Studies on Higgs Boson Yukawa Couplings and Self-coupling at ATLAS Experiment

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What’s the fundamental building block of matter? And what’s the origin of mass?

A Long Time Ago…

- Our Chinese ancestors: Fire, Water, Wood, Metal and Earth are the Five Elements (referred as “Wuxing”)

- Greek philosophers: everything is composed of “uncuttable” elementary particles

- After going through a long Dark Ages, then followed by the Renaissance and Scientific Revolution…

Modern Science Came

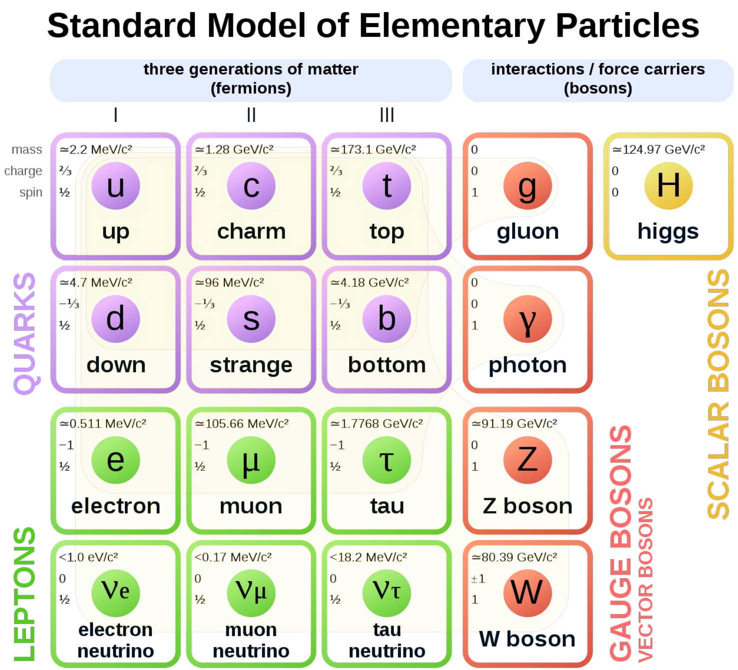
- J. Dalton proposed the atom theory in the 19^{th} century
- In 1897 J.J. Thomson discovered electron  Nobel prize in 1906
- E. Rutherford discovered the nucleus in 1911
- Later Bohr model was proposed to describe the structure of atom  Nobel prize in 1922
- Proton was discovered in 1917
- J. Chadwick discovered neutron in 1932  Nobel prize in 1935
- Nucleus was found to consist of protons and neutrons at the center of atom

Then Particle Accelerators Came

- A large variety of particles were discovered through the collisions (referred as “particle zoo”)
- To classify these particles, M. Gell-Mann* and G. Zweig proposed the “quark model”  [*Nobel Prize in 1969]
  - Later quantum chromodynamics (QCD) was developed to describe the strong interactions  [Nobel Prize in 2004]
- S. Glashow, A. Salam and S. Weinberg developed the electroweak theory to unify electromagnetic and weak forces  [Nobel Prize in 1979]
  - W and Z bosons discovered in 1983  [Nobel Prize in 1984]

Standard Model

- Describe the elementary particles and their interactions
- The cornerstones of the SM:
  - Gauge invariance (based on SU(3)×SU(2)×U(1)): depicting strong and electroweak interactions
  - Higgs mechanism: trigger the EWSB; W, Z bosons and fermions acquire masses through EWSB; predicts the Higgs boson



The "God Particle" Higgs boson discovered at the LHC in 2012!

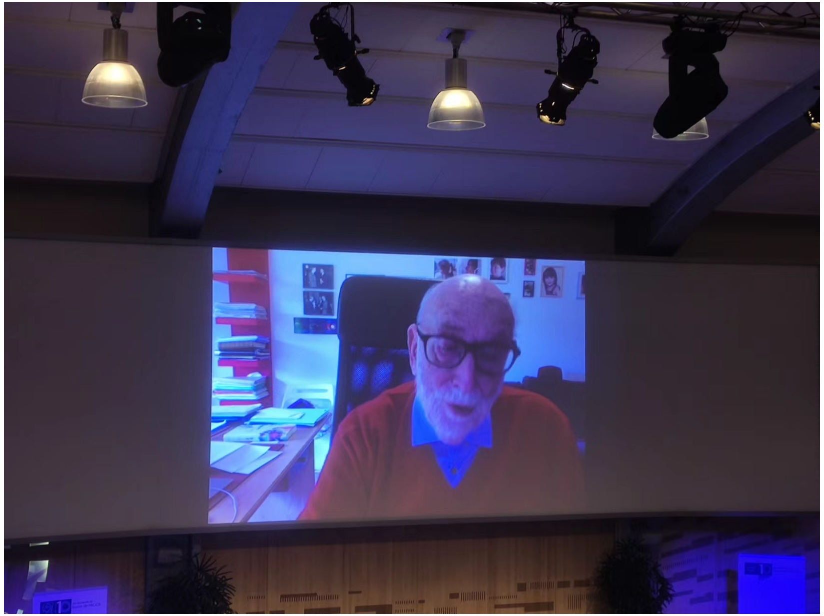
Nobel Prize in Physics in 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

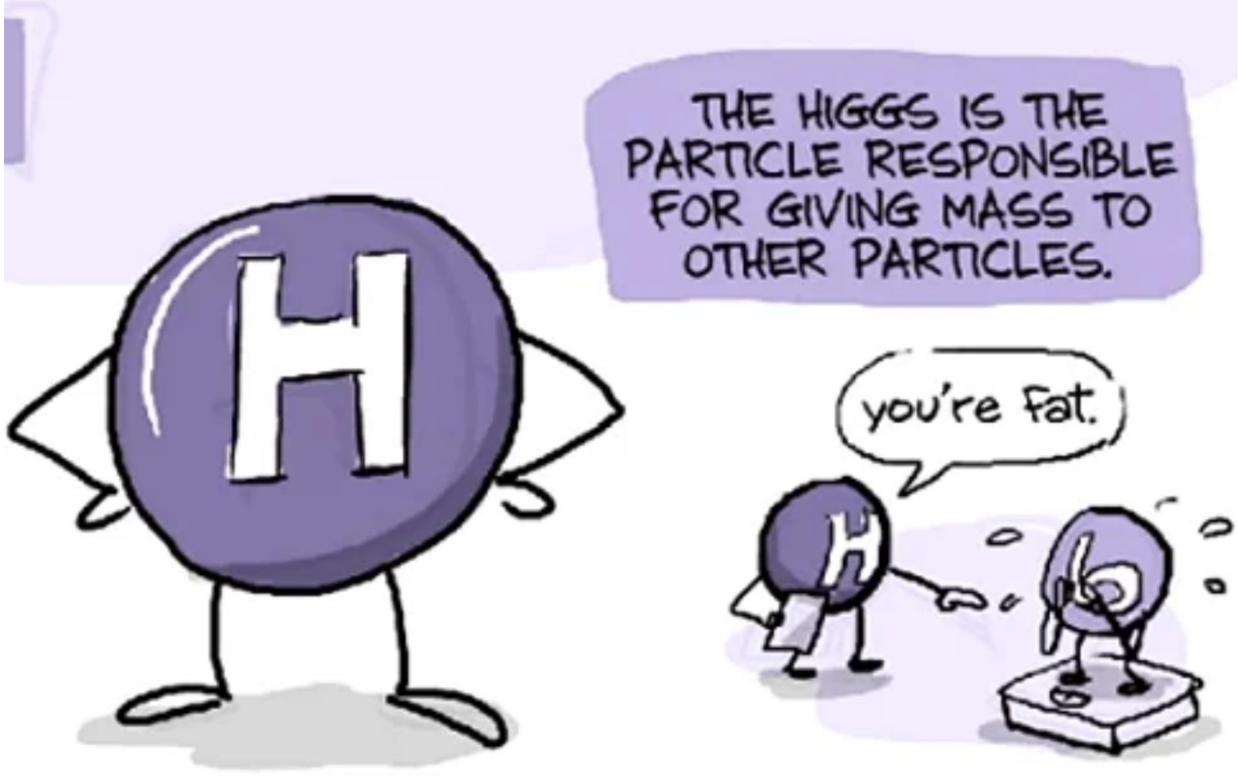
Brout passed away in 2011

July 4th, 2022: 10th Anniversary of Higgs Discovery



A Big Discovery in Particle Physics

- Not just a discovery of another particle
- The Higgs discovery to particle physics is like the DNA discovery to biology

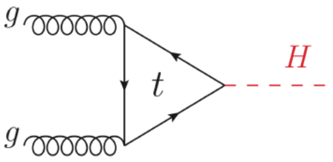


It’s Not the End…

- **A New Chapter**: measuring Higgs boson properties including couplings is crucial for our understanding on origin of mass and new physics probe
  - Does it also couple to all the massive particles (including fermions) as predicted by the SM ?
  - What are its mass, width, rate, and other quantum numbers (spin and parity) ?
  - Is it an elementary or composite particle ?
  - Will it decay to other final states not predicted by the SM ?
  - How to access the structure of the Higgs potential?
  - …

Higgs Production and Decay at LHC

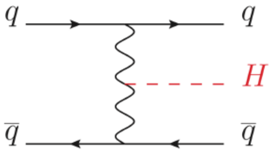
ggF



Gluon fusion process

~8 M events produced

VBF

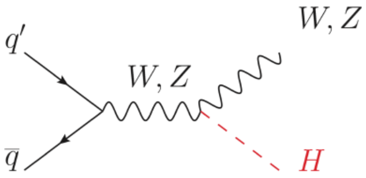


Vector Boson Fusion

Two forward jets and a large rapidity gap

~600 k events produced

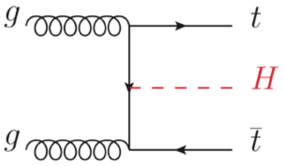
VH



W and Z Associated Production

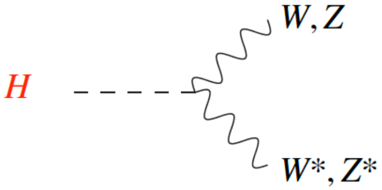
~400 k events produced

ttH



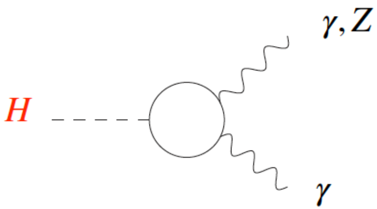
Top Assoc. Prod.

~80 k evts produced



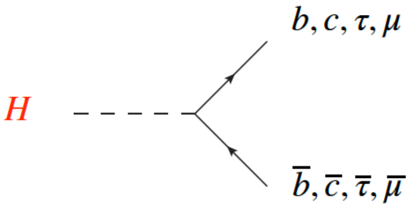
$\mathrm{Br}(H \to WW^*) = 22\,\%$

$\mathrm{Br}(H \to ZZ^*) = 3\,\%$



$\mathrm{Br}(H \to \gamma\gamma) = 0.2\,\%$

$\mathrm{Br}(H \to Z\gamma) = 0.2\,\%$



$\mathrm{Br}(H \to b\bar{b}) = 57\,\%$

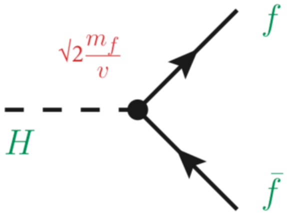
$\mathrm{Br}(H \to \tau^+\tau^-) = 6.3\,\%$

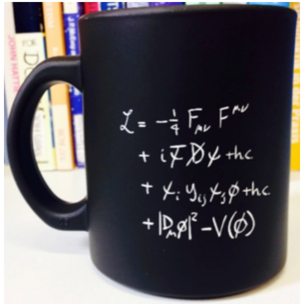
$\mathrm{Br}(H \to c\bar{c}) = 3\,\%$

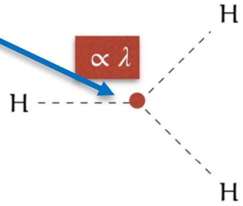
$\mathrm{Br}(H \to \mu^+\mu^-) = 0.02\,\%$

Higgs Yukawa Couplings and Self-coupling

- Higgs boson couples to fermions through Yukawa interactions
  - ➢ Giving masses to quarks and leptons
  - ➢ Coupling strength is proportional to fermion's mass
- Higgs potential: $V(h) = \frac{1}{4}\lambda h^4 + \lambda v h^3 + \lambda v^2 h^2$
  - ➢ In SM, $\lambda \approx 0.13$ give $m_H \approx 125$ GeV
- HH productions provide directly access to Higgs self-coupling κ_λ ($\lambda_{HHH}/\lambda_{SM}$)

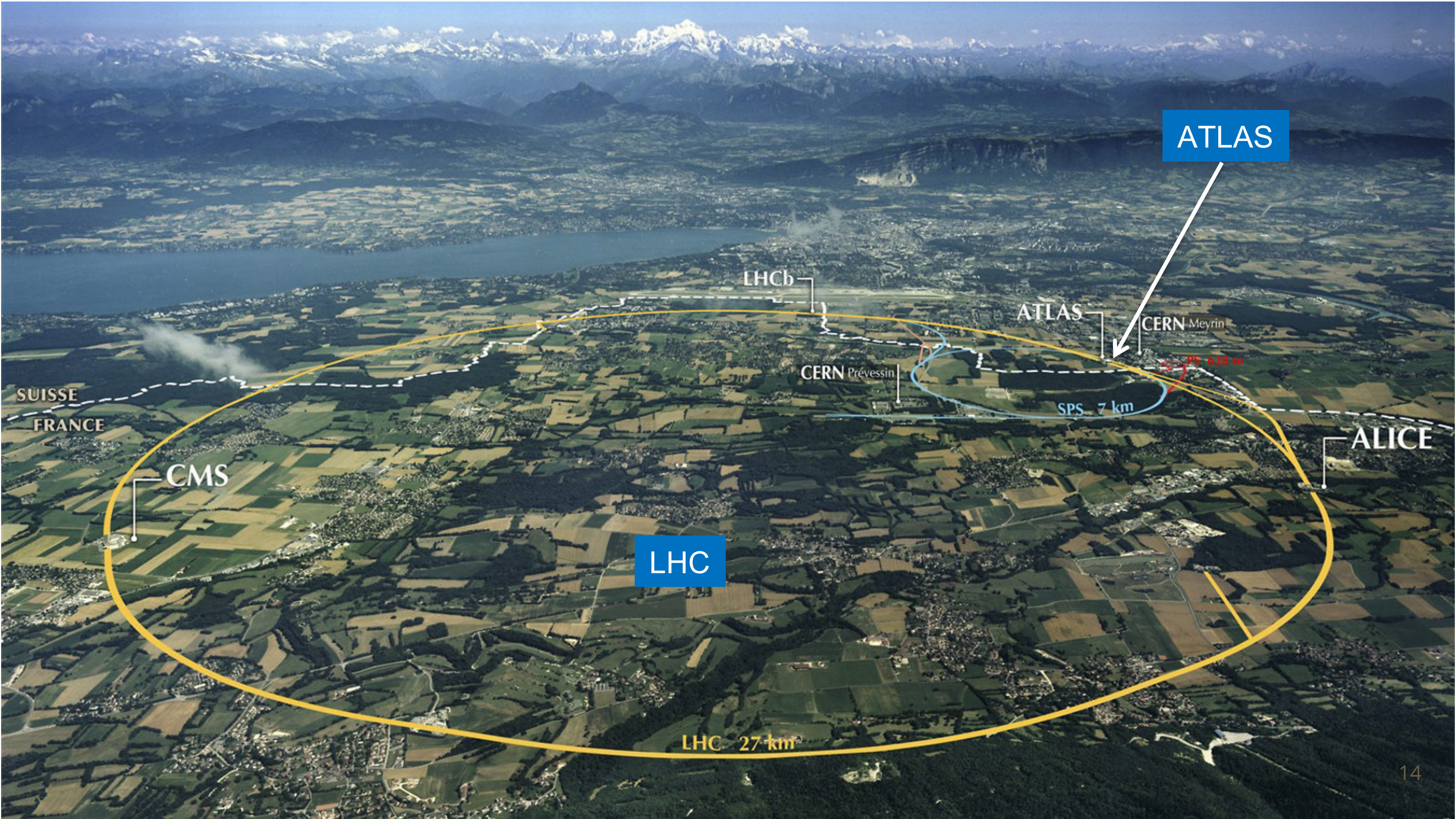




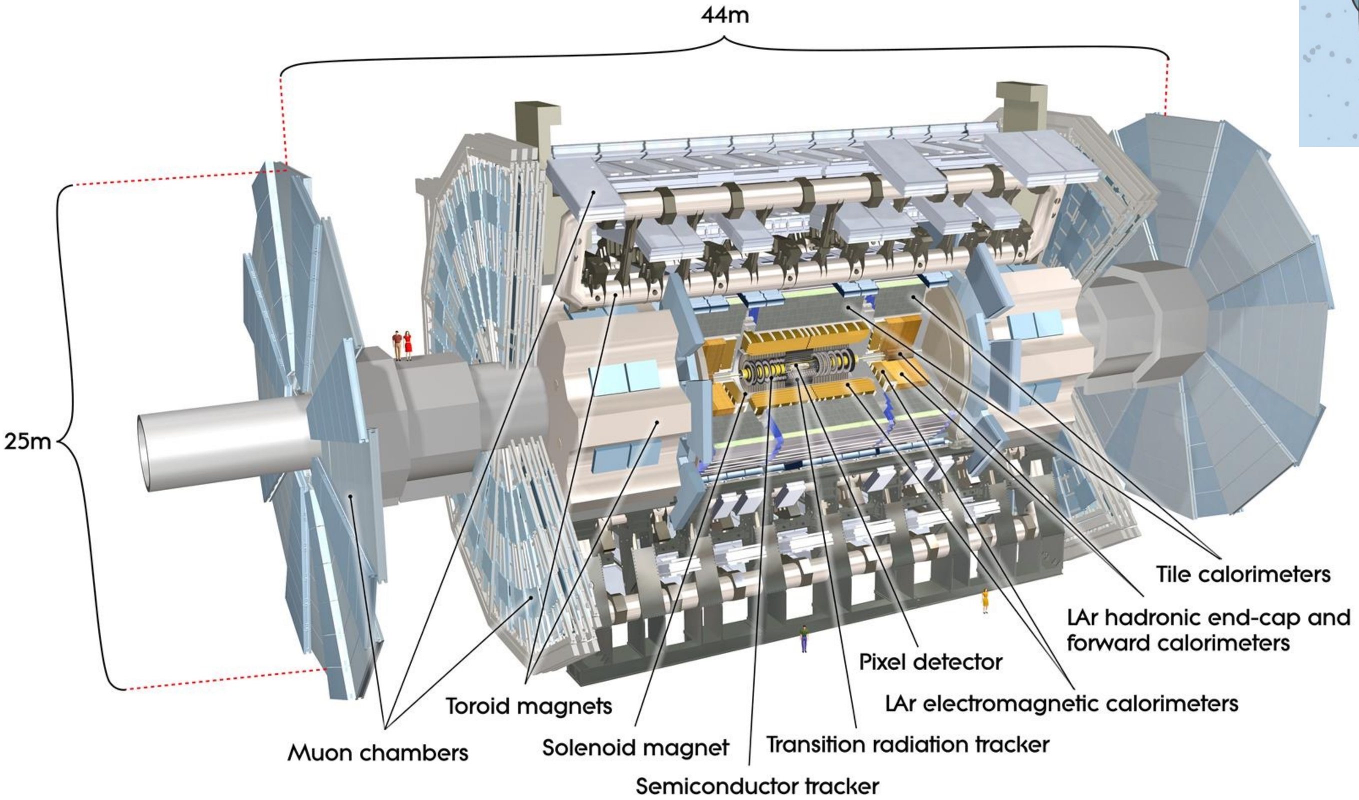


Topics to be Covered Today

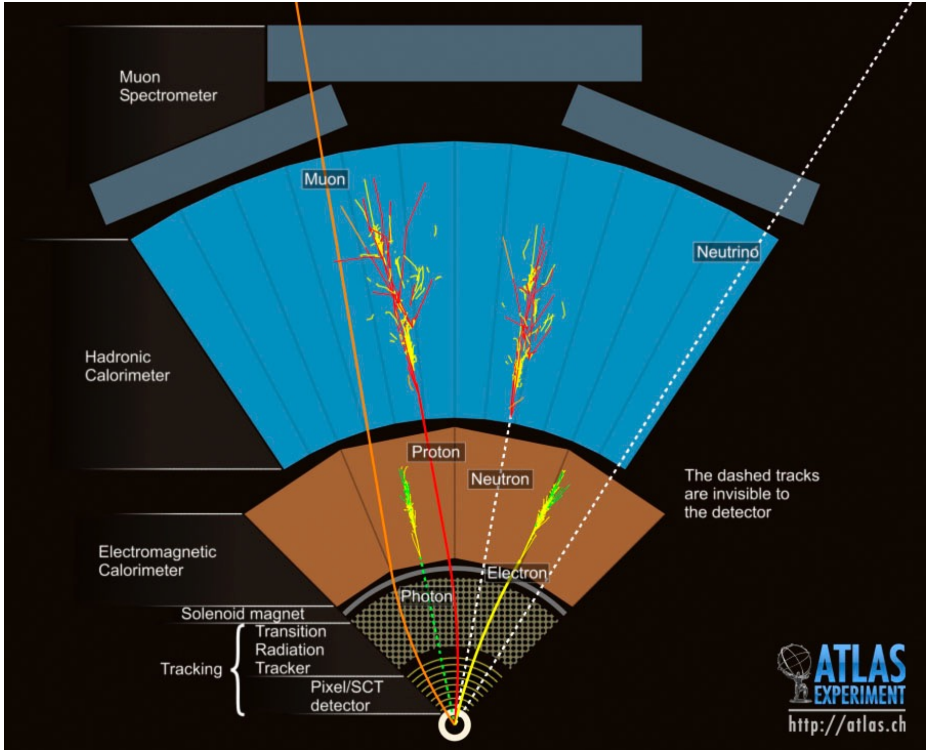
- CP Property of the Top-quark Yukawa Coupling via ttH/tH (H→$\gamma\gamma$): Yukawa coupling to 3rd generation fermion
- Search for SM H→μμ: Yukawa coupling to 2nd generation fermion
- HH→bb$\tau\tau$ and HH(+H) combination: Higgs boson trilinear self coupling


ATLAS
LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC
LHC 27 km

Our “Camara”: ATLAS Detector



Particle Identifications at ATLAS

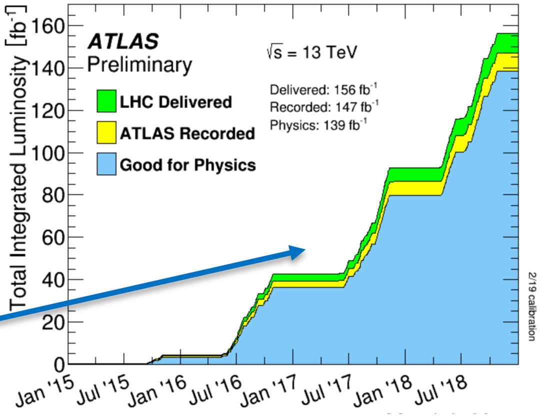


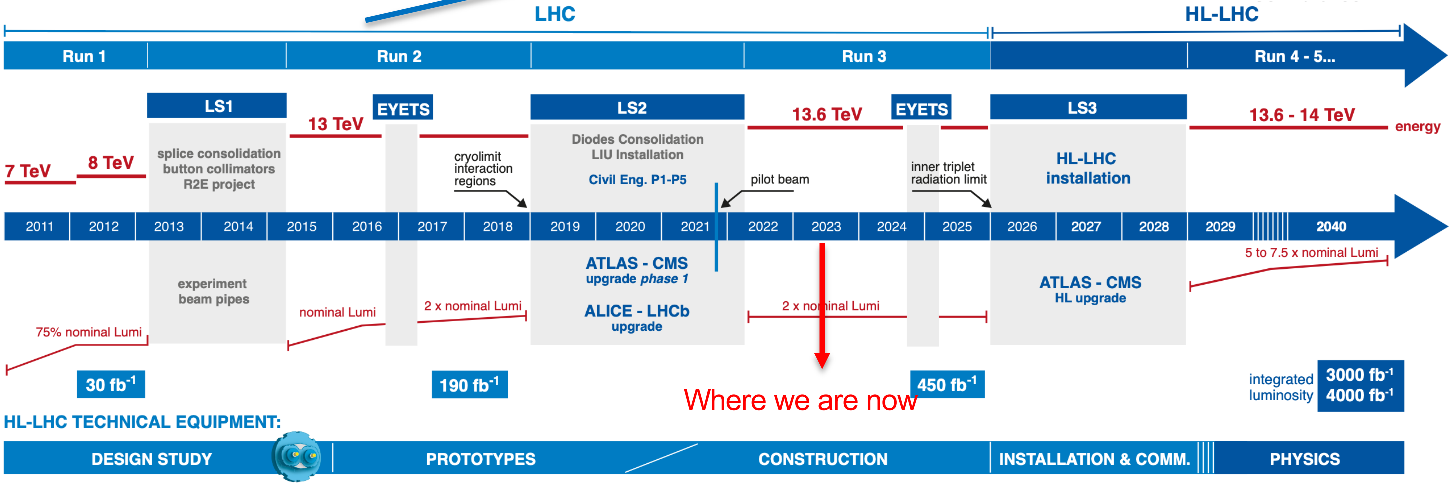
The main final-state particles used for the physics analysis: electron, muon, tau, jet, b-jet, and missing transverse energy E_T^{miss}

Different types of particles interact with certain sensitive sub-detectors and give different responses in the experiments

Run 2 Dataset

- Great performance of ATLAS detector and operation of the LHC
- 139 fb^{-1} of 13 TeV pp collision data collected for physics by the ATLAS detector during the LHC Run 2





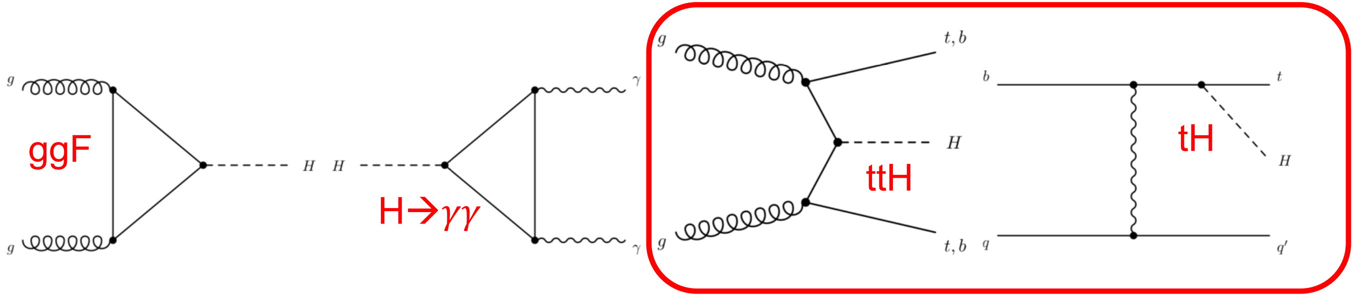
CP Property of the Top-quark Yukawa Coupling via ttH/tH (H→$\gamma\gamma$)

Why Doing This?

- Large matter-antimatter asymmetry in universe: crucial to look for additional CP violation sources
- Yukawa couplings provide an unambiguous and more sensitive probe of a CP-mixed state compared to Higgs-gauge-boson couplings
- First direct probe to the CP property of the top-Higgs Yukawa coupling (strongest one) using ttH/tH at tree level
  - Lagrangian written as: $\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + \mathrm{i}\sin(\alpha)\gamma_5\right]\psi_t\right\} H$ J. Ellis et al.
  - κ_t (>0): Yukawa coupling strength; α: CP-mixing angle
  - In SM, $\kappa_t = 1$, α = 0 (CP is purely even)

How to Probe this?

- The presence of a CP-odd component in the t-H coupling have impact on:
  - ➢ rate and kinematics of ggF process
  - ➢ rate of H→$\gamma\gamma$ decay
  - ➢ rate and kinematics of ttH and tH processes



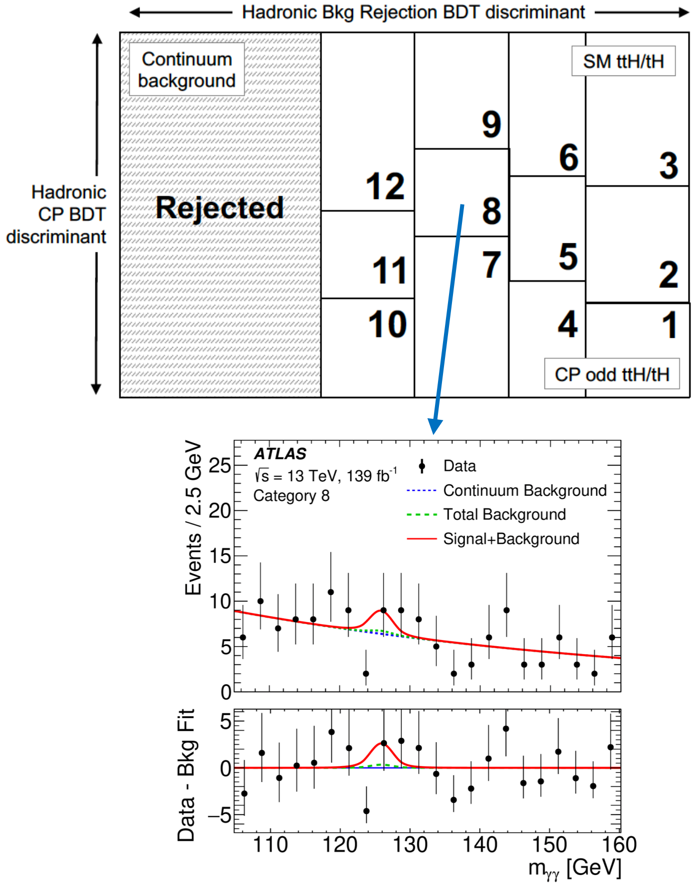
- Measure the rate of ttH/tH processes and shapes of observables sensitive to the CP nature of the t-H coupling

Why in H→$\gamma\gamma$ Channel?

- $\gamma\gamma$ channel: small rate, but clean signature and good resolution; solid bkg. estimation from data sideband → most sensitive channel to study ttH process
- $\gamma\gamma$ selection: two isolated photons with p_T > 35/25 GeV; 105 GeV < $m_{\gamma\gamma}$ < 160 GeV
- ttH/tH selection: ≥1 b-tagged jet
  - "Lep" region (≥1 top decay leptonically): ≥ 1 isolated electron or muon with p_T > 15 GeV
  - "Had" region (both tops decay hadronically): 0 selected lepton, ≥ 3 jets

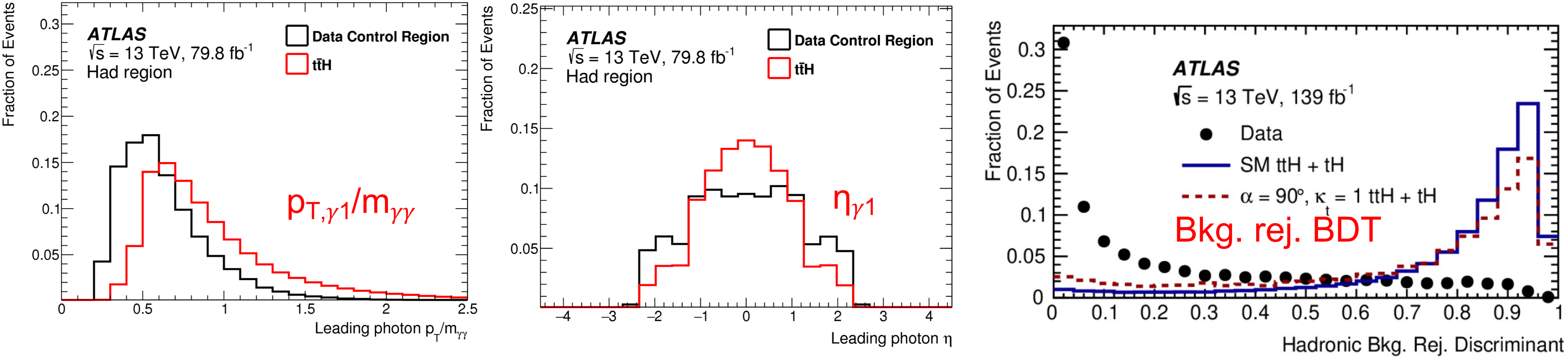
Analysis Methodology

- In each region, trained two BDTs:
  - Bkg. rejection BDT: separate ttH-like events from $\gamma\gamma$+jets/tt$\gamma\gamma$ bkg.
  - CP BDT: separate CP-even and CP-odd couplings using ttH/tH
- Categorize events based on 2D BDTs: 12 categories in Had and 8 in Lep
- Signal extraction: simultaneous fit to $m_{\gamma\gamma}$ spectra in all 20 categories



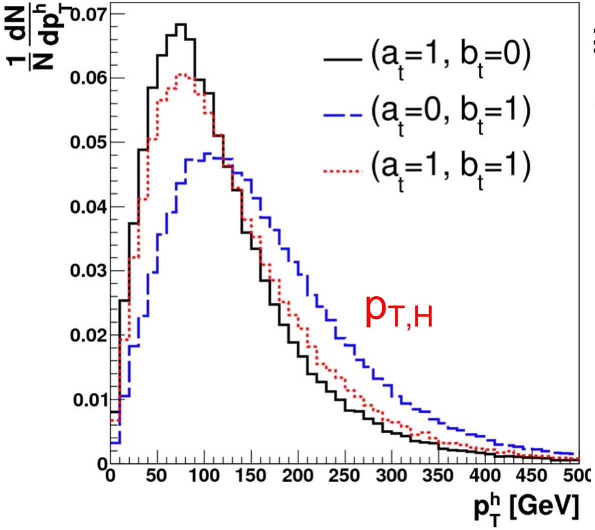
Background Rejection BDT

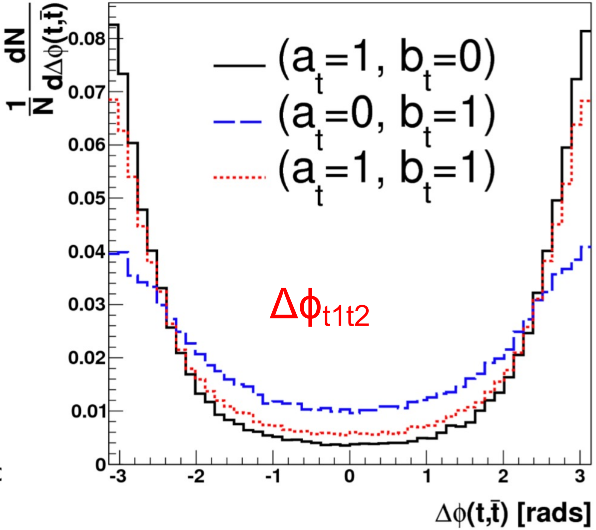
- Trained with low-level input variable like 4 vector info of γ, j, l, and MET
- Good separation power between ttH/tH and background, no strong dependence on CP mixing angle

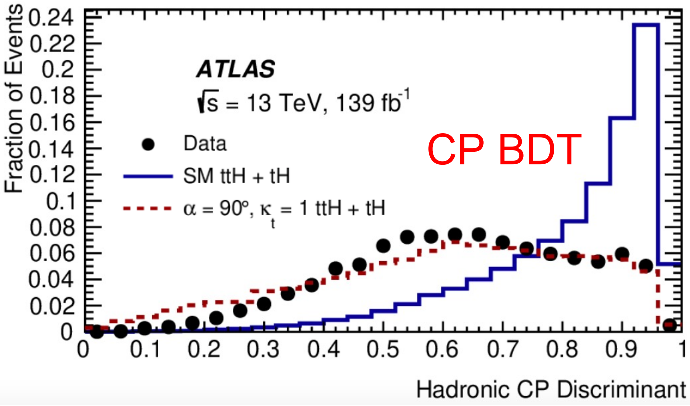


CP BDT

- Training variables: p_T/η of $\gamma\gamma$ system and two top candidates (t1, t2); $\phi_{\gamma\gamma,t1}$ and $\phi_{\gamma\gamma,t2}$; $\Delta\eta_{t1t2}$ and $\Delta\phi_{t1t2}$; $m_{\gamma\gamma,\ t1}$, m_{t1t2}, etc







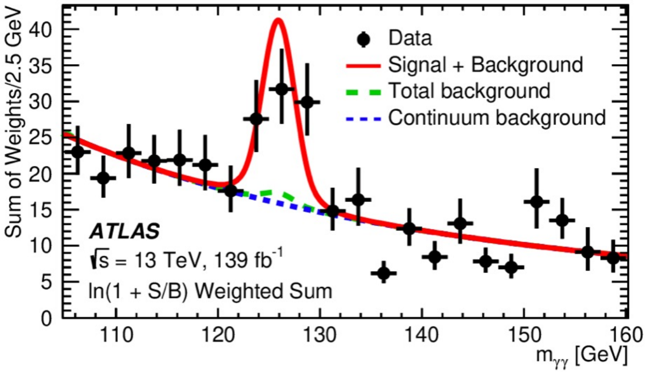
Ref: PRD 92, 015019 (2015)

Signal Significance for ttH($\rightarrow\gamma\gamma$)

- Assuming CP-even coupling, the measured signal strength ($\mu=\sigma_{obs}/\sigma_{SM}$) for ttH via H$\rightarrow\gamma\gamma$ is:

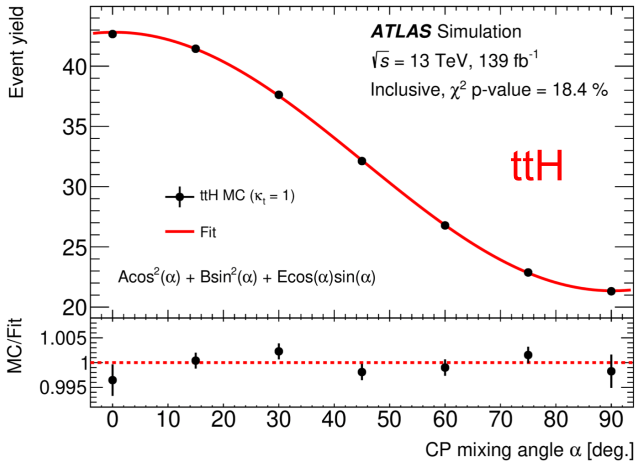
$$\mu = 1.43 \; {}^{+0.33}_{-0.31}(stat.) \; {}^{+0.21}_{-0.15}(sys.)$$

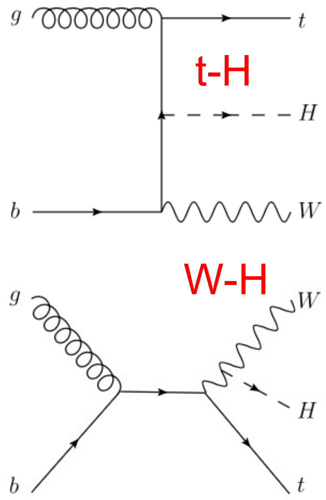
- The background-only hypothesis is rejected with an observed (expected) significance of 5.2σ (4.4σ) → ttH observation in single Higgs decay channel

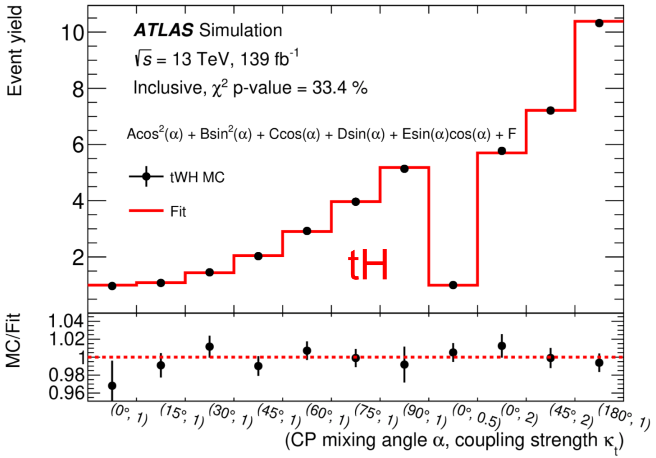


ttH/tH Signal Yield Parametrization

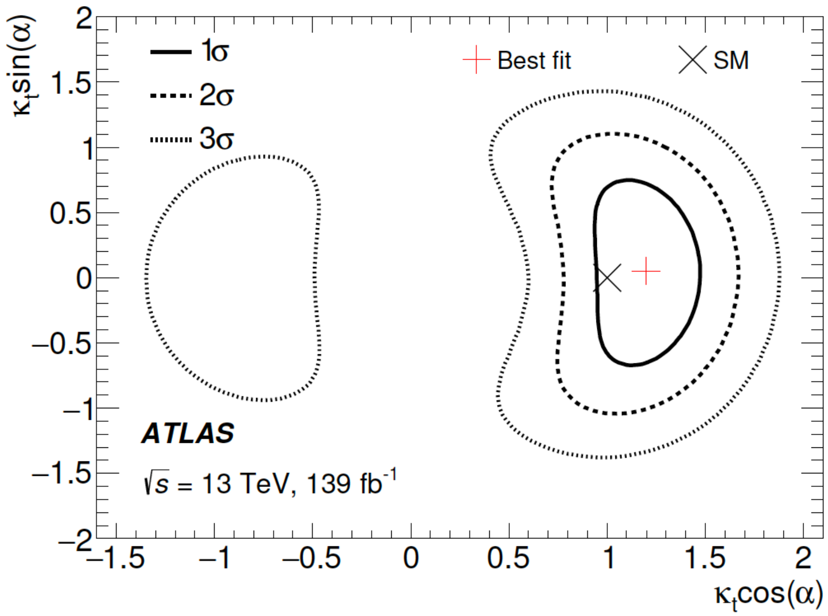
- ttH/tH yields parametrized into κ_t and α in each category
- ttH following the form: $A\kappa_t^2\cos^2(\alpha) + B\kappa_t^2\sin^2(\alpha) + E\kappa_t^2\sin(\alpha)\cos(\alpha)$
- tH: $A\kappa_t^2\cos^2(\alpha) + B\kappa_t^2\sin^2(\alpha) + C\kappa_t\cos(\alpha) + D\kappa_t\sin(\alpha) + E\kappa_t^2\sin(\alpha)\cos(\alpha) + F$
  - ➢ Need to consider the interference between t-H and W-H couplings







Results on CP Constraint

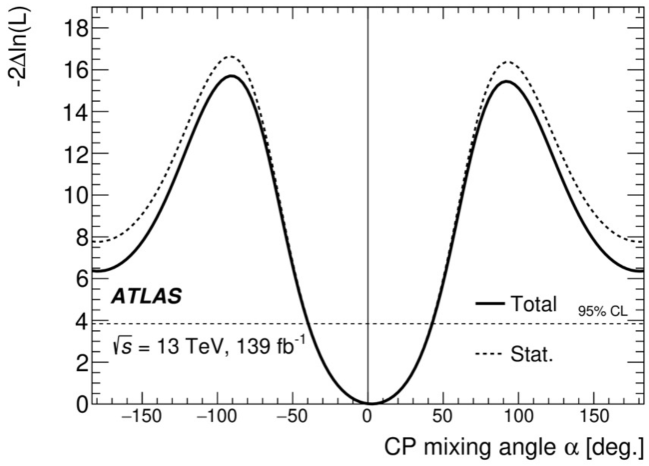


H→$\gamma\gamma$/ggF loops constrained by the Higgs combination result (link)

The measurements consistent with the SM prediction, and no sign of CP violation in the top-Yukawa interaction observed

Exclusions for CP-odd Component

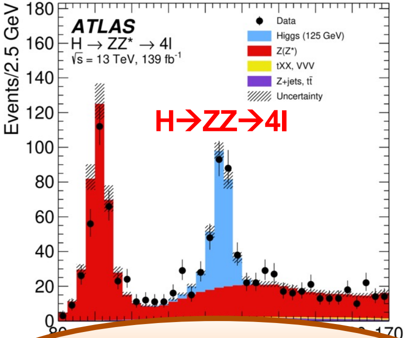
- Likelihood scan of α with κ_t floating in the fit
- |α|>43° is excluded at 95% C.L.
- Pure CP-odd hypothesis is excluded at 3.9σ → stringent exclusion result for CP-odd component in the top-Yukawa interaction to date

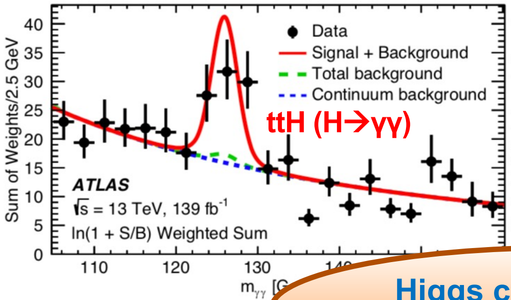


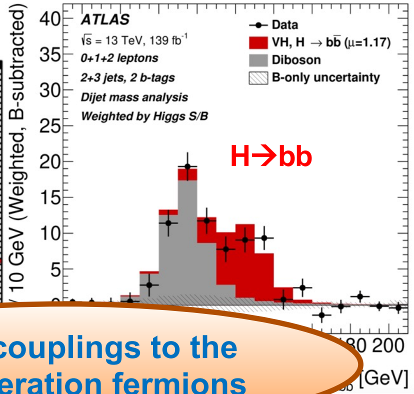
Phys. Rev. Lett. 125 (2020) 061802

Search for SM H→μμ

What We've Learned about the Higgs

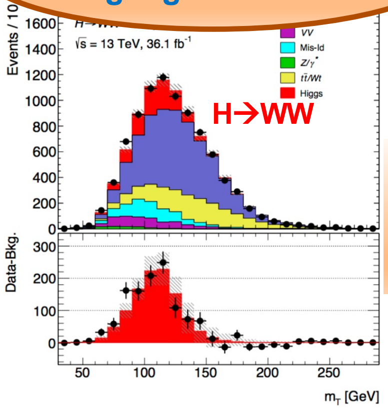




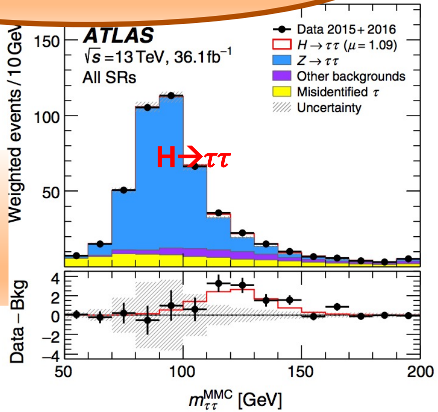


Higgs coupling to gauge bosons

Higgs couplings to the 3rd generation fermions

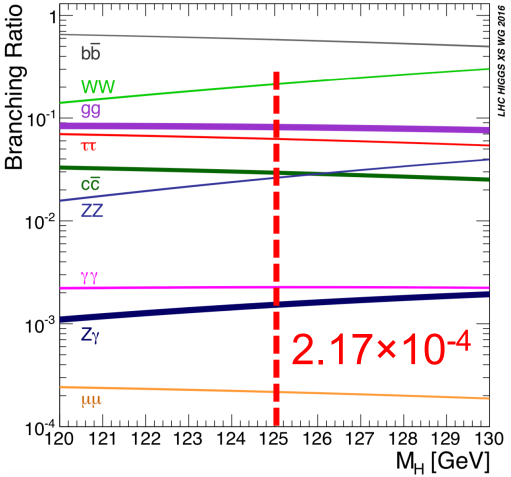


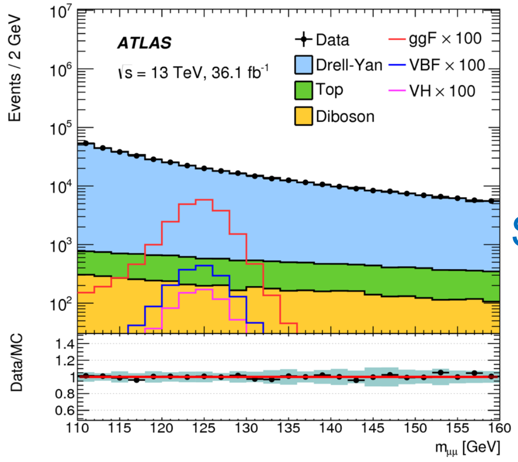
One of the next big milestones: Higgs couplings to the 2nd generation fermions



Physics Motivation

- H→μμ: most promising channel to explore Yukawa coupling to the 2nd generation fermions
  - ➢ H→cc not very sensible under the current luminosity
- Major challenge for H→μμ: low branching ratio and large irreducible background from Drell-Yan





S/B: ~0.1%

Overview of Analysis Strategy

- Sig. signatures: two isolated muons with opposite charge
- BDT-based categorization to enhance signal sensitivity
  - Driven by the different Higgs boson production modes
- Data driven approach used for bkg. estimation
- Sig.+Bkg. PDF used to fit the observed $m_{\mu\mu}$ spectra simultaneously in all the categories to extract the signal
  - Sig. and bkg. modeled by analytic functions

Event Selection for H→μμ

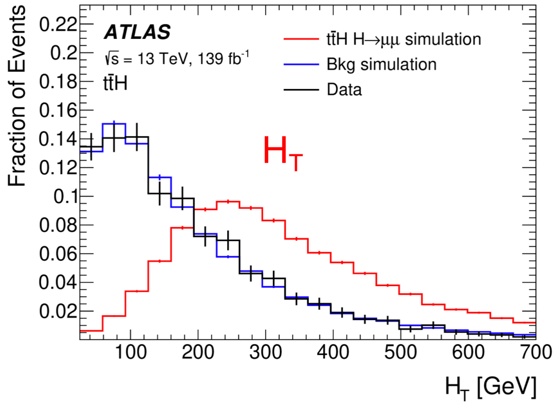
- Single muon trigger with p_T threshold of 26 or 50 GeV

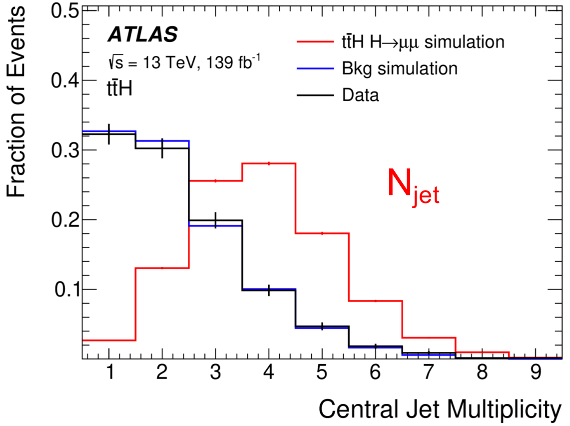
	Selection
Common preselection	Primary vertex Two opposite-charge muons Muons: $\|\eta\| < 2.7$, $p_T^{lead} > 27$ GeV, $p_T^{sublead} > 15$ GeV (except VH 3-lepton)
Fit Region	$110 < m_{\mu\mu} < 160$ GeV
Jets	$p_T > 25$ GeV and $\|\eta\| < 2.4$ or with $p_T > 30$ GeV and $2.4 < \|\eta\| < 4.5$
$t\bar{t}H$ Category	at least one additional e or μ with $p_T > 15$ GeV, at least one b-jet (85% WP)
VH 3-lepton Categories	$p_T^{sublead} > 10$ GeV, one additional e (μ) with $p_T > 15(10)$ GeV, no b-jets (85% WP)
VH 4-lepton Category	at least two additional e or μ with $p_T > 8, 6$ GeV, no b-jets (85% WP)
ggF +VBF Categories	no additional μ, no b-jets (60% WP)

Selected events sorted into 20 categories in total, which are mutually exclusive and in the order of ttH(1) →VH(3)→VBF(4)→ggF(12)

ttH Categorization

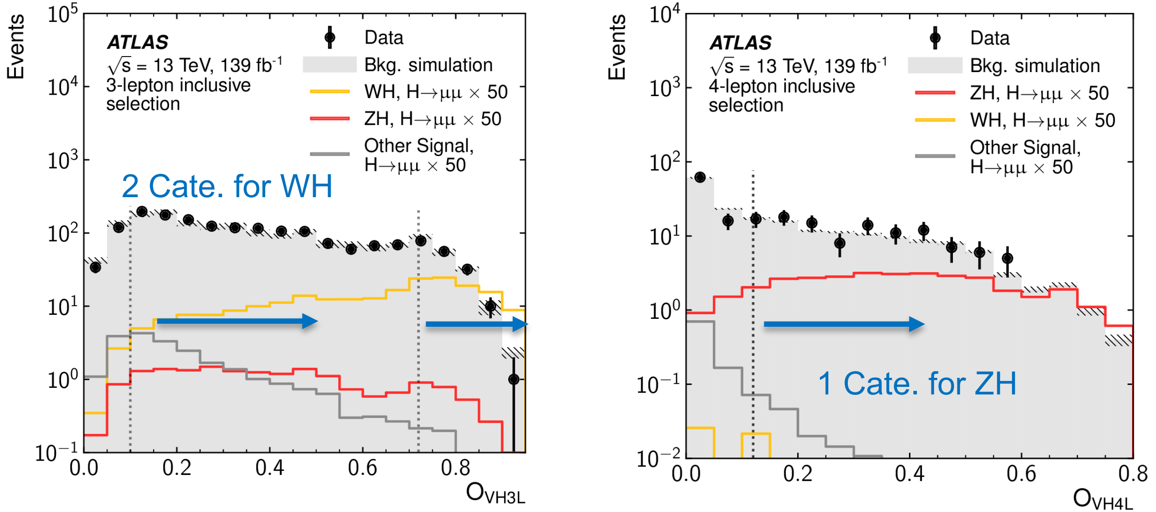
- Target semi/dileptonic decays of top pair
  - ≥1 extra e/μ and ≥1 b-tagged jet
  - Two highest-p_T muons with opposite charge as the Higgs candidate
- BDT trained to distinguish ttH sig. from all bkgs. (ttbar, ttZ, diboson, etc)
  - Training variables: p_T of e/μ, invariant masses of leptons/tops, as well as N_{jet} and $N_{b\text{-}jet}$, and H_T



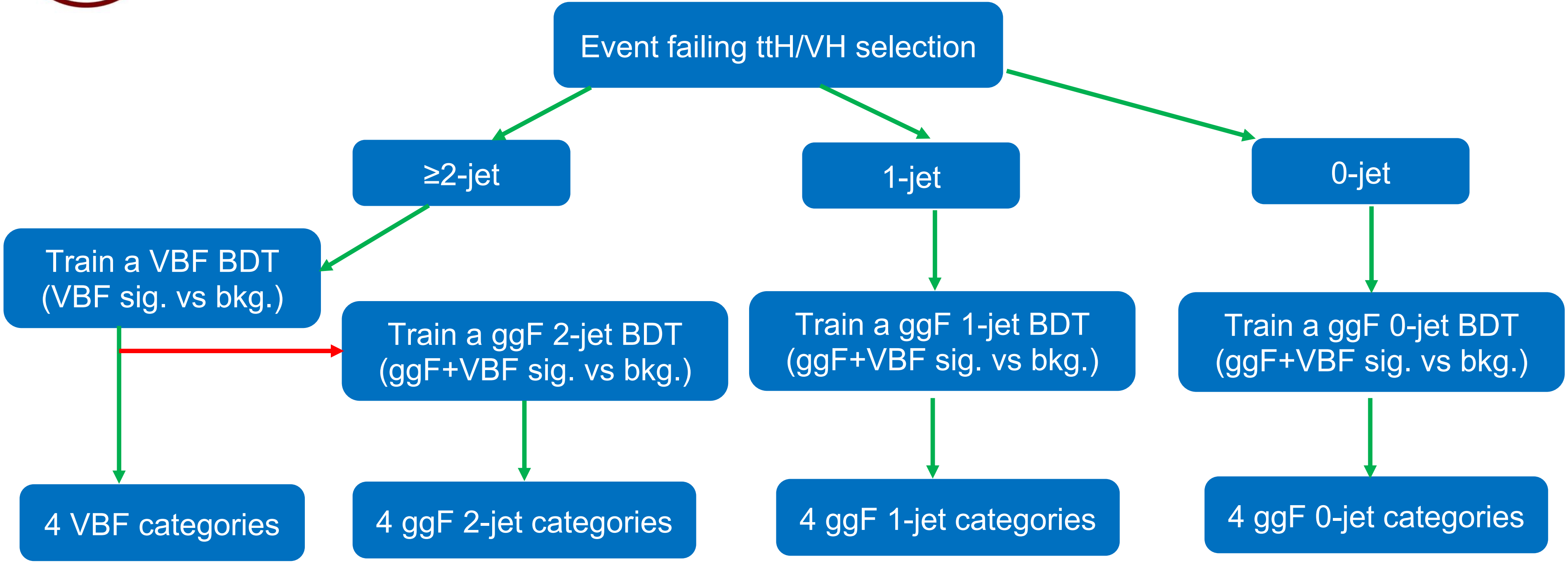


VH Categorization

- Target WH/ZH in leptonic decays: 1/2 additional leptons except muon pair
- Two BDTs trained for WH and ZH using invariant mass and angular variables of lepton systems as well as E_T^{miss} and N_{jet}

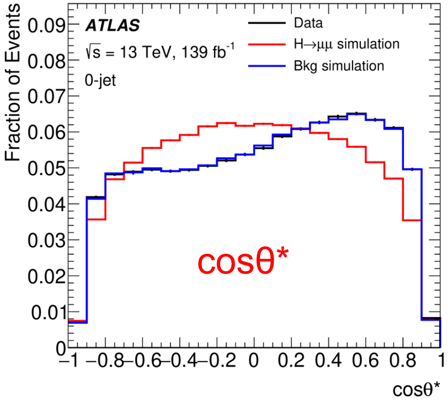


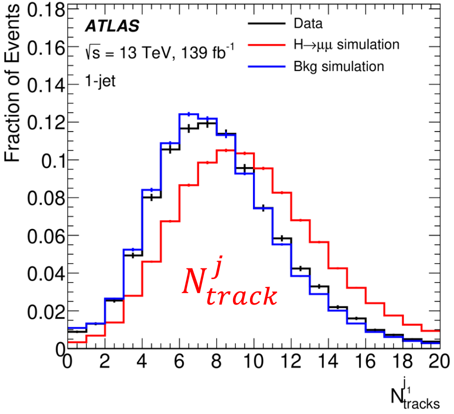
VBF/ggF Categorization (1)

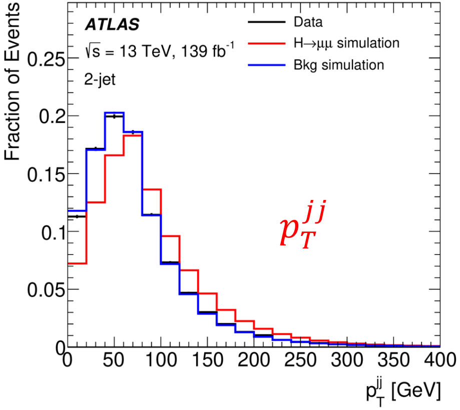


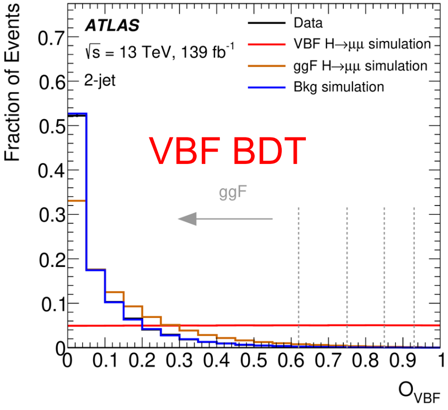
Training variables: $p_T^{\mu\mu}$, $y_{\mu\mu}$, cosθ*, p_T and η of jets, p_T^{jj}, y_{jj}, $\Delta\phi_{jj,\mu\mu}$, m_{jj}, N_{track}^{j}, etc

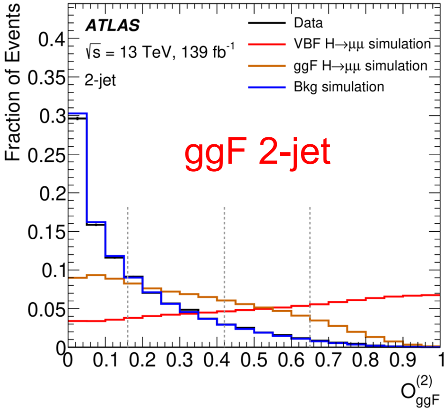
VBF/ggF Categorization (2)







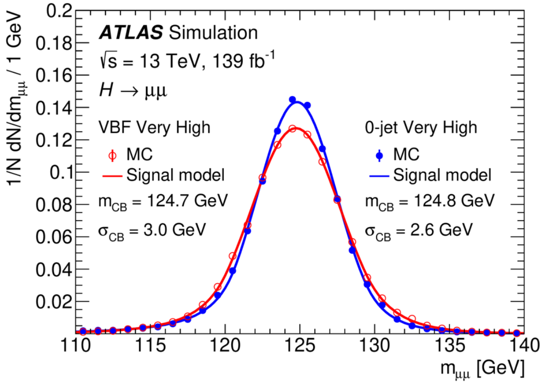


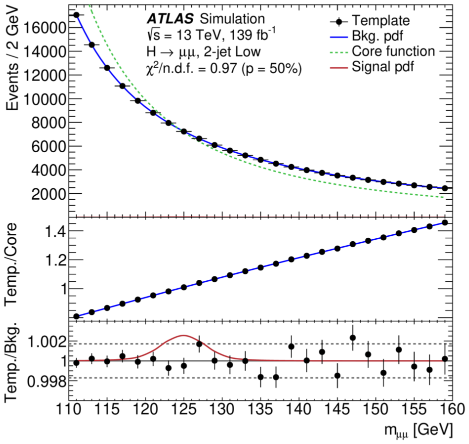


- Four groups of categories: VBF, ggF 2-jet, ggF 1-jet and ggF 0-jet
- In each group, four categories defined based on the signal purity

Signal and Background Modeling

- Signal: double-sided Crystal Ball containing a Gaussian core and power-law tails (σ_{CB} ranging from 2.6-3.2 GeV)
- Background: a "core function" multiplied by an "empirical function"
  - Core function: Drell-Yan mass shape convoluted with Gaus. function
  - Empirical function: correct for distortions of the mass shape and smaller bkg.
  - Potential bkg. mis-modeling treated as sys. unc. ("spurious signal")





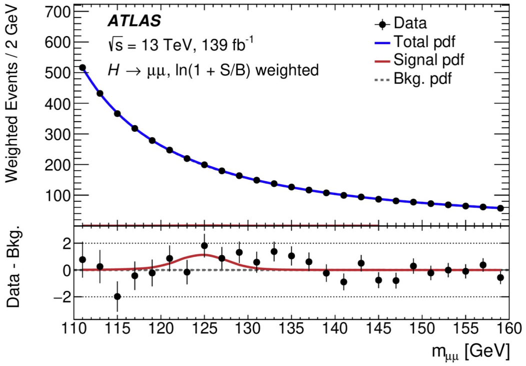
H→μμ Results

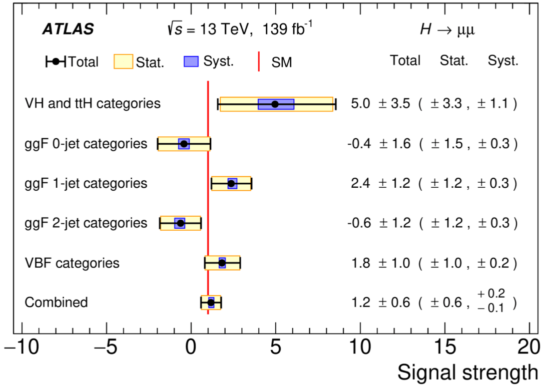
- A simultaneous maximum-likelihood fit performed to the observed $m_{\mu\mu}$ spectra in 20 categories
- The measured signal strength is:

Combined μ = 1.17 $\pm 0.58(Stat.)^{+0.18}_{-0.13}(sys.)$

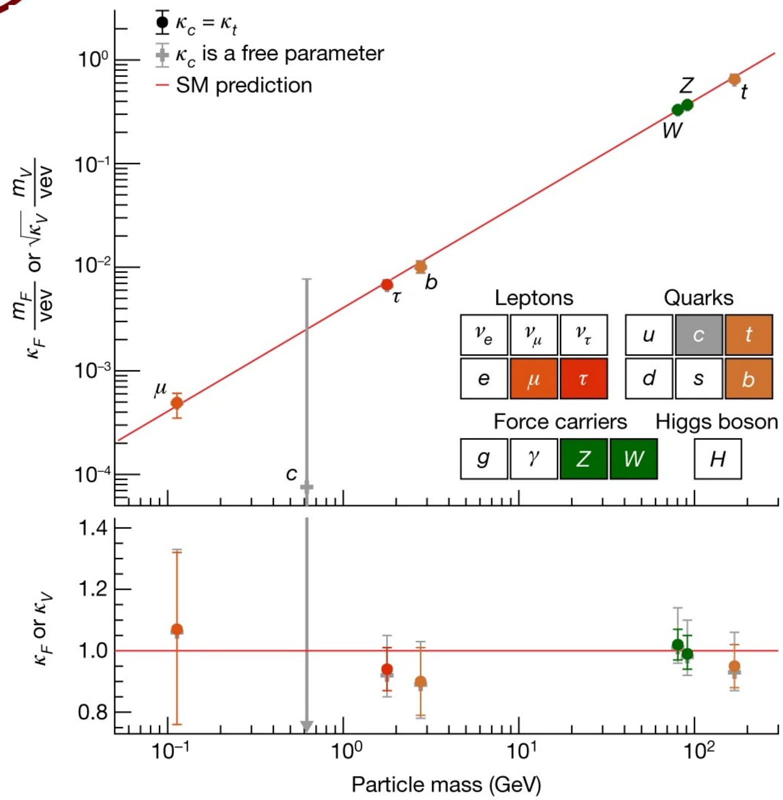
- Results are statistical uncertainty dominated
- The obs. (exp.) significance is 2.0 (1.7) σ

Phys. Lett. B 812 (2021) 135980
Phys. Rev. Lett. 119 (2017) 051802





Higgs Couplings

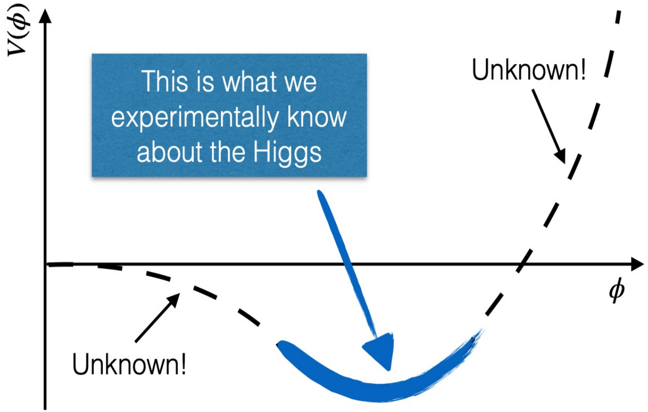


- Up to now, five main production channels and five main decay channels observed and being used for measurements
- Global signal strength: 1.05±0.06

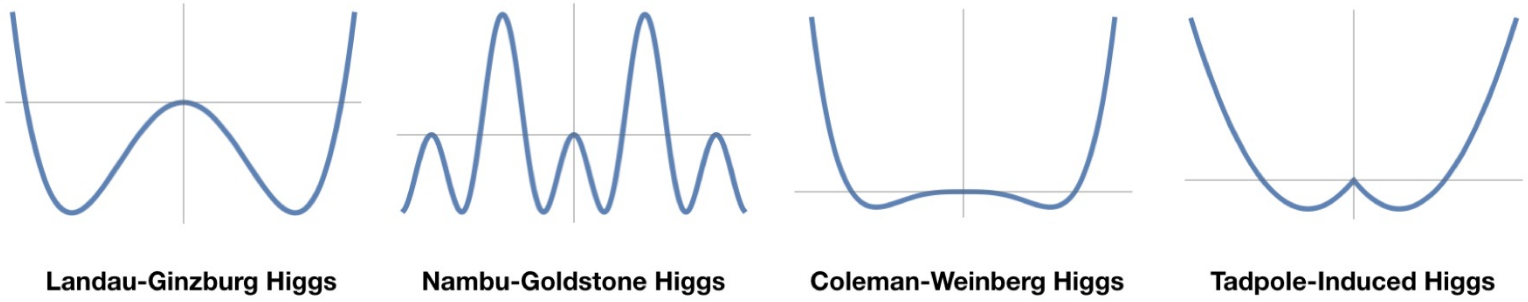
[Nature 607, 52–59 (2022)]

Search for HH→bb$\tau\tau$

Higgs Potential Not Determined Yet



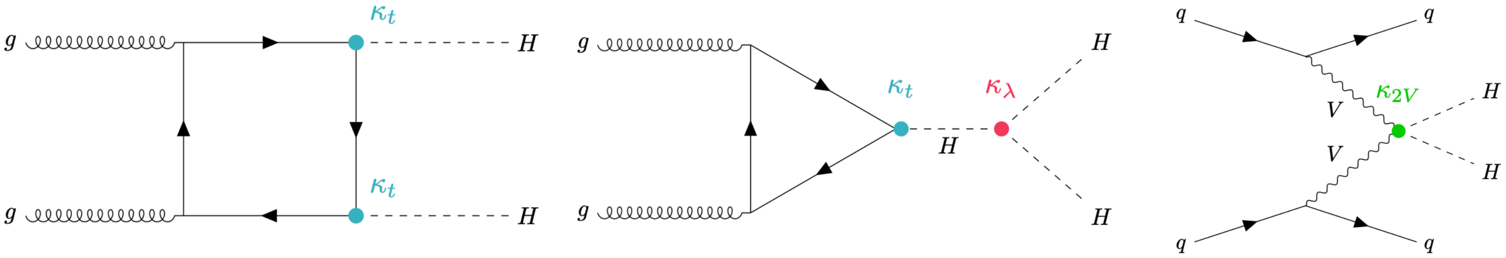
- New physics (e.g. first order electroweak phase transition) can cause a significant deviation away from SM predicted Higgs potential
- Measurements of Higgs self-coupling can provide discrimination between different scenarios/models



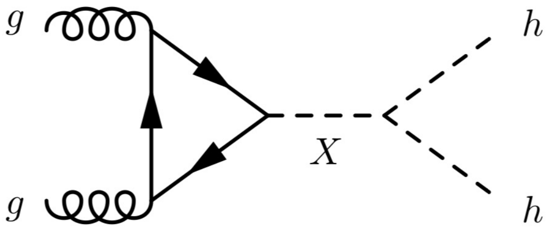
Ref: Phys. Rev. D 101, 075023 (2020)

HH Production

- SM non-resonant HH: σ_{HH}^{ggF}= 31.05 fb, σ_{HH}^{VBF}= 1.72 fb
  - Direct access to Higgs self-coupling (κ_λ) and potential
  - VBF: unique process to probe HHVV coupling (κ_{2V})



- Various BSM theories predict heavy resonances decaying into HH
  - Narrow width approximation
  - 2HDM as benchmark model

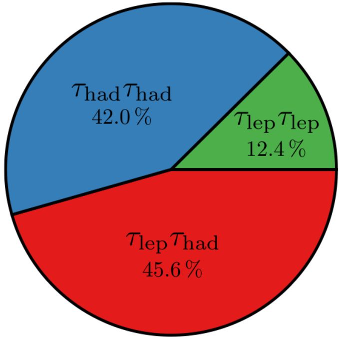


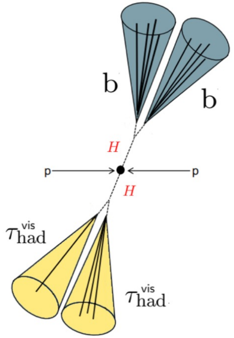
bb$\tau\tau$ Final State

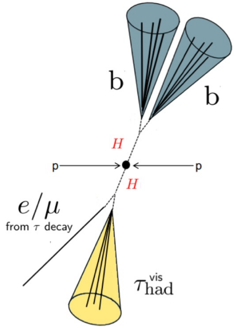
HH Branching Ratios

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39 %		
ZZ	3.1%	1.2%	0.34 %	0.076 %	
γγ	0.26 %	0.10 %	0.029 %	0.013 %	0.005 3%

Di-τ Branching Ratios







- bb$\tau\tau$: moderate BR, relatively clean signature
- Split into two channels depending on τ decay: $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$

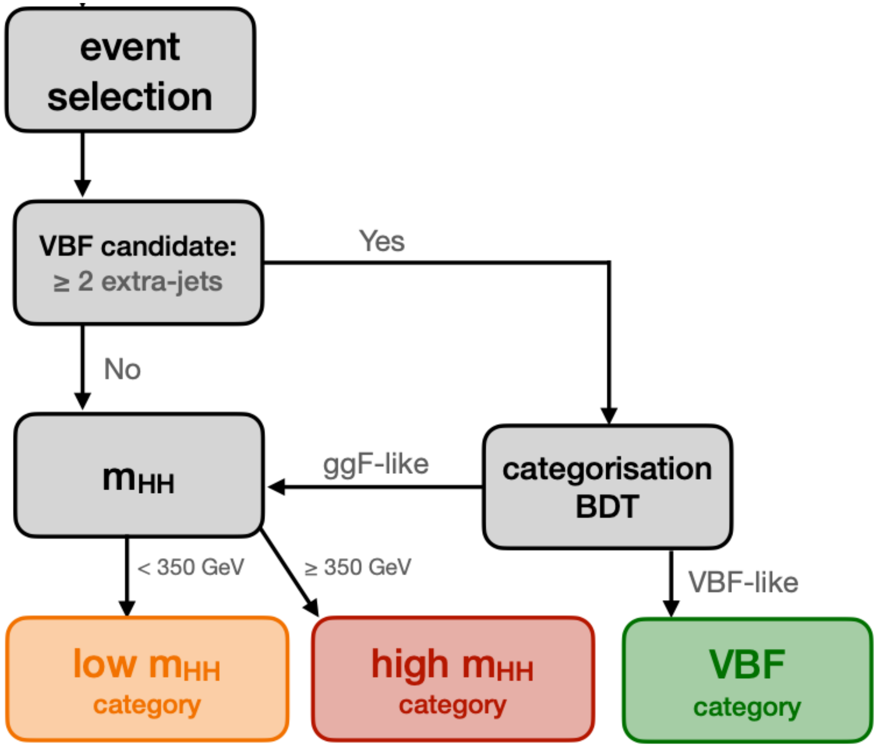
Event Selection

- Signal signature: two b-jets (DNN-based tagger, 77%) and $\tau_{had}\tau_{had}/\tau_{lep}\tau_{had}$ with opposite charge

Signal region	Tau/Lepton	Trigger
$\tau_{had}\tau_{had}$	2 hadronic τ	Single or Di-tau Trigger (STT/DTT)
$\tau_{lep}\tau_{had}$ SLT	1 hadronic τ + 1 e/μ	Single lepton trigger (SLT)
$\tau_{lep}\tau_{had}$ LTT	1 hadronic τ + 1 e/μ	Lepton+tau trigger (LTT)

- Trigger-dependent thresholds on e/μ/τ_{had} and jets
- e/μ veto for $\tau_{had}\tau_{had}$; exactly 1 e/μ for $\tau_{lep}\tau_{had}$
- $m_{\tau\tau}^{MMC}$ > 60 GeV for all channels; m_{bb} < 150 GeV for $\tau_{lep}\tau_{had}$

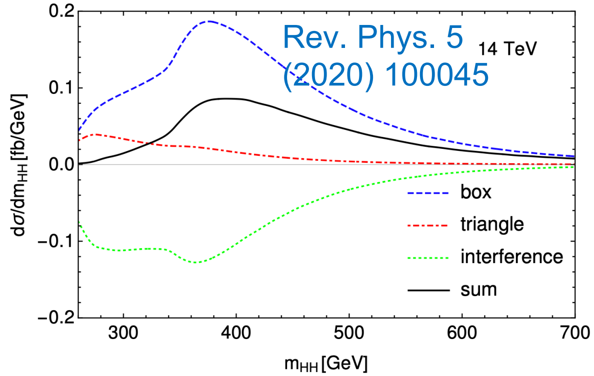
Categorization Strategy

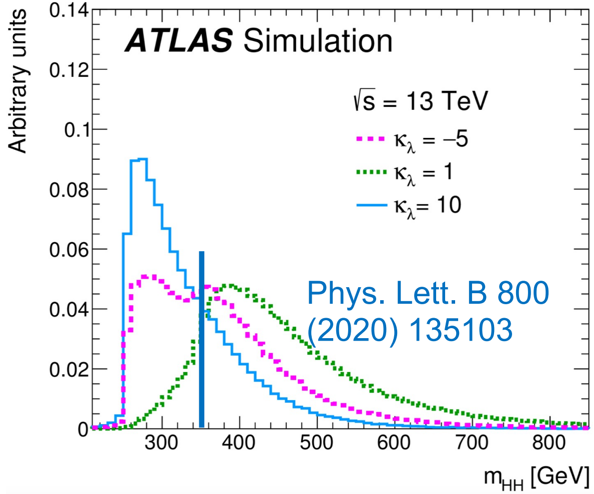


BDT trained on κ_λ=10 ggF signal vs bkg.

BDT trained on SM ggF signal vs bkg.

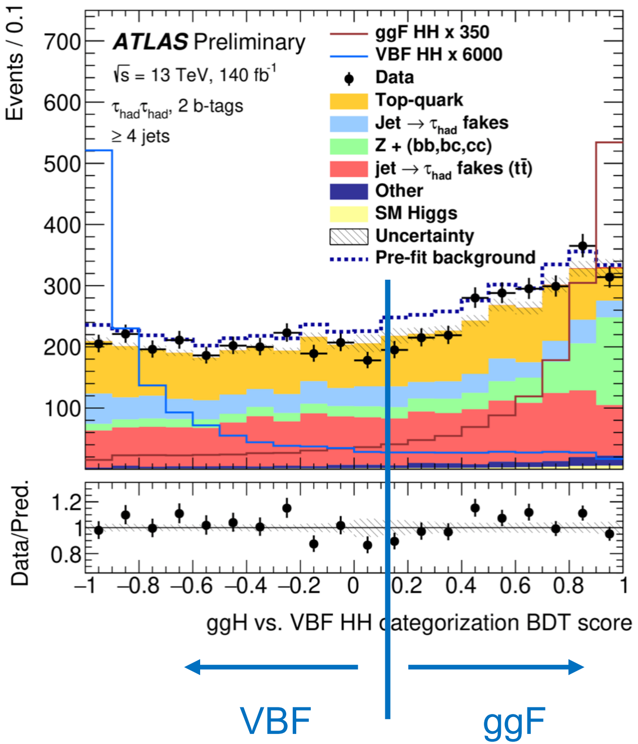
BDT trained on SM VBF signal vs bkg.





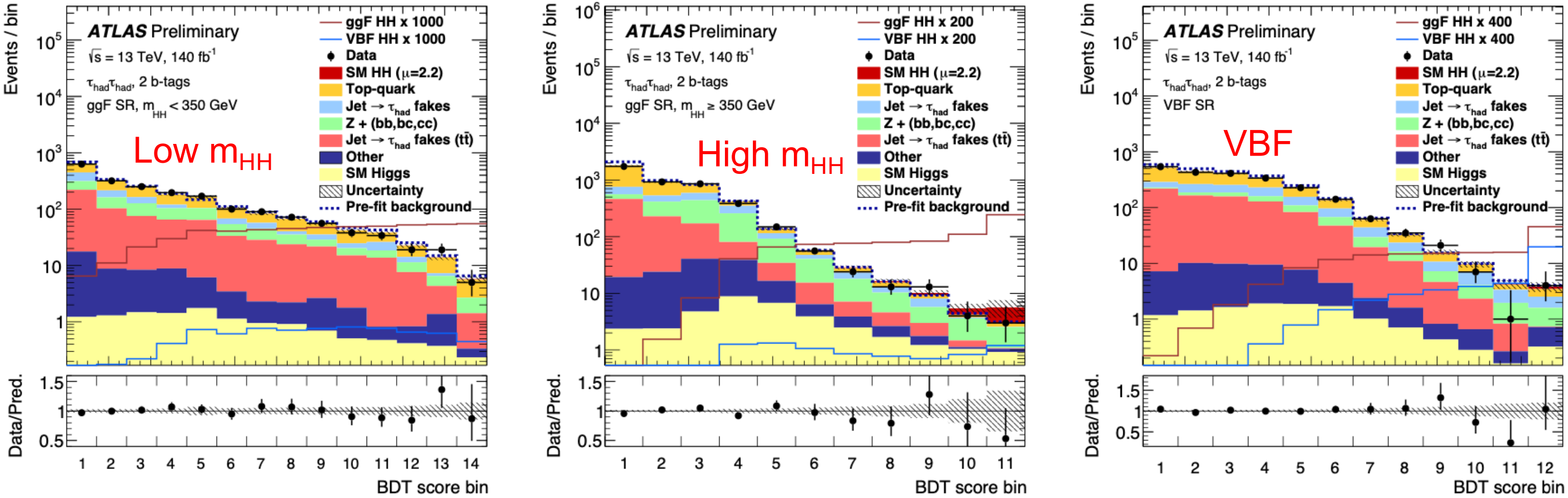
ggF vs VBF Categorization BDT

- BDT trained to separate ggF HH from VBF HH on events with 4 jets (two VBF-jet candidates + two $H \rightarrow bb$)
- Input variables: m_{jj}^{VBF}, ΔR_{jj}^{VBF}, $\eta_{j1} \times \eta_{j2}$, etc
- BDT cuts optimized in each SR to achieve the best limit on HH as well as constraint for κ_λ and κ_{2V}



Discriminant BDTs

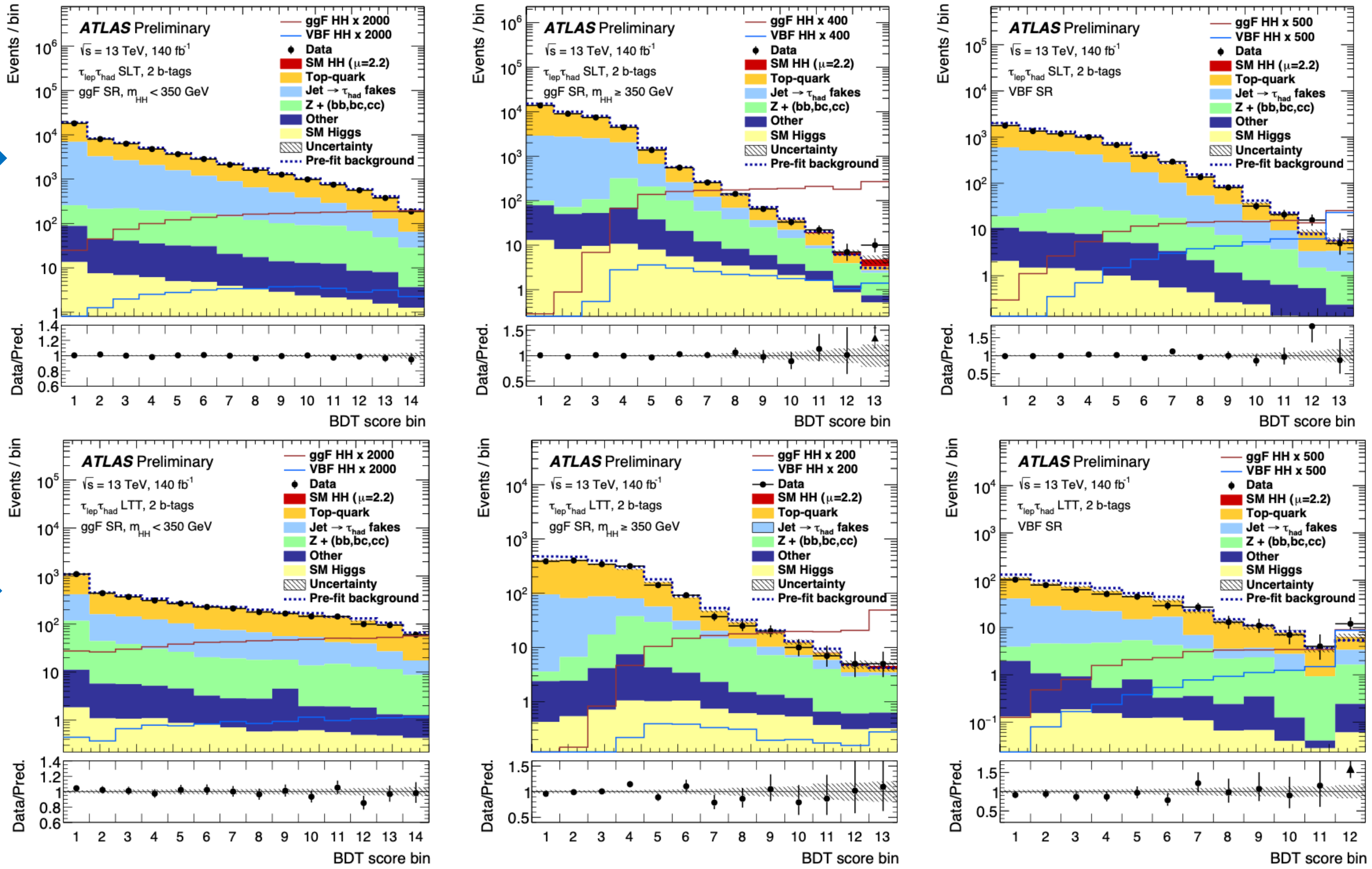
- In each SR, BDTs trained in low m_{HH}, high m_{HH} and VBF categories respectively and used as final discriminants
  - Input variables: m_{HH}, m_{bb}, $m_{\tau\tau}^{MMC}$, $\Delta R(b,b)$, $\Delta R(\tau,\tau)$, E_T^{miss}, etc



Discriminant BDTs in $\tau_{lep}\tau_{had}$

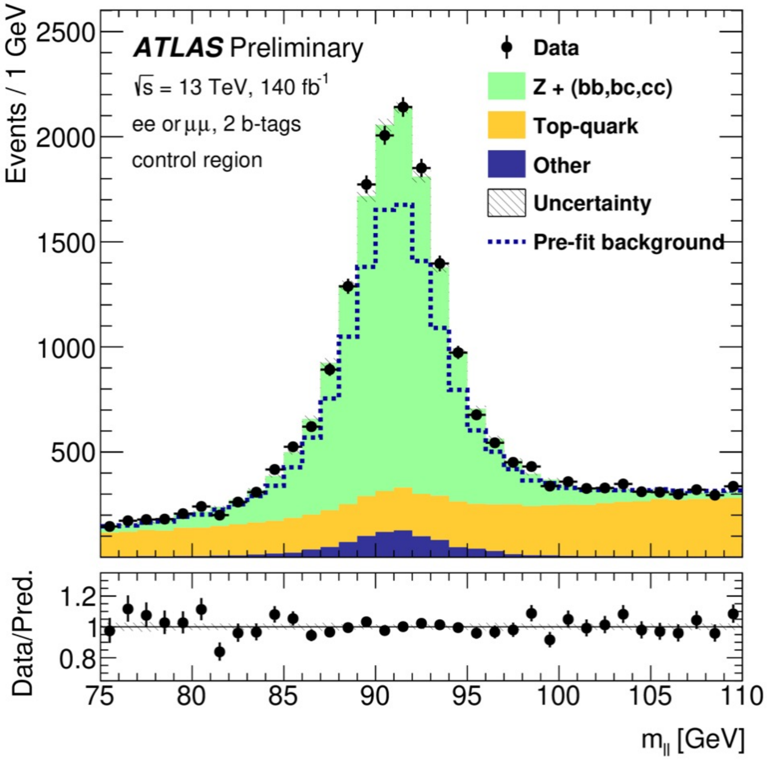
SLT

LTT



Background Estimation

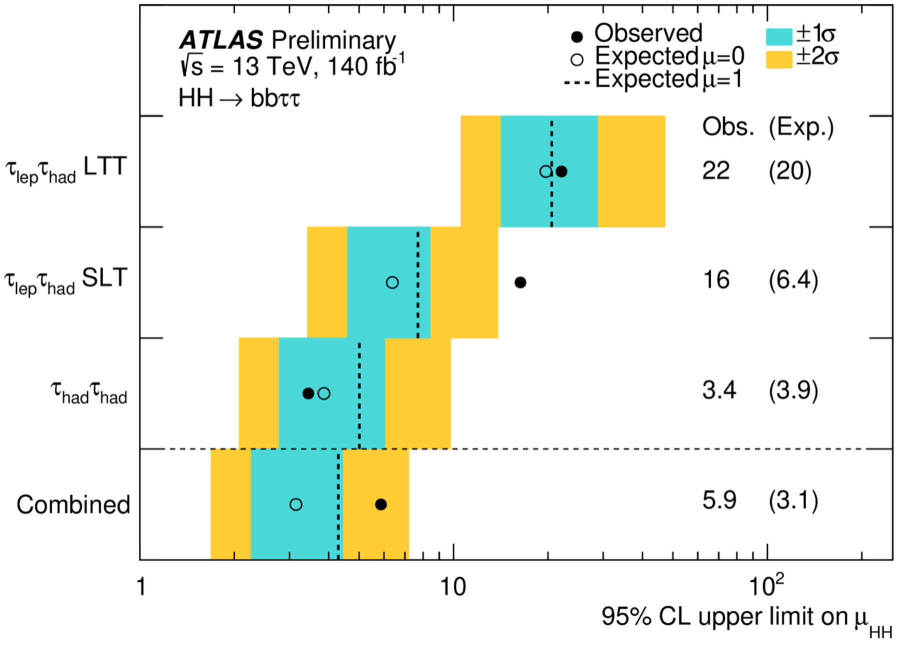
- ttbar and Z+heavy-flavor processes: shape from simulation, normalizations determined from the control region
- Single Higgs and other processes: estimated from simulation
- Jets → fake τ_{had} background: estimated with data-driven approach (including fake factor a.k.a. ABCD method and scale factor method)



Upper Limit on Non-resonant HH XS

[ATLAS-CONF-2023-071]

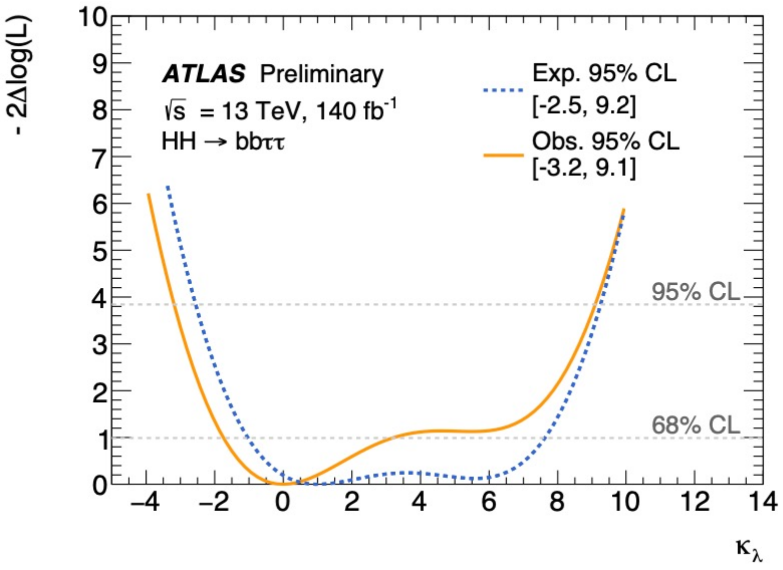
- No significant excess seen above the SM prediction (μ=1)
- Obs. (exp.) limit on HH XS is 5.9 (3.1) × σ_{SM}
  - ➢ The exp. limit represents the best constraint on HH XS in single channel
- Obs. limit higher than exp. due to a statistical fluctuation in the $\tau_{lep}\tau_{had}$ SLT high m_{HH} region

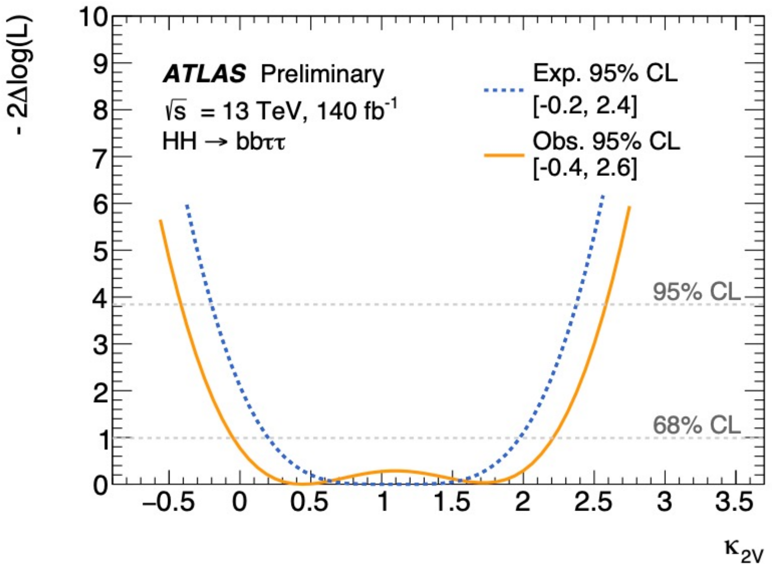


Major uncertainties coming from data/MC statistics as well as theory unc. on top and single Higgs processes

Constraints for κ_λ and κ_{2V}

ATLAS-CONF-2023-071



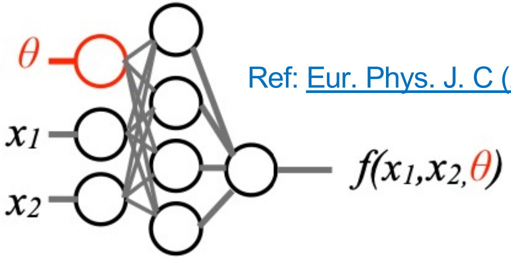


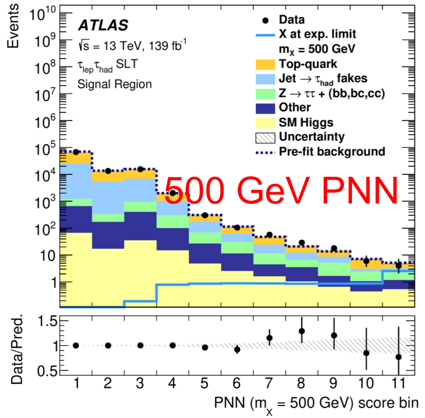
Obs. (exp.) constraint on κ_λ: $-3.2 \leq \kappa_\lambda \leq 9.1$ ($-2.5 \leq \kappa_\lambda \leq 9.2$)

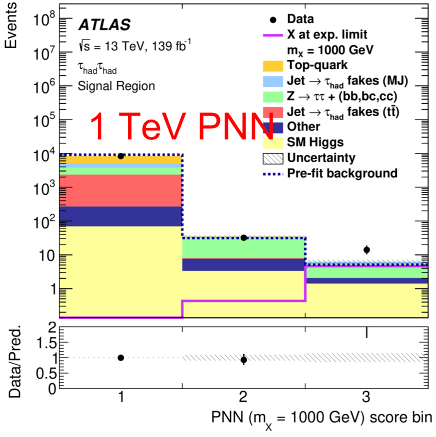
Obs. (exp.) constraint on κ_{2V}: $-0.4 \leq \kappa_\lambda \leq 2.6$ ($-0.2 \leq \kappa_\lambda \leq 2.4$)

Resonant Signal Extraction

Ref: Eur. Phys. J. C (2016) 76:235

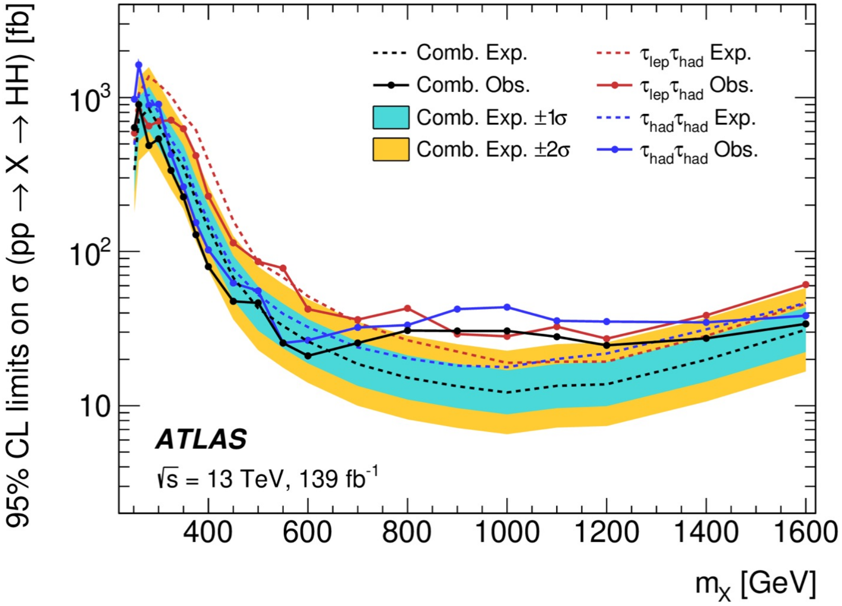






- Parametrized neural networks (PNN) used as discriminant
  - Parametrized in mass of scalar ($\theta = m_X$)
  - Training variables same as non-resonant
- It provides near-optimal sensitivity and continuity over the entire range

Resonant HH→bb$\tau\tau$ Results



JHEP 07 (2023) 040

Obs. (exp.) upper limits: 920-23 fb (840-12 fb) depending on the mass region
Local (global) significance for 1 TeV is 3.0σ (2.0σ)

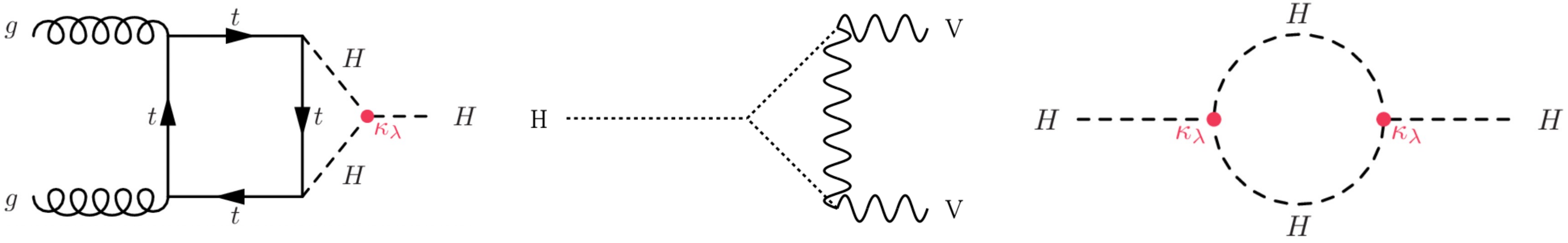
HH(+H) Combination

HH Combination

- Performed statistical combination for different HH decay channels to maximize sensitivity to HH production
- Considered three major channels: HH→bb$\tau\tau$, HH→bb$\gamma\gamma$ and HH→bbbb
- Systematics correlated where appropriate (like luminosity, flavor tagging, signal theory uncertainties, etc)

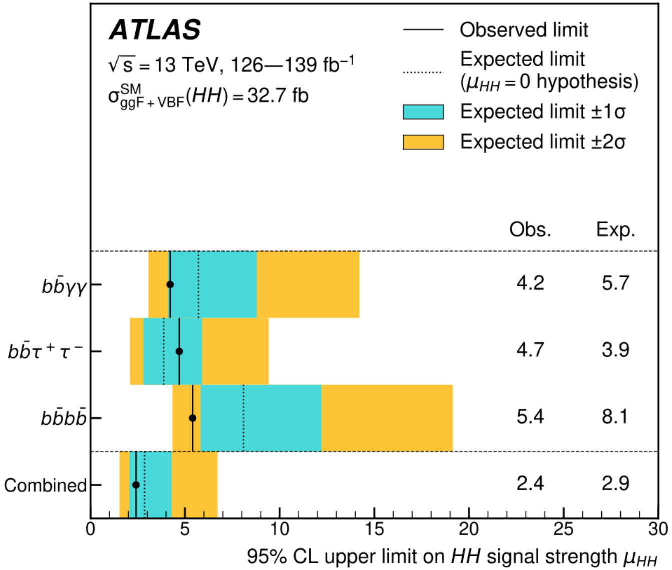
κ_λ Constraint from Single Higgs

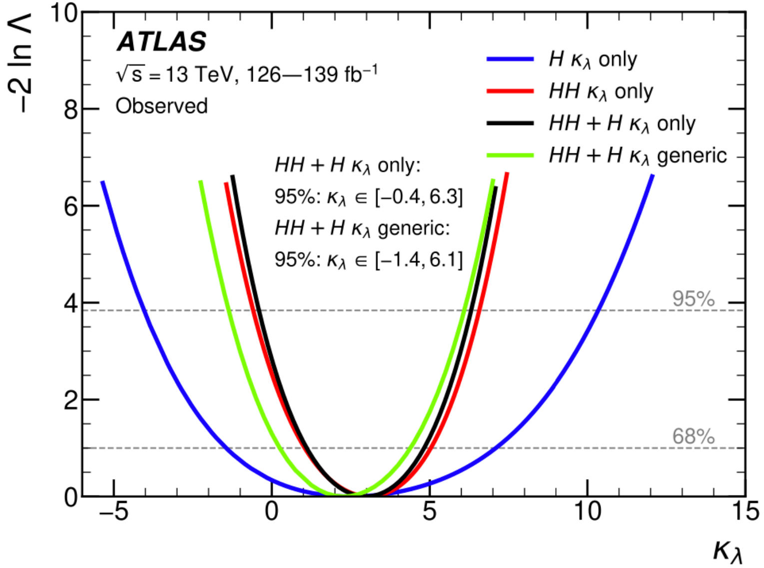
- κ_λ also can be probed through NLO EW correction of single Higgs processes (e.g. in the production, decay, Higgs self-energy)



- Combination of HH and single Higgs is expected to provide the most sensitive results of κ_λ

Results from HH+H Combination





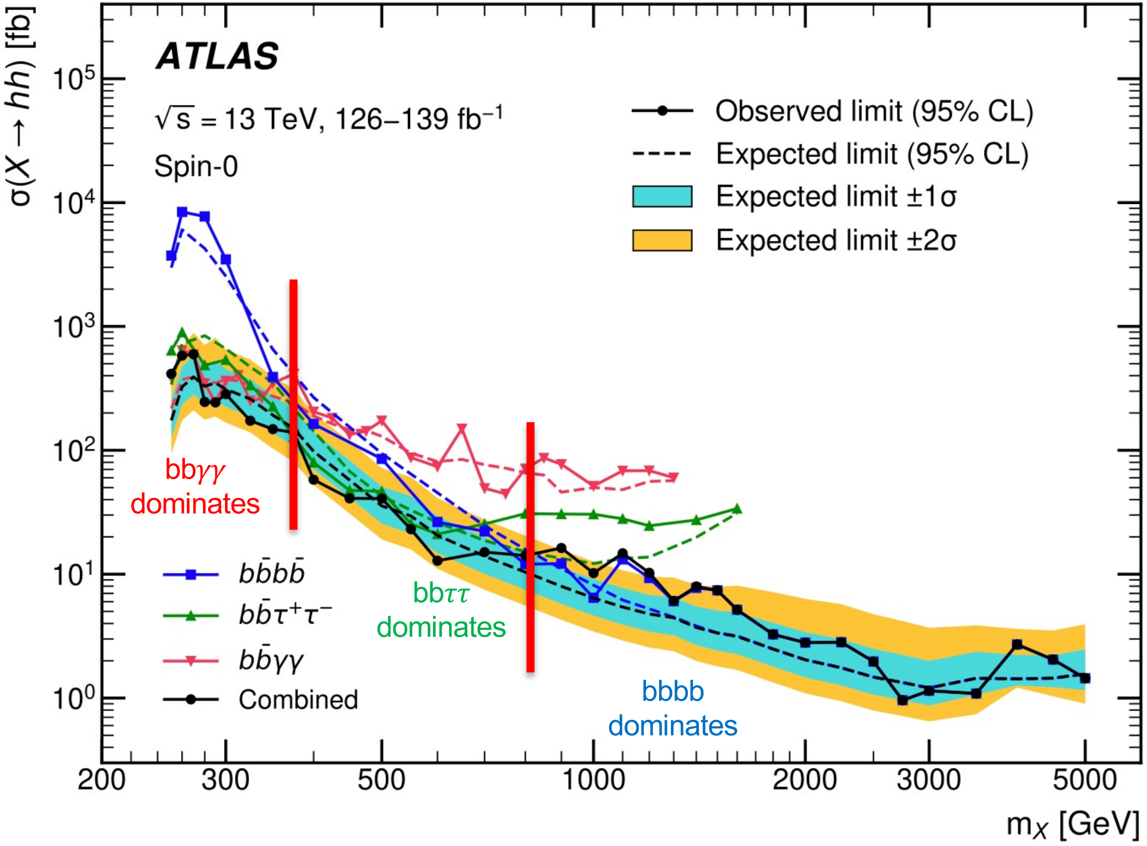
Obs. (exp.) limits: 2.4 (2.9) × σ_{SM}

Obs. (exp.) κ_λ constraint: -0.4 ≤ κ_λ ≤ 6.3 (-1.9 ≤ κ_λ ≤ 7.6)

The best constraints on HH signal strength and κ_λ to date

Phys. Lett. B 843 (2023) 137745

Resonant HH Combination Result



No statistically significant excess found, largest excess at 1.1 TeV: local (global) significance is 3.2σ (2.1σ)

arXiv:2311.15956 (submitted to PRL)

Summary

- Presented the Yukawa couplings and self-coupling studies based on the Run 2 dataset
- The measurements are in line with the SM prediction, and the most stringent results obtained at ATLAS
- The LHC Run 3 is expected to provide more room for exploring the Yukawa couplings and Higgs self-coupling
  - Possible evidence for $H\rightarrow\mu\mu$ at ATLAS, observation combining ATLAS and CMS analyses

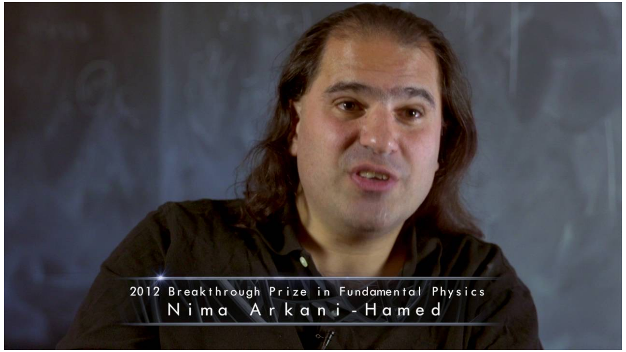
To Be Continued…

Higgs is Really New Physics!

* We've never seen anything like it
* Harbinger of Profound New Principles at work in quantum vacuum

PUT IT UNDER MICROSCOPE

STUDY IT TO DEATH



From Nima Arkani-Hamed

HL-LHC Projection

ATL-PHYS-PUB-2022-053

	Significance [σ]				Combined signal
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination	strength precision [%]
No syst. unc.	2.3	4.0	1.8	4.9	−21/+22
Baseline	2.2	2.8	0.99	3.4	−30/+33
Theoretical unc. halved	1.1	1.7	0.65	2.1	−47/+48
Run 2 syst. unc.	1.1	1.5	0.65	1.9	−53/+65

Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]

We Were Doing Better than Projection

Higgs Pair Production in the $H(\to \tau\tau)H(\to b\bar{b})$ channel at the High-Luminosity LHC

ATL-PHYS-PUB-2015-046

ing SM background and SM signal, we expect to set an upper limit of the cross section for the di-Higgs production of $4.3 \times \sigma(HH \to b\bar{b}\tau^+\tau^-)$ at 95% Confidence Level. Using an effective Lagrangian for the Higgs potential, and allowing its trilinear self-coupling to vary, we can project an exclusion of $\lambda_{HHH}/\lambda_{SM} \leq -4$ and $\lambda_{HHH}/\lambda_{SM} \geq 12$.

We Were Doing Better than Projection

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ATL-PHYS-PUB-2015-046

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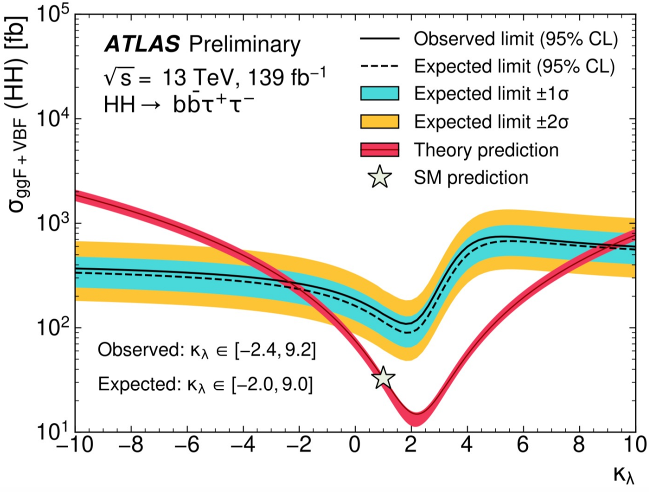
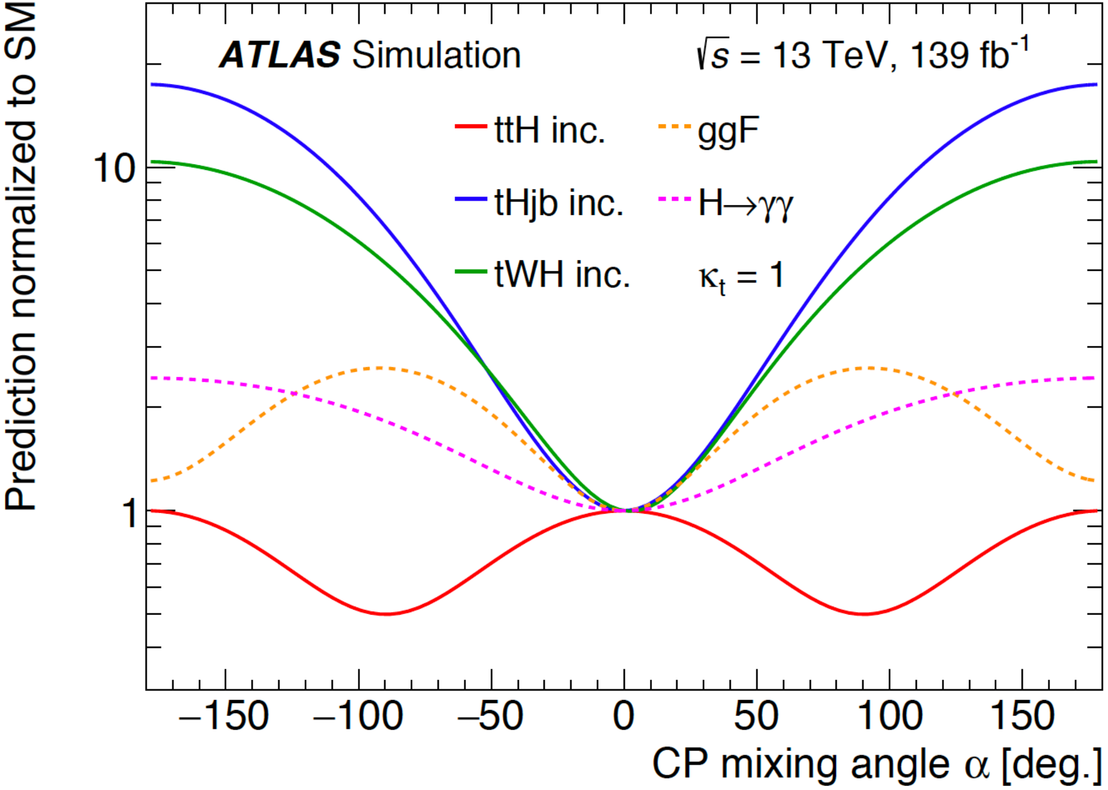


Obs. (exp.) limit on HH: 4.7 (3.9) × σ_{SM}

Obs. (exp.) κ_λ constraint: $-2.4 \leq \kappa_\lambda \leq 9.2$ ($-2.0 \leq \kappa_\lambda \leq 9.0$)

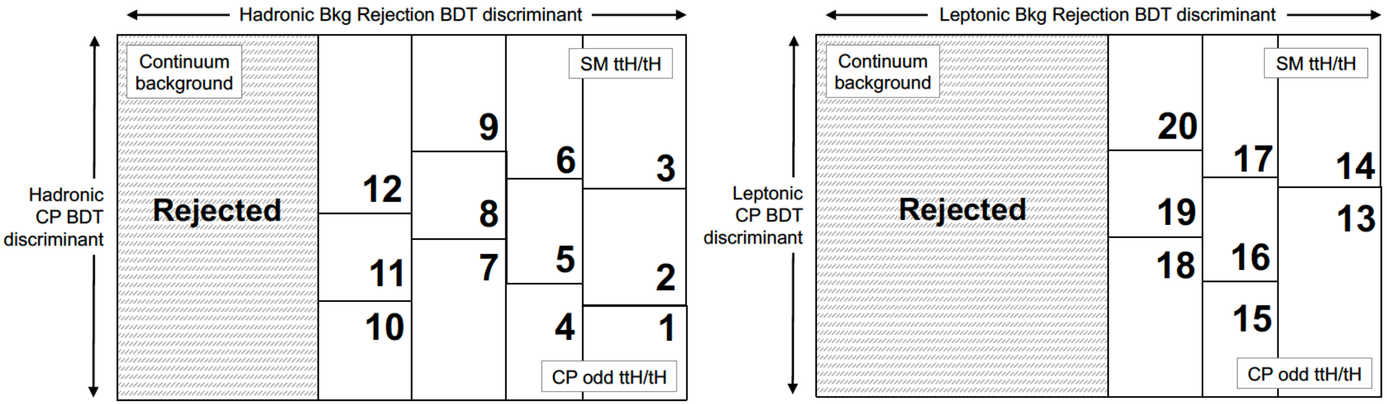
The HL-LHC projection (3 ab^{-1}) in 2015 was surpassed with just 139 fb^{-1} data

Backup

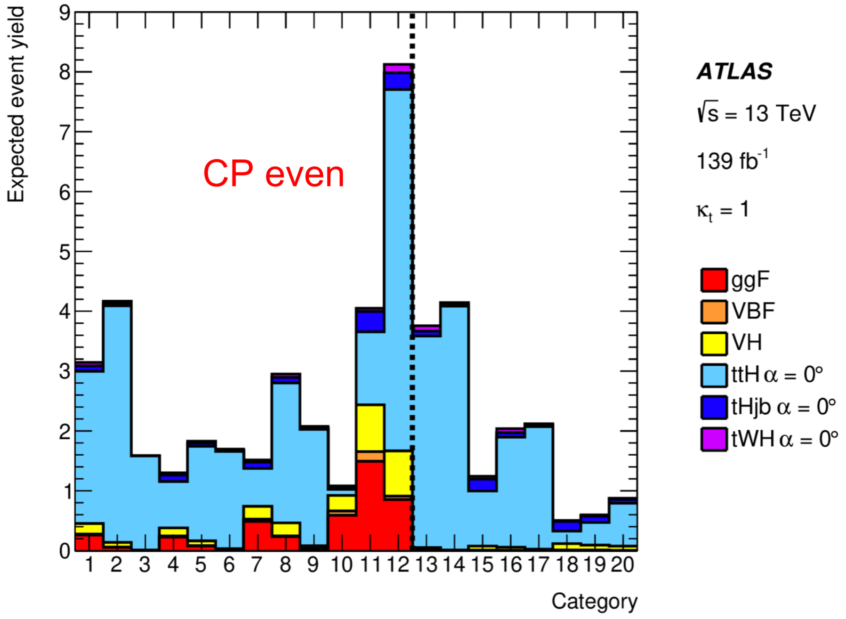

ATLAS Simulation
√s = 13 TeV, 139 fb-1
ttH inc.
ggF
tHjb inc.
H→γγ
tWH inc.
κt = 1
Prediction normalized to SM
10
1
−150
−100
−50
0
50
100
150
CP mixing angle α [deg.]

Event Categorization

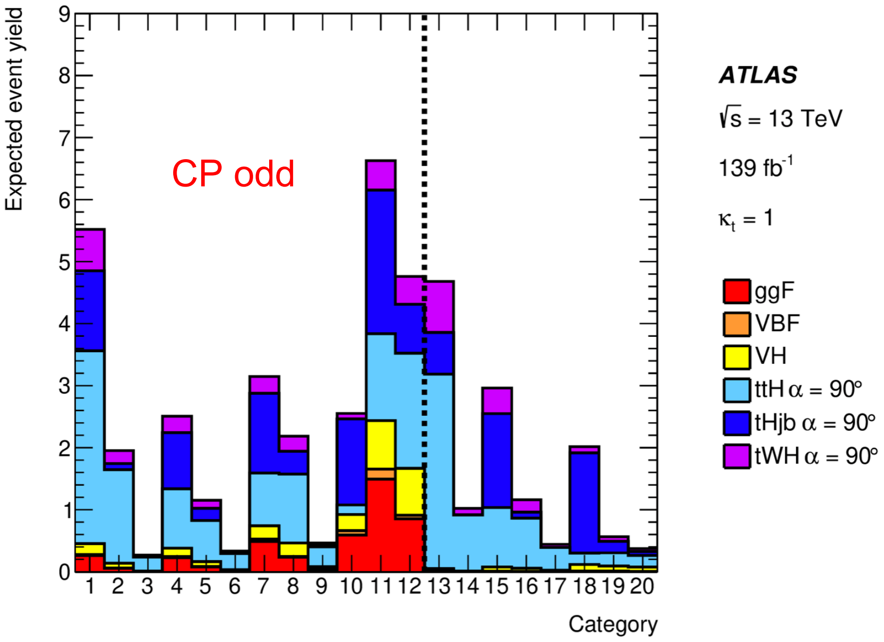
- Categorization is done in Had and Lep regions separately



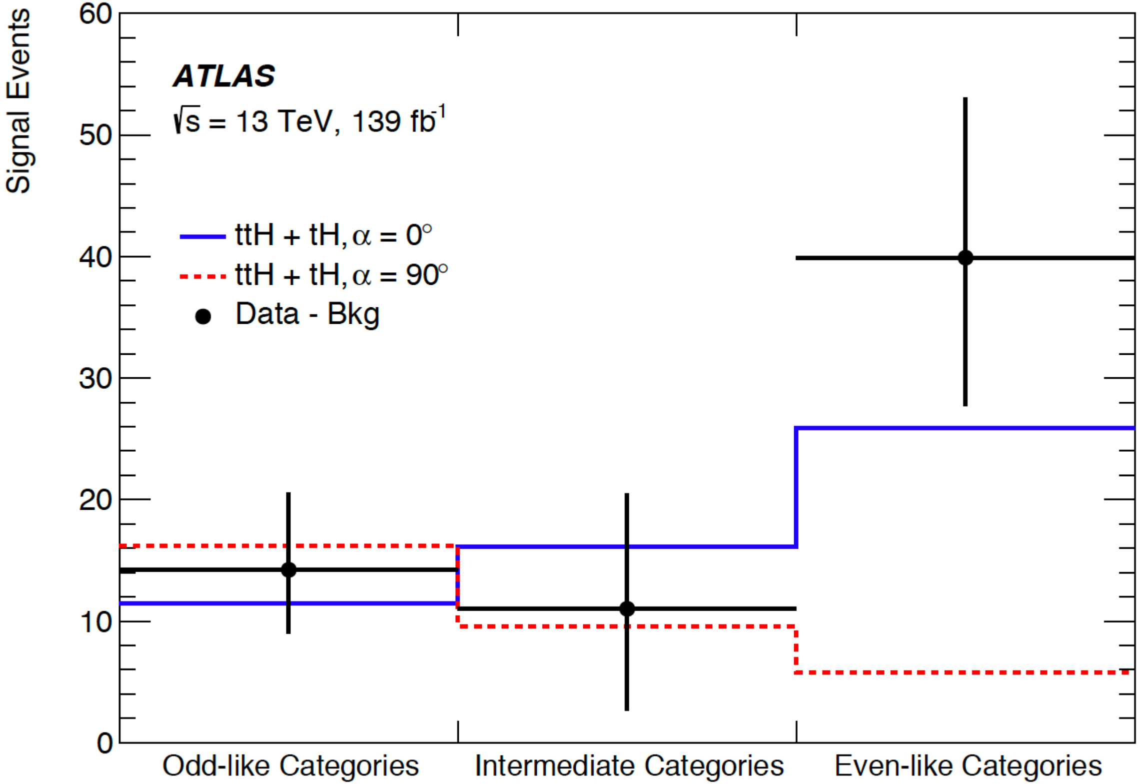
- The boundaries are chosen to achieve a strong separation between CP-even and CP-odd signals, as well as a good sensitivity to ttH process



CP even
Expected event yield
Category
ATLAS
√s = 13 TeV
139 fb-1
κt = 1
ggF
VBF
VH
ttH α = 0°
tHjb α = 0°
tWH α = 0°

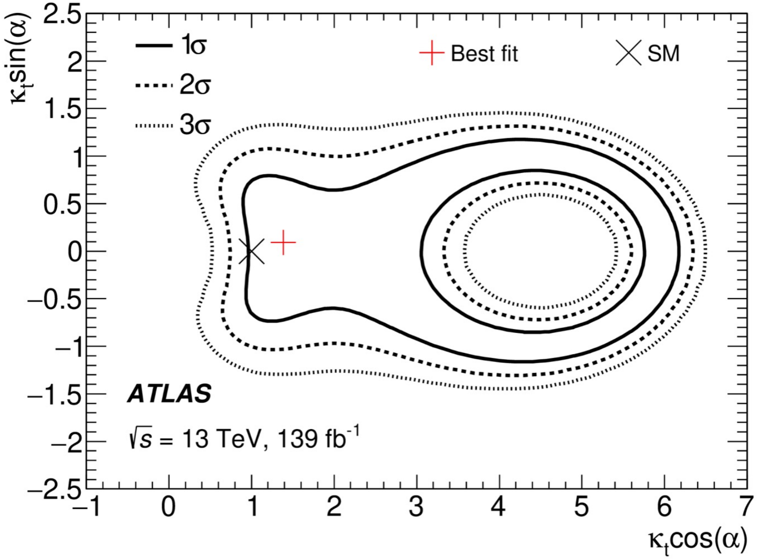


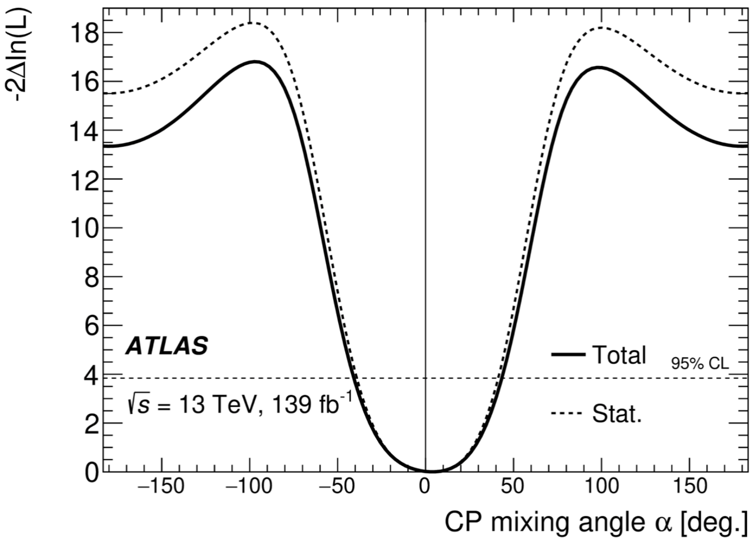
CP odd
Expected event yield
Category
ATLAS
√s = 13 TeV
139 fb-1
κt = 1
ggF
VBF
VH
ttH α = 90°
tHjb α = 90°
tWH α = 90°


ATLAS
√s = 13 TeV, 139 fb-1
ttH + tH, α = 0°
ttH + tH, α = 90°
Data - Bkg
Signal Events
0
10
20
30
40
50
60
Odd-like Categories
Intermediate Categories
Even-like Categories

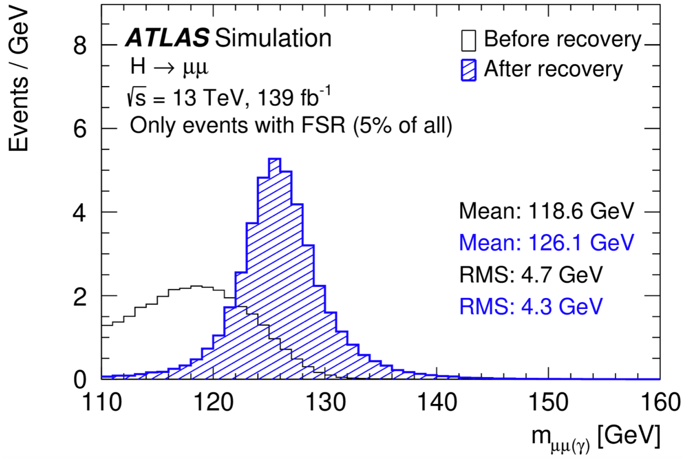
$$c_g^2 = \mu_{gg} \simeq \kappa_t^2 + 2.6\tilde{\kappa}_t^2 + 0.11\kappa_t(\kappa_t - 1)\,,$$
$$c_\gamma^2 = \mu_{\gamma\gamma} \simeq (1.28 - 0.28\kappa_t)^2 + (0.43\tilde{\kappa}_t)^2\,.$$

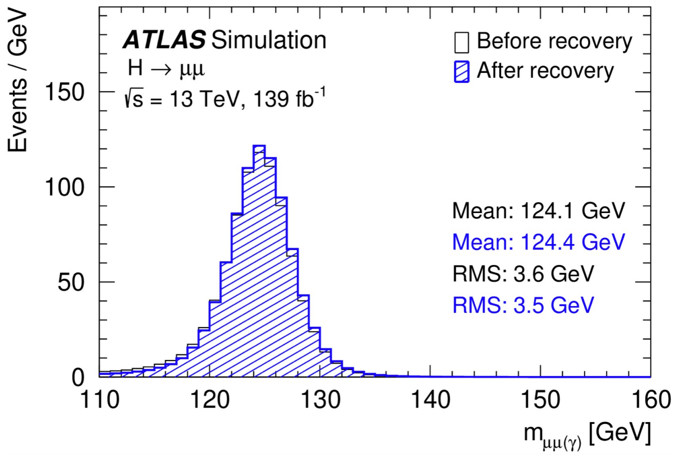
JHEP 04 (2014) 004





H→μμ: FSR Recovery





Categorization Performance (1)

Category	Data	S_{SM}	S	B	$S/\sqrt{B}$	S/B [%]	σ [GeV]
VBF Very High	15	2.81 ± 0.27	3.3 ± 1.7	14.5 ± 2.1	0.86	22.6	3.0
VBF High	39	3.46 ± 0.36	4.0 ± 2.1	32.5 ± 2.9	0.71	12.4	3.0
VBF Medium	112	4.8 ± 0.5	5.6 ± 2.8	85 ± 4	0.61	6.6	2.9
VBF Low	284	7.5 ± 0.9	9 ± 4	273 ± 8	0.53	3.2	3.0
2-jet Very High	1030	17.6 ± 3.3	21 ± 10	1024 ± 22	0.63	2.0	3.1
2-jet High	5433	50 ± 8	58 ± 30	5440 ± 50	0.77	1.0	2.9
2-jet Medium	18 311	79 ± 15	90 ± 50	18 320 ± 90	0.66	0.5	2.9
2-jet Low	36 409	63 ± 17	70 ± 40	36 340 ± 140	0.37	0.2	2.9
1-jet Very High	1097	16.5 ± 2.4	19 ± 10	1071 ± 22	0.59	1.8	2.9
1-jet High	6413	46 ± 7	54 ± 28	6320 ± 50	0.69	0.9	2.8
1-jet Medium	24 576	90 ± 11	100 ± 50	24 290 ± 100	0.67	0.4	2.7
1-jet Low	73 459	125 ± 17	150 ± 70	73 480 ± 190	0.53	0.2	2.8
0-jet Very High	15 986	59 ± 11	70 ± 40	16 090 ± 90	0.55	0.4	2.6
0-jet High	46 523	99 ± 13	120 ± 60	46 190 ± 150	0.54	0.3	2.6
0-jet Medium	91 392	119 ± 14	140 ± 70	91 310 ± 210	0.46	0.2	2.7
0-jet Low	121 354	79 ± 10	90 ± 50	121 310 ± 280	0.26	0.1	2.7
VH4L	34	0.53 ± 0.05	0.6 ± 0.3	24 ± 4	0.13	2.6	2.9
VH3LH	41	1.45 ± 0.14	1.7 ± 0.9	41 ± 5	0.27	4.2	3.1
VH3LM	358	2.76 ± 0.24	3.2 ± 1.6	347 ± 15	0.17	0.9	3.0
$t\bar{t}H$	17	1.19 ± 0.13	1.4 ± 0.7	15.1 ± 2.2	0.36	9.2	3.2

Calculated in the 120-130GeV region

Major sensitive ones are VBF, ggF 2-jet and 1-jet categories

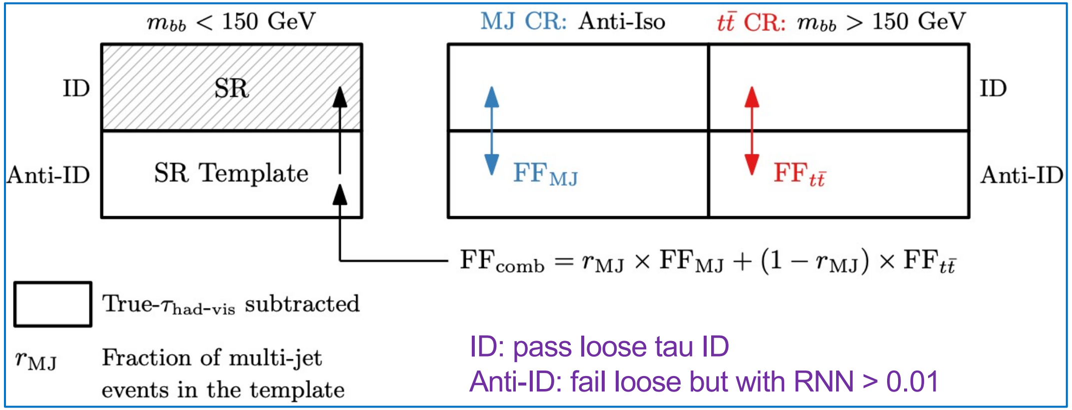
Background Model Selection Criteria

- $P(\chi 2) > 1\%$ for background only fits with
  - Data sideband
  - Full simulation
  - Fast simulation (before and after reweighing to the data sidebands)
- SS within 20% of the signal statistical unc. normalized to data statistics
- Smallest degree of freedom
- Smallest SS value

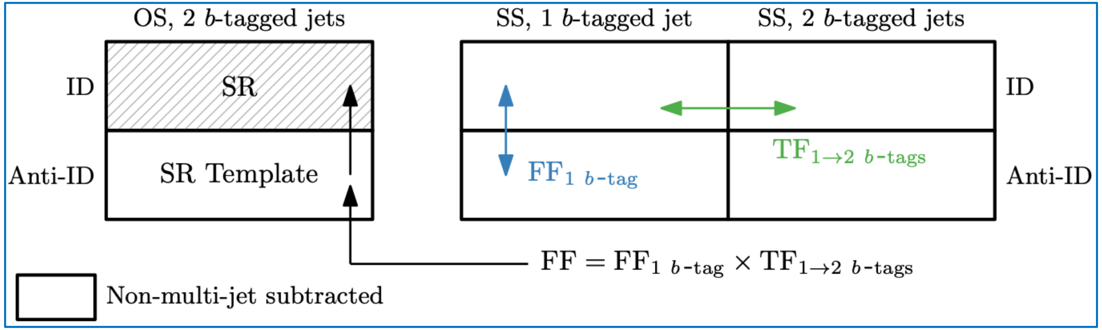
In the order of priority decreasing

Fake Factor Method

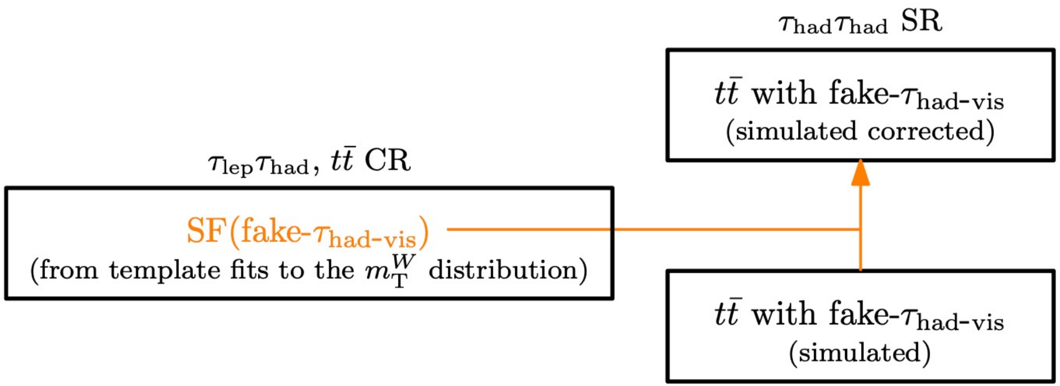
Combined FFs derived for ttbar and multi-jet in $\tau_{lep}\tau_{had}$



FF method used for multi-jet in $\tau_{had}\tau_{had}$



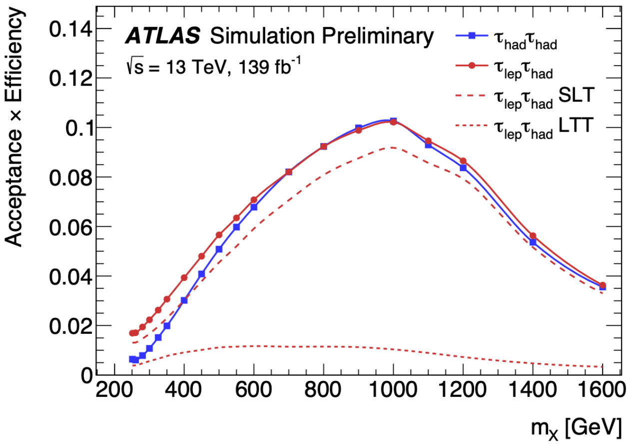
Scale Factor Method in $\tau_{had}\tau_{had}$



- Fake τ_{had} from ttbar in $\tau_{had}\tau_{had}$ channel estimated using simulation
- SFs used to correct τ_{had} misidentification eff.: determined by fitting m_T^W distribution of MC to data in ttbar CR of $\tau_{lep}\tau_{had}$ SLT category
  - 1 prong: close to 1 below 40 GeV, ~0.6 above 70 GeV
  - 3 prong: ~20% larger than the 1 prong SFs

Signal Acceptance × Efficiency

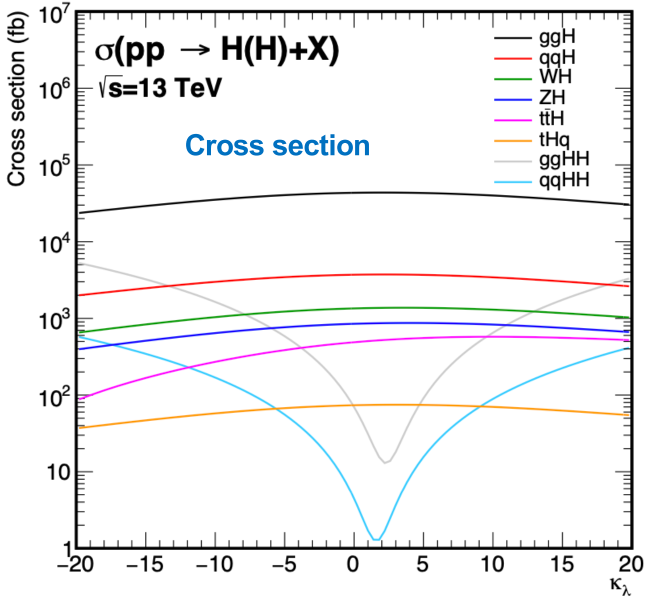
- The acceptance times efficiency for the non-resonant ggF+VBF evaluated w.r.t. targeted τ decay modes
  - $\tau_{had}\tau_{had}$: 4.0%, $\tau_{lep}\tau_{had}$ SLT: 4.0%, $\tau_{lep}\tau_{had}$ LTT: 1.0%
- Around factor 2 improvement on signal acceptance compared with previous publication*
- Driven by improved reconstruction and identification of τ_{had} and b-jets**

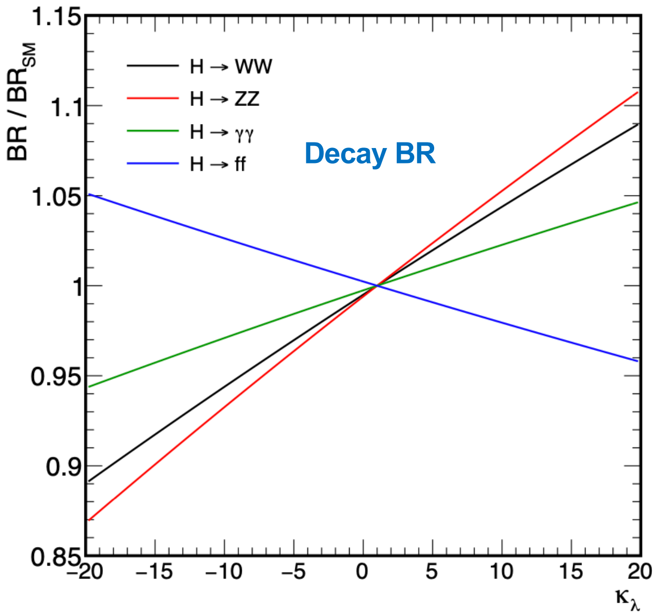


*Phys. Rev. Lett. 121, 191801

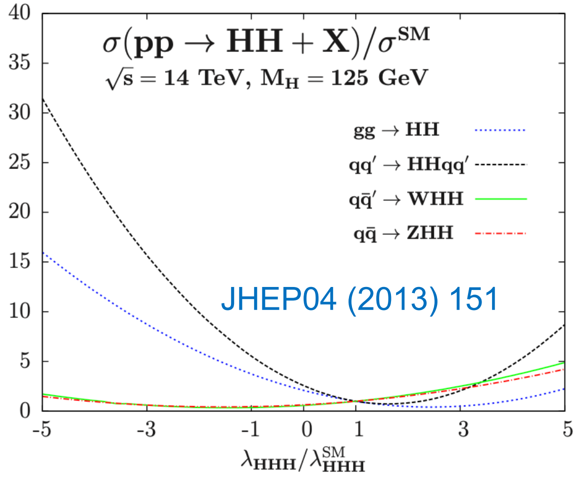
**ATL-PHYS-PUB-2017-003, ATL-PHYS-PUB-2017-013, ATL-PHYS-PUB-2019-033

κ_λ-dependence of XS and BR

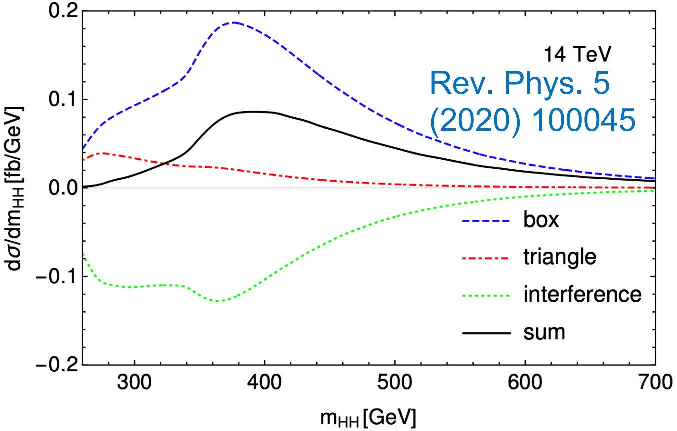


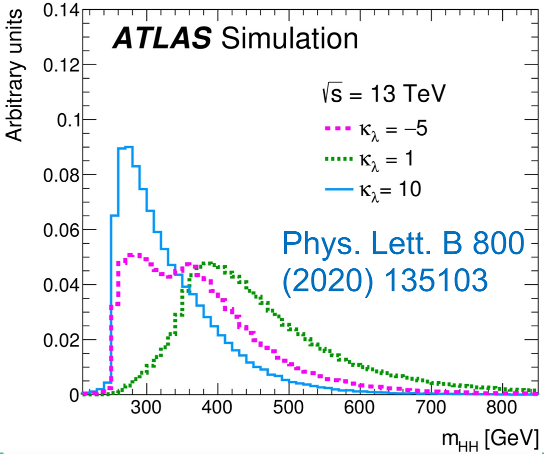


BSM Physics in HH Processes

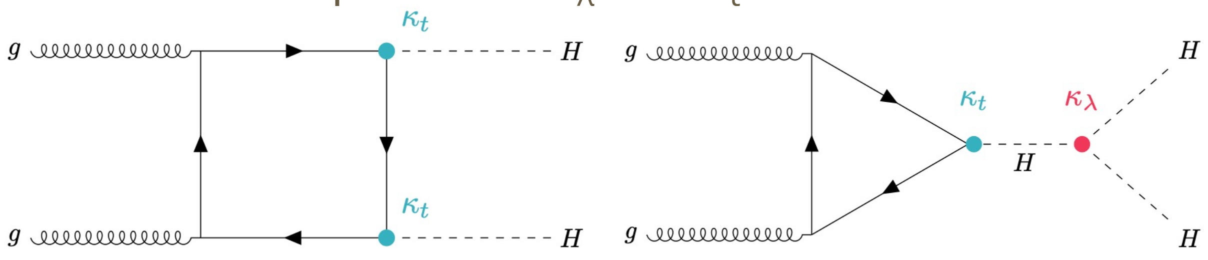


Anomalous κ_λ would result in enhanced HH XS and modified kinematics of the process due to different contributions and interference of diagrams



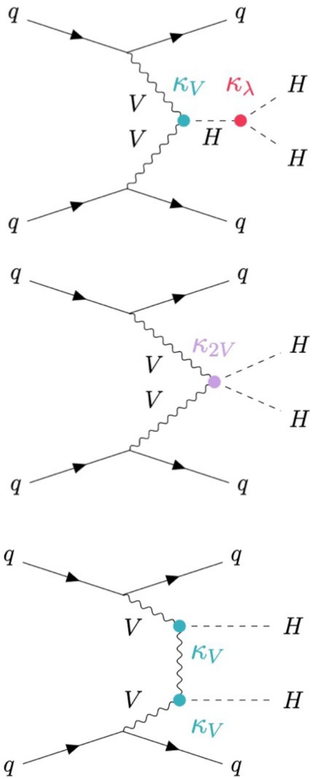


- ggF HH cross section depends on κ_λ and κ_t



- Any (κ_λ , κ_t) can be obtained via a linear combination of three basis samples at different κ_λ values with κ_t = 1

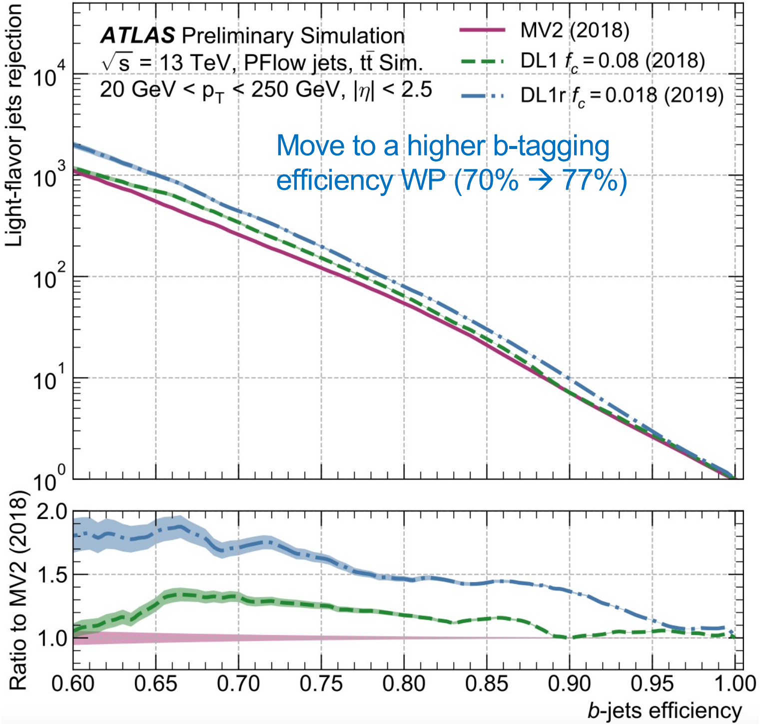
$$\text{sample}(\kappa_\lambda, \kappa_t) = \kappa_t^2 \left[\left(\kappa_t^2 + \frac{\kappa_\lambda^2}{20} - \frac{399}{380}\kappa_\lambda\kappa_t \right) \cdot \text{sample}(0,1) + \left(\frac{40}{38}\kappa_\lambda\kappa_t - \frac{2}{38}\kappa_\lambda^2 \right) \cdot \text{sample}(1,1) + \left(\frac{\kappa_\lambda^2 - \kappa_\lambda\kappa_t}{380} \right) \cdot \text{sample}(20,1) \right]$$



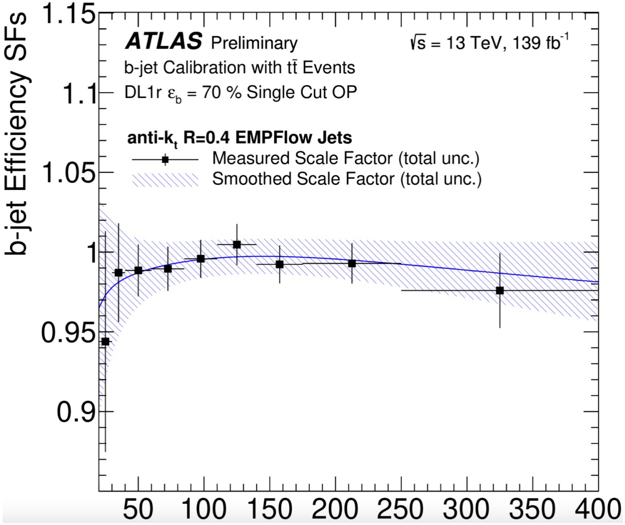
- VBF HH XS depends on κ_{2V}, κ_λ and κ_V
- A linear combination of 6 samples with different (κ_{2V}, κ_λ, κ_V) values
- Rank 1 basis used

$$
\begin{aligned}
&\left(\frac{\kappa_{2V}^2}{5} - \frac{\kappa_{2V}\kappa_V^2}{5} - \frac{\kappa_{2V}\kappa_V\kappa_\lambda}{10} + \frac{\kappa_V^3\kappa_\lambda}{10}\right) \times \sigma(3,1,1) + \\
&\left(\frac{4\kappa_{2V}^2}{5} - \frac{4\kappa_{2V}\kappa_V^2}{5} - \frac{12\kappa_{2V}\kappa_V\kappa_\lambda}{5} + \frac{12\kappa_V^3\kappa_\lambda}{5}\right) \times \sigma\left(\frac{1}{2},1,1\right) + \\
&\left(-\frac{5\kappa_{2V}\kappa_V^2}{4} + \frac{5\kappa_{2V}\kappa_V\kappa_\lambda}{4} + \frac{\kappa_V^3\kappa_\lambda}{8} - \frac{\kappa_V^2\kappa_\lambda^2}{8}\right) \times \sigma(1,2,1) + \\
&\left(-\kappa_{2V}\kappa_V^2 + \kappa_{2V}\kappa_V\kappa_\lambda + \kappa_V^4 - \kappa_V^3\kappa_\lambda\right) \times \sigma(0,0,1) + \\
&\left(\frac{\kappa_{2V}\kappa_V^2}{36} - \frac{\kappa_{2V}\kappa_V\kappa_\lambda}{36} - \frac{\kappa_V^3\kappa_\lambda}{72} + \frac{\kappa_V^2\kappa_\lambda^2}{72}\right) \times \sigma(1,10,1) + \\
&\left(-\kappa_{2V}^2 + \frac{29\kappa_{2V}\kappa_V^2}{9} + \frac{5\kappa_{2V}\kappa_V\kappa_\lambda}{18} - \frac{29\kappa_V^3\kappa_\lambda}{18} + \frac{\kappa_V^2\kappa_\lambda^2}{9}\right) \times \sigma(1,1,1)
\end{aligned}
$$

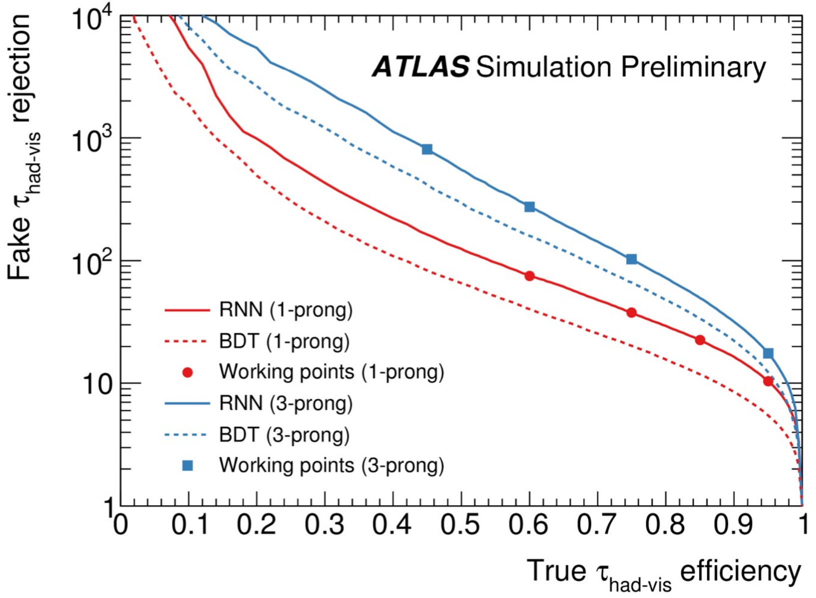
Flavor Tagging Improvement



Likelihood-based calibration provides >2x reduction in uncertainties



τ Identification Improvement



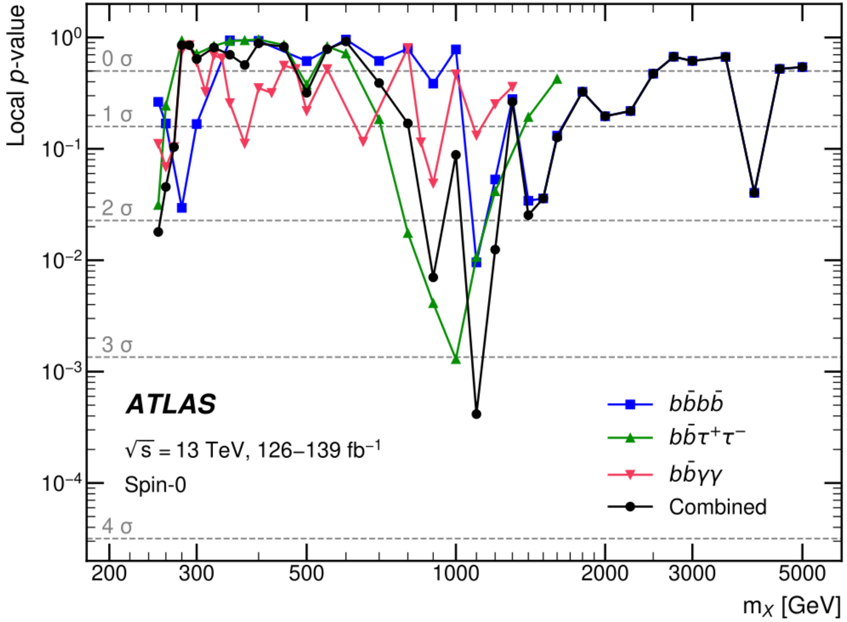
RNN ID shows 2x improvement compared with BDT

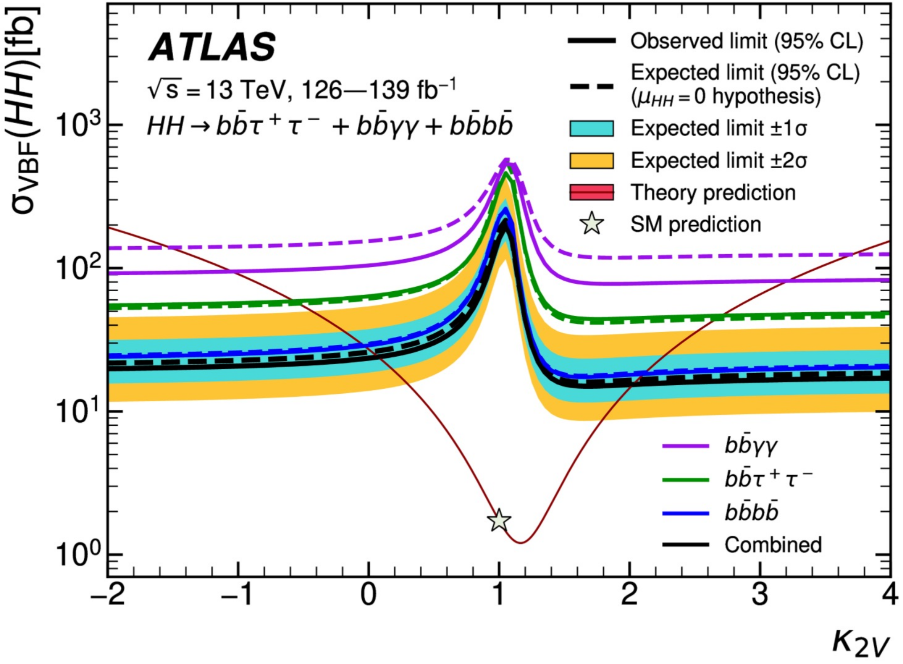
Moved from “medium” to “loose” WP

Per-tau efficiency:

1-prong: 75% → 85%

3-prong: 60% → 75%


ATLAS
√s = 13 TeV, 126–139 fb⁻¹
Spin-0
Local p-value
m_X [GeV]
0 σ
1 σ
2 σ
3 σ
4 σ
bb̄bb̄
bb̄τ⁺τ⁻
bb̄γγ
Combined


ATLAS
√s = 13 TeV, 126—139 fb⁻¹
HH → bb̄τ⁺τ⁻ + bb̄γγ + bb̄bb̄
Observed limit (95% CL)
Expected limit (95% CL)
(μ_HH = 0 hypothesis)
Expected limit ±1σ
Expected limit ±2σ
Theory prediction
SM prediction
bb̄γγ
bb̄τ⁺τ⁻
bb̄bb̄
Combined
σ_VBF(HH)[fb]
κ_2V