UNIVERSITY OF CAMBRIDGE

Murray Edwards College
University of Cambridge

ATLAS EXPERIMENT

Searches for SUSY (and additional Higgses)

34th Rencontres de Blois Particle Physics and Cosmology
Dr Sarah Williams, on behalf of the ATLAS and CMS collaborations

Introduction: Motivation for BSM searches

4th July 2012

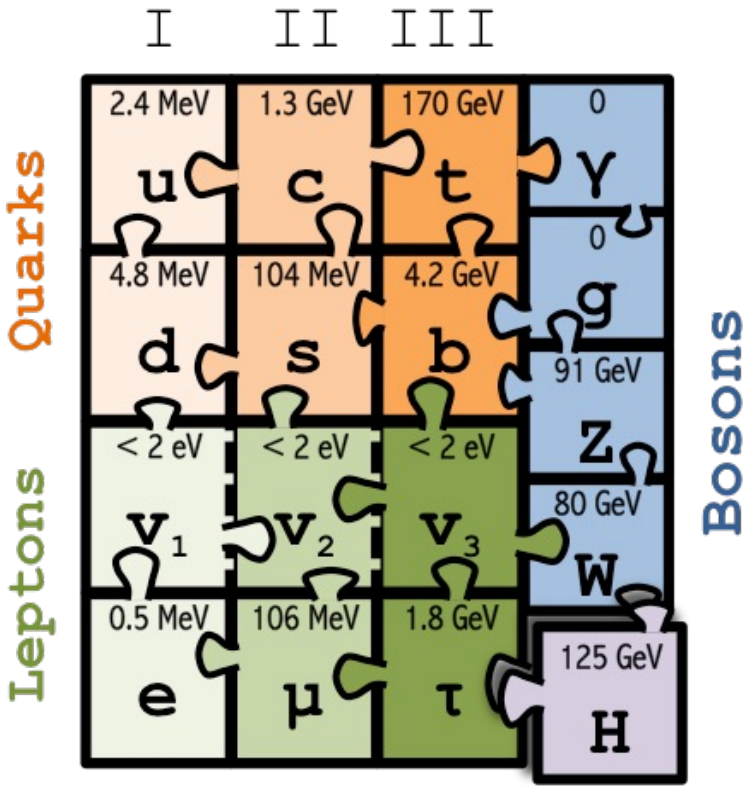
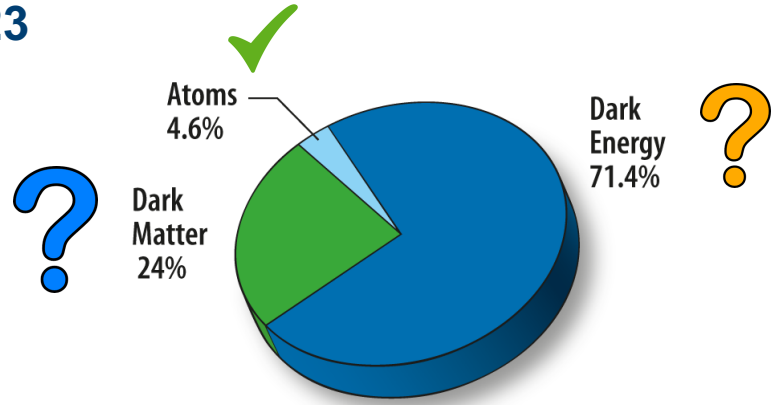


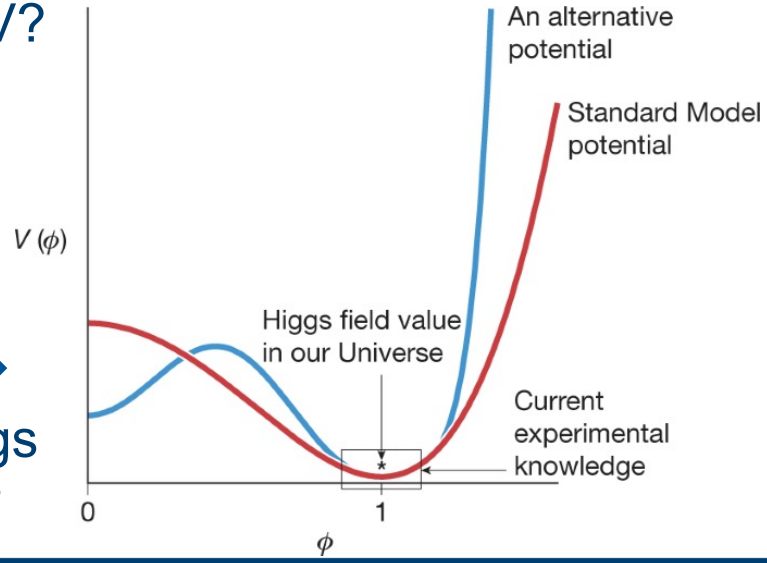
Image credit: A. Sfyrla

May 2023

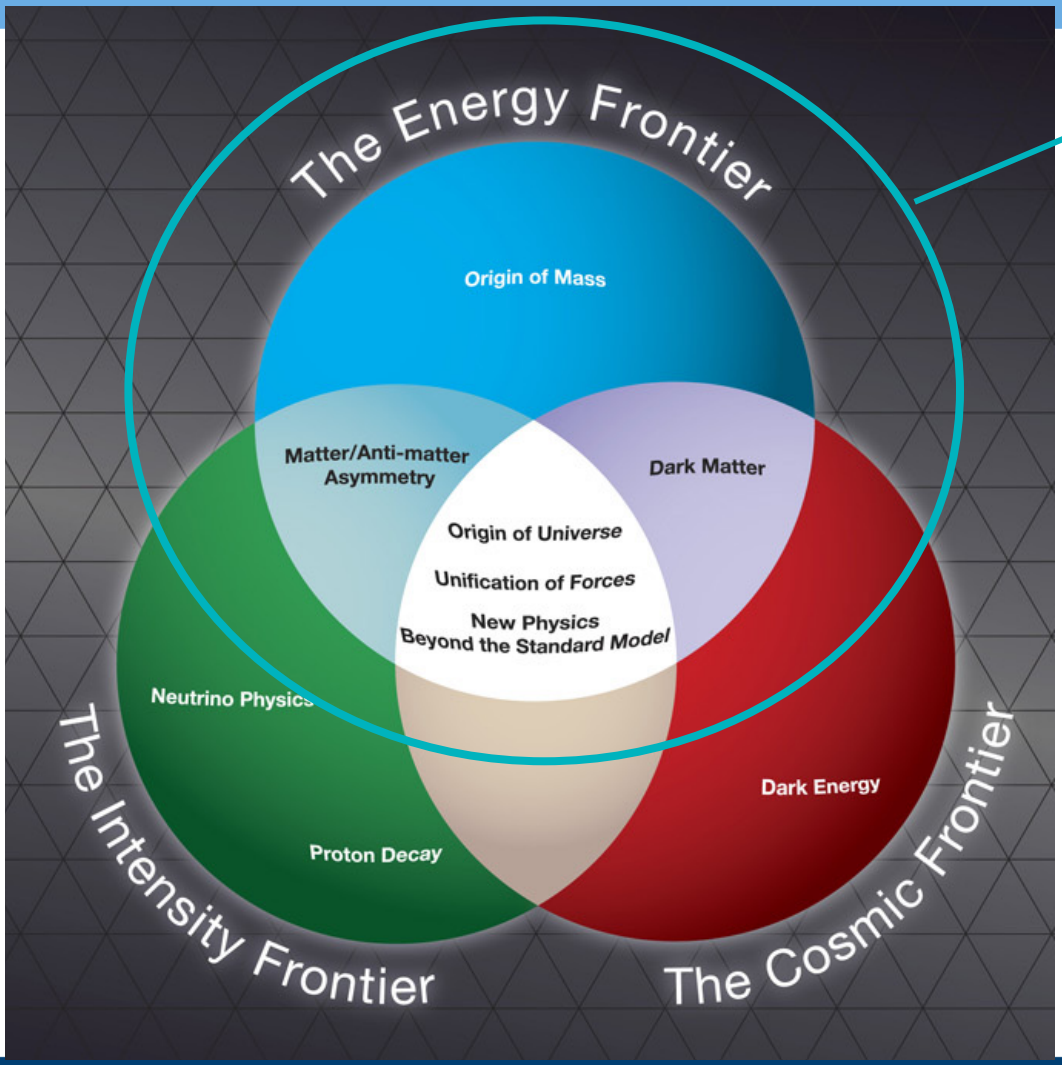


Why 125 GeV?

Is the 125 Higgs the SM Higgs?



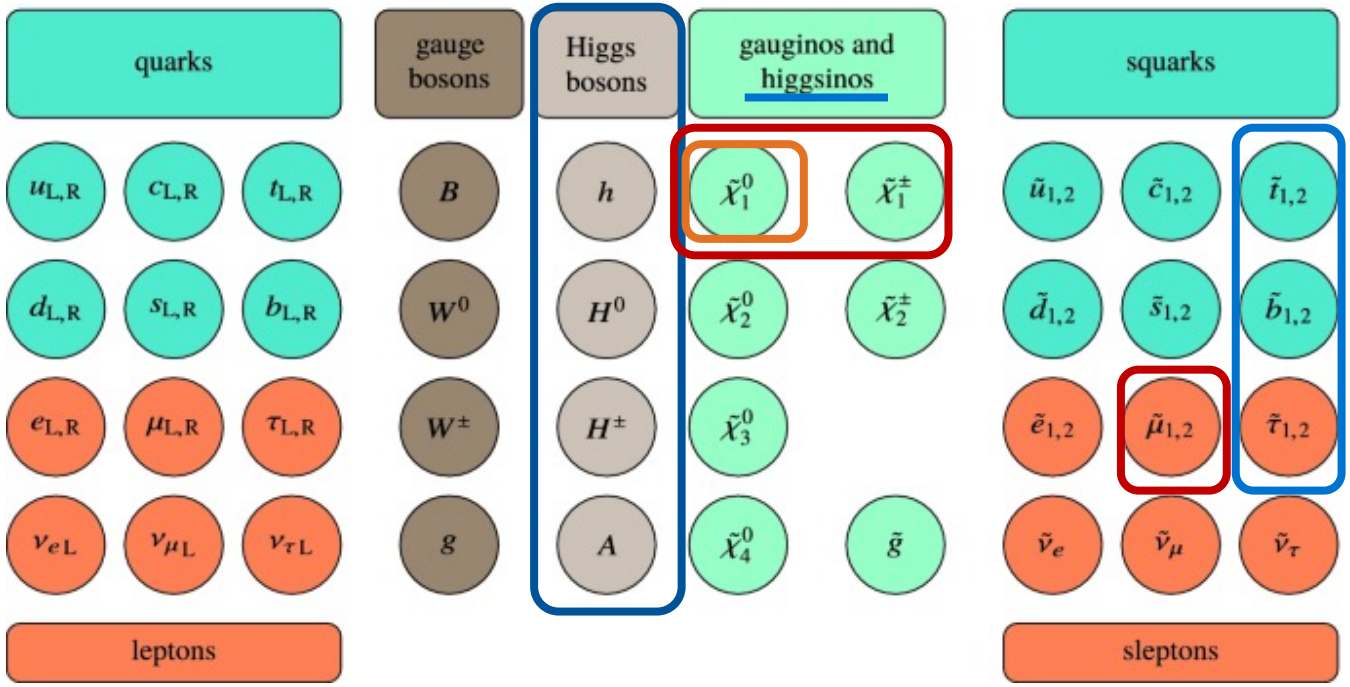
Overview of my talk



- This talk will focus on ATLAS and CMS searches for:
  - (Promptly decaying) supersymmetry.
  - Additional Higgses.
- But won't discuss exotic Higgs decays, long-lived particles, BSM + exotics searches (covered elsewhere)
- Aiming to provide a broad overview and highlight new and exciting results!

The “minimal” supersymmetric Standard Model

Introduce (heavier) superpartners for all SM particles…



Extended Higgs sector

Dark matter (R-parity conserving)

Natural Higgs mass (?)

Anomalous muon g-2

- Simplify search strategy by focusing on a particular sector. Most LHC searches focus on **simplified models** within the **(phenomenological-) MSSM**.
- Key point: whether or not you “believe” in SUSY it provides an effective framework to access a rich range of BSM phenomenology.

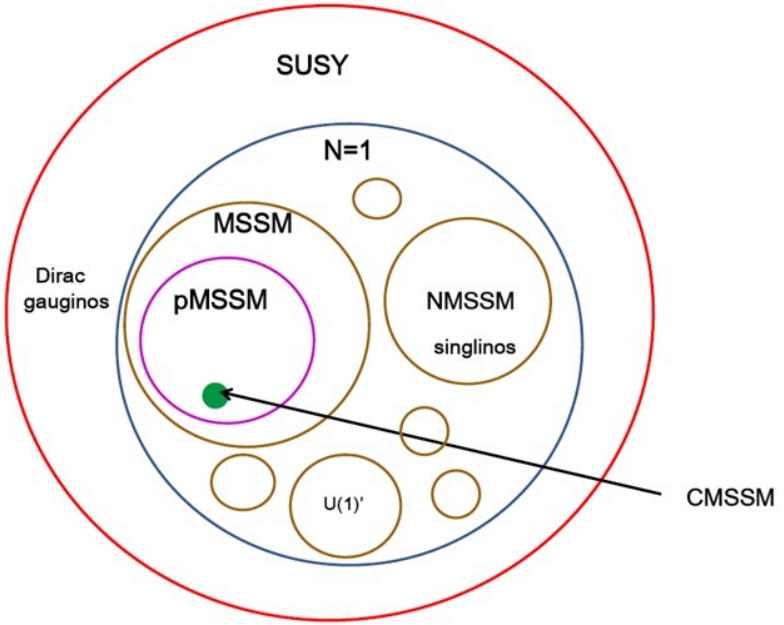
Beyond the (phenomenological) MSSM?

For SUSY…

- ”NMSSM” (=MSSM+ additional gauge singlet)
- Assume a SUSY breaking mechanism i.e. GGM
- "Stealth” SUSY

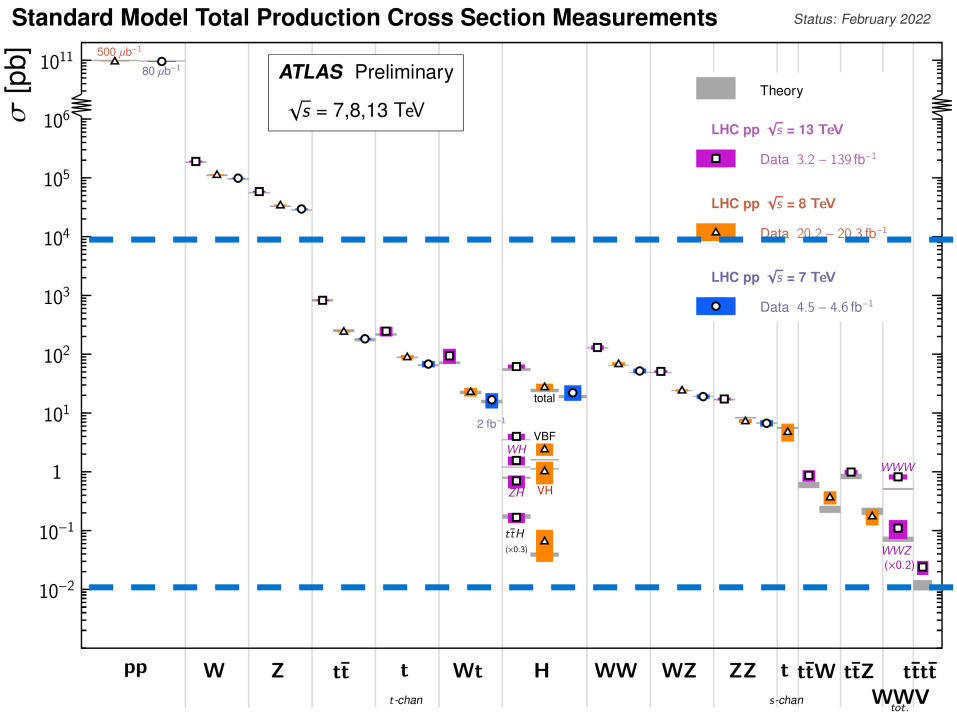
… extended Higgs sectors

- 2HDM (type 1,2,3…)
- 2HDM + X. (where X could be an additional scalar S, pseudoscalar a)

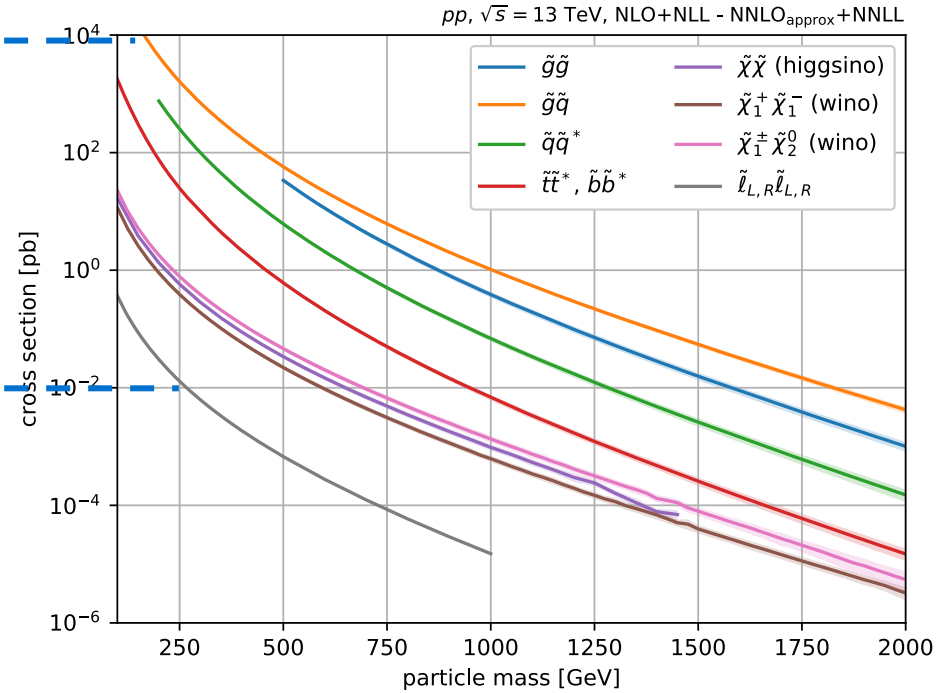


We should see our strong constraints in simplified models as a challenge to look further, rather than a reason to dispair

Searching for new particles



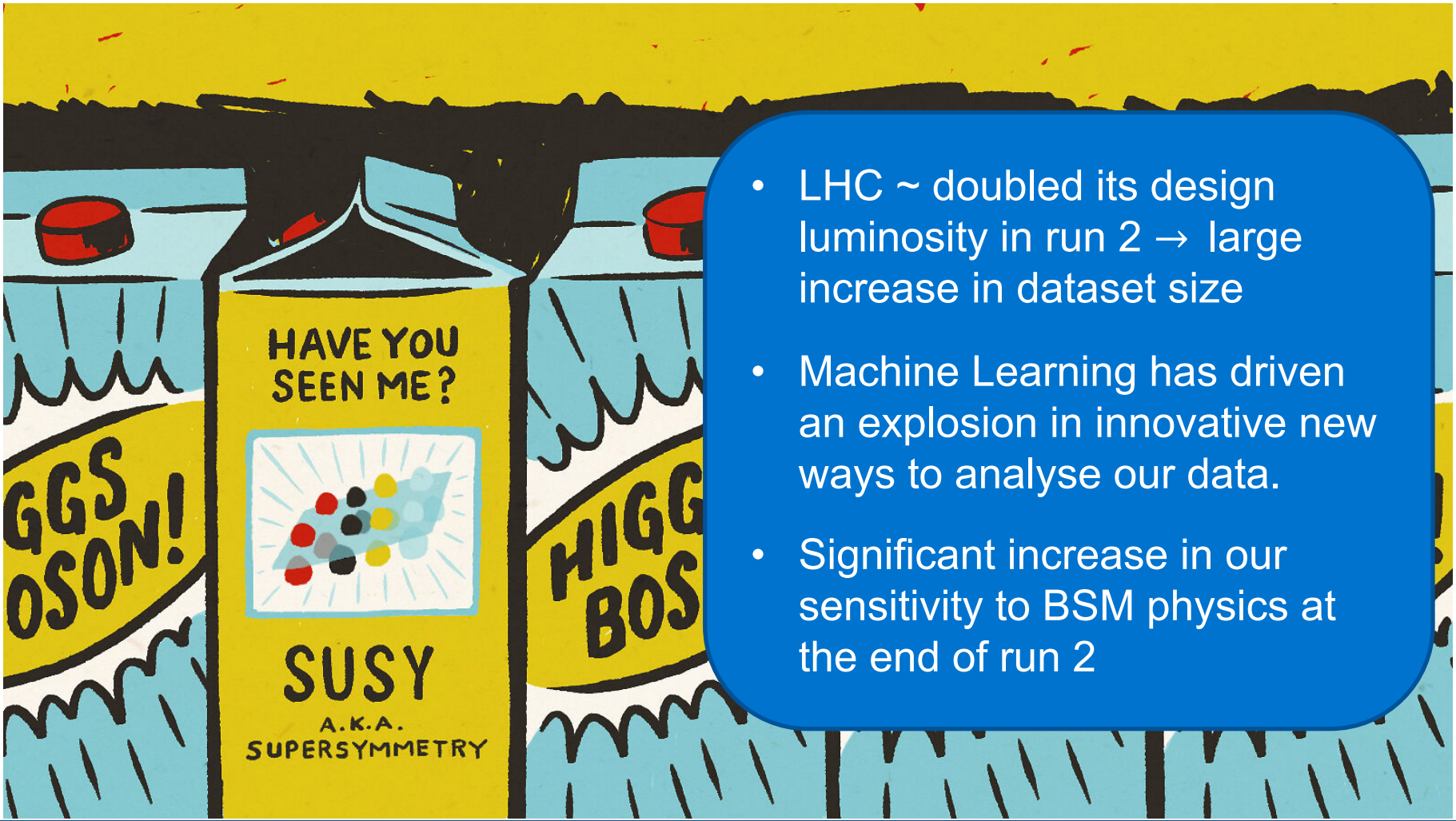
Depending on mass/production mode, expect signal to be rarer than the rarest SM processes we have observed!



First two data taking runs of the LHC have enabled us to measure the SM to impressive precision.

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections

Run 2 searches for SUSY/additional Higgs



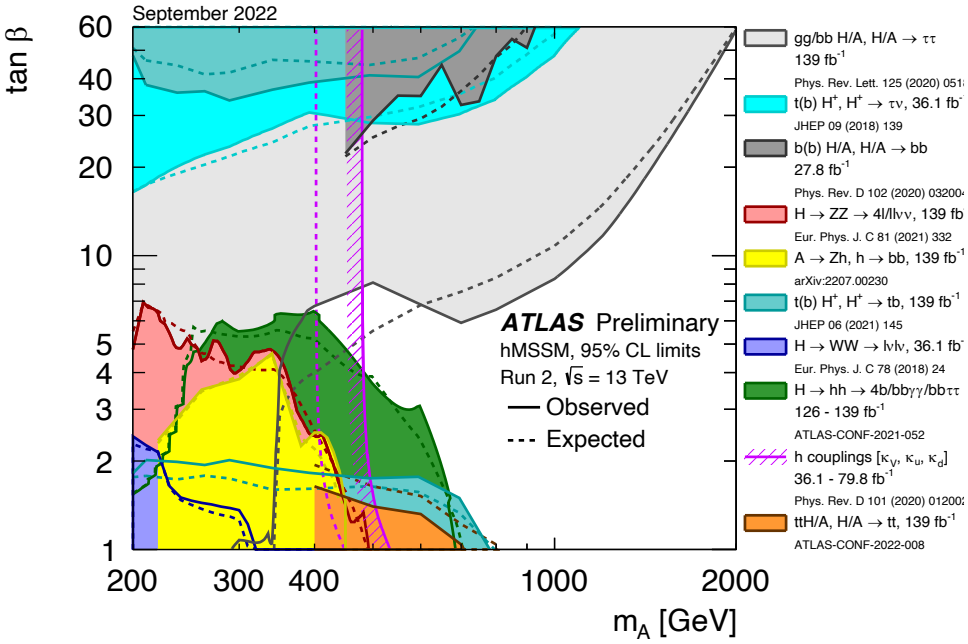
- LHC ~ doubled its design luminosity in run 2 → large increase in dataset size
- Machine Learning has driven an explosion in innovative new ways to analyse our data.
- Significant increase in our sensitivity to BSM physics at the end of run 2

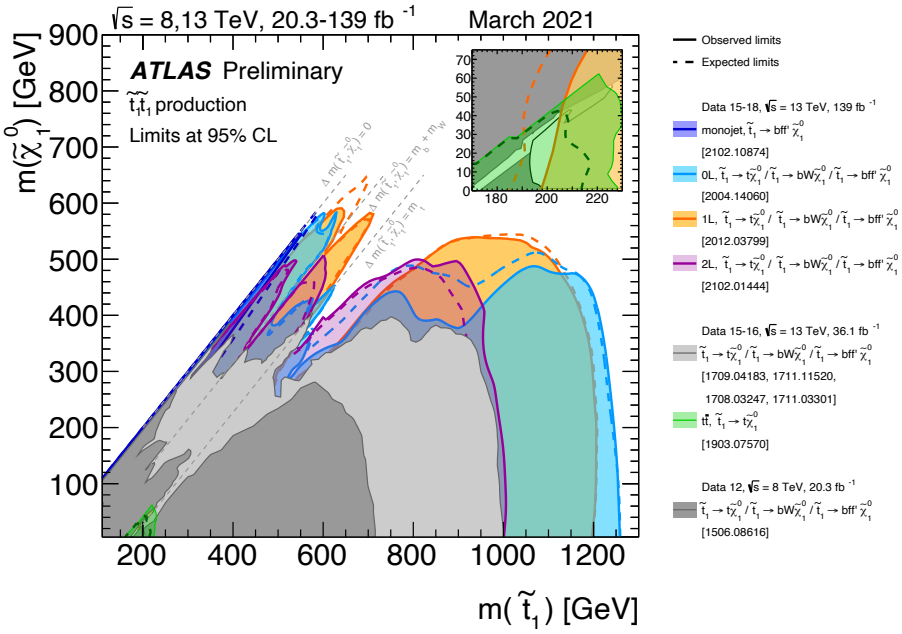
No we haven't… but…

ATL-PHYS-PUB-2022-043

ATL-PHYS-PUB-2023-005

Impressive limits on BSM parameter space from growing number of search channels, and precision measurements.





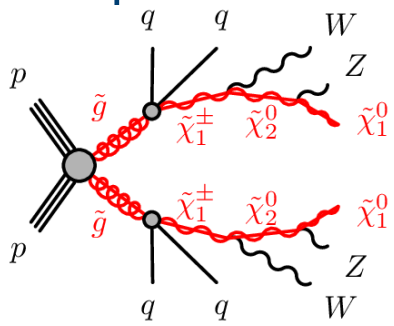
Note: I have used the ATLAS summary plots but the picture for CMS would be similar!

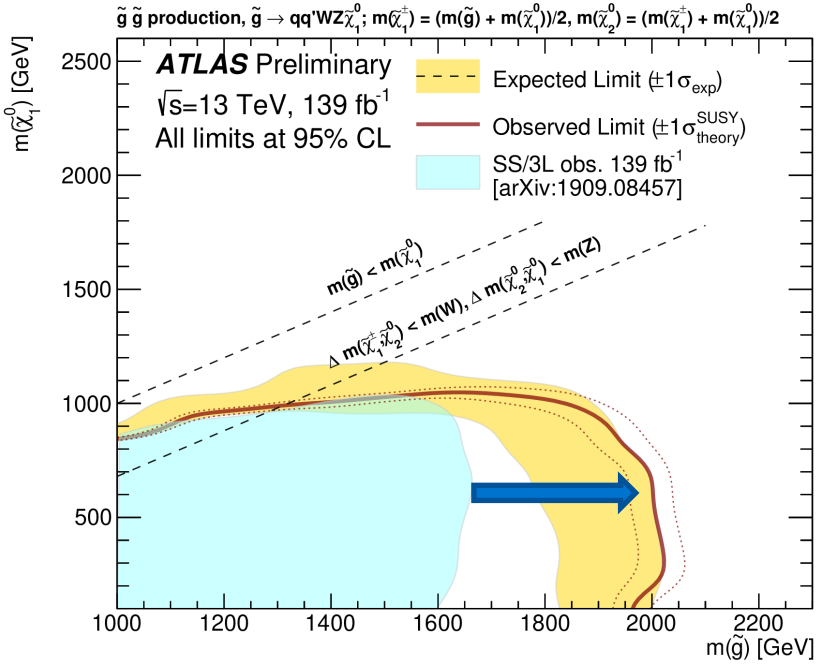
Strong(er) constraints on strong production

ATLAS-CONF-2023-017

New result targeting RPC and RPV decays of strongly produced squarks and gluinos decaying via sleptons or gauge bosons to final states with two same-sign or three leptons.

- Improved search strategy (new SRs) and background estimation (WZ, fake and charge mis-identification).
- No signs of SUSY ☹ but impressive limits in a number of simplified models.

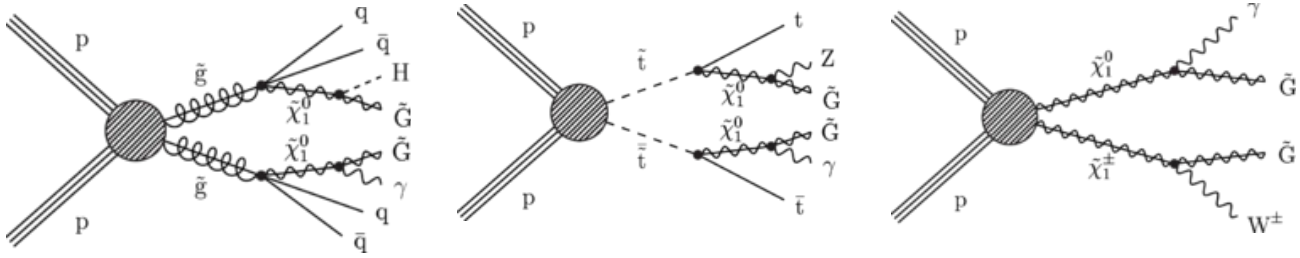




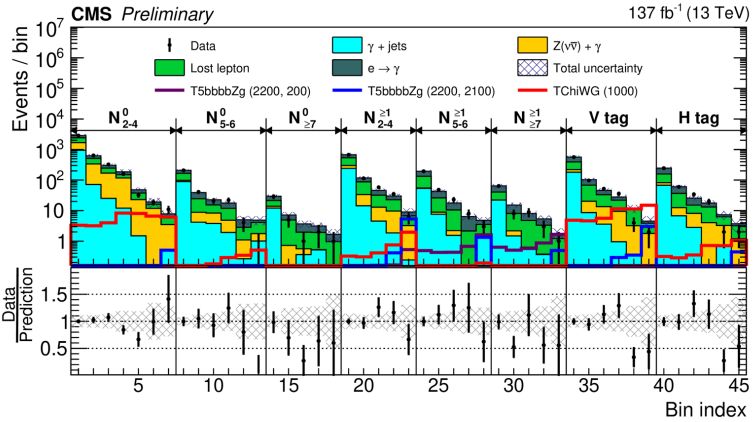
New physics in multijet+photon final state

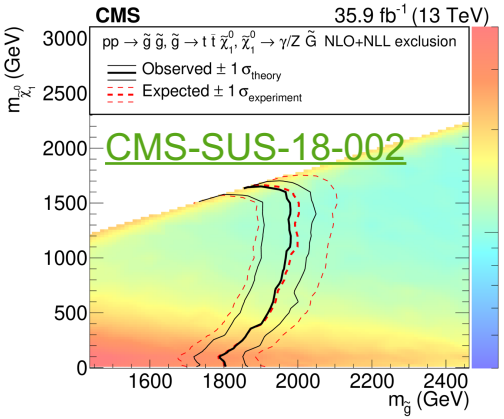
CMS-PAS-SUS-21-009

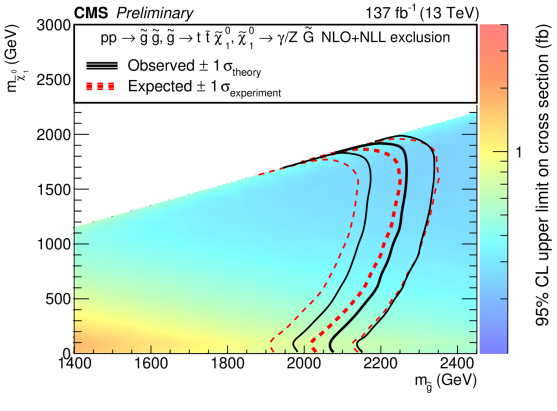
Target strong and EW GGM production in final states with jets, missing transverse momentum and at least one photon.



Targeting strong and EWK GGM models!





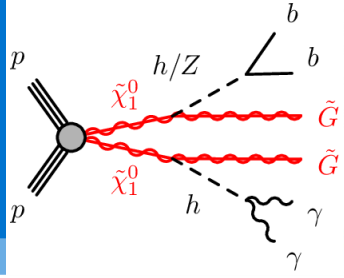


- Events separated into orthogonal categories and binned in missing transverse momentum.

Significant improvement over partial run-2 limits

New search for Higgsinos

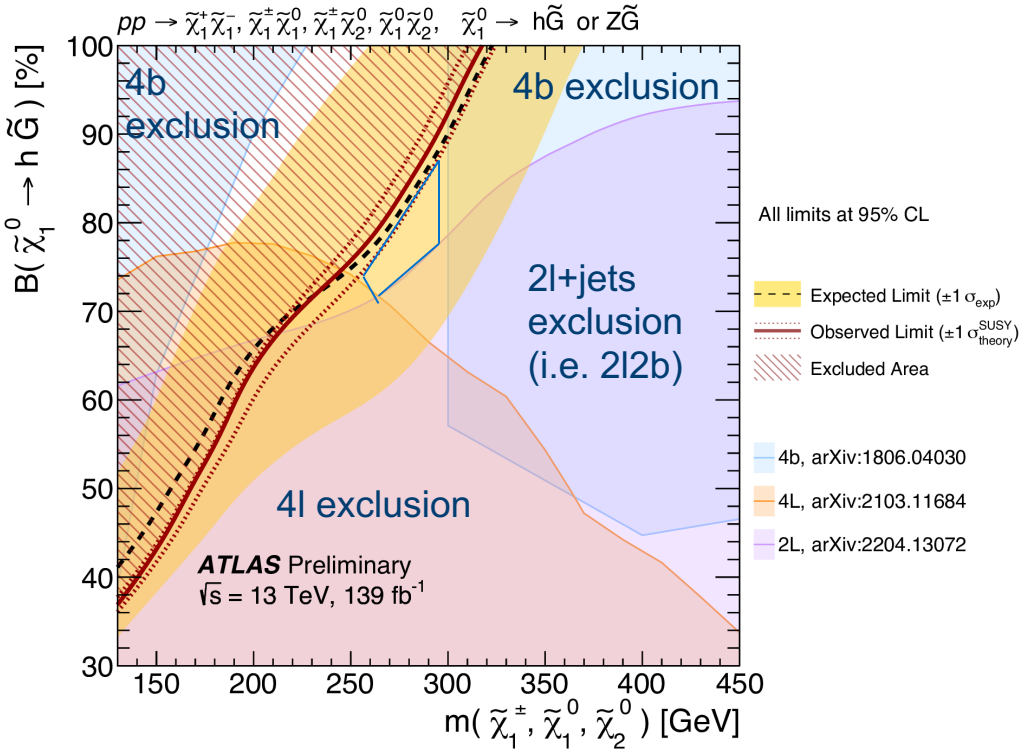
ATLAS-CONF-2023-009



ATLAS EXPERIMENT

- Target on-shell decays of h/Z to di-photon di-b-jet final states.
- Cut-based analysis targeting different NLSP masses and decay modes.
- Data-driven estimation of non-resonant background using "2x2D sideband method"

For more detail see talk by Tina Potter in collider parallel session later today!

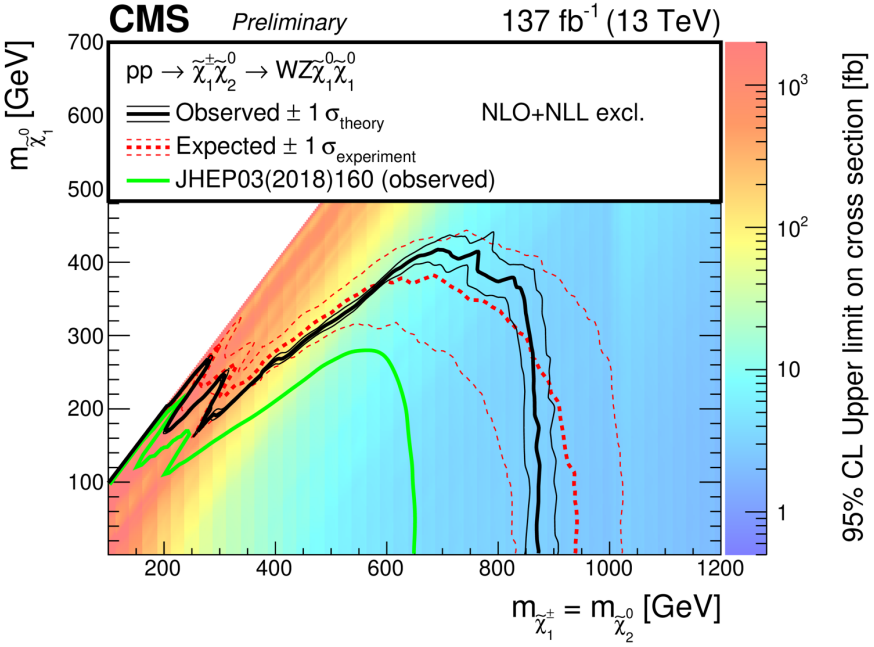


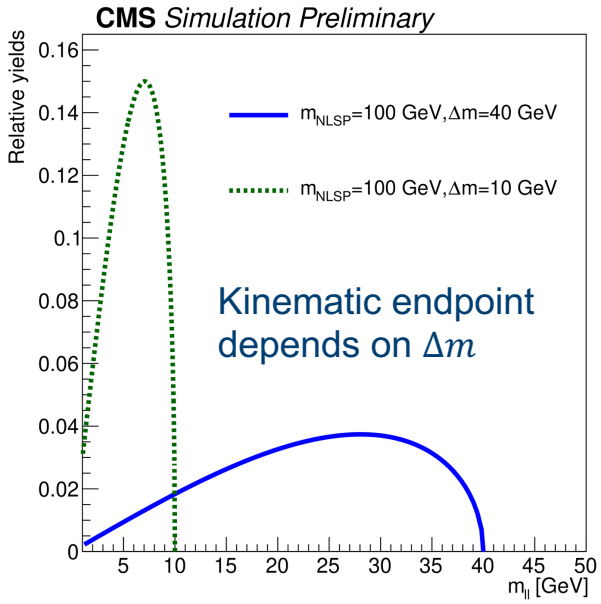
Helps fill previous gap in sensitivity. Great prospects for combinations...

New Electroweak SUSY combinations

CMS-PAS-SUS-21-008

Maximise sensitivity through combination of several searches for winos, binos, higgsinos, sleptons, with updated search using "soft" leptons and missing transverse momentum



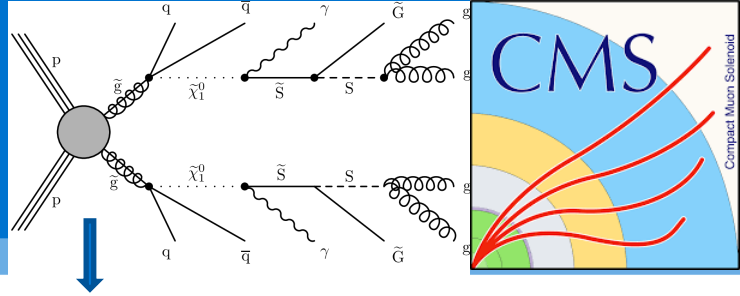


Statistical combination of 2l (on-Z, non-res), 2/3l "soft", ≥ 3l, 1l2b, 4b, hadronic

Parametric binning as a function of Δm to maximise sensitivity.

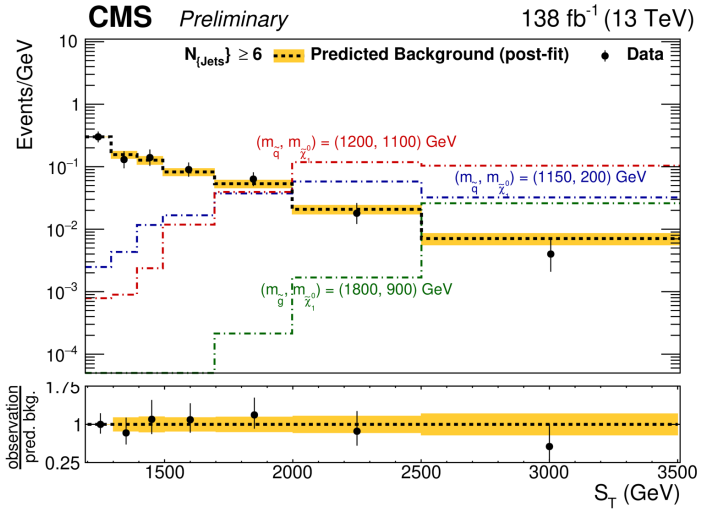
Could SUSY be stealthy?

CMS-PAS-SUS-19-001



No signs so far…

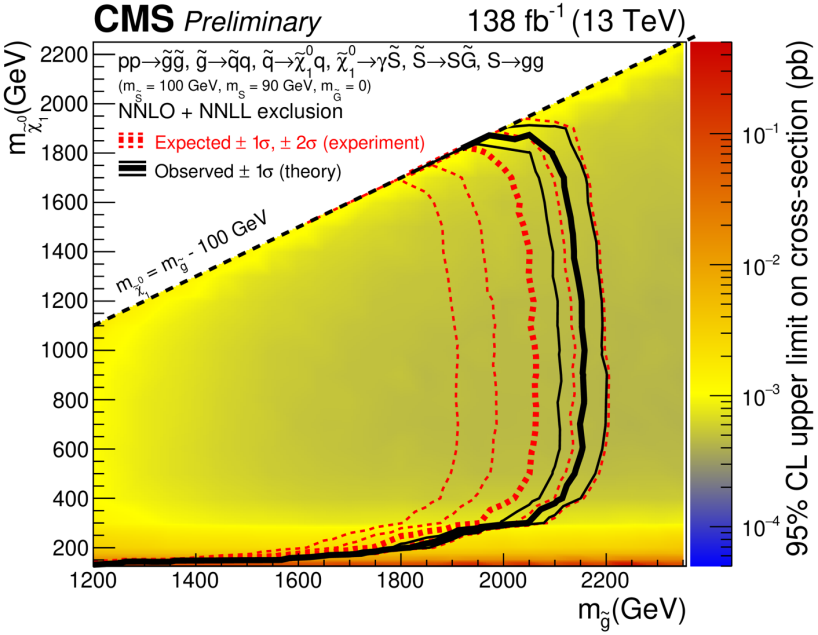
- New search in final states with two photons, jets and low missing transverse momentum.



- Total background estimated using extension of "S_T shape invariance" method.

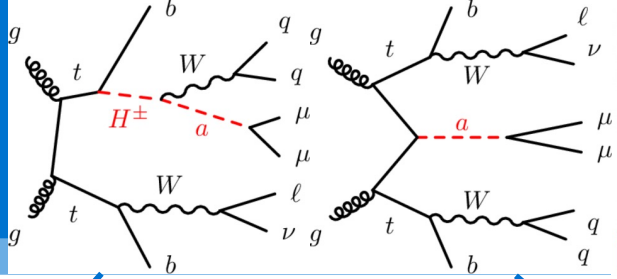
Small mass splitting between singlet and singlino suppresses momentum of LSP!

Events divided into search categories based on jet multiplicity at high values of S_T

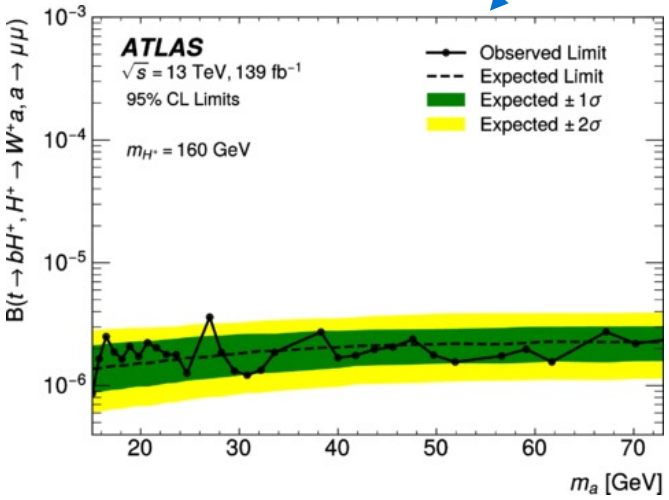


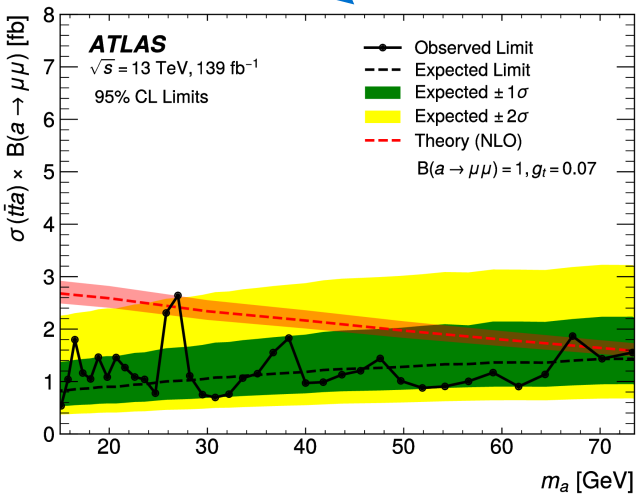
Searching for extra Higgses

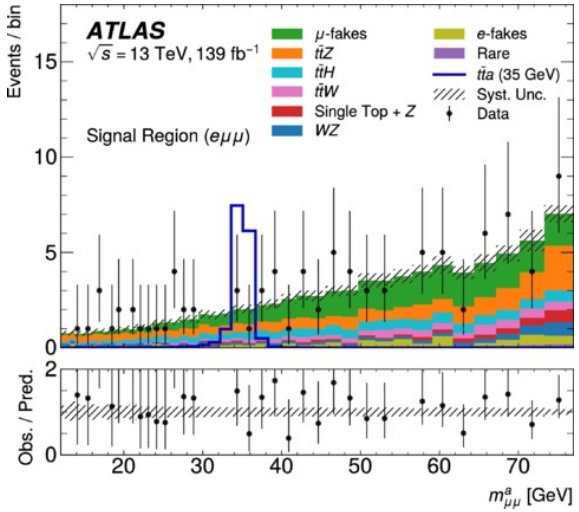
arXiv:2304.14247 (submitted to PRD)



Search for $pp \rightarrow t\bar{t}a$ production or $pp \rightarrow t\bar{t}$ with $t \rightarrow H^{\pm}b, H^{\pm} \rightarrow W^{\pm}a$ and $a \rightarrow \mu\mu$ in final states with $e\mu\mu$ or $\mu\mu\mu$ (only one top decays leptonically).





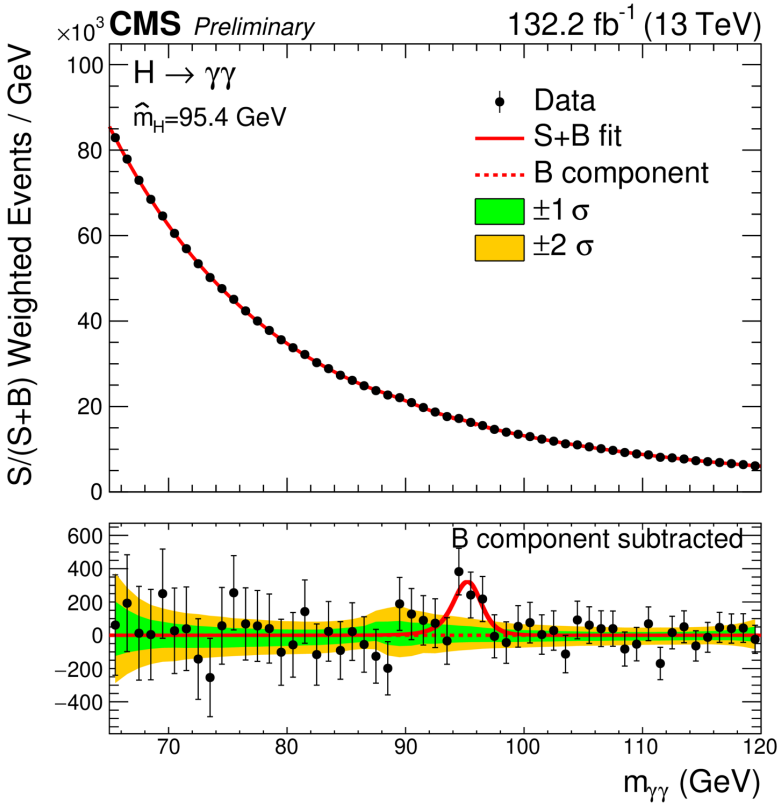


- Data-driven estimate for ttZ through CR binned in jet multiplicity and estimate for background with one non-prompt muon using fake factor method.
- Exclusion limits above show combination of both channels.

Is the 125 GeV Higgs the lightest Higgs?

CMS-PAS-HIG-20-002

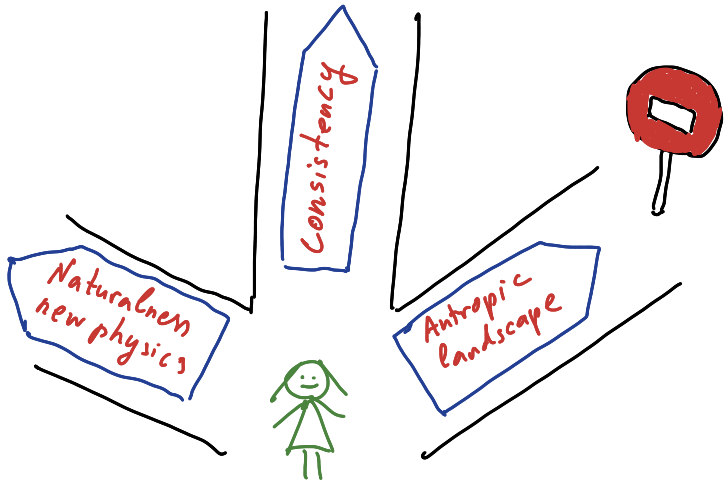
Target "SM-like" Higgs in mass range between 70 and 110 GeV through localized excess in diphoton mass spectrum.



- Extensive use of ML (reconstruction of diphoton vertex, photon ID, and classification of diphoton events, including VBF).
- Maximal observed excess for a mass hypothesis of 95.4 GeV and local (global) significance of 2.9 (1.3).
- First search for diphoton resonances in this mass range using full run 2 dataset.

Conclusions/outlook

- The ATLAS and CMS collaborations at CERN are continuing to exploit the LHC datasets in innovative ways.
- More exciting results still in the pipeline using run 2 data, with run 3 already underway.
- Closing gaps in sensitivity is essential, and we should be proud (not despondent) with the results achieved so far.



Taken from ”outlook” of Blois2021!

There’s still a long road ahead to deliver a thorough exploration of BSM physics at the (HL-) LHC. Watch this space!

Backup

Backup: The "phenomenological" MSSM

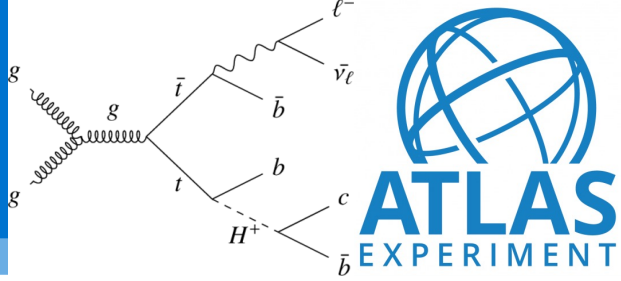
Apply set of theoretical and experimental constraints on the general MSSM-> reduce number of parameters from 105 to 19:

pMSSM parameter	Meaning
$\tan\boldsymbol{\beta}$	Ratio of VEVs of the two Higgs doublets
M_A	CP-odd Higgs boson mass parameter
$\boldsymbol{\mu}$	Higgsino mass parameter
$\boldsymbol{M_1}, \boldsymbol{M_2}, M_3$	Bino, wino and gluino mass parameters
A_t, A_b, A_τ	Third generation trilinear couplings
$m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}, m_{\tilde{l}}, m_{\tilde{e}_R}$	First/second generation sfermion masses
$m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}, m_{\tilde{L}}, m_{\tilde{\tau}_R}$	Third generation sfermion masses

The mixing of the bino, wino and higgsino states into the resulting electroweakino mass eigenstates (set by parameters in bold) has a huge impact on the phenomenology of the electroweak SUSY sector.

Backup: ATLAS charge Higgs search

arXiv:2302.11739

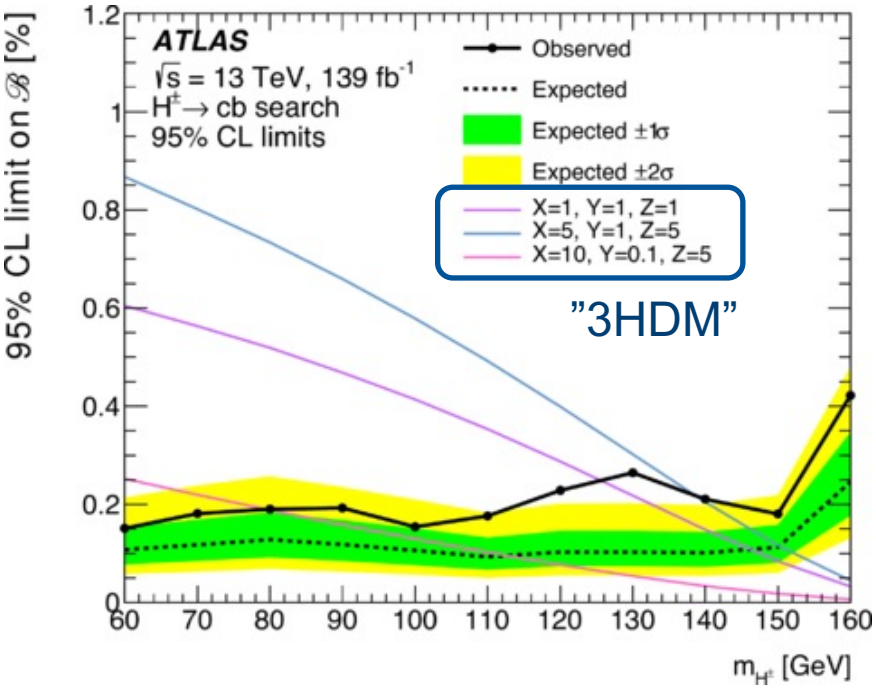


N_j \ N_b	**2b + 1bl:** exactly two *b*-tagged jets (60% OP) plus one loose *b*- tagged jet (70% OP)	**3b:** exactly three *b*-tagged jets (60% OP)	**≥4b:** at least four *b*-tagged jets (60% OP)
4j: exactly four jets	**4j, 2b + 1bl** (data-based $t\bar{t}$ corrections, 10 bins)	**4j, 3b** (signal region, 10 bins)	**4j, 4b** ($t\bar{t}$ + ≥ 1b background control region and large *S/B* region, 1 bin)
5j: exactly five jets	**5j, 2b + 1bl** (data-based $t\bar{t}$ corrections, 10 bins)	**5j, 3b** (signal region, 10 bins)	**5j,≥ 4b** ($t\bar{t}$ + ≥ 1b background control region and large *S/B* region, 1 bin)
6j: exactly six jets	**6j, 2b + 1bl** (data-based $t\bar{t}$ corrections, 10 bins)	**6j, 3b** (signal region, shape correction for the NN discriminant in low *S/B* bins, 10 bins)	**6j,≥ 4b** ($t\bar{t}$ + ≥ 1b background control region, 1 bin)

Regions used to derive $t\bar{t}$ correction — Regions for NN training and fit

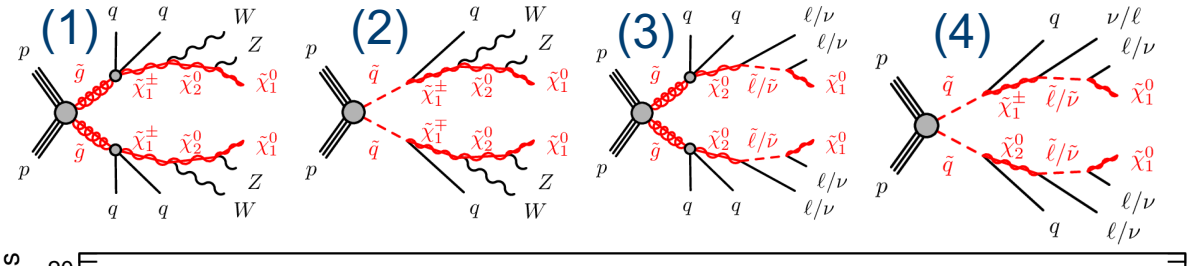
Set of regions used to derived data-driven corrections to improve $t\bar{t}$ modelling.

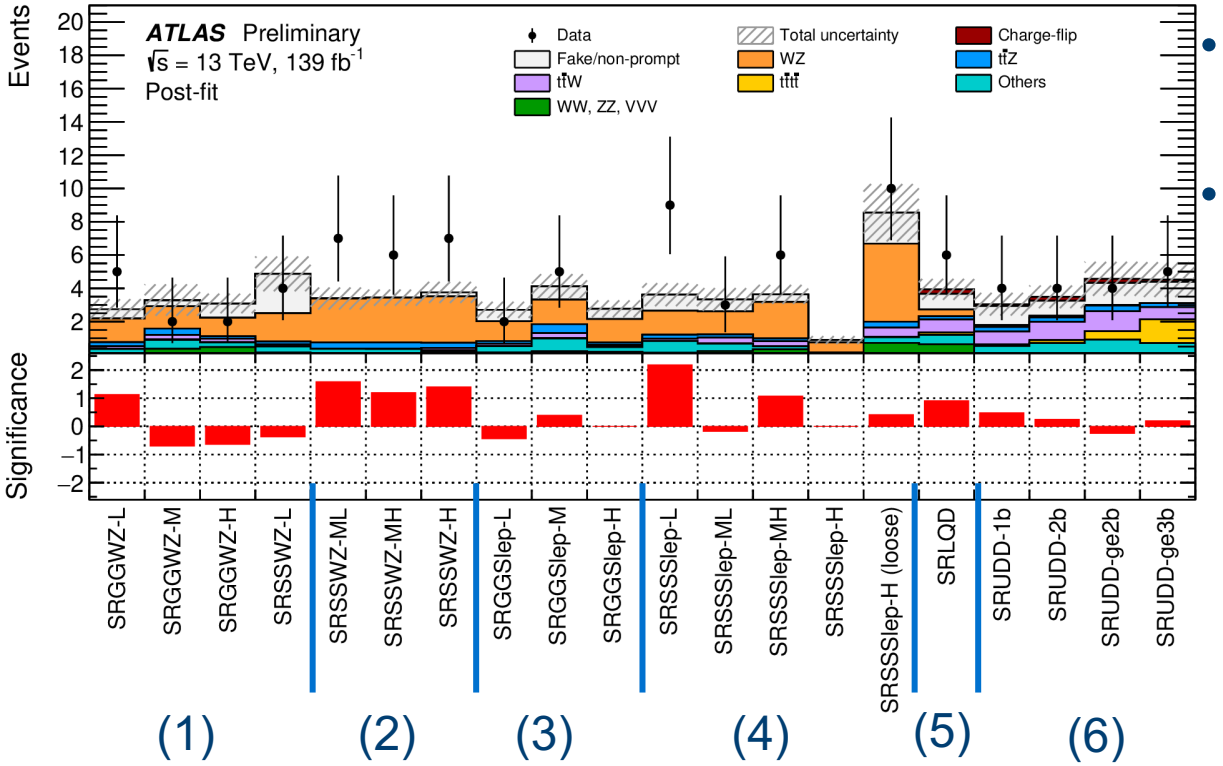
Search uses neural net classifier that exploits kinematic differences between signal and background



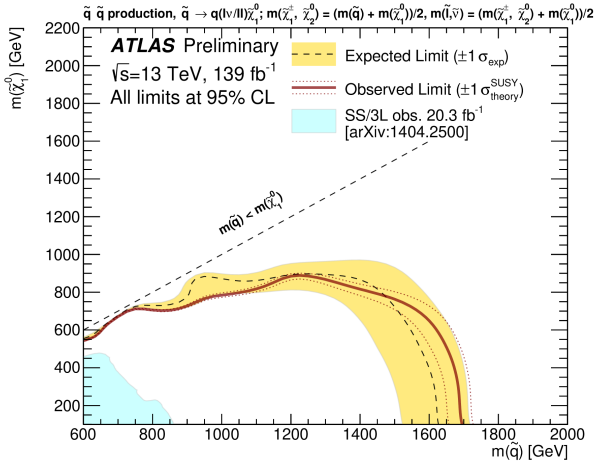
Backup: ATLAS strong SS/3L search

ATLAS-CONF-2023-017





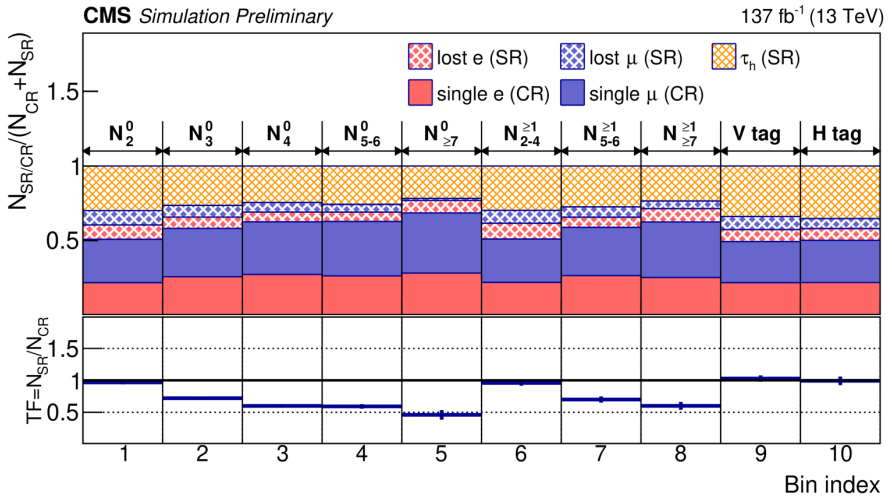
- Overlapping SRs targeting different simplified models.
- Significant extension of limits for squarks



Backup: CMS photon + multijet search

CMS-PAS-SUS-21-009

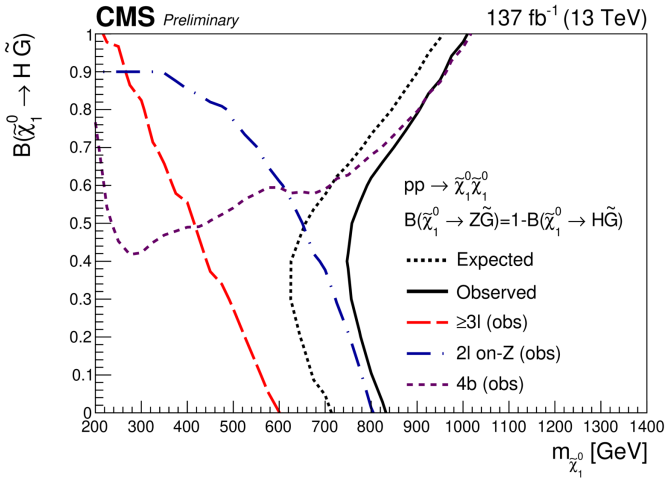
p_T^{miss}	> 300 GeV for SRs and $\in [200, 300]$ GeV for CRs
N_{jets} ($p_T > 30$ GeV, $\|\eta\| < 2.4$)	≥ 2
γ ($p_T > 100$ GeV, $\|\eta\| < 2.4$)	≥ 1
$S_T = \sum_{jets} p_T + p_T^{\gamma}$	> 300 GeV
$\Delta\phi(\text{jet}\vec{p}_T, \vec{p}_T^{miss})$	> 0.3 for 2 highest p_T jets
Number of leptons (e, μ)	0
Number of isolated tracks	0

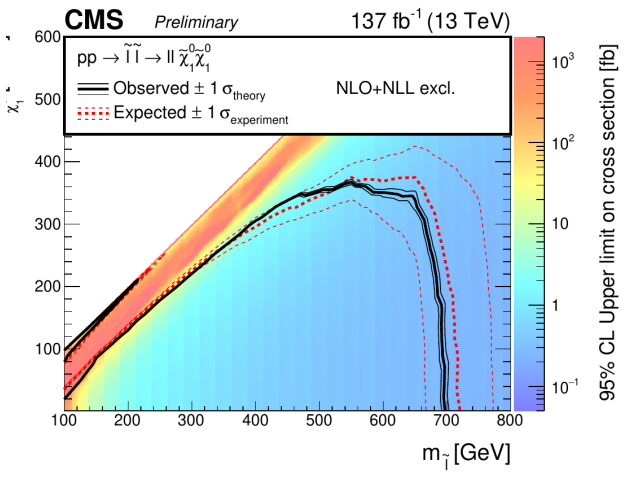


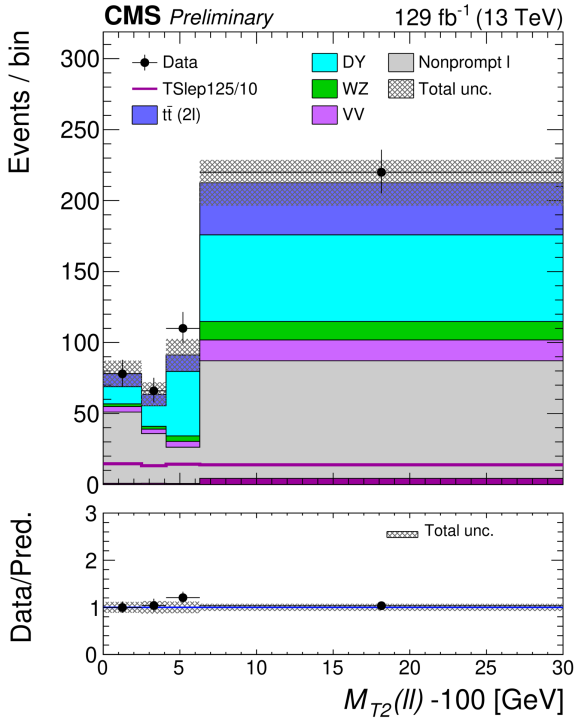
- "lost-lepton" background from lepton failing reconstruction, identification, isolation, being out of acceptance or hadronically decaying taus not failing isolated track veto estimated using 1-lepton CRs and applying a transfer factor.
- Additional data-driven techniques for estimating electrons and jets faking photons and for the $Z\gamma$+jets background.

Backup: CMS EWK SUSY combinations

CMS-PAS-SUS-21-008







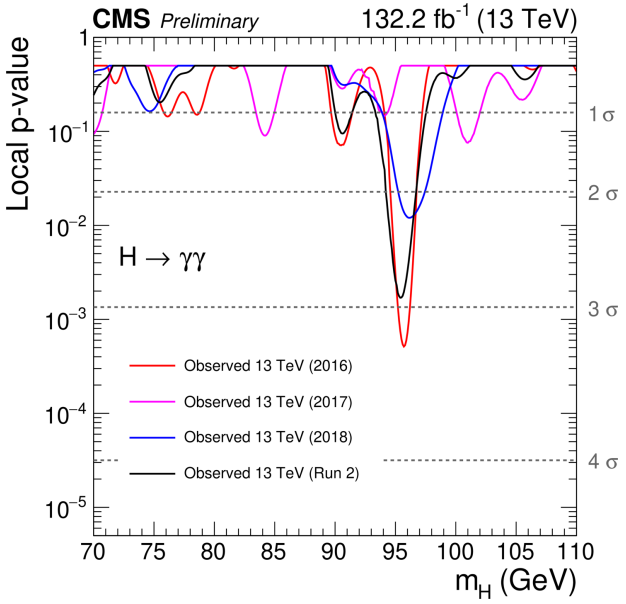
Search	gaugino WZ	gaugino WH	GMSB ZZ	GMSB HZ	GMSB HH	higgsino-bino WW	higgsino-bino HH	higgsino-bino WH	sleptons $\ell^+\ell^-$
2/3ℓ soft [17]	all								2ℓ soft
2ℓ on-Z [15]	EW		EW	EW					
2ℓ non-res. [15]									Slepton
$\geq$3ℓ [18]	SS, A(NN)	SS, A–F	all	all	all			SS, A–F	
1ℓ2b [16]		all						all	
4b [19]					all		3-b, 4-b, 2-bb		
Hadr. WX [20]	all	b-tag				b-veto		b-tag	

Result of parametric binning targeting sleptons for the low-p_T^{miss} regions of "2l" soft analysis targeting sleptons

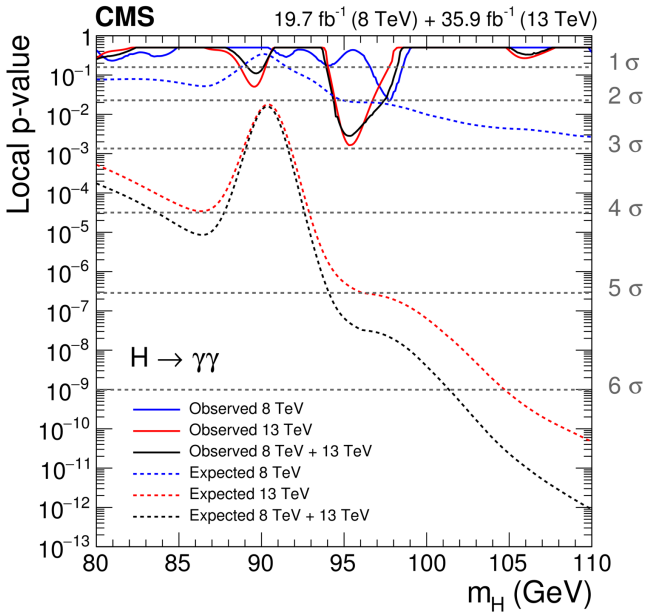
Backup: Low-mass diphoton searches

CMS-PAS-HIG-20-002 *Phys. Lett. B 793 (2019) 320*

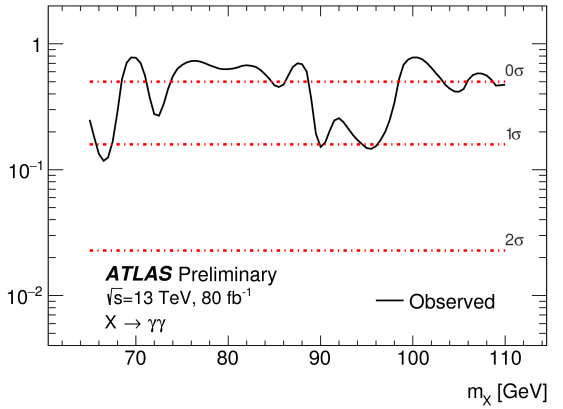
Observed local p-value



Previous CMS result



ATLAS 80 fb^{-1} search



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This targets generic resonance "X"

- Previous CMS excess around 95.3 GeV with local significance of 2.8σ
- Also check out boosted diphoton resonances search from ATLAS which probes 10-70 GeV (arXiv:2211.04172 , submitted to JHEP)