First Results on Higgs Pair Production in Multi-Lepton Channels

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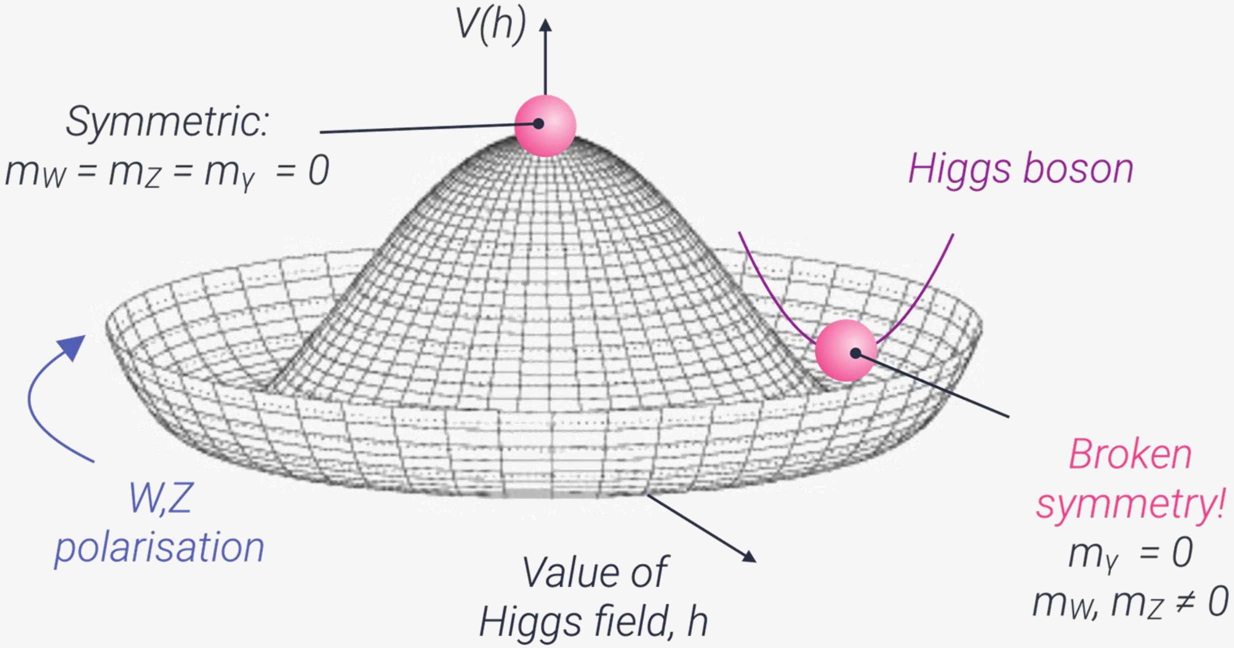
Electroweak Symmetry Breaking



Refer to Katharine's Talk

Direct measurement of λ_{HHH} via HH production

Strength of λ_{HHH} relative to SM prediction $(\lambda_{HHH}/\lambda_{SM}) = \kappa_\lambda$

$$V(h) = \frac{1}{2}m_H^2h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \cdots$$

Minimum of the potential

$m_H = \sqrt{2\lambda v} \approx 125\ \mathrm{GeV}$

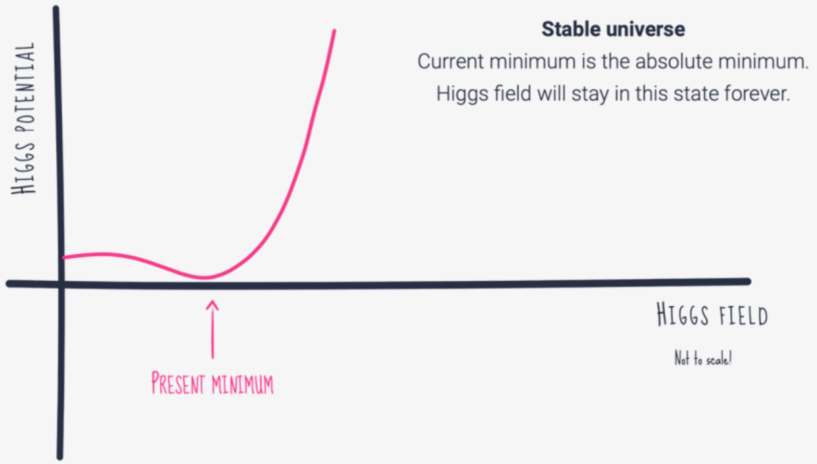
$\lambda_{SM} \approx 0.13$

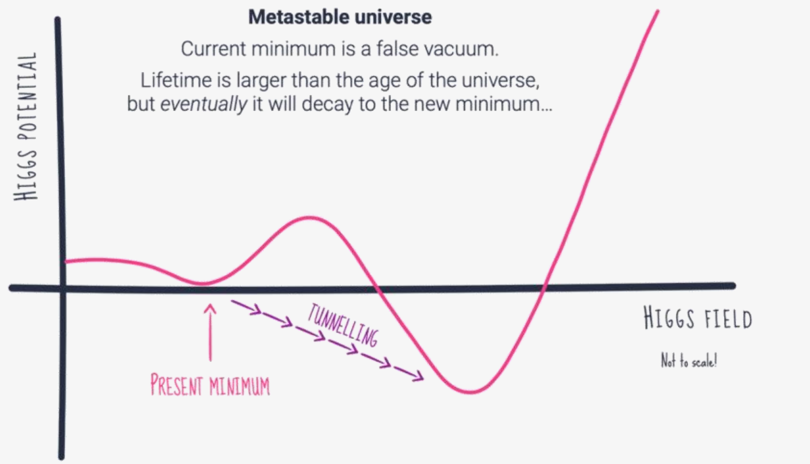
λ_{HHHH}

Too far for now…

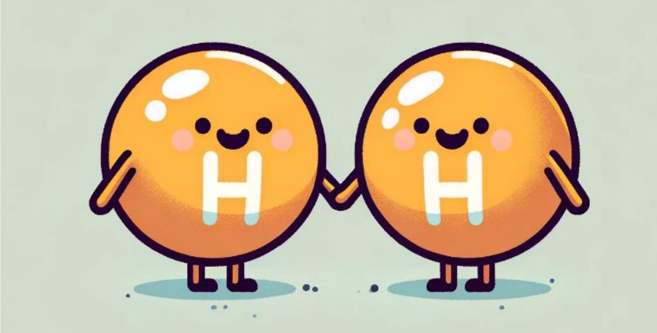
Higgs Self-Coupling

- Higgs boson discovered 11 years ago (**no deviations from SM observed so far)**
- Higgs can couple to Higgs itself ($\lambda_{HHH}, \lambda_{HHHH}$). (The only particle in SM with self-coupling)
- λ_{HHH} is **not a free parameter** → closure test of SM
- λ_{HHH} is **the parameter** regulating **Higgs potential shape** → EWSB and vacuum stability test
- Deviation of λ_{HHH} from SM can allow *first order EW transition (BSM!)*



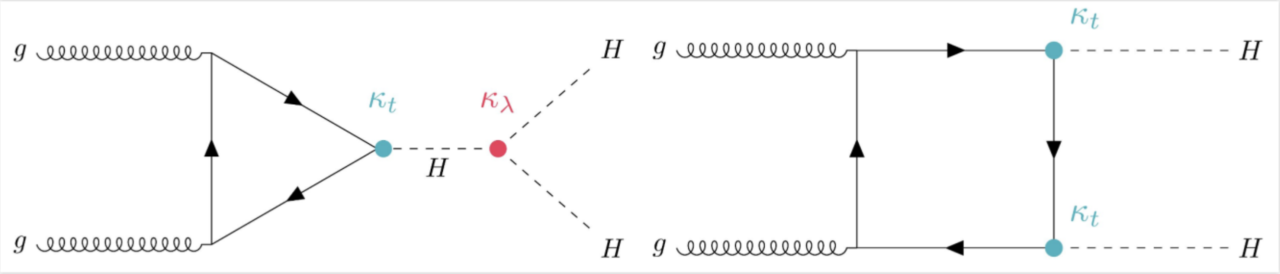


Double Higgs

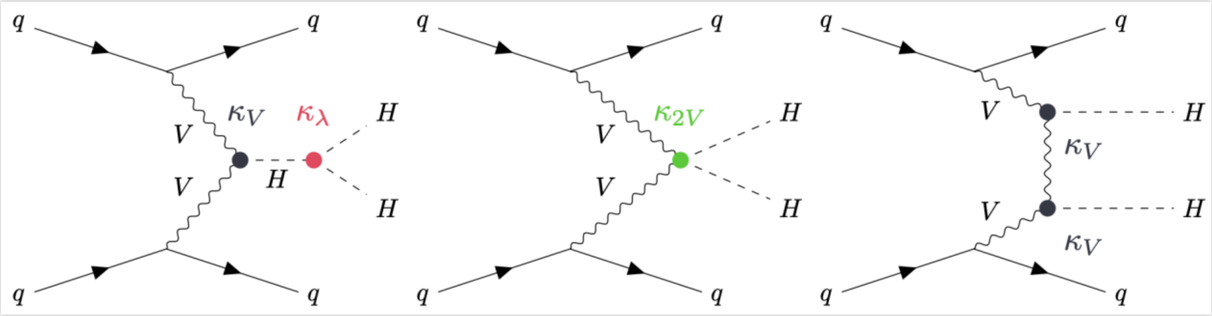


Double Happiness

Non-resonant HH production at the LHC



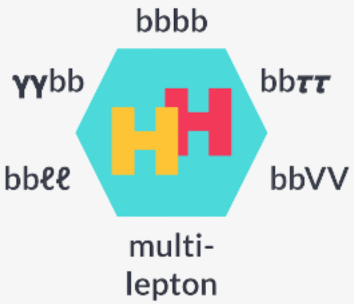
Gluon-gluon Fusion (ggF): $\sigma_{HH}^{SM} = \mathbf{31.05} \pm 3\% \, (\text{PDF} + \alpha_s)^{+6\%}_{-23\%} \, (\text{Scale} + m_{\text{top}}) \, \text{fb}$



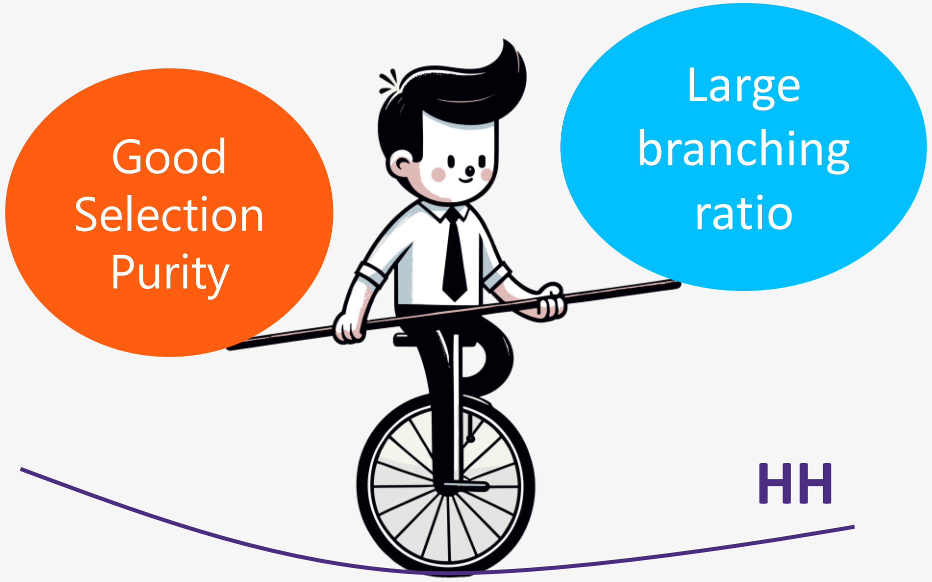
Vector Boson Fusion (VBF): $\sigma_{HH}^{SM} = \mathbf{1.726} \pm 2\% \, (\text{PDF} + \alpha_s)^{+0.03\%}_{-0.04\%} \, (\text{Scale}) \, \text{fb}$

- Cross-section ~1000x smaller than single Higgs production for Run 2 (**13 TeV**)
- Test BSM effective models with anomalous couplings: κ_λ, κ_t, κ_V, and κ_{2V}

Direct HH Searches



Balance between branching ratio and final states



No single "Golden" channel

BR (%)	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34				
WW	25	4.6			
$\tau\tau$	7.3	2.7	0.39		
ZZ	3.1	1.1	0.33	0.069	
$\gamma\gamma$	0.26	0.10	0.028	0.012	0.00005

- Historic three HH channels: $bbbb$, $bb\gamma\gamma$, $bb\tau\tau$
- Other HH channels: $bbVV\,(0/1\ell)$, $bb\ell\ell$, and **multilepton**

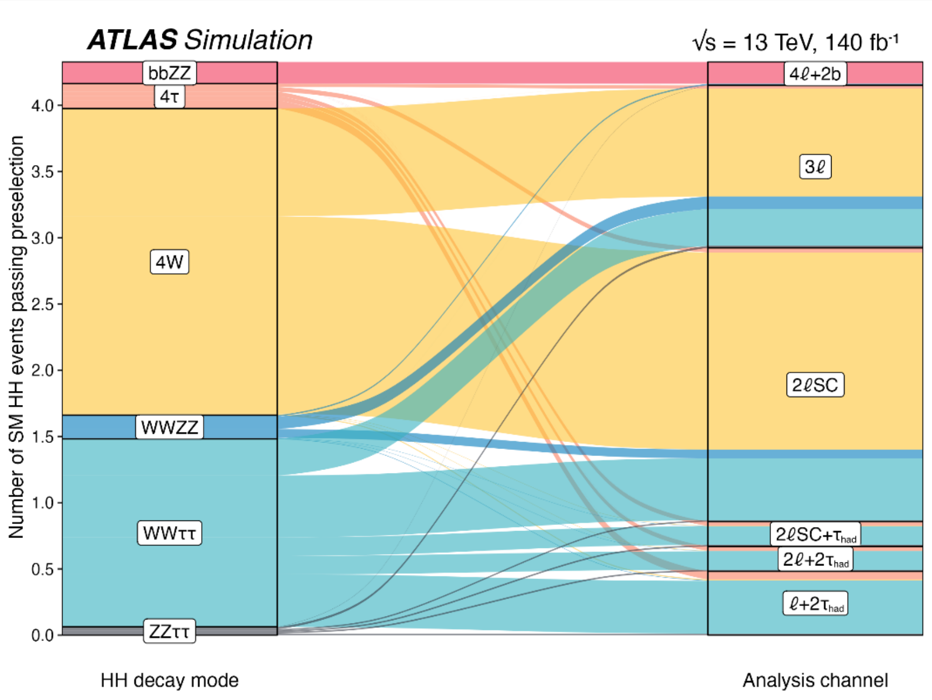
First result

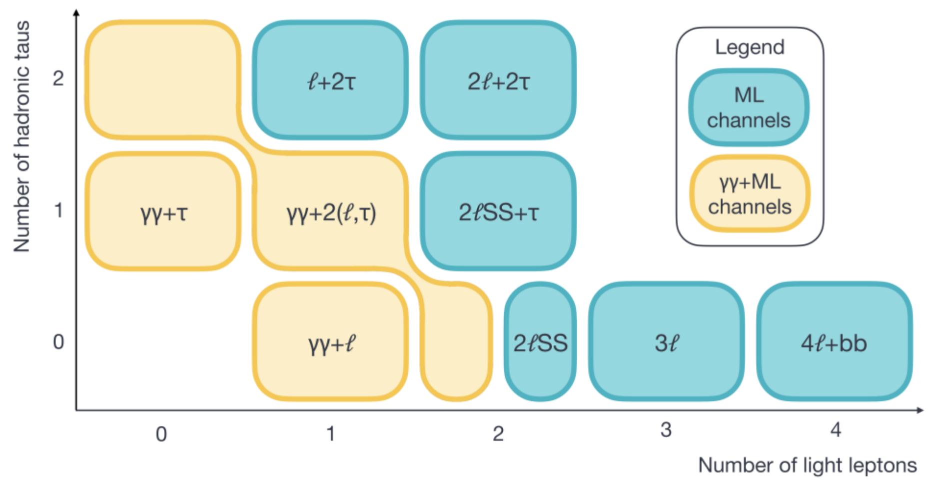
HH → Multilepton Channel

- Targeting on ~6.5% of HH events decay to final states where the HH system cannot be fully reconstructed and none of these are covered by other analyses.
- Use *a common analysis strategy* for the same final states
- Categorize final states by number of e, μ, τ_h, named by **$\gamma\gamma + ML$ channel** (3) and **Multilepton channel** (6), **9 orthogonal channels in total**

- Two same-sign light leptons w/wo τ_h: $2\ell SS0\tau_h$ and $2\ell SS + 1\tau_h$
- Three light leptons: 3ℓ → **most sensitive channel**
- One/Two light leptons and two τ_h: $1/2\ell + 2\tau$
- 4 light leptons originated from $H \to ZZ$ and 2 b-jet: $b\bar{b}4\ell$

- Two photons with light leptons and τ_h: $\gamma\gamma + 1\ell 0\tau, \gamma\gamma + 0\ell 1\tau, \gamma\gamma + 2\ell$





Object Definition and Baseline Selection

- Huge efforts to **harmonize** object definitions and event selections.
- Dedicated control regions to estimate norm factors (included in simultaneous fit)
- Validation region to check Data/MC agreement

	Electrons				Muons			
	Baseline (B)	Loose (L)	Tight (T)	$\gamma\gamma$+ML (P)	Baseline (B)	Loose (L)	Tight (T)	$\gamma\gamma$+ML (P)
Minimum p_T	10 GeV ($4\ell+bb$ channel: 4.5 GeV)				10 GeV ($4\ell+bb$ channel: 3 GeV)			
η	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$				$\|\eta\| < 2.5$			
Identification	Loose		Tight	Medium	Loose		Medium	
Isolation	✗			Loose	✗			Loose
PLV isolation	✗	Loose	Tight	✗	✗	Loose	Tight	✗
Charge mis-ID BDT	✗	✓		✗	-			
e/γ ambiguity	✗	✓		✗	-			
$\|d_0\|/\sigma_{d_0}$	< 5				< 3			
$\|z_0 \sin\theta\|$	< 0.5 mm				< 0.5 mm			

Channel	ℓ	$\tau_{\text{had-vis}}$	Photons	E_T^{miss}	b-jets
$\gamma\gamma+2\ell$	$N_\ell(\text{P}) + N_\tau = 2$ $m_{2(\ell,\tau)} > 12$ GeV		$N_\gamma = 2$ $E_T(\gamma_1) > 35$ GeV 105 GeV $< m_{\gamma\gamma} <$ 160 GeV $\gamma_1 : p_T/m_{\gamma\gamma} > 0.35$ $\gamma_2 : p_T/m_{\gamma\gamma} > 0.25$	$E_T^{miss} > 35$ GeV	$N_{b\text{-jet}} = 0$
$\gamma\gamma+\ell$	$1\ell(\text{P})$	$N_\tau = 0$	$N_\gamma = 2$ $E_T(\gamma_1) > 35$ GeV 105 GeV $< m_{\gamma\gamma} <$ 160 GeV $\gamma_1 : p_T/m_{\gamma\gamma} > 0.35$ $\gamma_2 : p_T/m_{\gamma\gamma} > 0.25$	$\gamma\gamma+e$: $E_T^{miss} > 35$ GeV $\gamma\gamma+\mu$: -	$N_{b\text{-jet}} = 0$
$\gamma\gamma+\tau$	$N_{\ell(P)} = 0$	$N_\tau = 1$	$N_\gamma = 2$ $E_T(\gamma_1) > 35$ GeV 105 GeV $< m_{\gamma\gamma} <$ 160 GeV $\gamma_1 : p_T/m_{\gamma\gamma} > 0.35$ $\gamma_2 : p_T/m_{\gamma\gamma} > 0.25$	$E_T^{miss} > 35$ GeV	$N_{b\text{-jet}} = 0$

Channel	ℓ	$\tau_{\text{had-vis}}$	Photons	Jets	b-jets
$4\ell+bb$	$4\ell(\text{B})$ $p_T(\ell_1) > 20$ GeV $p_T(\ell_2) > 15$ GeV $p_T(\ell_3) > 10$ GeV ℓ_3 or ℓ_4 pass 'loose' PLV 2 SFOS pairs $50 < m^{SFOS}_{\text{lead-}\ell\ell} < 106$ GeV $5 < m^{SFOS}_{\text{sublead-}\ell\ell} < 115$ GeV All pairs $\Delta R(\ell_i, \ell_j) > 0.02$ 115 GeV $< m_{4\ell} <$ 135 GeV	$N_\tau = 0$	$N_\gamma = 0$	$N_{\text{jet}} \geq 2$	$1 \leq N_{b\text{-jet}} \leq 3$
3ℓ	$\ell_{OS}(\text{L})$, $p_T > 10$ GeV $\ell_{SS1}(\text{T})$, $p_T > 15$ GeV $\ell_{SS2}(\text{T})$, $p_T > 15$ GeV All $m^{SFOS}_{\ell\ell} > 12$ GeV Z-veto $\|m_{3\ell} - m_Z\| > 10$ GeV.	$N_\tau = 0$	$N_\gamma = 0$	$N_{\text{jet}} \geq 1$	$N_{b\text{-jet}} = 0$
2ℓSS	$2\ell(\text{T})$, $p_T > 20$ GeV SS charge $m_{\ell\ell} > 12$ GeV	$N_\tau = 0$	$N_\gamma = 0$	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$
2ℓSS+τ	$2\ell(\text{T})$, $p_T > 20$ GeV SS charge $m_{\ell\ell} > 12$ GeV	$N_\tau = 1$ $p_T > 25$ GeV OS charge to ℓ	$N_\gamma = 0$	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$
$2\ell+2\tau$	$2\ell(\text{L})$ OS charge $m_{\ell\ell} > 12$ GeV Z-veto	$N_\tau = 2$ OS charge $\Delta R(\tau_1, \tau_2) < 2$	$N_\gamma = 0$	-	$N_{b\text{-jet}} = 0$
$\ell+2\tau$	$1\ell(\text{L})$ $m_{\ell\ell} > 12$ GeV	$N_\tau = 2$ OS charge $\Delta R(\tau_1, \tau_2) < 2$	$N_\gamma = 0$	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$

Channel	Region	Lepton Configuration	$N_{\tau_{\text{had}}}^{\sum Q_i^\ell}$	N_{jet}	$N_{b-\text{jet}}$	Additional Selections
$4\ell+bb$	$t\bar{t}$ CR	$\boldsymbol{\ell^\pm\ell^\mp + e^\pm\mu^\mp}$	0	≥ 2	≥ 1 and ≤ 3	$\|m_{\ell\ell}^{\text{SFOS}} - m_Z\| > 10$
	$t\bar{t}Z$ CR	$\boldsymbol{\ell^\pm\ell^\mp + e^\pm\mu^\mp}$	0	≥ 2	≥ 1 and ≤ 3	$\|m_{\ell\ell}^{\text{SFOS}} - m_Z\| < 10$
	VV+Higgs CR	$\ell^\pm\ell^\mp\ell^\pm\ell^\mp$	0	≥ 2	**0**	
	Z+jets CR	$\ell^\pm\ell^\mp\ell^\pm\ell^\mp$	0	≥ 2	≥ 1 and ≤ 3	$\|m_{\ell\ell}^{\text{SFOS}} - m_Z\| < 10$
	VR	$\ell^\pm\ell^\mp\ell^\pm\ell^\mp$	0	≥ 2	≥ 1 and ≤ 3	$\boldsymbol{\|m_{4\ell} - m_{\text{H}}\| \geq 10}$
3ℓ	WZ CR	$\ell^\pm\ell^\mp\ell^\mp$	0	≥ 1	0	$\|m_{3\ell} - m_Z\| > 10$, $\boldsymbol{\|m_{\ell\ell}^{\text{SFOS}} - m_Z\| < 10}$ $E_T^{\text{miss}} > 30$
	Conv CR	$\ell^\pm\ell^\mp\ell^\mp$	0	≥ 1	0	$\boldsymbol{\|m_{3\ell} - m_Z\| < 10}$
	HF-e CR	$\ell^\pm e^\mp e^\mp$	0	≥ 2	**≥ 2**	$\|m_{3\ell} - m_Z\| > 10$
	HF-μ CR	$\ell^\pm\mu^\mp\mu^\mp$	0	≥ 2	**≥ 2**	$\|m_{3\ell} - m_Z\| > 10$
	VR	$\ell^\pm\ell^\mp\ell^\mp$	0	≥ 1	0	**BDT < 0.55**

Channel	Region	Lepton Configuration	$N_{\tau_{\text{had}}}^{\sum Q_i^\ell}$	N_{jet}	$N_{b-\text{jet}}$	Additional Selections
$2\ell SC$	WZ CR	$\boldsymbol{\ell^\pm\ell^\mp\ell^\mp}$	0	≥ 2	0	$\|m_{3\ell} - m_Z\| > 10, \|m_{\ell\ell}^{\text{SFOS}} - m_Z\| < 10$ **BDT < −0.4**, $\text{BDT}_{\text{Vjets}} > -0.8$ $E_T^{\text{miss}} > 30$
	$VVjj$ CR	$\ell^\pm\ell^\pm$	0	≥ 2	0	$\|m_{\ell\ell}^{\text{SFSS}} - m_Z\| > 10$ **BDT < −0.4**, $\text{BDT}_{\text{Vjets}} > -0.8$ $m_{jj} > 300$
	QmisID	$e^\pm e^\pm / e^\pm e^\mp$	0	**< 2**	0	$78.5 < m_{\ell\ell}^{\text{SFOS}} < 102.3$ $76.5 < m_{\ell\ell}^{\text{SFSS}} < 101.3$
	Conv CR	$\ell^\pm\ell^\pm$	0	≥ 2	**≥ 1**	
	QED CR	$\ell^\pm\ell^\pm$	0	≥ 2	**≥ 1**	
	HF-e CR	$\ell^\pm e^\pm$	0	2 or 3	**1 or 2**	
	HF-μ CR	$\ell^\pm\mu^\pm$	0	2 or 3	**≥ 1**	
	VR	$\ell^\pm\ell^\pm$	0	≥ 2	0	**BDT < −0.4**
2ℓSC+τ	Fake τ_{had} CR	$\boldsymbol{\ell^\pm\ell^\mp}$	$1^{\pm1}$	≥ 2	0	$\|m_{\ell\ell}^{\text{SFOS}} - m_Z\| > 10$
	VV CR	$\ell^\pm\ell^\pm$	$1^{\pm1}$	≥ 2	0	**BDT < −0.2**
	HF-e CR1	$\ell^\pm e^\pm$	$1^{\pm1}$	≥ 2	**1**	
	HF-e CR2	$\ell^\pm e^\pm$	$1^{\pm1}$	≥ 2	**2**	
	HF-μ CR	$\ell^\pm\mu^\pm$	$1^{\pm1}$	≥ 2	**≥ 1**	
	VR	$\ell^\pm\ell^\pm$	$1^{\pm1}$	**≤ 1**	0	
$\ell+2\tau$	Z+jets CR	$\boldsymbol{\ell^+\ell^-}$	$2^{\pm2}$	≥ 0	0	$\|m_{\ell\ell}^{\text{SFOS}} - m_Z\| < 10$
	$t\bar{t}$ CR	$\boldsymbol{\ell^+\ell^-}$	$2^{\pm2}$	≥ 0	1	$\|m_{\ell\ell}^{\text{SFOS}} - m_Z\| > 10$
	VR	$\ell^\pm$	$\boldsymbol{2^{\pm2}}$	≥ 2	0	
$2\ell+2\tau$	Z+jets CR	$\ell^+\ell^-$	$2^{\pm2}$	≥ 0	0	$\boldsymbol{\|m_{\ell\ell}^{\text{SFOS}} - m_Z\| < 10}$
	$t\bar{t}$ CR	$\ell^+\ell^-$	$2^{\pm2}$	≥ 0	**1**	$\|m_{\ell\ell}^{\text{SFOS}} - m_Z\| > 10$
	VR	$\boldsymbol{\ell^\pm\ell^\pm}$	$2^{\pm2}$	≥ 0	0	
$\gamma\gamma$+ML	Fit background CR	$0/\ell^\pm/\ell^\pm\ell^\mp$	≥ 0	≥ 0	0	$\boldsymbol{\|m_{\gamma\gamma} - 125\| > 5}$

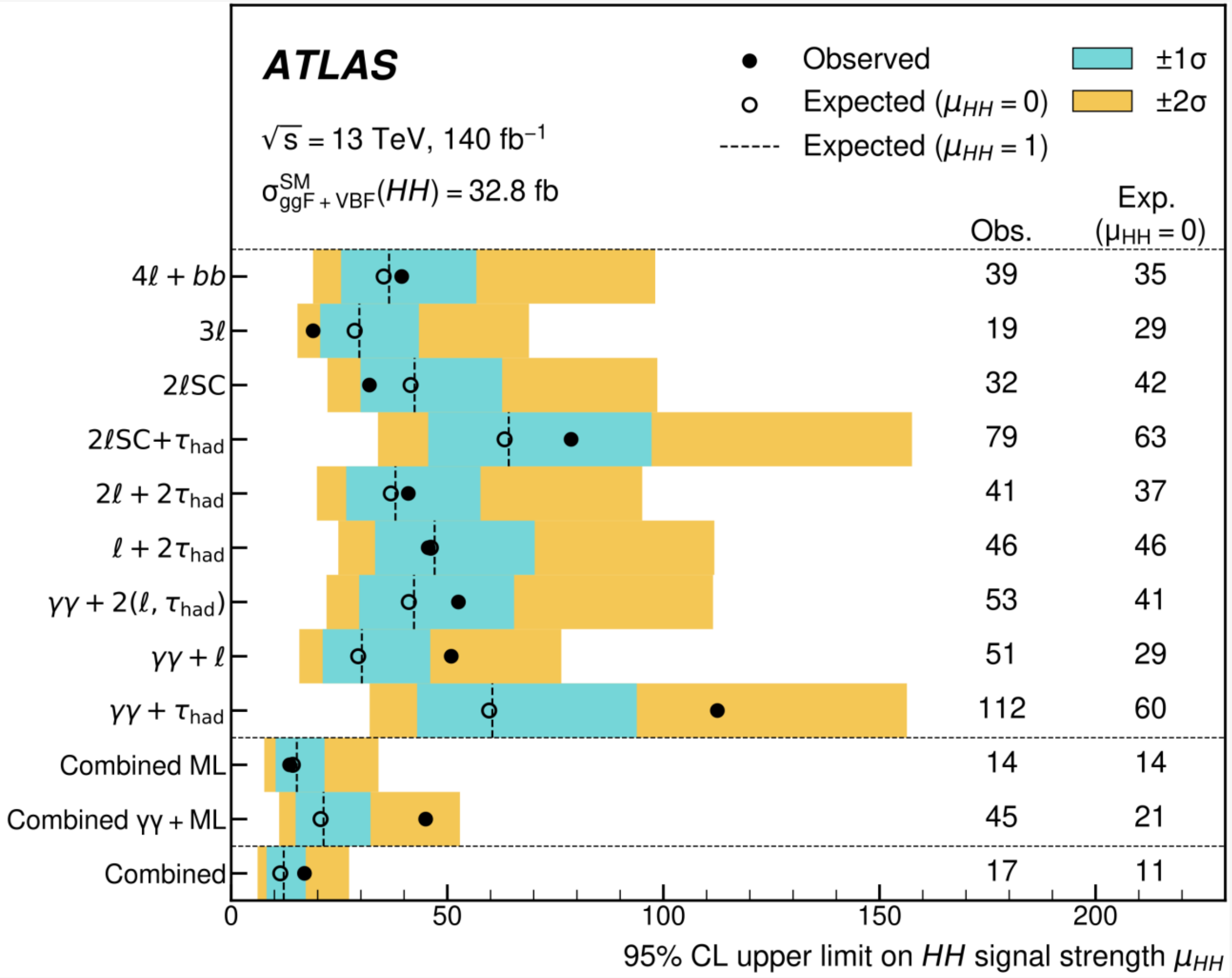
Analysis Strategy

Pre-selections → Background Modelling → MVA (BDTG) → Combined Fit

- Background Modelling:
  - Irreducible backgrounds: MC (with **data-driven corrections** in CR if dominant)
  - Fake backgrounds:
    - **Template Fit** (TF) for fake light leptons
    - **Fake Factor** (FF) / **Scale Factor** (SF) methods for fake τs
  - MC continuum background ($V+\gamma\gamma$, $t\bar{t}+\gamma\gamma$, $\gamma\gamma+$ jets): modeled with an analytical function

	$2\ell SC$	$2\ell SC+\tau$	3ℓ	$1\ell+2\tau$	$2\ell+2\tau$	$4\ell+b\bar{b}$	$\gamma\gamma+ML$
Model	Gradient Boosted Decision Tree in TMVA						
Input variables	16	13	22	10	8	22	21
K-Fold Training	2	5	3	2	2	Single	4
Signal	$\mathrm{ggF}+\mathrm{VBF}$						
Background	$t\bar{t}$, VV, $Z+$ jets separately	VV	Total Background	VV	VV	Total Background	Total Background
SR definition	>-0.4	>-0.2	>-0.55	–	–	–	–

First Result for Multilepton



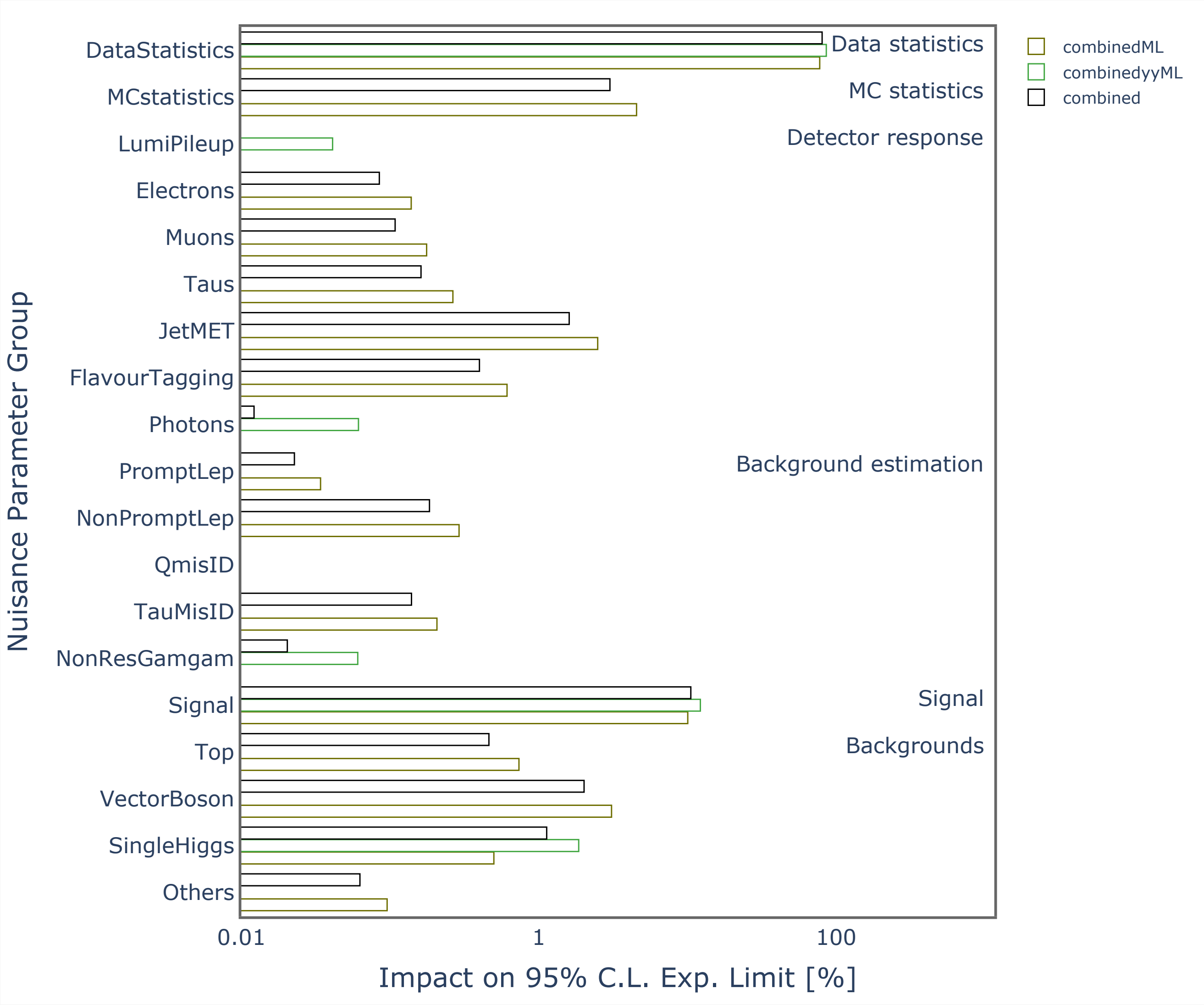
ML best-fit $\mu = -0.09 \pm 5.08$

$\gamma\gamma$ + ML best-fit $\mu = 18.40 \pm 11.02$

Combined best-fit $\mu = 5.78 \pm 4.19$

	-2σ	-1σ	Exp.	$+1\sigma$	$+2\sigma$	Obs.
Syst.	6	8	11	17	27	**17**

Systematics Breakdown

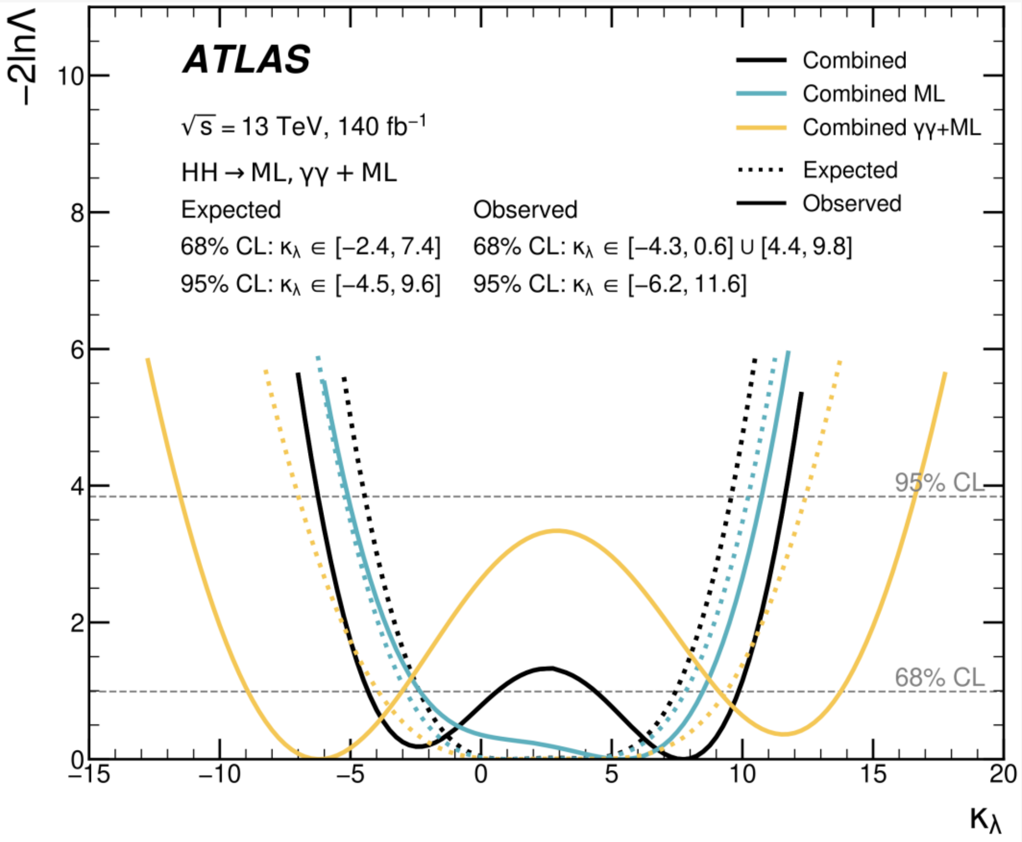


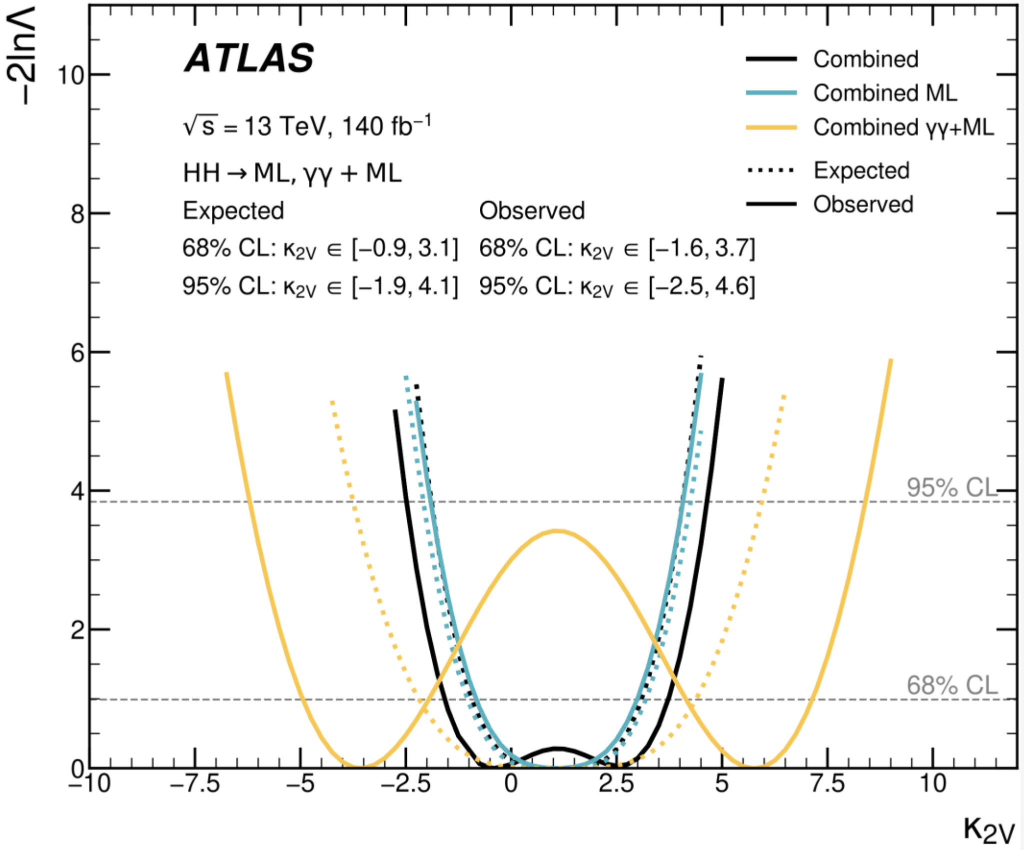
NPs	ML	$\gamma\gamma$ + ML	Combined
Data Statistics	77.6%	86.0%	80.5%
All Systematics	22.3%	14.0%	19.43%
MC Statistics	4.6%	< 0.1%	3.0%
Experimental	4.9%	0.2%	3.2%
Detector Response	4.0%	0.1%	2.6%
Background Estimation	0.6%	0.1%	0.4%
Theoretical	13.3%	13.9%	13.3%
Signal	10.1%	12.2%	10.5%
Backgrounds	3.6%	1.9%	3.1%

Dominated by Data Statistics ~80%

Constraints on κ_λ & κ_{2V}

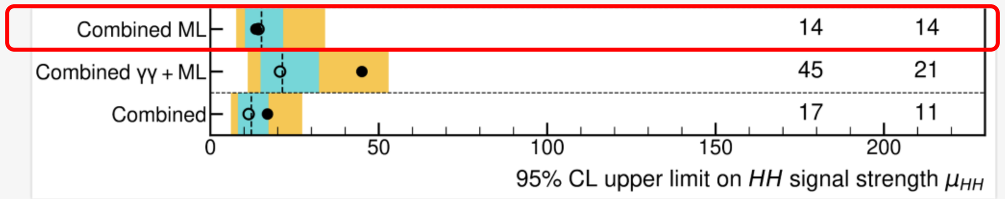
- Constructed parameterized kappa workspace including $\kappa_\lambda, \kappa_t, \kappa_{2V}, \kappa_V$ with 3 ggF and 6 VBF samples
- $4\ell + b\bar{b}$ is the most sensitive channel for κ_λ scan.
- κ_λ scan reaches **better results than $b\bar{b}b\bar{b}$**.

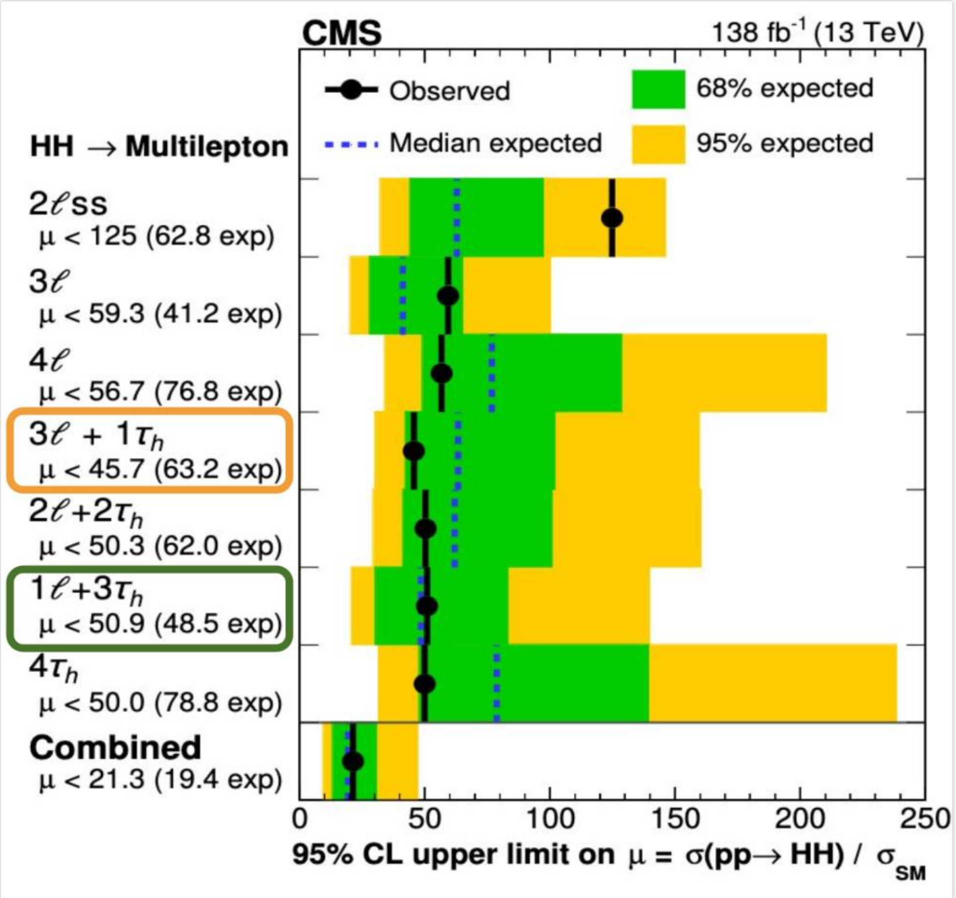




Summary

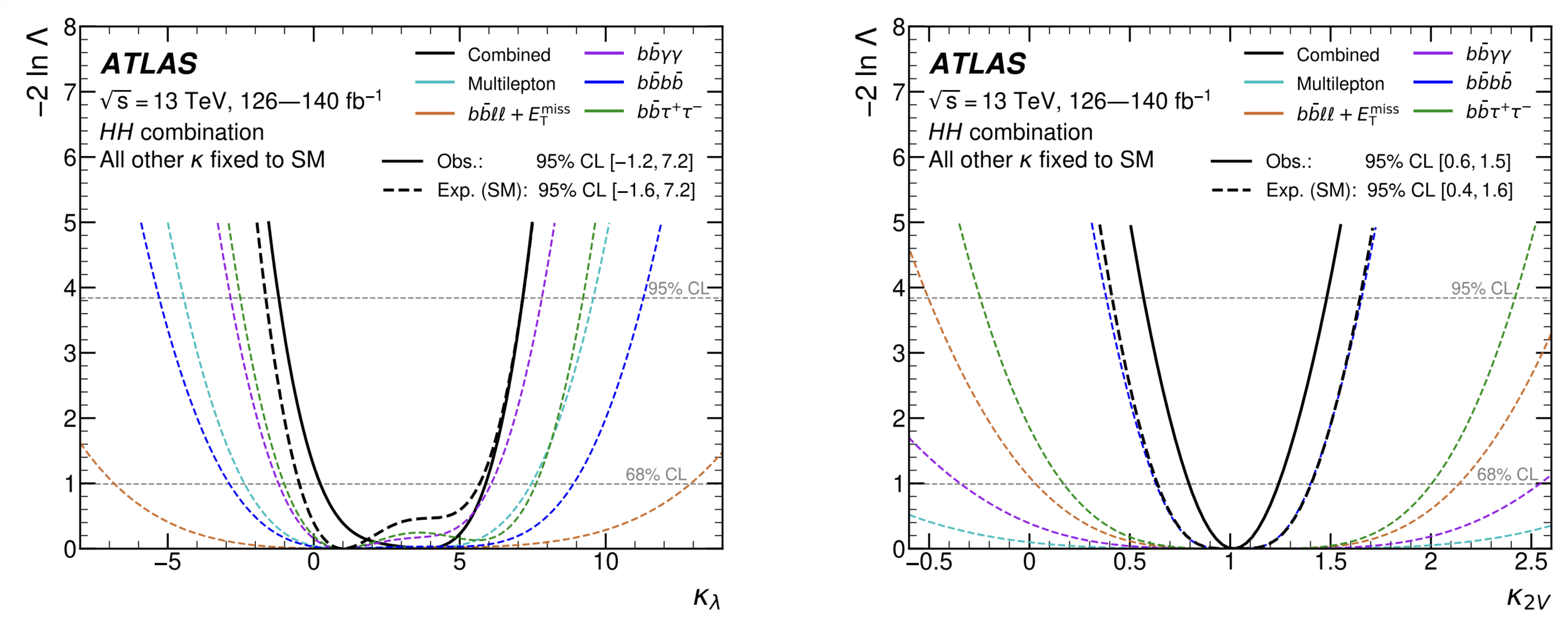
- **First result** of 95% C.L. combined observed upper limit reaches 17 on the HH cross-section over SM for $HH \rightarrow$ multilepton final states with the full Run 2 data with 140^{-1} fb luminosity. **arXiv: 2405.20040**
- *Machine learning techniques are introduced in multilepton for the first time, achieved an order of magnitude increasement in expected sensitivity for 3-lepton channel.*
  - 1.7-fold gain from higher luminosity
  - 2-fold enhancement with optimized identification and isolation criteria
  - 2.8-fold increase due to the advanced use of MVA techniques
- Advanced MVA techniques are under investigation for RUN 3:
  - Preliminary study of **using GNN on 3-lepton** gives expected upper limit (stats. only) of **20.51** (current: 23.82)





Backup

Kappa Scan in HH channels



Trigger

- The trigger strategies refer to the ttH multilepton $80\ \text{fb}^{-1}$ study [link] and follow the recommendation.
- single-lepton triggers (**SL**) and di-lepton triggers (**DL**)
- Channels with ≥ 2 light leptons: **SL** OR **DL**
- $1\ell + 2\tau_h$: **SL**
- Trigger Scale Factor calculated by *TrigGlobalEfficiencyCorrection* package [link]
- Di-photon triggers are applied for $\boldsymbol{\gamma\gamma}$+ multilepton:
  - HLT_g35_loose_g25_loose (2015/2016).
  - HLT_g35_loose_g25_medium_L12EM20VH (2017/2018).

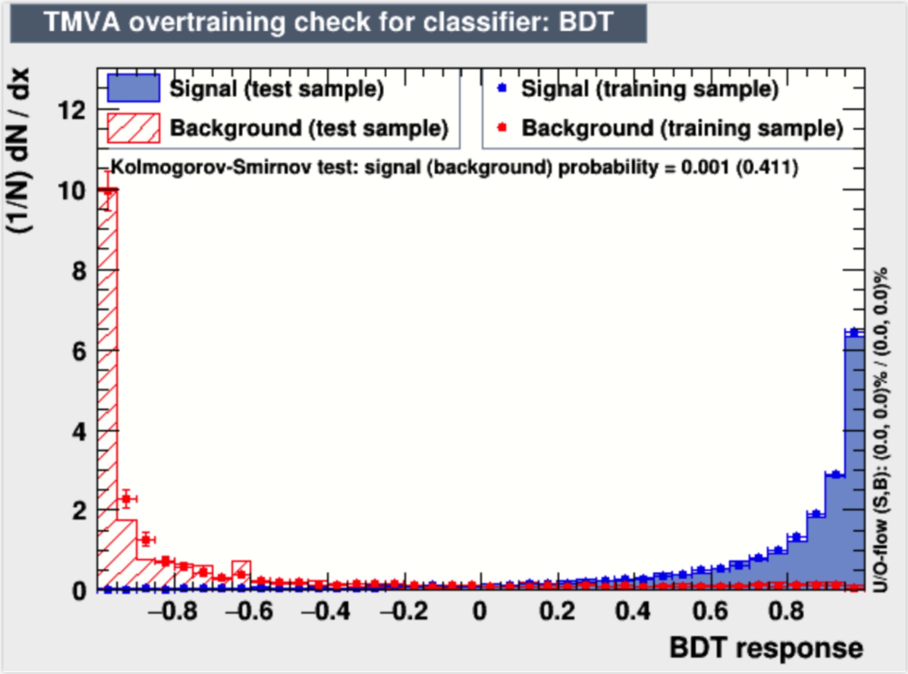
	Single lepton triggers (2015)
μ	HLT_mu20_iloose_L1MU15, HLT_mu50
e	HLT_e24_lhmedium_L1EM20VH, HLT_e60_lhmedium, HLT_e120_lhloose
	Dilepton triggers (2015)
$\mu\mu$ (asymm.)	HLT_mu18_mu8noL1
ee (symm.)	HLT_2e12_lhloose_L12EM10VH
$e\mu, \mu e$ ($\sim$symm.)	HLT_e17_lhloose_mu14
	Single lepton triggers (2016)
μ	HLT_mu26_ivarmedium, HLT_mu50
e	HLT_e26_lhtight_nod0_ivarloose, HLT_e60_lhmedium_nod0, HLT_e140_lhloose_nod0
	Dilepton triggers (2016)
$\mu\mu$ (asymm.)	HLT_mu22_mu8noL1
ee (symm.)	HLT_2e17_lhvloose_nod0
$e\mu, \mu e$ ($\sim$symm.)	HLT_e17_lhloose_nod0_mu14
	Single lepton triggers (2017 / 2018)
μ	HLT_mu26_ivarmedium, HLT_mu50
e	HLT_e26_lhtight_nod0_ivarloose, HLT_e60_lhmedium_nod0, HLT_e140_lhloose_nod0
	Dilepton triggers (2017 / 2018)
$\mu\mu$ (asymm.)	HLT_mu22_mu8noL1
ee (symm.)	HLT_2e24_lhvloose_nod0
$e\mu, \mu e$ ($\sim$symm.)	HLT_e17_lhloose_nod0_mu14

$b\bar{b}4\ell$: MVA

MVA strategy

- 80% of the total events from the signal and full backgrounds which pass the event selection. The rest of events are used for testing.

Variables	Symbol	Description	Separation
lep_Pt_0	p_{T,l_1}	p_T of the first lepton	2.432e-01
lep_Pt_3	p_{T,l_4}	p_T of the fourth lepton	2.275e-01
m_41	m_{41}	Invariant mass of the quadruplet	2.235e-01
met met	MET	Missing transverse energy	2.131e-01
HT	HT	Scalar sum of p_T of all the objects	1.941e-01
lep_Pt_1	p_{T,l_2}	p_T of the second lepton	1.924e-01
m_12	$m_{\text{leading pair}}$	Invariant mass of the leading lepton pair	1.812e-01
lep_Pt_2	p_{T,l_3}	p_T of the third lepton	1.600e-01
p_jj	$p_{T,jj}$	p_T of the leading jet pair	1.528e-01
lep_Etcone30_3	Etcone30_4	$(\sum_{\Delta R<0.3} E_T)/E_T$ of the fourth lepton	1.331e-01
nbjets	$N_{b\text{Jets}}$	Number of b-jets	1.227e-01
lep_Etcone30_0	Etcone30_1	$(\sum_{\Delta R<0.3} E_T)/E_T$ of the first lepton	1.165e-01
Dphi_met_jets	$\Delta_{\text{MET\&jets}}$	$\Delta\Phi$ of the MET and leading jets	1.062e-01
lep_Etcone30_1	Etcone30_2	$(\sum_{\Delta R<0.3} E_T)/E_T$ of the second lepton	9.586e-02
jet_Pt_0	$p_{T,\text{leading jet}}$	p_T of the first jet	9.547e-02
lep_Etcone30_2	Etcone30_3	$(\sum_{\Delta R<0.3} E_T)/E_T$ of the third lepton	7.792e-02
m_34	$m_{\text{sub-leading pair}}$	Invariant mass of the sub-leading lepton pair	6.869e-02
m_jj	m_{jj}	Invariant mass of the leading jet pair	6.680e-02
lep_Eta_3	η_4	η of the fourth lepton	2.084e-02
lep_Eta_2	η_3	η of the third lepton	1.970e-02
lep_Eta 1	η_2	η of the second lepton	1.474e-02
lep_Eta_0	η_1	η of the first lepton	9.422e-03



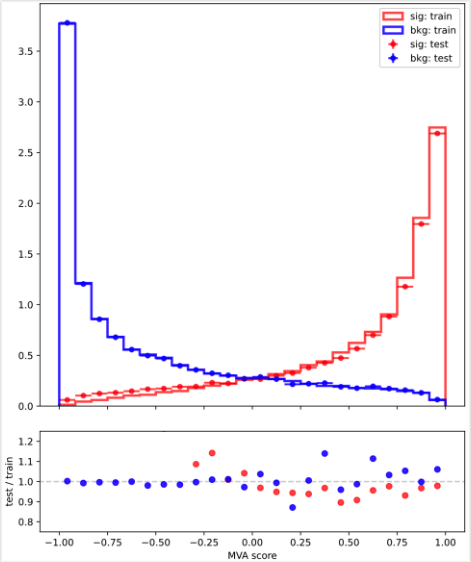
3ℓ: MVA

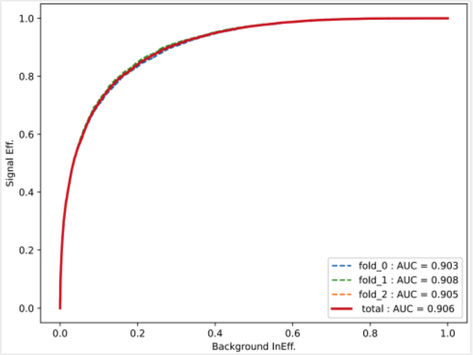
Low BDTG validation region: BDT score < 0.55
Signal Region: BDT score ≥ 0.55

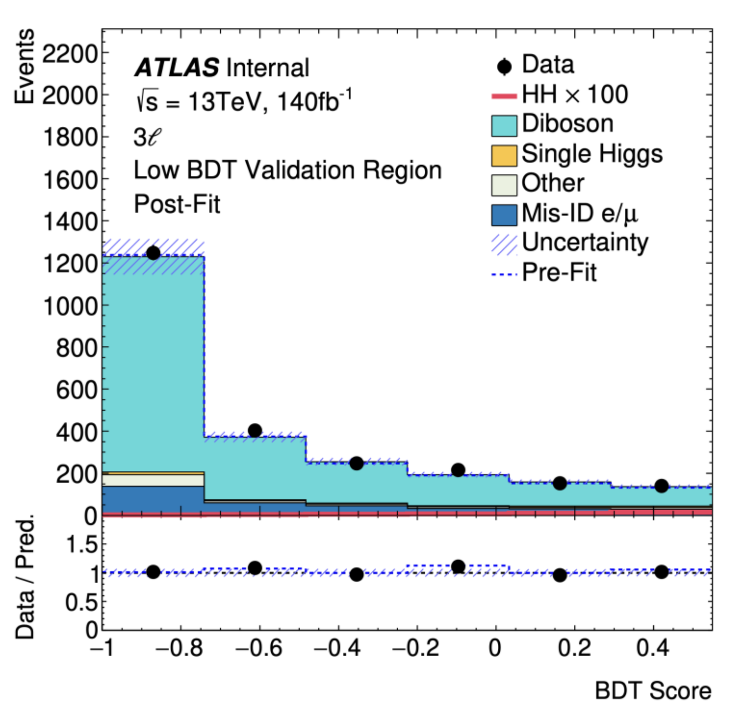
MVA strategy

- 3-fold training over signal and all background samples

Variable	Description	Separation
$\Delta R_{l_0 l_1}$	Distance in $\eta - \phi$ space between lepton 0 and lepton 1	32.62%
$m_{l_0 l_1}$	Invariant mass of lepton 0 and lepton 1	26.90%
min. m_{ll}^{OS}	Minimum invariant mass of opposite-sign lepton pairs	26.23%
$\Delta R_{l_2 j}$	Distance in $\eta - \phi$ space between lepton 2 and nearest jet	23.90%
$\Delta R_{l_1 l_2}$	Distance in $\eta - \phi$ space between lepton 1 and lepton 2	12.67%
min. m_{ll}^{OSSF}	Minimum invariant mass of opposite-sign same-flavor lepton pairs	11.41%
$m_{ll}^{Z\text{-matched}}$	Invariant mass of lepton pair closest to Z mass	11.38%
$m_{lll jj}$	Invariant mass of all three leptons and two leading jets	3.49%
m_{lll}	Invariant mass of all three leptons	2.94%
$m_{l_2 j}$	Invariant mass of lepton 2 and nearest jet	2.40%
$m_{l_0 l_2}$	Invariant mass of lepton 0 and lepton 2	2.11%
$E\!\!\!/_T$	Missing transverse energy	1.80%
$\Delta R_{l_0 j}$	Distance in $\eta - \phi$ space between lepton 0 and nearest jet	1.20%
FlavorCategory	Categorization of lepton flavors, details in Sec. 7.2.1	1.17%
HT_{lep}	Scalar sum of lepton p_T's and missing transverse momentum	0.96%
HT	Scalar sum of jet p_T's	0.52%
$\Delta R_{l_1 j}$	Distance in $\eta - \phi$ space between lepton 1 and nearest jet	0.33%
$\Delta R_{l_0 l_2}$	Distance in $\eta - \phi$ space between lepton 0 and lepton 2	0.26%
$m_{l_1 j}$	Invariant mass of lepton 1 and nearest jet	0.19%
HT_{jets}	Scalar sum of jet p_T's	0.05%
$m_{l_0 j}$	Invariant mass of lepton 0 and nearest jet	0.01%
$m_{l_1 l_2}$	Invariant mass of lepton 1 and lepton 2	0.01%







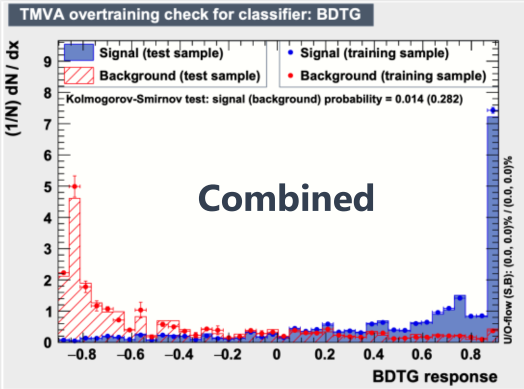
$2\ell SC$: MVA

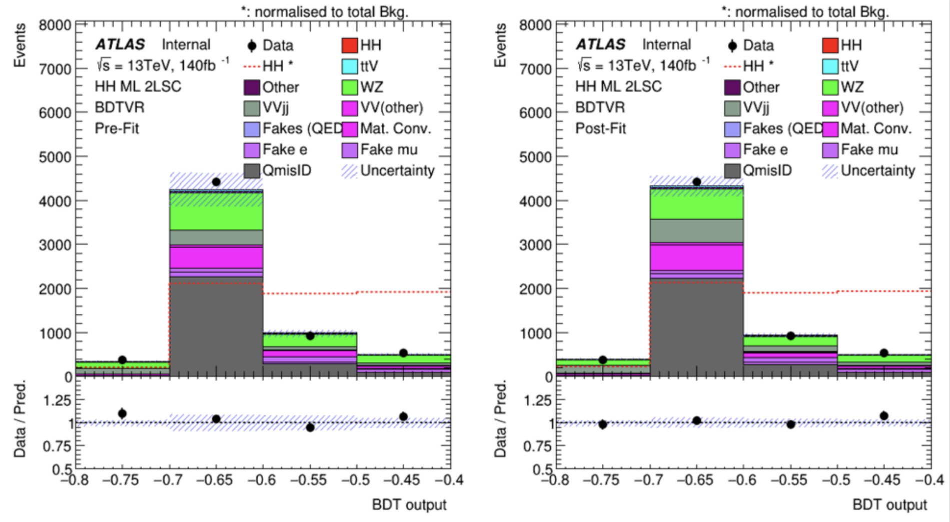
Low BDTG validation region: BDT score < -0.4
Signal Region: BDT score ≥ 0.4

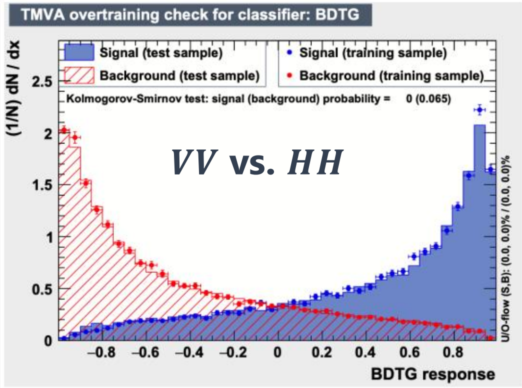
MVA strategy

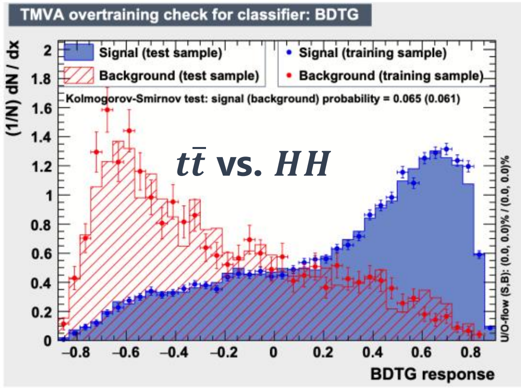
- Three specific BDTs to target the leading three background. A combined BDT using them as input.
- Signal region: High BDT region of the combined BDT

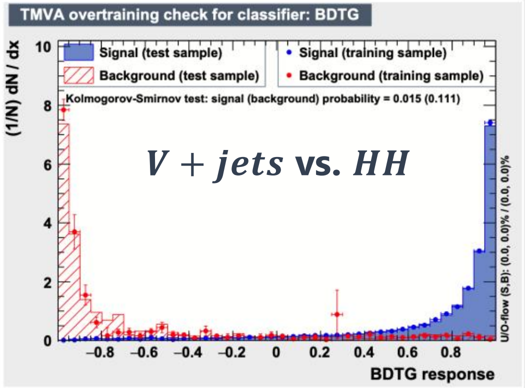
- $M_{\ell\ell}$: invariant mass of the di-lepton system
- M_{all}: invariant mass of all selected objects: leptons and jets
- $M_{\ell 0j}$: invariant mass of the leading lepton and its closest jet
- $M_{\ell 1j}$: invariant mass of the subleading lepton and its closest jet
- M^T_{W0} and M^T_{W1}: the transverse mass of the leptonically decay W boson (reconstructed by the MET with leading lepton and subleading lepton, respectively).
- E_T^{miss}: missing transverse energy
- η_0 and η_1: η of the leading and the subleading leptons
- $\Delta\eta$: absolute value of η_0-η_1
- Number of jets
- H_T: scalar sum of transverse momentum of all visible objects
- $H_T\,(lep)$: scalar sum of transverse momentum of the leptons
- Dilep_type: =1 if $\mu\mu$, =2 if $e\mu$ or μe, =3 if ee
- $\Delta R_{min\ell 0jets}$: minimum distance between the leading lepton and its closest jet
- $\Delta R_{min\ell 1jets}$: minimum distance between the subleading lepton and its closest jet
- $\Delta R_{\ell\ell}$: Distance between the leading and the subleading leptons
- Total_charge: Sum of the charge of the leading and the subleading lepton which could be +2 or −2 as leptons have to have same electric charge. The total charge is specific to the VV BDT. In the 2LSS, VV background is mainly due to WZ events. Unlike the HH final state, a charge asymmetry is therefore expected in the VV final state.





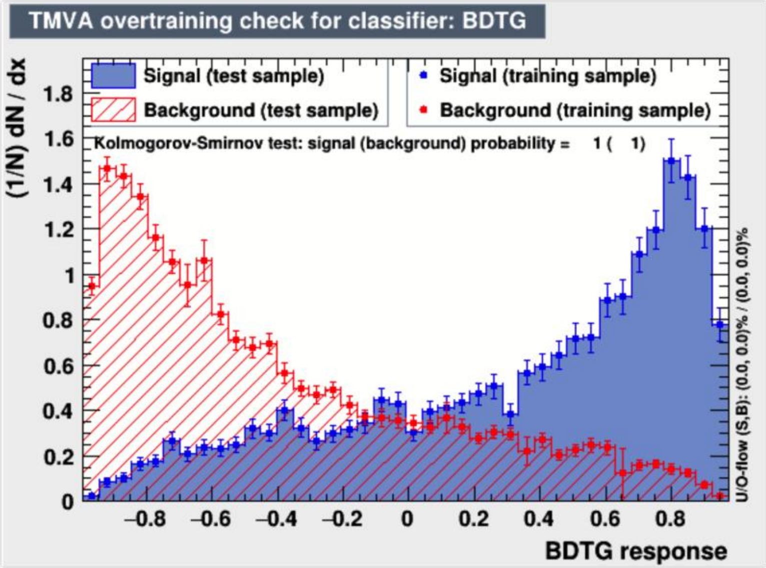




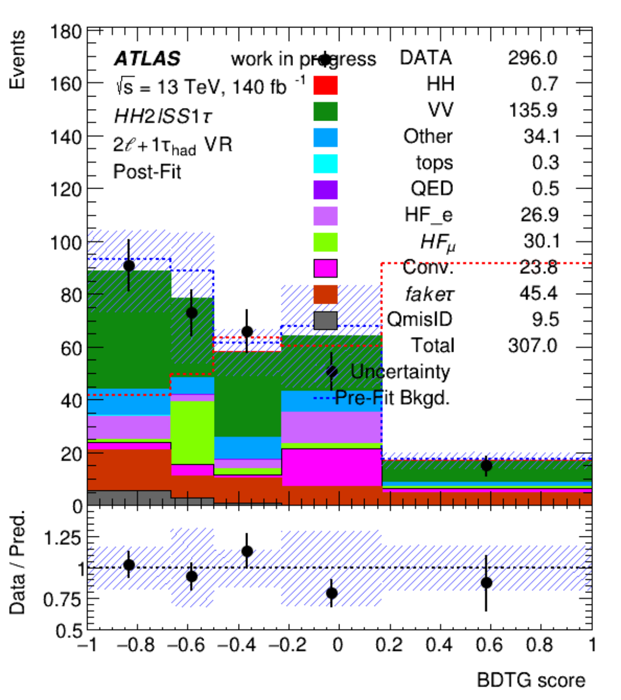


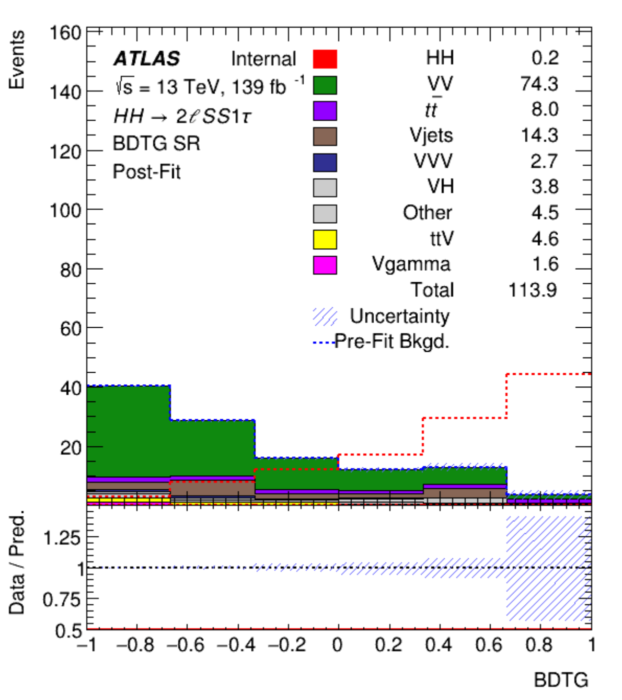
$2\ell SC + 1\tau_h$: MVA

- MVA strategy
  - 5-fold training over signal and dominant background samples ($\boldsymbol{VV}$)



Validation region: nJets < 2
Signal Region: BDT score ≥ -0.2 & nJets ≥ 2



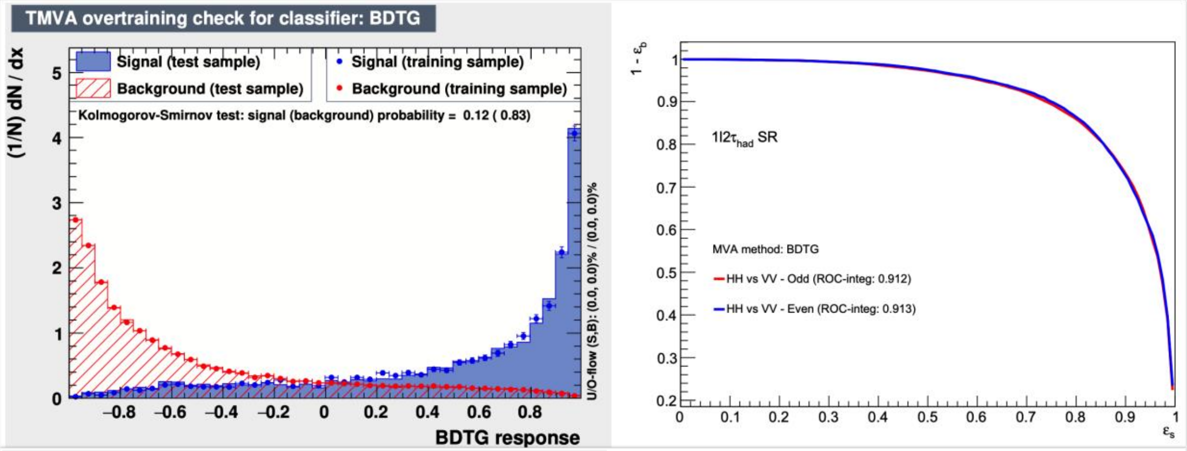


Variable	Description	Rank	Separation power
$\Delta R(\ell_0,\ \ell_1)$	Distance between leading and sub-leading leptons	1	12.48%
$M(\ell_0,\ \text{jet}_{\text{leading}})$	Invariant mass of leading lepton and leading jet	2	11.57%
$M(\ell_0,\ \text{closet}-\text{jet})$	Invariant mass of leading lepton and it's closet jet	3	11.39%
$\Delta R(\ell_0,\ \text{closet jet})$	Distance between leading lepton and it's closet jet	4	10.24%
$\Delta R(\ell_0,\ \text{jet}_{\text{leading}})$	Distance between leading lepton and leading jet	5	9.11%
$M(\ell_1,\ \text{jet}_{\text{leading}})$	Invariant mass of sub-leading lepton and leading jet	6	9.04%
$\Theta(boost\ell_0, \ell_1, \tau_{\text{had}}, \text{jet}_{\text{leading}})$	Angle between tau and leading jet after lorentz boost to two leading leptons system	7	8.50%
$\Theta(boost\ell_0, \ell_1, \tau_{\text{had}}, \text{jet}_{\text{sub-leading}})$	Angle between tau and sub-leading jet after lorentz boost to two leading leptons system	9	6.87%
$\Delta R(\ell_1,\ \text{closet jet})$	Distance between sub-leading lepton and it's closet jet	10	6.60%
$\Delta R(boost\ell_0, \tau_{\text{had}}, \ell 0, \text{jet}_{\text{sub-leading}})$	Distance between leading lepton and sub-leading jet after lorentz boost to tau and leading leptons system	11	6.48%
$M(\ \tau_{\text{had}}, \ell closet)$	Invariant mass of tau and it's closet lep	12	6.00%
$\Delta R(boost\ell_1, \tau_{\text{had}}, \ell 1, \text{jet}_{\text{leading}})$	Distance between sub-leading lepton and leading jet after lorentz boost to tau and sub-leading leptons system	13	5.88%
$M(\ell_0,\ \text{jet}_{\text{sub-leading}})$	Invariant mass of leading lepton and sub-leading jet	14	5.85%

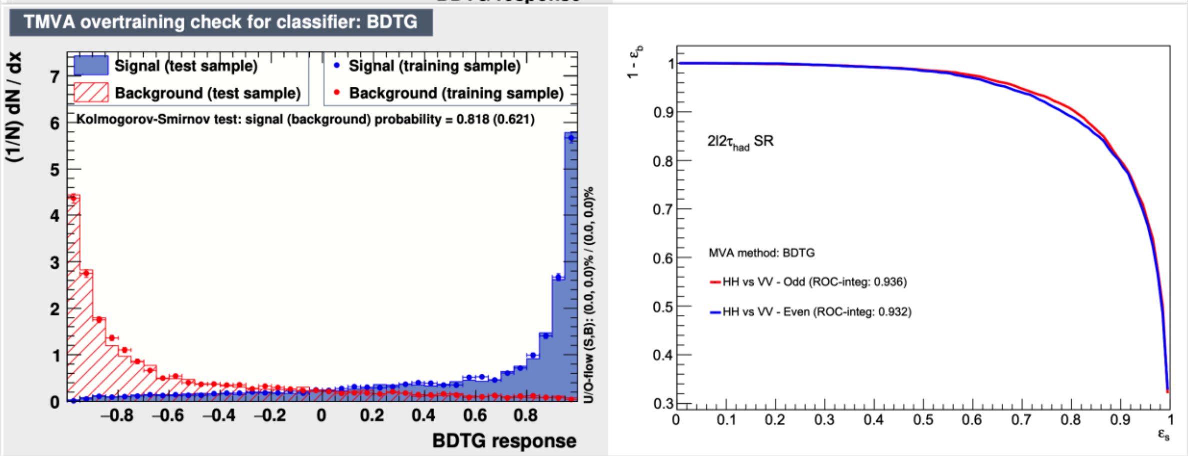
$1/2\ell + 2\tau_h$: MVA

- MVA strategy
  - HH signal is trained against VV. The V + jets and $t\bar{t}$ background samples are not used in the training due to the low statistics. (no impact)
  - Odd-Even training.

Variable	Description	Separation power
$M(\ell_0,\ \text{jet})$	Invariant mass of lepton and its closest jet	27.34%
$M(\tau_{\text{had}0},\ \tau_{\text{had}1})$	Ditau invariant mass	21.61%
$\Delta R(\ell_0,\ \text{jet}_{\text{lead}})$	Distance between lepton and leading jet	16.81%
$\Delta R(\ell_0,\ \tau_{\text{had}0}\tau_{\text{had}1})$	Distance between lepton and ditaus	16.70%
$jet_{\text{lead}}\ p_T$	Leading jet transverse momentum	16.57%
$\Delta R(\ell_0,\ \text{jet}_{\text{sublead}})$	Distance between lepton and sub-leading jet	10.06%
$M(\ell_0,\ \tau_{\text{had}0}\tau_{\text{had}1})$	Invariant mass of lepton and ditaus	7.42%
Sum $p_T\,(\ell_0,\ \text{jet})$	Vector sum of lepton and it's closest jet transverse momenta	5.41%
Sum $p_T\,(\tau_{\text{had}0},\ \tau_{\text{had}1})$	Vector sum of ditau transverse momenta	4.28%
MET	Missing energy	3.65%



Variable	Description	Separation power
$M(\ell_0,\ \ell_1)$	Dilepton invariant mass	29.04%
Lepton flavor	Bin 1 $\mu\mu$, bin 2 and 3 opposite flavor, bin 4 ee	23.58%
$M(\tau_{\text{had}0},\ \tau_{\text{had}1})$	Ditau invariant mass	22.84%
$\Delta R(\ell_0,\ \ell_1)$	Distance between leading and sub-leading leptons	14.28%
Sum $p_T\,(\tau_{\text{had}0},\ \tau_{\text{had}1})$	Sum of ditau transverse momenta	9.95%
$\Delta R(\ell_1,\ \tau_{\text{had}0})$	Distance between sub-leading lepton and leading tau	6.95%
$\Delta R(\ell_0,\ \tau_{\text{had}0}\tau_{\text{had}1})$	Distance between leading lepton and ditaus	6.01%
$M(\ell_1,\ \tau_{\text{had}0})$	Invariant mass of sub-leading lepton and leading taus	5.35%



HH Combination