Determination of Higgs boson properties and searches for new resonance using highly boosted objects with the ATLAS experiment

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On behalf of the ATLAS Collaboration

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SLAC NATIONAL ACCELERATOR LABORATORY

ATLAS EXPERIMENT

Stanford University | U.S. DEPARTMENT OF ENERGY

Outline

- BSM narrow resonance search in the $Z(\ell^+\ell^-)\gamma$ final state

  ANA-HIGG-2018-44

- Probing CP nature of the top-Higgs Yukawa coupling in $t\bar{t}H$ & tH events with $H \to b\bar{b}$ decays

  arXiv:2303.05974 Submitted to PLB

- Study of $t\bar{t}b\bar{b}$ & $t\bar{t}W$ background modeling for $t\bar{t}H$ analyses

  ATL-PHYS-PUB-2022-026

BSM High-mass resonance $[Z\gamma]$

- BSM narrow resonance $(m_x) \rightarrow Z(\ell^+\ell^-)\gamma$ spin-0 and spin-2 high mass resonance predicted by Higgs-like model
- Old searches
  - ATLAS leptonic with 36.1 fb-1 13TeV data 250 GeV to 24 TeV constraints
  - ATLAS leptonic 139 fb-1 from 1.0 to 6.8 TeV constraints
  - CMS hadronic hadronic 35.9fb-1 from 1.0 to 6.8 TeV and combined from 0.35 to 4.0 TeV
- **This result for 220 GeV to 3.4 TeV resonance** with **special treatment for boosted electrons/photons**
- **Dataset**: Full Run-2 dataset (2015-2018): 139 fb-1
- **Signal MC:**
  - **Spin 0 resonance ggF** simulated at LO with PowhegBox v1
    - mx = [200, 300, 500, 1000, 1500, 2000, 2500, 3000, 3500]GeV and width 4 MeV
  - **Spin 2 resonance ggF and qqbar** states generated at LO with FxFx MadGraph/Pythia8
    - mx = [200, 250, 300, 500, 750, 1000, 1500, 2000, 2500, 3000, 3500] GeV and width 4 MeV
- **Background :** relatively small
  - Dominant SM Z+ gamma simulated with Sherpa 2.2.2. at LO
  - Sub dominant Z+jets: data driven modeling with control region enhanced by jets misidentified as photons

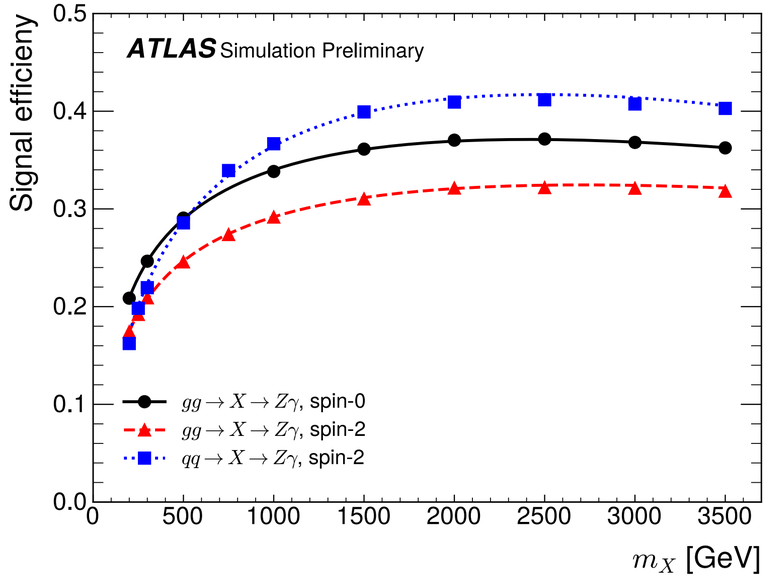
ANA-HIGG-2018-44

BSM High-mass resonance [$Z\gamma$]

- Leptonic & photonic triggers
- Two effects at high mass region
  - Merged electrons
  - Sub-leading electron often reconstructed as photon
- Dedicated MVA method based on a Gradient Boosting Decision Tree (GBDT) with track-based and shower shape variables as input
  - Additional new variables # of TRT hits and $\Delta\phi$ between the cluster energy & associated track in presamples
- Signal efficiency (reco events after selection/expected events)
  - Efficiency evaluated at different mass points & extrapolated using

$$\epsilon = a + b \cdot m_X + c \cdot ln(m_X + d)$$

Selection	Muon	Electron	Electron as photon	Photon
p_T	> 10 GeV	> 10 GeV	> 50 GeV	> 15 GeV
$\lvert\eta\rvert$	< 2.7	< 2.47 Exclude [1.37, 1.52]	< 2.47 Exclude [1.37, 1.52]	< 2.37 Exclude [1.37, 1.52]
$\lvert d_0\rvert/\sigma_{d_0}$	< 3	< 5		
$\lvert\Delta z_0 \sin\theta\rvert$	< 0.5 mm	< 0.5 mm		
Identification	*Medium*	Mixed	MVA	*Tight*
Isolation	Track-based *Tight*	Track-based *Tight*		*Loose*
$\Delta R(\text{track}, \gamma)$			< 0.1	
ee or $\mu\mu$ pair	≥ 2, opposite charge			
$e\gamma$ pair			$\Delta R(e,\gamma) < 1$ $\lvert p_T^e - p_T^\gamma\rvert / p_T^{e \text{ or } \gamma} > 5\%$	
Categorization	lepton pair closest to $m_Z = 91.2$ GeV, decide electron or muon channel			
Event selections	$\lvert m_{\ell\ell}^{\text{corrected}} - m_Z\rvert < 15$ GeV, $m_Z = 91.2$ GeV Trigger match, overlap removal $p_T^\gamma / m_{Z\gamma} > 0.2$, SR: $200 < m_{Z\gamma} < 3500$ GeV			



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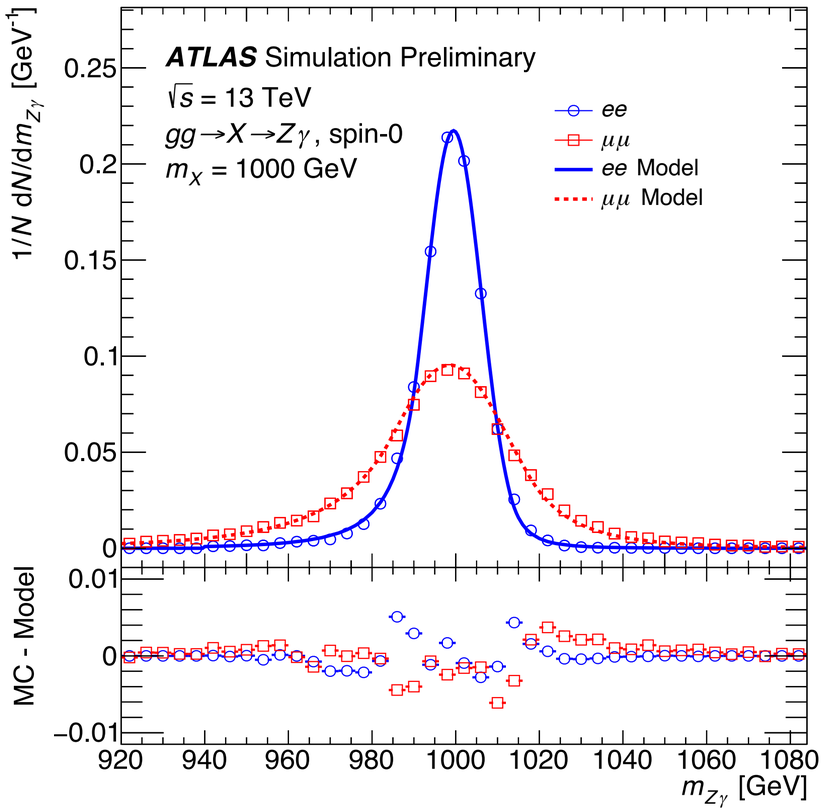
BSM High-mass resonance [$Z\gamma$]

- Analytical models to extract the signal and background yields from the $m_{Z\gamma}$ distribution of the data.
- Signal Modelling
  - $m_{Z\gamma}$ modeled by a Double-Sided Crystal Ball (DSCB) function
  - Signal shape interpolated by simultaneously fitting all signal samples at different $m_{Z\gamma}$
- Background : smooth falling distribution as a function of $m_{Z\gamma}$
  - Total background distribution product of Z+gamma distribution in MC with exponential func for Z+jets/Z+γ obtained from data
  - Analytical background function determined by reducing the bias (estimated using spurious signal) on the extracted signal yield
    - Dijet function used for both ee and $\mu\mu$ channels
      - $f_{bkg}(x; b, a_0) = N(1-x)^b x^{a_o}$, where $x = m_{Z\gamma}/\sqrt{N}$ is normalization factor



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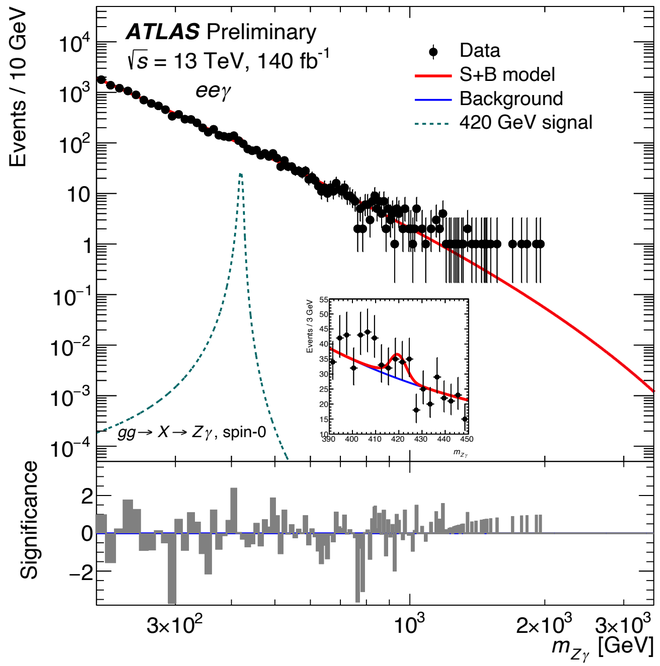
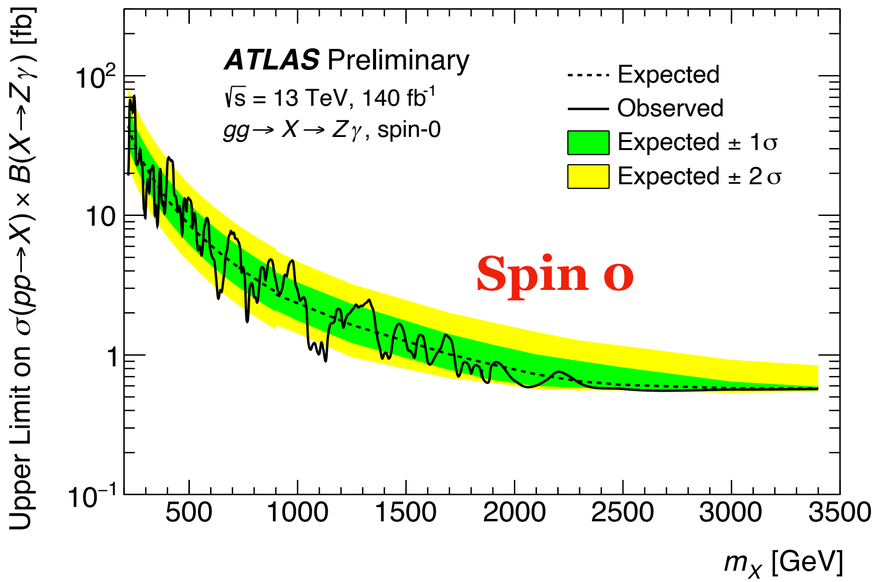
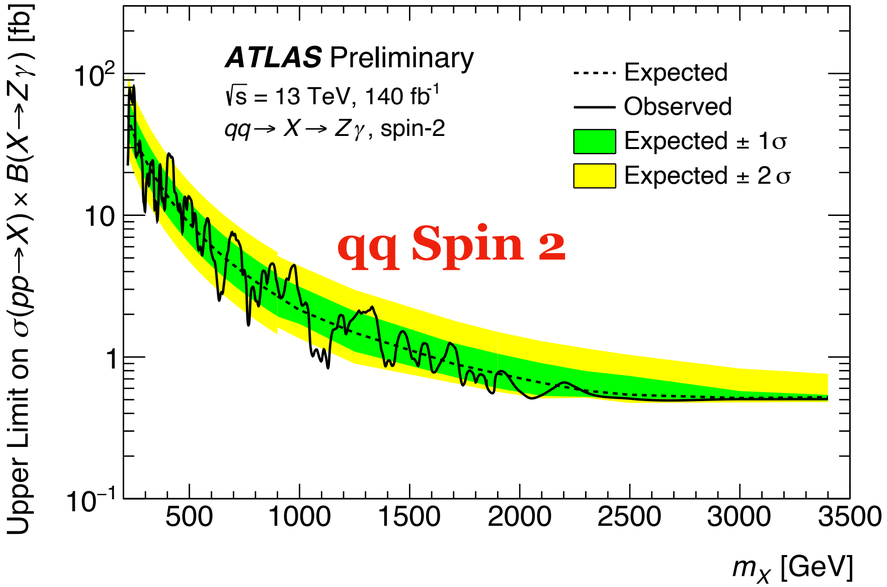
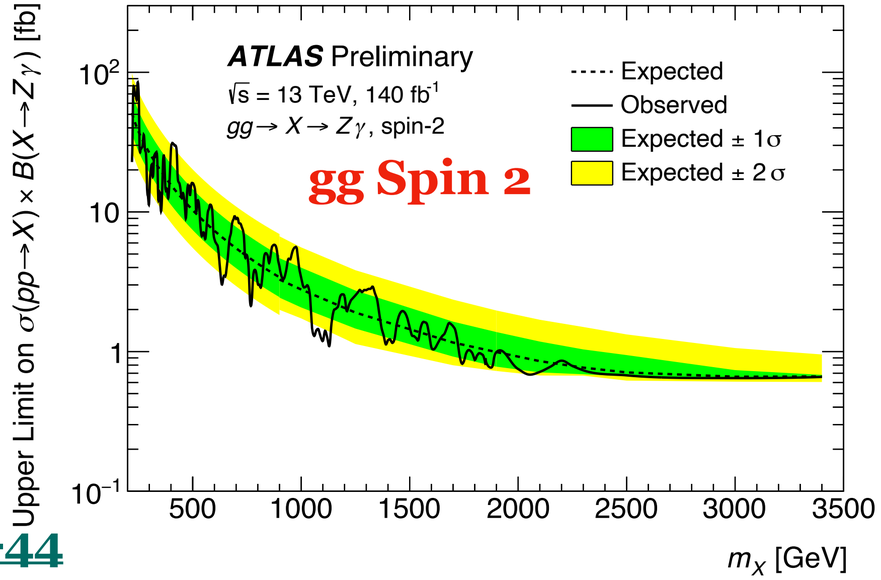
BSM High-mass resonance [$Z\gamma$]

Separate parametrization for 3 models & $Z \to ee$ and $Z \to \mu\mu$ final states









- Results
  - An unbinned profile-likelihood-ratio fit
    - Both channels fitted simultaneously with the signal plus background models

95% CL upper limits of $\sigma(pp \to X) \cdot \mathcal{B}(X \to Z\gamma)$	Observed	Expected
ggX spin-0	65.5 fb – 0.6 fb	43.3 fb – 0.6 fb
ggX spin-2	77.4 fb – 0.6 fb	50.8 fb – 0.6 fb
$q\bar{q}X$ spin-2	76.1 fb – 0.5 fb	50.3 fb – 0.5 fb

ANA-HIGG-2018-44

CP Nature of top-Higgs Coupling

- Probe CP nature of top-Higgs Yukawa Coupling
- Recent full Run-2 results from ATLAS & CMS in $t\bar{t}H$ events with $H \rightarrow \gamma\gamma$ decays
  - Excludes pure CP-odd top-Higgs couplings at more than 3σ significance
- Admixture of CP-odd and CP-even could still be probed, any non-zero CP-odd coupling implies new physics

$$\mathscr{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}(cos\alpha + i\gamma_5 sin\alpha)\psi_t,$$

to extract κ_t' & α from data

  - For SM $\kappa_t' = 1$ & $\alpha = 0$,
  - For BSM anomalous value of α changes diff-xs and κ_t' changes the total cross-section
- This measurement with Full Run-2 ATLAS dataset in tH small contribution & $t\bar{t}H$ production mode with $H \rightarrow b\bar{b}$ decays and final state where at least one quark decays semi leptonically to electrons or muons

arXiv:2303.05974 Submitted to PLB

CP Nature of top-Higgs Coupling

- Signal Modelling
  - $t\bar{t}H$
    - SM samples generated with MadGraph at fixed order NLO QCD+EWk
    - samples with varying $\kappa_t^{'}$ and α generated using NLO Higgs Characterization model implemented in MadGraph5
  - tH : two subprocess (tWH & tHjb) generated with MadGraph
- Background
  - $t\bar{t} + b$ jets (or jets or light flavor jets)
    - Dominant
    - Simulated at NLO QCD with PowhegBox
    - ttbar+ bjets background normalization based on analyses data
  - Others <10% of background [$W +$ jets , $Z +$ jets, $t\bar{t}W, t\bar{t}Z$, tZq, $tWZ, t\bar{t}t\bar{t}$, & VV] events
    - All of these modeled with state-of-the-art MC simulations

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CP Nature of top-Higgs Coupling

- Event Preselection
  - Two channels
    - Lepton + jets
      - At least 5 (4) jets (b-jets)
    - Dilepton
      - At least 3 (3) jets (b-jets)
      - $m_{\ell\ell} > 15$ GeV if SFOS outside Z mass window
  - Jets
    - 70% b-tagging efficiency
    - For events with high p_T Higgs boson
      - Large-R jets ($R = 1.0$) with m_{jet}GeV > 50, $p_T > 200$ GeV & at least two constituent jets with $R = 0.4$

- Two step event categorization
  - First based on jet multiplicity, b-tagging & large-R jets identify training & control regions

Region	Dilepton					ℓ+jets				
	$TR^{\geq 4j,\geq 4b}$	$CR^{\geq 4j,3b}_{hi}$	$CR^{\geq 4j,3b}_{lo}$	$CR^{3j,3b}_{hi}$		$TR^{\geq 6j,\geq 4b}$	$CR^{5j,\geq 4b}_{hi}$	$CR^{5j,\geq 4b}_{lo}$		$TR_{boosted}$
N_{jets}	≥ 4			$= 3$		≥ 6	$= 5$			≥ 4
$N_{b\text{-tag}}$ @85%	–					≥ 4				
$N_{b\text{-tag}}$ @77%	–					–				$\geq 2^{\dagger}$
$N_{b\text{-tag}}$ @70%	≥ 4	$= 3$				≥ 4				–
$N_{b\text{-tag}}$ @60%	–	$= 3$	< 3	$= 3$		–	≥ 4	< 4		–
$N_{boosted\ cand.}$	–					0				≥ 1
Fit observable	–	Yield				–	ΔR^{avg}_{bb}			–

Boosted identified with DNN

  - In TR, two sets of BDT
    - One to identify jets from top vs Higgs decay
    - Two for signal/bkg classification trained on SM $t\bar{t}H$ samples with inputs as BDT1 output, DNN output, b-tagging score and kinematic features

Channel (TR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton ($TR^{\geq 4j,\geq 4b}$)	$CR^{\geq 4j,\geq 4b}_{no\text{-}reco}$	–	$\Delta\eta_{\ell\ell}$
	$CR^{\geq 4j,\geq 4b}$	$BDT^{\geq 4j,\geq 4b} \in [-1, -0.086)$	b_4
	$SR^{\geq 4j,\geq 4b}_1$	$BDT^{\geq 4j,\geq 4b} \in [-0.086, 0.186)$	b_4
	$SR^{\geq 4j,\geq 4b}_2$	$BDT^{\geq 4j,\geq 4b} \in [0.186, 1]$	b_4
ℓ+jets ($TR^{\geq 6j,\geq 4b}$)	$CR^{\geq 6j,\geq 4b}_1$	$BDT^{\geq 6j,\geq 4b} \in [-1, -0.128)$	b_2
	$CR^{\geq 6j,\geq 4b}_2$	$BDT^{\geq 6j,\geq 4b} \in [-0.128, 0.249)$	b_2
	$SR^{\geq 6j,\geq 4b}$	$BDT^{\geq 6j,\geq 4b} \in [0.249, 1]$	b_2
ℓ+jets ($TR_{boosted}$)	$SR_{boosted}$	$BDT^{boosted} \in [-0.05, 1]$	$BDT^{boosted}$

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CP Nature of top-Higgs Coupling

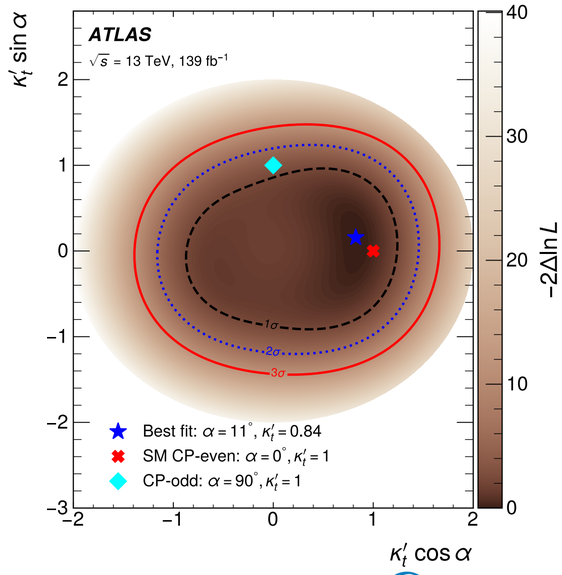
- Probing CP Nature
  - Dedicated CP-sensitive observables in various SR

lepton+jets *SR & CRs* **Dilepton** *SRs & CRs*

$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}, \text{ and } b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

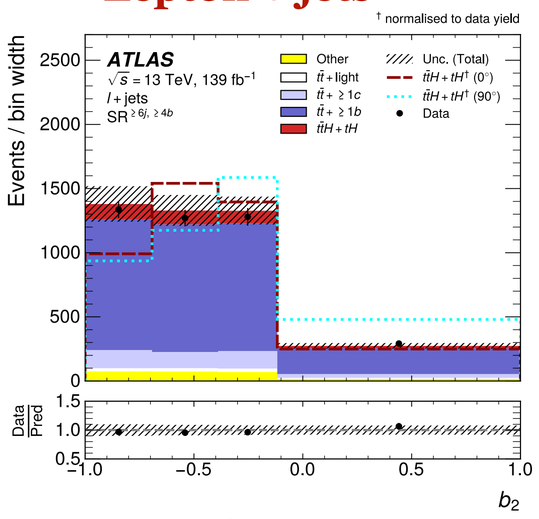
  - Binned profile likelihood fit $\mathscr{L}(\alpha, \kappa_t^{'}, \theta)$ with simultaneous fit of the all regions to determine $\kappa_t^{'}$ & α
    - Free floating $t\bar{t} + \geq 1b$ background NF
  - **Measured parameters agree with SM predictions**

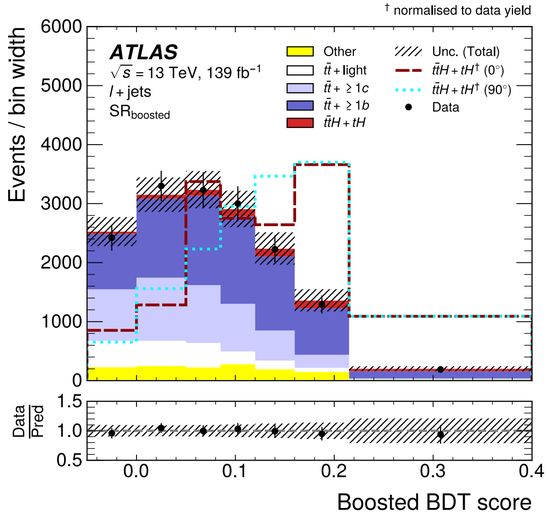
$$\alpha = 11^{\circ}{}^{+52^{\circ}}_{-73^{\circ}} \ \& \ \kappa_t^{'} = 0.84^{+0.30}_{-0.46}$$



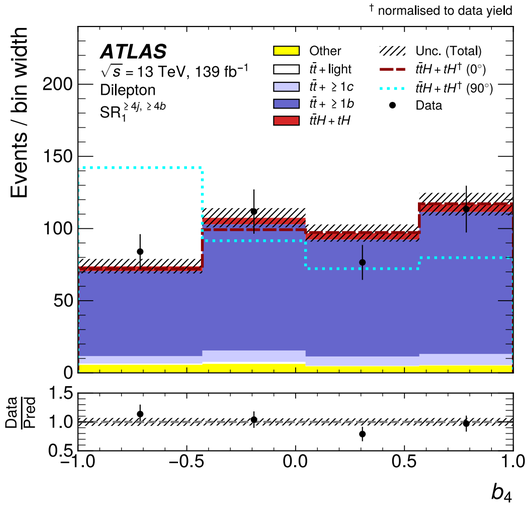
Lepton + jets

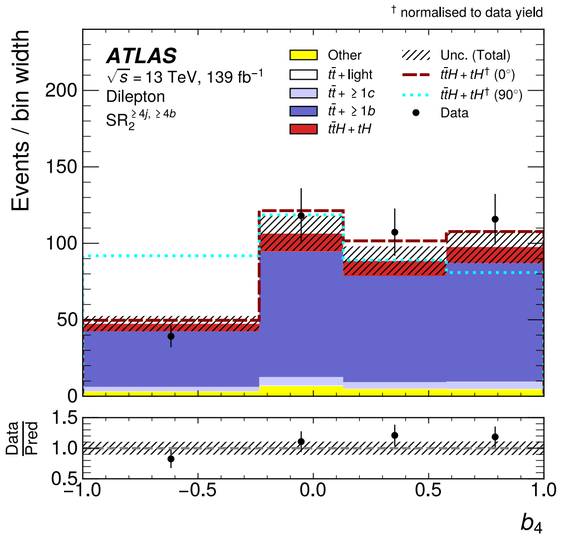
Large separation power in boosted SR





Dilepton





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$t\bar{t}b\bar{b}$ & $t\bar{t}W$ Background Modelling

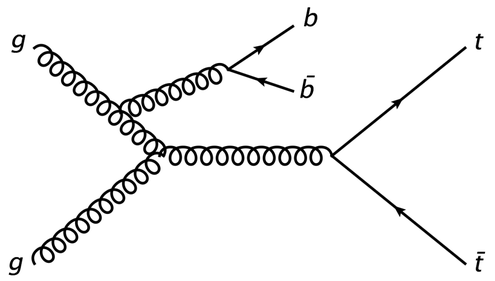
✦ $t\bar{t}b\bar{b}$

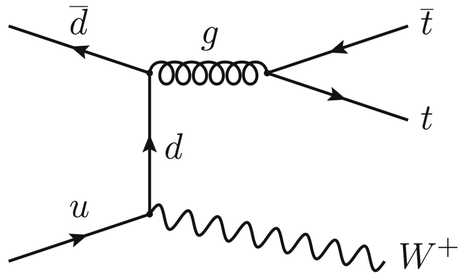
- Important background for $t\bar{t}H$ measurements in the multi-lepton final states and $H \to b\bar{b}$ decay channel

✦ $t\bar{t}W$

- Important background for $t\bar{t}H$ measurements in the multi-lepton final states sensitive to $H \to WW^*$ ($\tau\tau$, & ZZ^*) decays

- Understand these dominant backgrounds essential for SM (BSM) measurements in both regular and boosted regimes
- Also treatment of associated theory uncertainties for full Run-2 $t\bar{t}H$ ATLAS & CMS results combination





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$t\bar{t}b\bar{b}$ & $t\bar{t}W$ Background Modelling

- $t\bar{t}b\bar{b}$ Comparison
  - 3 Samples
    - Powheg $t\bar{t}b\bar{b}$
      - Nominal with 4 flavor scheme NLO and $h_{bzd} = 5$ [variations set to 2]
      - Renormalization scale $m_{T,i} = \sqrt{(m_i^2 + p_{T,i}^2)}$, i is t or b quark
      - Factorization scale depends on average transverse mass of outgoing partons
    - Sherpa $t\bar{t}b\bar{b}$
      - Same factorization and renormalization scale
    - Inclusive $t\bar{t}$
      - Generated using Powheg v2NLO and Madgraph+Pythia using 5 flavor scheme
      - Renormalization & factorization scale set to average m_T of t & $\bar{t}$

- Object/Fiducial Volume Selection: particle level comparisons
  - Truth jets using anti-k_t4
  - b-jets contains at least 1 B-hadron with $p_T > 5$ GeV
  - leptons/jets with $|\eta| \leq 2.5$ & $p_{T,leptons\ (jets)} > 27(25)$ GeV
  - Two channels
    - Single lepton: exactly 1 lepton & at least 6 jets
    - Dilepton: exactly 2 leptons & at least 4 jets
- Comparison as a function of following observables

Variable	Description	Channel
$\Delta R_{bb}^{\min\Delta R}$	ΔR of the two b-jets in the event which are closest in ΔR	dilepton
$m_{bb}^{\min\Delta R}$	Invariant mass of the two b-jets closest in ΔR	dilepton
N_{jets}	Number of jets in the event (all jet flavours)	dilepton
Light jet p_{T}	Transverse momentum of the light jets in the event	dilepton
$N_{b\text{-jets}}$	Number of b-jets in the event	single lepton
$H_{\text{T}}^{\text{jets}}$	Scalar sum of p_{T} of jets in the event (all jet flavours)	single lepton
Leading b-jet p_{T}	p_{T} of b-jet with largest p_{T} in the event	single lepton
Fourth b-jet p_{T}	p_{T} of b-jet with fourth largest p_{T} in the event	single lepton

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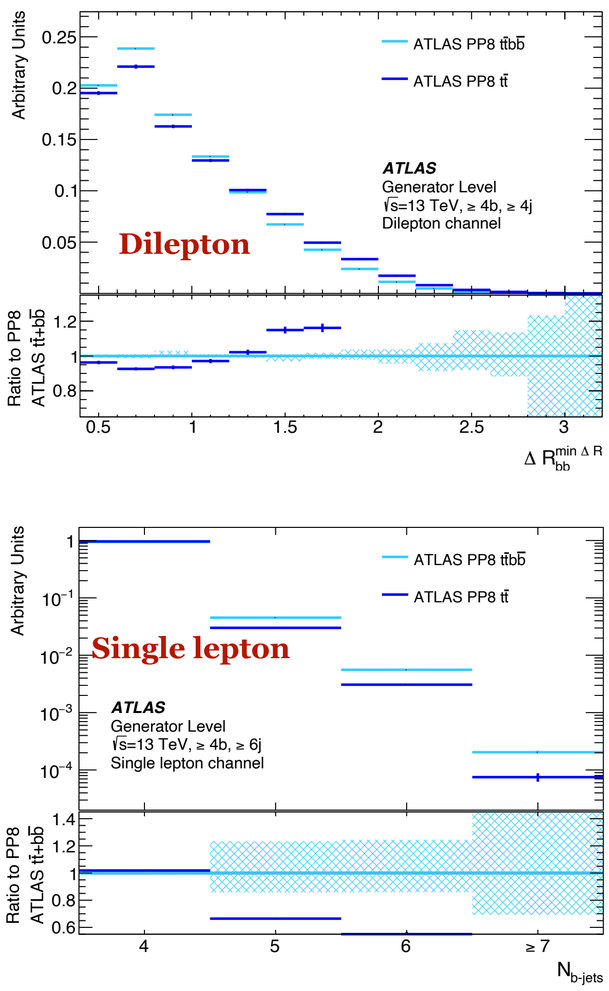
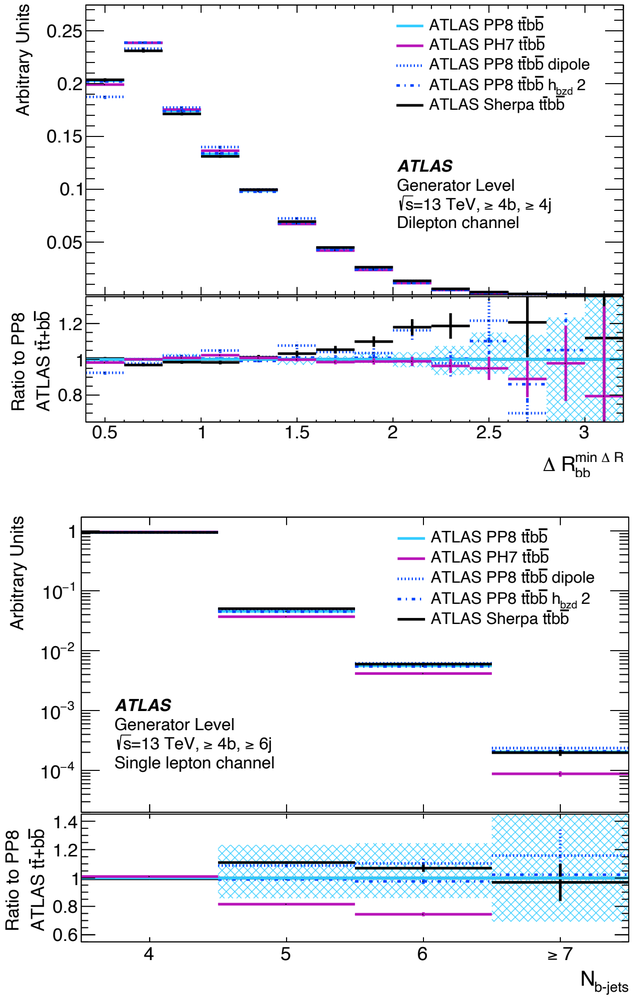
$t\bar{t}b\bar{b}$ & $t\bar{t}W$ Background Modelling

✦ $t\bar{t}b\bar{b}$ Comparison

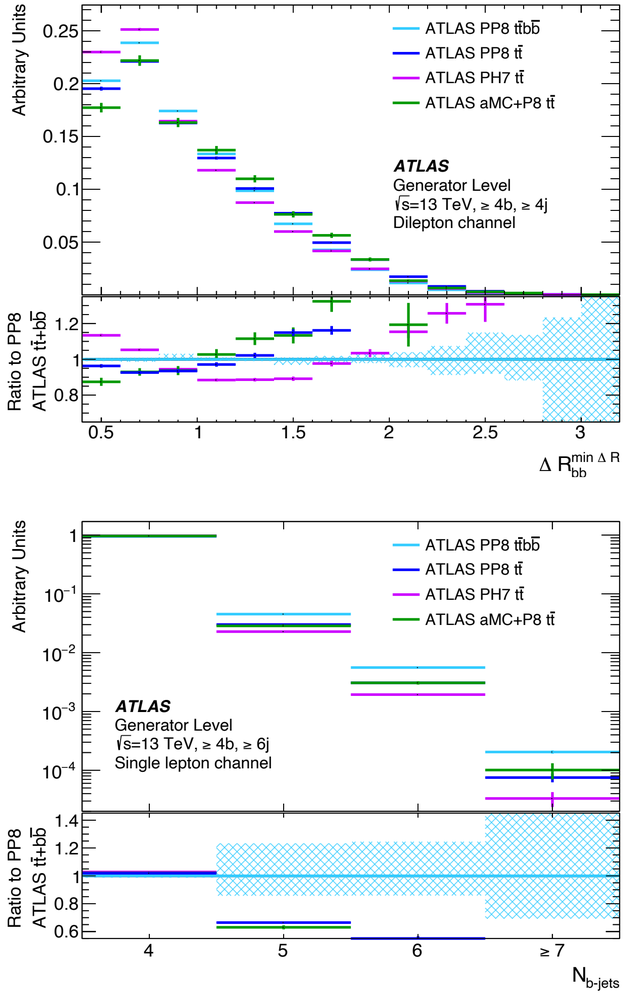
Nominal pred. vs MC used in Run-2



Nominal pred. vs different matching/PS & Sherpa



Comparison showing systematic modeling uncertainties



- Difference between predictions exceed uncertainties
- For combination with CMS the latest ones with smaller uncertainties to be used

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$t\bar{t}b\bar{b}$ & $t\bar{t}W$ Background Modelling

✦ $t\bar{t}W$

- 4 Samples
  - Nominal Inclusive Sherpa 2.2.10 with NNPDF3.0 NLO PDF
    - NLO ME up to one additional Parton & LO up to 2 additional pistons with Comix and OpenLoops
    - Renormalization & factorization scale at $\mu_R = \mu_F = H_T/2$
  - Additional Sherpa 2.2.10 sample with EW corrections
  - Alternative MadGraph5_aMC@NLO 2.3.3 at NLO up to 1 additional parton emission
    - Same μ_R/μ_F scale and PDF set as nominal
  - Additional FxFx MadGraph5_aMC@NLO 2.3.3 sample

- Object/Event Selection

Object reconstruction and selection
Jets: build from stable final state particles with anti-k$_t$ algorithm with radius R = 0.4 the prompt "dressed" leptons and neutrinos are vetoed from jet b-jets: Jets ghost matched to B-hadrons with $p_{\mathrm{T}} > 5$ GeV Jets and b-Jets: $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$
light leptons (electrons and muons) dressed with photons within $\Delta R < 0.1$ Overlap removal: remove light lepton if $\Delta R(jet, lepton) < 0.4$ leptons: $\lvert\eta\rvert < 2.5$ and $p_{\mathrm{T}} > 25(20)$ GeV for leading (subleading) lepton hadronicaly decaying τ leptons (before decay): $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$

Event selection for 2ℓSS
exactly 2 leptons with same charge $N_{\mathrm{jets}} \geq 3$ $N_{b-\mathrm{jets}} \geq 1$

Region	Selection
1	$N_{b-\mathrm{jets}} = 1$, $N_{\mathrm{jets}} \geq 4$, 0-τ_{had}
2	$N_{b-\mathrm{jets}} \geq 2$, $N_{\mathrm{jets}} \geq 4$, 0-τ_{had}
3	$N_{b-\mathrm{jets}} = 1$, $N_{\mathrm{jets}} = 3$, 0-τ_{had}
4	$N_{b-\mathrm{jets}} \geq 2$, $N_{\mathrm{jets}} = 3$, 0-τ_{had}
5	$N_{b-\mathrm{jets}} \geq 1$, $N_{\mathrm{jets}} \geq 3$, 1-τ_{had}

- Comparison

Variable	Description	Regions
N_{jets}	Jet multiplicity	1,2,5
N_{b-jets}	Number of b-jets	1,2,5
$H_{\mathrm{T}}^{\mathrm{jets}}$	Scalar sum of transverse momentum of all jets in the event	1,2,3,4
p_{T}^{b0}	Leading b-jet transverse momentum	1,2
$p_T^{\ell 0}$	Leading lepton transverse momentum	1,2,5
$\Delta R_{\ell 0\mathrm{jets}}$	Minimum angular separation between the leading lepton and the nearest jet	1,2
$\Delta R_{\ell 0 \ell 1}$	Angular distance between the two leptons	1,2,5
$max\lvert\eta_\ell\rvert$	Value of the highest lepton's pseudorapidity in the event	1,2

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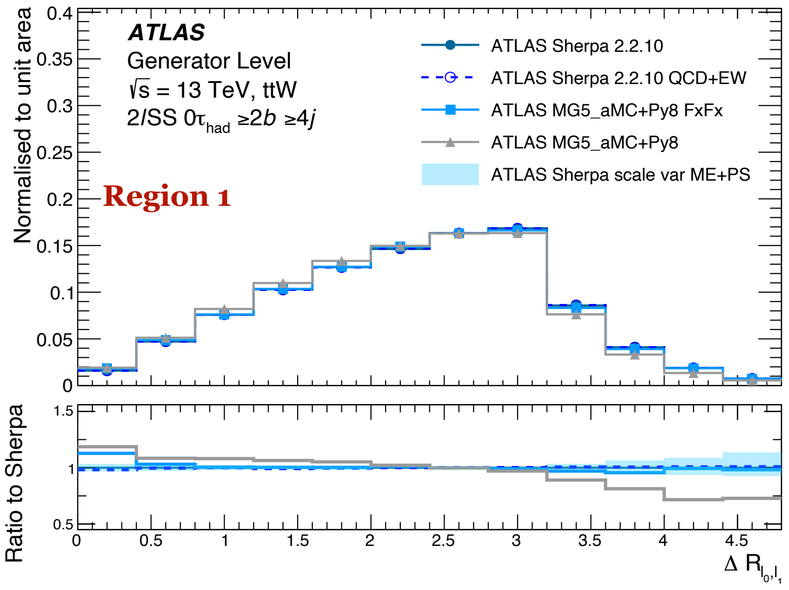
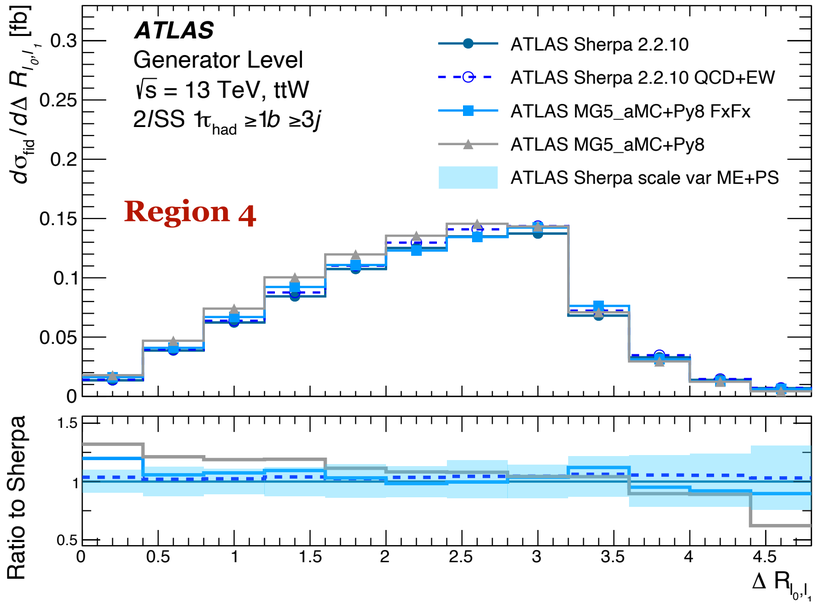
$t\bar{t}b\bar{b}$ & $t\bar{t}W$ Background Modelling

✦ $t\bar{t}W$

- Generally, differences between different model predictions mostly within the scale uncertainty band
- Inclusion of tree-level EW effects only causes minor shape effects but can lead to up to 20% difference in cross section at high jet multiplicity.
- Including the FxFx algorithm into the MG5_aMC@NLO+Pythia8 prediction leads to significant effects in all regions, especially at low HT.
- Comparison to be used for future comparisons with CMS to derive a theory uncertainty model for a combination measurement





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Conclusion

- Presented three results from ATLAS related to measuring Higgs properties with boosted objects
- BSM narrow resonance search in the $Z(\ell^+\ell^-)\gamma$ final state
  - Uses special boosted electron identification technique to place limits form 0.35 to 4.0 TeV
- Probing CP nature of the top-Higgs Yukawa coupling in $t\bar{t}H$ & tH events with $H \to b\bar{b}$ decays
  - Uses boosted + regular signal regions to extract CP odd parameters
- Study of $t\bar{t}b\bar{b}$ & $t\bar{t}W$ background modeling for $t\bar{t}H$ analyses
  - Comparison of different generators and uncertainties useful for future measurements and combination

ATL-PHYS-PUB-2022-026

Back up

BSM High-mass resonance $[Z\gamma]$

- Dedicated MVA method based on a Gradient Boosting Decision Tree (GBDT) with track-based and shower shape variables as input
  - Additional new variables # of TRT hits and $\Delta\phi$ between the cluster energy & associated track in presamples
  - Input variables optimized based on separation power compared at $m_X = 5$ TeV mass peak and background sideband
- 99% signal efficiency & 76% background rejection
- Signal efficiency (reco events after selection/expected events)
  - Efficiency evaluated at different mass points & extrapolated using

    $$\epsilon = a + b \cdot m_X + c \cdot ln(m_X + d)$$
  - Differences in different model related to the different distributions of the transverse momentum and pseudo-rapidity of the Z boson and photon.

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BSM High-mass resonance $[Z\gamma]$

- Overlap Removal
  - For electrons,
    - If leading object has $pT < 500$ GeV, electron clusters closer than $|\Delta\eta| < 0.075$ and $|\Delta\phi| < 0.125$ are removed.
    - If leading electron has $pT > 500$ GeV, electron clusters closer than $|\Delta\eta| < 0.05$ and $|\Delta\phi| < 0.05$ are removed.
    - If the track of the electron candidate is within a distance $\Delta R < 0.02$ of the track of a muon candidate, the electron is rejected.
  - Photon candidates are rejected within $\Delta R < 0.3$ of the selected lepton pair to suppresses the FSR $Z + \gamma$ events and additional possible contributions from photons mis-identified as electrons.
  - There is no overlap removal applied between the ordinary electron and the electron mis-reconstructed as a photon because of their closeness to each other.

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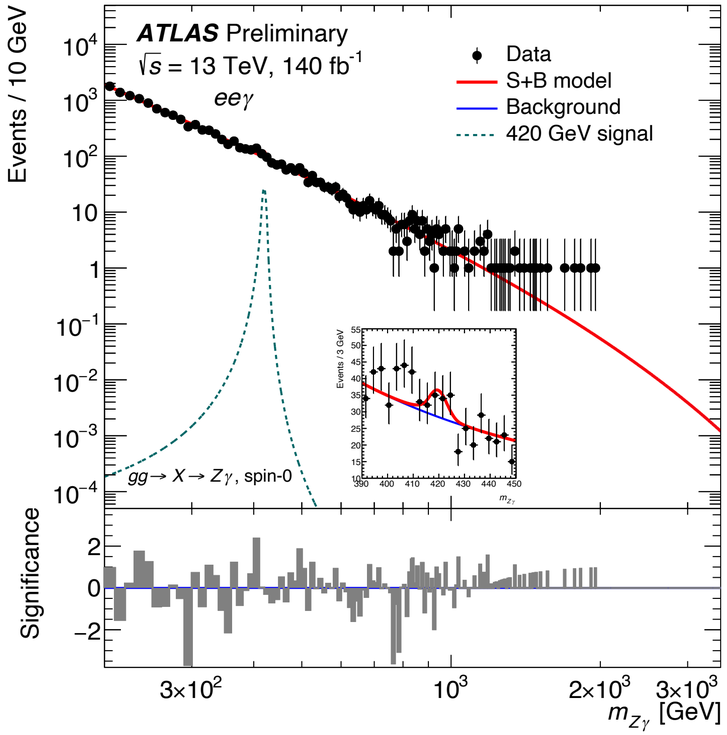
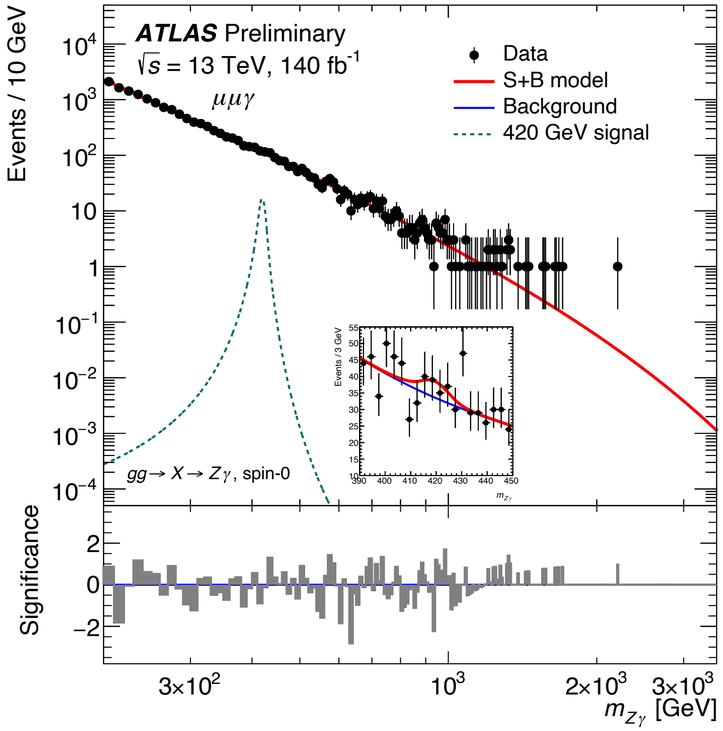
BSM High-mass resonance $[Z\gamma]$

- Systematic Uncertainty
  - Dominant from background modeling in both channels

Category	$\mu\mu\gamma$	$ee\gamma$
Luminosity	0.83%	
Signal Efficiency		
Photon ID/ISO/TRIG efficiency	1.0 – 1.5%	1.0 – 1.7%
Muon ISO efficiency	1.0 – 1.2%	–
Muon RECO efficiency	0.22 – 6%	–
Muon TTVA efficiency	0.14 – 0.23%	–
Muon TRIG efficiency	0.6 – 1.0%	–
Electron ID/ISO/RECO/TRIG efficiency	–	2.9 – 4%
Customized electron ID efficiency	–	1.0 – 1.1%
Pile-up	< 0.016%	–
Signal modelling on μ_{CB}		
Electron and photon energy scale	0.33 – 0.4%	0.15 – 0.7%
Muon momentum scale/sagitta bias	< 0.023%	–
Signal modelling on σ_{CB}		
Electron and photon energy resolution	2.5 – 10%	7 – 60%
Muon ID resolution	0.4 – 1.8%	–
Muon MS resolution	0.6 – 1.9%	–
Extra Smearing on muon p_T	2.4%	–
Background modelling		
Spurious signal	0.01 – 10.00	0.003 – 9.44

- An unbinned profile-likelihood-ratio fit
  - Both channels fitted simultaneously with the signal plus background models





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CP Nature of top-Higgs Coupling

- Signal Modelling
  - $t\bar{t}H$
    - SM samples generated with MadGraph5_aMC@NLO at fixed order NLO QCD+EWk
      - Renormalization and factorization scale set to $\sqrt[3]{m_T(t) \cdot m_T(\bar{t} \cdot m_T(H)}$
    - samples with varying $\kappa_t^{'}$ and α generated using NLO Higgs Characterization model implemented in MadGraph5_aMC@NLO with FeynRules
    - K-factor of 1.1 derived from fixed order calculation applied to all ttH samples
  - tH : two subprocess generated with MadGraph5_aMC@NLO.
    - tWH
    - tHjb
- Background
  - $t\bar{t} + b$ jets (or jets or light flavor jets)
    - Dominant
    - Simulated at NLO QCD with PowhegBoxRes (PowhegBox v2)
    - ttbar+ bjets background normalization based on analyses data
    - 100% uncertainty included on ttbar+c (or light flavor) normalization
  - Others <10% of background [$W +$ jets , $Z +$ jets, $t\bar{t}W, t\bar{t}Z$, tZq, $tWZ, t\bar{t}t\bar{t}$, & VV] events
    - All of these modeled with state-of-the-art MC simulations

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CP Nature of top-Higgs Coupling

- Event Preselection
  - Two channels
    - Lepton + jets
    - Dilepton
  - Electron:
    - $p_T > 10$ GeV, $|\eta| < 2.47$ excluding transition region
    - "Tight" ID
  - Muon
    - $p_T > 10$ GeV, $|\eta| < 2.5$
    - "Medium" ID
  - For Dilepton channel
    - $m_{\ell\ell} > 15$ GeV
    - If SFOS outside Z mass window
  - Jets
    - Lepton + jet
      - At least 5 (4) jets (b-jets)
    - Dilepton
      - At least 3 (3) jets (b-jets)
    - 70% b-tagging efficiency
    - For events with high p_T Higgs boson
      - Large-R jets ($R = 1.0$) with m_{jet}GeV $> 50 p_T > 200$ GeV & at least two constituent jets with $R = 0.4$

Uncertainty source	$\Delta\alpha$ [°]	
Process modelling		
Signal modelling	+8.8	-14
$t\bar{t} + \geq 1b$ modelling		
$t\bar{t} + \geq 1b$ 4V5 FS	+23	-37
$t\bar{t} + \geq 1b$ NLO matching	+22	-33
$t\bar{t} + \geq 1b$ fractions	+14	-21
$t\bar{t} + \geq 1b$ FSR	+5.2	-9.9
$t\bar{t} + \geq 1b$ PS & hadronisation	+16	-24
$t\bar{t} + \geq 1b$ $p_T^{b\bar{b}}$ shape	+5.4	-4.6
$t\bar{t} + \geq 1b$ ISR	+14	-24
$t\bar{t} + \geq 1c$ modelling	+6.6	-11
$t\bar{t}$ + light modelling	+2.5	-4.7
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+8.7	-15
c-mis-tag rates	+6.7	-11
l-mis-tag rates	+2.3	-2.7
Jet energy scale and resolution		
b-jet energy scale	+1.6	-3.8
Jet energy scale (flavour)	+7.8	-11
Jet energy scale (pileup)	+5.2	-7.9
Jet energy scale (remaining)	+8.1	-13
Jet energy resolution	+5.7	-9.3
Luminosity	$\leq \pm 1$	
Other sources	+4.9	-8
Total systematic uncertainty	+41	-54
$t\bar{t} + \geq 1b$ normalisation	+8.2	-13
κ_t'	+17	-33
Total statistical uncertainty	+32	-49
Total uncertainty	+52	-73

Uncertainty source	$\Delta\kappa_t'$	
Process modelling		
Signal modelling	+0.10	-0.10
$t\bar{t} + \geq 1b$ modelling		
$t\bar{t} + \geq 1b$ 4V5 FS	+0.08	-0.23
$t\bar{t} + \geq 1b$ NLO matching	+0.15	-0.30
$t\bar{t} + \geq 1b$ fractions	+0.09	-0.21
$t\bar{t} + \geq 1b$ FSR	+0.01	-0.02
$t\bar{t} + \geq 1b$ PS & hadronisation	+0.09	-0.20
$t\bar{t} + \geq 1b$ $p_T^{b\bar{b}}$ shape	+0.07	-0.11
$t\bar{t} + \geq 1b$ ISR	+0.07	-0.17
$t\bar{t} + \geq 1c$ modelling	+0.04	-0.10
$t\bar{t}$ + light modelling	+0.00	-0.01
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+0.06	-0.12
c-mis-tag rates	+0.03	-0.07
l-mis-tag rates	+0.01	-0.03
Jet energy scale and resolution		
b-jet energy scale	+0.02	-0.02
Jet energy scale (flavour)	+0.01	-0.05
Jet energy scale (pileup)	+0.02	-0.05
Jet energy scale (remaining)	+0.04	-0.08
Jet energy resolution	+0.03	-0.09
Luminosity	$\leq \pm 0.01$	
Other sources	+0.03	-0.07
Total systematic uncertainty	+0.29	-0.45
$t\bar{t} + \geq 1b$ normalisation	+0.05	-0.15
α	+0.08	-0.07
Total statistical uncertainty	+0.09	-0.10
Total uncertainty	+0.30	-0.46

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