The multi-lepton anomalies at the LHC and implications

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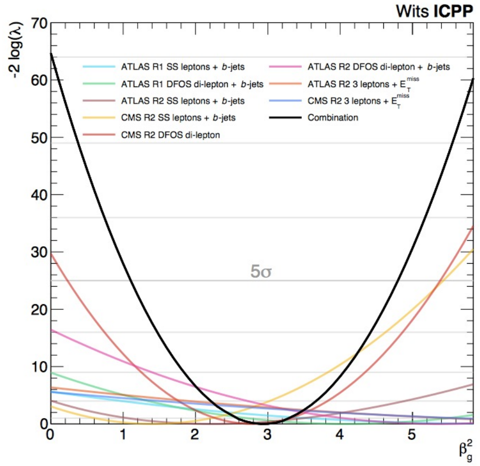
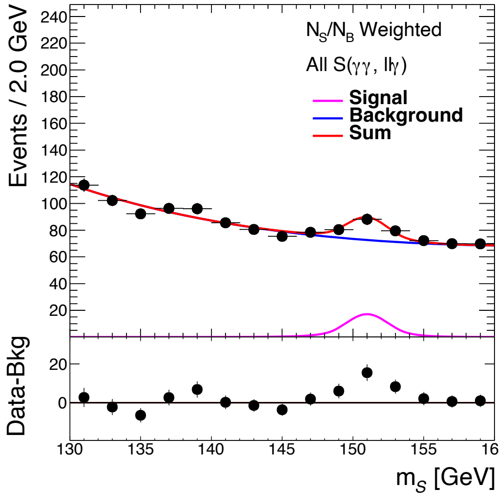
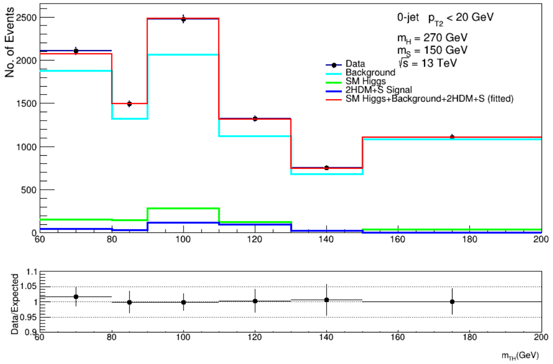
Outline

- The simplified model
- The multilepton problem
  - Methodology
  - The anatomy of the anomalies
- A possible candidate of S
  - $\gamma\gamma$, $Z\gamma$ and ll+MET results
  - Prospects for Run 3





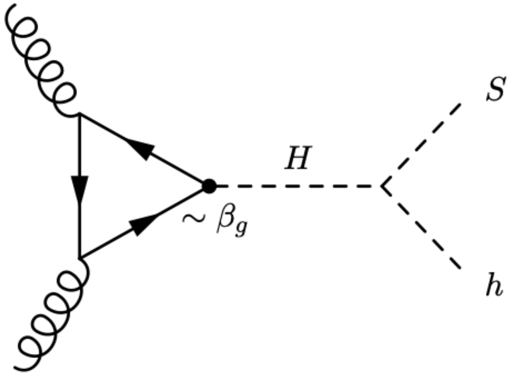


The Simplified Model and 2HDM+S

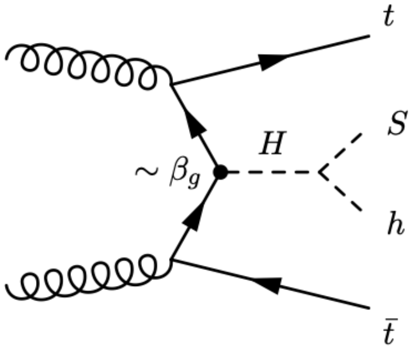
Eur. Phys. J. C (2016) 76:580

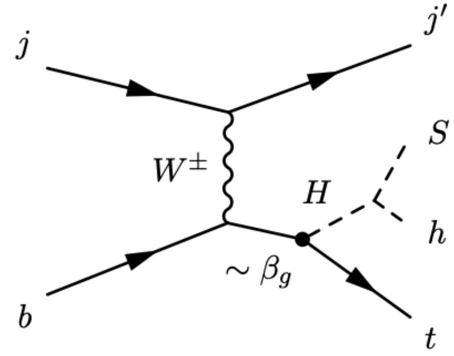
The simplified Model (from Run I)

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).





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

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

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

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

Introduce singlet real scalar, S.

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

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

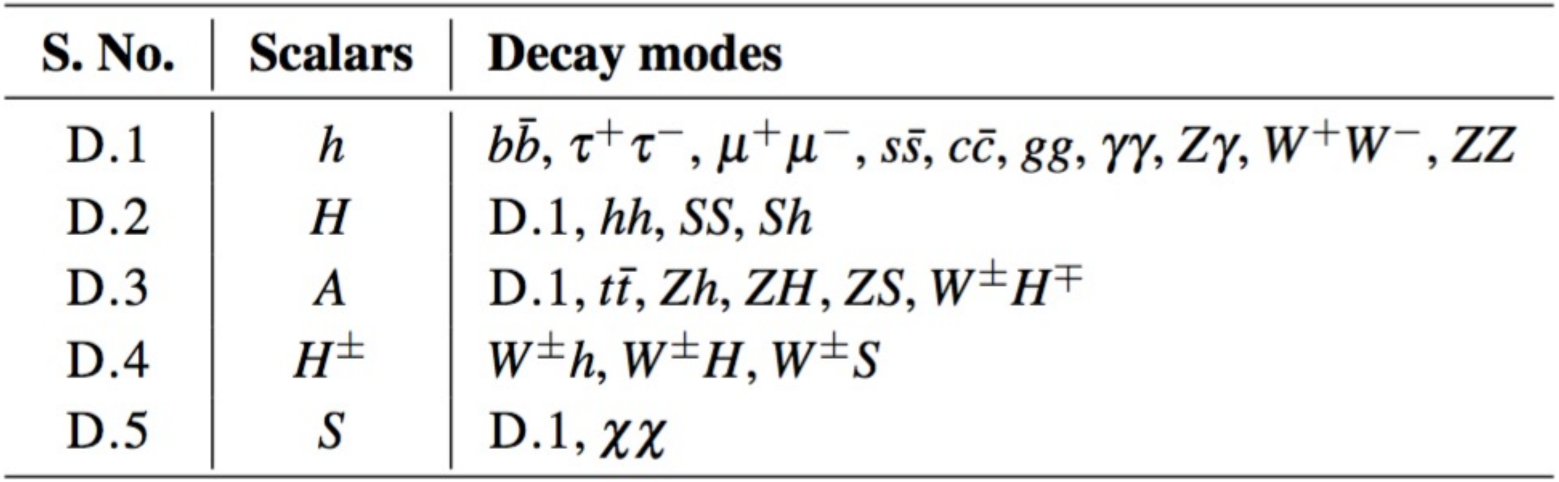
2HDM+S potential

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

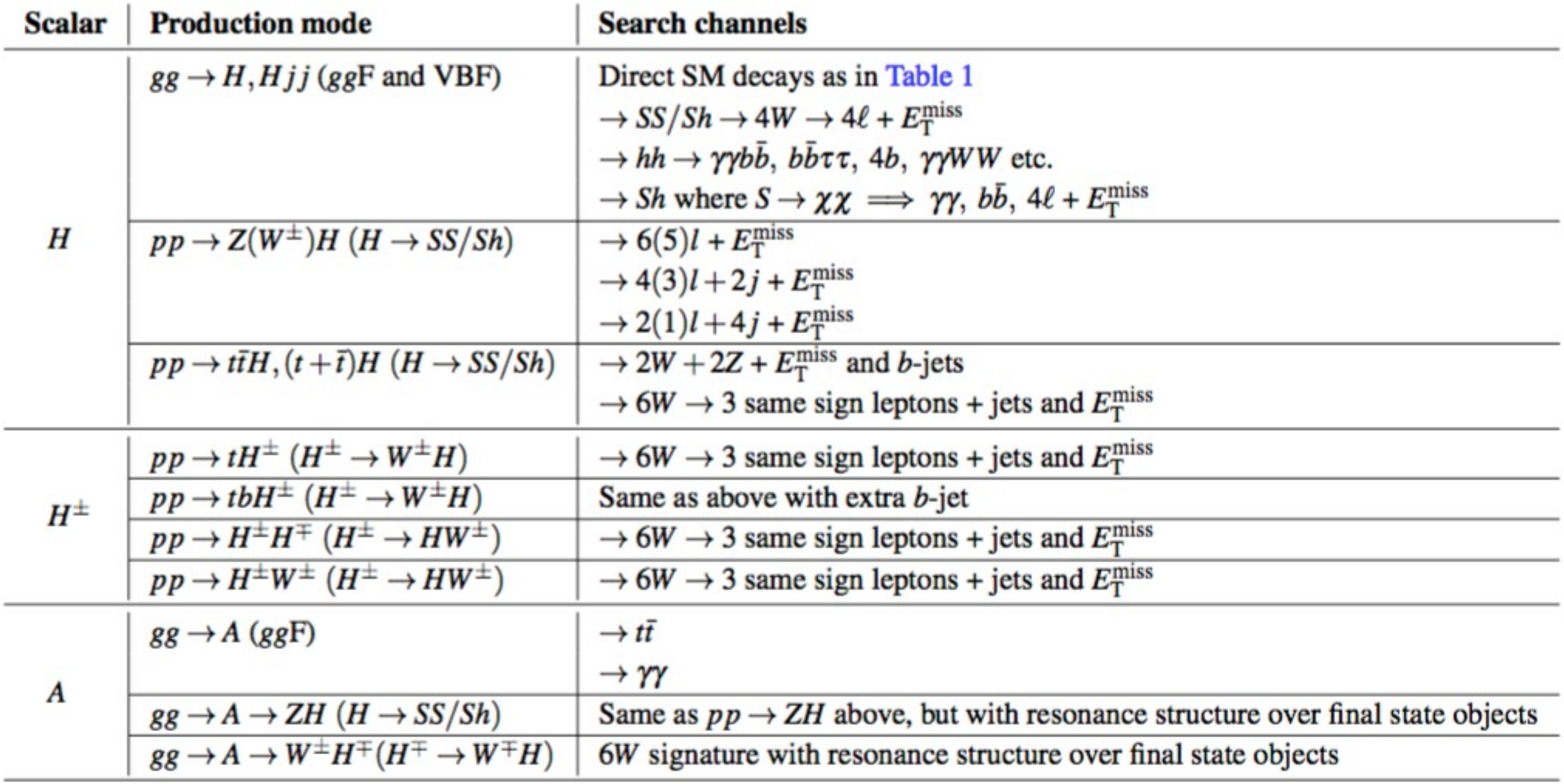
Out of considerations of simplicity, assume S to be Higgs-like, which is not too far fetched.

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

arXiv:1606.01674



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, $\chi\chi$



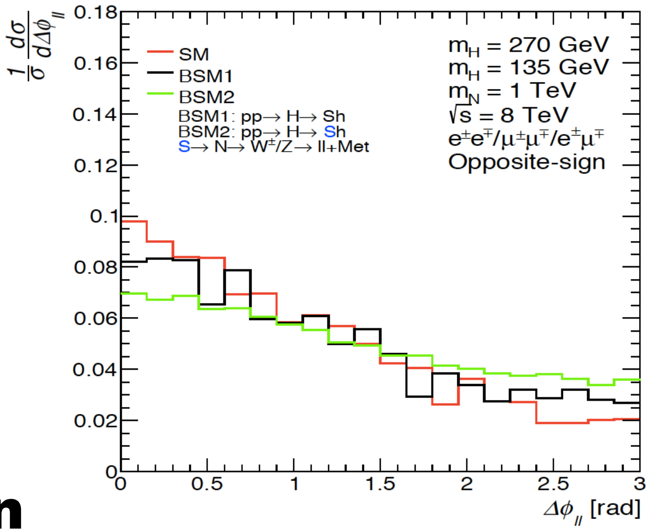
Scalar	Production mode	Search channels
H	$gg \to H, Hjj$ (ggF and VBF)	Direct SM decays as in Table 1 $\to SS/Sh \to 4W \to 4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ $\to hh \to \gamma\gamma b\bar{b}$, $b\bar{b}\tau\tau$, $4b$, $\gamma\gamma WW$ etc. $\to Sh$ where $S \to \chi\chi \implies \gamma\gamma$, $b\bar{b}$, $4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$
	$pp \to Z(W^{\pm})H$ ($H \to SS/Sh$)	$\to 6(5)l + E_{\mathrm{T}}^{\mathrm{miss}}$ $\to 4(3)l + 2j + E_{\mathrm{T}}^{\mathrm{miss}}$ $\to 2(1)l + 4j + E_{\mathrm{T}}^{\mathrm{miss}}$
	$pp \to t\bar{t}H, (t+\bar{t})H$ ($H \to SS/Sh$)	$\to 2W + 2Z + E_{\mathrm{T}}^{\mathrm{miss}}$ and b-jets $\to 6W \to 3$ same sign leptons + jets and $E_{\mathrm{T}}^{\mathrm{miss}}$
$H^{\pm}$	$pp \to tH^{\pm}$ ($H^{\pm} \to W^{\pm}H$)	$\to 6W \to 3$ same sign leptons + jets and $E_{\mathrm{T}}^{\mathrm{miss}}$
	$pp \to tbH^{\pm}$ ($H^{\pm} \to W^{\pm}H$)	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 $E_{\mathrm{T}}^{\mathrm{miss}}$
	$pp \to H^{\pm}W^{\pm}$ ($H^{\pm} \to HW^{\pm}$)	$\to 6W \to 3$ same sign leptons + jets and $E_{\mathrm{T}}^{\mathrm{miss}}$
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

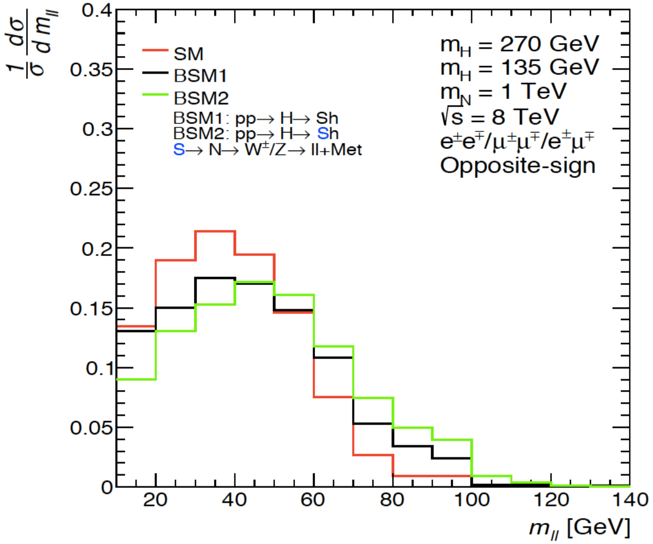
Multi-lepton final states

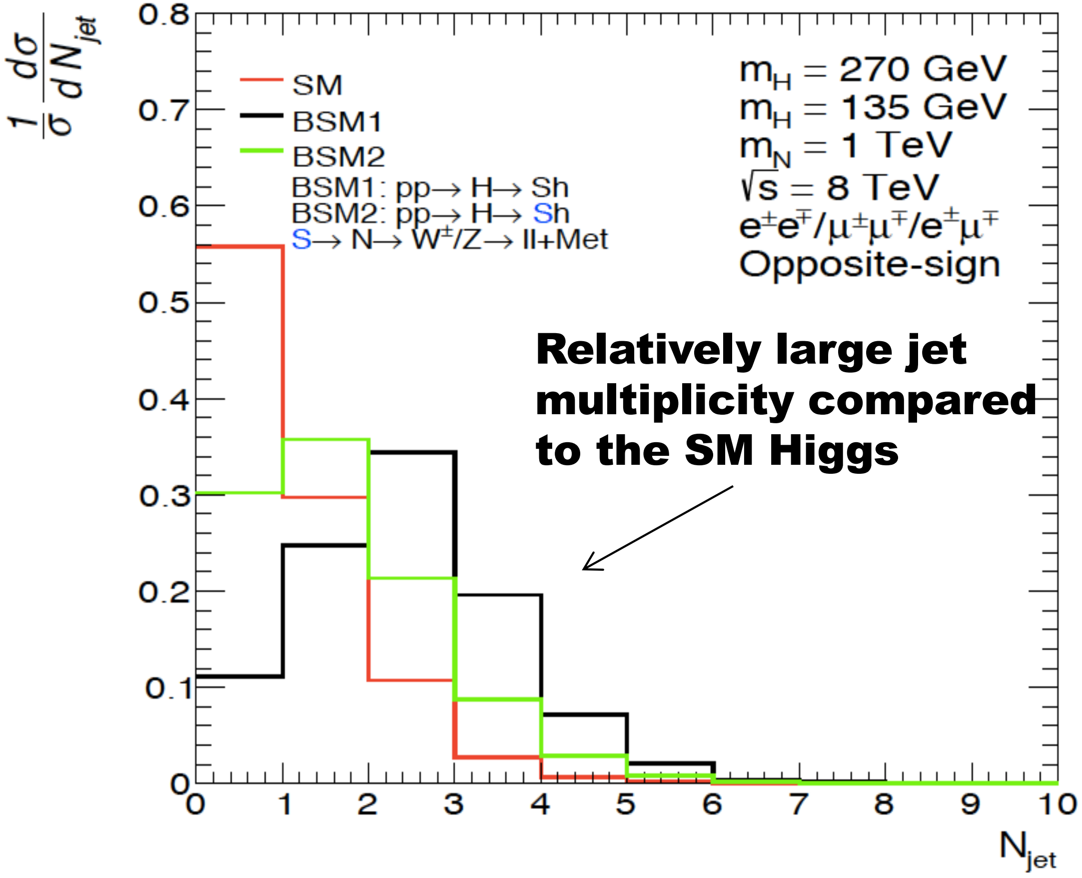
It is paramount to remark that the excesses are seen in final states that were predicted 2015/2016 on the basis of a simplified model and not the result of scan of the available phase-space. Additionally, the parameters of the model where fixed then leaving only one degree of freedom: normalization Thus,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

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

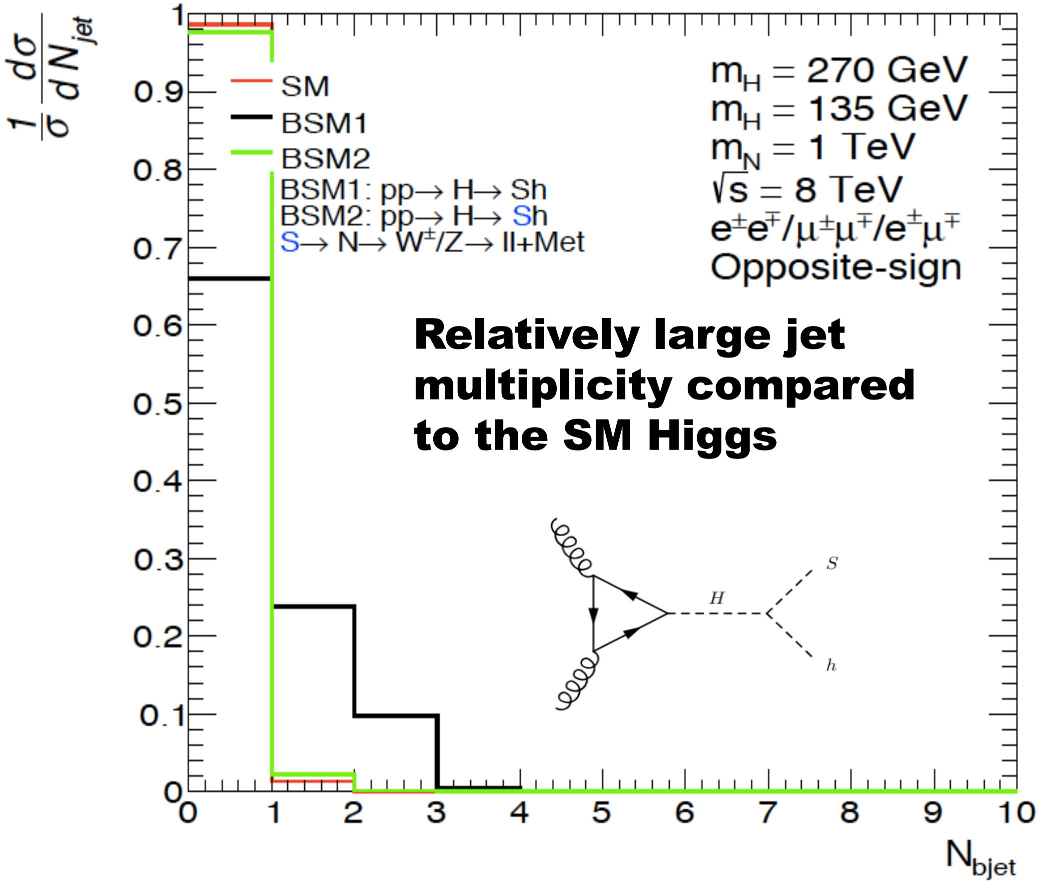
Expect di-leptons (m_{ll}<100 GeV) with jets and b-jets with rates comparable to that of the SM Higgs boson







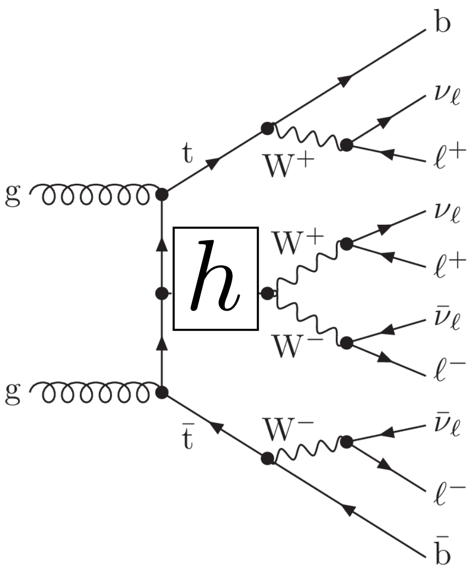
Relatively large jet multiplicity compared to the SM Higgs

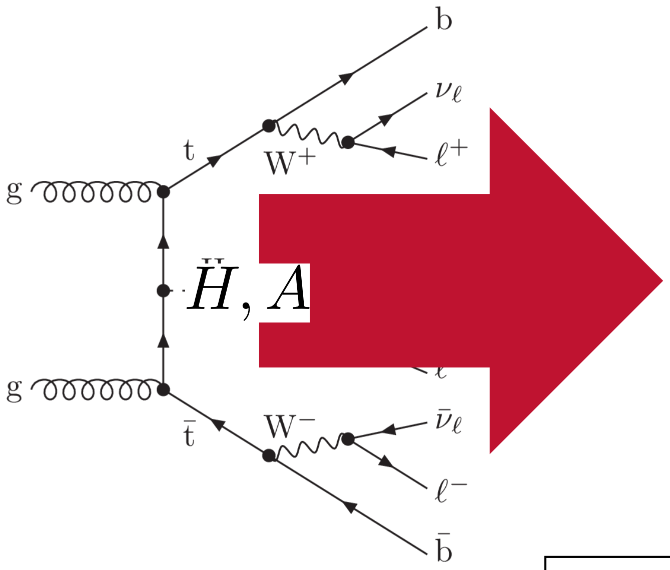


Relatively large jet multiplicity compared to the SM Higgs

Top associated Higgs production

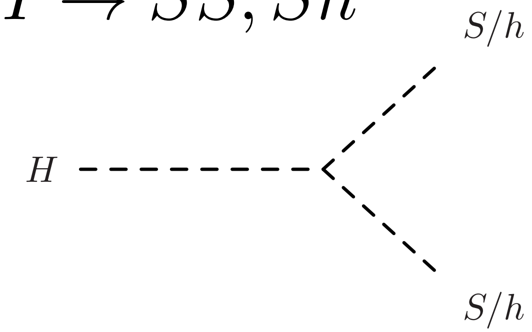
(Multi-lepton final states)





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

$$H \to SS, Sh$$



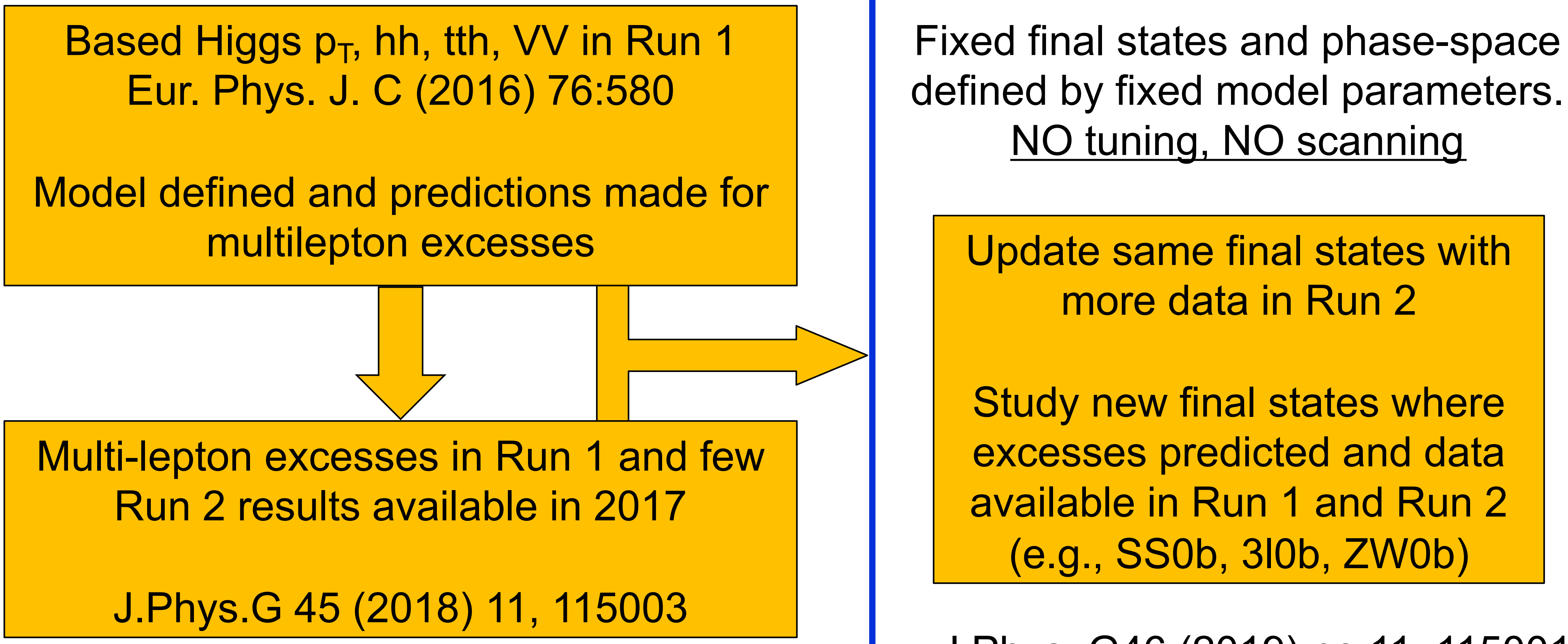
Reduced cross-section of ttH+tH is compensated by di-boson, (SS, Sh) decay and large Br(S→WW). Production of same sign leptons, three leptons is enhanced. Enhanced tH cross-section

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 parameters fixed in 2017 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.
NO tuning, NO scanning

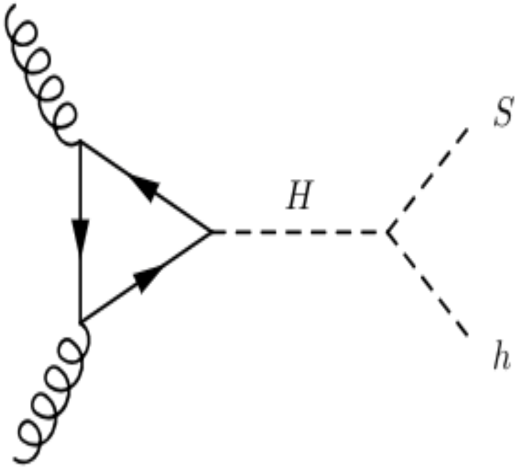
Update same final states with more data in Run 2

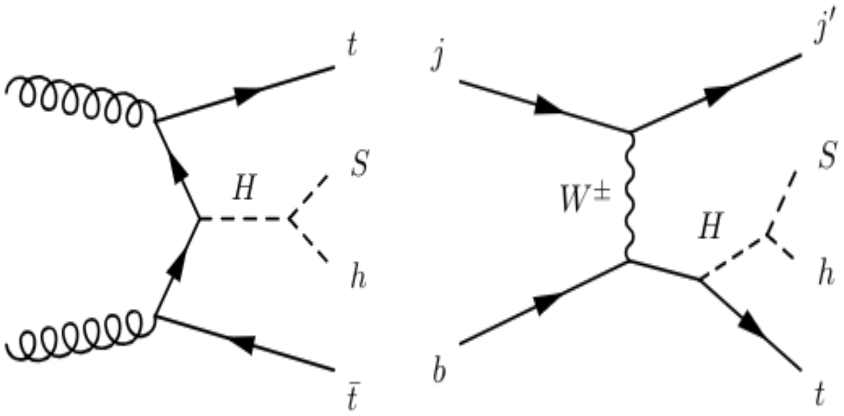
Study new final states where excesses predicted and data available in Run 1 and Run 2 (e.g., SS0b, 3l0b, ZW0b)

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

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* → *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**





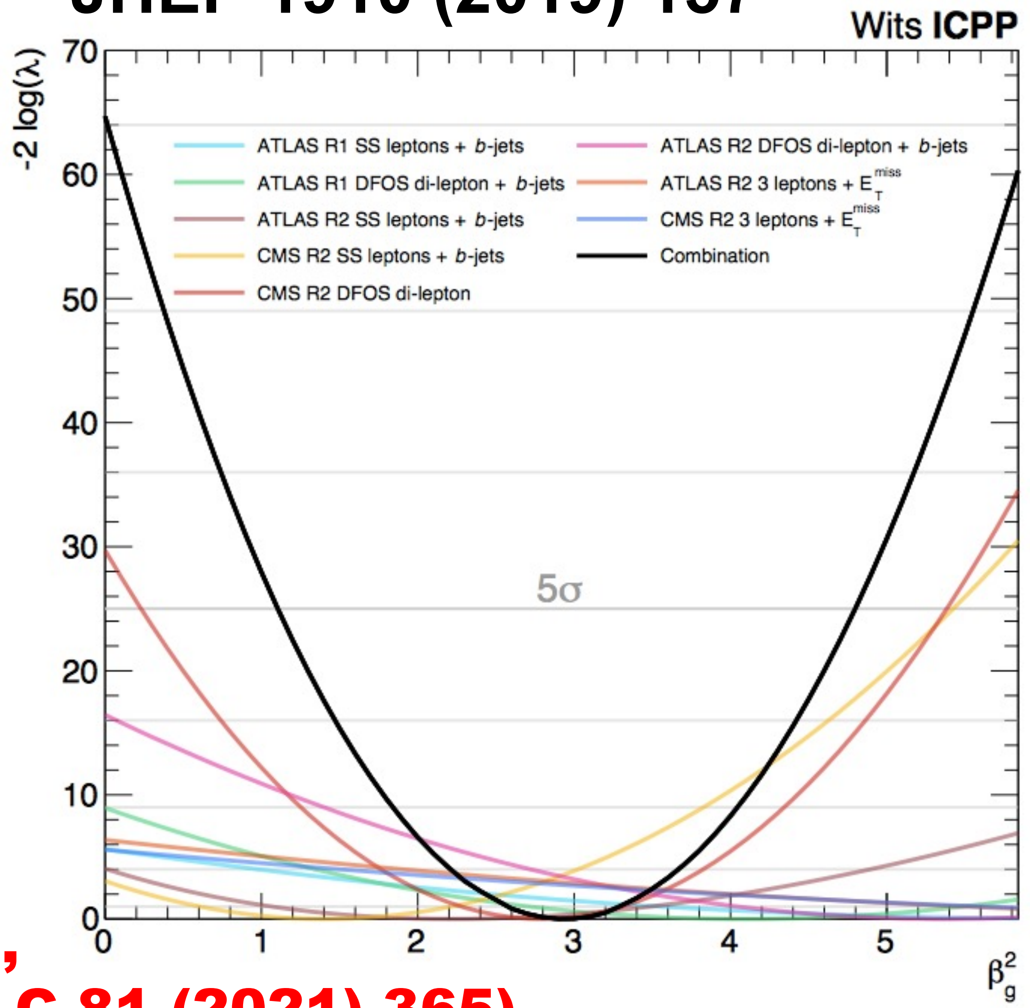
Combination of fit results (2019)

- 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

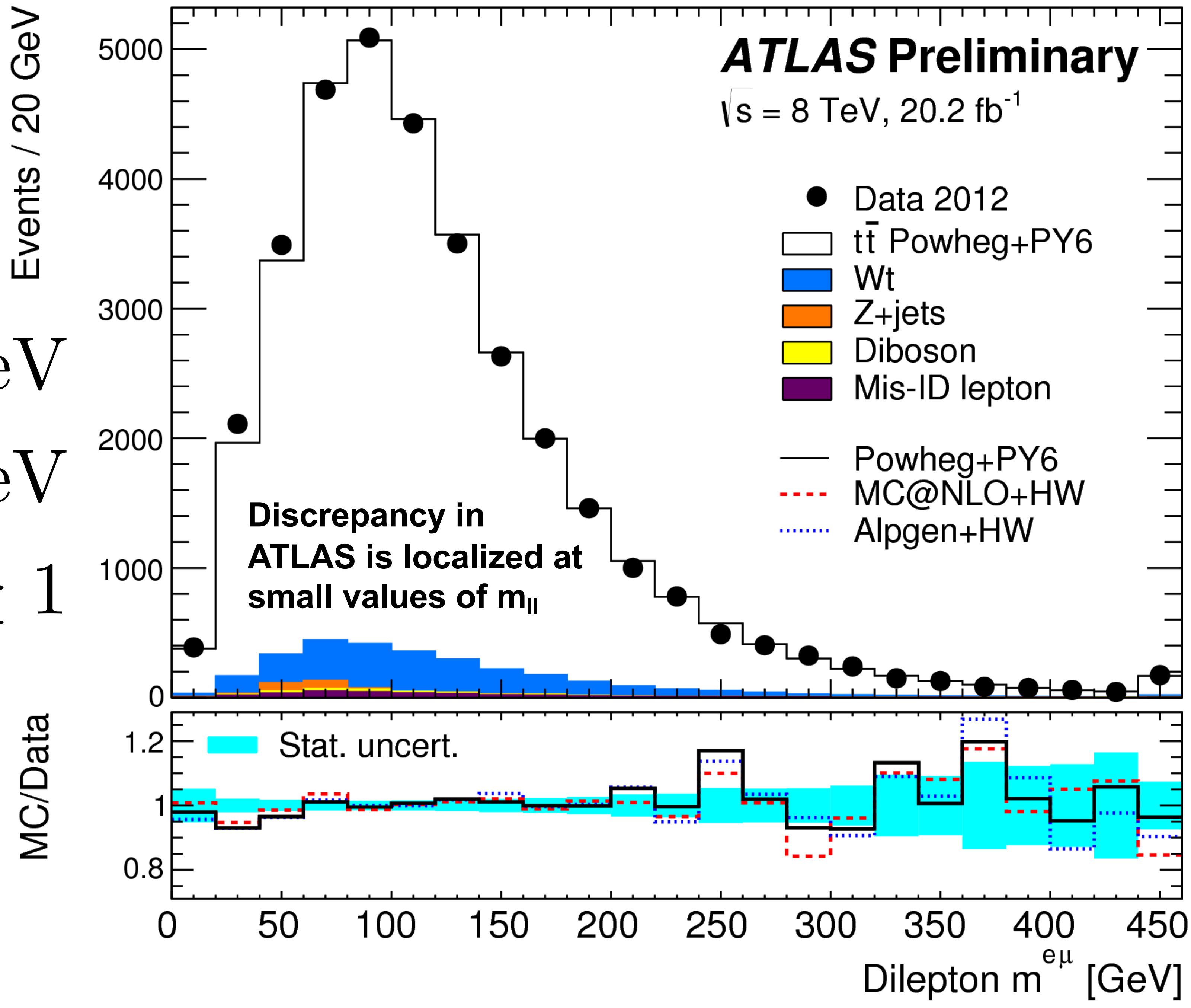
Eur. Phys. J. C 77 (2017) 804

Is the discrepancy due to ttbar events?

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

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

$$N_{bjet} \geq 1$$

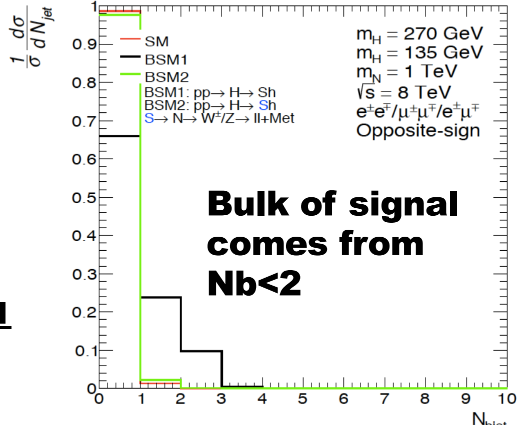


Discrepancy in ATLAS is localized at small values of m_{ll}

arXiv:1805.07399

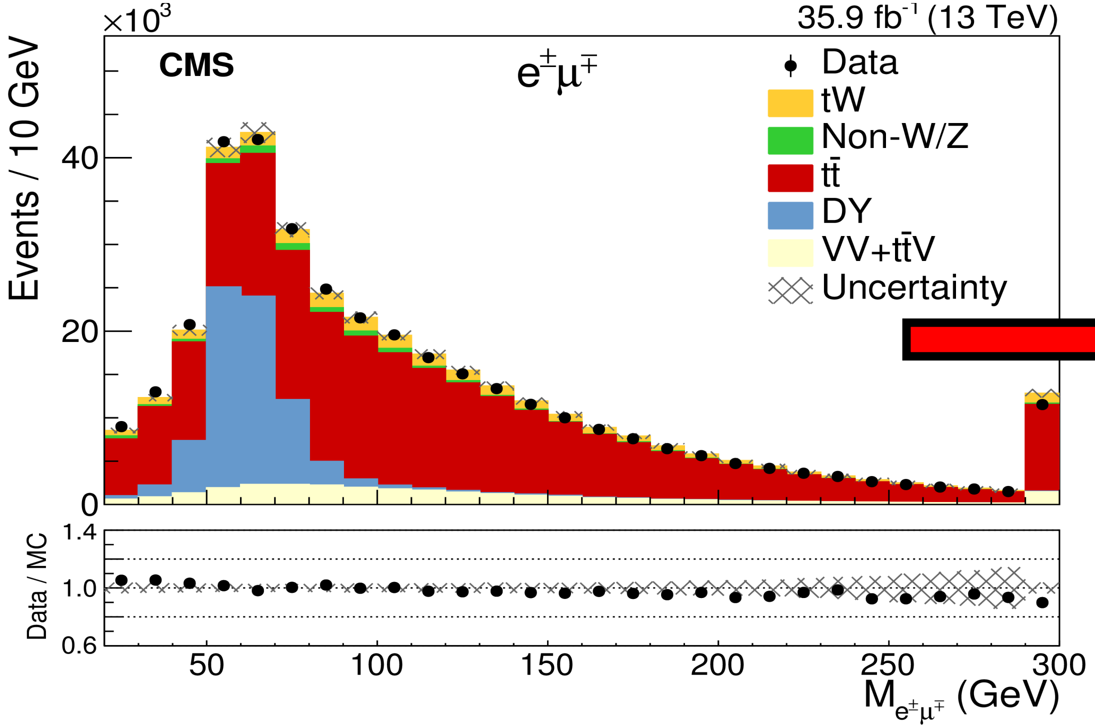
CMS-TOP-17-018; CERN-EP-2018-074

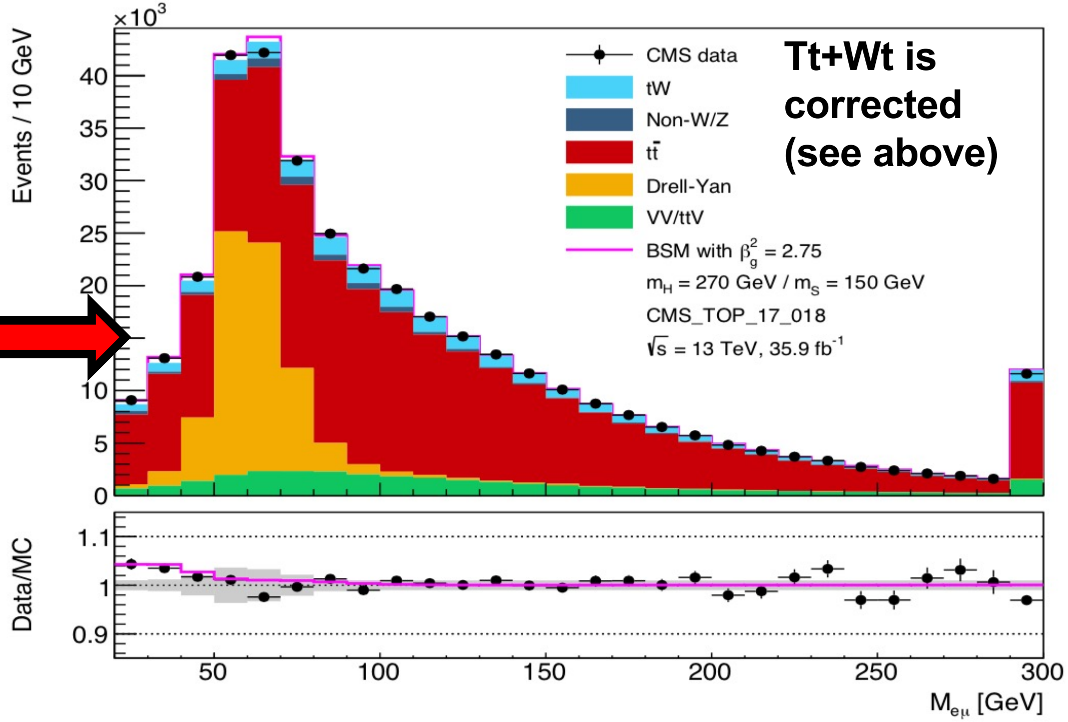
- Poor modeling of POWHEG + Pythia8 distribution is improved through reweighting
- We fix the normalisation of the SM by scaling it to the data in the region $m_{ll} > 110$ GeV
  - ○ A normalisation systematic of 3% is applied to all but DY
  - ○ DY systematic = 6.8%. 3% systematic on m_{ll} shape in 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



Bulk of signal comes from Nb<2

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



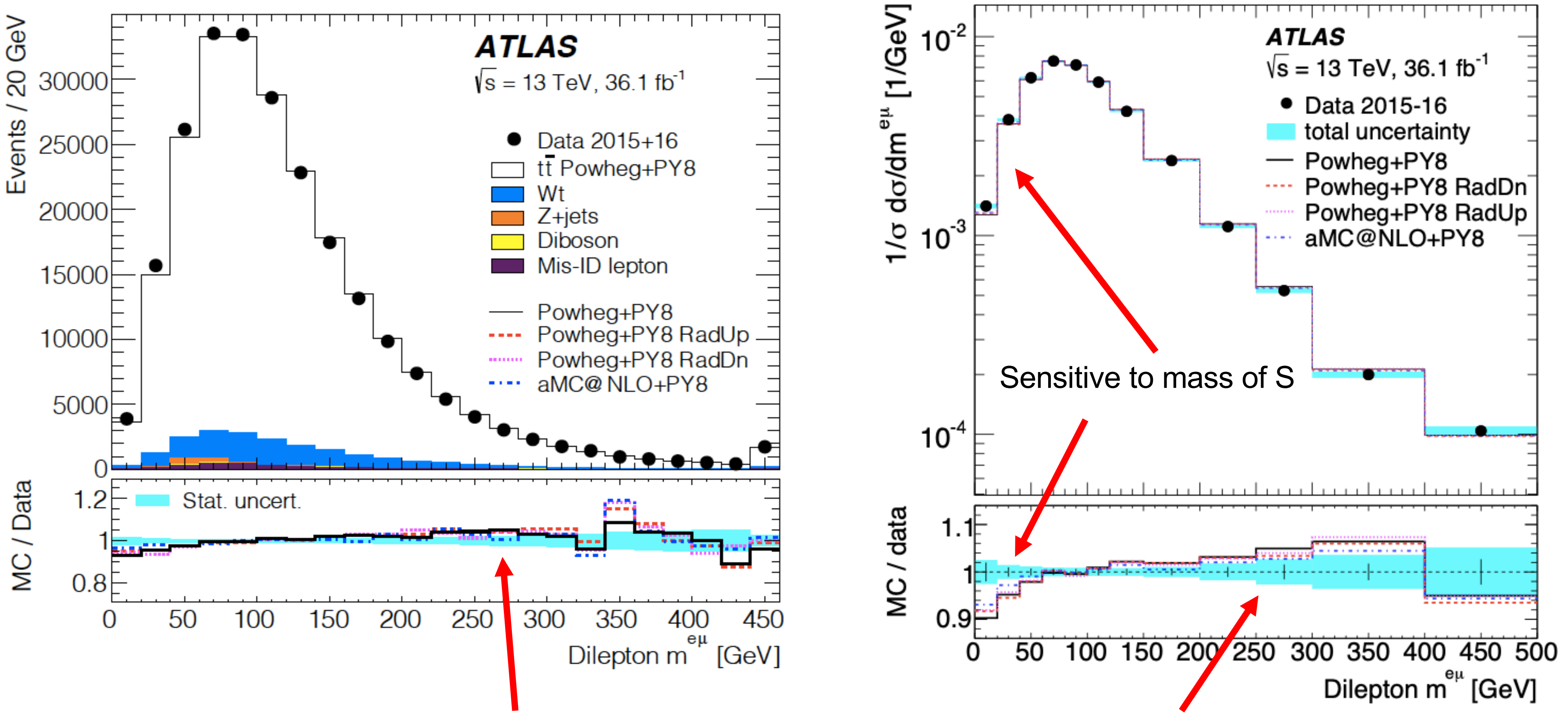


Tt+Wt is corrected (see above)

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

Results not included in the combination

Eur. Phys. J. C 80 (2020) 528



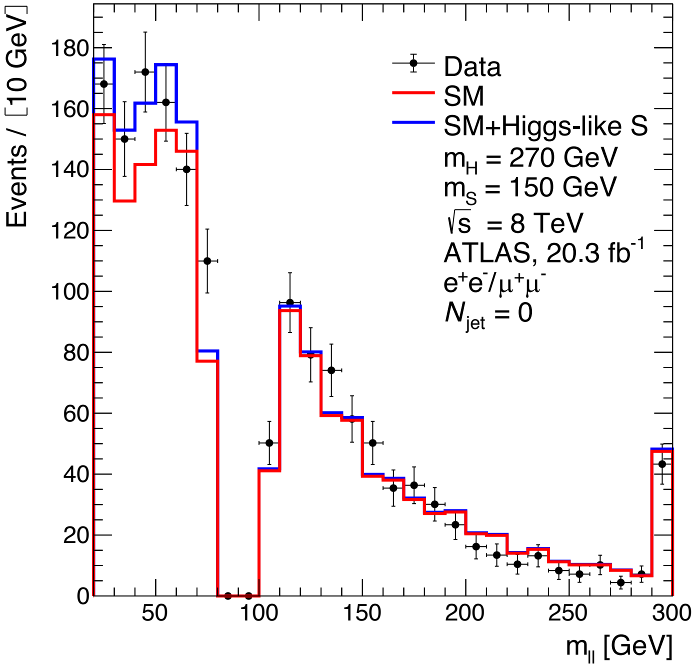
Residual discrepancies at high m_{ll} will be fixed with missing NNLO QCD and NLO EW corrections

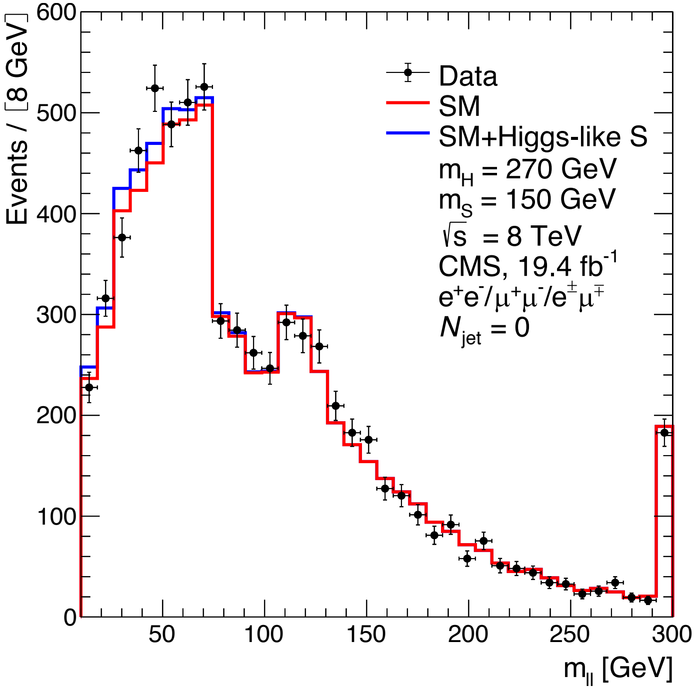
Excess at low mll remains prevalent, indicating that effects seen in Run 1 were not statistical fluctuations. NNLO QCD corrections do not fix the issue (see Mitov et al.)

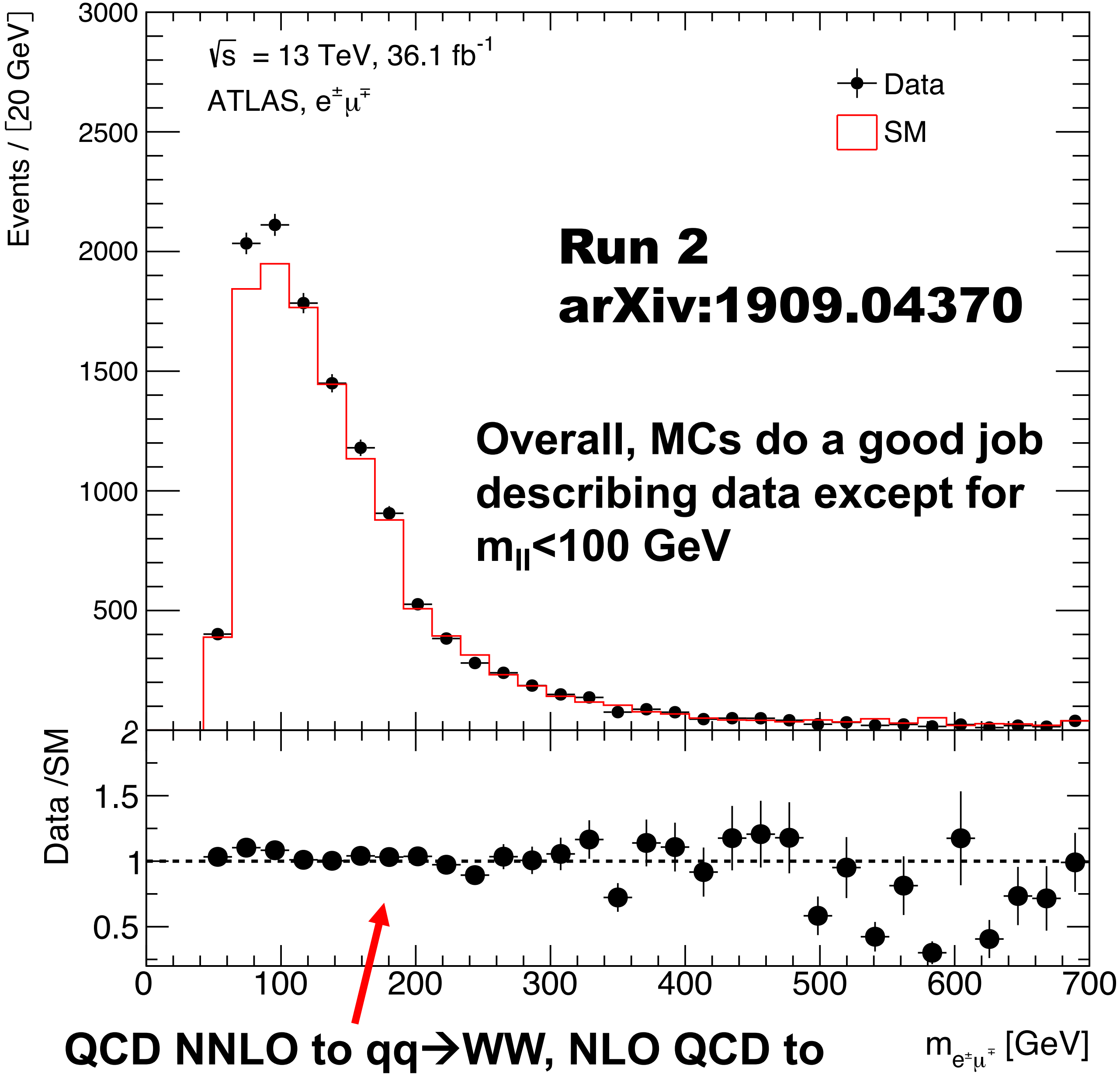
Excesses in di-leptons with full-jet veto not included above

From Run 1 multi-lepton excesses model-dependent prediction of $m_s = 150 \pm 5$ GeV

Run 1, J.Phys. G45 (2018) no.11, 115003





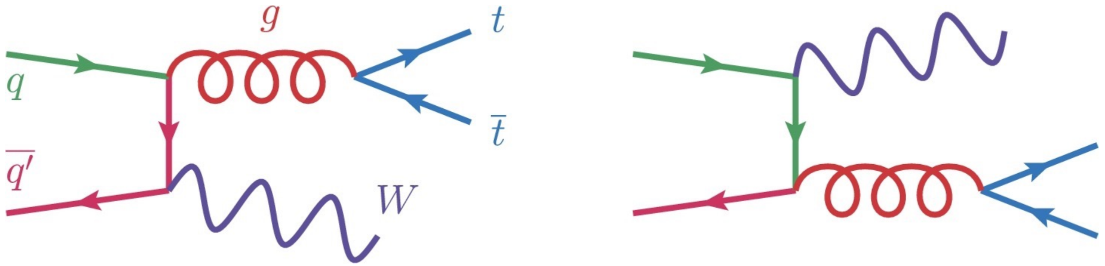


Run 2
arXiv:1909.04370

Overall, MCs do a good job describing data except for m_{ll}<100 GeV

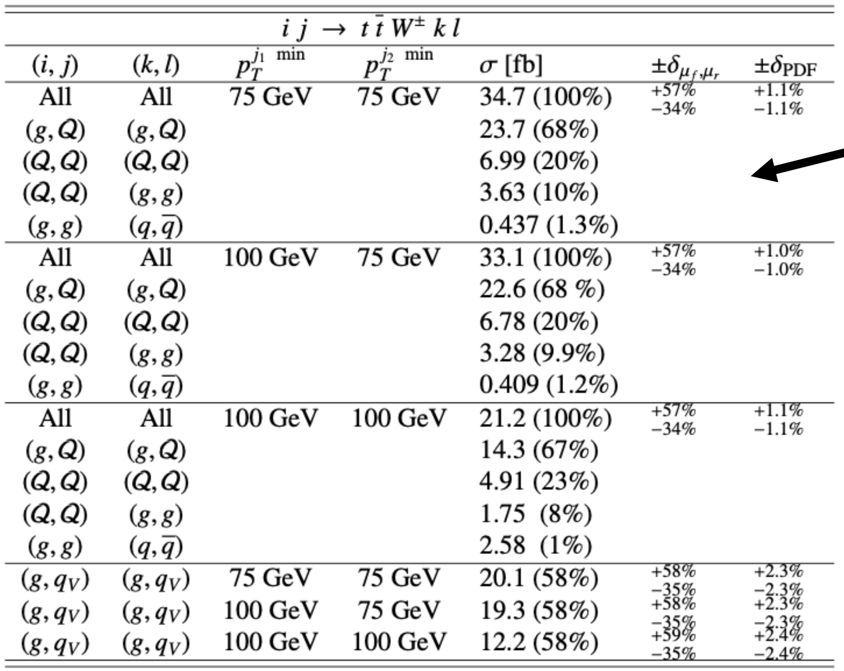
QCD NNLO to qq→WW, NLO QCD to gg→WW and NLO EW corrections applied

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

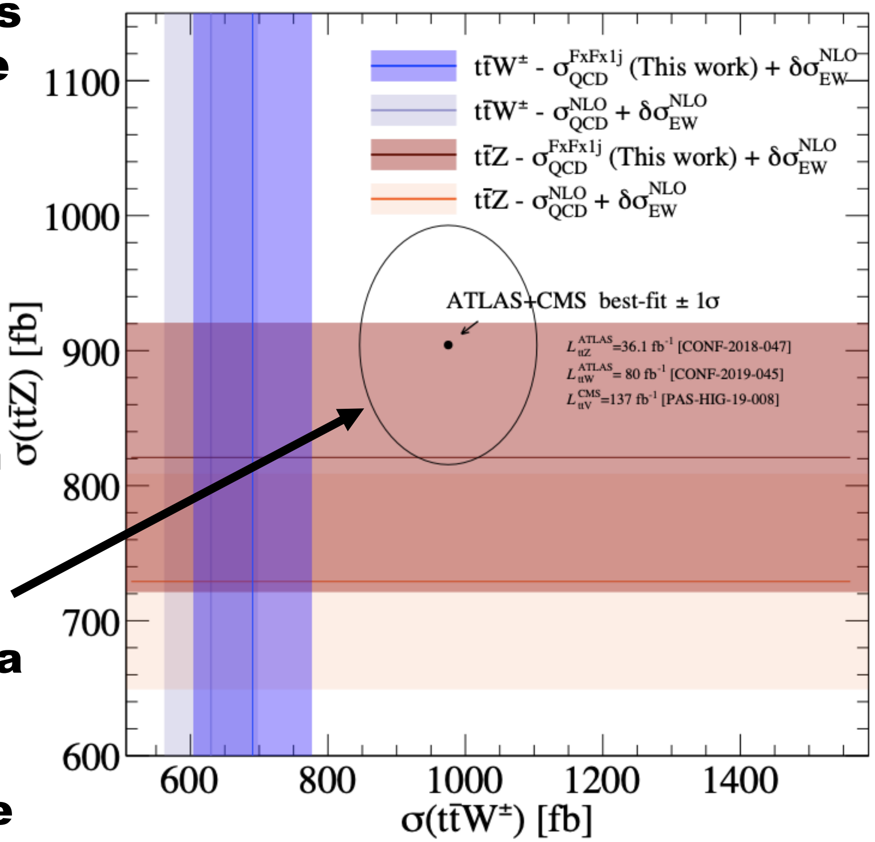


$i\,j \to t\,\bar{t}\,W^{\pm}\,k\,l$

(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

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	$>5\sigma$
l^+l^- + full-jet veto	$m_{ll}<100$ GeV	WW	$\sim 3\sigma$
$l^\pm l^\pm$ & $l^\pm l^\pm l$ + b-jets	Moderate H_T	ttW, 4t	$>3\sigma$
$l^\pm l^\pm$ & $l^\pm l^\pm l$ et al., no b-jets	In association with h	Wh, (WWW)	4.2σ
$Z(\rightarrow l^+l^-)+l$	$p_{TZ}<100$ GeV	ZW	$>3\sigma$

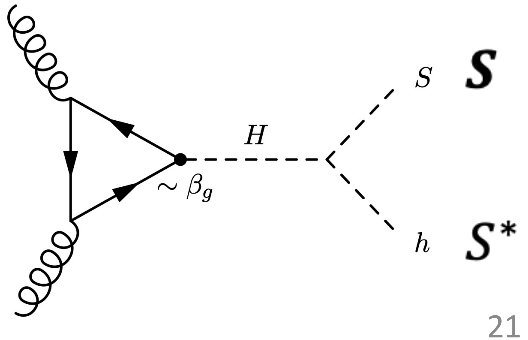
Anomalies cannot be explained by mismodelling of a particular process, e.g. ttbar production alone.

A possible candidate of S

Procedure

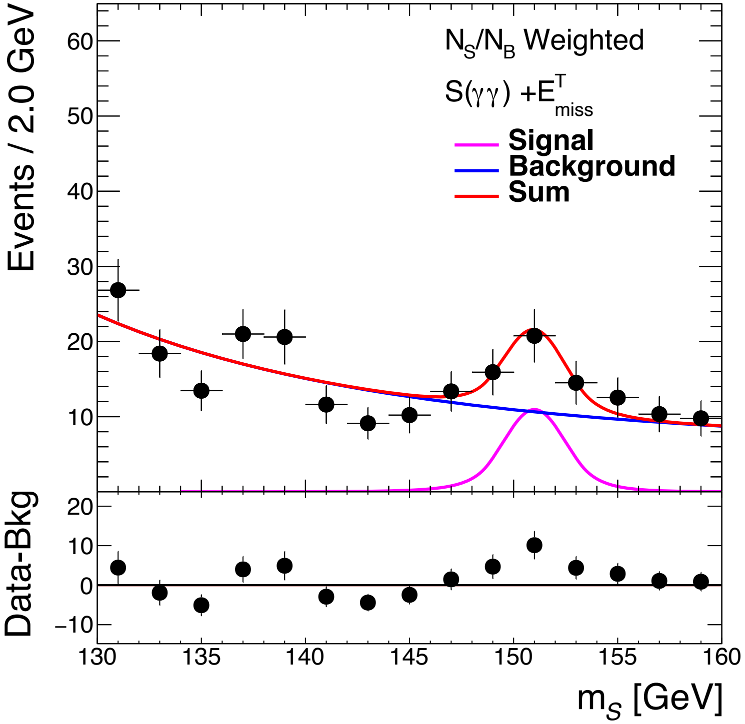
(avoiding “cherry picking”)

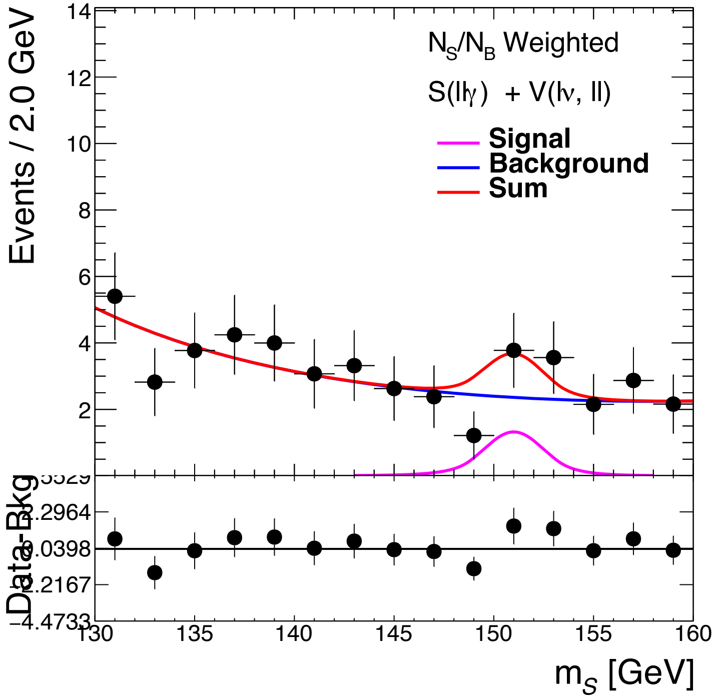
- **Setting a well-defined procedure is essential to the integrity of a search. Scanning nullifies significance**
- **From the di-lepton anomalies: $m_h < m_s < 170$ GeV**
  - **It is critical that search be localized and motivated**
- **Focus on $\gamma\gamma$ and $Z\gamma$ decays**
- **As per the model that described the multi-lepton anomalies, we select final state according to di-boson signatures. S is produced via the decay of something heavier and not directly**
  - **Re-use Higgs boson data**
  - **Remove VBF and boosted topologies**
    - **Related to direct production**

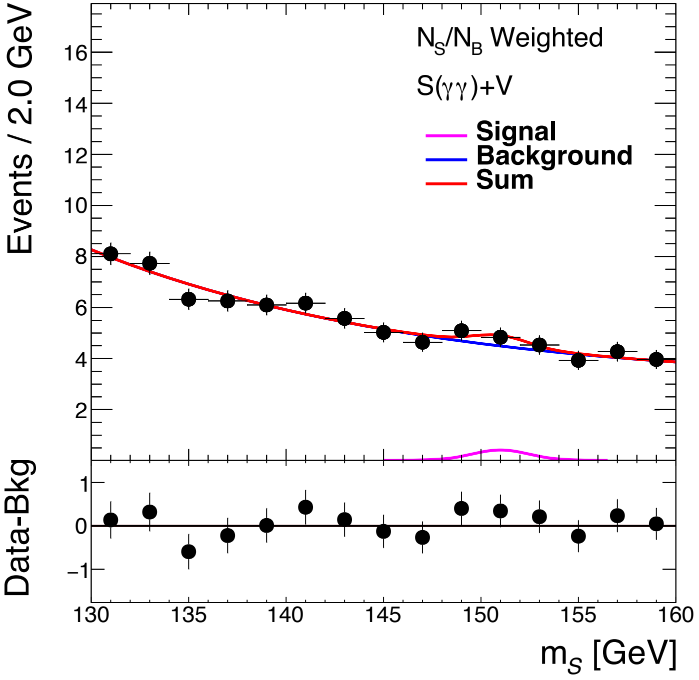


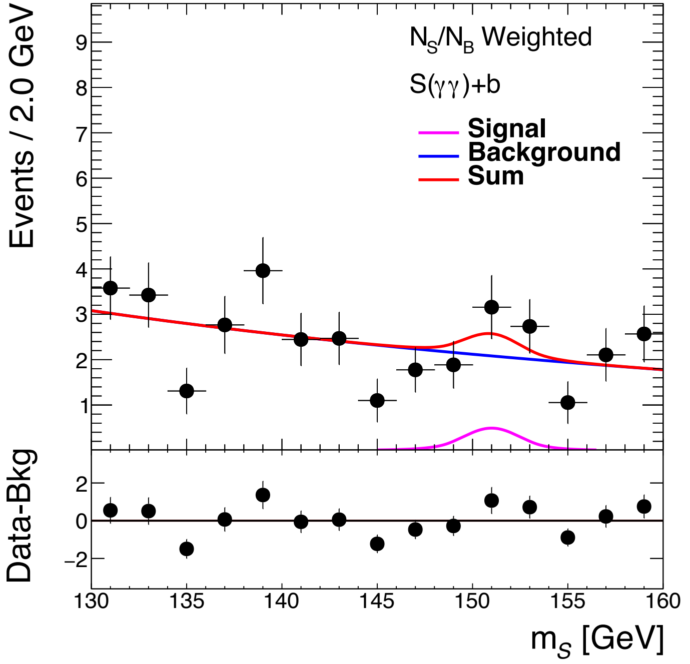
From Run 1 multi-lepton excesses model-dependent prediction of $m_s = 150 \pm 5$ GeV

A.Crivellin et al. https://arxiv.org/abs/2109.02650





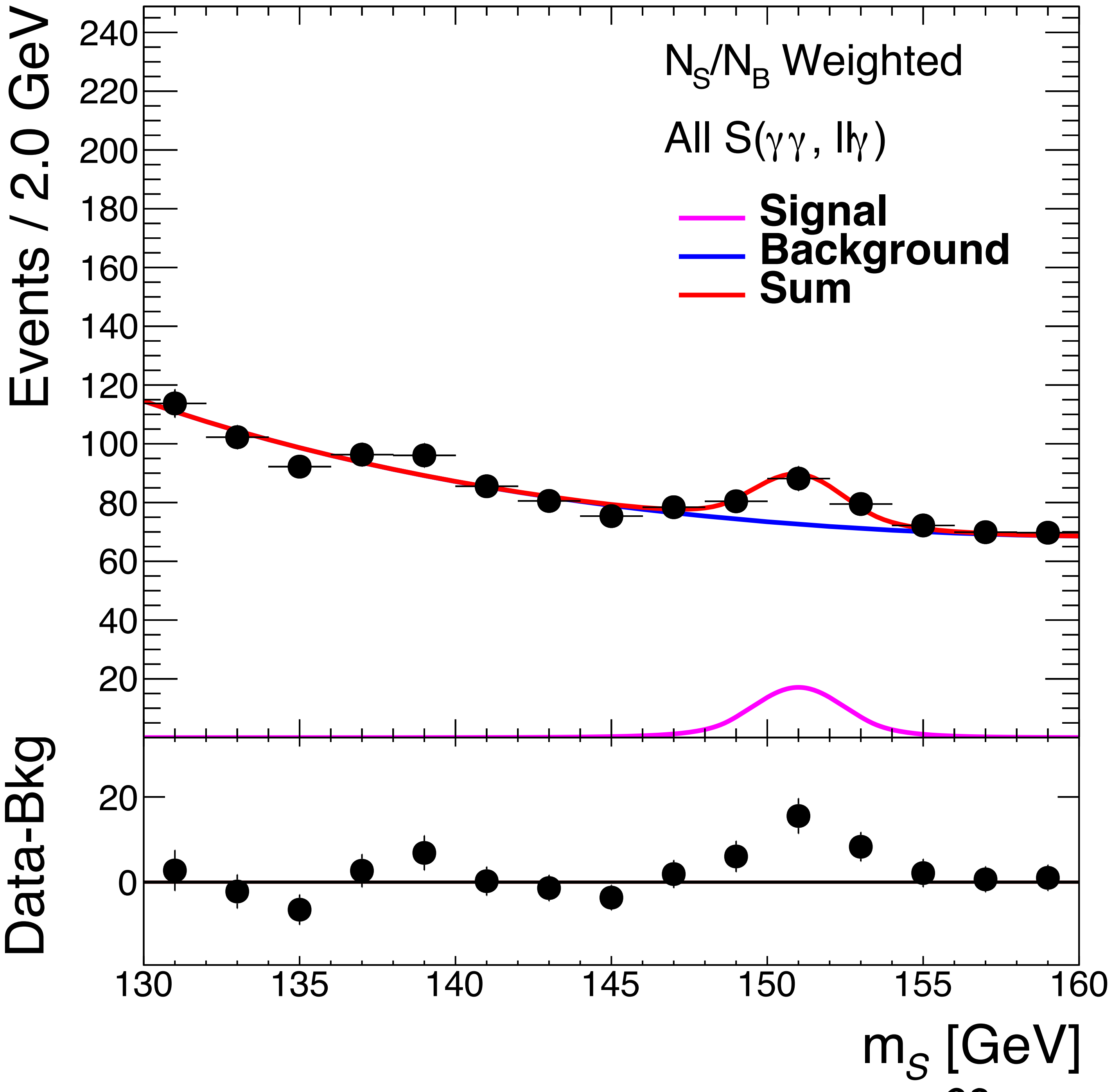




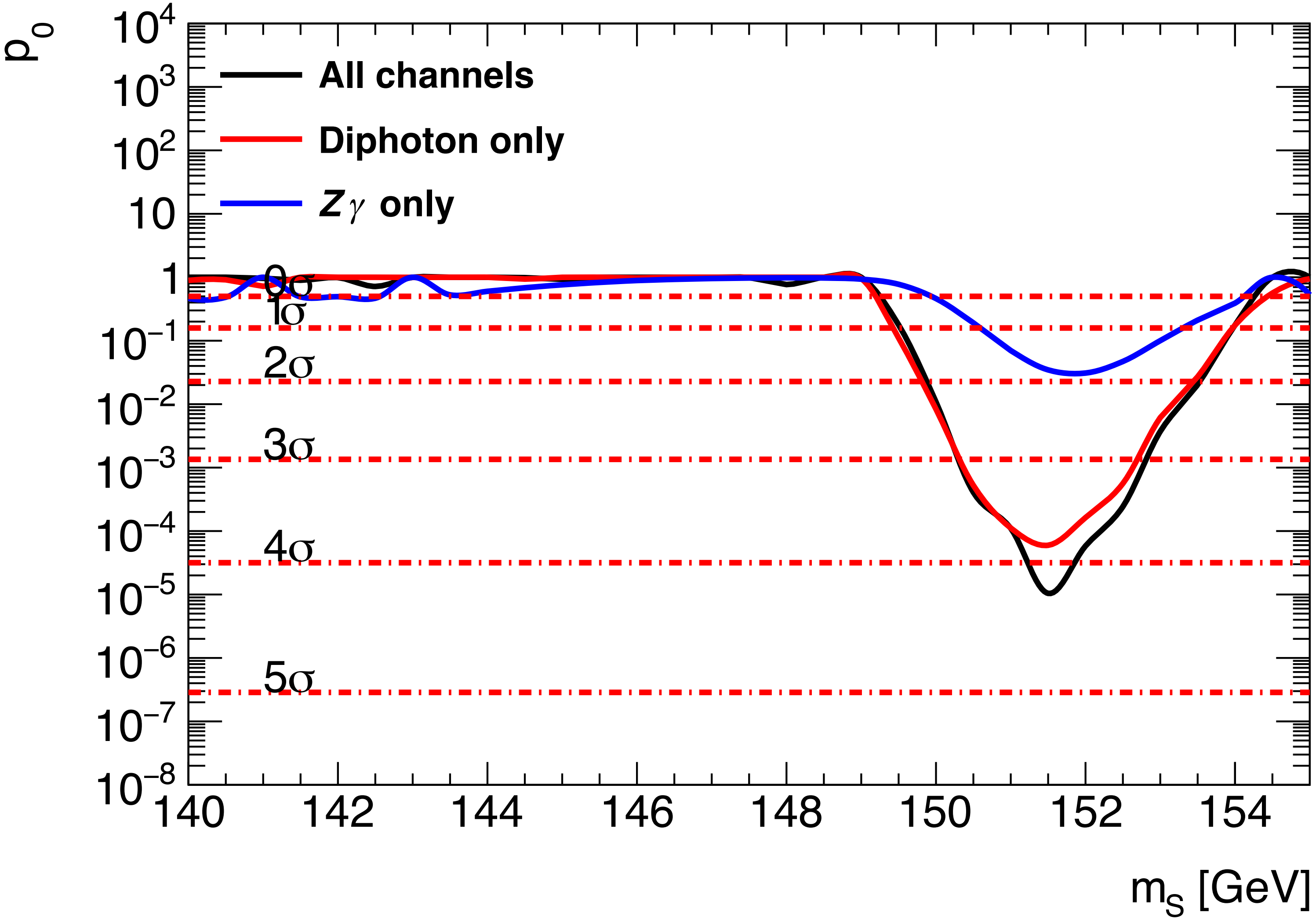
Analysis of publicly available $\gamma\gamma$, $Z\gamma$ spectra in associated production gives an excess at m_S=151.5 GeV.

Fiducial yields consistent with H→SS* hypothesis with m_H=270 GeV, which is used for the extraction of significance.

Excess not seen in S→ZZ→4l



Result is obtained with public results from the LHC experiments. Using a simplified model and two degrees of freedom and residual LEE global significance drops to 3.9σ at 151.5 GeV.



Available on the CERN CDS information server

CMS PAS HIG-20-013

CMS Physics Analysis Summary

https://cds.cern.ch/record/2803738/files/HIG-20-013-pas.pdf

Contact: cms-pag-conveners-higgs@cern.ch

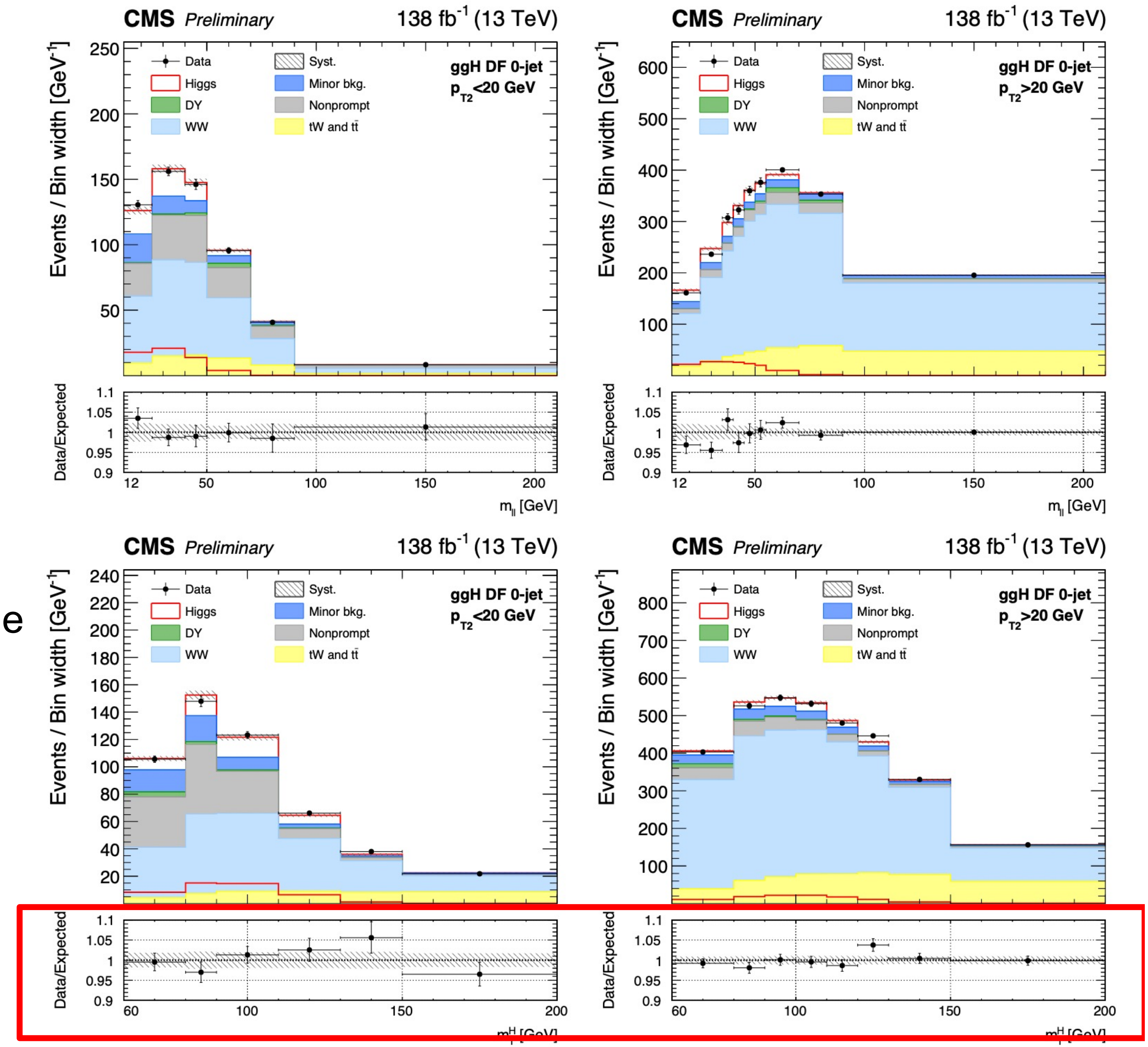
2022/03/11

Measurements of properties of the Higgs boson in the W boson pair decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Recently released h→WW→ll+MET analysis present discrepancy with the data.

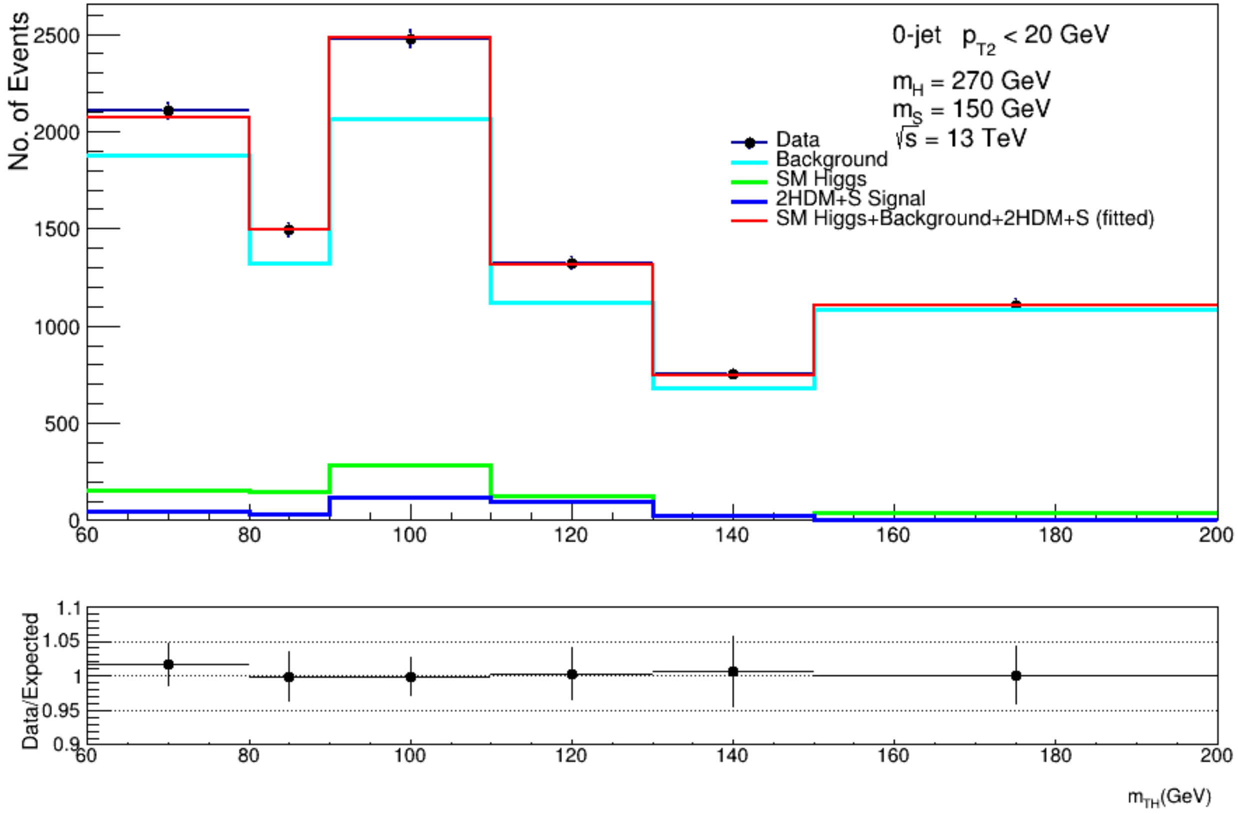
Here we to add H→SS*, with S→WW→ll+MET to the SM processes. Using the simplified model with the mass fixed at m_S=151 GeV

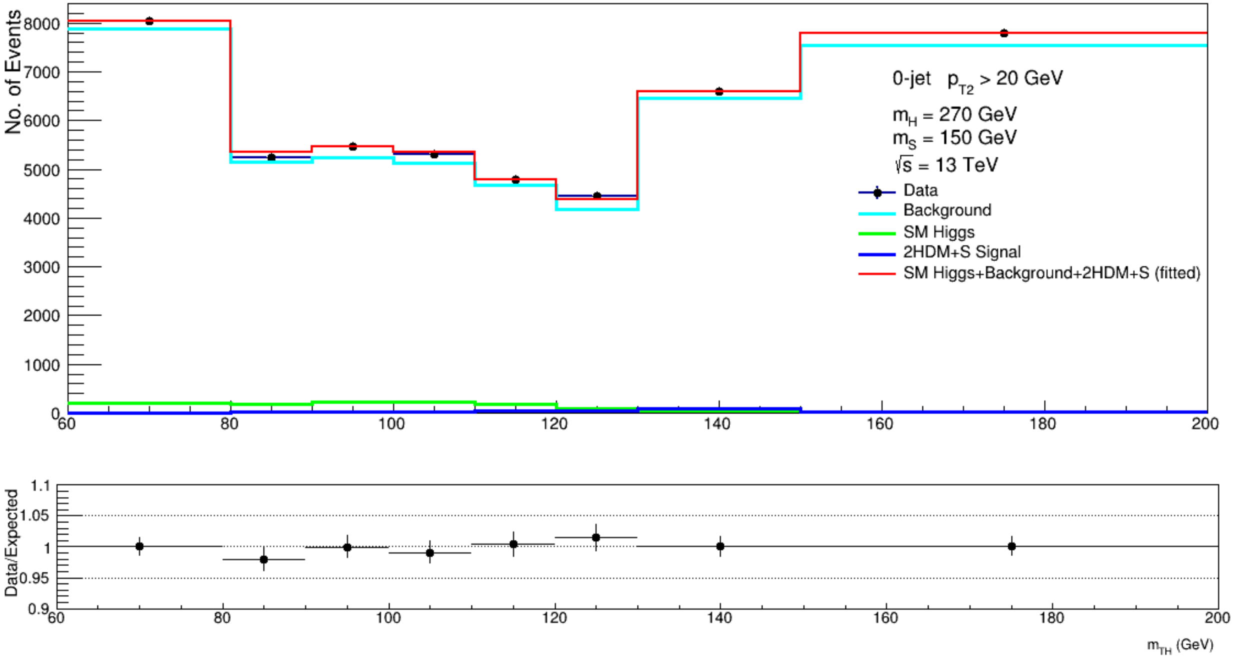


Here we to add H→SS*, with S→WW→ll+MET to the SM processes. Using the simplified model with the mass fixed at m_S=151 GeV

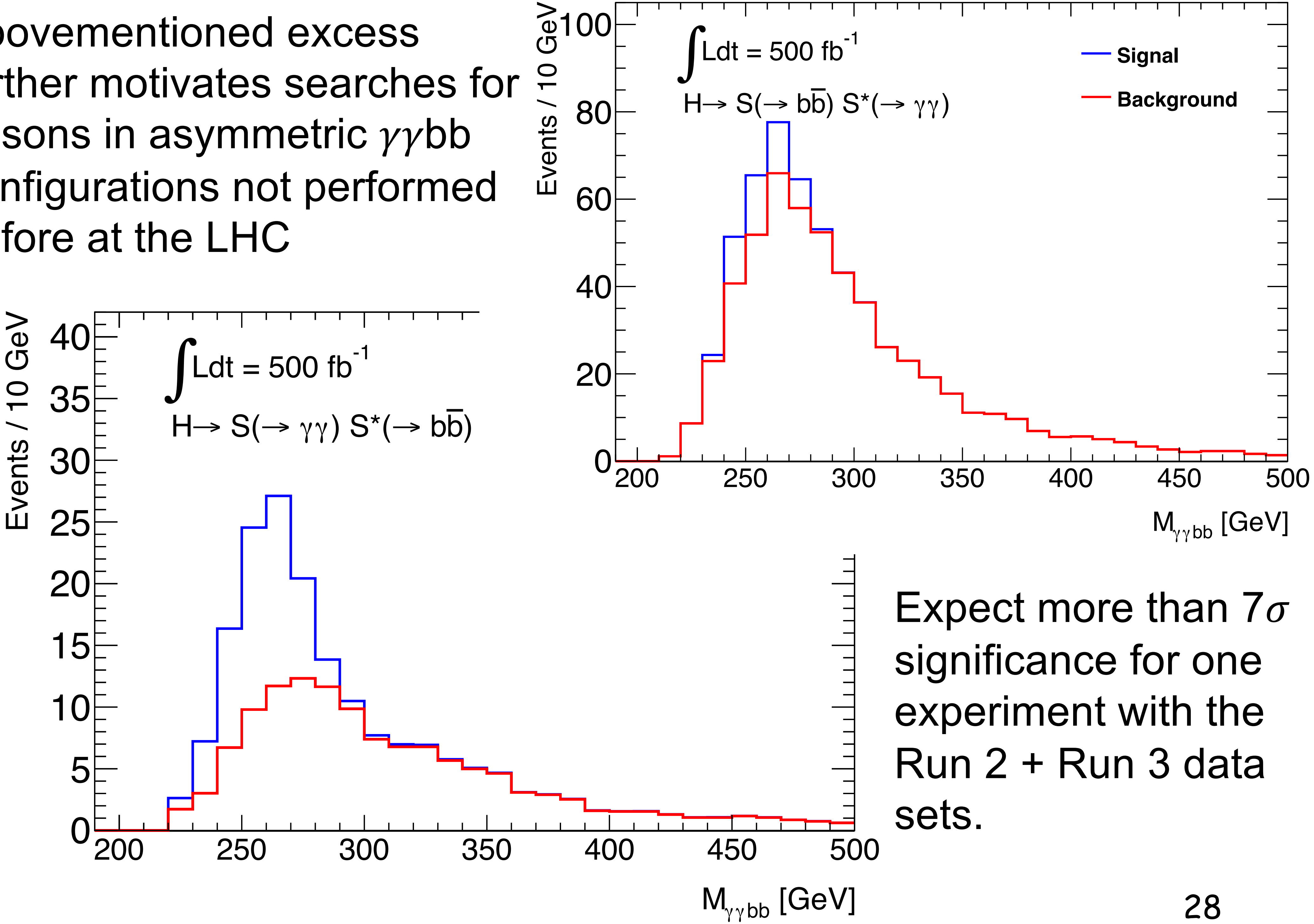
Extracted BSM signal strength consistent with the simplified model described above within statistical errors. Results point at somewhat higher jet-veto survival probability compared to the simplified model. This will be taken into account when performing combination with $\gamma\gamma$, $Z\gamma$ results described above

Global fits with ATLAS results in progress.





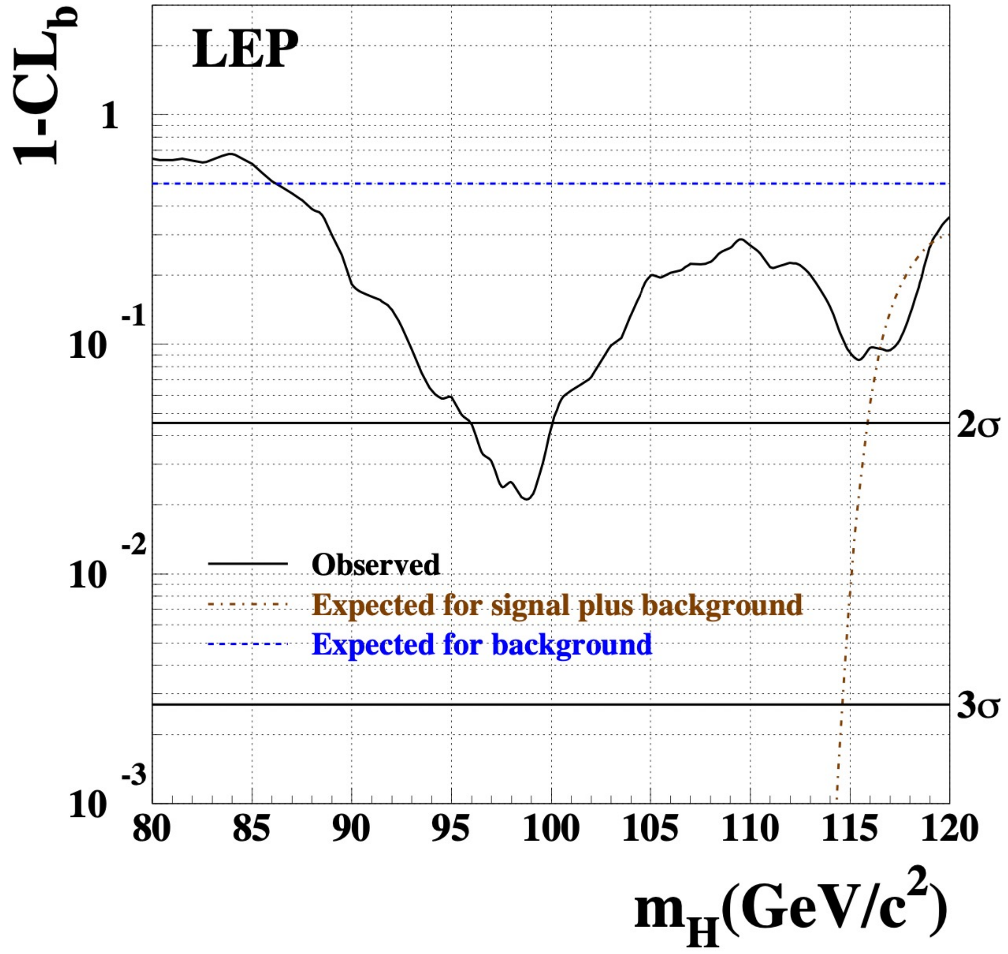
Abovementioned excess further motivates searches for bosons in asymmetric $\gamma\gamma$bb configurations not performed before at the LHC



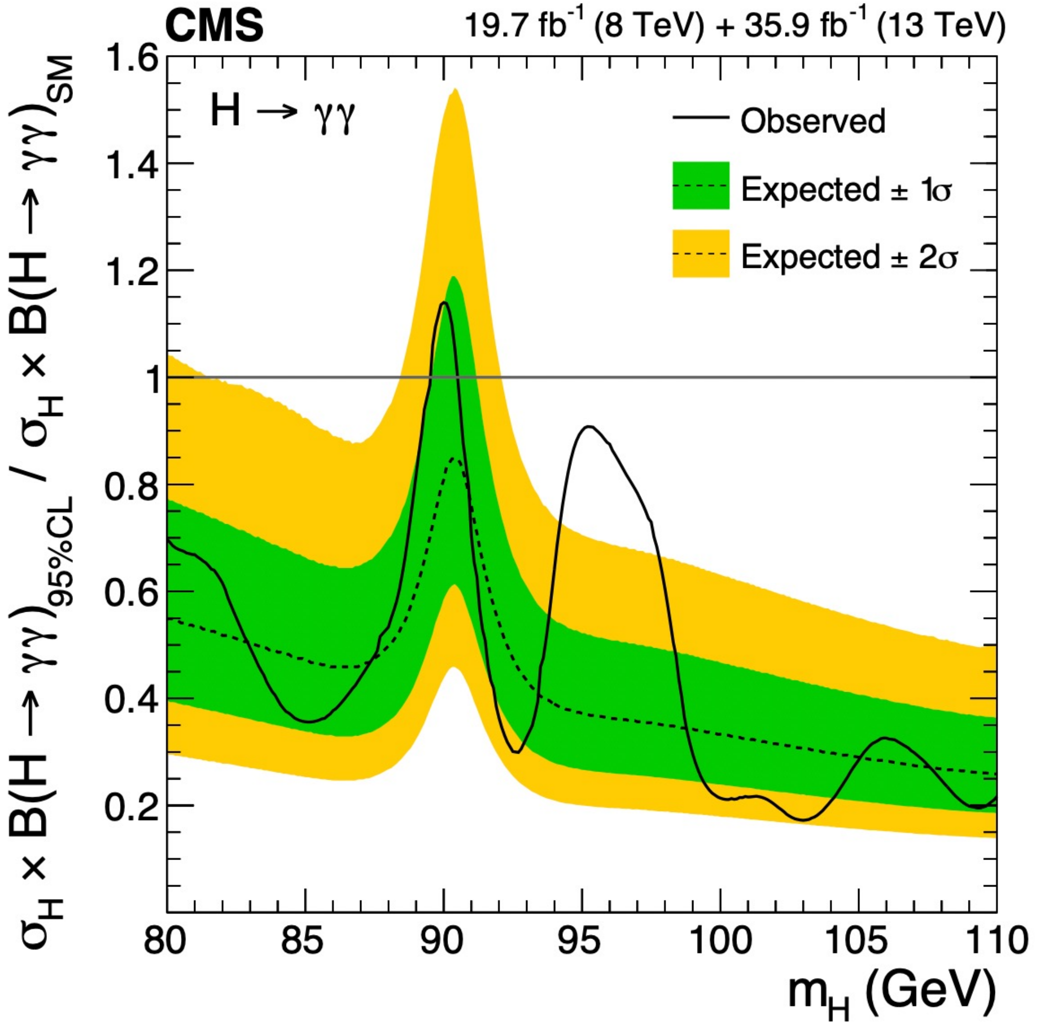
Expect more than 7σ significance for one experiment with the Run 2 + Run 3 data sets.

Some tantalizing results around 96 GeV from LEP and CMS, not contradicted by ATLAS. Interesting to see what the full Run 2 data set has to say. Further motivates asymmetric searches H→SS'…

LEP, Phys. Lett. B 565 (2003) 61–75



CMS, Phys. Lett. B 793 (2019) 320–347



Eur.Phys.J.C 82 (2022) 8, 665

Unveiling Hidden Physics at the LHC

Oliver Fischer[†,1], Bruce Mellado[†,2,3],
Stefan Antusch[4], Emanuele Bagnaschi[5], Shankha Banerjee[6], Geoff Beck[2],
Benedetta Belfatto[7,8], Matthew Bellis[9], Zurab Berezhiani[10,11], Monika
Blanke[12,13], Bernat Capdevila[14,15], Kingman Cheung[16], Andreas
Crivellin[5,6,17], Nishita Desai[18], Bhupal Dev[19], Rohini Godbole[20], Tao Han[21],
Philip Harris[22, 23], Martin Hoferichter[24], Matthew Kirk[25,26], Suchita
Kulkarni[27], Clemens Lange[28], Kati Lassila-Perini[29], Zhen Liu[30], Farvah
Mahmoudi[6,31], Claudio Andrea Manzari[5,17], David Marzocca[32], Biswarup
Mukhopadhyaya[33], Antonio Pich[34], Xifeng Ruan[2], Luc Schnell[35, 36], Jesse
Thaler[22, 23], and Susanne Westhoff[37]

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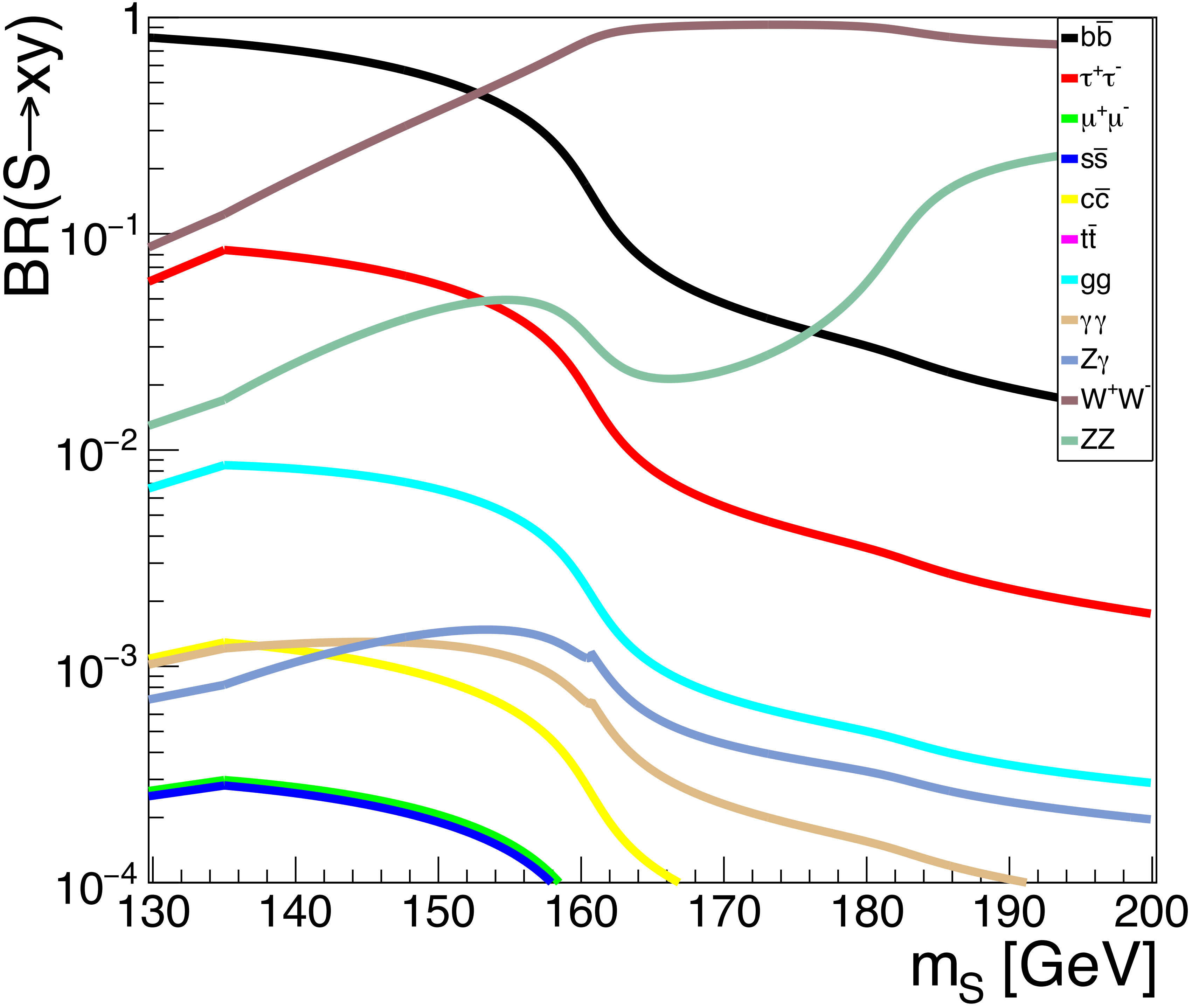
Outlook and Conclusions

- ☐ **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, WWW)**
    - **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**
- ☐ **Analysis of $\gamma\gamma$/Zγ spectra in associated production gives a large global excess around 151 GeV**
  - ☐ **Excess also appears in ll+MET trans. mass spectrum**
  - ☐ **Motivates H→SS*,Sh→$\gamma\gamma$bb searches, where asymmetric configurations play an important role**

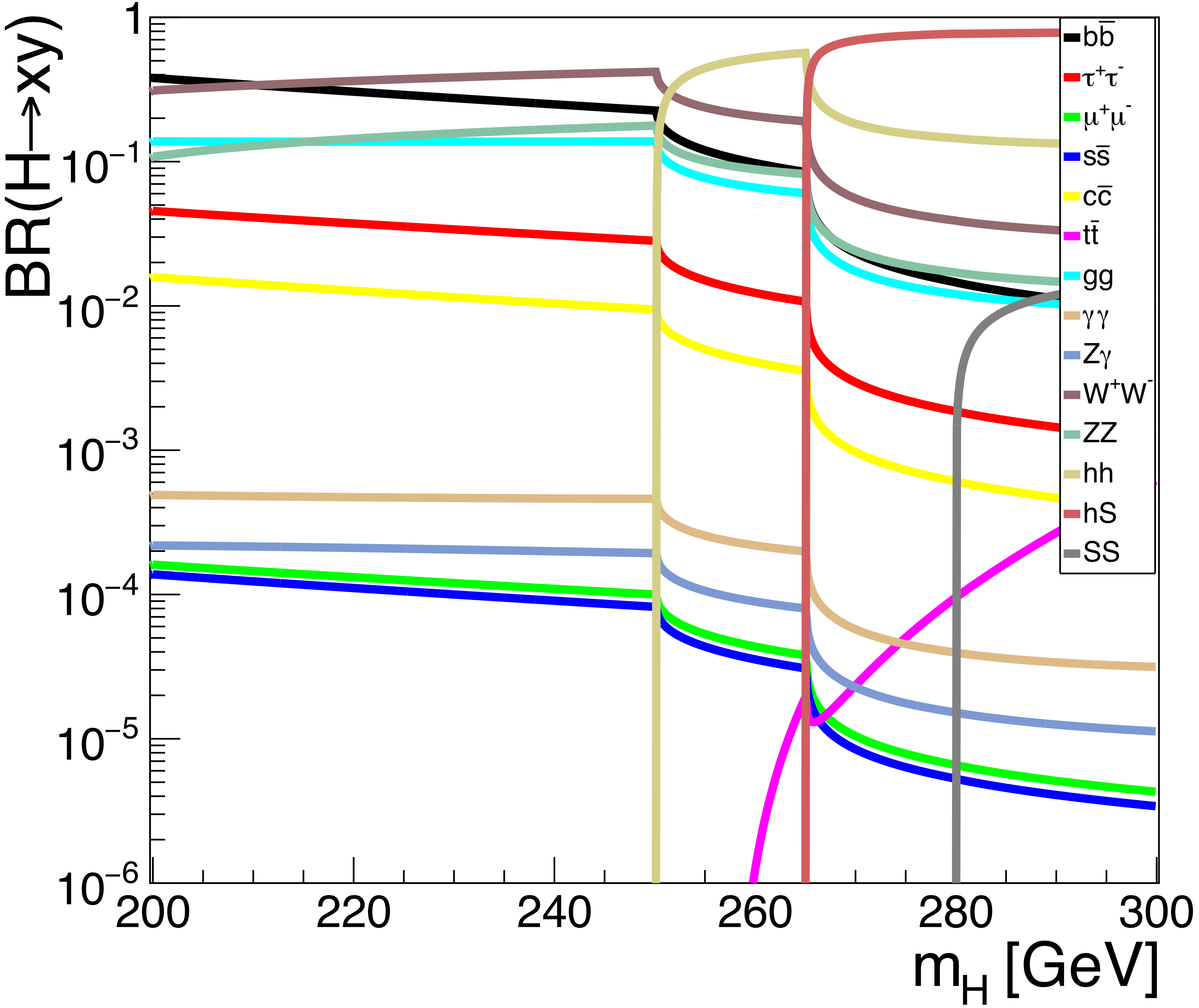
Additional Slides

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



J.Phys. G46 (2019) no.11, 115001

J.Phys. G46 (2019) no.11, 115001



Masses in the 2HDM+S

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

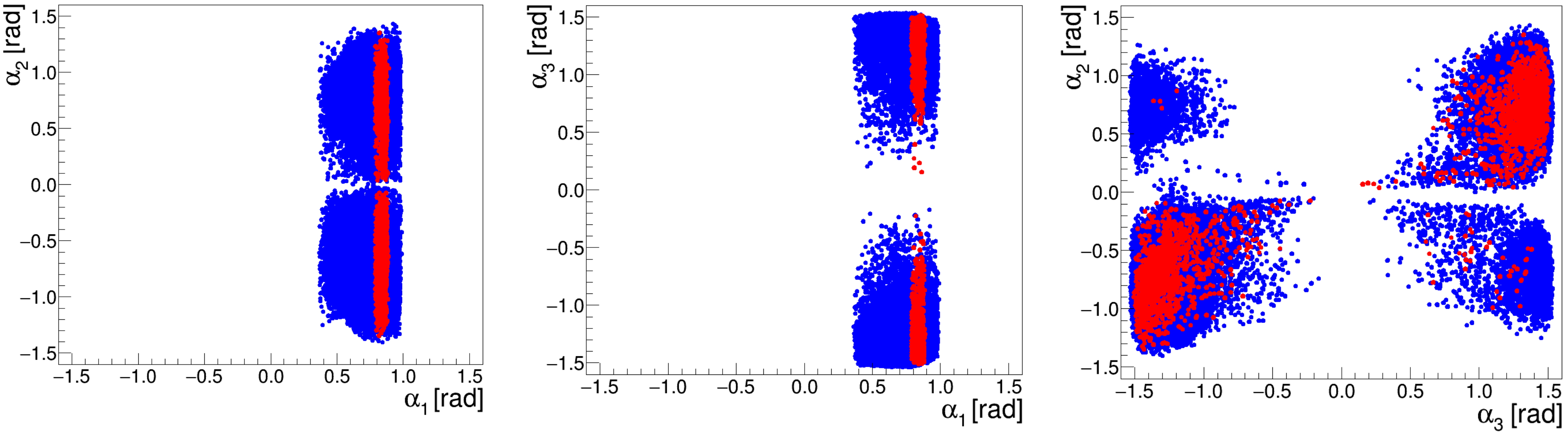
Mass-matrix for the CP-even scalar sector will modified with respect to 2HDM and that needs a 3 x3 matrix (three mixing angles). Couplings are modified.

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

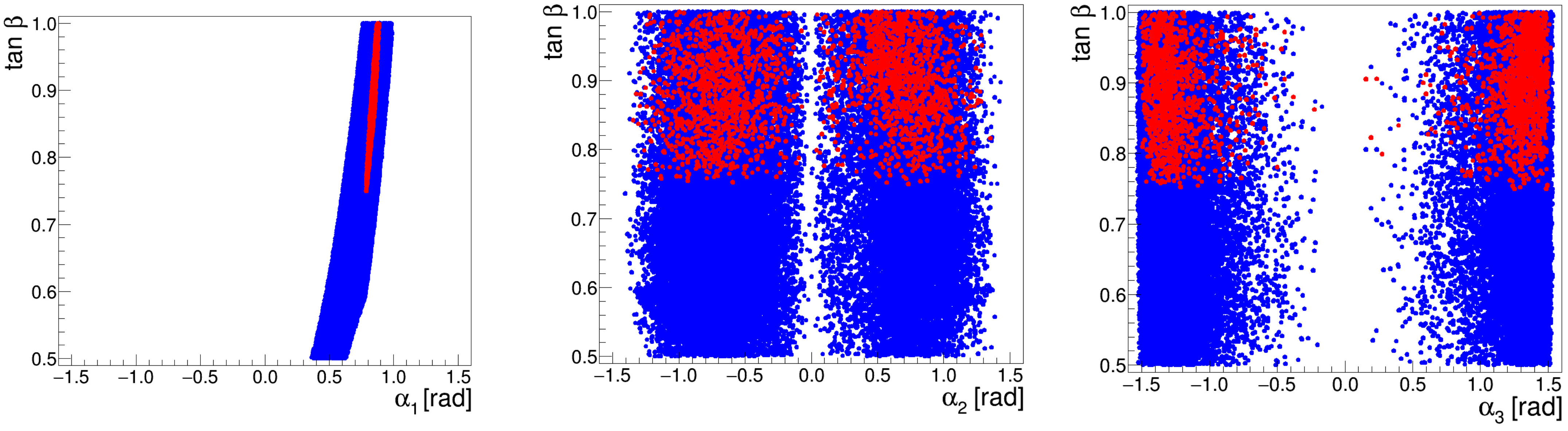
$$M^2_{\mathrm{CP-even}} = \begin{pmatrix} 2\lambda_1 v_1^2 - m_{12} \frac{v_2}{v_1} & m_{12} + \lambda_{345} v_1 v_2 & 2\kappa_1 v_1 v_S \\ m_{12} + \lambda_{345} v_1 v_2 & -m_{12} \frac{v_2}{v_1} + 2\lambda_2 v_2^2 & 2\kappa_2 v_2 v_S \\ 2\kappa_1 v_1 v_S & 2\kappa_2 v_2 v_S & \frac{1}{3}\lambda_S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

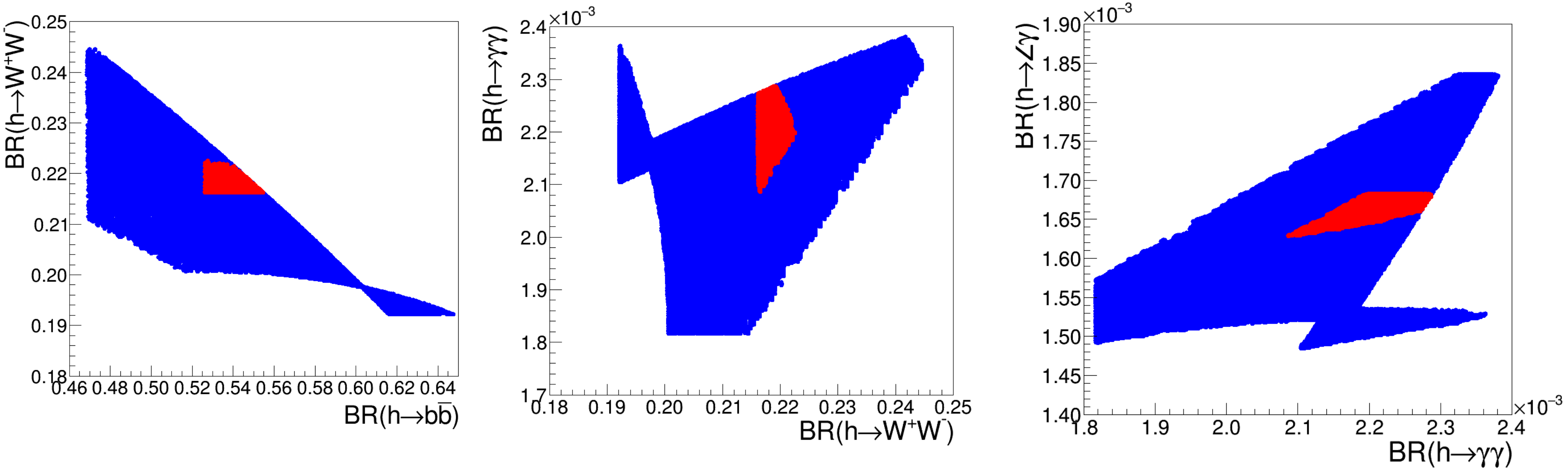
$$
\begin{aligned}
m_{H_1}^2 &= v_S \sin\alpha_2 \left[\lambda_7 v \cos\alpha_1 \cos\alpha_2 \cos\beta + \lambda_8 v \sin\alpha_1 \cos\alpha_2 \sin\beta + \lambda_6 v_S \sin\alpha_2\right], \\
m_{H_2}^2 &= (\cos\alpha_1 \cos\alpha_3 - \sin\alpha_1 \sin\alpha_2 \sin\alpha_3) \Big[\cos\alpha_1 \cos\alpha_2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

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 $\tan^2\beta$)

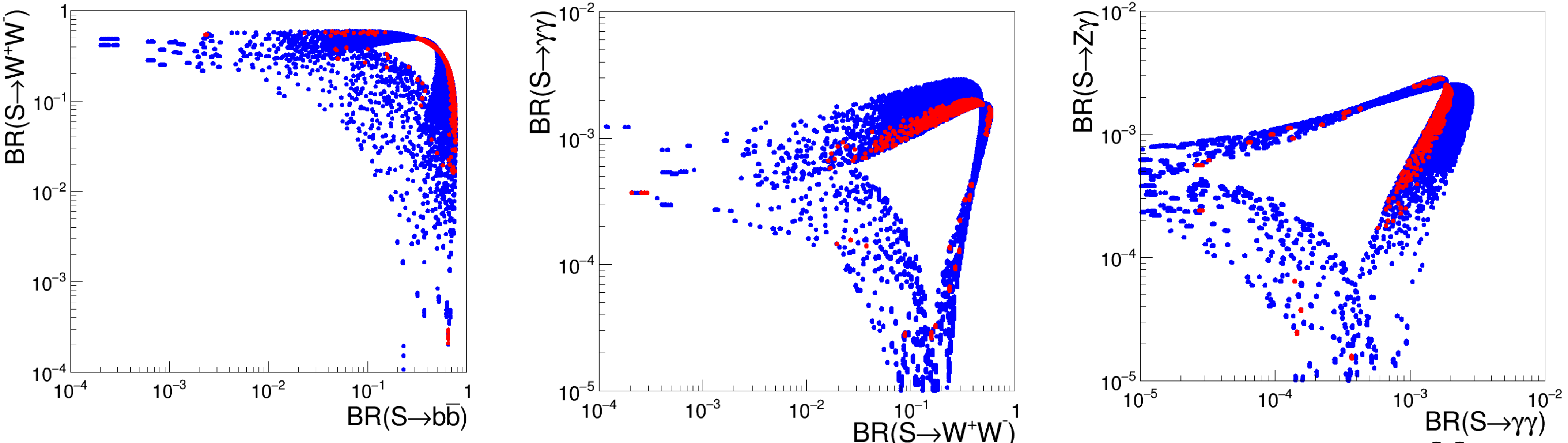


Correlation plots for the three mixing angles and tanβ. Blue (red) points correspond to Br(h→SM) within 10% (20%) of the SM h values (J.Phys. G46 (2019) no.11, 115001)





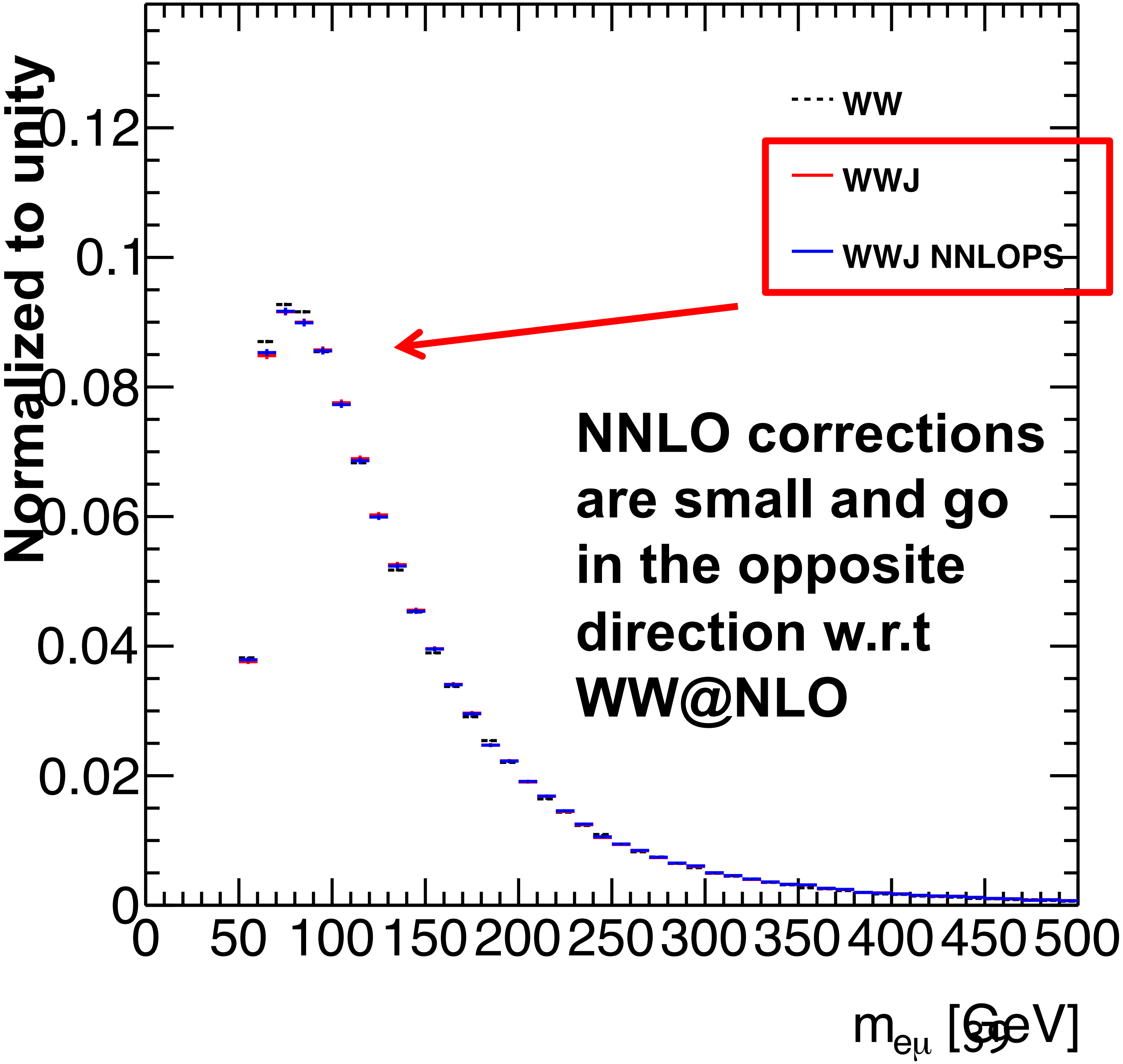
Results using N2HDECAY (arXiv:1612.01309) for one benchmark point



Impact of NNLO QCD in WW

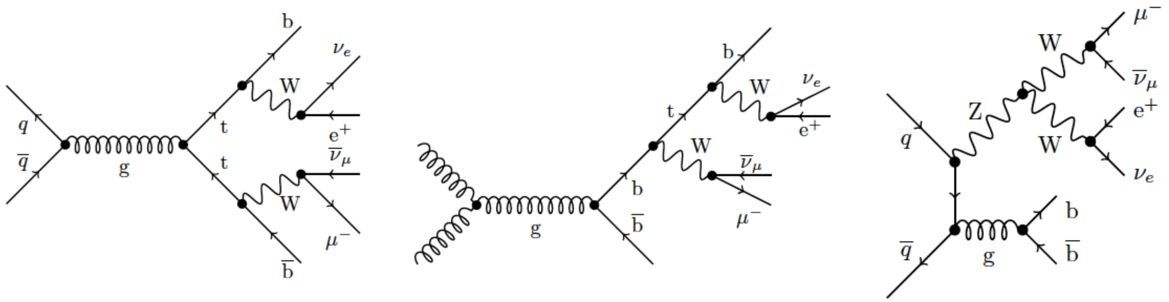
The NNLO QCD corrections shift the m_{ll} spectrum towards larger values.

The discrepancy becomes larger in the region of interest with m_{ll}<100 GeV

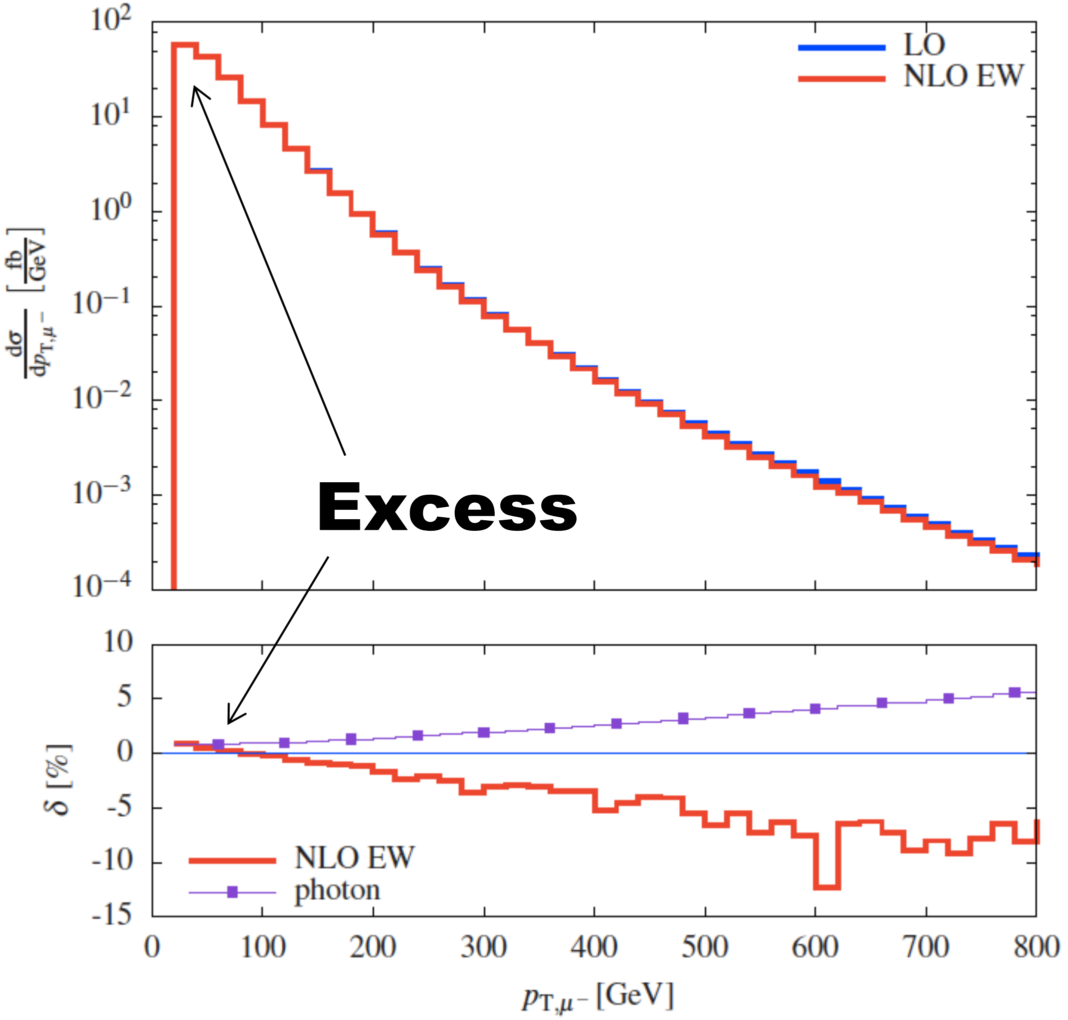


NNLO corrections are small and go in the opposite direction w.r.t WW@NLO

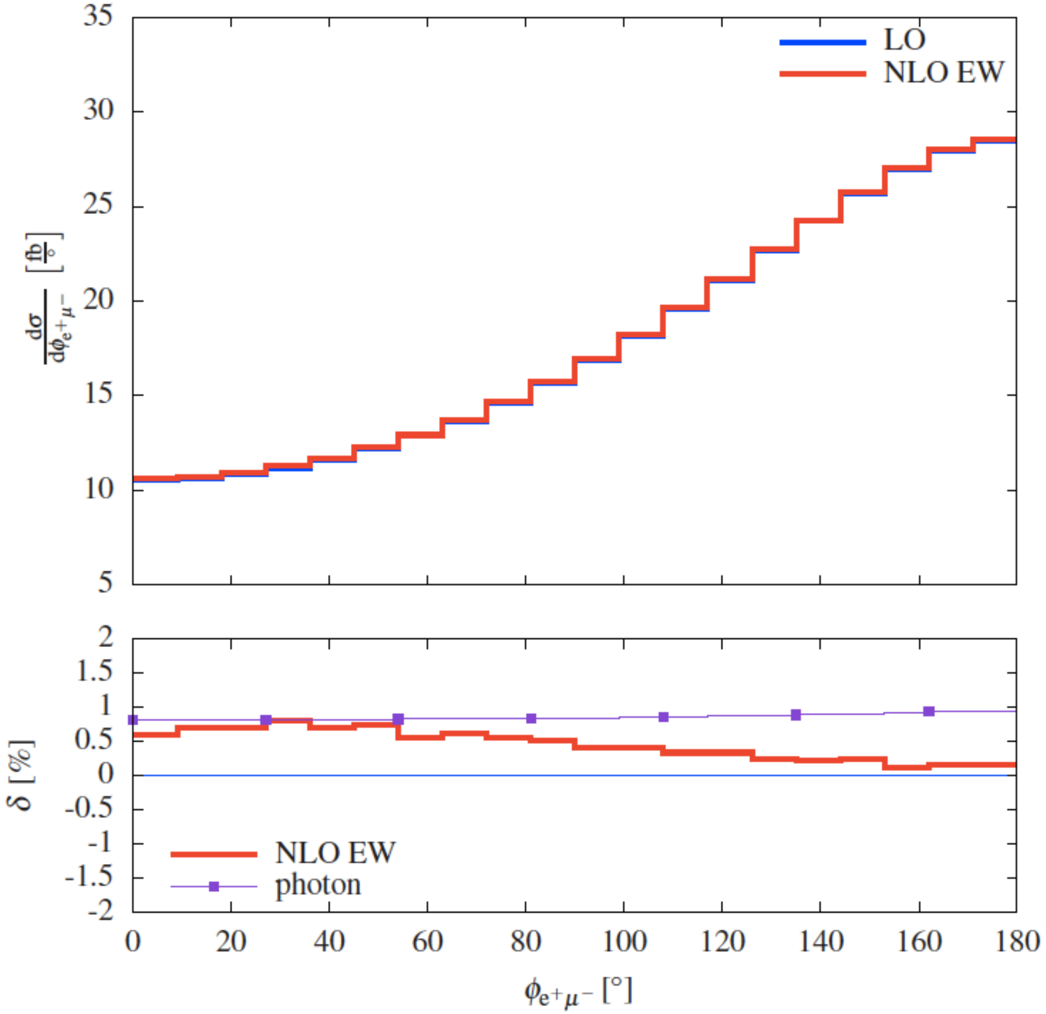
A.Denner, M.Pellen, arXiv:1607.05571



EW corrections are important at high p_T due to Sudakov logarithms. Effect is less than 1% for m_{ll}<100 GeV, where discrepancies are seen.



Excess



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.

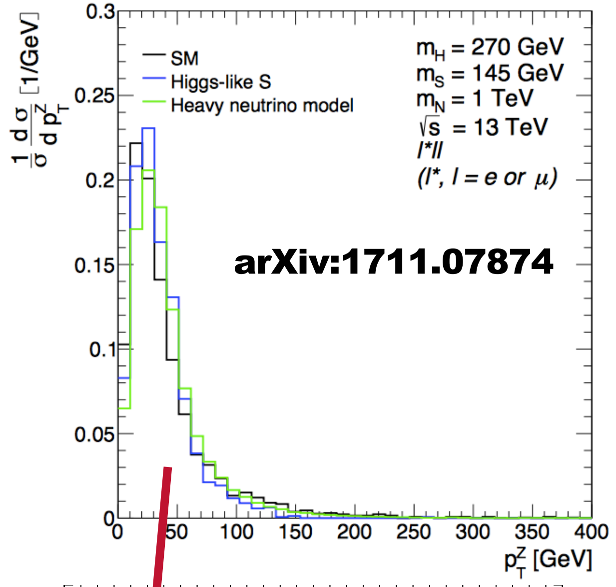
Functional form of luminosity and its variations (not necessary for us).

Functional form of systematic variation with nuisance parameter αp.

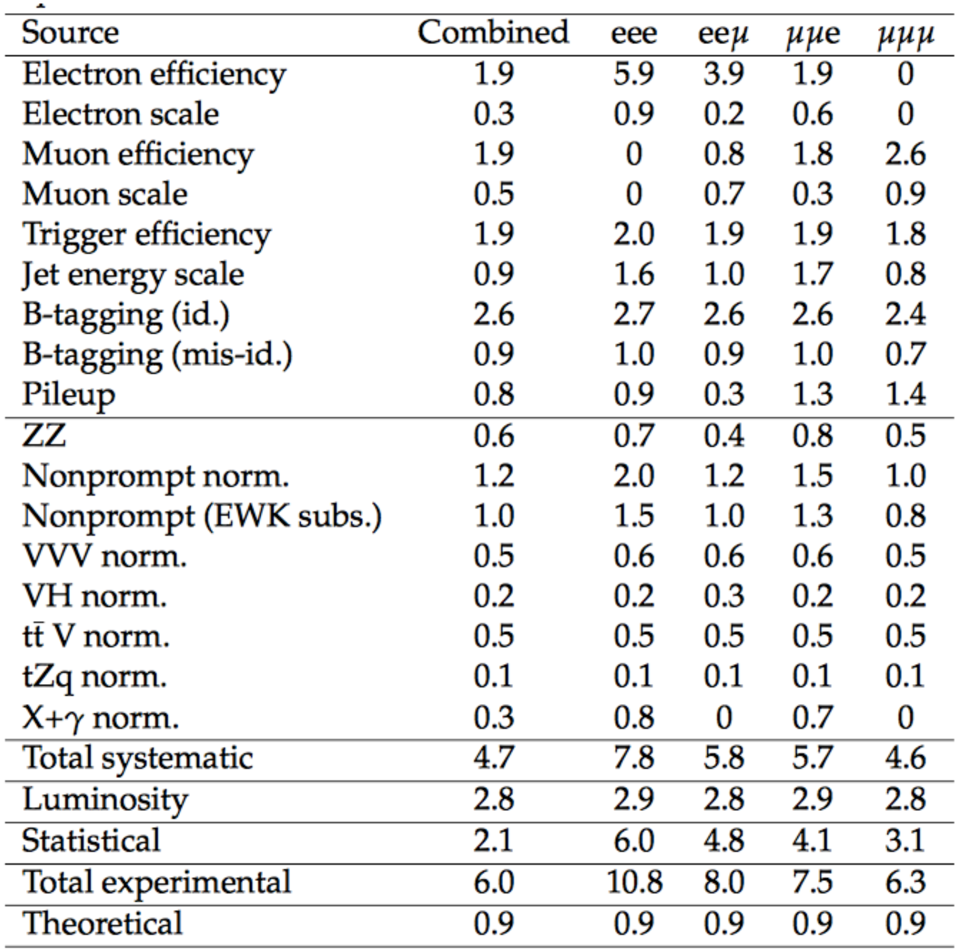
3l with Z→ll (ZW cross-section)

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 %

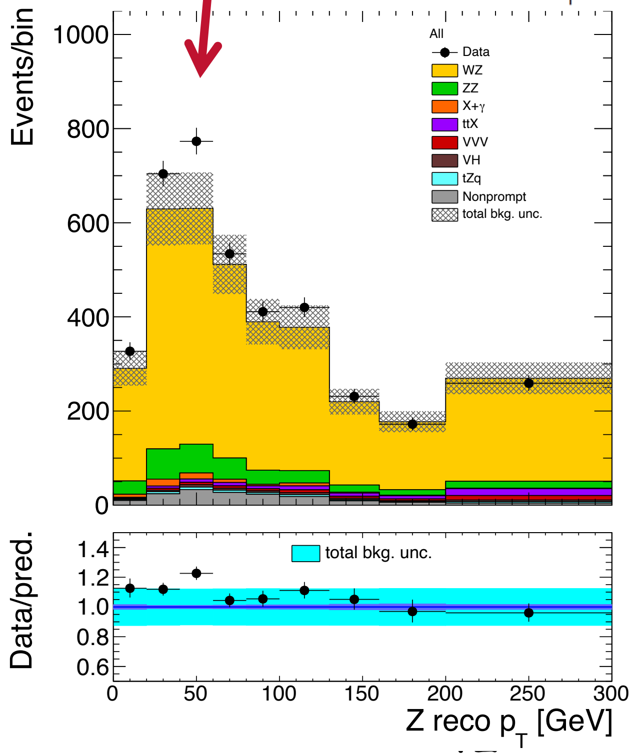


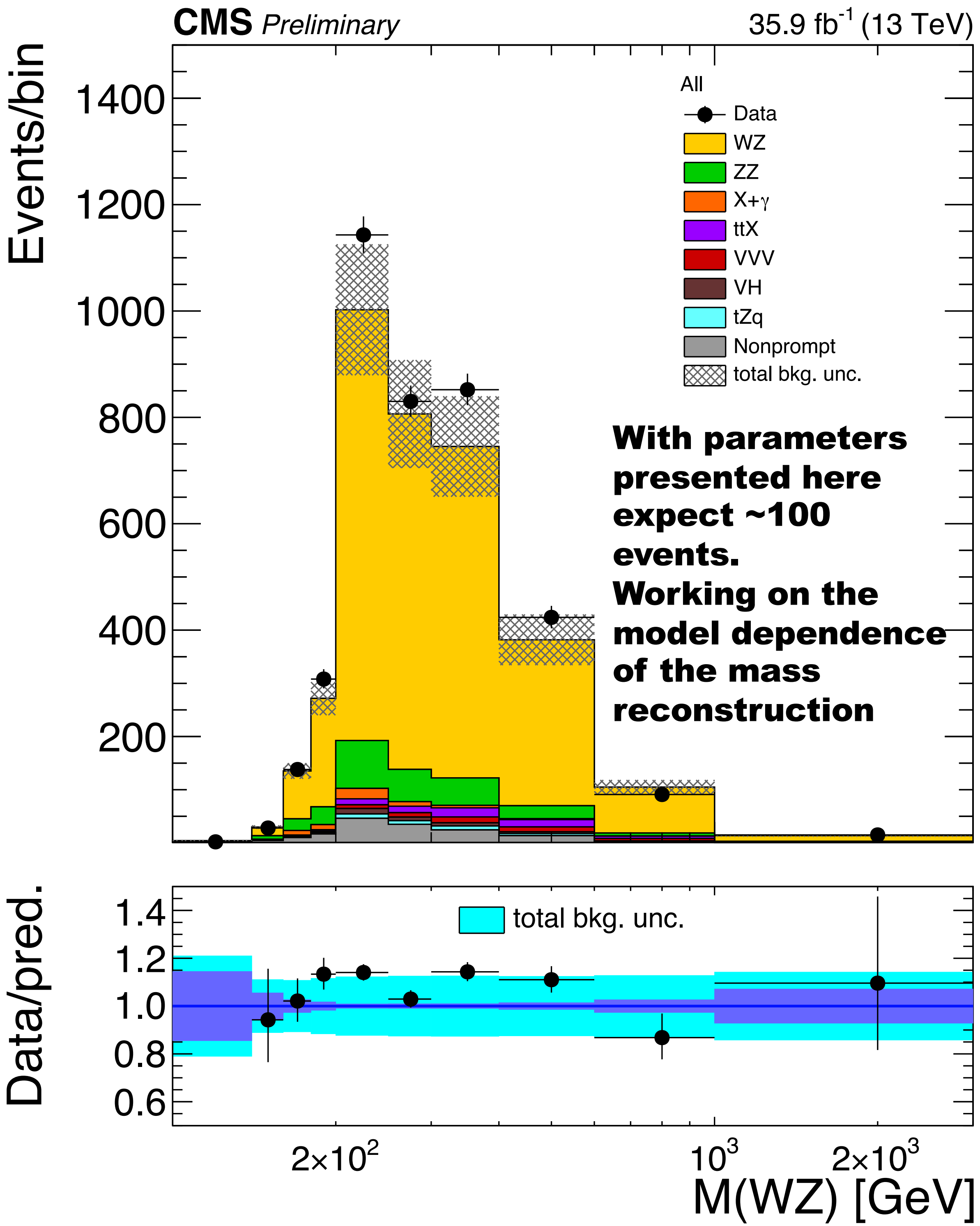
arXiv:1711.07874



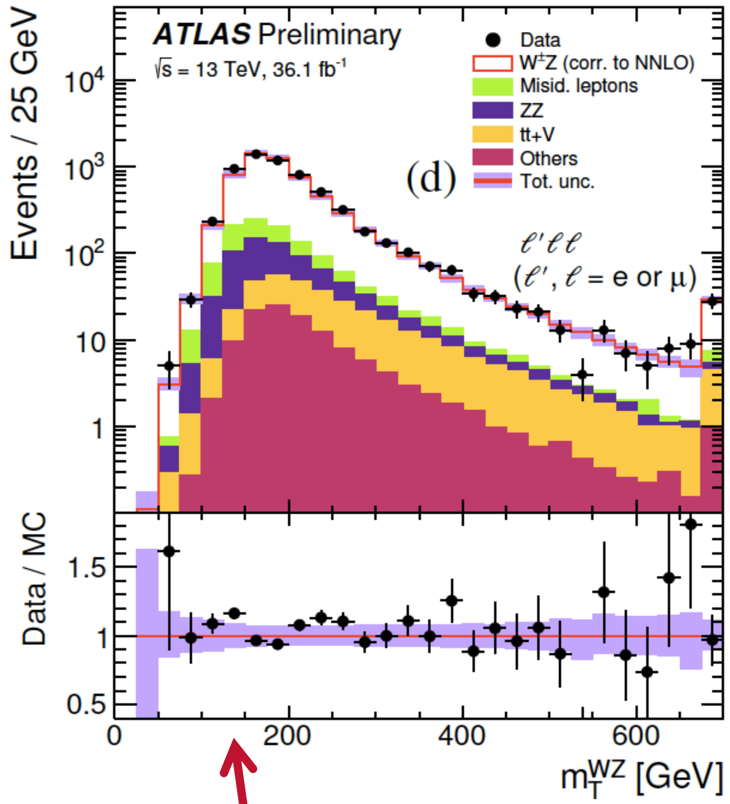
Source	Combined	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$
Electron efficiency	1.9	5.9	3.9	1.9	0
Electron scale	0.3	0.9	0.2	0.6	0
Muon efficiency	1.9	0	0.8	1.8	2.6
Muon scale	0.5	0	0.7	0.3	0.9
Trigger efficiency	1.9	2.0	1.9	1.9	1.8
Jet energy scale	0.9	1.6	1.0	1.7	0.8
B-tagging (id.)	2.6	2.7	2.6	2.6	2.4
B-tagging (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

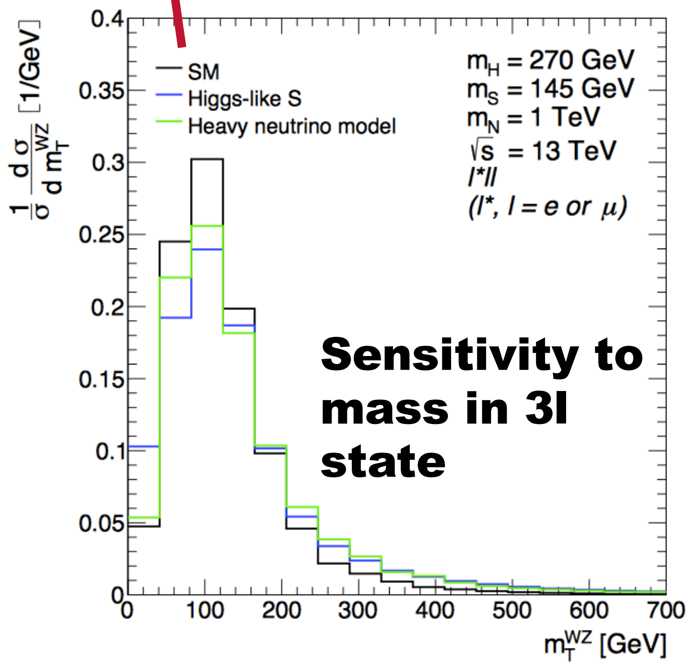




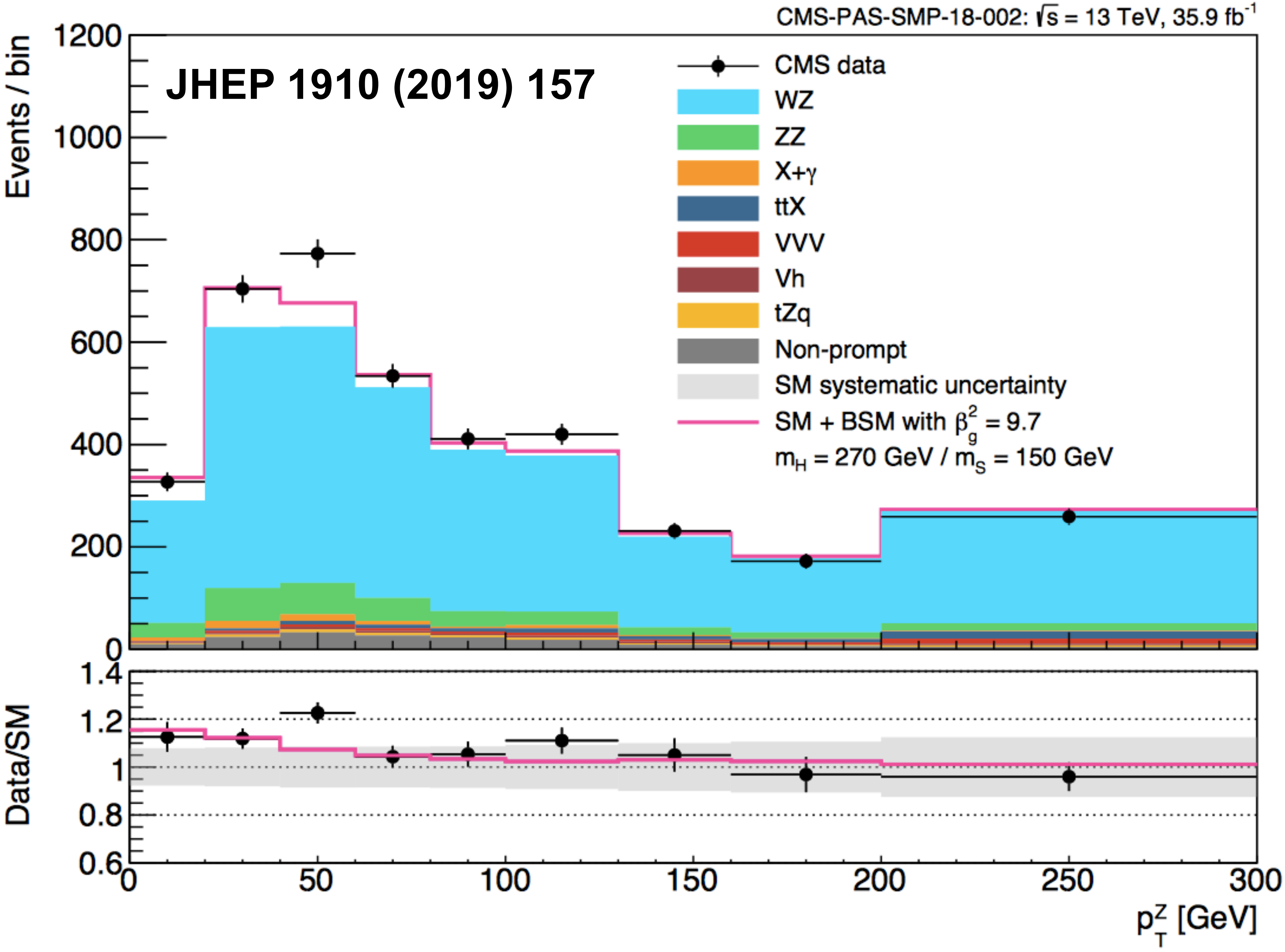
With parameters presented here expect ~100 events.
Working on the model dependence of the mass reconstruction

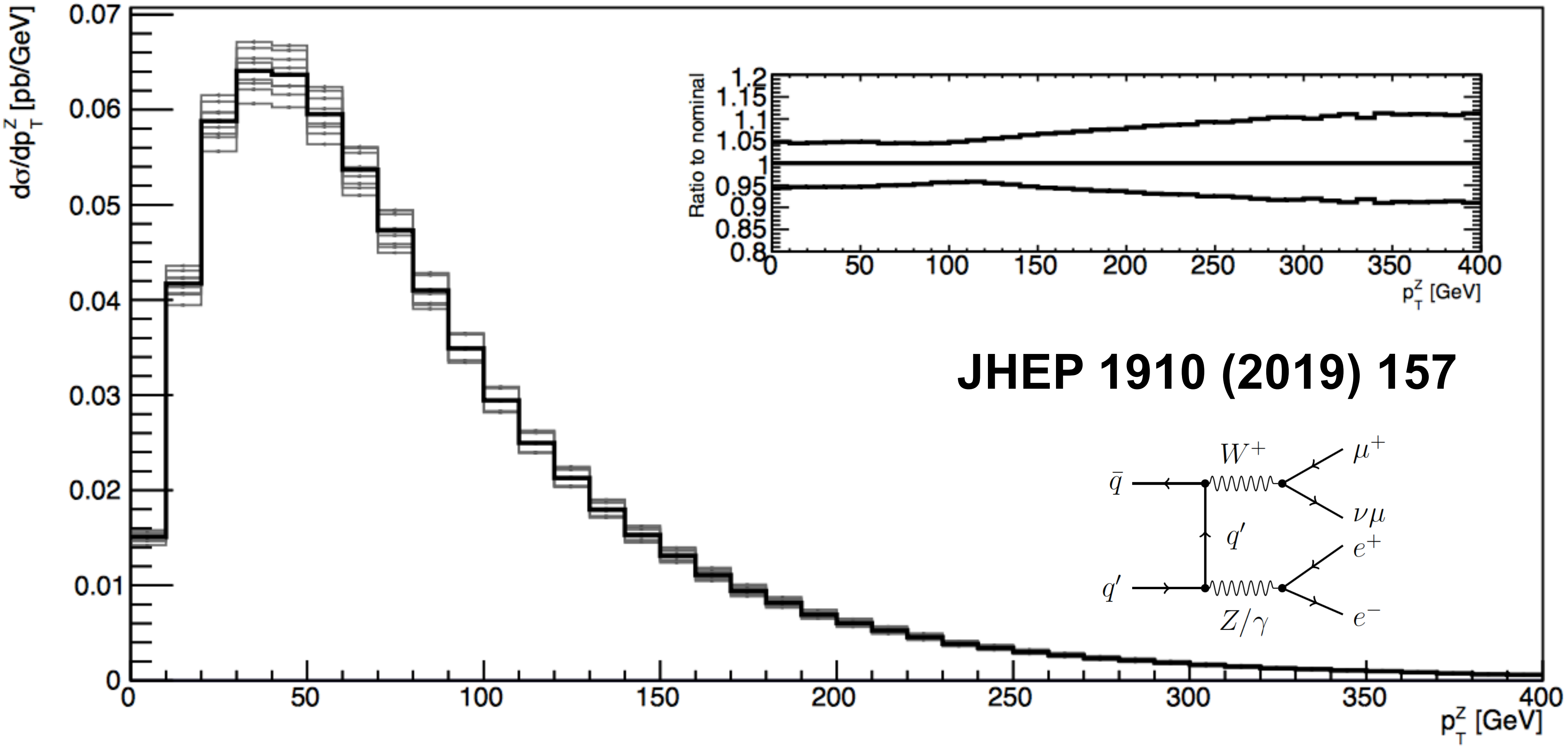


arXiv:1711.07874



Sensitivity to mass in 3l state


CMS-PAS-SMP-18-002: $\sqrt{s}$ = 13 TeV, 35.9 fb^{-1}
JHEP 1910 (2019) 157
Events / bin
1200
1000
800
600
400
200
0
CMS data
WZ
ZZ
X+γ
ttX
VVV
Vh
tZq
Non-prompt
SM systematic uncertainty
SM + BSM with β_g^2 = 9.7
m_H = 270 GeV / m_S = 150 GeV
Data/SM
1.4
1.2
1
0.8
0.6
0
50
100
150
200
250
300
p_T^Z [GeV]



JHEP 1910 (2019) 157

Figure 10: The effects of scale variations in the differential cross section of the SM WZ process as a function of the Z p_T. Here, `aMC@NLO` and `Pythia 8` were used to generate the events. The thick black line represents the spectrum at the nominal scale, and each grey line is a variation of the scale. The insert shows the maximum and minimum relative deviations for all scale variations.

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 $\beta_g^2 = 0$ corresponds to the SM-only hypothesis**

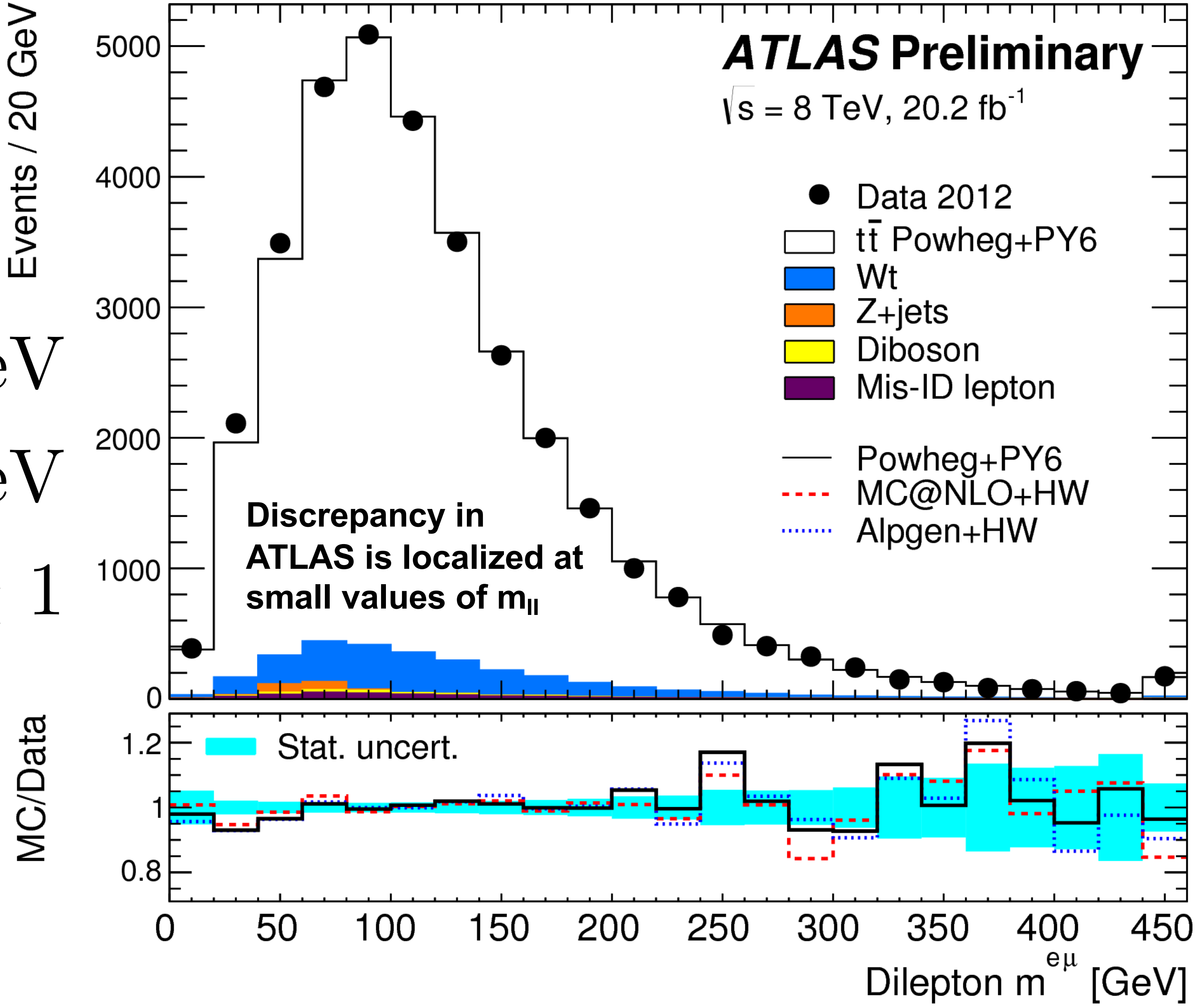
Eur. Phys. J. C 77 (2017) 804

Is the discrepancy due to ttbar events?

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

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

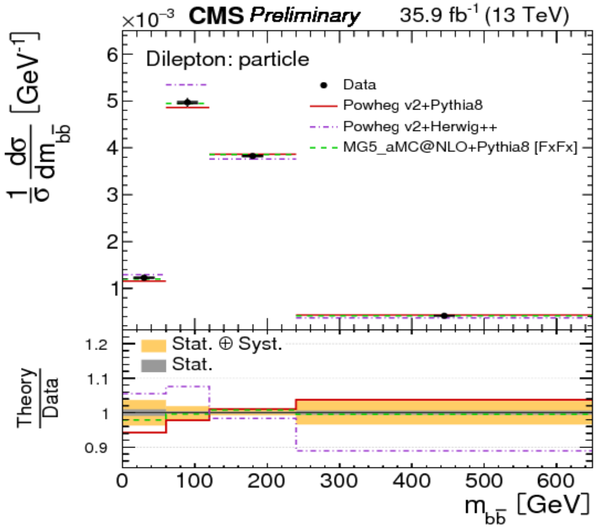
$$N_{bjet} \geq 1$$

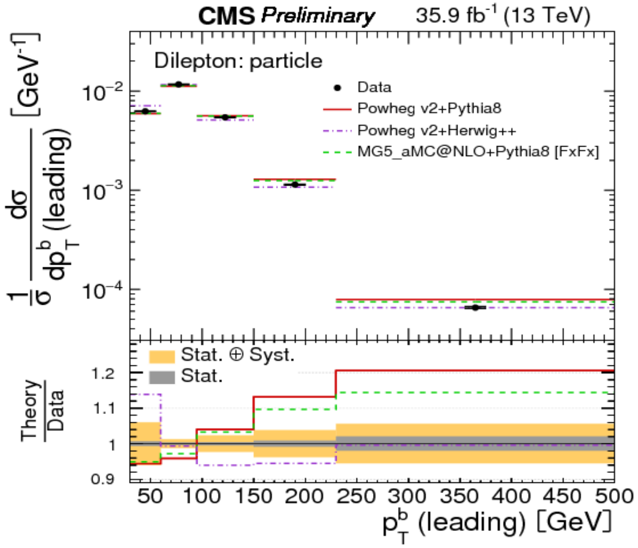


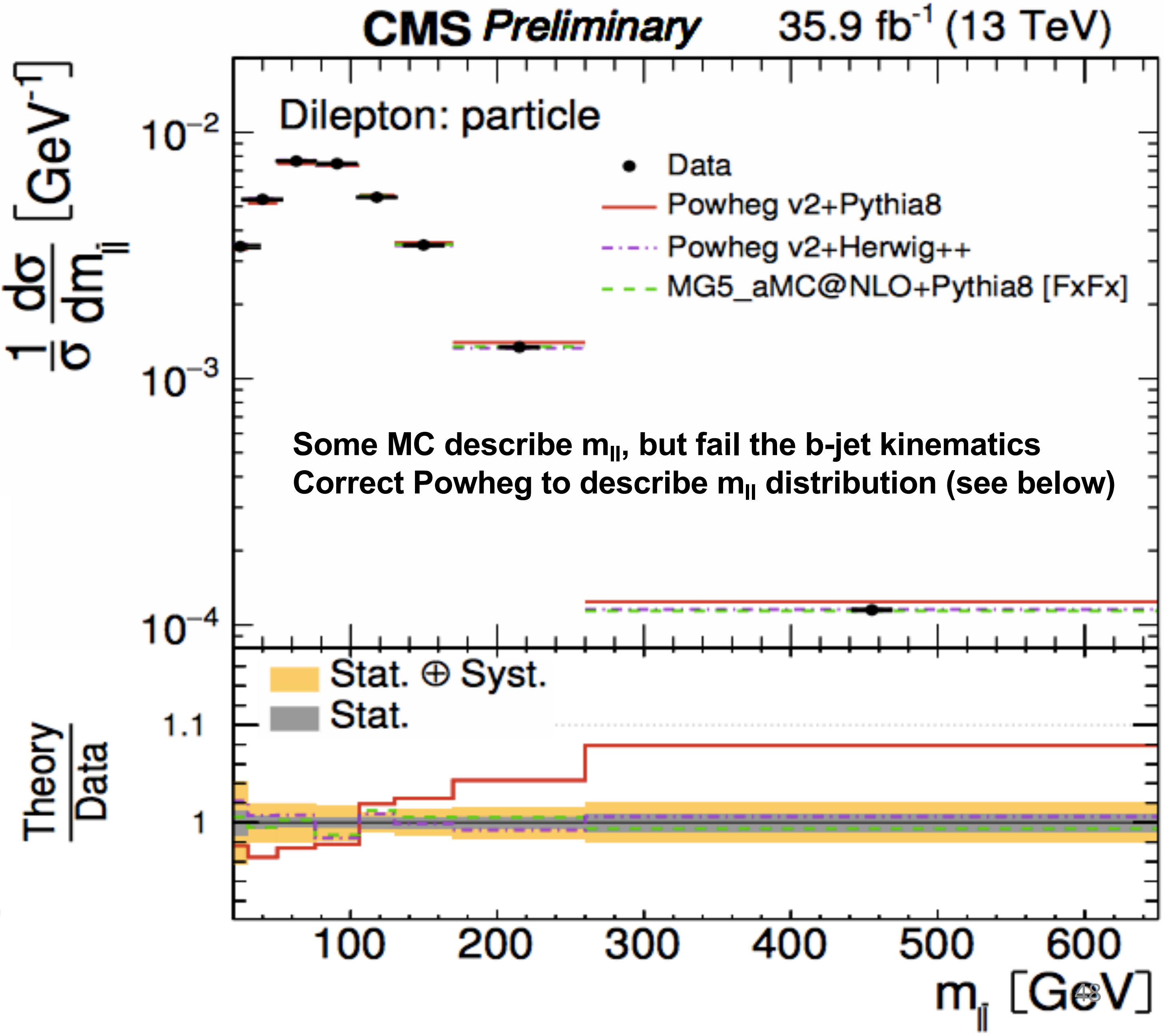
Discrepancy in ATLAS is localized at small values of m_{ll}

CMS PAS TOP-17-014

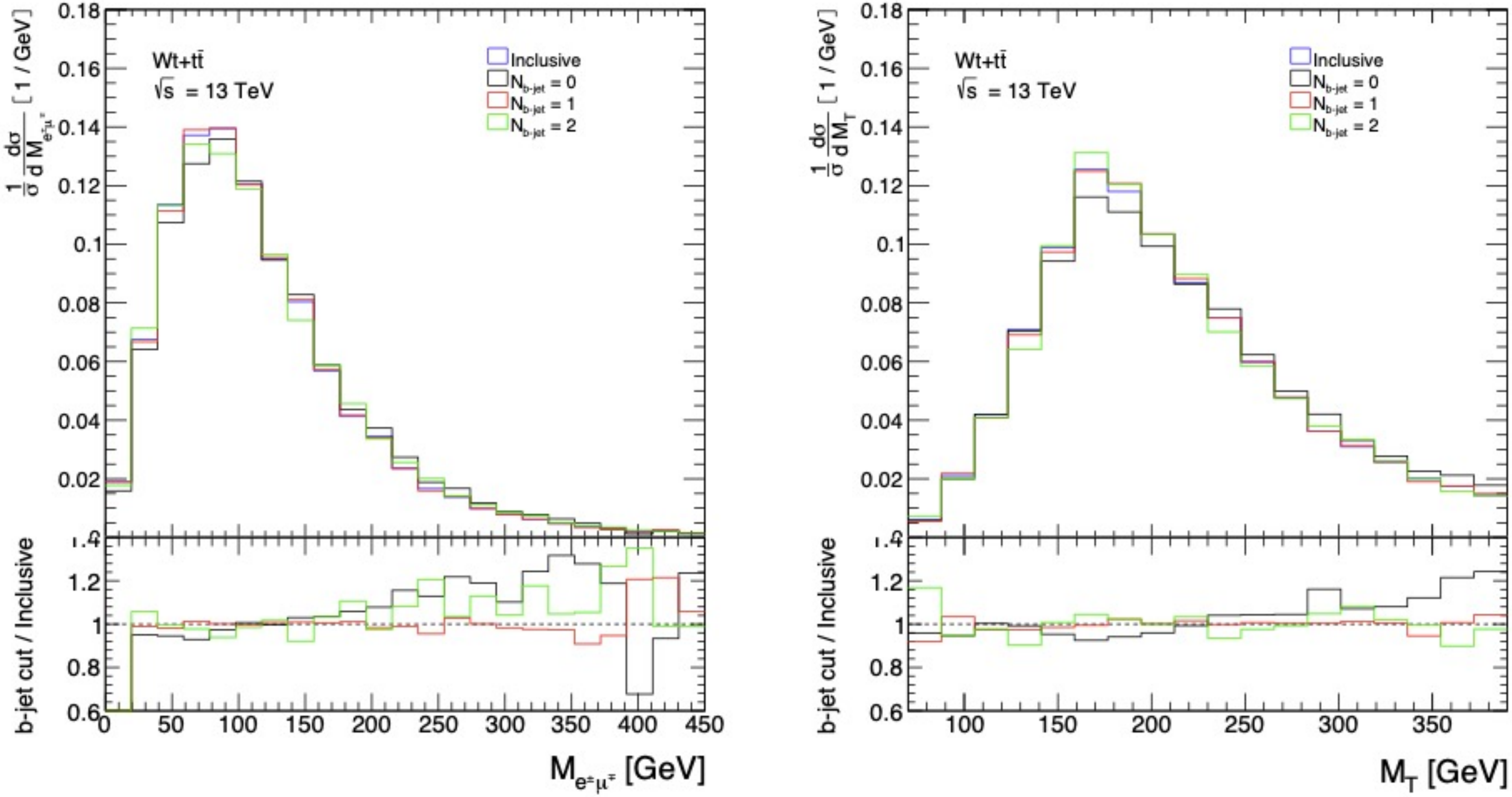
Event selection with exactly two leptons (e,μ), m_{ll}>20 GeV and at least 2b-jets







Some MC describe m_{ll}, but fail the b-jet kinematics
Correct Powheg to describe m_{ll} distribution (see below)



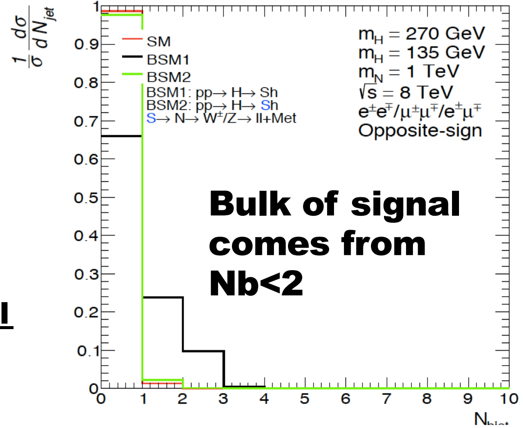
b-jet multiplicity is robust theoretically

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

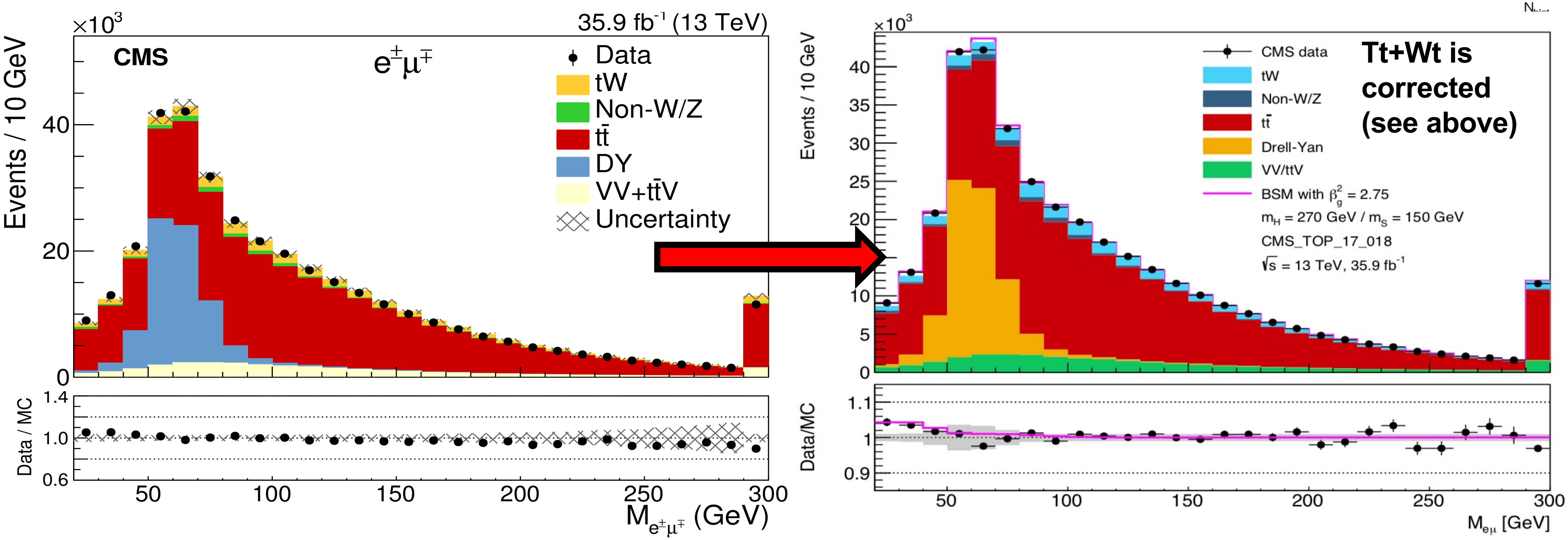
CMS-TOP-17-018; CERN-EP-2018-074

- 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



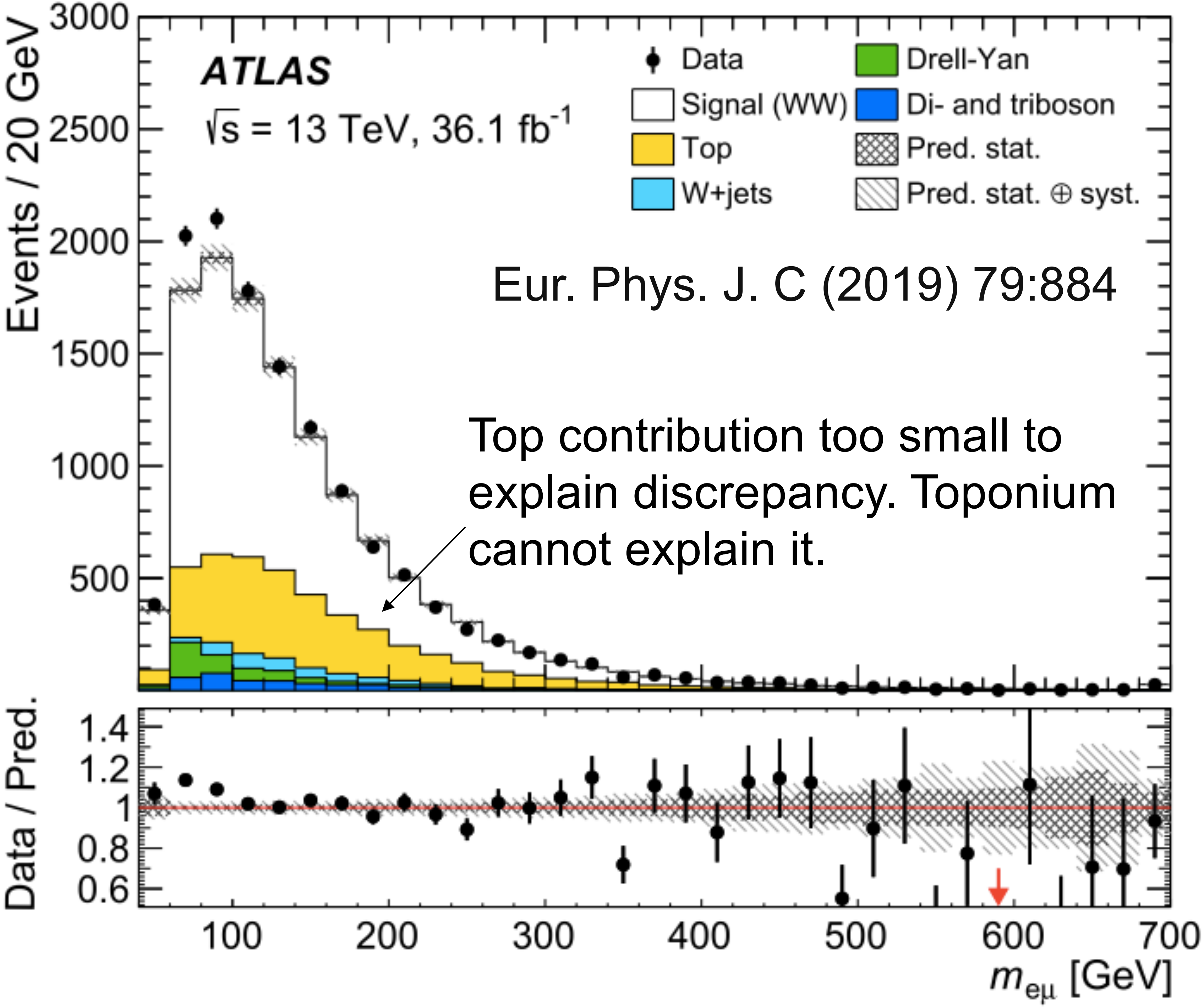
Bulk of signal comes from Nb<2

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



Tt+Wt is corrected (see above)

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



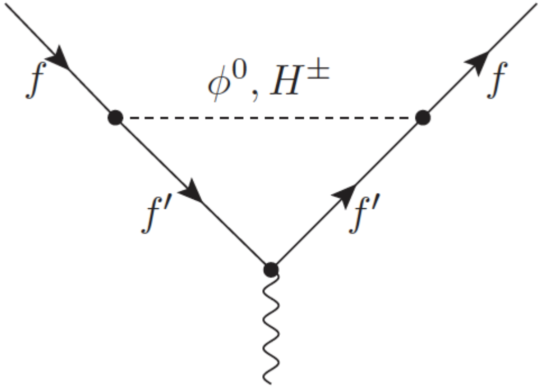
Eur. Phys. J. C (2019) 79:884

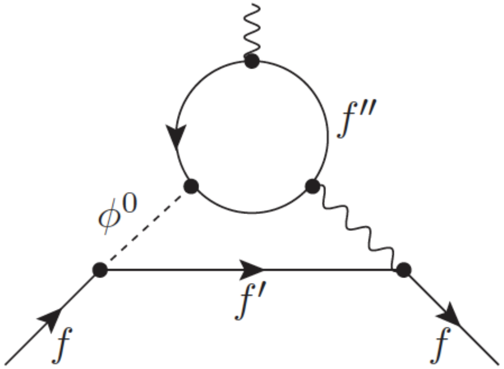
Top contribution too small to explain discrepancy. Toponium cannot explain it.

Chin.Phys.C 44 (2020) 6, 063103

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

The Muon g-2 and the 2HDM+S



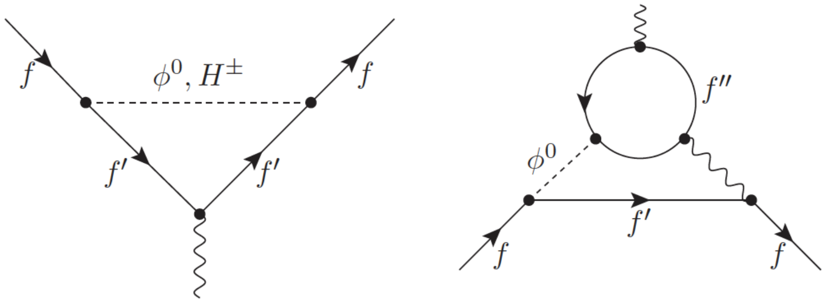


2HDM+S potential with fixed parameters from multi-lepton anomalies at the LHC

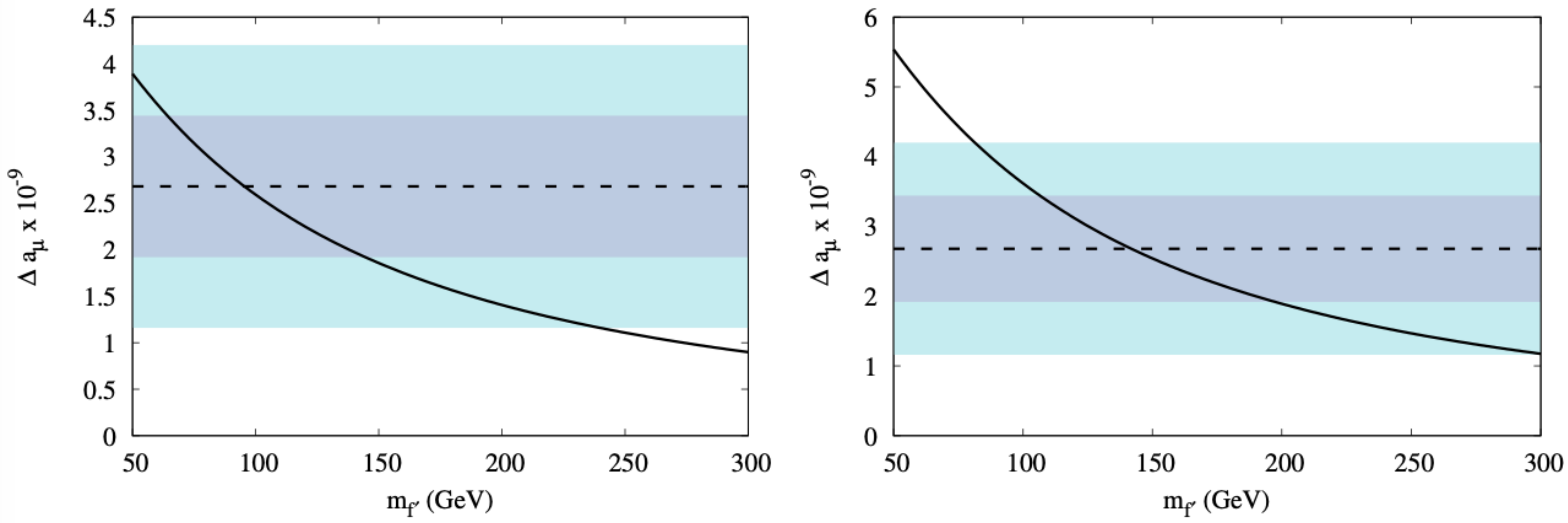
$$
\begin{aligned}
&V(\Phi_1,\Phi_2,\Phi_S)\\
&= m_{11}^2\left|\Phi_1\right|^2 + m_{22}^2\left|\Phi_2\right|^2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \text{h.c.}\right)\\
&+ \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right)\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

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

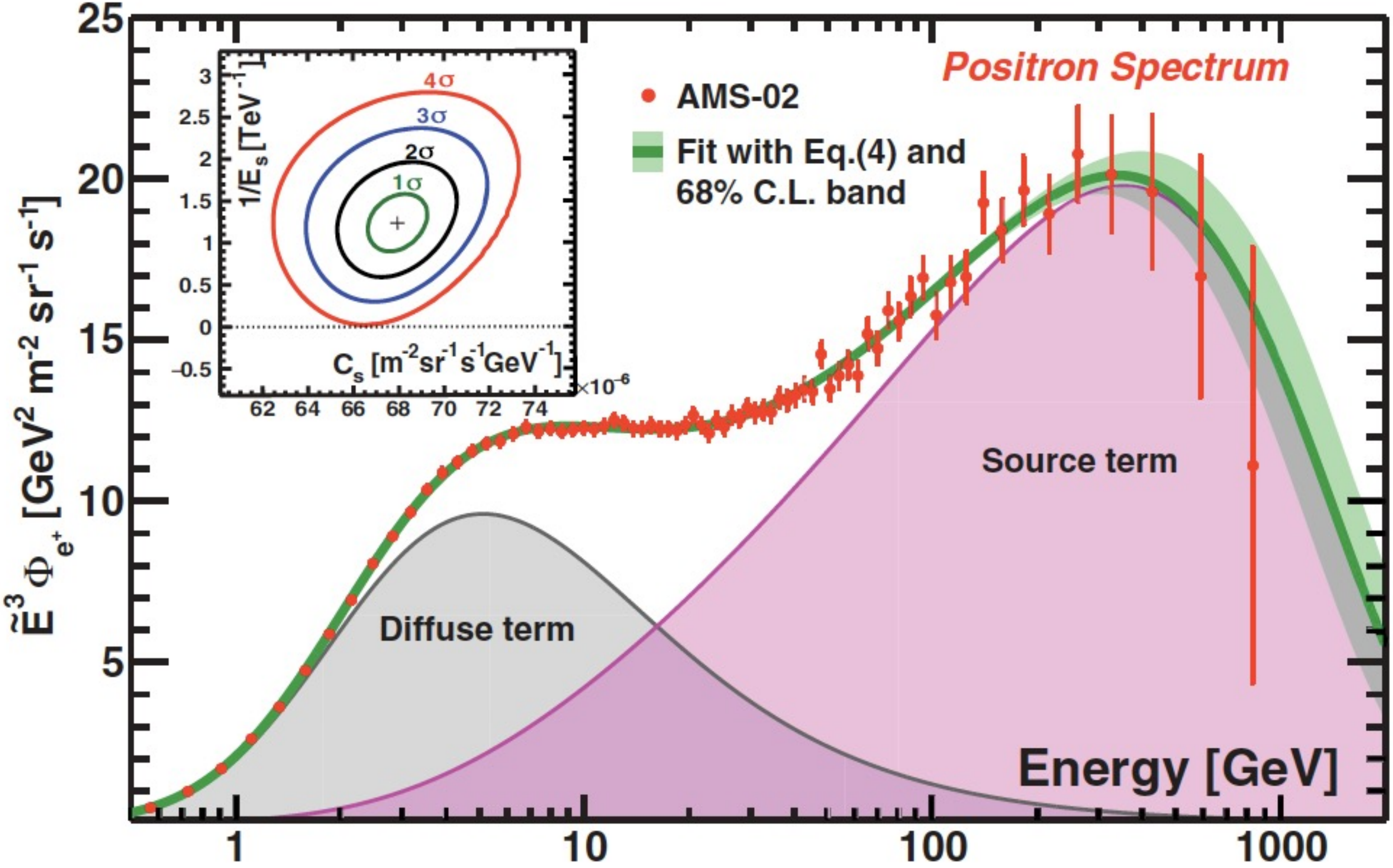


G.Beck, E.Malwa, M.Kumar, R.Temo and B.M., 2102.10596

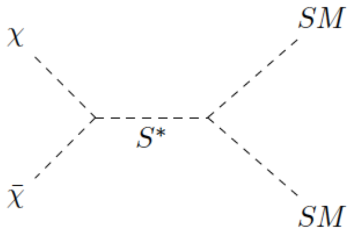
The multi-lepton anomalies and excesses in astrophysics

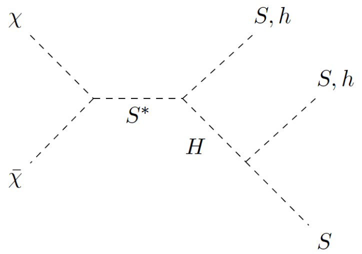
AMS02, PRL 122, 041102 (2019)

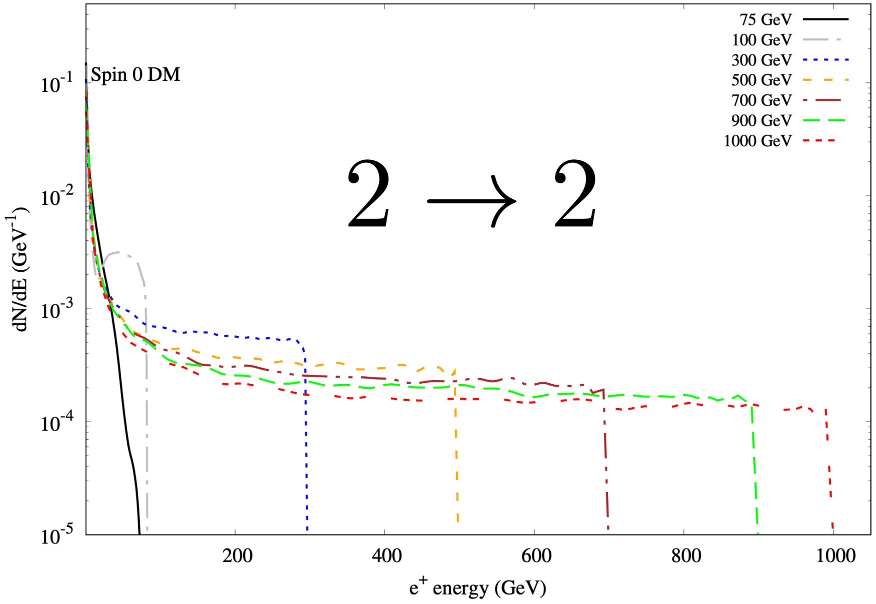
Leptophilic excesses, such as positron rise in PAMELA/AMS02

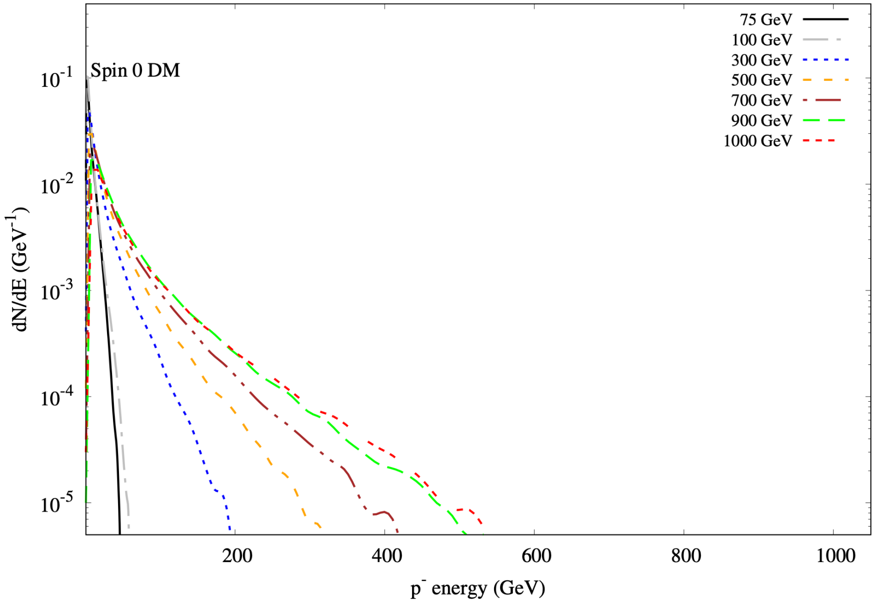


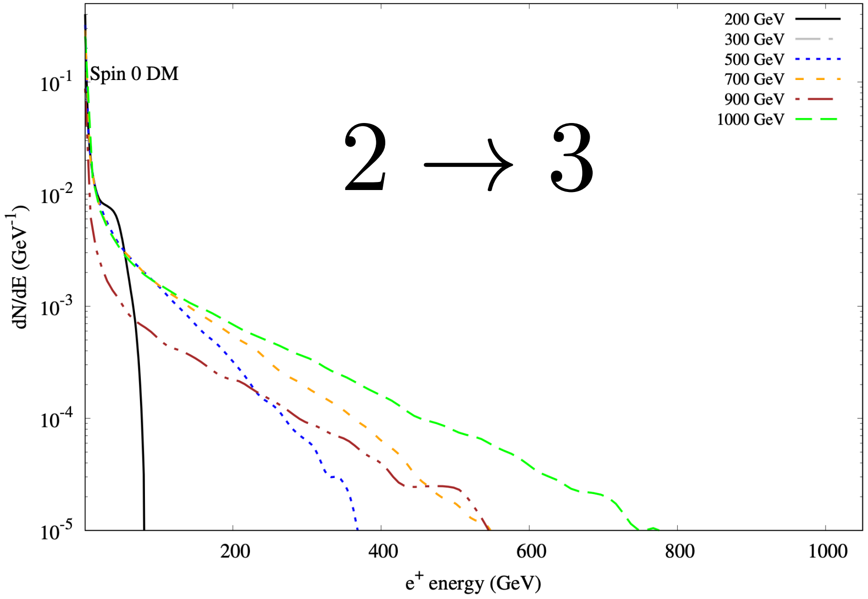
Dark matter annihilation.
Leptons, photons and protons
from the decays of S.

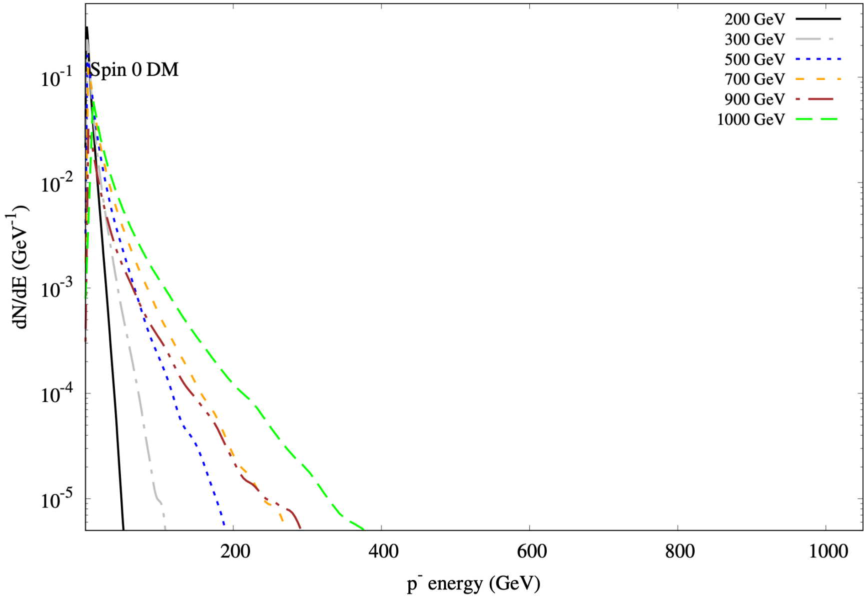


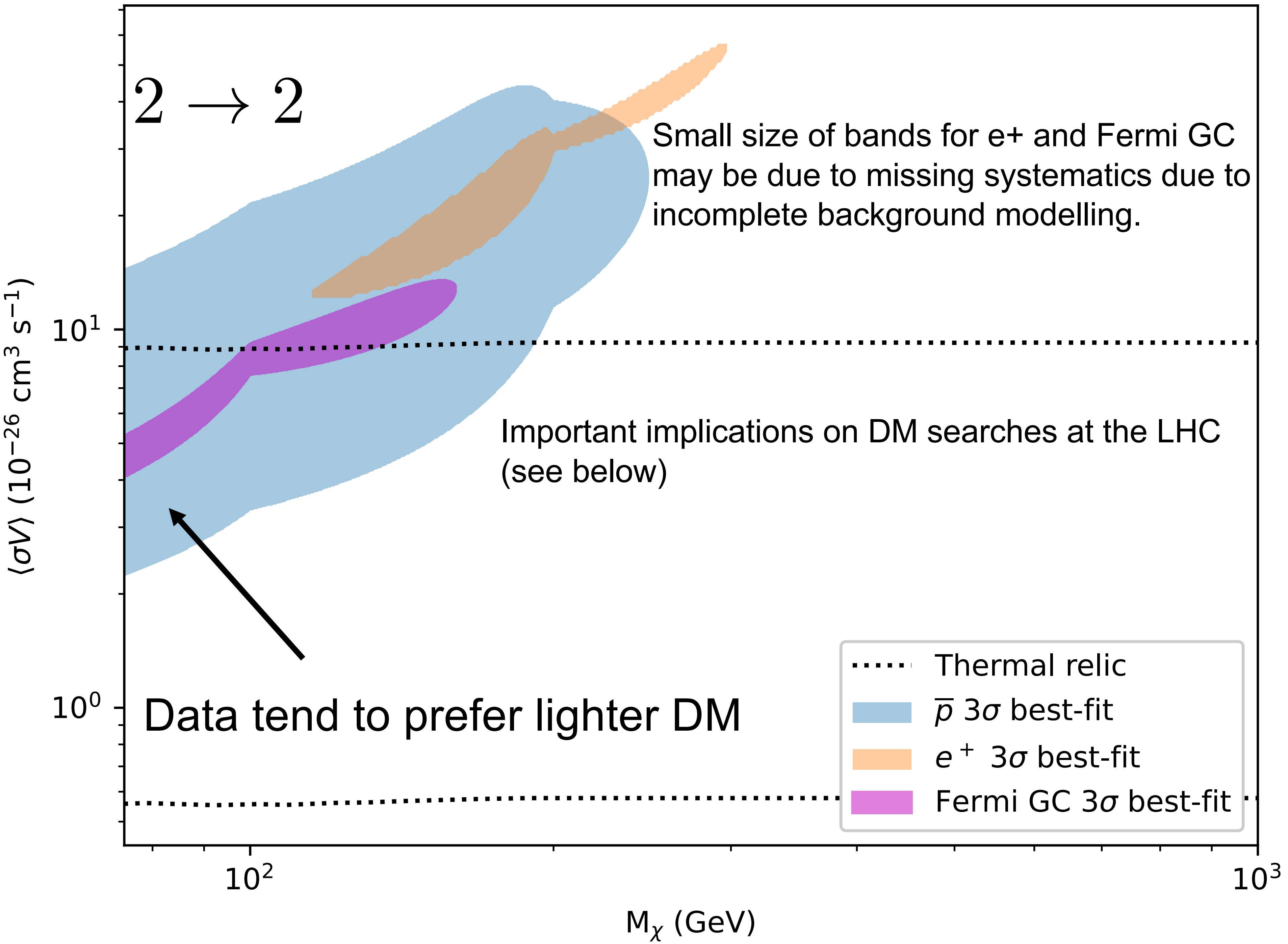










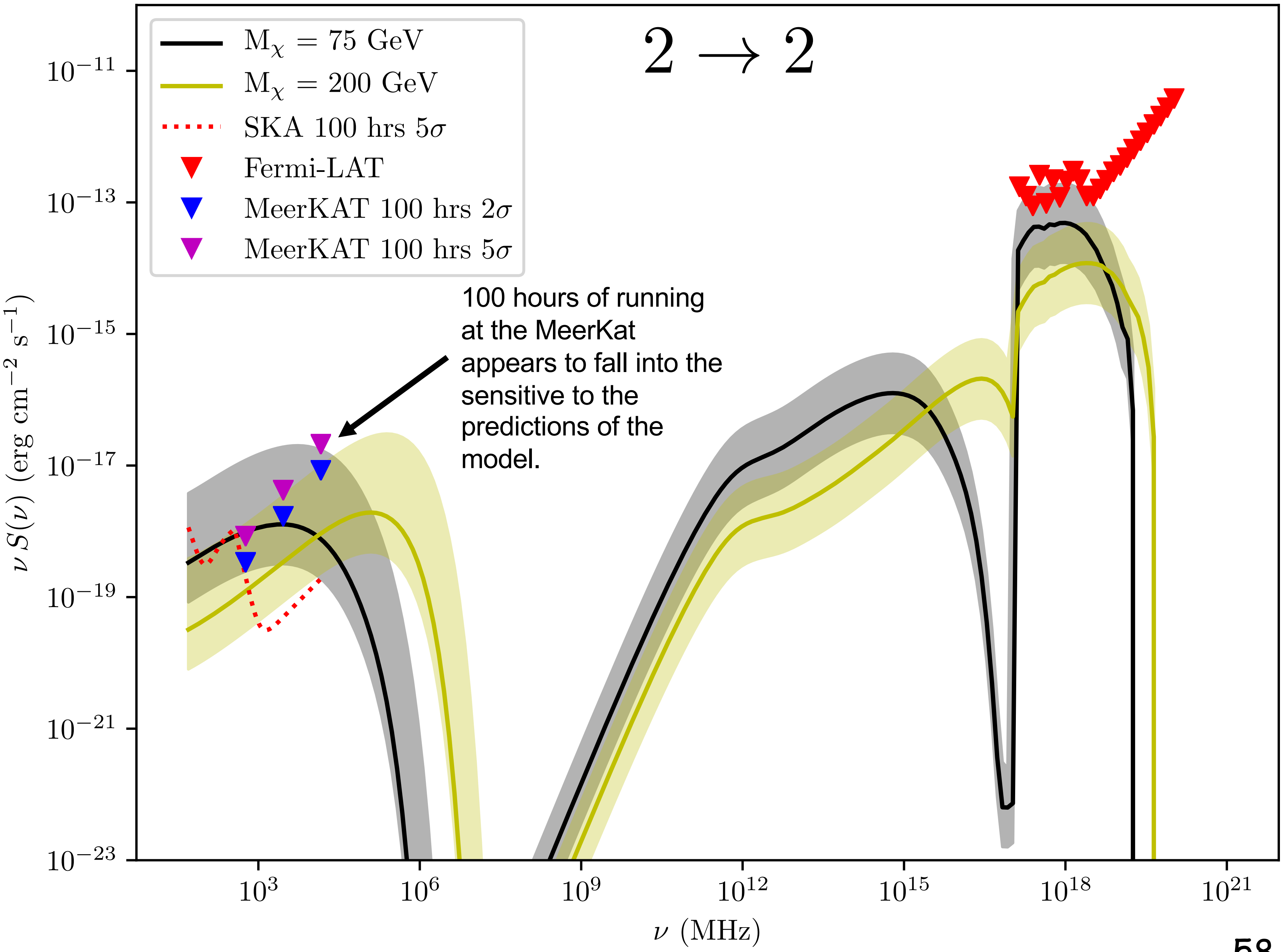


$2 \to 2$

Small size of bands for e+ and Fermi GC may be due to missing systematics due to incomplete background modelling.

Important implications on DM searches at the LHC (see below)

Data tend to prefer lighter DM



100 hours of running at the MeerKat appears to fall into the sensitive to the predictions of the model.

Table 2: Overview of the selection defining the analysis categories.

Category	Number of leptons	Number of jets	Sub-categorization
ggH	2	-	(DF, SF) × (0 jets, 1 jet, ≥ 2 jets)
VBF	2	≥ 2	(DF, SF)
VH2j	2	≥ 2	(DF, SF)
WHSS	2	≥ 1	(DF, SF) × (0 jets, 1 jet)
WH3ℓ	3	0	SF lepton pair with opposite or same sign
ZH3ℓ	3	≥ 1	(1 jet, 2 jets)
ZH4ℓ	4	-	(DF, SF)

Table 3: Summary of the selection used in different flavor ggH categories.

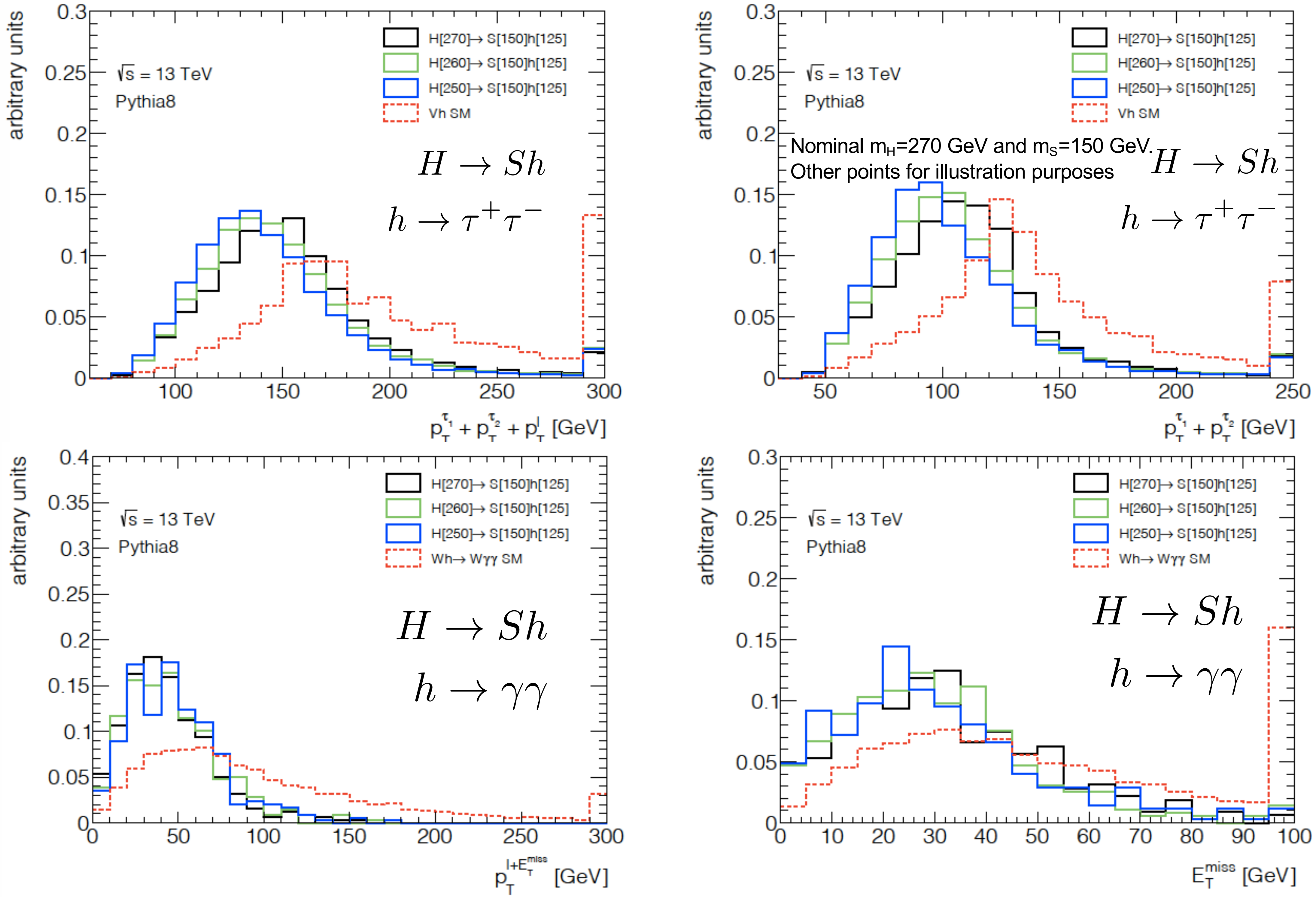
Category	Sub-categories	Selection
Global selection	-	$p_{T1} > 25$ GeV, $p_{T2} > 10$ GeV (2016) or 13 GeV $p_T^{miss} > 20$ GeV, $p_T^{\ell\ell} > 30$ GeV, $m_{\ell\ell} > 12$ GeV eμ pair with opposite charge
0-jet ggH tagged	$\ell^\pm\ell^\mp$, $p_{T2} \lesseqgtr 20$ GeV	$m_T^H > 60$ GeV, $m_T(\ell 2, p_T^{miss}) > 30$ GeV $p_{T2} \lesseqgtr 20$ GeV No jet with $p_T > 30$ GeV No b-tagged jet with $p_T > 20$ GeV
	Top CR	As SR, no m_T^H requirement, $m_{\ell\ell} > 50$ GeV At least 1 b-tagged jet with 20 GeV $< p_T <$ 30 GeV
	$\tau^+\tau^-$ CR	As SR but with $m_T^H < 60$ GeV 30 GeV $< m_{\ell\ell} <$ 80 GeV
1-jet ggH tagged	$\ell^\pm\ell^\mp$, $p_{T2} \lesseqgtr 20$ GeV	$m_T^H > 60$ GeV, $m_T(\ell 2, p_T^{miss}) > 30$ GeV $p_{T2} \lesseqgtr 20$ GeV 1 jet with $p_T > 30$ GeV No b-tagged jet with $p_T > 20$ GeV
	Top CR	As SR, no m_T^H requirement, $m_{\ell\ell} > 50$ GeV At least 1 b-tagged jet with $p_T > 30$ GeV
	$\tau^+\tau^-$ CR	As SR but with $m_T^H < 60$ GeV 30 GeV $< m_{\ell\ell} <$ 80 GeV
2-jet ggH tagged	SR	$m_T^H > 60$ GeV, $m_T(\ell 2, p_T^{miss}) > 30$ GeV $p_{T2} \lesseqgtr 20$ GeV At least 2 jets with $p_T > 30$ GeV No b-tagged jet with $p_T > 20$ GeV $m_{jj} < 65$ GeV or 105 GeV $< m_{jj} <$ 120 GeV
	Top CR	As SR, no m_T^H requirement, $m_{\ell\ell} > 50$ GeV At least 1 of the leading jets b-tagged
	$\tau^+\tau^-$ CR	As SR but with $m_T^H < 60$ GeV 30 GeV $< m_{\ell\ell} <$ 80 GeV

Impact on Higgs Physics

The presence of a BSM signal of the type H→Sh would lead to:

- ☐ The presence of extra leptons in association with h. Affects the Wh measurement (Eur.Phys.J.C 81 (2021) 365)
- ☐ Distortion of Higgs p_T and rapidity (under study)

No tuning of model parameters performed. Look at fixed corners of the phase-space fixed with parameters of 2017.



Nominal m_H=270 GeV and m_S=150 GeV.
Other points for illustration purposes

Survey of LHC results on Vh (V=W,Z) production (Eur.Phys.J.C 81 (2021) 365)

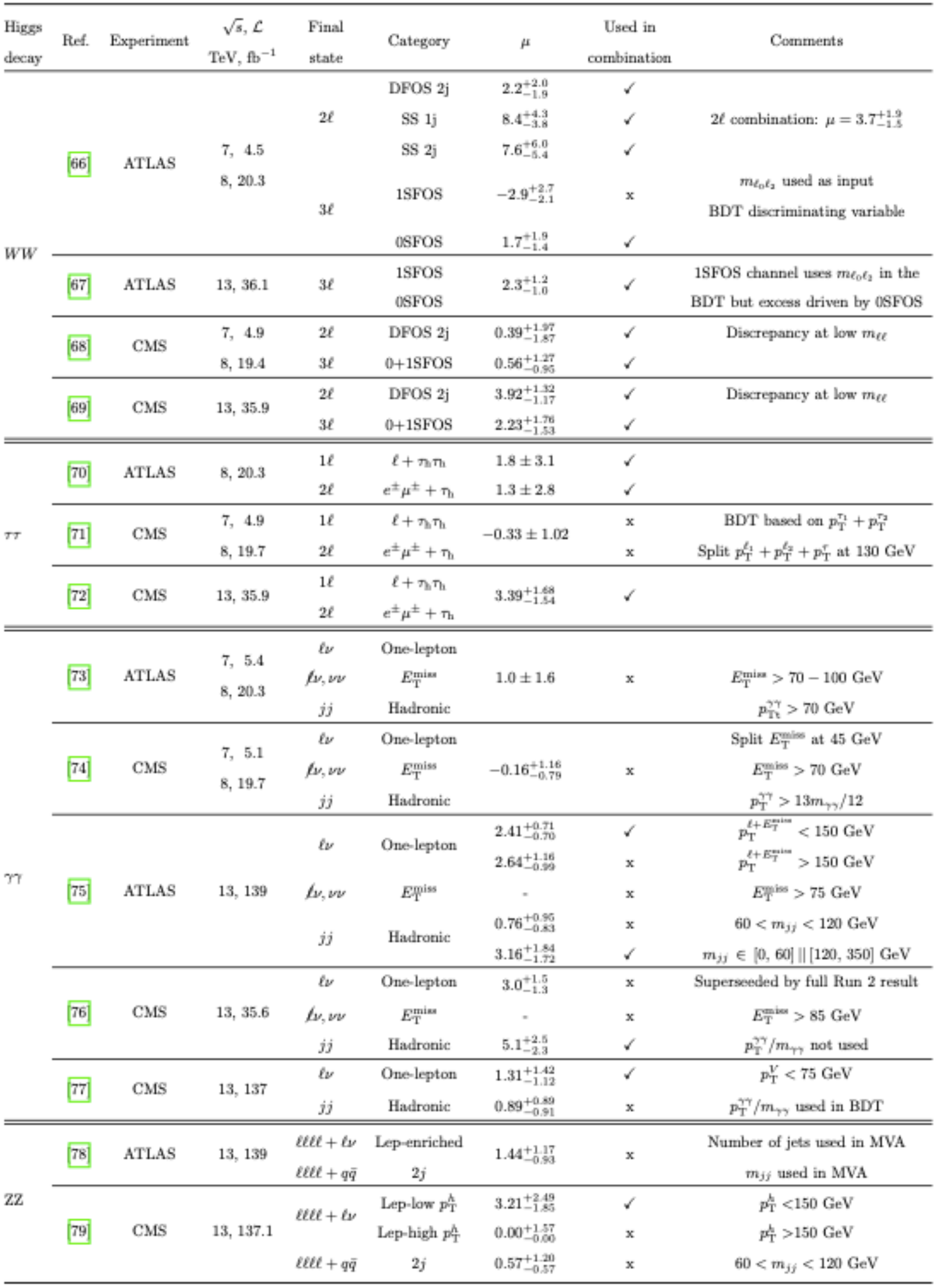
The BSM (H→Sh) signal appears at low p_{Th} and the SM signal is prevalent at larger p_{Th} (no tuning of parameters)

Include those results from ATLAS and CMS where no requirements on p_{Th} (or correlated observables) is not done or used in an MVA.

Those results where the final state is treated more "inclusively" display elevated signal strengths for Wh production:

$$\mu(Wh) = 2.41 \pm 0.37$$

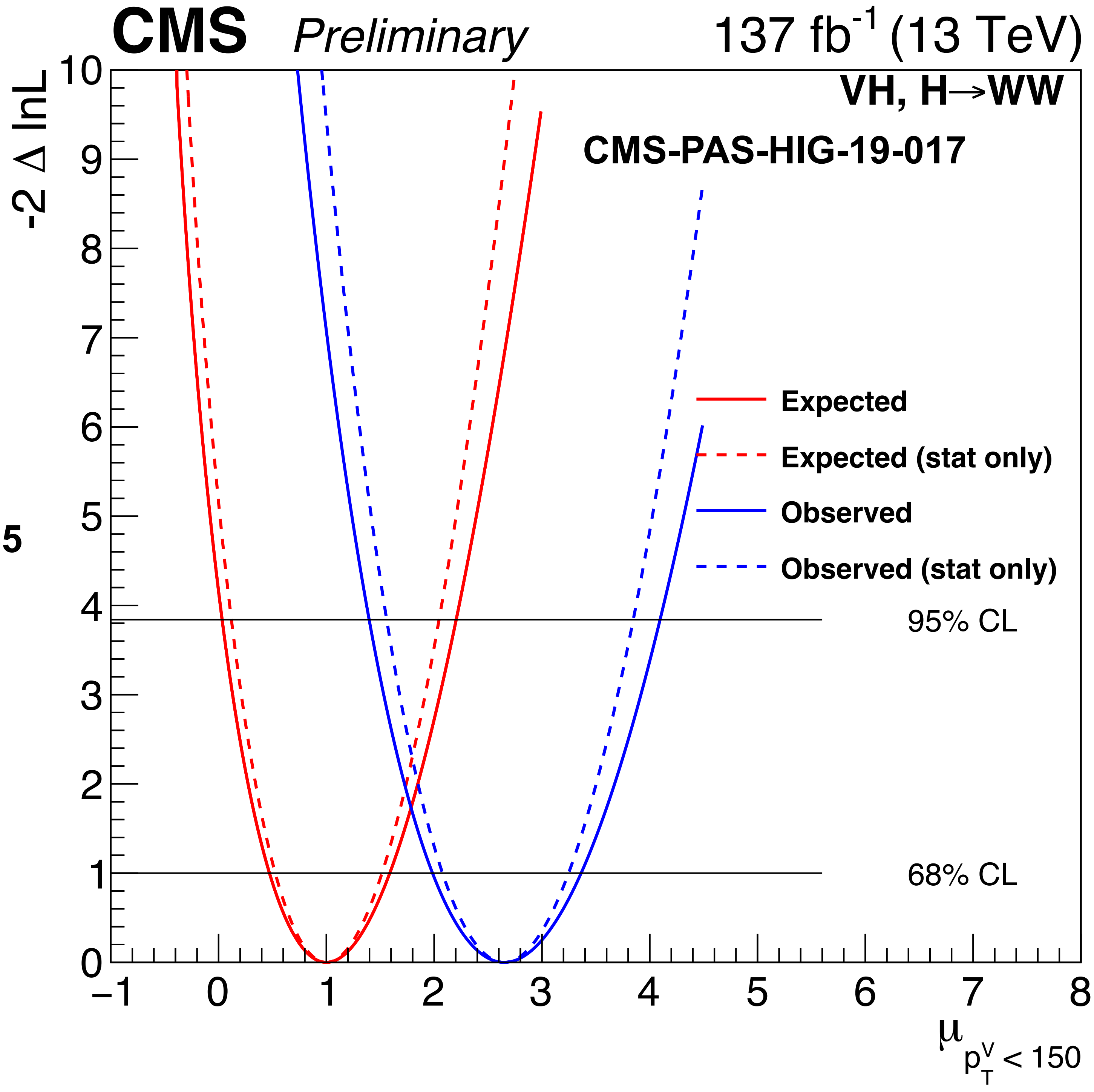
This represents a 3.8σ deviation from the SM value of 1. BSM signal normalization less than expected from multilepton excesses assuming Br(H→Sh)=100%. Indicates that Br(H→SS) > Br(H→Sh)



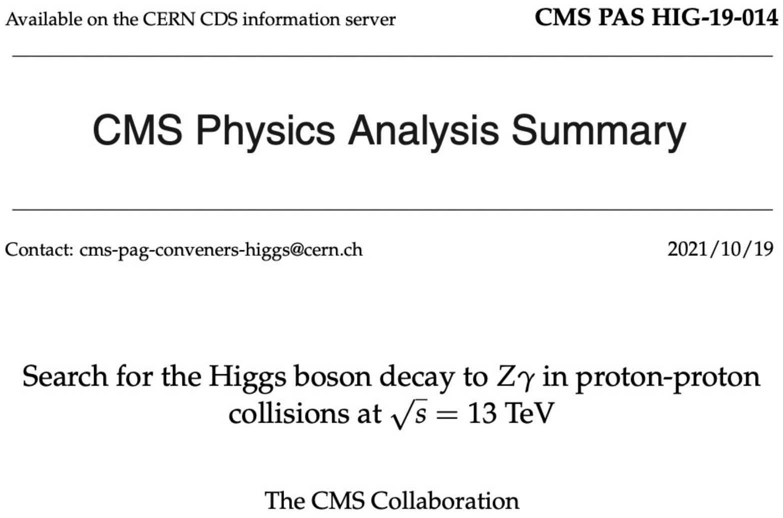
Higgs decay	Ref.	Experiment	$\sqrt{s}$, $\mathcal{L}$ TeV, fb^{-1}	Final state	Category	μ	Used in combination	Comments
WW	[66]	ATLAS	7, 4.5 8, 20.3	2ℓ	DFOS 2j	$2.2^{+2.0}_{-1.9}$	✓	2ℓ combination: $\mu = 3.7^{+1.9}_{-1.5}$
					SS 1j	$8.4^{+4.3}_{-3.8}$	✓	
					SS 2j	$7.6^{+6.0}_{-5.4}$	✓	
				3ℓ	1SFOS	$-2.9^{+2.7}_{-2.1}$	x	$m_{\ell_0\ell_2}$ used as input BDT discriminating variable
					0SFOS	$1.7^{+1.9}_{-1.4}$	✓	
	[67]	ATLAS	13, 36.1	3ℓ	1SFOS 0SFOS	$2.3^{+1.2}_{-1.0}$	✓	1SFOS channel uses $m_{\ell_0\ell_2}$ in the BDT but excess driven by 0SFOS
	[68]	CMS	7, 4.9 8, 19.4	2ℓ	DFOS 2j	$0.39^{+1.97}_{-1.87}$	✓	Discrepancy at low $m_{\ell\ell}$
				3ℓ	0+1SFOS	$0.56^{+1.27}_{-0.95}$	✓	
	[69]	CMS	13, 35.9	2ℓ	DFOS 2j	$3.92^{+1.32}_{-1.17}$	✓	Discrepancy at low $m_{\ell\ell}$
				3ℓ	0+1SFOS	$2.23^{+1.76}_{-1.53}$	✓	
$\tau\tau$	[70]	ATLAS	8, 20.3	1ℓ	$\ell + \tau_h\tau_h$	1.8 ± 3.1	✓	
				2ℓ	$e^\pm\mu^\pm + \tau_h$	1.3 ± 2.8	✓	
	[71]	CMS	7, 4.9 8, 19.7	1ℓ	$\ell + \tau_h\tau_h$	-0.33 ± 1.02	x	BDT based on $p_T^{\tau_1} + p_T^{\tau_2}$
				2ℓ	$e^\pm\mu^\pm + \tau_h$		x	Split $p_T^{\ell_1} + p_T^{\ell_2} + p_T^{\tau}$ at 130 GeV
	[72]	CMS	13, 35.9	1ℓ	$\ell + \tau_h\tau_h$	$3.39^{+1.68}_{-1.54}$	✓	
				2ℓ	$e^\pm\mu^\pm + \tau_h$			
$\gamma\gamma$	[73]	ATLAS	7, 5.4 8, 20.3	$\ell\nu$	One-lepton			
				$\not{\ell}\nu, \nu\nu$	E_T^{miss}	1.0 ± 1.6	x	$E_T^{miss} > 70 - 100$ GeV
				jj	Hadronic			$p_{Tt}^{\gamma\gamma} > 70$ GeV
	[74]	CMS	7, 5.1 8, 19.7	$\ell\nu$	One-lepton			Split E_T^{miss} at 45 GeV
				$\not{\ell}\nu, \nu\nu$	E_T^{miss}	$-0.16^{+1.16}_{-0.79}$	x	$E_T^{miss} > 70$ GeV
				jj	Hadronic			$p_T^{\gamma\gamma} > 13m_{\gamma\gamma}/12$
	[75]	ATLAS	13, 139	$\ell\nu$	One-lepton	$2.41^{+0.71}_{-0.70}$	✓	$p_T^{\ell+E_T^{miss}} < 150$ GeV
						$2.64^{+1.16}_{-0.99}$	x	$p_T^{\ell+E_T^{miss}} > 150$ GeV
				$\not{\ell}\nu, \nu\nu$	E_T^{miss}	-	x	$E_T^{miss} > 75$ GeV
				jj	Hadronic	$0.76^{+0.95}_{-0.83}$	x	$60 < m_{jj} < 120$ GeV
						$3.16^{+1.84}_{-1.72}$	✓	$m_{jj} \in [0, 60] \parallel [120, 350]$ GeV
	[76]	CMS	13, 35.6	$\ell\nu$	One-lepton	$3.0^{+1.5}_{-1.3}$	x	Superseeded by full Run 2 result
				$\not{\ell}\nu, \nu\nu$	E_T^{miss}	-	x	$E_T^{miss} > 85$ GeV
				jj	Hadronic	$5.1^{+2.5}_{-2.3}$	✓	$p_T^{\gamma\gamma}/m_{\gamma\gamma}$ not used
	[77]	CMS	13, 137	$\ell\nu$	One-lepton	$1.31^{+1.42}_{-1.12}$	✓	$p_T^V < 75$ GeV
				jj	Hadronic	$0.89^{+0.89}_{-0.91}$	x	$p_T^{\gamma\gamma}/m_{\gamma\gamma}$ used in BDT
ZZ	[78]	ATLAS	13, 139	$\ell\ell\ell + \ell\nu$	Lep-enriched	$1.44^{+1.17}_{-0.93}$	x	Number of jets used in MVA
				$\ell\ell\ell + q\bar{q}$	$2j$			m_{jj} used in MVA
	[79]	CMS	13, 137.1	$\ell\ell\ell + \ell\nu$	Lep-low p_T^h	$3.21^{+2.49}_{-1.85}$	✓	p_T^h <150 GeV
					Lep-high p_T^h	$0.00^{+1.57}_{-0.00}$	x	p_T^h >150 GeV
				$\ell\ell\ell + q\bar{q}$	$2j$	$0.57^{+1.20}_{-0.57}$	x	$60 < m_{jj} < 120$ GeV

New results from CMS in the measurement of Vh, h→WW add to the anomalies reported in Eur.Phys.J.C 81 (2021) 365

Deviation from the SM becomes stronger with p_{TV}<150 Gev



https://cds.cern.ch/record/2784454/files/HIG-19-014-pas.pdf



Available on the CERN CDS information server **CMS PAS HIG-19-014**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-higgs@cern.ch 2021/10/19

Search for the Higgs boson decay to $Z\gamma$ in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

CMS observes what appears to be an upward fluctuation of the $h \to Z\gamma$ in the di-jet bin optimized for the measurement of Wh production. The Signal strength deviates from unity by 3.2σ.