2HDM+S and its impact on e^+e^- collisions

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Outline

- The simplified model
  - 2HDM+S
- Compatibility with multilepton data
- Impact on e^+e^- collisions
- Outlook and Conclusions

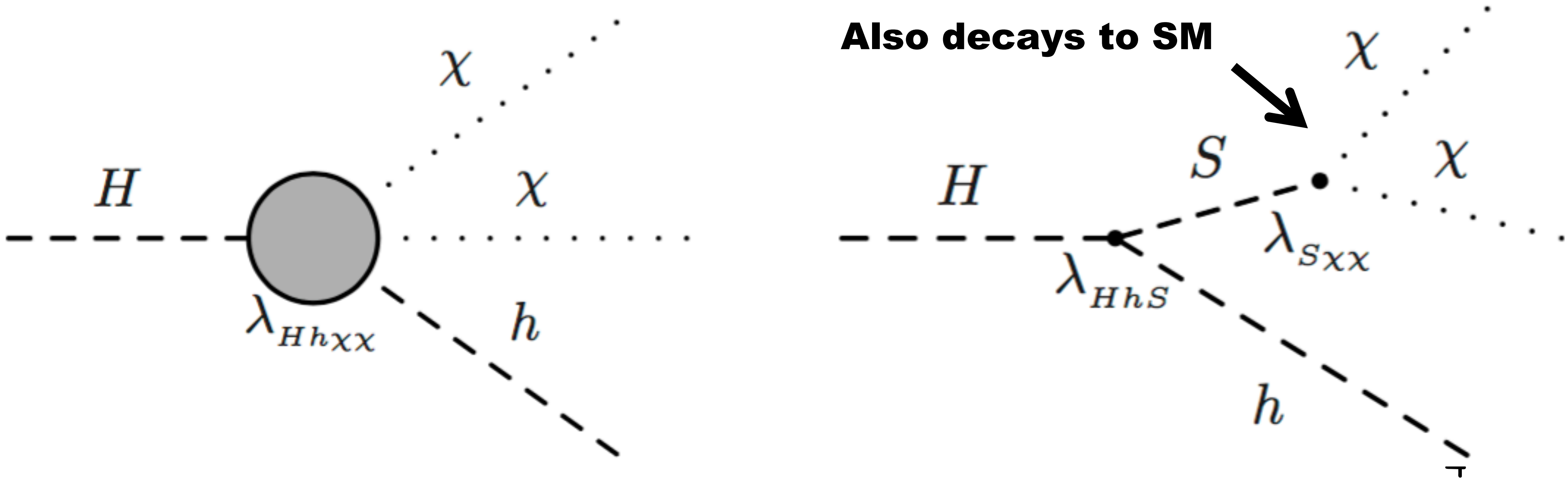
This presentation is not a complete survey of LHC data
Views expressed here are of the authors only

arXiv:1506.00612
arXiv:1603.01208
arXiv:1606.01674
arXiv:1608.03466
arXiv:1702.03426
arXiv:1706.02477
arXiv:1706.06659
arXiv:1709.09419
arXiv:1711.07874

The Simplified Model and 2HDM+S

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 Lagrangian

Can be embedded into 2HDM+S (N2HDM)
See also M.Muhlleitner et al.
arXiv:1612.01309
arXiv:1708.01578

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

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

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

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

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

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

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.

The 2HDM+S

arXiv:1606.01674

Introduce singlet real scalar, S.

2HDM potential, $\mathscr{V}(\Phi_1, \Phi_2)$

$$= m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \text{h.c.}\right)$$
$$+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2$$
$$+ \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left|\Phi_1^\dagger \Phi_2\right|^2$$
$$+ \frac{1}{2}\lambda_5 \left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right]$$
$$+ \left\{\left[\lambda_6 \left(\Phi_1^\dagger \Phi_1\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right)\right] \Phi_1^\dagger \Phi_2 + \text{h.c.}\right\}$$

2HDM+S potential

$$\mathscr{V}(\Phi_1, \Phi_2) + \frac{1}{2} m_{S_0}^2 S^2 + \frac{\lambda_{S_1}}{2} \Phi_1^\dagger \Phi_1 S^2$$
$$+ \frac{\lambda_{S_2}}{2} \Phi_2^\dagger \Phi_2 S^2 + \frac{\lambda_{S_3}}{4} (\Phi_1^\dagger \Phi_2 + \text{h.c}) S^2$$
$$+ \frac{\lambda_{S_4}}{4!} S^4 + \mu_1 \Phi_1^\dagger \Phi_1 S + \mu_2 \Phi_2^\dagger \Phi_2 S$$
$$+ \mu_3 \left[\Phi_1^\dagger \Phi_2 + \text{h.c}\right] S + \mu_S S^3.$$

Out of considerations of simplicity, assume S to be Higgs-like, leading to strong reduction of free parameters

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

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

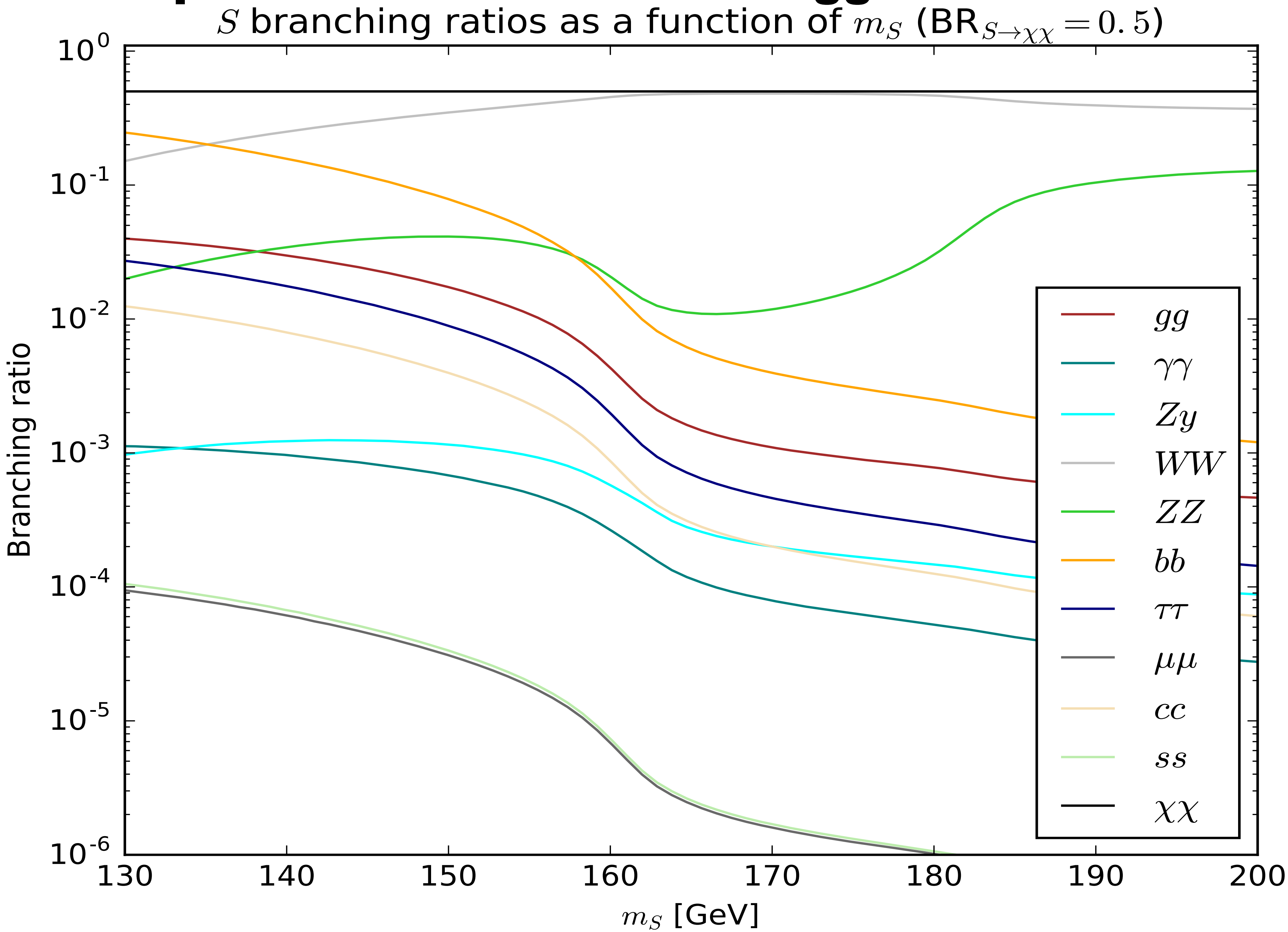
$$+ \quad H \to SS, Sh, hh$$

Dominant decays

Diboson decay

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

In a simplified model treat S as Higgs-like



The model leads to rich phenomenology. Of particular interest are multilepton signatures

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

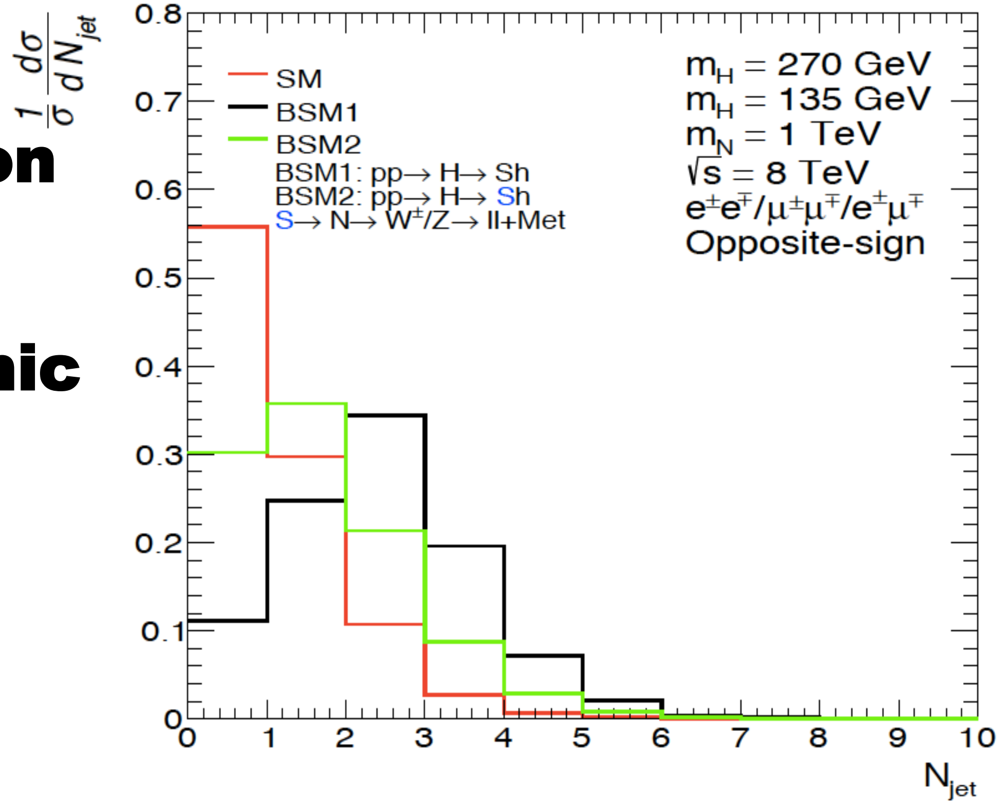
arXiv:1606.01674

arXiv:1706.06659

Impact on SM-like h measurements

- **The most prominent feature pertains to additional production mechanism (i.e. H→Sh) of h with large jet activity (from S→jets, model dependency). Expect distortion of the p_T spectrum, as well.**

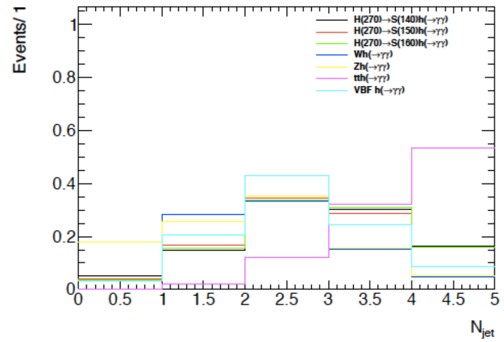
- **At this point we are studying the contamination of the H→Sh production mechanism on measurement with hadronic final states: h+≥2j, VBF, V(→jj)h, Vh(→bb) (not discussed here) h signal strengths**

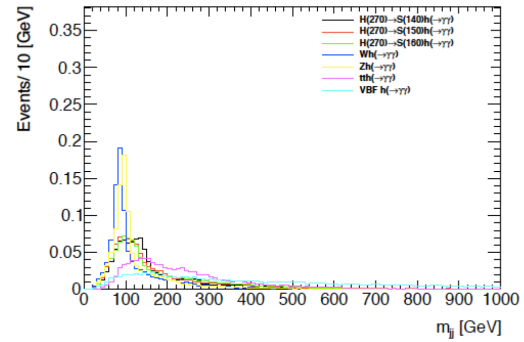


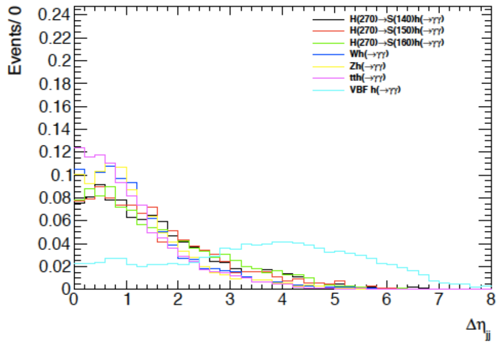
$$\sigma(H) = 10\,\mathrm{pb}$$

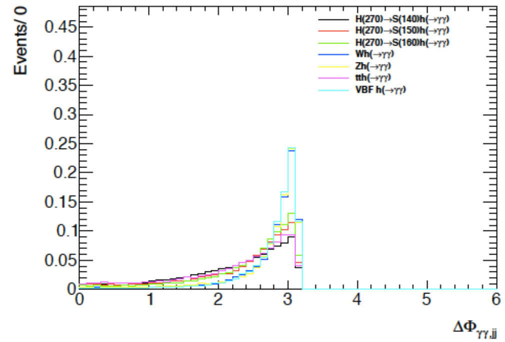
Table 1. Expected yields for $36\,\mathrm{fb}^{-1}$ of integrated luminosity for 13 TeV proton-proton center of mass energy for the VBF, Vh event selections described in Secs. 3.1 and 3.2. The $H \to Sh$ production mechanism is compared to SM associated production mechanisms. Errors correspond to the statistical error of the MC sample.

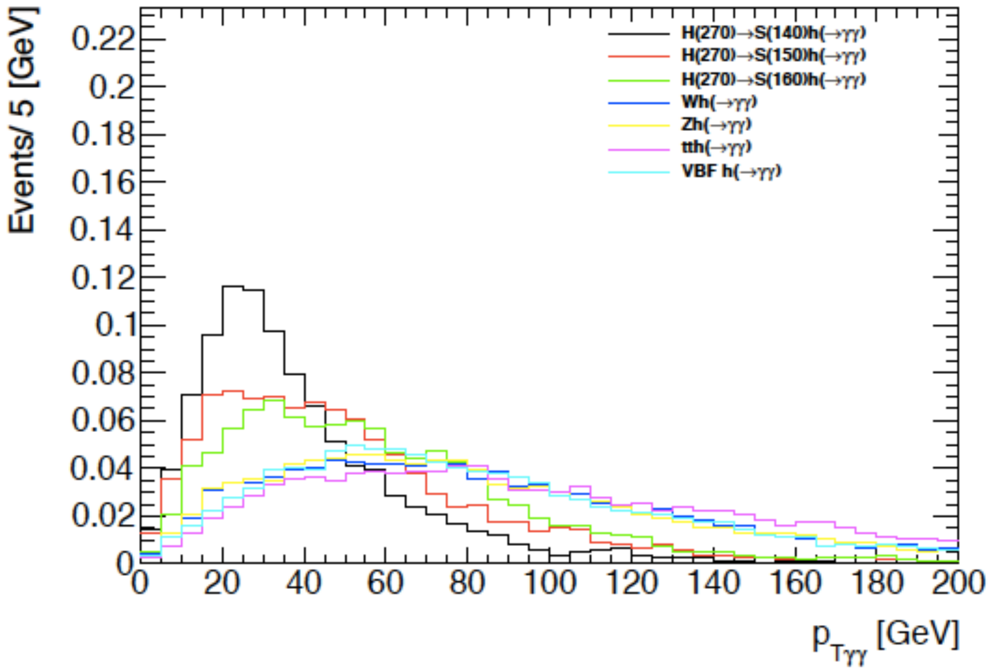
Production mechanism	VBF $h \to \gamma\gamma$	$Vh, V \to jj, h \to \gamma\gamma$
$H(270) \to S(140)h(\to \gamma\gamma)$	2.86±0.07	0.16±0.02
$H(270) \to S(150)h(\to \gamma\gamma)$	1.94±0.06	1.14±0.04
$H(270) \to S(160)h(\to \gamma\gamma)$	2.89±0.07	1.97±0.06
$Wh(\to \gamma\gamma)$	0.22±0.01	1.90±0.03
$Zh(\to \gamma\gamma)$	0.14±0.01	1.31±0.02
$tth(\to \gamma\gamma)$	0.09±0.00	0.22±0.01
VBF $h(\to \gamma\gamma)$	25.81±0.20	0.30±0.02

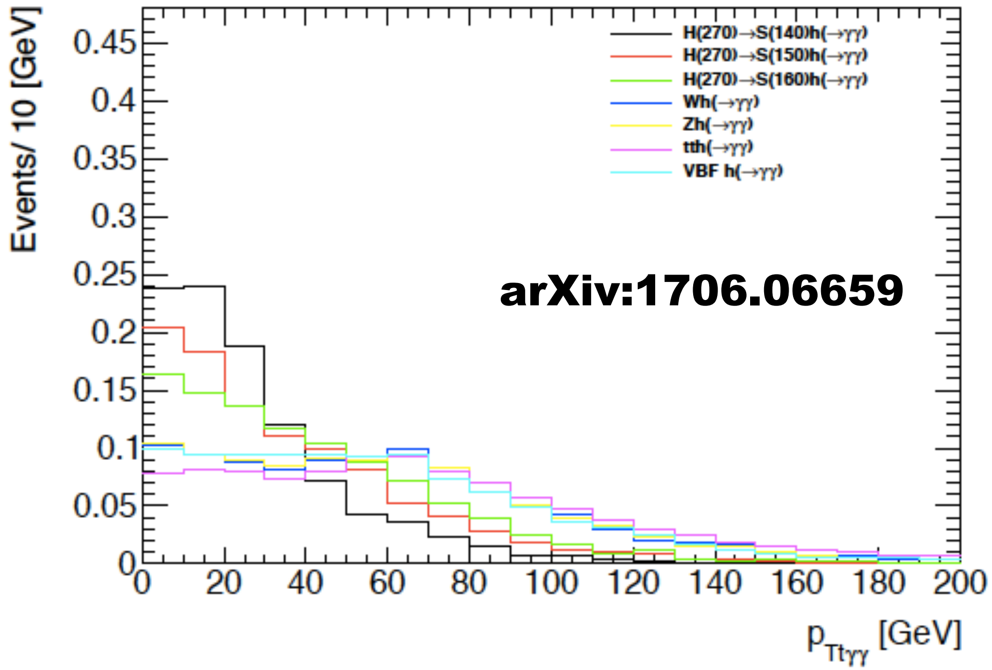












With the following inputs from Run I and Run II:

$$\mu_{fid}^{\gamma\gamma,ZZ} = 1.068 \pm 0.0745(\text{exp})$$

$$\mu_{h+2j(ggF+2j)} = 1.99 \pm 0.29$$

~3σ tension driven by Run I results

Symptoms in Higgs data:

1. **More jets**
2. **Presence of soft Ws**
3. **Elevated tth->NI**

$$\mu_{0j,1j}^{WW} = 0.9 \pm 0.14$$

$$\mu_{VBF} = 1.22 \pm 0.19$$

$$\mu_{Vh,V\to jj}^{II} = 2.04 \pm 1.1$$

and assuming H→Sh, with S being SM-like, one gets:

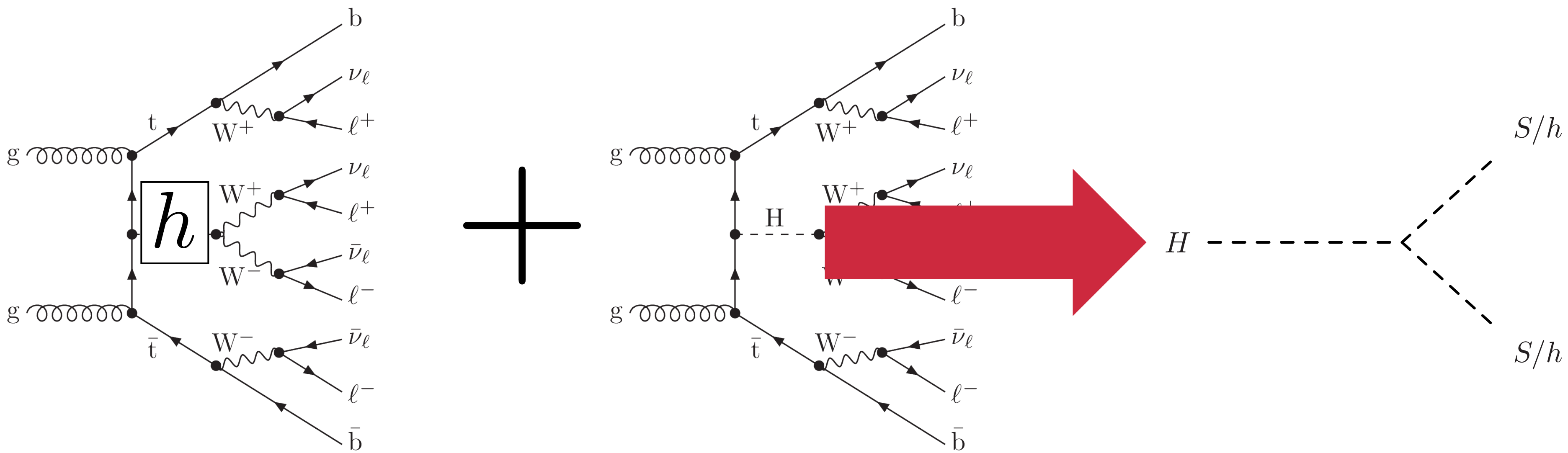
To be updated with new results from the LHC

$$\beta_g^2 = 1.4 \pm 0.4$$

$$\mu_h = 0.79 \pm 0.12$$

Compatibility with Multilepton data

Top associated Higgs production
(Multilepton final state)



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

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

Reference	Channel	Measured μ_{tth}
CMS Run 1 [35]	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 [36]	$2\ell 0\tau_{\mathrm{had}}$	$2.8^{+2.1}_{-1.9}$
	3ℓ	$2.8^{+2.2}_{-1.8}$
	$2\ell 1\tau_{\mathrm{had}}$	$-0.9^{+3.1}_{-2.0}$
	4ℓ	$1.8^{+6.9}_{-2.0}$
	$1\ell 2\tau_{\mathrm{had}}$	$-9.6^{+9.6}_{-9.7}$
	Combination	$2.1^{+1.4}_{-1.2}$
CMS Run 2 [37]	Same-sign 2ℓ	$1.7^{+0.6}_{-0.5}$
	3ℓ	$1.0^{+0.8}_{-0.7}$
	4ℓ	$0.9^{+2.3}_{-1.6}$
	Combination	$1.5^{+0.5}_{-0.5}$
ATLAS Run 2 [38]	$2\ell 0\tau_{\mathrm{had}}$	$4.0^{+2.1}_{-1.7}$
	3ℓ	$0.5^{+1.7}_{-1.6}$
	$2\ell 1\tau_{\mathrm{had}}$	$6.2^{+3.6}_{-2.7}$
	4ℓ	< 2.2
	Combination	$2.5^{+1.3}_{-1.1}$
Error weighted mean		1.92 ± 0.38

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:

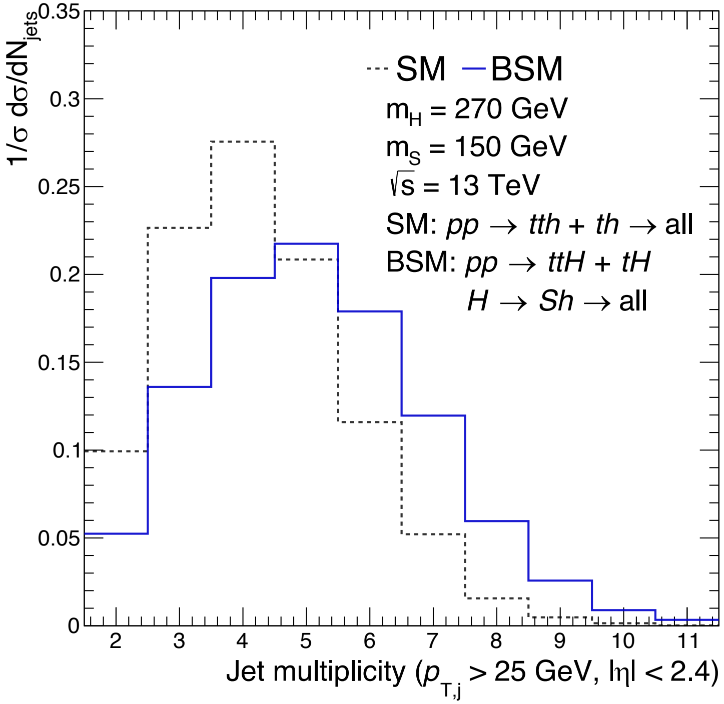
$$\mu = 1.92 \pm 0.38$$

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

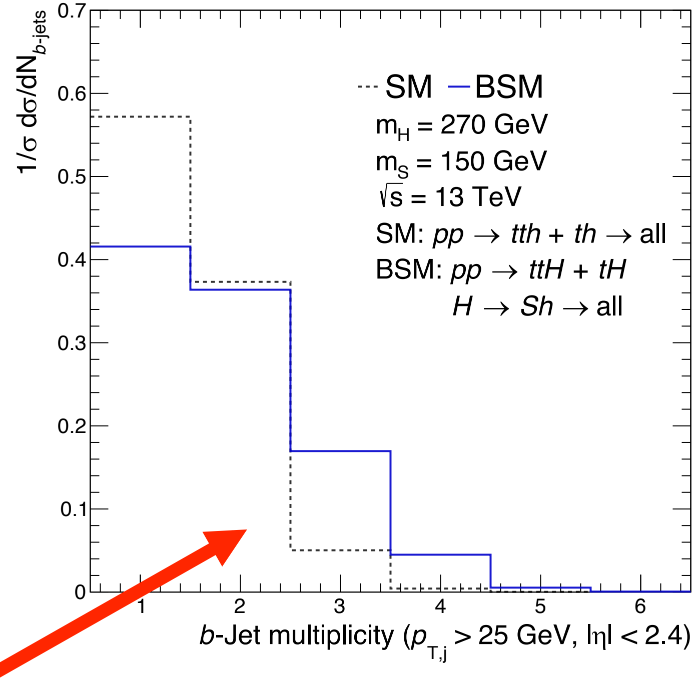
Need insight into the kinematics of the leptons and jet activity of these events.

New results do not change picture (see below)

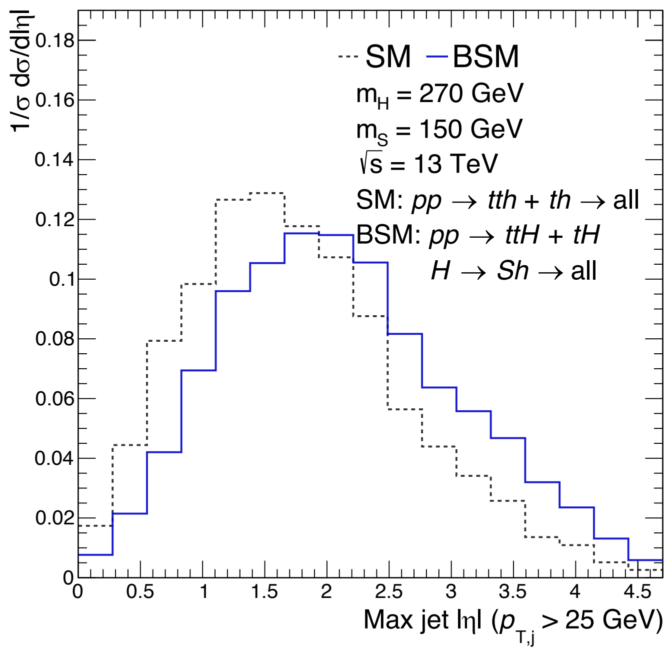
arXiv:1711.07874

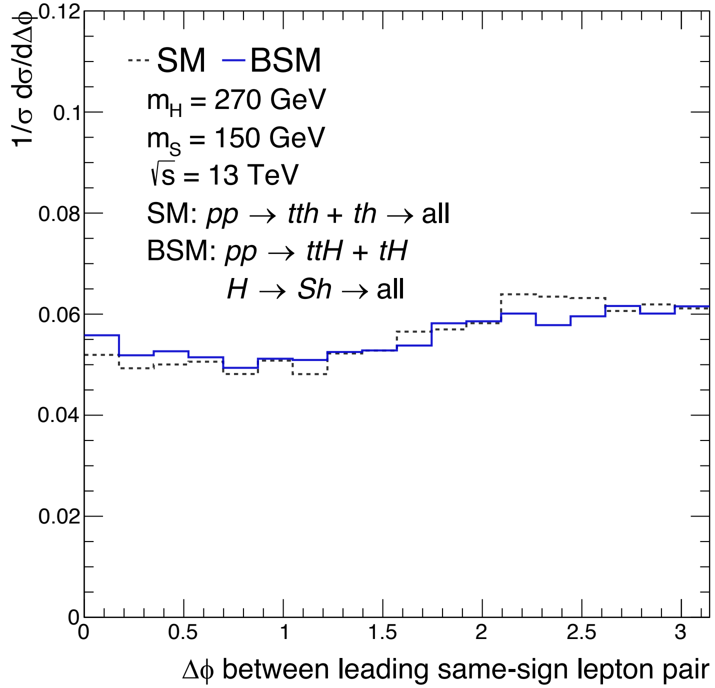


Relevant kinematic distributions for SS and 3 or more leptons



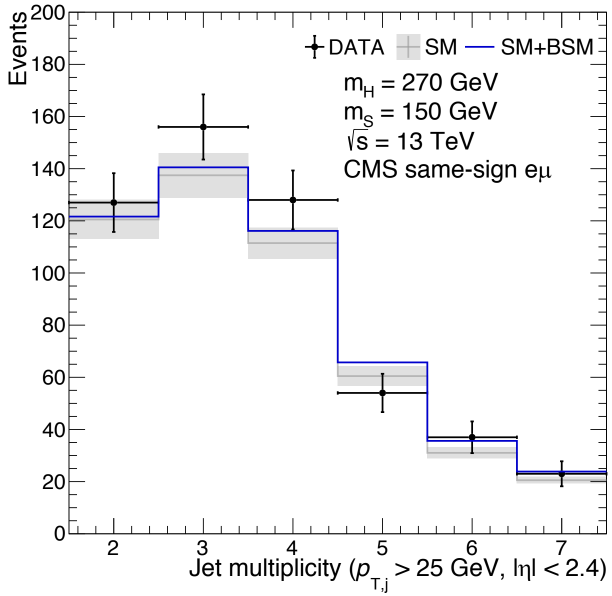
The production with SS+3l with 3 or more b-jets is a very important prediction of the simplified model



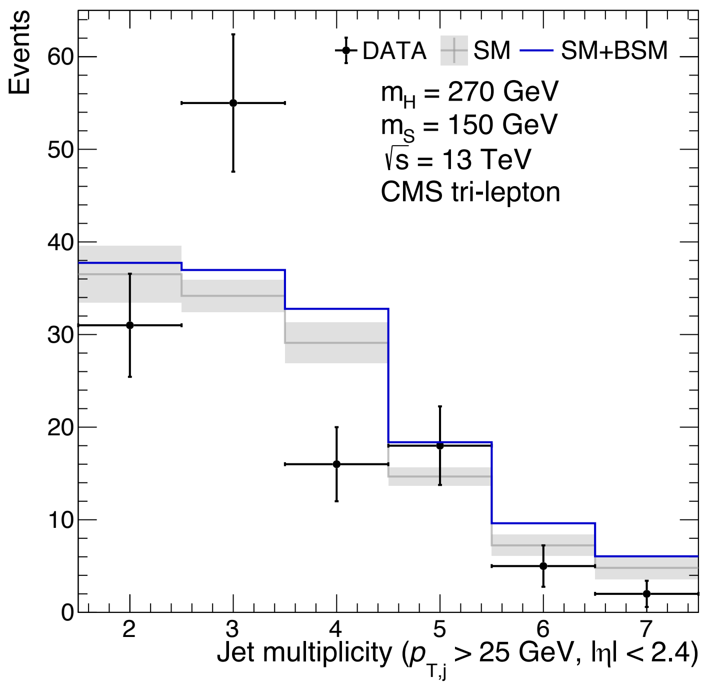


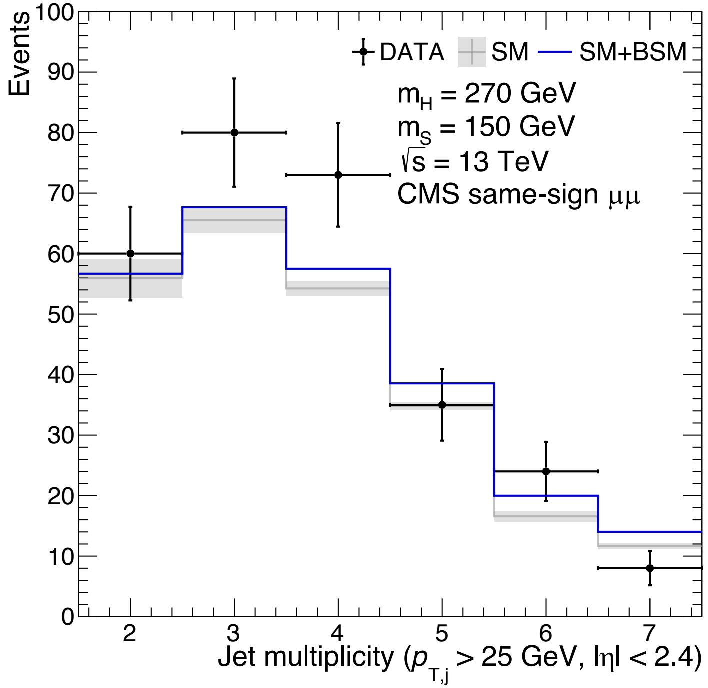
Data & SM MC from CMS-PAS-HIG-17-005

Event selection	
No lepton pair with $m_{\ell\ell} < 12$ GeV $N_{b\text{-jets}} \geq 1$ $N_{\text{jets}} \geq 1$ (not including b-jets)	
Event categorisation	
Same-sign 2 lepton	*Tri-lepton*
Exactly 2 same-sign leptons $\ell\ell = e\mu$ or $\mu\mu$ Leading lepton $p_T > 25$ GeV Sub-leading lepton $p_T > 15$ GeV	Exactly 3 leptons Leading lepton $p_T > 25$ GeV Second and third lepton $p_T > 15$ GeV No lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 15$ GeV



Study of SS di-lepton and 3 or more leptons with at least one b-jet





Channel	Number of BSM candidate events	β_g^2
$e\mu$	37.04 ± 12.10	3.03 ± 0.99
$\mu\mu$	37.22 ± 17.52	4.25 ± 2.00
Tri-lepton	6.00 ± 5.52	0.75 ± 0.69
Combined		1.69 ± 0.54

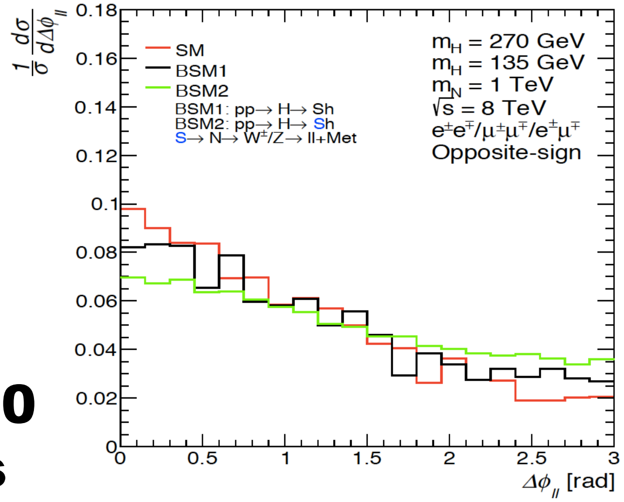
Table 2 The number of BSM candidate events and the corresponding values of β_g^2 for each channel in the CMS Run 2 search in Ref. [38] (see text). The combined result is calculated as the error weighted mean of the individual values calculated for each channel.

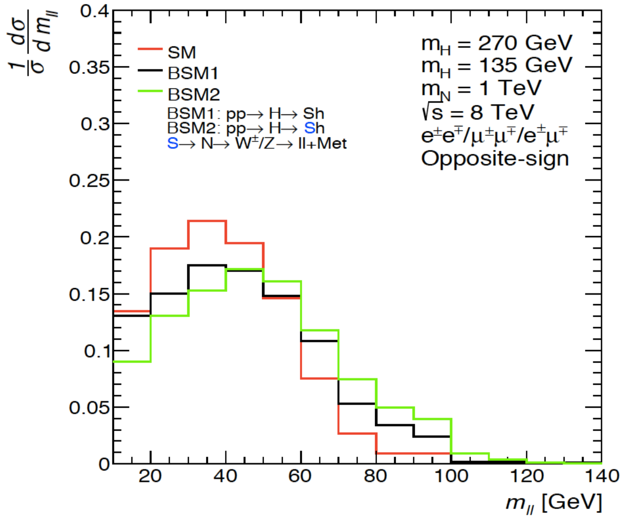
What appears as a ~1σ discrepancy in terms of μ_{tth}, is coupled with a 3.1σ effect in the distributions studied. Is μ_{tth} the measure of the compatibility of the data with the SM? Combined with the rest of μ_{tth} results leads to an effect of 3.8σ in available multi-lep + b-jet data.

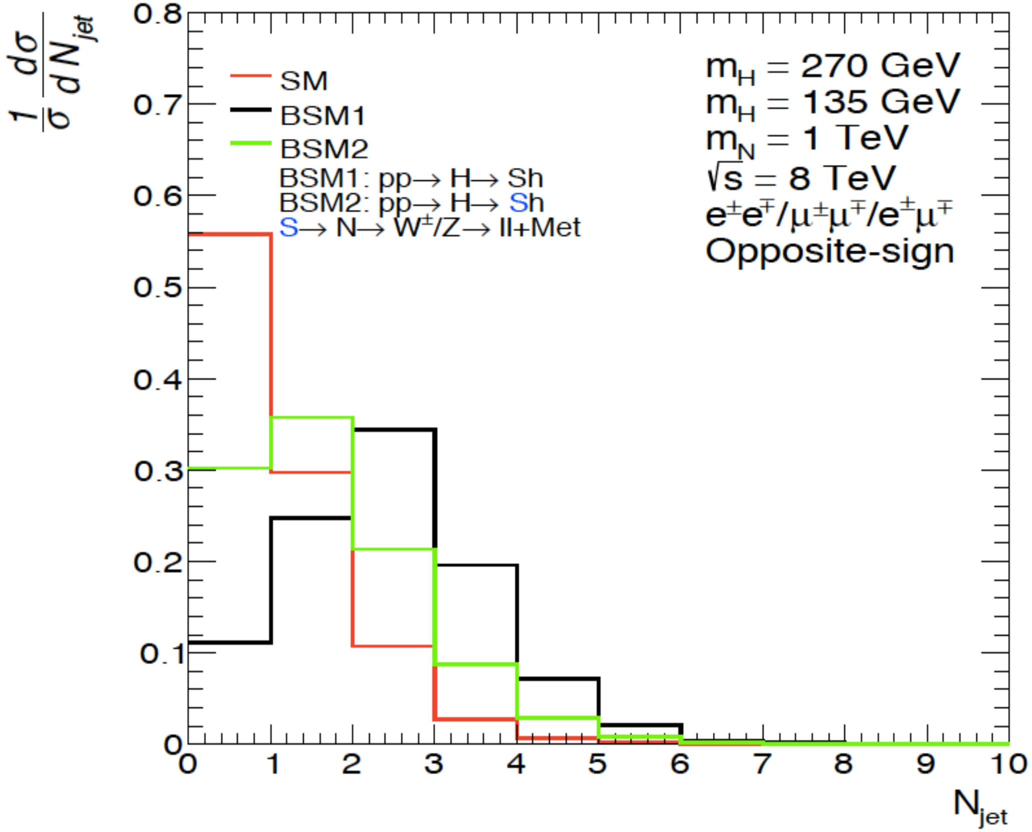
A prediction:
$H \rightarrow Sh, hh \rightarrow l^+l^- + \text{jets} + \text{MET}$

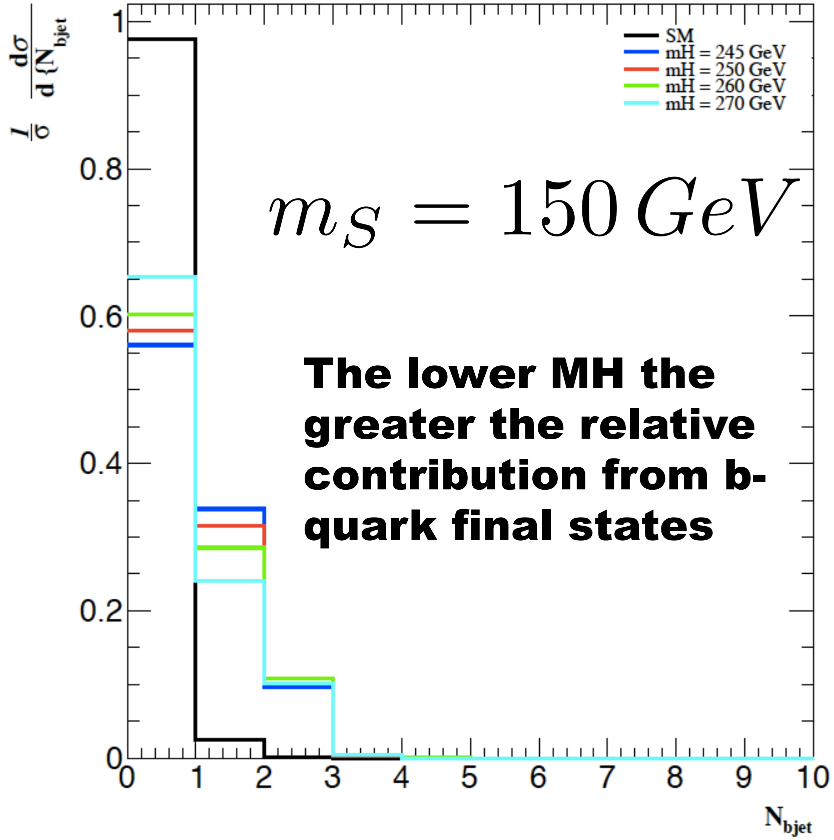
$$pp \to H \to Sh$$
$$\to \ell^+\ell^- + X$$

Expect di-leptons (m_{ll}<100 GeV) with jets and b-jets









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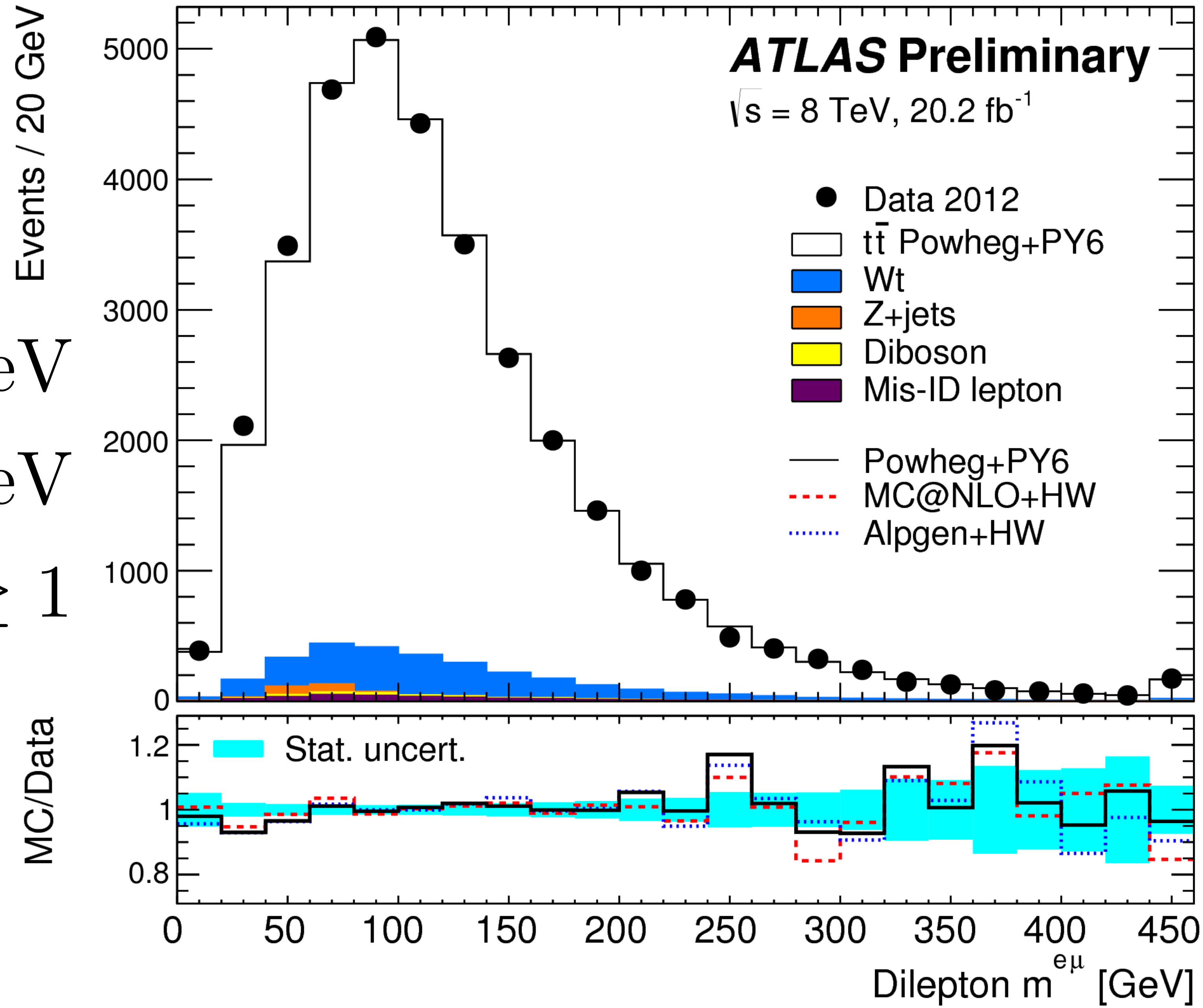
$$p_{T\ell} > 25\,\mathrm{GeV}$$

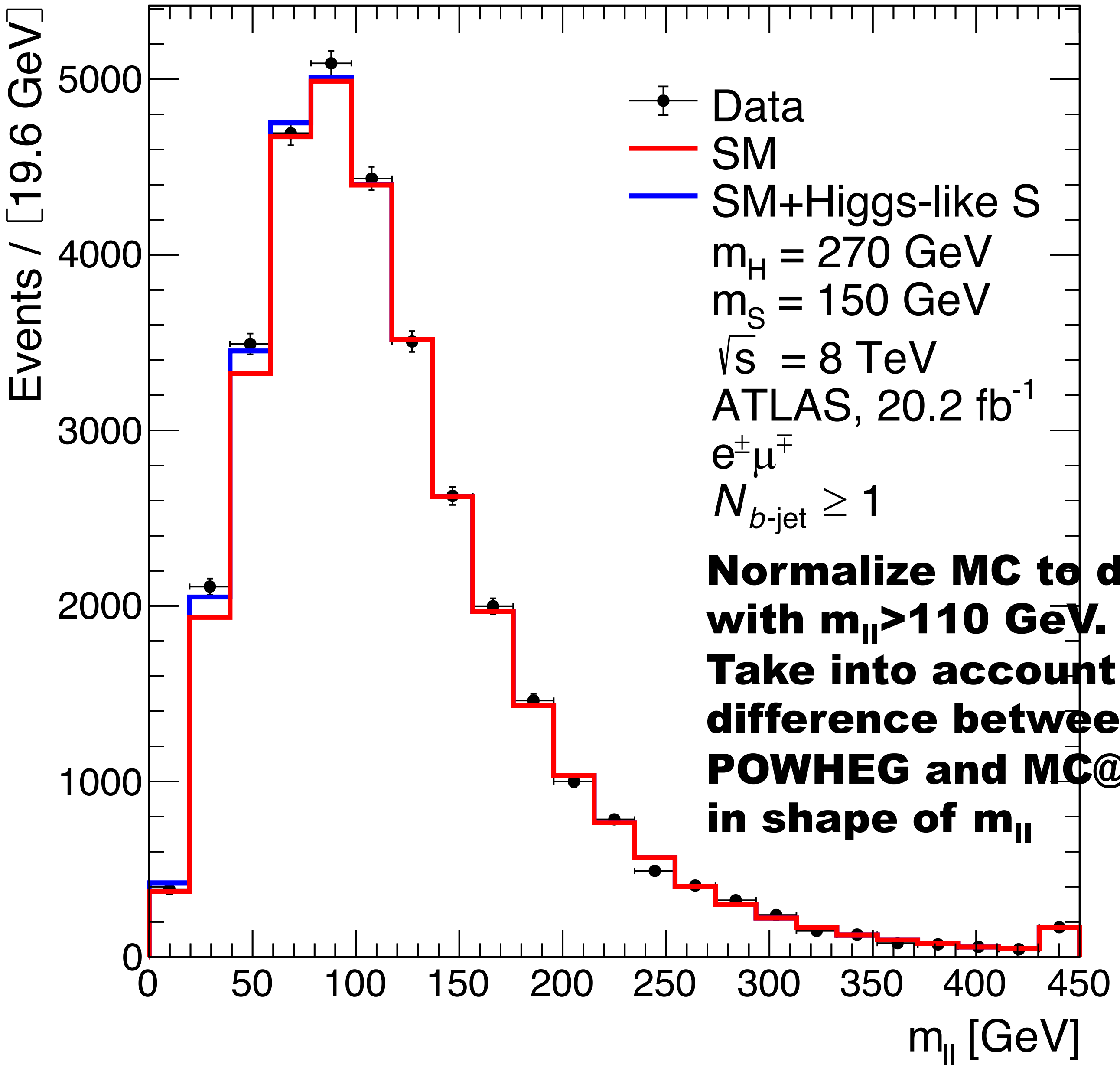
$$p_{Tb} > 25\,\mathrm{GeV}$$

$$N_{bjet} \geq 1$$

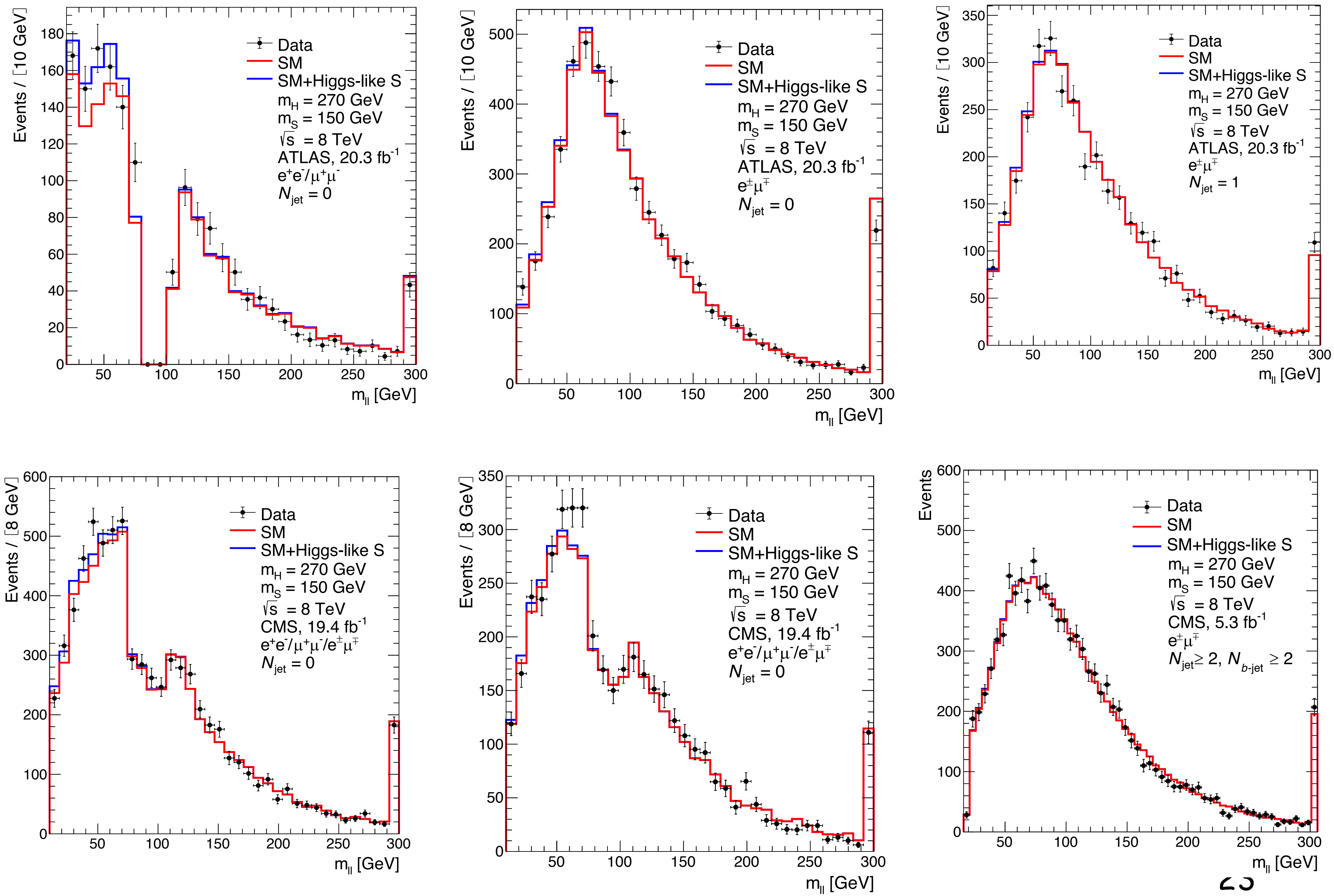


Performed scan floating m_S (m_H=270 GeV), for m_{ll}<100 GeV
Best fit 150±5 GeV.

arXiv:1711.07874



Normalize MC to data with m_{ll}>110 GeV. Take into account difference between POWHEG and MC@NLO in shape of m_{ll}


Events / [10 GeV]
Data
SM
SM+Higgs-like S
m_H = 270 GeV
m_S = 150 GeV
√s = 8 TeV
ATLAS, 20.3 fb^-1
e+e-/μ+μ-
N_jet = 0
m_ll [GeV]
Events / [10 GeV]
Data
SM
SM+Higgs-like S
m_H = 270 GeV
m_S = 150 GeV
√s = 8 TeV
ATLAS, 20.3 fb^-1
e±μ∓
N_jet = 0
m_ll [GeV]
Events / [10 GeV]
Data
SM
SM+Higgs-like S
m_H = 270 GeV
m_S = 150 GeV
√s = 8 TeV
ATLAS, 20.3 fb^-1
e±μ∓
N_jet = 1
m_ll [GeV]
Events / [8 GeV]
Data
SM
SM+Higgs-like S
m_H = 270 GeV
m_S = 150 GeV
√s = 8 TeV
CMS, 19.4 fb^-1
e+e-/μ+μ-/e±μ∓
N_jet = 0
m_ll [GeV]
Events / [8 GeV]
Data
SM
SM+Higgs-like S
m_H = 270 GeV
m_S = 150 GeV
√s = 8 TeV
CMS, 19.4 fb^-1
e+e-/μ+μ-/e±μ∓
N_jet = 0
m_ll [GeV]
Events
Data
SM
SM+Higgs-like S
m_H = 270 GeV
m_S = 150 GeV
√s = 8 TeV
CMS, 5.3 fb^-1
e±μ∓
N_jet ≥ 2, N_b-jet ≥ 2
m_ll [GeV]

arXiv:1711.07874

Measurement	Reference	Expected events	Post-fit event yield	β_g^2	$\chi^2_{SM} - \chi^2_{SM+BSM}$
ATLAS, 20.2 fb^{-1} $e^\pm\mu^\mp$ $N_{b\text{-jet}} \geq 1$	[28]	112 ± 26	397 ± 93	4.89 ± 1.15	12.11
ATLAS, 20.3 fb^{-1} $e^\pm\mu^\mp$ $N_{\text{jet}} = 0$	[29]	28 ± 6	48 ± 46	2.37 ± 2.27	0.43
ATLAS, 20.3 fb^{-1} e^+e^-, $\mu^+\mu^-$ $N_{\text{jet}} = 0$	[29]	16 ± 4	82 ± 20	7.07 ± 1.73	7.31
ATLAS, 20.3 fb^{-1} $e^\pm\mu^\mp$ $N_{\text{jet}} = 1$	[30]	70 ± 16	20 ± 36	0.39 ± 0.71	0.16
CMS, 19.4 fb^{-1} e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$ $N_{\text{jet}} = 0$	[31]	46 ± 11	136 ± 58	4.08 ± 1.74	3.31
CMS, 19.4 fb^{-1} e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$ $N_{\text{jet}} = 1$	[31]	111 ± 26	46 ± 43	0.57 ± 0.53	0.58
CMS, 5.3 fb^{-1} e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$ $N_{\text{jet}} \geq 2$, $N_{b\text{-jet}} \geq 2$	[32]	25 ± 6	17 ± 58	0.94 ± 3.20	-0.04

Table 1 Best fits to the di-lepton invariant mass spectra reported by ATLAS and CMS at a proton-proton centre of mass of $\sqrt{s} = 8$ TeV. The post-fit event yield reflects the number of BSM events required to fit the data (in excess of the SM prediction). The value of β_g^2 corresponding to the post-fit event yield is reported along with the test statistic $\chi^2_{SM} - \chi^2_{SM+BSM}$ in order to gauge the significance of the fit. The mass of the heavy scalar is fixed at $m_H = 270$ GeV and the mass of S is allowed to vary, where the best fit is found for $m_S = 150$ GeV. For simplicity, it is assumed that H decays exclusively into Sh.

Systematic excess in di-lepton data with predicted rate.
Assuming simplified model, 3.2σ excess

arXiv:1711.07874

Interpretation of data with m_H=270 GeV and m_S=150 GeV ($gg \rightarrow H \rightarrow Sh$)

Data set	Extracted β_g^2
Higgs boson signal strengths, h+jets···	$\beta_g^2 = 1.38 \pm 0.32$
Leptons + b-jets	$\beta_g^2 = 1.69 \pm 0.54$
Dileptons + jets	$\beta_g^2 = 1.22 \pm 0.38$

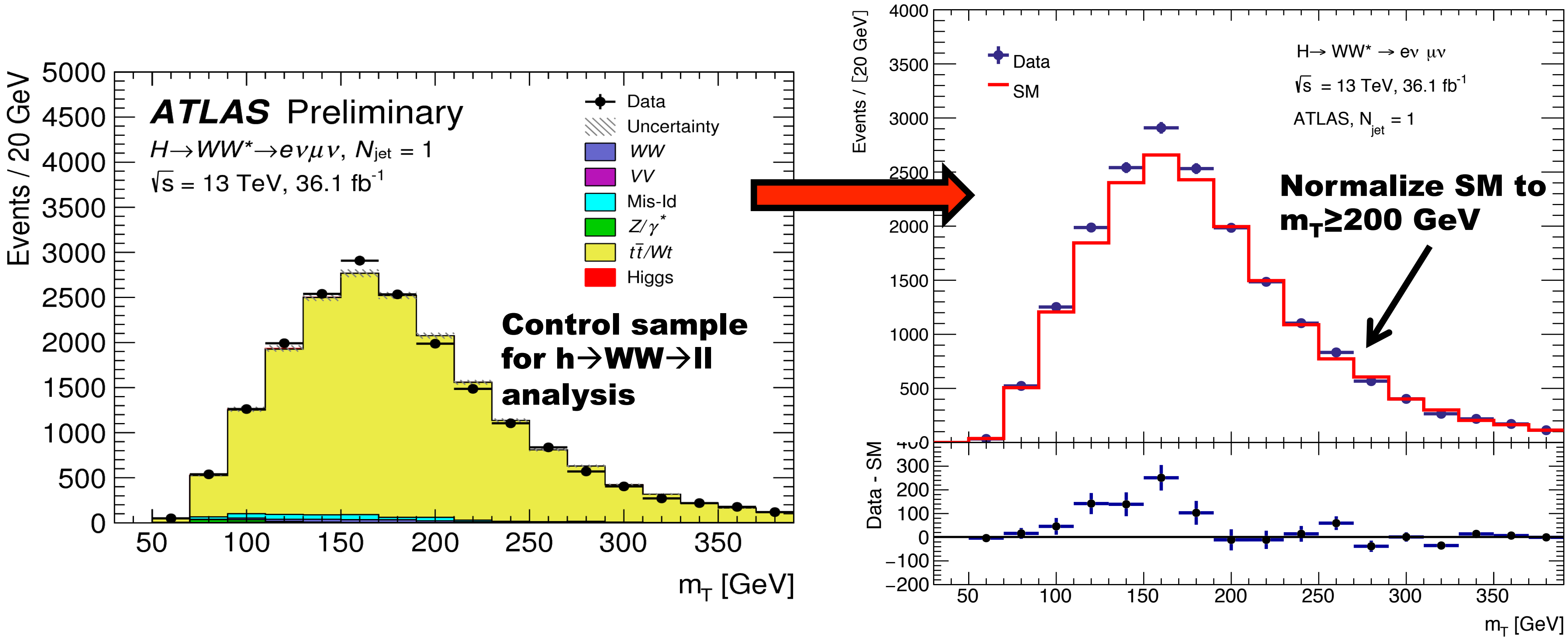
$$\beta_g^2 = 1.38 \pm 0.22$$

Where the absence of BSM signal would correspond to β_g^2=0. This strong deviation from 0 does not include the analysis of the hh, VV and other deviations in the data. This is to come (paper in preparation).

First l^+l^- + MET+ b-jet results in Run II

ATLAS−CONF−2018−004

Process	Matrix Element (Alternative)	PDF	PS (Alternative)	Precision σ
$t\bar{t}$	POWHEG-BOX v2 [38] SHERPA 2.2.1	NNPDF3.0NLO	PYTHIA 8 [39] (HERWIG 7)	NNLO+NNLL [40]
Wt	POWHEG-BOX v1 [41]	CT10 [35]	PYTHIA 6.428 [42]	NLO [41]



Top control sample with exactly two leptons, one b-jet and no more jets. Expect relative enhancement of Wt w.r.t. tt. <u>Currently studying effect of Wt/tt interferences.</u>

Impact on e^+e^- collisions

Coupling of the SM-like h boson to VV

M.Kumar et al. in preparation

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = \mathbb{R} \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix},$$

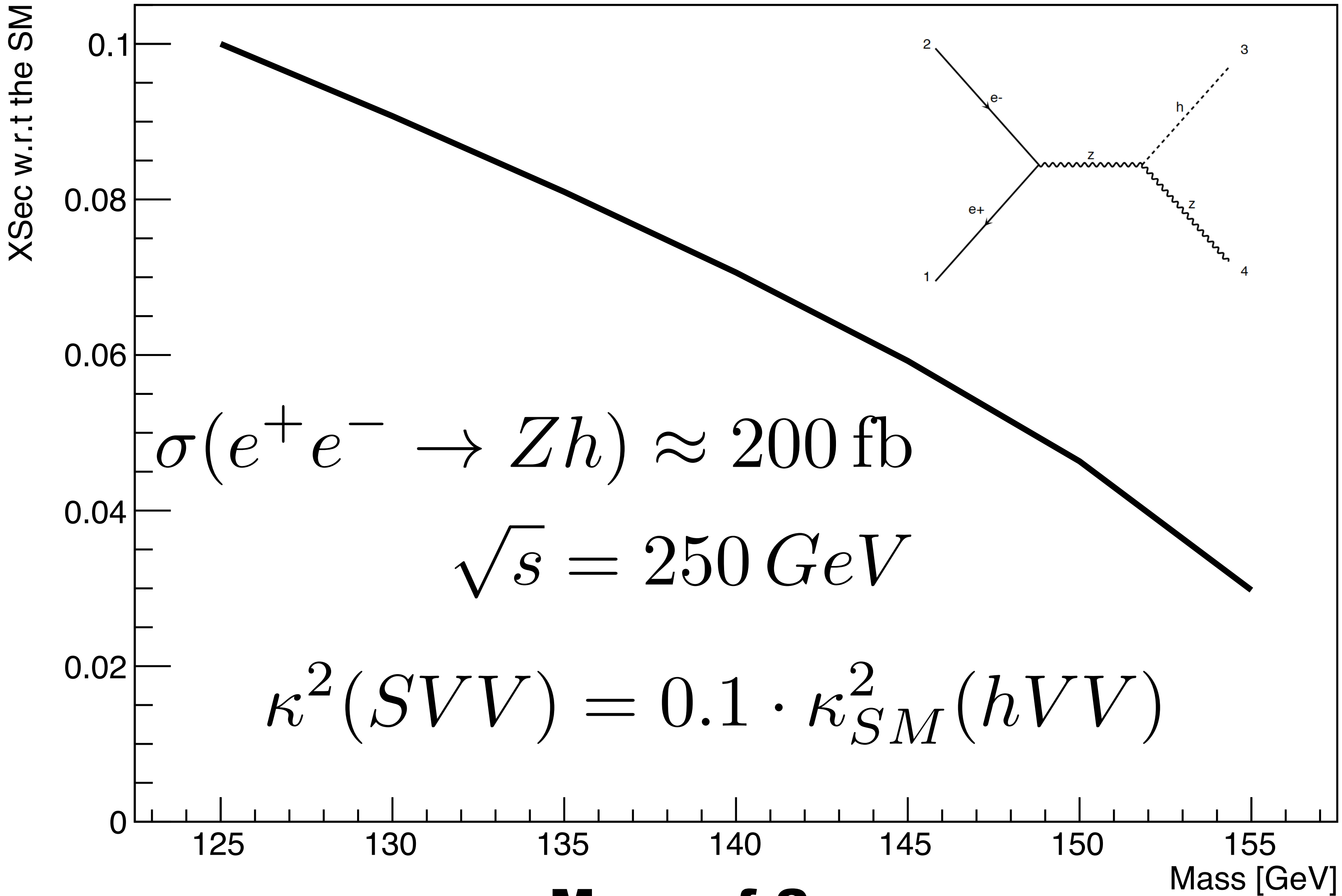
Mass-matrix for the CP-even scalar sector will modified with respect to 2HDM and that needs a 3 x3 matrix (three mixing angles). Couplings are modified.

$$\mathbb{R} = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

$$M^2_{\mathrm{CP-even}} = \begin{pmatrix} 2\lambda_1 v_1^2 - m_{12}\frac{v_2}{v_1} & m_{12} + \lambda_{345} v_1 v_2 & 2\kappa_1 v_1 v_S \\ m_{12} + \lambda_{345} v_1 v_2 & -m_{12}\frac{v_2}{v_1} + 2\lambda_2 v_2^2 & 2\kappa_2 v_2 v_S \\ 2\kappa_1 v_1 v_S & 2\kappa_2 v_2 v_S & \frac{1}{3}\lambda_S v_S^2 \end{pmatrix}$$

$$\kappa(hVV) < \kappa_{SM}(hVV)$$

Cross-section of S through s-channel $e^+e^- \rightarrow Z^* \rightarrow Zh$



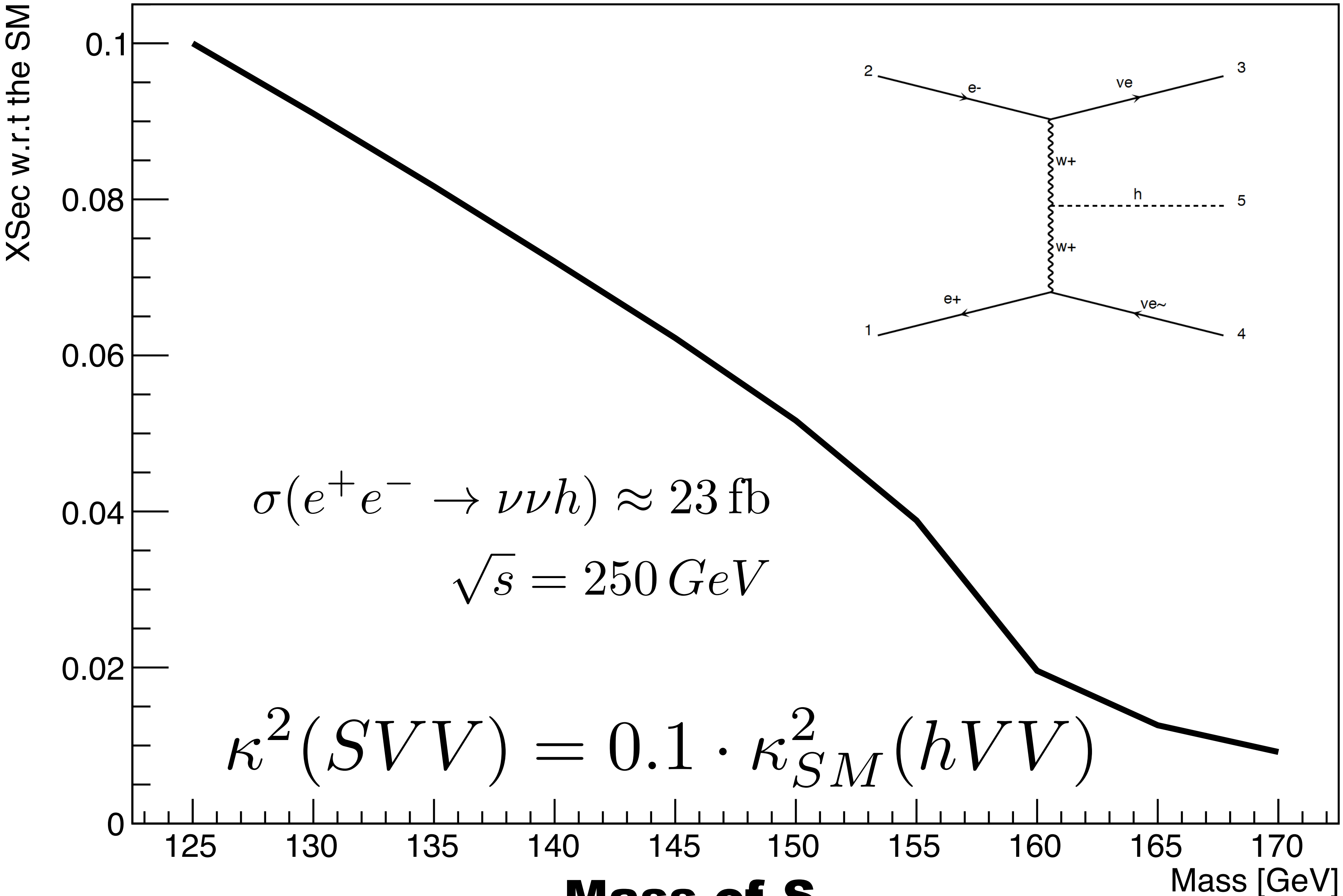
$$\sigma(e^+e^- \rightarrow Zh) \approx 200\,\mathrm{fb}$$

$$\sqrt{s} = 250\,GeV$$

$$\kappa^2(SVV) = 0.1 \cdot \kappa^2_{SM}(hVV)$$

Mass of S

Cross-section of S through t-channel $e^+e^-\to vvh$



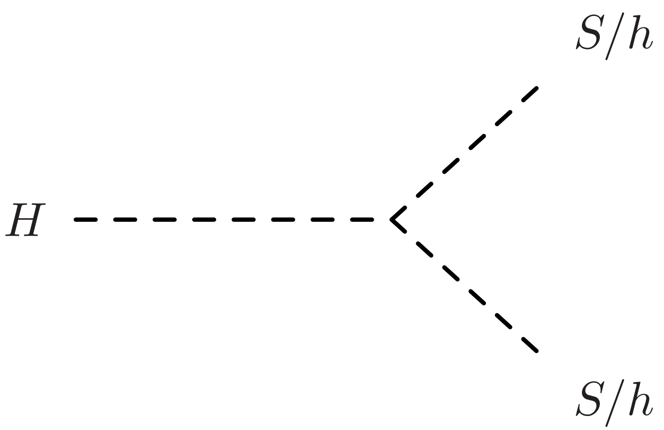
Mass of S

Outlook and Conclusions

- A simplified model that introduces two scalars, H and S is introduced. This simplified model is embedded into a 2HDM+S structure
- Phenomenology of 2HDM+S becomes more complex with respect to a plain 2HDM
- Of particular relevance is the anomalous production of multiple leptons, which can also be produced in association with b-jets
- Started to look at the impact on e+e-
  - The coupling of the SM-like h to VV is reduced, which can be probed in e^+e^- collisions
  - Given current constraints from the LHC, a Higgs-like scalar, S, has sufficiently large cross-section in e^+e^- with a CME around 250 GeV.

Additional Slides

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

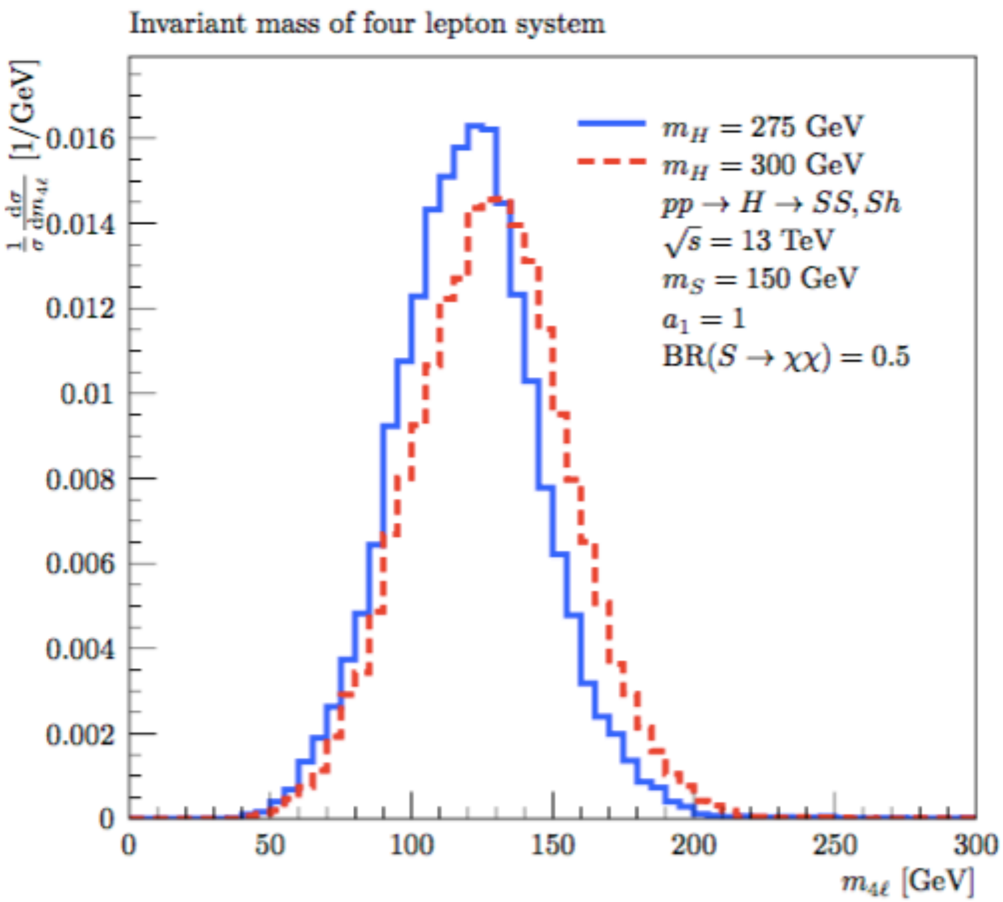


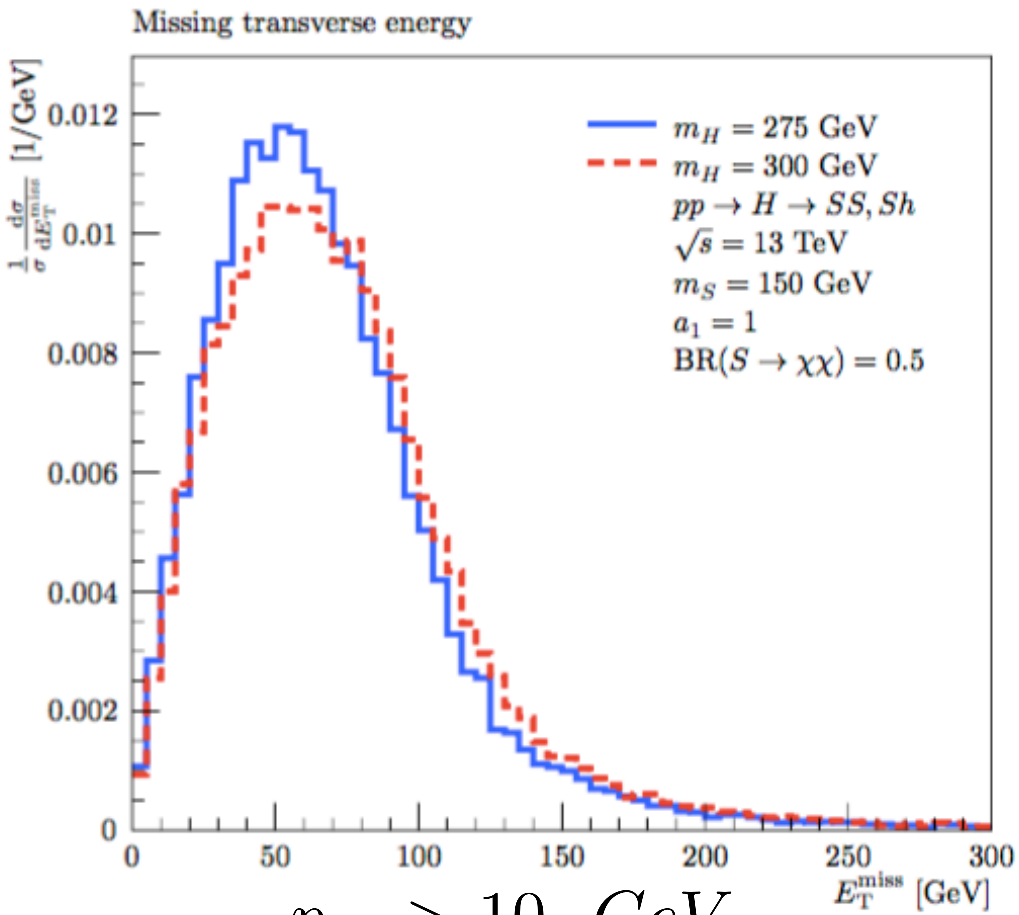
$$S, h \to WWWW, WWZZ, ZZ$$
$$\to 4l + X$$

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

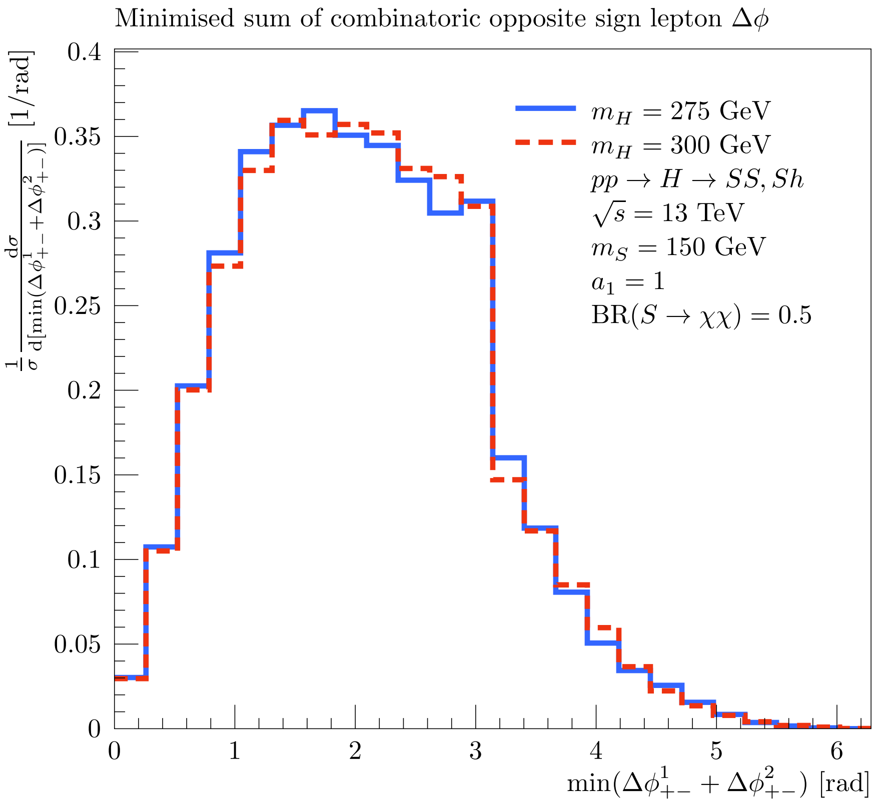


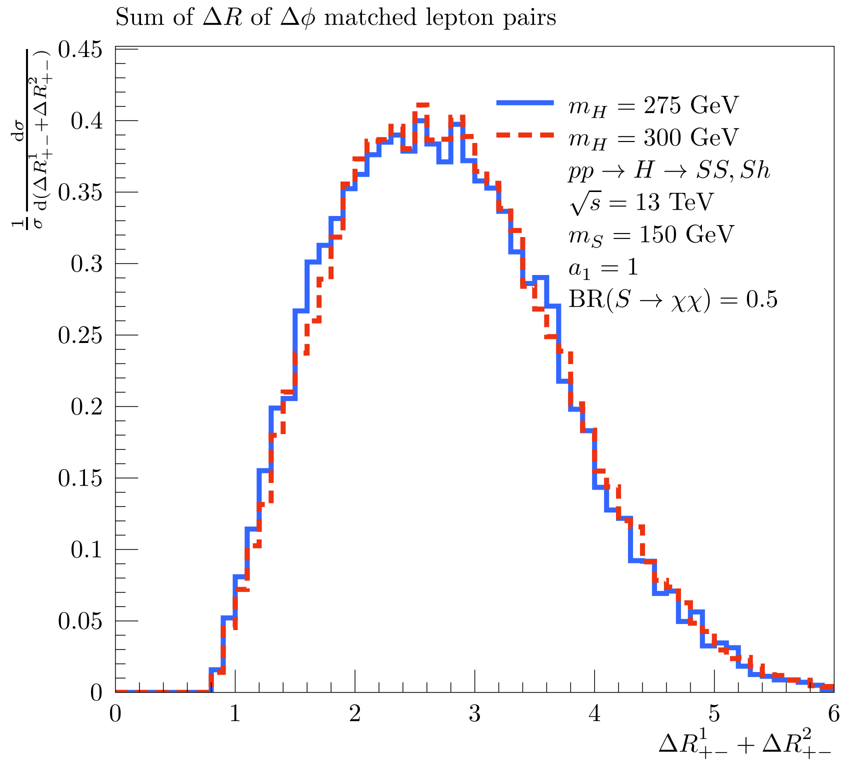


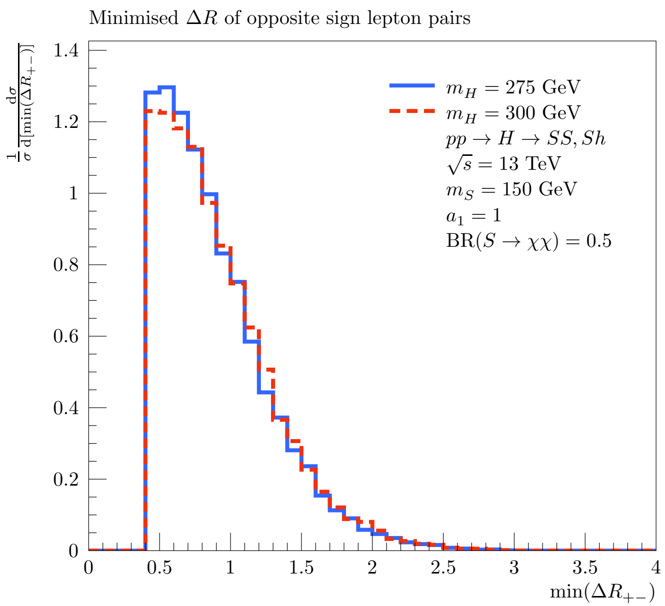
$p_{Tl} > 10 \quad GeV$

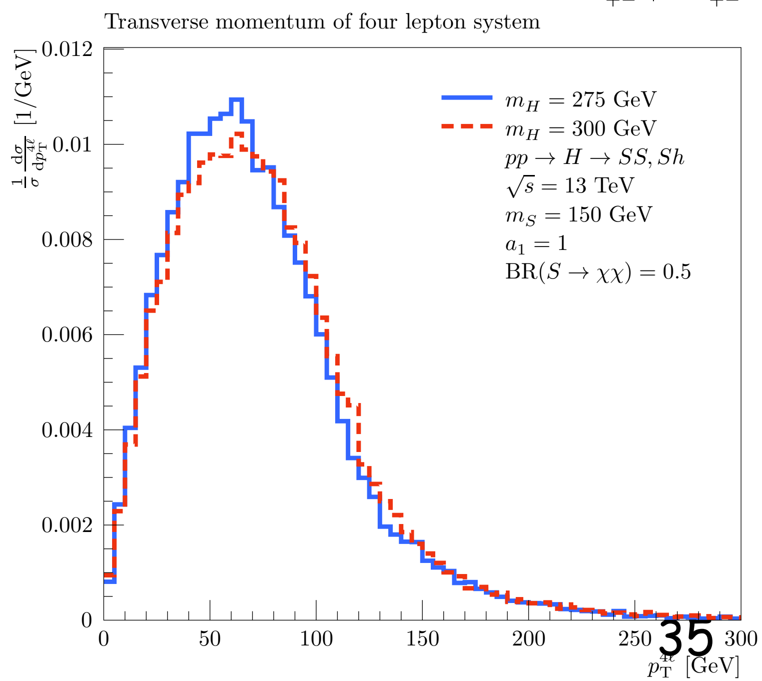
Predict ~1 fb of fiducial cross-section

$|\eta_l| < 2.5$


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
$a_1 = 1$
$\mathrm{BR}(S \to \chi\chi) = 0.5$
$\Delta R^1_{+-} + \Delta R^2_{+-}$

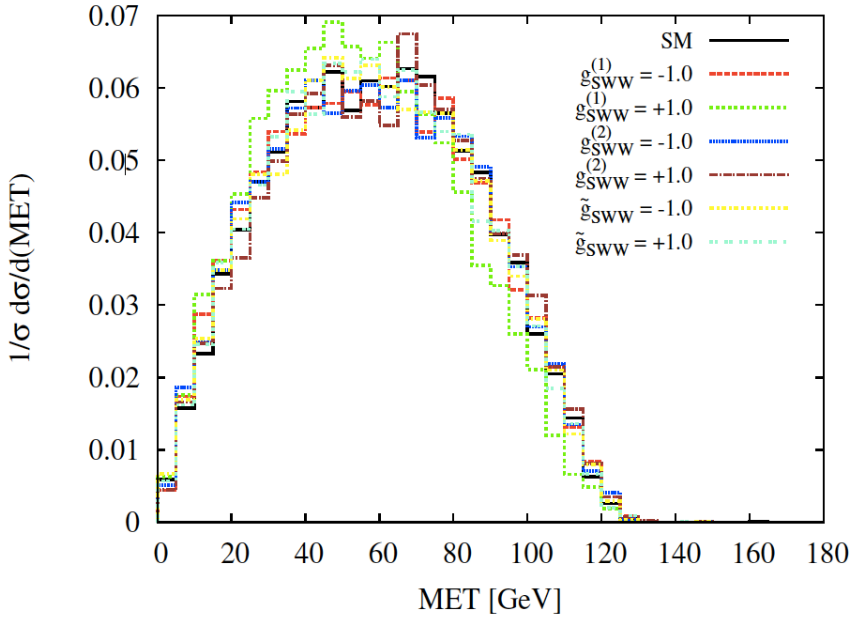

Minimised ΔR of opposite sign lepton pairs
$\frac{1}{\sigma}\frac{d\sigma}{d[\min(\Delta R_{+-})]}$
$m_H = 275$ GeV
$m_H = 300$ GeV
$pp \to H \to SS, Sh$
$\sqrt{s} = 13$ TeV
$m_S = 150$ GeV
$a_1 = 1$
$\mathrm{BR}(S \to \chi\chi) = 0.5$
$\min(\Delta R_{+-})$

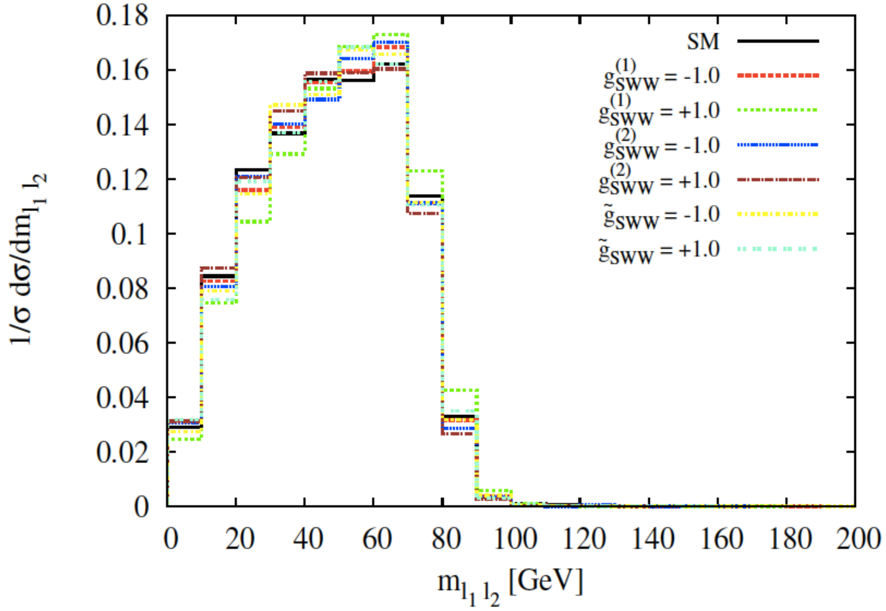

Transverse momentum of four lepton system
$\frac{1}{\sigma}\frac{d\sigma}{dp_T^{4\ell}}$ [1/GeV]
$m_H = 275$ GeV
$m_H = 300$ GeV
$pp \to H \to SS, Sh$
$\sqrt{s} = 13$ TeV
$m_S = 150$ GeV
$a_1 = 1$
$\mathrm{BR}(S \to \chi\chi) = 0.5$
$p_T^{4\ell}$ [GeV]

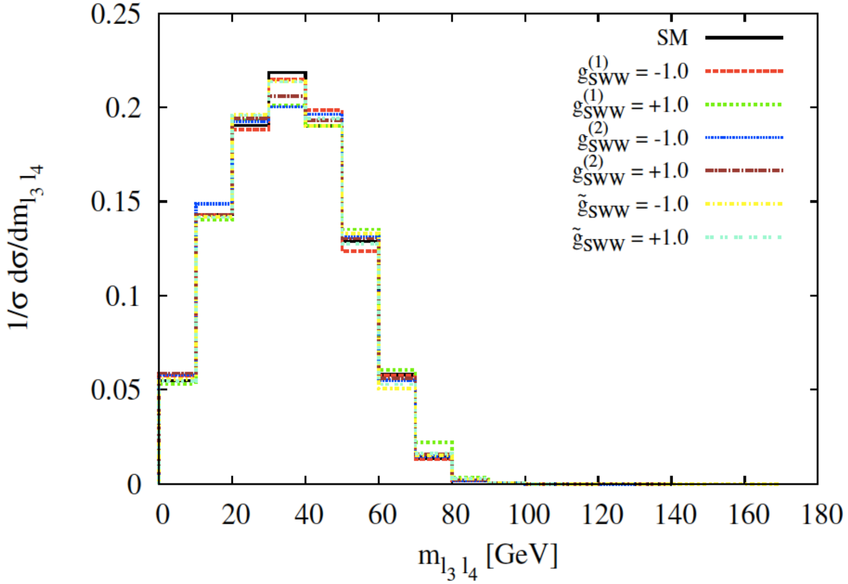
Impact of extended tensor structure of SWW is small

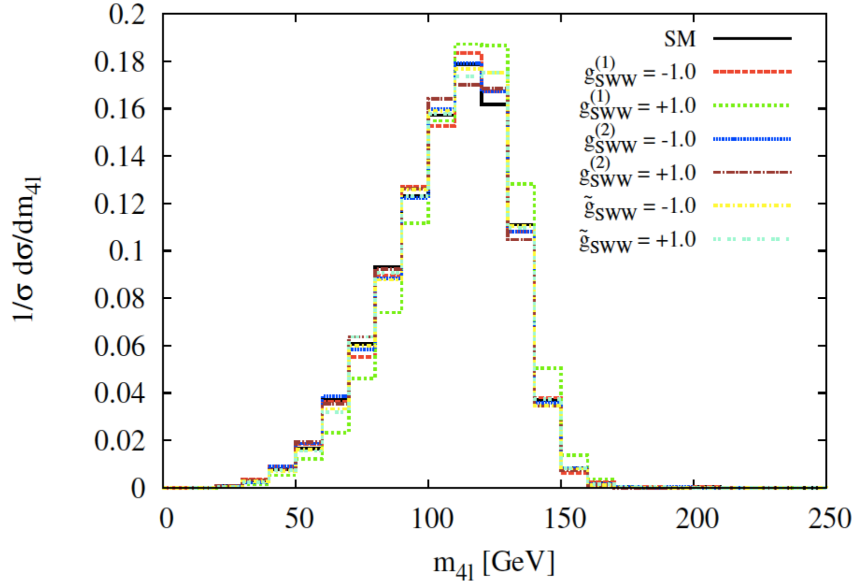
$$\mathcal{L}^{(3)}_{hWW} = -g\Big[\frac{g^{(1)}_{hWW}}{2m_W} W^{\mu\nu}W^{\dagger}_{\mu\nu}h + \frac{g^{(2)}_{hWW}}{m_W}(W^{\nu}\partial^{\mu}W^{\dagger}_{\mu\nu}h + \text{h.c}) + \frac{\tilde{g}_{hWW}}{2m_W} W^{\mu\nu}\widetilde{W}^{\dagger}_{\mu\nu}h\Big],$$

M. Kumar et al, to appear





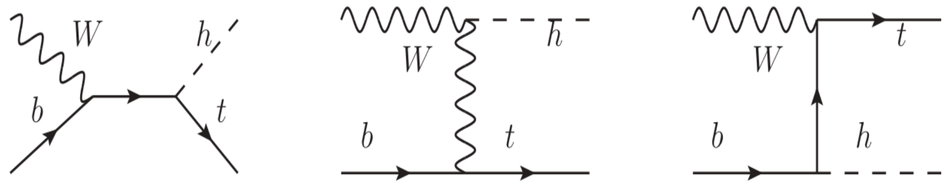




Enhancement of tH production

- **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 ($\sigma_{tH} \simeq \sigma_{ttH}$)**

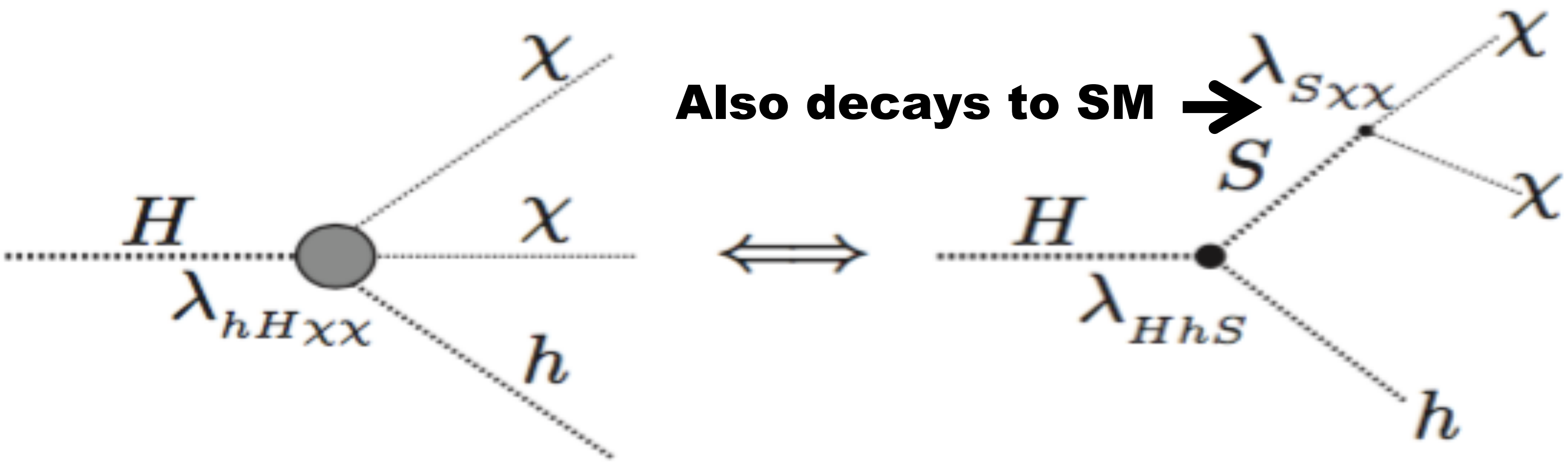
M. Farina, C. Grojean, F. Maltoni, E. Salvioni and A. Thamm, JHEP **1305**, 022 (2013).

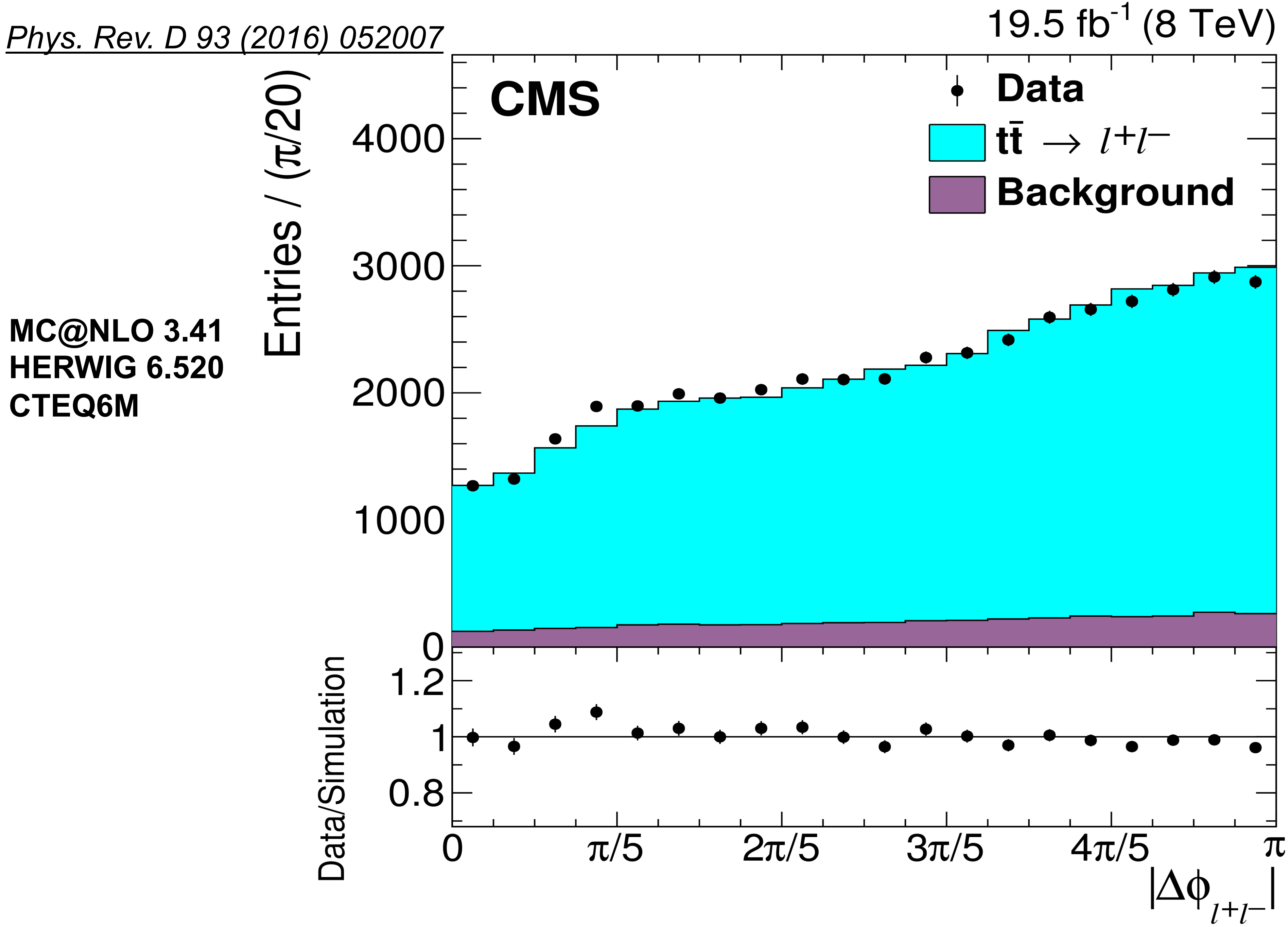
The intermediate scalar, S

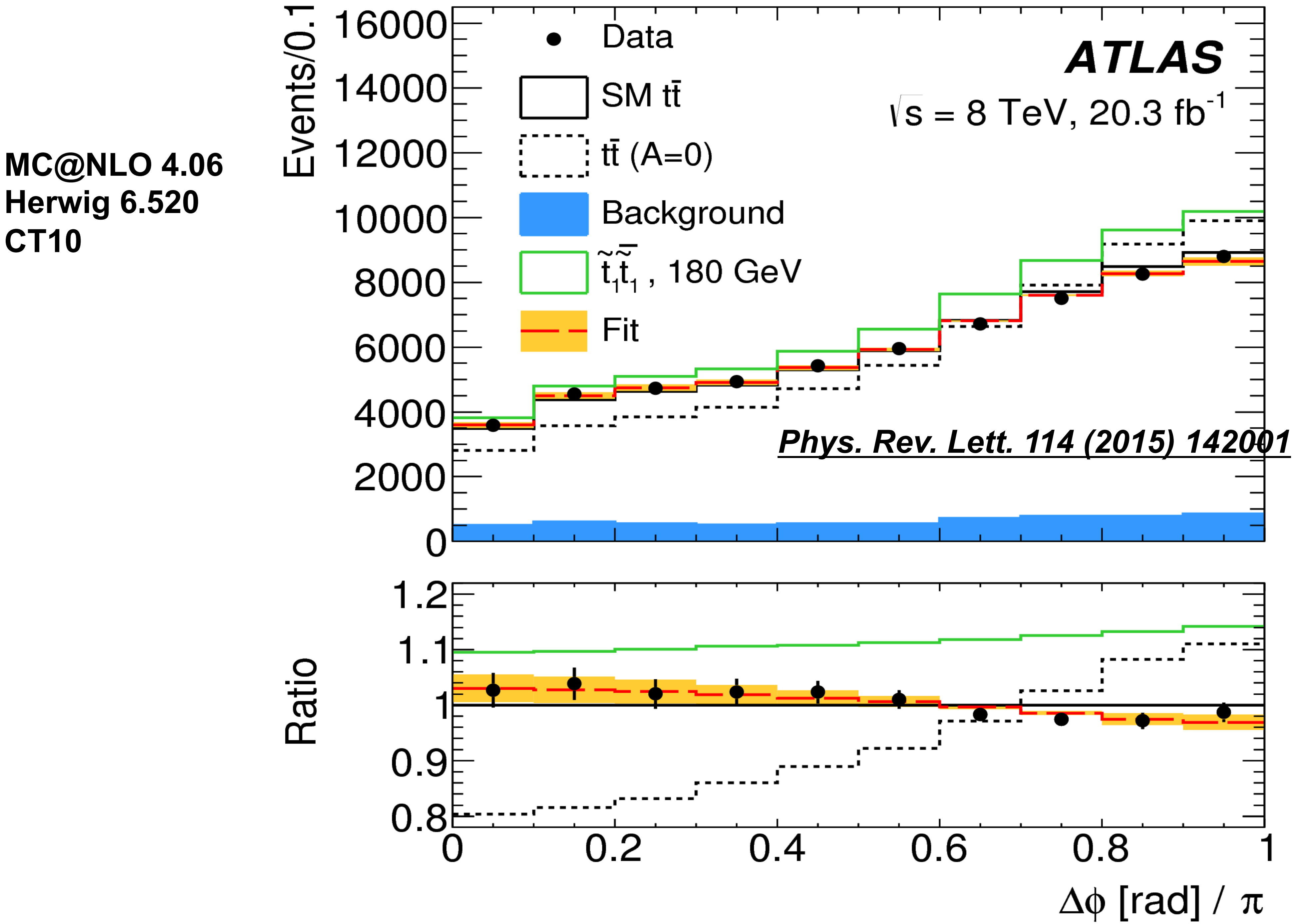
- **Dark Matter is introduced in the form of a scalar and the decay H→h\chi\chi via effective quartic couplings**

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

- **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**




Phys. Rev. D 93 (2016) 052007
19.5 fb-1 (8 TeV)
CMS
Data
tt̄ → l+l−
Background
MC@NLO 3.41
HERWIG 6.520
CTEQ6M
Entries / (π/20)
4000
3000
2000
1000
0
Data/Simulation
1.2
1
0.8
0
π/5
2π/5
3π/5
4π/5
π
|Δφl+l−|


MC@NLO 4.06
Herwig 6.520
CT10
ATLAS
√s = 8 TeV, 20.3 fb-1
Data
SM tt̄
tt̄ (A=0)
Background
t̃1t̃1, 180 GeV
Fit
Phys. Rev. Lett. 114 (2015) 142001
Events/0.1
Ratio
Δφ [rad] / π
0
2000
4000
6000
8000
10000
12000
14000
16000
0.8
0.9
1
1.1
1.2
0
0.2
0.4
0.6
0.8
1