Andreas Crivellin

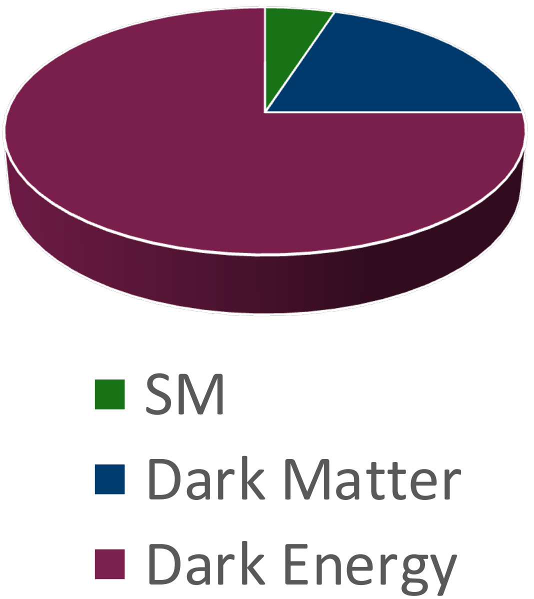
PSI & UZH

New Higgses at the Electroweak Scale and the Multi-Lepton Anomalies

Vienna, 30.04.2024

Physics Beyond the Standard Model

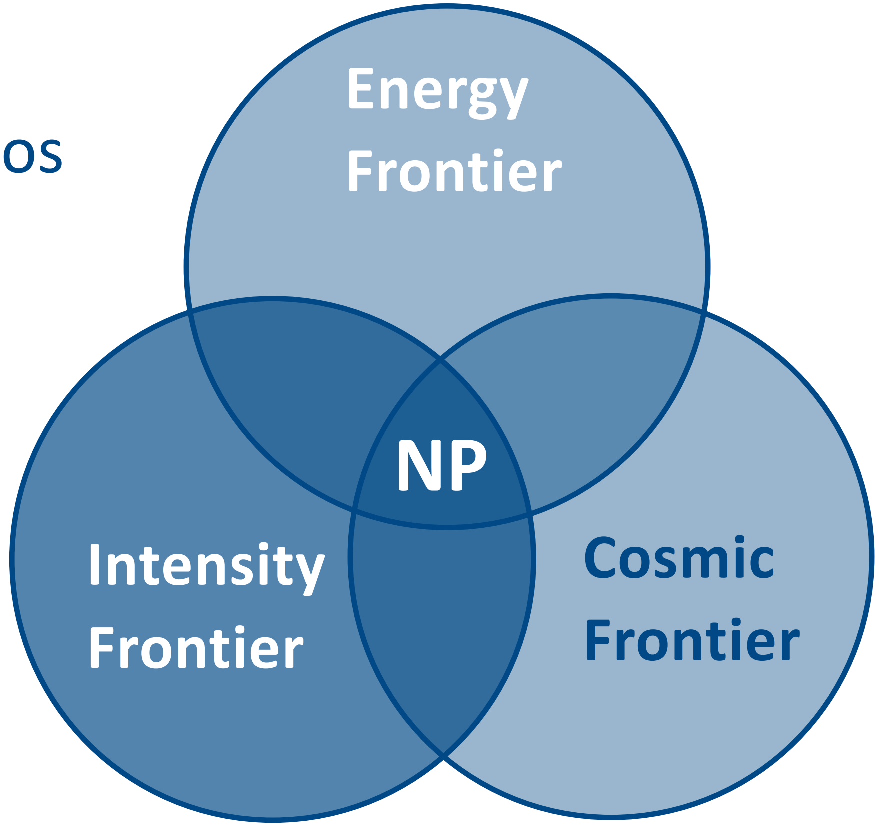
- Dark Matter existence established at cosmological scales
  - New weakly interacting particles
- Neutrinos not exactly massless
  - Right-handed (sterile) neutrinos
- Matter anti-matter asymmetry
  - Additional CP violating interactions



The SM must be extended!
What is the underlying fundamental theory?

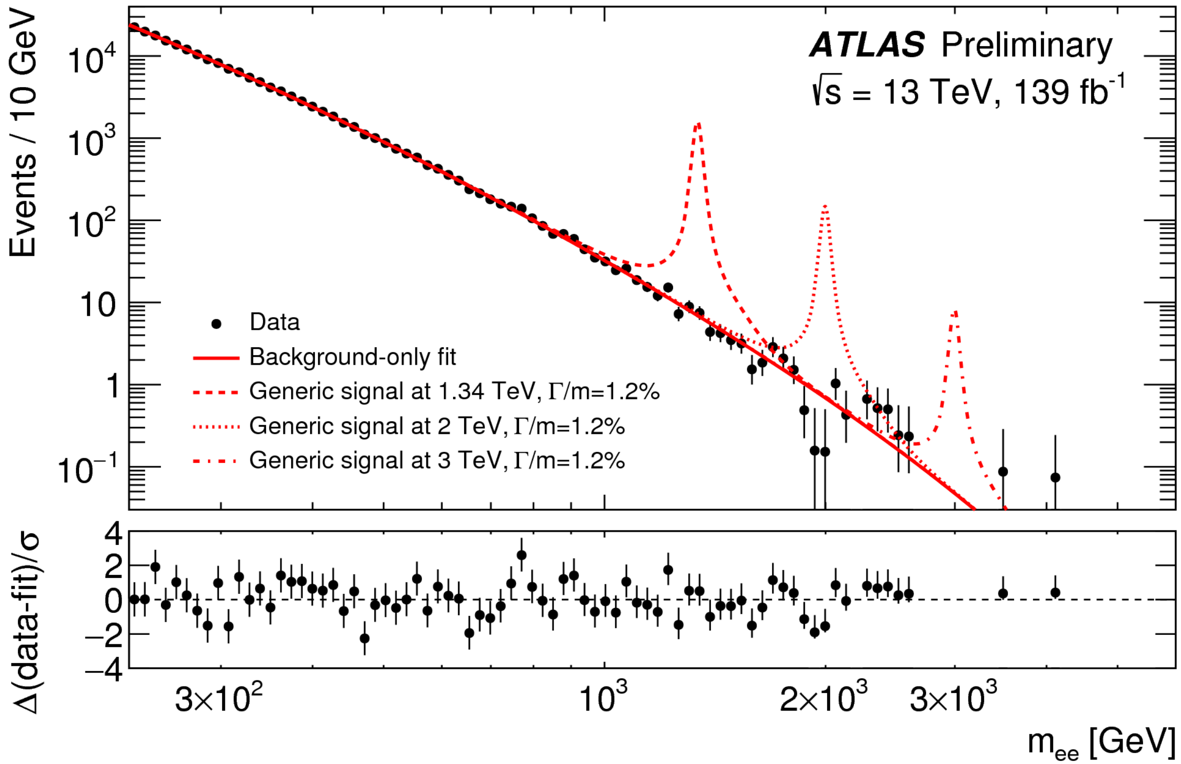
Discovering New Physics

- Cosmic Frontier
  - Cosmic rays and neutrinos
  - Dark Matter
  - Dark Energy
- Energy Frontier
  - LHC
  - Future colliders
- Intensity Frontier
  - Flavour
  - Neutrino-less double-β decay
  - Test of fundamental symmetries
  - Proton decay



Direct Searches for New Physics

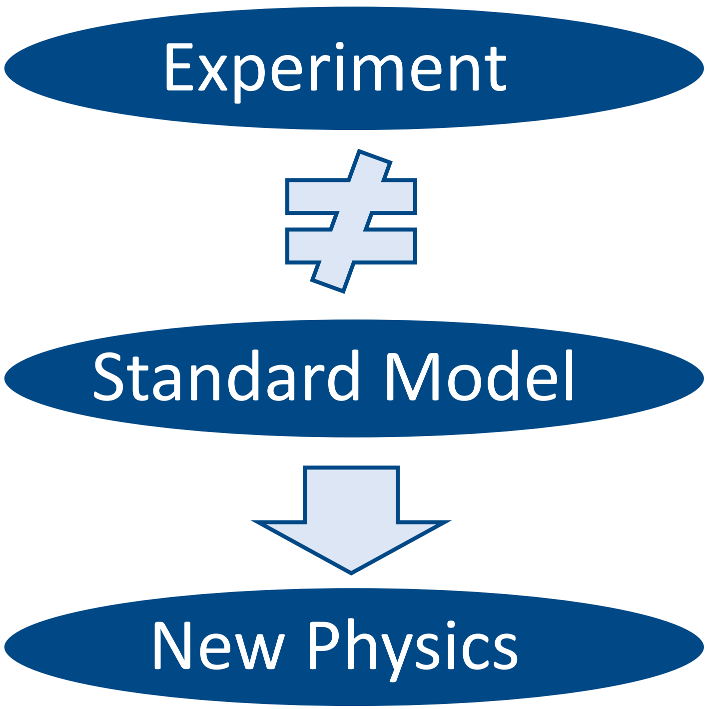
- Searches for resonances in the spectrum
- Direct information on the mass

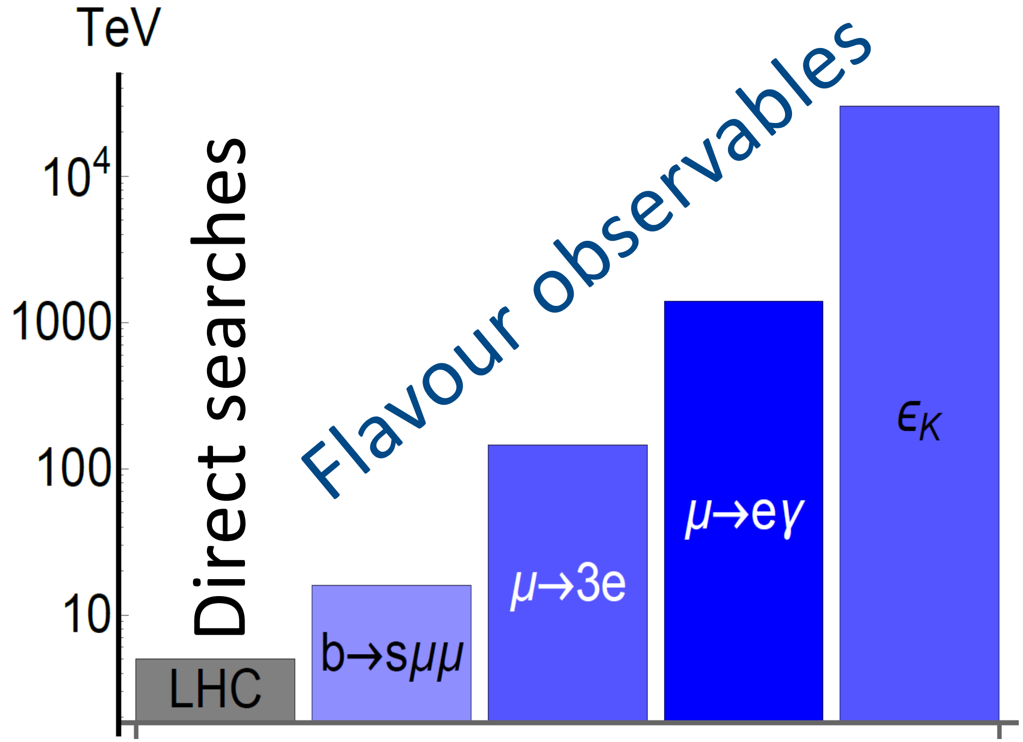


Limited by the available energy of the collider

Indirect Searches for New Physics

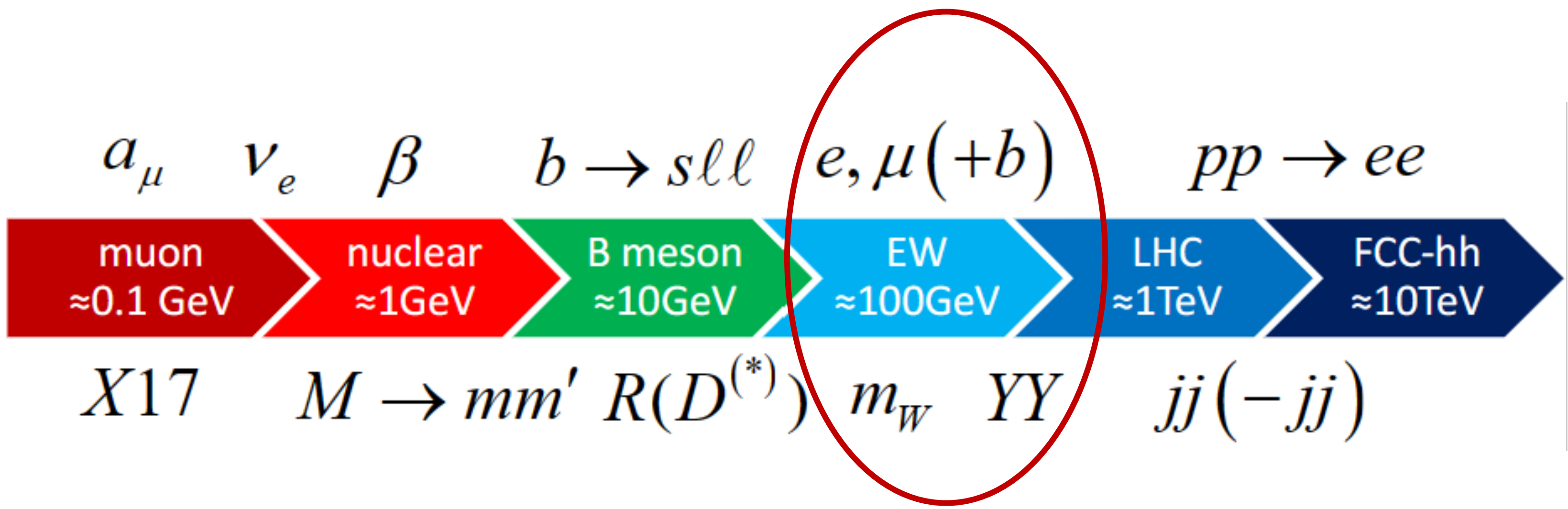
- Perform high-statistics measurements to search for the quantum effects of new particles





Flavour observables can be sensitive to higher energy scales than collider searches

Anomalies



a_μ
ν_e
β
$b \to s\ell\ell$
$e, \mu(+b)$
$pp \to ee$
muon ≈0.1 GeV
nuclear ≈1GeV
B meson ≈10GeV
EW ≈100GeV
LHC ≈1TeV
FCC-hh ≈10TeV
$X17$
$M \to mm'$
$R(D^{(*)})$
m_W
YY
$jj(-jj)$

Higgs Sector of the SM

$$L_{\Phi}^{SM} = \mu^2 \Phi^\dagger \Phi + \frac{\lambda}{4}\left(\Phi^\dagger \Phi\right)^2$$

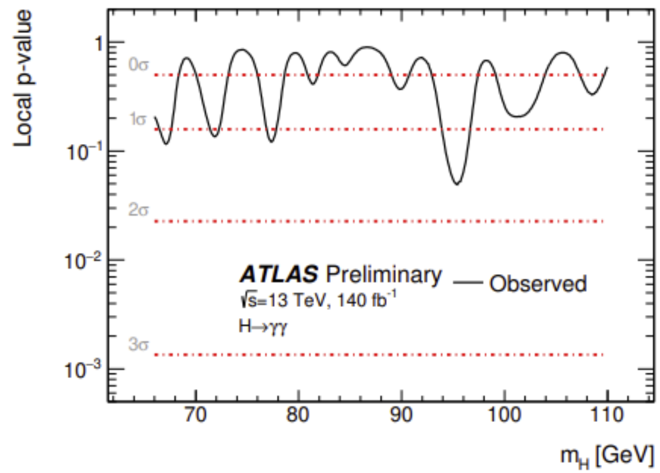
$$L_{Y}^{SM} = -Y^d \bar{Q} \Phi d - Y^u \bar{Q} \tilde{\Phi} u - Y^\ell \bar{Q} \Phi \ell$$

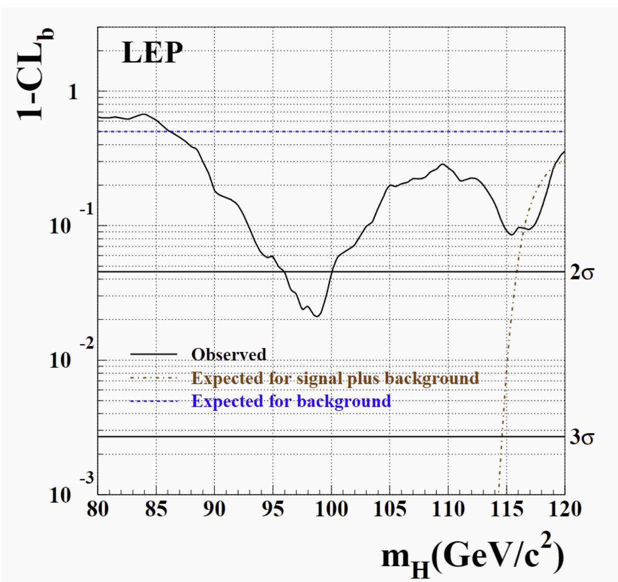
- Custodial symmetry
- Single Higgs gives rise to all fermion masses
- No principle forbids the extension of the Higgs sector
- Extensions possible if the effect on the ρ parameter SM-Higgs signal strength is small
- Scalars decaying to W bosons and/or produced in associate production weakly constrained

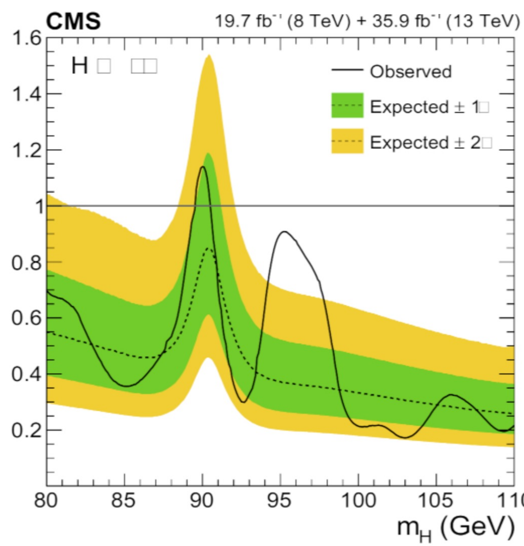
EW scale extension of the SM Higgs sector possible

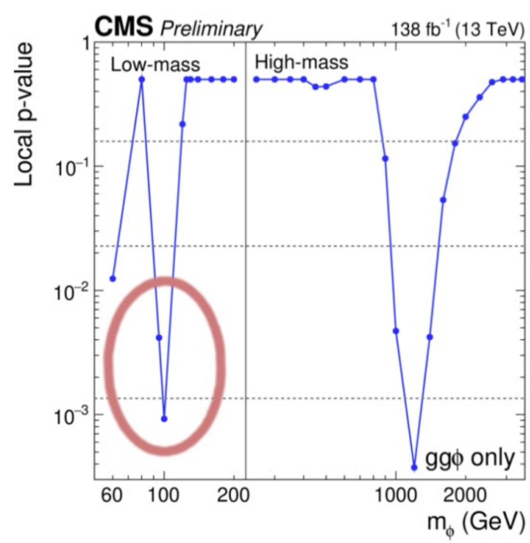
Hints for a 95 GeV Higgs

- LEP: Z+bb
- ATLAS & CMS: γγ
- CMS: ττ
- 680⟶95+125







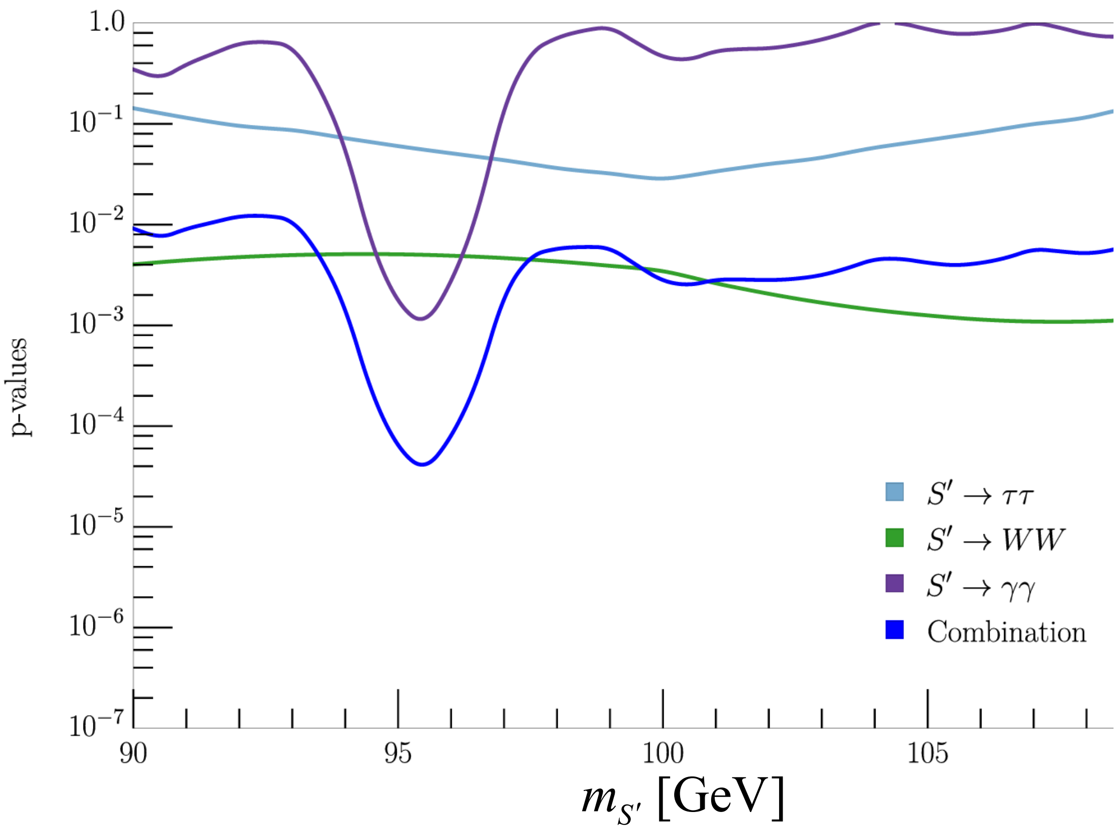


Multiple channels, no associated search

95 GeV Combination

S. Bhattacharya, G. Coloretti, A. Crivellin, et al. arXiv:2306.17209

- LEP used to reduce the LLE
- No ATLAS signal in ττ; reduced significance

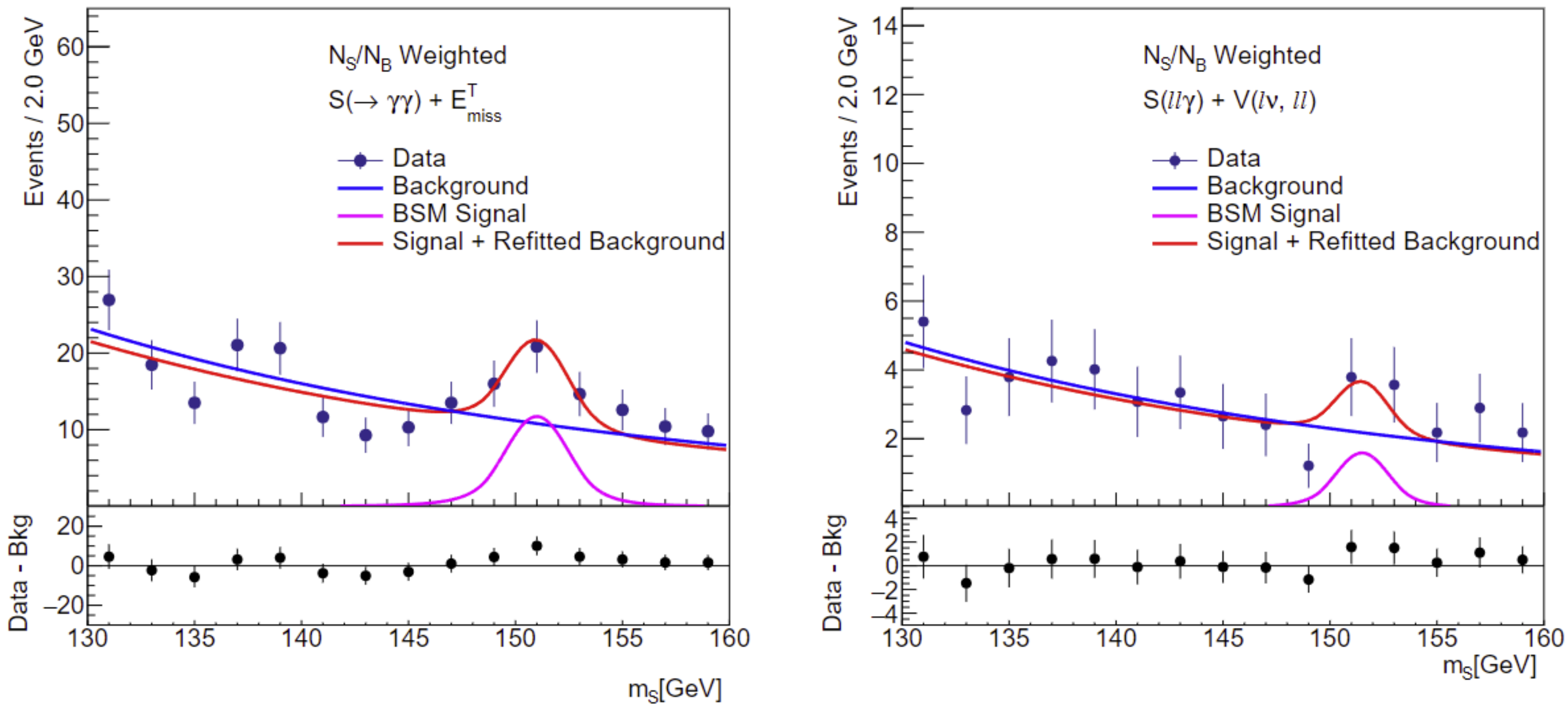


3.8σ global significance

Hints for a 152 GeV scalar

PAUL SCHERRER INSTITUT PSI

- Motivated by the mass range from the MLA



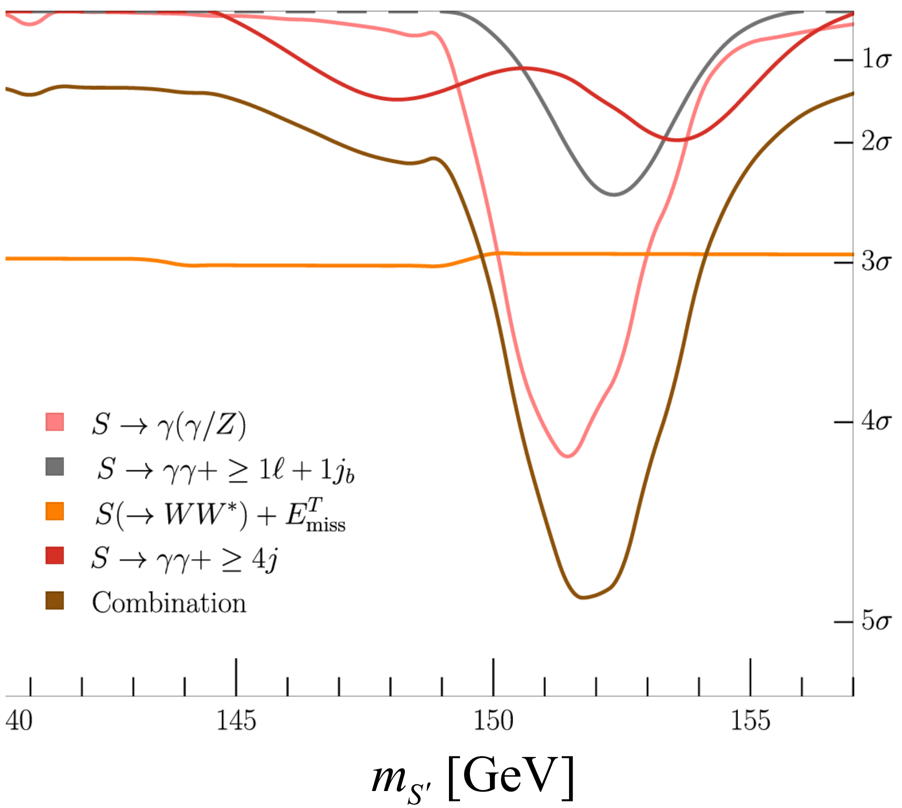
ATLAS: 2301.10486

- Hints for a resonance decaying to photons, Zγ in associated production, with l, MET, jets

Dominant channels are γγ+X

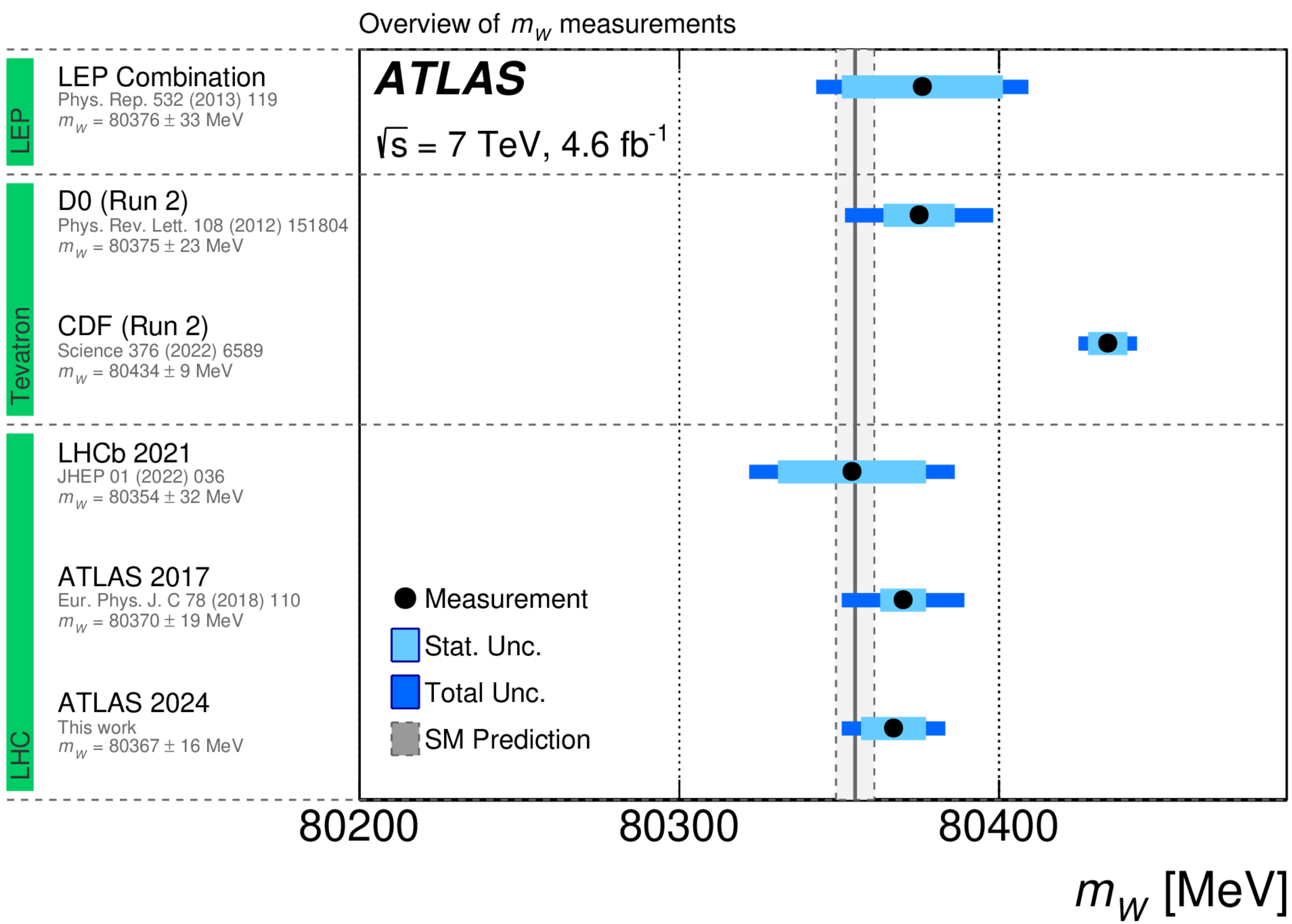
Hints for new Scalars at 152 GeV

- Combination within the simplified model $H \to SS^*$ with $S \to WW$, MET, $\gamma\gamma$



4.7σ global significance

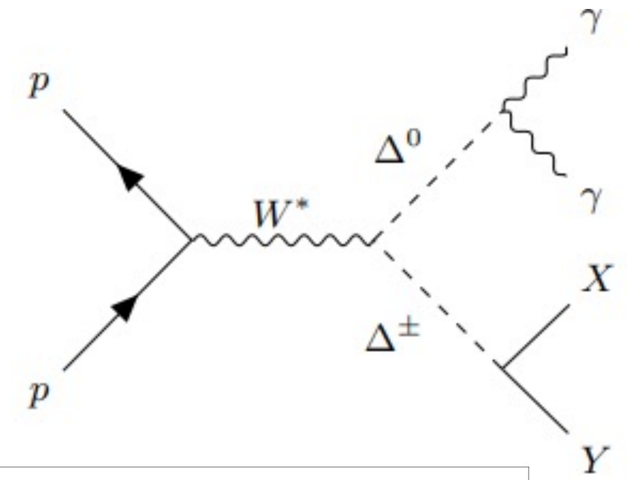
W mass

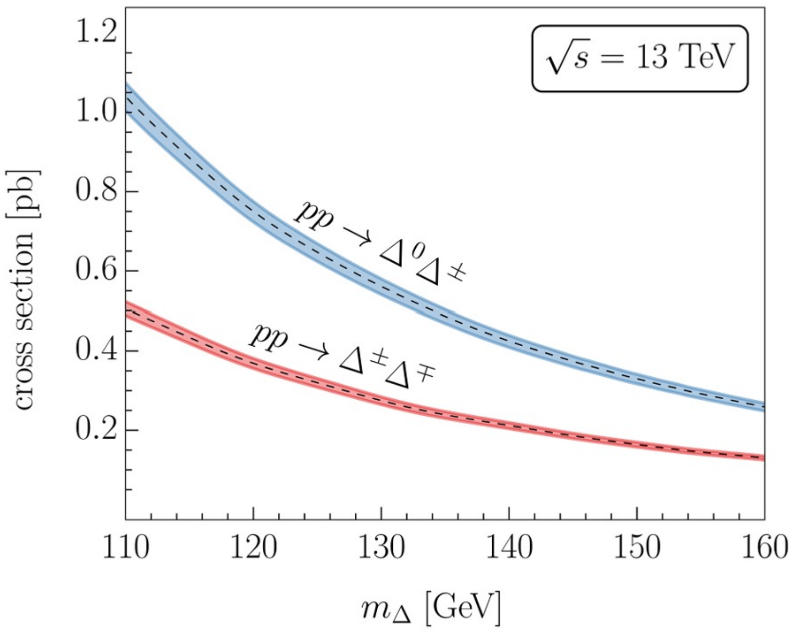


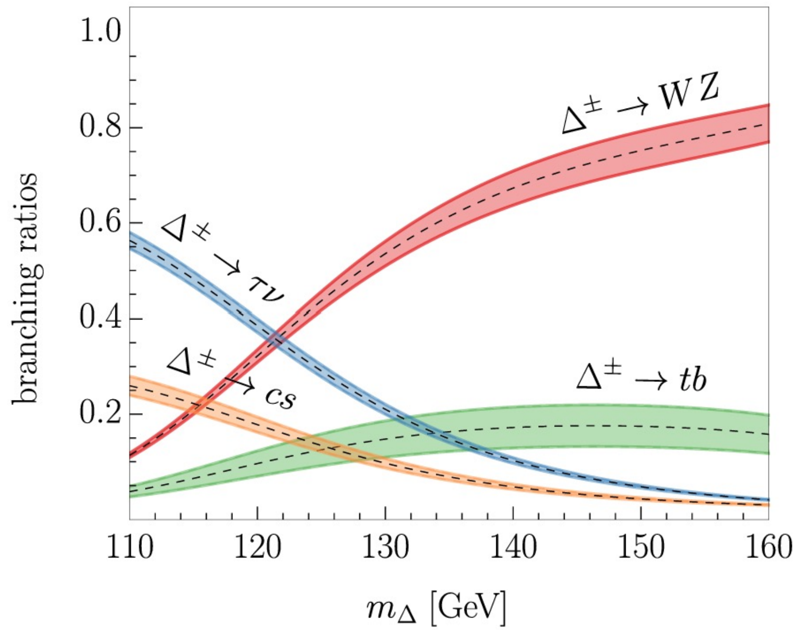
3.7σ, Triplet with Y=0 gives positive-definite effect

Is the 152 GeV Higgs a Triplet (Δ)?

- Δ^0 decays dominantly to WW and only suppressed to ZZ
- Positive shift in the W mass as preferred by the EW fit







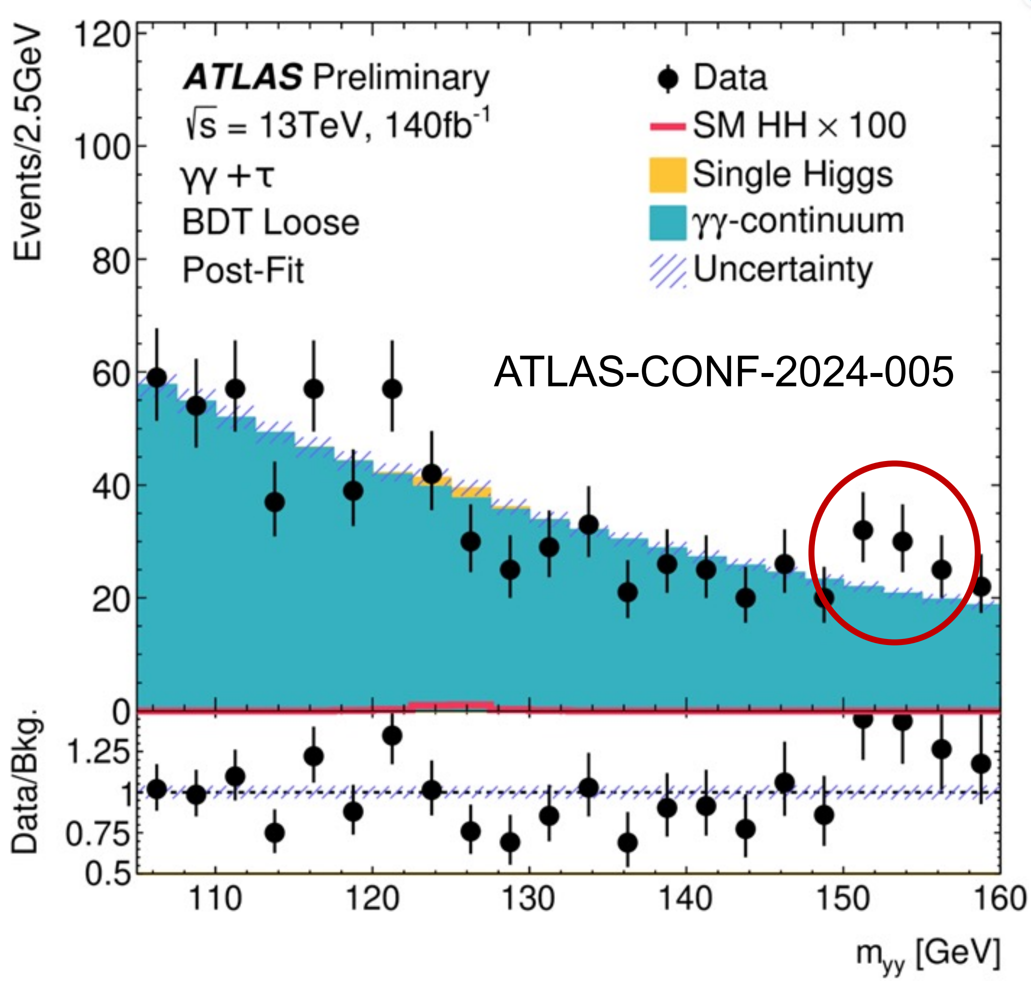
Drell-Yan production at the LHC

h→γγ+X from ATLAS

JHEP 07 (2023) 176
ATLAS-CONF-2024-005

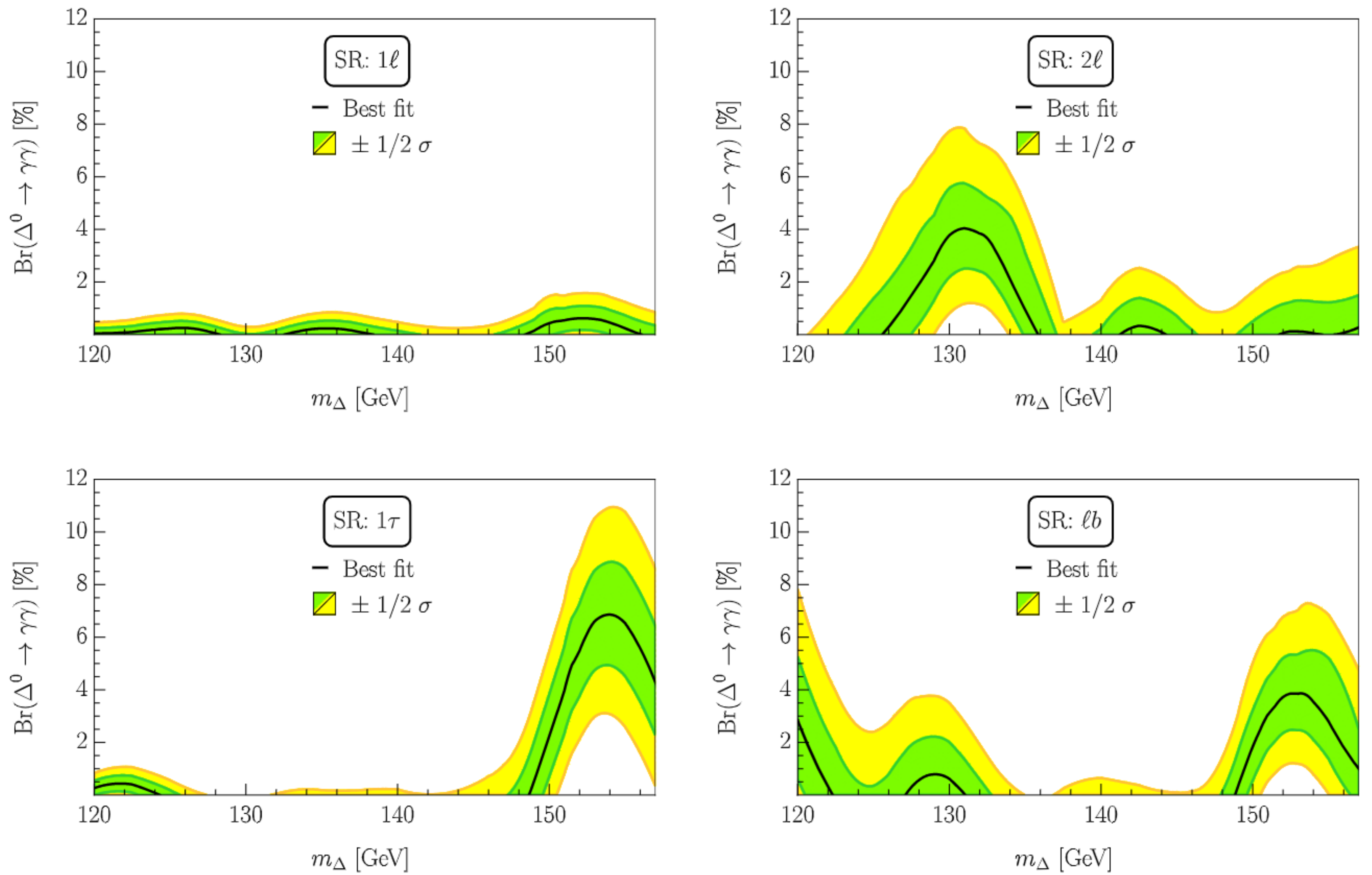
- Analysis of h→γγ+X
- 23 channels (X=l,MET,4j,...)
- 8 sensitive to the triplet
- Only mass and Br($\Delta^0 \to \gamma\gamma$) are relevant free parameters

S. Ashanujjaman, S. Banik, G. Coloretti, A.C. S. P. Maharathy, B. Mellado, 2402.00101



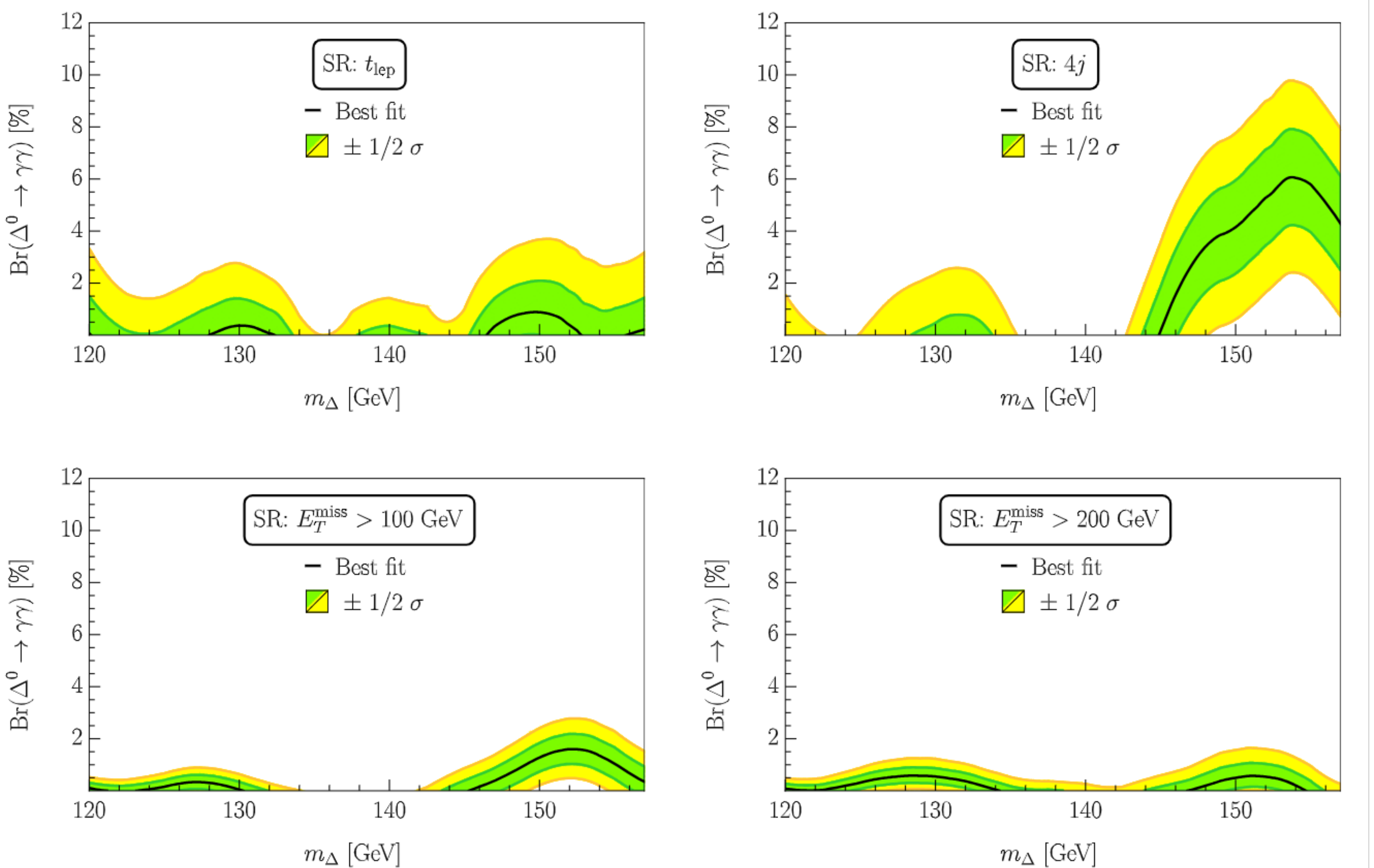
Triplet consistently explains h→γγ+X excesses

h→γγ+X from ATLAS



Triplet consistently explains h→γγ+X excesses

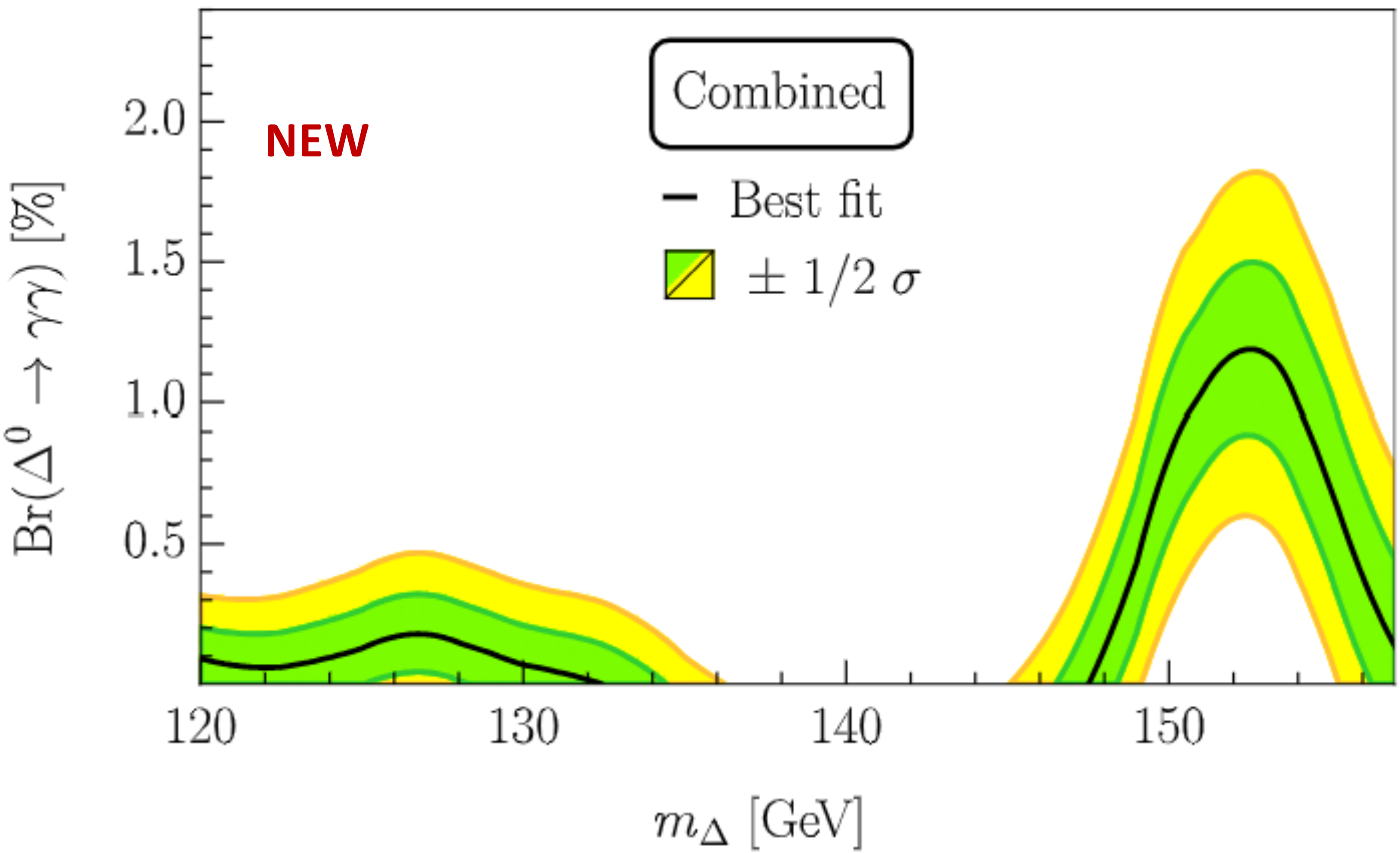
h→γγ+X Channels



Triplet consistently explains h→γγ+X excesses

Combination

S. Ashanujjaman, S. Banik, G. Coloretti, A.C. S. P. Maharathy, B. Mellado, 2404.xxxxx



4.3σ excess at 152GeV

Multi-lepton Anomalies

- Deviations from the SM predictions in LHC processes involving two or more leptons, with and without (b-)jets

Final state	Characteristics	SM backgrounds	Significance
$\ell^+\ell^-$+(b-jets)[62,65,66]	$m_{\ell\ell} < 100$ GeV, $(1b, 2b)$	$t\bar{t}, Wt$	$> 5\sigma$
$\ell^+\ell^-$+(no jet)[61,67]	$m_{\ell\ell} < 100$ GeV	W^+W^-	$\approx 3\sigma$
$\ell^\pm\ell^\pm, 3\ell$ + (b-jets)[64,68,69]	Moderate H_T	$t\bar{t}W^\pm, t\bar{t}t\bar{t}$	$> 3\sigma$
$\ell^\pm\ell^\pm, 3\ell$, (no b-jet)[63,70,71]	In association with h	$W^\pm h(125), WWW$	$\gtrsim 4\sigma$
$Z(\to \ell\ell)\ell$, (no b-jet)[62,72]	$p_T^Z < 100$ GeV	$ZW^\pm$	$> 3\sigma$

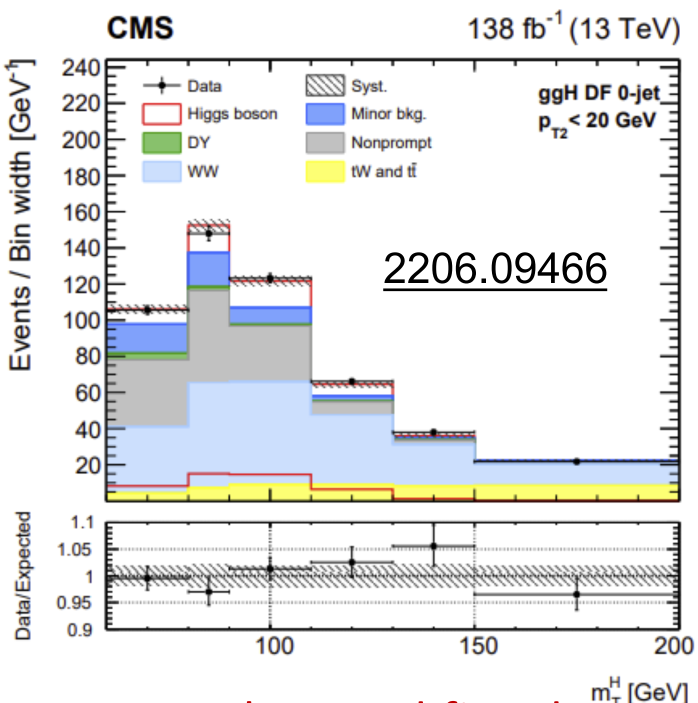
A.C., B. Mellado, arXiv:2309.03870
Buddenbrock et al. arXiv:1901.05300
O. Fischer et al. arXiv: 2109.06065

- 1711.07874 found m_S=150±5GeV
- Here focus on:
  - WW
  - Top-quark differential distributions

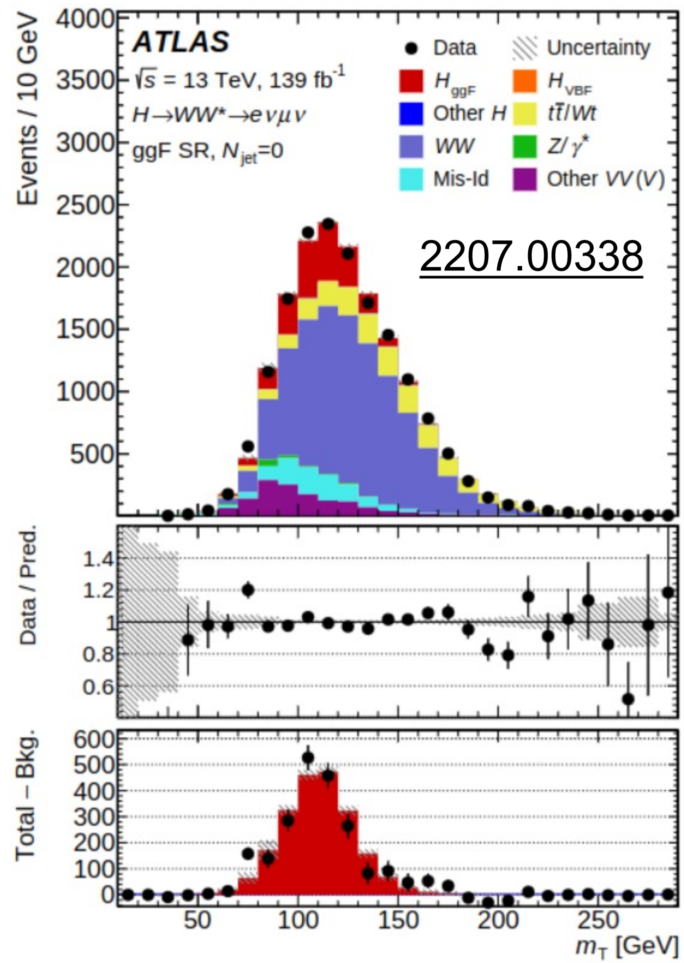
Statistically significant, motivate new EW scale scalars

Low mass WW seraches

- No dedicated low-mass WW search
- Recast SM Higgs analyses



Background fitted

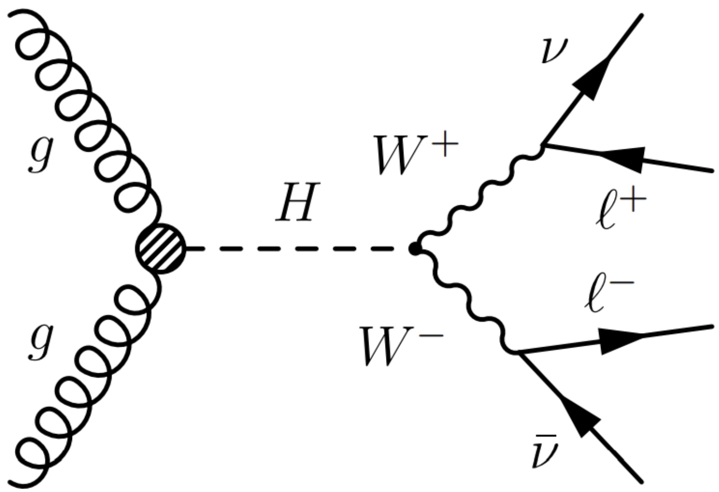


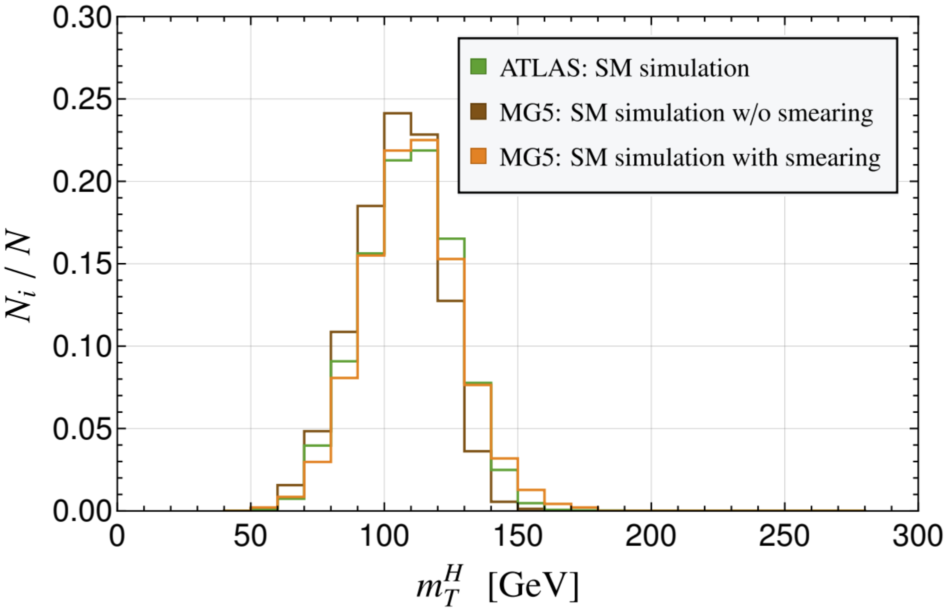
SM Higgs rescaled by 1.16

Room for NP

Simulation and Setup

- Opposite sign, different flavour leptons with full jet veto
- New scalar H produced via gluon fusion
- Correcting for fast simulation by tuning signal vial smearing to the SM Higgs signal

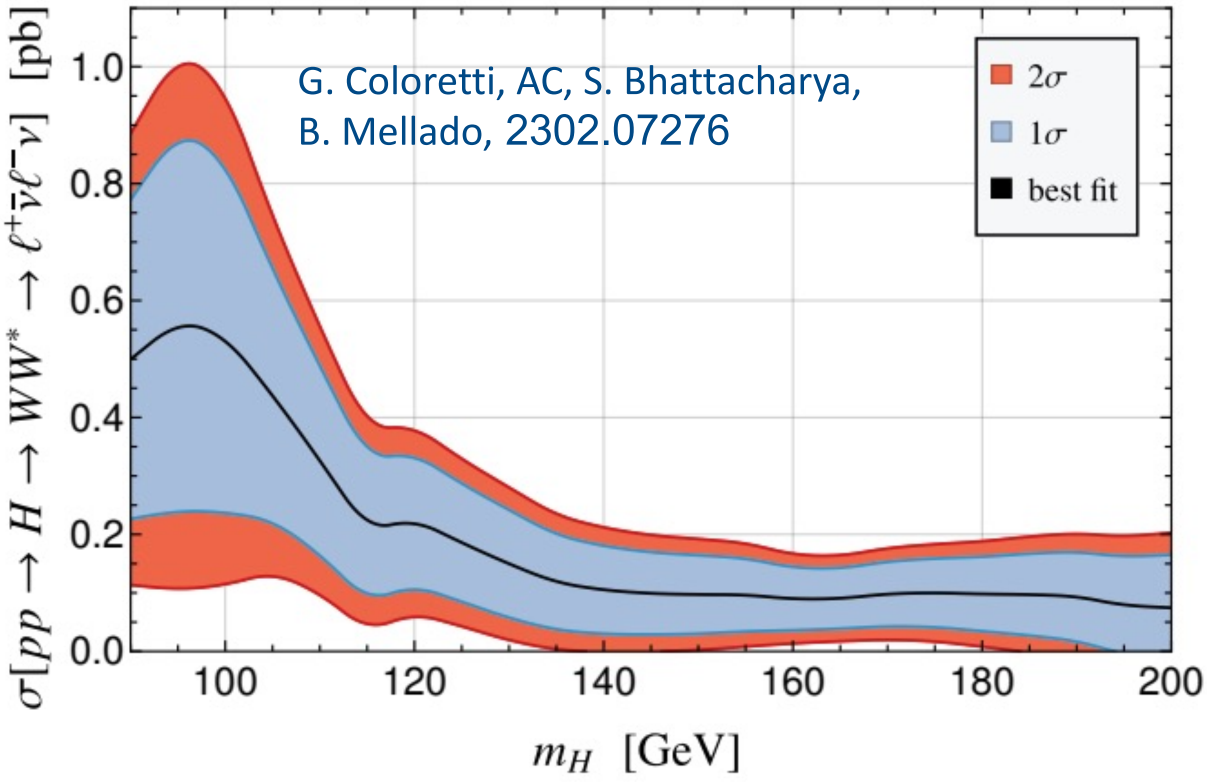




Simulation validated

Low mass WW resonances searches

- ATLAS and CMS combination

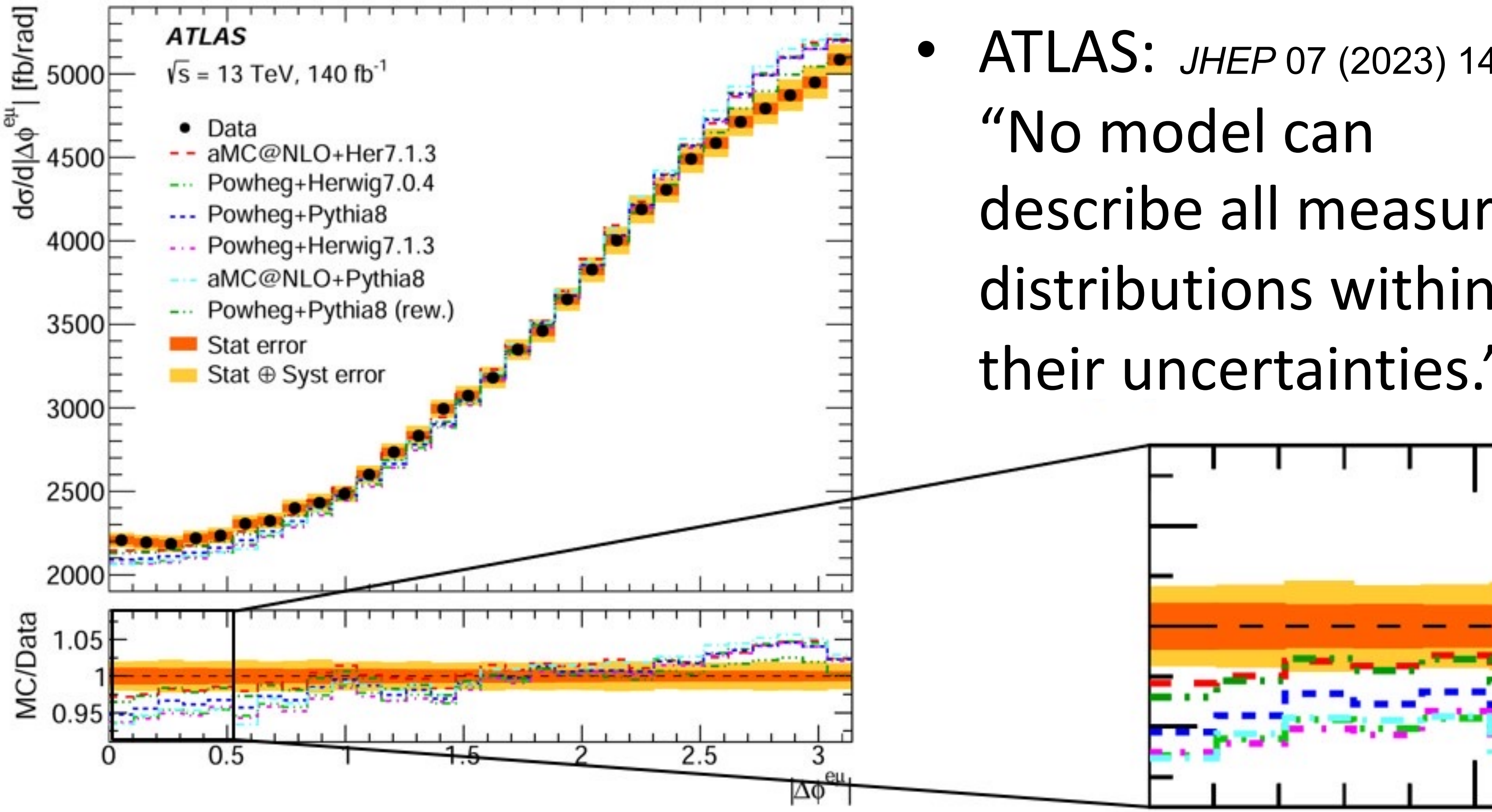


Transverse mass sensitive to additional missing energy from associated production

- New physics effect preferred over the whole range

Related to 95GeV and 151GeV?

Differential Top-Quark Distributions

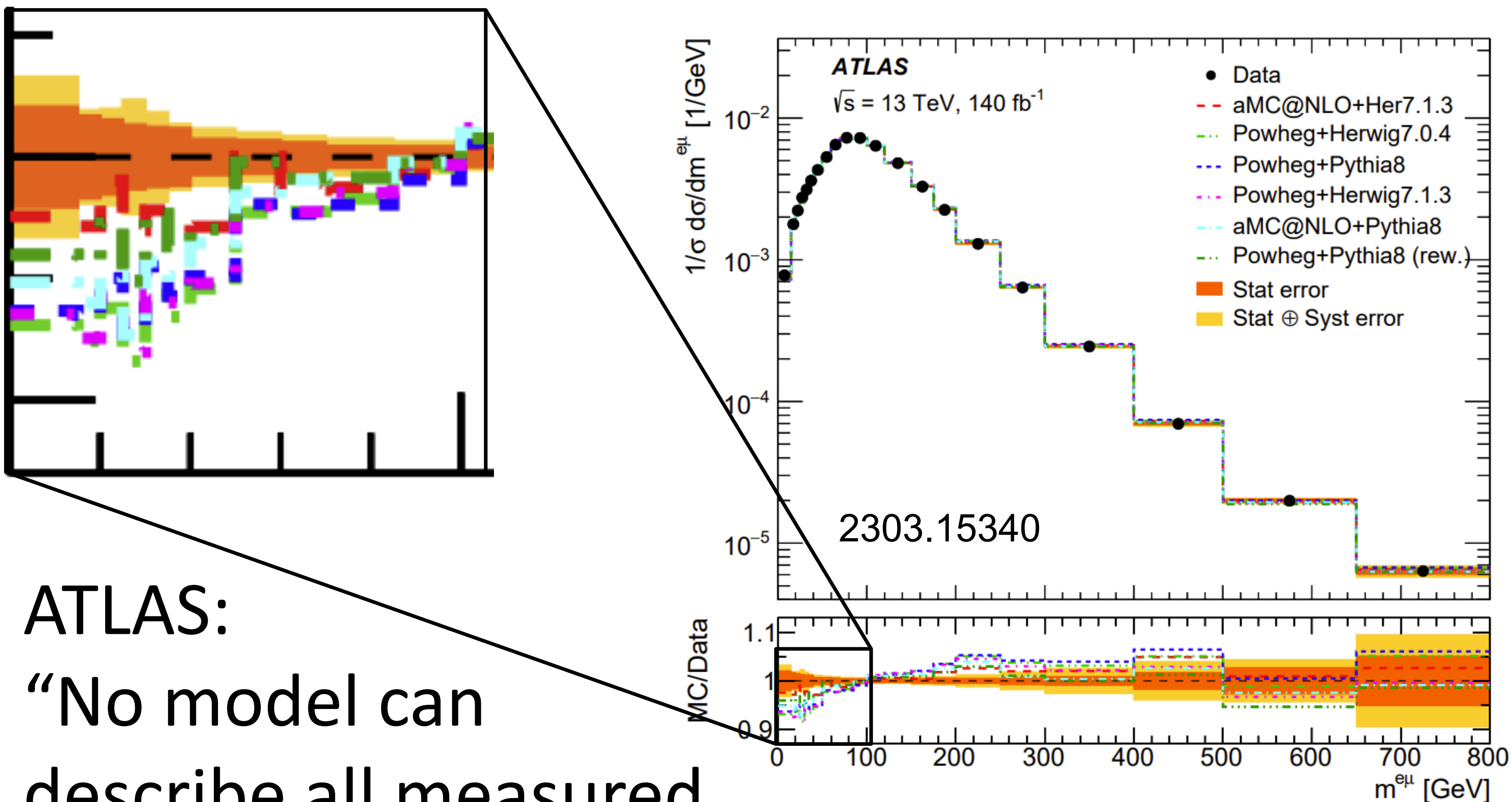


- ATLAS: *JHEP* 07 (2023) 141
  "No model can describe all measured distributions within their uncertainties."

- $\Delta\phi^{e\mu}$ angle between the leptons from the W decays

New Physics pollution of this SM measurement?

Differential Top-Quark Distributions

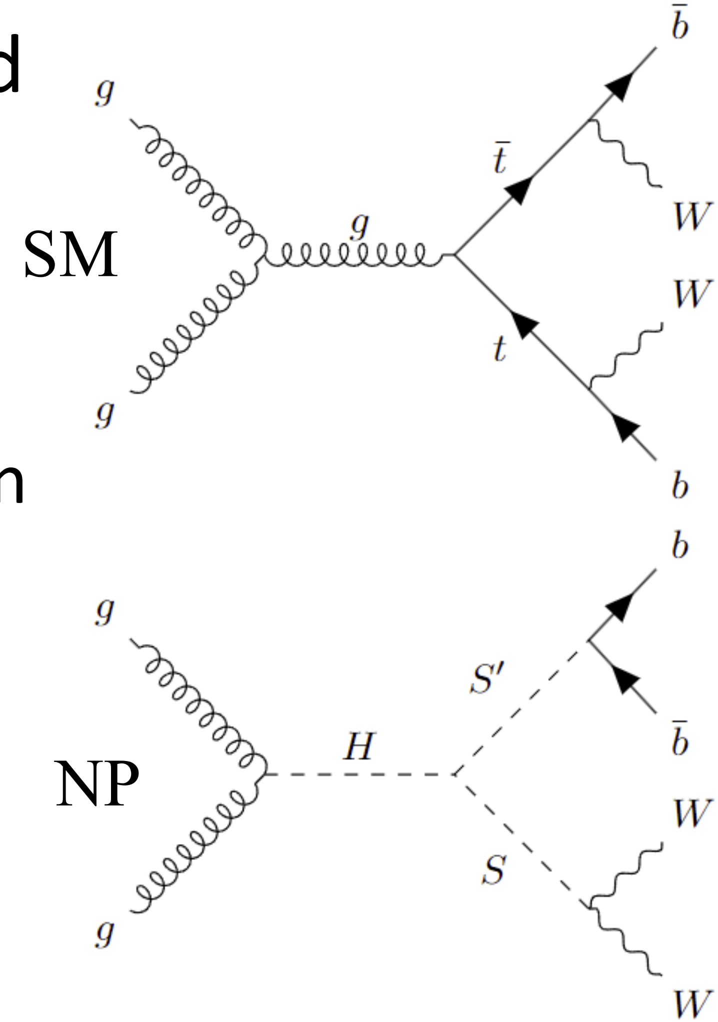


- ATLAS:
  "No model can describe all measured distributions within their uncertainties."

New Physics pollution of this SM measurement?

New Physics in Top-Quark Distributions

- ATLAS analysis normalized to the total cross section
  - only sensitive to the shape of NP
  - NP at small angels can explain deficit at large angles
- Associated production of new scalars decaying to WW and bb has a top-like signature

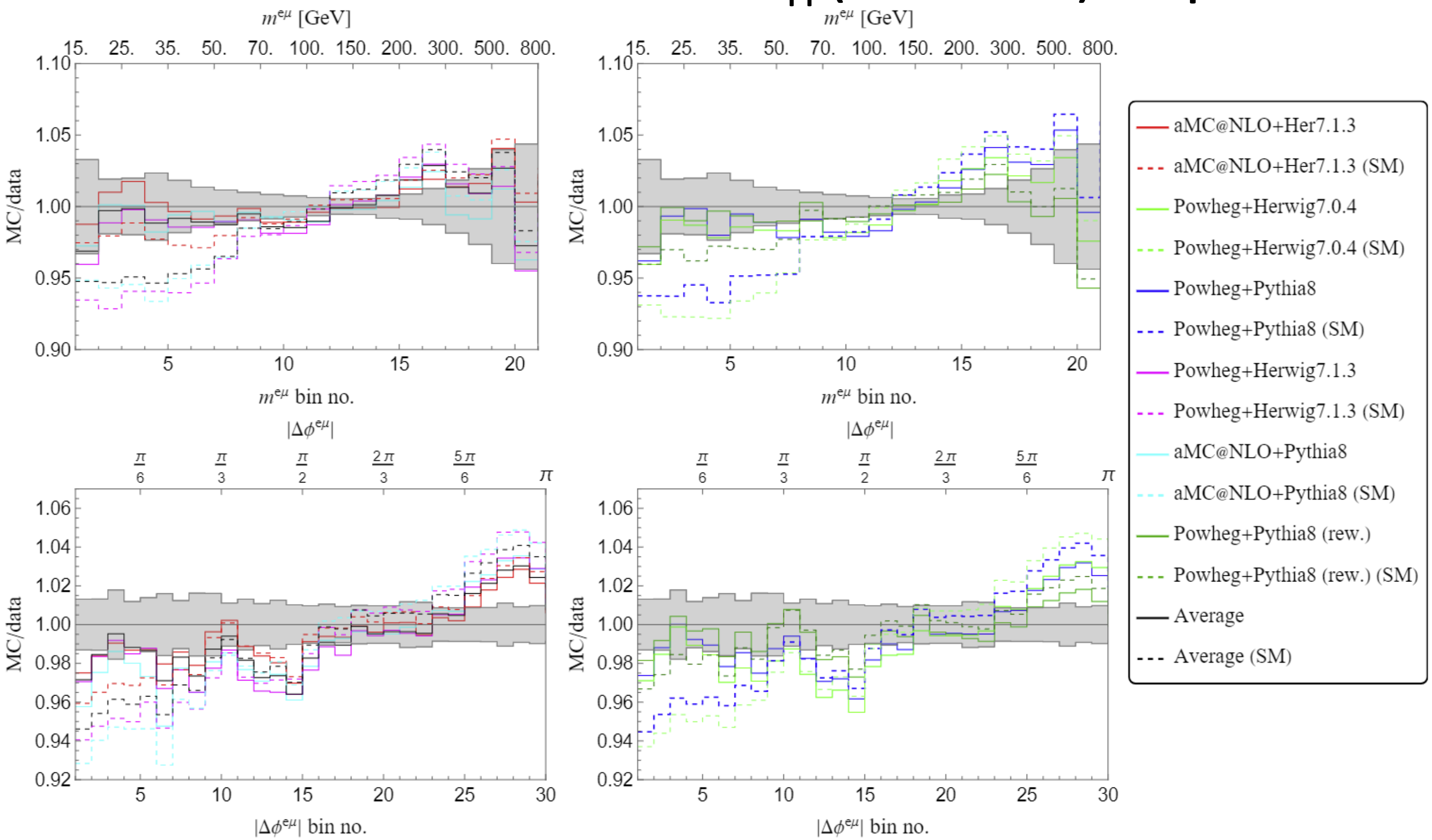


Related to the 95 GeV and 151.5 GeV hints?

Simplified Model: H→SS'→WWbb

2308.07953

- Fix m_S=151.5GeV and $m_{S'}$=95GeV by the hints for narrow resonances. Weak m_H (270GeV) dependence.



Also deficit at large $\Delta\phi^{e\mu}$ & $m^{e\mu}$ explained

Simplified Model: H→SS'→WWbb

2308.07953

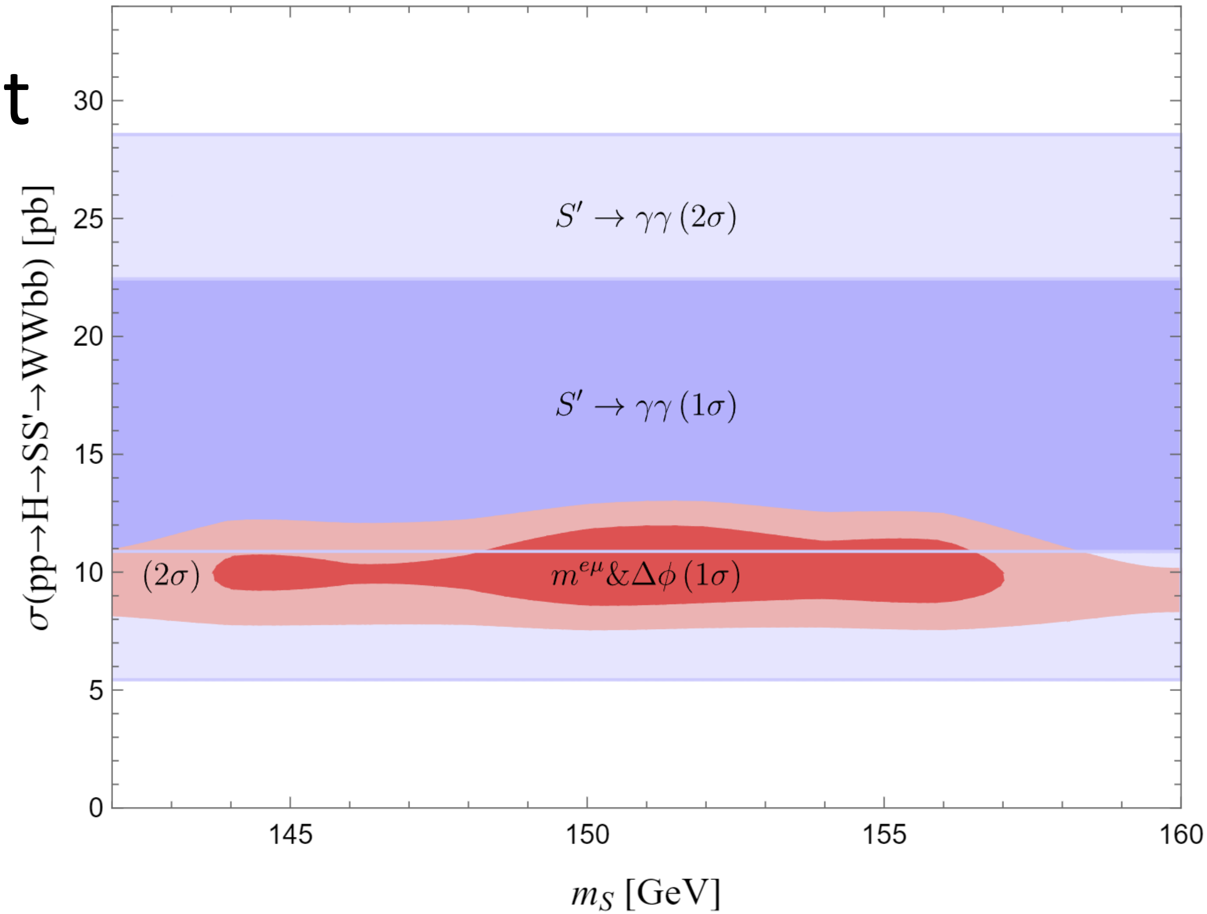
Monte Carlo	χ^2_{SM}	χ^2_{NP}	σ_{NP}	Sig.	m_S[GeV]
Powheg+Pyhtia8	213	102	9pb	10.5σ	$143-156$
aMC@NLO+Herwig7.1.3	102	68	5pb	5.8σ	$--$
aMC@NLO+Pythia8	291	163	10pb	11.3σ	148-157
Powheg+Herwig7.1.3	261	126	10pb	11.6σ	149-156
Powheg+Pythia8 (rew)	69	35	5pb	5.8σ	$--$
Powheg+Herwig7.0.4	294	126	12pb	13.0σ	149-156
Average	182	88	9pb	9.6σ	143-157

- Improvement of SM prediction imperative!

Agreement with data significantly improved (>5σ)

Is 95 GeV a singlet? Relation to 151.5 GeV?

- S'(95): Singlet decays dominantly to bb
- S(151.5): decays dominantly to WW

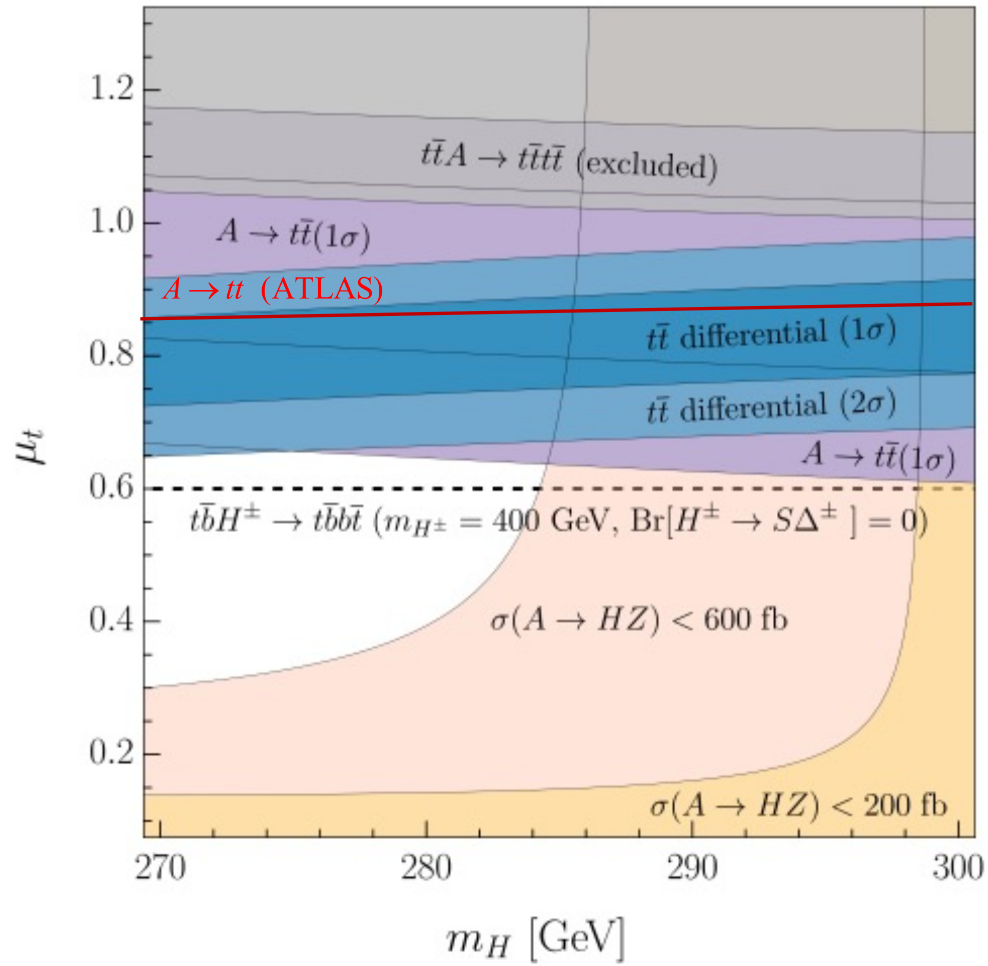


Consistent with 95 GeV γγ signal strength & a mass of S with 151.5 GeV

Δ2HDMS and top-quark production

Field	$SU(2)_L$	$U(1)_Y$
ϕ_s	2	0
ϕ_2	2	1/2
ϕ_1	2	1/2
Δ	3	0

G. Coloretti, A.C. and B. Mellado, 2312.17314



Explains:

- Top-quark differential distributions
- Di-photon excesses
- Resonant top-quark production Elevated 4-top cross section

Combined explanation possible

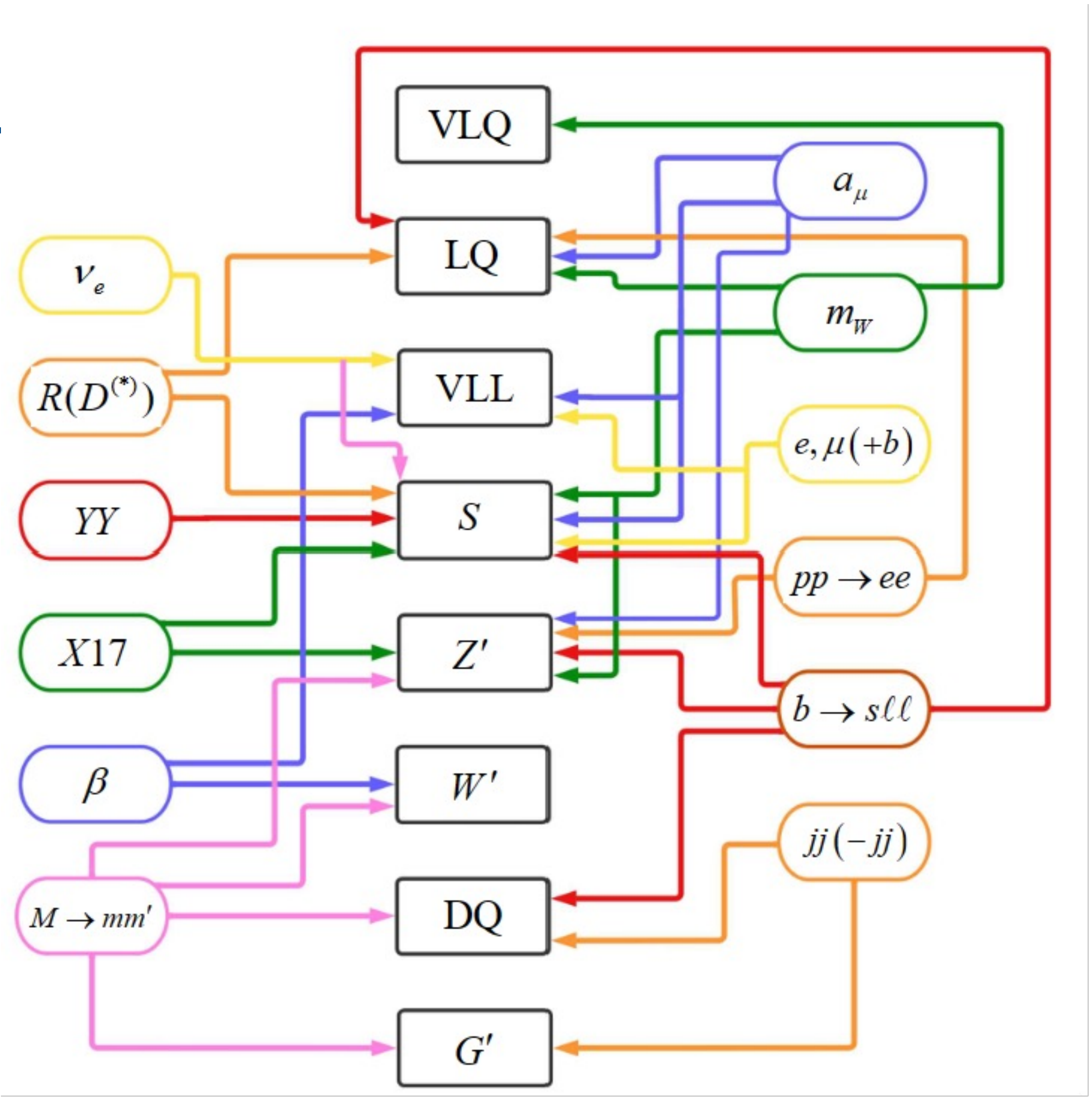
Conclusions

- Hints for narrow resonances at 95 GeV & 151.5 GeV
- Significant tensions in top quark differential distributions (>5σ)
- Can be explained via pp→H→SS' with masses consistent with the narrow resonances
- 95 GeV decays to dominantly to bb ➡ singlet?
- 151.5 GeV decays dominantly to WW ➡ triplet?
- γγ+X excesses consistent with DY production of triplet
- New CMS excess in ttZ explained

Most significant hints for new particles at the LHC

Outlook

- Intriguing anomalies emerged in the last years which point towards new particles



The Standard Model is crumbling

Backup

Multi-leptons history

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

Talk of Bruce Mellado at ZPW 2023

Higgs Sector of the SM

$$L_{\Phi}^{SM} = \mu^2 \Phi^\dagger \Phi + \frac{\lambda}{4}\left(\Phi^\dagger \Phi\right)^2$$

$$L_{Y}^{SM} = -Y^d \bar{Q}\Phi d - Y^u \bar{Q}\tilde{\Phi} u - Y^\ell \bar{Q}\Phi \ell$$

- Custodial symmetry
- Single Higgs gives rise to all fermion masses
- Is the Higgs sector really minimal?
- Extensions possible if the effect on the ρ parameter SM-Higgs signal strength is small
- Scalars decaying to W bosons and/or produced in associate production weakly constrained

EW scale extension of the SM Higgs sector possible

Multi-lepton Anomalies

- Deviations from the SM predictions in LHC processes involving two or more leptons, with and without (b-)jets

Final state	Characteristics	SM backgrounds	Significance
$\ell^+\ell^-$+(b-jets)[62,65,66]	$m_{\ell\ell} < 100\,\text{GeV}$, $(1b, 2b)$	$t\bar{t}, Wt$	$> 5\sigma$
$\ell^+\ell^-$+(no jet)[61,67]	$m_{\ell\ell} < 100\,\text{GeV}$	W^+W^-	$\approx 3\sigma$
$\ell^\pm\ell^\pm, 3\ell$ + (b-jets)[64,68,69]	Moderate H_T	$t\bar{t}W^\pm, t\bar{t}t\bar{t}$	$> 3\sigma$
$\ell^\pm\ell^\pm, 3\ell$, (no b-jet)[63,70,71]	In association with h	$W^\pm h(125), WWW$	$\gtrsim 4\sigma$
$Z(\to \ell\ell)\ell$, (no b-jet)[62,72]	$p_T^Z < 100\,\text{GeV}$	$ZW^\pm$	$> 3\sigma$

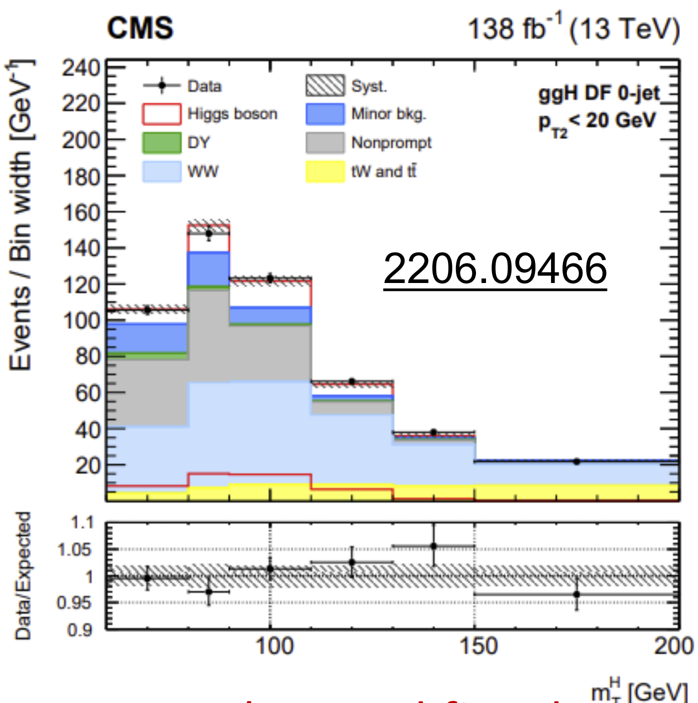
A.C., B. Mellado, arXiv:2309.03870
Buddenbrock et al. arXiv:1901.05300
O. Fischer et al. arXiv: 2109.06065

- 1711.07874 found m_S=150±5GeV
- Here focus on:
  - WW
  - Top-quark differential distributions

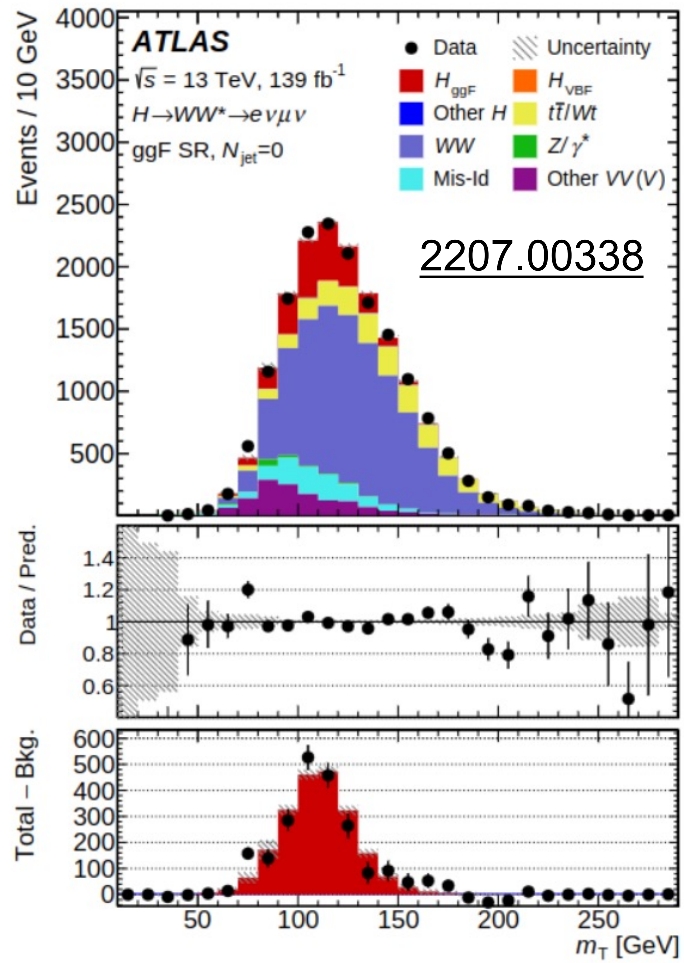
Statistically significant, motivate new EW scale scalars

Low mass WW seraches

- No dedicated low-mass WW search
- Recast SM Higgs analyses



Background fitted

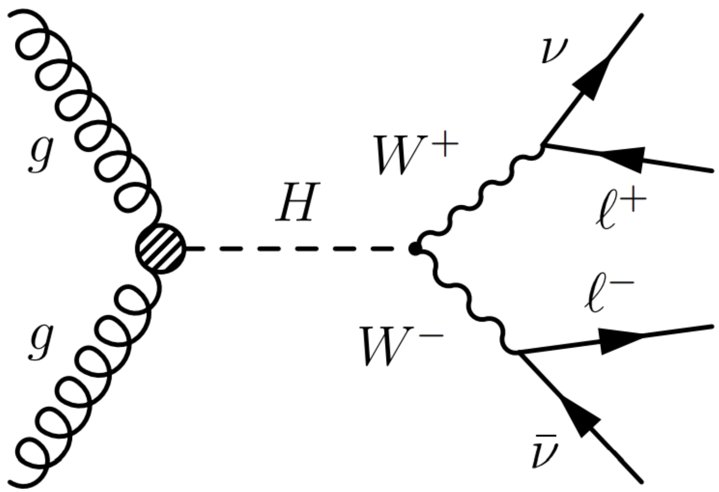


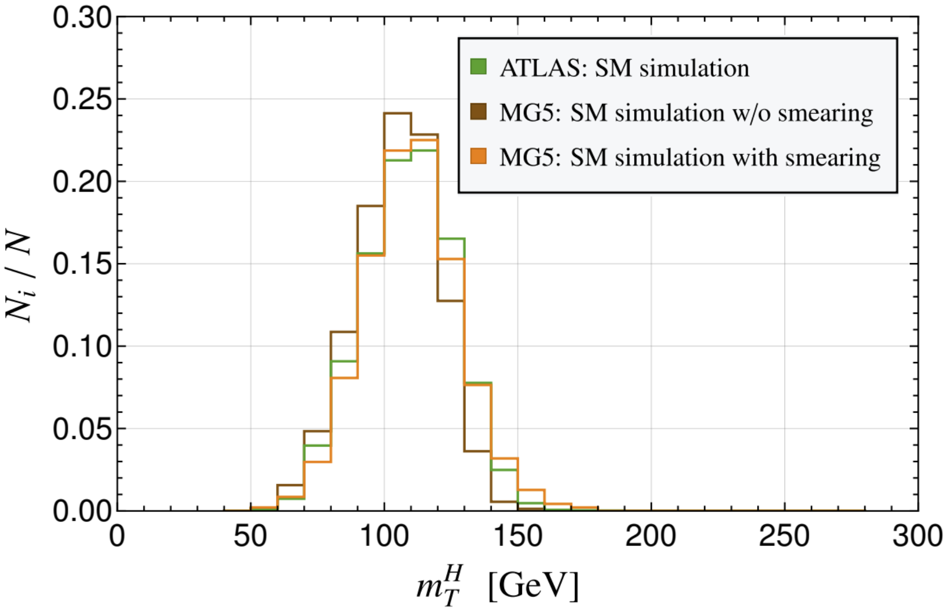
SM Higgs rescaled by 1.16

Room for NP

Simulation and Setup

- Opposite sign, different flavour leptons with full jet veto
- New scalar H produced via gluon fusion
- Correcting for fast simulation by tuning signal vial smearing to the SM Higgs signal

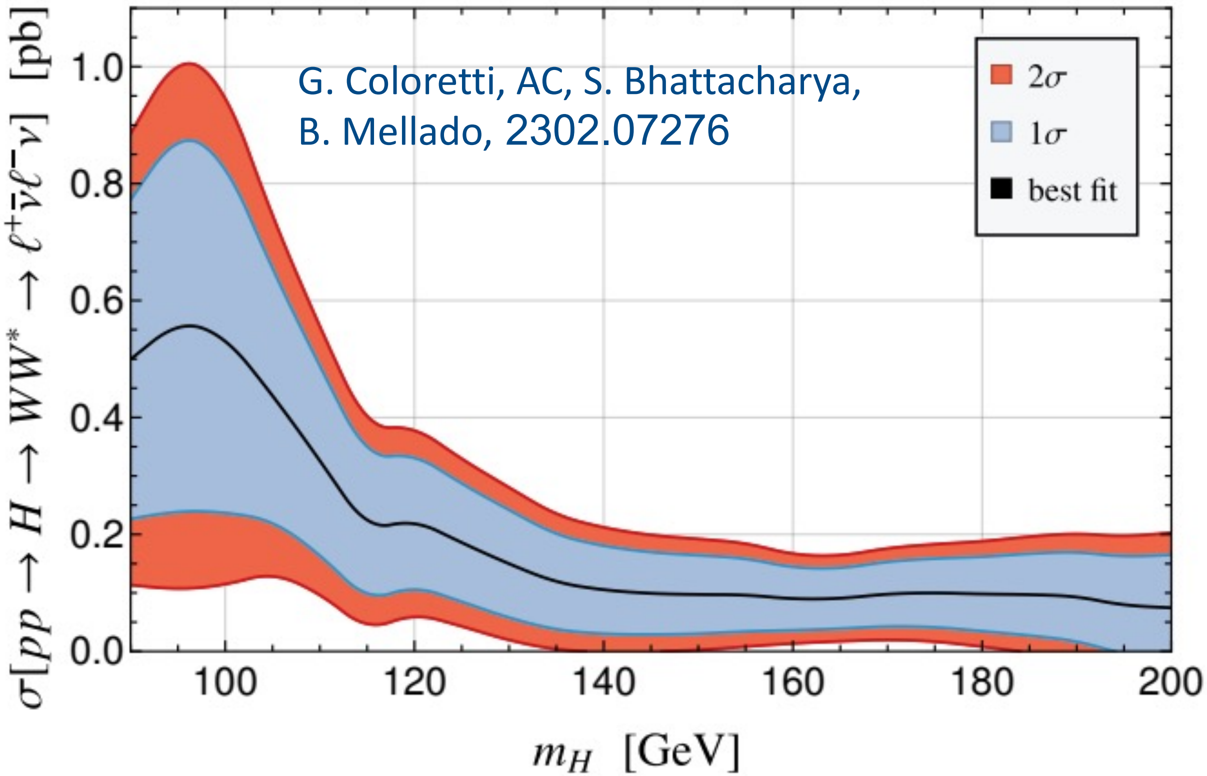




Simulation validated

Low mass WW resonances searches

- ATLAS and CMS combination



Transverse mass sensitive to additional missing energy from associated production

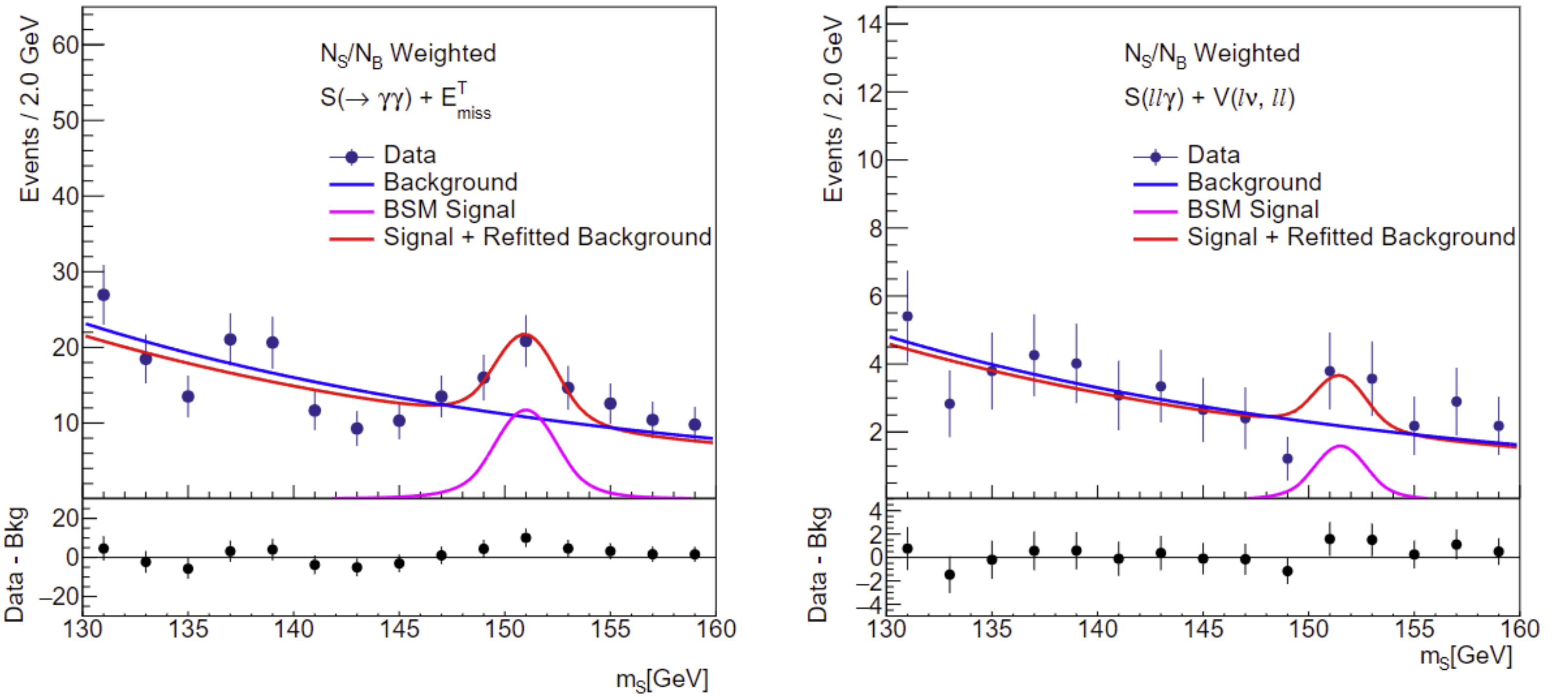
- New physics effect preferred over the whole range

Related to 95GeV and 151GeV?

Hints for a 152 GeV scalar

PAUL SCHERRER INSTITUT

- Motivated by the mass range of 1711.07874 (not included)



ATLAS: 2301.10486

- Hints for a resonance decaying to photons and Zγ

New Scalar (Higgs) boson? Relation to DM?