Multi-lepton anomalies at the LHC and implications

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The Simplified Model and 2HDM+S

The 2HDM+S

Eur. Phys. J. C (2016) 76:580
See also M.Muhlleitner et al.
arXiv:1612.01309
arXiv:1708.01578

Introduce singlet real scalar, S.

2HDM potential, $\mathcal{V}\left(\Phi_1,\Phi_2\right)$

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

2HDM+S potential

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

Out of considerations of simplicity, assume S to be Higgs-like, which is not too far fetched.

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

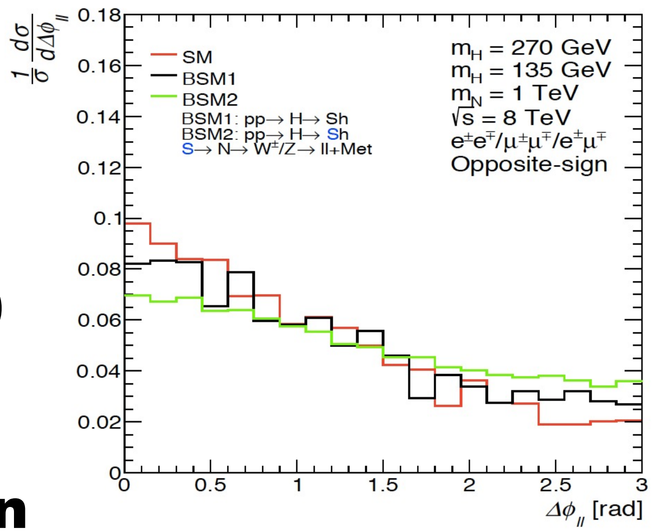
$$H \to h(+X), S(+X)$$

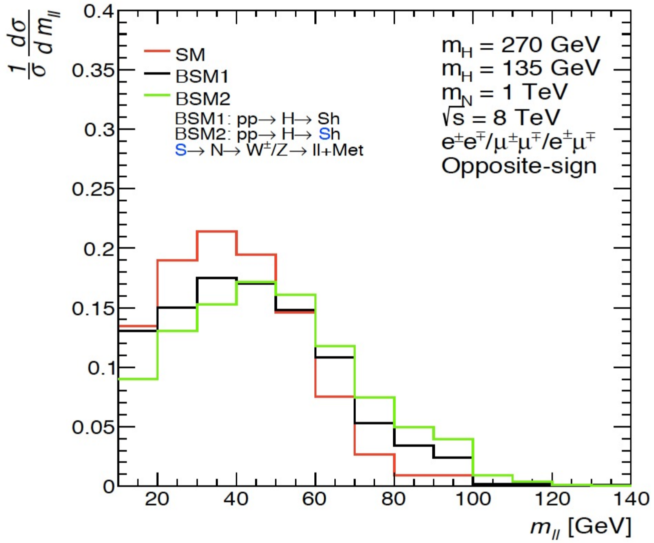
Multi-lepton final states

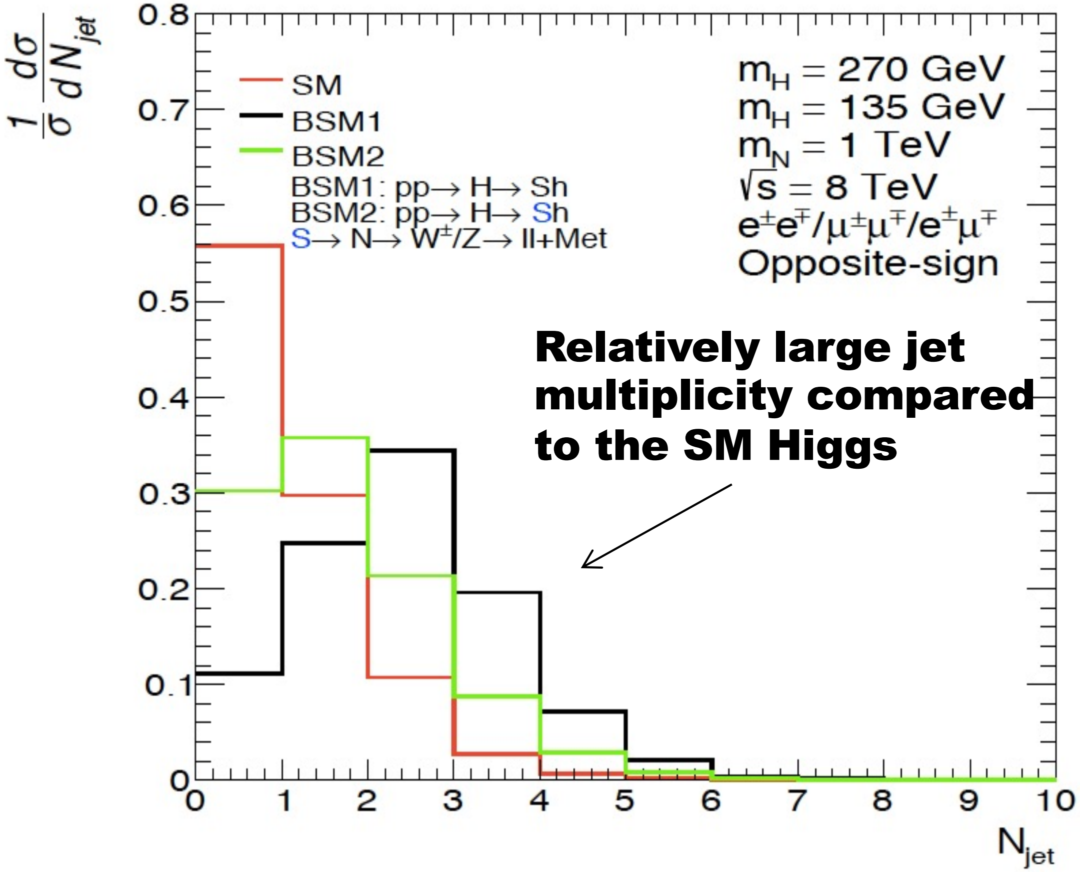
It is paramount to remark that the excesses are seen in final states that were predicted 2015/2016 on the basis of a simplified model and not the result of scan of the available phase-space. Additionally, the parameters of the model where fixed then leaving only one degree of freedom: normalization Thus, no look-elsewhere effects in parameter or phase-space

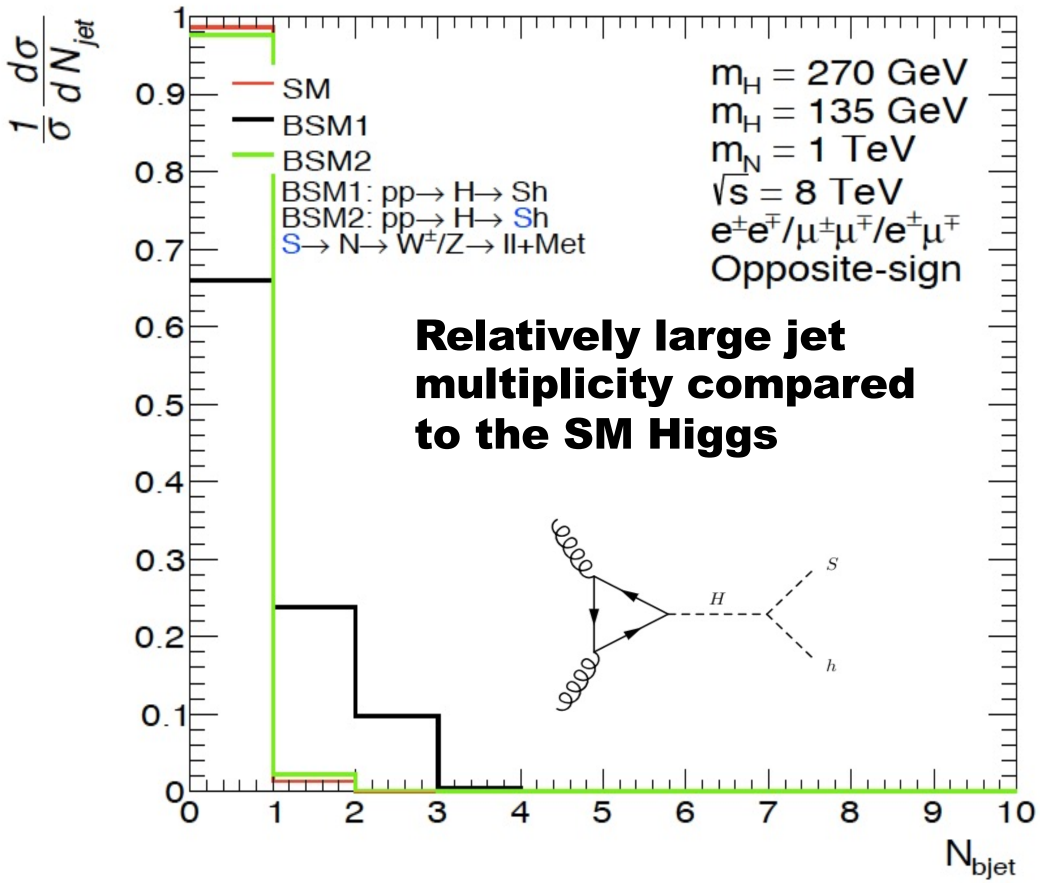
$$pp \to H \to Sh$$
$$\to \ell^+\ell^- + X$$

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

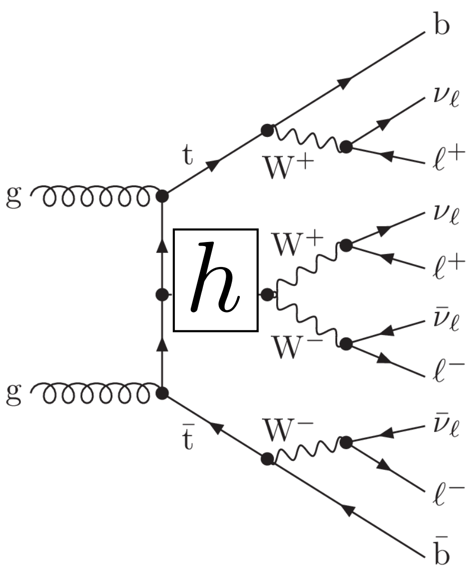


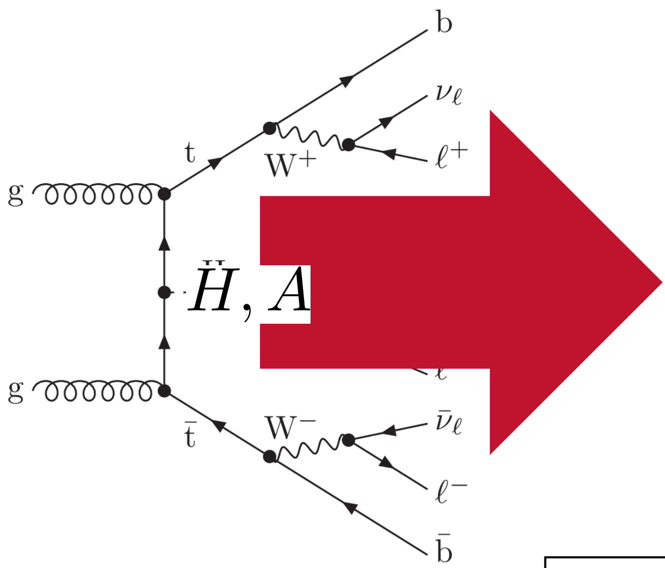






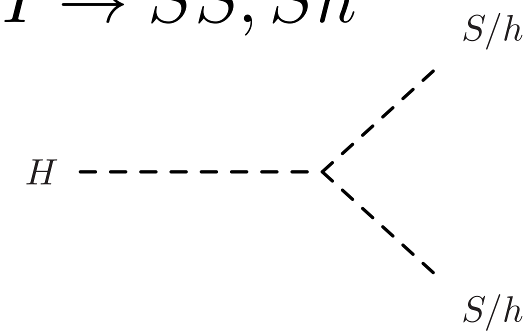
Top associated Higgs production
(Multi-lepton final states)





$$A \to t\bar{t}, ZH$$

$$H \to SS, Sh$$



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

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

Explains anomalously large ttW+tth+4t cross-sections seen by ATLAS and CMS

Methodology

(to avoid biases and look-else-where effects)

Based Higgs p_T, hh, tth, VV in Run 1
Eur. Phys. J. C (2016) 76:580

Model defined and predictions made for multilepton excesses

Multi-lepton excesses in Run 1 and few Run 2 results available in 2017

J.Phys.G 45 (2018) 11, 115003

Model <u>parameters fixed in 2017</u> with
m_H=270 GeV, m_S=150 GeV,
S treated as SM Higgs-like,
dominance of H→Sh,SS

Fixed final states and phase-space defined by fixed model parameters.
<u>NO tuning, NO scanning</u>

Update same final states with more data in Run 2

Study new final states where excesses predicted and data available in Run 1 and Run 2 (e.g., SS0b, 3l0b, ZW0b)

J.Phys. G46 (2019) no.11, 115001
JHEP 1910 (2019) 157
Chin.Phys.C 44 (2020) 6, 063103
Physics Letters B 811 (2020) 135964
Eur.Phys.J.C 81 (2021) 365

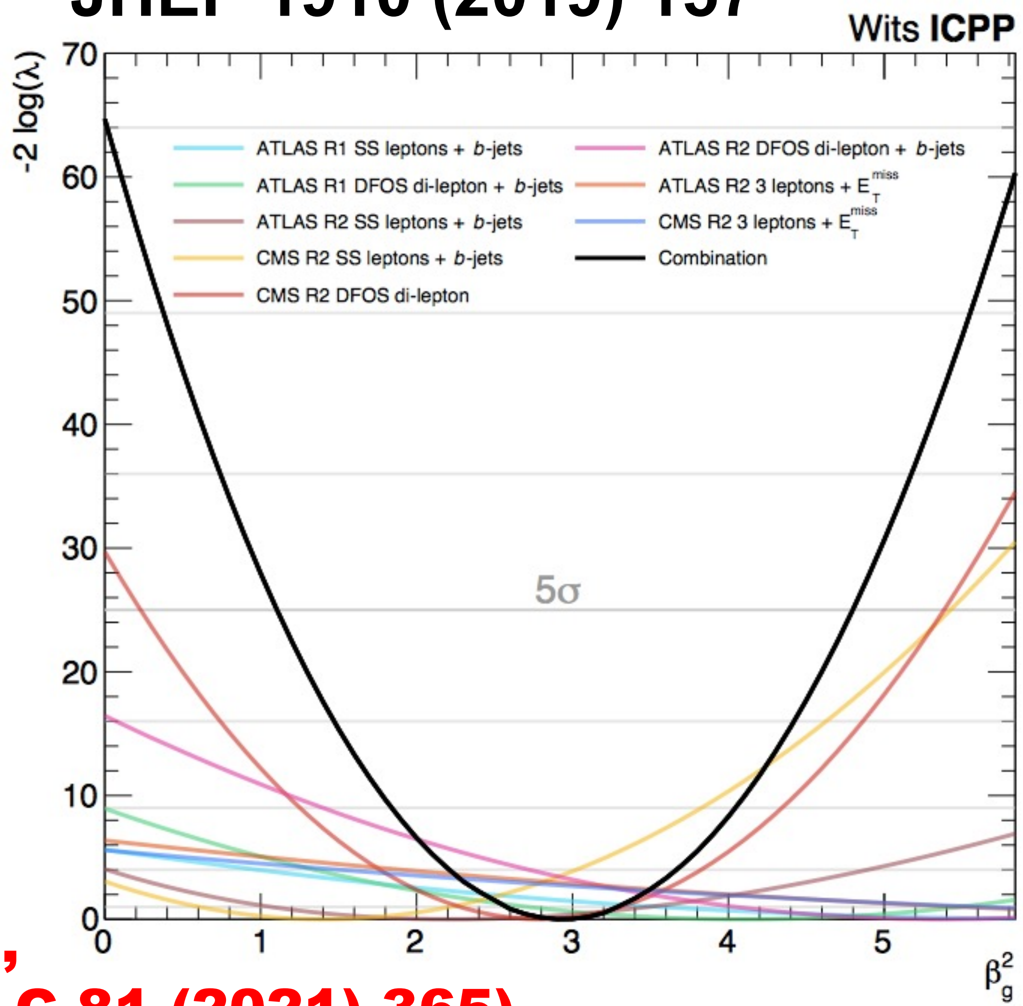
Combination of fit results (2019)

- **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: $\beta_g^2 = 2.92 \pm 0.35$**
- **Corresponds to 8.04σ**

JHEP 1910 (2019) 157



Excesses have been growing since, and new have emerged (Eur.Phys.J.C 81 (2021) 365)

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

Anatomy of the multi-lepton anomalies

Final state	Characteristic	Dominant SM process	Significance
l^+l^- + jets, b-jets	m_{ll}<100 GeV, dominated by 0b-jet and 1b-jet	tt+Wt	>5σ
l^+l^- + full-jet veto	m_{ll}<100 GeV	WW	~3σ
$l^\pm l^\pm$ & $l^\pm l^\pm l$ + b-jets	Moderate H_T	ttW, 4t	>3σ
$l^\pm l^\pm$ & $l^\pm l^\pm l$ et al., no b-jets	In association with h	Wh	3.8σ
$Z(\to l^+l^-)+l$	p_{TZ}<100 GeV	ZW	~3σ

Anomalies cannot be explained by mismodelling of a particular process, e.g. ttbar production alone.

We do not think that the Toponium will explain away any of the multi-lepton anomalies described there, as excess in l^+l^-+b-jets appears in low b-jet multiplicity and inconsistent with tt events. See seminar in Korea

However, we believe it is important that the experiments need to incorporate the Toponium into the MCs since it will improve the description of ttbar final states.

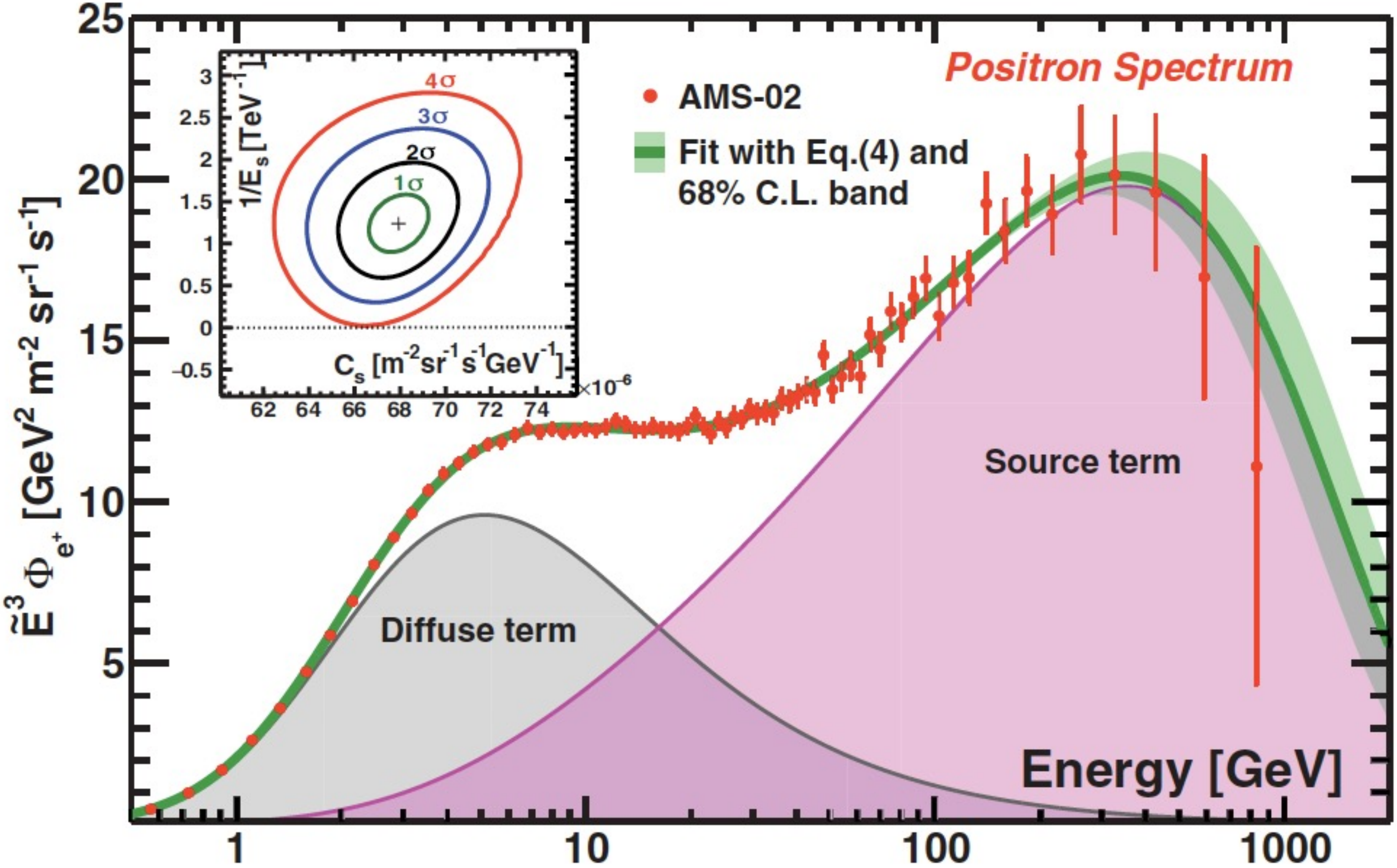
Want to thank authors of Toponium paper because they have been among the first to realise that the excess in l^+l^-+ b-jets may not be due to MC mismodelling, but due to something missing in the description of the data.

G.Beck, E.Malwa, M.Kumar, R.Temo and B.M., 2102.10596

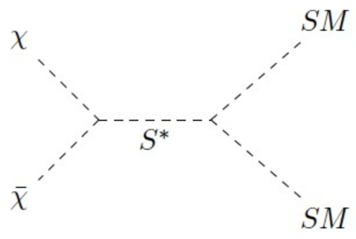
The multi-lepton anomalies and excesses in astrophysics

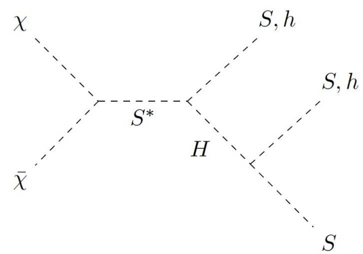
AMS02, PRL 122, 041102 (2019)

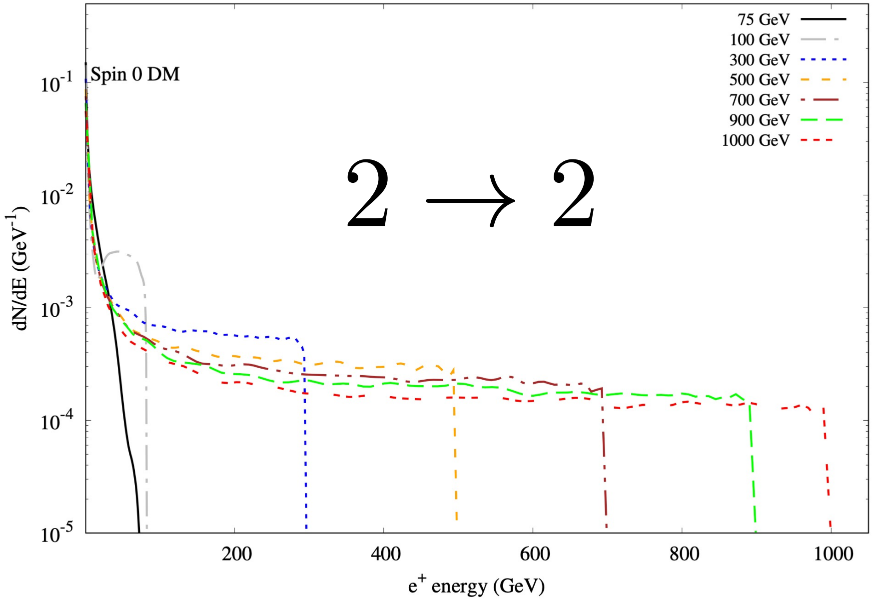
Leptophilic excesses, such as positron rise in PAMELA/AMS02

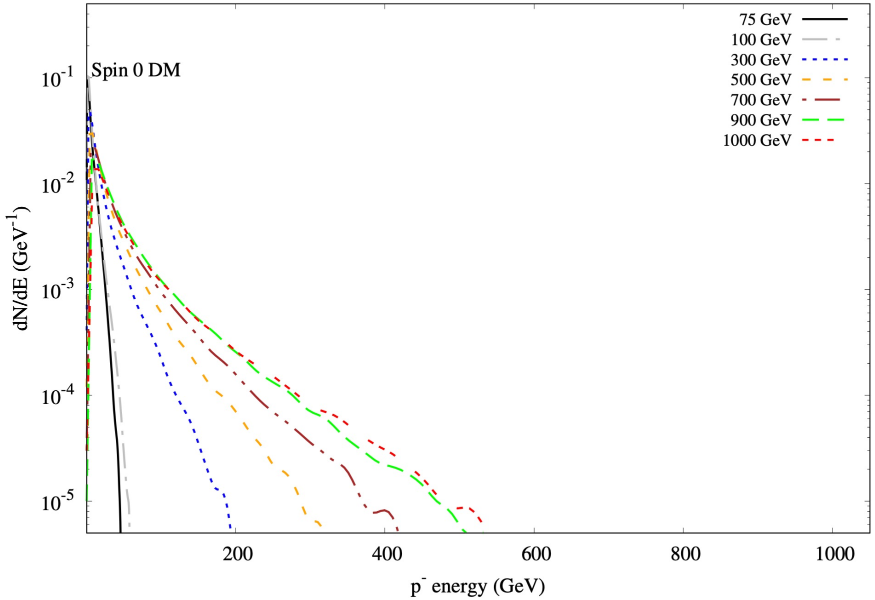


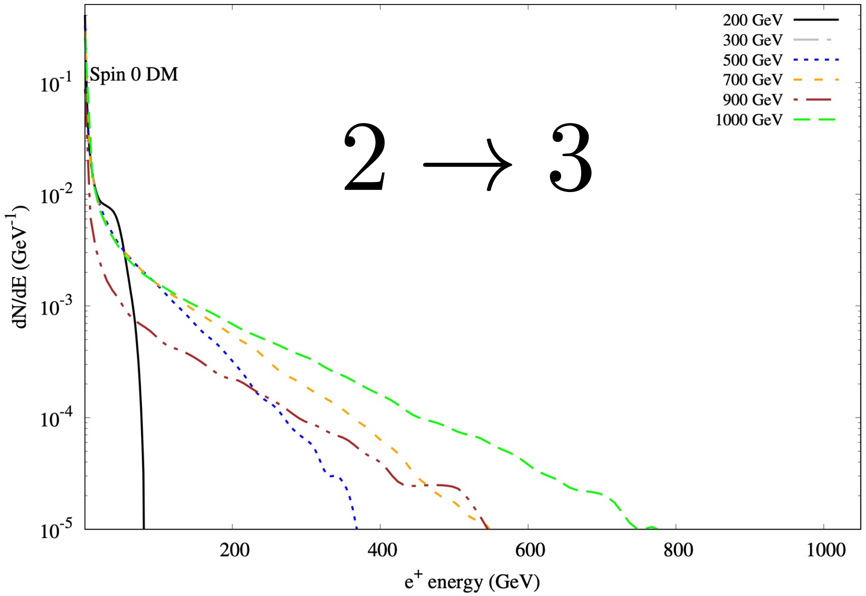
Dark matter annihilation.
Leptons, photons and protons
from the decays of S.

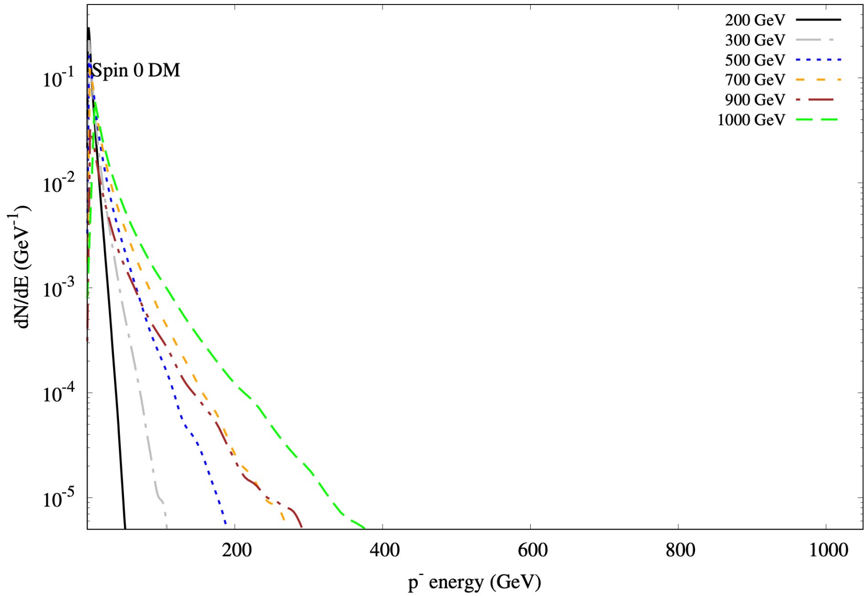


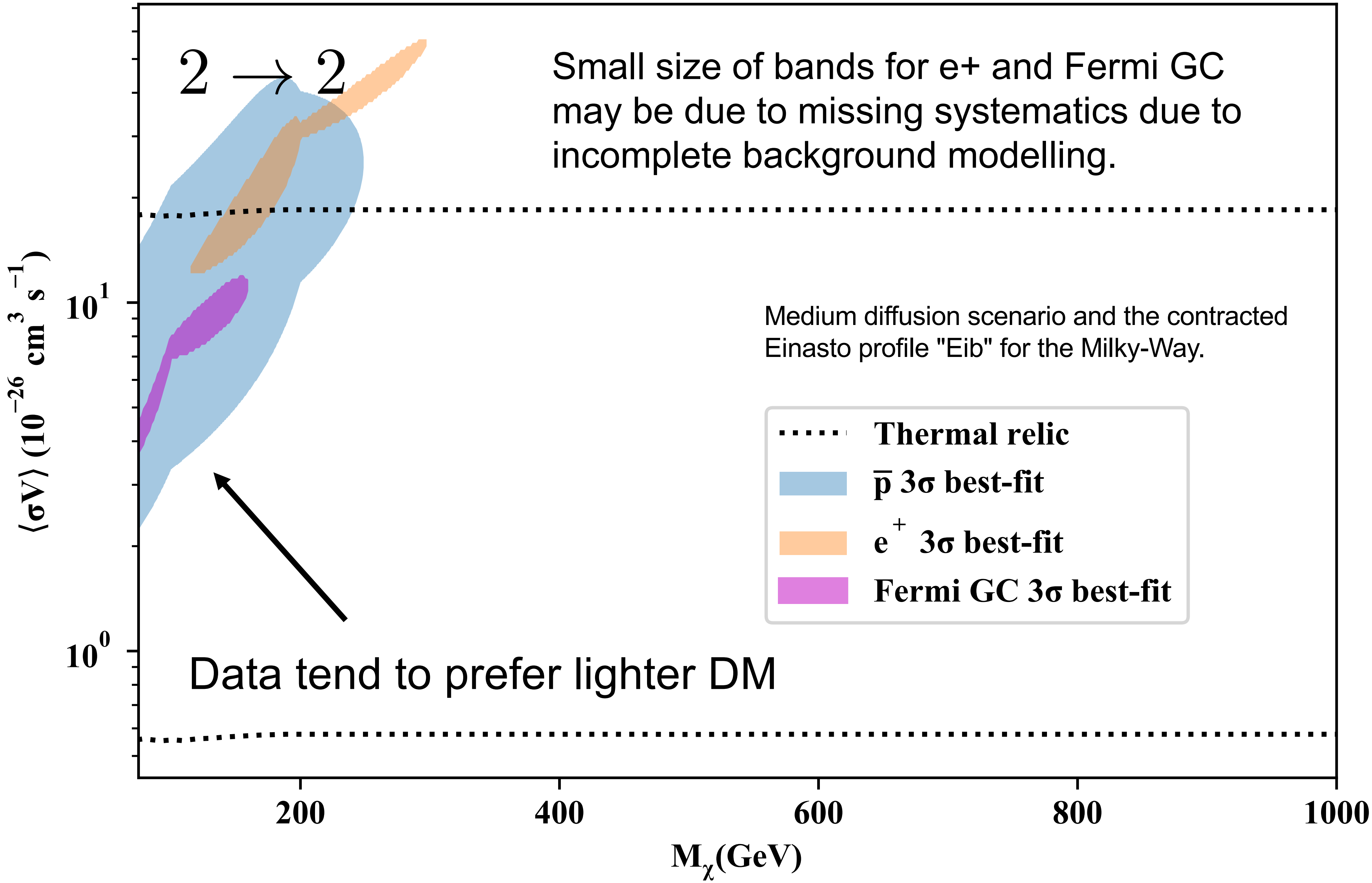




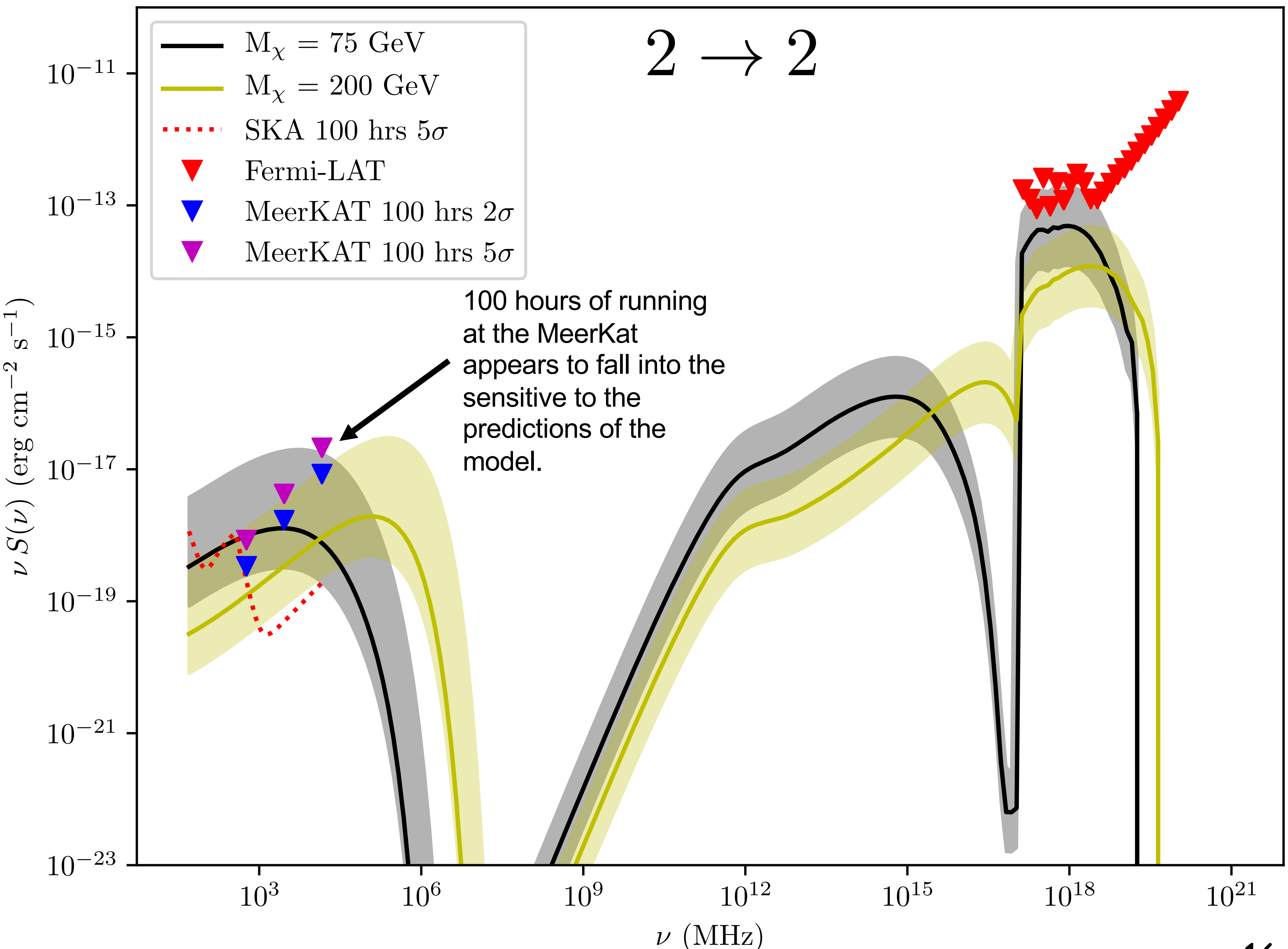








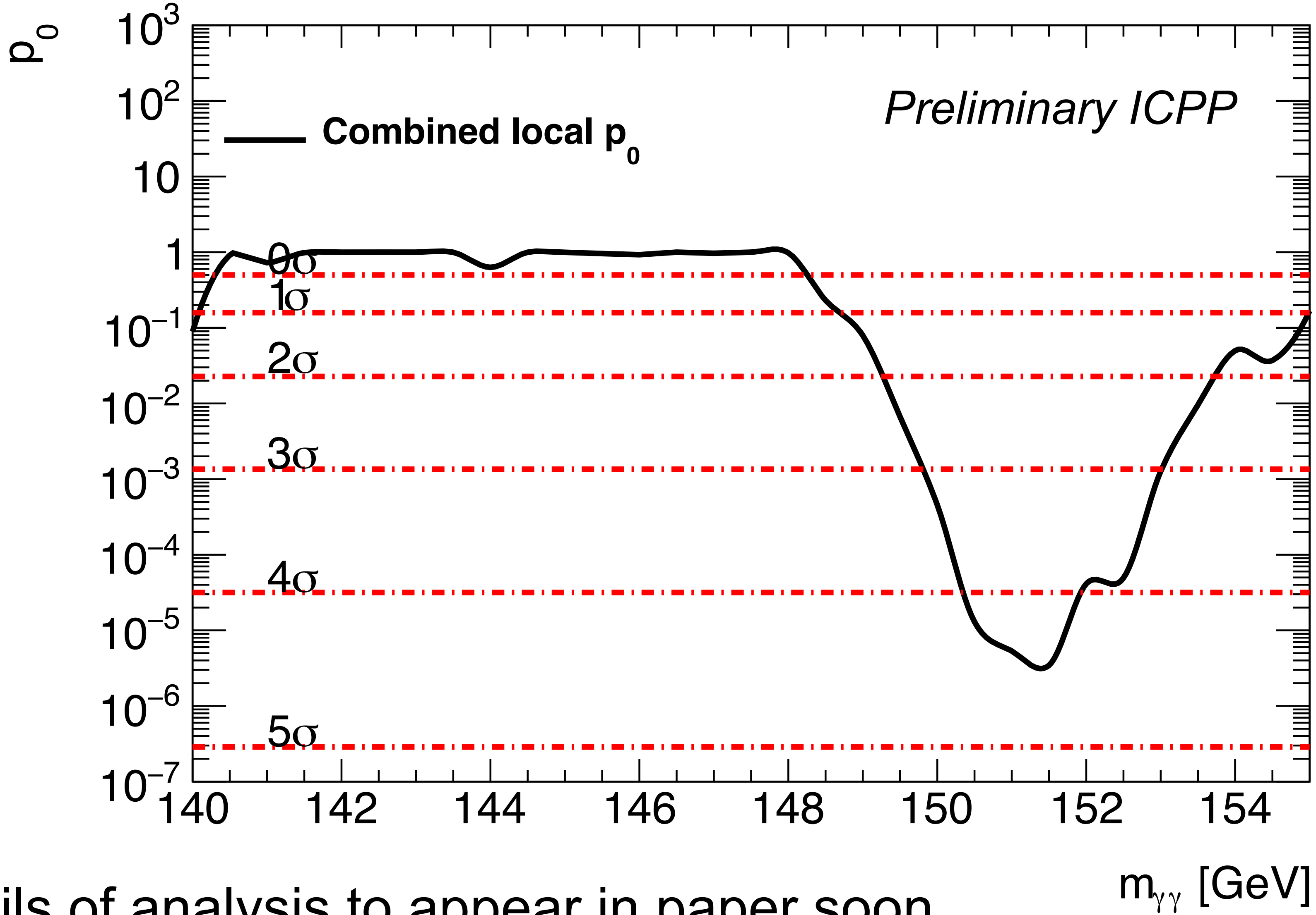
$2 \to 2$
Small size of bands for e+ and Fermi GC may be due to missing systematics due to incomplete background modelling.
Medium diffusion scenario and the contracted Einasto profile "Eib" for the Milky-Way.
Thermal relic
$\bar{p}$ 3σ best-fit
e^+ 3σ best-fit
Fermi GC 3σ best-fit
Data tend to prefer lighter DM
$\langle\sigma V\rangle$ (10^{-26} cm^3 s^{-1})
10^1
10^0
200
400
600
800
1000
M_χ(GeV)



$2 \rightarrow 2$
M_χ = 75 GeV
M_χ = 200 GeV
SKA 100 hrs 5σ
Fermi-LAT
MeerKAT 100 hrs 2σ
MeerKAT 100 hrs 5σ
100 hours of running at the MeerKat appears to fall into the sensitive to the predictions of the model.
$\nu\, S(\nu)$ (erg cm^{-2} s^{-1})
ν (MHz)

A possible candidate of S

Analysis of publicly available di-photon spectra in associated production gives >4σ excess around 151 GeV. Fiducial yields consistent with H→SS* hypothesis with m_H=270 GeV (see above)



Details of analysis to appear in paper soon

Outlook and Conclusions

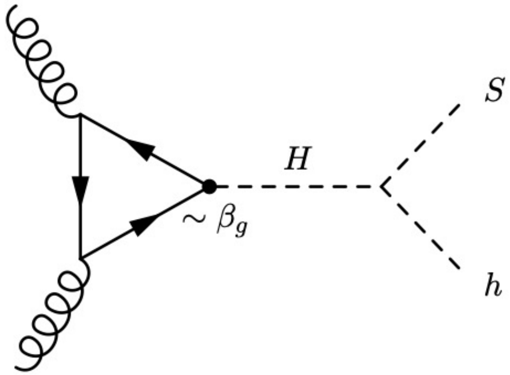
- **Discrepancies in multi-lepton final states at LHC w.r.t. current MCs are not statistical fluctuations**
  - **They appear in corners of the phase-space dominated by different processes (Wt/tt/4t, VV, ttV, Vh)**
    - **Hard to explain with MC mismodelling**
  - **Discrepancies interpreted with simplified model where H→SS, Sh is treated as SM Higgs-like and one parameter is floated**
- **Features of the Higgs data from LHC agree with predictions the simplified model used here**
- **Connection made with excesses in astro-physics, where MeerKat has sensitivity to probe**
- **Analysis of di-photon spectra in associated production gives >4σ excess around 151 GeV**

Additional Slides

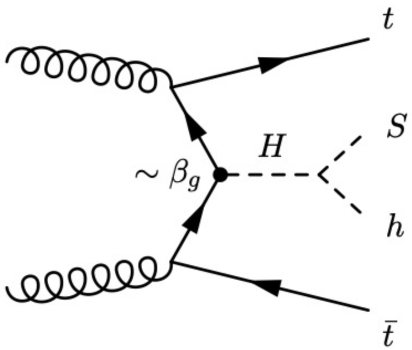
Eur. Phys. J. C (2016) 76:580

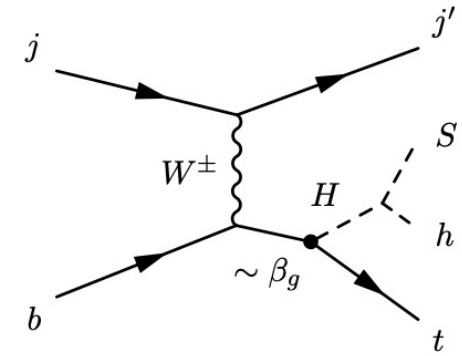
The simplified Model (from Run I)

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 250-280 GeV
2. In order to avoid large quartic couplings, incorporate a mediator scalar, S, that interacts with the SM and Dark Matter.
3. Dominance of H→Sh,SS decay over other decays



(a) Gluon fusion (ggF).

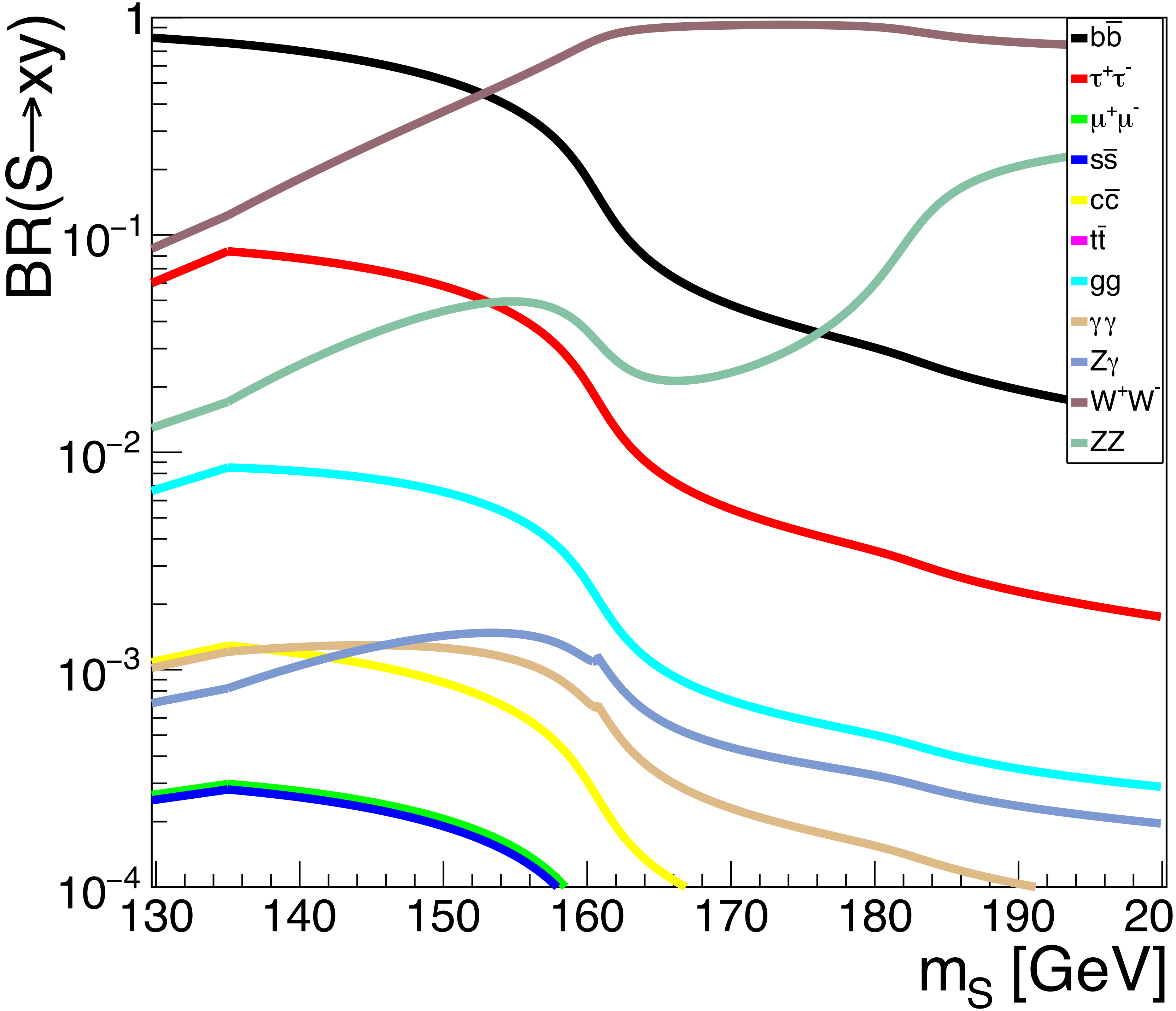




$$\mathcal{L}_{\text{int}} \supset -\beta_g \frac{m_t}{v} t\bar{t}H + \beta_V \frac{m_V^2}{v} g_{\mu\nu} V^\mu V^\nu H$$

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

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



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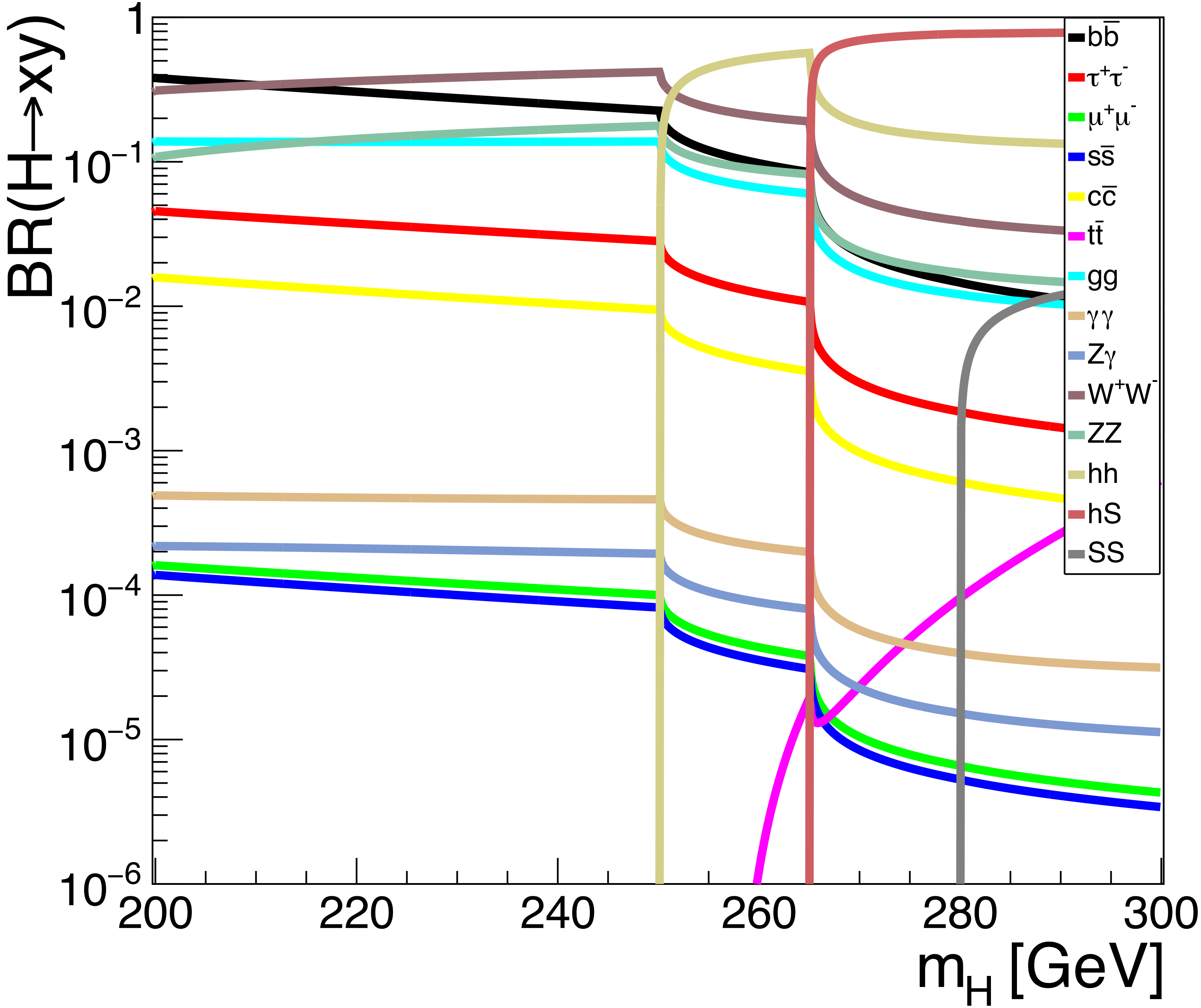


The model leads to rich phenomenology. ***Of particular interest are multilepton signatures***

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

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

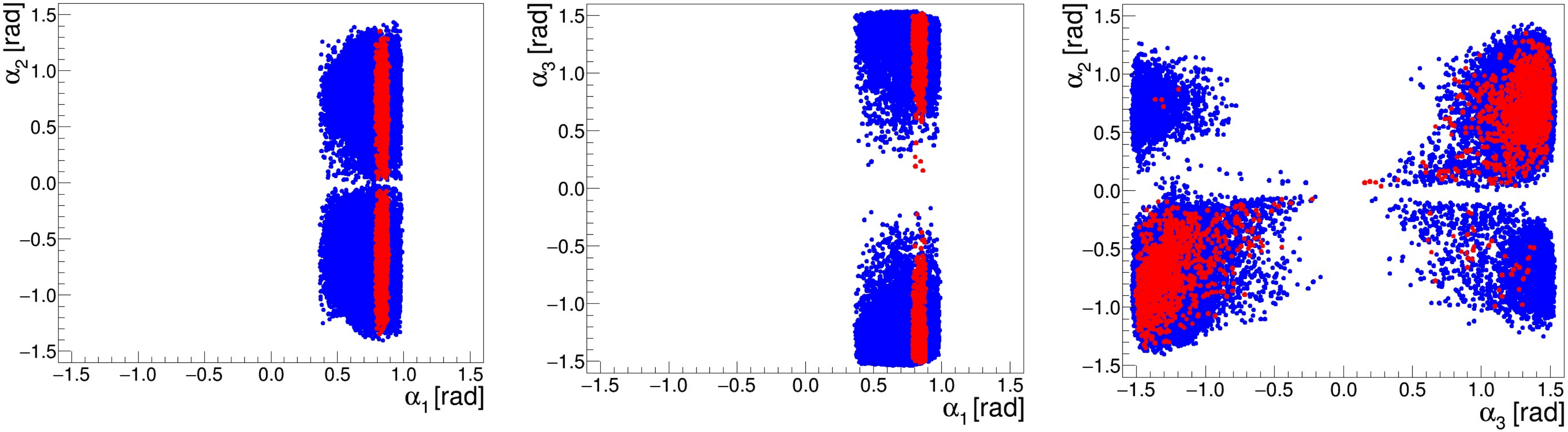
Mass-matrix for the CP-even scalar sector will modified with respect to 2HDM and that needs a 3 x3 matrix (three mixing angles). Couplings are modified.

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

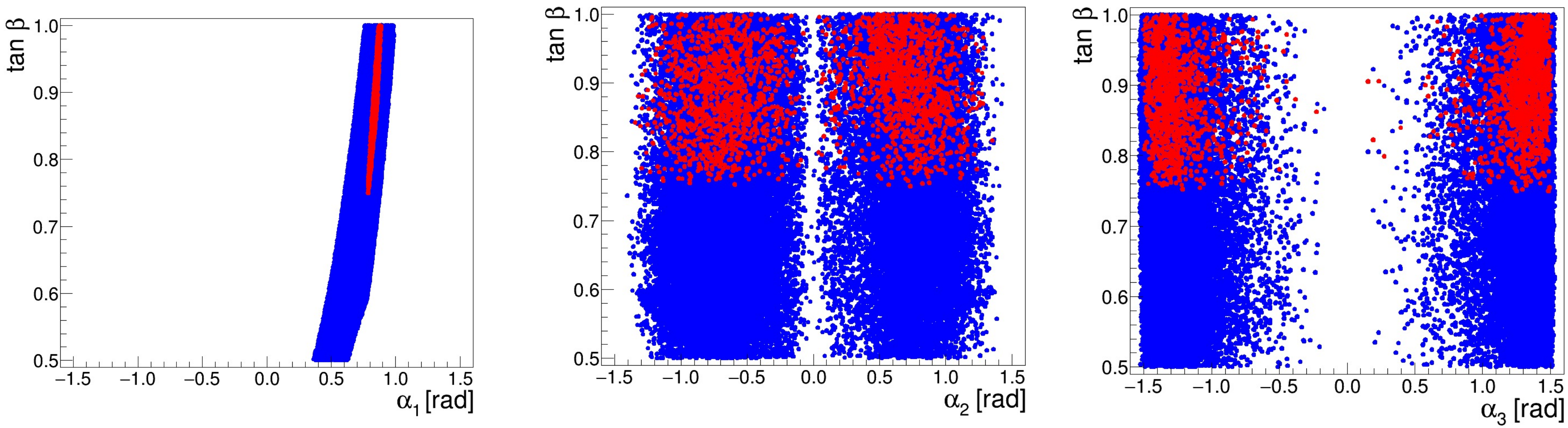
$$M^2_{\mathrm{CP-even}} = \begin{pmatrix} 2\lambda_1 v_1^2 - m_{12} \frac{v_2}{v_1} & m_{12} + \lambda_{345} v_1 v_2 & 2\kappa_1 v_1 v_S \\ m_{12} + \lambda_{345} v_1 v_2 & -m_{12} \frac{v_2}{v_1} + 2\lambda_2 v_2^2 & 2\kappa_2 v_2 v_S \\ 2\kappa_1 v_1 v_S & 2\kappa_2 v_2 v_S & \frac{1}{3} \lambda_S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

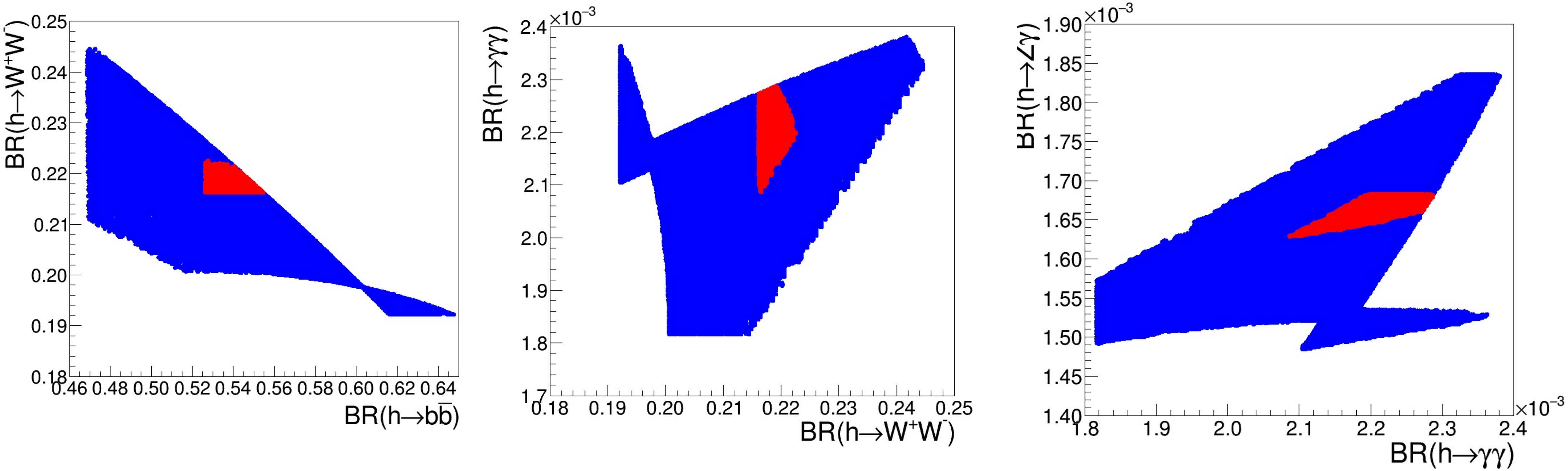
$$
\begin{aligned}
m_{H_1}^2 &= v_S \sin\alpha_2 \left[\lambda_7 v \cos\alpha_1 \cos\alpha_2 \cos\beta + \lambda_8 v \sin\alpha_1 \cos\alpha_2 \sin\beta + \lambda_6 v_S \sin\alpha_2\right], \\
m_{H_2}^2 &= (\cos\alpha_1 \cos\alpha_3 - \sin\alpha_1 \sin\alpha_2 \sin\alpha_3)\Big[\cos\alpha_1 \cos\alpha_2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

Perform scans after fixing masses of physical bosons(m_{h1}=125 GeV, m_{h2}=140, m_{h3}=270 GeV, m_A=600 GeV, $m_H\pm$=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 $\tan^2\beta$)

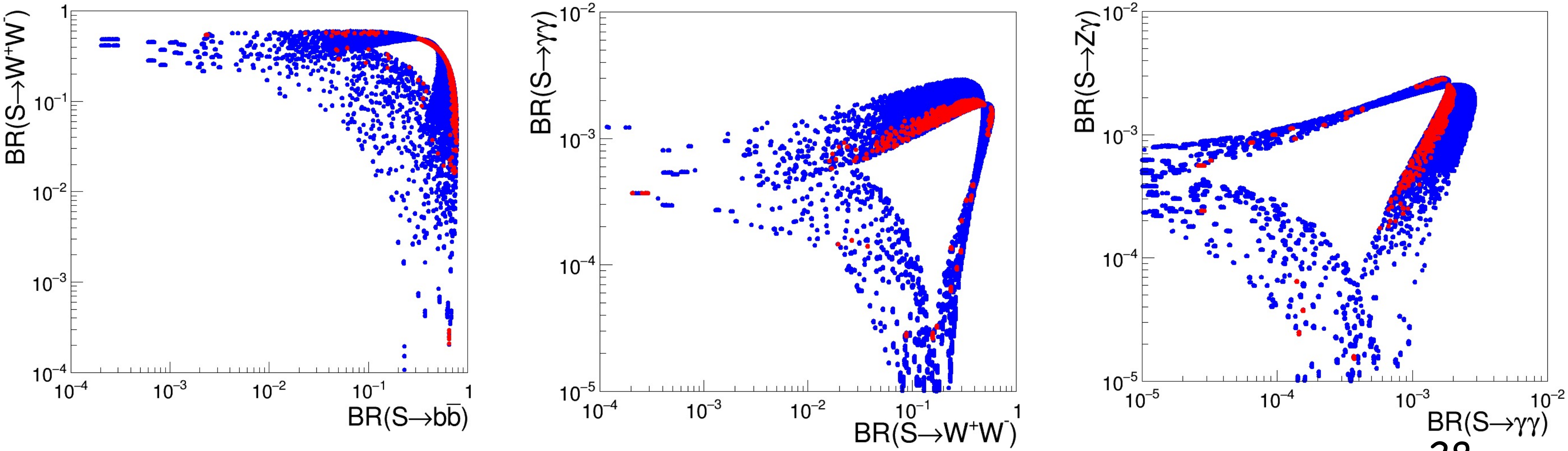


Correlation plots for the three mixing angles and tanβ. Blue (red) points correspond to Br(h→SM) within 10% (20%) of the SM h values **(J.Phys. G46 (2019) no.11, 115001)**





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



The fitting procedure

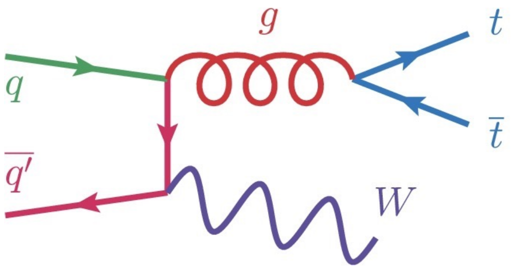
- **The RooStats workspace is made by HistFactory**
- **From the workspace, a profile likelihood ratio is calculated,**

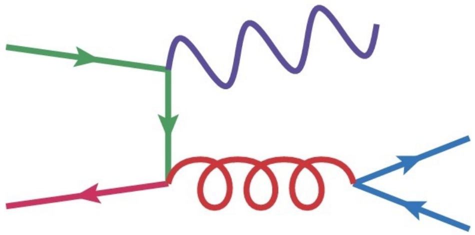
$$\lambda\left(\beta_g^2\right) = \frac{L\left(\beta_g^2 \mid \hat{\hat{\theta}}\right)}{L\left(\hat{\beta}_g^2 \mid \hat{\theta}\right)}$$

(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 √(-2 log λ(0)), since β_g^2 = 0 corresponds to the SM-only hypothesis**

The anatomy of inclusive ttW at the LHC





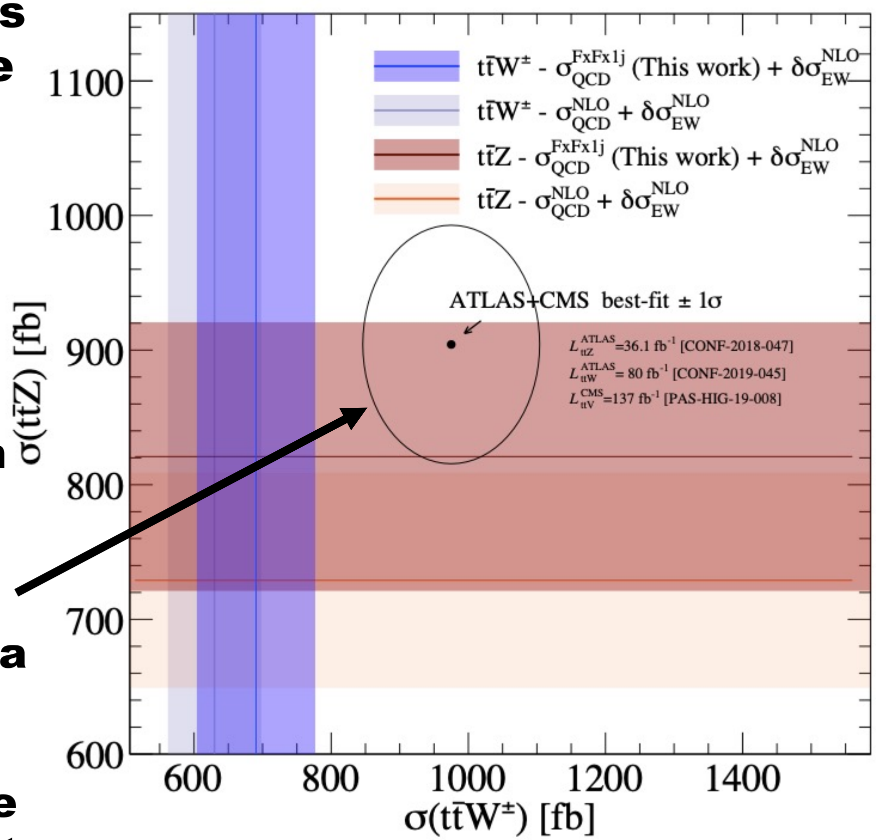
S.Buddenbrock, R.Ruiz and B.M.
Physics Letters B 811 (2020) 135964

Using fixed order computations at $\mathcal{O}(\alpha_s^4\alpha)$ and NLO multi-jet matching yielding similar (10%-14%) corrections to the inclusive rate

$i\,j \to t\,\bar{t}\,W^{\pm}\,k\,l$						
(i, j)	(k, l)	$p_T^{j_1\ \min}$	$p_T^{j_2\ \min}$	σ [fb]	$\pm\delta_{\mu_f,\mu_r}$	$\pm\delta_{\rm PDF}$
All	All	75 GeV	75 GeV	34.7 (100%)	$^{+57\%}_{-34\%}$	$^{+1.1\%}_{-1.1\%}$
(g, Q)	(g, Q)			23.7 (68%)		
(Q, Q)	(Q, Q)			6.99 (20%)		
(Q, Q)	(g, g)			3.63 (10%)		
(g, g)	$(q, \bar{q})$			0.437 (1.3%)		
All	All	100 GeV	75 GeV	33.1 (100%)	$^{+57\%}_{-34\%}$	$^{+1.0\%}_{-1.0\%}$
(g, Q)	(g, Q)			22.6 (68 %)		
(Q, Q)	(Q, Q)			6.78 (20%)		
(Q, Q)	(g, g)			3.28 (9.9%)		
(g, g)	$(q, \bar{q})$			0.409 (1.2%)		
All	All	100 GeV	100 GeV	21.2 (100%)	$^{+57\%}_{-34\%}$	$^{+1.1\%}_{-1.1\%}$
(g, Q)	(g, Q)			14.3 (67%)		
(Q, Q)	(Q, Q)			4.91 (23%)		
(Q, Q)	(g, g)			1.75 (8%)		
(g, g)	$(q, \bar{q})$			2.58 (1%)		
(g, q_V)	(g, q_V)	75 GeV	75 GeV	20.1 (58%)	$^{+58\%}_{-35\%}$	$^{+2.3\%}_{-2.3\%}$
(g, q_V)	(g, q_V)	100 GeV	75 GeV	19.3 (58%)	$^{+58\%}_{-35\%}$	$^{+2.3\%}_{-2.3\%}$
(g, q_V)	(g, q_V)	100 GeV	100 GeV	12.2 (58%)	$^{+59\%}_{-35\%}$	$^{+2.4\%}_{-2.4\%}$

Table 2: Total cross sections [fb] at $\sqrt{s}$ = 13 TeV for the $pp \to t\bar{t}W^{\pm}jj$ process at LO, with scale and PDF uncertainties [%], for representative $p_T^{j_k\ \min}$ with $|\eta^j| < 4.0$. Also shown is the decomposition according to partonic channel, for $q_V \in \{u, d\}$, $q \in \{u, d, c, s\}$, and $Q \in \{q, \bar{q}\}$.

Detailed studies that include the decomposition in partonic channels and differential distributions



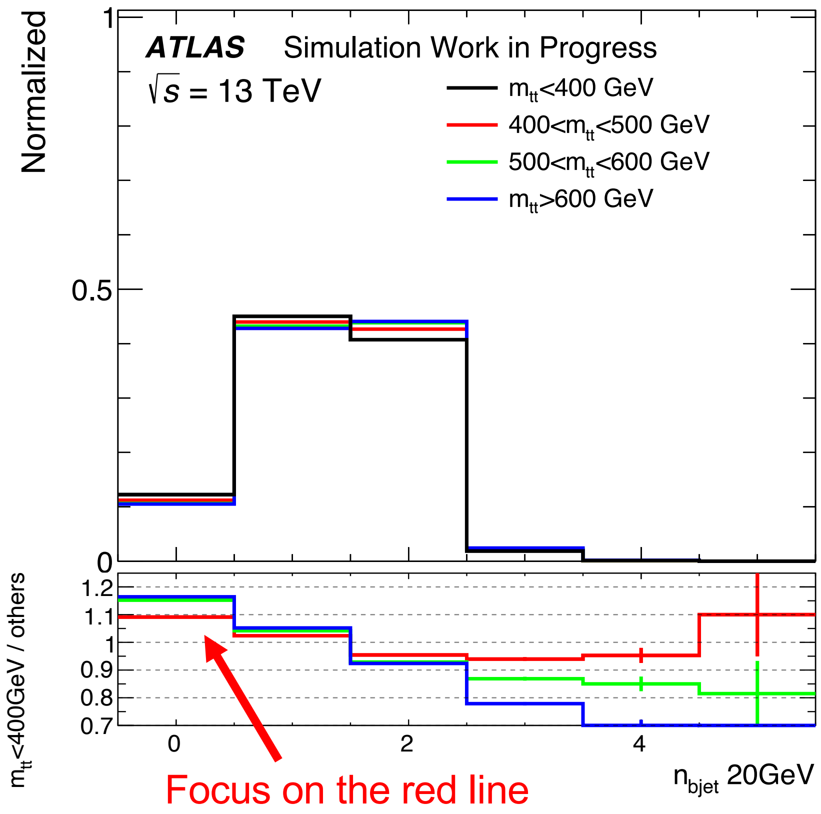
Tension between data and predictions does not wane.
For this process a complete NNLO computation is needed to reduce theory uncertainty

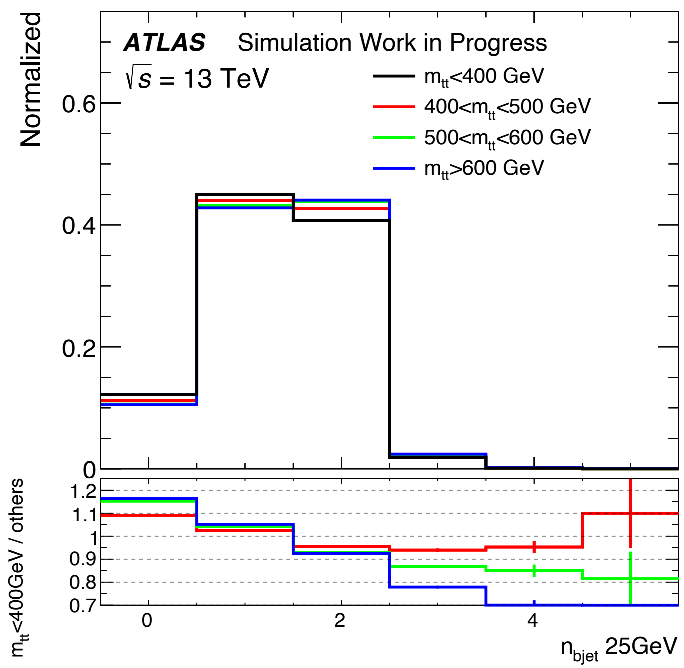
Can Toponium explain the anomalies

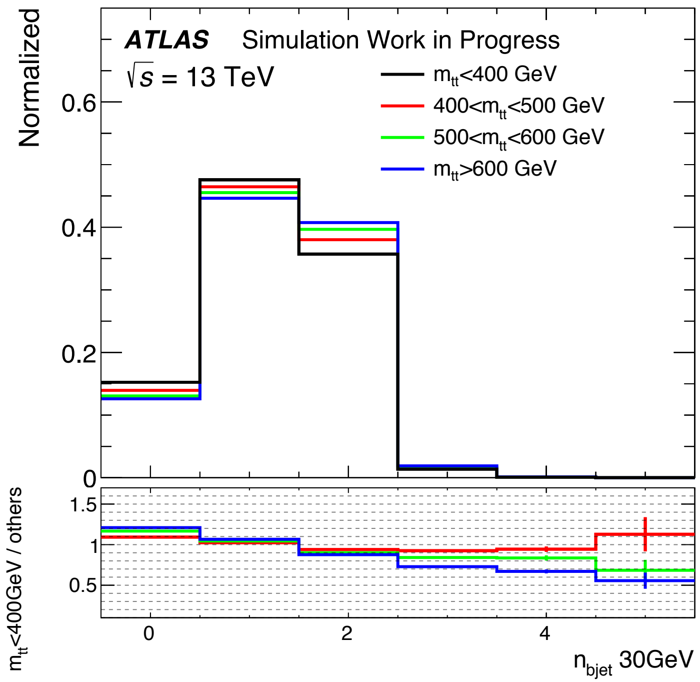
Final state	Characteristic	Dominant SM process	Toponium
l^+l^- + jets, b-jets	m_{ll}<100 GeV, dominated by 0b-jet and 1b-jet	tt+Wt	Let's take a closer look
l^+l^- + full-jet veto	m_{ll}<100 GeV	WW	No
$l^\pm l^\pm$ & $l^\pm l^\pm l$ + b-jets	Moderate H_T	ttW, 4t	No
$l^\pm l^\pm$ & $l^\pm l^\pm l$ et al., no b-jets	In association with h	Wh	No
$Z(\rightarrow l^+l^-)+l$	p_{TZ}<100 GeV	ZW	No

Toponium leads to a tt final state and contributes to l^+l^- + b-jets with large b-jet multiplicity. BUT the excess prefers low b-jet multiplicity.

B. Lieberman







Toponium will produce tt at threshold. MC studies show that the b-jet multiplicity changes little with the ttbar invariant mass. Note small difference in b-jet multiplicity for m_{tt}<400 vs 400<m_{tt}<500 GeV. The effect would need to be an order of magnitude higher to explain the excess with OS di-leptons with b-jets.

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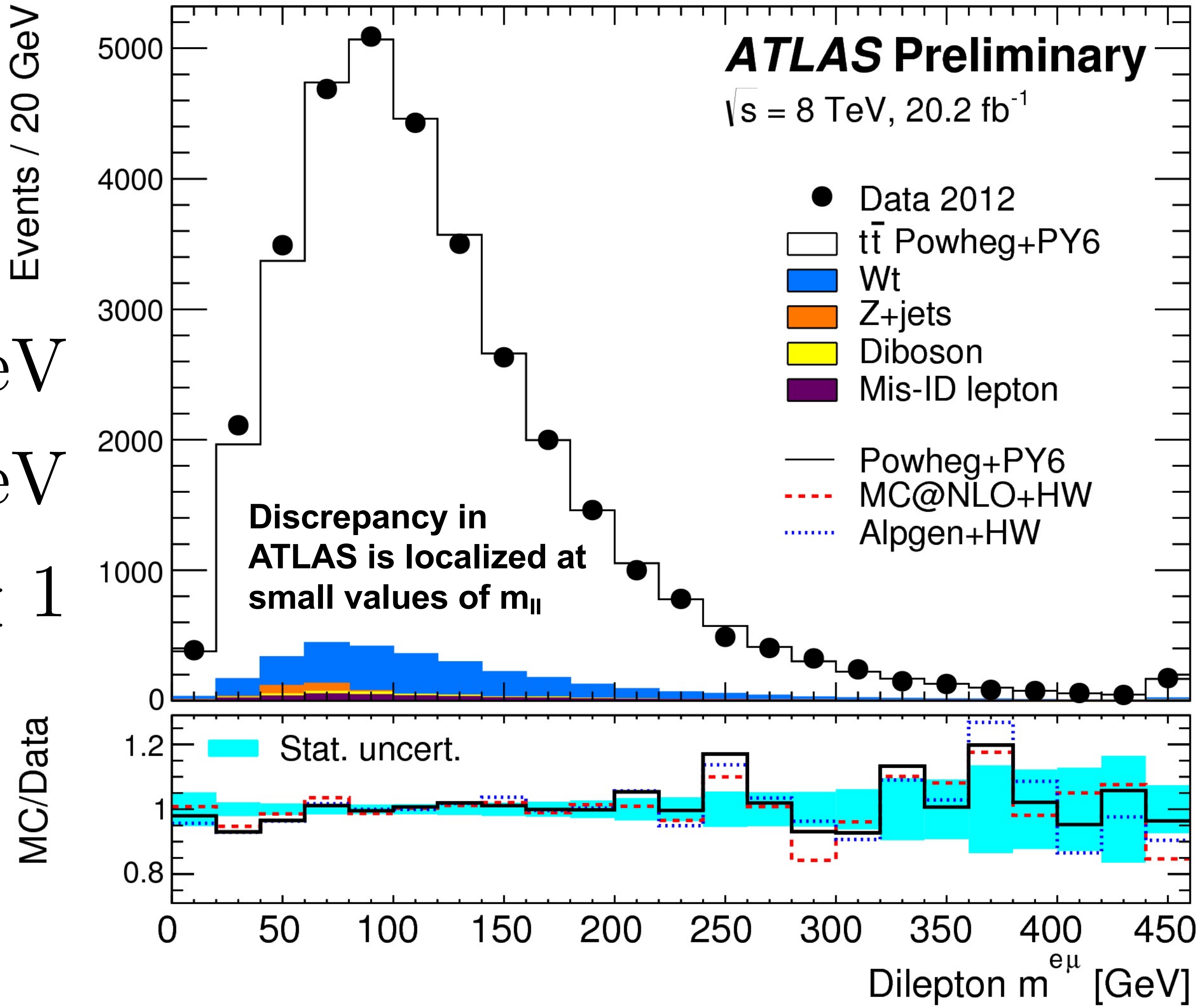
Is the discrepancy due to ttbar events?

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

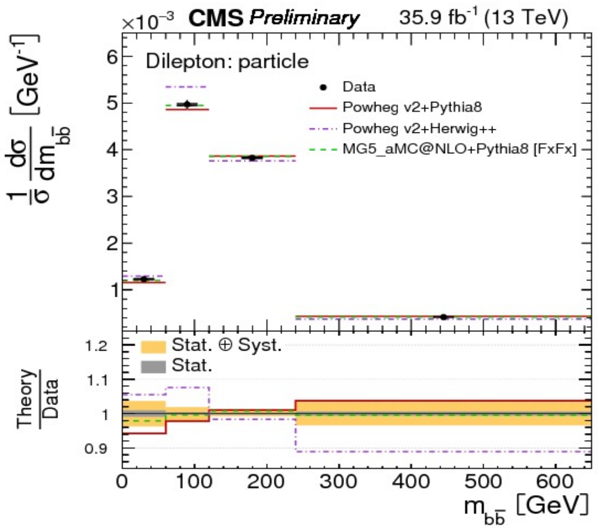
$$p_{Tb} > 25\,\mathrm{GeV}$$

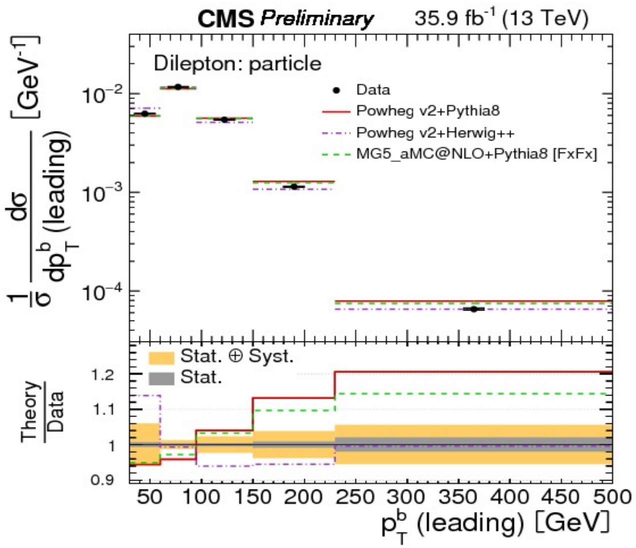
$$N_{bjet} \geq 1$$

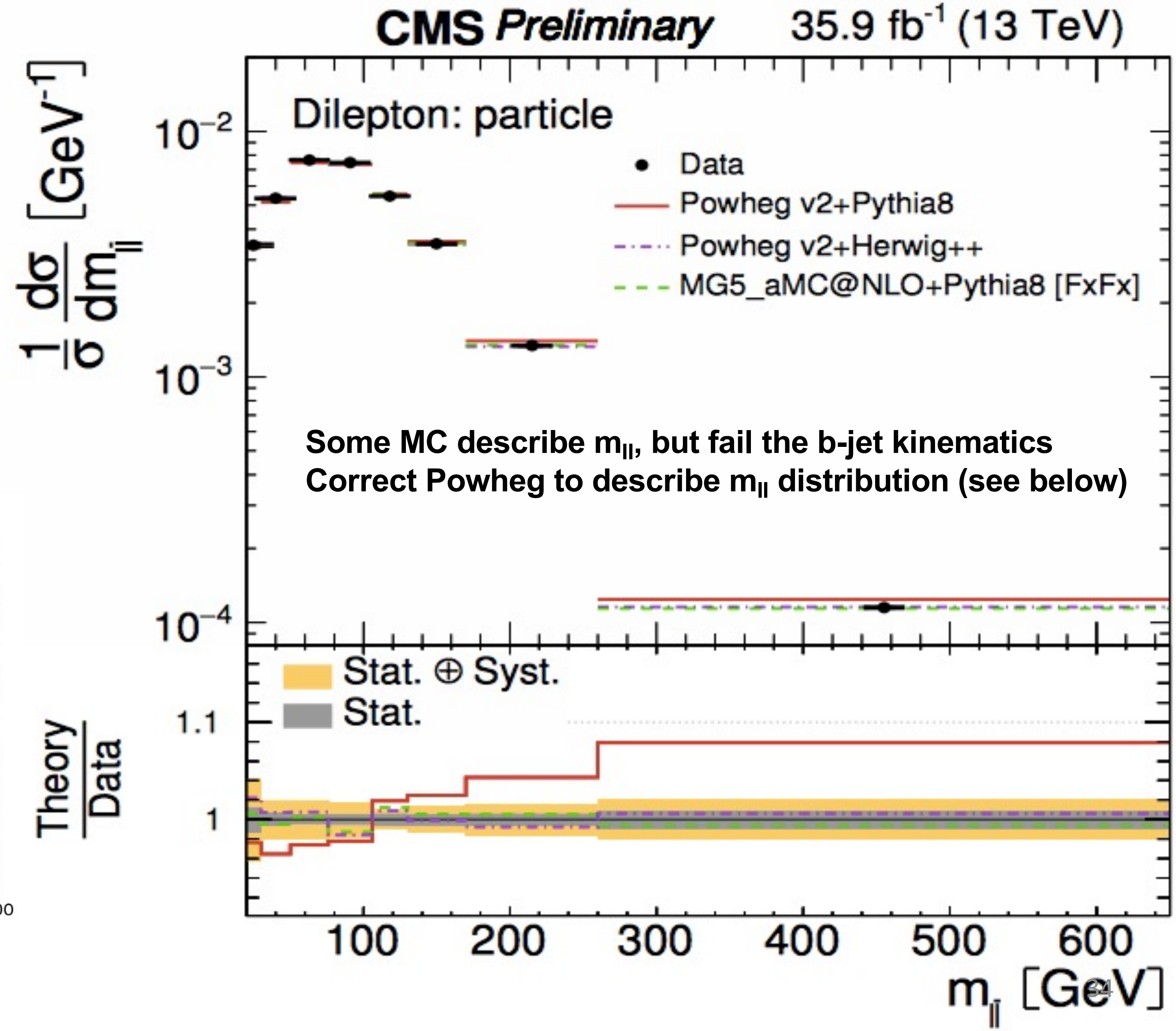


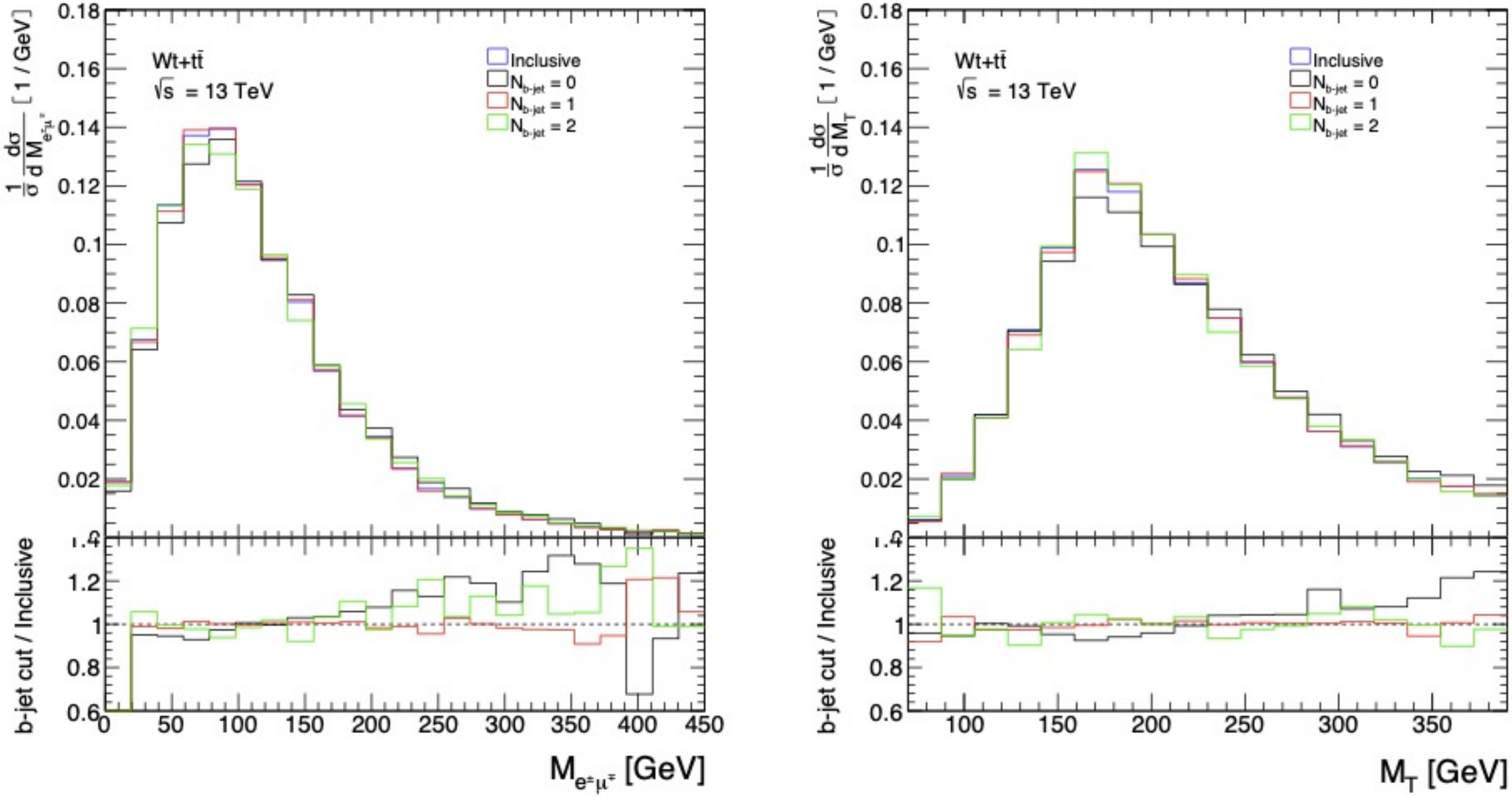
CMS PAS TOP-17-014

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









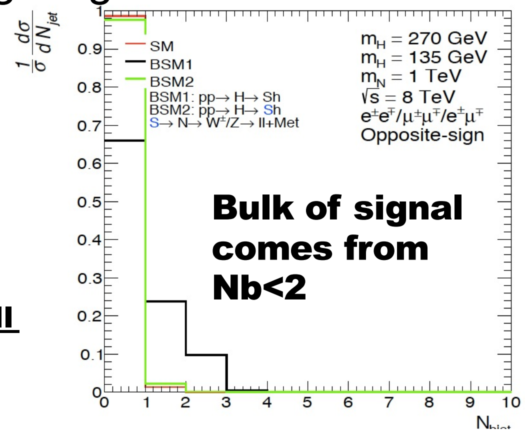
b-jet multiplicity is robust theoretically

Figure 9: Leptonic distributions produced by $t\bar{t}$ and tW processes (see text) as a function of the b-tagged jet multiplicity. The di-lepton invariant mass (left) and the transverse mass of the di-lepton and missing transverse energy system are displayed. Distributions are normalised to unity. The insert shows the ratio of the distributions with exclusive b-tagged jet bins relative to that obtained inclusively.

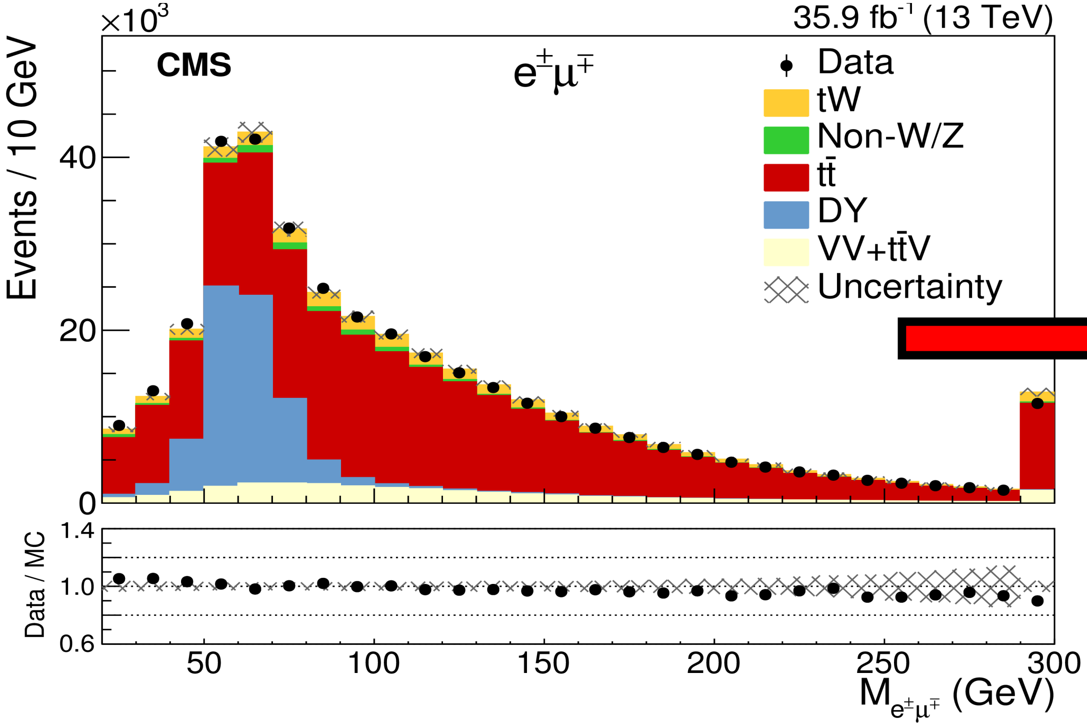
arXiv:1805.07399

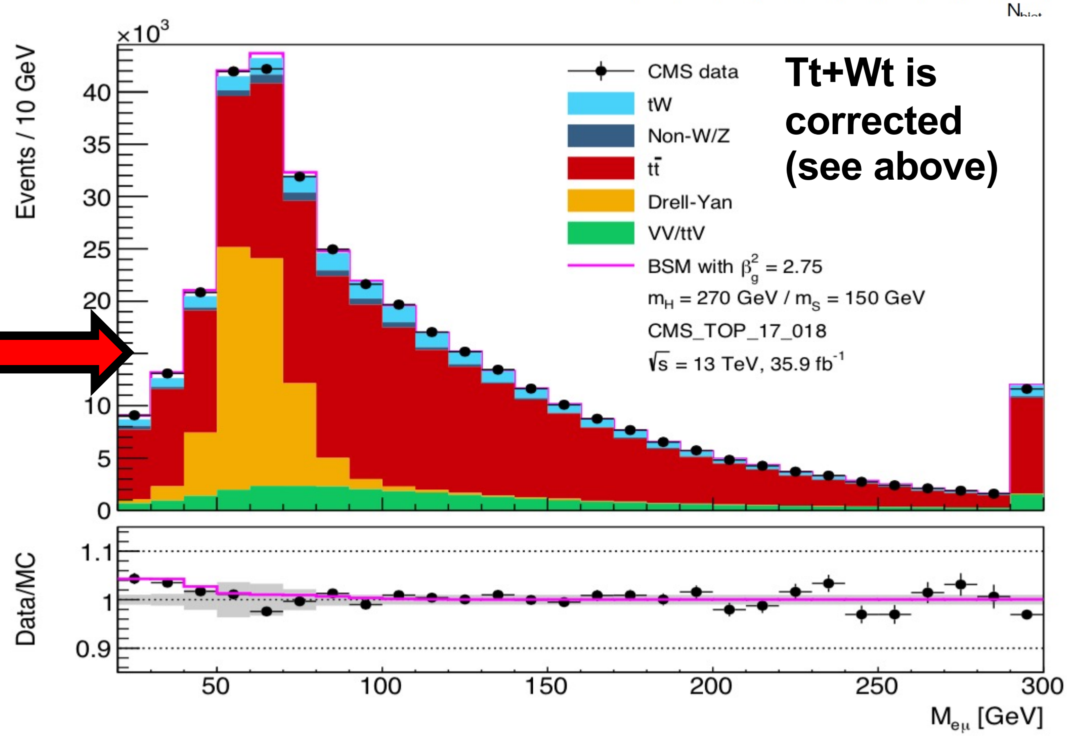
CMS-TOP-17-018; CERN-EP-2018-074

- 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



<u>Negligible MC dependence, as m_{ll} shape comes from data</u>





Used conservative assumption that l^+l^-+2b-jet final state is perfectly described by the SM. The discrepancy comes from events with N_b<2. Excess unlikely due to tt

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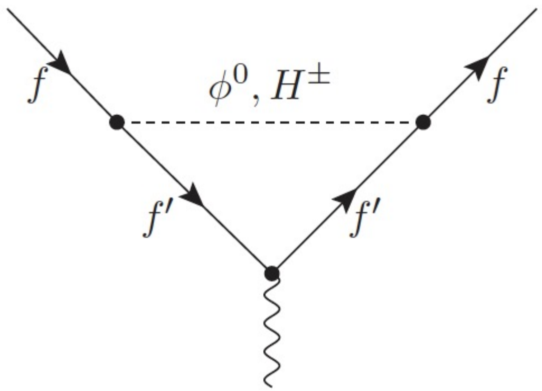
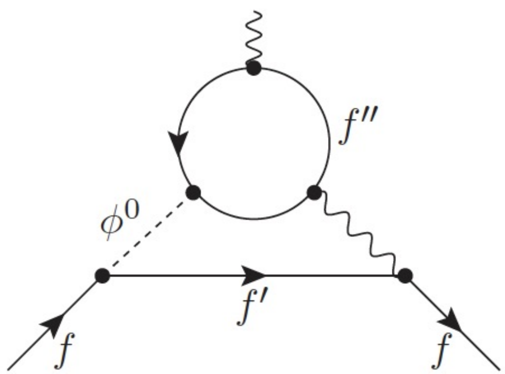
$$\Delta a_\mu = a_\mu^{\rm Exp} - a_\mu^{\rm SM} = 2.87(80) \times 10^{-9}$$

The Muon g-2 and the 2HDM+S



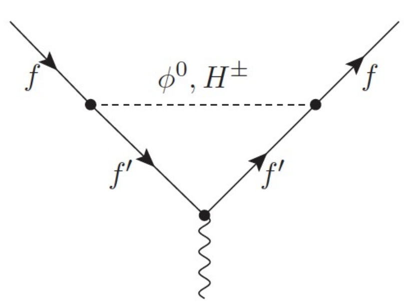


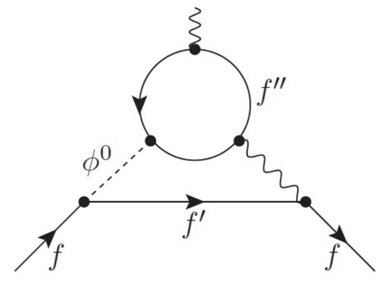
2HDM+S potential with fixed parameters from multi-lepton anomalies at the LHC

$$
\begin{aligned}
V(\Phi_1, \Phi_2, \Phi_S) &= m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \text{h.c.}\right) \\
&+ \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) \\
&+ \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right] \\
&+ \frac{1}{2} m_S^2 \Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}\left(\Phi_1^\dagger \Phi_1\right)\Phi_S^2 + \frac{\lambda_8}{2}\left(\Phi_2^\dagger \Phi_2\right)\Phi_S^2
\end{aligned}
$$

Consider extra degrees of freedom in the form of SM singlet vector-like fermions

$$
\mathcal{L} \supset -y_{f'}^S \overline{l_R} \Phi_S f'_L - \sum_{i=1}^{2} y_{f'}^i \overline{L_l} \Phi_i f'_R + \text{h.c.},
$$





Allowed fermion masses with different choices of Yukawa couplings