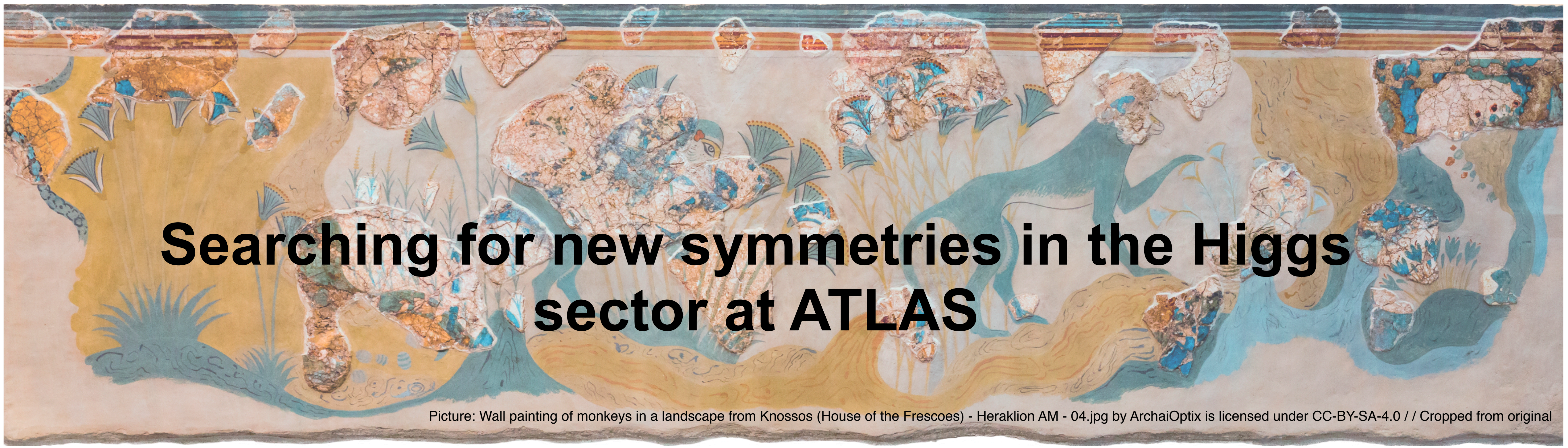


Searching for new symmetries in the Higgs sector at ATLAS

Shubham Bansal (shubham.bansal@cern.ch)
on behalf of the ATLAS collaboration

XII International Conference on New Frontiers in Physics (ICNFP), Kolymbari, Crete, Greece
July 14, 2023

ATLAS EXPERIMENT

UNIVERSITÄT BONN

ICNFP

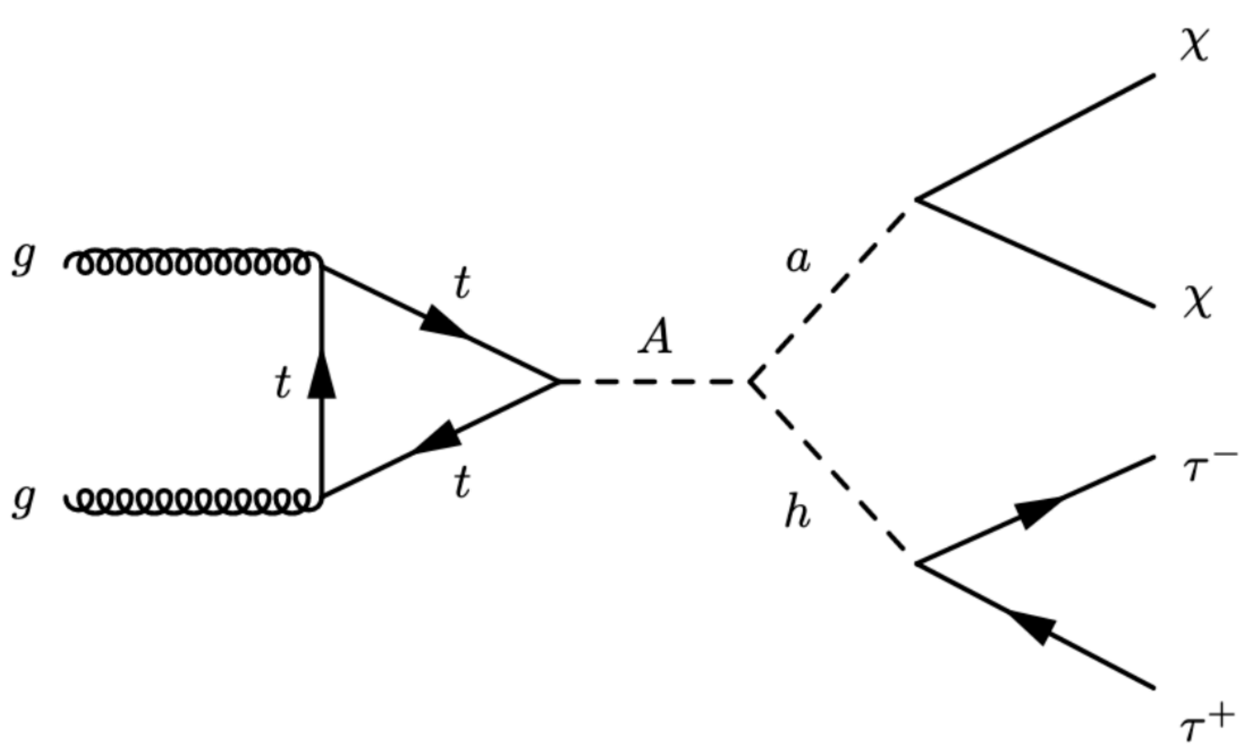
Bundesministerium für Bildung und Forschung

FSP ATLAS
Erforschung von Universum und Materie

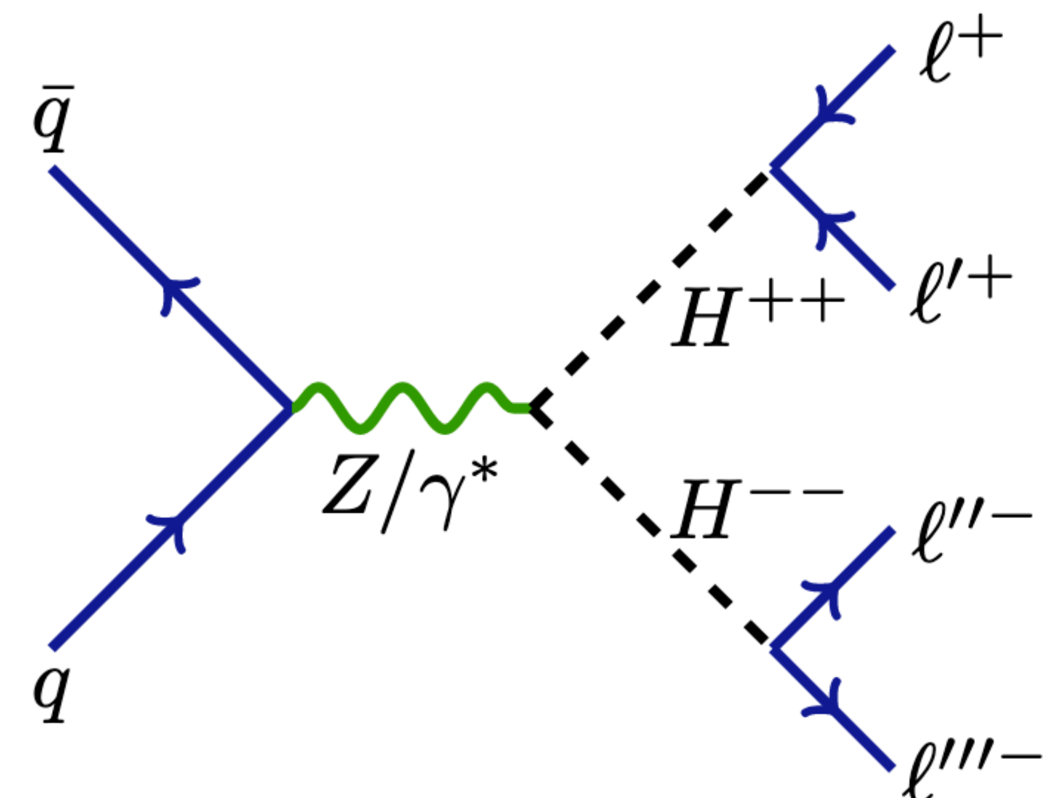
Higgs: a paradigm of new Physics

- Electroweak symmetry breaking (EWSB) well established by Higgs mechanism of Standard Model (SM)
- SM in agreement with experiments, though cannot explain dark matter (DM), matter asymmetry, smallness of neutrino masses, and many others

- Some of them can be addressed in Beyond Standard Model (BSM) scenarios, like:
  - 2 Higgs doublet model (2HDM): $h, H, A, H^{\pm}$
  - 3HDM: 2 additional Higgs doublet; Georgi-Machacek (GM) Model: 1 Higgs doublet + 2 triplets



Pseudo-scalar *a* couples to DM candidate (χ)



Doubly charged Higgs H^{++}:predicted in neutrino models

Analyses covered in this talk

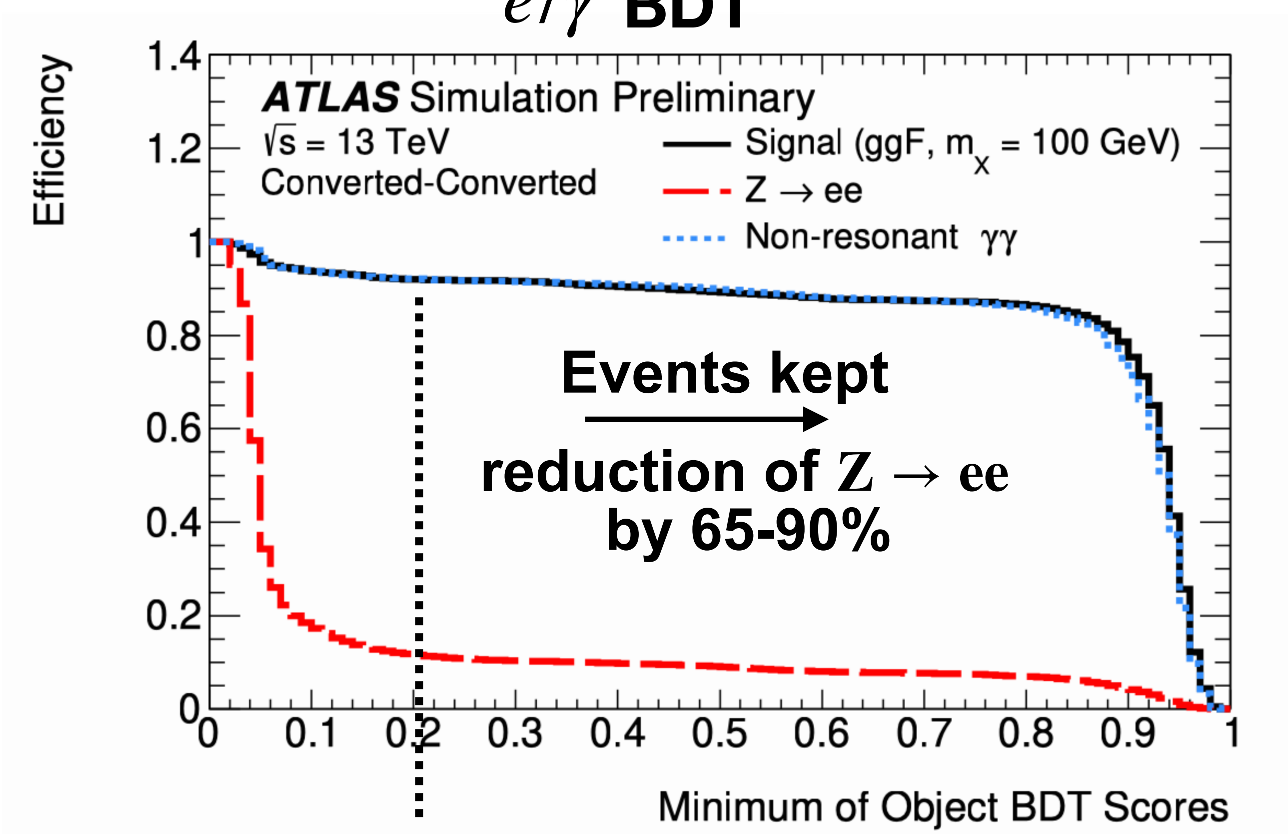
- Multitude of BSM searches involving Higgs sector within ATLAS: Public Results
- **Low and high mass searches with neutral Higgs:**
  - Low mass $H/X \to \gamma\gamma$ [ATLAS-CONF-2023-035]
  - High mass $X \to Z\gamma$ [ATLAS-CONF-2023-030]
- **Searches involving neutral Higgs/pseudo-scalar in more complex systems:**
  - $X \to SH \to VV\tau\tau$ [ATLAS-CONF-2023-031]
  - $A \to ZH$ [ATLAS-CONF-2023-034]
  - $a \to \mu\mu$ in $t\bar{t}$ events [arXiv:2304.14247, Submitted to Phys. Rev. D]
- All searches use full Run-2 dataset (centre-of-mass energy = 13 TeV *p-p* collisions) with integrated luminosity of 140 fb^{-1}
- Closely related talks:
  - "Searches for BSM resonances in ATLAS", by Monica Verducci
  - "Searches for Dark Matter with the ATLAS Experiment at the LHC", by Tae Min Hong

Low mass H/X $\rightarrow \gamma\gamma$

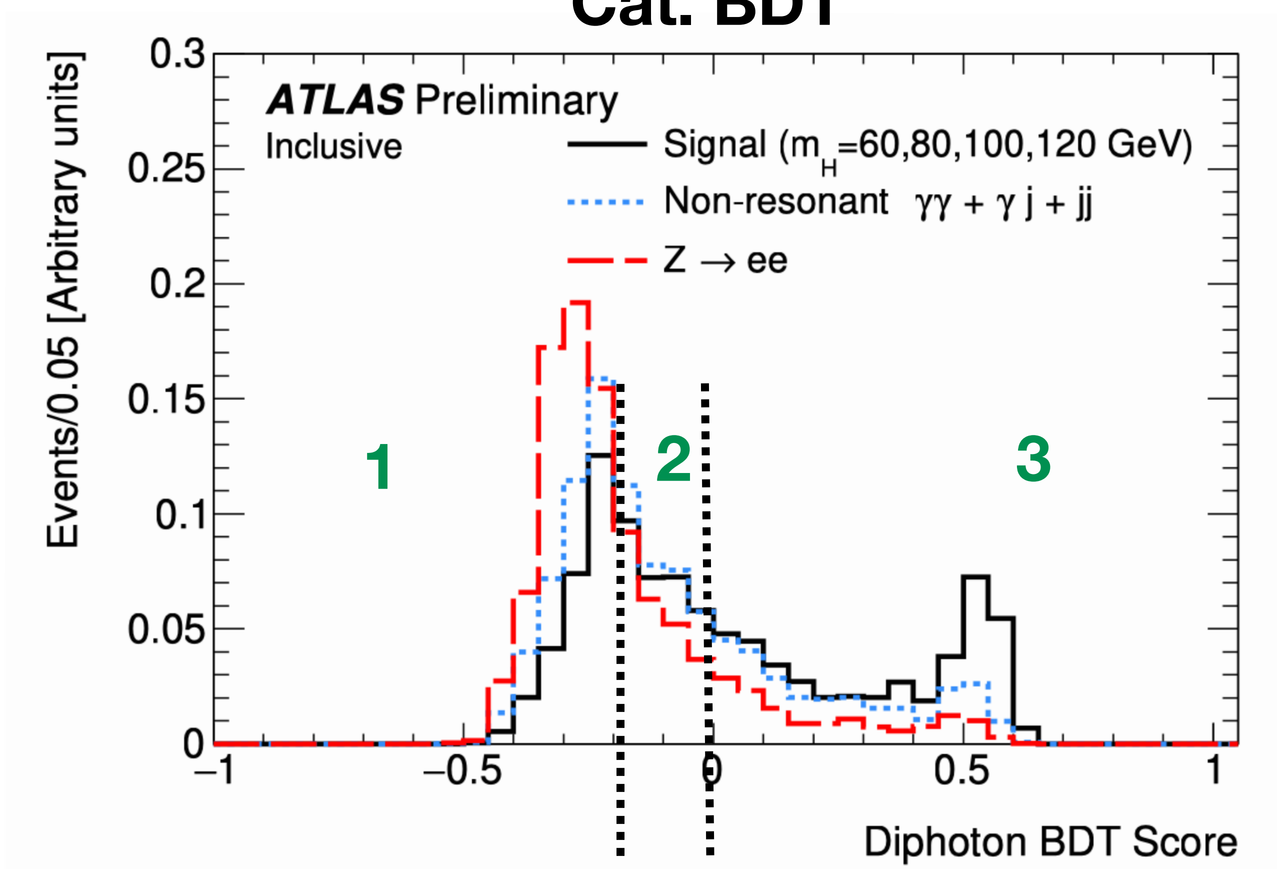
ATLAS-CONF-2023-035

- 2 different measurements: Generic spin-0 $m_X = 66 - 110$ GeV (**model independent**), and $m_h < 125$ GeV **(model dependent)**
- Backgrounds: **non-resonant background** ($\gamma\gamma$ / γ jet / jet jet), **Drell-Yan** ($Z \rightarrow ee$) process
- 2 types of Boosted Decision Trees (BDTs) used: e/γ classification BDT to reduce e- fakes, signal (**S**) / background (**B**) categorisation BDT (cat. BDT)
- Different regions targeted based on photon conversion categories:
  - **model independent**: 3, UU, UC, CC [U = unconverted, C = converted]
  - **model dependent**: 9, {UU, UC, CC} $\times$ {3 **regions** of cat. BDT}

e/γ BDT



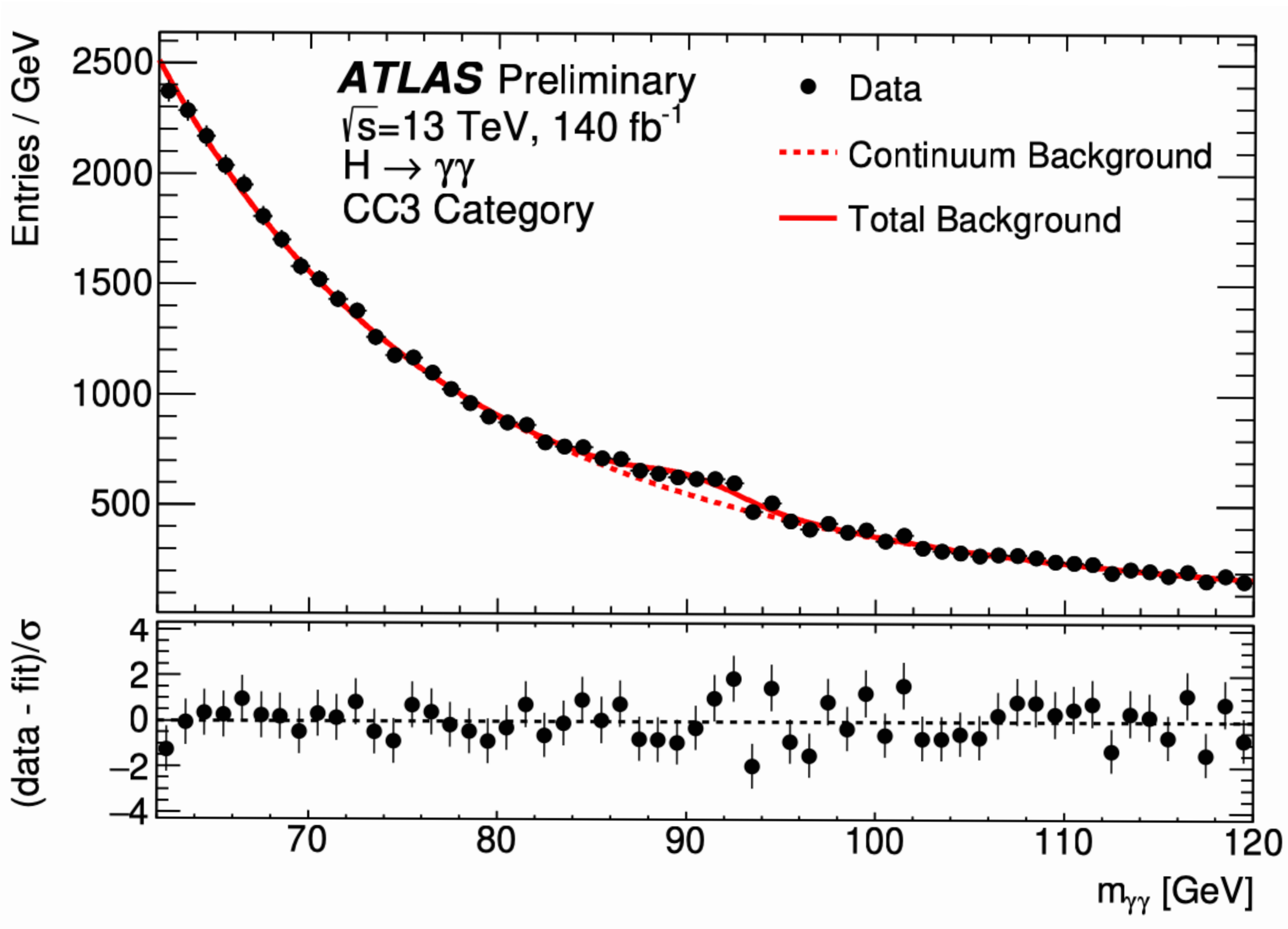
Cat. BDT



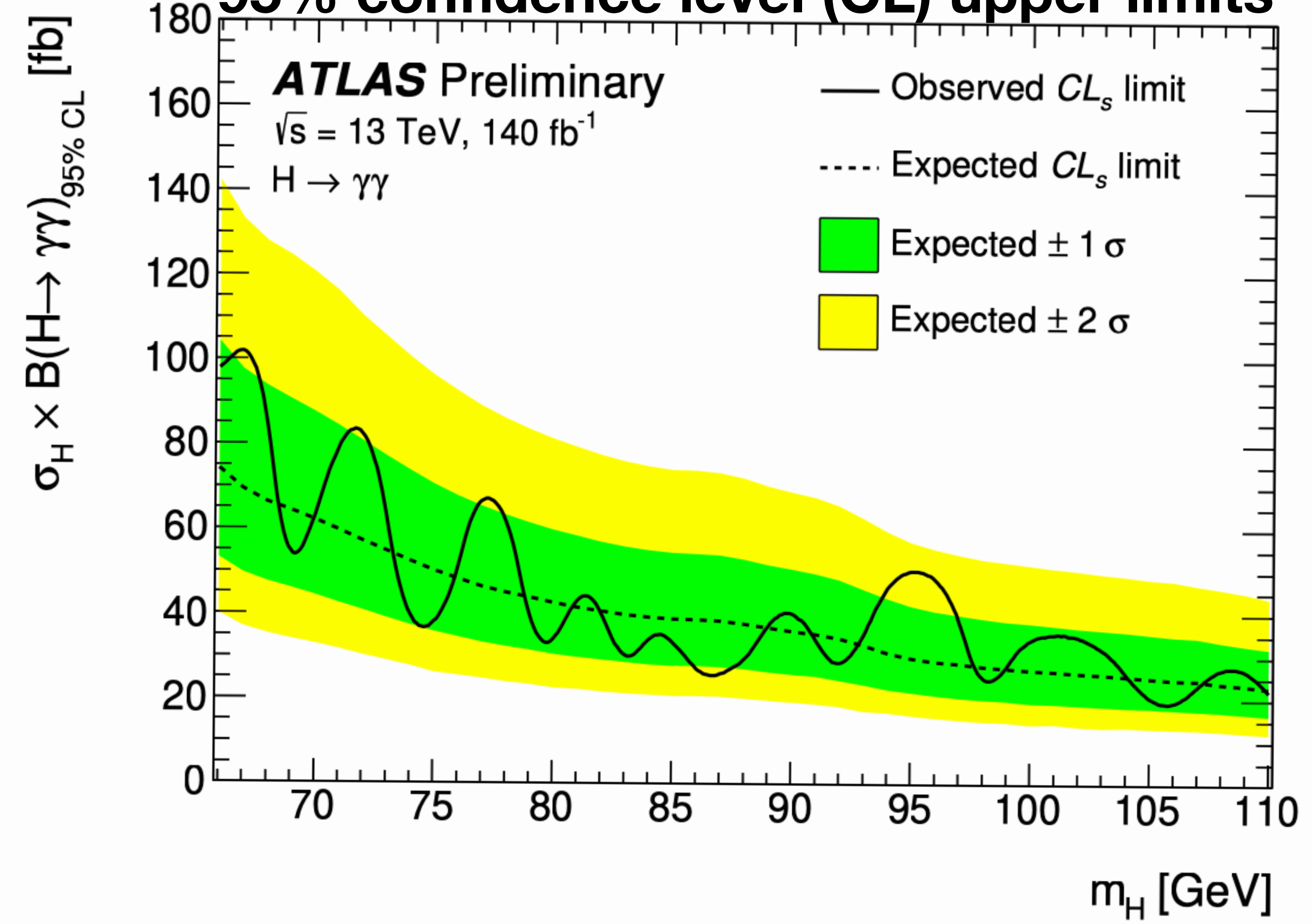
Low mass H/X $\rightarrow \gamma\gamma$

ATLAS-CONF-2023-035

- Fit variable: invariant mass of di-photon system, $m_{\gamma\gamma}$
- Signal and Drell-Yan background modelled by double-sided Crystal Ball (DSCB) function, non-resonant background modelled by exponentiated polynomials
- Search dominated by non-resonant background modelling uncertainties



Model dependent result
95% confidence level (CL) upper limits

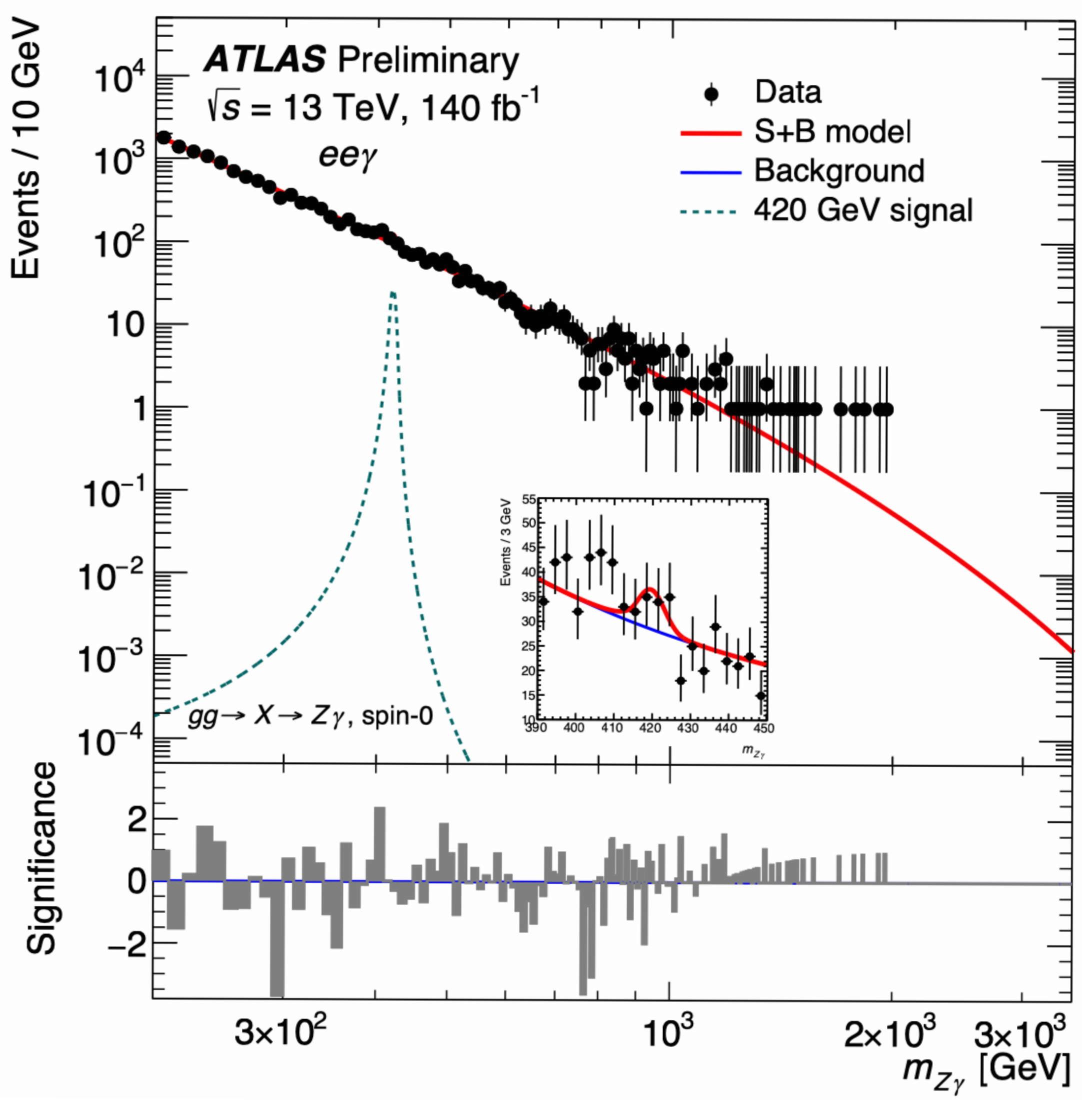


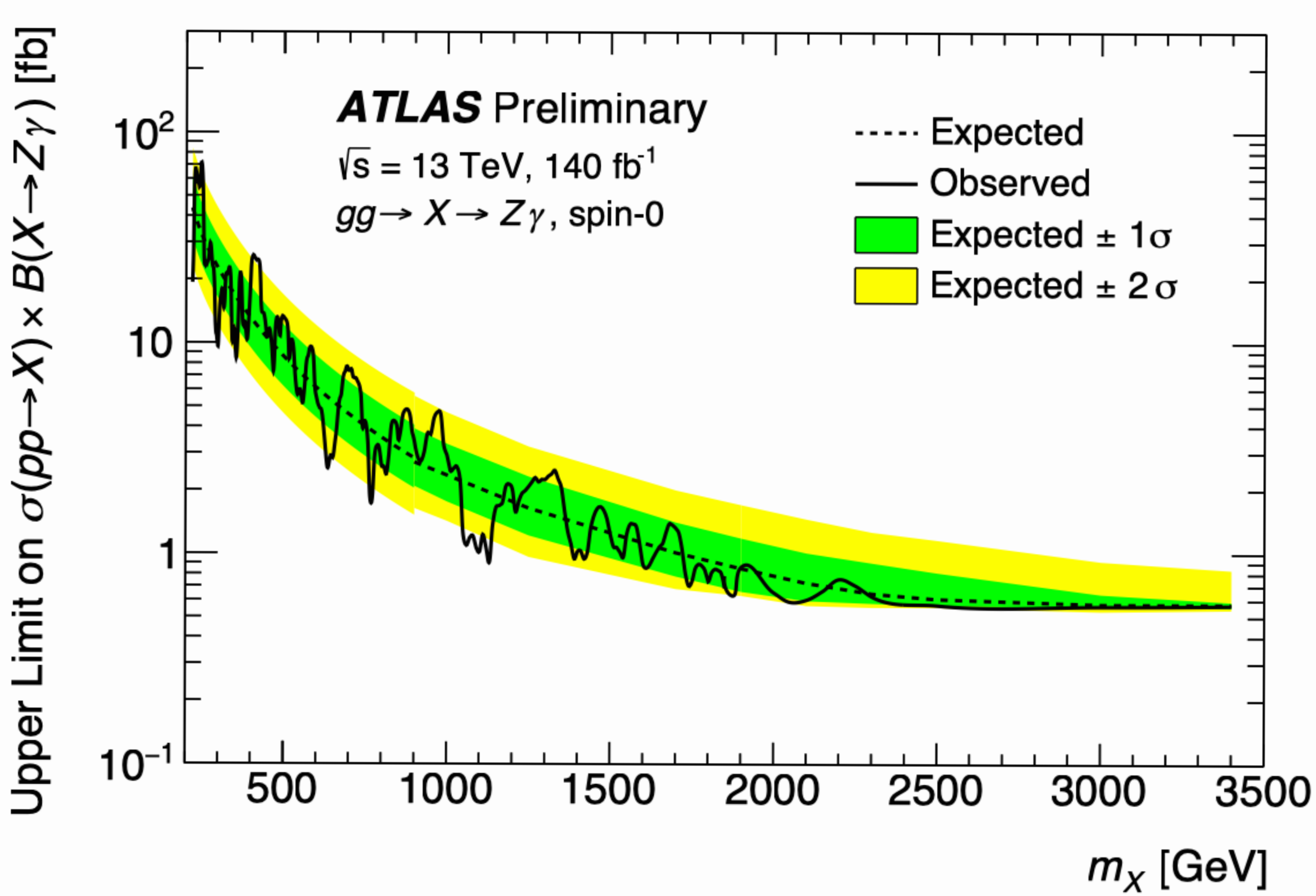
- No evidence of signal observed
- Predicted in Next-to-two Higgs doublet model (N2HDM), Axion-like-particles (ALP)..

High mass $X \to Z\gamma$

ATLAS-CONF-2023-030

- Generic spin-0 (*gg*) / spin-2 (*gg, qq*) $m_X = 220 - 3400$ GeV, $X \to Z(\to ll)\gamma, l = e/\mu$
- Dominant Background: **non-resonant $Z(\to ll)\gamma$, Z+jets**
- electron identification (ID) difficult at high masses due to large boost, use a **BDT based ID**: improve signal efficiency from 6% to 12.7%, at high masses, when merged with default ID
- Fit variable: $m_{Z\gamma}$, background modelling uncertainties forms the largest systematics, local excess of 2.3 σ observed at $m_X = 420$ GeV

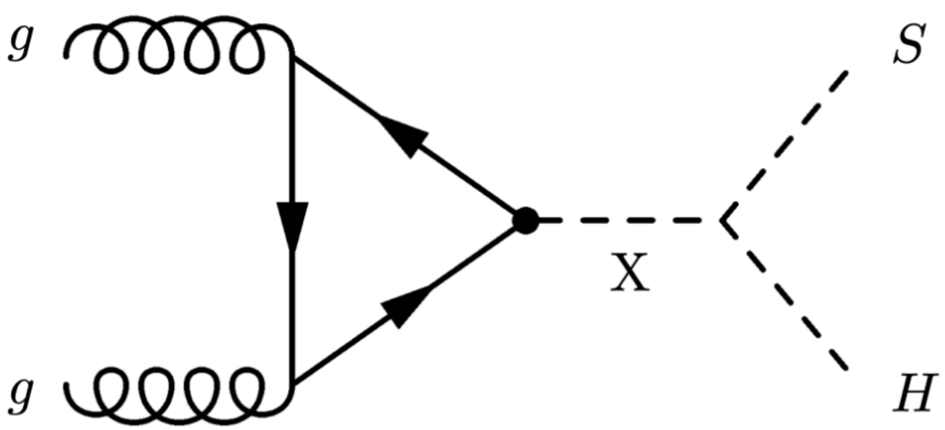




$X \to SH \to VV\tau\tau$

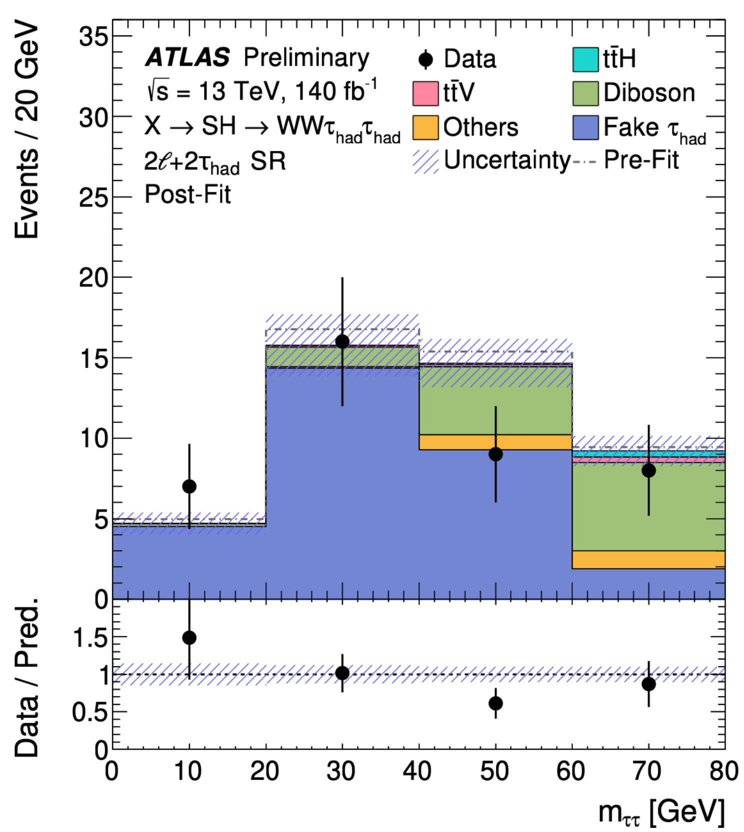
- $S \to WW/ZZ, H(125) \to \tau\tau$, probe high masses: $m_X = 500 - 1500$ GeV, $m_S = 200 - 500$ GeV

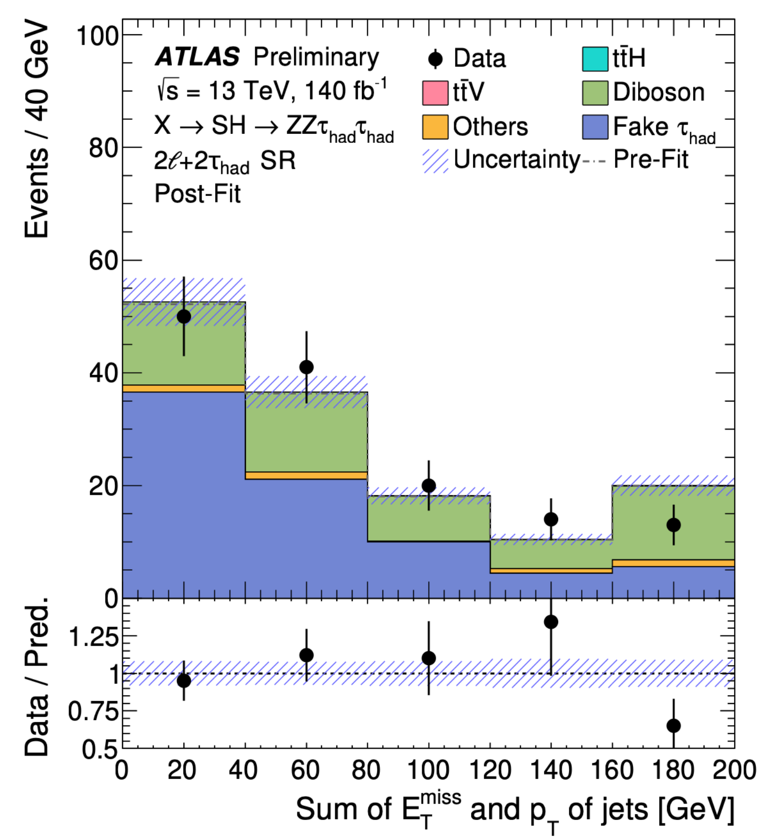
ATLAS-CONF-2023-031



S: generic high mass scalar
Focus on the most sensitive:
$1l2\tau_{had}/2l2\tau_{had}$ *+ jets final state*

- Dominant backgrounds: τ_{had} **-fakes** (data driven fake-factor method), **VV** (MC based)
- 3 **signal regions (SRs)**: $WW1l2\tau_{had}$, $WW2l2\tau_{had}$, $ZZ2l2\tau_{had}$ (2 leptons with opposite sign)
- BDTs used to separate **S** from **B**, parametrised in m_X for an m_S

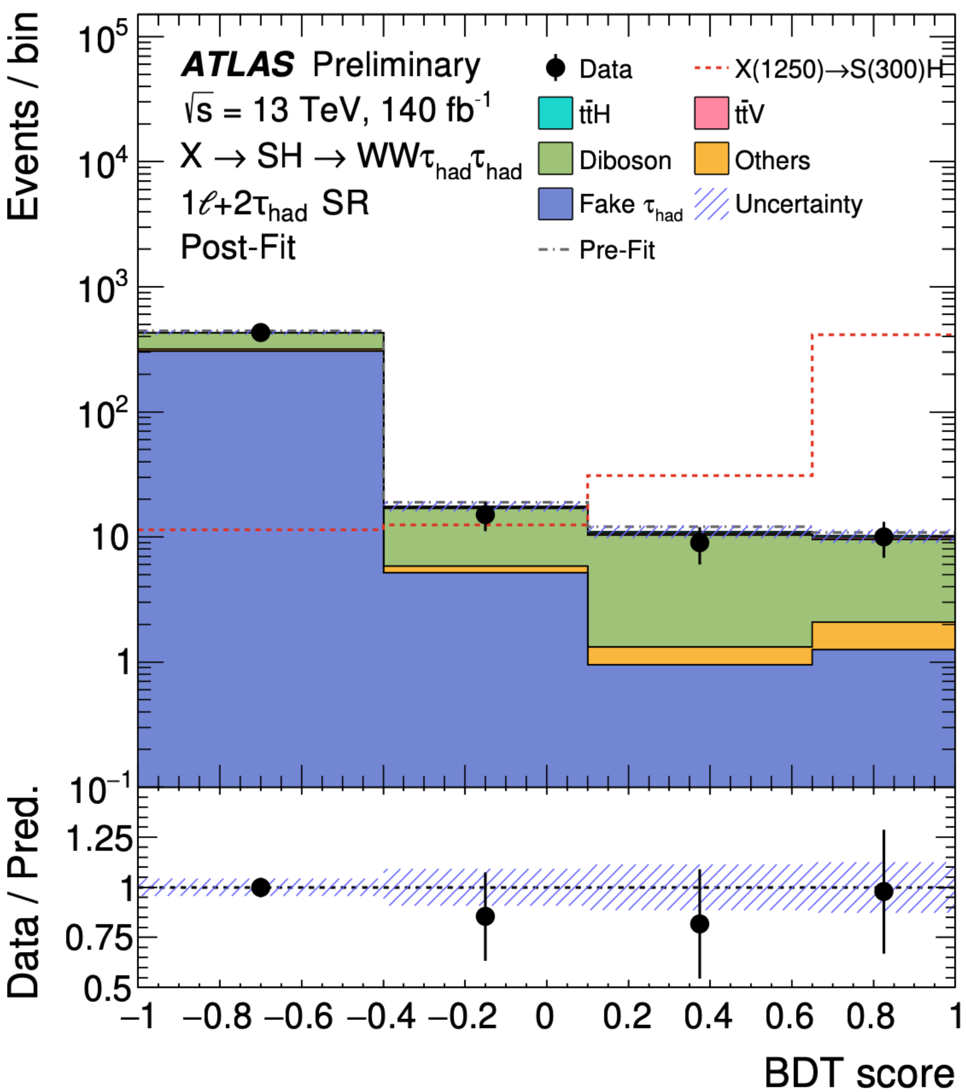


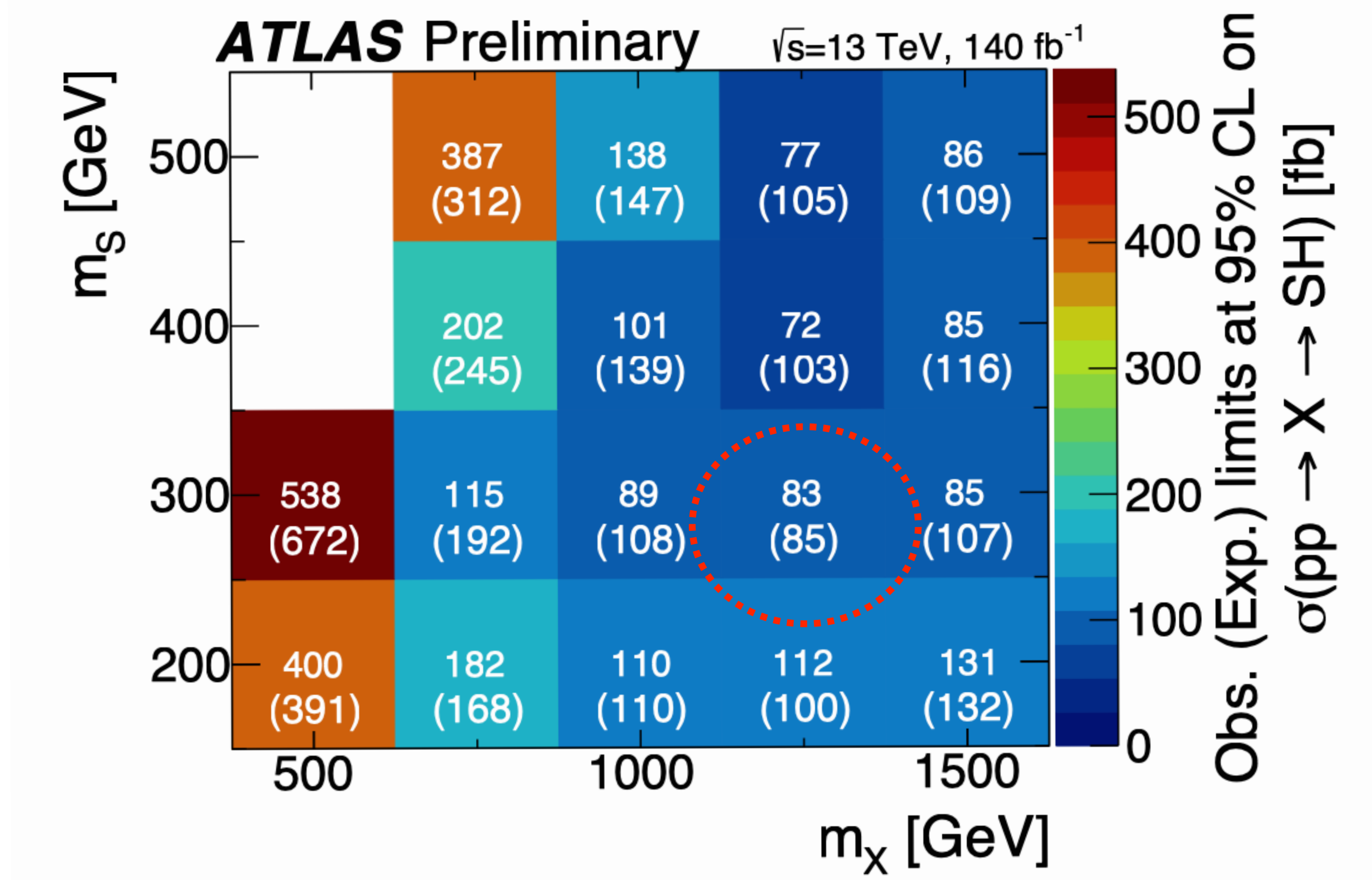


$X \rightarrow SH \rightarrow VV\tau\tau$

ATLAS-CONF-2023-031

- Fit variable: BDT score in each SR



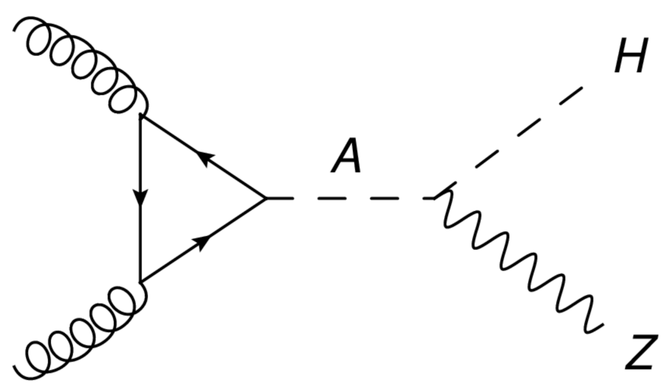


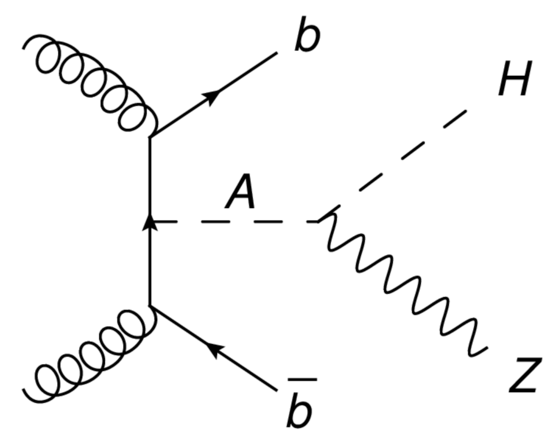
- Combined limit dominated by $WW1l2\tau_{had}$, improves by 26-53% on adding the 2 lepton channels
- Data limits compared with predictions of Next-to-minimalistic supersymmetric SM (NMSSM)

A → ZH

ATLAS-CONF-2023-034

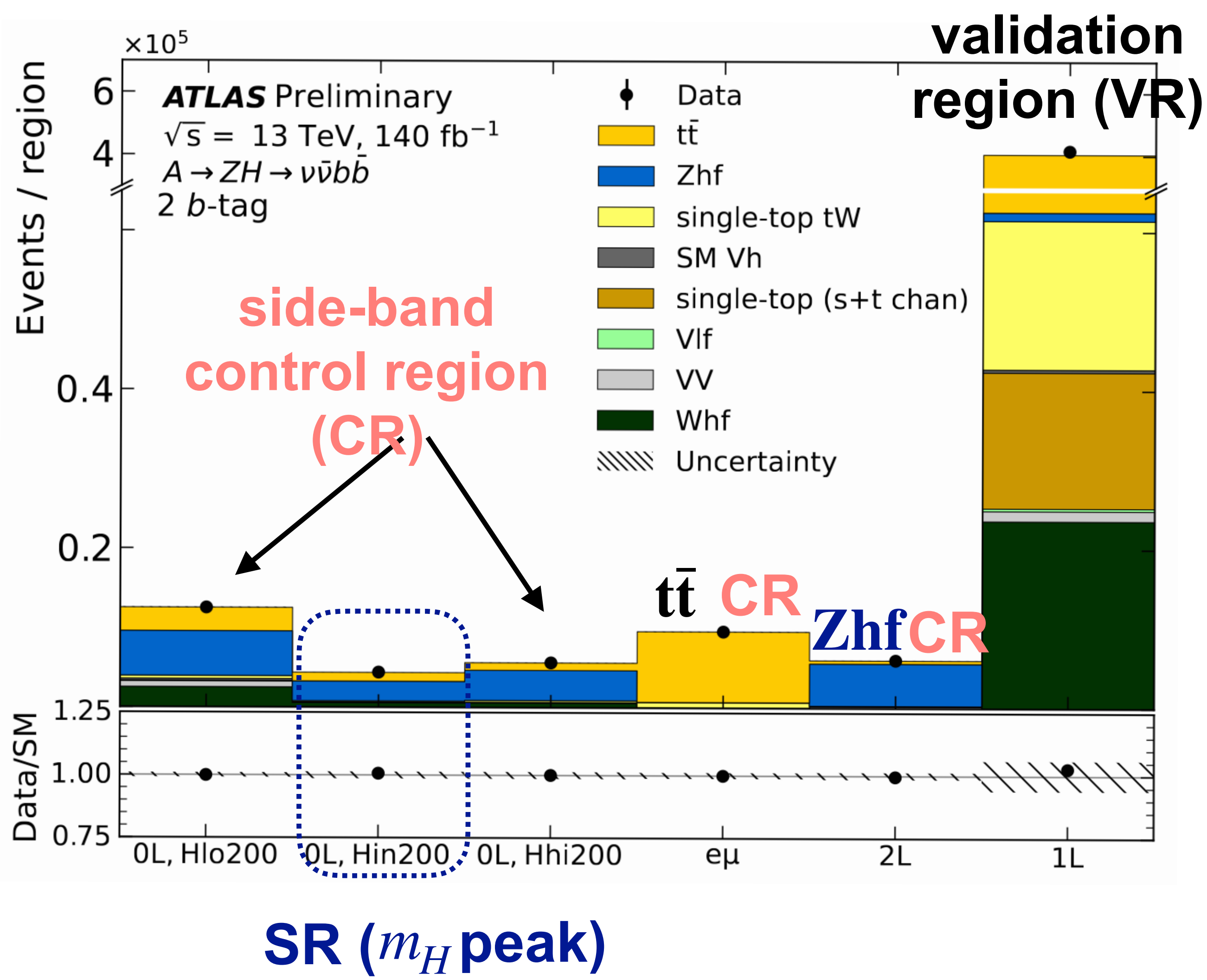
- $Z \to \nu\nu / l\bar{l}, H \to bb / t\bar{t}$, with $m_A = 350 - 1200$ GeV, $m_H = 130 - 800$ GeV

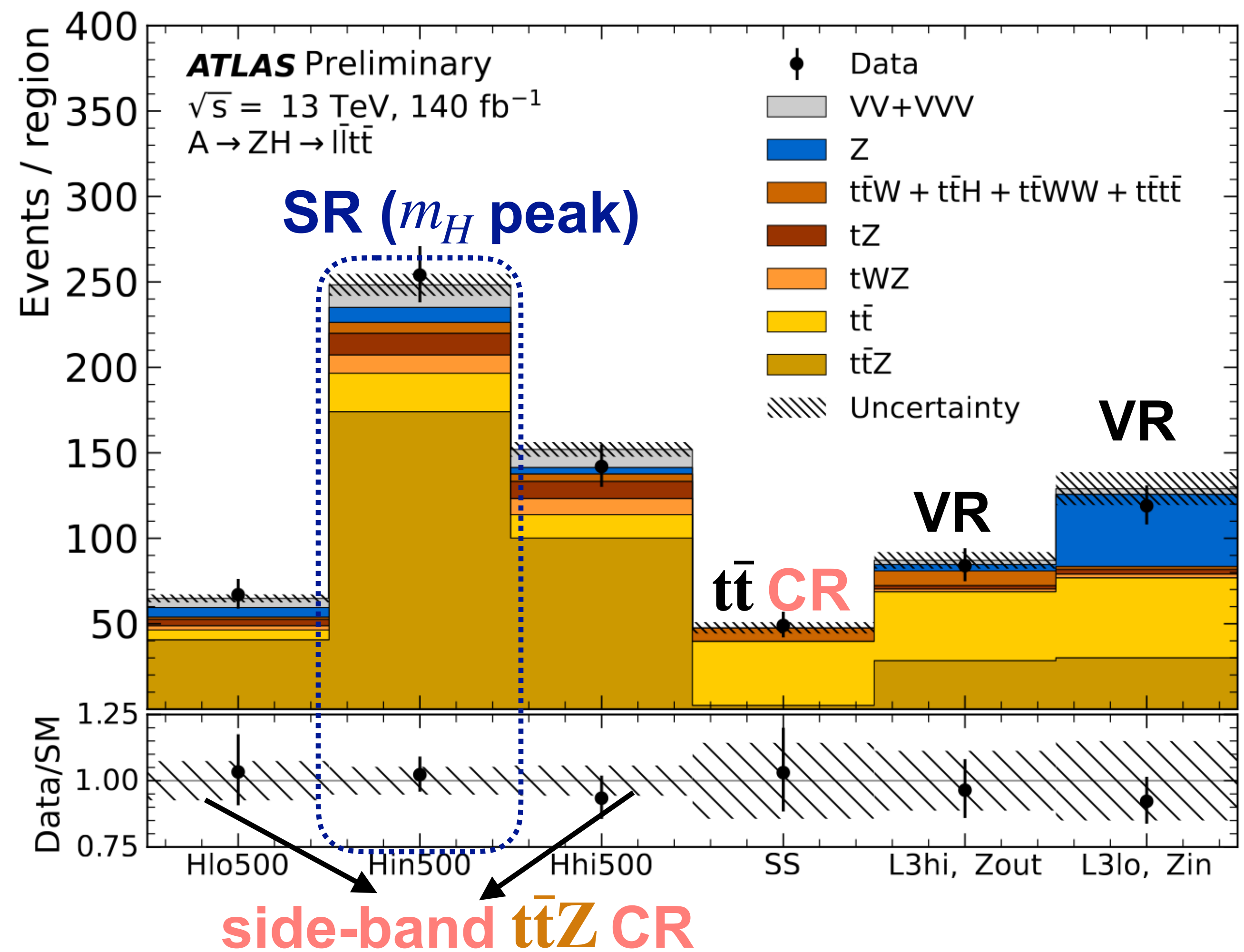




Final state:
$\nu\nu b\bar{b}$: $E_{T_{miss}}$ *+ jets*
$llt\bar{t}$ *: leptons + jets*

- Dominant backgrounds: $\nu\nu b\bar{b}$ - $\mathbf{t\bar{t}}$, Z+ heavy flavour (**Zhf**) $llt\bar{t}$ - $\mathbf{t\bar{t}Z}$, $\mathbf{t\bar{t}}$

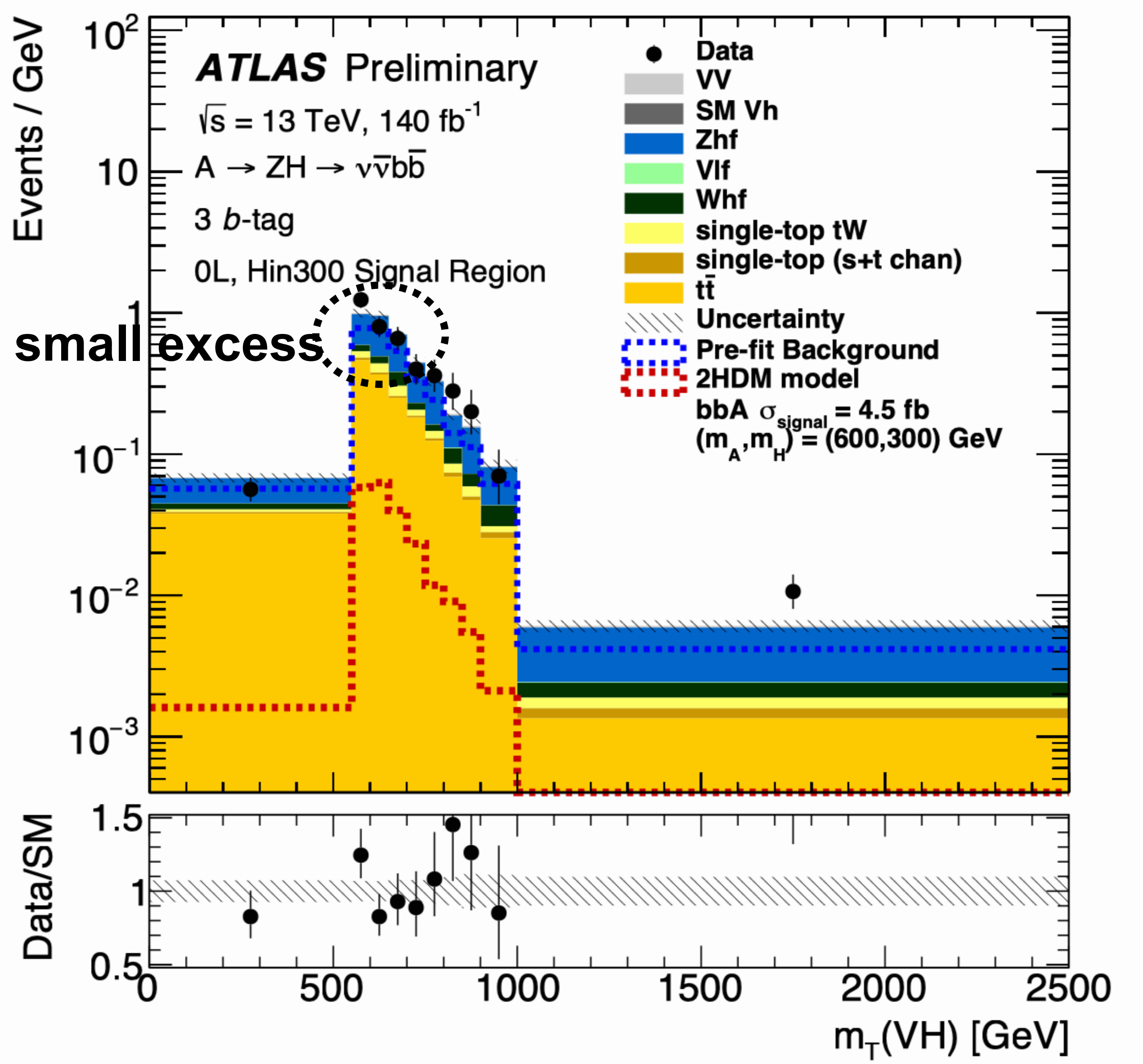


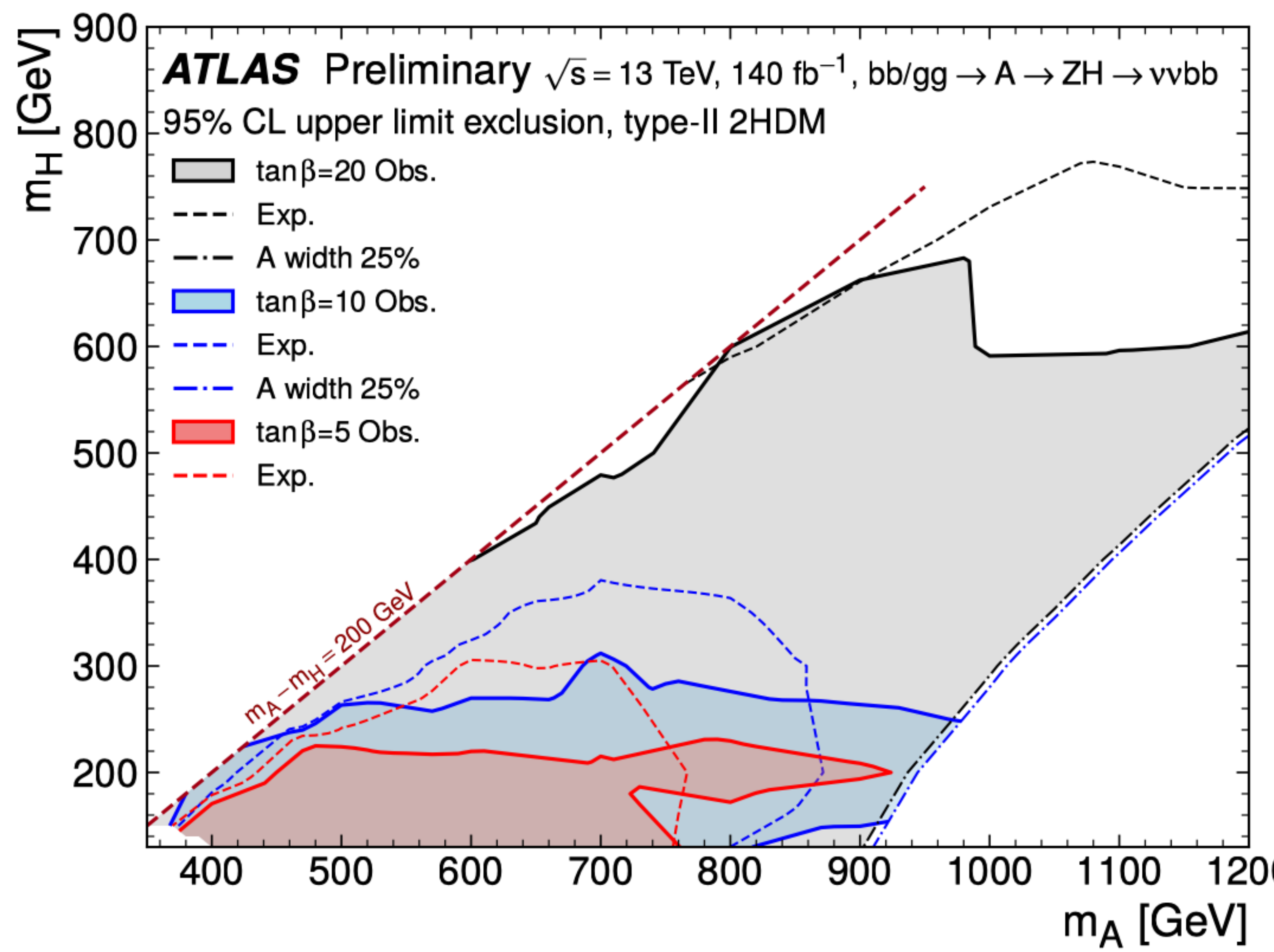


$A \to ZH \to \nu\nu b\bar{b}$

ATLAS-CONF-2023-034

- Fit variable: transverse mass of *A* boson defined for 2 and 3 b-tag region
- Dominant uncertainties:
  - low m_A (**Zhf** modelling), high m_A (statistical and systematic at same level)



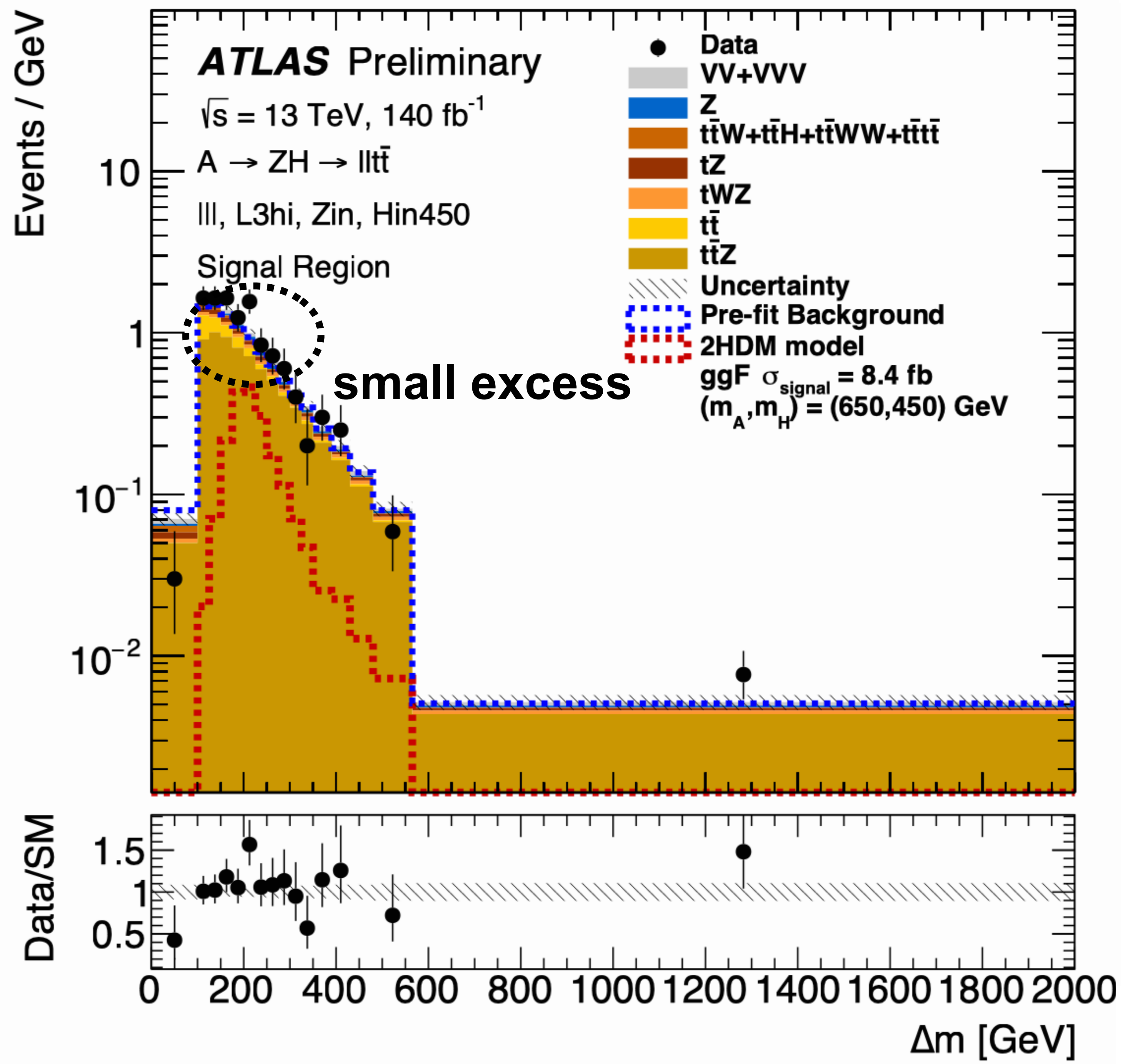


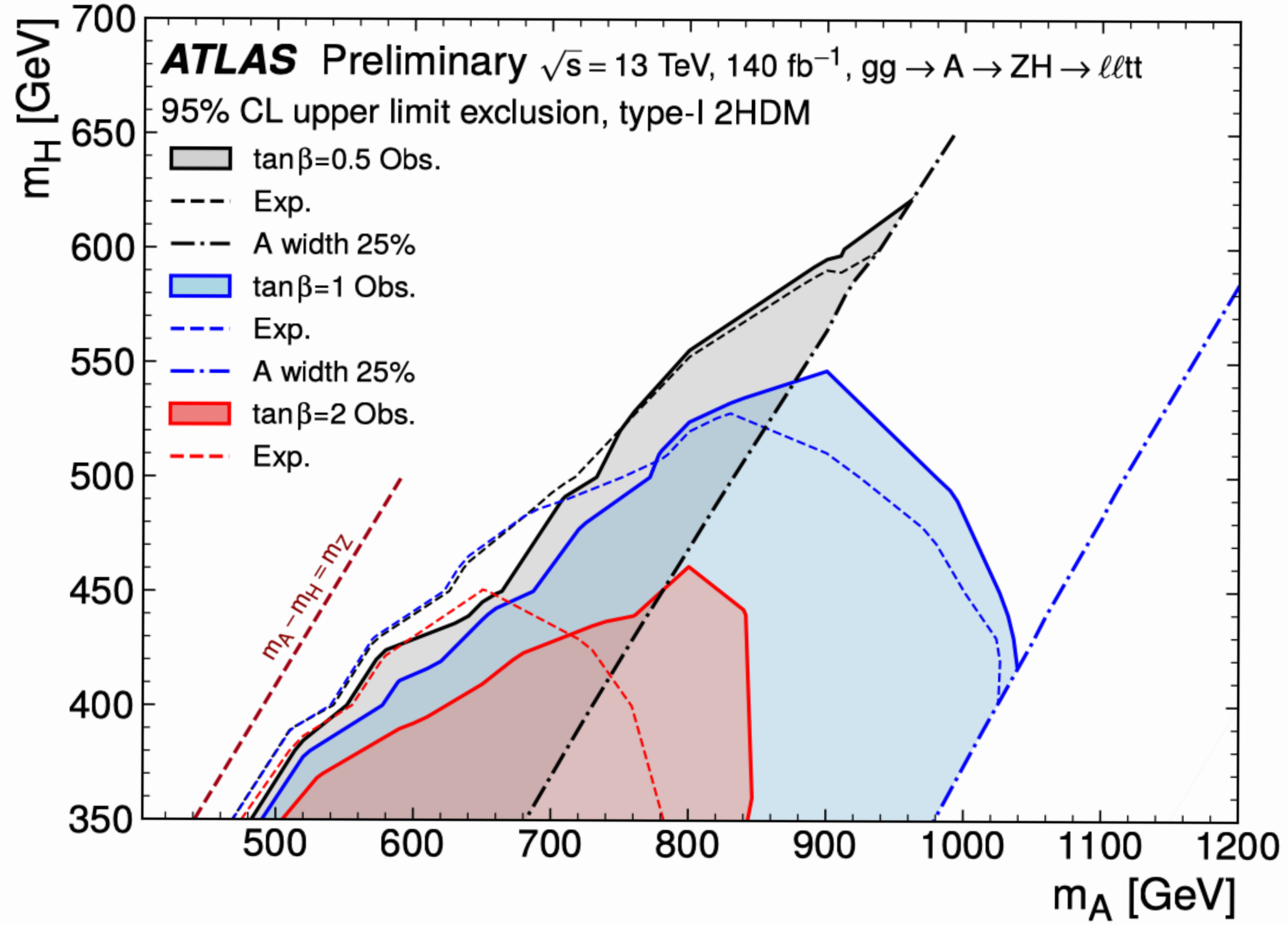
- Small data excess around $550 < m_T(VH) < 650$ GeV
- Channel sensitive at higher m_A for $m_H < 350$ GeV

$A \rightarrow ZH \rightarrow l\bar{l}t\bar{t}$

ATLAS-CONF-2023-034

- Fit variable: $\Delta m = m_A - m_H$ (difference of reconstructed masses of A and H)

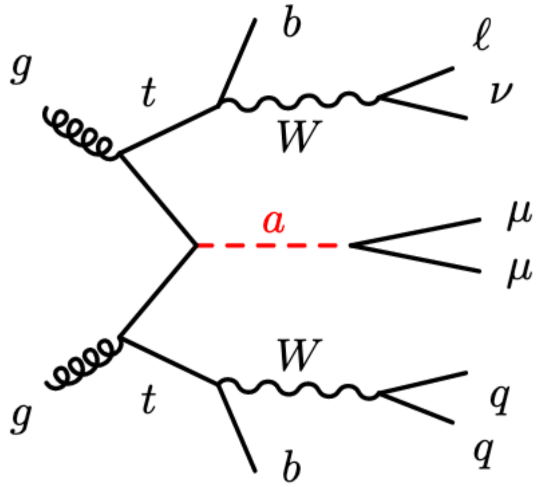


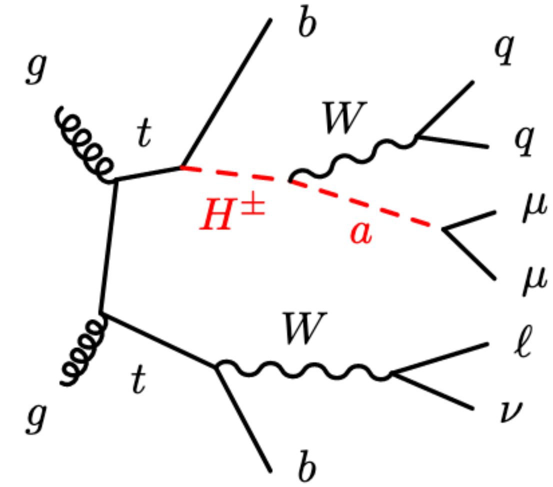


- Small data excess around $(m_A, m_H) = (650{,}450)$ GeV : local excess of 2.85 σ
- Channel sensitive for $m_H > 350$ GeV

$a \to \mu\mu$ in $t\bar{t}$ events

- Light pseudo-scalar search, $a \to \mu\mu$ targeted due to excellent resolution, $15 < m_a < 72$ GeV



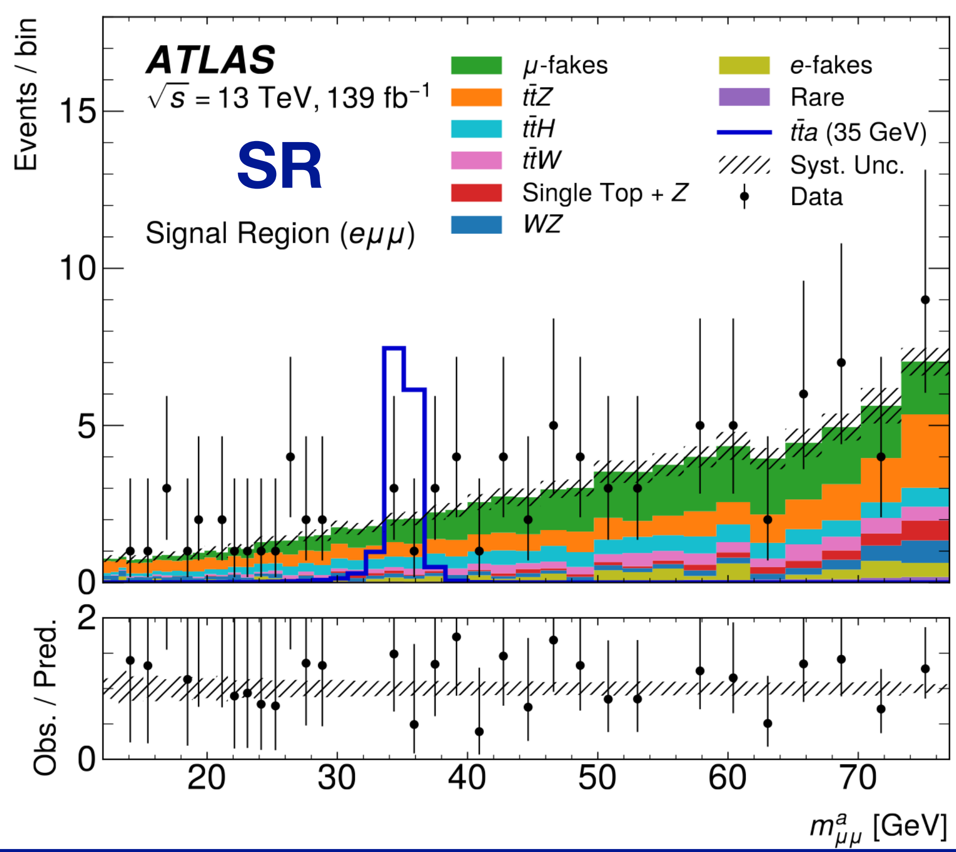


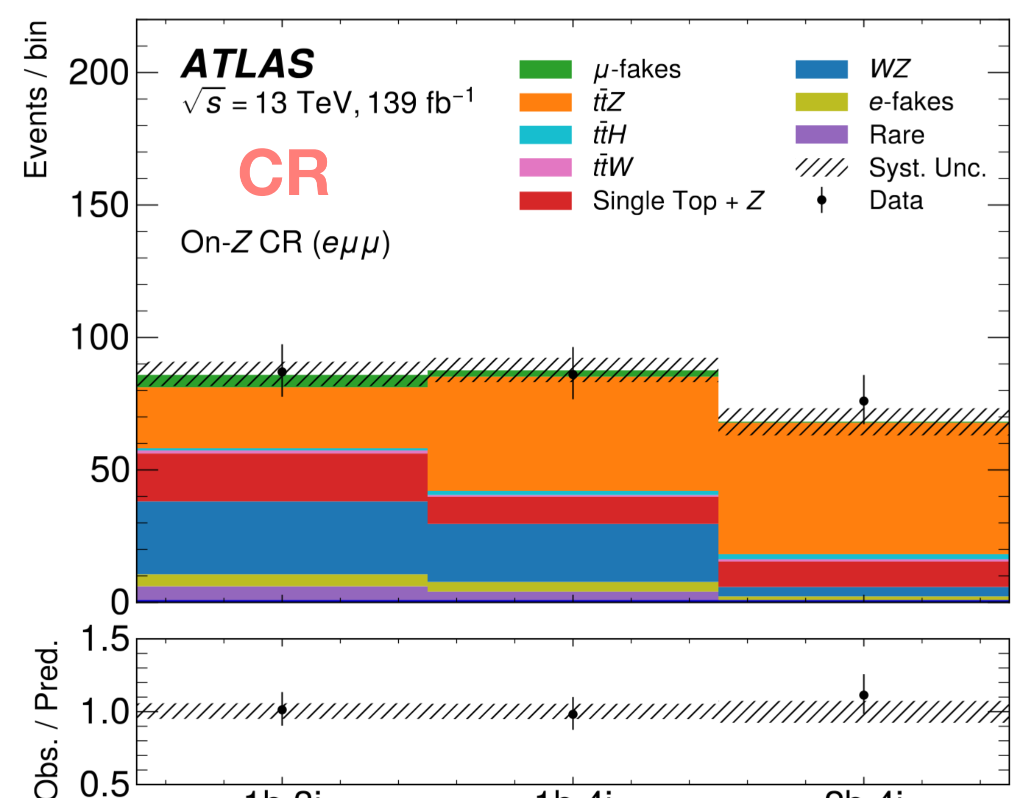
arXiv:2304.14247

$l = e/\mu$

3 leptons + jets final state

- Dominant backgrounds: $\mathbf{t\bar{t}Z}$, $\mathbf{WZ}$, μ- **fakes**
- 2 **SRs** ($n_{e/\mu}, m_{\mu\mu}, n_{\text{jet,b-jet}}$) each for $e\mu\mu/\mu\mu\mu$ channel
- 2 categories of **CRs**: on-Z CR to constrain $\mathbf{t\bar{t}Z}$, $\mathbf{t\bar{t}}$ CR to constrain μ- **fakes**

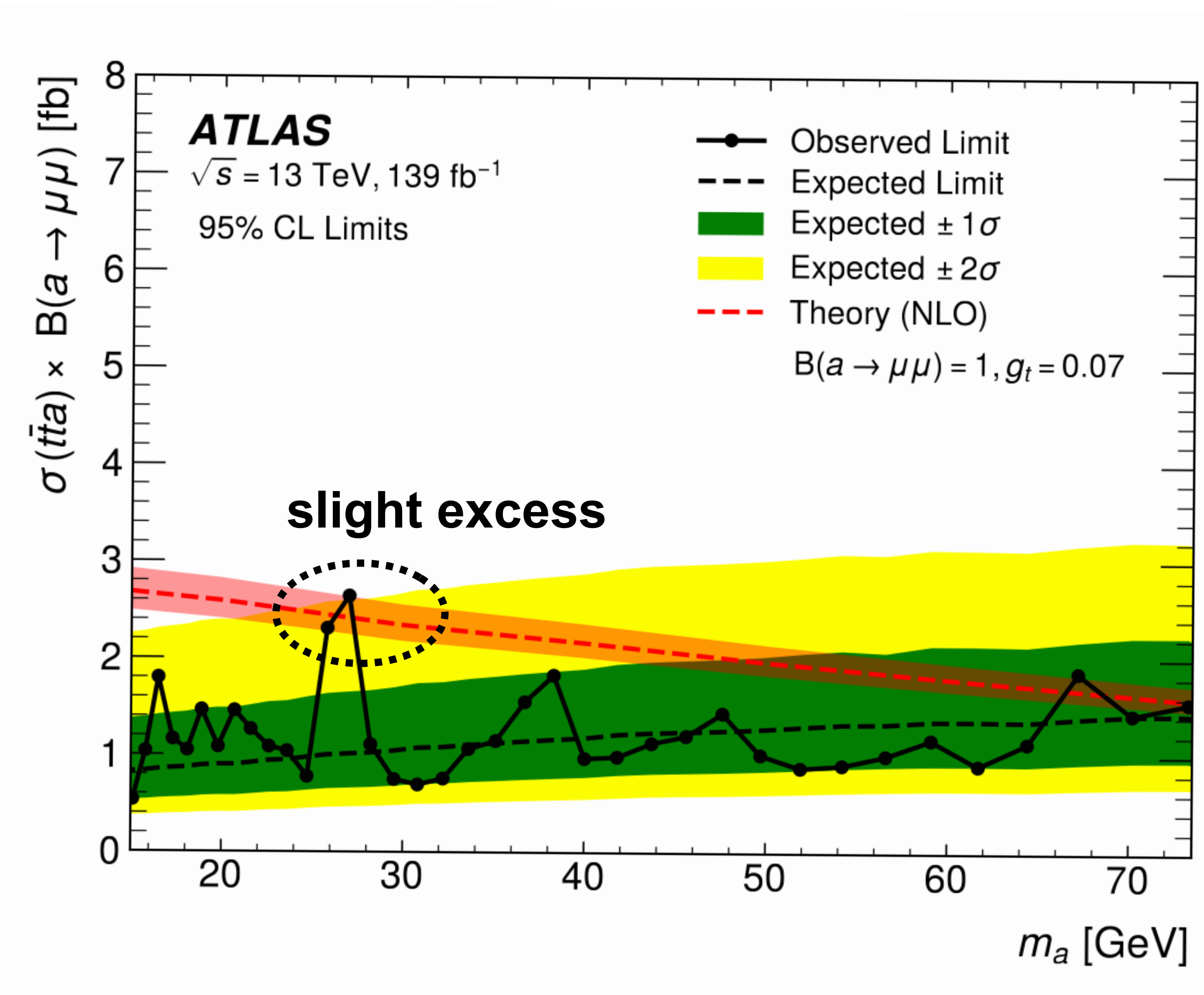


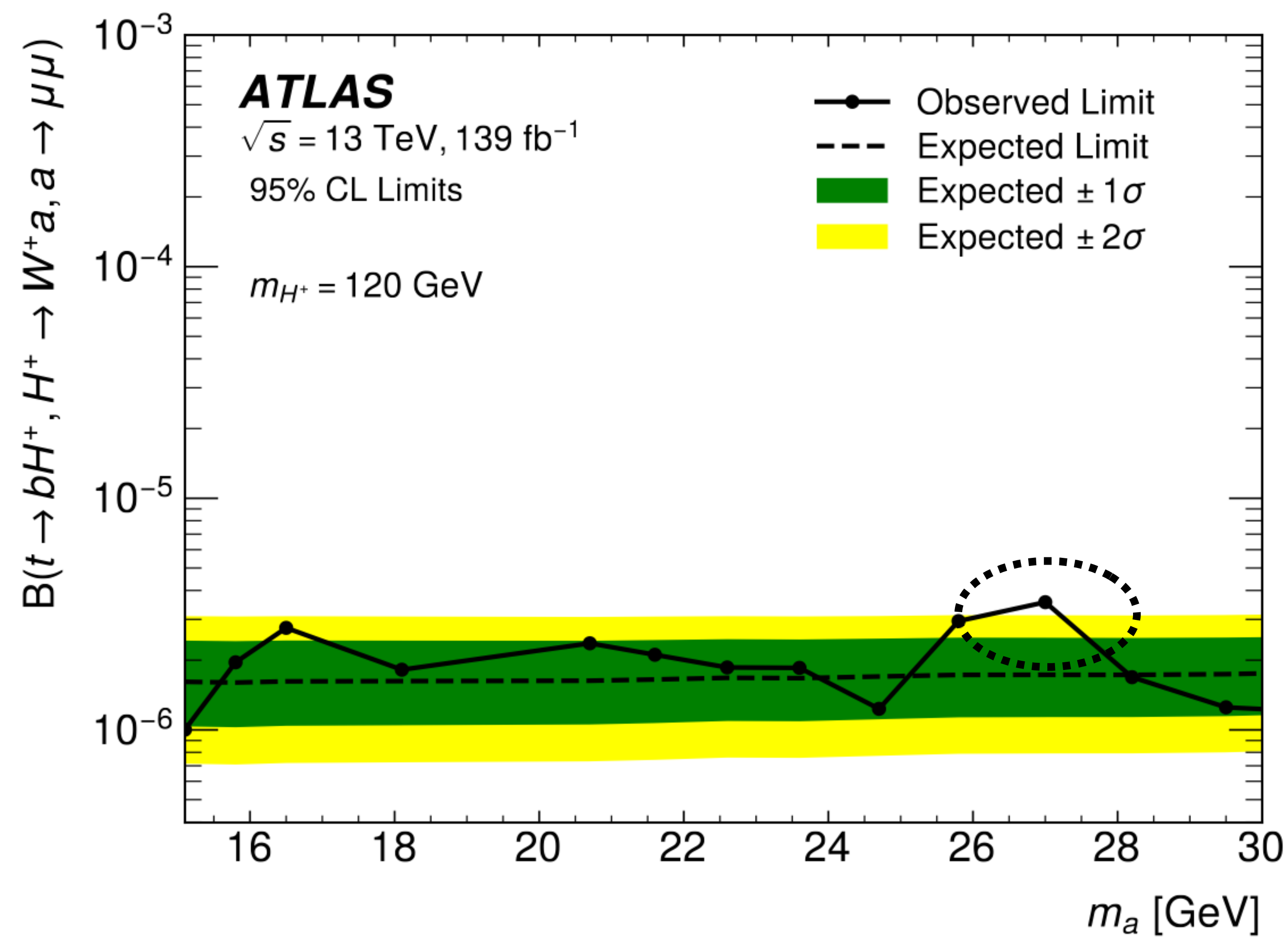


$a \to \mu\mu$ in $t\bar{t}$ events

arXiv:2304.14247

- Fit variable: invariant mass of di-muon system, $m_{\mu\mu}$
- Slight local excess of 2.4 σ at 27 GeV

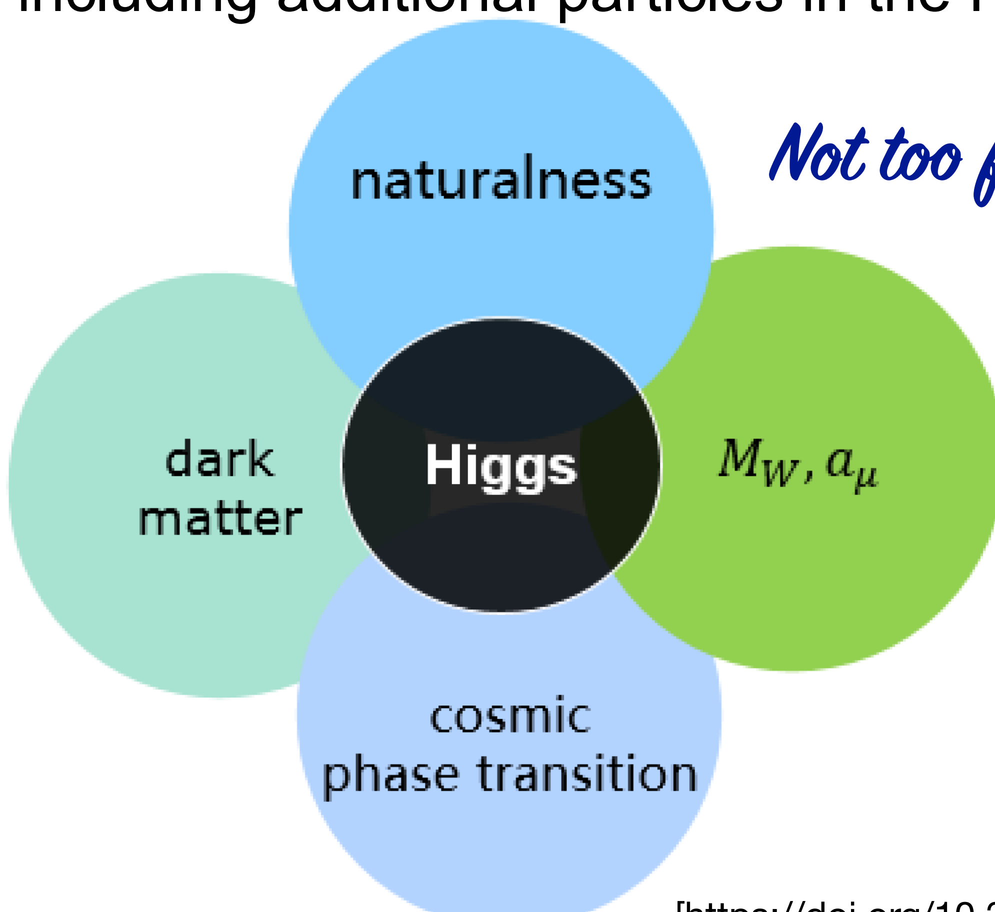




- Interpreted in single top-quark Yukawa coupling model with cross section calculated at next-to-leading (NLO) order with $a \to \mu\mu$ decays only

Summing up..

- ATLAS collaboration actively involved in the search for new physics including the Higgs sector
- New and improved techniques employed to increase the sensitivity of analyses targeting various final states and topologies
- No signs of new physics beyond the SM observed so far (few local excesses seen which needs to be investigated)
- **Exciting times ahead:** Ongoing Run-3 dataset will increase the sensitivity of searches for new BSM couplings including additional particles in the Higgs sector



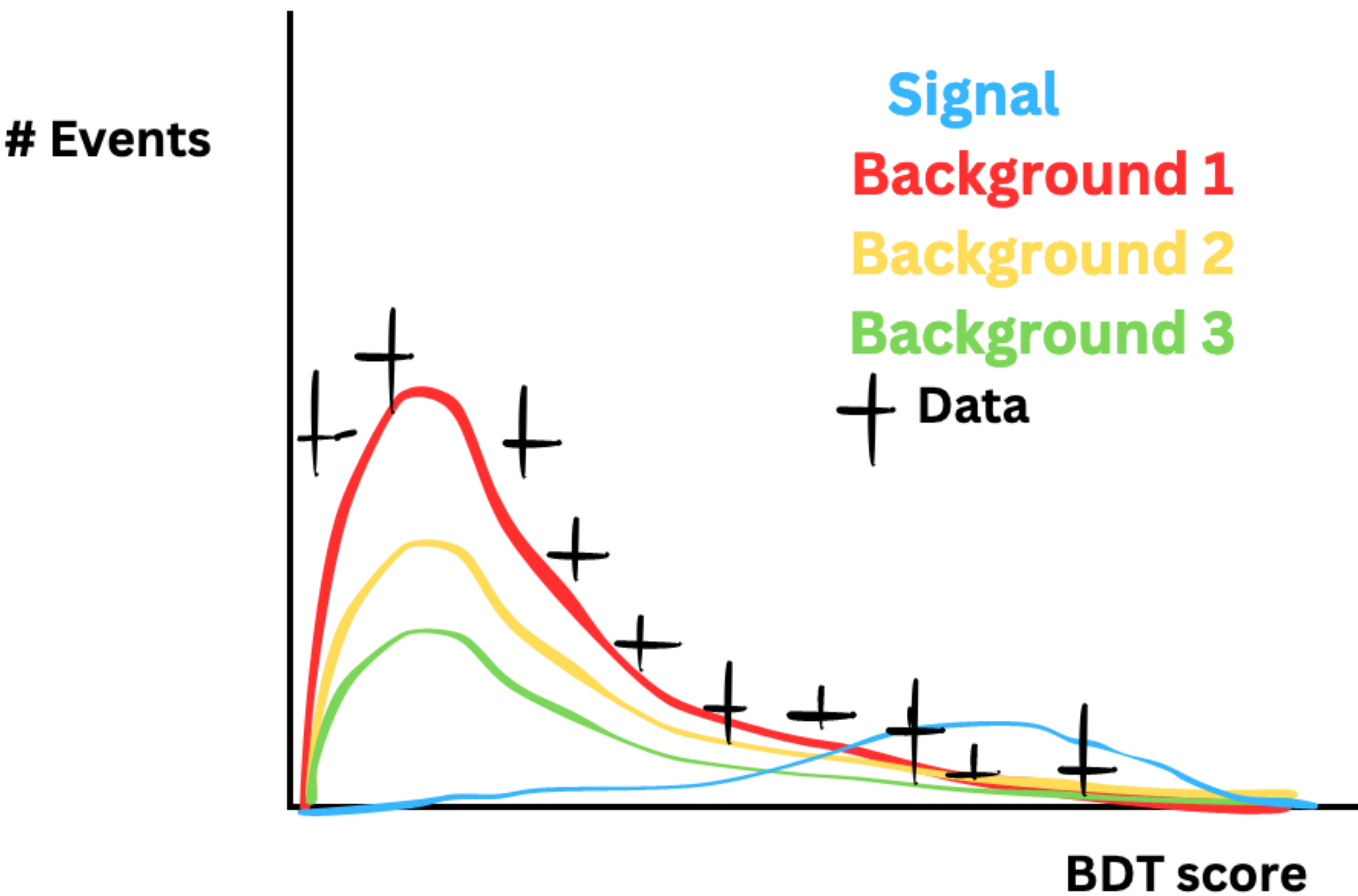
Not too far: We can, we will!!

[https://doi.org/10.3390/universe9040178]

Back-up

Search for new physics

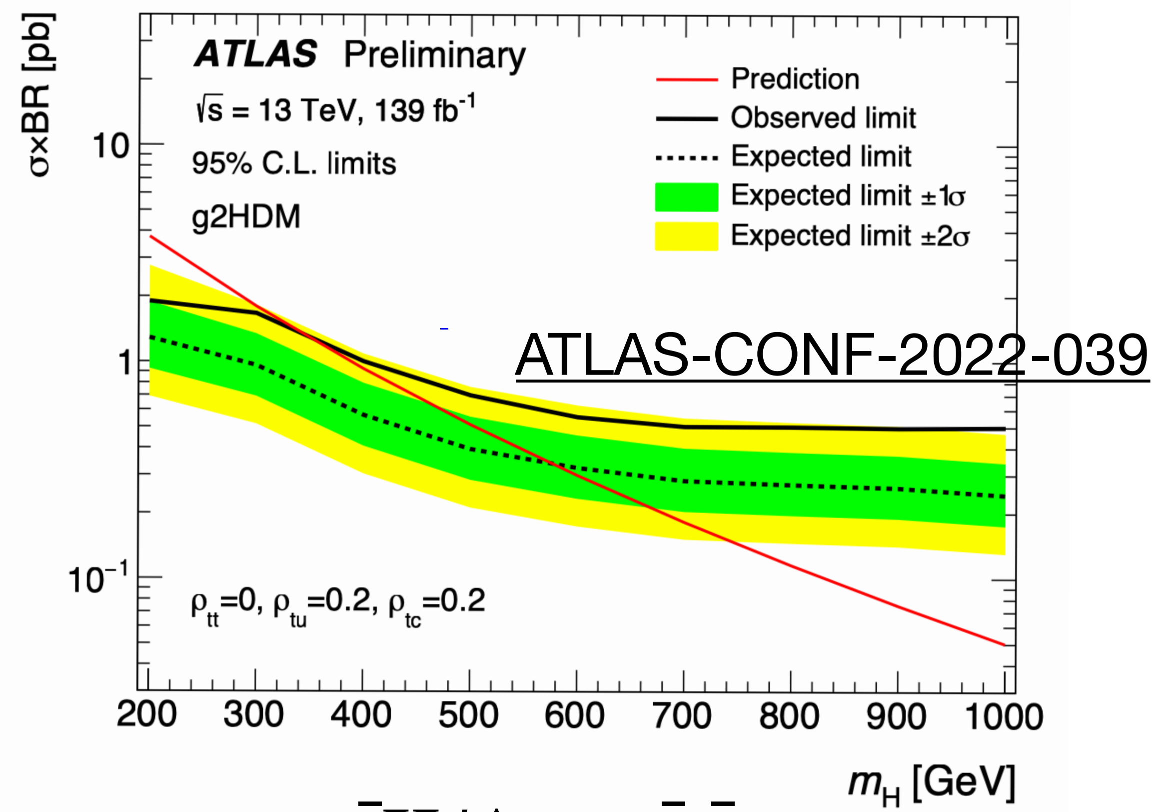
- Impressive ATLAS detector resolution + continuously evolving new techniques: lepton ID, flavour tagging of jets..etc
- Define a suitable discriminant to separate **S** from **B**: BDTs, invariant mass of the targeted particle…



- Set upper limits on the signal strength using a likelihood fit to data
- Interpret results in variety of models

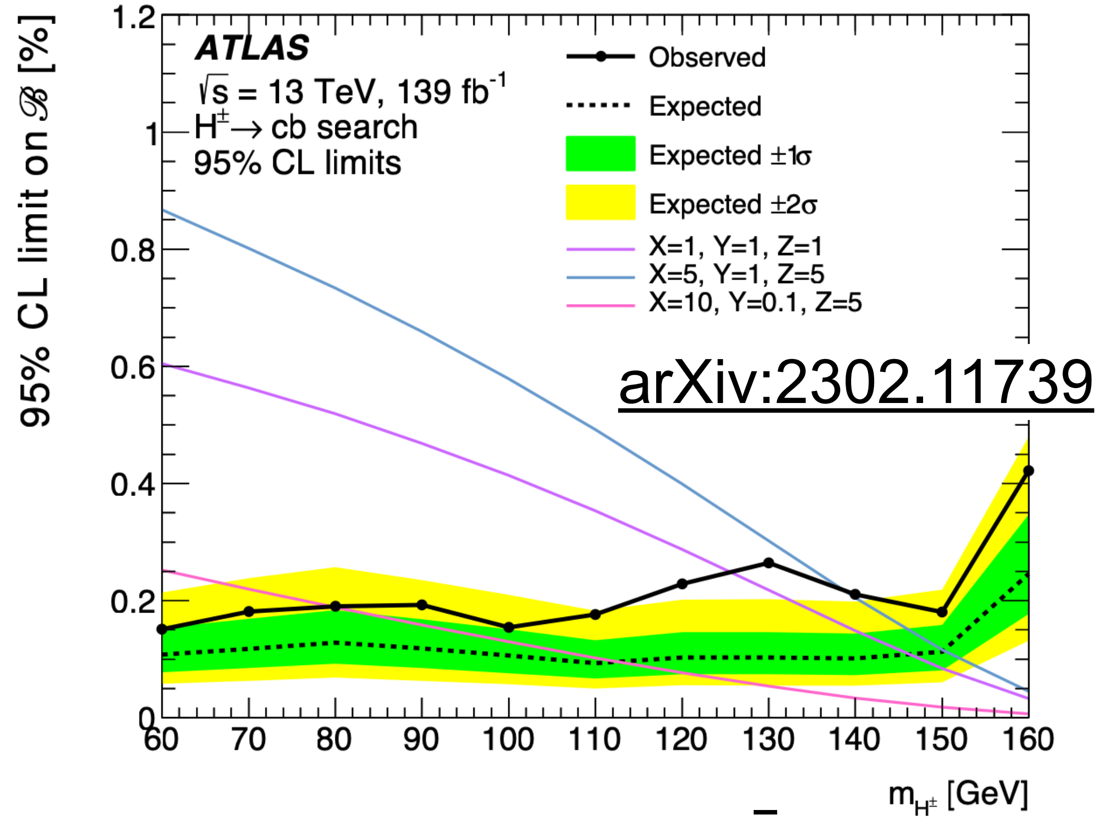
Other recent results

Heavy Higgs in 2HDM



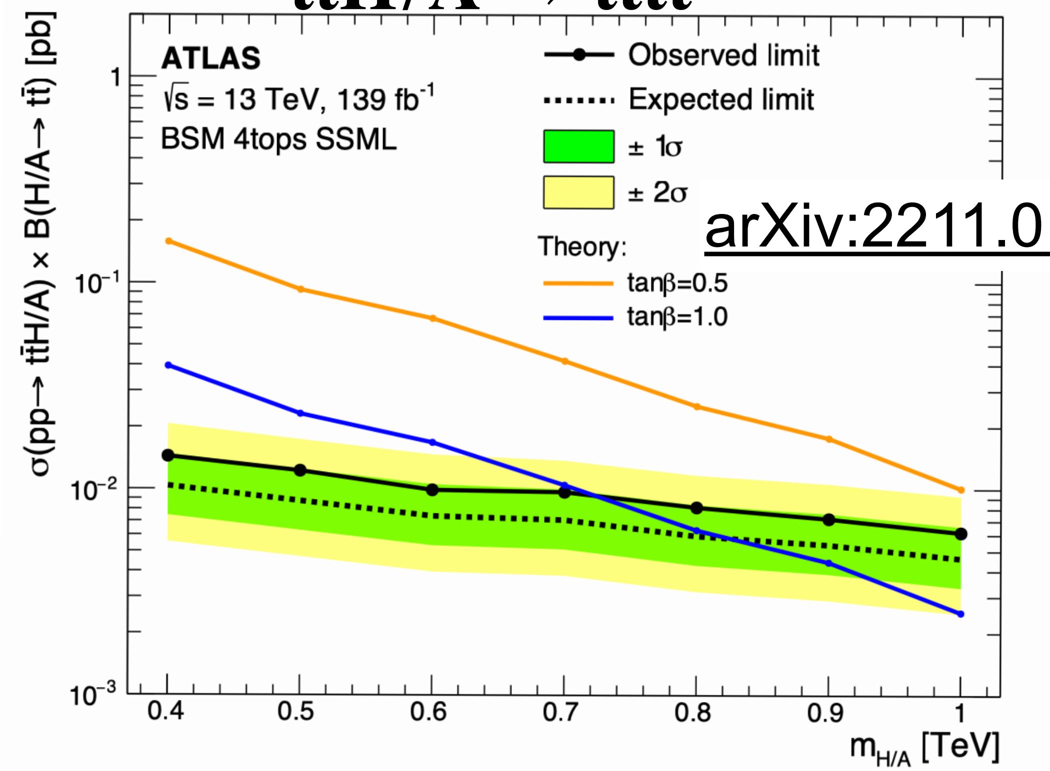
ATLAS-CONF-2022-039

$H^+ \to cb$



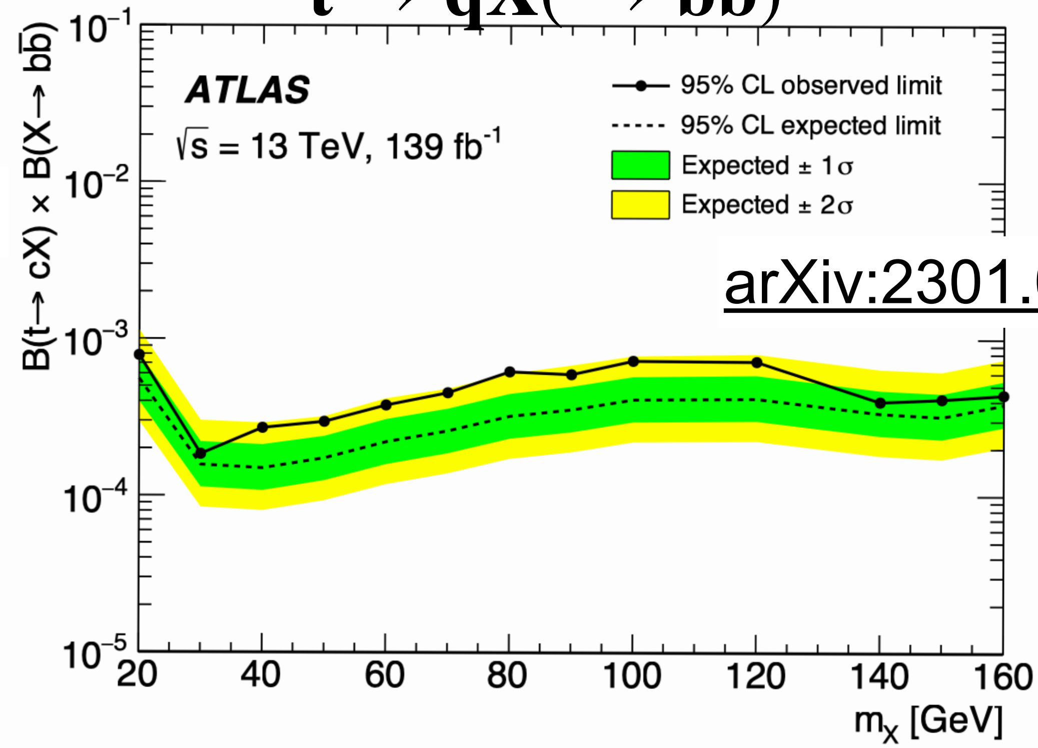
arXiv:2302.11739

$t\bar{t}H/A \to t\bar{t}t\bar{t}$



arXiv:2211.01136

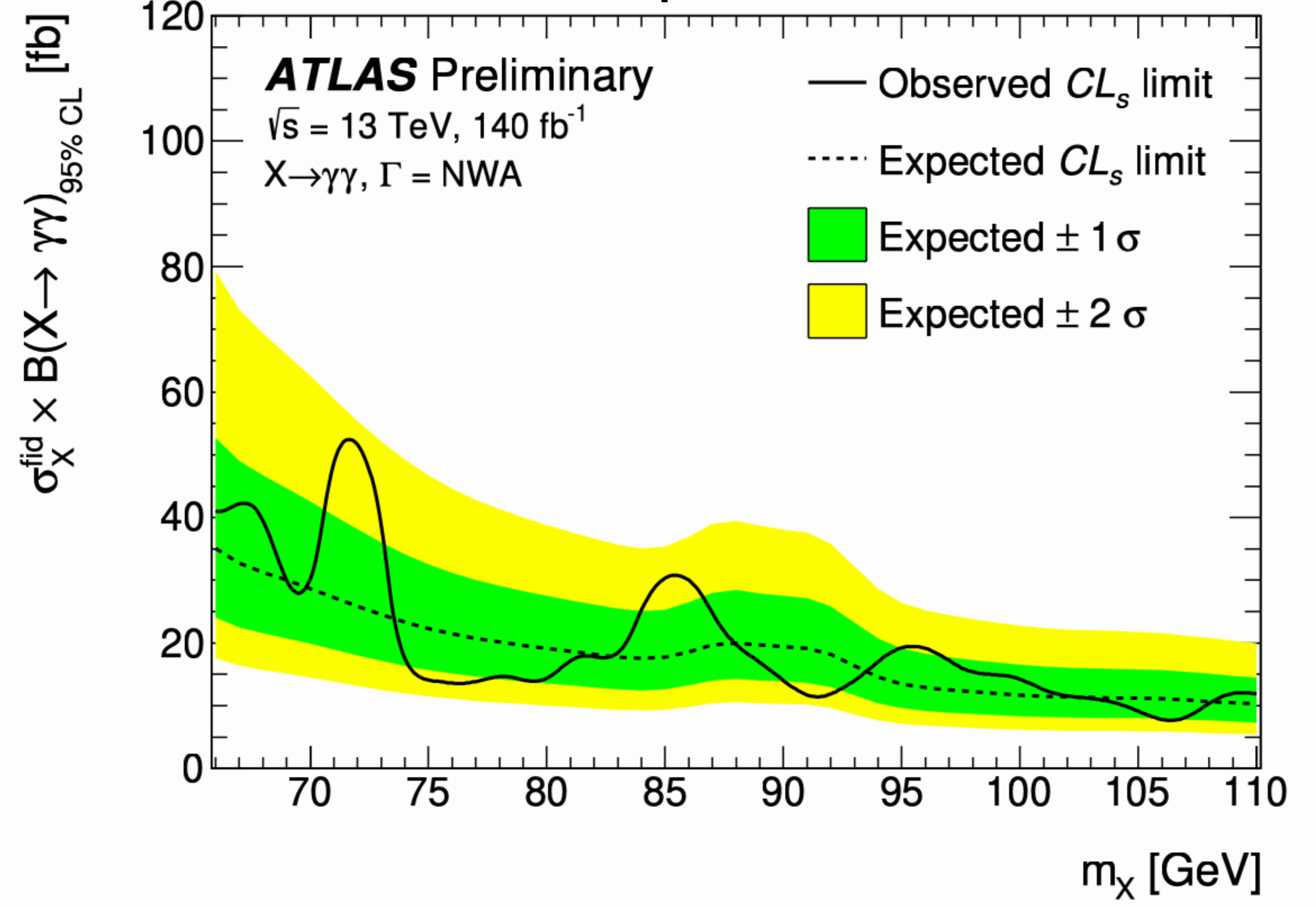
$t \to qX(\to b\bar{b})$



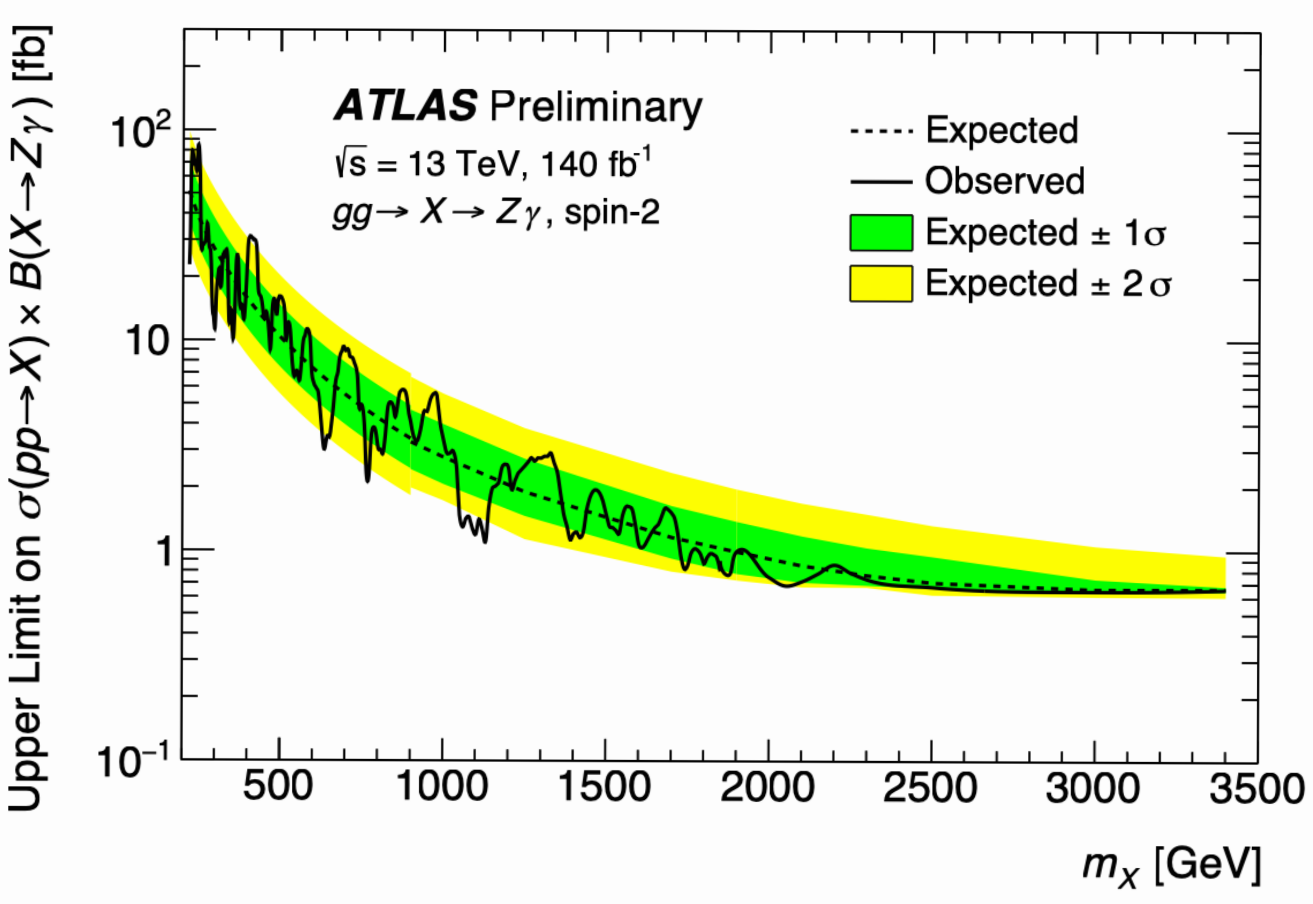
arXiv:2301.03902

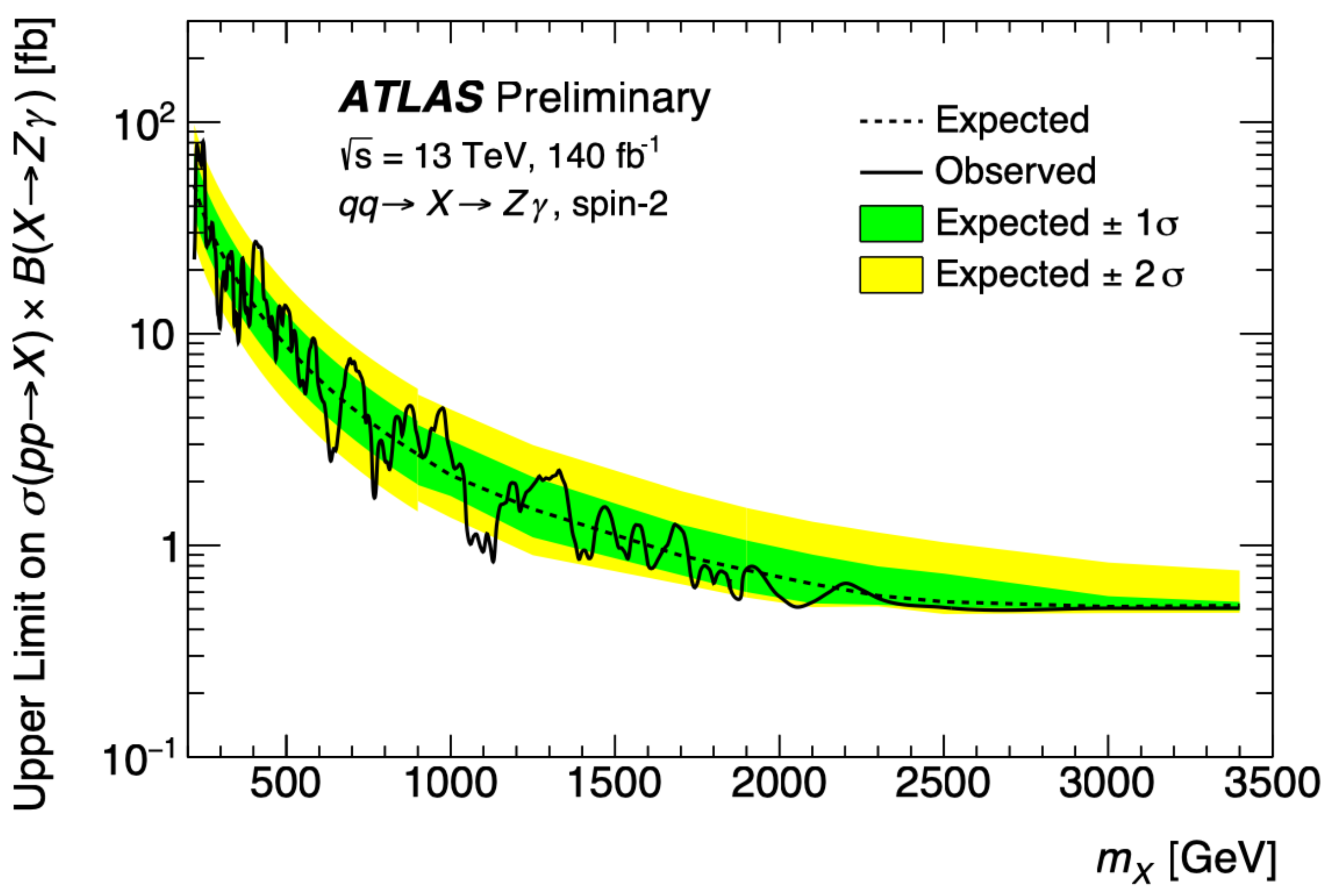
Low mass H/X → $\gamma\gamma$

Model independent result



High mass $X \to Z\gamma$





$A \to ZH$

$\nu\nu bb$

Cut	Regions				
	2L (CR)	**eμ (CR)**	**1L (VR)**	**Hlo / Hhi (CR)**	**Hin (SR)**
N jets	2-5				
N b-jets	> 2				
m_H^{cand}	> 50 GeV				
N hadronically decaying τ-leptons	0				
$p_{\text{T}}(V)$	> 150 GeV				
$\min_i \Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, \vec{p}_i^{\text{jet}})$	$> \pi/10$				
$\Delta R(b_1, b_2)$	< 3.3 (2 b-jets) < 3.5 (≥ 3 b-jets)				
N leptons	2		1	0	
Lepton flavour	$ee/\mu\mu$	$e\mu$	e/μ	-	
$p_{\text{T}}(\ell_1)$	> 27 GeV			-	
$\lvert m_Z^{\text{cand}} - m_Z \rvert$	< 10 GeV	-			
$\mathcal{S}_{\text{MET}}$	< 5	-	> 3	> 10	
$m_{\text{top}}^{\text{near}}$	-			> 180 GeV	
$m_{\text{top}}^{\text{far}}$	-			> 200 GeV	
$\lvert m_H^{\text{cand}} - m_H^{\text{hypo}} \rvert$	-			$> 0.2 \cdot m_H^{\text{hypo}}$	$< 0.2 \cdot m_H^{\text{hypo}}$

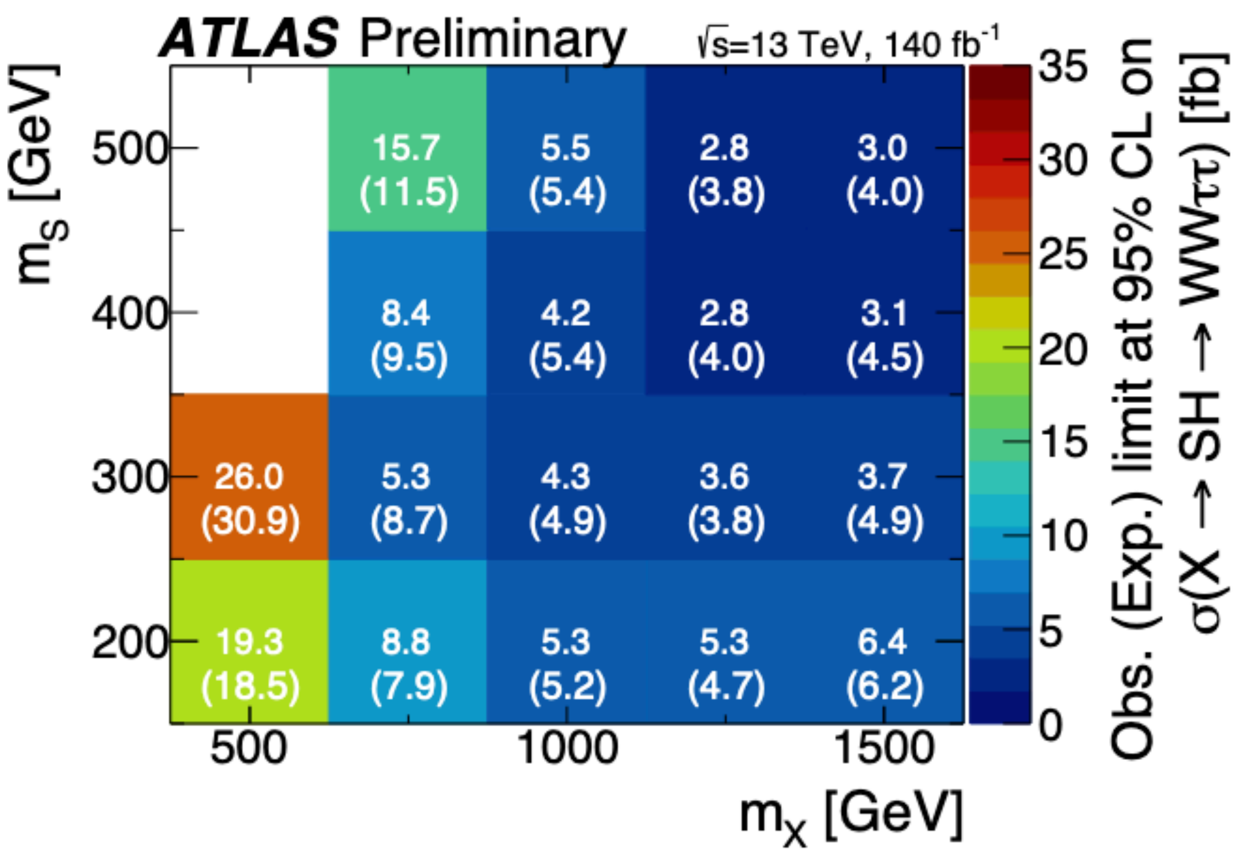
$lltt$

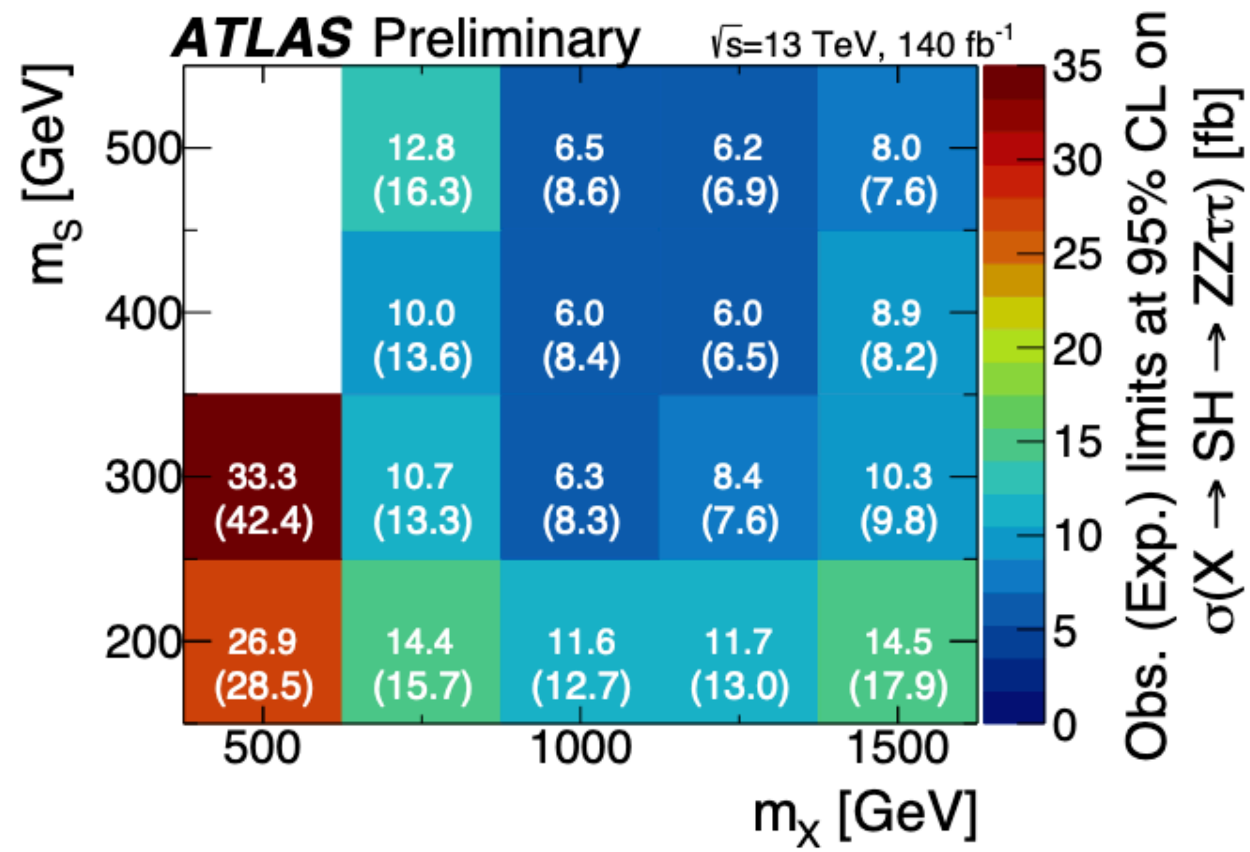
Cut	Regions				
	ss (CR)	**L3hi_Zout (VR)**	**Hlo / Hhi (CR)**	**Hin (SR)**	**L3lo_Zin (VR)**
N leptons	3				
$p_{\text{T}}\ (\ell_1)$	> 27 GeV				
N jets	≥ 4				
N b-jets	2				
$\lvert \eta_{H-\text{cand}}^{ZH-\text{r.fr.}} \rvert$	$< 2.2 + 0.0004 \cdot m_H^{\text{cand}} - 0.0011 \cdot m_A^{\text{cand}}$				
$p_{\text{T}}\ (\ell_3)$	> 13 GeV				> 7 GeV & < 13 GeV
Lepton flavour	$ee\mu/\mu\mu e$	$eee/ee\mu/\mu\mu e/\mu\mu\mu$			
OSSF lepton pairs	0	≥ 1			
$\lvert m_Z^{\text{cand}} - m_Z \rvert$	< 20 GeV	> 10 GeV & < 20 GeV	< 10 GeV		
$\lvert m_H^{\text{cand}} - m_H^{\text{hypo}} \rvert$, $m_H^{\text{hypo}} < 500$ GeV	-		$> 0.32 \cdot m_H^{\text{hypo}}$	$< 0.32 \cdot m_H^{\text{hypo}}$	-
$\lvert m_H^{\text{cand}} - m_H^{\text{hypo}} \rvert$, $m_H^{\text{hypo}} > 500$ GeV			$> 0.24 \cdot m_H^{\text{hypo}}$	$< 0.24 \cdot m_H^{\text{hypo}}$	

$X \to SH \to VV\tau\tau$

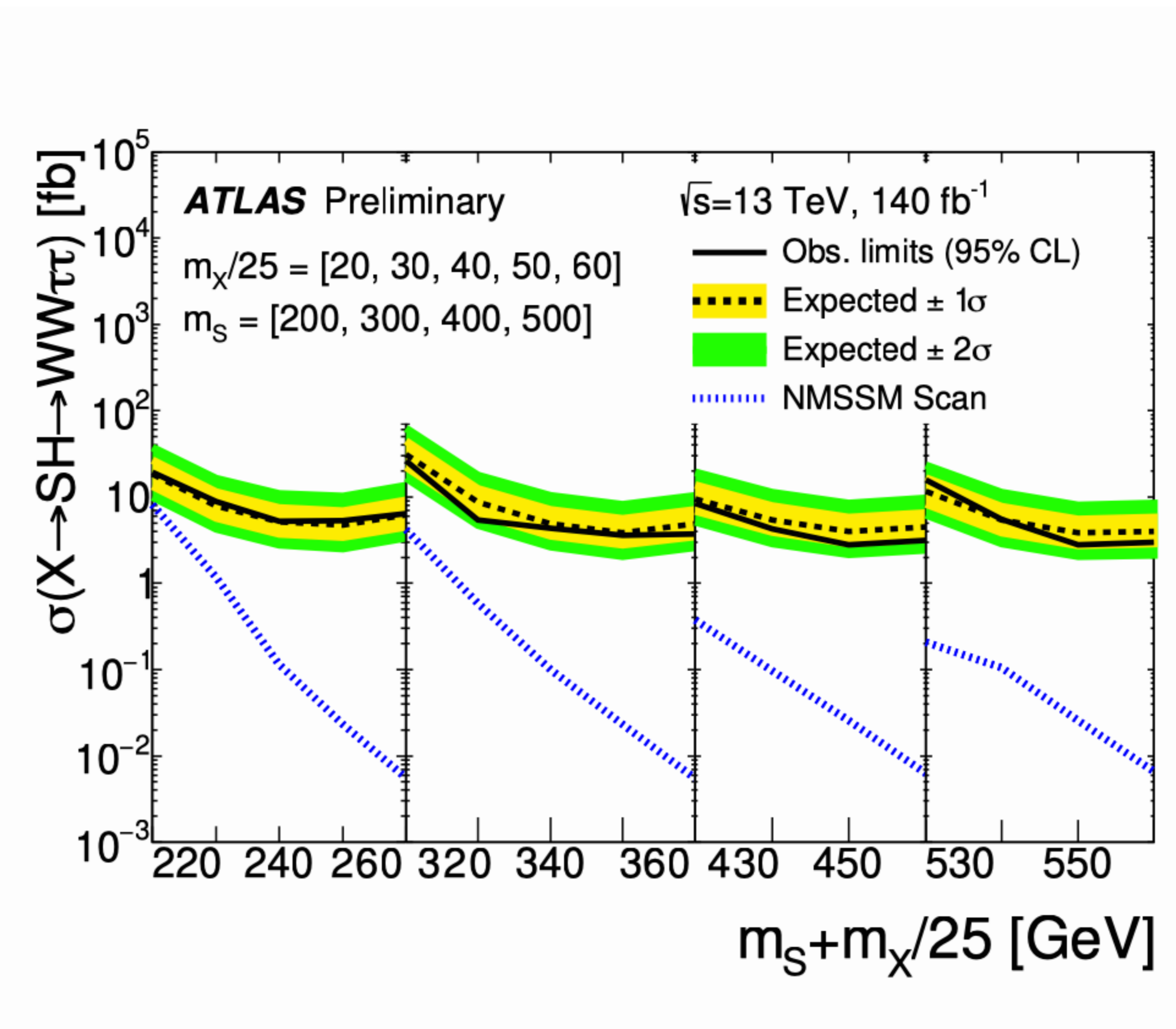
Channels	Selections
$WW1\ell2\tau_{\mathrm{had}}$	exactly one light lepton (electron or muon): p_{T} >27 GeV, $\lvert\eta\rvert < 2.5$ exactly two RNN medium τ_{had} with opposite-sign: p_{T} >20 GeV, $\lvert\eta\rvert < 2.5$ ΔR between two τ_{had} candidates: $\Delta R_{(\tau_0,\tau_1)} \leq 2$ number of jets and b-jets: $N_{\mathrm{jets}} \geq 2$ and $N_{b-\mathrm{jets}} == 0$
$WW2\ell2\tau_{\mathrm{had}}$	exactly two light leptons with opposite-sign: p_{T} >10 GeV, $\lvert\eta\rvert < 2.5$ exactly two RNN medium τ_{had} with opposite-sign: p_{T} >20 GeV, $\lvert\eta\rvert < 2.5$ invariant dilepton mass: $m_{\ell\ell} > 12$ GeV Z-veto ($\lvert m_{\ell\ell} - m_Z\rvert$>10 GeV) for same-flavor leptons $\Delta R_{(\tau_0,\tau_1)} \leq 2$ $N_{b-\mathrm{jets}} == 0$
$ZZ2\ell2\tau_{\mathrm{had}}$	exactly two same-flavor light leptons with opposite-sign: p_{T} >10 GeV, $\lvert\eta\rvert < 2.5$ exactly two RNN medium τ_{had} with opposite-sign: p_{T} >20 GeV, $\lvert\eta\rvert < 2.5$ Z-peak selection ($\lvert m_{\ell\ell} - m_Z\rvert$<10 GeV) $\Delta R_{(\tau_0,\tau_1)} \leq 2$ $N_{b-\mathrm{jets}} == 0$

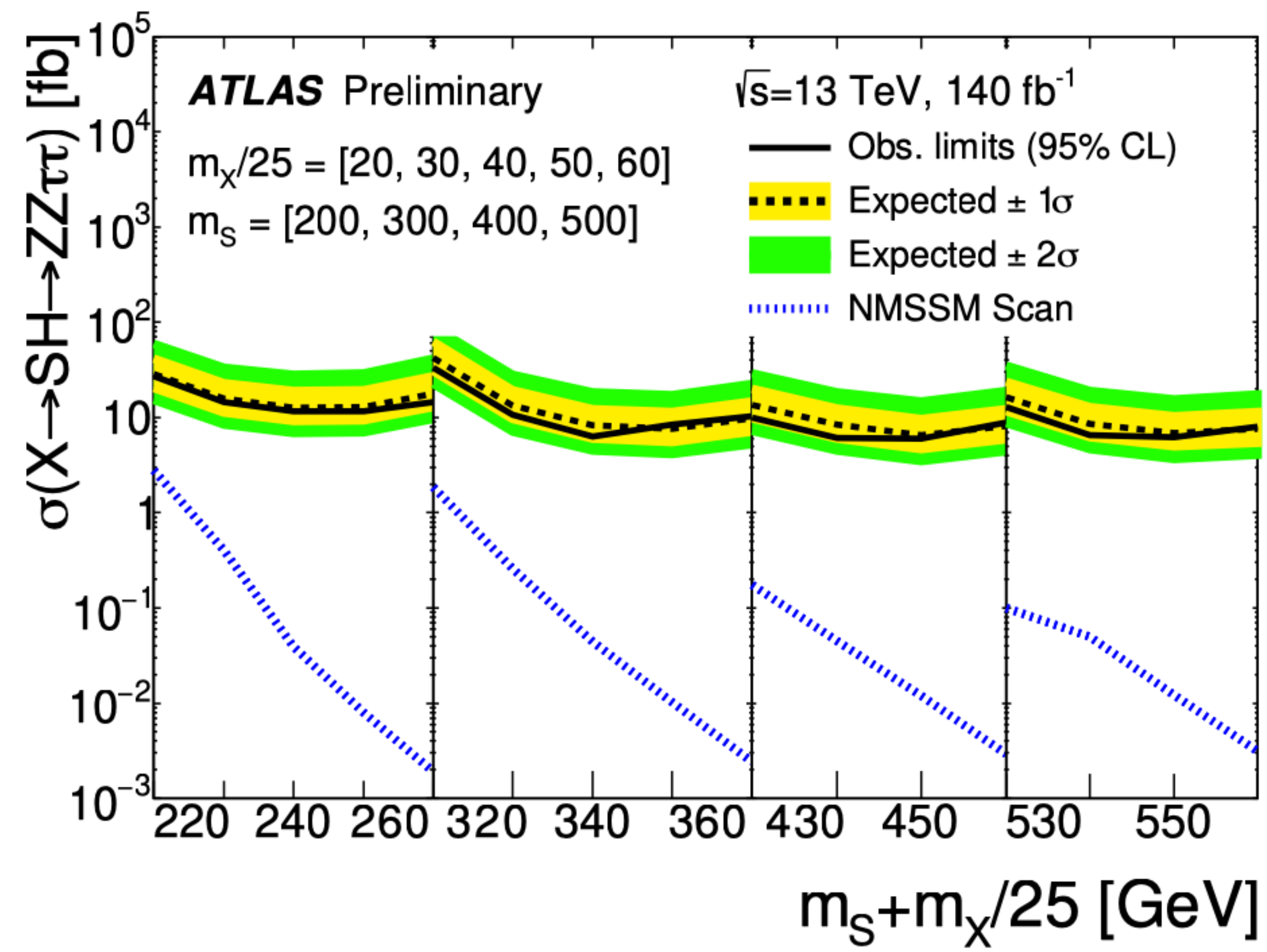
$X \to SH \to VV\tau\tau$



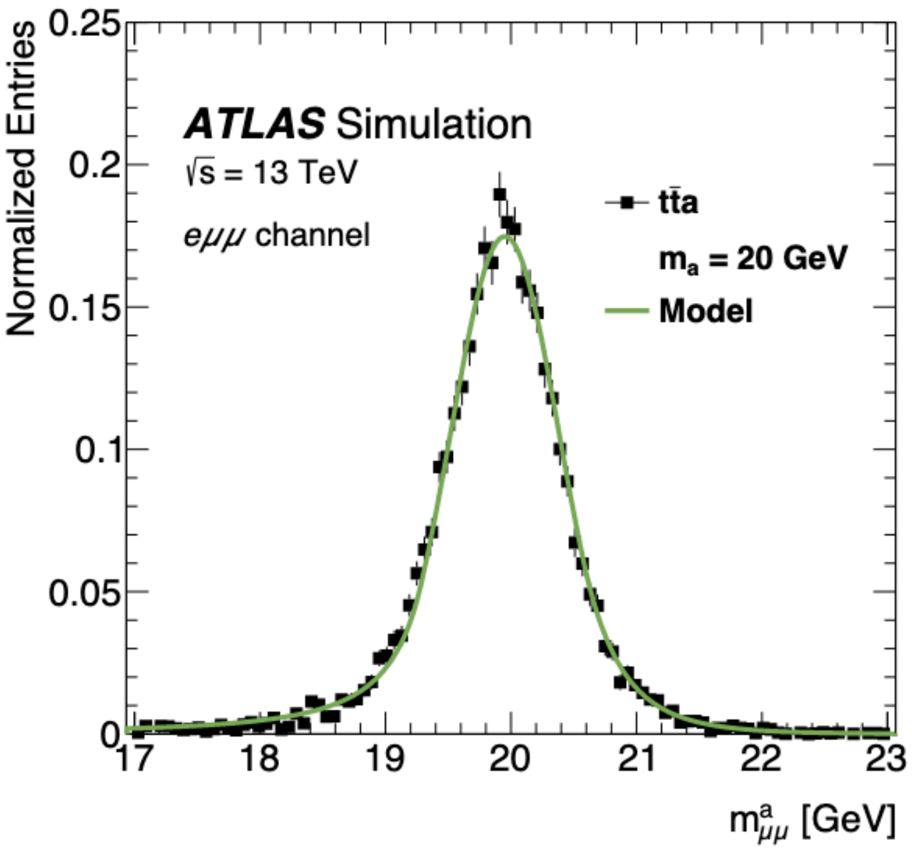


X → SH → VVττ


ATLAS Preliminary
√s=13 TeV, 140 fb⁻¹
mX/25 = [20, 30, 40, 50, 60]
mS = [200, 300, 400, 500]
Obs. limits (95% CL)
Expected ± 1σ
Expected ± 2σ
NMSSM Scan
σ(X→SH→WWττ) [fb]
220 240 260 320 340 360 430 450 530 550
mS+mX/25 [GeV]


ATLAS Preliminary
√s=13 TeV, 140 fb⁻¹
mX/25 = [20, 30, 40, 50, 60]
mS = [200, 300, 400, 500]
Obs. limits (95% CL)
Expected ± 1σ
Expected ± 2σ
NMSSM Scan
σ(X→SH→ZZττ) [fb]
220 240 260 320 340 360 430 450 530 550
mS+mX/25 [GeV]

$a \rightarrow \mu\mu$ in $t\bar{t}$



$120 \leq m_{H^+} \leq 160$ GeV

	Signal Regions		**on-Z Control Region**		**$t\bar{t}$ Control Region**
Channel	$e\mu\mu$	$\mu\mu\mu$	$e\mu\mu$	$\mu\mu\mu$	$e\mu\mu$
Binning	$m^a_{\mu\mu}$	$m^a_{\mu\mu}$	$n_{\text{jets}}, n_{b\text{-jets}}$	$n_{\text{jets}}, n_{b\text{-jets}}$	$p_{\text{T}}^{\mu,\text{fake}}$
$n_{\text{electrons}}$	1	0	1	0	1
n_{muons}	2	3	2	3	2
$m_{\mu\mu}$ [GeV]	$12 < m^a_{\mu\mu} < 77$ -	$12 < m^a_{\mu\mu} < 77$ and $m^{\text{other}}_{\mu\mu} < 77$ or > 107	$77 < m^a_{\mu\mu} < 107$ -	$77 < m^a_{\mu\mu} < 107$ or $77 < m^{\text{other}}_{\mu\mu} < 107$	$12 < m^a_{\mu\mu} < 77$ -
n_{jets}	≥ 3				1 or 2
$n_{b\text{-jets}}$	≥ 1				1