$t\bar{t}HH$ or the Quest for the 3rd Higgs Pair Production Mode

Djamel Boumediene, Arthur Lafarge

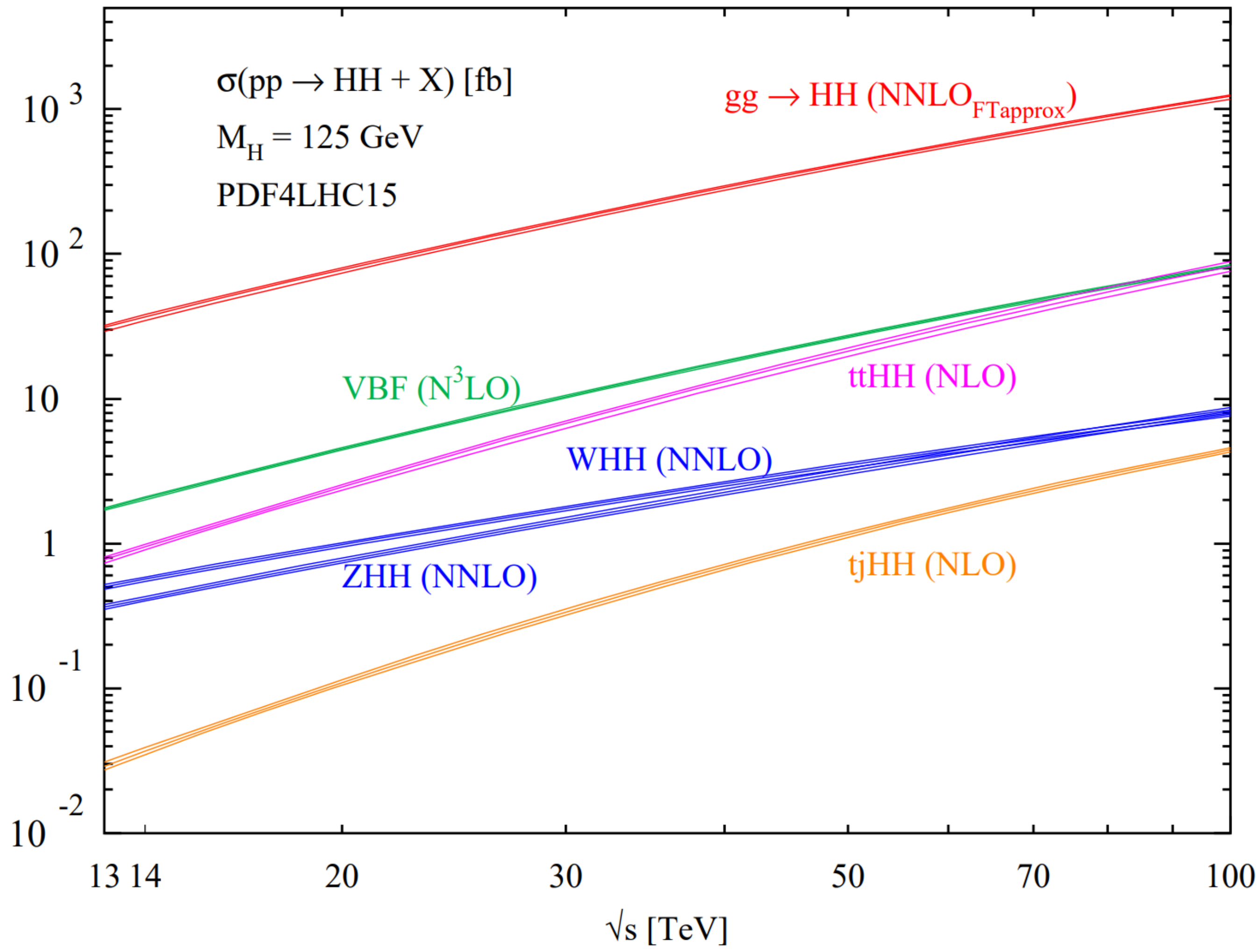
Where is $t\bar{t}HH$

THE 3rd HH PRODUCTION MODE

- **At 13.6 GeV at LHC**

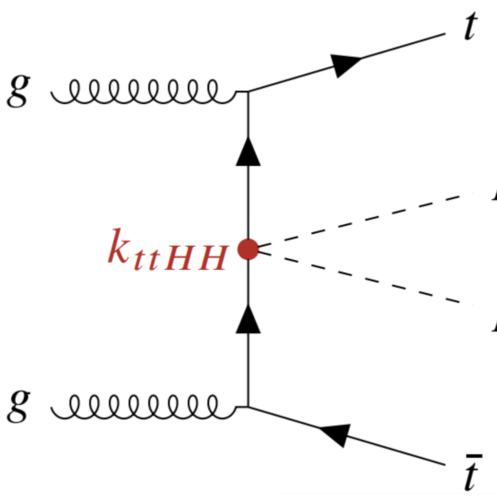
52340 fb	ggF - H	
		÷1534
34.13 fb	ggF - HH	
		÷18
1.87 fb	VBF - HH	
		÷2
0.87 fb	ttHH	

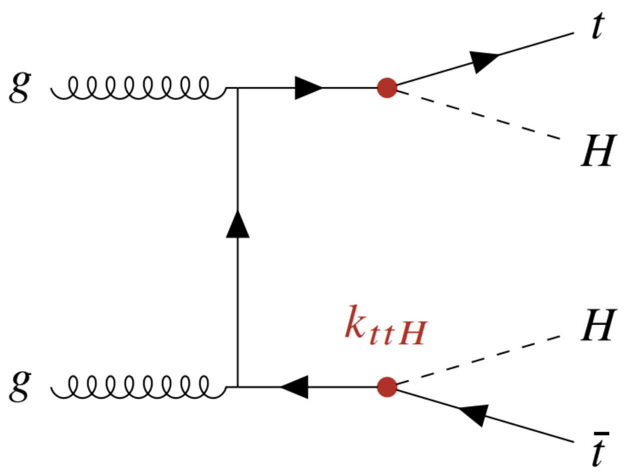
According the SM, $\sim 170\ t\bar{t}HH$ events produced in ATLAS (at 200 fb^{-1})

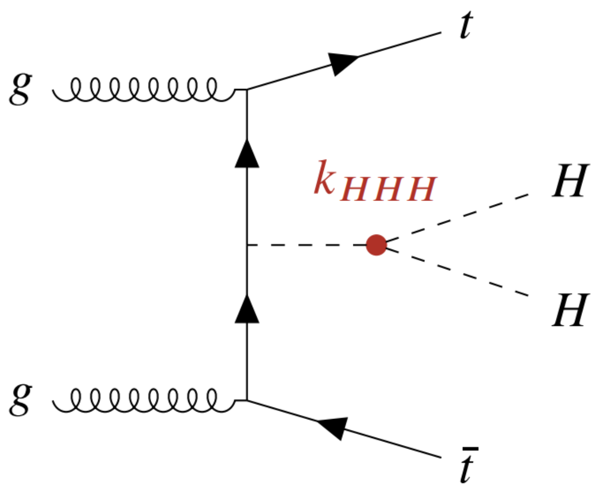


THE 1st EVER SEARCH IN ATLAS

- **Access to 3 couplings**
  - Very interesting for BSM searches
- **Linking Higgs and top sectors**
- **EFT constraints**
  - HEFT and SMEFT models under study
- **3 final states extensively explored**
  - <u>1L</u>: $HH \rightarrow b\bar{b}b\bar{b}$
  - <u>Multi-leptons</u>: non all-hadronic HH decays
  - <u>$b\bar{b}\gamma\gamma$</u>



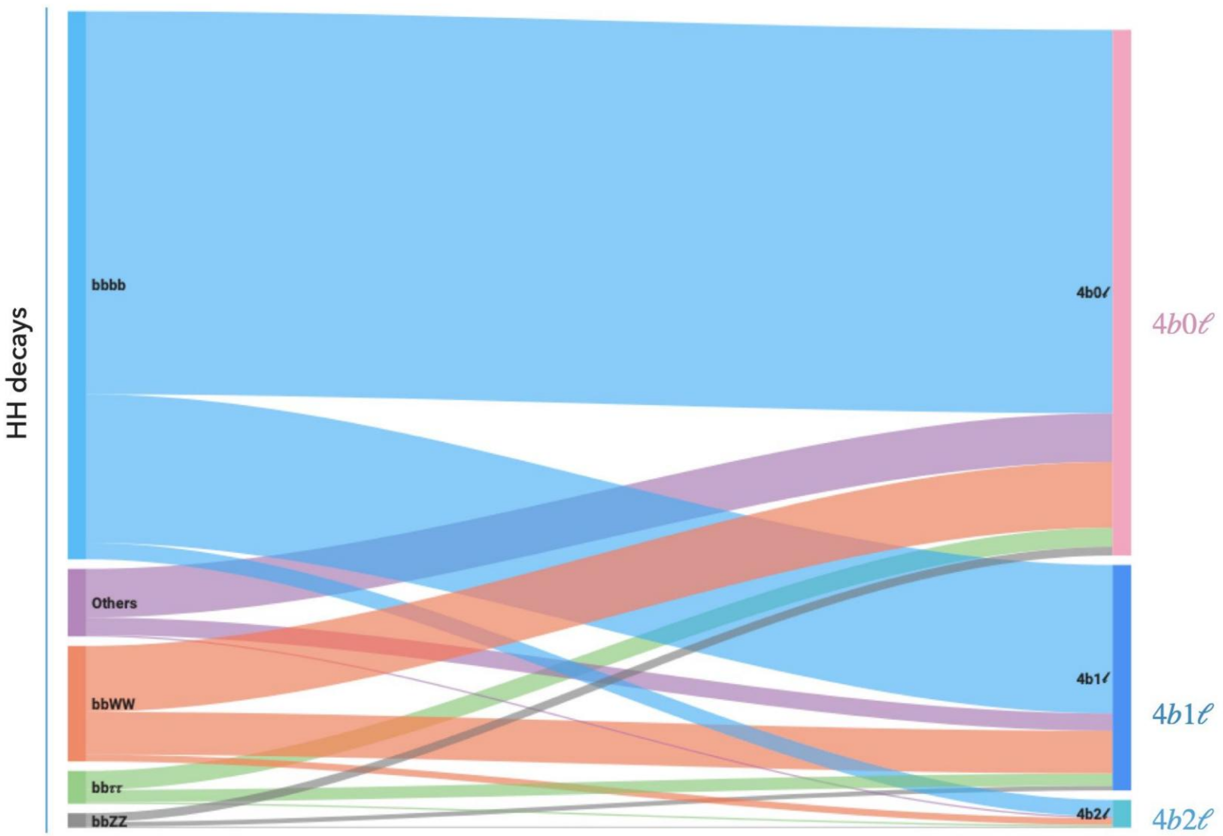




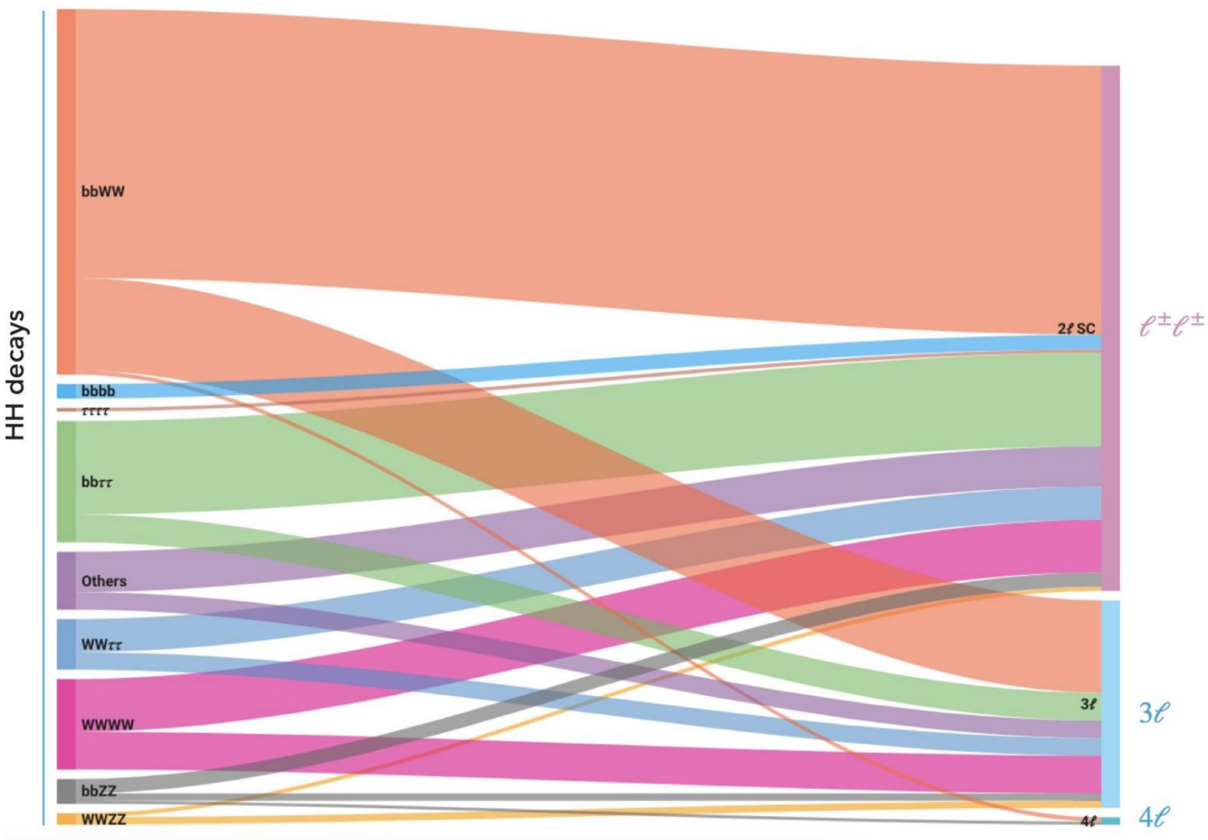
Main channels under investigation in *ATLAS*

DECAY MODES OF HH PAIR

4b



Same Sign Multi-Leptons



1 LEPTONS & 2 OPPOSITE SIGN LEPTONS (4b)

- **Primarily target the $HH \to b\bar{b}b\bar{b}$ decay mode**
  - 20% of all produced $t\bar{t}HH$ events

  → Large branching ratio

- **irreducible $tt + jets$ background**
  - cross-section ~6 orders of magnitude bigger than $t\bar{t}HH$
  - Challenging background modelling
    - Data-driven kinematic reweighting

- **SRs and CRs**
  - Defined by b-jets multiplicity with different b-tagging working points

    → Correct the flavour components rate by normalizing factors
  - Results derived from MVA scores used in SRs

OS: opposite sign L: lepton

Pre-selection

- At least 3 b-jets at 85% with GN2v01
- $H_T > 400\ GeV$
- $5 < N_j < 12$
- [1L] - exactly one matched loose lepton
  - $p_T^{leading}$ > 27 GeV
- [OS2L] – 2OS loose leptons
  - $p_T^{leading}$ > 27 GeV
  - $p_T^{sub-leading}$ > 20 GeV
- [OS2L]- $m_{2l} \notin$ [83, 99] GeV

MULTILEPTONS – SAME SIGNS

- **Target non all-hadronic HH decay modes**
  - $bbWW, bbZZ, bb\tau\tau, WW, \ldots$
  - 7% of all produced $t\bar{t}HH$ events
- **Complementary to previous channels**
  - 2 charged leptons with same electric charge
  - At least 3 leptons
- **Irreducible background**
  - Large contribution from $t\bar{t}$W in SRs
- **Contribution from fake/non-prompt leptons**
  - Data-driven approach to constraint contributions from HF and light mesons
- **Contribution from charge misID**
  - Rate estimation from $Z \rightarrow e^+e^-$

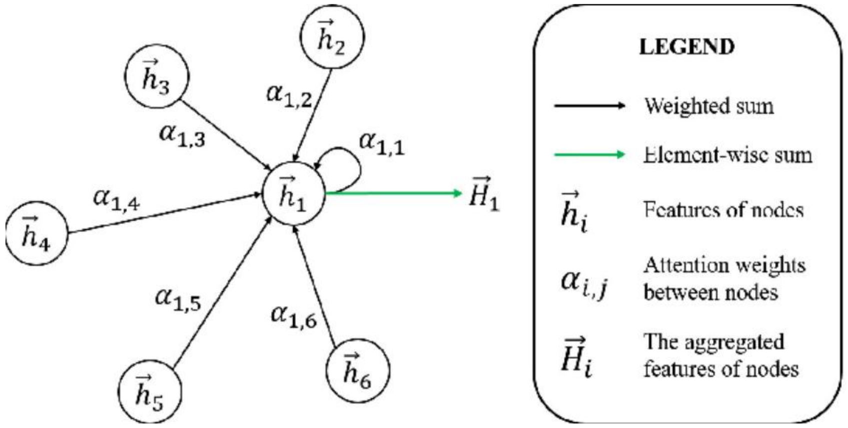
Pre-selection

- At least 2 loose leptons
  - $p_T^{leading} > 28$ GeV
  - $p_T^{sub-leading} > 15$ GeV
- $m_{2l} \notin [81, 101]$ GeV
- At least 1 b-jets at 85% with GN2
- [SS2L] - exactly 2SS tight leptons
- [3L] - at least 3 tight leptons

CATEGORIZATION

- **Graph Attention Network**
  - Self-attention mechanism to weight nodes
  - Focus on more relevant connections
  - SALT framework used

- **Multi-class training**
  - Objects kinematic and multiplicity features
    - isJet, isEl, isMu, isLepton, isMET, pt, eta, phi, E, PCBT, charge, isTight
  - Signal vs different backgrounds
  - Output:
    - logarithm of the ratio of probability of the signal class and background classes



- **Better performance than BDT obtained**
  - $\sim 20\%$ improvement on the upper limit [1L]

PROBING $c_{t\bar{t}HH}$

- **Standard Model Effective Field Theory [SMEFT]**
  - $\mathcal{L}_{SM}$ extended with a complete basis of dimension 6 operators
  - Only dim-6 is considered
  - Drawback:

    → Does not give access directly to $c_{t\bar{t}HH}$

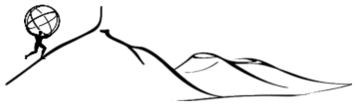
- **Higgs Effective Field Theory [HEFT]**
  - Give access to $c_{t\bar{t}HH}$
  - Drawback:

    → Limitation for the $t\bar{t}HH$ signature

arXiv:2304.01968

SMEFT to HEFT mapping

c_{ttHH} *could be parametrized according SMEFT operators*



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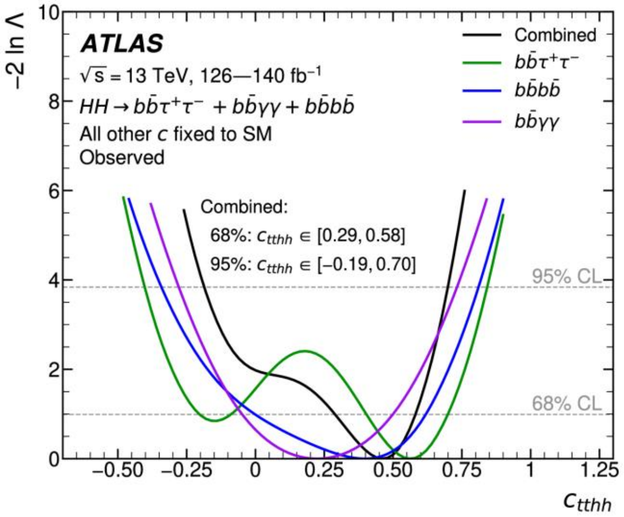
SMEFT to HEFT mapping
c_{ttHH} *could be parametrized according SMEFT operators*

Strong quadratic dependence of σ_{ttHH} w.r.t. c_{ttHH}

$$\frac{\sigma_{ttHH}(c_{ttHH}=2)}{\sigma_{ttHH}(c_{ttHH}=0)} \sim 10$$

arXiv:2406.09971



- **Investigation of $c_{t\bar{t}HH}$ vs κ_λ**

Let’s turn to something rarer: $\bar{b}b\gamma\gamma$ channel

AS MUCH AS POSSIBLE

- **Search for 0.26% of $t\bar{t}HH$ of events**
  - Among Run 2 $(140\ fb^{-1})$ + partial Run 3 $(59\ fb^{-1})$

0.3 expected events

Pre-selection

- Di-photon triggers
- $105 < m_{\gamma\gamma} < 160\ GeV$
- 2 photons (tight & Iso)
- At least 2 b-jets @90% WP
  - New GN2 tagger
- No veto on leptons

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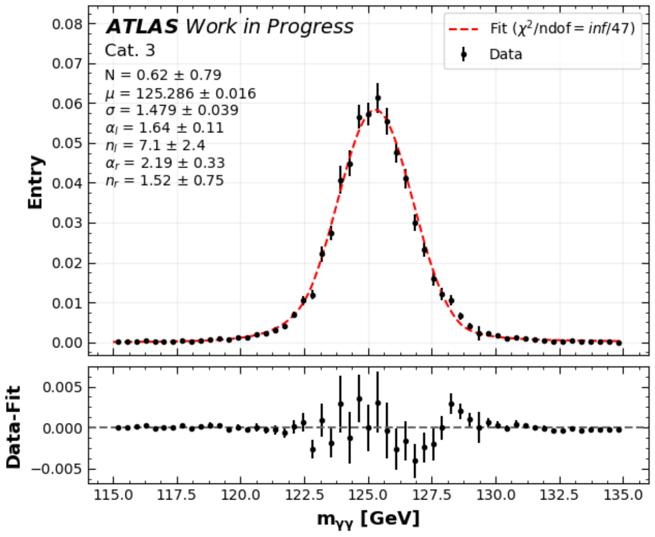
- **Relying on $H \to \gamma\gamma$ fit strategy**
  - Targeting 2 photons and at least 2 b-jets
  - Very good resolution on $m_{\gamma\gamma}$ (~1.5 GeV)



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Shape & yields from MC samples
(*fit with double sided crystal ball*)

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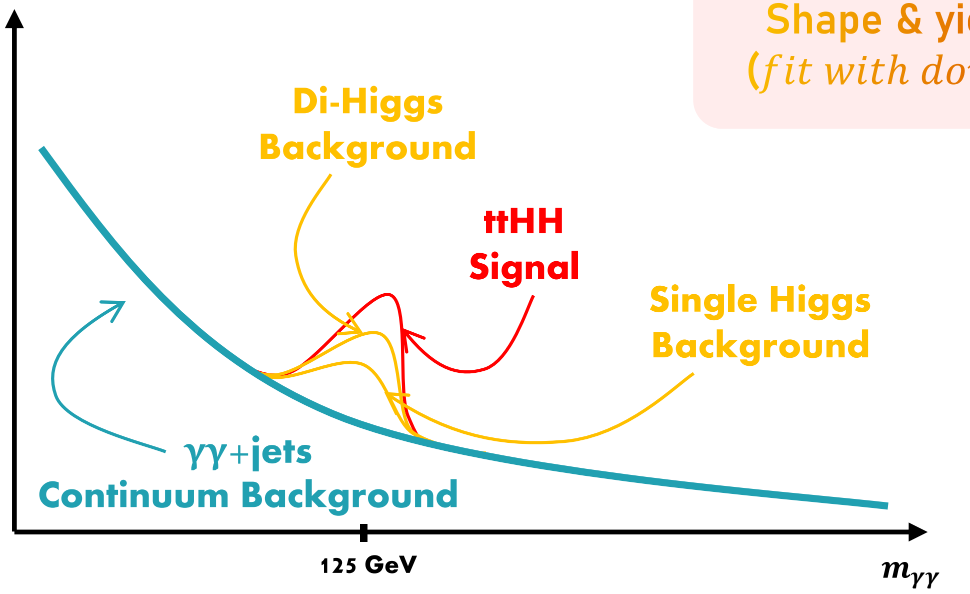


Shape & yield from data sidebands
$(unbinned\ fit\ with\ exponential$
$+\ blinded\ signal\ region)$

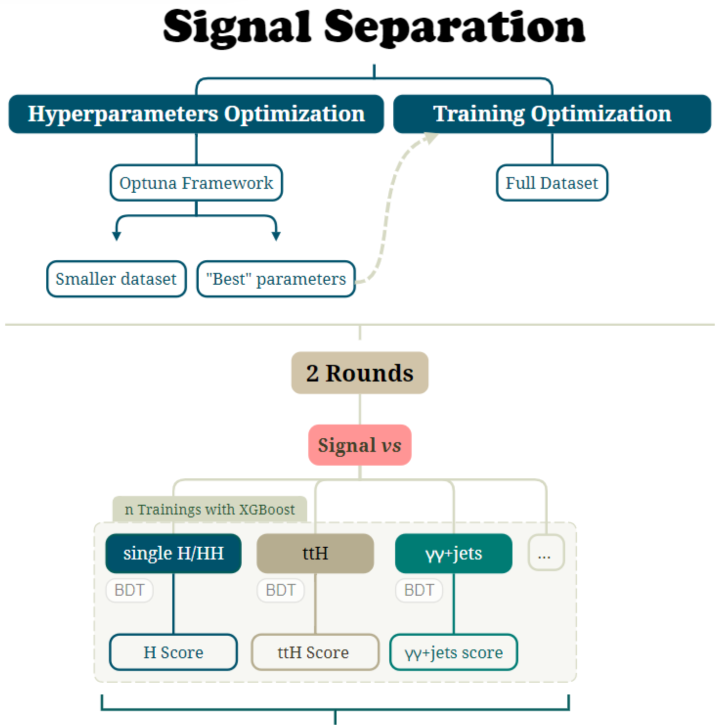
$Sidebands \doteq m_{\gamma\gamma} \in [105,120] \cup [130,160]$

SEPARATION & CATEGORIZATION

- **4 BDTs to identify signal from backgrounds**

$\gamma\gamma + jets$ | $t\bar{t}(H \rightarrow \gamma\gamma)$ | $H \,\&\, HH$ | $t\bar{t}\gamma\gamma$

- For each BDT
  - Hyperparameters optimization
  - Separate training



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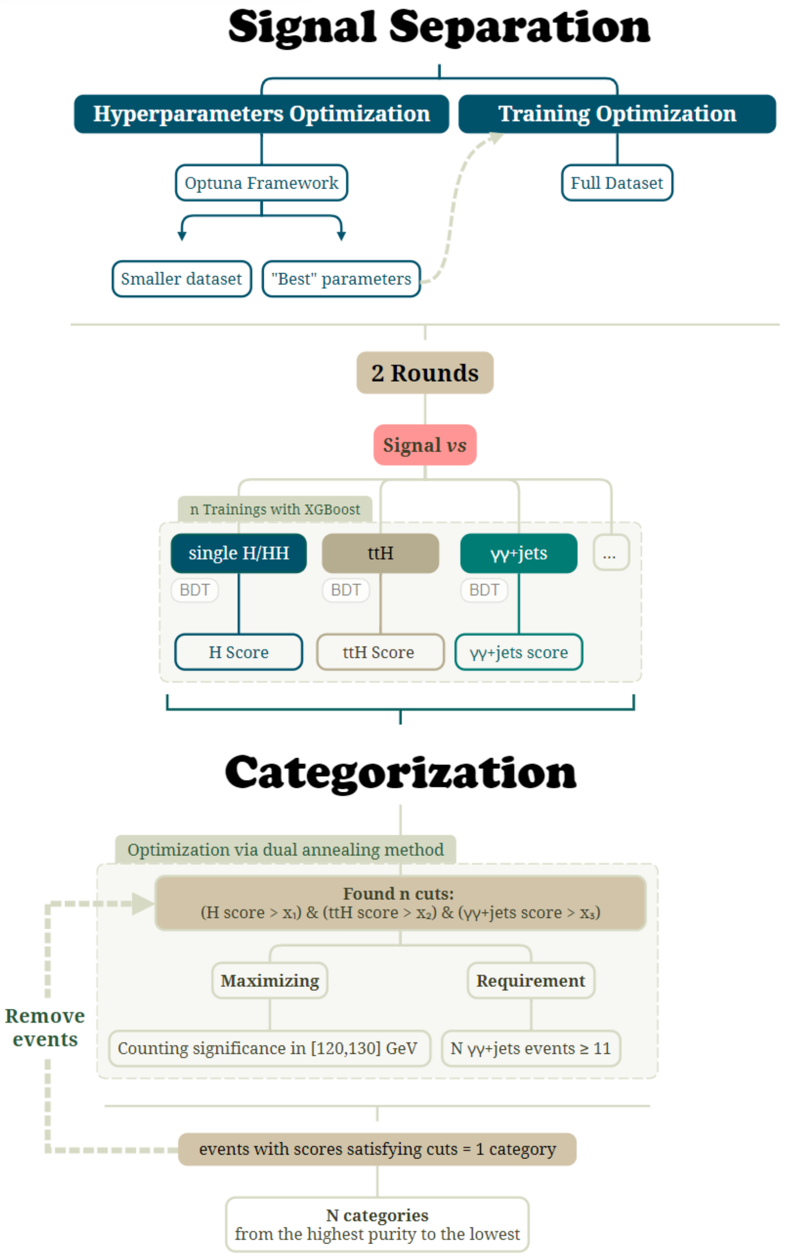
  - For each BDT
    - Hyperparameters optimization
    - Separate training

- **2 requirements for categorization**
  - Counting significance is maximized
  - A min. number of events in sidebands is requested

  → 1 category based on 8 cuts on scores
    - Found via dual annealing method

One of the main point of this analysis strategy is to <u>lower the requirement</u>



LOWERING THE REQUIREMENT

- **Definition of CR and SR**
  - Use of data CR to constraint continuum background shape in signal categories

CR: 2 b-jets

SR: 3+ b-jets

  - Assuming the independence of photon reconstruction from b-jets

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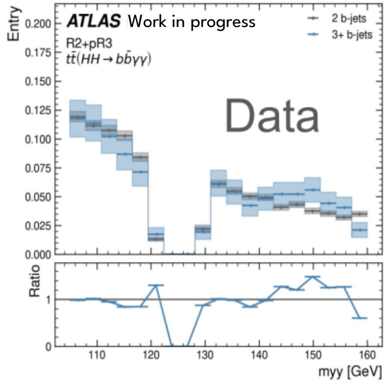
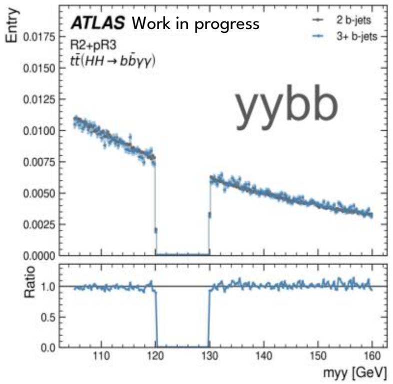
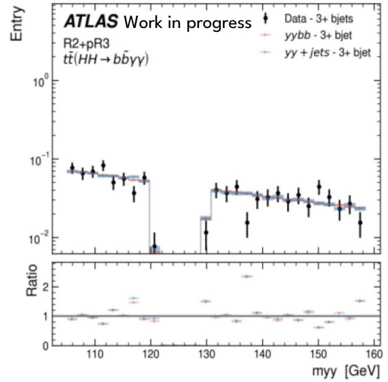




- **Ensuring same modelling**
  - Varying the shapes as an impact of less than 0.5%
    - Accounted as a systematic

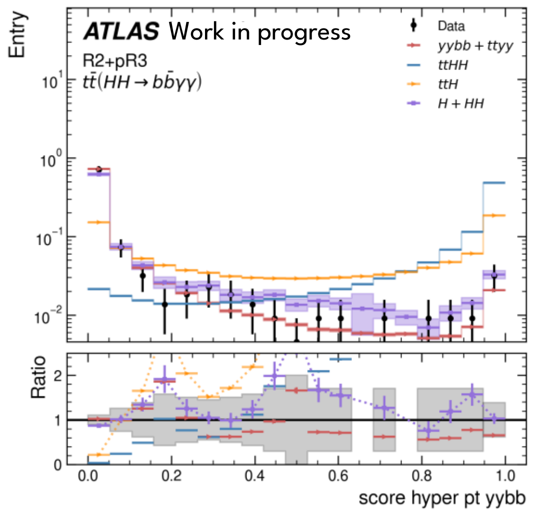
Category	data β slope	$\gamma\gamma b\bar{b}$ β slope	N in data sidebands
CR	0.02637 ± 0.00275	0.02250 ± 0.00006	6616
SR - 1	0.00695 ± 0.01004	0.02039 ± 0.00060	35
SR - 2	0.01554 ± 0.01537	0.02024 ± 0.00102	12
SR - 3	0.49985 ± 0.08291	0.02014 ± 0.00210	1

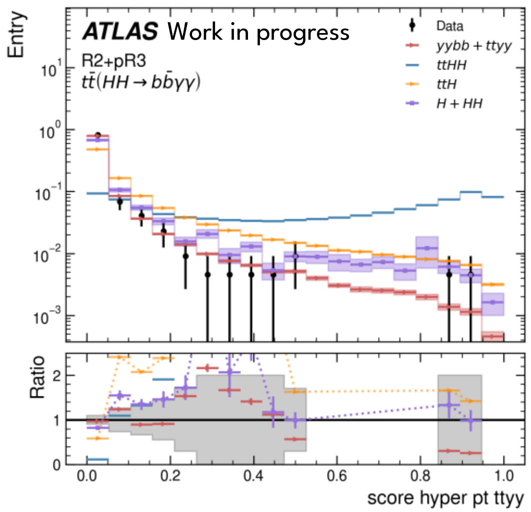
*Table to be updated

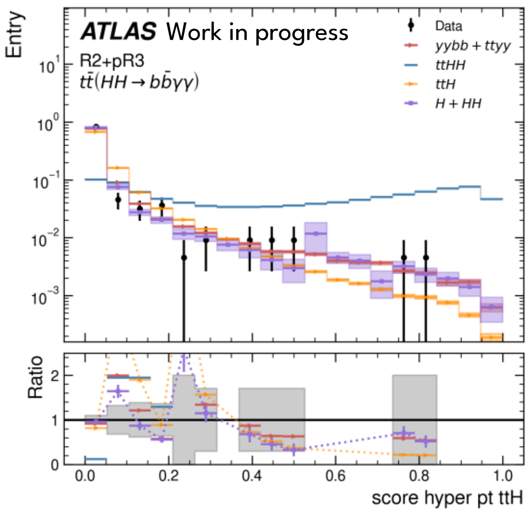


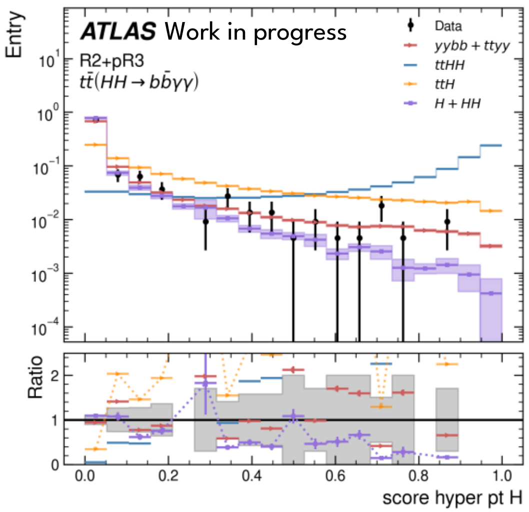
SEPARATION PERFORMANCE

- **Trainings results**









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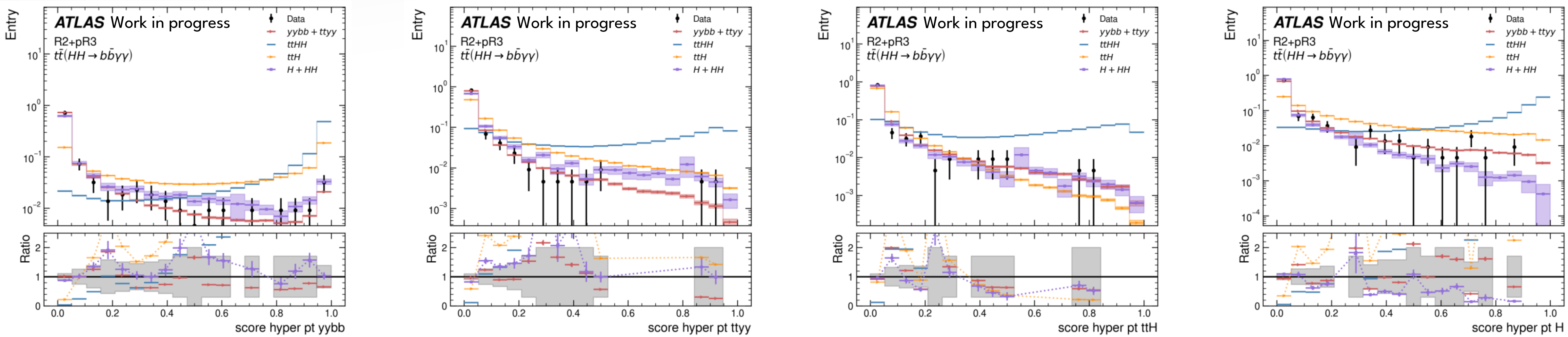
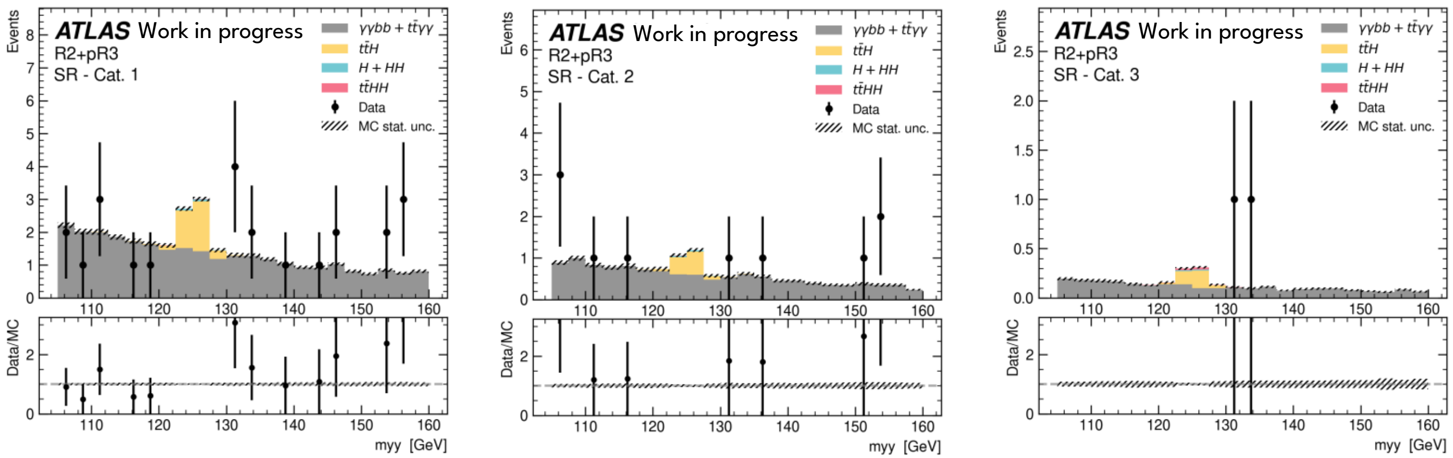


- **Signal Regions after categorization**

  - Descent sensitivity obtained
    - Compared to other channels…
    - …and with $100 \times$ smaller BR



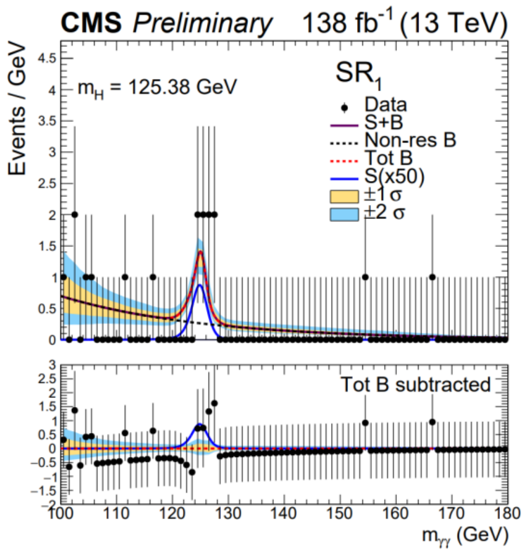
OTHER EXPERIMENTS

CMS SEARCH

PAS HIG-23-004

- **CMS released the 1st ever search for $t\bar{t}HH$**
  - Targetting $\gamma\gamma + XX,\ X \in [b, W^{\pm}, \tau^{\pm}]$ with Run 2 dataset [138 fb^{-1}]
  - Similar modelling strategy
    - Different treatment of uncertainty attached to continuum background modelling
  - Categorization based on single BDT
    - 2 SRs derived from 2 tightest cuts
    - Dedicated BDT to identified b-jets coming from H

95% CL upper limit on $\mu_{t\bar{t}HH}$ = 120 (86)



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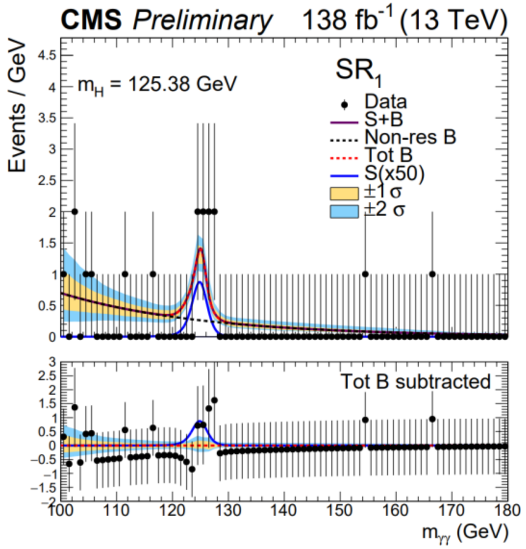
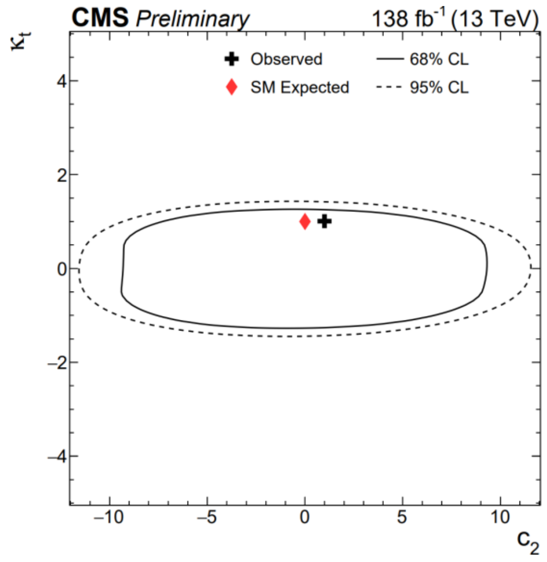


- **Multiple BSM models probed**
  - **HEFT**
    - $\kappa_{\lambda}, \kappa_t, c_{2g}, c_g, c_2$
    - Similar sensitivity on the constraint of c_2, κ_t than H and HH search
  - **2HDM**
    - targeting heavy neutral CP-even Higgs produced with top quarks
  - **VLQ**
    - Searching for heavy top partner pair production



No deviation observed

PREPARING THE FUTURE

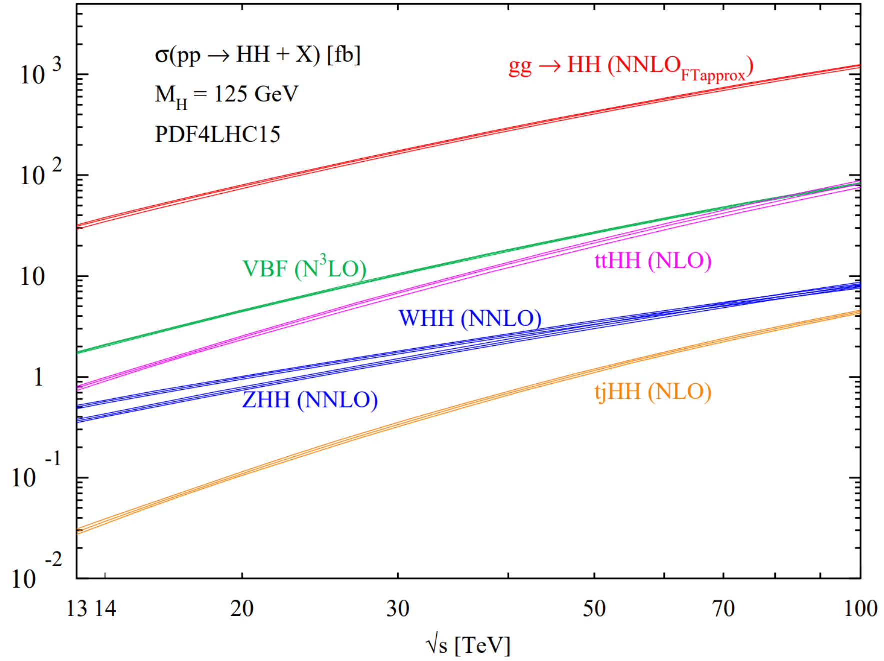
- **A production mode relevant at future colliders**
  - A faster growing cross-section
    - Ratio between modes

vs ggF

$39\ (13.6\ \text{TeV}) \rightarrow 14\ (100\ \text{TeV})$

vs VBF

$2.1\ (13.6\ \text{TeV}) \rightarrow\ < 1\ (100\ \text{TeV})$



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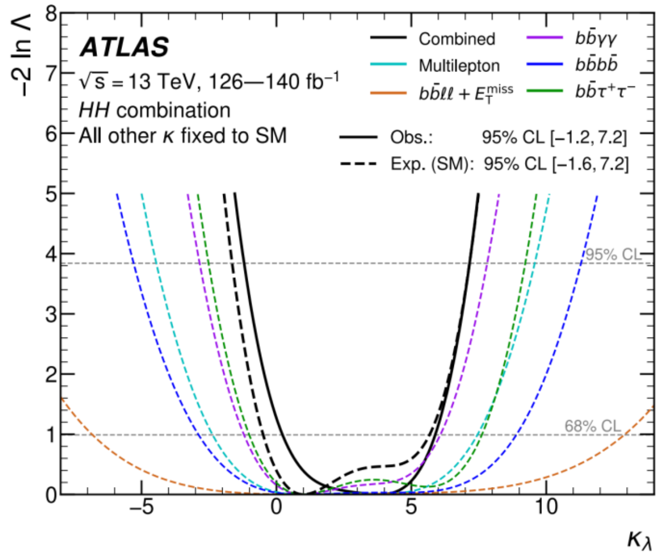
- **A probe of Higgs self-coupling**
  - Increased sensitivity toward a higher value of the self-coupling.
    - Could help to dissipate the non SM degeneracy
    - Constructive interference involved compared to the destructive one for ggF-HH

arXiv:2406.09971



- **A unique topology for BSM physics**
  - Unique access to c_{ttHH}

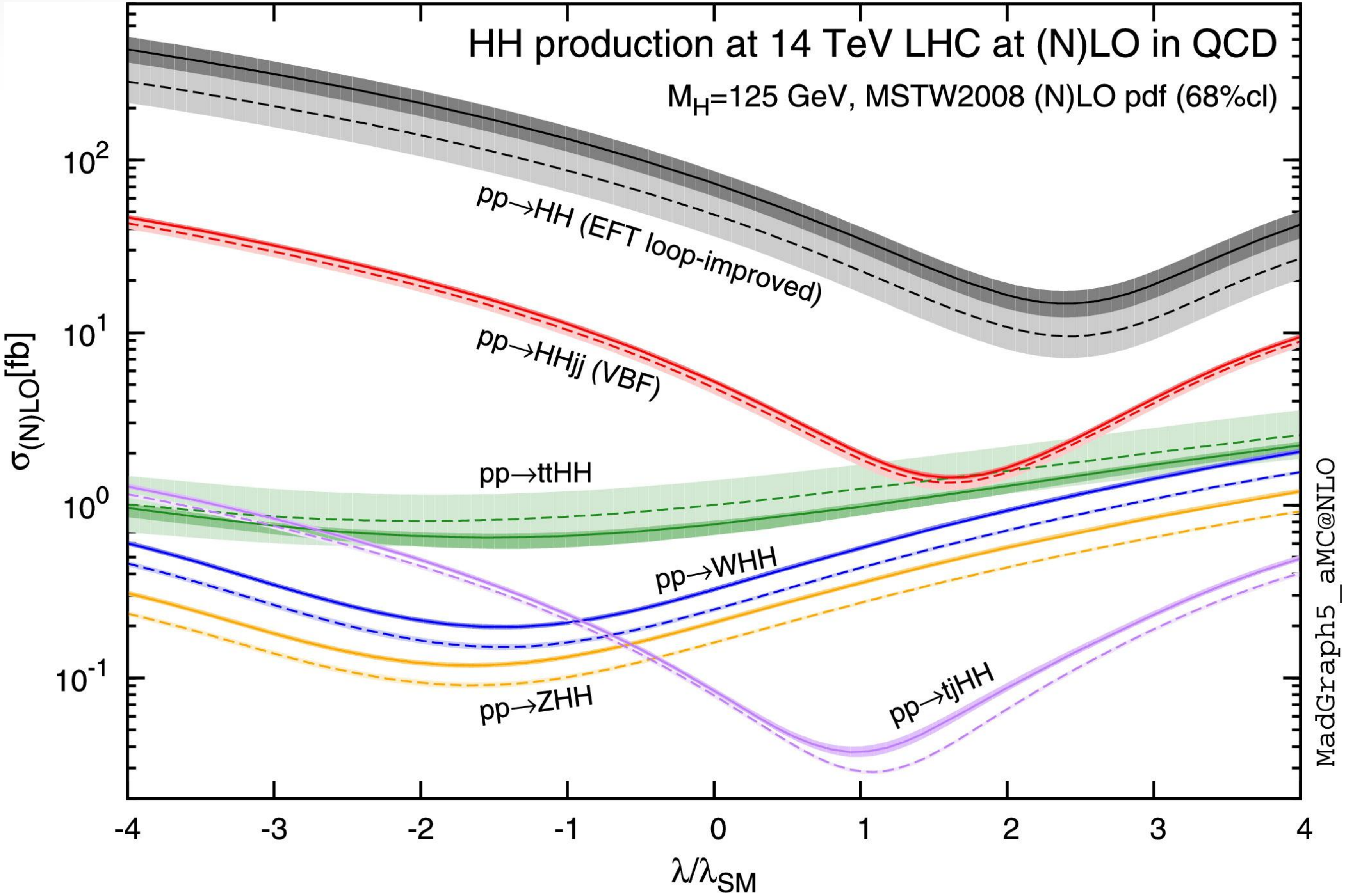
PREPARING THE NEAR FUTURE

- **1^{st} search of the $t\bar{t}HH$ signature is ongoing in ATLAS**
  - CMS provided 1^{st} ever results
- **$bb\gamma\gamma$ channel will greatly benefit of full run 3 statistics**
  - Statistically limited channel
  - mc23e campaign will add $\sim 110\ fb^{-1}$
- **Huge gain in sensitivity possible**
  - Additional channels ($\boldsymbol{b\bar{b}\tau\tau}$)
  - High rate of ML developments (GAT, GNN, …)

BACKUP

VARIATION OF σ_{ttHH} W.R.T. κ_λ

arXiv:1401.7340



SAMPLES

- **Shared with $HH \to b\bar{b}\gamma\gamma$ analysis**
  - Benefit of the strong involvement of the HH team
  - ptag: 6490/6491

- **3 main categories**
  - Signal $t\bar{t}(HH \to b\bar{b}\gamma\gamma)$
  - Resonant background
    - $ggF \to H,\ VBF \to H,\ ttH,\ VH,\ tWH,\ tHjb$
    - $ggF \to HH, VBF \to HH$
  - Continuum background
    - $\gamma\gamma + jets$ decomposed in $\gamma\gamma\bar{b}b + t\bar{t}\gamma\gamma$

Signal $[ttHH]$

DSID	Generator	PDF (ME)	PDF+Tune (PS)	Prod. Mode	Events in AOD
545837	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF30NLO	A14NNPDF23LO	$t\bar{t}HH(HH \to b\bar{b}\gamma\gamma)$	(Run2) 1,018k (FS) (Run3) 600k (FS)

Resonant background $[H \,\&\, HH]$

DSID	Generator	PDF (ME)	PDF+Tune (PS)	Prod. Mode	Events in AOD
603559	POWHEG + PYTHIA8 + EVTGEN	PDFLHC21	A14NNPDF23LO	SM ggF HH ($k_\lambda = 1$)	(Run2) 1580k (FS) (Run3) 730k (AF3)
525376	MADGRAPH + PYTHIA8 + EVTGEN	NNPDF30NLO	A14NNPDF23LO	SM VBF HH ($k_\lambda = 1, k_{VV} = 1, k_V = 1$)	(Run2) 3954k (FS) (Run3) 160k (FS)
343981 602421	POWHEG + PYTHIA8 + EVTGEN	NNPDF30NNLO PDF4LHC21	AZNLOCTEQ6 A14NNPDF23LO	ggH	(Run2) 18268k (FS) (Run3) 8920k (FS)
346214 601482	POWHEG+PYTHIA8+EVTGEN	NNPDF30 PDF4LHC21	AZNLOCTEQ6 A14NNPDF23LO	VBF	(Run2) 6984k (FS) (Run3) 4380k (FS)
345318 601484	POWHEG MiNLO [111]+PYTHIA8+EVTGEN	NNPDF30 PDF4LHC21	AZNLOCTEQ6 A14NNPDF23LO	W^+H	(Run2) 3492k (FS) (Run3) 600k (FS)
345317 601483	POWHEG MiNLO [111]+PYTHIA8+EVTGEN	NNPDF30 PDF4LHC21	AZNLOCTEQ6 A14NNPDF23LO	W^-H	(Run2) 3243.5k (FS) (Run3) 590k (FS)
345319 601523	POWHEG MiNLO [111]+PYTHIA8+EVTGEN	NNPDF30 PDF4LHC21	AZNLOCTEQ6 A14NNPDF23LO	$qq \to ZH$	(Run2) 7067.3k (FS) (Run3) 1180k (FS)
345061 601522	POWHEG MiNLO [111]+PYTHIA8+EVTGEN	NNPDF30 PDF4LHC21	AZNLOCTEQ6 A14NNPDF23LO	$gg \to ZH$	(Run2) 688k (FS) (Run3) 200k (FS)
346525 602422	POWHEG + PYTHIA8 + EVTGEN	NNPDF30 PDF4LHC21	A14NNPDF23LO A14NNPDF23LO	ttH	(Run2) 7785k (FS) (Run3) 1570k (FS)
345315 601710	POWHEG + PYTHIA8 + EVTGEN	NNPDF30 PDF4LHC21	A14NNPDF23LO A14NNPDF23LO	bbH	(Run2) 390k (FS) (Run3) 400k (FS)
346677 545636	MGMCatNLO + PYTHIA8 + EVTGEN	NNPDF30 NNPDF30	A14NNPDF23LO A14NNPDF23LO	tHjb	(Run2) 1988k (FS) (Run3) 950k (FS)
346759 545639	MGMCatNLO + PYTHIA8 + EVTGEN	NNPDF30 NNPDF30	A14NNPDF23LO A14NNPDF23LO	tHW	(Run2) 1045k (FS) (Run3) 980k (FS)

Continuum background $[\gamma\gamma + jets]$

DSID	Generator	PDF (ME)	PDF+Tune (PS)	Prod. Mode	Events in AOD
700980	SHERPA 2.2.14	NNPDF30NNLO		$\gamma\gamma$+0,1(NLO),2,3(LO), $m_{\gamma\gamma} \in (90, 175)$ GeV	(Run2) 1211376k (AF3) (Run3) 606450k (AF3)
700711	SHERPA 2.2.14	NNPDF30NNLO		$\gamma\gamma + b\bar{b}$(NLO), $m_{\gamma\gamma} \in (90, 175)$ GeV	(Run2) 39330k (AF3) (Run3) 15980k (AF3)
542860	MGMCatNLO + PYTHIA8 + EVTGEN	NNPDF30NLO	A14NNPDF23LO	$t\bar{t}\gamma\gamma$ (noallhad)	(Run2) 4990k (AF3) (Run3) 1190k (FS)
542859	MGMCatNLO + PYTHIA8 + EVTGEN	NNPDF30NLO	A14NNPDF23LO	$t\bar{t}\gamma\gamma$ (allhad)	(Run2) 4850k (AF3) (Run3) 2000k (FS)