The search for $HH \to b\bar{b}\tau^+\tau^-$

IX Reunião Geral - Projeto Especial FAPESP: Física e Instrumentação de Altas Energias com o LHC-CERN

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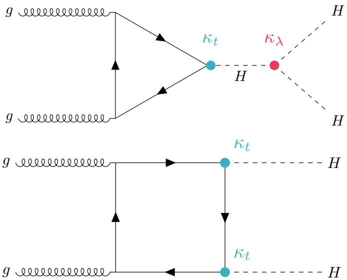
Why study Higgs boson pairs?

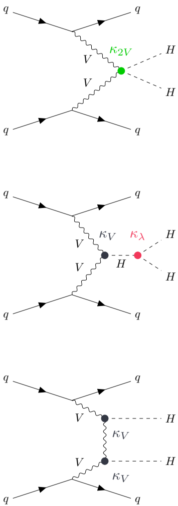
- The Higgs boson is now established experimentally, but an important question remains: how does the Higgs field interact with itself?
- Higgs-boson pair production gives direct access to that self-interaction and therefore to the shape of the Higgs potential.
- Measuring this process tests whether electroweak symmetry breaking really behaves as predicted by the Standard Model.
- Because Higgs-pair production is very rare, any deviation from the Standard Model could be a particularly clean sign of new physics.
- The $HH \to b\bar{b}\tau^+\tau^-$ final state offers one of the best balances between branching fraction and background rejection.

Why $b\bar{b}\tau^+\tau^-$?

- There is a significant discovery potential even if we do not find evidence in single Higgs couplings measurements (10.1038/s42254-021-00341-2).
- Helps to address questions related to the electroweak phase transition, electroweak symmetry breaking, and vacuum stability (10.1007/JHEP08(2012)098)
- Probing the Higgs potential in HL-LHC is a high priority.
- In the κ-framework for considering Higgs couplings, it is good to spot large deviations from the Standard Model.
- The Higgs trilinear self-coupling modifier κ_λ rescales the Higgs three-point self-interaction relative to its Standard Model value, $\kappa_\lambda \equiv \lambda_{HHH}/\lambda_{HHH}^{\mathrm{SM}}$.
- The Higgs–vector-boson quartic coupling modifier κ_{2V} rescales the $HHVV$ contact interaction relative to its Standard Model value, $\kappa_{2V} \equiv g_{HHVV}/g_{HHVV}^{\mathrm{SM}}$.

The signal: Higgs pair production in ggHH & VBF





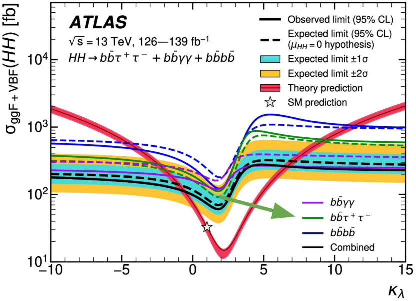
- ggHH sensitive to κ_t, κ_λ
- VBF sensitive to κ_V, κ_{2V}, κ_λ

Why $b\bar{b}\tau^+\tau^-$?

- The horizontal axis is the Higgs trilinear self-coupling modifier

$$\kappa_\lambda \equiv \lambda_{HHH}/\lambda_{HHH}^{\mathrm{SM}}\,.$$

- $\kappa_\lambda = 1$: Standard Model prediction
- $\kappa_\lambda = 0$: no Higgs self-coupling
- $\kappa_\lambda = 2$: twice the Standard Model coupling
- $\kappa_\lambda < 0$: opposite-sign coupling
- Two amplitudes interfere:
  - $gg \to H \to HH$ (triangle diagram), which contains the self-coupling λ_{HHH} and
  - $gg \to HH$ (box diagram), which does not.



Around $\kappa_\lambda \sim 2$–3, the destructive interference is strongest, so the HH rate is smallest. If no signal is seen, the most sensitive channel gives the lowest excludable HH rate. In the SM-like nonresonant search considered here, $b\bar{b}\tau^+\tau^-$ is one of the most sensitive channels and is the most sensitive

Why $b\bar{b}\tau^+\tau^-$?

- The Higgs–vector-boson quartic coupling modifier is

$$\kappa_{2V} \equiv g_{HHVV}/g_{HHVV}^{\text{SM}}\,.$$

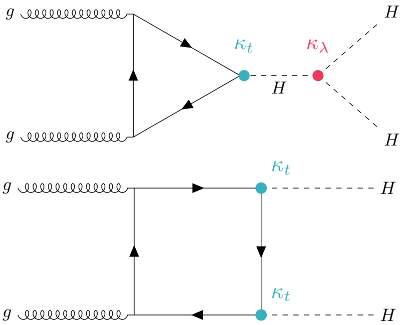
- $\kappa_{2V} = 1$: Standard Model prediction
- $\kappa_{2V} = 0$: no direct *HHVV* quartic coupling
- $\kappa_{2V} = 2$: twice the Standard Model coupling
- $\kappa_{2V} < 0$: opposite-sign quartic coupling
- VBF *HH* production probes this coupling through

$$VV \to HH.$$

- In the Standard Model, diagrams with *HHVV*, *HVV*, and *HHH* vertices interfere to keep the high-energy rate under control (contributions cancel rather than add uncontrollably).
- If $\kappa_{2V} \neq 1$, this cancellation is spoiled, so the VBF *HH* rate grows, especially at high m_{HH}.

Higgs pair production

- Higgs pair production probes the Higgs self-coupling κ_λ through the shape of the Higgs potential.
- In the Standard Model, ggF dominates HH production.
- In HH production, κ_λ matters because one production amplitude contains an off-shell Higgs boson that connects to the HH final state through the Higgs self-coupling.
- κ_{2V} tells us how strongly two W/Z bosons talk to two Higgs bosons at once.

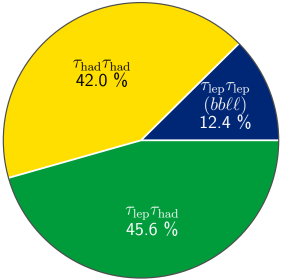


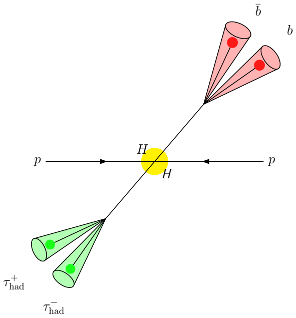
- Search target: non-resonant $HH \to b\bar{b}\tau^+\tau^-$ in Run 2 plus 2022–2023 Run 3 data ($140\ \mathrm{fb}^{-1}$ at 13 TeV and $56\ \mathrm{fb}^{-1}$ at 13.6 TeV)
- The Standard Model single-H production cross-section is three orders of magnitude greater than the HH production cross-section. Standard Model HH production is tiny!
- However, the combined $HH \to b\bar{b}\tau^+\tau^-$ final state has a *relatively* large branching fraction of about 7.3 %, together with *relatively* good background rejection from the $\tau^+\tau^-$ signature. This gives a good tradeoff between branching fraction and signal purity.

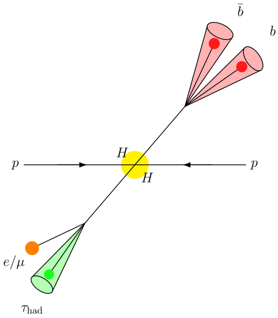
	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34 %				
WW	25 %	4.6 %			
$\tau\tau$	7.3 %	2.7 %	0.39 %		
ZZ	3.1 %	1.1 %	0.33 %	0.069 %	
$\gamma\gamma$	0.26 %	0.10 %	0.028 %	0.012 %	0.0005 %

- ggF HH is directly sensitive to κ_λ through the interference between the box and triangle diagrams.
- VBF HH is smaller but directly probes κ_{2V} (the quartic coupling modifier, which is much harder to access elsewhere), κ_V, and κ_λ.
- In the quoted note and its comparison set, the $b\bar{b}\tau^+\tau^-$ final state is the most sensitive ATLAS single channel for SM HH.
- This analysis therefore targets both inclusive μ_{HH} and separate ggF/VBF interpretations.

- Channels: full-hadronic decays $\tau_{\text{had}}\tau_{\text{had}}$ and semileptonic decays $\tau_{e/\mu}\tau_{\text{had}}$
- HadHad final state: two b-jets and two opposite-signed τ decays



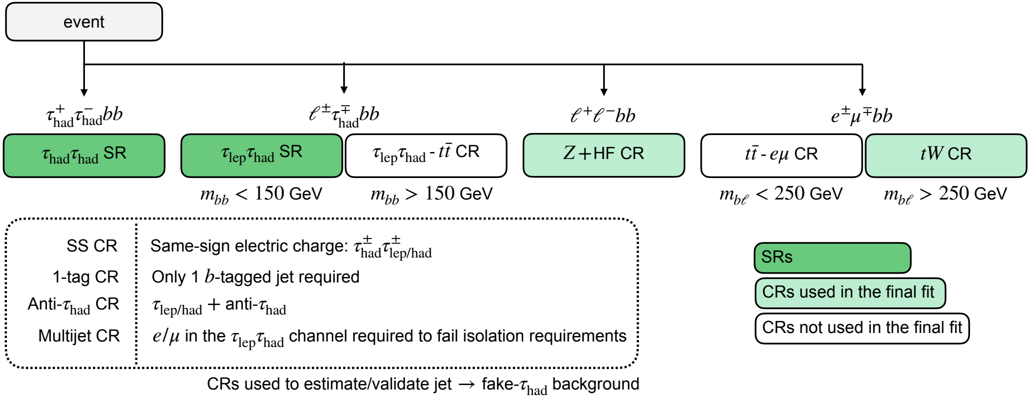




The analysis

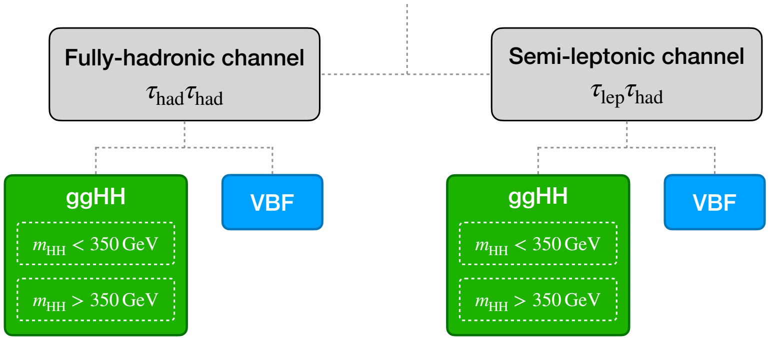
- Both channels are split into low-m_{HH} ggF, high-m_{HH} ggF, and VBF signal regions by respective GNN-based categorisation (previous strategy was BDT).
- Event-level and object-level inputs are used for multiclass HH categorisation, high-mass signal versus background, H and t parents.
- Fitting by binned simultaneous profile-likelihood fit
- Results: measurement of di-Higgs and constraints on Higgs coupling modifiers

Signal and Control Region map



- Main backgrounds: $t\bar{t}$, jets faking τ_{had} in $t\bar{t}$, $Z+\text{HF}(bb, bc, cc, bl)$, tW, diboson, single H (*e.g.* ZH and $t\bar{t}H$), jets faking τ_{had} in QCD multijet production
- Observables entering the fit: GNN score for all SRs, m_{ll} in $Z+$HF CR, m_{bl} in tW CR

Analysis full chain to physics interpretation



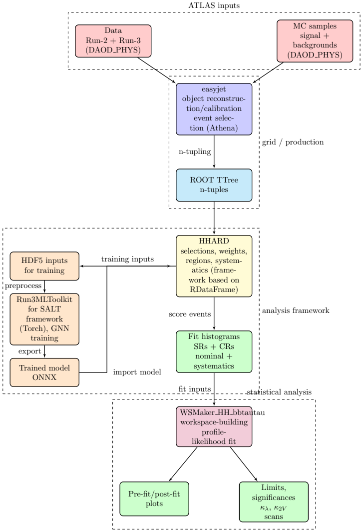
$\mu_{\rm HH}$	$\mu_{\rm ggHH}$ $\mu_{\rm VBF}$	κ_λ κ_{2V}

The status

- Fast-paced (analysis started in 2024): Marco Leite and Mariasilvia Donadelli launching efforts at USP when the analysis was first designed: Indico 1344492
- 21 May: 5th Editorial Board meeting: Indico 1686799
- Top secret/exciting: unblinding scheduled for 1 June
- ATLAS-only, follow status: Glance
- ATLAS Restricted: ATL-COM-PHYS-2025-825

Analysis framework

- **easyjet**: common *HH* analysis framework used to process centrally produced analysis datasets
- Input workflow: DAOD_PHYS $\rightarrow$ analysis ntuples (Athena)
- **HHARD**: post-processing stage built on ROOT RDataFrame-style workflows, converting n-tuples into analysis-ready histograms
- MVA infrastructure: production of multivariate model inputs and evaluation of trained classifiers
- **Run3MLToolKit**: validation of MVA inputs, preprocessing, training with the Salt framework (Torch), and inference
- **WSMaker**: construction of the statistical model and fit inputs for the final likelihood analysis



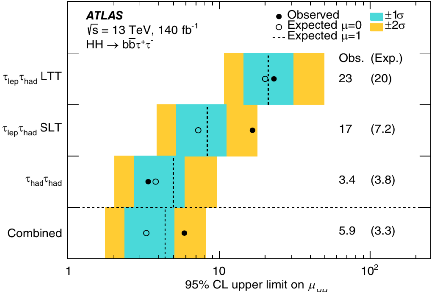
Statistical model and template binning

- Final results come from a simultaneous binned profile-likelihood fit with Poisson terms per bin.
- Parameters of interest include μ_{HH}, μ_{ggF}, μ_{VBF}, κ_{λ}, and κ_{2V}.
- Gaussian-constrained nuisance parameters encode detector and modelling uncertainties.
- Background MC statistical uncertainties are represented with one Beeston-Barlow-style γ parameter per merged bin.
- Blinding is applied to the most signal-sensitive part of the MVA distributions.

Uncertainties

- Dominated by data statistics! (need HL-LHC!)
- Next in importance:
  - acceptance uncertainty on single-Higgs plus heavy-flavour production,
  - ggF *HH* cross-section uncertainty.

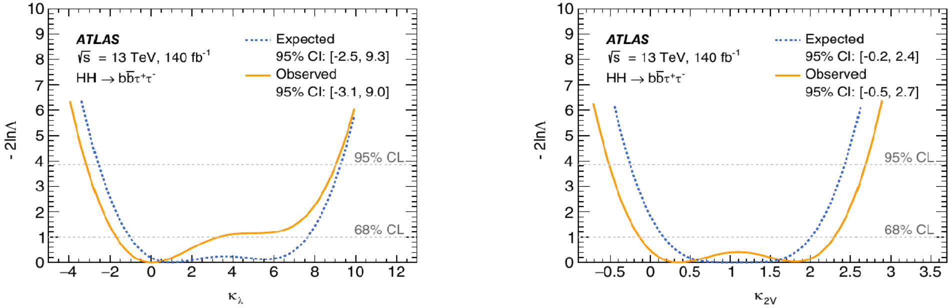
Results (2024!): *HH* limits



- Summary of observed (filled circles) and expected (open circles) 95% CL upper limits on μ_{HH} for each individual channel and for the combined fit.
- Dashed markers show the expected 95% CL limit in the SM signal hypothesis, $\mu_{HH} = 1$.
- Inner and outer bands indicate the $\pm 1\sigma$ and $\pm 2\sigma$ variations on the expected limit around the background-only hypothesis.
- Reference: 10.1103/PhysRevD.110.032012

USP

Results (2024!): Likelihood scans for Higgs coupling modifiers



- Coupling modifiers shown on negative log-likelihood plots. Values of $-2\ln\Lambda$ for different κ_λ and κ_{2V} Standard Model hypotheses obtained from fits to the data (orange) and an Asimov dataset (blue).
- Reference: 10.1103/PhysRevD.110.032012

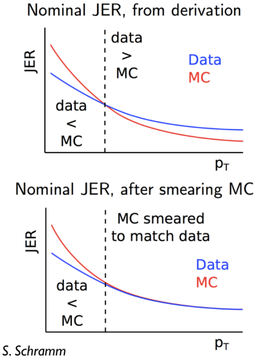
Contributions: HHARD and WSMaker

- Transition of n-tuple production versions (v6, v7, v8)
- Procedures for SAMPA/local CVMFS productions
- Cut-flow challenges
- Code contributions (HHARD and WSMaker)
- Documentation/tutorial

- JER matters directly for $HH \to b\bar{b}\tau^+\tau^-$ because the measured jet energies affect the reconstructed $b\bar{b}$ mass, the overall event kinematics, and the determination of $E_{\mathrm{T}}^{\mathrm{miss}}$.
- If JER is mismodelled in simulation, then signal acceptance, background shapes, and fitted nuisance-parameter behaviour can all become biased.
- ATLAS provides JER uncertainty components as nuisance parameters with up/down variations, for example
  - `JET_JER_EffectiveNP_1`,
  - `JET_JER_EffectiveNP_12restTerm`,
  - `JET_JER_DataVsMC_MC16`.
- For this kind of precision analysis, the relevant prescription is *FullJER*, which is designed to preserve the correct statistical behaviour of JER nuisance parameters in the fit.

FullJER: MC Smearing and pseudodata smearing

- JER variations are propagated by Gaussian smearing of jet energies in simulation.
- If a variation worsens the resolution, MC jets can be smeared directly.
- If a variation would make the resolution better, the effect is represented with a complementary *pseudodata-smear* construction rather than trying to “unsmear” MC.
- This is essential when a JER component changes sign across phase space: FullJER preserves the resulting correlations and anti-correlations across regions, while simpler MC-only schemes do not.



Template construction and HHARD implementation

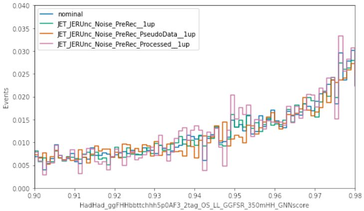
- For each nuisance parameter and direction, HHARD produces MC-smeared and pseudodata-smeared histograms on the same nominal event sample.
- The processed up/down templates are then built as

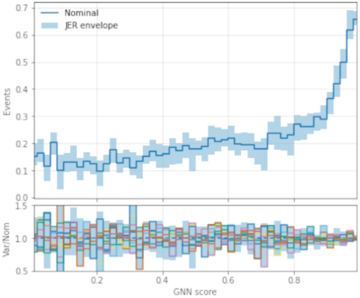
$$T = N + H_{\mathrm{MC}_{\mathrm{smear}}} - H_{\mathrm{PD}_{\mathrm{smear}}} ,$$

  with the appropriate nuisance-parameter direction.
- This was successfully implemented and validated as a HHARD post-processing step converting HHARD outputs to fit-ready histograms, and is in use since last month.
- In a sentence, the code converts raw JER systematic ingredients (MC-smear and pseudodata-smear histograms) into fit-ready JER up/down template histograms using

$$H_{\mathrm{processed}} = H_{\mathrm{nominal}} + H_{\mathrm{MC}_{\mathrm{smear}}} - H_{\mathrm{PD}_{\mathrm{smear}}} .$$

- The top picture is a cropped snapshot of the MVA score with JER uncertainties.
- The upper panel of the lower plot shows the nominal yield versus GNN score, with a shaded band spanning the largest processed up/down JER shifts.
- The lower panel of the lower plot shows the variation-to-nominal ratios, with the five most deviant nuisance parameters overlaid.
- Basically a check that processed FullJER templates are behaving sensibly in this analysis region.





Contributions: tau trigger efficiency

- Both channels of the analysis involve tau decays (with HadHad using single-τ triggers, di-τ triggers and di-b triggers).
- HadHad is the most sensitive $b\bar{b}\tau^{+}\tau-$ channel. If tau trigger efficiency is poor, our best channel loses acceptance directly.
- Tau trigger acceptance directly controls the usable *HH* signal yield, especially in the HadHad channel, where τ and b-jet trigger combinations are needed to keep signal efficiency while controlling QCD rates.
- Taking on the role of n-tuple production Tau Trigger and TauCP/offline efficiency scale-factor measurements using framework xTauFW and tag-and-probe analyses, for tau trigger and offline analyses (and maintaining/updating calibrations/selections).
- Measurement of 2025/2026 tau trigger efficiency scale factors (tag-and-probe measurement involving GNTau and mc23g)

- HL-LHC pile-up, which would otherwise degrade jets, b-tagging, τ_{had} reconstruction, $E_{\text{T}}^{\text{miss}}$, and VBF-category purity, can be suppressed with precision timing in the forward region $2.4 < |\eta| < 4.0$.
- Enter the HGTD with 30 ps track-time resolution at the start of operation.
- This matters particularly in the VBF HH topology, in which forward jets are part of the signal definition. The HGTD should reject pile-up jets and assign tracks to the correct hard-scatter vertex, improving sensitivity to κ_{2V}.
- The HGTD can survive the brutal radiation with its Low Gain Avalanche Detectors (LGAD) sensors, and it makes the high-pile-up $HH \to b\bar{b}\tau^+\tau^-$ analysis not limited by luminosity, but technically feasible in the HL-LHC era.
- However, current tracking methods do not have enough throughput to operate in the extreme HL-LHC conditions – some new, fast tracking methods are needed.
- Advertisement: *Tomorrow: Guilherme & Rodrigo*

The future

- End of Run-3, start of serious upgrades to launch HL-LHC era
- The Standard Model single-H production cross-section is three orders of magnitude greater than the HH production cross-section.
- With Run 2 plus Run 3 data, the expected sensitivity is about 1.2σ for HH, with an upper limit around 1.9 times the SM rate. At the HL-LHC, the expected sensitivity is about 3.5σ with $3000\ \text{fb}^{-1}$ at 14 TeV.

References & acknowledgements

- ATLAS Restricted: ATL-COM-PHYS-2025-825
- Note status: Glance
- ATLAS Week at Glasgow
- HEPIC, ATLAS-USP, Tau Trigger group, FAPESP – *Obrigado!*

Information | Discussion (28) | Files

Internal Note

Report number	ATL-COM-PHYS-2025-825
Title	**A search for non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ final state using Run 2 + partial Run 3 data recorded by the ATLAS detector**
Author(s)	Ali, Shahzad (California State University (US)) (+) ; Almeida De Assis, Victor (Federal University of of Rio de Janeiro (BR)) (+) ; Amini, Baktash (University of Freiburg (DE)) (+) ; Baer, Tamas Marton (University of Michigan (US)) (+) ; Behr, Janna Katharina (Deutsches Elektronen-Synchrotron (DE)) (+) ; Bernardi, Gregorio (Centre National de la Recherche Scientifique (FR)) (+) ; Betti, Alessandra (Sapienza Universita e INFN, Roma I (IT)) (+) ; Bhattarai, Prajita (SLAC National Accelerator Laboratory (US)) (+) ; Bijl, Pim (University of Freiburg (DE)) (+) ; Bokan, Petar (Uppsala University (SE)) (+) ; Bortoletto, Daniela (University of Oxford (GB)) (+) ; Breaden Madden, William Dmitri (Universidade de Sao Paulo (USP) (BR)) (+) ; Cadamuro, Luca (Université Paris-Saclay (FR)) (+) ; Cairo, Michael Andrew (University of Pennsylvania (US)) (+) ; Carquin Lopez, Edson (Federico Santa Maria Technical University (CL)) (+) ; Castiglioni, Whitmaur Robert (University of Chicago (US)) (+) ; 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Abstract	This note summarizes the ATLAS search for non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ final state using Run 2 + partial Run 3 data. The search is conducted using $140\,\mathrm{fb}^{-1}$ of proton-proton collision data recorded at $\sqrt{s} = 13\,\mathrm{TeV}$ and up to $56\,\mathrm{fb}^{-1}$ recorded at $\sqrt{s} = 13.6\,\mathrm{TeV}$. An event selection targeting events with at least one hadronically decaying τ lepton is used to select candidate events that are further categorized according to their likelihood of being either gluon-gluon fusion or vector boson fusion events as well as their reconstructed invariant di-Higgs mass. Transformer-based neural networks are then used to separate the signal from the backgrounds and provide a score that is used as a fit discriminant. The main results will be added to the abstract once they are available.

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Obrigado – Questões?