Update on the Di-Higgs search with full Run-2 and partial Run-3 datasets WG-2

Status Report

FAPESP Thematic 2020/04867-2

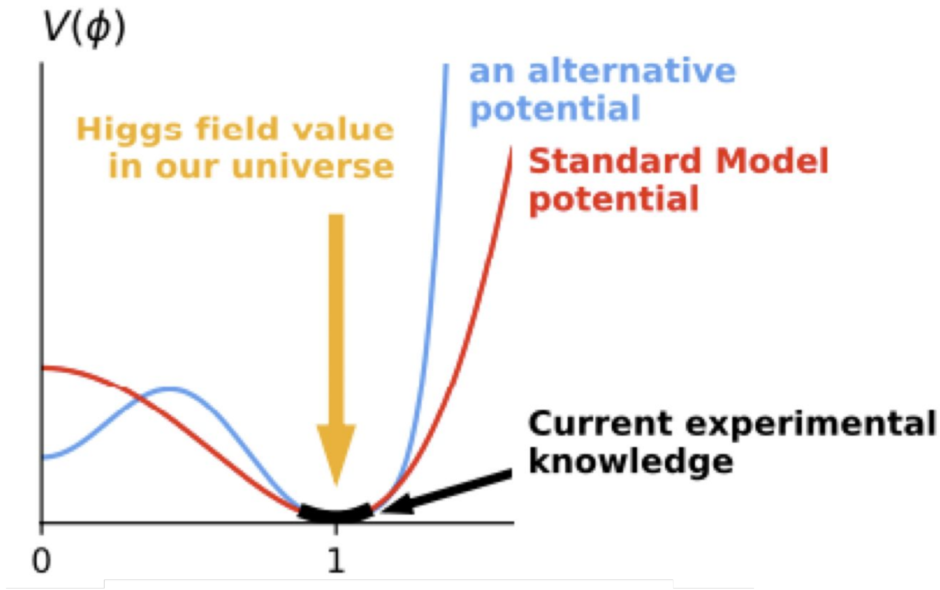
February 22nd 2024

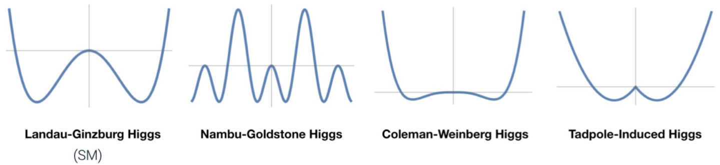
Marisilvia Donadelli - USP/UERJ

WG-2: Summary

1. Physics analysis
   1.1. HH→ bb$\tau\tau$ with full Run2 dataset (140 fb^{-1})
      1.1.1. brief overview of the publications (including combination): setting the stage for Run-3
      1.1.2. areas of contribution and analysis strategy
   1.2. HH→ bb$\tau\tau$ with full Run-2 and partial Run-3 datasets (200 fb^{-1})
      1.2.1. brief overview of CP and trigger improvements
      1.2.2. WG2 plans

The shape of the Higgs potential matters

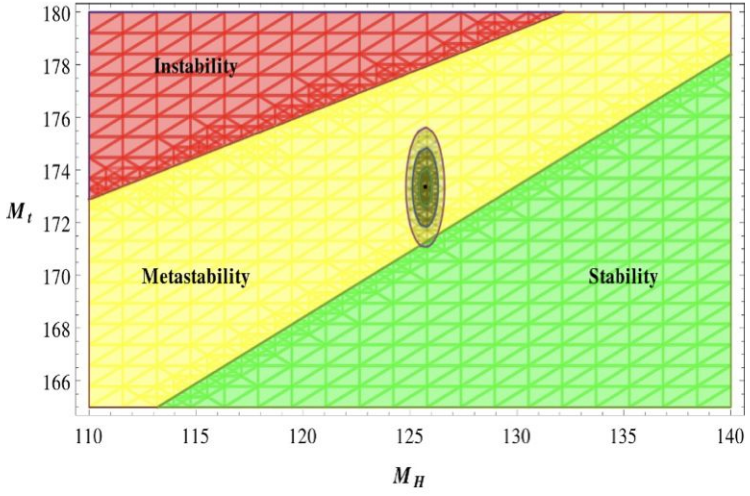




Phys. Rev. D 101, 075023

"The Higgs boson mass of 125 GeV is a remarkable value, meaning that the underlying state of the Universe, the vacuum, sits very close to the border between stable and metastable, which may hint at deeper physics beyond the standard model".

Nature Reviews Physics **3**, 608–624 (2021)



JHEP09(2014)182

Investigating the Higgs potential

In the SM, the Higgs self-coupling is uniquely determined by the structure of V($\mathbf{\Phi}$), which takes the following form in terms of the physical *H* field:

$$V = \frac{m_H^2}{2}H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4}H^4, \quad \lambda_3 = \lambda_4 = \lambda_{HHH} = \frac{m_H^2}{2v^2}$$

- the sign and value of the parameters μ^2 and λ_{HHH} are a priori arbitrary
- the positive sign of λ_{HHH} is necessary for the stability of the potential at large ϕ
- … thus, experimentally measuring $\boldsymbol{\lambda}_{\mathrm{HHH}}$ is a crucial test of the electroweak symmetry breaking mechanism.

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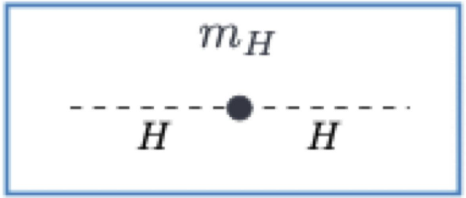

First estimation from the Higgs mass measurement

$\boldsymbol{\lambda}_{HHH}^{SM} \sim 0.13$

Investigating the Higgs potential

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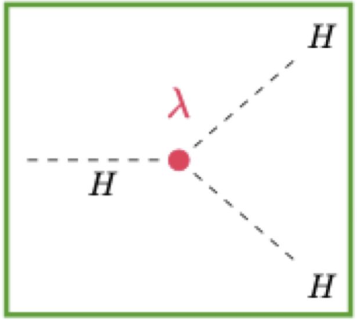

Direct access to **λ** through Higgs pair production

coupling strength: $\kappa_\lambda = \lambda_{HHH} / \lambda_{SM}$

Investigating the Higgs potential

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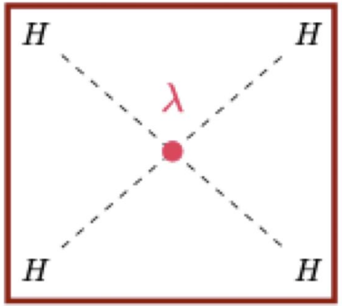


Quartic interaction: out of reach

HH production modes at the LHC

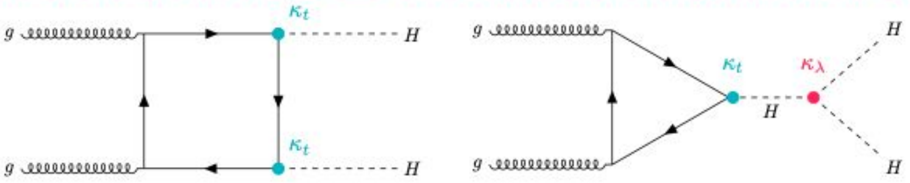
coupling strength:

$$\kappa_c = c / c_{SM}$$

gluon-gluon Fusion (ggF)

$\sim \kappa_\lambda$

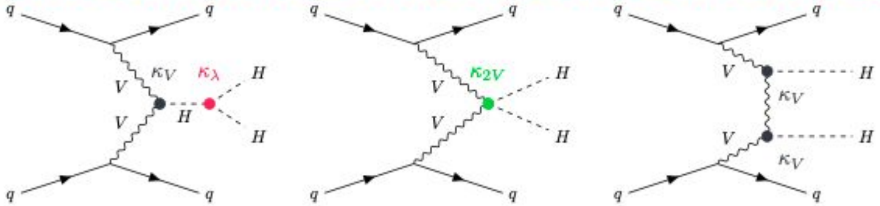
$\sigma \sim 31.0$ fb



Vector Boson Fusion (VBF)

$\sim \kappa_\lambda, \kappa_{2V}$

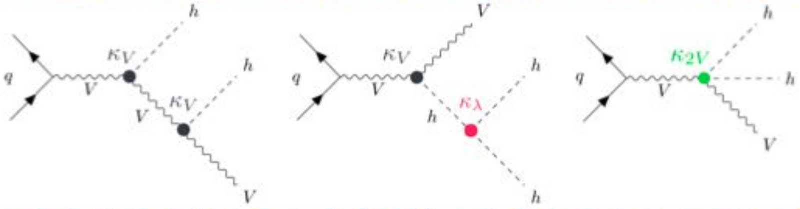
$\sigma \sim 1.72$ fb



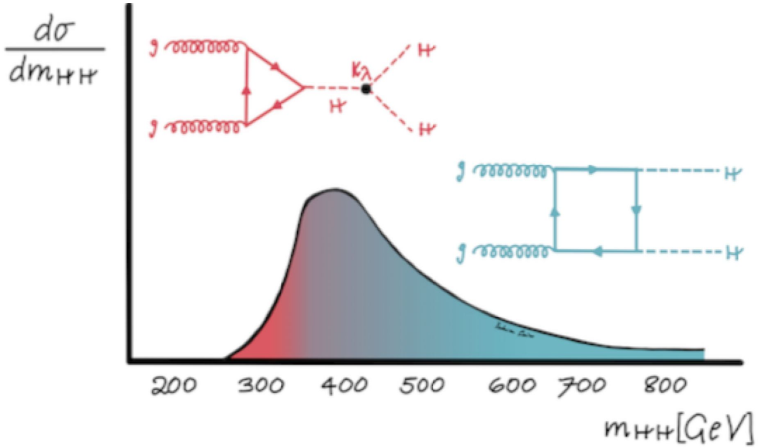
Vector Boson Associated (VHH)

$\sim \kappa_\lambda, \kappa_{2V}$

$\sigma \sim 0.86$ fb



Why so small?



- small cross section due to destructive interference between the triangle and box diagrams
- low m_{HH}: essential to constrain trilinear self coupling κ_λ
- m_{HH}: shape very dependent on κ_λ

gluon-fusion

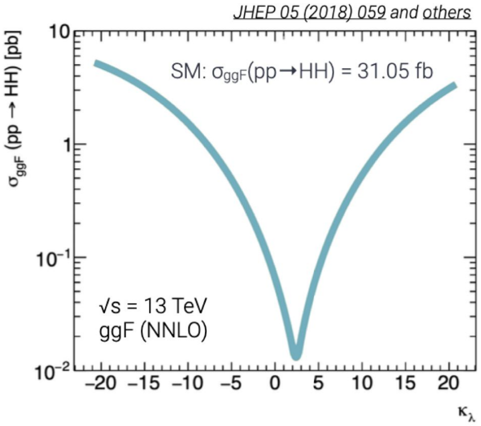
$\sigma_{ggF}(pp \rightarrow HH)$ = 31.05 fb

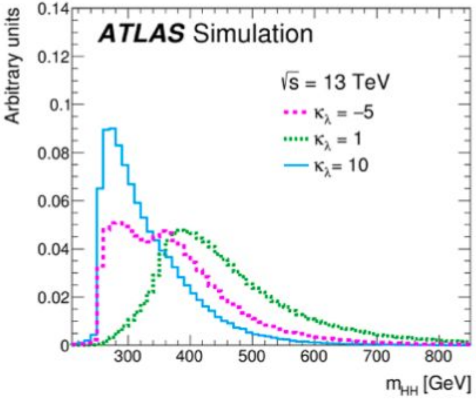
1000X smaller than single *H*!

σ_{HH} increases with $\sqrt{s}$

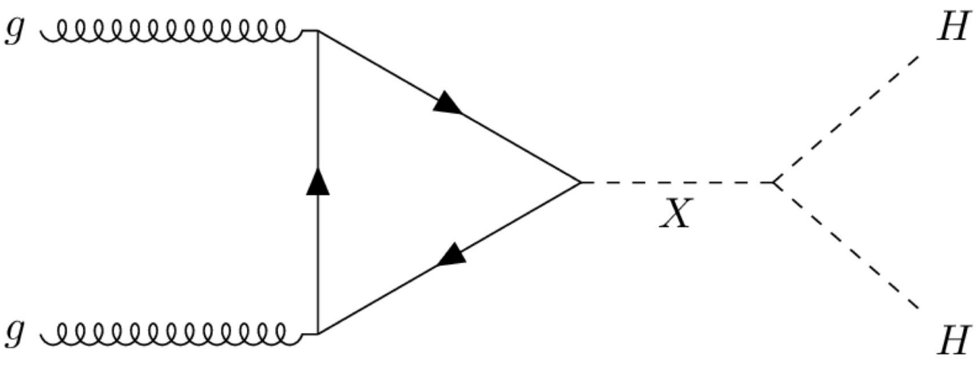
13 TeV → 13.6 TeV: +11%

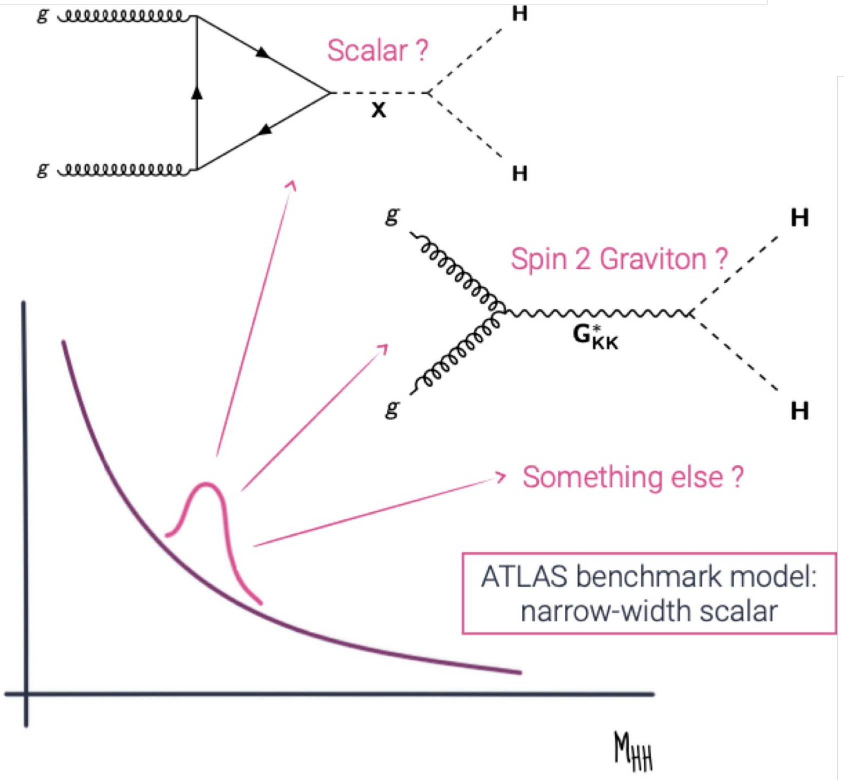
13.6 TeV → 14 TeV: + 7 %





Resonant HH production

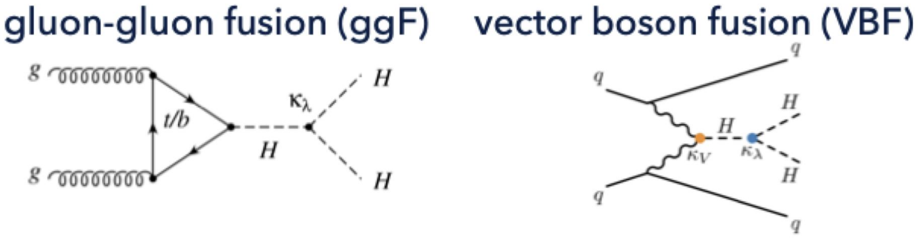


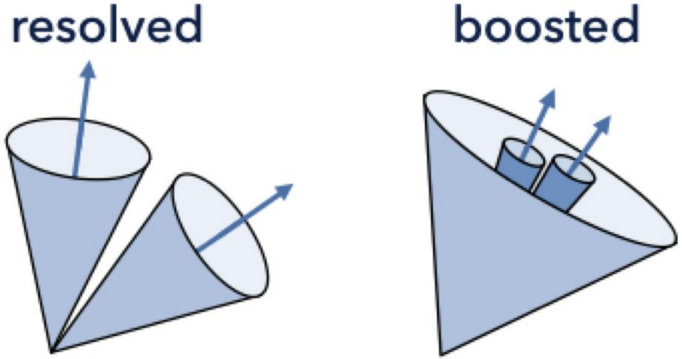


HH decay modes

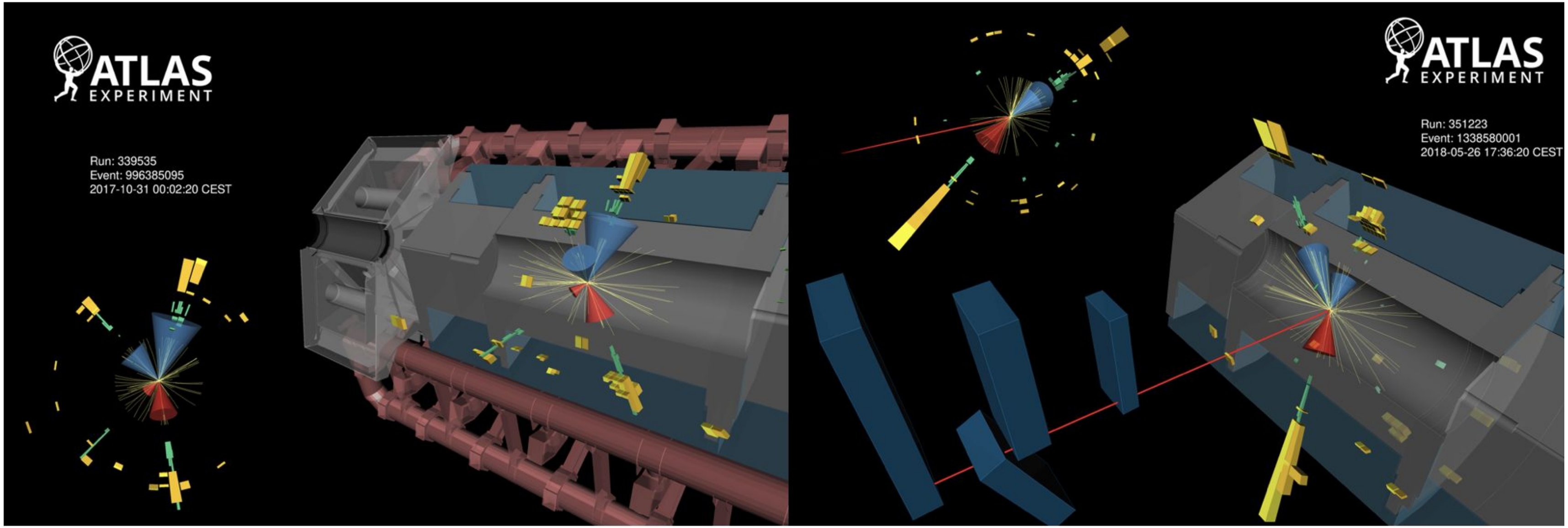
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

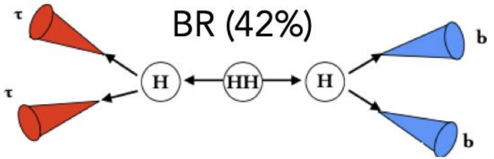
- Analyses challenge: compromise between BR and higher purity
- Variety of final states
- Hbb highest BR
- Leptonic final states: high background suppression
- complementary topologies in acceptance



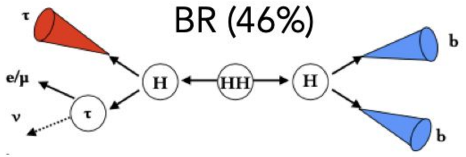


The HH→ $bb\tau\tau$ sub-channels





HH → $bb\tau_{had}\tau_{had}$

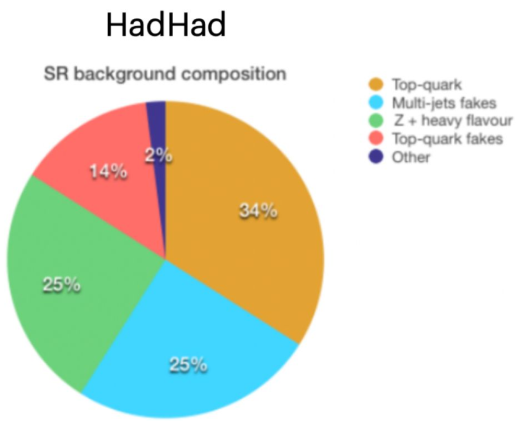


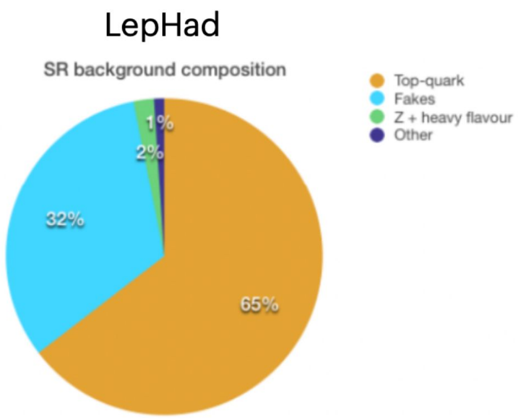
HH → $bb\tau_{lep}\tau_{had}$

x

The background composition

HH →bb$\tau\tau$





- Main backgrounds:
  ttbar and Z+heavy flavour jets (with real τ), modelled with Monte Carlo simulations
- Events with jets faking hadronically decaying τ from ttbar and QCD multi-jet data-driven (fake-factor and scale factor methods)

Run-2 accomplishments

Run 2 Resonant HH→ bbττ

JHEP

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ACCEPTED: *February 5, 2023*
PUBLISHED: *July 5, 2023*

Search for resonant and non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ decay channel using 13 TeV pp collision data from the ATLAS detector

ATLAS EXPERIMENT

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

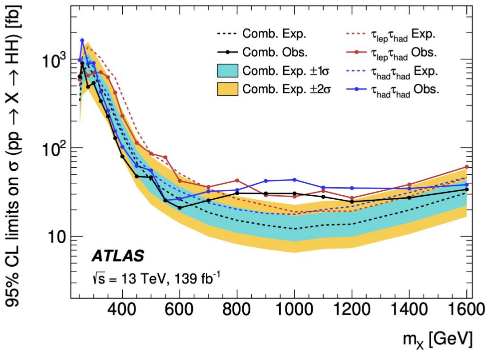
Details on *kick-off meeting*

JHEP07(2023)040

ABSTRACT: A search for Higgs boson pair production in events with two b-jets and two τ-leptons is presented, using a proton–proton collision dataset with an integrated luminosity of 139 fb^{-1} collected at $\sqrt{s}$ = 13 TeV by the ATLAS experiment at the LHC. Higgs boson pairs produced non-resonantly or in the decay of a narrow scalar resonance in the mass range from 251 to 1600 GeV are targeted. Events in which at least one τ-lepton decays hadronically are considered, and multivariate discriminants are used to reject the backgrounds. No significant excess of events above the expected background is observed in the non-resonant search. The largest excess in the resonant search is observed at a resonance mass of 1 TeV, with a local (global) significance of 3.1σ (2.0σ). Observed (expected) 95% confidence-level upper limits are set on the non-resonant Higgs boson pair-production cross-section at 4.7 (3.9) times the Standard Model prediction, assuming Standard Model kinematics, and on the resonant Higgs boson pair-production cross-section at between 21 and 900 fb (12 and 840 fb), depending on the mass of the narrow scalar resonance.

KEYWORDS: Higgs Physics, Hadron-Hadron Scattering, Proton-Proton Scattering

- Paper: JHEP07(2023)040
- Sensitivity improved by factor of four on the previous ATLAS search (Phys. Rev. Lett. 121, 191801 (2018))
- M. Donadelli
  - contributions in : $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ channels (MVA, MC validation, statistical analysis)
- A narrow CP-even scalar particle (X) with a mass between 251 and 1600 GeV is used as the benchmark model for the resonant signal.



Many implications for Run 3 over the next years see (next slides)

Run-2 Non-resonant HH→ $bb\tau\tau$

ATLAS CONF Note

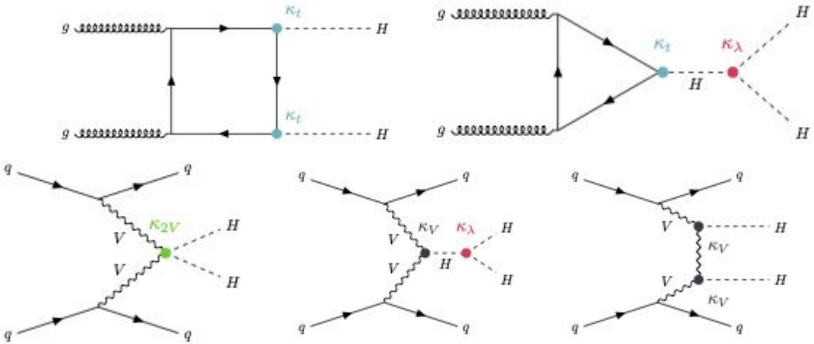
ATLAS-CONF-2023-071

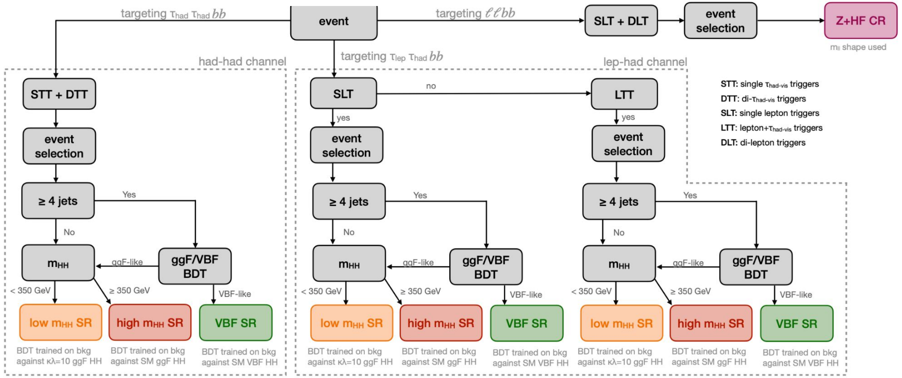
25th November 2023

Search for the non-resonant production of Higgs boson pairs via gluon fusion and vector-boson fusion in the $b\bar{b}\tau^+\tau^-$ final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

- CONF note for [Higgs 2023]
- paper draft with EFT interpretations ready for ATLAS circulation





Full Run-2 dataset analysis (140 fb^{-1}) with focus on κ_λ and κ_{2V} optimisation

M. Donadelli:

- contact editor, MVA analysis strategy, VBF/ggF categorisation
- contributions in : $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ channels

Details on [kick-off meeting]

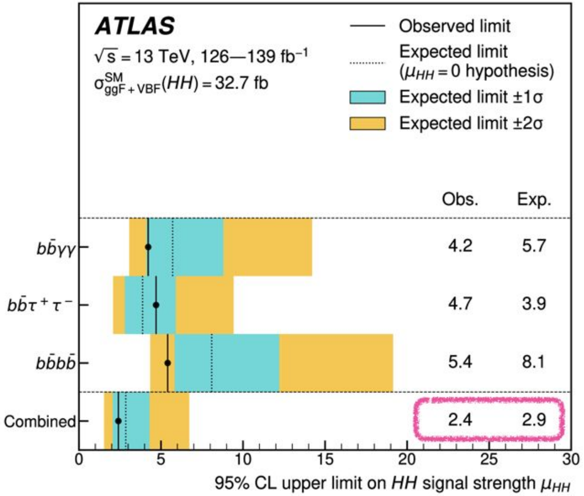
- Many implications for Run 3 over the next years:
  - improve sensitivity to HH searches ($bb\tau\tau$ amongst the 3 most sensitive channels), set stricter constraints on the Higgs boson self-coupling, with increasing precision of non-resonant HH!

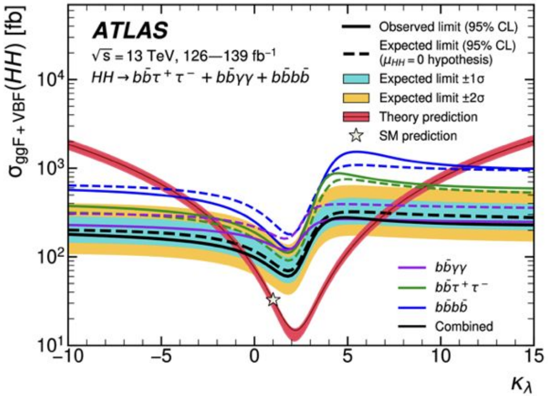
Run 2 Non-resonant HH combination

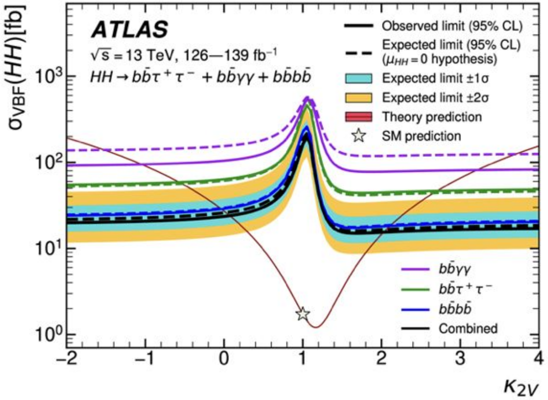
- multiple search channels, trade-offs between BR vs final state

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

- results for the combination of the three most sensitive channels: bbbb, bbττ and bbγγ







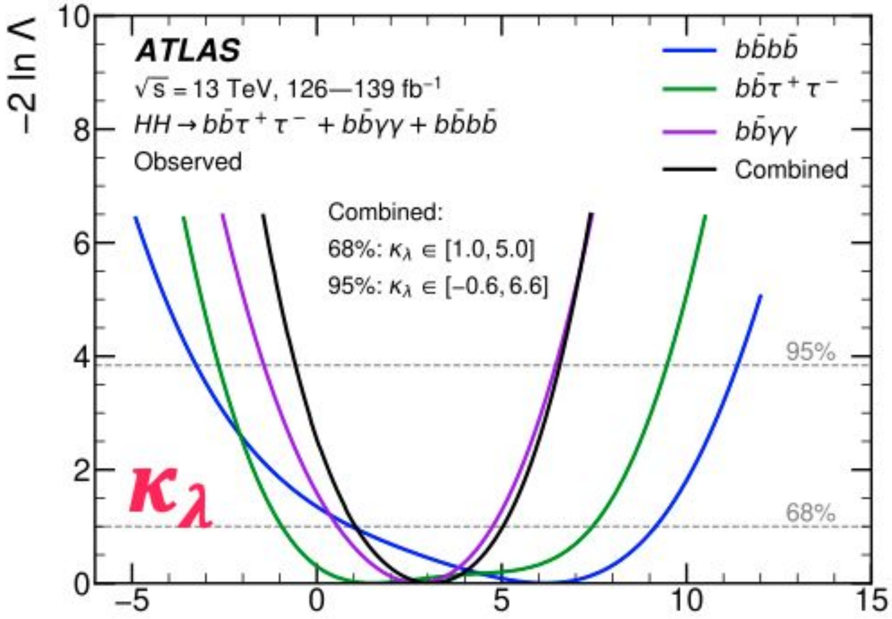
- bbγγ most sensitive for large variations of κ_λ
- bbττ most sensitive for κ_λ values close to the SM
- bbbb most sensitive to VBF production and variations of κ_{2V}

X

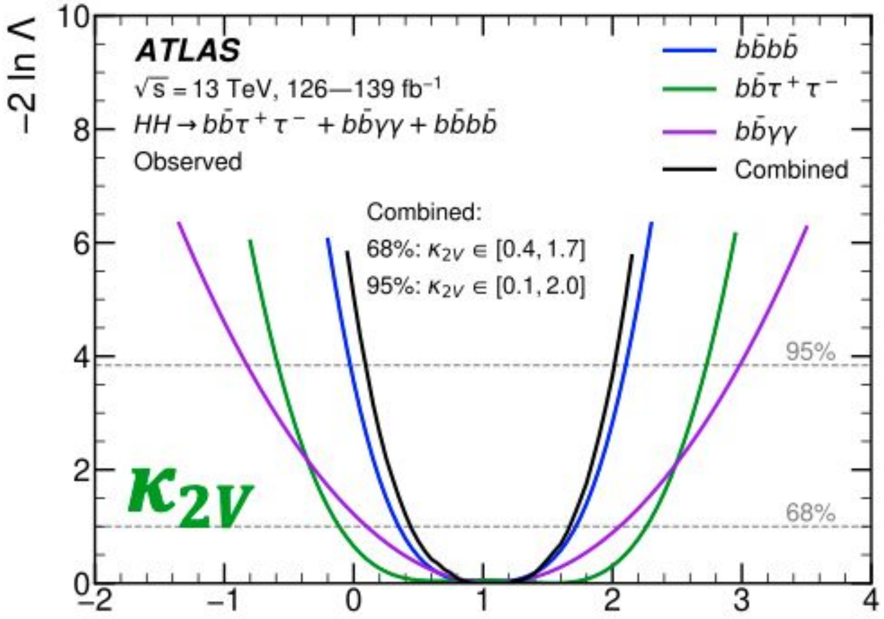
- **most stringent upper limit on HH production to date**

Phys Lett B 843 (2023), 137745

Run 2 Non-resonant HH combination



$-0.6 < \kappa_\lambda < 6.6$ (95% CI)

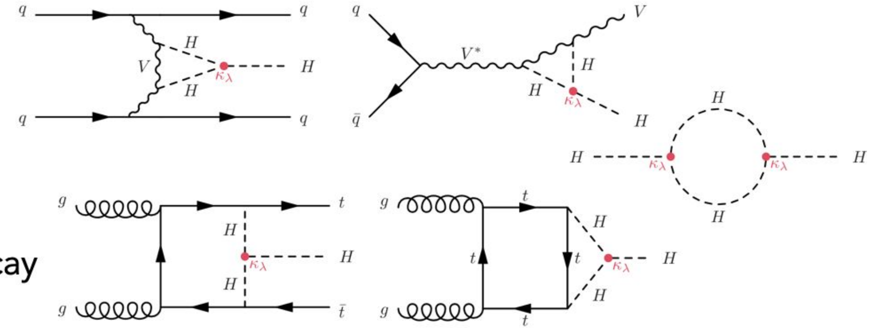


$0.1 < \kappa_{2V} < 2.0$ (95% CI)

[Phys Lett B 843 (2023), 137745]

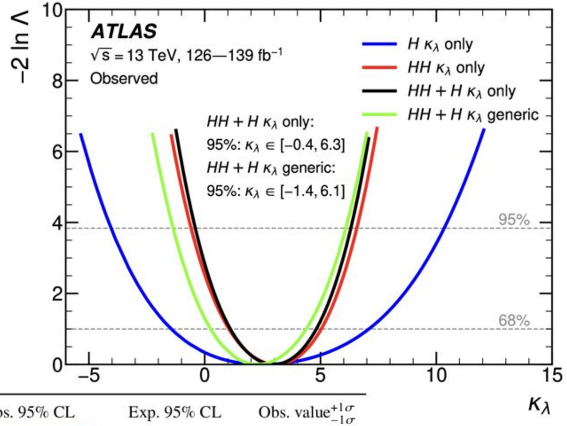
Run 2 HH+H combination

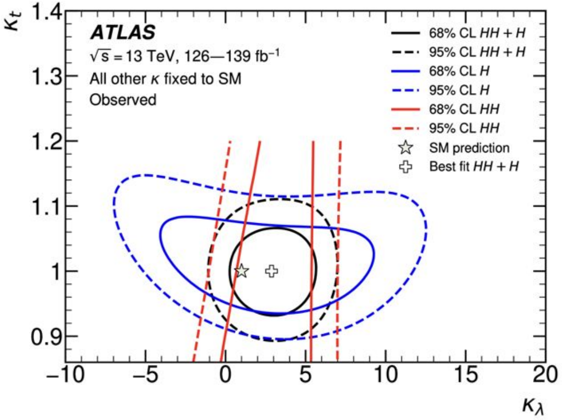
Phys Lett B 843 (2023), 137745



- exploits direct sensitivity to κ_λ of HH and indirect sensitivity to κ_λ of single H through NLO EW corrections affecting single H production and decay

Channel
$HH \to b\bar{b}\gamma\gamma$
$HH \to b\bar{b}\tau^+\tau^-$
$HH \to b\bar{b}b\bar{b}$
$H \to \gamma\gamma$
$H \to ZZ^* \to 4\ell$
$H \to \tau^+\tau^-$
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)
$H \to b\bar{b}$ (VH)
$H \to b\bar{b}$ (VBF)
$H \to b\bar{b}$ $(t\bar{t}H)$

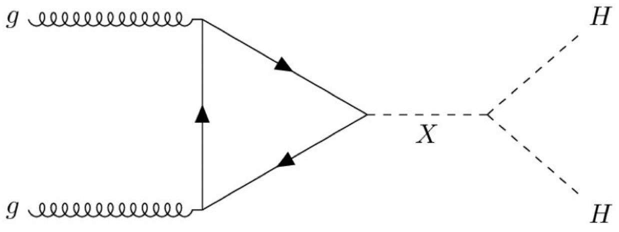




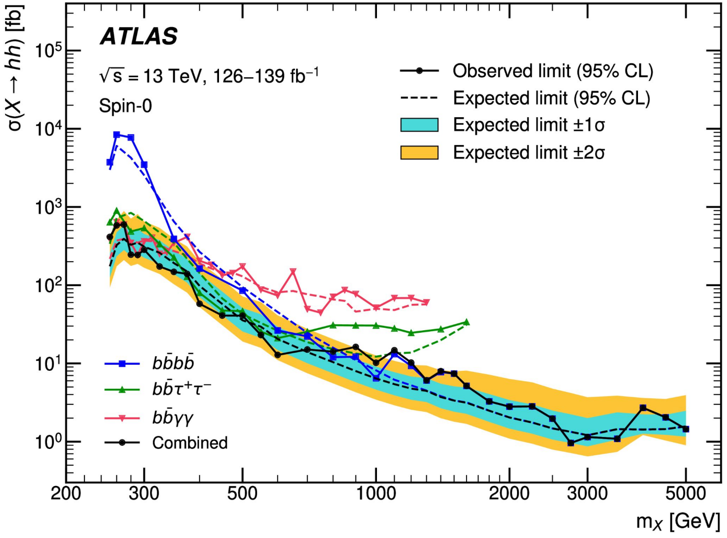
Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

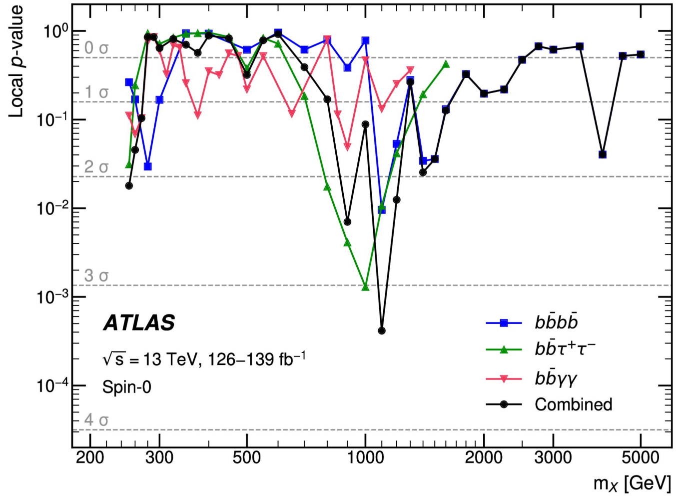
- study provides the **most stringent constraints on κ_λ** to date
- κ_λ interval less constrained in a more generic model

Run 2 Resonant HH combination



Submitted to Phys. Rev. Lett.



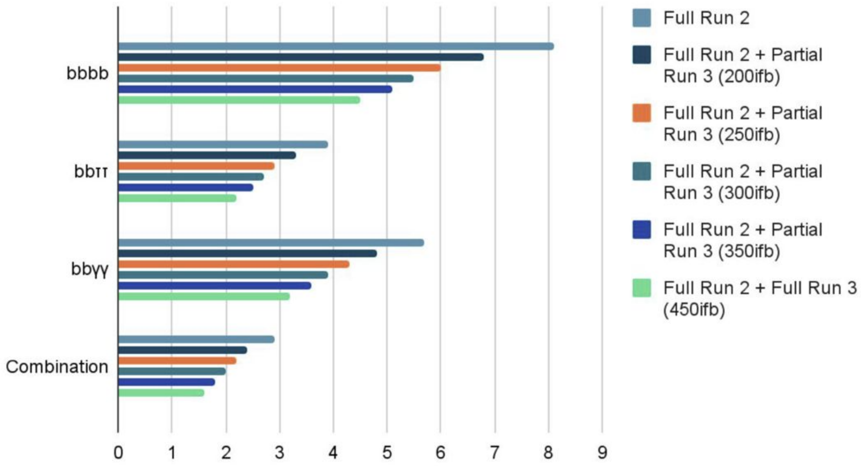


- most sensitive channels: bbbb, bb$\tau\tau$ and bb$\gamma\gamma$
- 251 GeV - 5 TeV (resolved and boosted regimes)
- improvement of a factor of 2-5, depending on m_X with respect to previous ATLAS result (Phys. Lett. B **800** (2020) 135103)
- excess at 1 TeV (3.3 σ local): will be an interesting follow-up with new data and improved techniques

Setting the stage for Run-3

Plans for non-resonant HH in Run 3

Lumi scaling of limit on SM HH μ:



σ_{HH} increases with √s
13 TeV → 13.6 TeV: +11%
13.6 TeV → 14 TeV: + 7 %

ATLAS can reach limit of μ = 1.6 from luminosity scaling

Early Run3 with the most sensitive channels: bbbb, bbττ and bbγγ

potentially other channels if they are sensitive

Results with early Run 3 planned for 2025, in combination with Run2.

Then do full Run3 with all channels and release full Run2 combined with full Run3.

Plans include EFT interpretations and HH+H combination.

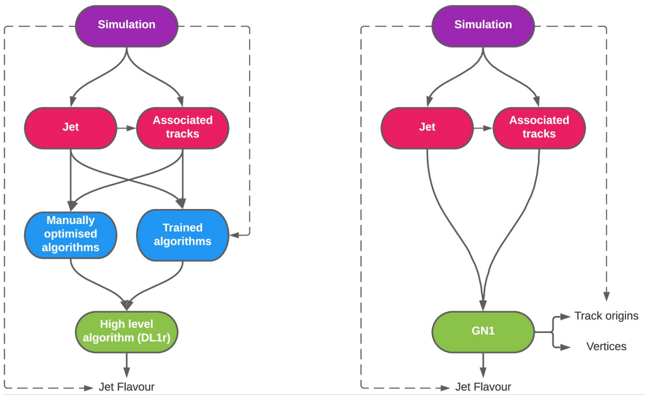
Also consider to include other production modes, eg. ttHH

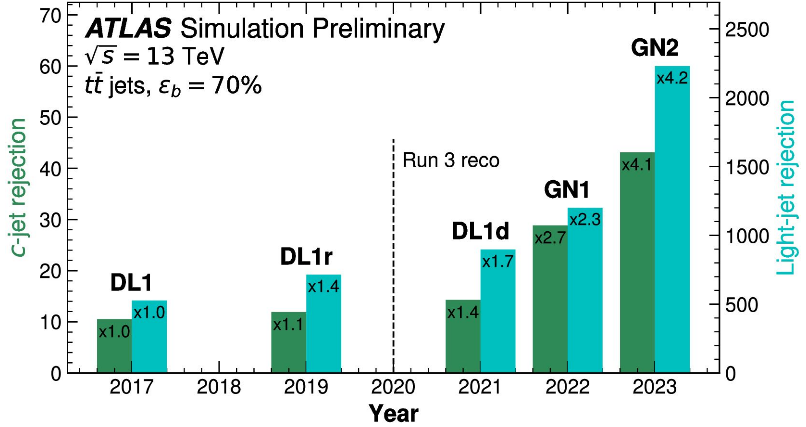
Combine ATLAS+CMS

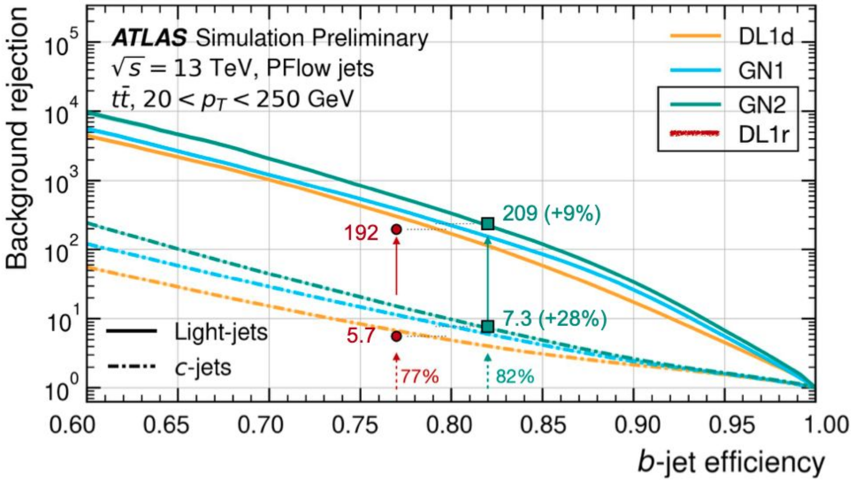
GN2 - better flavour tagging

End-to-end Graph Neural Network (GNN) approach

Do not rely on those manual crafted algorithms any more







GN2 allows 82% b-WP offers better charm- and light rejection than DL1r at 77% WP (default in Run-2)

ATL-PHYS-PUB-2022-027

FTAG-2023-01

The trigger challenges in HH

- Searches in HH: wide range of final states
  - leptons and photons usually provide good handles to trigger on
  - hadronic final states are much more difficult to trigger on
- Triangle diagram tend to contribute to low m_{HH}.
- BSM scenarios tend to produce soft signals and populate low m_{HH}.
  - Important to improve the efficiency in low m_{HH} region

	bb	WW	ττ	ZZ	γγ
bb	34%				
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ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
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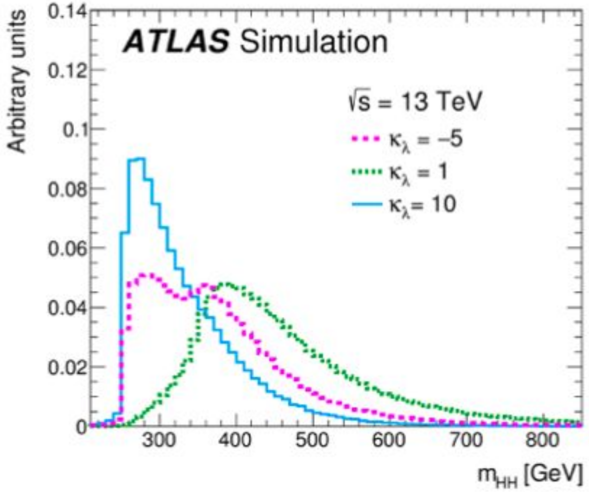
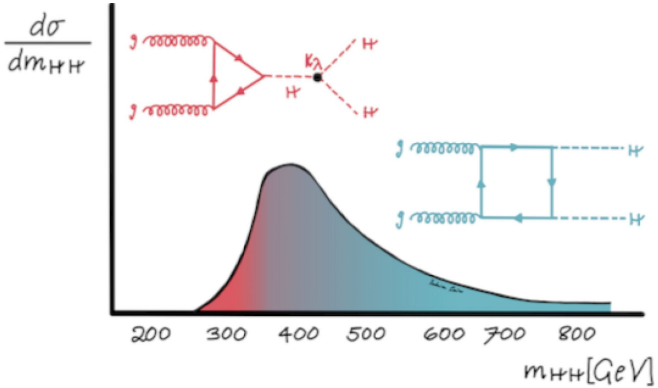
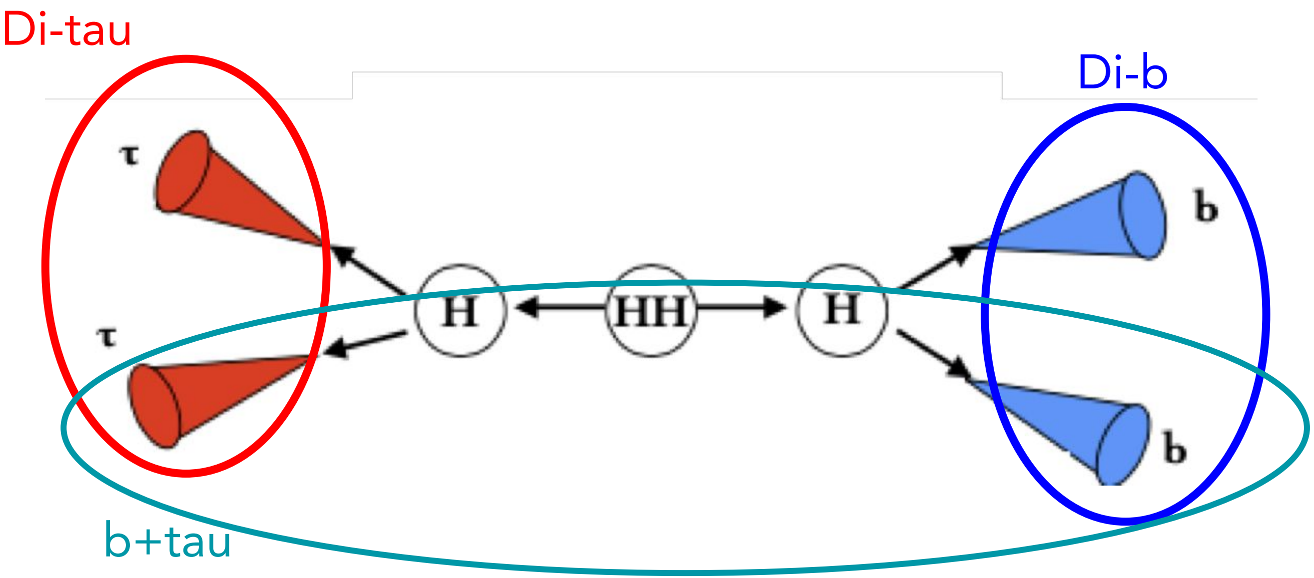




Trigger studies: Run 3 HH→ $bb\tau\tau$

- Define triggers based on objects in the final state
- Apply offline selections to emulate the impact on the analysis di-tau and di-b triggers:
  - >=2 taus, both Loose RNN ID, 1 or 3 prong, p_T > 25(20) GeV, |η|<2.5
  - >=2 b-jets, 82% eff GN2, p_T > 20 GeV, |η|<2.5
  - check overall efficiency and rate
- b+tau triggers under development

$HH \rightarrow \tau_{had}\tau_{had}$

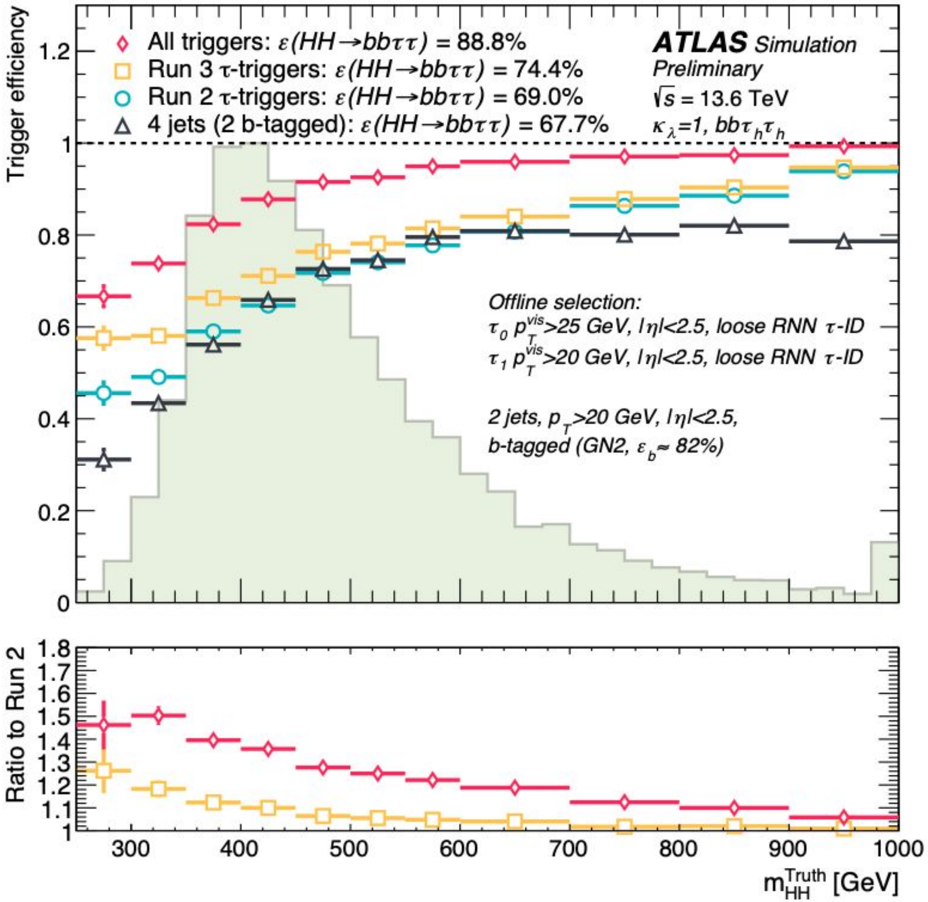


Trigger improvements: Run 3 HH→ $bb\tau\tau$

Reco selection

- Efficiency studies using κ_λ=1.0 SM HH signal samples at 13.6 TeV
  - 4 jets (2b-tagged): asymmetric four-jet selection (p_T > 75,50,25,20) with 2 b-tags at 77%WP
  - Run 2 **τ**-triggers: di-**τ** + jet triggers (p_T > 35, 25 GeV) combined with a single-**τ** trigger (p_T > 160 GeV)
  - Run 3 **τ**-triggers: di-**τ** + jet triggers (p_T > 30, 20 GeV) combined with a single-**τ** trigger (p_T > 160 GeV)
- Lower p_T thresholds from (35, 25) GeV to (30, 20) GeV], activated during 2023
- efficiency for all triggers combined: 89%

Tau trigger public results



Trigger improvements: Run 3 HH→ $bb\tau\tau$

- A full new chain of VBF triggers waiting for us (not present in Run2)

L1MJJ-500-NFF (dijet mass) seeded

Dijet mass L1	
Main stream	
HLT_e10_lhmedium_ivarloose_j70_j50a_j0_DJMASS900j50_L1MJJ-500-NFF	EWK SUSY
HLT_mu10_ivarmedium_j70_j50a_j0_DJMASS900j50_L1MJJ-500-NFF	
HLT_tau25_mediumRNN_tracktwoMVA_tau20_mediumRNN_tracktwoMVA_03dRAB_j70_j50a_j0_DJMASS900j50_L1MJJ-500-NFF	VBF+tautau
Delayed stream	
HLT_j70_j50a_j0_DJMASS1000j50dphi200x400deta_L1MJJ-500-NFF	inclusive VBF
HLT_2e5_lhmedium_j70_j50a_j0_DJMASS900j50_L1MJJ-500-NFF	VBF+tautau
HLT_2mu6_2j50a_j0_DJMASS900j50_L1MJJ-500-NFF	
HLT_j70_j50a_j0_DJMASS1000j50dphi240_xe90_tcpufit_xe50_cell_L1MJJ-500-NFF	VBF+MET
HLT_j70a_j50a_2j35a_SHARED_2j35_0eta290_020jvt_bdl1d70_j0_DJMASS1000j50_pf_ftf_presela60XXa40XX2a25_L1MJJ-500-NFF	VBF+bb
HLT_mu4_j70_j50a_j0_DJMASS1000j50_xe50_tcpufit_L1MJJ-500-NFF	

L1J25p0ETA23_2J15p31ETA49 (central+forward jets) seeded

B-jet + X
B-jet + forward jet
HLT_j55_0eta290_020jvt_bdl1d70_2j45f_pf_ftf_preselj45XX2f40_L1J25p0ETA23_2J15p31ETA49
HLT_j80_0eta290_020jvt_bdl1d70_j60_0eta290_020jvt_bdl1d85_j45f_pf_ftf_preselj60XXj45XXf40_L1J40p0ETA25_2J25_J20p31ETA49
HLT_j80c_j60_j45f_SHARED_2j45_0eta290_020jvt_bdl1d60_pf_ftf_preselc60XXj45XXf40_L1J40p0ETA25_2J25_J20p31ETA49

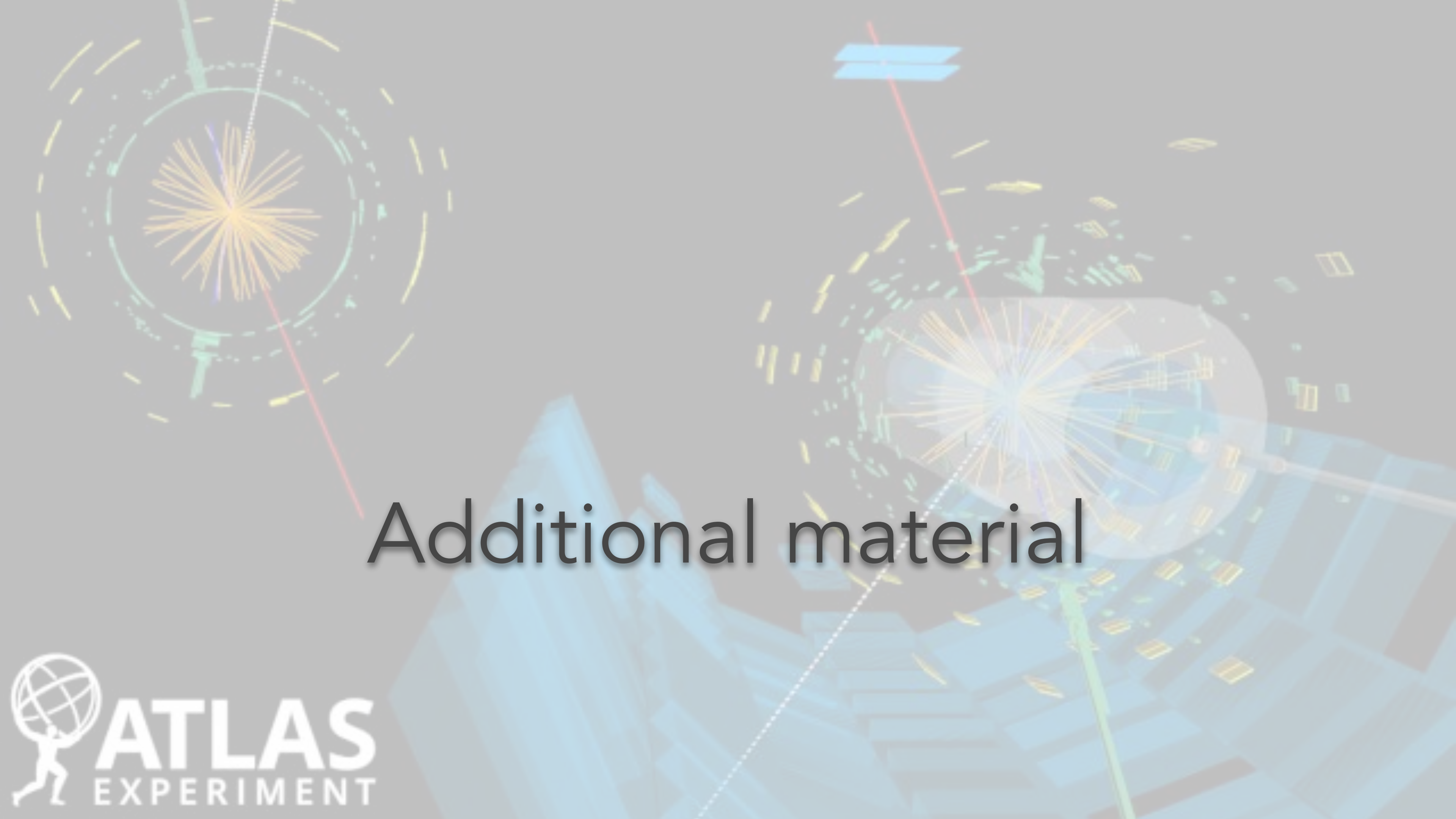
Plans for WG2 involvement in Run 3 HH→ bb$\tau\tau$

- analysis framework development, common amongst all HH subgroups
  - initial tasks include: implementation of trigger and object selection
  - FTAG and Tau WG tasks
- WG2 interest targets significant contribution to the ggF/VBF production modes keeping ggF/VBF orthogonality
  - ramping up with trigger efficiency studies in both $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$
  - further contributions include:
    - dedicated VBF triggers efficiency studies
    - MVA specific tasks
    - sensitivity studies based on the figure of merit
    - statistical interpretation of the results: fit and binning

Concluding remarks

- ATLAS has produced plenty of results on HH searches in many final states in Run-2
- increasing precision of non-resonant HH
  - HH > $bb\tau\tau$ drives the sensitivity for κ_λ close to the SM
  - combined upper limit on μ^{SM}_{HH} is 2.4
  - HH+H combination provides most stringent κ_λ to date ($-0.4 < \kappa_\lambda < 6.3$)
- Spin 0 X -> HH resonant search
  - probed m_X range between 251 GeV - 5 TeV
  - no new physics has been found, but some interesting excess have been observed

- Run-3 efforts are ramping up
  - GN2 brings better flavour-tagging (GNN)
  - new trigger spark more areas for WG2 contribution
    - promising efficiency results in the low m_{HH} region
    - dedicated VBF chains



Additional material

Investigating the Higgs potential

The Higgs potential, before spontaneous symmetry breaking, reads:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

$$V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4$$

$$V(\Phi) = -\frac{\mu^2}{2} |\Phi|^2 + \frac{\lambda}{4} |\Phi|^4$$

$\mathbf{\Phi}$: SU(2) doublet scalar field

$\phi = \boldsymbol{v} + H$

$\boldsymbol{v}$: v.e.v

condition of a minimum of the potential:

$$\lambda = \frac{m_H^2}{2v^2}, \quad \mu^2 = \frac{m_H^2}{2}, \quad m_H^2 = \frac{\partial^2 V}{\partial \phi^2}$$

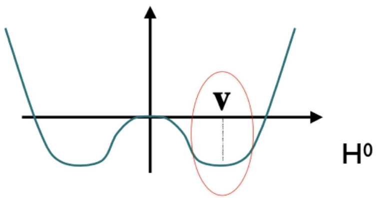
One central question to the progress of HEP

Future Colliders: why? what?

LHC Chamonix Workshop 2023
23-26 Jan 2023

Michelangelo L. Mangano
Theory Department,
CERN, Geneva

But there is one central question to the progress of HEP, which can only be addressed by colliders



$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Where does this come from?

The SM Higgs mechanism provides the *minimal* set of *ingredients* required to enable a consistent breaking of the EW symmetry, as manifest in the experimental data over decades of measurements.

Where these *ingredients* come from, what possible additional infrastructure comes with them, whether their presence is due to purely anthropic or more fundamental reasons, we don't know, the SM doesn't tell us ...

Trigger improvements: Run 3 HH→ bb$\tau\tau$

Truth-matched selection

- Efficiency studies using $\boldsymbol{\kappa_\lambda}$=1.0 SM HH signal samples at 13.6 TeV
  - 4 jets (2b-tagged): asymmetric four-jet selection (p_T > 75,50,25,20) with 2 b-tags at 77%WP
  - Run 2 **τ**-triggers: di-**τ** + jet triggers (p_T > 35, 25 GeV) combined with a single-**τ** trigger (p_T > 160 GeV)
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- Lower p_T thresholds from (35, 25) GeV to (30, 20) GeV], activated during 2023
- efficiency for all triggers combined: 78%