Universidad de Oviedo
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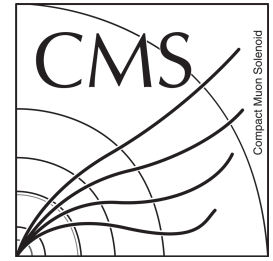


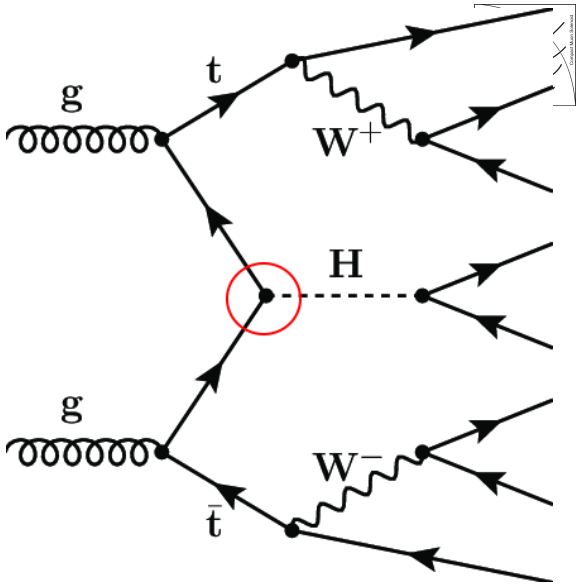
SERGIO SÁNCHEZ CRUZ
ON BEHALF OF THE CMS COLLABORATION

ICHEP 2020

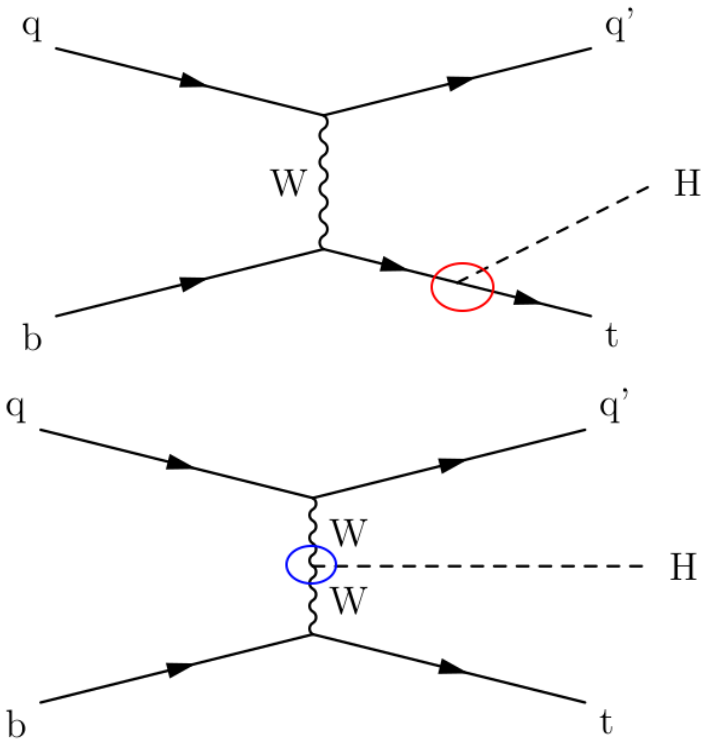
MEASUREMENTS OF $t\bar{t}H$ AND tH ASSOCIATED PRODUCTION AT CMS

sergio.sanchez.cruz@cern.ch

Introduction (I)



- One of the only direct probes of the top-Higgs interaction
- Allows to measure the strength of the Yukawa coupling, CP violation
- $t\bar{t}H$ production is a challenging process to study
  - $\sigma \approx 0.5$ pb
- Rich topologies due to the different Higgs and top decay modes



- tH production is even rarer, $\sigma \approx 74$ fb
- Sensitive to y_t and g_W couplings
- Interference between y_t and g_W diagrams
- ITC ($\kappa_t/\kappa_W = -1$) enhances cross section by ≈ 10
- ITC has no effect on $t\bar{t}H$ cross section

Analysis strategy

- Different channels to search for these processes
- $t\bar{t}H$ observation when combining all channels (PRL 120, 231801 (2018))

$b\bar{b}$ decay modes (**HIG-18-030**)

- Most of the branching ratio, but large backgrounds

$\gamma\gamma$ decay mode (**2003.10866**)

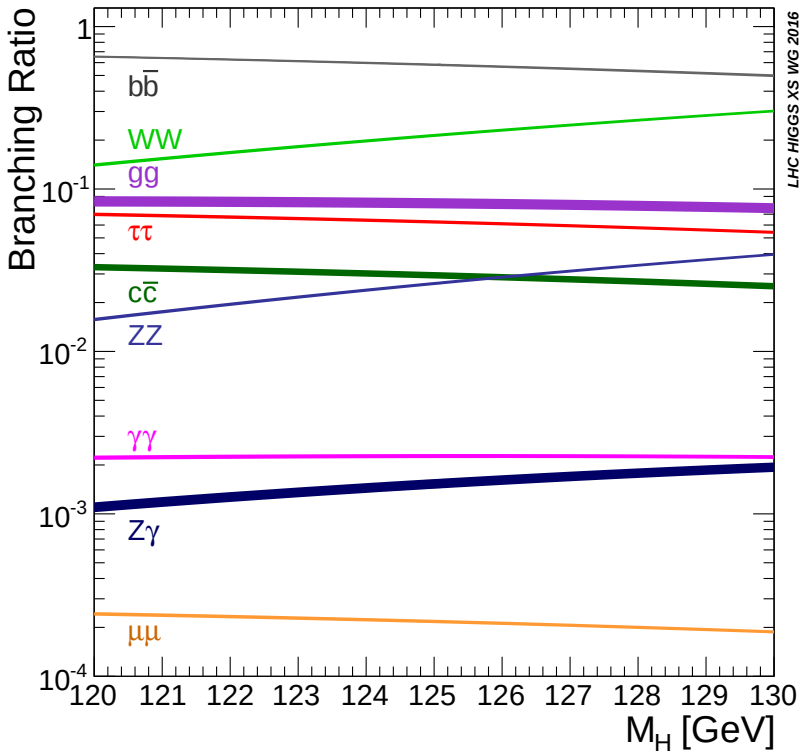
- More $H \to \gamma\gamma$ in **H. Mei's talk**
- Low background, but low branching ratio
- Allows to reconstruct the Higgs system

Covered in this talk

WW, ZZ and $\tau\tau$ decay modes (multilepton, HIG-19-008)

- Moderate background, but significant branching ratio

New result!



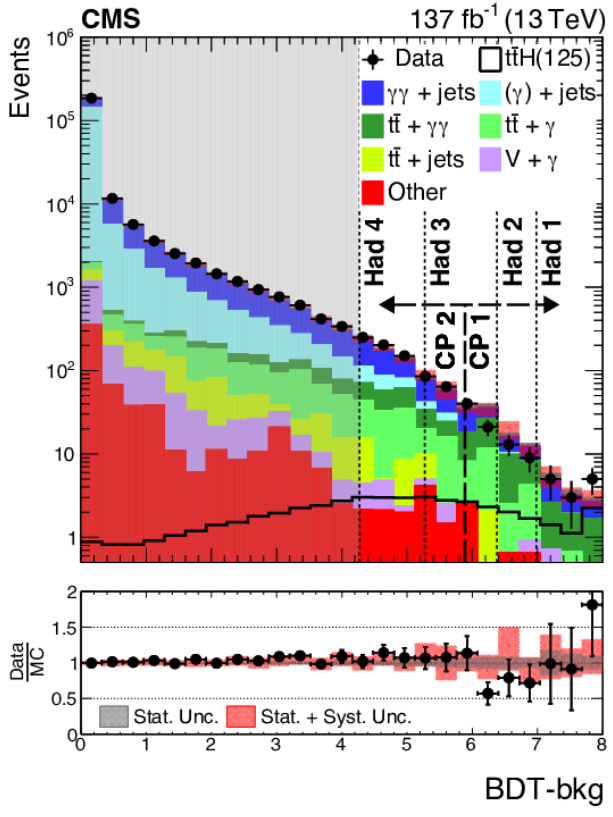
- Showing Run 2 legacy results
- Obtained analyzing 137 fb^{-1} of data

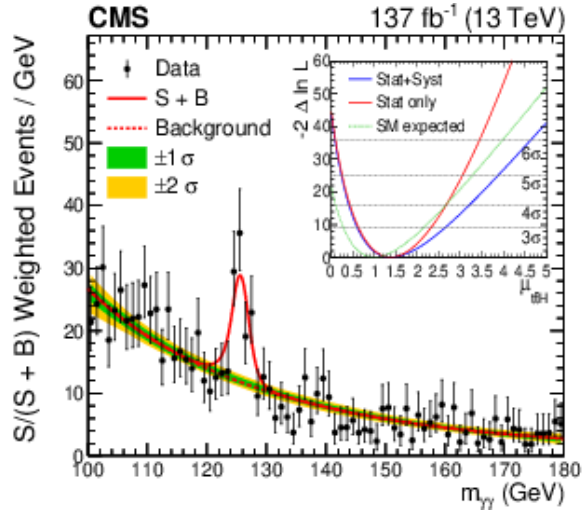
DIPHOTON SEARCH

- Events with two photons and targeting hadronic or leptonic top quark decays
- Main backgrounds from $t\bar{t} + \gamma\gamma$
- Usage of BDTs to reject backgrounds
- Signal $\Rightarrow$ Gaussian + CB function
- Background $\Rightarrow$ discrete profiling method

- Signal strength of $1.38^{+0.36}_{-0.29}$, compatible with SM
- Observed significance of 6.6 σ wrt no signal hypothesis

- CP studies on this channel in **S. Kyriacou's talk**

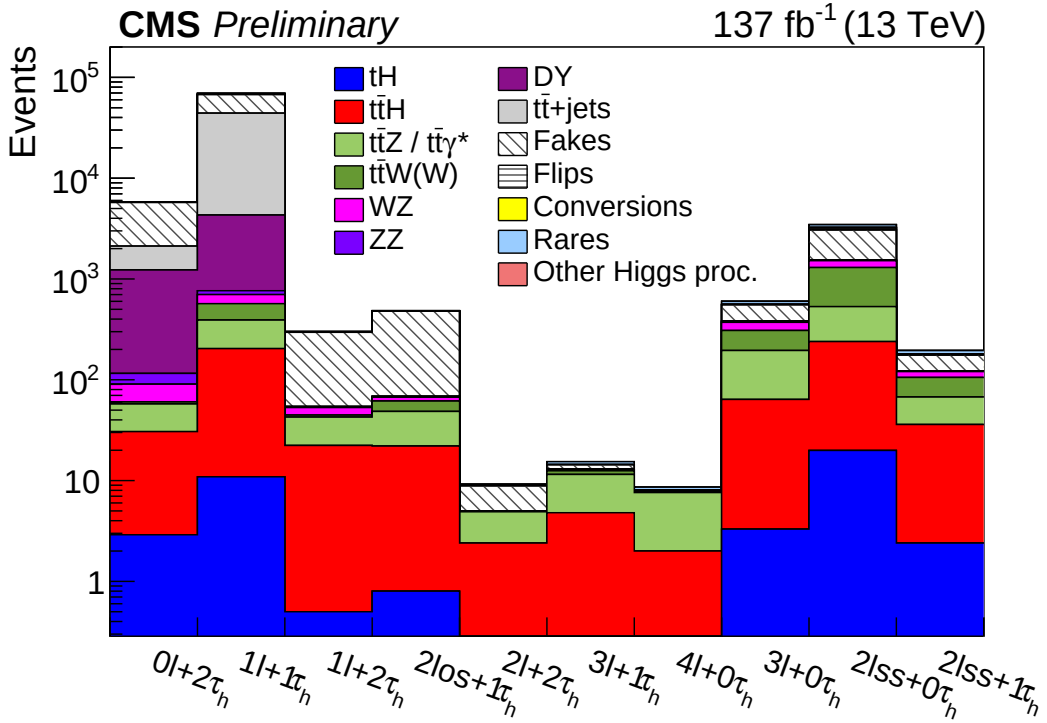




MULTILEPTON SEARCH

Signal regions

- 10 disjoint categories according to lepton (e or μ) and τ_h multiplicity
- Different background composition in each category
- Lepton charge consistent with the expected final state
- Jet multiplicity according to the $t\bar{t}H$ final state



- $2l\,ss + 0\tau_h$, $2l\,ss + 1\tau_h$ and $3l + 0\tau_h$ enlarged to accept tH events
  - Allowing events with one light (forward) jet and one b tag

Control regions

- Control regions with 3 and 4 leptons and a Z boson candidate used to constrain $t\bar{t}Z$ background

Background discrimination

- Signal regions are mostly dominated by background
- MVA discriminators are used to separate signals from backgrounds
- Input variables:
  - 3-momenta of jets, leptons and τ_h
  - Invariant masses, angular distances, object multiplicities
  - Taggers to identify decay products of top quarks and H

$2l ss + 0\tau_h$, $2l ss + 1\tau_h$, $3l + 0\tau_h$ regions

- Using multiclass DNNs to discriminate $t\bar{t}H$, tH and backgrounds
- Categories built based on DNN and event topology (next slide)

Rest of the regions

- No sensitivity expected for tH $\Rightarrow$ using BDT discriminating $t\bar{t}H$ against backgrounds
- Classifying according to the BDT score

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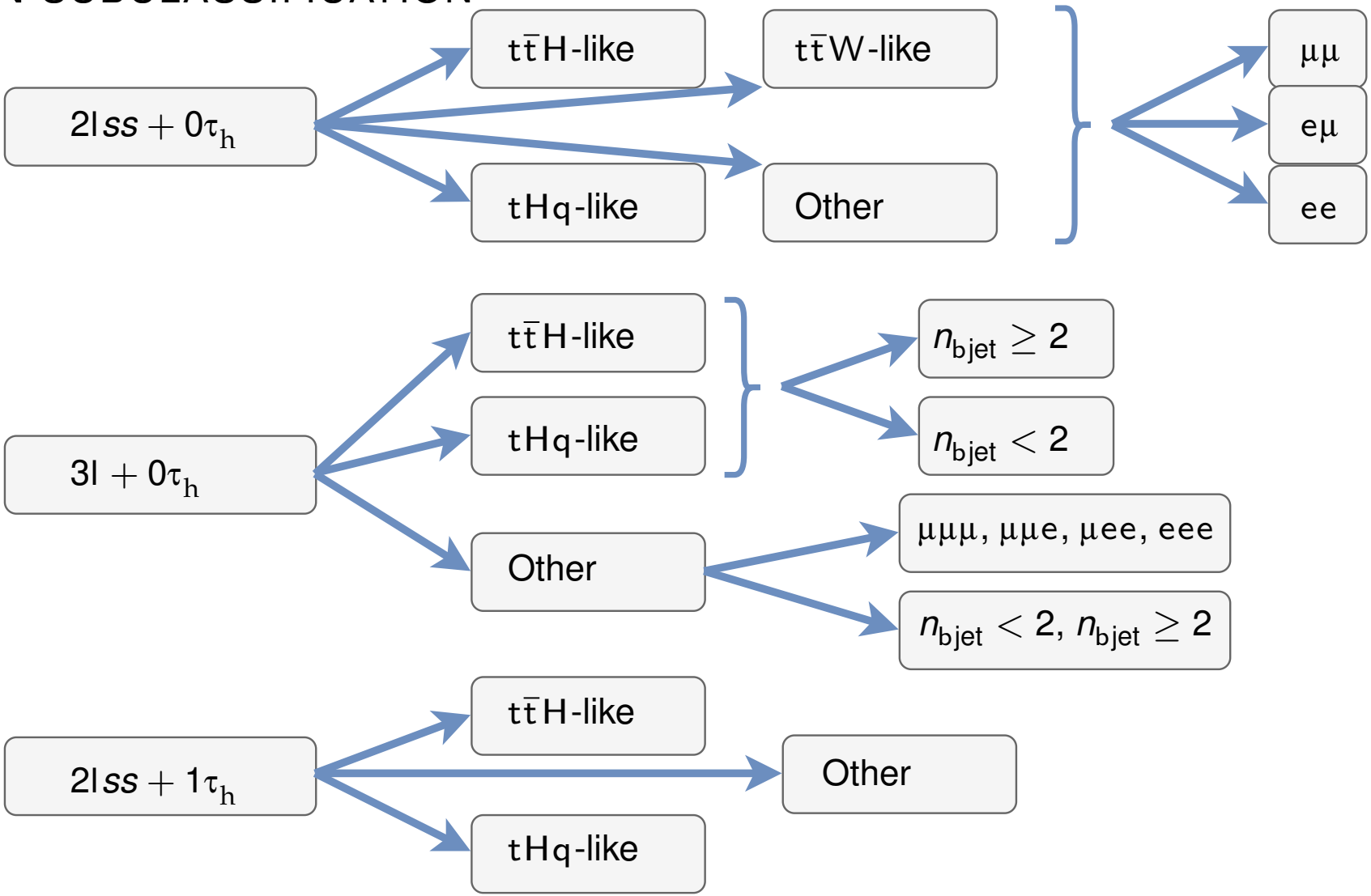
DNN SUBCLASSIFICATION



- DNN and event topology-based classification
- Further classification is performed based on the score of the most probable process

BACKGROUNDS

Estimation of backgrounds is key in this analysis

Reducible backgrounds due to

- Non-prompt leptons and misidentified τ_h
- Electron charge flips

} Estimated with data-driven methods

- Photon conversions

} Estimated with simulations

Irreducible backgrounds due to

- $t\bar{t}Z$, $t\bar{t}W$
- Less importantly, WZ, ZZ, rares (tZq, $t\bar{t}t\bar{t}$, ...)
- $t\bar{t}$ and DY events are also irreducible in the $1l + 1\tau_h$ and $0l + 2\tau_h$ categories
- Estimated using state-of-the-art MC simulations and normalized to the more precise theory calculations

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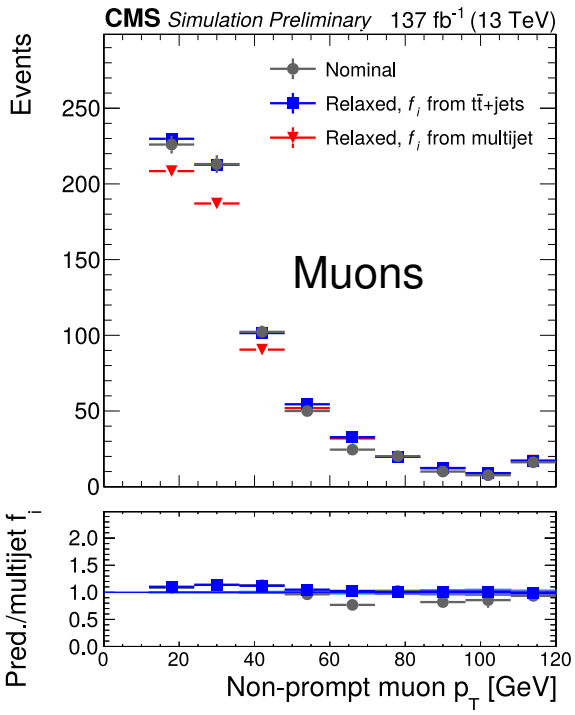
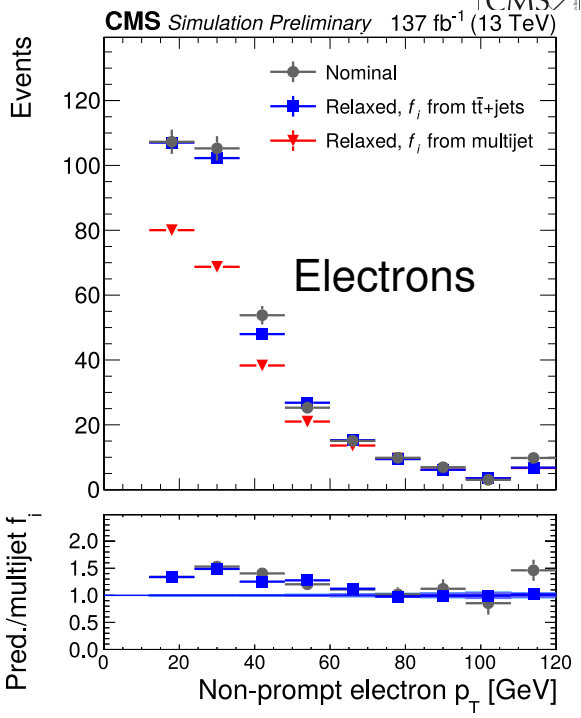
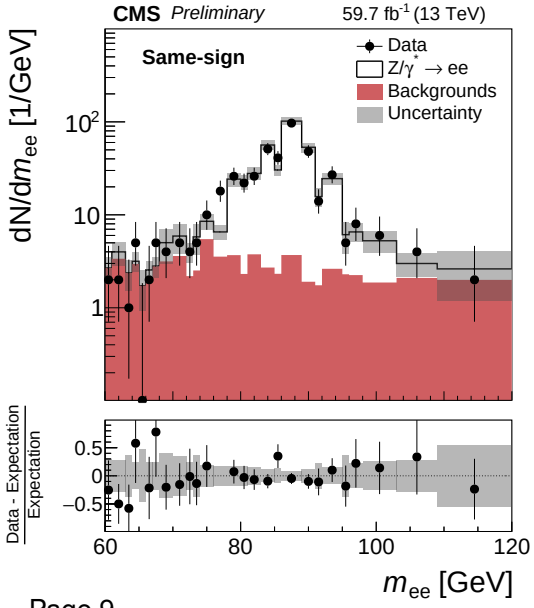
REDUCIBLE BACKGROUNDS

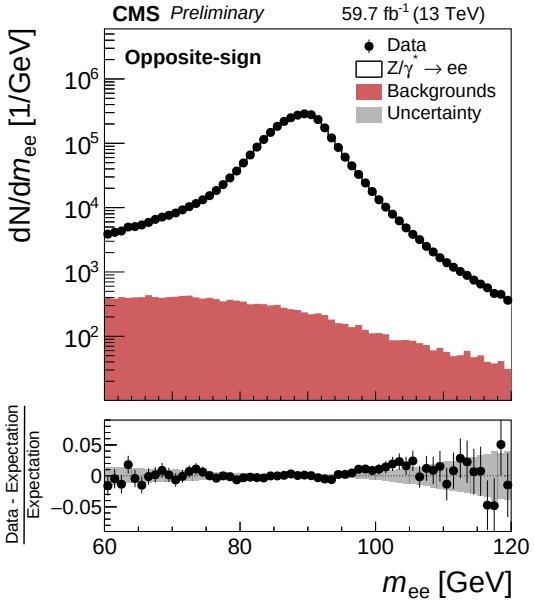
Non-prompt leptons

- Largely suppressed with MVA techniques in the lepton identification
- A tiny portion leak into signal regions
- Using the tight-to-loose method
  - Transfer factor in multijet events
- Check the method in $t\bar{t}$ simulations
- Similar procedure followed for misidentified τ_h









Electron charge flips

- Small fraction of events measured with opposite-charge sign
- Estimated from a opposite-sign sideband

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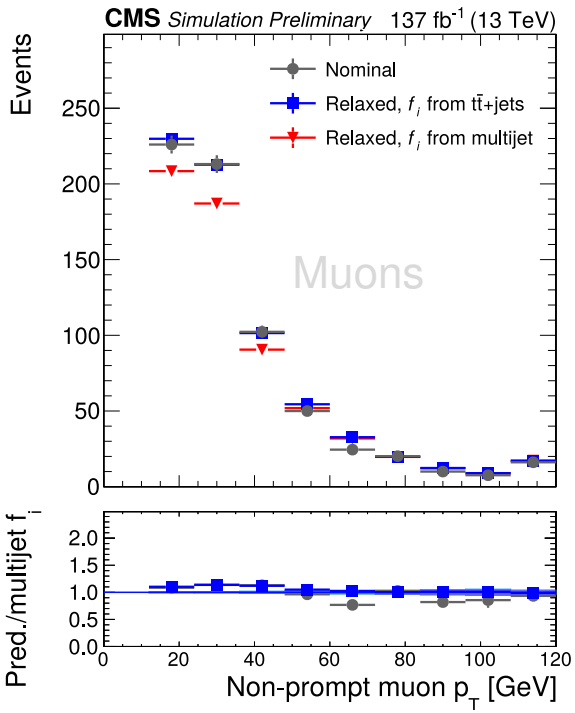

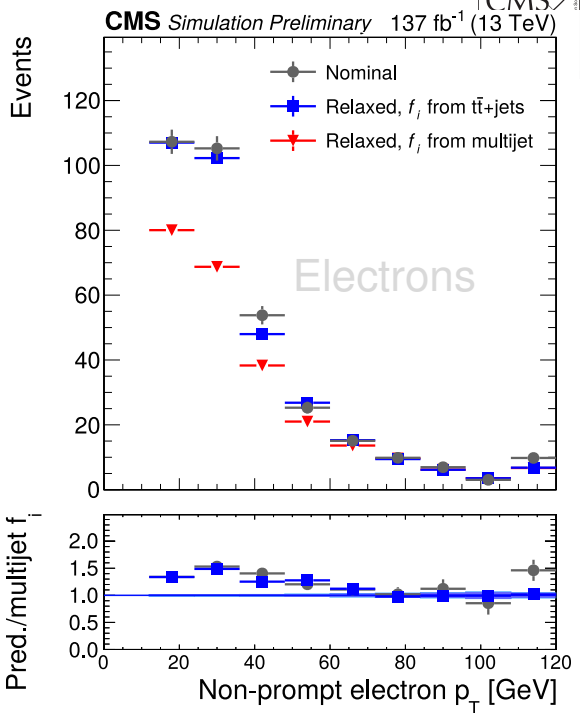

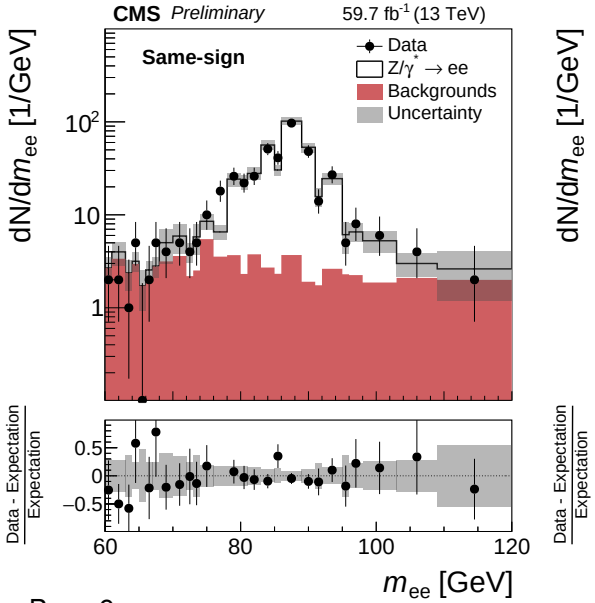

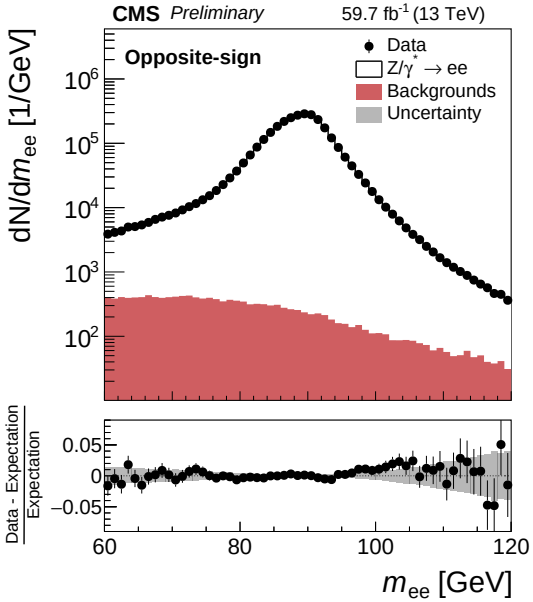

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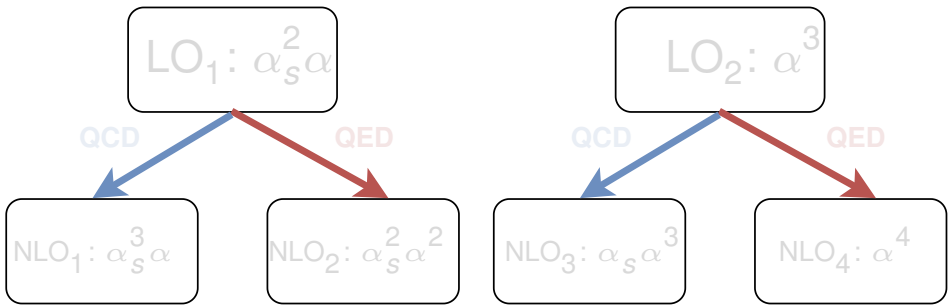
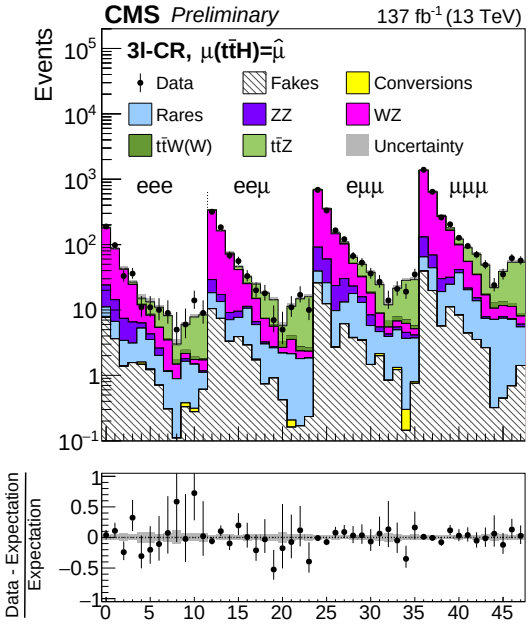
IRREDUCIBLE BACKGROUNDS

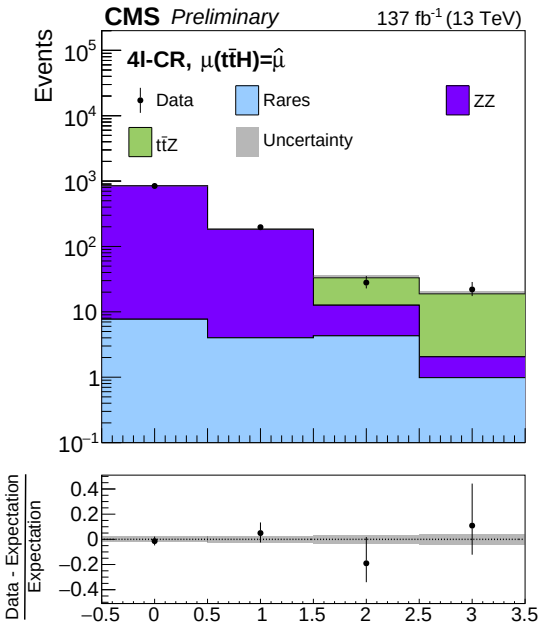
- $t\bar{t}Z$ and $t\bar{t}W$ normalization are determined in the signal extraction fit
  - No assumption made on the total cross section
- Dedicated control region for $t\bar{t}Z$
  - 3l with a Z boson candidate
  - 4l with a Z boson candidate
- Dedicated $t\bar{t}W$ category in the $2l ss + 0\tau_h$, built with the DNN score

- $t\bar{t}Z$ and $t\bar{t}H$ simulated with NLO QCD
- tH simulated at LO
- $t\bar{t}W$ simulated at NLO QCD, including α^3 and $\alpha^3\alpha_s$ corrections



Using the most state-of-the-art generators





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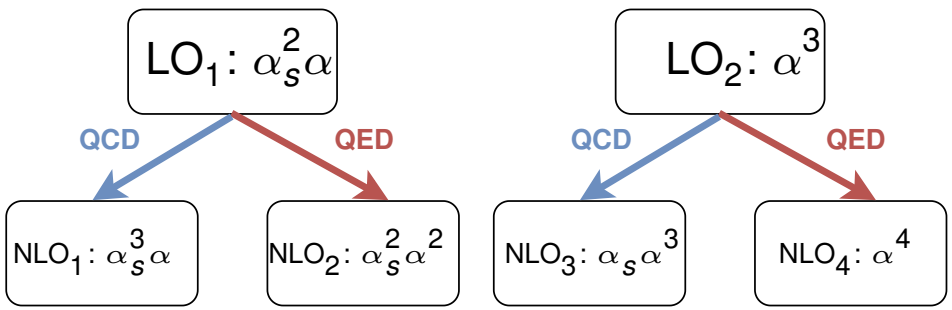

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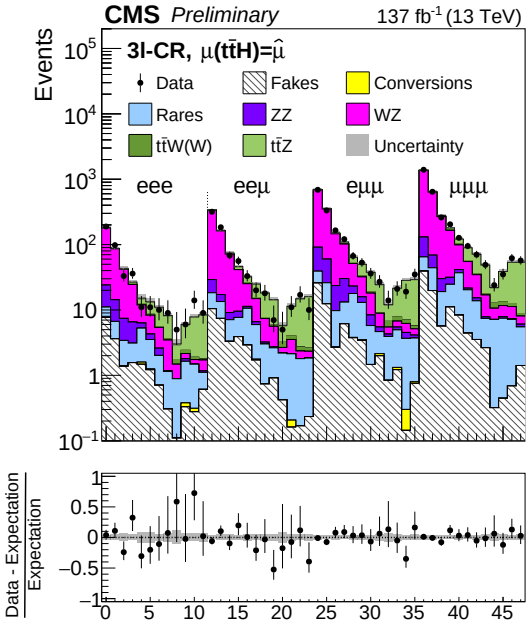
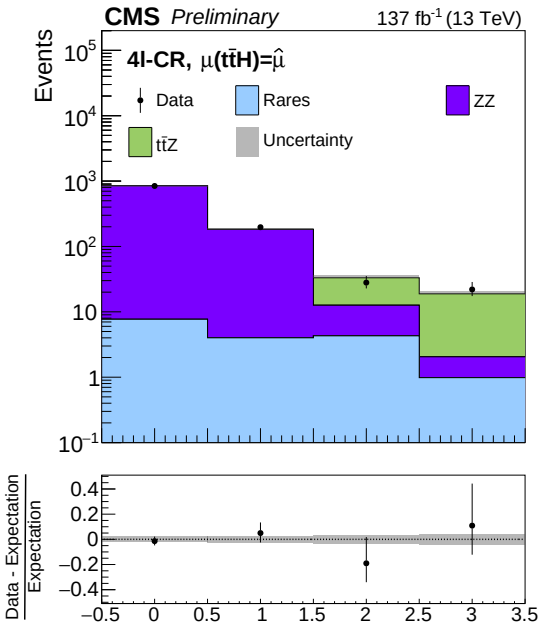
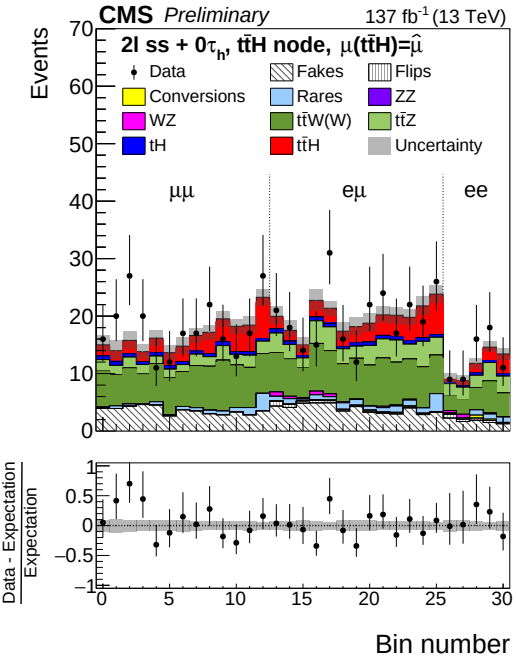
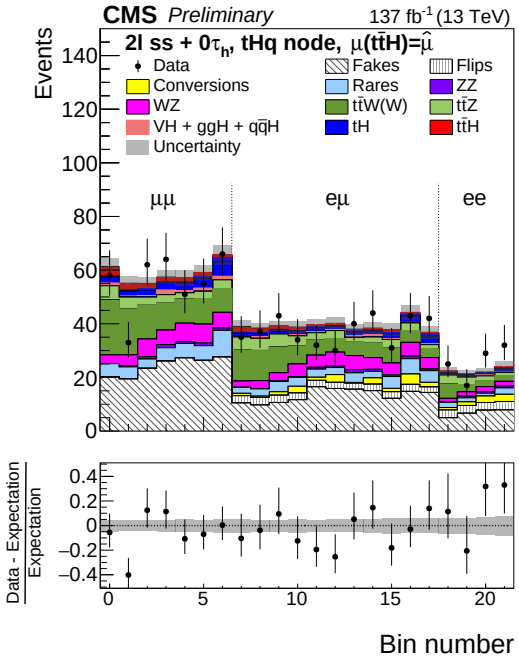




RESULTS





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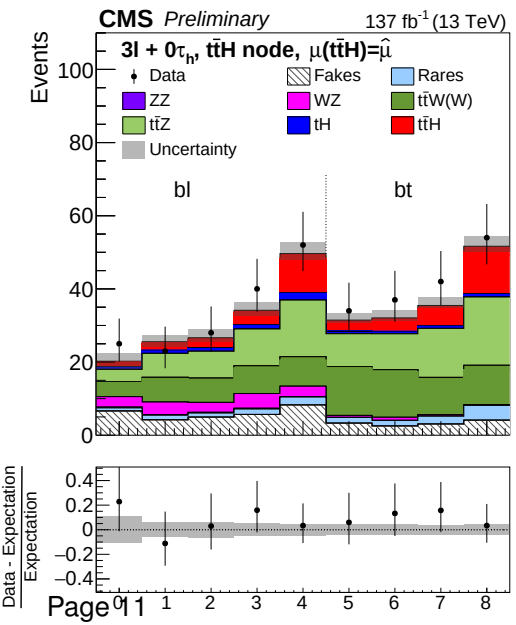

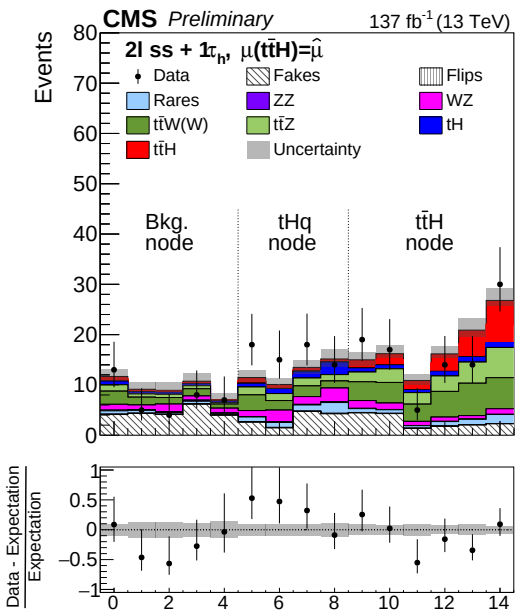

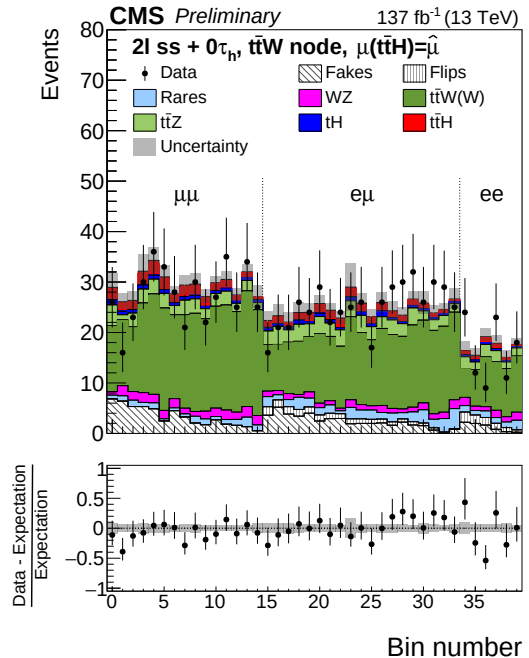

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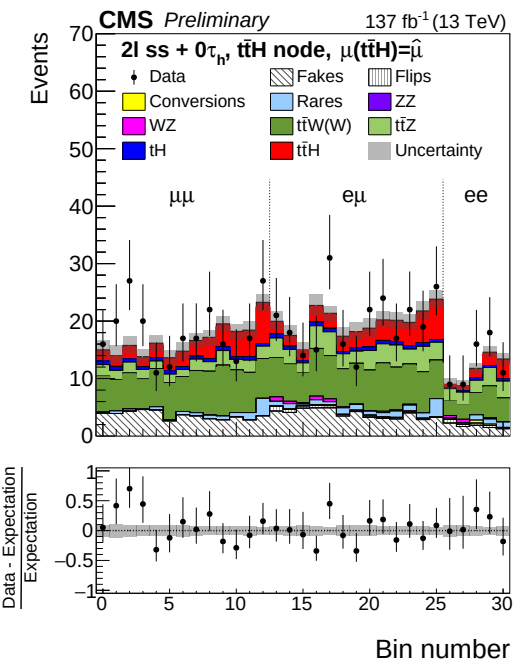

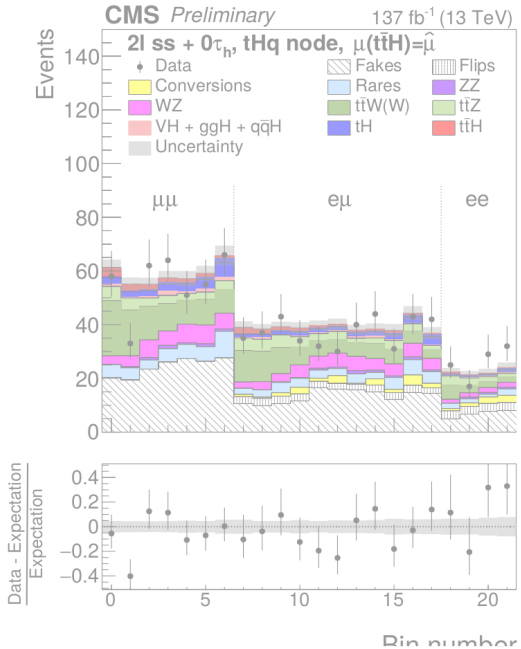

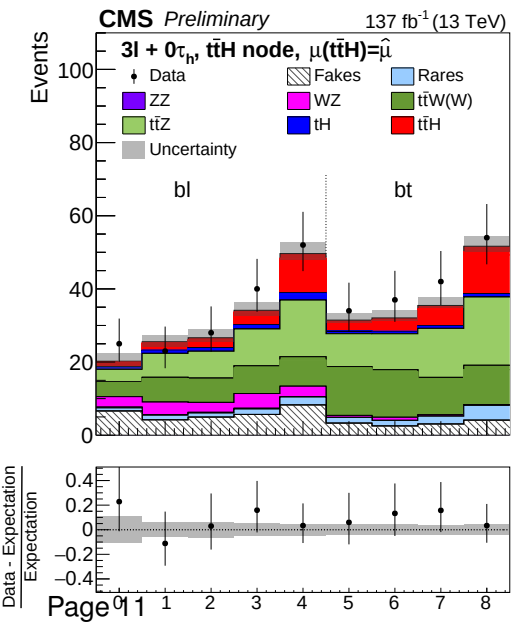

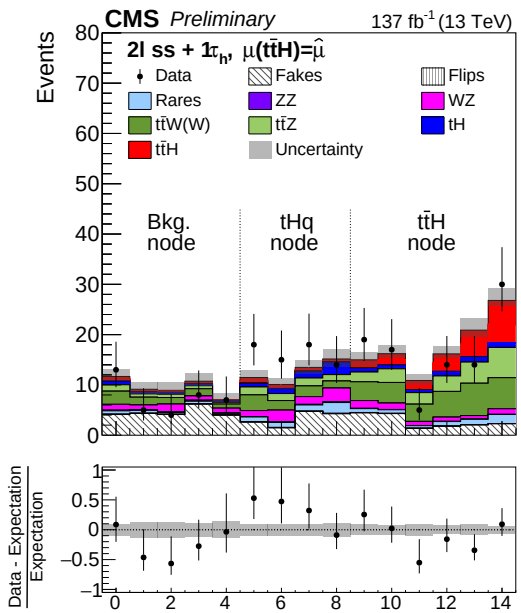

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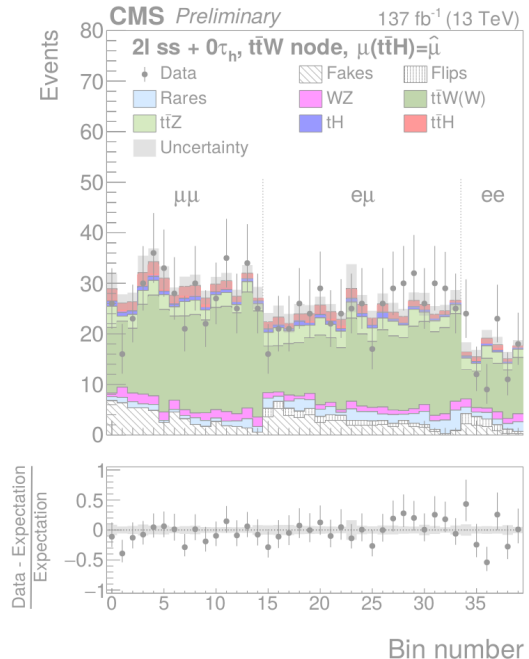

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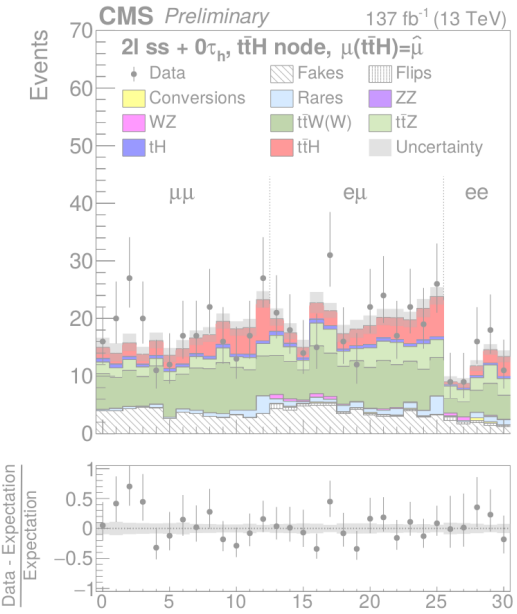

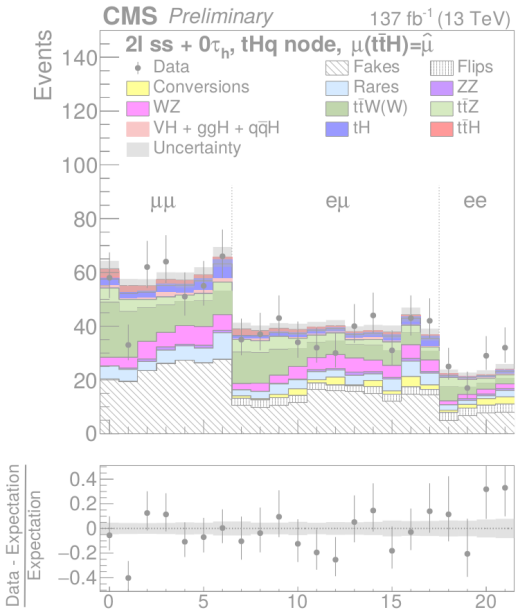

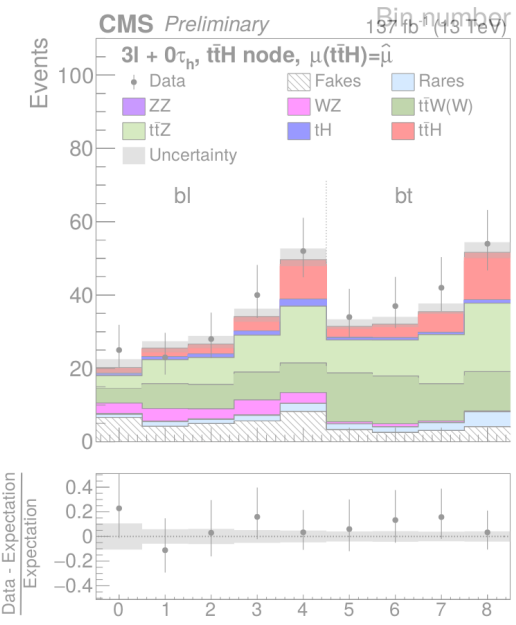

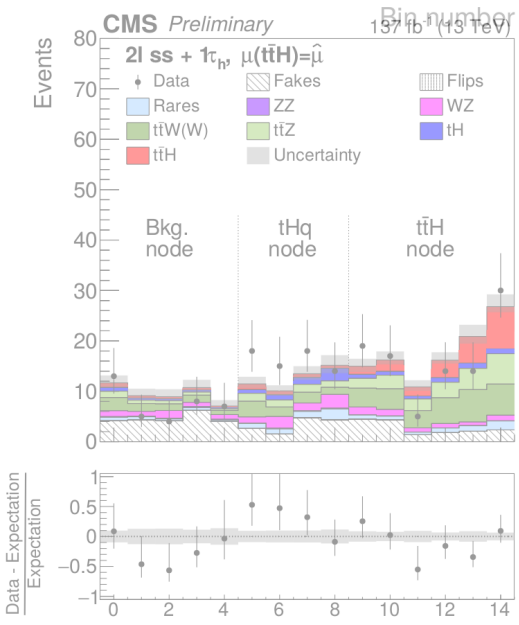

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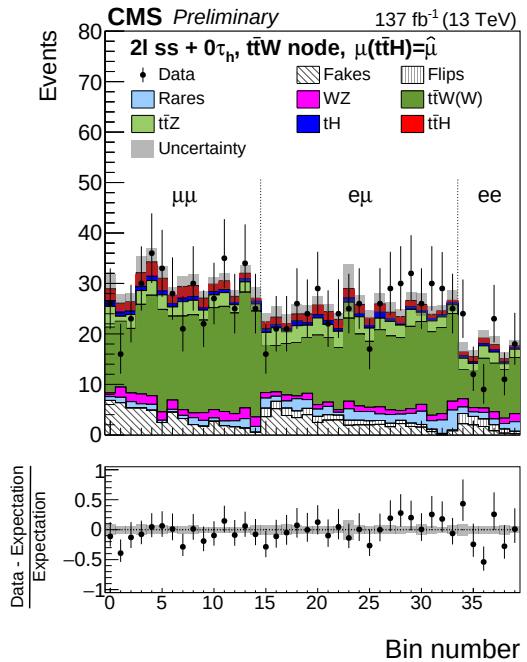
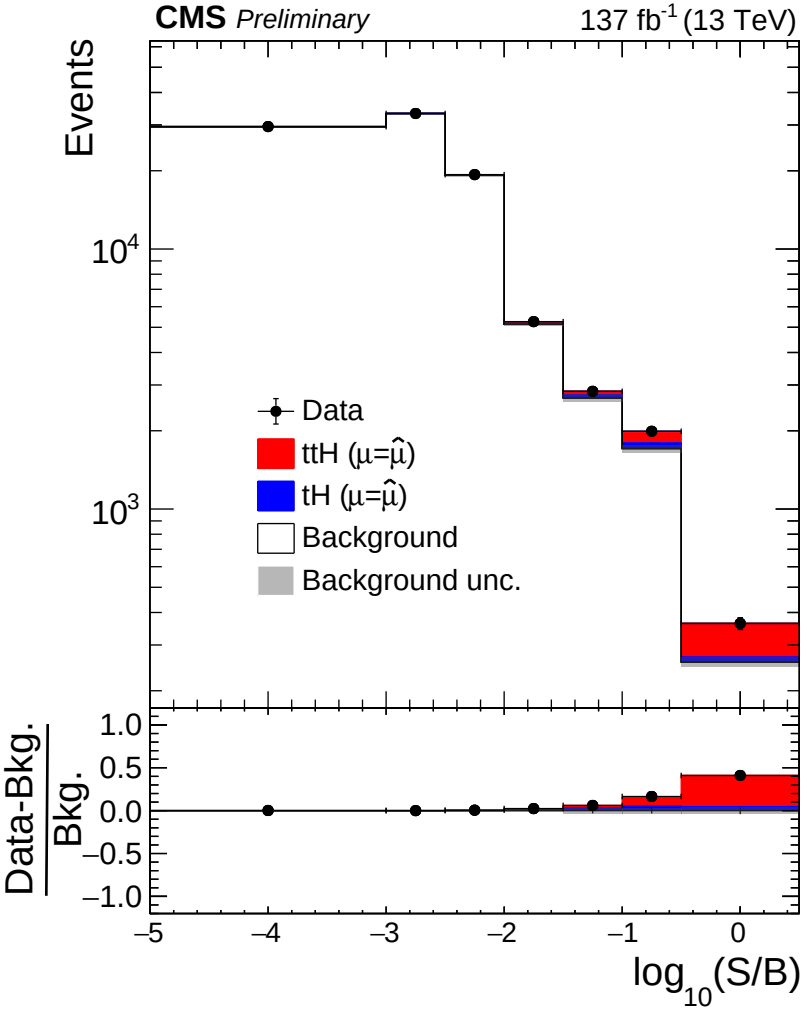
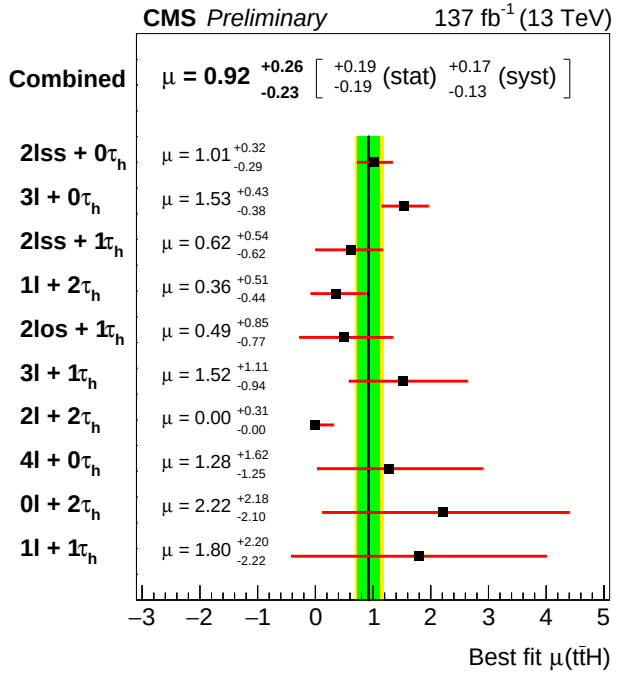


SIGNAL EXTRACTION



- Signals are extracted fitting data in all the categories
- Sensitivity to $t\bar{t}H$ production of 5.2 σ
- Sensitivity to tH production of 0.3 σ

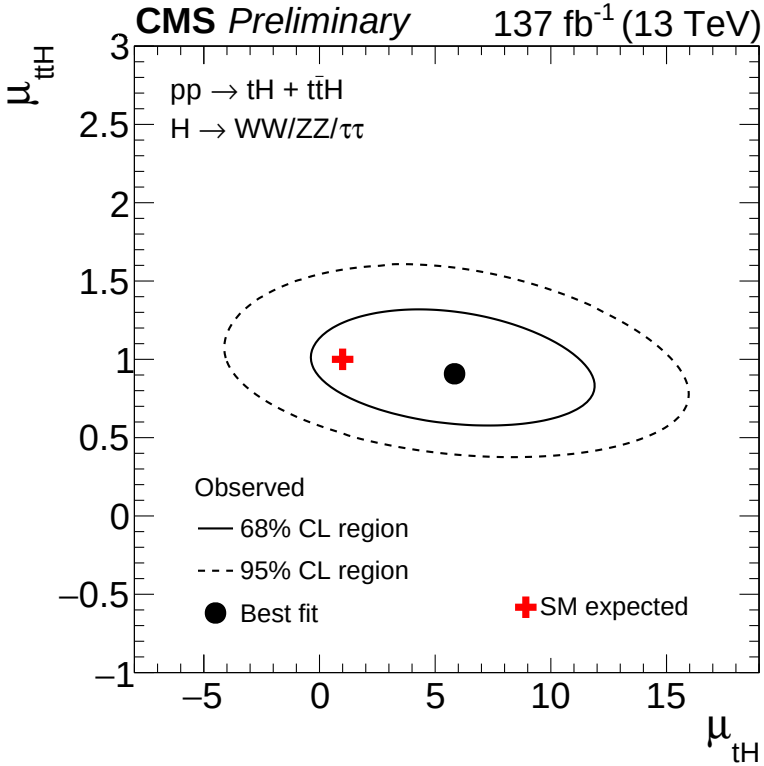


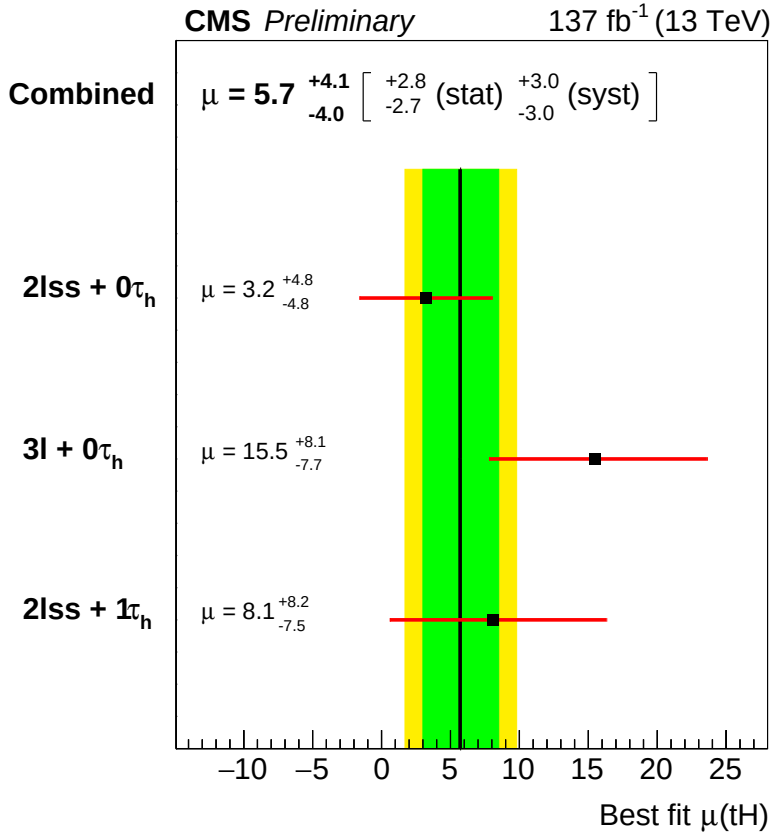
- Observed signal strengths consistent with SM
- $t\bar{t}W$ production above expectation

Process	Signal strength
$t\bar{t}H$	$0.92^{+0.26}_{-0.23}$
tH	$5.7^{+4.1}_{-4.0}$
$t\bar{t}Z$	1.03 ± 0.14
$t\bar{t}W$	1.43 ± 0.21

Signal extraction (II)

- Combined extraction of $t\bar{t}H$ and tH:



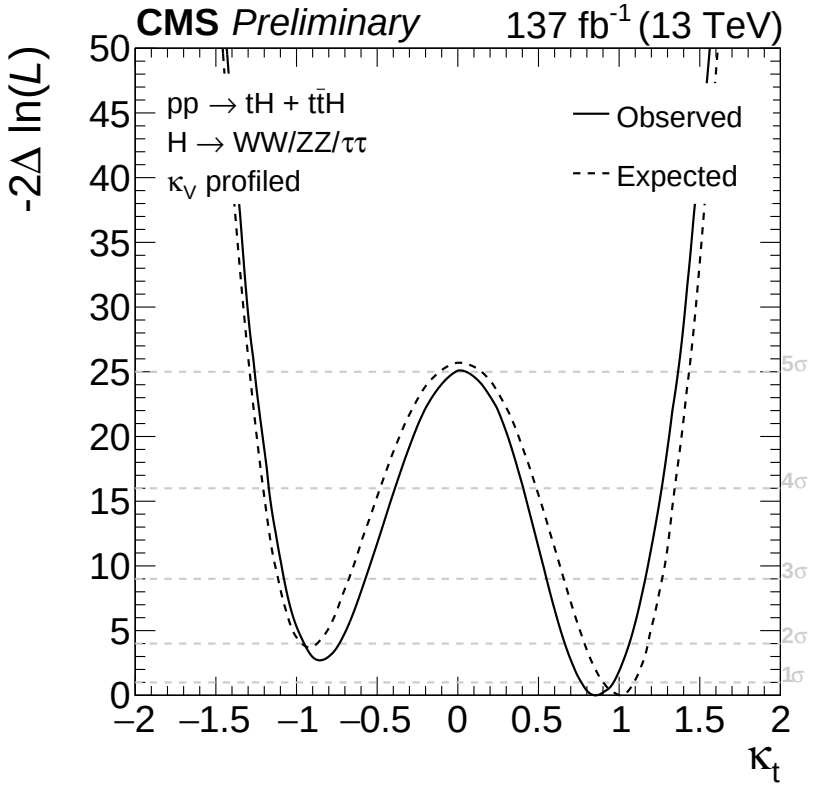


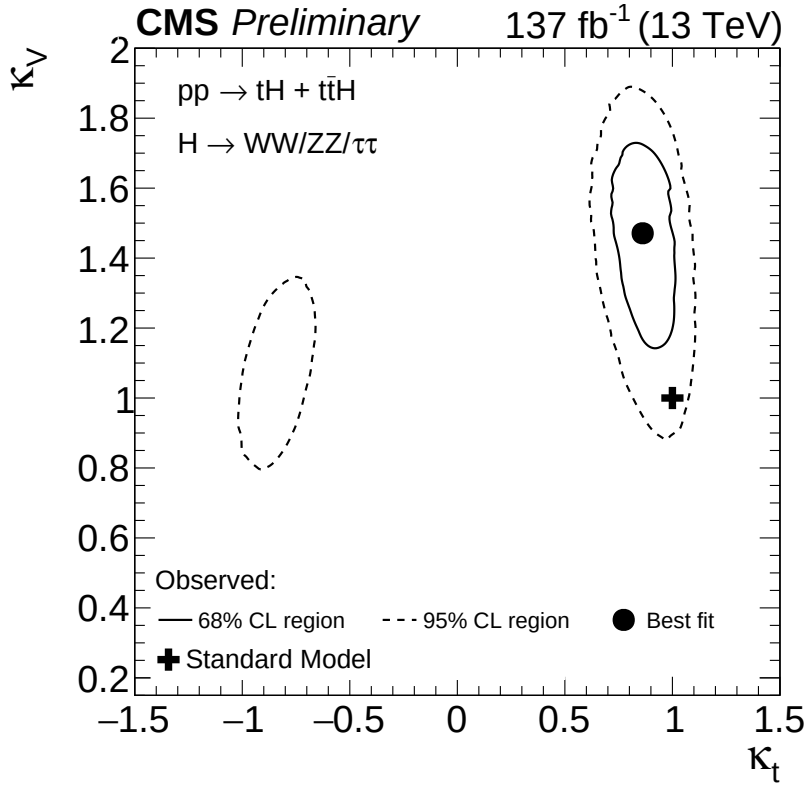
Observed significances

- Observed significance for $t\bar{t}H$ production: 4.7 σ
- Observed significance for tH production: 1.4 σ

κ FRAMEWORK RESULTS

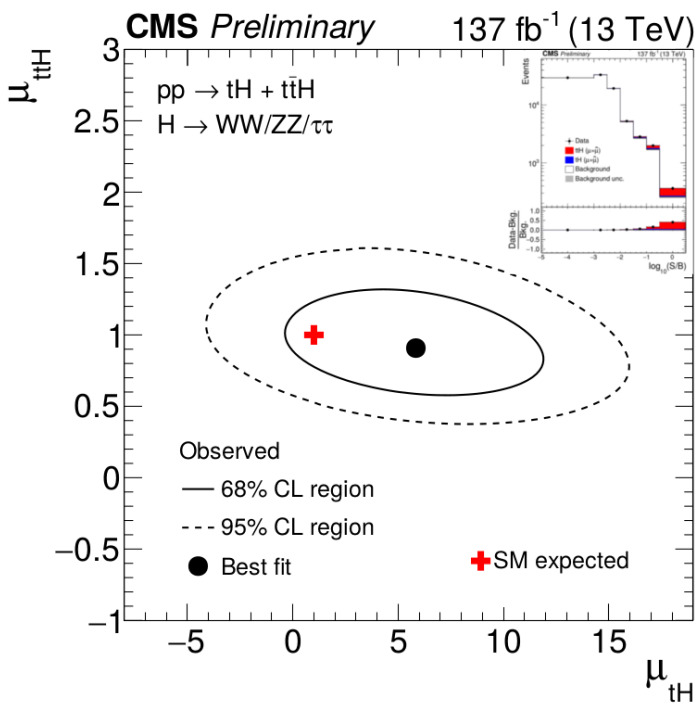
- Interpretation of yields in terms of κ_t and κ_V
  - Effect on tH kinematics and Higgs branching ratios taken into account
- Likelihood scans as a function of κ_t and κ_V
- Best fit consistent with the SM expectation
- κ_t constrained to be within $-0.9 < \kappa_t < -0.7$ or $0.7 < \kappa_t < 1.1$ at 95% C.L.

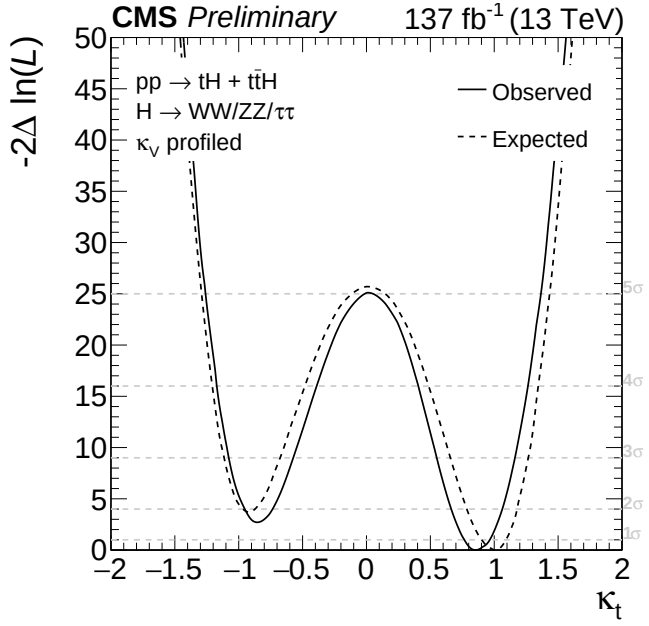




SUMMARY

- $t\bar{t}H$ and tH production have been measured in the multilepton and diphoton channel
- Using the complete run 2 dataset collected by CMS, corresponding to 137 fb^{-1}
- Observation of $t\bar{t}H$ production in the diphoton channel
- More than 5 σ sensitivity to $t\bar{t}H$ production in multilepton
- $t\bar{t}H$ signal strength measured to be $0.92^{+0.26}_{-0.23}$
- Observed (expected) significance of 4.7 (5.2) σ
- tH signal strength measured to be $5.7^{+4.1}_{-4.0}$
- Observed (expected) significance of 1.4 (0.3) σ
- Results interpreted in terms of Higgs coupling modifiers
- κ_t constrained to be within $-0.9 < \kappa_t < -0.7$ or $0.7 < \kappa_t < 1.1$ at 95% C.L.

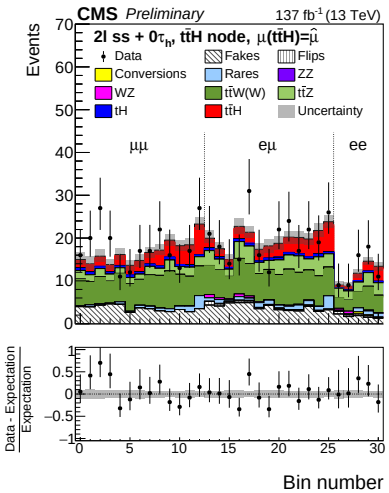


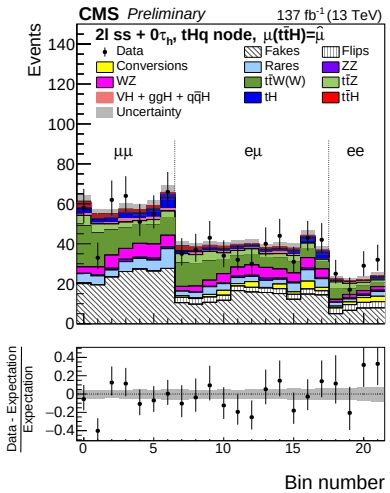


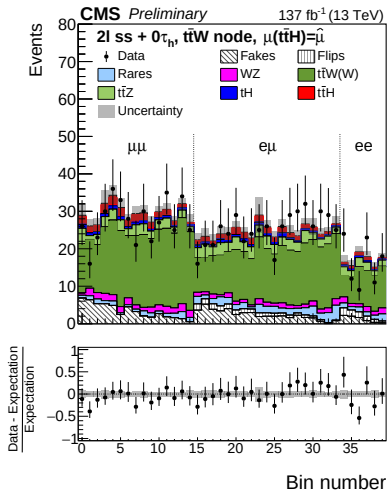
Back-up

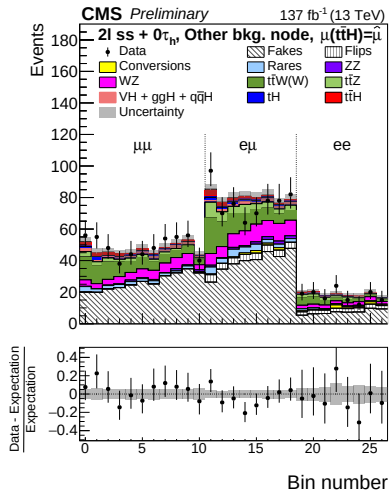
RESULTS

$2l\,ss + 0\tau_h$



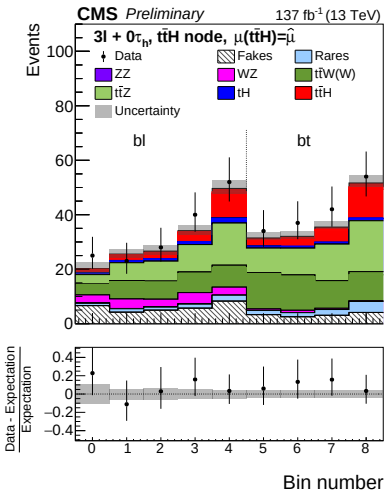


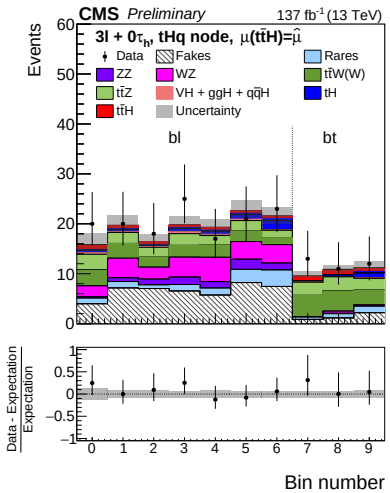


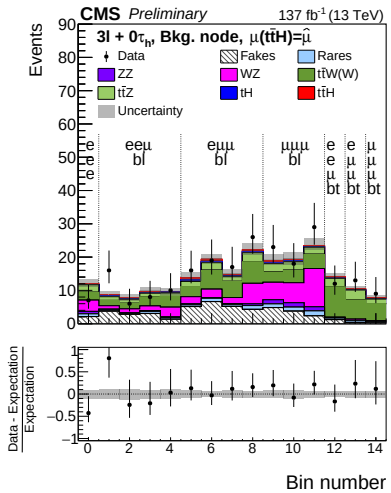


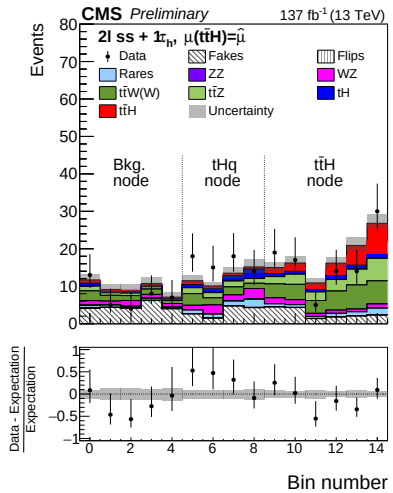
RESULTS

$3l + 0\tau_h$ and $2lss + 1\tau_h$



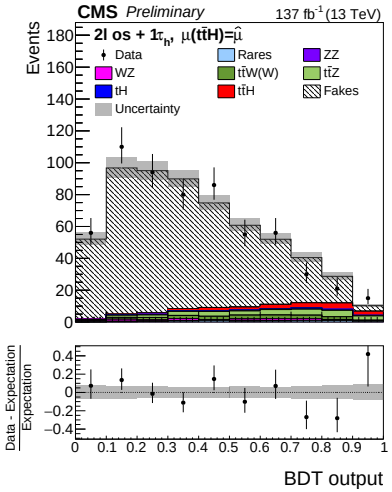


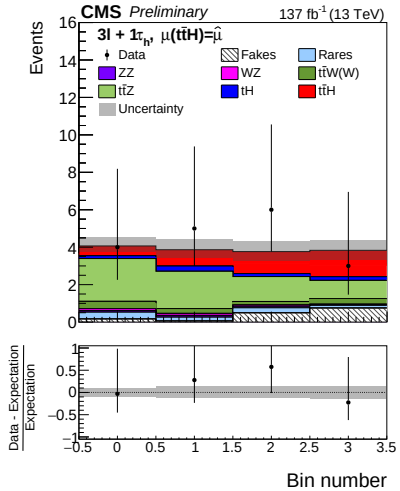


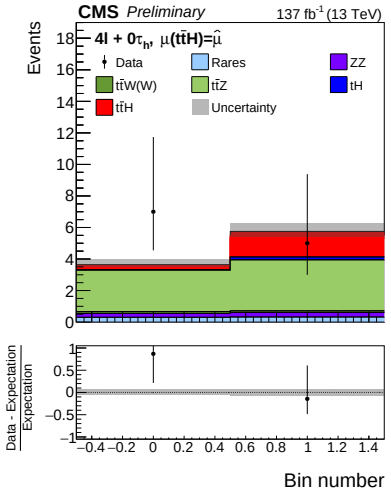


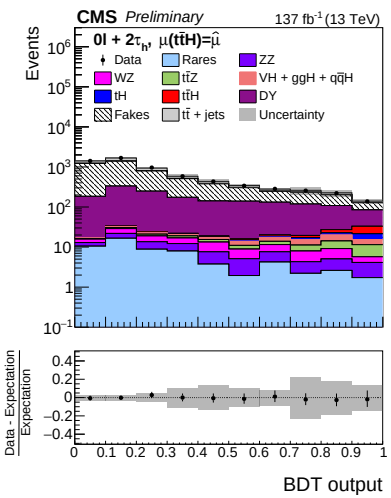
RESULTS

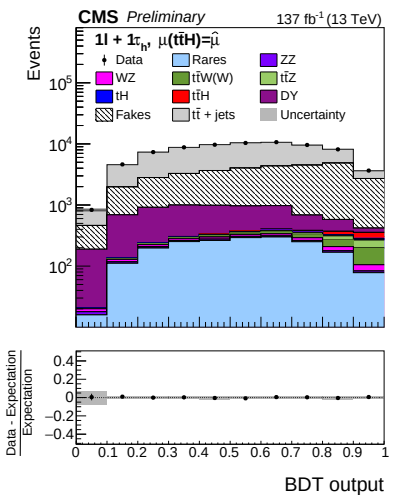
Other categories

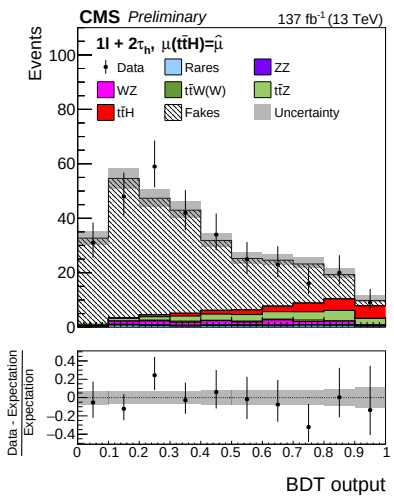


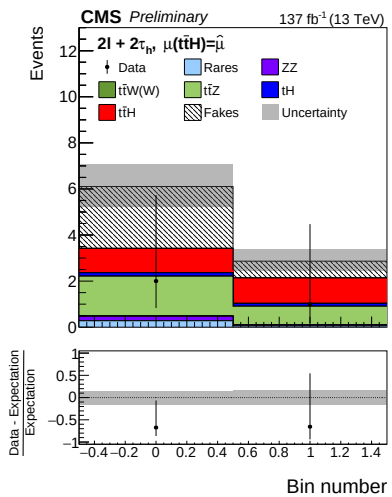












IRREDUCIBLE BACKGROUNDS

- Signals, $t\bar{t}Z$ and $t\bar{t}W$ normalization are freely floating
  - No assumption on total cross section
- Modeling of irreducible processes follows the most accurate calculations available

$t\bar{t}H$ and $t\bar{t}Z$ production

- Generated at NLO QCD with MADGRAPH5_aMC@NLO
- Normalized NLO QCD+EWK (**arXiv:1610.07922**)

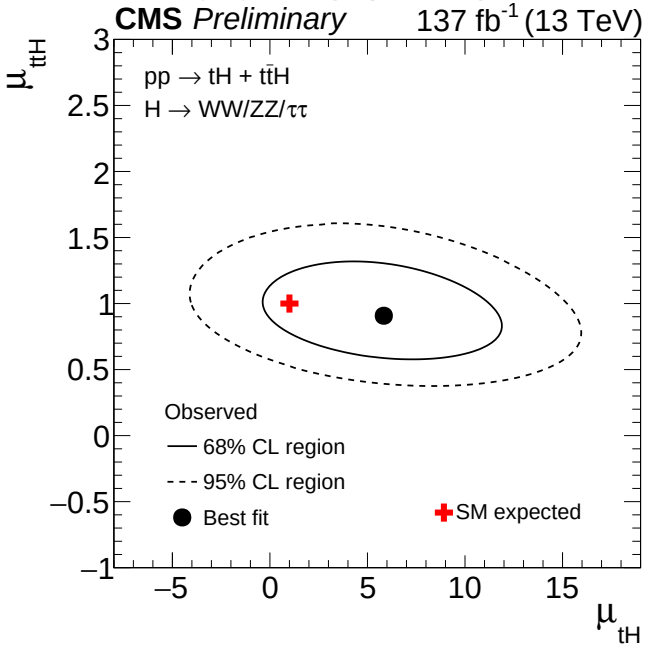
tHq and tHW

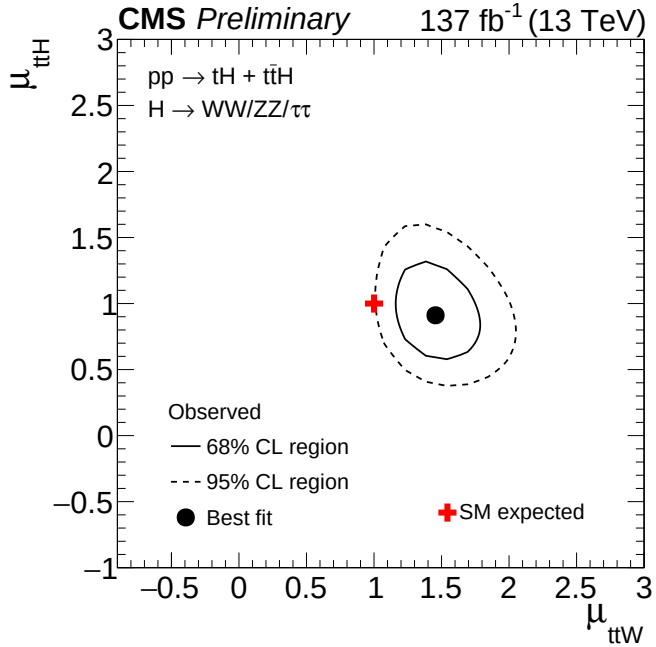
- Generated at LO with MADGRAPH5_aMC@NLO
- Normalized at NLO QCD (**arXiv:1610.07922**)

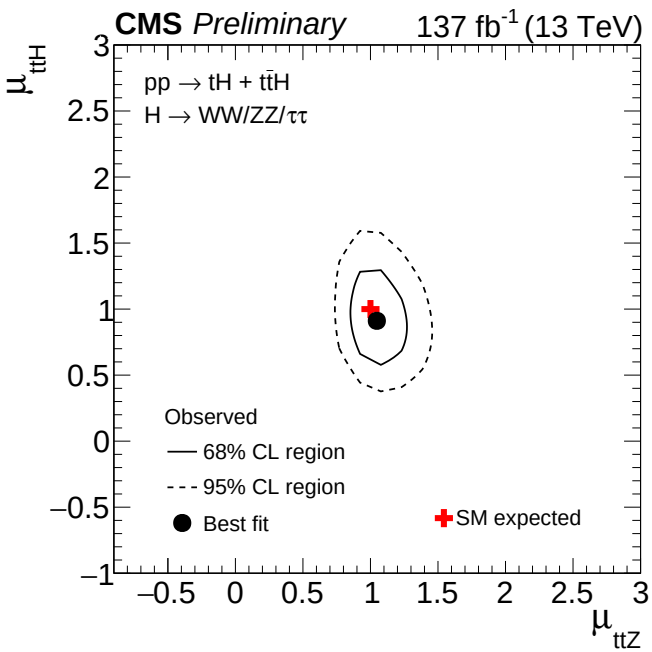
$t\bar{t}W$ production

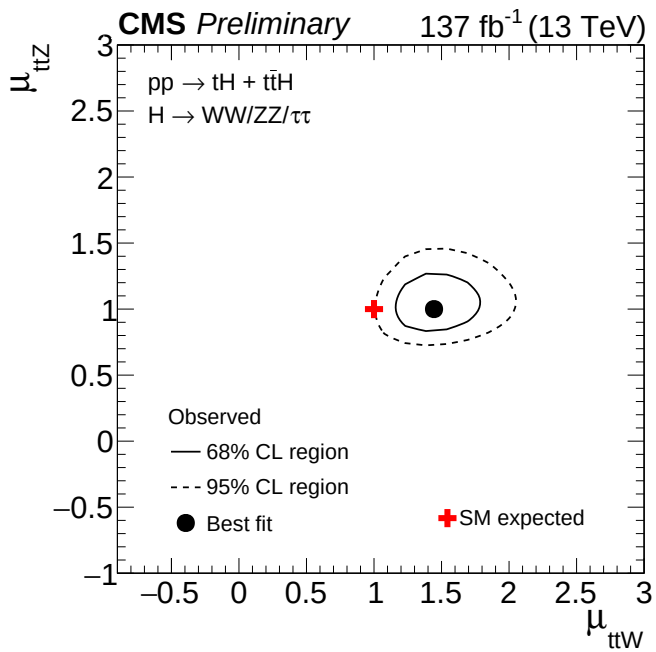
- Generated at NLO QCD with MADGRAPH5_aMC@NLO
  - Normalized to NLO QCD + EWK (**arXiv:1610.07922**)
- α^3 and $\alpha_s\alpha^3$ corrections are added on top (**arXiv:2004.09552**)

2D LIKELIHOOD SCANS









SYSTEMATIC UNCERTAINTIES

Source	$\Delta\mu_{ttH}/\mu_{ttH}$ [%]	$\Delta\mu_{tH}/\mu_{tH}$ [%]	$\Delta\mu_{ttW}/\mu_{ttW}$ [%]	$\Delta\mu_{ttZ}/\mu_{ttZ}$ [%]
Trigger efficiency	2.3	8.1	1.2	1.9
e, μ reconstruction and identification efficiency	2.9	7.1	1.7	3.2
τ_h identification efficiency	4.6	9.1	1.7	1.3
b tagging efficiency and mistag rate	3.6	13.6	1.3	2.9
Misidentified leptons and flips	6.0	36.8	2.6	1.4
Jet energy scale and resolution	3.4	8.3	1.1	1.2
MC and sideband statistical uncertainty	7.1	27.2	2.4	2.3
Theory-related sources	4.6	18.2	2.0	4.2
Normalization of MC-estimation processes	13.3	12.3	13.9	11.3
Luminosity	2.2	4.6	1.8	3.1
Statistical uncertainty	20.9	48.0	5.9	5.8

Selection step	$2\ell\mathrm{ss}+0\tau_\mathrm{h}$	$2\ell\mathrm{ss}+1\tau_\mathrm{h}$
Targeted $\mathrm{t\bar{t}H}$ decay	$\mathrm{t}\to\mathrm{b}\ell\nu$, $\mathrm{t}\to\mathrm{bqq}'$ with $\mathrm{H}\to\mathrm{WW}\to\ell\nu\mathrm{qq}'$	$\mathrm{t}\to\mathrm{b}\ell\nu$, $\mathrm{t}\to\mathrm{bqq}'$ with $\mathrm{H}\to\tau\tau\to\ell\nu\nu\tau_\mathrm{h}\nu$
Targeted tH decays	$\mathrm{t}\to\mathrm{b}\ell\nu$, $\mathrm{H}\to\mathrm{WW}\to\ell\nu\mathrm{qq}$	$\mathrm{t}\to\mathrm{b}\ell\nu$, $\mathrm{H}\to\tau\tau\to\ell\tau_\mathrm{h}+\nu'\mathrm{s}$
Trigger	Single- and double-lepton triggers	
Lepton p_T	$p_\mathrm{T}>25$ / 15 GeV	$p_\mathrm{T}>25$ / 15 GeV (e) or 10 GeV (μ)
Lepton η	$\lvert\eta\rvert<2.5$ (e) or 2.4 (μ)	
τ_h p_T	—	$p_\mathrm{T}>20$ GeV
τ_h η	—	$\lvert\eta\rvert<2.3$
τ_h identification	—	very-loose
Charge requirements	2 same-sign leptons and charge quality requirements	2 same-sign leptons and charge quality requirements $\sum_{\ell,\tau_\mathrm{h}} q=\pm1$
Multiplicity of central jets	$\geq$3 jets	$\geq$3 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	$L_\mathrm{D}>30\,\mathrm{GeV}^\dagger$	
Dilepton invariant mass	$\lvert m_{\ell\ell}-m_\mathrm{Z}\rvert>10\,\mathrm{GeV}^\ddagger$ and $m_{\ell\ell}>12$ GeV	

Selection step	$3\ell + 0\tau_h$	$3\ell + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to b\ell\nu$ with $H \to WW \to \ell\nu qq'$ $t \to b\ell\nu$, $t \to bqq'$ with $H \to WW \to \ell\nu\ell\nu$ $t \to b\ell\nu$, $t \to bqq'$ with $H \to ZZ \to \ell\ell qq'$ or $\ell\ell\nu\nu$	$t \to b\ell\nu$, $t \to b\ell\nu$ with $H \to \tau\tau \to \ell\nu\nu\tau_h\nu$
Targeted tH decays	$t \to b\ell\nu$, $H \to WW \to \ell\nu\ell\nu$	—
Trigger	Single-, double- and triple-lepton triggers	
Lepton p_T	$p_T > 25$ / 15 / 10 GeV	
Lepton η	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)	
τ_h p_T	—	$p_T > 20$ GeV
τ_h η	—	$\lvert\eta\rvert < 2.3$
τ_h identification	—	very-loose
Charge requirements	$\sum_\ell q = \pm 1$	$\sum_{\ell,\tau_h} q = 0$
Multiplicity of central jets	$\geq$2 jets	
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	$L_D > 0$ / 30 / 45 GeV[‡]	
Dilepton invariant mass	$m_{\ell\ell} > 12$ GeV and $\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV[§]	
Four-lepton invariant mass	$m_{4\ell} > 140$ GeV[¶]	—

Selection step	$0\ell + 2\tau_h$	$1\ell + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to bqq'$, $t \to bqq'$ with $H \to \tau\tau \to \tau_h\nu\tau_h\nu$	$t \to bqq'$, $t \to bqq'$ with $H \to \tau\tau \to \ell\nu\nu\tau_h\nu$
Trigger	Double-τ_h trigger	Single-lepton and lepton+τ_h triggers
Lepton p_T	—	$p_T > 30$ (e) or 25 GeV (μ)
Lepton η	—	$\lvert\eta\rvert < 2.1$
τ_h p_T	$p_T > 40$ GeV	$p_T > 30$ GeV
τ_h η	$\lvert\eta\rvert < 2.1$	
τ_h identification	loose	medium
Charge requirements	$\sum_{\tau_h} q = 0$	$\sum_{\ell,\tau_h} q = 0$
Multiplicity of central jets	$\geq$4 jets	
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Dilepton invariant mass	$m_{\ell\ell} > 12$ GeV	

Selection step	$1\ell + 2\tau_h$	$2\ell + 2\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to bqq'$ with $H \to \tau^+\tau^- \to \tau_h\nu\tau_h\nu$	$t \to b\ell\nu$, $t \to b\ell\nu$ with $H \to \tau^+\tau^- \to \tau_h\nu\tau_h\nu$
Trigger	Single-lepton and lepton+τ_h triggers	Single- and double-lepton triggers
Lepton p_T	$p_T > 30$ (e) or 25 GeV (μ)	$p_T > 25$ / 10 (15) GeV (e)
Lepton η	$\lvert\eta\rvert < 2.1$	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)
τ_h p_T	$p_T > 30$ / 20 GeV	$p_T > 20$ GeV
τ_h η	$\lvert\eta\rvert < 2.1$	$\lvert\eta\rvert < 2.3$
τ_h identification	medium	medium
Charge requirements	$\sum_{\ell,\tau_h} q = \pm 1$	$\sum_{\ell,\tau_h} q = 0$
Multiplicity of central jets	$\geq$3 jets	$\geq$2 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	—	$L_D > 0$ / 30 / 45 GeV†
Dilepton invariant mass	$m_{\ell\ell} > 12$ GeV	

Selection step	$2\ell\text{os} + 1\tau_h$	$4\ell + 0\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to bqq'$ with $H \to \tau^+\tau^- \to \ell\nu\nu\tau_h\nu$	$t \to b\ell\nu$, $t \to b\ell\nu$ with $H \to WW \to \ell\nu\ell\nu$ $t \to b\ell\nu$, $t \to b\ell\nu$ with $H \to ZZ \to \ell\ell qq'$ or $\ell\ell\nu\nu$
Trigger	Single- and double-lepton triggers	Single-, double- and triple-lepton triggers
Lepton p_T	$p_T > 25$ / 15 GeV (e) or 10 GeV (μ)	$p_T > 25$ / 15 / 15 / 10 GeV
Lepton η	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)	
τ_h p_T	$p_T > 20$ GeV	—
τ_h η	$\lvert\eta\rvert < 2.3$	—
τ_h identification	tight	—
Charge requirements	$\sum_\ell q = 0$ and $\sum_{\ell,\tau_h} q = \pm 1$	$\sum_\ell q = 0$
Multiplicity of central jets	$\geq$3 jets	$\geq$2 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	$L_D > 30$ GeV[†]	$L_D > 0$ / 30 / 45 GeV[‡]
Dilepton invariant mass	$m_{\ell\ell} > 12$ GeV	$\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV[§] and $m_{\ell\ell} > 12$ GeV
Four-lepton invariant mass	—	$m_{4\ell} > 140$ GeV[¶]