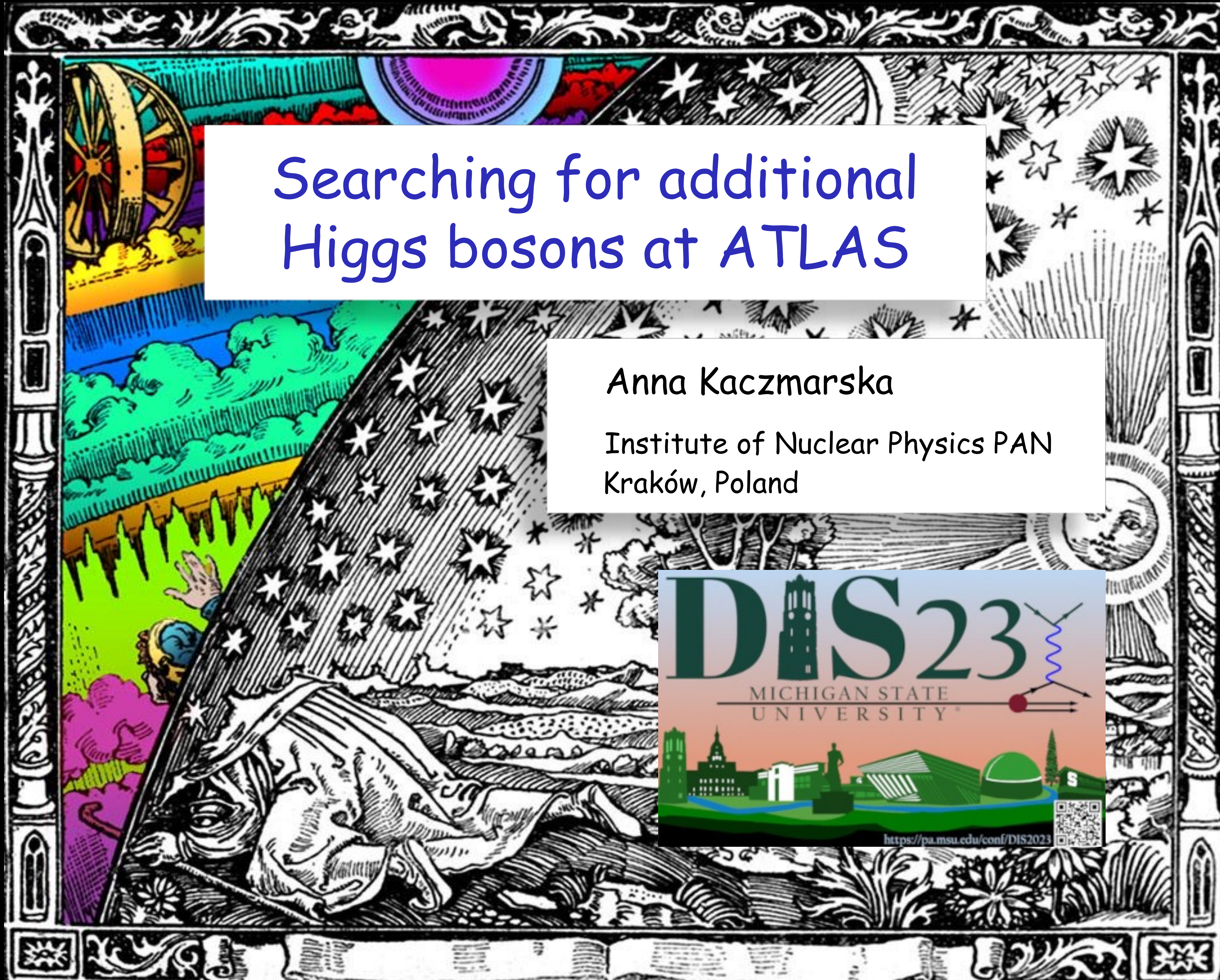


Searching for additional Higgs bosons at ATLAS

Anna Kaczmarska

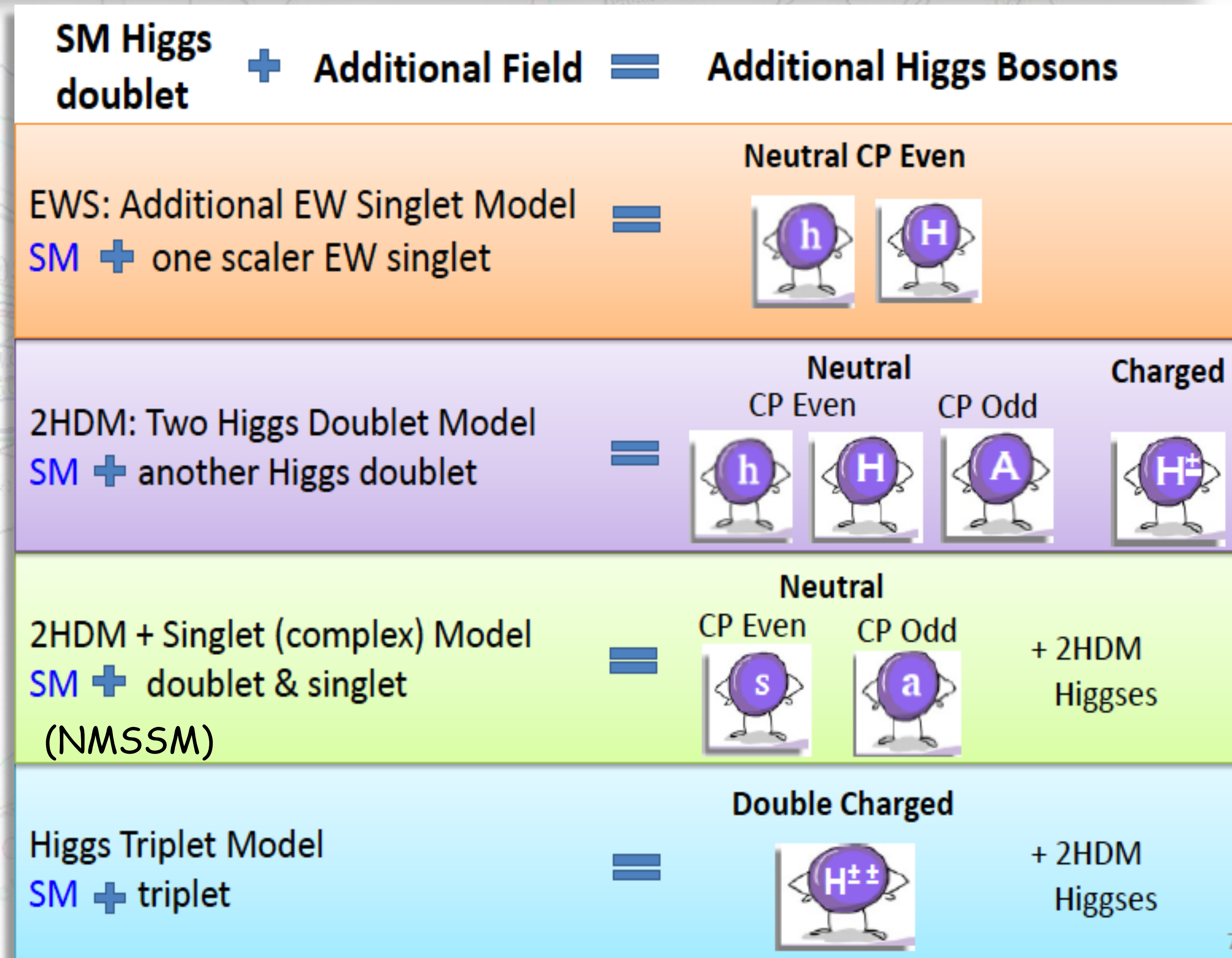
Institute of Nuclear Physics PAN
Kraków, Poland

DIS23
MICHIGAN STATE UNIVERSITY
https://pa.msu.edu/conf/DIS2023

Higgs boson(s) Beyond the Standard Model

- So far Higgs(125 GeV) looks like from SM, but consistent with SM ≠ incompatible with BSM

- Is there only one Higgs doublet or the Higgs sector is more complex?
- Extended scalar sector appears in many extensions of the SM →



- Searches for additional Higgs bosons are of great importance to probe BSM physics!

courtesy of N. Ilic

Disclaimer:

Will show some of the most recent ATLAS results with the full Run 2 dataset corresponding to 139 fb^{-1}

▻ very incomplete set of analysed Higgs channels

Many other ATLAS analyses with very interesting results (feel free to look those up!)

See also DIS2023 talks (**WG3**):

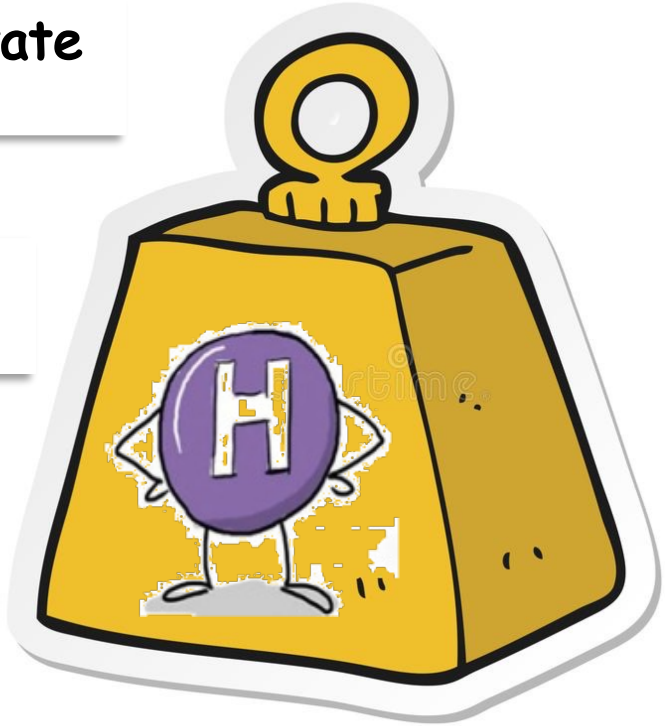
- *Searches for Dark Matter with the ATLAS Experiment at the LHC* by John Stupak
- *Search for rare decays and lepton-flavor-violating decays of Higgs boson at the ATLAS experiment* by Pawel Bruckman
- *Search for new light diphoton resonances at the ATLAS experiment* by Chris Meyer
- *Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS* by Bartlomiej Zabinski

Heavy neutral Higgs boson searches

$t\bar{t}$ H/A → $t\bar{t}t\bar{t}$ in the multilepton final state
arXiv:2211.01136

Heavy scalar H->multileptons + b-jets
ATLAS-CONF-2022-039

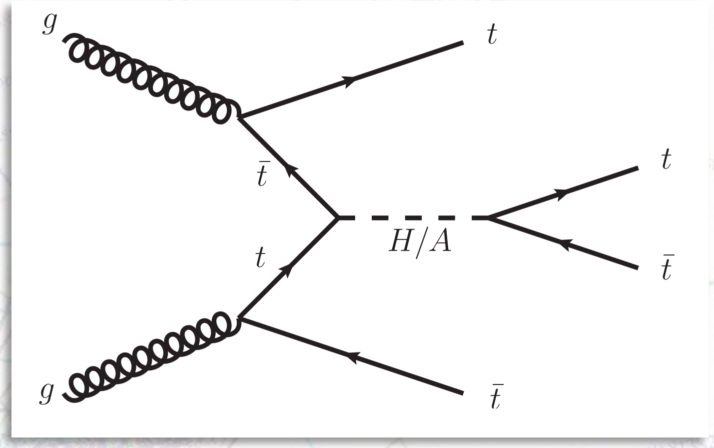
FCNC t→qX (q=u,c) → qbb
arXiv:2301.03902



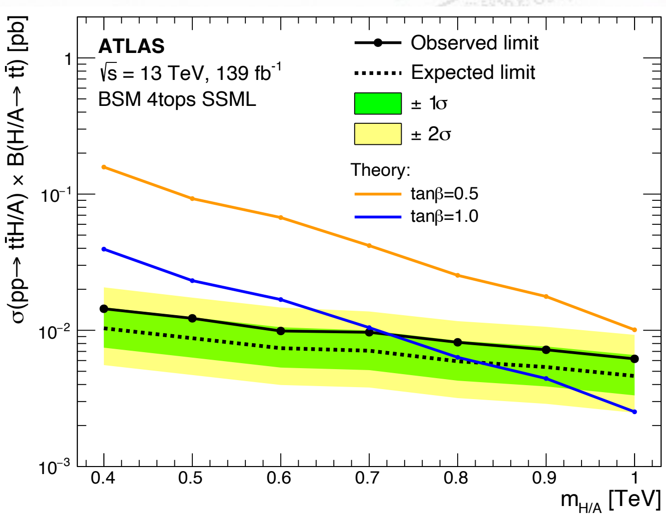
$t\bar{t}$ H/A → $t\bar{t}t\bar{t}$ in the multilepton final state

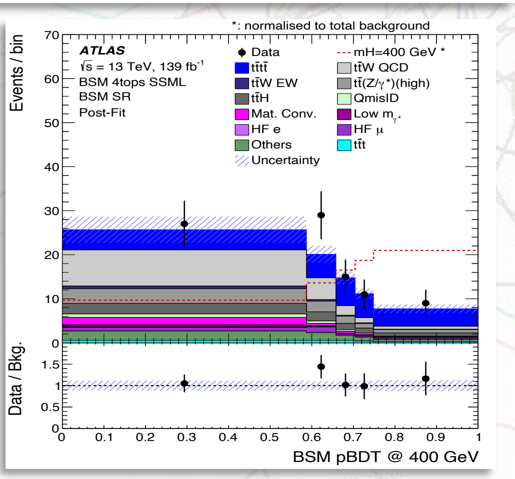
arXiv:2211.01136

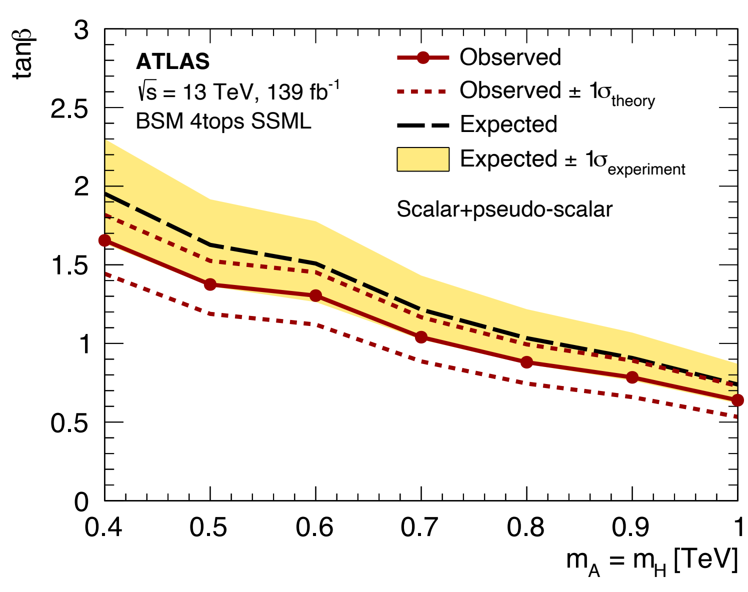
- Target: 2HDM type-II $t\bar{t}$ H/A → $t\bar{t}t\bar{t}$ signal and interpretation on low tanβ region in the alignment limit
  - m(A/H) = 400 GeV – 1 TeV
  - dominant decay mode H/A → $t\bar{t}$
- No large negative interference from SM $t\bar{t}$ as in pp →H → $t\bar{t}$
- Final state: 2SS leptons 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 → $t\bar{t}t\bar{t}$ vs all bkgs
    => Discriminant in likelihood fit



- No excess above SM predictions observed
- Results interpreted in Type-II 2HDM model



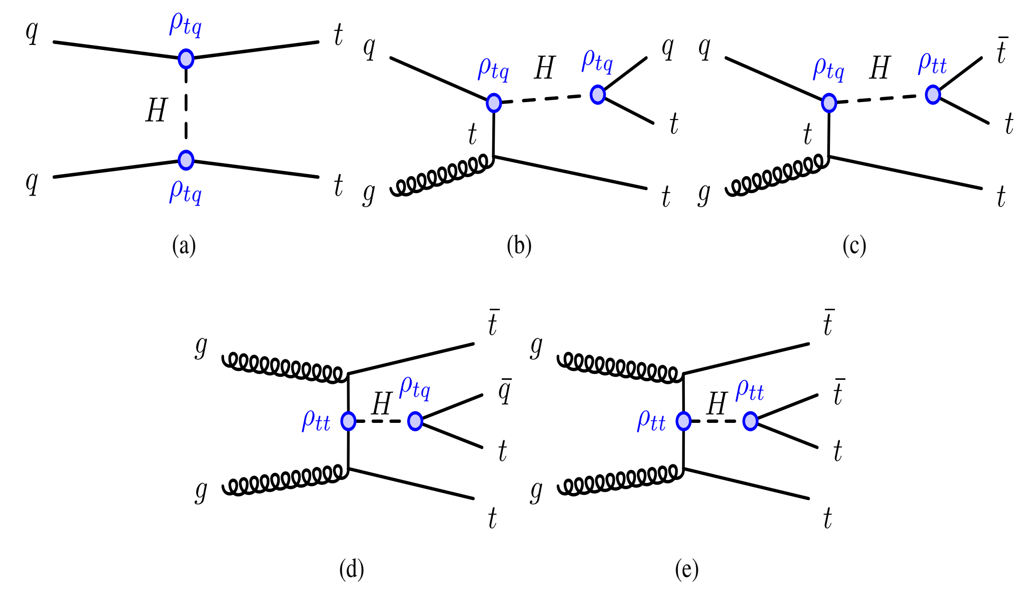




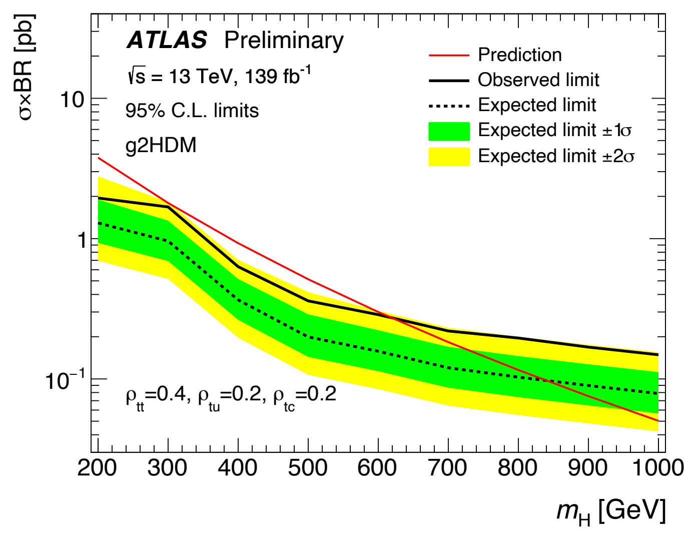
Heavy scalar H → multiple leptons + b-jets

ATLAS-CONF-2022-039

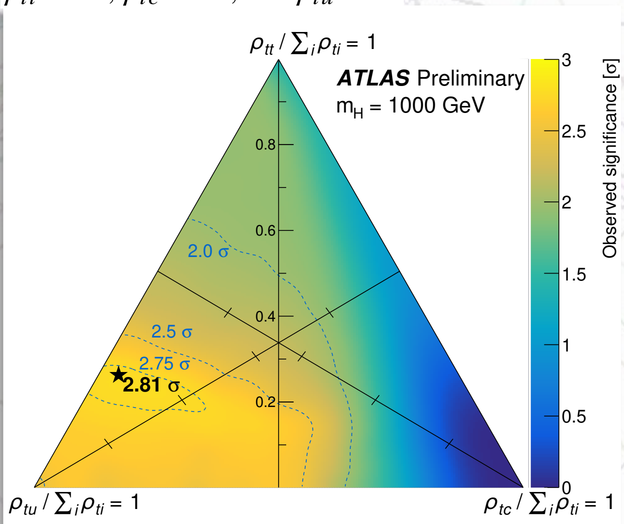
- Target: heavy scalar H from general 2HDM without Z_2 symmetry
  - extra FCNH Yukawa couplings
  - only FCNH couplings involving top quarks considered: ρ_{tt}, ρ_{tu}, ρ_{tc} - parameters of the model
  - m_H = 200 GeV - 1 TeV
- Final state: multiple leptons (e,mu) and b-jets
  - considered: 2lSS, 3l, 4l



- 17 SRs (DNN trained to classify the different signal channels) + 10 CRs => 27 analysis regions
- DNN trained over each SR region to separate signal and background



ρ_{tt}=0.32, ρ_{tc}=0.05, and ρ_{tu}=0.85



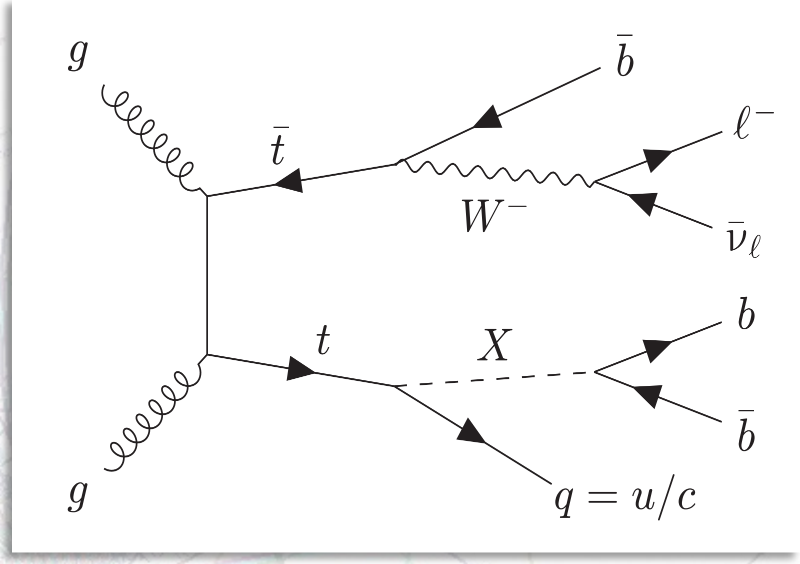
The first search targeting 3 top BSM production and first with 2HDM with flavour violation

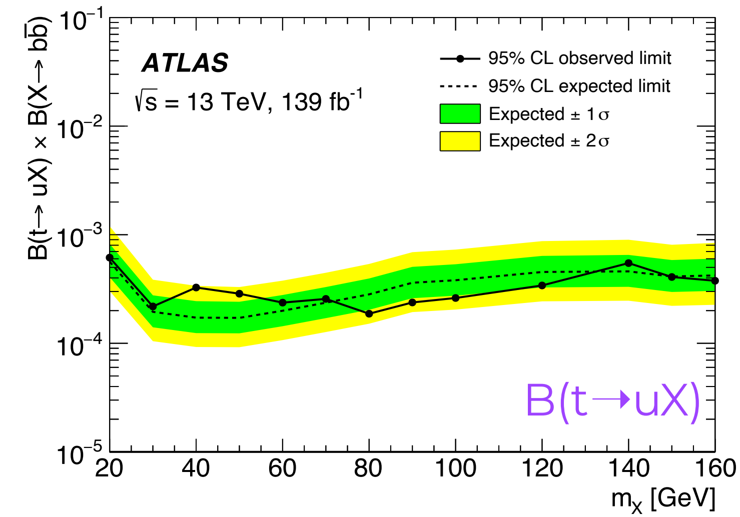
Most significant deviation observed at m_H=1000 GeV with local significance of 2.81 σ

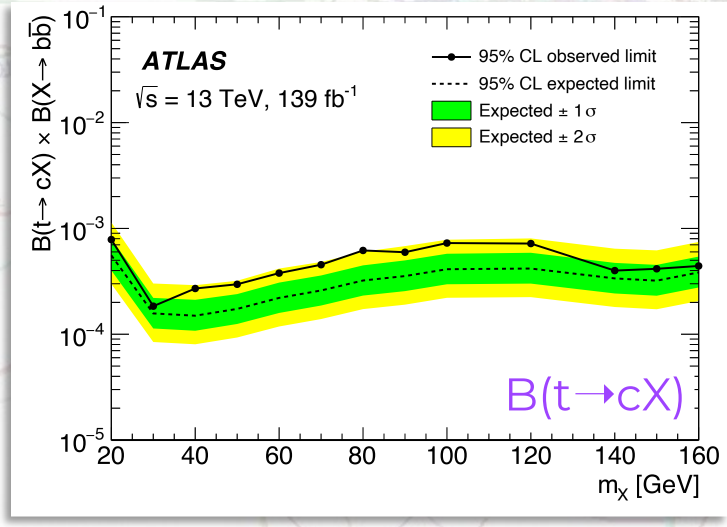
FCNC t→qX (q=u,c) → qbb

arXiv:2301.03902

- Target: scalar **X(flavon)** with flavour charge introduced in Froggatt-Nielsen mechanism
  - m(X)=20-160 GeV
  - leading decay **X→bb**
- Generic search for top-quark pair production where
  - one top quark decays to X and up-type quark (u/c), other top quark decays to Wb
- Events 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





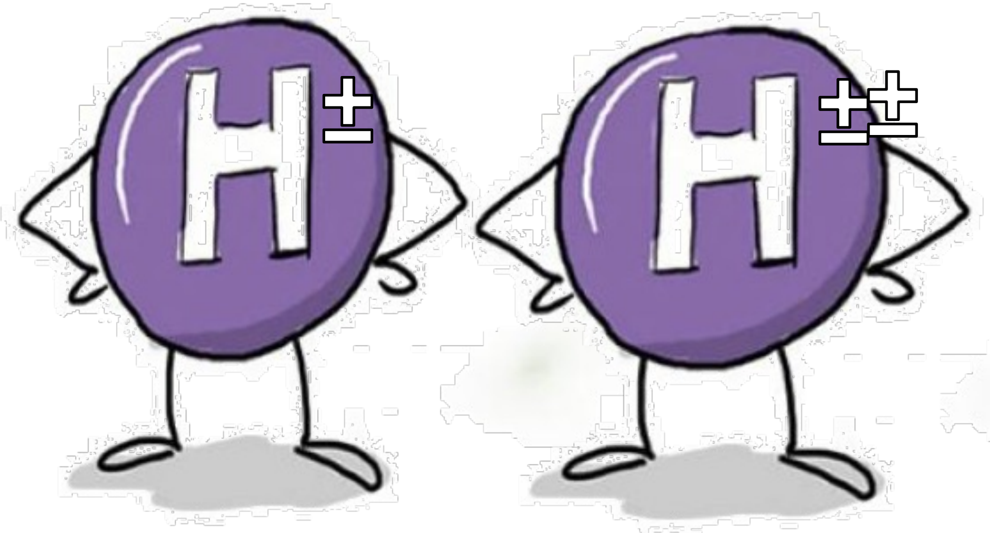


- No significant excess over SM backgrounds observed
- Expected and observed upper limits for B(t→cX) and B(t→uX)
- Slight excess (1.8σ) at 40 GeV in t→uX channel
- ~2σ broad excess in t→cX channel
  - X is expected to be much narrower

Charged Higgs boson searches

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

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

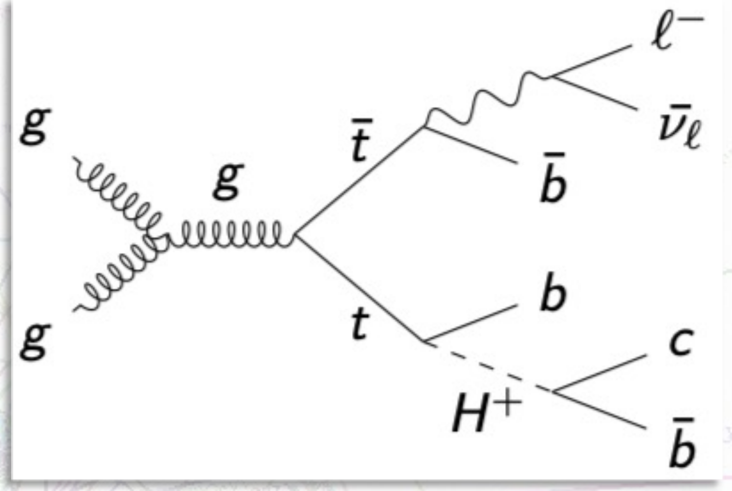


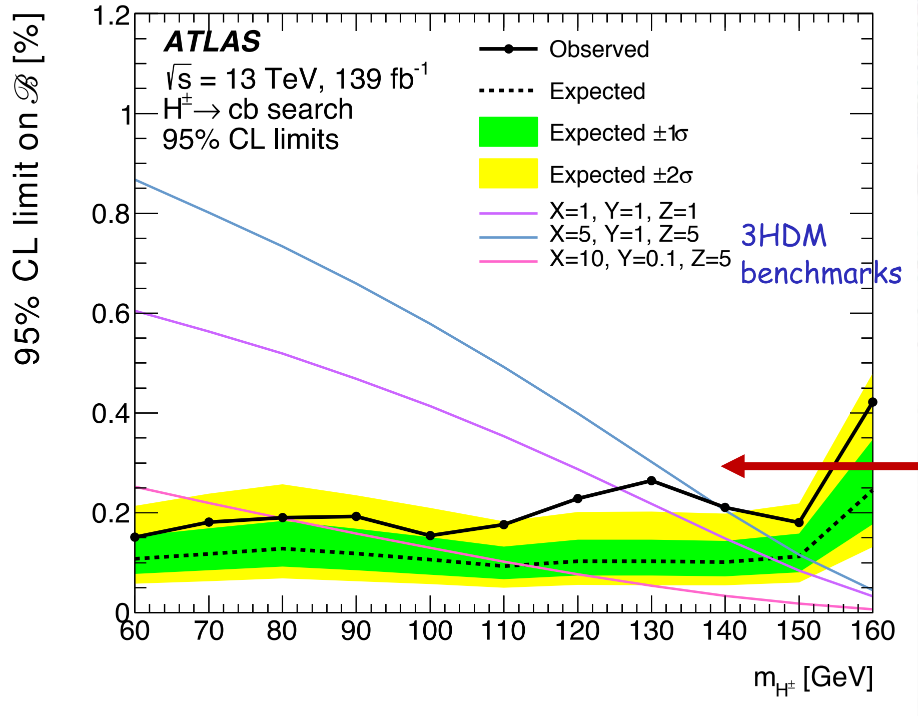
Light $H^\pm$ in $t \to H^\pm b$ decays, with $H^\pm \to cb$, in the lepton+jets final state

arXiv:2302.11739

- 3HDMs feature two $H^\pm$, the lightest one can be lighter than top quark
- Target: low mass $H^\pm$ production via the top decays $t \to H^\pm b$ with $H^\pm \to cb$
  - m($H^\pm$) 60 GeV - 160 GeV

- Final state: 1 lepton, 3 b-jets, 1 c-jet
- Categories based on number of jets and b-jets
- Use mass-parametrised NN, total of 29 input variables
- Fit NN score distributions in regions with 3 b-jets simultaneously (SRs) and the total yields in regions with ≥ 4 b-jets (CRs)





- No significant excess of data events above the background expectation
- Upper limits on BR
  - 0.15%-0.42% for m($H^\pm$)= 60-160 GeV

Small excess corresponds to a local (global) significance 3 σ (2.5 σ) at m($H^\pm$)= 130 GeV

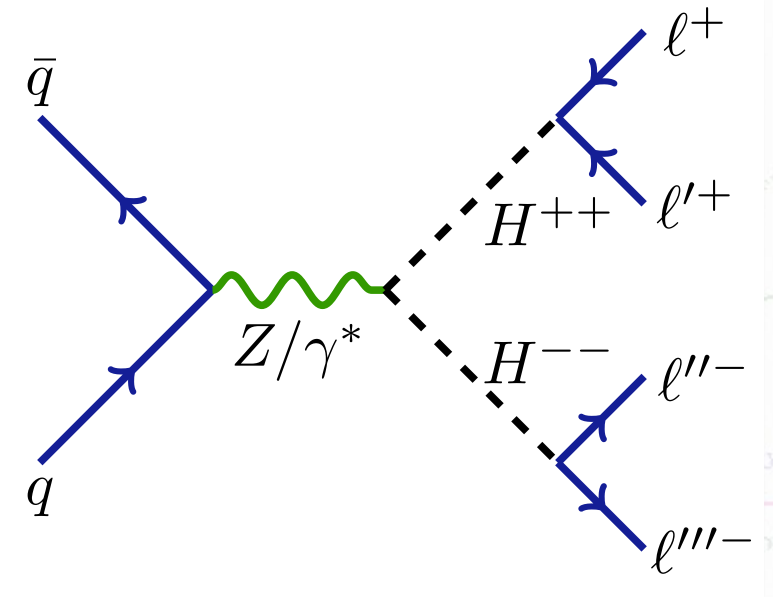
Broad excess is consistent with the expected mass resolution

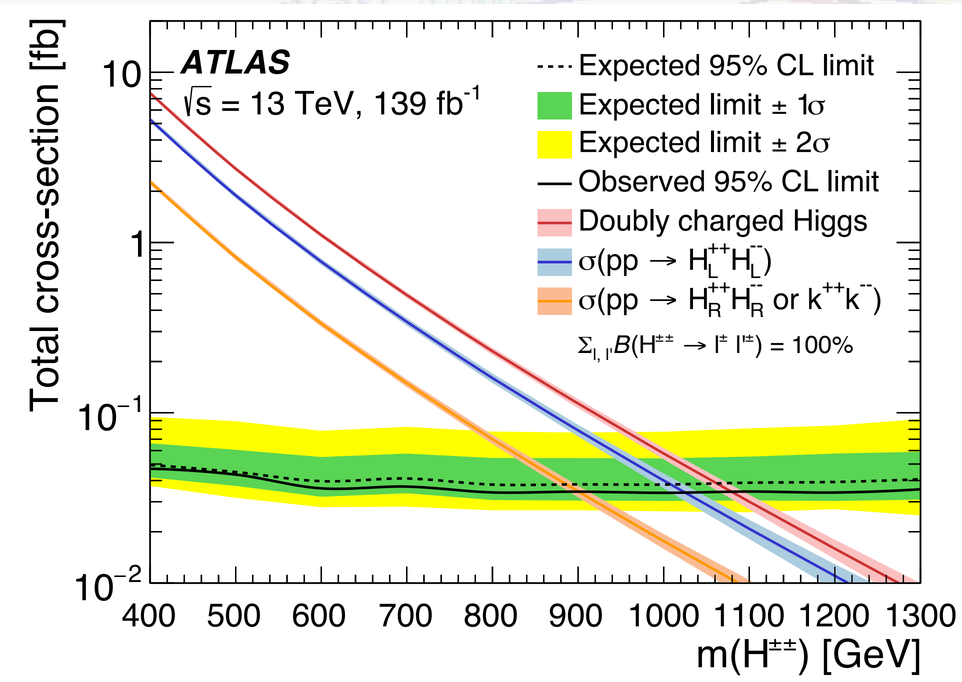
$H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$

arXiv:2211.07505

- Target: $H^{\pm\pm}$ predicted by Left-Right Symmetric Models (LRSM) or Zee-Babu model
  - LRSM => $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ => different production cross-sections
- Dominant production at the LHC: DY pair production
- For low vev considered $H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$ dominates (over $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$)
- Decays to same-charge lepton pairs
- LFV decays permitted
- $m(H^{\pm\pm})$ = 300 – 1300 GeV

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





- No excess over predicted backgrounds observed
- 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
- First direct test of the Zee-Babu model at the LHC

Exotic decays of the already discovered Higgs boson

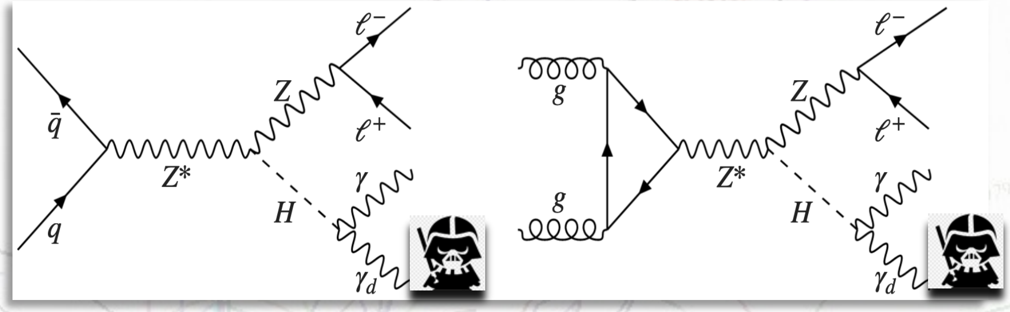
Dark photons from Higgs boson decays via ZH production
JHEP 01 (2022) 063

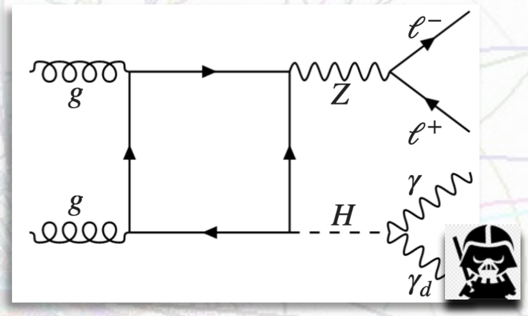
Dark photons from Higgs boson decays via ZH production

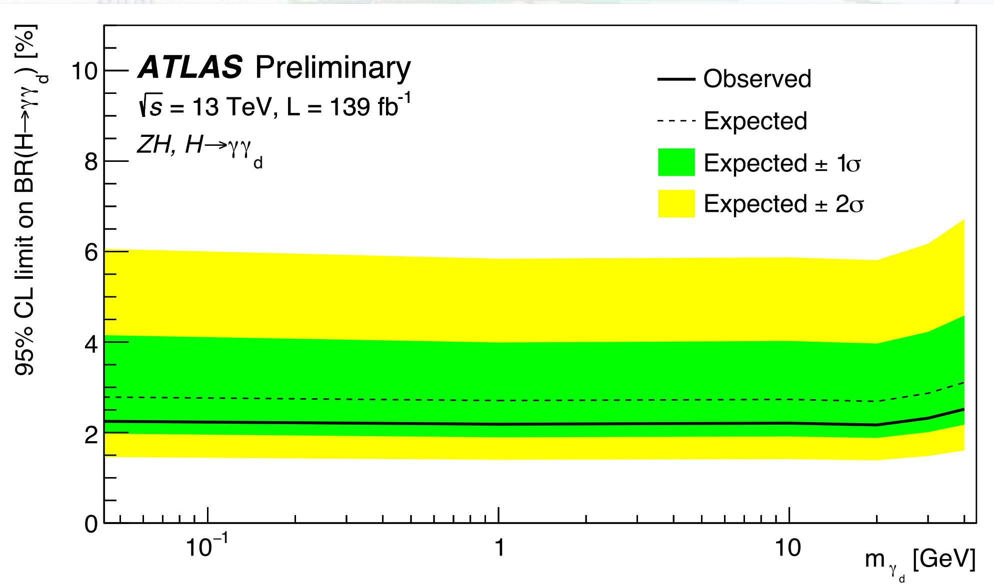
arXiv:2212.09649

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

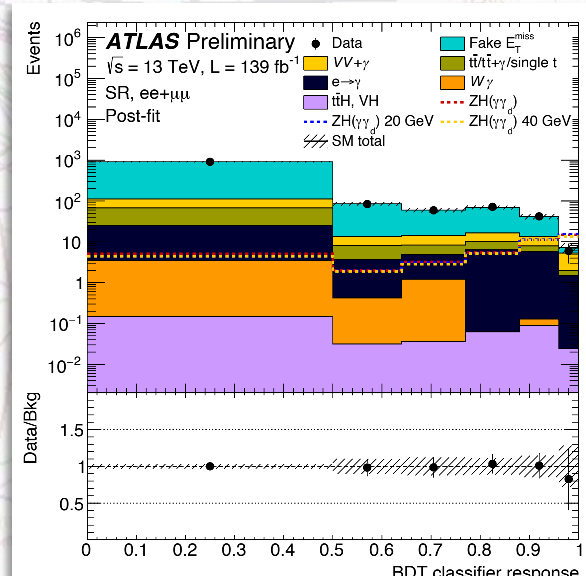
- ZH production
- Clean final state:
  - l^+l^-(trigger)
  - $\gamma\ \gamma_{dark}$ (one isolated γ + MET)
- The BDT classifier output used as discriminant for the final statistical analysis







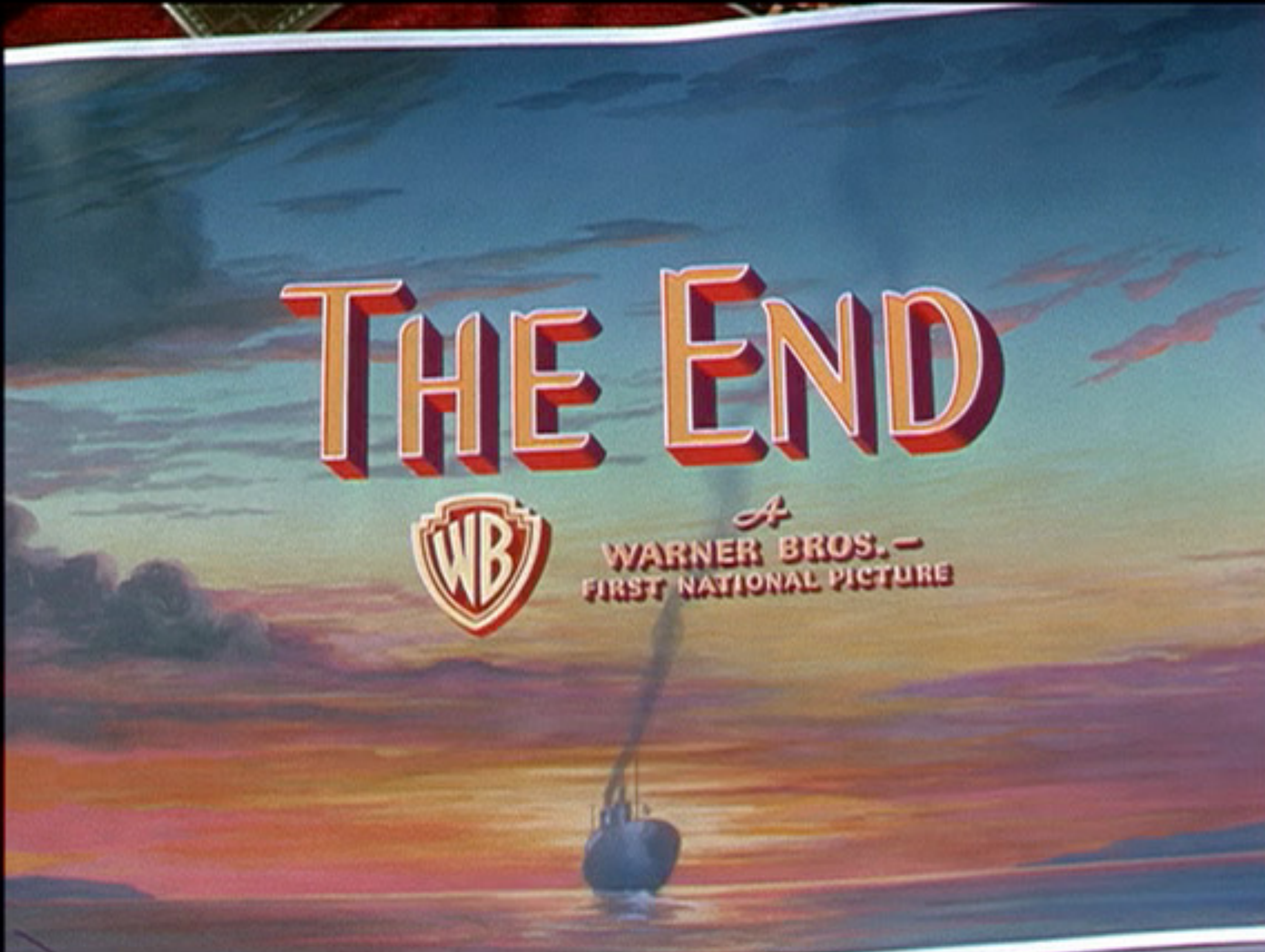
- No excess observed, limit set on BR($H \rightarrow \gamma\gamma_{dark}$)
- For massless γ_{dark}, upper limit on BR($H\rightarrow \gamma\gamma_{dark}$) of 2.28% is set at 95% CL



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.
    - $t\bar{t}$ H/A $\rightarrow t\bar{t}t\bar{t}$ => 4x improvement wrt previous ATLAS result
    - FCNC $t \rightarrow qX$ (q=u,c) $\rightarrow$ qbb => 3x improvement wrt previous ATLAS result
    - $t \rightarrow H^{\pm}b$ decays, with $H^{\pm} \rightarrow cb$ => 5x improvement wrt previous CMS result
    - $H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$ => 2x improvement wrt previous ATLAS result
    - ZH production with dark photons => 2x improvement wrt CMS 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!

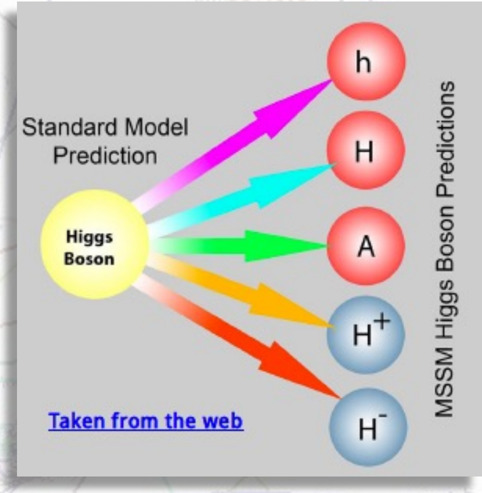

THE END
A
WARNER BROS.–
FIRST NATIONAL PICTURE

Beyond the Standard Slides

Courtesy of J. Keller

Two Higgs Doublet Model (2HDM)

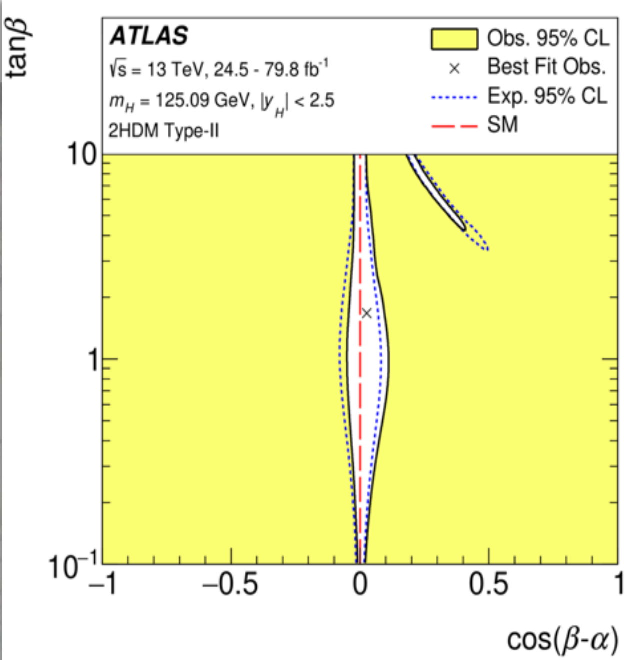
- Generic class with second Higgs doublet.
- Four variants to couple SM fermions to the 2HDs. No FCNCs-> all fermions with the same electric charge couple to one Higgs doublet only:
  - Type I: all quarks and leptons couple to only one doublet
  - Type II: one doublet couples to up-type quarks, the other 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



- 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

Phys. Rev. D 101 (2020) 012002



tt H/A-> tt tt

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
$t\bar{t}t$	+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	$e^\pm e^\pm \parallel e^\pm \mu^\pm$	$4 \le N_j < 6$	≥ 1	$m_{ee}^{CV} \in [0, 0.1]$ GeV $200 < H_T < 500$ GeV	m_{ee}^{PV}
CR HF e	$eee \parallel ee\mu$		$= 1$	$100 < H_T < 250$ GeV	Yield
CR HF μ	$e\mu\mu \parallel \mu\mu\mu$		$= 1$	$100 < H_T < 250$ GeV	Yield
CR $t\bar{t}W$	$e^\pm\mu^\pm \parallel \mu^\pm\mu^\pm$	≥ 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 $N_b \ge 3$, $H_T < 500$ 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 $\ge$ 0.55	BSM pBDT

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

ATLAS-CONF-2022-039

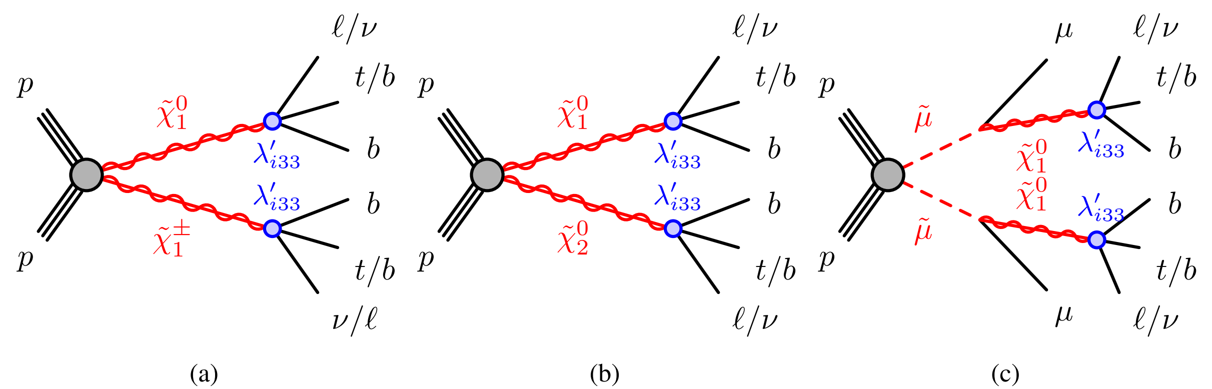
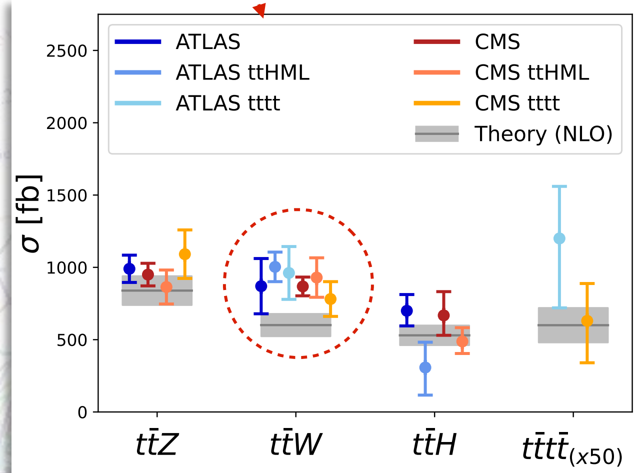


Figure 2: Signal diagrams for the RPV SUSY signals used as additional interpretation in the analysis. The subsequent decay can lead to a final state with high multiplicity of leptons and b-jets which is targeted by the search.



- 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.**

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	
$\|m_{\ell^+\ell^-}^{OS-SF} - m_Z\|$ [GeV]	–	>10	
N_{jets}	≥ 2		
$N_{b-\text{jets}}$	$\geq 1\ b^{60\%}$ || $\geq 2\ b^{77\%}$		
Region split	(sstt, ttq, ttt, tttq, tttt) $\times$ (Q^{++}, Q^{--})	(ttt, tttq, tttt) $\times$ (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		
	2ℓSS −− CAT tttq		
	2ℓSS −− CAT tttt		

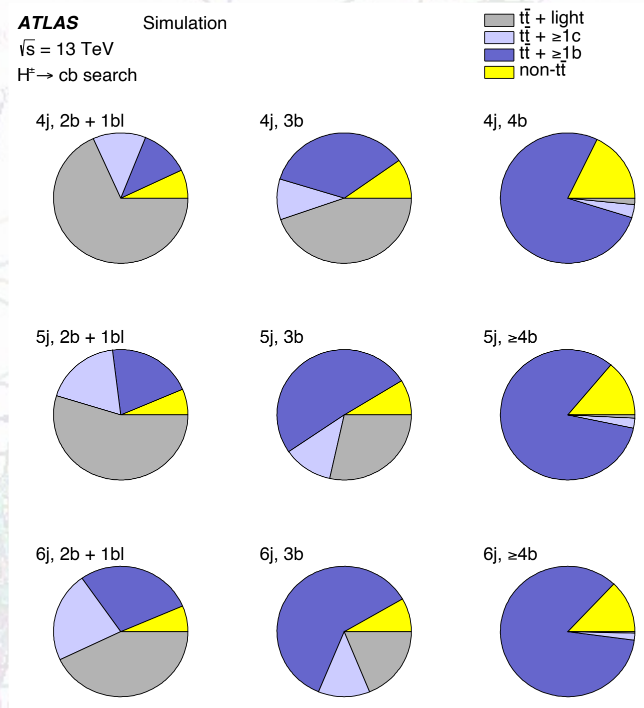
H±->cb

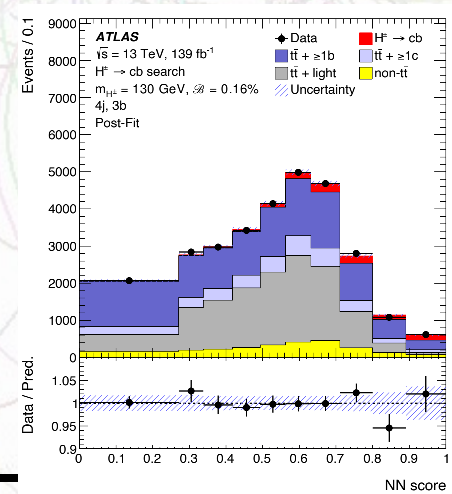
arXiv:2302.11739

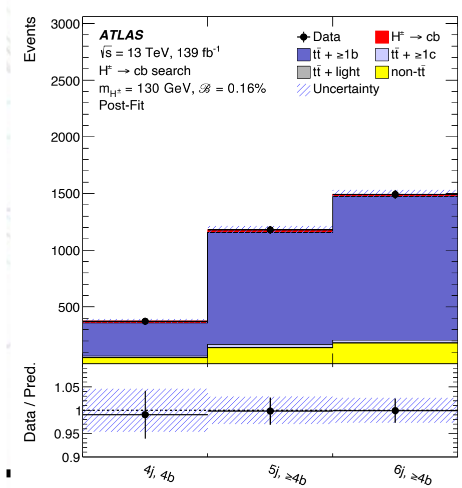
Pre-selection	
Trigger	single-lepton trigger
Leptons	= 1 isolated e or μ
Jets	$\geq$ 4 jets
B-tagged jets	$\geq$ 2 b-tagged jets
MET	> 20 GeV
MET + m_T^W	> 60 GeV

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** ($t\bar{t}+\geq$ 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,$\geq$ 4b** ($t\bar{t}+\geq$ 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,$\geq$ 4b** ($t\bar{t}+\geq$ 1b background control region, 1 bin)

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





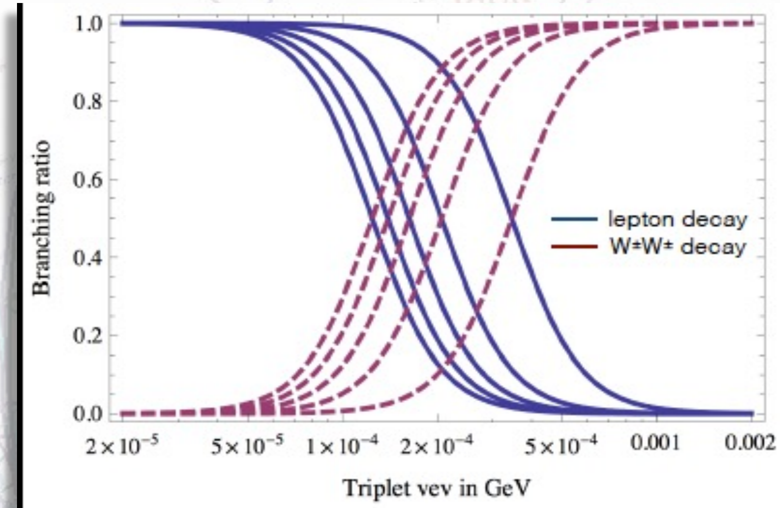


The leading uncertainties affecting the signal extraction by the fit are found to be related to the c-tagging calibration, the calibration of light-jet mis-tagging rate and the choice of $t\bar{t}$ NLO generator in fit regions with four jets. Other uncertainties with a sizeable impact on the signal-strength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

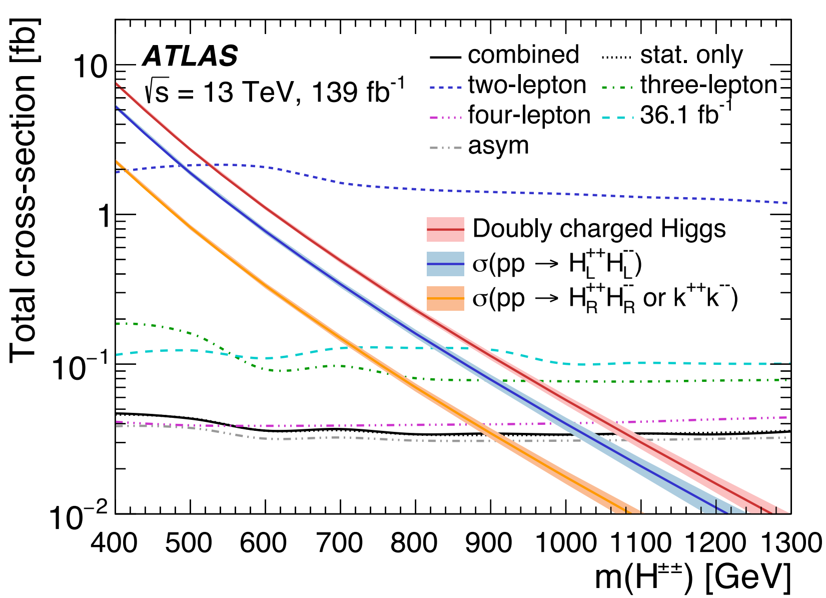
$H^{\pm\pm} \to l^{\pm}l^{\pm}$

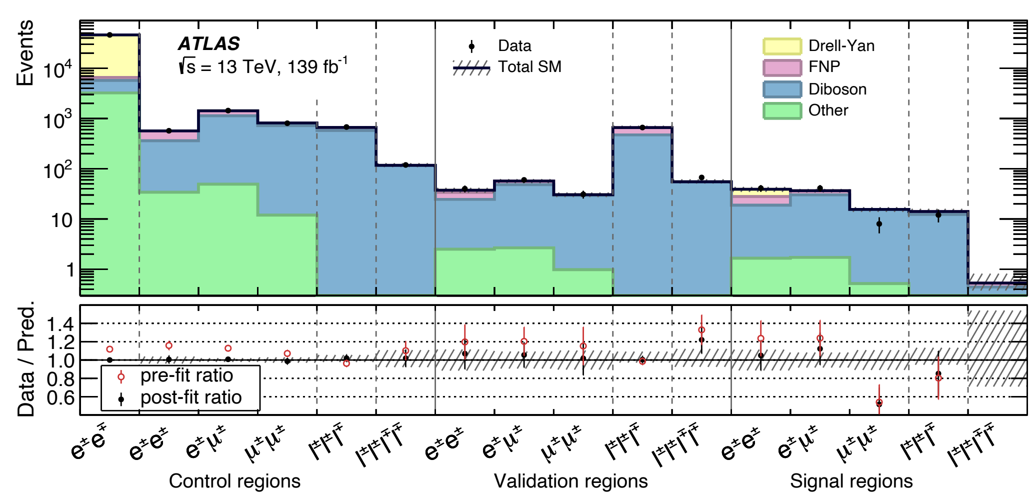
arXiv:2211.07505

- 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, $t\bar{t}$) 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



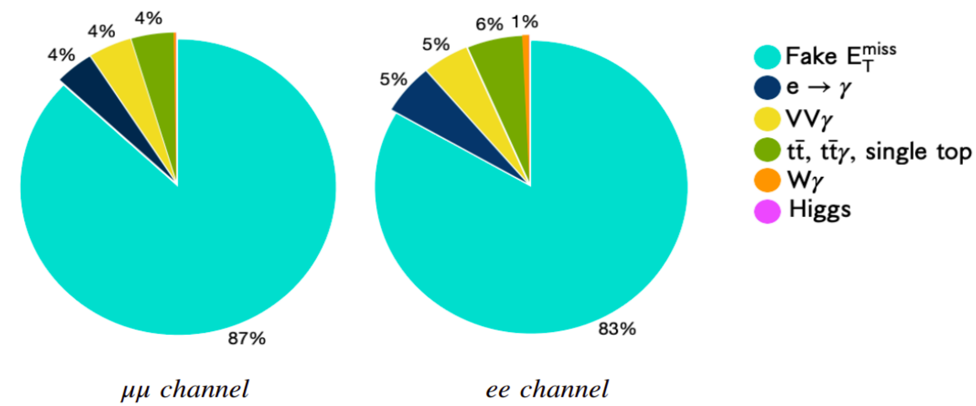


Dark photons from Higgs boson decays via ZH production

ATLAS-CONF-2022-064

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)

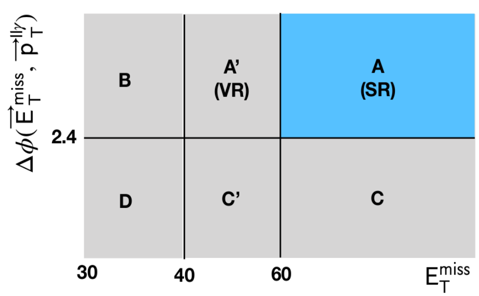


Main backgrounds
- ○ Irreducible background from VVγ final states with bosons decaying leptonically, obtained from simulation
- ○ Reducible background from biased MET measurement, data-driven

- **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},
- $m_{ll\gamma}$,
- $\frac{|\vec{E}_T^{miss} + \vec{p}_T^{\gamma}| - p_T^{ll}}{p_T^{ll}}$

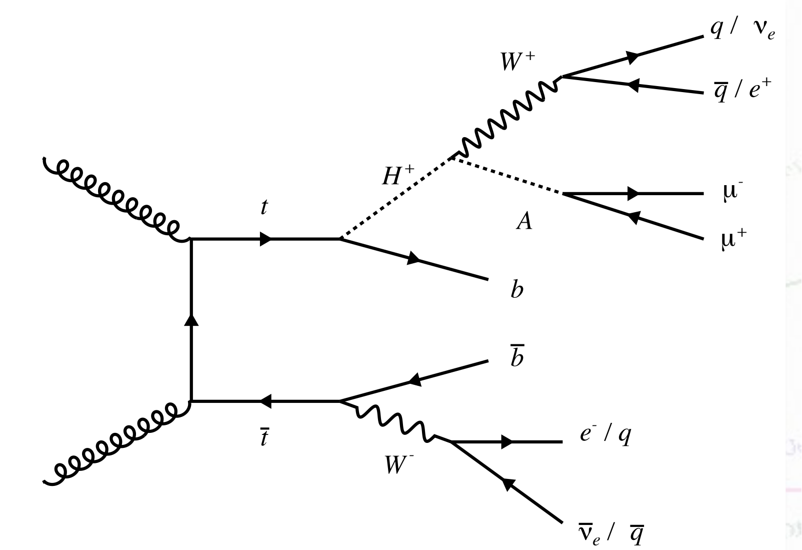
- L,R : scalar messengers

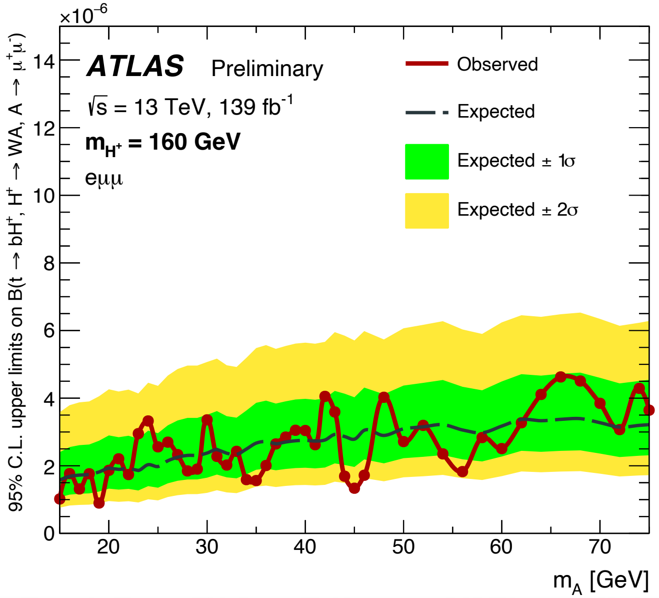
Light $H^\pm \to AW^\pm$, $A \to \mu\mu$

ATLAS-CONF-2021-047

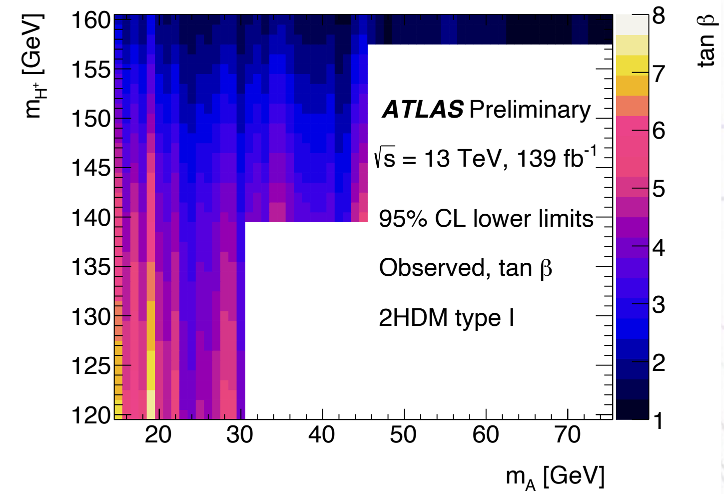
- Target: 2HDM with bosonic decays of $H^\pm$
  - when kinematically allowed (light A), can dominate fermionic channels (tau nu, cs/cb)
- Light CP-odd scalar A can account for the anomalous muon magnetic moment
- $m(H^\pm)$ = 100–160 GeV
- m(A) = 15-75 GeV

- Final state: $e^\pm\mu^+\mu^-$ and ≥ 3 jets (≥ 1 b-tagged)
- Scan the m(μμ) invariant mass bins for event excesses, for different $m(H^\pm)$
- Single-bin fit for each A mass window: counting experiment
  - mass windows 1.5->4 GeV depending on m(μμ) mass





- No significant excess observed
- Upper limits as a function of m(A) for various $m(H^\pm)$
- Set limits on tanβ in a 2HDM type-I model in the $(mH^\pm, mA)$ parameter space for the first time

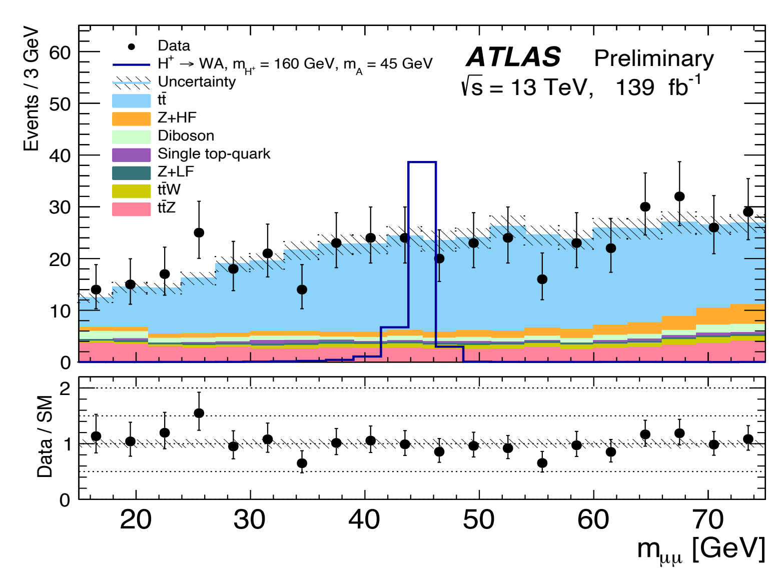


H±->AW±, A-> $\mu\mu$

ATLAS-CONF-2021-047

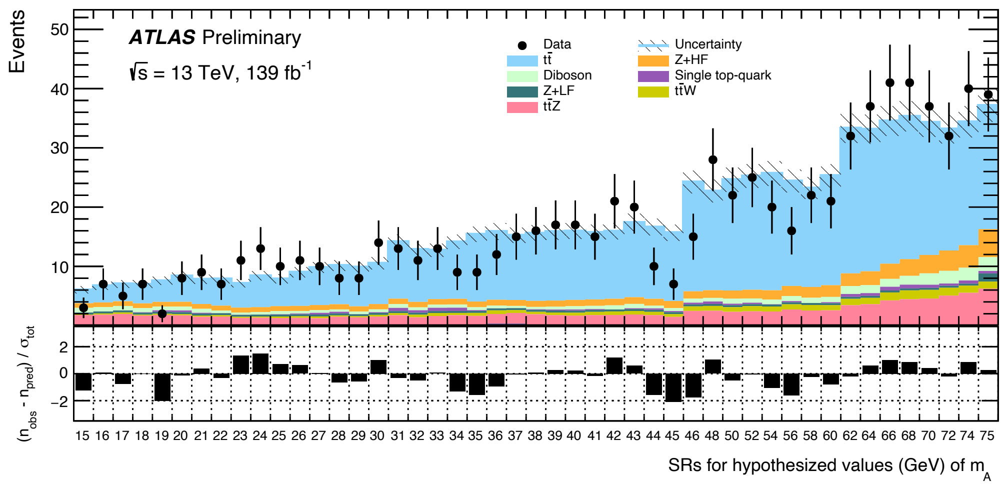
Background estimation: MC constrained with data in Control Regions

- Free floating parameters for major backgrounds are determined in a likelihood fit to the data
- Systematic uncertainties implemented as nuisance parameters in the fit; propagated as uncertainties on transfer factors



Background distribution in SR:

- Dominated by ttbar with one non-prompt lepton (80%), ttZ (6%), Z+jets (6%)

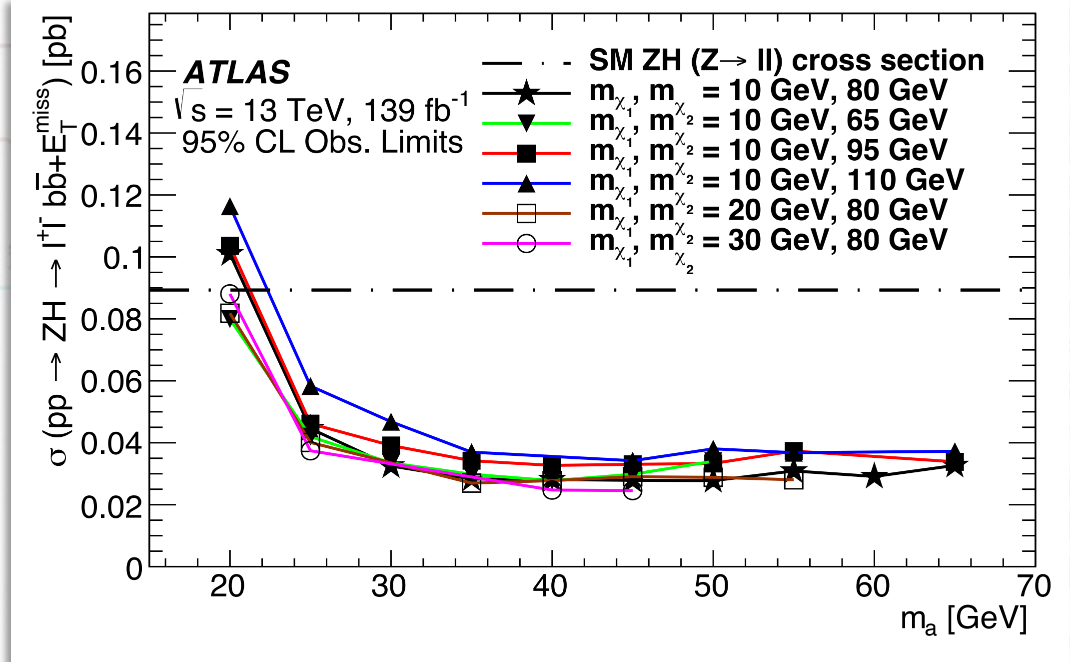


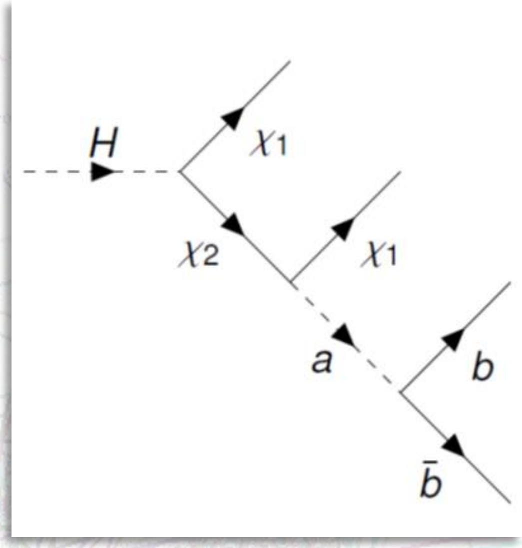
Source	Total background [%]	Signal [%]
$t\bar{t}$: hadronization/parton-shower	9–17	–
$t\bar{t}$: hard-scatter generation	7–13	–
$t\bar{t}$: ISR/FSR	1–4	–
$t\bar{t}$: normalization	4–7	–
ttZ: normalization	3–8	–
Diboson: cross-section	2-7	–
MC statistics	4–7	2
Jet energy resolution	3–6	
Signal: PDF & α_s	–	4
Signal: QCD scale	–	3.5
Signal: mass	–	3

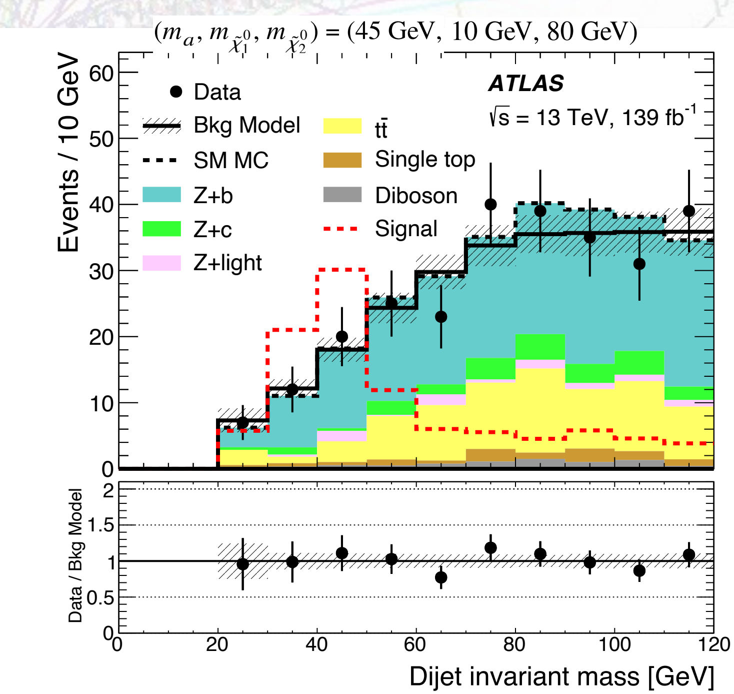
H(125) → bb + MET

JHEP 01 (2022) 063
arXiv:2109.02447

- Target: NMSSM in the Peccei-Quinn limit
  - $H \to \tilde{\chi}_2^0 \tilde{\chi}_1^0 \to a \tilde{\chi}_1^0 \tilde{\chi}_1^0$ dominates (over H →aa)
- m(a) considered 20-65 GeV, a→ bb dominates
- ZH production mode, with Z → l^+l^- (l=e,μ)
- Final state: 2l OS, 2 b-jets, large MET
- Discriminant: dijet invariant mass





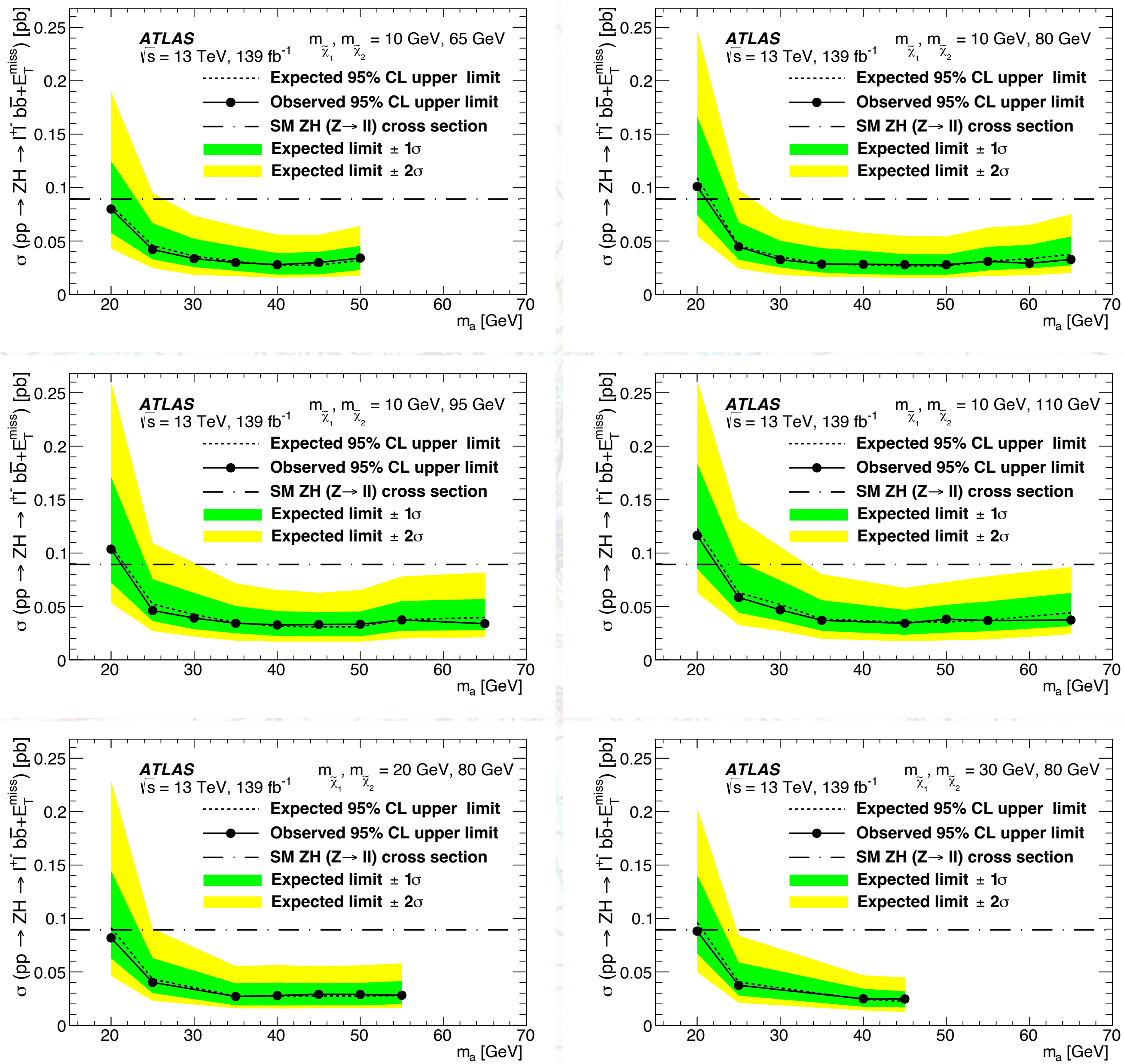


- The observation consistent with the SM background model
- Upper limits on the pp → ZH x BRs for a three-dimensional scan of masses of the $\tilde{\chi}1$, $\tilde{\chi}2$ and a boson.
- The first direct limits on this exotic Higgs boson decay from the LHC

H-> bb +MET

JHEP 01 (2022) 063
arXiv:2109.02447

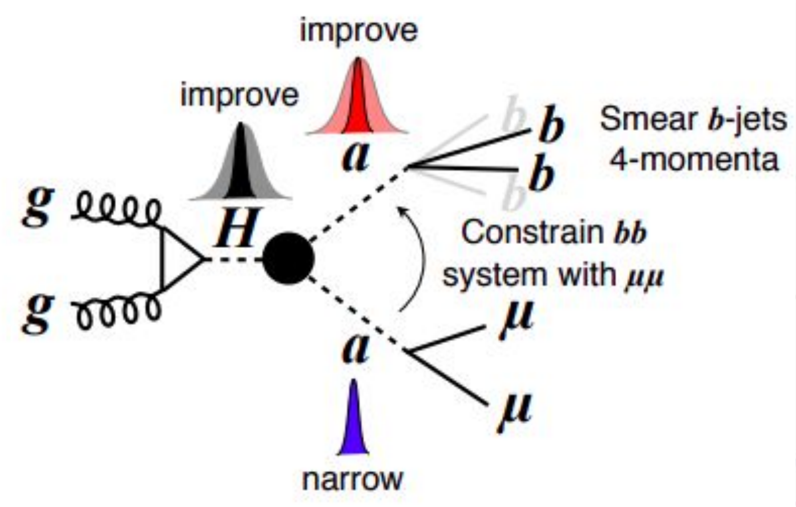
- The dominant background processes in the SR are Z+b,c jets (Z+HF) and ttbar
- The shape of the m(dijet) distribution in the SR from data in CRZ and CRTop to obtain the m(dijet) templates for Z+HF and ttbar.
- These templates combined with relative weights obtained from MC.
- Subdominant background contributions (Z+light, single-top and diboson) modeled with MC
- QCD multijet background negligible

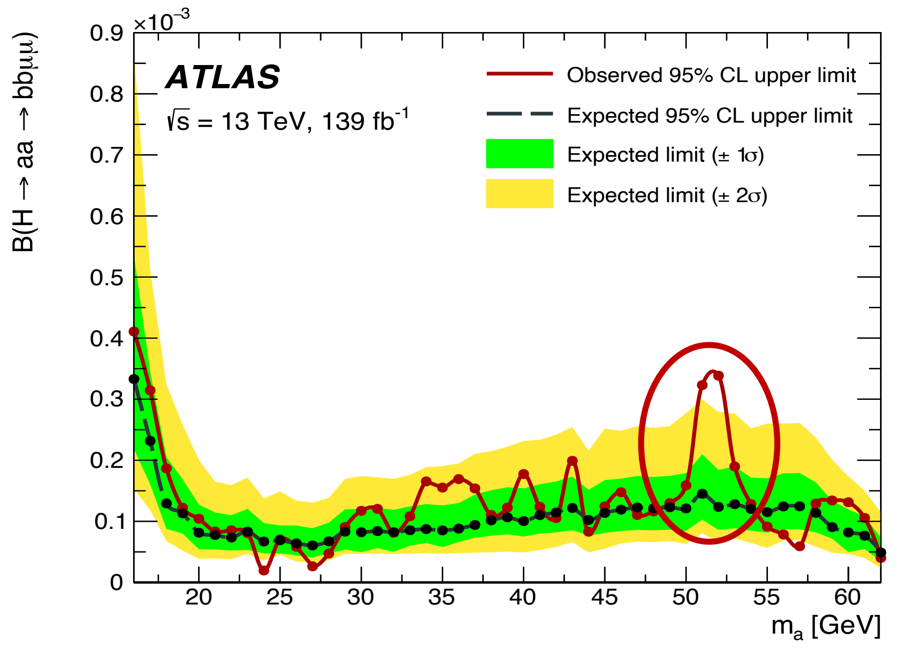


H(125)-> aa -> bbμμ

Phys. Rev. D 105 (2022) 012006
arXiv:2110.00313

- Target: decays of H(125) into two pseudoscalars a
  - one a→bb (high BR) and the other a→μμ (high mass resolution and trigger)
  - m(a)= 16 GeV - 62 GeV
- Kinematic likelihood fit to to constrain the m(bb) to the m(μμ) and improve the resolution of the m(μμbb) peak
- For each mass point of a pseudoscalar BDT is trained
  - cut on BDT score to separate signal from the DY and ttbar backgrounds
- Looking for excess in m(μμ) invariant distribution
  - fit in 2 (3) GeV m(μμ) bins for m(a) < (>) 45 GeV



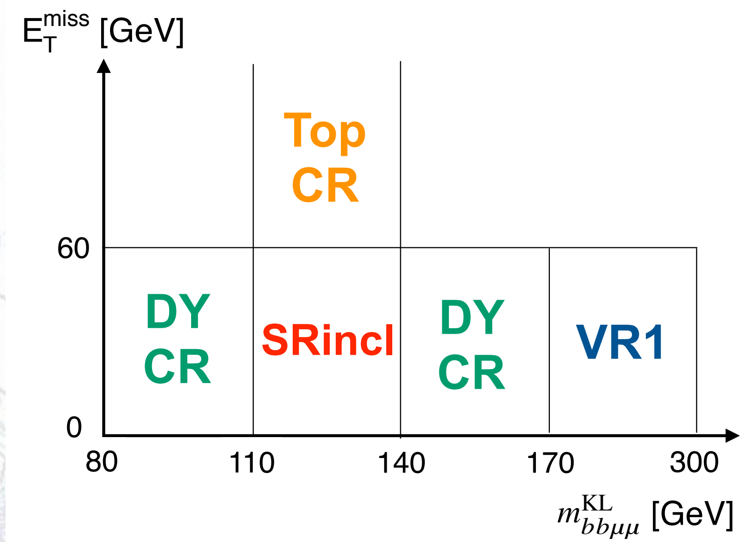


- No significant excess of the data above the SM backgrounds observed
- Upper limits are set on Br(H→aa→bbμμ) for different m(a)
- Excess of 3.3σ (1.7σ) local (global) observed at m(a)=52 GeV

H-> aa -> bb$\mu\mu$

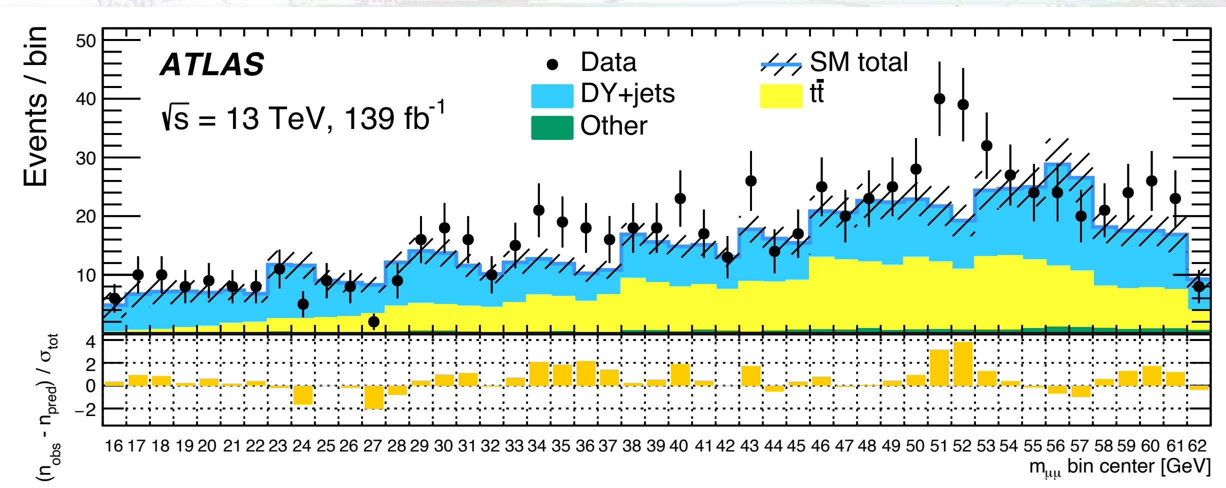
Variables used in BDT

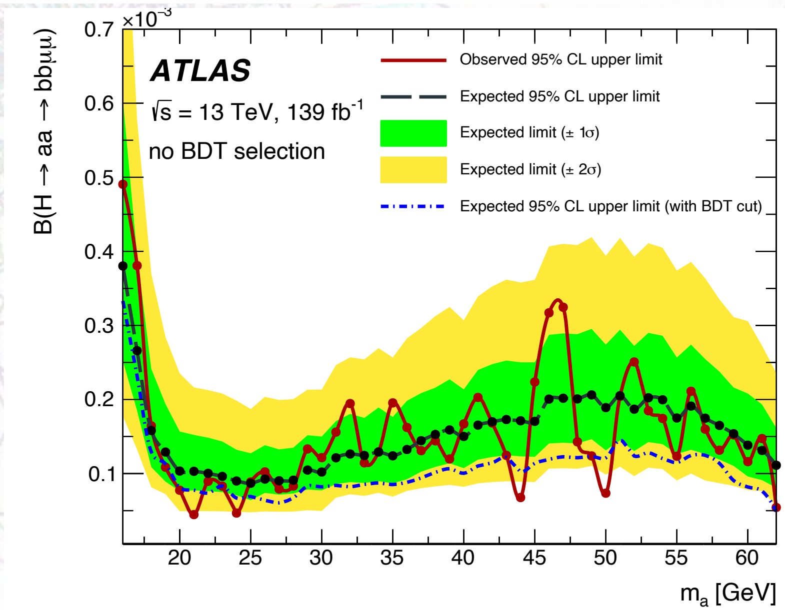
- Dibjet mass
- klfit loglikelihood
- ΔR (a,a), ΔR (μ1,μ2), ΔR (b1,b2)
- Average ΔR(b,μ), average m(b,μ)



Main backgrounds

- ttbar: obtained from simulation.
- Drell-Yan: estimated from data driven method.

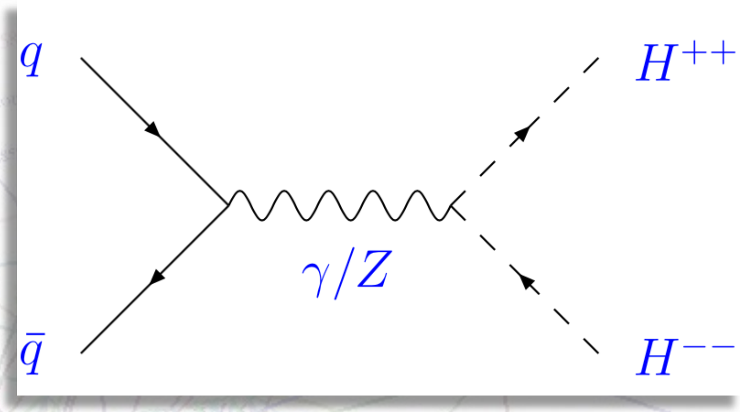




$H^{\pm\pm}$: Production and Decays

$H^{\pm\pm}$ predicted by variety of BSM models:

- Left-Right Symmetric Models (LRSM)
  - addition of two scalar triplets $SU(2)_R$ and $SU(2)_L$
- Higgs Triplet Model (HTM)
  - addition of $SU(2)_L$ scalar triplet
- Zee-Babu models, Georgi–Machacek models



Production at the LHC:
pair-produced $H^{\pm\pm}$ via the Drell-Yan process
(dominant in LRSM and HTM)

Motivations

- Restoring parity symmetry in weak interactions at higher energy (LRSM)
- Explain light neutrino masses through See-Saw mechanism

Most unique feature of such models: $H^{\pm\pm}$

- left and right-handed in LRSM or left-handed only in HTM

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