
and
now
for something
completely different

Searches for new physics in the Higgs sector at ATLAS

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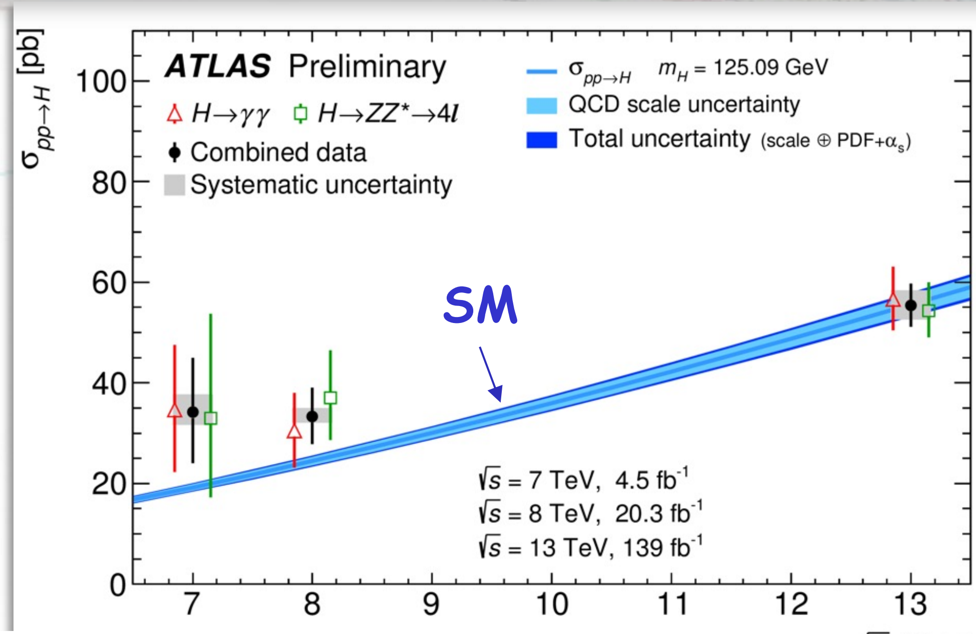
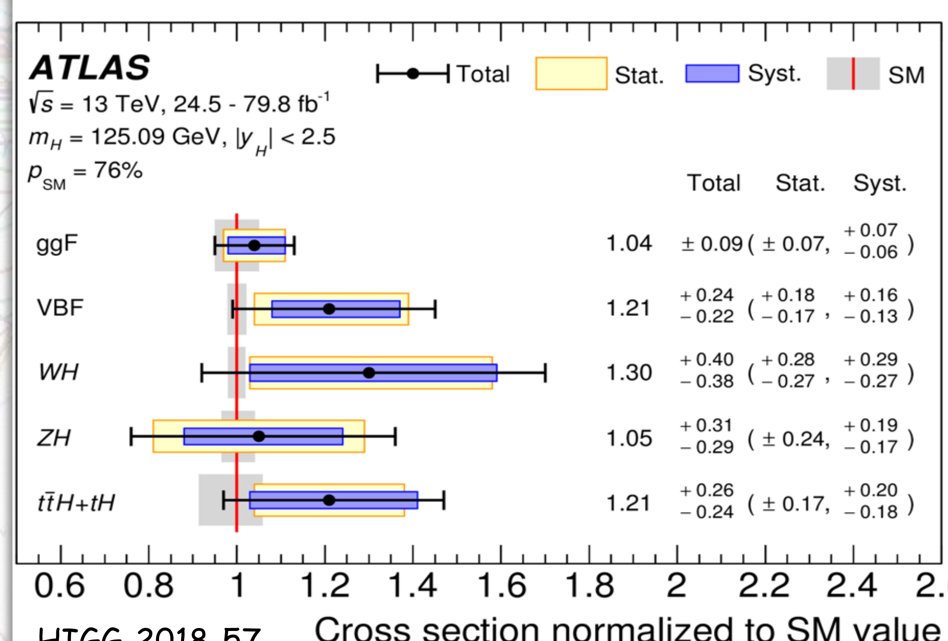
Standard Model Higgs

- So far…
  - Discovery of a neutral scalar particle of mass ~125 GeV confirmed the predicted electroweak symmetry mechanism of the SM
  - Experimental results show consistency with the SM Higgs boson
- The SM is a very successful theory but fails to describe dark matter, matter asymmetry, gravity etc.
- Fortunately, consistency with the SM doesn't exclude Beyond SM scenarios



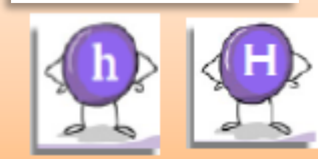
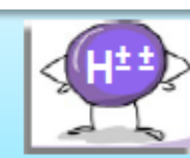
ATLAS-CONF-2019-032



HIGG-2018-57

Higgs boson(s) Beyond the Standard Model

- The SM Higgs sector is the most minimalistic approach to describe EWS breaking
- Extended scalar sector appears in many extensions of the SM
- Searches for additional Higgs bosons are of great importance to probe BSM physics!

SM Higgs doublet + Additional Field	=	Additional Higgs Bosons
EWS: Additional EW Singlet Model SM + one scaler EW singlet	=	Neutral: 
2HDM: Two Higgs Doublet Model SM + another Higgs doublet	=	Neutral / Charged: 
2HDM + Singlet (complex) Model SM + doublet & singlet	=	Neutral:  + 2HDM Higgses
Higgs Triplet Model SM + triplet	=	Double Charged:  + 2HDM Higgses

courtesy of N. Ilic

Disclaimer:

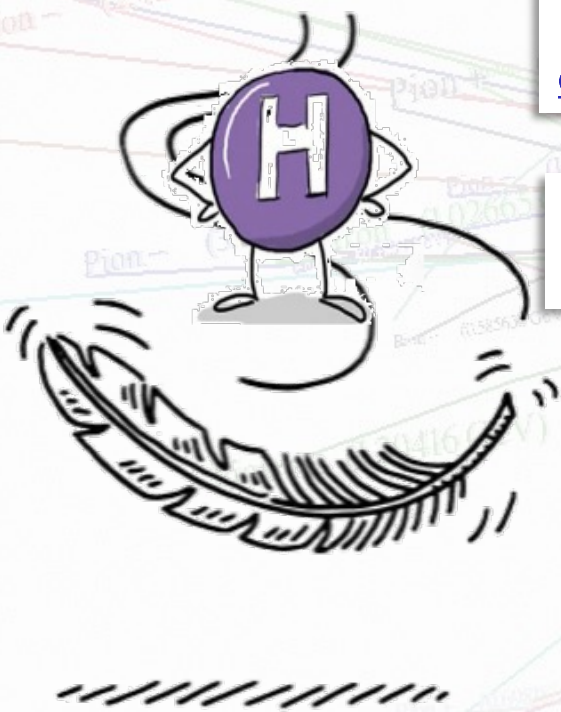
This talk will present a few recent searches for additional neutral and charged Higgs bosons using full Run 2 data collected by the ATLAS detector at 13 TeV

- very incomplete set of analysed Higgs channels!

Many other ATLAS analyses with very interesting results

- feel free to look those up!

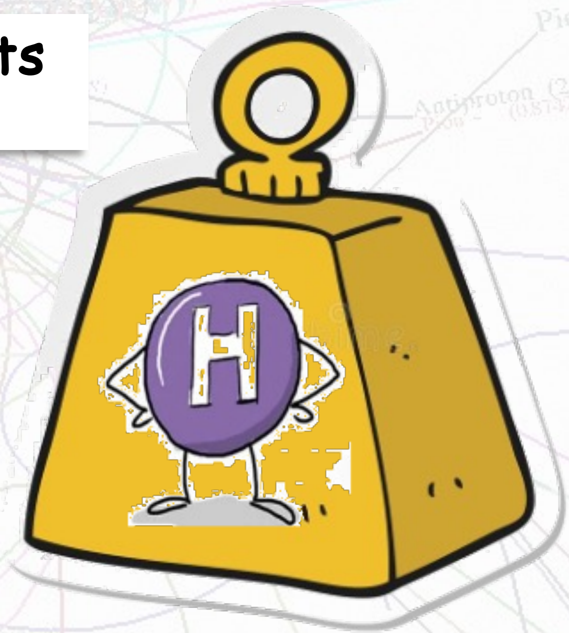
Neutral Higgs boson searches



Search for diphoton resonances
ATLAS-CONF-2023-035

FCNC t→qX (q=u,c) → qbb
arXiv:2301.03902

Heavy scalar H->multileptons + b-jets
arXiv:2307.14759



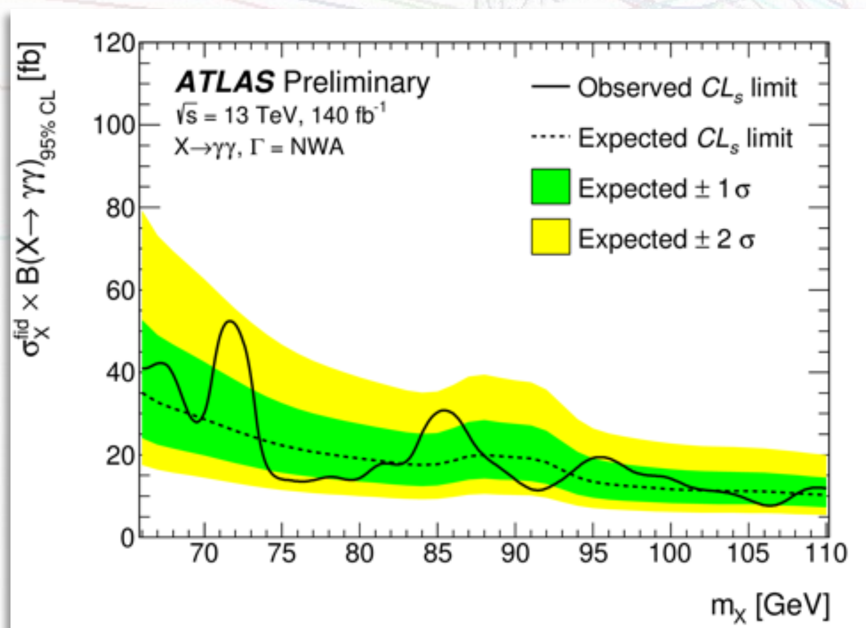
Low-mass diphoton resonances

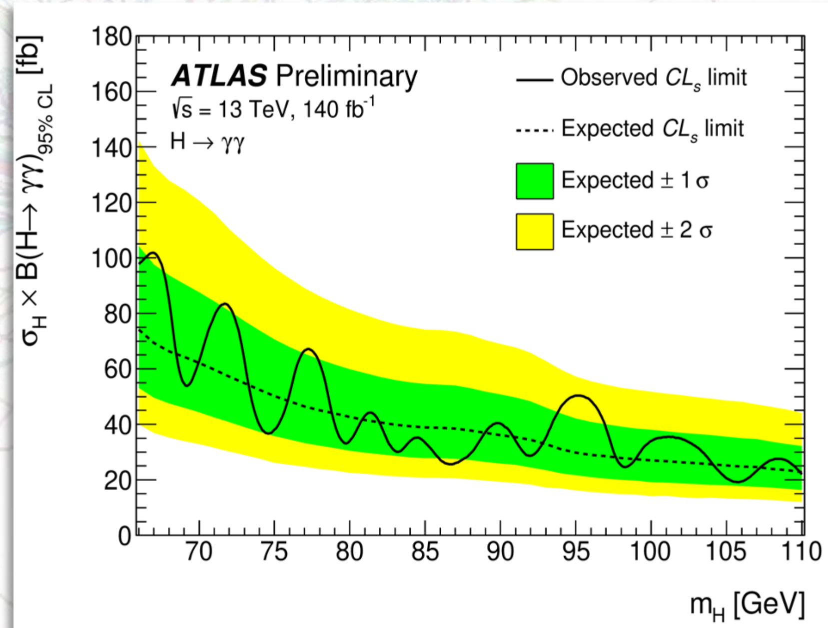
ATLAS-CONF-2023-035

- Target: possible light scalars e.g. (N)2HDM and ALPs
  - $m_{\gamma\gamma}$ = 66-110 GeV
- Two searches considered:
  - model-independent for a generic spin-0 scalar
  - model-dependent using a SM-like Higgs boson as a benchmark

- Several categories based on photon conversion status (+categories from S/B BDT in model-dependent search)
- The resonant signal and background modelled using analytic functions

- Likelihood fit on invariant mass of diphoton system, $m_{\gamma\gamma}$





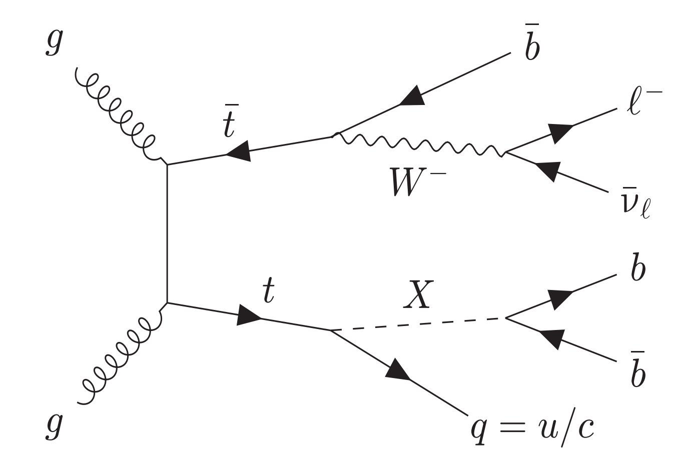
Model-independent search:
Local significance of 2.2σ at 71.8 GeV

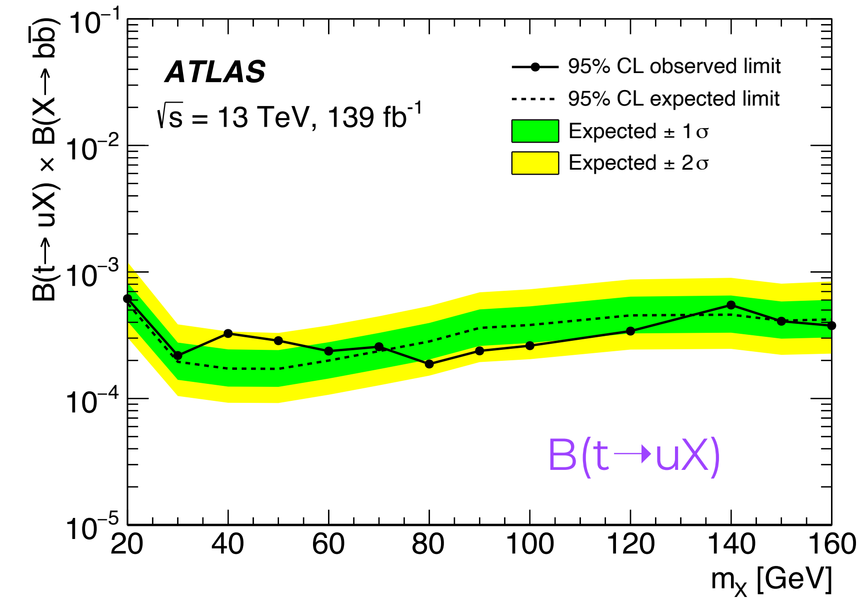
Model-dependent search:
Local significance of 1.7σ at 95.4 GeV

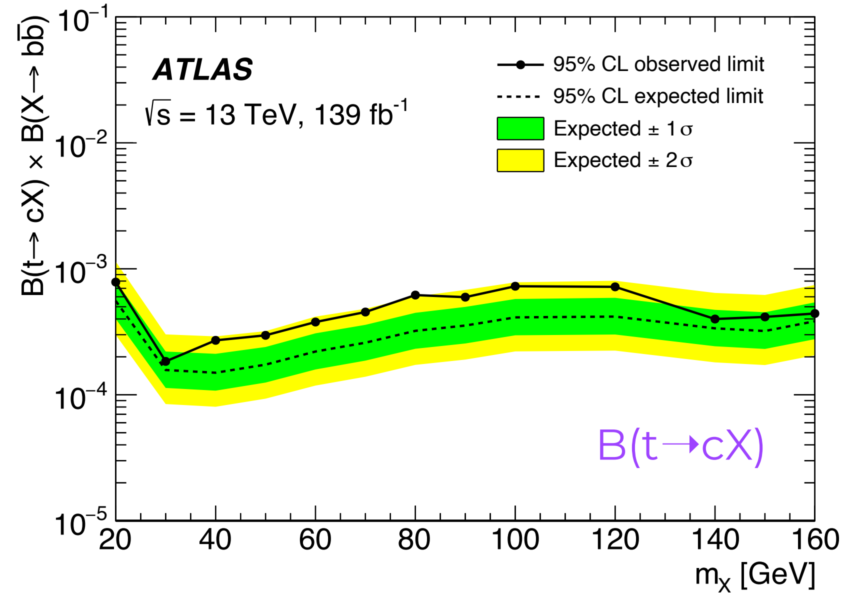
Flavour-changing neutral current $t \to qX$ (q=u,c) → qbb

arXiv:2301.03902

- Target: search for light scalar particle X from flavour-changing neutral current top-decays e.g. flavon with flavour charge
  - m(X)=20-160 GeV
- Categories according to number of jets and b-jets (3 SRs with 3 b-jets and 3 CRs with ≥4 b-jets)
- Signal discrimination using mass-parametrised NN
- Likelihood fit on NN score





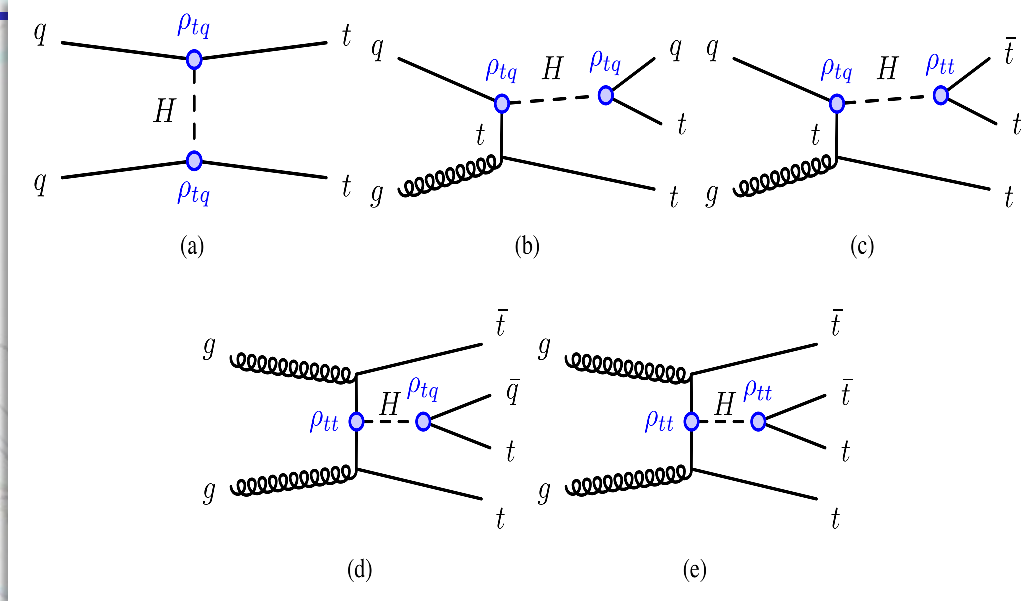


- Mild excess 1.8σ at 40 GeV in $t \to uX$ channel
- ~2σ broad excess in $t \to cX$ channel => X is expected to be much narrower

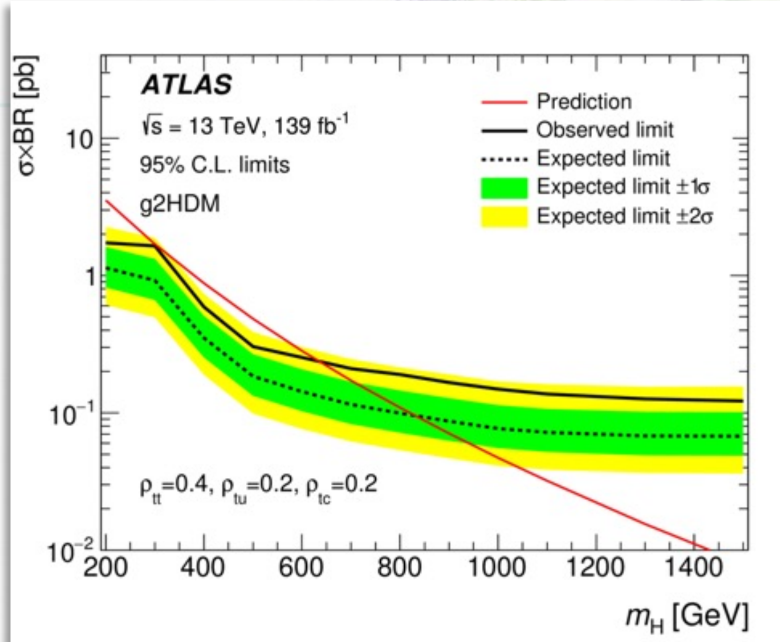
Heavy H → multiple leptons + b-jets

arXiv:2307.14759

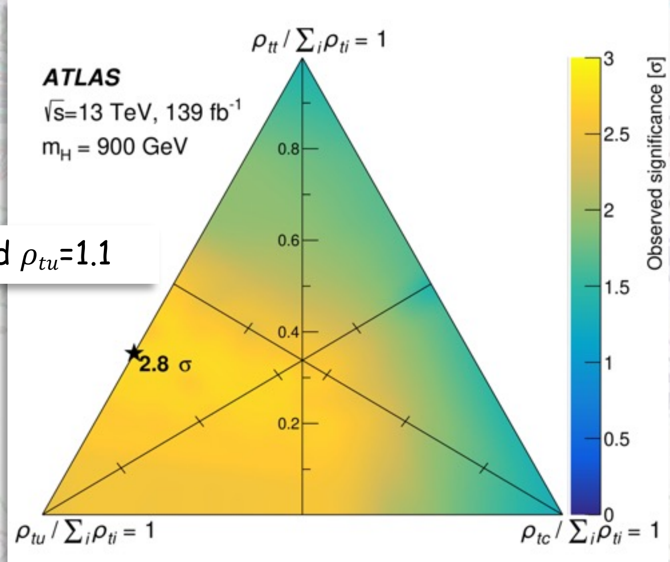
- Target: heavy H from 2HDM with flavour changing neutral Higgs (FCNH) couplings
  - only FCNH couplings involving top quarks considered: ρ_{tt}, ρ_{tu}, ρ_{tc} - parameters of the model
  - m_H = 200 GeV – 1.5 TeV
- Final state: multiple leptons (e,mu) and b-jets
  - considered: 2lSS, 3l, 4l



- 17 SRs + 10 CRs => 27 analysis regions
- DNN trained over each SR region for signal discrimination



ρ_{tt}=0.6, ρ_{tc}=0.0, and ρ_{tu}=1.1

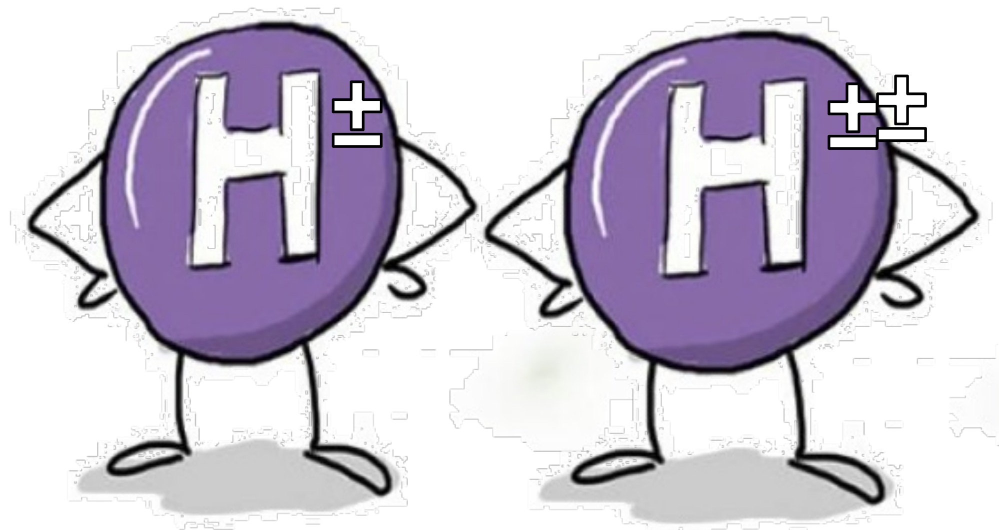


Most significant deviation observed at m_H=900 GeV with local significance of 2.8 σ

Charged Higgs boson searches

Light $H^{\pm}$ in $t \rightarrow H^{\pm}b$ decays, with $H^{\pm} \rightarrow cb$, in the lepton+jets final state
arXiv:2302.11739

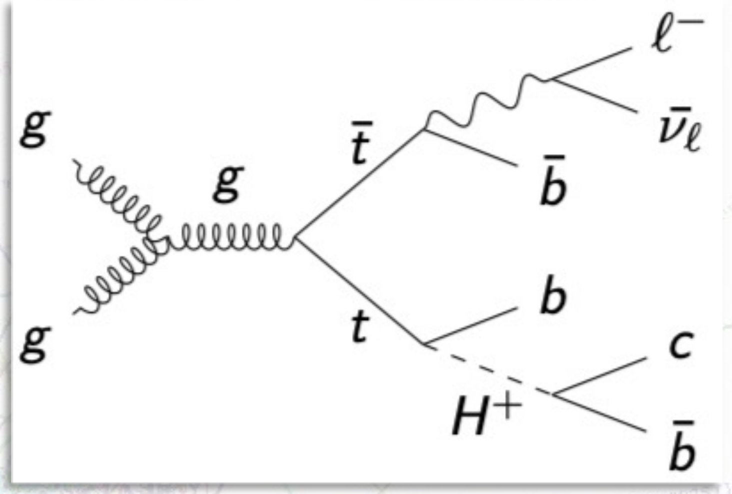
$H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$
arXiv:2211.07505

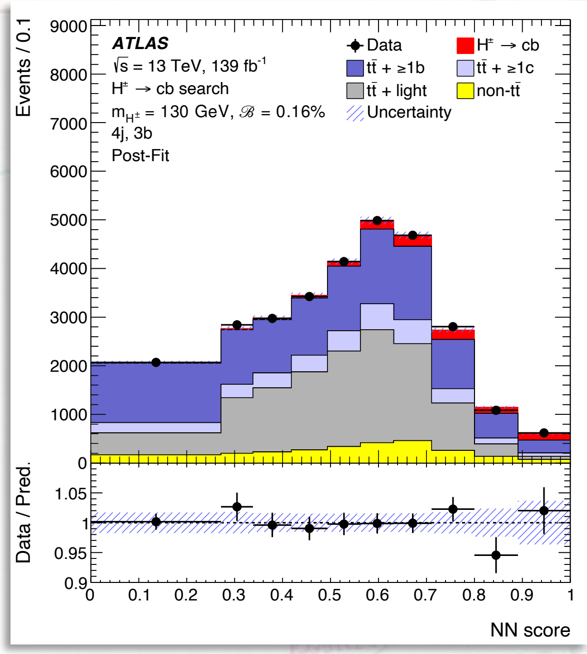


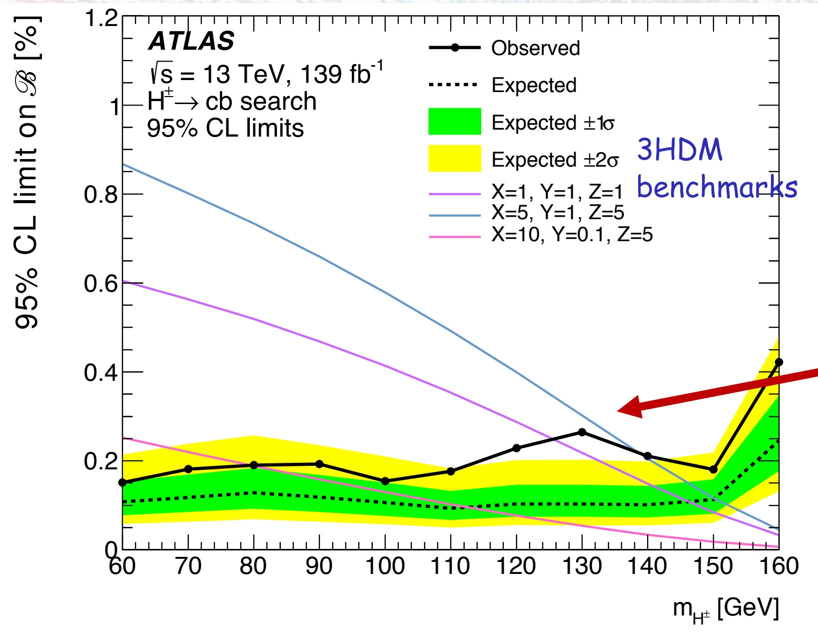
Light H± in t → H±b decays, with H± → cb, in the lepton+jets final state

arXiv:2302.11739

- Three Higgs doublet model (3HDMs) feature two H±,
- Target: low mass H± production via the top decays t→H±b with H±→cb
    - m(H±) = 60 GeV - 160 GeV
- Final state: 1 lepton, 3 b-jets, 1 c-jet
- Categories based on the number of jets and b-jets
- Use mass-parametrised NN for signal discrimination
- PNN score used in likelihood fit







Small excess corresponds to a local significance 3σ at m(H±)= 130 GeV

Broad excess is consistent with the expected mass resolution

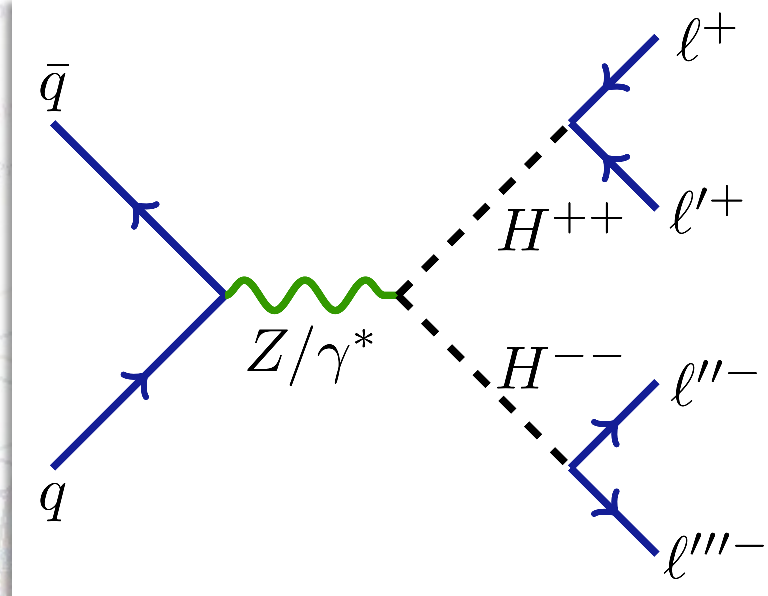
$H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$

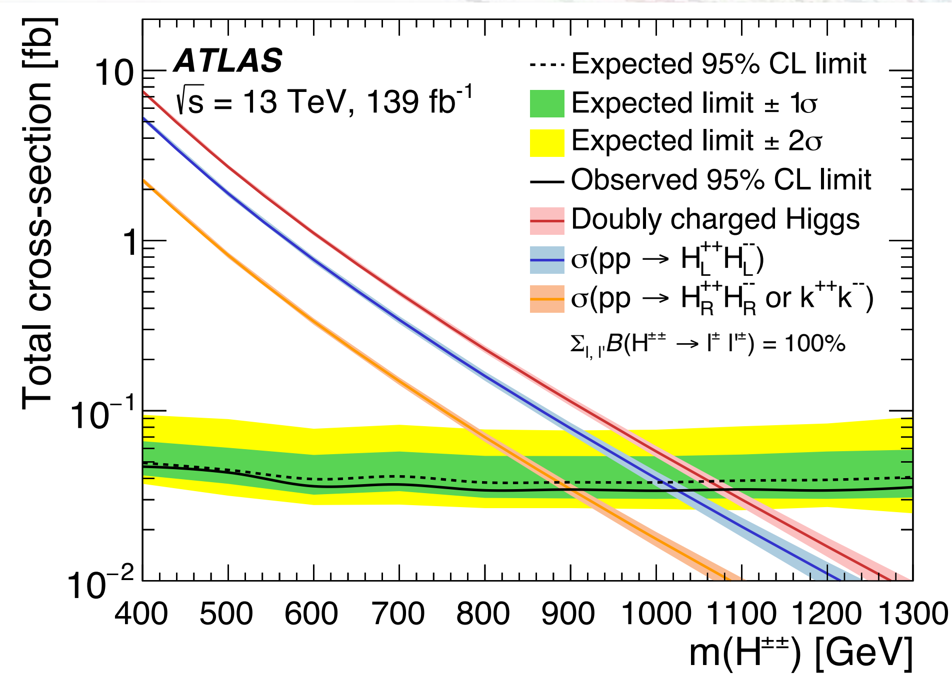
arXiv:2211.07505

- Target: $H^{\pm\pm}$ predicted by Left-Right Symmetric Models (LRSM) or Zee-Babu model

- Dominant production at the LHC: DY pair production
- For low vev considered $H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$ dominates
- Decays to same-charge lepton pairs with LFV
- $m(H^{\pm\pm})$ = 300 GeV – 1.3 TeV

- Categories based on lepton multiplicities (2/3/4L)
- Discriminant: leading $m(L^{\pm},L'^{\pm})$ in 2/3L regions; total yield in 4L regions

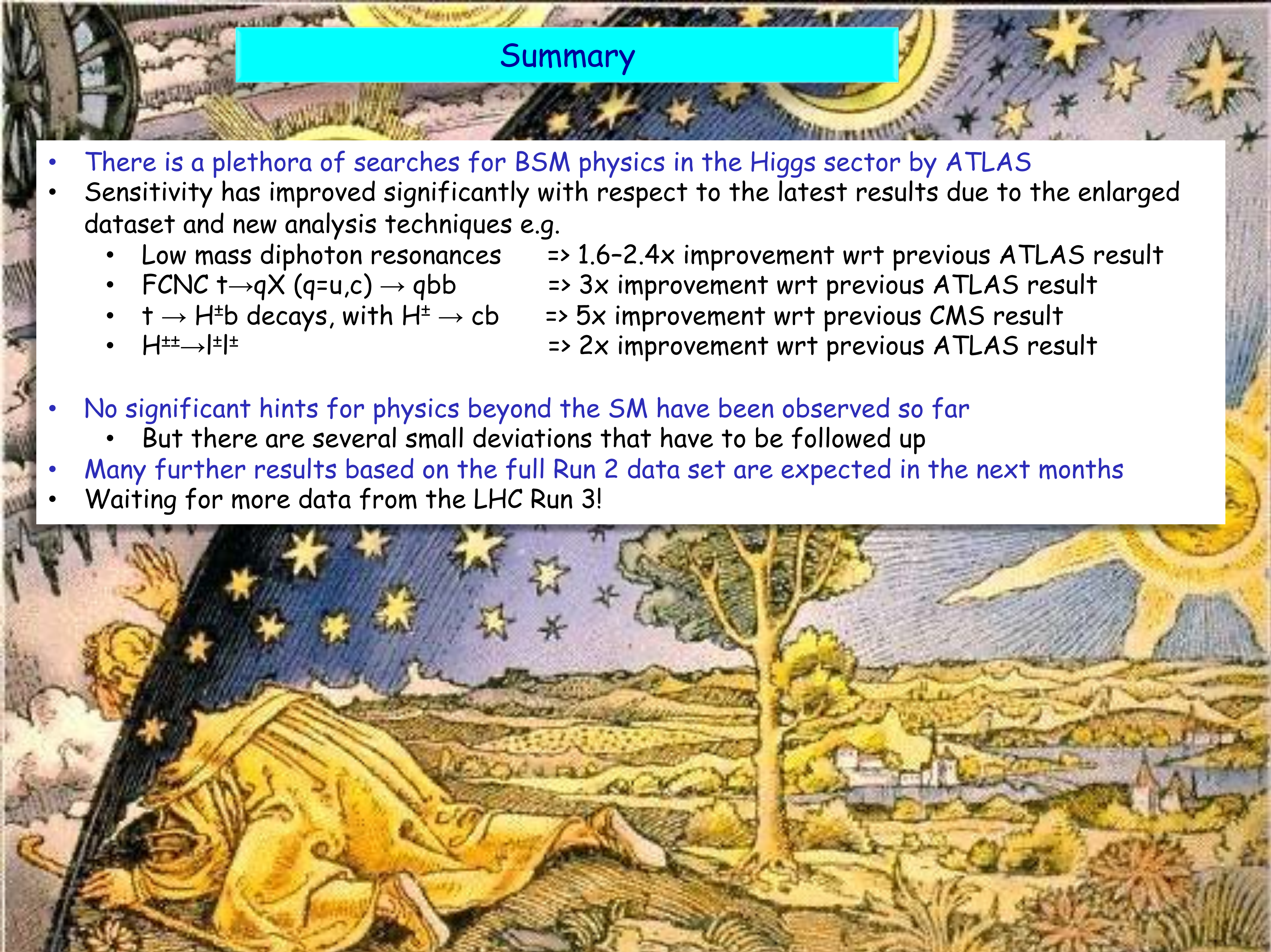




- Upper limits set on the total production cross-section of $H^{\pm\pm}$ in the context of LRSM and Zee-Babu model

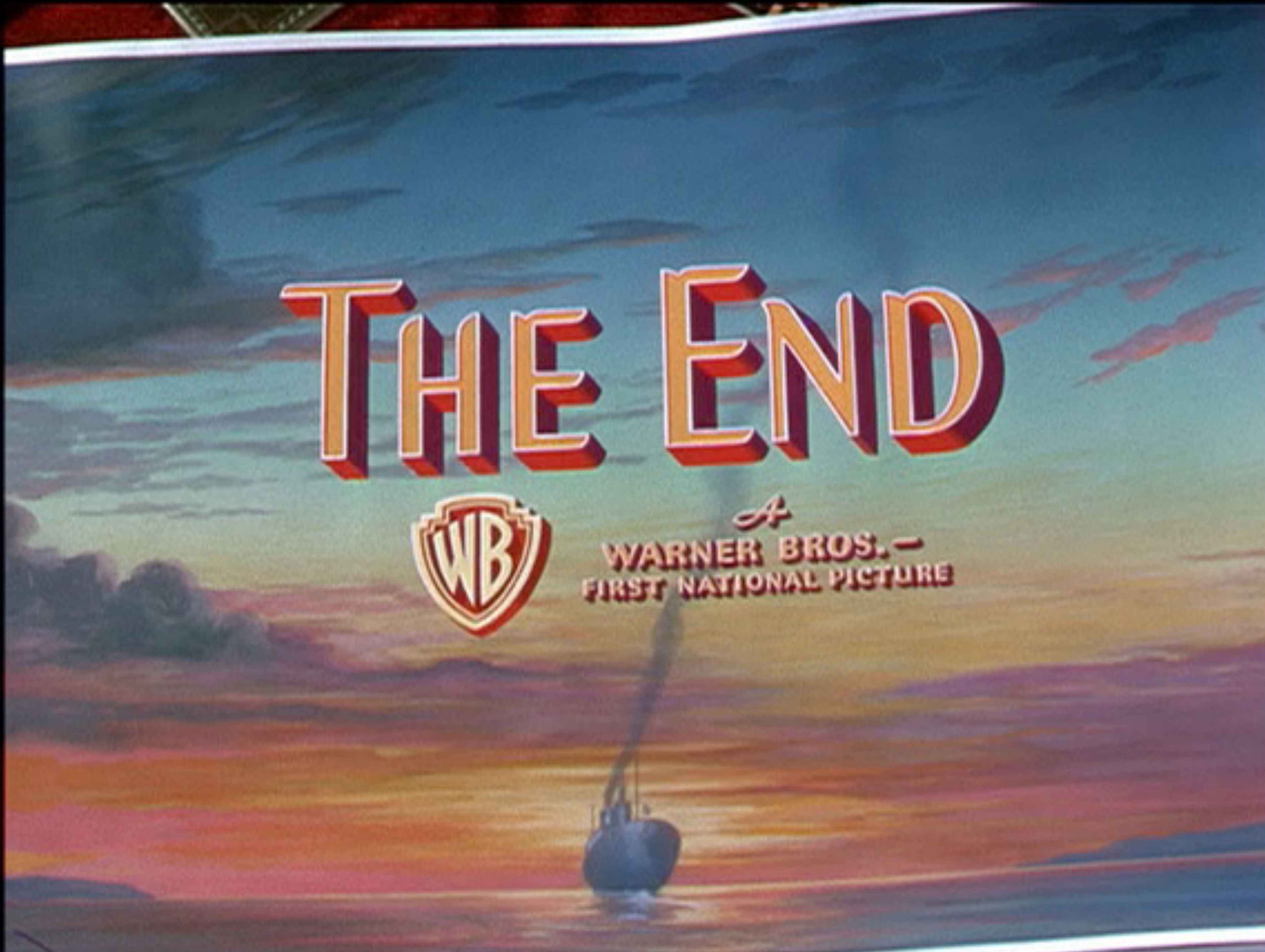
- Higher sensitivity to LH scalars, due to larger production cross section

- Doubly charged Higgs excluded for masses below 1080 GeV within LRSMs and 900 GeV within the Zee-Babu model.



Summary

- There is a plethora of searches for BSM physics in the Higgs sector by ATLAS
- Sensitivity has improved significantly with respect to the latest results due to the enlarged dataset and new analysis techniques e.g.
  - Low mass diphoton resonances => 1.6–2.4x improvement wrt previous ATLAS result
  - FCNC $t \to qX$ ($q=u,c$) $\to qbb$ => 3x improvement wrt previous ATLAS result
  - $t \to H^{\pm}b$ decays, with $H^{\pm} \to cb$ => 5x improvement wrt previous CMS result
  - $H^{\pm\pm} \to l^{\pm}l^{\pm}$ => 2x improvement wrt previous ATLAS result
- No significant hints for physics beyond the SM have been observed so far
  - But there are several small deviations that have to be followed up
- Many further results based on the full Run 2 data set are expected in the next months
- Waiting for more data from the LHC Run 3!


THE END
A
WARNER BROS.—
FIRST NATIONAL PICTURE

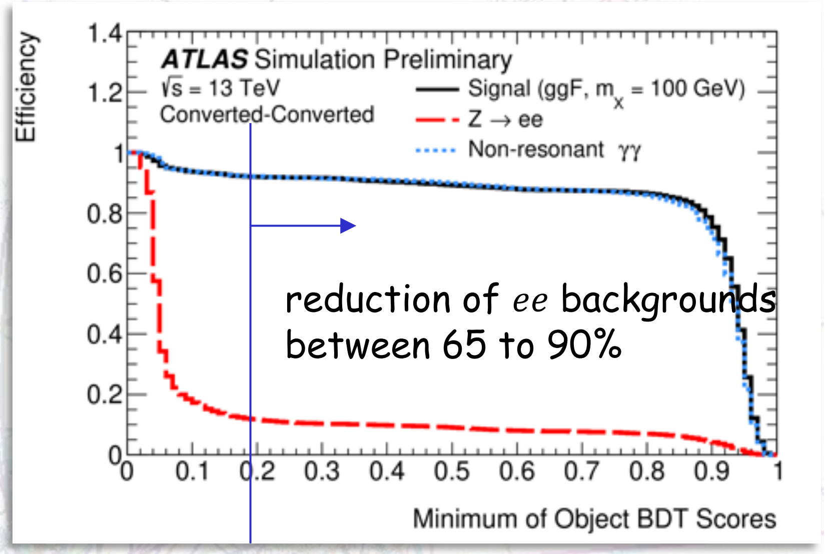
Beyond the Standard Slides

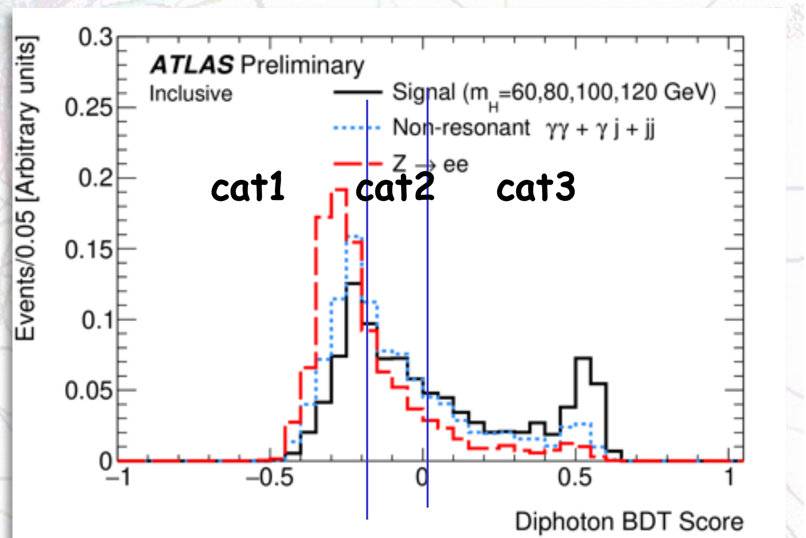
Courtesy of J. Keller

Diphoton resonances in 66 to 110 GeV

ATLAS-CONF-2023-035

- Search for a low-mass diphoton resonance in the region $m_{\gamma\gamma} \in [66, 110]$ GeV as a follow-up to a 2018 80 ifb ATLAS-CONF-2018-025
- Theoretical motivation: possible light scalars in extended Higgs sectors (2HDM, N2HDM, NMSSM, ALP, Composite Higgs, R-axions)
- CMS probes a similar mass range and sees a 2.9σ excess at 95 GeV - CMS-HIG-20-002
- Two searches considered:
  - model-independent for a generic spin-0 scalar
  - model-dependent using a SM-like Higgs boson as a benchmark.
- Selection: $\gamma\gamma$ with ET > 22 GeV and ET/$m_{\gamma\gamma}$> 0.38;
- Four significant background components are identified: $\gamma\gamma$, γj and jj pairs from QCD production (continuum non-resonant backgrounds) + ee from DY production
  - classification BDT to reduce - fakes
- Several categories defined based on photon conversion status (+ BDT categories) for a model-independent (model-dependent) search

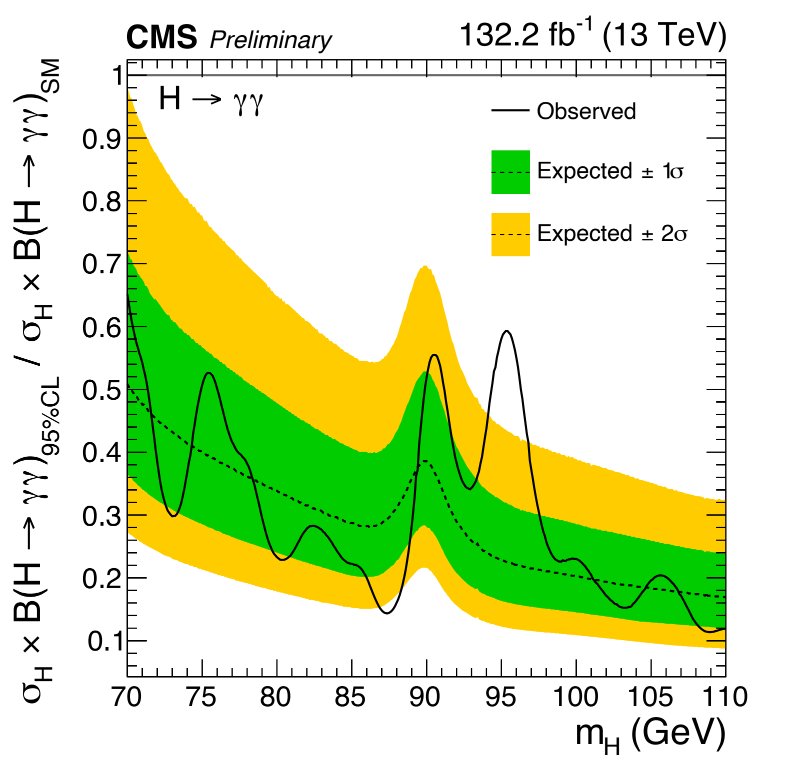


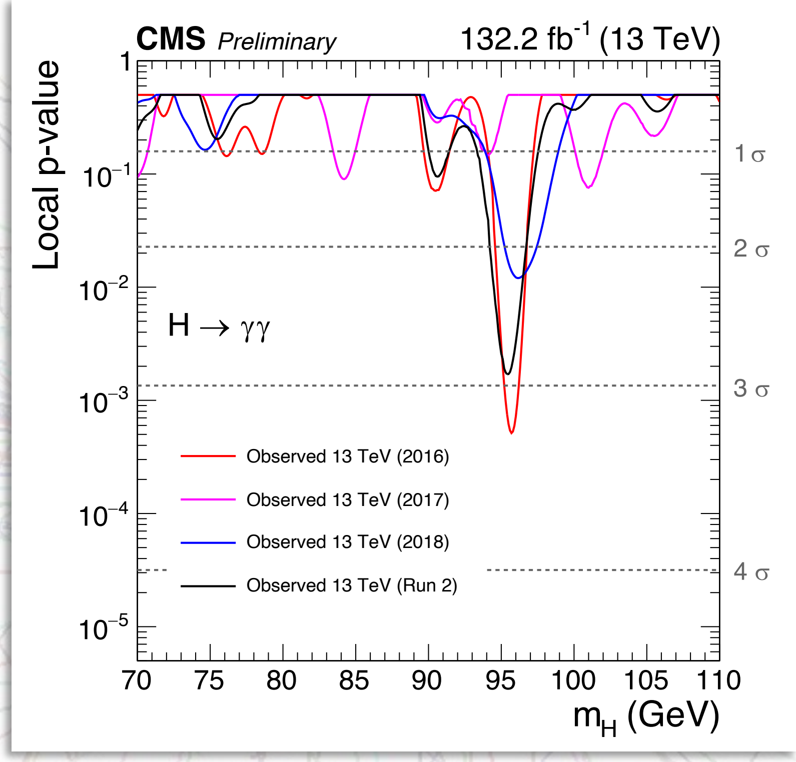


Diphoton resonances in 70 to 110 GeV

CMS PAS HIG-20-002

Search for a standard model-like Higgs boson in the mass range between 70 and 110 GeV in the diphoton final state





local (global) 2.9 (1.3) σ @ mH ≈ 95.4 GeV

Heavy scalars with FV decays in final states with multiple leptons and b-jets

ATLAS-CONF-2022-039

Table 3: Event selection summary in the signal regions. Leptons are ordered by p_T in the 2ℓSS and 4ℓ regions. In the 3ℓ regions the lepton with opposite-sign charge is taken first, followed by the two same-sign leptons in p_T order. In the lepton selection, *T, M, L* stand for Tight, Medium and Loose lepton definitions. In the region naming, the "CAT ttX" denotes the category based on the DNN^{cat} output enriched in the signal process "ttX". Each of these regions is split according to the lepton charge of the same-sign lepton pair ("++" or "- -").

Lepton category	2ℓSS	3ℓ	4ℓ
Lepton definition	(T,T) with $\geq 1\ b^{60\%}$ ‖ (T,M) with $\geq 2\ b^{77\%}$	(L,T,M) with $\geq 1\ b^{60\%}$ ‖ (L,M,M) with $\geq 2\ b^{77\%}$	(L,L,L,L)
Lepton p_T [GeV]	(20, 20)	(10, 20, 20)	(10, 10, 10, 10)
$m_{\ell^+\ell^-}^{OS-SF}$ [GeV]	–	>12	
$\lvert m_{\ell^+\ell^-}^{OS-SF} - m_Z \rvert$ [GeV]	–	>10	
N_{jets}	≥ 2		
$N_{b\text{-jets}}$	$\geq 1\ b^{60\%}$ ‖ $\geq 2\ b^{77\%}$		
Region split	(sstt, ttq, ttt, tttq, tttt) × (Q^{++}, Q^{--})	(ttt, tttq, tttt) × (Q^{+}, Q^{-})	–
Region naming	2ℓSS ++ CAT sstt	3ℓ ++ CAT ttt	4ℓ
	2ℓSS ++ CAT ttq	3ℓ ++ CAT tttq	
	2ℓSS ++ CAT ttt	3ℓ ++ CAT tttt	
	2ℓSS ++ CAT tttq	3ℓ −− CAT ttt	
	2ℓSS ++ CAT tttt	3ℓ −− CAT tttq	
	2ℓSS −− CAT sstt	3ℓ −− CAT tttt	
	2ℓSS −− CAT ttq		
	2ℓSS −− CAT ttt		
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Heavy scalars with FV decays in final states with multiple leptons and b-jets

ATLAS-CONF-2022-039

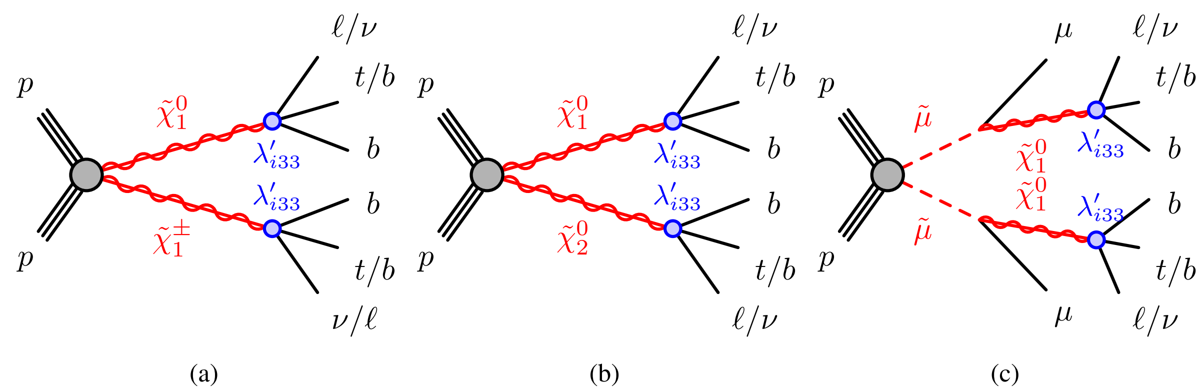
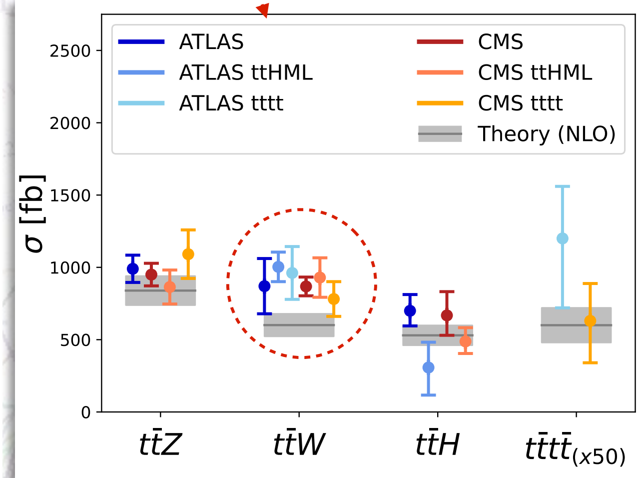


Figure 2: Signal diagrams for the RPV SUSY signals used as additional interpretation in the analysis. The subsequent decay can lead to a final state with high multiplicity of leptons and b-jets which is targeted by the search.



- **Main backgrounds:** ttW, ttZ, VV – from MC with normalisation during the fit

The systematic uncertainties with the largest impact on the signal strength originate from the modelling of $t\bar{t}W$ with and without additional heavy flavour jets, $t\bar{t}Z$, $t\bar{t}H$, and $t\bar{t}t\bar{t}$ processes. **The search is dominated by statistical uncertainties.**

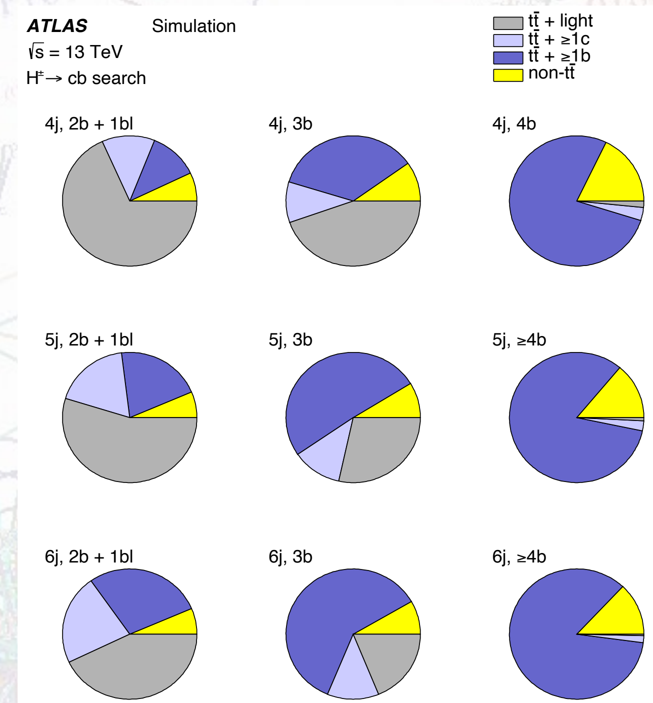
H±->cb

arXiv:2302.11739

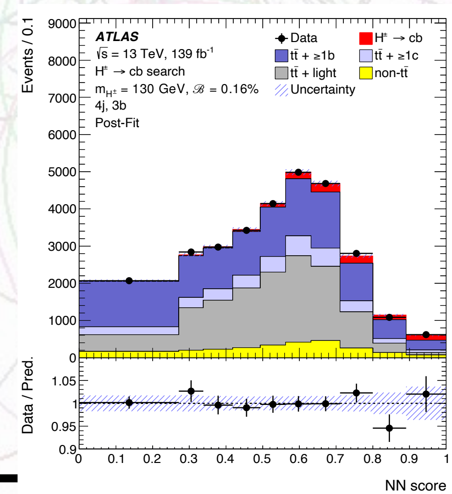
Pre-selection	
Trigger	single-lepton trigger
Leptons	$= 1$ isolated e or μ
Jets	≥ 4 jets
B-tagged jets	≥ 2 b-tagged jets
MET	> 20 GeV
MET + m_T^W	> 60 GeV

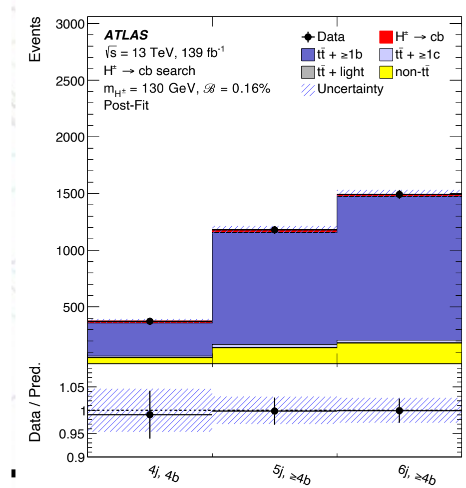
N_b → / N_j ↓	**2b + 1bl:** exactly two b-tagged jets (60% OP) plus one loose b- tagged jet (70% OP)	**3b:** exactly three b-tagged jets (60% OP)	**$\geq$4b:** at least four b-tagged jets (60% OP)
4j: exactly four jets	**4j, 2b + 1bl** (data-based $t\bar{t}$ corrections, 10 bins)	**4j, 3b** (signal region, 10 bins)	**4j, 4b** ($t\bar{t} + \geq 1$b 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,$\geq$ 4b** ($t\bar{t} + \geq 1$b 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,$\geq$ 4b** ($t\bar{t} + \geq 1$b background control region, 1 bin)

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



The leading uncertainties affecting the signal extraction by the fit are found to be related to the c-tagging calibration, the calibration of light-jet mis-tagging rate and the choice of $t\bar{t}$ NLO generator in fit regions with four jets. Other uncertainties with a sizeable impact on the signal-strength measurement include $t\bar{t}$+≥1b and $t\bar{t}$+≥1c normalisation uncertainties.

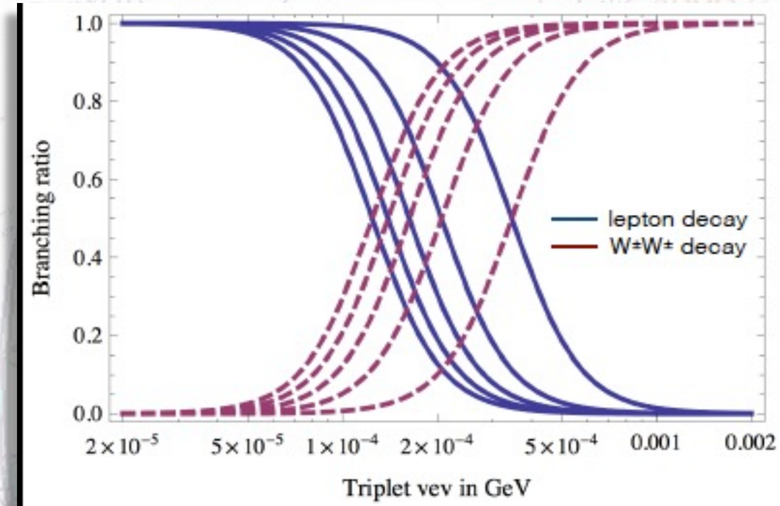




$H^{\pm\pm} \to l^{\pm} l^{\pm}$

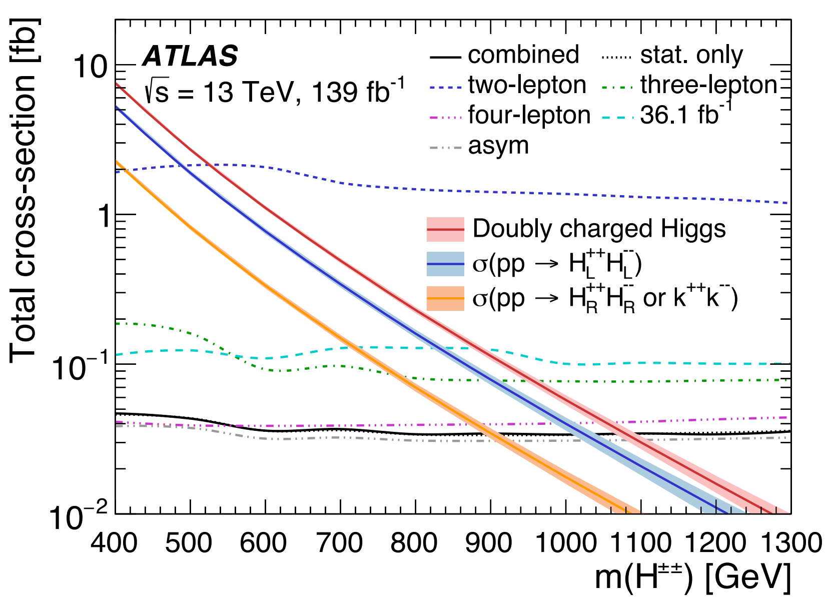
arXiv:2211.07505

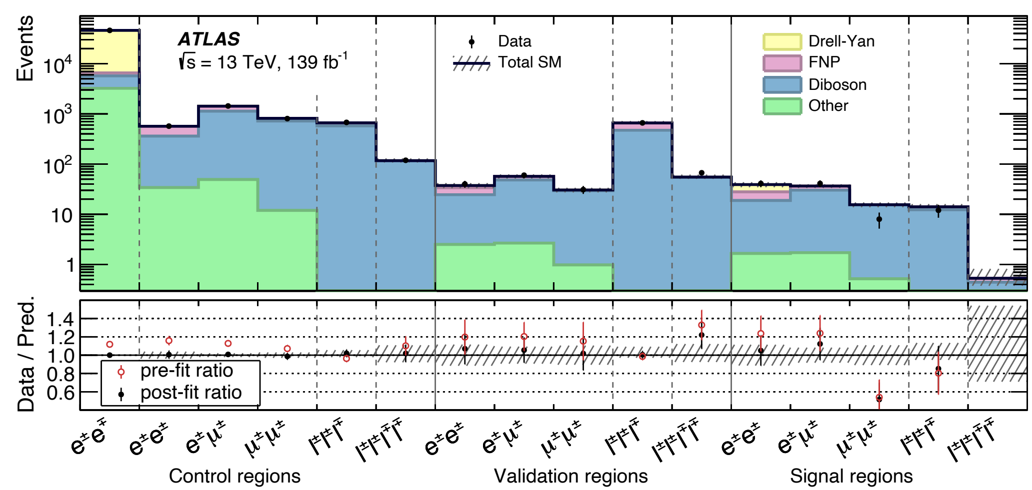
- Main backgrounds: fake/non-prompt, diboson, Drell-Yan, rare-top, single-top, ttbar, multiboson.
- Background estimation strategy:
  - prompt SM backgrounds (diboson, DY, ...) estimated from MC simulation,
    - Normalisation of DY, diboson from CR in the final fit
  - events containing at least one fake lepton are estimated using data-driven fake factor method,
  - electron charge flip strategy (Drell-Yan, *tt*) from the EGamma group



Decays: $H^{\pm\pm} \to l^{\pm} l^{\pm}$ or $H^{\pm\pm} \to W^{\pm} W^{\pm}$

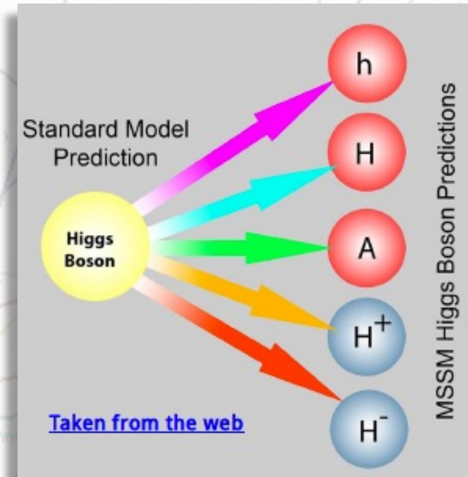
- BR ~ f($m_{H^{\pm\pm}}$, vev of Higgs triplet)
- Low $m_{H^{\pm\pm}}$ and low vev : $H^{\pm\pm} \to l^{\pm} l^{\pm}$ dominates



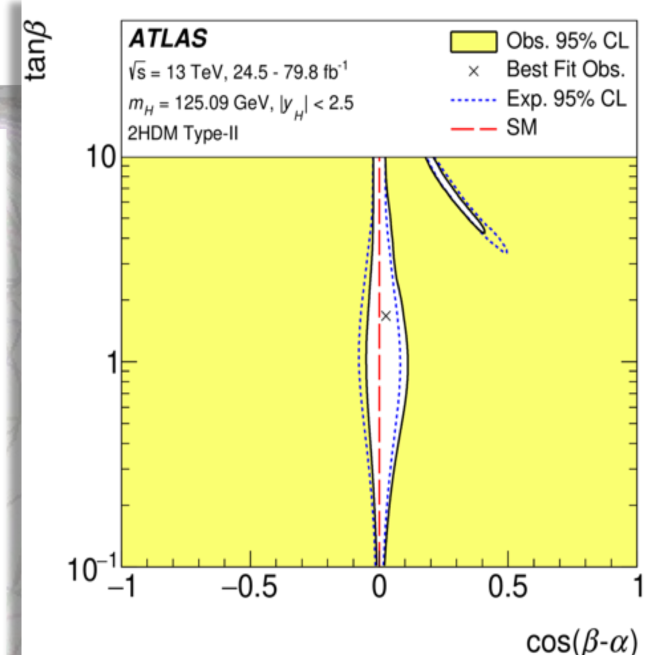


Two Higgs Doublet Model (2HDM)

- Generic class with second Higgs doublet.
- Four variants to couple SM fermions to the 2HDs. No FCNCs-> all fermions with the same electric charge couple to one Higgs doublet only:
  - Type I: all quarks and leptons couple to only one doublet
  - Type II: one doublet couples to up-type quarks, the other to down-type quarks and leptons: „MSSM-like"
  - Lepton-specific: couplings to quarks as in the Type I model and to leptons as in Type II
  - Flipped: couplings to quarks as in the Type II model and to leptons as in Type I



Phys. Rev. D 101 (2020) 012002



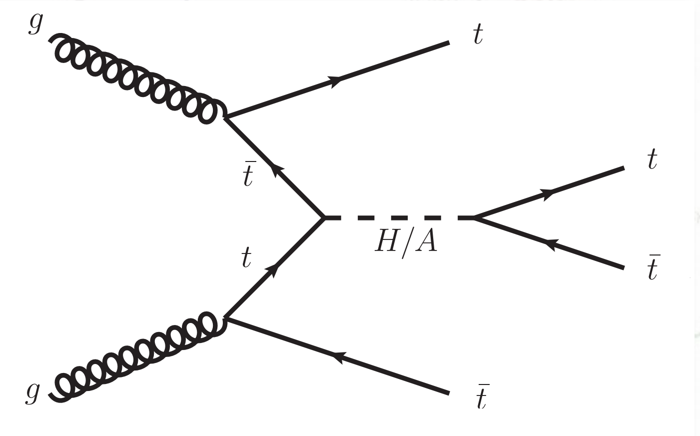
- 5 Higgs bosons: h, H, A, H^+, H^-
- Free parameters: tanβ (ratio between the vevs of the doublets), α (mixing angle between h and H) and m_A
- Minimal Supersymmetric SM (MSSM) is a special case of 2HDM:
  - "type II" with fixed α
  - numerous benchmark models: hMSSM, m_h^{mod+}, etc.

- SM Higgs results give big constraints on 2HDM. Data prefers alignment limit: cos(β- α)=0 – h recovers properties of the SM Higgs

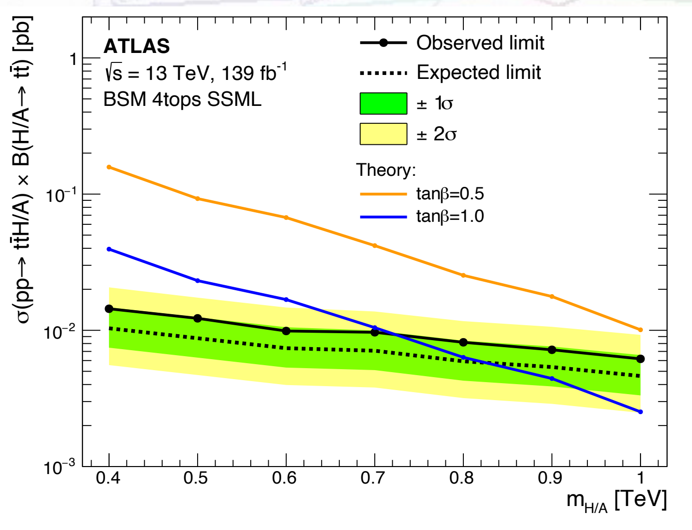
$t\bar{t}$ H/A ($\rightarrow t\bar{t}$) in the multilepton final state

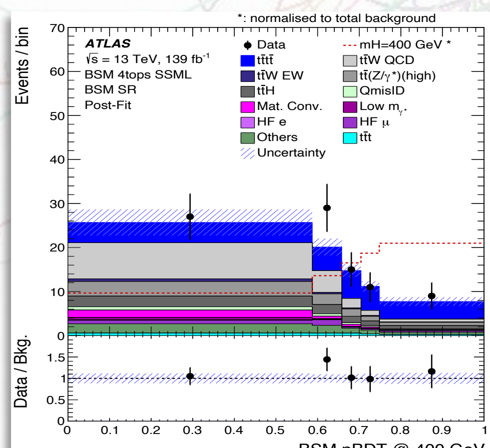
arXiv:2211.01136

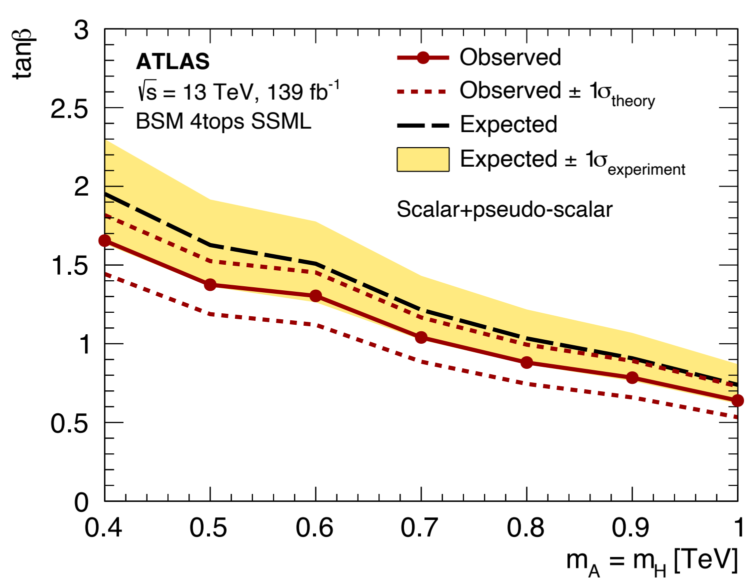
- Target: 2HDM $t\bar{t}$ H/A ($\rightarrow t\bar{t}$) signal and interpretation on low tanβ region in the alignment limit
  - m(A/H) = 400 GeV - 1 TeV
- No large negative interference from SM $t\bar{t}$ as in pp $\rightarrow$H $\rightarrow t\bar{t}$
- Final state: 2SS leptons or ≥3 leptons + ≥ 6j, ≥2b-jets, H_T=∑p(l)+∑p(j) ≥ 500GeV (SR)
- Two BDTs used for signal discrimination
  - SM BDT: to extract $t\bar{t}t\bar{t}$ -like events from remaining bkgs
    => Used to define final SR (SM BDT > 0.55)
  - mass-parametrised BDT for signal $t\bar{t}$ H/A $\rightarrow t\bar{t}t\bar{t}$ vs all bkgs
    => Discriminant in likelihood fit



- Results interpreted in Type-II 2HDM model





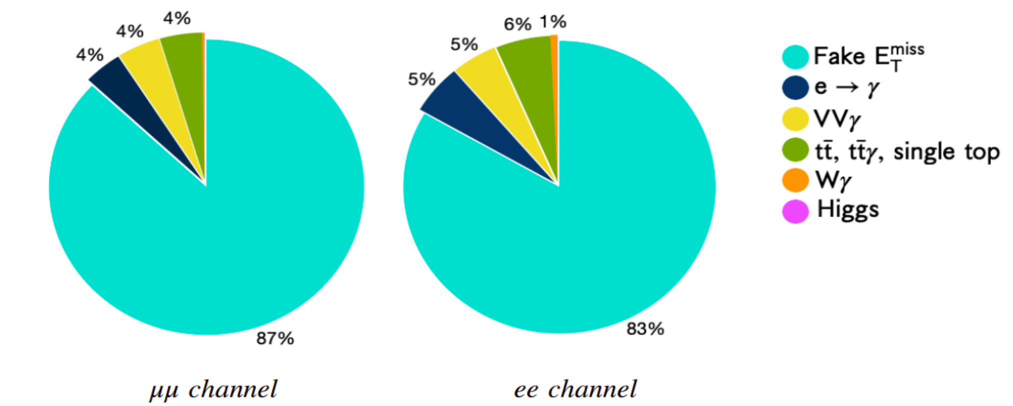


Dark photons from Higgs boson decays via ZH production

arXiv:2212.09649

Table 3: Optimised kinematic selections defining the signal region for $\ell^+\ell^-\gamma+E_T^{miss}$.

Two same flavour, opposite sign, medium ID and loose isolated leptons, with leading $p_T > 27$ GeV, sub-leading $p_T > 20$ GeV
Veto events with additional lepton(s) with loose ID and $p_T > 10$ GeV
$76 \text{ GeV} < m_{\ell\ell} < 116$ GeV
Only one tight ID, tight isolated photon with $E_T^\gamma > 25$ GeV
$E_T^{miss} > 60$ GeV with $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{\,\ell\ell\gamma}) > 2.4$ rad
$m_{\ell\ell\gamma} > 100$ GeV
$N_{jet} \leq 2$, with $p_T^{jet} > 30$ GeV, $\lvert\eta\rvert < 4.5$
Veto events with b-jet(s)

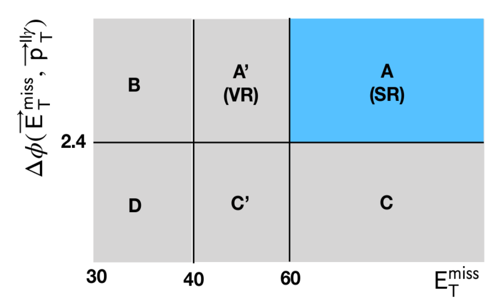


Main backgrounds
- Irreducible background from VVγ final states with bosons decaying leptonically, obtained from simulation
- Reducible background from biased MET measurement, data-driven

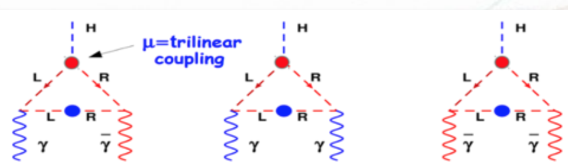
- **ABCD method**, based on E_T^{miss} and $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{\,\ell\ell\gamma})$ variables:

$$N_A^{fakeMET} = R\frac{N_B N_C}{N_D} \quad , \quad R = \frac{N^{MC}_{A+A'} N^{MC}_D}{N^{MC}_{C+C'} N^{MC}_B}$$

  - R takes into account possible correlation between the 2 variables
  - N_X is number observed data in region X, after subtraction of the contribution from non fake E_T^{miss} backgrounds



BDT variables:
- E_T^{miss} significance,
- $m_T(\gamma, E_T^{miss})$,
- photon p_T,
- m_{ll},
- $m_{ll\gamma}$,
- $\frac{\lvert \vec{E}_T^{miss} + \vec{p}_T^{\,\gamma} \rvert - p_T^{ll}}{p_T^{ll}}$



- L,R : scalar messengers

$t\bar{t}$ H/A-> $t\bar{t}$ $t\bar{t}$

arXiv:2211.01136

Backgrounds:

- Physics processes: (~75%)
  - SM tttt (constrained to SM prediction with 20% cross section uncertainty)
  - ttW QCD and tt γ* (MC corrected to data in dedicated CR)
  - ttW EW+jets, ttZ+jets, ttH+jets and minor processes (constrained to SM prediction)
- Instrumental and fake backgrounds: (~25%)
  - Charge mis-identification → likelihood fit to find best agreement in OS and SS $Z \to ee$ data binned by p and $|\eta|$ (with additional *MPV* for CR Conv.) with rates varying from 0.001% to 10%
  - Non-prompt leptons from heavy-flavor decays and photon conversion (MC corrected to data in CRs)
  - Fake leptons from light mesons and quark/gluon jets, and minor backgrounds (constrained to SM prediction)

signal strength μ assuming m_H = 400 GeV,

Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}H(\to t\bar{t})$	+0.01	−0.00
Background modelling		
$t\bar{t}t\bar{t}$	+0.17	−0.17
$t\bar{t}W$	+0.07	−0.07
$t\bar{t}$	+0.06	−0.05
Non-prompt leptons	+0.05	−0.05
$t\bar{t}Z$	+0.05	−0.05
$t\bar{t}H$	+0.03	−0.03
Other background	+0.03	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.09
Jet flavour tagging (b-jets)	+0.05	−0.04
Jet flavour tagging (light-flavour jets)	+0.04	−0.03
Luminosity	+0.03	−0.02
Jet flavour tagging (c-jets)	+0.02	−0.02
Other experimental uncertainties	+0.02	−0.02
MC statistical uncertainty		
Simulation sample size	+0.04	−0.04
Total systematic uncertainty	+0.31	−0.28
Statistical		
HF, Mat. Conv., and Low $m_{\gamma*}$ normalisation	+0.05	−0.04
$t\bar{t}W$ QCD normalisation	+0.05	−0.04
Total statistical uncertainty	+0.35	−0.32
Total uncertainty	+0.46	−0.41

Region	Channel	N_j	N_b	Other selection requirements	Fitted variable
CR Conv	$e^\pm e^\pm \,\|\|\, e^\pm\mu^\pm$	$4 \leq N_j < 6$	≥ 1	$m_{ee}^{CV} \in [0, 0.1]$ GeV $200 < H_T < 500$ GeV	m_{ee}^{PV}
CR HF e	$eee \,\|\|\, ee\mu$		$= 1$	$100 < H_T < 250$ GeV	Yield
CR HF μ	$e\mu\mu \,\|\|\, \mu\mu\mu$		$= 1$	$100 < H_T < 250$ GeV	Yield
CR $t\bar{t}W$	$e^\pm\mu^\pm \,\|\|\, \mu^\pm\mu^\pm$	≥ 4	≥ 2	$m_{ee}^{CV} \notin [0, 0.1]$ GeV, $\|\eta(e)\| < 1.5$ for $N_b = 2$, $H_T < 500$ GeV or $N_j < 6$; for $N_b \geq 3$, $H_T < 500$ GeV	$\sum p_T^\ell$
CR lowBDT	SS+3L	≥ 6	≥ 2	$H_T > 500$ GeV, SM BDT < 0.55	SM BDT
BSM SR	SS+3L	≥ 6	≥ 2	$H_T > 500$ GeV, SM BDT ≥ 0.55	BSM pBDT

Exotic decays of the already discovered Higgs boson

Dark photons from Higgs boson decays via ZH production
JHEP 01 (2022) 063

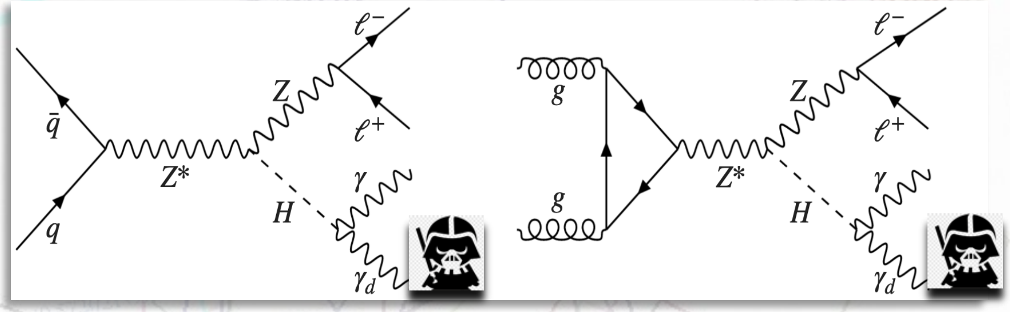
Dark photons from Higgs boson decays via ZH production

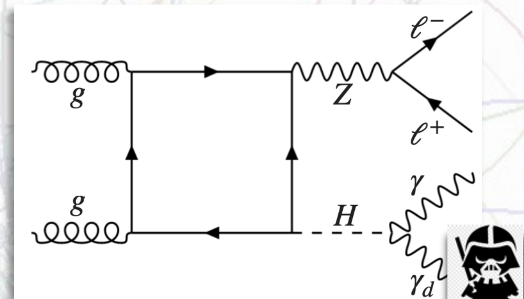
arXiv:2212.09649

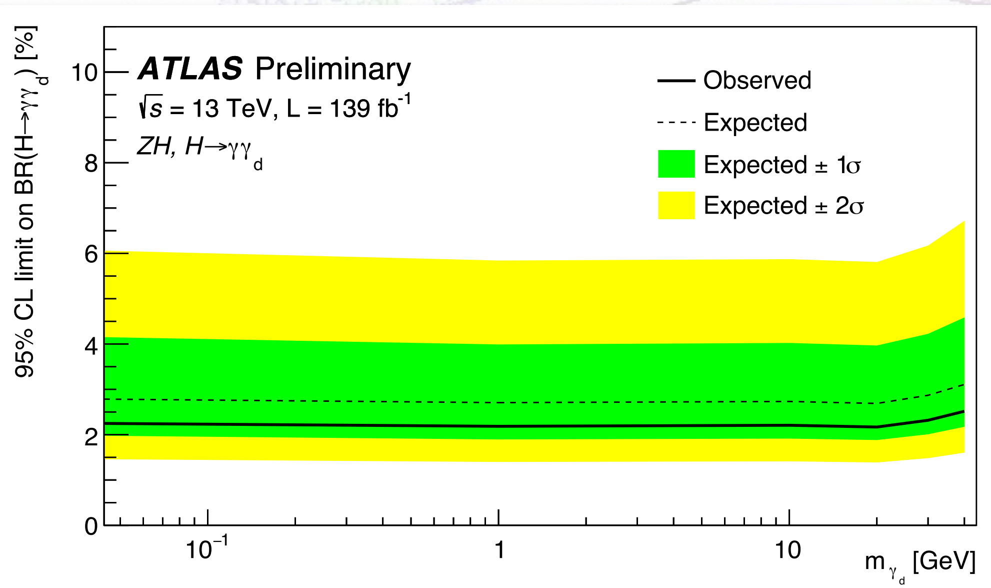
- Higgs boson as portal to Dark Sector
- Target: dark photon => predicted in hidden-sector models with an unbroken dark $U(1)_d$ gauge symmetry
- Massless and light dark-photon (up to 40 GeV)

- ZH production
- Clean final state:
  - l^+l^-(trigger)
  - $\gamma\ \gamma_{dark}$ (one isolated γ + MET)

- The BDT classifier output used as discriminant for the final statistical analysis







For massless γ_{dark}, upper limit on BR(H→ $\gamma\gamma_{dark}$) of 2.28% is set at 95% CL