Andreas Crivellin

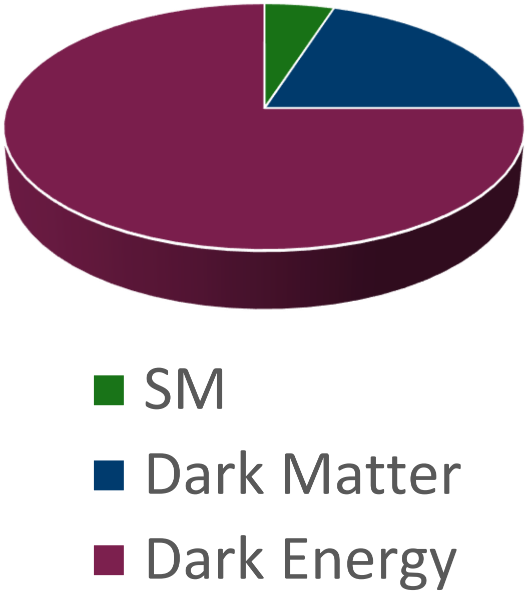
PSI & UZH

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

Munich, MPI, 19.11.2024

Physics Beyond the Standard Model

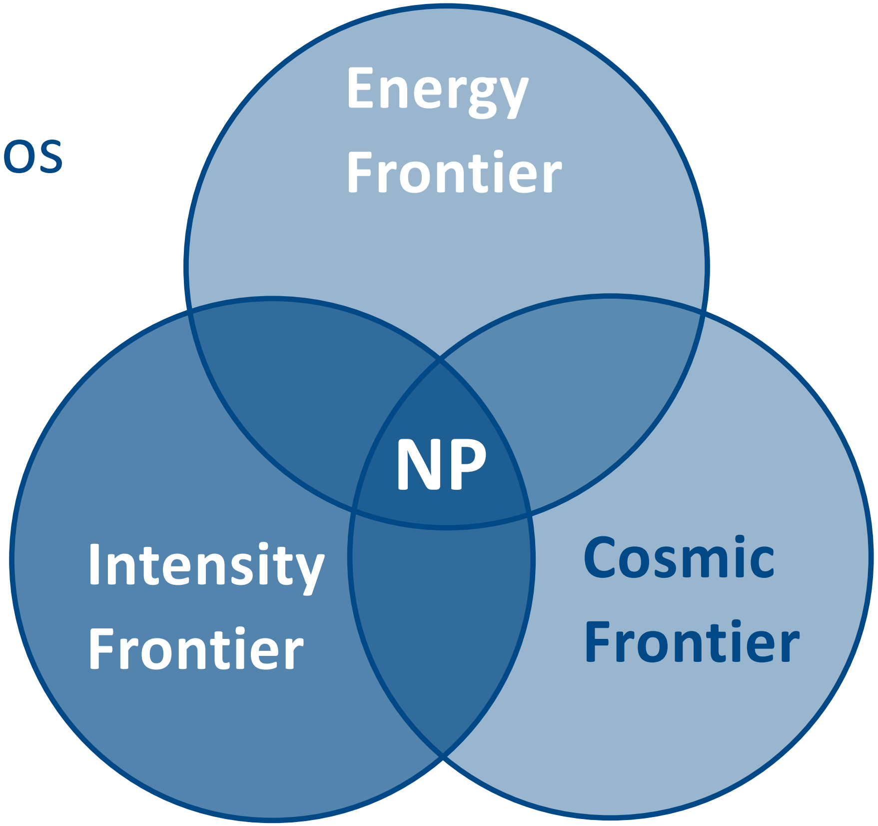
- Dark Matter existence established at cosmological scales
  - New weakly interacting particles
- Neutrinos not exactly massless
  - Right-handed (sterile) neutrinos
- Matter anti-matter asymmetry
  - Additional CP violating interactions



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



Indirect Searches for New Physics

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

Experiment

$\neq$

Standard Model

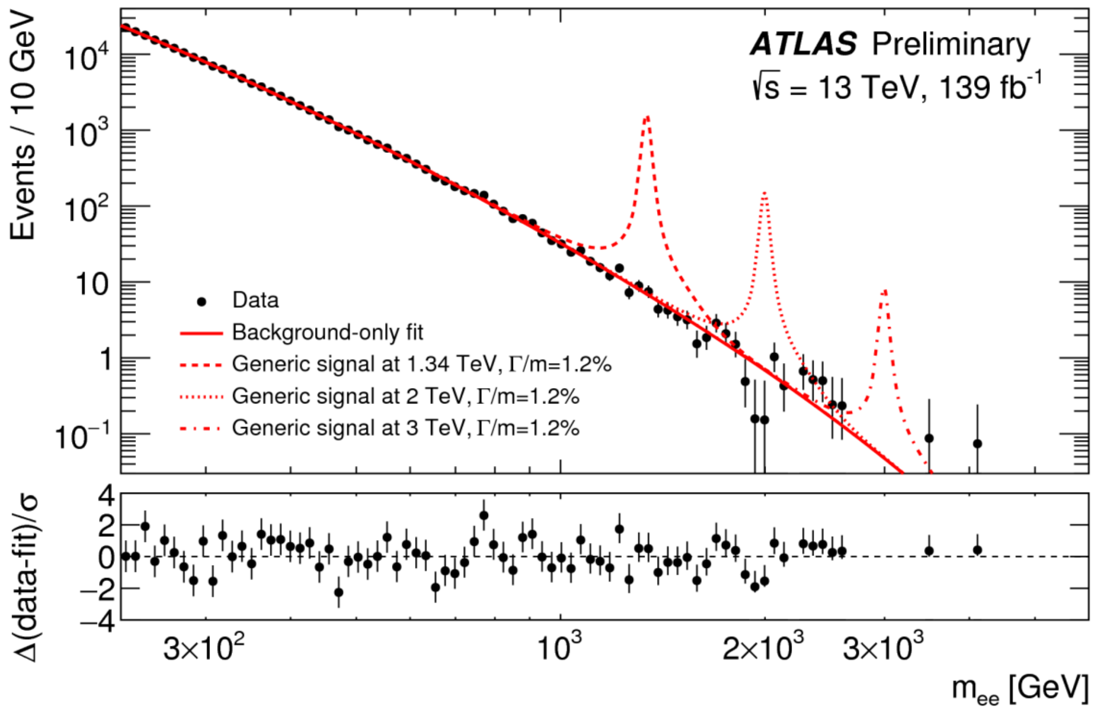
$\Downarrow$

New Physics

Can be very sensitive to NP, but only measure g^2/M^2

Direct Searches for New Physics

- Searches for resonances in the spectrum
- Direct information on the mass
- Clear signatures, few theory input needed



Golden discovery channels, but energy limited

Higgs Sector of the SM

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

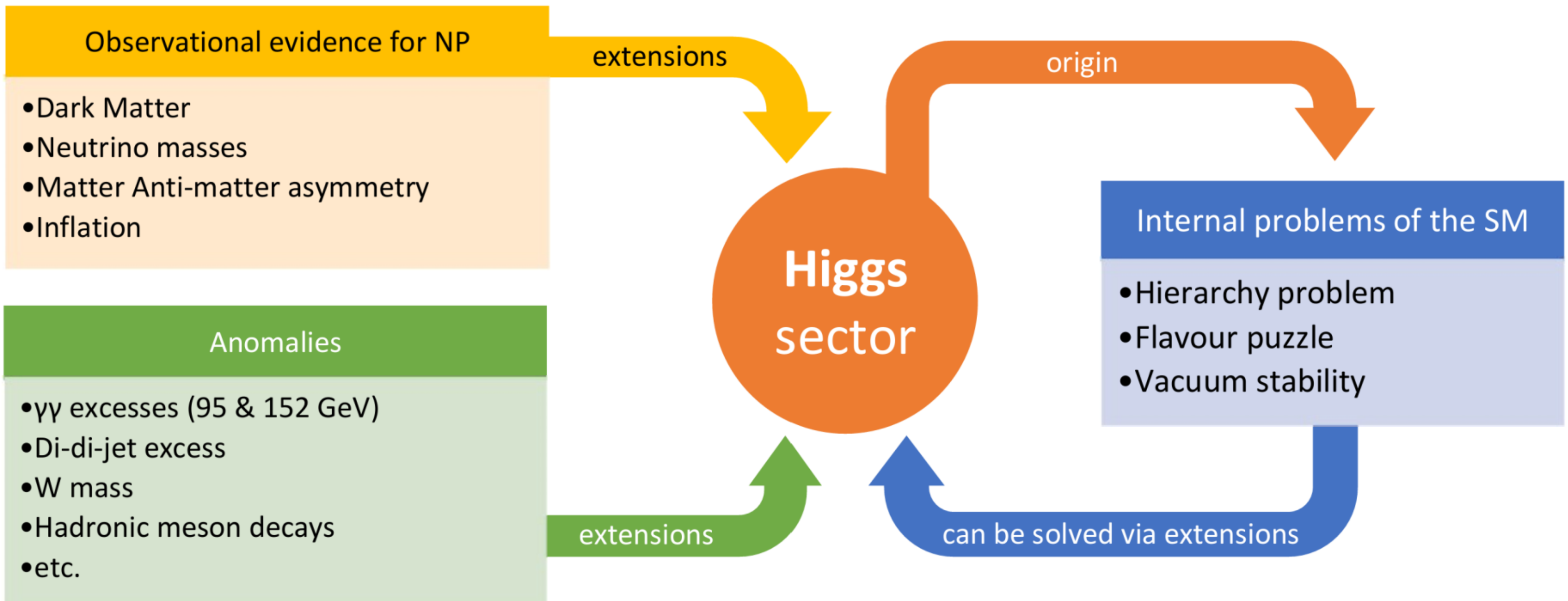
$$L_{Y}^{SM} = -Y^d \bar{Q}\Phi d - Y^u \bar{Q}\tilde{\Phi} u - Y^\ell \bar{Q}\Phi \ell$$

- Custodial symmetry at tree-level
- Single Higgs gives rise to all fermion masses
- Higgs signal strength measurements in agreement with SM predictions
- Global Electroweak fit in good agreement (maybe not the W mass)

EW symmetry breaking and generation of fermion and gauge boson masses driven by the SM Higgs

Why new Higgses

- No theoretical principle forbids new Higgses
- Nearly all top-down approached have new scalars



Higgs sector very promising place to expect NP

New Higgses at the Electroweak Scale

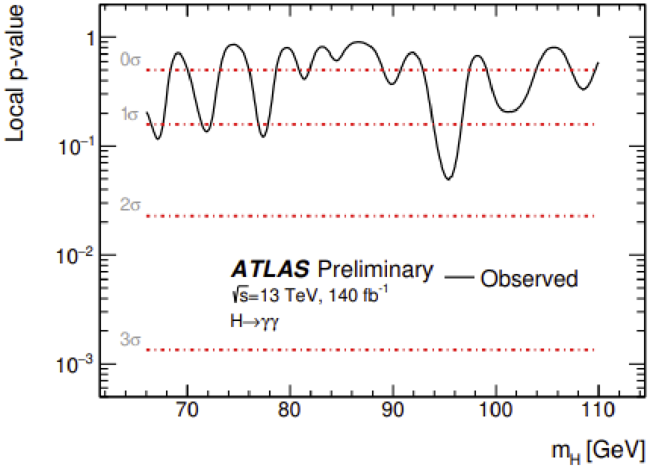
- Signatures of new Higgses expected to be sub-leading compared to the SM Higgs
- Small p_T leads to low detector efficiencies
- Large SM background
- Non-resonant signatures, like scalars decaying to W bosons (directly or via top quarks) are weakly constrained

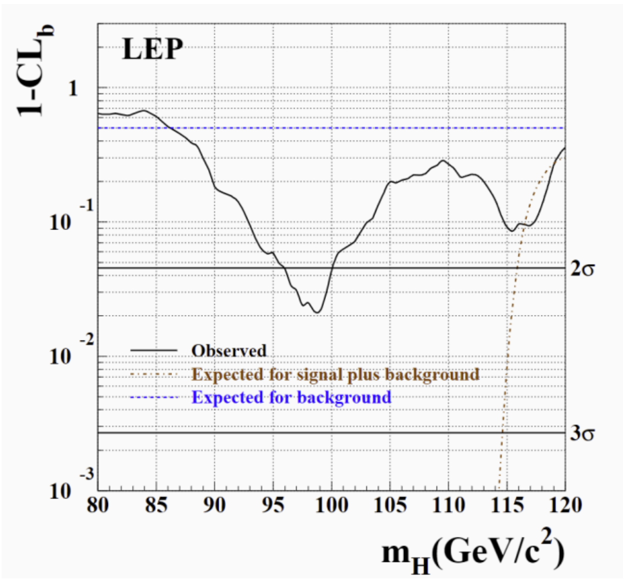
EW scale Higgses could be hiding in the LHC data

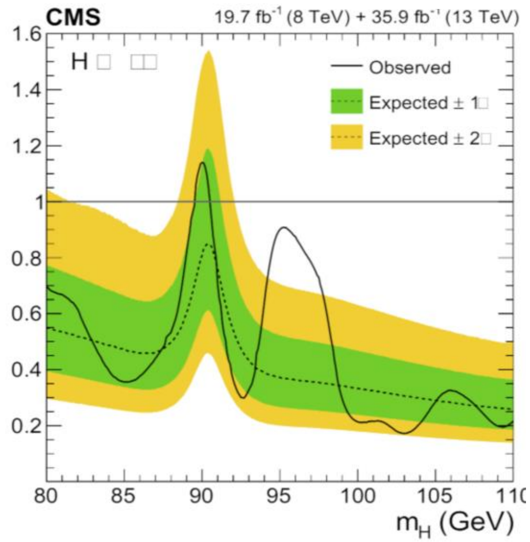
- Associated searches can significantly reduce the ratio of signal over background!

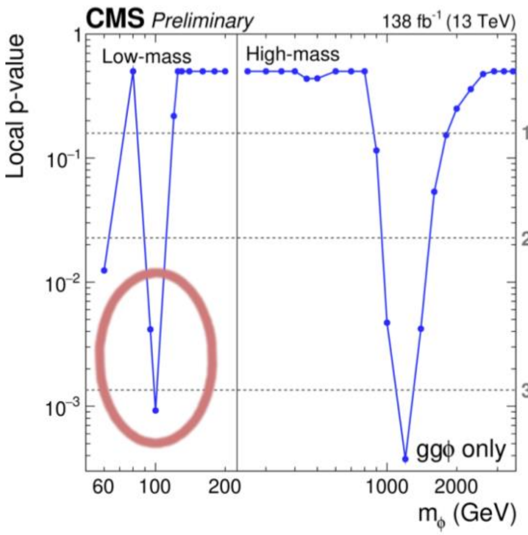
Hints for a 95 GeV Higgs

- LEP: Z+bb
- ATLAS & CMS: γγ
- CMS: ττ (no signal in ATLAS)
- 680⟶95+125







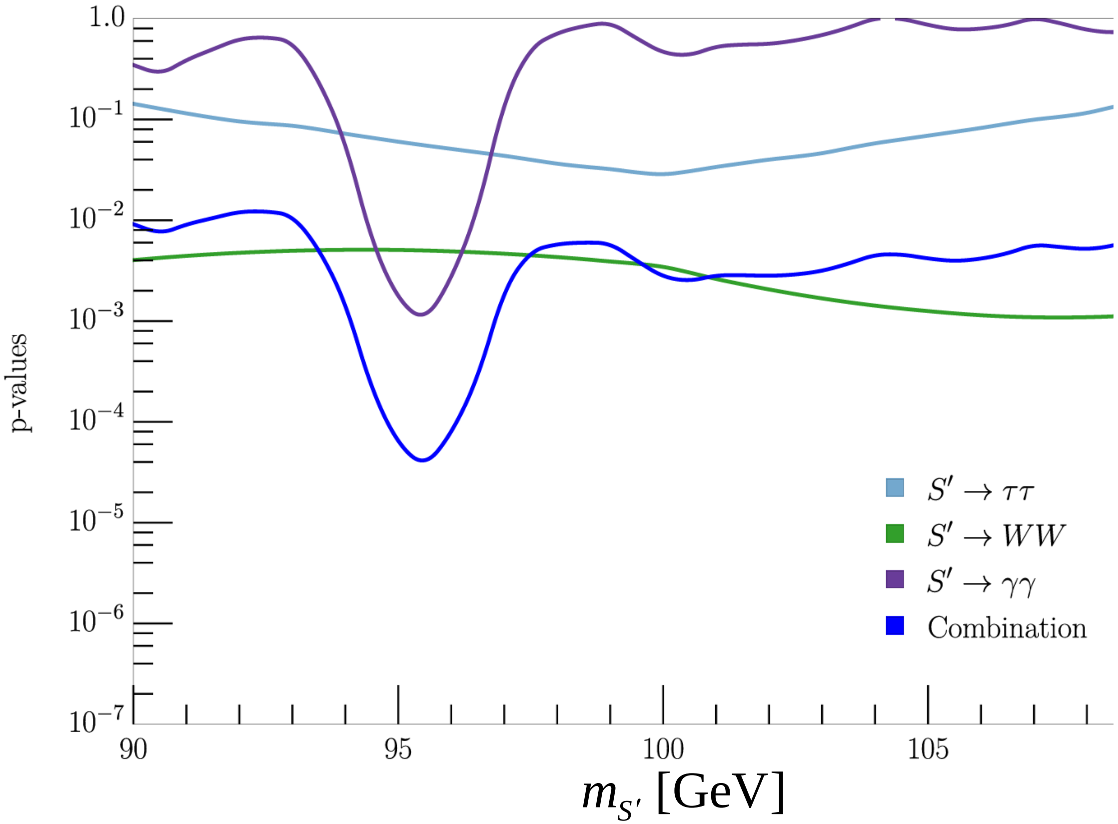


Multiple channels, no associated search

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

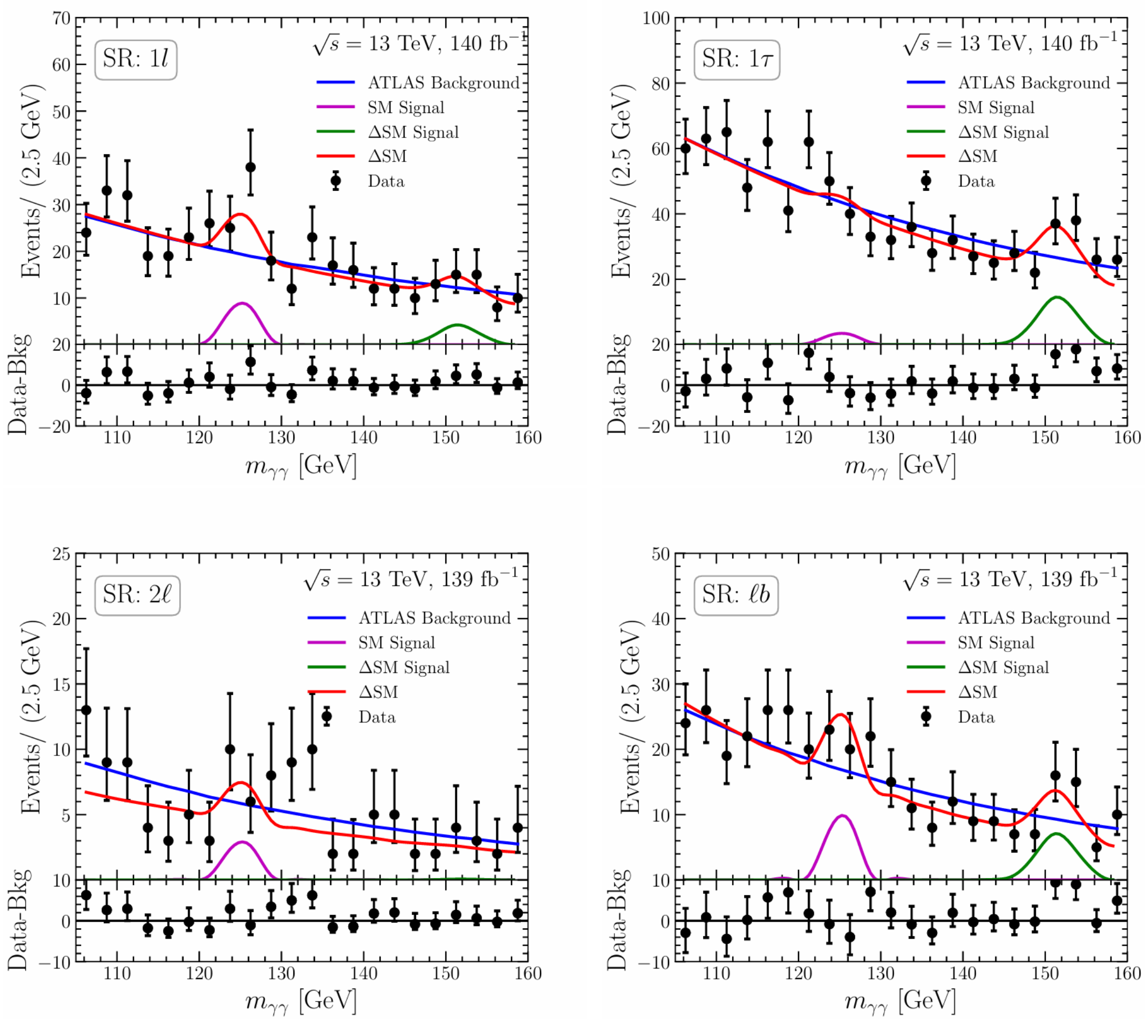


3.4σ global significance

Hints for a 152 GeV scalar

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

- Hints for a resonance decaying to photons in association with leptons missing energy and b-jets



Dominant channels are γγ+X

Hints for a 152 GeV scalar

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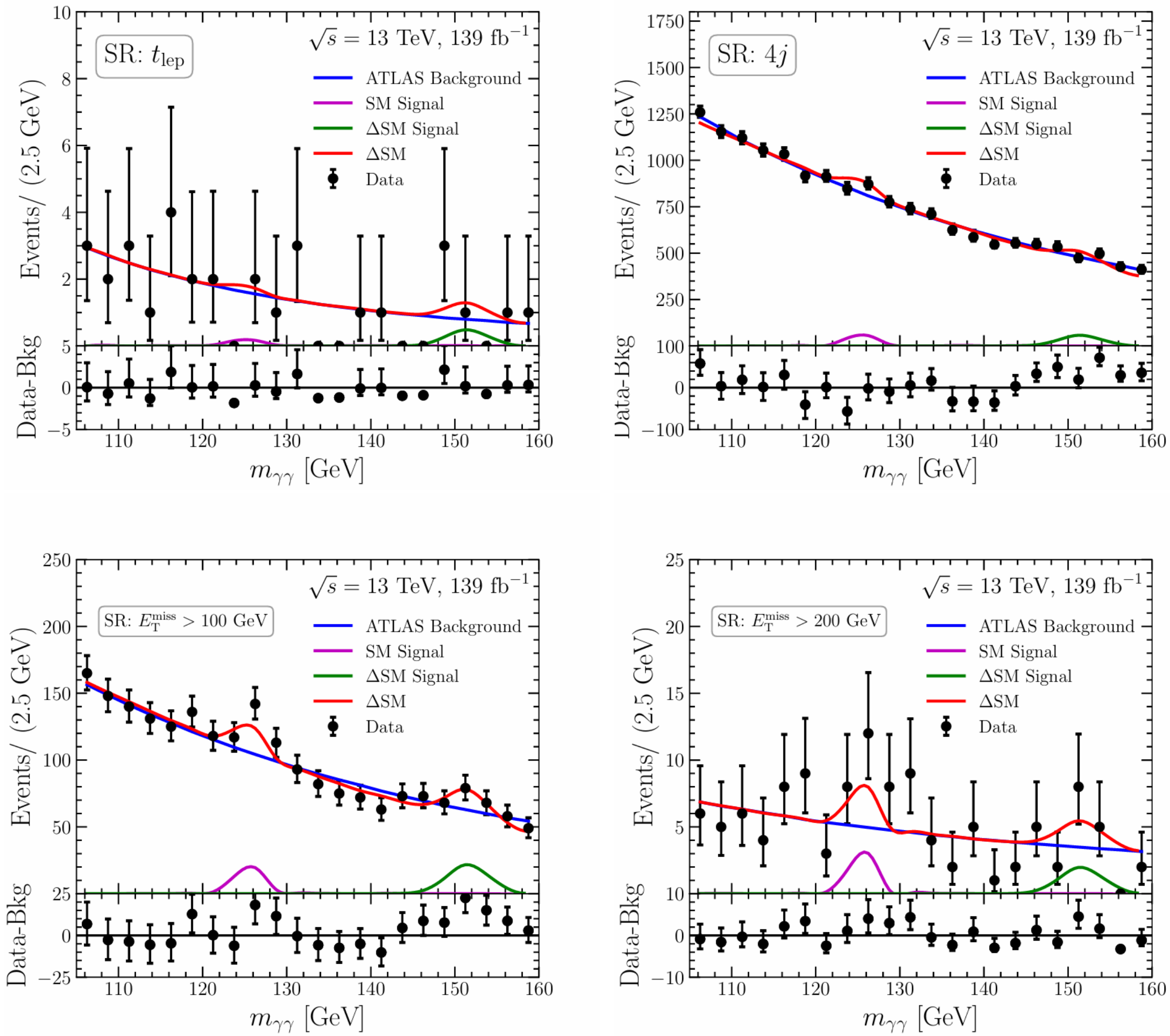
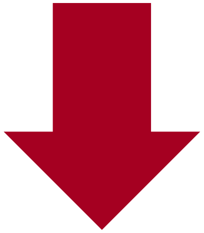


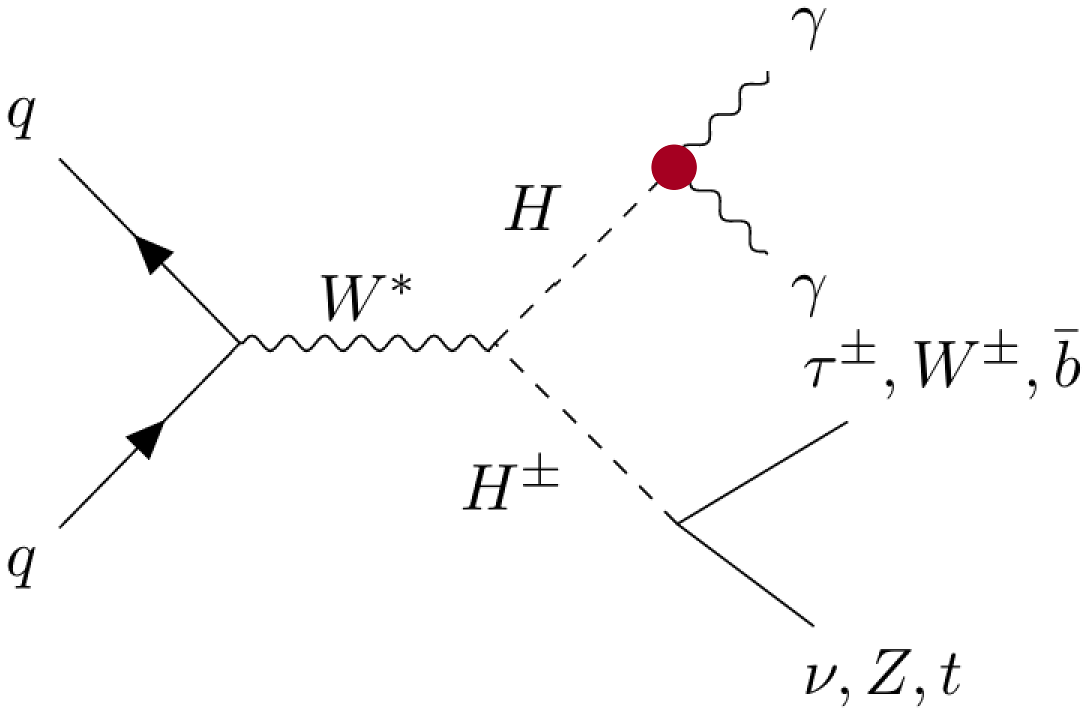
Dominant channels are γγ+X

Drell-Yan Production

- One leptons, but not two leptons
- One tau but not two taus
- lb but not t_{lep}
- Moderate MET



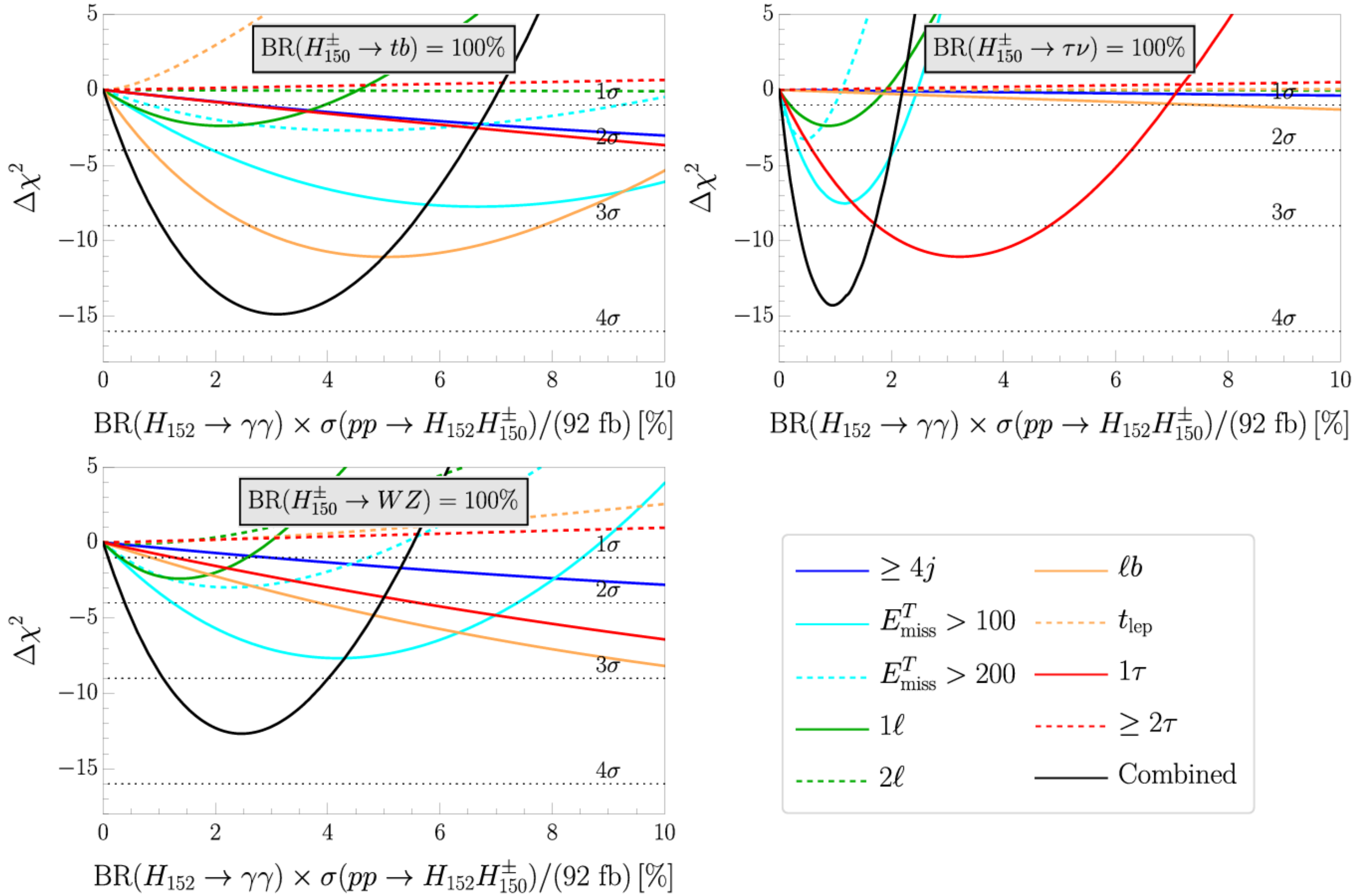
- DY production of charged and neutral Higgs



New Scalar with non-trivial SU(2) representation

Simplifed Model Analysis

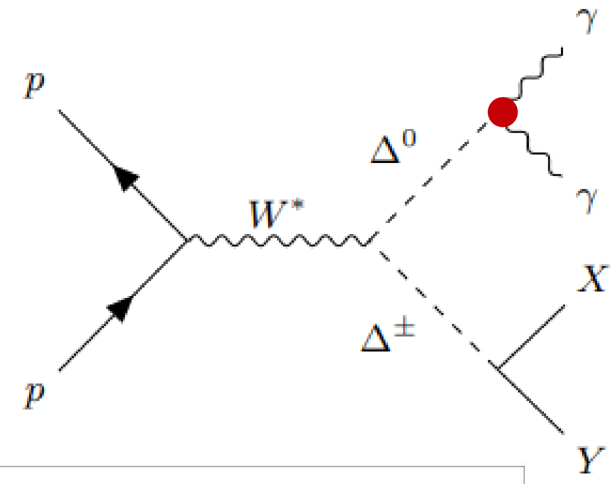
S. Banik, AC, 2407.06267

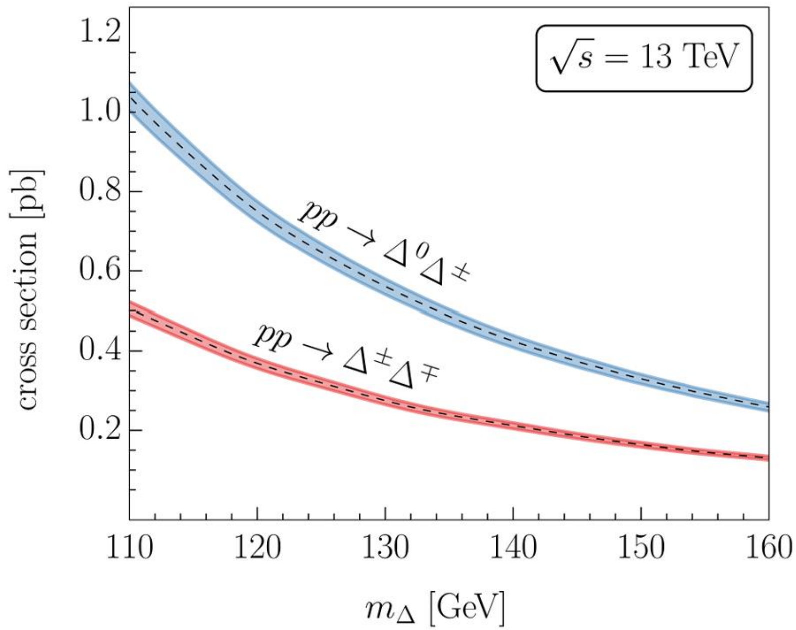


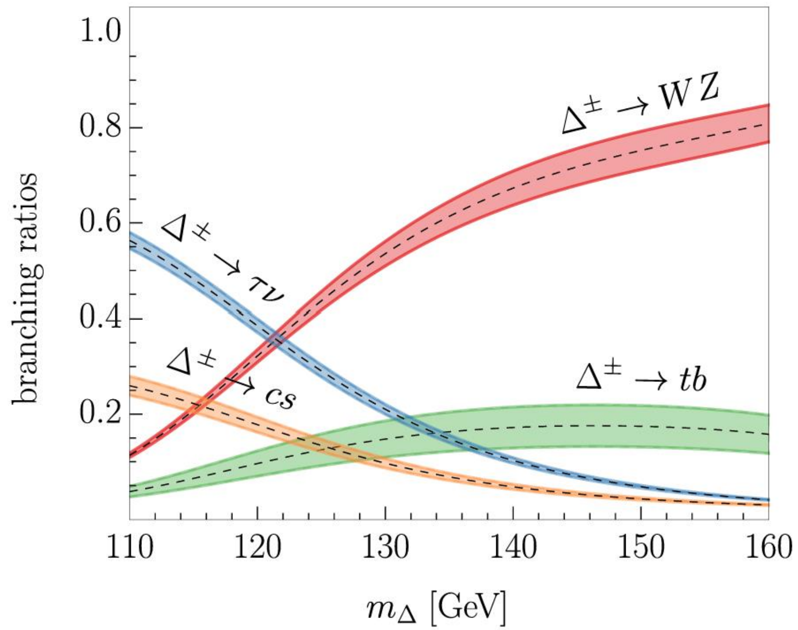
Triplet or Doublet?

Is the 152 GeV Higgs a Triplet (Δ)?

- Δ^0 decays dominantly to WW
- Positive shift in the W mass as preferred by the EW fit
- Quasi degenerate in mass



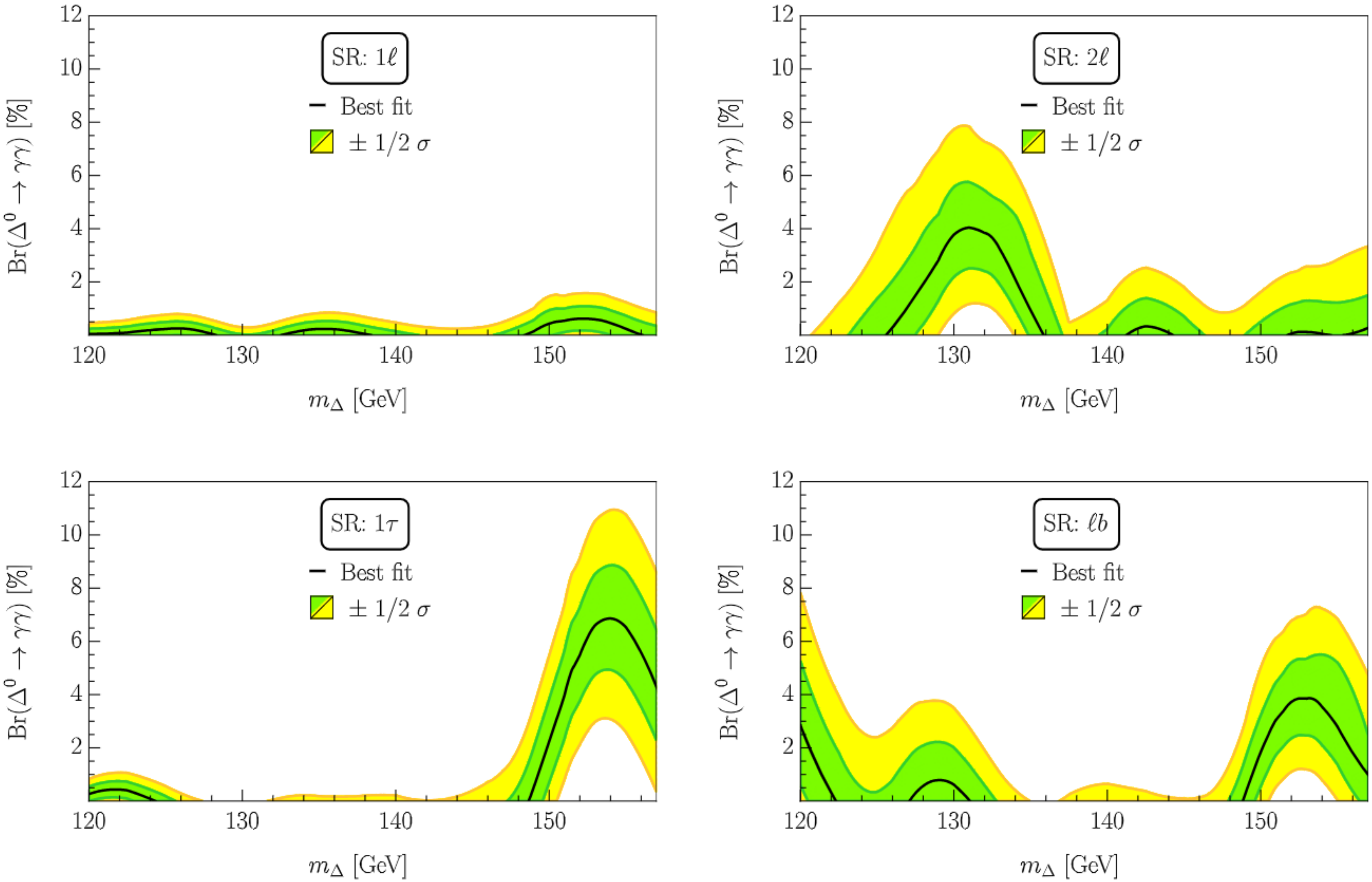




Drell-Yan production at the LHC

h⟶γγ+X from ATLAS

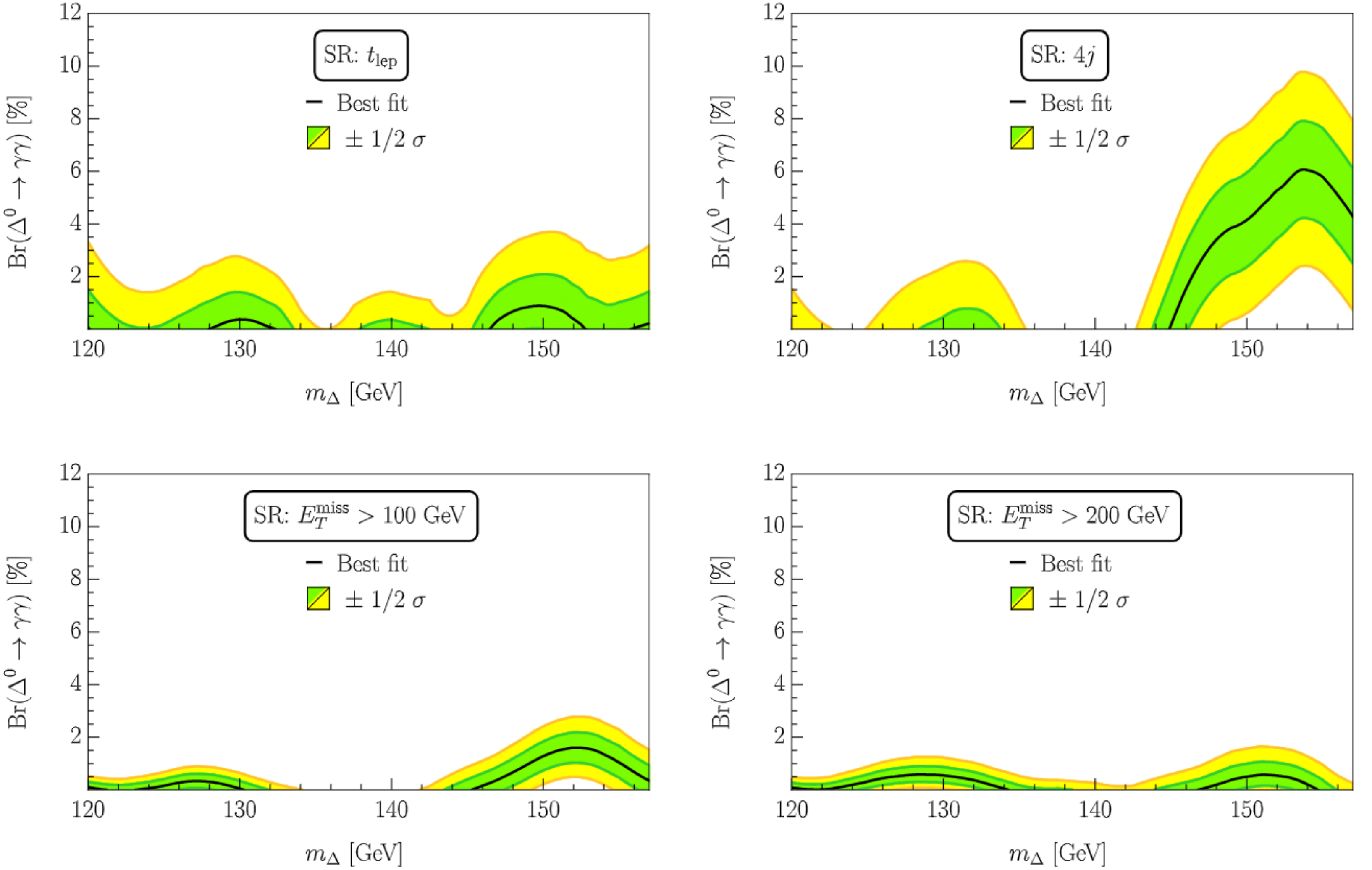
S. Ashanujjaman, S. Banik, G. Coloretti, A.C. S. P. Maharathy, B. Mellado, 2404.14492



Triplet consistently explains h→γγ+X excesses

h→γγ+X Channels

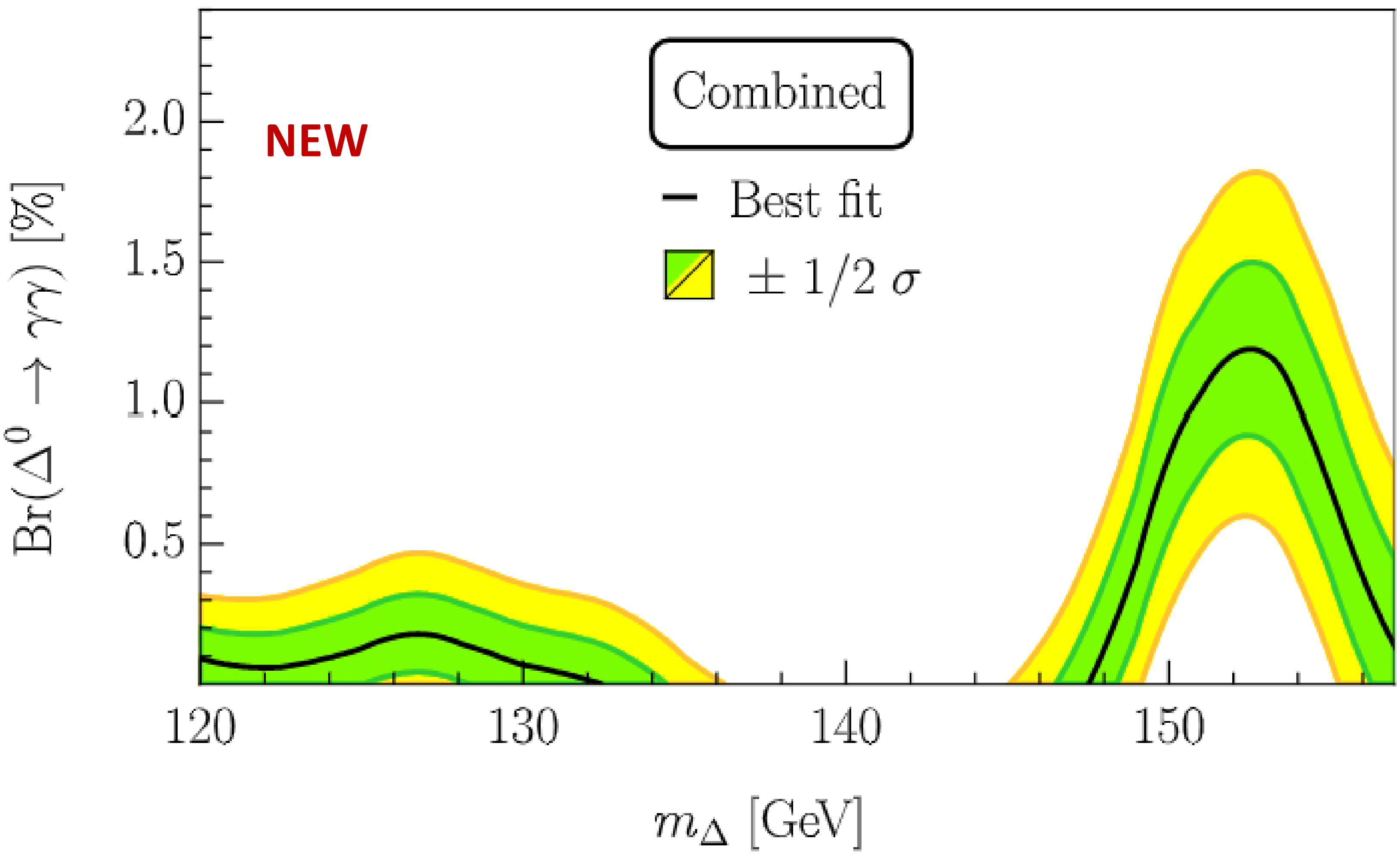
S. Ashanujjaman, S. Banik, G. Coloretti, A.C. S. P. Maharathy, B. Mellado, 2404.14492



Triplet consistently explains h→γγ+X excesses

Combination

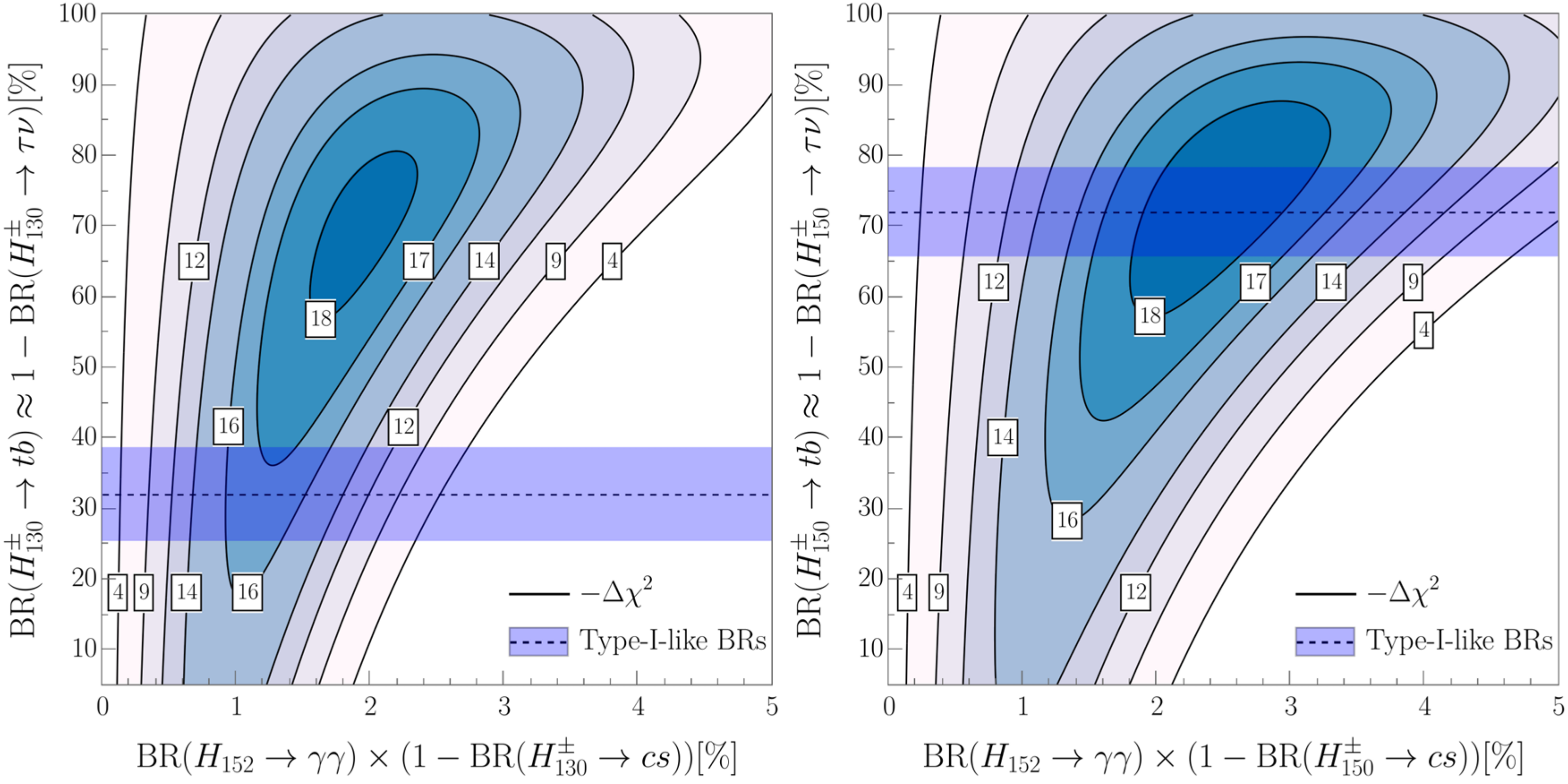
S. Ashanujjaman, S. Banik, G. Coloretti, A.C. S. P. Maharathy,
B. Mellado, 2404.14492



≈4σ excess at 152GeV

Two-Higgs Doublet Model type-I

- $\text{Br}\left(H^{\pm} \to WZ\right) = 0$ (at tree-level)

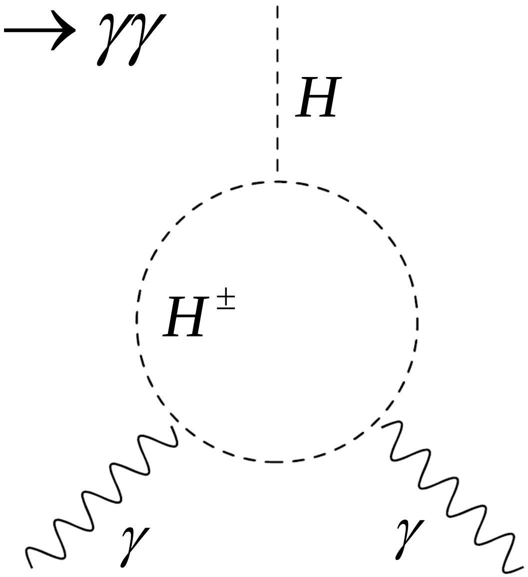


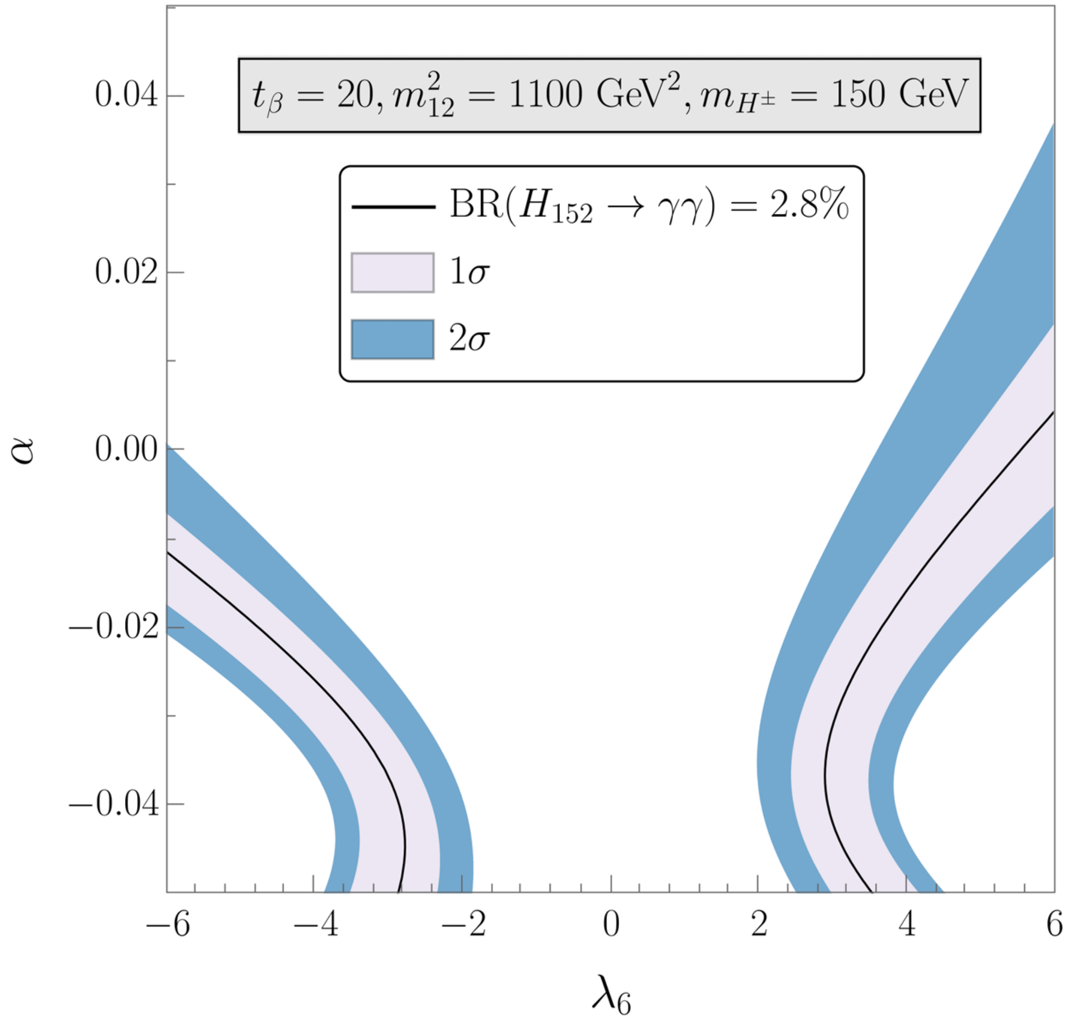
Above 4σ, large Br needed

Large Br(H_{152}→γγ) via Z_2 breaking in 2HDMs

$\lambda_6 H_1^\dagger H_1 H_2^\dagger H_1$

- Dominant effect in
  $H \to \gamma\gamma$
  but suppressed in
  $h \to \gamma\gamma$





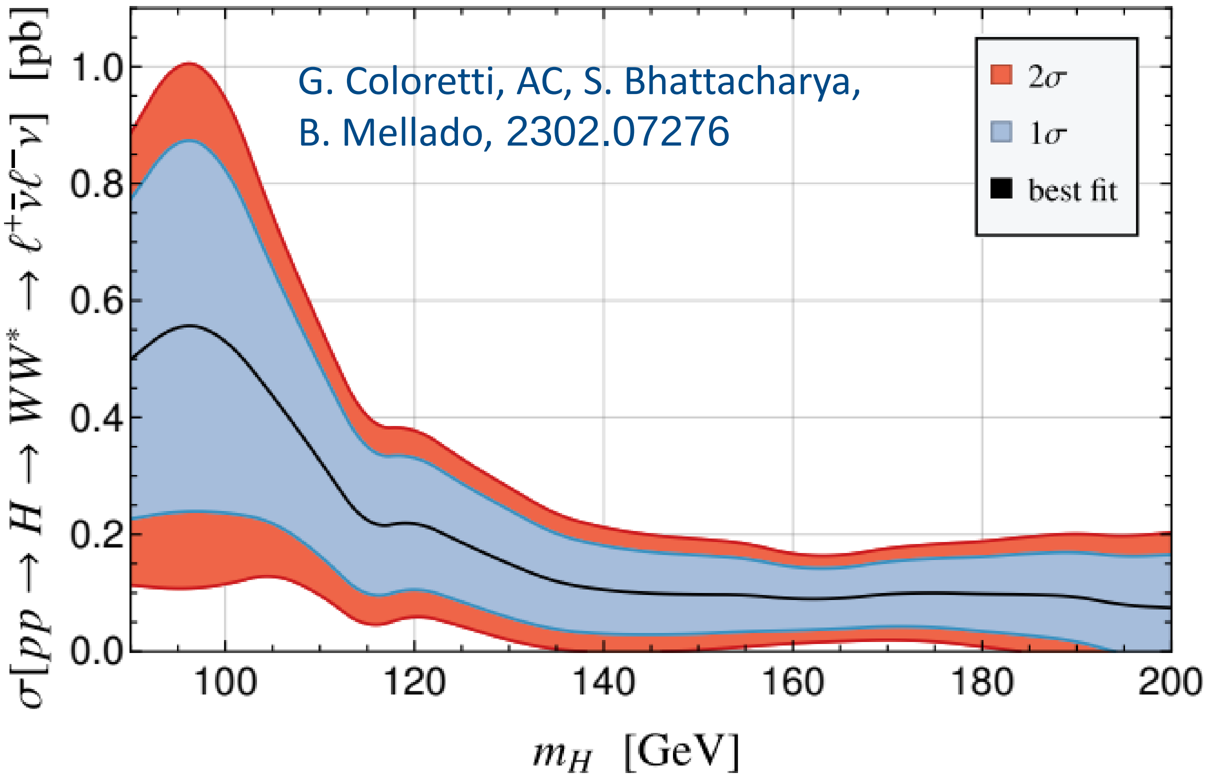
Consistent with vacuum stability, perturbativity

Multi-lepton anomalies

Dominant SM process(es)	Experimental signature	New Physics contamination
$WW, h \to WW$	$e^{\pm}\mu^{\mp} + \not{E}$	$H \to WW, H \to SS' \to WW + \text{MET}$ $H \to (N \to W\ell)\nu$
tt, tW	$e^{\pm}\mu^{\mp} + \geq 1b$	$H \to SS' \to WWbb, A \to W(H \to tb)$ $T\overline{T} \to bb(H^{+} \to t\bar{b})(H^{-} \to \bar{t}b)$
$ttW, tttt$	$\ell^{\pm}\ell^{\pm}, 3\ell + \geq 1b$	$A \to W(H^{\pm} \to tb), tt(H \to tt)$ $A \to Z^{*}(H \to tt), tt(H \to WW)$
$3W, W(h \to WW)$	$\ell^{\pm}\ell^{\pm}, 3\ell + \not{E}$	$A \to Z^{*}(H \to WW)$ $NN \to WW\ell\ell, W(H \to WW)$
ZW	$(Z \to \ell\ell) + \ell + \not{E}$	$A \to Z(H \to WW)$ $NN \to Z\nu W\ell$

Low mass WW resonances searches

- ATLAS and CMS combination

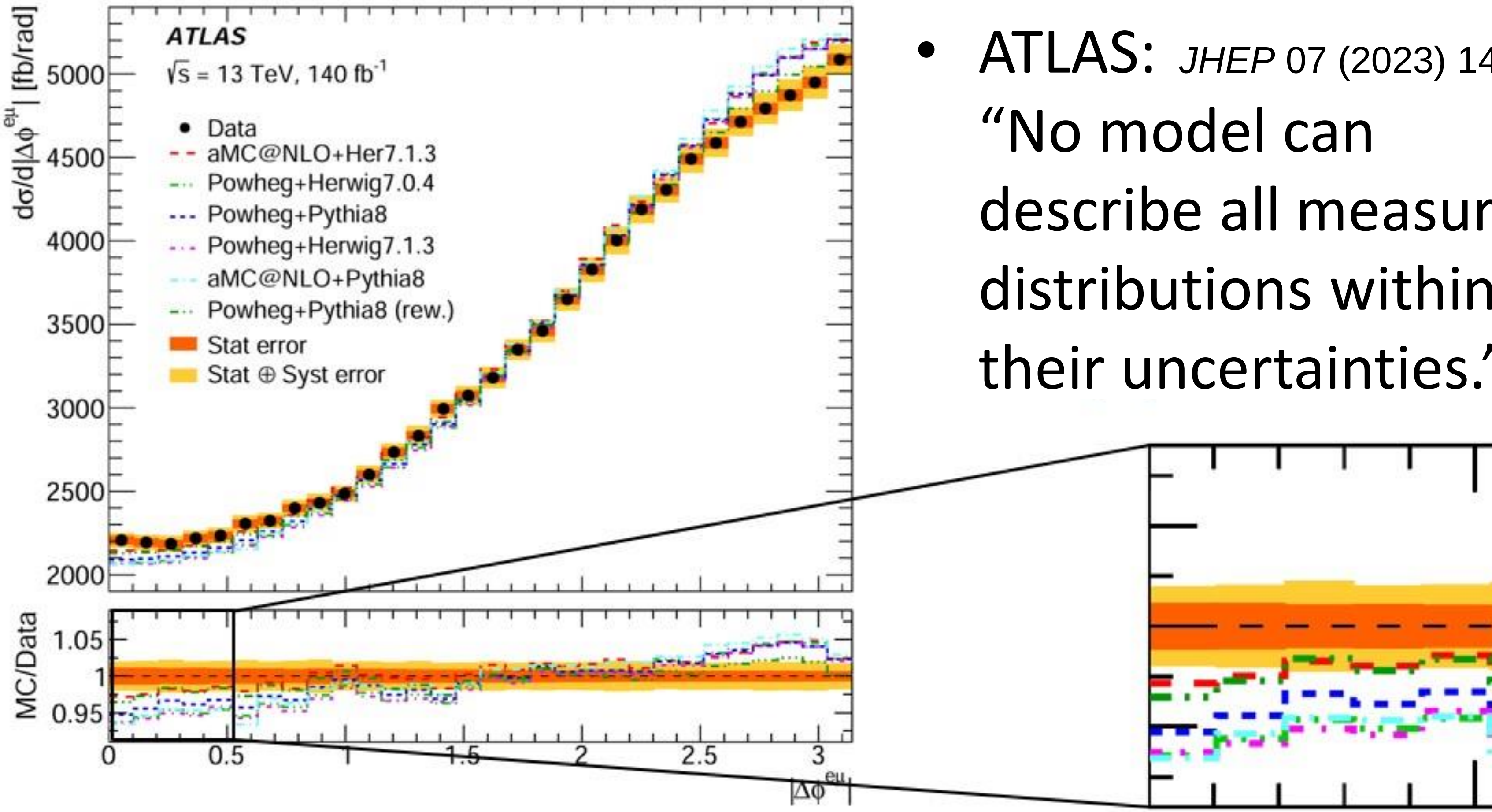


Transverse mass sensitive to additional missing energy from associated production

- New physics effect preferred over the whole range

Related to 95GeV and 151GeV?

Differential Top-Quark Distributions

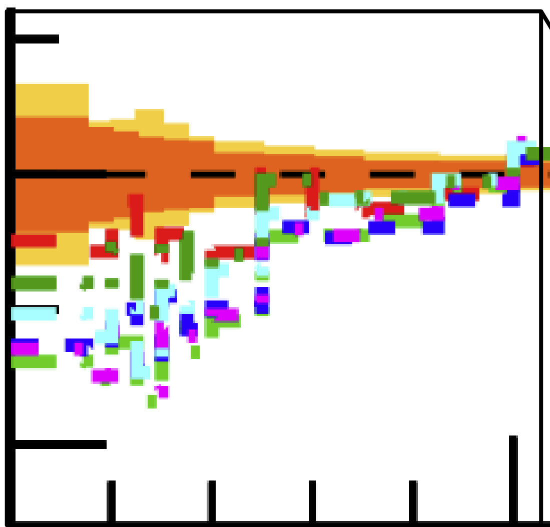


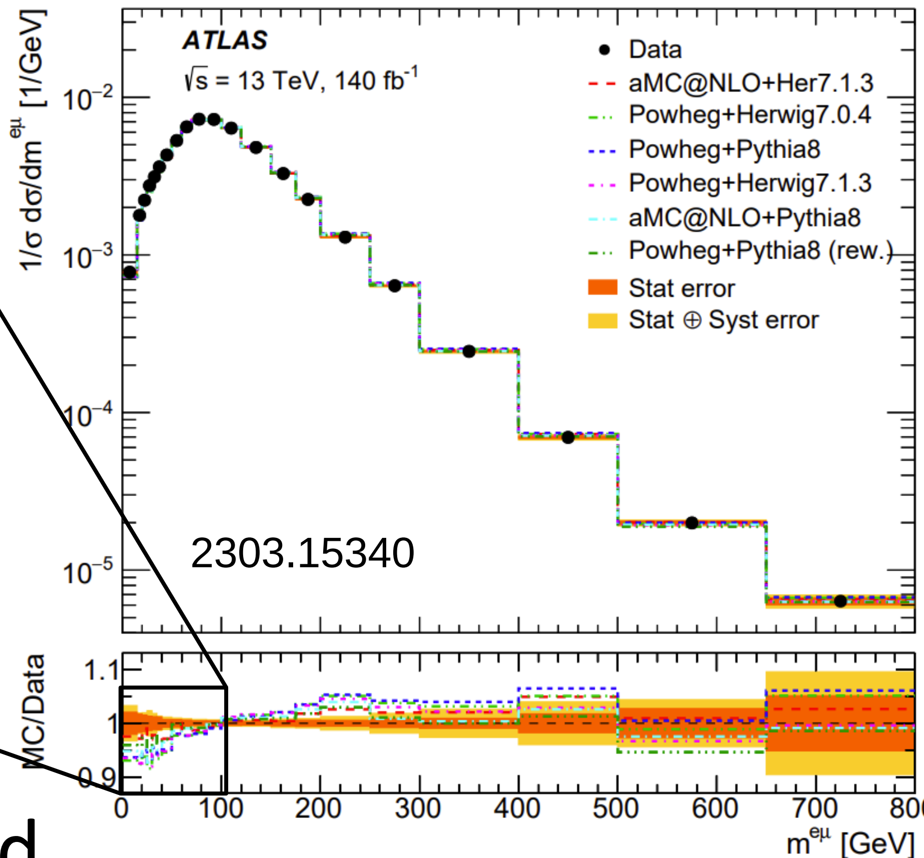
- ATLAS: *JHEP* 07 (2023) 141
  "No model can describe all measured distributions within their uncertainties."

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

New Physics pollution of this SM measurement?

Differential Top-Quark Distributions



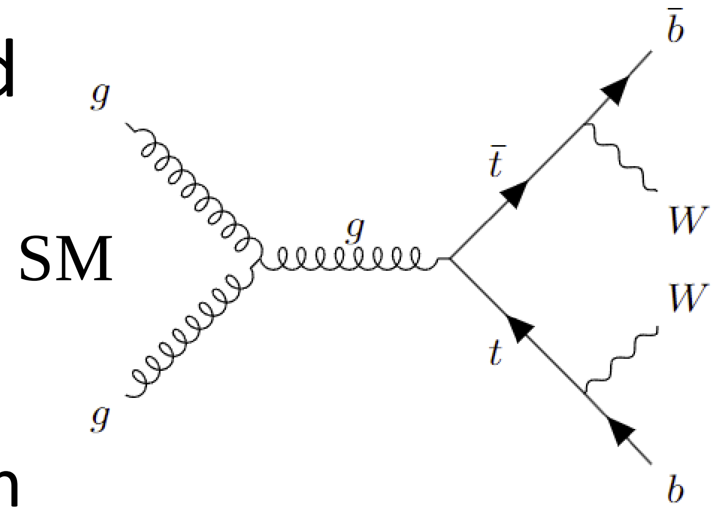


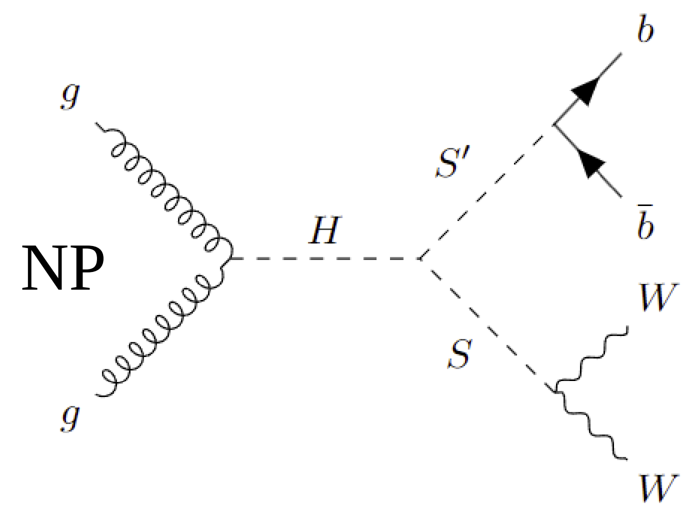
- ATLAS:
  "No model can describe all measured distributions within their uncertainties."

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



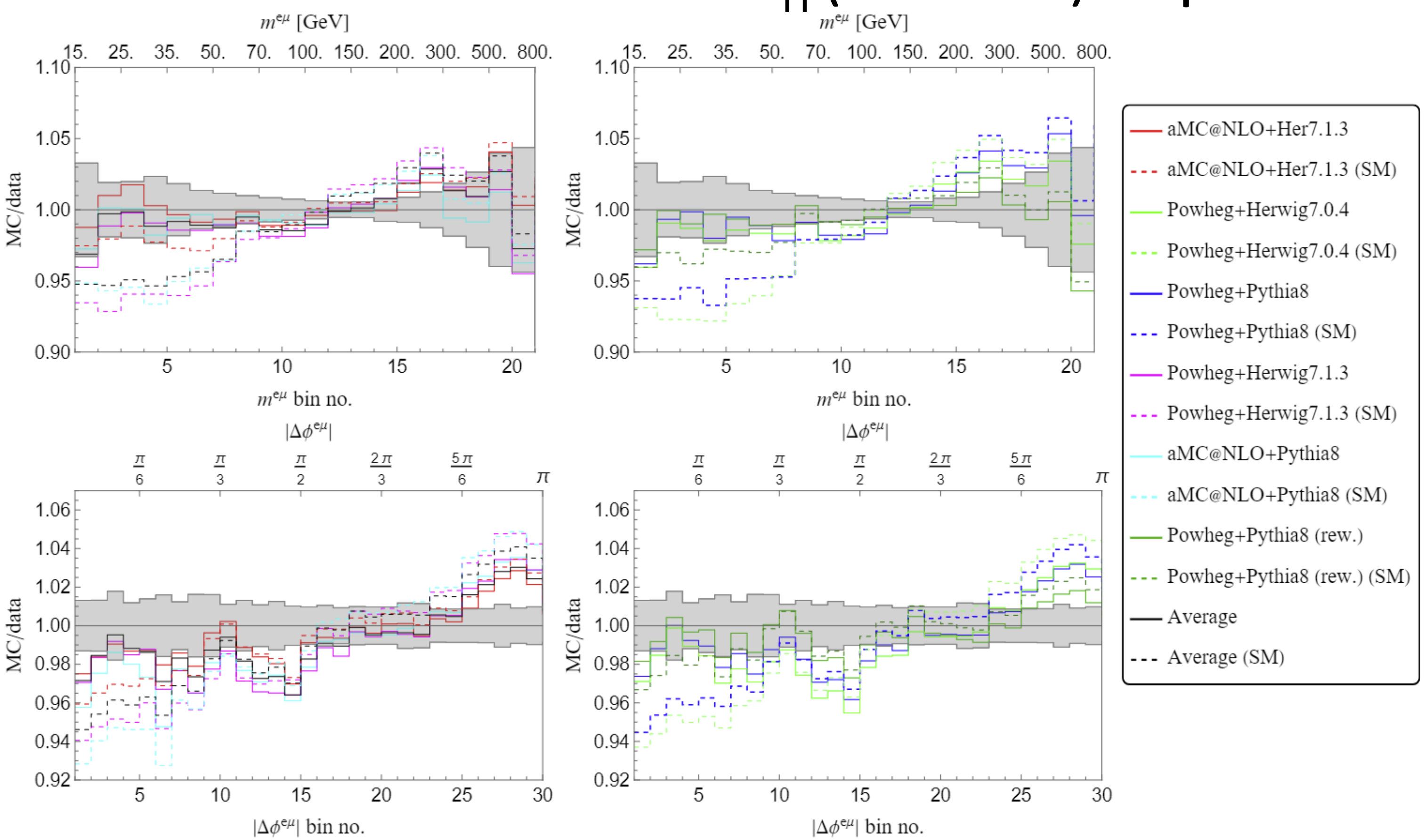


Related to the 95 GeV and 151.5 GeV hints?

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.



Deficit at large $\Delta\phi^{e\mu}$ & $m^{e\mu}$ explained as well

Simplified Model: H→SS'→WWbb

2308.07953

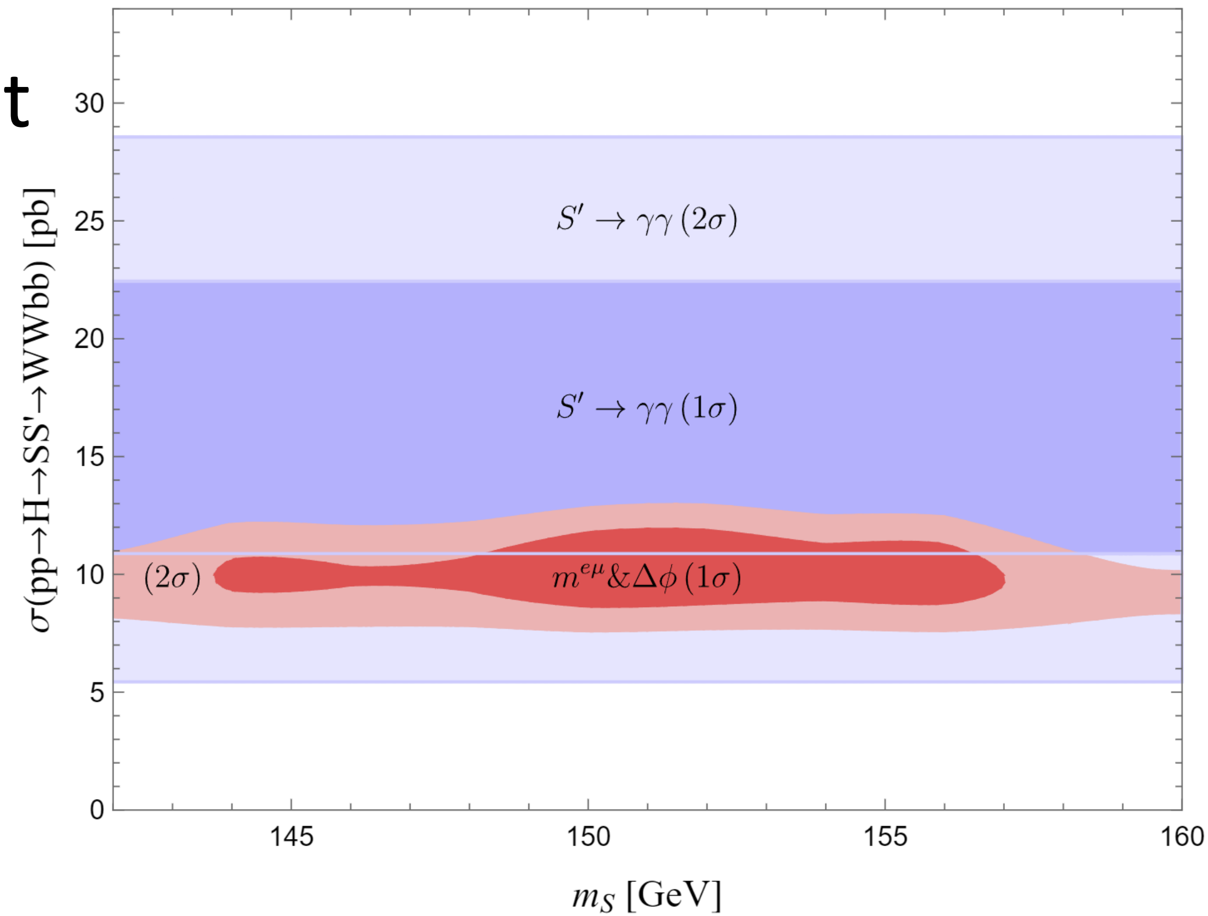
Monte Carlo	χ^2_{SM}	χ^2_{NP}	σ_{NP}	Sig.	m_S[GeV]
Powheg+Pyhtia8	213	102	9pb	10.5σ	$143-156$
aMC@NLO+Herwig7.1.3	102	68	5pb	5.8σ	$--$
aMC@NLO+Pythia8	291	163	10pb	11.3σ	148-157
Powheg+Herwig7.1.3	261	126	10pb	11.6σ	149-156
Powheg+Pythia8 (rew)	69	35	5pb	5.8σ	$--$
Powheg+Herwig7.0.4	294	126	12pb	13.0σ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

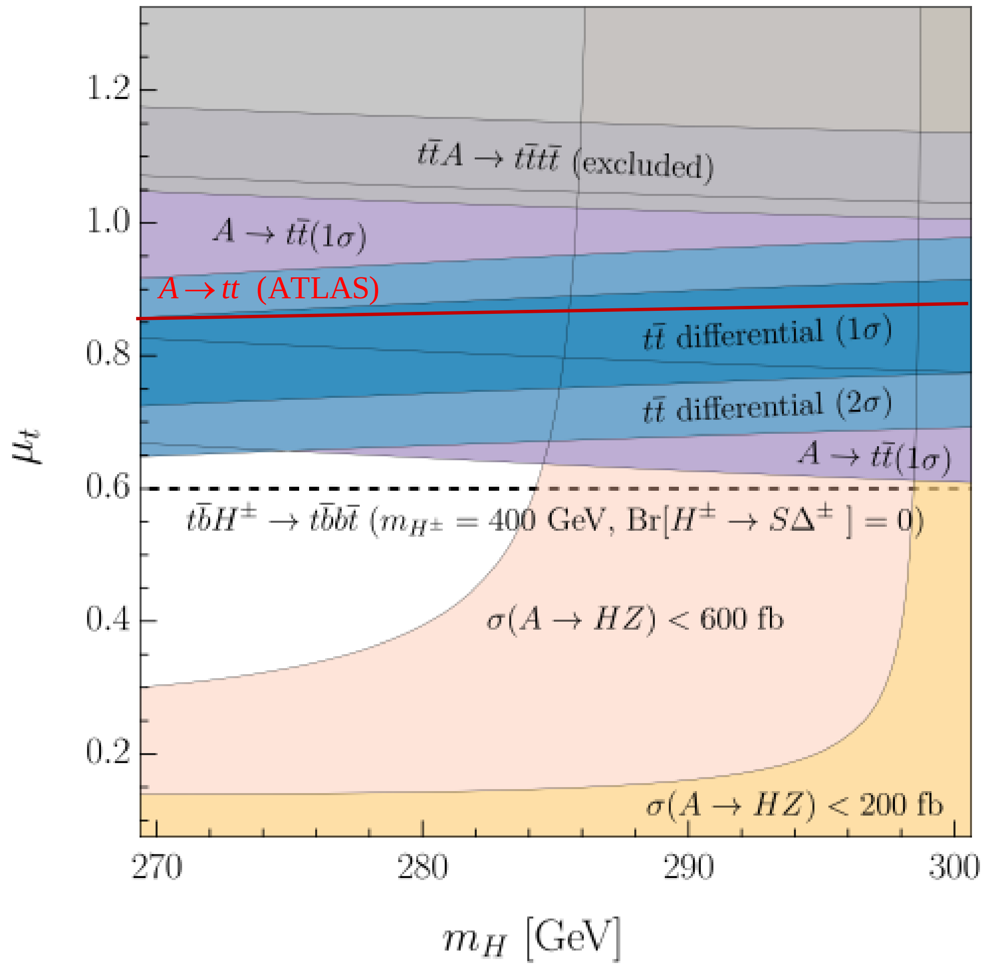


Consistent with 95 GeV γγ signal strength & a mass of S with 151.5 GeV

Δ2HDMS and top-quark production

Field	$SU(2)_L$	$U(1)_Y$
ϕ_s	1	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

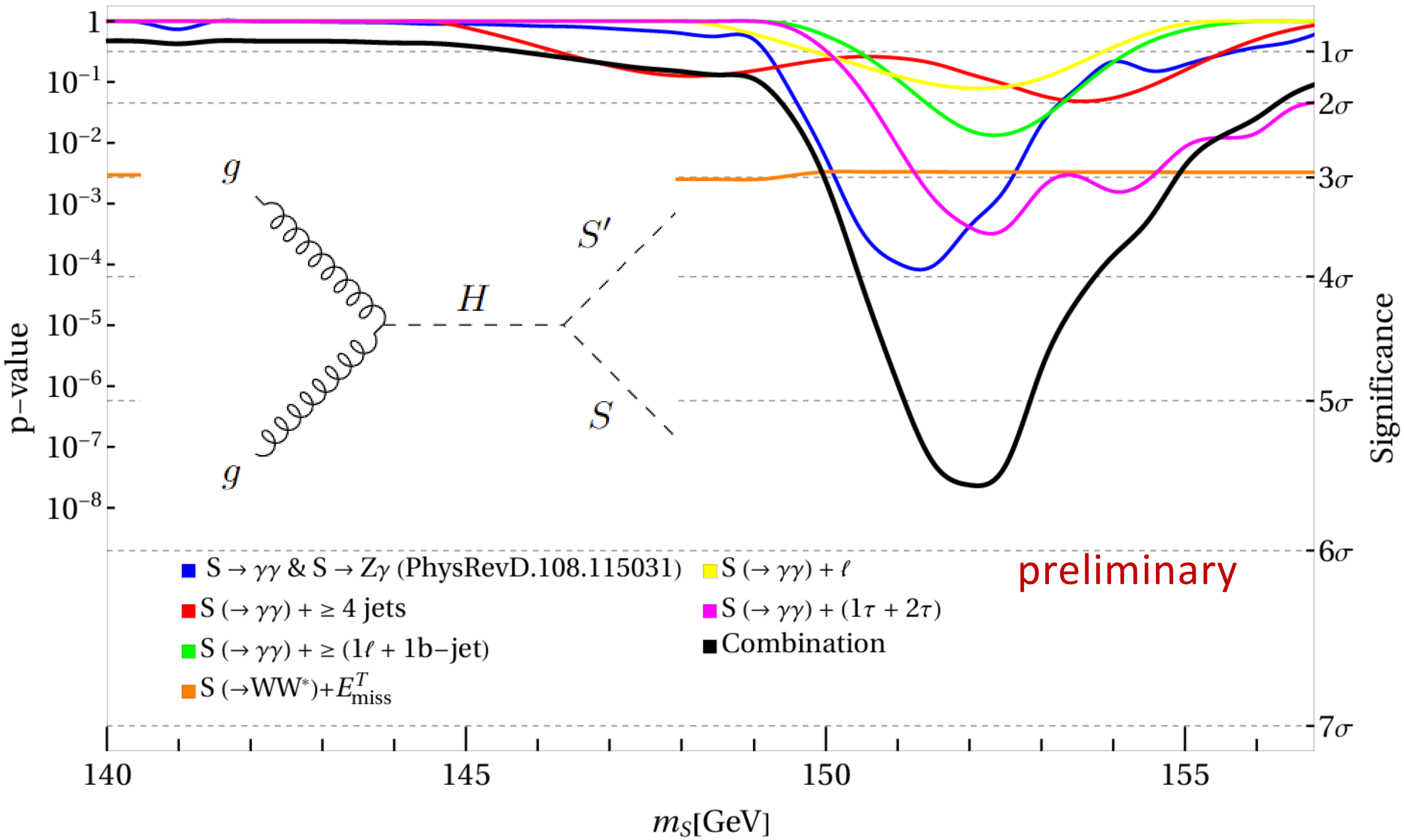
Conclusions

- Hints for narrow resonances at 95 GeV & 152 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?
- 152 GeV decays dominantly to WW ➡ triplet?
- γγ+X excesses consistent with DY production of triplet
- Doublet alternative option

Most significant hints for new particles at the LHC

Hints for new Scalars at 152 GeV

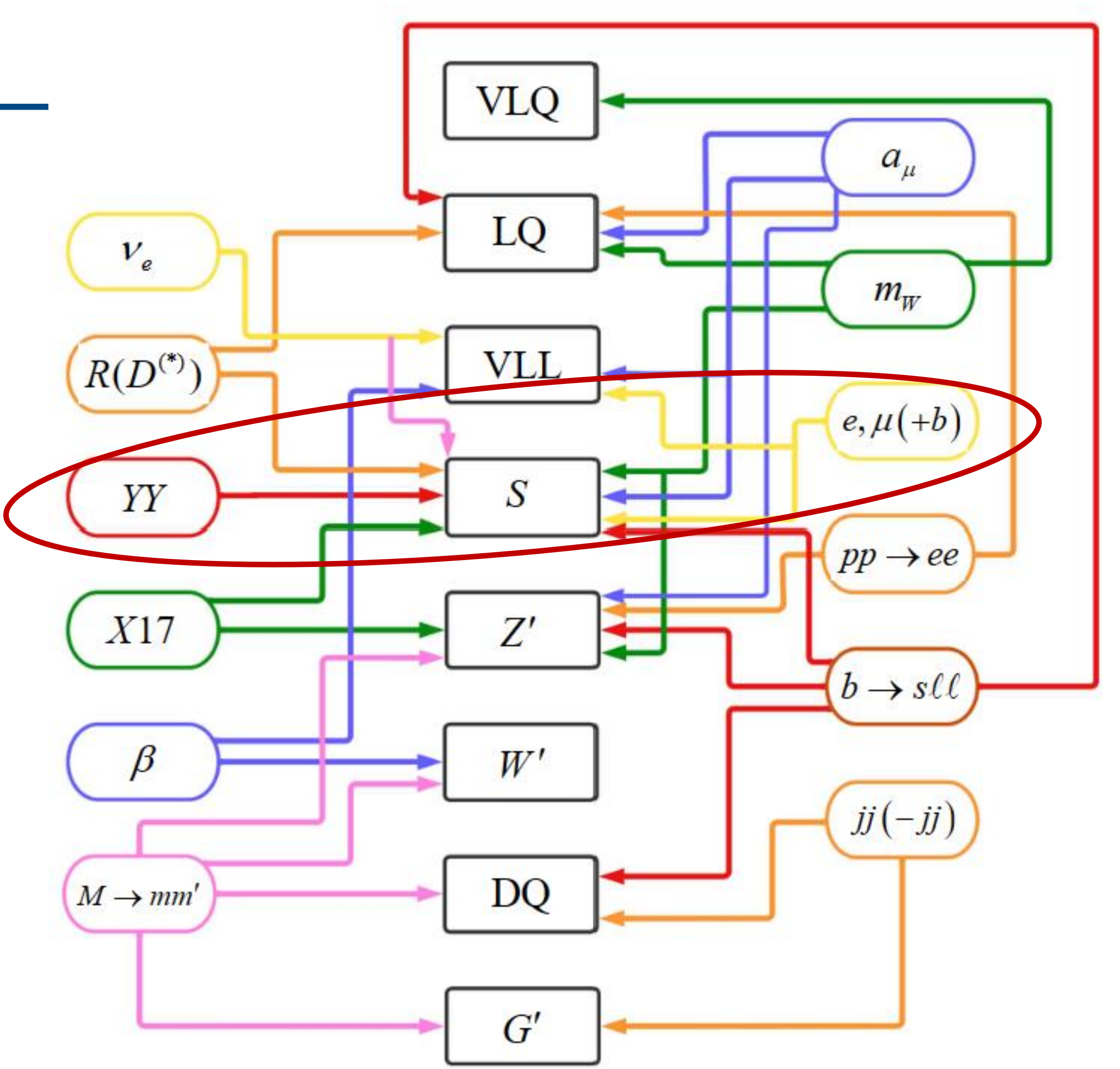
- Combination within the simplified model
  H→SS* with S→WW, MET, γγ



>5σ global significance for simplified model

Outlook

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



The Standard Model is crumbling

Backup

Multi-leptons history

PAUL SCHERRER INSTITUT PSI

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

Multi-lepton Anomalies

PAUL SCHERRER INSTITUT PSI

- 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	$W^\pm h(125), WWW$	$\gtrapprox 4\sigma$
$Z(\to \ell\ell)\ell$, (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