Di-Higgs production and Higgs self-coupling in ATLAS at HL-LHC

Petar Bokan
on behalf of the ATLAS collaboration

HL/HE LHC Meeting, Fermilab 4-6 April 2018

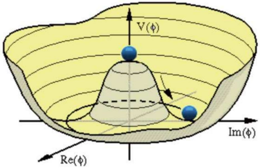
Overview

- Higgs self-coupling
- Di-Higgs production at the LHC
- Run-2 results
- Di-Higgs prospects at the HL-LHC
  - $hh \to b\bar{b}b\bar{b}$
  - $hh \to b\bar{b}\gamma\gamma$
  - $hh \to b\bar{b}\tau^+\tau^-$

Higgs potential

- Important to measure the shape of the Higgs potential

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

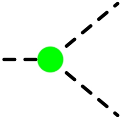


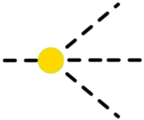
Expanding about minimum: $V(\phi) \to V(v+h)$

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

$$= V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4 + \ldots$$

mass term $\quad hh$-production $\quad hhh$-production





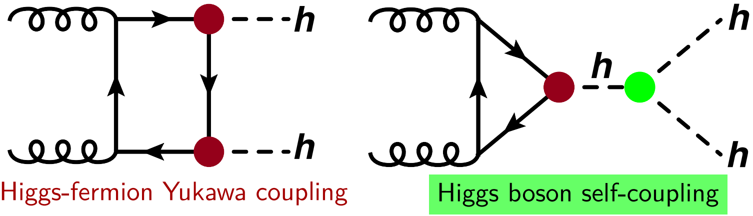
Standard Model (SM):

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

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

SM Higgs boson pair production at the LHC

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



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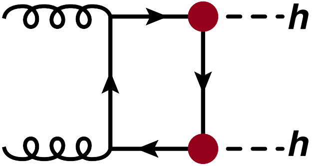
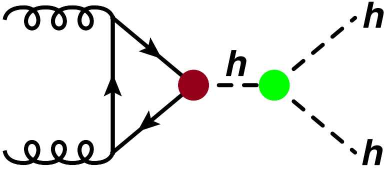
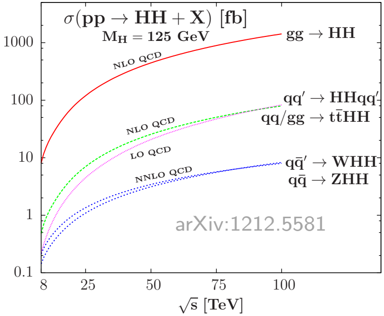


Higgs-fermion Yukawa coupling



Higgs boson self-coupling



Production cross-section small

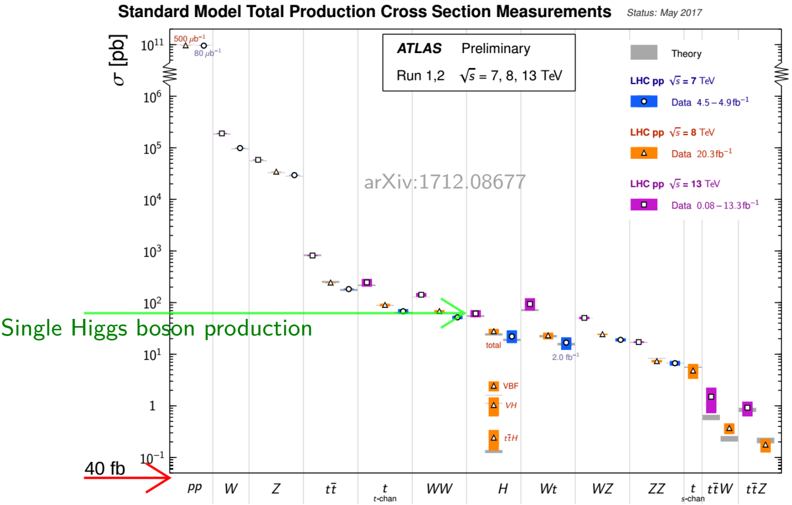
– two massive final state particles

– destructive interference

production mode	Cross-section (14 TeV)
gluon-gluon fusion	~ 40 fb
vector boson fusion	~ 2 fb
Higgs-strahlung	~ 1 fb
$t\bar{t}hh$	~ 1 fb

arXiv:1610.07922

SM Higgs boson pair production at the LHC



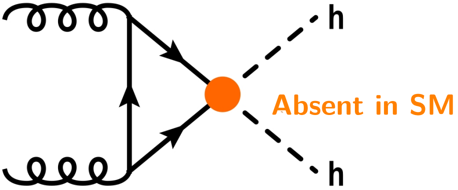
- SM hh-production $\sim 1000\times$ smaller compared to h-production
- Current LHC dataset won't be large enough to reach the sensitivity

BSM Higgs boson pair production

Sensitivities to BSM hh-production interesting already at LHC.

Non-resonant enhancements:

- Modified Yukawa/self-coupling
- New couplings



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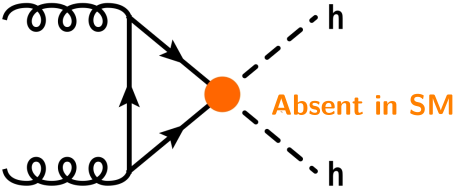
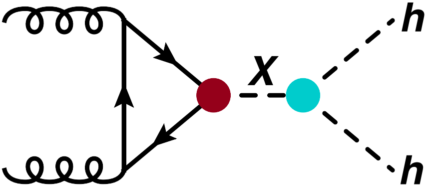


Resonant Higgs boson pair production

Benchmark BSM hypotheses:

- Randall-Sundrum graviton $G \to hh$ (spin=2)
- Heavy Higgs $H \to hh$ (spin=0)



Di-Higgs final states

Di-Higgs decay modes and relative branching fractions:

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.070%	
γγ	0.26%	0.10%	0.028%	0.012%	0.00052%

10.23731/CYRM-2017-002

The most sensitive channels to the SM hh:

$hh \to b\bar{b}b\bar{b}$: the highest branching fraction, large multijet background

$hh \to b\bar{b}\tau^+\tau^-$: relatively large branching fraction, cleaner final state

$hh \to b\bar{b}\gamma\gamma$: small branching fraction, clean signal extraction due to the narrow $h \to \gamma\gamma$ mass peak

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feasibility studies:
$bbZZ$, $WW\tau\tau$ and 4τ

dedicated boosted analyses, VBF-hh investigated

SM Higgs pair production, Run-2 Results

- Observed (expected) 95% C.L. limit on $\sigma/\sigma_{\rm SM}$ (Run-2 published results):

channel	bbbb	bbWW	bb$\tau\tau$	bb$\gamma\gamma$	WW$\gamma\gamma$
ATLAS	13 (21)	-	-	117 (161)	747 (386)
CMS	342 (308)	79 (89)	28 (25)	19 (17)	-

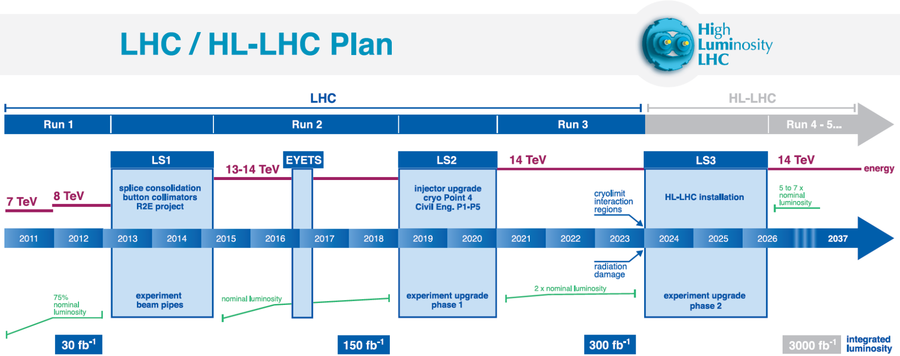
2.3-3.2 fb^{-1} 13.3 fb^{-1} 27.5-35.9 fb^{-1}

- ATLAS publications using the $2015 + 2016$ dataset expected.
- In the context of the HL-LHC prospects studies this is important for those analyses which perform an extrapolation of the Run-2 result.
- Possible statistical combination.

ATLAS $b\bar{b}b\bar{b}$: Preliminary   ATLAS $b\bar{b}\gamma\gamma$: ATLAS-CONF-2016-004   ATLAS $WW\gamma\gamma$: ATLAS-CONF-2016-071

CMS $b\bar{b}b\bar{b}$: PAS HIG-16-002   CMS $b\bar{b}WW$: PAS-HIG-17-006

CMS $b\bar{b}\tau\tau$: Phys. Lett. B 778 (2018) 101   CMS $b\bar{b}\gamma\gamma$: PAS-HIG-17-008



SM hh HL-LHC prospects

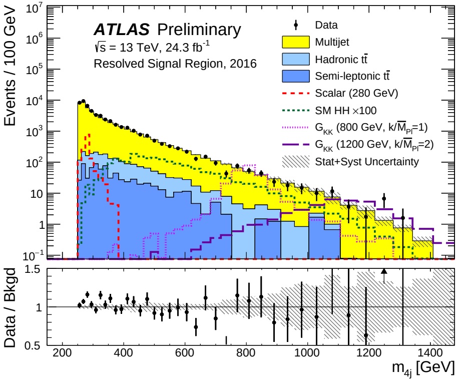
Two alternative approaches:

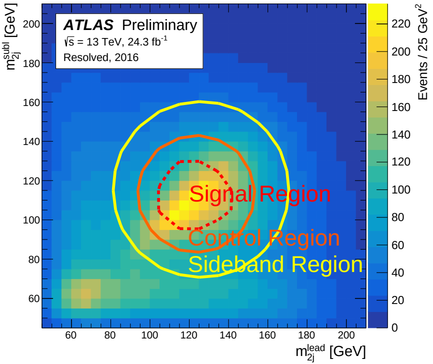
(1) extrapolation of the Run-2 results $\rightarrow \sqrt{s} = 14\,\mathrm{TeV},\ \int L dt = 3000$ fb^{-1}

(2) 14 TeV samples with the upgraded detector geometry, upgrade performance functions

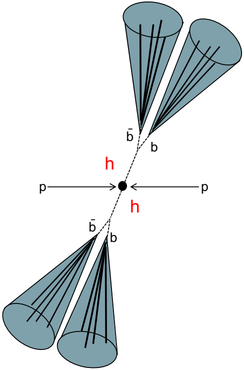
Run-2 resolved $hh \to b\bar{b}b\bar{b}$

- Background:
  $\sim 90\%$ multijet and $\sim 10\%$ $t\bar{t}$
- Data-driven estimation of the multijet background
  $\to 2b + 2j$ events model $4b$





- The reweighting is performed using one-dimensional distributions iteratively
- $t\bar{t}$ normalization from data



SM $hh \to b\bar{b}b\bar{b}$
HL-LHC prospects

ATL-PHYS-PUB-2016-024

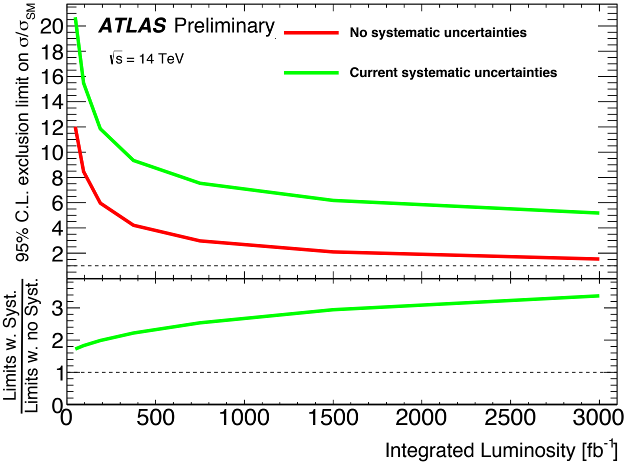
extrapolation of the previous Run-2 result: $\int Ldt = 10.1 \to \int Ldt = 3000$ fb^{-1}

Signal and background distributions scaled by $f = \int Ldt|_{\text{target}} / \int Ldt|_{\text{current}}$

All distributions are scaled by 1.18 to account for an increase in cross-section.

Normalizations fixed to the best Run-2 fit values.

Extrapolated sensitivity



systematic uncertainties in units of signal strength

Source	$\Delta\mu$
Luminosity	0.05
Jet Energy	0.09
b-tagging	0.34
Theoretical	0.10
Multijet	1.85
$t\bar{t}$	2.83

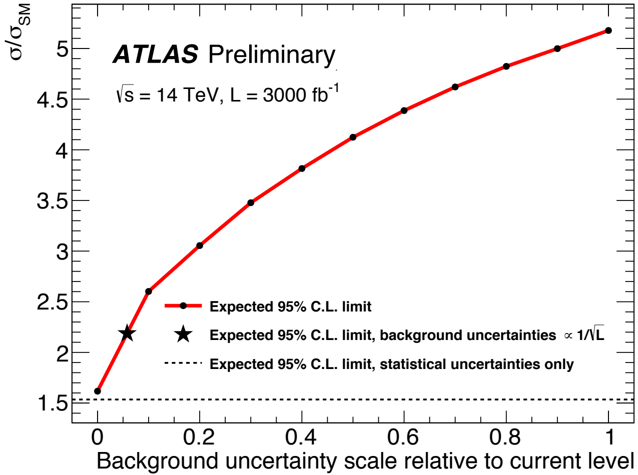
- Extrapolation of the 95% C.L. exclusion limit:

  without systematics: $\sigma/\sigma_{SM} = 1.5$

  with current level of systematics: $\sigma/\sigma_{SM} = 5.2$

Background uncertainty reduction

ATL-PHYS-PUB-2016-024

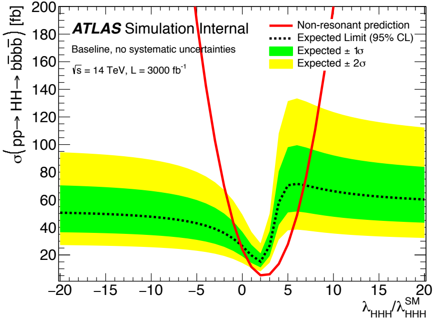


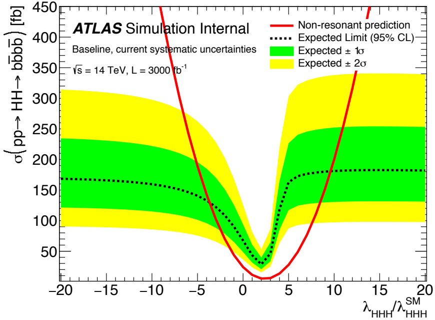
- Significant improvements in (data-driven) background modeling possible with larger dataset

Limits on Higgs self-coupling (Pixel TDR)

Updated in respect to ATL-PHYS-PUB-2016-024

- extrapolated using a full $2015 + 2016$ dataset and
- includes improved ITk b-tagging expected efficiency





- Extrapolation of the 95% C.L. exclusion limit:

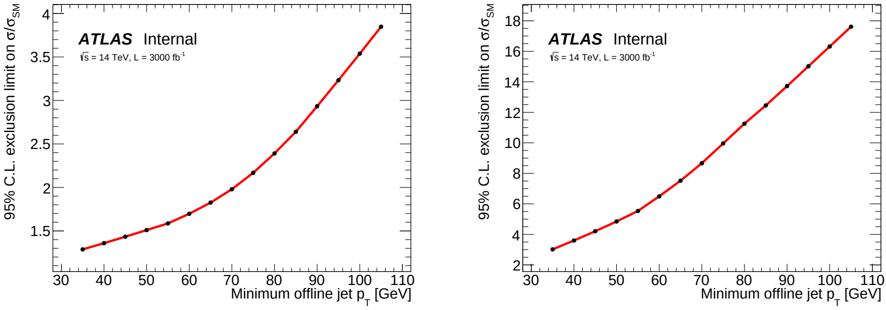
  without systematics: $0.2 < \lambda_{hhh}/\lambda_{hhh}^{\rm SM} < 7.0$

  with systematics: $-3.5 < \lambda_{hhh}/\lambda_{hhh}^{\rm SM} < 11.0$

Minimum jet p_{T} thresholds (TDAQ TDR)

Updated in respect to ATL-PHYS-PUB-2016-024

- extrapolated using a full $2015 + 2016$ dataset and
- includes improved ITk b-tagging expected efficiency



(a) No Systematics *(b) With Systematics*

- Non-resonant $hh \to 4b$ $\sigma/\sigma_{\mathrm{SM}}$ 95% exclusion limit as a function of the minimum offline jet p_T
- $2j35\_b60\_2j35$ trigger most important for Run-2 SM hh (efficient for 85$\%$ of signal)

SM $hh \rightarrow b\bar{b}\gamma\gamma$ **HL-LHC prospects**

ATL-PHYS-PUB-2017-001, Pixel TDR

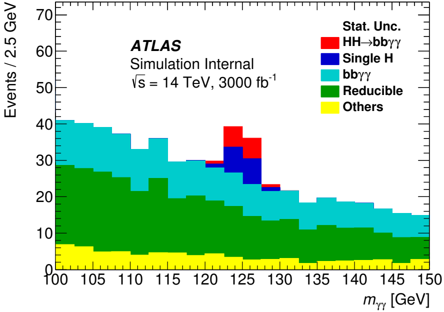
The study is based on $\sqrt{s} = 14$ TeV Monte Carlo (MC) simulations.

The final state particles at truth level are smeared according to the expected detector resolutions assuming a pile-up scenario with 200 overlapping events ($< \mu >= 200$).

The expected efficiencies and fake rates for identifying b-jets and photons are used.

Background composition

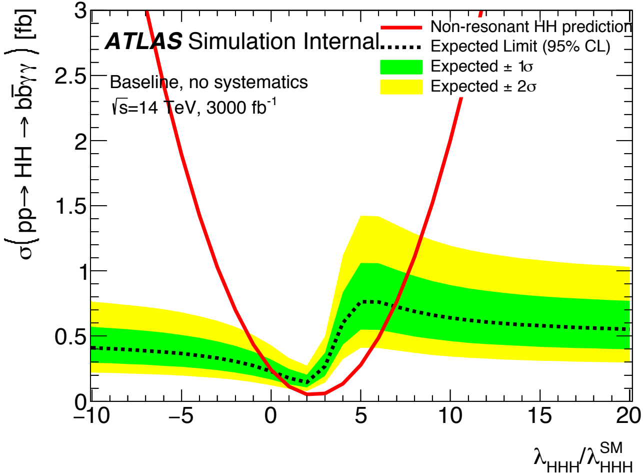
- Main backgrounds arise from processes with multiple jets and photons:
  - Processes with a single Higgs boson
  - Continuum background ($b\bar{b}\gamma\gamma$, $c\bar{c}\gamma\gamma$, $jj\gamma\gamma$, $b\bar{b}j\gamma$, $c\bar{c}j\gamma$, $b\bar{b}jj$)
- Other backgrounds include $Z(b\bar{b})\gamma\gamma$, $t\bar{t}$ and $t\bar{t}\gamma$ processes.



Di-photon invariant mass distribution after the selection except for m_{bb} cut

- Significance (Pixel TDR): 1.5σ
  (based on improved b-tagging performance and photon energy resolution)
- ATL-PHYS-PUB-2017-001: 1.05σ

Limits on Higgs self-coupling



- Result without systematics (Pixel TDR): $0.2 < \lambda_{hhh}/\lambda_{hhh}^{\rm SM} < 6.9$
  (based on improved b-tagging performance and photon energy resolution)
- ATL-PHYS-PUB-2017-001: $-0.8 < \lambda_{hhh}/\lambda_{hhh}^{\rm SM} < 7.7$

SM $hh \to b\bar{b}\tau^+\tau^-$ ***HL-LHC prospects***

ATL-PHYS-PUB-2015-046

The study is based on $\sqrt{s} = 14$ TeV Monte Carlo (MC) simulations.

The final state particles at truth level are smeared according to the expected detector resolutions assuming a pile-up scenario with 140 overlapping events ($<\mu>= 140$).

The expected efficiencies and fake rates for identifying b-jets and τs are used.

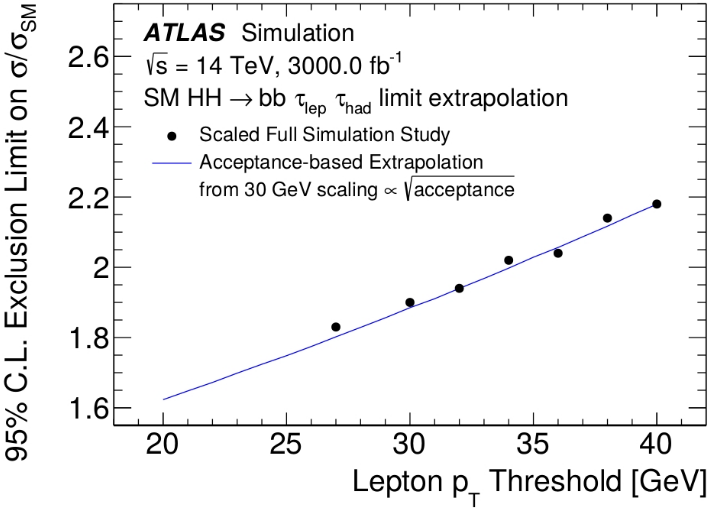
All di-τ final states considered.

Results with systematics: 0.6σ

$$-4.0 < \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}} < 12$$

Single lepton trigger (TDAQ TDR)

- SM $hh \to b\bar{b}\tau^{+}_{\text{lep}}\tau^{-}_{\text{had}}$ Run-2 result extrapolation based study (w/o syst)



Summary table

channel	$\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}$ allowed interval @ 95% C.L.	significance
$hh \to b\bar{b}b\bar{b}$ current syst	[-3.5,11.0]	
$hh \to b\bar{b}\gamma\gamma$ w/o syst	[0.2,6.9]	1.5σ
$hh \to b\bar{b}\tau^+\tau^-$ syst	[-4.0,12.0]	0.6σ

- Very conservative estimations!

Conclusion and Outlook

- Other ggF channels and the VBF category for the most sensitive channels could contribute to overall sensitivity
- Statistical uncertainty dominant for all Run-2 analyses
- Main systematic uncertainties: b-tagging, τ-identification, ...
- Background modeling uncertainties can be reduced with an increased amount of data.
- Triggering stays the limiting factor (topological triggers could be helpful). Inner detector upgrades important for hh
- Hoping for updated results soon. This will provide more realistic estimations and better understanding of the needed detector performance.

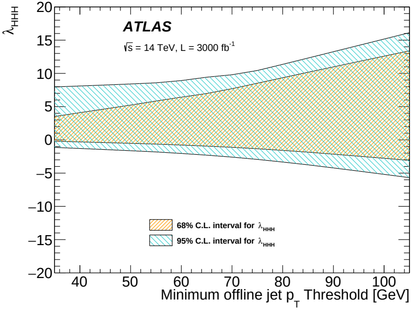
Thank you for your attention!

backup slides

Minimum jet p_{T} thresholds (TDAQ TDR)

Updated in respect to ATL-PHYS-PUB-2016-024

- extrapolated using a full $2015 + 2016$ dataset and
- includes improved ITk b-tagging expected efficiency



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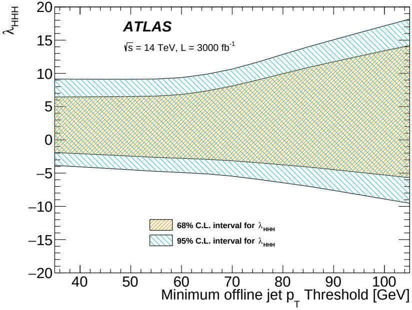

(b) With Systematics

- Allowed intervals for the λ_{hhh} parameter assuming the SM as function of the minimum offline jet p_T.
- $2j35\_b60\_2j35$ trigger most important for Run-2 SM hh (efficient for 85$\%$ of signal)