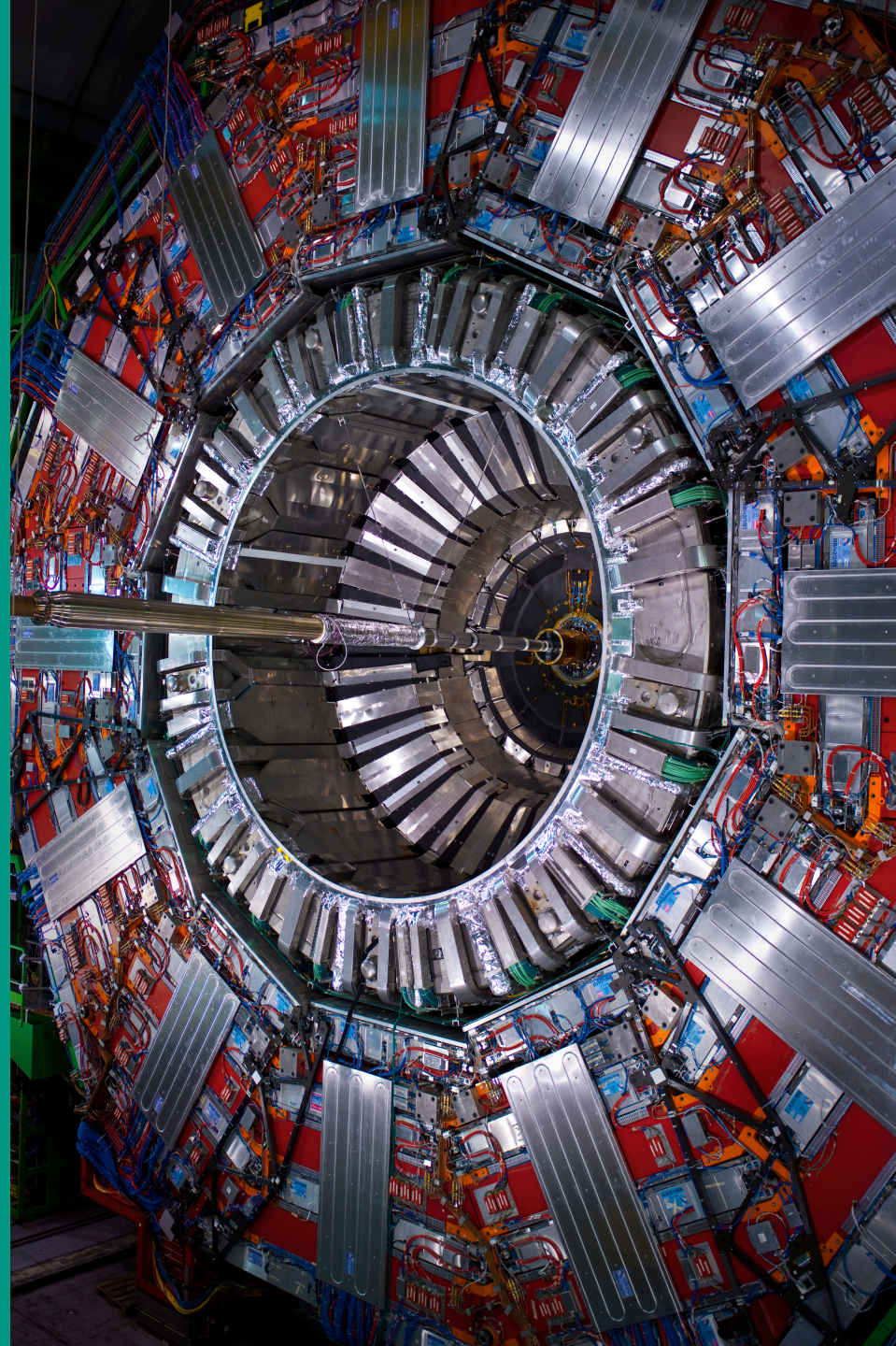


Towards a differential cross section measurement of $t\bar{t}H$ production in multilepton final states with CMS Run 3 data

57. Herbstschule Bad Honnef, 4 Sep 2026

Joscha Ahäuser, Lara Fuchs, Jan Kieseler



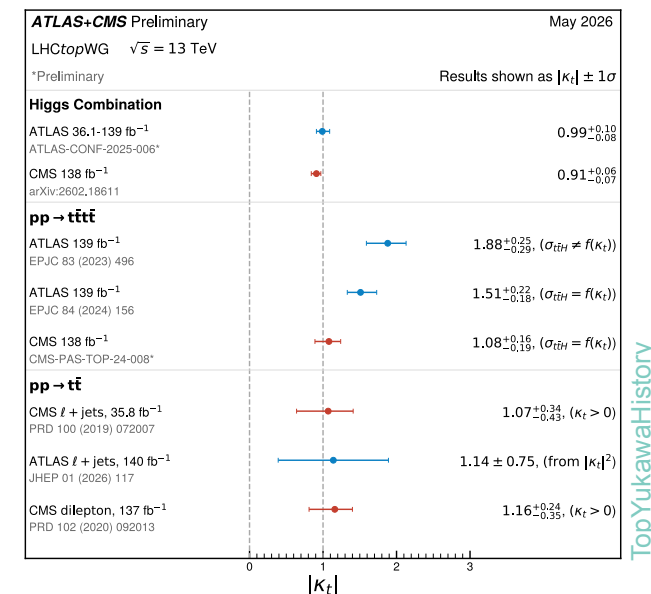
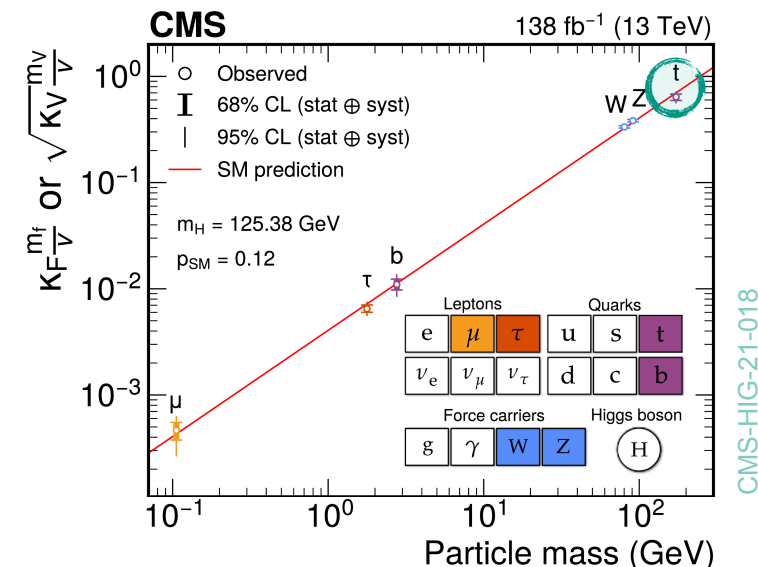
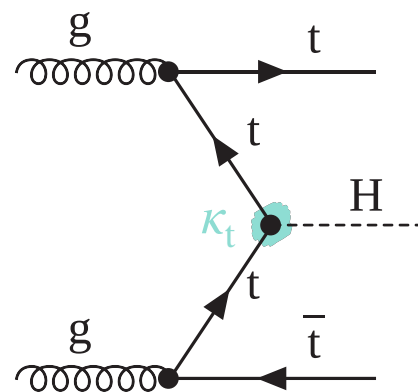
Introduction and motivation

Testing the Standard Model with Higgs coupling measurements

- Mass generation through electroweak symmetry breaking
- SM prediction for fermion masses: **Yukawa coupling** $y_f^{\text{SM}} = m_f/v$
- Any deviation from $\kappa_f = y_f/y_f^{\text{SM}} = 1$ is a clear sign of BSM physics

Probing the top-Yukawa coupling via $t\bar{t}H$

- Heaviest known elementary particle ($m_t = 173 \text{ GeV}$)
 ➡ strongest coupling $y_t \sim \mathcal{O}(1)$
- $t\bar{t}H$ production as **direct probe** of $|\kappa_t|$ via $\sigma_{t\bar{t}H} \propto \kappa_t^2$
- Separation of analyses by final state:
 $H \rightarrow b\bar{b}, H \rightarrow \gamma\gamma, t\bar{t}H \rightarrow \text{multileptons}$



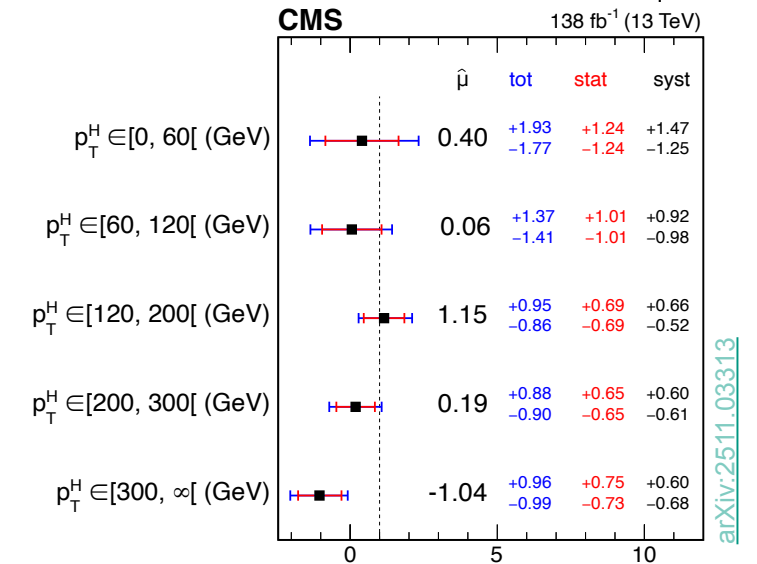
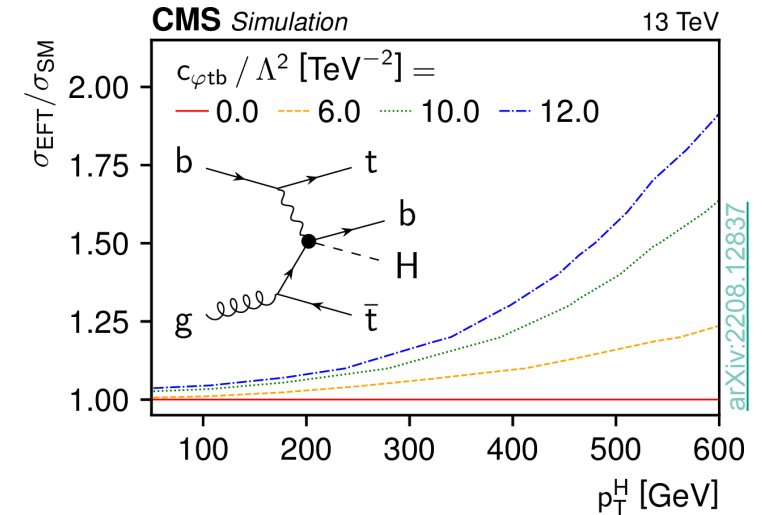
From inclusive rates to differential distributions

Limitation of an inclusive $t\bar{t}H$ measurement

- Reduced sensitivity to energy-dependent BSM effects
 - e.g. EFT enhancement in high p_T^H -tails

Differential cross section measurements

- Common approach: measuring $\sigma_{t\bar{t}H}$ in bins of p_T^H
- Challenging reconstruction for multilepton final states



$$\hat{\mu} = \hat{\sigma}/\sigma_{\text{SM}}$$

From inclusive rates to differential distributions

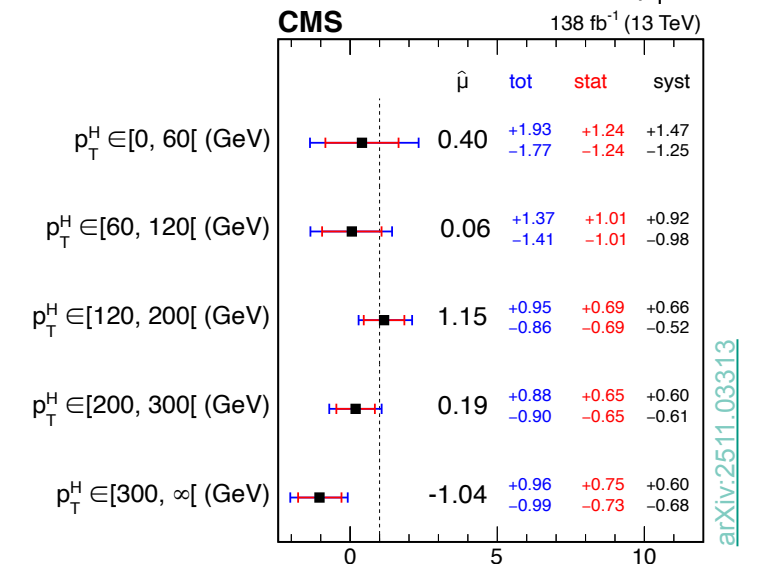
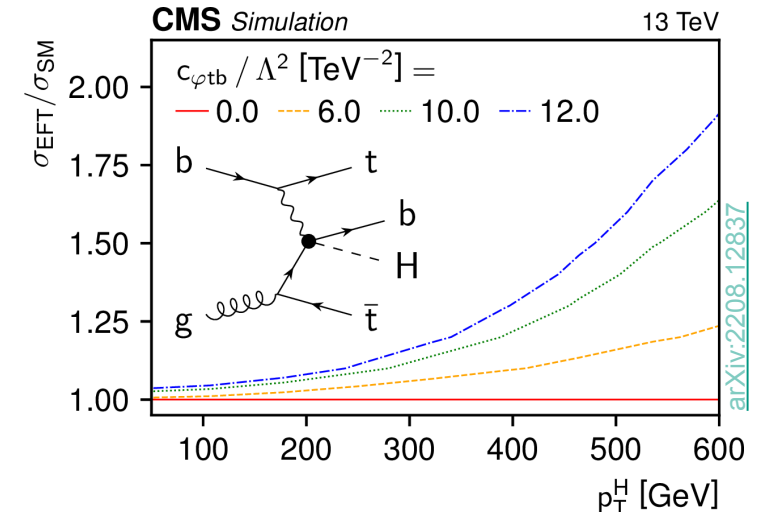
Limitation of an inclusive $t\bar{t}H$ measurement

- Reduced sensitivity to energy-dependent BSM effects
 - e.g. EFT enhancement in high p_T^H -tails

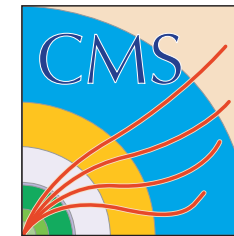
Differential cross section measurements

- Common approach: measuring $\sigma_{t\bar{t}H}$ in bins of p_T^H
- Challenging reconstruction for multilepton final states

Goal: finding alternative observables for differential measurements combining enhanced BSM sensitivity with high precision



CMS experiment



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel ($100 \times 150 \mu\text{m}^2$) $\sim 1 \text{ m}^2$ $\sim 66\text{M}$ channels
Microstrips ($80\text{--}180 \mu\text{m}$) $\sim 200 \text{ m}^2$ $\sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000 \text{ A}$

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips $\sim 16 \text{ m}^2$ $\sim 137,000$ channels

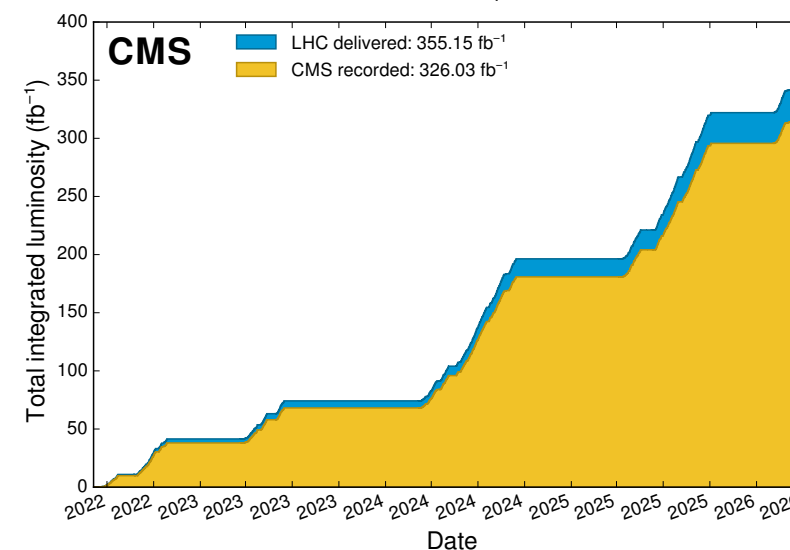
FORWARD CALORIMETER
Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels

Dataset

- Full CMS Run 3 (2022-2026): 326 fb^{-1} of pp collision data recorded at $\sqrt{s} = 13.6 \text{ TeV}$



Analysis scope

- Done: full implementation of 2022-2023 data (61.9 fb^{-1})
- Ongoing: integration of 2024 data (109.9 fb^{-1})

Analysis strategy

- Final states with two to four (light) leptons ($\ell = e, \mu$) and hadronically decaying τ_h producing distinct signatures
- Simultaneous analysis of $t\bar{t}H$ and tH
 - Extraction of magnitude and sign (interference in tH) of top-Yukawa coupling

Analysis pipeline

1. Event categorization and selection

10 non-overlapping channels based on lepton multiplicity

2. Background modeling

Data-driven background estimation, validation in control regions

3. Signal extraction

Classifier training and statistical analysis

4. Extension to differential cross section measurements

Targeted decay modes
$H \rightarrow WW$
$\hookrightarrow \ell^+ \nu_\ell qq'$
$\hookrightarrow \ell^+ \nu_\ell \ell^- \bar{\nu}_\ell$
$H \rightarrow ZZ$
$\hookrightarrow \ell^+ \ell^- qq'$
$\hookrightarrow \ell^+ \ell^- \nu \bar{\nu}$
$H \rightarrow \tau\tau$
$\hookrightarrow \ell^+ \nu_\ell \bar{\nu}_\tau \ell^- \bar{\nu}_\ell \nu_\tau$
$\hookrightarrow \ell^+ \nu_\ell \bar{\nu}_\tau \tau_h \nu_\tau$
$\hookrightarrow \tau_h \bar{\nu}_\tau \tau_h \nu_\tau$
$t \rightarrow bW^+$
$\hookrightarrow b \ell^+ \nu_\ell$
$\hookrightarrow b qq'$

Analysis channels

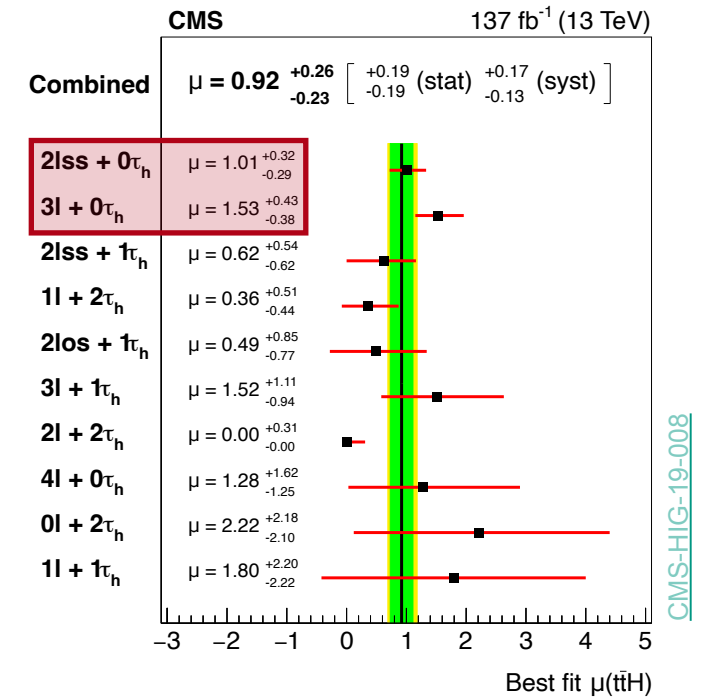
- Classification according to the number of ℓ ($= e, \mu$) and τ_h

→ 10 non-overlapping channels

		lepton multiplicity		
τ_h multiplicity		$2\ell\text{SS} + 0\tau_h$	$3\ell + 0\tau_h$	$4\ell + 0\tau_h$
	$1\ell + 1\tau_h$	$2\ell\text{SS} + 1\tau_h$ $2\ell\text{OS} + 1\tau_h$	$3\ell + 1\tau_h$	
	$0\ell + 2\tau_h$	$2\ell + 2\tau_h$		

- Most sensitive (and $t\bar{t}H$ -enriched) channels: $2\ell\text{SS} + 0\tau_h$, $3\ell + 0\tau_h$

same-sign



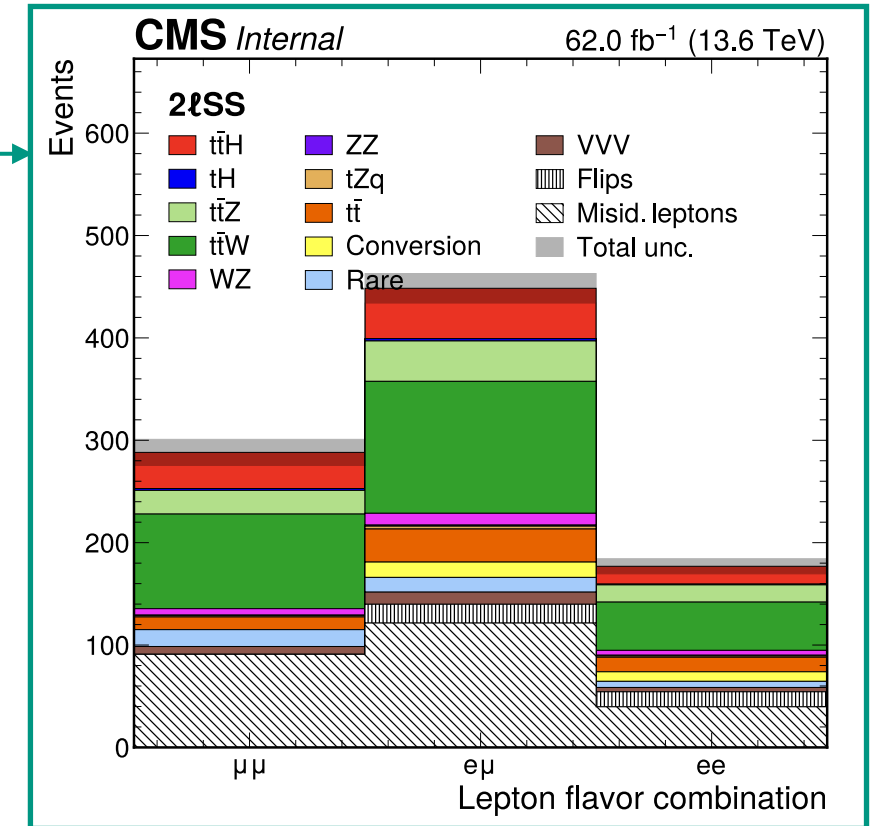
Analysis channels

$2\ell SS + 0\tau_h$

- Targeted Higgs decay: $H \rightarrow WW \rightarrow \ell\nu qq'$
- Select same-sign (SS) leptons only to reduce $t\bar{t}$ background

$3\ell + 0\tau_h$

- Targeted Higgs decays: $H \rightarrow WW \rightarrow \ell\nu qq'$
 $H \rightarrow WW \rightarrow \ell\nu\ell\nu$
 $H \rightarrow ZZ \rightarrow \ell\ell qq', \ell\ell\nu\nu$
- Dominant background sources: $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$, ...



Analysis channels

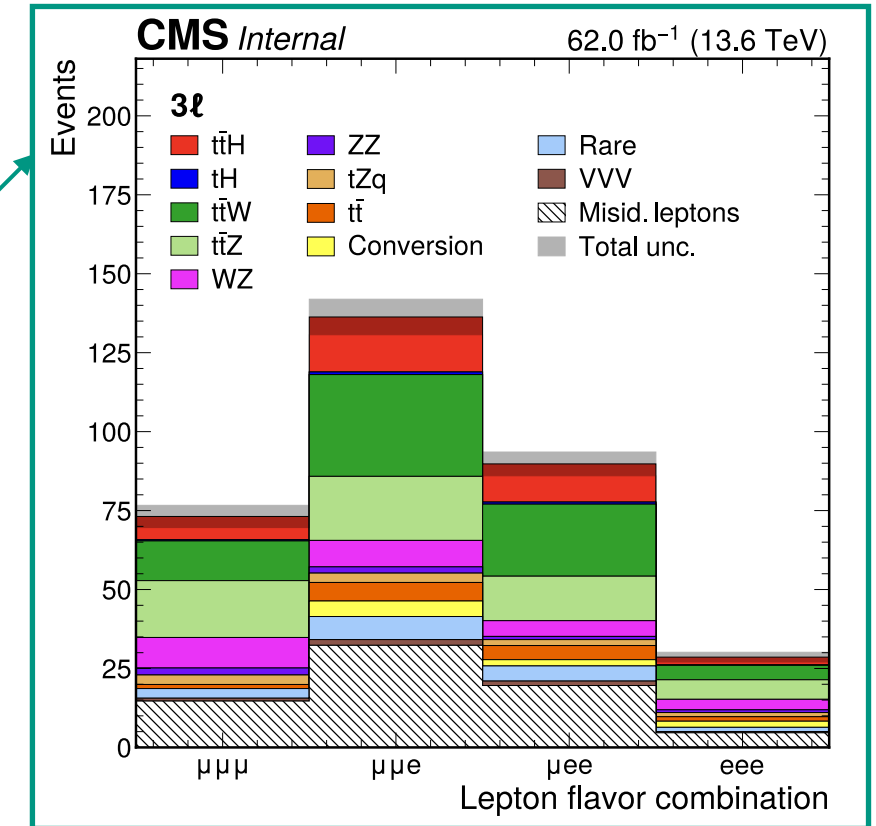
$$2\ell\text{SS} + 0\tau_h$$

- Targeted Higgs decay: $H \rightarrow WW \rightarrow \ell\nu qq'$
- Select same-sign (SS) leptons only to reduce $t\bar{t}$ background

$$3\ell + 0\tau_h$$

- Targeted Higgs decays: $H \rightarrow WW \rightarrow \ell\nu qq'$
 $H \rightarrow WW \rightarrow \ell\nu\ell\nu$
 $H \rightarrow ZZ \rightarrow \ell\ell qq', \ell\ell\nu\nu$

- Dominant background sources: $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$, ...



Reducible background

- Dominant background sources: $t\bar{t}W(W)$, $t\bar{t}Z$, $t\bar{t}$, ...
 - Not all reconstructed leptons are genuine and prompt
- ➡ Categorization into **reducible** and irreducible background

1. Misidentified leptons

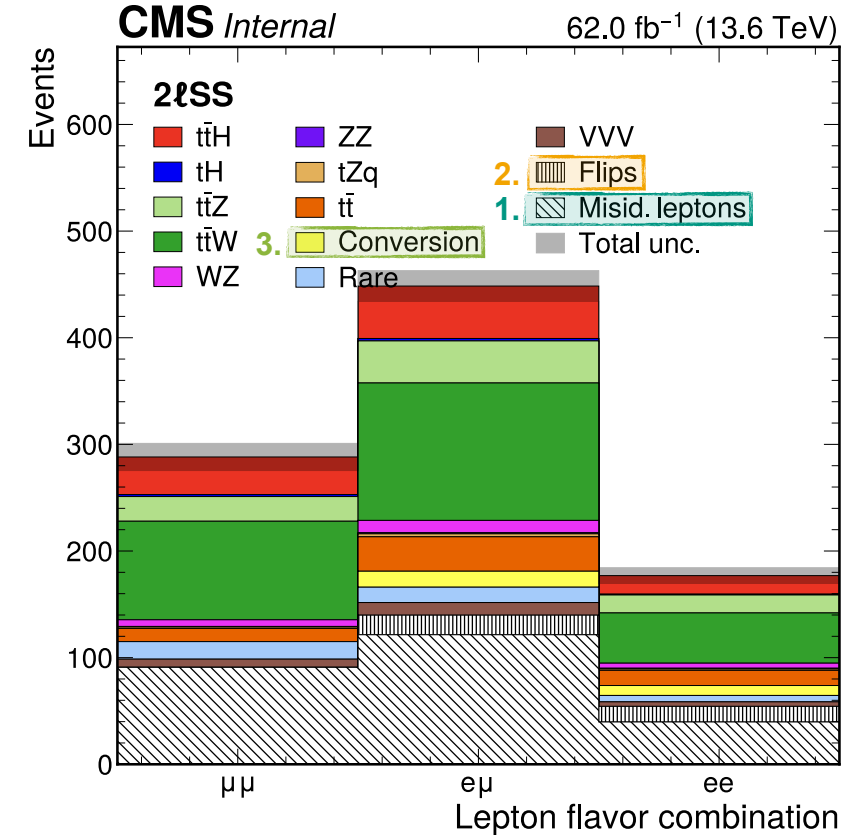
- Non-prompt leptons or hadrons
- Main contribution from $t\bar{t}$ events
- Data-driven estimation

2. Flips

- Misidentified electron charges (2ℓ SS channels)
- Main contribution from $t\bar{t}$ events
- Data-driven estimation

3. Conversions

- Asymmetric photon conversions
- Main contribution from $t\bar{t}\gamma$ events
- Modeled using simulation



Irreducible background

- All reconstructed leptons are genuine and prompt
- Validation via control regions

3 ℓ -CR

Targeting $t\bar{t}Z$ and WZ backgrounds

Based on $3\ell + 0\tau_h$ signal region with SFOS* lepton pair $|m_{\ell\ell} - m_Z| < 10 \text{ GeV}$

Binned in jet multiplicity and lepton flavor

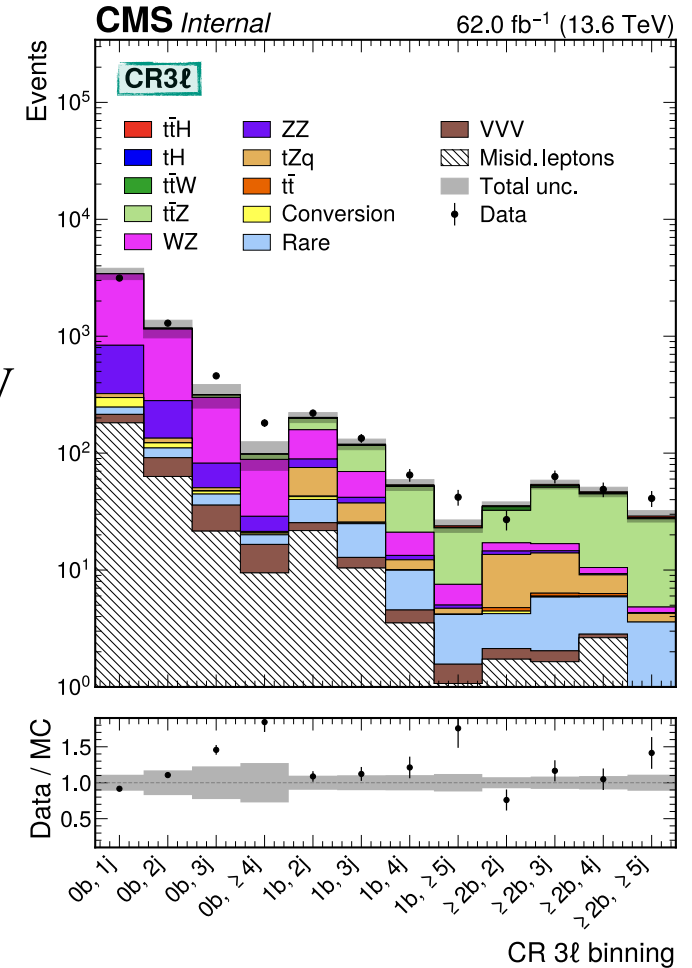
4 ℓ -CR

Targeting ZZ background

Based on $4\ell + 0\tau_h$ sign with SFOS lepton pair with $|m_{\ell\ell} - m_Z| < 10 \text{ GeV}$

Binned in jet multiplicity and number of $Z \rightarrow \ell^+\ell^-$ candidates

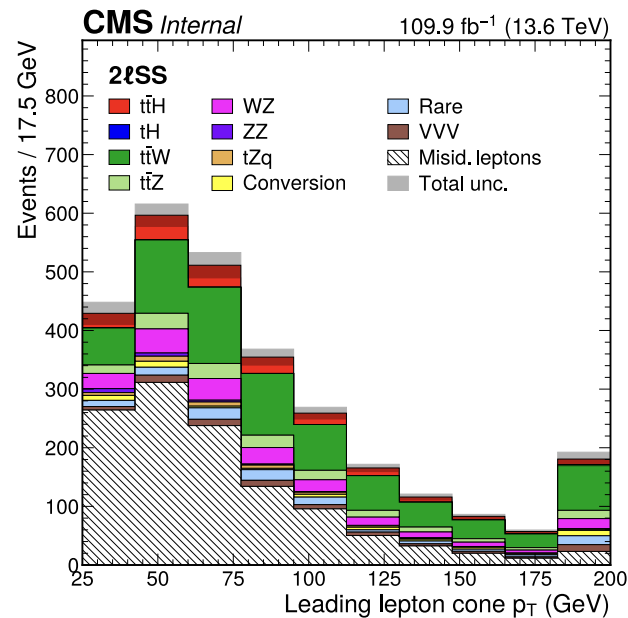
➡ Input to signal extraction



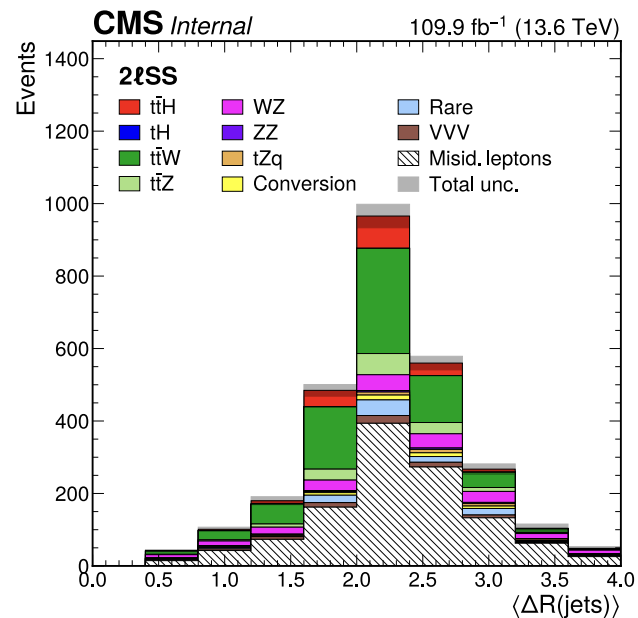
Signal vs. background classification

- Cut-based background rejection is unfeasible → training multi-class DNNs to classify signal and background
- Classifier output as input to signal extraction
 - Simultaneous Maximum Likelihood fit across all channels and data taking periods

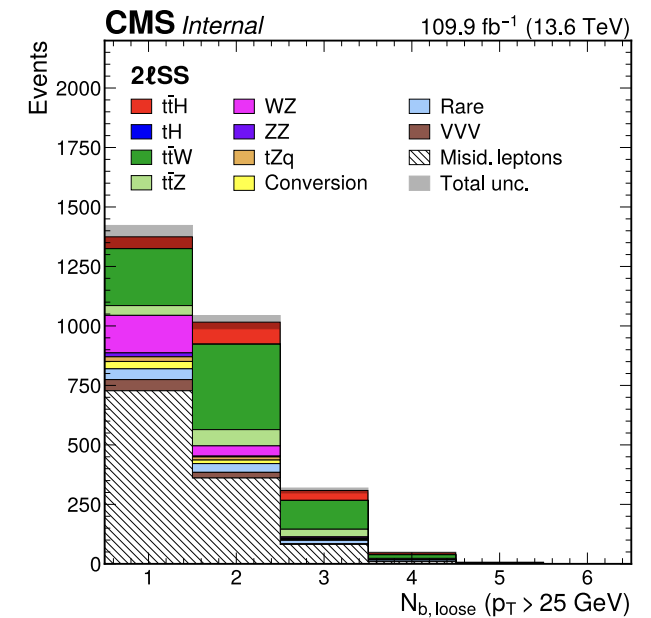
$t\bar{t}H$ vs. $t\bar{t}V$



$t\bar{t}H$ vs. reducible background



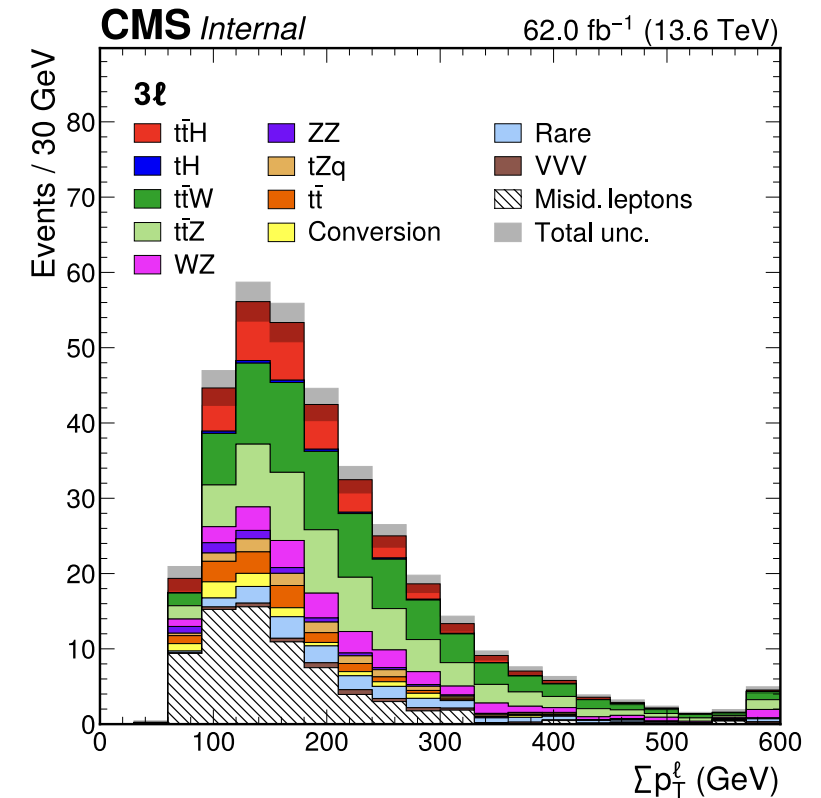
$t\bar{t}H$ vs. other background



Towards a differential cross section measurement

Challenge: finding optimal observables for differential distributions

- Requirements: sensitivity, experimental robustness, reinterpretability
- Option 1: Standard intuition-driven observables
 - e.g. p_T^H , p_T^t , $\Sigma p_T^{\text{jets}/\ell}$, ...
- Option 2: Machine-learned observables
 - Often complex and difficult to interpret



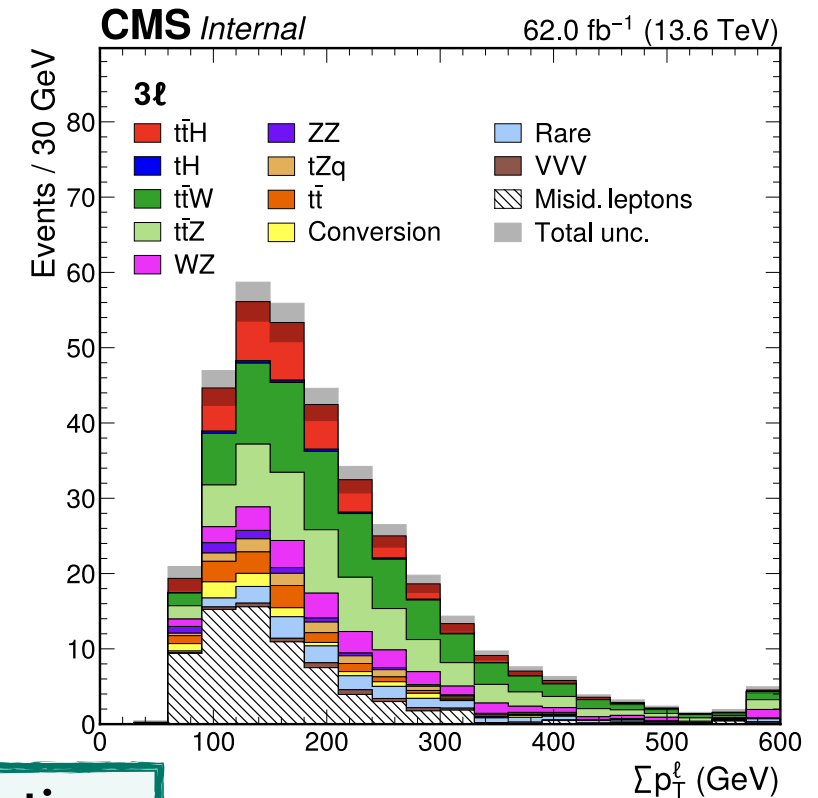
Towards a differential cross section measurement

Challenge: finding optimal observables for differential distributions

- Requirements: sensitivity, experimental robustness, reinterpretability
- Option 1: Standard intuition-driven observables
 - e.g. p_T^H , p_T^t , $\Sigma p_T^{\text{jets}/\ell}$, ...
- Option 2: Machine-learned observables
 - Often complex and difficult to interpret

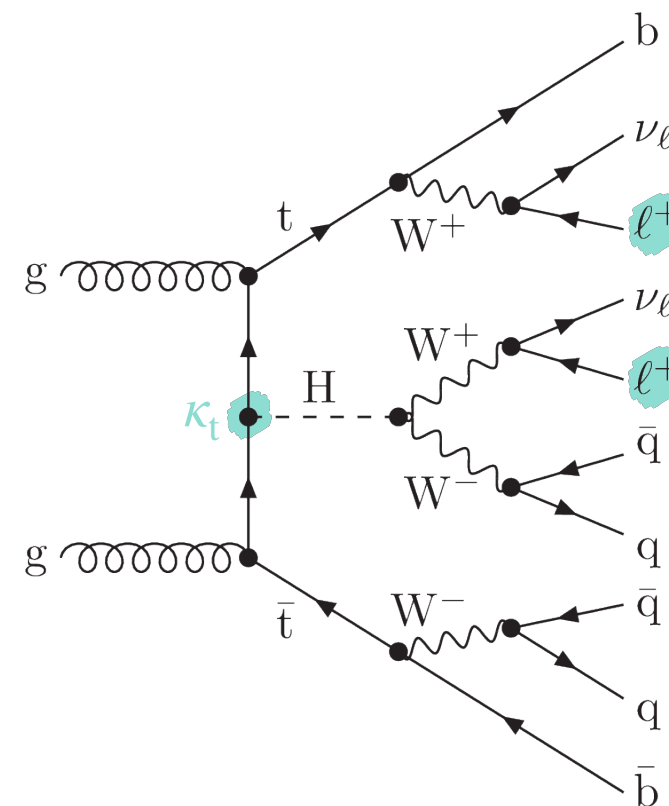
Outlook: Exploring ML frameworks for optimal observable construction

- Case study: Optimal Observable Machine (T. Mohr et al., [arXiv:2601.08813](https://arxiv.org/abs/2601.08813))
- Simultaneous training of two MLPs with generator- and detector-level input
- Unfolding- and uncertainty-aware training



Conclusion

- **Direct probe of the top-Yukawa coupling:** Measuring $t\bar{t}H$ production in multilepton final states targeting $H \rightarrow WW$, $H \rightarrow ZZ$ and $H \rightarrow \tau\tau$ decays
- **Experimental strategy:** Analysis in exclusive channels, background modeling, DNNs for signal/background classification
- **Towards a differential measurement:** Exploring modern ML frameworks for optimal observable construction

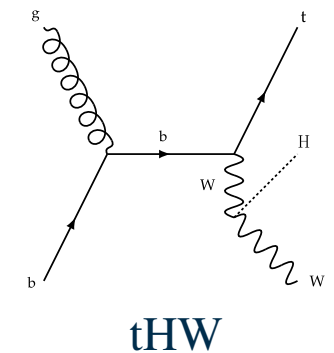
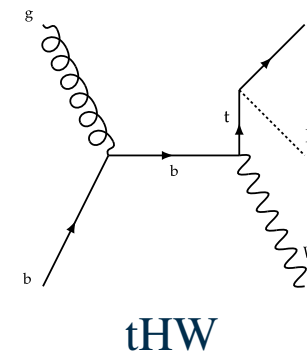
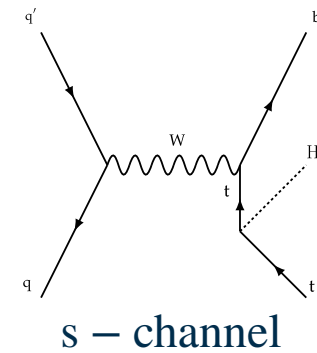
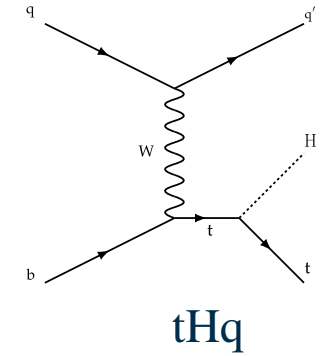
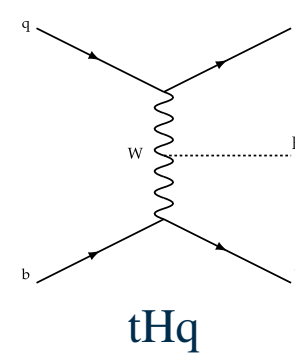
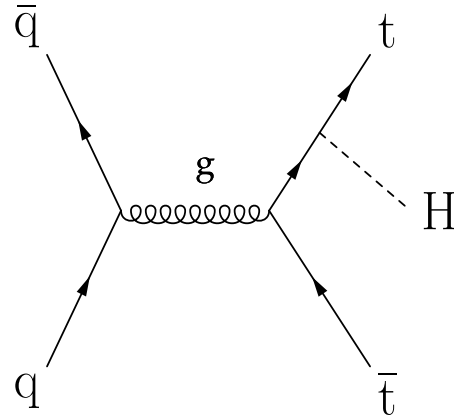
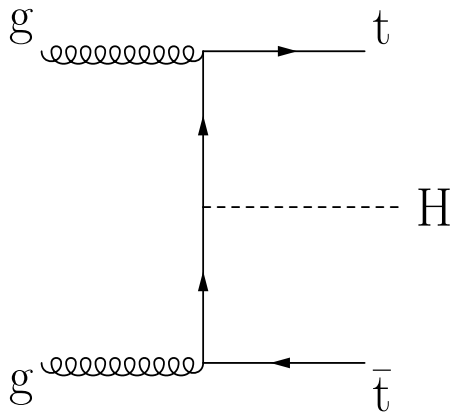


Leveraging the full Run 3 dataset to perform high-precision inclusive and differential $t\bar{t}H$ measurements will provide a strong test of the Standard Model

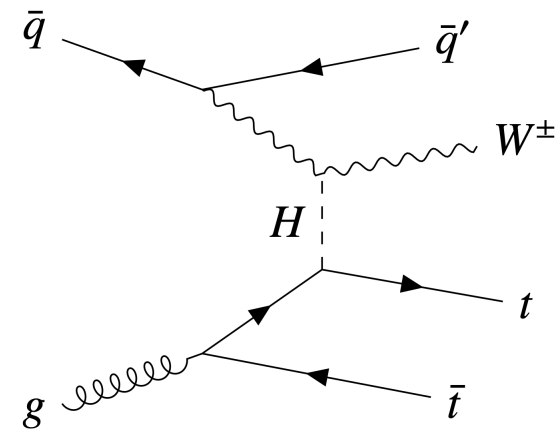
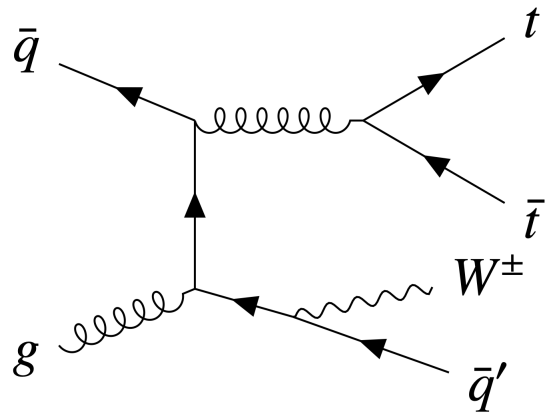
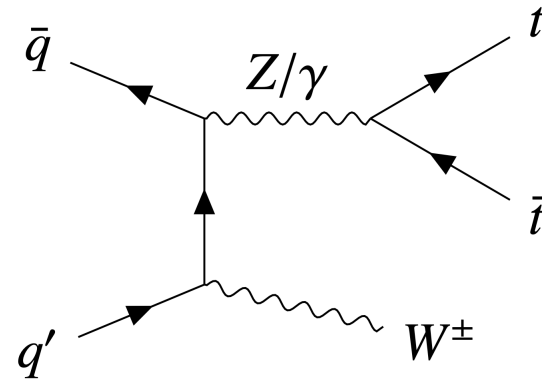
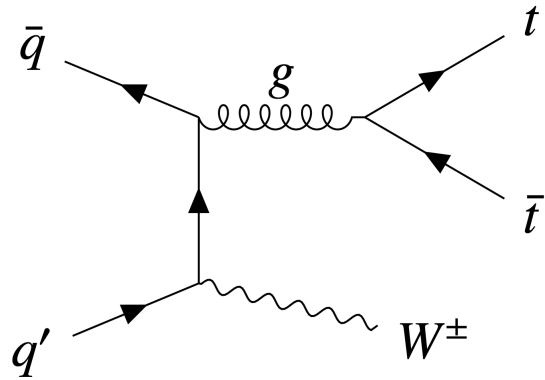


Backup

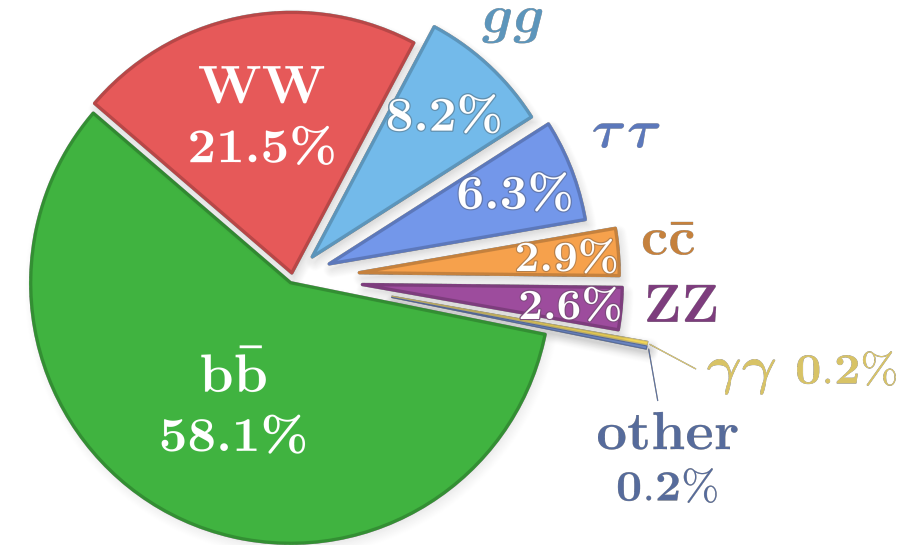
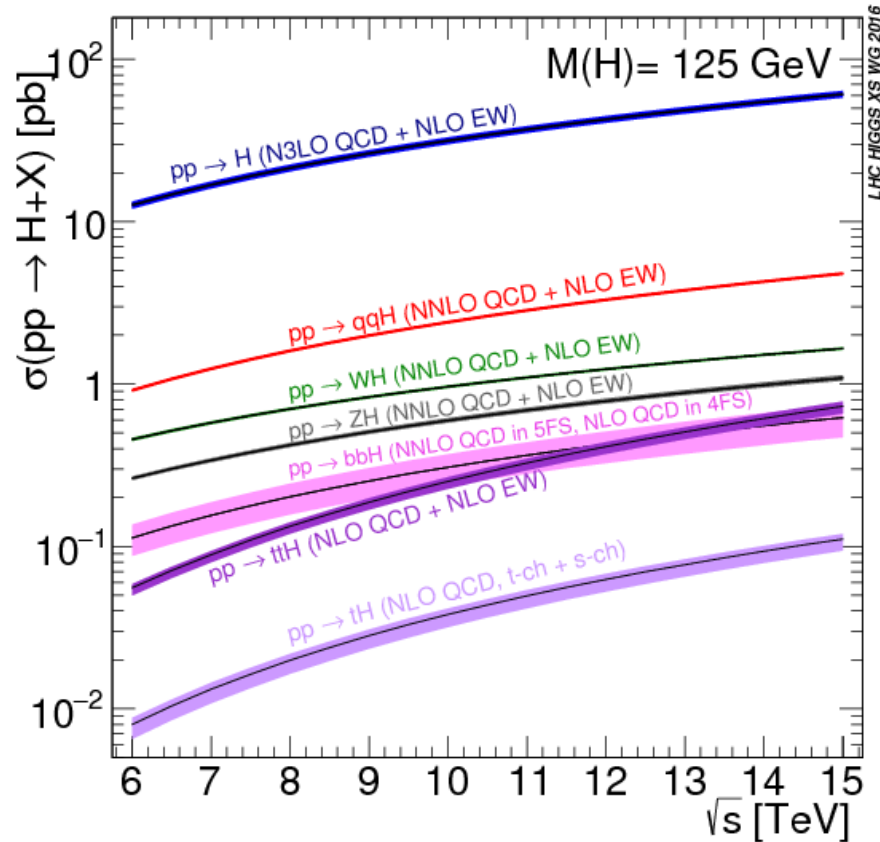
$t\bar{t}H + tH$ production diagrams



$t\bar{t}W$ production



Higgs production cross sections and branching fractions



Event selection

Selection step	$2\ell\text{SS}$	3ℓ
Targeted $t\bar{t}H$ decay	$t \rightarrow b\ell\nu, t \rightarrow qq'$ with $H \rightarrow WW \rightarrow \ell\nu qq'$	$t \rightarrow b\ell\nu, t \rightarrow b\ell\nu$ with $H \rightarrow WW \rightarrow \ell\nu qq'$ $t \rightarrow b\ell\nu, t \rightarrow qq'$ with $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ $t \rightarrow b\ell\nu, t \rightarrow qq'$ with $H \rightarrow ZZ \rightarrow \ell\ell qq'$ or $\ell\ell\nu\nu$
Trigger	Single- and double-lepton	Single-, double- and triple-lepton
Lepton multiplicity	$N_{\ell,\text{FO}} \geq 2, N_{\ell,\text{tight}} \leq 2$	$N_{\ell,\text{FO}} \geq 3, N_{\ell,\text{tight}} \leq 3$
Lepton p_T	$p_T(\ell_1) > 25 \text{ GeV}, p_T(\ell_2) > 15 \text{ GeV}$	$p_T(\ell_1) > 25 \text{ GeV}, p_T(\ell_2) > 15 \text{ GeV}, p_T(\ell_3) > 10 \text{ GeV}$
Charge requirements	2 SS leptons, tight charge req.	$\sum_{\ell} q = \pm 1$, tight charge req. (e)
Jet multiplicity	$N_{\text{jets}}(p_T > 25 \text{ GeV}) \geq 4$	$N_{\text{jets}}(p_T > 25 \text{ GeV}) \geq 2$
b tagging requirements		$N_{\text{b,loose}} \geq 2$ or $N_{\text{b,medium}} \geq 1$
Dilepton invariant mass		$m_{\ell\ell} > 12 \text{ GeV}, m_{\ell\ell} - m_Z > 10 \text{ GeV}$ (SFOS)
Four-lepton invariant mass	—————	$ m_{4\ell} - m_H > 10 \text{ GeV}$
τ_h veto		$N_{\tau_h} = 0$

Results (Run 2 analysis)

- Fit result from all channels (combined and individual)
 - $2\ell + 2\tau_h$ constrained to ≥ 0
 - Highest sensitivity in $2\ell SS + 0\tau_h$

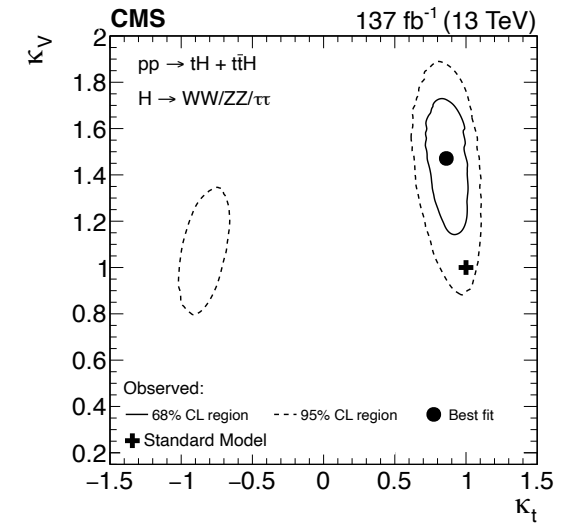
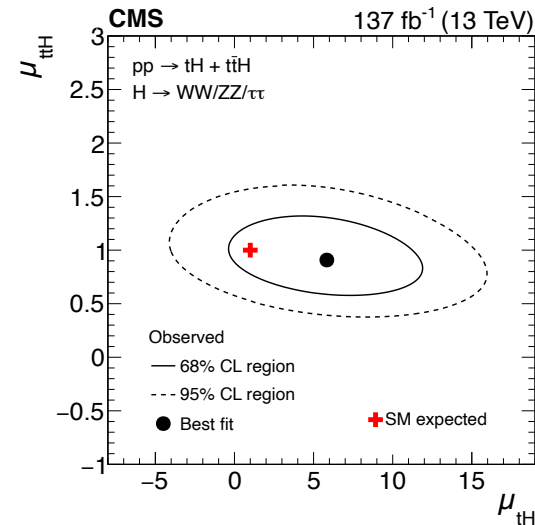
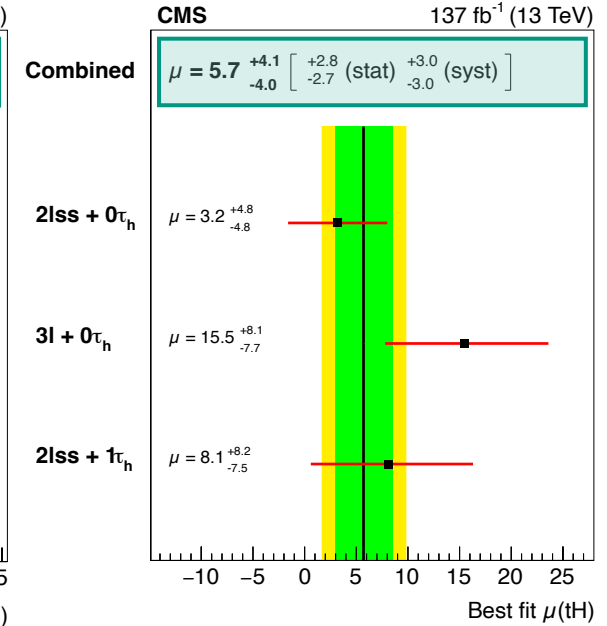
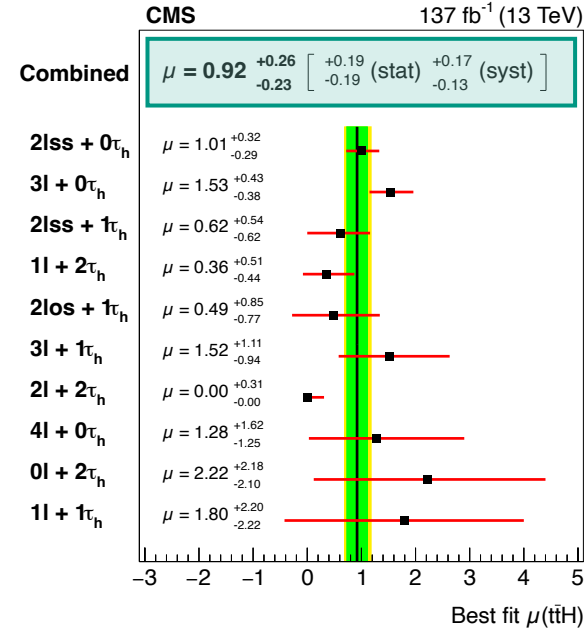
Production rate ($\times$ SM exp.)	Obs. (exp.) significance
$\mu_{t\bar{t}H} = 0.92 \pm 0.19(\text{stat})^{+0.17}_{-0.13}(\text{syst})$	4.7σ (5.2σ)
$\mu_{tH} = 5.7 \pm 2.7(\text{stat}) \pm 3.0(\text{syst})$	1.4σ (0.3σ)

- Two intervals of κ_t compatible with data

$$\rightarrow -0.9 < \kappa_t < -0.7 \text{ or } 0.7 < \kappa_t < 1.1 \text{ at } 95\% \text{ C.L.}$$

Inverted top coupling scenario $\kappa_t < 0$

SM expectation κ_t



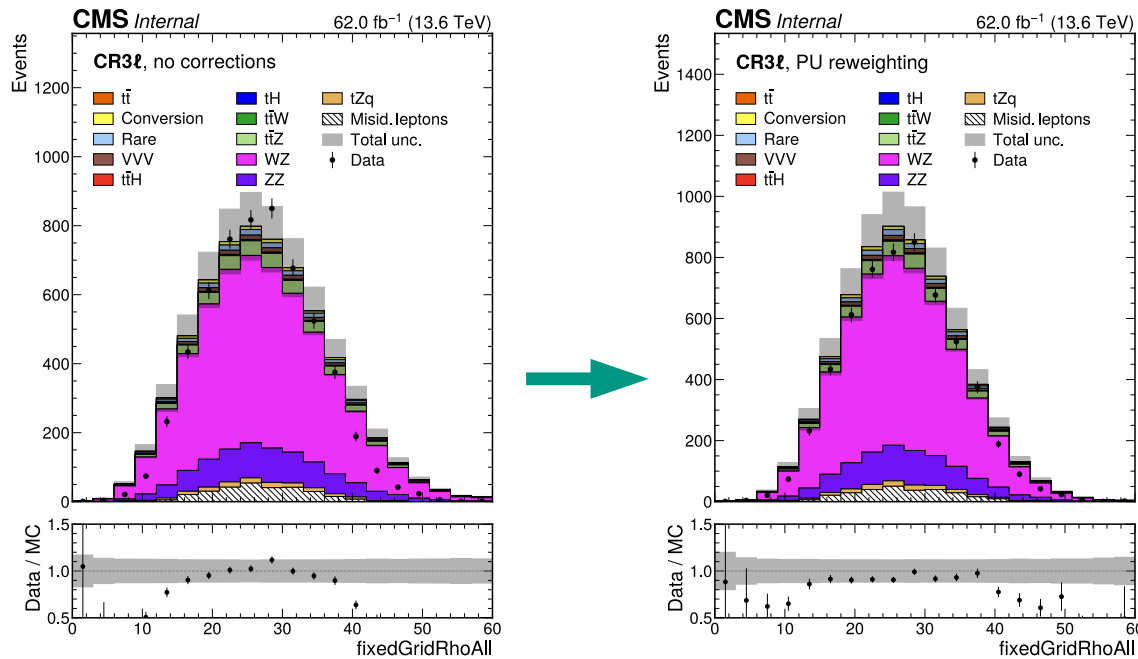
Uncertainties (Run 2 analysis)

Source	$\Delta\mu_{t\bar{t}H}/\mu_{t\bar{t}H}[\%]$	$\Delta\mu_{t\bar{t}H}/\mu_{t\bar{t}H}[\%]$	$\Delta\mu_{t\bar{t}W}/\mu_{t\bar{t}W}[\%]$	$\Delta\mu_{t\bar{t}Z}/\mu_{t\bar{t}Z}[\%]$
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 sample and sideband statistical uncertainty	7.1	27.2	2.4	2.3
Theory-related sources affecting acceptance and shape of distributions	4.6	18.2	2.0	4.2
Normalization of MC-estimated processes	13.3	12.3	13.9	11.3
Integrated luminosity	2.2	4.6	1.8	3.1
Statistical uncertainty	20.9	48.0	5.9	5.8

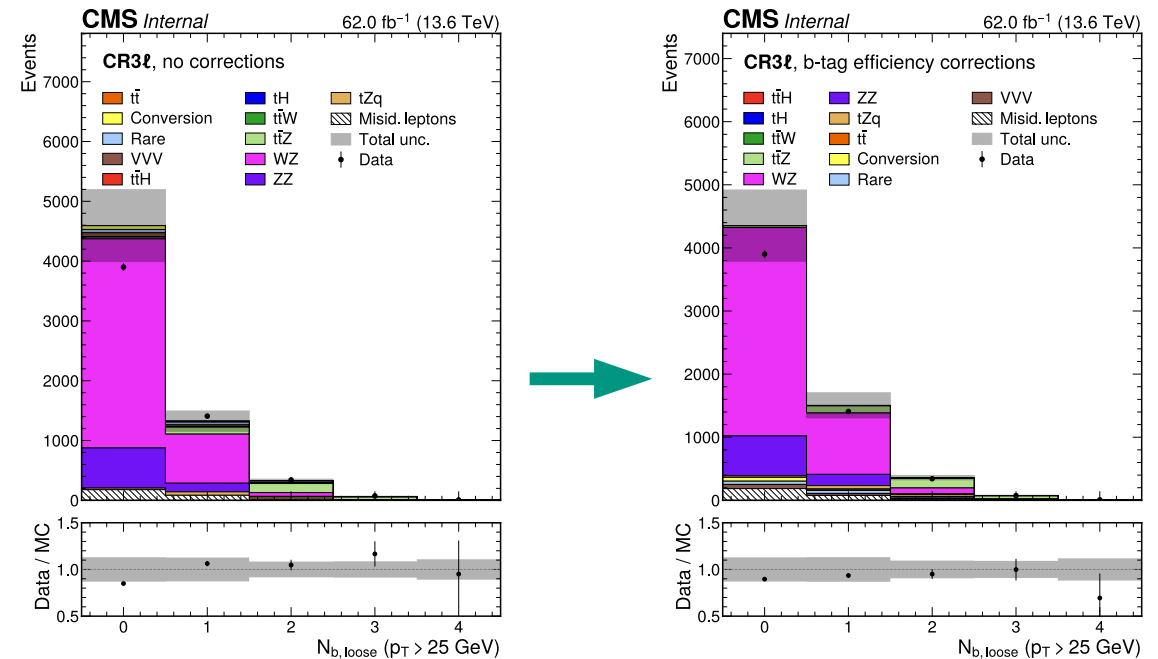
Data-to-MC corrections

- Improve MC modeling by accounting for detector differences in simulation and real Run 3 collision data
- Applied corrections and scale factors:
 - Pileup reweighting, lepton ID, trigger, b-tag, missing energy, τ_h ID and energy

Example 1: Pileup reweighting



Example 2: b-tag efficiency and mistag scale factors



Towards a differential cross section measurement

Motivation: from inclusive rates to differential distributions

- Enhanced sensitivity to BSM effects by exploring phase-space and probing underlying dynamics
- Unfolded $d\sigma/d\mathcal{O}$ distributions allow direct comparison with future theoretical models for
long-term reinterpreatability

Method: Optimal Observable Machine (T. Mohr et al., <https://arxiv.org/pdf/2601.08813>)

- Goal: Construct 1D generator-level observable $\mathcal{O}$ maximizing sensitivity to parameter of interest
- Simultaneous training of two MLPs (Φ_g, Φ_d) with generator- and detector-level input
- Unfolding- and uncertainty-aware training: likelihood-based loss embedding detector response, binning and systematic uncertainties
- Proof of principle: optimal observable for toponium measurement

 **Outlook: Deploying OOM to $t\bar{t}H$ analysis for unfoldable, high-precision differential measurements**