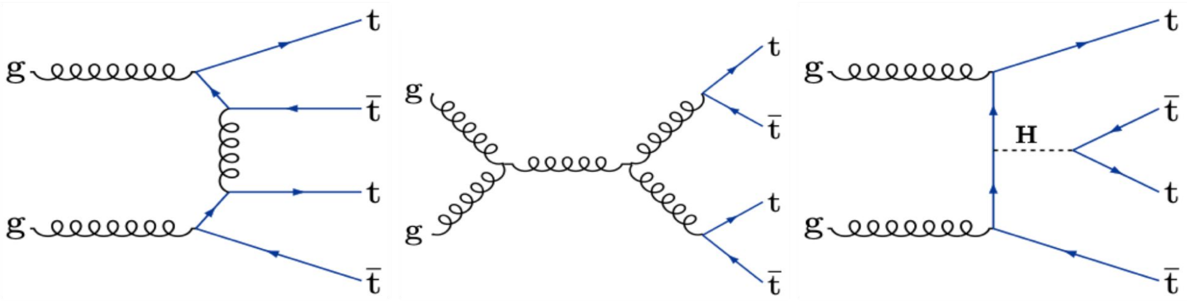
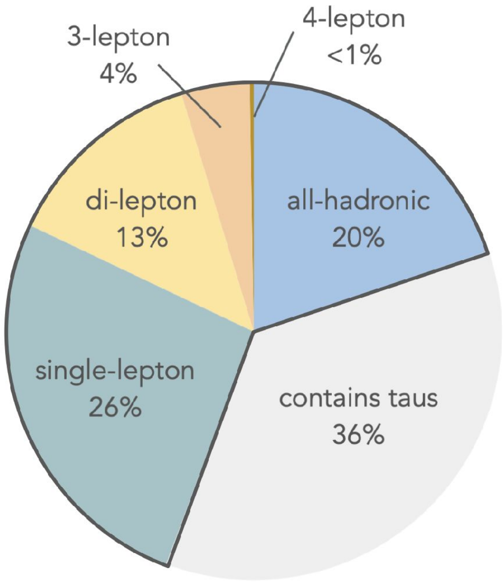
Introduction





- Rare Standard Model process with ~12 fb (NLO QCD + EW: JHEP 02 (2018) 031)
- Important test of SM at large mass scales
- Enhancement of cross section predicted by some beyond-the-Standard-Model (BSM) physics
- Results from the combination of single-, di-lepton, and all-hadronic decay channels

Event Selection & Triggers

	Single Lepton	Opposite Sign Dilepton*	All Hadronic
Triggers & Leptons	single-lepton triggers, one isolated (or loosely isolated with large H_T) (e or μ)	di-lepton triggers, two oppositely charged muons and/or electrons (ee, $\mu\mu$, or $e\mu$)	OR of 6-jet / b-tag / H_T cross triggers. Veto on leptons (e & μ)
HT	H_T > 500 GeV	H_T > 500 GeV	H_T > 700 GeV
# AK4 jets	6+, p_T > 30 GeV	4+, p_T > 30 GeV	9+, p_T > 35 GeV
#b-tagged jets	2+	2+	3+
Other	p_T^{miss} > 60 GeV	Additional invariant mass cuts in ee and $\mu\mu$ channels	1+ tagged resolved tops

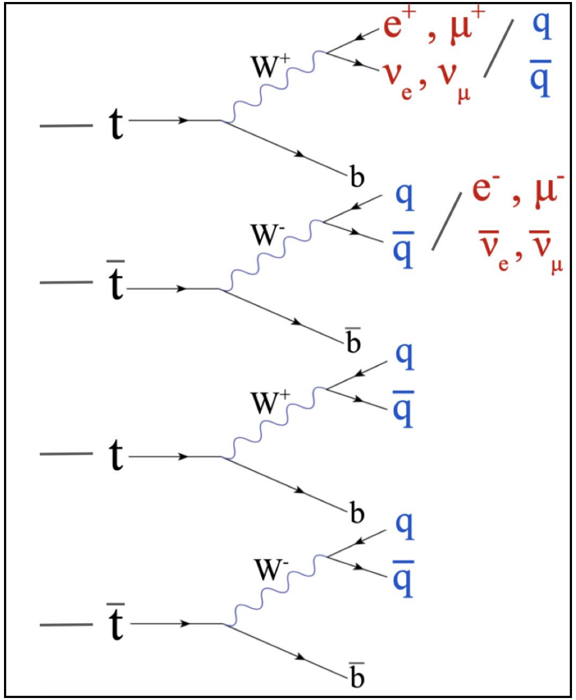
*OSDL 2017 and 2018 combined with published 2016 results

Analysis Strategies

	Single Lepton	Opposite Sign Dilepton	All Hadronic
Baseline selection	1 lepton, H_T > 500 GeV 6+ jets, 2+ b-jets, p_T^{miss} > 60 GeV	2 opposite sign leptons H_T > 500 GeV, 4+ jets, 2+ b-jets, invariant mass selections (ee, $\mu\mu$)	0 leptons, H_T > 700 GeV, 9+ jets, 3+b-tags, 1+ resolved tops
Major backgrounds	tt	tt	tt and QCD
Background estimation	simulation	simulation	tt and QCD estimated from data, others from simulation
Signal region categorization	e or μ channel, jet/b-tag multiplicity, resolved t multiplicity	ee, $\mu\mu$, or $e\mu$ channel, jet/b-tag multiplicity	resolved/boosted t multiplicity & H_T
Discriminating variable	BDT	HT	BDT

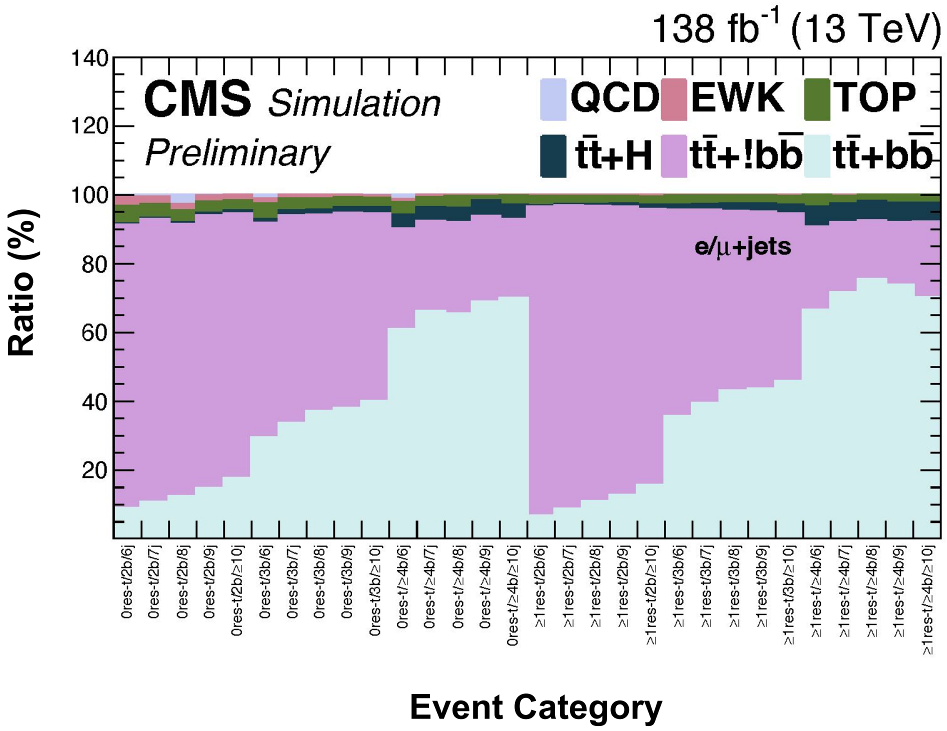
Single Lepton Channel - Event categorization

- Events categorized by lepton flavor, AK4 jet multiplicity, b-tagged jet multiplicity, and resolved t-tagged jet multiplicity
    - single-e or single-μ
    - AK4 jets: 6/7/8/9/10+
    - b-jets: 2/3/4+ (2 b-tag categories are used as a control region)
    - Resolved t-candidates: 0/1+
- Signal regions are characterized by high jet/b-jet/t-tag multiplicity.



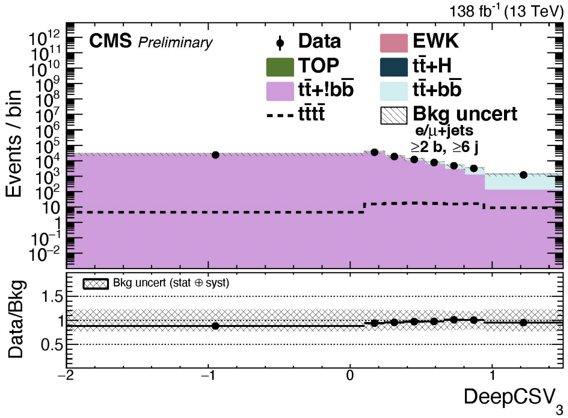
Backgrounds

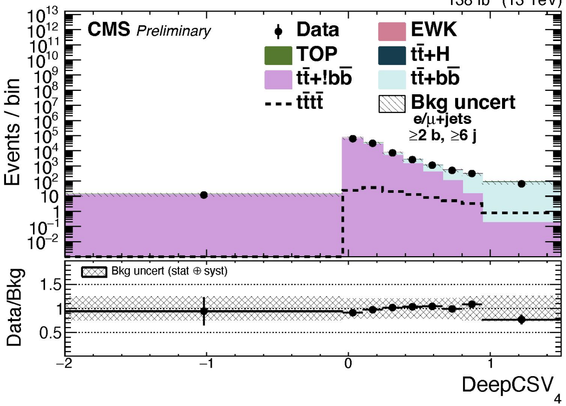
- Background > 90% tt in all regions
- Background-like regions dominated by tt+!bb, while signal-like regions dominated by tt+bb
- tt+bb normalization is corrected using a factor of 1.2 from CMS measurements ([JHEP 07 (2020) 125](#))

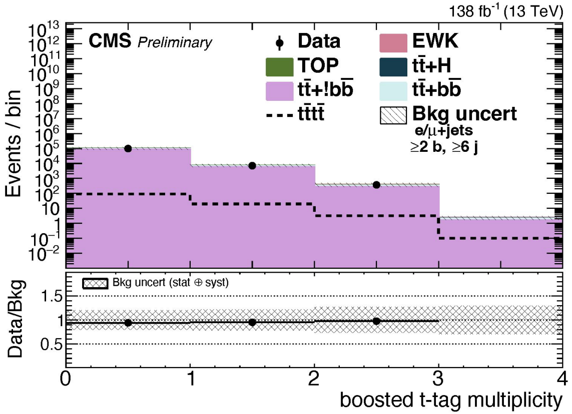


BDT Analysis

- BDT trained with tttt as signal and tt as background in ≥6j/≥2b inclusive region
- Prefit modeling validated using 2+ b-jet inclusive region



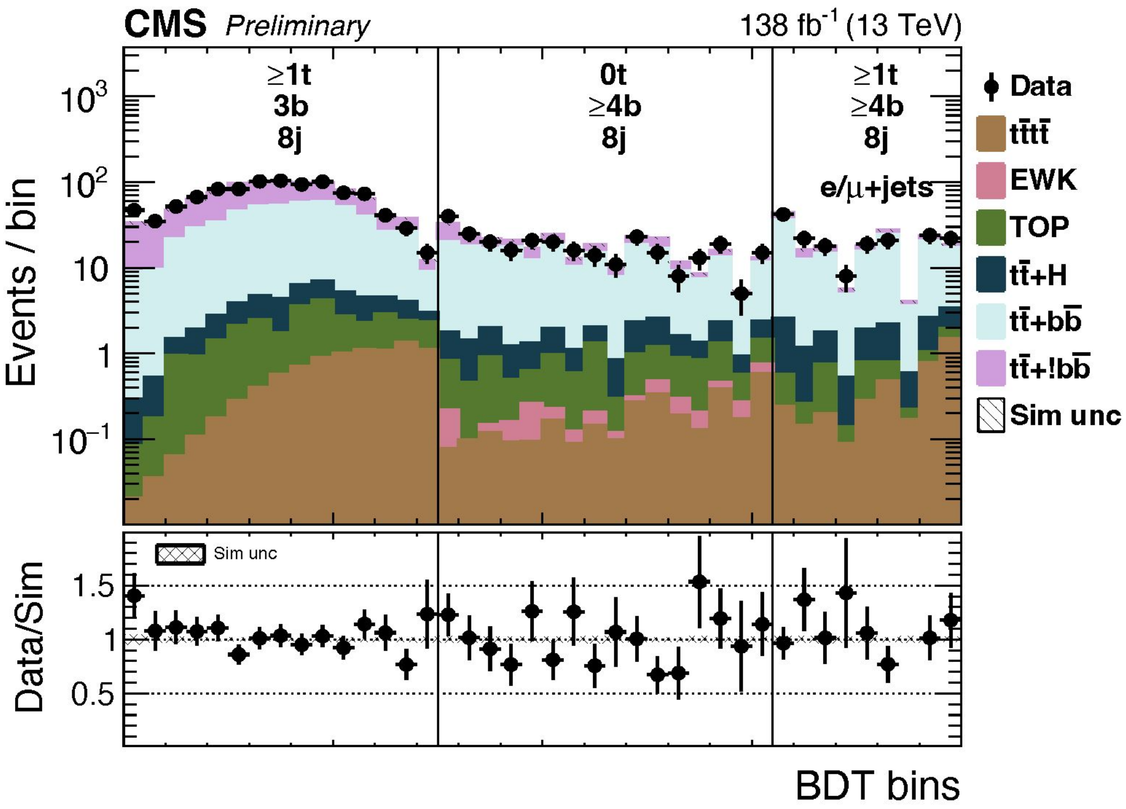




Data/MC agreement within uncertainties (statistical + systematic)

Postfit Results

- BDT template fit
- Results shown in BDT bins for 3 different top / b-tag categories
- Combined single-e and single-μ channels for 8+ jets

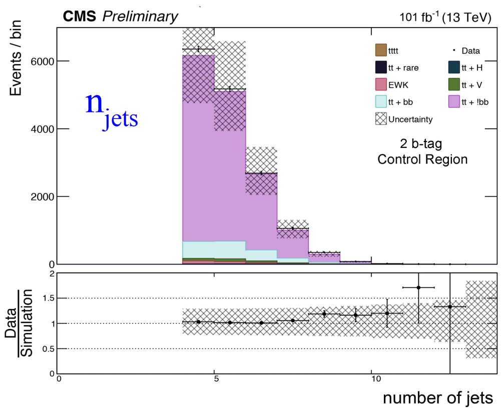


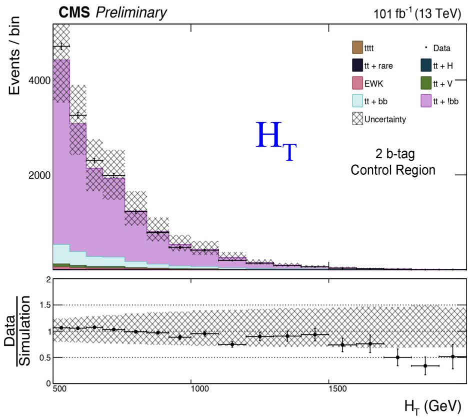
Opposite Sign Dilepton Channel Data Categorization and Fit

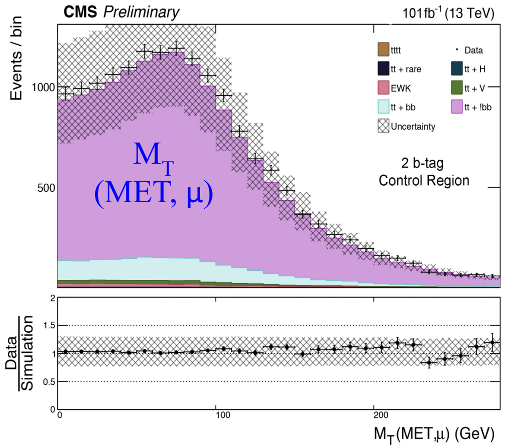
- Events categorized by:
  - Year (2017, 2018)
  - Lepton channel *(ee, $\mu\mu$, $e\mu$)*
  - Jet multiplicity (4, 5, 6, 7, 8+)
  - b tag multiplicity (2, 3, 4+)
- **The largest backgrounds in the signal-rich categories are** tt+bb, tt+!bb, tt+H
- Background modeling validated using 2 b-tag, 4+ jets control region
- H_T is used as the discriminating variable
- A binned maximum likelihood fit is performed simultaneously in all categories

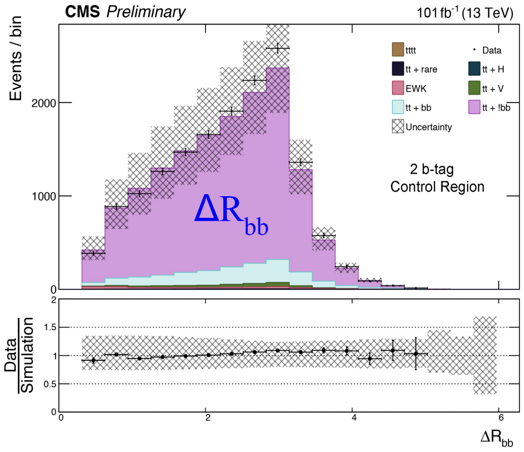
Prefit Distributions

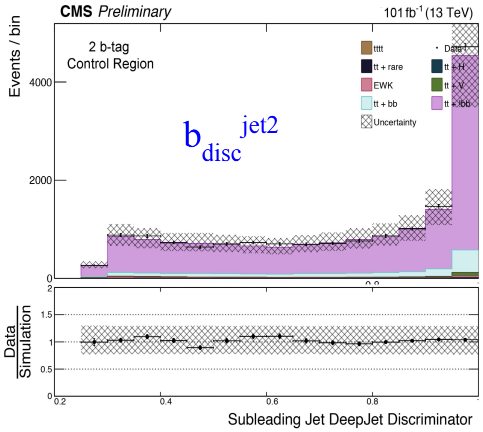
2 btags and 4+ jets
Control Region









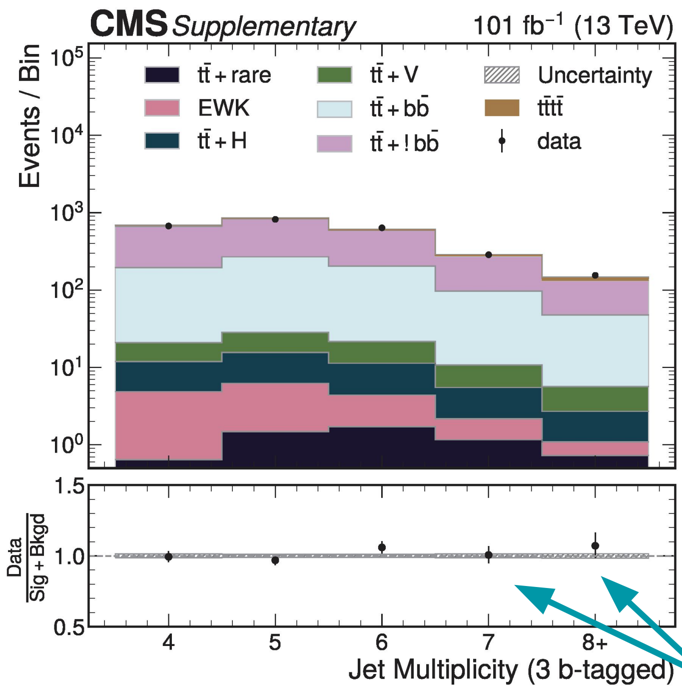


Good modeling of all kinematic and ID variables

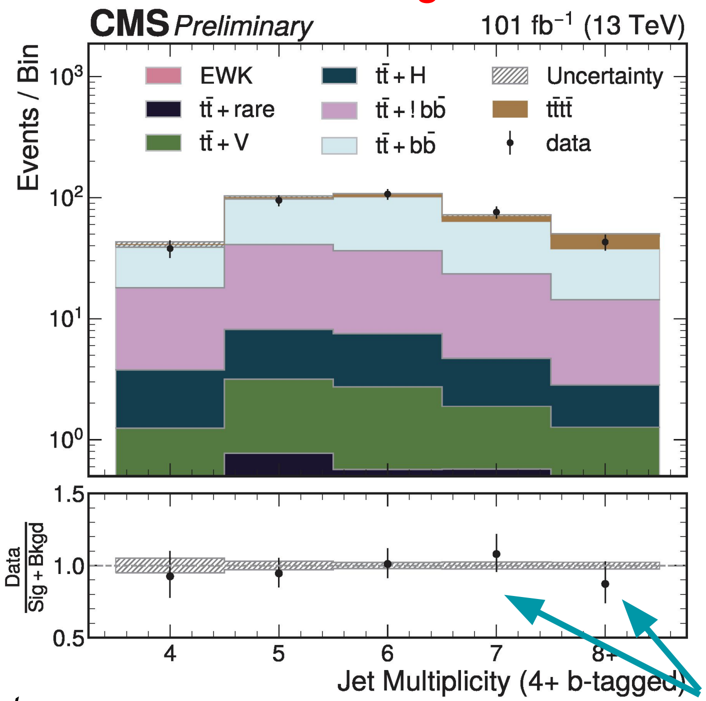
Postfit Results

2017+18 Data
All Channels Combined

3 b-tags



4+ b-tags



3rd/4th most signal-sensitive categories

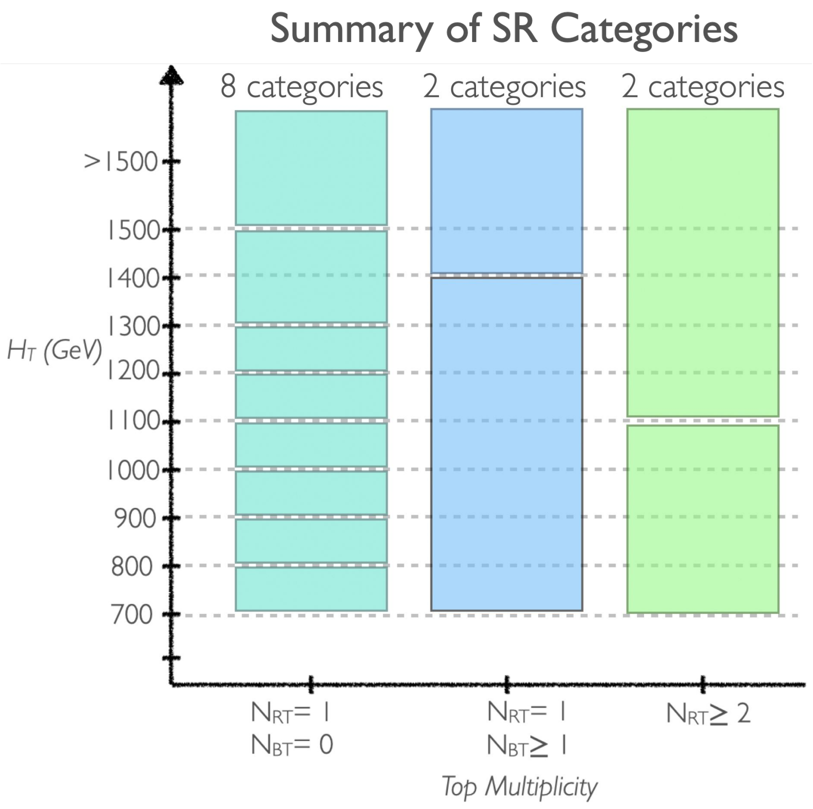
two most signal-sensitive categories

All Hadronic Channel
Signal Region

Baseline Selection:

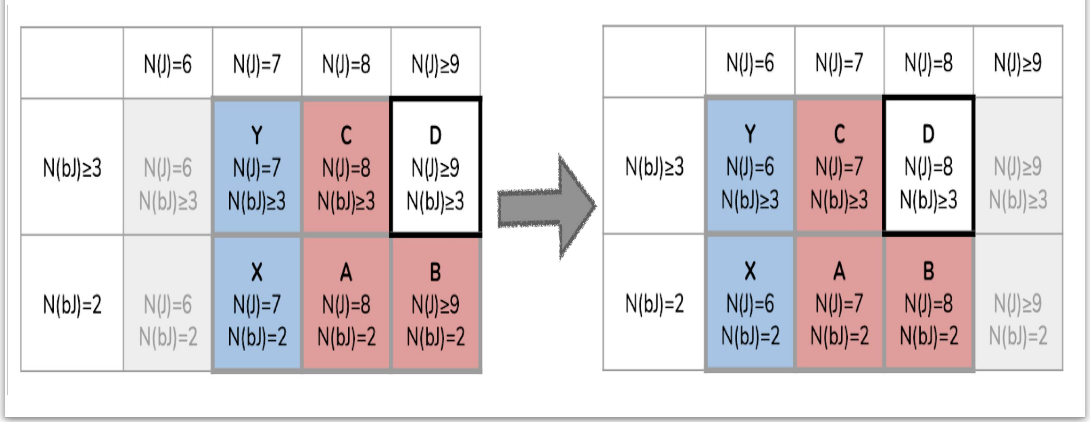
N(leptons)=0, N(jets)≥9, N(bjets)≥3, HT≥700 GeV

- Signal region (SR) = baseline + 1 or more resolved tops
- SR bins split by HT and resolved+boosted top multiplicity
  - Splitting by top multiplicity found to be highly discriminatory
  - Optimized to achieve most sensitivity while maintaining sufficient signal statistics per bin



All-hadronic Channel

Data-driven method to predict most significant backgrounds (QCD+tt)


SR and corresponding CR

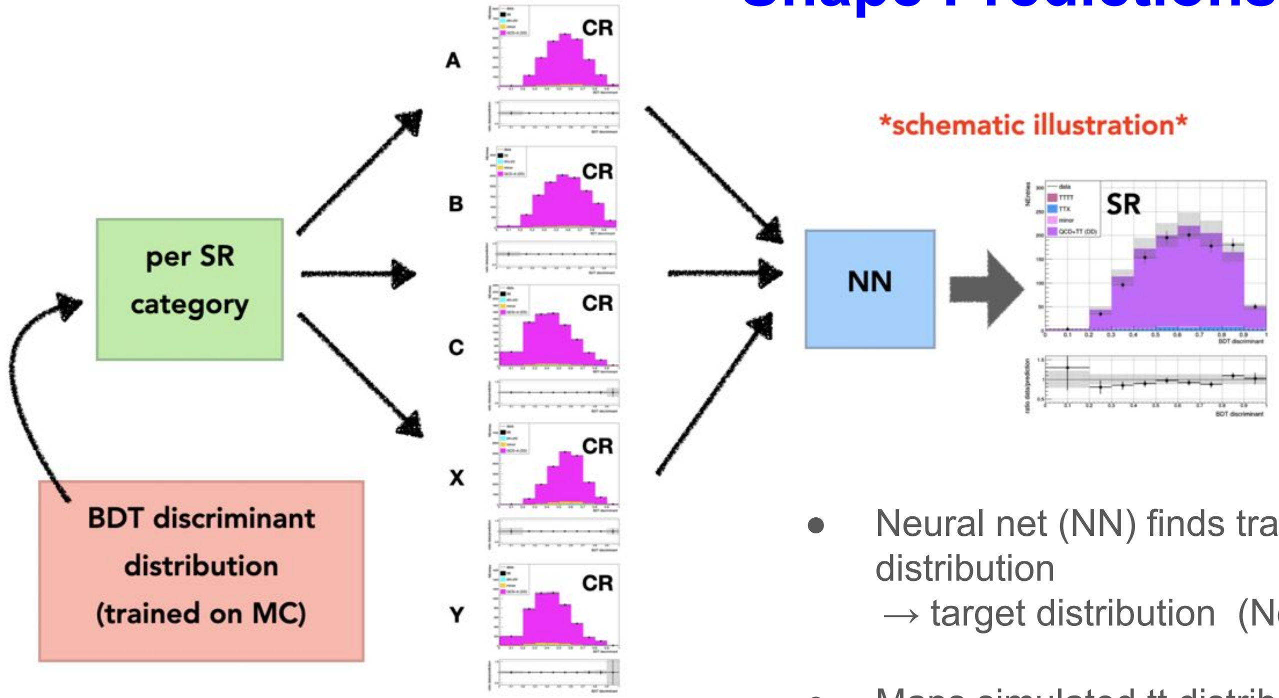
	N(J)=6	N(J)=7	N(J)=8	N(J)≥9
N(bJ)≥3	N(J)=6 N(bJ)≥3	Y N(J)=7 N(bJ)≥3	C N(J)=8 N(bJ)≥3	D N(J)≥9 N(bJ)≥3
N(bJ)=2	N(J)=6 N(bJ)=2	X N(J)=7 N(bJ)=2	A N(J)=8 N(bJ)=2	B N(J)≥9 N(bJ)=2

VR and corresponding CR

	N(J)=6	N(J)=7	N(J)=8	N(J)≥9
N(bJ)≥3	Y N(J)=6 N(bJ)≥3	C N(J)=7 N(bJ)≥3	D N(J)=8 N(bJ)≥3	N(J)≥9 N(bJ)≥3
N(bJ)=2	X N(J)=6 N(bJ)=2	A N(J)=7 N(bJ)=2	B N(J)=8 N(bJ)=2	N(J)≥9 N(bJ)=2

- Define orthogonal CR (signal insensitive) and SR regions
- Correct data yields in CR by subtracting off simulated non-QCD and tt background
- Model the QCD + tt background in CR using an extended ABCD treatment (normalization) + NN (shape)
- Validate combined model in region closest to SR (8 jets instead of 9 jets for SR). Compare to data - simulated non-QCD and tt background
- Perform a BDT analysis using the data-driven model + other simulated backgrounds

Shape Predictions for BDT and H_T



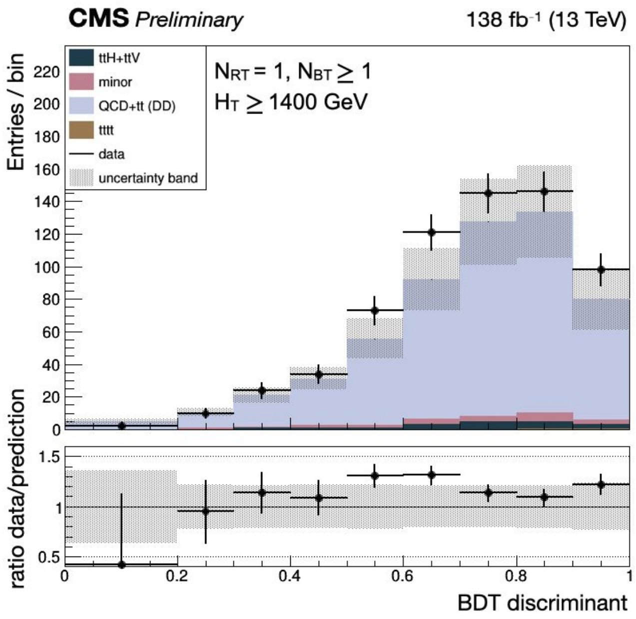
- Neural net (NN) finds transformation from input distribution → target distribution (Neural autoregressive flow)

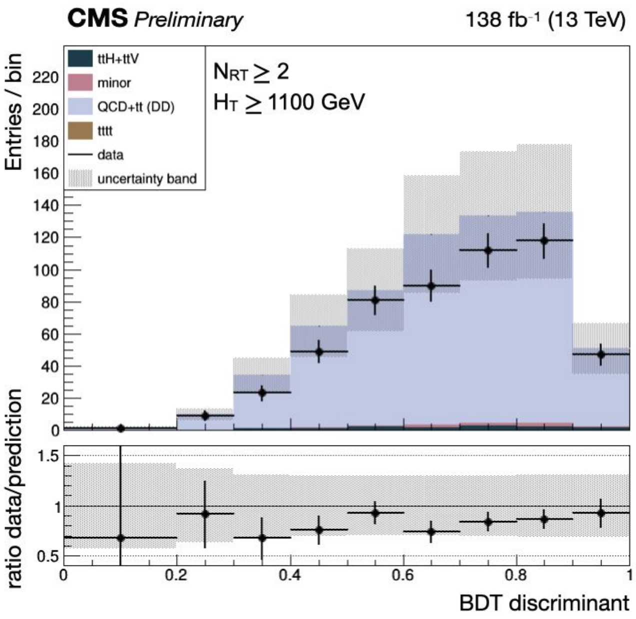
- Maps simulated tt distributions onto tt + QCD distributions in 5 CR distributions for BDT & H_T simultaneously

*Huang, Krueger, Lacoste, Courville. *Neural Autoregressive Flows.* arXiv:1804.00779
*S. Choi. arXiv:2008.0363

Modeling in the Validation Region

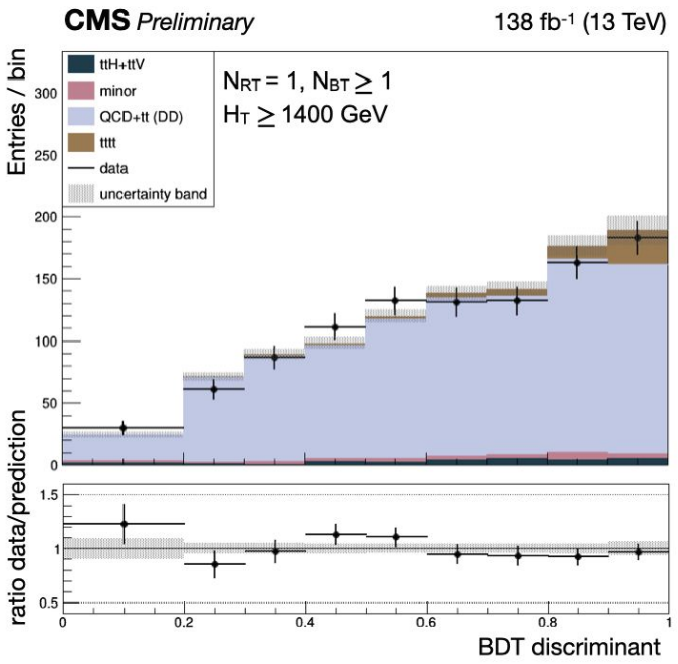
Prefit
BDT Discriminant
shape predictions
for
most sensitive
categories
2016-2018
combined

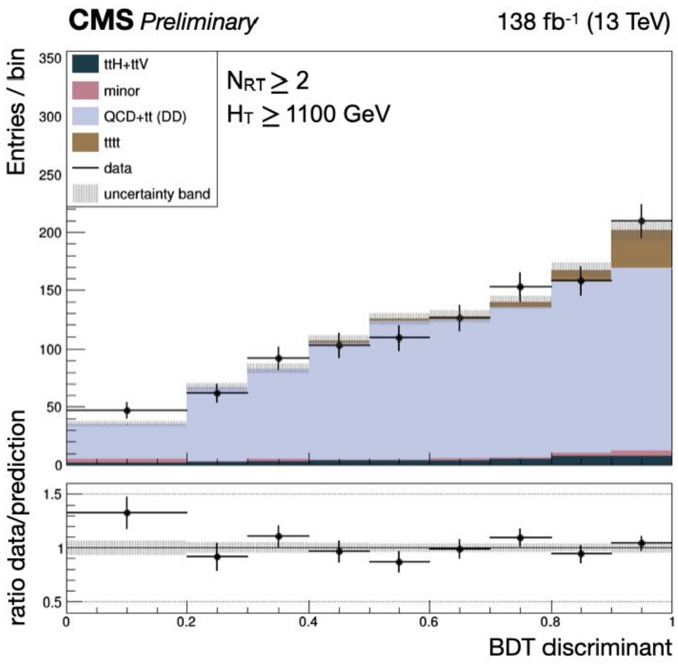




Results in the Signal Region

Postfit
BDT Discriminant
distributions in
most sensitive
categories
for 2016-2018
combined



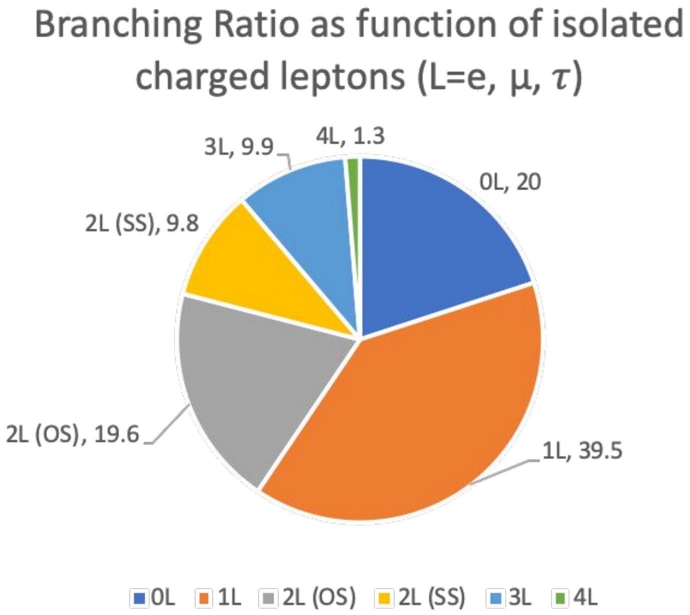


Final States Entering the Combined Result

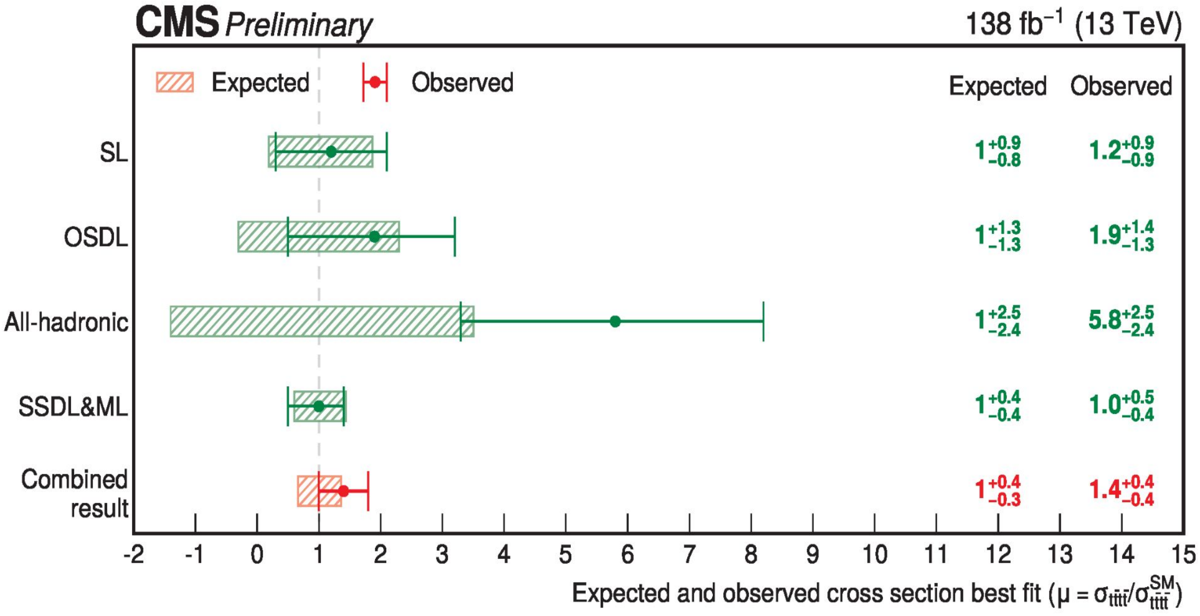
- 2016 Opposite-sign dilepton search
  JHEP 11 (2019) 082
- 2016-18 Same-sign dilepton and multi-lepton search
  EPJC 80 (2020) 75
- This analysis: 2016-18 Single-lepton search
- This analysis: 2017-18 Opposite-sign dilepton search
- This analysis: 2016-18 All-hadronic search

Analysis of full CMS Run 2 dataset in all channels excluding the tau decays

tt+X, Renorm./Fact. scale, ISR/FSR are the dominant uncertainties (detailed breakdown in backup)



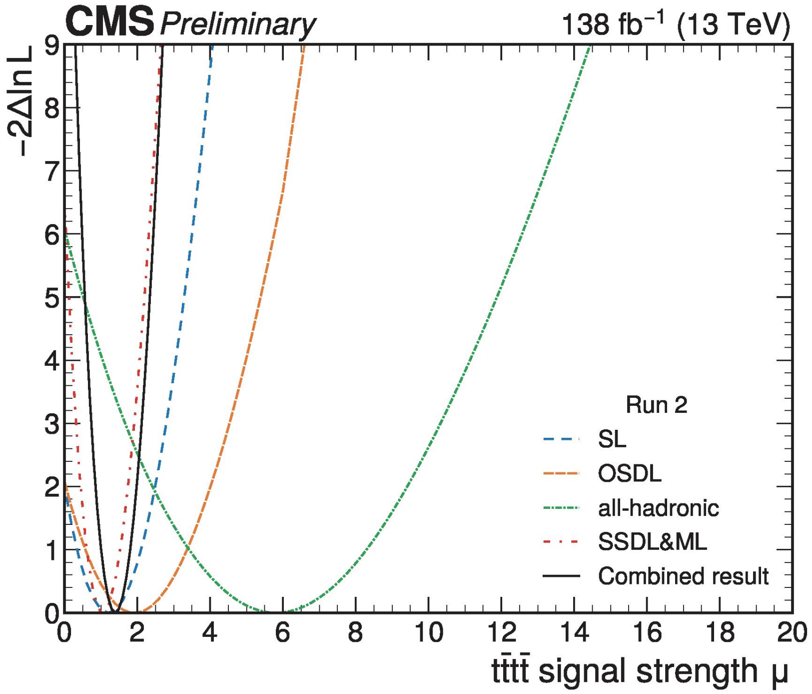
Signal Strength



Observed Signal strength
1.4 ± 0.4 x SM

higher than current SM predictions but also consistent with them

Signal Strength



Run 2

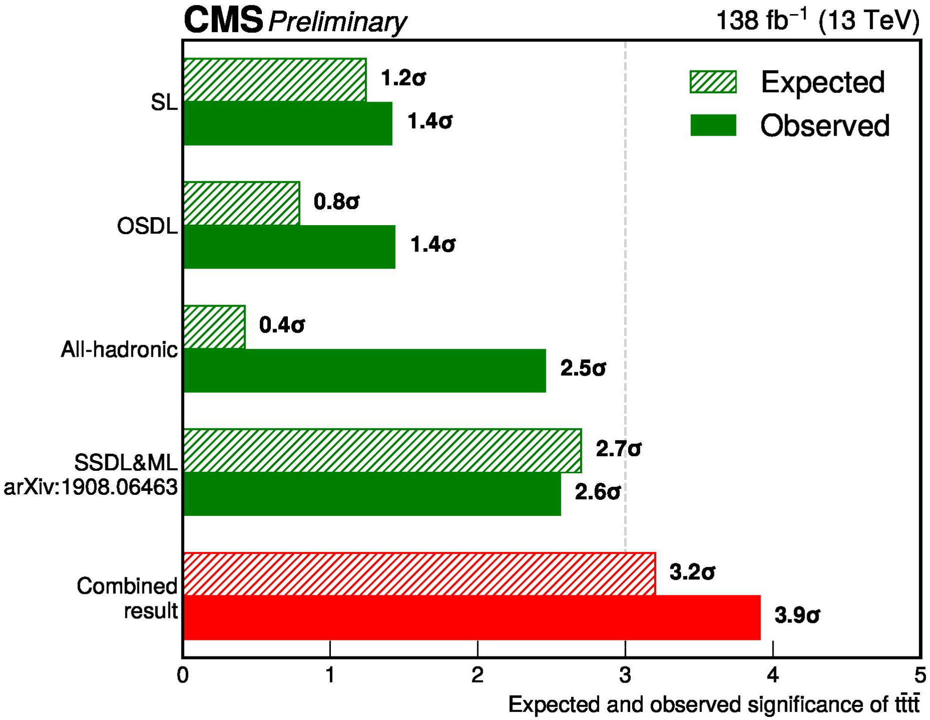
tttt signal strength scans

for each channel separately

and for

the combined results

Significance



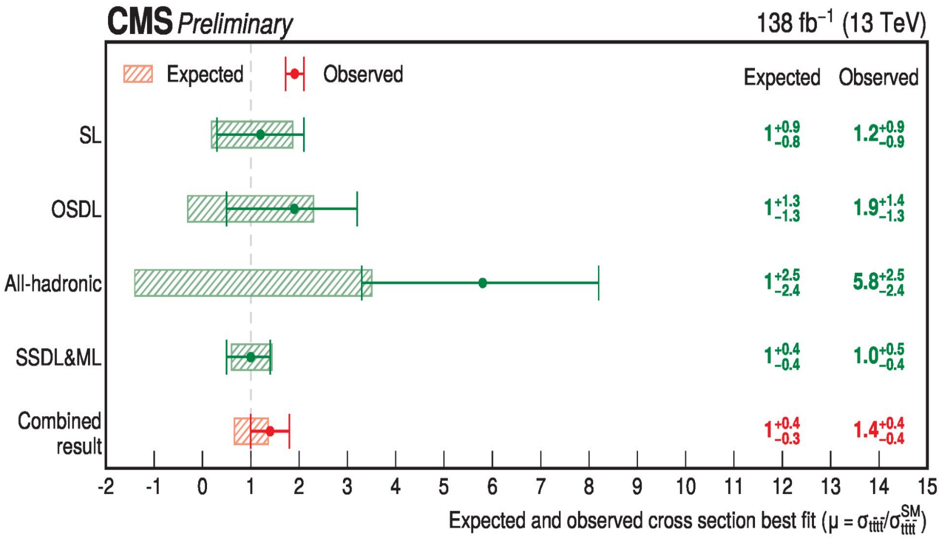
Analysis	Expected significance	Observed significance
Run 2 Single-lepton	1.2	1.4
Run 2 Opposite ** sign dilepton	0.8	1.4
Run 2 All-hadronic	0.4	2.5
Run 2 Same sign dilepton & multilepton*	2.7	2.6
Combined	**3.2**	**3.9**

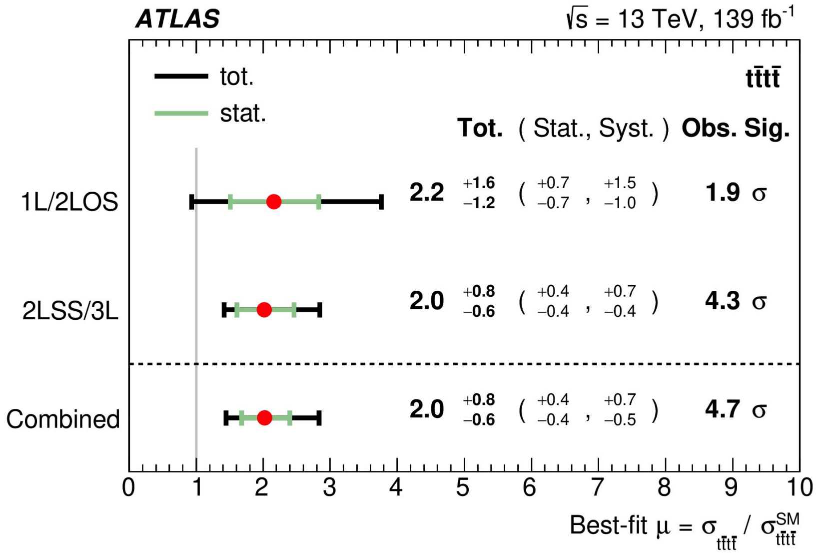
** includes published 2016 result
* published SSDL/ML result

CMS and ATLAS Results

CMS-PAS-TOP-21-005

ATLAS JHEP 11 (2021) 118





expected significance: 3.2 σ
observed significance: 3.9 σ

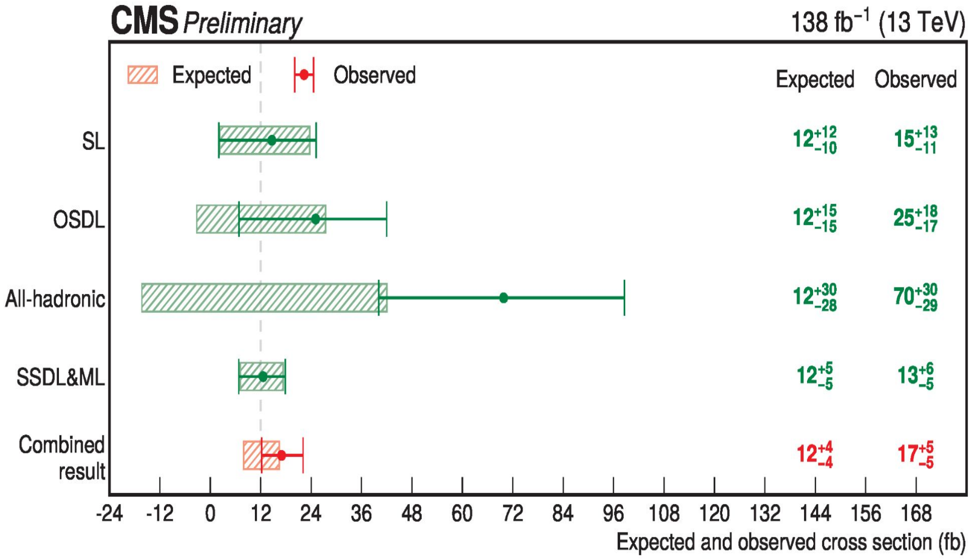
expected significance: 2.6 σ
observed significance: 4.7 σ

Summary

- First tttt analysis to include all-hadronic channel
- Expected significance: 3.2 σ
- Observed significance: 3.9 σ
- Observed cross section higher than current SM predictions but also consistent with them

Observed cross section:

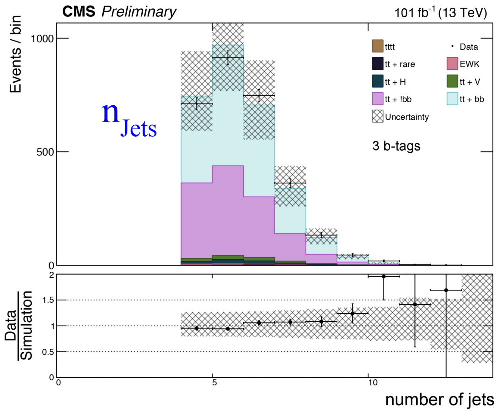
17 ± 5 fb



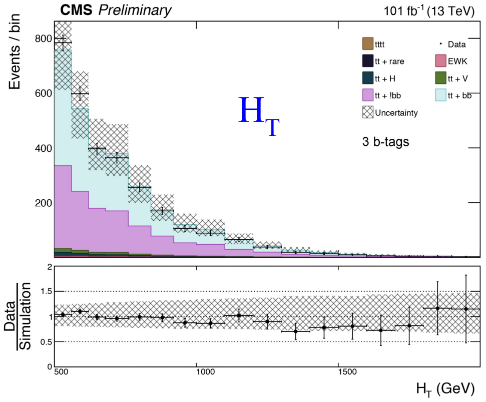
Similar behavior to that seen by ATLAS

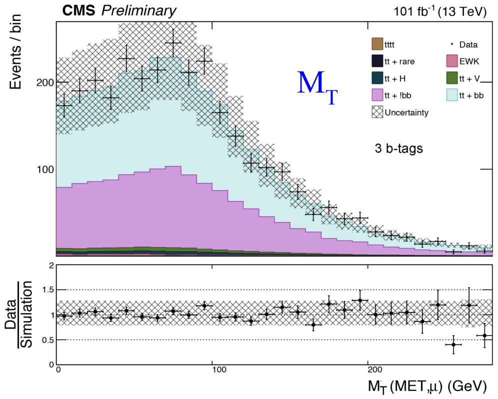
Backup Material

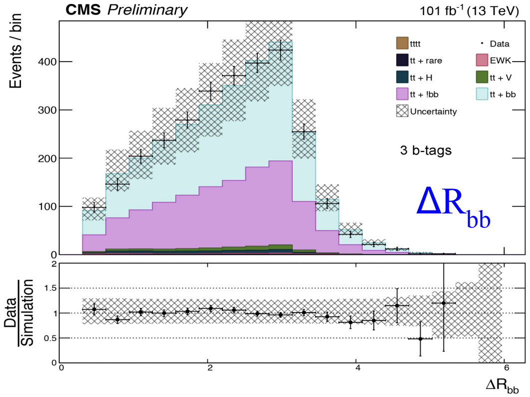
Prefit Distributions

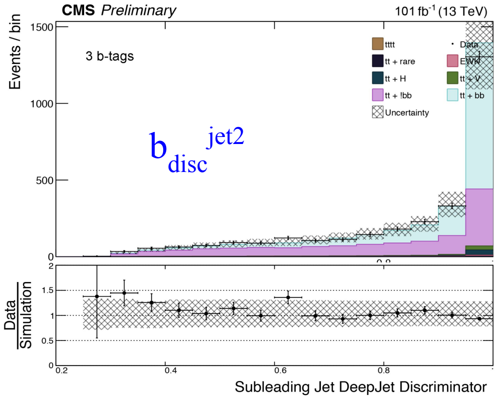


3+ btags and 4+ jets





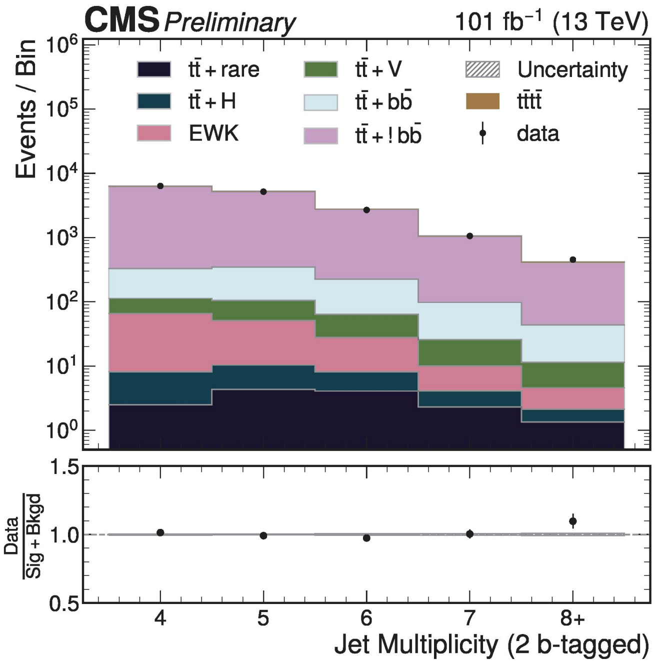




good agreement for both years in all three channels

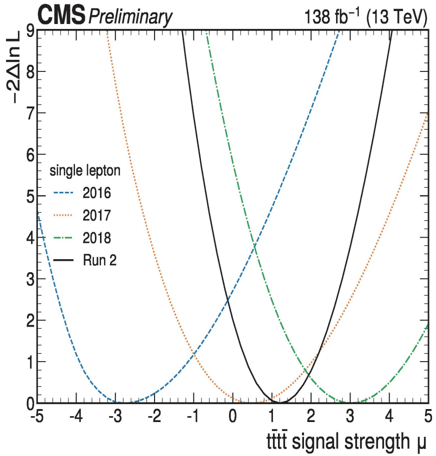
Postfit Results

OSDL 2017+18
All Channels Combined

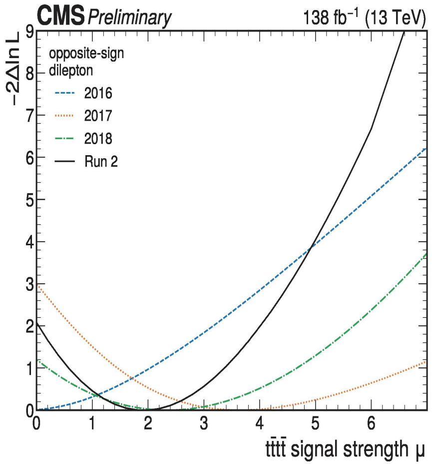


2 b-tag Control Region

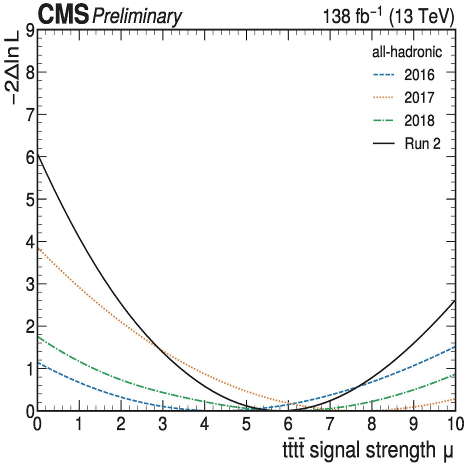
Signal Strength - by Year and by Channel



Single Lepton Channel



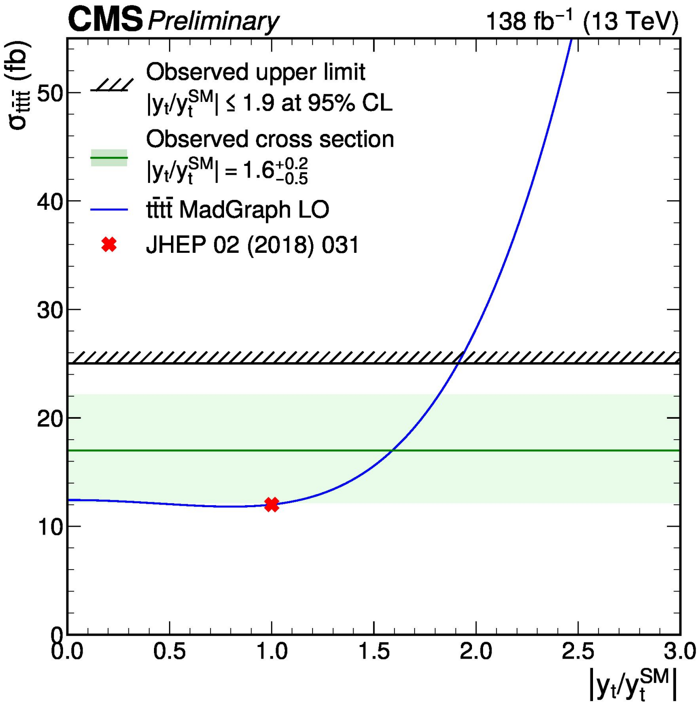
Opposite Sign Dilepton Channel



All Hadronic Channel

tttt signal strength scans for each channel - separated by year and combined

Top Yukawa Coupling from tttt cross section



Cross section measurement

95 % CL upper limit on top Yukawa coupling value is 1.9