Four-top-quark production in final states with hadronically decaying tau leptons and search for vector-like leptons at $\sqrt{s}$ = 13 TeV

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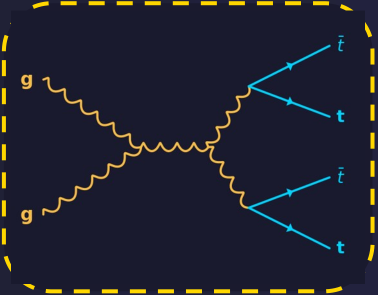
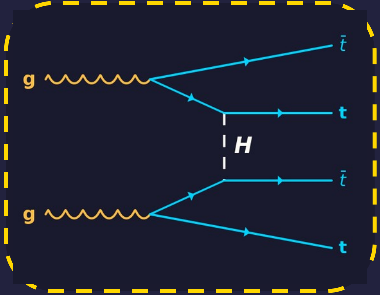
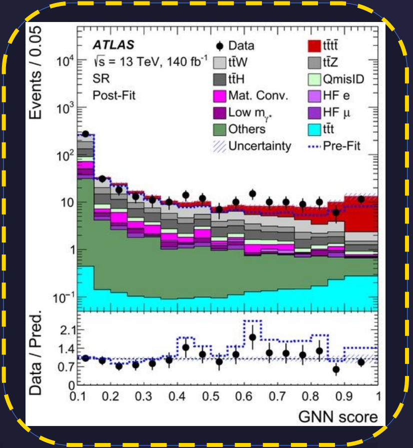
on behalf of the CMS Collaboration

After the discovery of tttt in 2023: tension persists



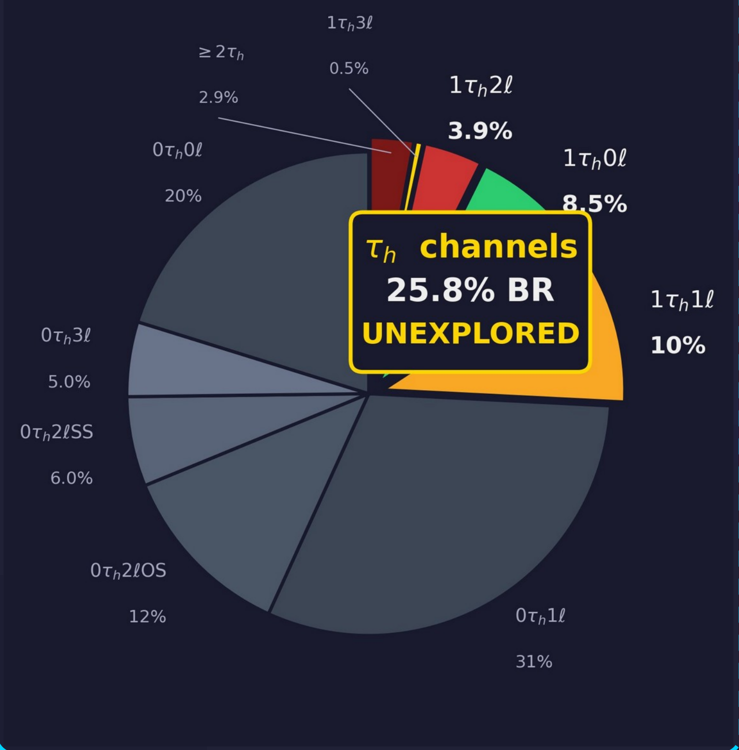


- tttt: the most energetic process ever discovered at LHC
- Stress test QCD in high energy regions
- Sensitive to top Yukawa coupling
- Many BSM theories predict enhanced cross section



- ATLAS: σ = $22.5^{+6.6}_{-5.5}$ fb | CMS: σ = $17.7^{+3.7}_{-3.5}$ fb in SS/ML final state
- ATLAS is 1.7σ above theory σ = $13.4^{+1.0}_{-1.8}$ fb (NLO+NLL´, absolute-mass resummation)
- CMS and ATLAS also search tttt in SL+2OS and hadronic (CMS only): observed significance > expected too
- Latest theory: σ(tttt) @ 13 TeV = **$10.4^{+1.8}_{-1.6}$ fb** (NLO+NLL´, invariant-mass resummation)

τ_h final state of tttt: last territory charted



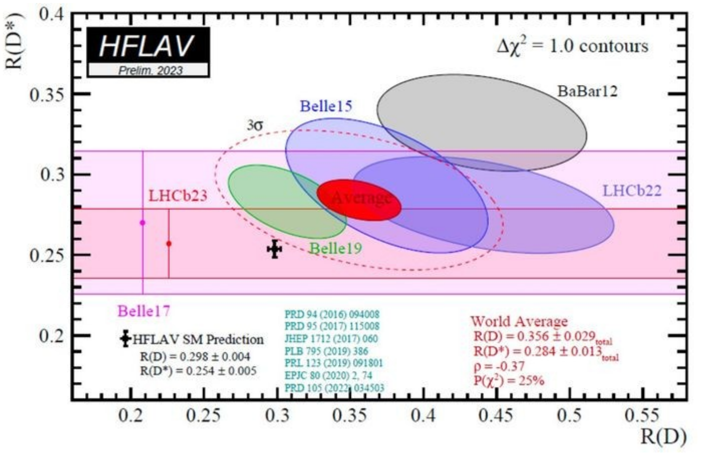
Why τ_h final state?

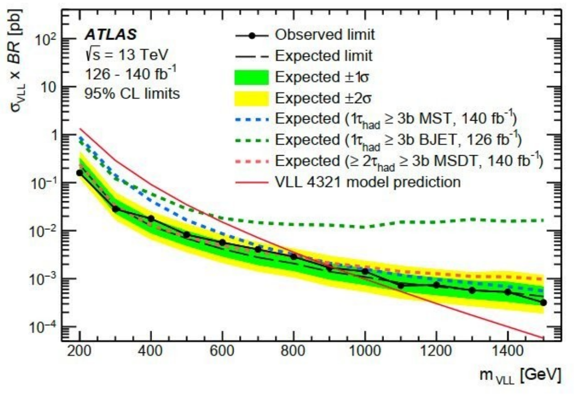
- Last unexplored final state: cross-checks the upward trend from data in other final states of tttt
- τ_h final state: substantial branching ratio of 26% → contributes to precision measurement of tttt
- τ_h-rich final state → probes BSM with enhanced 3rd-generation couplings (e.g. vector-like leptons, 4321 model)

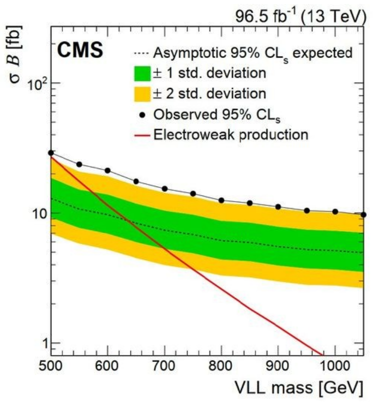
Three channels of τ_h final states explored

- Divided into $1\tau_h0\ell$, $1\tau_h1\ell$, $1\tau_h2\ell$ — different background compositions
- $1\tau_h0\ell$, $1\tau_h1\ell$, $1\tau_h2\ell$ constitute ~87% of the total τ_h final state
- $1\tau_h3\ell$ and $\geq 2\tau_h$ channels dropped — low branching ratio

Vector-like leptons and the 4321 model







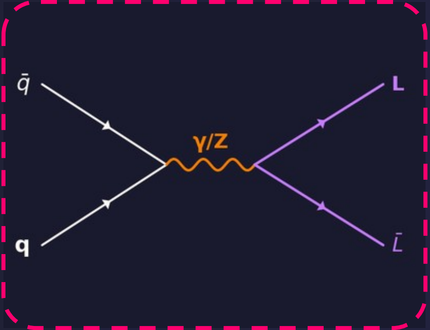
4321 model

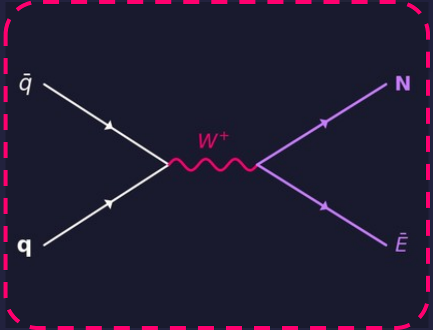
- Extends SM → $SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$
- Motivated by lasting R(D)/R(D*) anomaly
- VLLs: lightest new states, mass < 1 TeV

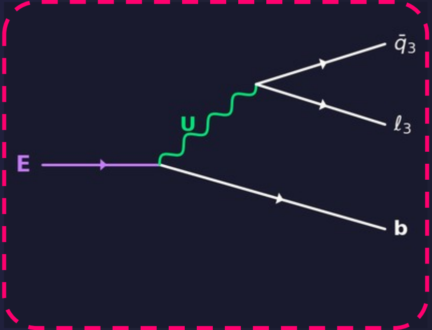
Previous VLL Searches

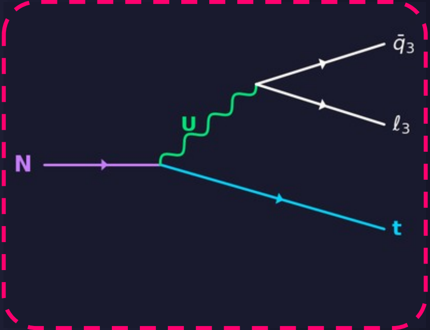
- CMS & ATLAS searched for VLLs in hadronic channels
- CMS: 2.8σ excess at m ~ 600 GeV
- ATLAS: no excess, limit at 910 GeV
- Excess real or not? More verification needed!

VLL pair production and decay topology









$1\tau_h\ 0\ell$

$EE \rightarrow b(t\nu_\tau)b(t\nu_\tau) \rightarrow \tau+4b+2q+3\nu_\tau$

$EN \rightarrow b(t\nu_\tau)t(b\tau) \rightarrow \tau+4b+4q+1\nu_\tau$

$NN \rightarrow t(t\nu_\tau)t(t\nu_\tau) \rightarrow \tau+4b+6q+2\nu_\tau$

8 decay modes in total

$1\tau_h\ 1\ell$

$EE \rightarrow b(t\nu_\tau)b(t\nu_\tau) \rightarrow \tau+1\ell+4b+3\nu_\tau+1\nu_\ell$

$EN \rightarrow b(t\nu_\tau)t(b\tau) \rightarrow \tau+1\ell+4b+2q+1\nu_\tau+1\nu_\ell$

$NN \rightarrow t(t\nu_\tau)t(t\nu_\tau) \rightarrow \tau+1\ell+4b+4q+1\nu_\tau+1\nu_\ell$

7 decay modes in total

$1\tau_h\ 2\ell$

$EN \rightarrow b(t\nu_\tau)t(t\nu_\tau) \rightarrow \tau+2\ell+4b+3\nu_\tau+2\nu_\ell$

$EN \rightarrow b(b\tau)t(t\nu_\tau) \rightarrow \tau+2\ell+4b+1\nu_\tau+2\nu_\ell$

$NN \rightarrow t(t\nu_\tau)t(t\nu_\tau) \rightarrow \tau+2\ell+4b+4q+3\nu_\tau+2\nu_\ell$

5 decay modes in total

Analysis strategy of τ_h final state

BASELINE Hadronic triggers

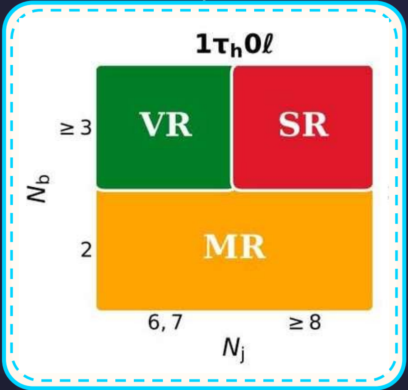
$H_T > 500$ GeV · $N_{jet} \geq 6$ · 6th jet $p_T > 40$ GeV · $N_b \geq 2$

BASELINE Leptonic triggers

$H_T > 200$ GeV · $N_{jet} \geq 4$ · $N_b \geq 2$ · Z veto

$1\tau_h 0\ell$

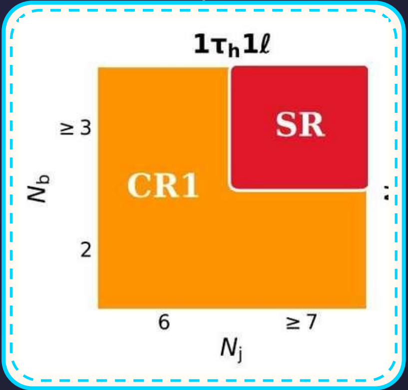
$N_\tau = 1,\ N_\ell = 0$



Major background: tt+jets and QCD

$1\tau_h 1\ell$

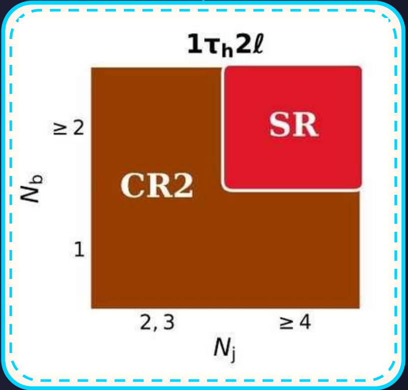
$N_\tau = 1,\ N_\ell = 1$



Major background: tt+jets and ttX (X for W, Z and H)

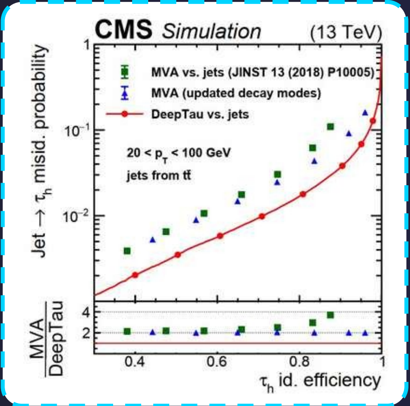
$1\tau_h 2\ell$

$N_\tau = 1,\ N_\ell = 2$



Major background: ttX

Bottleneck to sensitivity: τ_h reconstruction

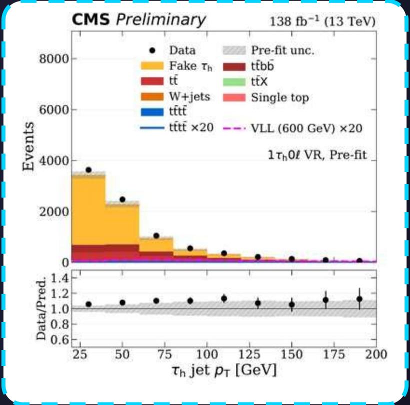


τ_h reconstruction damages sensitivity from both sides

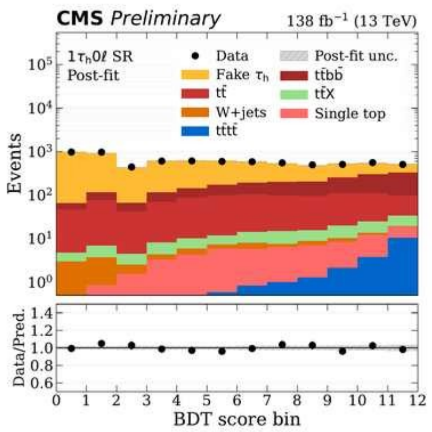
- Low τ_h ID efficiency suppresses signal acceptance: ID efficiency 70% at chosen WP; ~30% of tttt taus have pT below 20 GeV; combined acceptance < 50%
- Background extremely sensitive to mis-ID rate in high-multiplicity jet phase space: P(background passes τ_h ID) = 1 − (1 − f)^N_jet

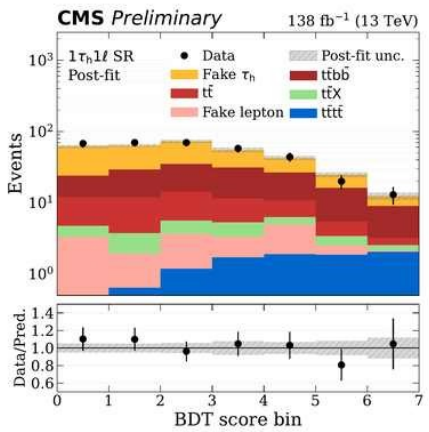
Nonprompt τ_h background from the τ_h mis-identification

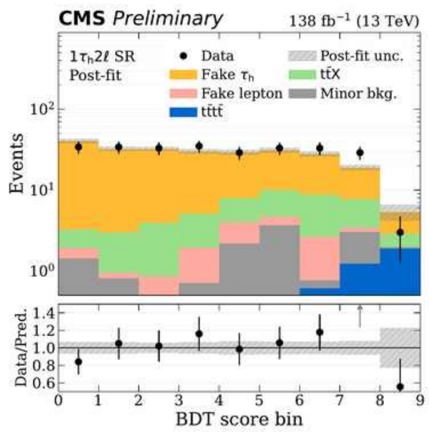
- Loose-to-tight data-driven method used to estimate the nonprompt τ_h background
- Mis-identification rate measured in $1\tau_h0\ell$ MR: close to signal regions and enriched with jets
- Validated nonprompt τ_h in various regions: $1\tau_h0\ell$ VR, $1\tau_h1\ell$ CR1, $1\tau_h2\ell$ CR2



BDT distribution of tttt in 3 τ_h channels

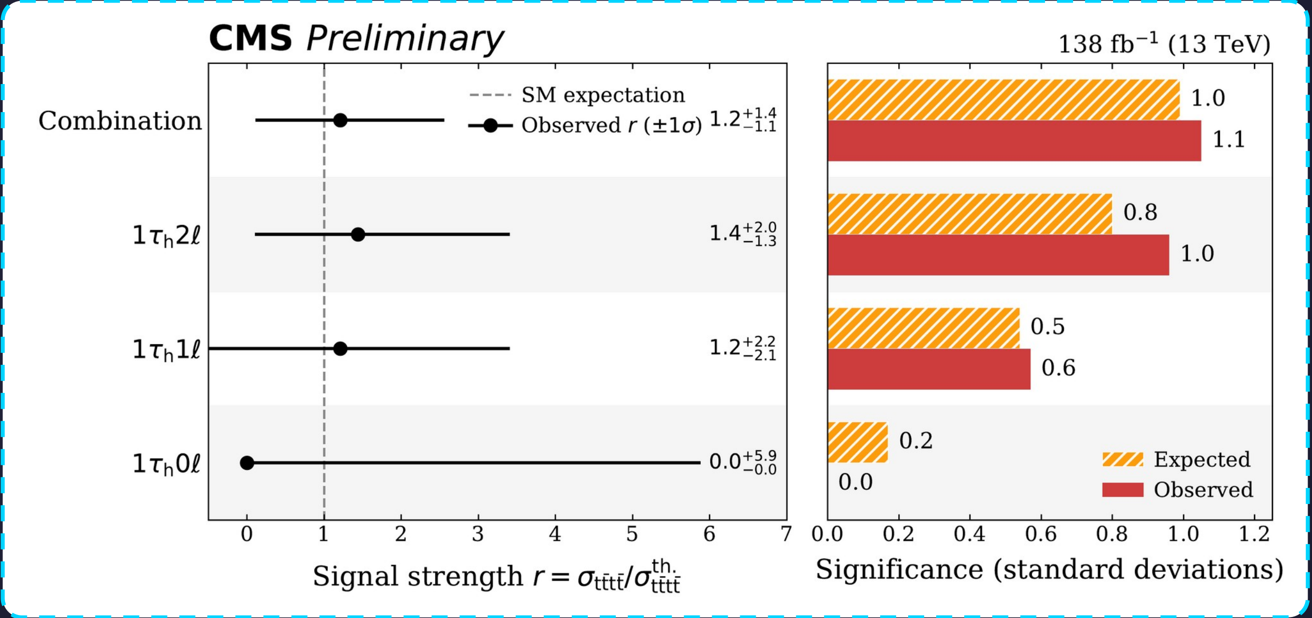






- $1\tau_h 0\ell$ has the highest tttt signal yield, yet lowest sensitivity — overwhelming QCD and tt+jets backgrounds
- $1\tau_h 1\ell$ and $1\tau_h 2\ell$ are the sensitive channels — no QCD because of lepton identification
- tt+jets background modeled by combining the inclusive tt and dedicated tt+bb samples (with overlap removal); the tt+bb component is critical in the high-BDT region of $1\tau_h 0\ell$ and $1\tau_h 1\ell$

Results of tttt in τh final state



σ(tttt)

16^{+18}_{-15} fb

stat: $^{+14}_{-12}$

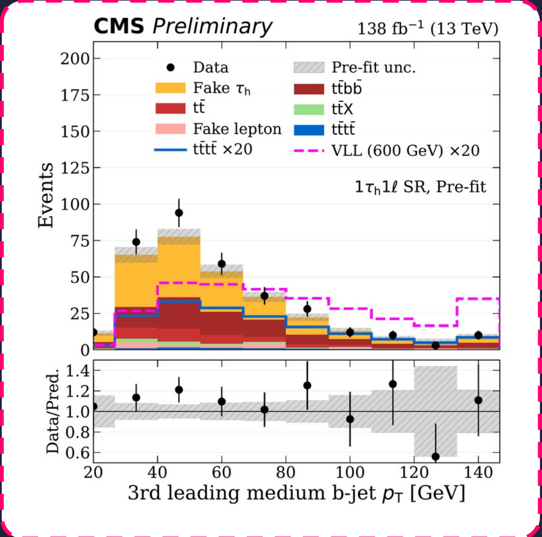
syst: $^{+12}_{-8}$

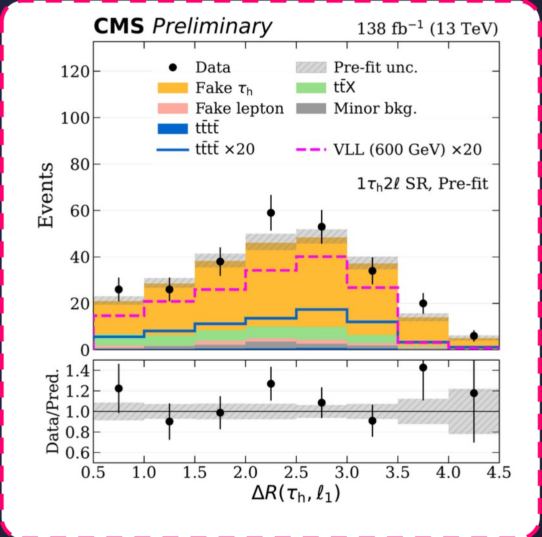
SM: $13.4^{+1.0}_{-1.8}$ fb

Combination: Obs 1.1σ • Exp 1.0σ

Sensitivity similar to SL+2ℓOS final states

VLL analysis strategy and signal regions





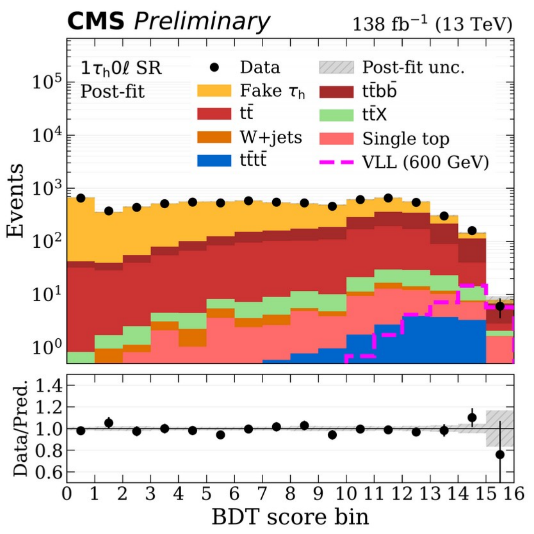
Similar final state as tttt τ_h

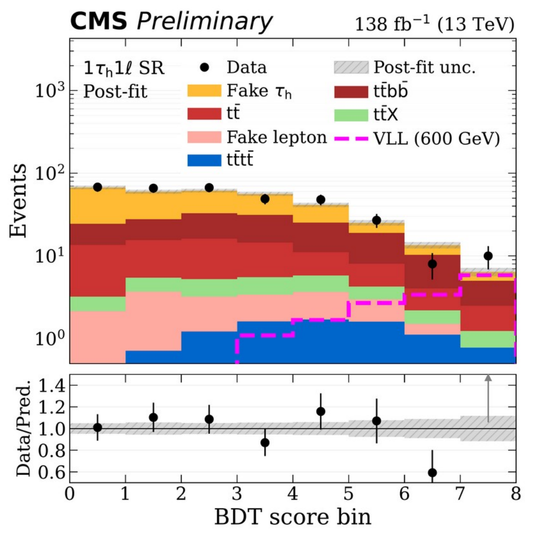
- Exactly 4 b-jets, same as tttt
- Rich in tau multiplicity, 1 τ_h channel best sensitivity
- Same region definition as tttt
- Background estimation same as tttt study

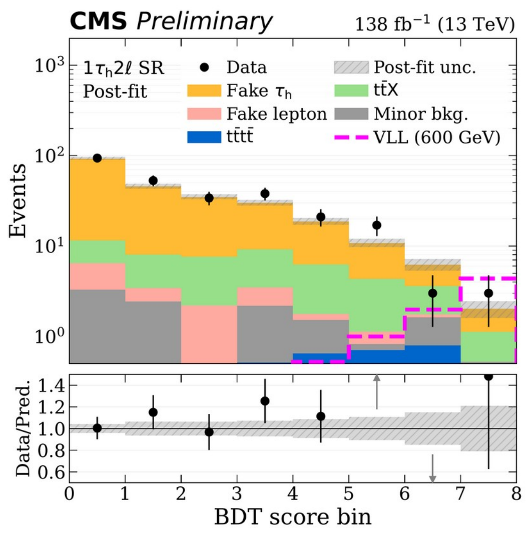
Separate BDT for the search of VLL

- VLL decay is 1→3 while top decay is 1→2, leading to different kinematics in the decay products
- VLL much heavier than the top quark, so its decay products carry harder momentum
- Separate BDT trained per VLL mass point, critical for good performance

BDT distributions for VLL: signal regions

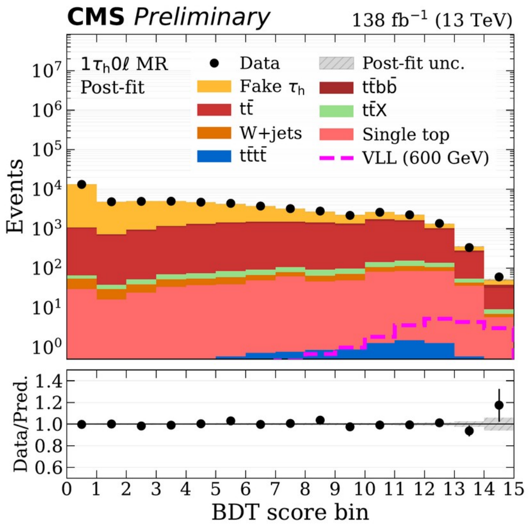


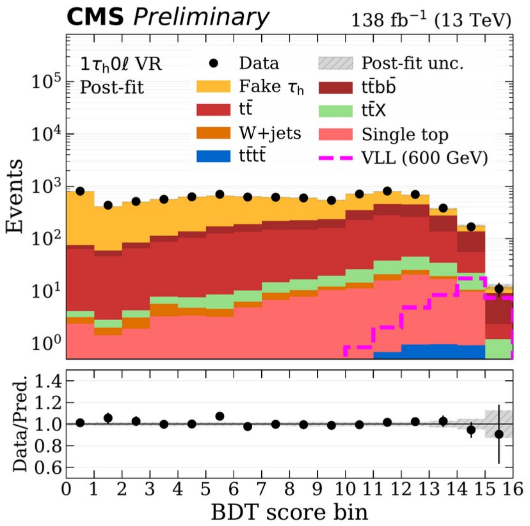


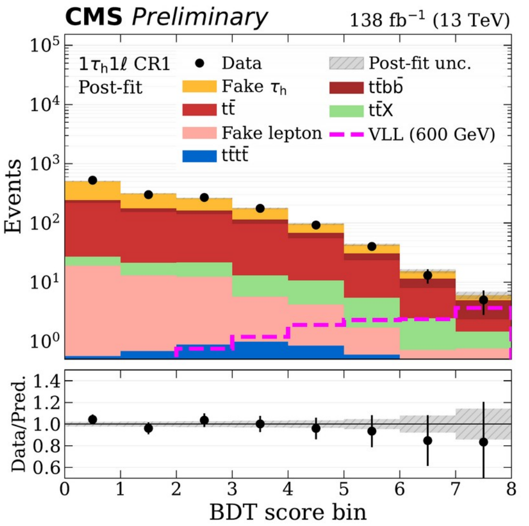


- Data agrees well with background (SM) hypothesis, no obvious excess at any mass point

BDT distributions for VLL: control regions

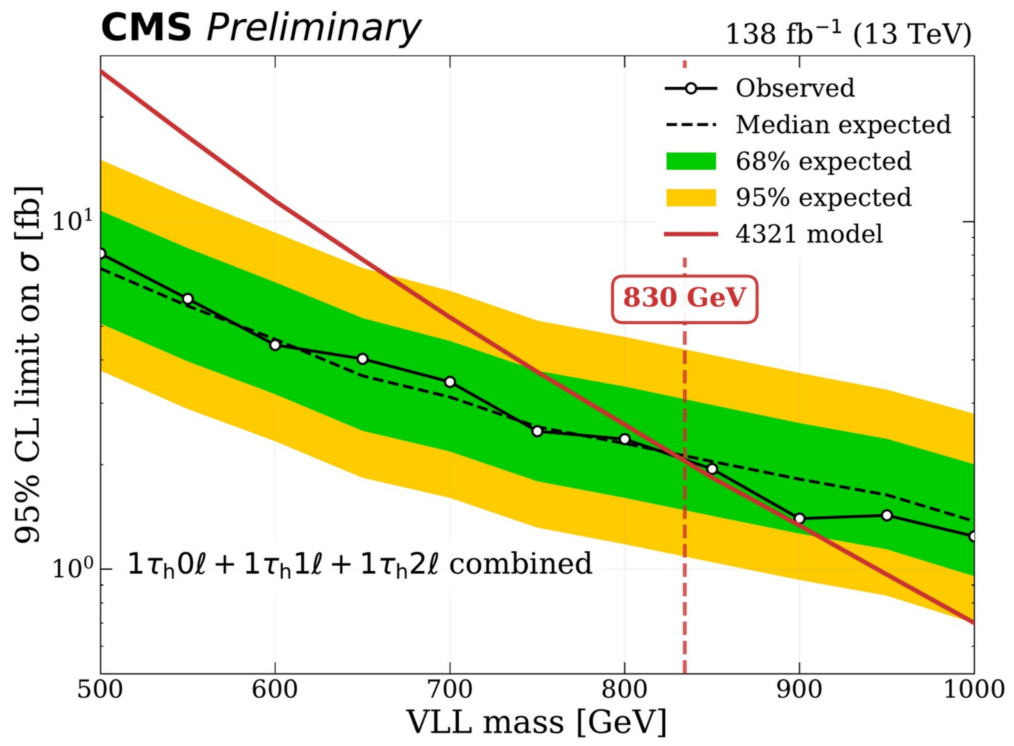






- Control regions also added in the fit to enhance sensitivity, except 1τ_h2ℓ CR2

VLL mass limit in the 4321 model



Mass limit

VLL > 830 GeV

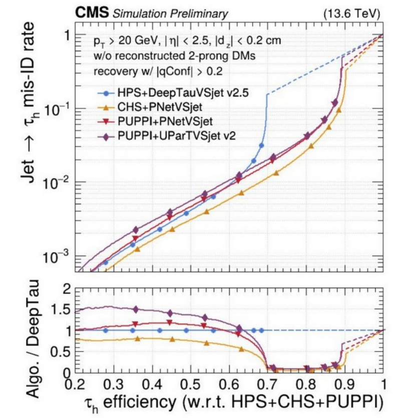
(observed, 95% CL)

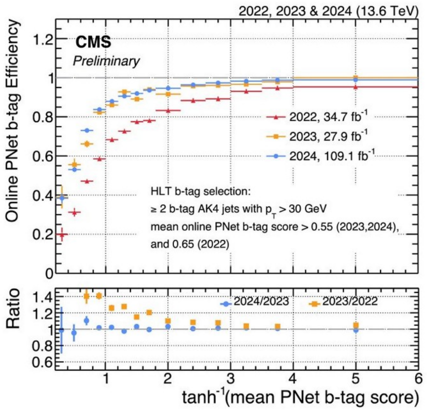
Combined channels:

$1\tau_h 0\ell + 1\tau_h 1\ell + 1\tau_h 2\ell$

Summary and outlook

- First measurement of tttt in τ_h final states: $\sigma(\mathrm{tttt})$ = **16^{+18}_{-15} fb**, observed significance ~1.1σ
- CMS search for VLLs in 4321 model with hadronic τ: no excess, mass > 830 GeV @ 95% CL, first search from lepton channels





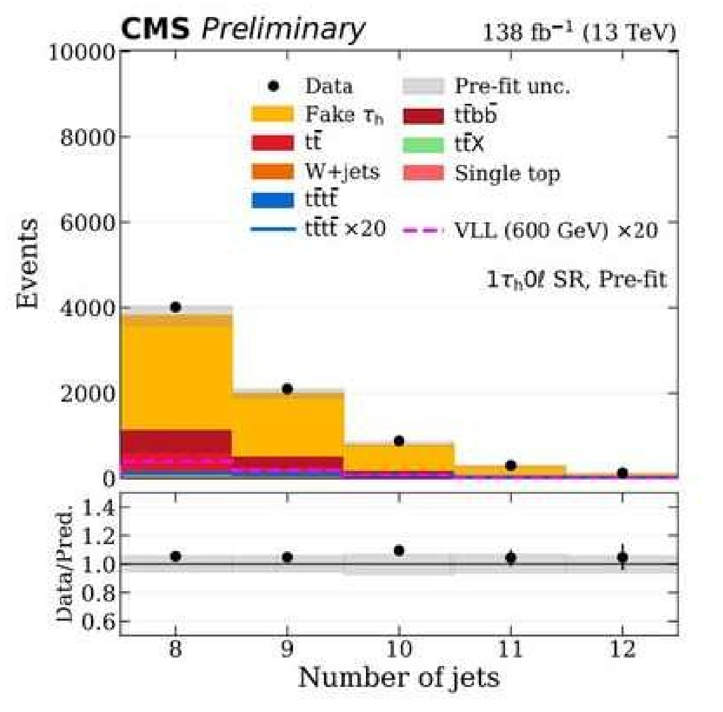
Toward Run 3 and HL-LHC

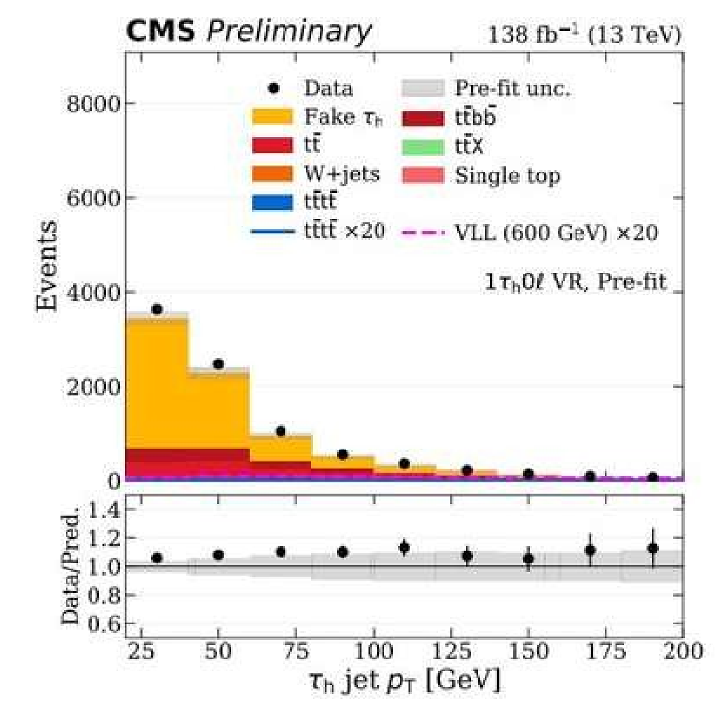
- DeepTau v2.5: 30-50% mistag improvement vs v2.1; PNet and UParT even better → much stronger background rejection
- New HT280 + 2 b-tags + 4 jets HLT trigger from Run 3 → improved signal acceptance
- HL-LHC projection: 6% precision on $\sigma(\mathrm{tttt})$ from SS/ML alone (ATLAS+CMS combined)

Backup

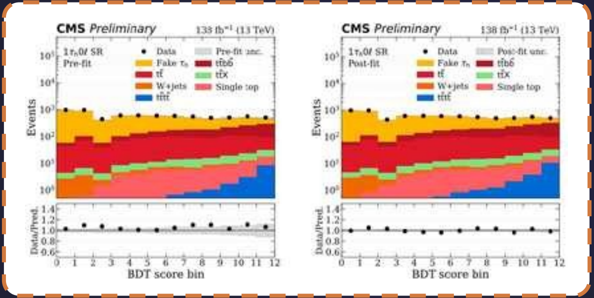
Additional material follows

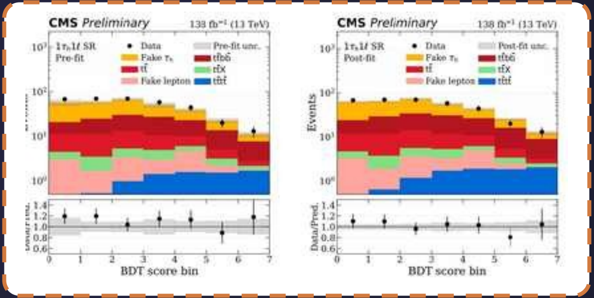
tttt: validation of nonprompt tau background

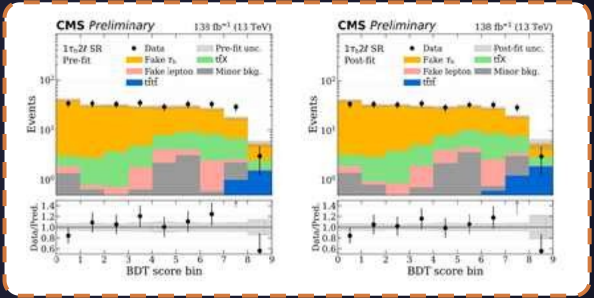




tttt: prefit vs postfit BDT distributions





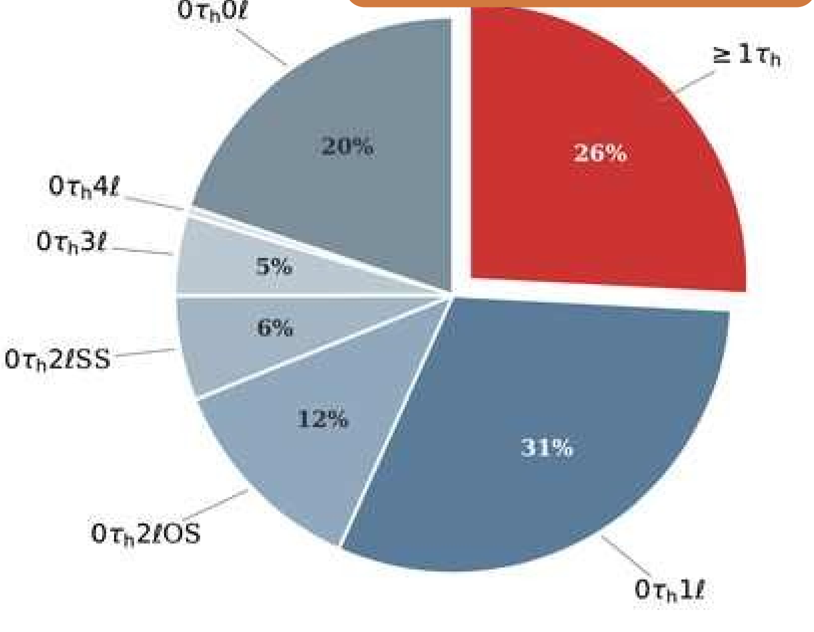


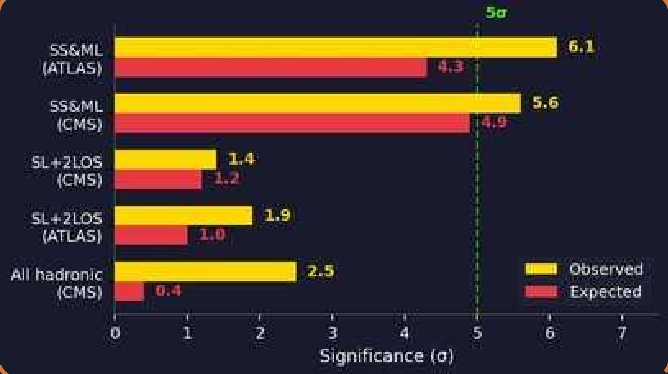
tttt: theory predictions with threshold resummation

$\sqrt{S}$ [TeV]	μ_0	NLO [fb]	NLO+NLL [fb]	$\mathcal{K}^{\mathrm{NLL}}$	NLO+NLL′ [fb]	$\mathcal{K}^{\mathrm{NLL}'}$
13.6	$M/2$	$13.83^{+23.0\%}_{-22.6\%}$	$14.38^{+39.6\%}_{-23.1\%}$	1.04	$12.38^{+24.1\%}_{-20.8\%}$	0.90
	$Q/2$	$10.16^{+30.1\%}_{-23.6\%}$	$10.55^{+27.9\%}_{-18.6\%}$	1.04	$12.00^{+15.8\%}_{-14.9\%}$	1.18
	$H_T/2$	$11.70^{+29.3\%}_{-23.8\%}$	$11.89^{+31.7\%}_{-20.1\%}$	1.02	$12.25^{+17.3\%}_{-15.7\%}$	1.05
13	$M/2$	$11.61^{+22.9\%}_{-22.7\%}$	$12.05^{+39.4\%}_{-23.0\%}$	1.04	$10.43^{+23.6\%}_{-20.8\%}$	0.90
	$Q/2$	$8.56^{+30.2\%}_{-23.7\%}$	$8.90^{+27.9\%}_{-18.6\%}$	1.04	$10.16^{+15.7\%}_{-14.8\%}$	1.19
	$H_T/2$	$9.84^{+29.4\%}_{-23.9\%}$	$10.00^{+31.5\%}_{-20.0\%}$	1.02	$10.35^{+17.1\%}_{-15.7\%}$	1.05
$\sqrt{S}$ [TeV]	μ_0	$\mathrm{NLO_{QCD}}$ [fb]	$\mathrm{NLO_{QCD}}$+NLL [fb]	$\mathcal{K}^{\mathrm{NLL}}$	$\mathrm{NLO_{QCD}}$+NLL′ [fb]	$\mathcal{K}^{\mathrm{NLL}'}$
13.6	$M/2$	$13.13^{+25.2\%}_{-24.5\%}$	$13.68^{+42.6\%}_{-24.9\%}$	1.04	$11.68^{+26.2\%}_{-21.7\%}$	0.89
	$Q/2$	$9.38^{+33.3\%}_{-25.8\%}$	$9.77^{+30.7\%}_{-20.2\%}$	1.04	$11.22^{+17.3\%}_{-16.2\%}$	1.20
	$H_T/2$	$10.88^{+32.3\%}_{-25.8\%}$	$11.08^{+34.7\%}_{-21.8\%}$	1.02	$11.43^{+19.0\%}_{-16.8\%}$	1.05
13	$M/2$	$11.00^{+24.9\%}_{-24.4\%}$	$11.44^{+42.1\%}_{-24.7\%}$	1.04	$9.82^{+25.5\%}_{-21.8\%}$	0.89
	$Q/2$	$7.90^{+33.3\%}_{-25.8\%}$	$8.24^{+30.6\%}_{-20.2\%}$	1.04	$9.50^{+17.1\%}_{-16.1\%}$	1.20
	$H_T/2$	$9.14^{+32.1\%}_{-25.9\%}$	$9.31^{+34.4\%}_{-21.7\%}$	1.02	$9.66^{+18.6\%}_{-16.8\%}$	1.06

Experimental landscape of tttt: intriguing upward trend

τ_h channels unexplored!





- ATLAS: $\sigma = 22.5^{+6.6}_{-5.5}$ fb | CMS: $\sigma = 17.7^{+3.7}_{-3.5}$ fb in SS/ML → both show positive trend
- SS/ML channel covers only 11% of the total branching ratio
- Observed significance exceeds expected in all channels — intriguing!
- What's it going to look like in the final uncharted τ_h final state?