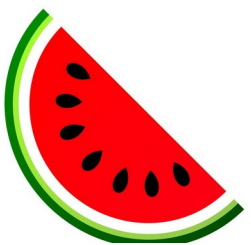
University of Zurich[UZH]

Swiss National Science Foundation

Di-photon excesses and connection to tt and ttZ/ttW

S. Banik, **G. Coloretti**, A. Crivellin, B. Mellado

10.1007/JHEP01(2025)155
10.1103/PhysRevD.110.073001

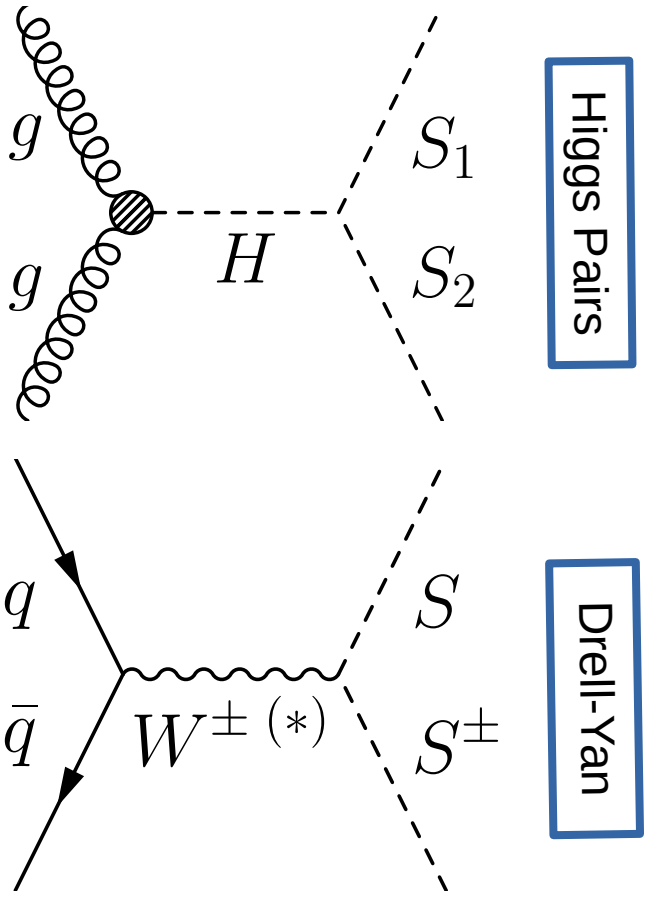


Guglielmo Coloretti
University of Zurich

Higgs-Capri-2025
Capri, 09.10.2025

(Asymmetric-) Associated Production

- Provides a yet unexplored window on new physics
  [ATLAS and CMS reviews]
- Additional particles required in the signal regions (on top of the decays of the NP candidate)
- **Reduced SM background and enhanced NP sensitivity**



Multi-Lepton Anomalies

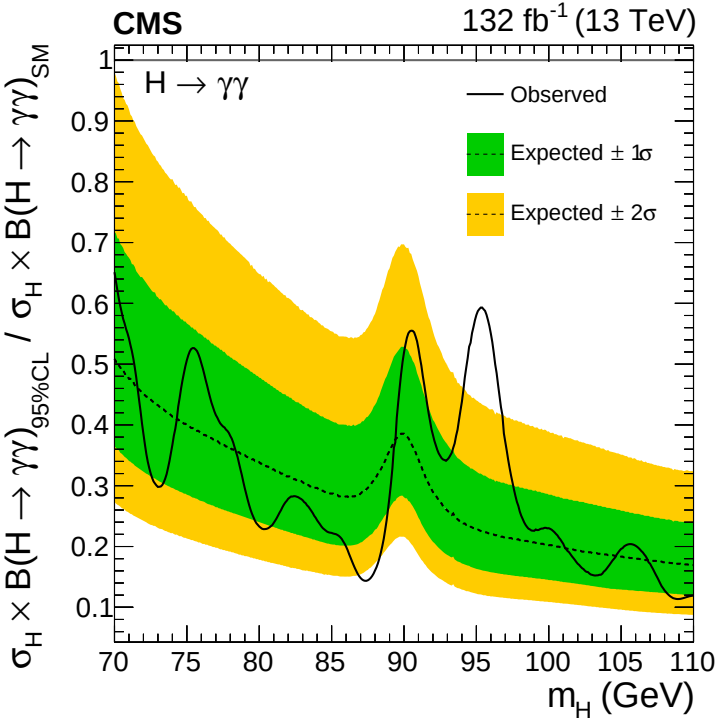
Deviations from SM in final states with **two or more leptons,** sometimes accompanied by (b-)jets and occasionally including missing transverse energy

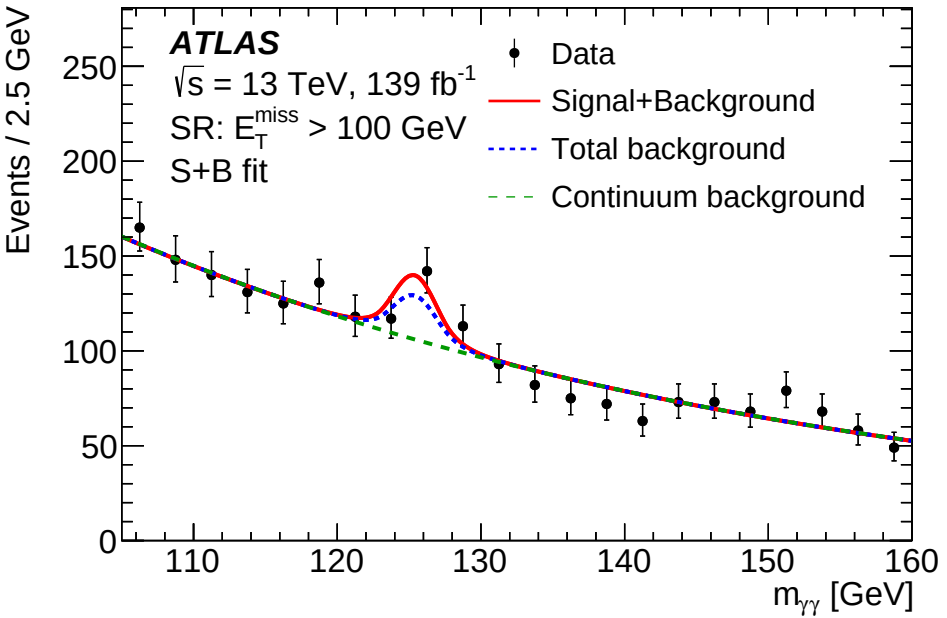
Final state		Properties	SM backgrounds
$\ell^+\ell^-$	b-jets	$m_{\ell\ell} < 100$ GeV	$t\bar{t}$, Wt
$\ell^+\ell^-$	—	$m_{\ell\ell} < 100$ GeV	WW
$\ell^+\ell^-$, 3ℓ	b-jets	Moderate H_T	ttW, $t\bar{t}t\bar{t}$, $t\bar{t}Z/tWZ$
$\ell^+\ell^-$, 3ℓ	no b-jets	In association with h	Wh, WWW
$(Z \to \ell^+\ell^-)\ell$	no b-jets	$p_T^Z < 100$ GeV	ZW

- Already appeared in Run 1, consolidated and extended in Run 2
- Constrains from statistics but not from c.o.m. energy (**in reach of LHC program**)
- Point to new Higgses at the EW scale in **associated production (152 GeV)**

Resonant Hints

NEXT TALK BY THOMAS!





- Inclusive channel
- Dedicated search

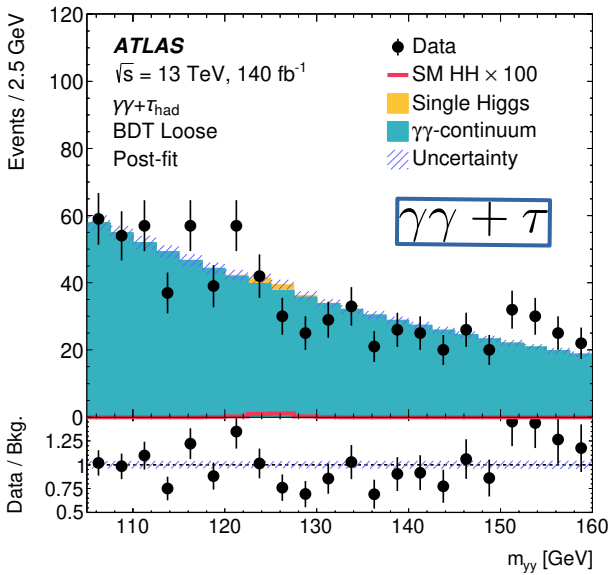
- SM analysis (associated production)
- Background refitting

Excesses at 152 GeV

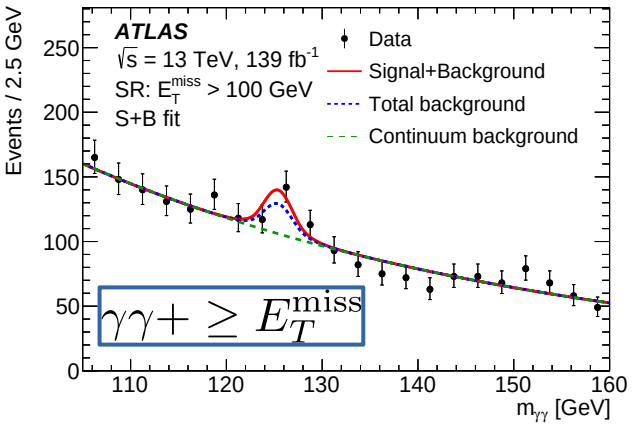
TALK **BY SAYAD!**

- Several signal regions (2 ATLAS analyses)
- Associated **SM Higgs** boson production

[ATLAS-1]



[ATLAS-2]



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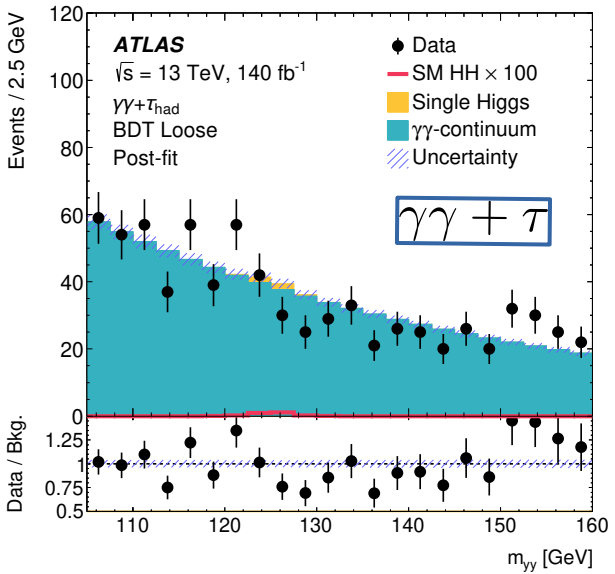
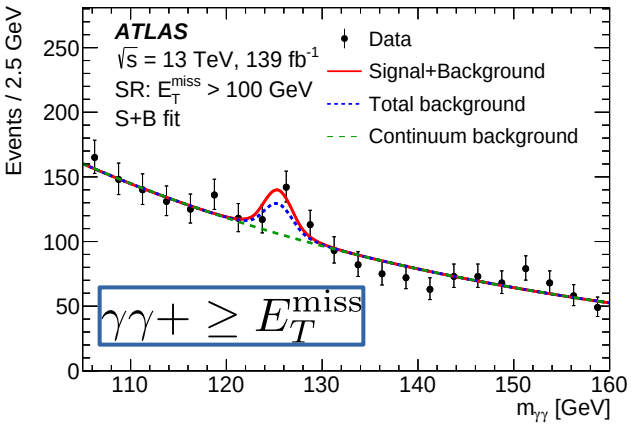
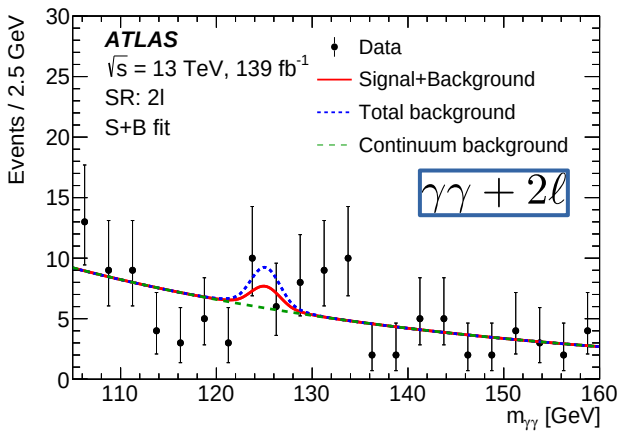


[ATLAS-2]





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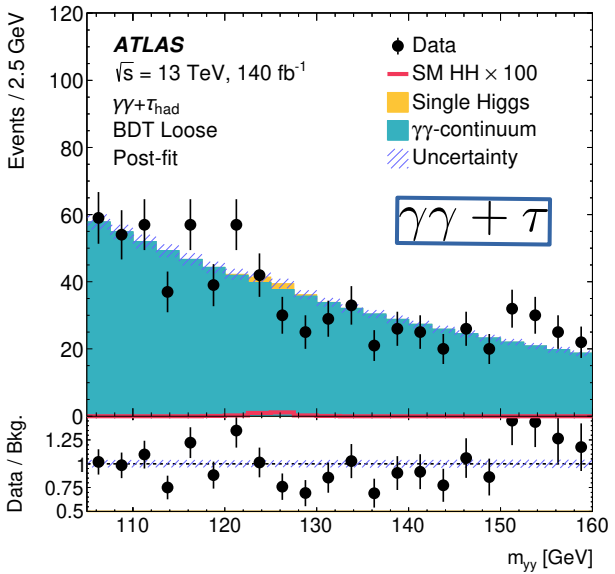
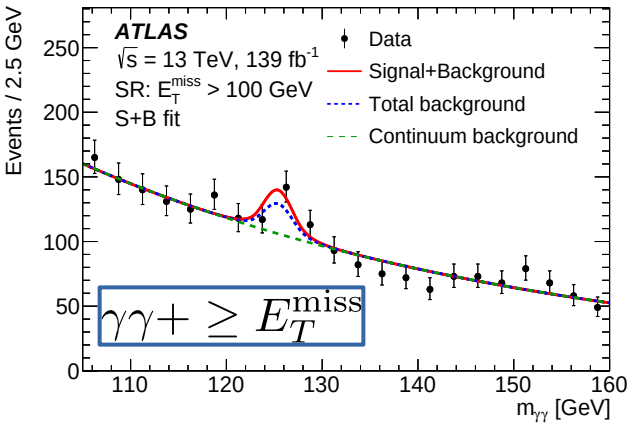
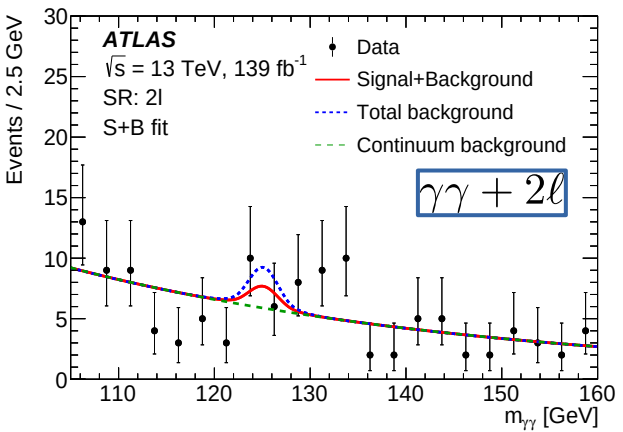


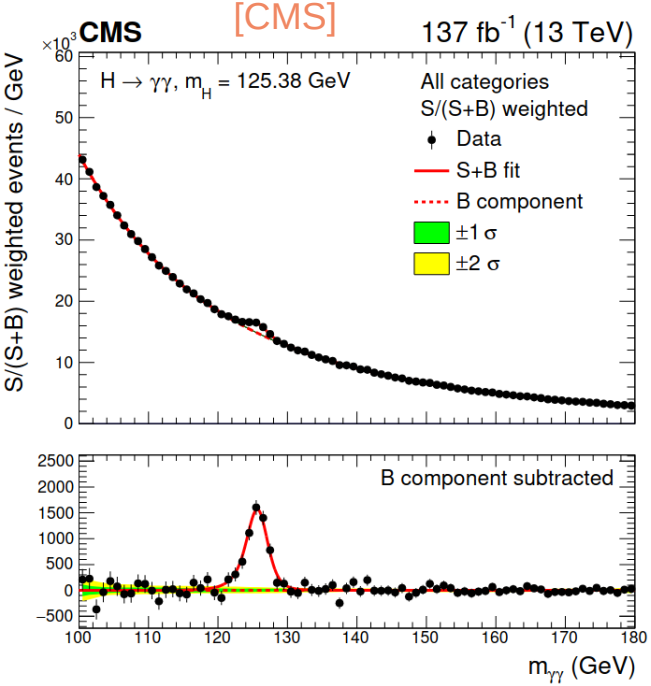
[ATLAS-2]





Only mild excess in inclusive analyses

[CMS]



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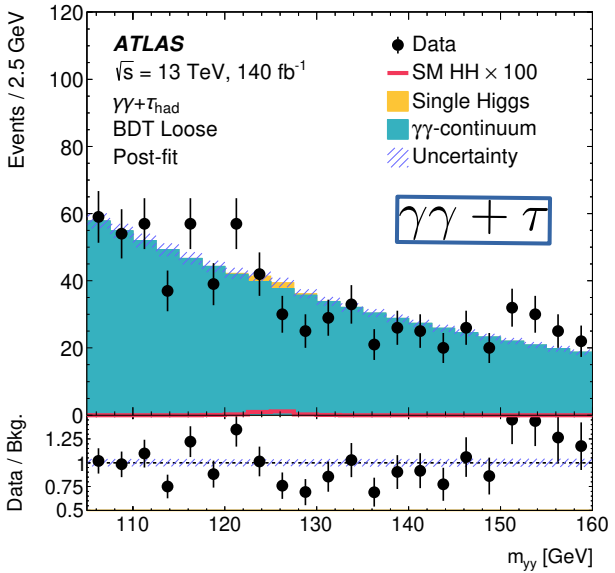

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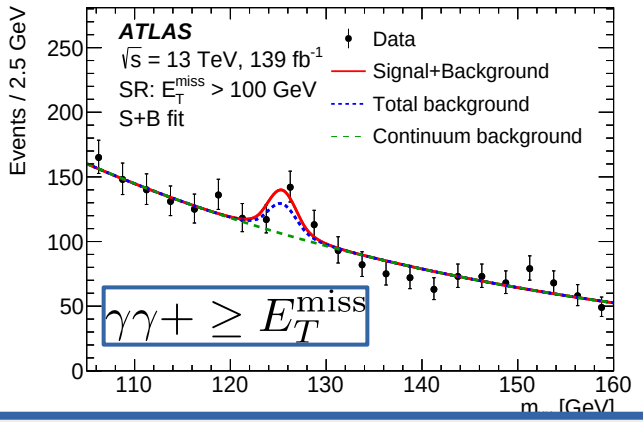
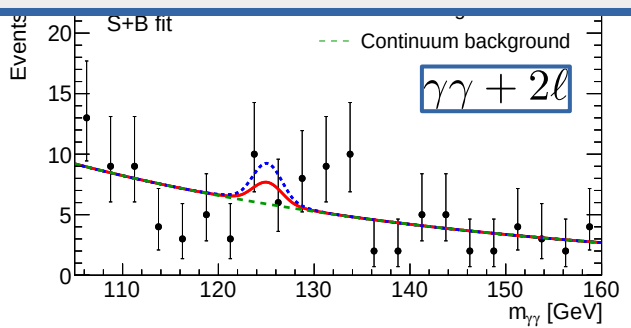


Associated production of a neutral Higgs!



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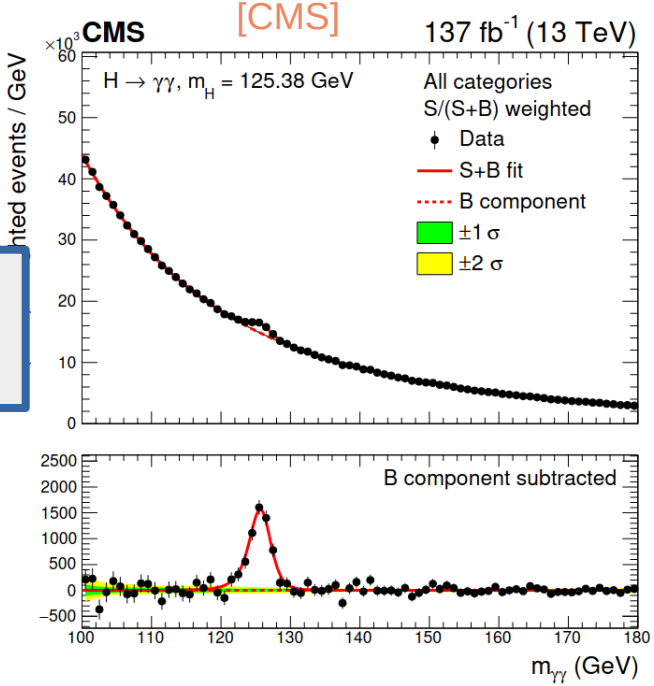
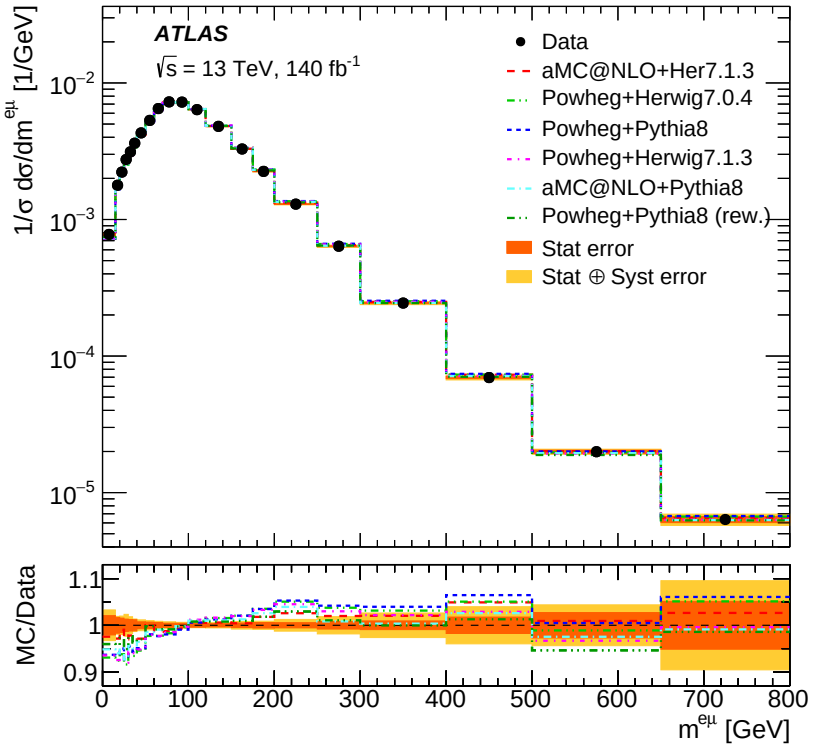


Top-quark differential distributions

[ATLAS]



- After Run3, LHC will provide approximately 10^9 top-quark pairs
- Top-quark data in quite good agreement with SM higher order computations (NNLO in QCD, NLO in EW)

Top-quark differential distributions

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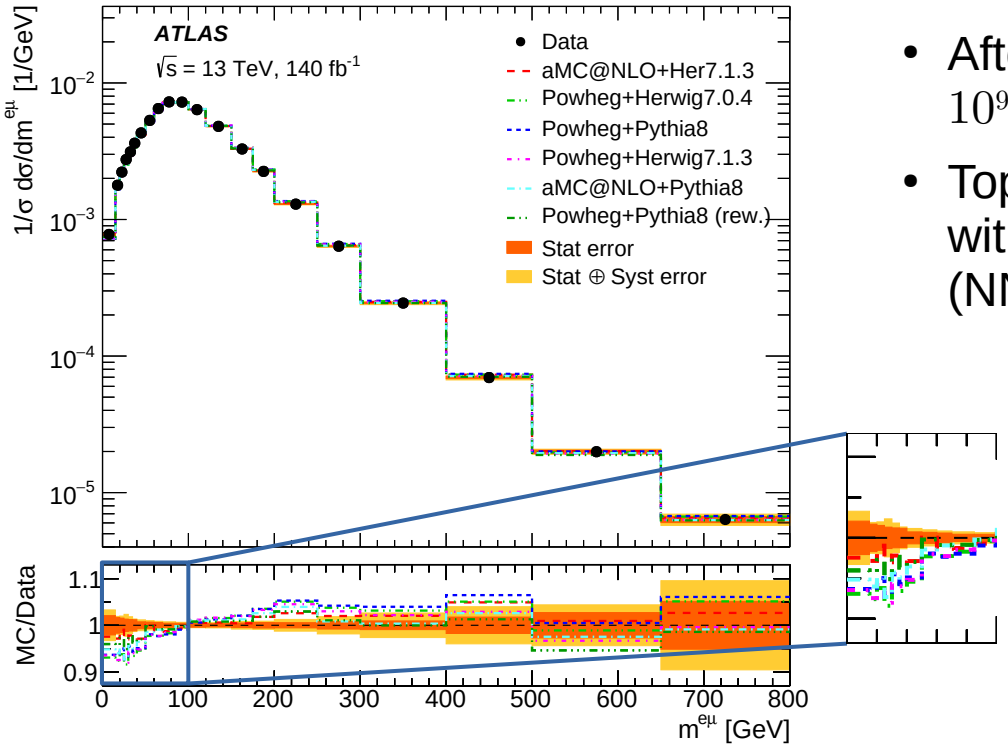

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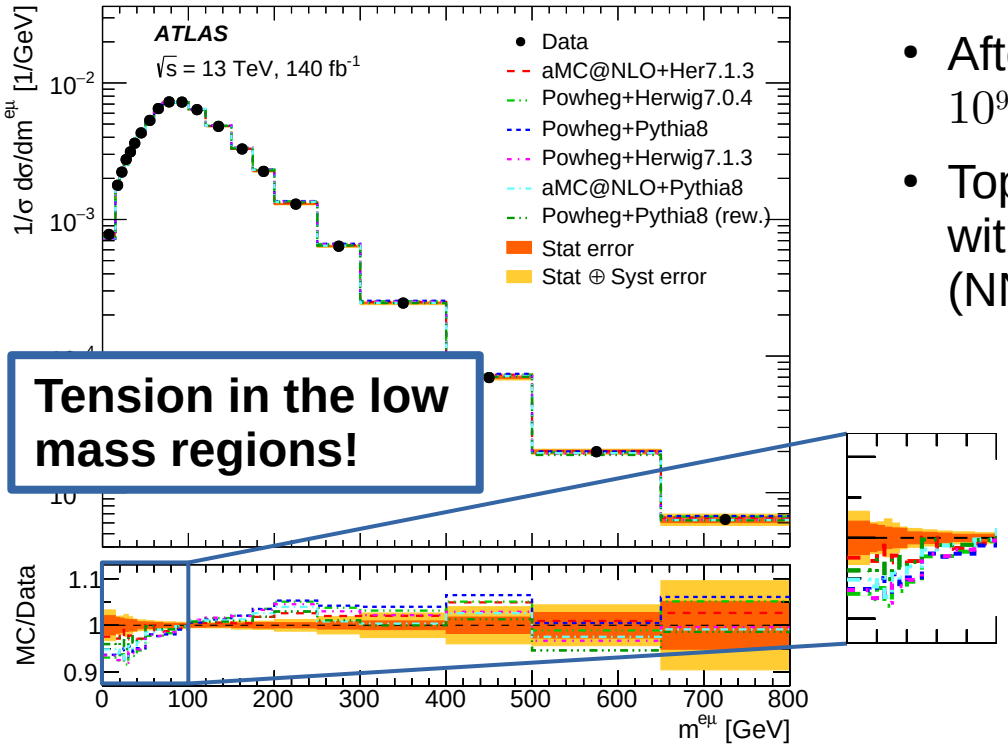

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"No model can describe all measured distributions within their uncertainties."

Top-quark differential distributions

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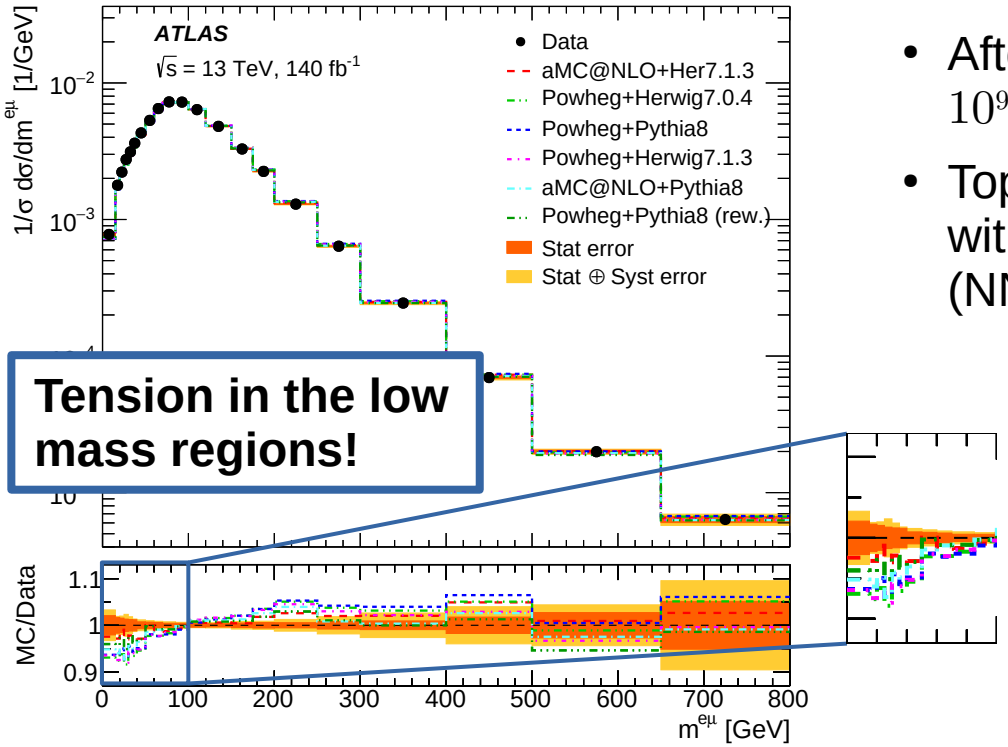


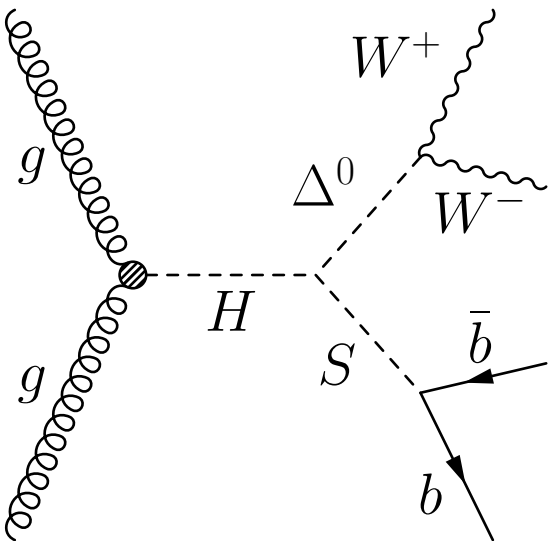
Tension in the low mass regions!

- After Run3, LHC will provide approximately 10^9 top-quark pairs
- Top-quark data in quite good agreement with SM higher order computations (NNLO in QCD, NLO in EW)

"No model can describe all measured distributions within their uncertainties."

- Higher order corrections? Toponium?
- New Physics pollution of this SM measurement?

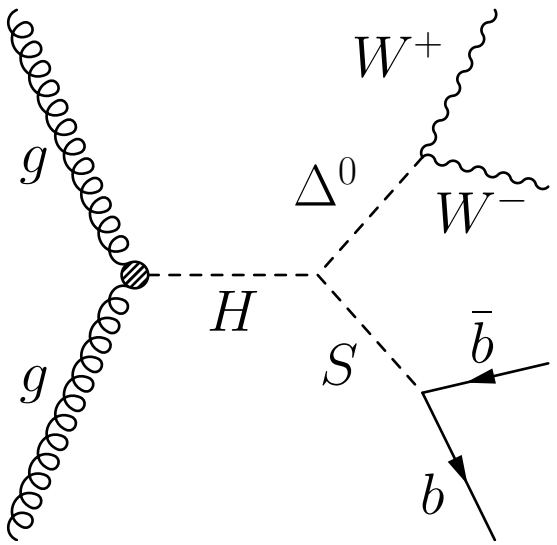
Simplified Model



- Excesses in $m_{e\mu}$ is not localized
- Real triplet model predicts a scalar decaying to WW with a mass of $152\,\mathrm{GeV}$
- Excesses are accumulating **more in 1 b-jet events over 2 b-jets**
- Masses fixed with di-photon resonant hints

$$m_\Delta = 152\mathrm{GeV} \quad m_S = 95\mathrm{GeV}$$

Simplified Model



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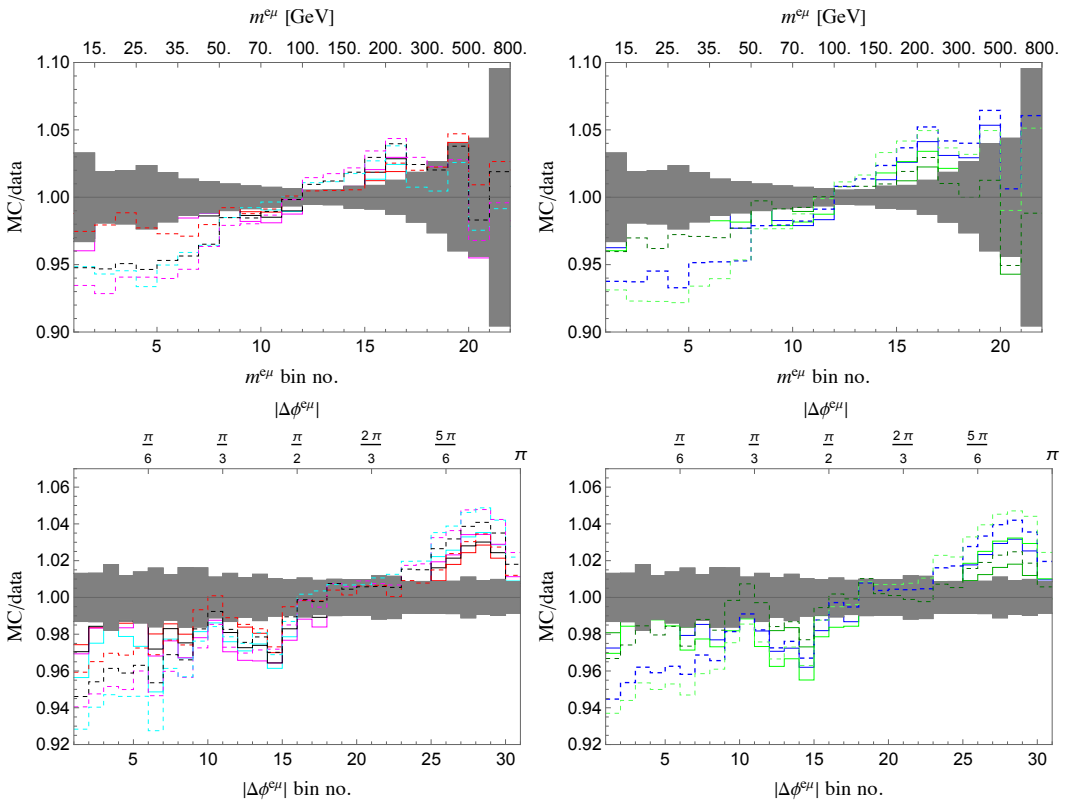
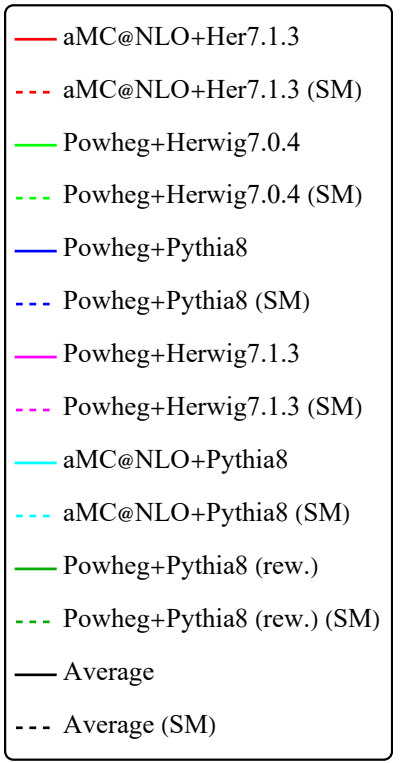
$$m_\Delta = 152\mathrm{GeV} \quad m_S = 95\mathrm{GeV}$$

- Weak dependence on m_H (distributions are **normalized** to SM!)
- m_Δ is the most sensitive parameter as it controls the lepton system
- m_S **predicts a peak** in the bb invariant mass spectrum

Results

Simplified model is in great agreement with observed data!





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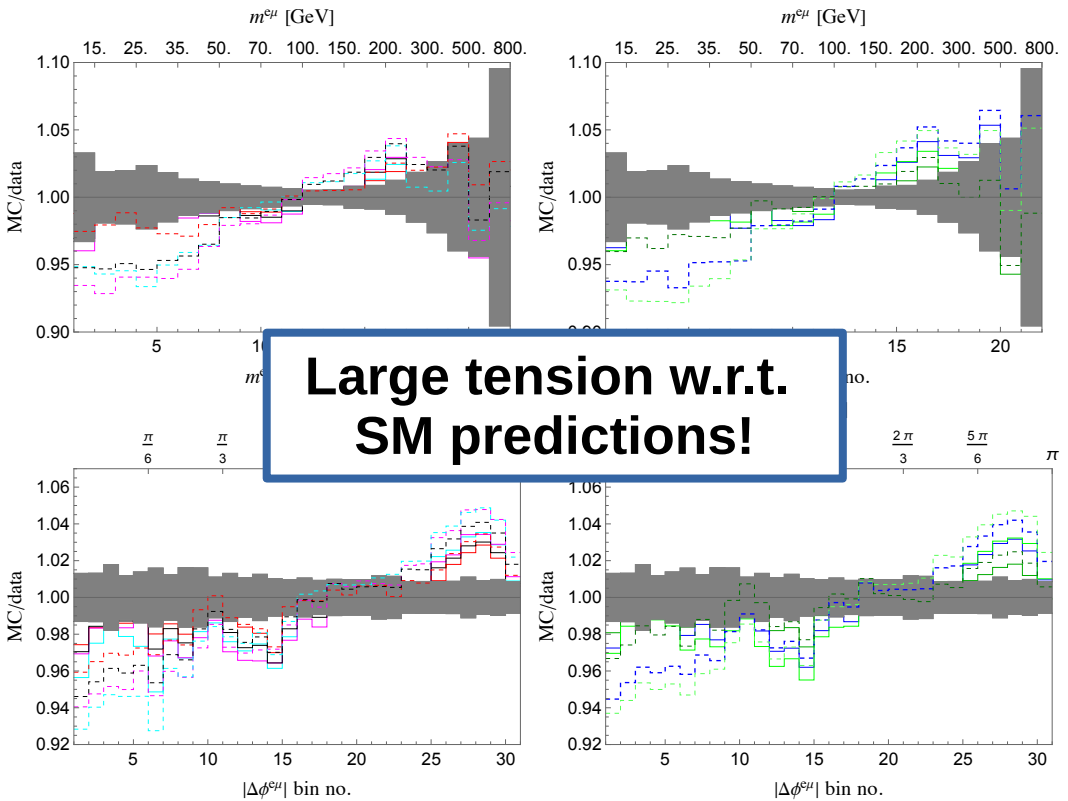
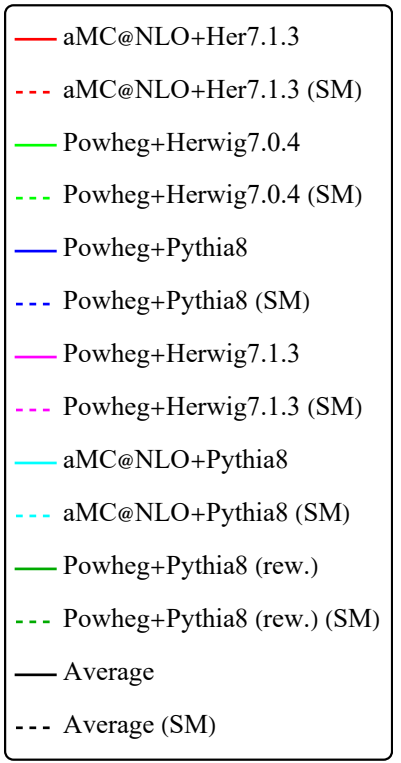
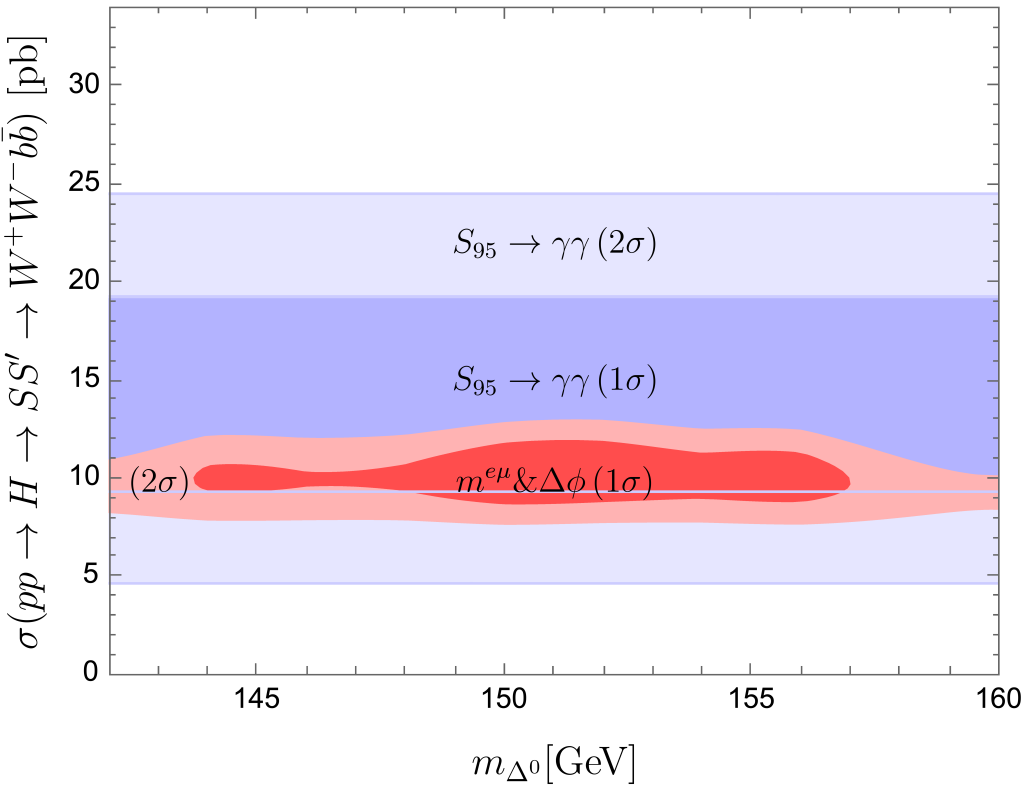




Towards a Model

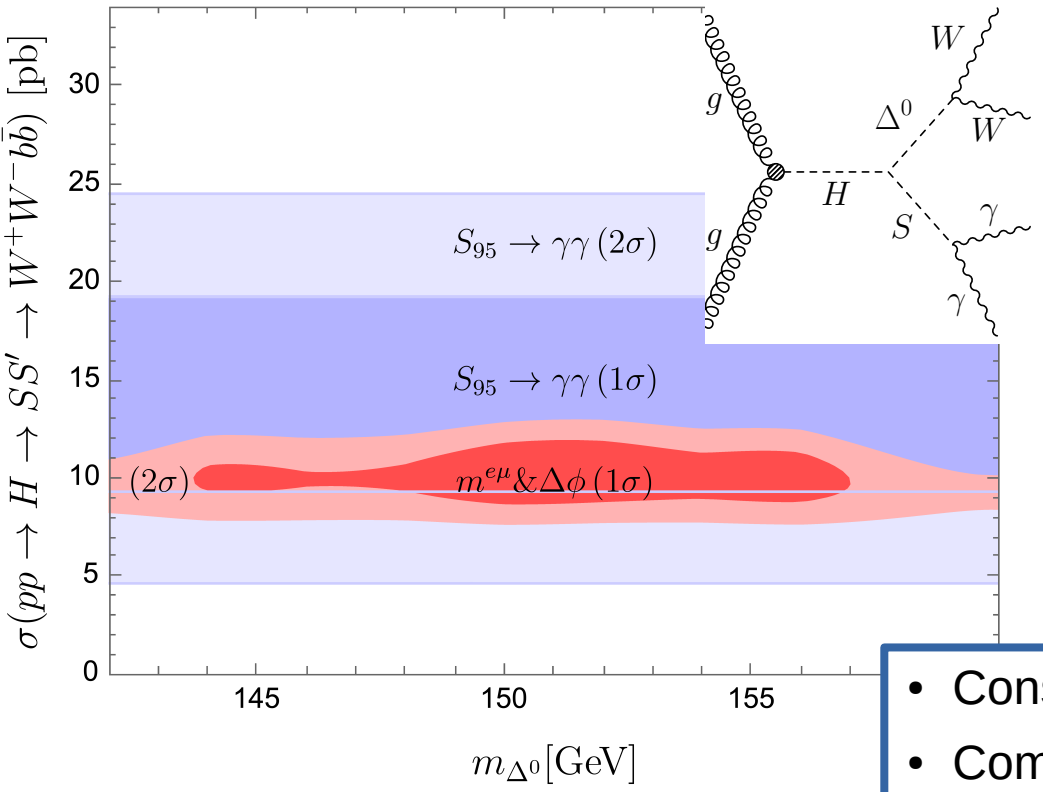


- Specific representations for the scalars set their branching ratios

Triplet	152 GeV	$\mathrm{Br}[\Delta^0 \to WW] \approx 1$
Singlet	95 GeV	$\mathrm{Br}[S \to b\bar{b}] \approx 0.86$

- **Fix production cross section** with preferred signal from tt distribution (10 pb)
- Predict different signatures

Towards a Model



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- **Fix production cross section** with preferred signal from tt distribution (10 pb)
- Predict different signatures

- Consistent with real Higgs triplet $m_\Delta = 152\,\mathrm{GeV}$
- Compatible with $\gamma\gamma$ signal strength at $95\,\mathrm{GeV}$

[T. Biekotter, S. Heinemeyer, G. Weiglein]

The Δ2HDMS

	S	H_1	H_2	Δ
$SU(2)_L$	1	2	2	3
$U(1)_Y$	0	1/2	1/2	0
Fields	S	$H, A, H^\pm$	h	$\Delta^0, \Delta^\pm$
Z_2^1	$+$	$-$	$+$	$-$
Z_2^2	$-$	$+$	$-$	$+$

The Δ2HDMS: Mixing

	S	H_1	H_2	Δ
$SU(2)_L$	1	2	2	3
$U(1)_Y$	0	1/2	1/2	0
Fields	S	$H, A, H^\pm$	h	$\Delta^0, \Delta^\pm$
Z_2^1	+	−	+	−
Z_2^2	−	+	−	+

- Avoid large mixing among the different scalar fields

Large $\tan(\beta)$ limit

$v_S, v_1, v_\Delta \ll v_2$

Can be small

Custodial symmetry

The Δ2HDMS: Potential

	S	H_1	H_2	Δ
$SU(2)_L$	1	2	2	3
$U(1)_Y$	0	1/2	1/2	0
Fields	S	$H, A, H^\pm$	h	$\Delta^0, \Delta^\pm$
Z_2^1	+	−	+	−
Z_2^2	−	+	−	+

- CP-conserving scalar potential
- Only one term allowed which involves all different fields

$$\mathcal{V} \subset -\lambda\, S H_1^\dagger \Delta H_2 + \text{H.c.}$$

The Δ2HDMS: Yukawas

	S	H_1	H_2	Δ
$SU(2)_L$	1	2	2	3
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Fields	S	$H, A, H^\pm$	h	$\Delta^0, \Delta^\pm$
Z_2^1	$+$	$-$	$+$	$-$
Z_2^2	$-$	$+$	$-$	$+$

- Yukawa structure corresponding to the type-I version of the 2HDM
- Z_2 symmetry breaking in the top sector

$$-\mathcal{L}_Y^{\not{Z}_2} = \mu_t \sqrt{2} \frac{m_t}{v} \bar{Q}_3 \widetilde{H}_1 u_3$$

The Δ2HDMS

	S	H	A	$H^{\pm}$	Δ^0	$\Delta^{\pm}$
Mass [GeV]	95	300	400	400	152	152
Decay modes	$b\bar{b}, \tau\bar{\tau}, \gamma\gamma$	$\Delta^0 S$	$t\bar{t}, ZH$	$\Delta^{\pm} S$	$WW, \gamma\gamma$	$WZ, \tau\nu, tb$

Inclusive di-photon excesses at 95 GeV

[CMS] [ATLAS]

tt differential distributions

[ATLAS]

Di-photon excesses at 152 GeV in associated production

[ATLAS-1] [ATLAS-2]

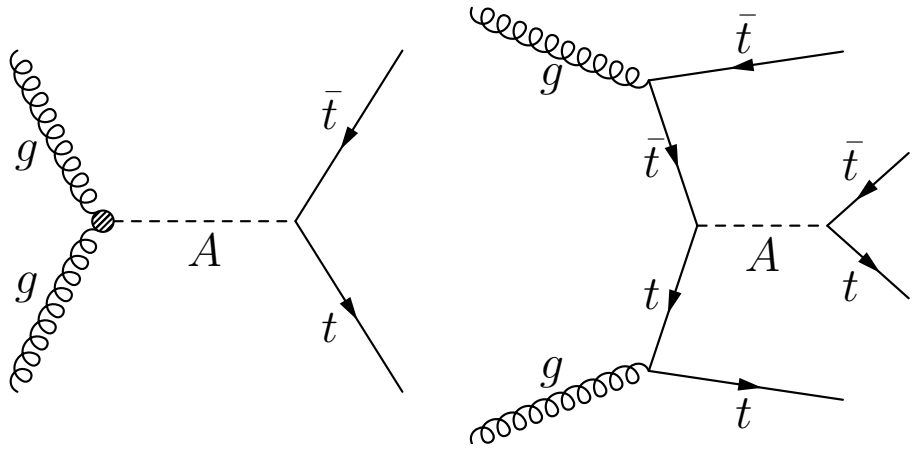
$v_{\Delta} \approx O(1)$ GeV

[T. Blank, W. Hollik]

The Δ2HDMS: CP-odd scalar

	S	H	A	$H^{\pm}$	Δ^0	$\Delta^{\pm}$
Mass [GeV]	95	300	400	400	152	152
Decay modes	$b\bar{b}, \tau\bar{\tau}, \gamma\gamma$	$\Delta^0 S$	$t\bar{t}, ZH$	$\Delta^{\pm} S$	$WW, \gamma\gamma$	$WZ, \tau\nu, tb$

- Resonant tt excess at 400 GeV
  [CMS] [ATLAS]
- Higher than expected $4t$ cross section
  [CMS] [ATLAS-1] [ATLAS-2]



The Δ2HDMS: CP-odd scalar

	S	H	A	$H^{\pm}$	Δ^0	$\Delta^{\pm}$
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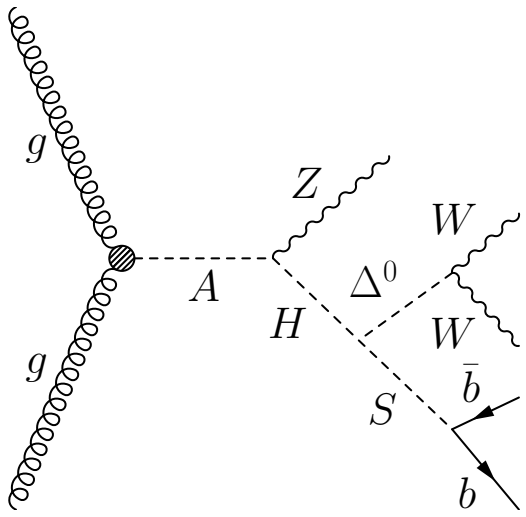
- ttZ signature (room for new physics – about 200 fb)
  [ATLAS-1] [ATLAS-2]

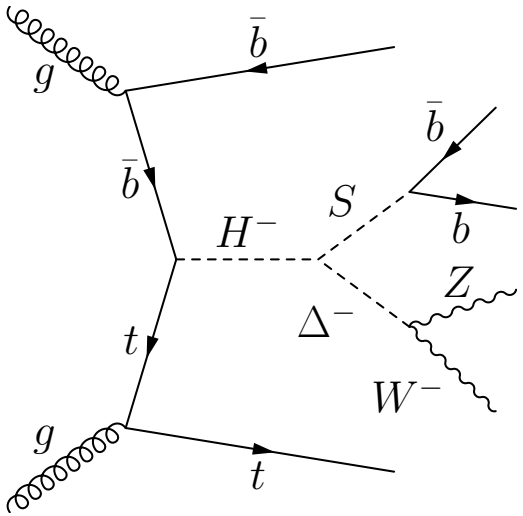


The Δ2HDMS: Charged Higgs

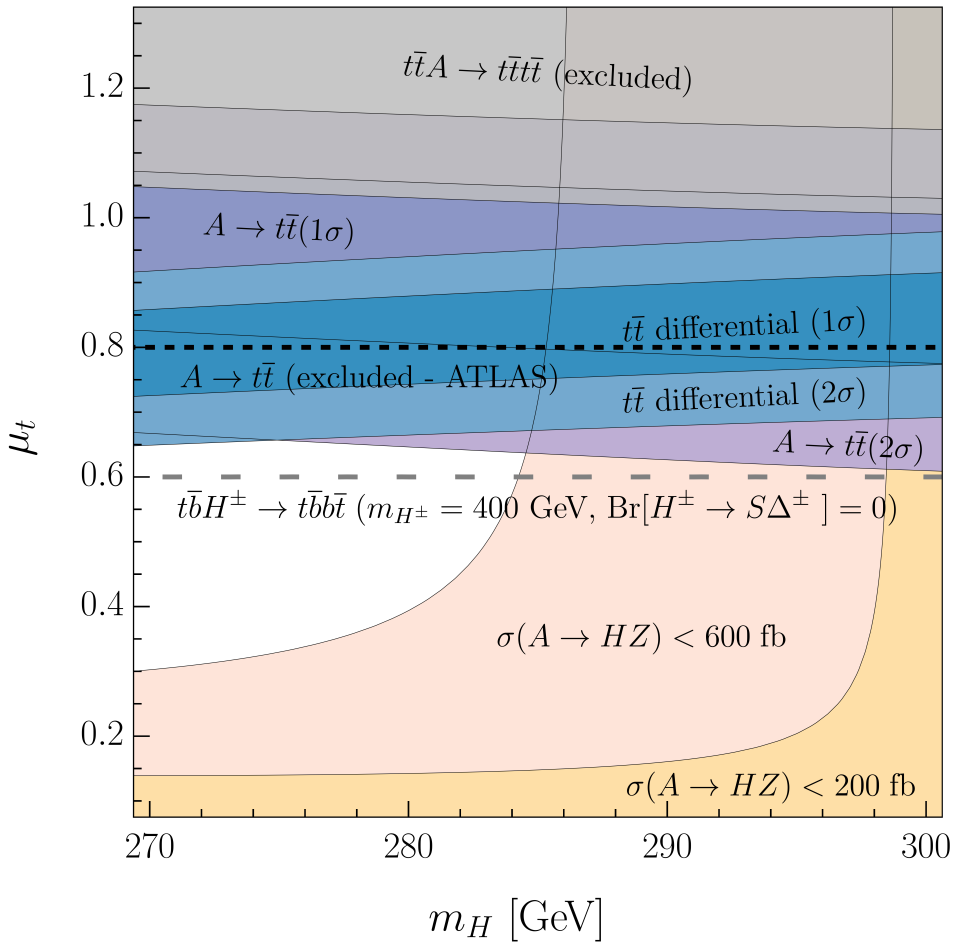
	S	H	A	$H^{\pm}$	Δ^0	$\Delta^{\pm}$
Mass [GeV]	95	300	400	400	152	152
Decay modes	$b\bar{b}, \tau\bar{\tau}, \gamma\gamma$	$\Delta^0 S$	$t\bar{t}, ZH$	$\Delta^{\pm} S$	$WW, \gamma\gamma$	$WZ, \tau\nu, tb$

- Same Yukawa coupling induces charged Higgs production
- Scalar coupling to explain the tt differential distributions
- ttZ/ttW signatures

[ATLAS-1] [ATLAS-2] [ATLAS-3] [ATLAS-4] [CMS]



The Δ2HDMS: Results

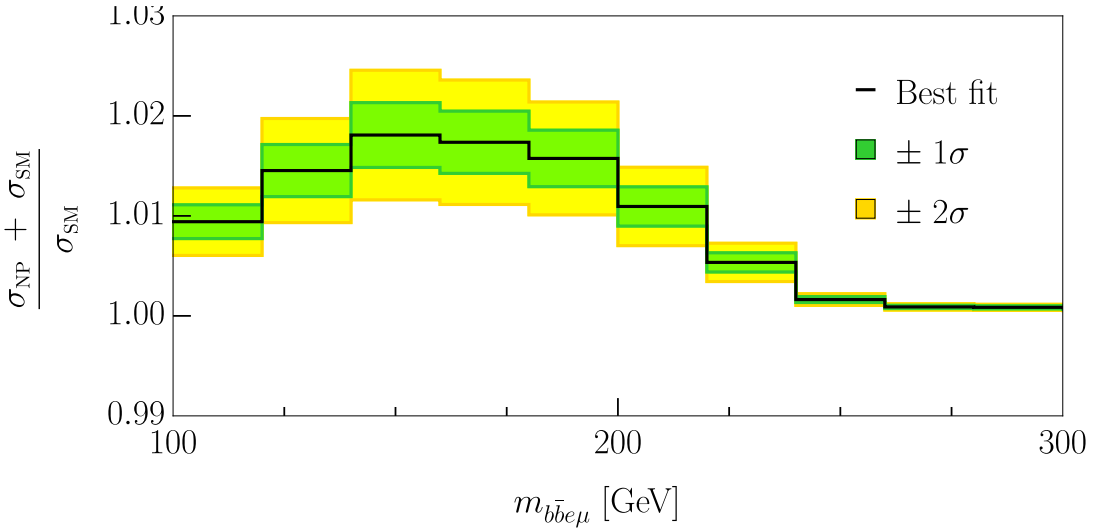


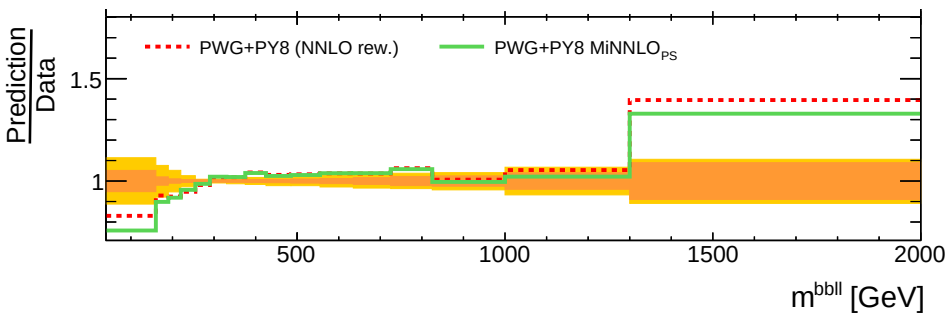
- tt differential distributions
- Resonant tt excess at $400\,\mathrm{GeV}$
- Elevated $4t$ cross section
- ttZ and ttW signatures
- Baryogenesis [Ramsey-Musolf et al.]

Combined explanation of several Multi-Lepton anomalies

The Δ2HDMS: Remarks

- There is a more recent ATLAS analysis for the tt kinematic differential distributions related to the di-lepton system **measuring smaller excesses**
- However strict requirement of **at least 2 b–jets:** data align with our model!
- Furthermore: predictions for deviations in $m_{e\mu bb}$ confirmed!





Conclusions

- Associated production of scalars is an exciting probe for new physics withing the reach of the LHC program
- Top quark still represents and active area for new physics searches and can be used as a testing platform for multi-Higgs models scenarios
- The recent di-photon excesses at 95 GeV and 152 GeV can be bridged to tt and ttZ/ttW signatures
- The Δ2HDMS provides a combined explanation of di-photon excesses, top quark excesses and multi-lepton anomalies

THANK YOU FOR THE ATTENTION!