Searching for pair production of Higgs bosons in the $b\bar{b}\tau^+\tau^-$ final state with the ATLAS detector

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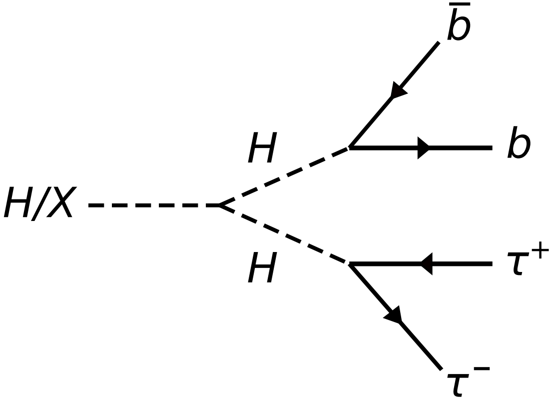
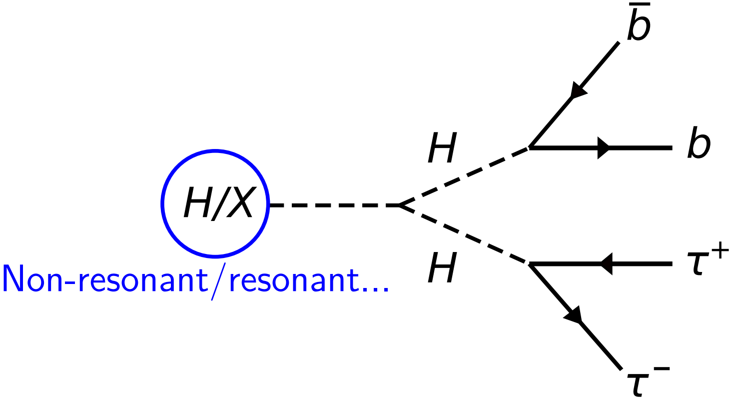
Uppsala University, Georg-August-Universität Göttingen
supervisors: Arnaud Ferrari, Stan Lai

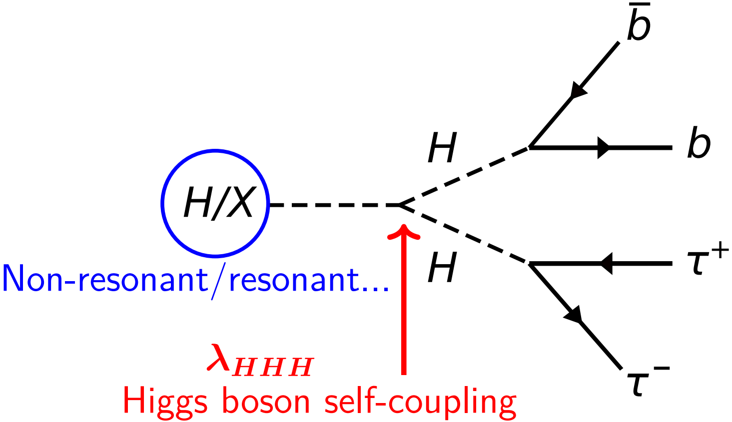
Final PhD Seminar – April 23, 2020

Outline...





Non-resonant/resonant...

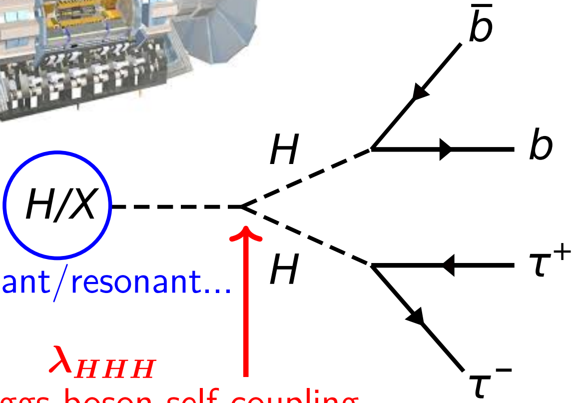


Non-resonant/resonant...

$\boldsymbol{\lambda}_{HHH}$

Higgs boson self-coupling

Experimental setup



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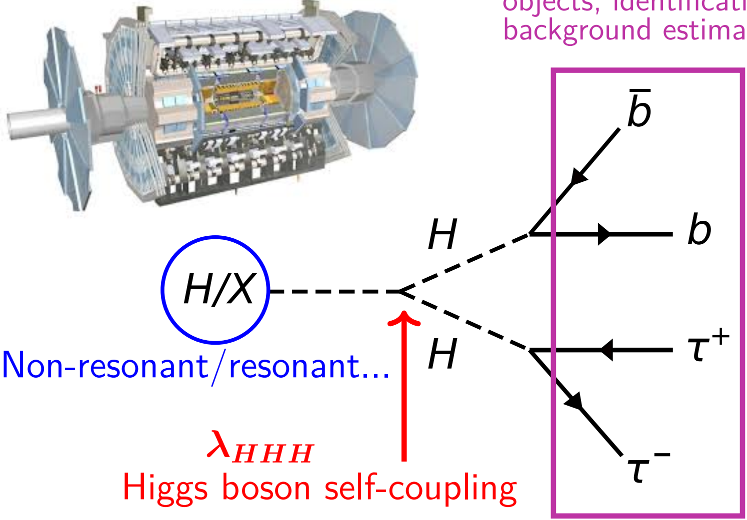
Experimental setup

$bb\tau\tau$ final state
objects, identification,
background estimation, ...



Non-resonant/resonant...

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Higgs boson self-coupling

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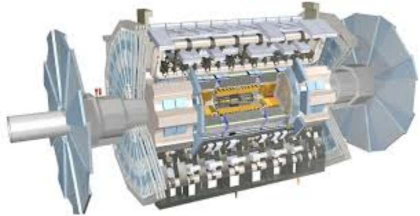

$bb\tau\tau$ final state

objects, identification,
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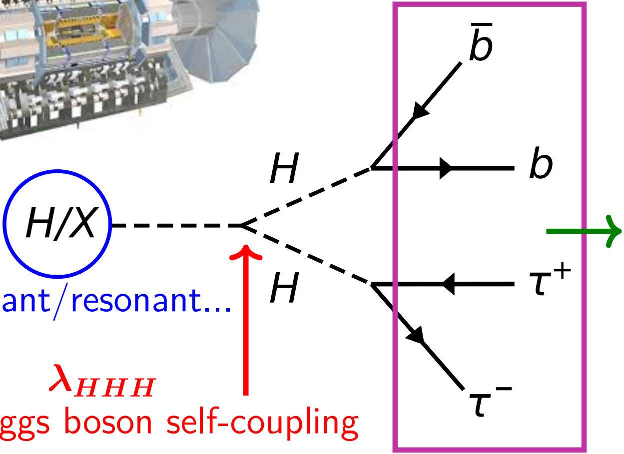

Non-resonant/resonant...

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Signal extraction
Multivariate Analysis (MVA)

Experimental setup

$bb\tau\tau$ final state

objects, identification,
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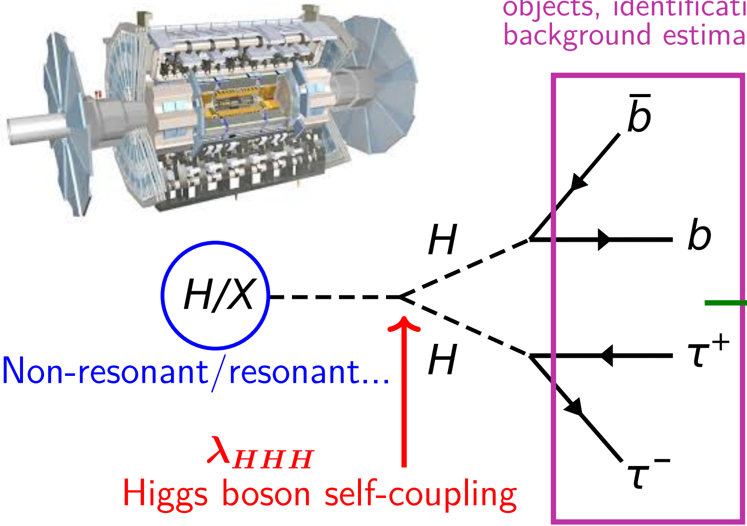
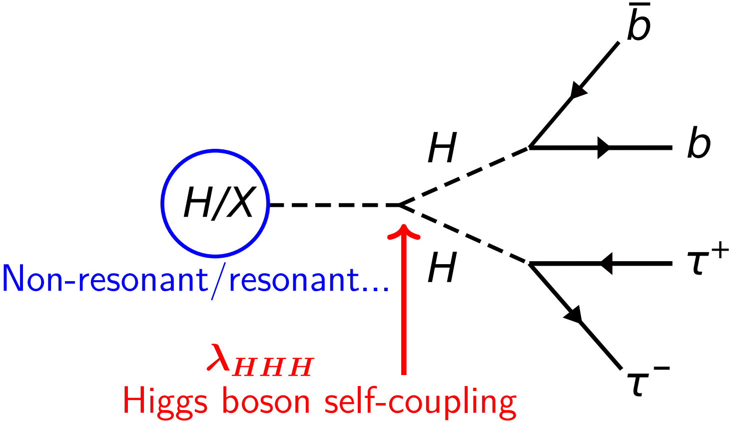


Non-resonant/resonant...

λ_{HHH}
Higgs boson self-coupling

→ Signal extraction
Multivariate Analysis (MVA)

⟶ Results, more results, near and far future...



Non-resonant/resonant...

λ_{HHH}

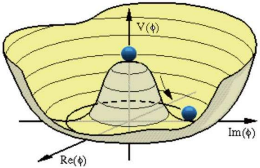
Higgs boson self-coupling

Higgs potential

- Important to measure the shape of the Higgs potential

$$V(\phi) = -\mu^2(\Phi^\dagger\Phi) + \frac{1}{4}\lambda(\Phi^\dagger\Phi)^2$$

arXiv:1201.6045

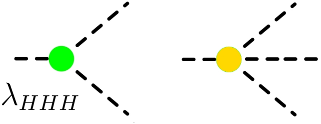


Expanding about minimum: $V(\Phi) \to V\left(\begin{smallmatrix}0\\ v+H\end{smallmatrix}\right)$

$$V = V_0 + \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4 + \dots$$

$$= V_0 + \frac{1}{2}m_H^2 H^2 + \frac{m_H^2}{2v^2} v H^3 + \frac{1}{4}\frac{m_H^2}{2v^2} H^4 + \dots$$

mass term HH-production HHH-production



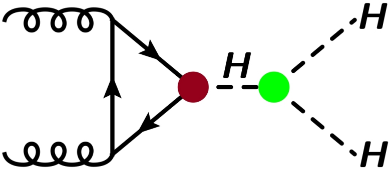
Standard Model (SM):

$$v = \frac{\mu}{\sqrt{\lambda}} = 246\,\mathrm{GeV}$$

$$\lambda = \frac{m_h^2}{2v^2} \approx 0.13$$

SM Higgs boson pair production at the LHC

1 SM Higgs boson pair production (gluon-gluon fusion - ggF):



Higgs boson self-coupling

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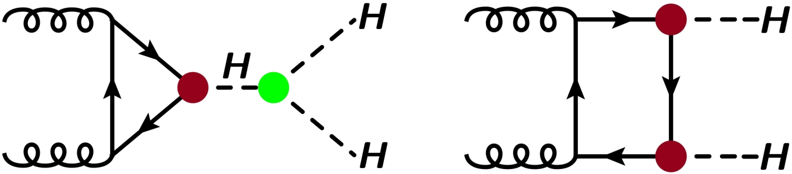


Higgs boson self-coupling

Higgs-fermion Yukawa coupling

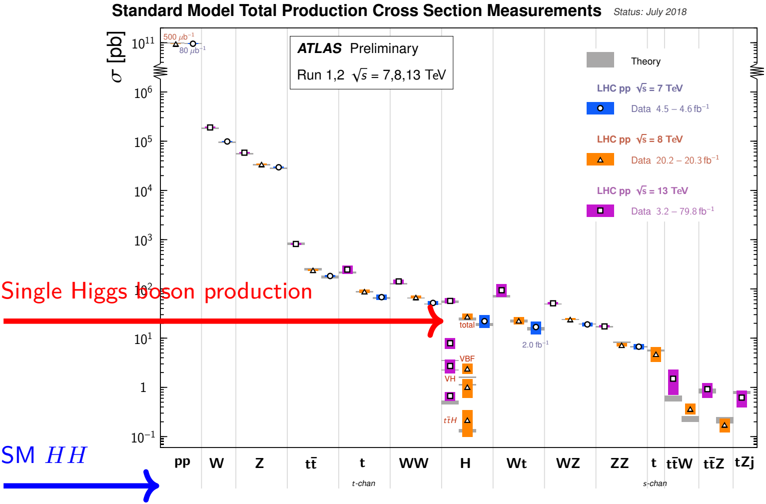
Small production cross-section:

$$\sigma^{\mathrm{ggF}}_{\mathrm{SM}} = 31.02 \text{ fb at } \sqrt{s} = 13 \text{ TeV}$$

o two massive final state particles

o destructive interference

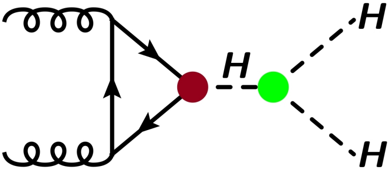
SM Higgs boson pair production at the LHC



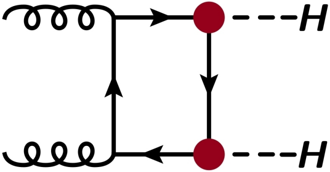
- SM HH production $\sim 1000\times$ lower compared to the single-H production
- Current LHC dataset won't be enough to reach the sensitivity

Higgs boson pair production at the LHC

1. SM Higgs boson pair production (gluon-gluon fusion - ggF):



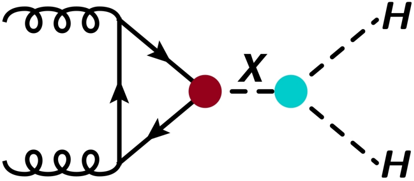
Higgs boson self-coupling



Higgs-fermion Yukawa coupling

2. Potential non-resonant BSM enhancements
(new couplings, modified Yukawa and/or self-couplings)

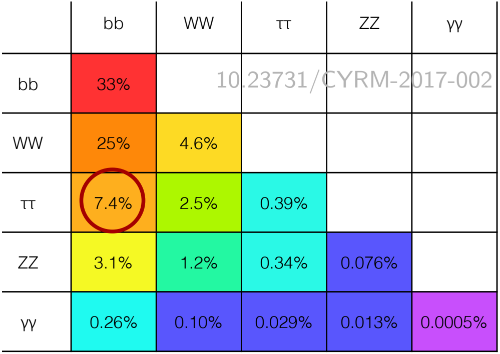
3. Benchmark BSM resonance hypotheses:
   - Randall-Sundrum graviton $G \to HH$ (spin=2)
   - $S \to HH$ (spin=0)



Resonant production

Di-Higgs final states

Di-Higgs decay modes and relative branching fractions:



	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%	0.0005%

10.23731/CYRM-2017-002

Some of the most sensitive channels:

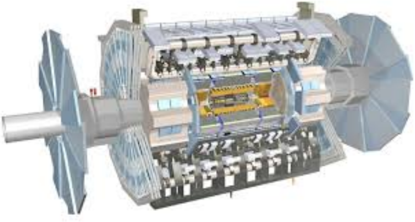
$HH \to b\bar{b}b\bar{b}$: the highest BR, large multijet background

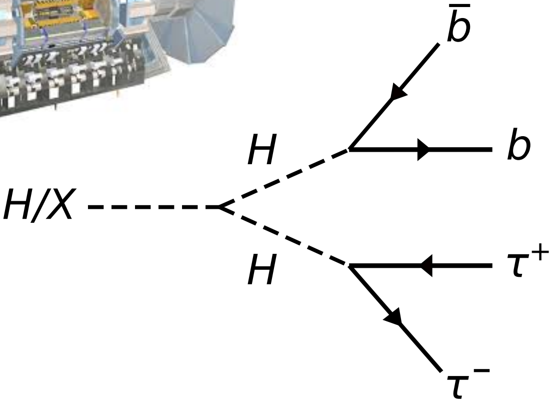
$HH \to b\bar{b}\tau^+\tau^-$: relatively large BR, cleaner final state

$HH \to b\bar{b}\gamma\gamma$: small BR, clean signal extraction thanks to a good $\gamma\gamma$ mass resolution

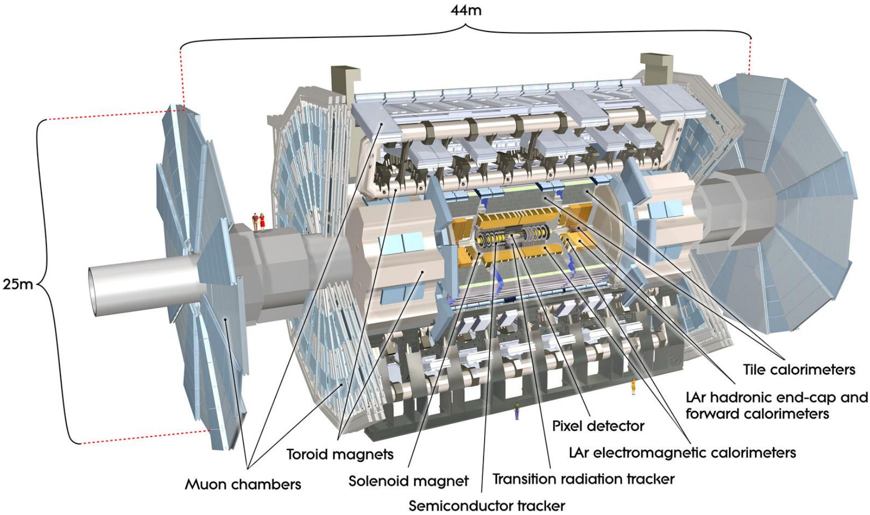
No golden channel! Important to consider different final states!

Experimental setup

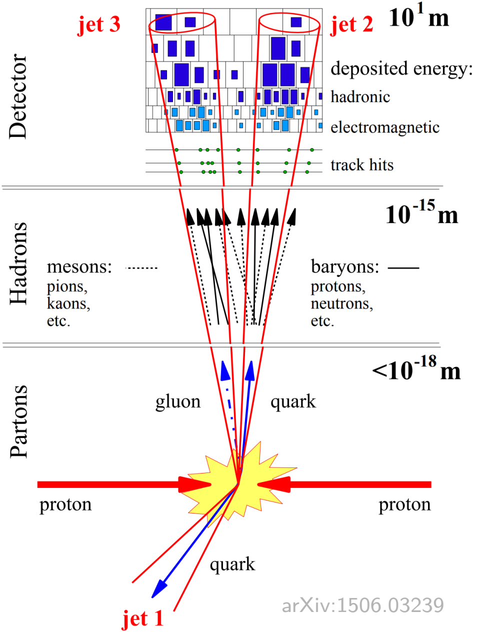




ATLAS Detector

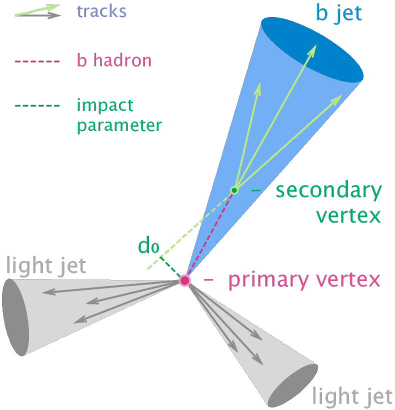


Identifying a b-jet



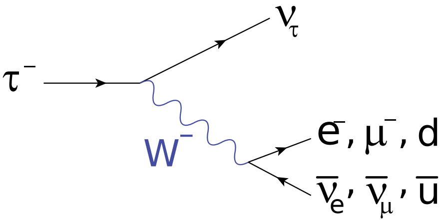
arXiv:1506.03239

cartoon taken from wikimedia



We can tag some types of jets:
e.g. ***b*-jets**

Tau leptons



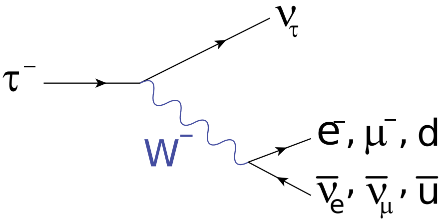
Leptonically decaying τ leptons:

$e/\mu +$ missing energy

Hadronically decaying τ leptons:

narrow jets with low track multiplicity $+$ missing energy

Tau leptons



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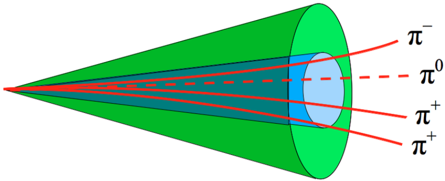
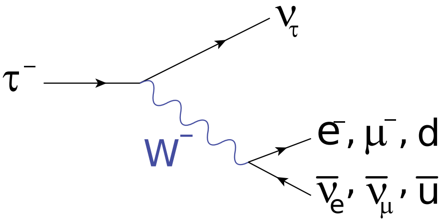


Typically decaying into 1 or 3 $\pi^\pm$ and some number of π^0

Machine learning used for identification

Tau leptons



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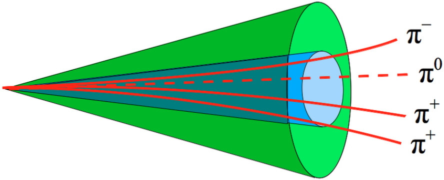

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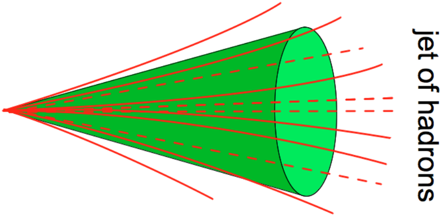
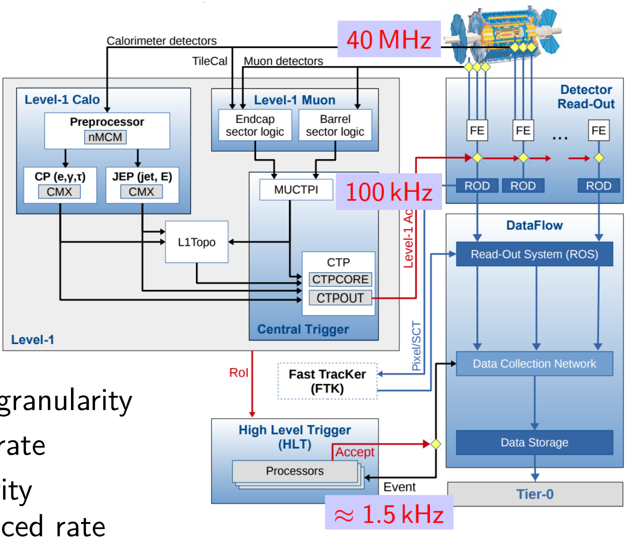


Quark- and gluon-initiated jets can be misidentified as τ leptons

Usually not very well described in simulations

ATLAS Trigger System

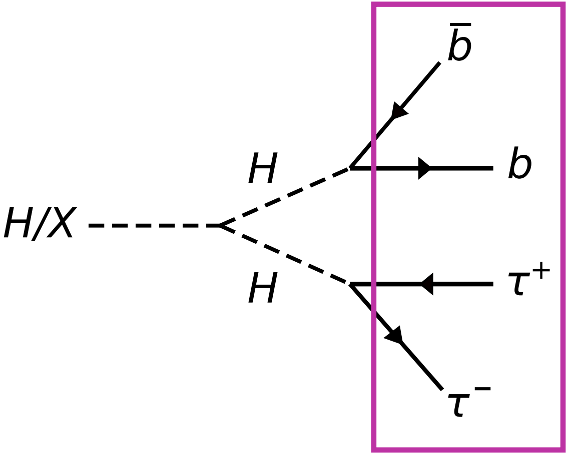


Level-1 - reduced granularity information at full rate

HLT - full granularity information at reduced rate

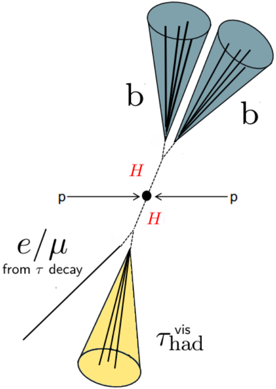
$bb\tau\tau$ final state

objects, identification,
background estimation, ...

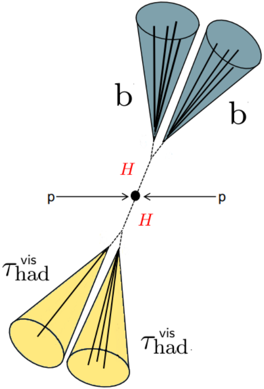


$HH \rightarrow bb\tau\tau$ analysis strategy (2015+2016 data)

$b\bar{b}\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$		$b\bar{b}\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	
Single lepton trigger $p_T^{e/\mu} > 27$ GeV	Lepton+tau trigger (to improve sensitivity)	Single tau trigger (to improve sensitivity)	Di-tau trigger $p_T^{\tau_0,\tau_1} > 40, 30$ GeV



$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ BR $\approx 46\%$



$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ BR $\approx 42\%$

$HH \to bb\tau\tau$ analysis strategy (2015+2016 data)

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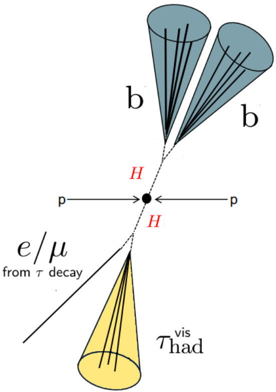
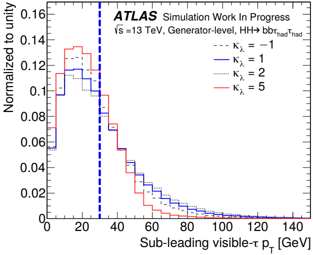
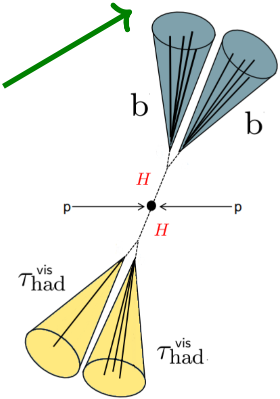




Trigger is one of the limiting factors.



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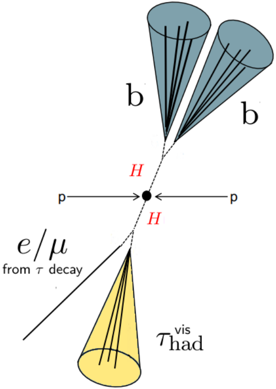
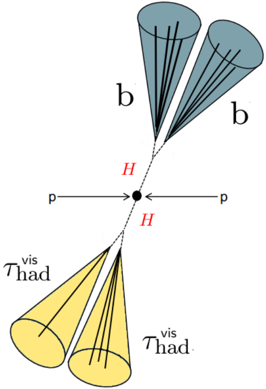


3 Signal Regions:

- Opposite charge of the visible τ decay products
- 2 b-tagged jets



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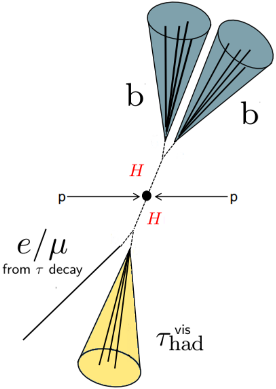
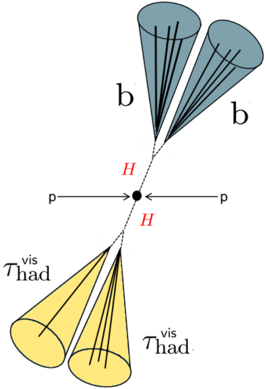


3 Signal Regions:

- Opposite charge of the visible τ decay products
- 2 b-tagged jets

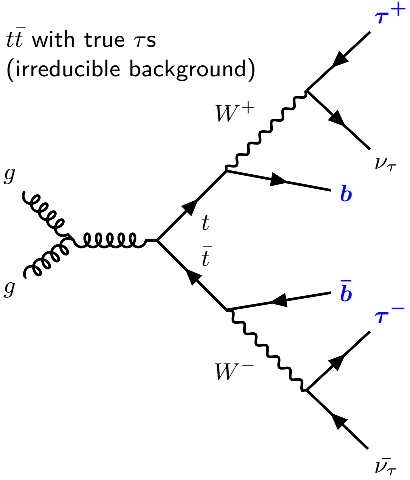
Control Regions:

- 0,1 b-tagged jet
- Same charge
- $Z\mu\mu + b\bar{b}$, ...

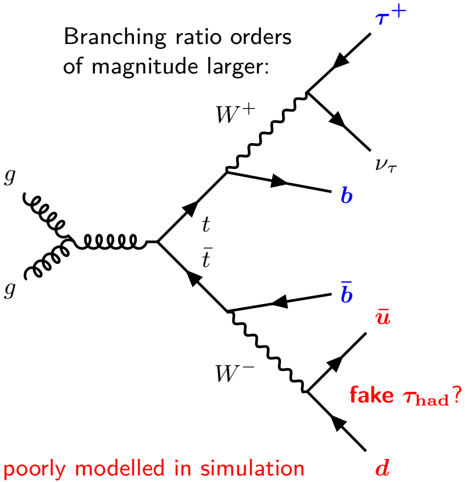


$t\bar{t}$ background with fake-τ_{had}

$t\bar{t}$ with true τs
(irreducible background)



Branching ratio orders
of magnitude larger:

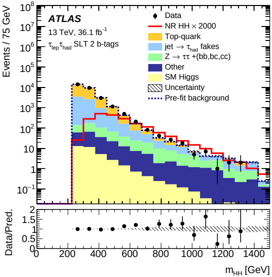


fake τ_{had}?

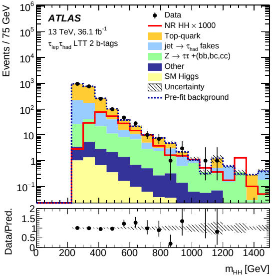
poorly modelled in simulation
measuring misidentification probability
in data, applying it to MC

Background estimation

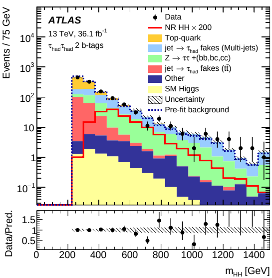
- Example: modeling of the HH-system invariant mass in 3 signal regions:



$\tau_{\rm lep}\tau_{\rm had}$ SLT



$\tau_{\rm lep}\tau_{\rm had}$ LTT



$\tau_{\rm had}\tau_{\rm had}$

PRL 121, 191801

Background estimation

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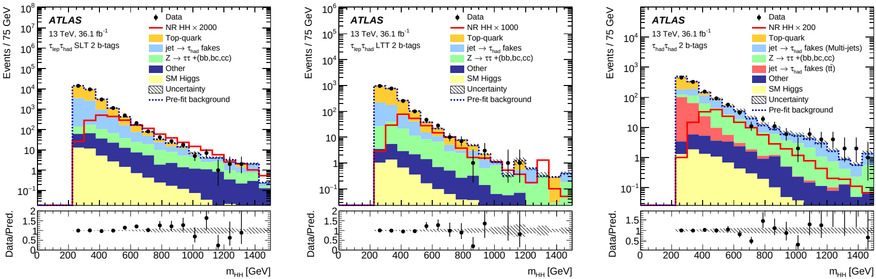


PRL 121, 191801

$\tau_{\text{lep}}\tau_{\text{had}}$ SLT

$\tau_{\text{lep}}\tau_{\text{had}}$ LTT

$\tau_{\text{had}}\tau_{\text{had}}$

$t\bar{t}$ background with true τs (MC), normalization from data

Jet → fake τ_{had}
from $t\bar{t}$, multijet and W+jets processes

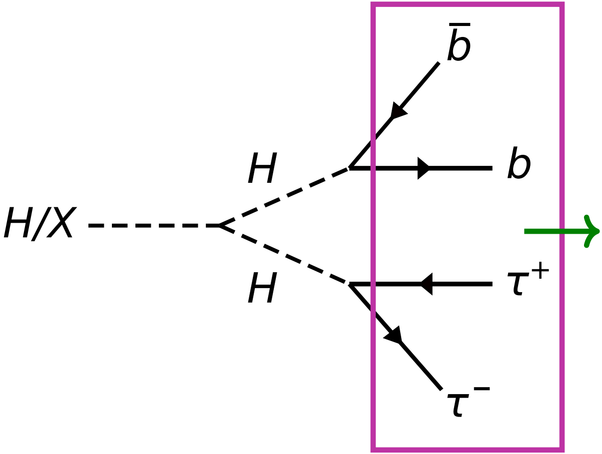
Jet → fake τ_{had}
from multijet processes

Jet → fake τ_{had}
from $t\bar{t}$ processes

data-driven

$Z \rightarrow \tau\tau + \text{bb}$ (MC), normalization from data

Other backgrounds estimated using Monte Carlo

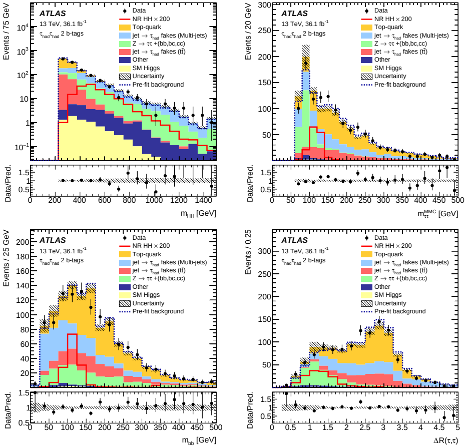


Signal extraction
Multivariate Analysis (MVA)

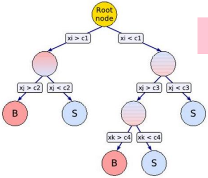
Boosted Decision Tree

- BDT used to separate signal from background

$\tau_{\text{had}}\tau_{\text{had}}$ shown here (equivalent for $\tau_{\text{lep}}\tau_{\text{had}}$)



+ other variables



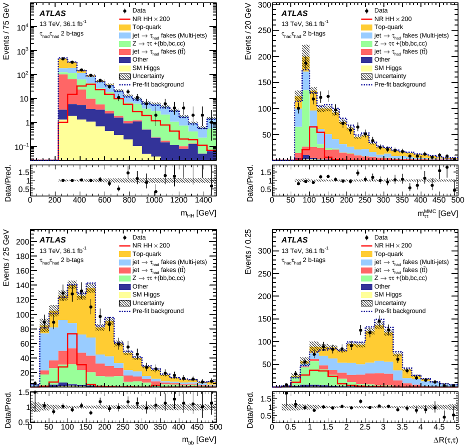
BDT

PRL 121, 191801

Boosted Decision Tree

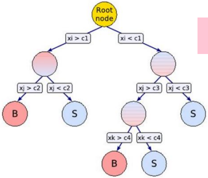
- BDT used to separate signal from background

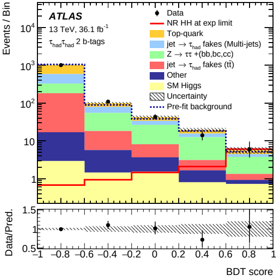
$\tau_{\rm had}\tau_{\rm had}$ shown here (equivalent for $\tau_{\rm lep}\tau_{\rm had}$)



+ other variables

BDT



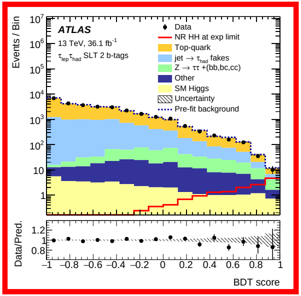


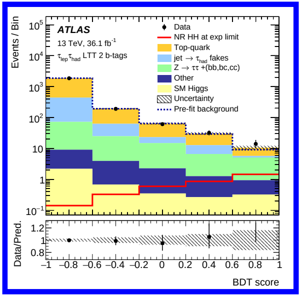
(SM HH) BDT Score - final discriminant

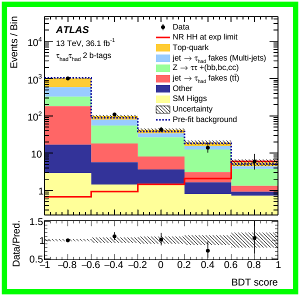
PRL 121, 191801

$HH \to bb\tau\tau$ analysis strategy (2015+2016 data)

$b\bar{b}\tau_{\text{lep}}\tau_{\text{had}}$		$b\bar{b}\tau_{\text{had}}\tau_{\text{had}}$	
Single lepton trigger	Lepton+tau trigger	Single tau trigger	Di-tau trigger







PRL 121, 191801

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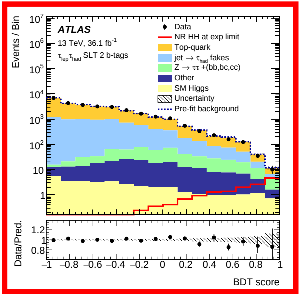
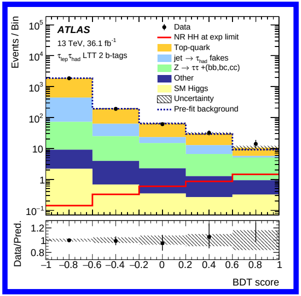
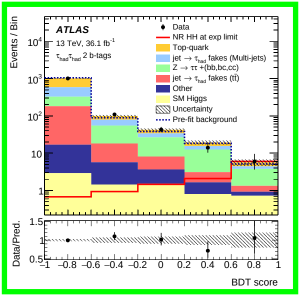
Single lepton trigger	Lepton+tau trigger	Single tau trigger	Di-tau trigger







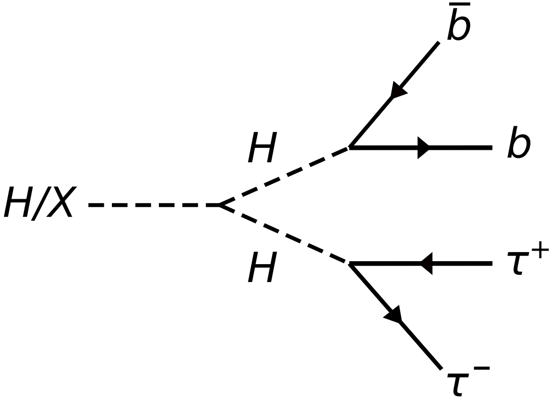
Simultaneous profile likelihood fit of the BDT score distributions

Limit on $\sigma_{HH}/\sigma_{HH}^{SM}$:

-1σ	Expected	$+1\sigma$	Observed
10.7	14.8	20.6	12.7

(95% CL)

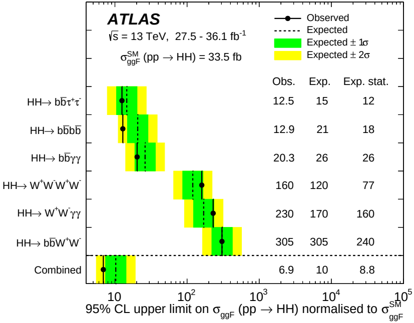
PRL 121, 191801

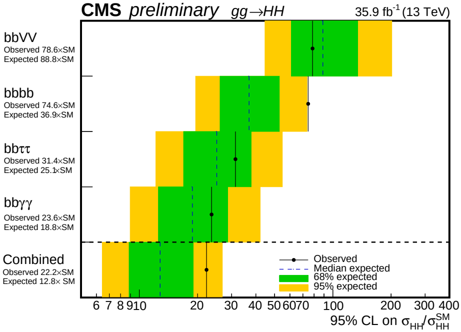


⟶ Results, **more results**, near and far future...

SM HH production, combined results

- Most recent ATLAS and CMS combinations of di-Higgs searches
- $bb\tau\tau$ proves to be one of the most sensitive channels





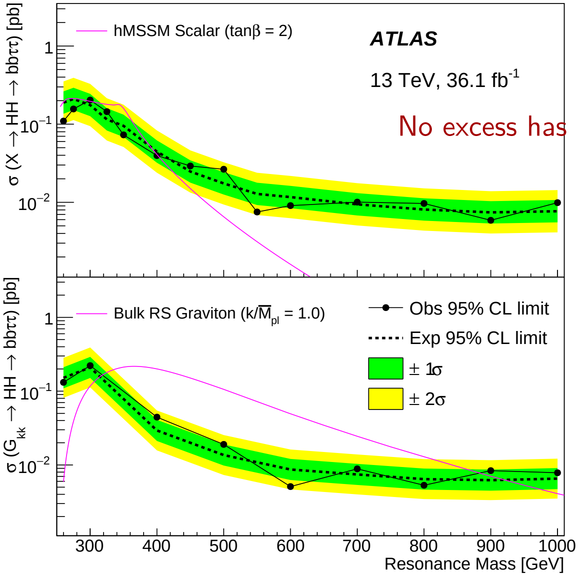
Phys. Lett. B 800 (2020) 135103

CMS-PAS-HIG-17-030

	$bb\tau\tau$ obs (exp)	combined obs (exp)
ATLAS	12.5 (15.0)	6.9 (10)
CMS	31.4 (25.1)	22.2 (12.8)

Resonant production, spin=0, 2

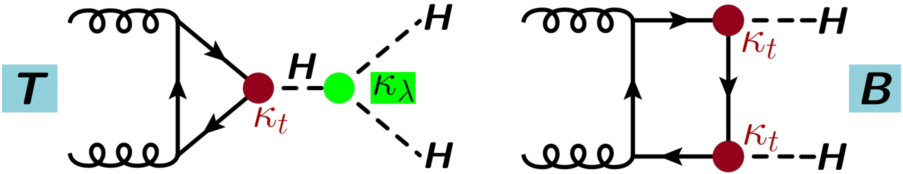
PRL 121, 191801



No excess has been found

Varied Higgs self-coupling

- Potential non-resonant BSM enhancements (ggF):



Higgs boson self-coupling

Higgs-fermion Yukawa coupling

using coupling scale-factors: $\kappa_t = g_{t\bar{t}H}/g^{SM}_{t\bar{t}H}$ and $\kappa_\lambda = \lambda_{HHH}/\lambda^{SM}_{HHH}$
to modify the SM Higgs boson pair production

$$A(\kappa_t, \kappa_\lambda) = \kappa_t^2 B + \kappa_t \kappa_\lambda T$$

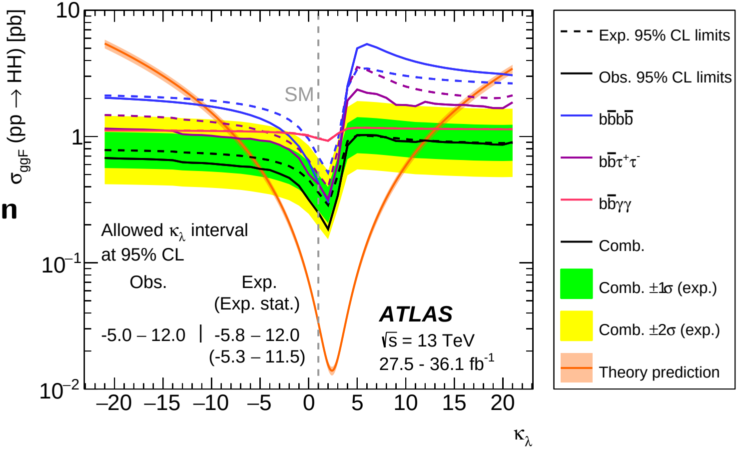
Limits on the cross-section as a function of κ_λ

$4b$

$bb\tau\tau$

$bb\gamma\gamma$

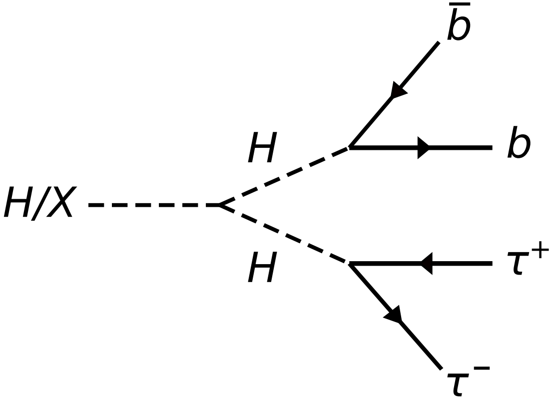
combination



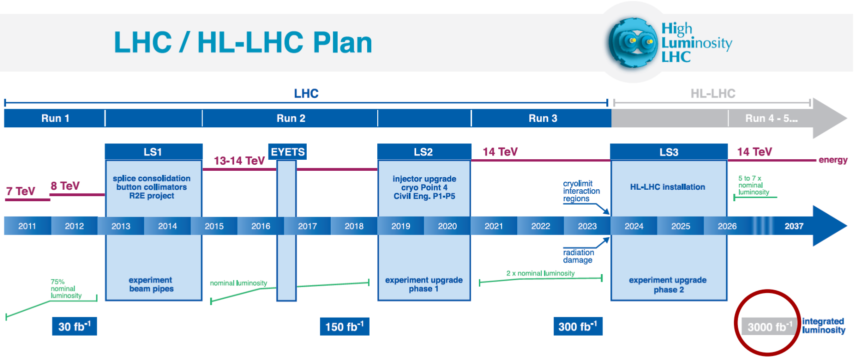
Phys. Lett. B 800 (2020) 135103

Limits on κ_λ:	Expected	Observed
$bb\tau\tau$	$\kappa_\lambda \in [-8.8, 16.7]$	$\kappa_\lambda \in [-7.3, 15.7]$
combination	$\kappa_\lambda \in [-5.8, 12.0]$	$\kappa_\lambda \in [-5.0, 12.1]$

(95% CL)



⟶ Results, more results, near and **far future**...



- The HL-LHC will allow to do measurements which are currently statistically limited
- SM HH production important physics case for building the HL-LHC
- The sensitivity to $HH \rightarrow bb\tau\tau$ estimated by extrapolating the current result
- Taking into account different scenarios for systematic uncertainties, triggers, b-tagging efficiency, etc.

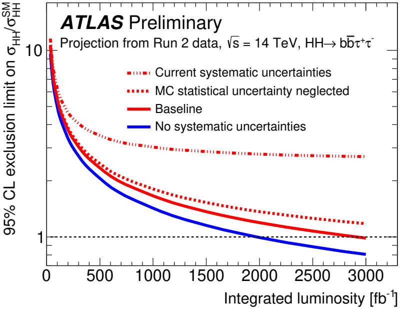
$$\int L dt = 36.1 \rightarrow 3000 \text{ fb}^{-1}$$

$$\sqrt{s} = 13 \rightarrow 14 \text{ TeV}$$

ATL-PHYS-PUB-2018-053

Results of the extrapolation

ATL-PHYS-PUB-2018-053



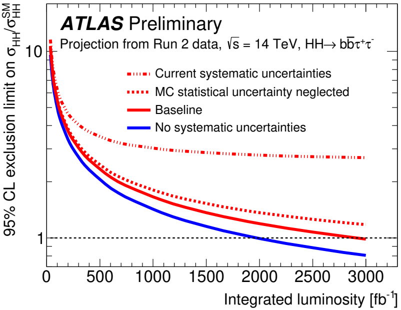
95% CL expected limit on $\sigma_{HH}/\sigma_{HH}^{\mathrm{SM}}$

	Expected limit
No syst. unc.	0.80
Baseline scenario*	0.99

*Baseline scenario: MC stat. unc. neglected, theory unc. reduced, assumed detector performance taken into account

Results of the extrapolation

ATL-PHYS-PUB-2018-053



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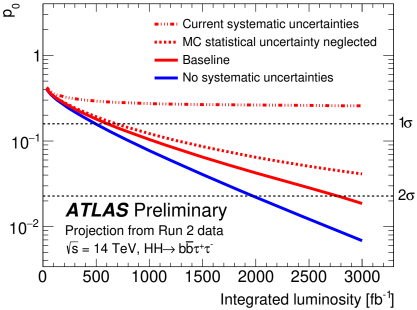


Expected significance

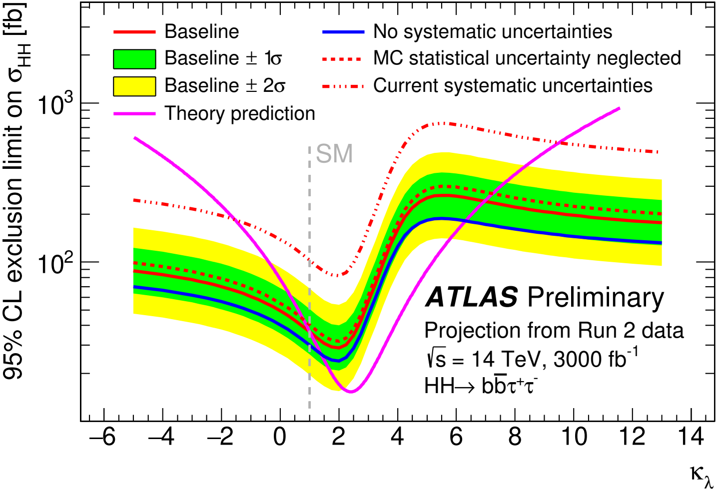
	Expected limit	Expected significance [σ]
No syst. unc.	0.80	2.5
Baseline scenario*	0.99	2.1

*Baseline scenario: MC stat. unc. neglected, theory unc. reduced, assumed detector performance taken into account

Limits on the cross-section as a function of κ_λ

- Allowed 95% CL κ_λ interval, Asimov dataset: $\sigma_{HH} = 0$

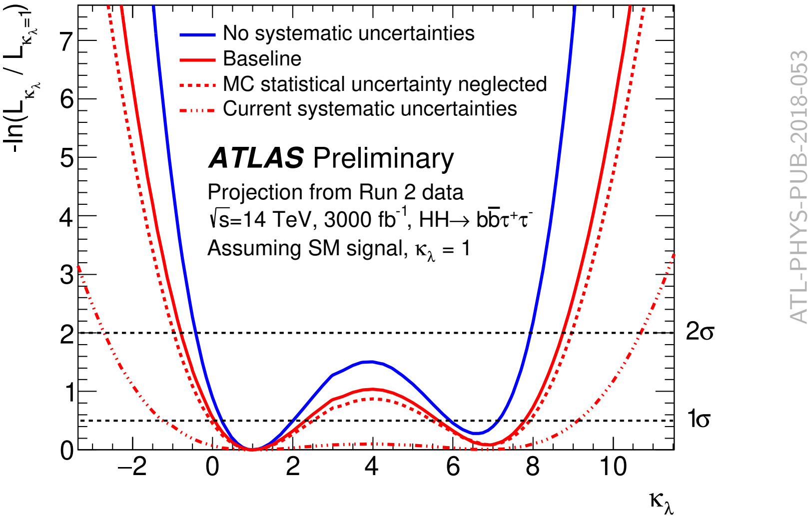
  no syst. unc.: $\kappa_\lambda \in [1.4, 6.3]$, baseline scenario: $\kappa_\lambda \in [1.0, 7.0]$

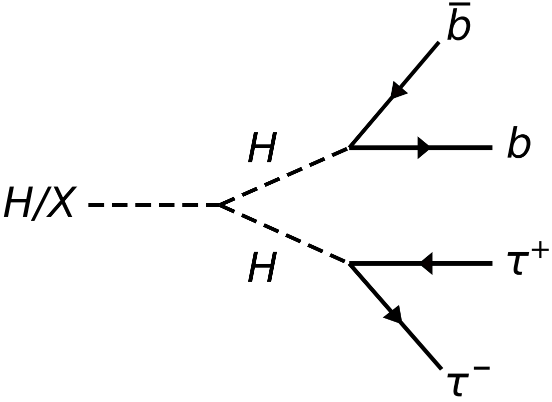


ATL-PHYS-PUB-2018-053

Limits on κ_λ, assuming SM HH ($\kappa_\lambda = 1$)

- Allowed 1σ and 2σ CL intervals, Asimov dataset: includes SM HH

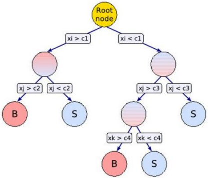


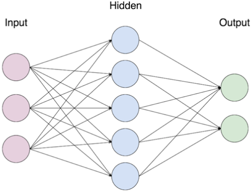


⟶ Results, more results, **near** and far **future**...

Run 2 legacy result

- More data: $36.1\ \text{fb}^{-1} \rightarrow 139\ \text{fb}^{-1}$
- Updated trigger and object reconstruction
  (new triggers, τ_{had} reconstruction, PFlow jets, etc.)
- τ_{had}-identification: BDT→RNN
  Recurrent neural network, ATL-PHYS-PUB-2019-033
- b-jet identification: MV2c10→DL1r
  Deep Learning Heavy Flavour Tagger, FTAG-2019-001
- Re-deriving and improving data-driven background modelling
- Exploring new multivariate techniques





Neural Networks

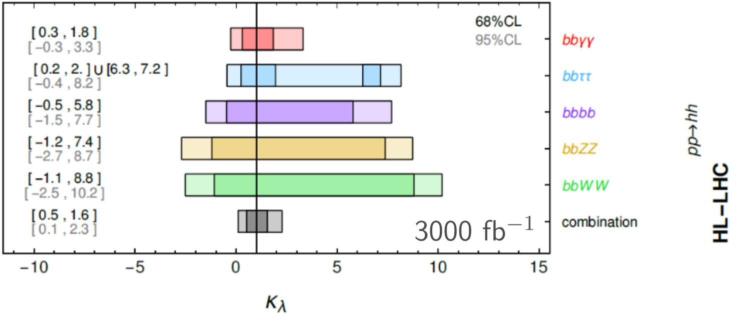
- **How much we can improve?**

Conclusion & Outlook

- $HH \rightarrow bb\tau\tau$ is one of the most sensitive channels
- Constraints on the SM HH cross-section and κ_λ set using 36.1 fb^{-1} of data
- Analysis using the full Run 2 dataset ongoing. Promising HL-LHC prospects

CERN Yellow Report, expected constraints on κ_λ

HL-LHC ATLAS+CMS combination:



arXiv:1902.00134 [hep-ph]

Conclusion & Outlook

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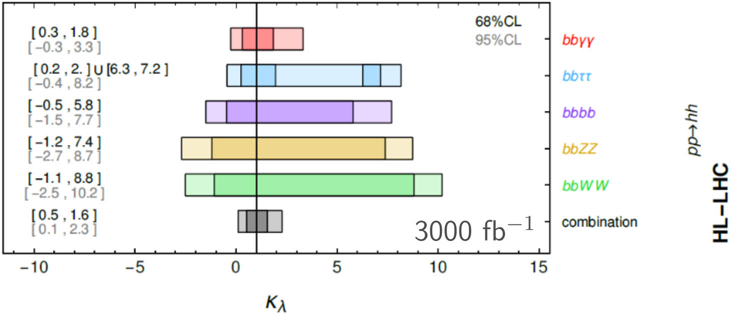


arXiv:1902.00134 [hep-ph]

Thanks for your attention!

backup slides

Dominant trig category

Trigger-dependent event preselection

$\tau_{\text{lep}}\tau_{\text{had}}$		$\tau_{\text{had}}\tau_{\text{had}}$	
Lepton+tau trigger LTT	**Single lepton trig** SLT	Single tau trigger STT	**Di-tau trigger** DTT
1 e/μ and 1 τ		**2 τs**	
18 GeV $< p_T^e <$SLT threshold 15 GeV$< p_T^\mu <$ SLT threshold $p_T^\tau > 30$ GeV	$p_T^{e/\mu} > 25 - 27$ GeV $p_T^\tau > 20$ GeV	$p_T^{\text{lead}\tau} > 100 - 180$ GeV $p_T^{\text{subl}\tau} > 20$ GeV	$p_T^{\text{lead}\tau} > 40$ GeV $p_T^{\text{subl}\tau} > 30$ GeV
$\geq$ 2 central jets			
$p_T > 80, 20$ GeV **2017 and 2018:** $p_T > 45, 20$, $p_T^\tau > 40$ GeV **OR** $p_T > 80, 20$ GeV with $\Delta R_{\tau\tau} < 2.5$ **OR** $p_T > 45, 45$ GeV	$p_T > 45, 20$ GeV	$p_T > 45, 20$ GeV	**2016:** $p_T > 80, 20$ GeV **2017 and 2018:** $p_T > 80, 20$ GeV with $\Delta R_{\tau\tau} < 2.5$ **OR** $p_T > 45, 45$ GeV
$m_{\tau\tau}^{\text{MMC}} > 60$ GeV			

- LTT and DTT studies for 2017 and 2018 ongoing, the decisions are not final

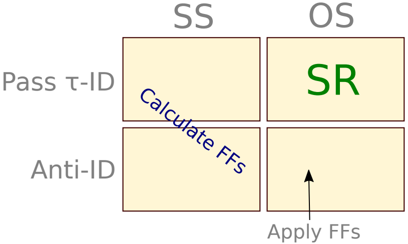
Multijet (fake-$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$) estimate

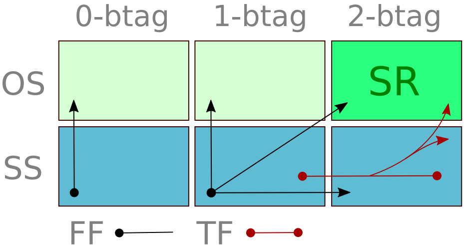
Assumption: jet→ τ_{had} misidentification probability the same
in same-sign-charge (SS) and opposite-sign-charge (OS) regions

$$FF = N^{\mathrm{SS}}_{\mathrm{ID}} / N^{\mathrm{SS}}_{\mathrm{Anti-ID}}$$

$(N = \mathrm{data} - \mathrm{MC})$

- Anti-ID: at least one τ fails τ-ID
- Binned in #track, trigger, p_T^{τ}



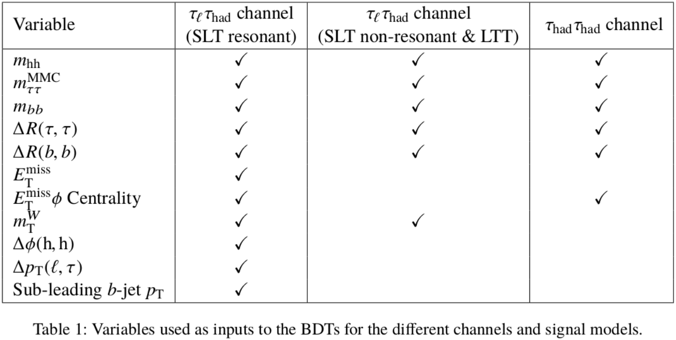


$$N^{\mathrm{SR}}_{\mathrm{multijet}} = FF \times N^{\mathrm{OS}}_{\mathrm{Anti-ID}}$$

- Modelling checked in validation regions

Boosted Decision Tree

τ_{ha}



Variable	$\tau_\ell \tau_{\mathrm{had}}$ channel (SLT resonant)	$\tau_\ell \tau_{\mathrm{had}}$ channel (SLT non-resonant & LTT)	$\tau_{\mathrm{had}} \tau_{\mathrm{had}}$ channel
m_{hh}	✓	✓	✓
$m_{\tau\tau}^{\mathrm{MMC}}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau, \tau)$	✓	✓	✓
$\Delta R(b, b)$	✓	✓	✓
$E_{\mathrm{T}}^{\mathrm{miss}}$	✓		
$E_{\mathrm{T}}^{\mathrm{miss}} \phi$ Centrality	✓		✓
m_{T}^{W}	✓	✓	
$\Delta\phi(\mathrm{h}, \mathrm{h})$	✓		
$\Delta p_{\mathrm{T}}(\ell, \tau)$	✓		
Sub-leading b-jet p_{T}	✓		

Table 1: Variables used as inputs to the BDTs for the different channels and signal models.

- Separate BDTs trained for each signal (and mass) hypothesis
- In resonant case the BDT is trained on the hypothesis + two neighboring mass points.
- Dedicated BDT used for κ_λ scan.

T

BDT Score - final discriminant

Phys. Rev. Lett. 117 (2016) 012001

Profile likelihood fit

Using probability density function of the form:

$$\mathcal{P}(n_c, a_p \mid \phi_p, \alpha_p, \gamma_b) =$$

$$\prod_{c\in\text{channels}} \prod_{b\in\text{bins}} \text{Pois}(n_{cb}|\mu\nu_{cb}^{\text{sig}} + \nu_{cb}^{\text{bkg}}) \cdot G(L_0|\lambda, \Delta_L) \cdot \prod_{p\in\mathbb{S}+\Gamma} f_p(a_p|\alpha_p)$$

$b \in$ bins
$c \in$ channels
$s \in$ samples
$p \in$ parameters

ϕ_p: unconstrained normalization
$\mathbb{S} = \{\alpha_p\}$: external constraints
$\Gamma = \{\gamma_{csb}\}$: bin-by-bin uncertainties

μ: Parameter Of Interest
$\mu = 0 \leftarrow$ background-only hypothesis

Poisson probability of obtaining n_{cb} events when ν_{cb} are expected

Gaussian constraint term with luminosity parameter λ and nominal value L_0

Constraint term describing an auxiliary measurement a_p that constraints the nuisance parameter α_p

If one imagines the data as being fixed, then this equation depends on μ and is called the likelihood function $L(\mu)$

Upper Limits

Using maximum likelihood ratio:

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}})}{L(\hat{\mu}, \hat{\theta})}$$

$\leftarrow$ maximizes L
for specified μ

$\leftarrow$ maximizes L

Test statistic used for upper limits:

$$q_\mu = \begin{cases} -2\ln\lambda(\mu), & \text{if } \hat{\mu} \leq \mu \\ 0, & \text{if } \hat{\mu} > \mu \end{cases} \tag{1}$$

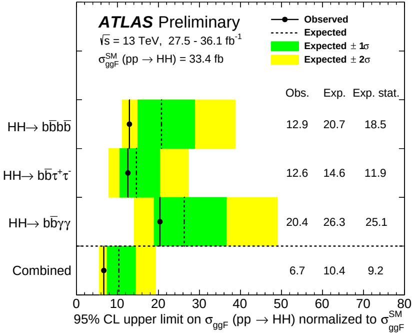
From observed q_μ find p-value:

$$p_\mu = \int_{q_{\mu,\mathrm{obs}}}^{\infty} f(q_\mu \mid \mu) dq_\mu$$

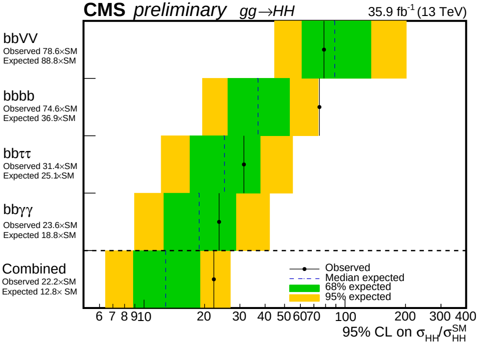
95% CL upper limit on μ is highest value
for which p-value is not less than 0.05

SM HH production, combined results

- Most recent ATLAS and CMS combinations of di-Higgs searches
- $bb\tau\tau$ proves to be one of the most sensitive channels



ATLAS-CONF-2018-043



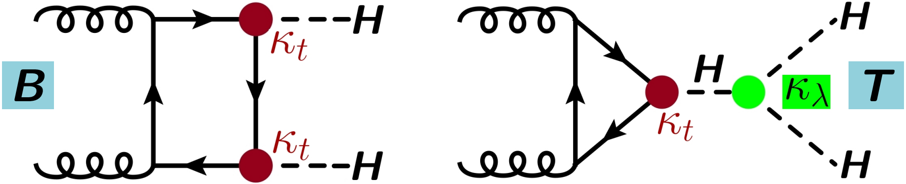
CMS-PAS-HIG-17-030

	$bb\tau\tau$ obs (exp)	combined obs (exp)
ATLAS	12.6 (14.6)	6.7 (10.4)
CMS	31.4 (25.1)	22.2 (12.8)

Varied trilinear Higgs self-coupling

HH production modified

(using scale factors: $\kappa_t = g_{t\bar{t}H}/g^{SM}_{t\bar{t}H}$ and $\kappa_\lambda = \lambda_{HHH}/\lambda^{SM}_{HHH}$)



$$A(\kappa_t, \kappa_\lambda) = \kappa_t^2 B + \kappa_t \kappa_\lambda T$$

$$A(1,0) = B \qquad A(1,1) = B + T \qquad A(1,2) = B + 2T$$

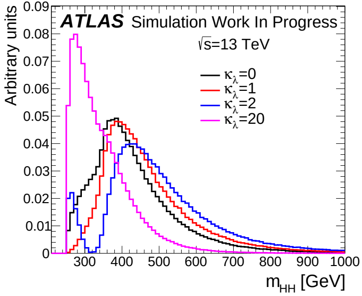
Express $|B|^2$, $|T|^2$ and $(BT^* + TB^*)$ in terms of $|A(1,0)|^2$, $|A(1,1)|^2$ and $|A(1,2)|^2$, which leads to:

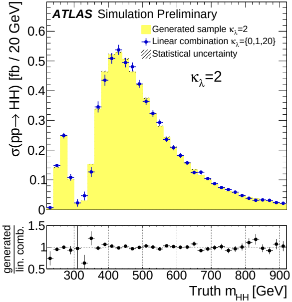
$$|A(\kappa_t, \kappa_\lambda)|^2 = a(\kappa_t, \kappa_\lambda)|A(1,0)|^2 + b(\kappa_t, \kappa_\lambda)|A(1,1)|^2 + c(\kappa_t, \kappa_\lambda)|A(1,2)|^2$$

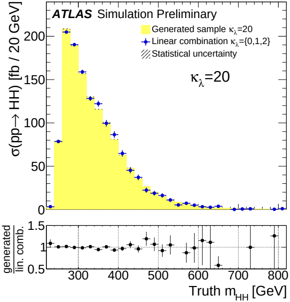
Any $(\kappa_t, \kappa_\lambda)$ combination at LO can be obtained from a **linear combination** of some 3 $(\kappa_t \neq 0, \kappa_\lambda)$ samples!

Linear combination

- Showing generator level m_{HH} for: $\kappa_\lambda = \{0, 1, 2, 20\}$ (other parameters fixed to the SM)
- Different bases tested for linear combination (e.g. $\kappa_\lambda = \{0, 1, 2\}$ vs $\kappa_\lambda = \{0, 1, 20\}$)
- Remaining sample used for validation (very good closure at generator level)





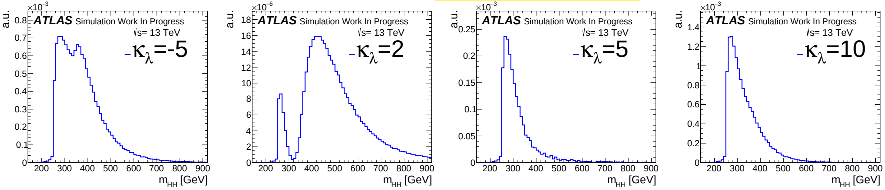


ATL-PHYS-PUB-2019-007

Trilinear Higgs self-coupling scan strategy

1 $m_{HH}^{\kappa_\lambda=x}$, for $x = \{-20, -19, ..., 20\}$, at generator level, at LO

obtained using the linear combination :



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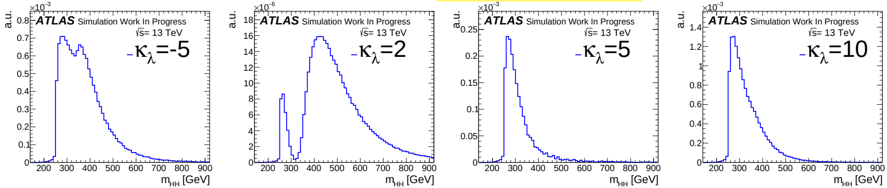
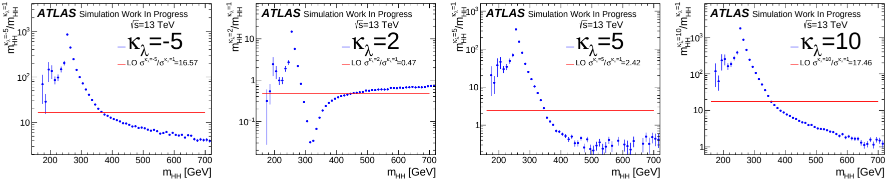


2

Weights, binned in m_{HH}, obtained as: $m_{HH}^{\kappa_\lambda=x}|_{\mathrm{bin}\,i} / m_{HH}^{\kappa_\lambda=1}|_{\mathrm{bin}\,i}$



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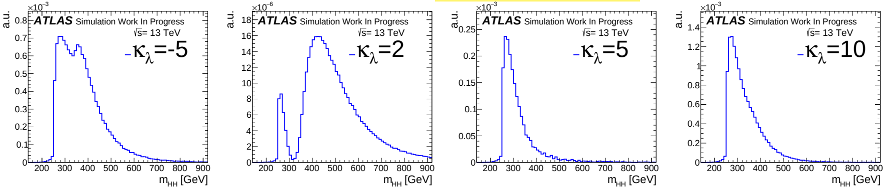
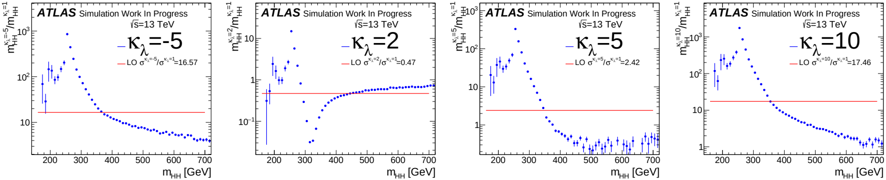


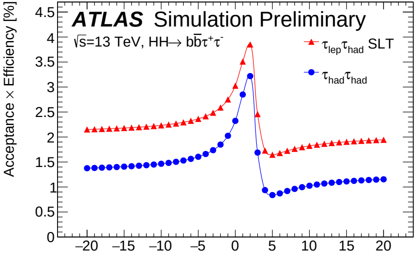
2 Weights, binned in m_{HH}, obtained as: $m_{HH}^{\kappa_\lambda = x}|_{\text{bin}\, i} / m_{HH}^{\kappa_\lambda = 1}|_{\text{bin}\, i}$



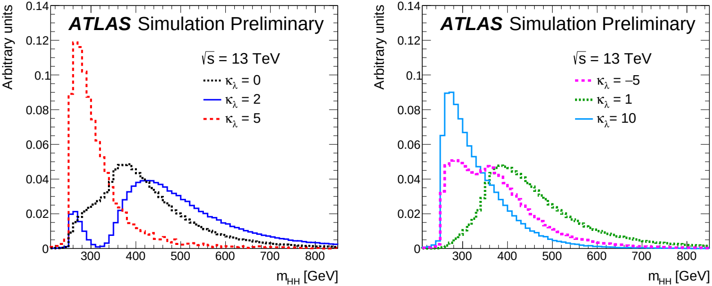
3 These weights are applied to the fully reconstructed NLO SM sample to obtain any κ_λ point, assuming that the LO to NLO factorization does not depend on κ_λ

Differences compared to the SM HH search

- Acceptance changes significantly as a function of κ_λ
- A dedicated BDT, trained on $\kappa_\lambda = 20$ signal is used since it performs good for all κ_λ points.



variations of the m_{HH} spectrum with κ_λ:



ATLAS-CONF-2018-043

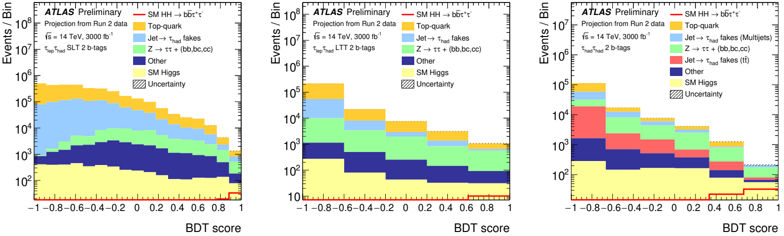
Extrapolation scenarios

1. Current systematic uncertainties
2. Current systematic uncertainties, MC stat. uncertainty neglected

   Fractional impact on $\Delta\mu$ goes from 18% (Run 2) to 84% (HL-LHC)
3. **Baseline**
   - $Z+$heavy-flavor and $t\bar{t}$ normalization uncertainties scaled down with lumi
   - Significant reduction assumed for the VH and $t\bar{t}H$ uncertainties
   - MC statistical uncertainty neglected
   - Statistical unc. on the data-driven backgrounds adjusted to follow Poisson statistics
   - Cross-section uncertainties reduced
4. **No systematic uncertainties**

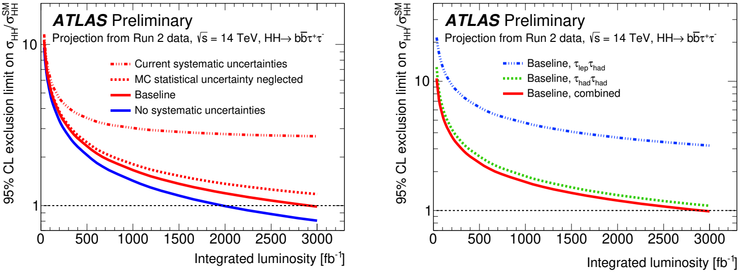
Results of the extrapolation

- 3 signal regions: $\tau_{\rm lep}\tau_{\rm had}$ SLT, $\tau_{\rm lep}\tau_{\rm had}$ LTT, $\tau_{\rm had}\tau_{\rm had}$

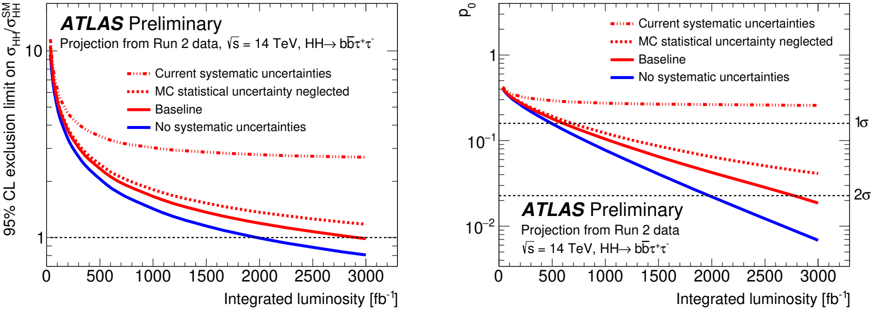


ATL-PHYS-PUB-2018-053

95% CL upper limit on $\sigma(pp \to HH)/\sigma_{SM}$ (background-only hypothesis):



Results of the extrapolation

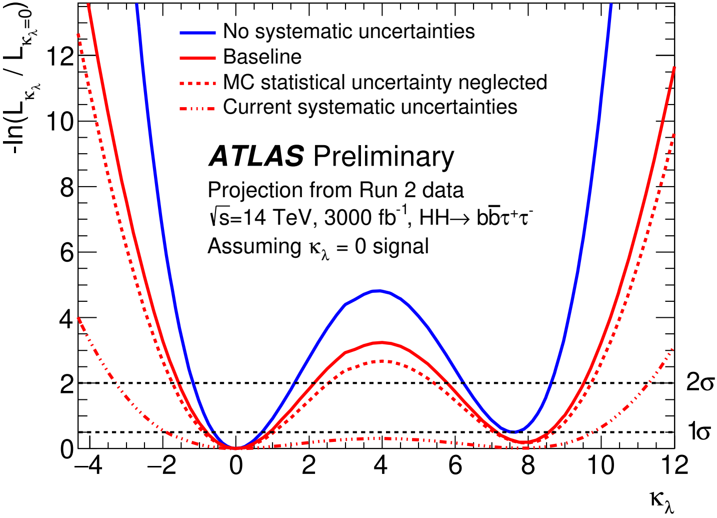


Scenario	-1σ	Expected limit	$+1\sigma$	Significance $[\sigma]$
No systematic uncert.	0.58	0.80	1.12	2.5
Baseline	0.71	0.99	1.37	2.1
MC statistical uncert. neglected	0.8	1.2	1.6	1.7
Current systematic uncert.	1.9	2.7	3.7	0.65

ATL-PHYS-PUB-2018-053

Limits on κ_λ, assuming $\kappa_\lambda = 0$ and $\kappa_t = 1$

- Allowed 1σ and 2σ CL intervals, Asimov dataset: includes $\kappa_\lambda = 0$ signal



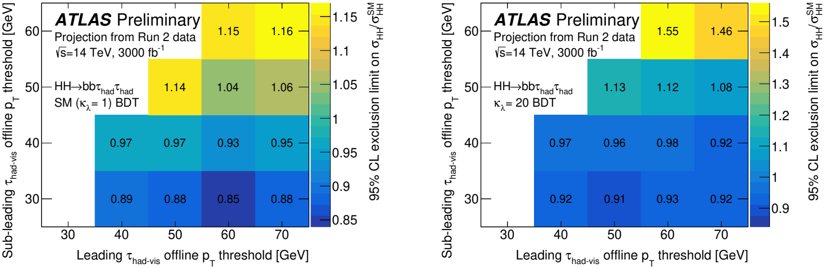
ATL-PHYS-PUB-2018-053

Breakdown of the systematics - baseline

Source	Uncertainty (%)
Total	±52
Data statistics	±43
Simulation statistics	±0
Total systematic uncertainty	±30
Experimental uncertainties	
Luminosity	±4.3
Pile-up reweighting	±7.0
$\tau_{\text{had-vis}}$	±13
Fake-$\tau_{\text{had-vis}}$ estimation	±8.3
b- tagging	±8.1
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±3.5
Electron and muon	±5.1
Total experimental uncertainties	±18
Theoretical and modelling uncertainties	
Top	±6.6
Signal	±8.6
$Z/\gamma^* \to \tau^+\tau^-$	±11
SM Higgs boson	±8.5
Other backgrounds	±4.4
Total theoretical and modelling uncertainties	±17

ATL-PHYS-PUB-2018-053

Di-tau trigger studies



ATL-PHYS-PUB-2018-053

Expected 95% CL upper limit on $\sigma(pp \to HH)/\sigma_{SM}$ (without systematic uncertainties) as a function of the leading and sub-leading $\tau_{had-vis}$ minimum p_{T} thresholds, using the (a) nominal BDT classifier and (b) using the $\kappa_\lambda = 20$ BDT

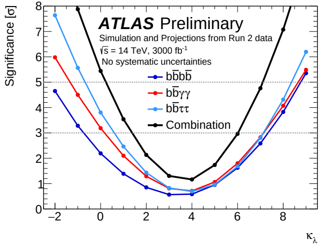
- The loss in sensitivity is expected to be even more pronounced (the effect masked by $+80$ GeV jet requirement)
- Sensitivity to the Higgs self-coupling is affected more by raising the p_{T} thresholds (softer p_T spectrum), so the study is repeated for $\kappa_\lambda = 20$ BDT

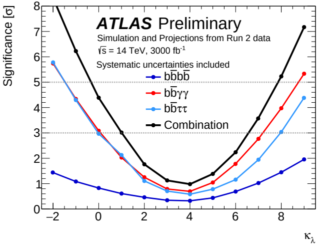
HL-LHC HH combination

- Significance (no systematics, baseline):

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.4	0.61
$HH \to b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5	3.0

- Significance as a function of κ_λ (no systematics, baseline):

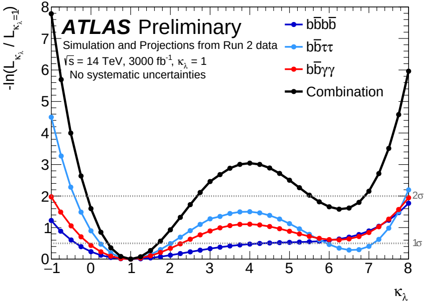




ATL-PHYS-PUB-2018-053

HL-LHC HH combination

- Limits on the κ_λ, assuming SM signal (no systematics, baseline):



ATL-PHYS-PUB-2018-053

- Confidence intervals on κ_λ from the combination (no systematics):
  - 68%: $0.4 < \kappa_\lambda < 1.7$
  - 95%: $-0.1 < \kappa_\lambda < 2.7$ U $5.5 < \kappa_\lambda < 6.9$
- Confidence intervals on κ_λ from the combination (with systematics):
  - 68%: $0.3 < \kappa_\lambda < 1.9$
  - 95%: $-0.4 < \kappa_\lambda < 7.3$