Growing excesses of new scalars at the Electro-weak scale at the LHC

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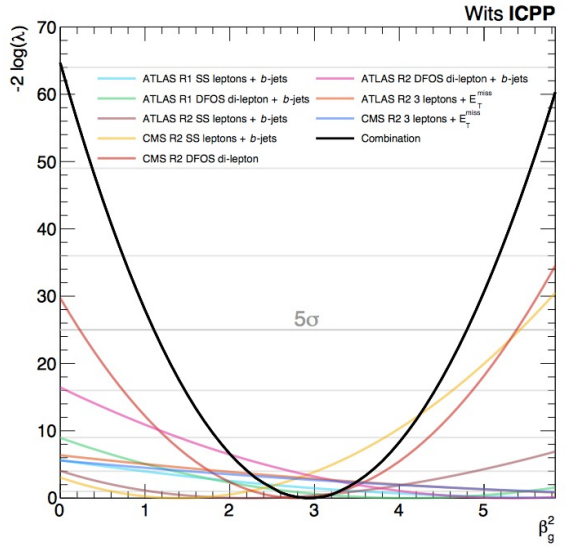
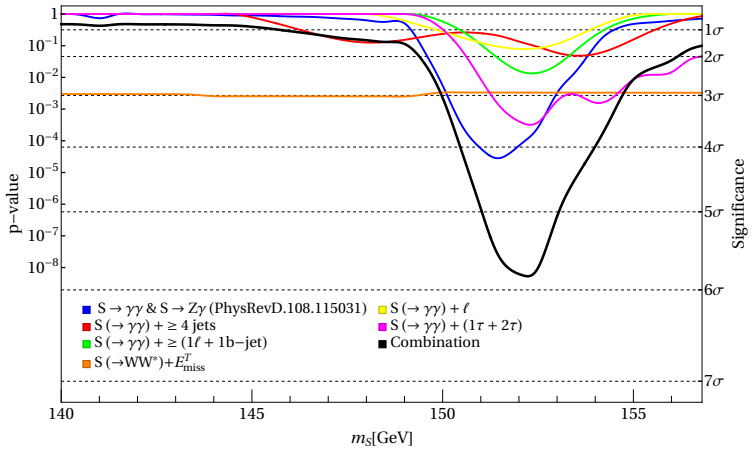
NRF National Research Foundation | iThemba LABS Laboratory for Accelerator Based Sciences

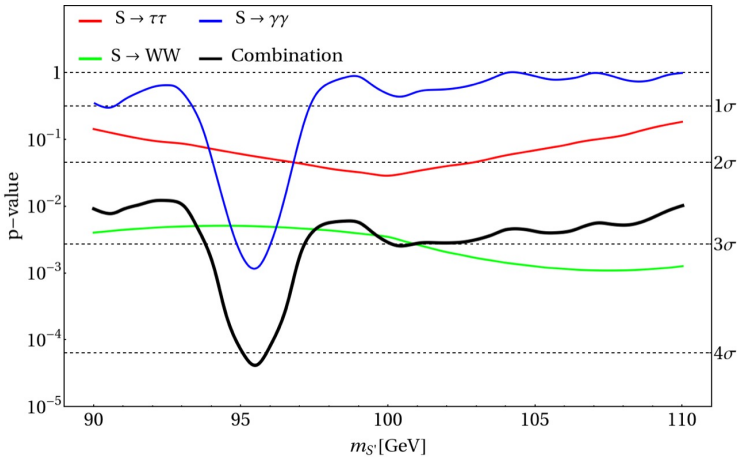
HEP seminar, University of Liverpool, 26/04/24

Outline

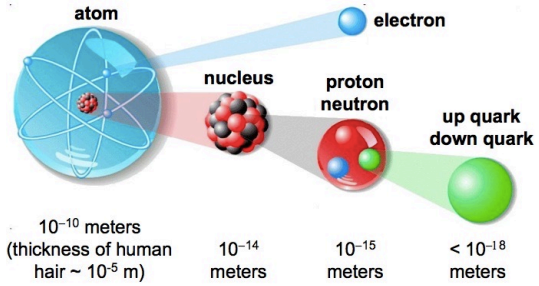
- Introduction
- The multilepton anomalies
  - Methodology
  - The anatomy
- The S(152) candidate
  - First combination of $\gamma\gamma$, $Z\gamma$
  - New results
- The S(95) candidate
- Impact on e^+e^- colliders



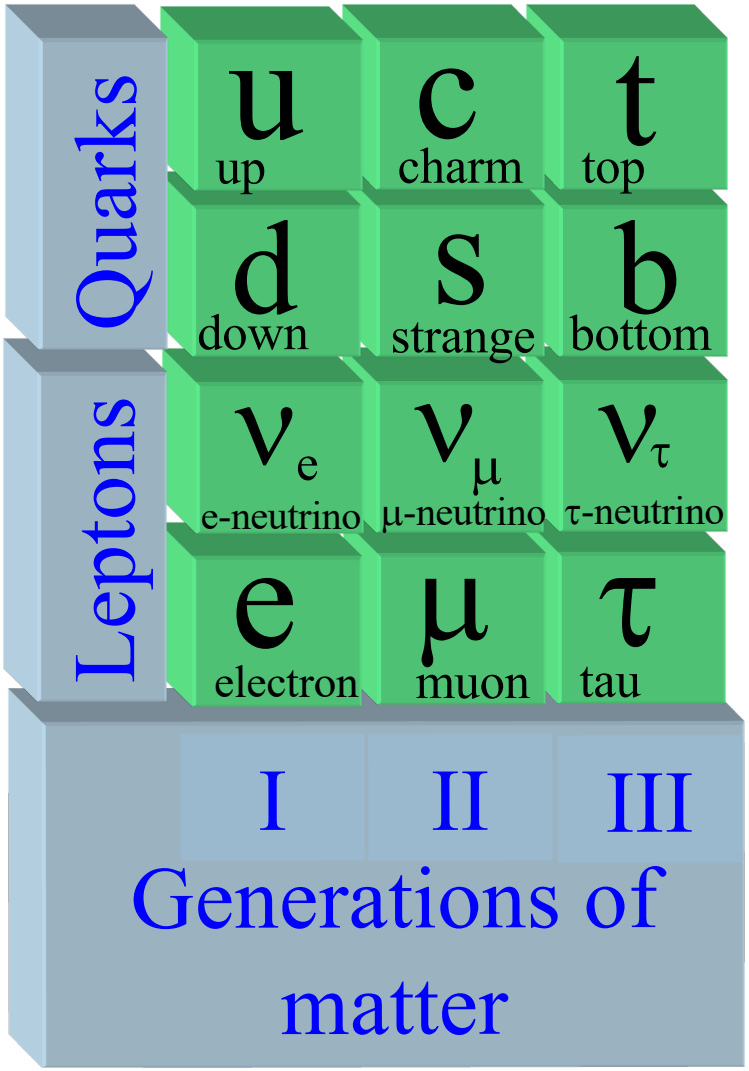




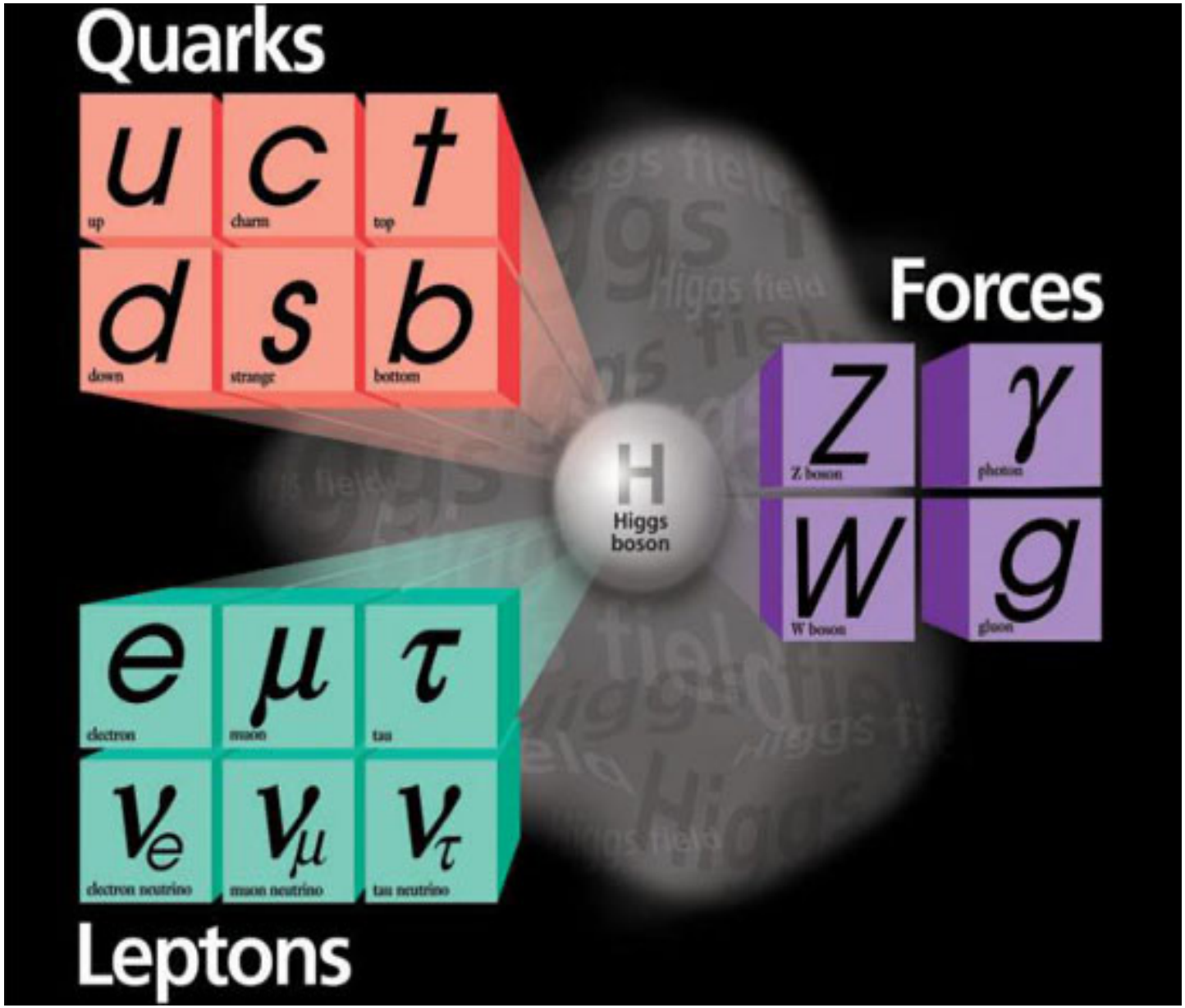
Building Blocks of Matter in the Standard Model



- Quarks and leptons are organized in families or generations of matter
  - So far we observe three generations (I, II ,II)
    - Second and third generations are copies of the first, only much heavier
  - All have intrinsic angular momentum (spin) of ½ (fermions)
- All particles have anti-particles
  - Display same mass and spin
  - Opposite electric charge



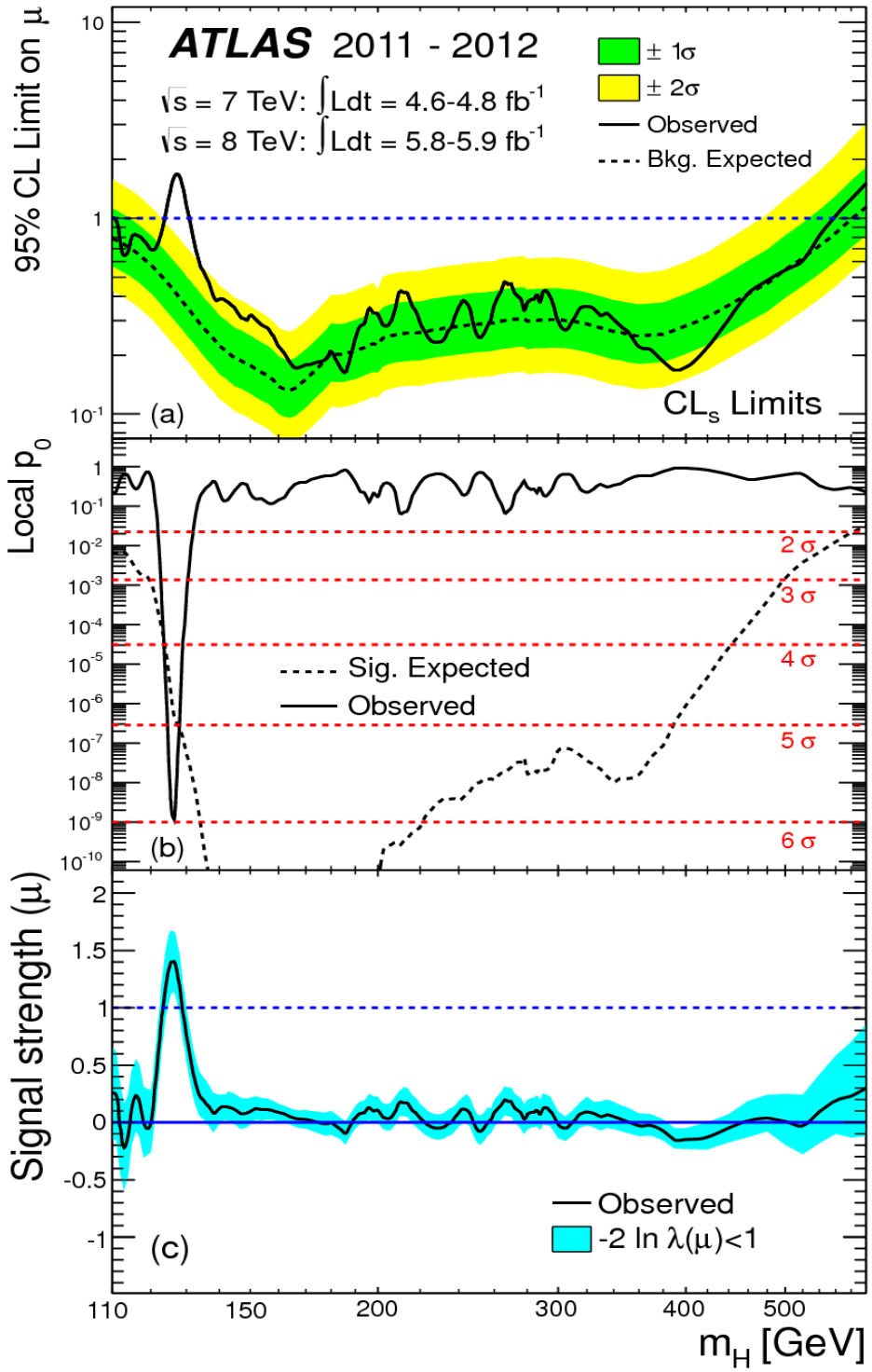
The Higgs boson provides for explanation for the mass of quarks, leptons and weak bosons. It is a cornerstone of the theory of fundamental interactions.

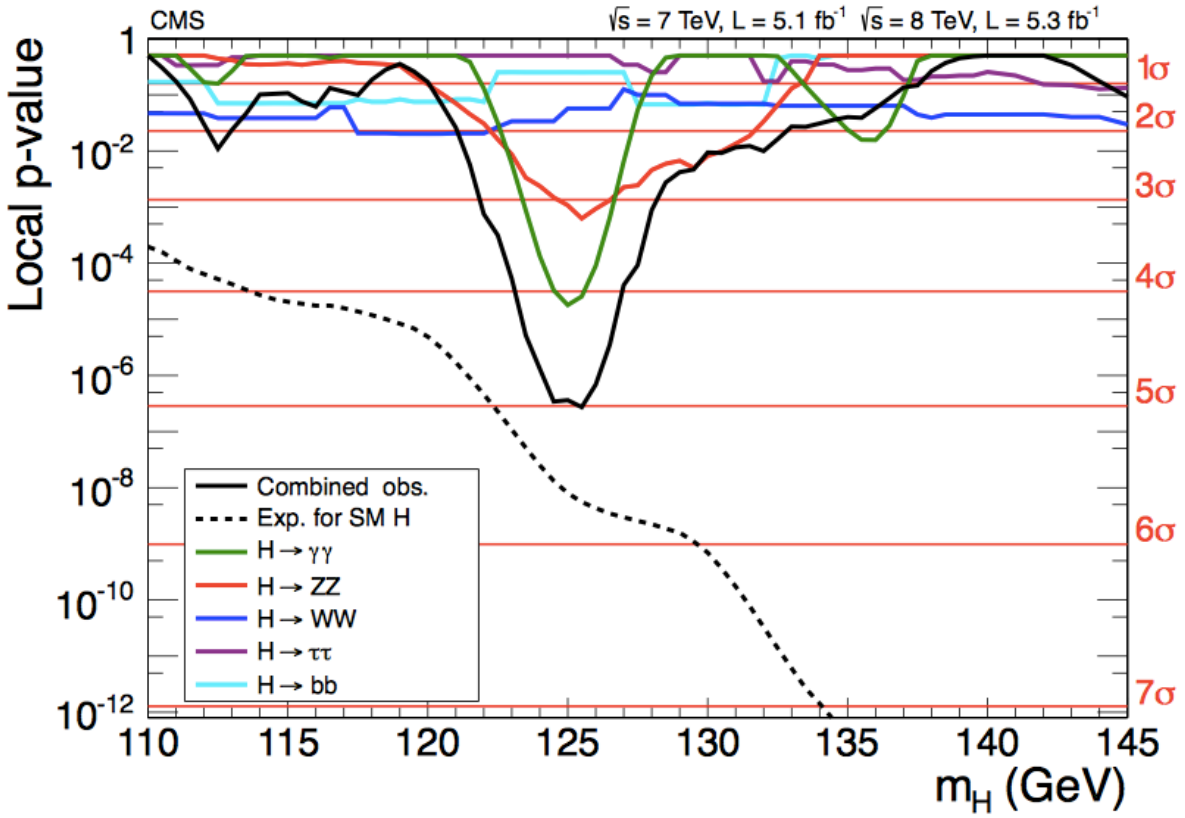


Habemus novum Boson

Phys.Lett. B716 (2012) 1-29
Phys.Lett. B716 (2012) 30-61

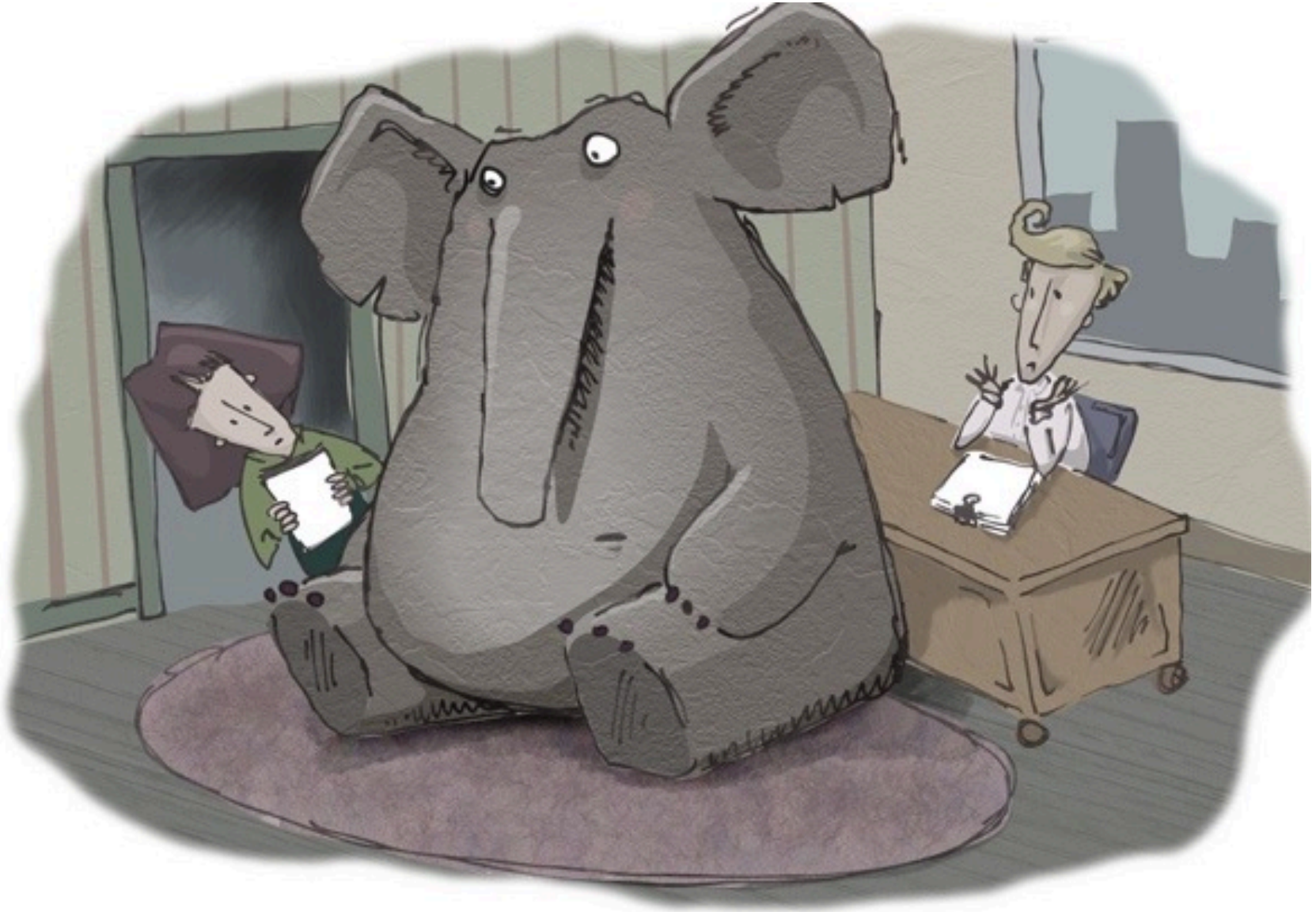
On July 4th 2012 reported both experiments reported ~5σ effects



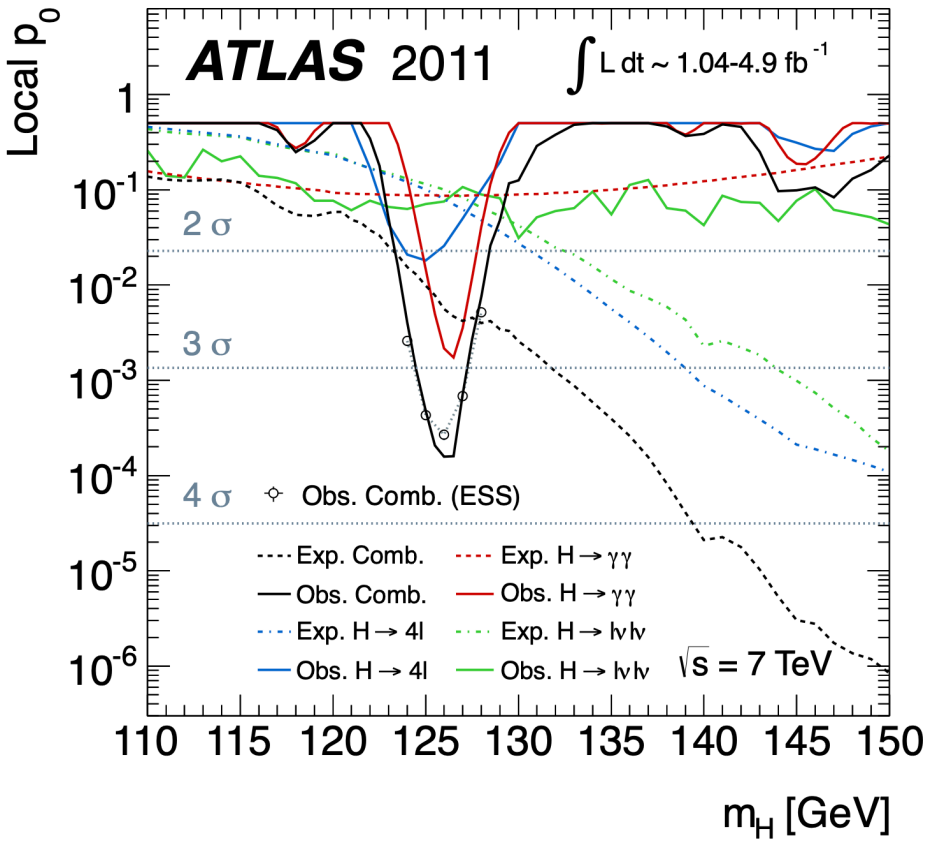


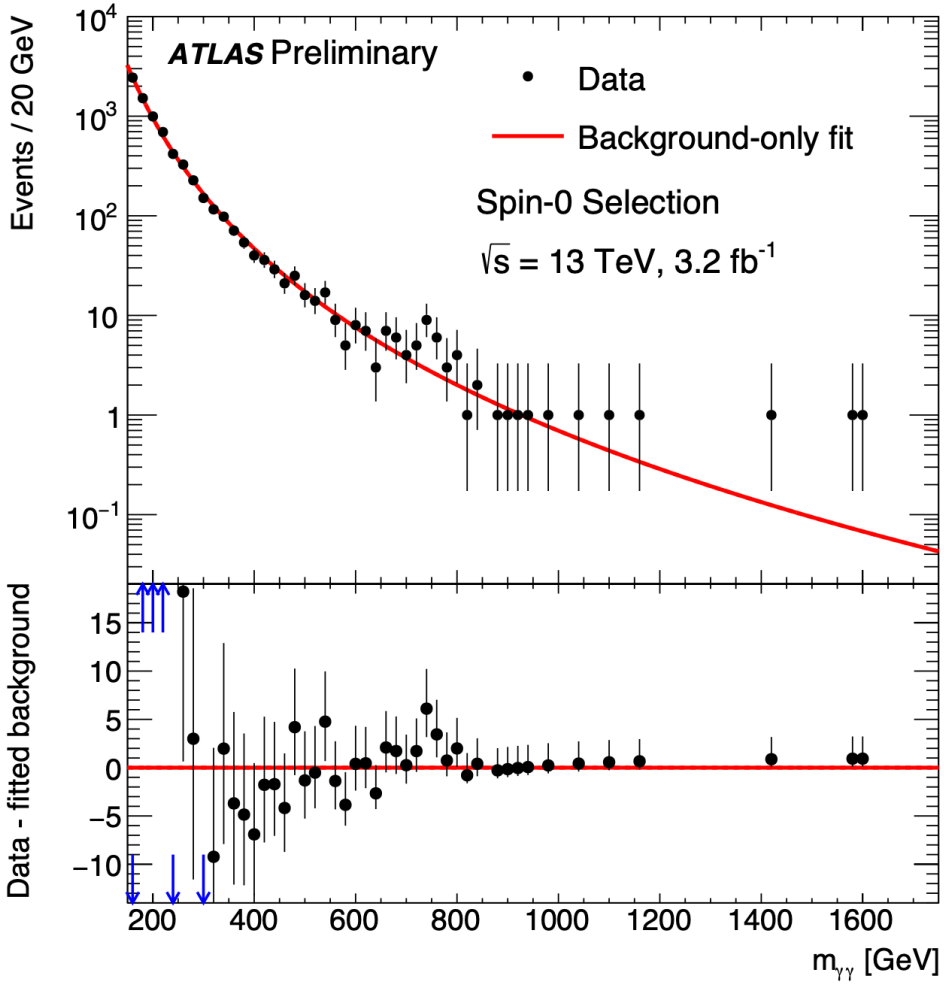

I wonder if there are
others like me.
H

Let’s address the Big Elephant in the room



ATLAS, *Phys.Lett.B* 710 (2012) 49-66





125 GeV	Criterion	750 GeV
YES	Multiple final states	NO
YES	Indirect evidence	NO
YES	Theoretical motivation and explanation	?

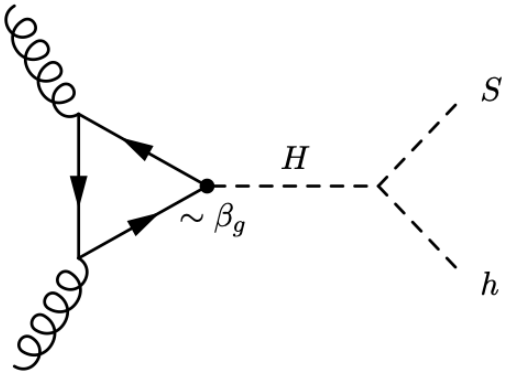
The 750 GeV excess had several red flags from inception

The Simplified Model

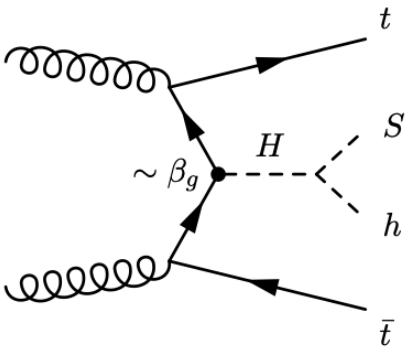
Eur. Phys. J. C (2016) 76:580

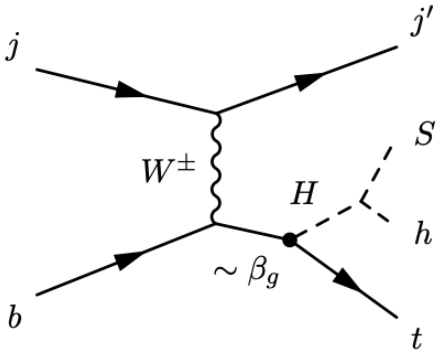
The simplified Model (from Run I)

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

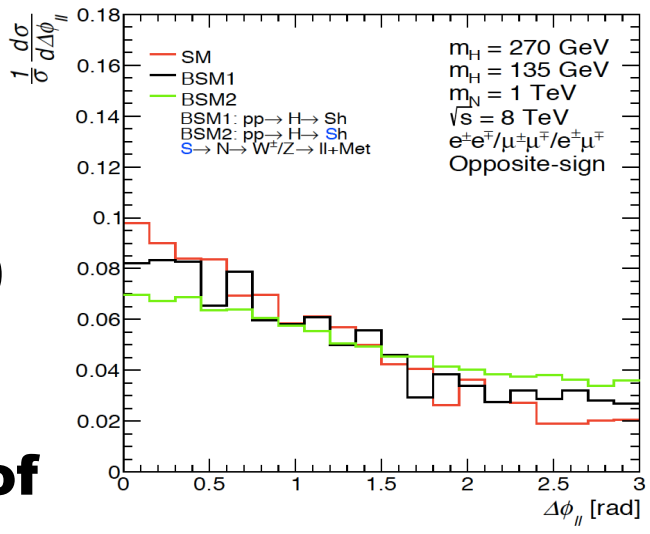
$$H \to h(+X), S(+X)$$

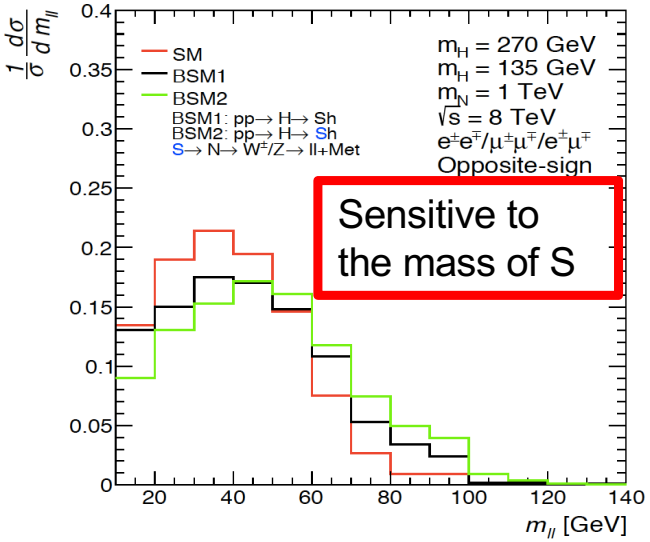
Multi-lepton final states

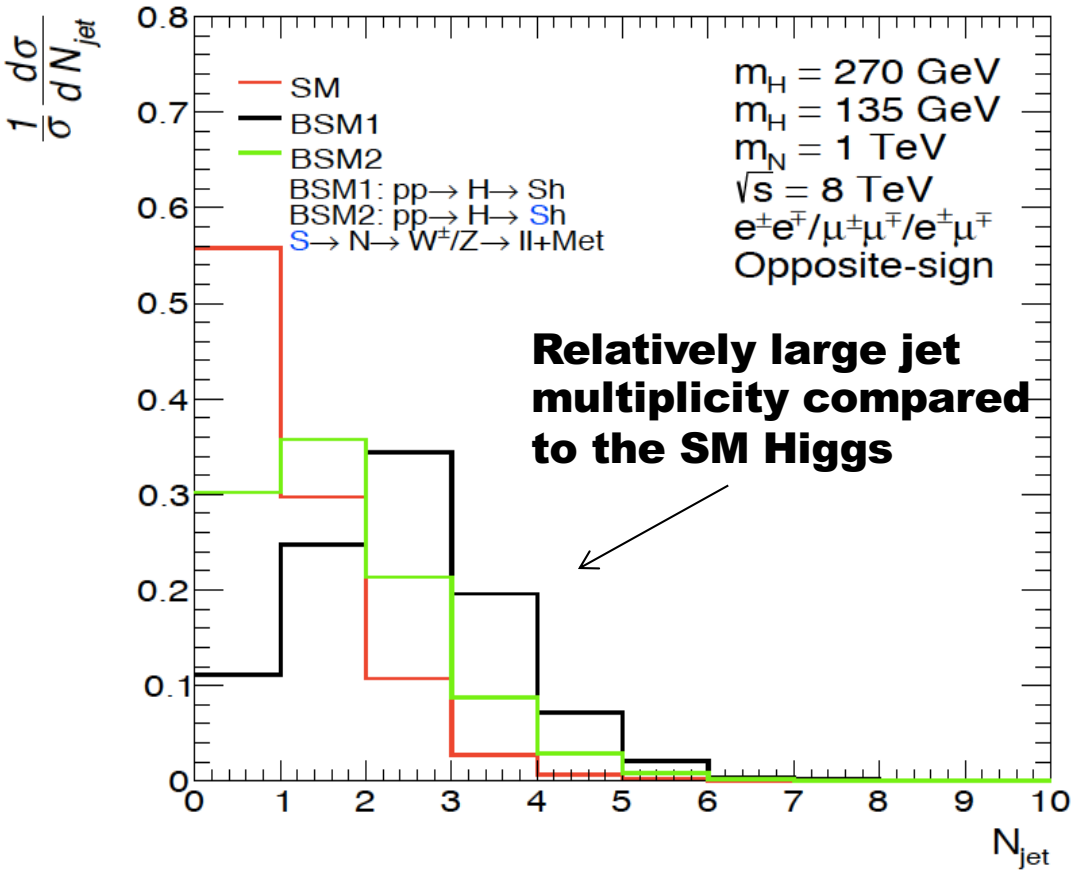
It is paramount to remark that the excesses are seen in final states that were predicted 2015/2016 on the basis of a simplified model and not the result of scan of the available phase-space. Additionally, the parameters of the model where fixed then leaving only one degree of freedom: normalization Thus,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

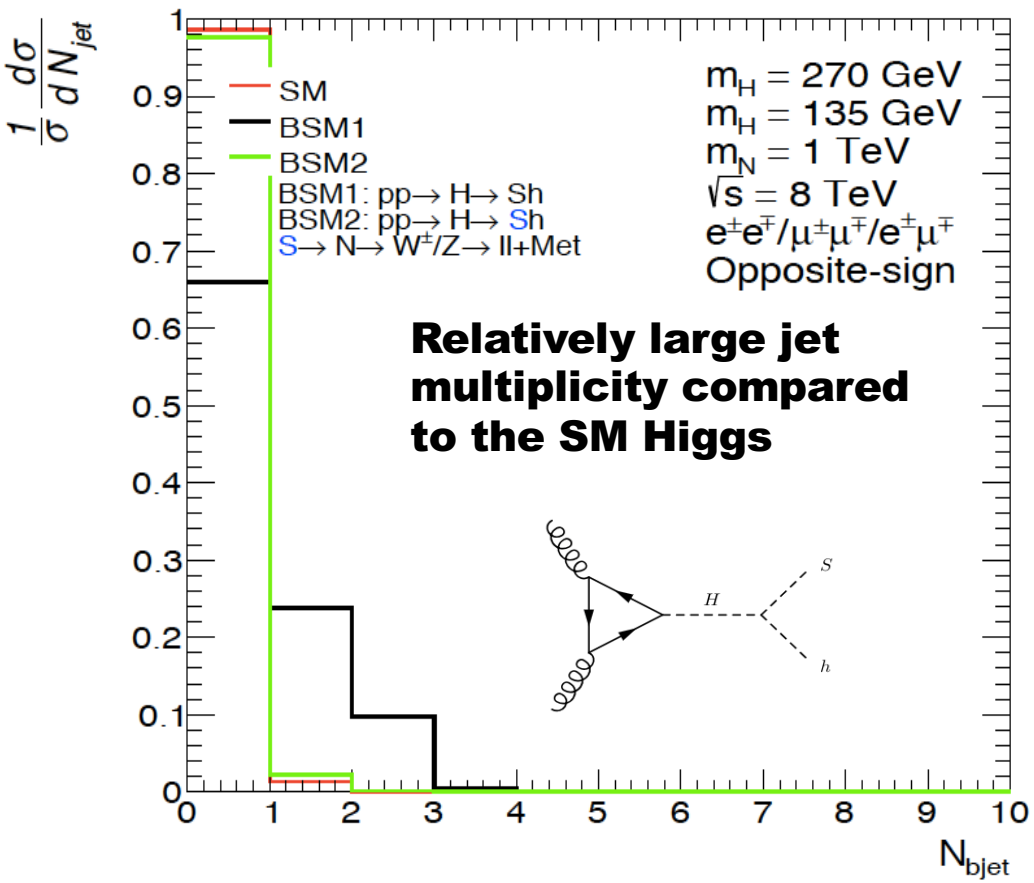
$$pp \to H \to Sh, SS \to \ell^+ \ell^- + X$$

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



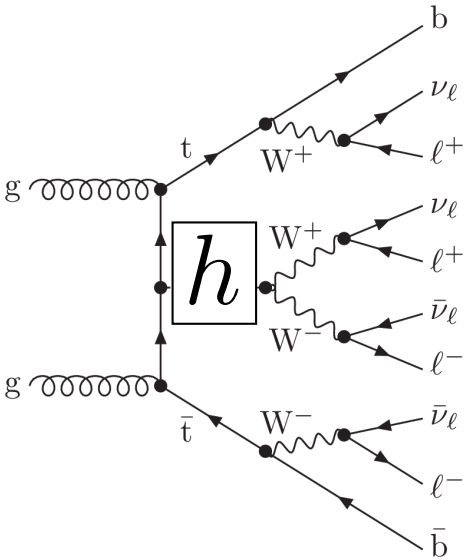


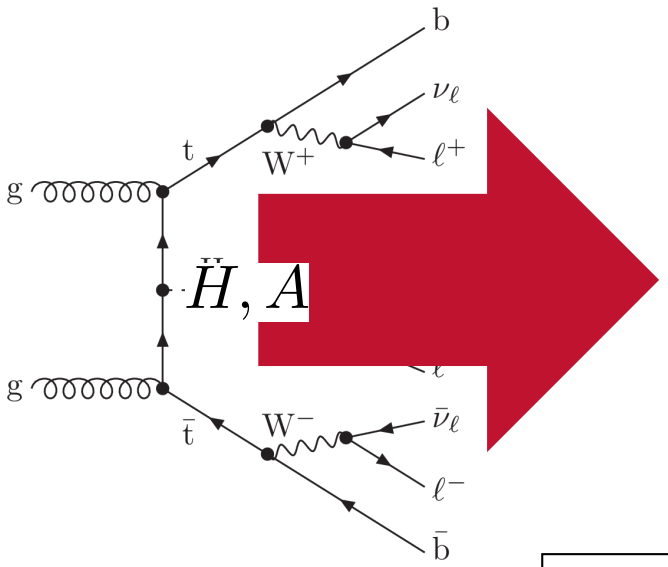




Top associated Higgs production

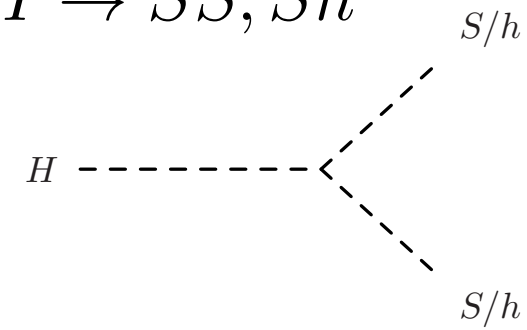
(Multi-lepton final states)





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

$$H \to SS, Sh$$



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

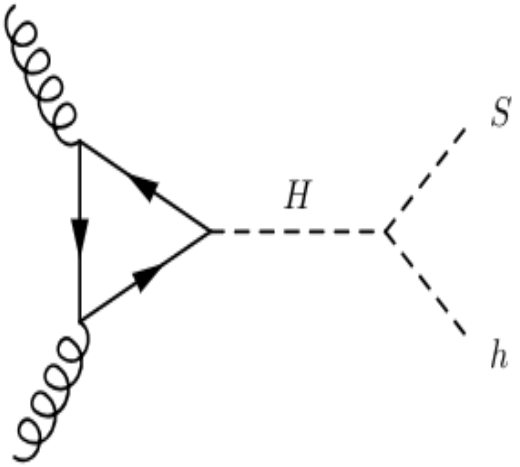
Update same final states with more data in Run 2

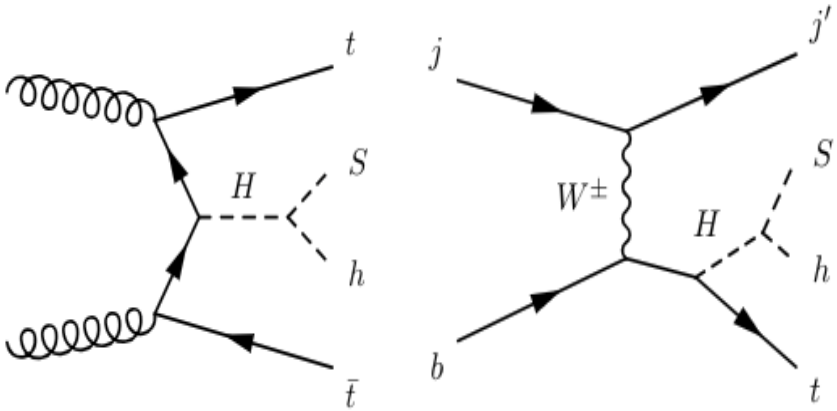
Study new final states where excesses predicted and data available in Run 1 and Run 2 (e.g., SS0b, 3l0b, ZW0b)

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 $H \rightarrow Sh$ is fixed to 100%**
  - **e. The BRs of *S* are Higgs-like**
- **Therefore, the only free parameter in the fits is β_g^2**



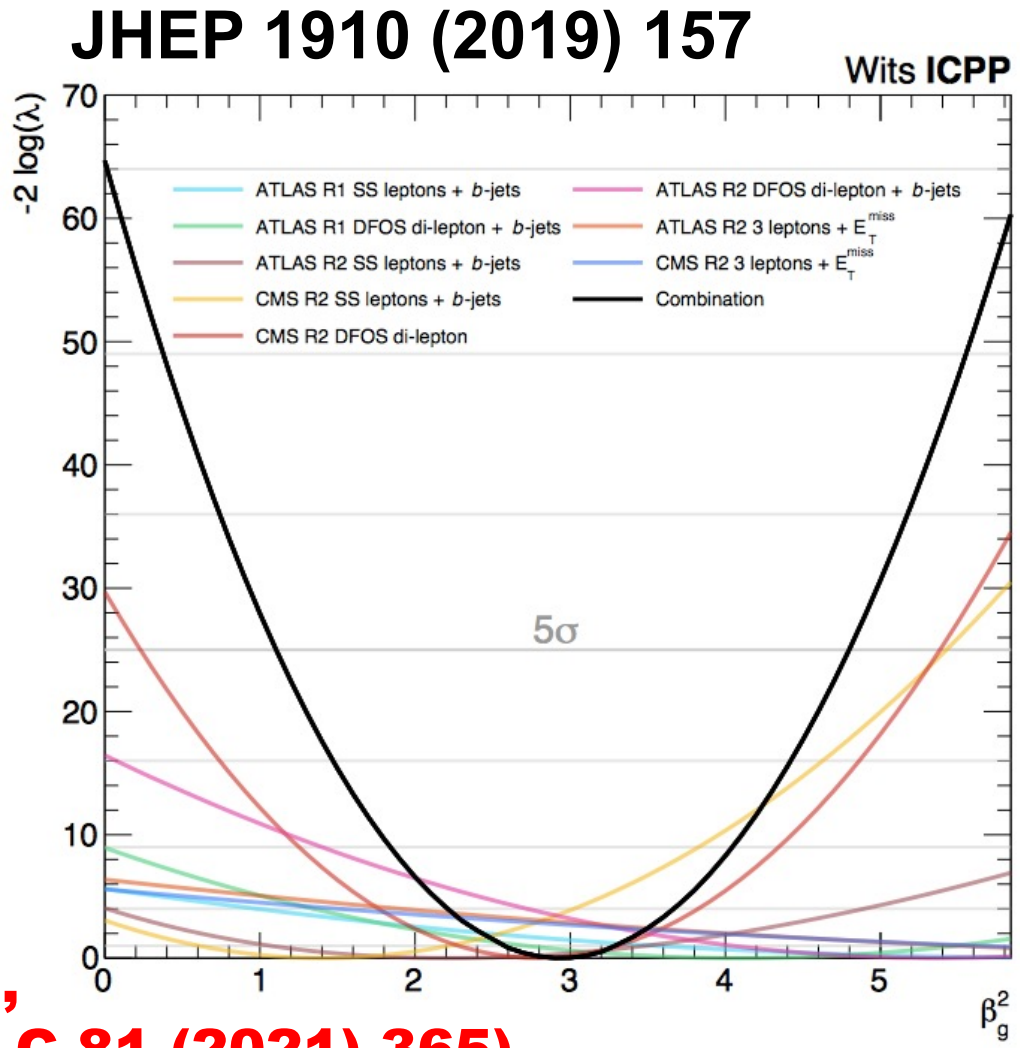


Combination of fit results (2019)

- **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**



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

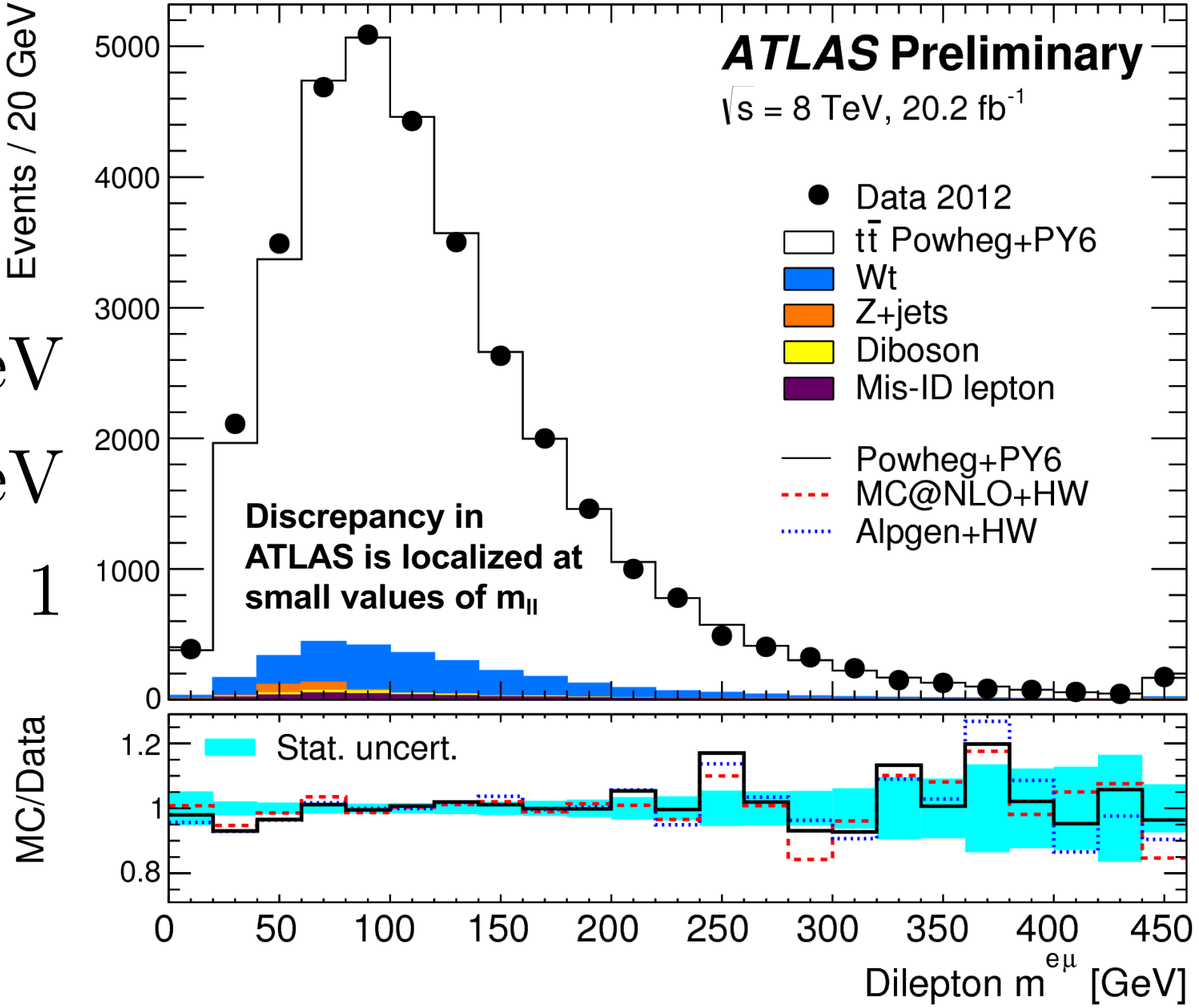
Is the discrepancy due to ttbar events?

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

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

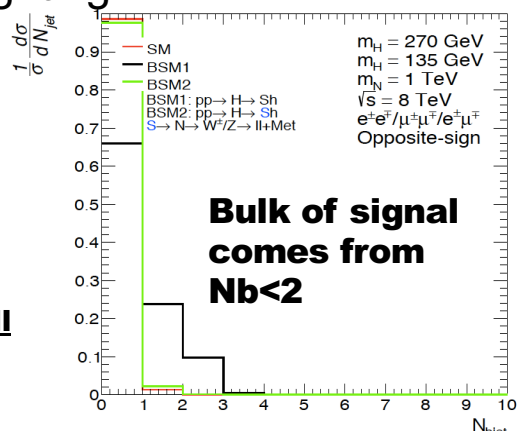
$$N_{bjet} \geq 1$$

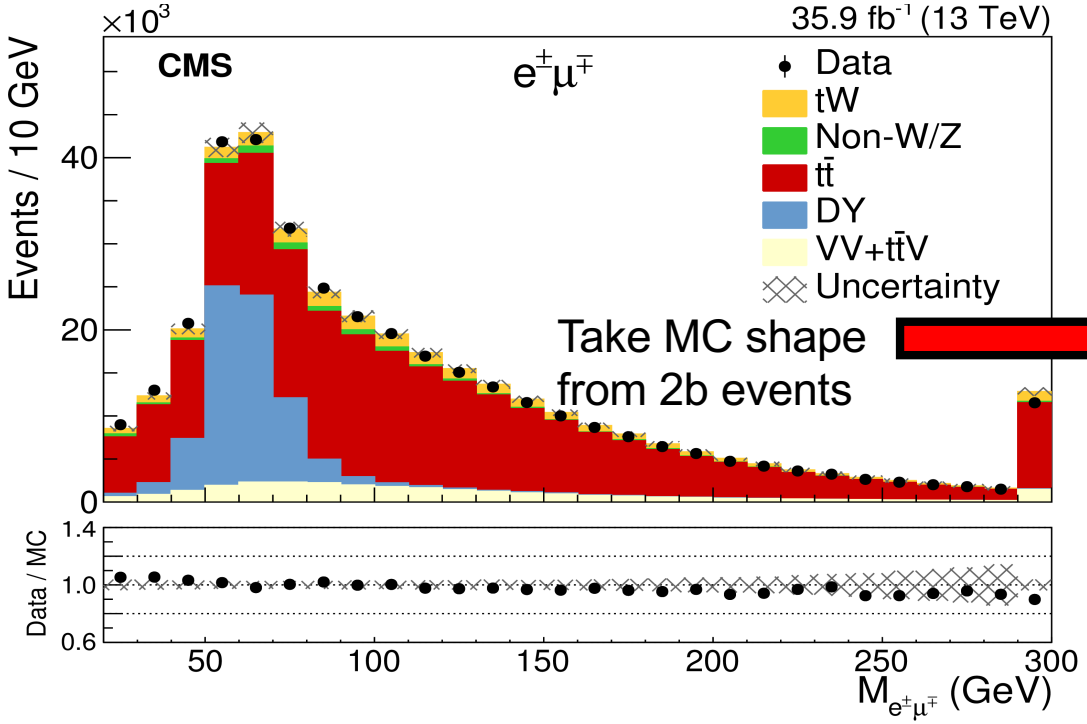
Eur. Phys. J. C 77 (2017) 804

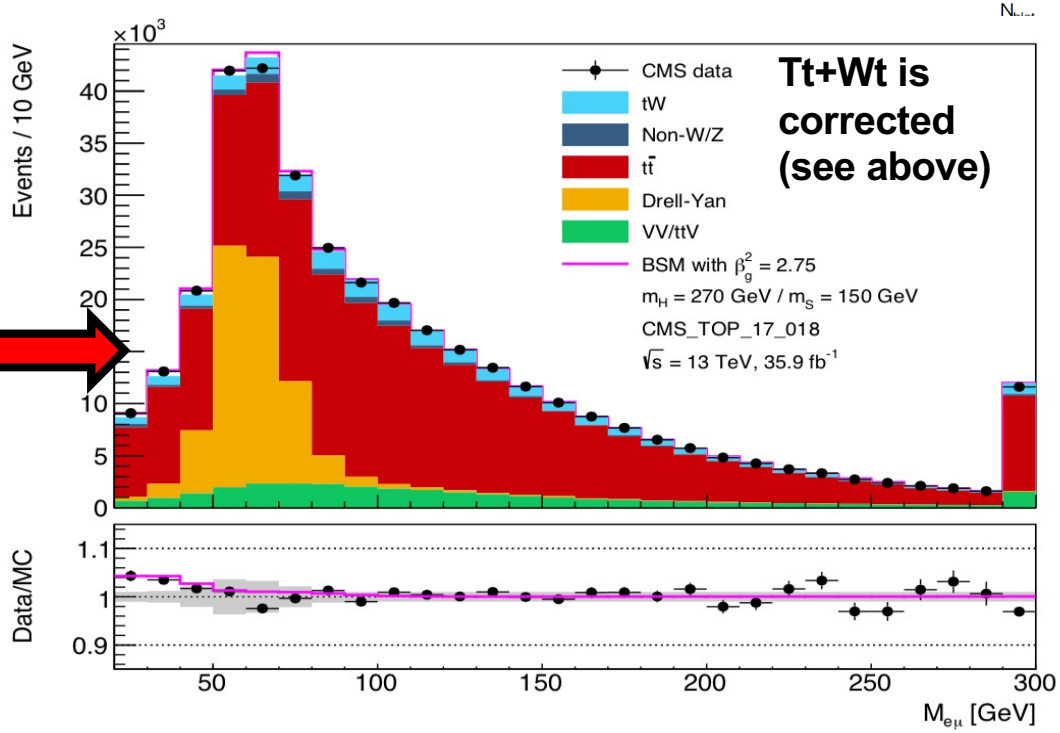


- Poor modeling of POWHEG + Pythia8 distribution is improved through reweighting
- We fix the normalisation of the SM by scaling it to the data in the region m_{ll} > 110 GeV
  - A normalisation systematic of 3% is applied to all but DY
  - DY systematic = 6.8%. 3% systematic on m_{ll} shape in top
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

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



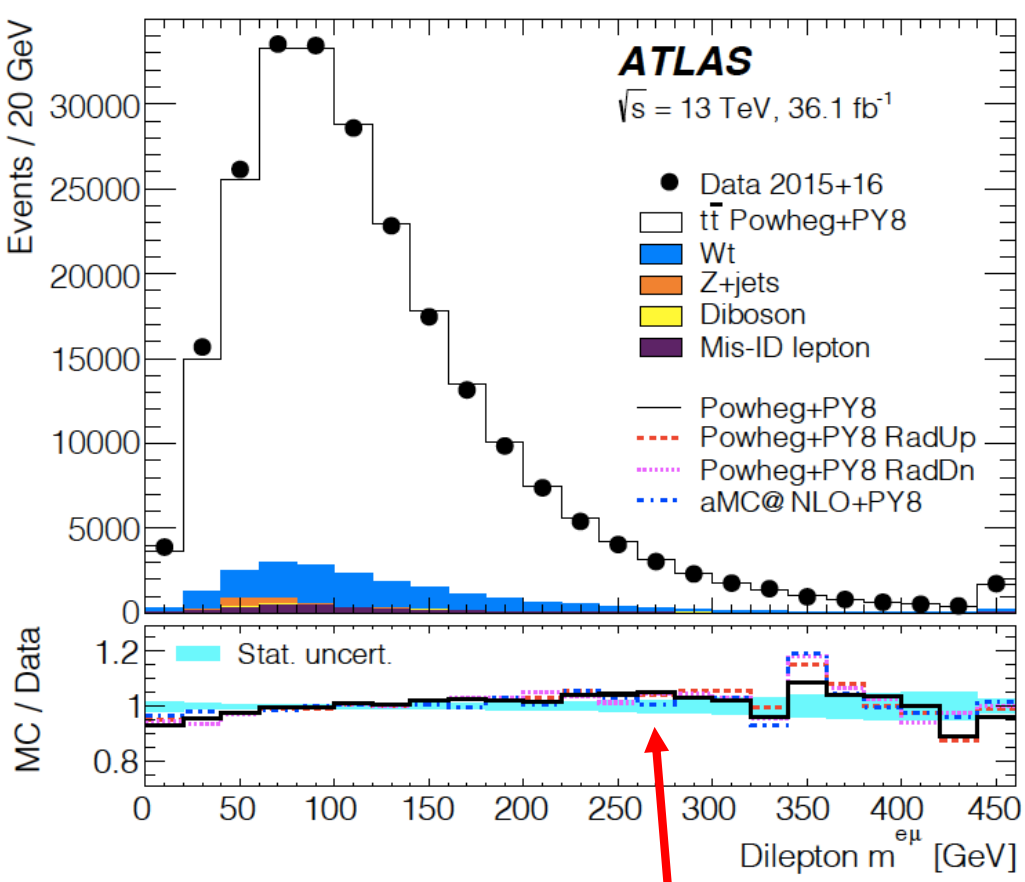


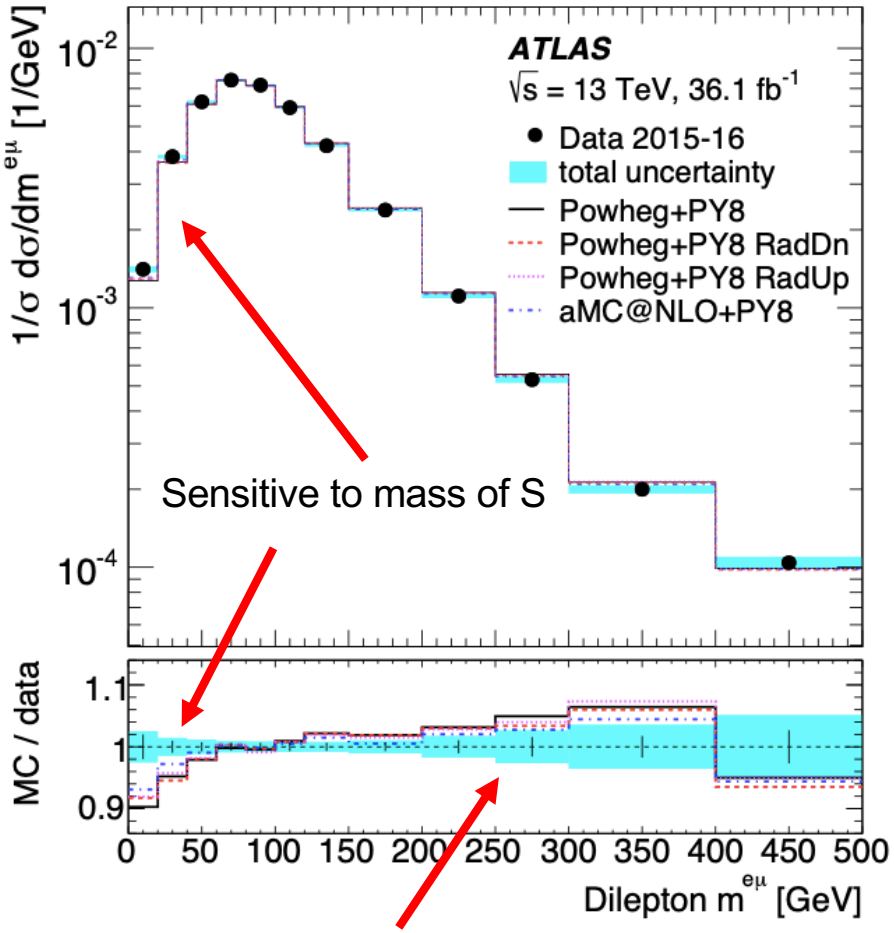


Used conservative assumption that l^+l^-+2b-jet final state is well described by the SM. The discrepancy comes from events with N_b<2. Excess unlikely due to tt

Excesses confirmed with Run 2 results

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

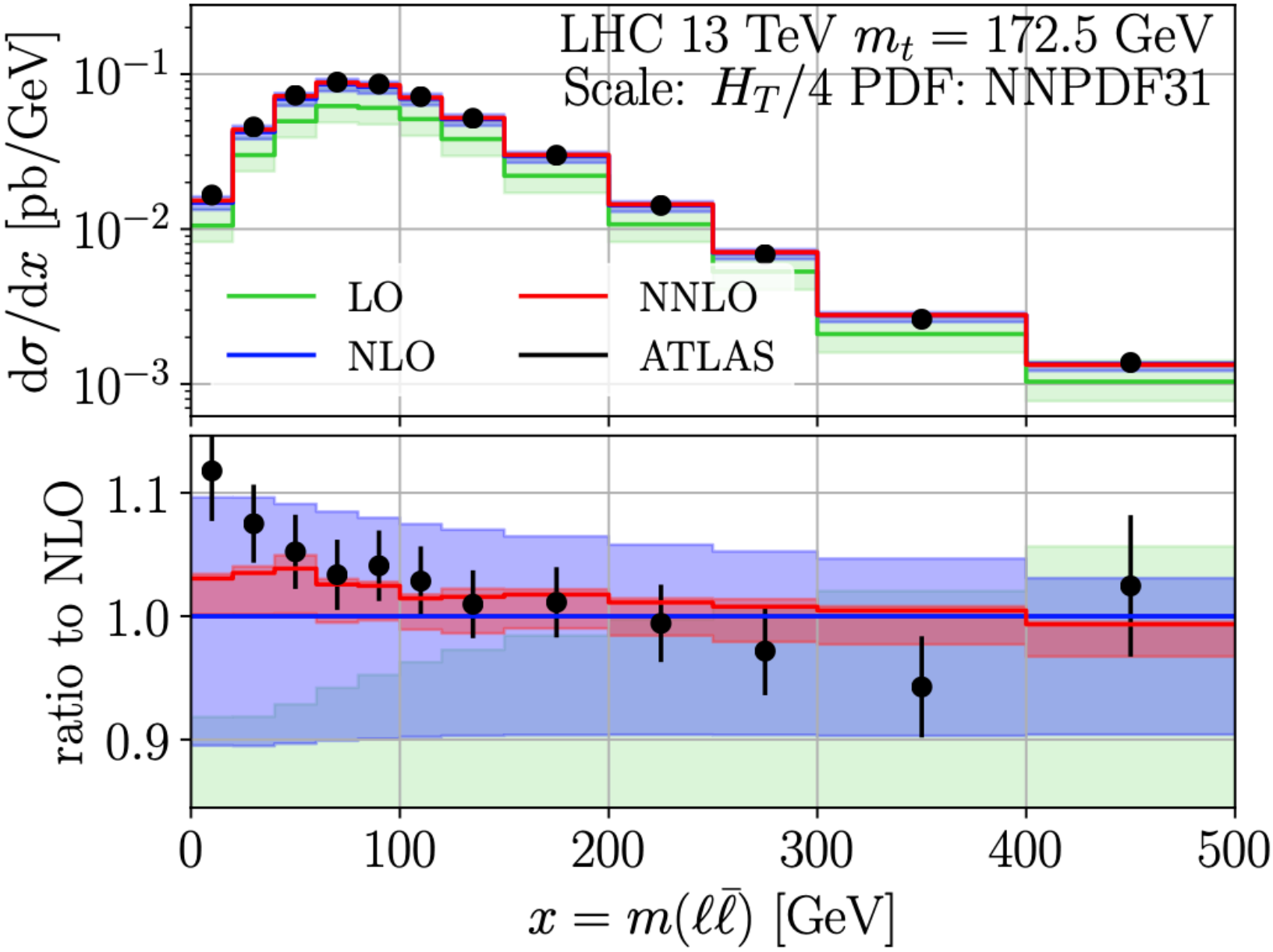




Residual discrepancies at high m_{ll} will be fixed with missing NNLO QCD and NLO EW corrections

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.)

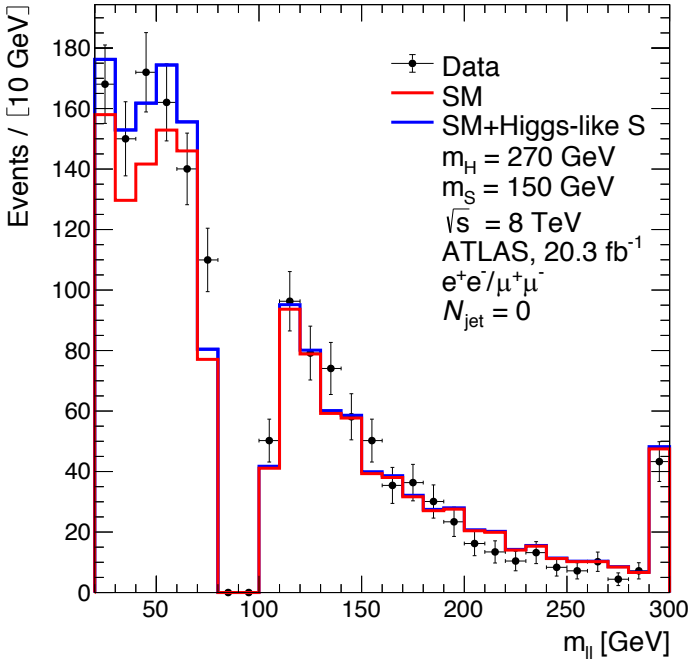
M.Czakon, A.Mitov, R.Poncelet *JHEP* 05 (2021) 212

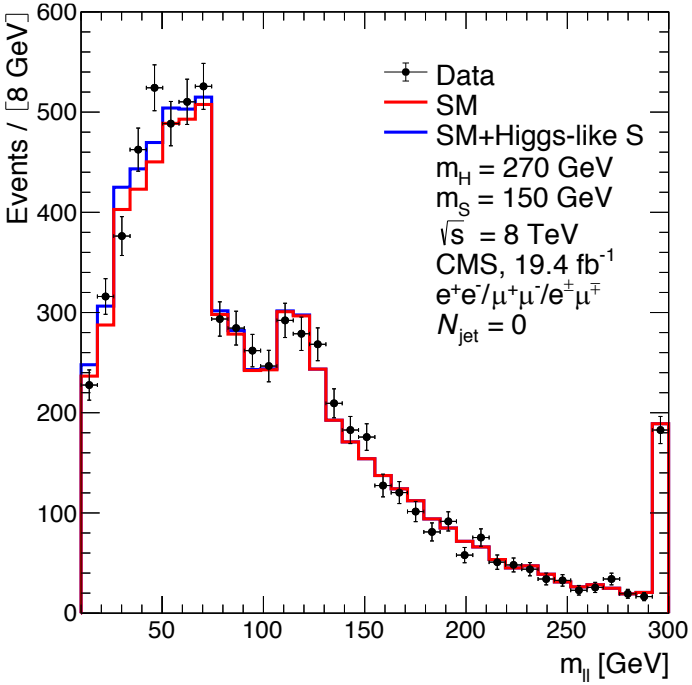


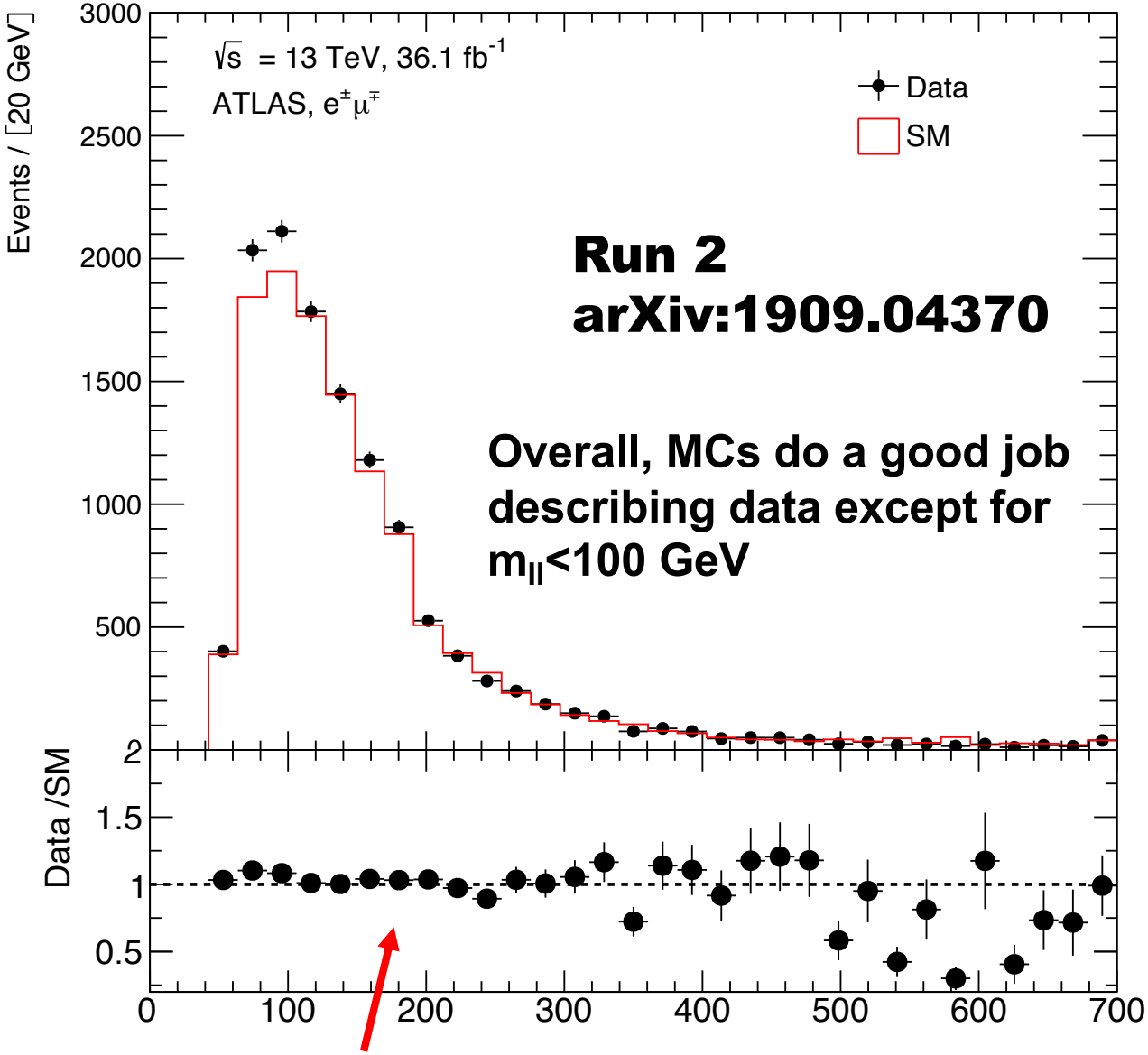
Excesses in di-leptons with full-jet veto. Excludes tt as source.

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

Nature Rev.Phys. (2024), https://www.nature.com/articles/s42254-024-00703-6

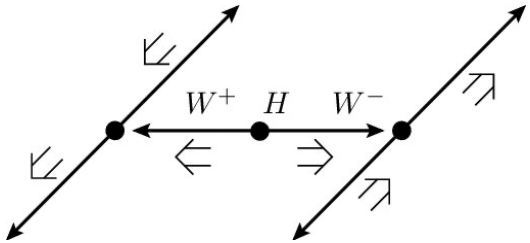
Anatomy of the multi-lepton anomalies (2024)

Final state	Characteristic	Dominant SM process	Significance
l^+l^- + jets, b-jets	m_{ll}<100 GeV, dominated by 0b-jet and 1b-jet	tt+Wt	>5σ
l^+l^- + full-jet veto	m_{ll}<100 GeV	WW	~3σ
$l^\pm l^\pm$ & $l^\pm l^\pm l$ + b-jets	Moderate H_T	ttW, 4t, ttZ/tWZ	>3σ
$l^\pm l^\pm$ & $l^\pm l^\pm l$ et al., no b-jets	In association with h	Wh, WWW	4.2σ
$Z(\rightarrow l^+l^-)+l$	p_{TZ}<100 GeV	ZW	>3σ

Di-lepton invariant mass in MLA predict a scalar with a mass 150±5 GeV (J.Phys. G45 (2018) no.11, 115003, see also Phys.Rev.D 108 (2023) 11, 115031 and arXiv:2306.17209) in association with leptons and jets.

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

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

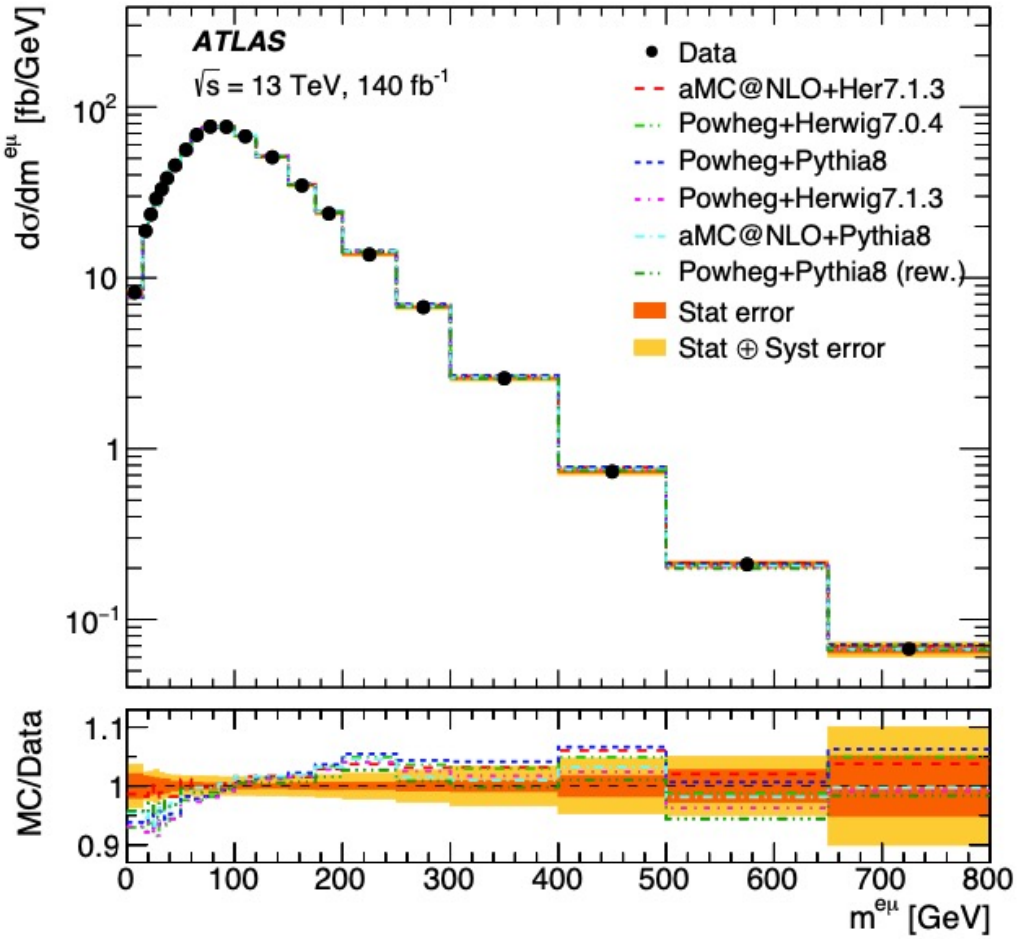


J.Phys. G45 (2018) no.11, 115003

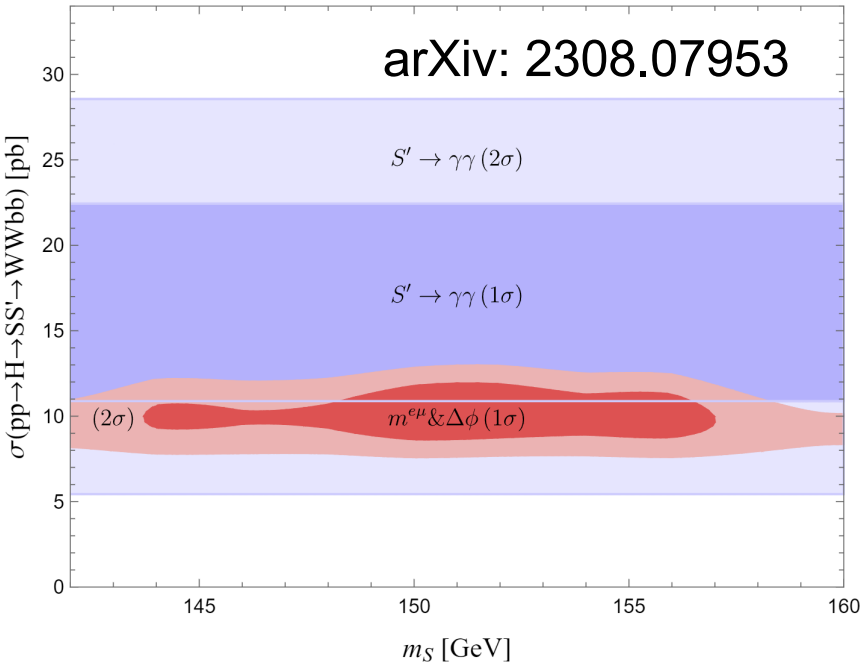
The 152 GeV Candidate

Confirmed with new measurement in arXiv:2308.07953

ATLAS, JHEP07(2023)141



New determination of m_S with di-lepton events with ATLAS di-lepton tt measurement

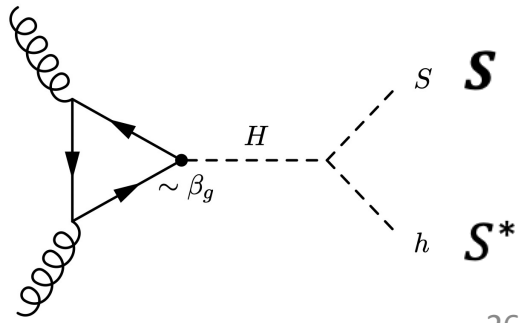


$m^{e\mu}$ bins [GeV]	$d\sigma/dm^{e\mu}$ [fb/GeV]	Data stat. [%]	MC stat. [%]	$t\bar{t}$ mod. [%]	Lep. [%]	Jets/ b-tag. [%]	Bkg. [%]	Lumi + E_{beam} [%]	Total unc. [%]
0.0–15.0	8.21	2.08	0.47	2.38	0.90	0.14	1.31	0.93	3.69
15.0–20.0	18.81	1.71	0.36	0.59	0.85	0.12	0.76	0.92	2.36
20.0–25.0	23.48	1.54	0.33	1.19	0.84	0.12	0.73	0.92	2.45
25.0–30.0	29.02	1.33	0.30	1.72	0.84	0.09	1.07	0.92	2.75
30.0–35.0	33.04	1.24	0.29	1.17	0.85	0.09	0.79	0.92	2.28
35.0–40.0	38.24	1.19	0.26	0.37	0.84	0.09	0.74	0.93	1.93
40.0–50.0	45.49	0.75	0.18	0.75	0.84	0.10	0.80	0.93	1.84
50.0–60.0	56.16	0.70	0.21	0.45	0.85	0.11	0.74	0.93	1.71
60.0–70.0	68.55	0.63	0.20	0.51	0.84	0.11	0.72	0.93	1.67
70.0–85.0	76.71	0.47	0.13	0.67	0.80	0.11	0.70	0.93	1.65
85.0–100.0	76.44	0.47	0.10	0.48	0.77	0.12	0.68	0.92	1.54
100.0–120.0	67.32	0.44	0.09	0.56	0.75	0.13	0.68	0.92	1.55

Confirmation of early determination of m_S with Run 2 data and using a different final state (ll+b-jets)

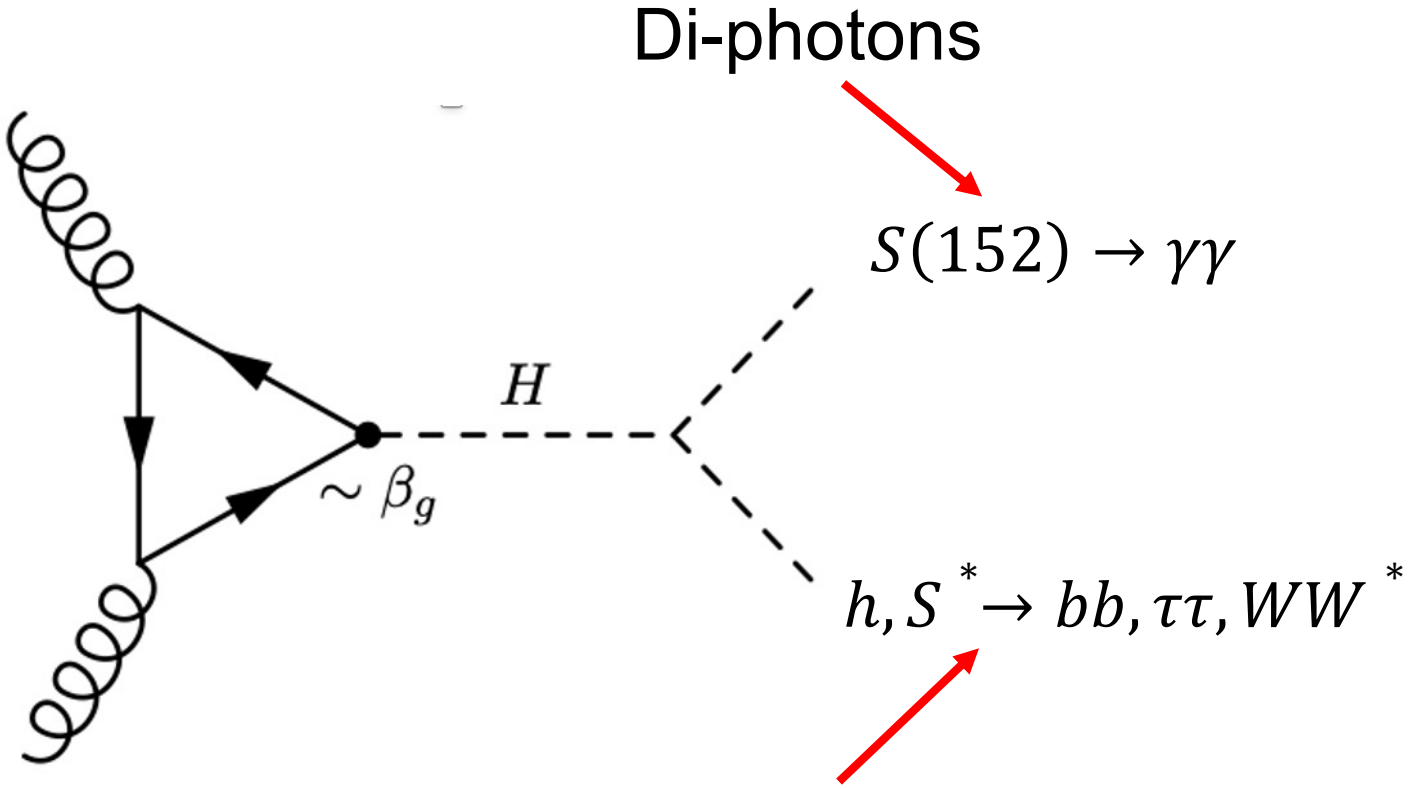
Procedure
(avoiding "cherry picking")

- 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



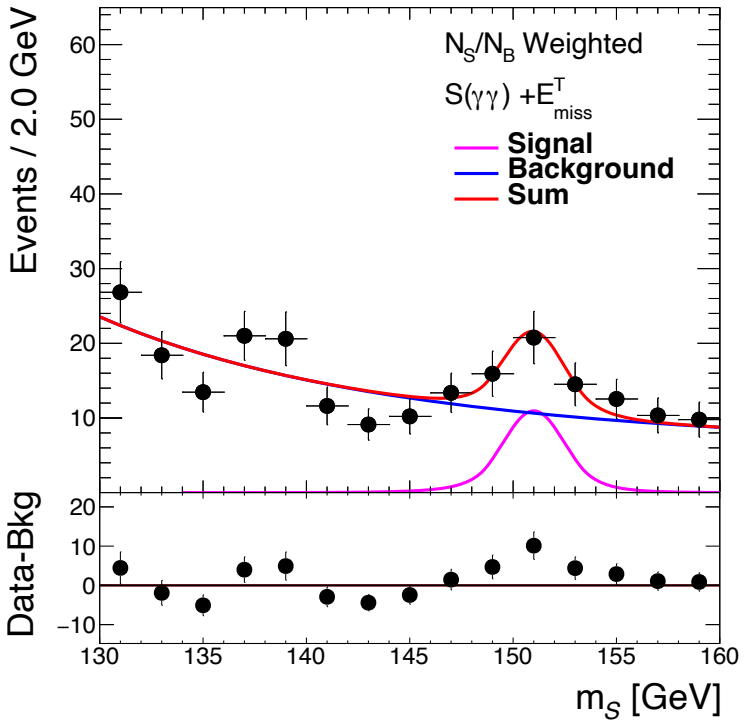
From Run 1 multi-lepton excesses model-dependent prediction of $m_s = 150 \pm 5$ GeV

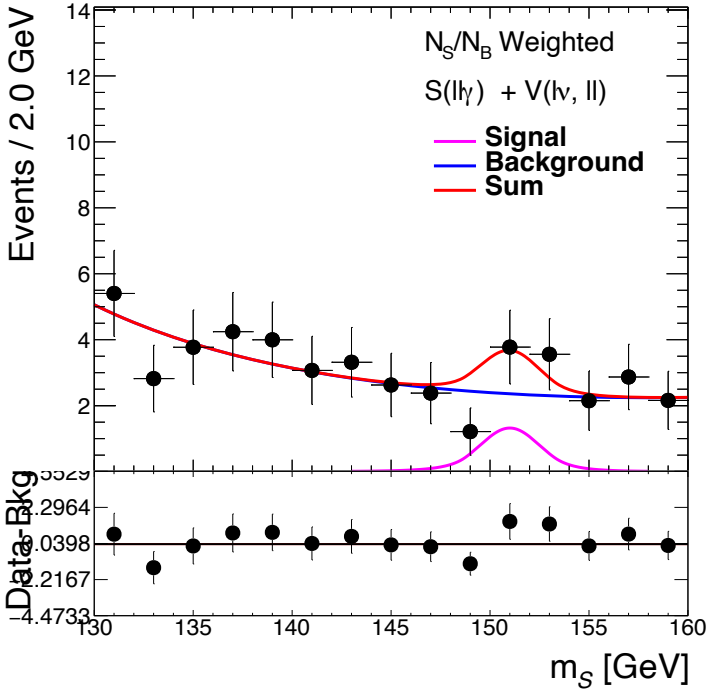
Procedure to choose final state: di-photon in association with b-jets, τ-had, leptons (e/μ) and jets

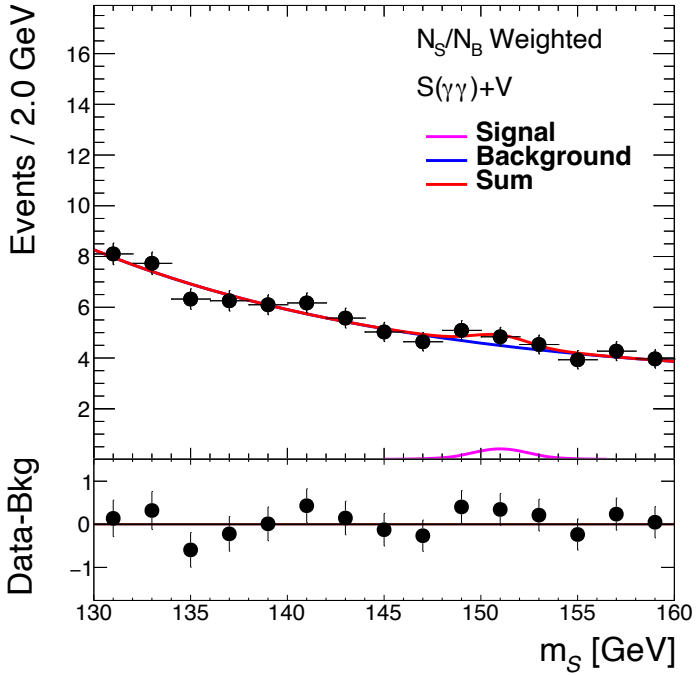


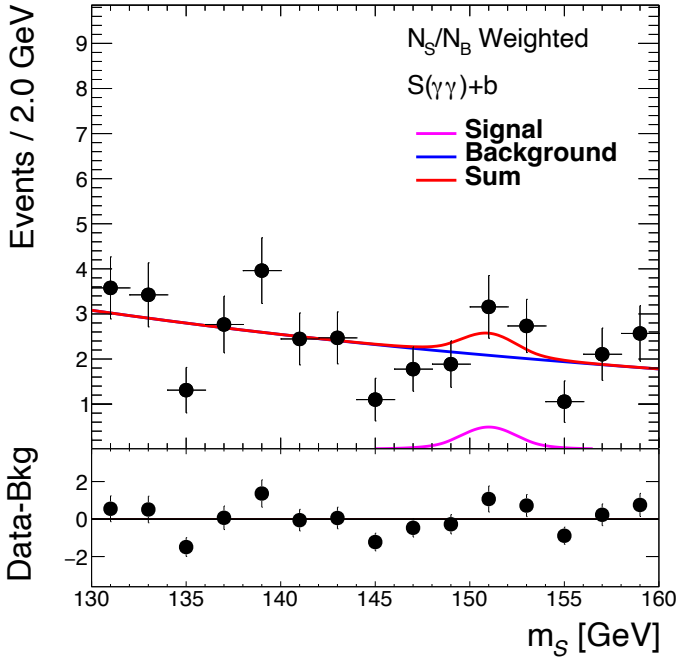
In *Eur.Phys.J.C* 76 (2016) 10, 580 also considered S→MET

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





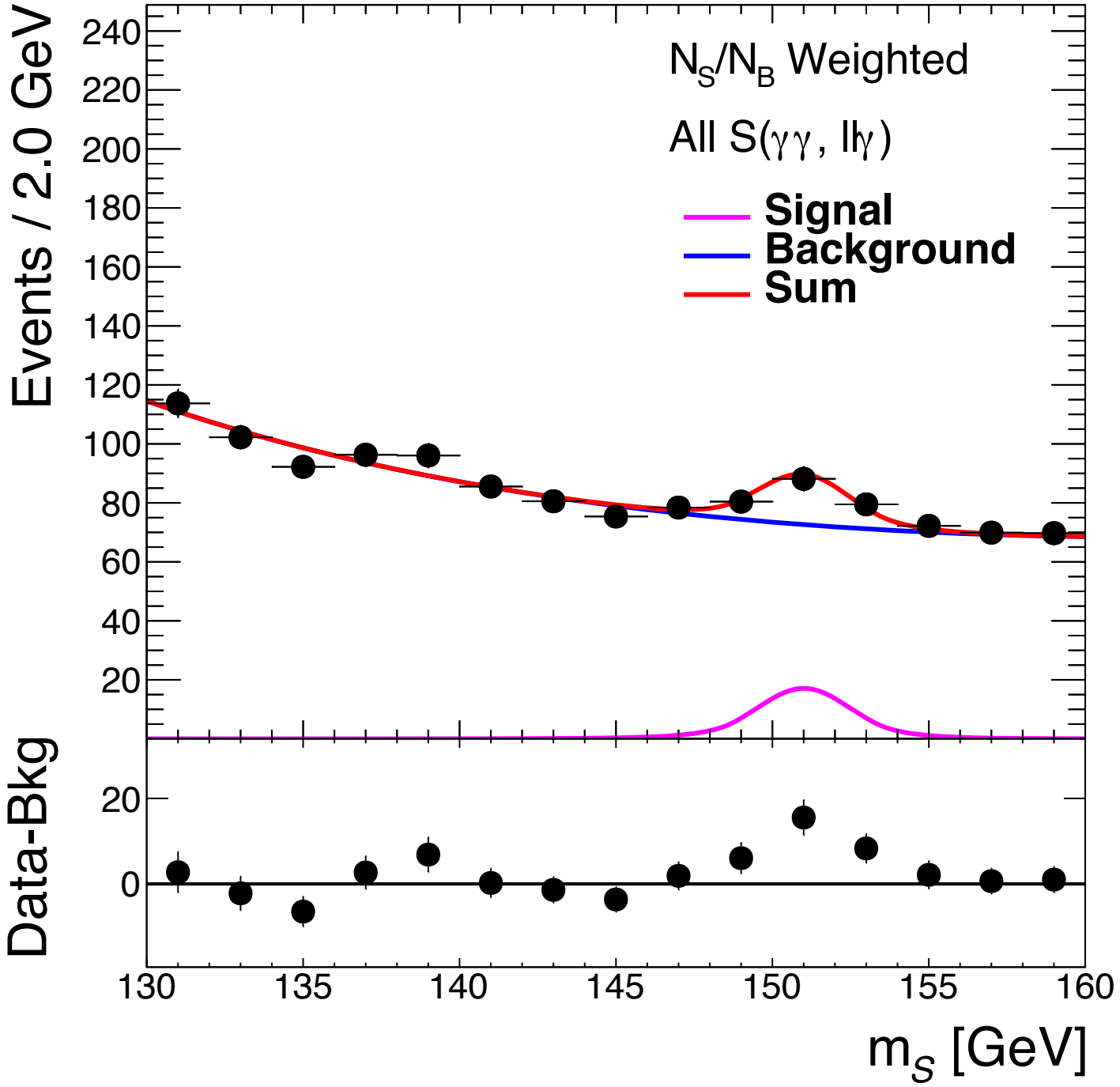




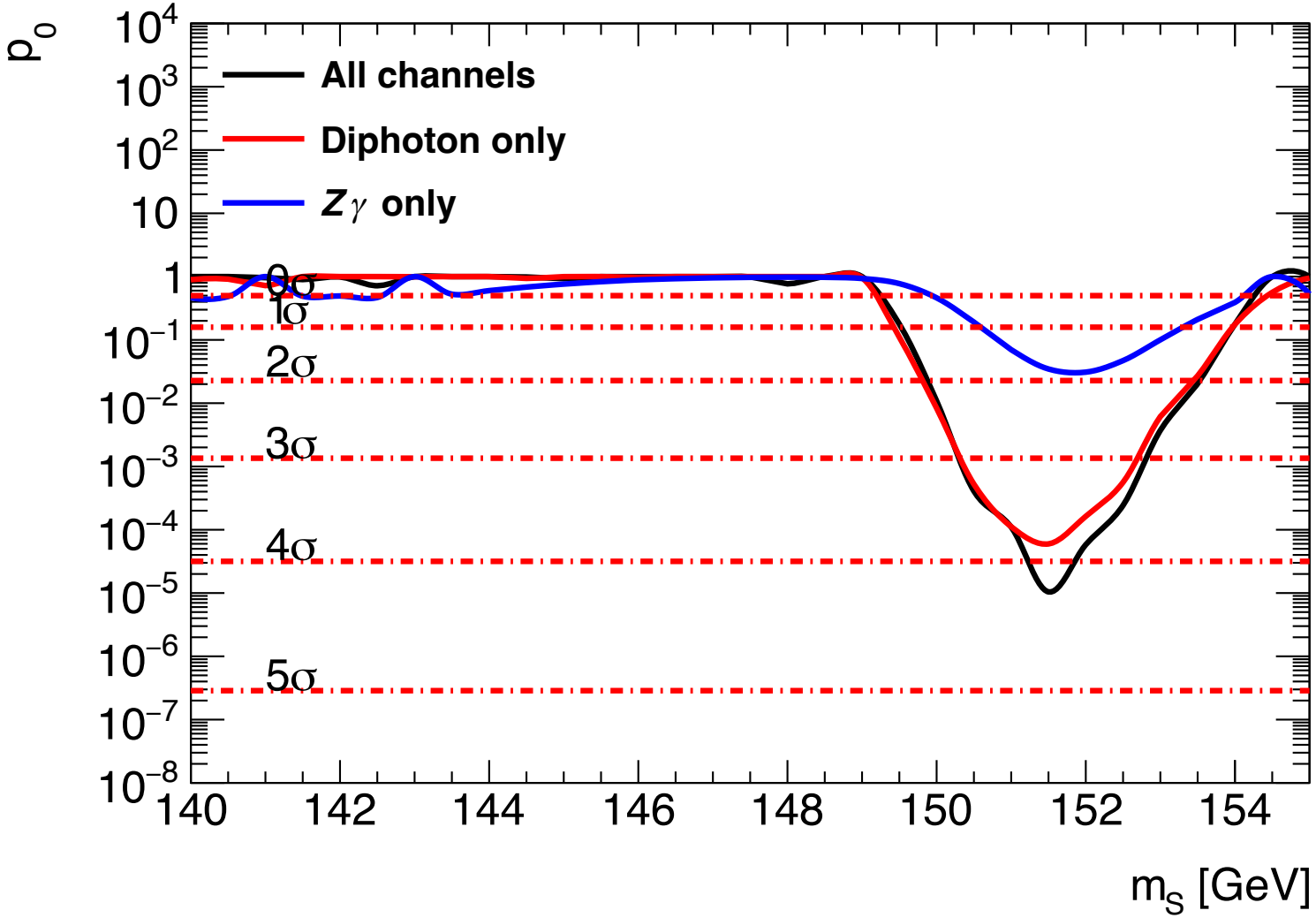
Analysis of publicly available $\gamma\gamma$, $Z\gamma$ spectra in associated production gives an excess at m_S=151.5 GeV.

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



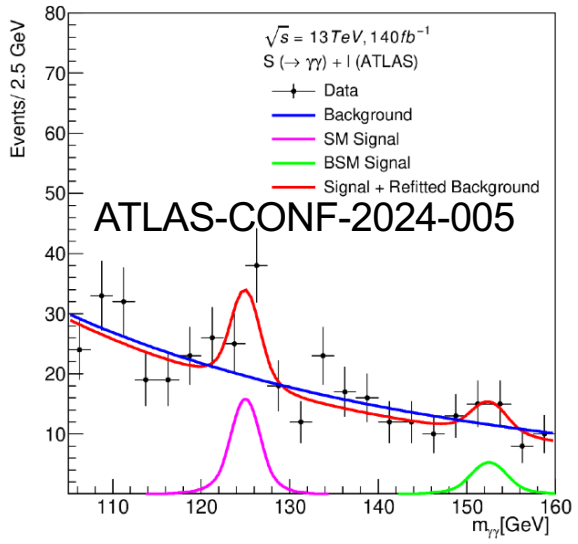
Result is obtained with public results from the LHC experiments. Using a simplified model and two degrees of freedom to include the decay of S→MET (as in Eur.Phys.J.C 76 (2016) 10, 580) and residual LEE, global significance goes to 3.9σ at 151.5 GeV.



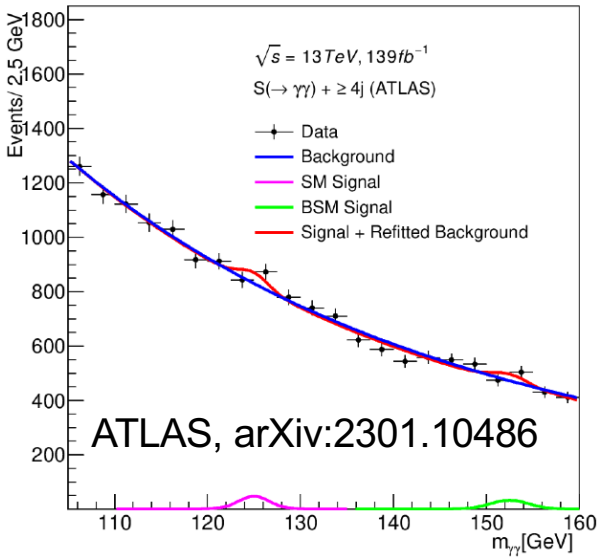
New excesses @151.5 GeV that appeared after the first combination (see above) in topologies consistent with associated production:

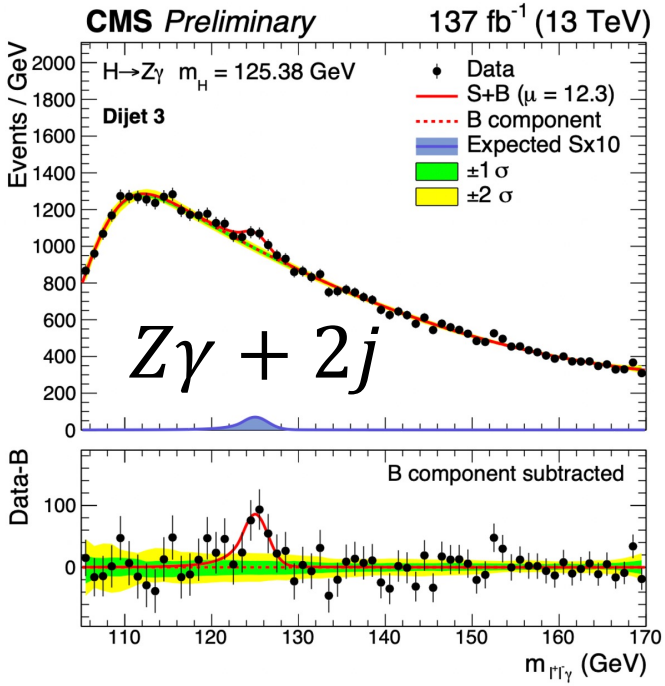
CMS-PAS-HIG-19-014

$\gamma\gamma + l\ (b - veto)$

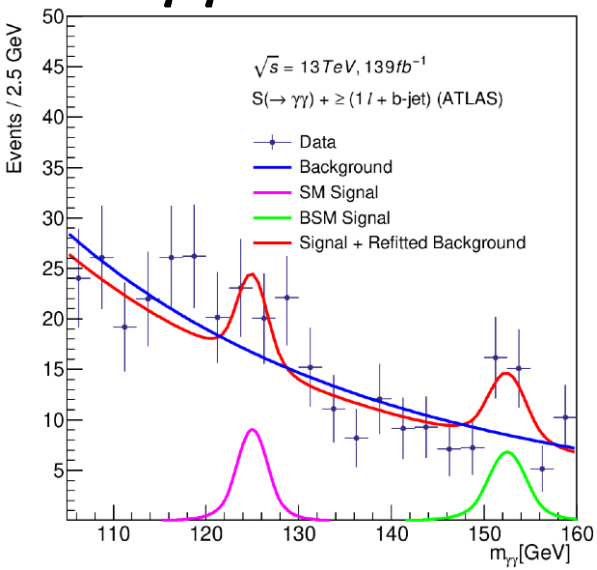


$\gamma\gamma + 4j$





$\gamma\gamma + l + b$



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

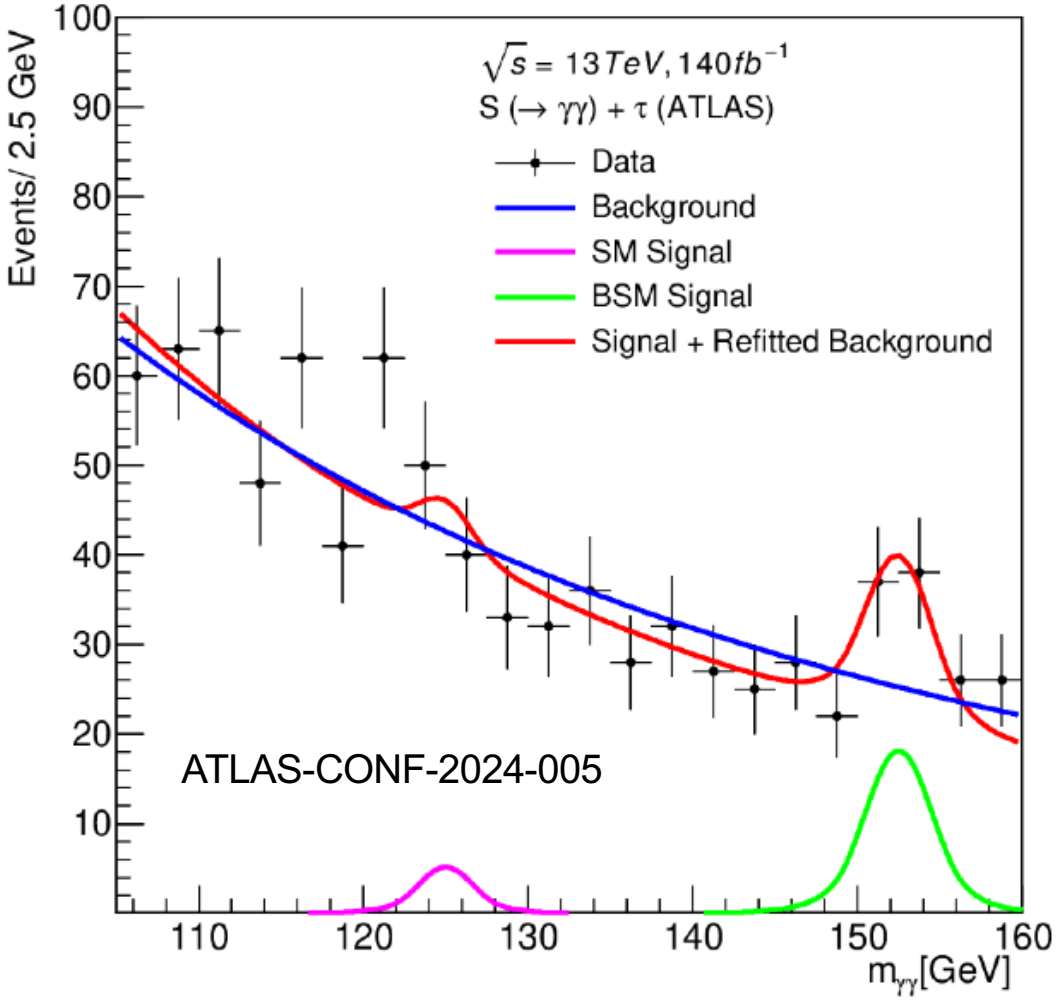
Bin for associated production VH, ttH, where excess is seen with di-photons.

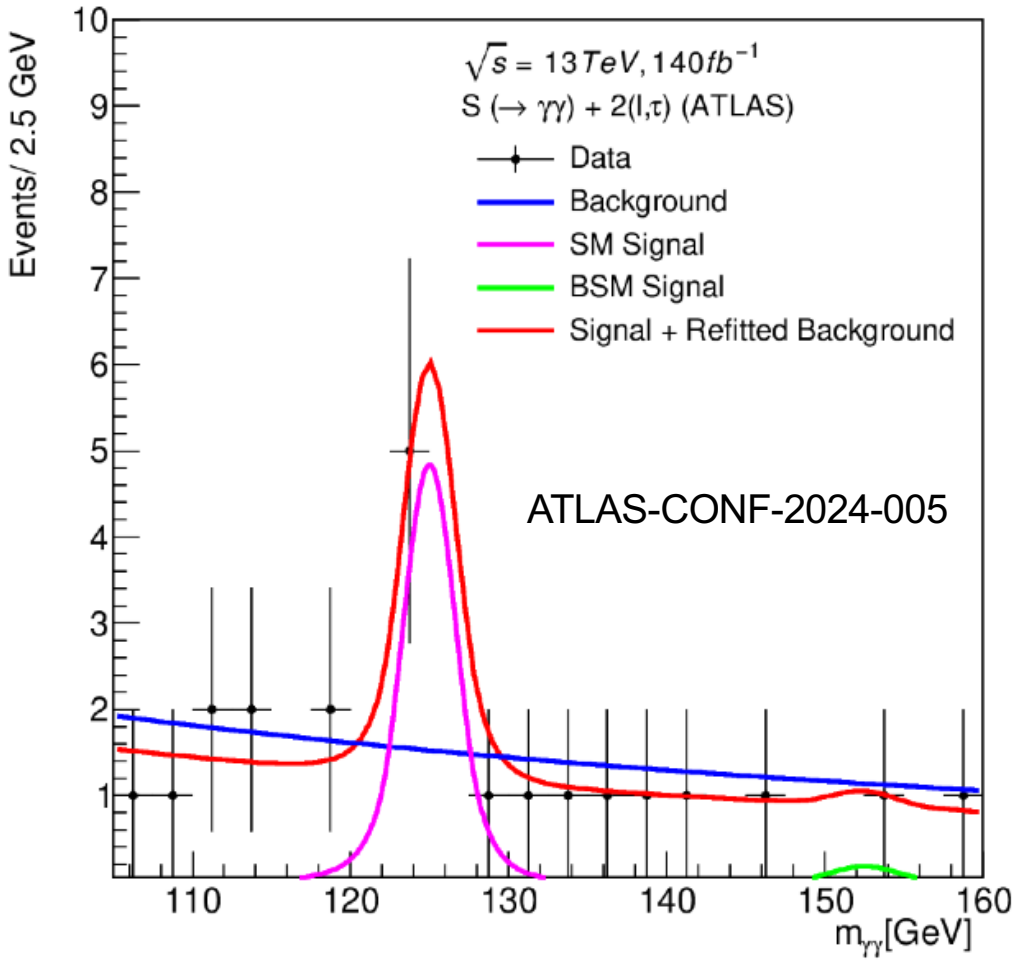
ATLAS, arXiv:2301.10486

https://cds.cern.ch/record/2894145/files/ATLAS-CONF-2024-005.pdf

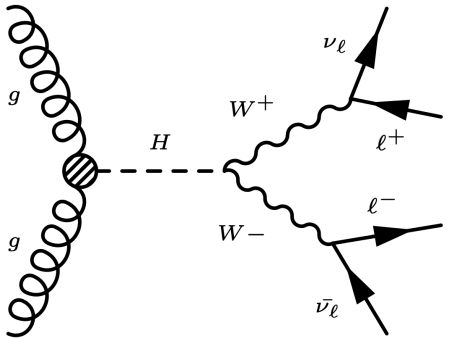
$\gamma\gamma + \tau$

$\gamma\gamma + 2(\tau, \ell)$

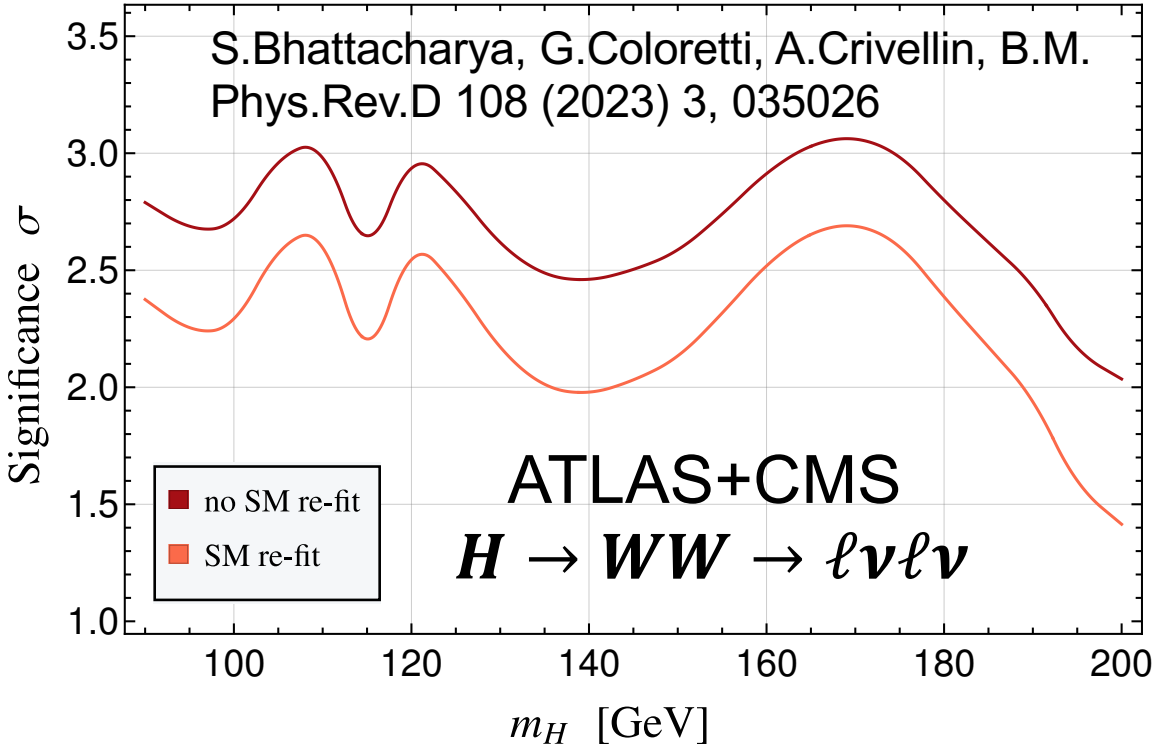


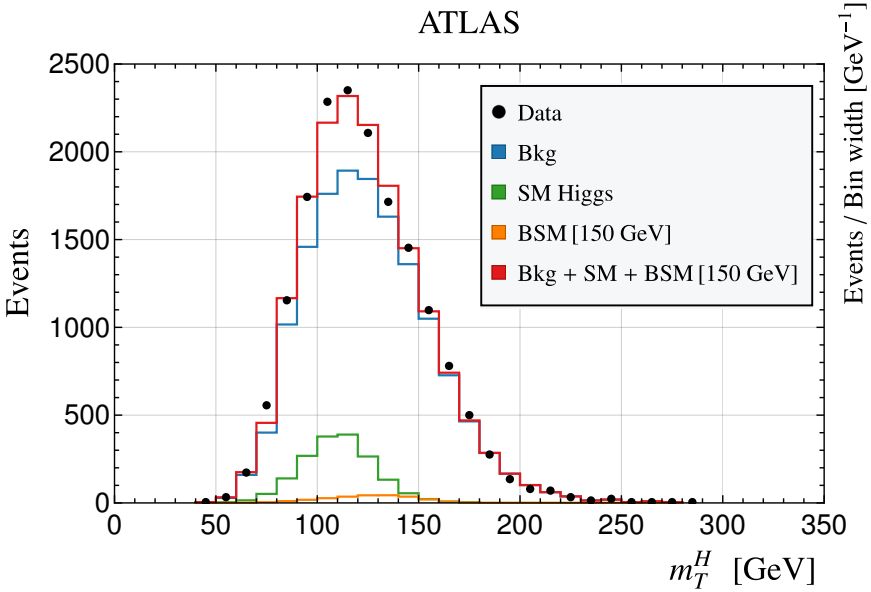


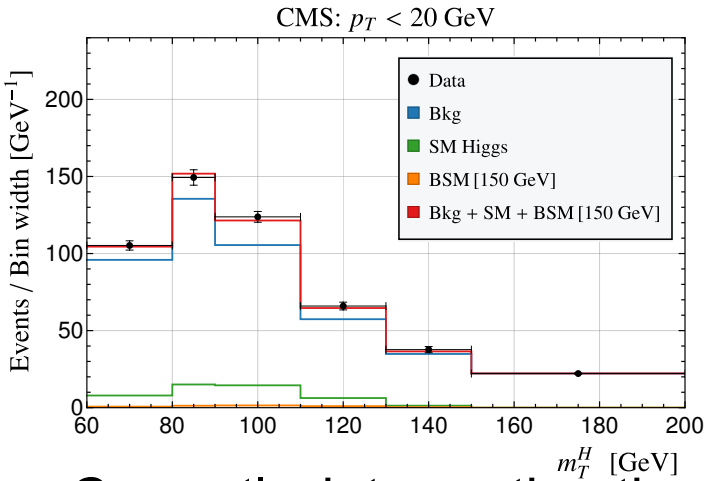
Single and double tau are combined assuming H→SS*

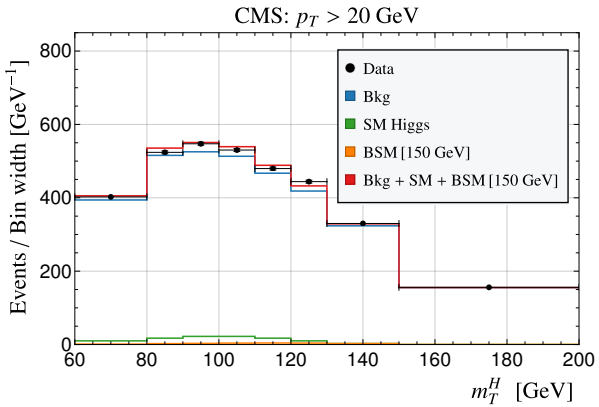


SM Higgs hypothesis alone. alone is having difficulty describing the ll+MET transverse mass spectra, giving room to other Higgs-like signals, including S(151).



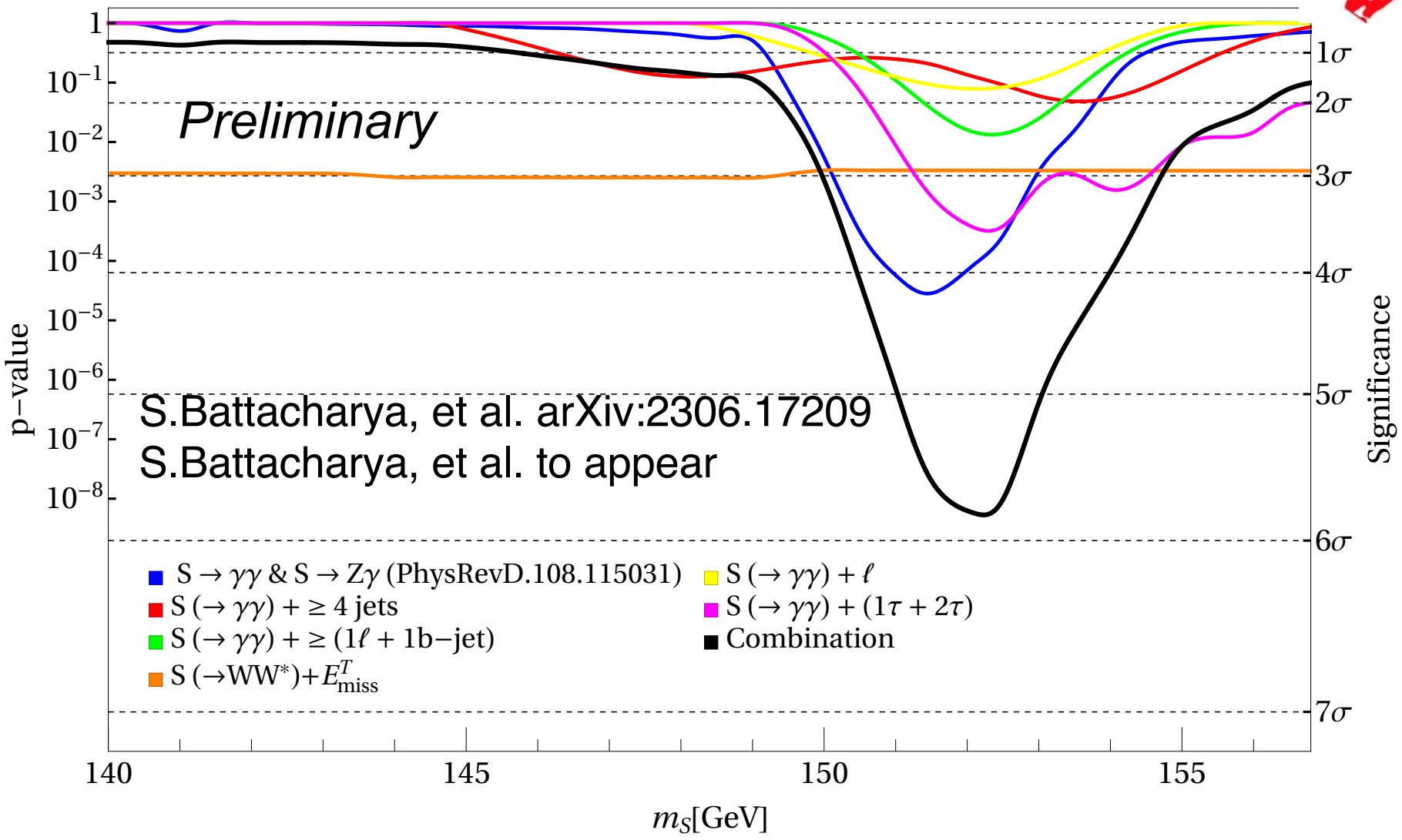






Currently, interpreting the broad excess in terms of H→S+MET, which appears to be the leading final state in excess described above

Current status of the combination, based on the Fischer method with 6 n.d.o.f yields largest global significance of a narrow structure beyond the SM at the LHC



Fiducial cross-sections in fb

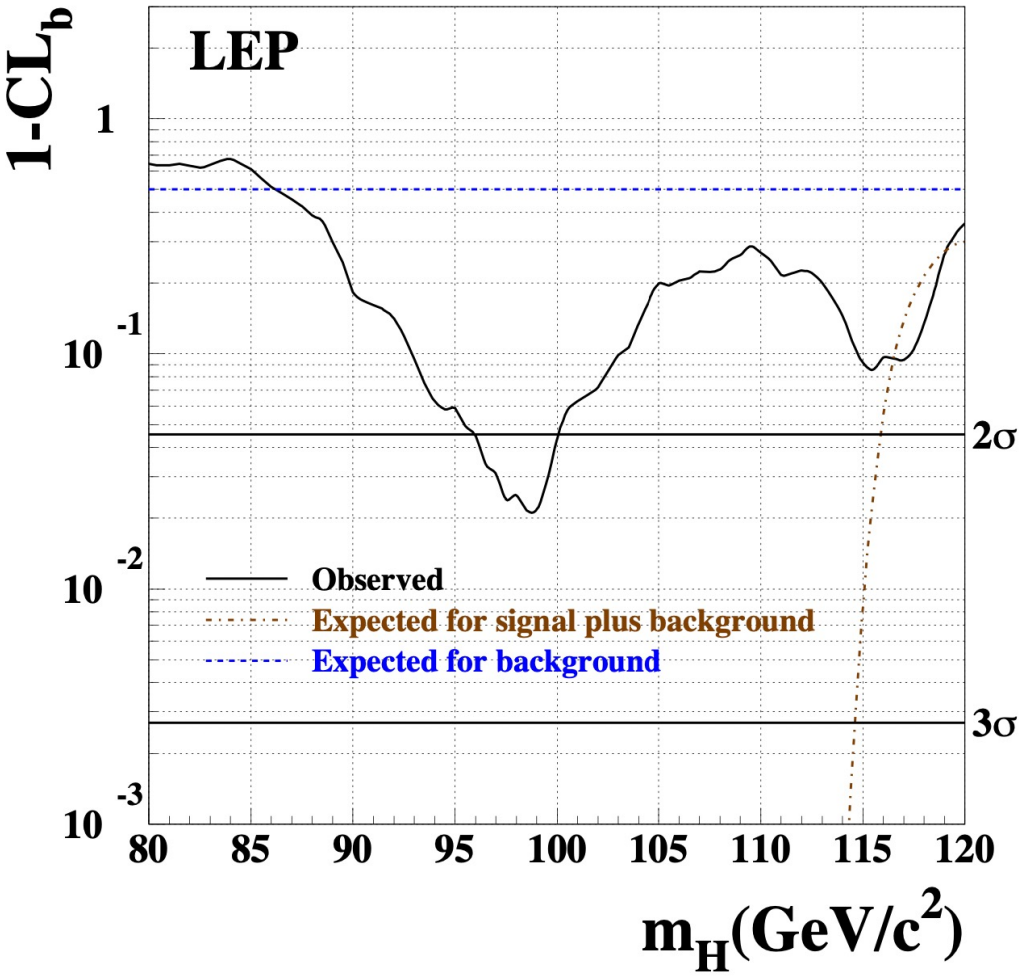
Preliminary

Channel	N_{Sig}	Significance	σ_F in fb
$S(\to \gamma\gamma) + \tau$	36.04 ± 9.86	3.93	0.54 ± 0.15
$S(\to \gamma\gamma) + \ell$	10.52 ± 6.22	1.73	0.14 ± 0.08
$S(\to \gamma\gamma) + \geq 1\ell + 1b-$ jet	13.55 ± 6.16	2.46	0.24 ± 0.11
$S(\to \gamma\gamma) + \geq 4$ jet	66.68 ± 35.30	1.69	0.80 ± 0.42
$S(\to Z(\to \ell^+\ell^-)\gamma) + jj$	92.43 ± 58.75	1.30	2.16 ± 1.37
$S(\to Z(\to \ell^+\ell^-)\gamma) + 1\ell$	4.51 ± 15.48	0.26	0.12 ± 0.41
$S(\to \gamma\gamma) + b-$jet	14.70 ± 5.82	2.60	0.23 ± 0.09
$S(\to \gamma\gamma) + E^T_{\mathrm{miss}}$ (Low)	18.33 ± 7.26	2.48	0.22 ± 0.09
$S(\to \gamma\gamma) + E^T_{\mathrm{miss}}$ (High)	7.54 ± 3.90	2.35	0.09 ± 0.05
$S(\to \gamma\gamma) + W, Z$ (CMS)	12.74 ± 14.52	0.78	0.15 ± 0.17
$S(\to \gamma\gamma) + W, Z$ (ATLAS)	4.69 ± 13.65	0.40	0.06 ± 0.17

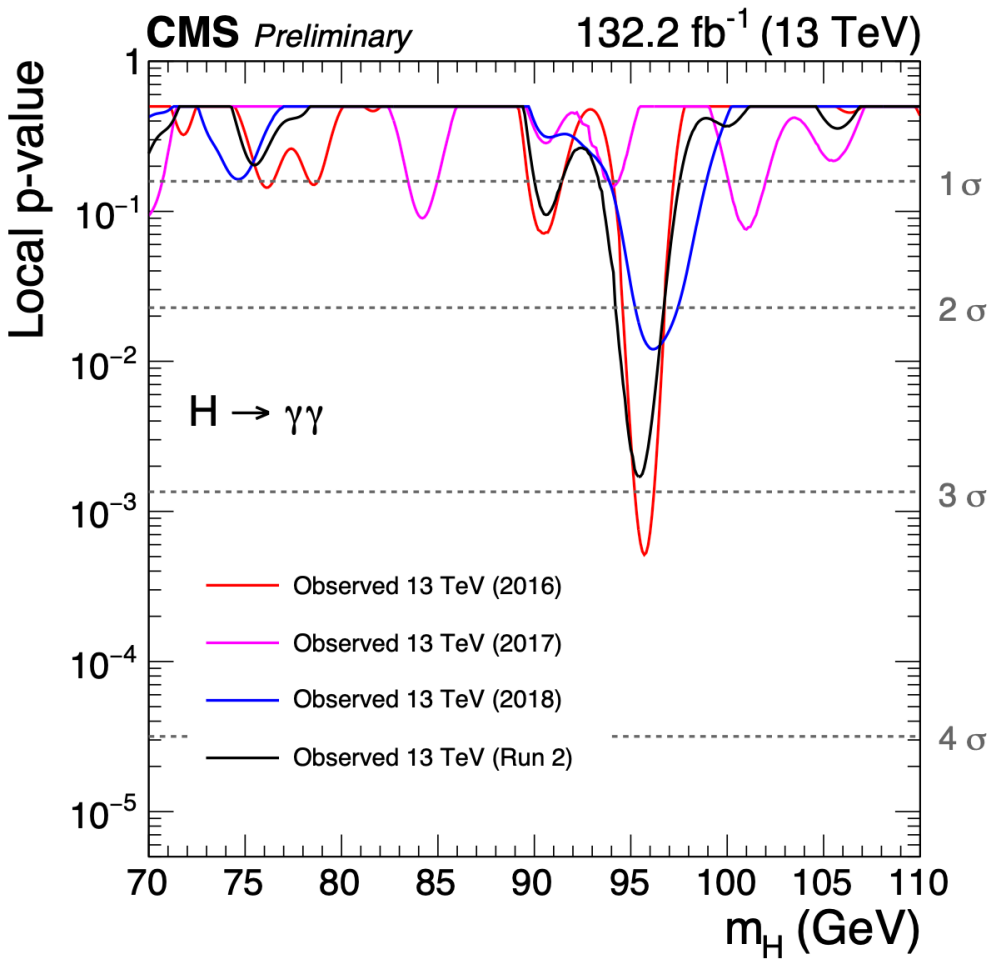
The 95 GeV Candidate

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 PAS HIG-20-002

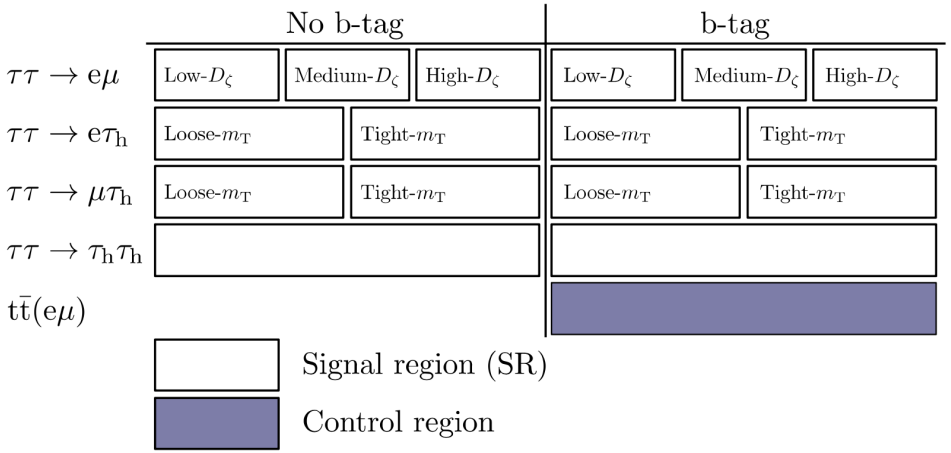


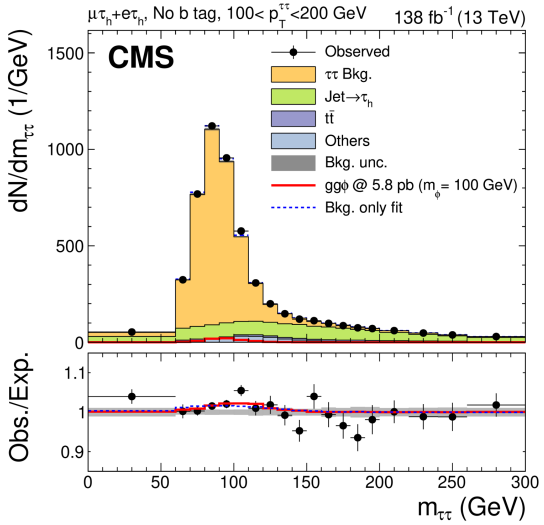
CMS, arXiv:2208.02717

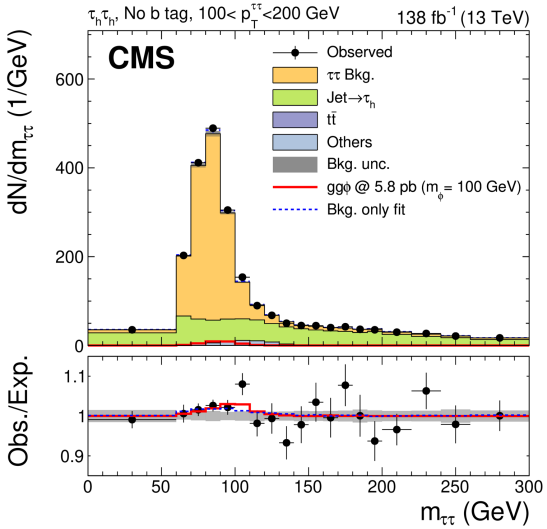
$H \to \tau\tau$

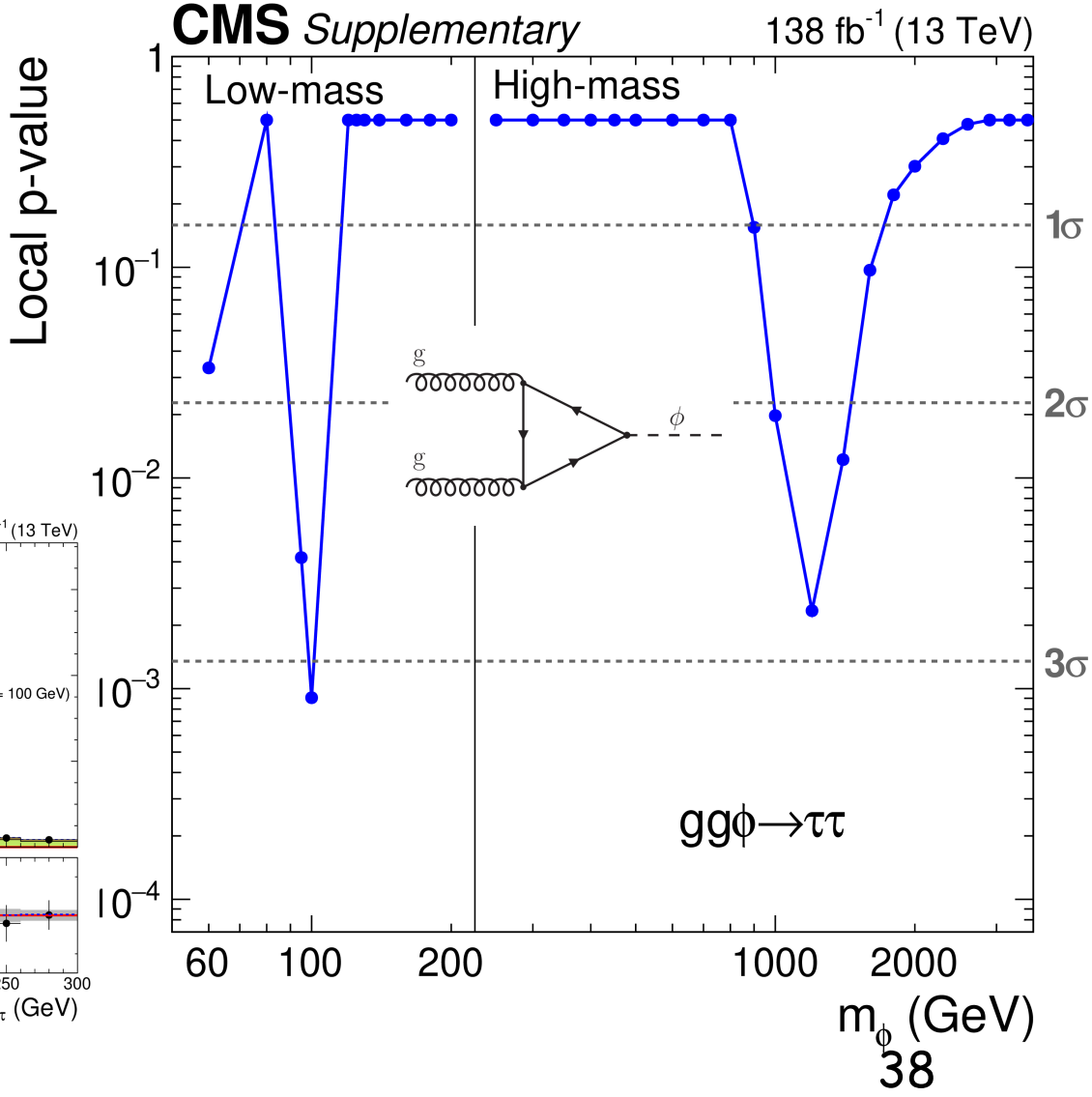
Dedicated search for scalar decaying into tau pairs. CMS observes a local (global) excess of 3.1 (2.7)σ at ~100 GeV.

Event classification scheme

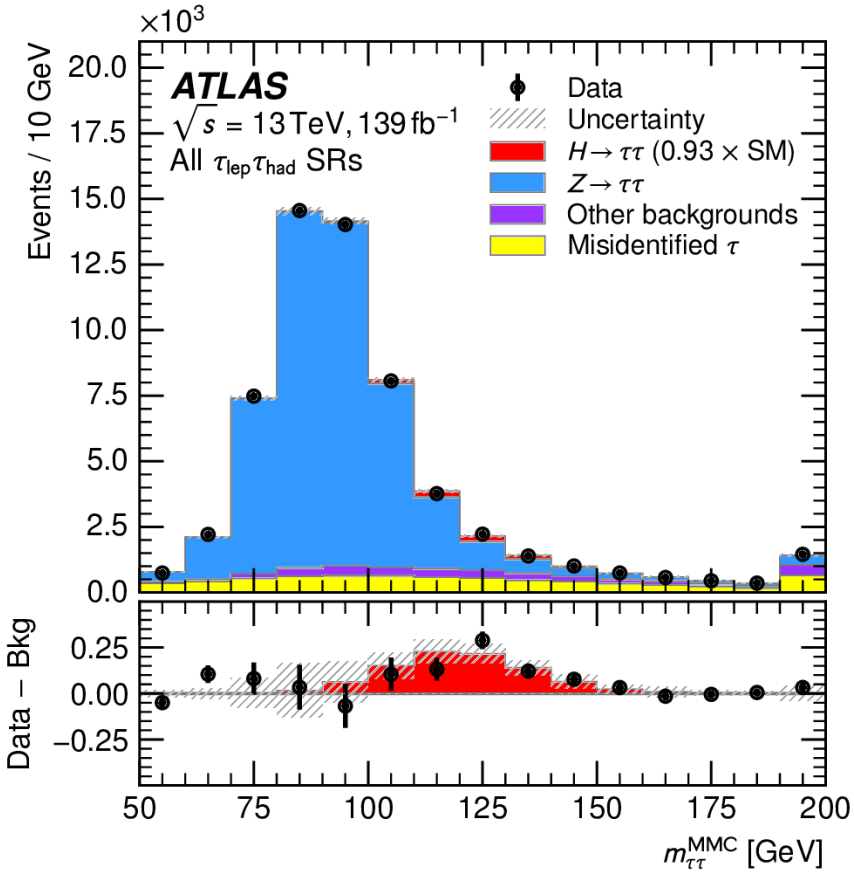


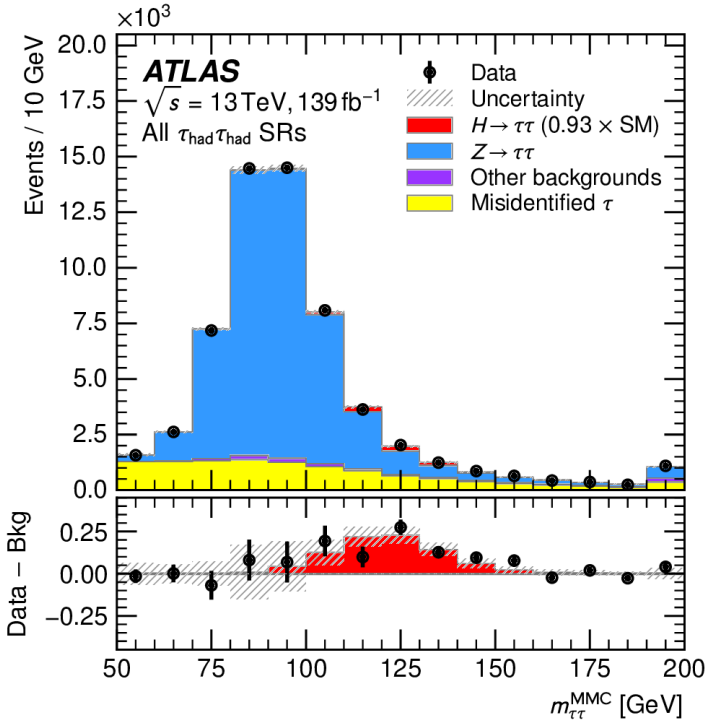


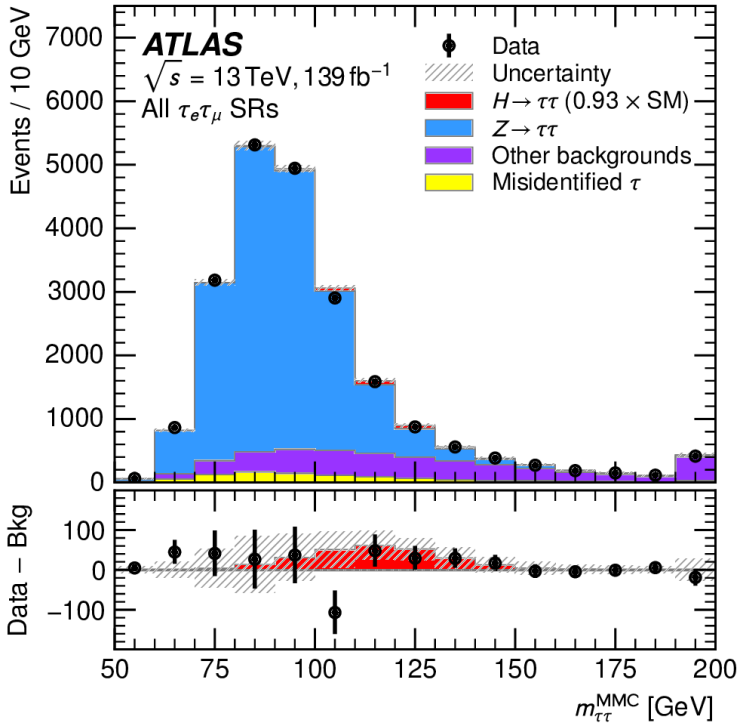




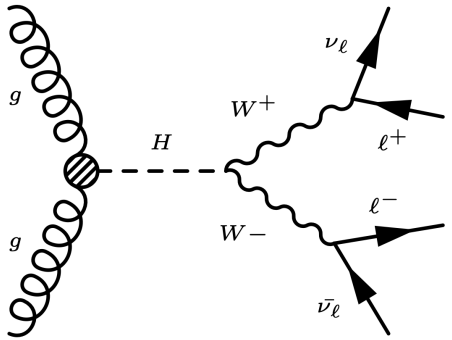
ATLAS, JHEP 08 (2022) 175 $H \to \tau\tau$

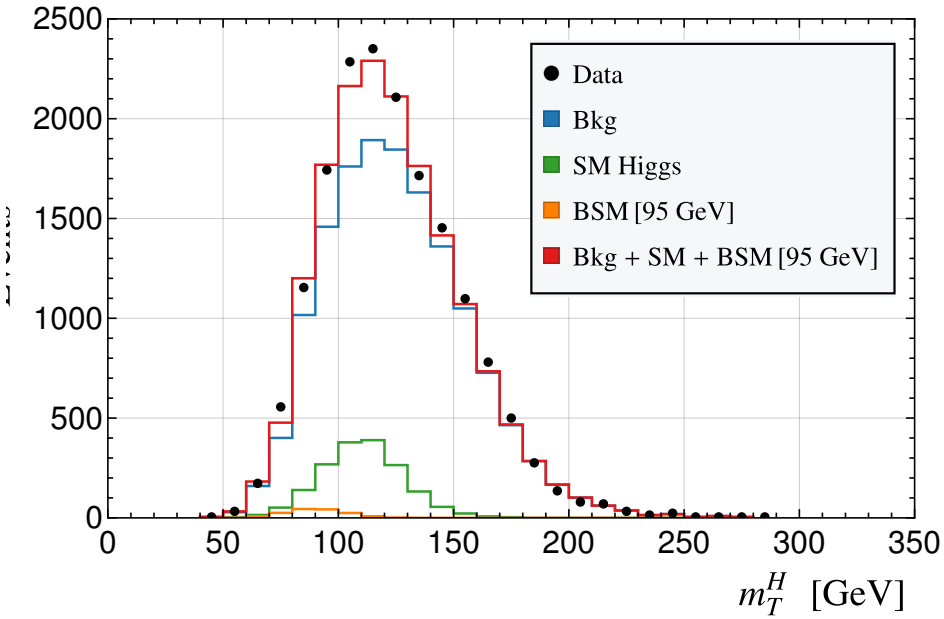




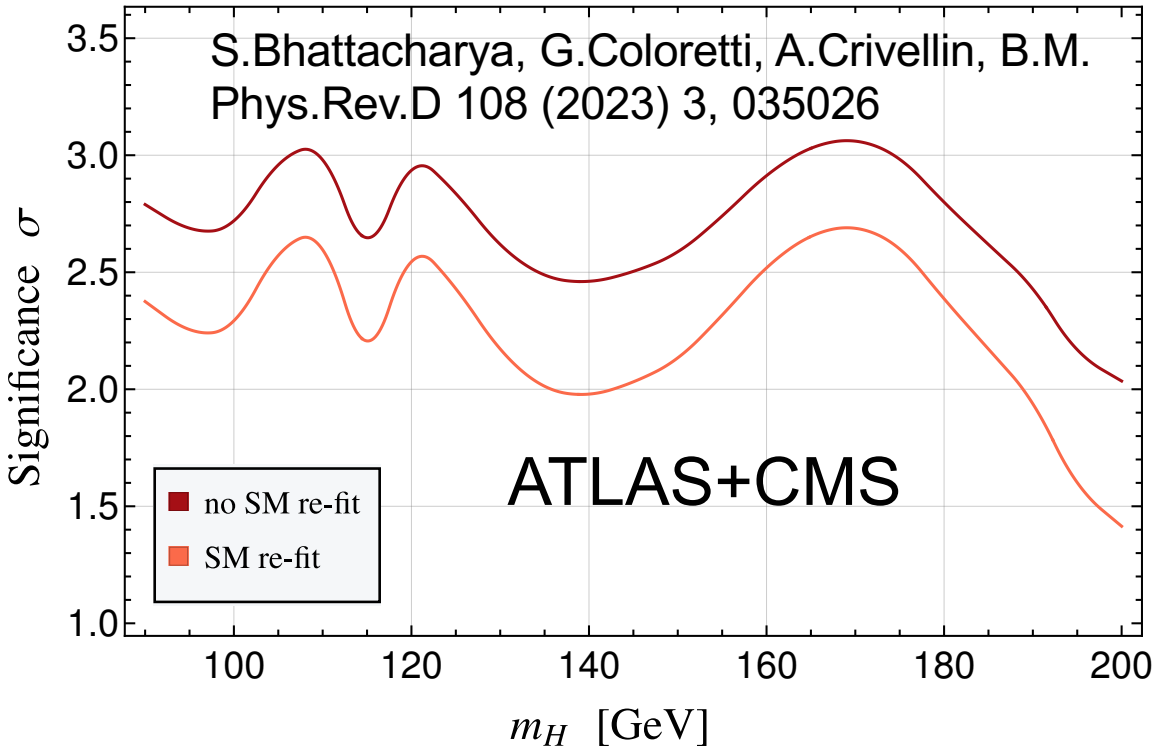


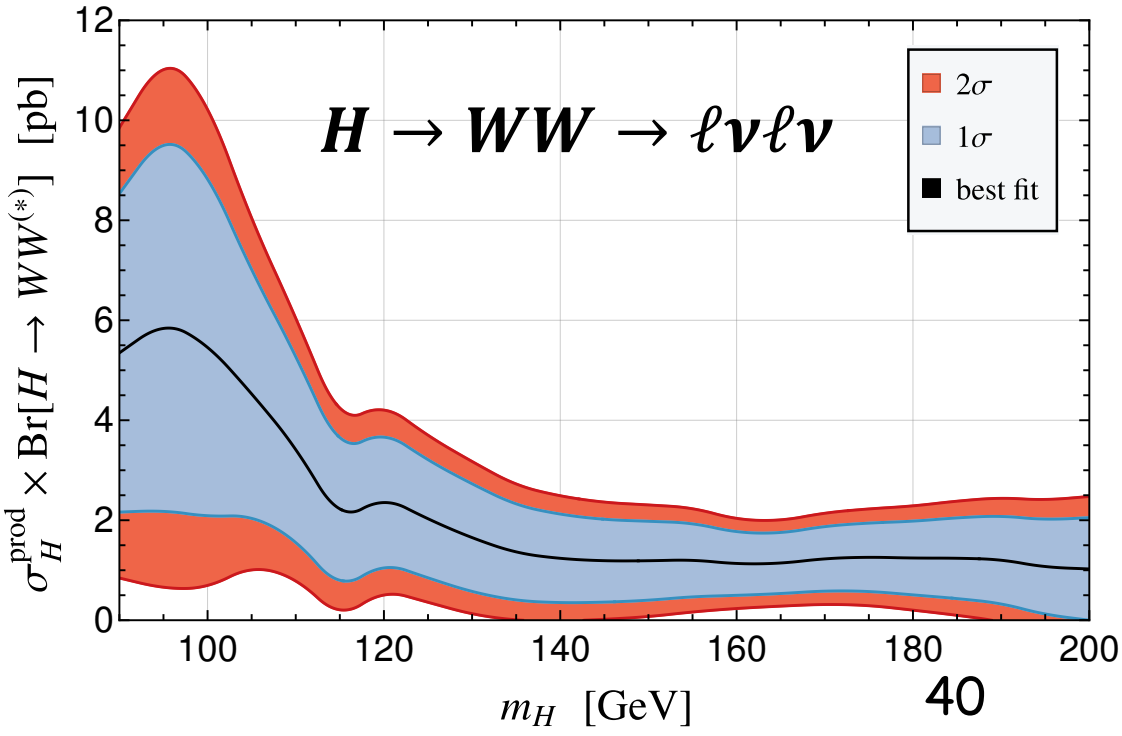
ATLAS has not performed a dedicated search for low mass scalar. That said we do not seem to see a clear excess around 95 GeV in the sideband. Is the CMS excess an upward fluctuation?



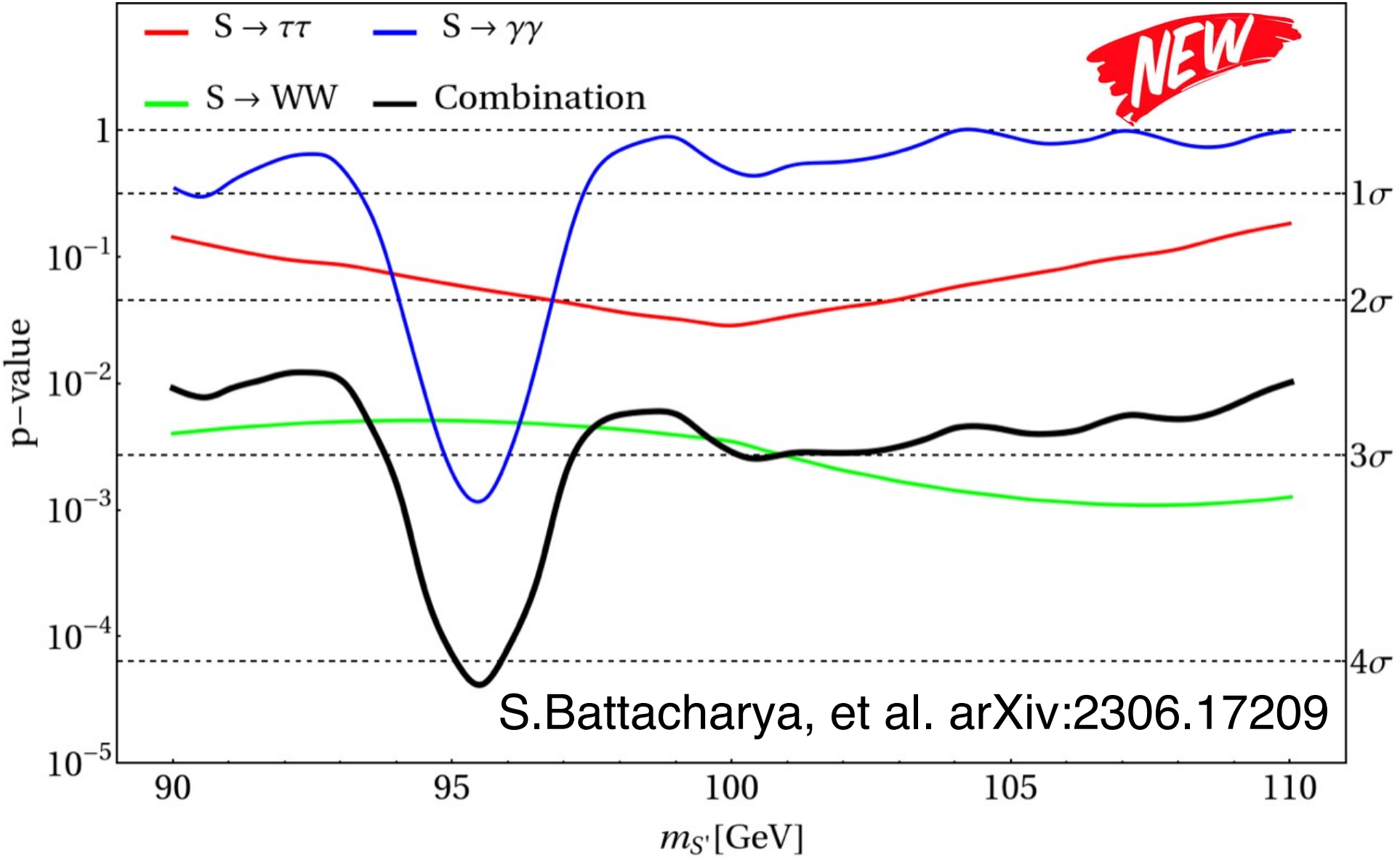


SM Higgs hypothesis alone. alone is having difficulty describing the ll+MET transverse mass spectra, giving room to other Higgs-like signals. Compatibility with other signals under study.

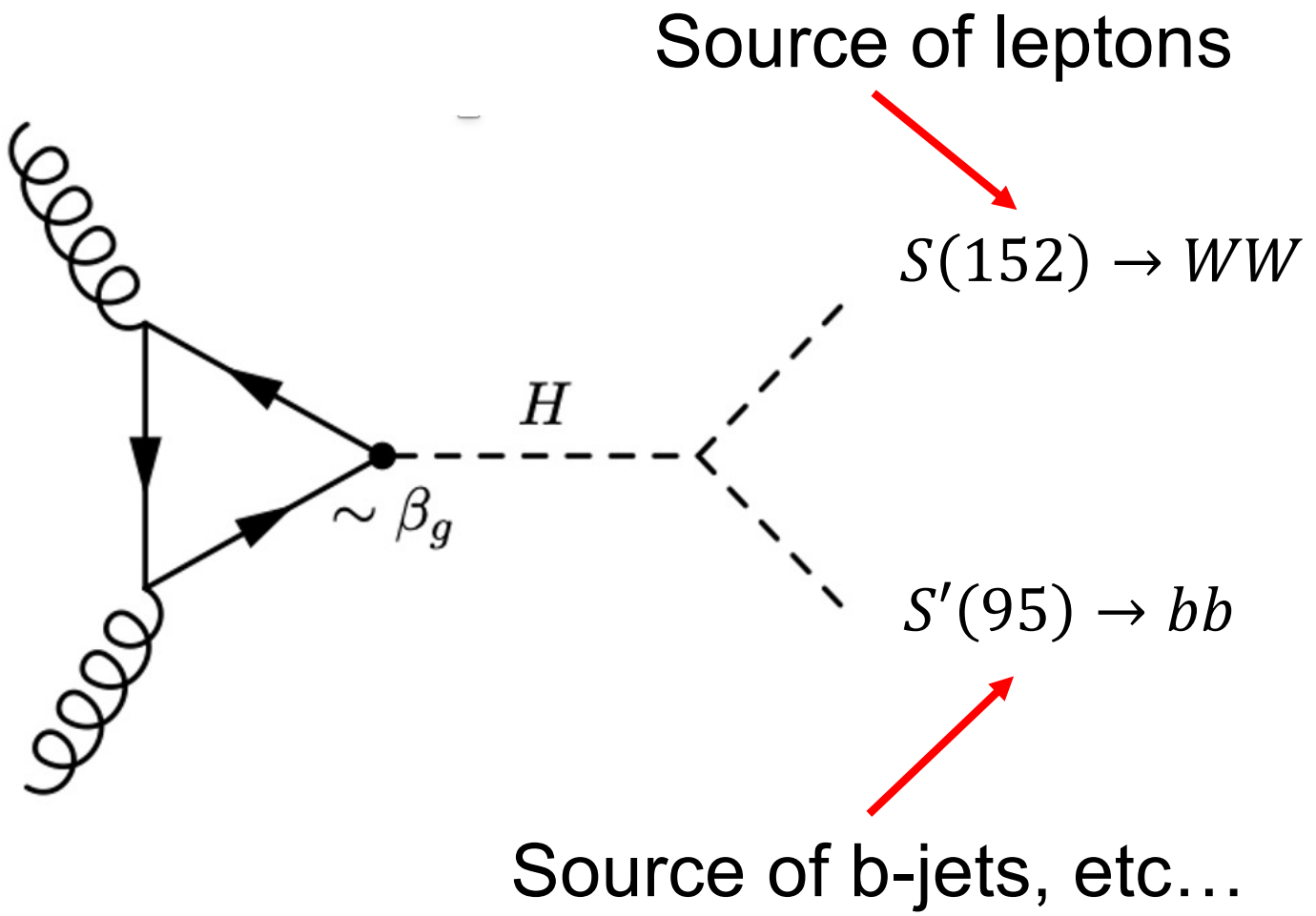




With recent results reported by the ATLAS experiment the significance of a narrow resonance at 95 GeV has reached 3.8σ global significance.



Potential contributor to multi-lepton anomalies at the LHC



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:

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

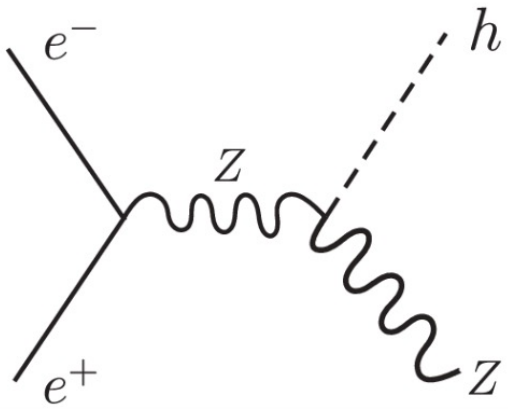
- Other types of topologies are also unexplored

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

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

Impact on Future e^+e^- Colliders

$S(95) \rightarrow bb$

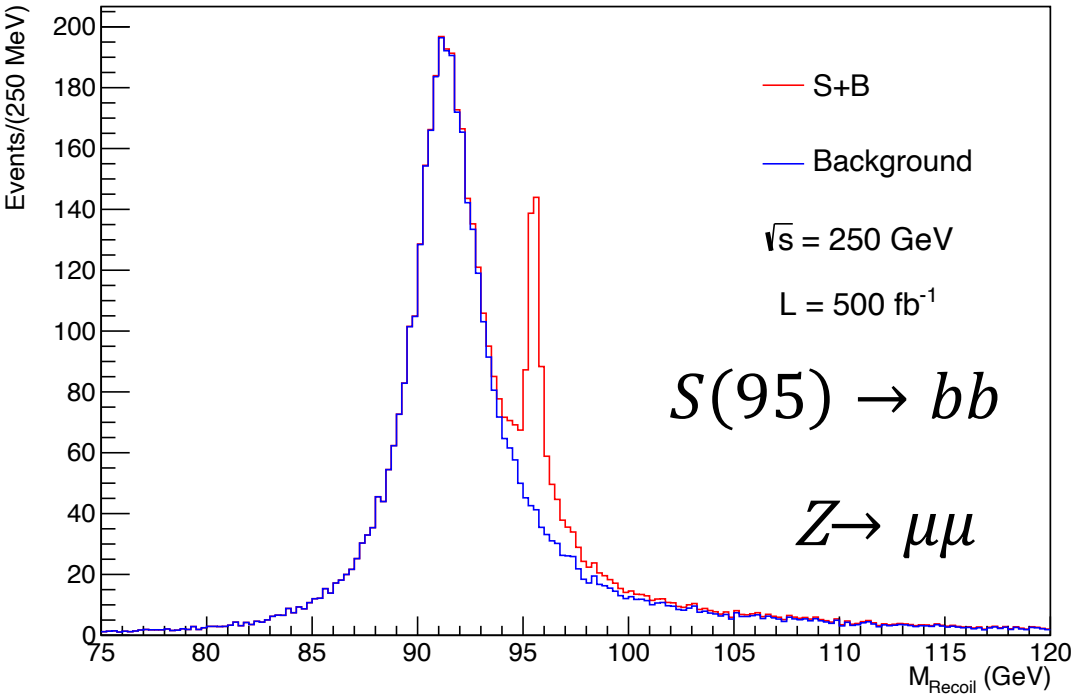


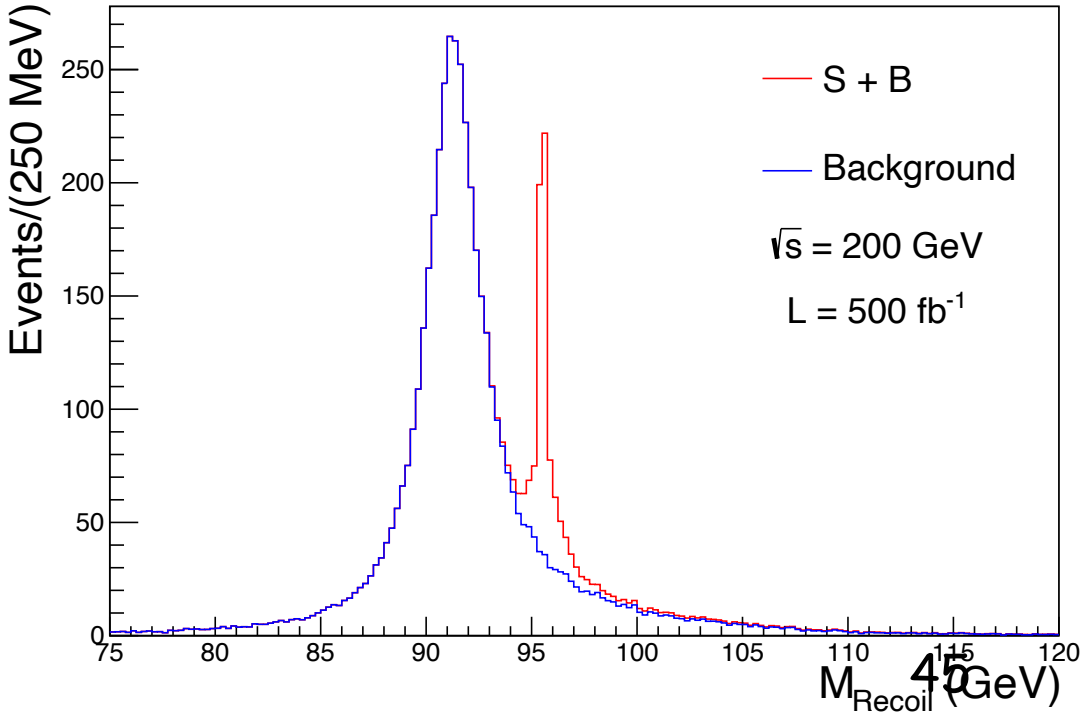
$Z \rightarrow \mu\mu$

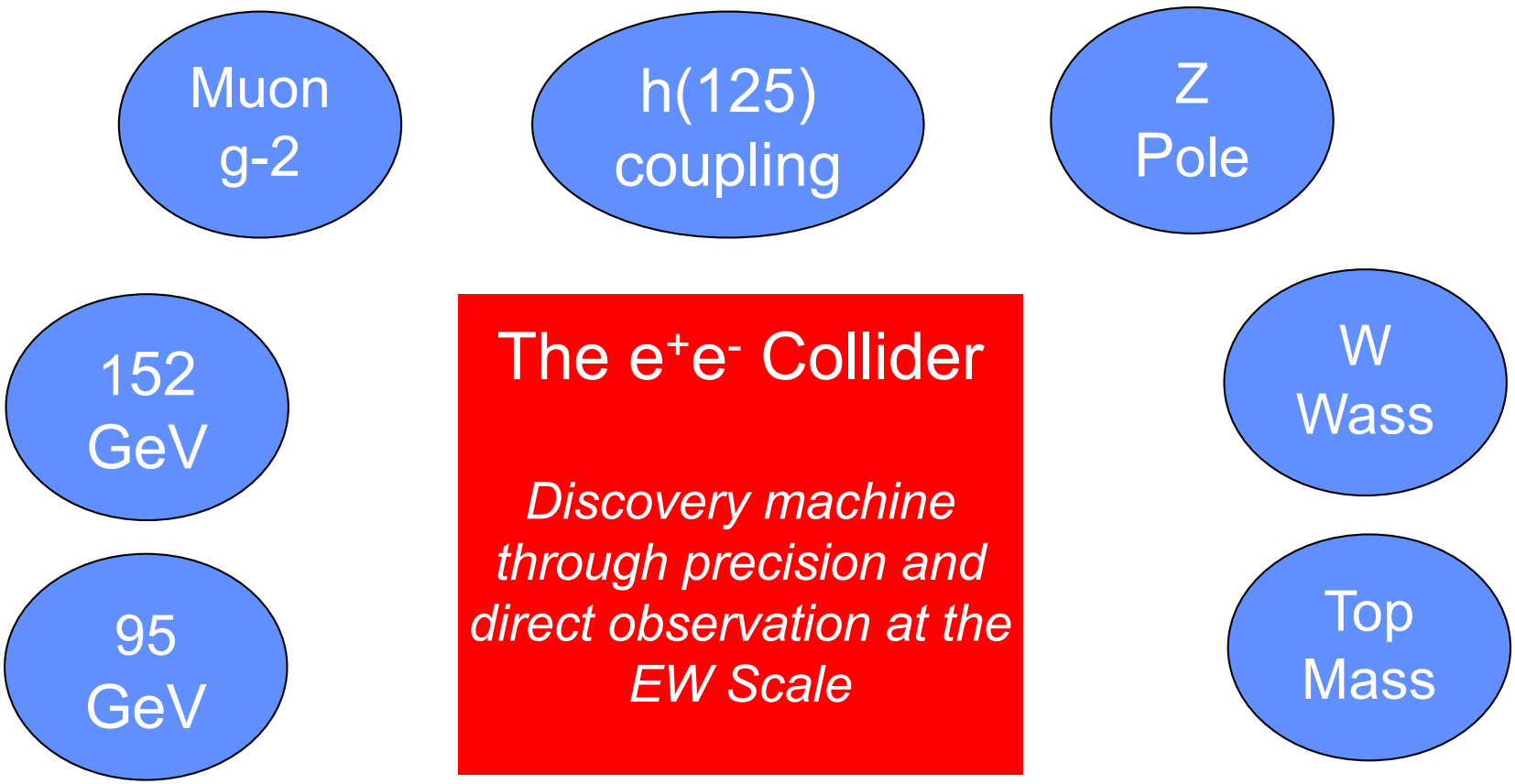
A light Higgs-like scalar like the S(95) candidate would be unequivocally observed in a Higgs factory.

Use superior resolution of Z mass recoil method

Work with Y.Fang, M.Ruan and M.Titov







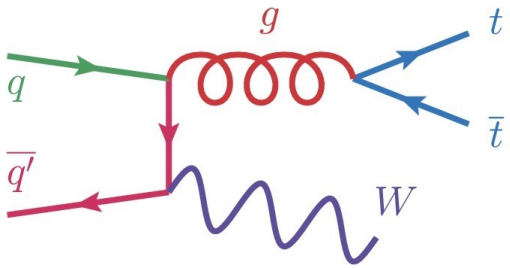
Anomalies in Particle Physics are indicative of unique discovery opportunities at the EW for future e^+e^- accelerators

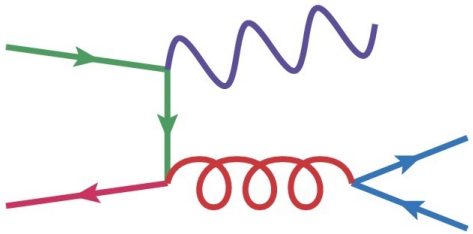
Outlook and Conclusions

- 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)
    - Excesses are Higgs-like with robust final states
- With these anomalies one predicts a scalar, S, with a mass 150±5 GeV from the decay of a heavier H.
- Analysis of in associated production gives a large (>5σ) global excess around 152 GeV
- Excesses at 95 GeV have grown, leading to 3.8σ global significance
  - Future e^+e^- collisions to give irrefutable observation
- The discovery potential of BSM at the EW scale at future is the strong suit of future e^+e^- colliders
  - Whether through direct observation or precision

Additional Slides

The anatomy of inclusive ttW at the LHC





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

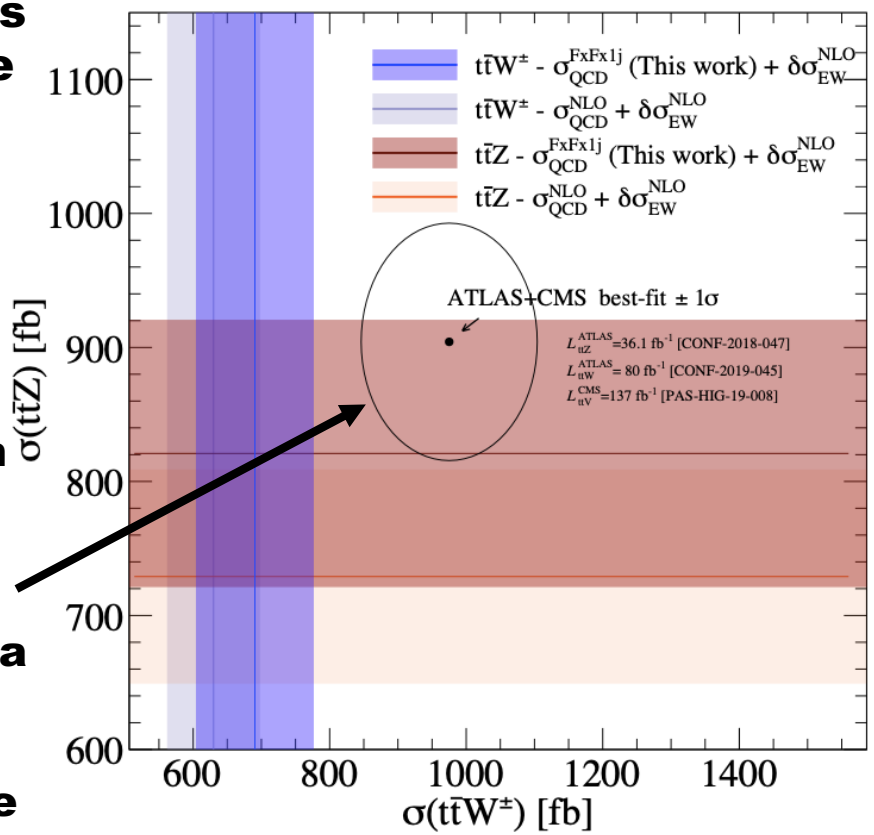
Using fixed order computations at $\mathcal{O}(\alpha_s^4\alpha)$ and NLO multi-jet matching yielding similar (10%-14%) corrections to the inclusive rate

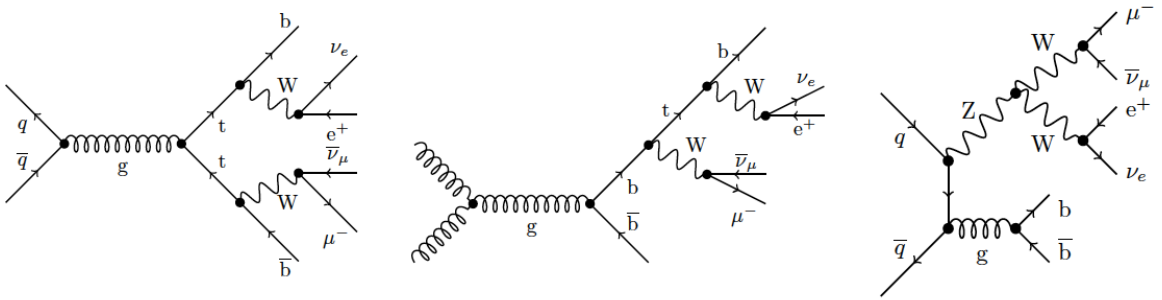
$i\,j \to t\bar{t}\,W^{\pm}\,k\,l$						
(i,j)	(k,l)	$p_T^{j_1\ \min}$	$p_T^{j_2\ \min}$	σ [fb]	$\pm\delta_{\mu_f,\mu_r}$	$\pm\delta_{\text{PDF}}$
All	All	75 GeV	75 GeV	34.7 (100%)	$^{+57\%}_{-34\%}$	$^{+1.1\%}_{-1.1\%}$
(g,Q)	(g,Q)			23.7 (68%)		
(Q,Q)	(Q,Q)			6.99 (20%)		
(Q,Q)	(g,g)			3.63 (10%)	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

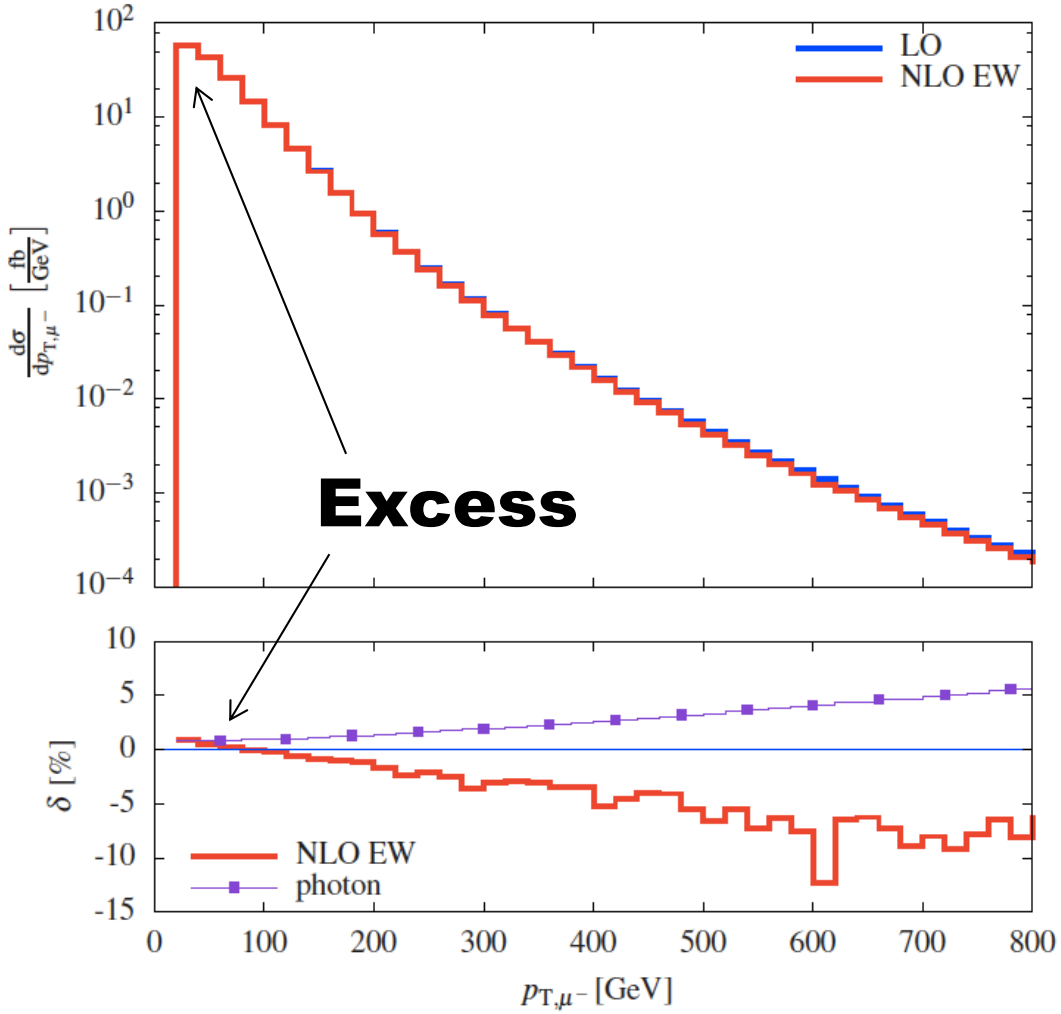
Tension between data and predictions does not wane.
For this process a complete NNLO computation is needed to reduce theory uncertainty

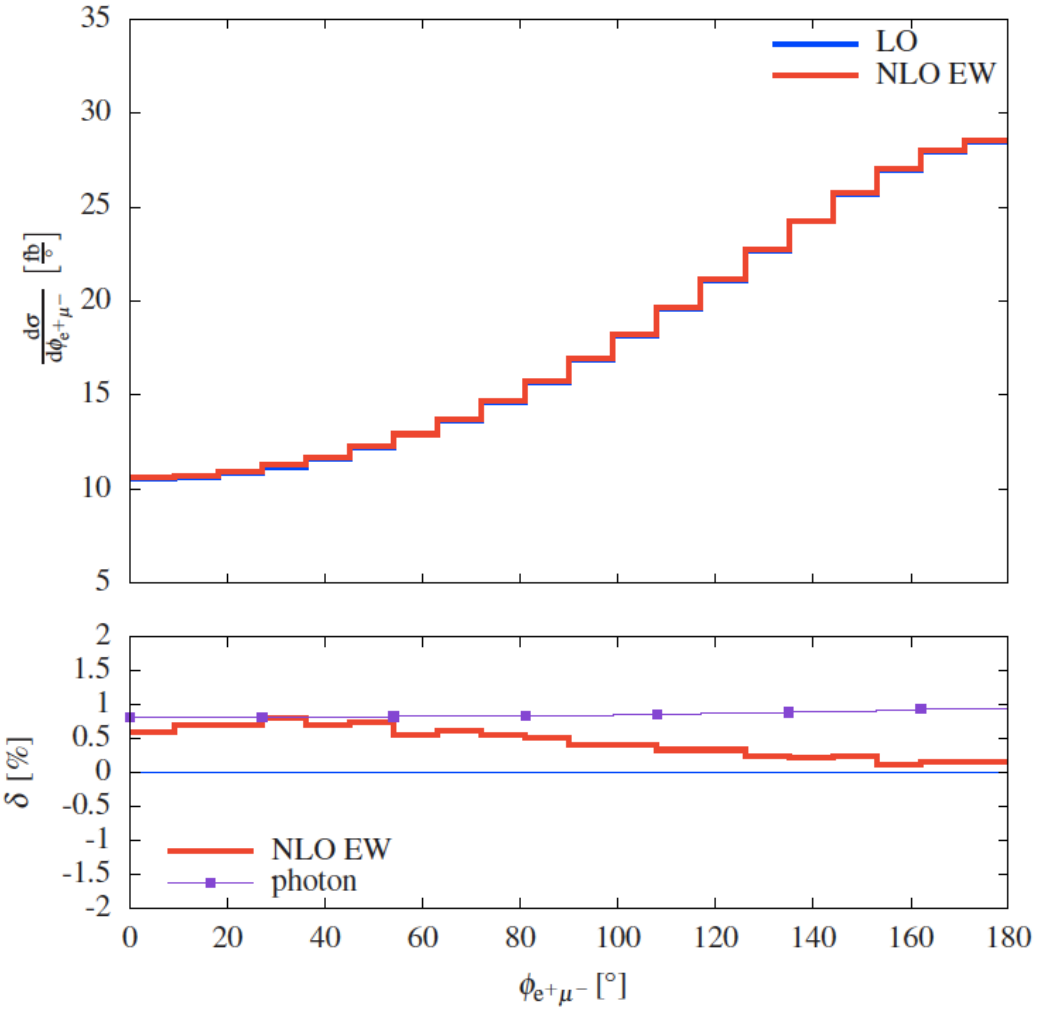




A.Denner, M.Pellen, arXiv:1607.05571

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.





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**

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

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.

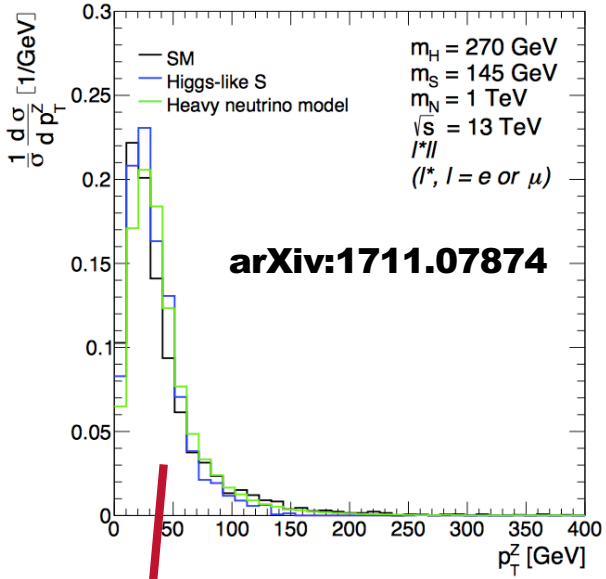
3l with Z→ll (ZW cross-section)

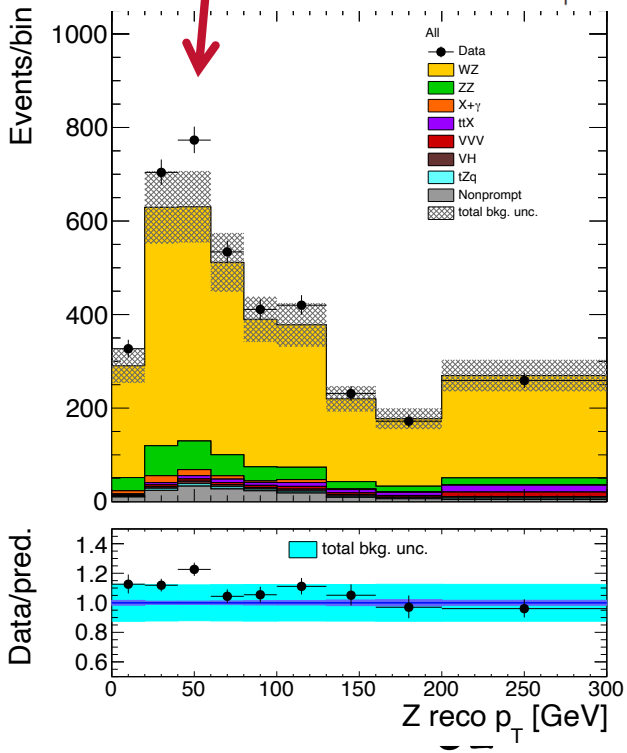
CMS PAS SMP-18-002

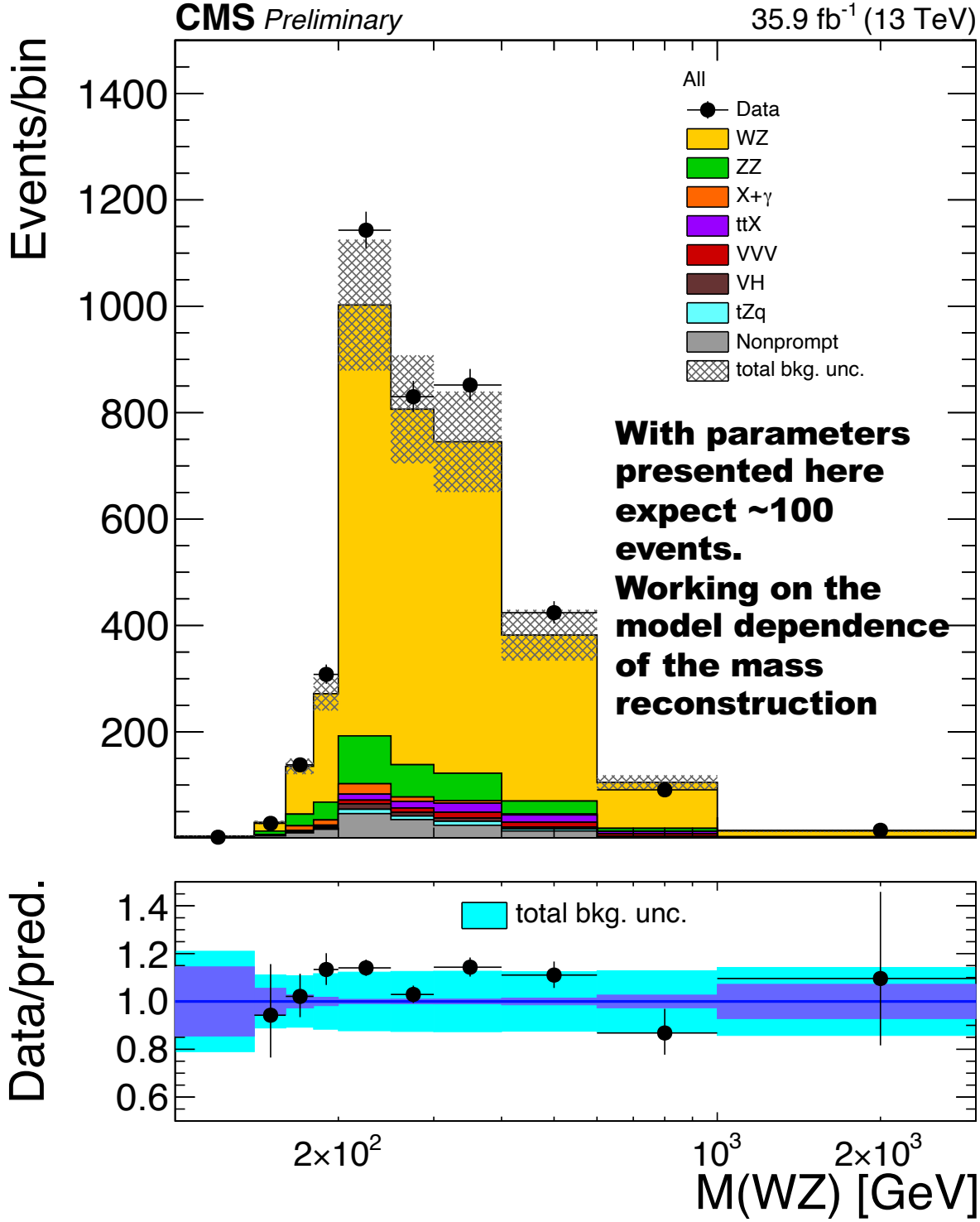
Errors in the plot are dominated by the 15% uncertainty on normalization to account NLO/NNLO differences. The uncertainty of the shape is much smaller of order of few %

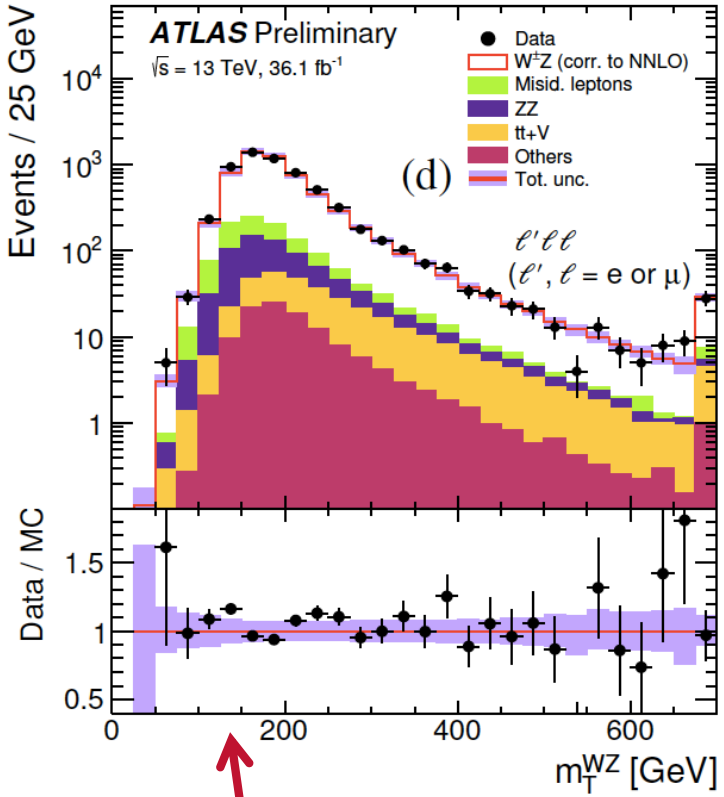
Source	Combined	eee	eeμ	μeμ	$\mu\mu\mu$
Electron efficiency	1.9	5.9	3.9	1.9	0
Electron scale	0.3	0.9	0.2	0.6	0
Muon efficiency	1.9	0	0.8	1.8	2.6
Muon scale	0.5	0	0.7	0.3	0.9
Trigger efficiency	1.9	2.0	1.9	1.9	1.8
Jet energy scale	0.9	1.6	1.0	1.7	0.8
B-tagging (id.)	2.6	2.7	2.6	2.6	2.4
B-tagging (mis-id.)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

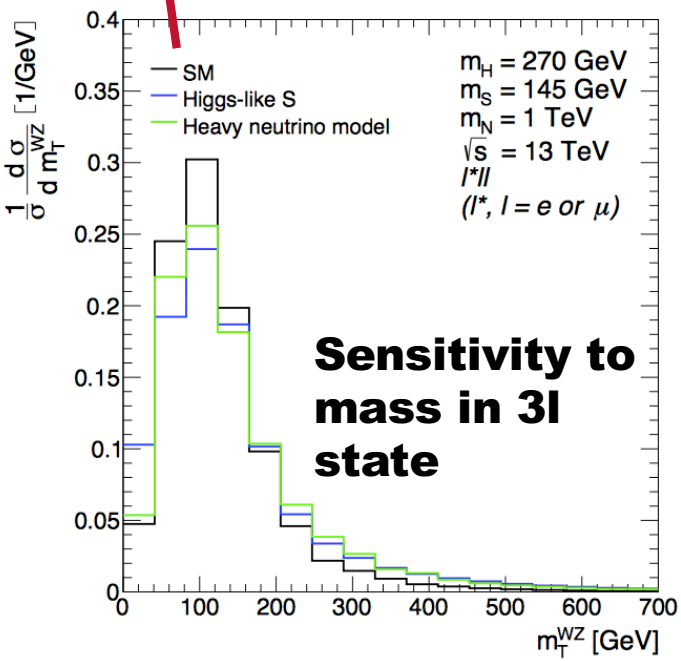
Systematics that will directly affect the shape



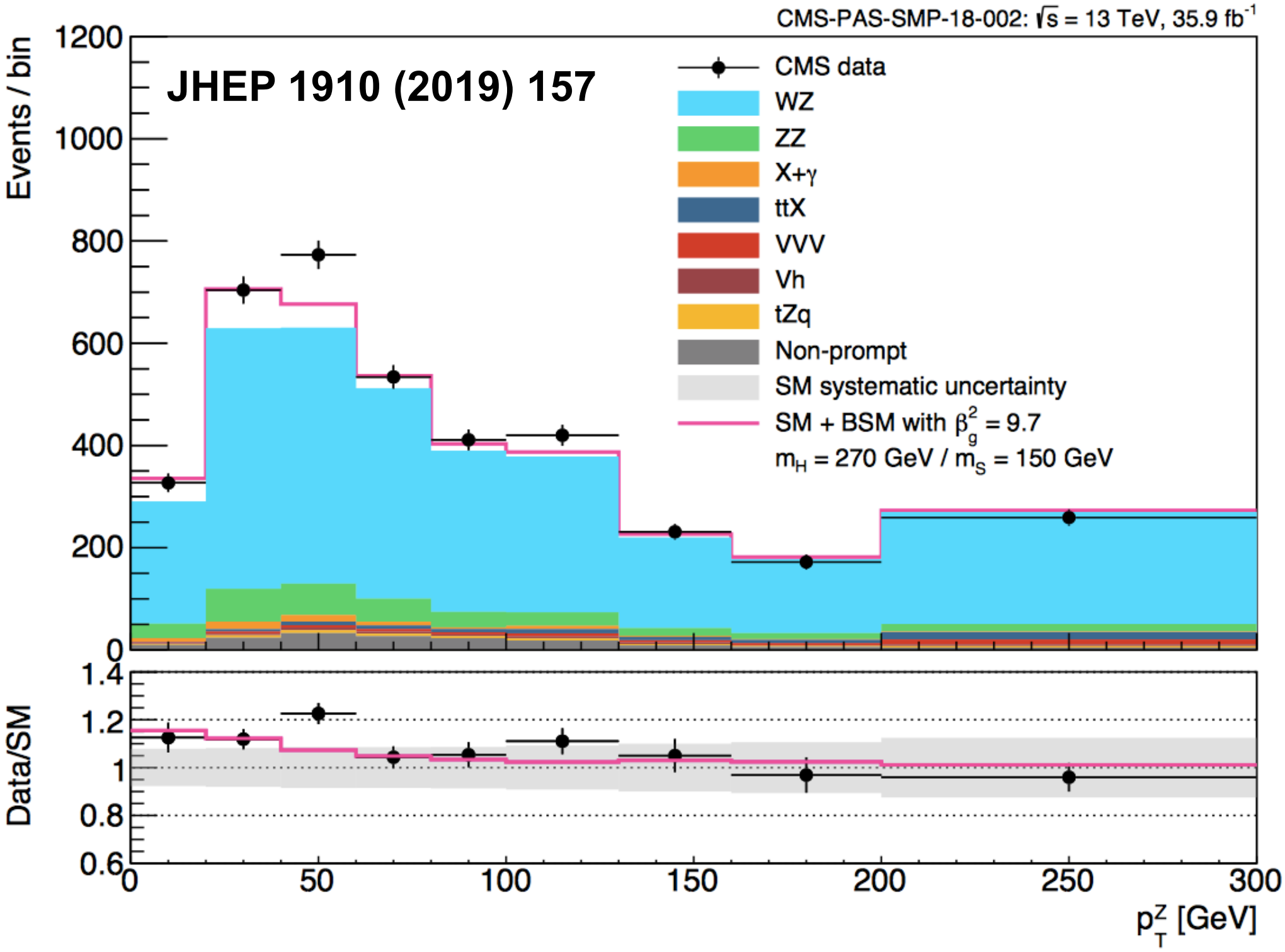








arXiv:1711.07874


CMS-PAS-SMP-18-002: √s = 13 TeV, 35.9 fb-1
JHEP 1910 (2019) 157
CMS data
WZ
ZZ
X+γ
ttX
VVV
Vh
tZq
Non-prompt
SM systematic uncertainty
SM + BSM with β2g = 9.7
mH = 270 GeV / mS = 150 GeV
Events / bin
Data/SM
pZT [GeV]

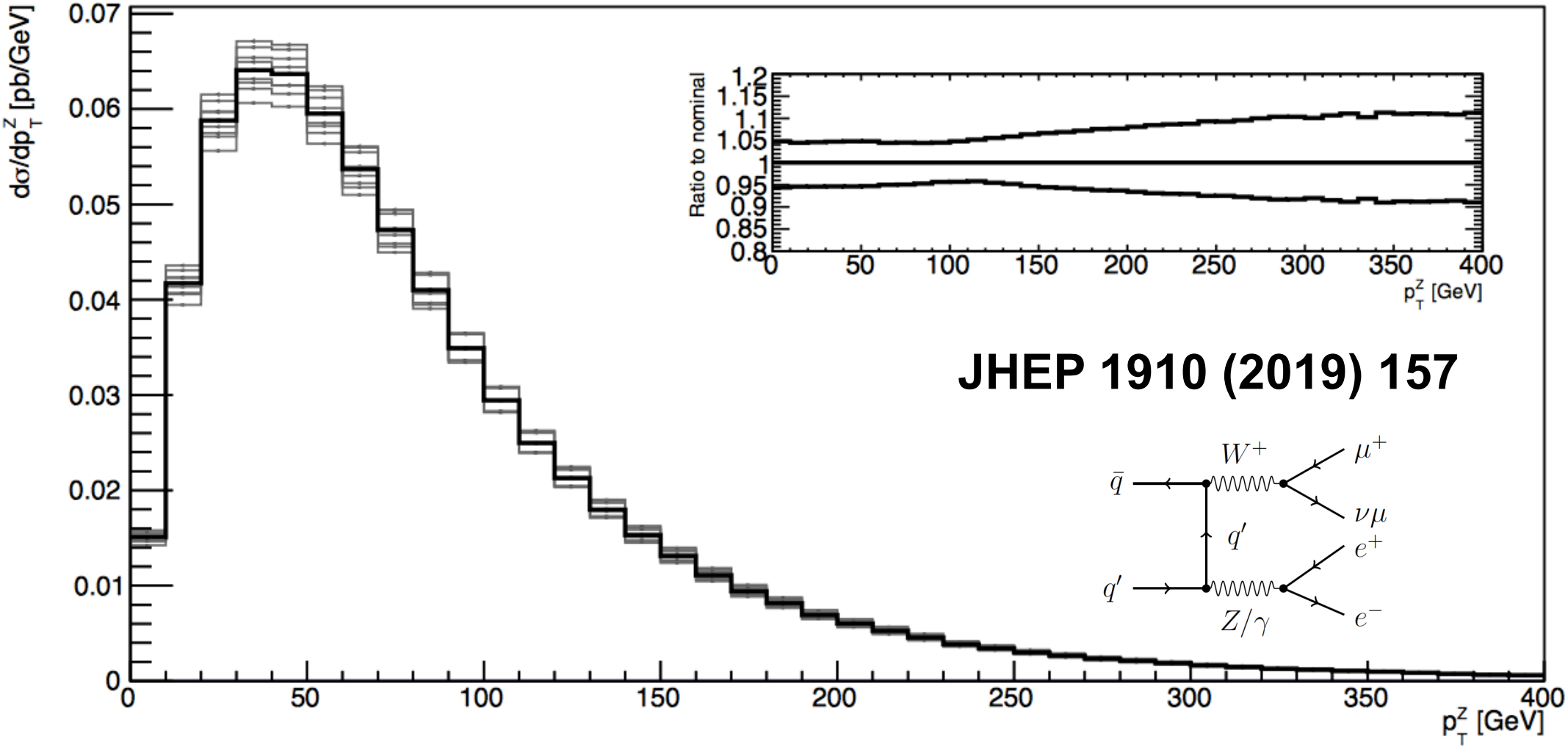


Figure 10: The effects of scale variations in the differential cross section of the SM WZ process as a function of the Z p_{T}. Here, `aMC@NLO` and `Pythia 8` were used to generate the events. The thick black line represents the spectrum at the nominal scale, and each grey line is a variation of the 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,**

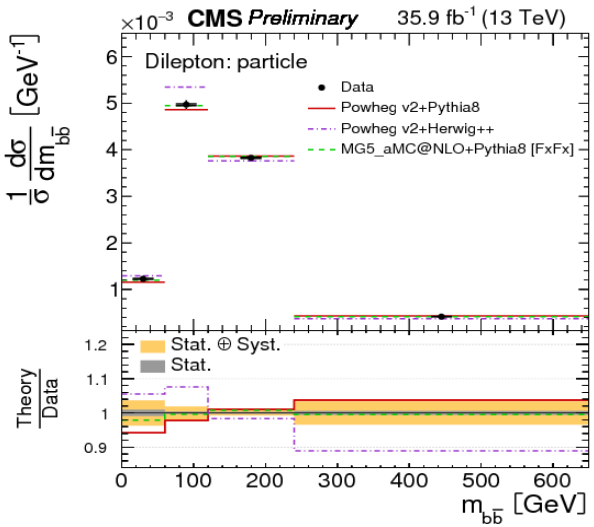
$$\lambda\left(\beta_g^2\right) = \frac{L\left(\beta_g^2 \mid \hat{\hat{\theta}}\right)}{L\left(\hat{\beta}_g^2 \mid \hat{\theta}\right)}$$

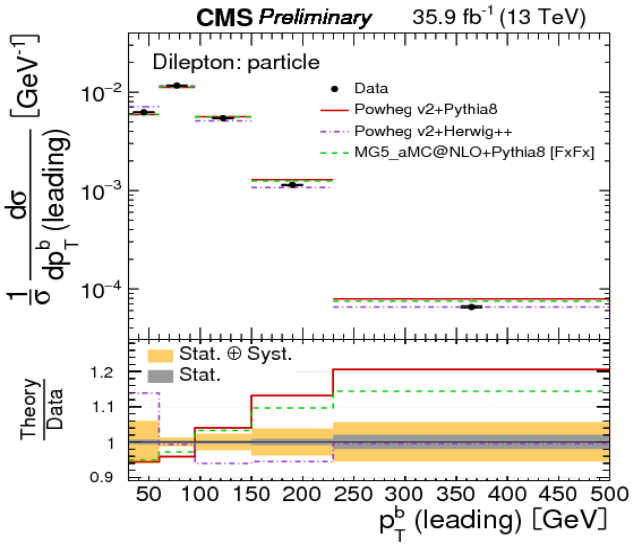
(here θ denotes the nuisance parameters)

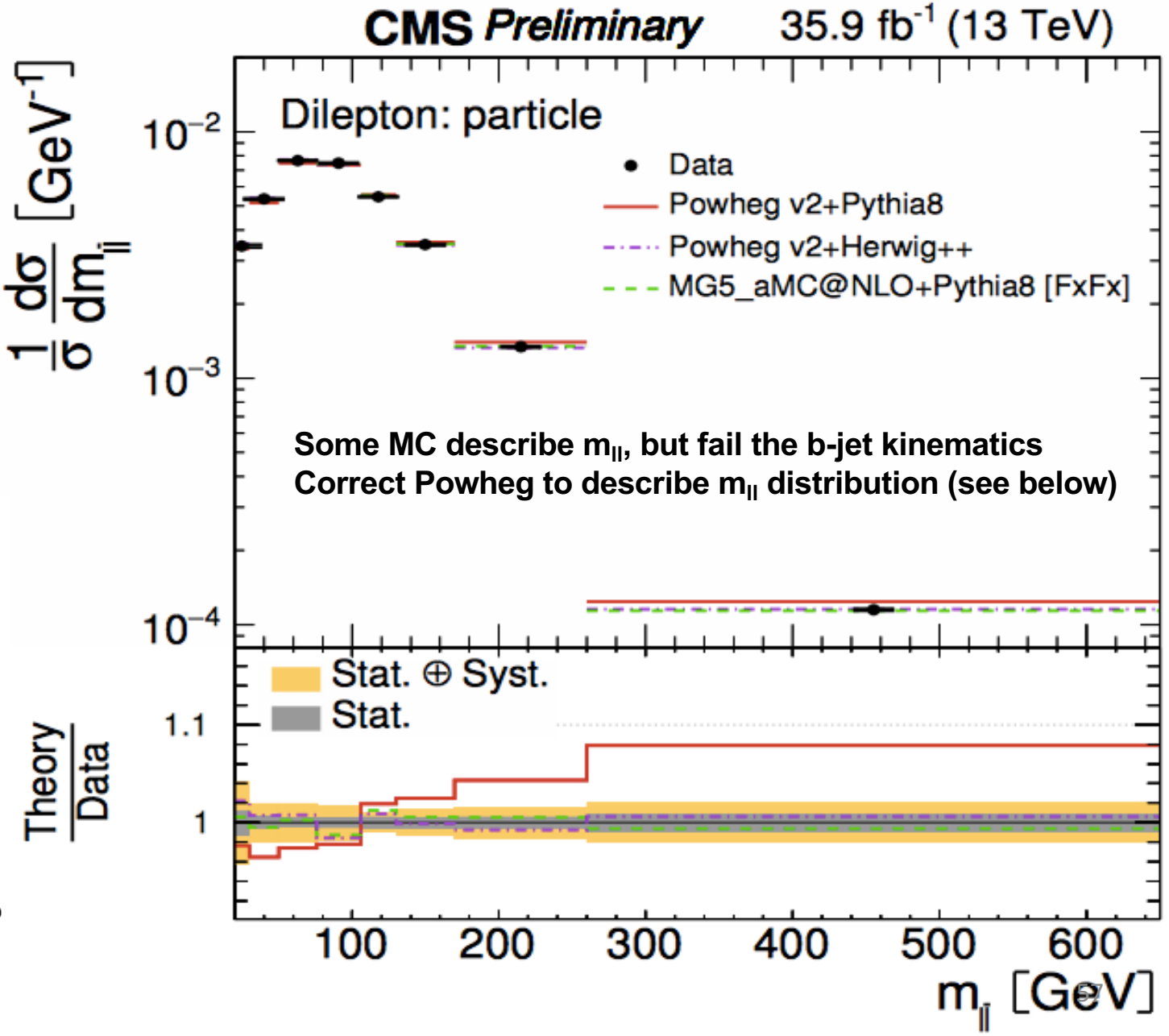
- **The best-fit value of β_g^2 is then calculated as the minimum of -2log(λ), with an error corresponding to a unit of deviation in this quantity from the best-fit point**
- **The significance is calculated as $\sqrt{(-2 \log \lambda(0))}$, since $\beta_g^2 = 0$ corresponds to the SM-only hypothesis**

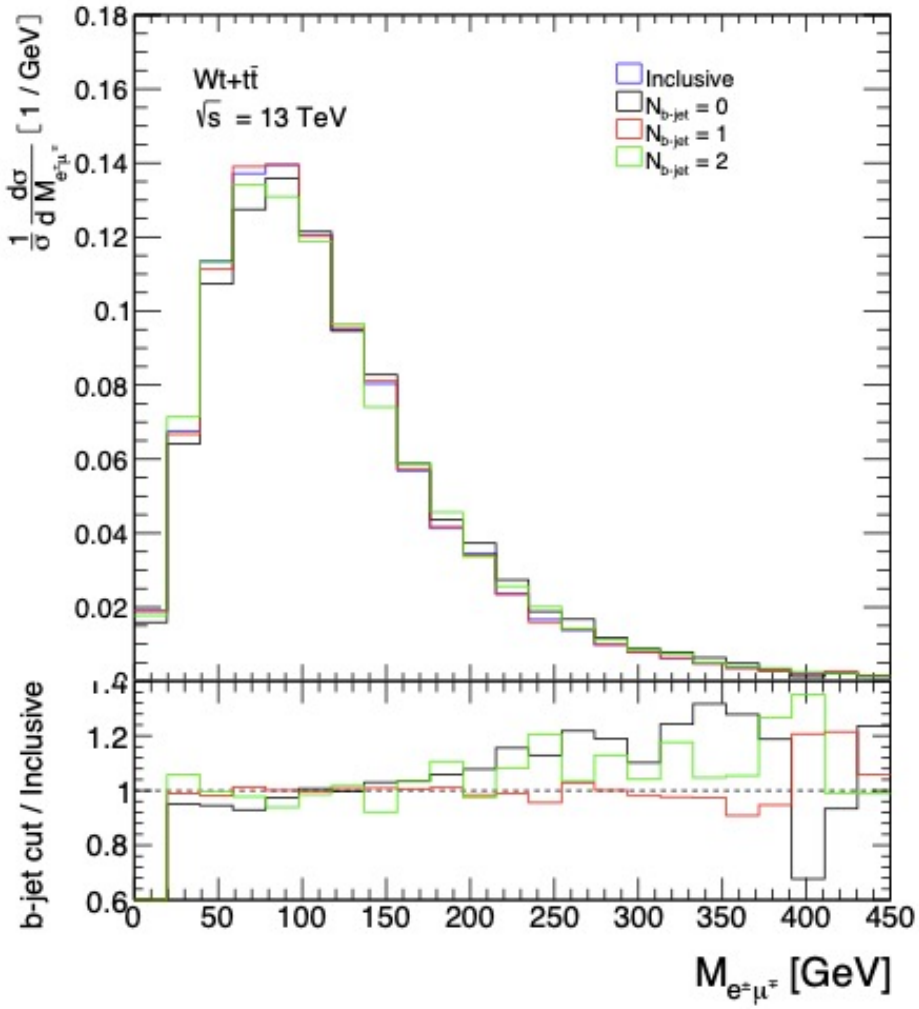
CMS PAS TOP-17-014

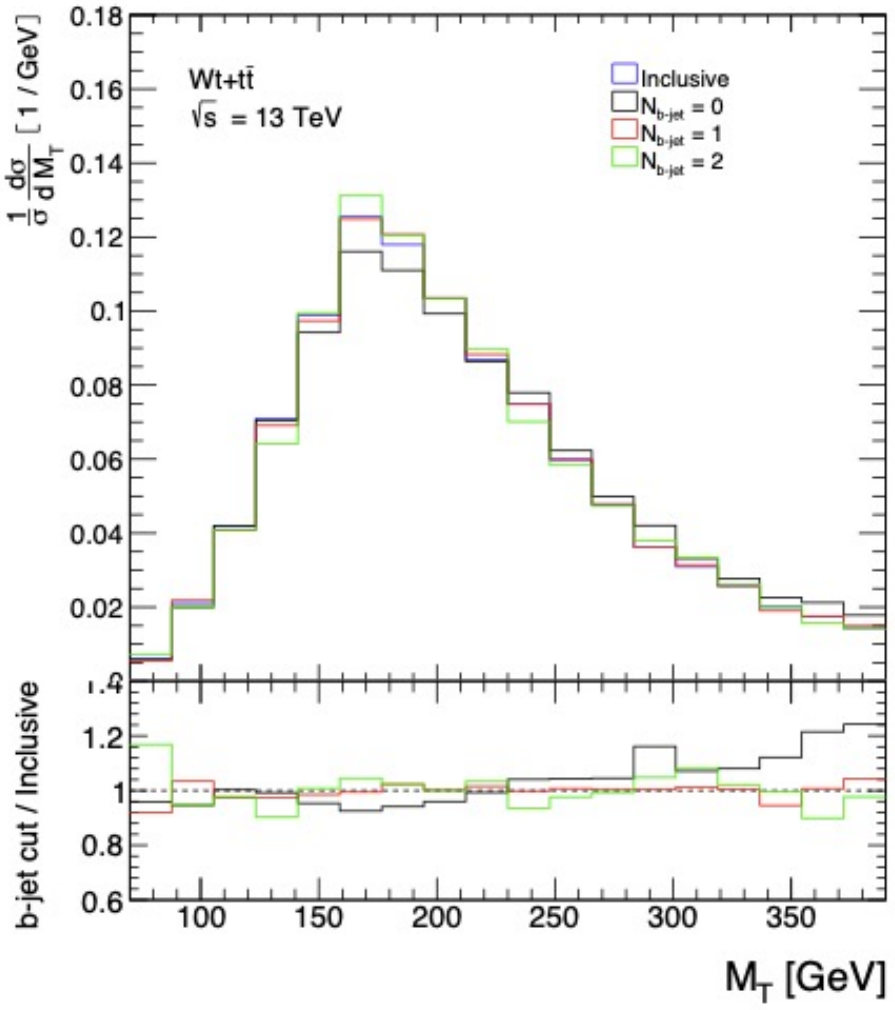
Event selection with exactly two leptons (e,μ), m_{ll}>20 GeV and at least 2b-jets





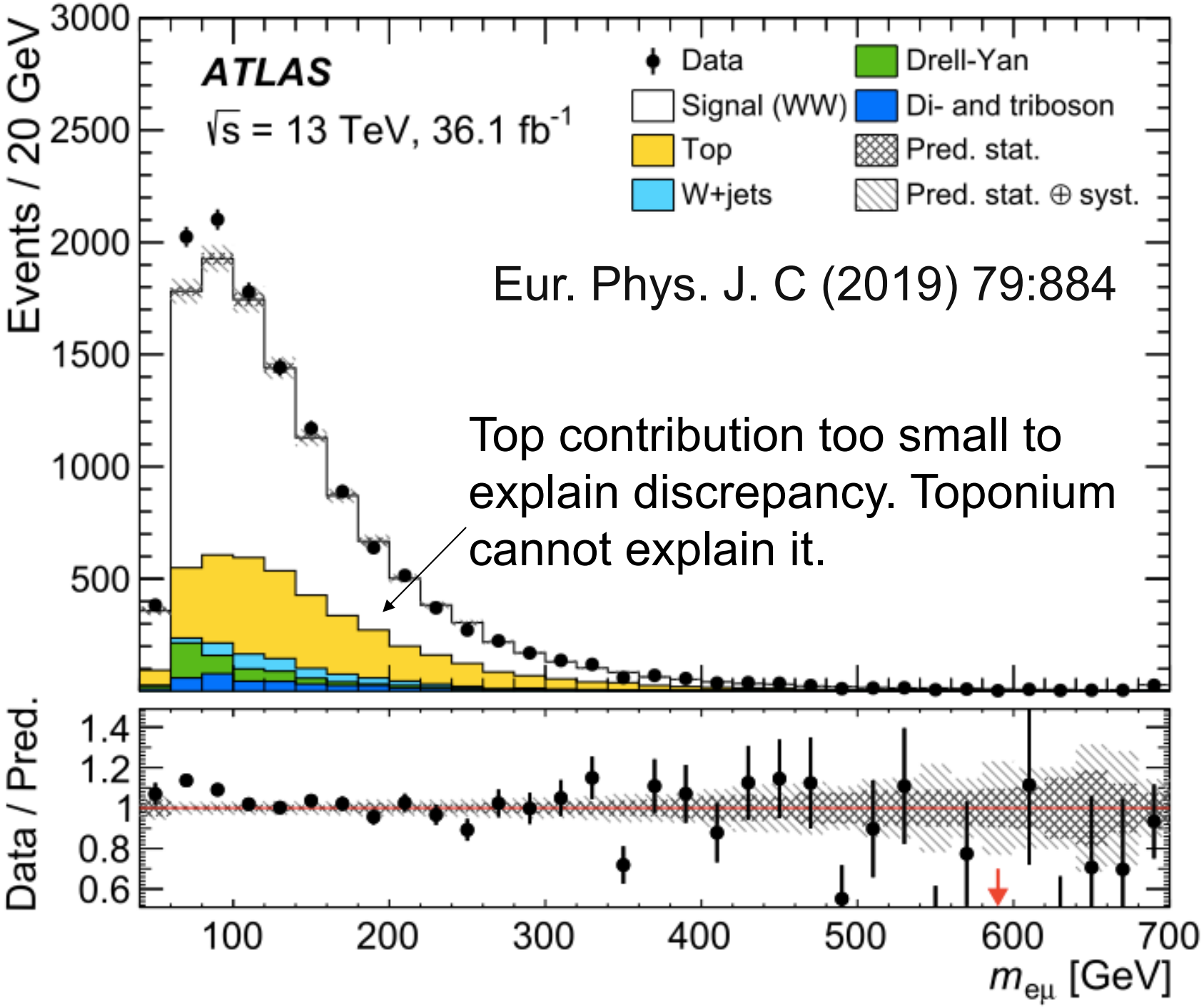






b-jet multiplicity is robust theoretically

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



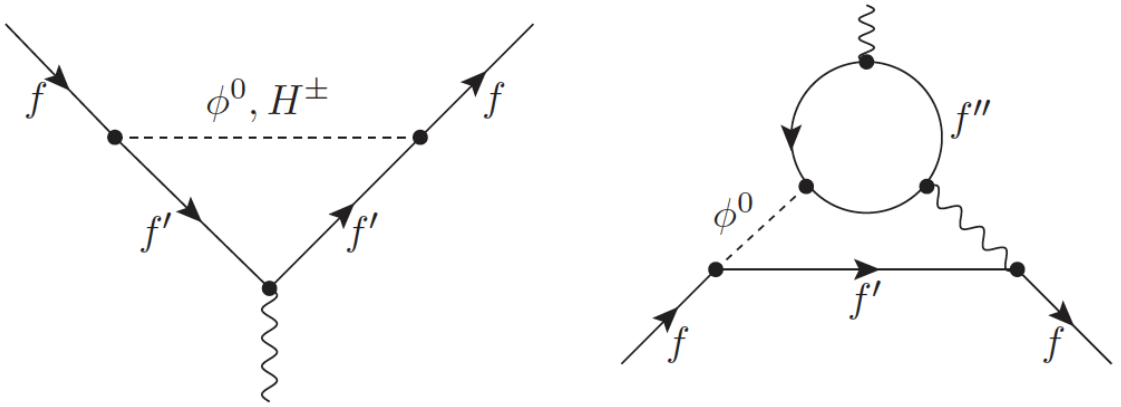
Eur. Phys. J. C (2019) 79:884

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

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

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

The Muon g-2 and the 2HDM+S

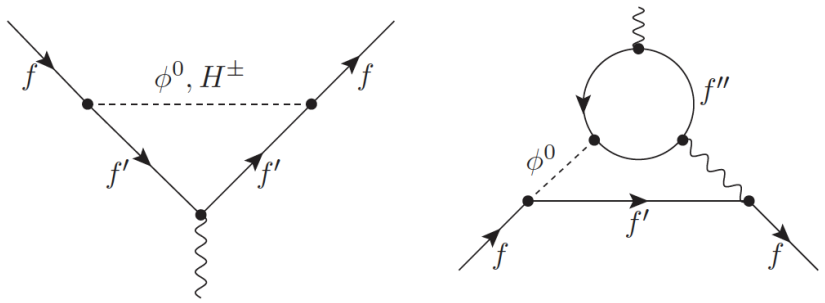


2HDM+S potential with fixed parameters from multi-lepton anomalies at the LHC

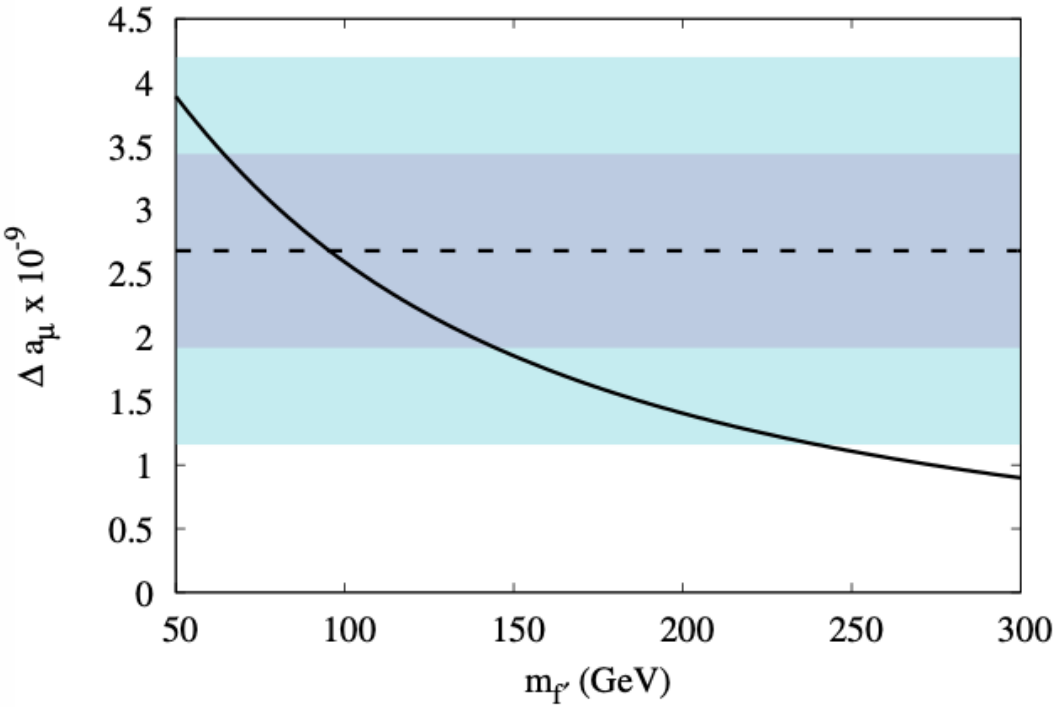
$$
\begin{aligned}
&V(\Phi_1, \Phi_2, \Phi_S) \\
&= m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \text{h.c.}\right) \\
&+ \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger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

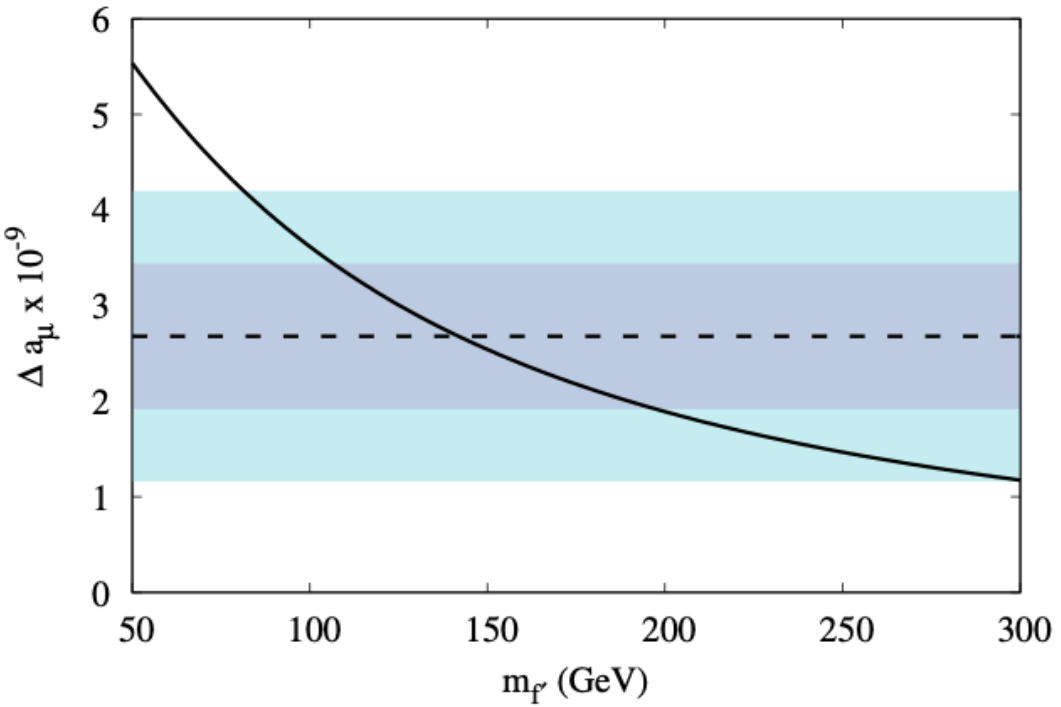
Consider extra degrees of freedom in the form of SM singlet vector-like fermions

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



Allowed fermion masses with different choices of Yukawa couplings



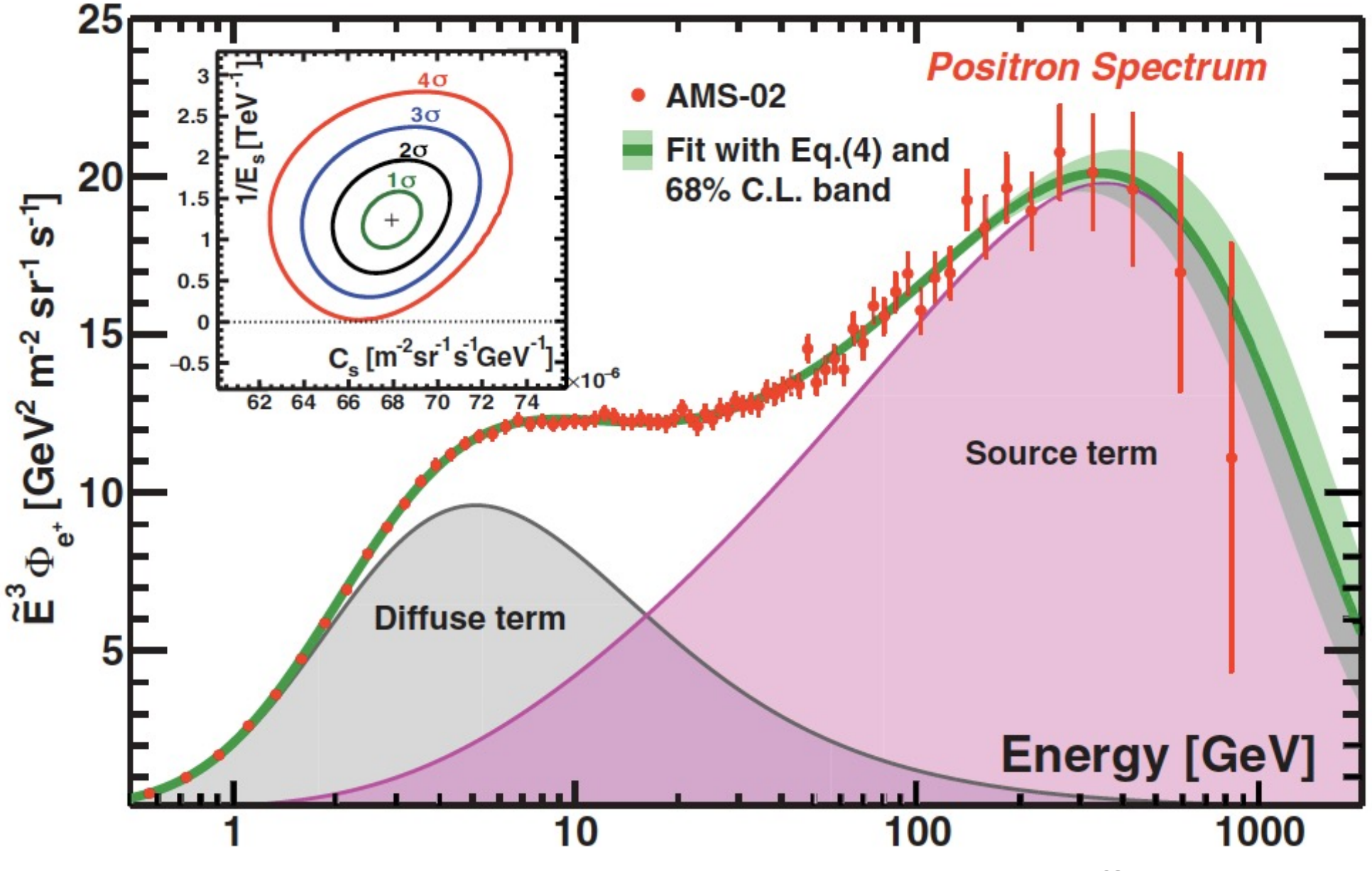


G.Beck, E.Malwa, M.Kumar, R.Temo and B.M., 2102.10596

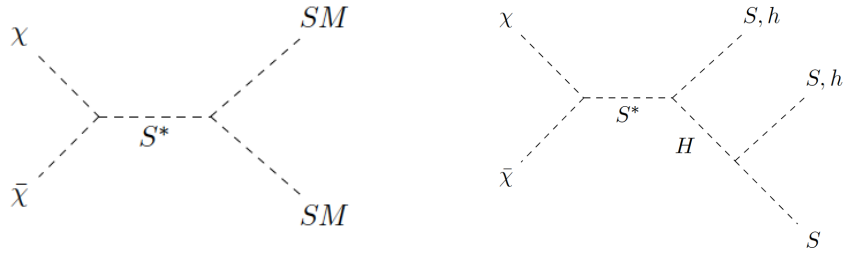
The multi-lepton anomalies and excesses in astrophysics

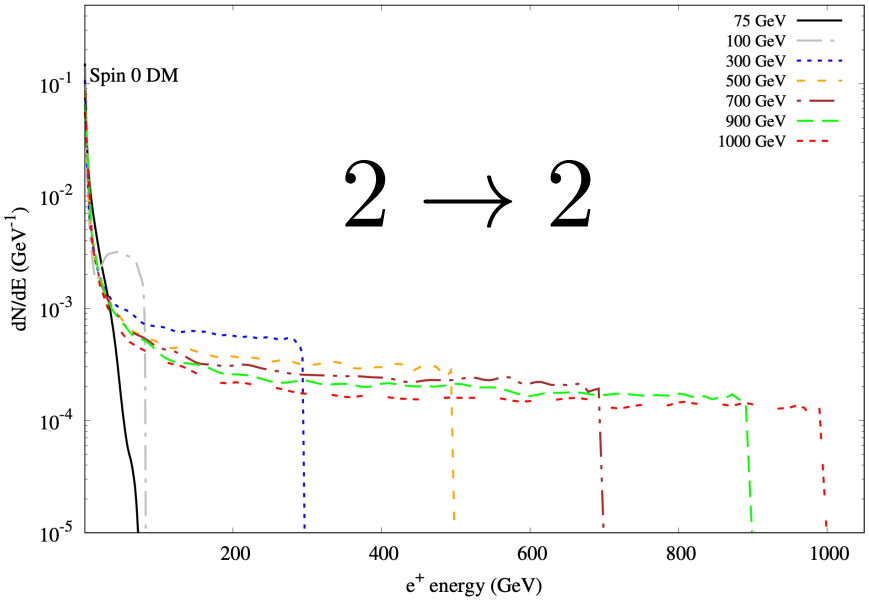
AMS02, PRL 122, 041102 (2019)

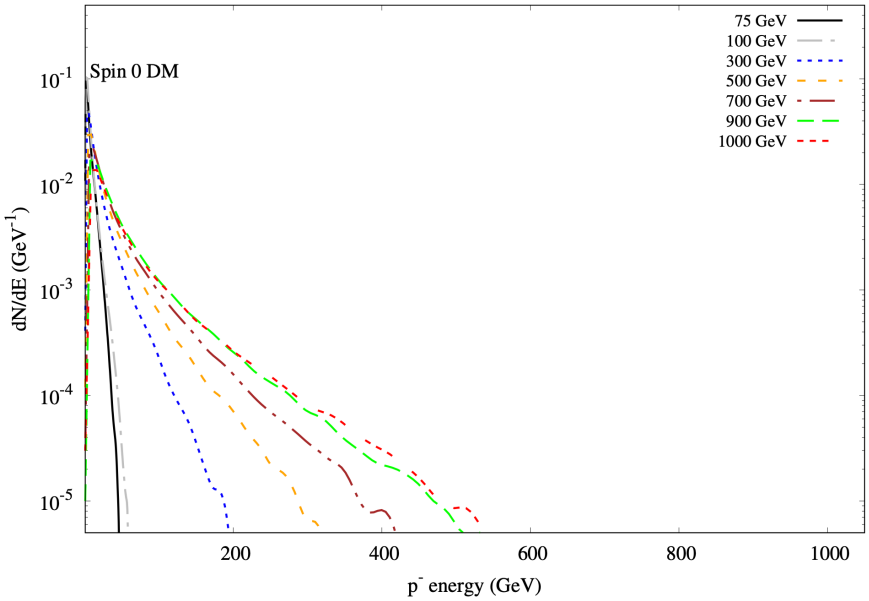
Leptophilic excesses, such as positron rise in PAMELA/AMS02

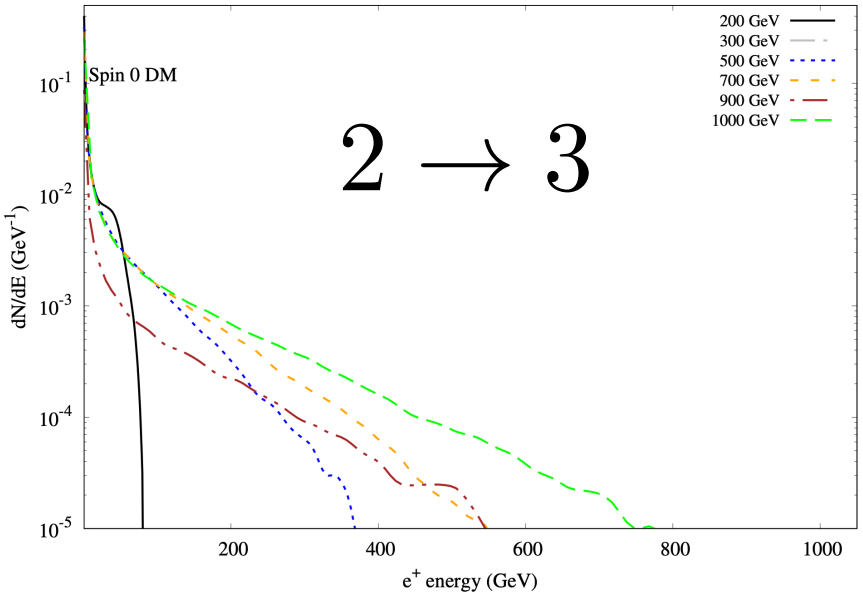


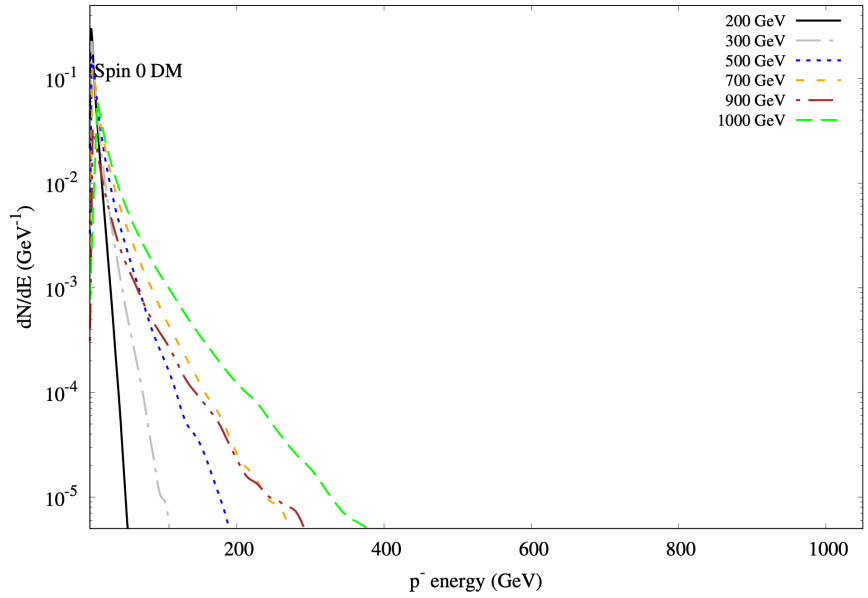
Dark matter annihilation.
Leptons, photons and protons from the decays of S.

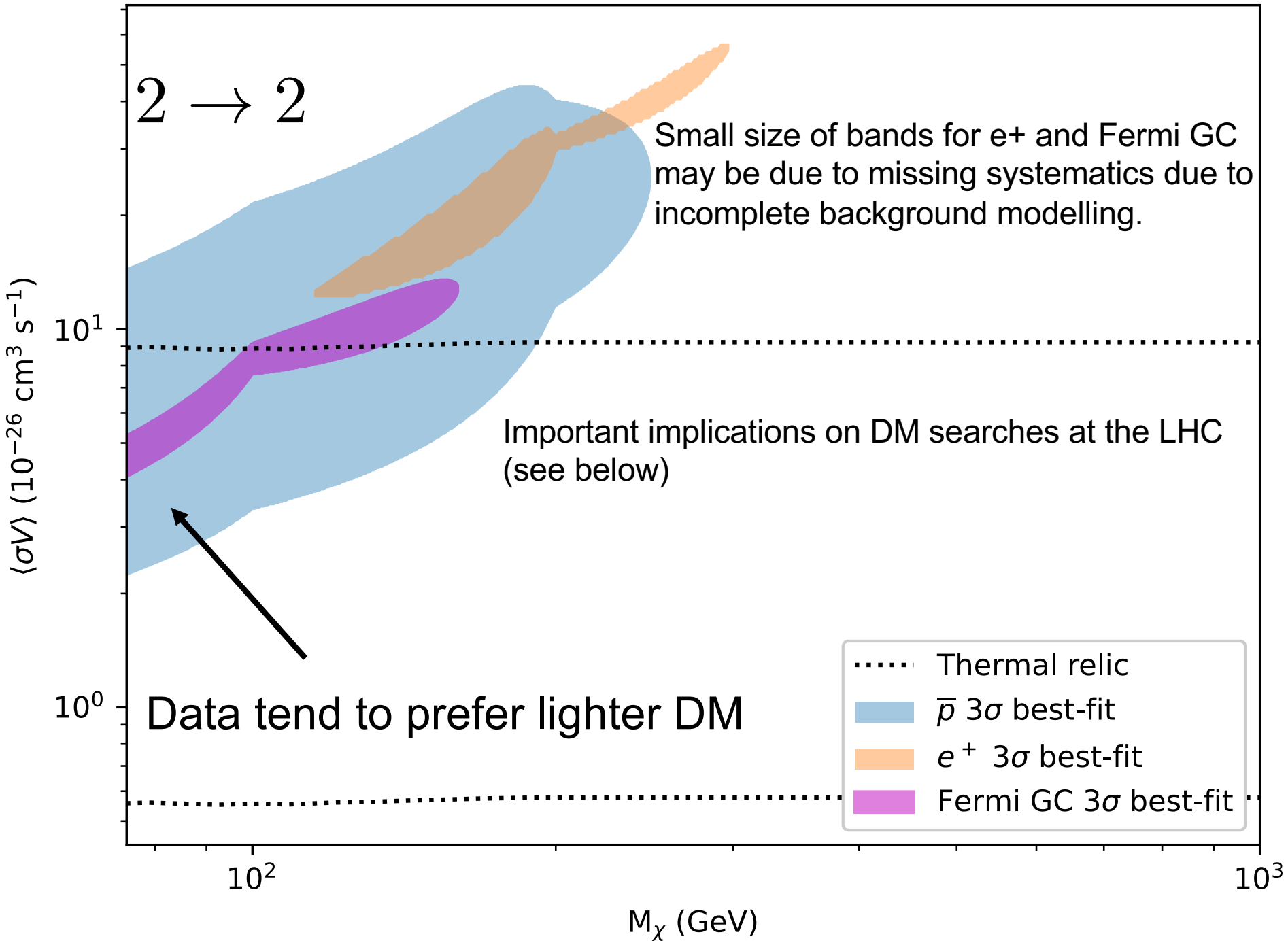











$2 \to 2$
Small size of bands for e+ and Fermi GC may be due to missing systematics due to incomplete background modelling.
Important implications on DM searches at the LHC (see below)
Data tend to prefer lighter DM
Thermal relic
$\overline{p}$ 3σ best-fit
e^+ 3σ best-fit
Fermi GC 3σ best-fit
$\langle \sigma V \rangle$ (10^{-26} cm^3 s^{-1})
10^1
10^0
10^2
10^3
M_χ (GeV)

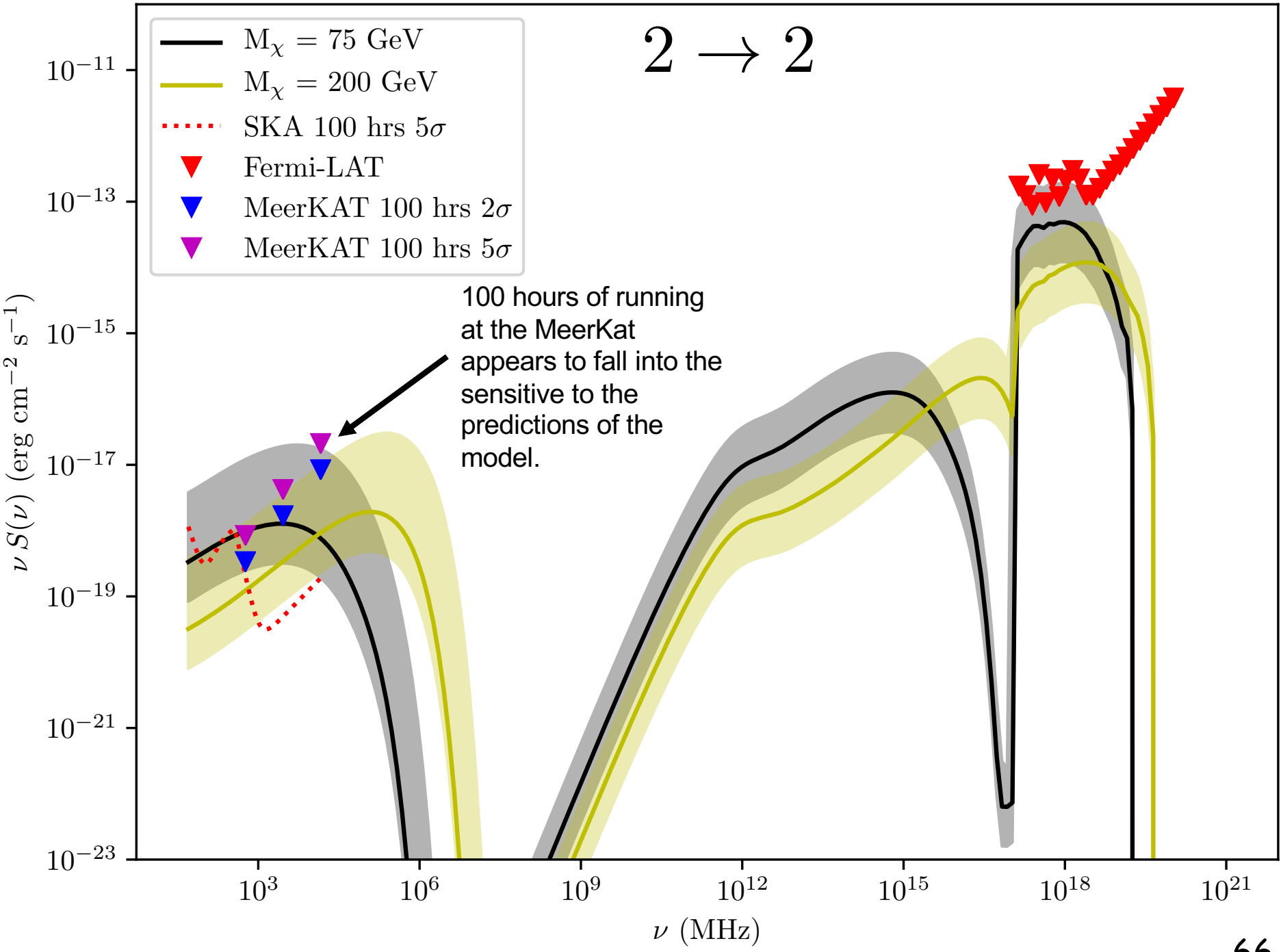

$M_\chi = 75$ GeV
$M_\chi = 200$ GeV
SKA 100 hrs 5σ
Fermi-LAT
MeerKAT 100 hrs 2σ
MeerKAT 100 hrs 5σ
$2 \to 2$
100 hours of running at the MeerKat appears to fall into the sensitive to the predictions of the model.
$\nu\, S(\nu)$ (erg cm^{-2} s^{-1})
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
10^{21}
ν (MHz)

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

Category	Number of leptons	Number of jets	Sub-categorization
ggH	2	-	$(\mathrm{DF}, \mathrm{SF}) \times (0\,\text{jets}, 1\,\text{jet}, \geq 2\,\text{jets})$
VBF	2	≥ 2	$(\mathrm{DF}, \mathrm{SF})$
VH2j	2	≥ 2	$(\mathrm{DF}, \mathrm{SF})$
WHSS	2	≥ 1	$(\mathrm{DF}, \mathrm{SF}) \times (0\,\text{jets}, 1\,\text{jet})$
WH3ℓ	3	0	SF lepton pair with opposite or same sign
ZH3ℓ	3	≥ 1	$(1\,\text{jet}, 2\,\text{jets})$
ZH4ℓ	4	-	$(\mathrm{DF}, \mathrm{SF})$

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

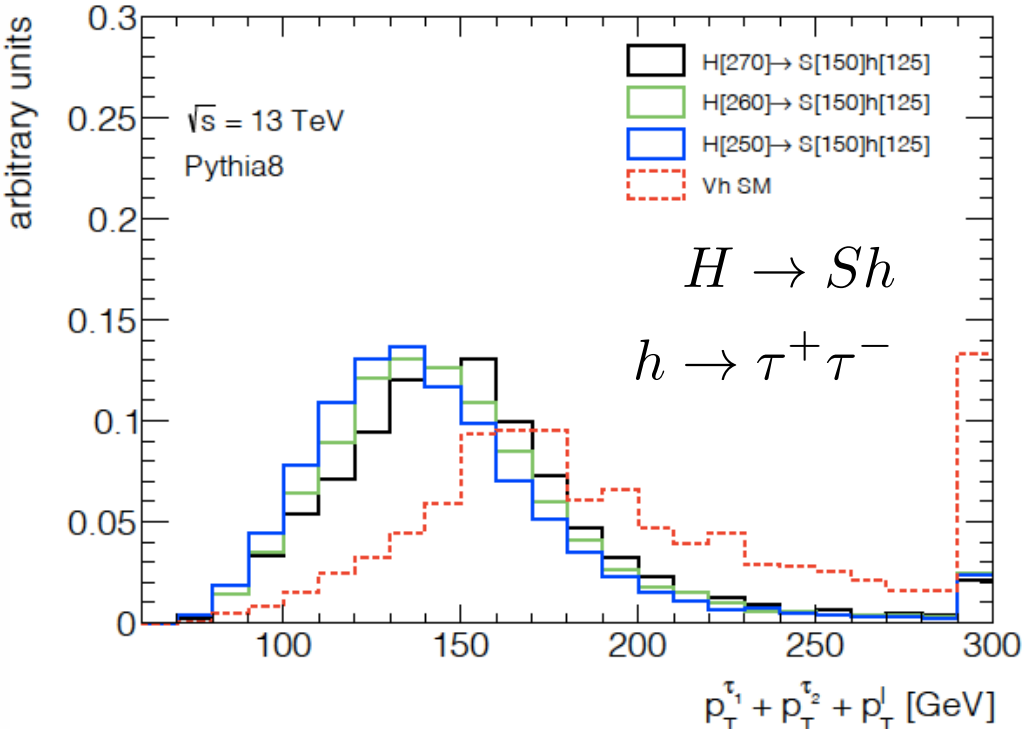
Category	Sub-categories	Selection
Global selection	-	$p_{T1} > 25$ GeV, $p_{T2} > 10$ GeV (2016) or 13 GeV $p_T^{miss} > 20$ GeV, $p_T^{\ell\ell} > 30$ GeV, $m_{\ell\ell} > 12$ GeV eμ pair with opposite charge
0-jet ggH tagged	$\ell^\pm\ell^\mp$, $p_{T2} \leqslant 20$ GeV	$m_T^H > 60$ GeV, $m_T(\ell 2, p_T^{miss}) > 30$ GeV $p_{T2} \leqslant 20$ 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	$\ell^\pm\ell^\mp$, $p_{T2} \leqslant 20$ GeV	$m_T^H > 60$ GeV, $m_T(\ell 2, p_T^{miss}) > 30$ GeV $p_{T2} \leqslant 20$ 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 $p_{T2} \leqslant 20$ 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

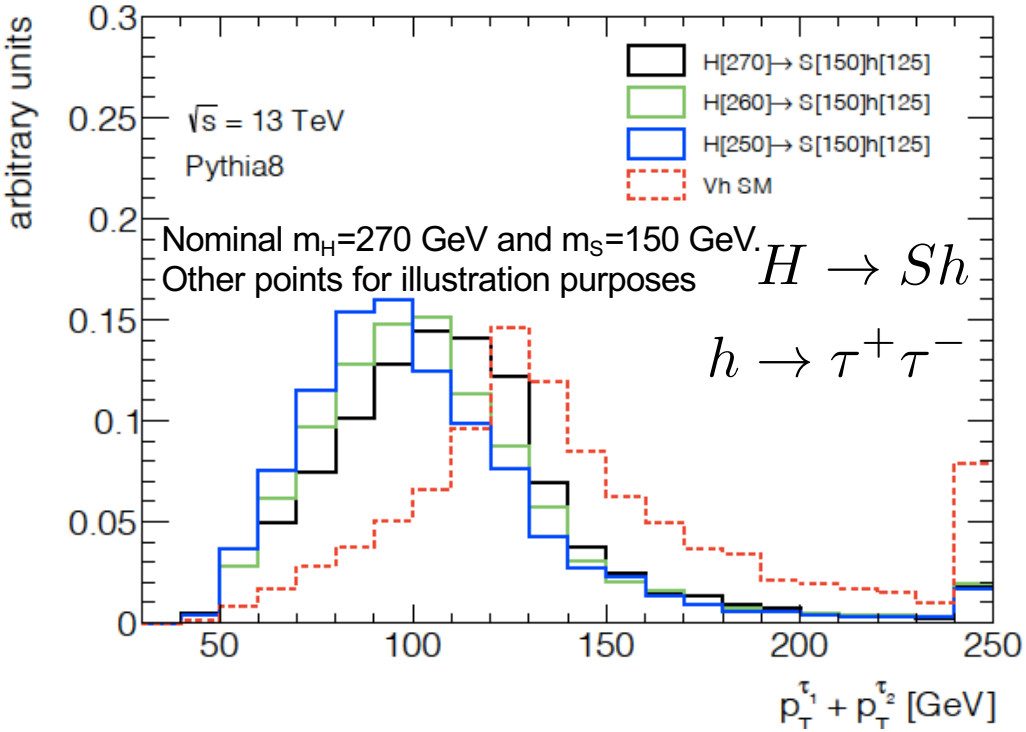
Impact on Higgs Physics

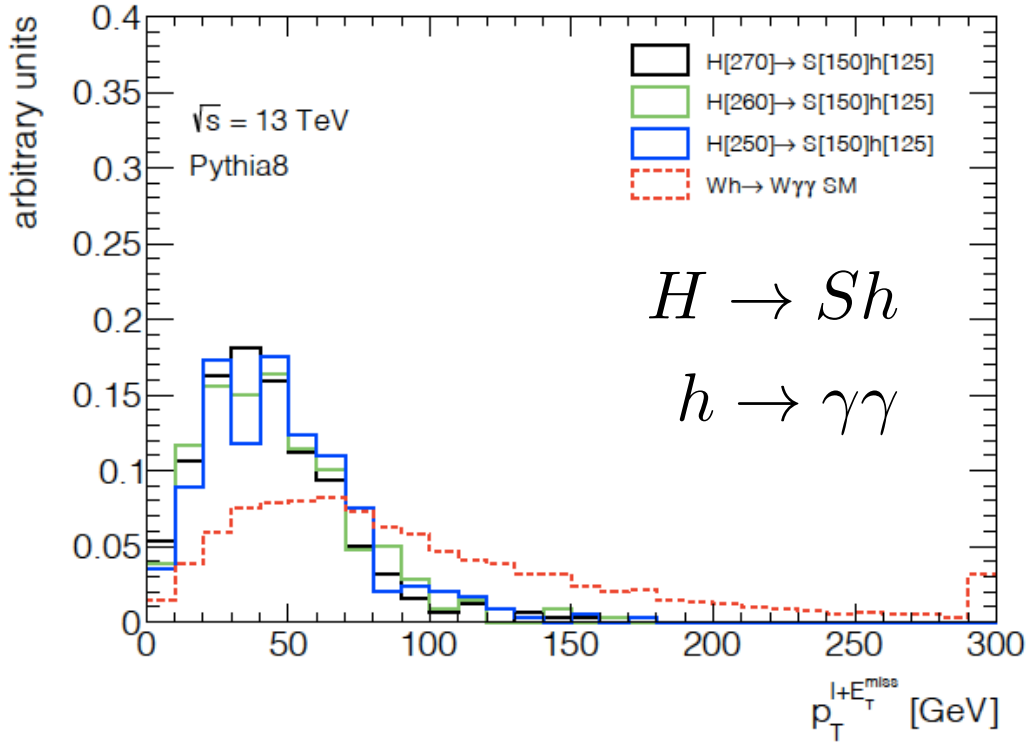
The presence of a BSM signal of the type H→Sh would lead to:

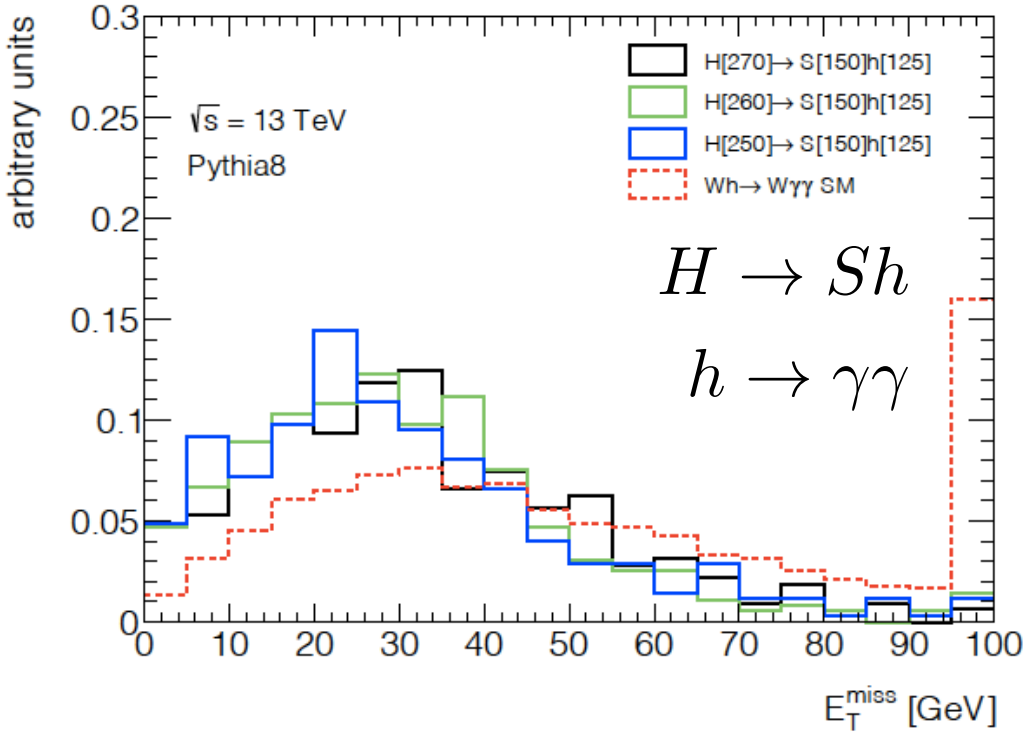
- **The presence of extra leptons in association with h. Affects the Wh measurement (Eur.Phys.J.C 81 (2021) 365)**
- **Distortion of Higgs p_T and rapidity (under study)**

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


arbitrary units
√s = 13 TeV
Pythia8
H[270]→ S[150]h[125]
H[260]→ S[150]h[125]
H[250]→ S[150]h[125]
Vh SM
$H \to Sh$
$h \to \tau^+\tau^-$
$p_T^{\tau_1} + p_T^{\tau_2} + p_T^{l}$ [GeV]


arbitrary units
√s = 13 TeV
Pythia8
H[270]→ S[150]h[125]
H[260]→ S[150]h[125]
H[250]→ S[150]h[125]
Vh SM
Nominal m_H=270 GeV and m_S=150 GeV.
Other points for illustration purposes
$H \to Sh$
$h \to \tau^+\tau^-$
$p_T^{\tau_1} + p_T^{\tau_2}$ [GeV]


arbitrary units
√s = 13 TeV
Pythia8
H[270]→ S[150]h[125]
H[260]→ S[150]h[125]
H[250]→ S[150]h[125]
Wh→ Wγγ SM
$H \to Sh$
$h \to \gamma\gamma$
$p_T^{l+E_T^{miss}}$ [GeV]


arbitrary units
√s = 13 TeV
Pythia8
H[270]→ S[150]h[125]
H[260]→ S[150]h[125]
H[250]→ S[150]h[125]
Wh→ Wγγ SM
$H \to Sh$
$h \to \gamma\gamma$
E_T^{miss} [GeV]

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:

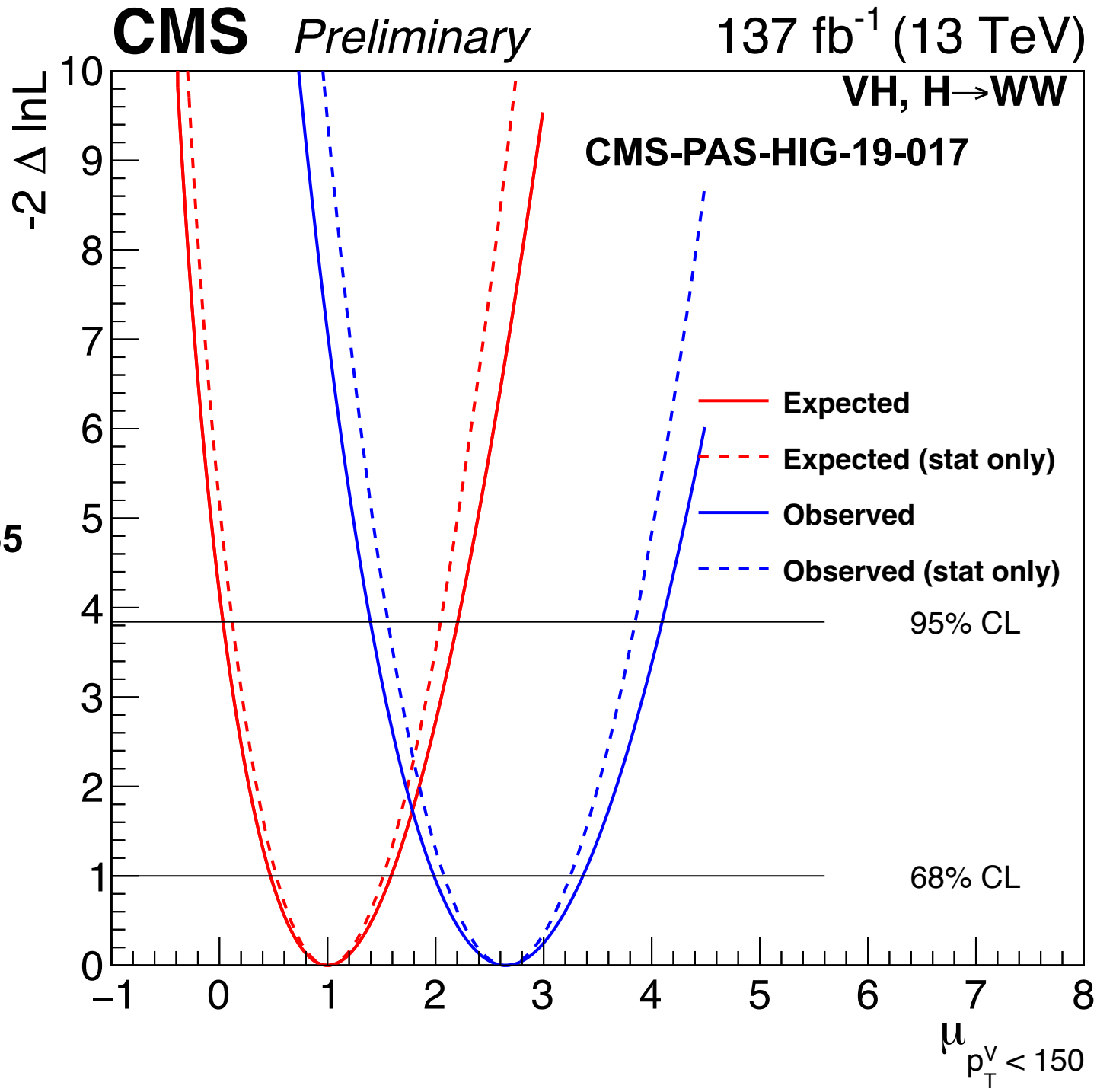
$$\mu(Wh) = 2.41 \pm 0.37$$

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	$2.2^{+2.0}_{-1.9}$	✓	
					SS 1j	$8.4^{+4.3}_{-3.8}$	✓	2ℓ combination: $\mu = 3.7^{+1.9}_{-1.5}$
					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	$2.3^{+1.2}_{-1.0}$	✓	1SFOS channel uses $m_{\ell_0\ell_2}$ in the BDT but excess driven by 0SFOS
					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	1.0 ± 1.6	x	$E_T^{miss} > 70 - 100$ GeV $p_{T_t}^{\gamma\gamma} > 70$ GeV
				$\ell\nu, \nu\nu$	E_T^{miss}			
				jj	Hadronic			
	74	CMS	7, 5.1 8, 19.7	$\ell\nu$	One-lepton	$-0.16^{+1.16}_{-0.79}$	x	Split E_T^{miss} at 45 GeV $E_T^{miss} > 70$ GeV $p_T^{\gamma\gamma} > 13m_{\gamma\gamma}/12$
				$\ell\nu, \nu\nu$	E_T^{miss}			
				jj	Hadronic			
	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
				$\ell\nu, \nu\nu$	E_T^{miss}	-	x	$E_T^{miss} > 75$ GeV
				jj	Hadronic	$0.76^{+0.95}_{-0.83}$	x	$60 < m_{jj} < 120$ GeV
						$3.16^{+1.84}_{-1.72}$	✓	$m_{jj} \in [0, 60] \,\|\|\, [120, 350]$ GeV
	76	CMS	13, 35.6	$\ell\nu$	One-lepton	$3.0^{+1.5}_{-1.3}$	x	Superseeded by full Run 2 result
				$\ell\nu, \nu\nu$	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	$\ell\ell\ell\ell + \ell\nu$	Lep-enriched	$1.44^{+1.17}_{-0.93}$	x	Number of jets used in MVA
				$\ell\ell\ell\ell + q\bar{q}$	2j			m_{jj} used in MVA
	79	CMS	13, 137.1	$\ell\ell\ell\ell + \ell\nu$	Lep-low p_T^{Δ}	$3.21^{+2.49}_{-1.85}$	✓	$p_T^{\Delta} < 150$ GeV
					Lep-high p_T^{Δ}	$0.00^{+1.57}_{-0.00}$	x	$p_T^{\Delta} > 150$ GeV
				$\ell\ell\ell\ell + q\bar{q}$	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

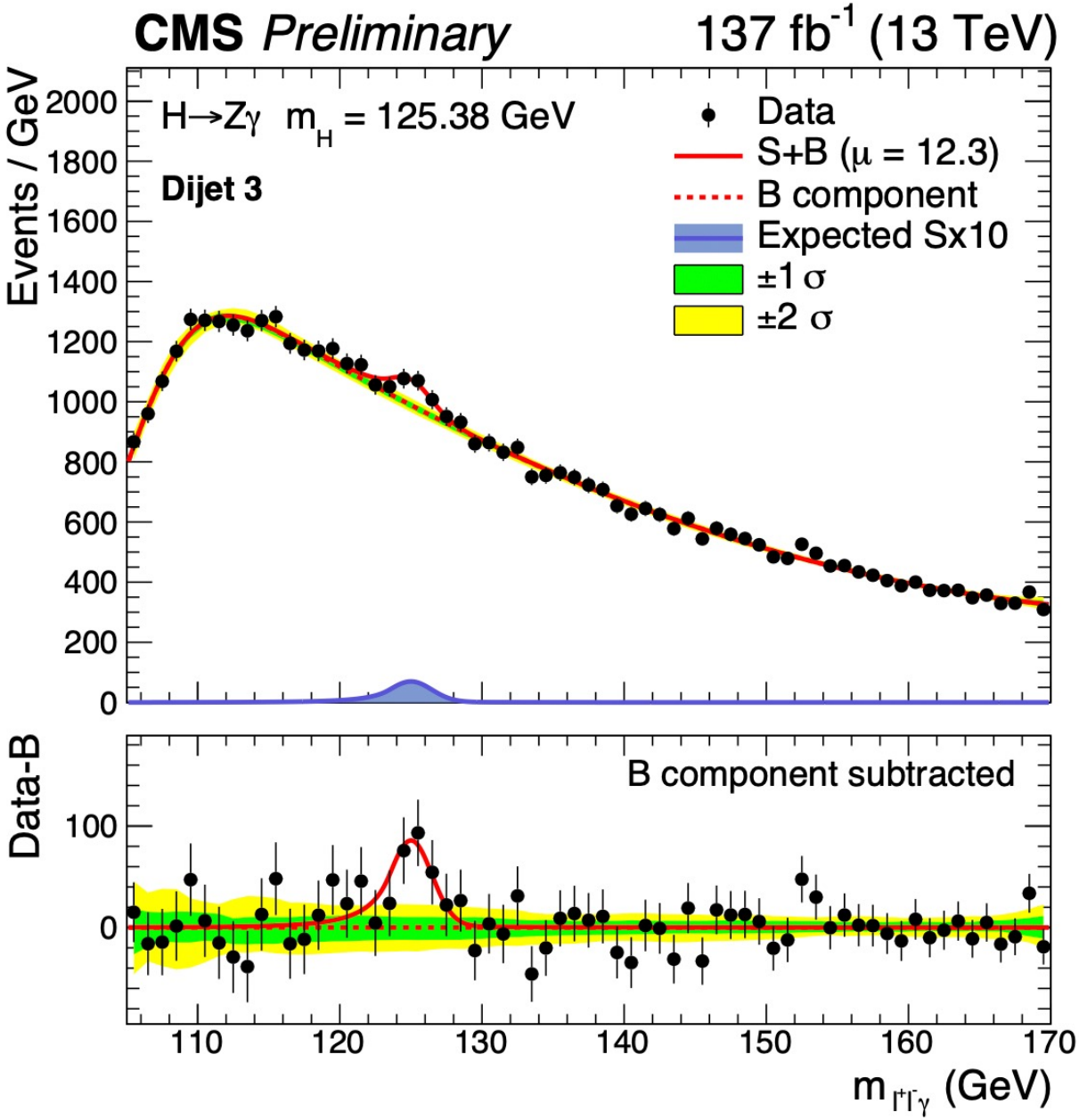
Contact: cms-pag-conveners-higgs@cern.ch

2021/10/19

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

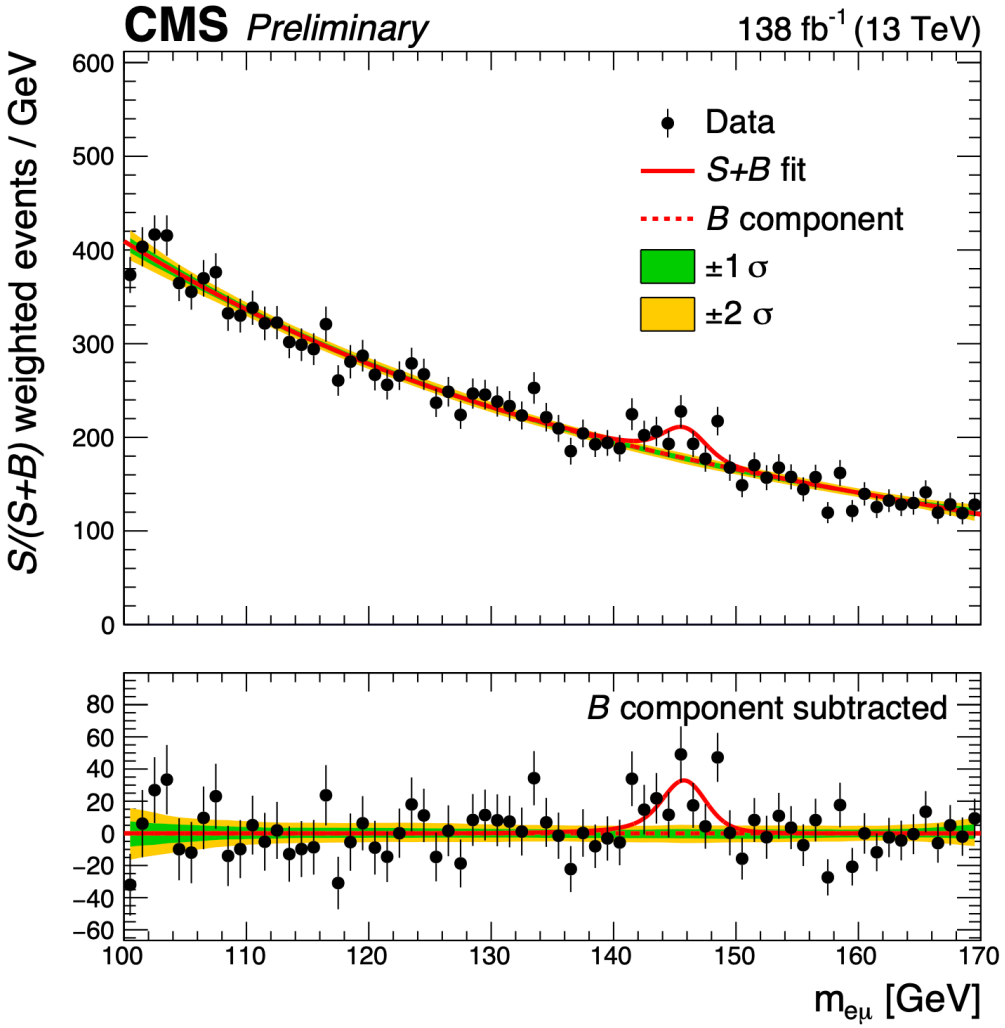
The CMS Collaboration

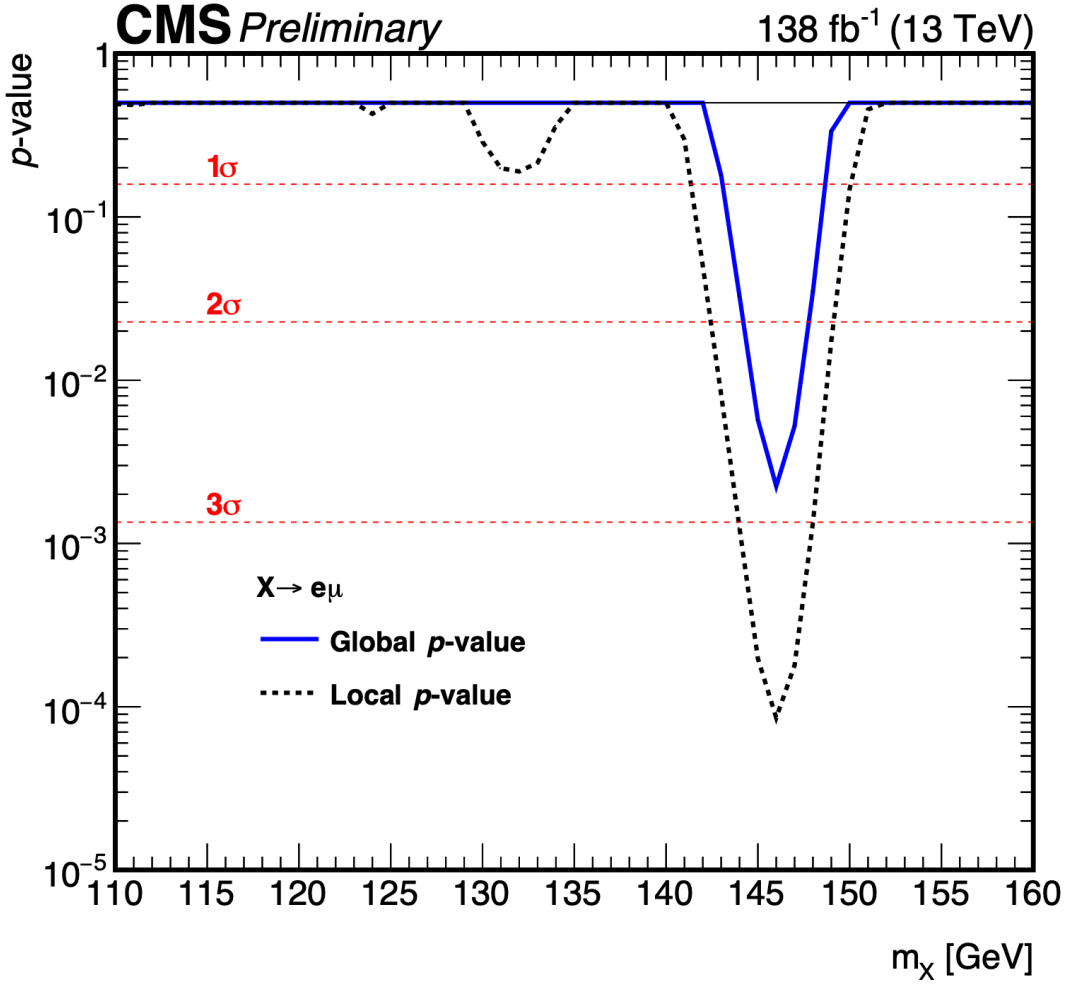
CMS observes what appears to be an upward fluctuation of the $h \to Z\gamma$ in the di-jet bin optimized for the measurement of Wh production. The Signal strength deviates from unity by 3.2σ.



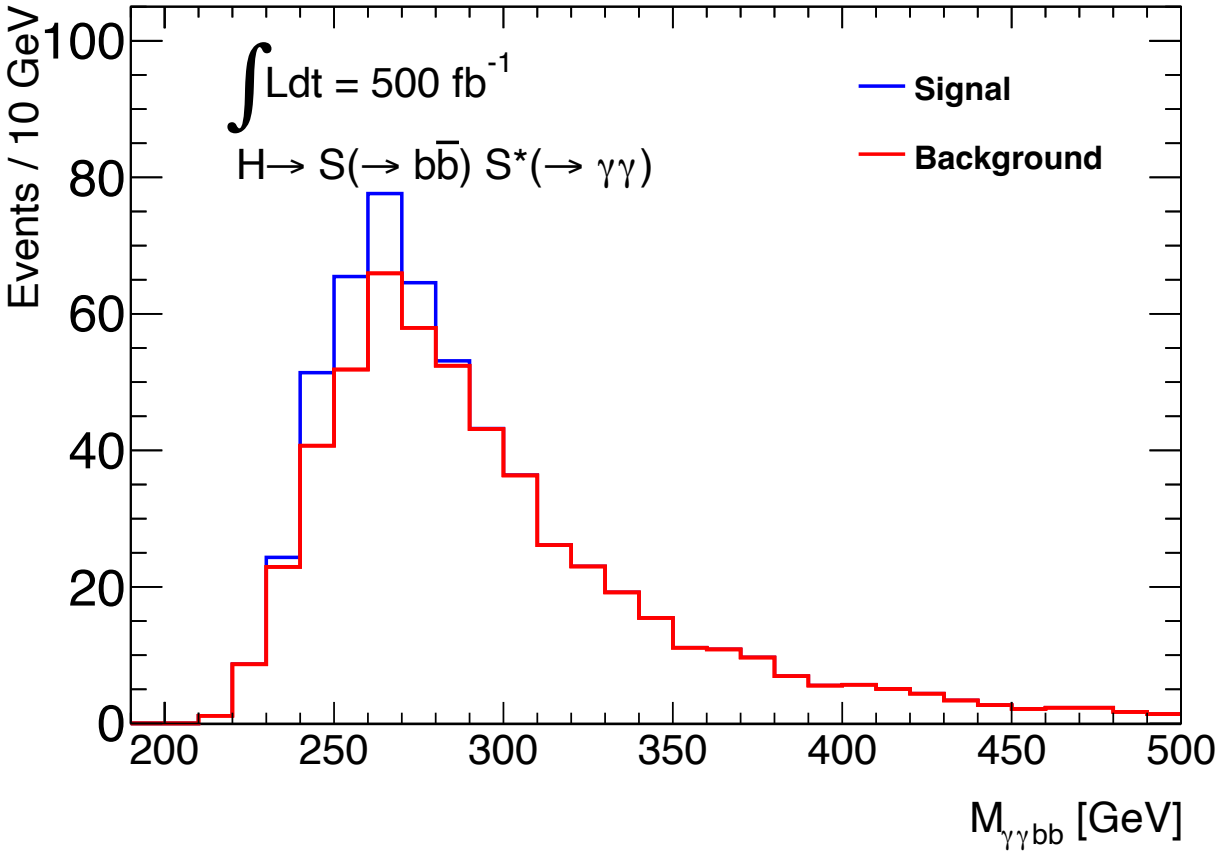
https://cds.cern.ch/record/2851512/files/HIG-22-002-pas.pdf

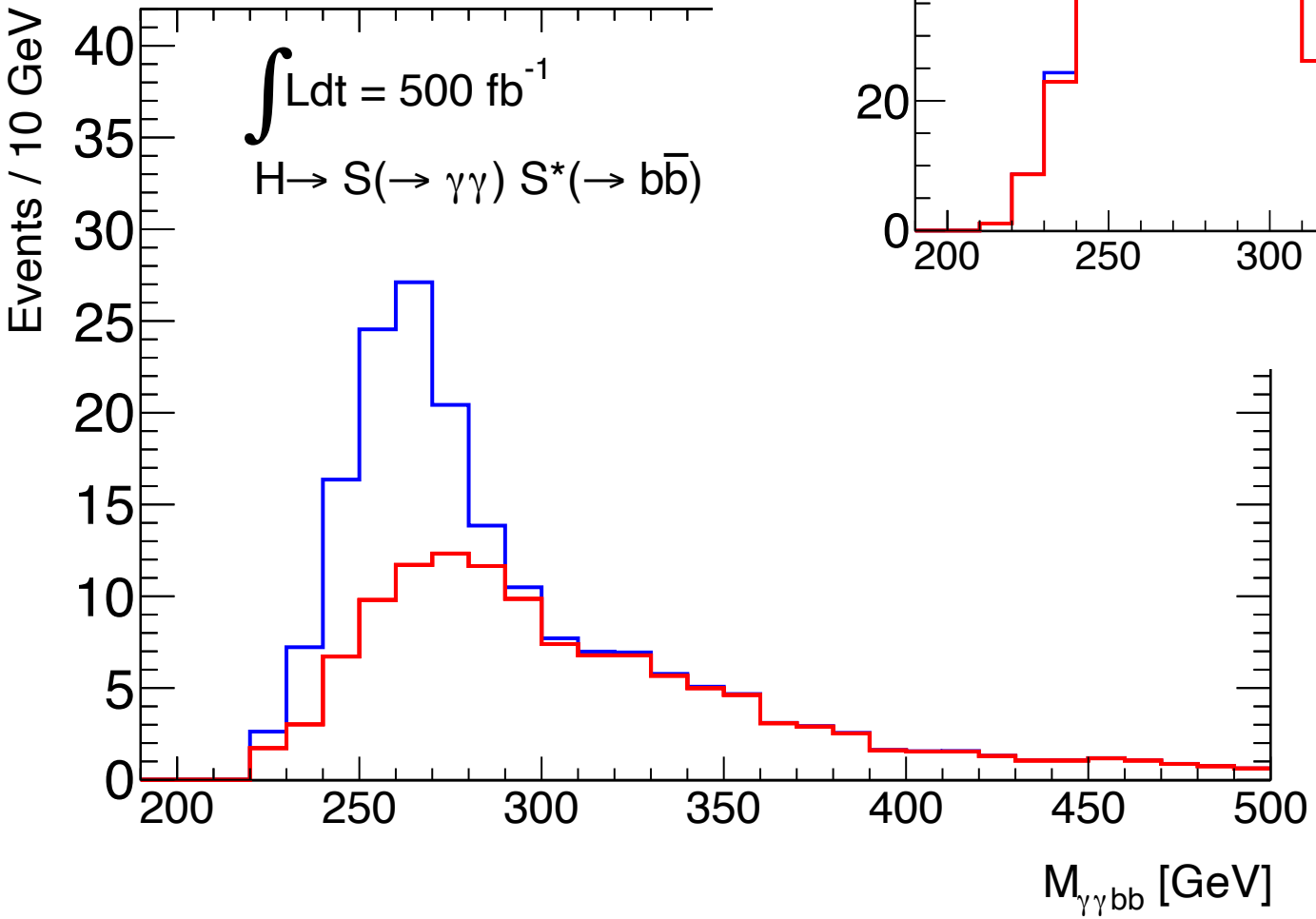
Search for the lepton flavor violating decay of a Higgs boson in the eμ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV





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.

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Unveiling Hidden Physics at the LHC

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