ATLAS Searches for low mass resonances (resolved signatures)

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On behalf of the ATLAS collaboration

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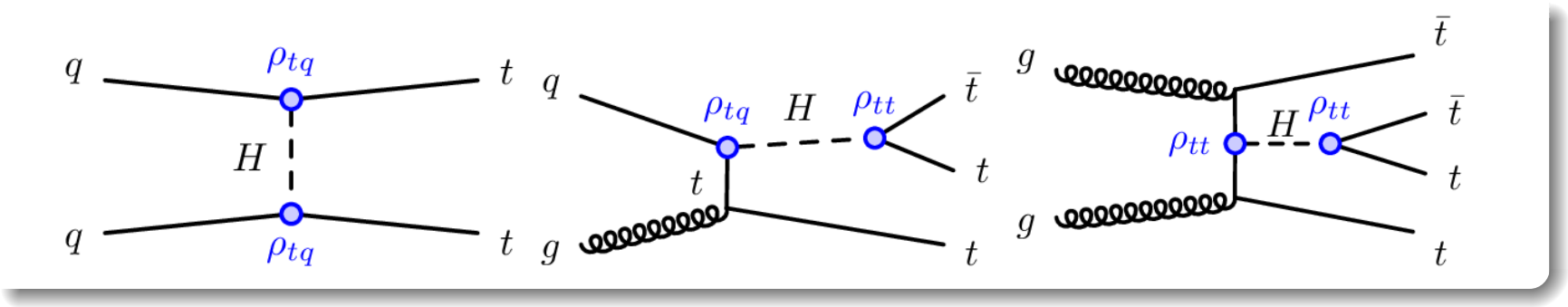
Additional scalar in BSM Higgs searches

- Two-Higgs-Double-Models (2HDM), 2HDM+S, Axion Like Particles (ALPs), etc
- Additional Scalars have mixing with SM Higgs
- Current 95% CL BR(Higgs $\rightarrow$ invisible) < 0.107 PLB 842 (2023) 137963, BR(Higgs $\rightarrow$ undetected) < 0.12 Nature 607, 52 (2022) $\Longrightarrow$ still allows significant BSM Higgs decay
- Higgs portal to Dark Sector.
- Presenting analyses using p-p collisions, at $\sqrt{S} = 13$ TeV, $\mathcal{L} = 139$ fb^{-1}

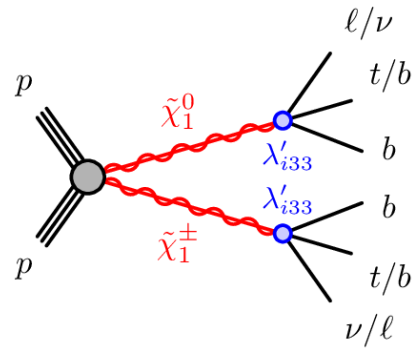
Analysis	Mass range [GeV]	Reference
2HDM multi-b multi-lepton	200 - 1500	JHEP_271P_0723
$t \rightarrow qX, X \rightarrow b\bar{b}$	20 - 160	JHEP_108P_0123
$h \rightarrow 2a \rightarrow 2b2\mu$	16 - 62	DK12786
$4\ell + MET$	160 - 1300	JHEP_133P_0124
"Boosted" $di-\gamma$ resonances	10 - 70	JHEP_073P_1122
$di-\gamma$ resonances	66 - 110	arXiv:2407.07546

2HDM multi-b multi-lepton JHEP_271P_0723

- **Motivation**: (General) g2HDM, no Z_2 symmetry $\rightarrow$ alignment limit (extra scalars have vanishingly small mixing with the SM Higgs).
  - Heavy Higgs boson features Flavour-Changing-Neutral-Higgs (FCNH) couplings with top-quarks: ρ_{tt}, ρ_{tq} (q = u, c quarks)
  - $\Longrightarrow$ 2 same sign (**SS**) tops, 3-top, 4-top production
  - Bench mark couplings: $\rho_{tt} = 0.4$, $\rho_{tq} = 0.2$
  - First g2HDM search, first BSM production for 3-top
  - Signatures: multi-e/μ, multi-jets with b-jets, charge asymmetry



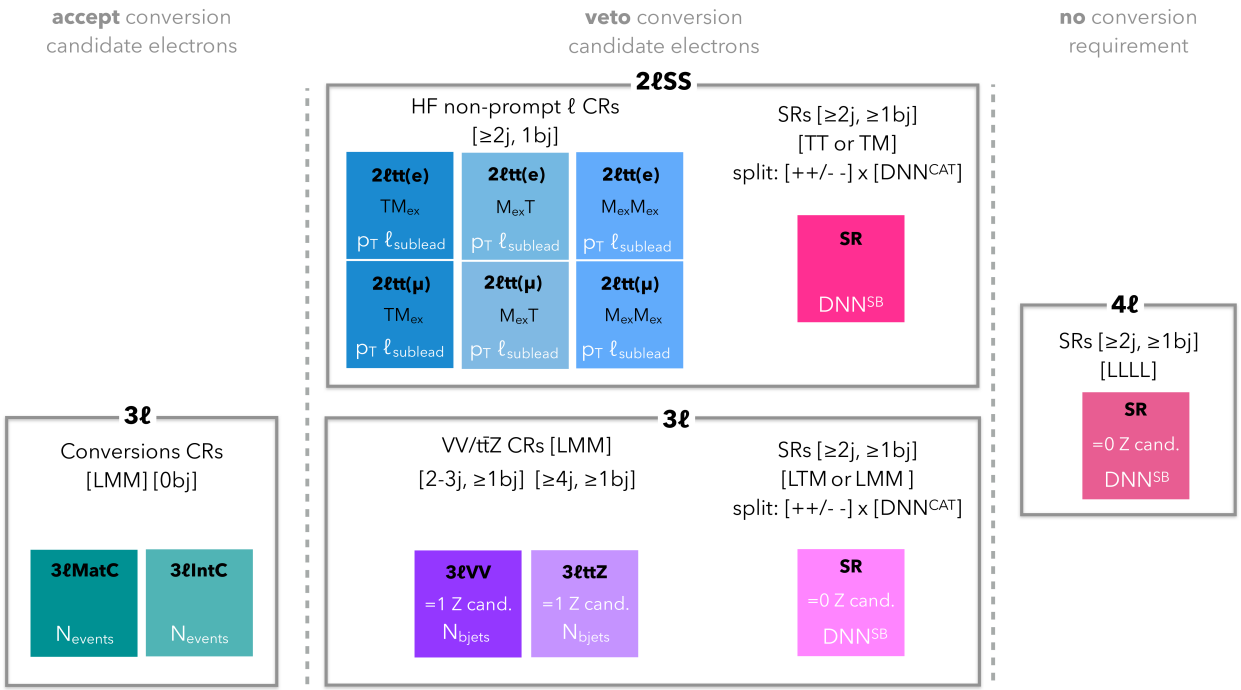
- Extra: R-parity-violating (RPV) SUSY model motivated by lepton flavour and muon (g-2) anomalies



2HDM multi-b multi-lepton, Analysis method

- **Signal categorization** into signal regions (SRs) based on
  - The number of leptons (e/μ)
  - The total lepton charge
  - multi-output deep neural network (DNN) score

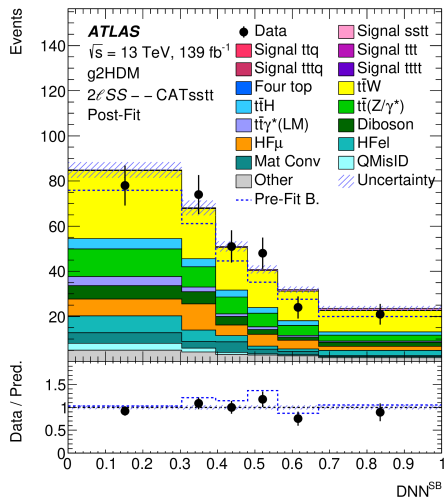
- **Background Estimate**
  - Irreducible (prompt lepton): $t\bar{t}$W, $t\bar{t}t\bar{t}$, $t\bar{t}$Z/γ^*, VV
  - Reducible (non-prompt): $t\bar{t}$, V+jets, single-top-quark
  - Dedicated control regions (CRs) are exploited



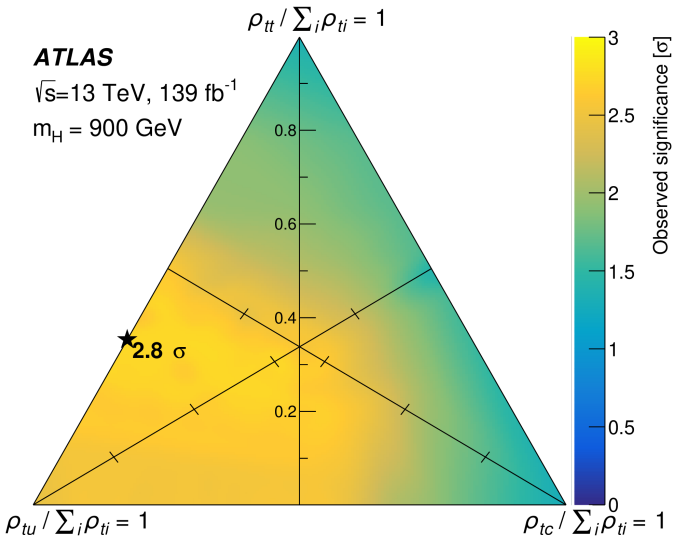
2HDM multi-b multi-lepton, Results

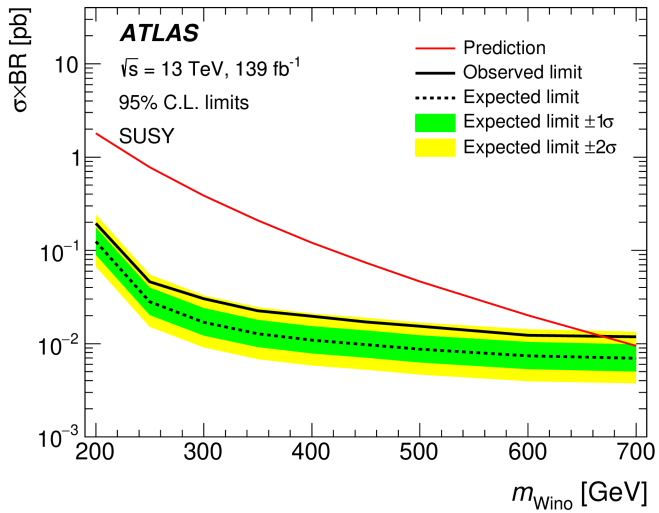
- Additional uncertainty for the MC modeling of $t\bar{t}$ V and $t\bar{t}$+jets events with additional heavy-flavor jets".
- Dominated by statistical uncertainty
- Maximum-likelihood fit in the 27 SRs + CRs
- No significant excess is observed
- Highest excess: 2.8 σ, at $m_H = 900$ GeV and $\rho_{tt} = 0.6$, $\rho_{tc} = 0.0$, $\rho_{tu} = 1.1$

A DNN output score



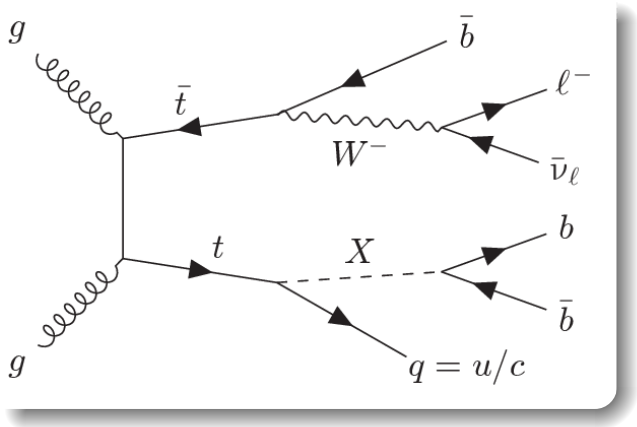
Observed significance g2HDM couplings, 95% CL upper limit RPV XS





- **Motivation**: Flavour Changing Neutral Current (FCNC)
  - BSM version of FCNC $t \to qH$
  - Model with Froggatt-Nielsen mechanism: field X charged under flavour charge (flavon) symmetry $U(1)_F$, which is then broken
  - $\Longrightarrow$ decays of a top quark to up type quarks (u, c) and a scalar boson X, $X \to b\bar{b}$
  - Light m_X: [20, 160] GeV ($< m_{top}$)

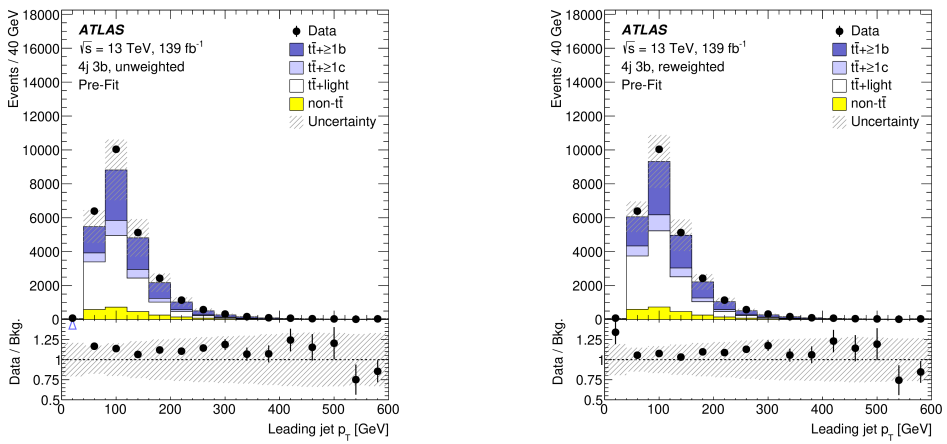
- **Signatures**:
  - Consider top-quark pair decays
    - a top decay to exotic qX
    - a top decay to SM Wb
  - Final state: 1 electron or μ and $\geq$ 4 jets.
  - Main background: $t\bar{t}$ production in association with jets



$t \to qX, X \to b\bar{b}$, Analysis method

- **Categorized** according to the multiplicities of jets and b-jets
  - 3 SRs: 4j 3b, 5j 3b and 6j 3b,
  - 3 CRs: 4j 4b, 5j $\geq$4b and 6j $\geq$4b.
  - Using a NN to discriminate signal against bkg with info from jets, lepton, invariant masses, angular separation

Leading jet p_{T} before and after reweighting



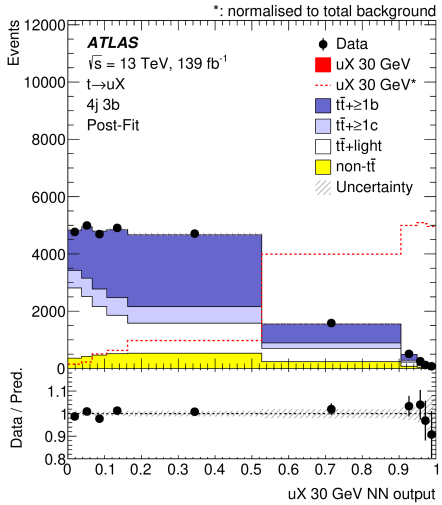
Background Estimate

- 3 additional regions: 2b 1bl-jet (with 4, 5, 6 jets in total). bl-jet is a looser b-jet.
- Deriving weights based on H_T^{all}, the scalar sum of the transverse momenta of all selected objects
- $\Longrightarrow$ to correct mismodelling of MC predictions in $t\bar{t}$ and $W \to cb$

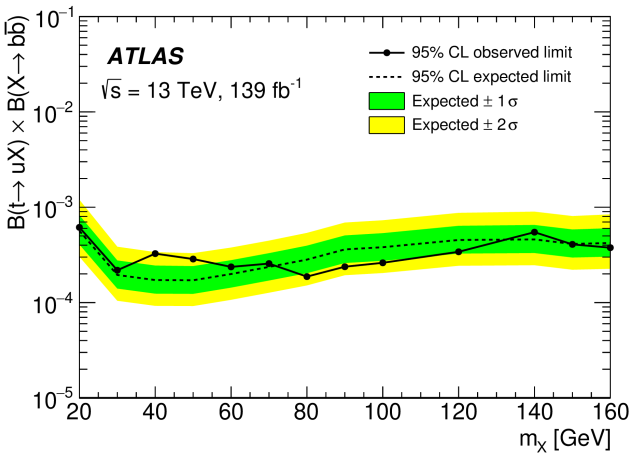
$t \to qX, X \to b\bar{b}$, Results

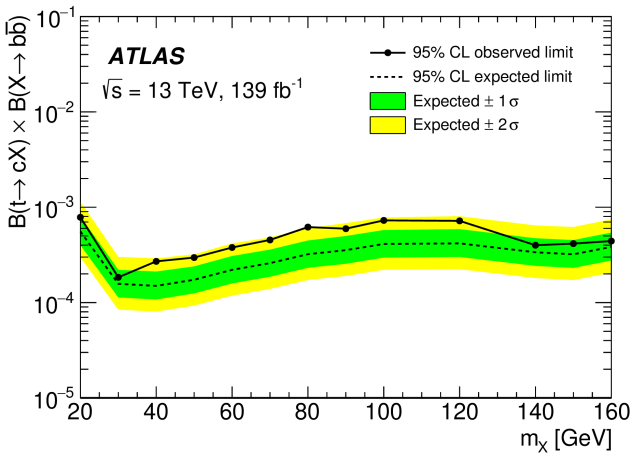
- Maximum-likelihood fit on signal NN output distributions in 3 SRs and the bkg total yields in 3 CRs
- Dominating systematic uncertainty: $t\bar{t}$ modelling, jet energy scale and resolution, or jet tagging
- No significant excess is observed
- Highest local excess: 1.8 σ in the $t \to uX$ channel at $m_X = 40$ GeV

A DNN output score



95% CL upper limit for $BR(t \to u/cX) \times BR(X \to b\bar{b})$

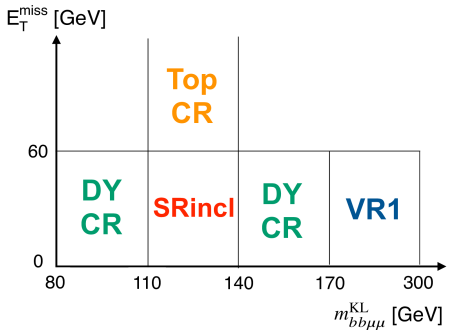




$h \to 2a \to 2b2\mu$, DK12786

- **Motivation**: Light (pseudo) scalars a that couples to the 125 GeV Higgs boson
  - Naturalness problem, couple to dark sector
  - Muon (g-2) anomaly
  - $m_a < \frac{m_H}{2}$: [16, 62] GeV
- **Signatures**:
  - Final state: Pair of $b\bar{b}$ and $\mu^+\mu^-$, (4 fermions coming from a Higgs decay).
  - Main background: Drell-Yan (DY) di-muon in association with b-quarks, $t\bar{t}$ where $W \to \mu\nu$. Estimated using 2 dedicated CRs (DYCR and TCR). Then validated in 2 validation regions (VRs)
- Kinematic likelihood fit exploiting $m_{\mu\mu} \sim m_{bb} \Longrightarrow$ improving $m^{KL}_{bb\mu\mu}$
- A boosted decision tree (BDT) classifier to separate S vs B
- SR bins after inclusive selection: $|m_{\mu\mu} - m_a| < X$ and $BDTm_a > 0.2$, where X = 1 (1.5) GeV for $m_a \leq$ 45 (>45) GeV.

Summary of CRs, SRs and VRs

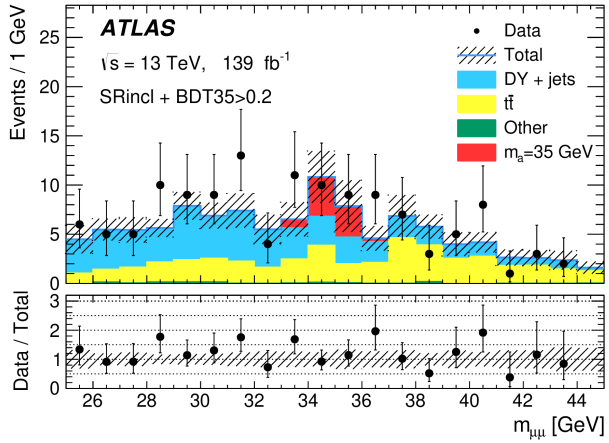


	TCR	DYCR	SRincl	VR1	VR2
$m_{\mu\mu}$ [GeV]	[15, 65]				
$m^{KL}_{bb\mu\mu}$ [GeV]	[110, 140]	[80, 110] or [140, 170]	[110, 140]	[170, 300]	[110, 140]
E_T^{miss} [GeV]	> 60	< 60			
$\ln(L^{max})$	> −8				[−11, −8]
SR bins	SRincl & BDT$m_a > 0.2$ 2-GeV-wide (3-GeV-wide) $m_{\mu\mu}$ bins for $m_a \leq 45$ GeV ($m_a > 45$ GeV)				

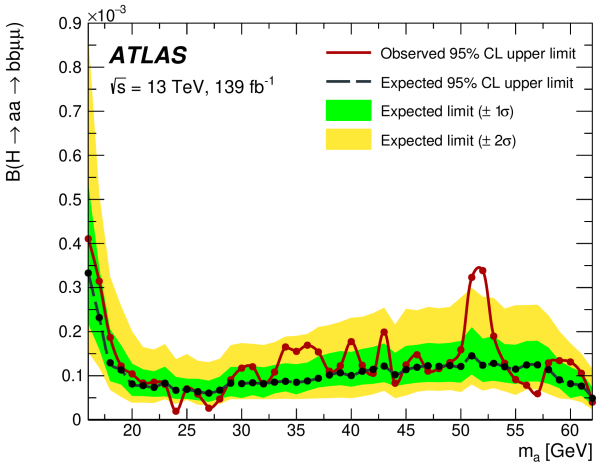
$h \to 2a \to 2b2\mu$, Method and Results

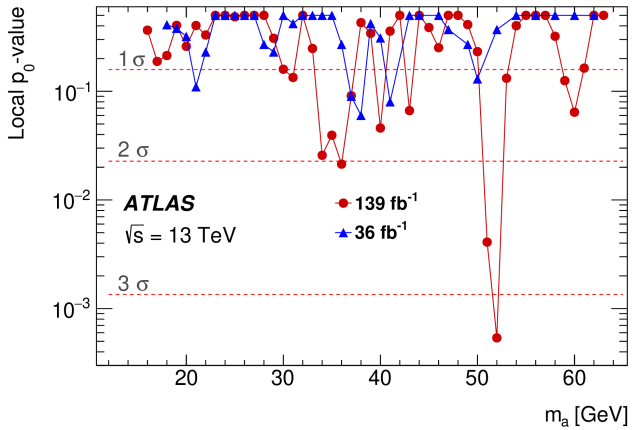
- Maximum-likelihood fit on $m_{\mu\mu}$ in SR + CRs
- Dominating systematic uncertainty: Statistical uncertainty, then b-tagging
- No significant excess is observed
- Highest excess: local (global) of 3.3 (1.7) σ, at $m_{\mu\mu} = 52$ GeV

$m_{\mu\mu}$ with BDT35 > 0.2



95% CL upper limit for BR($h \to 2a \to 2b2\mu$) and p_0-value





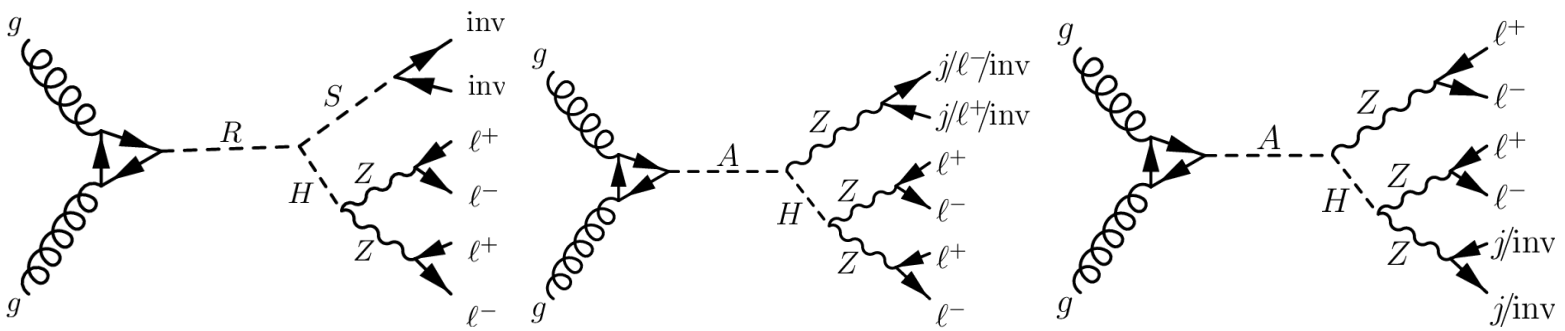
$4\ell + MET$, JHEP_133P_0124

- **Motivation**:
  - 2HDM+S: additional scalar S $\rightarrow$ Dark Matter portal
    - S decays invisibly $\rightarrow$ missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$). Mass fixed at 160 GeV
    - Added a heavy R scalar, $R \rightarrow S + H$
    - $m_H > m_H^{SM}$: $>$ 200 GeV
  - Baryongenesis: $A \rightarrow Z + H \rightarrow 4\ell + 2\ell$/2-jets/2 invisibles
  - Narrow Width Approximation (NWA) for all scalars

- **Signatures**:
  - Final state: 4 charged leptons (e/μ), $E_{\mathrm{T}}^{\mathrm{miss}}$ or 2 jets
  - Main background: $q\bar{q} \rightarrow ZZ$ (>86%), $gg \rightarrow ZZ$, etc.

Signal region	$R \rightarrow SH \rightarrow 4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ and $A \rightarrow ZH \rightarrow 4\ell + X$			
SR1	$n_{b\text{-jets}} = 0$	$n_{\mathrm{jets}} = 0$	$p_{\mathrm{T}}^{4\ell} > 20$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance >2.0
SR2		$n_{\mathrm{jets}} \geq 1$	$p_{\mathrm{T}}^{4\ell} > 10$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 3.5
SR3			$p_{\mathrm{T}}^{4\ell} < 10$ GeV	2.5 < $E_{\mathrm{T}}^{\mathrm{miss}}$ significance < 3.5
	$A \rightarrow ZH \rightarrow 4\ell + X$			
SR4	$n_{b\text{-jets}} = 0$	$n_{\mathrm{jets}} \geq 2$	$\lvert m_{jj} - m_Z \rvert < 20$ GeV	
SR5			$\lvert m_{jj} - m_Z \rvert > 20$ GeV	
SR6		$n_{\mathrm{jets}} = 1$		
SR7	$n_{b\text{-jets}} \geq 1$			

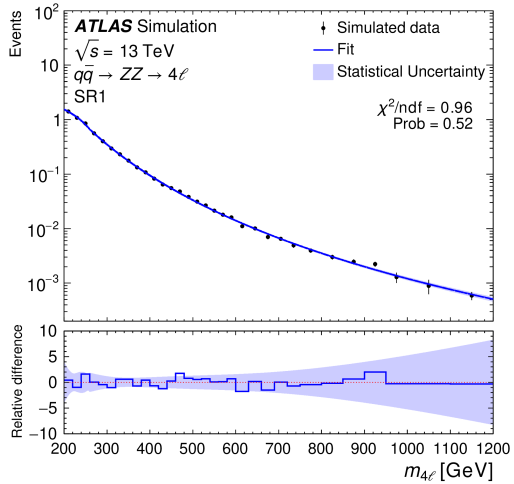
- MC is used to model, then parameterise $m_{4\ell}$ distribution in bkgs



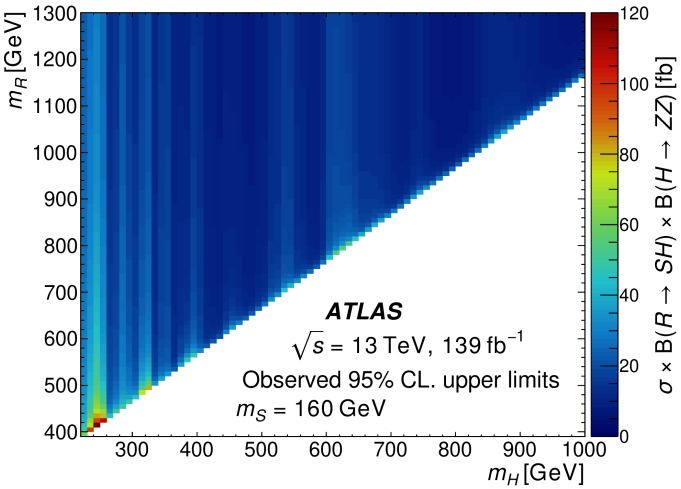
$4\ell + MET$, Method and Results

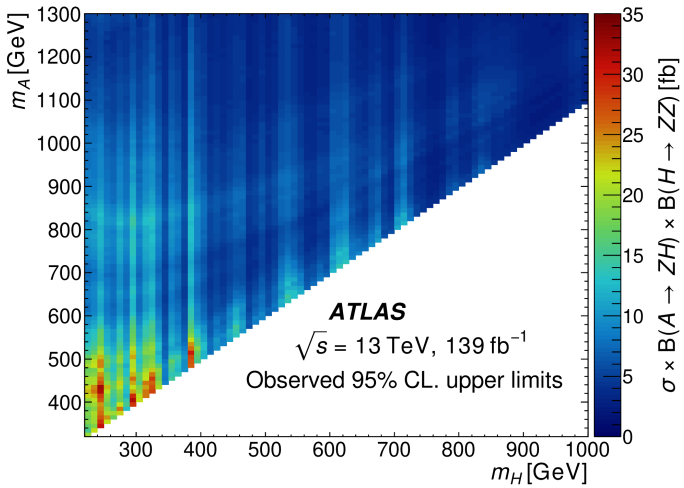
- Maximum-likelihood fit on $m_{4\ell}$ in SR
- In each SR, the normalisation for the ZZ bkg ($q\bar{q}/gg \to ZZ$) is extracted from the fit to data.
- Dominating uncertainty: MC modeling, flavour tagging
- No significant excess is observed
- Highest excess: local significance 2.5 σ, at $(m_A, m_H) = (510, 380)$ GeV

Analytical form – $q\bar{q} \to ZZ$



95% CL observed upper limit on XS times Branching Ratio (NWA)



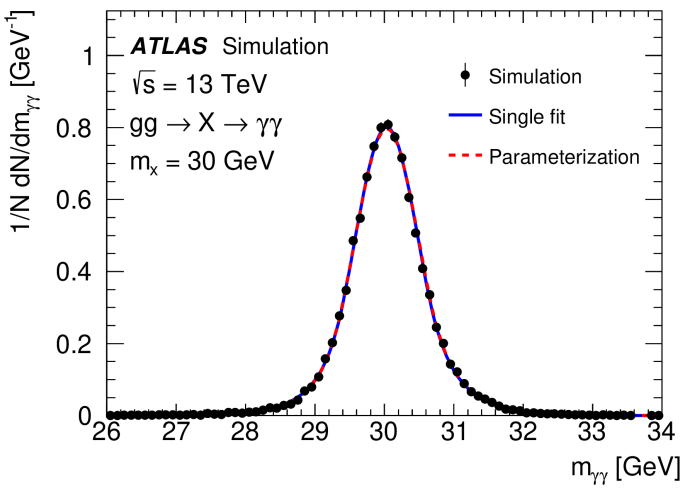


"Boosted" $di-\gamma$ resonances, JHEP_073P_1122

- **Motivation**:
  - New phenomena: narrow resonances X with mass range [10, 70] GeV
  - Pseudo Nambu–Goldstone bosons (pNGBs) associated with spontaneously broken approximate global symmetries at the TeV scale or above, ALPs
  - All resonances are considered with NWA
- **Signatures**:
  - Final state: pair of closely spaced photons, large $di-\gamma$ p_{T}
  - Signal MC samples: $gg \to X \to \gamma\gamma$ ($+ \leq 2$ associated jets)
  - Background MC samples: $di-\gamma$ ($+$ associated jets)

- Using analytic functions to describe the S/B components
  - Double-sided Crystal Ball function (DSCB) for signal
  - Bkg MC template is smoothed by the Gaussian Process fit
- **Fiducial volume**: 2 γ with $E_{\mathrm{T}}^{\gamma} > 22\ \mathrm{GeV}, |\eta^{\gamma}| < 2.37, p_{\mathrm{T}}^{\gamma\gamma} > 50\ \mathrm{GeV}$

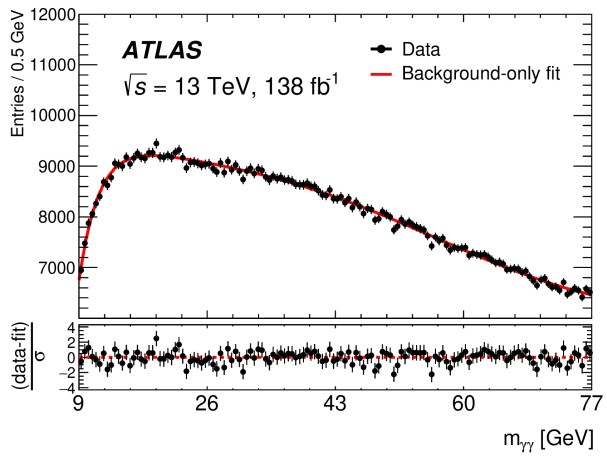
DSCB function fit, $m_X = 30$ GeV



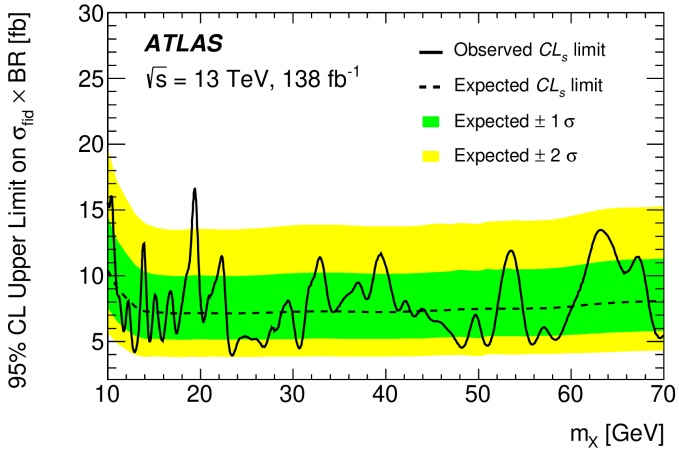
"Boosted" $di-\gamma$ resonances, Method and Results

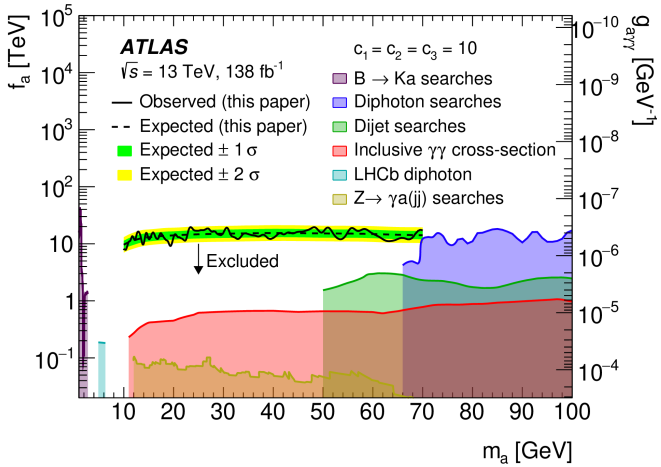
- Maximum-likelihood fit to data $m_{\gamma\gamma}$ distribution and analytic functions for S/B
- Dominating uncertainties: data statistic, bkg modelling
- No significant excess is observed
- Highest excess: local (global) significance of 3.1 (1.5) σ, at $m_{\gamma\gamma} = 19.4$ GeV

$m_{\gamma\gamma}$ after all selections



95% CL upper limit for production fiducial XS of resonance X, and ALPs





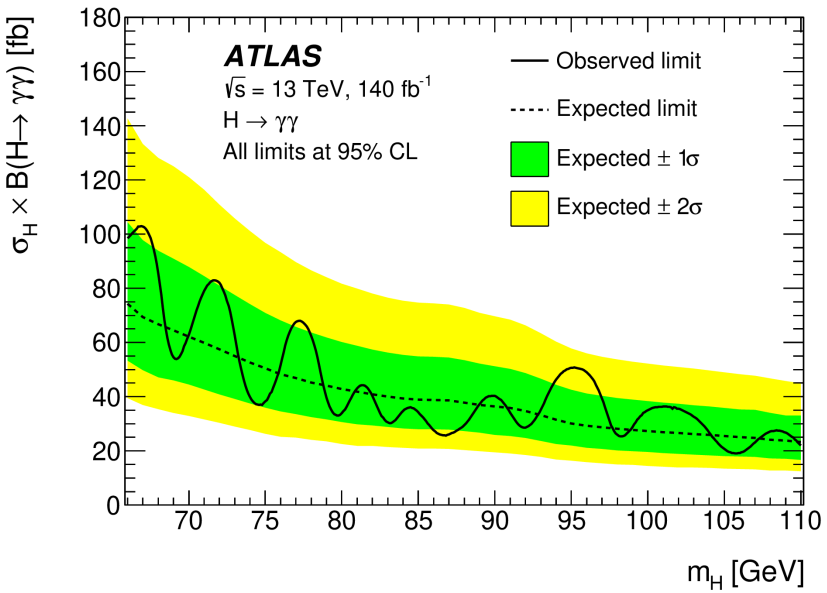
f_a: decay constant, governs ALP coupling with SM field

$di-\gamma$ resonances, arXiv:2407.07546

- **New compared to "Boosted analysis"**:
  - Covering high-mass region: range [66, 110] GeV
  - More: a model-dependent search for additional low-mass Higgs boson
  - More: Drell-Yan ee bkg with e faking γ
  - More: Events splitted to 3 categories based on γ conversion, then further splitting to 3 BDT categories in model-dependent case to discriminate continuum $\gamma\gamma$ bkg and low-mass Higgs boson signal

- No significant excess is observed
- Highest excess: local significance of
  - Model-independent: 2.2 σ at $m_{\gamma\gamma}$ 71.8 GeV
  - Model-dependent:
    - Large Width Approximation: 1.7 σ at $m_{\gamma\gamma}$ 85.2 GeV,
    - NWA: 1.7 σ at $m_{\gamma\gamma}$ 95.4 GeV (CMS saw 2.9 σ arXiv:2405.18149)

95% CL upper limit on XS $\times$ BR



Low-mass Higgs boson interpretation

Conclusion

- Presented summaries of 6 low-mass additional scalar resonance searches
- No significant excess but some interesting local excesses.
- The usage of multivariate techniques and especially machine learning bring important boost to analyses
- Some searches are statistically limited.
  - Looking forward to Run 3 analyses with more data, advanced analysis techniques
  - At HL-LHC, much larger dataset will allow substantial improvements

THANK YOU