



# HH Hunting in ATLAS

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Tatjana Lenz (U Bonn)

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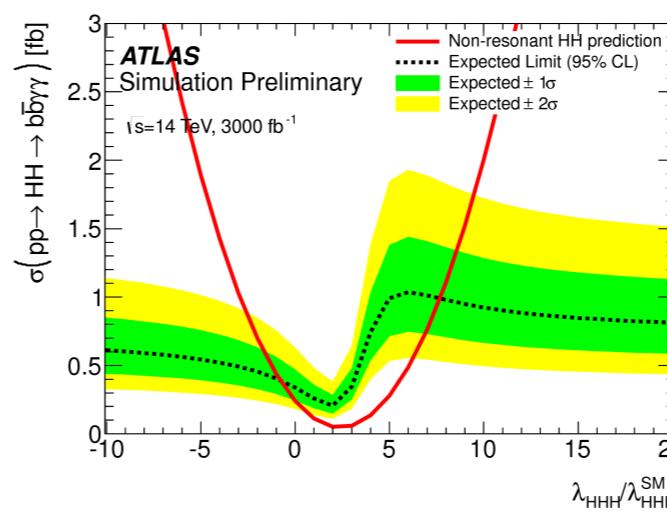
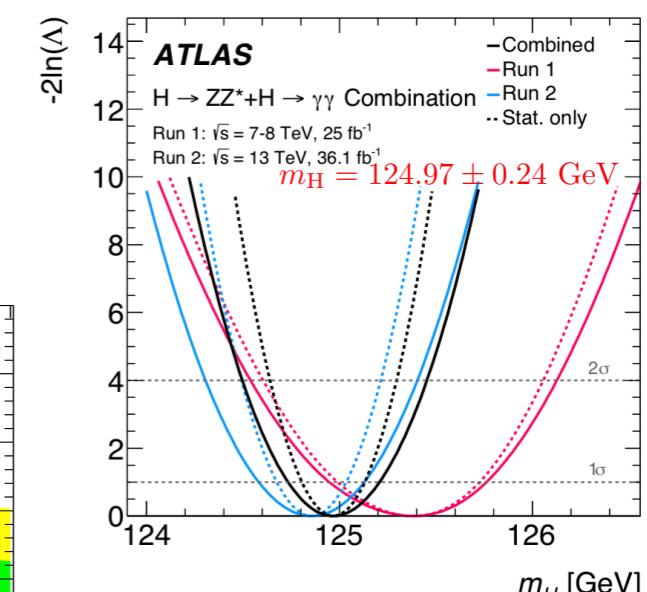
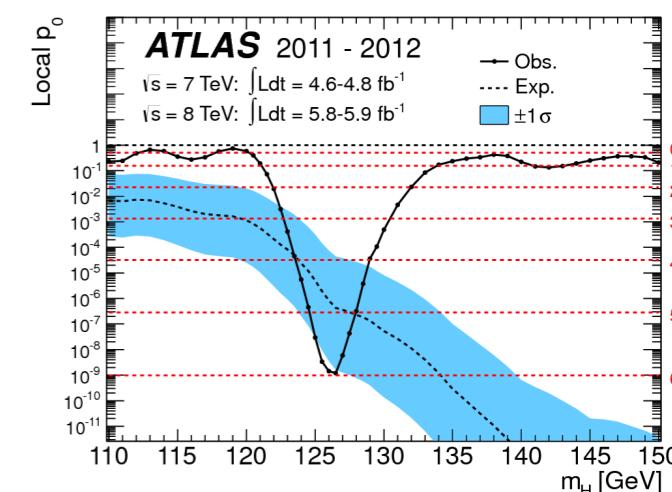
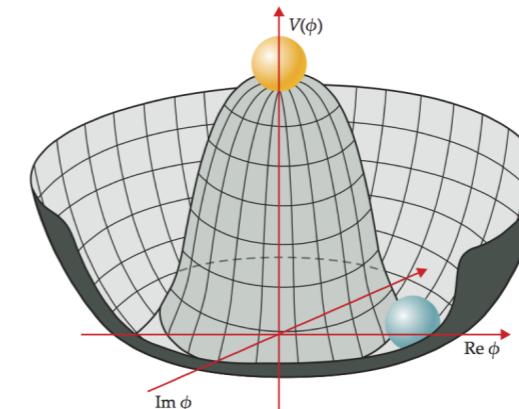
# Why Higgs Physics?

## Unique role in the SM

- only elementary scalar
- only field with a non-zero vev
- masses of particles via Higgs couplings

## Open questions:

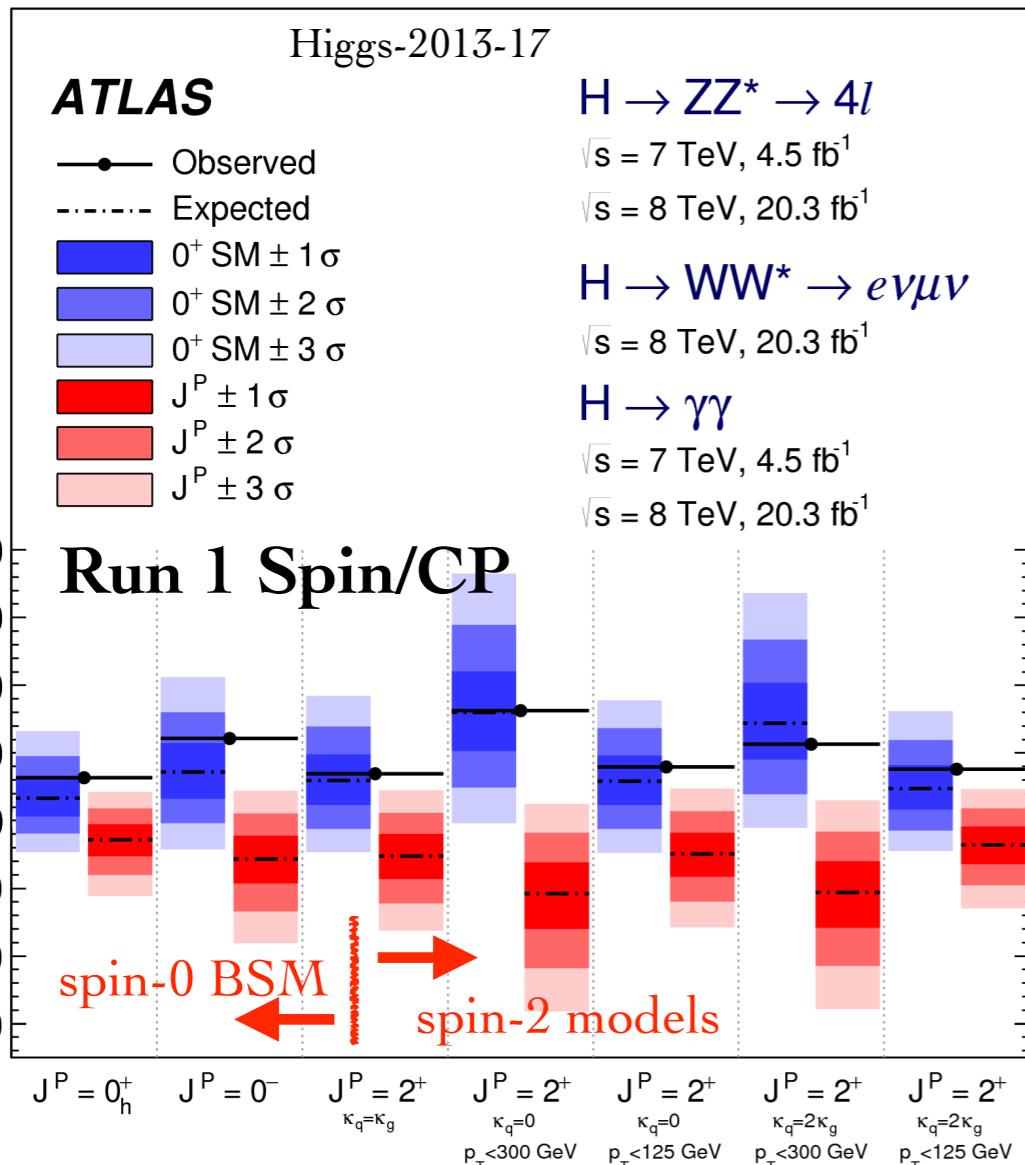
- the SM Higgs boson?
- responsible for masses of all particles?
- produced via top quark loops or BSM particles?
- and many other ???



# Higgs Physics

## Run 1 highlights

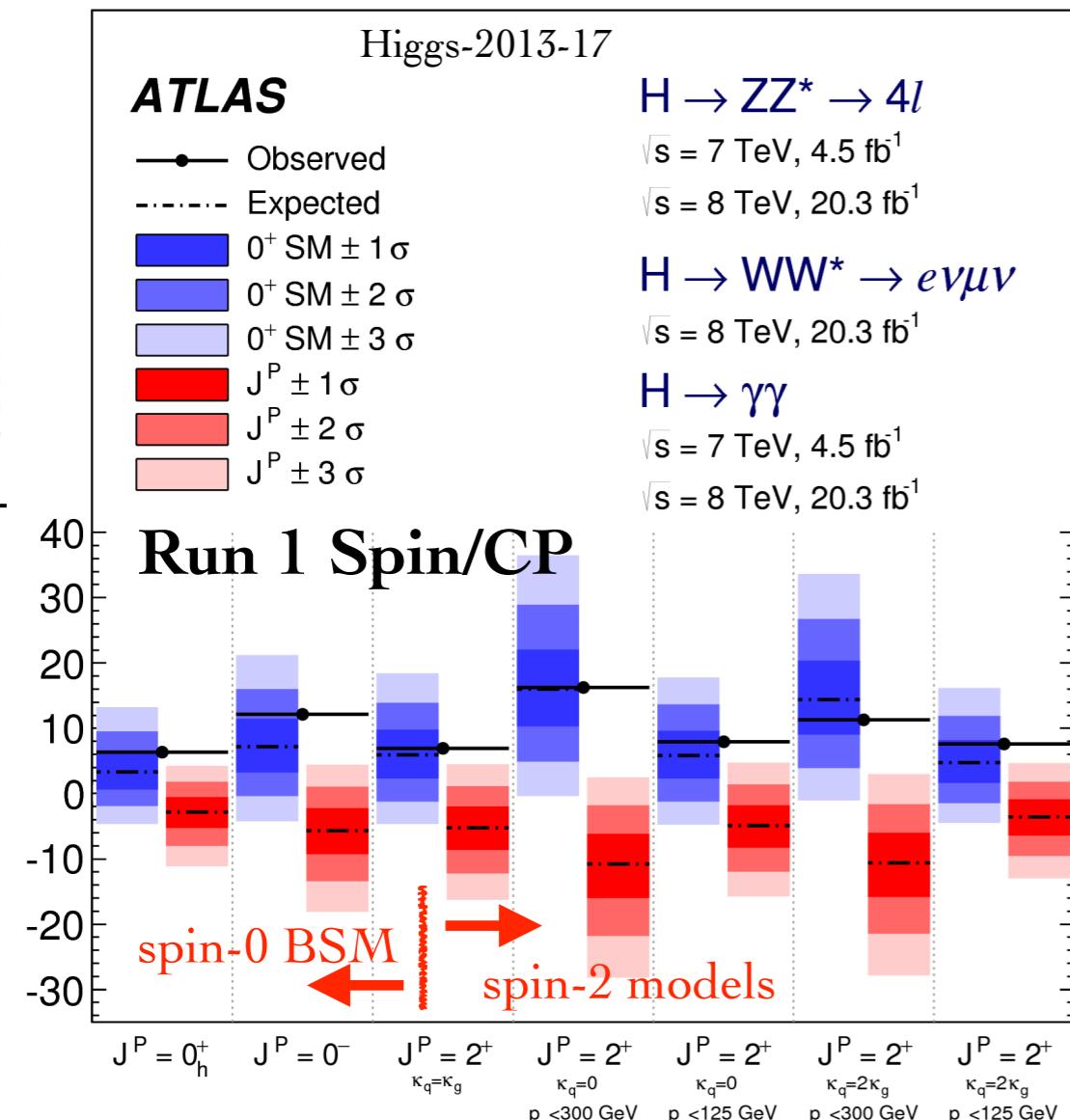
- discovery
- observation of  $\gamma\gamma$ , ZZ, WW,  $\tau\tau$  and VBF
- couplings, spin and CP  $\rightarrow$  SM-like H
- H mass
- BSM exclusions



# Higgs Physics

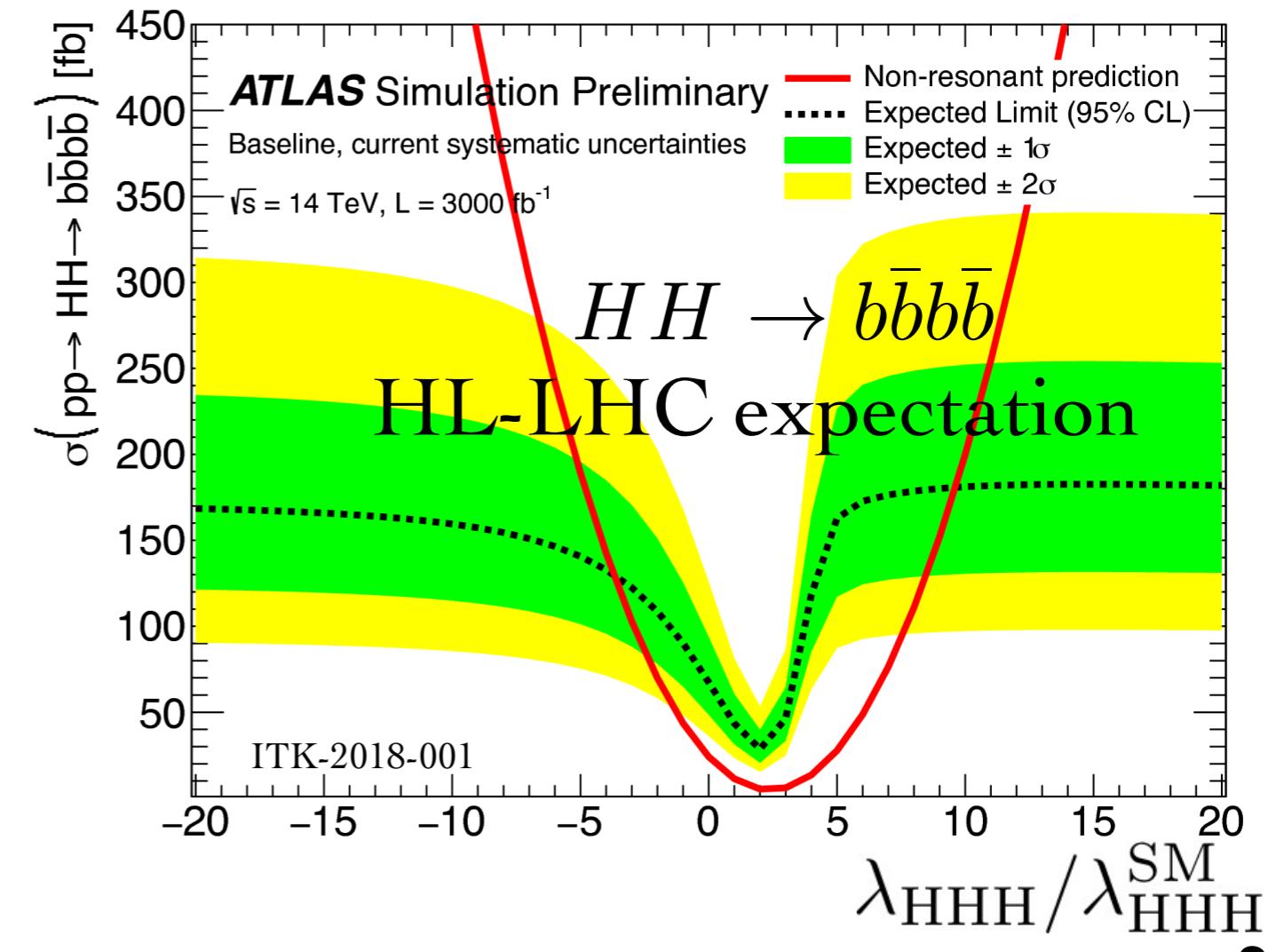
## Run 1 highlights

- discovery
- observation of  $\gamma\gamma$ , ZZ, WW,  $\tau\tau$  and VBF
- couplings, spin and CP  $\rightarrow$  SM-like H
- H mass
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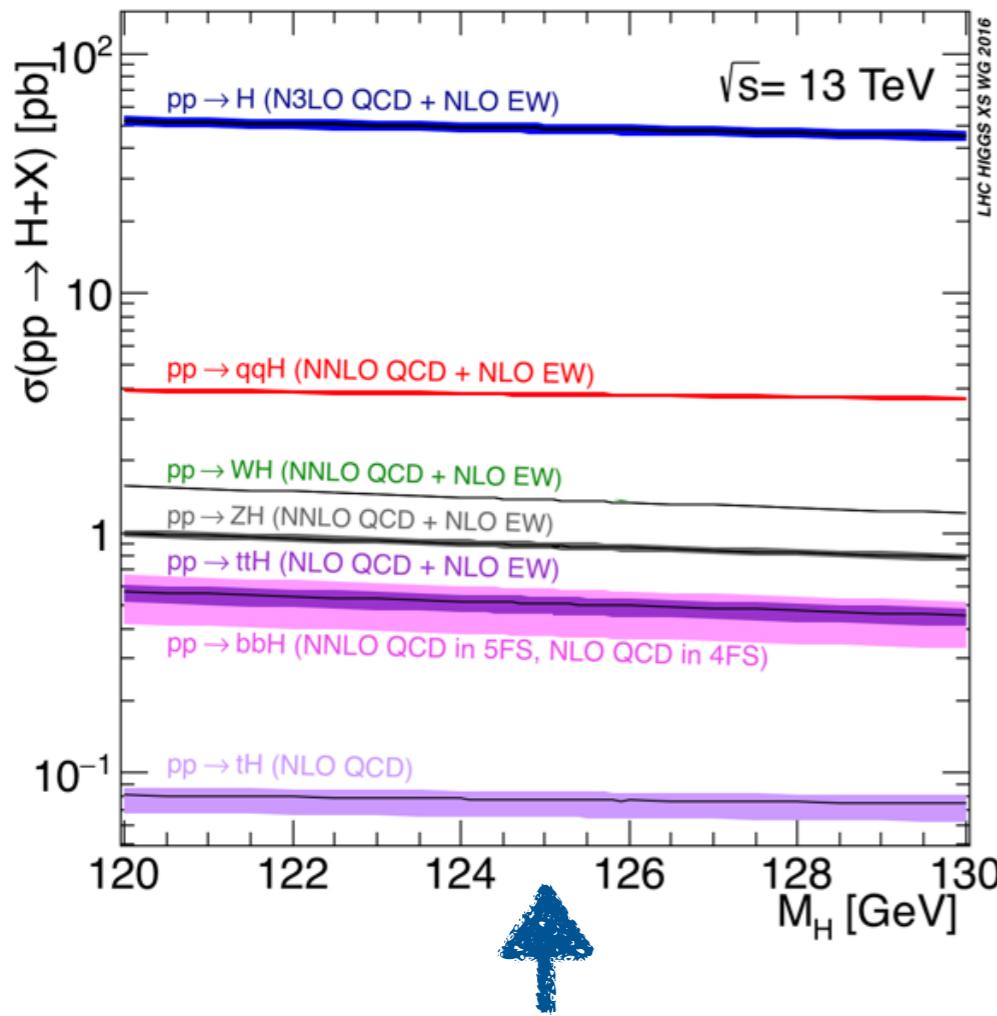
## Run 2 and beyond (wish) list

- differential and fiducial cross sections, H mass
- observation of VH, ttH and bb,  $\mu\mu$ , cc, ...
- HH production and Higgs self-coupling
- New Physics

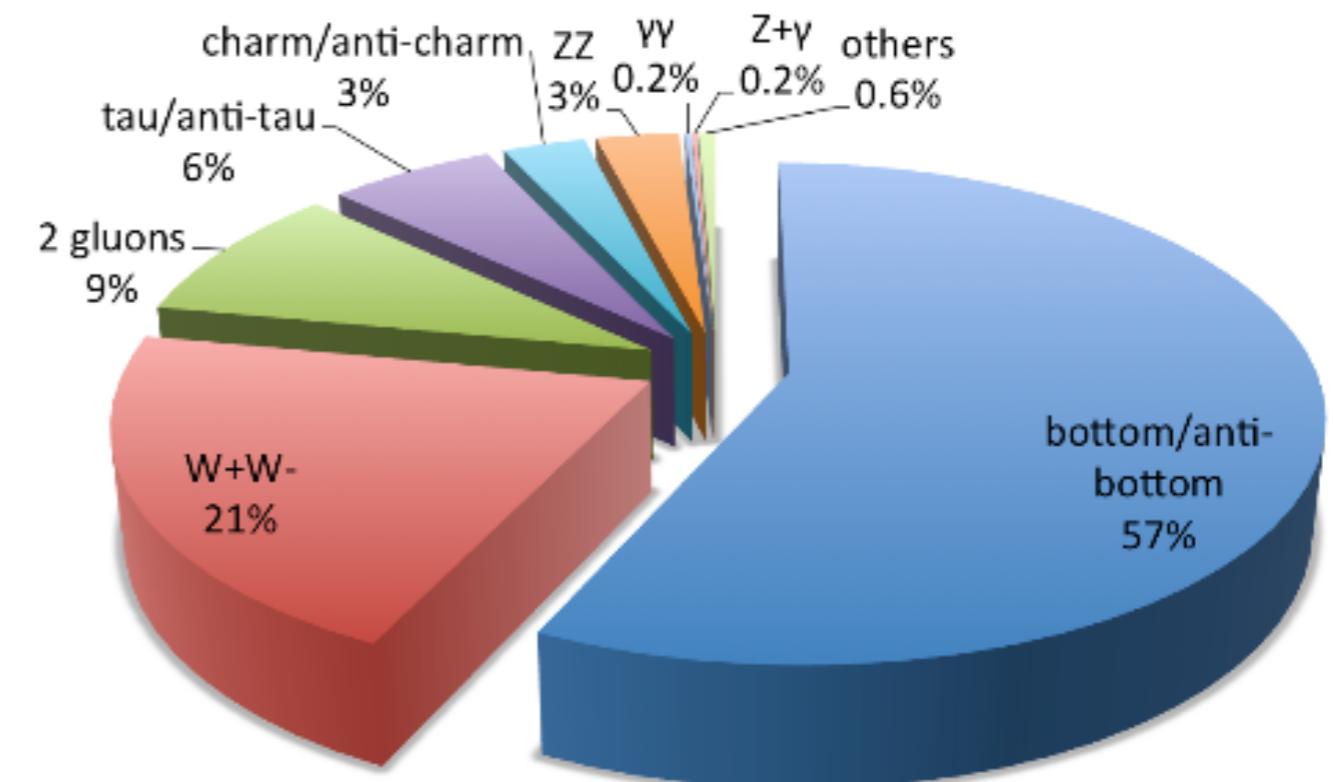


# Higgs Boson Portrait

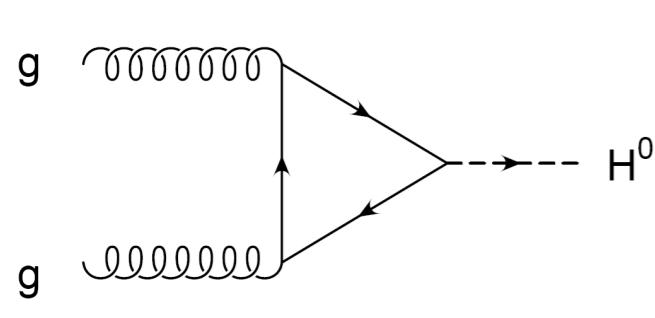
## Production



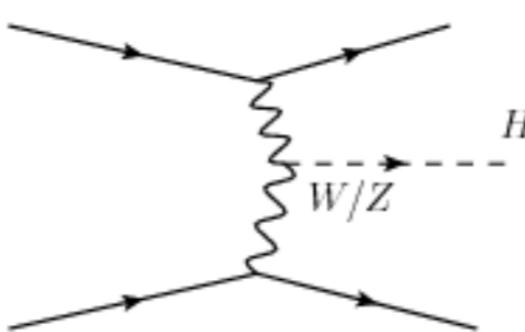
## Decay $H \rightarrow XX$



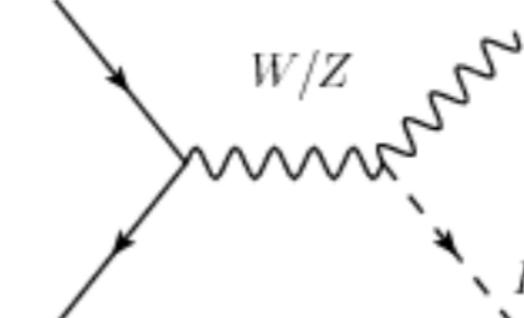
$gg \rightarrow H$  @ 86%



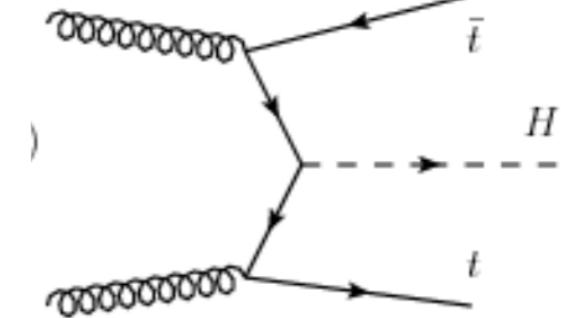
$qqH$  @ 7%



$VH$  @ 5%

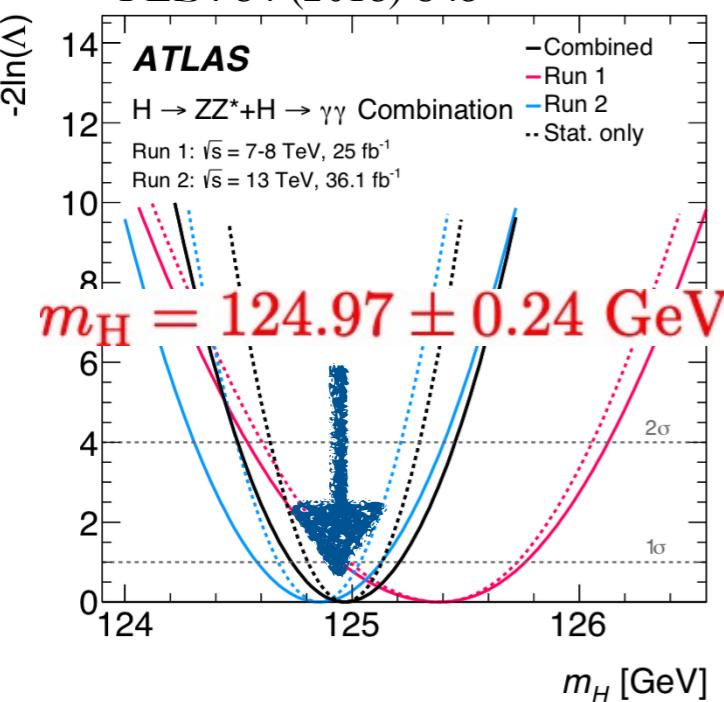
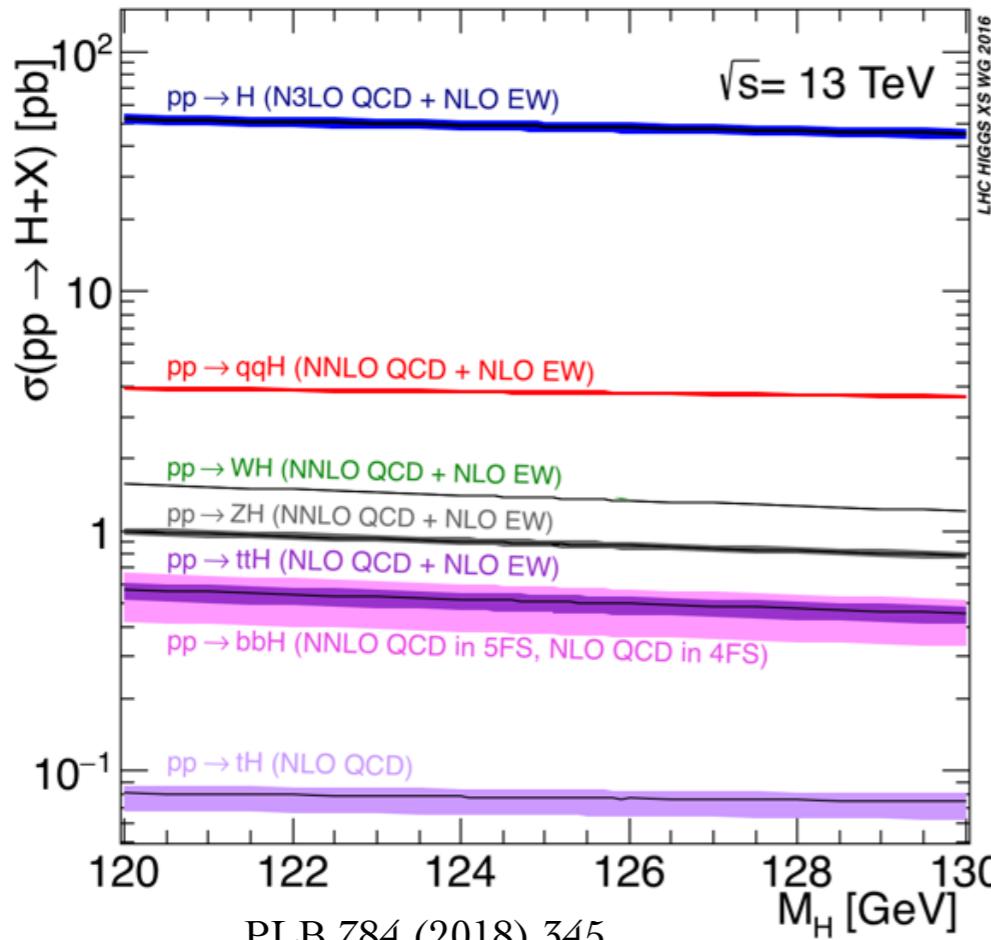


$ttH$  @ 0.6%

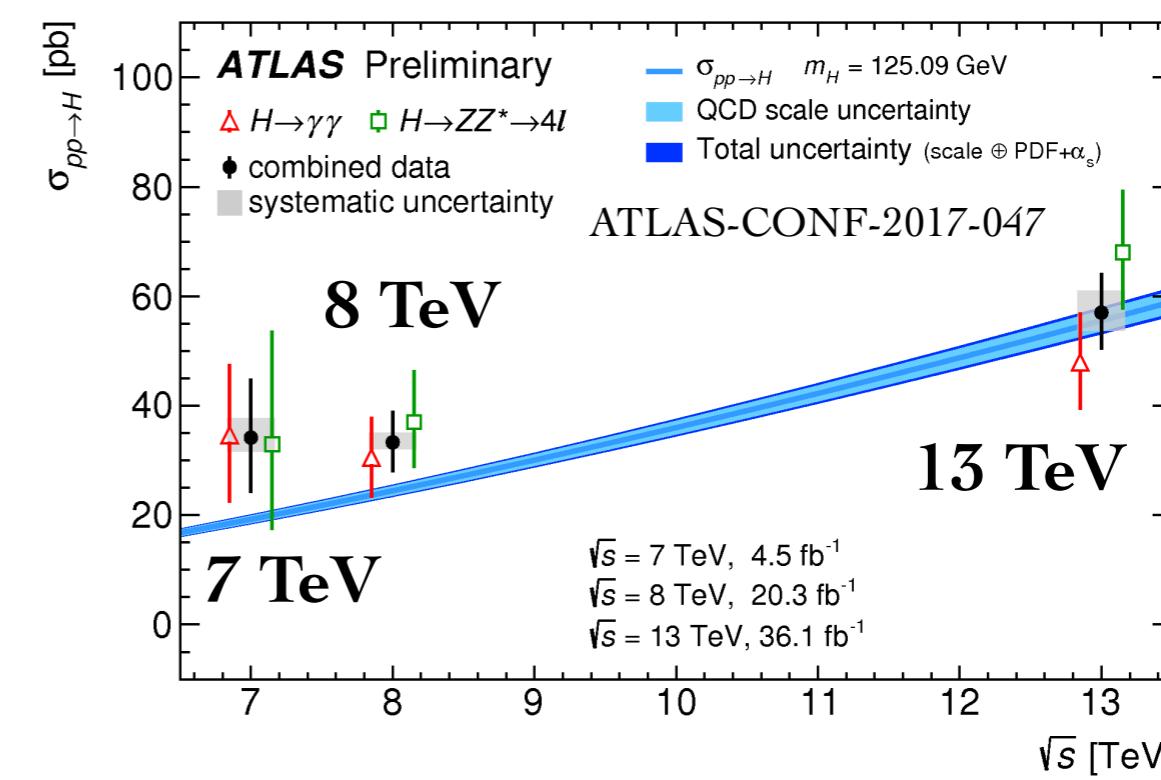
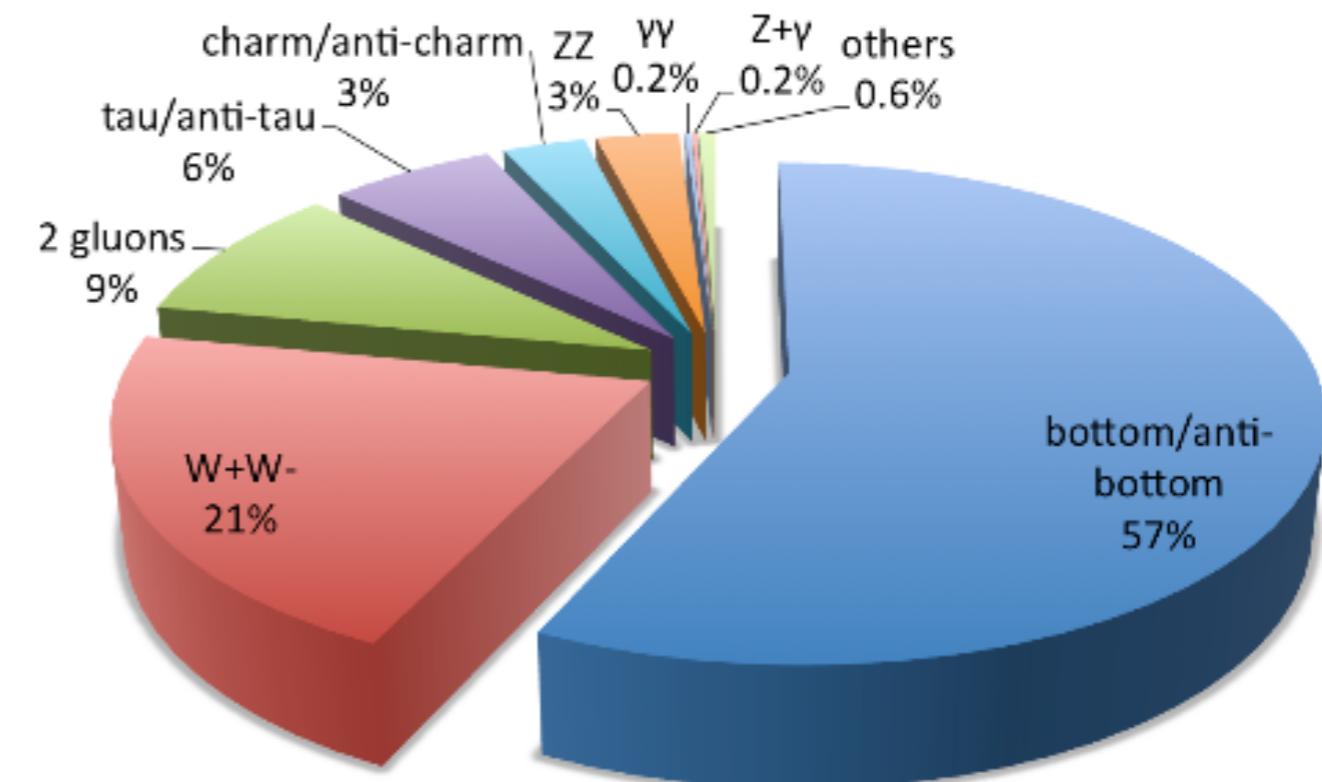


# Higgs Boson Portrait

## Production



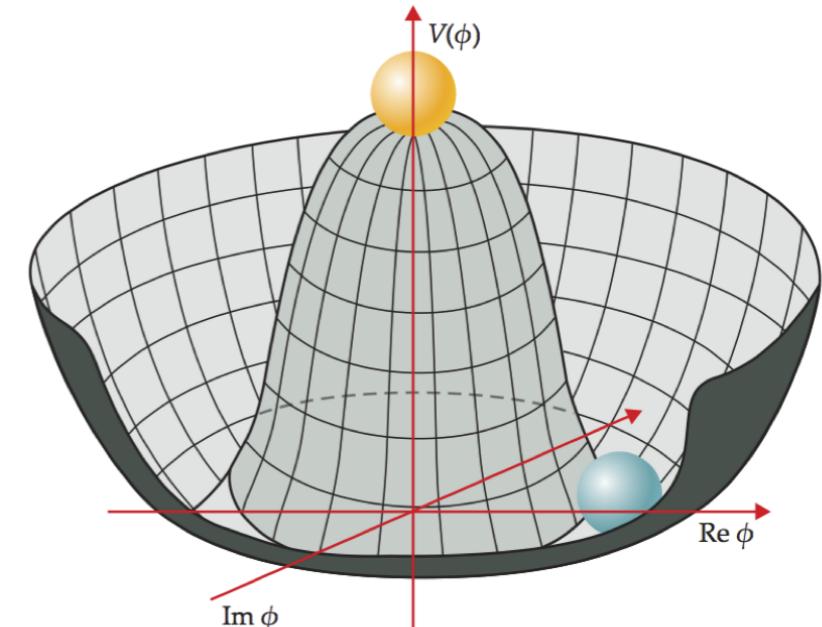
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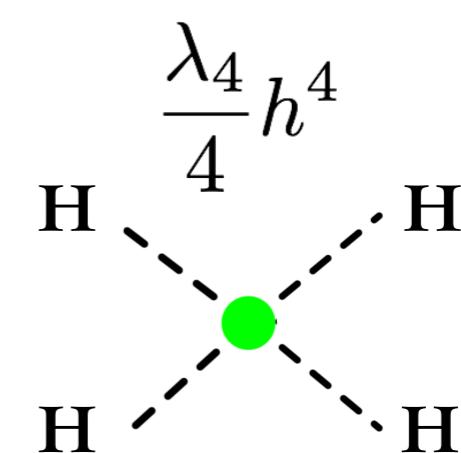
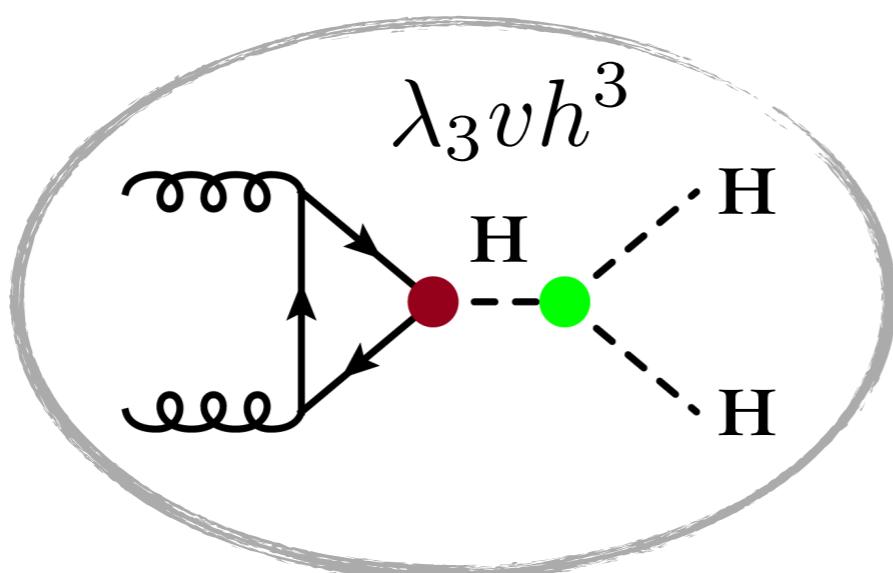
# Higgs Self-Coupling

- **HH production** allows a direct test of Higgs potential and Higgs self-coupling

$$V(h) = \frac{m_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

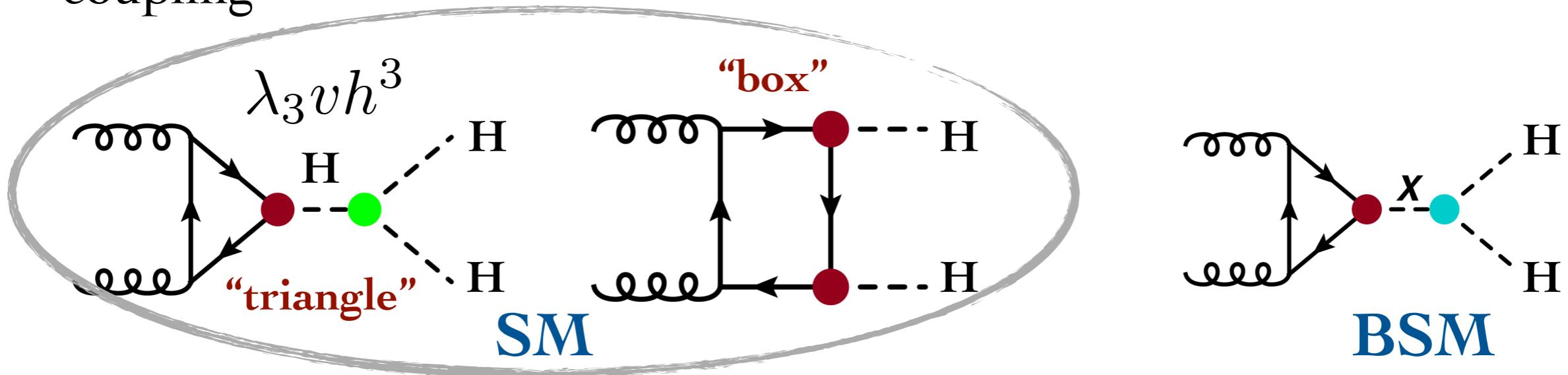


SM:  $\lambda_3 = \lambda_4 = \lambda = \frac{m_h^2}{2v^2} = 0.13$



# Higgs Self-Coupling

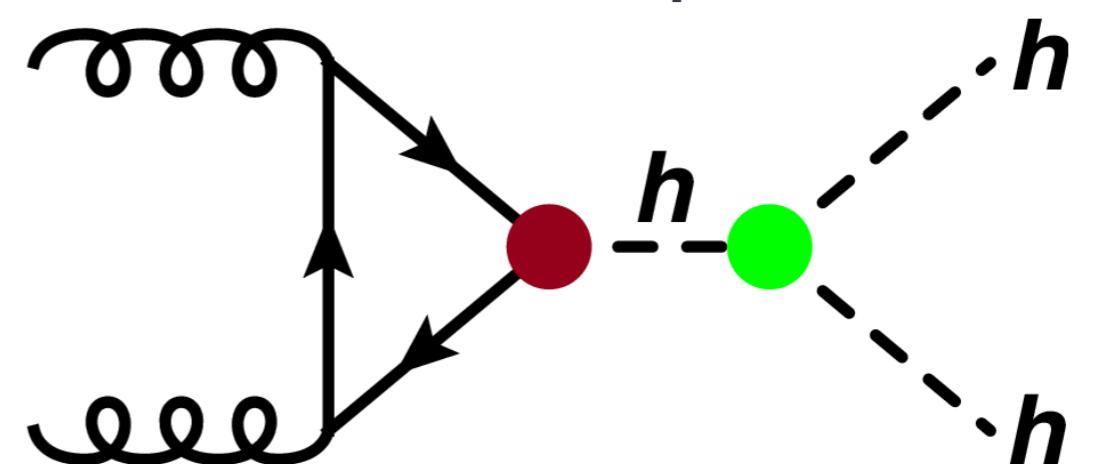
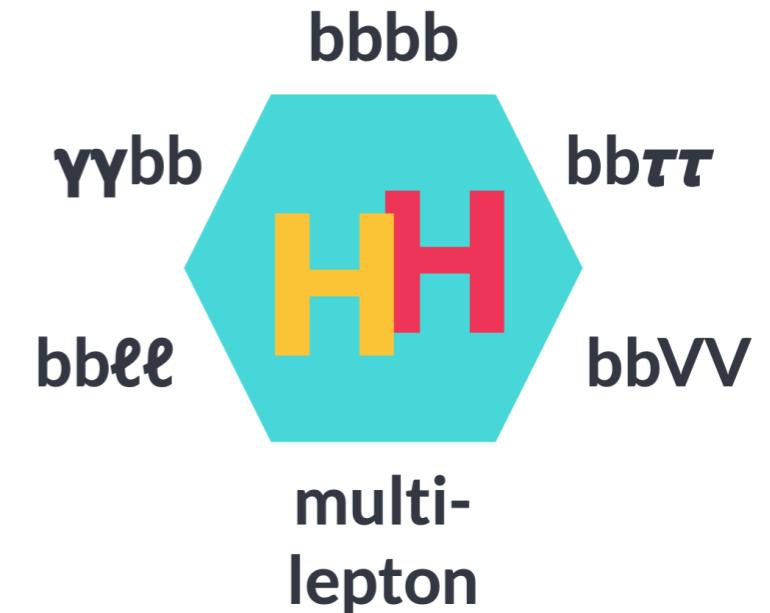
- **HH production** allows a direct test of Higgs potential and Higgs self-coupling



- **SM HH production** cross section 1000 times smaller than  $pp \rightarrow H$ 
  - two diagrams with **destructive interference** =  $33 \text{ fb}$  @ 13 TeV
- **BSM** can lead to enhancement in the HH production
  - **non-resonant** production due to modified  $\lambda$ , new vertices or new particles in the loop
  - **resonant** production modes: KK gravitons, H in 2HDM, new scalar singlets, cross sections up to  $O(\text{pb})$

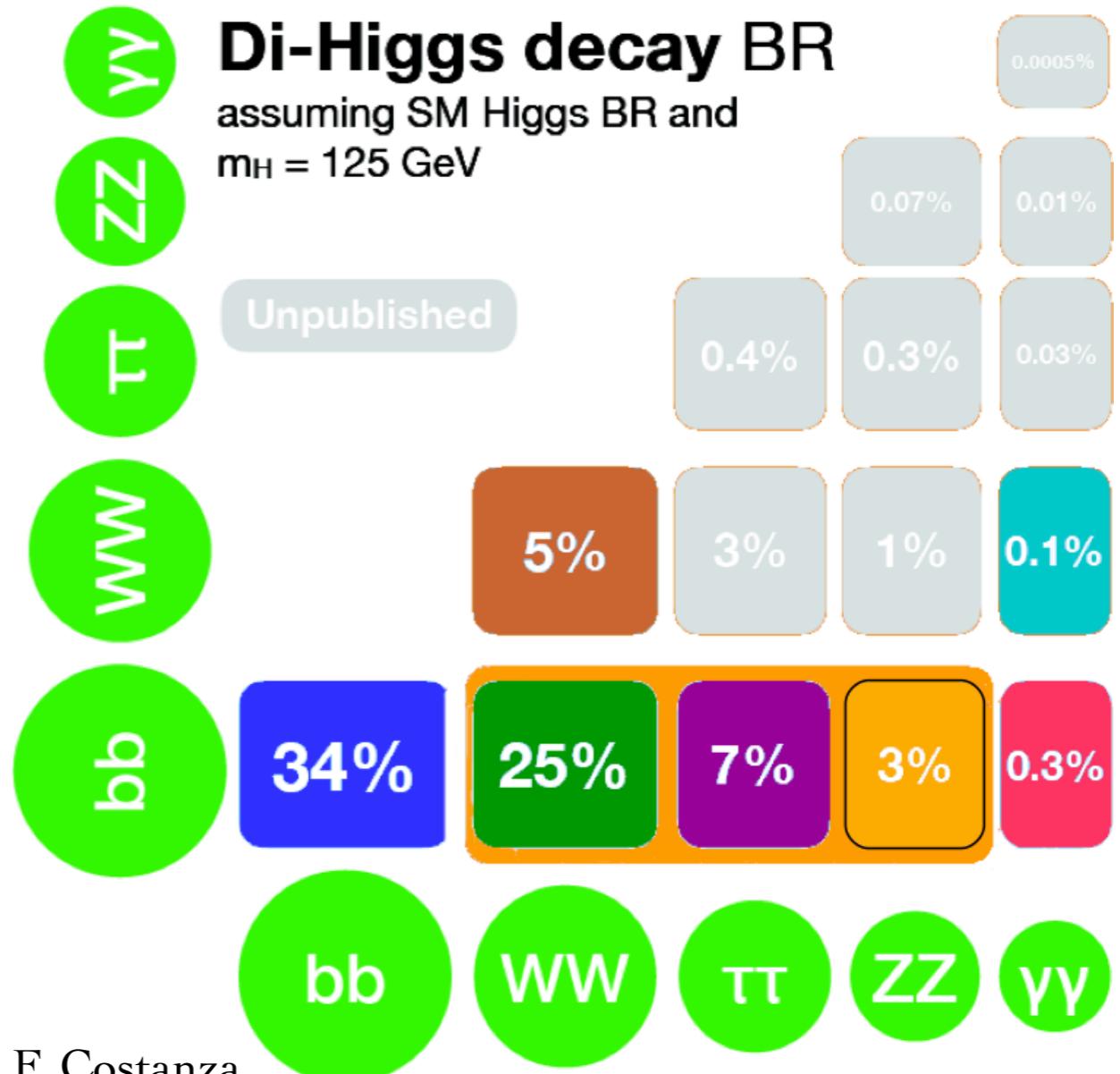
# Outline

- search for the HH production
  - non-resonant (SM) production
  - resonant production
- Higgs self-coupling
  - HH and H analyses
- HH prospects



# HH Decays

Channel	Lumi, $fb^{-1}$	Reference
4b	28-36	JHEP 01 (2019) 030
2b2W	36	JHEP 04 (2019) 029
2b2 $\tau$	36	PRL 121 (2018) 191801
4W	36	JHEP 05 (2019) 124
2b2 $\gamma$	36	JHEP 11 (2018) 40
2W2 $\gamma$	36	EPJC 78 (2018) 1007
comb	36	1906.02025
2blvlv	140	1908.0676
VBF 4b	126	ATLAS-CONF-2019-030

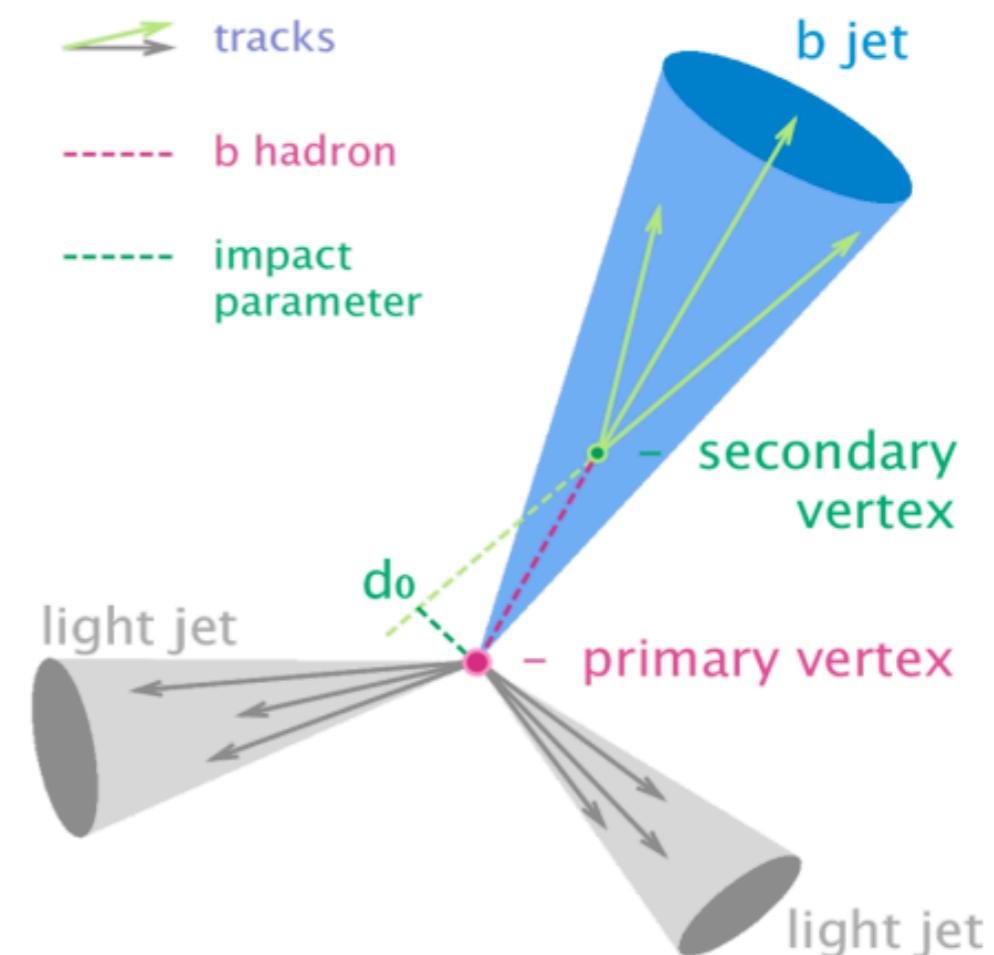


F. Costanza

most promising channels at LHC: 4b, bb $\tau\tau$  and bb $\gamma\gamma$

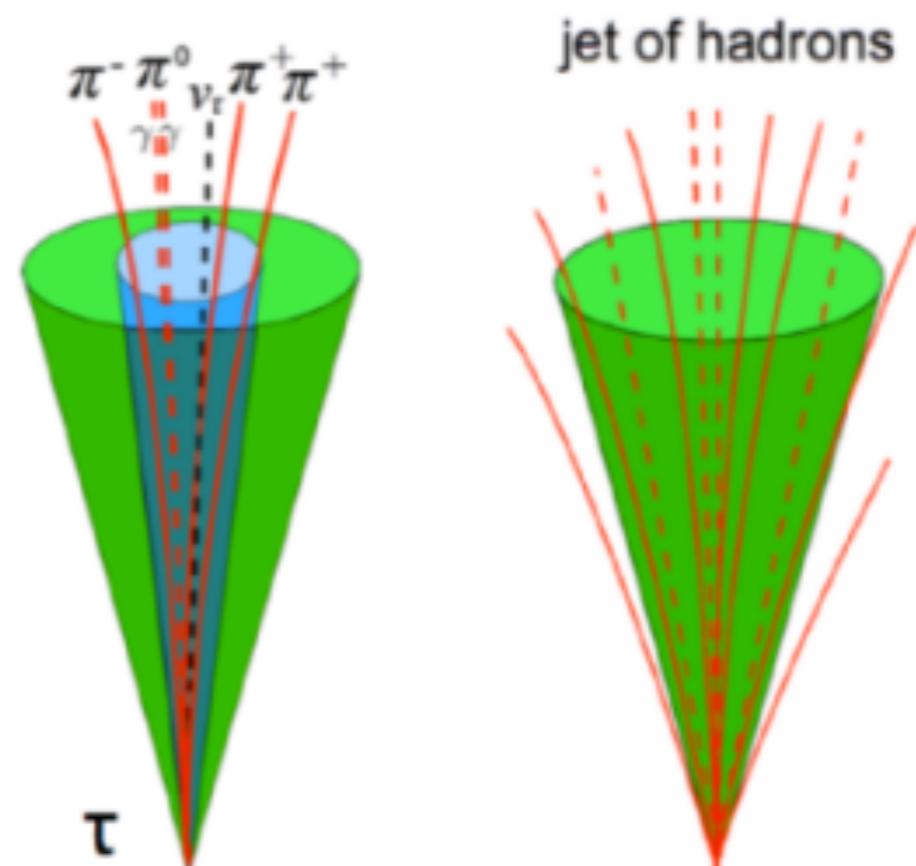
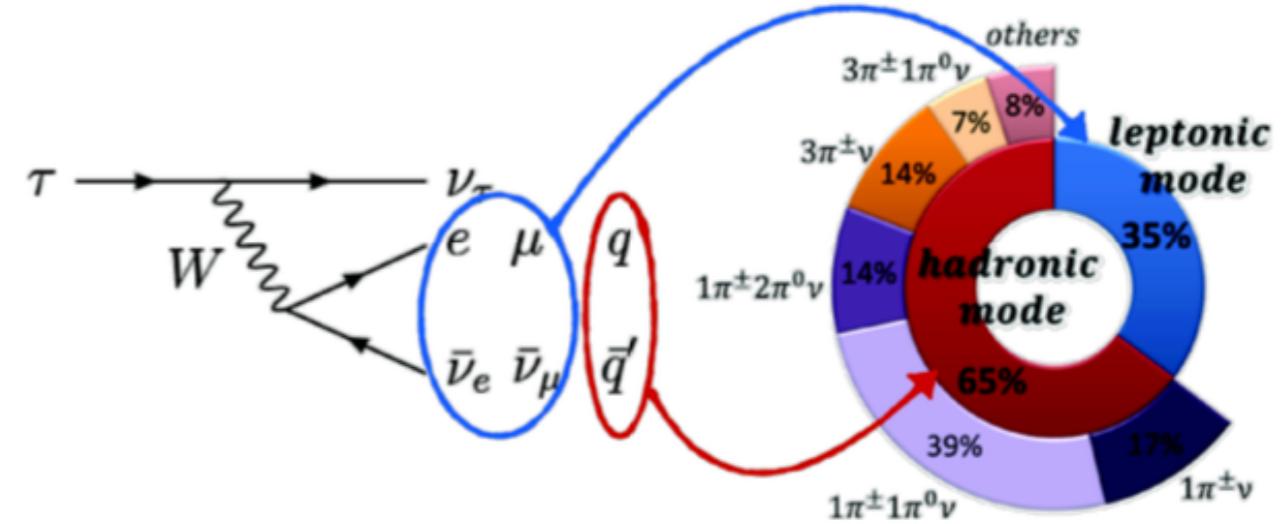
# b-jet Tagging

- jets = collimated bunch of hadrons
  - hadronisation of quarks and gluons
- types of jets: **b-jets**, charm-jets, (hadronic)  $\tau$ -jets and light jets
- **b-tagging algorithms** explore properties of B-hadrons:
  - relatively **long lifetime** (1.6 pc)-> measurable decay length (2-3mm @  $p_T = 50$  GeV)
  - **decay vertex** displaced from the interaction vertex, B-hadron **mass**, B-hadron carries most of b-jet energy (**fragmentation**)
- combined in **multivariate classifier** (BDT)
  - working point (WP): 70% b-jet efficiency and 0.1% light jet efficiency

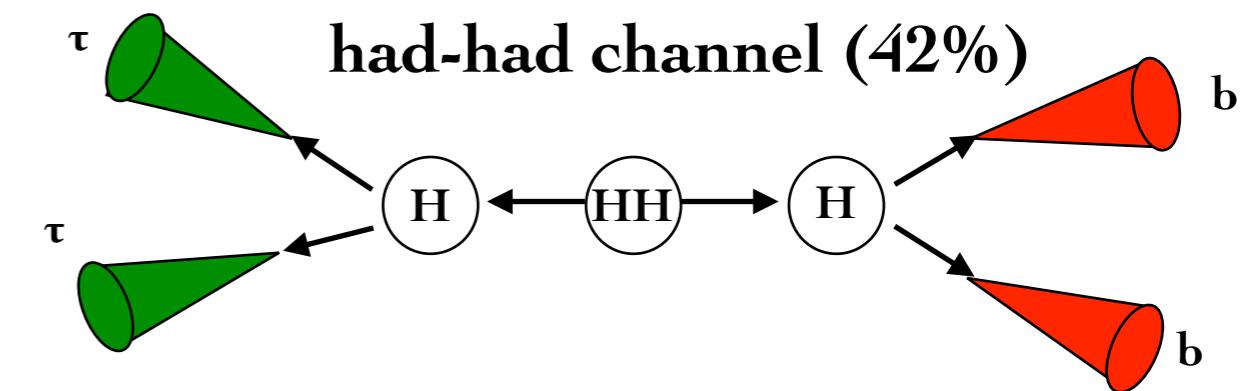
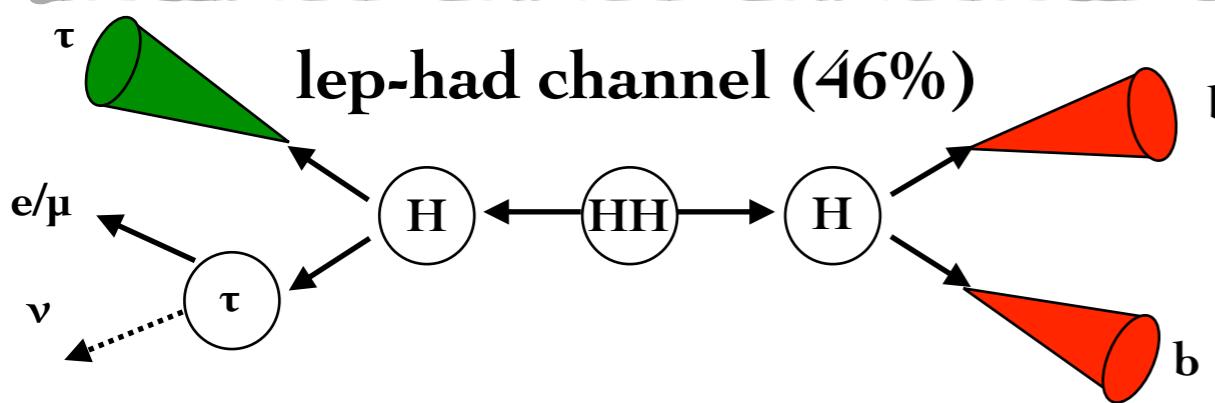


# $\tau$ Lepton Reconstruction

- **$\tau$ -lepton decays**
  - 65% hadronically with 1 or 3 charged pions
  - 35% leptonically
- **hadronic  $\tau$ -lepton identification (ID)** explores differences between  $\tau$ -jets and QCD-jets
  - number of tracks ( $==1$  or  $==3$ )
  - lateral shape
  - track momenta and inv. mass
- combined in **multivariate classifier (BDT)**
  - $\tau$ -ID at 55% efficiency WP (multijet efficiency  $\sim 1\%$ )



# HH $b\bar{b}\tau\bar{\tau}$

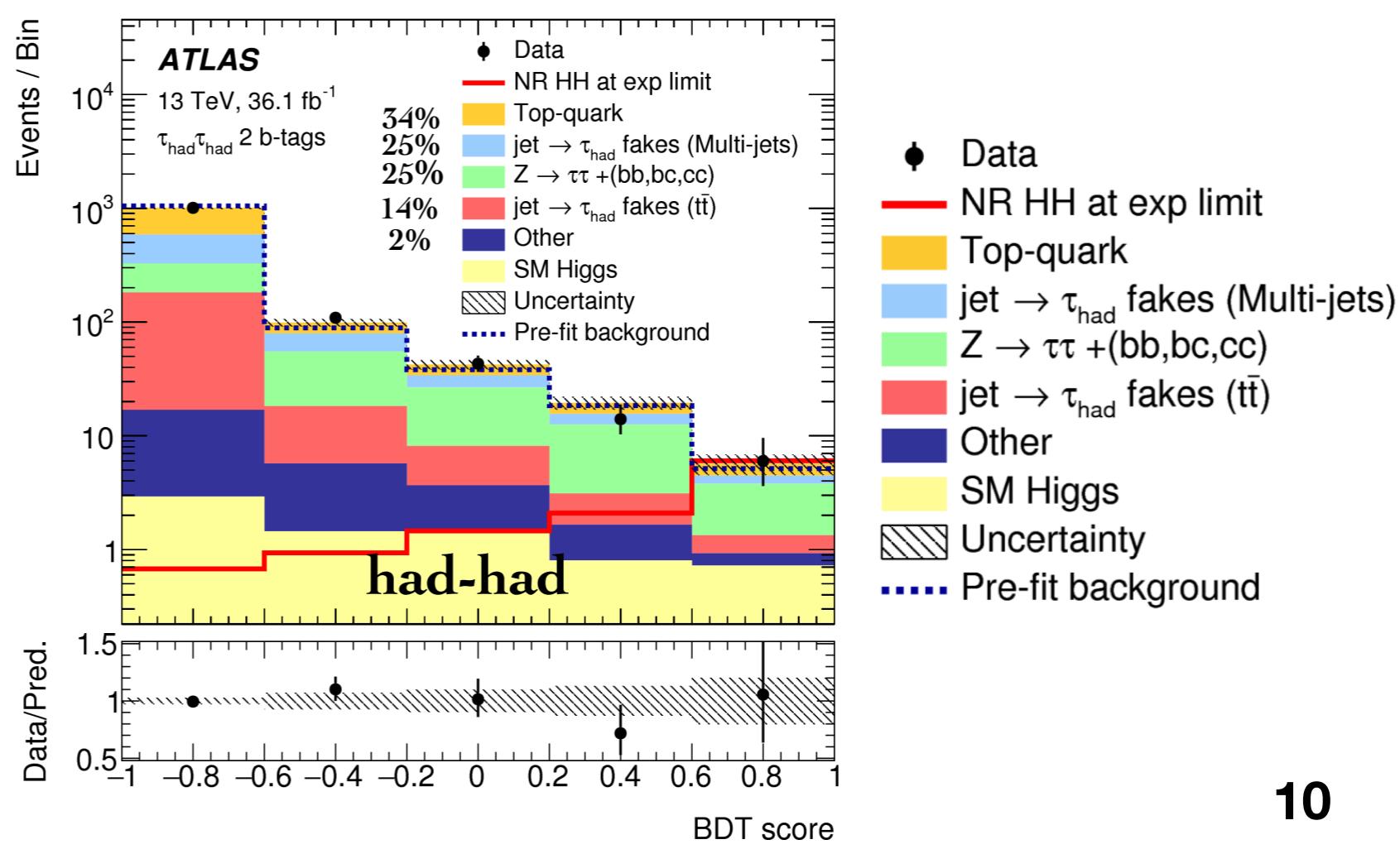
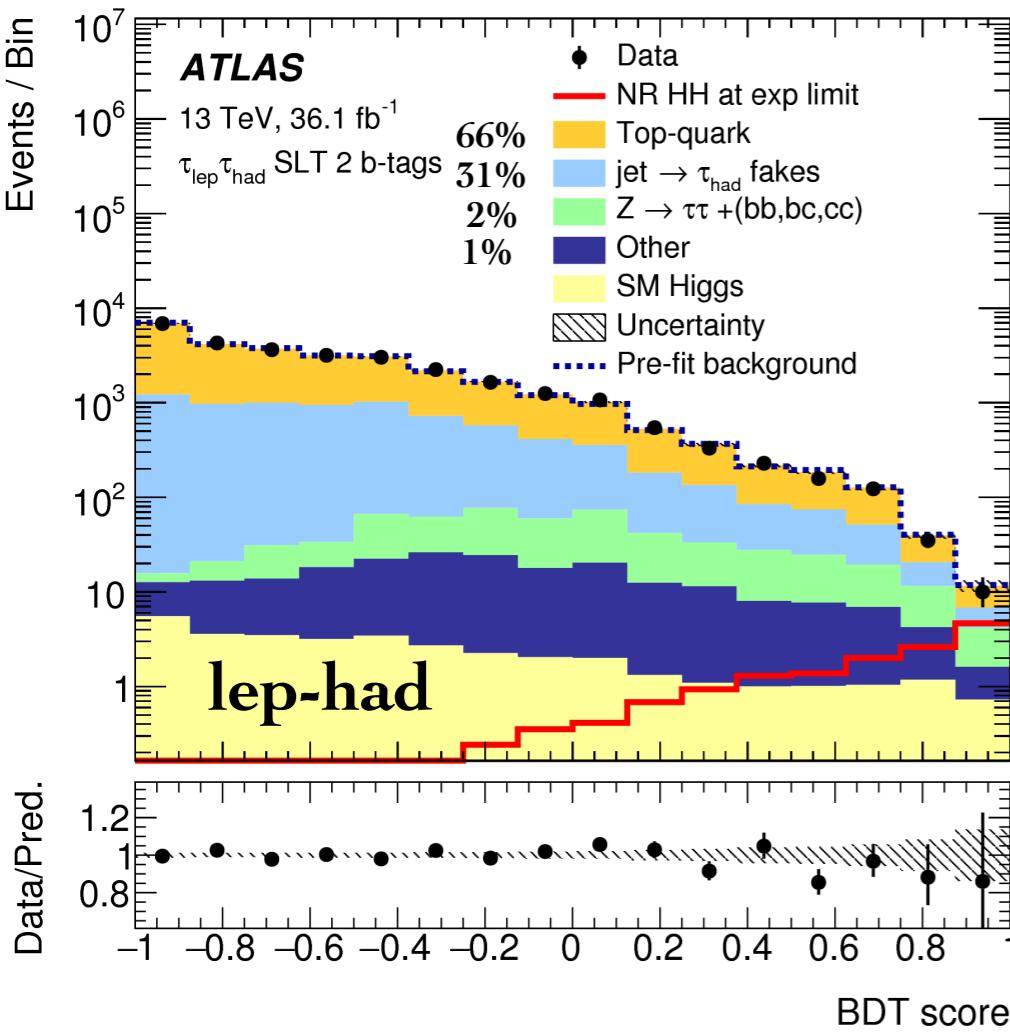


## pros:

- sizeable branching ratio (7%)
- moderate bkg contamination

## contras:

- neutrinos in  $\tau$  decays
- challenging had.  $\tau$  reco and triggering



# HH bb $\tau\tau$ : Fake $\tau$ -had Bkg

- jets can **fake** hadronic  $\tau$ 's
  - source: multijet, W+jets, tt
  - fake-probability depends on jet-type: gluon- or quark-jet
    - ~30% higher for quark-jets
- **data-driven approach** for all three sources
- fake-enriched sample:  $\tau$  fails medium (55% WP)  $\tau$ -ID but satisfies very loose  $\tau$ -ID

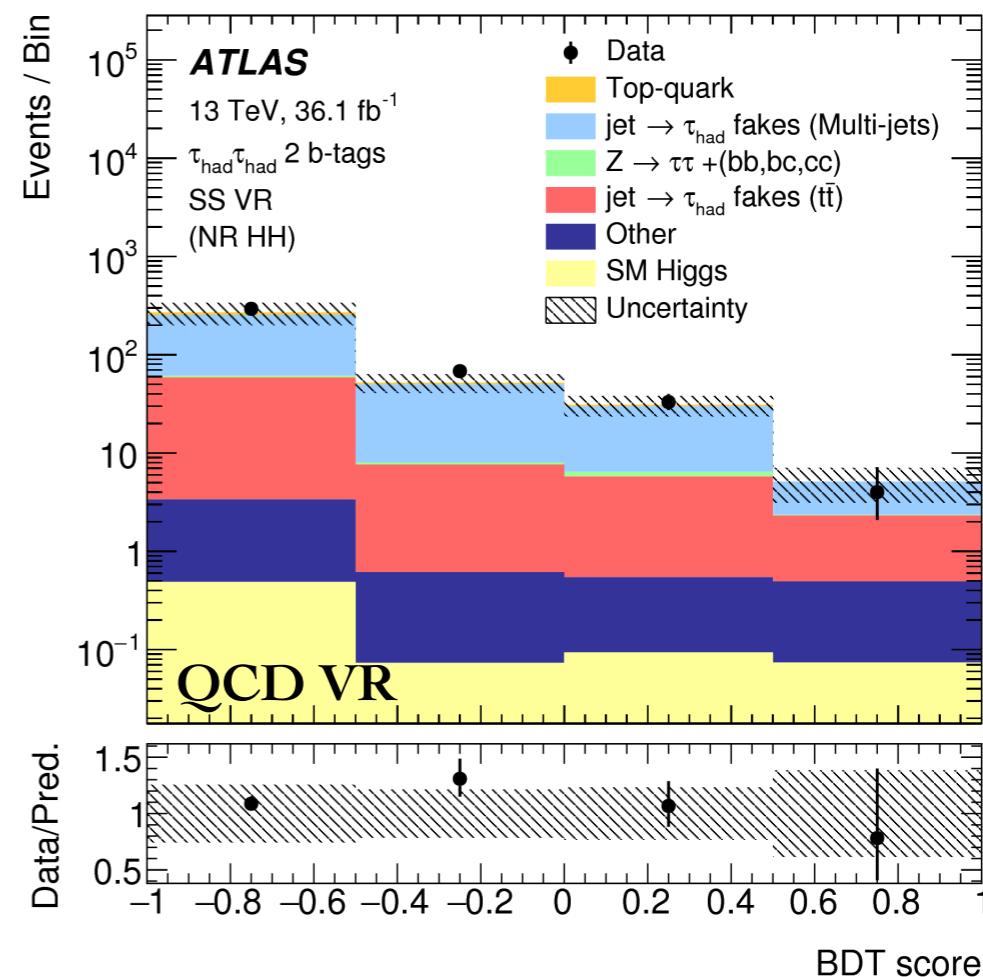
**multijet fakes in hadhad**

A	B
OS	SS
ID- $\tau$	ID- $\tau$
C	D
OS	SS
Anti-ID- $\tau$	Anti-ID- $\tau$

$$FF = \frac{N_B}{N_D}$$

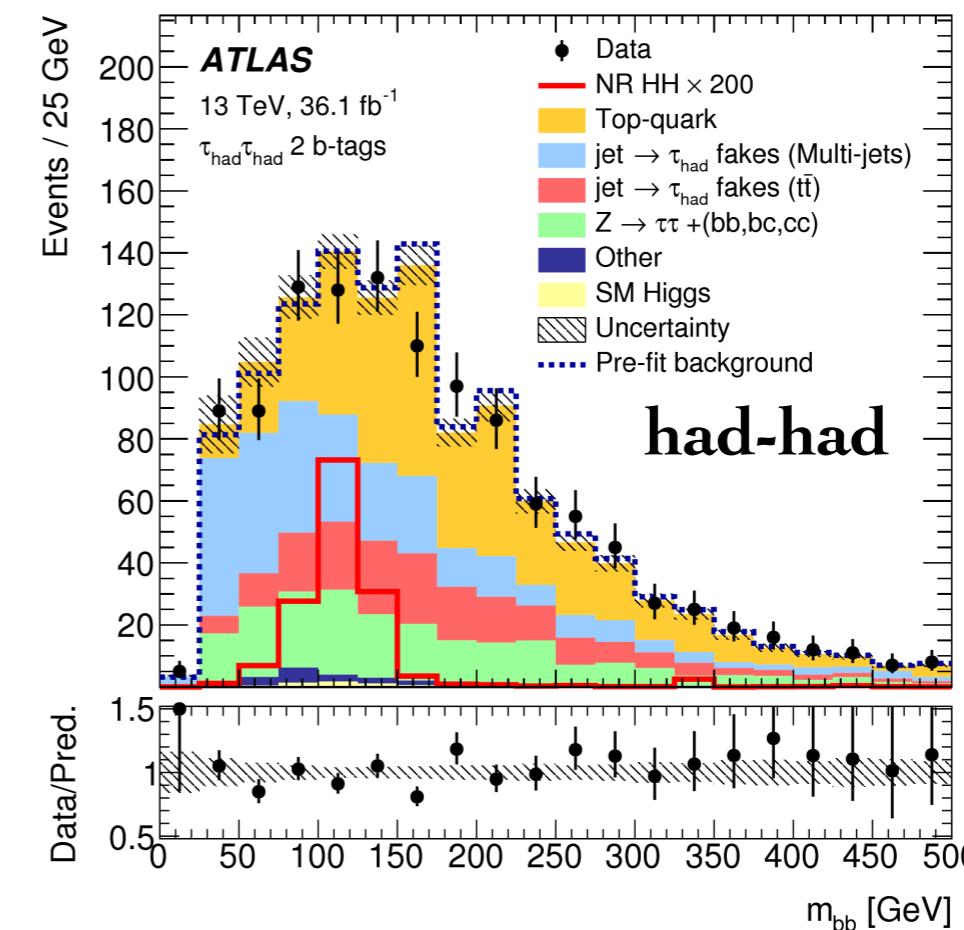
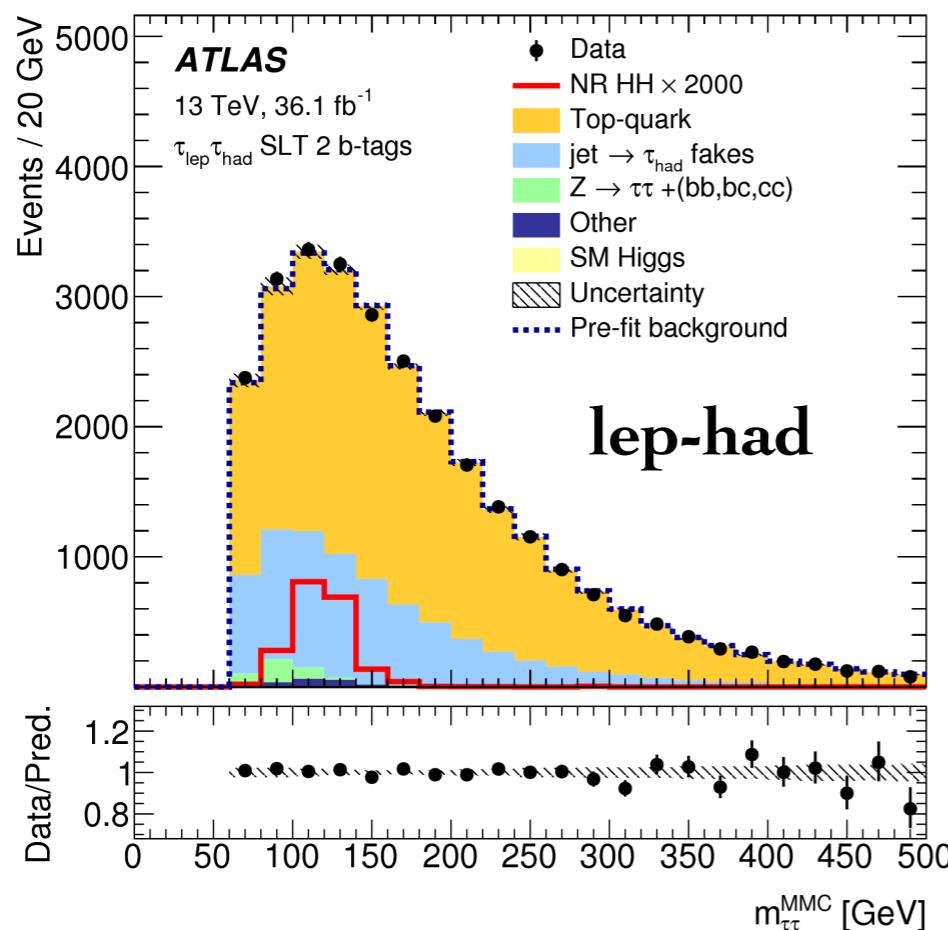
$$N_A = \frac{N_B}{N_D} \cdot N_C = FF \cdot N_C$$

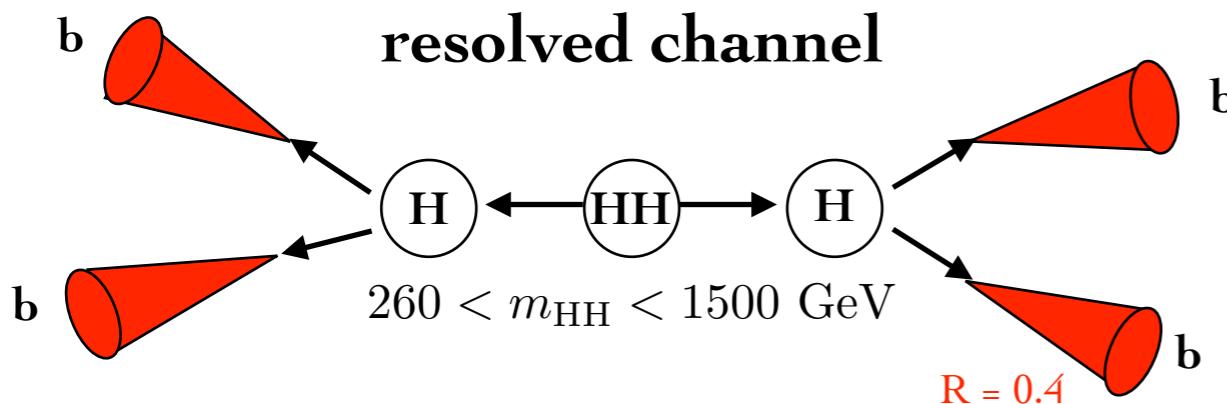
contribution from non-fake bkg's  
evaluated using MC



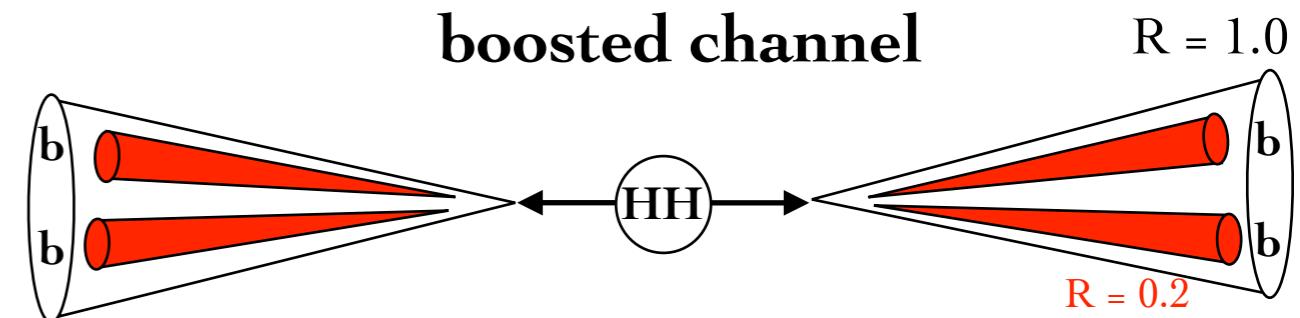
# HH bb $\tau\tau$ : BDT Analysis

- considerable gain using BDTs to separate signal and bkgds
  - more than 20% better limits
- 6 - 11 variables depending on the channel
  - strongest separation: inv. mass of HH-, bb- and  $\tau\tau$ -systems and angular distance between b-jets and  $\tau$ 's
- use **BDT score** as final **discriminant** in the binned likelihood fit

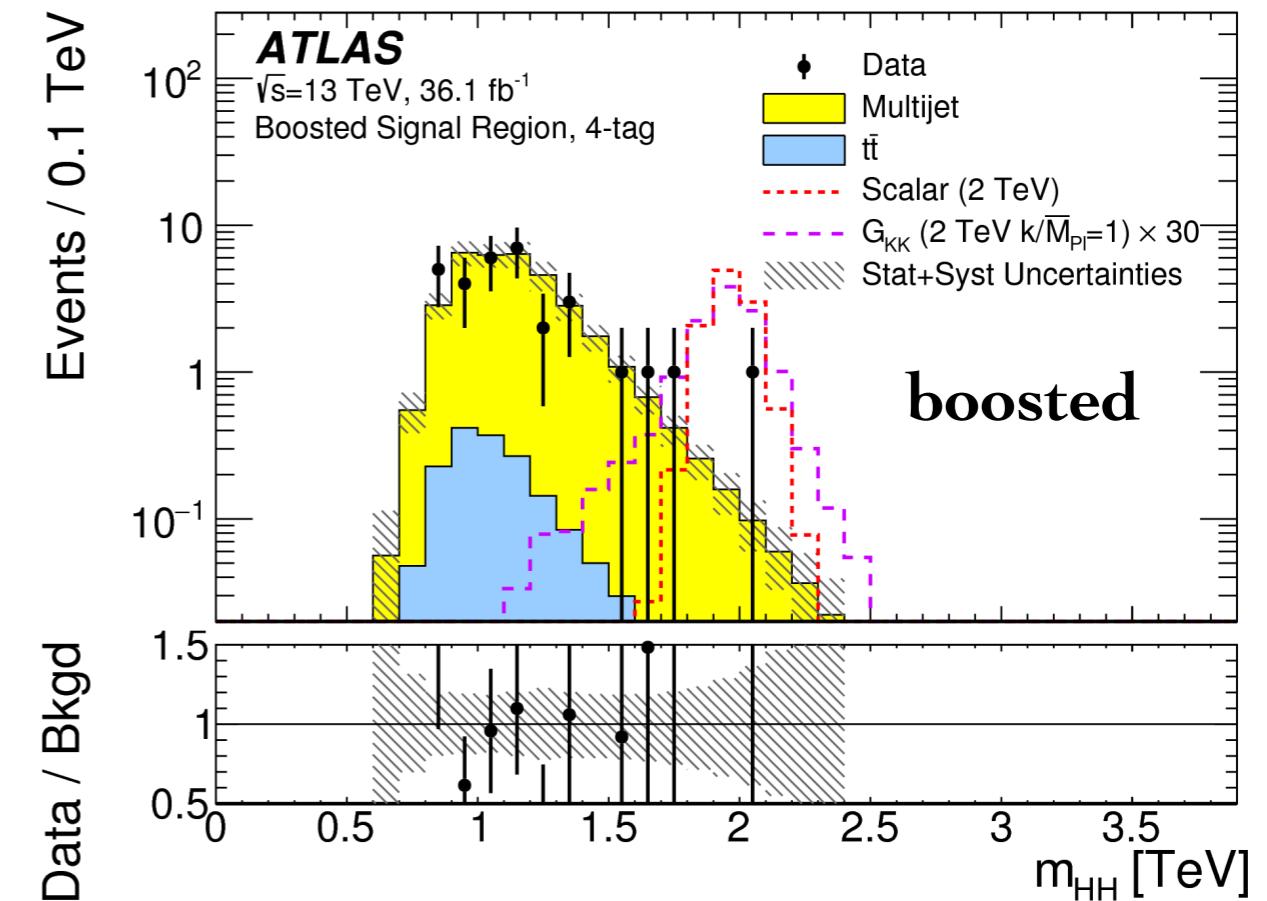
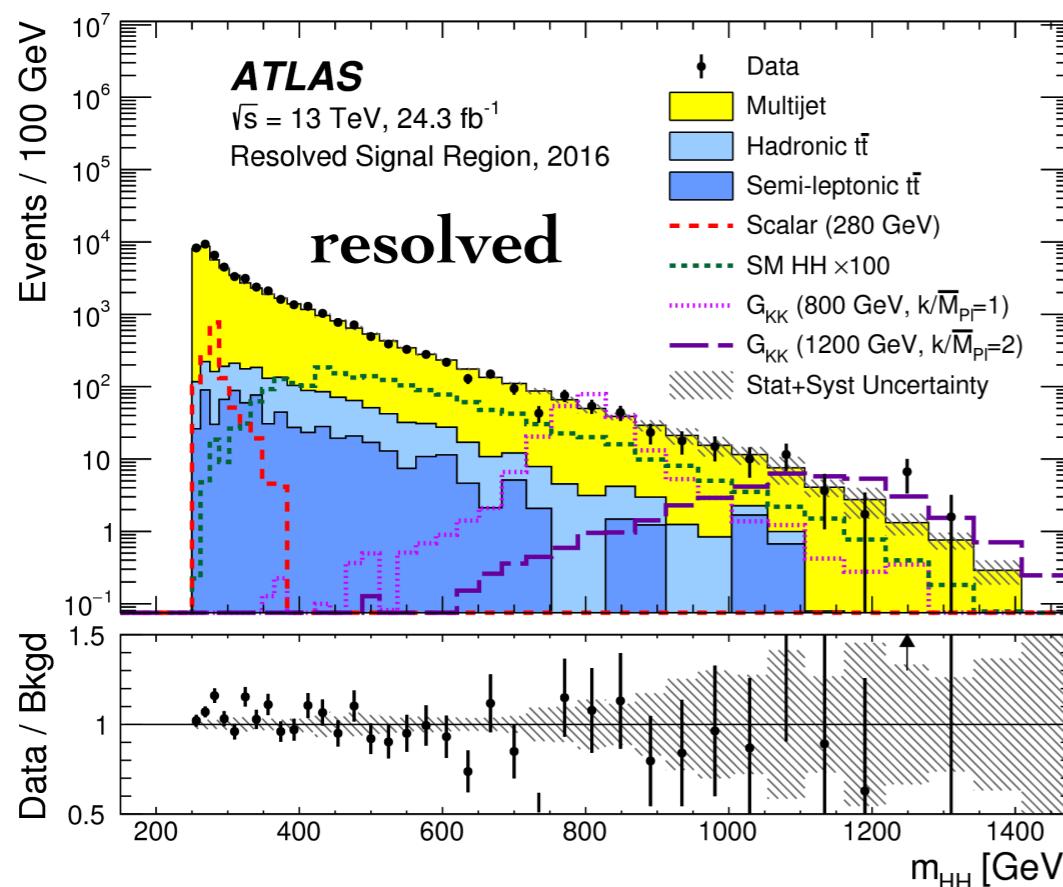


**pros:**

- highest branching ratio (34%)

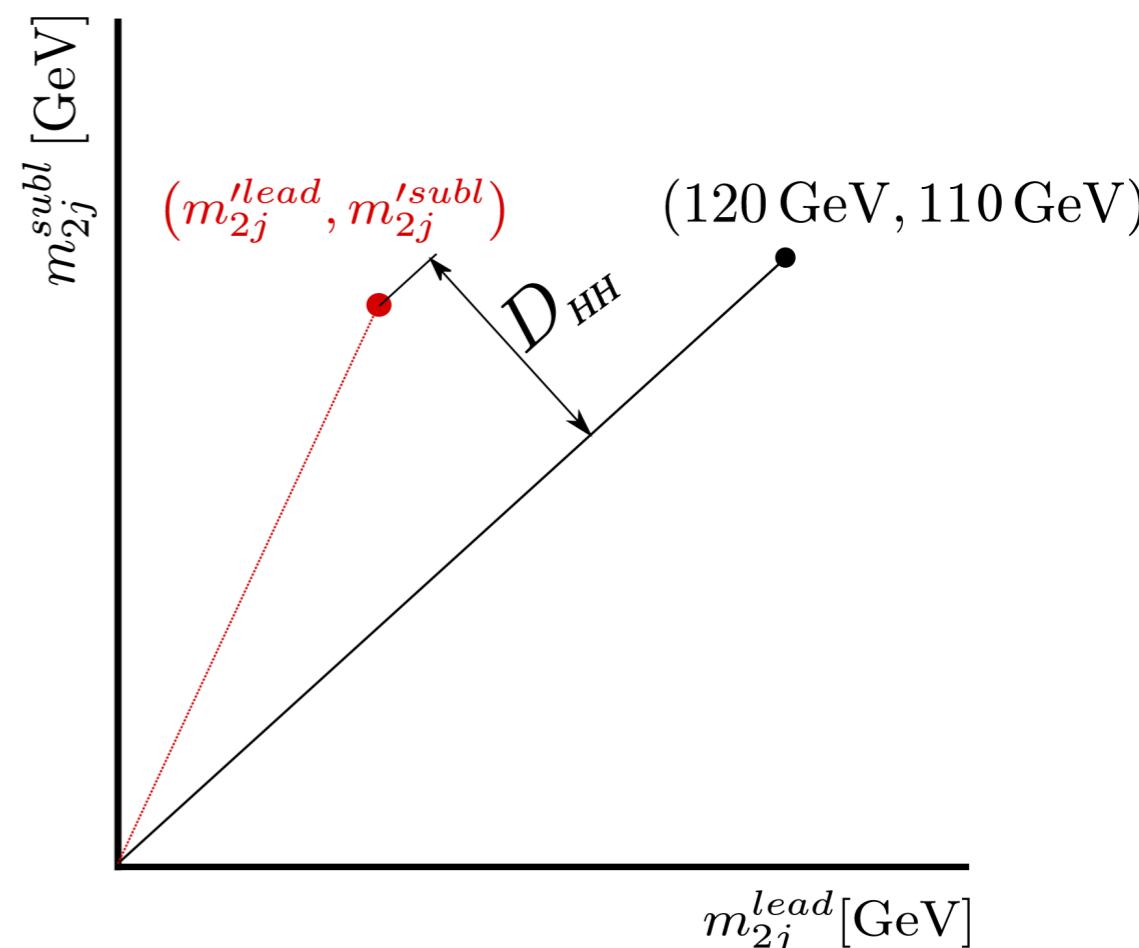
**contras:**

- high multijet background



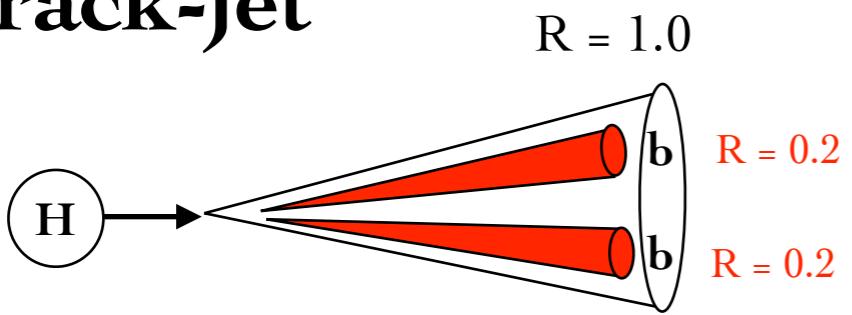
# HH 4b: Resolved Analysis Strategy

- select 4 b-jets with the highest b-tag score and build all possible combinations of b-jet pairs
- apply  $m(4j)$ -dependent  $\Delta R(jj)$  cuts
- assign b-jet pairs based on minimum mass difference  $D_{\text{HH}}$
- Higgs  $p_T$  and  $\Delta\eta(\text{HH})$ , W and top mass requirements to suppress bkgs
- model the multijet bkg using 2-b-jet events; tt bkg from MC
- use  $\mathbf{m}(4j)$  as discriminant in the binned likelihood fit



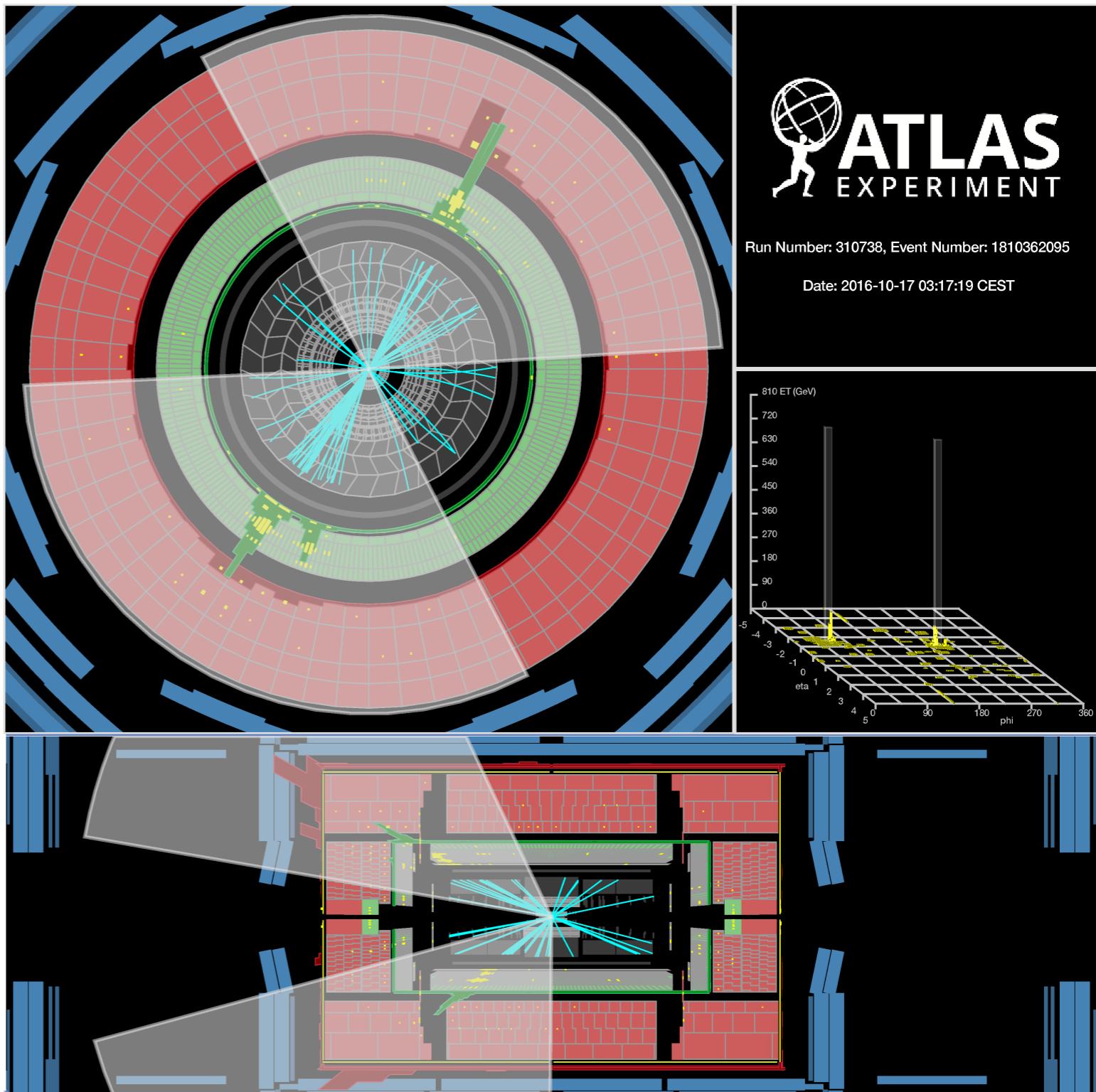
# HH 4b: Boosted Analysis Strategy

- select 2 highest  $p_T$   
anti-kt  $R=1.0$   
trimmed large- $R$  jets  
with at least one  
ghost-associated b-  
tagged anti-kt  $R=0.2$   
**track-jet**

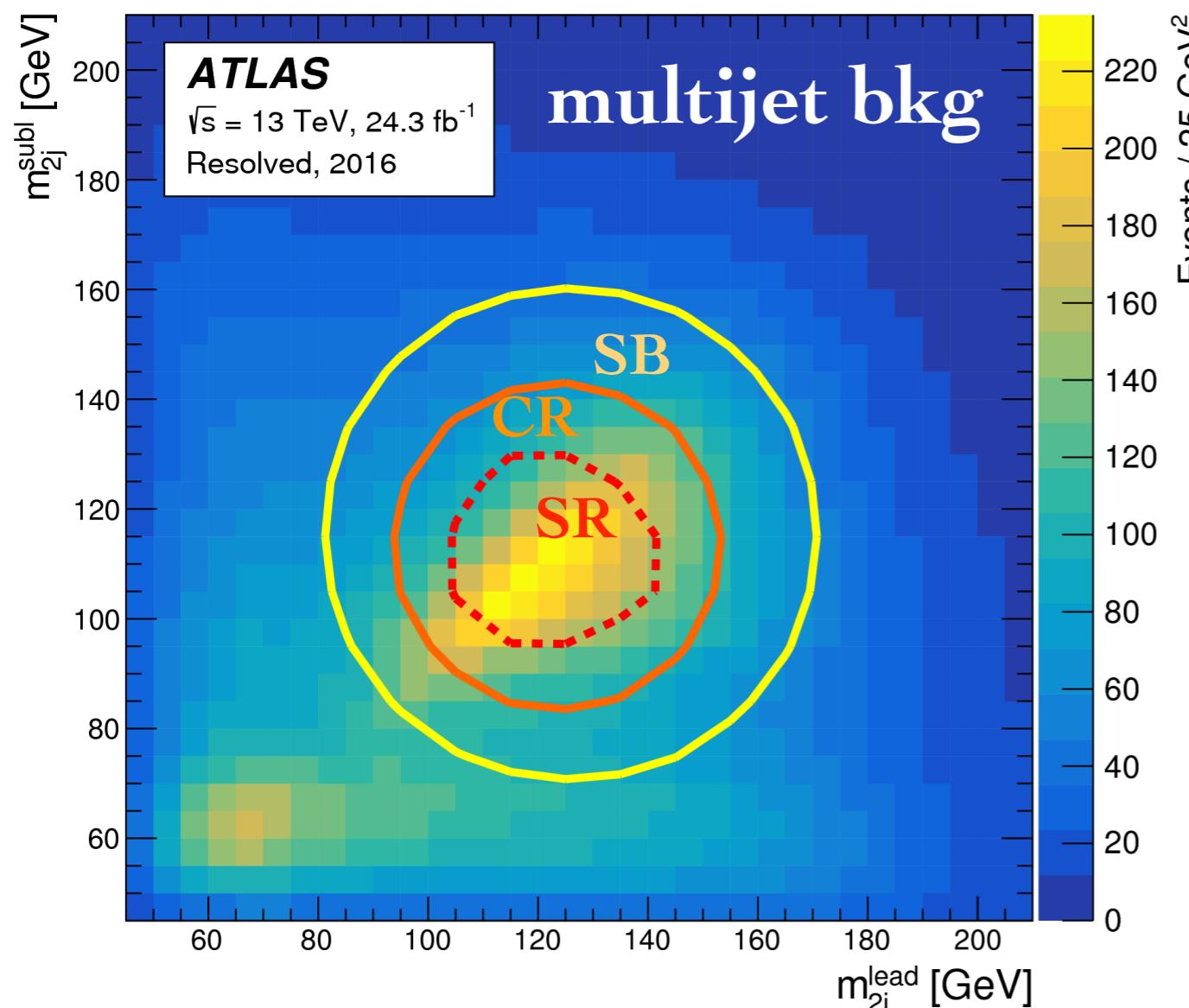


- veto resolved events
- $m(2J)$  distribution  
used in the binned  
likelihood fit

$m_{JJ} = 3.89 \text{ TeV}, p_{T,1} = 748 \text{ GeV}, p_{T,2} = 747 \text{ GeV}$



# HH 4b: Analysis Regions



**Signal region (SR):**  
for the final search

$$X_{HH} = \sqrt{\left(\frac{m_{2j}^{\text{lead}} - 120 \text{ GeV}}{0.1 m_{2j}^{\text{lead}}}\right)^2 + \left(\frac{m_{2j}^{\text{subl}} - 110 \text{ GeV}}{0.1 m_{2j}^{\text{subl}}}\right)^2} < 1.6,$$

**Sideband region (SB):**  
to derive bkg's

$$\sqrt{(m_{2j}^{\text{lead}} - 126 \text{ GeV})^2 + (m_{2j}^{\text{subl}} - 116 \text{ GeV})^2} < 45 \text{ GeV},$$

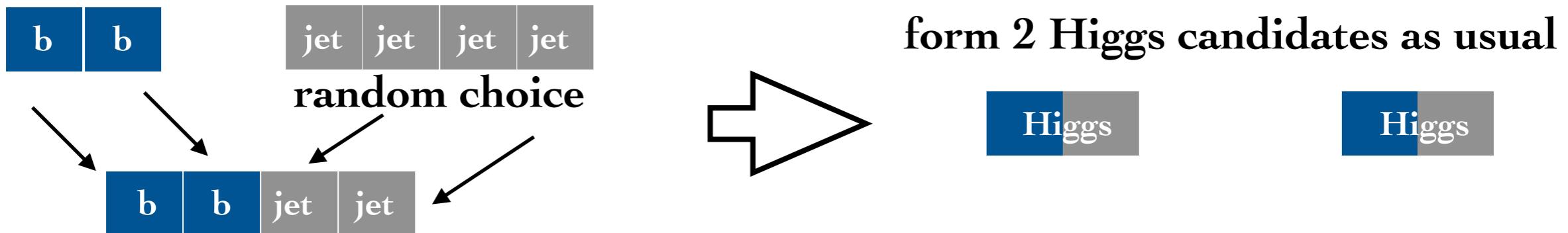
**Control region (CR):**  
to test bkg's and derive systs

$$\sqrt{(m_{2j}^{\text{lead}} - 124 \text{ GeV})^2 + (m_{2j}^{\text{subl}} - 113 \text{ GeV})^2} < 30 \text{ GeV},$$

- same strategy is used in the **boosted** analysis but the numerical values are re-optimised

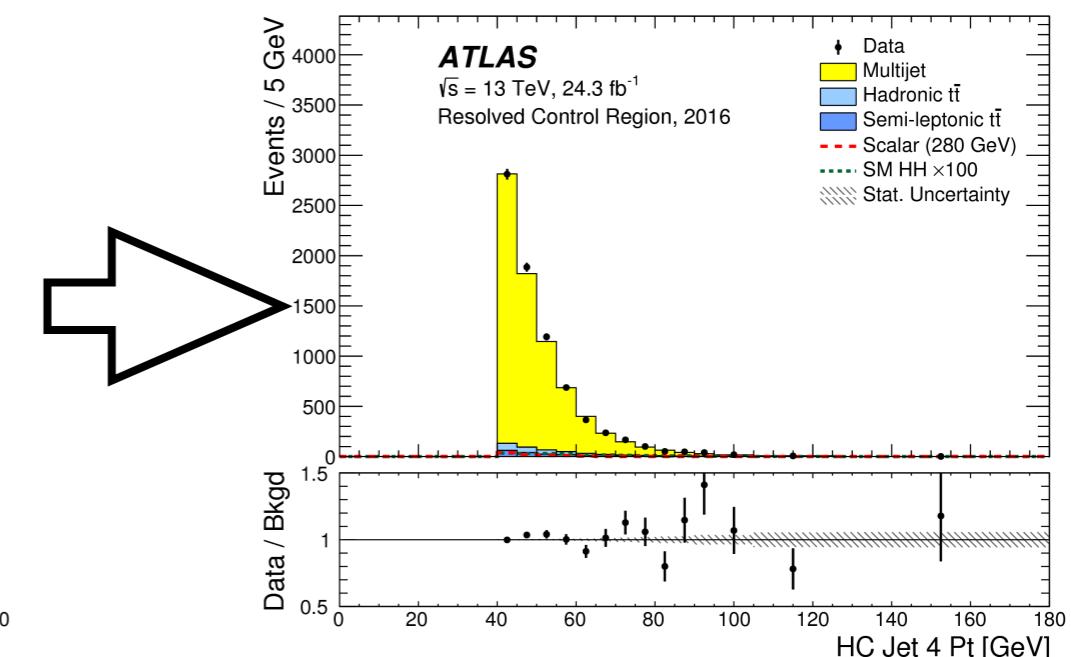
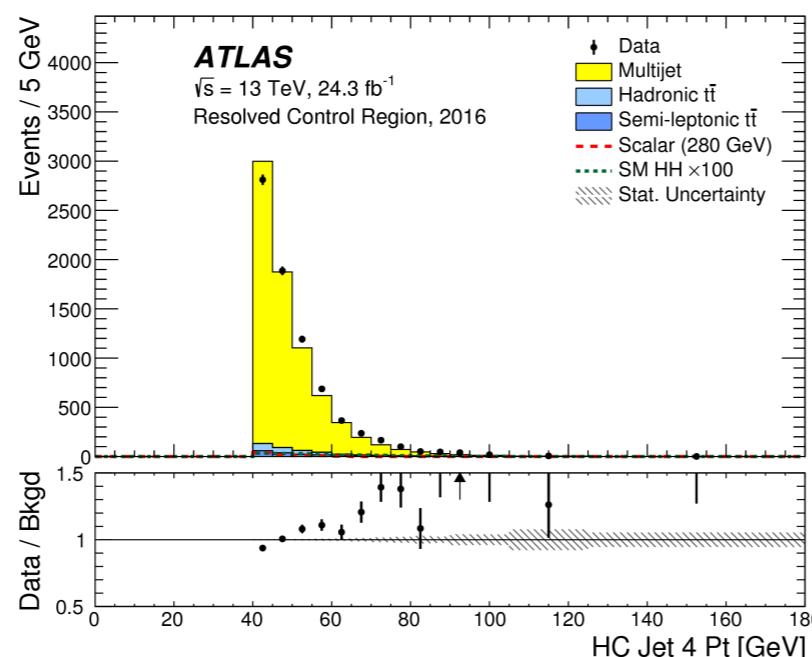
# HH 4b: Multijet Bkg

- use 2 b-jets events to model 4 b-jets bkg
  - select 2 b-jets and **randomly** 2 non-tagged jets

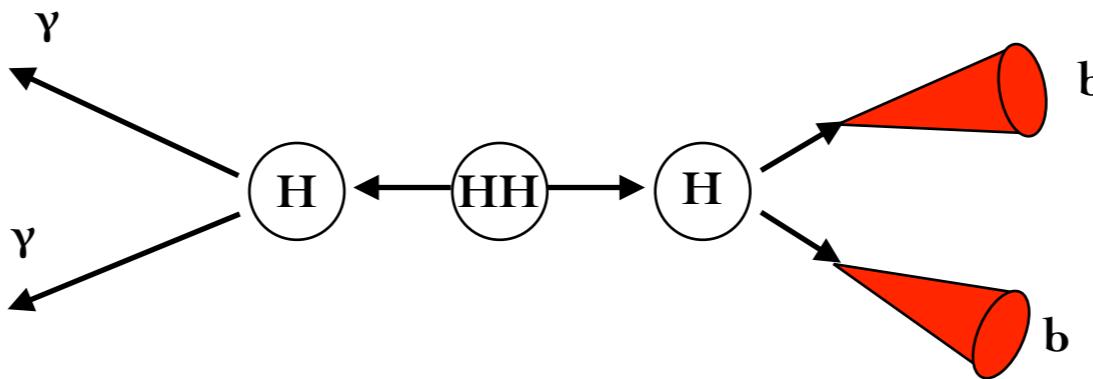


- combinatoric factor** for selection 2 non-tagged jets **multiplied** with the **transfer factor** for “pseudo-tagging”
  - jet kinematics depend on the number of jets
  - b-tagging depend on jet kinematics

**iterative kinematic reweighting using 5 variables with the largest discrepancy**



# HH bb $\gamma\gamma$

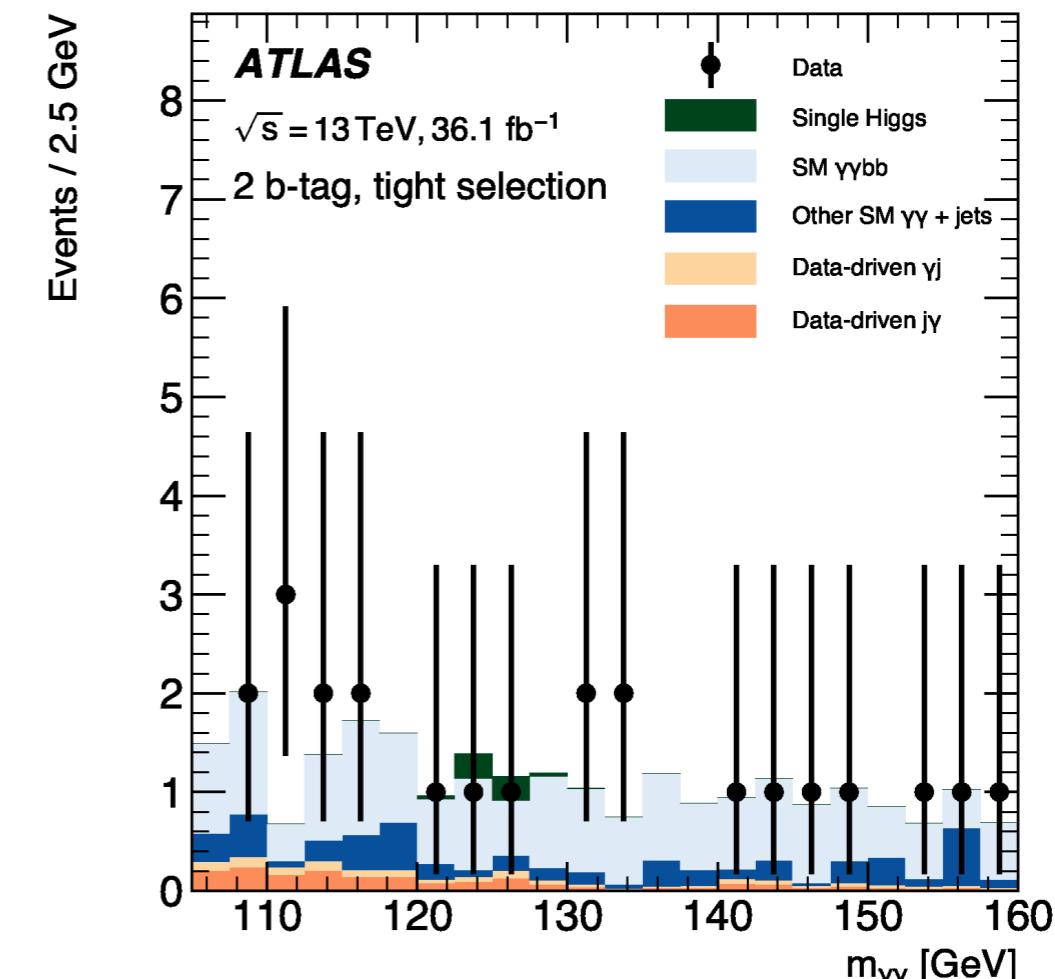
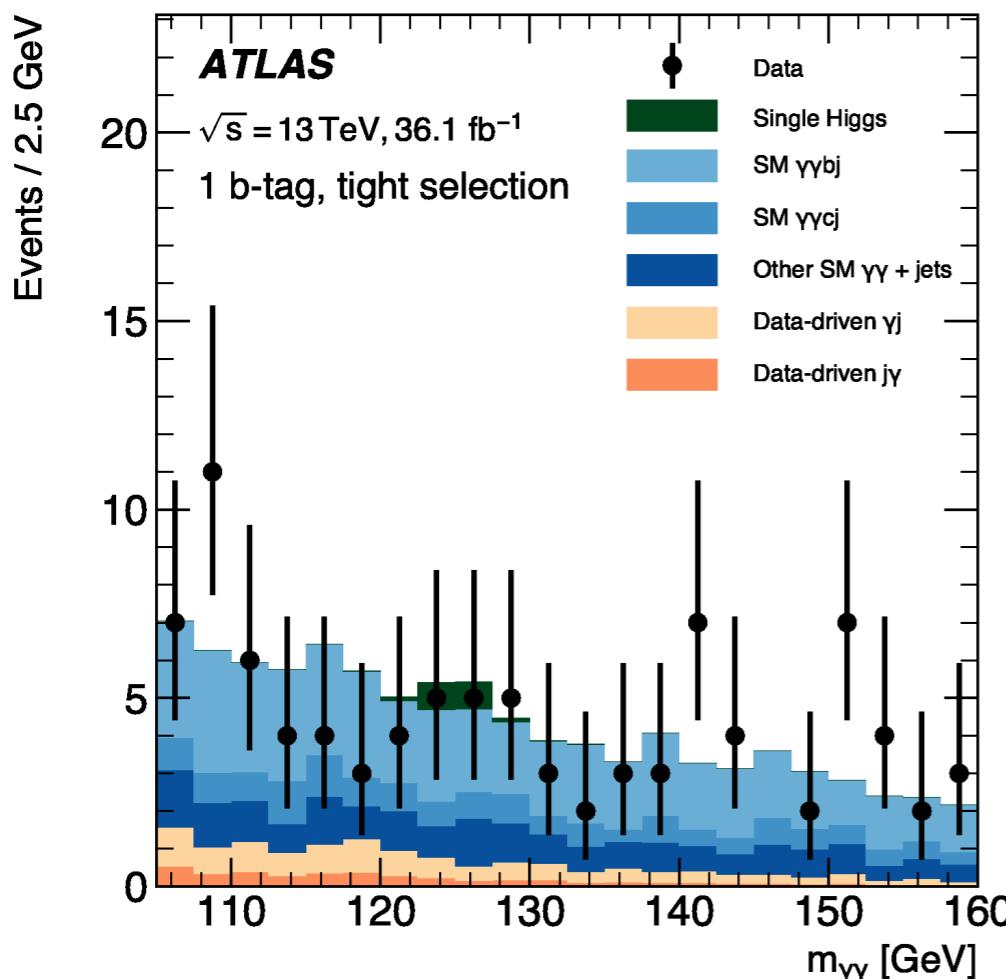


## pros:

- low background
- excellent  $m(\gamma\gamma)$  resolution

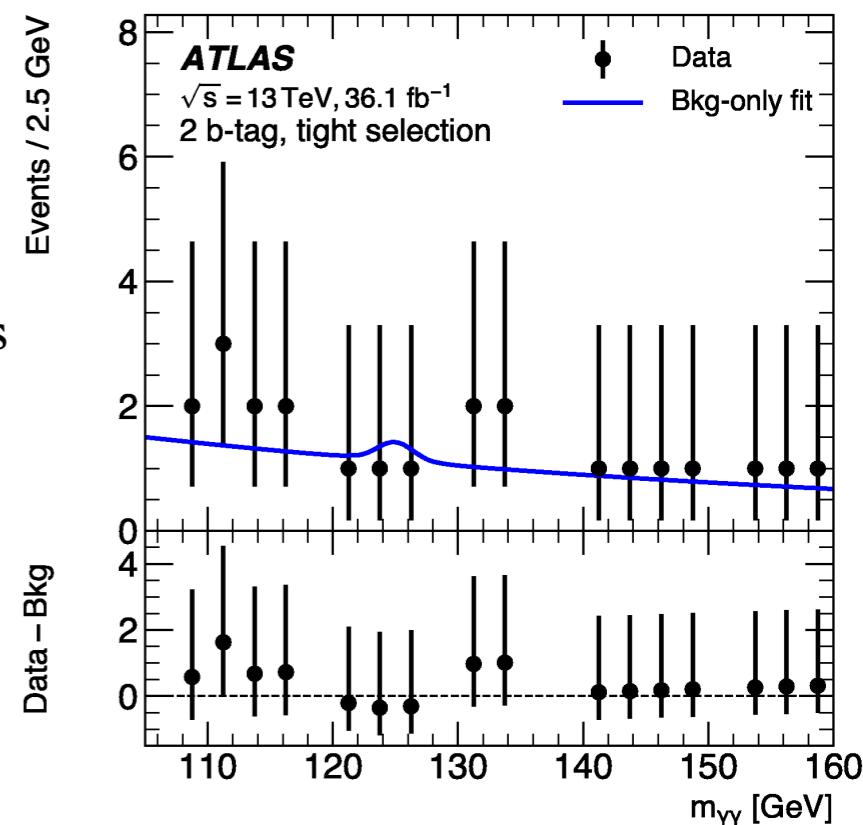
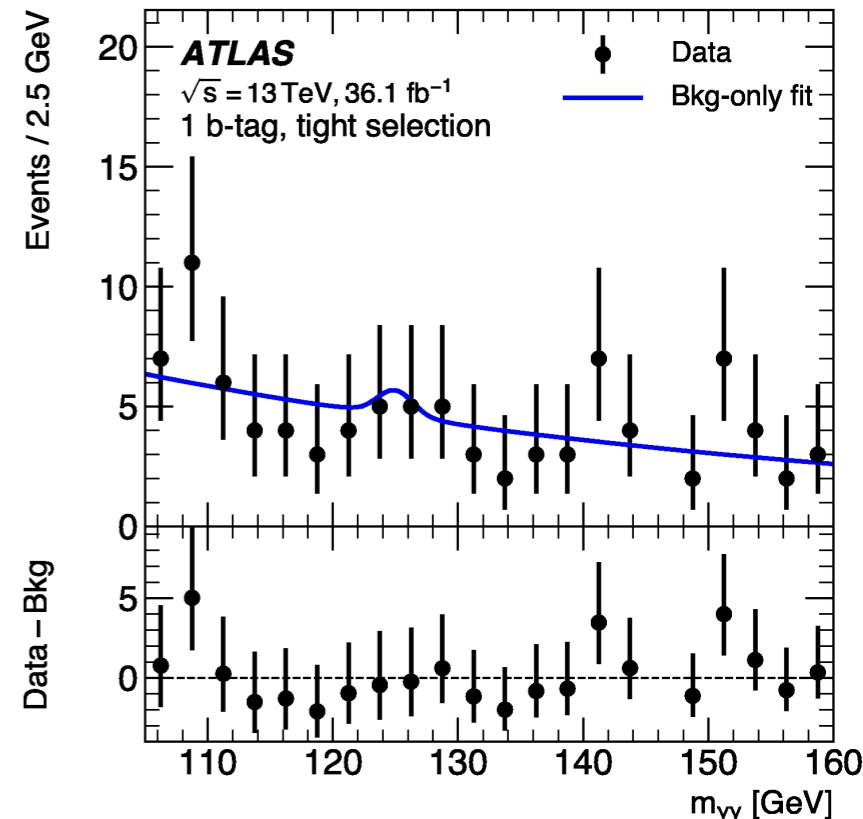
## contras:

- low branching ratio (0.3%)



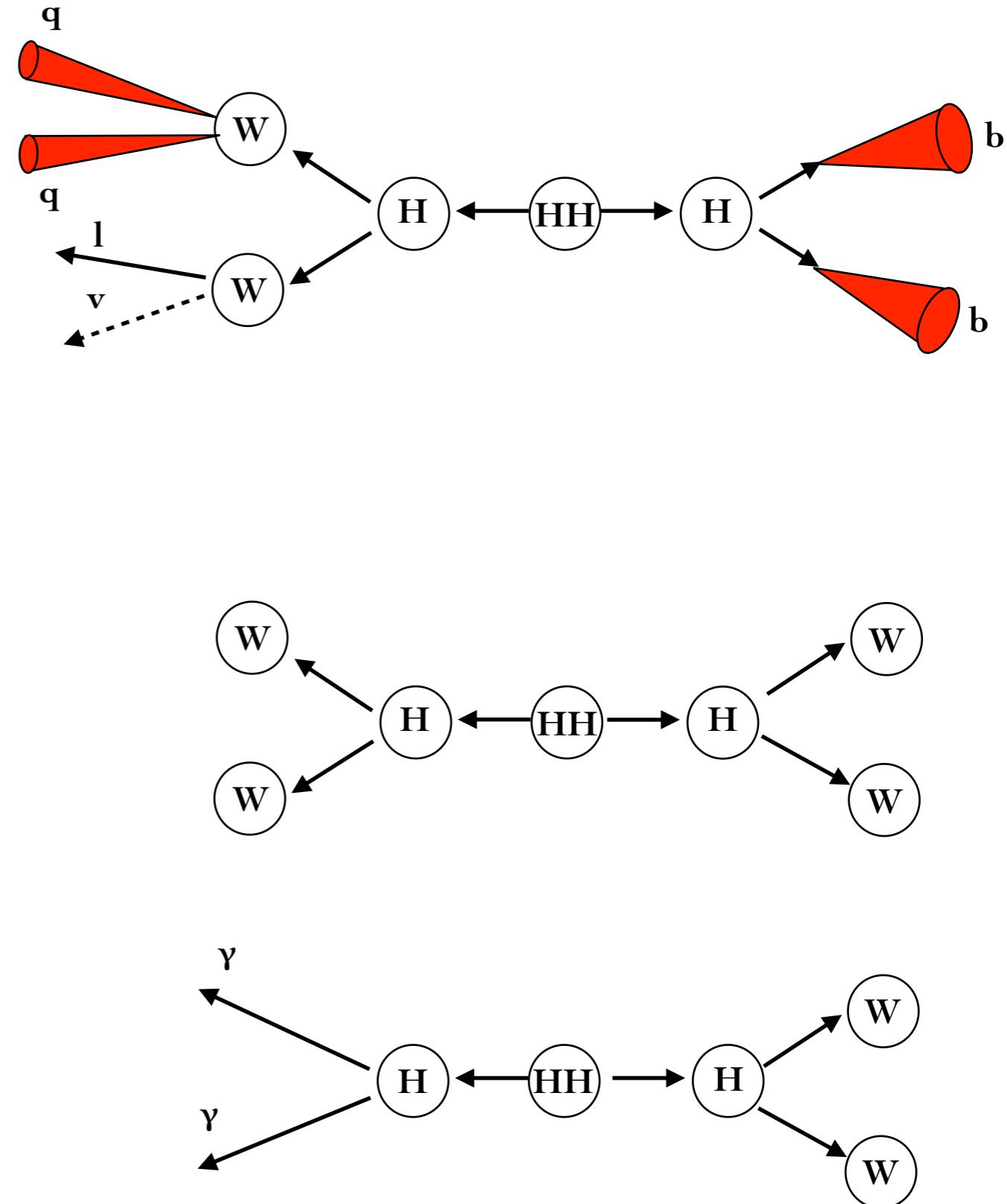
# HH bb $\gamma\gamma$ : Analysis Strategy

- select events with **two photons** and at least **one b-tagged jet**
- signal region:** events with **1 or 2 b-tags**
  - 0-tag region only for cross checks
  - 2nd jet in the 1 b-tag region is chosen by a **BDT**
- “**loose**” and “**tight**” selections depending on the tested signal hypothesis
  - looser/tighter requirements on  $m(bb)$ ,  $m(\gamma\gamma)$  and jet pT
- bkg** templates derived from MC
  - re-weighted using **data in the sidebands** derived by varying photon ID and isolation criteria
- unbinned likelihood fit**
  - resonant:  $m(\gamma\gamma bb)$  and non-resonant:  $m(\gamma\gamma)$  distributions
  - signal: double-sided Cristal Ball function (Gaussian core with power law tails)
  - bkgs: Novosibirsk (loose sel.) or exponential (tight sel.) functions

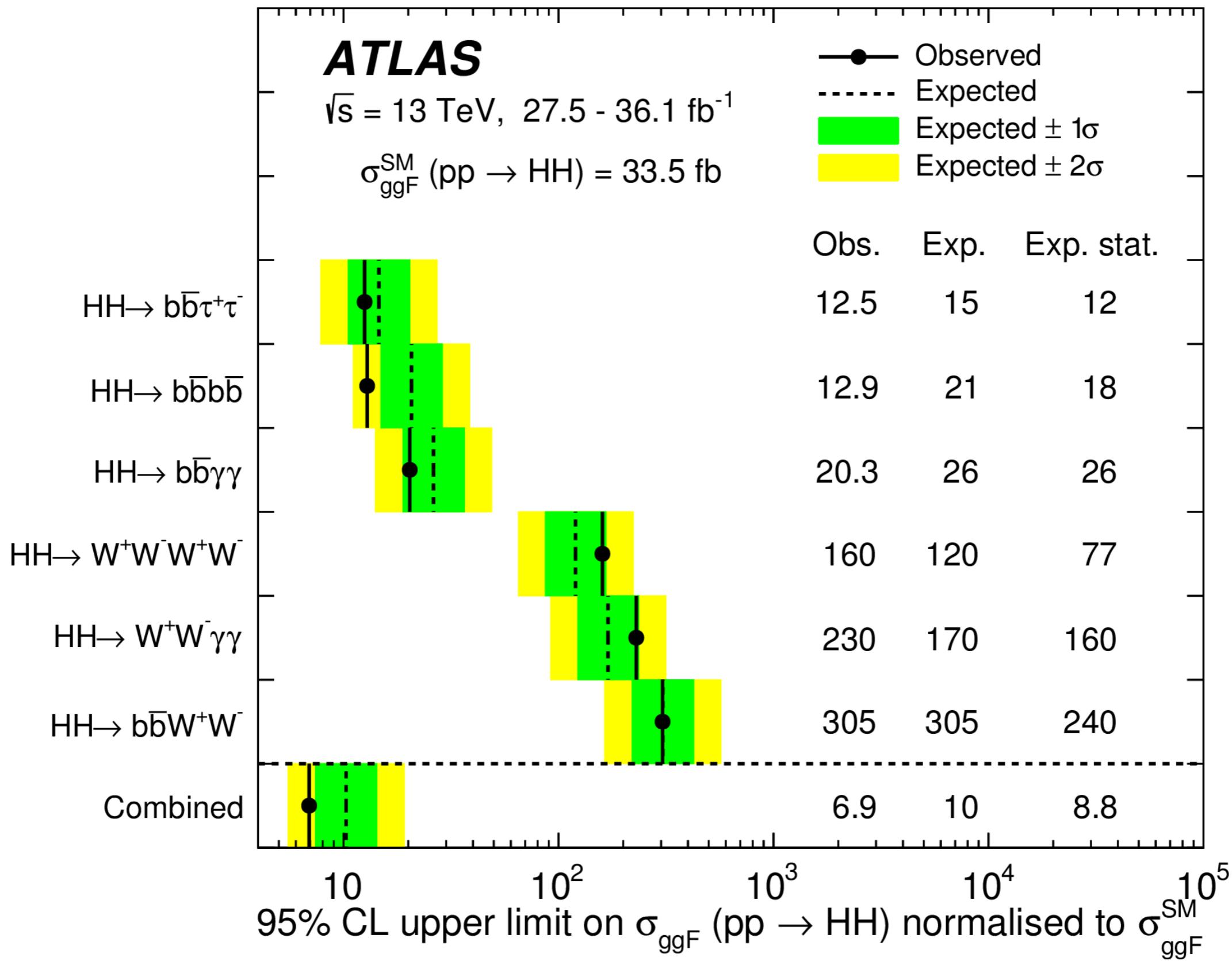


# Other HH Channels

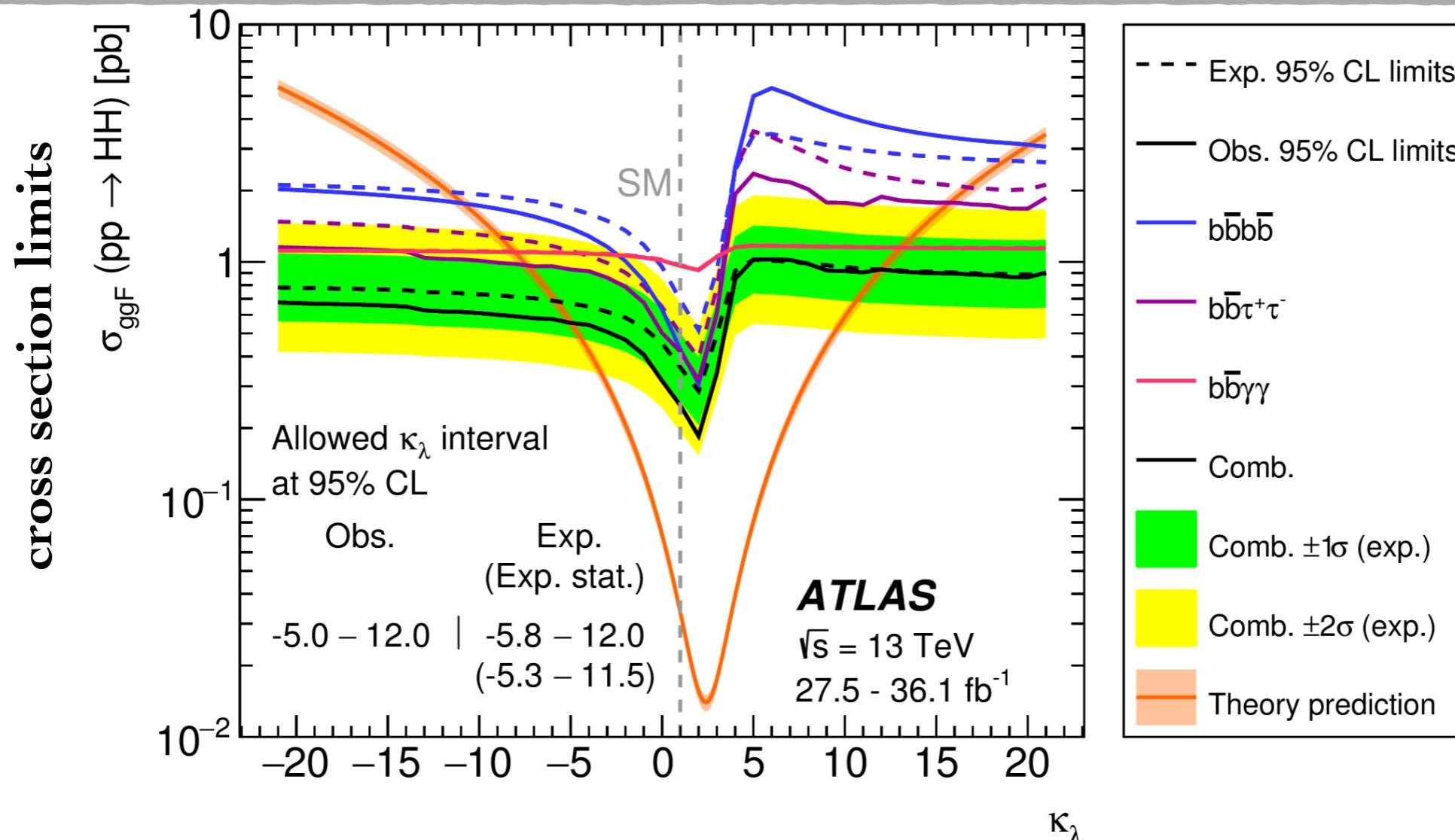
- $\text{HH} \rightarrow \text{bb} \text{ WW} \rightarrow \text{bb} \text{ lv qq}$ 
  - high branching fraction but high ttbar bkg
  - leptonic decays to trigger but reduced rate and neutrinos in the final state
- $\text{HH} \rightarrow \text{WW WW}$  (multilepton)
  - high rate
  - but neutrinos in the final state and bkggs from prompt leptons or ZZ
- $\text{HH} \rightarrow \text{WW} \gamma\gamma$ 
  - reduced background and excellent  $m(\gamma\gamma)$  resolution
  - low rate



# HH Non-Resonant Results

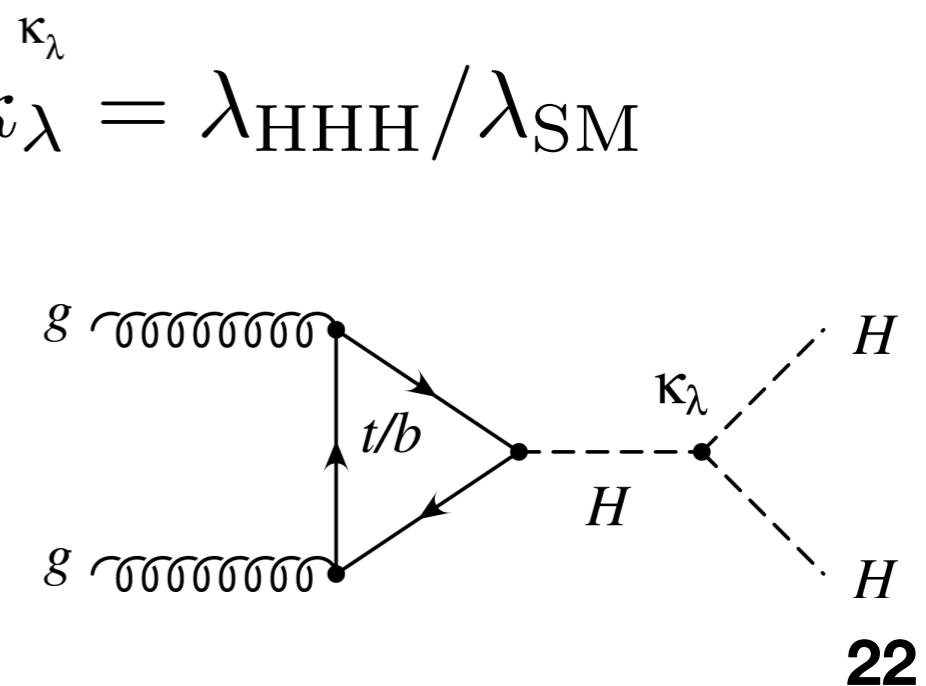


# Higgs Self-Coupling Results

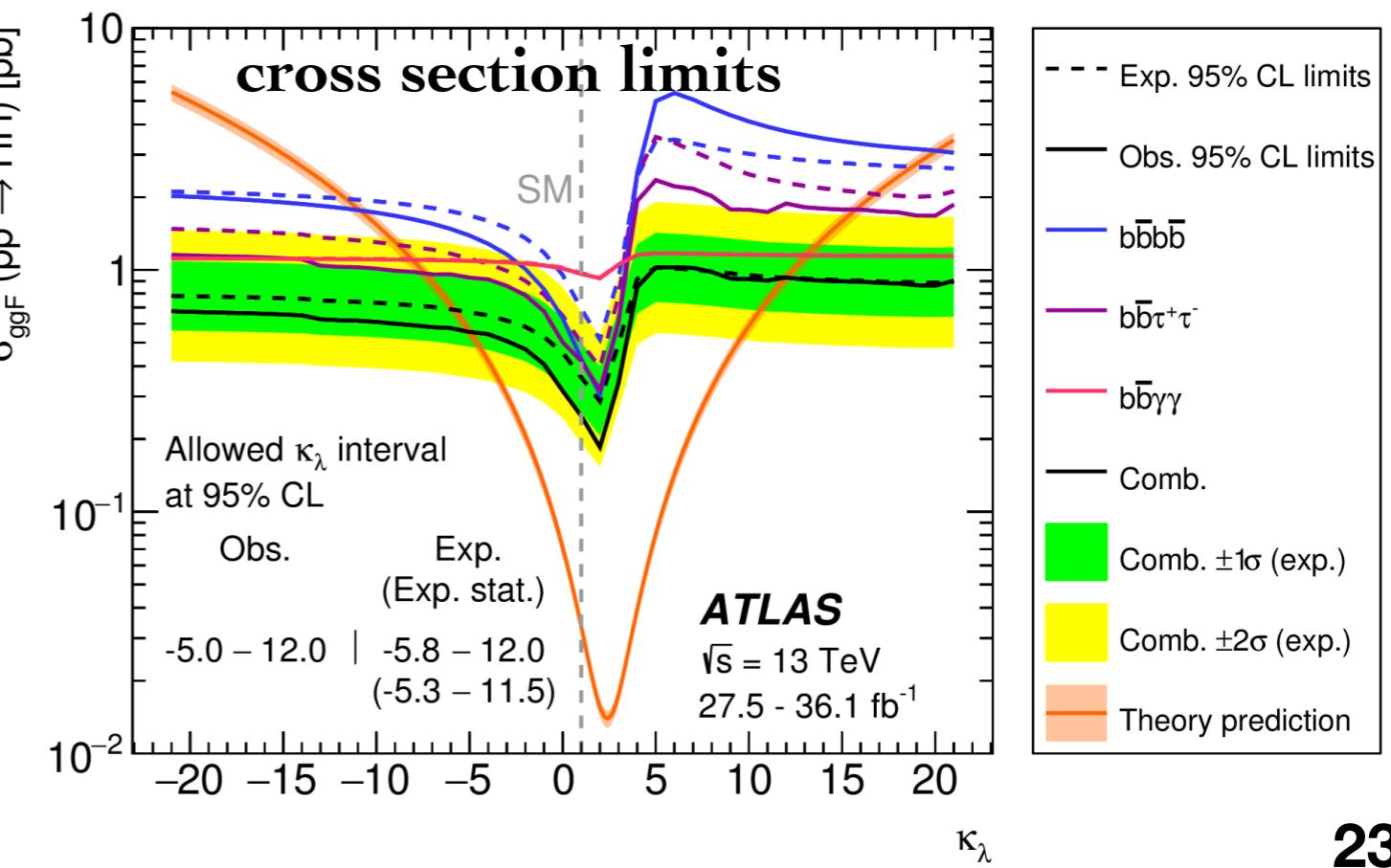
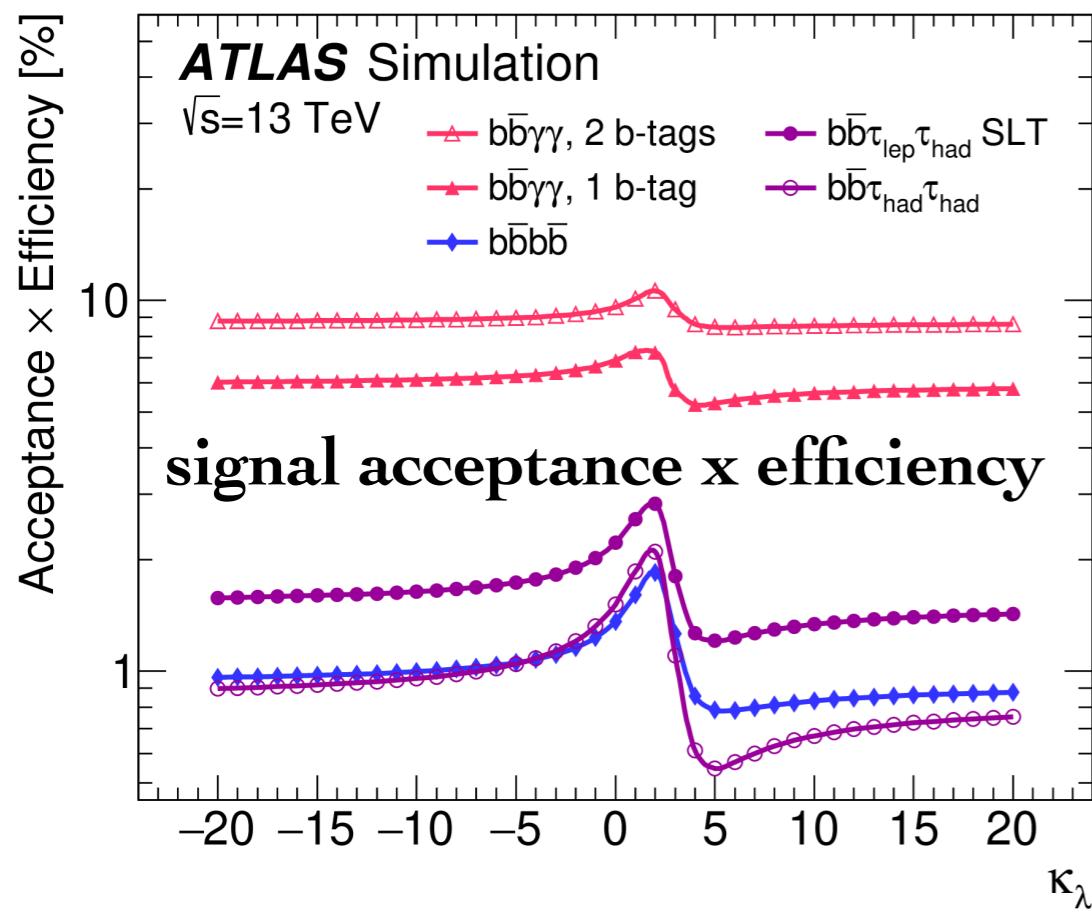
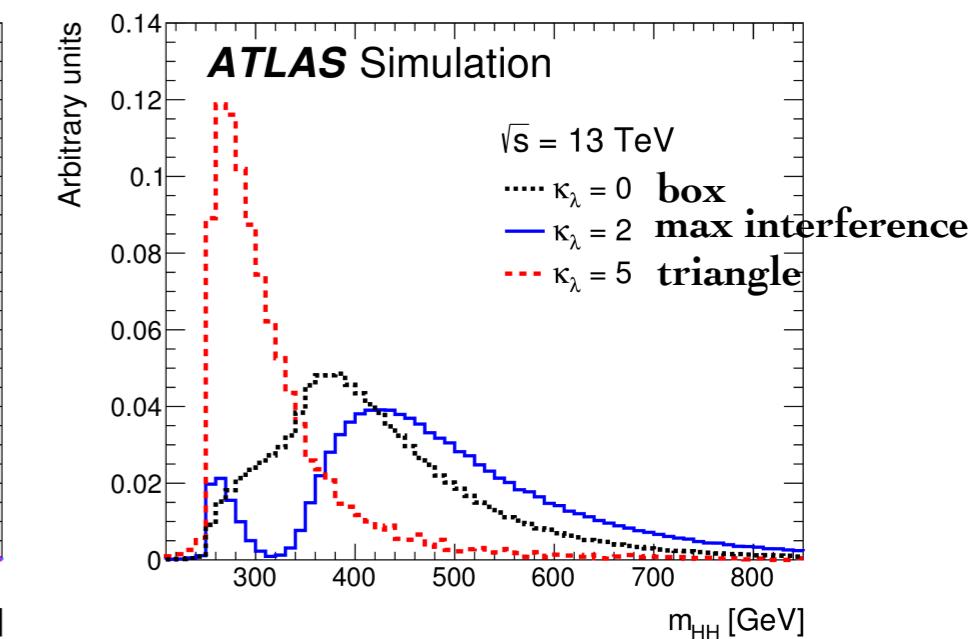
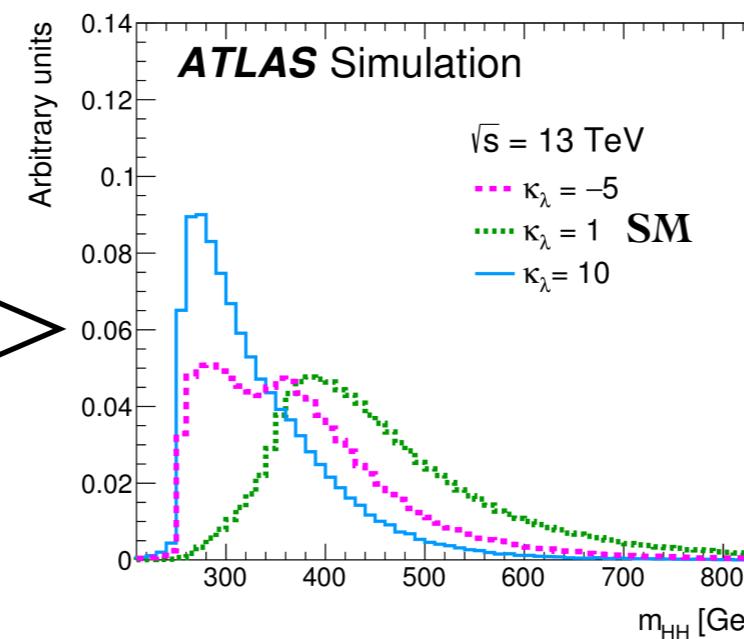
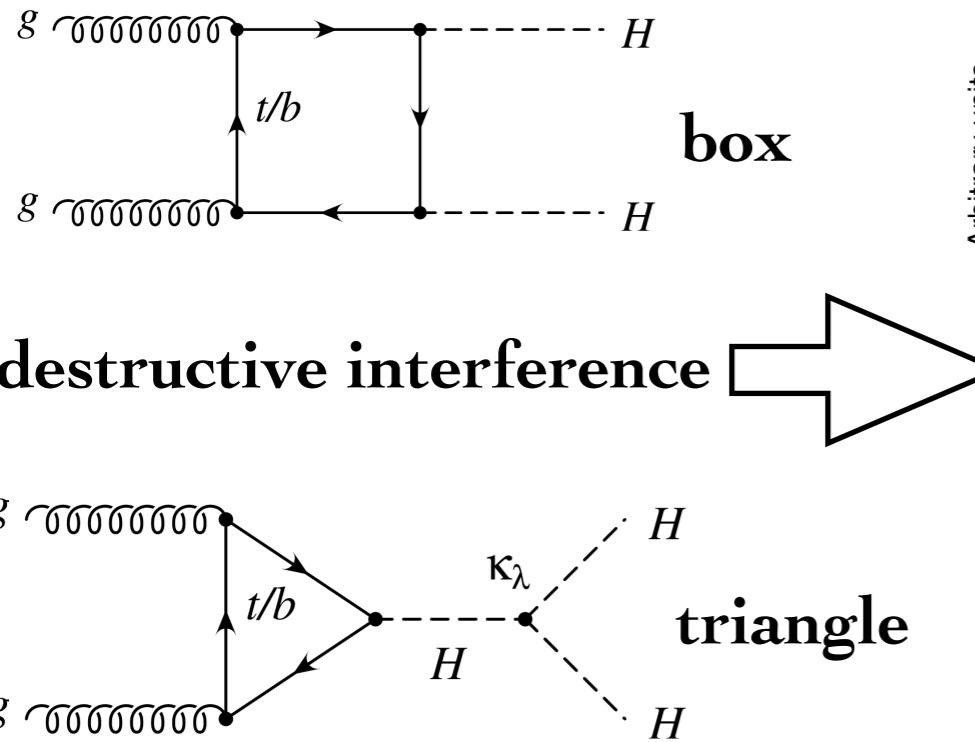


Higgs boson self-coupling modifier:  $\kappa_\lambda = \lambda_{\text{HHH}}/\lambda_{\text{SM}}$

Final state	Allowed $\kappa_\lambda$ interval at 95% CL		
	Obs.	Exp.	Exp. stat.
$b\bar{b}b\bar{b}$	-10.9 – 20.1	-11.6 – 18.8	-9.8 – 16.3
$b\bar{b}\tau^+\tau^-$	-7.4 – 15.7	-8.9 – 16.8	-7.8 – 15.5
$b\bar{b}\gamma\gamma$	-8.1 – 13.1	-8.1 – 13.1	-7.9 – 12.9
Combination	-5.0 – 12.0	-5.8 – 12.0	-5.3 – 11.5

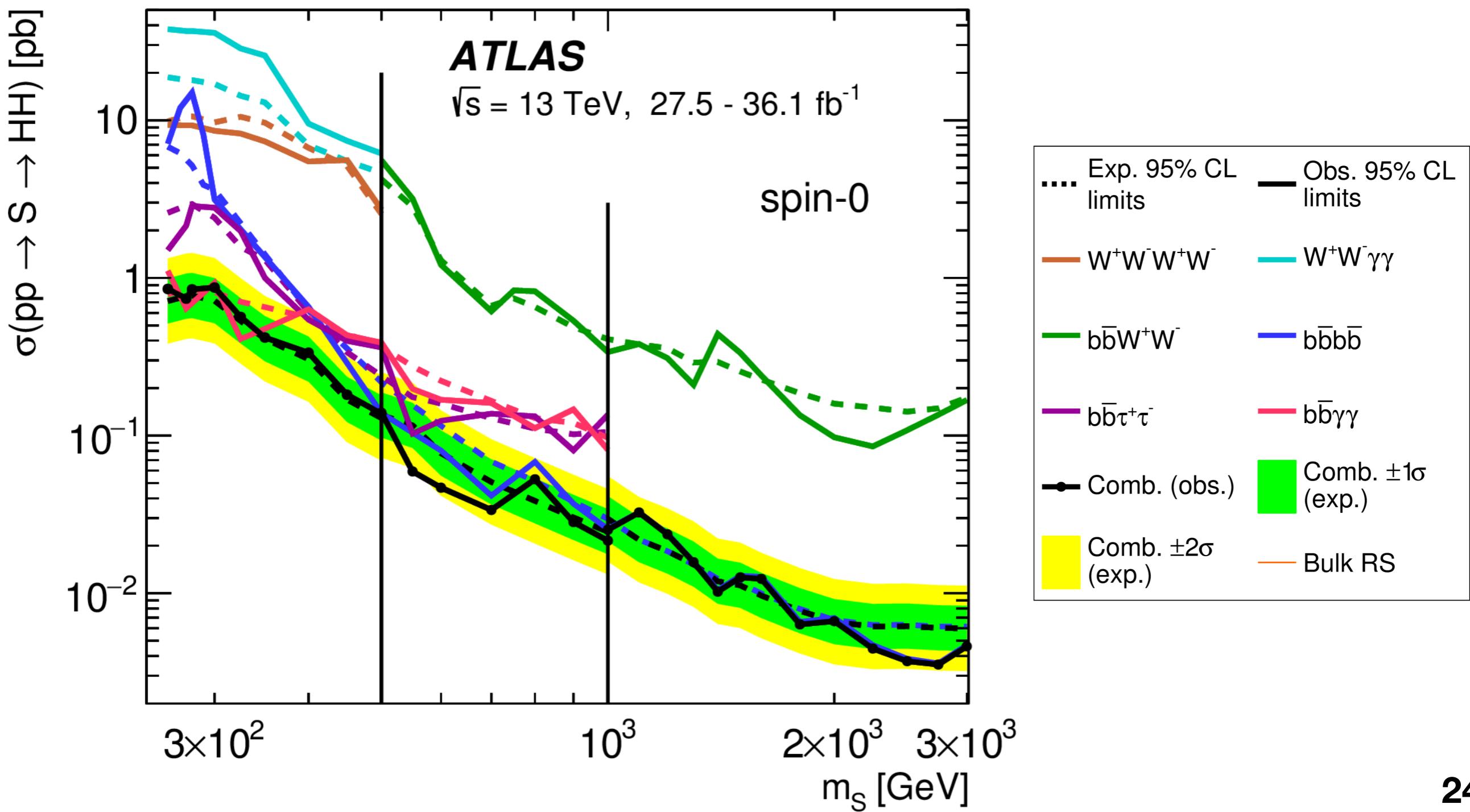


# Higgs Self-Coupling Results



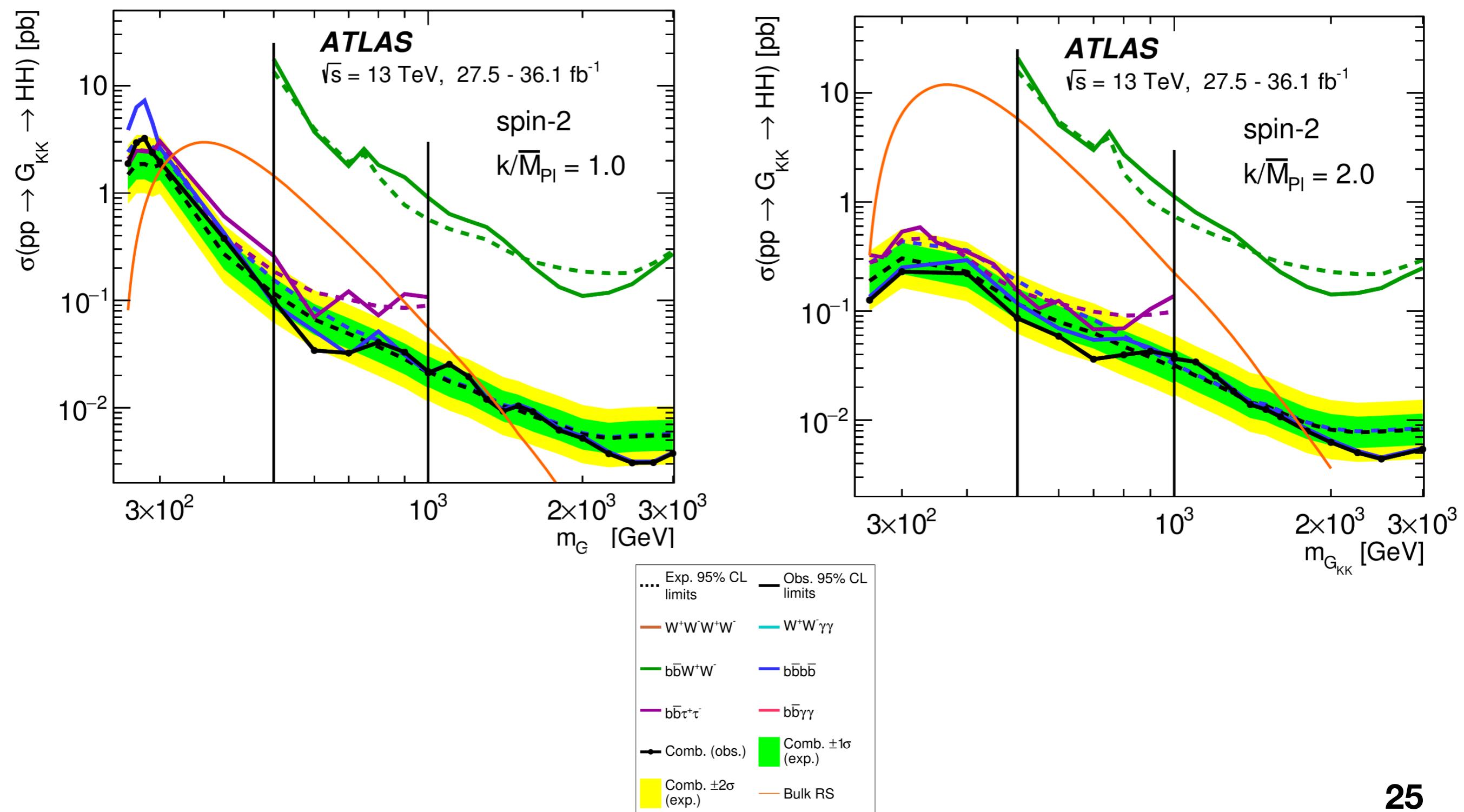
# HH Spin-0 Results

Spin-0 heavy scalar (Heavy Higgs in Two Higgs Doublet and Electroweak Singlet Models)



# HH Spin-2 Results

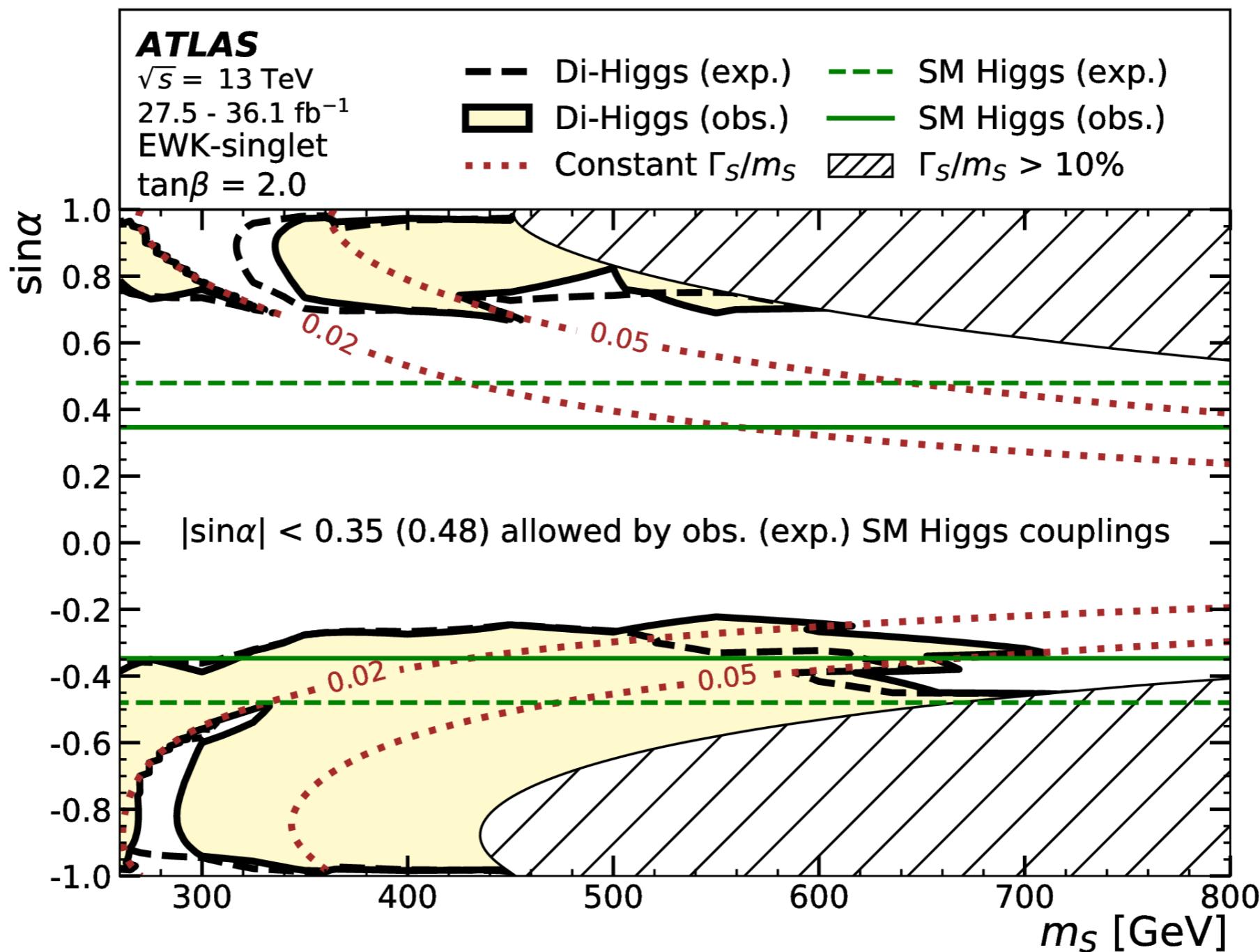
Spin-2 heavy particle (Randall-Sundrum Graviton)

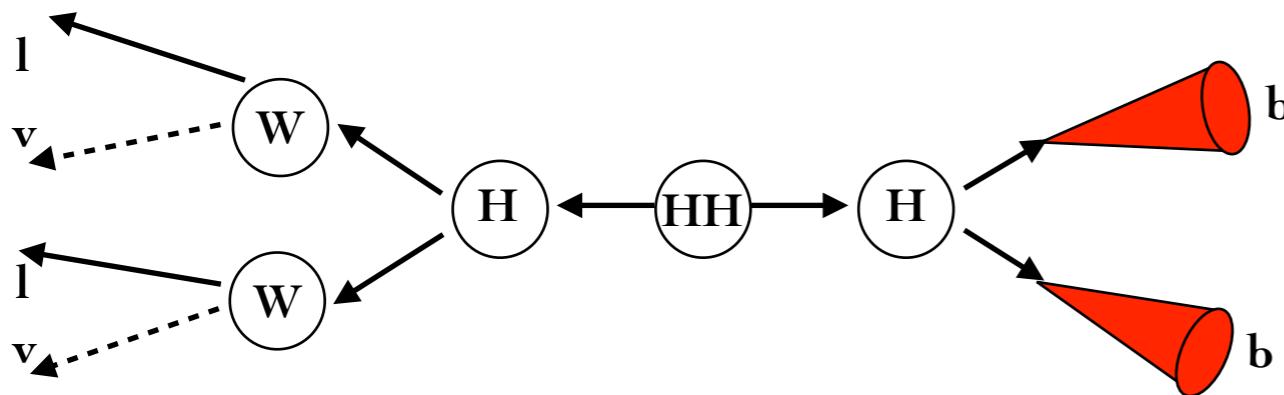


# HH EWK-Singlet Results

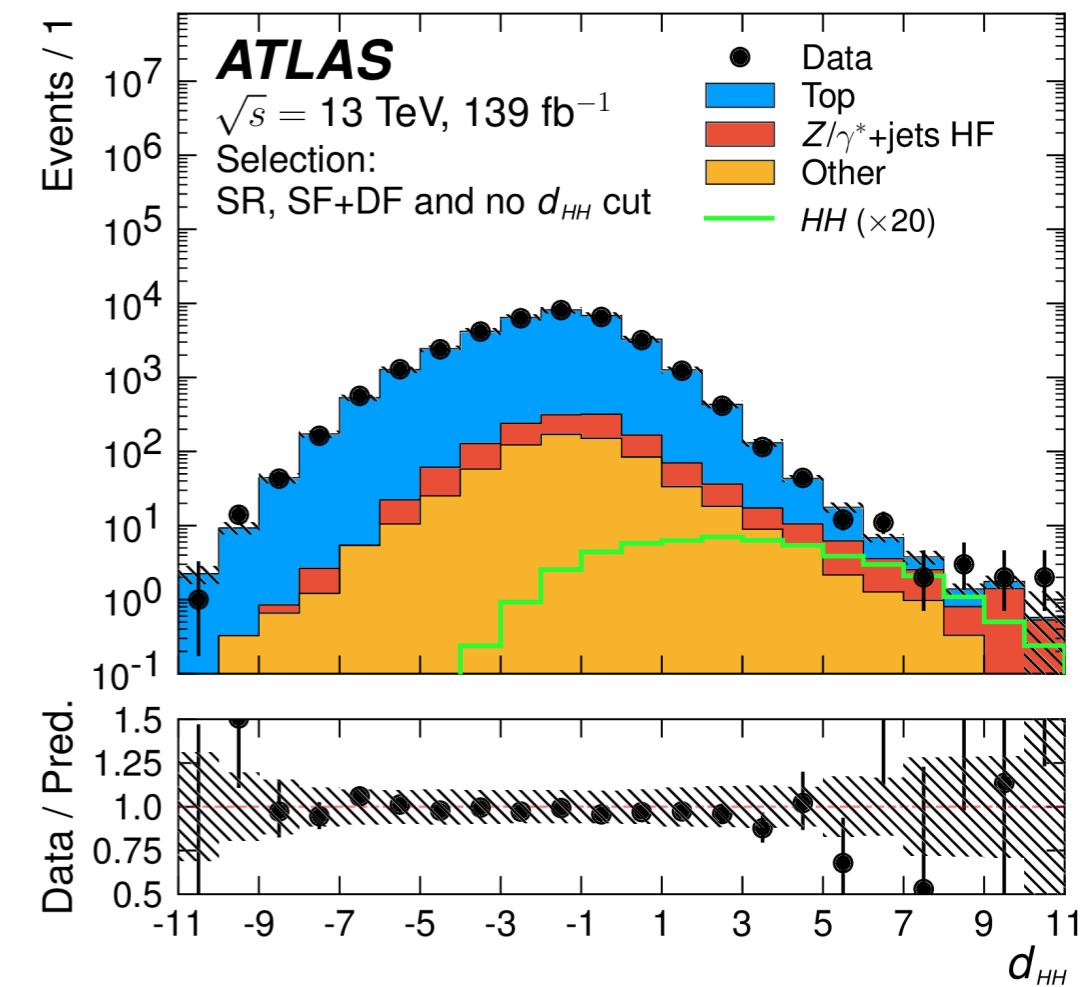
Constraints on Electroweak Singlet and hMSSM models as a function of the scalar mass,  $\tan \beta$  and  $\sin \alpha$

example:





- new analysis on **full Run 2 data** (140/fb)
- search for **2 lepton** decays of  $H \rightarrow WW, ZZ$  and  $\tau\tau$
- analysis uses multi-class deep neural network (**DNN**)
- counting experiment in 4 regions:
  - same- and different lepton flavour signal regions
  - top-quark and Z+heavy flavour control regions

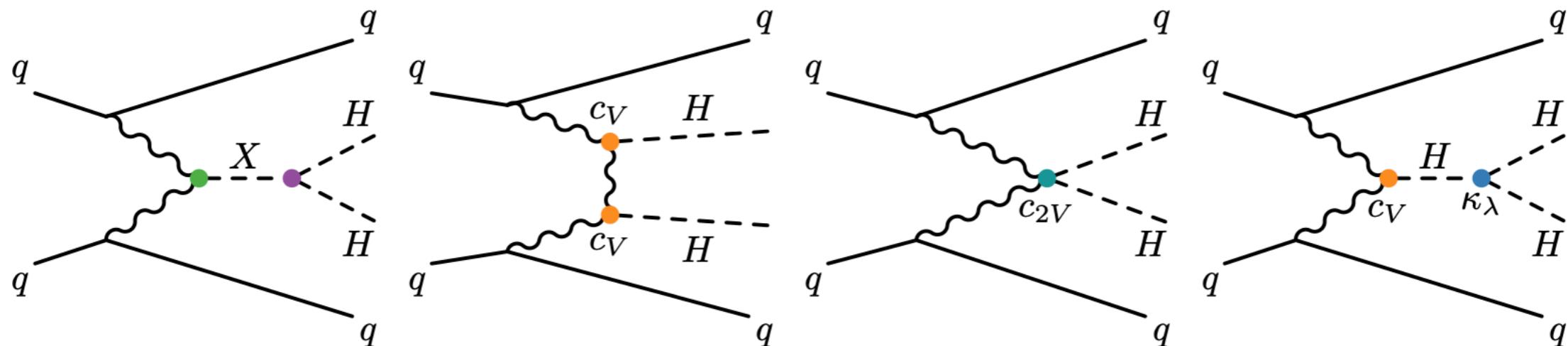


$$d_{HH} = \ln \left[ p_{HH} / (p_{\text{Top}} + p_{Z-\ell\ell} + p_{Z-\tau\tau}) \right]$$

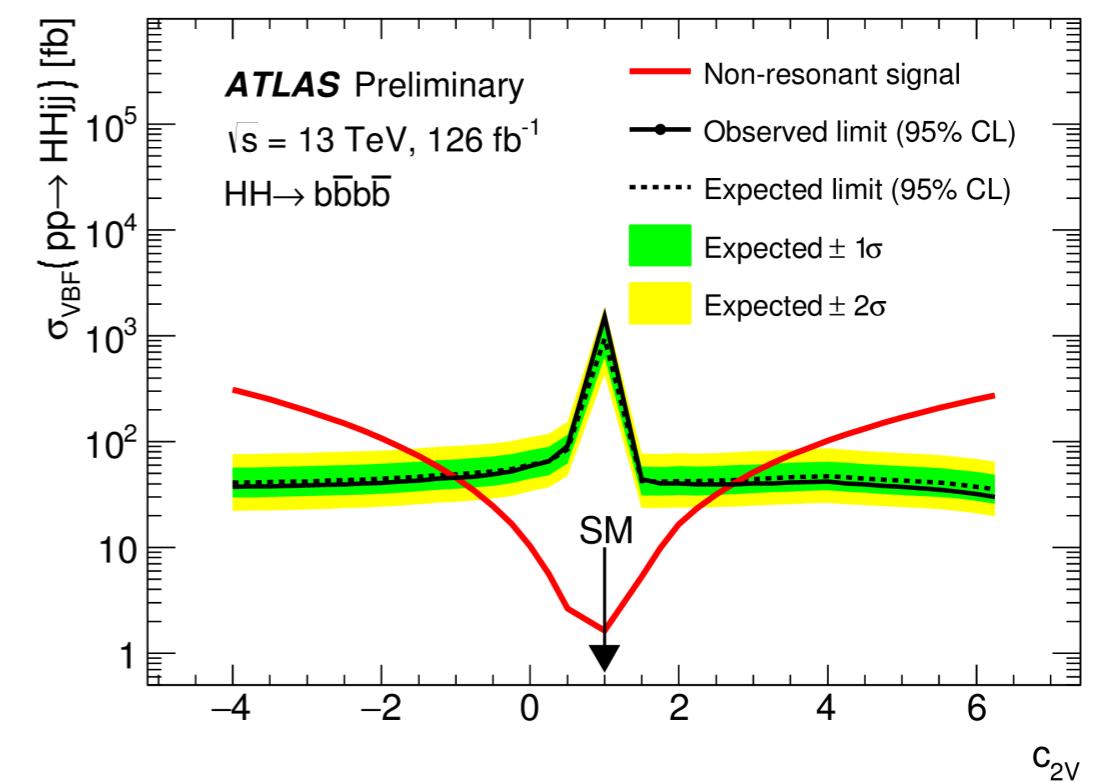
	$-2\sigma$	$-1\sigma$	Expected	$+1\sigma$	$+2\sigma$	Observed
$\sigma(gg \rightarrow HH) [\text{pb}]$	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma(gg \rightarrow HH) / \sigma^{\text{SM}}(gg \rightarrow HH)$	14	20	29	43	62	40

**NEW**

# VBF HH 4b hhVV coupling

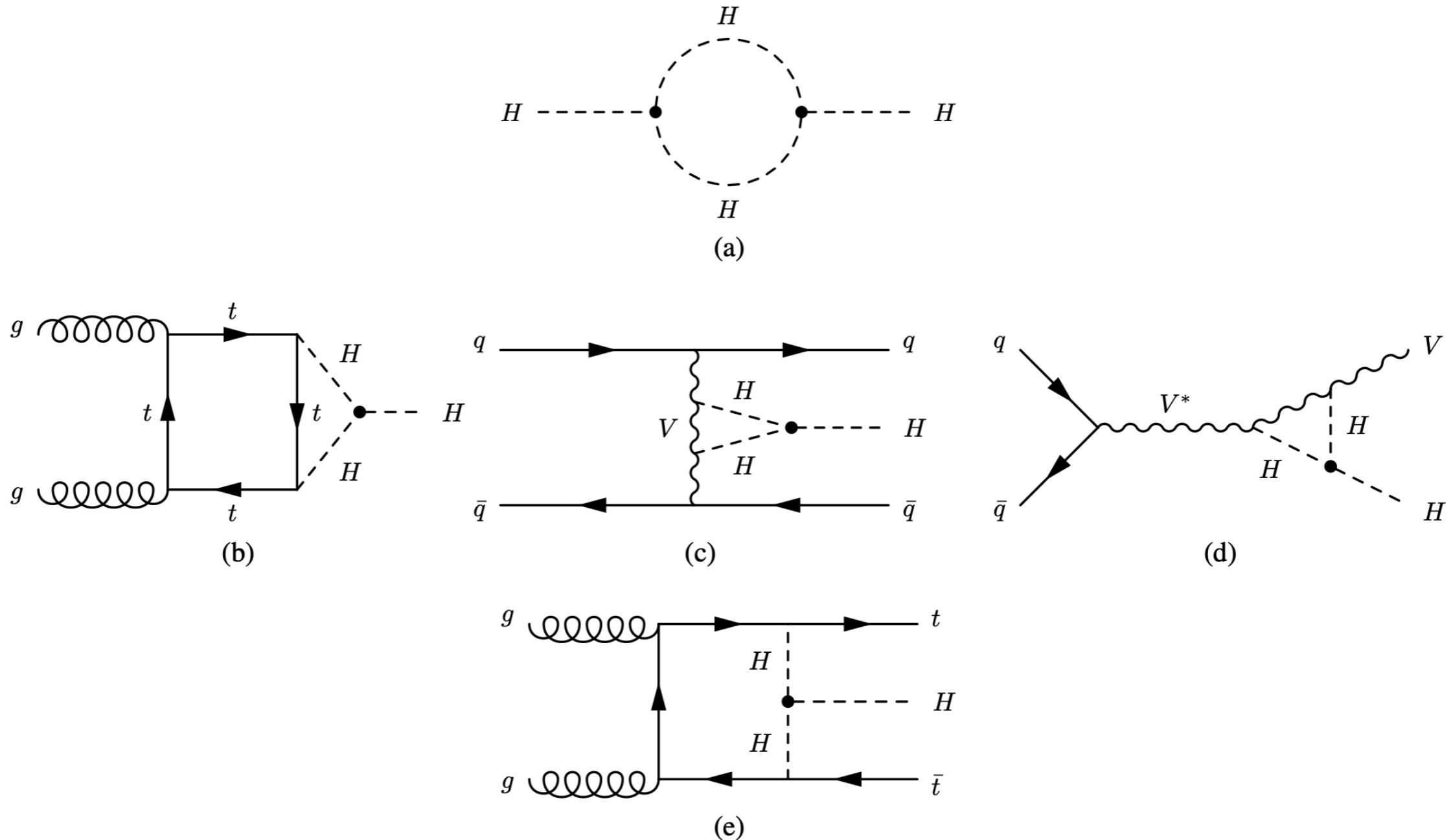


- first ATLAS search for **HH via VBF** production
  - unique: sensitive to **hhVV coupling**
- **SM cross-section  $\sim 1.7 \text{ fb}$  at 13 TeV**
  - unique signature due to **two forward jets**
  - small derivations from the SM => large changes in the production rate
  - low sensitivity to SM HH (1000xSM)



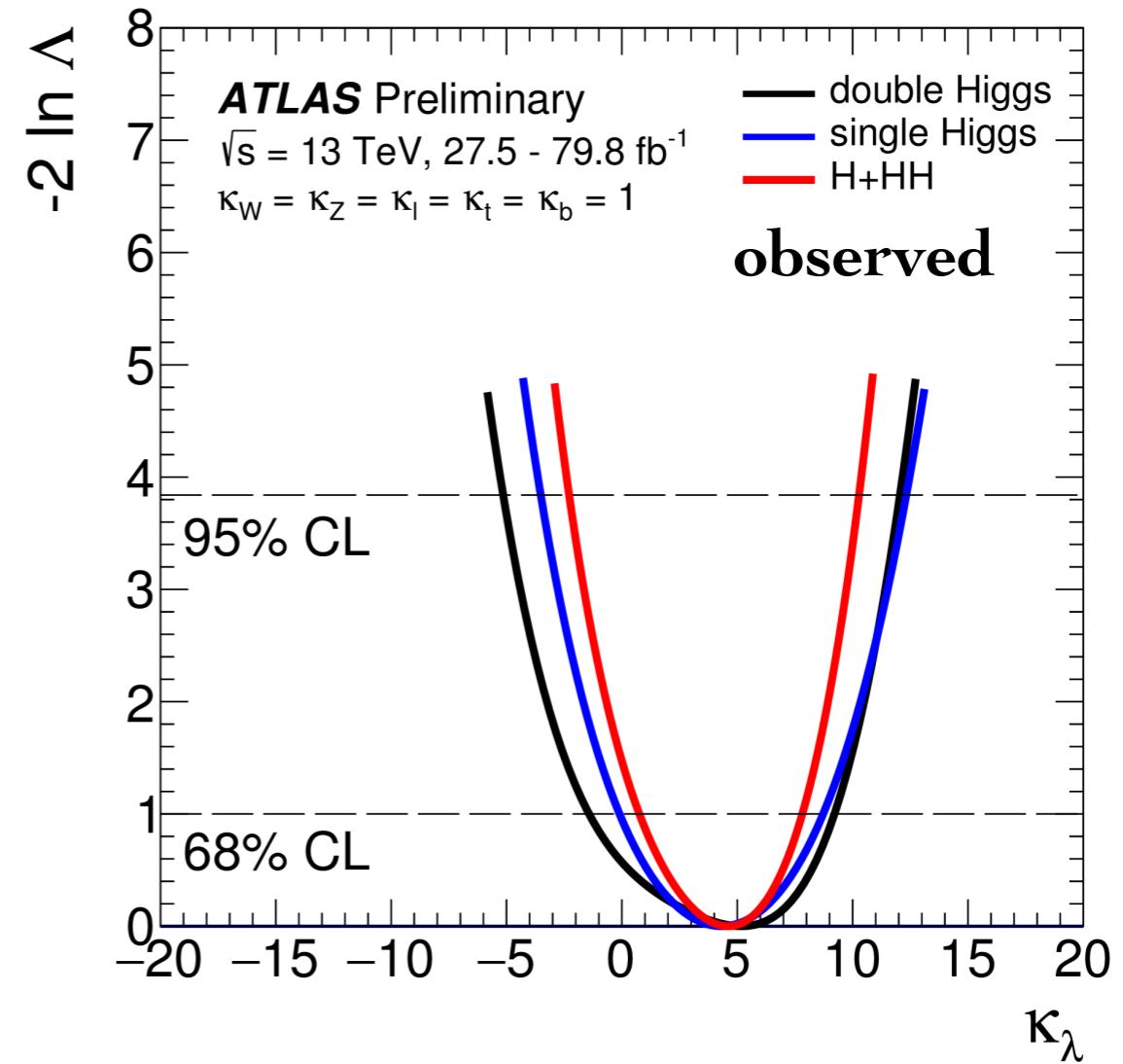
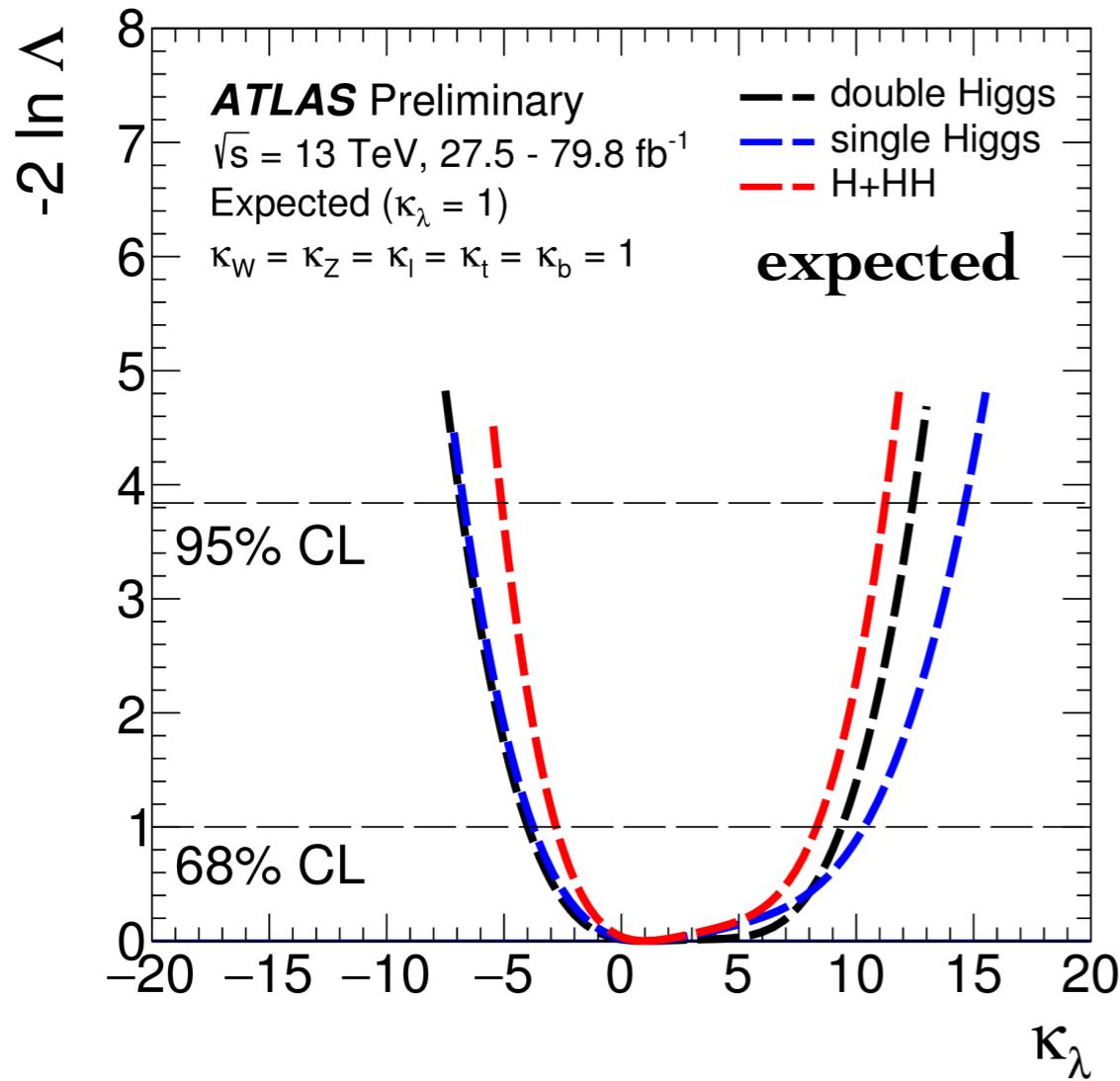
**excluded:**  $c_{2V} < -1.02$  and  $c_{2V} > 2.71$   
@ 95% CL

# Higgs Self-Coupling in Single Higgs



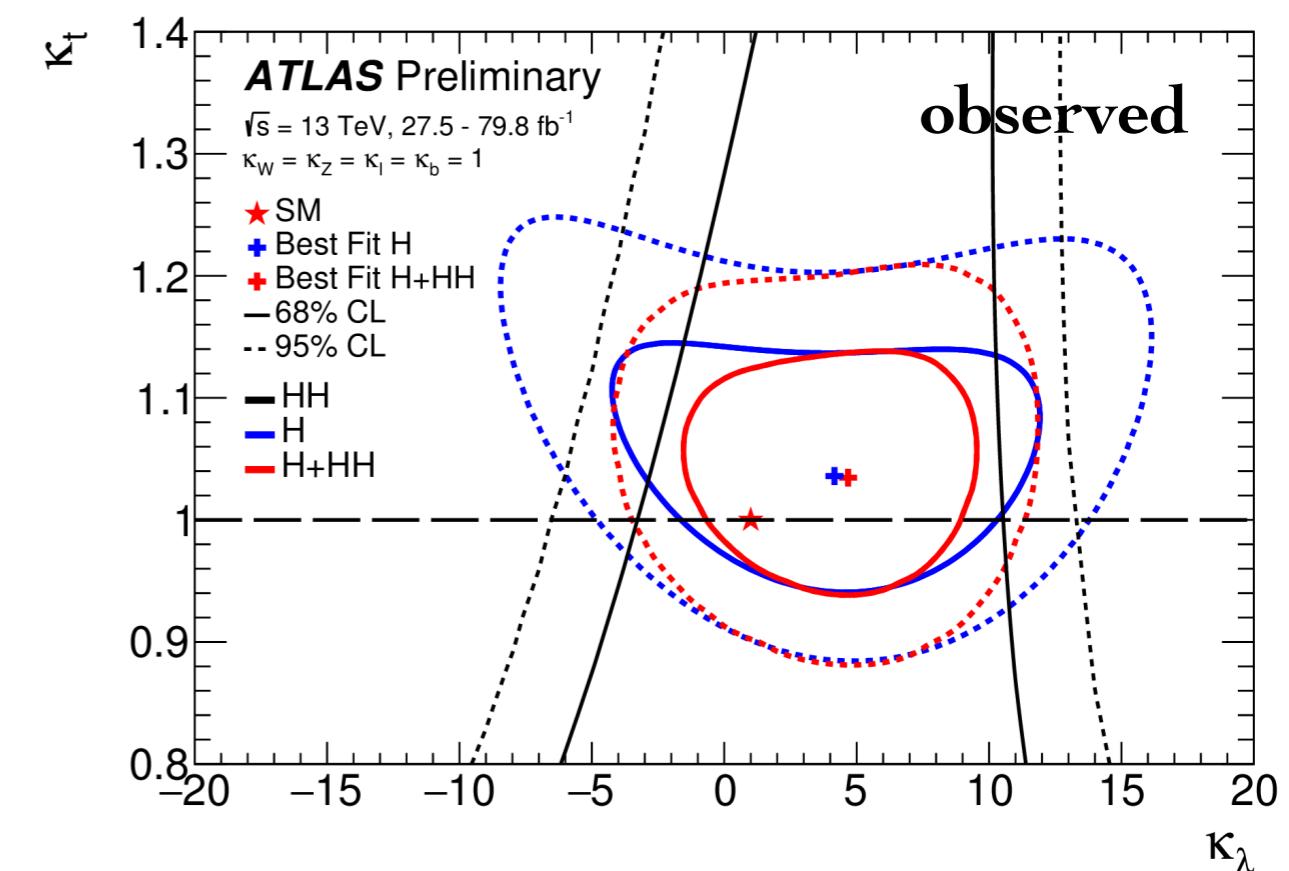
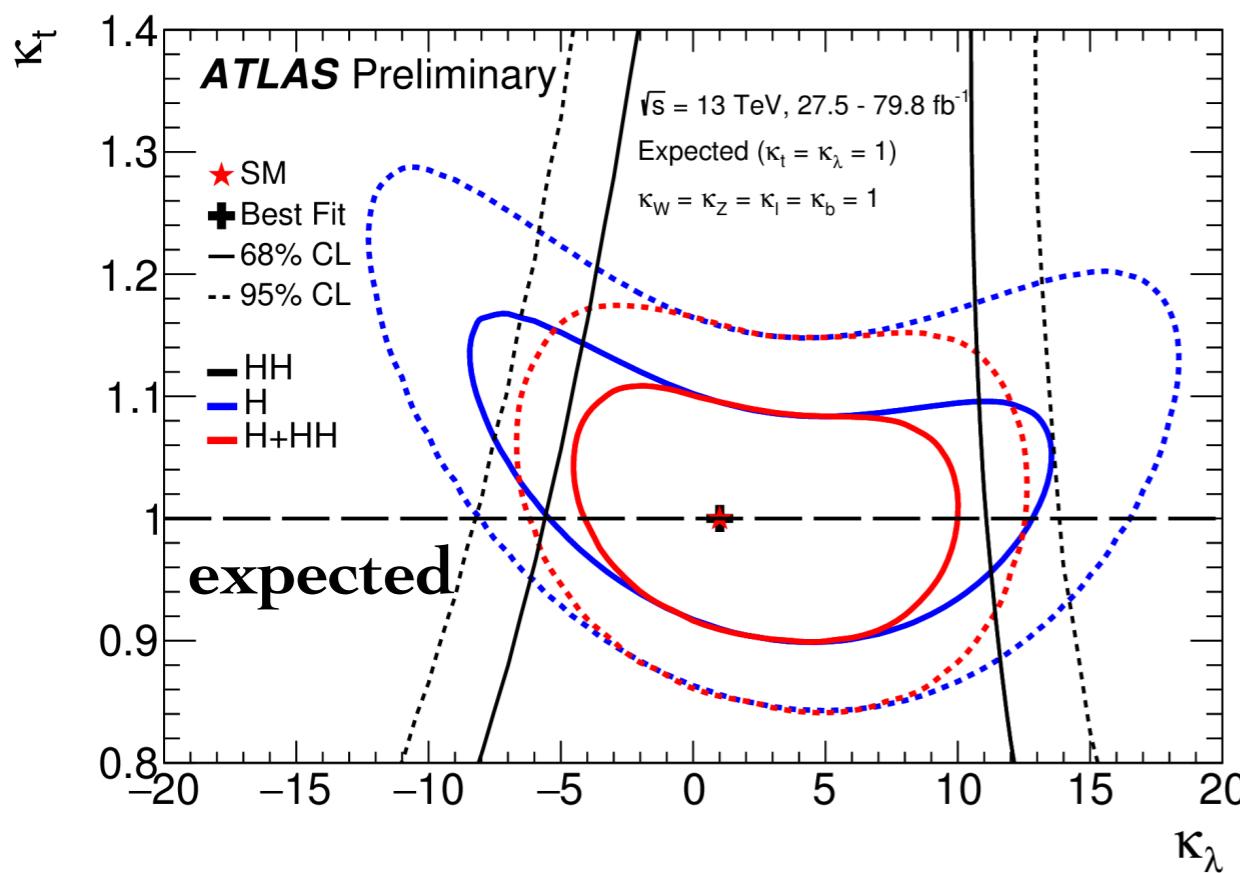
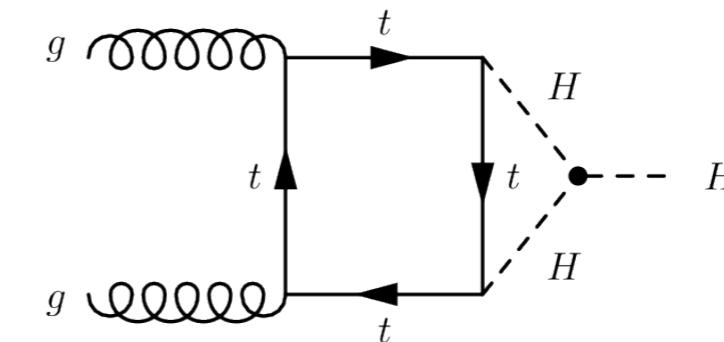
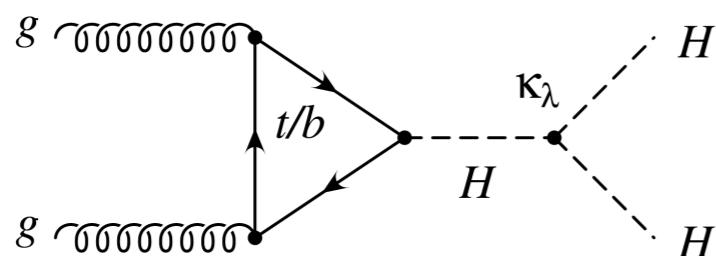
- single Higgs production is sensitive to Higgs self-coupling via next-to-leading order electroweak corrections
- combine H and HH analyses

# Higgs Self-Coupling H + HH

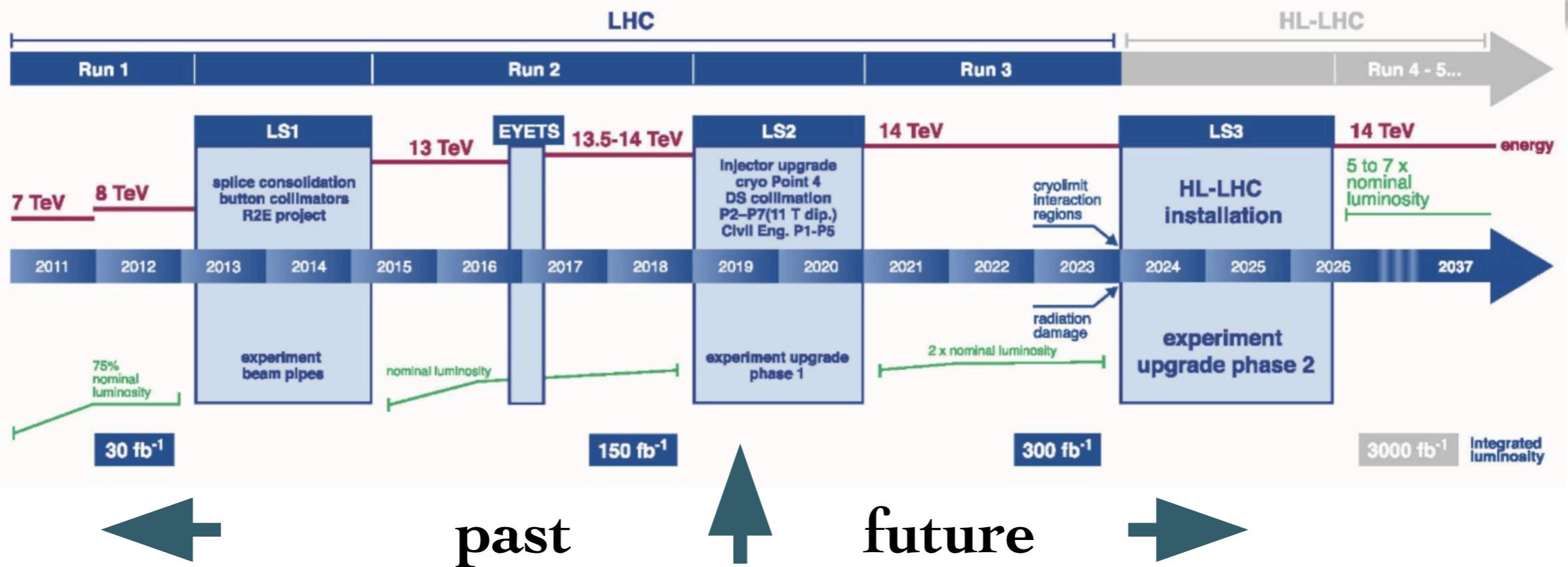


Model	$\kappa_w^{+1\sigma}_{-1\sigma}$	$\kappa_z^{+1\sigma}_{-1\sigma}$	$\kappa_t^{+1\sigma}_{-1\sigma}$	$\kappa_b^{+1\sigma}_{-1\sigma}$	$\kappa_\ell^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda [95\% \text{ CL}]$	
$\kappa_\lambda$ -only	1	1	1	1	1	$4.6^{+3.2}_{-3.8}$ $1.0^{+7.3}_{-3.8}$	$[-2.3, 10.3]$ $[-5.1, 11.2]$	obs. exp.
Generic	$1.03^{+0.08}_{-0.08}$	$1.10^{+0.09}_{-0.09}$	$1.00^{+0.12}_{-0.11}$	$1.03^{+0.20}_{-0.18}$	$1.06^{+0.16}_{-0.16}$	$5.5^{+3.5}_{-5.2}$	$[-3.7, 11.5]$	obs.
	$1.00^{+0.08}_{-0.08}$	$1.00^{+0.08}_{-0.08}$	$1.00^{+0.12}_{-0.12}$	$1.00^{+0.21}_{-0.19}$	$1.00^{+0.16}_{-0.15}$	$1.0^{+7.6}_{-4.5}$	$[-6.2, 11.6]$	exp.

# Higgs Self-Coupling $H + HH$



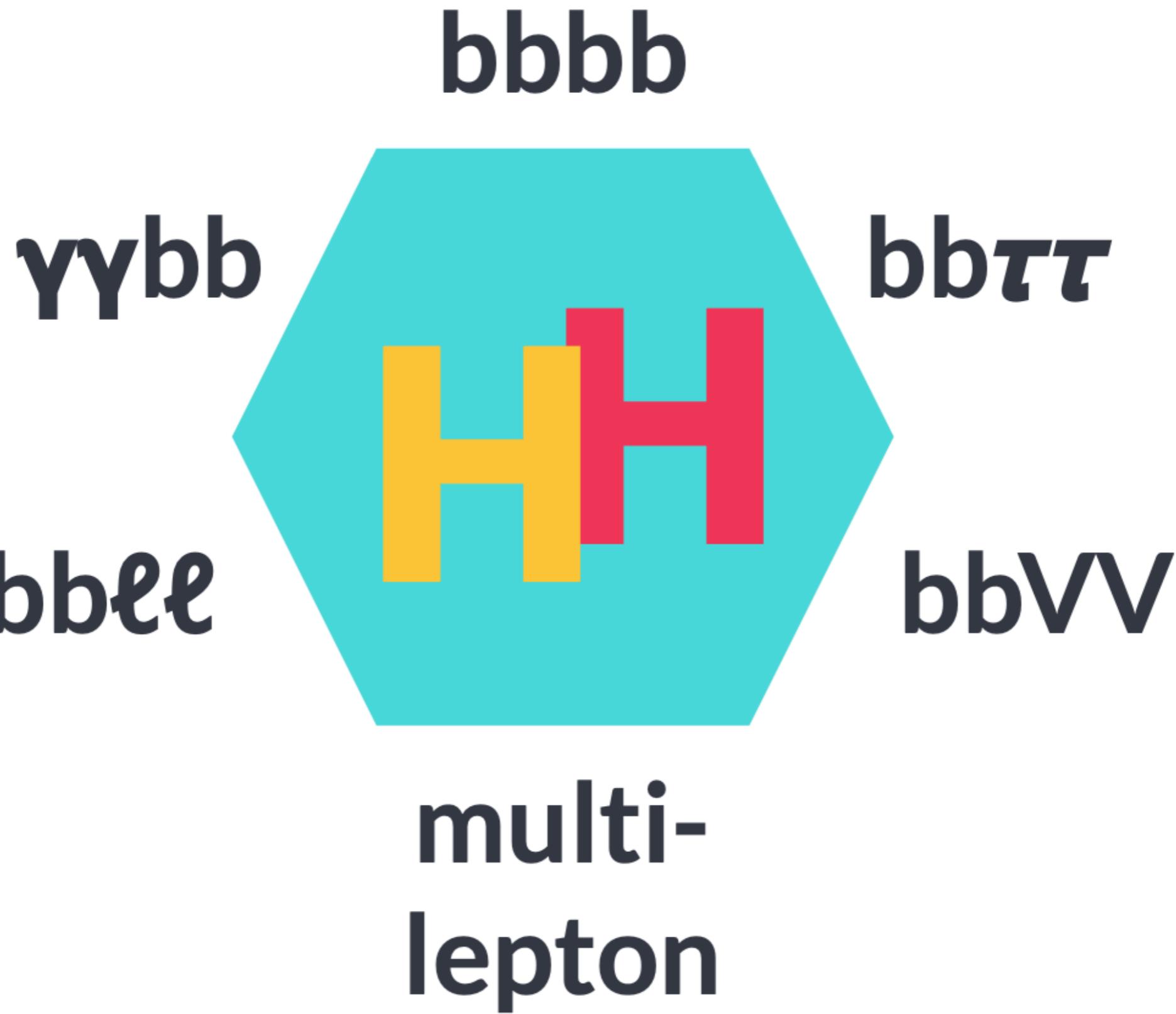
- top quark appears in loops
- simultaneous fit of top-Higgs and H self-couplings



- pile-up increase to  $\sim 200$  average pp collisions (now  $\sim 40$ )
- analysis **projections** for the new environment
  - include estimates for detector **improvements**, amount of data and collision energy, analysis methods and tools
- expected significance to observe **SM HH production** at 14 TeV and 3000/fb of data, including extrapolated **uncertainties**
  - ATLAS:  $3\sigma$ , ATLAS+CMS:  $4\sigma$  over bkg-only hypothesis
  - ATLAS + CMS @ 68%CL with systematics:  $0.52 \leq \kappa_\lambda \leq 1.5$

# Conclusions

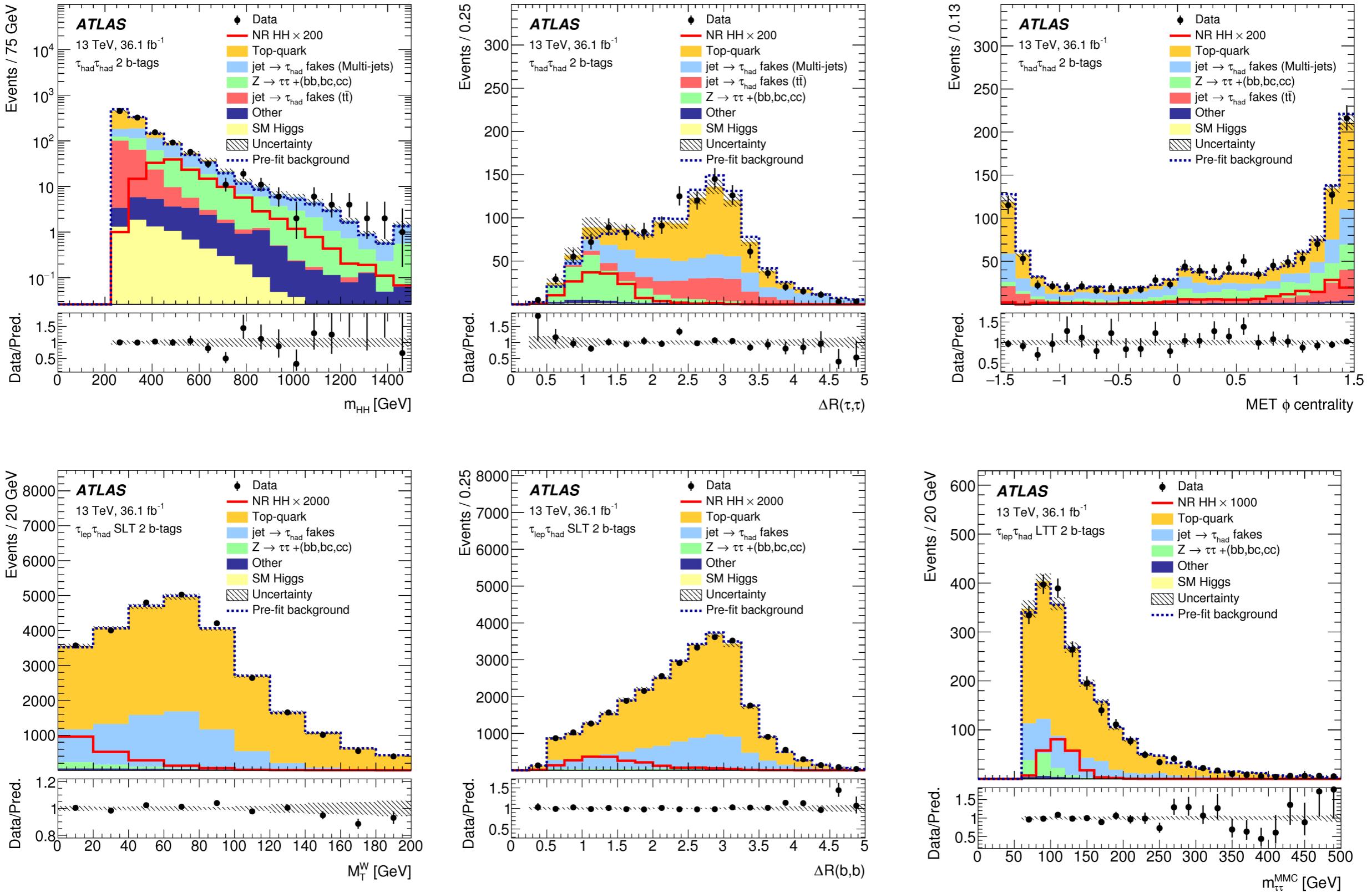
- **strong program** of searches for non-resonant and resonant HH production and determination of Higgs self-coupling
- ATLAS reaches **6.9 x SM** for the HH production with the partial Run-2 data set (**36/fb**)
- first analyses on the **full Run-2 dataset**(140/fb) become available
- first attempt to constrain the hhVV coupling in the VBF HH 4b channel
- promising projections at HL-LHC: **4 $\sigma$**  for HH production over bkg-only hypothesis combining ATLAS + CMS



# HH $b\bar{b}\tau\bar{\tau}$ : BDT

Variable	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT resonant)	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT non-resonant & LTT)	$\tau_{\text{had}}\tau_{\text{had}}$ channel
$m_{HH}$	✓	✓	✓
$m_{\tau\tau}^{\text{MMC}}$	✓	✓	✓
$m_{bb}$	✓	✓	✓
$\Delta R(\tau, \tau)$	✓	✓	✓
$\Delta R(b, b)$	✓	✓	✓
$E_{\text{T}}^{\text{miss}}$	✓		
$E_{\text{T}}^{\text{miss}}$ $\phi$ centrality	✓		✓
$m_{\text{T}}^W$	✓	✓	
$\Delta\phi(H, H)$	✓		
$\Delta p_{\text{T}}(\text{lep}, \tau_{\text{had-vis}})$	✓		
Sub-leading $b$ -jet $p_{\text{T}}$	✓		

# HH $b\bar{b}\tau\bar{\tau}$ : BDT variables



# HH $b\bar{b}\tau\tau$ : yields

	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT)	$\tau_{\text{had}}\tau_{\text{had}}$ channel (LTT)	$\tau_{\text{had}}\tau_{\text{had}}$ channel
$t\bar{t}$	$17800 \pm 1100$	$1475 \pm 94$	$360 \pm 100$
Single top	$1130 \pm 110$	$72.9 \pm 7.6$	$39.7 \pm 5.9$
Multi-jet fake- $\tau_{\text{had}}$	-	-	$294 \pm 57$
$t\bar{t}$ fake- $\tau_{\text{had}}$	-	-	$160 \pm 120$
Fake- $\tau_{\text{had}}$	$9000 \pm 1100$	$475 \pm 76$	-
$Z \rightarrow \tau\tau + (cc, bc, bb)$	$416 \pm 97$	$117 \pm 28$	$291 \pm 91$
Other	$197 \pm 32$	$14.5 \pm 2.3$	$22.9 \pm 5.9$
SM Higgs	$38 \pm 10$	$4.1 \pm 1.0$	$8.2 \pm 2.1$
Total Background	$28610 \pm 180$	$2159 \pm 46$	$1178 \pm 40$
Data	28612	2161	1180
$G_{\text{KK}}(300 \text{ GeV}, k/\overline{M}_{Pl} = 1)$	$23.6 \pm 3.7$	$7.5 \pm 1.2$	$13.1 \pm 2.6$
$G_{\text{KK}}(500 \text{ GeV}, k/\overline{M}_{Pl} = 1)$	$42.4 \pm 6.4$	$9.9 \pm 1.5$	$36.3 \pm 7.0$
$G_{\text{KK}}(1000/800(\text{LTT}) \text{ GeV}, k/\overline{M}_{Pl} = 1)$	$2.6 \pm 0.4$	$1.06 \pm 0.16$	$2.11 \pm 0.43$
$G_{\text{KK}}(300 \text{ GeV}, k/\overline{M}_{Pl} = 2)$	$327 \pm 50$	$82 \pm 13$	$240 \pm 46$
$G_{\text{KK}}(500 \text{ GeV}, k/\overline{M}_{Pl} = 2)$	$193 \pm 29$	$39.7 \pm 6.1$	$187 \pm 36$
$G_{\text{KK}}(1000/800(\text{LTT}) \text{ GeV}, k/\overline{M}_{Pl} = 2)$	$8.6 \pm 1.3$	$3.63 \pm 0.56$	$7.9 \pm 1.6$
$X(300 \text{ GeV})$	$39.1 \pm 6.3$	$11.8 \pm 1.9$	$17.9 \pm 3.6$
$X(500 \text{ GeV})$	$3.41 \pm 0.52$	$0.88 \pm 0.13$	$2.84 \pm 0.54$
$X(1000/800(\text{LTT}) \text{ GeV})$	$0.0267 \pm 0.0041$	$0.0228 \pm 0.0035$	$0.0222 \pm 0.0044$
NR $HH$	$0.96 \pm 0.13$	$0.219 \pm 0.032$	$0.73 \pm 0.14$

# HH $b\bar{b}\tau\tau$ : yields in last 2 BDT bins

	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT)	$\tau_{\text{had}}\tau_{\text{had}}$ channel (LTT)	$\tau_{\text{had}}\tau_{\text{had}}$ channel
$t\bar{t}$	$18.2 \pm 4.2$	$23.2 \pm 1.7$	$4.5 \pm 1.4$
Single top	$6.4 \pm 1.3$	$3.7 \pm 1.2$	$1.06 \pm 0.57$
Multi-jet fake- $\tau_{\text{had}}$	-	-	$3.89 \pm 0.87$
$t\bar{t}$ fake- $\tau_{\text{had}}$	-	-	$1.9 \pm 1.4$
Fake- $\tau_{\text{had}}$	$12.0 \pm 2.3$	$6.6 \pm 1.5$	-
$Z \rightarrow \tau\tau + (cc, bc, bb)$	$10.2 \pm 2.6$	$7.7 \pm 3.1$	$12.6 \pm 3.6$
Other	$3.89 \pm 0.69$	$1.51 \pm 0.36$	$1.09 \pm 0.32$
SM Higgs	$1.94 \pm 0.43$	$0.58 \pm 0.14$	$1.54 \pm 0.41$
Total Background	$52.7 \pm 4.5$	$39.5 \pm 3.0$	$26.7 \pm 3.5$
Data	45	47	20
NR $HH$	$0.48 \pm 0.07$	$0.16 \pm 0.02$	$0.54 \pm 0.10$

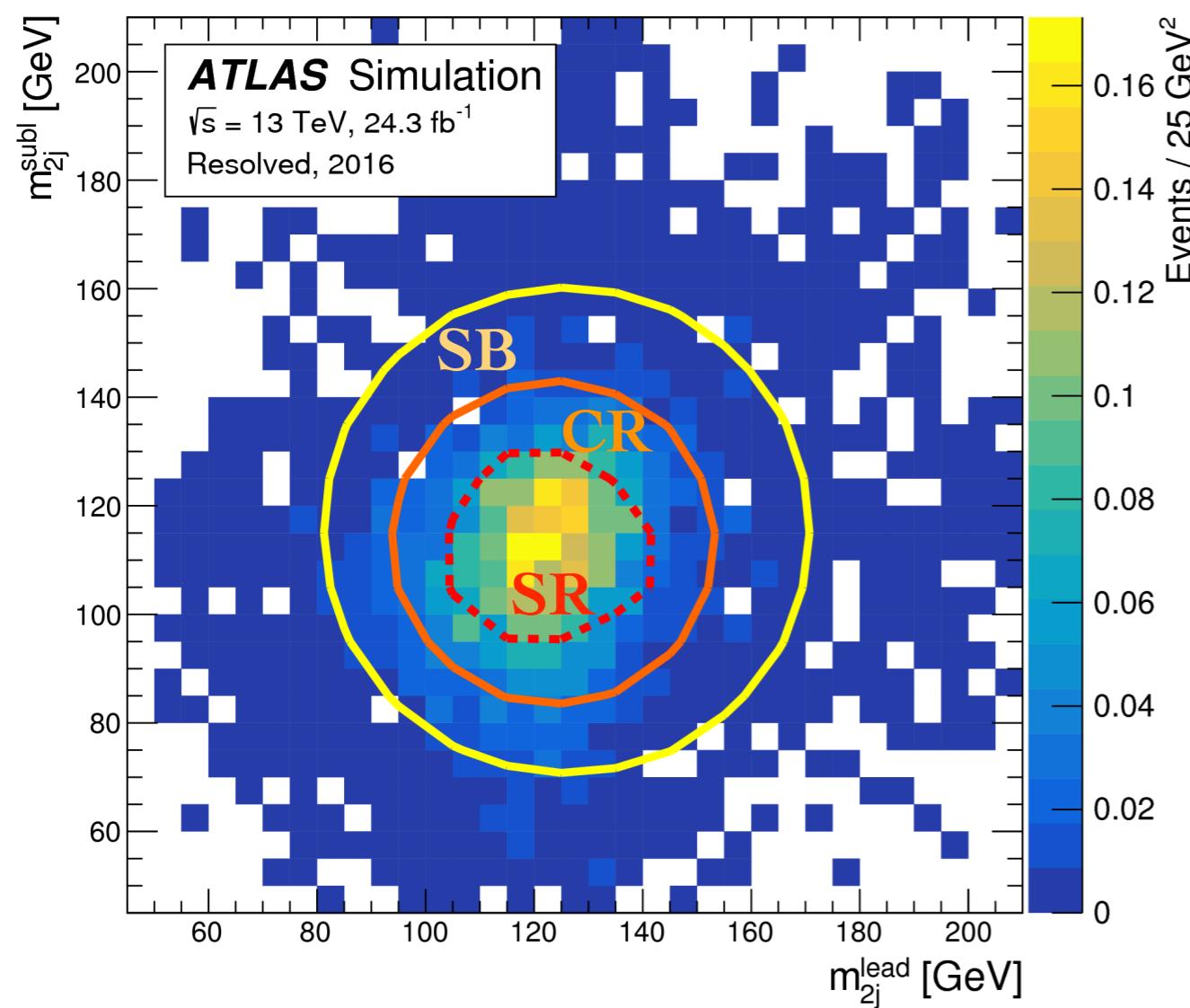
# HH $b\bar{b}\tau\bar{\tau}$ : systematics

Source	Uncertainty (%)
Total	$\pm 54$
Data statistics	$\pm 44$
Simulation statistics	$\pm 16$
Experimental Uncertainties	
Luminosity	$\pm 2.4$
Pileup reweighting	$\pm 1.7$
$\tau_{\text{had}}$	$\pm 16$
Fake- $\tau$ estimation	$\pm 8.4$
$b$ -tagging	$\pm 8.3$
Jets and $E_T^{\text{miss}}$	$\pm 3.3$
Electron and muon	$\pm 0.5$
Theoretical and Modeling Uncertainties	
Top	$\pm 17$
Signal	$\pm 9.3$
$Z \rightarrow \tau\tau$	$\pm 6.8$
SM Higgs	$\pm 2.9$
Other backgrounds	$\pm 0.3$

Table 2: The percentage uncertainties on the simulated non-resonant signal strength, i.e. the simulated NR  $HH$  yield assuming a cross-section times branching fraction equal to the 95% CL expected limit of 14.8 times the SM expectation.

# HH 4b: resolved analysis regions

## SM HH signal



**Signal region (SR):**  
 for the final search

$$X_{HH} = \sqrt{\left(\frac{m_{2j}^{\text{lead}} - 120 \text{ GeV}}{0.1m_{2j}^{\text{lead}}}\right)^2 + \left(\frac{m_{2j}^{\text{subl}} - 110 \text{ GeV}}{0.1m_{2j}^{\text{subl}}}\right)^2} < 1.6,$$

**Sideband region (SB):**  
 to derive bkgds

$$\sqrt{(m_{2j}^{\text{lead}} - 126 \text{ GeV})^2 + (m_{2j}^{\text{subl}} - 116 \text{ GeV})^2} < 45 \text{ GeV},$$

**Control region (CR):**  
 to test bkgds and derive systs

$$\sqrt{(m_{2j}^{\text{lead}} - 124 \text{ GeV})^2 + (m_{2j}^{\text{subl}} - 113 \text{ GeV})^2} < 30 \text{ GeV},$$

# HH 4b: resolved yields

Sample	2015 SR		2016 SR		2015 CR		2016 CR
Multijet	866	$\pm$ 70	6750	$\pm$ 170	880	$\pm$ 71	7110 $\pm$ 180
$t\bar{t}$ , hadronic	52	$\pm$ 35	259	$\pm$ 57	56	$\pm$ 37	276 $\pm$ 61
$t\bar{t}$ , semileptonic	13.9	$\pm$ 6.5	123	$\pm$ 30	20	$\pm$ 9	168 $\pm$ 40
Total	930	$\pm$ 70	7130	$\pm$ 130	956	$\pm$ 50	7550 $\pm$ 130
Data	928		7430		969		7656
$G_{KK}$ (800 GeV)	12.5	$\pm$ 1.9	89	$\pm$ 14			
Scalar (280 GeV)	24.0	$\pm$ 7.5	180	$\pm$ 57			
SM $HH$	0.607	$\pm$ 0.091	4.43	$\pm$ 0.66			

# HH 4b: boosted yields

Source	Two-tag		Three-tag		Four-tag	
	Sideband	Control	Sideband	Control	Sideband	Control
Multijet	17 280 $\pm$ 160	6848 $\pm$ 67	3551 $\pm$ 98	1425 $\pm$ 42	176 $\pm$ 23	70.4 $\pm$ 8.5
$t\bar{t}$	7850 $\pm$ 160	1485 $\pm$ 40	853 $\pm$ 82	162 $\pm$ 19	28 $\pm$ 19	6.4 $\pm$ 4.3
Total	25 140 $\pm$ 180	8333 $\pm$ 67	4404 $\pm$ 77	1587 $\pm$ 36	204 $\pm$ 14	76.8 $\pm$ 7.8
Data	25137	8486	4403	1553	204	81

# HH 4b: systematics (resolved)

Table 2: Summary of systematic relative uncertainties (expressed in percentage yield) in the total background and signal event yields in the signal region of the resolved analysis. Uncertainties are provided for both the 2015 and 2016 analyses for background, a  $G_{KK}$  resonance with  $k/\bar{M}_{\text{Pl}} = 1$  and  $m(G_{KK}) = 800 \text{ GeV}$ , a scalar with a mass of 280 GeV and SM non-resonant Higgs boson pair production. The total uncertainties include the effect of correlations.

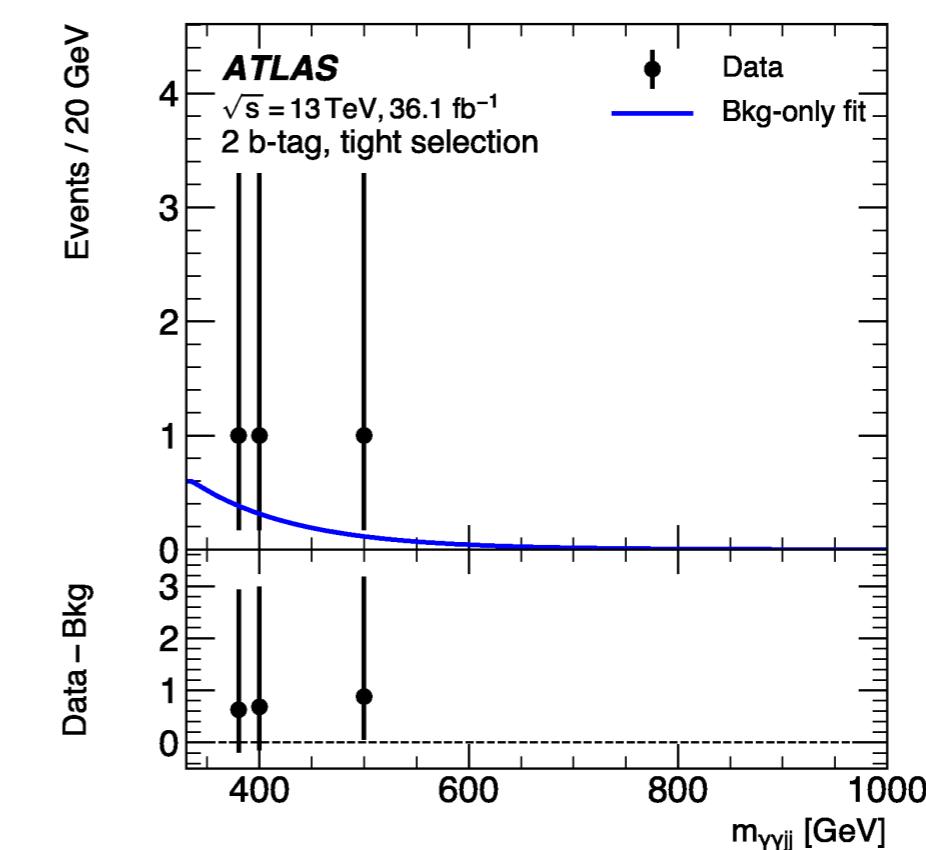
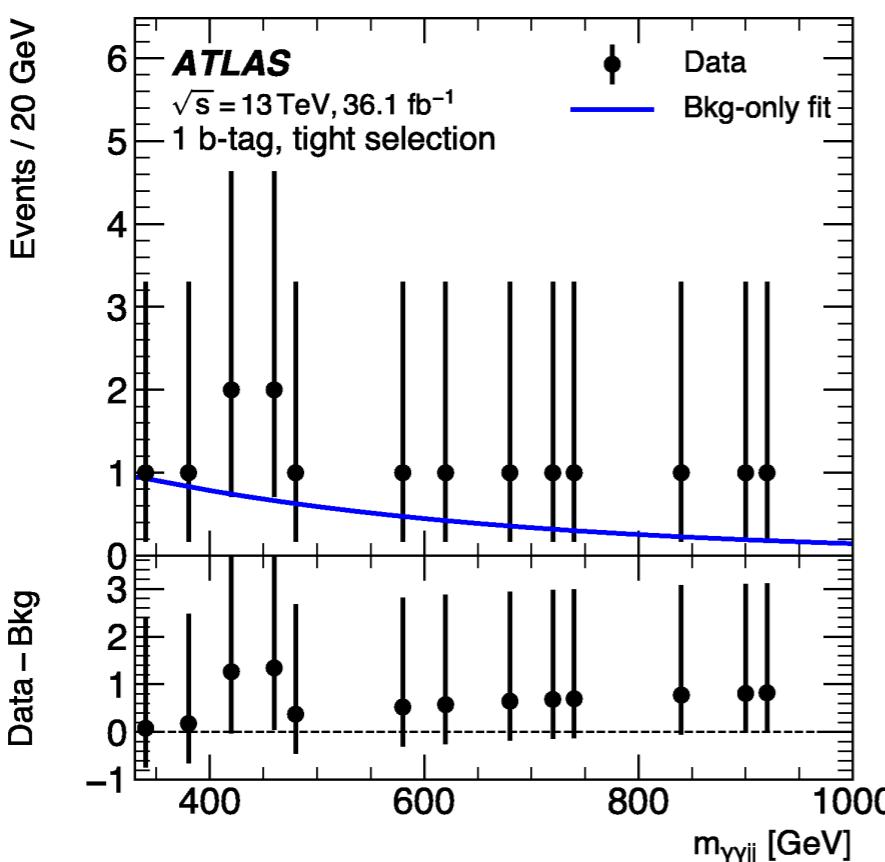
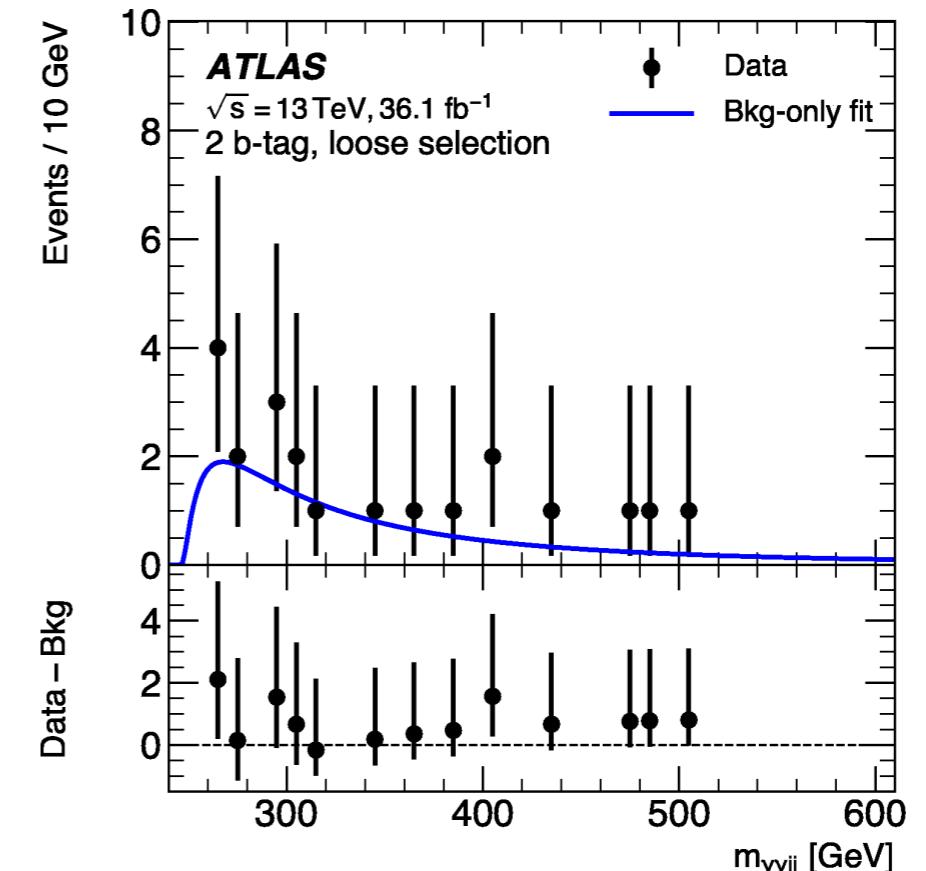
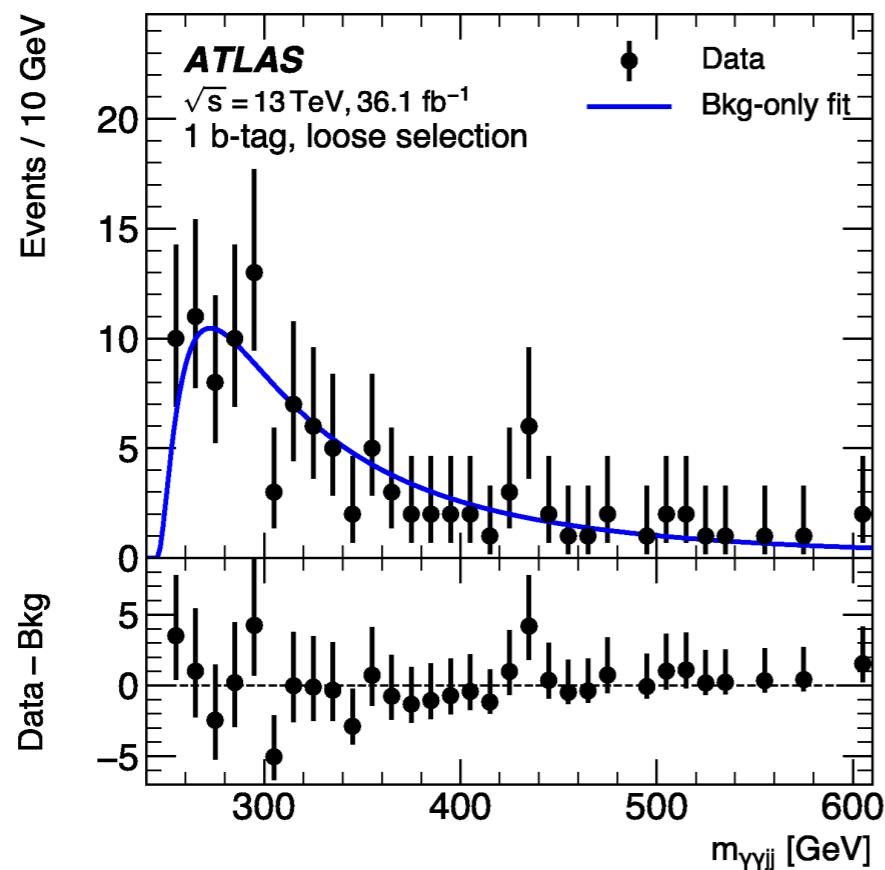
Source	2015					2016				
	Background	Scalar	SM $HH$	$G_{KK}$	Background	Scalar	SM $HH$	$G_{KK}$		
Luminosity	—	2.1	2.1	2.1	—	2.2	2.2	2.2		
Jet energy	—	17	7.1	3.7	—	17	6.4	3.7		
$b$ -tagging	—	13	12	14	—	13	12	14		
$b$ -trigger	—	4.0	2.3	1.3	—	2.6	2.5	2.5		
Theoretical	—	23	7.2	0.6	—	23	7.2	0.6		
Multijet stat	4.2	—	—	—	1.5	—	—	—		
Multijet syst	6.1	—	—	—	1.8	—	—	—		
$t\bar{t}$ stat	2.1	—	—	—	0.8	—	—	—		
$t\bar{t}$ syst	3.5	—	—	—	0.3	—	—	—		
Total	7.5	31	16	15	1.8	31	16	15		

# HH 4b: systematics (boosted)

Table 6: Summary of systematic uncertainties (expressed in percentage) in the total background and signal event yields in the signal region of the boosted analysis. Uncertainties are provided for each of the three samples for background, a 2 TeV scalar, and a  $G_{\text{KK}}$  with  $k/\bar{M}_{\text{Pl}} = 1$  and  $m = 2.0$  TeV.

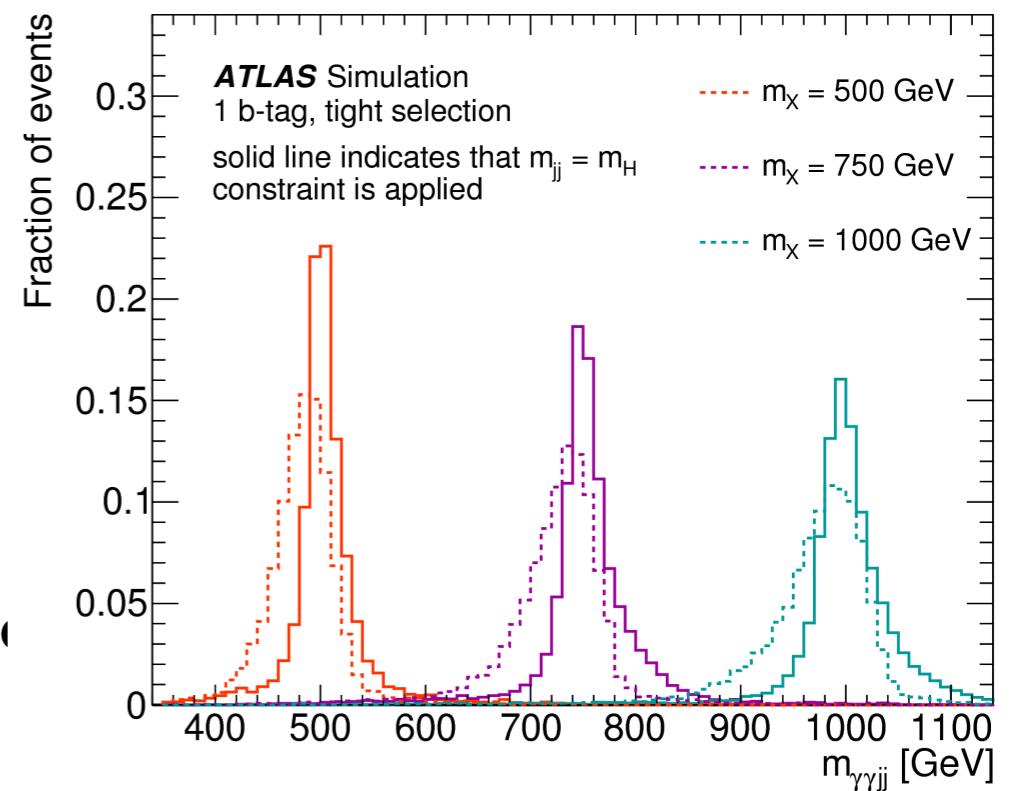
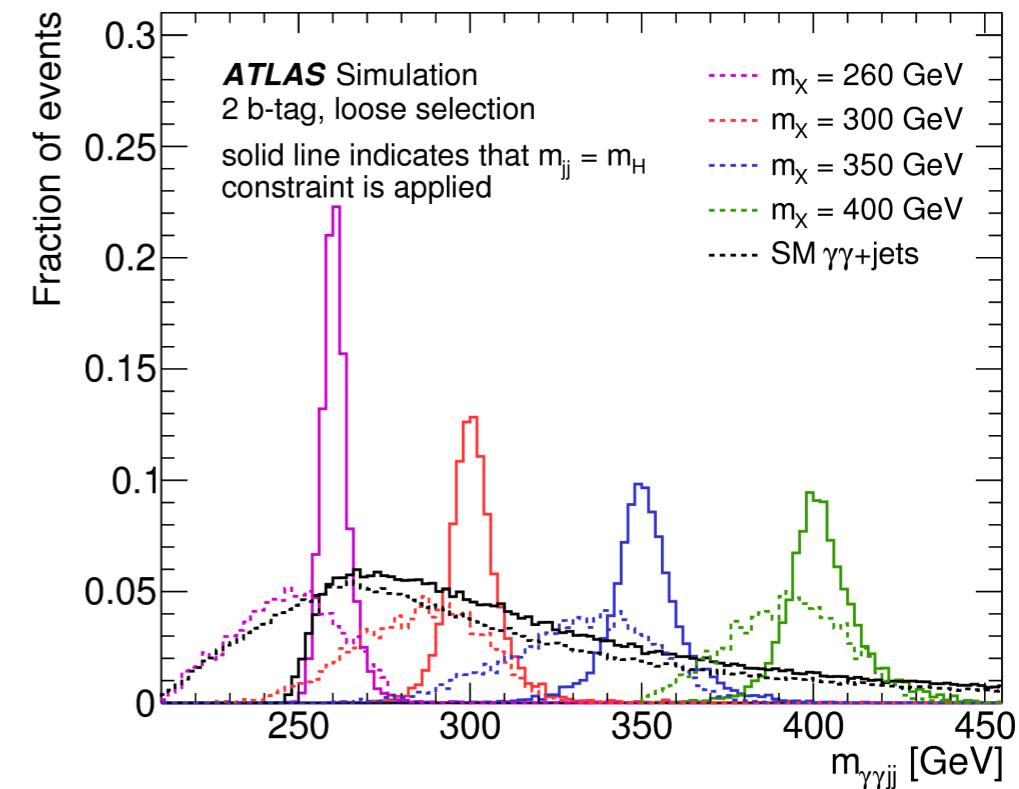
Source	Two-tag				Three-tag				Four-tag	
	Background	$G_{\text{KK}}$	Scalar	Background	$G_{\text{KK}}$	Scalar	Background	$G_{\text{KK}}$	Scalar	
Luminosity	-	2.1	2.1	-	2.1	2.1	-	2.1	2.1	2.1
JER	0.25	0.74	1	1.4	0.93	0.93	0.45	1.1	1.1	1.5
JMR	0.52	12	12	1.4	12	13	7.9	13	13	14
JES/JMS	0.43	1.7	2.1	2.0	1.9	2.2	1.3	3.7	3.7	5.7
$b$ -tagging	0.83	27	29	0.48	2	2.9	1.1	28	28	28
Bkgd estimate	2.8	-	-	5.8	-	-	16	-	-	-
Statistical	0.6	1.2	1.3	1.3	1.0	1.1	3.1	1.6	1.6	1.9
Total Syst	3.1	30	32	6.6	13	14	18	31	31	32

# HH $b\bar{b}\gamma\gamma$ : $m(\gamma\gamma b\bar{b})$



# HH bb $\gamma\gamma$ : selection

- **Loose selection:** used for resonant masses between 260 and 500 GeV and Higgs-self-coupling scan
  - jet  $p_T >= 40(25)$  GeV
  - $80 < m(bb) < 140$  GeV
  - resonant only:  $|m(\gamma\gamma) - m_H| < 4.7$  GeV
- **Tight selection:** used for resonant masses between 500 and 1000 GeV and SM non-resonant HH signal
  - jet  $p_T >= 100(30)$  GeV
  - $90 < m(bb) < 140$  GeV
  - resonant only:  $|m(\gamma\gamma) - m_H| < 4.3$  GeV
  - resonant only: di-Higgs 4-vector is scaled using single Higgs mass constraints to improve the  $m(bb\gamma\gamma)$  resolution

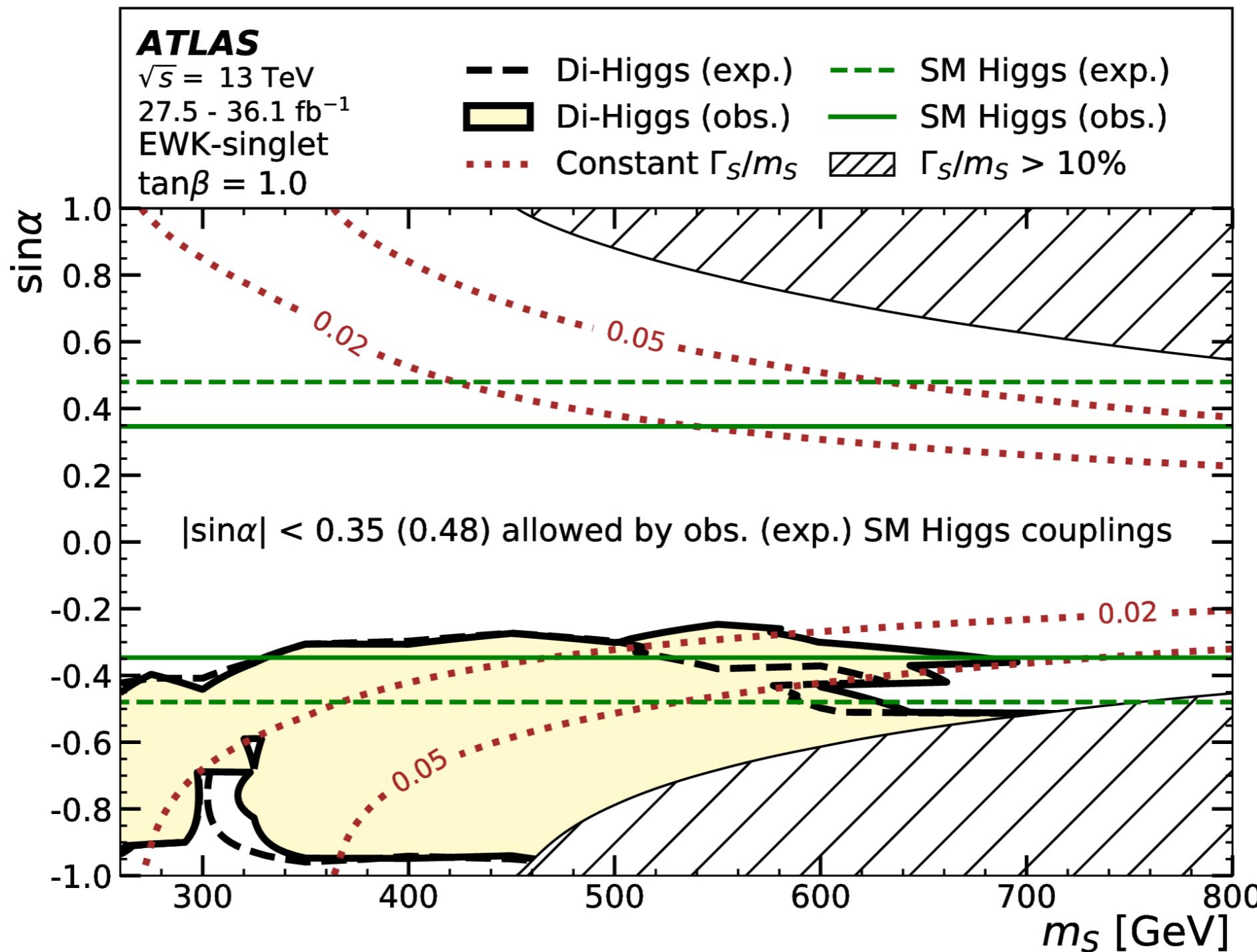


# HH $b\bar{b}\gamma\gamma$ : systematics

Source of systematic uncertainty	% effect relative to nominal in the 2-tag (1-tag) category								
	Non-resonant analysis				Resonant analysis: BSM $HH$				
	SM $HH$ signal		Single- $H$ bkg		Loose selection		Tight selection		
Luminosity	$\pm 2.1$	( $\pm 2.1$ )	$\pm 2.1$	( $\pm 2.1$ )	$\pm 2.1$	( $\pm 2.1$ )	$\pm 2.1$	( $\pm 2.1$ )	
Trigger	$\pm 0.4$	( $\pm 0.4$ )	$\pm 0.4$	( $\pm 0.4$ )	$\pm 0.4$	( $\pm 0.4$ )	$\pm 0.4$	( $\pm 0.4$ )	
Pile-up modelling	$\pm 3.2$	( $\pm 1.3$ )	$\pm 2.0$	( $\pm 0.8$ )	$\pm 4.0$	( $\pm 4.2$ )	$\pm 4.0$	( $\pm 3.8$ )	
Photon	identification	$\pm 2.5$	( $\pm 2.4$ )	$\pm 1.7$	( $\pm 1.8$ )	$\pm 2.6$	( $\pm 2.6$ )	$\pm 2.5$	( $\pm 2.5$ )
	isolation	$\pm 0.8$	( $\pm 0.8$ )	$\pm 0.8$	( $\pm 0.8$ )	$\pm 0.8$	( $\pm 0.8$ )	$\pm 0.9$	( $\pm 0.9$ )
	energy resolution	-		-		$\pm 1.0$	( $\pm 1.3$ )	$\pm 1.8$	( $\pm 1.2$ )
	energy scale	-		-		$\pm 0.9$	( $\pm 3.0$ )	$\pm 0.9$	( $\pm 2.4$ )
Jet	energy resolution	$\pm 1.5$	( $\pm 2.2$ )	$\pm 2.9$	( $\pm 6.4$ )	$\pm 7.5$	( $\pm 8.5$ )	$\pm 6.4$	( $\pm 6.4$ )
	energy scale	$\pm 2.9$	( $\pm 2.7$ )	$\pm 7.8$	( $\pm 5.6$ )	$\pm 3.0$	( $\pm 3.3$ )	$\pm 2.3$	( $\pm 3.4$ )
Flavour tagging	$b$ -jets	$\pm 2.4$	( $\pm 2.5$ )	$\pm 2.3$	( $\pm 1.4$ )	$\pm 3.4$	( $\pm 2.6$ )	$\pm 2.5$	( $\pm 2.6$ )
	$c$ -jets	$\pm 0.1$	( $\pm 1.0$ )	$\pm 1.8$	( $\pm 11.6$ )	-	-	-	-
	light-jets	$<0.1$	( $\pm 5.0$ )	$\pm 1.6$	( $\pm 2.2$ )	-	-	-	-
Theory	PDF+ $\alpha_S$	$\pm 2.3$	( $\pm 2.3$ )	$\pm 3.1$	( $\pm 3.3$ )	n/a		n/a	
	Scale	$+4.3$	( $+4.3$ )	$+4.9$	( $+5.3$ )	n/a		n/a	
		$-6.0$	( $-6.0$ )	$+7.0$	( $+8.0$ )	n/a		n/a	
	EFT	$\pm 5.0$	( $\pm 5.0$ )	n/a		n/a		n/a	

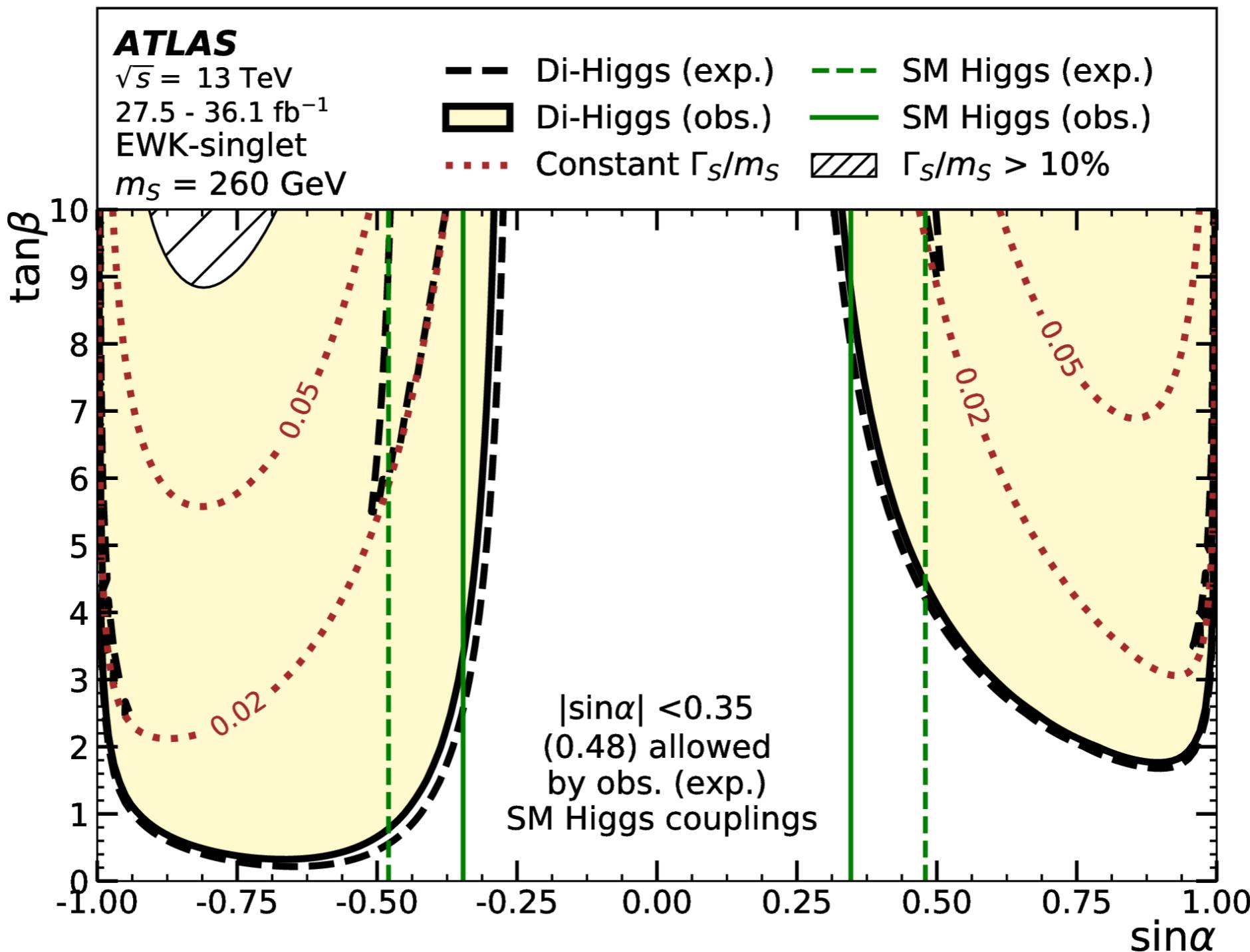
# HH EWK-singlet results

constraints on Electroweak Singlet and hMSSM models as a function of the scalar mass,  $\tan \beta$  and  $\tan \alpha$



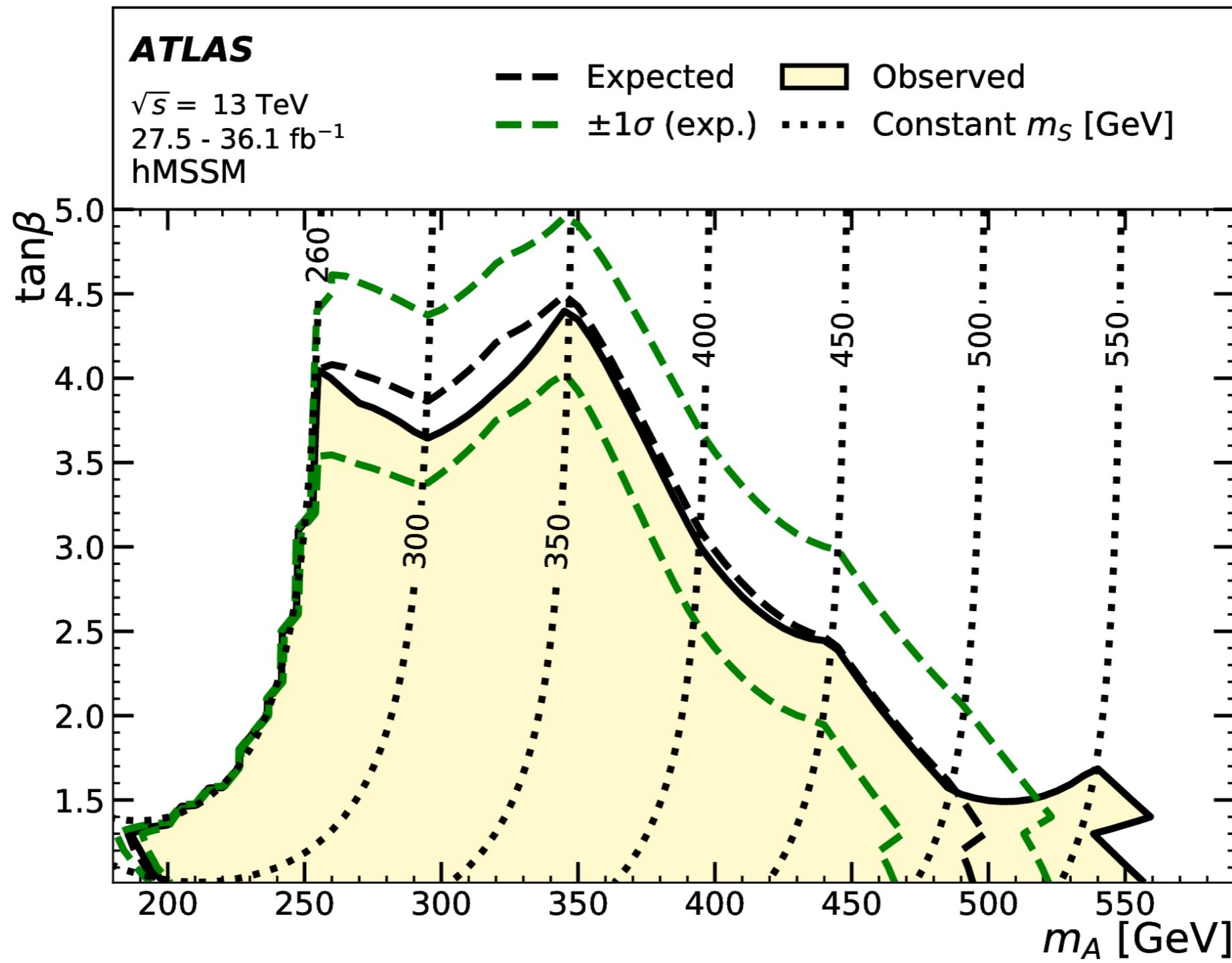
# HH EWK-singlet results

constraints on Electroweak Singlet and hMSSM models as a function of the scalar mass,  $\tan \beta$  and  $\tan \alpha$



# HH hMSSM results

constraints on Electroweak Singlet and hMSSM models as a function of the scalar mass,  $\tan \beta$  and  $\tan \alpha$



# HH combination systematics

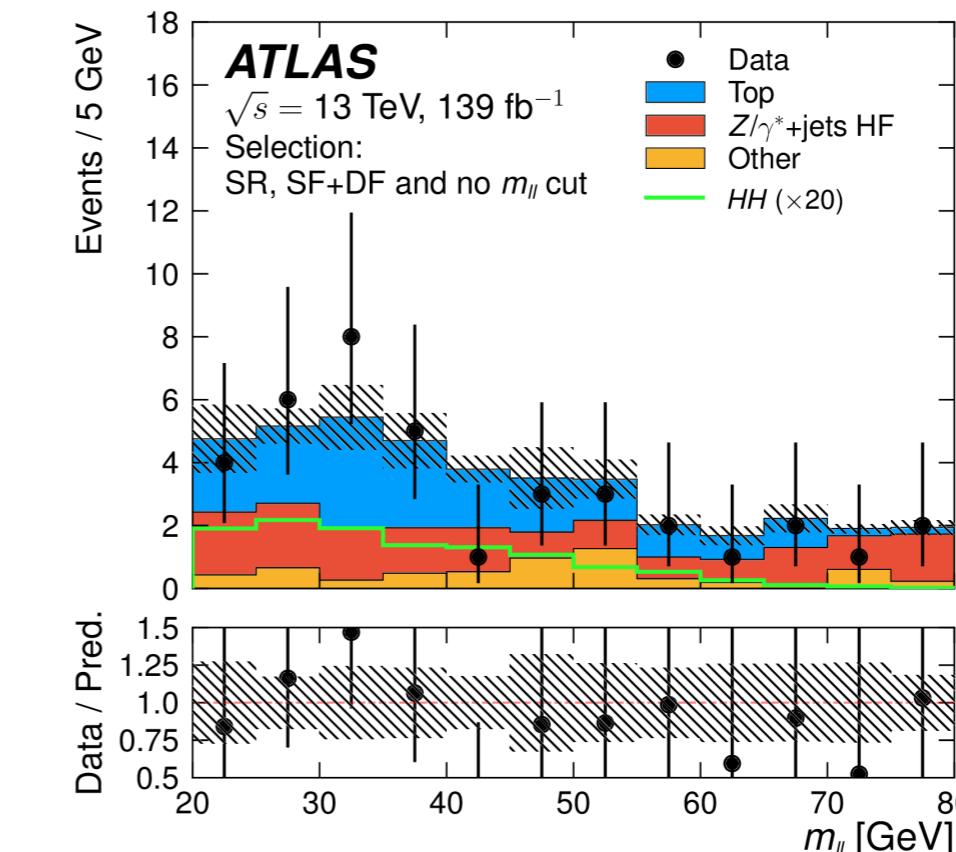
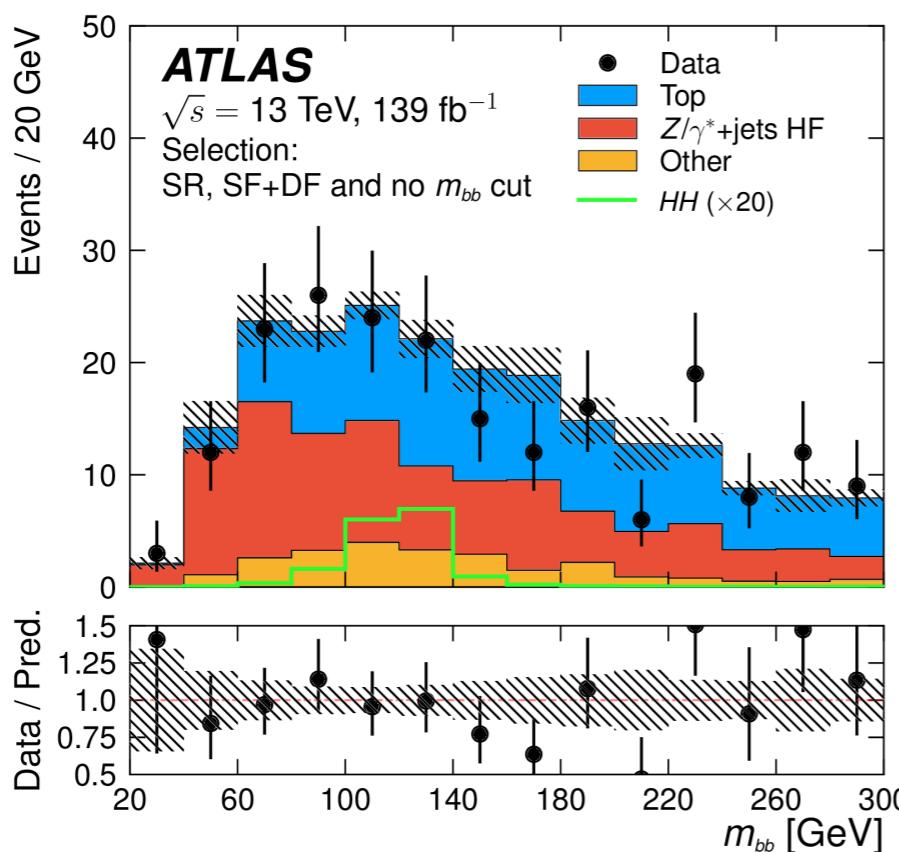
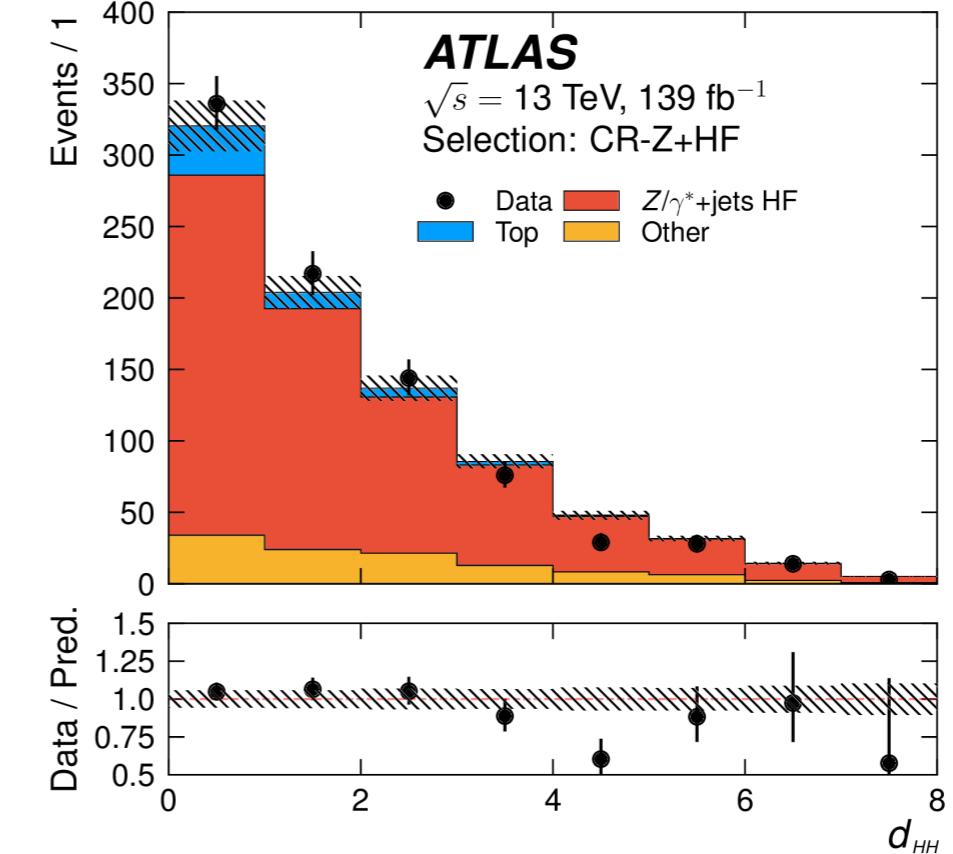
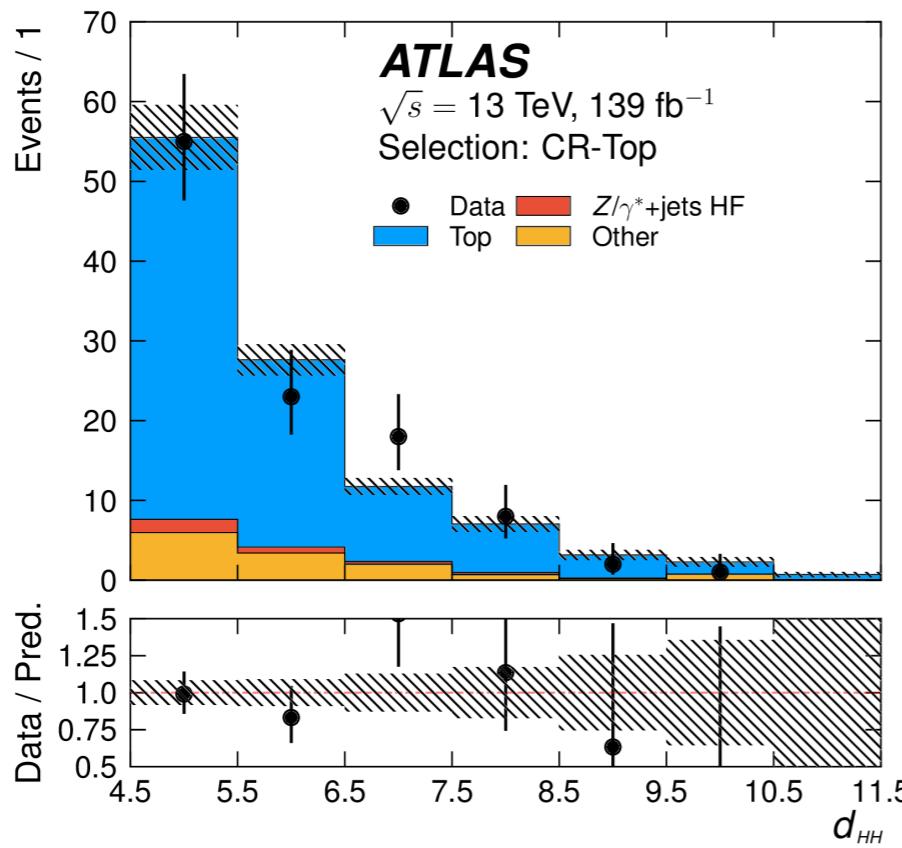
Upper limit percentage variation	NR	Spin-0		Spin-2 $k/\overline{M}_{\text{Pl}} = 1$		Spin-2 $k/\overline{M}_{\text{Pl}} = 2$	
		1 TeV	3 TeV	1 TeV	3 TeV	1 TeV	3 TeV
Simulation statistics	3%	1%	-	2%	-	1%	-
Background modelling	5%	7%	9%	11%	15%	16%	21%
Signal theory	1%	-	-	-	1%	-	-
Tau	2%	-	-	-	-	1%	-
Jet	-	1%	2%	2%	3%	5%	4%
$b$ -tagging	1%	2%	-	3%	-	4%	-
All	13%	12%	11%	19%	18%	29%	25%

# HH bblvlv: DNN variables

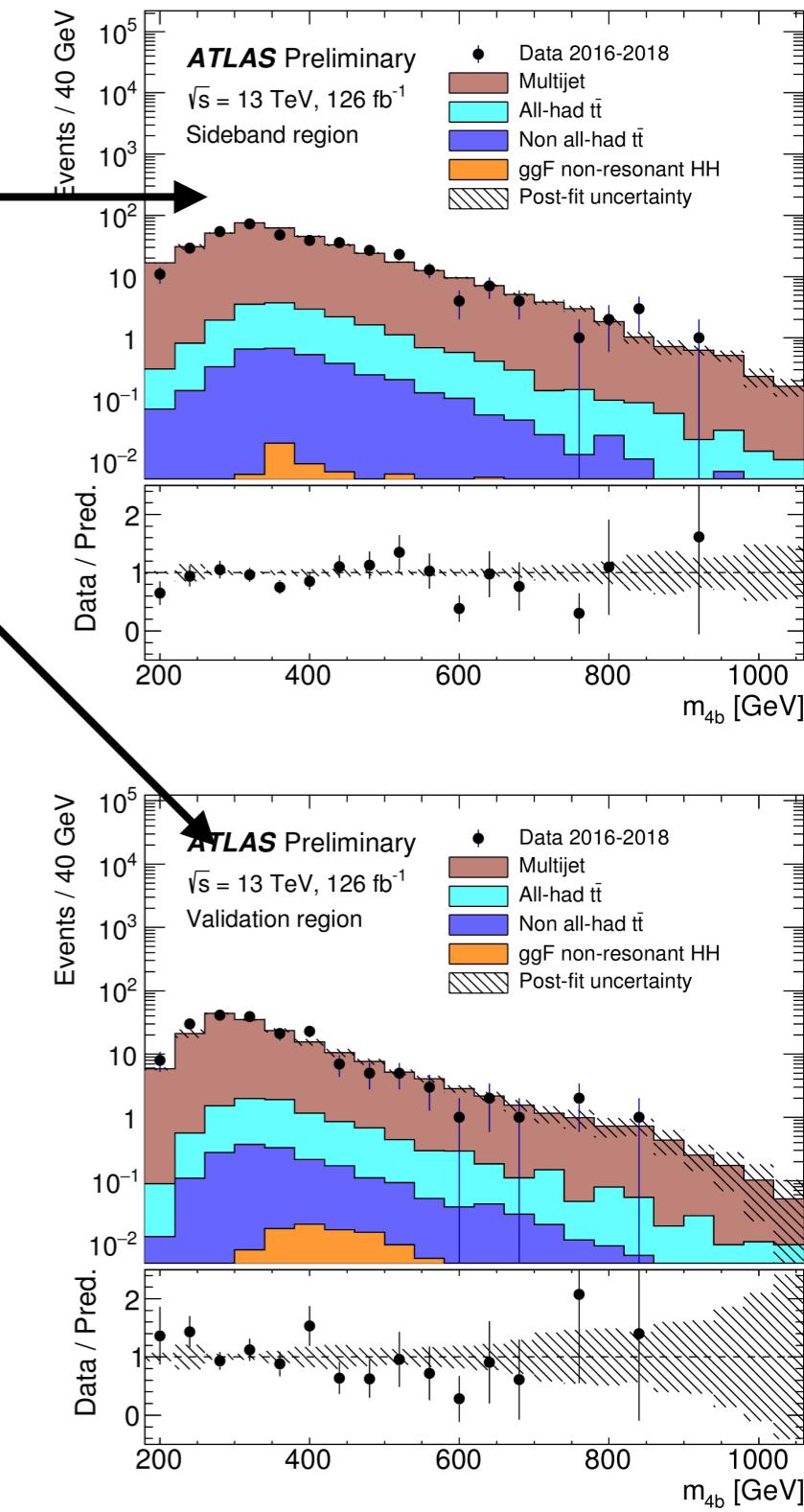
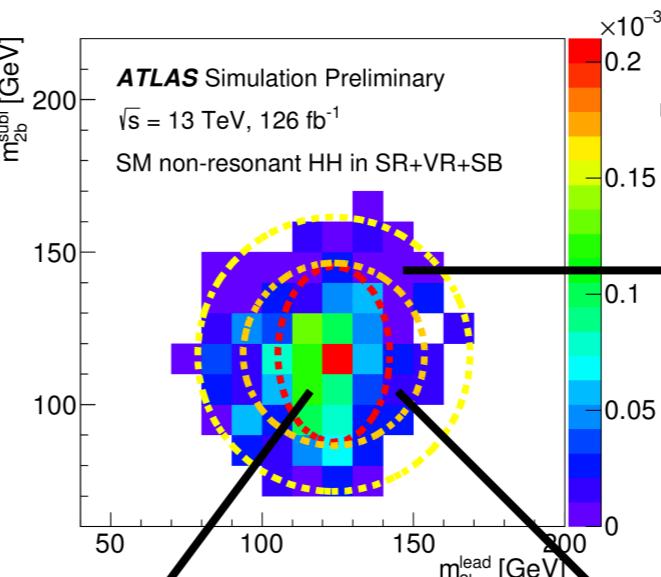
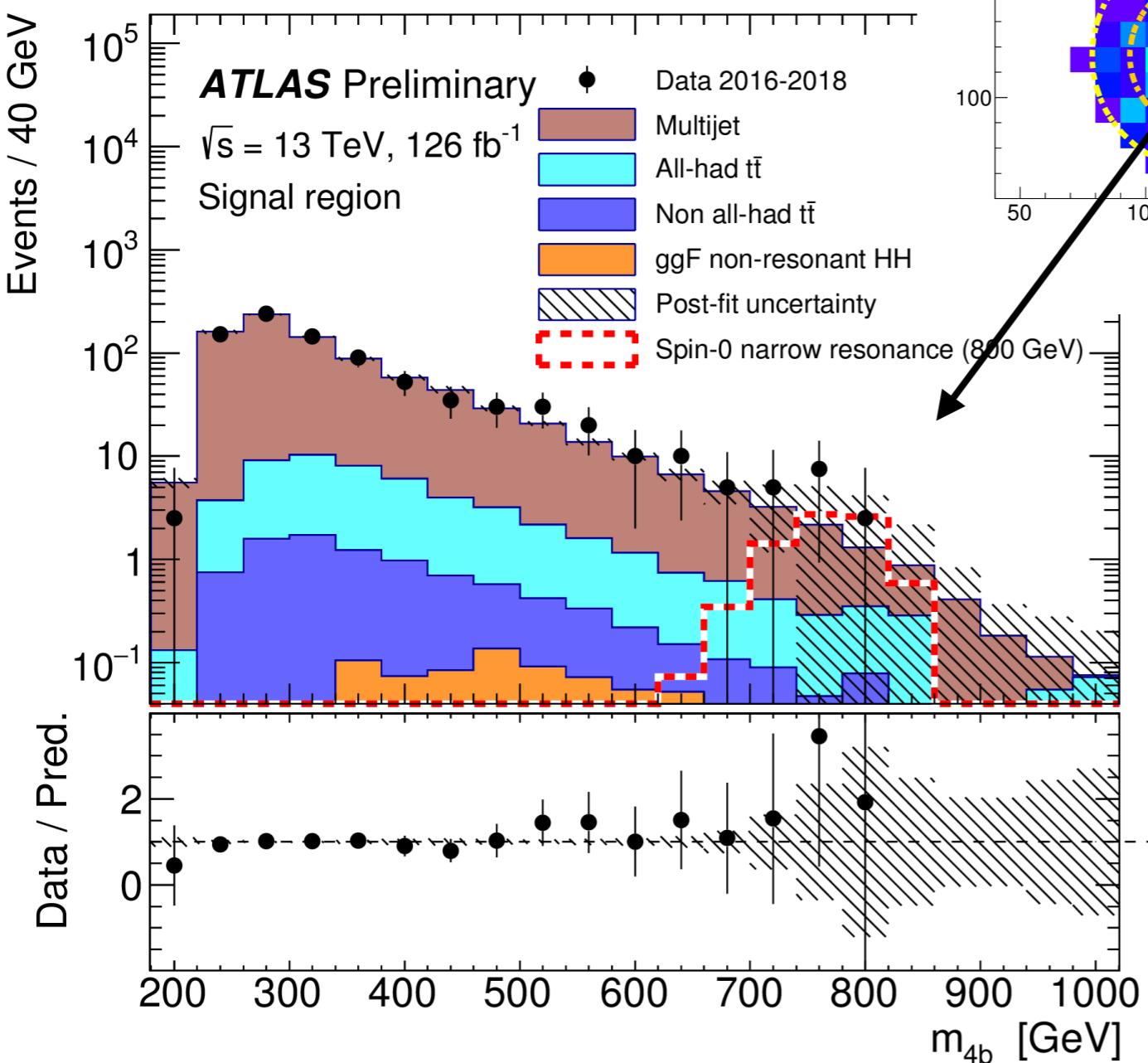
Table 2: Description of the variables used as inputs to the DNN classifier.

$(p_T, \eta, \phi)$	$p_T$ , $\eta$ , and $\phi$ of the leptons, leading two signal jets, and leading two $b$ -tagged jets
Dilepton flavour	Whether the event is composed of two electrons, two muons, or one of each
$\Delta R_{\ell\ell},  \Delta\phi_{\ell\ell} $	$\Delta R$ and magnitude of the $\Delta\phi$ between the two leptons
$m_{\ell\ell}, p_T^{\ell\ell}$	Invariant mass and the transverse momentum of the dilepton system
$E_T^{\text{miss}}, E_T^{\text{miss}} - \phi$	Magnitude of the missing transverse momentum vector and its $\phi$ component
$ \Delta\phi(\mathbf{p}_T^{\text{miss}}, \mathbf{p}_T^{\ell\ell}) $	Magnitude of the $\Delta\phi$ between the $\mathbf{p}_T^{\text{miss}}$ and the transverse momentum of the dilepton system
$ \mathbf{p}_T^{\text{miss}} + \mathbf{p}_T^{\ell\ell} $	Magnitude of the vector sum of the $\mathbf{p}_T^{\text{miss}}$ and the transverse momentum of the dilepton system
Jet multiplicities	Numbers of $b$ -tagged and non- $b$ -tagged jets
$ \Delta\phi_{bb} $	Magnitude of the $\Delta\phi$ between the leading two $b$ -tagged jets
$m_{T2}^{bb}$	$m_{T2}$ [119] using the leading two $b$ -tagged jets as the visible inputs and $\mathbf{p}_T^{\text{miss}}$ as invisible input
$H_{T2}$	Scalar sum of the magnitudes of the momenta of the $H \rightarrow \ell\nu\ell\nu$ and $H \rightarrow bb$ systems, $H_{T2} =  \mathbf{p}_T^{\text{miss}} + \mathbf{p}_T^{\ell,0} + \mathbf{p}_T^{\ell,1}  +  \mathbf{p}_T^{b,0} + \mathbf{p}_T^{b,1} $
$H_{T2}^R$	Ratio of $H_{T2}$ and scalar sum of the transverse momenta of the $H$ decay products, $H_{T2}^R = H_{T2}/(E_T^{\text{miss}} +  \mathbf{p}_T^{\ell,0}  +  \mathbf{p}_T^{\ell,1}  +  \mathbf{p}_T^{b,0}  +  \mathbf{p}_T^{b,1} ),$ where $\mathbf{p}_T^{\ell(b),0\{1\}}$ are the transverse momenta of the leading {subleading} lepton ( $b$ -tagged jet)

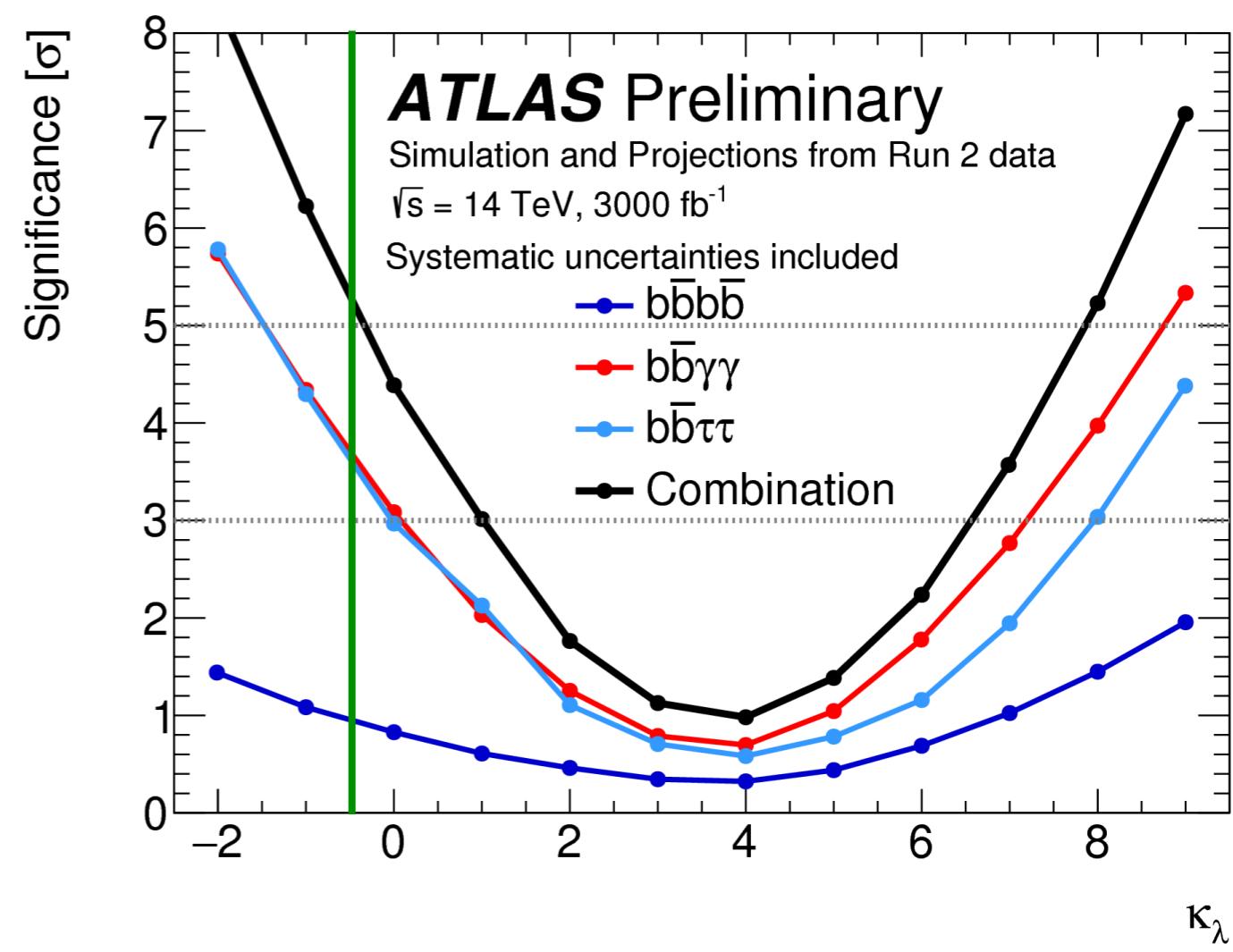
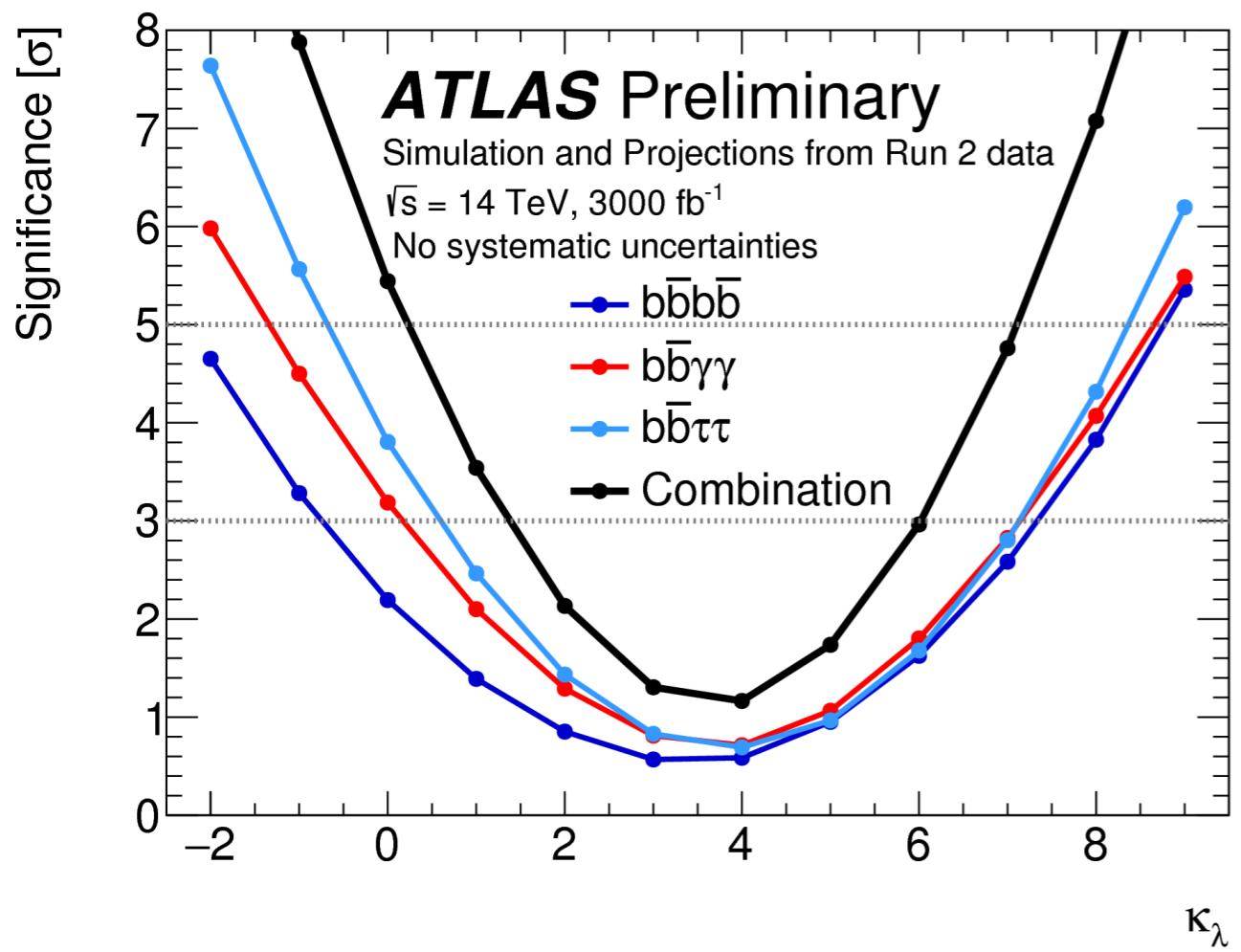
# HH bblvlv: observables



# VBF HH 4b



- expected significance to observe SM HH production with ATLAS at 14 TeV and 3000/fb of data
  - $3\sigma$  over background-only hypothesis
  - $1.4\sigma$  over signal + background hypothesis



## HH @ HL-LHC: ATLAS

