The production of additional bosons and the impact on the Large Hadron Collider

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HEP Seminar, IHEP, 24/05/17

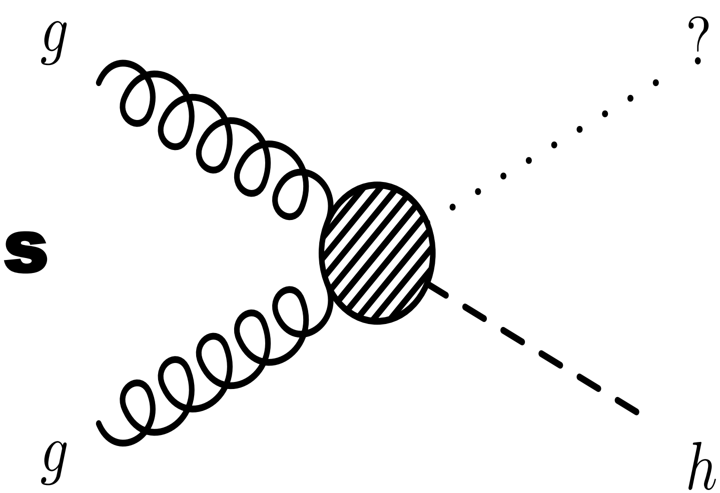
Outline

- ❑The Effective Lagrangian
- ❑Study with Run I data
- ❑Formulation of the hypothesis
- ❑Compatibility with Run II data
- ❑Prediction of signatures at the LHC
  - ❑Multi-lepton signatures

Views expressed here are of the authors only

Bottom-up approach: What if?

- Initially were interested in investigating the Higgs boson transverse momentum
- What if the Higgs boson is produced in association with something else…
- What can we fill the blob with?



The Lagrangian

arXiv:1506.00612
arXiv:1603.01208
arXiv:1606.01674

Introduce H and X fields with the interactions listed below

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{BSM}$$

$$\mathcal{L}_{BSM} = \mathcal{L}_K + \mathcal{L}_T + \mathcal{L}_Q + \mathcal{L}_{Hgg} + \mathcal{L}_{HVV}$$

$$\mathcal{L}_K = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}M_X^2 X^2 - \frac{1}{2}M_H^2 H^2$$

$$\mathcal{L}_T = -\frac{1}{2}\mu_1 h^2 H - \frac{1}{2}\mu_2 X^2 h - \frac{1}{2}\mu_3 X^2 H$$

$$\mathcal{L}_Q = -\frac{1}{4}\lambda_1 H^2 h^2 - \frac{1}{4}\lambda_2 X^2 h^2 - \frac{1}{4}\lambda_3 H^2 X^2 - \frac{1}{2}\lambda_4 H h X^2$$

$$\mathcal{L}_{Hgg} = -\frac{1}{4}\beta_g \ \kappa_{hgg}^{SM} G_{\mu\nu} G^{\mu\nu} H$$

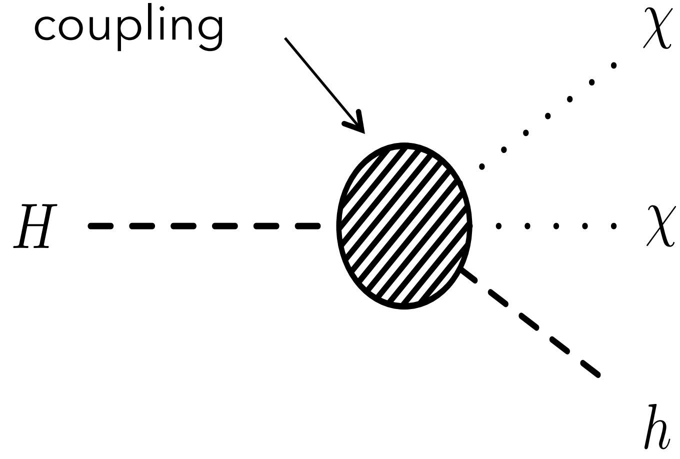
$$\mathcal{L}_{HVV} = \frac{2M_W^2}{v}\beta_W \ W_\mu W^\mu H + \frac{M_Z^2}{v}\beta_Z \ Z_\mu Z^\mu H$$

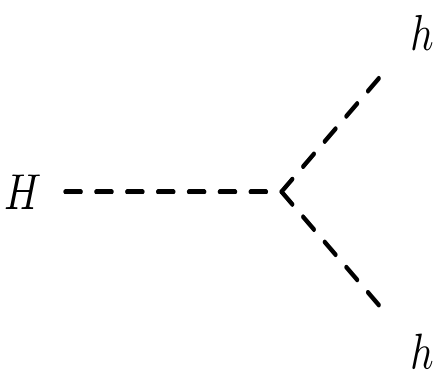
Main decay modes of *H*

Decay to single Higgs and a dark matter (DM) candidate

- DM is assumed scalar for simplicity
- This was our strategy, but we can infer different physics in the blob

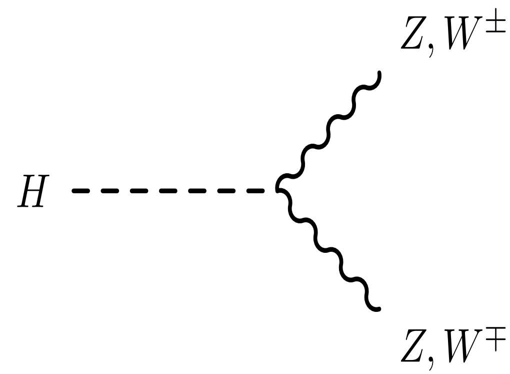
Used effective coupling





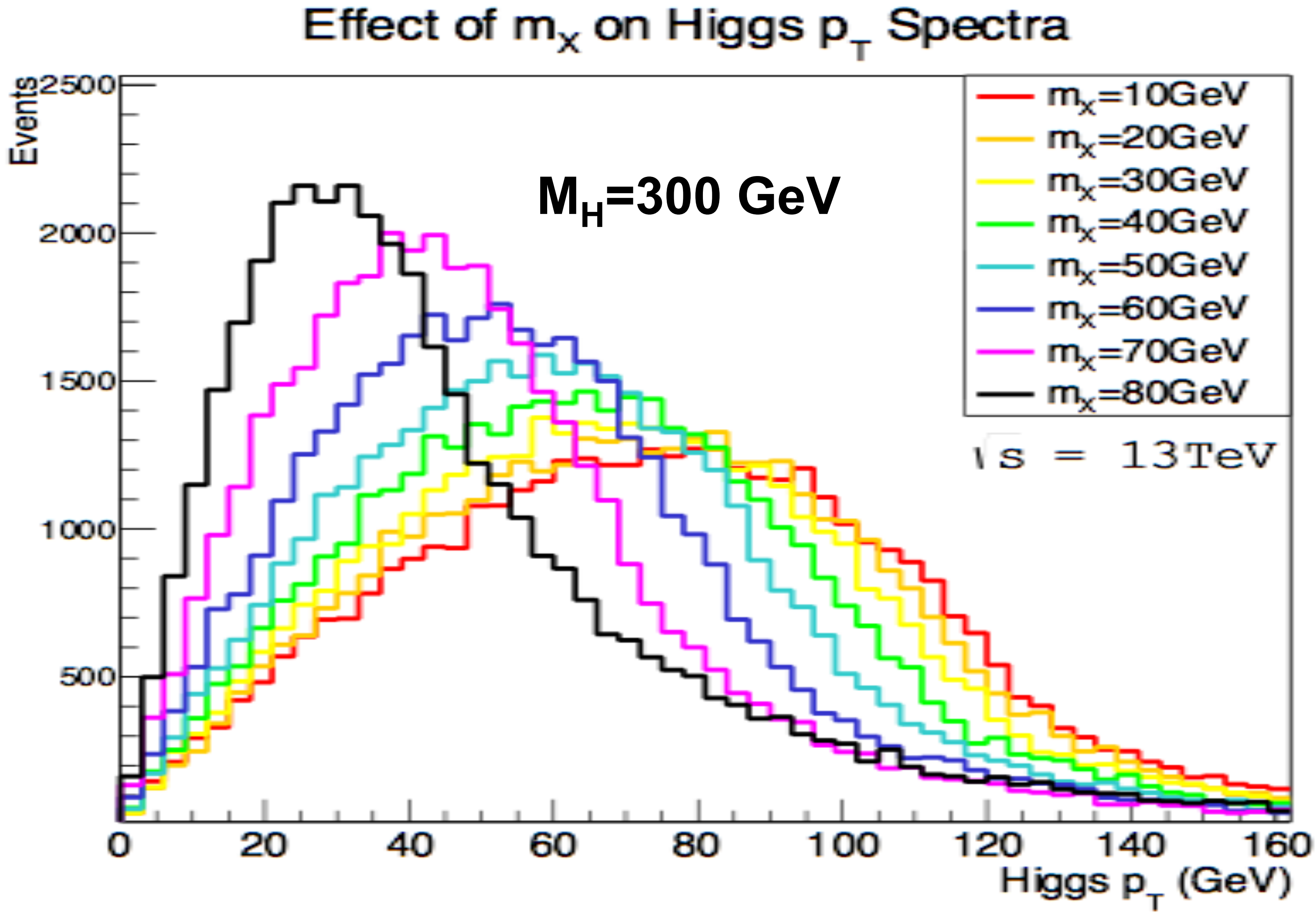
Decay to double Higgs pair.

Decay to vector boson pairs.



H->hxx

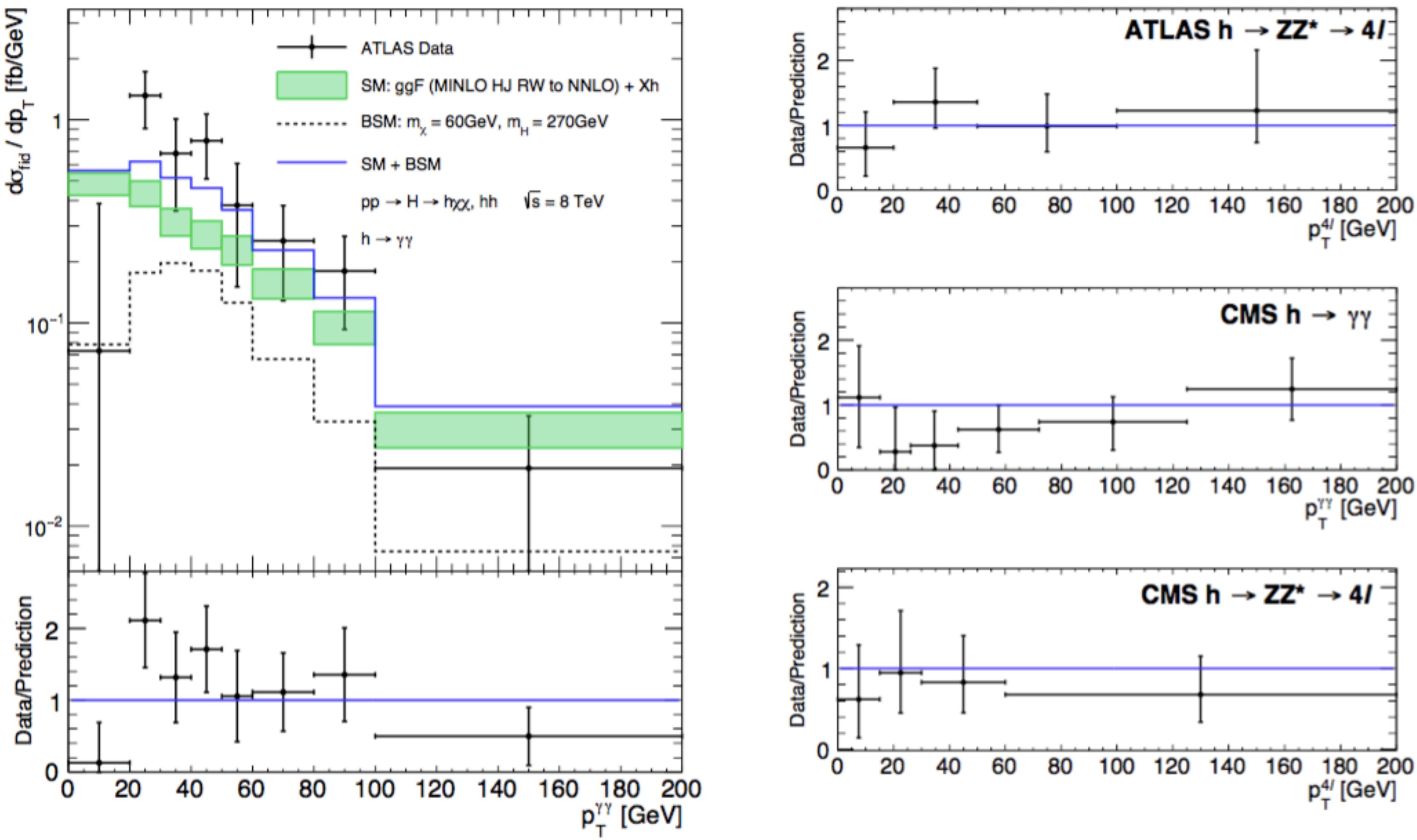
Higgs boson p_T Spectra



Results incorporated in the fit

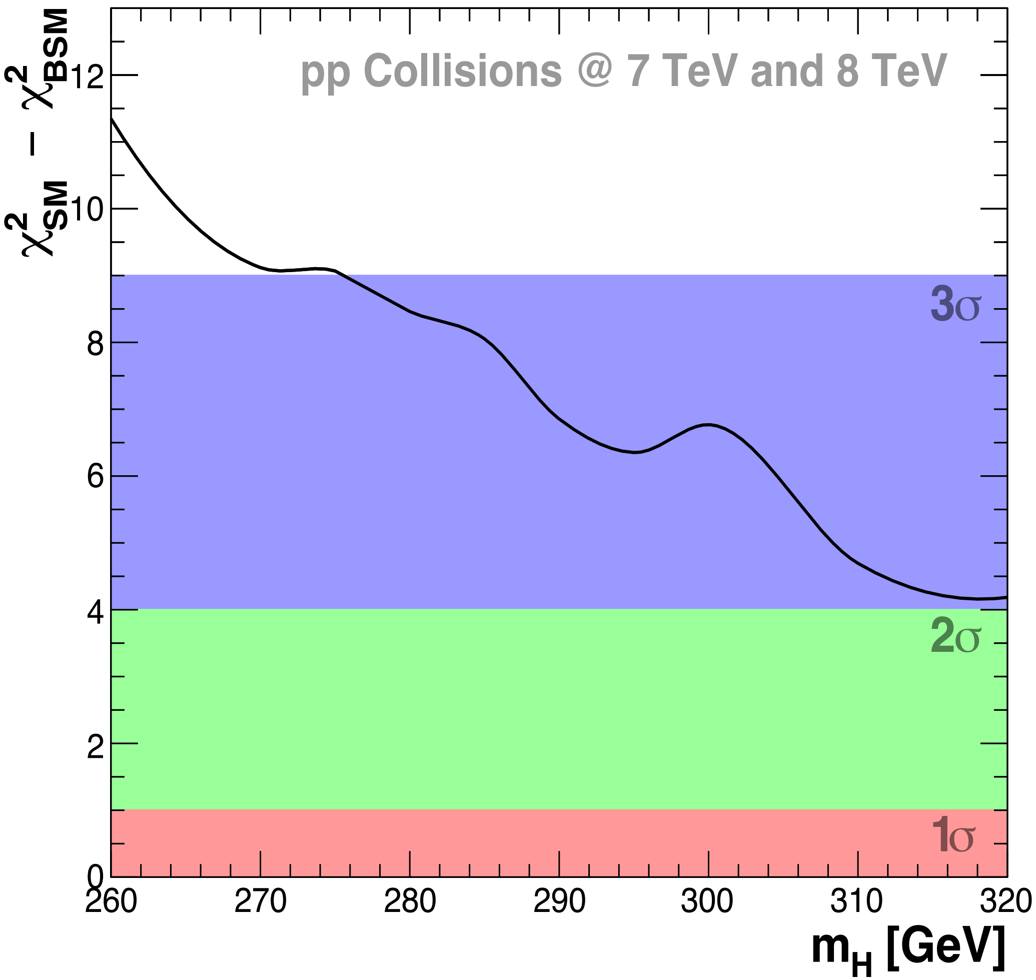
Four groups of final states received consideration

Category	Experiment	Result
Higgs p_T spectra	**ATLAS**	$h \to \gamma\gamma$ and $h \to ZZ$
	CMS	$h \to \gamma\gamma$ and $h \to ZZ$
Di-Higgs resonance searches	**ATLAS**	Limits on $H \to hh \to bb\tau\tau, \gamma\gamma WW, \gamma\gamma bb$, and $bbbb$
	CMS	Limits on $H \to hh \to bb\tau\tau, \gamma\gamma bb$, and multi-lepton
Top associated Higgs production	**ATLAS**	Limits on $h \to \gamma\gamma$ Measurements on $h \to bb$, and multi-lepton
	CMS	Measurements on $h \to \gamma\gamma$, $h \to bb$, and multi-lepton
Decays to weak vector bosons	**ATLAS**	Limits on $H \to ZZ$ and WW
	CMS	Limits on $H \to ZZ$ and WW



Satisfactory goodness of the global fit, including Higgs p_T

In terms of significance

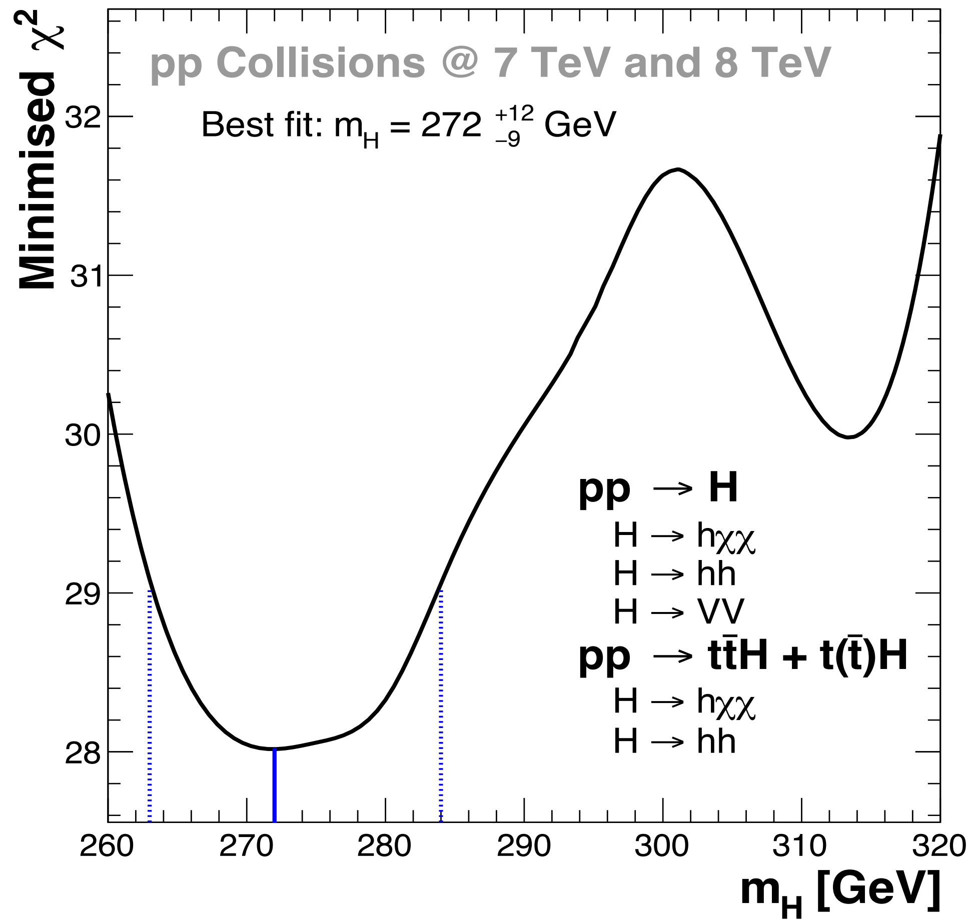


- To see how significant the result is, we use a test statistic: $\chi_{SM}{}^2$ - $\chi_{BSM}{}^2$
- This gives an improvement on the null hypothesis (the Standard Model) in units of sigma
- For one degree of freedom, the best fit point has a 3 sigma improvement. **This does not mean evidence yet.**

The combined result

- **Combining all of the results produces a best fit at m_H = 272 GeV**
- **The errors are +12 GeV and -9 GeV, which are one sigma deviations from the best fit point**

- **At this point:**



Interpret this as H→h+X

BR (H → hh)	BR (H → VV)	BR (H → h$\chi\chi$)	β_g
0.030 ± 0.037	0.082 ± 0.059	0.89 ± 0.096	1.5 ± 0.6

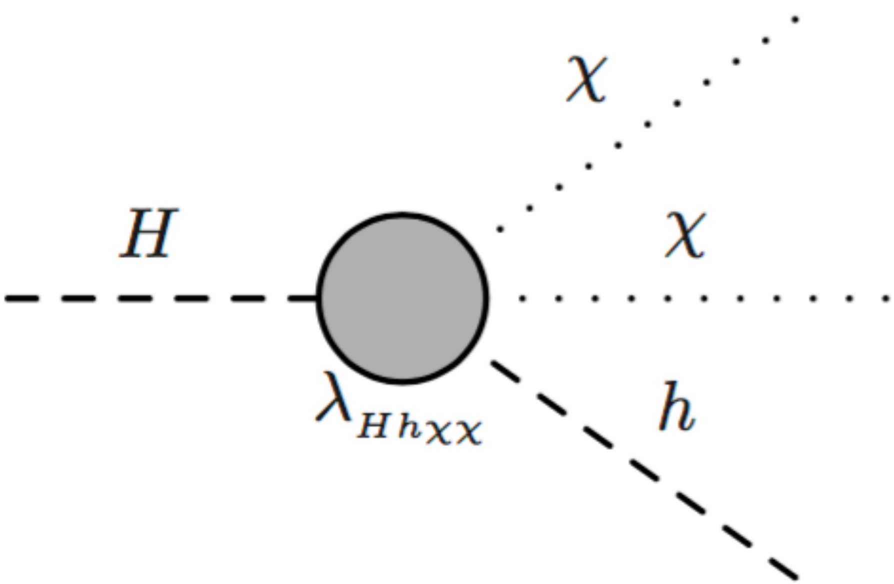
Close to one degree of freedom, β_g

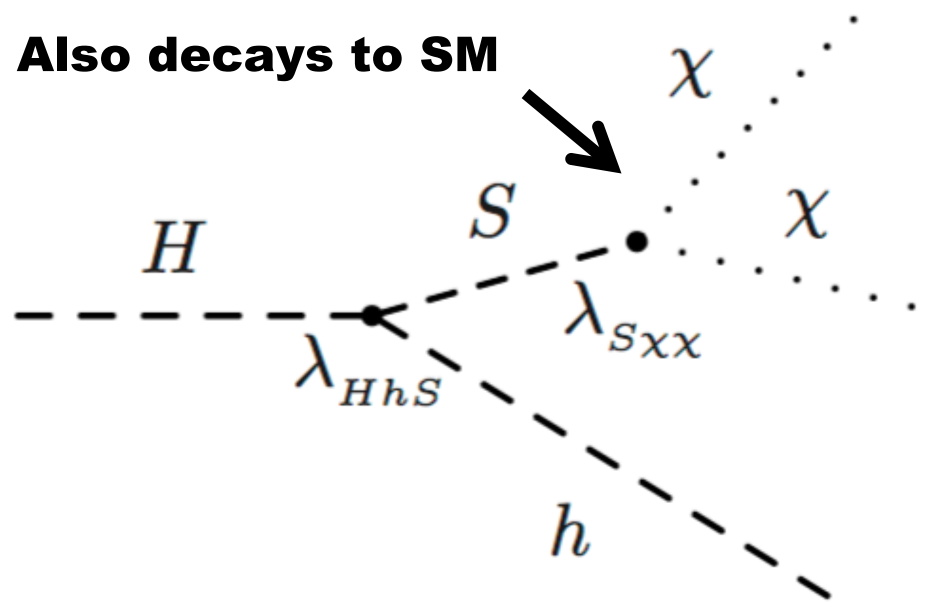
arXiv:1506.00612
arXiv:1603.01208
arXiv:1606.01674

Formulation of the Hypothesis

The Hypothesis

1. The starting point of the hypothesis is the existence of **a boson, H,** that contains Higgs-like interactions, with a mass **in the range 250-295 GeV**
2. In order to avoid large quartic couplings and to incorporate **a mediator with Dark Matter a real scalar, S,** is introduced. S interacts with the SM:



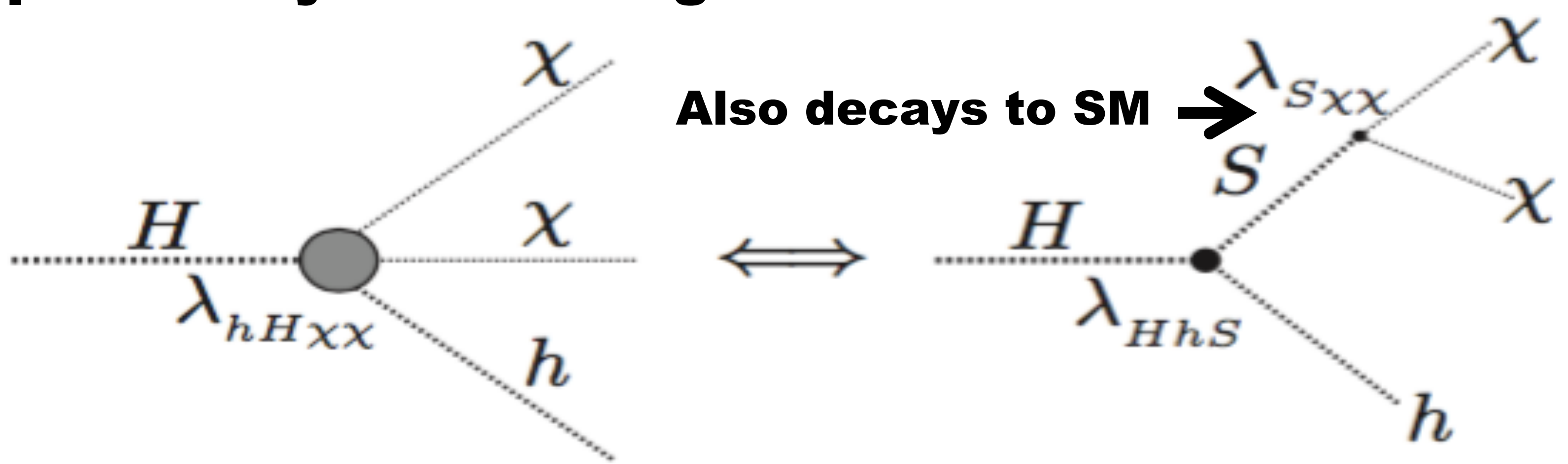


The intermediate scalar, S

- **Dark Matter is introduced in the form of a scalar and the decay H→h\chi\chi via effective quartic couplings**

$$\mathcal{L}_{\mathrm{Q}} = -\frac{1}{2}\lambda_{Hh\chi\chi} Hh\chi\chi - \frac{1}{4}\lambda_{HHhh} HHhh - \frac{1}{4}\lambda_{hh\chi\chi} hh\chi\chi - \frac{1}{4}\lambda_{HH\chi\chi} HH\chi\chi$$

- **Due to gauge invariance we encounter an awkward situation where a three body decay may be larger or comparable to a two body decay. This can be naturally explained by introducing an intermediate real scalar S**



The Lagrangian

$$\mathcal{L}_K = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 SS,$$

$$\mathcal{L}_{SVV'} = \frac{1}{4}\kappa_{S_{gg}} \frac{\alpha_s}{12\pi v} S G^{a\mu\nu} G^a_{\mu\nu} + \frac{1}{4}\kappa_{S_{\gamma\gamma}} \frac{\alpha}{\pi v} S F^{\mu\nu} F_{\mu\nu} + \frac{1}{4}\kappa_{S_{ZZ}} \frac{\alpha}{\pi v} S Z^{\mu\nu} Z_{\mu\nu}$$
$$+ \frac{1}{4}\kappa_{S_{Z\gamma}} \frac{\alpha}{\pi v} S Z^{\mu\nu} F_{\mu\nu} + \frac{1}{4}\kappa_{S_{WW}} \frac{2\alpha}{\pi s_w^2 v} S W^{+\mu\nu} W^-_{\mu\nu},$$

$$\mathcal{L}_{Sf\bar{f}} = -\sum_f \kappa_{S_f} \frac{m_f}{v} S \bar{f} f,$$

$$\mathcal{L}_{HhS} = -\frac{1}{2}\, v \left[\lambda_{hhS} hhS + \lambda_{hSS} hSS + \lambda_{HHS} HHS + \lambda_{HSS} HSS + \lambda_{HhS} HhS \right],$$

$$\mathcal{L}_{S\chi} = -\frac{1}{2}\, v\, \lambda_{S\chi\chi} S\chi\chi - \frac{1}{2}\lambda_{SS\chi\chi} SS\chi\chi.$$

$$\mathcal{L}_S = \mathcal{L}_K + \mathcal{L}_{SVV'} + \mathcal{L}_{Sf\bar{f}} + \mathcal{L}_{hHS} + \mathcal{L}_{S\chi}$$

Note that some of the effective quartic couplings shown earlier appear here as trilinear. What was formerly a three body decay is now a two body decay (see below).

The Decays of H

- **In the general case, H can have couplings as those displayed by a Higgs boson in addition to decays involving the intermediate scalar and Dark Matter**

$$H \to WW, ZZ, q\bar{q}, gg, Z\gamma, \gamma\gamma, \chi\chi$$

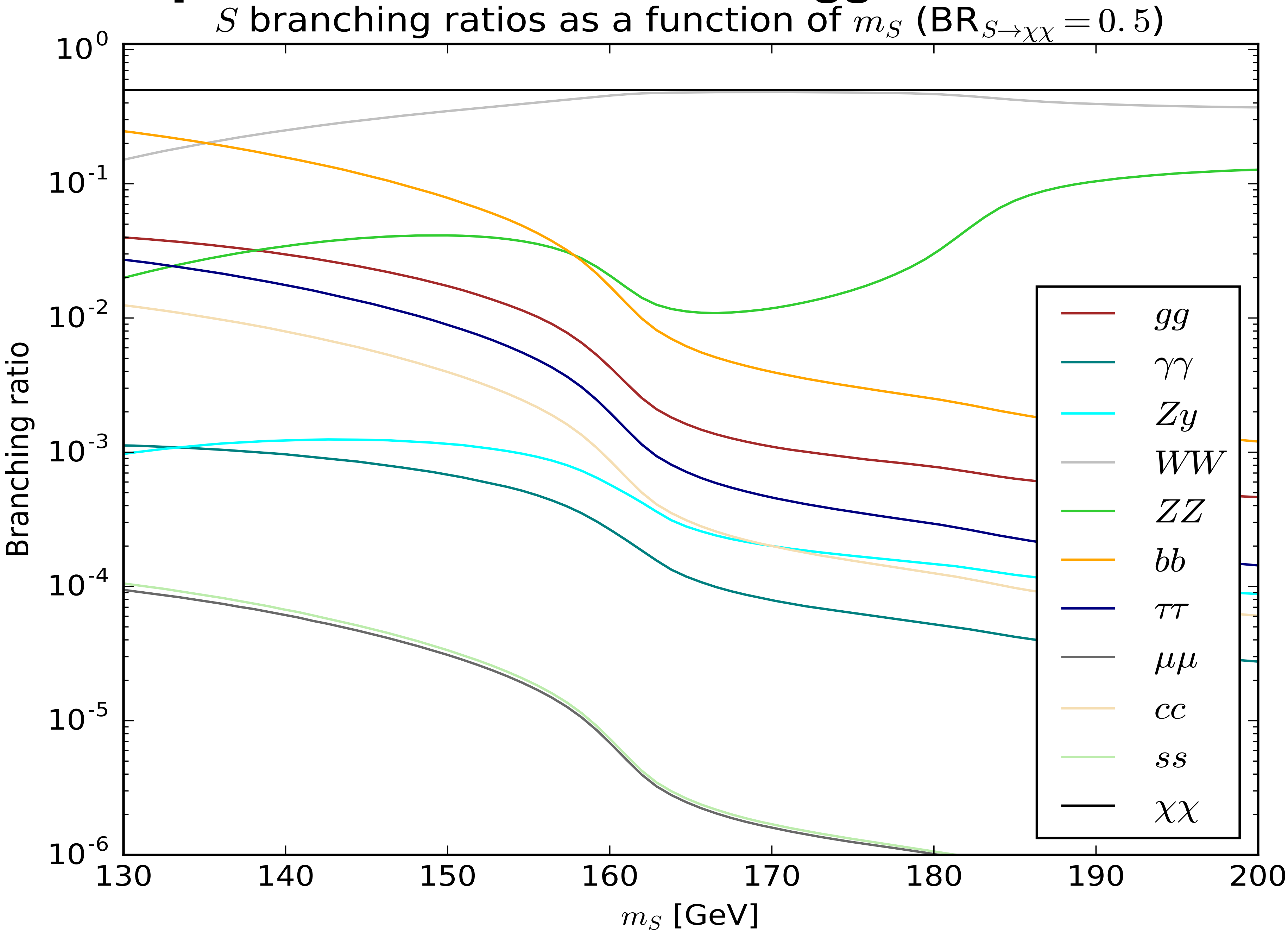
$$+ \quad H \to SS, Sh, hh$$

Dominant decays

Diboson decay

$$\boxed{H \to h(+X), S(+X)}$$

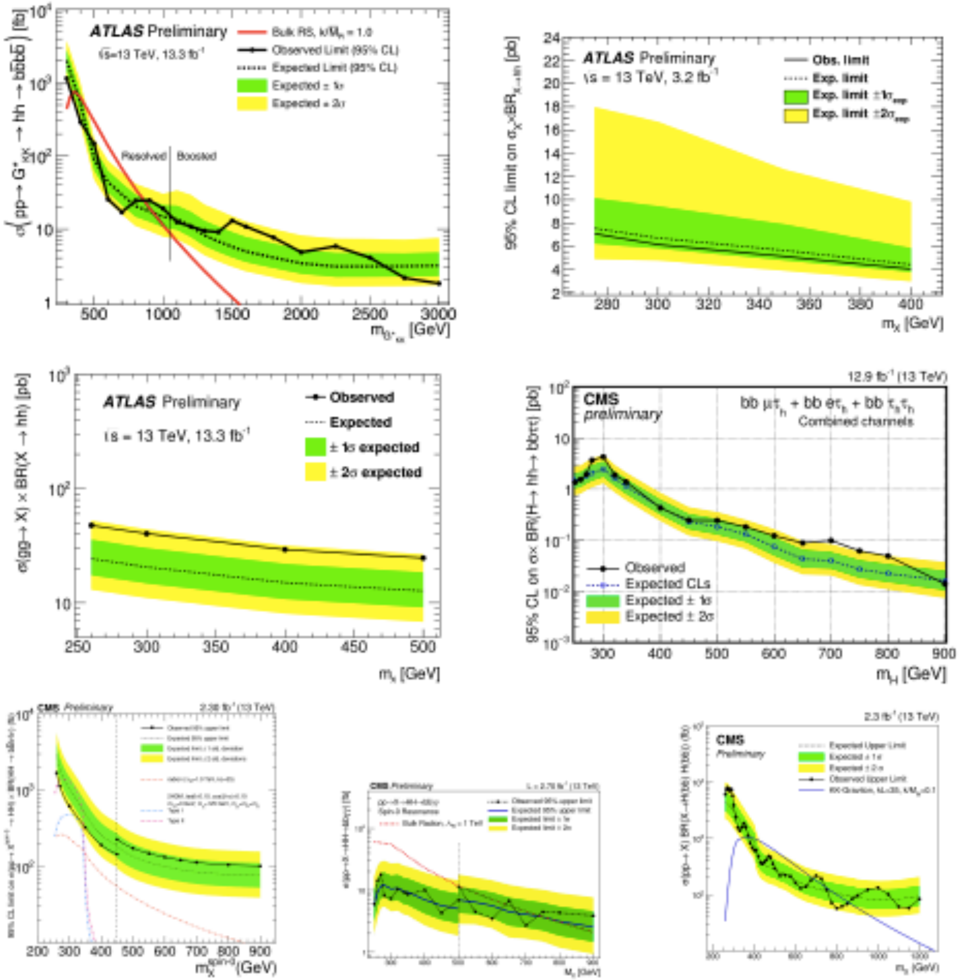
In a simplified model treat S as Higgs-like



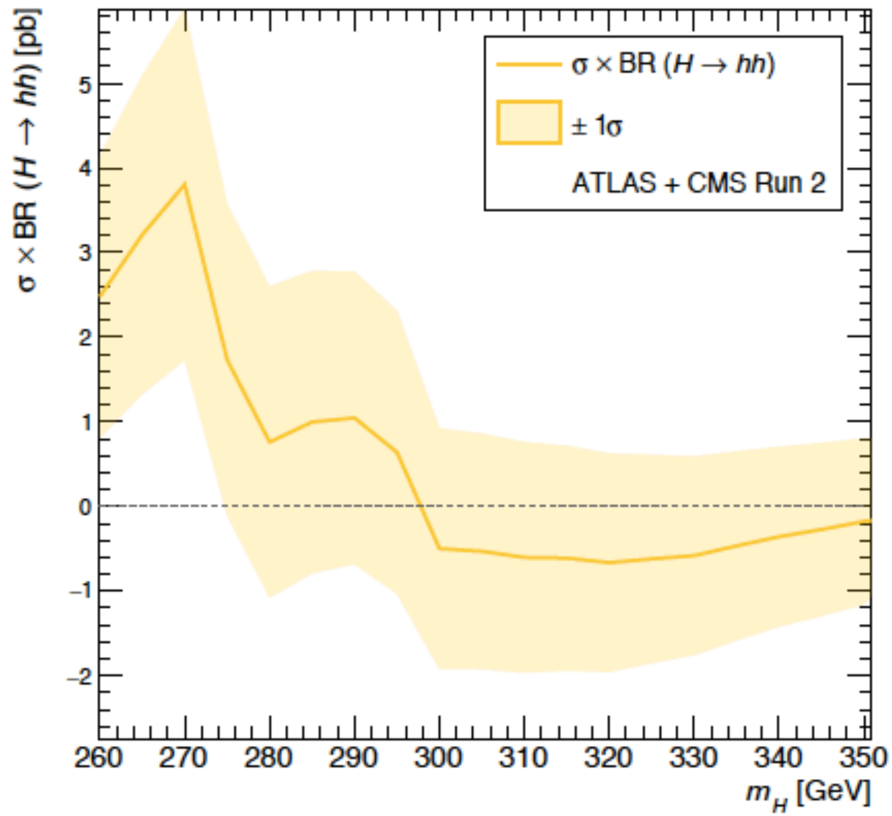
Compatibility with the Run II data

1. **hh limits**
2. **VV spectrum**
3. **tth→Nleptons search**
4. **Impact on measured Higgs boson cross-sections**
5. **Higgs boson P_T spectrum**

$$\sigma(pp \to H \to hh) \approx 600\, fb$$

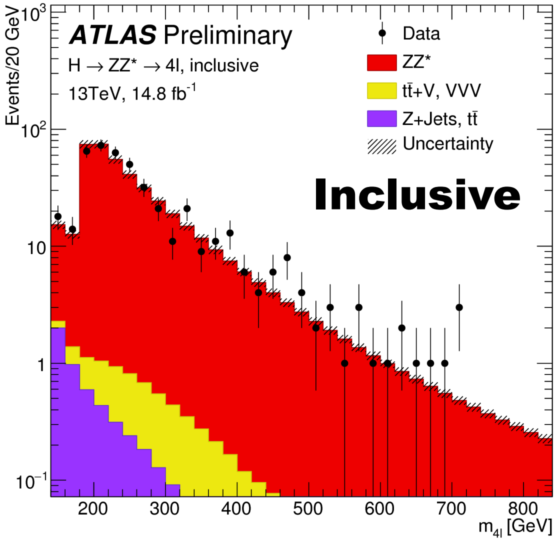


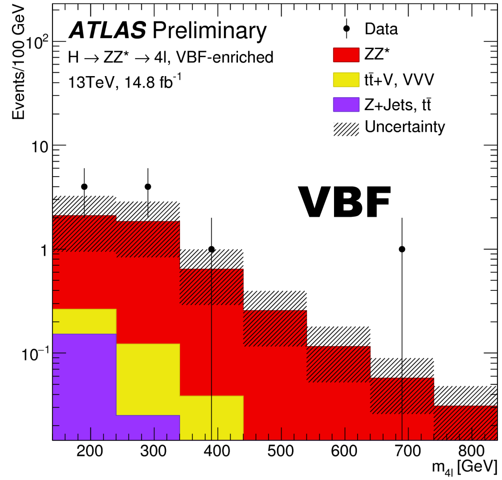
Run 2 $H \to hh$ rates
Combination
(before Moriond 2017)

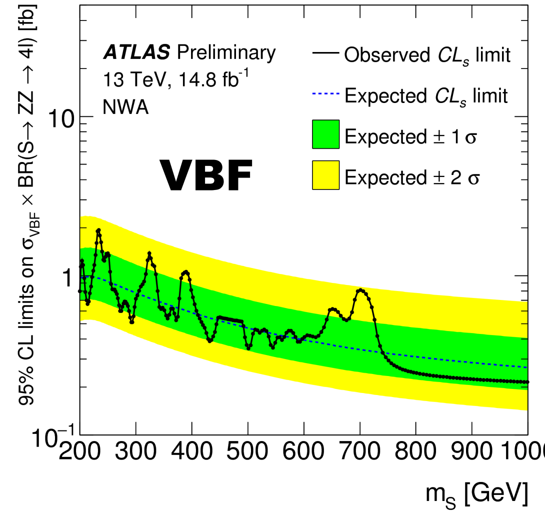


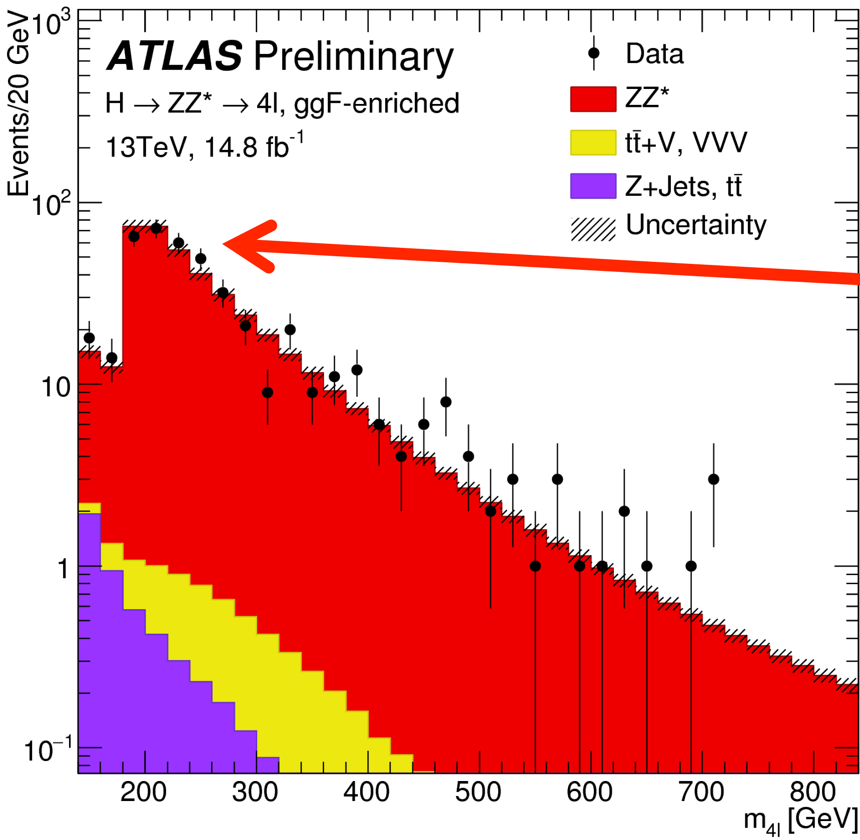
Current data, including recent results, still miss sensitive channels such as γγbb. Weak sensitivity to H→hh cross-section. New data will be important to determine H→hh.

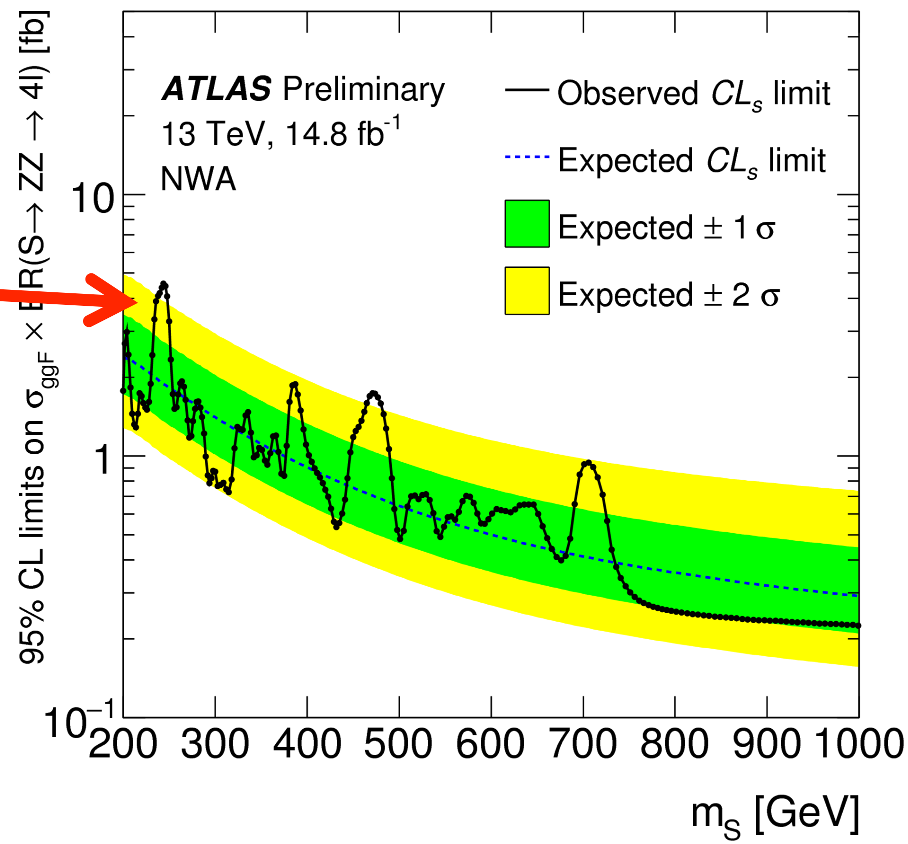
ATLAS-CONF-2016-079

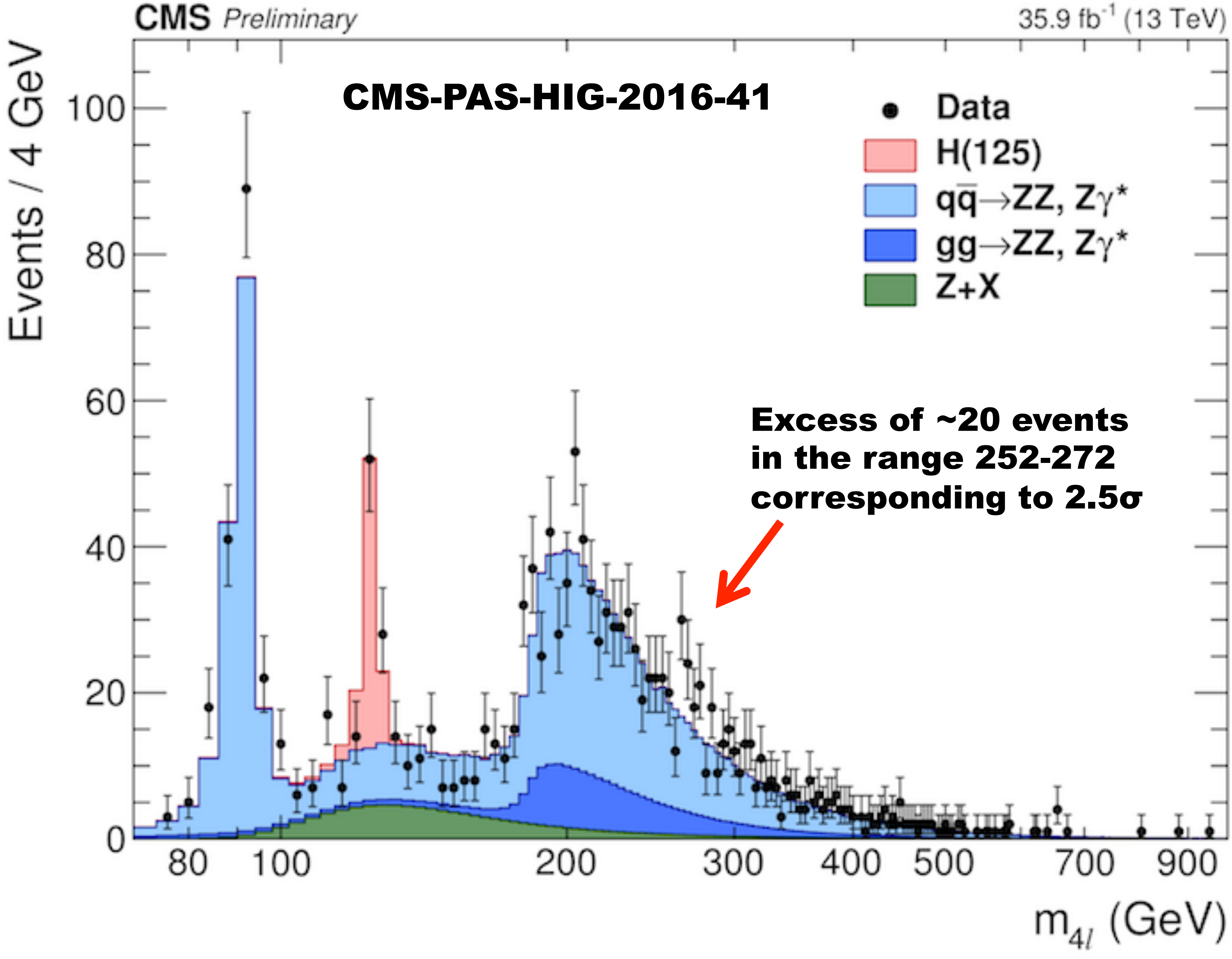






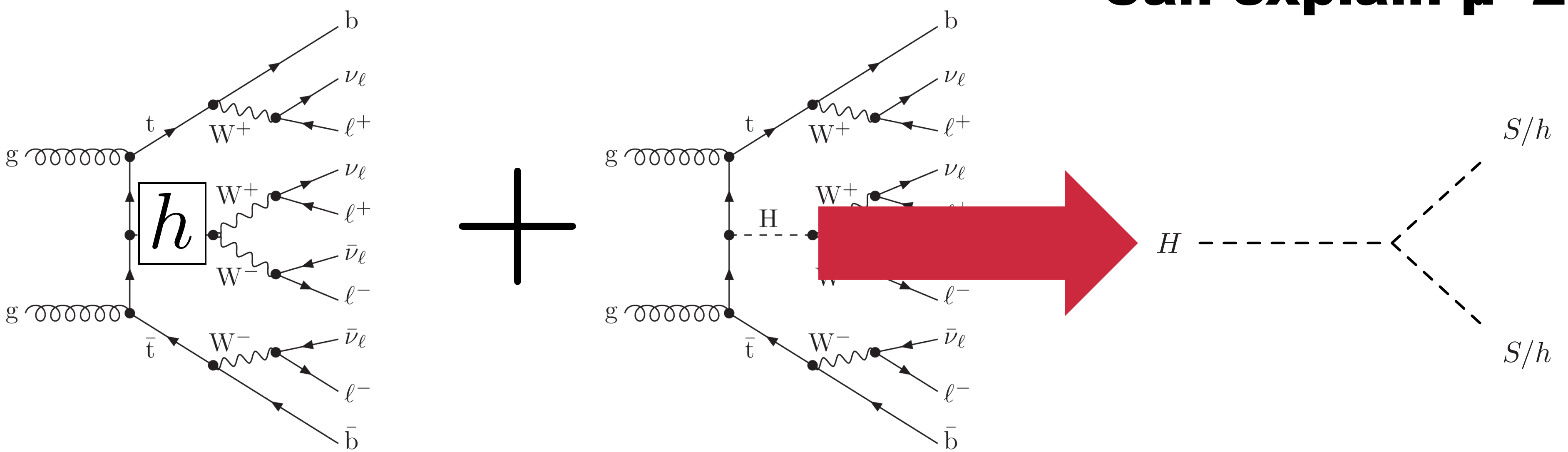





CMS Preliminary
35.9 fb-1 (13 TeV)
CMS-PAS-HIG-2016-41
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
Excess of ~20 events
in the range 252-272
corresponding to 2.5σ
Events / 4 GeV
m4l (GeV)
0
20
40
60
80
100
80
100
200
300
400
500
700
900

Top associated Higgs production
(Multilepton final state)

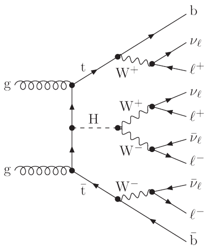
Can explain μ~2

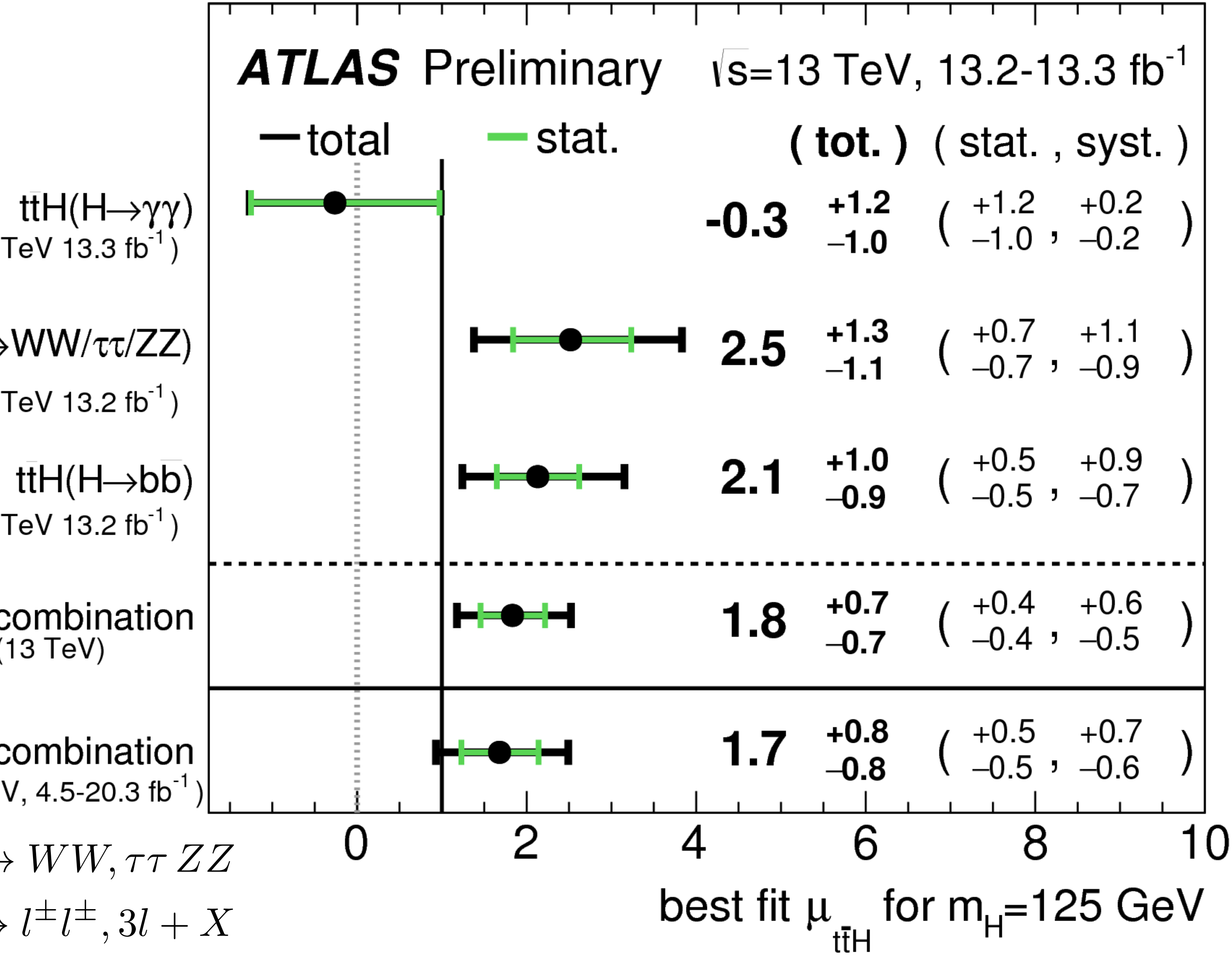


Reduced cross-section of ttH+tH is compensated by di-boson, (SS, Sh) decay and potentially large Br(S->WW). Production of same sign leptons, three leptons is enhanced

$$S, h \to WW, \tau\tau, ZZ$$

ATLAS-CONF-2016-058

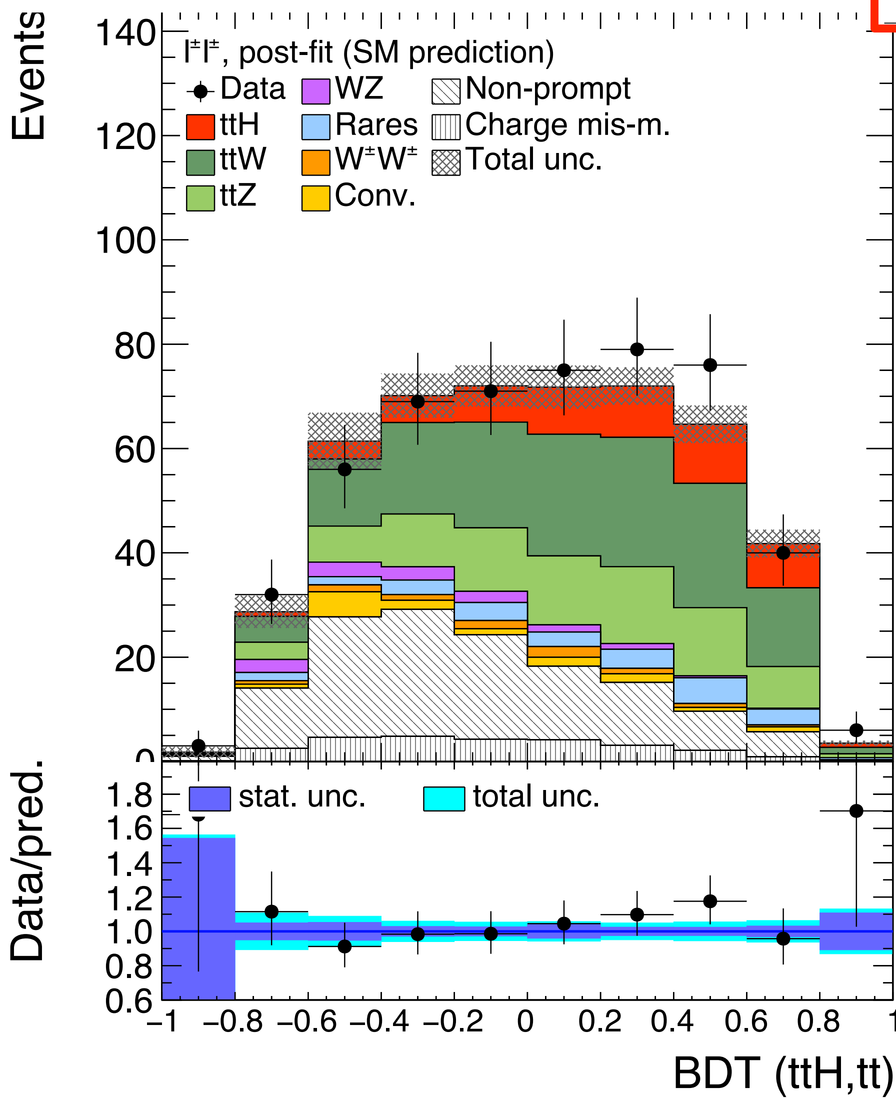


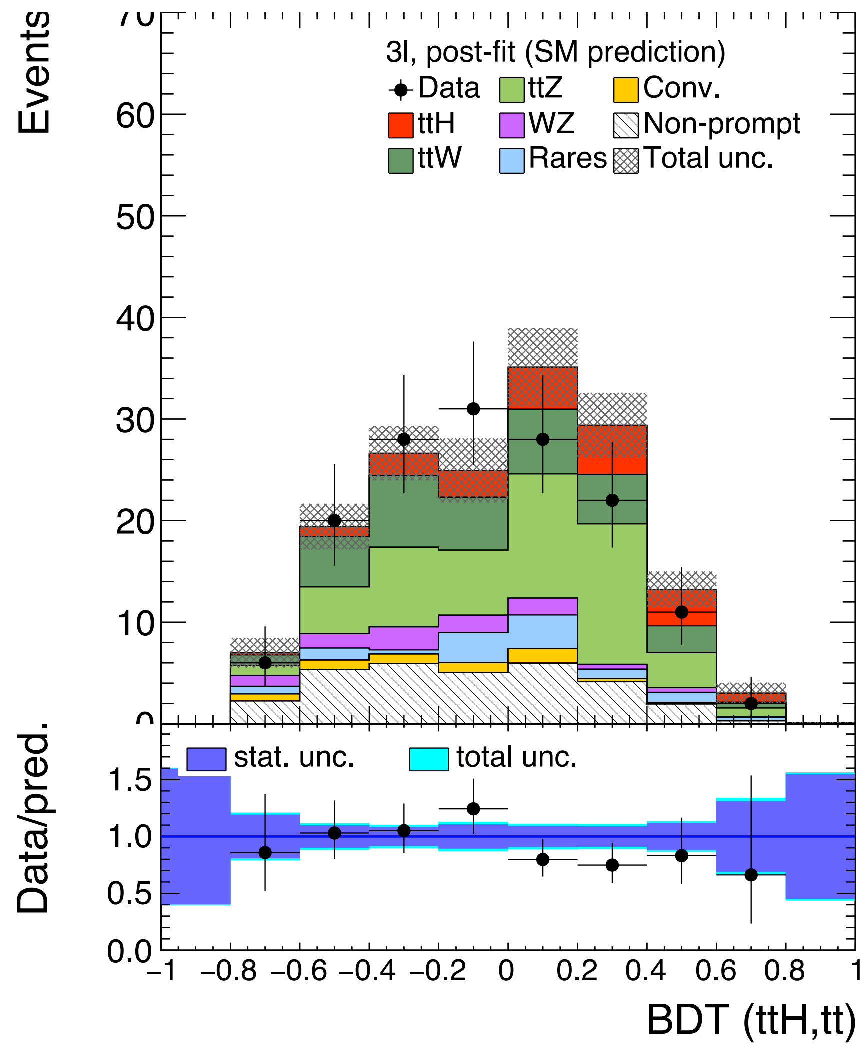


$$S, h \to WW, \tau\tau\, ZZ$$
$$\to l^{\pm} l^{\pm}, 3l + X$$

CMS-PAS-HIG-17-004
Latest Run II results form CMS

Category	Observed μ fit $\pm 1\sigma$	Expected μ fit $\pm 1\sigma$
Same-sign di-lepton	1.7 (−0.5) (+0.6)	1.0 (−0.5) (+0.5)
Three lepton	1.0 (−0.7) (+0.8)	1.0 (−0.7) (+0.8)
Four lepton	0.9 (−1.6) (+2.3)	1.0 (−1.6) (+2.4)
Combined (2016 data)	1.5 (−0.5) (+0.5)	1.0 (−0.4) (+0.5)
Combined (2015 data) [42]	0.6 (−1.1) (+1.4)	1.0 (−1.1) (+1.3)
Combined (2015+2016 data)	1.5 (−0.5) (+0.5)	1.0 (−0.4) (+0.5)





Reference	Channel	Measured μ_{tth}
CMS Run 1 [12]	Same-sign 2ℓ	$5.3^{+2.1}_{-1.8}$
	3ℓ	$3.1^{+2.4}_{-2.0}$
	4ℓ	$-4.7^{+5.0}_{-1.3}$
	Combination	$2.8^{+1.0}_{-0.9}$
ATLAS Run 1 [13]	$2\ell 0\tau_{\text{had}}$	$2.8^{+2.1}_{-1.9}$
	3ℓ	$2.8^{+2.2}_{-1.8}$
	$2\ell 1\tau_{\text{had}}$	$-0.9^{+3.1}_{-2.0}$
	4ℓ	$1.8^{+6.9}_{-2.0}$
	$1\ell 2\tau_{\text{had}}$	$-9.6^{+9.6}_{-9.7}$
	Combination	$2.1^{+1.4}_{-1.2}$
CMS Run 2 [14]	Same-sign 2ℓ	$2.7^{+1.1}_{-1.0}$
	3ℓ	$1.3^{+1.2}_{-1.0}$
	Combination	$2.3^{+0.9}_{-0.8}$
ATLAS Run 2 [15]	$2\ell 0\tau_{\text{had}}$	$4.0^{+2.1}_{-1.7}$
	3ℓ	$0.5^{+1.7}_{-1.6}$
	$2\ell 1\tau_{\text{had}}$	$6.2^{+3.6}_{-2.7}$
	4ℓ	< 2.2
	Combination	$2.5^{+1.3}_{-1.1}$
Error weighted mean		2.5 ± 0.5

Table with signal strength w.r.t the SM in the search for tth with multiple leptons

This table includes all data before Moriond QCD 2017
There CMS reported μ=1.5±0.5, resulting in:

$$\boxed{\mu = 1.92 \pm 0.38}$$

Very important to see results with the complete Run 2 data set.

Need insight into the kinematics of the leptons and jet activity of these events.

Contamination of H→Sh in Higgs measurements

Tables show the expected rate of signal events for 36.1 fb^{-1} at 13 TeV for both SM and H→Sh processes, assuming m_H=270 GeV. Have adopted cuts documented in most recent ATLAS notes. Output uses Delphes simulation

Contamination on VBF, Vh with h→γγ. Contamination depends on the treatment of S.

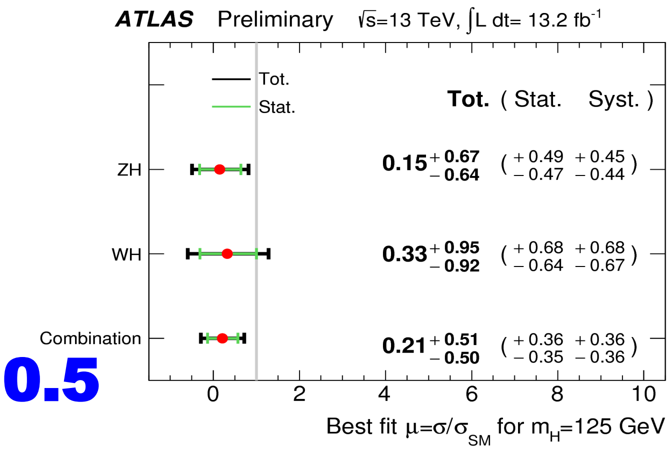
Samples	VBF	VH hadronic
mS=140 GeV	2.86±0.069	0.16±0.016
mS=150 GeV	1.94±0.06	1.14±0.04
mS=160 GeV	2.89±0.07	1.97±0.06
Wh	0.22±0.01	1.90±0.03
Zh	0.14±0.007	1.31±0.02
tth	0.09±0.004	0.22±0.007
VBF	25.81±0.20	0.30±0.02

Vh(→bb), no contamination

Samples	0 lepton	1 lepton	2 lepton, high pT(V)
mS=140 GeV	<0.10	0.21±0.15	<0.10
mS=150 GeV	0.52±0.23	2.39±0.50	<0.10
mS=160 GeV	<0.10	0.31±0.18	<0.10
Wh	21.10±1.00	100.76±2.20	<0.05
Z(→ *ll*)h	0.35±0.06	2.40±0.15	18.84±0.41
Z(→νν)h	62.40±1.07	<0.02	<0.02
tth	0.11±0.02	0.56±0.05	0.04±0.01
VBF	<0.79	<0.79	<0.79

Vh(→bb)

- **Topology of final state is well defined in the Standard Model**
  - **Large M_{VH} without large jet activity and other features**
- **Three results are available**
  - **CMS Run 1, 1310.3687, μ=1±0.5**
  - **ATLAS Run 1, 1409.612, μ=0.5±0.4**
  - **ATLAS Run 2, CONF-2016-91, μ=0.2±0.5**

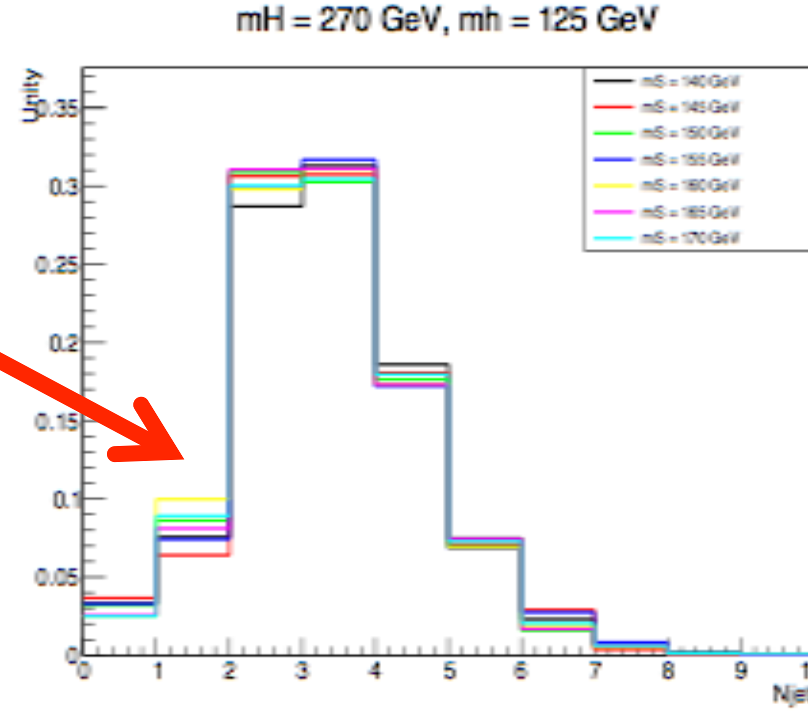


$$\boxed{\mu = 0.57 \pm 0.26}$$

- **Expect combined CMS+ATLAS sensitivity for 2015+2016 of about 4.5σ. This final state needs to be observed with Run 2 data set if no significant deviations from the SM exist**

Impact on measurement of h→WW→ll

Because the contamination from additional Higgs boson production from H→Sh comes with additional jets (or leptons) measurement of signal strengths depends on the decay.
In particular:



$$\frac{\mu^{\gamma\gamma,ZZ}_{Inclusive}}{\mu^{WW}_{0j,1j}} > 1$$

Contamination

Minimum contamination

$$\boxed{\mu^{\gamma\gamma,ZZ}_{Inclusive} = 1.087 \pm 0.084}$$

$$\boxed{\mu^{WW}_{0j,1j} = 0.78 \pm 0.136}$$

Work in progress with IHEP, Beijing

The survival probability of the H→Sh against a jet veto is model dependent. Here we assume S to be a Higgs-like scalar, for which the survival probability for 0j and 1j is ~10% (assuming Br(S→χχ)=0).

Assume dominance of H→Sh. With β_g^2~2, cross-section at 13 TeV is ~20 pb
Over-measurement the tth→Nlepton and undermeasurement of Vh(→bb) and h→WW→ll are a prediction of the model.

$$\boxed{\mu = 1.92 \pm 0.38}$$

tth→Nlepton searches (SS,3l,4l+b-jets)

$$\boxed{\mu = 1.087 \pm 0.084}$$

Inclusive fiducial cross-section (γγ, ZZ→4l)
Contamination from H→Sh is 35%

$$\boxed{\mu = 0.71 \pm 0.12}$$

Vh(→bb) and h→WW->ll
Final states with jet and lepton vetoes

Contamination from H→Sh

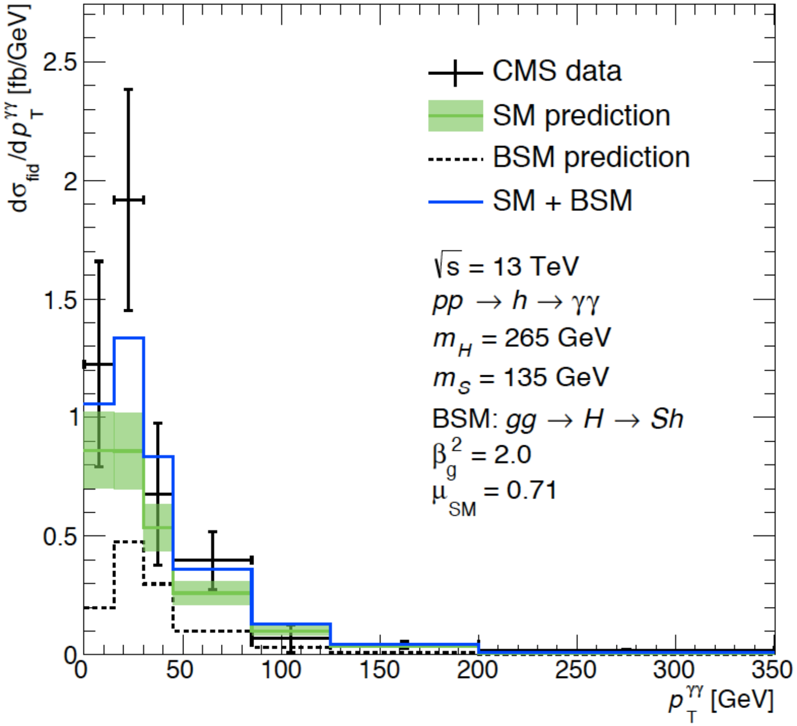
The tension between the upper and lower measurements is 3σ.
Below we are going to assume that the “true” rate of the SM (SM’) is given by the channels with no contamination (i.e. 0.71)

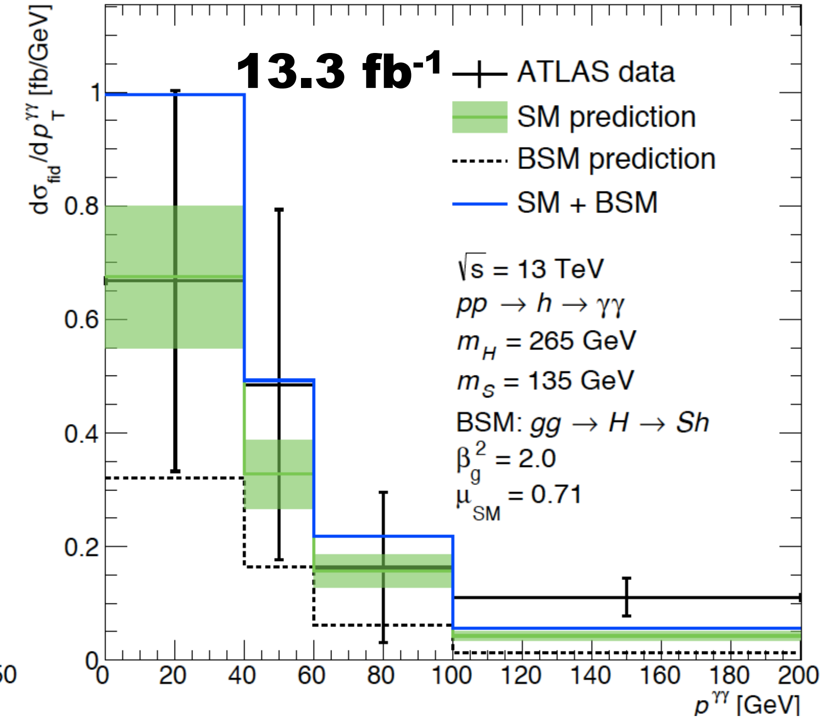
Higgs p_T Run II

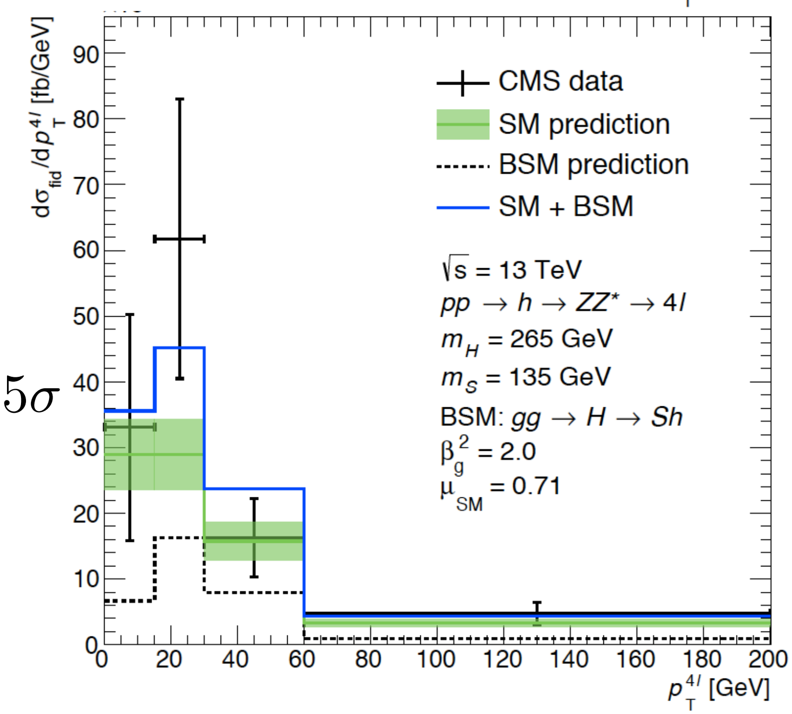
Normalizing the SM as described the previous slide. Results correspond to a fit to the four distributions simultaneously. ATLAS h→γγ corresponds to 13.3 fb^{-1}, while the rest to the entire 2015-2016 set. Obtain:

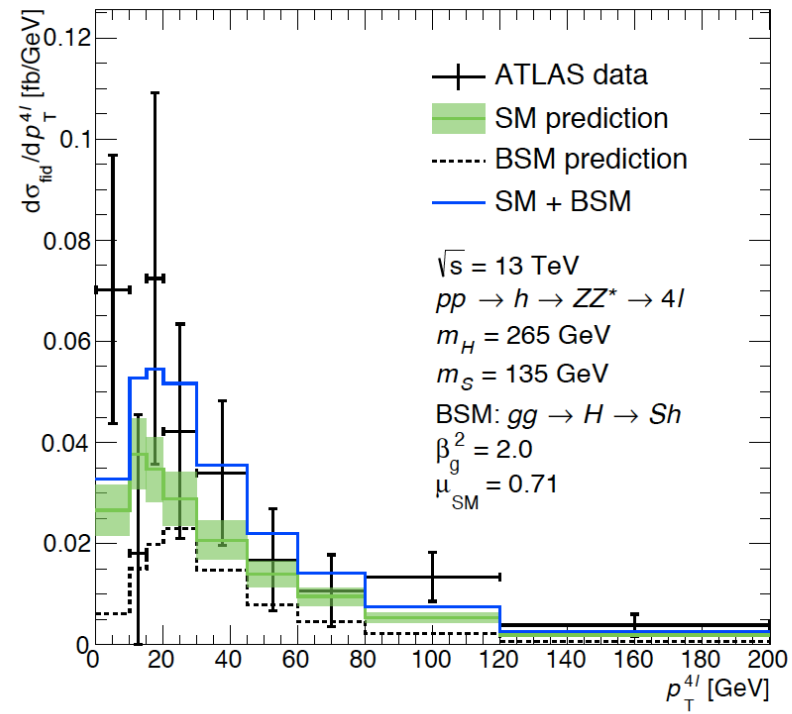
$$\chi^2_{SM'} - \chi^2_{BSM} = 3.35\sigma$$

out of which the choice of normalization explains 2.6









Additional predictions: Leptonic signatures at the LHC

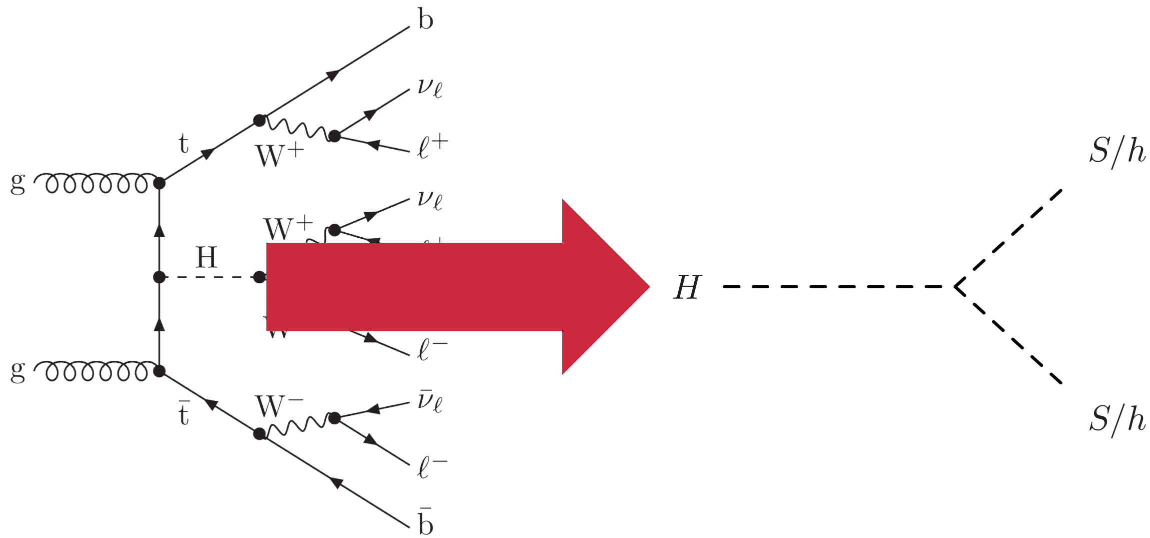
arXiv:1603.01208
arXiv:1606.01674

The hypothesis leads to rich phenomenology

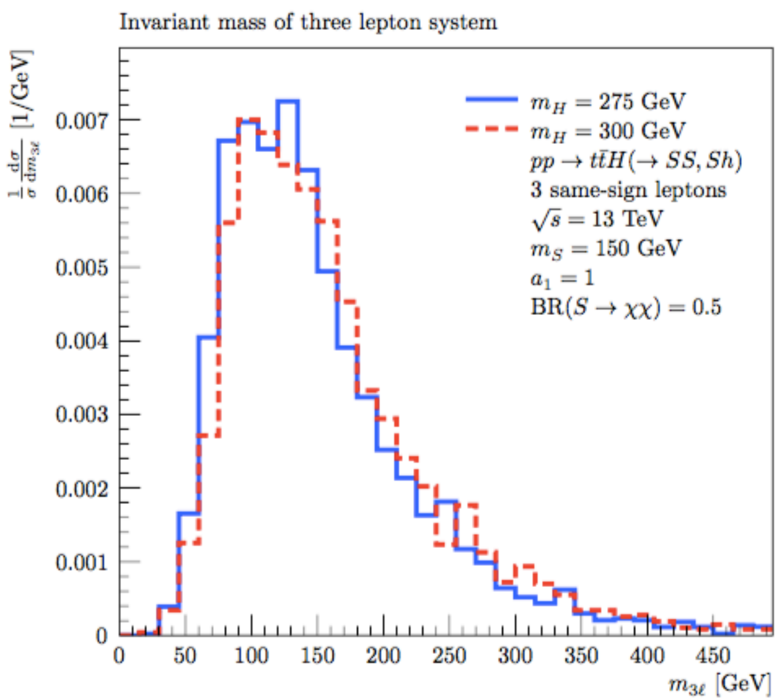
S. No.	Scalars	Decay modes
D.1	h	$b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, $s\bar{s}$, $c\bar{c}$, gg, $\gamma\gamma$, $Z\gamma$, W^+W^-, ZZ
D.2	H	D.1, hh, SS, Sh
D.3	A	D.1, $t\bar{t}$, Zh, ZH, ZS, $W^{\pm}H^{\mp}$
D.4	$H^{\pm}$	$W^{\pm}h$, $W^{\pm}H$, $W^{\pm}S$
D.5	S	D.1, $\chi\chi$

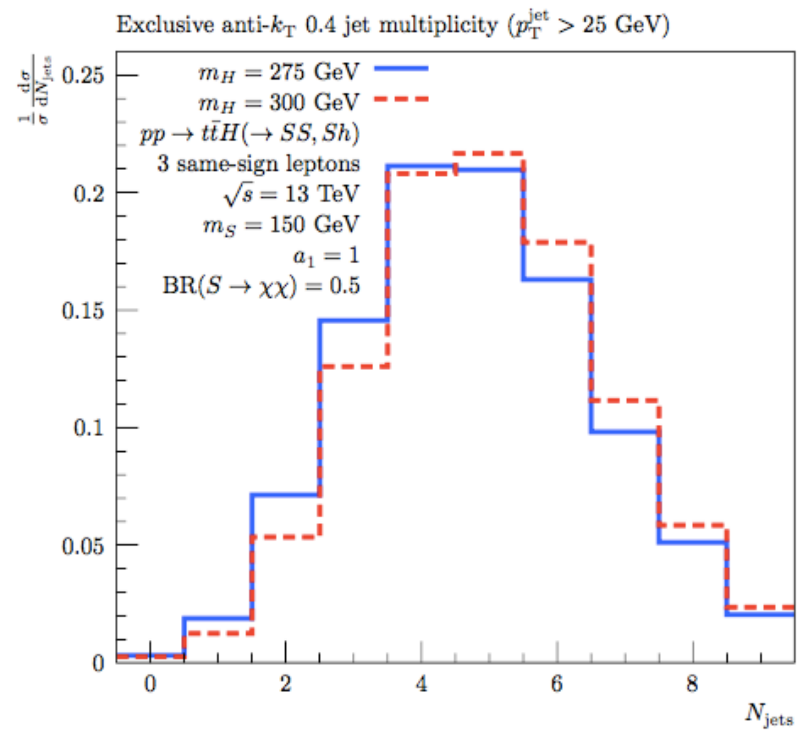
Scalar	Production mode	Search channels
H	$gg \to H, Hjj$ (ggF and VBF)	Direct SM decays as in Table 1 $\to SS/Sh \to 4W \to 4\ell + E_T^{miss}$ $\to hh \to \gamma\gamma b\bar{b}$, $b\bar{b}\tau\tau$, $4b$, $\gamma\gamma WW$ etc. $\to Sh$ where $S \to \chi\chi \implies \gamma\gamma$, $b\bar{b}$, $4\ell + E_T^{miss}$
	$pp \to Z(W^{\pm})H$ ($H \to SS/Sh$)	$\to 6(5)l + E_T^{miss}$ $\to 4(3)l + 2j + E_T^{miss}$ $\to 2(1)l + 4j + E_T^{miss}$
	$pp \to t\bar{t}H, (t+\bar{t})H$ ($H \to SS/Sh$)	$\to 2W + 2Z + E_T^{miss}$ and b-jets $\to 6W \to 3$ same sign leptons + jets and E_T^{miss}
$H^{\pm}$	$pp \to tH^{\pm}$ ($H^{\pm} \to W^{\pm}H$)	$\to 6W \to 3$ same sign leptons + jets and E_T^{miss}
	$pp \to tbH^{\pm}$ ($H^{\pm} \to W^{\pm}H$)	Same as above with extra b-jet
	$pp \to H^{\pm}H^{\mp}$ ($H^{\pm} \to HW^{\pm}$)	$\to 6W \to 3$ same sign leptons + jets and E_T^{miss}
	$pp \to H^{\pm}W^{\pm}$ ($H^{\pm} \to HW^{\pm}$)	$\to 6W \to 3$ same sign leptons + jets and E_T^{miss}
A	$gg \to A$ (ggF)	$\to t\bar{t}$ $\to \gamma\gamma$
	$gg \to A \to ZH$ ($H \to SS/Sh$)	Same as $pp \to ZH$ above, but with resonance structure over final state objects
	$gg \to A \to W^{\pm}H^{\mp}(H^{\mp} \to W^{\mp}H)$	$6W$ signature with resonance structure over final state objects

Production of three same sign leptons

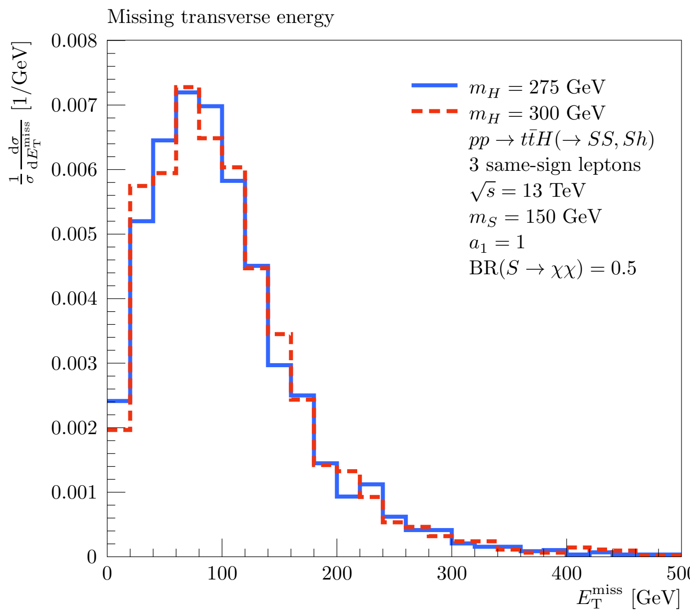


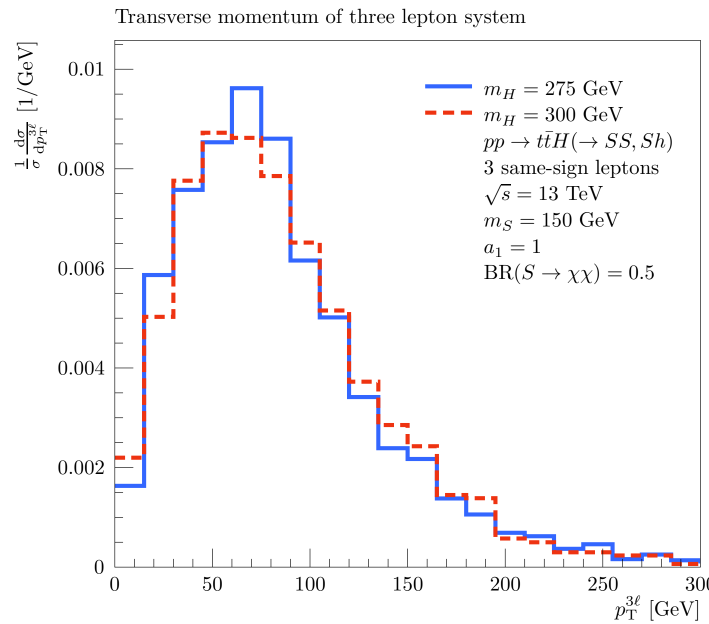
$$t(t)H \rightarrow 6W + X$$
$$\rightarrow l^{\pm}l^{\pm}l^{\pm} + X$$

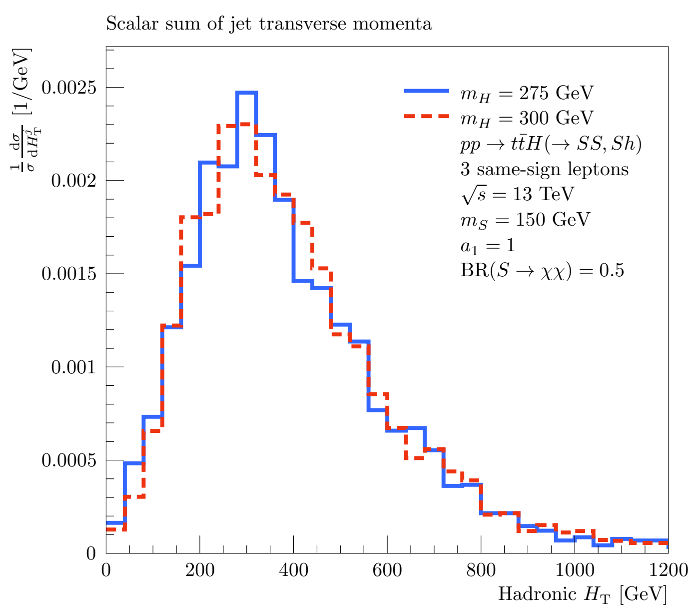


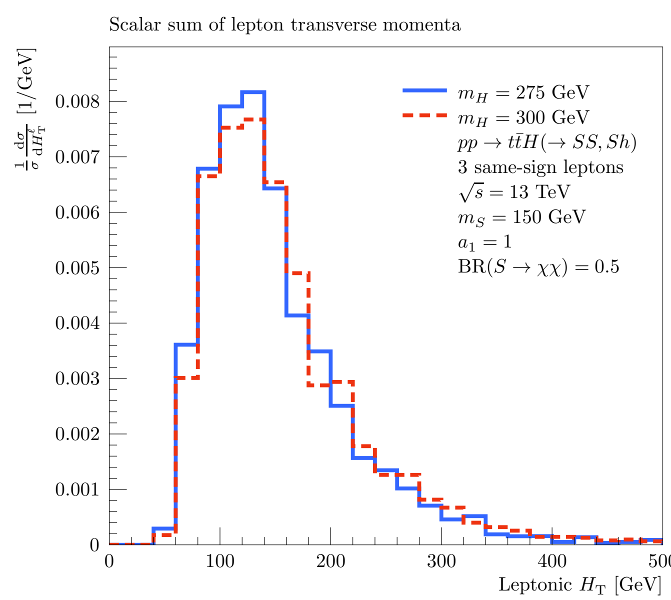


Production of three same sign leptons

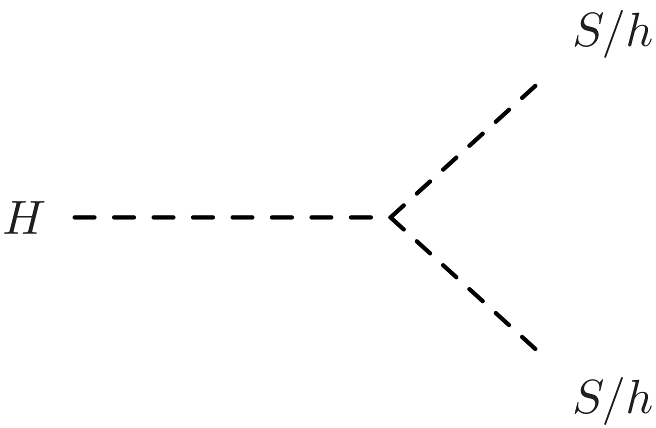








Production of 4 isolated leptons
Coming predominantly from production of 4W

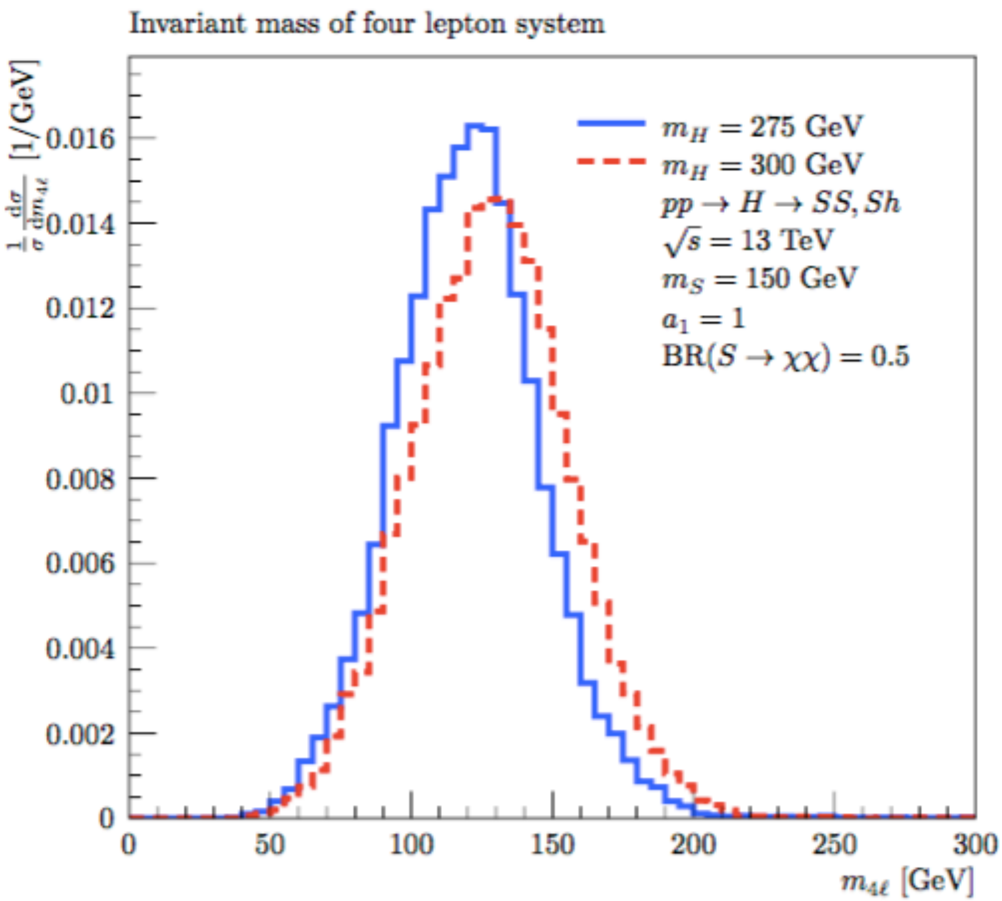


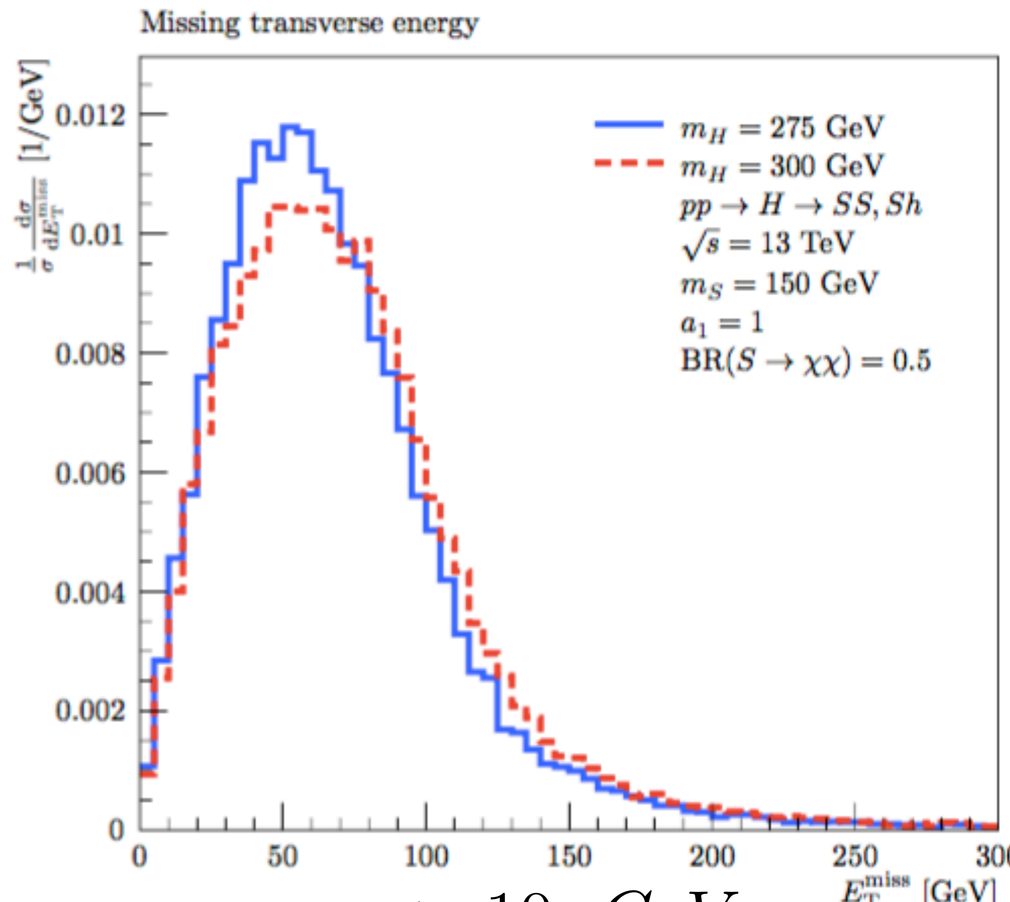
$$S, h \to WWWW, WWZZ, ZZ$$
$$\to 4l + X$$

Features:

1. **Low backgrounds -> excellent S/B**
2. **Clean signature with fake leptons under control**
3. **Unique signature of the hypothesis**
4. **Sensitive to the mass of H**

The production of 4W from a resonance is a unique signature leading to the production of 4 isolated charged leptons and missing energy. The LHC experiments have not reported on this signature to date

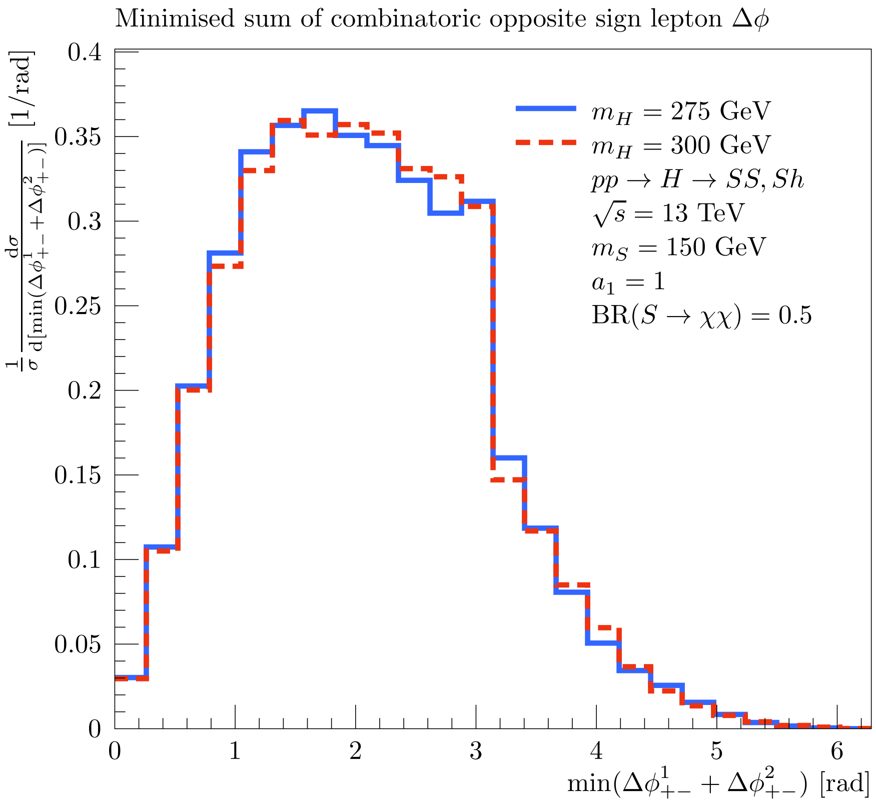


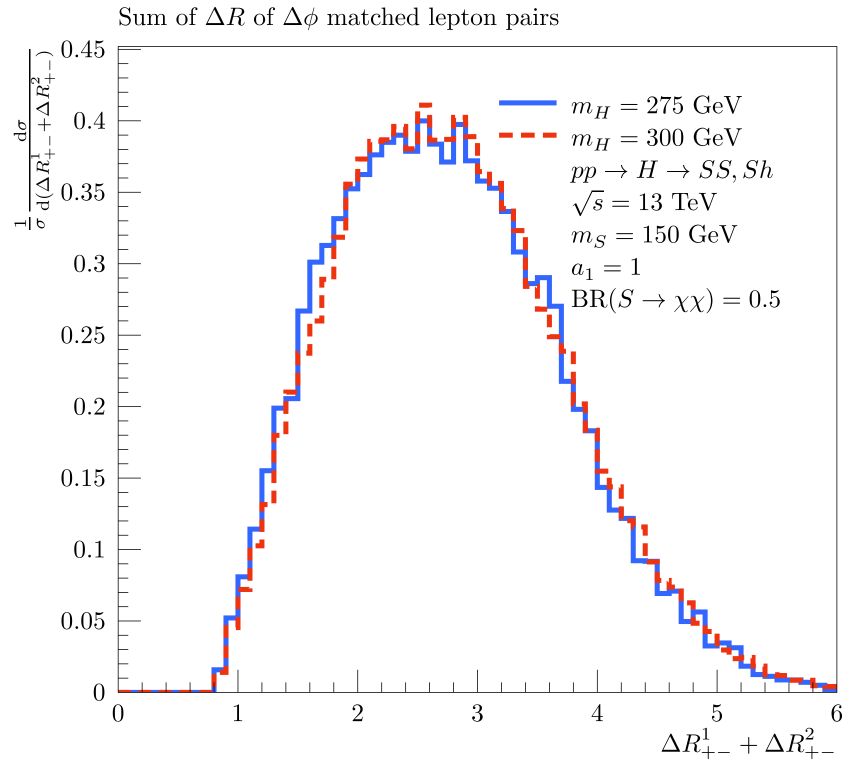


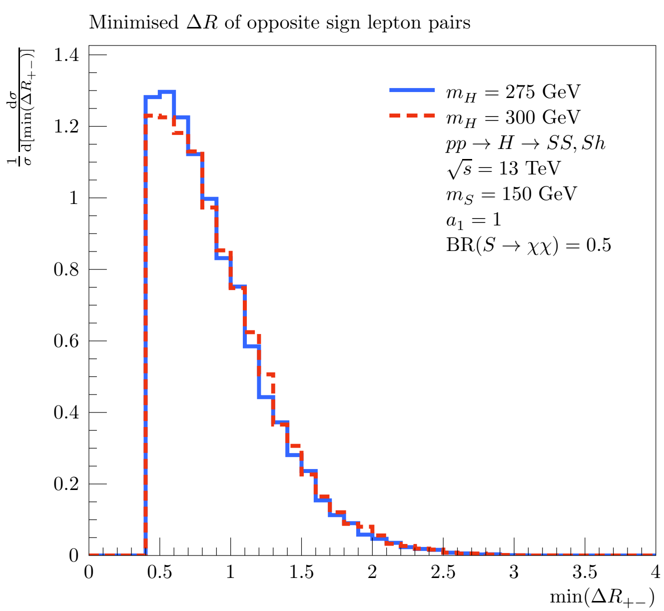
$$p_{Tl} > 10 \quad GeV$$

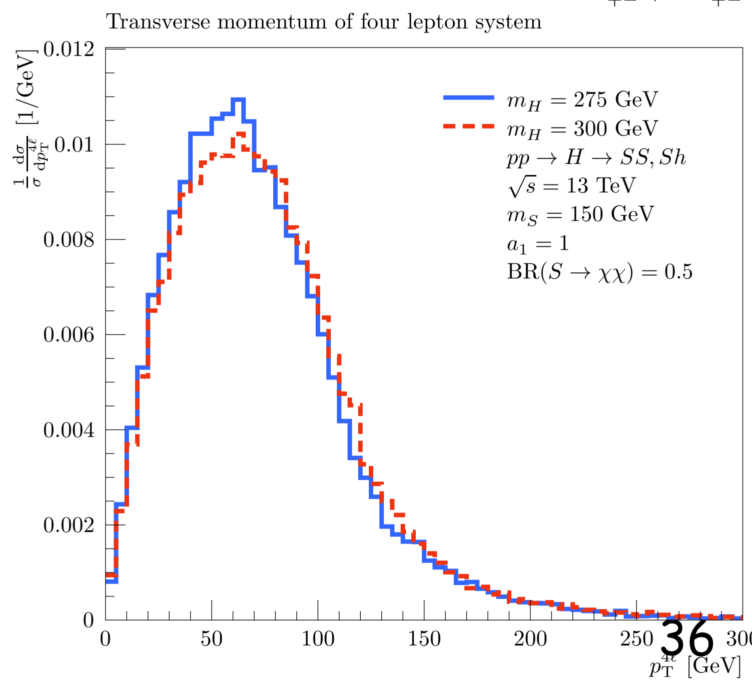
Predict ~1.5 fb of fiducial cross-section

$$|\eta_l| < 2.5$$


Minimised sum of combinatoric opposite sign lepton $\Delta\phi$
$\frac{1}{\sigma}\frac{d\sigma}{d[\min(\Delta\phi^1_{+-}+\Delta\phi^2_{+-})]}$ [1/rad]
$m_H = 275$ GeV
$m_H = 300$ GeV
$pp \to H \to SS, Sh$
$\sqrt{s} = 13$ TeV
$m_S = 150$ GeV
$a_1 = 1$
$\mathrm{BR}(S \to \chi\chi) = 0.5$
$\min(\Delta\phi^1_{+-} + \Delta\phi^2_{+-})$ [rad]


Sum of ΔR of $\Delta\phi$ matched lepton pairs
$\frac{1}{\sigma}\frac{d\sigma}{d(\Delta R^1_{+-}+\Delta R^2_{+-})}$
$m_H = 275$ GeV
$m_H = 300$ GeV
$pp \to H \to SS, Sh$
$\sqrt{s} = 13$ TeV
$m_S = 150$ GeV
$a_1 = 1$
$\mathrm{BR}(S \to \chi\chi) = 0.5$
$\Delta R^1_{+-} + \Delta R^2_{+-}$

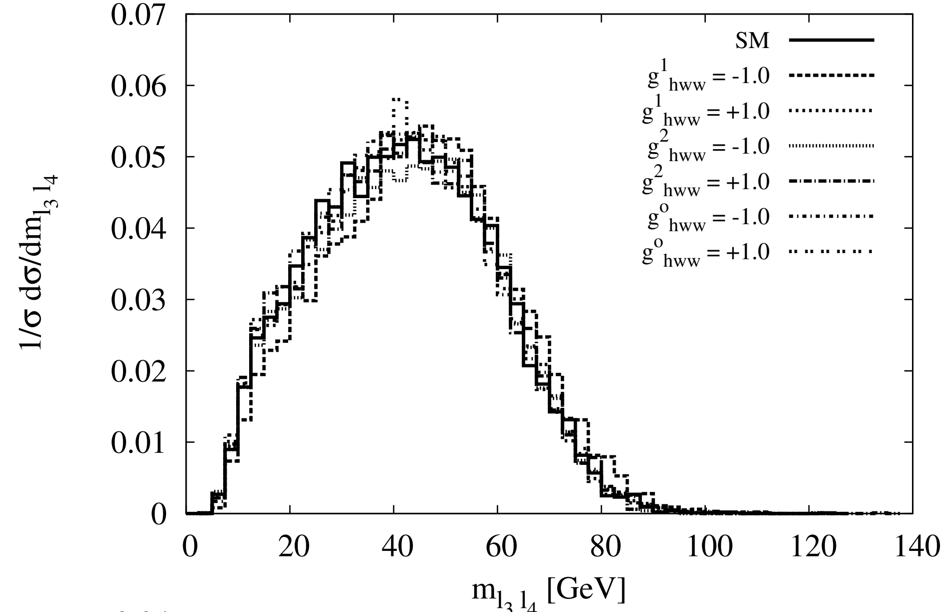

Minimised ΔR of opposite sign lepton pairs
$\frac{1}{\sigma}\frac{d\sigma}{d[\min(\Delta R_{+-})]}$
$m_H = 275$ GeV
$m_H = 300$ GeV
$pp \to H \to SS, Sh$
$\sqrt{s} = 13$ TeV
$m_S = 150$ GeV
$a_1 = 1$
$\mathrm{BR}(S \to \chi\chi) = 0.5$
$\min(\Delta R_{+-})$

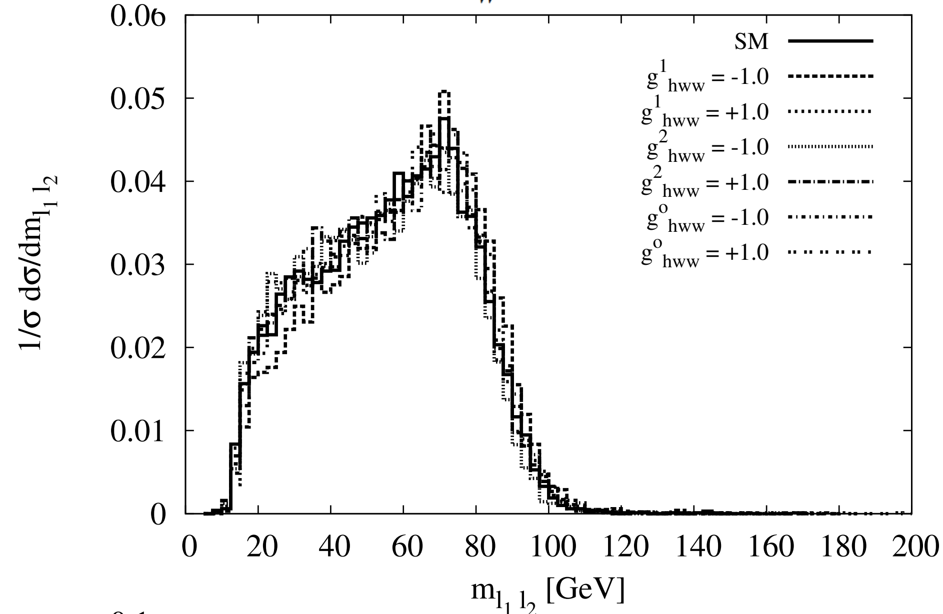

Transverse momentum of four lepton system
$\frac{1}{\sigma}\frac{d\sigma}{dp_T^{4\ell}}$ [1/GeV]
$m_H = 275$ GeV
$m_H = 300$ GeV
$pp \to H \to SS, Sh$
$\sqrt{s} = 13$ TeV
$m_S = 150$ GeV
$a_1 = 1$
$\mathrm{BR}(S \to \chi\chi) = 0.5$
$p_T^{4\ell}$ [GeV]

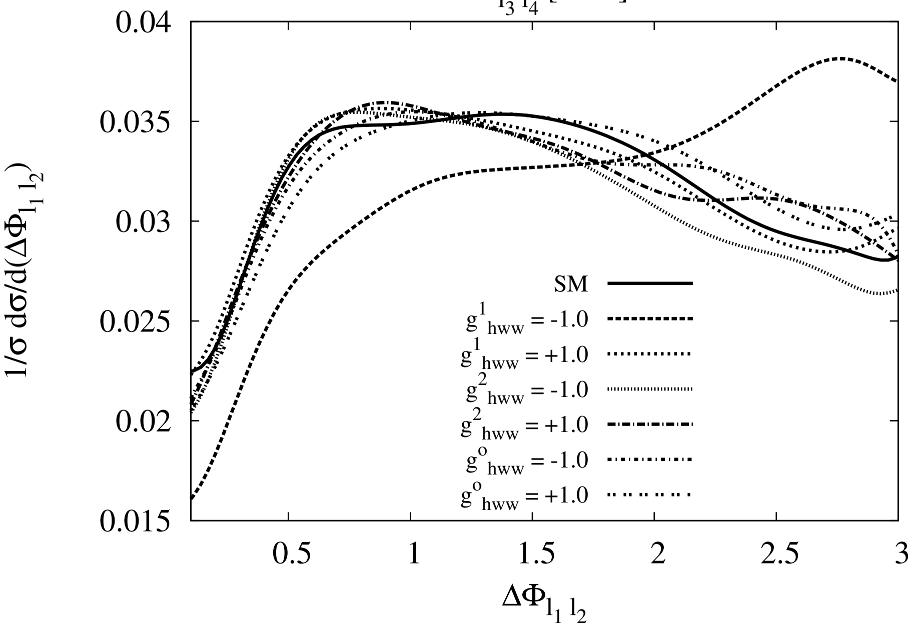
Impact of extended tensor structure of SWW is small

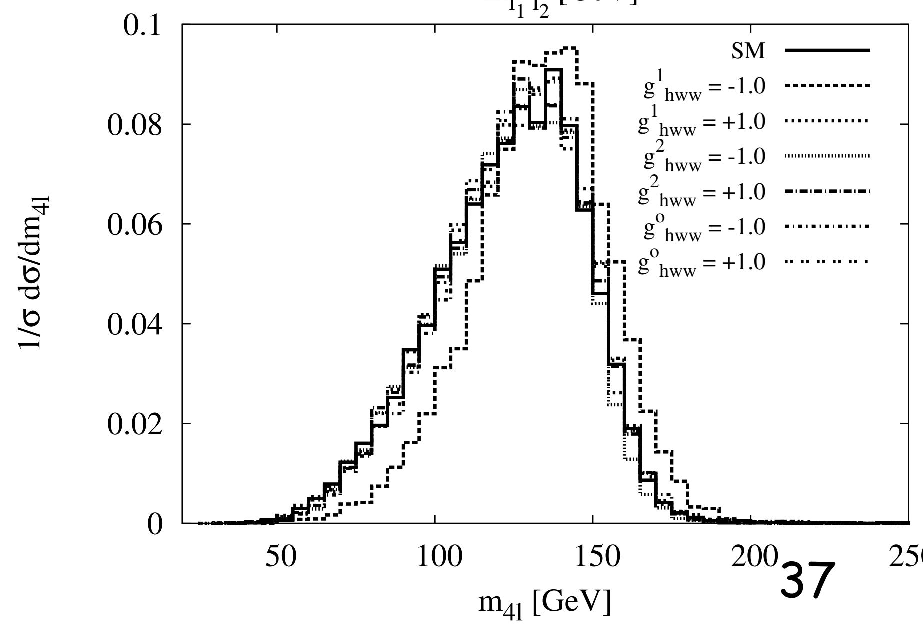
$$\mathcal{L}^{(3)}_{hWW} = -g\Big[\frac{g^{(1)}_{hWW}}{2m_W}W^{\mu\nu}W^{\dagger}_{\mu\nu}h + \frac{g^{(2)}_{hWW}}{m_W}(W^{\nu}\partial^{\mu}W^{\dagger}_{\mu\nu}h + \mathrm{h.c}) + \frac{\tilde{g}_{hWW}}{2m_W}W^{\mu\nu}\widetilde{W}^{\dagger}_{\mu\nu}h\Big],$$

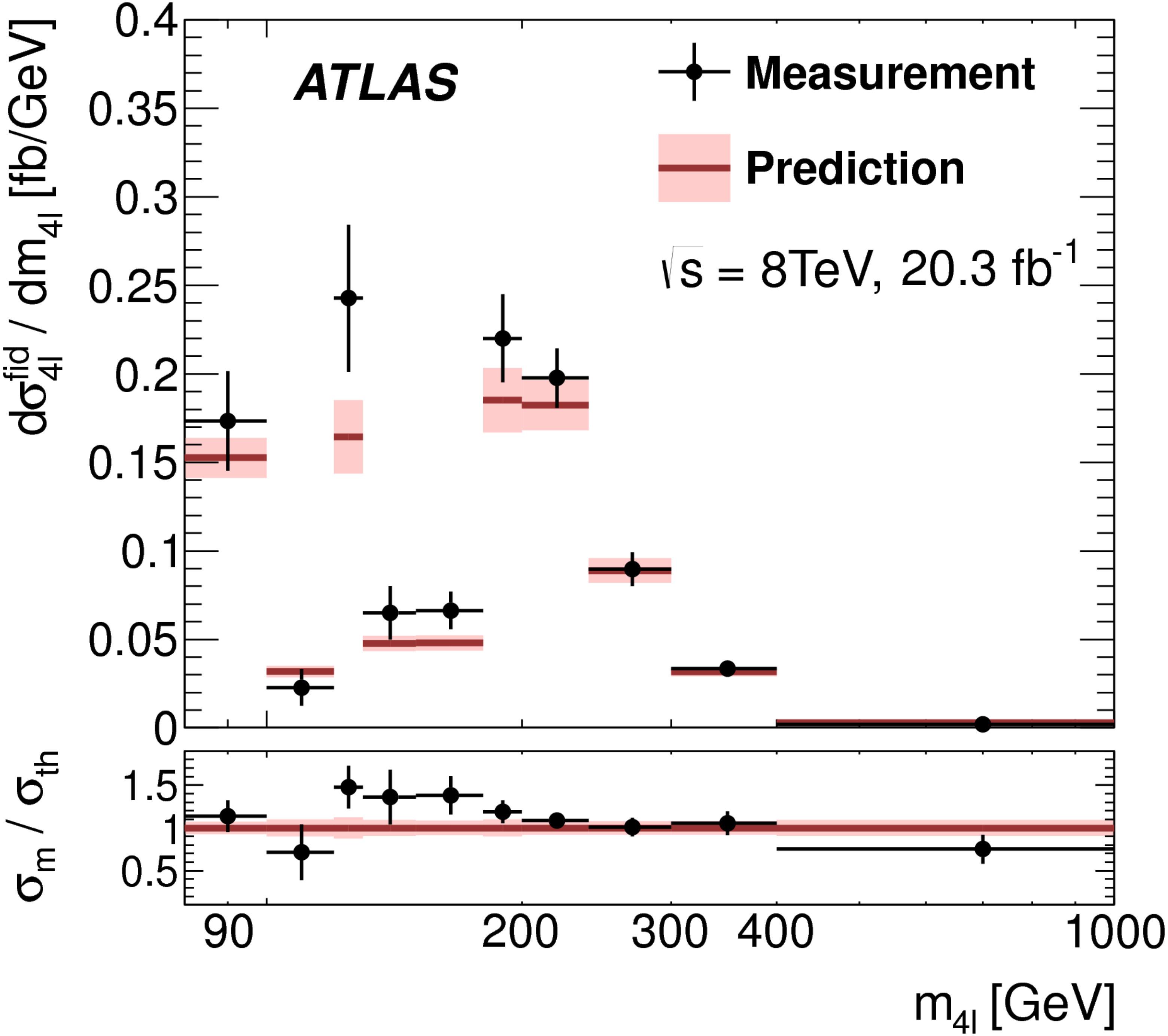
M. Kumar et al, to appear









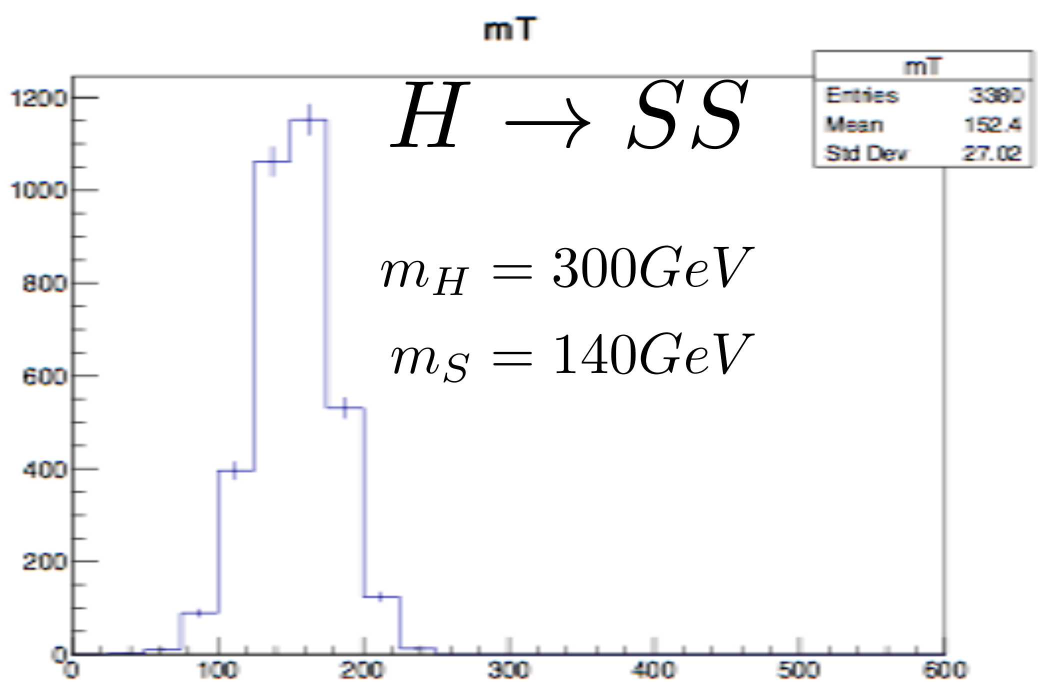


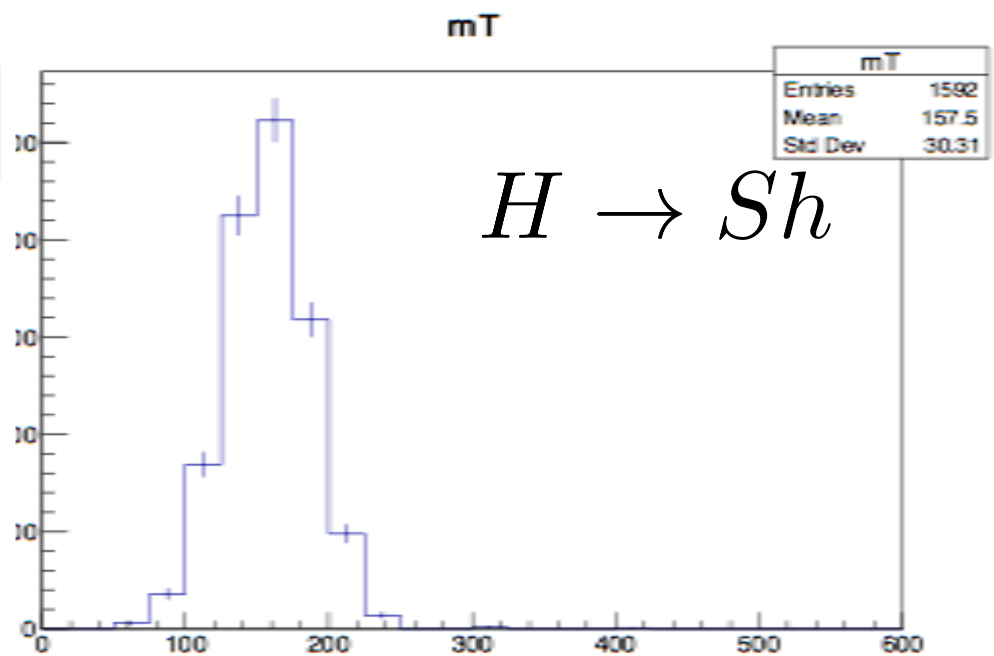
Physics Letters B 753 (2016) 552-572

It is very important to check if the production of 3 leptons, as predicted by the model is not excluded by the existing data. Below is the transverse mass (parton level, no detector smearing applied) after the application of requirements of leptons outlined in ATLAS-CONF-2016-043

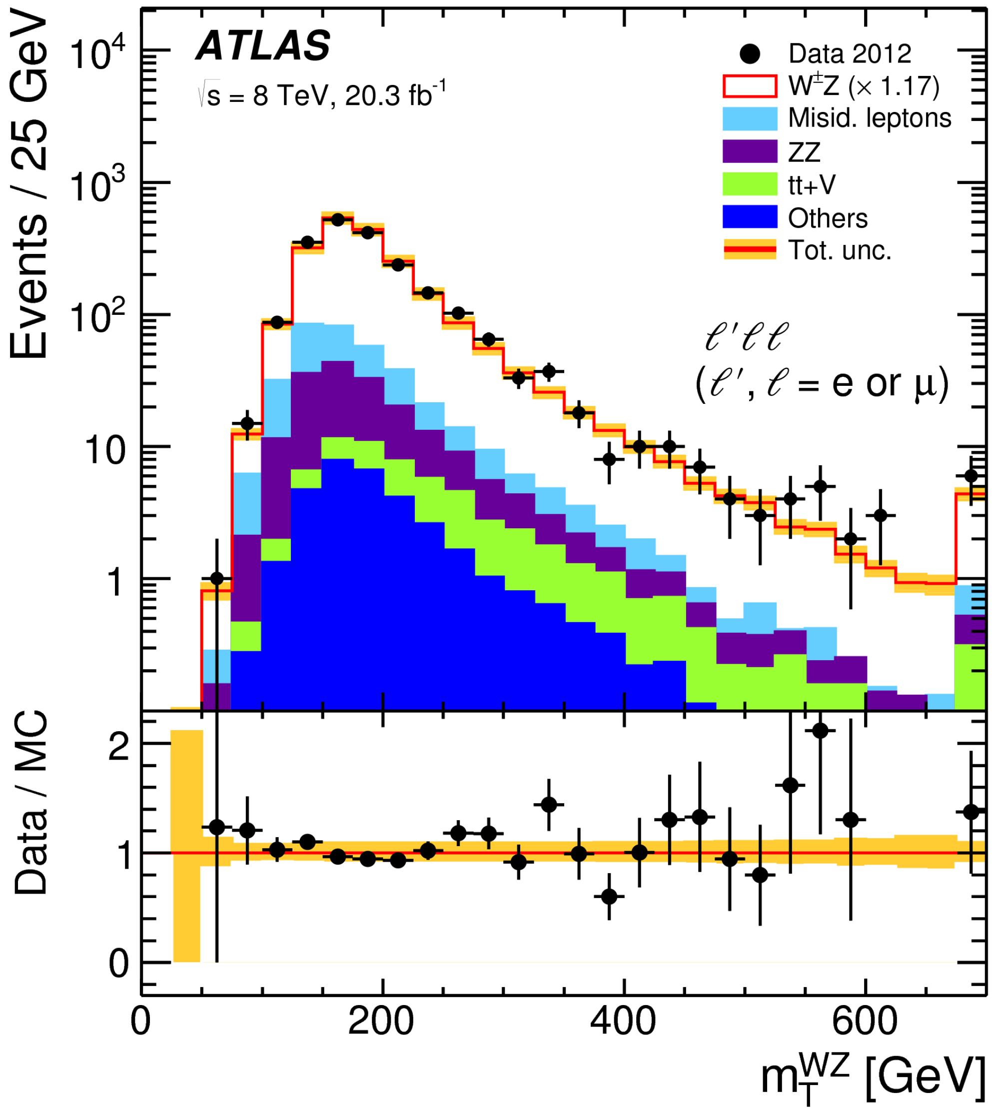
$$m_{\mathrm{T}}^{WZ} = \sqrt{\left(\sum_{\ell=1}^{3} p_{\mathrm{T}}^{\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left[\left(\sum_{\ell=1}^{3} p_{x}^{\ell} + E_{x}^{\mathrm{miss}}\right)^2 + \left(\sum_{\ell=1}^{3} p_{y}^{\ell} + E_{y}^{\mathrm{miss}}\right)^2\right]}.$$

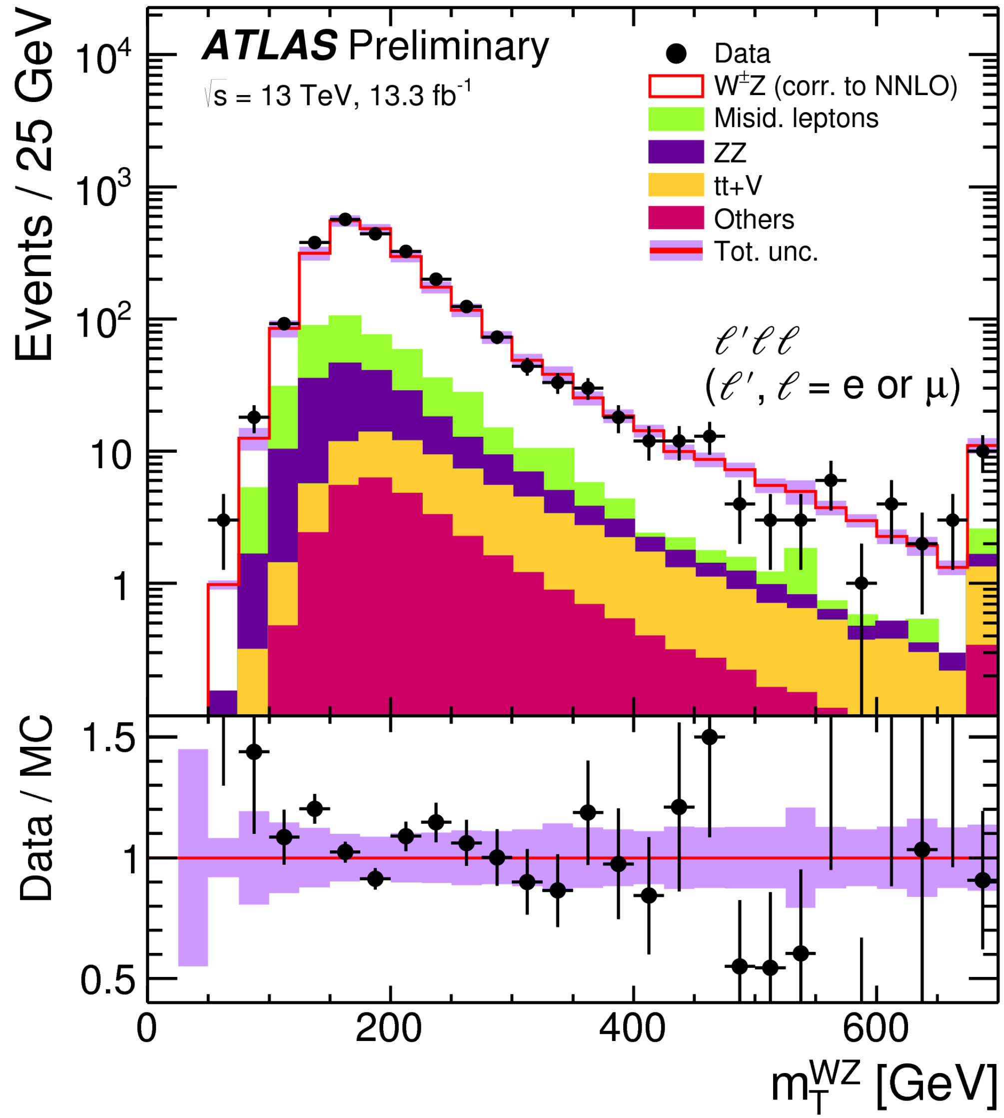
$$H \to SS, Sh \to 3l + X$$





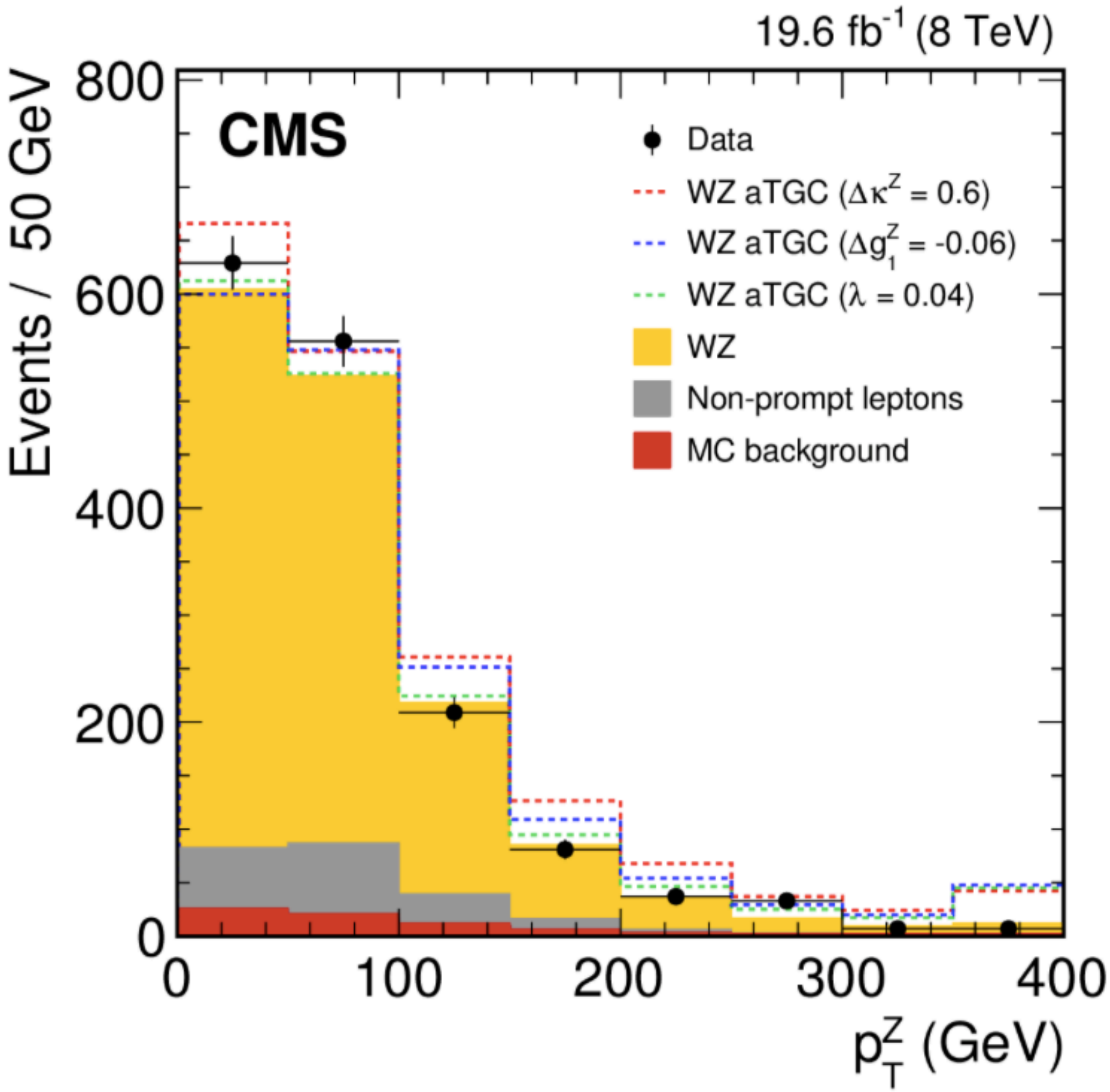
The data reported with Run I and Run II by ATLAS overshoots the MC with M_T<200 GeV. The 4W prediction is not excluded with the current results.



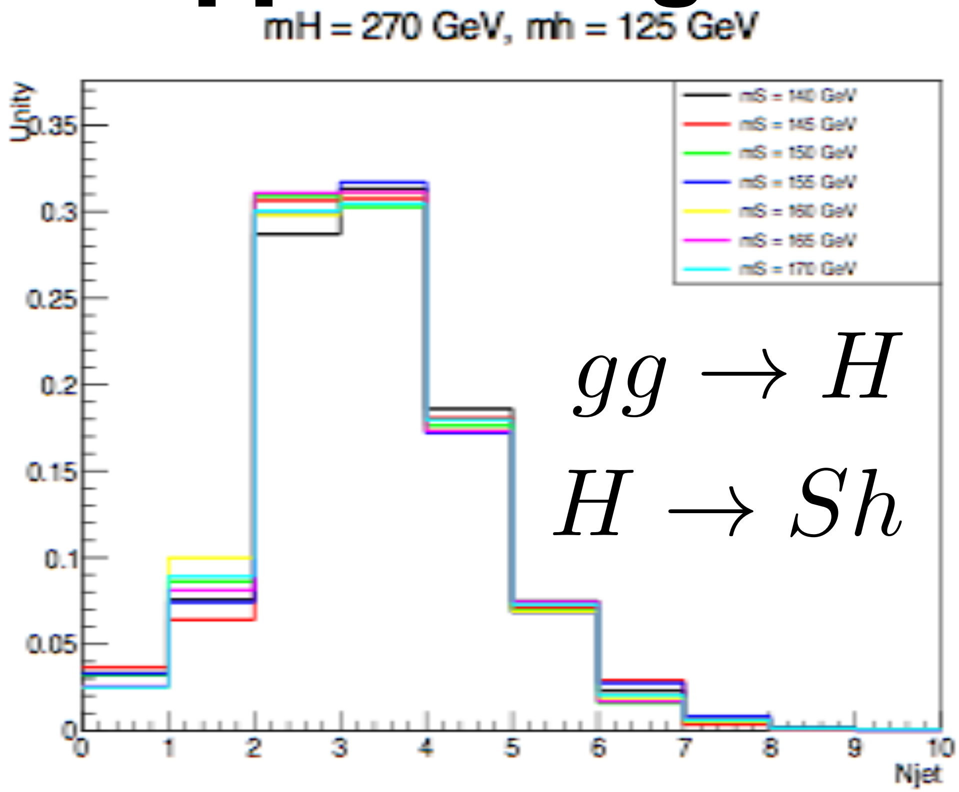


CMS has recently released paper with Run I ZW results. The M_{TZ} distribution is not shown. The transverse momentum of the Z boson is shown. Run II results (https://arxiv.org/abs/1607.06943) **contain 2.3 fb^{-1} only.**

https://arxiv.org/abs/1609.05721

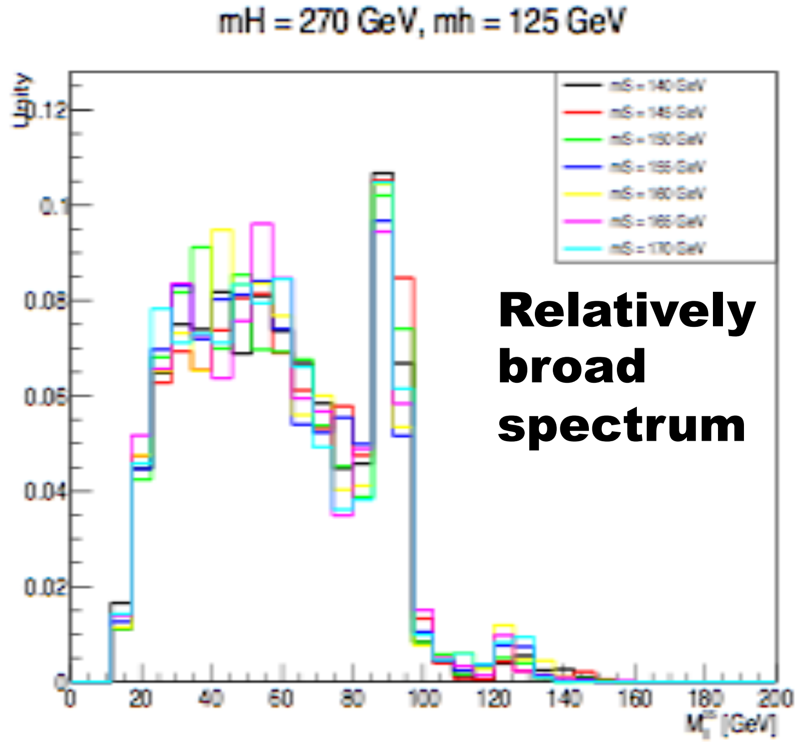


Opposite sign di-lepton production



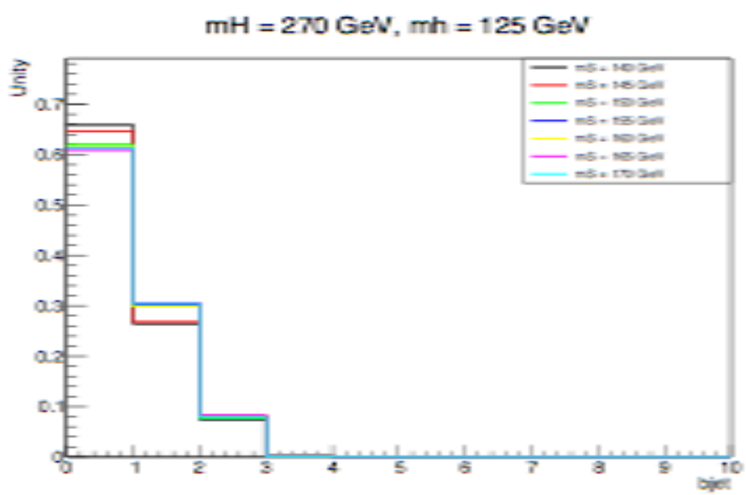
$$gg \to H$$

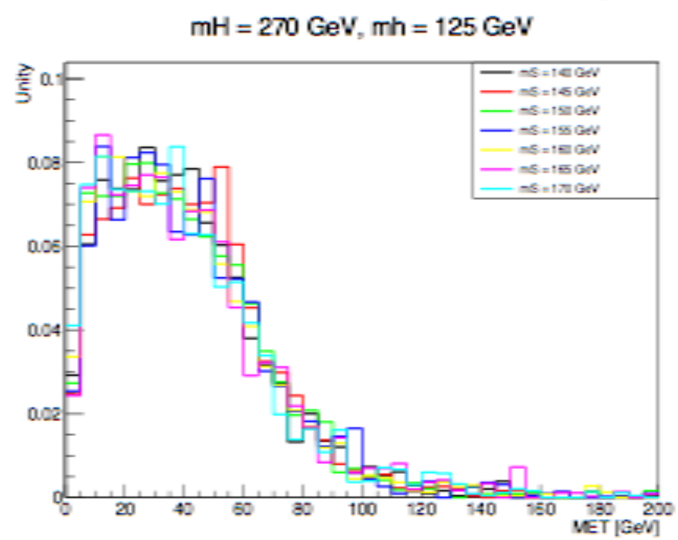
$$H \to Sh$$



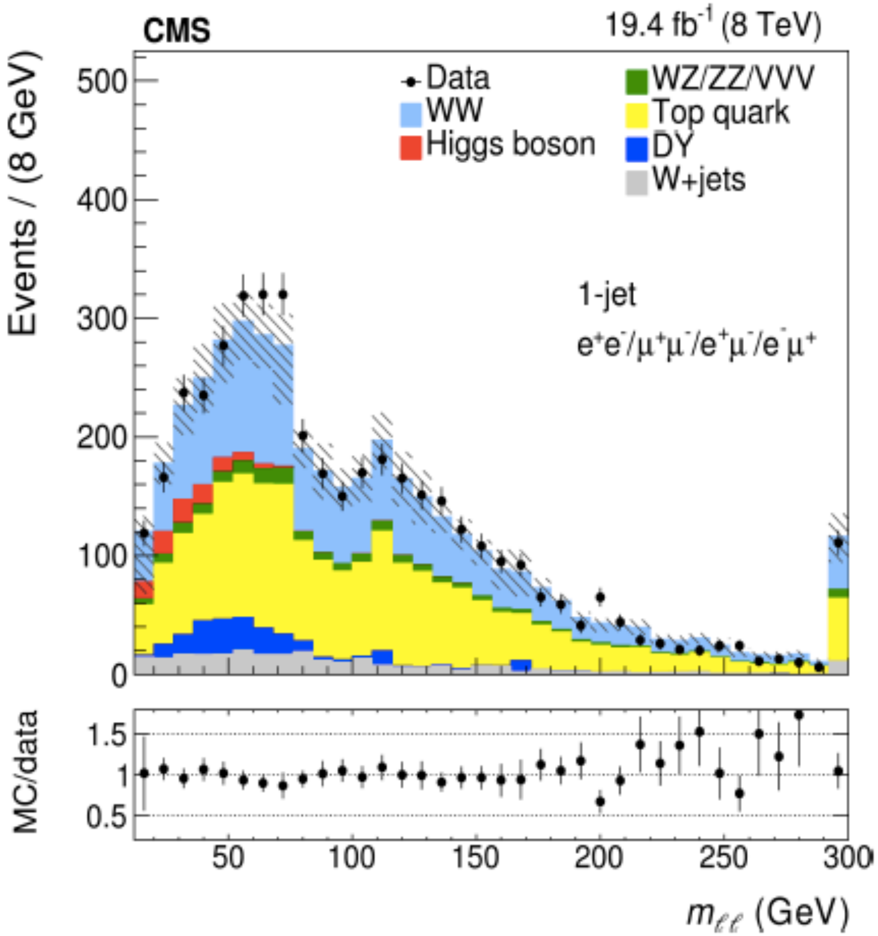
Relatively broad spectrum

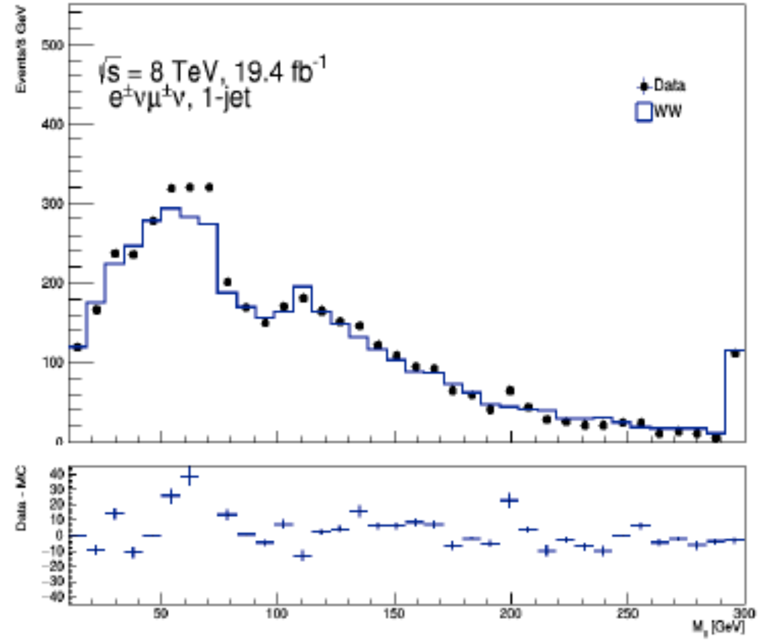
Distribution peaks at 2-3, where top backgrounds dominate. About 10% of events with < 2j





Significances do not include systematics. In principle the systematics related to the extrapolation from m_{ll}>110 GeV to m_{ll}<100 GeV could comparable to the size of the overall excess observed.





Events/Significance	Before scaling MC	MC normalized to $M_{ll} > 110$	
		$M_{ll} < 90$	$M_{ll} < 100$
MC	1653.51	2247.16	2402.36
Data	1629.82	2363.6	2513.6
Data - MC	-23.69	116.44	111.24
Significance	-0.586662	2.39496	2.21867

Samples	Events/Significance	Before scaling MC	MC normalized to $M_{ll} > 110$		Samples	Events/Significance	Before scaling MC	MC normalized to $M_{ll} > 110$	
			$M_{ll} < 90$	$M_{ll} < 100$				$M_{ll} < 90$	$M_{ll} < 100$
ATLAS	MC	1515.88	2668.35	3003.48	**CMS**	MC	2583.03	3866.03	4108.17
$\sqrt{8}$**TeV**	Data	1708.77	2732.69	3095.66	$\sqrt{8}$ **TeV**	Data	2573.21	4009.12	4271.11
20.3 fb^{-1}	Data - MC	192.89	64.34	92.18	**19.4 fb**$^{-1}$	Data - MC	-9.82	143.09	162.94
$e^{\pm}\nu\mu^{\pm}\nu$	Significance	4.66645	1.23093	1.65676	**0-jet,** $e^{\pm}\nu\mu^{\pm}\nu$	Significance	-0.19354	2.25979	2.49325
CMS	MC	1653.51	2247.16	2402.36	**ATLAS**	MC	592.628	817.282	817.282
$\sqrt{8}$**TeV**	Data	1629.82	2363.6	2513.6	$\sqrt{8}$ **TeV**	Data	663.734	902.14	902.14
19.4 fb^{-1}	Data - MC	-23.69	116.44	111.24	**20.3 fb**$^{-1}$	Data - MC	71.106	84.858	84.858
1-jet,$e^{\pm}\nu\mu^{\pm}\nu$	Significance	-0.586662	2.39496	2.21867	**0-jet,** $e^{\pm}\nu\mu^{\pm}\nu$ **channel**	Significance	2.76	2.82525	2.82525
ATLAS Preliminary	MC	534.05	485.262	660.66	**ATLAS**	MC	1175.45	1798.14	2024.5
$\sqrt{13}$ **TeV 3.16 fb**$^{-1}$	Data	521.201	478.87	679.884	$\sqrt{8}$ **TeV**	Data	1237.6	1810.55	2000.09
0-jet, $e^{\pm}\nu\mu^{\pm}\nu$	Data - MC	192.89	-6.392	19.224	**20.3 fb**$^{-1}$	Data - MC	62.15	12.41	-24.41
	Significance	-12.849	-0.292078	0.737285	$e^{\pm}\nu\mu^{\pm}\nu + 1$**jet**	Significance	1.76654	0.291744	-0.545962
CMS	MC	4113.79	4740.95	4740.95		-	-	-	-
$\sqrt{8}$ **TeV**	Data	3816.43	4824.15	5527.54		-	-	-	-
5.3 fb^{-1}	Data - MC	-297.36	83.2	75.13		-	-	-	-
top $e^{\pm}\mu^{\pm}\nu$	Significance	-4.81355	1.19794	1.01044		-	-	-	-

Significances do not include systematics. In principle the systematics related to the extrapolation from m_{ll}>110 GeV to m_{ll}<100 GeV could comparable to the size of the overall excess observed.

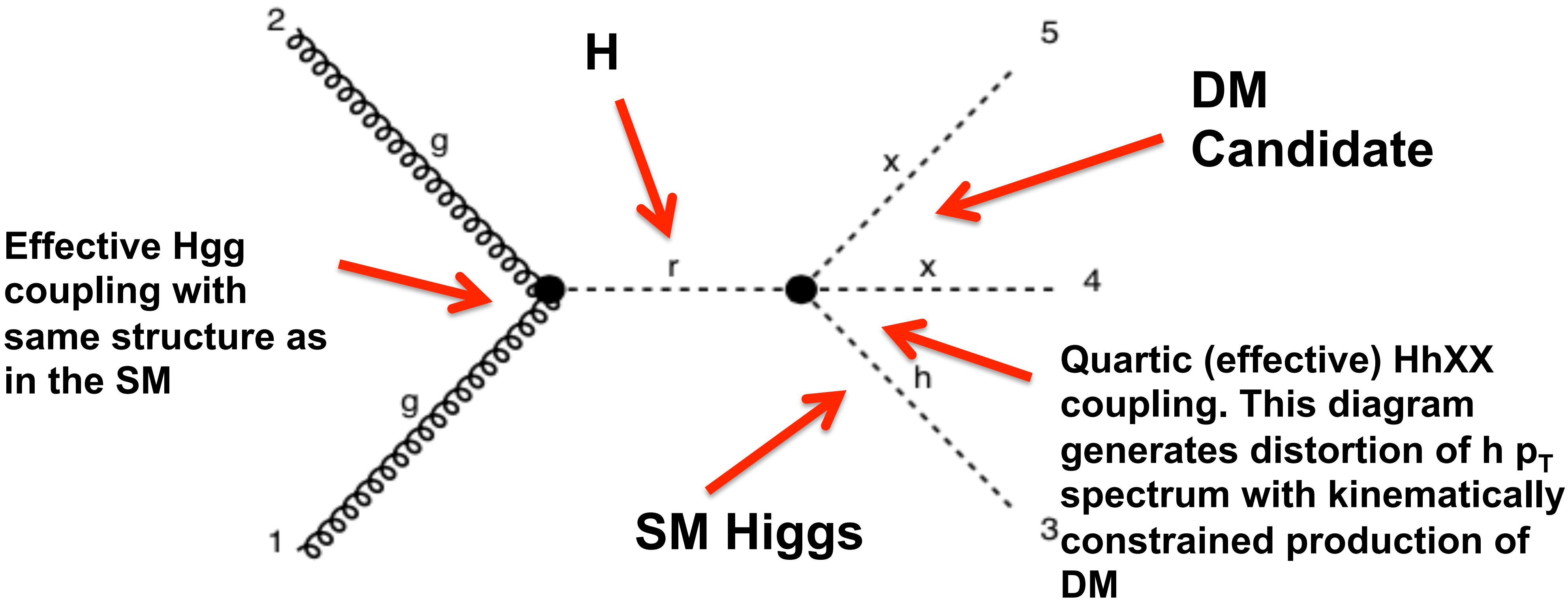
Outlook at Conclusions

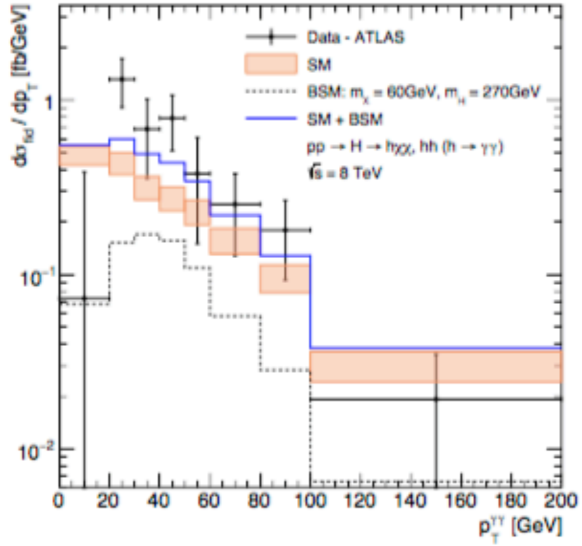
- A number of features of the Run I data triggered the development of a model that includes a scalar boson with the mass in the range 250-300 GeV, H, and a mediator, S, with dominance of H→Sh decay
  - Predict different levels of contamination in Higgs measurements
    - Maximum in tth→Nl searchers, minimum in Wh(→bb), H→WW→ll where jet (and lepton) vetoes are applied
- Including Run II data observe the following features, compatible with the model:
  1. Overshoot rate of tth→Nl and undershoot of Wh(→bb), H→WW→ll w.r.t. to SM with 3σ tension
  2. Run II H→ZZ→4l search displays 2σ (ATLAS), 2.5σ (CMS) in the region of 250-270 GeV
  3. When normalizing the SM to the combined from Wh(→bb), H→WW→ll measurements can describe inclusive Higgs p_T spectrum with a 3.35σ with respect to this assumption
- The production of 4W leading to 4l is a striking signature
  - Experimental data with 2 and 3 leptons cannot exclude the production of 4W, as predicted here

Additional Slides

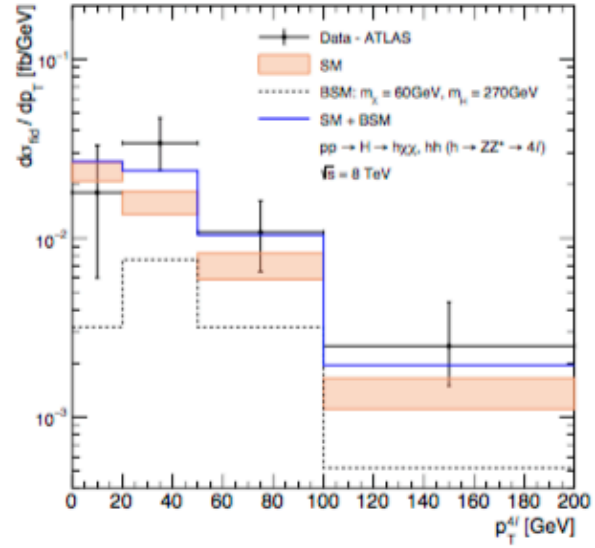
Event Generation

Generated complete Gauge invariant set of diagrams.
Suppressed hXX and hhXX couplings to study diagram below

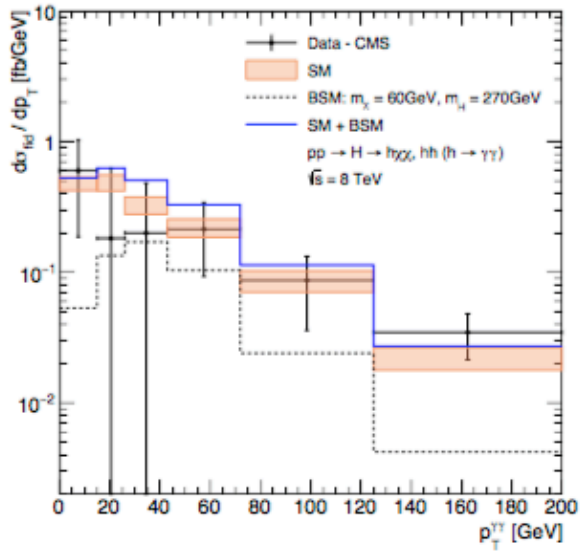




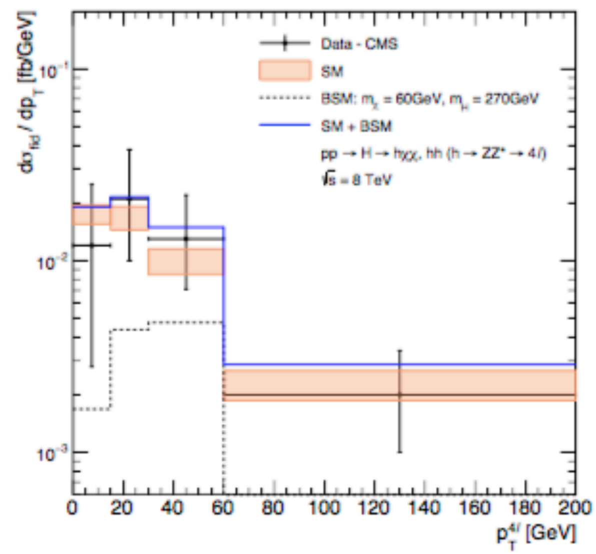
(a) ATLAS $h \to \gamma\gamma$



(b) ATLAS $h \to ZZ^* \to 4\ell$



(c) CMS $h \to \gamma\gamma$



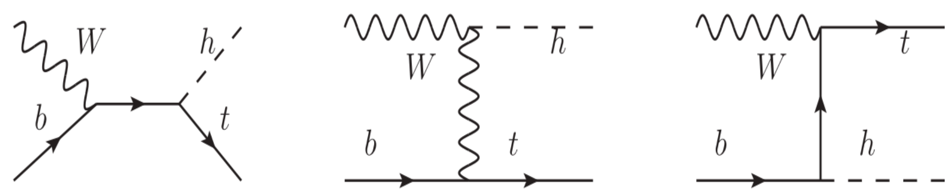
(d) CMS $h \to ZZ^* \to 4\ell$

Figure 3: Fits to the ATLAS and CMS Run I differential p_T spectra using the point $m_H = 270\,\text{GeV}$ and $m_\chi = 60\,\text{GeV}$.

Enhancement of tH production

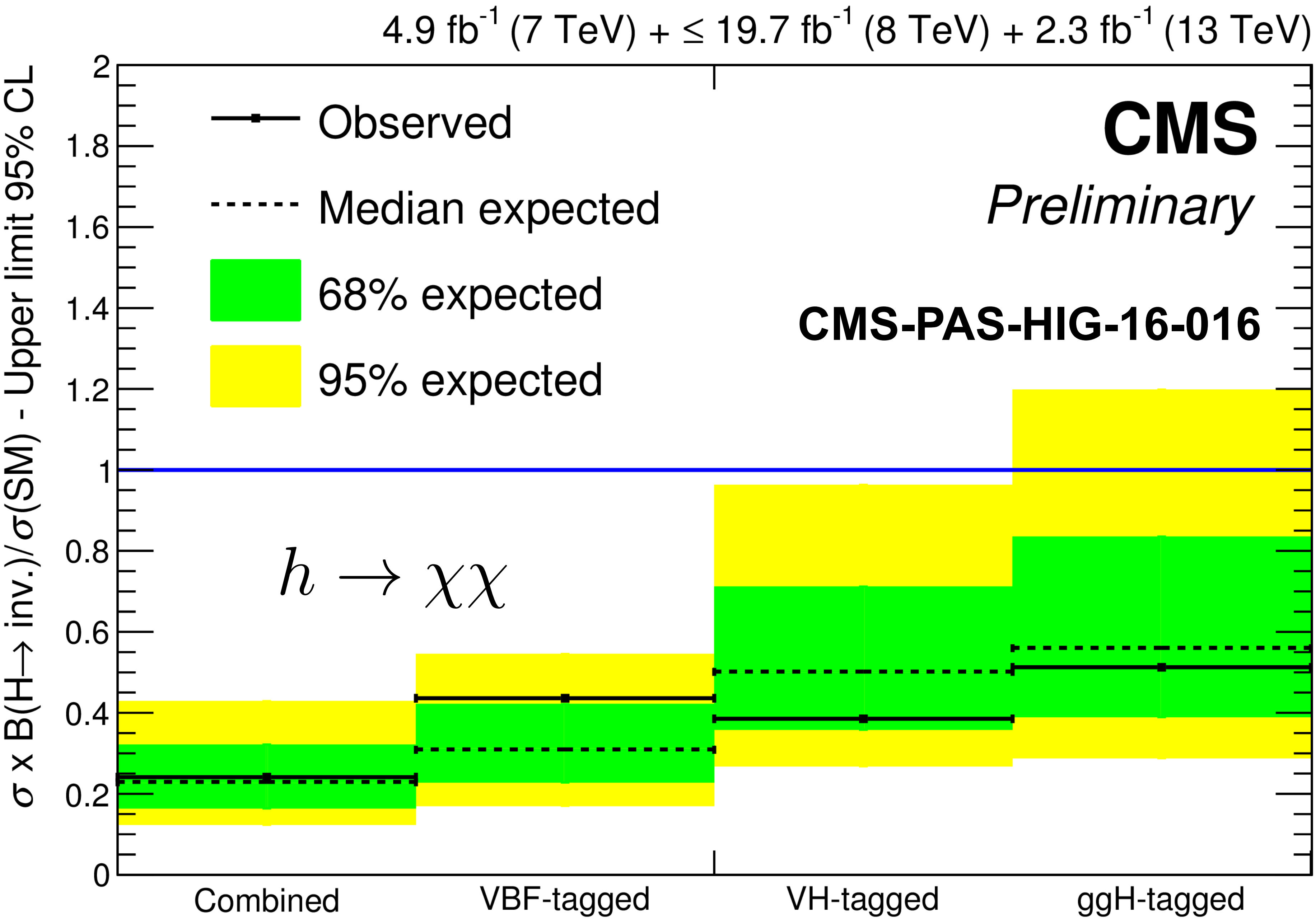
- **In experiment, top associated Higgs production is measured as a sum of single top and double top cross sections**
- **In the SM, we find that $\sigma_{th} \ll \sigma_{tth}$**

$$\mathcal{A} = \frac{g}{\sqrt{2}}\left[(c_F - c_V)\frac{m_t\sqrt{s}}{m_W v}\,A\left(\frac{t}{s},\varphi;\xi_t,\xi_b\right) + \left(c_V\,\frac{2m_W}{v}\frac{s}{t} + (2c_F - c_V)\,\frac{m_t^2}{m_W v}\right)\,B\left(\frac{t}{s},\varphi;\xi_t,\xi_b\right)\right]$$



- **For the heavy scalar considered here, $c_V \ll c_F$**
- **We expect a sizeable cross section to come from top associated heavy scalar production ($\sigma_{tH} \simeq \sigma_{ttH}$)**

M. Farina, C. Grojean, F. Maltoni, E. Salvioni and A. Thamm, JHEP **1305**, 022 (2013).



Room for invisible decays of the Higgs is narrowing down.
Seems reasonable to introduce a mediator S.

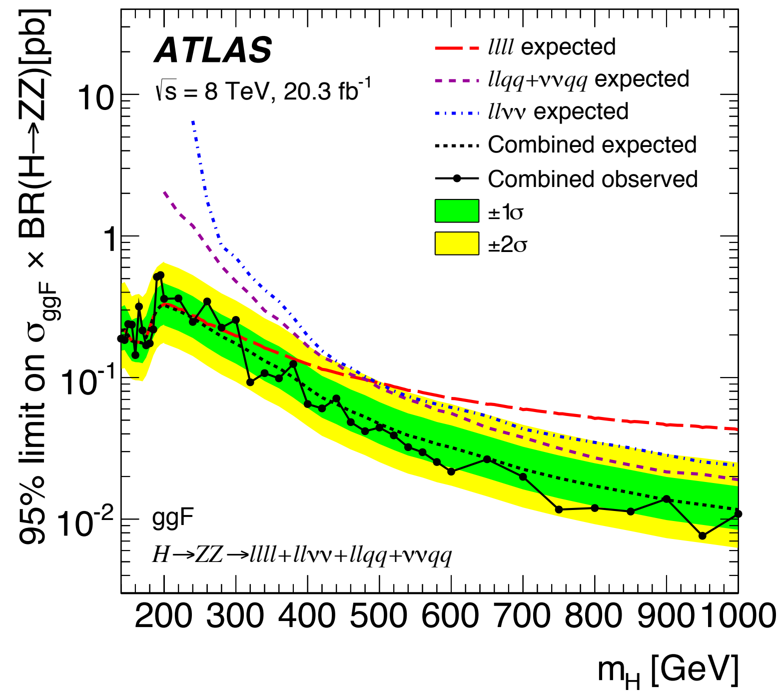
Calculating χ^2

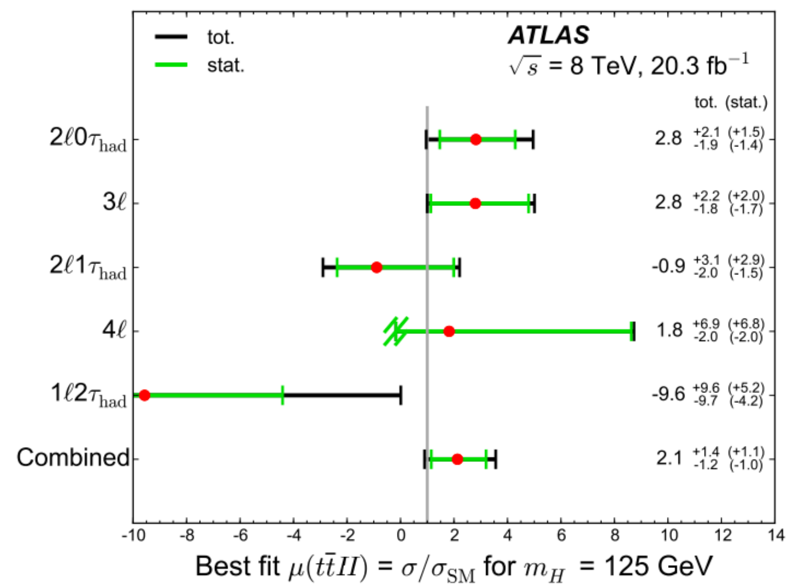
- Two types of results:
  - **Measurements**

$$\chi^2 = \frac{(\mu - \mu^{\text{th}})^2}{(\Delta\mu)^2 + (\Delta\mu^{\text{th}})^2}$$

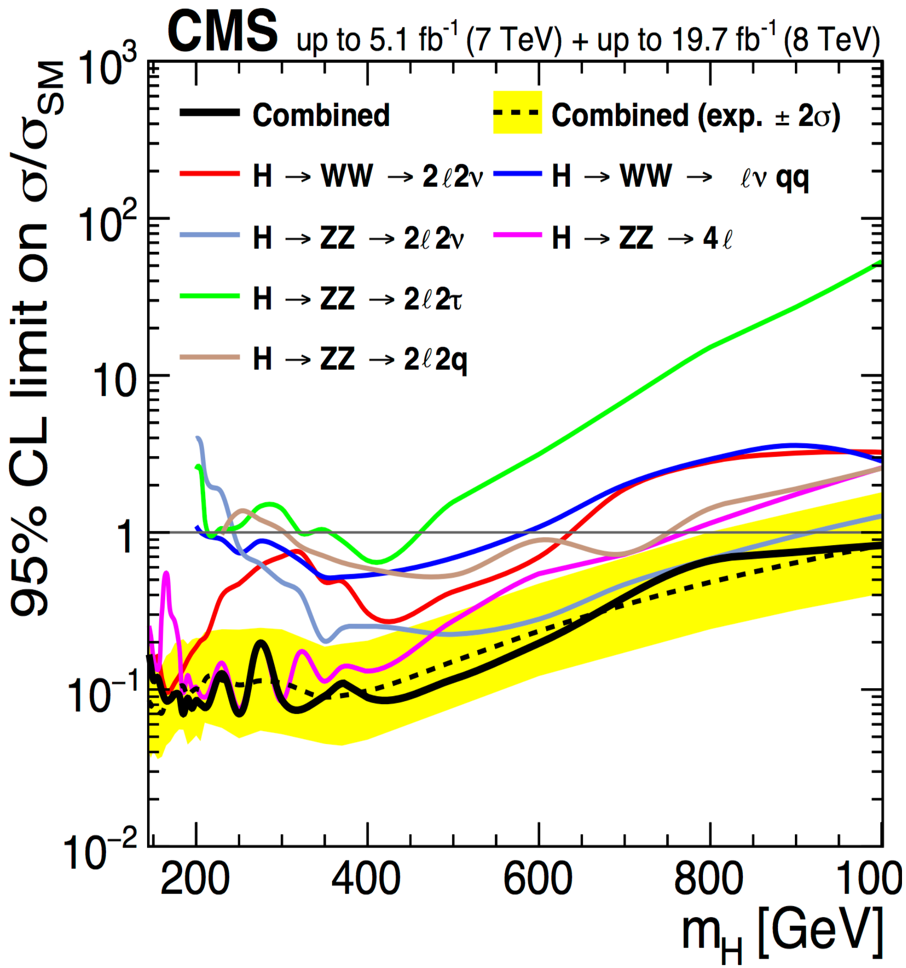
  - **Limits**

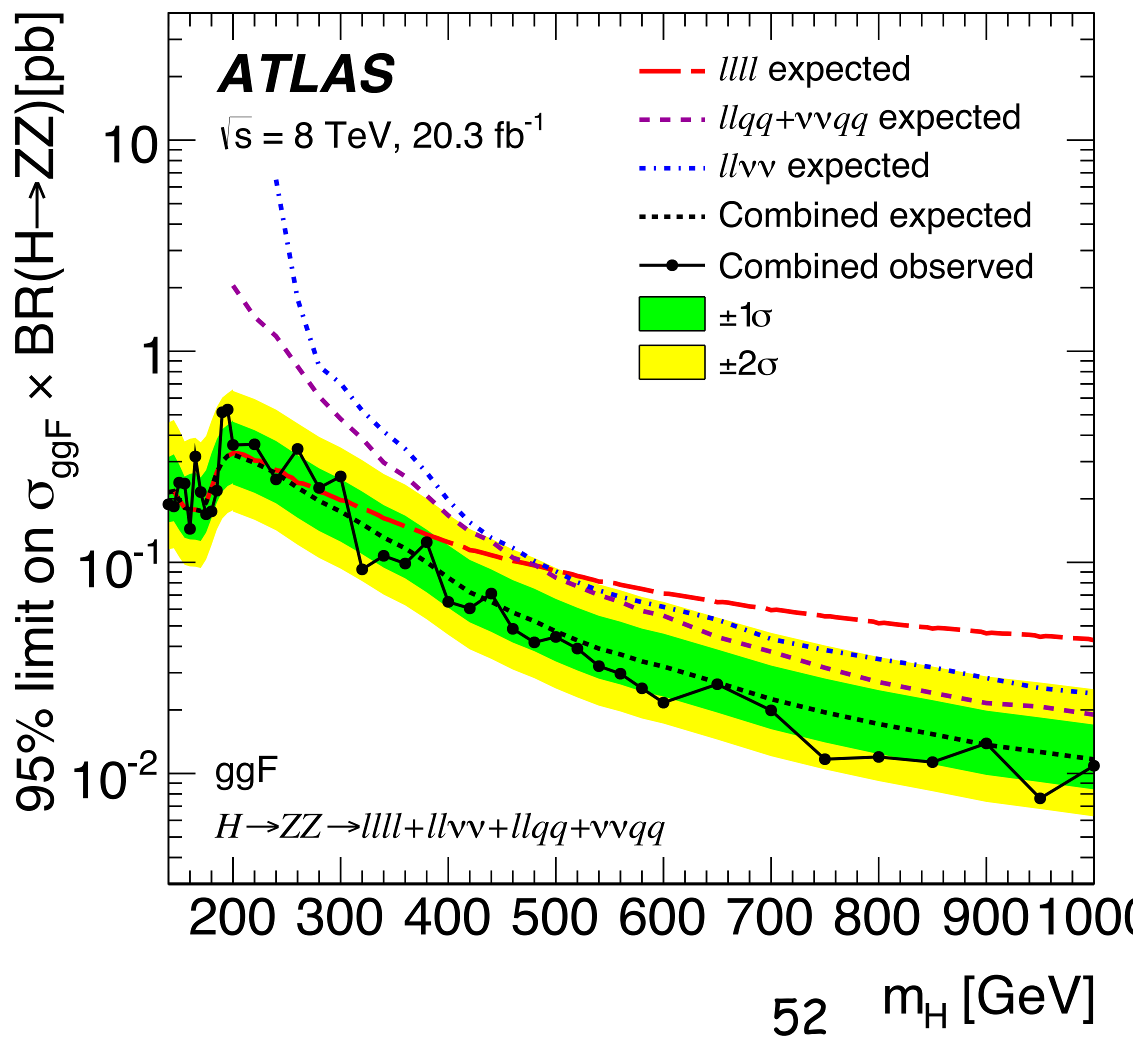
$$\chi^2 = \frac{(\mu^{\text{obs}} - \mu^{\text{exp}} - \mu^{\text{th}})^2}{(\mu^{\text{exp}}/1.96)^2}$$



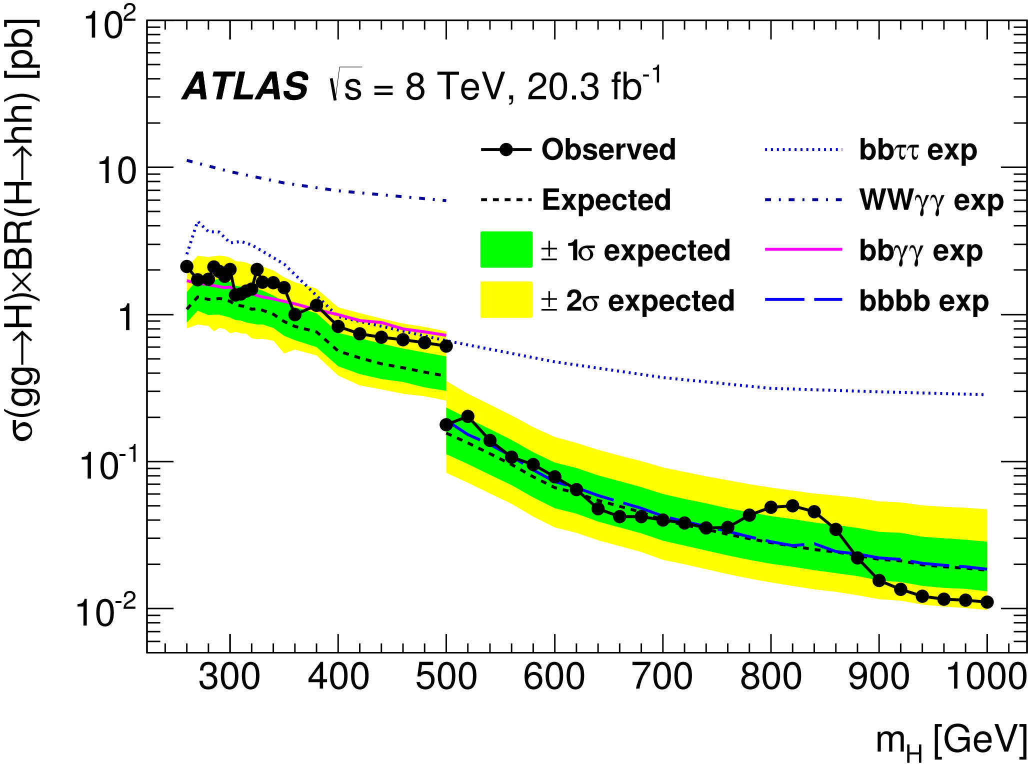


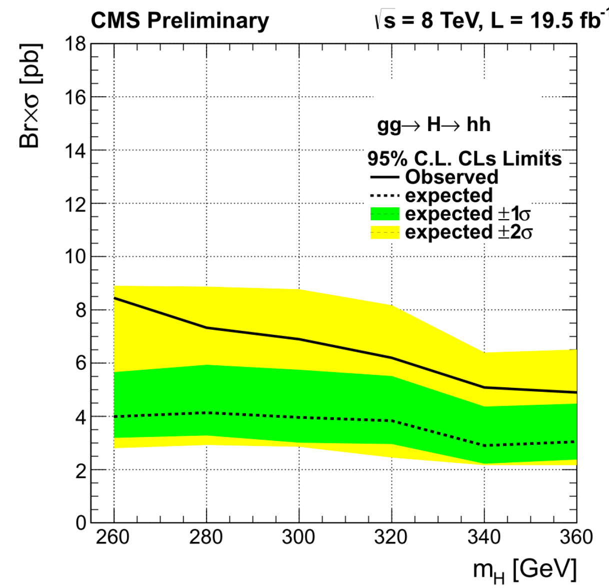
Inputs: Higgs decays to weak vector bosons

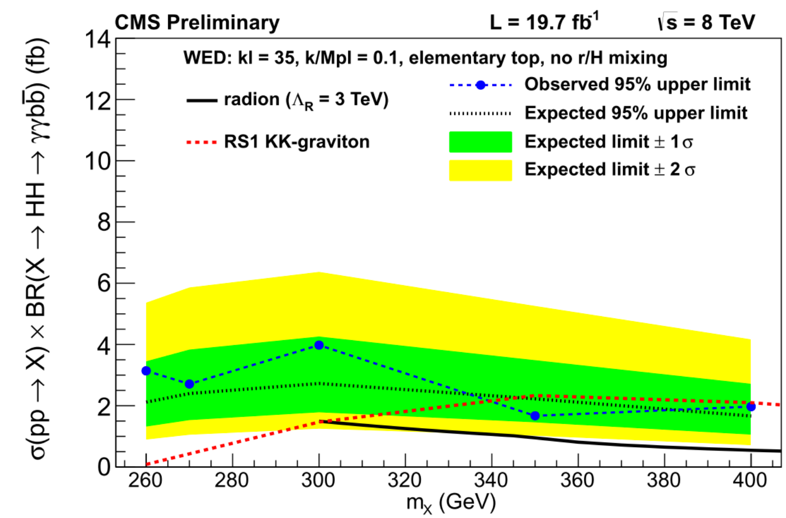




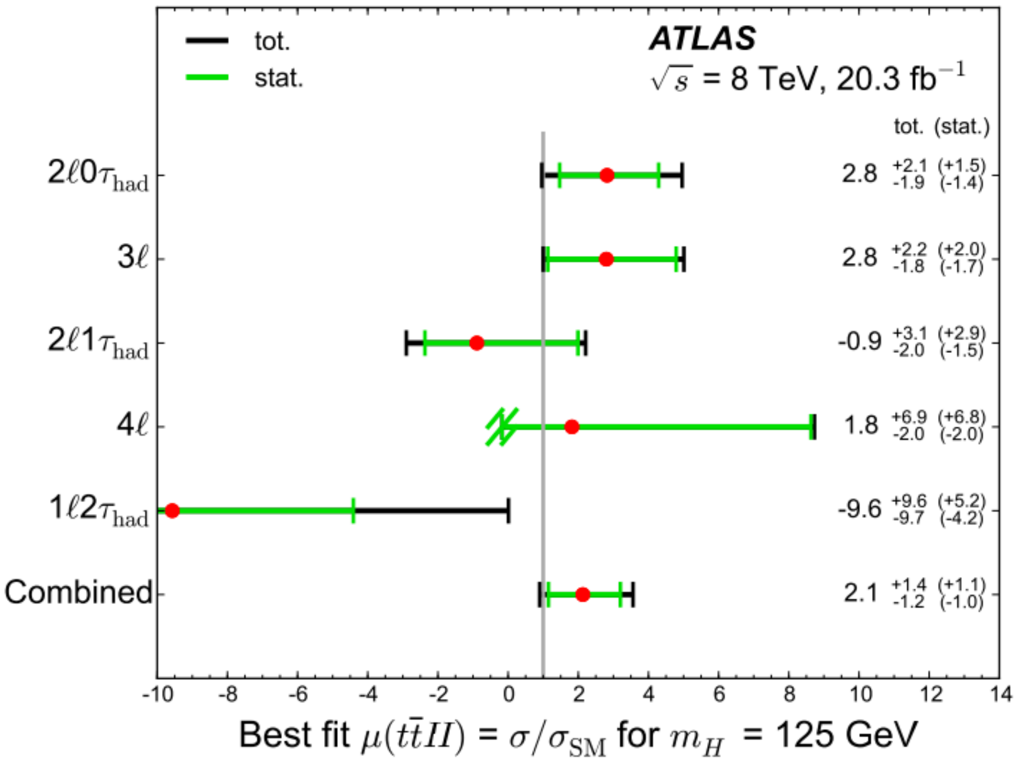
Inputs: Di-Higgs searches

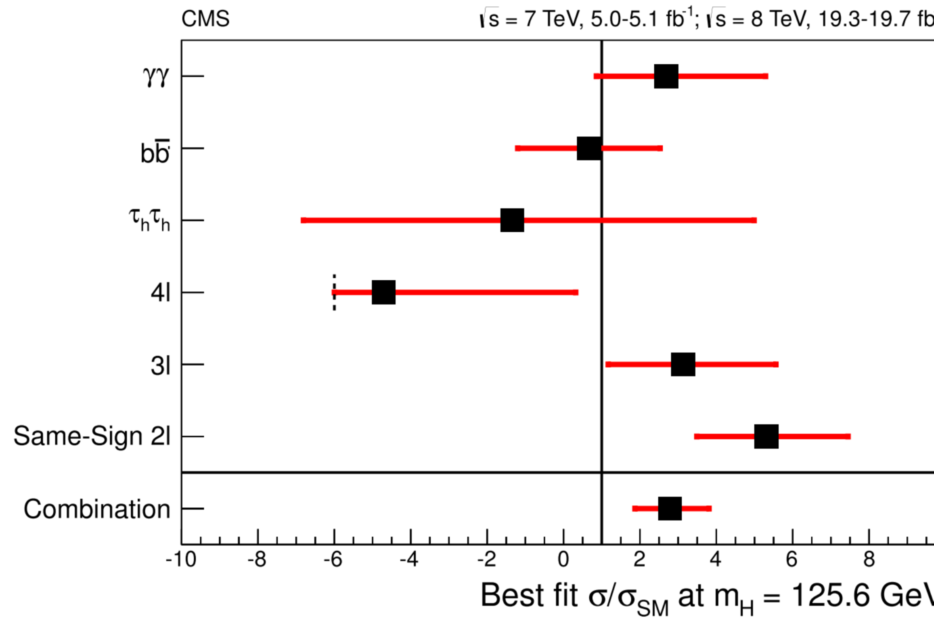






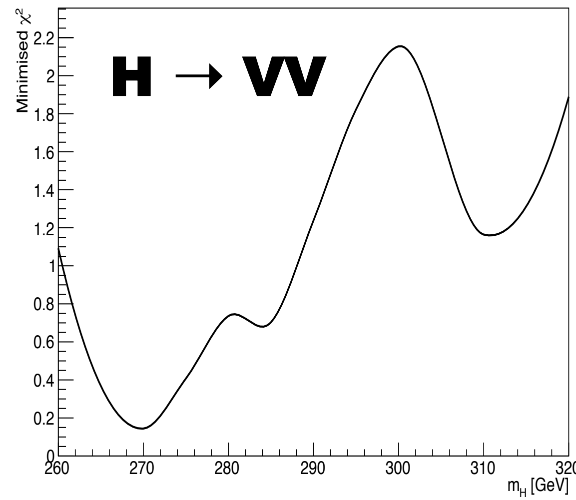
Inputs: Top associated Higgs production

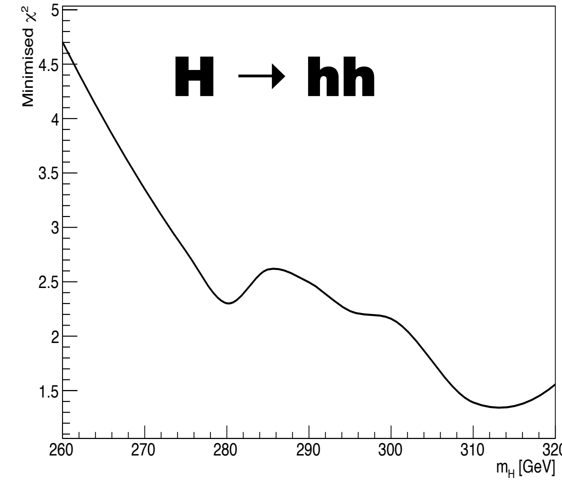


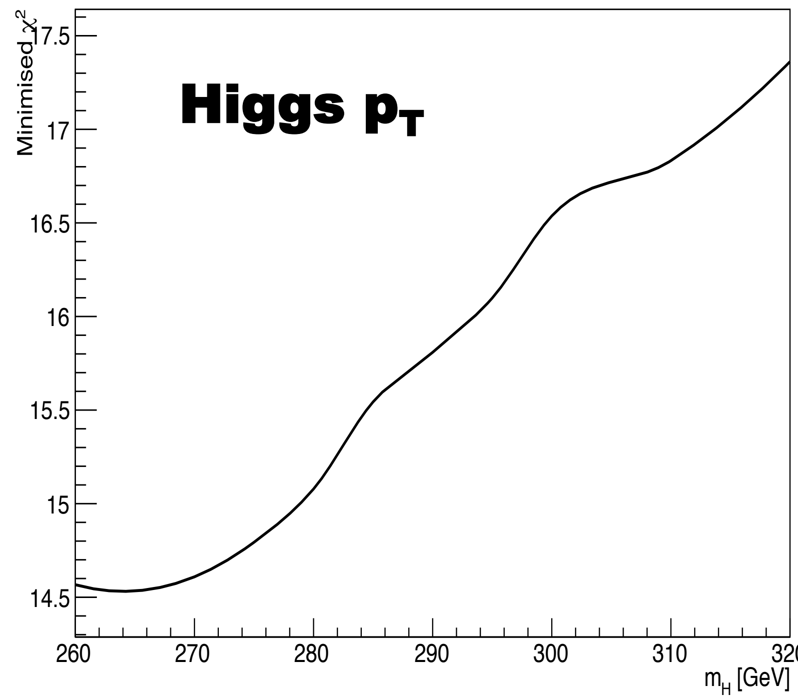


Step-by-step results

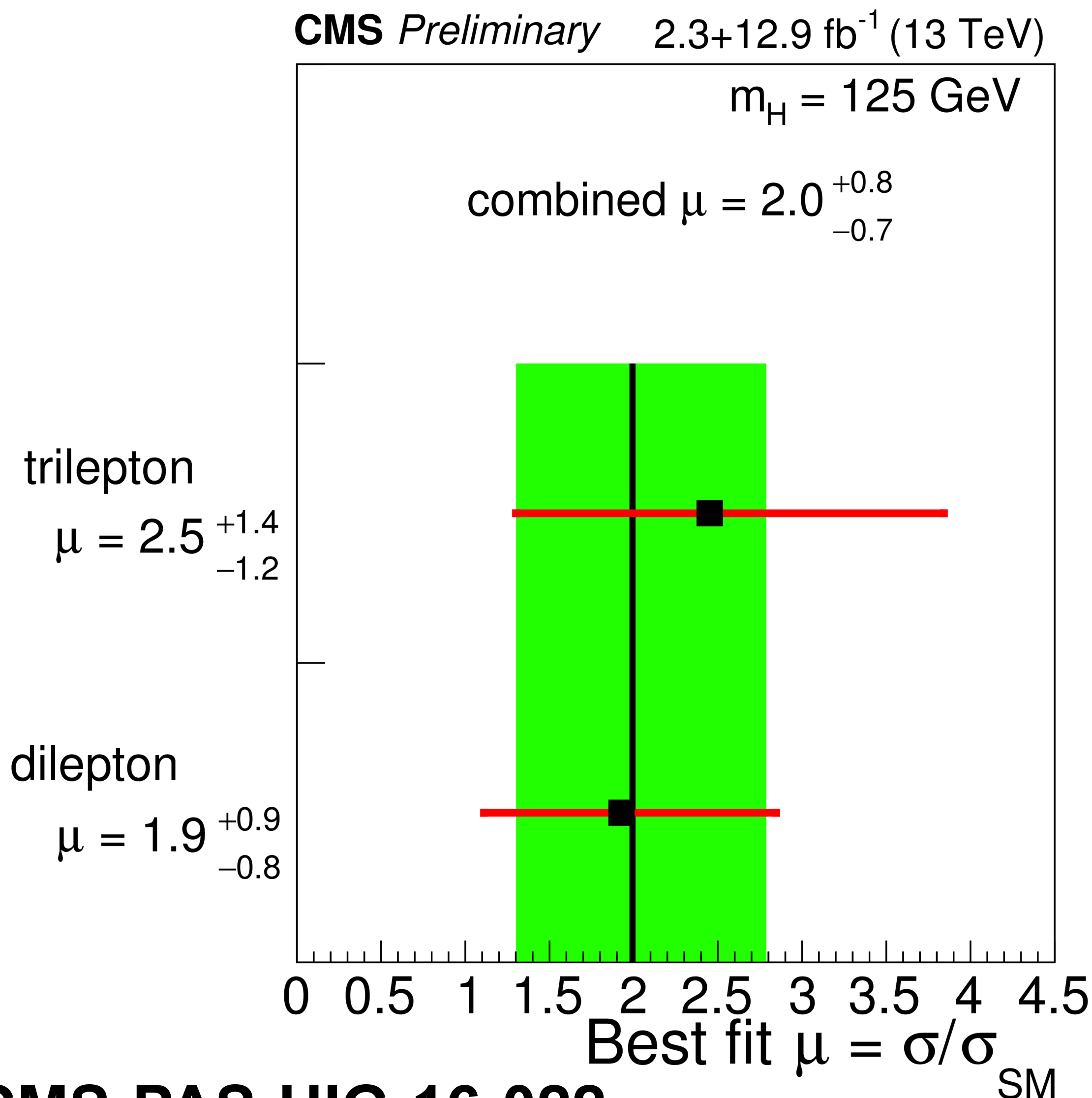
- The global χ^2 was calculated as a function of m_H and by marginalising β_g
  - p_T spectra
  - $H \rightarrow VV$ decays
  - $H \rightarrow hh$ decays
- These results are not significant on their own

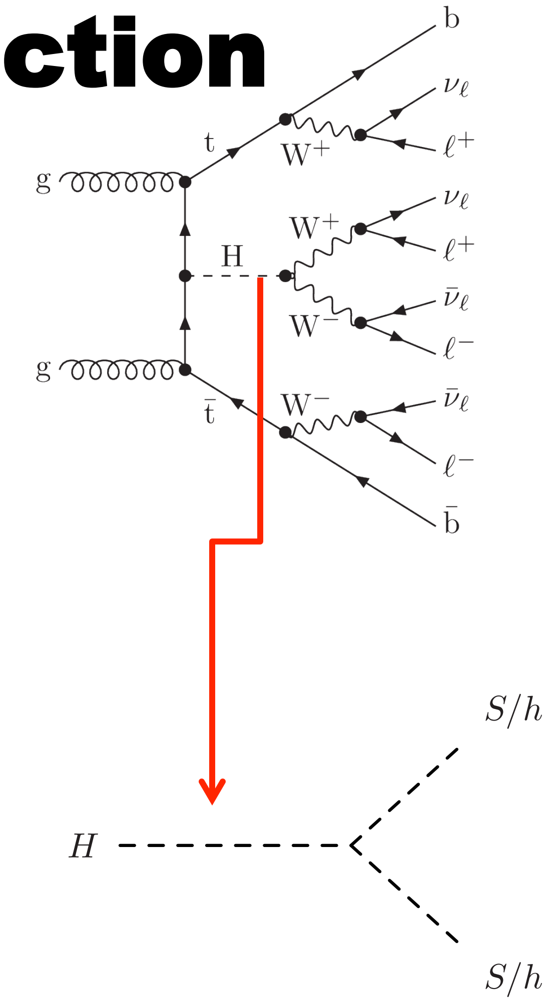






Top associated Higgs production (Run II)

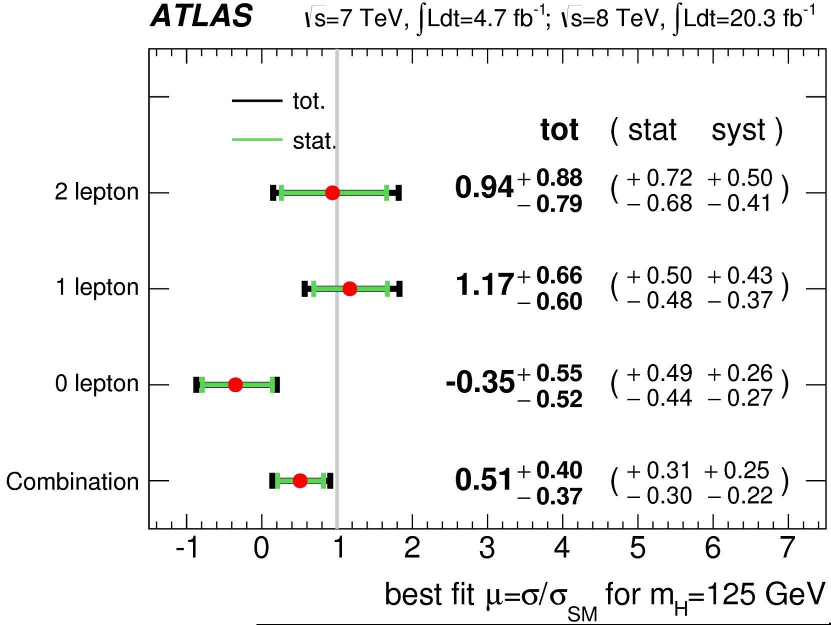


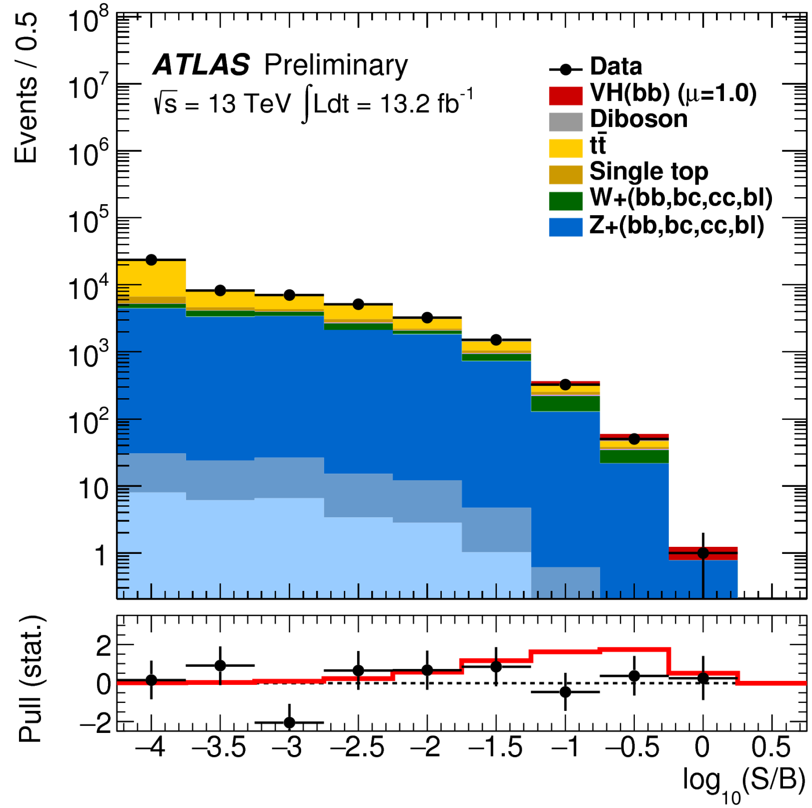


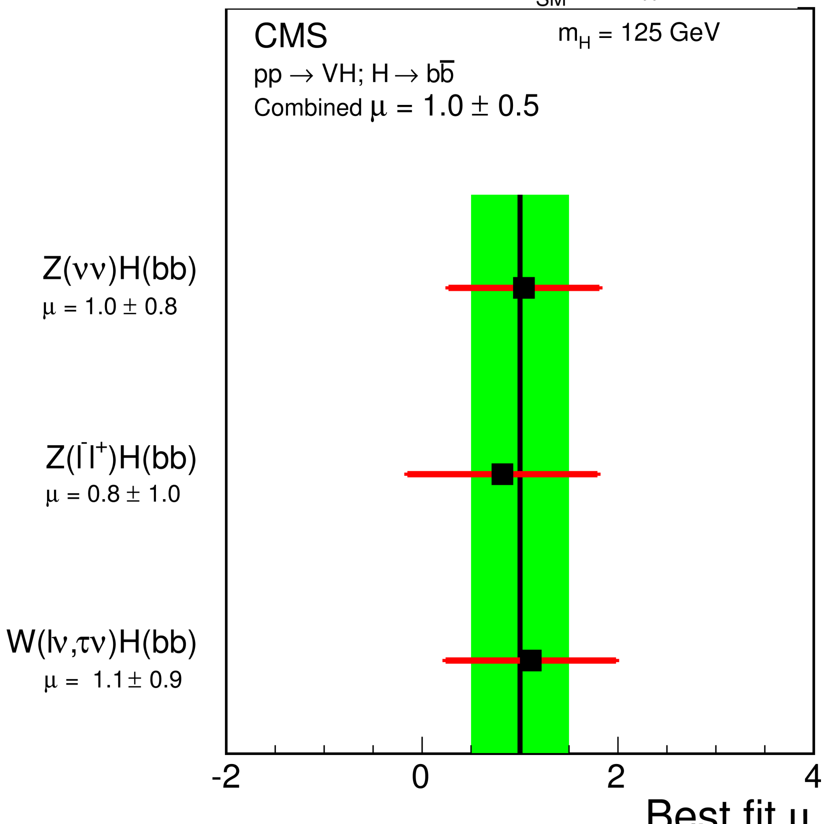
$$S, h \to WW, \tau\tau\; ZZ$$

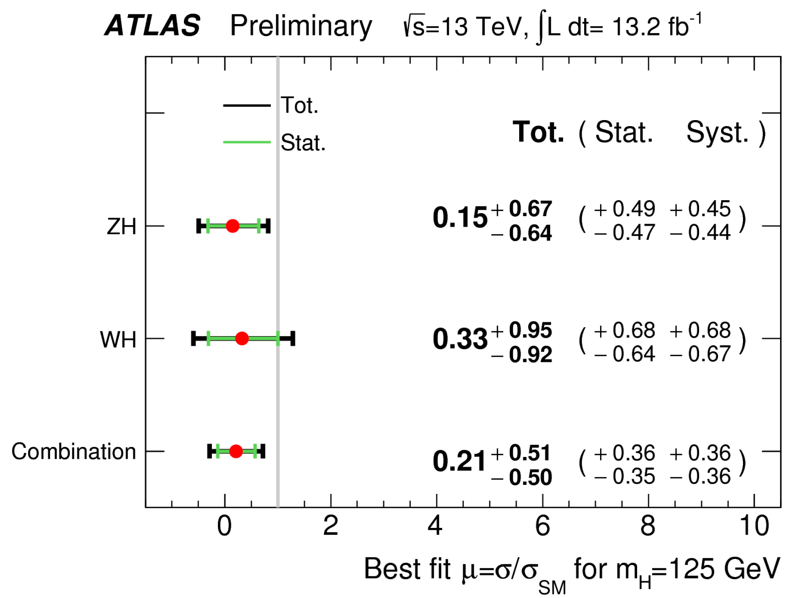
$$\to l^{\pm} l^{\pm}, 3l + X$$

CMS-PAS-HIG-16-022


ATLAS
√s=7 TeV, ∫Ldt=4.7 fb⁻¹; √s=8 TeV, ∫Ldt=20.3 fb⁻¹
tot.
stat.
tot (stat syst)
2 lepton
0.94 +0.88 −0.79 (+0.72 −0.68 +0.50 −0.41)
1 lepton
1.17 +0.66 −0.60 (+0.50 −0.48 +0.43 −0.37)
0 lepton
-0.35 +0.55 −0.52 (+0.49 −0.44 +0.26 −0.27)
Combination
0.51 +0.40 −0.37 (+0.31 −0.30 +0.25 −0.22)
best fit μ=σ/σ_SM for m_H=125 GeV


ATLAS Preliminary
√s = 13 TeV ∫Ldt = 13.2 fb⁻¹
Data
VH(bb) (μ=1.0)
Diboson
tt̄
Single top
W+(bb,bc,cc,bl)
Z+(bb,bc,cc,bl)
Events / 0.5
Pull (stat.)
log₁₀(S/B)


CMS
m_H = 125 GeV
pp → VH; H → bb̄
Combined μ = 1.0 ± 0.5
Z(νν)H(bb)
μ = 1.0 ± 0.8
Z(l⁻l⁺)H(bb)
μ = 0.8 ± 1.0
W(lν,τν)H(bb)
μ = 1.1 ± 0.9
Best fit μ


ATLAS Preliminary √s=13 TeV, ∫L dt= 13.2 fb⁻¹
Tot.
Stat.
Tot. (Stat. Syst.)
ZH
0.15 +0.67 −0.64 (+0.49 −0.47 +0.45 −0.44)
WH
0.33 +0.95 −0.92 (+0.68 −0.64 +0.68 −0.67)
Combination
0.21 +0.51 −0.50 (+0.36 −0.35 +0.36 −0.36)
Best fit μ=σ/σ_SM for m_H=125 GeV

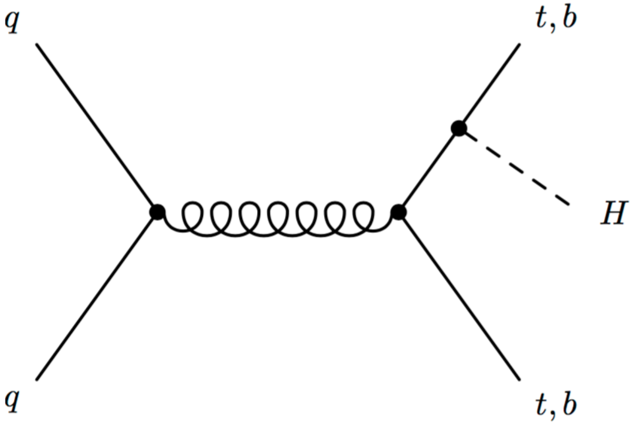
A simplified model
(cont.)

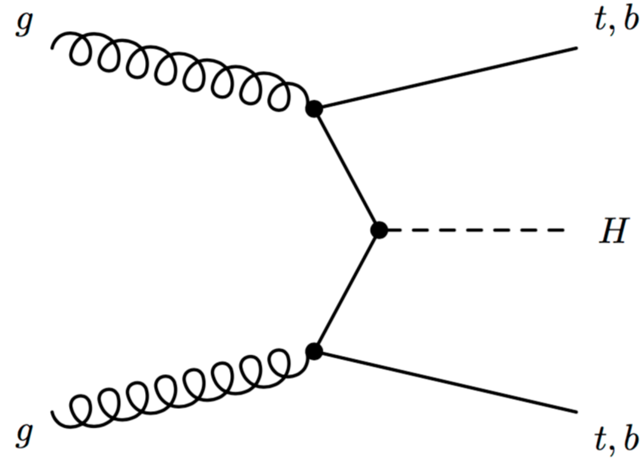
- The following parameters are considered:

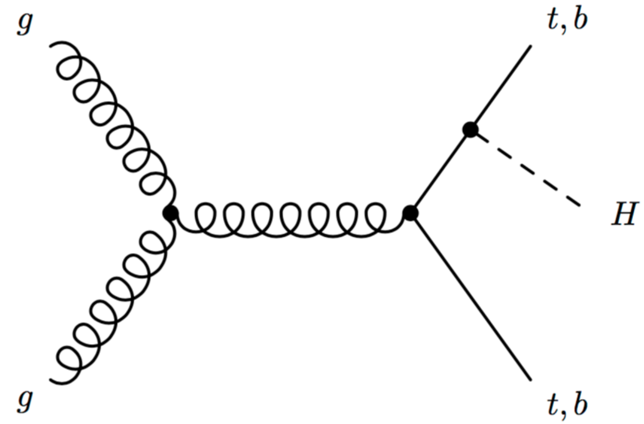
$$m_h < m_S < m_H - m_h$$

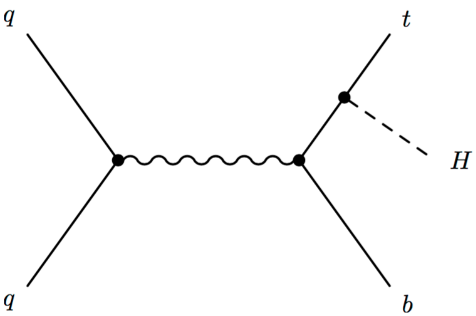
$$\frac{\Gamma(H \to SS)}{\Gamma(H \to Sh)}$$

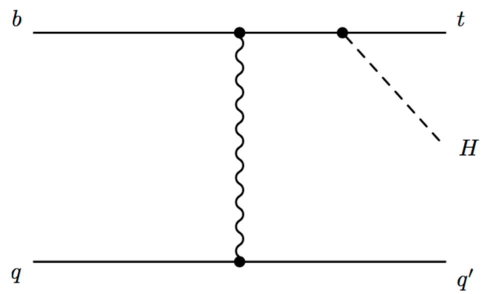
$$Br(S \to \chi\chi)$$

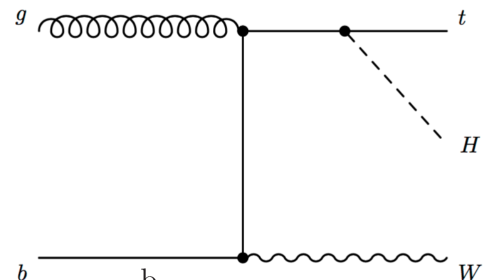

q
q
t, b
H
t, b

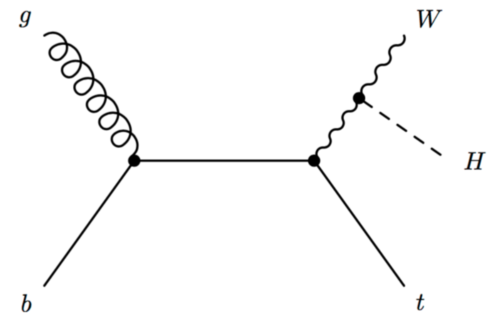

g
g
t, b
H
t, b

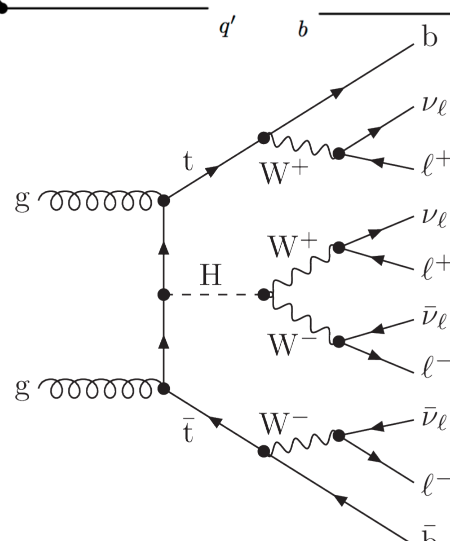

g
g
t, b
H
t, b

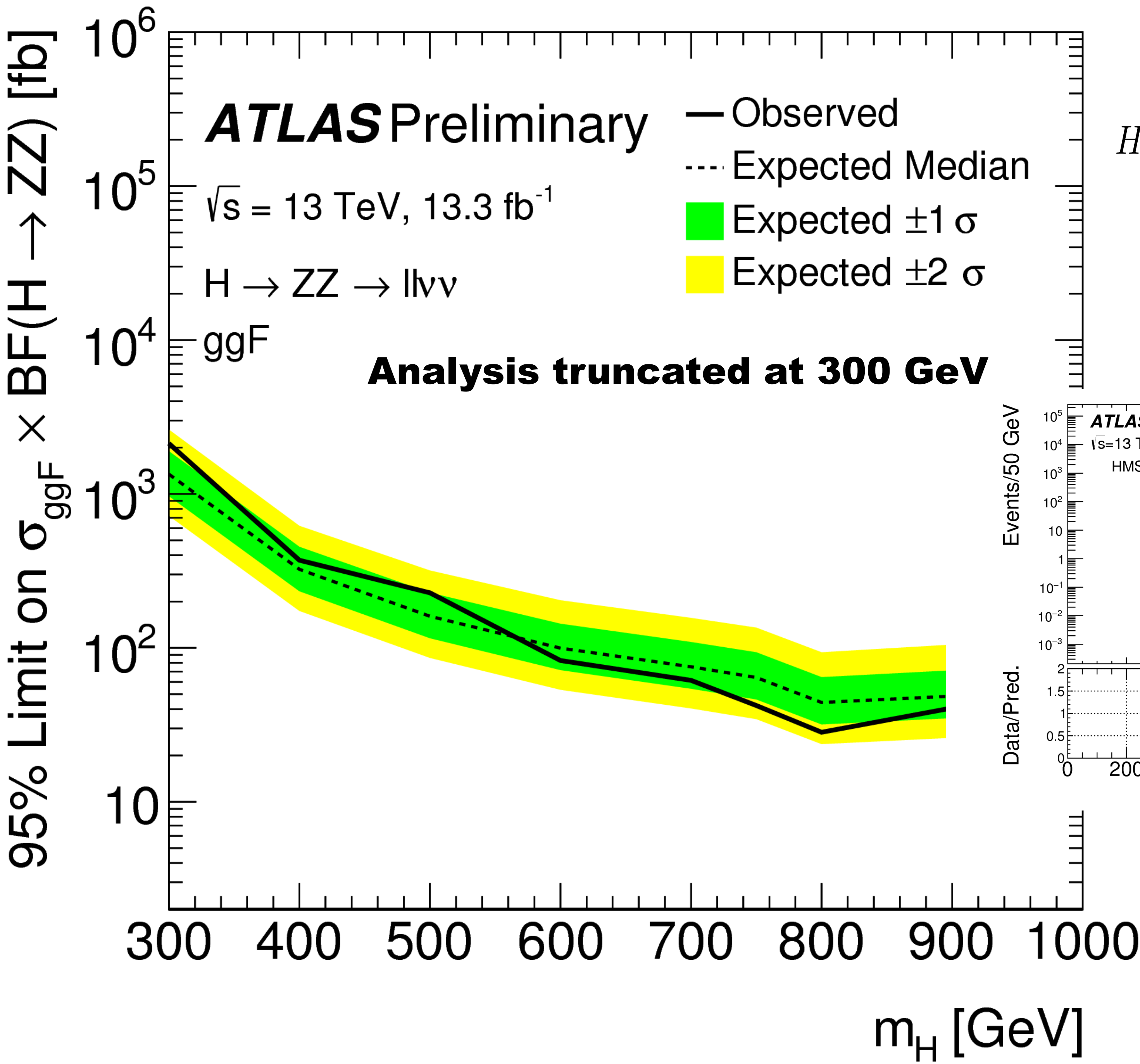

q
q
t
H
b

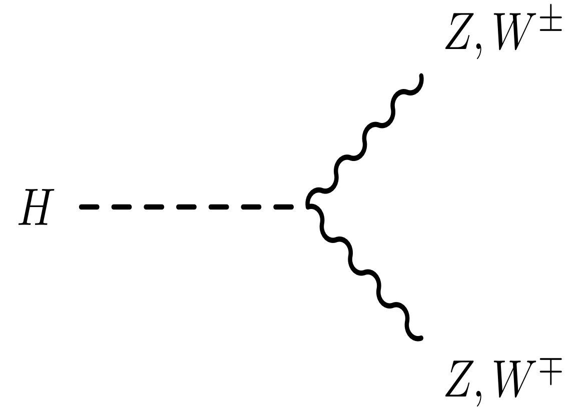

b
q
t
H
q′

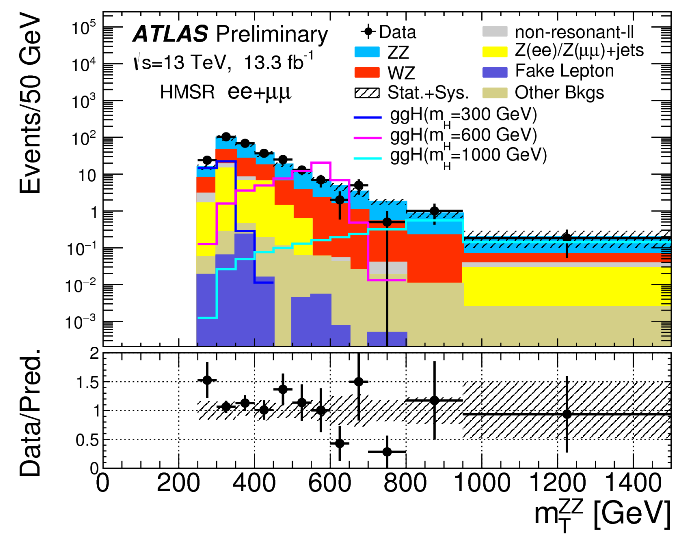

g
b
t
H
W


g
b
W
H
t


g
g
t
t̄
H
W+
W+
W−
W−
b
νℓ
ℓ+
νℓ
ℓ+
ν̄ℓ
ℓ−
ν̄ℓ
ℓ−
b̄


ATLAS Preliminary
√s = 13 TeV, 13.3 fb-1
H → ZZ → llνν
ggF
Observed
Expected Median
Expected ±1 σ
Expected ±2 σ
Analysis truncated at 300 GeV
95% Limit on σggF × BF(H → ZZ) [fb]
mH [GeV]


H
Z, W±
Z, W∓


ATLAS Preliminary
√s=13 TeV, 13.3 fb-1
HMSR ee+μμ
Data
ZZ
WZ
Stat.+Sys.
non-resonant-ll
Z(ee)/Z(μμ)+jets
Fake Lepton
Other Bkgs
ggH(mH=300 GeV)
ggH(mH=600 GeV)
ggH(mH=1000 GeV)
Events/50 GeV
Data/Pred.
mTZZ [GeV]

CMS-PAS-HIG-16-023

Search for high mass Higgs to WW with fully leptonic decays using 2015 data