New Physics at the EW Scalar and the production of multiple leptons at the LHC

The Wits ICPP/iThemba LABS with N.Chakrabarty

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Outline

- The 2HDM+S model
- Di-lepton or multilepton "problem"
  - Opposite sign di-leptons
  - Same sign leptons and three leptons
  - Three b-jet final states
- Combination
  - Other discrepancies not included
- Outlook and Conclusions

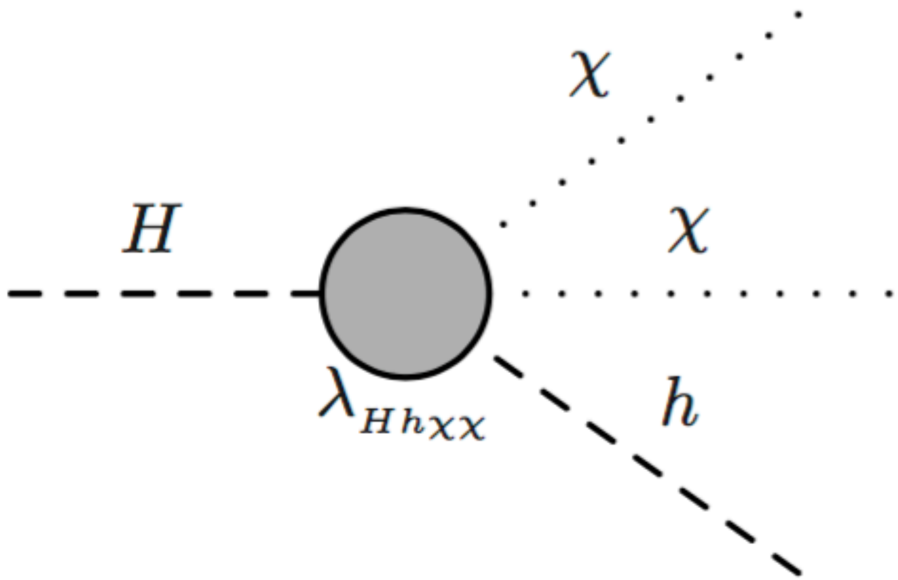
Views expressed here are of the authors only

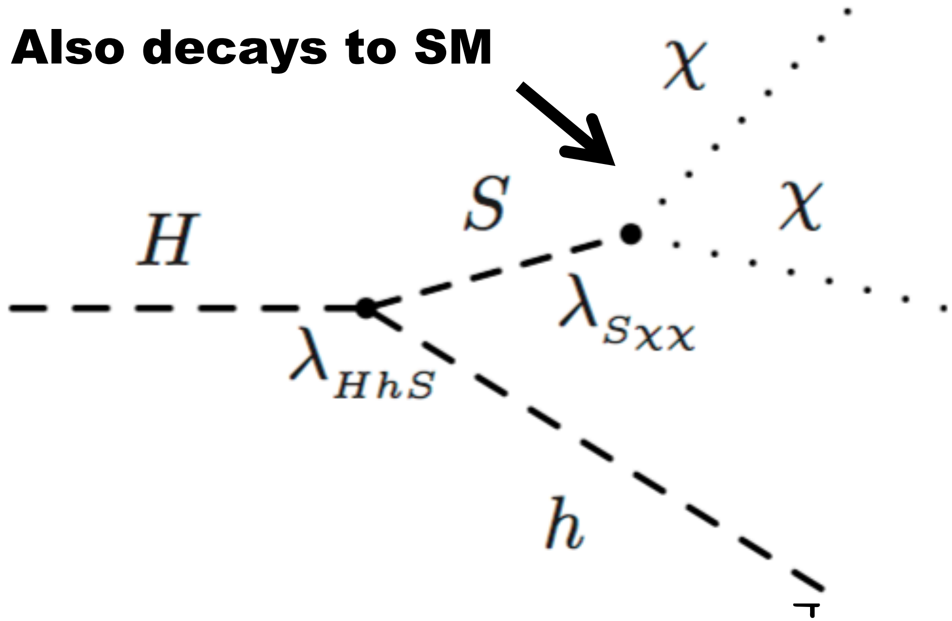
arXiv:1506.00612
arXiv:1603.01208
arXiv:1606.01674
arXiv:1706.02477
arXiv:1706.06659
arXiv:1709.09419
arXiv:1711.07874
asXiv:1809.06344

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 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

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

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, which is not too far fetched (see below)

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

Masses in the 2HDM+S

arXiv:1809.06344

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

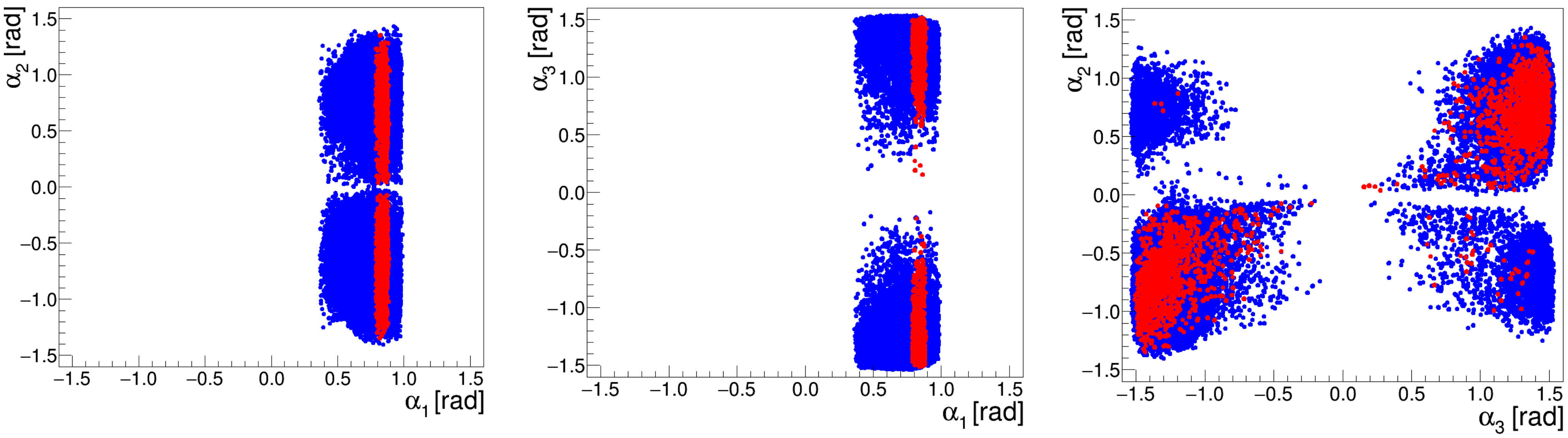
Mass-matrix for the CP-even scalar sector will modified with respect to 2HDM and that needs a 3 x3 matrix (three mixing angles). Couplings are modified.

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

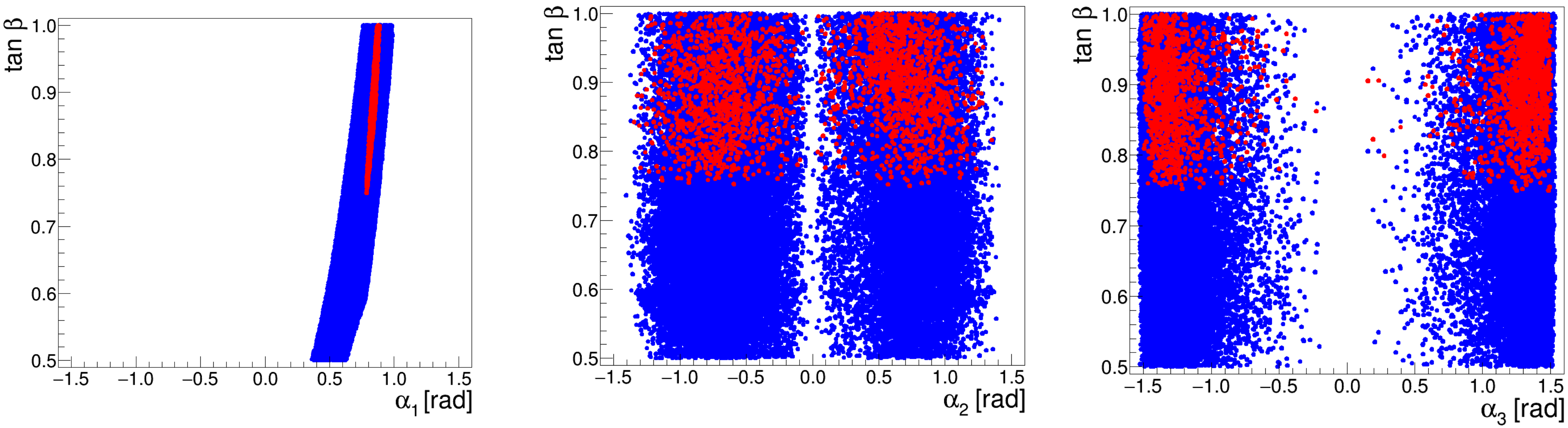
$$M^2_{\mathrm{CP-even}} = \begin{pmatrix} 2\lambda_1 v_1^2 - m_{12}\frac{v_2}{v_1} & m_{12} + \lambda_{345} v_1 v_2 & 2\kappa_1 v_1 v_S \\ m_{12} + \lambda_{345} v_1 v_2 & -m_{12}\frac{v_2}{v_1} + 2\lambda_2 v_2^2 & 2\kappa_2 v_2 v_S \\ 2\kappa_1 v_1 v_S & 2\kappa_2 v_2 v_S & \frac{1}{3}\lambda_S v_S^2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

$$
\begin{aligned}
m_{H_1}^2 &= v_S \sin\alpha_2 \left[\lambda_7 v \cos\alpha_1 \cos\alpha_2 \cos\beta + \lambda_8 v \sin\alpha_1 \cos\alpha_2 \sin\beta + \lambda_6 v_S \sin\alpha_2\right], \\
m_{H_2}^2 &= (\cos\alpha_1 \cos\alpha_3 - \sin\alpha_1 \sin\alpha_2 \sin\alpha_3) \Big[\cos\alpha_1 \cos\alpha_2 \left(\lambda_{345} v^2 \sin\beta\cos\beta - m_{12}^2\right) \\
&\quad + \sin\alpha_1 \cos\alpha_2 \left(m_{12}^2 \cot\beta + \lambda_2 v^2 \sin^2\beta\right) + \lambda_8 v v_S \sin\alpha_2 \sin\beta\Big], \\
m_{H_3}^2 &= (\sin\alpha_1 \sin\alpha_3 - \sin\alpha_2 \cos\alpha_1 \cos\alpha_3) \Big[\cos\alpha_1 \cos\alpha_2 \left(m_{12}^2 \tan\beta + \lambda_1 v^2 \cos^2\beta\right) \\
&\quad + \sin\alpha_1 \cos\alpha_2 \left(\lambda_{345} v^2 \sin\beta\cos\beta - m_{12}^2\right) + \lambda_7 v v_S \sin\alpha_2 \cos\beta\Big]. \qquad (2.17)
\end{aligned}
$$

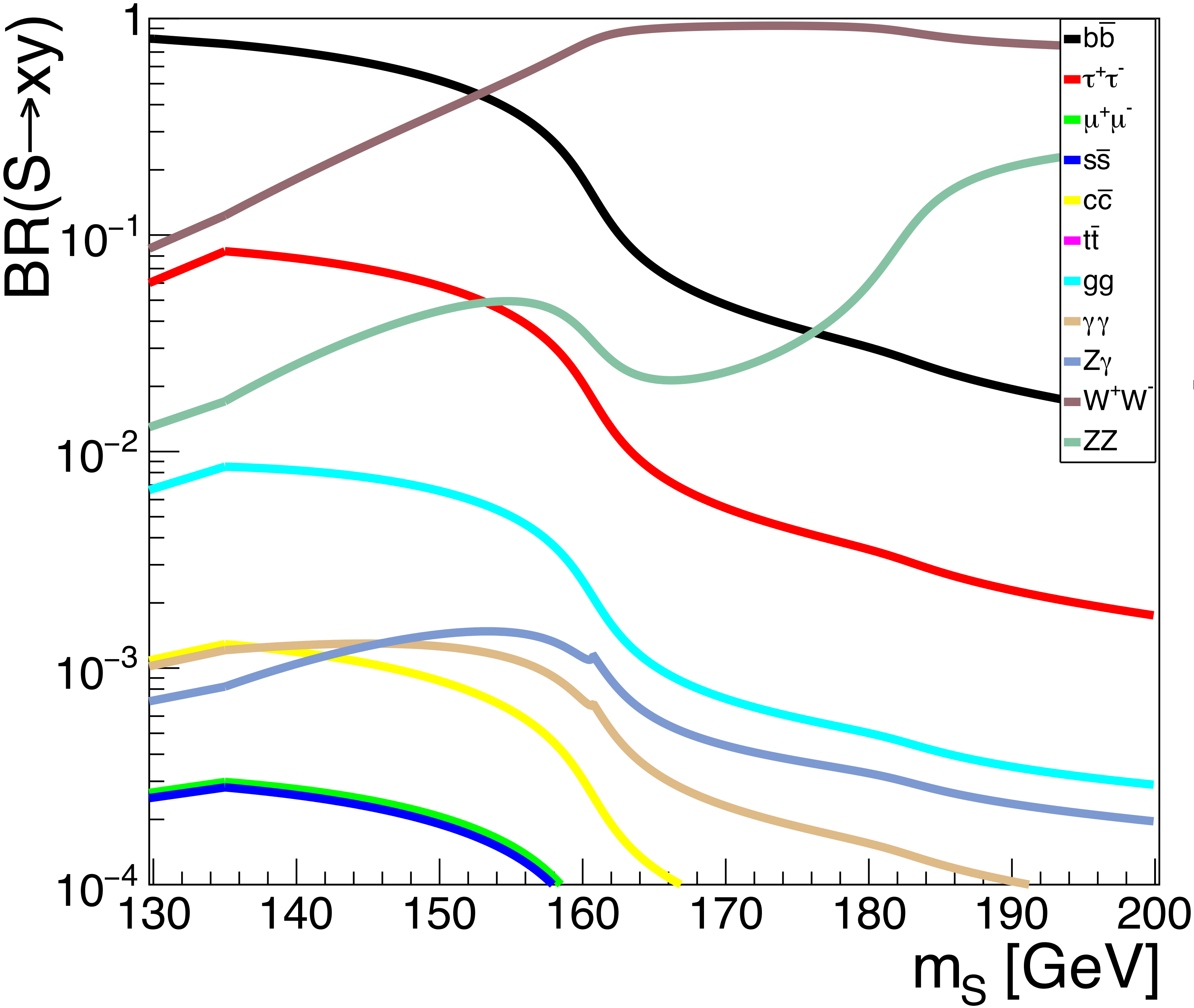
Perform scans after fixing masses of physical bosons(m_{h1}=125 GeV, m_{h2}=140, m_{h3}=270 GeV, m_A=600 GeV, m_H±=600 GeV) in addition to the constraints described in arXiv:1711.07874, including the signal Yukawa coupling strength of β_g^2=1.38±0.22 (translated into $\tan^2\beta$)



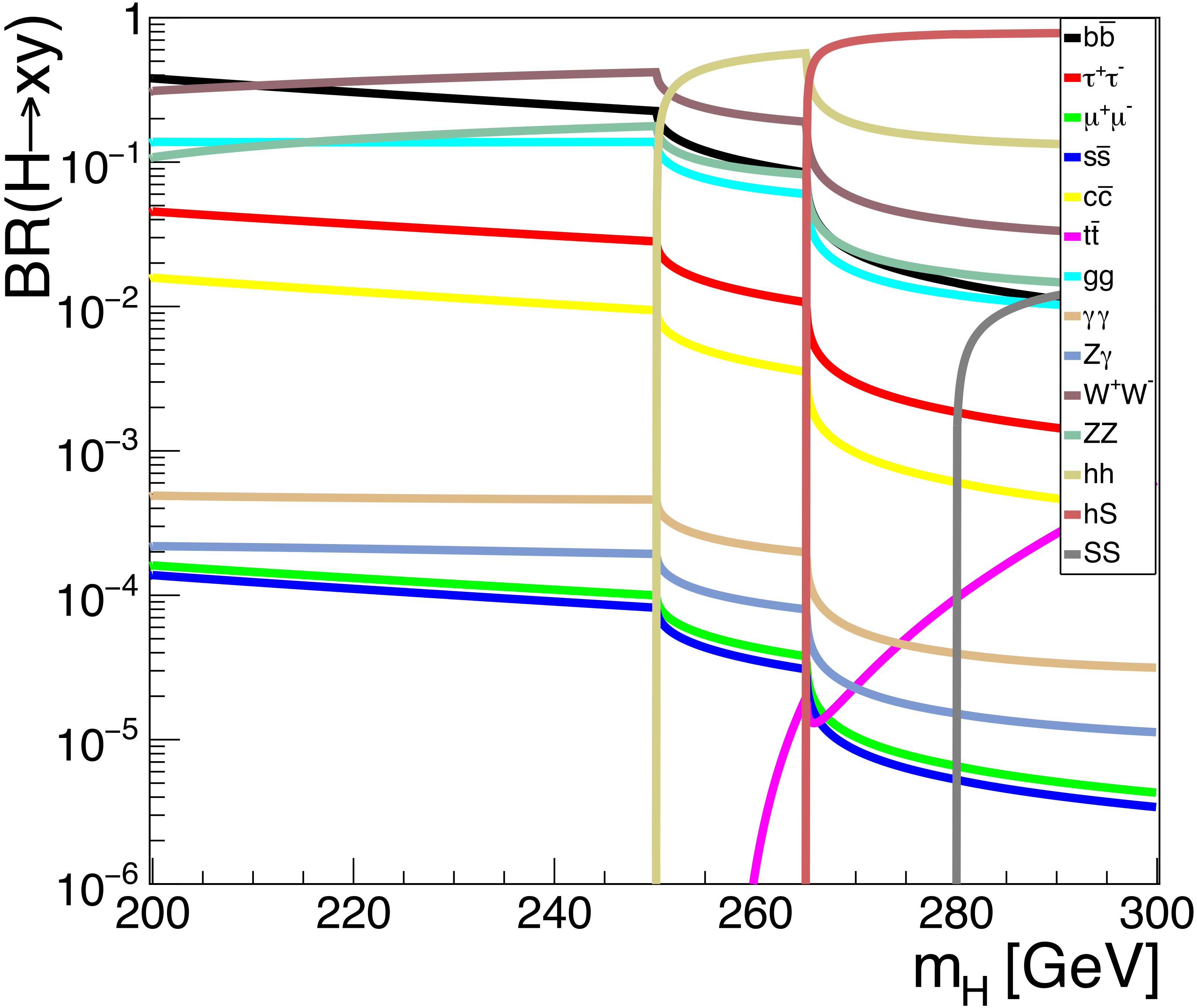
Correlation plots for the three mixing angles and tanβ. Blue (red) points correspond to Br(h→SM) within 10% (20%) of the SM h values



For simplicity we will assume that the S decays like the SM Higgs boson



Results using N2HDECAY (arXiv:1612.01309) for one benchmark point

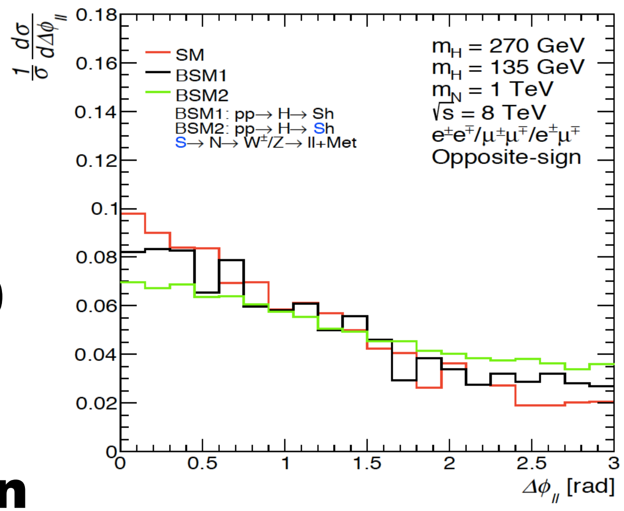


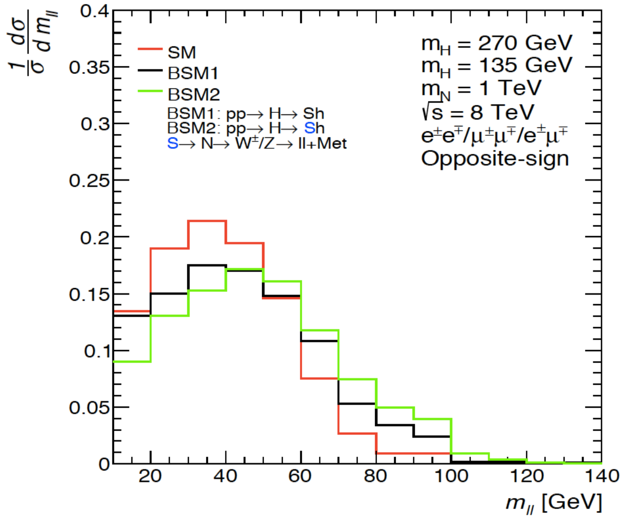
Results using N2HDECAY (arXiv:1612.01309) for one benchmark point

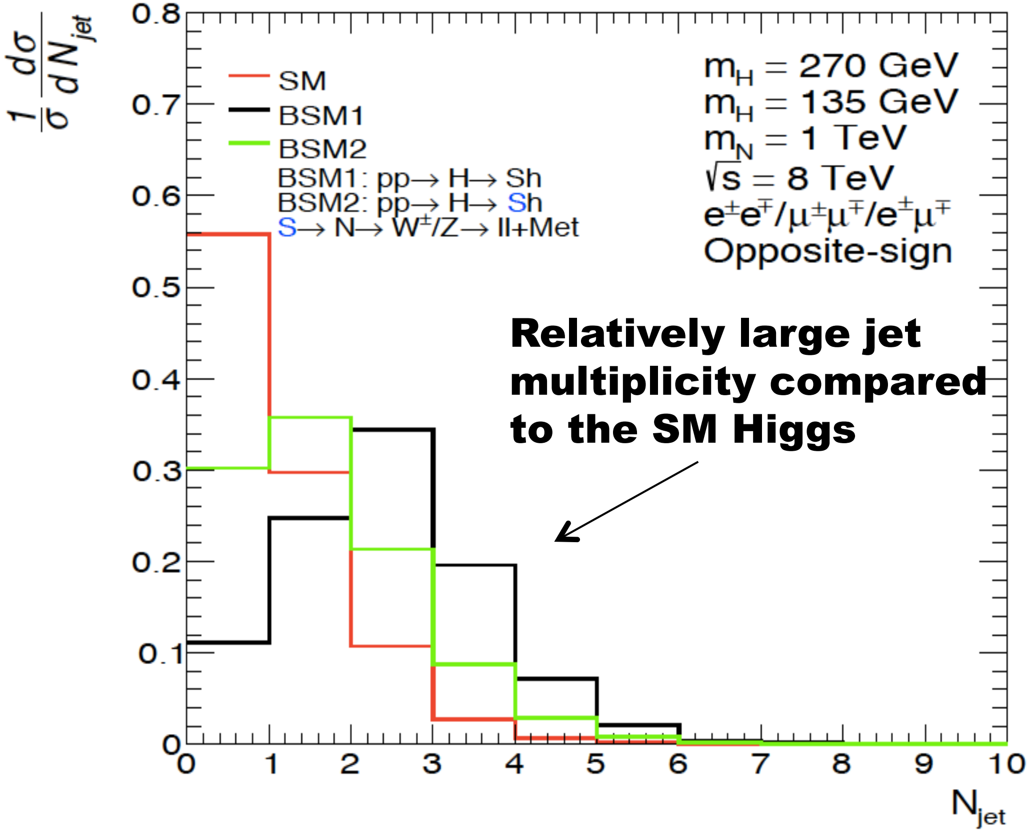
Multi-lepton final states

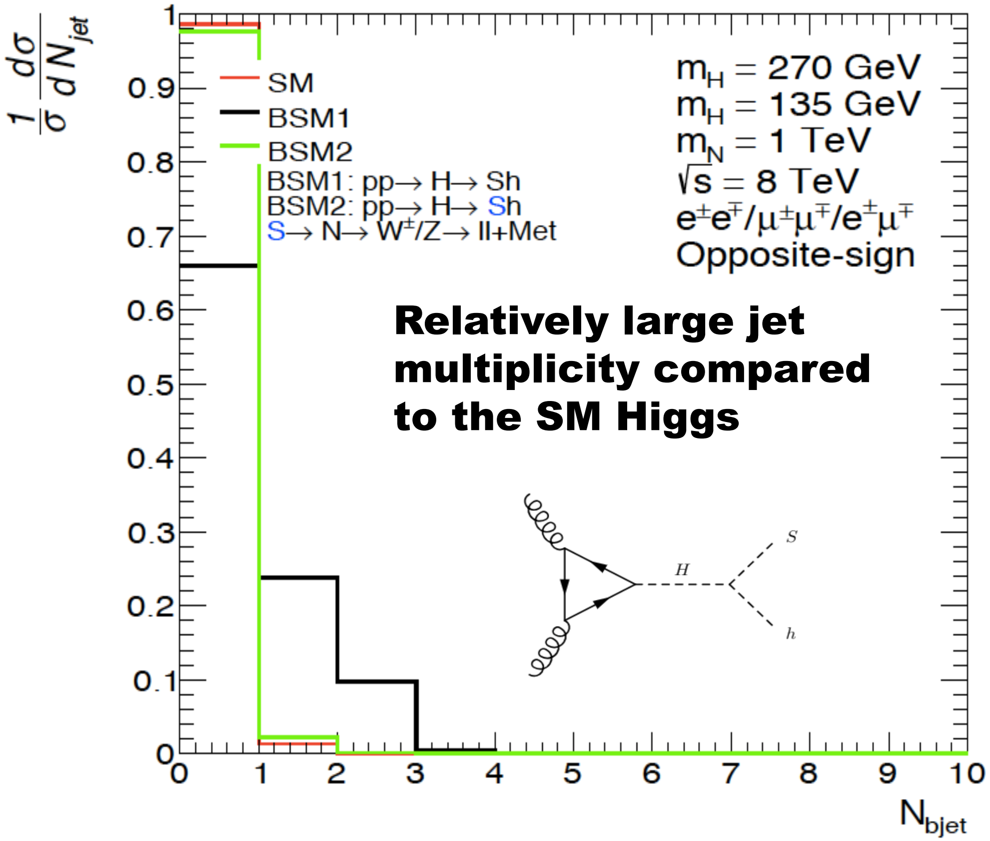
$$pp \to H \to Sh$$
$$\to \ell^+\ell^- + X$$

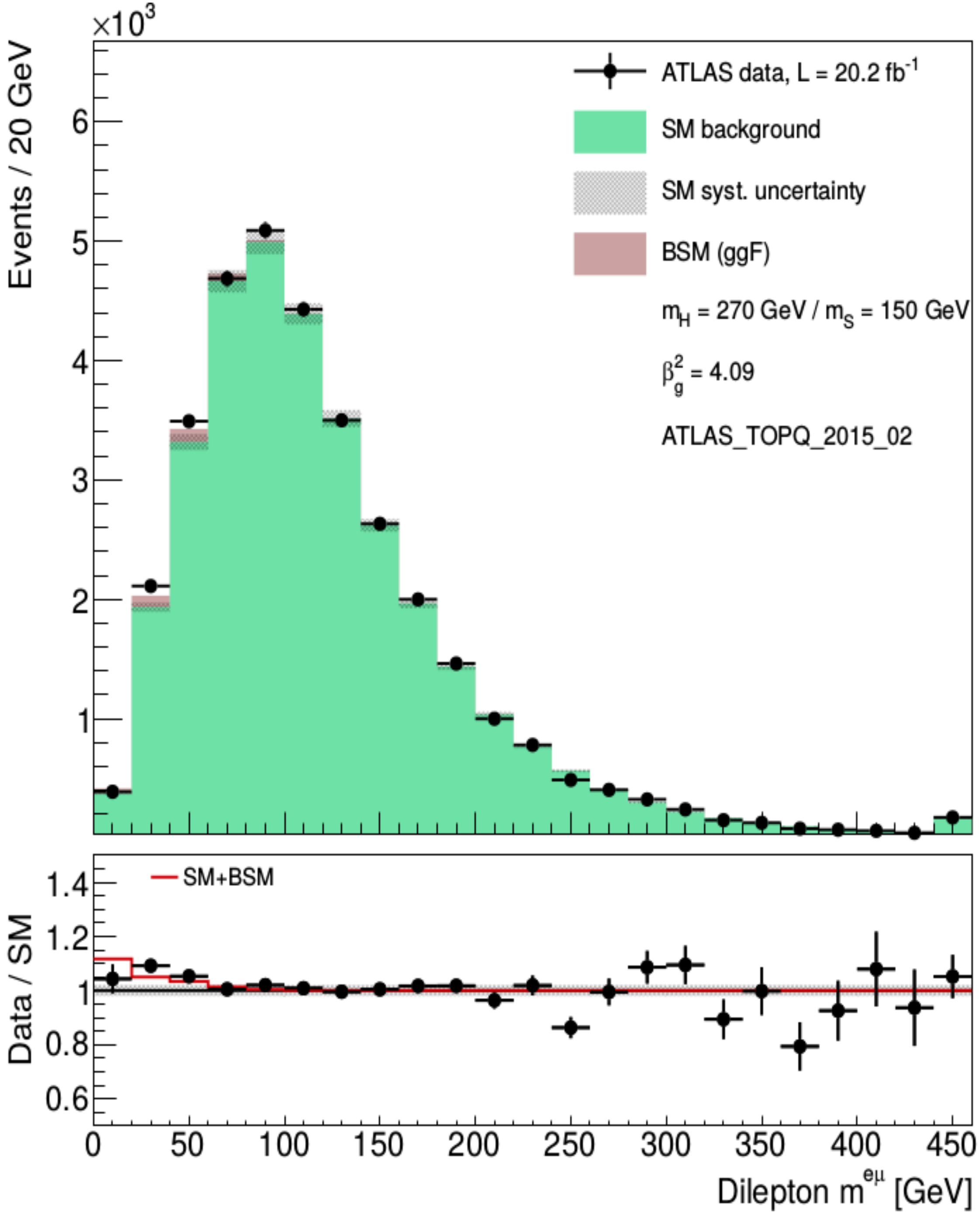
Expect di-leptons (m_{ll}<100 GeV) with jets and b-jets with rates comparable to that of the SM Higgs boson











Simple selection:

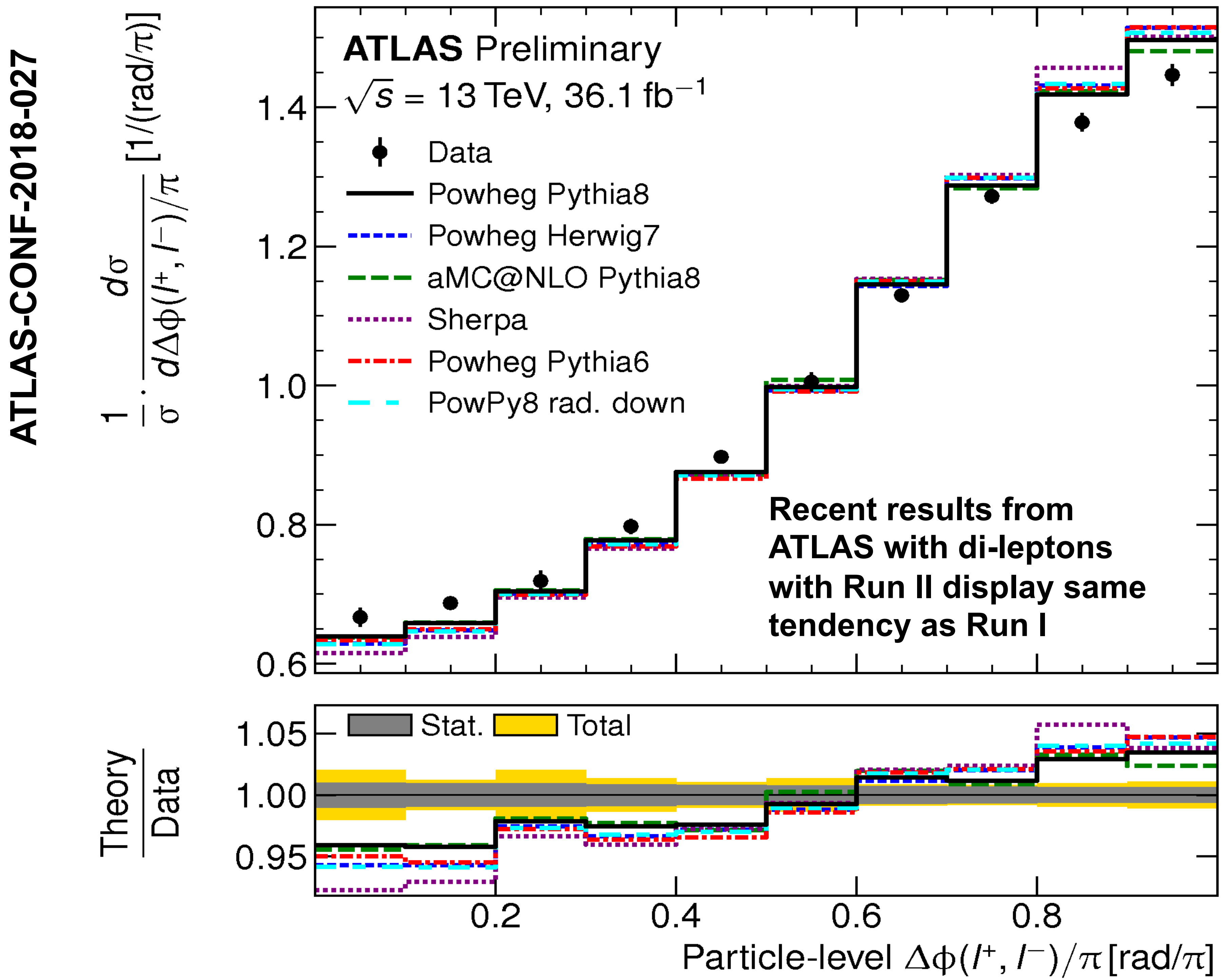
- **One DFOS lepton pair**
- **At least 1 *b*-tagged jet**

We fix the normalisation of the SM by scaling it to the data in the region m_{ll} > 110 GeV

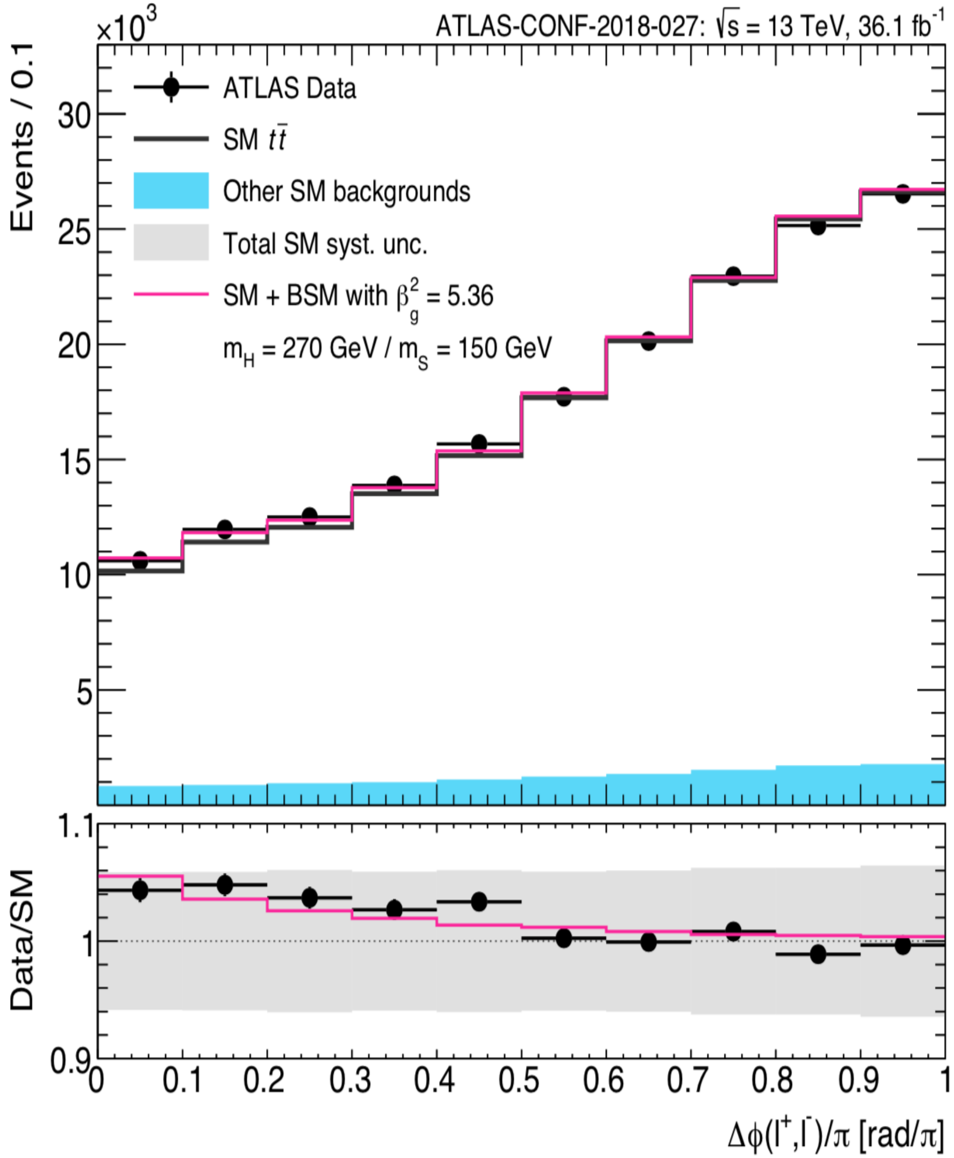
- **Scale factor: 0.984**
- **A normalisation systematic of 2% is applied**
- **The fit is done to the region below 110 GeV**

Fit results:

- **β_g^2 = 4.09 ± 1.37**


ATLAS-CONF-2018-027
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Data
Powheg Pythia8
Powheg Herwig7
aMC@NLO Pythia8
Sherpa
Powheg Pythia6
PowPy8 rad. down
Recent results from ATLAS with di-leptons with Run II display same tendency as Run I
$\frac{1}{\sigma} \cdot \frac{d\sigma}{d\Delta\phi(l^+,l^-)/\pi}$ [1/(rad/π)]
Stat.
Total
Theory / Data
Particle-level $\Delta\phi(l^+, l^-)/\pi$ [rad/π]

Fit results: ATLAS-CONF-2018-027



Simple selection:

- One DFOS lepton pair
- At least 1 *b*-tagged jet

Normalisation systematic: ~6.2%

Shape systematic:

- Discrepancy of SM prediction, particularly at high ΔΦ
- Choose SM prediction that best describes data (aMC@NLO) → systematic is percentage deviation away from mean SM prediction
- Varies between 1% and 2.6%

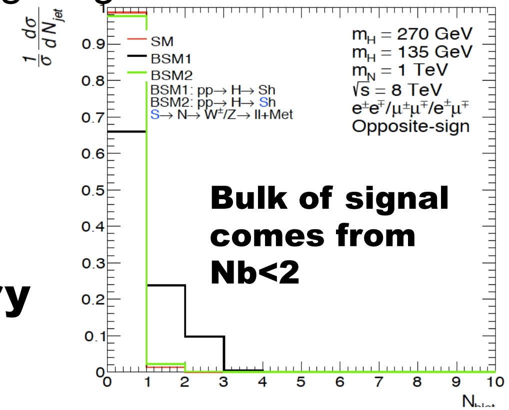
Fit results:

- $\beta_g^2 = 5.36 \pm 1.31$

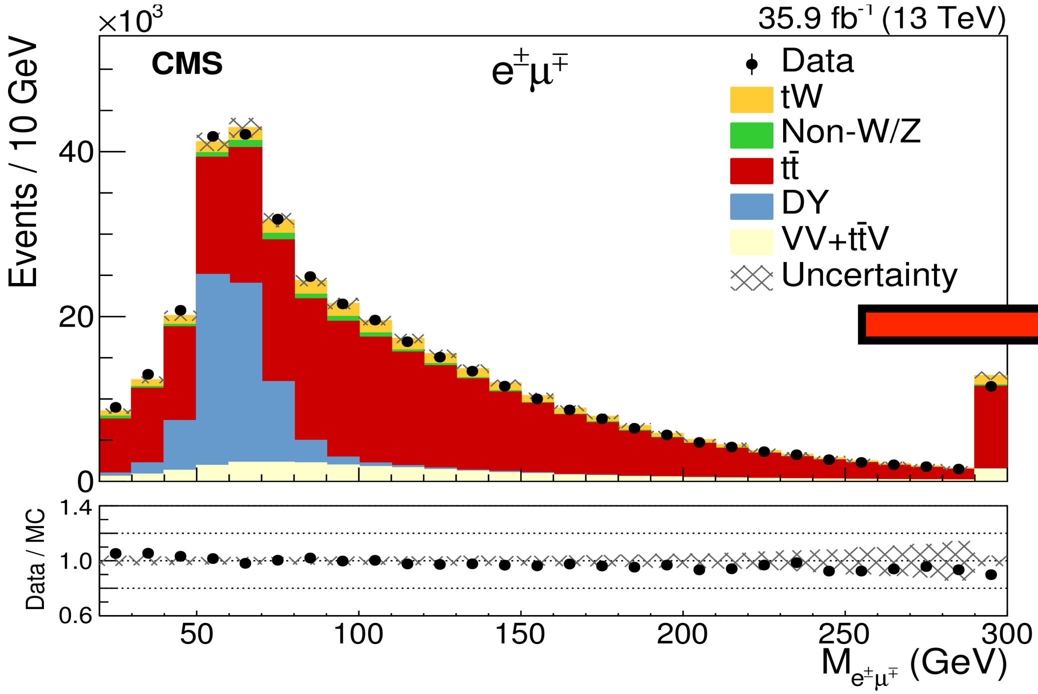
arXiv:1805.07399

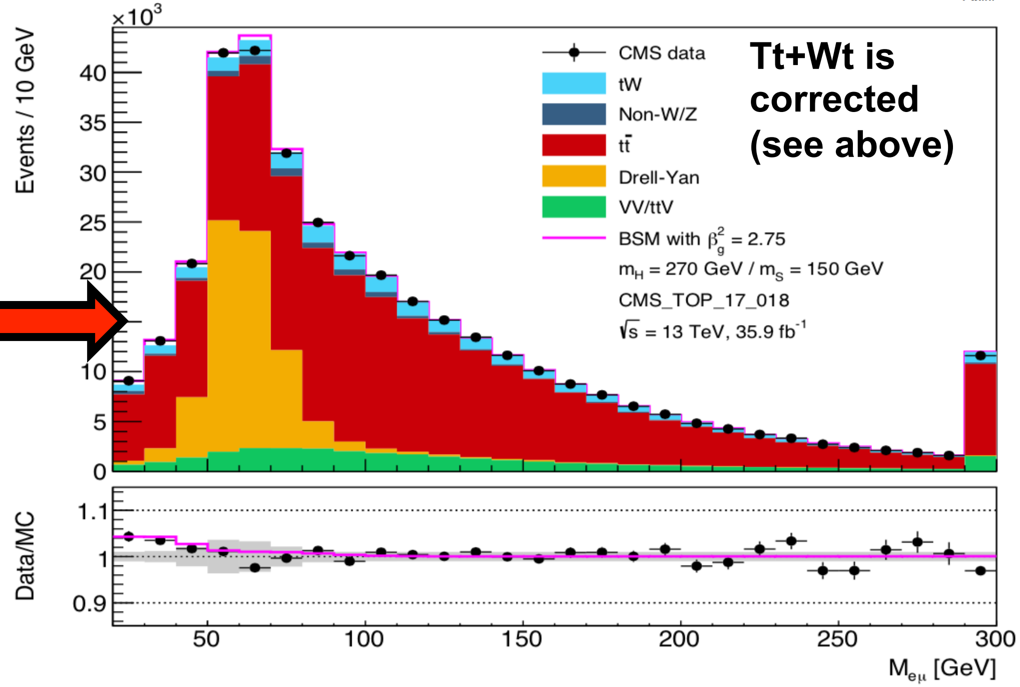
CMS-TOP-17-018; CERN-EP-2018-074

- Poor modeling of POWHEG + Pythia8 distribution is improved through reweighting
- We fix the normalisation of the SM by scaling it to the data in the region $m_{ll} > 110$ GeV
  - A normalisation systematic of 3% is applied to all but DY
  - DY systematic = 6.8%. 3% systematic on m_{ll} shape in top
  - The fit is done to the region below 110 GeV
- Fit results:
  - $\beta_g^2 = 2.79 \pm 0.52$
  - Fit is extremely well constrained



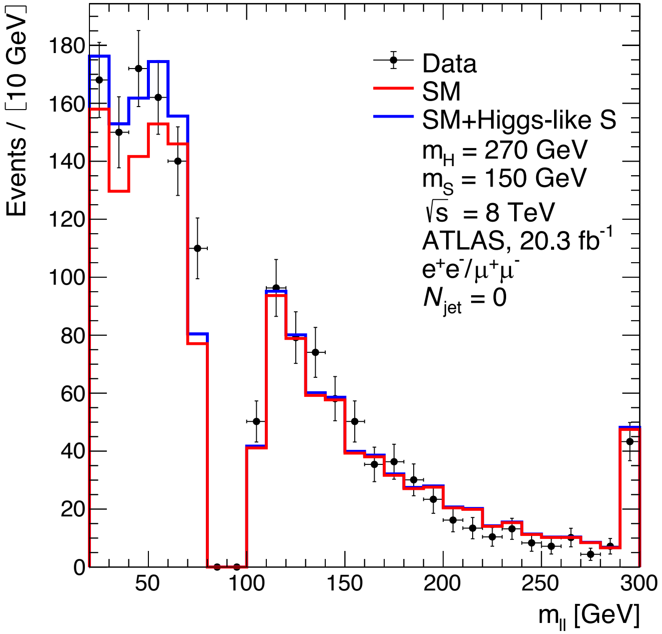
Theory systematics still preliminary

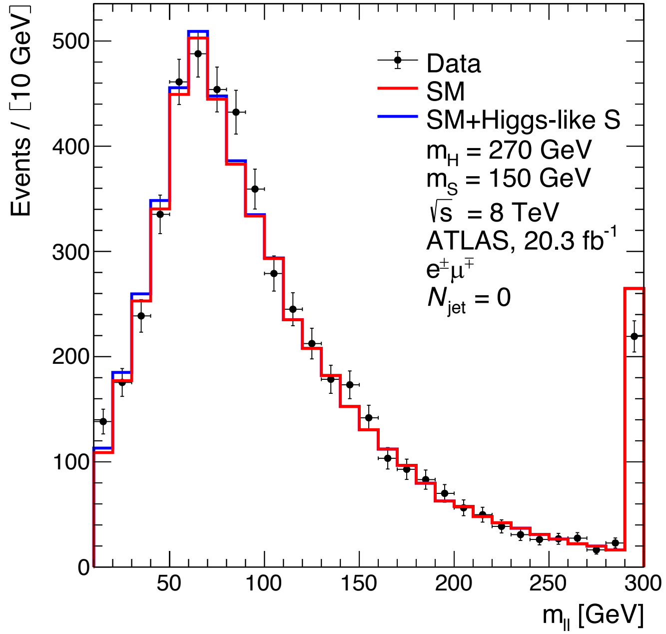




Used conservative assumption that ll+2b-jet final state is perfectly described by the SM. The discrepancy comes from events with N_b<2. Impact on h→WW→ll?

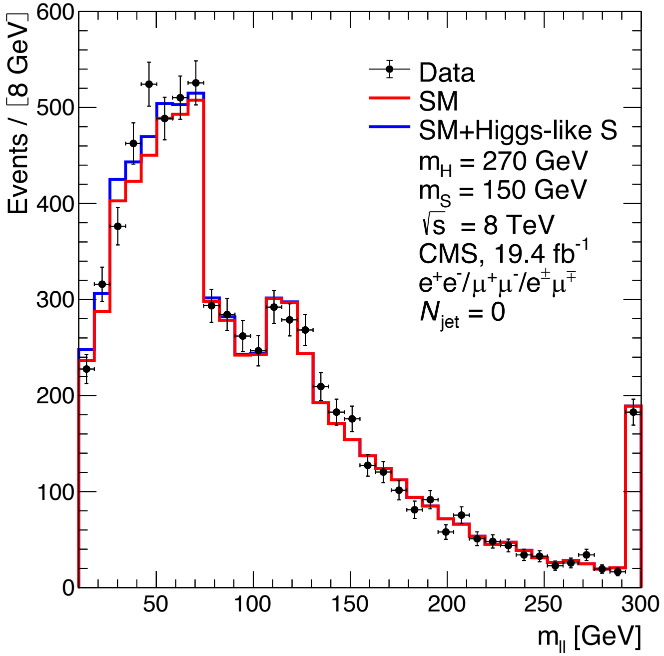
Are these discrepancies due to mismodelling of Wt/tt processes?



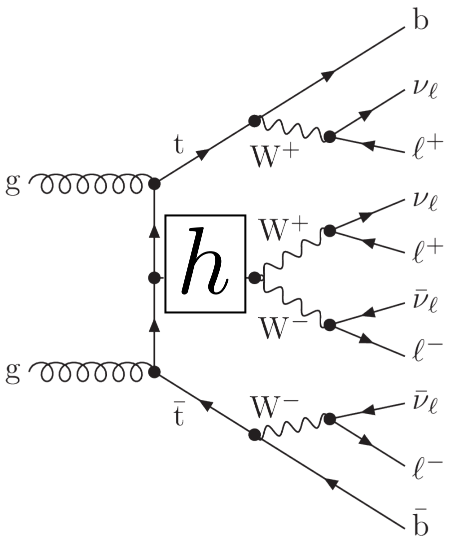


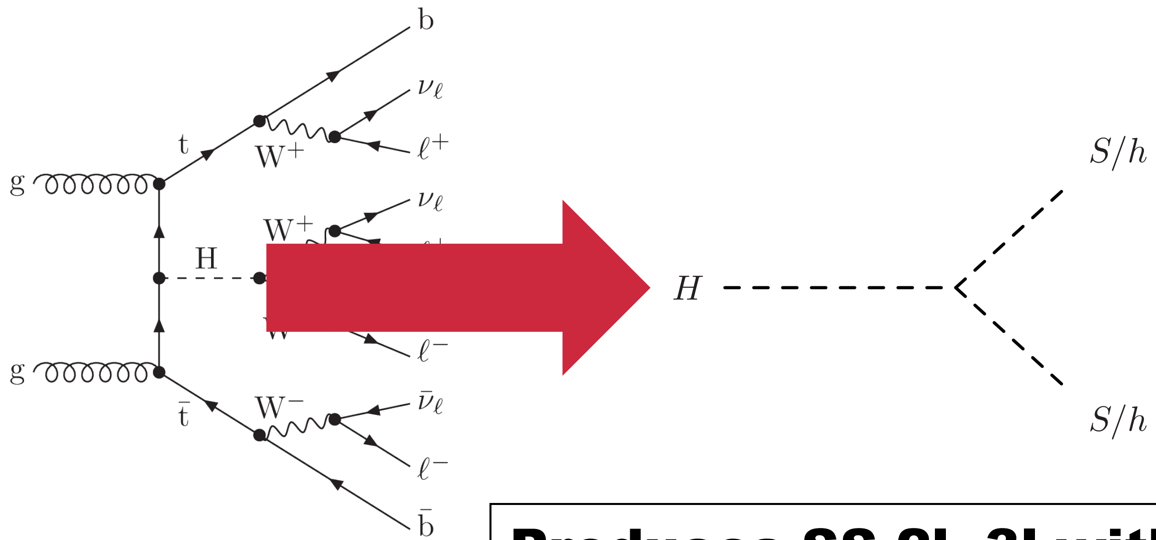
arXiv:1711.07874

Discrepancies in similar m_{ll} range also seems to appear in events with a full jet (b-jet) veto with Run I data (in the context of the WW cross-section measurement. Potential impact on h→WW→ll analysis where the WW is normalized with relatively low m_{ll} (factors of 1.1-1.2, different from high masses)



Top associated Higgs production
(Multi-lepton final state)s

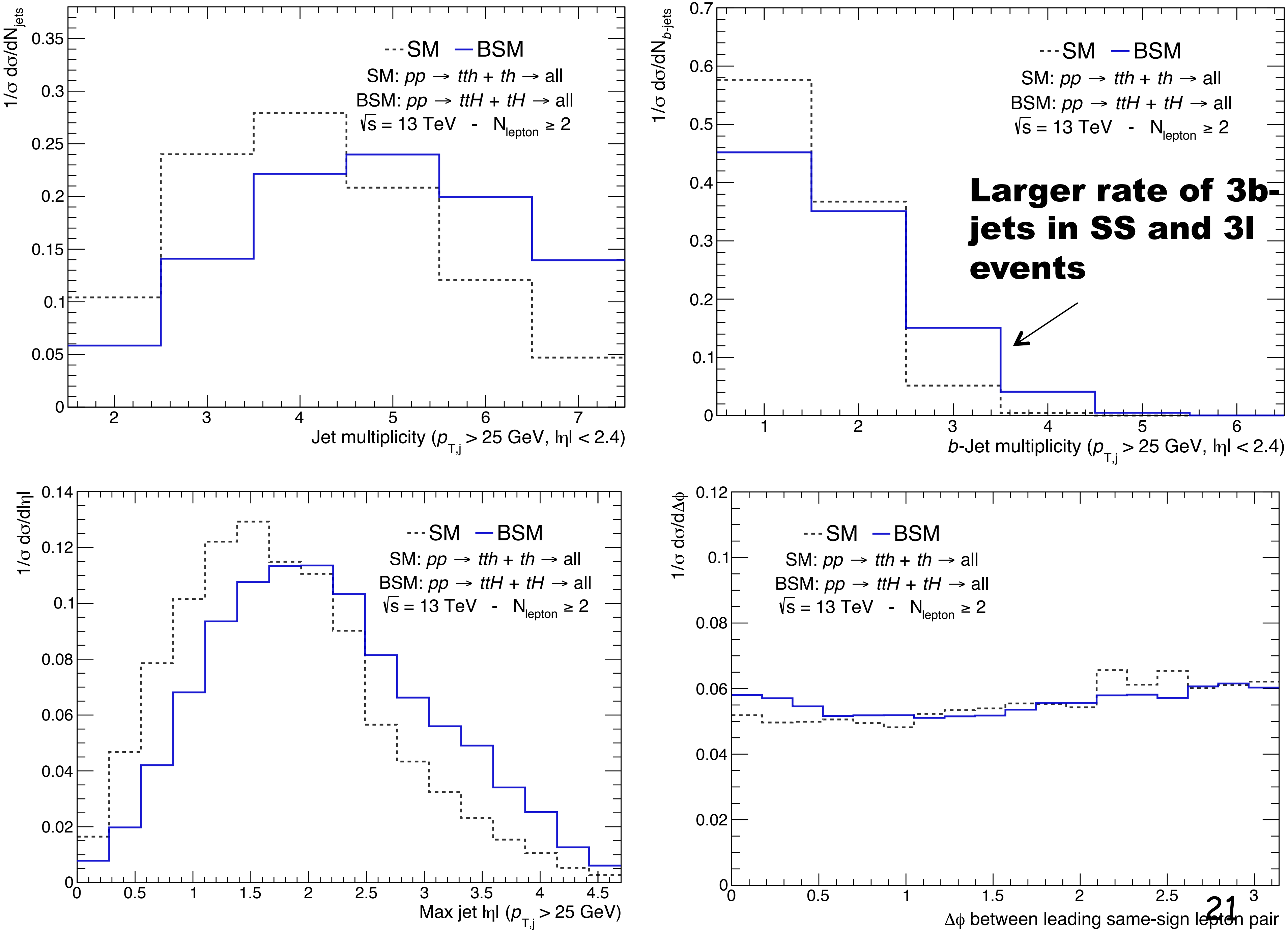




Produces SS 2l, 3l with b-jets, including 3 b-jets

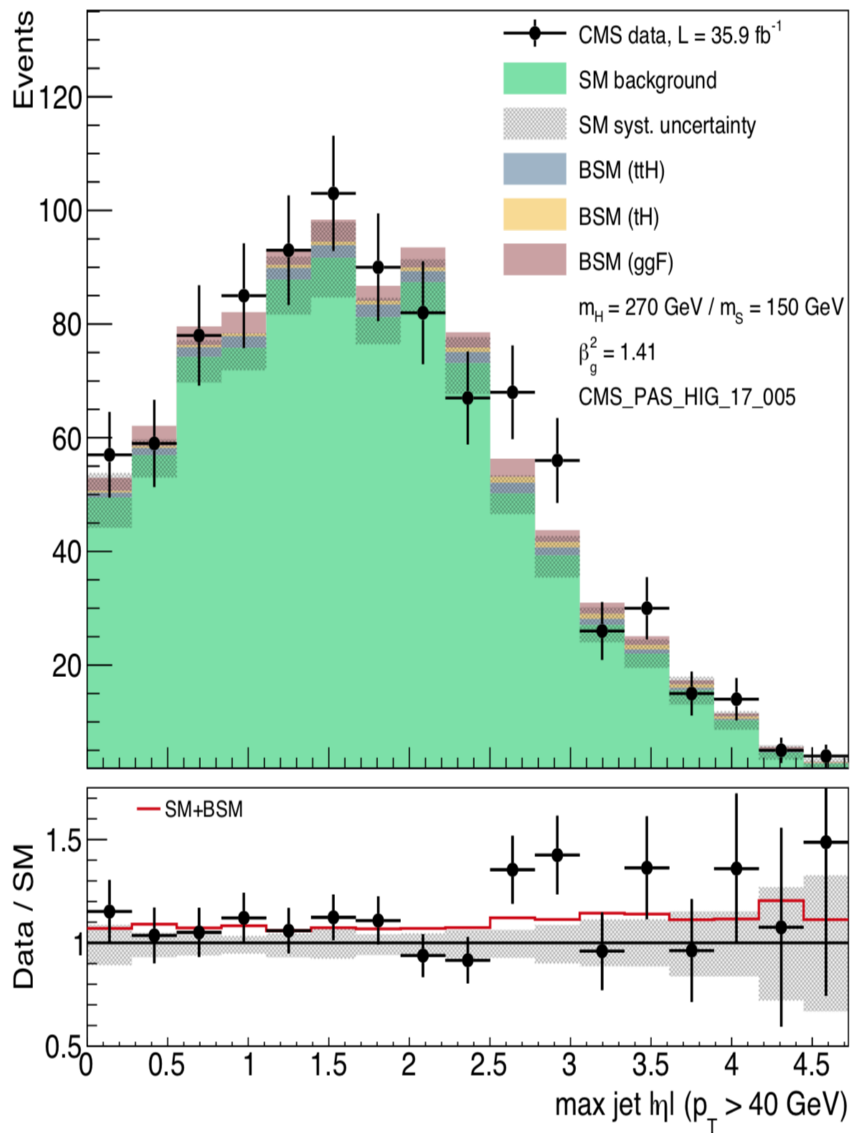
Reduced cross-section of ttH+tH is compensated by di-boson, (SS, Sh) decay and large Br(S→WW). Production of same sign leptons, three leptons is enhanced. Enhanced tH cross-section

arXiv:1711.07874

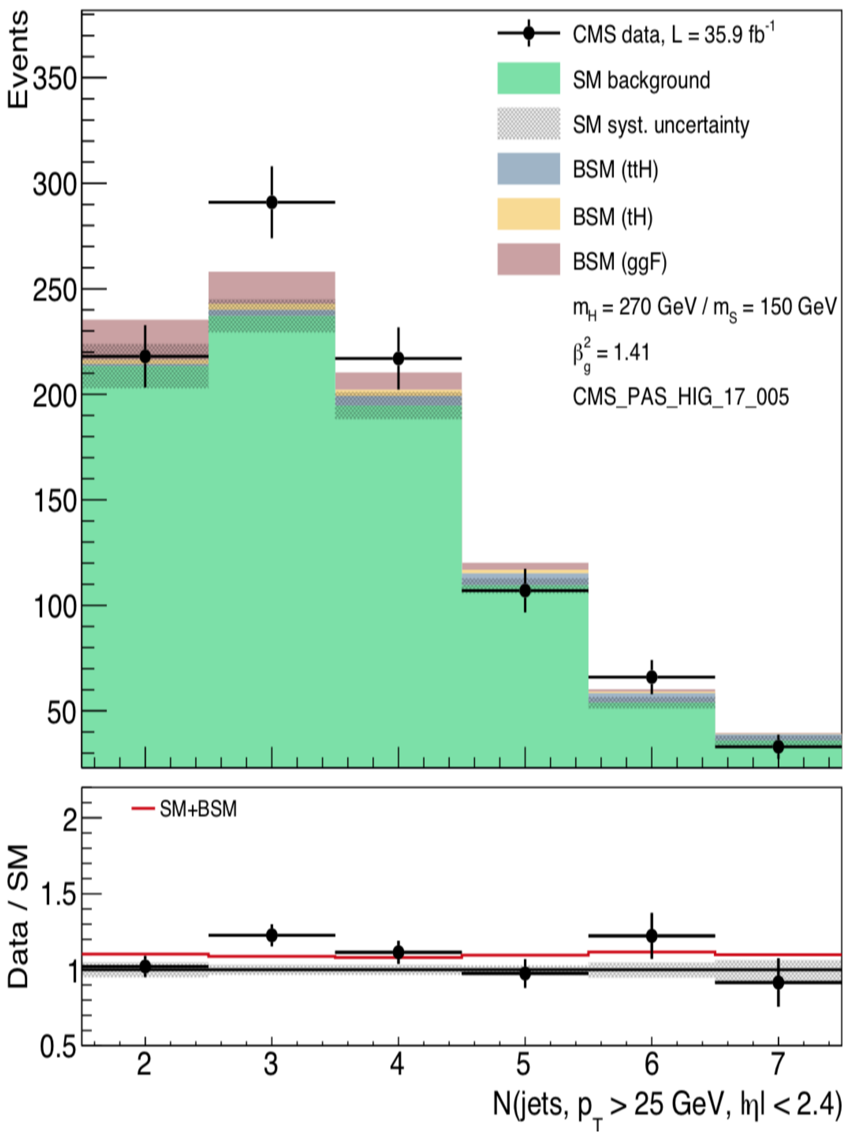


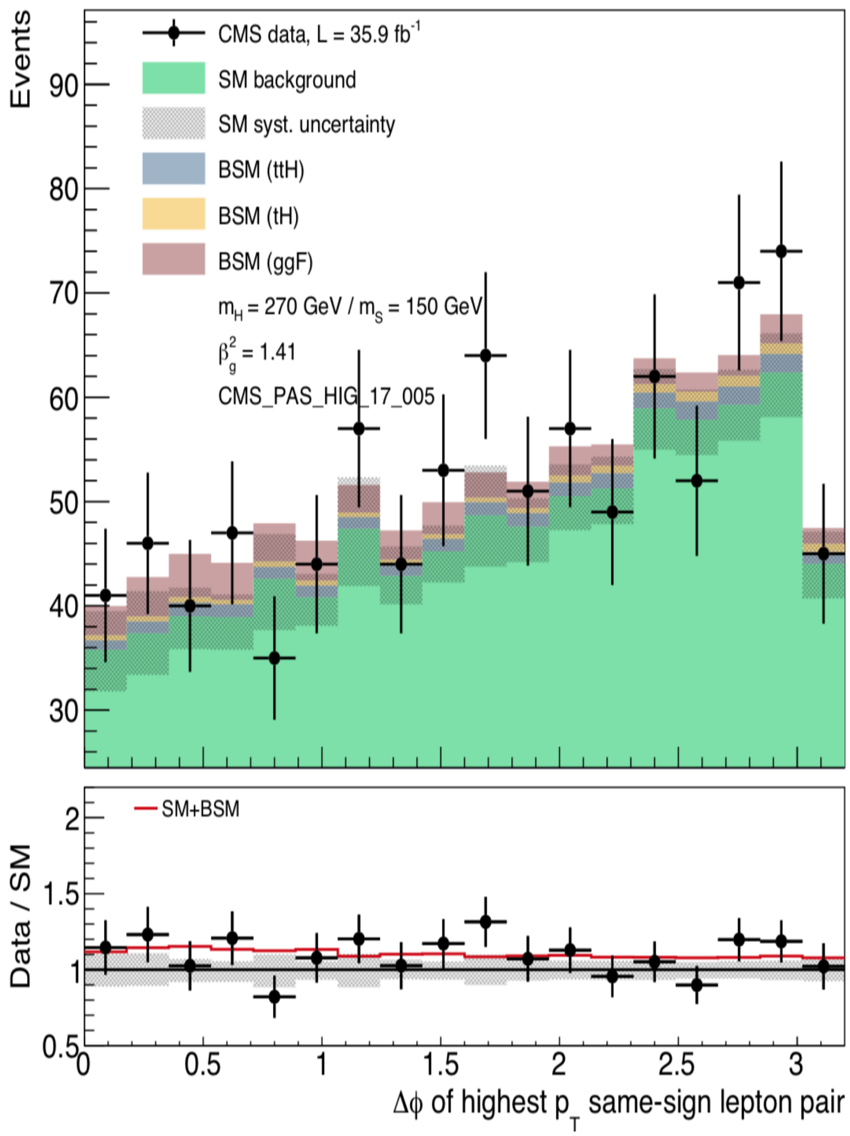
SS leptons: CMS-PAS-HIG-17-005

- CMS search for single top + Higgs production:
  - At least 2 SS leptons
  - At least 1 *b*-tagged jet
- The full analysis uses a BDT, so we compare to pre-selection plots
- Difficulty in estimating the probability of HF decay leptons to fake signal leptons
  - Not enough information in paper
- Fit results:
  - $\beta_g^2 = 1.41 \pm 0.80$
  - Weak measurement due to lack of statistics and large systematics



Fit results: CMS-PAS-HIG-17-005

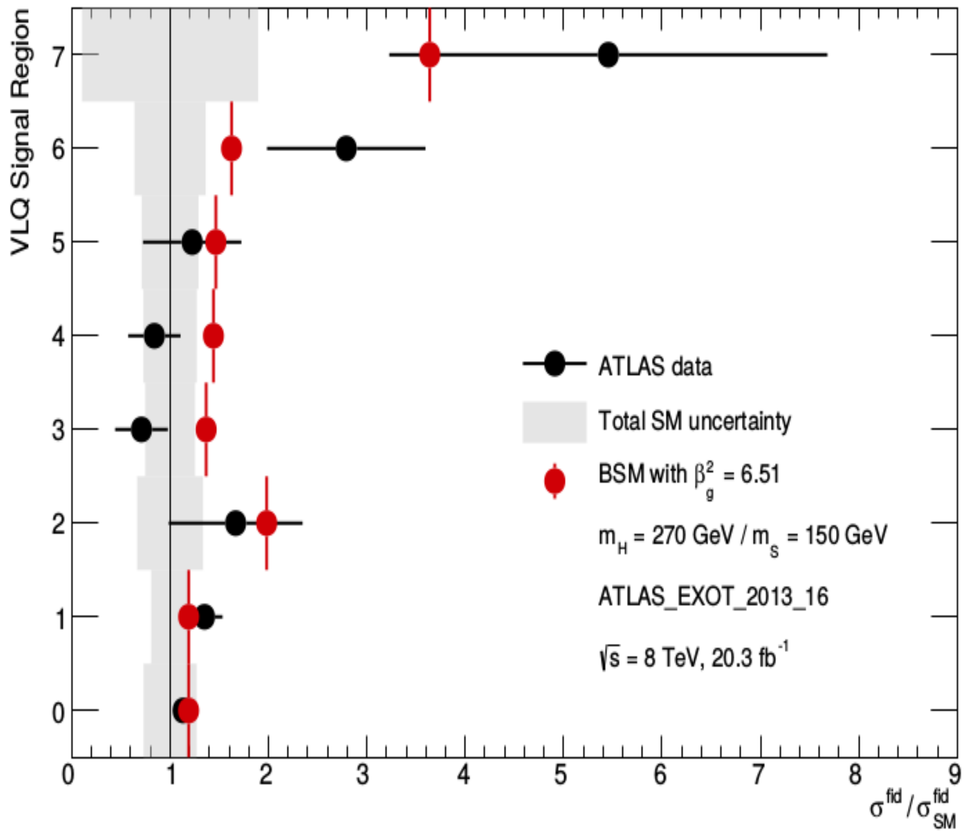




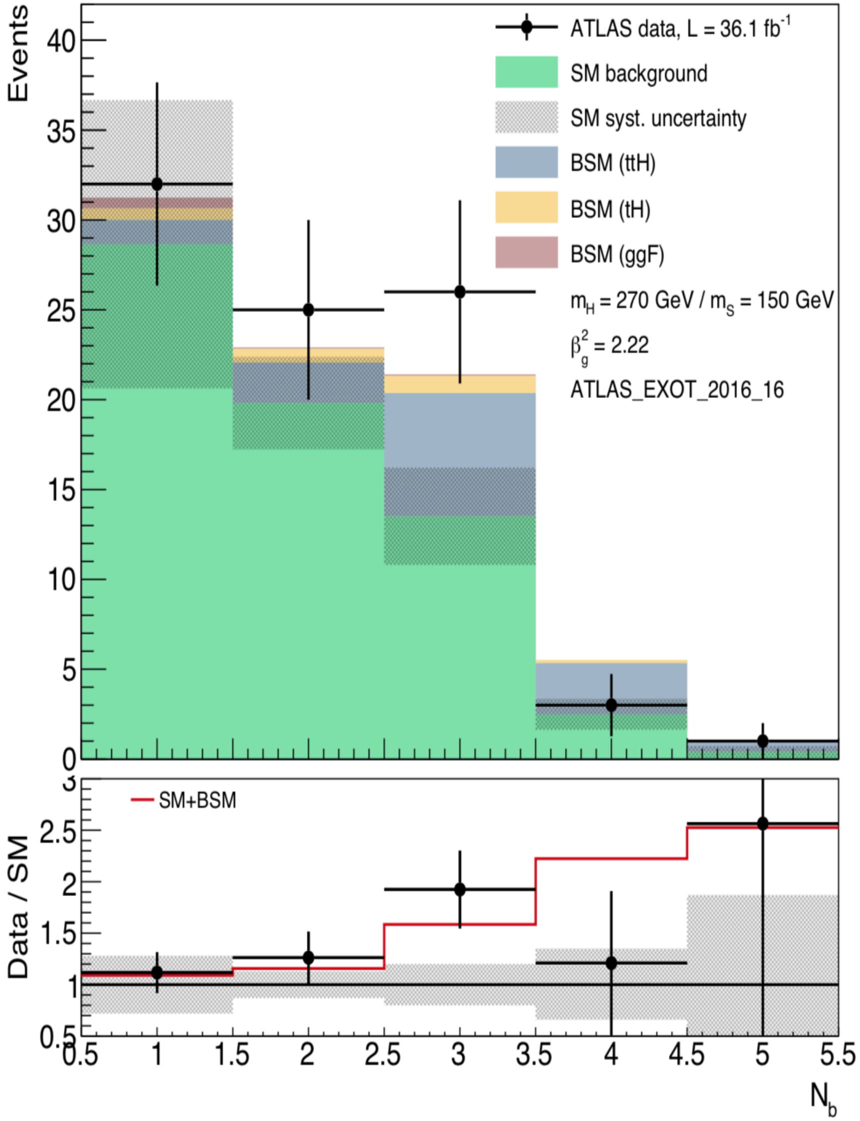
SS ll+b-jets: JHEP 10 (2015) 150

- **Final state search topology:**
  - 2 or 3 leptons (must be a same-sign pair)
  - At least 2 untagged jets
  - E_T^{miss} > 40 GeV, H_T > 400 GeV (binned into different signal regions)
- **Systematic uncertainty is large:**
  - In the fit, treated as a single normalisation uncertainty correlated over all SRs
- **Fit results:**
  - $\beta_g^2 = 6.51 \pm 2.99$
  - This is relatively high compared to other fit results

SR Key:
- 1 *b*-tagged jet: SRs 0, 3, 4
- 2 *b*-tagged jets: SRs 1, 5, 6
- ≥ 3 *b*-tagged jets: SRs 2, 7

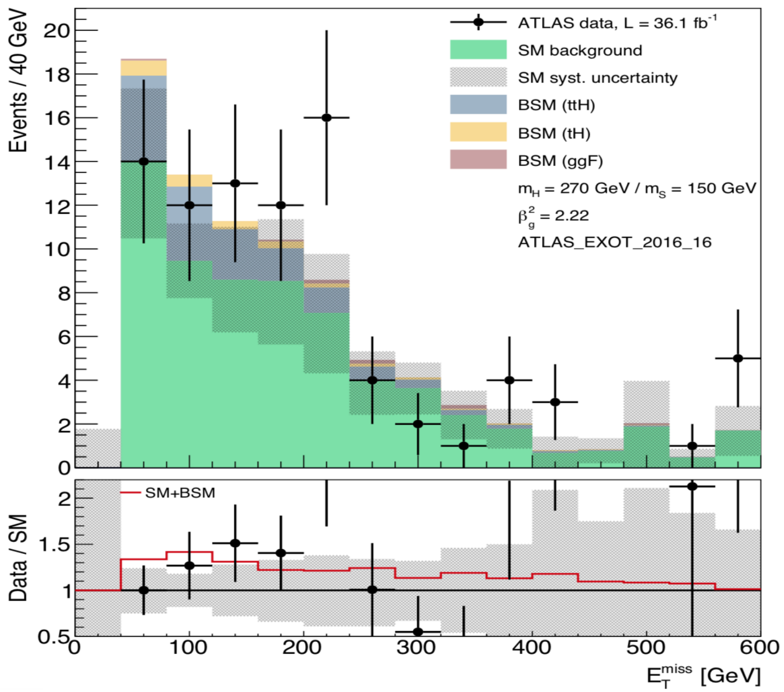


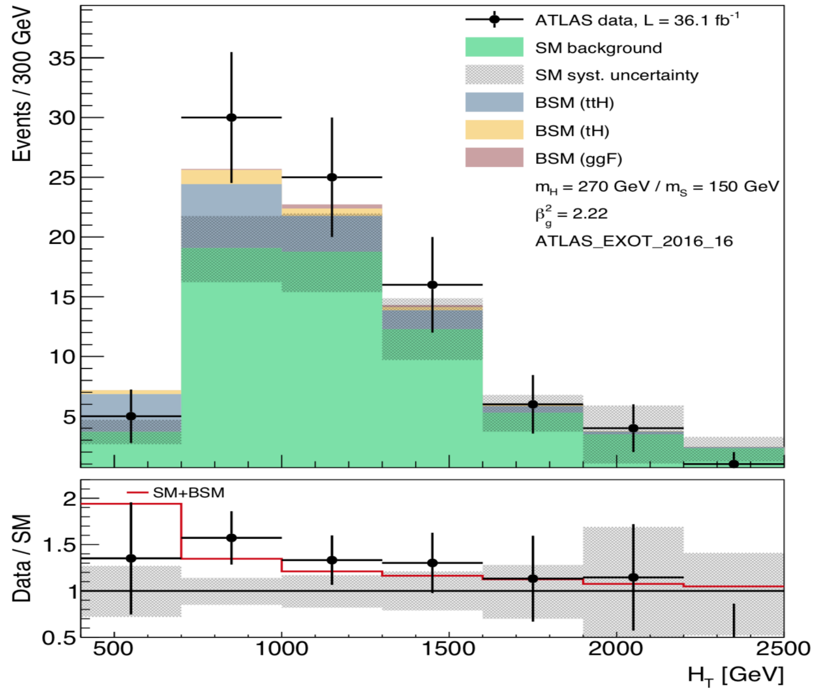
SS ll+ b-jets: ATLAS-EXOT-2016-16

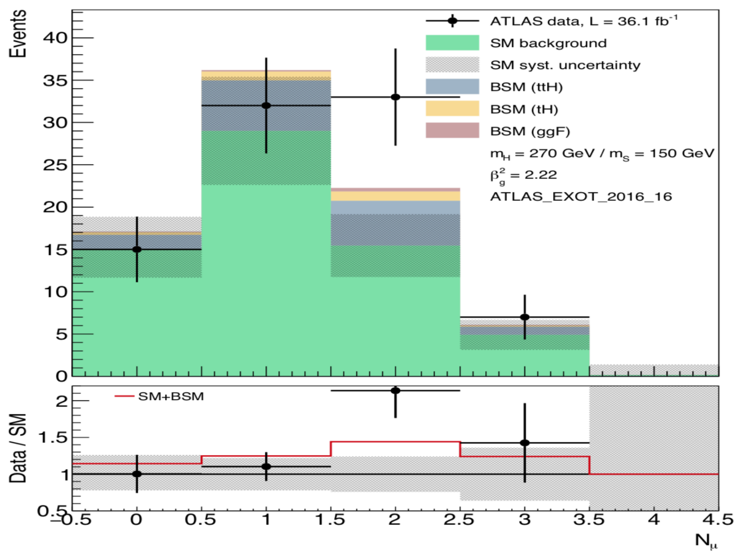


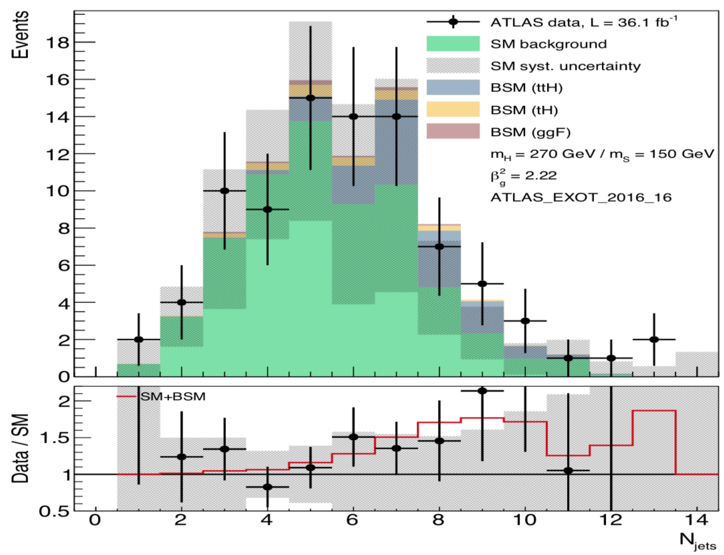
- **Run 2 version of SS + *b*-jet search:**
  - **At least 2 SS leptons**
  - **At least 1 *b*-tagged jet**
  - **Large E_T^{miss} and H_T**
- **Fit to inclusive SR distributions (auxiliary figures)**
- **Shows the strength of the model to fit the 3 *b*-jet excesses**
- **Fit results:**
  - **$\beta_g^2 = 2.22 \pm 1.19$**

SS ll + b-jets: ATLAS-EXOT-2016-16



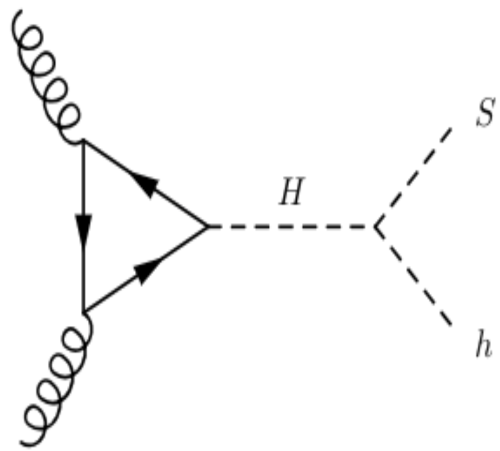


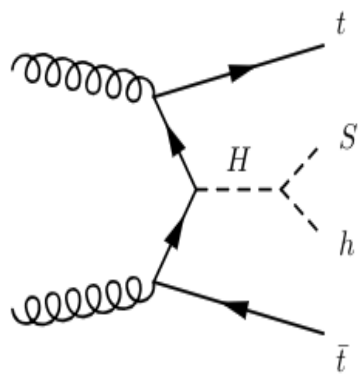


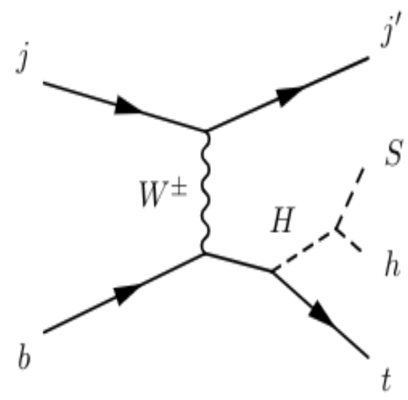


BSM inputs to the fit

- **The following <u>assumptions</u> are made:**
  - a. The masses of *H* and *S* are fixed to m_H = 270 GeV and m_S = 150 GeV
  - b. The only significant production mechanisms of *H* come from the *t-t-H* Yukawa coupling:
    - Gluon fusion
    - Top associated production
  - c. The Yukawa coupling is scaled away from the SM Higgs-like value by the free parameter β_g
  - d. The BR of $H \rightarrow Sh$ is fixed to 100%
  - e. The BRs of *S* are Higgs-like
- **Therefore, the only free parameter in the fits is β_g^2**





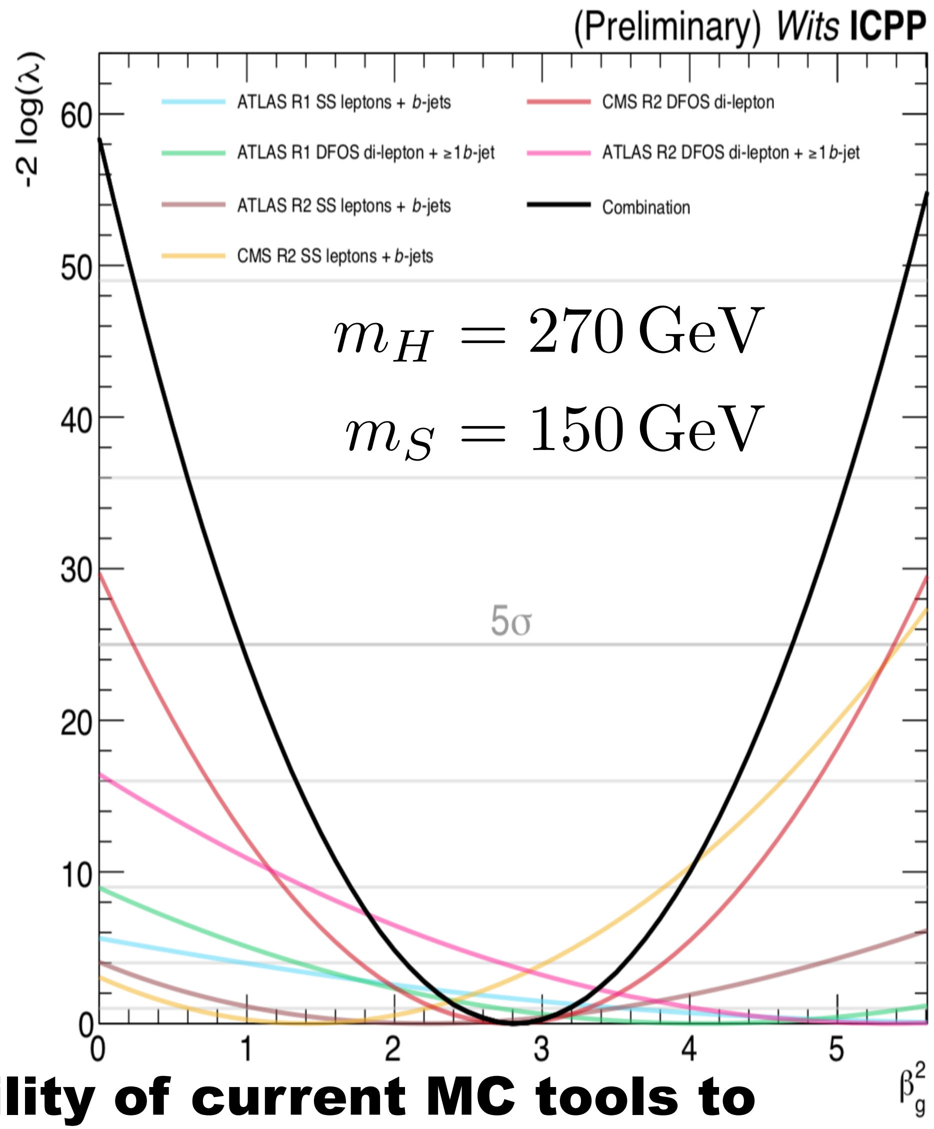


Combination of fit results

- Simultaneous fit for all measurements:
- To the right: (-2 log) profile likelihood ratio for each individual result and the combination of them all
- The significance for each fit is calculated as

$$\sqrt{-2\log\lambda(0)}$$

- Best-fit: $\beta_g^2 = 2.80 \pm 0.35$
- Corresponds to 7.64σ

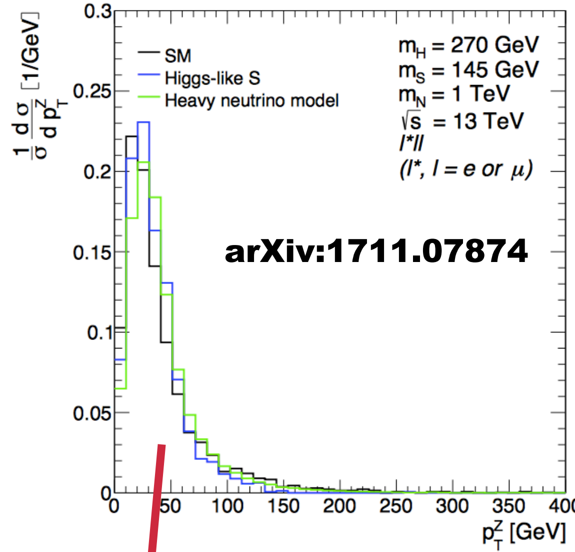


Interpretation: Measure of the inability of current MC tools to describe multiple-lepton data and how a simplified model with H→Sh is able to capture the effect with one parameter

3l with Z→ll (ZW cross-section)

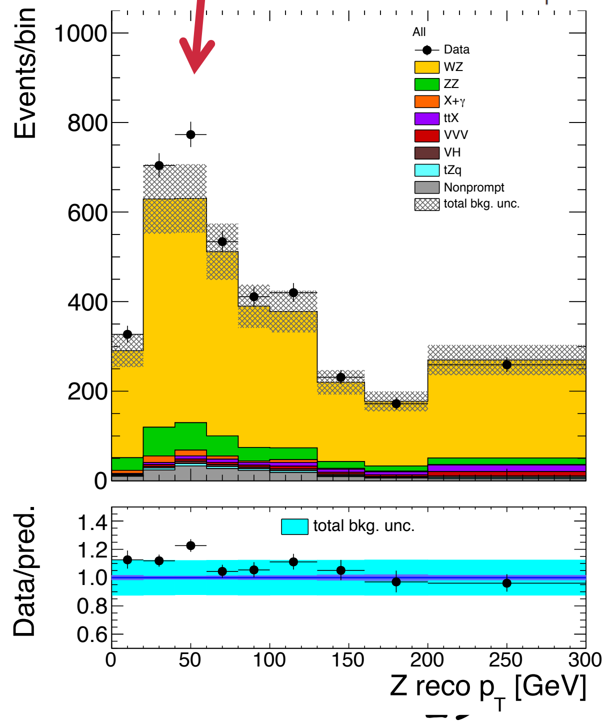
CMS PAS SMP-18-002

Errors in the plot are dominated by the 15% uncertainty on normalization to account NLO/NNLO differences. The uncertainty of the shape is much smaller of order of few %



Source	Combined	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
Electron efficiency	1.9	5.9	3.9	1.9	0
Electron scale	0.3	0.9	0.2	0.6	0
Muon efficiency	1.9	0	0.8	1.8	2.6
Muon scale	0.5	0	0.7	0.3	0.9
Trigger efficiency	1.9	2.0	1.9	1.9	1.8
Jet energy scale	0.9	1.6	1.0	1.7	0.8
B-tagging (id.)	2.6	2.7	2.6	2.6	2.4
B-tagging (mis-id.)	0.9	1.0	0.9	1.0	0.7
Pileup	0.8	0.9	0.3	1.3	1.4
ZZ	0.6	0.7	0.4	0.8	0.5
Nonprompt norm.	1.2	2.0	1.2	1.5	1.0
Nonprompt (EWK subs.)	1.0	1.5	1.0	1.3	0.8
VVV norm.	0.5	0.6	0.6	0.6	0.5
VH norm.	0.2	0.2	0.3	0.2	0.2
$t\bar{t}$ V norm.	0.5	0.5	0.5	0.5	0.5
tZq norm.	0.1	0.1	0.1	0.1	0.1
X+γ norm.	0.3	0.8	0	0.7	0
Total systematic	4.7	7.8	5.8	5.7	4.6
Luminosity	2.8	2.9	2.8	2.9	2.8
Statistical	2.1	6.0	4.8	4.1	3.1
Total experimental	6.0	10.8	8.0	7.5	6.3
Theoretical	0.9	0.9	0.9	0.9	0.9

Systematics that will directly affect the shape (ZZ through X+γ norm.)

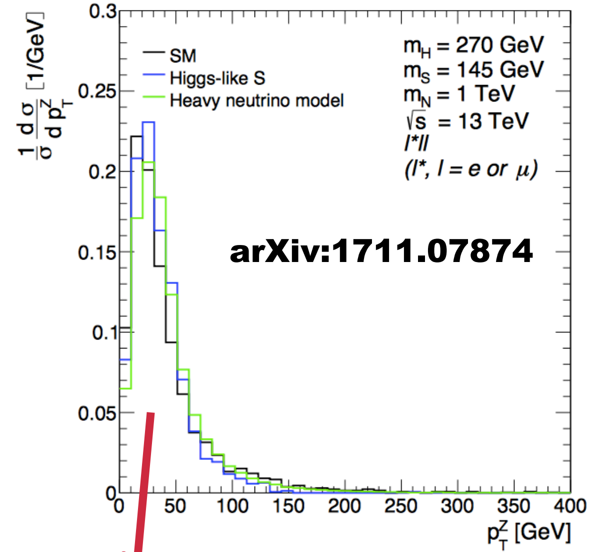


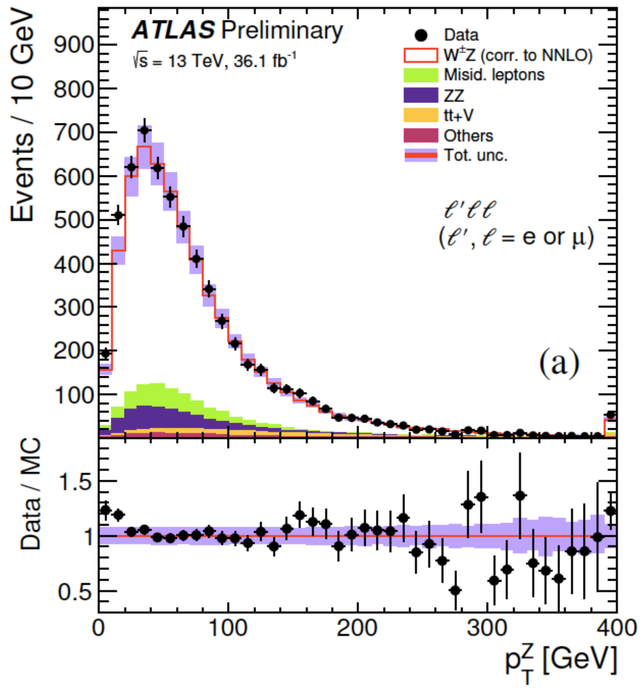
3l with Z→ll (ZW cross-section)

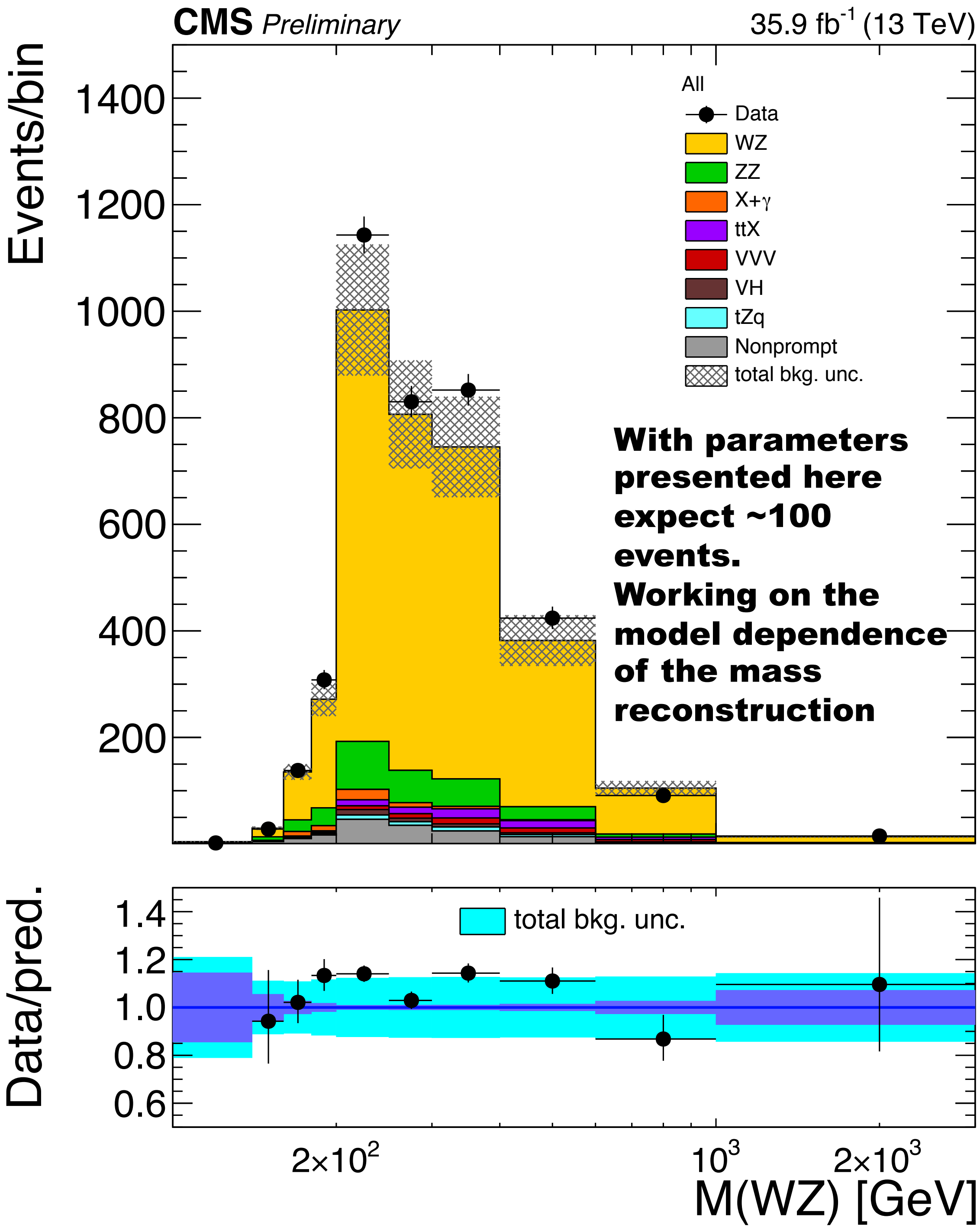
ATLAS-CONF-2018-034

Systematics that will directly affect the shape stand at few %

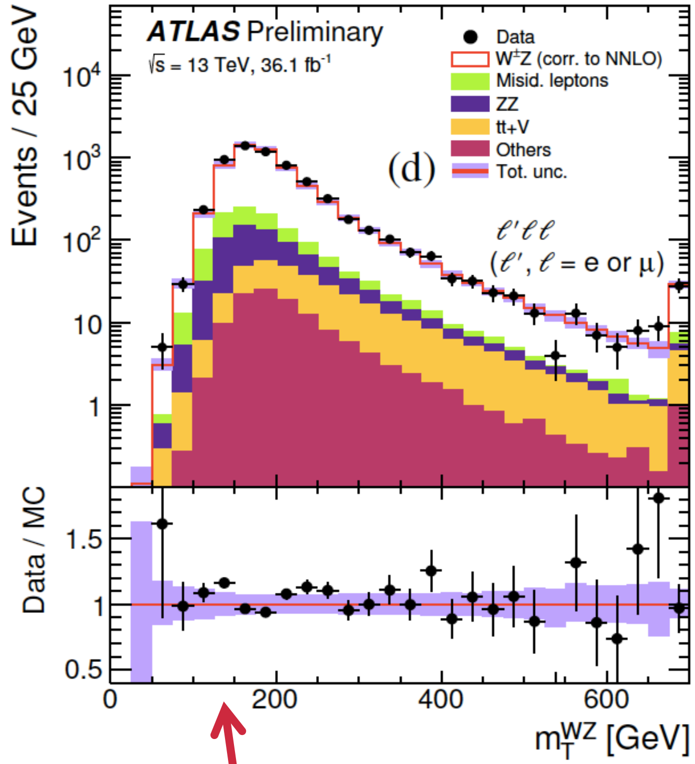
	eee	μee	$e\mu\mu$	$\mu\mu\mu$	combined
Relative uncertainties [%]					
e energy scale	0.2	0.1	0.1	< 0.1	0.1
e id. efficiency	2.8	1.8	1.0	< 0.1	1.1
μ momentum scale	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
μ id. efficiency	< 0.1	1.3	1.6	2.8	1.5
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	0.2	0.2	0.3	0.5	0.3
Trigger	< 0.1	< 0.1	0.2	0.3	0.2
Pileup	1.0	1.5	1.2	1.5	1.3
Misid. leptons background	4.7	1.1	4.5	1.6	1.9
ZZ background	1.0	1.0	1.1	1.0	1.0
Other backgrounds	1.6	1.5	1.4	1.2	1.4
Uncorrelated	0.7	0.6	0.7	0.5	0.3
Total systematics	6.0	3.5	5.4	4.1	3.6
Luminosity	2.4	2.4	2.4	2.4	2.4
Modelling	0.5	0.5	0.5	0.5	0.5
Statistics	3.6	3.3	3.2	2.7	1.6
Total	7.4	5.4	6.7	5.4	4.6



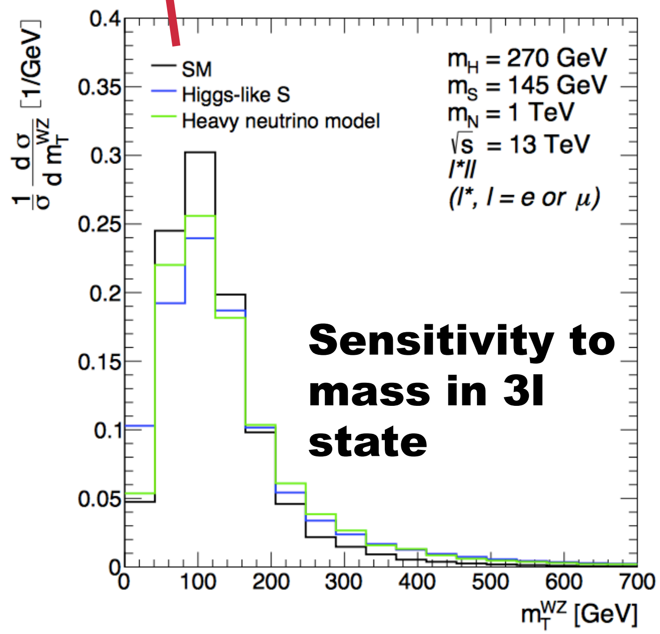




With parameters presented here expect ~100 events.
Working on the model dependence of the mass reconstruction



arXiv:1711.07874



Sensitivity to mass in 3l state

Outlook and Conclusions

- **Discrepancies in multi-lepton final states with current MC tools are strong**
  - **While significance is dominated by OS di-lepton final states, discrepancies appear in SS ll and 3l**
  - **They appear in corners of the phase-space dominated by different processes: Wt/tt, WW, ZW**
- **Discrepancies interpreted with simplified model where H→Sh, S is treated as SM Higgs-like and one parameter is floated: strength of H Yukawa coupling top quarks**
- **Simplified model is embedded into a 2HDM+S model**
  - **Model is now good shape for use by experiments to explore the multi-lepton discrepancies**
  - **N2HDECAY package is now available as well**
- **Run 2 will provide four times the data set**

Additional Slides

The Lagrangian

arXiv:1506.00612
arXiv:1603.01208
arXiv:1606.01674

Introduce H and X fields with the interactions listed below

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

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

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

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

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

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

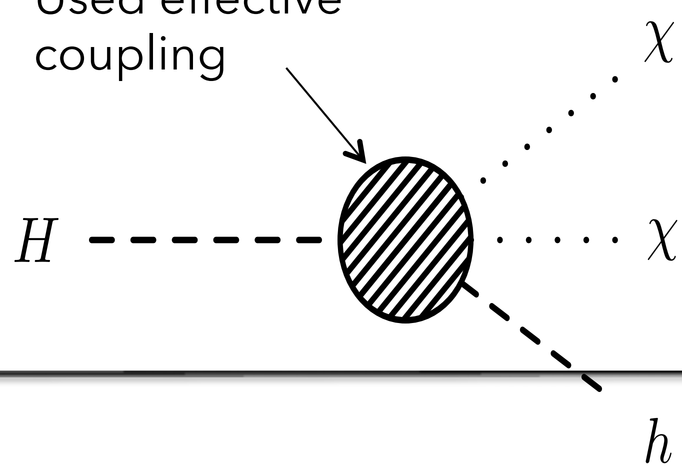
$$\mathcal{L}_{HVV} = \frac{2M_W^2}{v}\beta_W \ W_\mu W^\mu H + \frac{M_Z^2}{v}\beta_Z \ Z_\mu Z^\mu H$$

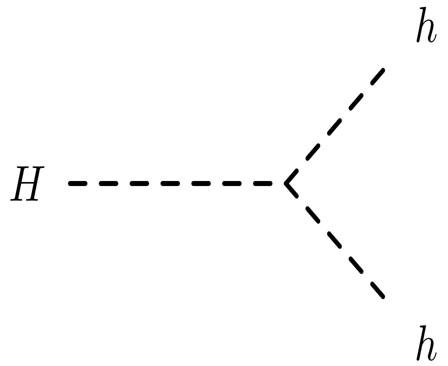
Main decay modes of *H*

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

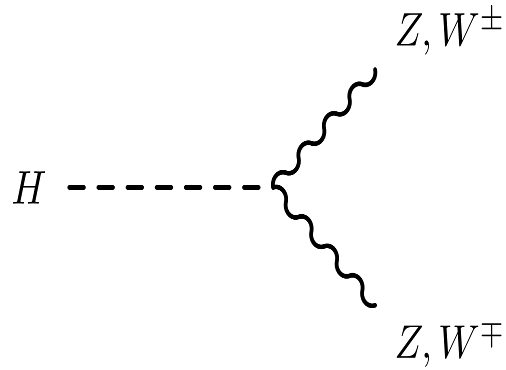
Used effective coupling





Decay to double Higgs pair.

Decay to vector boson pairs.

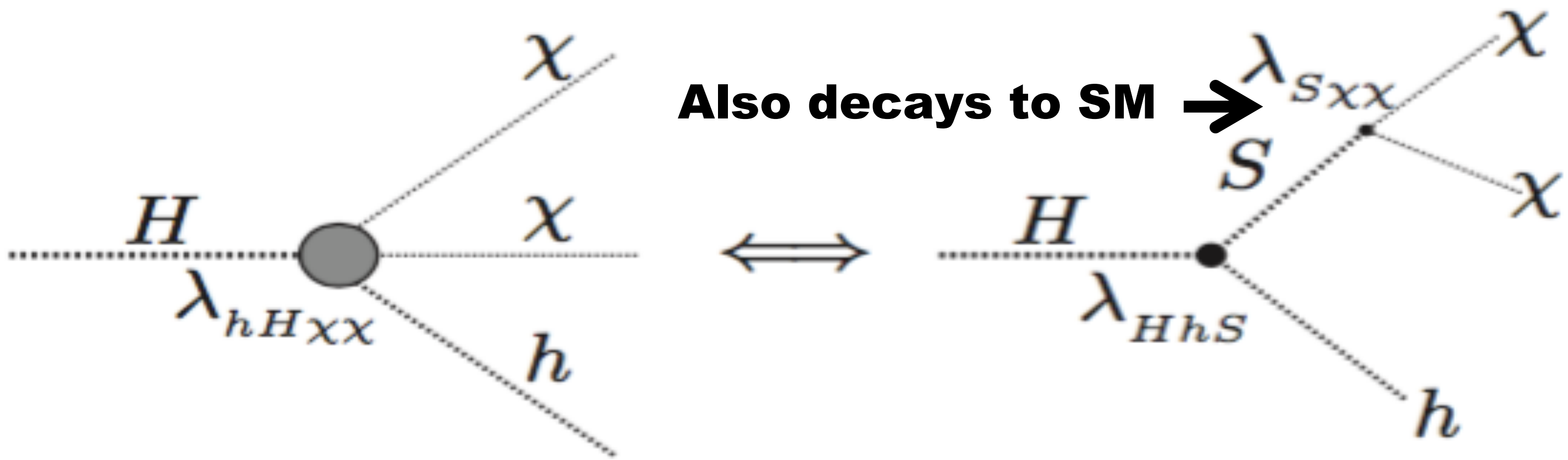


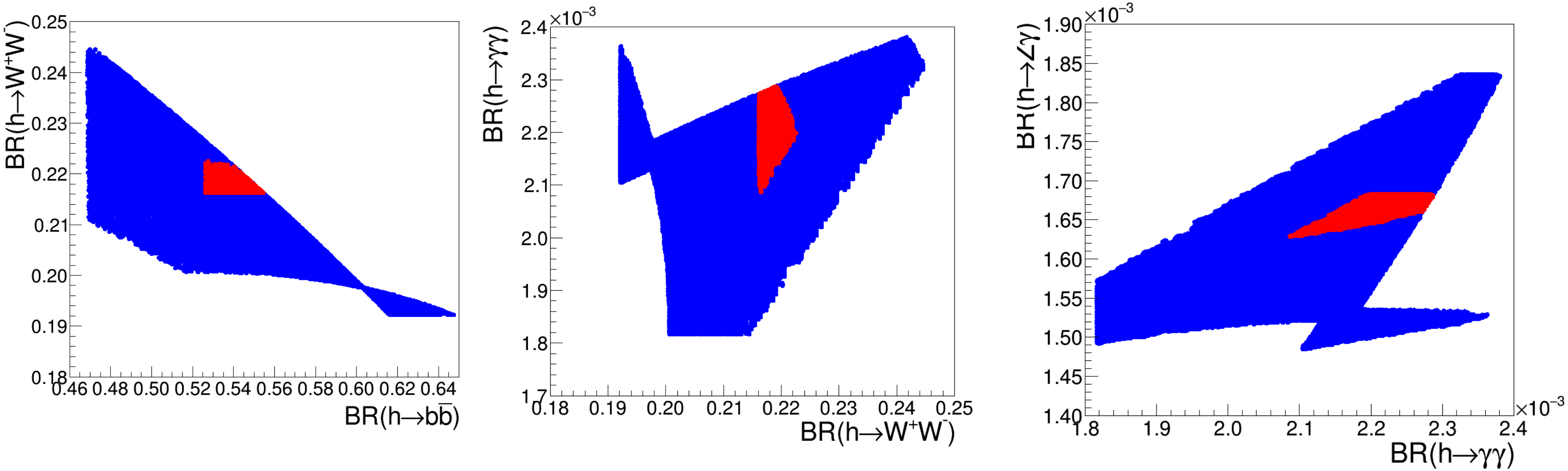
The intermediate scalar, S

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

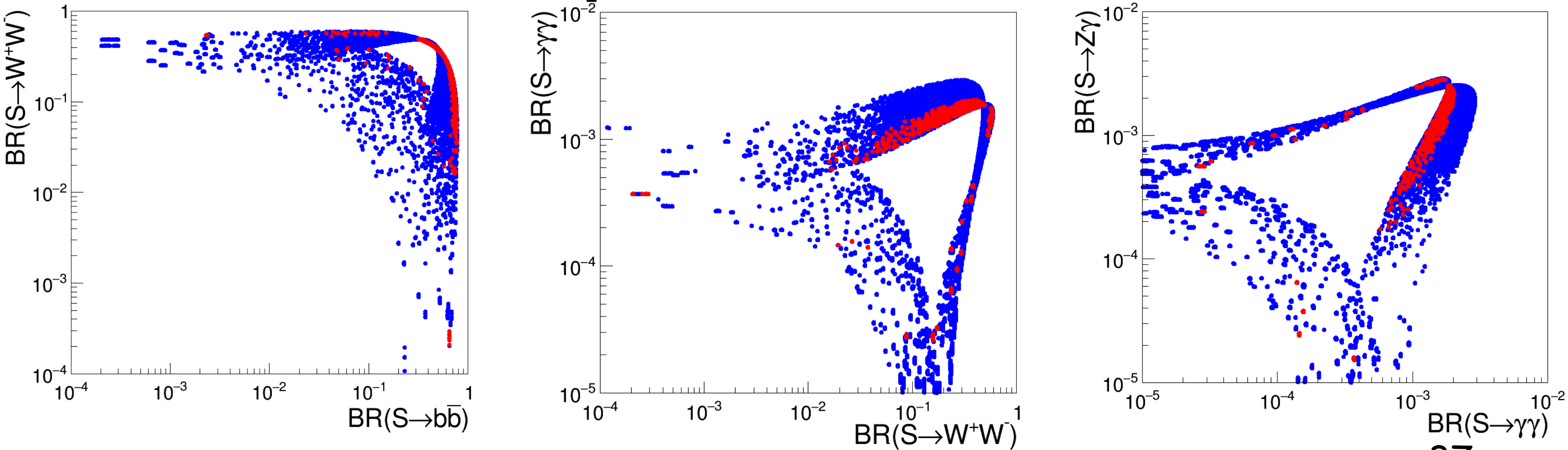
$$\mathcal{L}_{\rm Q} = -\frac{1}{2}\lambda_{Hh\chi\chi} Hh\chi\chi - \frac{1}{4}\lambda_{HHhh} HHhh - \frac{1}{4}\lambda_{hh\chi\chi} hh\chi\chi - \frac{1}{4}\lambda_{HH\chi\chi} HH\chi\chi$$

- **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**

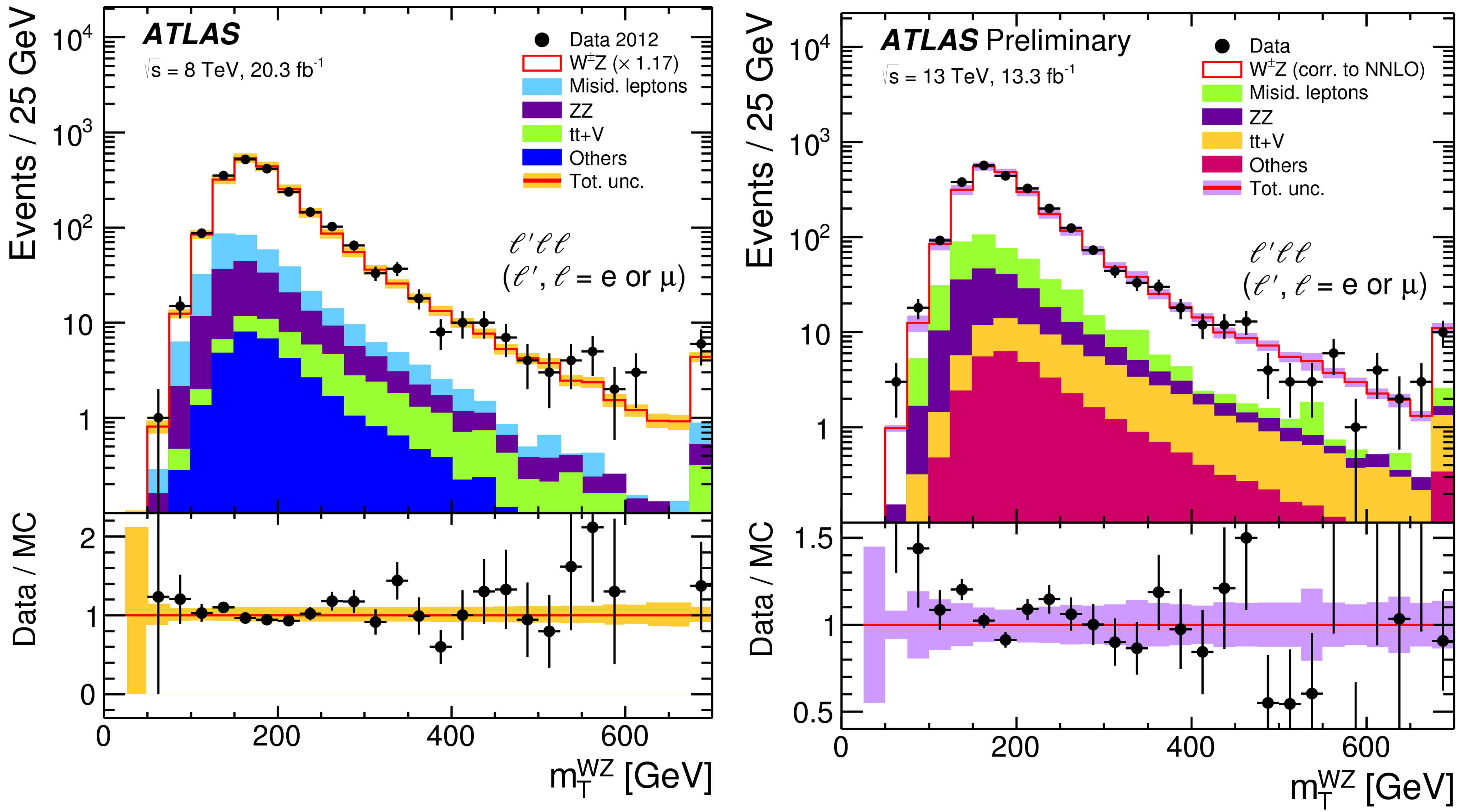


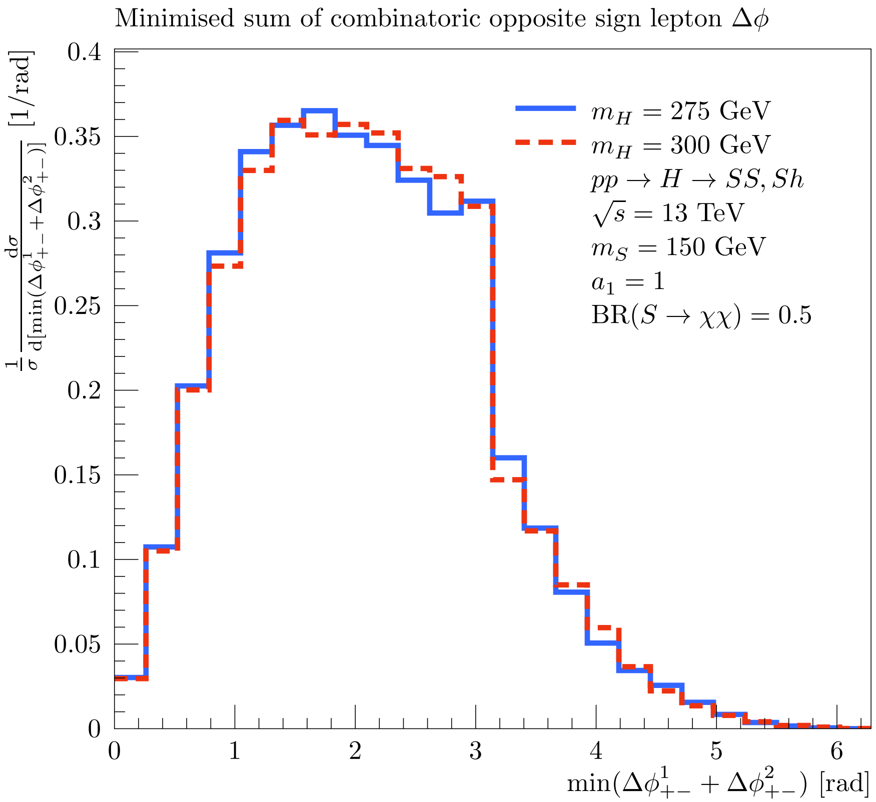


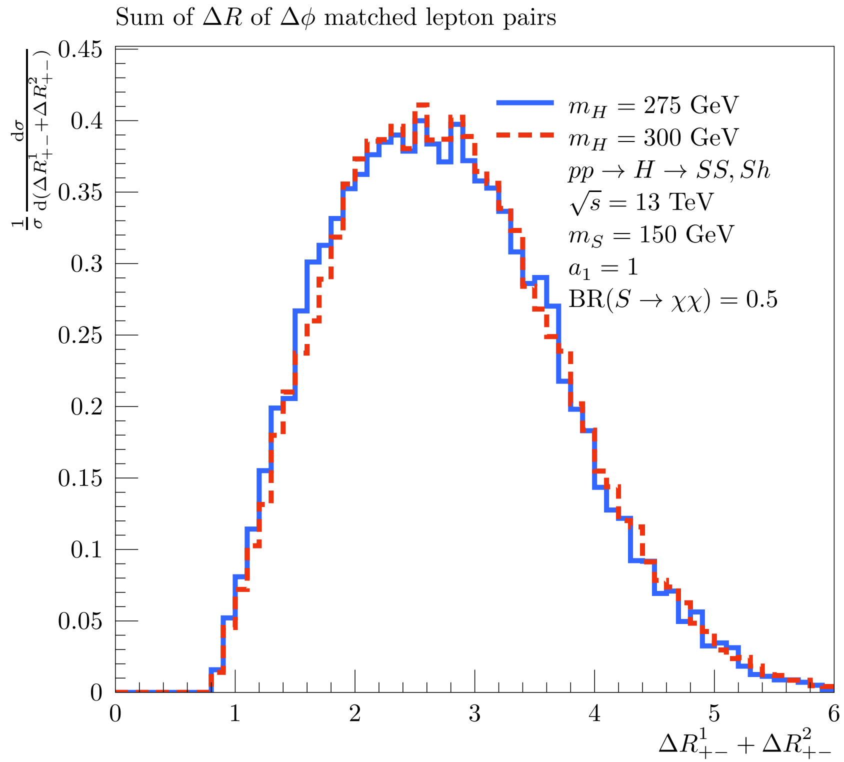
Results using N2HDECAY (arXiv:1612.01309) for one benchmark point

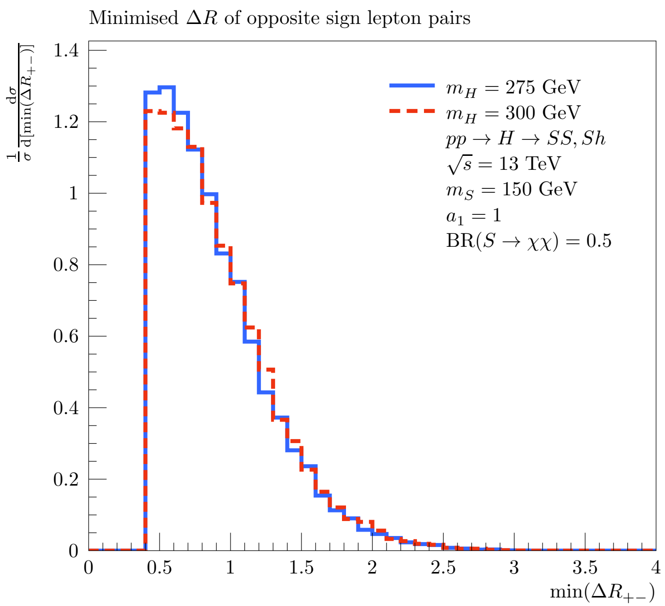


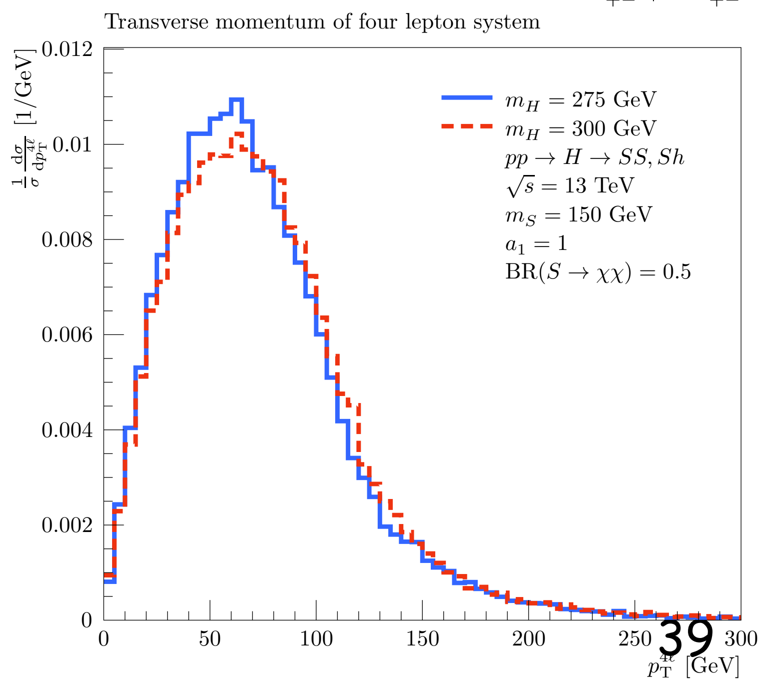
The data reported with Run I and Run II by ATLAS overshoots the MC with M_T<200 GeV. The 4W prediction is not excluded with the current results.




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

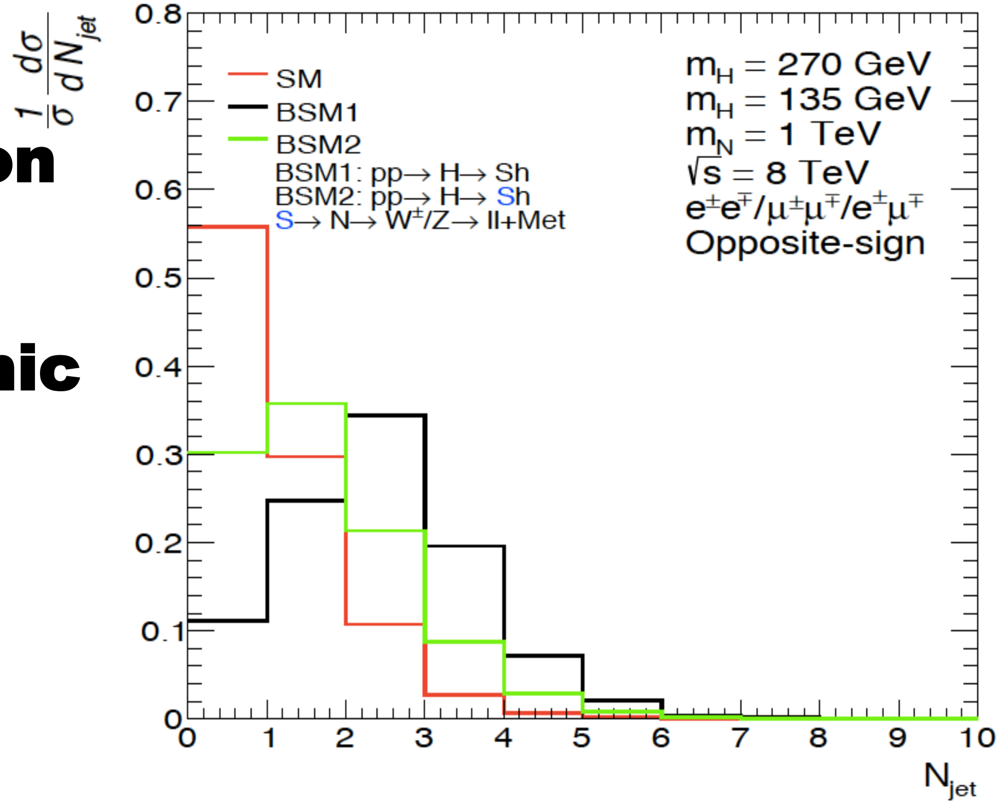

Minimised ΔR of opposite sign lepton pairs
$\frac{1}{\sigma}\frac{d\sigma}{d[\min(\Delta R_{+-})]}$
$m_H = 275$ GeV
$m_H = 300$ GeV
$pp \to H \to SS, Sh$
$\sqrt{s} = 13$ TeV
$m_S = 150$ GeV
$a_1 = 1$
$\mathrm{BR}(S \to \chi\chi) = 0.5$
$\min(\Delta R_{+-})$


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 on h boson 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.

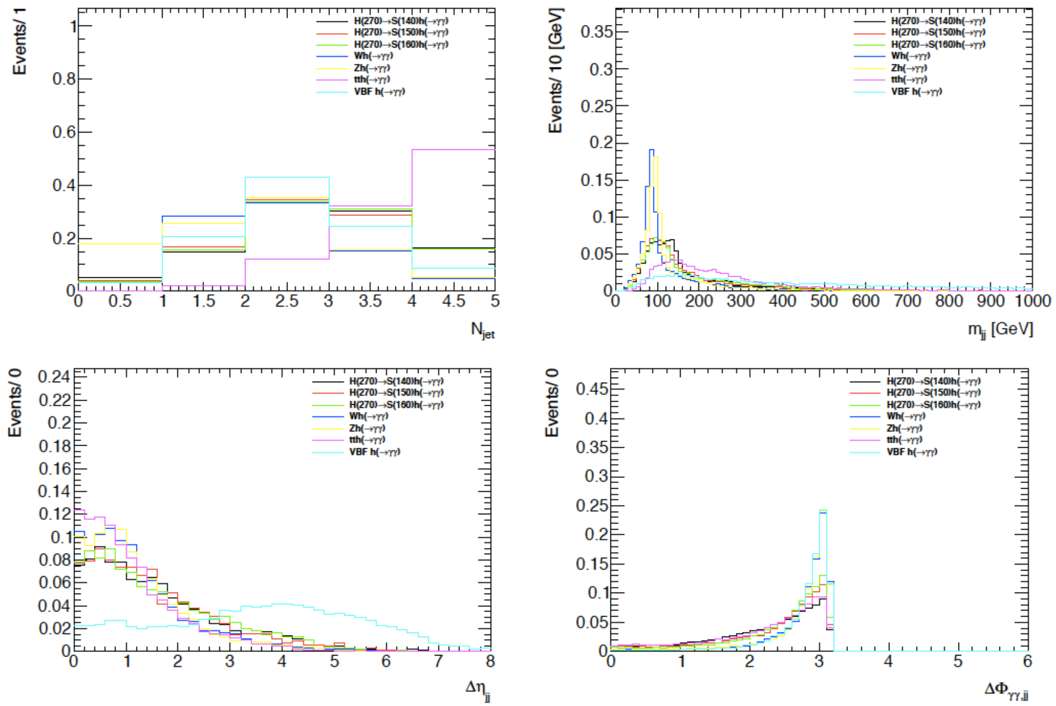
- At this point we are studying the contamination of the H→Sh production mechanism on measurement with hadronic final states: h+≥2j, VBF, V(→jj)h, Vh(→bb) (not discussed here) h signal strengths

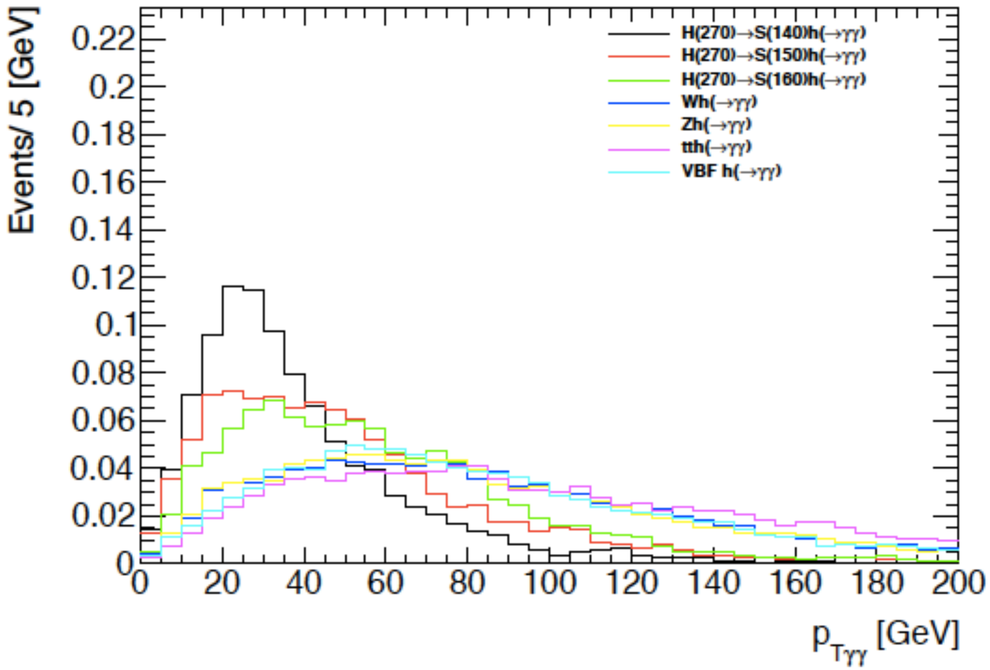


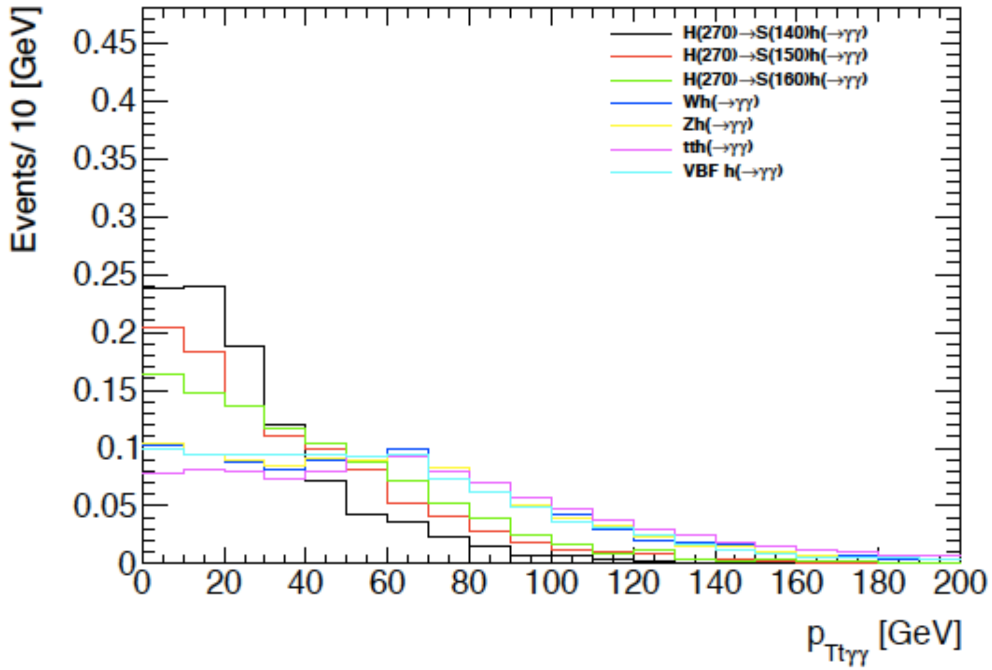
$\sigma(H) = 10\,\mathrm{pb}$

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.

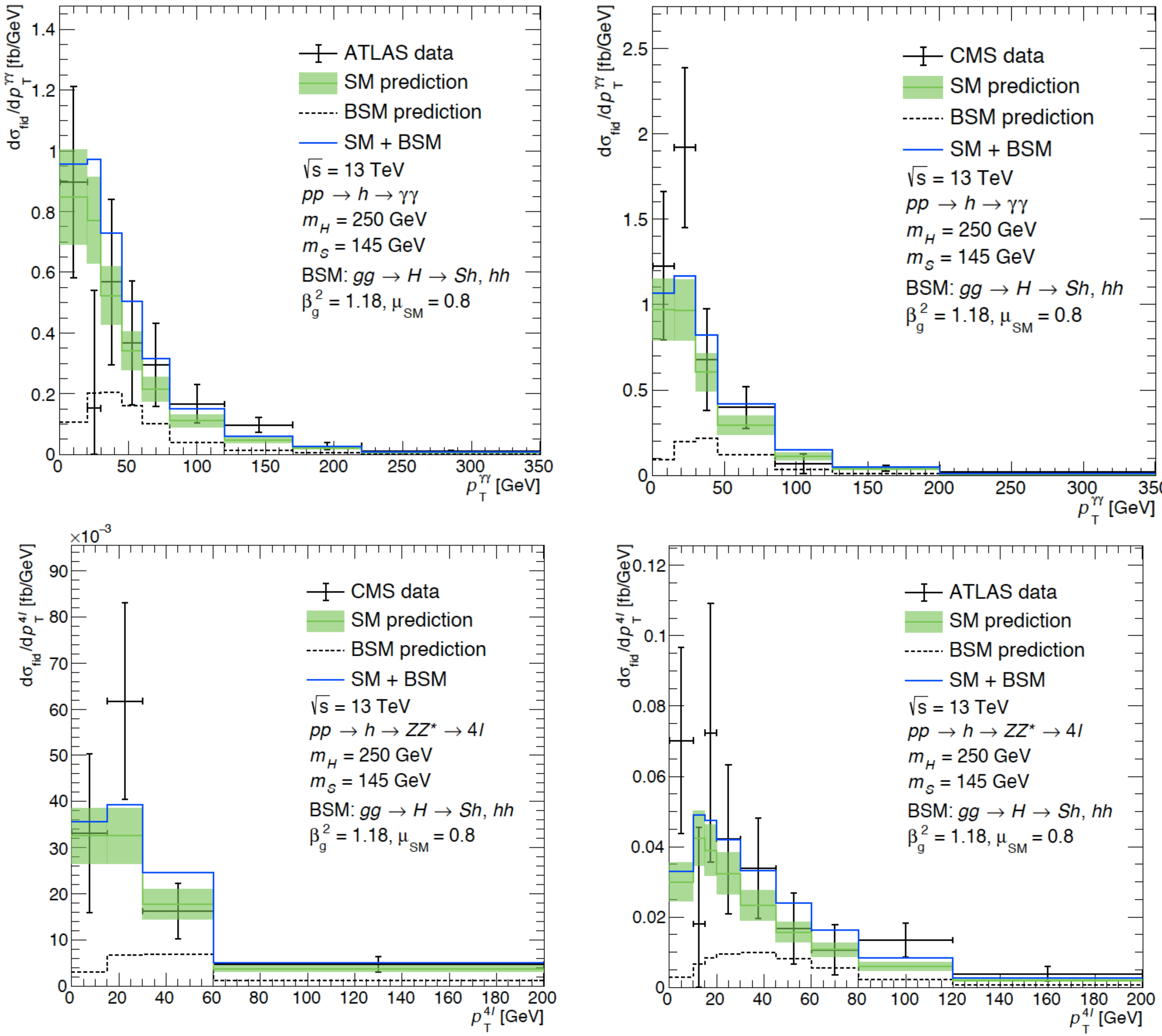
Production mechanism	VBF $h \to \gamma\gamma$	$Vh, V \to jj, h \to \gamma\gamma$
$H(270) \to S(140)h(\to \gamma\gamma)$	2.86±0.07	0.16±0.02
$H(270) \to S(150)h(\to \gamma\gamma)$	1.94±0.06	1.14±0.04
$H(270) \to S(160)h(\to \gamma\gamma)$	2.89±0.07	1.97±0.06
$Wh(\to \gamma\gamma)$	0.22±0.01	1.90±0.03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

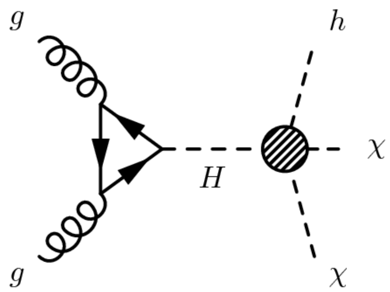






The data is somewhat harder than the SM, but not to a degree that is significant. Plots here are displayed as a consistency check. The Higgs boson p_T on its own does not provide a convincing argument.



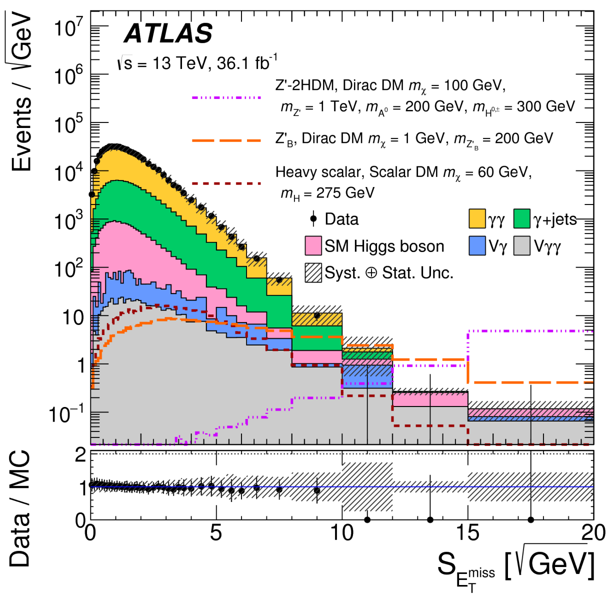


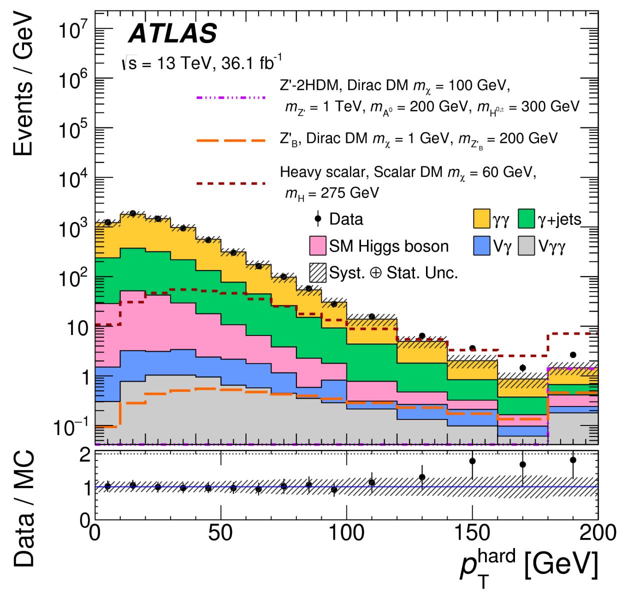
ATLAS, arXiv:1706.03948

Limits on h(→γγ)+MET

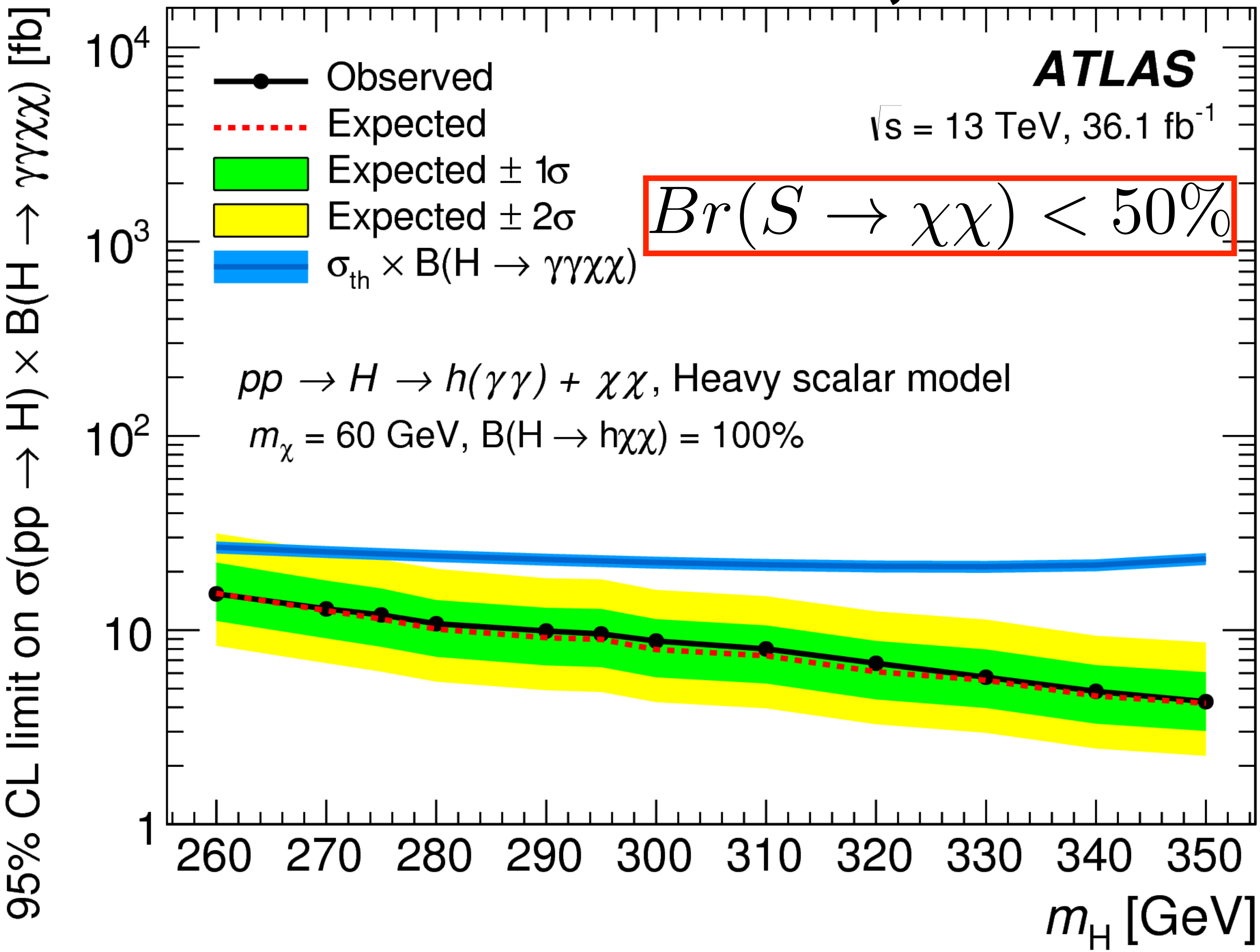
Category	Requirements
Mono-Higgs	$S_{E_{\mathrm{T}}^{\mathrm{miss}}} > 7\ \sqrt{\mathrm{GeV}}$, $p_{\mathrm{T}}^{\gamma\gamma} > 90$ GeV, lepton veto
High-$E_{\mathrm{T}}^{\mathrm{miss}}$	$S_{E_{\mathrm{T}}^{\mathrm{miss}}} > 5.5\ \sqrt{\mathrm{GeV}}$, $\lvert z_{\mathrm{PV}}^{\mathrm{highest}} - z_{\mathrm{PV}}^{\gamma\gamma} \rvert < 0.1$ mm
Intermediate-$E_{\mathrm{T}}^{\mathrm{miss}}$	$S_{E_{\mathrm{T}}^{\mathrm{miss}}} > 4\ \sqrt{\mathrm{GeV}}$, $p_{\mathrm{T}}^{\mathrm{hard}} > 40$ GeV , $\lvert z_{\mathrm{PV}}^{\mathrm{highest}} - z_{\mathrm{PV}}^{\gamma\gamma} \rvert < 0.1$ mm
Different-Vertex	$S_{E_{\mathrm{T}}^{\mathrm{miss}}} > 4\ \sqrt{\mathrm{GeV}}$, $p_{\mathrm{T}}^{\mathrm{hard}} > 40$ GeV , $\lvert z_{\mathrm{PV}}^{\mathrm{highest}} - z_{\mathrm{PV}}^{\gamma\gamma} \rvert > 0.1$ mm
Rest	$p_{\mathrm{T}}^{\gamma\gamma} > 15$ GeV

$$S_{E_{\mathrm{T}}^{\mathrm{miss}}} = E_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{\sum E_{\mathrm{T}}}$$





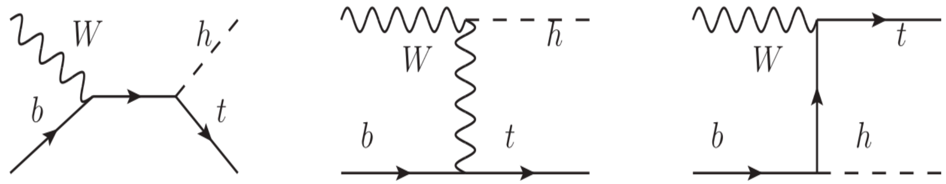
ATLAS, arXiv:1706.03948



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

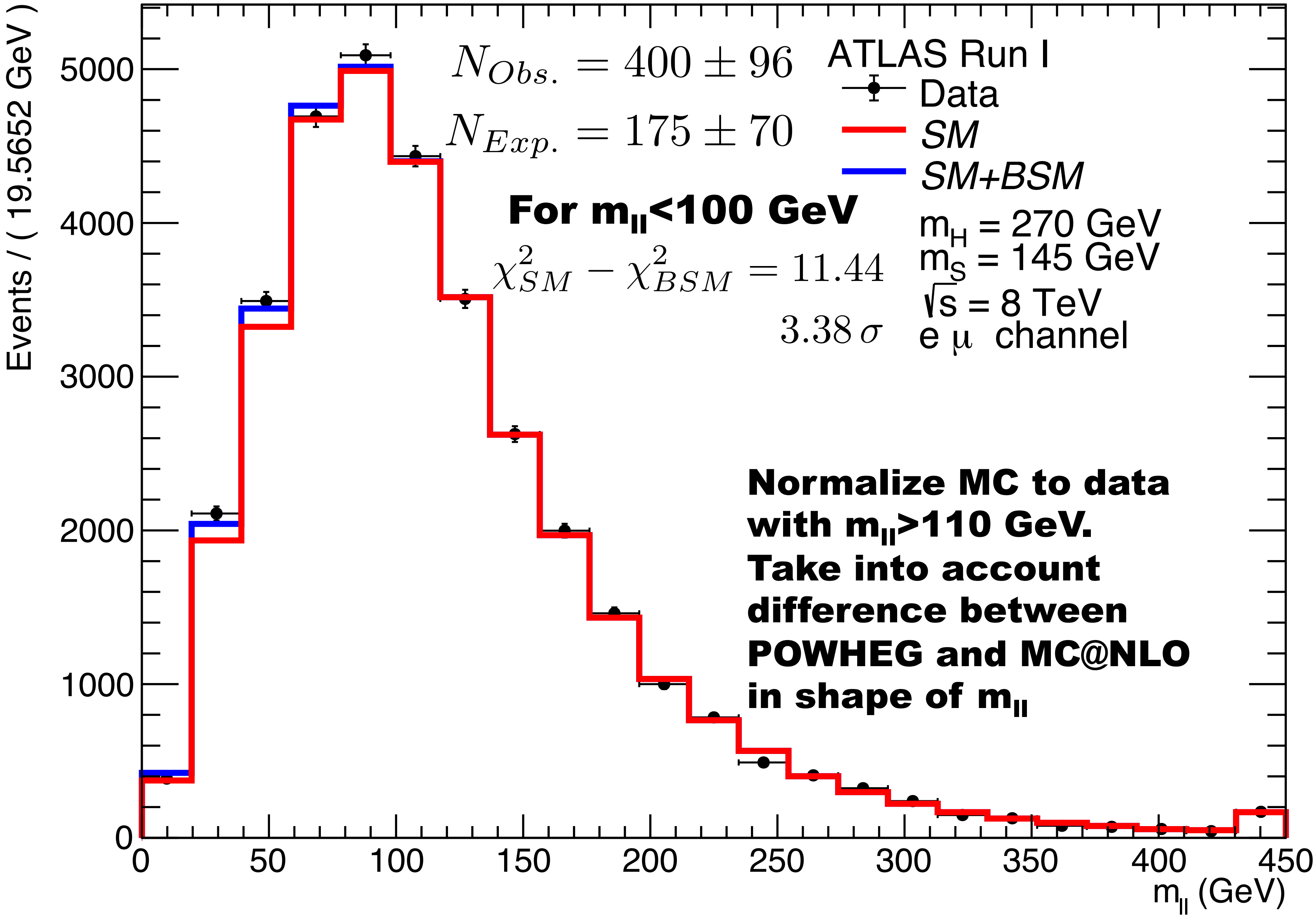
$$\mathcal{A} = \frac{g}{\sqrt{2}} \left[(c_F - c_V) \frac{m_t \sqrt{s}}{m_W v} A\left(\frac{t}{s}, \varphi; \xi_t, \xi_b\right) + \left(c_V \frac{2m_W}{v} \frac{s}{t} + (2c_F - c_V) \frac{m_t^2}{m_W v} \right) B\left(\frac{t}{s}, \varphi; \xi_t, \xi_b\right) \right]$$



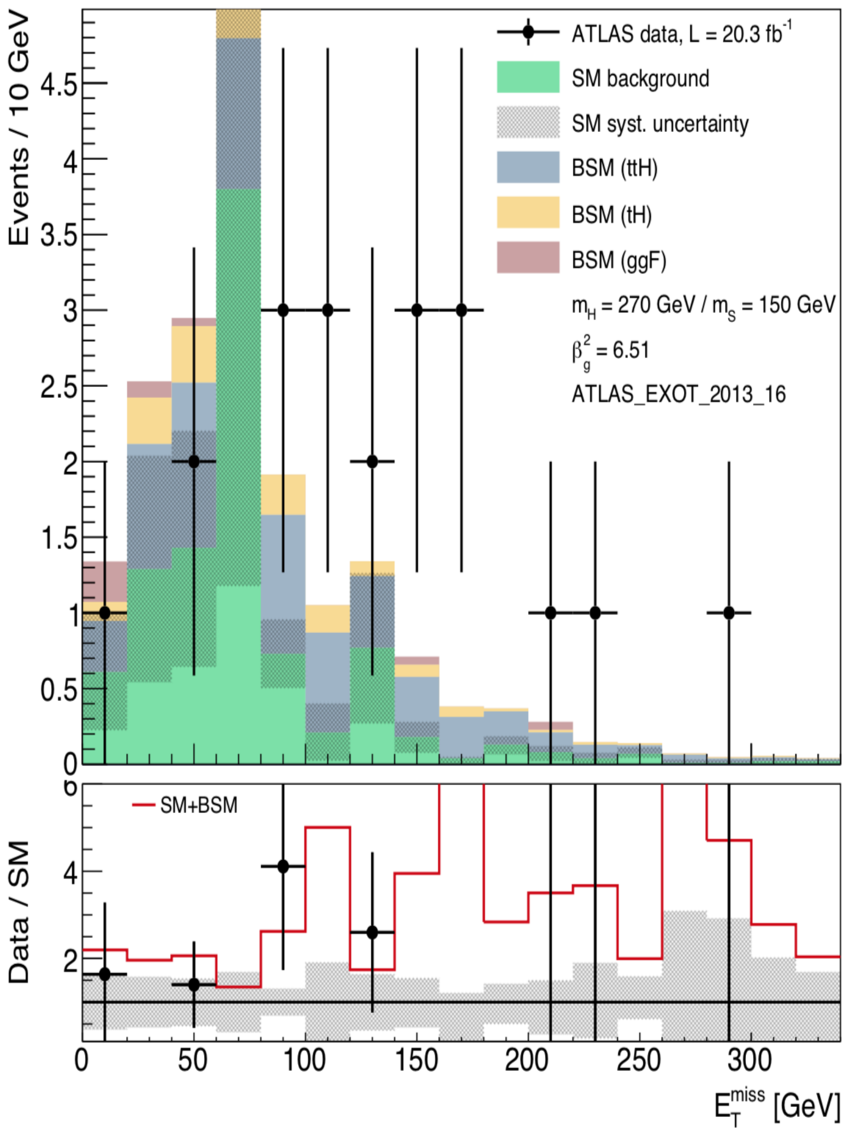
- **For the heavy scalar considered here, $c_V \ll c_F$**
- **We expect a sizeable cross section to come from top associated heavy scalar production ($\sigma_{tH} \simeq \sigma_{ttH}$)**

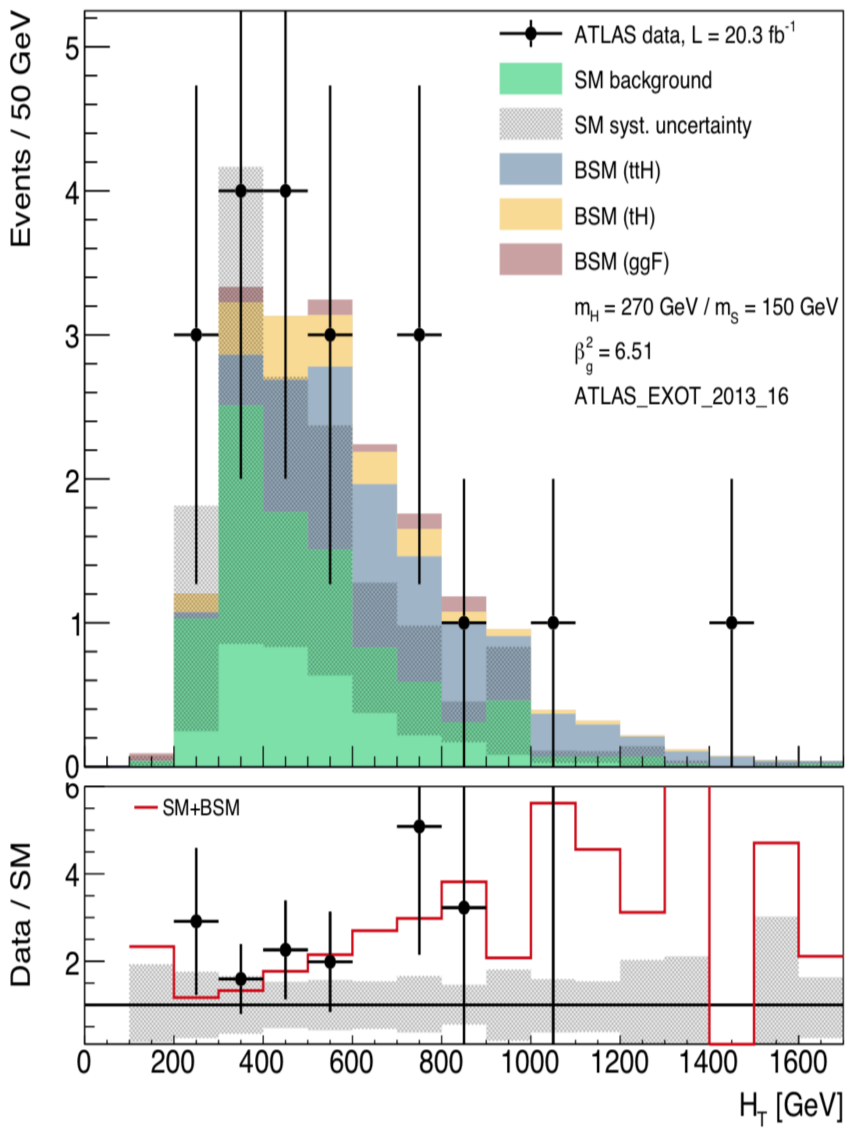
M. Farina, C. Grojean, F. Maltoni, E. Salvioni and A. Thamm, JHEP **1305**, 022 (2013).

Performed scan floating m_S (m_H=270 GeV), for m_{ll}<100 GeV
Best fit 145±5 GeV.



Fit results: ATLAS-EXOT-2013-16

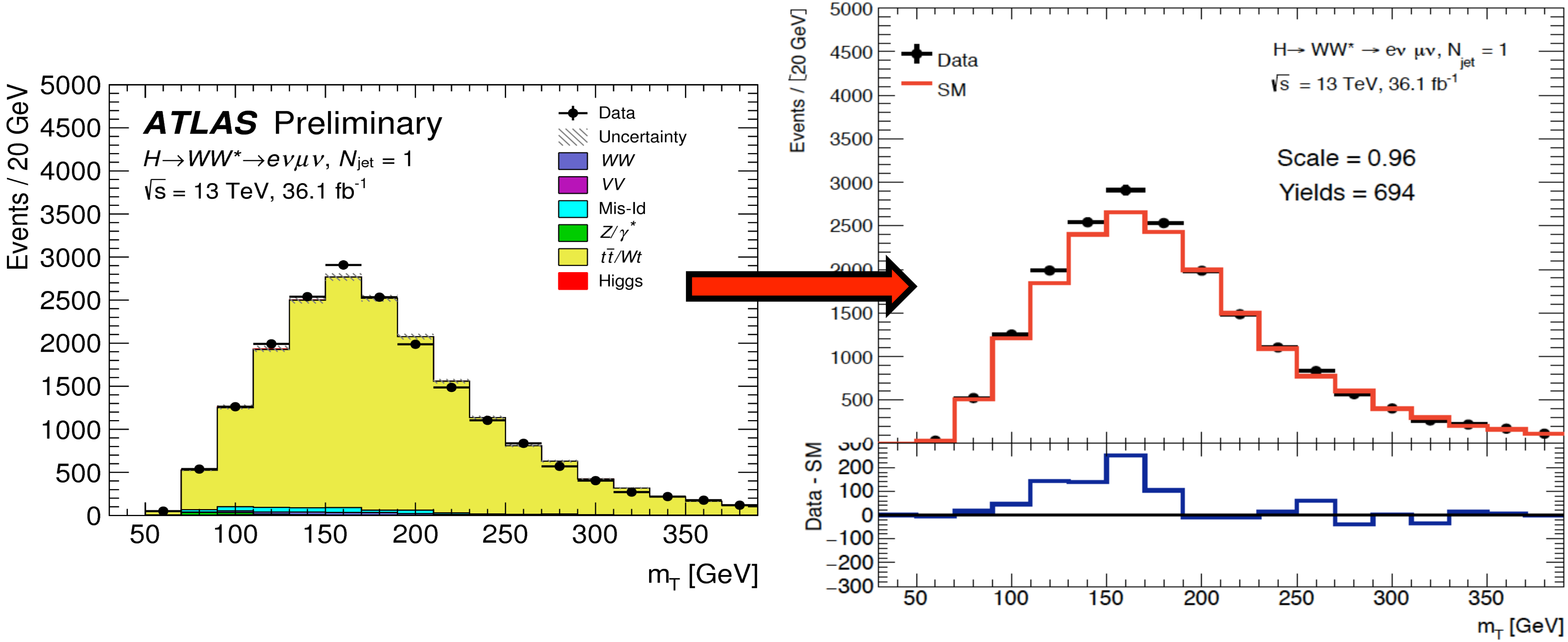




Results not included in combination as events are already included in top spin analysis

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 strong relative enhancement of Wt w.r.t. tt. MC studies in progress.

Wt/tt studies

- To understand structure in the transverse mass spectrum reported in the previous slide, have been trying to understand theoretical uncertainties with state-of-the-art MCs. This includes
  - DR vs DS schemes of double counting removal
  - PDF studies
  - Scale uncertainties
  - Pythia versus Herwig (in progress) PS
  - Using 2b4l, which contains the complete set of WWbb diagrams (in progress)
  - Need to incorporate the MC@NLO MC (in progress)

CMS PAS SMP-18-002

Region	N_ℓ	$p_T\{\ell_{Z1}\ell_{Z2}\ell_W, -\}$ [GeV]	N_{OSSF}	$\lvert M(\ell_{Z1}\ell_{Z2}) - m_Z \rvert$ [GeV]	p_T^{miss} [GeV]	$N_{b\ tag}$	$\min(M(\ell\ell'))$ [GeV]	$M(\ell_{Z1}\ell_{Z2}\ell_W)$ [GeV]
SR	$= 3$	$> \{25, 10, 25\}$	≥ 1	< 15	> 30	$= 0$	> 4	> 100
CR-top	$= 3$	$> \{25, 10, 25\}$	≥ 1	> 5	> 30	> 0	> 4	> 100
CR-ZZ	$= 4$	$> \{25, 10, 25, 10\}$	≥ 1	< 15	> 30	$= 0$	> 4	> 100
CR-Conv	$= 3$	$> \{25, 10, 25\}$	≥ 1	> 15	≤ 30	$= 0$	> 4	< 100

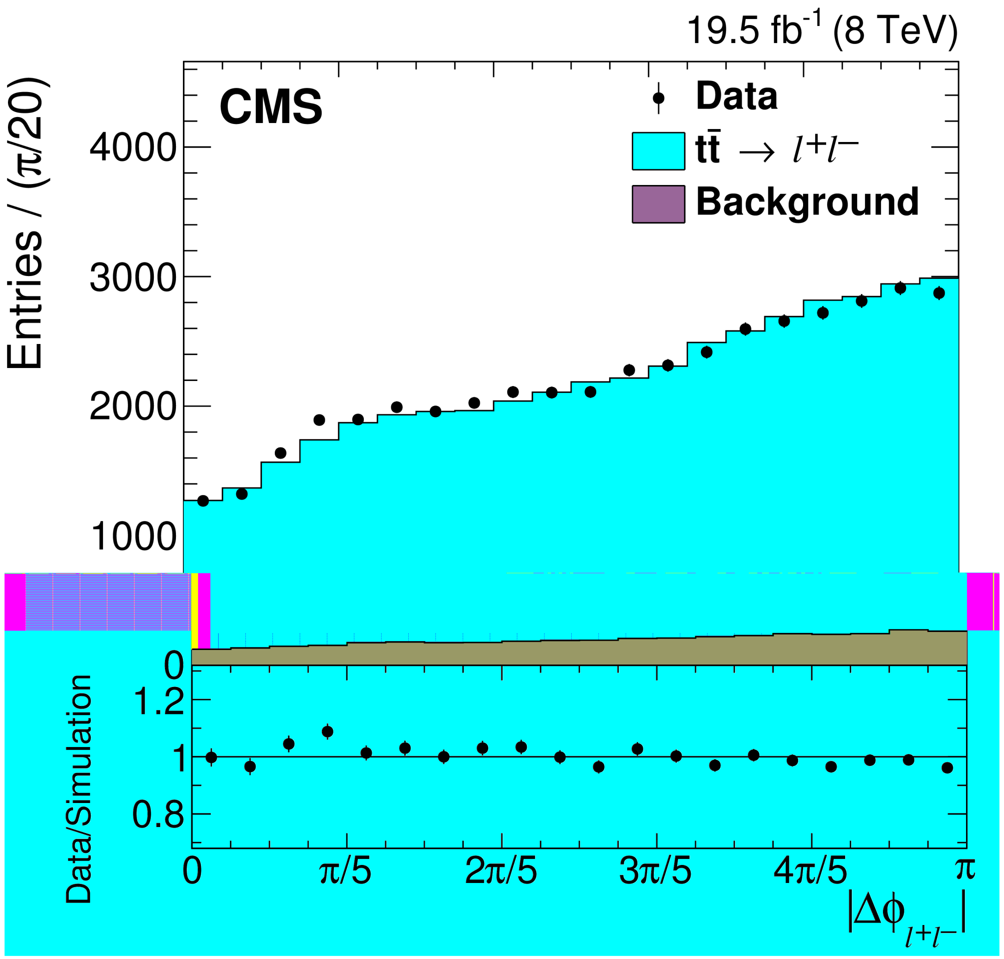
Phys. Rev. D 93 (2016) 052007

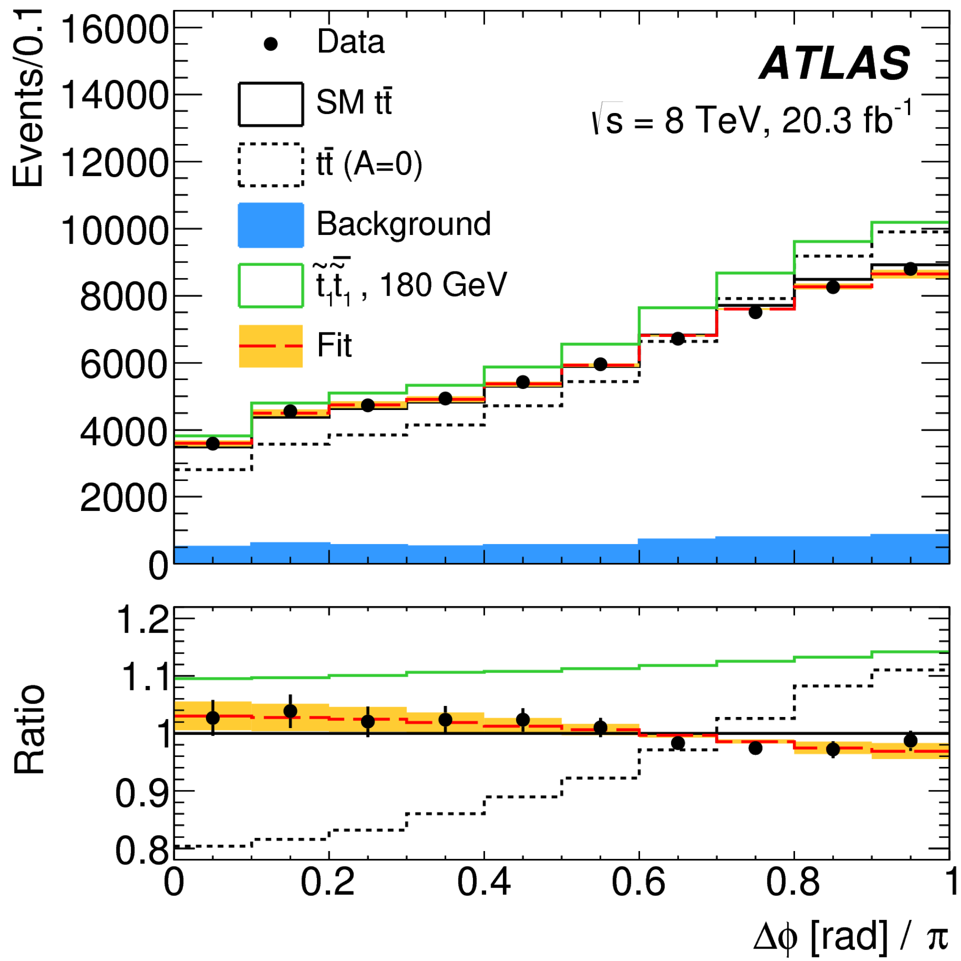
Phys. Rev. Lett. 114 (2015) 142001

The distortion of the $\Delta\varphi_{ll}$ spectrum is al ready present in Run 1, although statistically less compelling than in Run 2 for obvious reasons

MC@NLO 3.41
HERWIG 6.520
CTEQ6M

MC@NLO 4.06
Herwig 6.520
CT10





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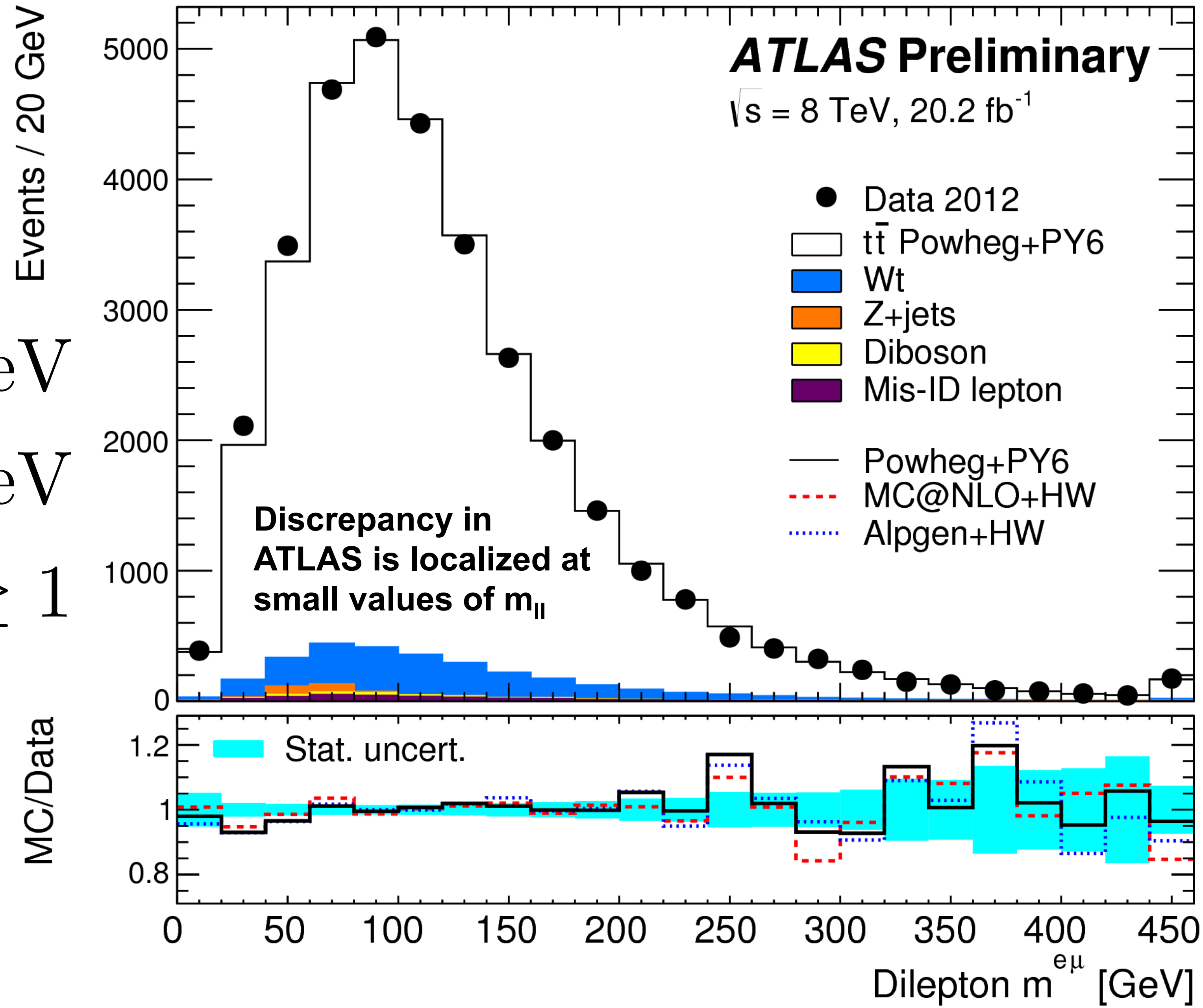
$$p_{T\ell} > 25\,\mathrm{GeV}$$

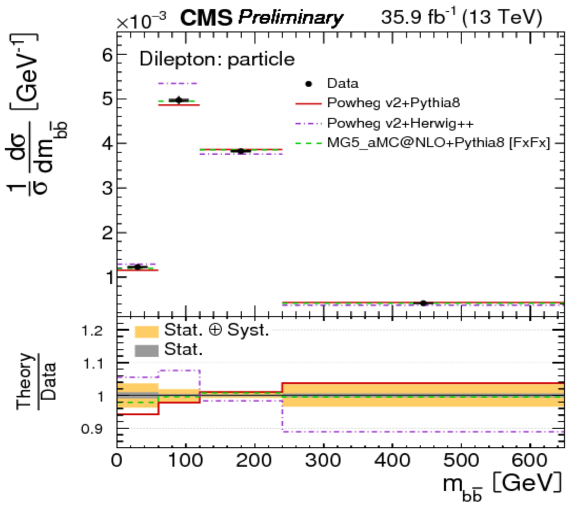
$$p_{Tb} > 25\,\mathrm{GeV}$$

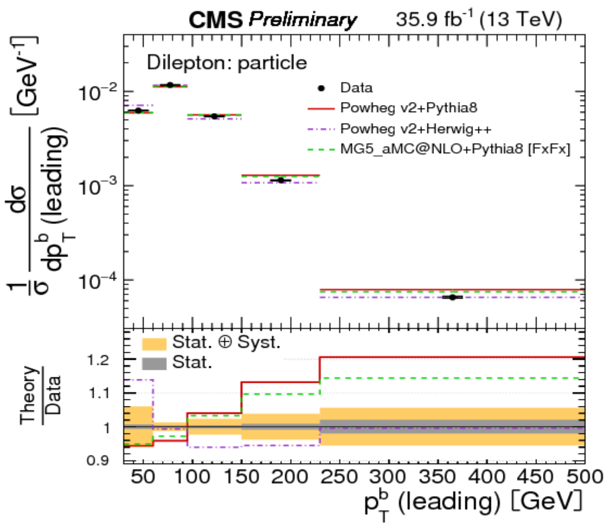
$$N_{bjet} \geq 1$$

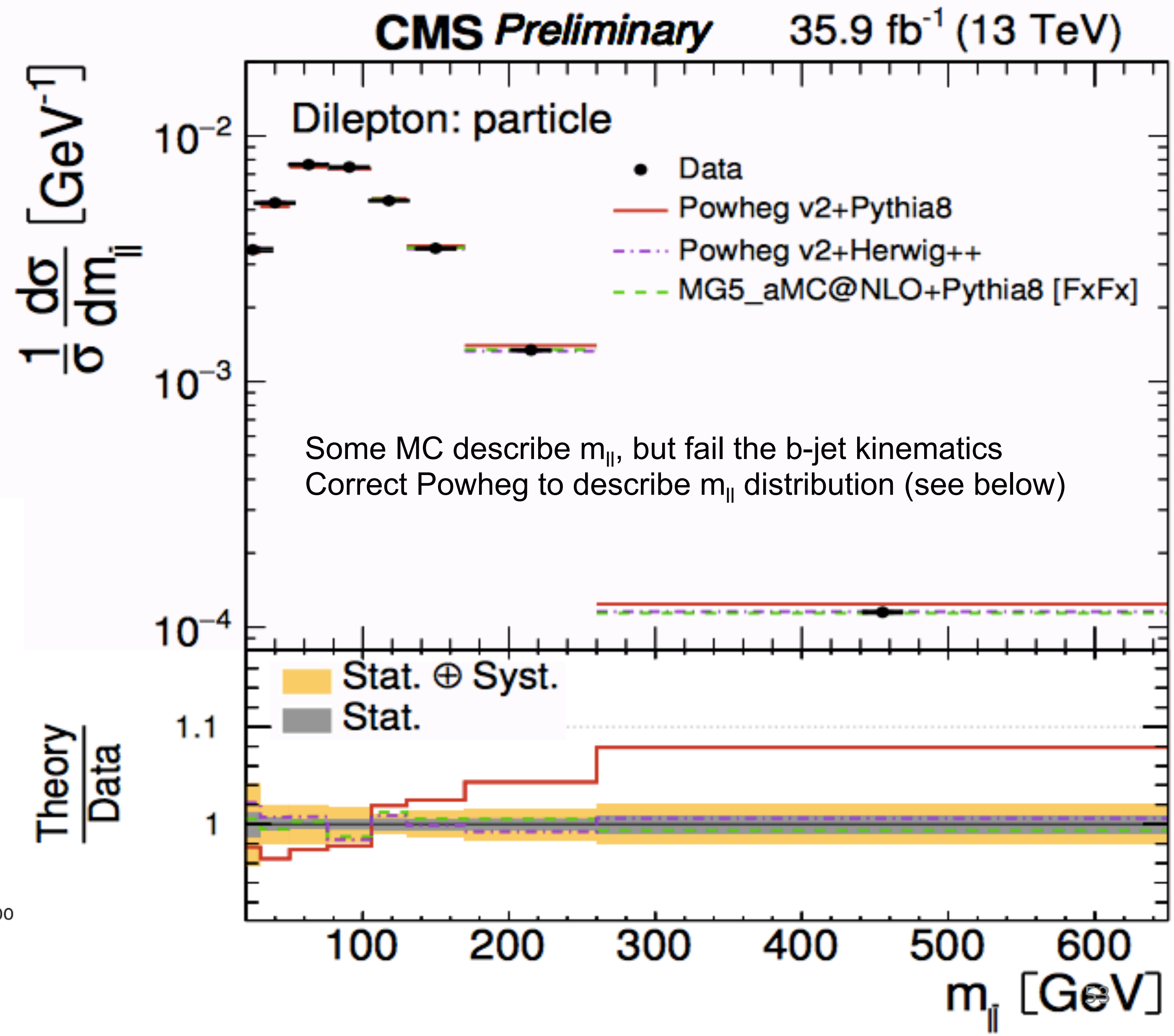


CMS PAS TOP-17-014

Event selection with exactly two leptons (e,μ), m_{ll}>20 GeV and at least 2b-jets







CMS PAS TOP-17-014, https://cds.cern.ch/record/2621975/files/TOP-17-014-pas.pdf

None of the MCs studied is able to describe simultaneously the kinematics of top decay products. M_T of the dilepton and MET system is not shown

Table 3: The χ^2/ndof and p values quantifying the agreement between theoretical predictions and data for normalised, particle-level measurements are shown.

	POWHEG+PYTHIA8		POWHEG+HERWIG++		MG5_aMC@NLO+PYTHIA8	
	χ^2/ndof	p-val.	χ^2/ndof	p-val.	χ^2/ndof	p-val.
p_T^l (leading)	244/4	$< 10^{-3}$	5/4	0.332	75/4	$< 10^{-3}$
p_T^l (trailing)	163/4	$< 10^{-3}$	9/4	0.051	39/4	$< 10^{-3}$
$m_{l\bar{l}}$	143/7	$< 10^{-3}$	4/7	0.802	5/7	0.626
$\Delta\phi(l,\bar{l})$	35/9	$< 10^{-3}$	17/9	0.044	13/9	0.146
$\Delta\|\eta\|(l,\bar{l})$	7/9	0.635	5/9	0.798	7/9	0.626
N_{jets}	13/5	0.022	38/5	$< 10^{-3}$	90/5	$< 10^{-3}$
p_T^b (leading)	32/4	$< 10^{-3}$	75/4	$< 10^{-3}$	16/4	0.002
p_T^b (trailing)	28/4	$< 10^{-3}$	135/4	$< 10^{-3}$	19/4	$< 10^{-3}$
η_b (leading)	12/7	0.114	15/7	0.031	22/7	0.003
η_b (trailing)	16/7	0.024	16/7	0.021	12/7	0.105
$p_T^{b\bar{b}}$	25/4	$< 10^{-3}$	326/4	$< 10^{-3}$	38/4	$< 10^{-3}$
$m_{b\bar{b}}$	3/3	0.371	17/3	$< 10^{-3}$	1/3	0.751

SS ll+b-jets: JHEP 10 (2015) 150

Definition			Name	
$e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_j \geq 2$				
$400 < H_{\mathrm{T}} < 700$ GeV	$N_b = 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRVLQ0	
	$N_b = 2$		SRVLQ1	SR4t0
	$N_b \geq 3$		SRVLQ2	SR4t1
$H_{\mathrm{T}} \geq 700$ GeV	$N_b = 1$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100$ GeV	SRVLQ3	
		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 100$ GeV	SRVLQ4	
	$N_b = 2$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100$ GeV	SRVLQ5	SR4t2
		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 100$ GeV	SRVLQ6	SR4t3
	$N_b \geq 3$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRVLQ7	SR4t4
$e^{+}e^{+}$, $e^{+}\mu^{+}$, $\mu^{+}\mu^{+}$, $N_j \in [2,4]$, $\Delta\phi_{\ell\ell} > 2.5$				
$H_{\mathrm{T}} > 450$ GeV	$N_b \geq 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRttee, SRtt$e\mu$, SRtt$\mu\mu$	

SS ll + b-jets: ATLAS-EXOT-2016-16

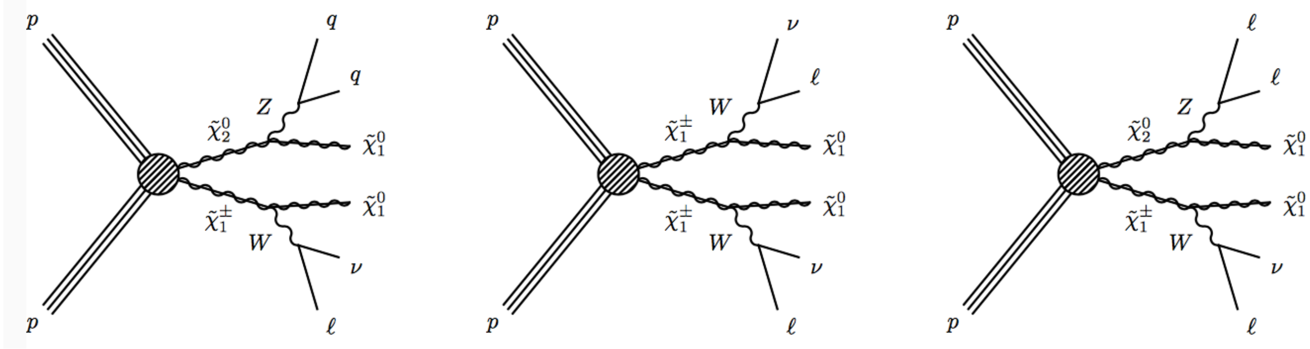
Region name	N_j	N_b	N_ℓ	Lepton charges	Kinematic criteria
VR1b2ℓ	≥ 1	1	2	$++$ or $--$	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR1b2ℓ	≥ 1	1	2	$++$ or $--$	$H_T > 1000$ GeV and $E_T^{miss} > 180$ GeV
VR2b2ℓ	≥ 2	2	2	$++$ or $--$	$H_T > 400$ GeV
SR2b2ℓ	≥ 2	2	2	$++$ or $--$	$H_T > 1200$ GeV and $E_T^{miss} > 40$ GeV
VR3b2ℓ	≥ 3	≥ 3	2	$++$ or $--$	$400 < H_T < 1400$ GeV or $E_T^{miss} < 40$ GeV
SR3b2ℓ_L	≥ 7	≥ 3	2	$++$ or $--$	$500 < H_T < 1200$ GeV and $E_T^{miss} > 40$ GeV
SR3b2ℓ	≥ 3	≥ 3	2	$++$ or $--$	$H_T > 1200$ GeV and $E_T^{miss} > 100$ GeV
VR1b3ℓ	≥ 1	1	3	any	$400 < H_T < 2000$ GeV or $E_T^{miss} < 40$ GeV
SR1b3ℓ	≥ 1	1	3	any	$H_T > 1000$ GeV and $E_T^{miss} > 140$ GeV
VR2b3ℓ	≥ 2	2	3	any	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR2b3ℓ	≥ 2	2	3	any	$H_T > 1200$ GeV and $E_T^{miss} > 100$ GeV
VR3b3ℓ	≥ 3	≥ 3	3	any	$H_T > 400$ GeV
SR3b3ℓ_L	≥ 5	≥ 3	3	any	$500 < H_T < 1000$ GeV and $E_T^{miss} > 40$ GeV
SR3b3ℓ	≥ 3	≥ 3	3	any	$H_T > 1000$ GeV and $E_T^{miss} > 40$ GeV

Compatibility with Higgs data

- Signal strength from fiducial cross-sections with di-photons and $h \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow WW \rightarrow ll$ with Run 2 results stands at 1.15±0.06(exp), which would lead to $\beta_g^2 \approx 1$. This would have some tension with the result of $\beta_g^2 = 2.80 \pm 0.35$ obtained above.
- Within the 2HDM+S this can be resolved by either considering $H \rightarrow SS$ decays or allowing $m_H < m_S + m_h$. The latter leads to $H \rightarrow S^*h, Sh^*$, resolving the tension.
  - Recent results from ATLAS using $H \rightarrow SS \rightarrow 4W \rightarrow 4l$ decays rule out $m_H > 280$ GeV decaying to SS (on-shell)
  - This leaves the option where $m_H < m_S + m_h$ to be investigated as it is not excluded with the current limits and requires re-optimization.

The GAMBIT collaboration, arXiv:1809.02097

Study of multi-leptons, where largest excess comes from the ATAS recursive jigsaw search with three leptons



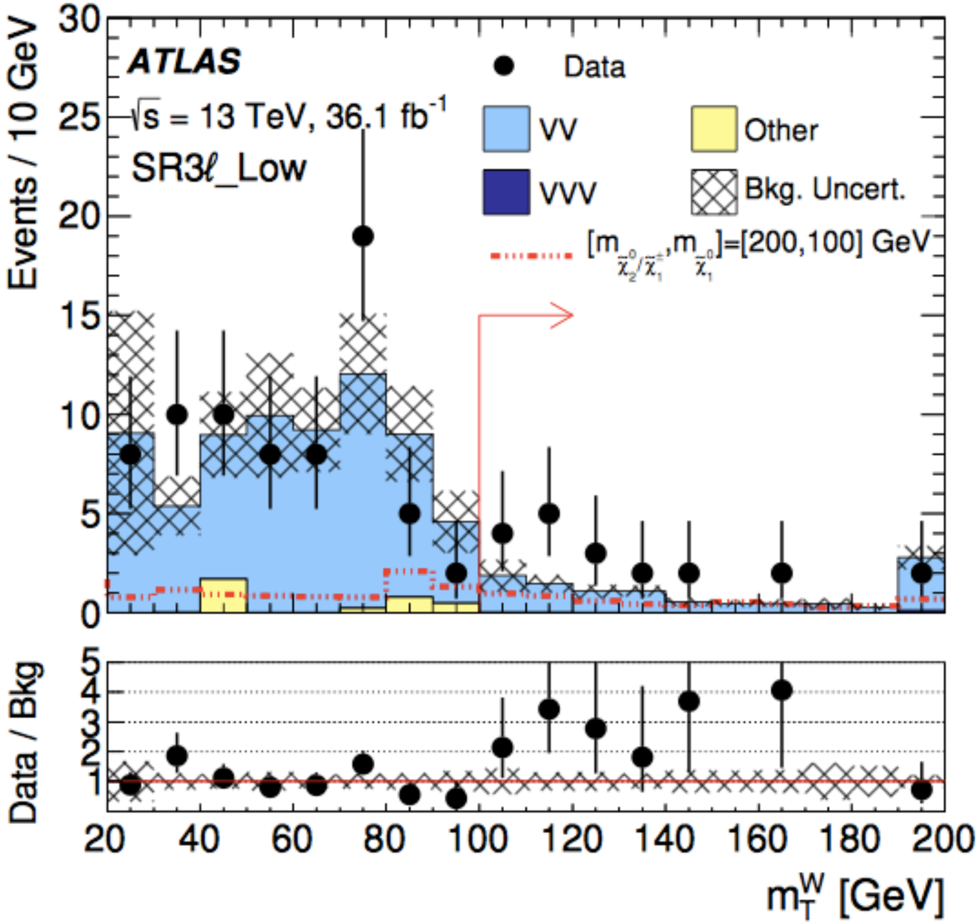
	Best expected SRs				All SRs; neglect correlations			
Analysis	Local signif. (σ)	SM fit (σ)	EWMSSM fit (σ)	#SRs	Local signif. (σ)	SM fit (σ)	EWMSSM fit (σ)	#SRs
Higgs invisible width	0.9	0.3	0.2	1	0.9	0.3	0.2	1
Z invisible width	0	1.3	1.3	1	0	1.3	1.3	1
ATLAS_4b	0.7	0	0	1	2.1	0	0	2*
ATLAS_4lep	2.3	2.0	0	1	2.5	1.0	0	4
ATLAS_MultiLep_2lep_0jet	0.9	0.3	0.1	1	1.3	0	0	6
ATLAS_MultiLep_2lep_jet	0	0	0.5	1	0.8	0.5	0.3	3
ATLAS_MultiLep_3lep	1.8	1.6	0.6	1	1.2	0.4	0.3	11
ATLAS_RJ_2lep_2jet	0	0.3	0.5	1	1.5	1.8	1.5	4
ATLAS_RJ_3lep	2.8	2.4	1.0	1	3.5	2.6	0.5	4
CMS_1lep_2b	0.9	0.3	0.3	1	0	0	0	2
CMS_2lep_soft	0.4	0.2	0.2	12	0.4	0.2	0.2	12
CMS_2OSlep	0	0.4	0.6	7	0	0.4	0.6	7
CMS_MultiLep_2SSlep	0.2	0	0	1	0.2	0	0	2
CMS_MultiLep_3lep	0	0	0.5	1	0	0	0	6
Combined	3.5	1.5	0.3	31	4.2	1.3	0	65

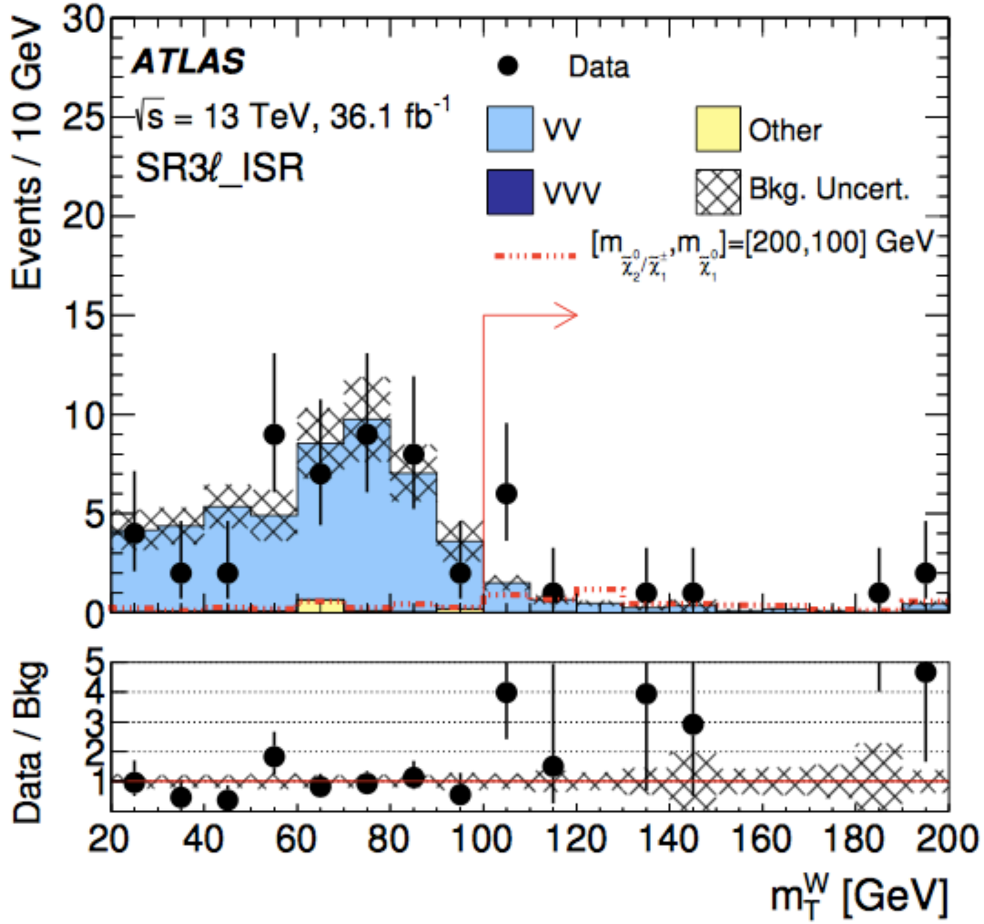
(Z→ll)+l' with m_T>100 GeV

ATLAS, arXiv:1806.02293

Region	n_{leptons}	n_{jets}	$n_{b\text{-tag}}$	$p_T^{\ell_1}$ [GeV]	$p_T^{\ell_2}$ [GeV]	$p_T^{\ell_3}$ [GeV]
CR3ℓ-VV	= 3	< 3	= 0	> 60	> 40	> 30
VR3ℓ-VV	= 3	< 3	= 0	> 60	> 40	> 30
SR3ℓ_High	= 3	< 3	= 0	> 60	> 60	> 40
SR3ℓ_Int	= 3	< 3	= 0	> 60	> 50	> 30
SR3ℓ_Low	= 3	= 0	= 0	> 60	> 40	> 30

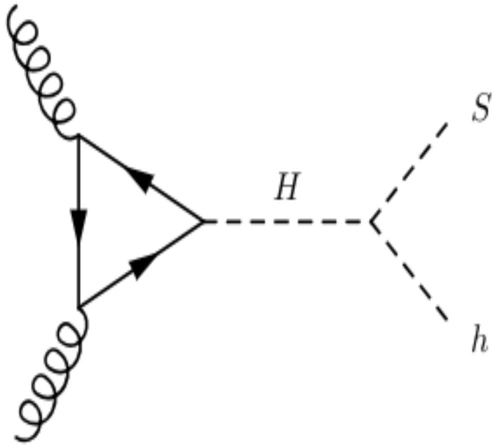
Region	$m_{\ell\ell}$ [GeV]	m_T^W [GeV]	$H_{3,1}^{PP}$ [GeV]	$\frac{p_{T\,PP}^{lab}}{p_{T\,PP}^{lab}+H_{T\,3,1}^{PP}}$	$\frac{H_{T\,3,1}^{PP}}{H_{3,1}^{PP}}$	$\frac{H_{1,1}^{P_b}}{H_{2,1}^{P_b}}$
CR3ℓ-VV	∈ (75, 105)	∈ (0, 70)	> 250	< 0.2	> 0.75	–
VR3ℓ-VV	∈ (75, 105)	∈ (70, 100)	> 250	< 0.2	> 0.75	–
SR3ℓ_High	∈ (75, 105)	> 150	> 550	< 0.2	> 0.75	> 0.8
SR3ℓ_Int	∈ (75, 105)	> 130	> 450	< 0.15	> 0.8	> 0.75
SR3ℓ_Low	∈ (75, 105)	> 100	> 250	< 0.05	> 0.9	–

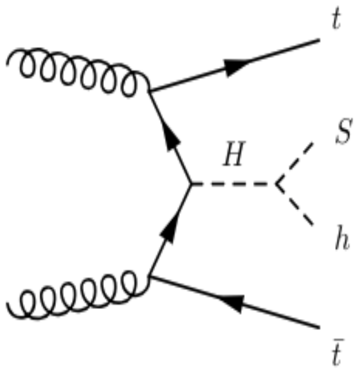


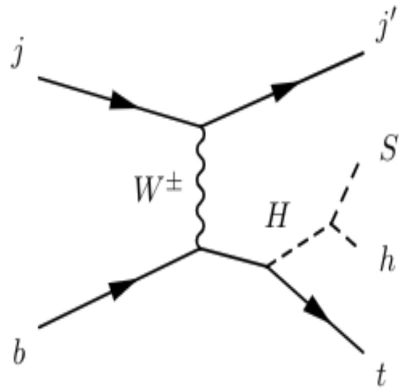


BSM inputs to the fit

- The following <u>assumptions</u> are made:
  - a. The masses of *H* and *S* are fixed to m_H = 270 GeV and m_S = 150 GeV
  - b. The only significant production mechanisms of *H* come from the *t*-*t*-*H* Yukawa coupling:
    - Gluon fusion
    - Top associated production
  - c. The Yukawa coupling is scaled away from the SM Higgs-like value by the free parameter β_g
  - d. The BR of $H \rightarrow Sh$ is fixed to 100%
  - e. The BRs of *S* are Higgs-like
- Therefore, the only free parameter in the fits is β_g^2







The HistFactory method

K. Cranmer, G. Lewis, L. Moneta, A. Shibata, and W. Verkerke, *HistFactory: A tool for creating statistical models for use with RooFit and RooStats*, CERN-OPEN-2012-016.

- **Constructs a likelihood function from template histograms**
- **Allows for a simple implementation of systematic uncertainties that affect normalisation and/or shape**

$$\mathcal{P}(n_{cb}, a_p \,|\, \phi_p, \alpha_p, \gamma_b) = \prod_{c\in\text{channels}} \prod_{b\in\text{bins}} \text{Pois}(n_{cb}|\nu_{cb}) \cdot G(L_0|\lambda, \Delta_L) \cdot \prod_{p\in\mathbb{S}+\Gamma} f_p(a_p|\alpha_p)$$

In our case, each "channel" is a different measurement.

The Poisson probability for the "expected" and "observed" number of events per bin.

Functional form of luminosity and its variations (not necessary for us).

Functional form of systematic variation with nuisance parameter αp.

The fitting procedure

- **The RooStats workspace is made by HistFactory**
- **From the workspace, a profile likelihood ratio is calculated,**

$$\lambda\left(\beta_g^2\right) = \frac{L\left(\beta_g^2 \mid \hat{\hat{\theta}}\right)}{L\left(\hat{\beta}_g^2 \mid \hat{\theta}\right)}$$

(here θ denotes the nuisance parameters)

- **The best-fit value of β_g^2 is then calculated as the minimum of -2log(λ), with an error corresponding to a unit of deviation in this quantity from the best-fit point**
- **The significance is calculated as $\sqrt{-2 \log \lambda(0)}$, since $\beta_g^2 = 0$ corresponds to the SM-only hypothesis**

Measurements considered in the fit

- **Results sensitive to the production of multiple leptons in association with jets, including *b*-tagged jets**

Report number	Description
ATLAS-EXOT-2013-16	ATLAS Run 1 search for 2 or 3 same-sign leptons with multiple *b*-tagged jets (with a VLQ interpretation)
ATLAS-TOPQ-2015-02	ATLAS Run 1 differential distributions for top pair production
ATLAS-EXOT-2016-16	ATLAS Run 2 search for 2 or 3 same-sign leptons with multiple *b*-tagged jets
CMS-PAS-HIG-17-005	CMS Run 2 search for 2 or 3 same-sign leptons with multiple *b*-tagged jets
CMS-TOP-17-018	CMS Run 2 single top production cross section measurement
ATLAS-CONF-2018-027	ATLAS Run 2 spin correlations for top pair production