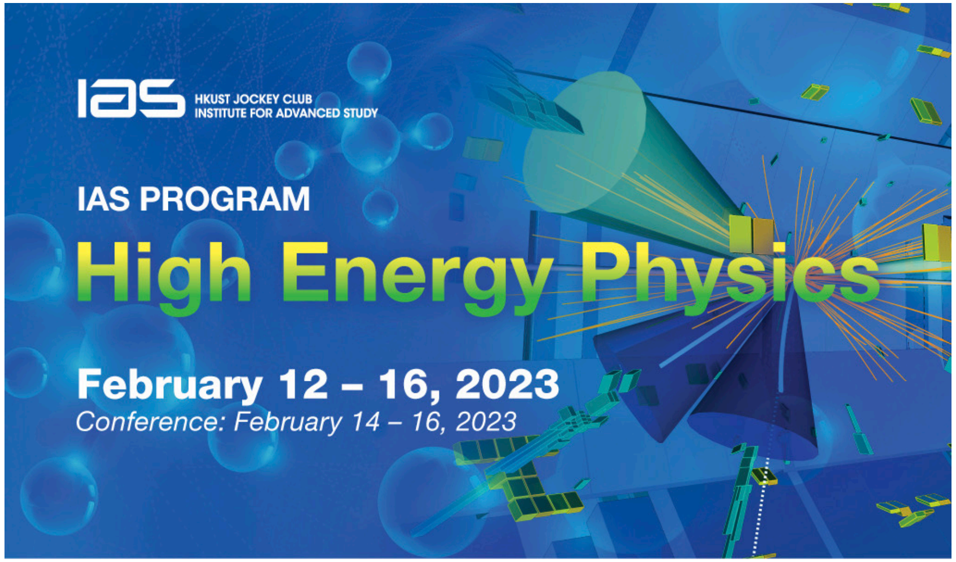
Excesses at the LHC and implications for (HL)-LHC and e^+e^- colliders

Bruce Mellado

Institute for Collider Particle Physics and iThemba LABS

Special thanks to S.Bhattacharya, G.Coloretti, A.Crivellin, S.-E.Dahbi, S.Heinemeyer, G.Lansberg



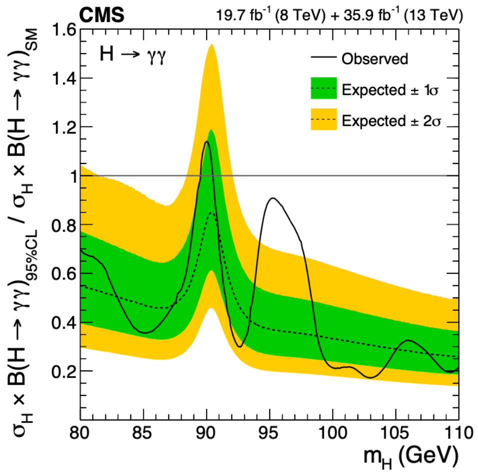
INSTITUTE FOR COLLIDER PARTICLE PHYSICS
UNIVERSITY OF THE WITWATERSRAND

NRF National Research Foundation

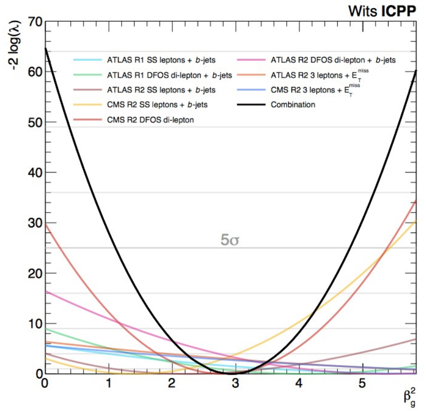
iThemba LABS Laboratory for Accelerator Based Sciences

Institute of Advanced Studies, HKUST, 15/02/23

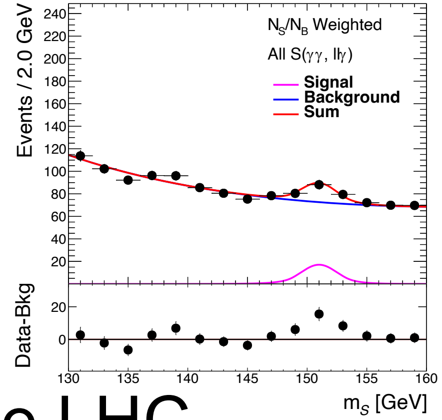
Outline



- ❑The 96 GeV candidate



- ❑The multilepton excesses
  - ❑The 151.5 GeV candidate



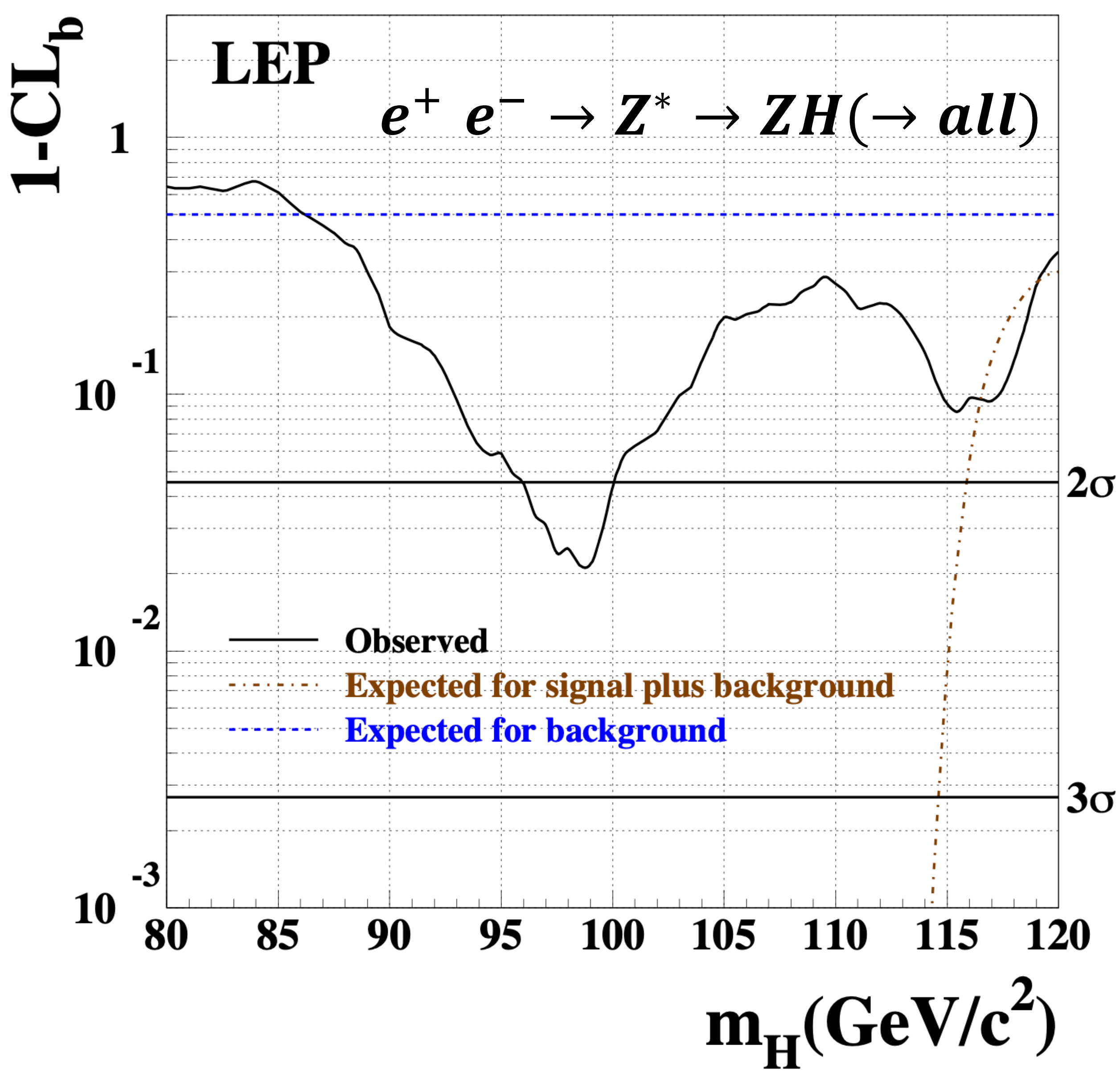
- ❑Excesses around 650-700 GeV
- ❑Excesses at the TeV scale

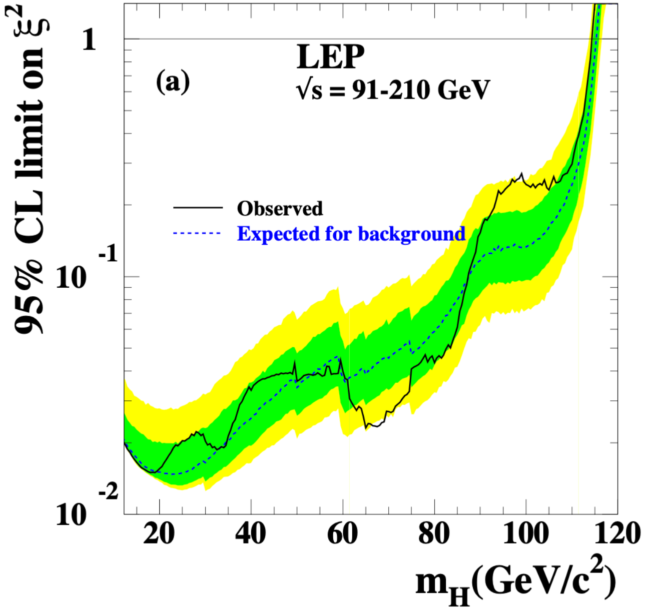
Disclaimer: this talk is not a summary of excesses at the LHC.
Focus on resonant-like excesses.

The 96 GeV candidate

ALEPH, DELPHI, L3 and OPAL Collaborations
The LEP Working Group for Higgs Boson Searches

CERN-EP/2003-011
LEP, Phys. Lett. B 565 (2003) 61–75





$$\xi^2 = (g_{\mathrm{HZZ}}/g_{\mathrm{HZZ}}^{\mathrm{SM}})^2$$

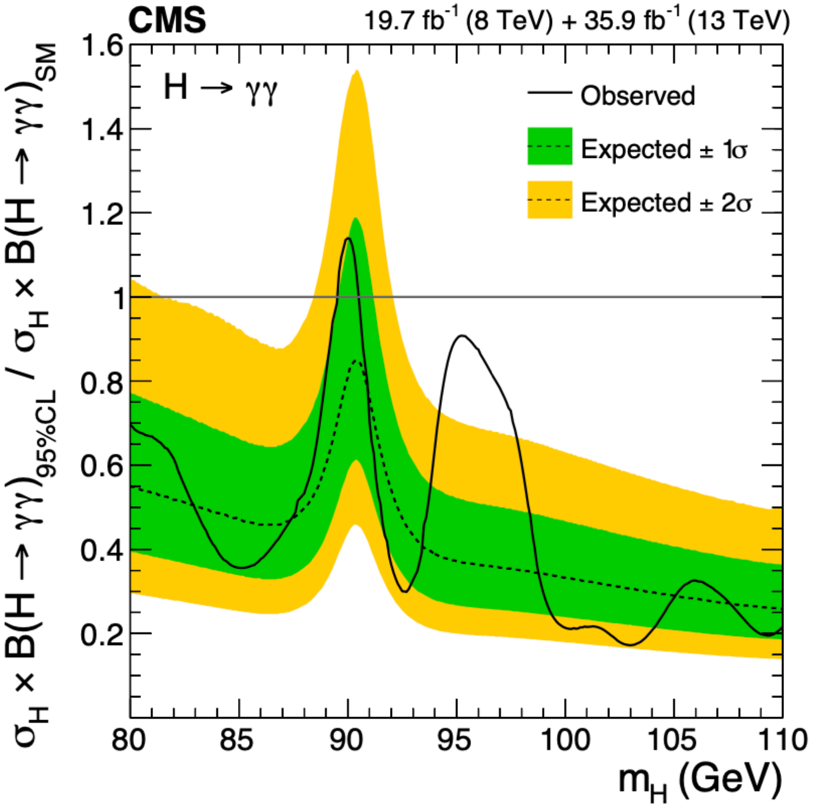
Combination of all SM Higgs-like decay modes

Search for SM Higgs-like boson with categorization according to SM-like production mechanisms (ggF, VBF, VH, ttH).

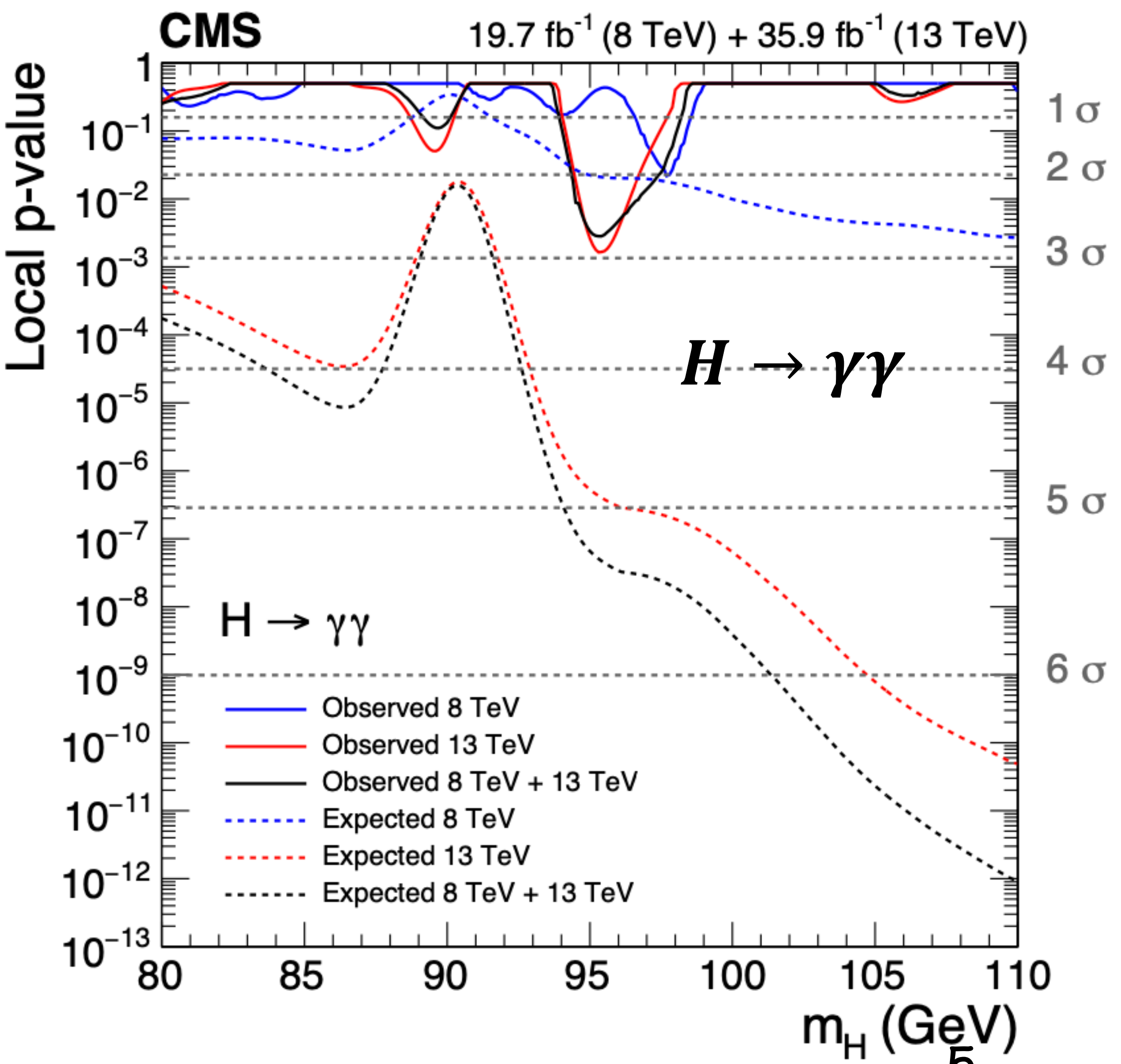
CMS, PLB 793 (2019) 320

$$\mu_{\mathrm{LEP}} = \frac{\sigma\left(e^+e^- \to Z\phi \to Zb\bar{b}\right)}{\sigma^{SM}\left(e^+e^- \to ZH_{\mathrm{SM}} \to Zb\bar{b}\right)} = 0.117 \pm 0.057$$

$$\mu_{\mathrm{CMS}} = \frac{\sigma\,(gg \to \phi \to \gamma\gamma)}{\sigma^{\mathrm{SM}}\,(gg \to H_{\mathrm{SM}} \to \gamma\gamma)} = 0.6 \pm 0.2$$

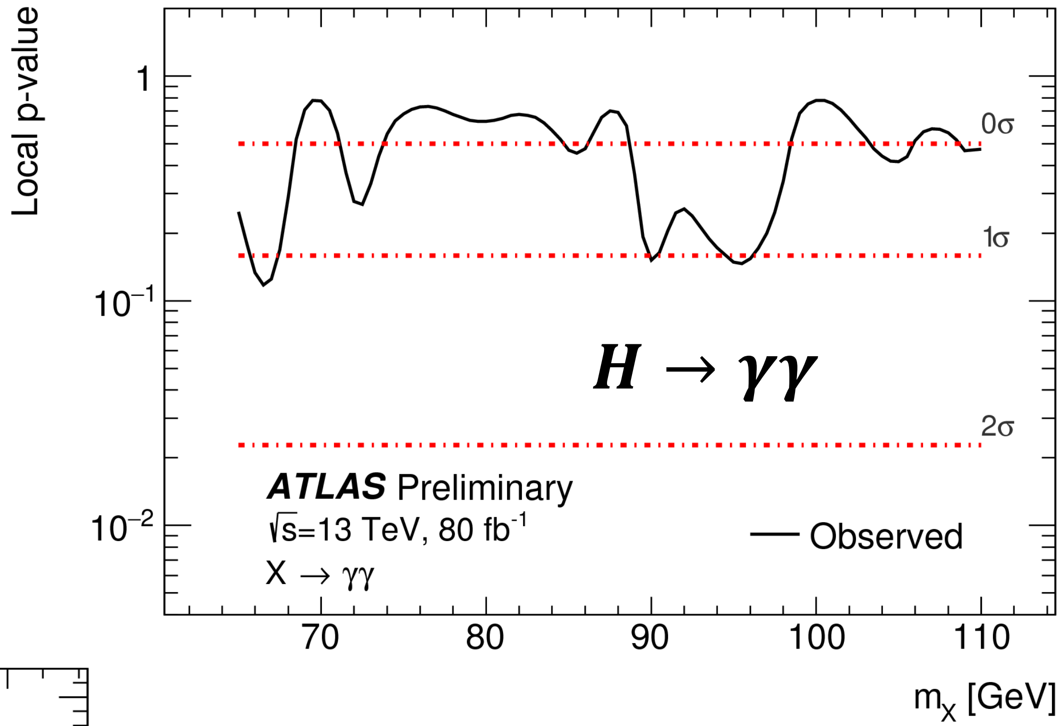


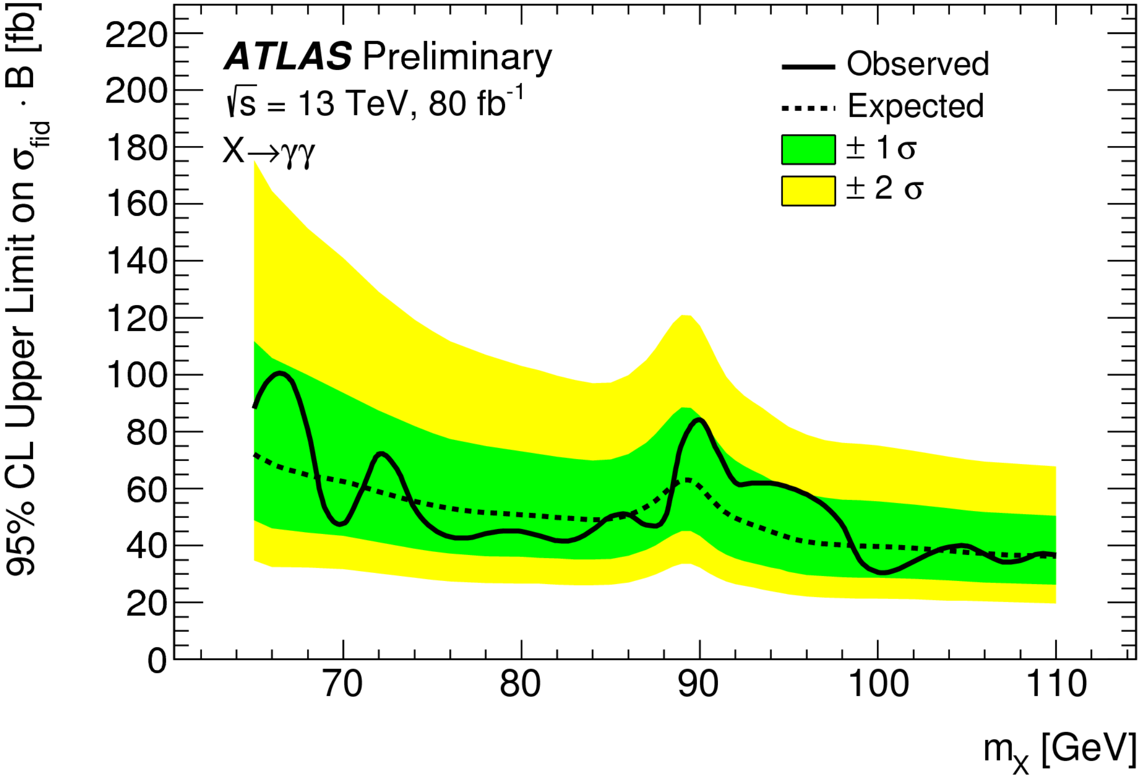
Local (global) 2.8 (1.3)σ @95.3 GeV



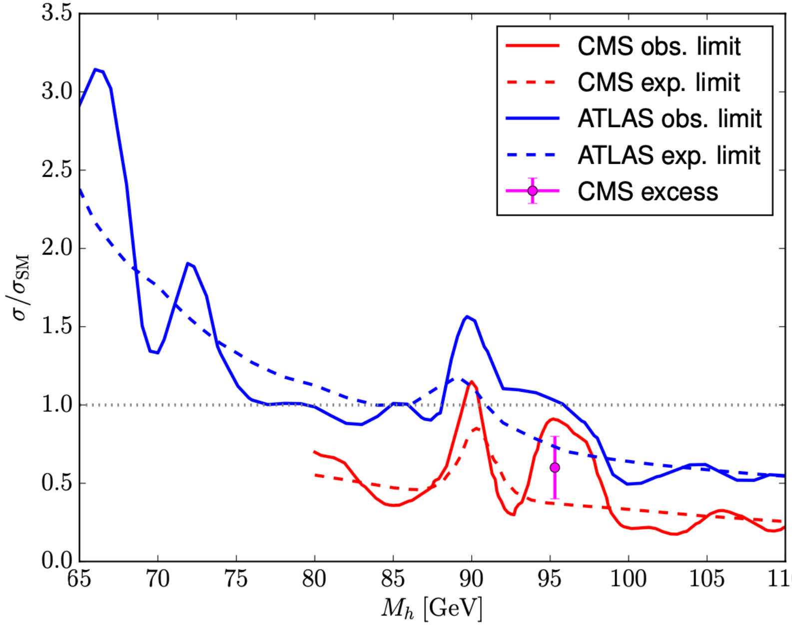
ATLAS-CONF-2018-025

Purely inclusive search with classification according to photon conversions (UU,UC,CC). ATLAS has less sensitivity w.r.t. CMS and does not exclude the excess.





S.Heinemeyer, T.Stefaniak

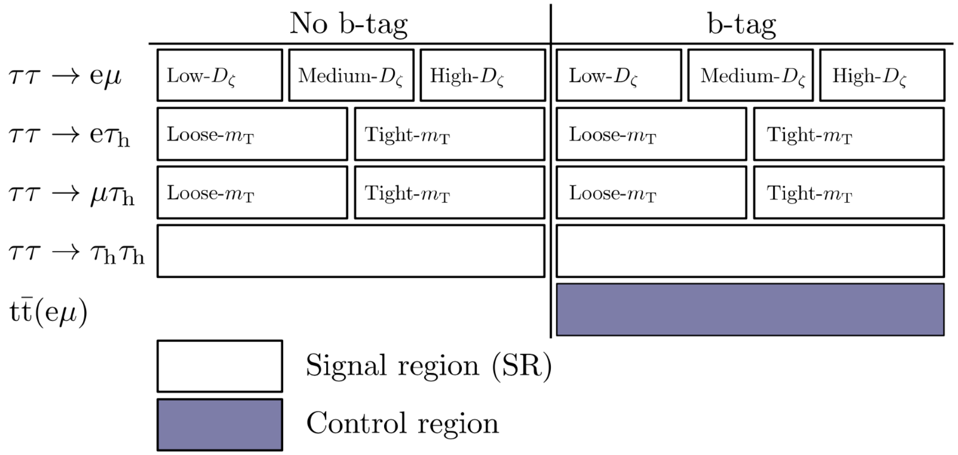


CMS, arXiv:2208.02717

$H \to \tau\tau$

Dedicated search for scalar decaying into tau pairs. CMS observes a local (global) excess of 3.1 (2.7)σ at ~100 GeV.

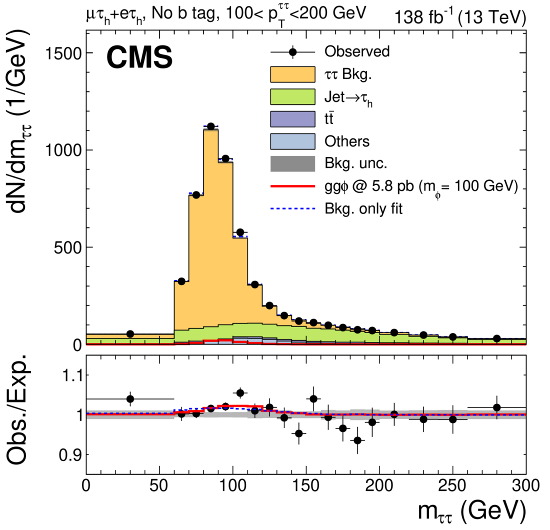
Event classification scheme

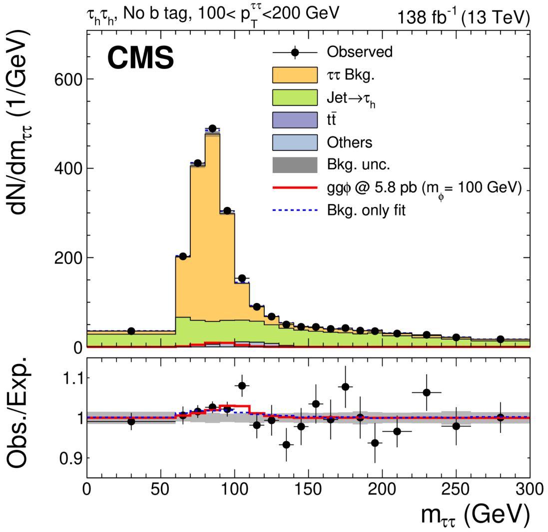


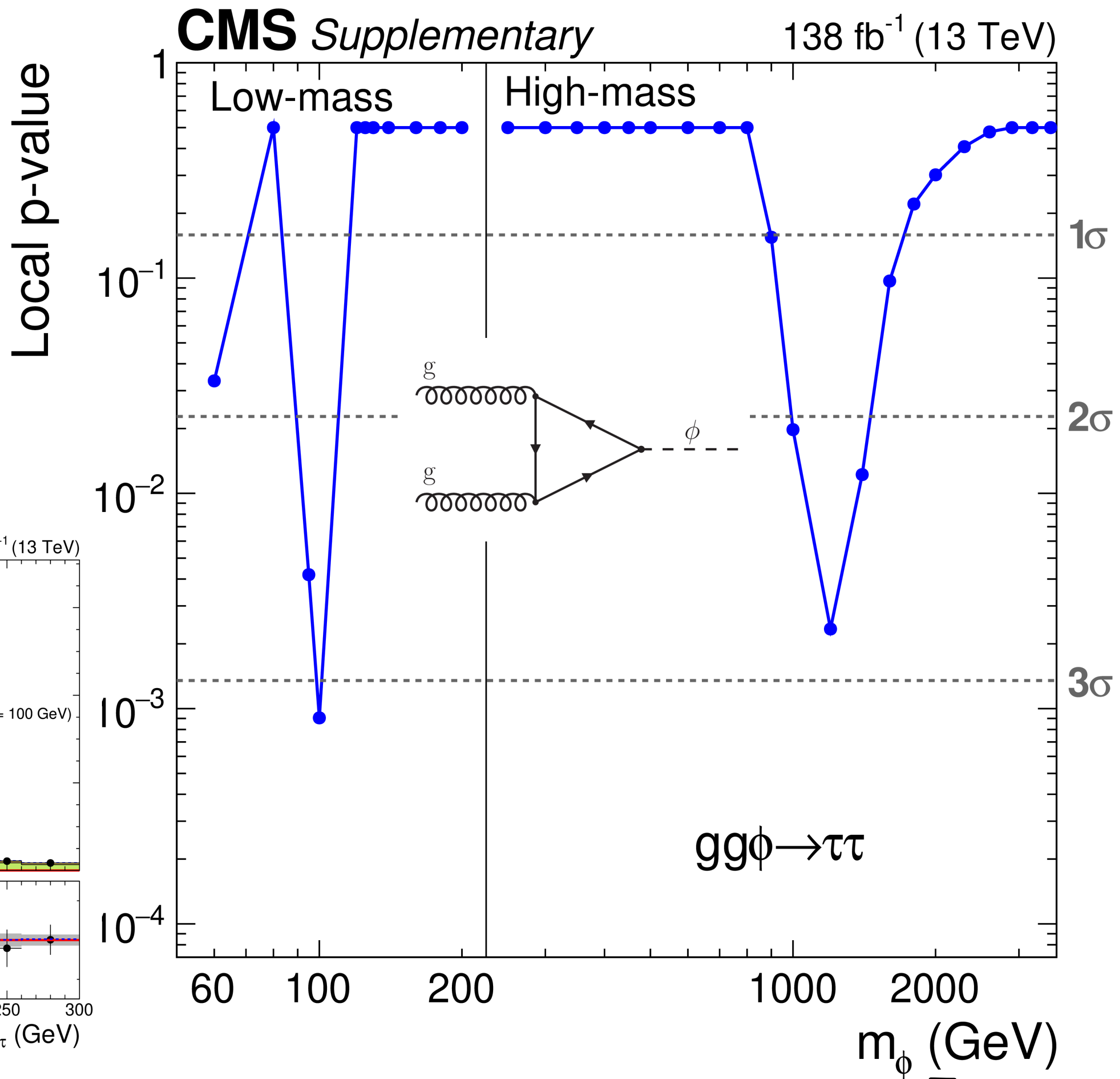
	No b-tag			b-tag		
$\tau\tau \to e\mu$	Low-D_ζ	Medium-D_ζ	High-D_ζ	Low-D_ζ	Medium-D_ζ	High-D_ζ
$\tau\tau \to e\tau_h$	Loose-m_T	Tight-m_T		Loose-m_T	Tight-m_T	
$\tau\tau \to \mu\tau_h$	Loose-m_T	Tight-m_T		Loose-m_T	Tight-m_T	
$\tau\tau \to \tau_h\tau_h$	☐			☐		
$t\bar{t}(e\mu)$				▨		

☐ Signal region (SR)

▨ Control region

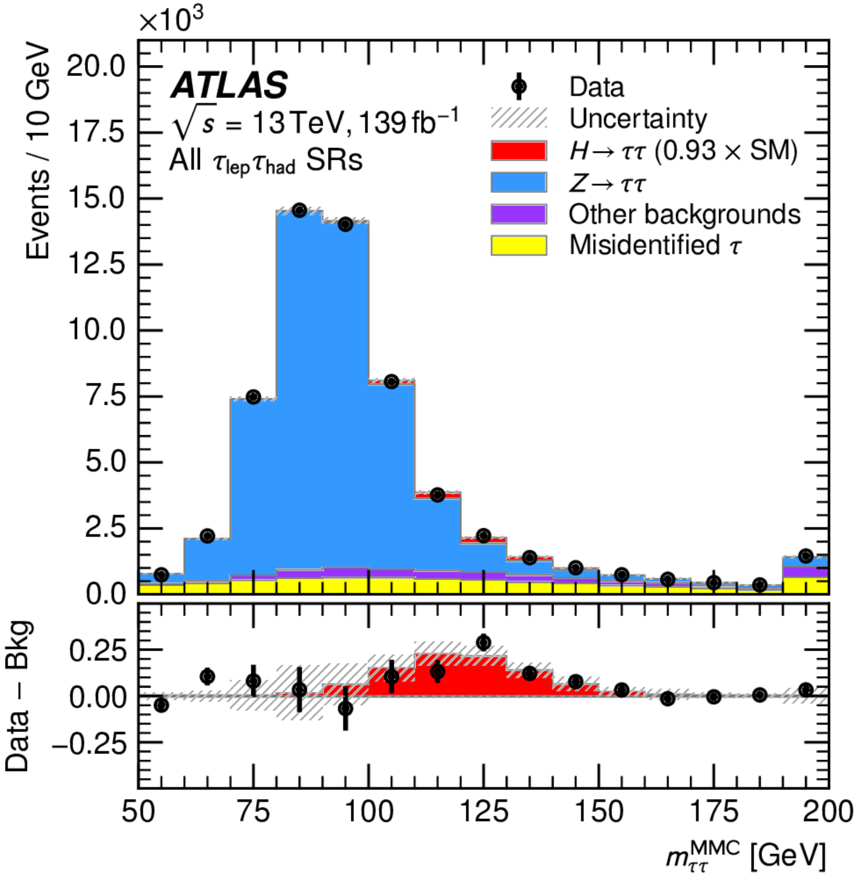


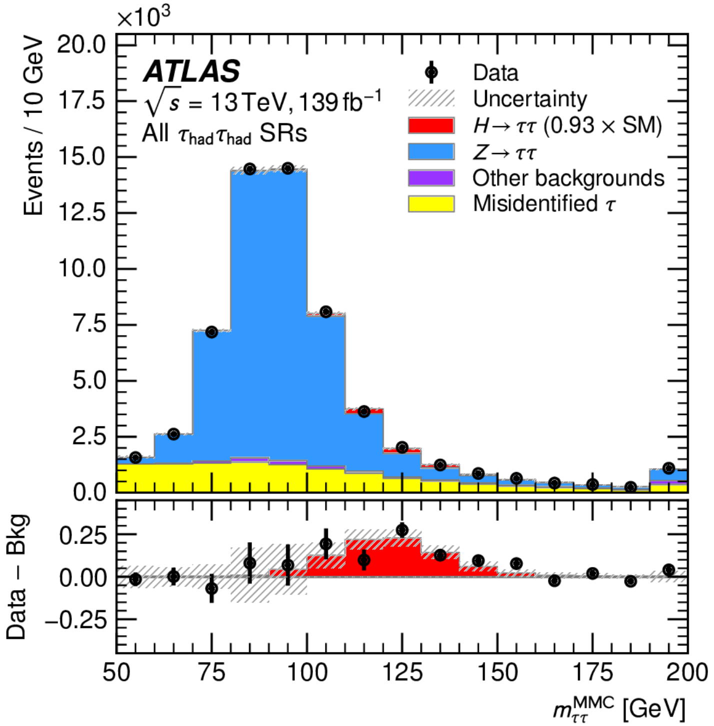




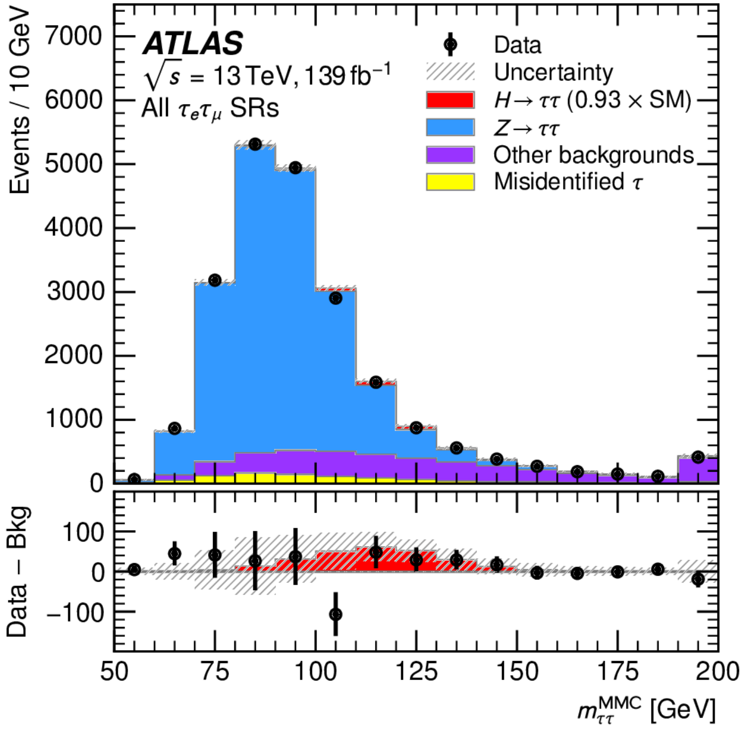
ATLAS, arXiv:2201.08269

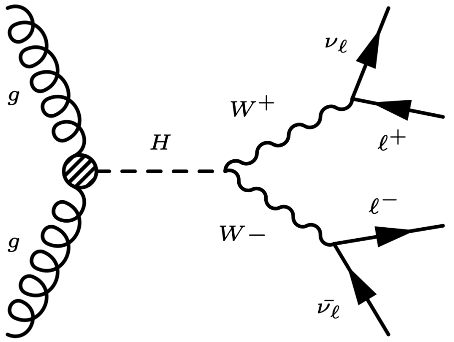
$H \to \tau\tau$

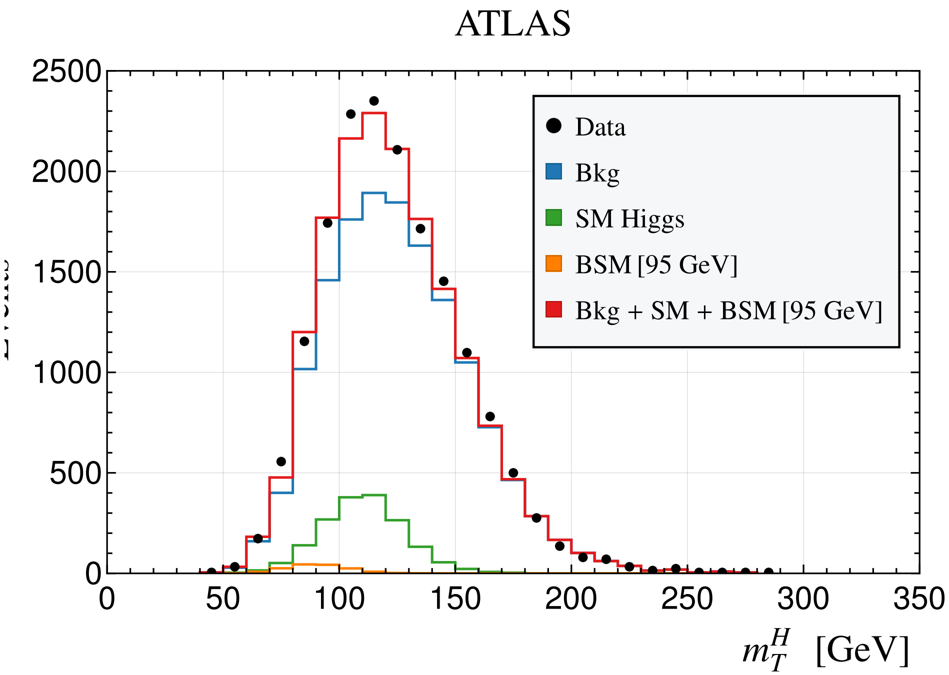




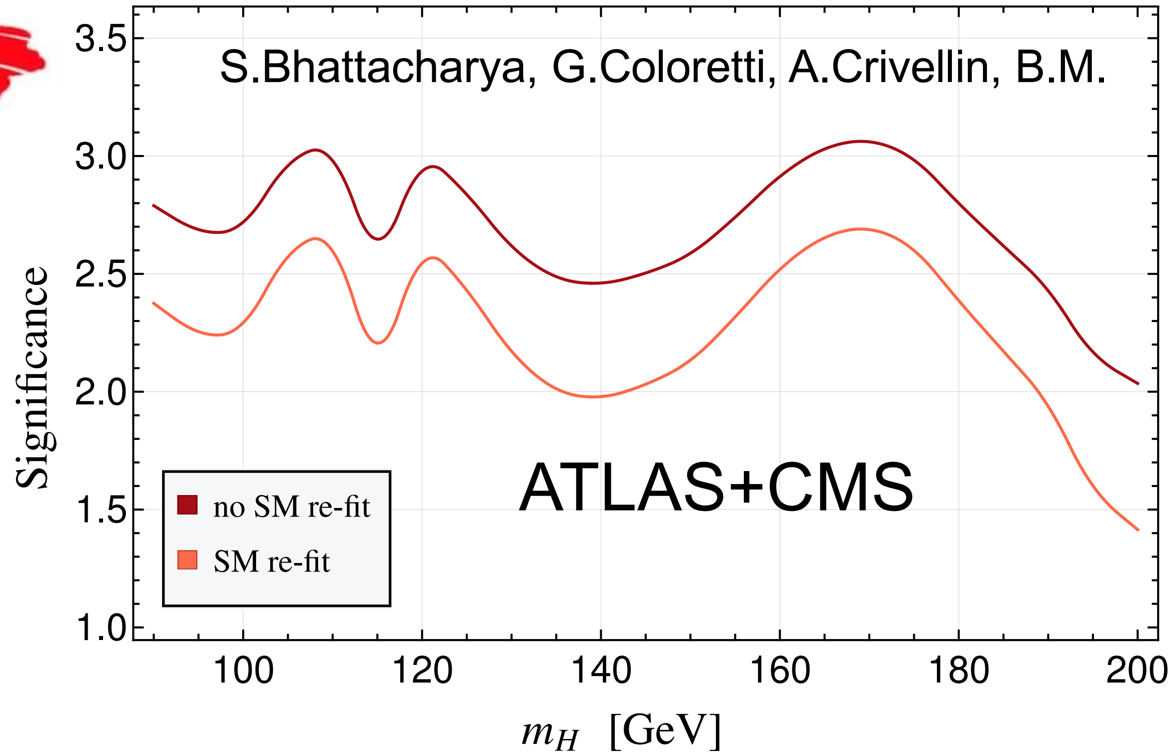
ATLAS has not performed a dedicated search for low mass scalar. That said we do not seem to see a clear excess around 95 GeV in the sideband. Is the CMS excess an upward fluctuation?

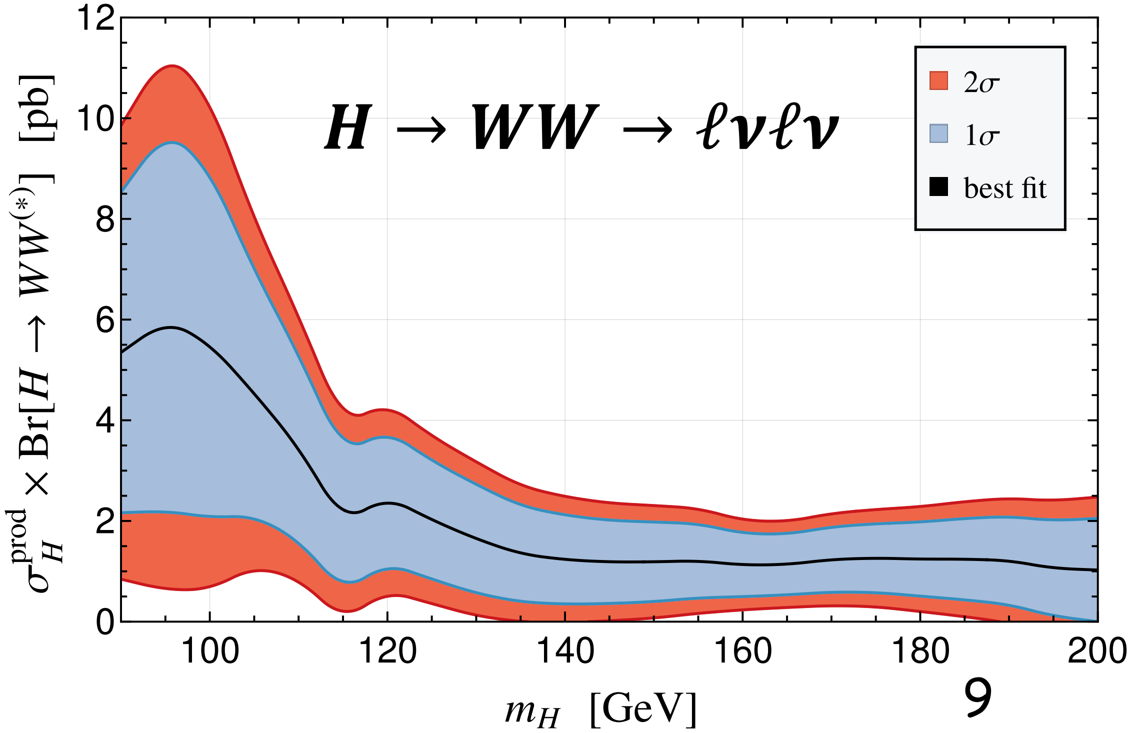




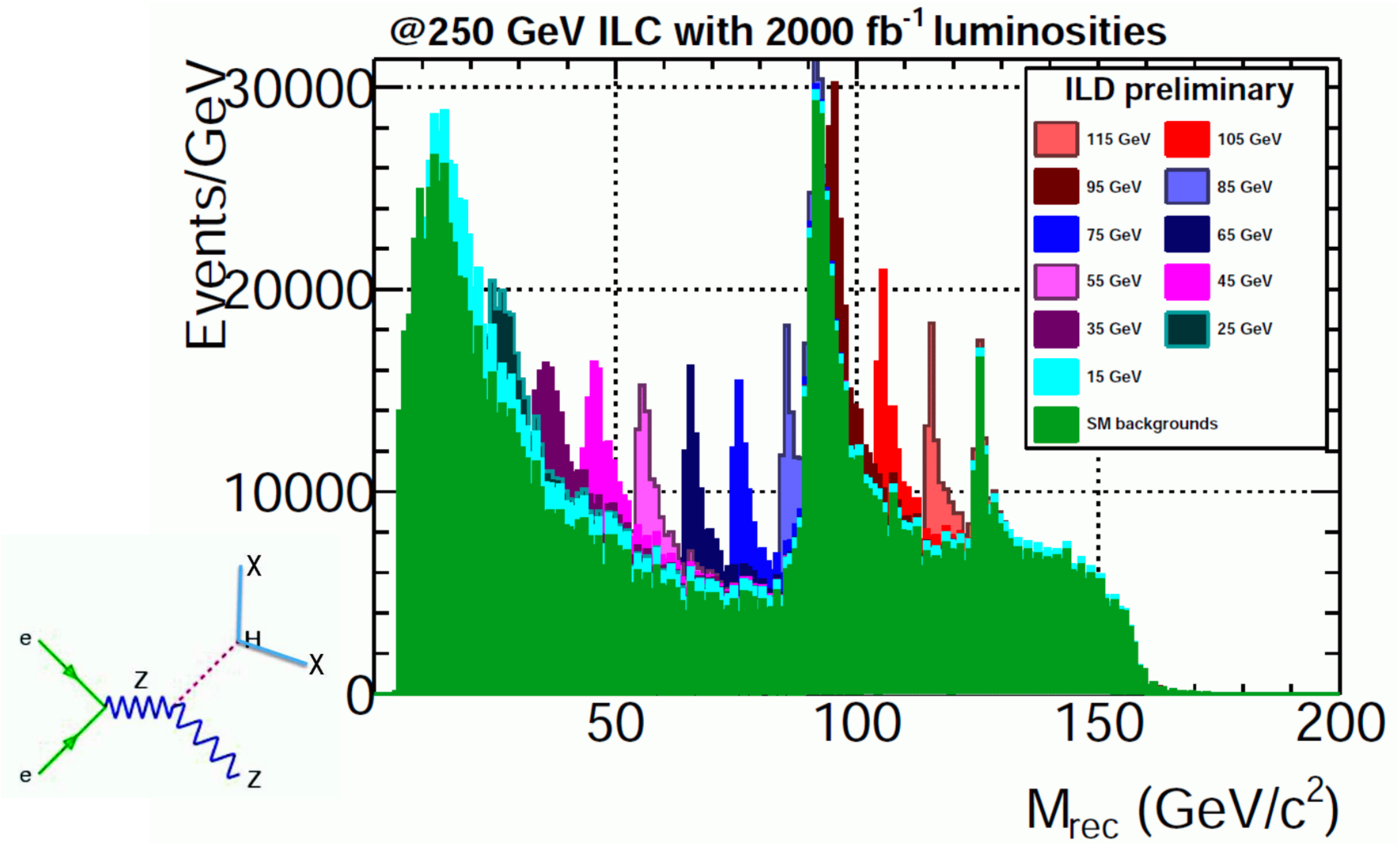


SM Higgs hypothesis alone. alone is having difficulty describing the ll+MET transverse mass spectra, giving room to other Higgs-like signals. Compatibility with other signals under study.



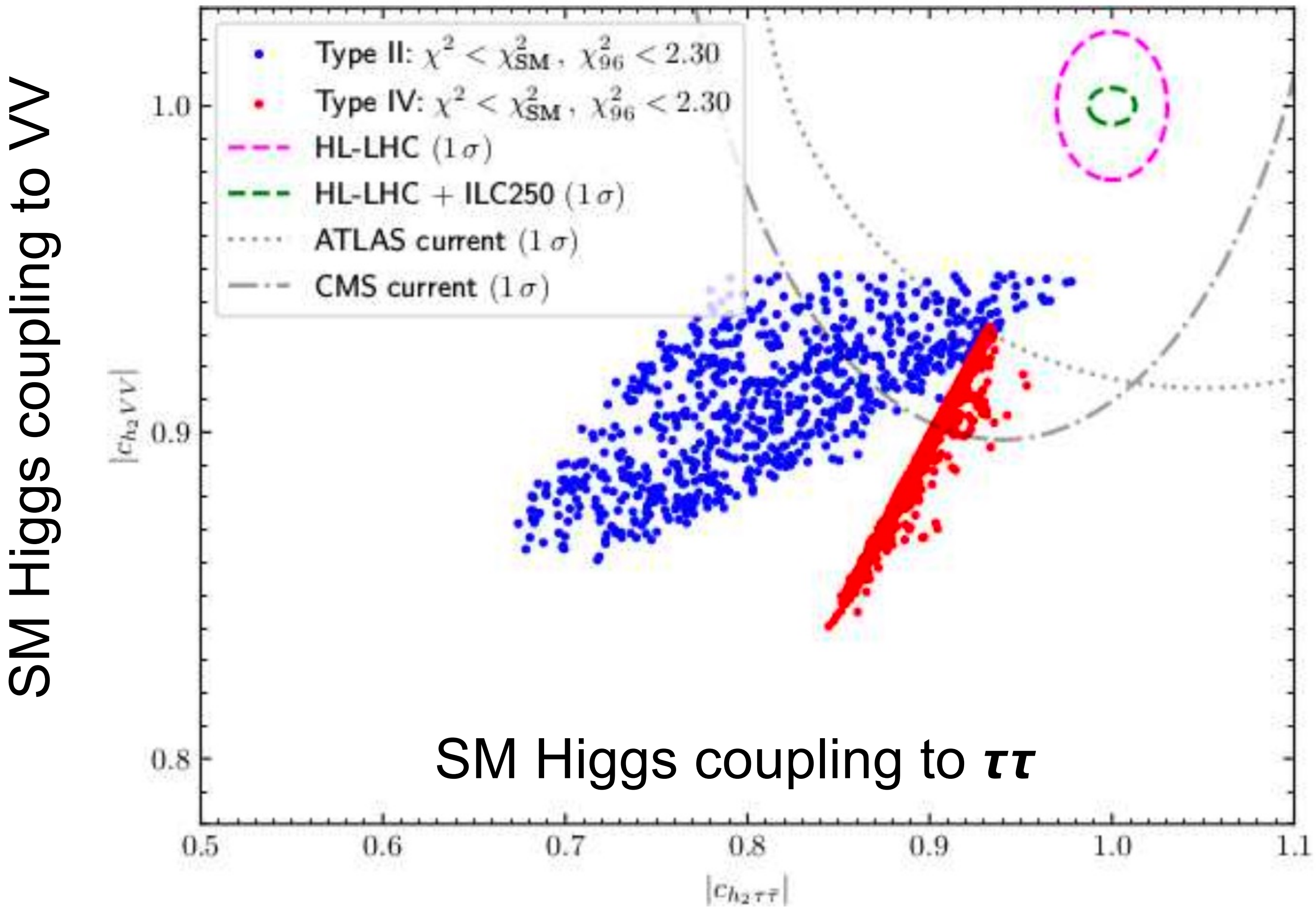


Search for invisibly decaying light Higgses via recoil method: [*Y. Wang et al. '18*]



HL-LHC/ILC h_{125} coupling measurements

[T. Biekötter, S.H., G. Weiglein – PRELIMINARY]



⇒ type II and IV show strong deviations from SM

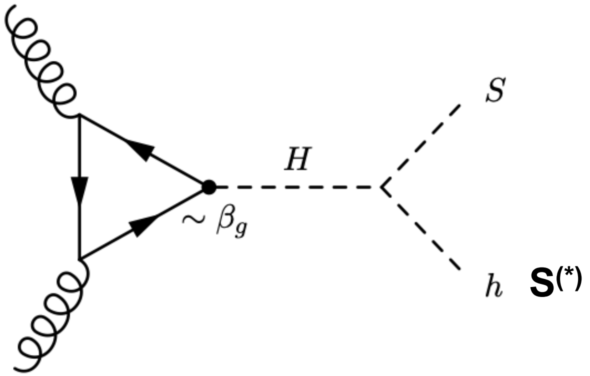
⇒ N2HDM can always be distinguished from SM at the ILC

The Multi-lepton Anomalies at the LHC

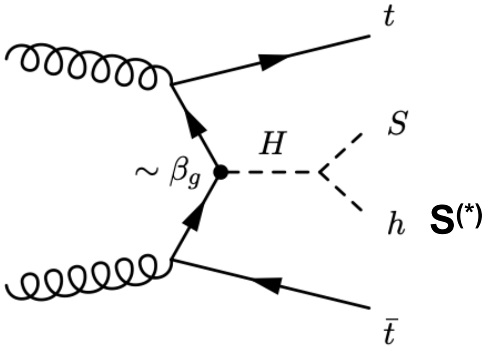
Eur. Phys. J. C (2016) 76:580

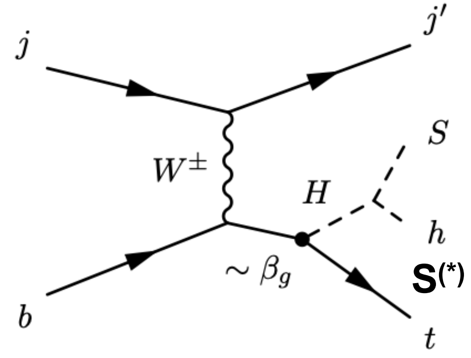
The simplified Model (from Run I)

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).



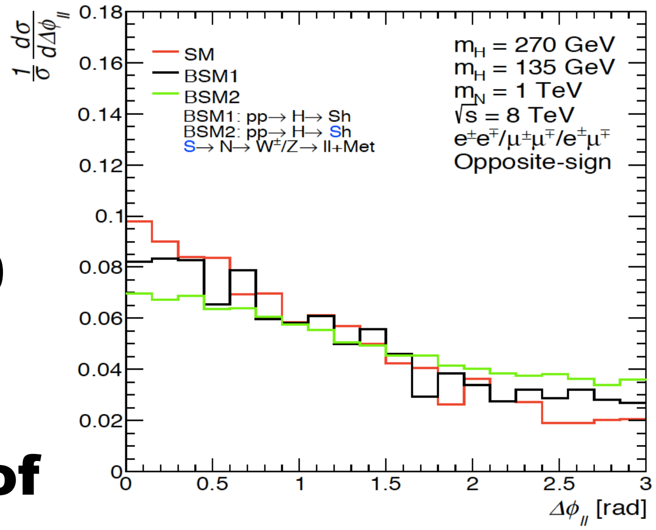


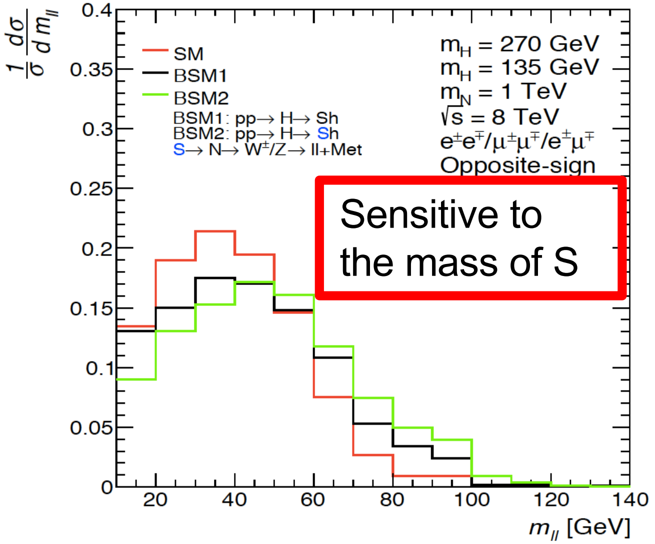
$$\mathcal{L}_{\text{int}} \supset -\beta_g \frac{m_t}{v} t\bar{t}H + \beta_V \frac{m_V^2}{v} g_{\mu\nu}\ V^{\mu}V^{\nu}H$$

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

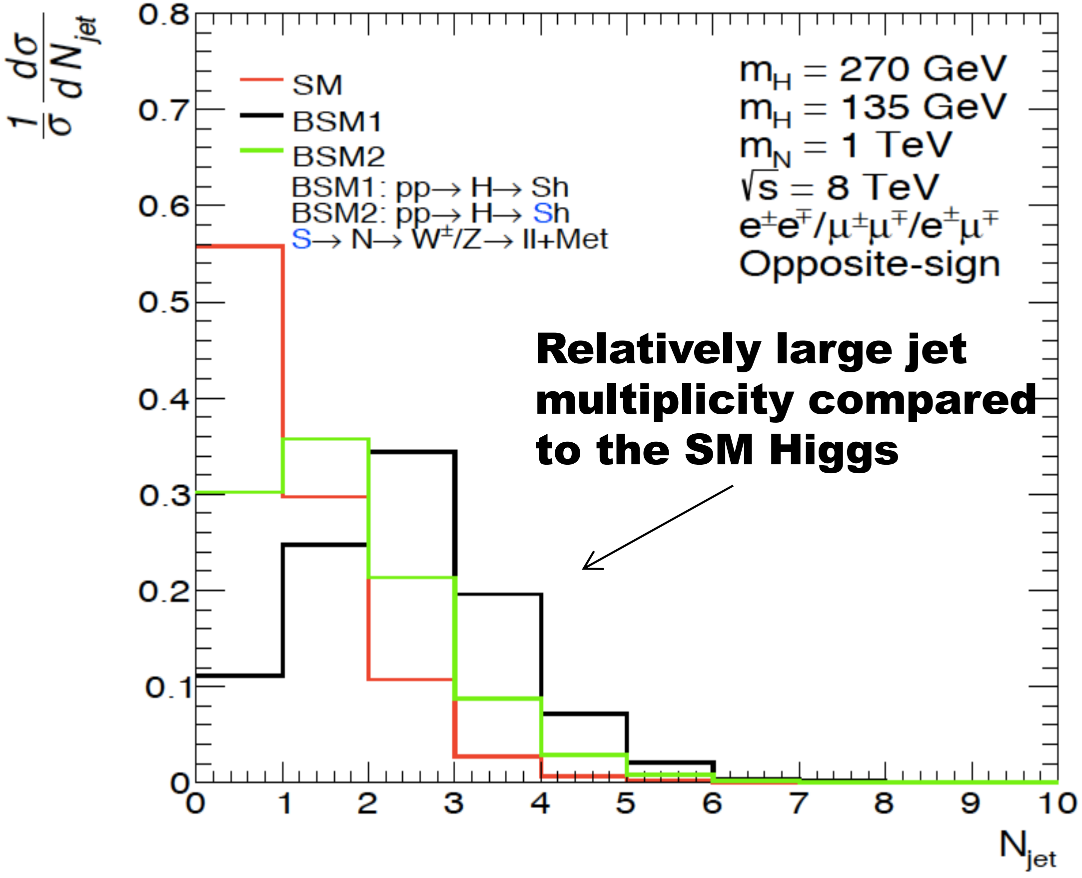
$pp \to H \to Sh, SS \to \ell^+ \ell^-$+X

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

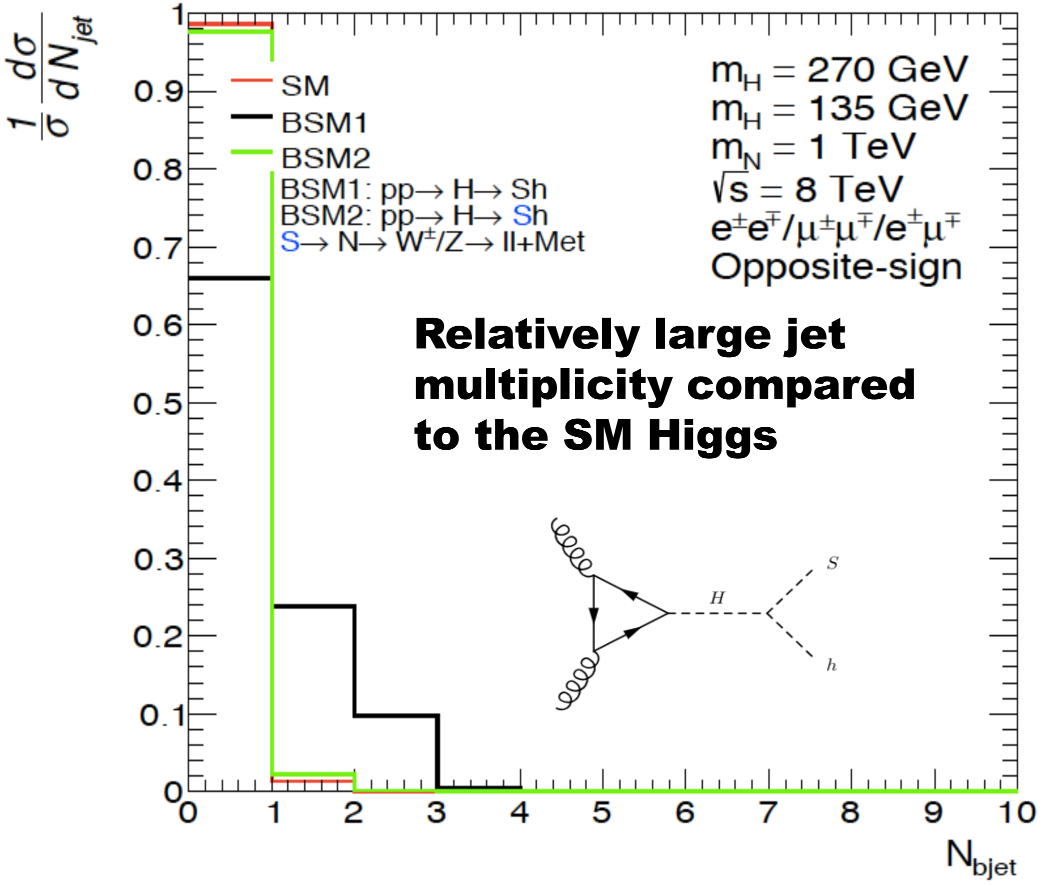




Sensitive to the mass of S



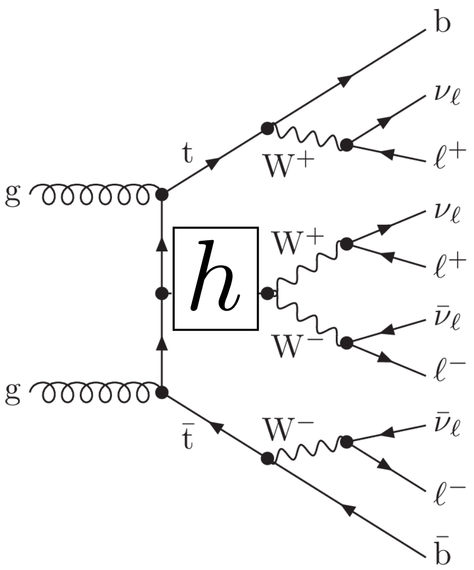
Relatively large jet multiplicity compared to the SM Higgs

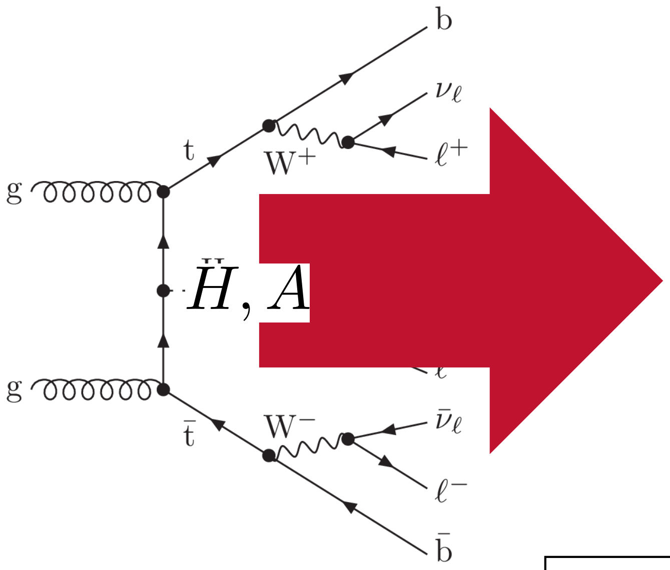


Relatively large jet multiplicity compared to the SM Higgs

Top associated Higgs production

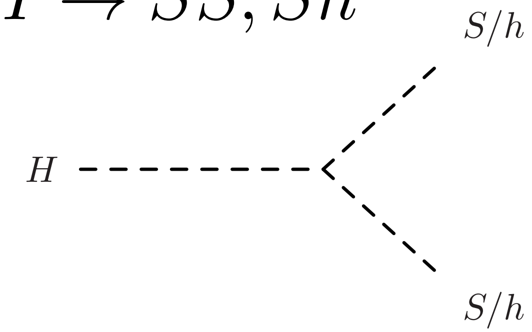
(Multi-lepton final states)





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

$$H \to SS, Sh$$



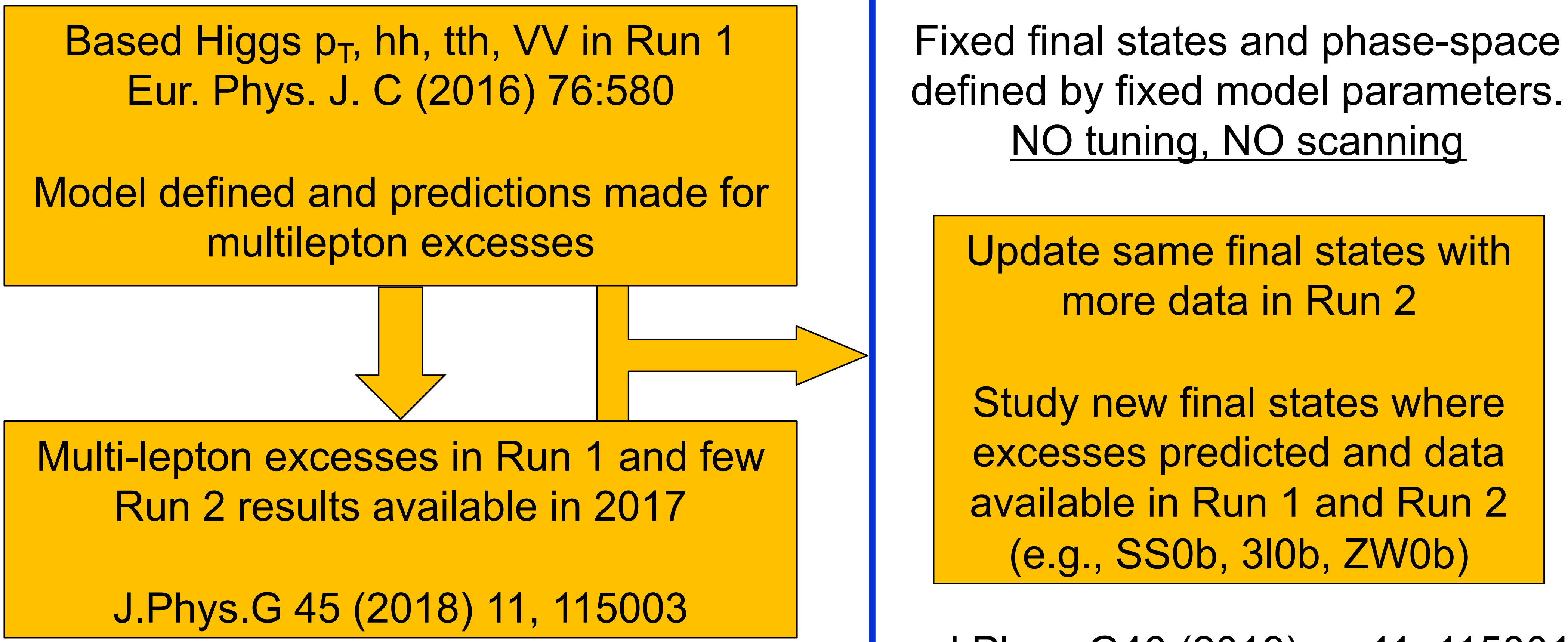
Reduced cross-section of ttH+tH is compensated by di-boson, (SS, Sh) decay and large Br(S→WW). Production of same sign leptons, three leptons is enhanced. Enhanced tH cross-section

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 <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

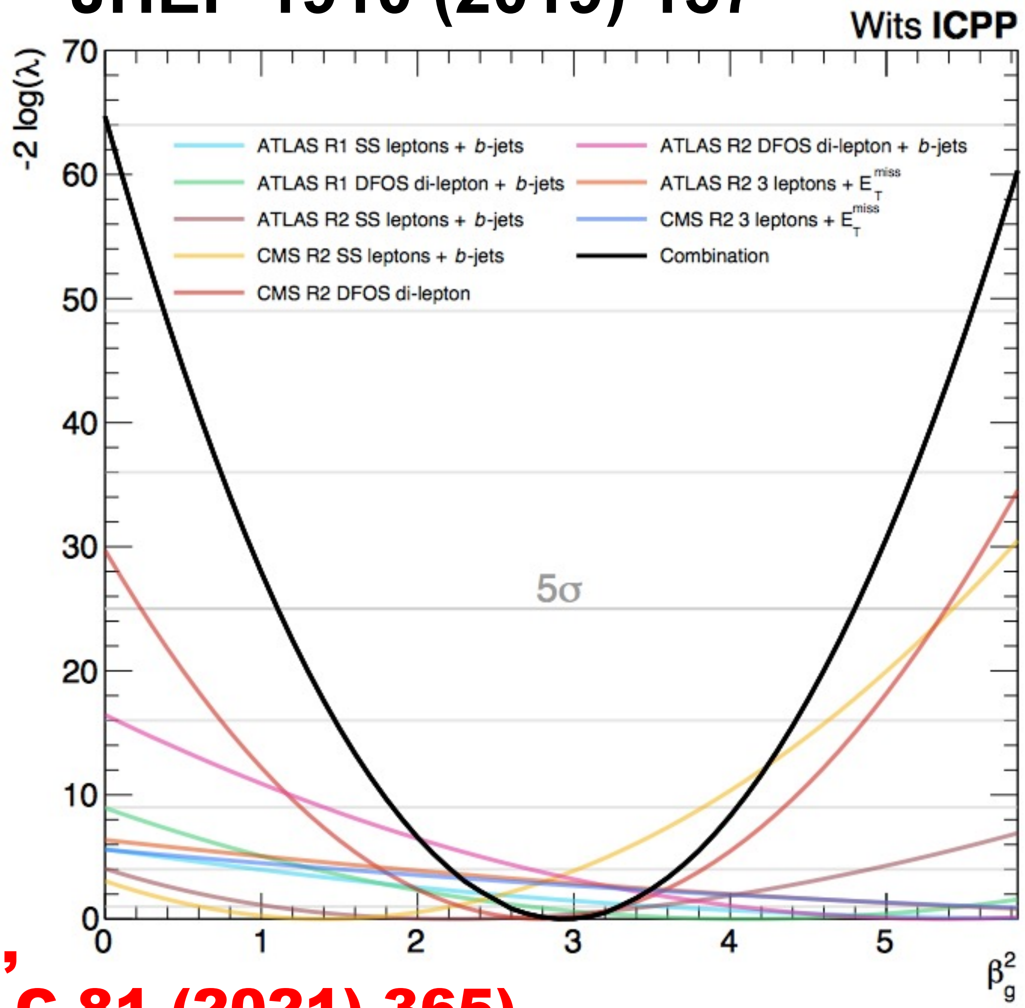
Combination of fit results (2019)

- **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

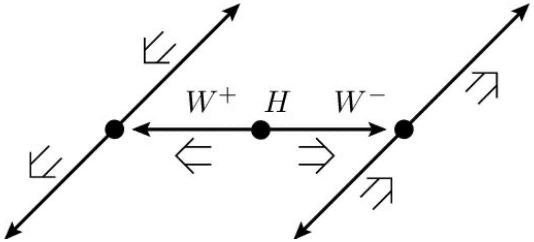
Anatomy of the multi-lepton anomalies (2023)

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	$\sim3\sigma$
$l^\pm l^\pm$ & $l^\pm l^\pm l$ + 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. Currently, every single type of excess has surpassed 3σ.

Prediction from the multi-lepton anomalies.
The di-lepton invariant mass is sensitive to the mass of S.
Assuming S→WW→llνν:

$$m_S = 150 \pm 5\ GeV$$



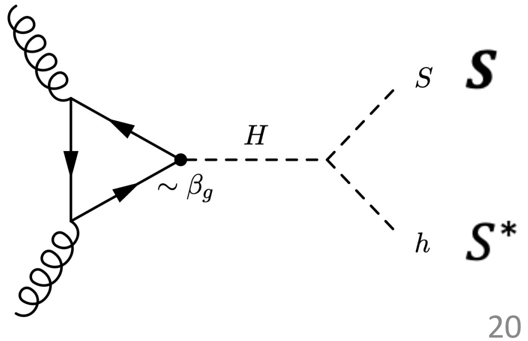
J.Phys. G45 (2018) no.11, 115003

The 151 GeV Candidate

Procedure

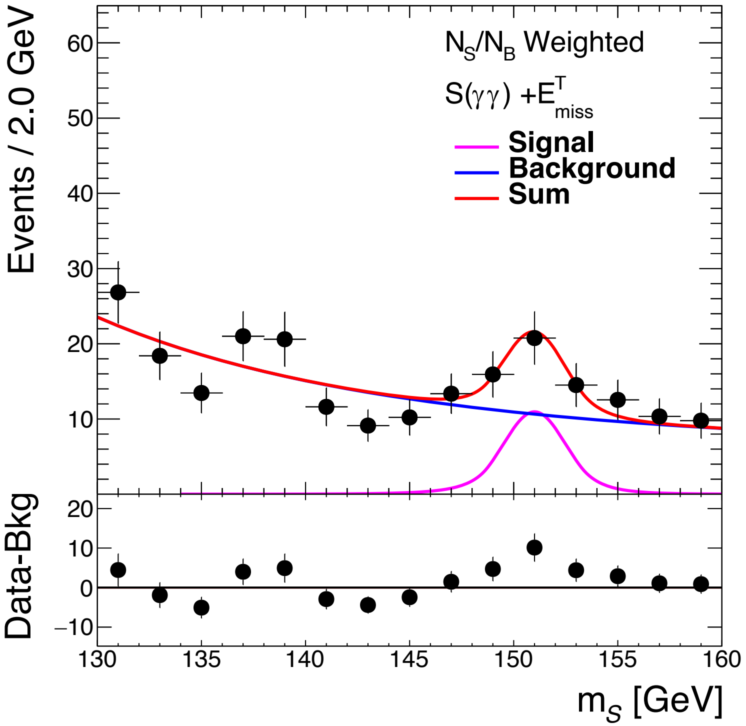
(avoiding “cherry picking”)

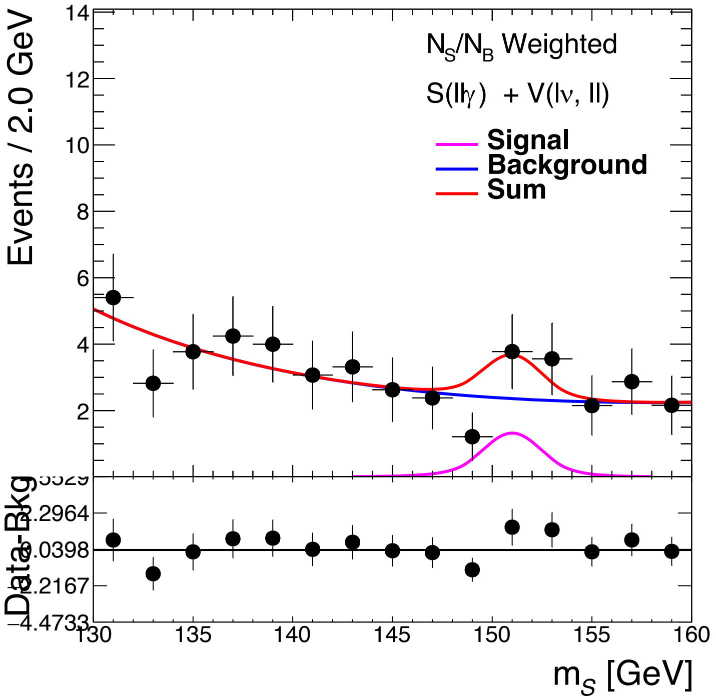
- **Setting a well-defined procedure is essential to the integrity of a search. Scanning nullifies significance**
- **From the di-lepton anomalies: $m_h < m_s < 170$ GeV**
  - **It is critical that search be localized and motivated**
- **Focus on $\gamma\gamma$ and $Z\gamma$ decays**
- **As per the model 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**

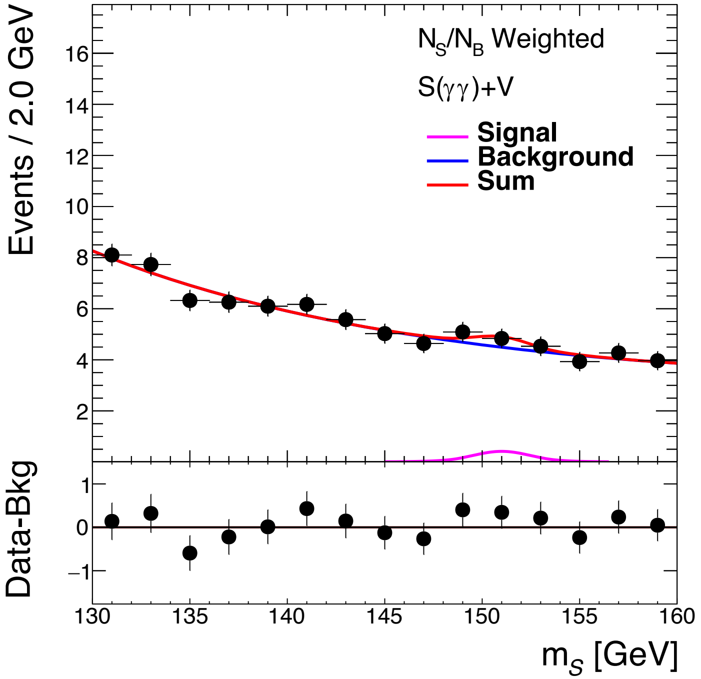


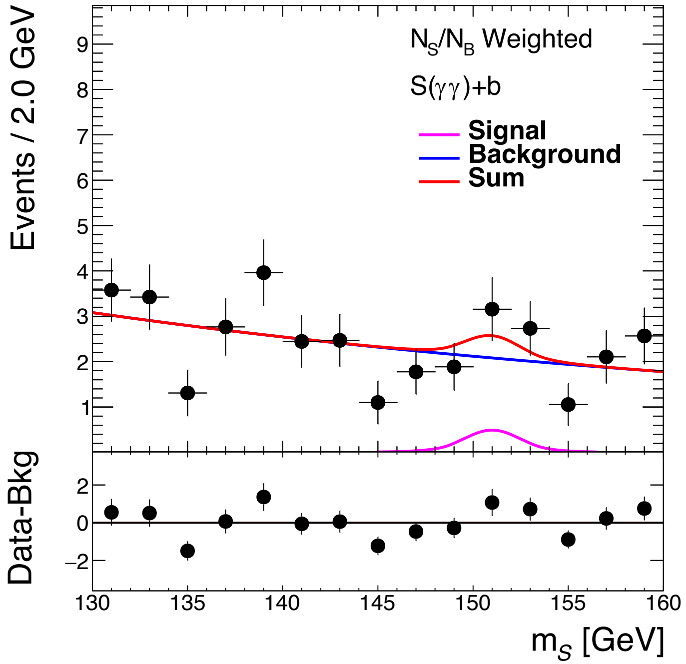
From Run 1 multi-lepton excesses model-dependent prediction of $m_s = 150 \pm 5$ GeV

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



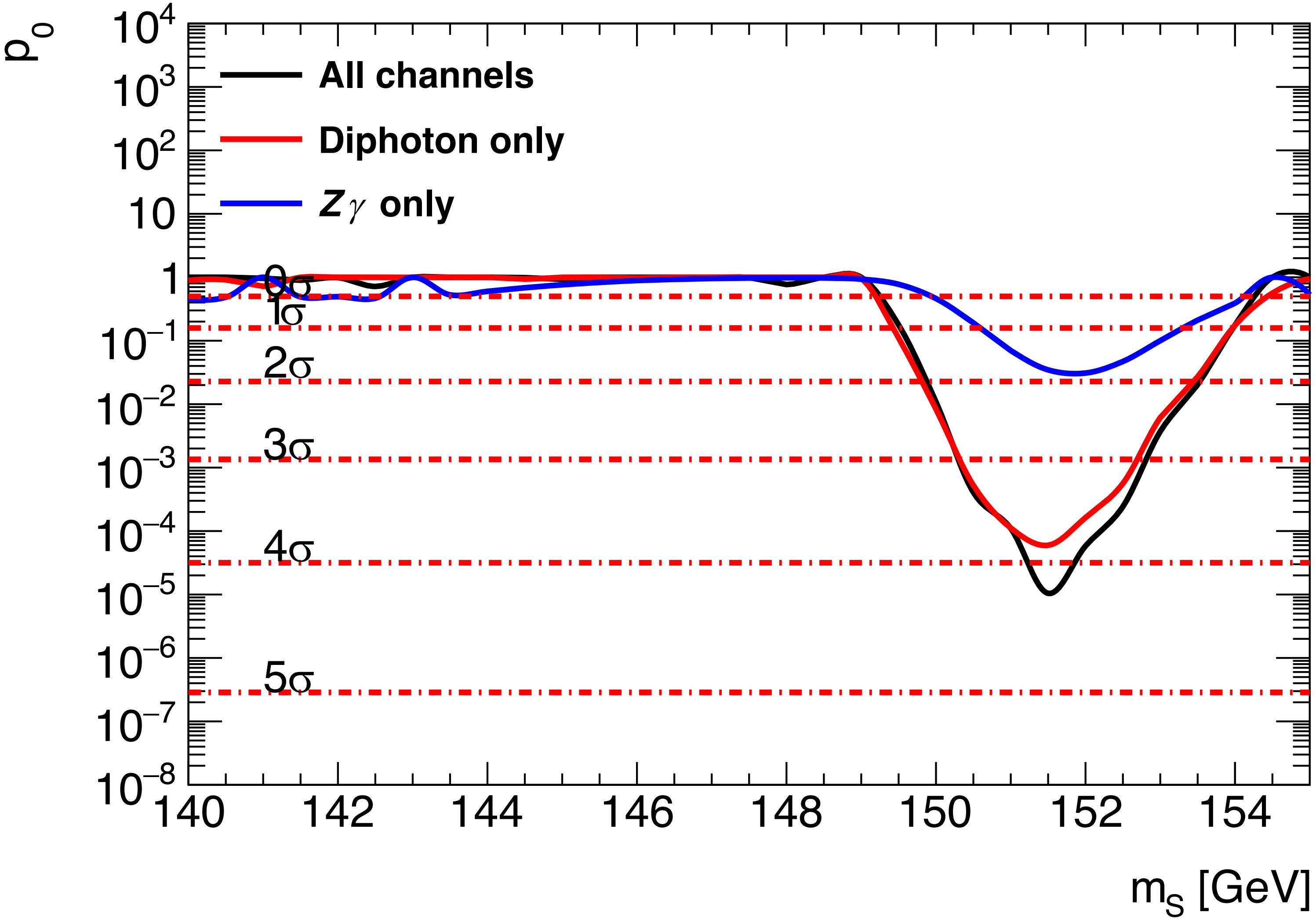






Excesses appear in both ATLAS and CMS data, in associated production

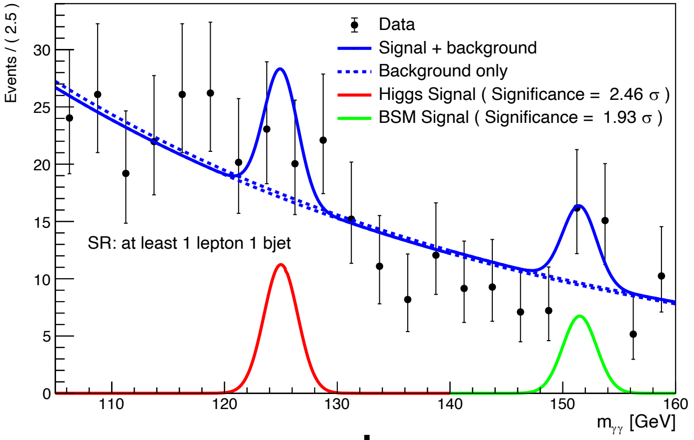
Result is obtained with public results from the LHC experiments. Using a simplified model and two degrees of freedom to include the decay of S→MET and residual LEE, global significance goes to 3.9σ at 151.5 GeV.



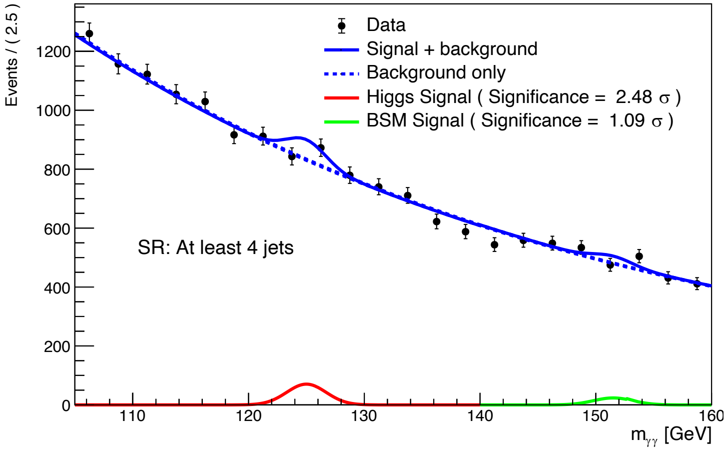
New excesses @151.5 GeV that appeared after the first combination (see above) in topologies consistent with associated production:

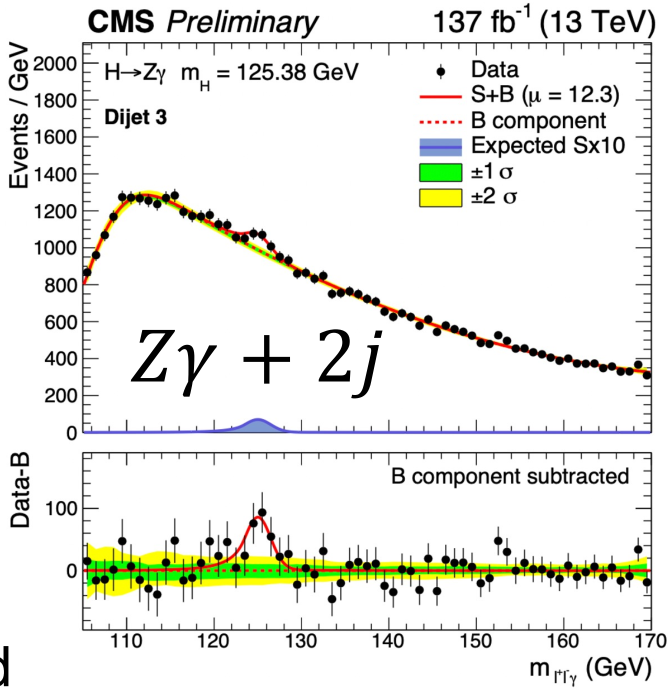
CMS-PAS-HIG-19-014

$\gamma\gamma + l + b$



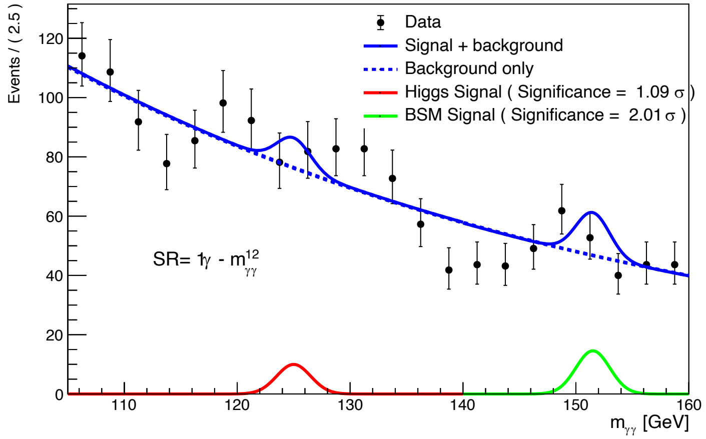
$\gamma\gamma + 4j$





$Z\gamma + 2j$

$\gamma\gamma + \gamma$

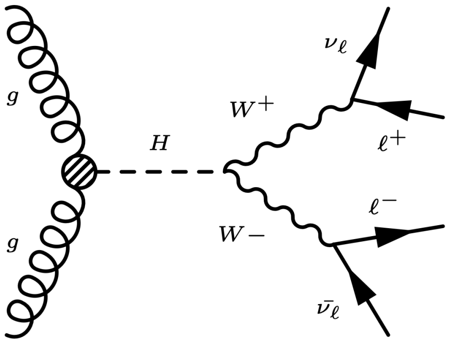


Excesses appear in corners of the phase-space predicted by the naive H→ SS* model with S being SM Higgs-like. In addition, seem to see S in association with MET and, possibly, with an extra photon

Bin for associated production VH, ttH, where excess is seen with di-photons.

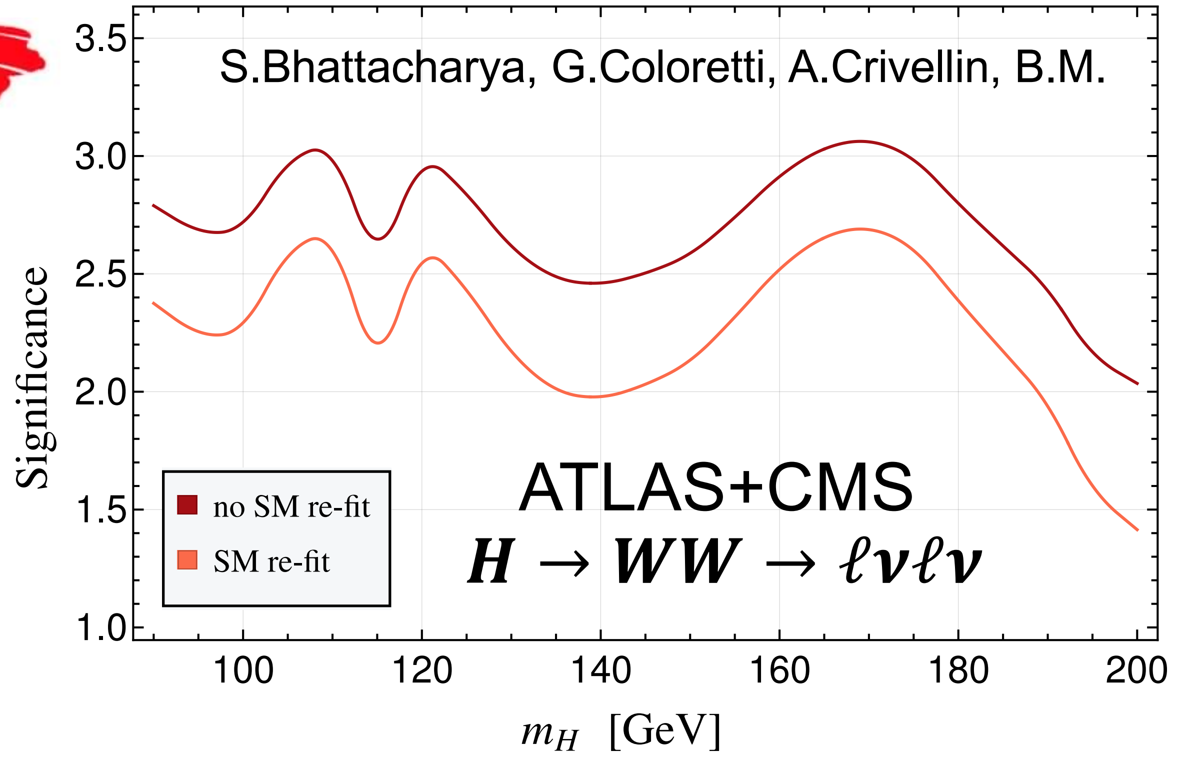
NEW

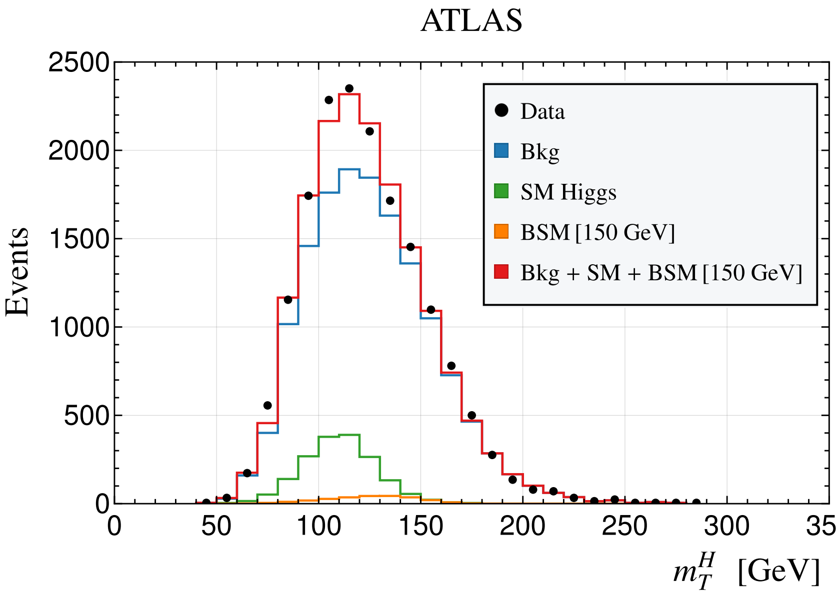
ATLAS, arXiv:2301.10486

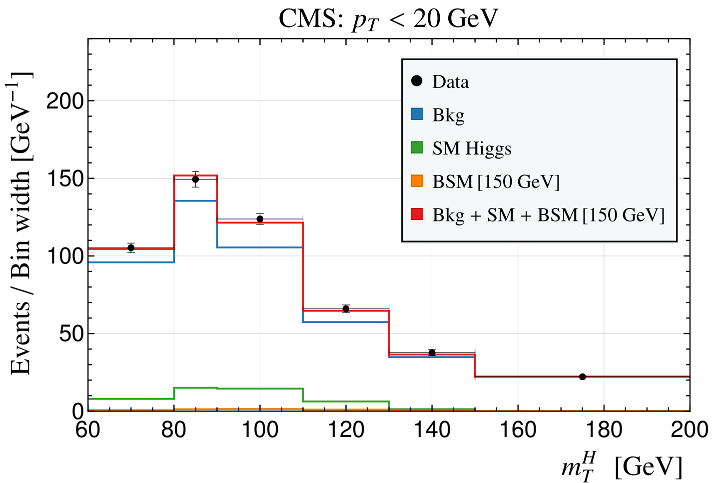


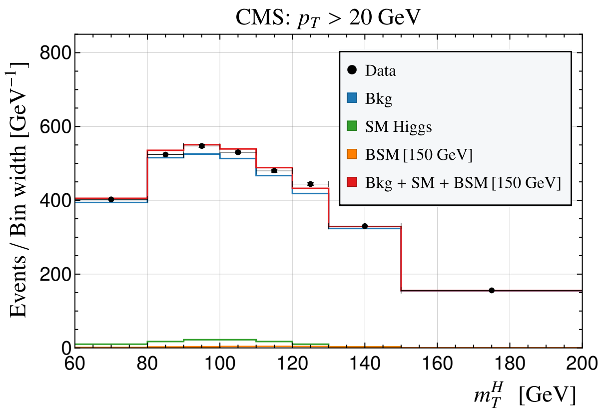
NEW

SM Higgs hypothesis alone. alone is having difficulty describing the ll+MET transverse mass spectra, giving room to other Higgs-like signals, including S(151).









Currently, interpreting the broad excess in terms of H→S+MET, which appears to be the leading final state in excess described above

Excesses ~650-700 GeV

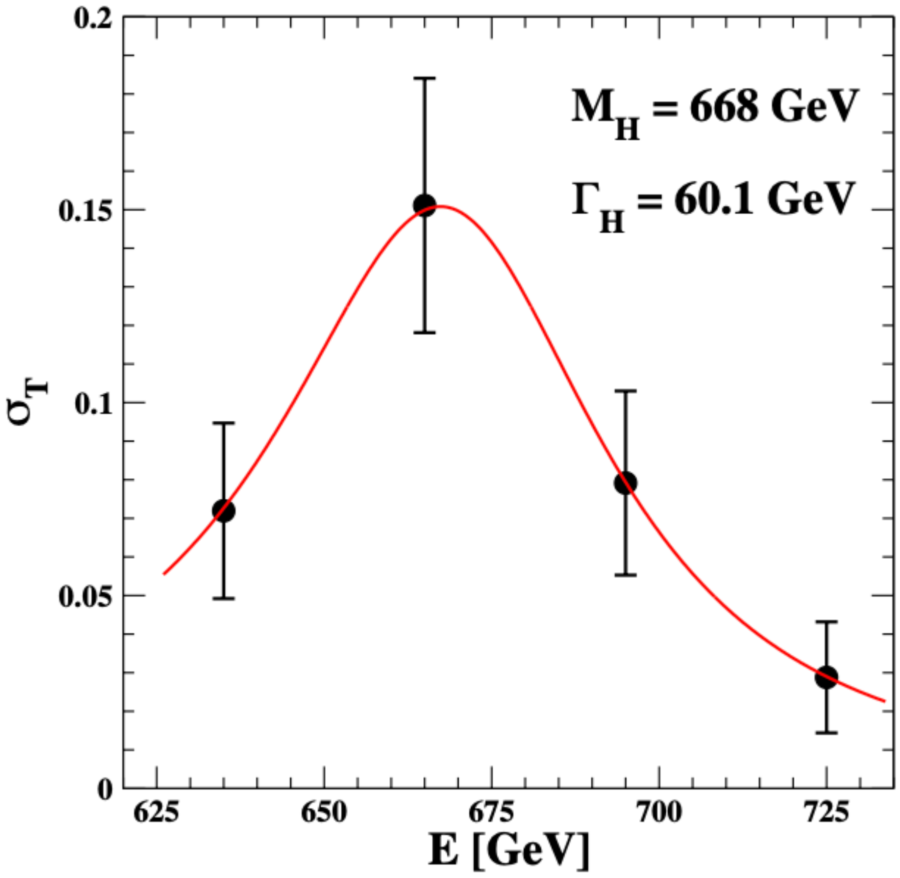
M. Consoli, L. Cosmai, PoS (ICHEP2022) 204

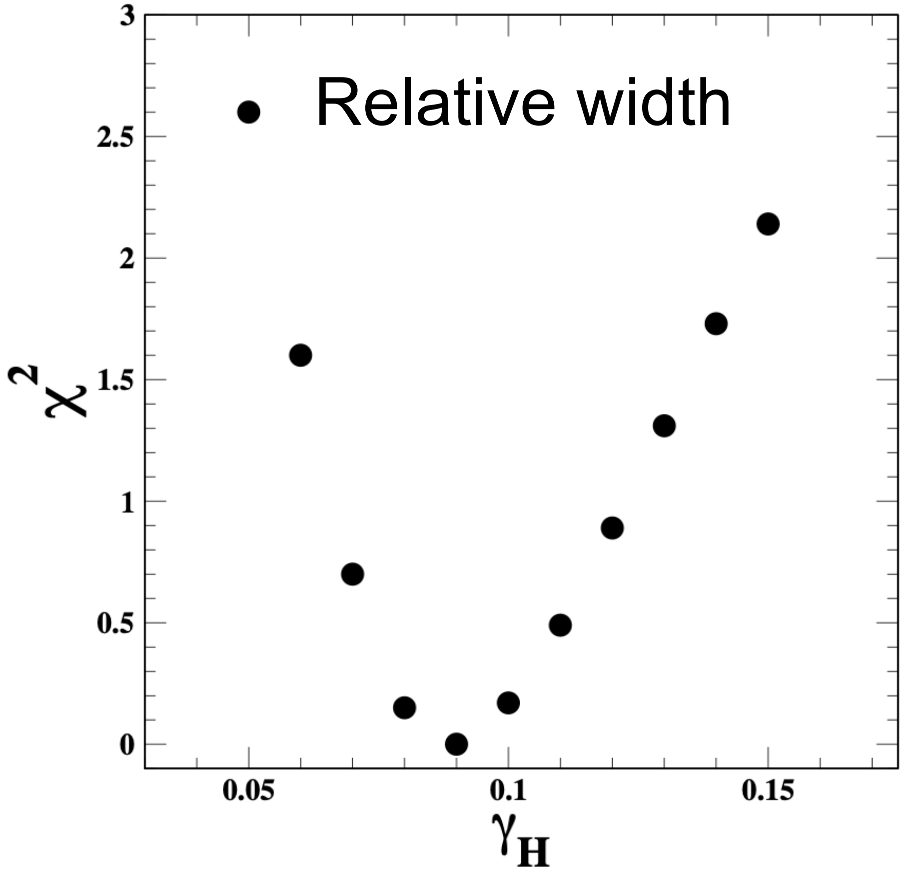
$$H \to ZZ \to 4\ell$$

ATLAS, Eur. Phys. J. C 81 (2021) 332

Authors looked at ATLAS 4l lepton events the m_{4l} on range 620-740 GeV, based on theoretical considerations:

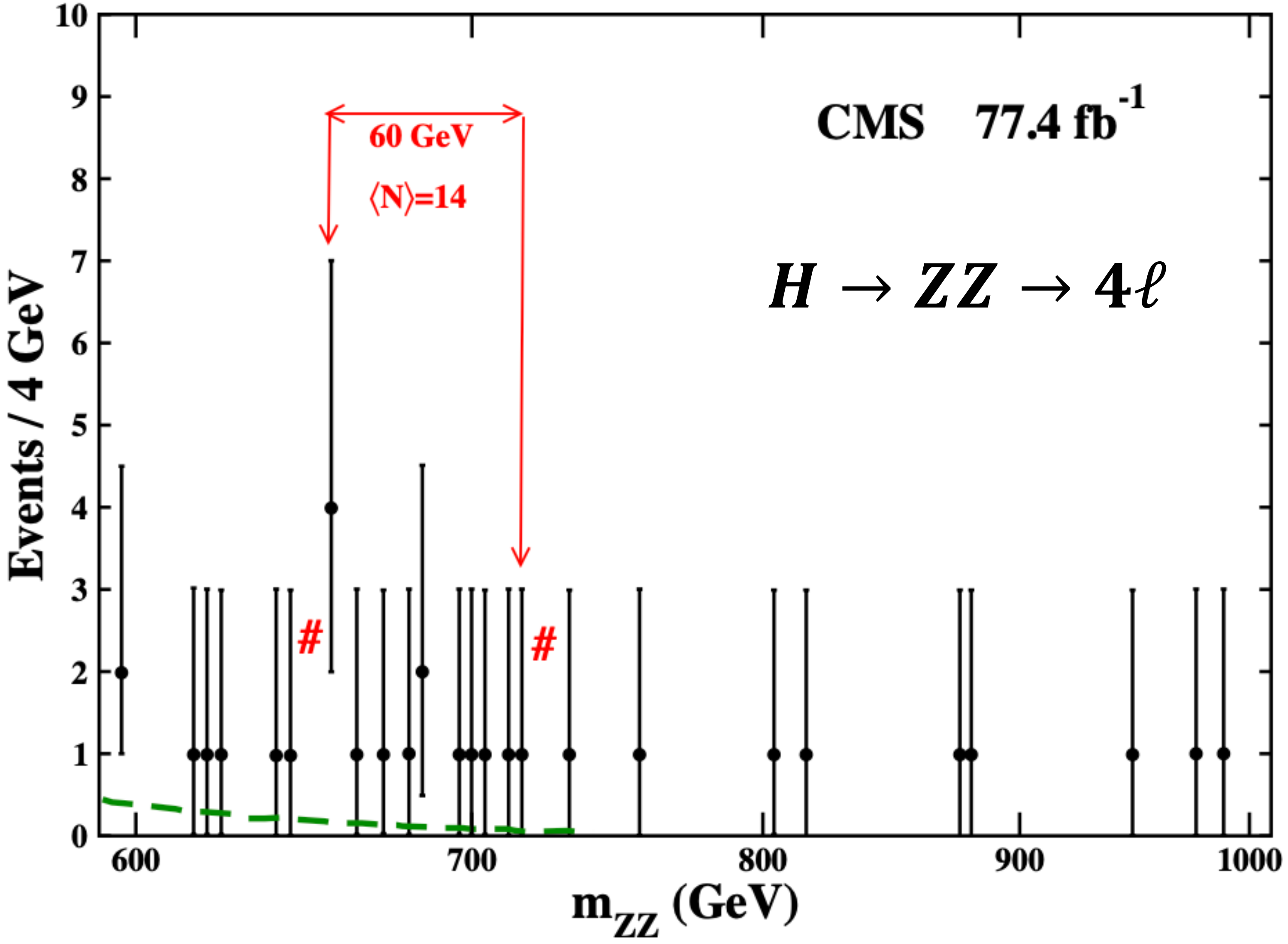
$$(M_H)^{\text{Theor}} = 690 \pm 10\ (\text{stat}) \pm 20\ (\text{sys})\ \text{GeV}$$

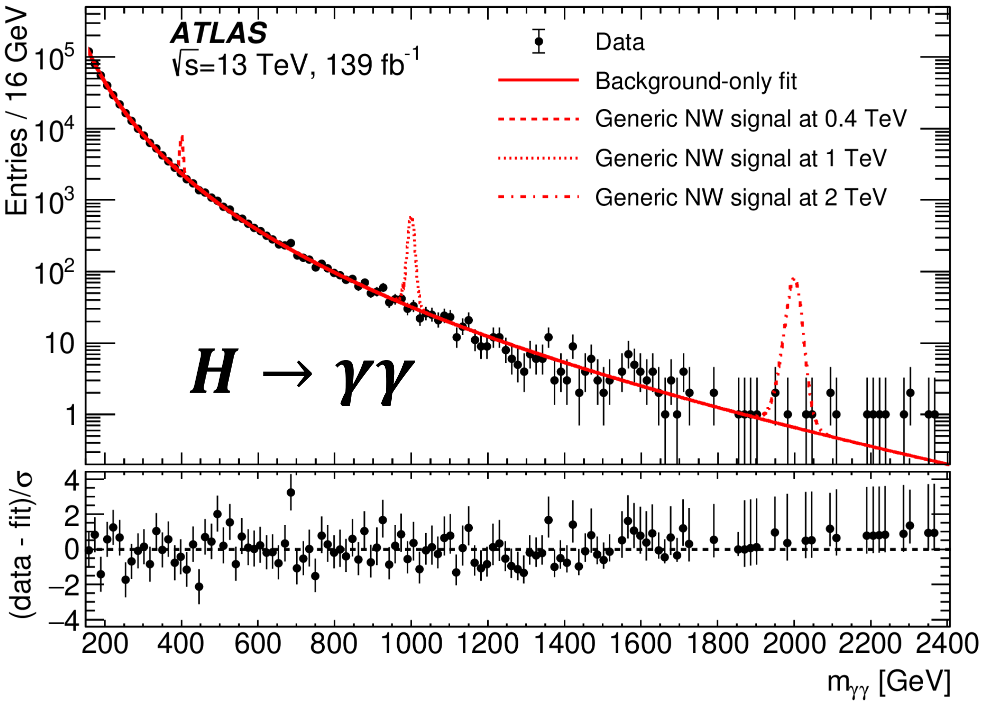




CMS PAS HIG-18-001

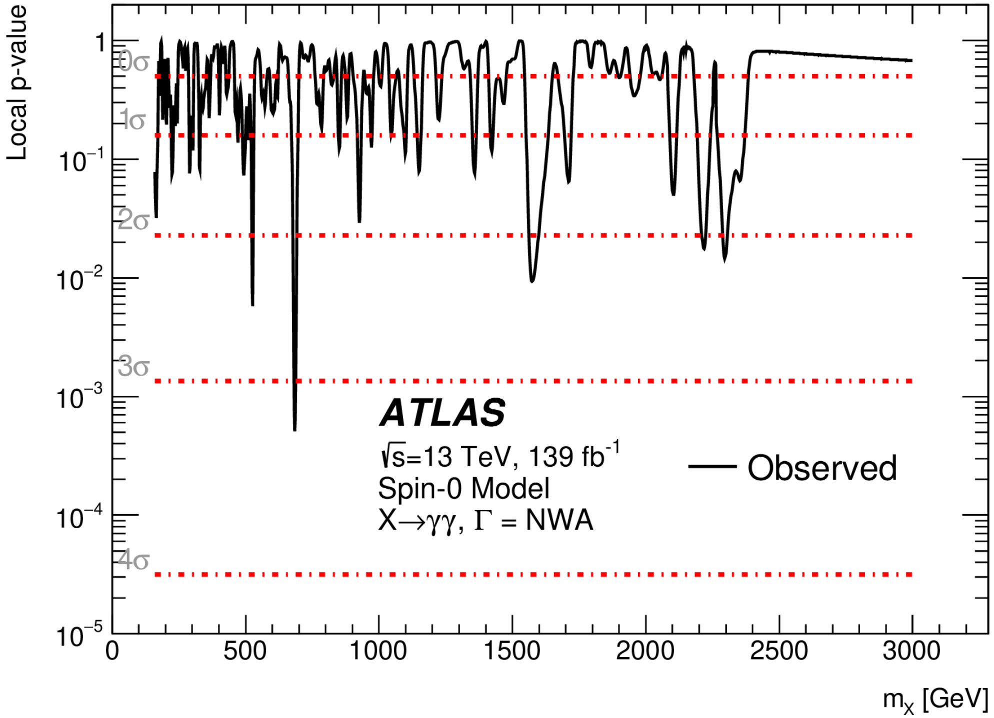
M. Consoli, L. Cosmai, *Int.J.Mod.Phys.A* 37 (2022) 14, 2250091

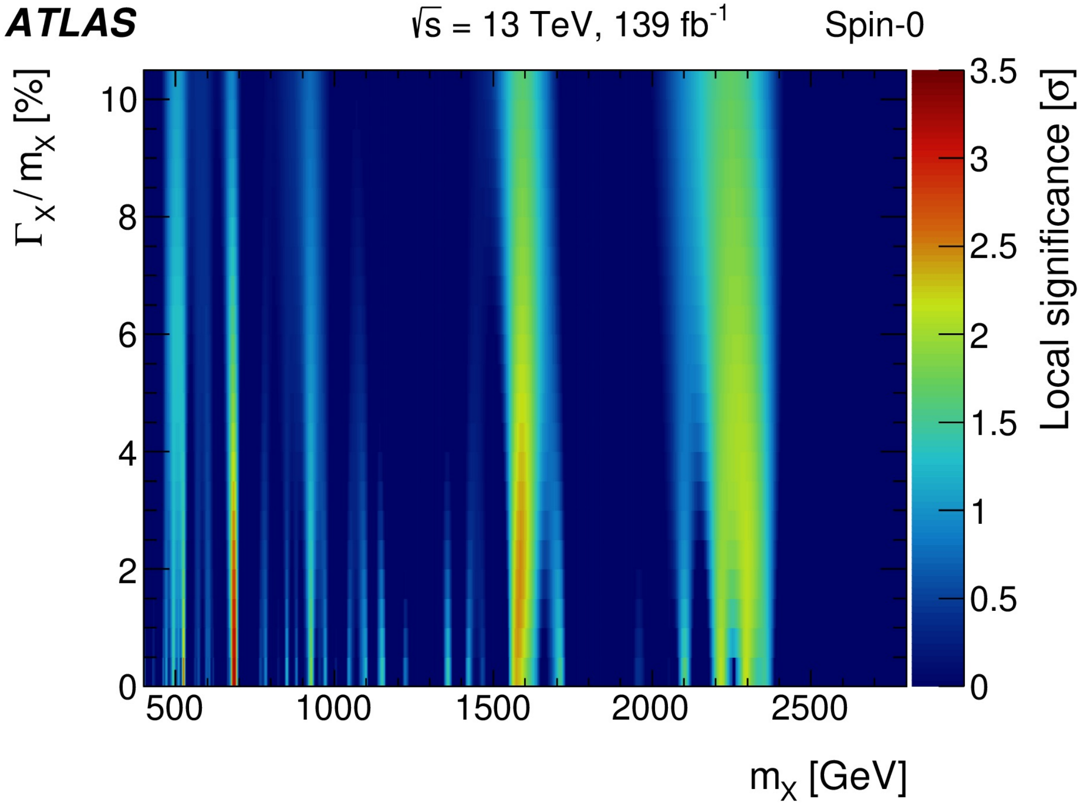




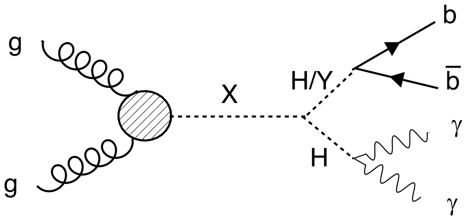
ATLAS, Phys. Lett. B 822 (2021) 136651

ATLAS sees an excess in the di-photon spectrum with local (global) significance of 3.3 (1.3) σ at 684 GeV. Excess is narrow, though.

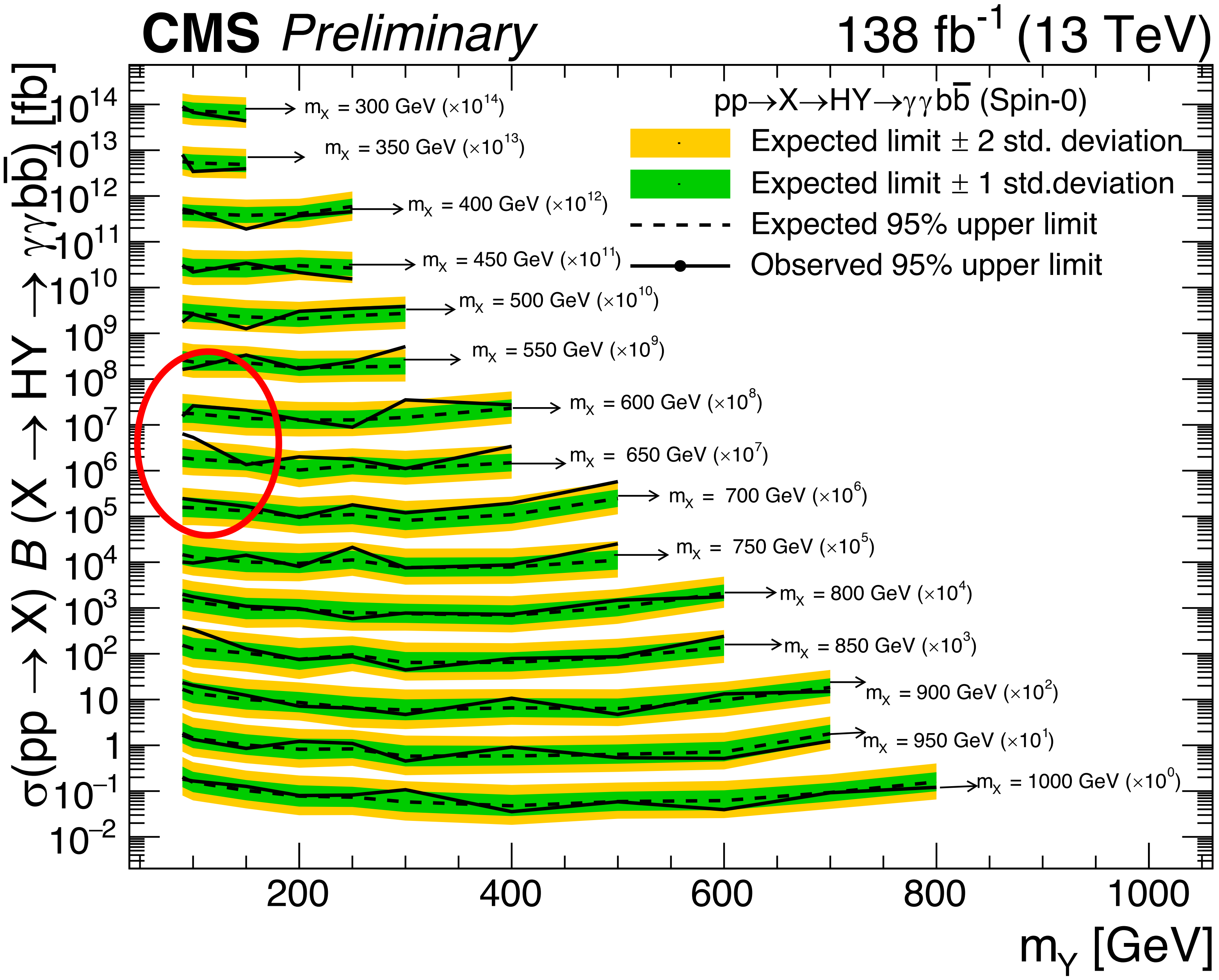




CMS-PAS-HIG-21-011



Excess with local (global) significance of 3.8 (2.8) σ for m_X=650 GeV and m_Y=90 GeV



The importance of two and multi-body decays for the (HL)-LHC

- ❑ **Certain types of two-body decays are unexplored in important regions of the phase-space:**

$$A \to BC \qquad A \to BB^*$$

- ❑ **Other types of topologies are also unexplored**

$$A \to BB^{(*)} \to C + X$$

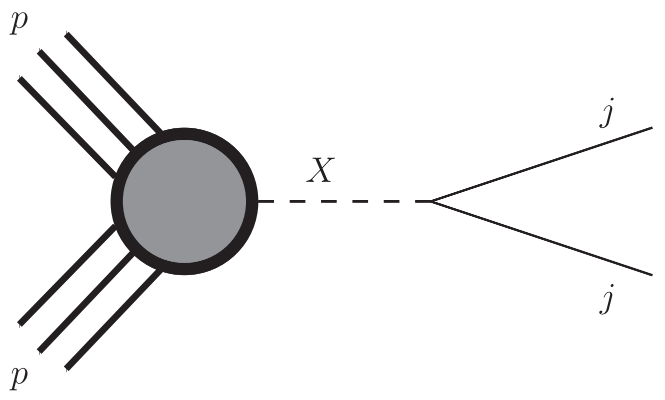
- ❑ **Machine Learning techniques, such as weak supervision, relevant to minimize model dependence, not used to its fullest potential**

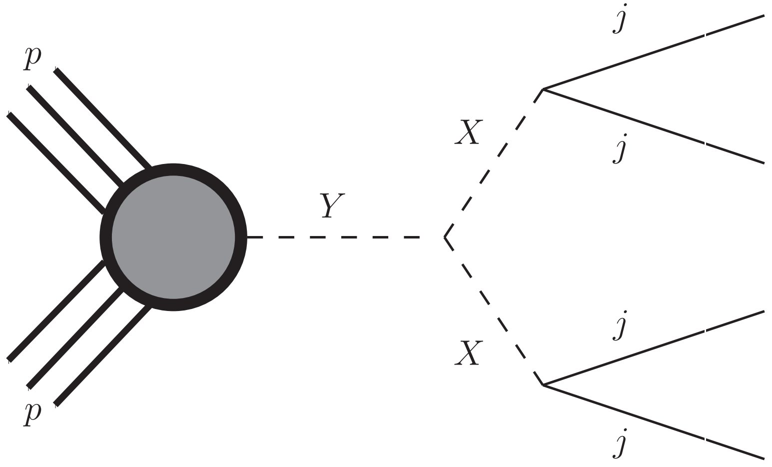
Excesses at the TeV Scale

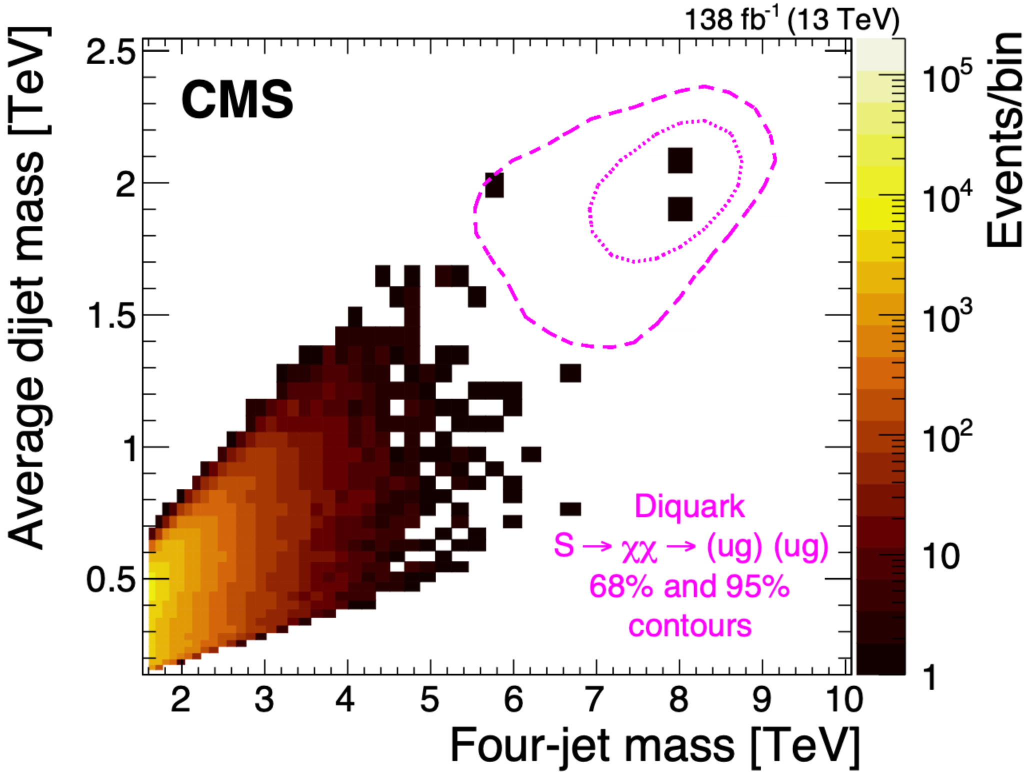
CMS, arXiv:2206.09997

Search for resonant and non-resonant production of pairs of di-jet resonances

$$\alpha = \frac{m_1 + m_2}{2 \cdot m_{4j}}$$



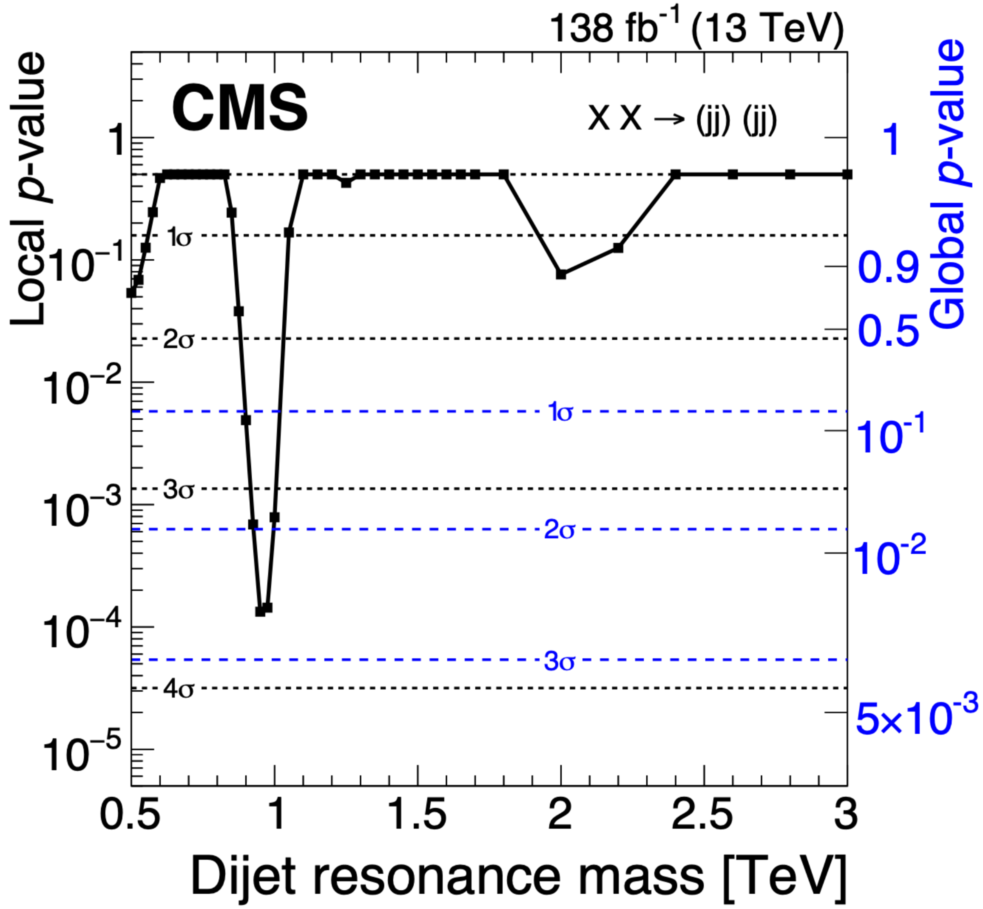


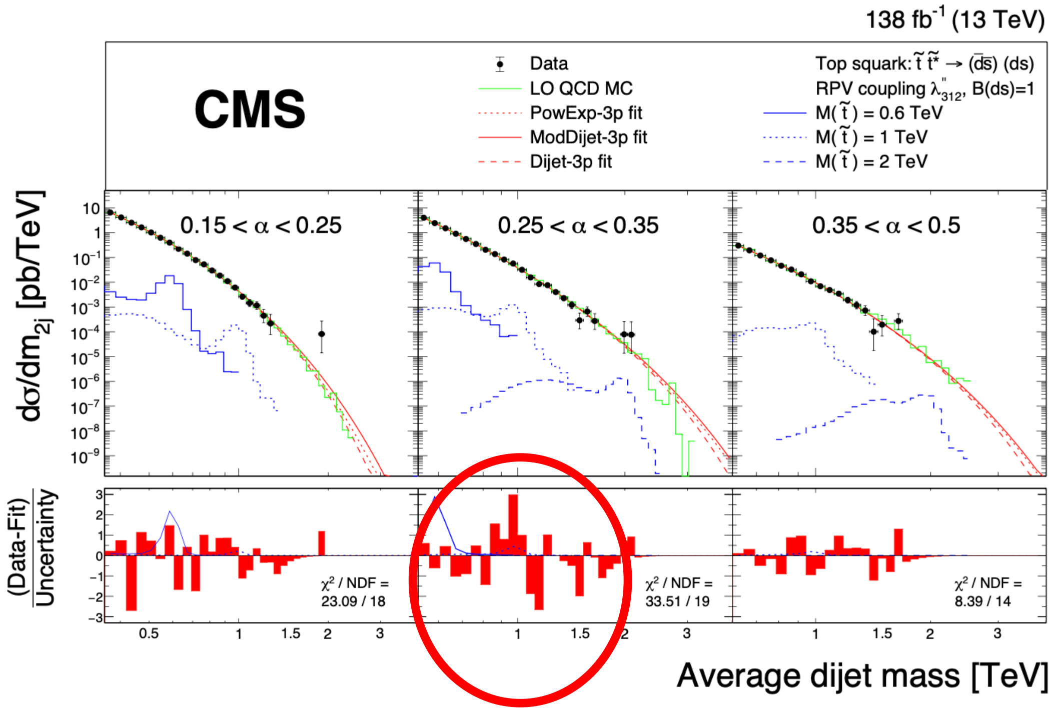


The dotted and dashed curves show the 68% and 95% probability contours, respectively, from a signal simulation of a diquark with a mass of 8.4 TeV, decaying to a pair of vector-like quarks, each with a mass of 2.1 TeV

CMS sees an excess with local (global) 3.6 (2.5) $\boldsymbol{\sigma}$ at 0.95 TeV in the non-resonant search. No results from ATLAS available

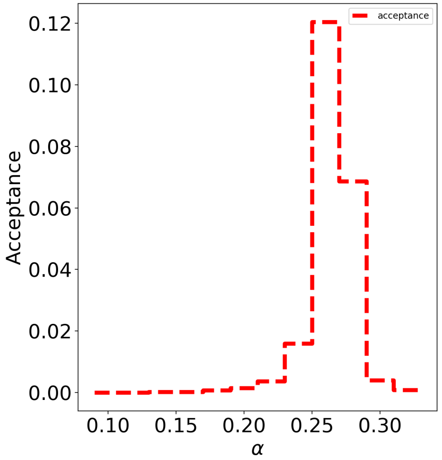
However, most of the excess appears in the range 0.25<$\boldsymbol{\alpha}$<0.35, consistent with a two-body decay (see next slide)



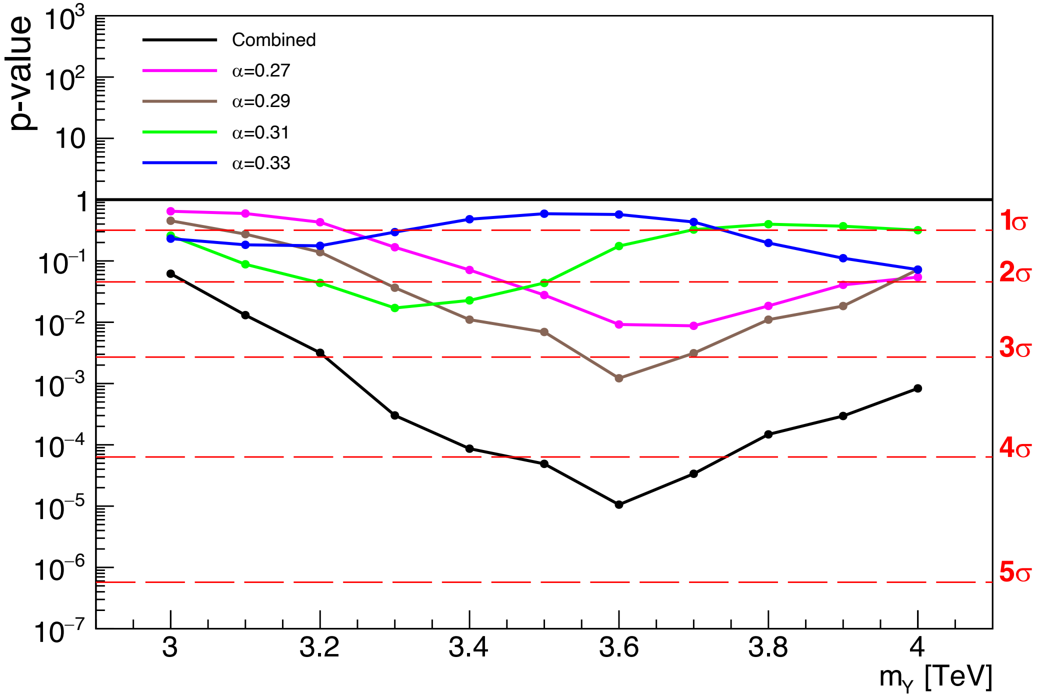


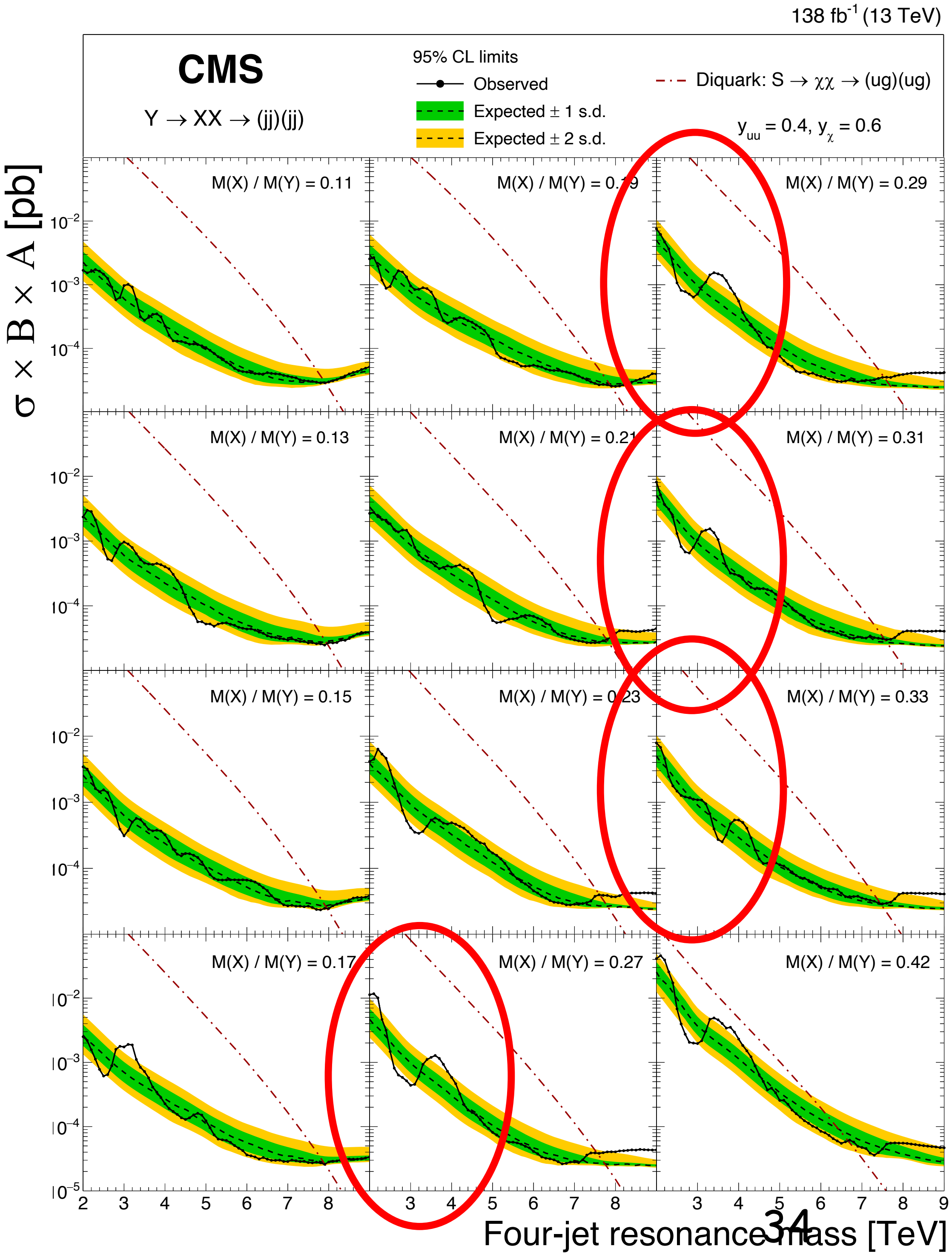
A. Crivellin, et al. arXiv:2208.12254

Simulation of Y(3.5)→XX, m_X=1 TeV



See local (global) 4.4 (3.6) ***σ*** at m_Y=3.6 TeV.





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]

[1] *Department of Mathematical Sciences, University of Liverpool, Liverpool, L69 7ZL, UK*
[2] *School of Physics and Institute for Collider Particle Physics, University of the Witwatersrand, Johannesburg, Wits 2050, South Africa.*
[3] *iThemba LABS, National Research Foundation, PO Box 722, Somerset West 7129, South Africa.*
[4] *Department of Physics, University of Basel, Klingelbergstr. 82, CH-4056 Basel, Switzerland*
[5] *Paul Scherrer Institut, CH–5232 Villigen PSI, Switzerland*
[6] *CERN Theory Division, CH–1211 Geneva 23, Switzerland*
[7] *Dipartimendto di Fisica "E. Fermi", Università di Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy*
[8] *INFN Sezione di Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy*
[9] *Siena College, 515 Loudon Road, Loudonville, NY 12211-1462, United States*
[10] *Dipartimendto di Fisica e Chimica, Università di L'Aquila, 67100 Coppito, L'Aquila, Italy*
[11] *INFN, Laboratori Nazionali del Gran Sasso, 67100 Assergi, L'Aquila, Italy*
[12] *Institute for Astroparticle Physics (IAP), Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany*
[13] *Institute for Theoretical Particle Physics (TTP), Karlsruhe Institute of Technology, Engesserstrasse 7, D-76128 Karlsruhe, Germany*

Summary

Mass	Decay channels	Global σ
96 GeV	bb, $\gamma\gamma$, $\boldsymbol{\tau\tau}$, ll+MET	> 4
Multi-lepton anomalies, (H→SS$^{(*)}$,Sh)	l^+l^- (w & w/o b), $l^\pm l^\pm$,3l (w & w/o b)	> 8
151 GeV	$\gamma\gamma$, Zγ, ll+MET + objects in associated production	> 4
650-700 GeV	ZZ, $\gamma\gamma$, WW(?),	?
1, 3.6 TeV	Di-jets, di-dijets	2.5, 3.6

The 96 and 151 GeV candidates, directly accessible at e^+e^- Higgs boson factories. Need to exploit topologies at (HL)-LHC that remain for the most part unexplored:

$$\boldsymbol{A \to BC \quad A \to BB^* \quad A \to BB^{(*)} \to C + X}$$

Additional Slides

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 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**

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

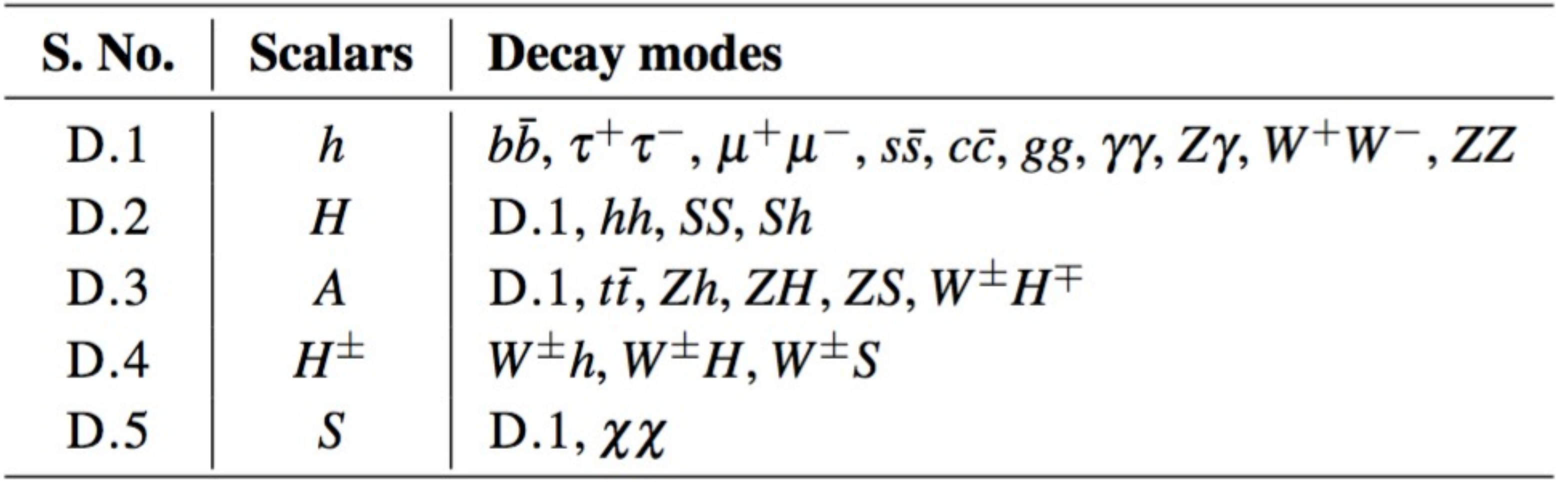
$$+ \quad H \to SS, Sh, hh$$

Dominant decays

Diboson decay

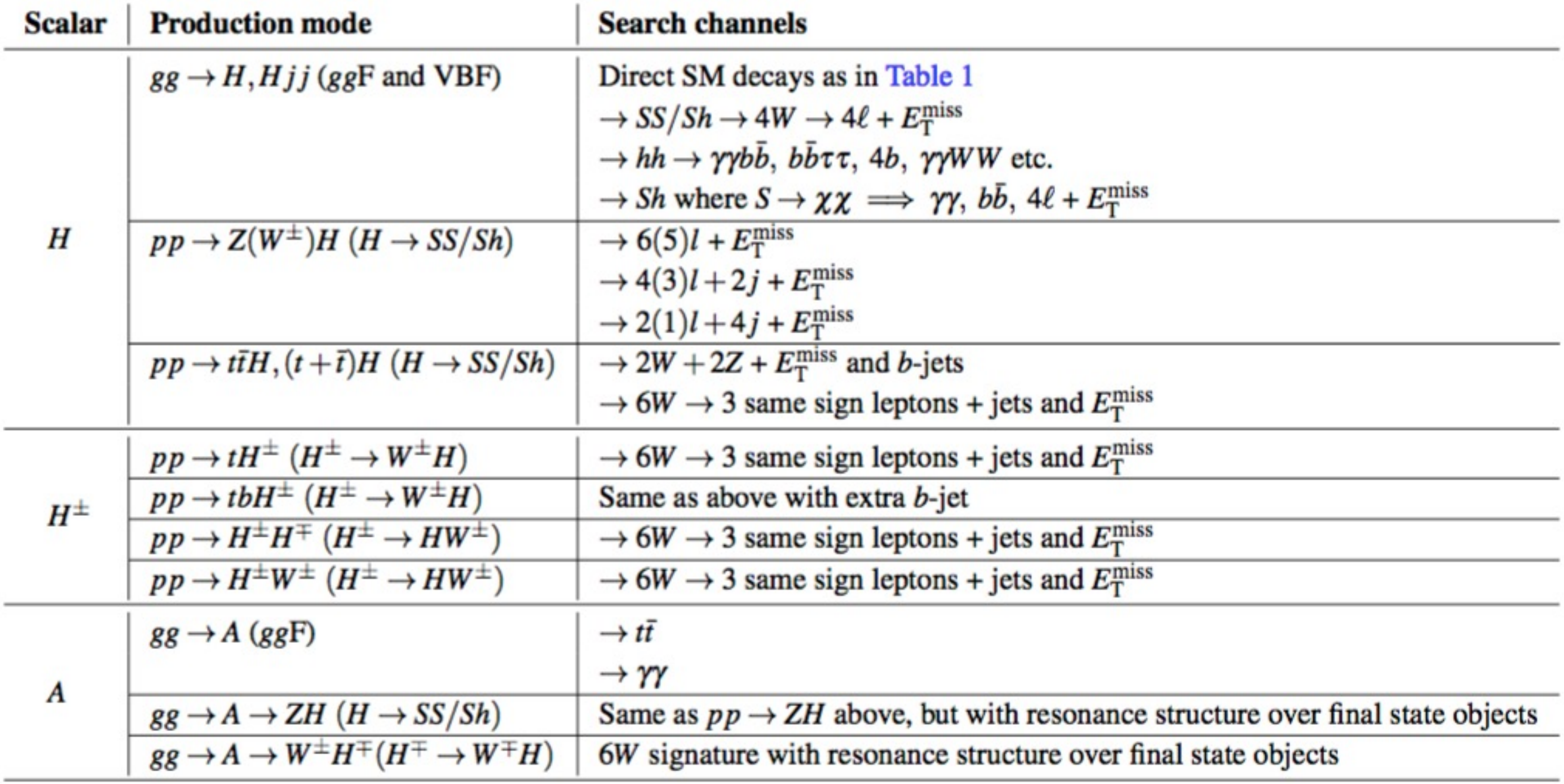
$$\boxed{H \to h(+X), S(+X)}$$

The 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, $\chi\chi$

arXiv:1606.01674



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

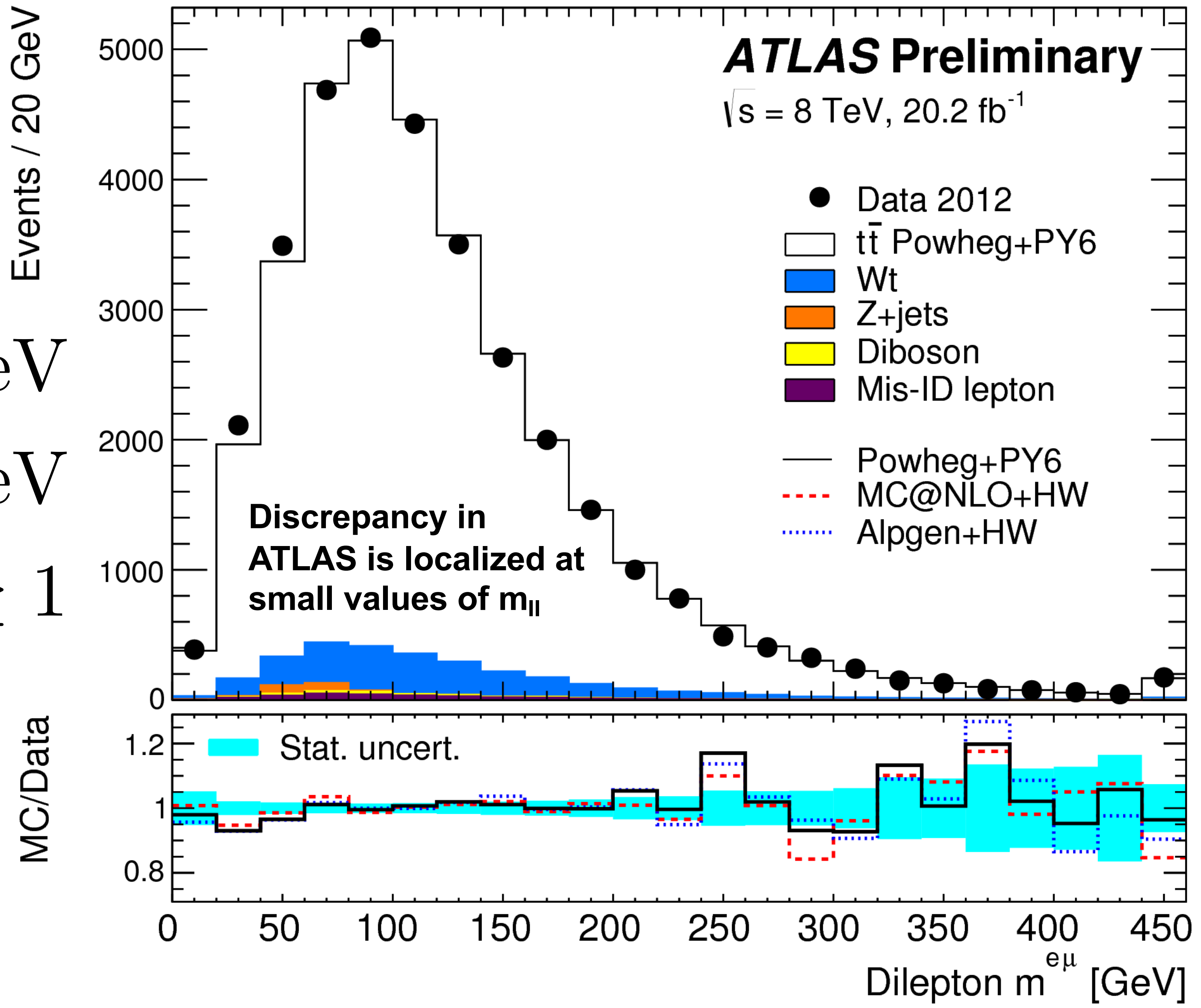
Eur. Phys. J. C 77 (2017) 804

Is the discrepancy due to ttbar events?

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

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

$$N_{bjet} \geq 1$$



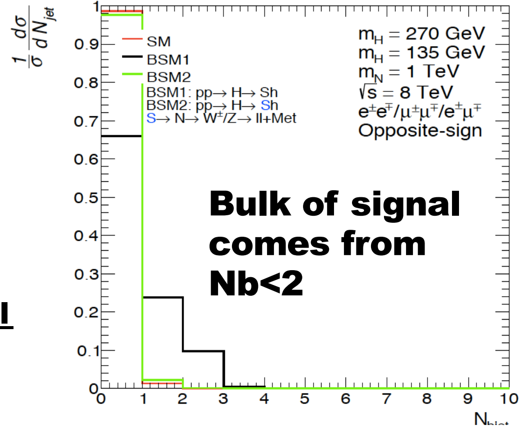
Discrepancy in ATLAS is localized at small values of m_{ll}

arXiv:1805.07399

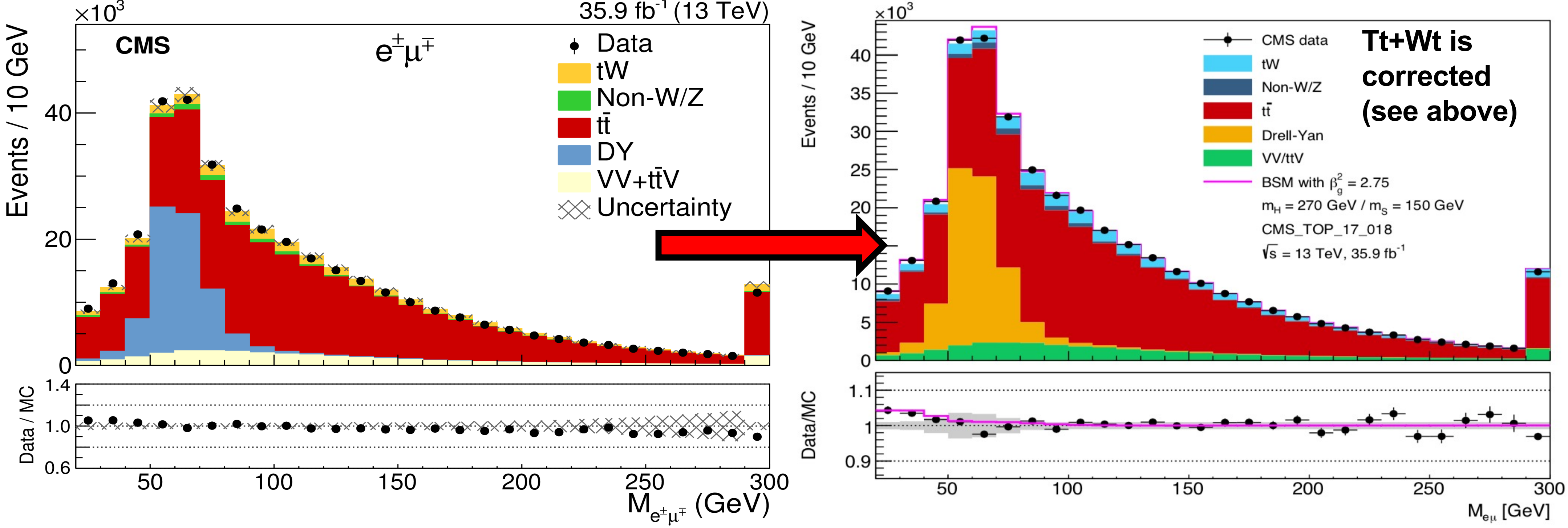
CMS-TOP-17-018; CERN-EP-2018-074

- 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

Negligible MC dependence, as m_{ll} shape comes from data



Bulk of signal comes from Nb<2



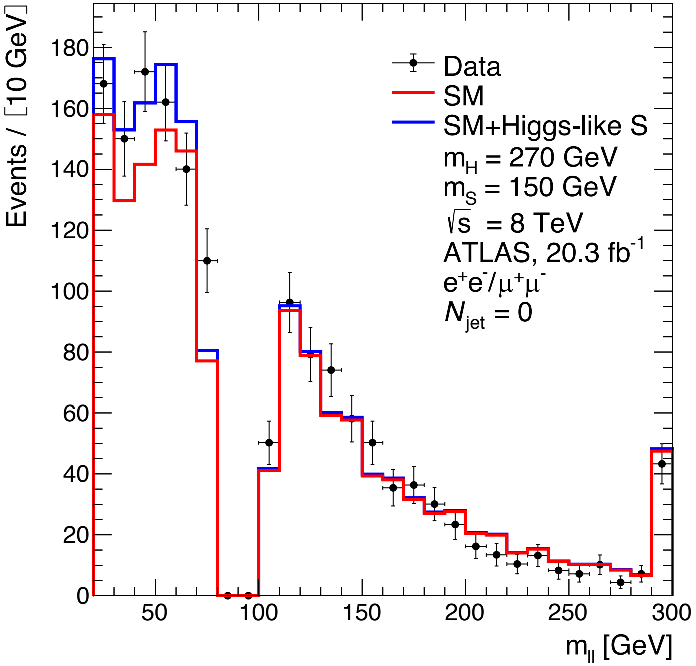
Tt+Wt is corrected (see above)

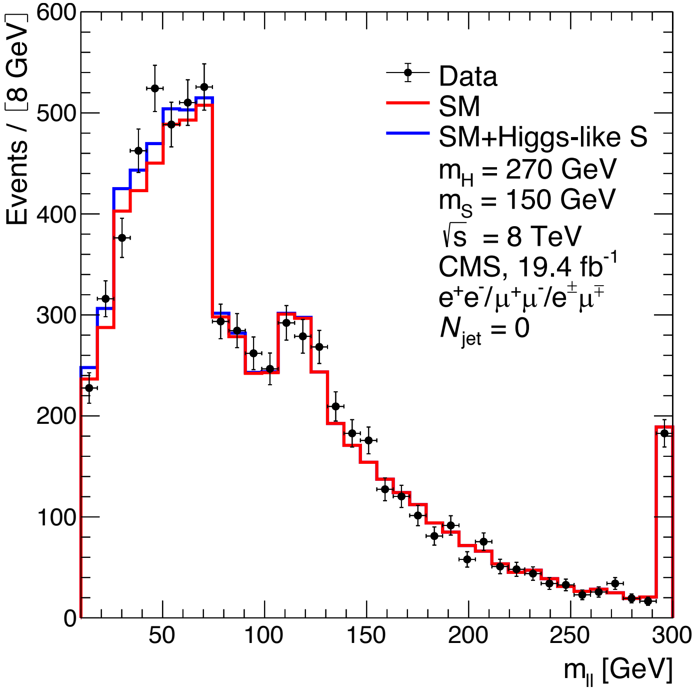
Used conservative assumption that l^+l^-+2b-jet final state is perfectly described by the SM. The discrepancy comes from events with $N_b<2$. Excess unlikely due to tt

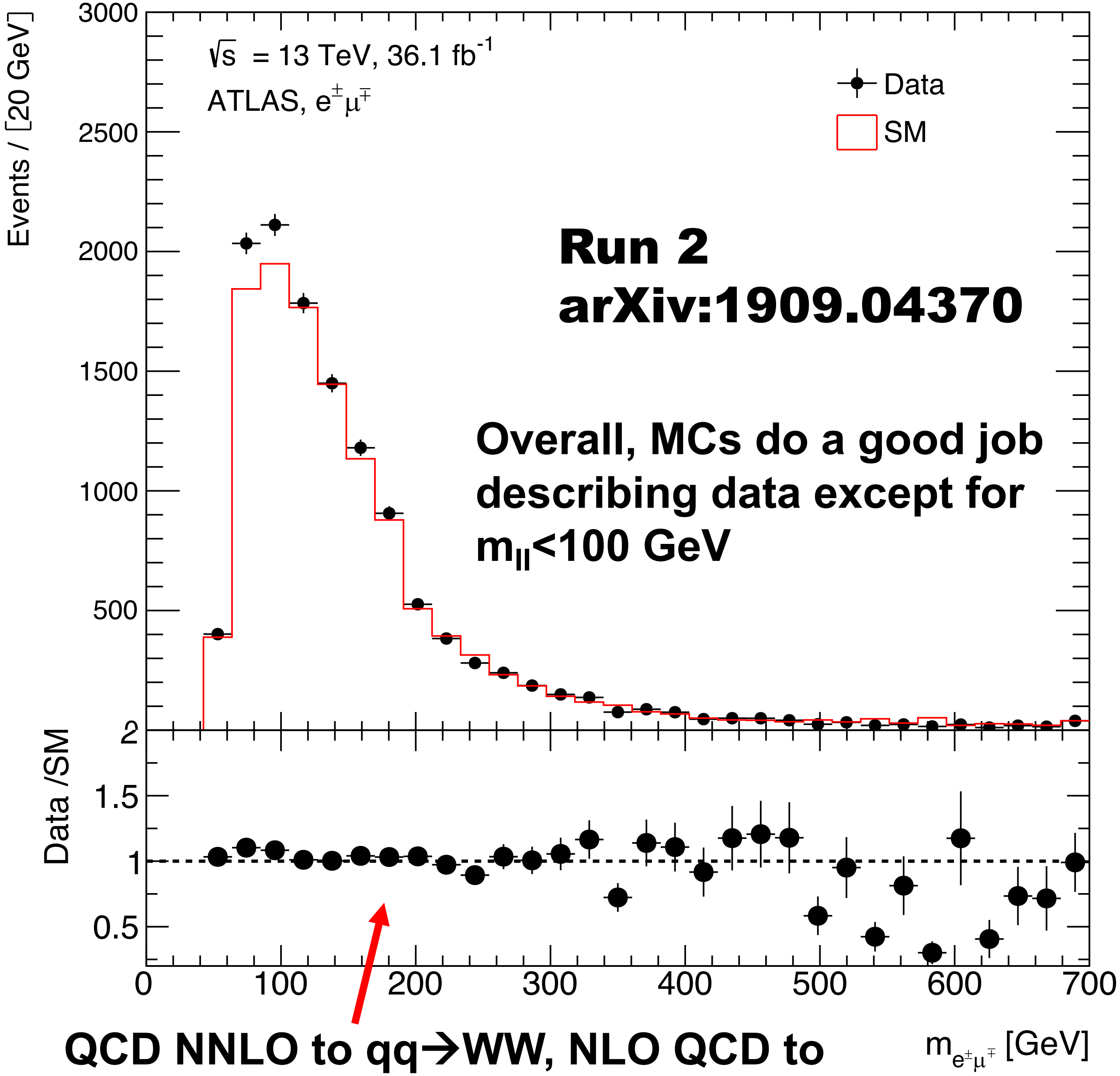
Excesses in di-leptons with full-jet veto not included above

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





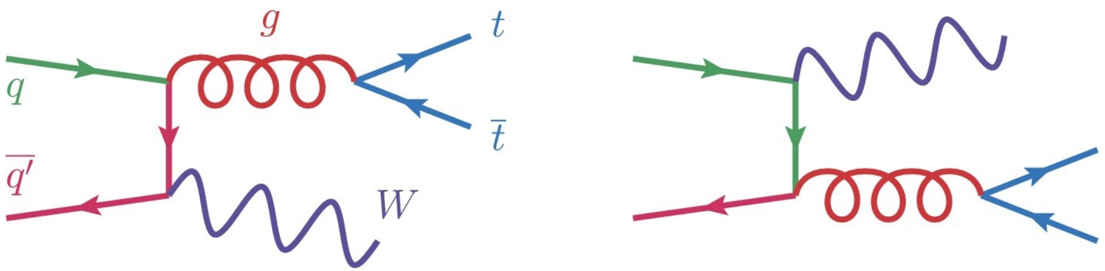


Run 2
arXiv:1909.04370

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

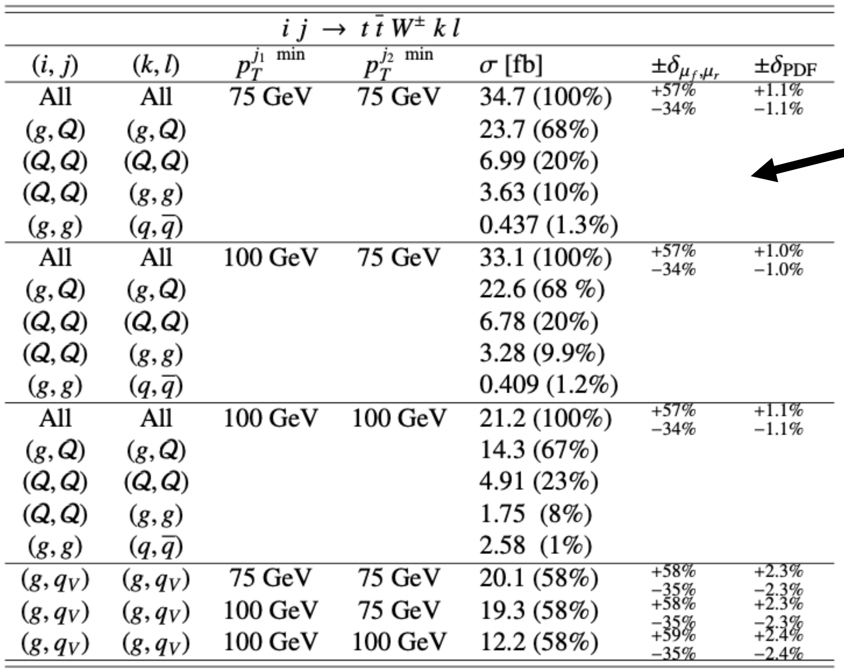
QCD NNLO to qq→WW, NLO QCD to gg→WW and NLO EW corrections applied

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

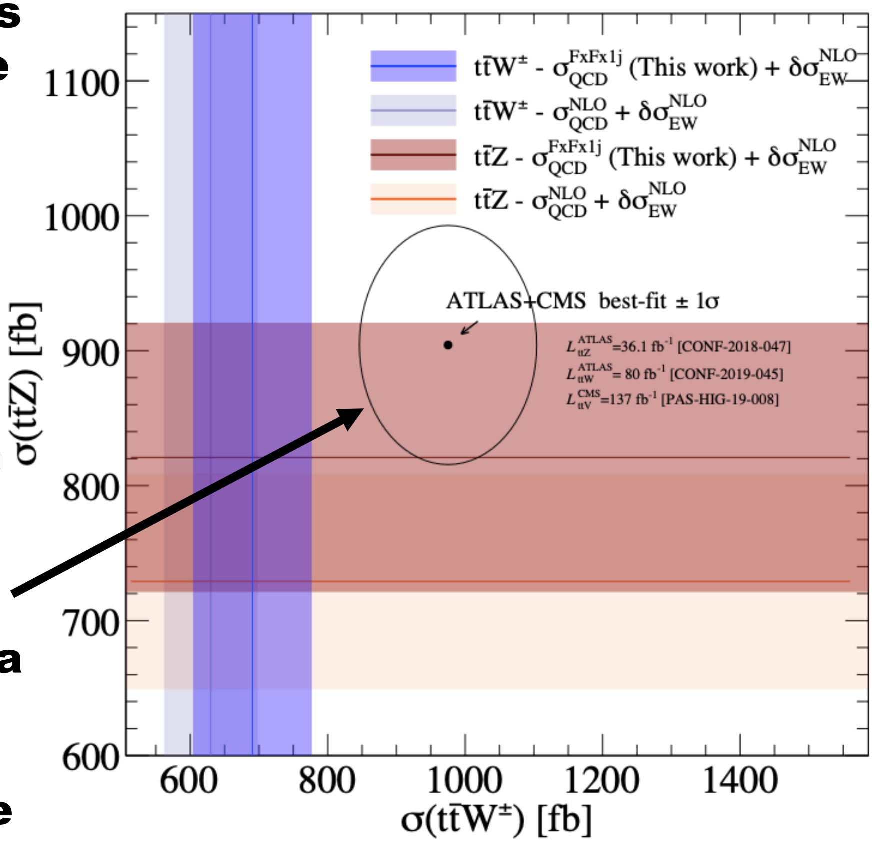


$i\,j \rightarrow t\,\bar{t}\,W^{\pm}\,k\,l$						
(i,j)	(k,l)	$p_T^{j_1\ \min}$	$p_T^{j_2\ \min}$	σ [fb]	$\pm\delta_{\mu_f,\mu_r}$	$\pm\delta_{\text{PDF}}$
All	All	75 GeV	75 GeV	34.7 (100%)	$^{+57\%}_{-34\%}$	$^{+1.1\%}_{-1.1\%}$
(g,Q)	(g,Q)			23.7 (68%)		
(Q,Q)	(Q,Q)			6.99 (20%)		
(Q,Q)	(g,g)			3.63 (10%)		
(g,g)	$(q,\overline{q})$			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)	$(q,\overline{q})$			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)	$(q,\overline{q})$			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 $pp \rightarrow t\bar{t}W^{\pm}jj$ 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 $Q \in \{q,\overline{q}\}$.

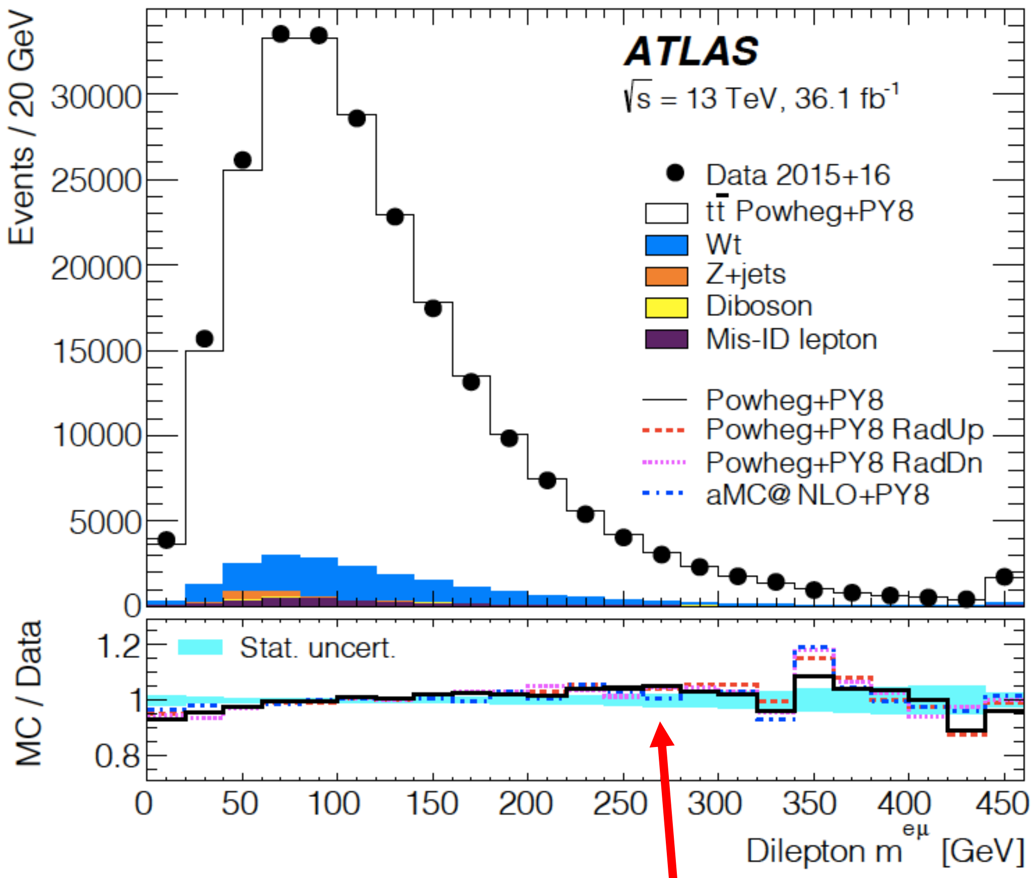
Detailed studies that include the decomposition in partonic channels and differential distributions

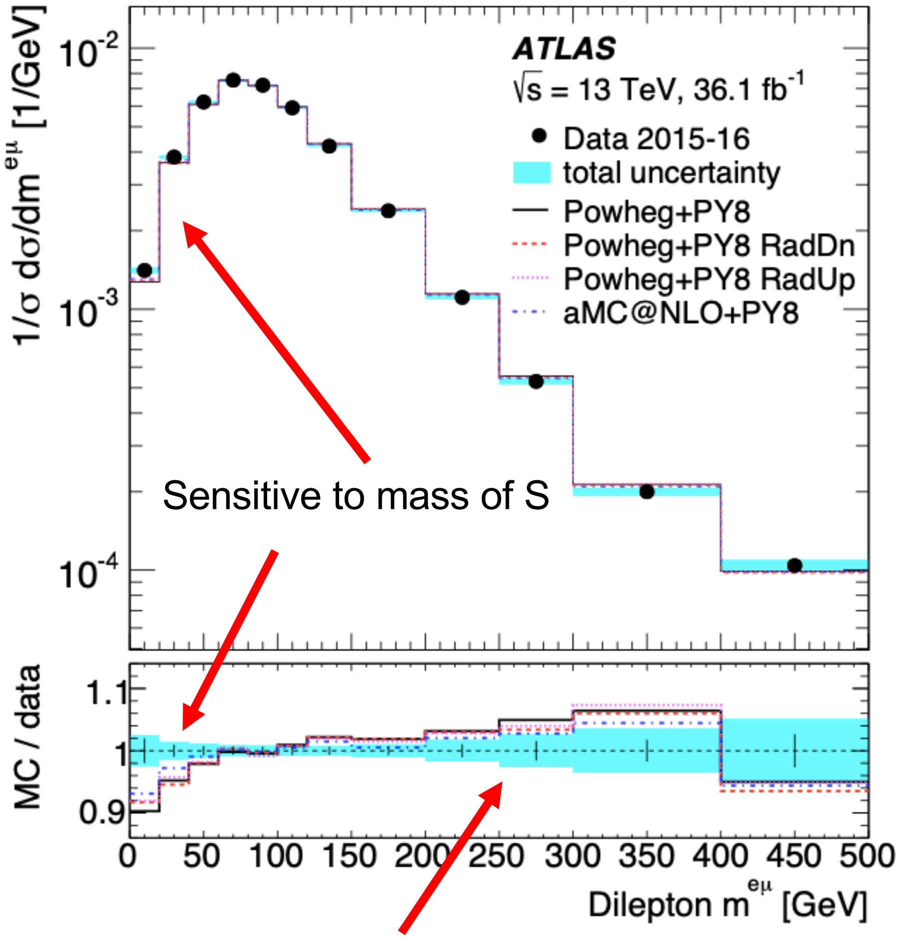
Tension between data and predictions does not wane.
For this process a complete NNLO computation is needed to reduce theory uncertainty



Results not included in the combination

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





Sensitive to mass of S

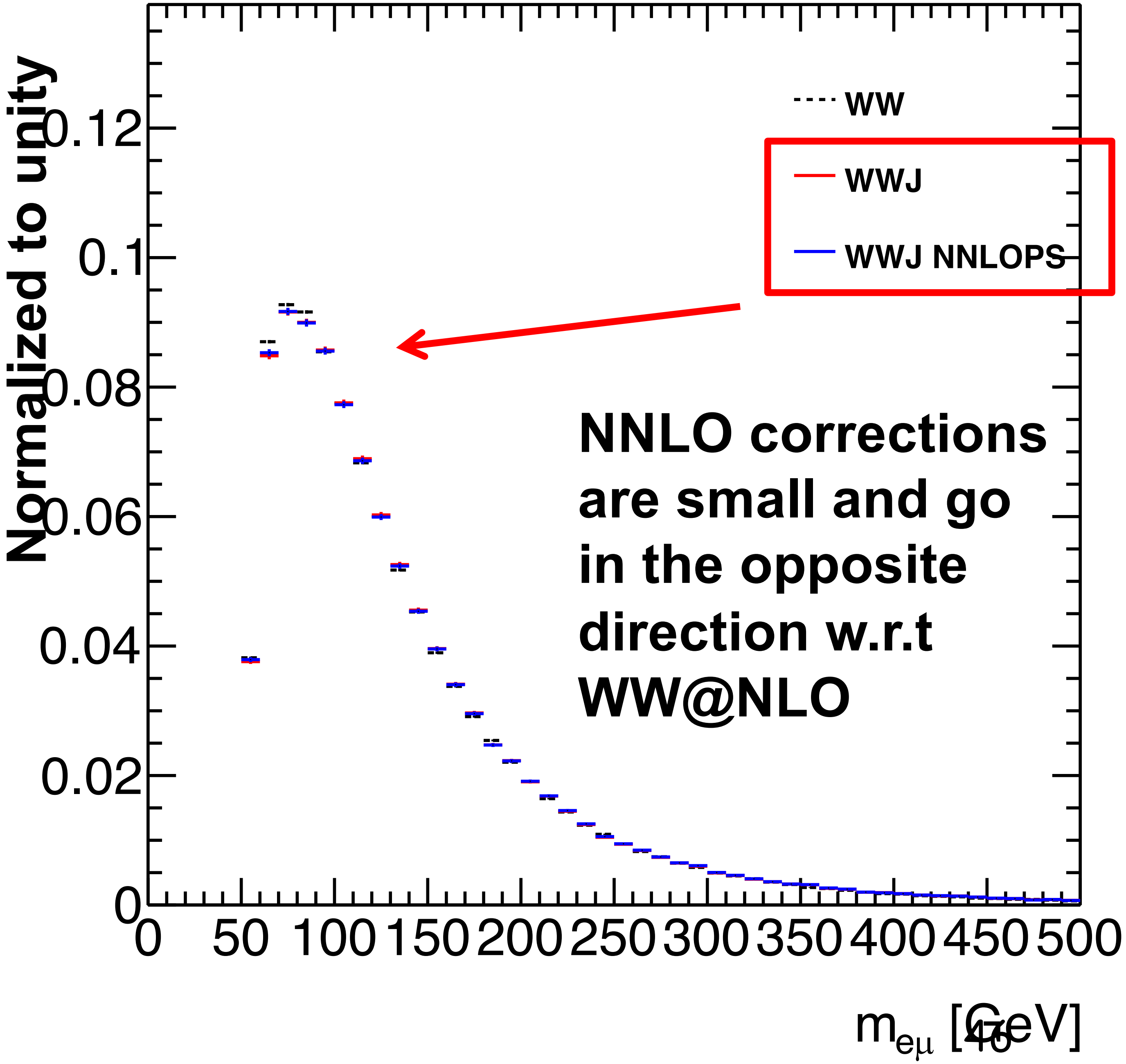
Residual discrepancies at high m_{ll} will be fixed with missing NNLO QCD and NLO EW corrections

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.)

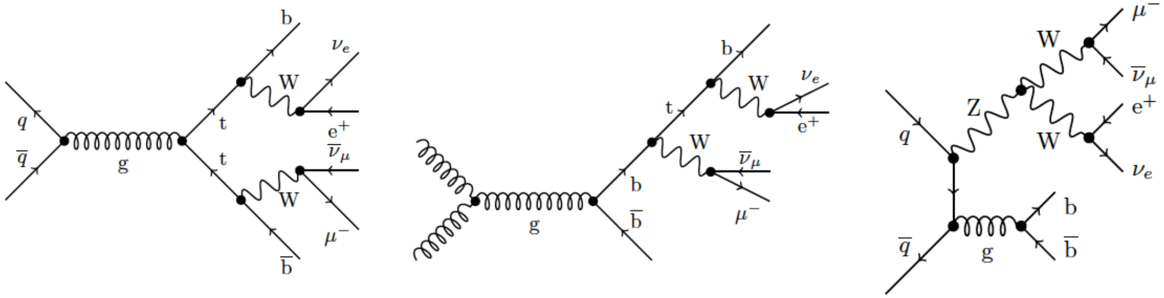
Impact of NNLO QCD in WW

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

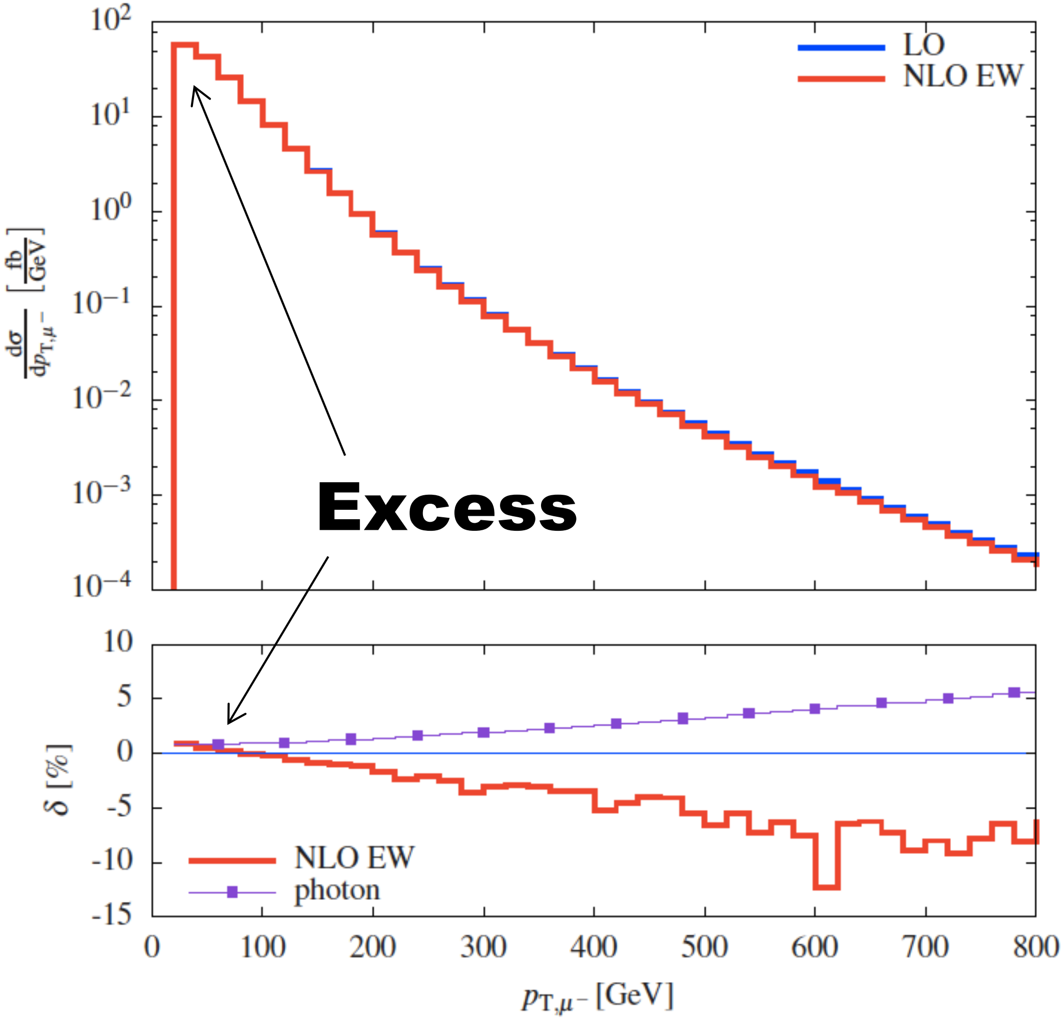


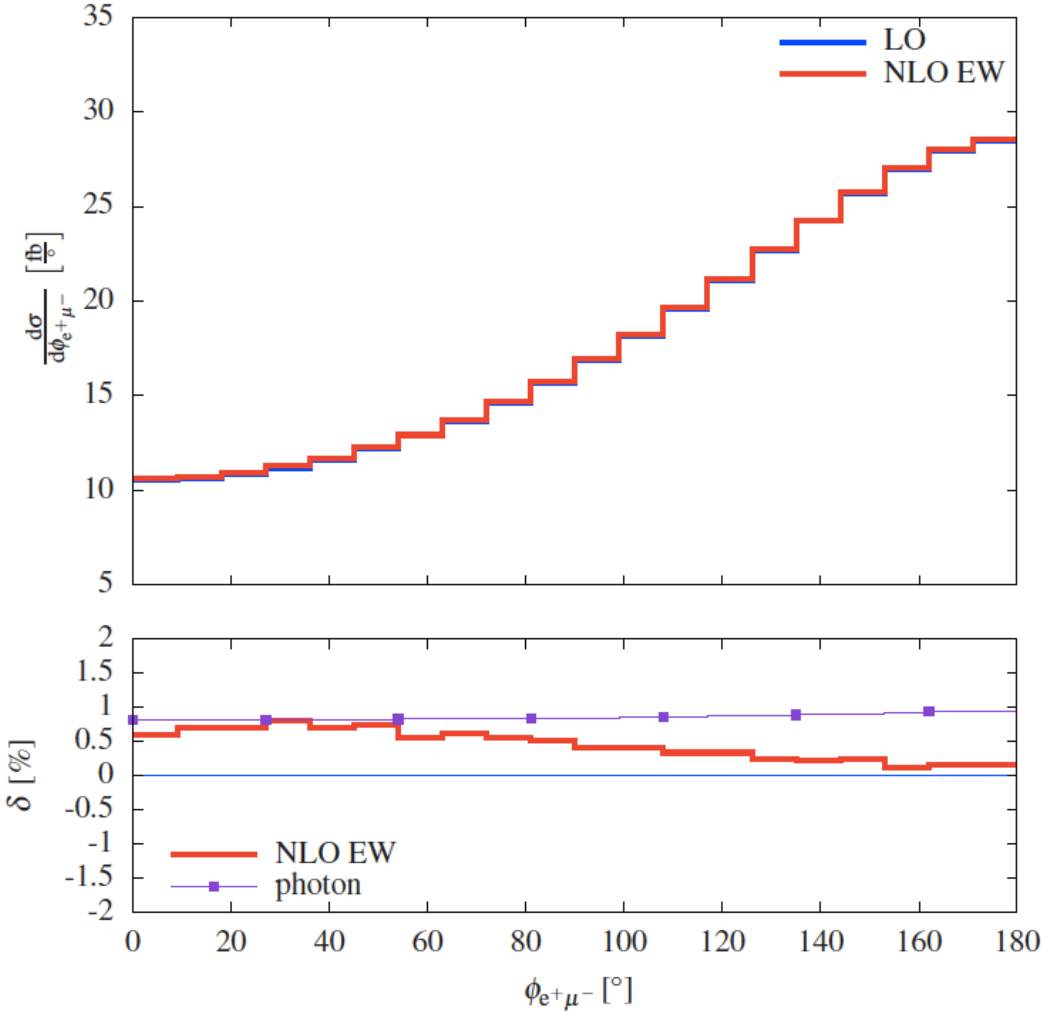
NNLO corrections are small and go in the opposite direction w.r.t WW@NLO



A.Denner, M.Pellen, arXiv:1607.05571

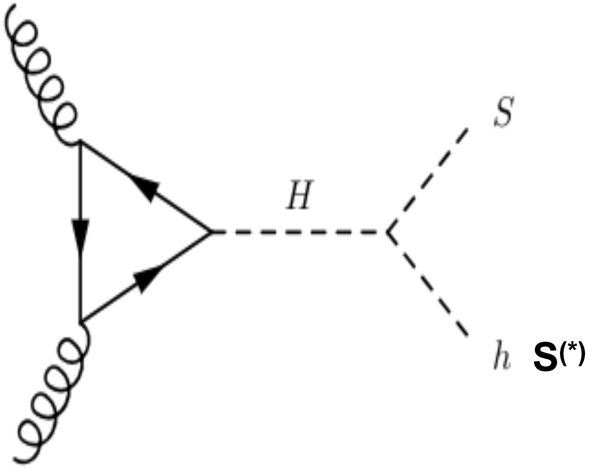
EW corrections are important at high p_T due to Sudakov logarithms. Effect is less than 1% for m_{ll}<100 GeV, where discrepancies are seen.

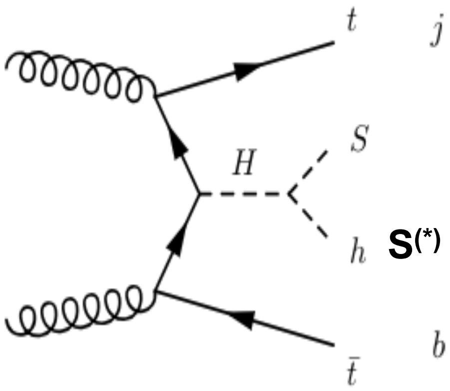


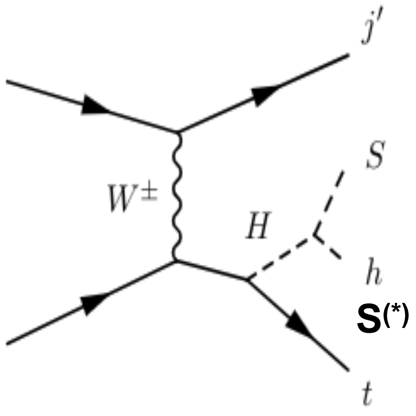


BSM inputs to the fit

- The following assumptions 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

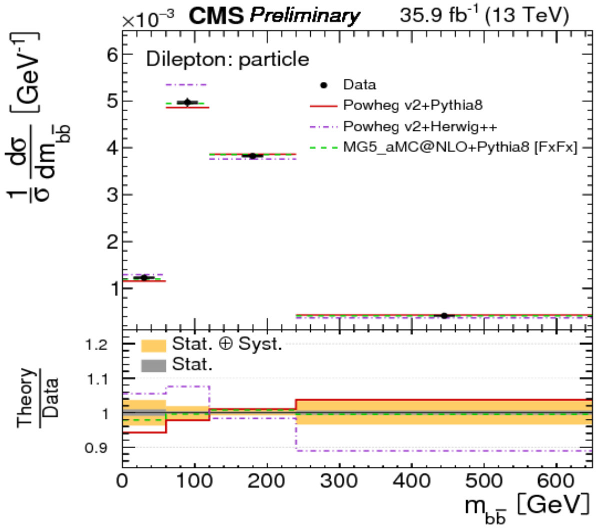


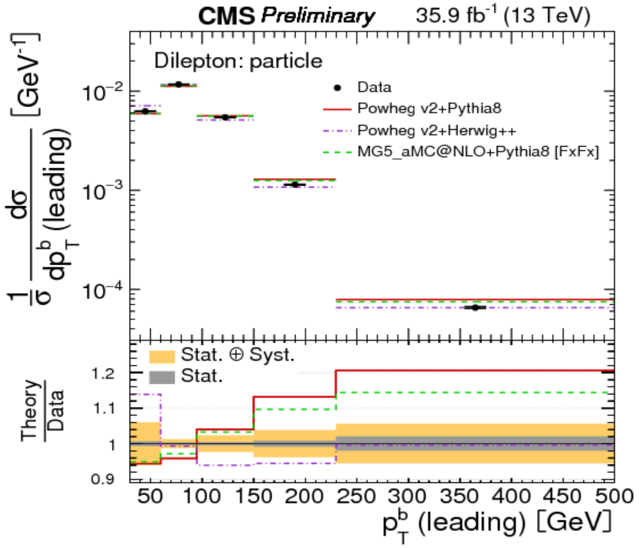


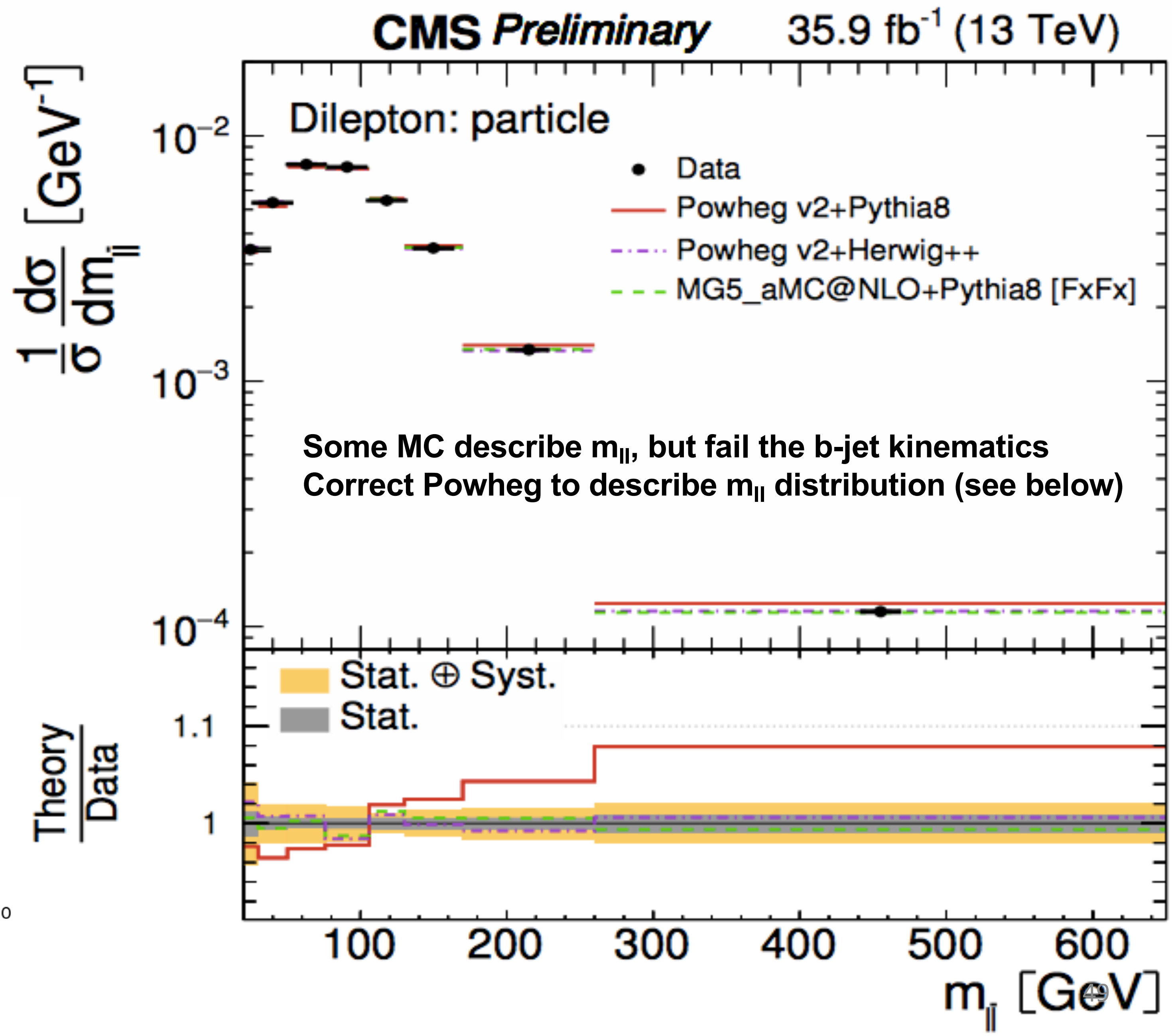


CMS PAS TOP-17-014

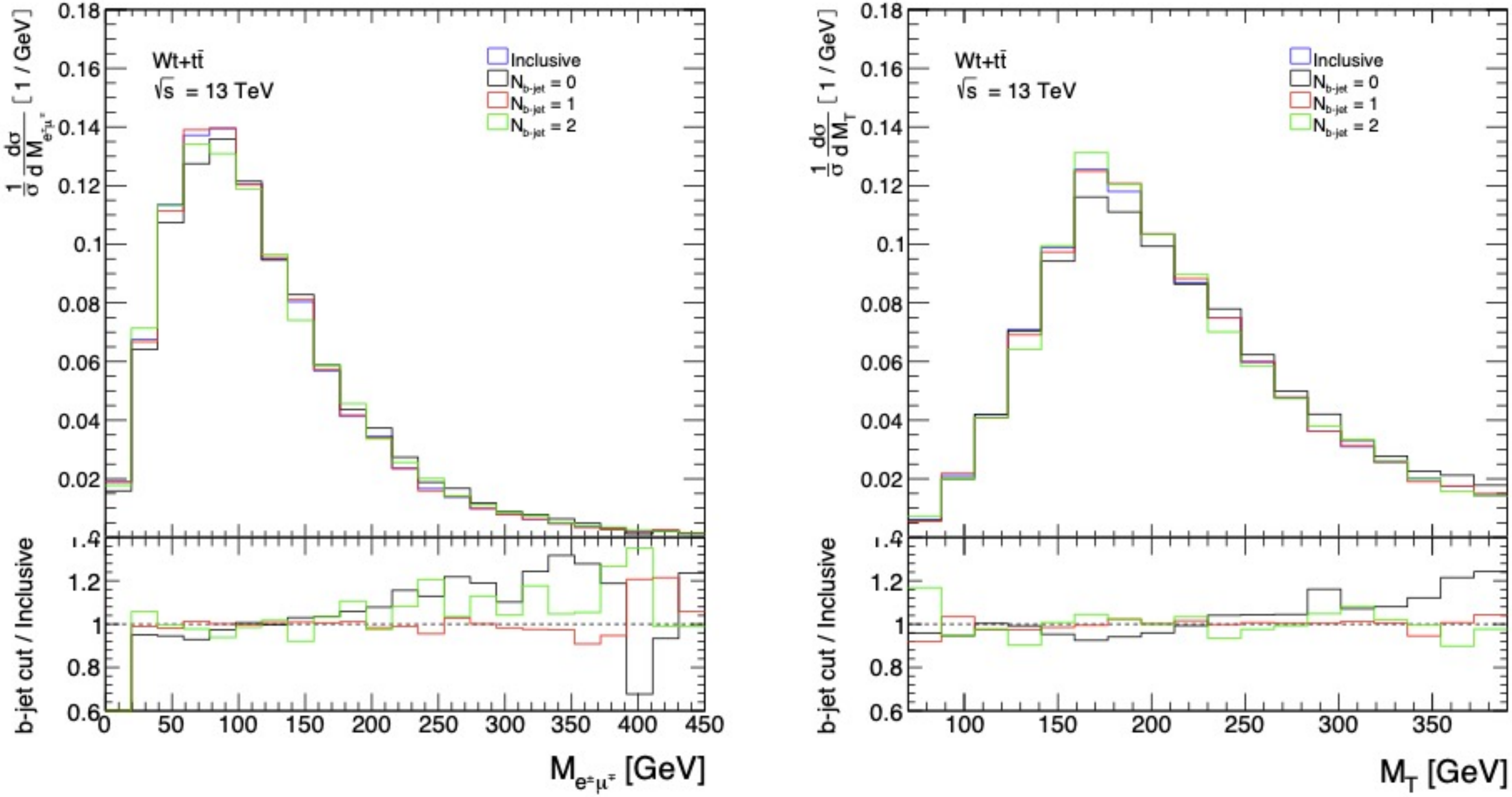
Event selection with exactly two leptons (e,μ), m_{ll}>20 GeV and at least 2b-jets







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



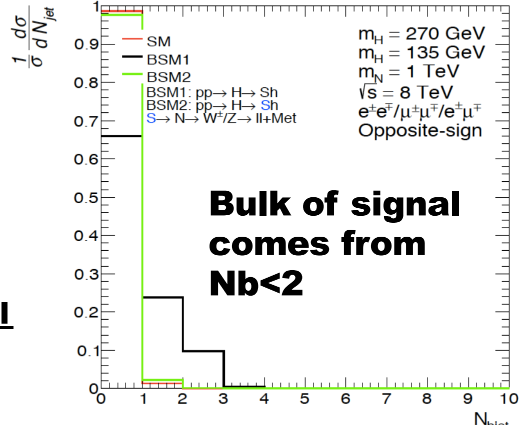
b-jet multiplicity is robust theoretically

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

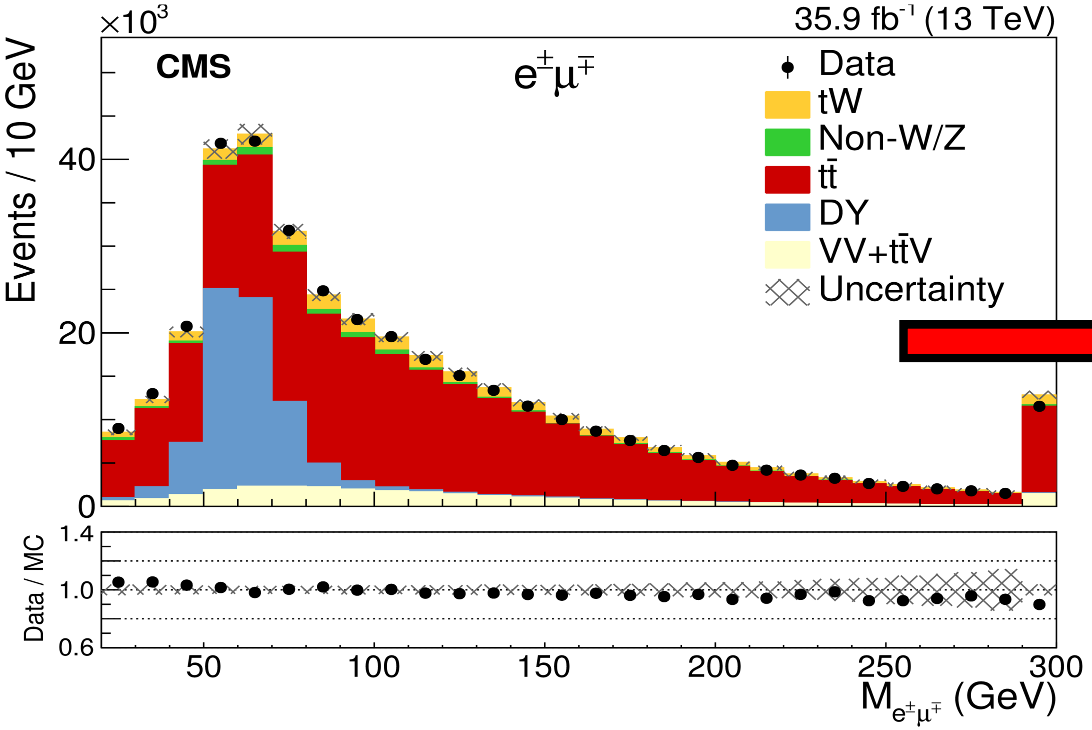
CMS-TOP-17-018; CERN-EP-2018-074

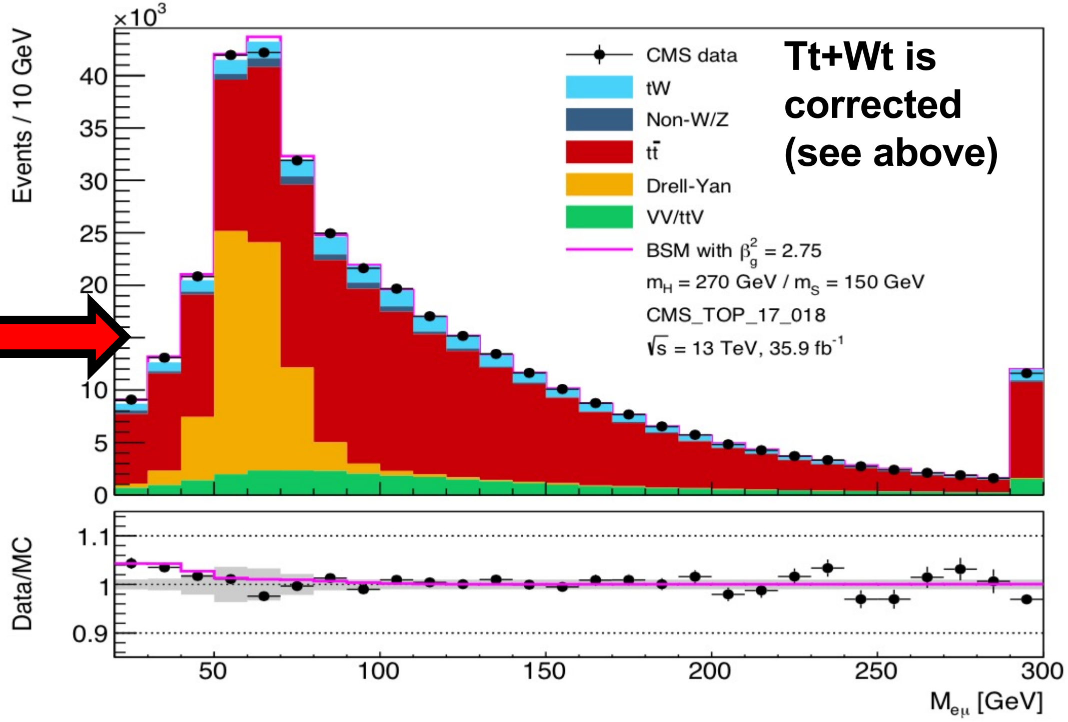
- Poor modeling of POWHEG + Pythia8 distribution is improved through reweighting
- We fix the normalisation of the SM by scaling it to the data in the region $m_{ll} > 110$ GeV
  - ○ A normalisation systematic of 3% is applied to all but DY
  - ○ DY systematic = 6.8%. 3% systematic on m_{ll} shape in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

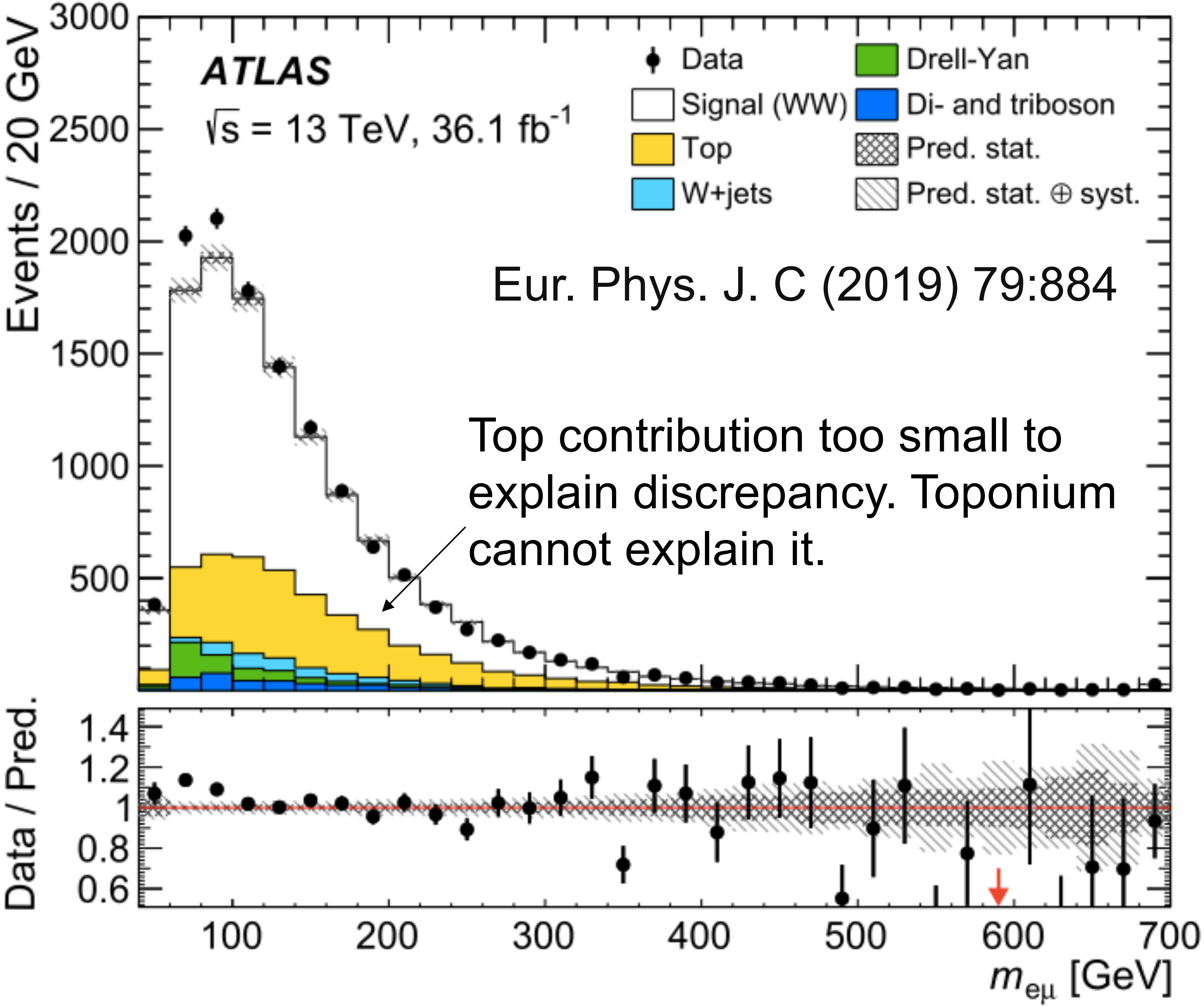
Negligible MC dependence, as m_{ll} shape comes from data





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



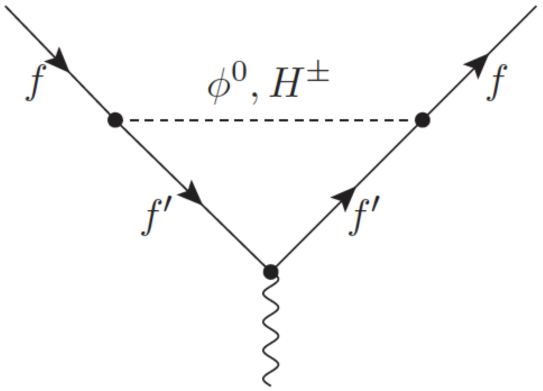
Eur. Phys. J. C (2019) 79:884

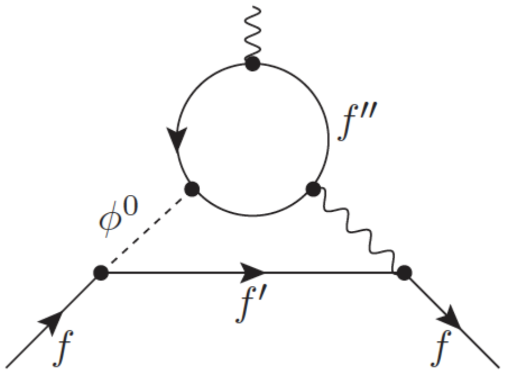
Top contribution too small to explain discrepancy. Toponium cannot explain it.

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

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

The Muon g-2 and the 2HDM+S



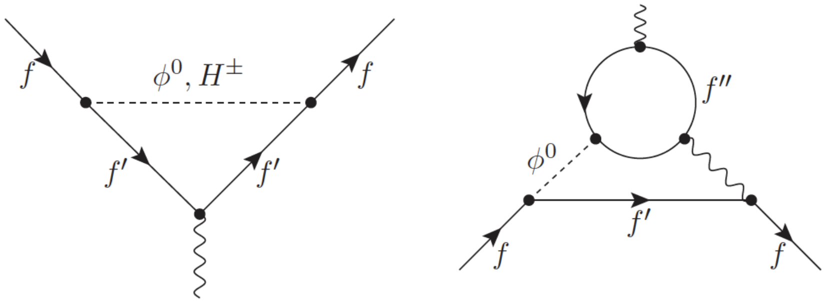


2HDM+S potential with fixed parameters from multi-lepton anomalies at the LHC

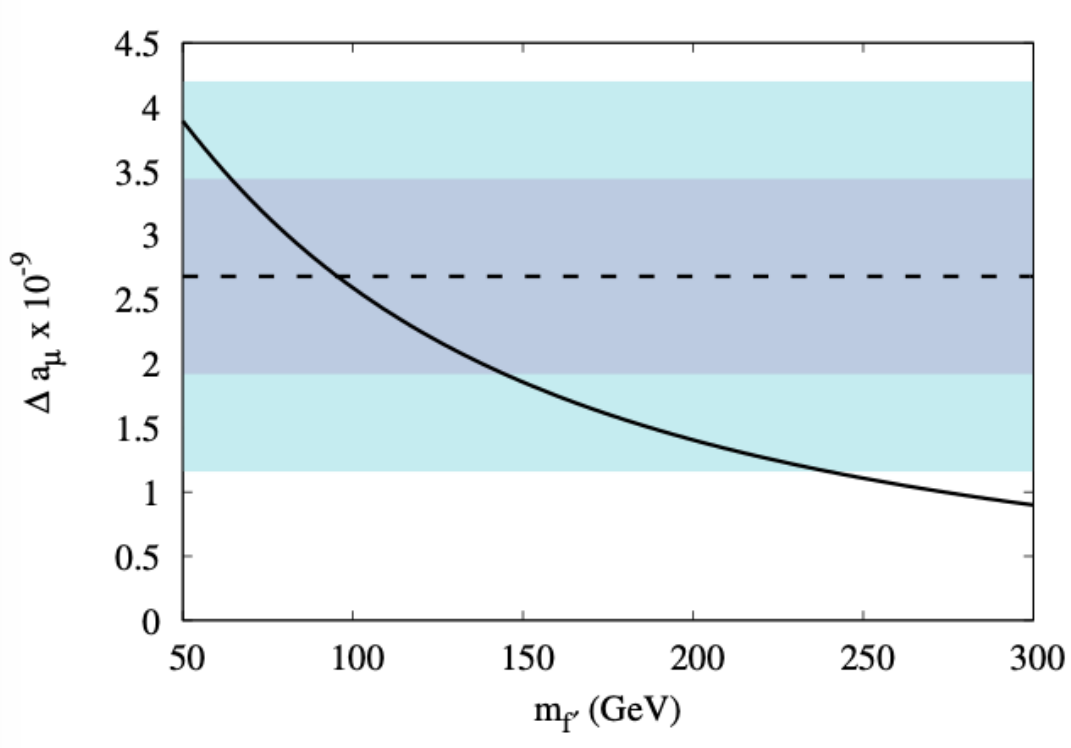
$$
\begin{aligned}
&V(\Phi_1, \Phi_2, \Phi_S) \\
&= m_{11}^2 \left|\Phi_1\right|^2 + m_{22}^2 \left|\Phi_2\right|^2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \text{h.c.}\right) \\
&+ \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2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

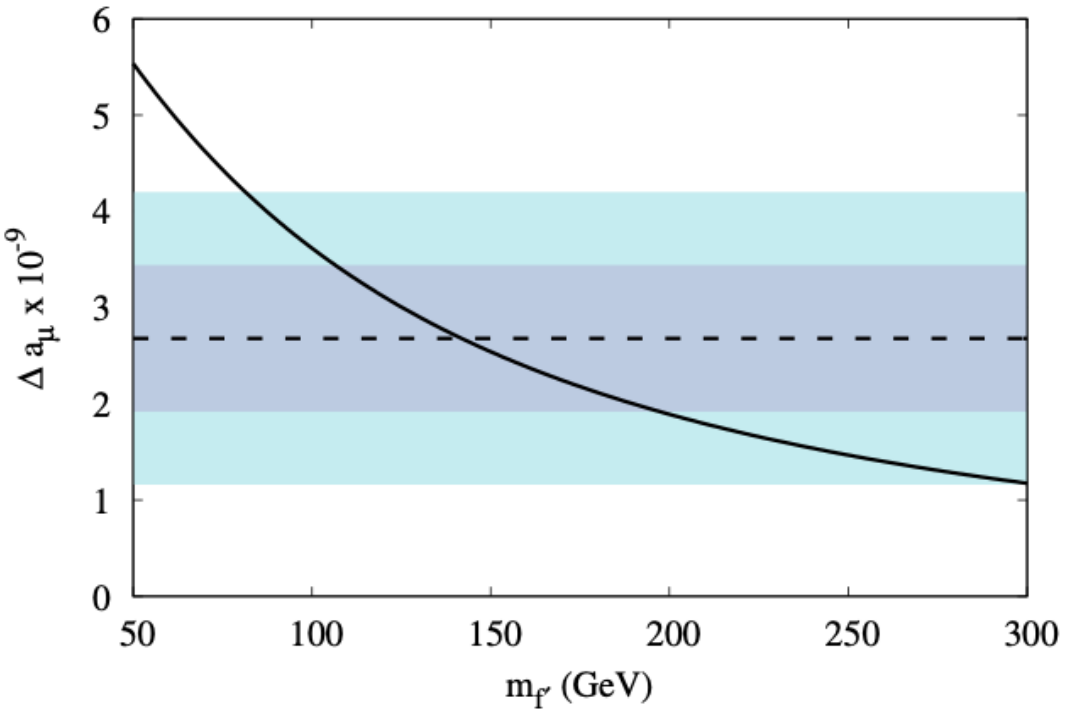
Consider extra degrees of freedom in the form of SM singlet vector-like fermions

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



Allowed fermion masses with different choices of Yukawa couplings



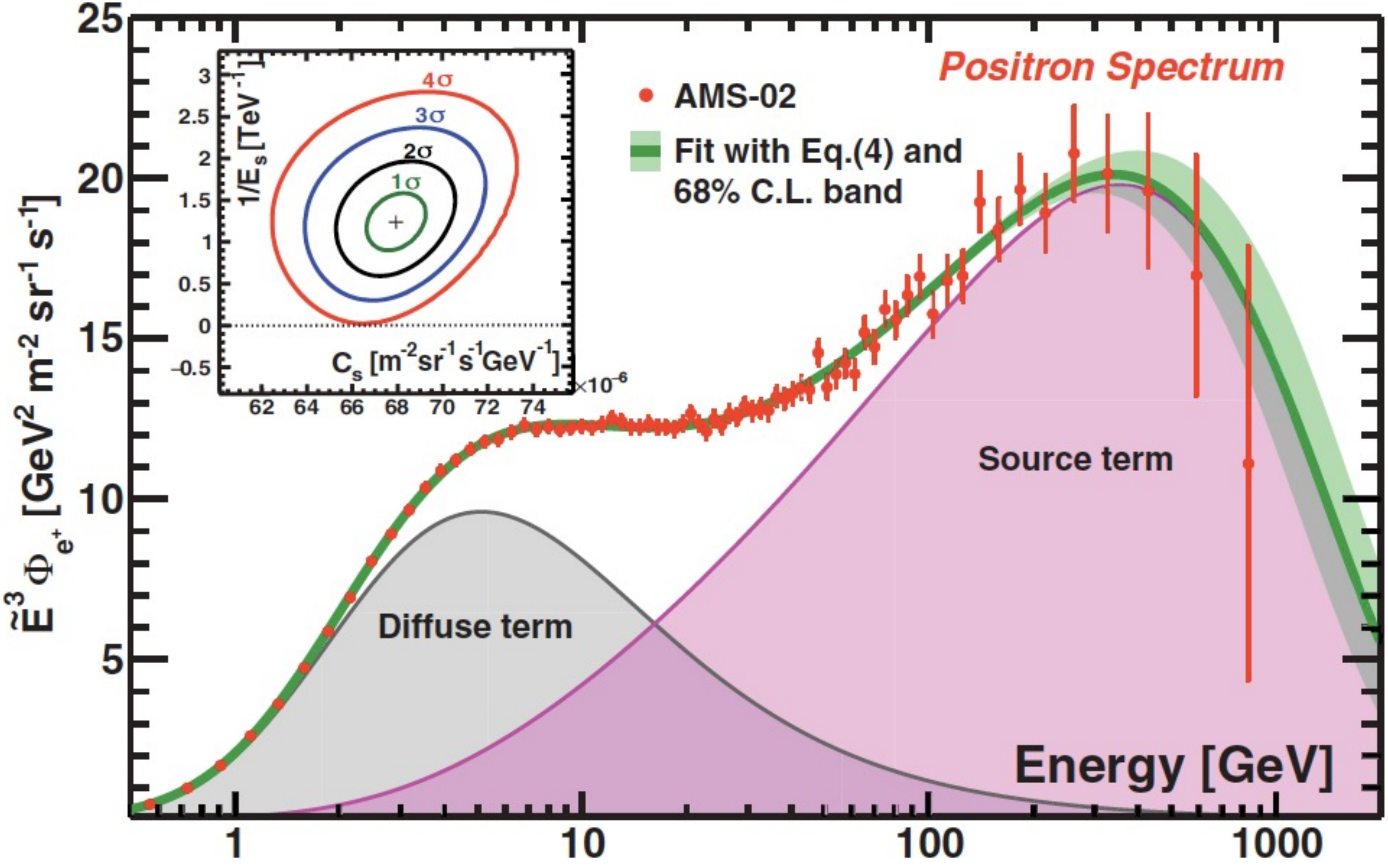


G.Beck, E.Malwa, M.Kumar, R.Temo and B.M., 2102.10596

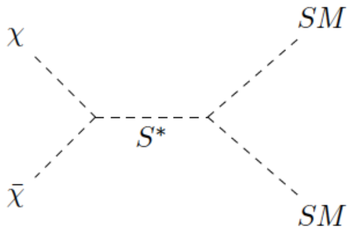
The multi-lepton anomalies and excesses in astrophysics

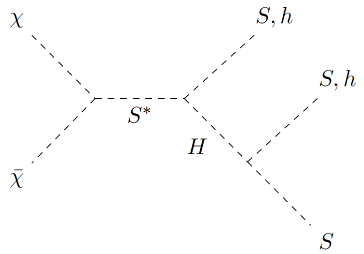
AMS02, PRL 122, 041102 (2019)

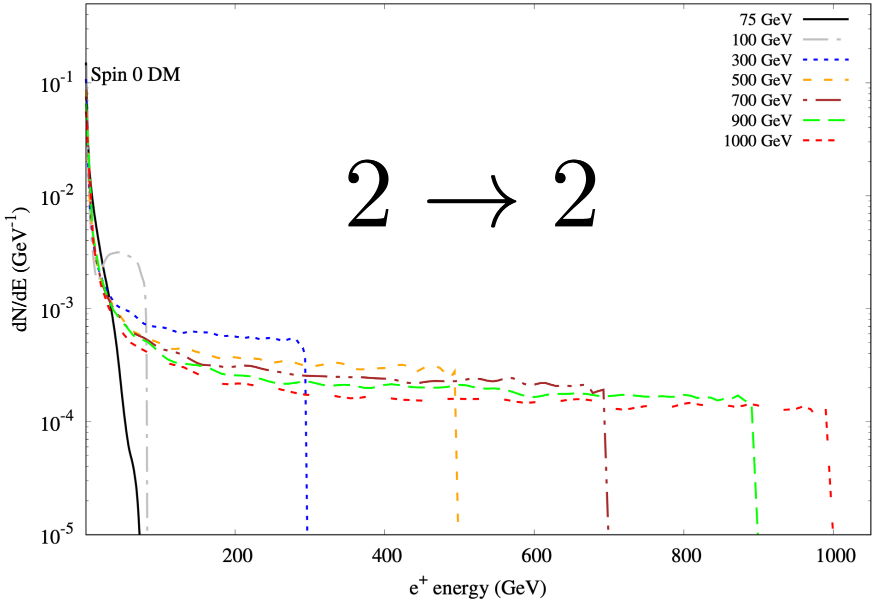
Leptophilic excesses, such as positron rise in PAMELA/AMS02

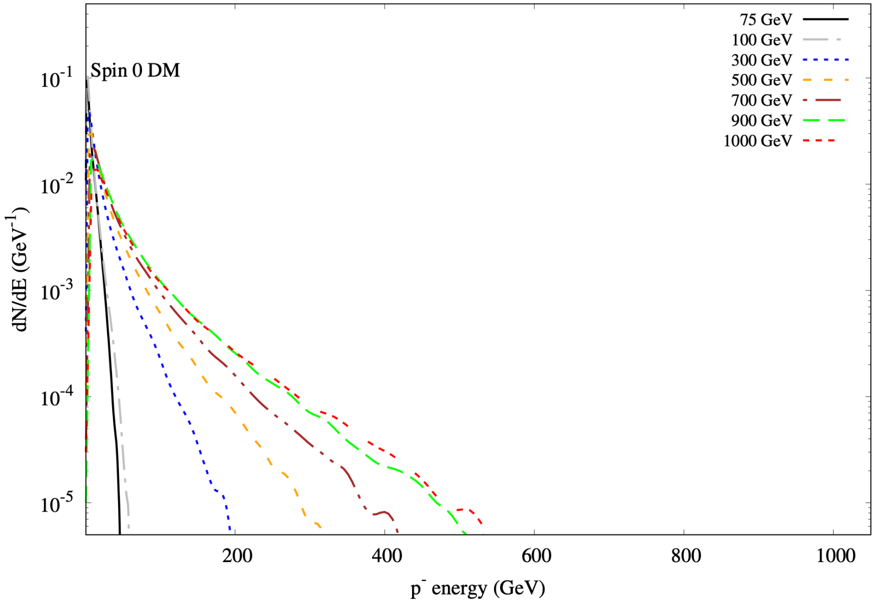


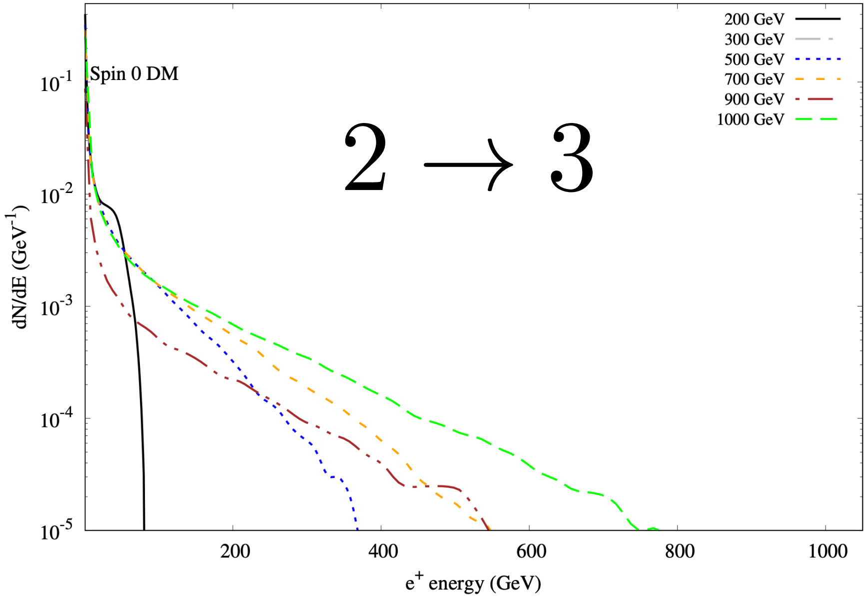
Dark matter annihilation. Leptons, photons and protons from the decays of S.

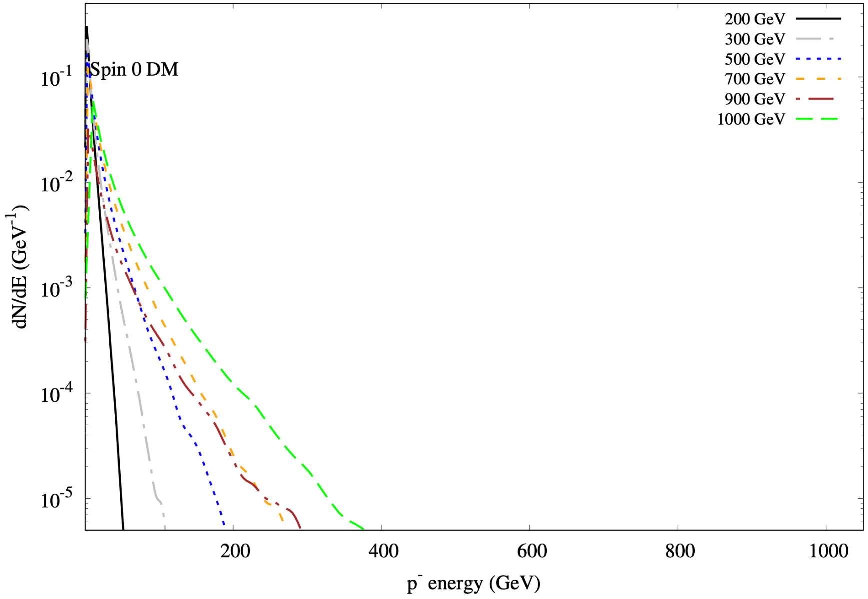


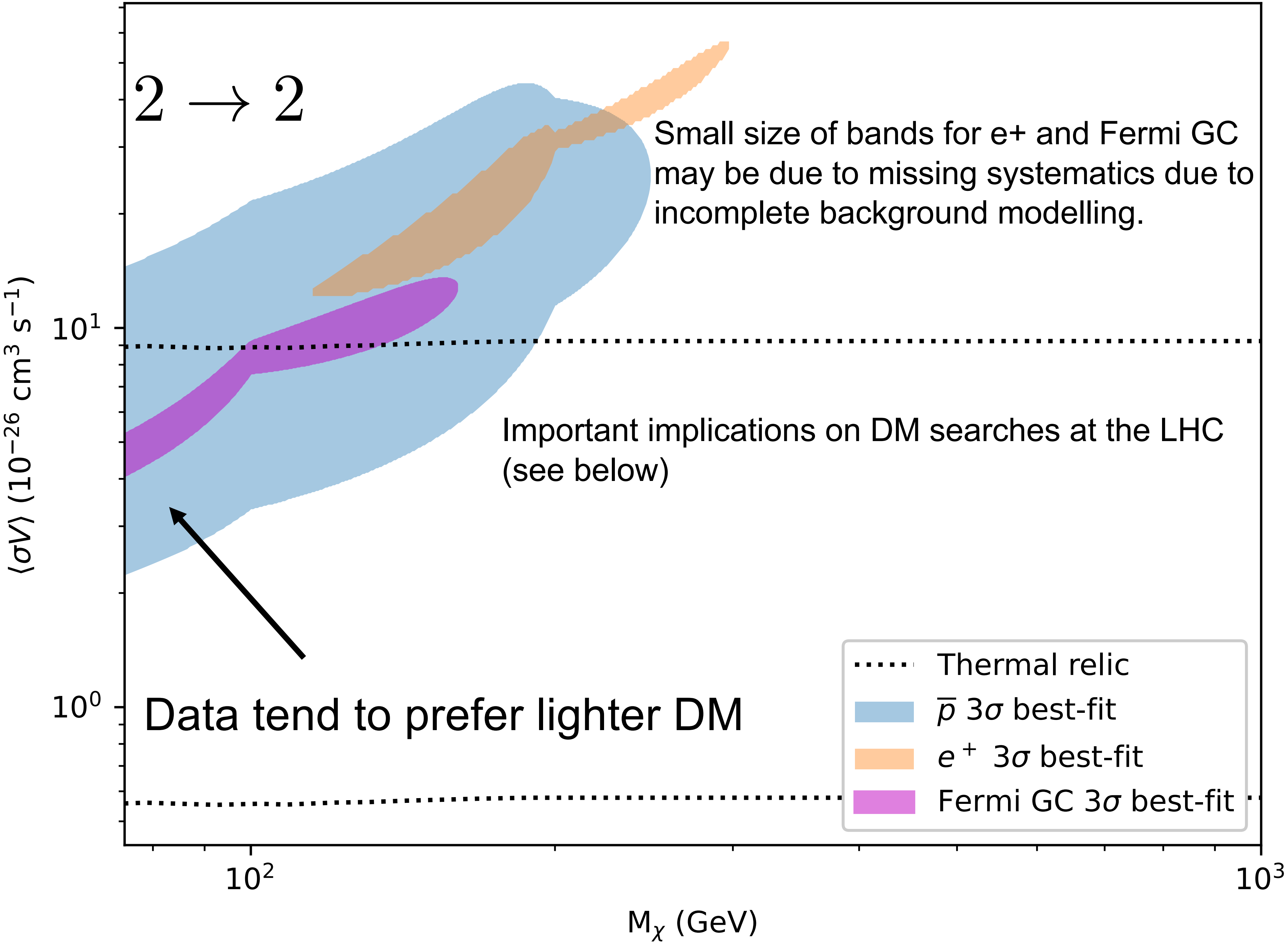












Small size of bands for e+ and Fermi GC may be due to missing systematics due to incomplete background modelling.

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

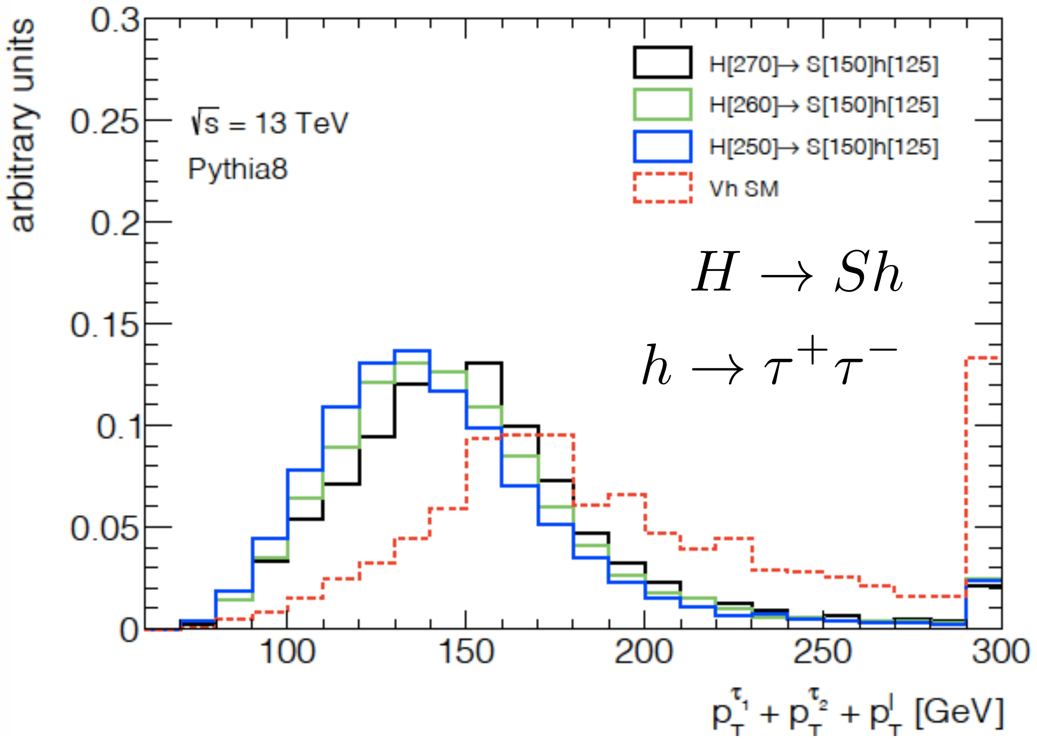
Data tend to prefer lighter DM

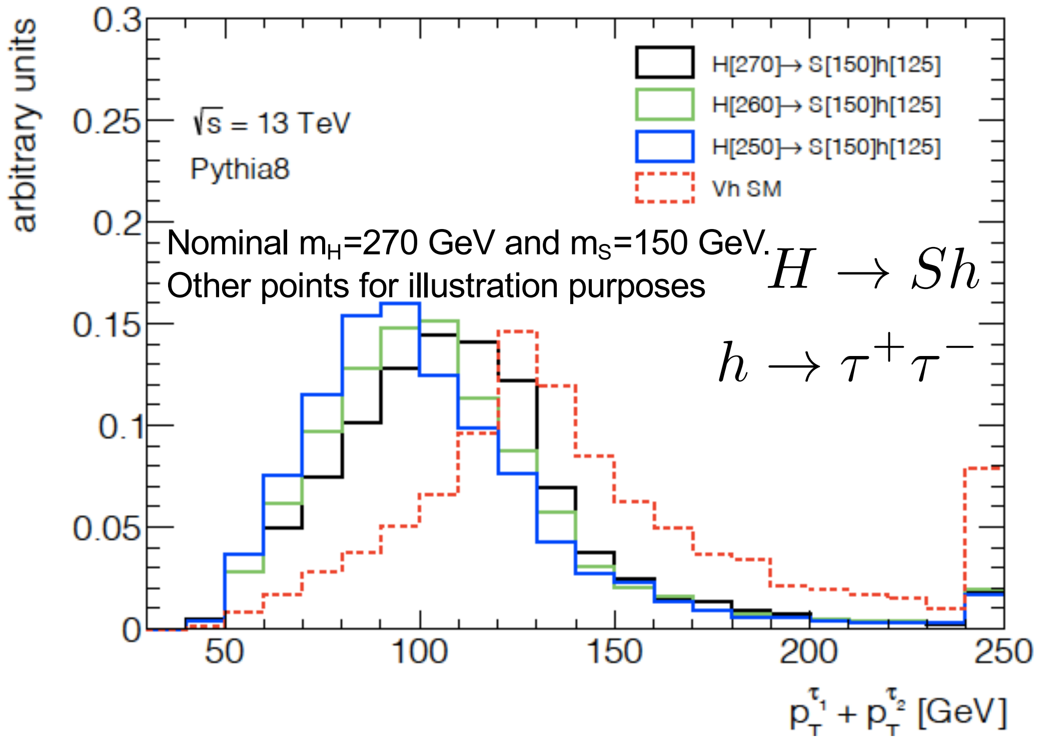
Impact on Higgs Physics

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

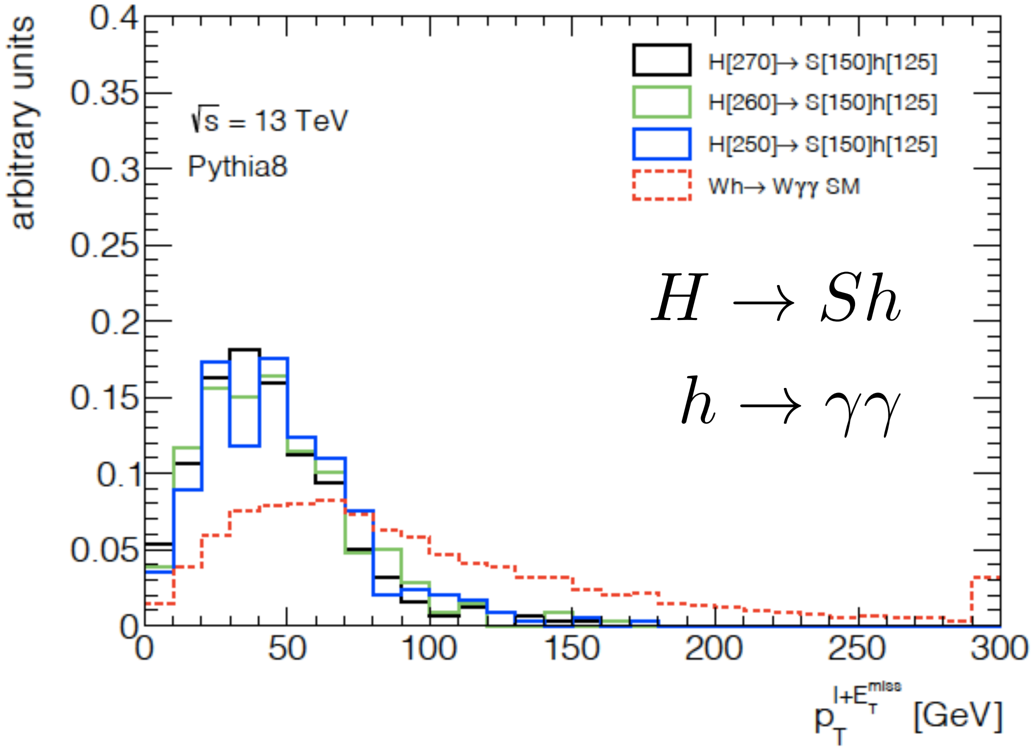
- ☐ **The presence of <u>extra leptons</u> in association with h. Affects the Wh measurement (Eur.Phys.J.C 81 (2021) 365)**
- ☐ **Distortion of Higgs p_T and rapidity (under study)**

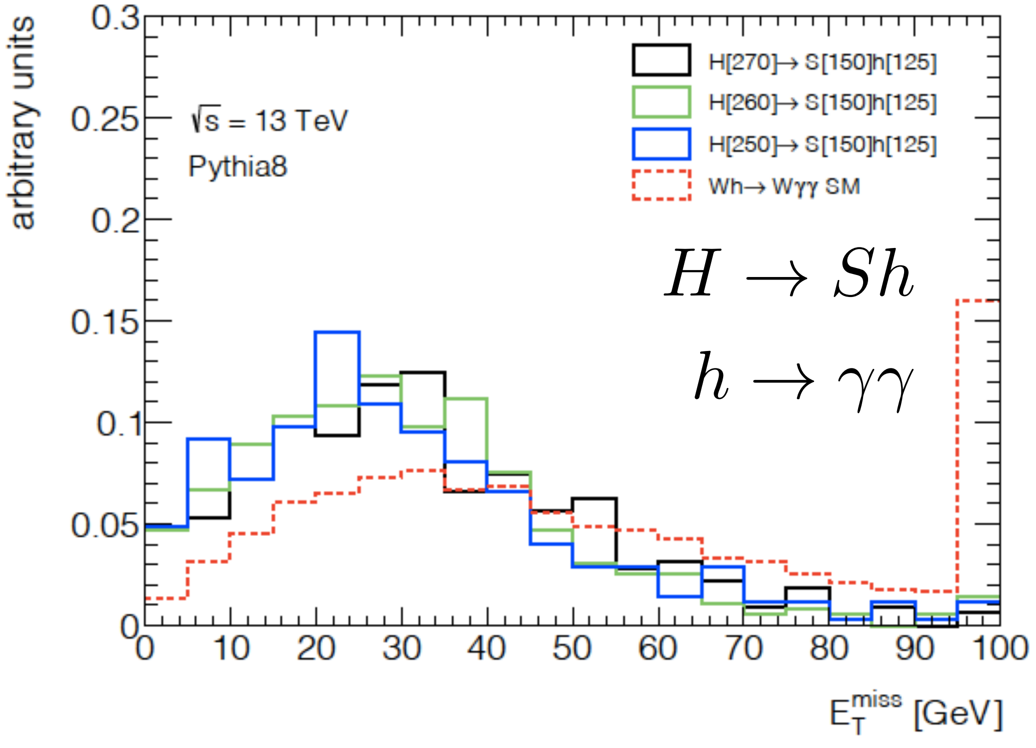
No tuning of model parameters performed. Look at fixed corners of the phase-space fixed with parameters of 2017.





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)

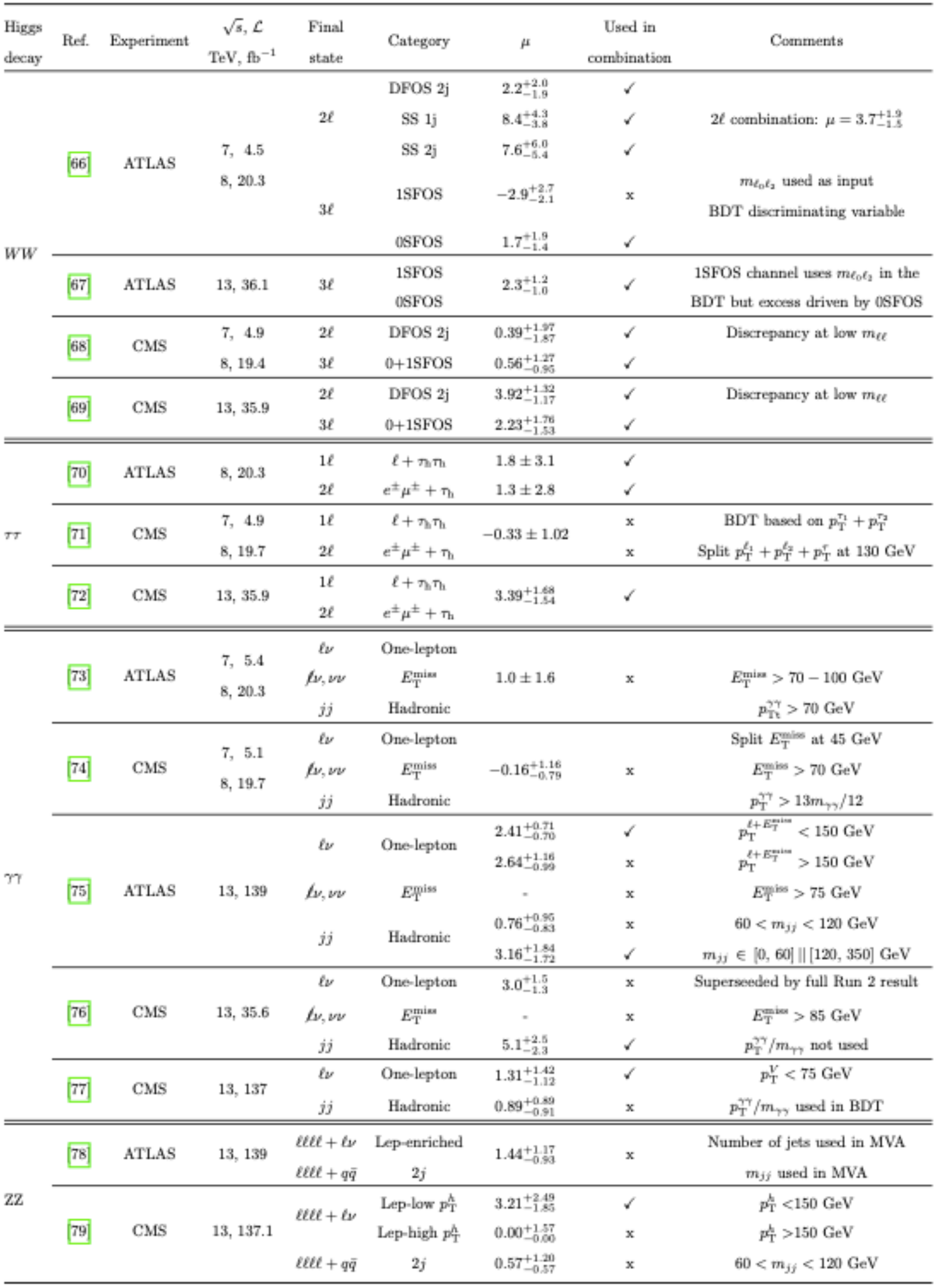
The BSM (H→Sh) signal appears at low p_{Th} and the SM signal is prevalent at larger p_{Th} (no tuning of parameters)

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:

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

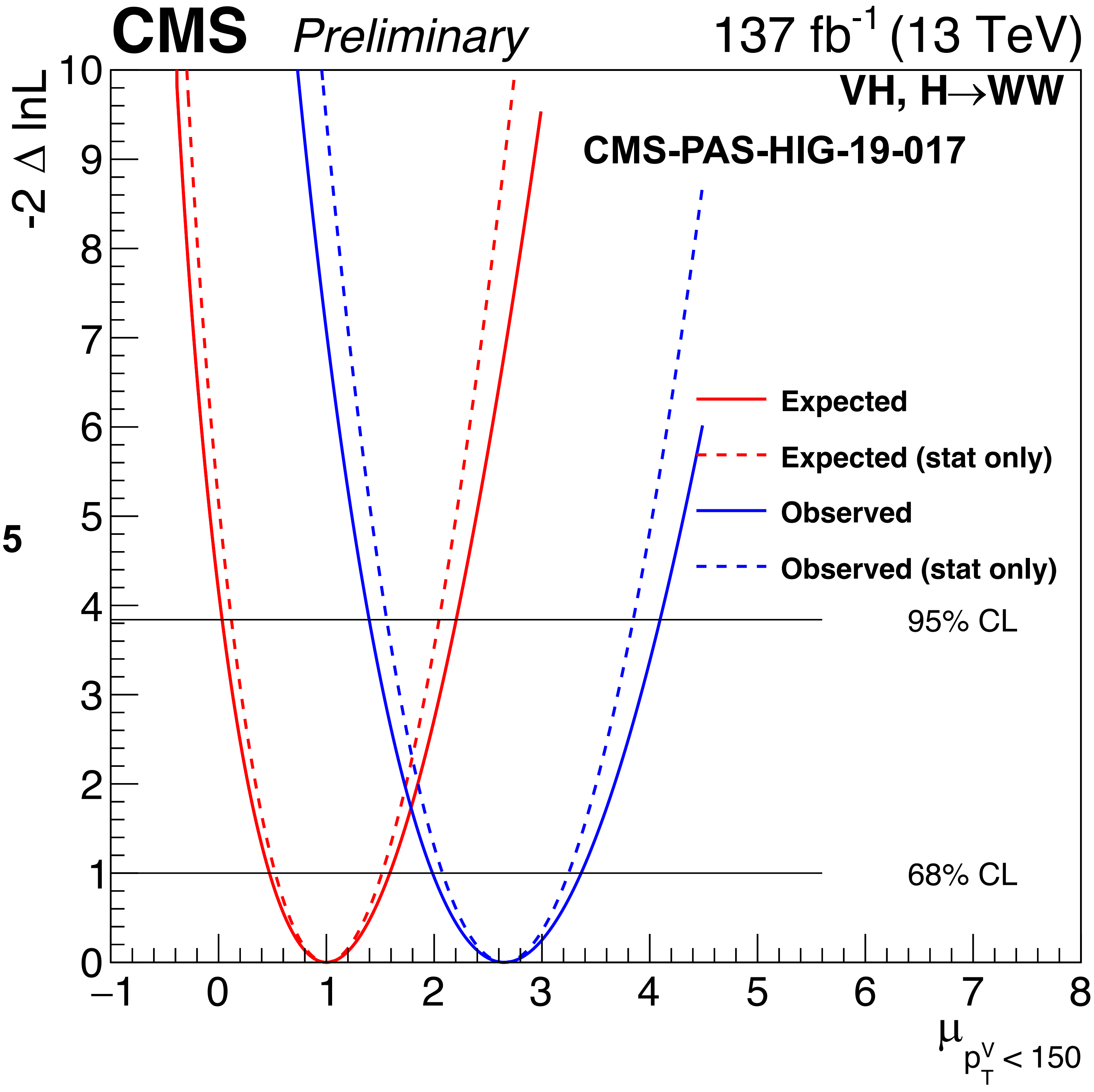
This represents a 3.8σ deviation from the SM value of 1. BSM signal normalization less than expected from multilepton excesses assuming Br(H→Sh)=100%. Indicates that Br(H→SS) > Br(H→Sh)



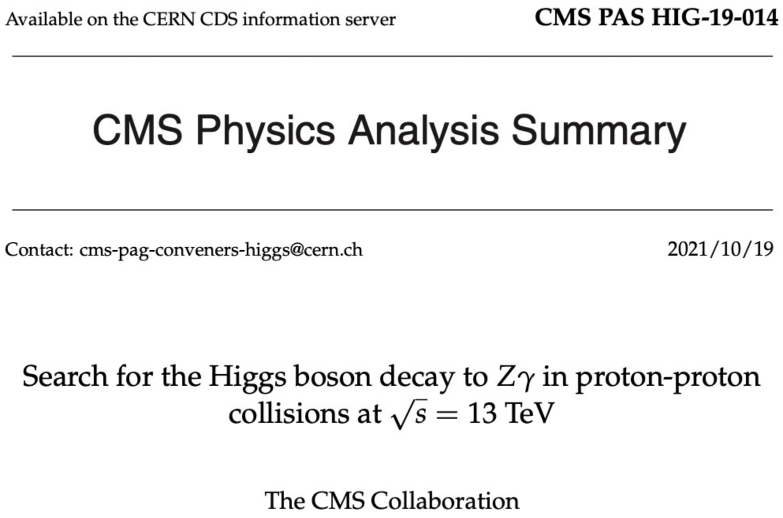
Higgs decay	Ref.	Experiment	$\sqrt{s}$, $\mathcal{L}$ TeV, fb^{-1}	Final state	Category	μ	Used in combination	Comments
WW	[66]	ATLAS	7, 4.5 8, 20.3	2ℓ	DFOS 2j	$2.2^{+2.0}_{-1.9}$	✓	2ℓ combination: $\mu = 3.7^{+1.9}_{-1.5}$
					SS 1j	$8.4^{+4.3}_{-3.8}$	✓	
					SS 2j	$7.6^{+6.0}_{-5.4}$	✓	
				3ℓ	1SFOS	$-2.9^{+2.7}_{-2.1}$	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	2ℓ	DFOS 2j	$0.39^{+1.97}_{-1.87}$	✓	Discrepancy at low $m_{\ell\ell}$
			8, 19.4	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	1ℓ	$\ell + \tau_h\tau_h$	-0.33 ± 1.02	x	BDT based on $p_T^{\tau_1} + p_T^{\tau_2}$
			8, 19.7	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**

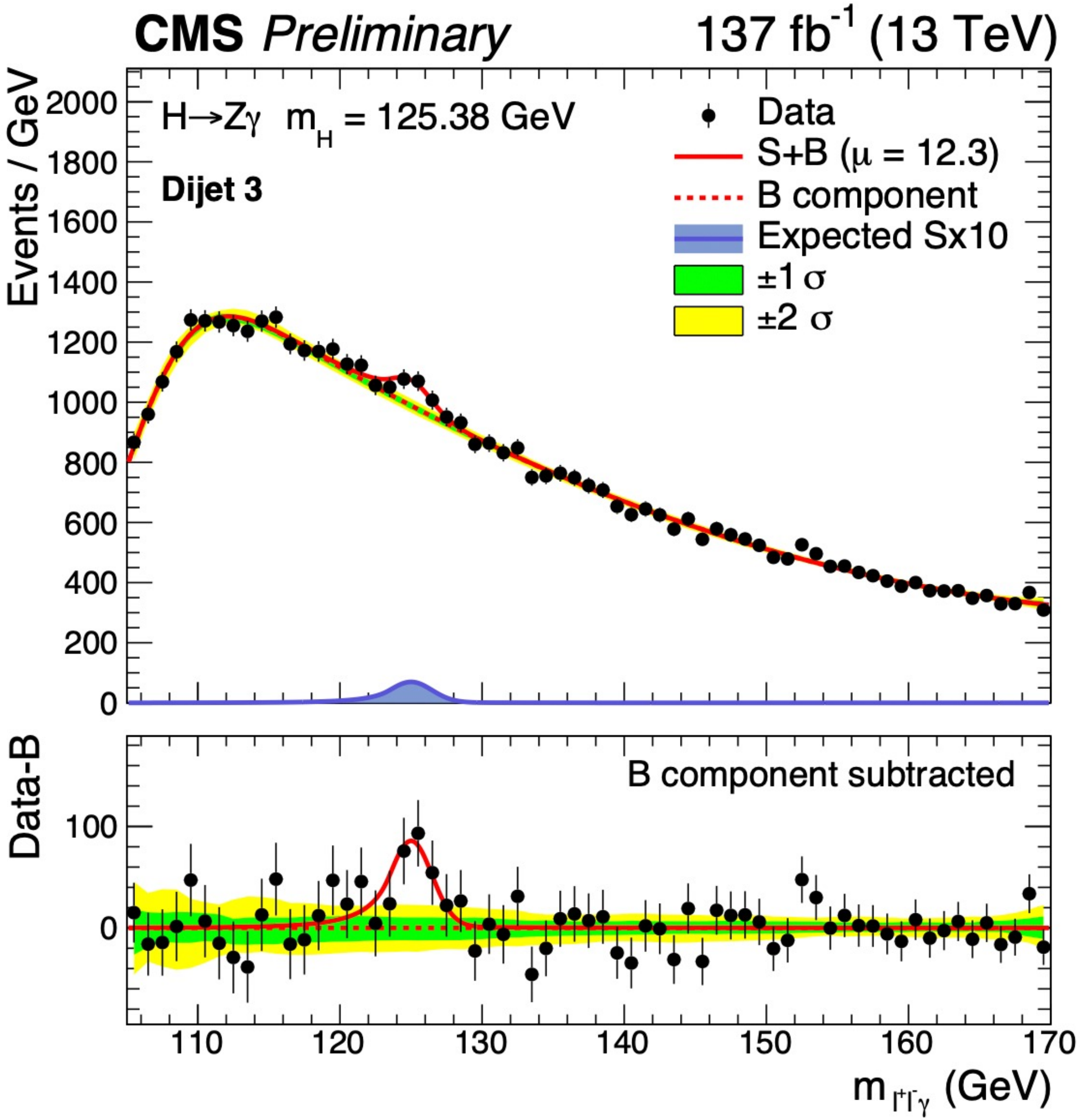
CMS Physics Analysis Summary

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

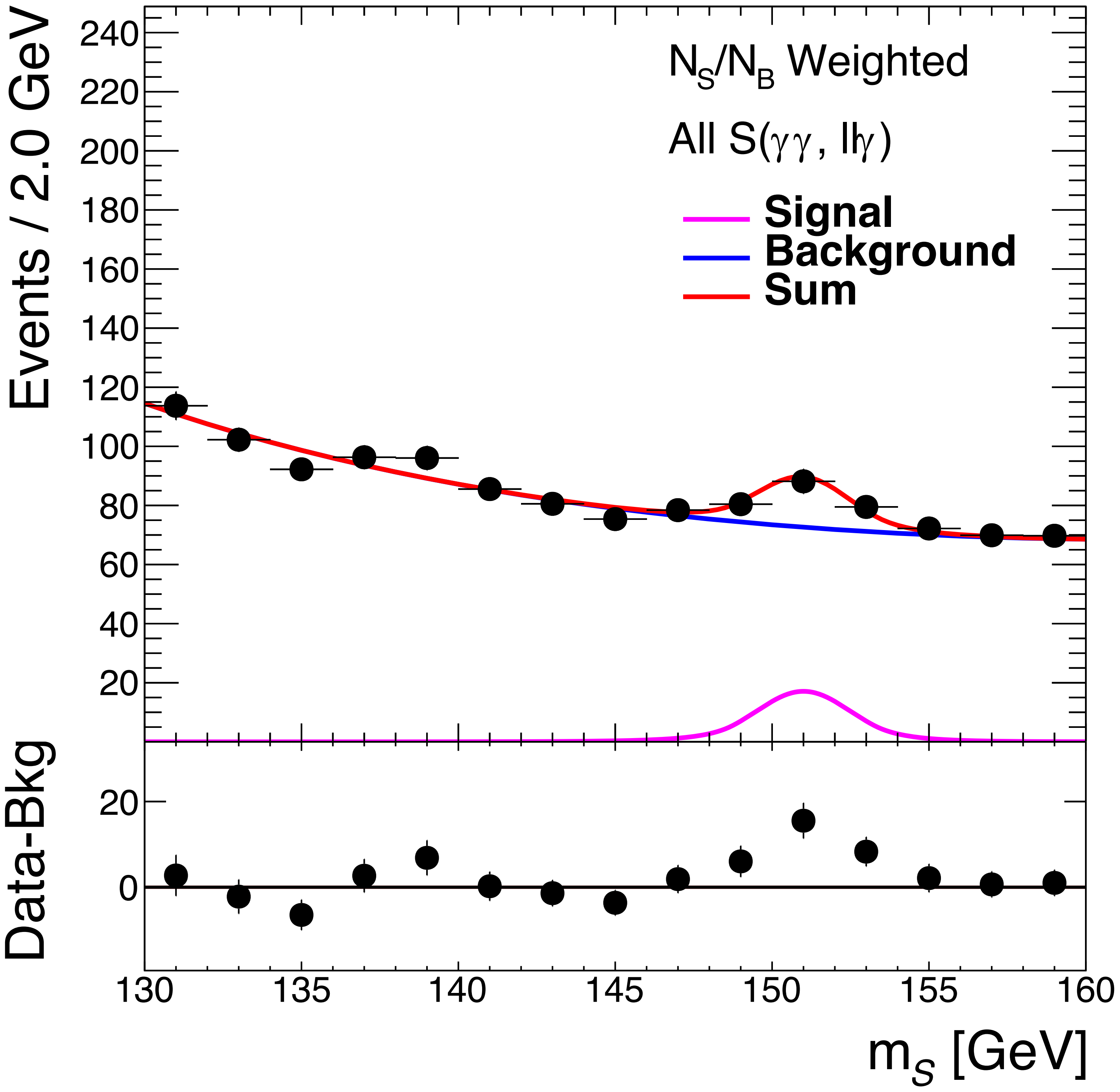
CMS observes what appears to be an upward fluctuation of the $h \to Z\gamma$ in the di-jet bin optimized for the measurement of Wh production. The Signal strength deviates from unity by 3.2σ.



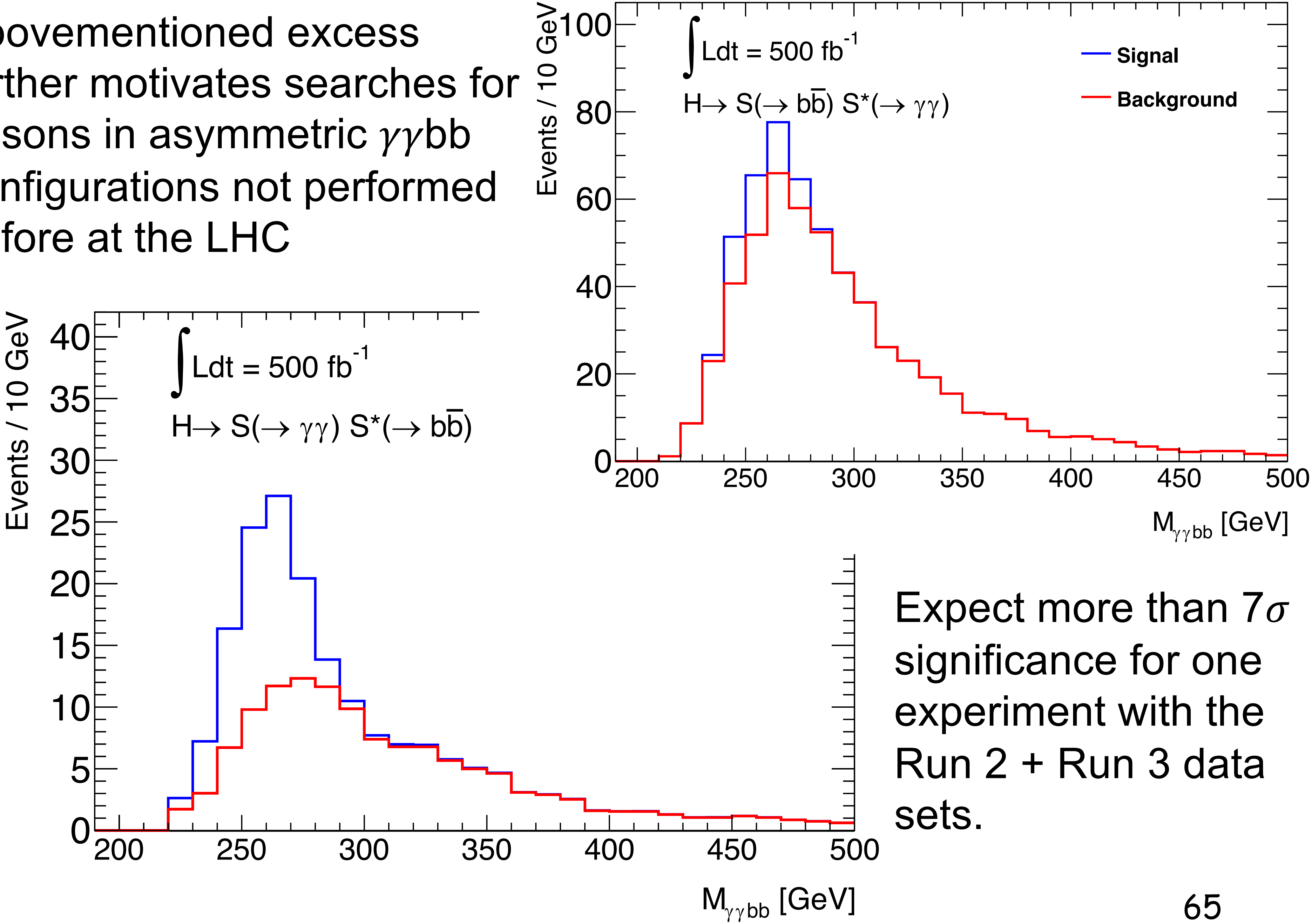
Analysis of publicly available $\gamma\gamma$, $Z\gamma$ spectra in associated production gives an excess at m_S=151.5 GeV.

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



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.