Phenomenological signatures of additional scalar bosons at the LHC

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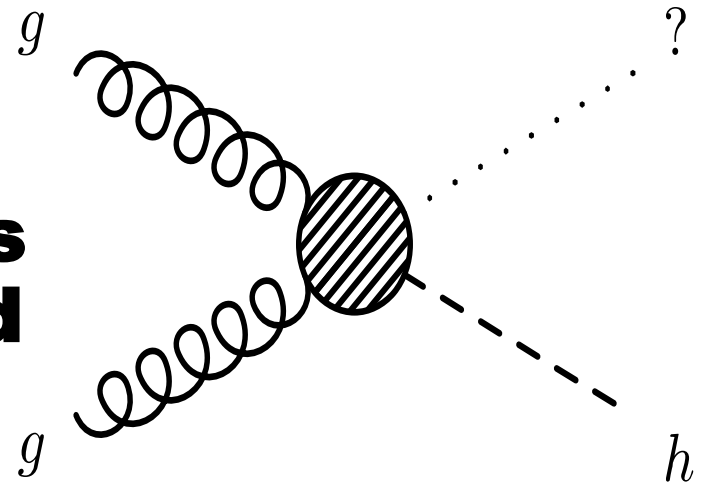
Outline

- The Effective Lagrangian
- Study with Run I data
- Formulation of the hypothesis
- Prediction of signatures at the LHC
  - Three same sign leptons
  - 4 W production

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 being also being 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

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

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

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

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

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

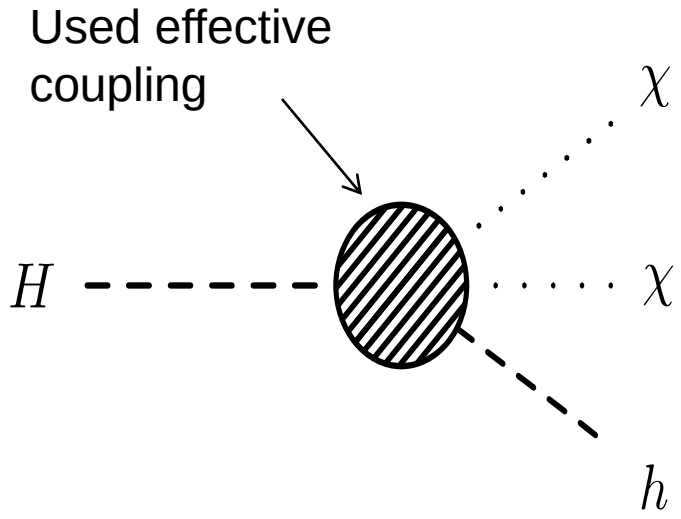
$$\mathcal{L}_{Hgg} = -\frac{1}{4}\beta_g \ \kappa_{hgg}^{SM} G_{\mu\nu} G^{\mu\nu} H$$

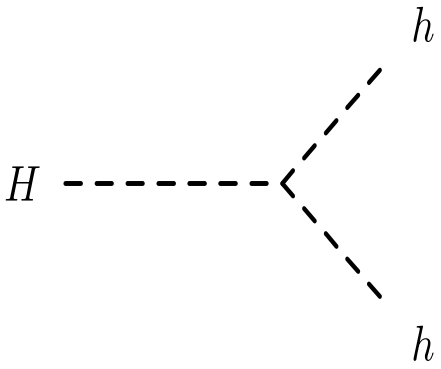
$$\mathcal{L}_{HVV} = \frac{2M_W^2}{v}\beta_W \ W_\mu W^\mu H + \frac{M_Z^2}{v}\beta_Z \ Z_\mu Z^\mu H$$

Main decay modes of *H*

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

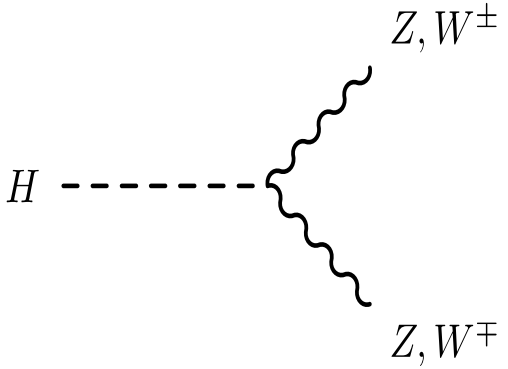
- DM is assumed scalar for simplicity
- This was our strategy, but we can infer different physics in the blob



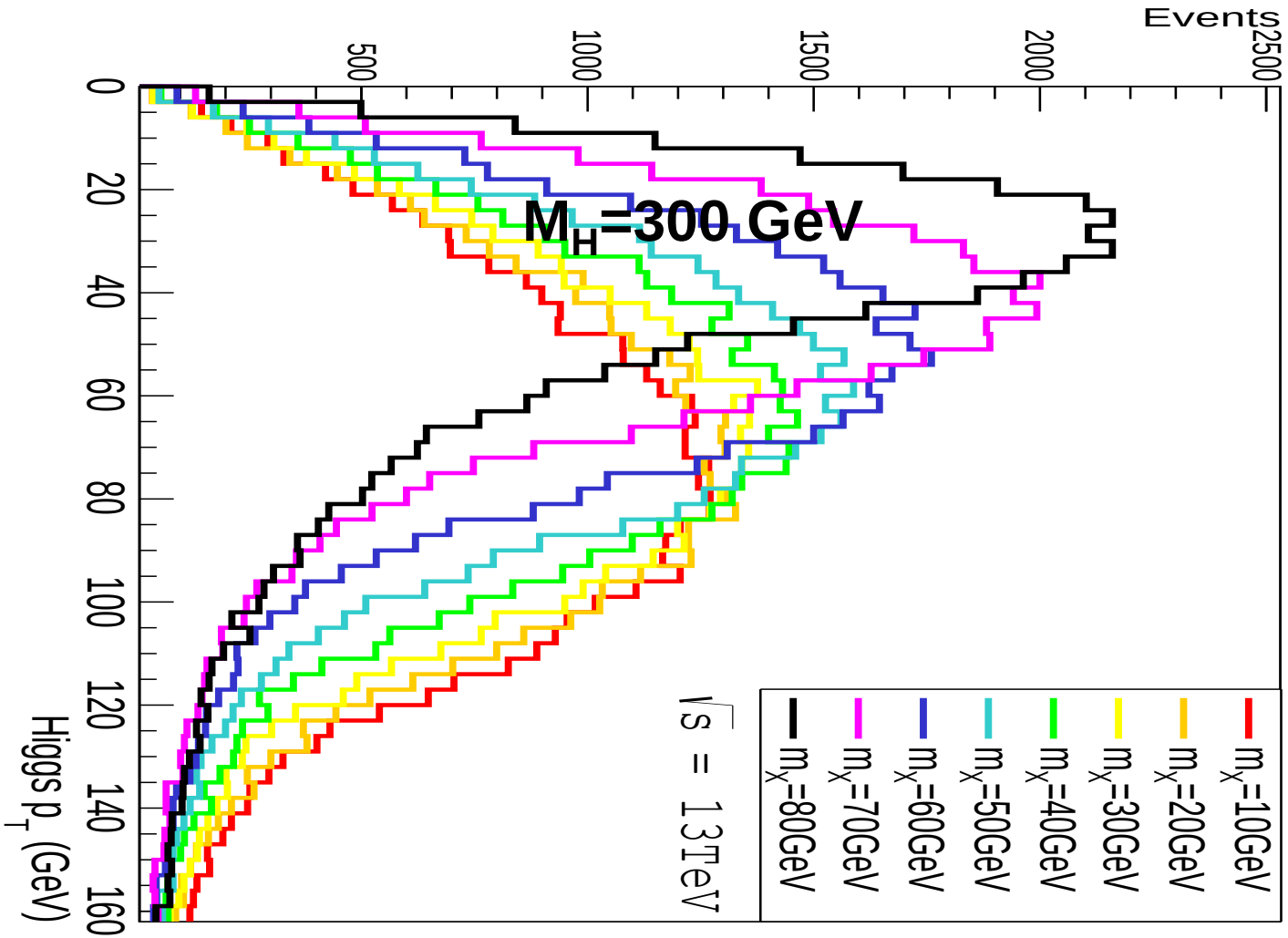


Decay to double Higgs pair.

Decay to vector boson pairs.



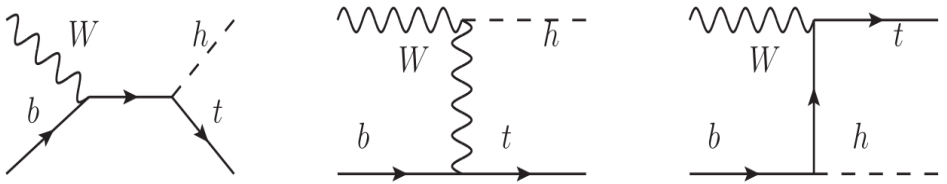
Higgs boson p_T Spectra



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 $\sigma_{th} \ll \sigma_{tth}$**

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



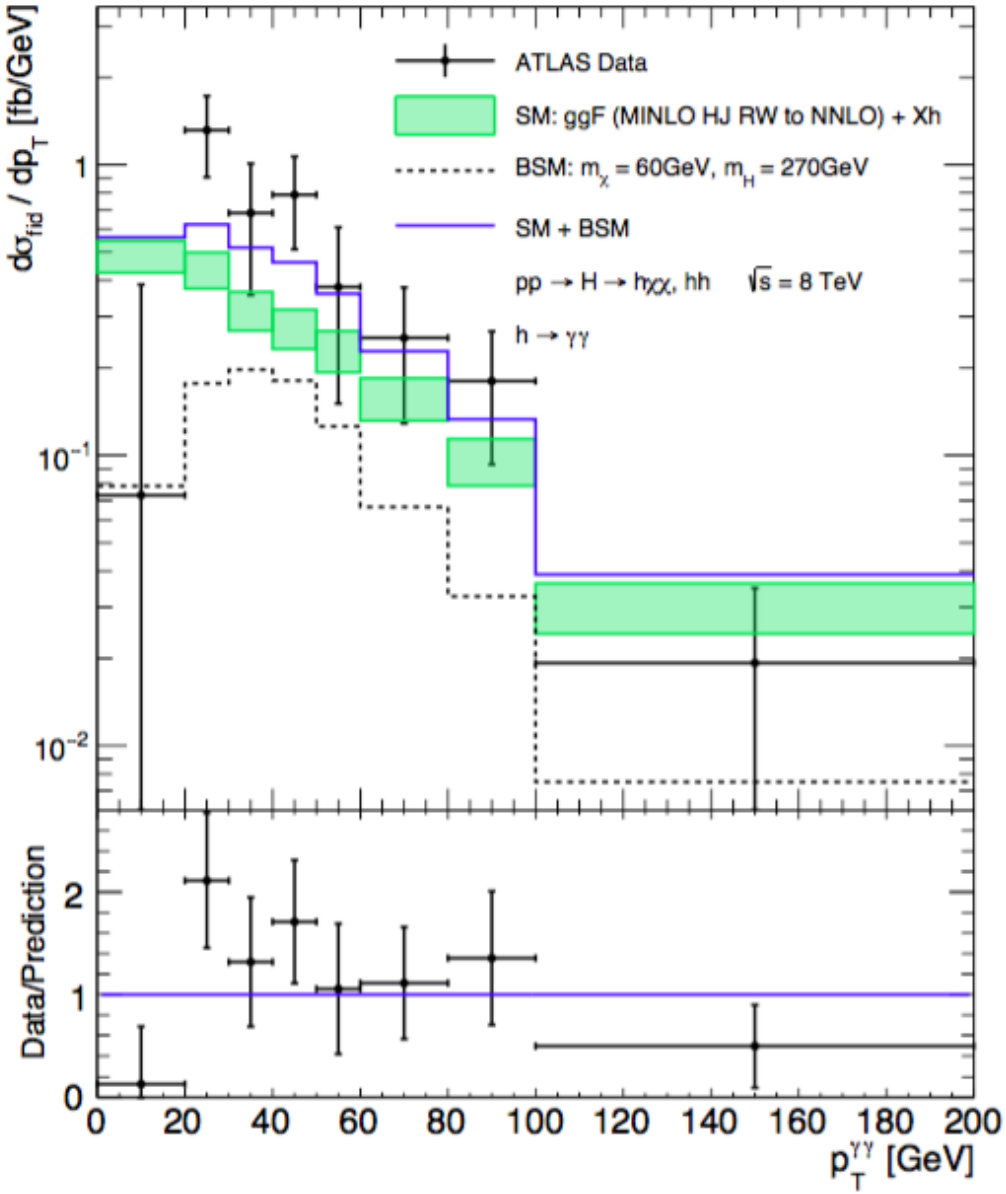
- **For the heavy scalar considered here, $c_V \ll c_F$**
- **We expect a sizeable cross section to come from top associated heavy scalar production ($\sigma_{tH} \simeq \sigma_{ttH}$)**

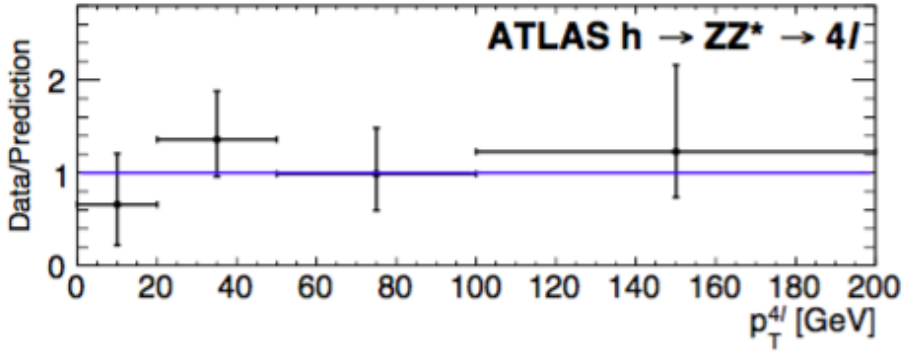
M. Farina, C. Grojean, F. Maltoni, E. Salvioni and A. Thamm, JHEP **1305**, 022 (2013).

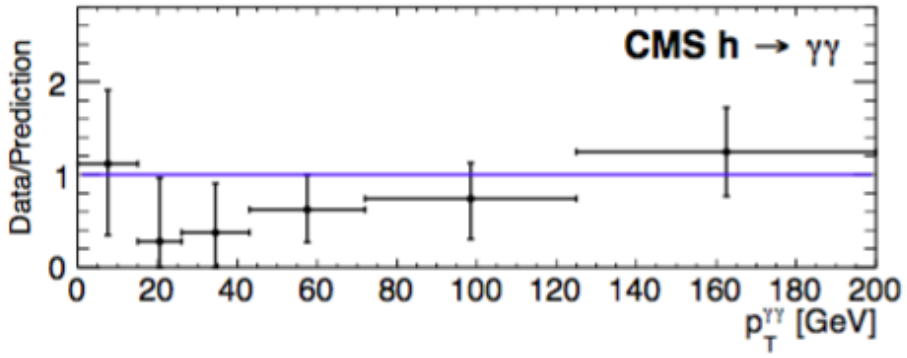
Results incorporated in the fit

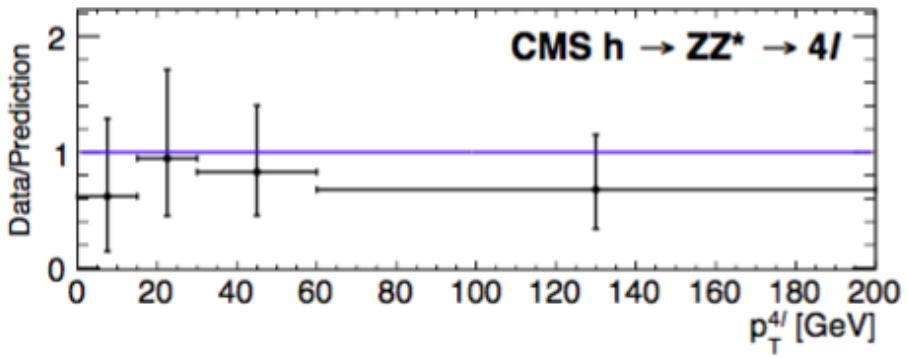
Four groups of final states received consideration

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







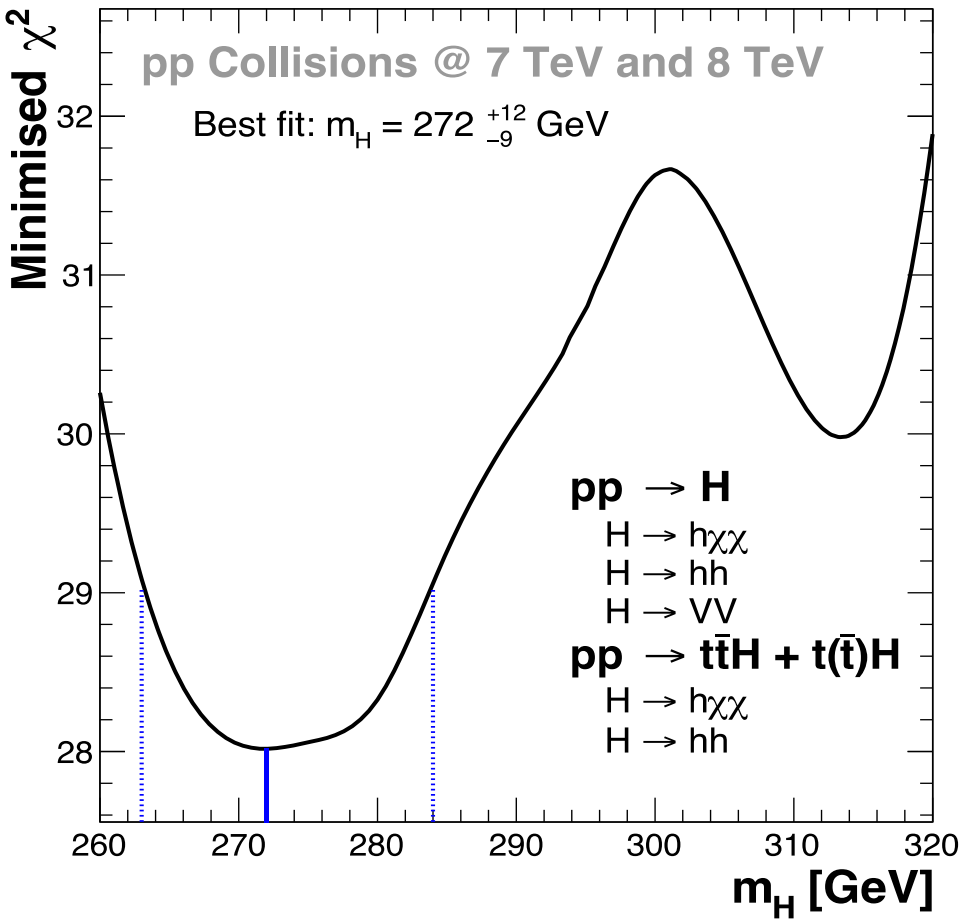


Satisfactory goodness of the global fit, including Higgs p_T

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:**

$$\beta_g = 1.5 \pm 0.6$$

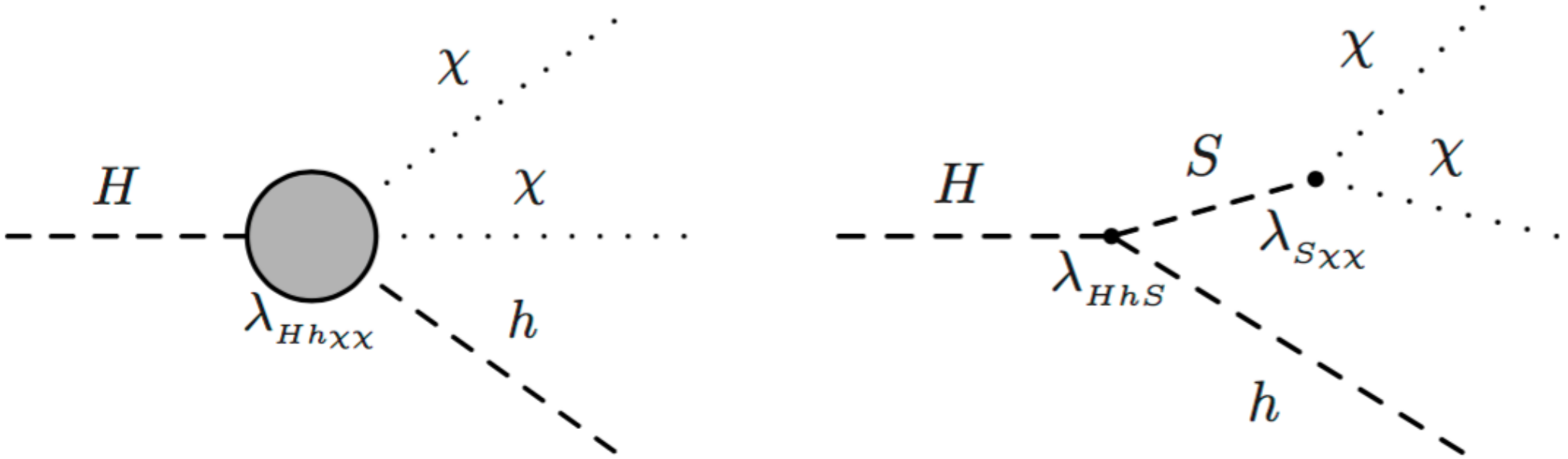


arXiv:1506.00612
arXiv:1603.01208
arXiv:1606.01674

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:**

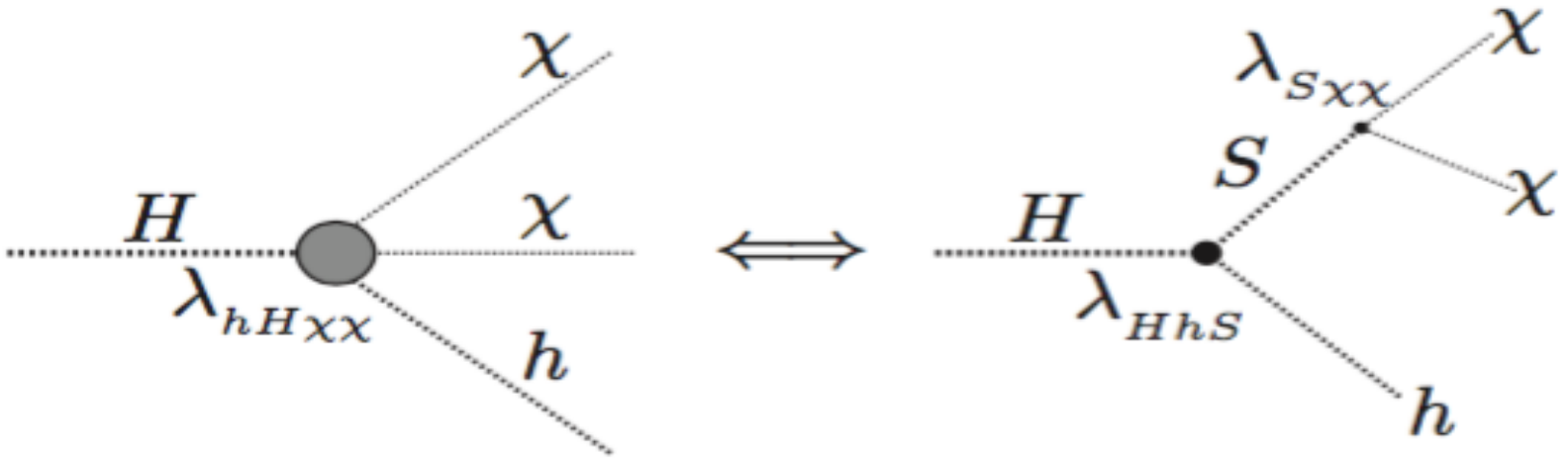


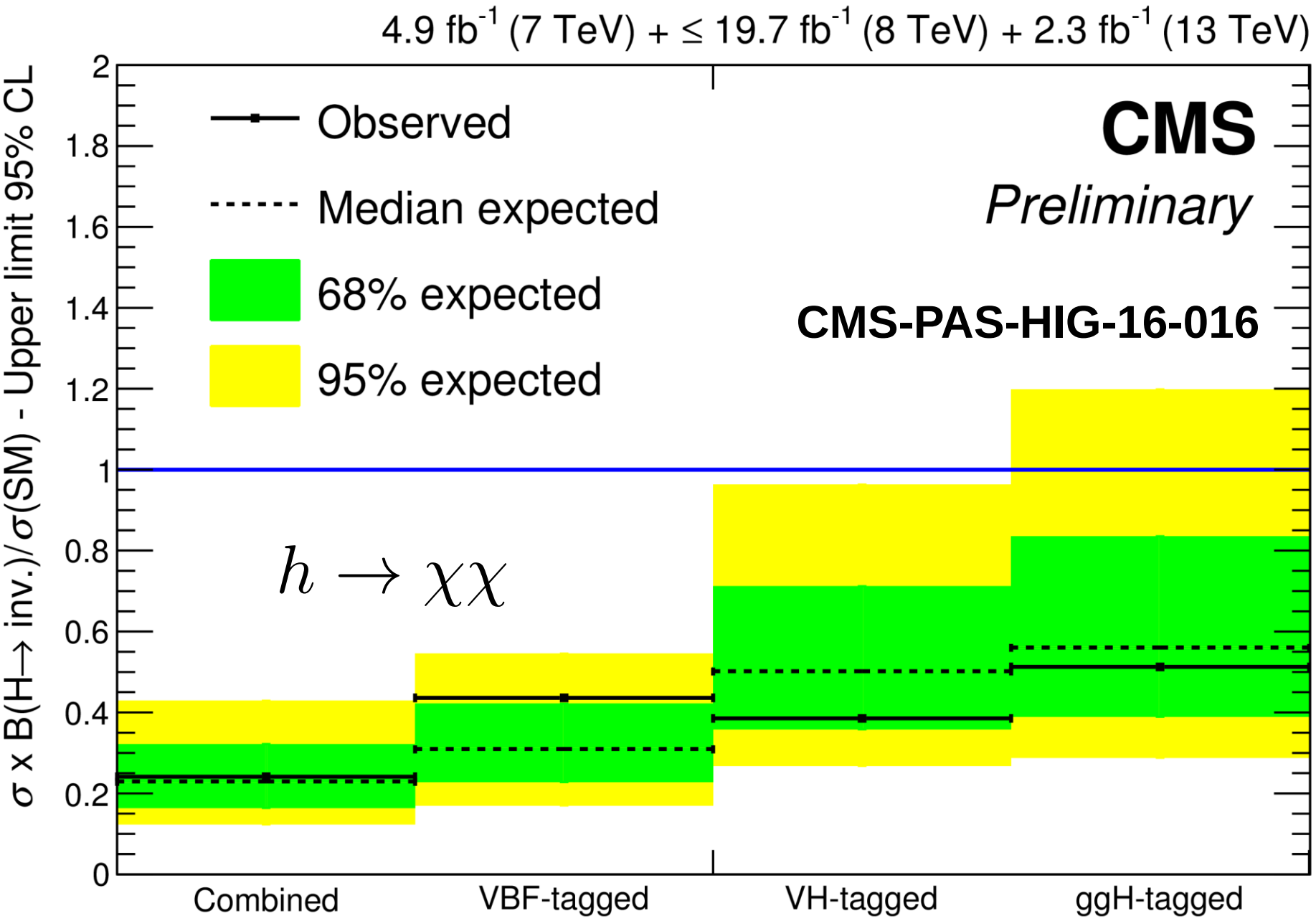
The intermediate scalar, S

- **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**





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

The Lagrangian

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

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

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

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

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

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

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**

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

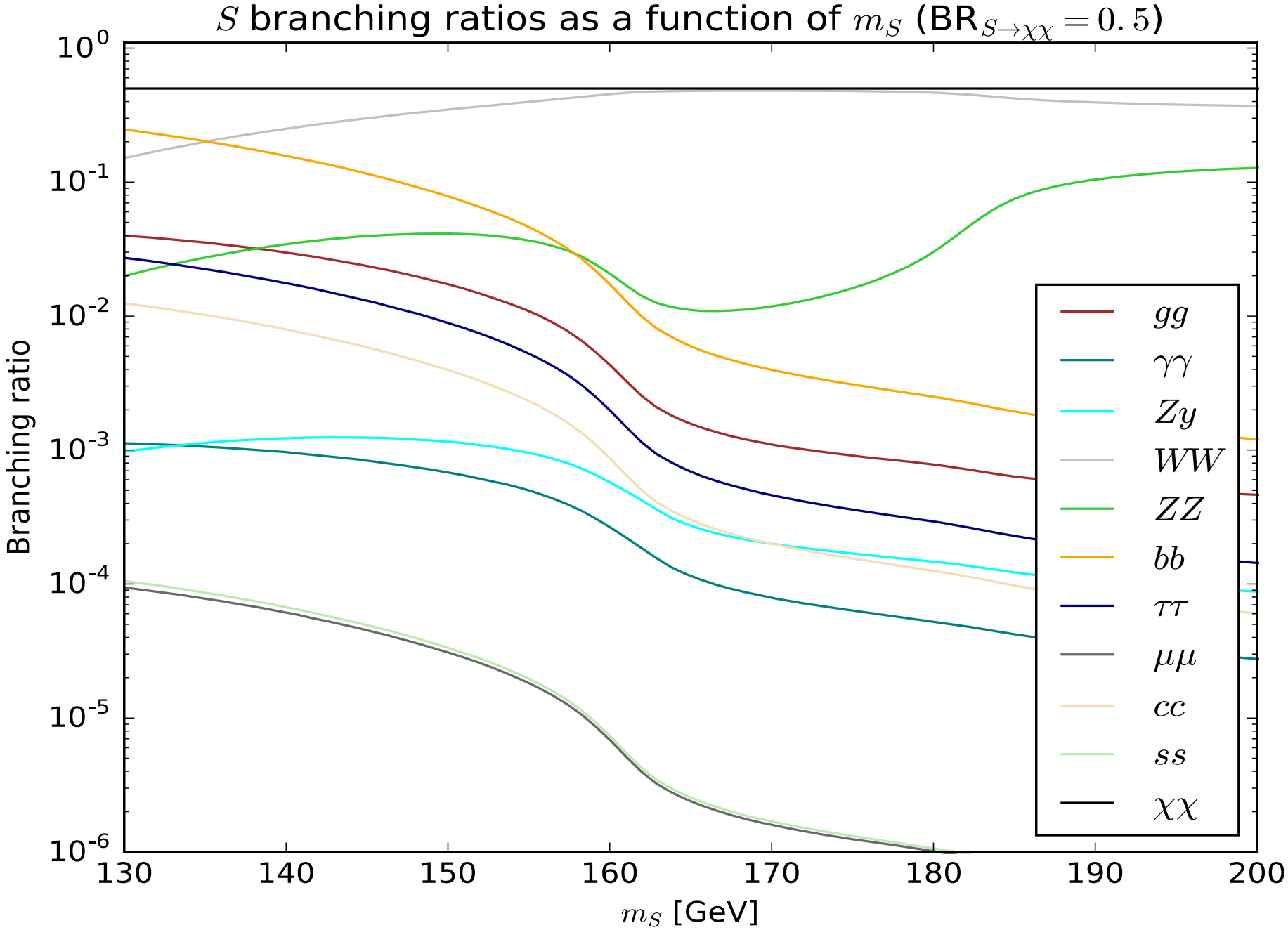
$$+ \quad H \to SS, Sh, hh$$

Dominant decays

Diboson decay

$$H \to h(+X), S(+X)$$

In a simplified model treat S as Higgs-like



A simplified model
(cont.)

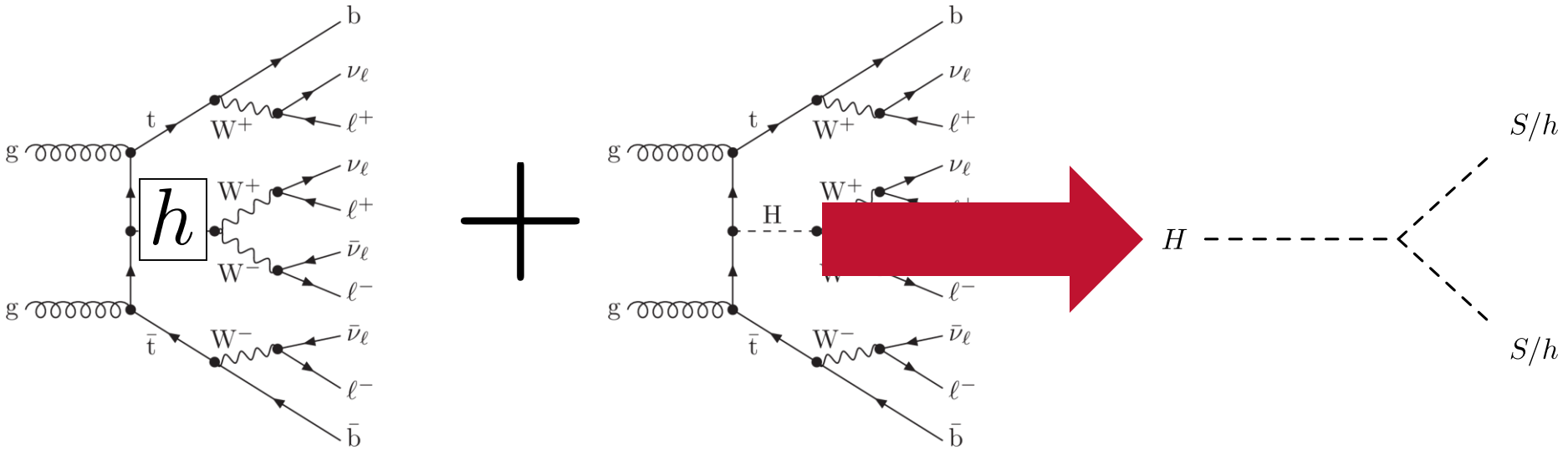
- **The following parameters are considered:**

$$m_h < m_S < m_H - m_h$$

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

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

Top associated Higgs production



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

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

“The philosophers have only interpreted the world, in various ways; the point is to change it”

The prediction of signatures at the LHC

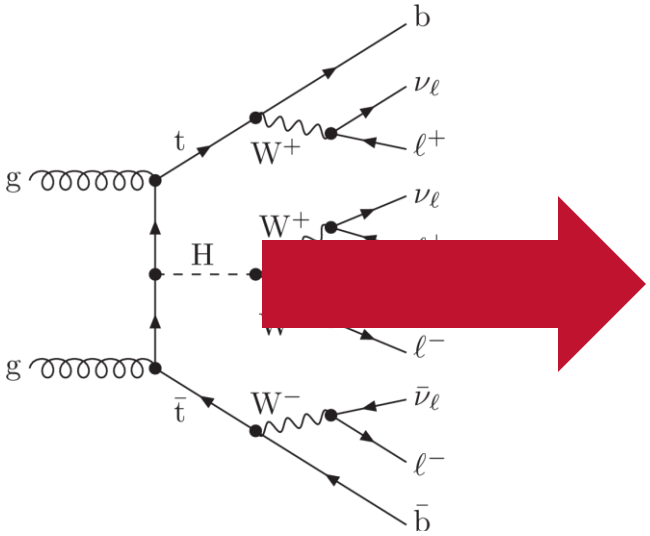
arXiv:1603.01208
arXiv:1606.01674

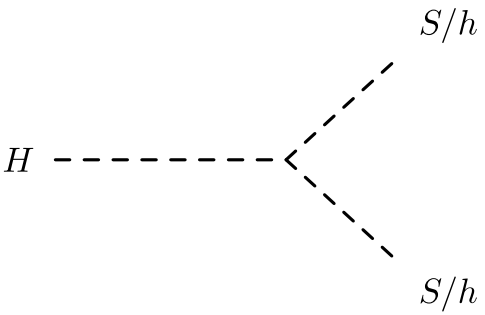
The hypothesis leads to rich phenomenology

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

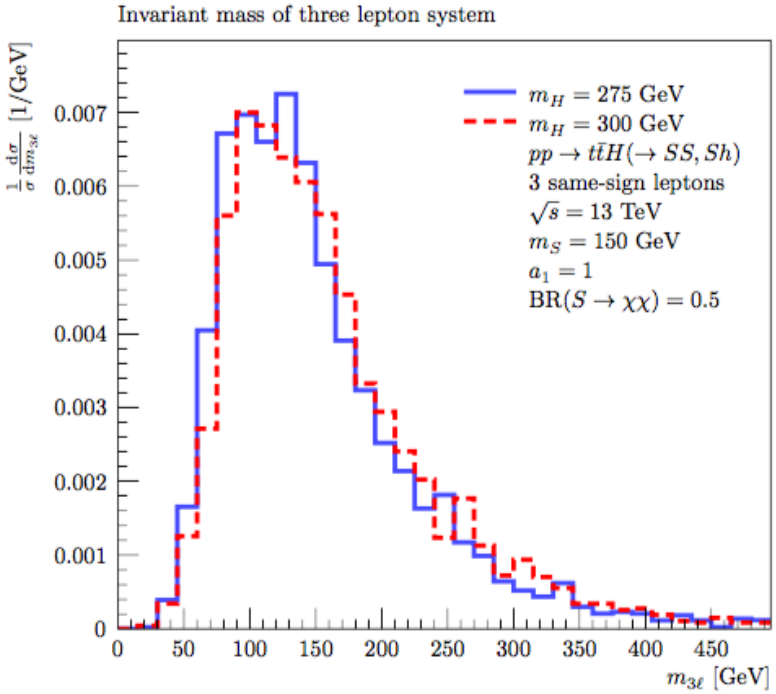
Production of three same sign leptons

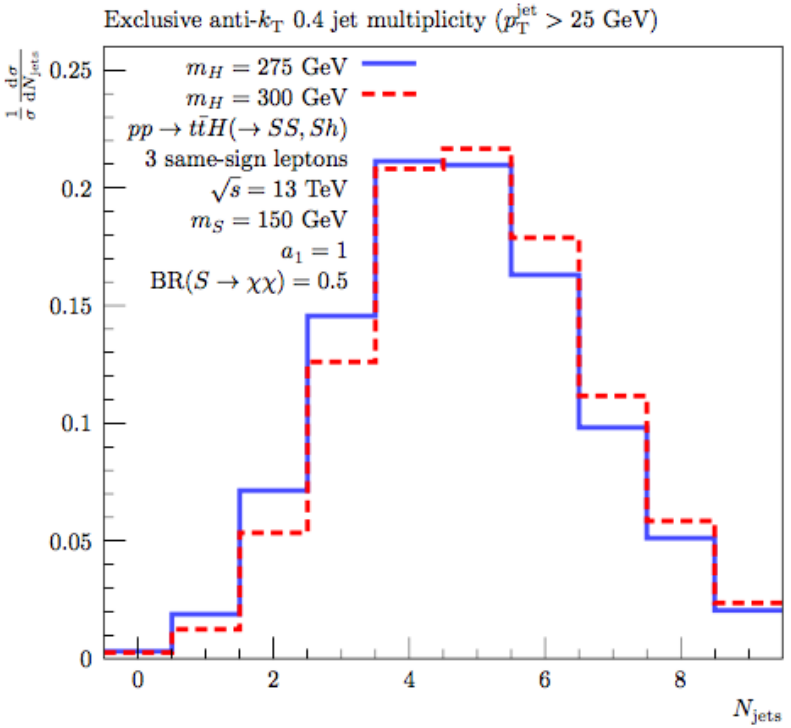




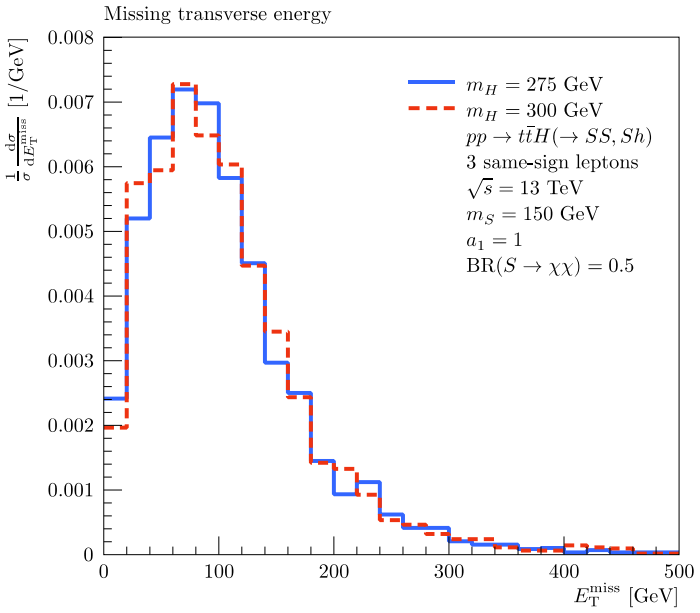
$$t(t)H \rightarrow 6W + X$$

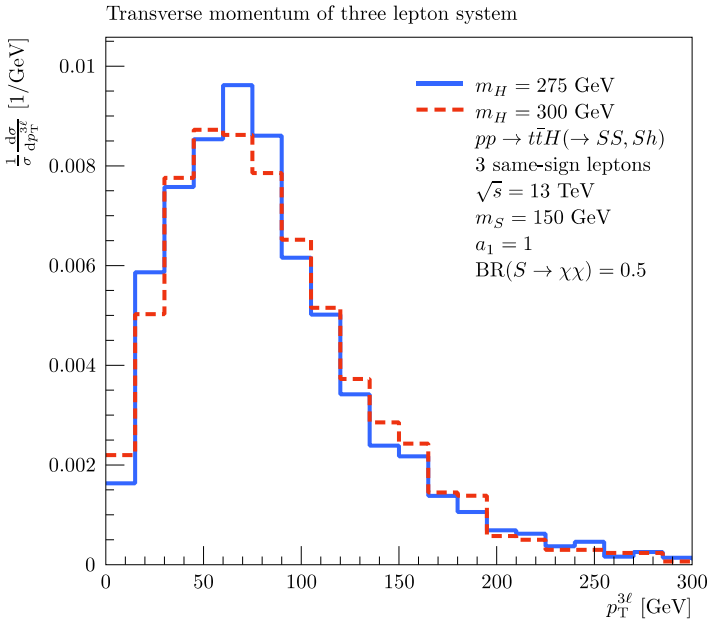
$$\rightarrow l^{\pm}l^{\pm}l^{\pm} + X$$

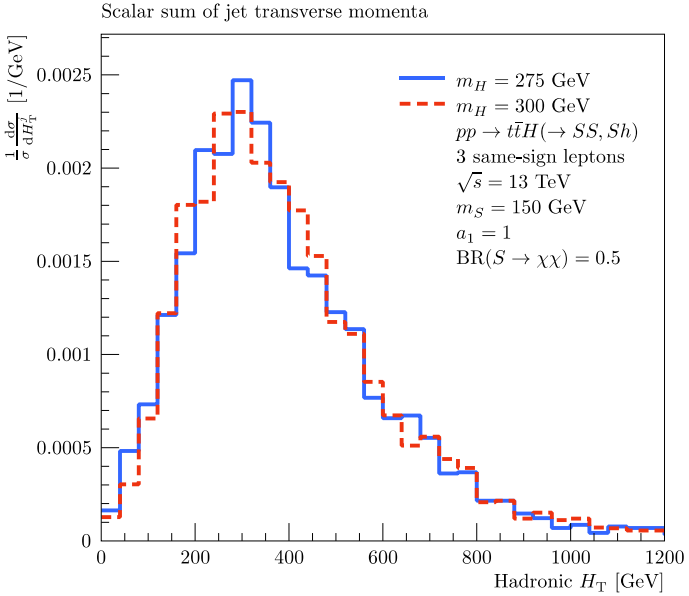


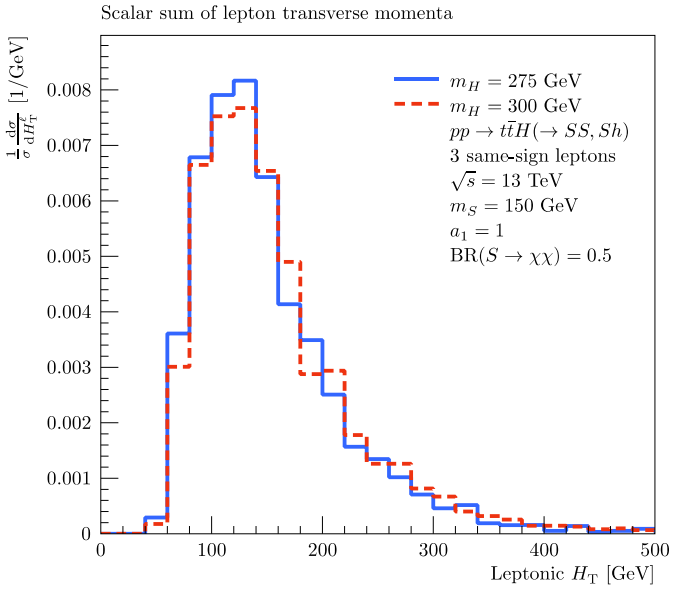


Production of three same sign leptons

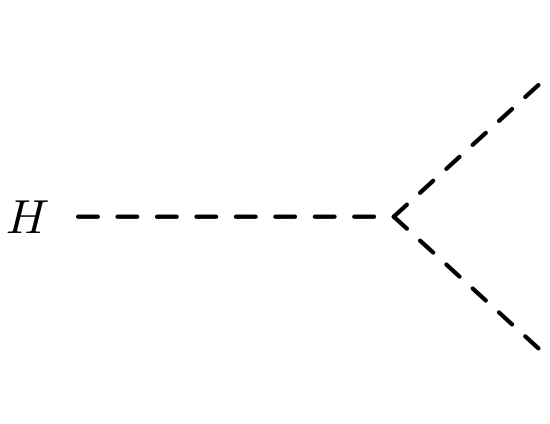








Production of 4 isolated leptons
Coming predominantly from production of 4W

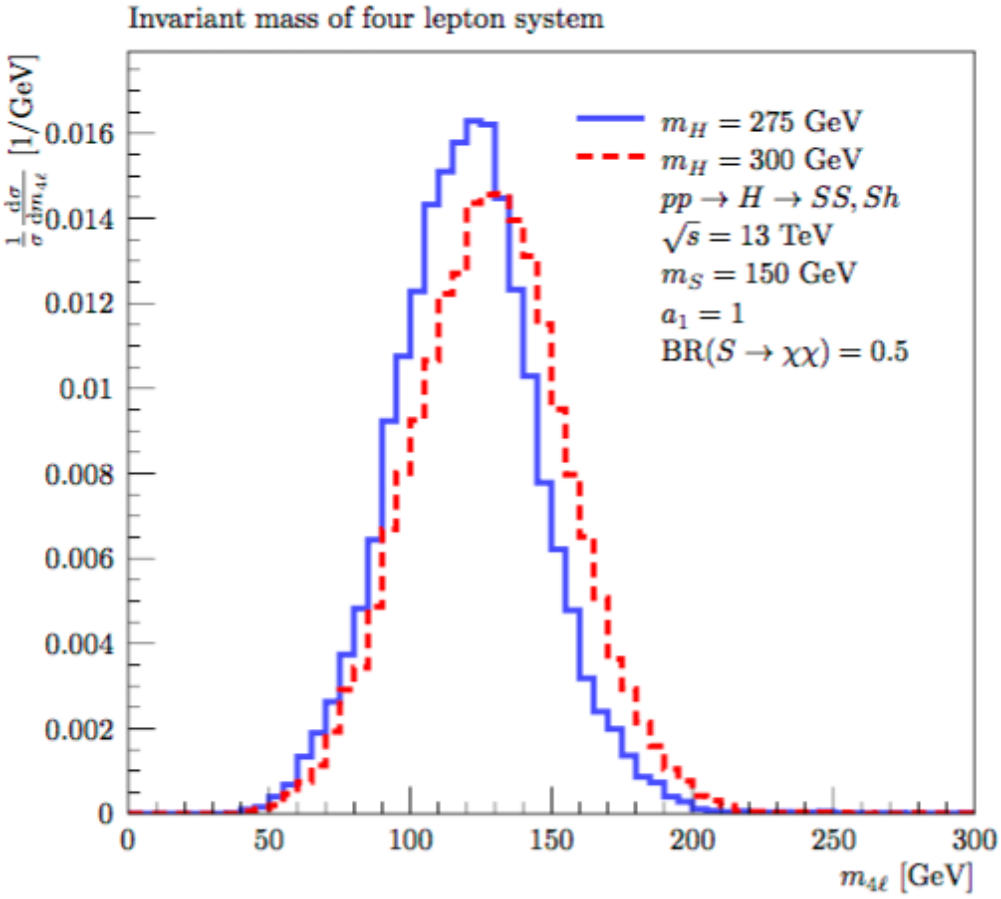


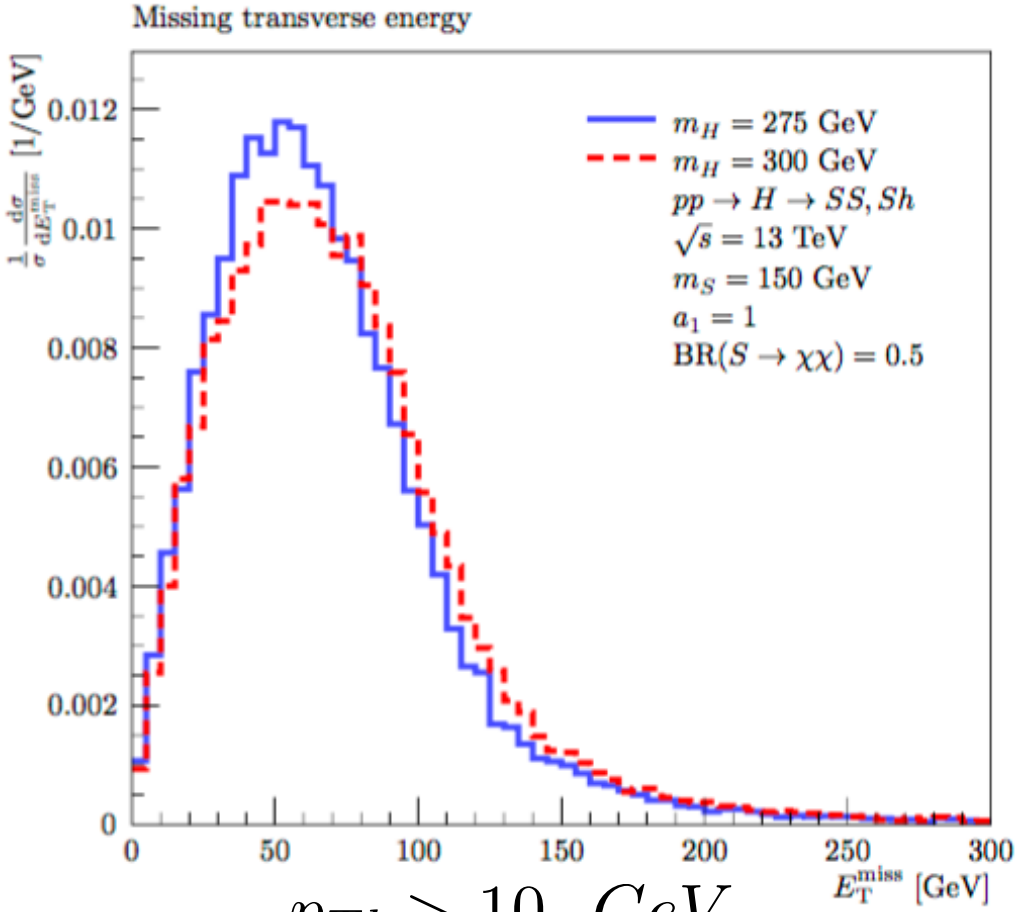
$$S, h \to WWWW, WWZZ, ZZ$$
$$\to 4l + X$$

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



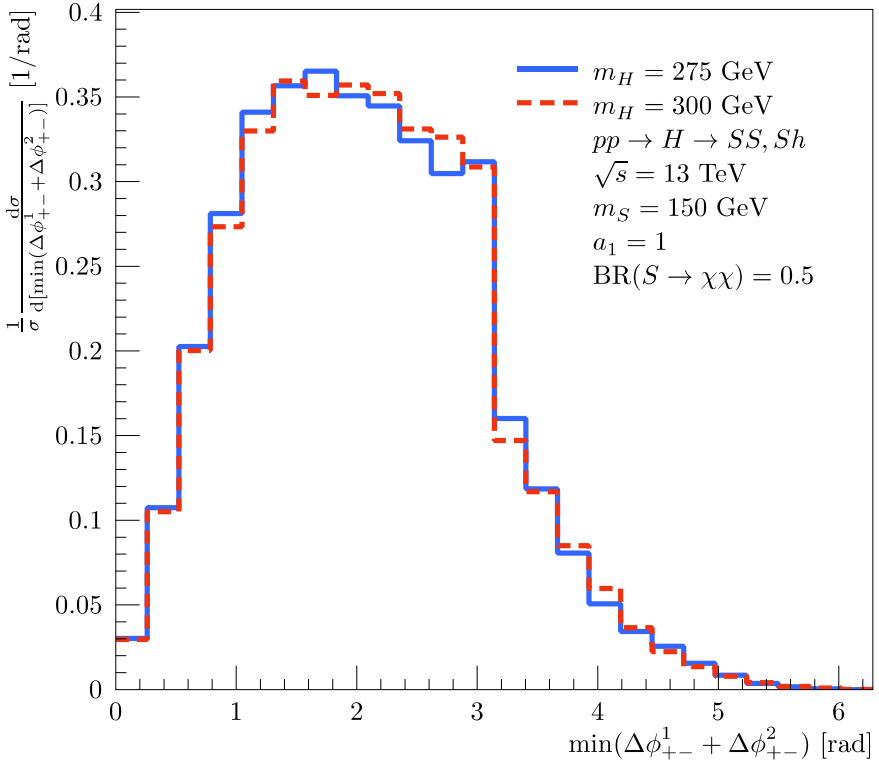


$p_{Tl} > 10 \;\; GeV$

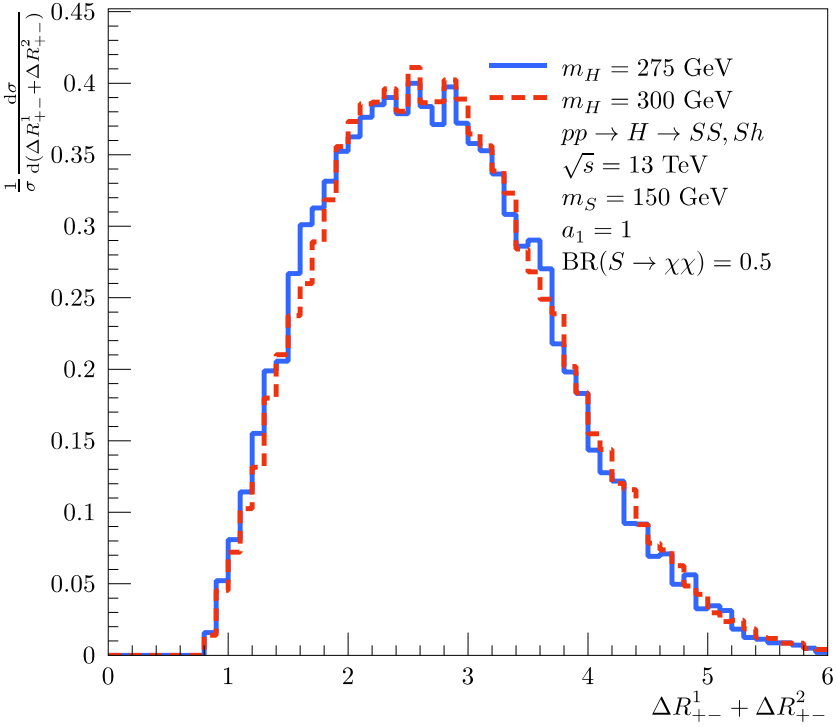
$|\eta_l| < 2.5$

Predict ~1.5 fb of fiducial cross-section

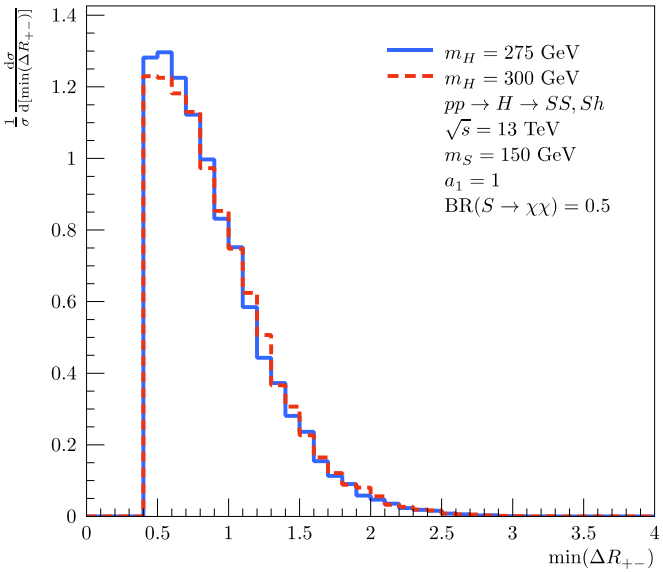
Minimised sum of combinatoric opposite sign lepton $\Delta\phi$



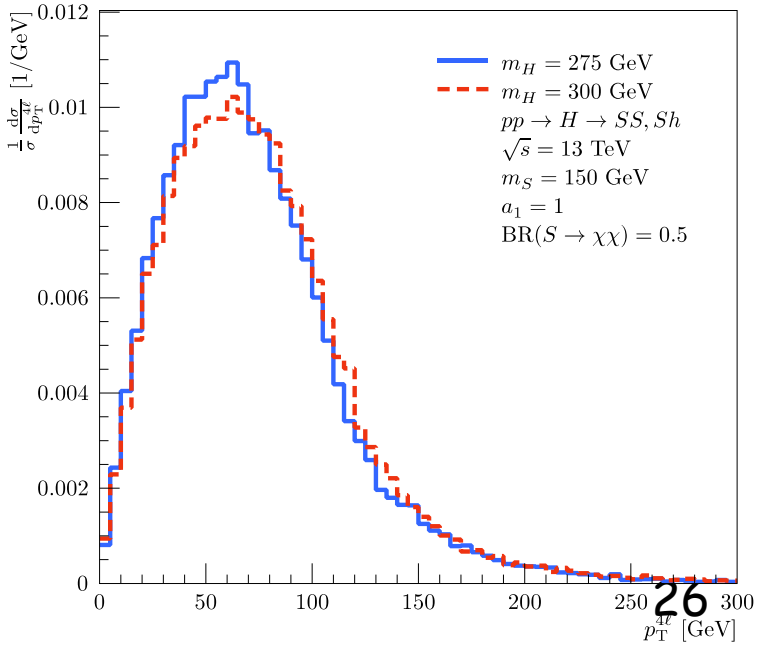
Sum of ΔR of $\Delta\phi$ matched lepton pairs



Minimised ΔR of opposite sign lepton pairs



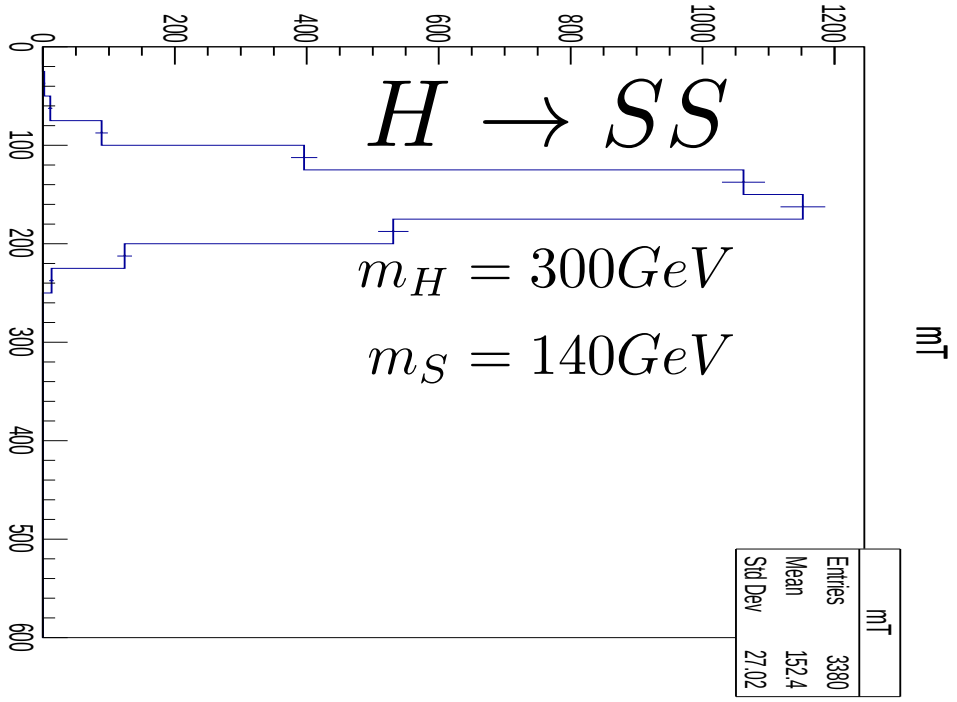
Transverse momentum of four lepton system

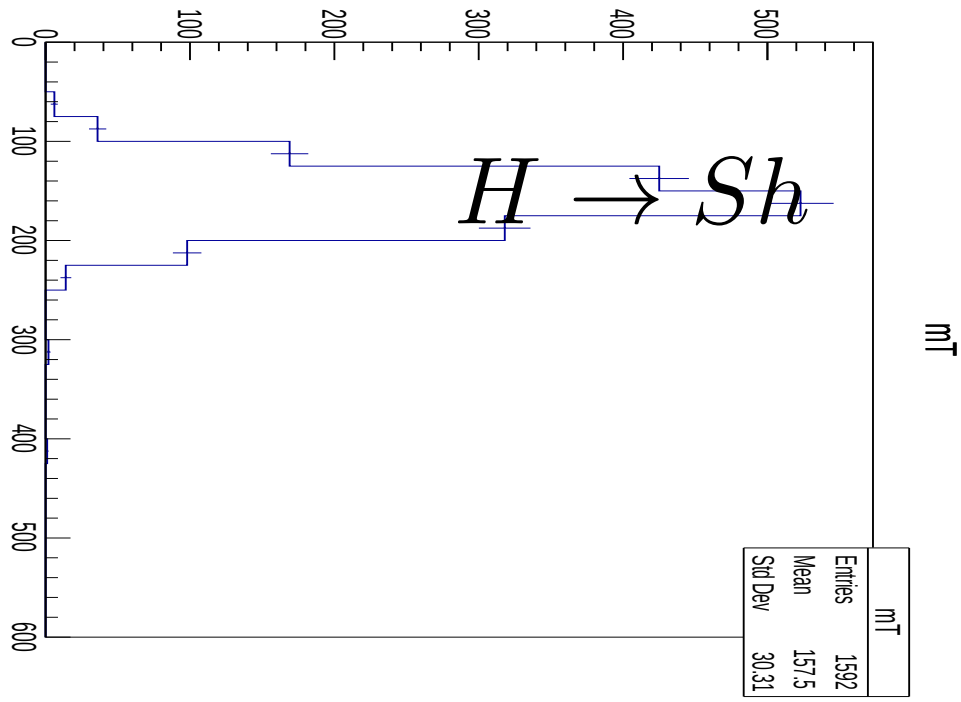


It is very important to check if the production of 3 leptons, as predicted by the model is not excluded by the existing data. Below is the transverse mass (parton level, no detector smearing applied) after the application of requirements of leptons outlined in ATLAS-CONF-2016-043

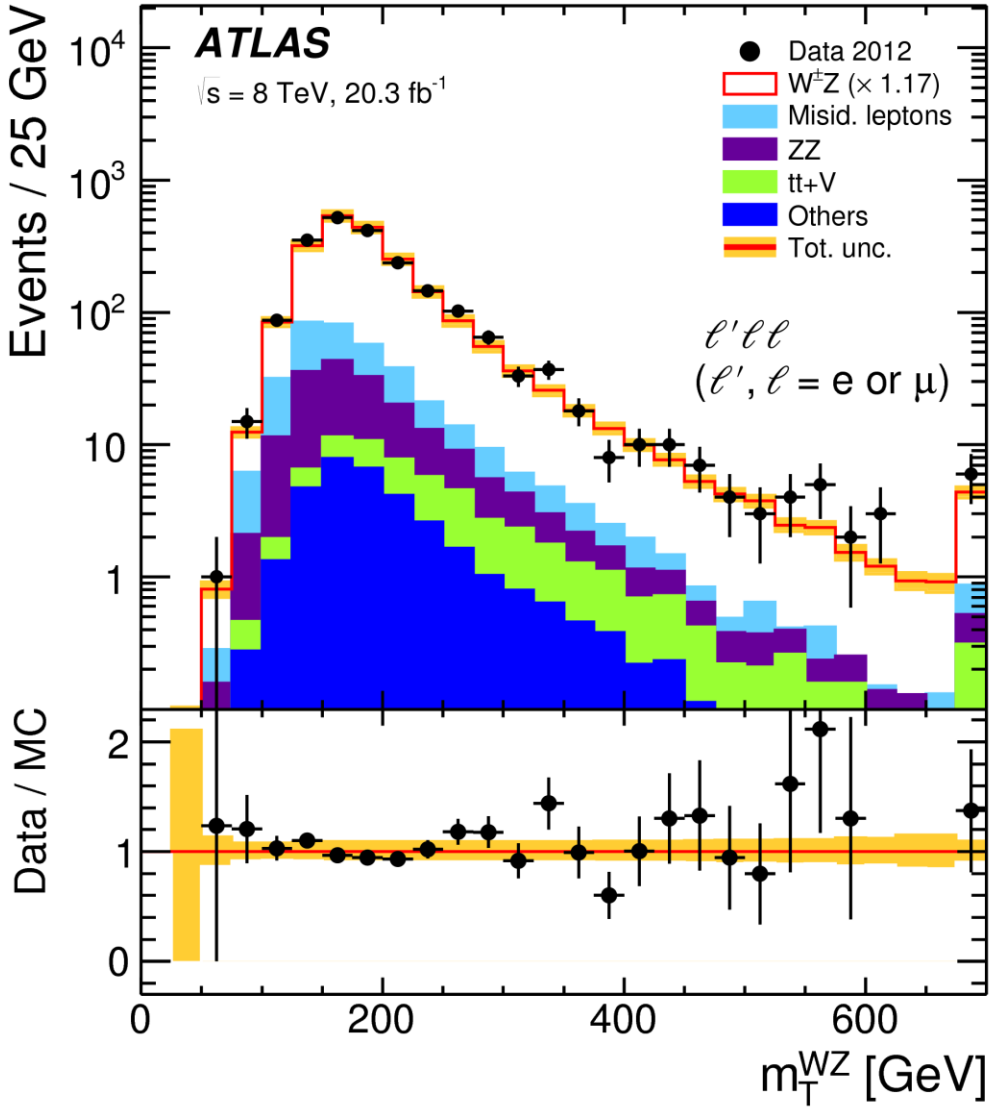
$$m_{\mathrm{T}}^{WZ} = \sqrt{\left(\sum_{\ell=1}^{3} p_{\mathrm{T}}^{\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left[\left(\sum_{\ell=1}^{3} p_x^{\ell} + E_x^{\mathrm{miss}}\right)^2 + \left(\sum_{\ell=1}^{3} p_y^{\ell} + E_y^{\mathrm{miss}}\right)^2\right]}$$

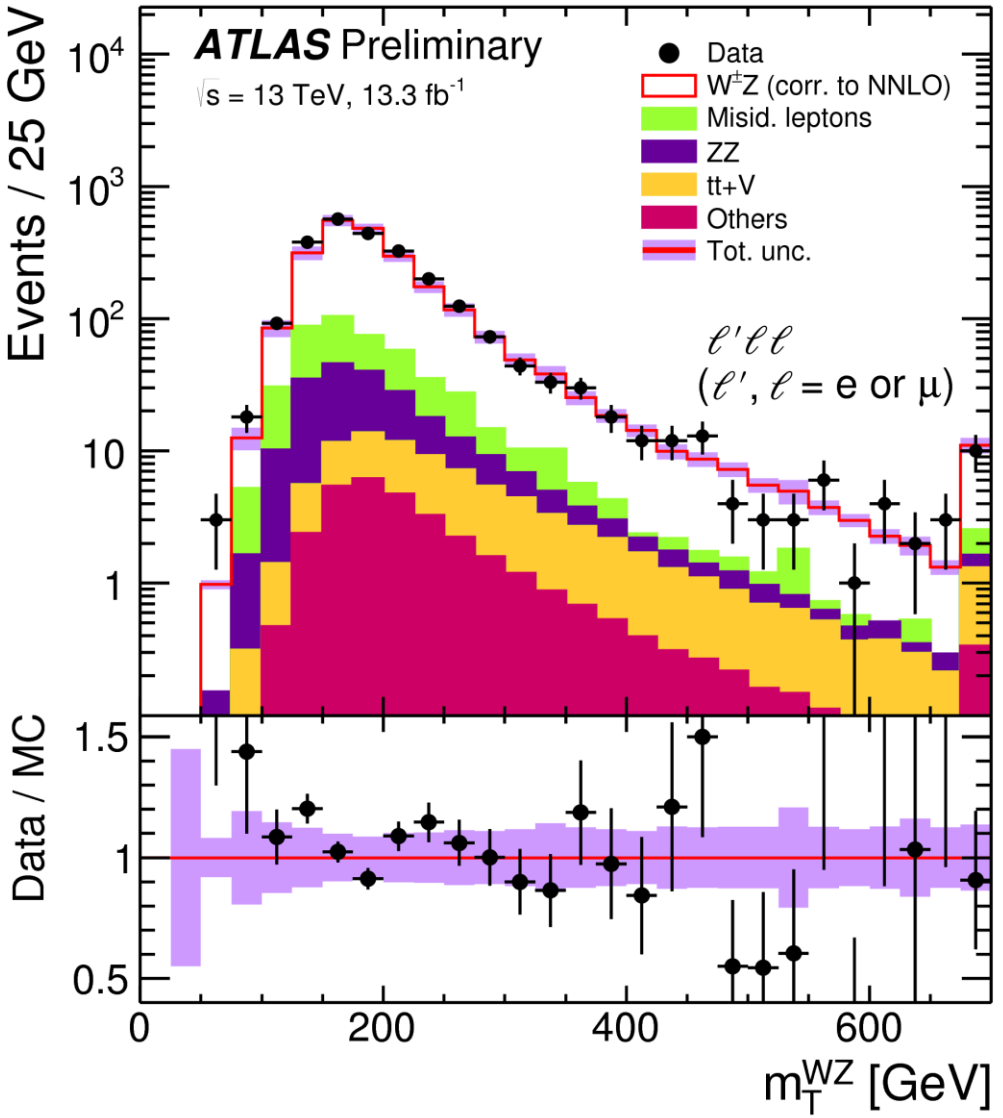
$$H \to SS, Sh \to 3l + X$$





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.

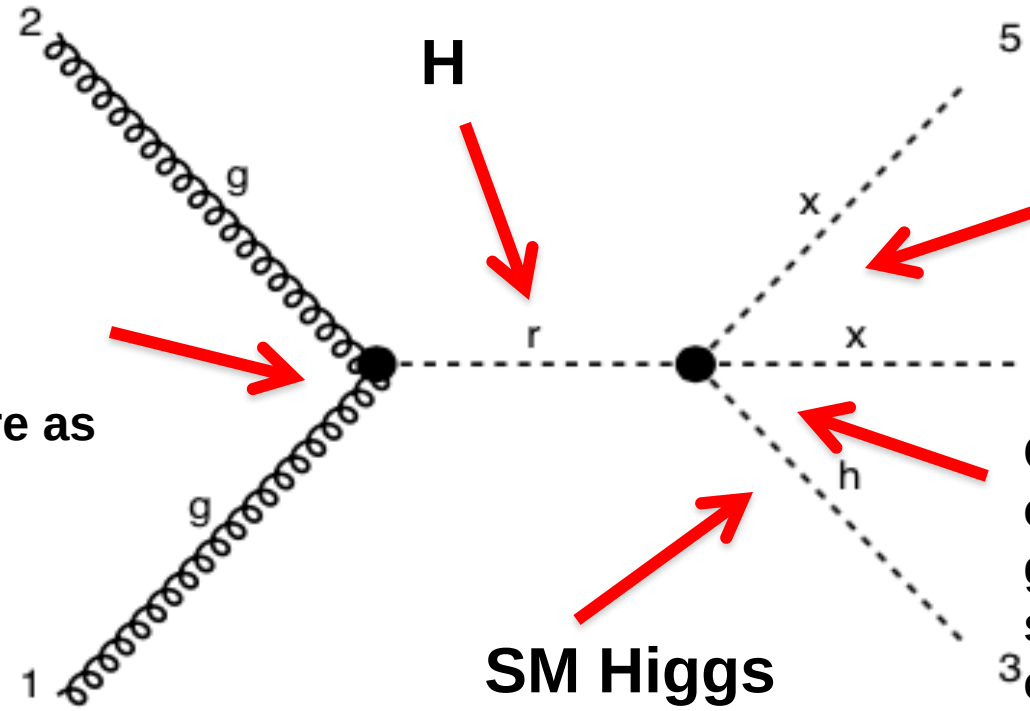


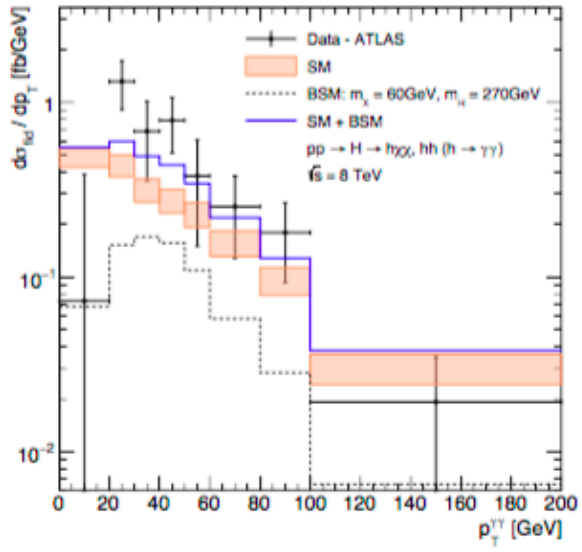


Additional Slides

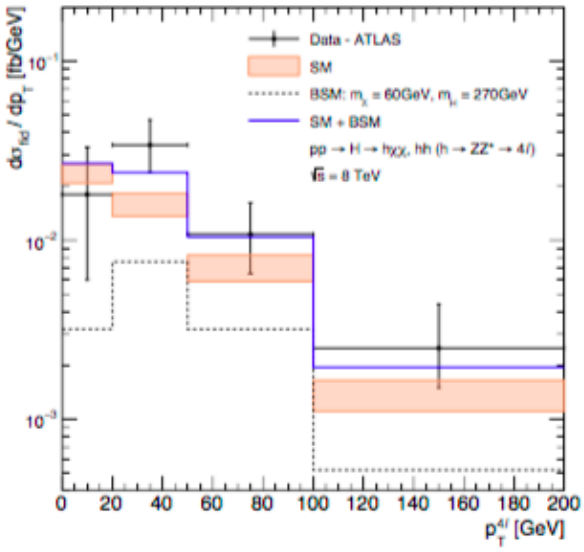
Event Generation

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

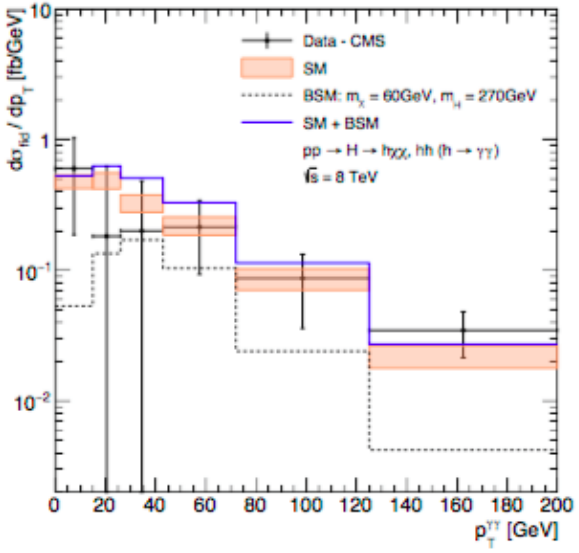




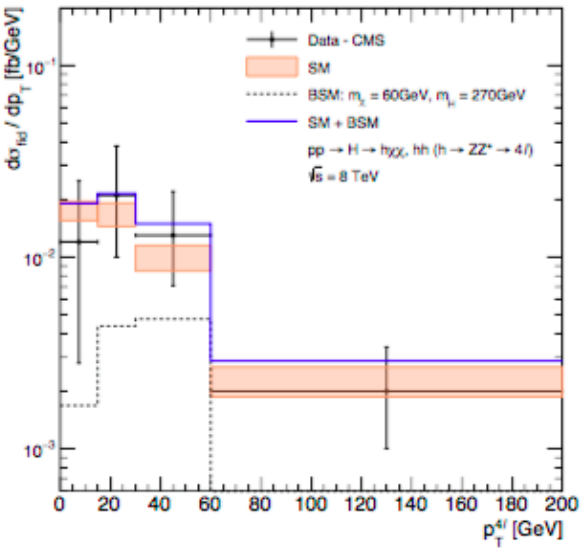
(a) ATLAS $h \to \gamma\gamma$



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



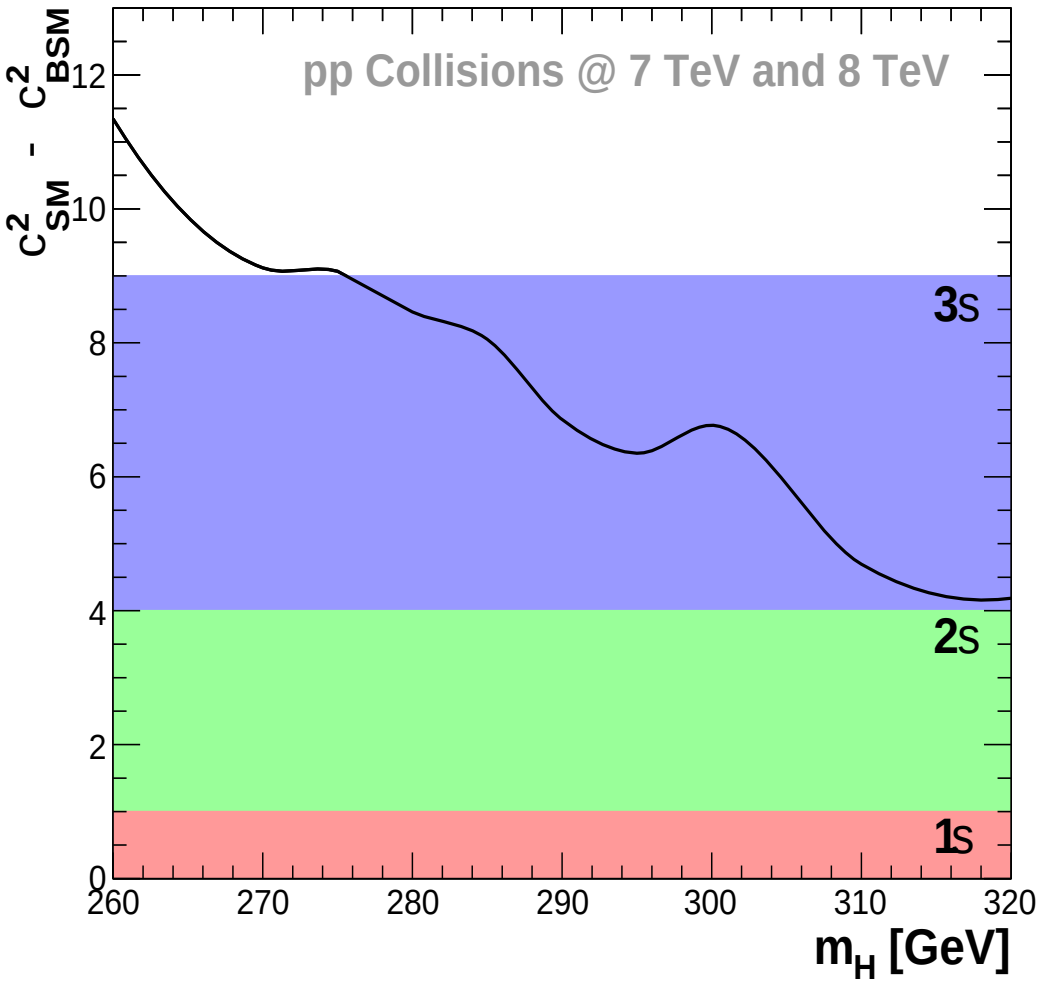
(c) CMS $h \to \gamma\gamma$



(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 $m_H = 270\,\mathrm{GeV}$ and $m_\chi = 60\,\mathrm{GeV}$.

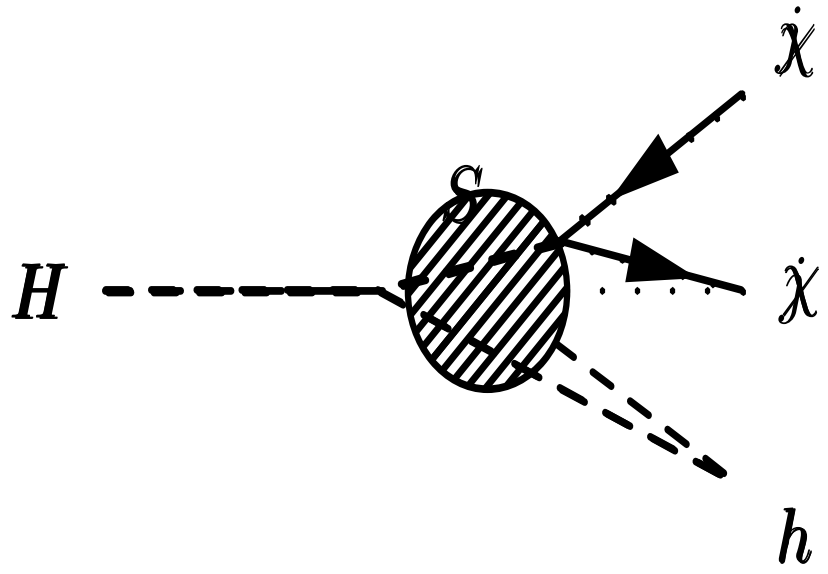
In terms of significance



- 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.

What is in the blob?

- Recall the effective interaction of $H \to h\chi\chi$
- Theoretical issues make this decay unnatural
- Propose the idea that H decays into an inert scalar S and the Higgs boson h
- S can also decay into jets



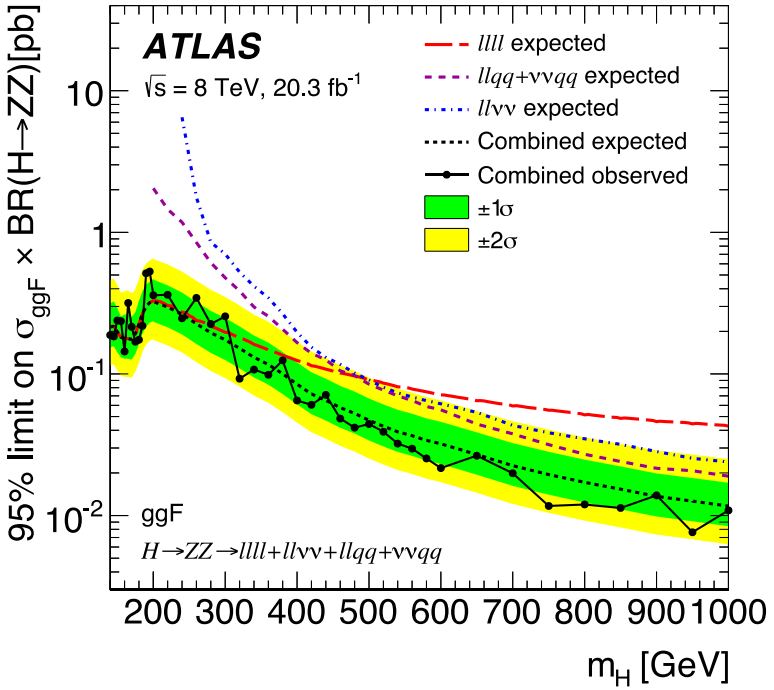
Calculating χ^2

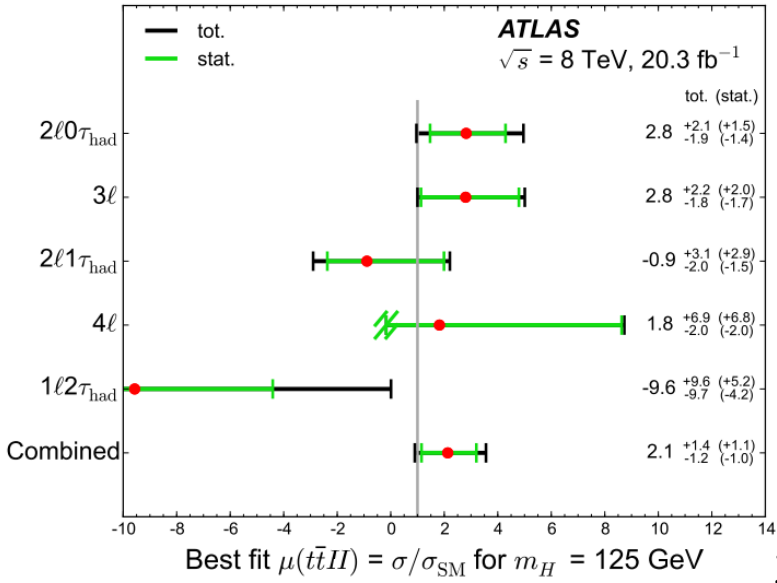
- **Two types of results:**
  - **Measurements**

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

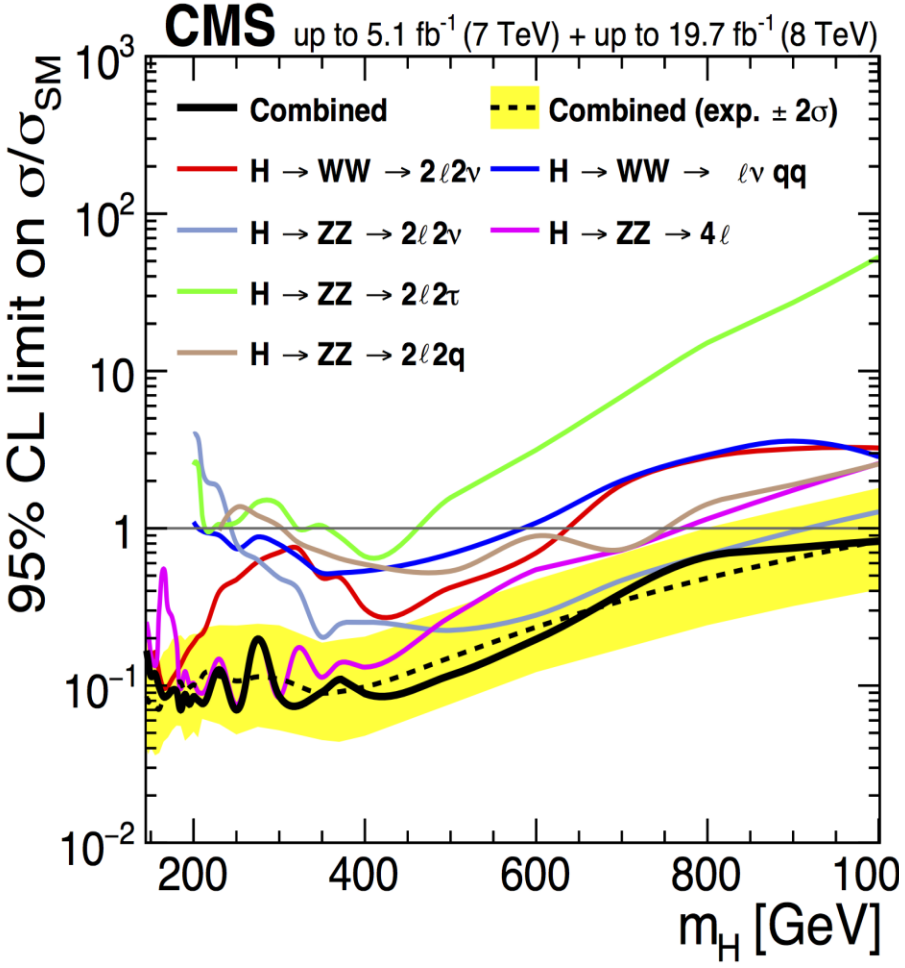
  - **Limits**

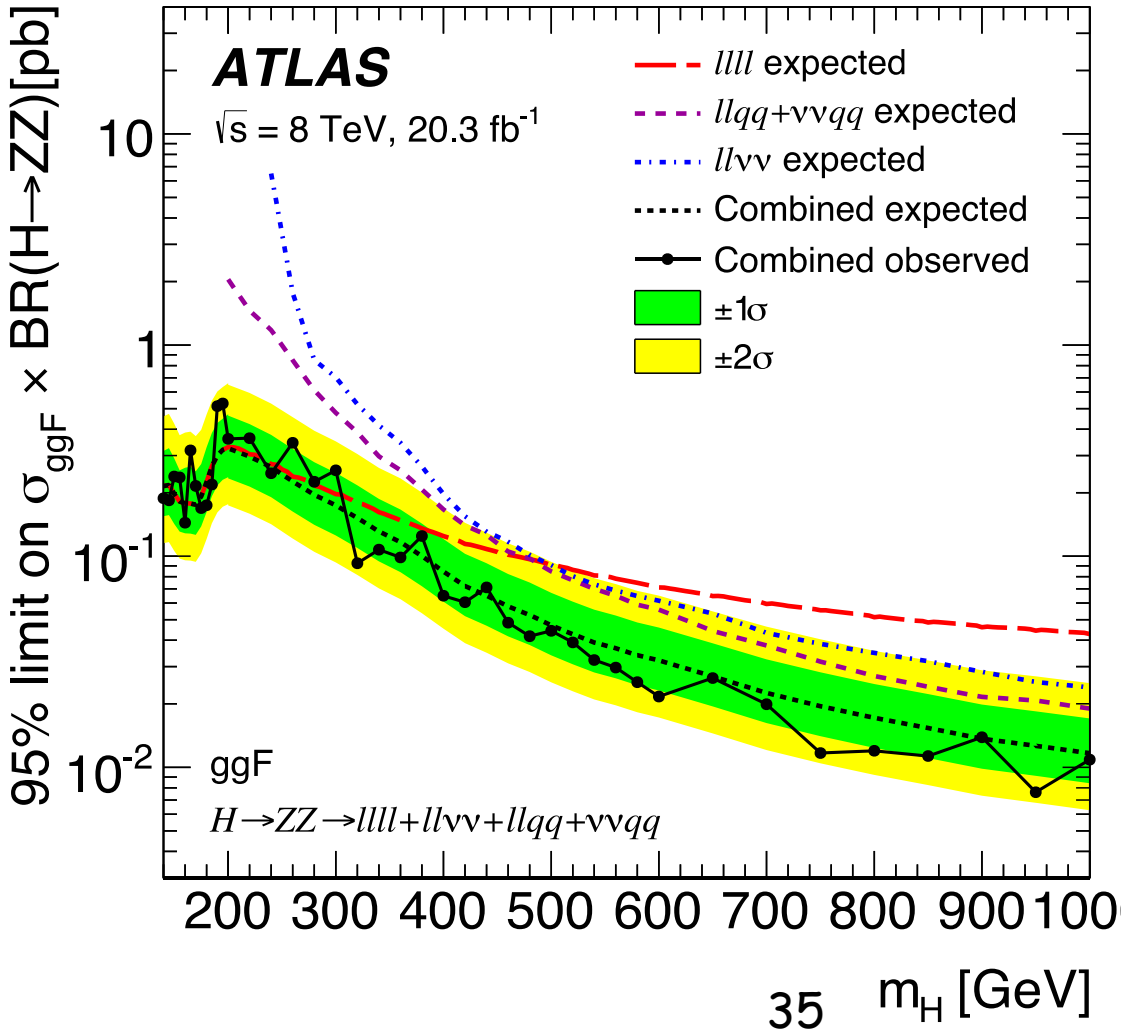
$$\chi^2 = \frac{(\mu^{\text{obs}}-\mu^{\text{exp}}-\mu^{\text{th}})^2}{(\mu^{\text{exp}}/1.96)^2}$$



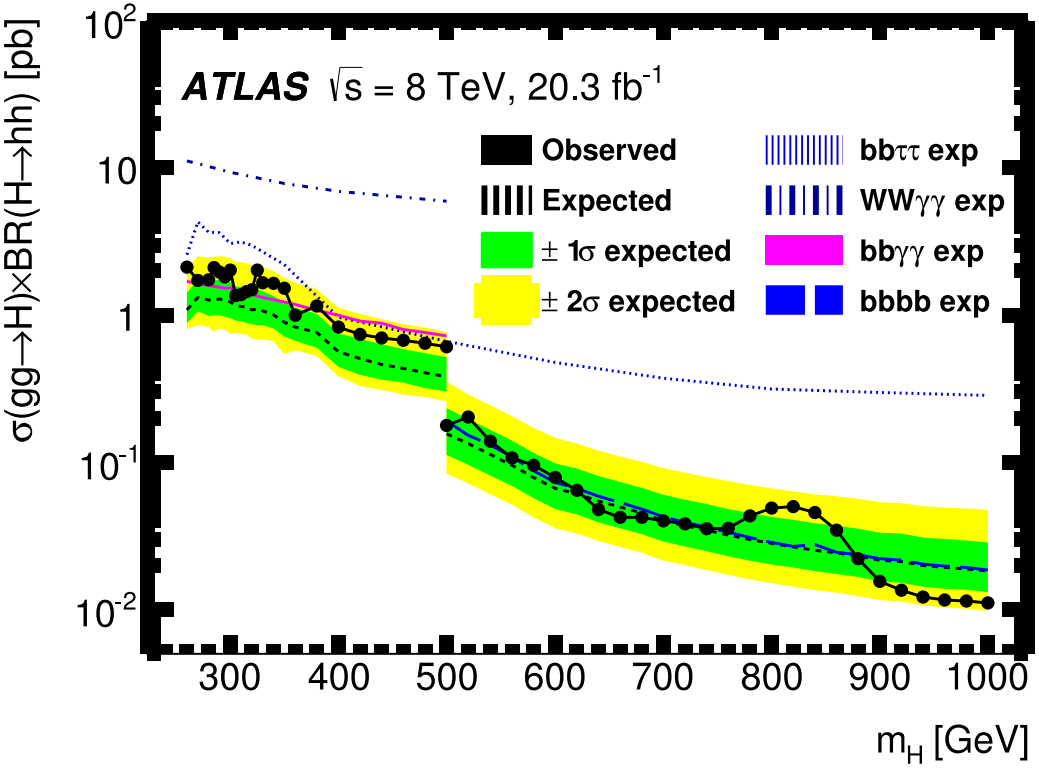


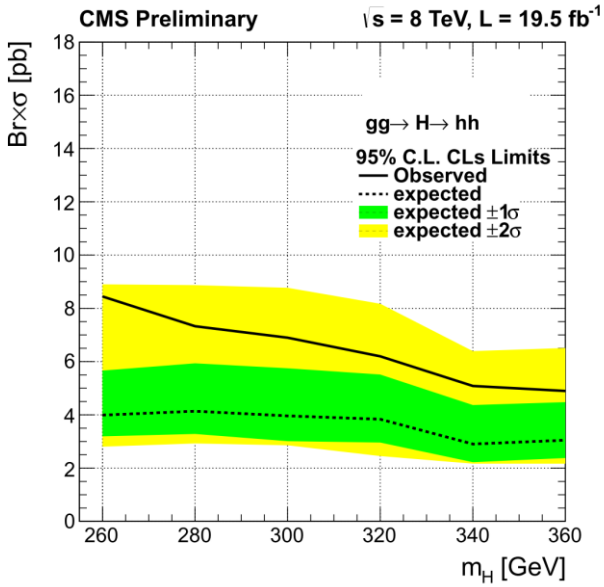
Inputs: Higgs decays to weak vector bosons

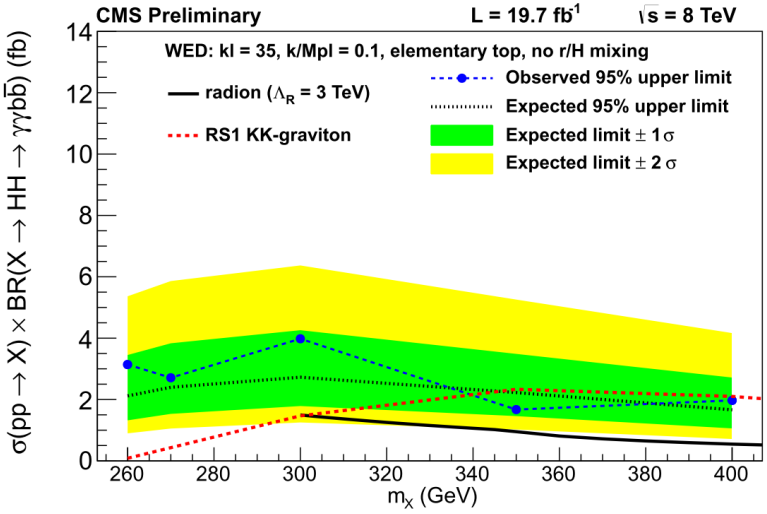




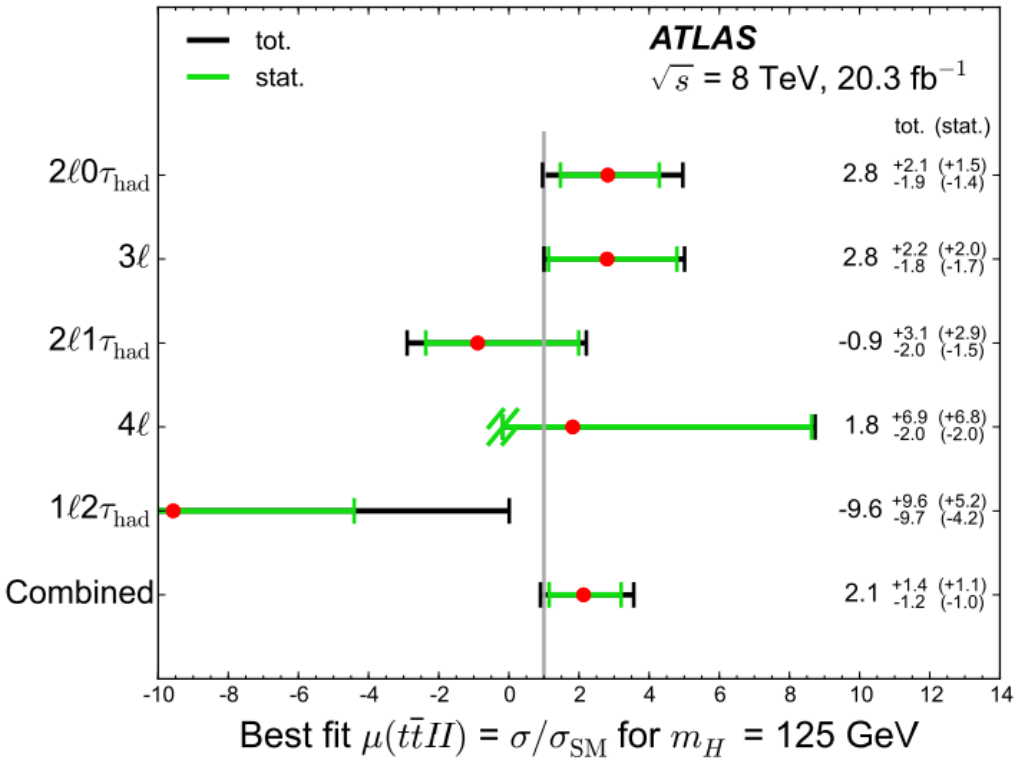
Inputs: Di-Higgs searches

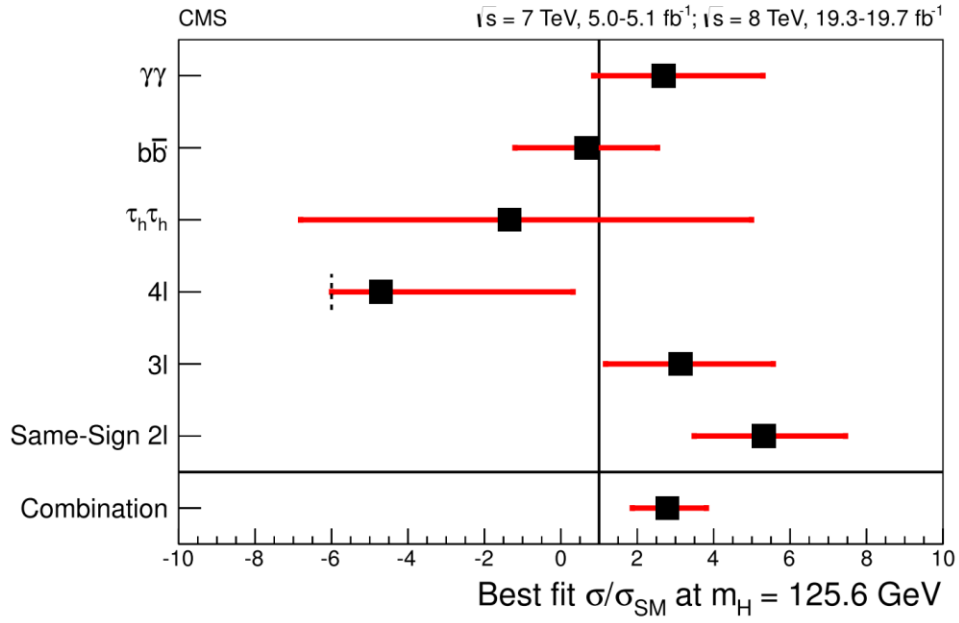






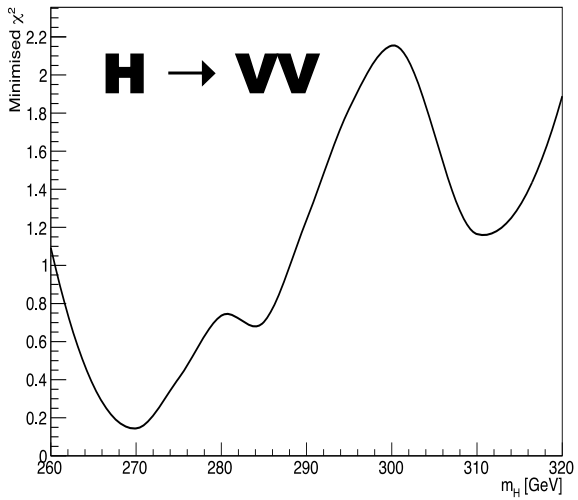
Inputs: Top associated Higgs production

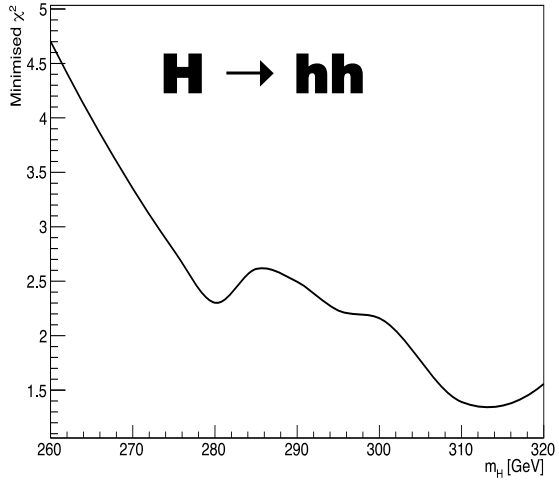


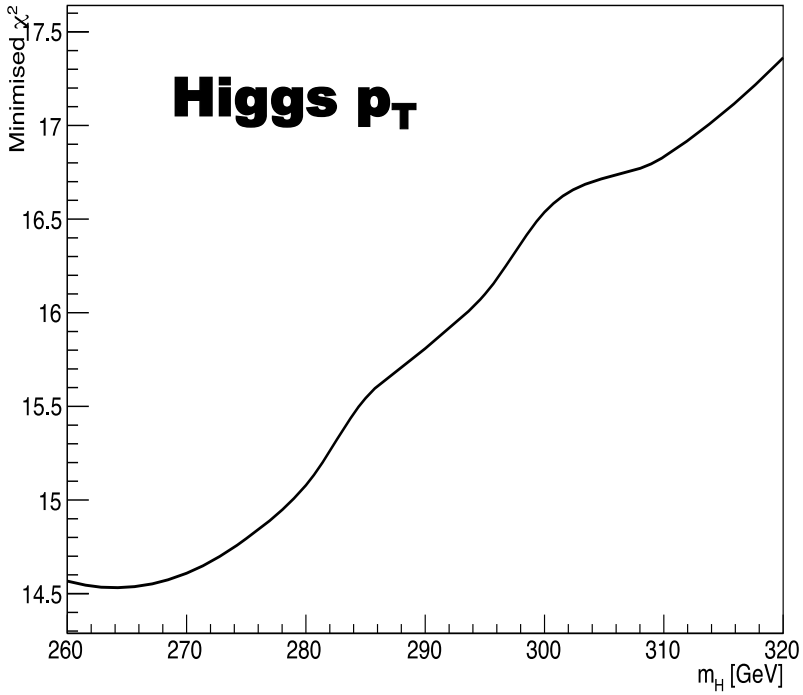


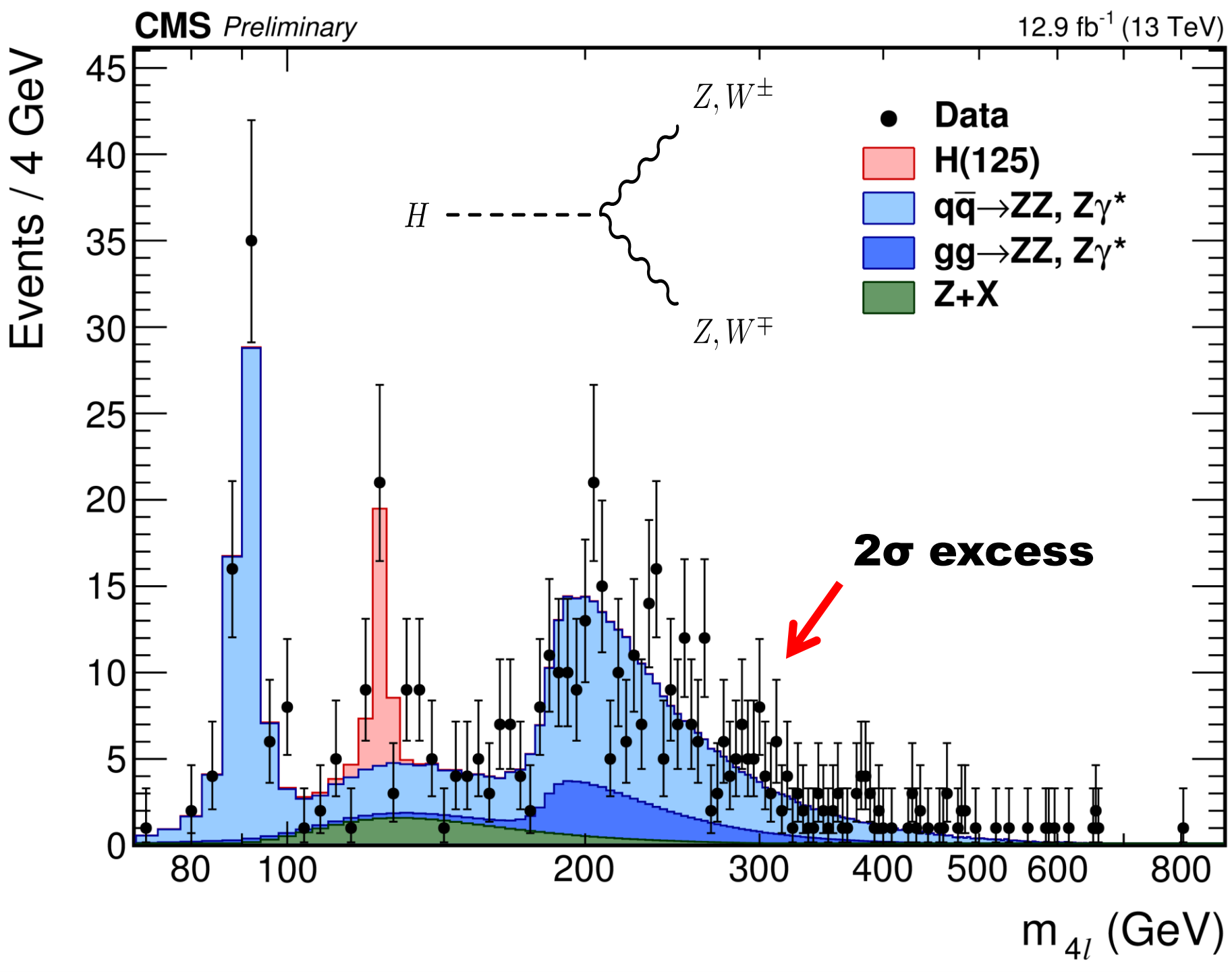
Step-by-step results

- 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

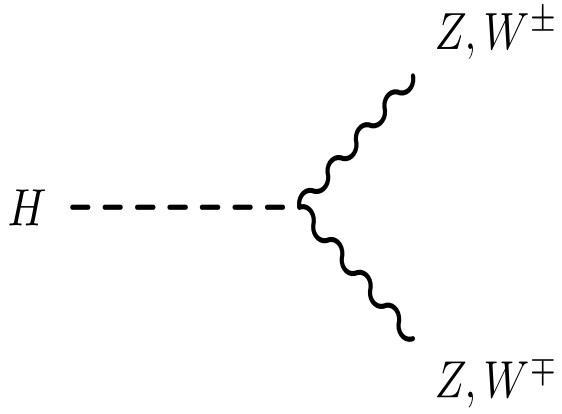


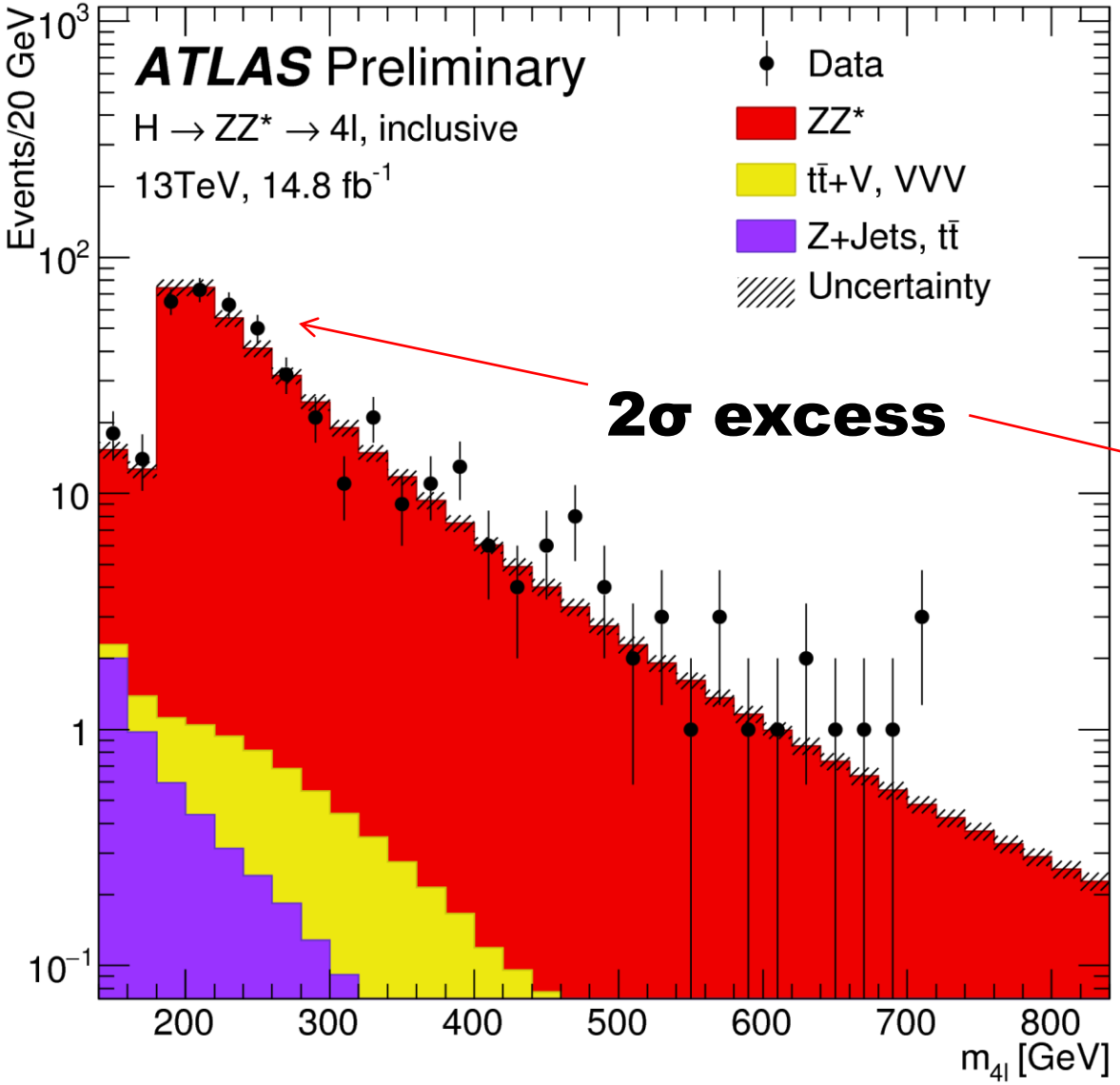




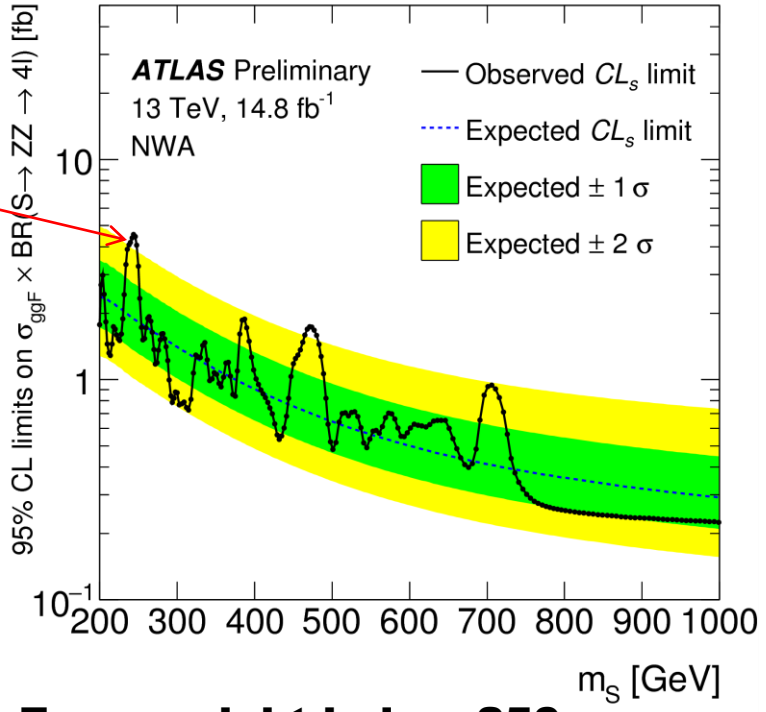

CMS Preliminary
12.9 fb-1 (13 TeV)
Events / 4 GeV
m4l (GeV)
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
H
Z, W±
Z, W∓
2σ excess
0
5
10
15
20
25
30
35
40
45
80
100
200
300
400
500
600
800

ATLAS-CONF-2016-079

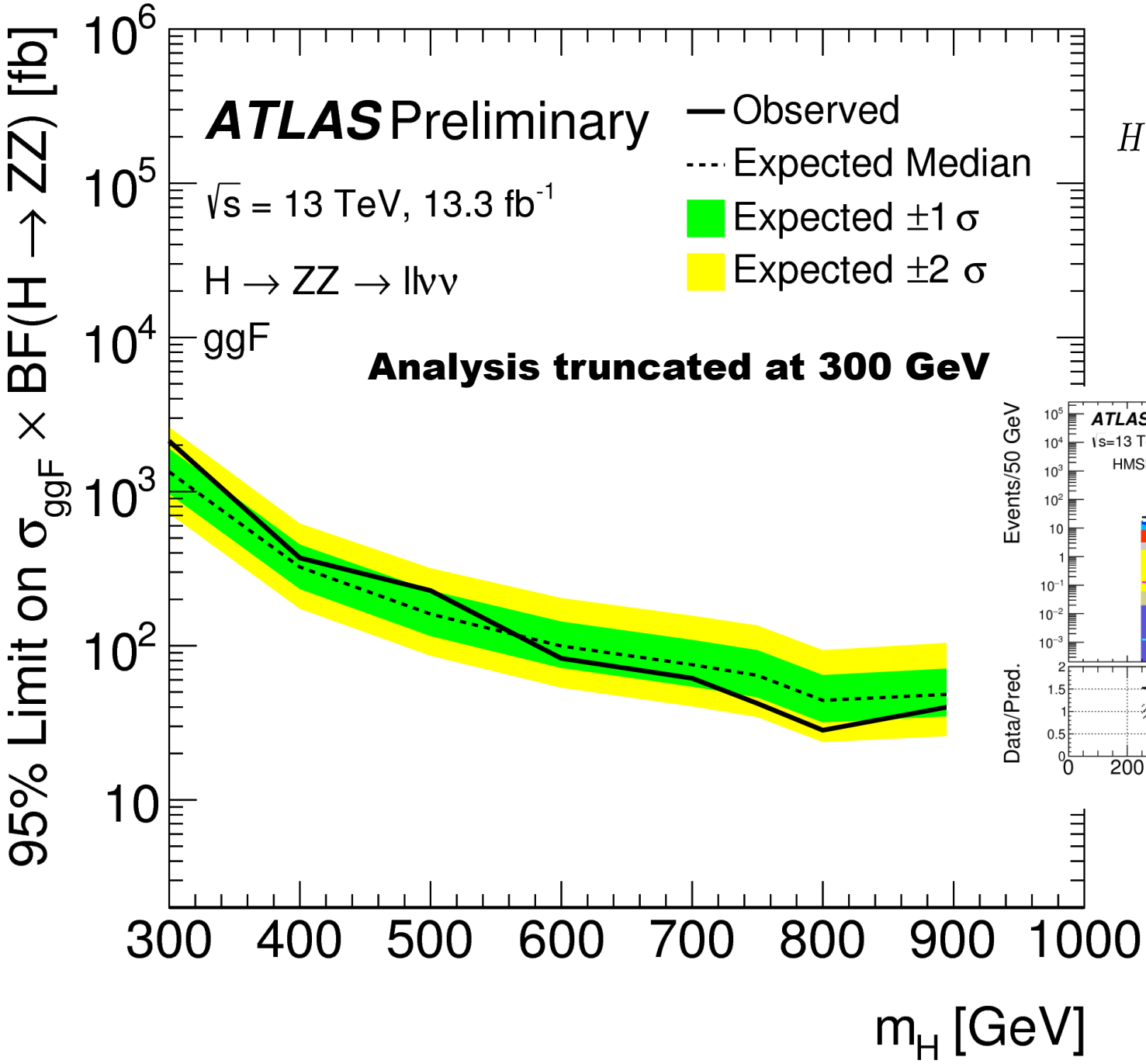


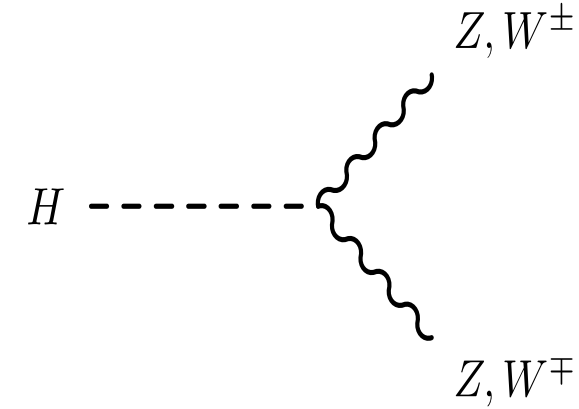


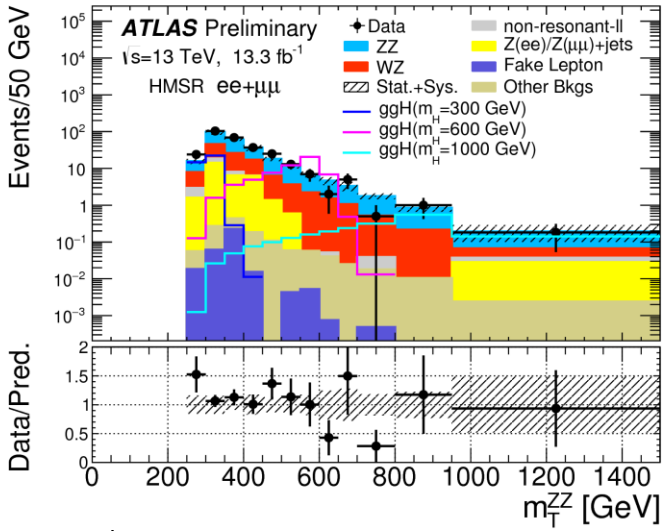
2σ excess



Excess right below 250, could consistent with Run I measurement

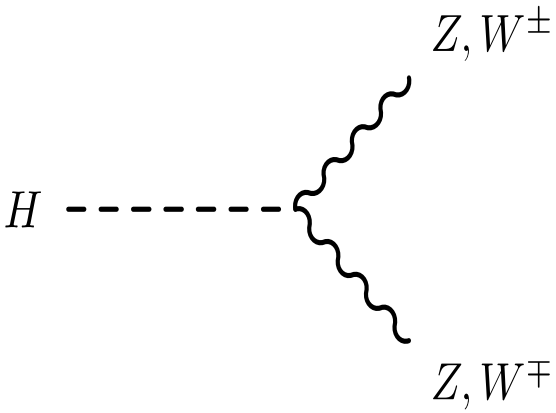

ATLAS Preliminary
√s = 13 TeV, 13.3 fb-1
H → ZZ → llνν
ggF
Observed
Expected Median
Expected ±1 σ
Expected ±2 σ
Analysis truncated at 300 GeV
95% Limit on σggF × BF(H → ZZ) [fb]
mH [GeV]

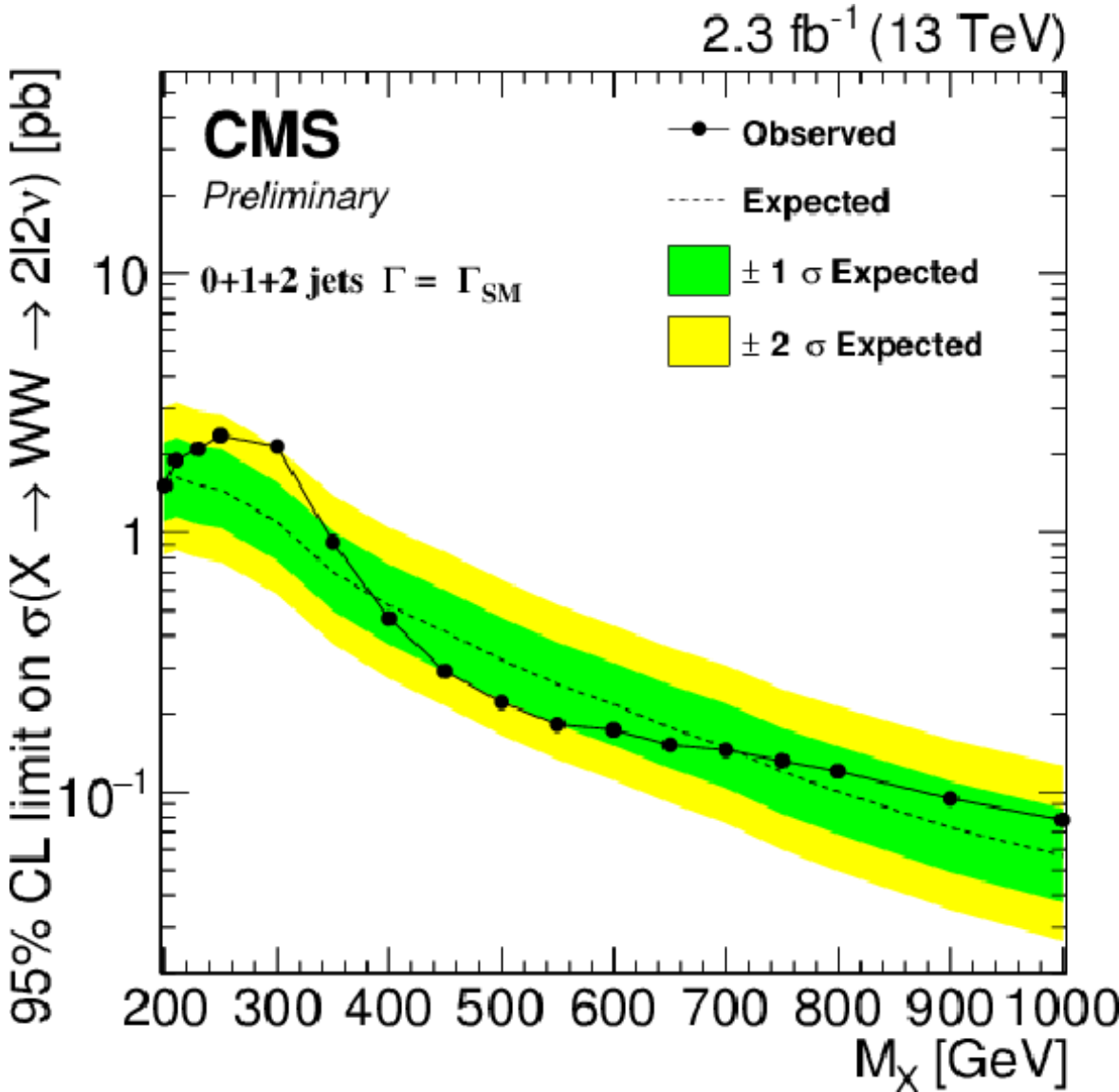

H
Z, W±
Z, W∓

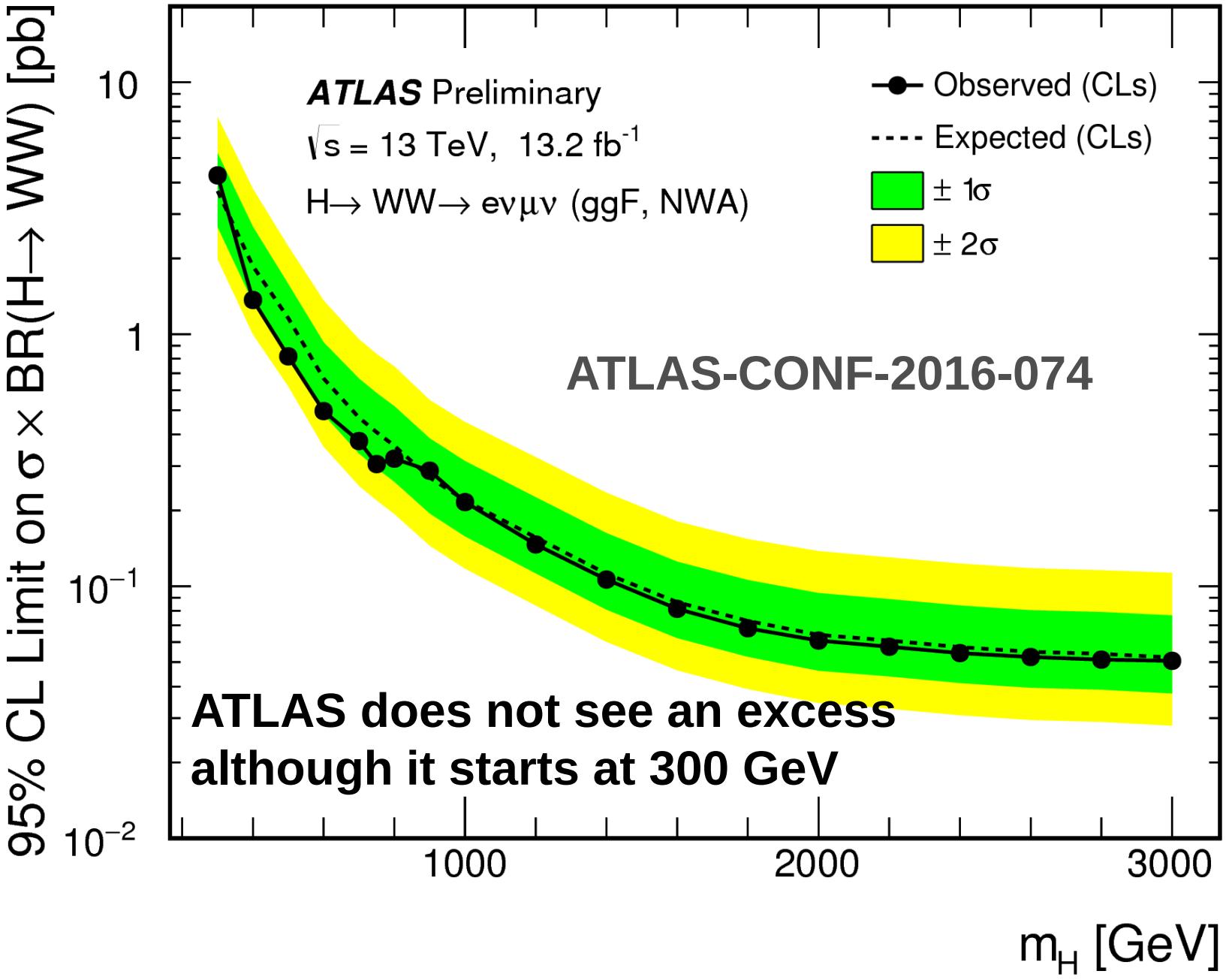

ATLAS Preliminary
√s=13 TeV, 13.3 fb-1
HMSR ee+μμ
Data
ZZ
WZ
Stat.+Sys.
non-resonant-ll
Z(ee)/Z(μμ)+jets
Fake Lepton
Other Bkgs
ggH(mH=300 GeV)
ggH(mH=600 GeV)
ggH(mH=1000 GeV)
Events/50 GeV
Data/Pred.
mTZZ [GeV]

CMS-PAS-HIG-16-023

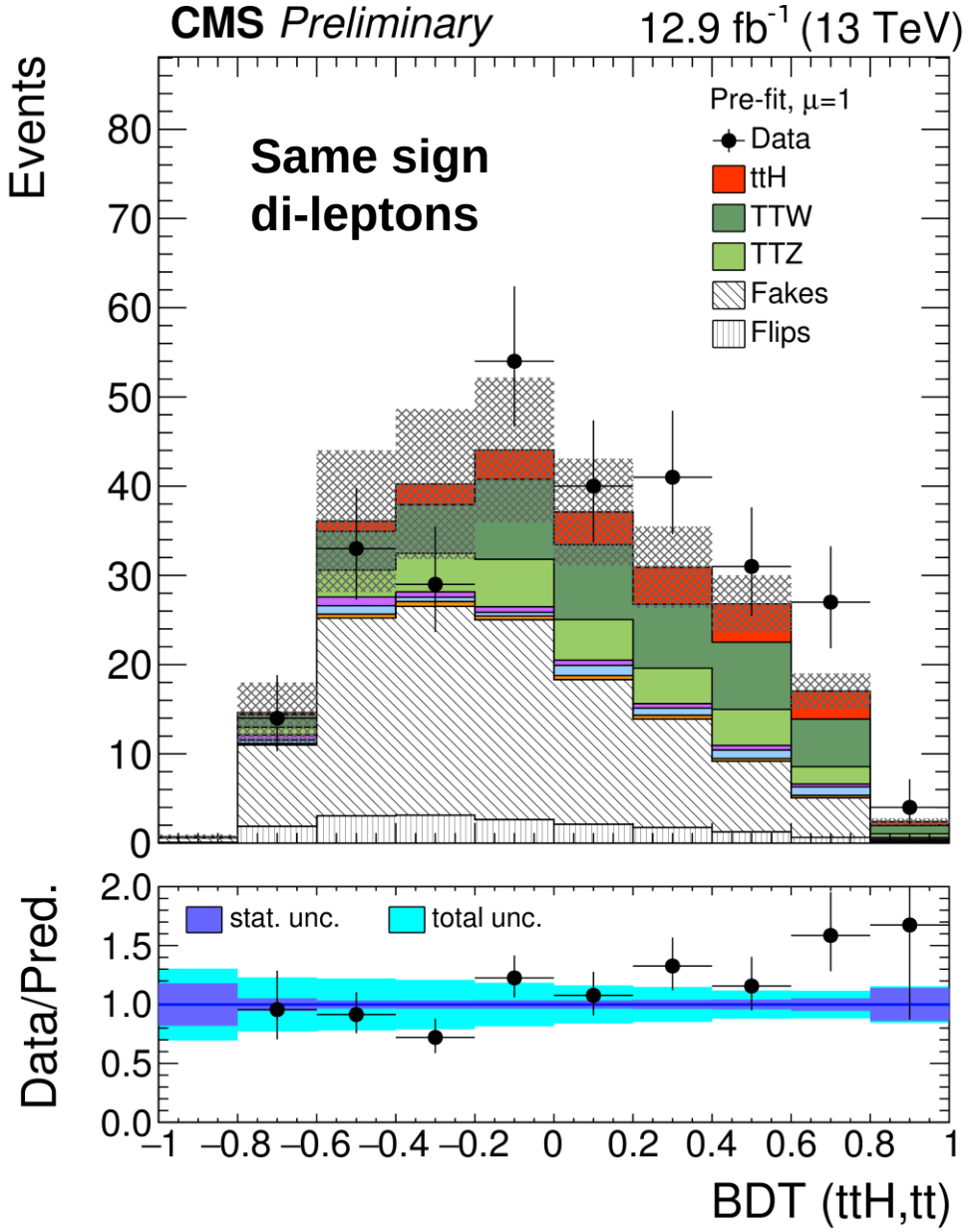
Search for high mass Higgs to WW with fully leptonic decays using 2015 data

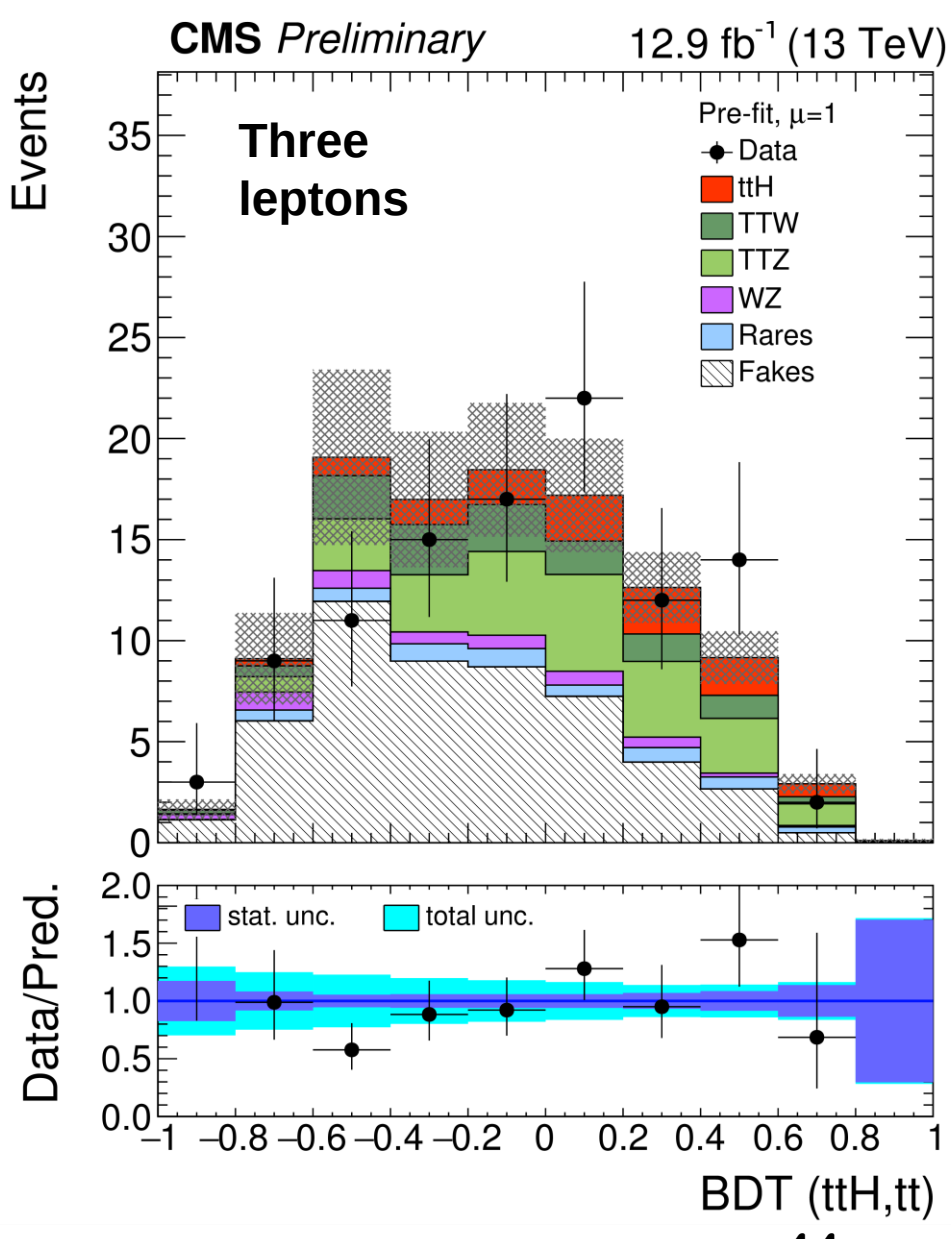


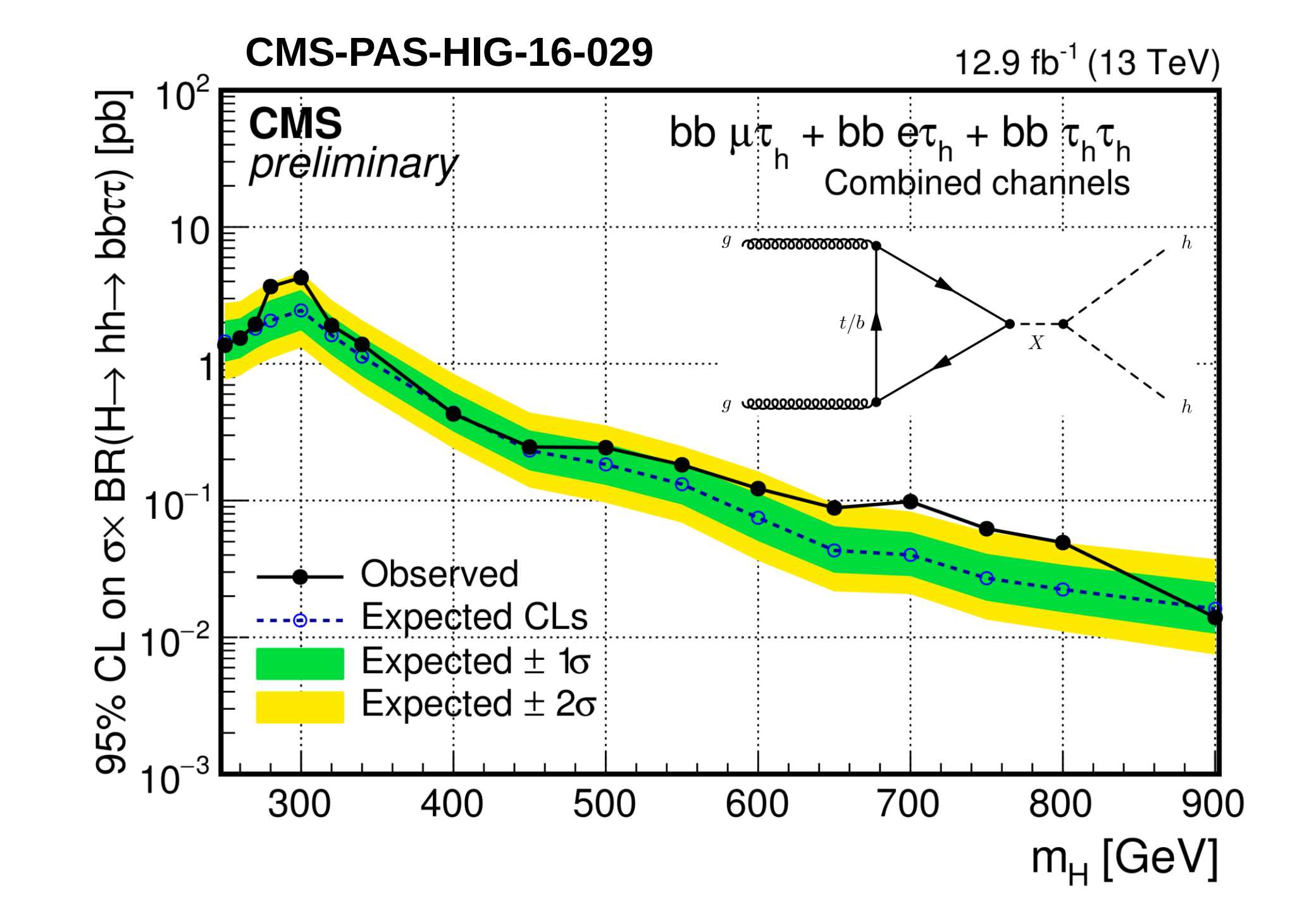


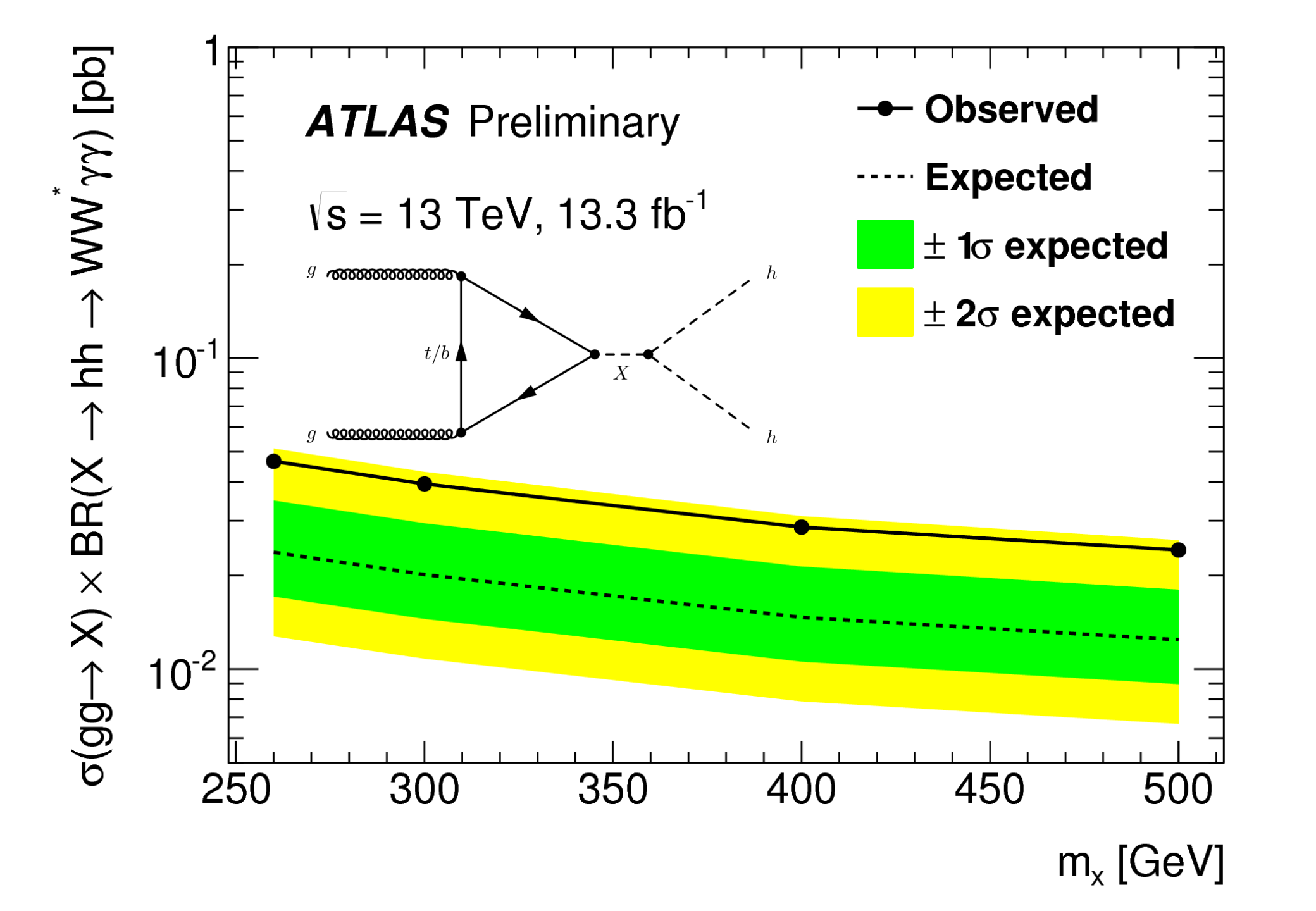

ATLAS Preliminary
√s = 13 TeV, 13.2 fb-1
H→ WW→ eνμν (ggF, NWA)
Observed (CLs)
Expected (CLs)
± 1σ
± 2σ
ATLAS-CONF-2016-074
ATLAS does not see an excess
although it starts at 300 GeV
95% CL Limit on σ × BR(H→ WW) [pb]
10
1
10−1
10−2
1000
2000
3000
mH [GeV]

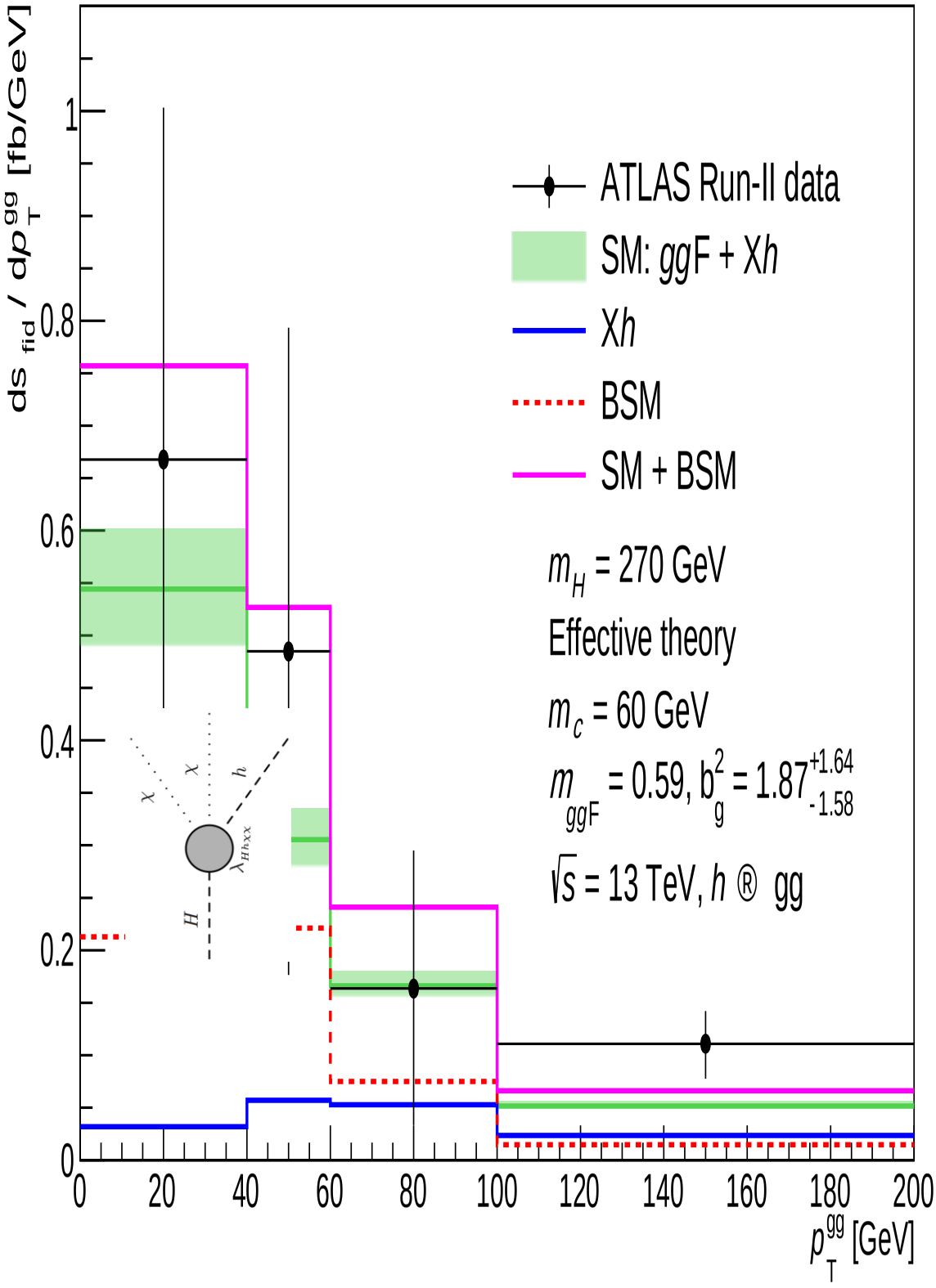
CMS-PAS-HIG-16-022






CMS-PAS-HIG-16-029
12.9 fb-1 (13 TeV)
CMS
preliminary
bb μτh + bb eτh + bb τhτh
Combined channels
g
g
t/b
X
h
h
Observed
Expected CLs
Expected ± 1σ
Expected ± 2σ
95% CL on σ× BR(H→ hh→ bbττ) [pb]
mH [GeV]
10-3
10-2
10-1
1
10
102
300
400
500
600
700
800
900

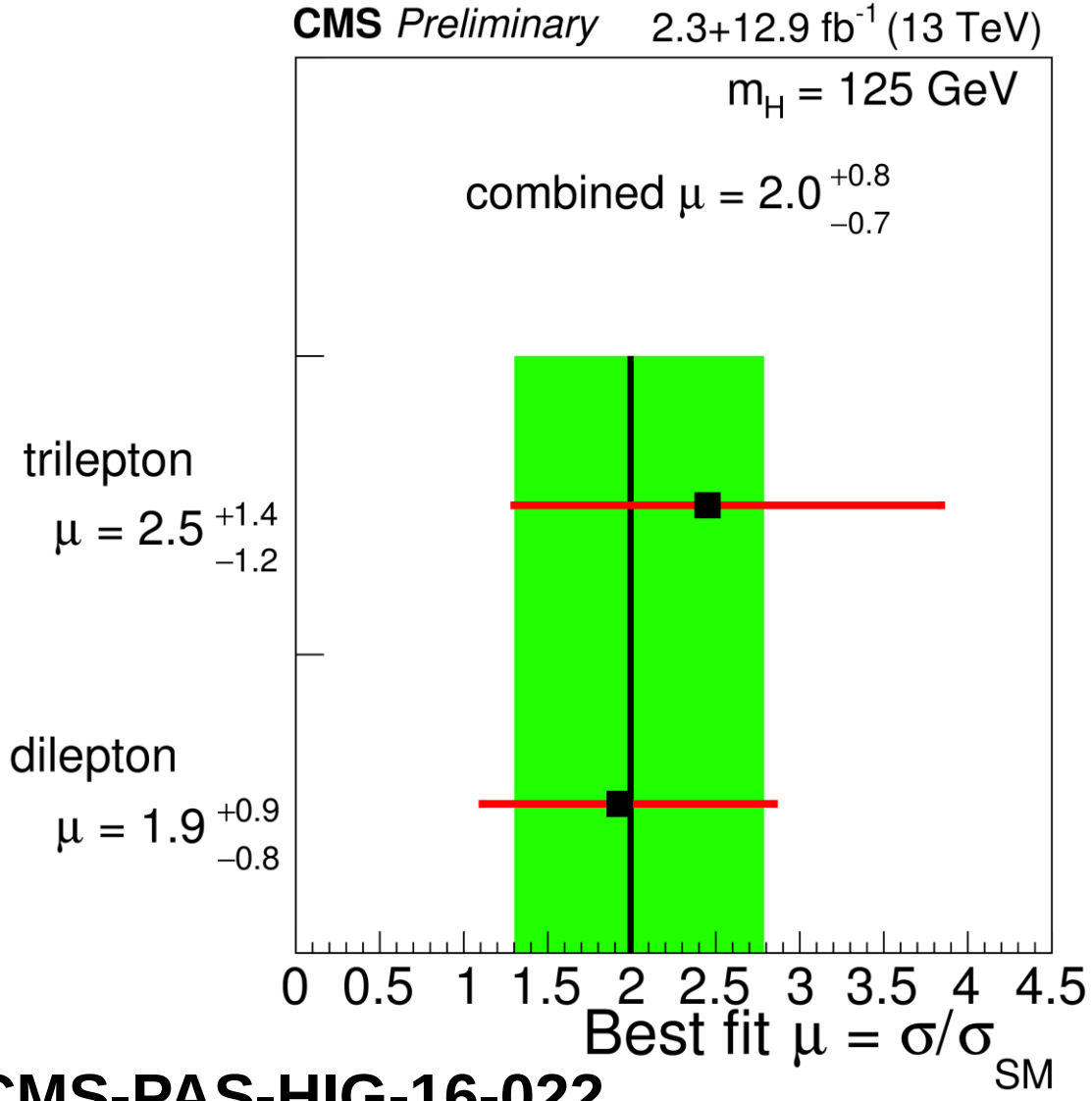

ATLAS Preliminary
√s = 13 TeV, 13.3 fb-1
Observed
Expected
± 1σ expected
± 2σ expected
σ(gg→ X) × BR(X → hh → WW*γγ) [pb]
mx [GeV]
1
10-1
10-2
250
300
350
400
450
500
g
g
t/b
X
h
h

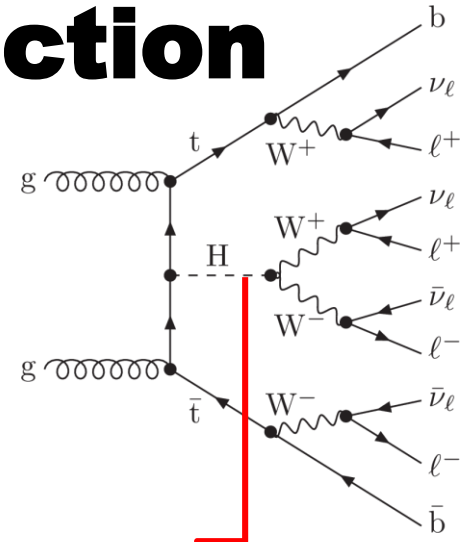

ATLAS Run-II data
SM: ggF + Xh
Xh
BSM
SM + BSM
m_H = 270 GeV
Effective theory
m_c = 60 GeV
m_{ggF} = 0.59, b_g^2 = $1.87^{+1.64}_{-1.58}$
$\sqrt{s}$ = 13 TeV, h ® gg
ds_{fid} / dp_T^{gg} [fb/GeV]
p_T^{gg} [GeV]
0
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100
120
140
160
180
200
χ
χ
h
H
λ_{Hhxx}

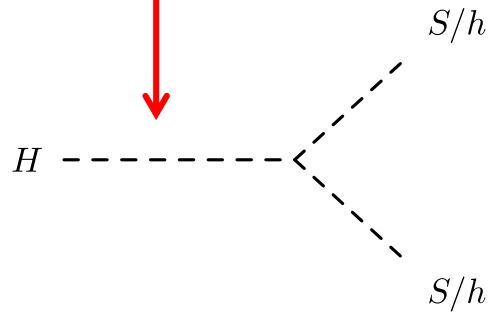
Type of final state	Final state	Significance
Decays to weak vector bosons	ZZ->4l, ZZ->llνν, WW->2llνν	2σ, 2σ, 2σ,1σ, 0σ
Top associated Higgs production	Leptons, γγ, bbar	1σ
Di-Higgs resonance searches	bbττ, WWγγ	2σ, 2σ
Higgs pT spectrum	γγ	1σ

Overall, positive fluctuations. One can argue that the new data does not contradict the original hypothesis
Combination underway (cannot add up in quadrature!)

Top associated Higgs production (Run II)





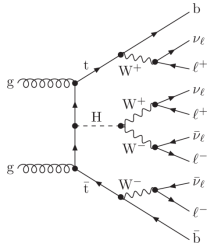


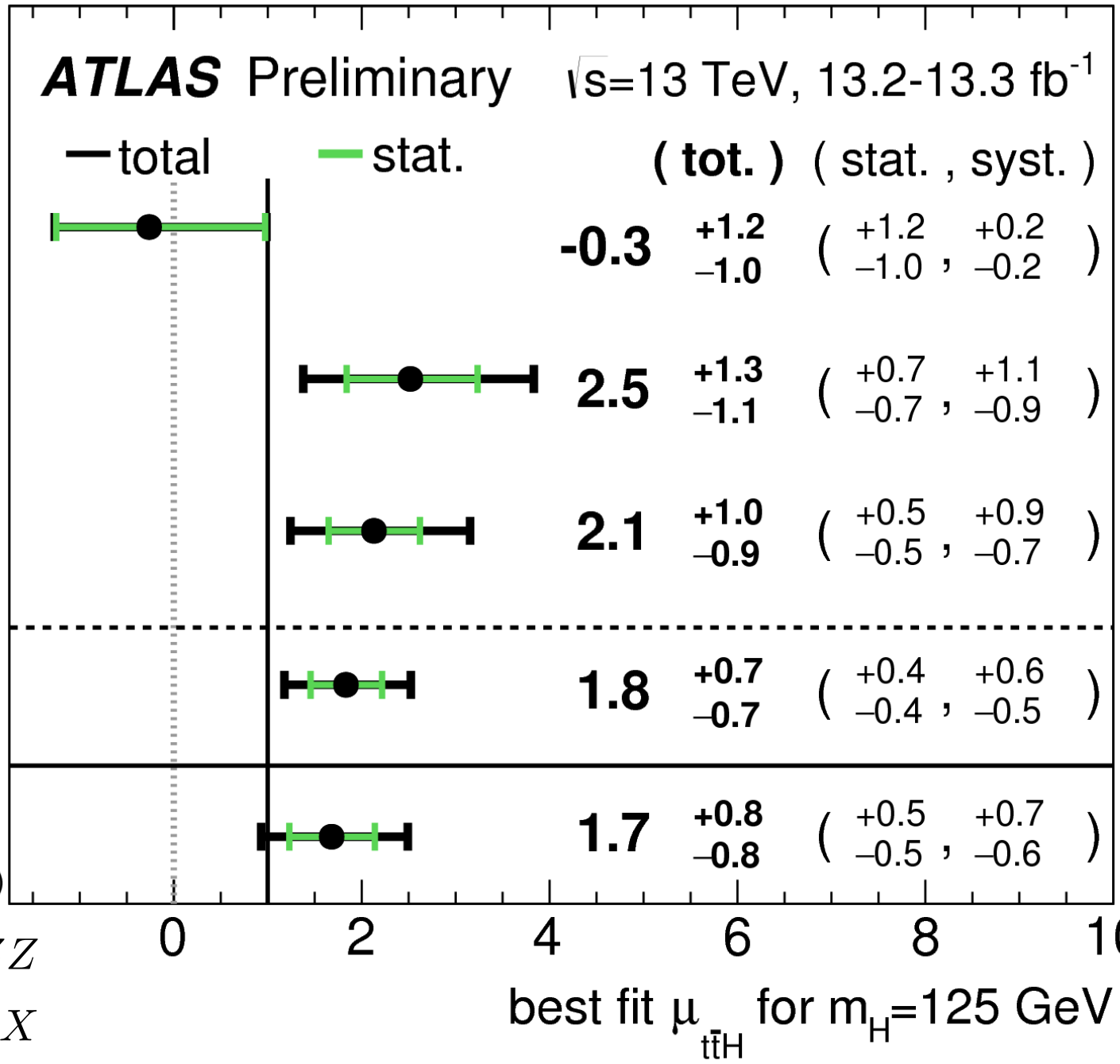
$$S, h \to WW, \tau\tau\, ZZ$$

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

CMS-PAS-HIG-16-022

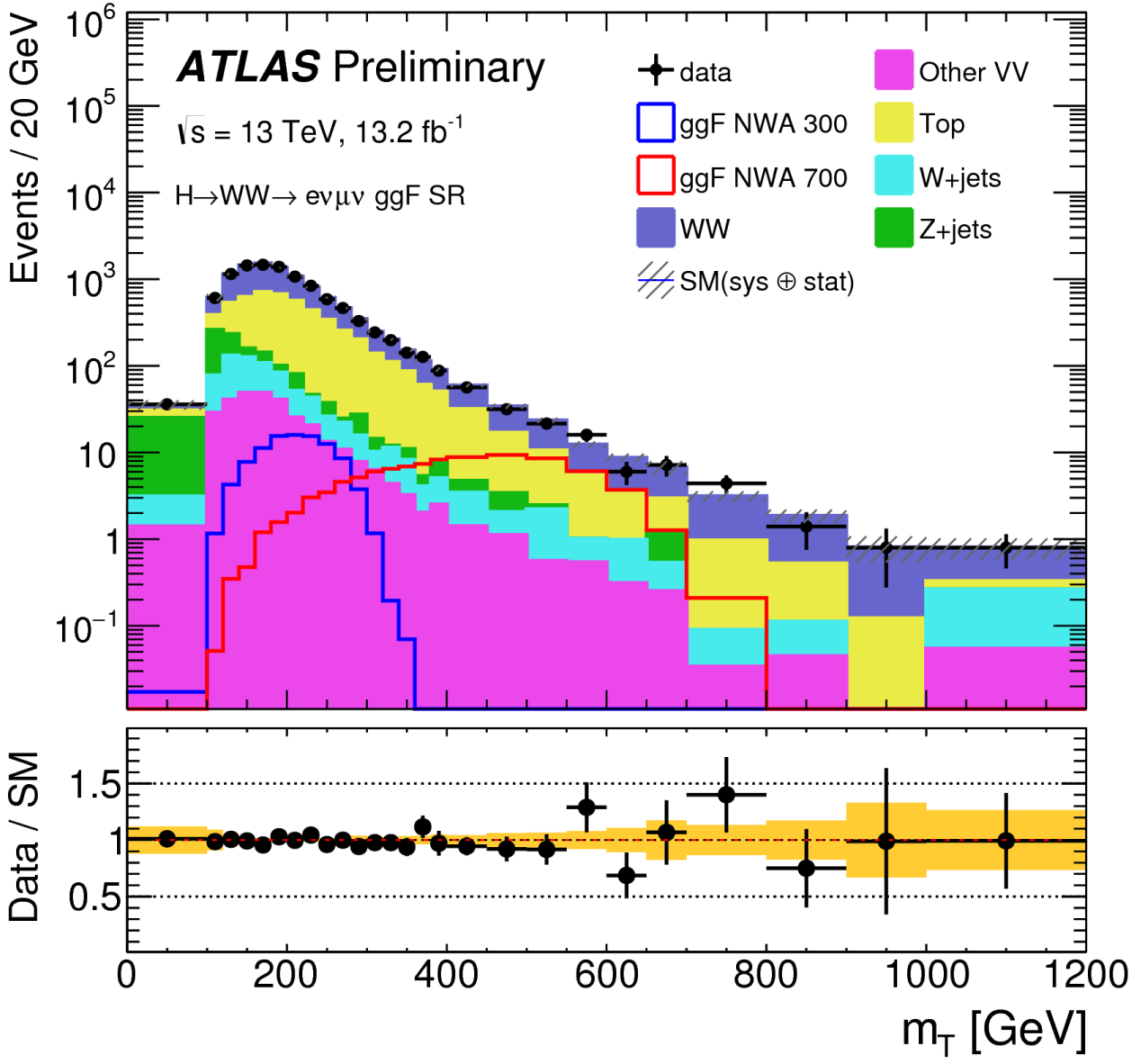
ATLAS-CONF-2016-058

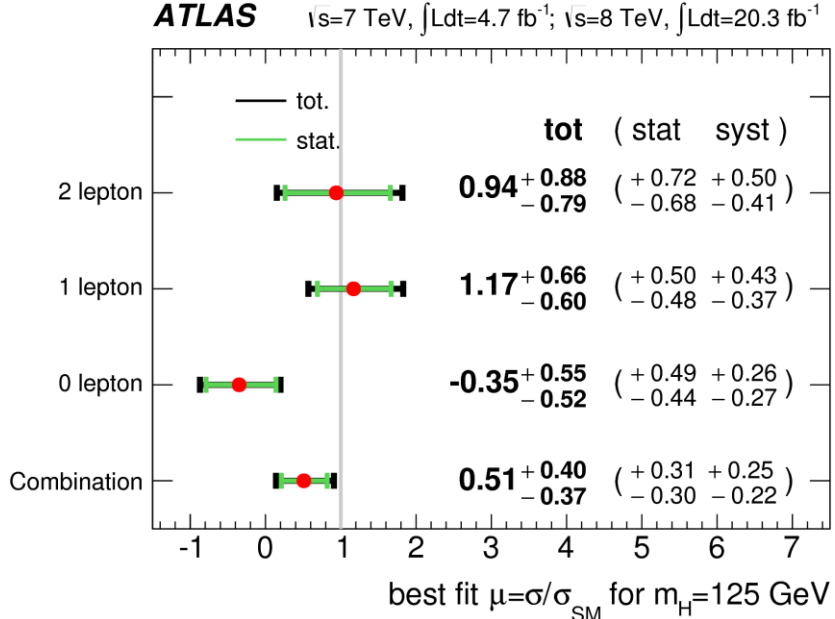


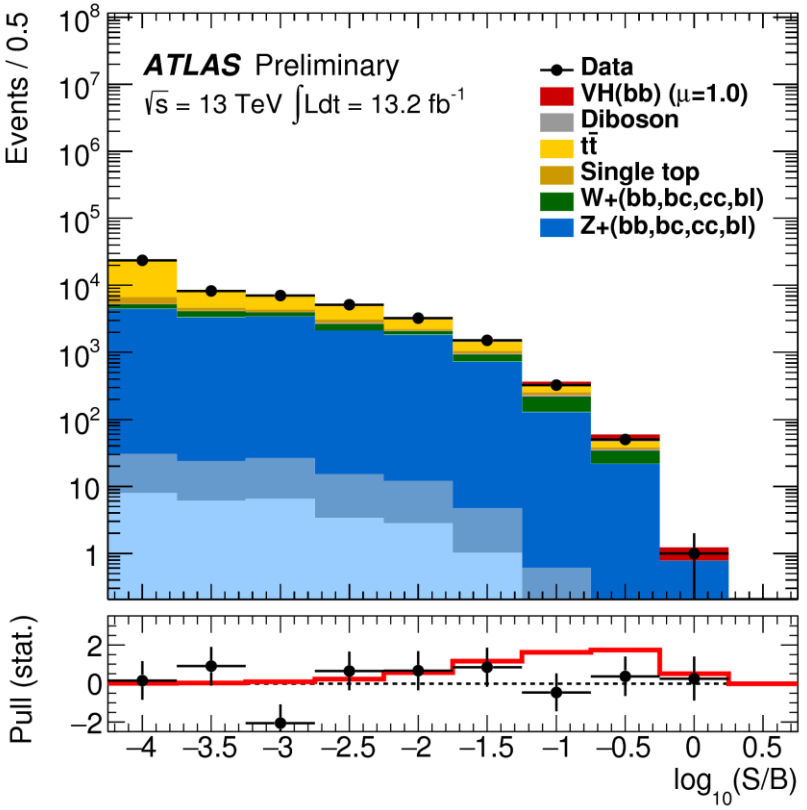


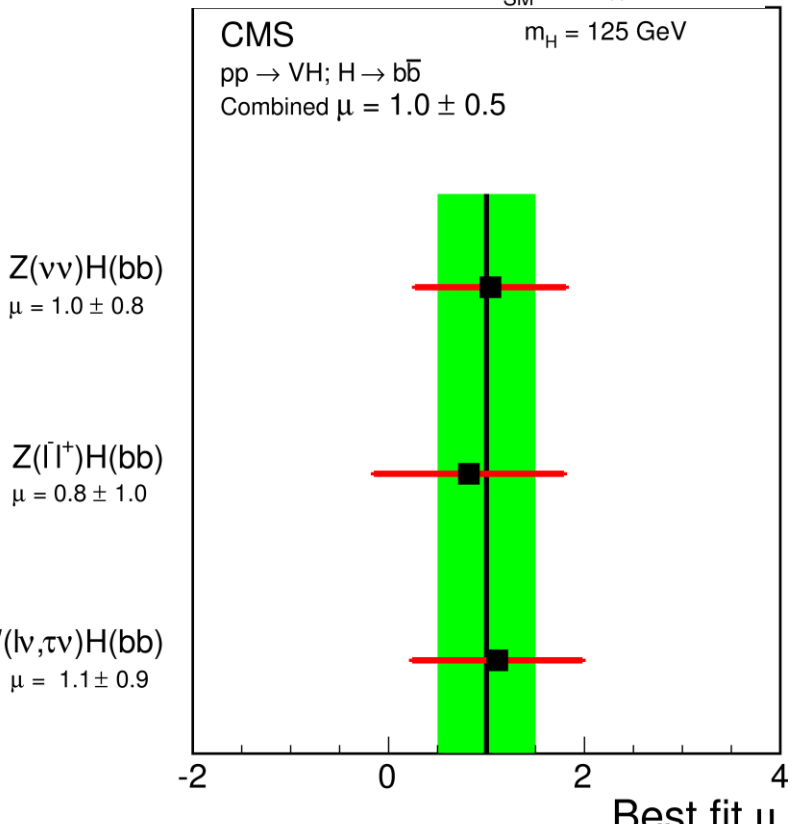
$S, h \to WW, \tau\tau\, ZZ$

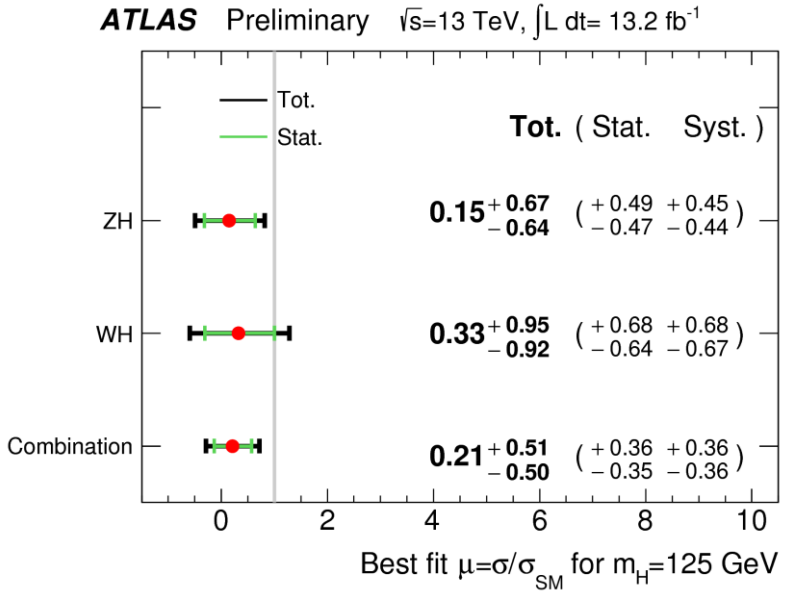
$\to l^{\pm}l^{\pm}, 3l + X$

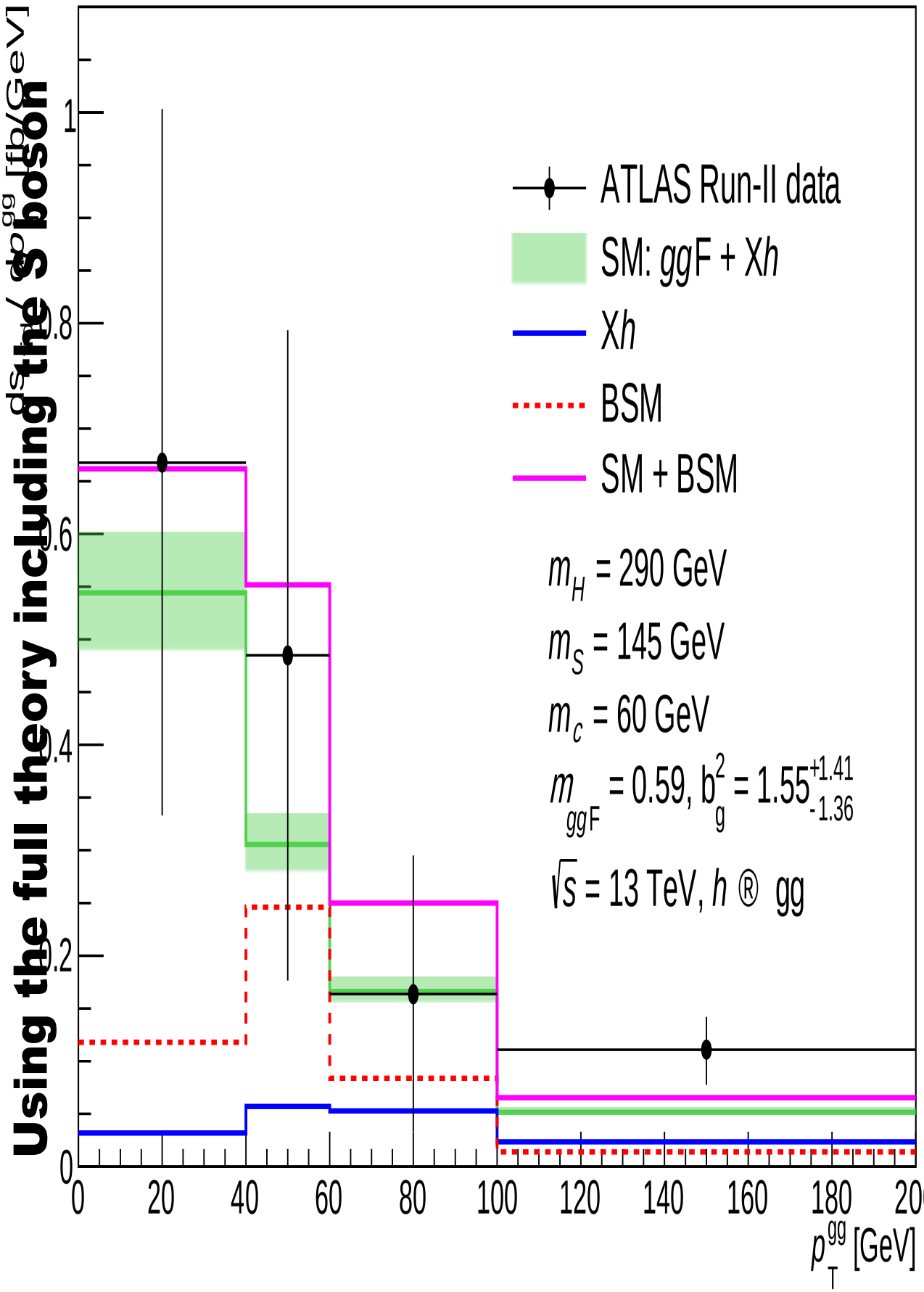

ATLAS Preliminary
√s = 13 TeV, 13.2 fb-1
H→WW→ eνμν ggF SR
data
ggF NWA 300
ggF NWA 700
WW
SM(sys ⊕ stat)
Other VV
Top
W+jets
Z+jets
Events / 20 GeV
Data / SM
mT [GeV]

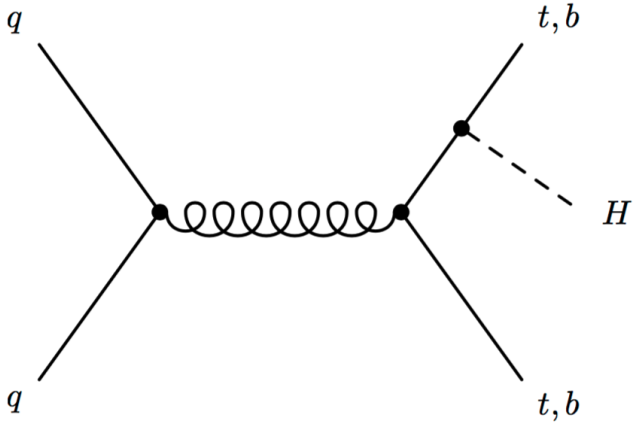

ATLAS √s=7 TeV, ∫Ldt=4.7 fb-1; √s=8 TeV, ∫Ldt=20.3 fb-1
tot.
stat.
tot (stat syst)
2 lepton
0.94 +0.88 −0.79 (+0.72 +0.50 −0.68 −0.41)
1 lepton
1.17 +0.66 −0.60 (+0.50 +0.43 −0.48 −0.37)
0 lepton
-0.35 +0.55 −0.52 (+0.49 +0.26 −0.44 −0.27)
Combination
0.51 +0.40 −0.37 (+0.31 +0.25 −0.30 −0.22)
-1 0 1 2 3 4 5 6 7
best fit μ=σ/σSM for mH=125 GeV

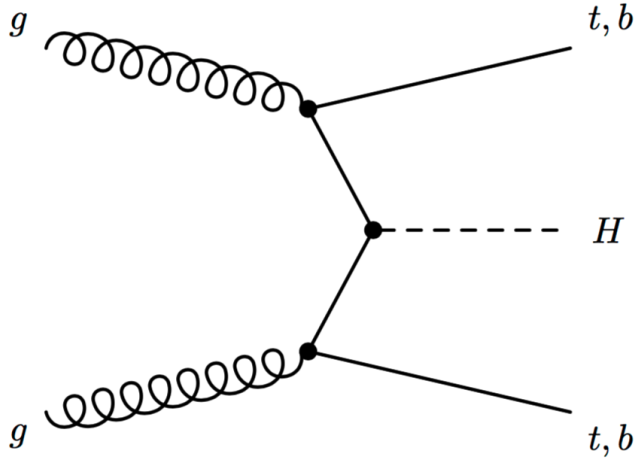

ATLAS Preliminary
√s = 13 TeV ∫Ldt = 13.2 fb-1
Data
VH(bb) (μ=1.0)
Diboson
tt̄
Single top
W+(bb,bc,cc,bl)
Z+(bb,bc,cc,bl)
Events / 0.5
Pull (stat.)
log10(S/B)

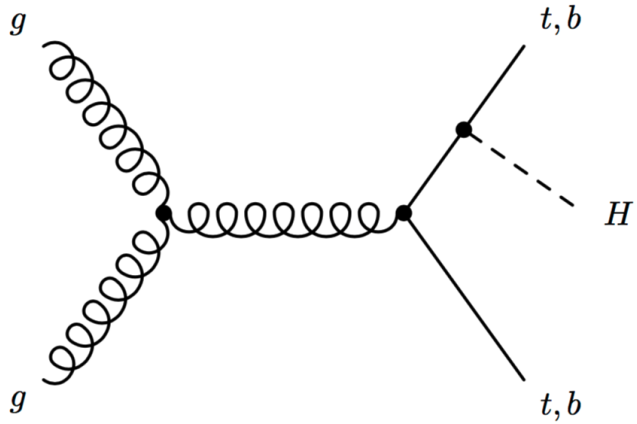

CMS
mH = 125 GeV
pp → VH; H → bb̄
Combined μ = 1.0 ± 0.5
Z(νν)H(bb)
μ = 1.0 ± 0.8
Z(l⁻l⁺)H(bb)
μ = 0.8 ± 1.0
W(lν,τν)H(bb)
μ = 1.1 ± 0.9
-2 0 2 4
Best fit μ

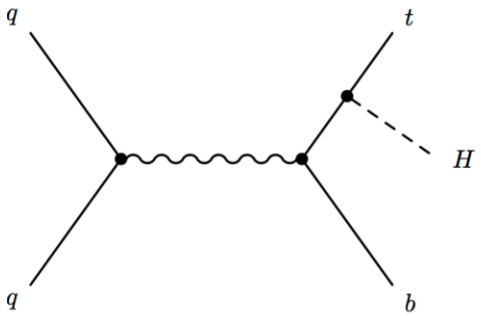

ATLAS Preliminary √s=13 TeV, ∫L dt= 13.2 fb-1
Tot.
Stat.
Tot. (Stat. Syst.)
ZH
0.15 +0.67 −0.64 (+0.49 +0.45 −0.47 −0.44)
WH
0.33 +0.95 −0.92 (+0.68 +0.68 −0.64 −0.67)
Combination
0.21 +0.51 −0.50 (+0.36 +0.36 −0.35 −0.36)
0 2 4 6 8 10
Best fit μ=σ/σSM for mH=125 GeV

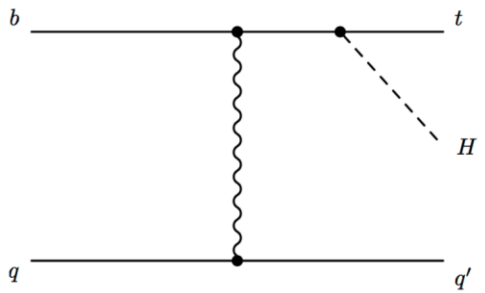

Using the full theory including the S boson
ATLAS Run-II data
SM: ggF + Xh
Xh
BSM
SM + BSM
m_H = 290 GeV
m_S = 145 GeV
m_c = 60 GeV
m_{ggF} = 0.59, $b_g^2 = 1.55^{+1.41}_{-1.36}$
$\sqrt{s}$ = 13 TeV, $h \to gg$
$d\sigma_{fid}^{gg}/dp_T^{gg}$ [fb/GeV]
p_T^{gg} [GeV]
0
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100
120
140
160
180
200

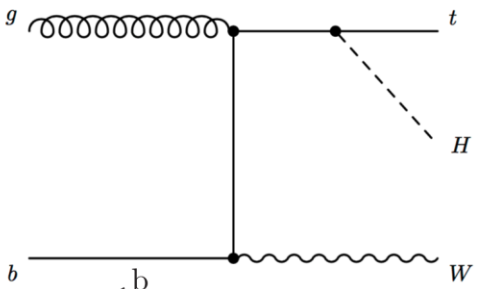

q
q
t, b
t, b
H

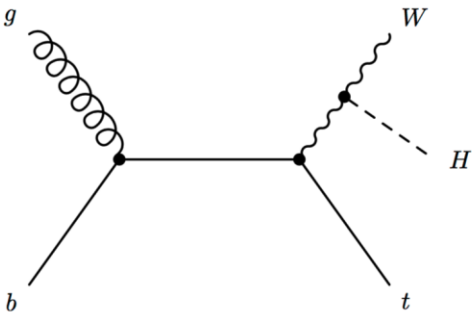

g
g
t, b
t, b
H

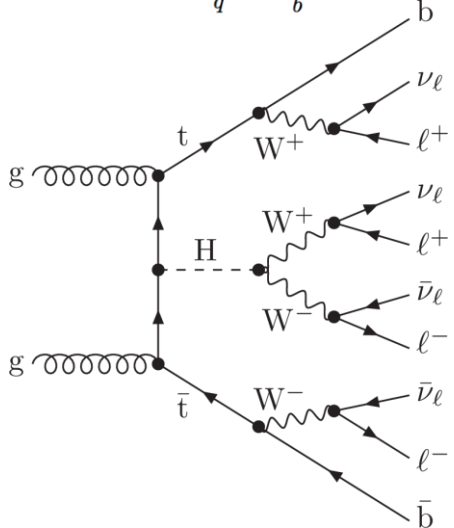

g
g
t, b
t, b
H

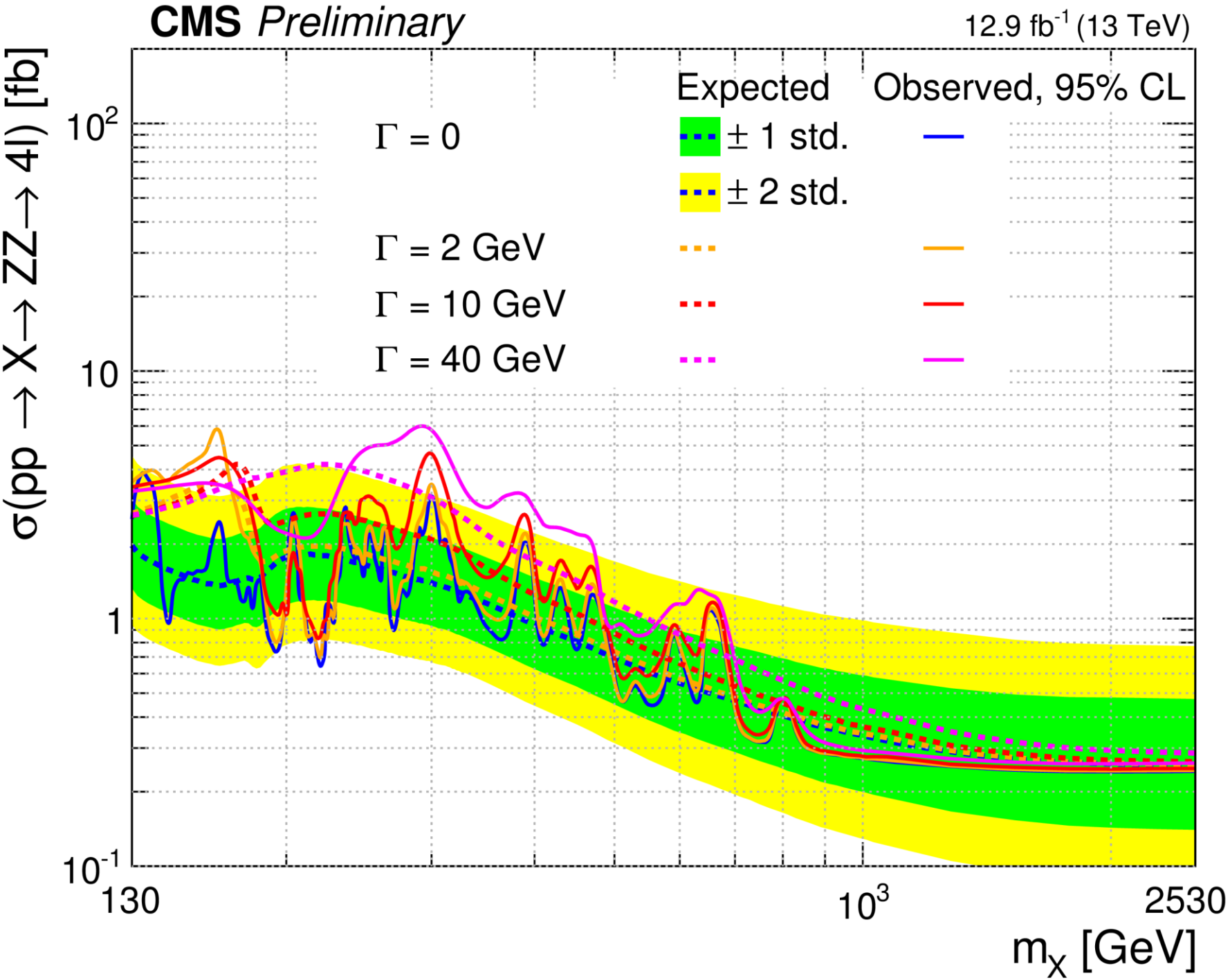

q
q
t
b
H


b
q
t
q′
H


g
b
t
W
H


g
b
W
t
H


g
g
t
t̄
H
W+
W+
W−
W−
b
ν_ℓ
ℓ+
ν_ℓ
ℓ+
ν̄_ℓ
ℓ−
ν̄_ℓ
ℓ−
b̄


CMS Preliminary
12.9 fb-1 (13 TeV)
Expected
Observed, 95% CL
± 1 std.
± 2 std.
Γ = 0
Γ = 2 GeV
Γ = 10 GeV
Γ = 40 GeV
σ(pp → X → ZZ → 4l) [fb]
10²
10
1
10⁻¹
130
10³
2530
mX [GeV]