Searches for additional scalar bosons (light, heavy, charged)

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on behalf of CMS and ATLAS Collaborations
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HIGGS2023 @IHEP Beijing

Outline

CMS results
ATLAS results

Introduction

Searches for additional scalar bosons

- with di-bosons ($\gamma\gamma, Z\gamma, VV$)
- with di-leptons ($e\mu, \mu\mu, \tau\tau$)
- with complex final state

  (top quark, in association with/decaying into the Standard Model H)

Why extra scalar bosons?

Many extensions of the SM adds scalar doublets, triplets to the Higgs sector, motivated by SUSY, extra source of spontaneous CP Violation for electroweak baryogenesis, flavor, hierarchy problem…

- 2HDM [Phys. Rept. 516(2012)1]
- 3HDM [Int. J. Mod. Phys. A32 (2017)1750145]
- 2HDM + scalar   [JHEP03(2018)178]
- Higgs triplets (Neutrino mass Seesaw) [Front. In Phys. 6(2018)40]
- axion model [Phys. Rept. 150(1987)1]
- …

These models predict extra scalar bosons ➔ benchmarks for searches

- $h, H, A, H^{\pm}, H^{\pm\pm}$

Search for new scalars with di-boson

New particles in $\gamma\gamma$ final state

CMS PAS HIG-20-002

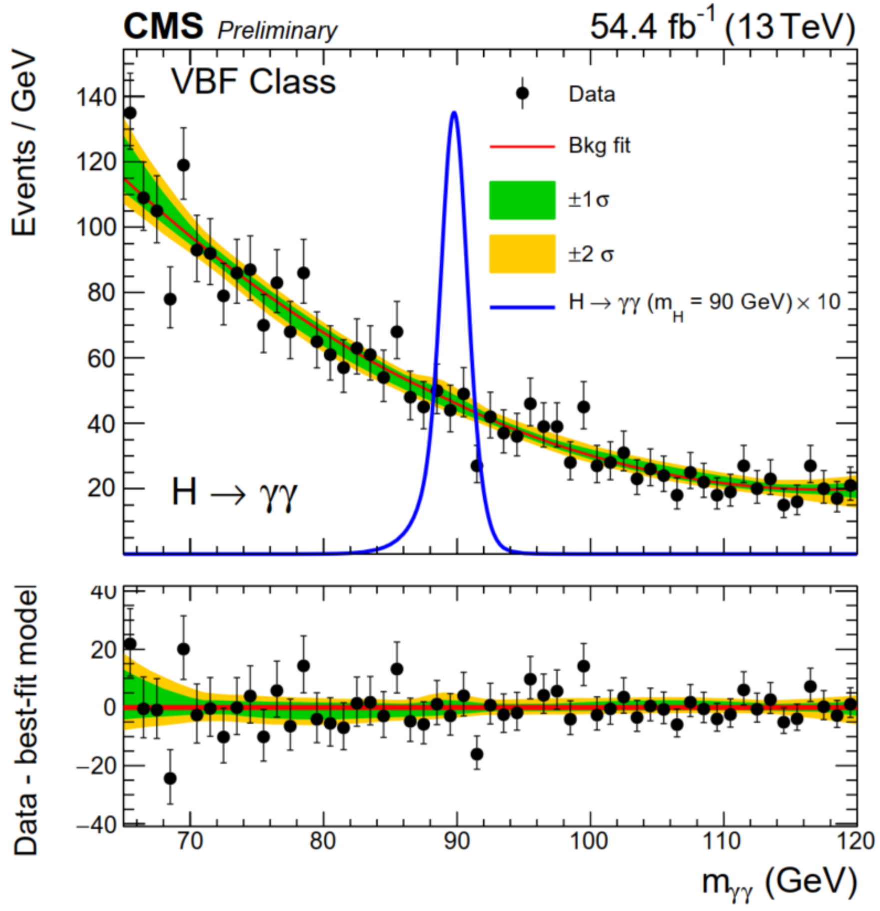
"clean final state": Excellent energy resolution, tremendous investments on background studies in the past

➔ good basis to search for new peaks!

CMS search strategy:

- $M_{\gamma\gamma}$ range: 70~110 GeV (benchmark: SM-like Higgs)
- BDT to select $\gamma\gamma$ vertex
- BDT for photon identification
- BDT to suppress continuum background
- Categories: 1 VBF + 3 classes defined by di-photon BDT
- Background estimation: fitting mass spectrum in 65-120 GeV with analytical functions
- 2016 data re-analyzed with improved detector calibration

2018 data



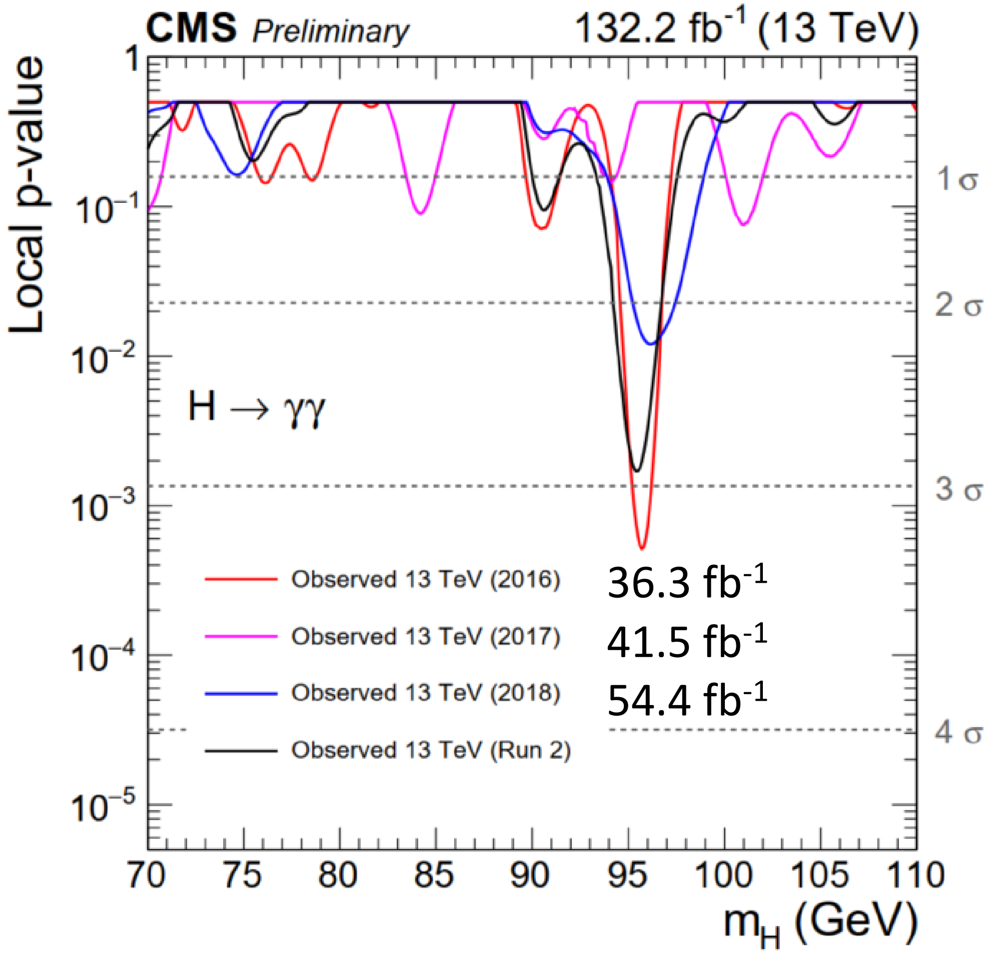
More details in talk by Muhammad Aamir Shahzad (BSM 1 parallel session)

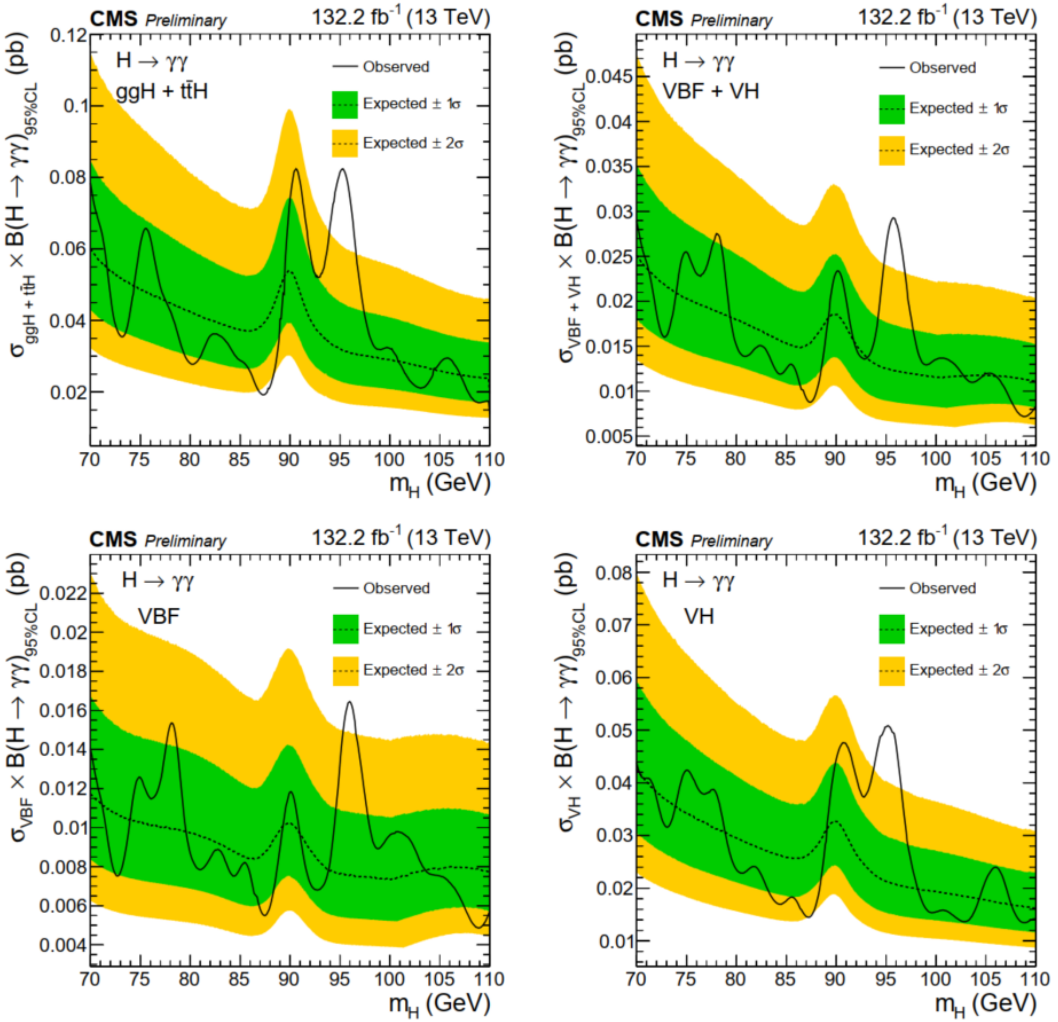
Significance and upper limits

Test statistic based on profile likelihood ratio constructed from the mass spectrum

2.9σ local (1.3σ global) at 95.4 GeV

SM-like benchmark

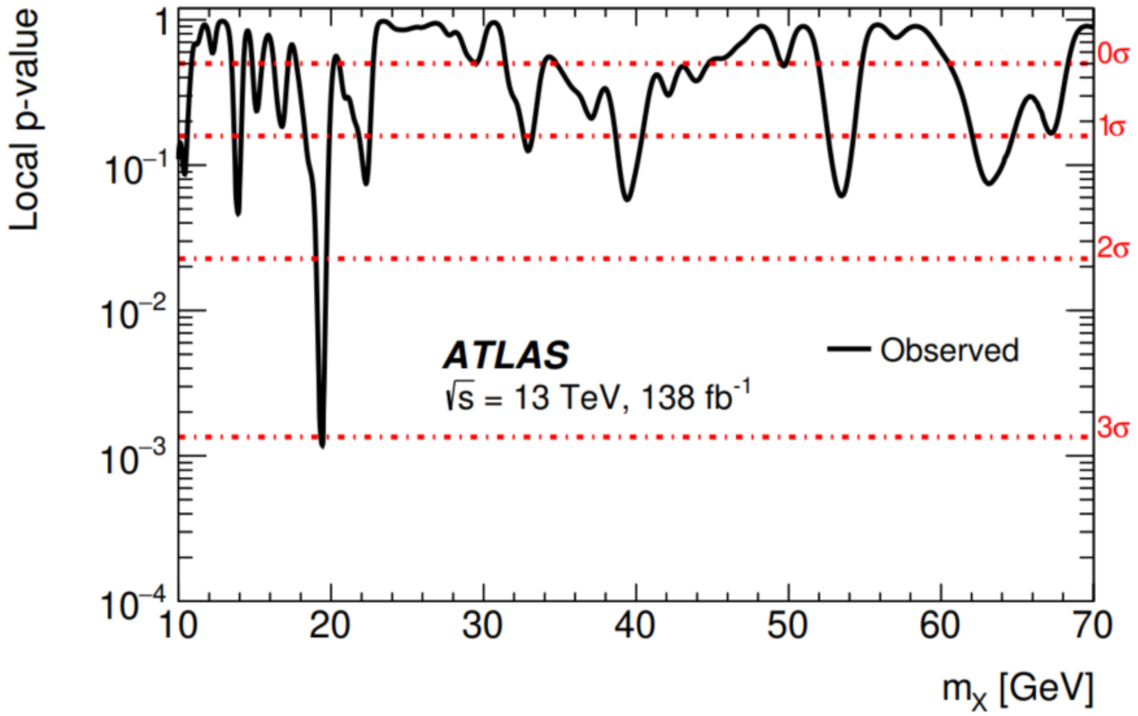




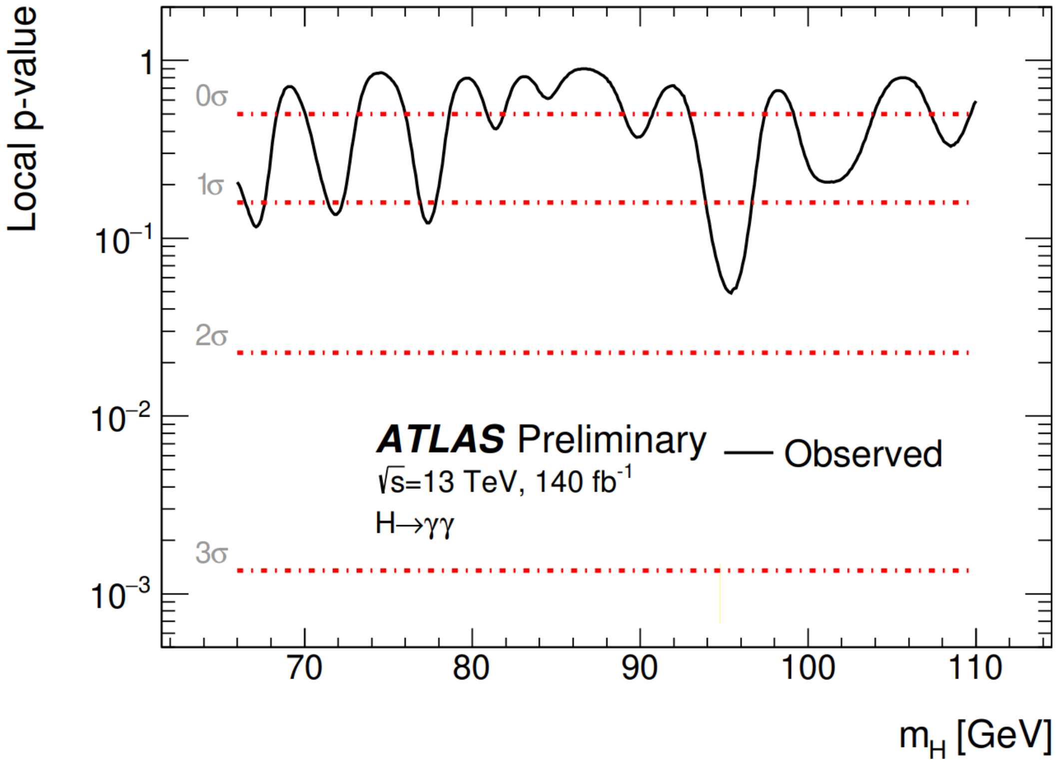
di-photon at ATLAS

JHEP 07 (2023) 155
ATLAS-CONF-2023-35

background decomposition: $\gamma\gamma$ template from MC,γj, jj from control regions in data



local 3.1σ (global 1.5σ) at 19.4 GeV



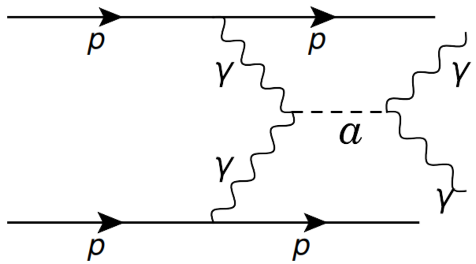
local 1.7σ at 95.4 GeV
(benchmark ggF SM Higgs-like)

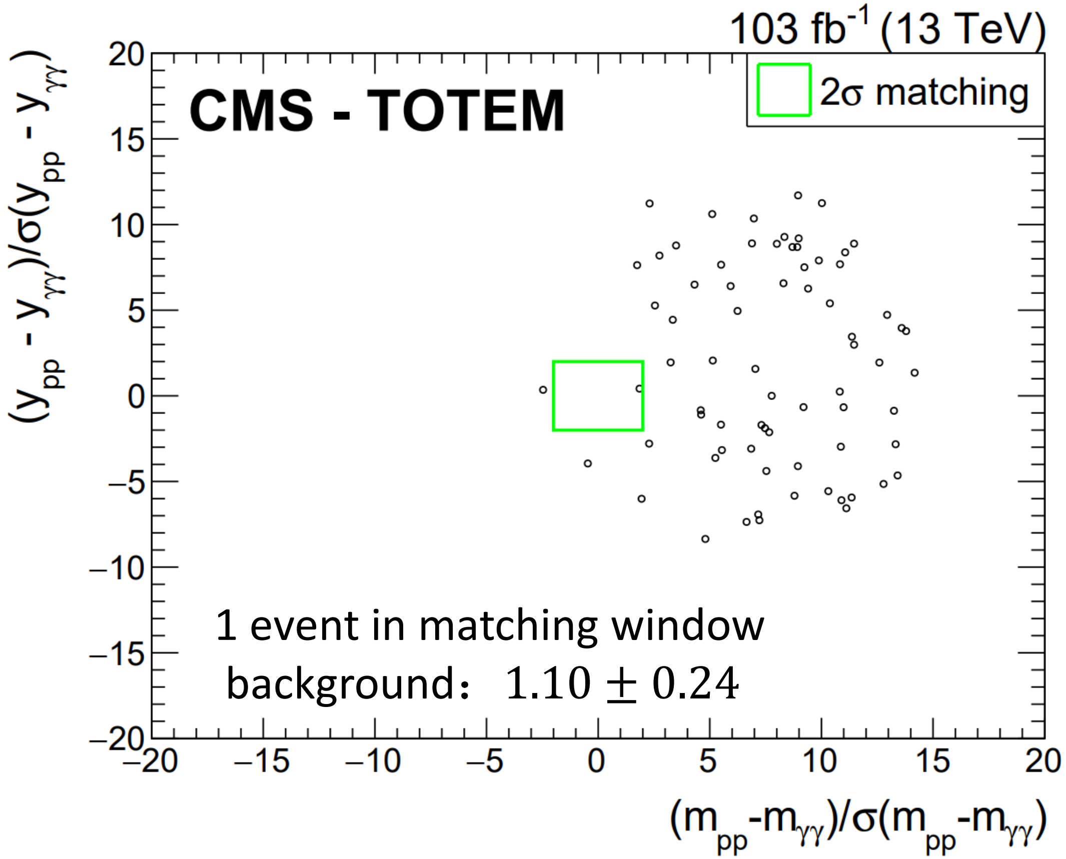
More details in talk by Tom KRESSE (BSM 1 parallel session)

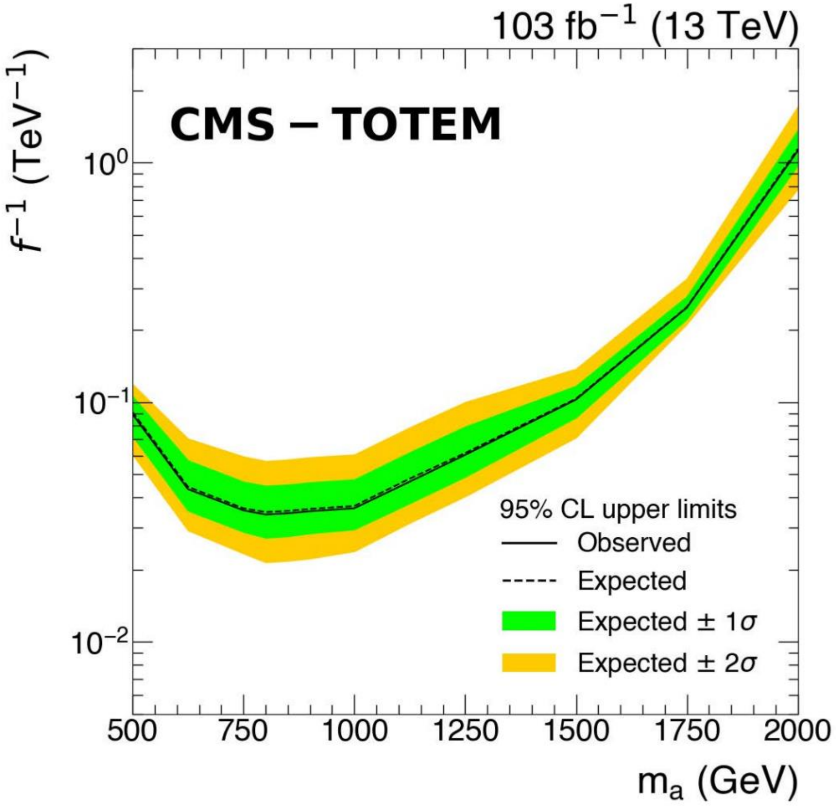
arXiv: 2311.02725

Exclusive ALP production

- s-channel production of ALP in two-photon process, exclusive signature:
  - Di-photon system measured by central detector ($M_{\gamma\gamma} > 350$ GeV, back-to-back)
  - intact protons tagged by TOTEM (energy loss of beam protons consistent with di-photon system)







Effective interactions

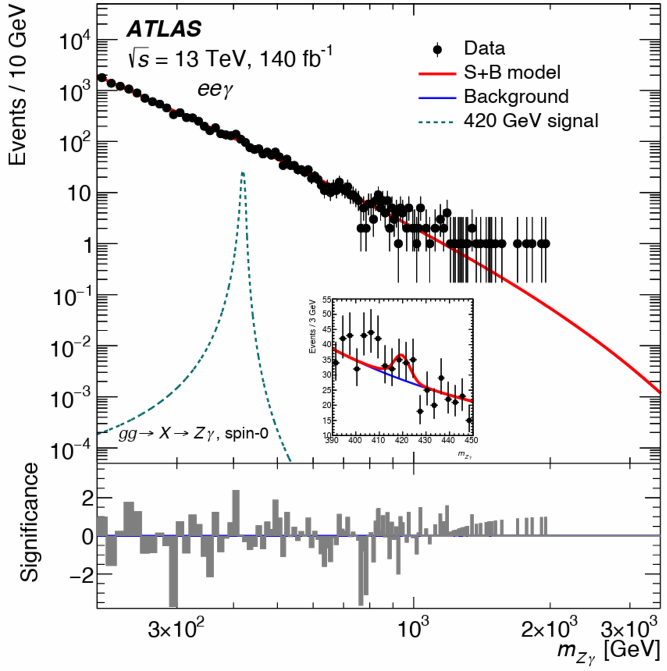
$$\mathcal{L}^{+} = \frac{1}{f} a F_{\mu\nu} F^{\mu\nu} \quad \text{(CP-even)}$$

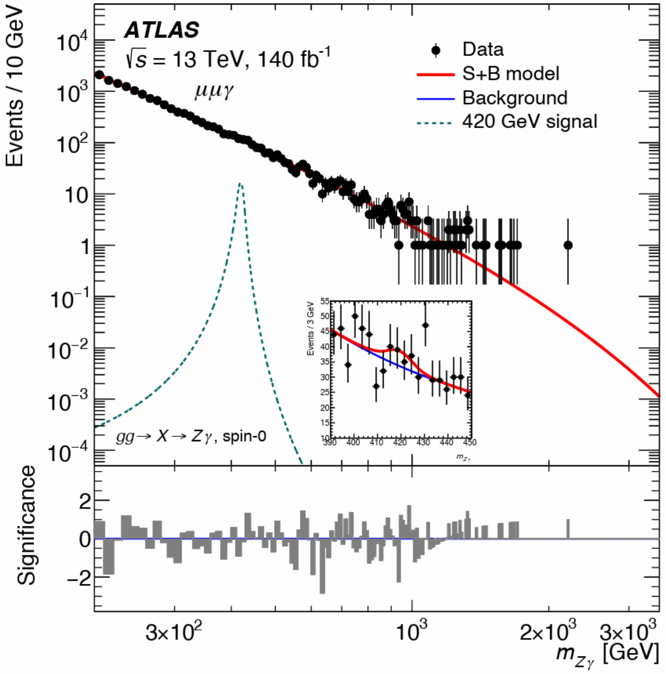
$$\mathcal{L}^{-} = \frac{1}{f} a F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \text{(CP-odd)}$$

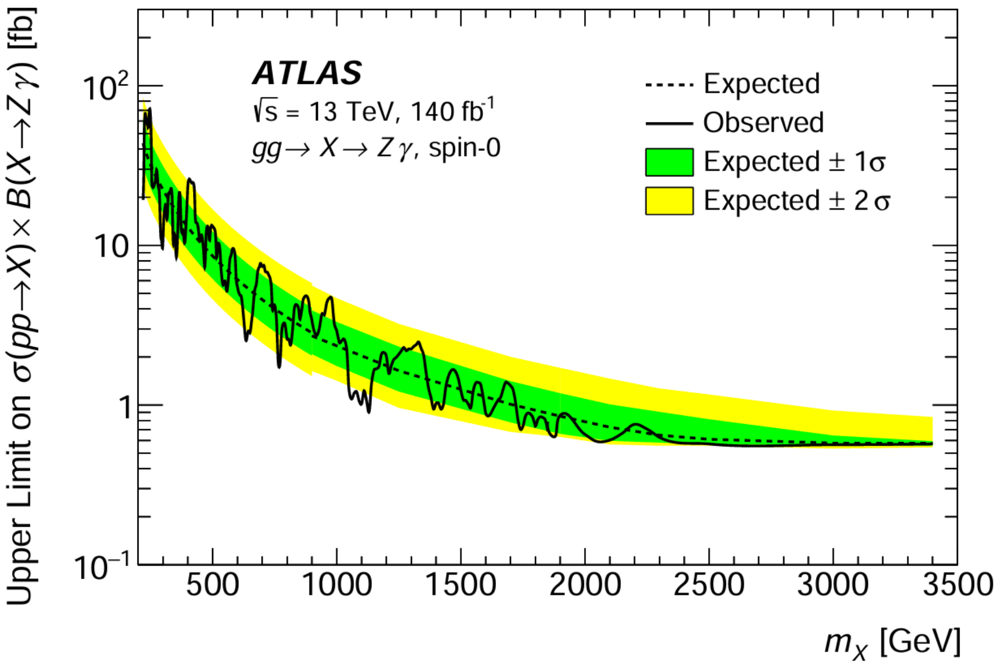
High mass $X \rightarrow Z\gamma$

arXiv:2309.04364

Signal benchmark:
Higgs Characterisation Model







Combination: 2.3σ at 420 GeV

Highly boosted Z boson for high mass X
XGBoost to reconstruct collinear electrons

More details in talk by Olof LUNDBERG (Di-Higgs 2 parallel session)

Extra scalar bosons in VV

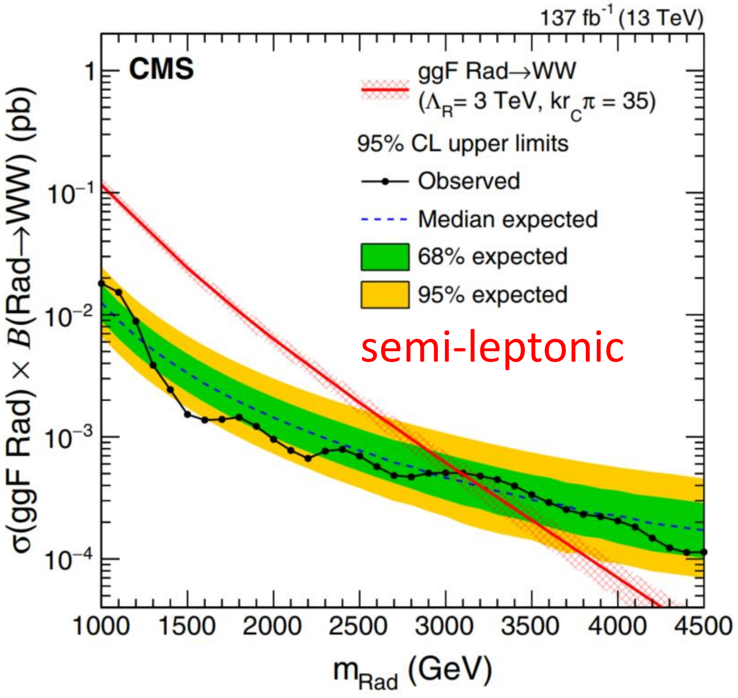
Phys.Rev.D 105(2022)032008

Phys.Lett.B 844(2023)137813

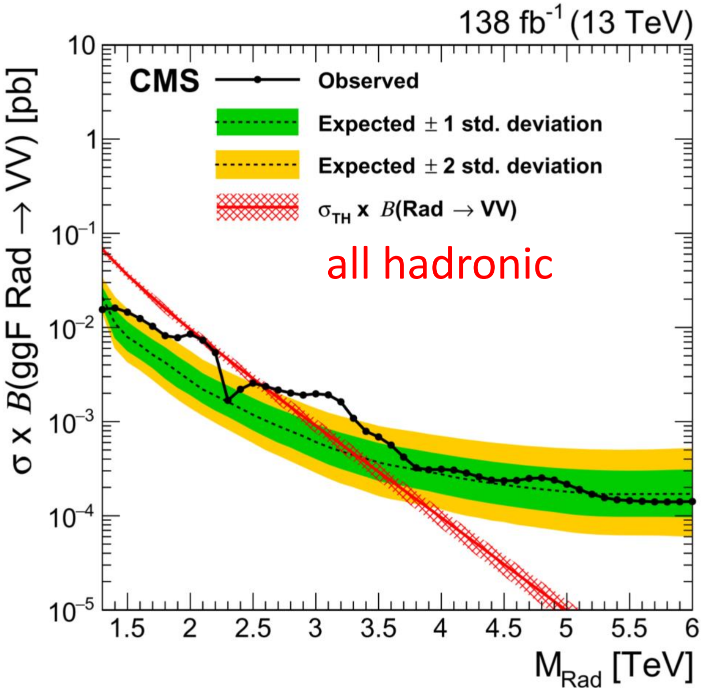
Benchmark: Radion in Randall-Sundrum model ($\kappa r_c \pi = 35, \Lambda_R = 3$ TeV)

Bosons reconstructed in 2 Anti-kT (R=0.8) jets or leptons+MET

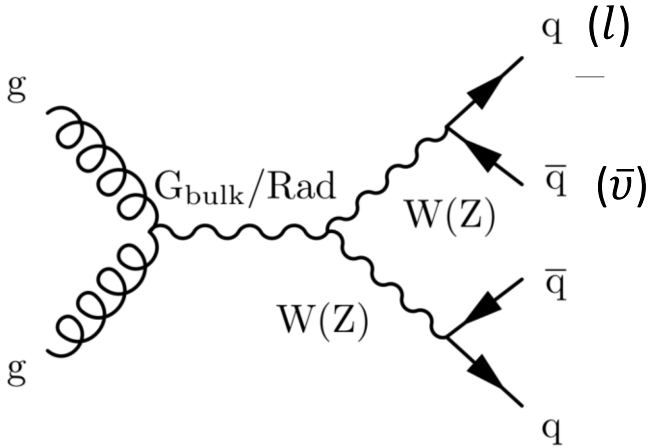
Maximum likelihood fit of (M_{WV}, M_J) or (M_{JJ}, M_{J1}, M_{J2})

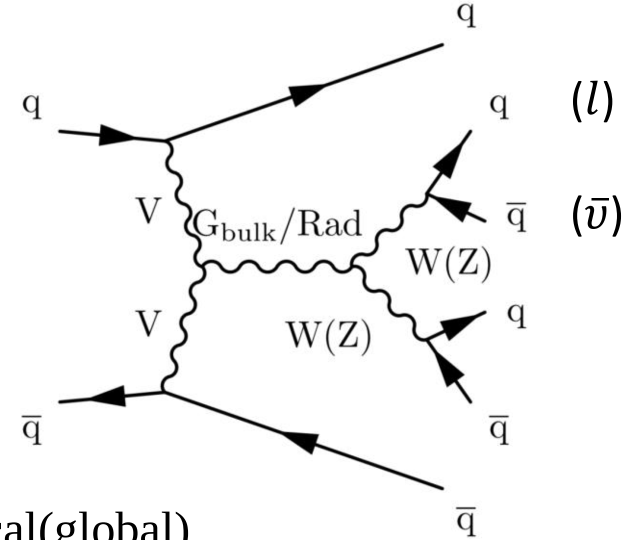


Excluded $M_{Rad} < 3.1$ TeV



Excluded $M_{Rad} < 2.7$ TeV
3.6σ (2.3σ) at 2.1 TeV and 2.9 TeV local(global)





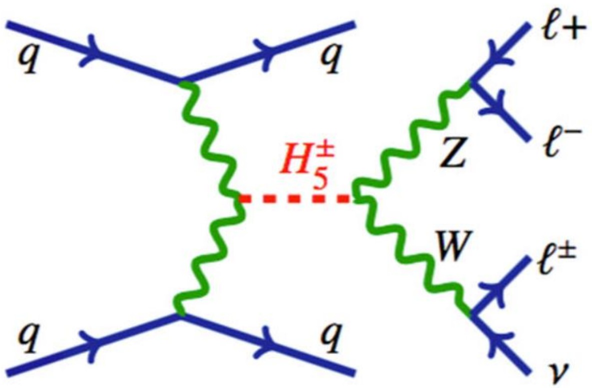
$H^+ \to WZ$ and $H^{++} \to W^+W^+$

EPJC 83(2023)633

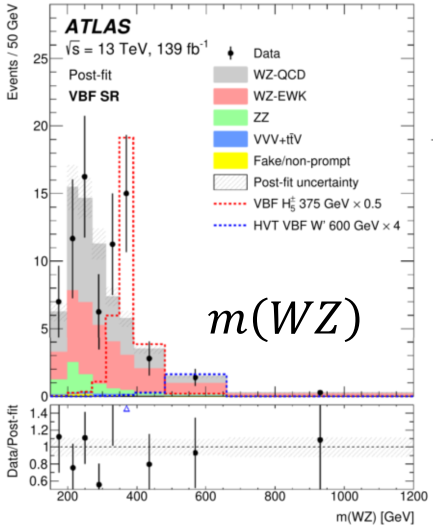
ATLAS-CONF-2023-023

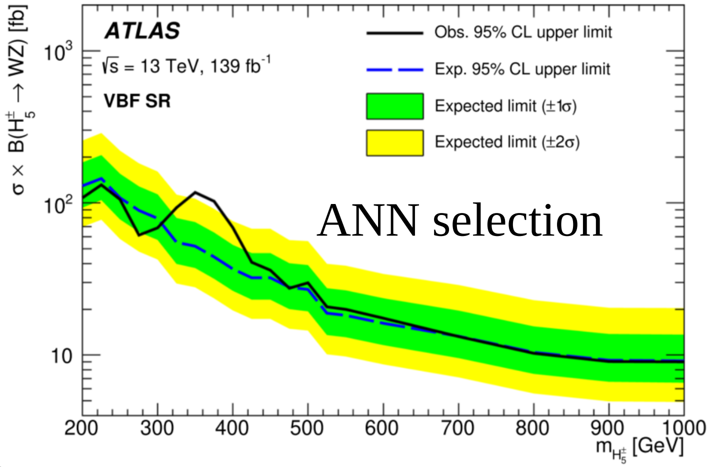
Georgi-Machacek model(Fermiophobic Higgs fiveplet)

$H^{+(+)}$ produced in VBF and decays to VV(multi-lepton final state)



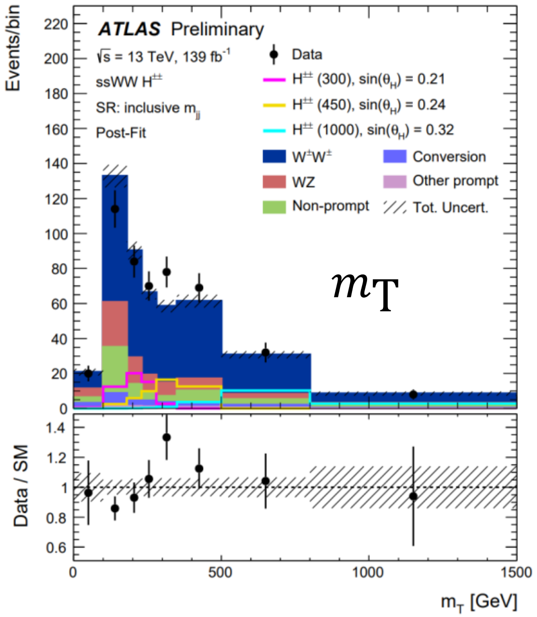
$H^+ \to WZ$

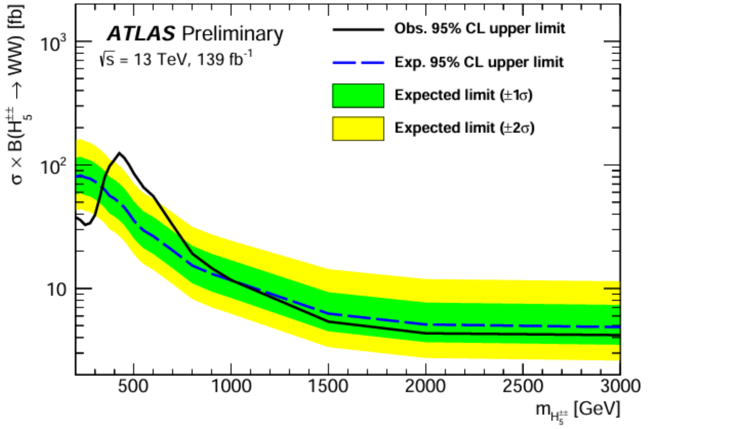




2.8σ local significance at 375 GeV

$H^{++} \to W^+W^+$





3.2σ(2.5σ) local(global) at 450 GeV

See also talk by Yanhui Ma (BSM 2 parallel session)

JHEP 09(2023)032

$H^+ \rightarrow W^+ H(\tau\tau)$

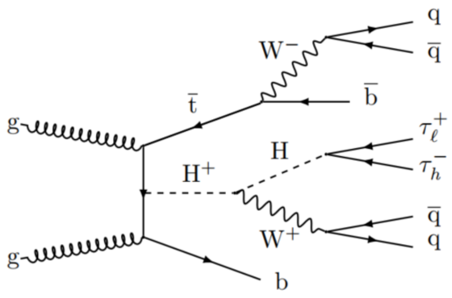
$l\tau_h$

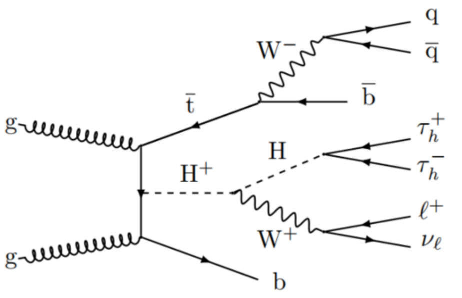
$l\tau_h\tau_h$

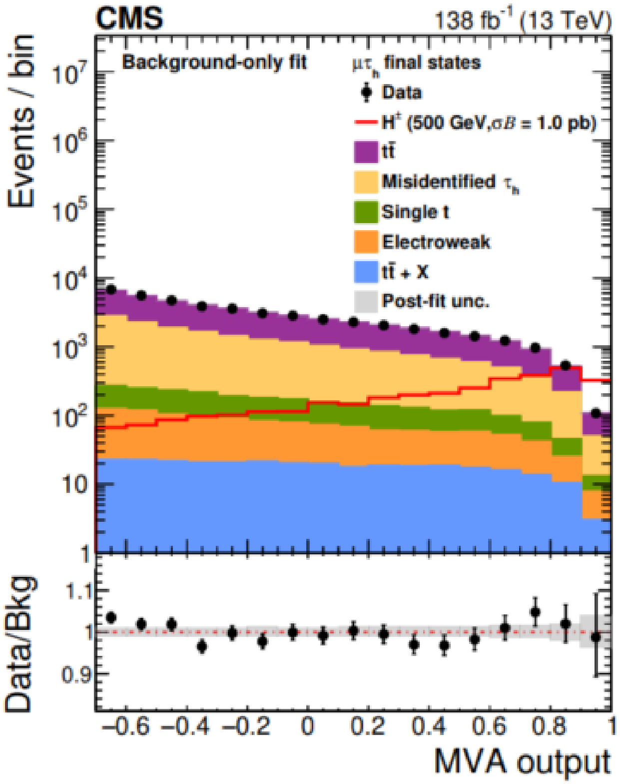
Benchmark: 2HDM, $m_H = 200$ GeV, $m_h = 125$ GeV

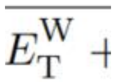
$l\tau_h, l\tau_h\tau_h$ final states split by lepton flavor/charge configurations

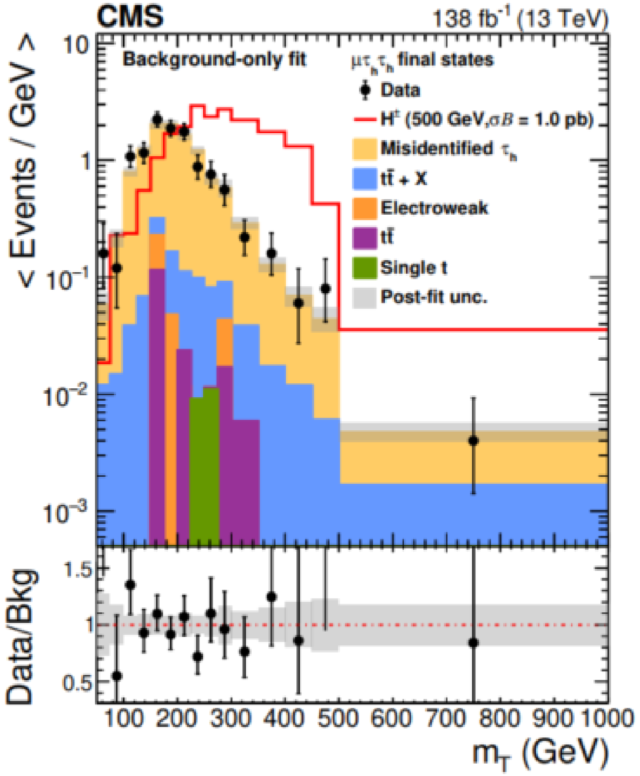
BDT ($l\tau_h\tau_h$) or transverse mass ($l\tau_h$) or as discriminant

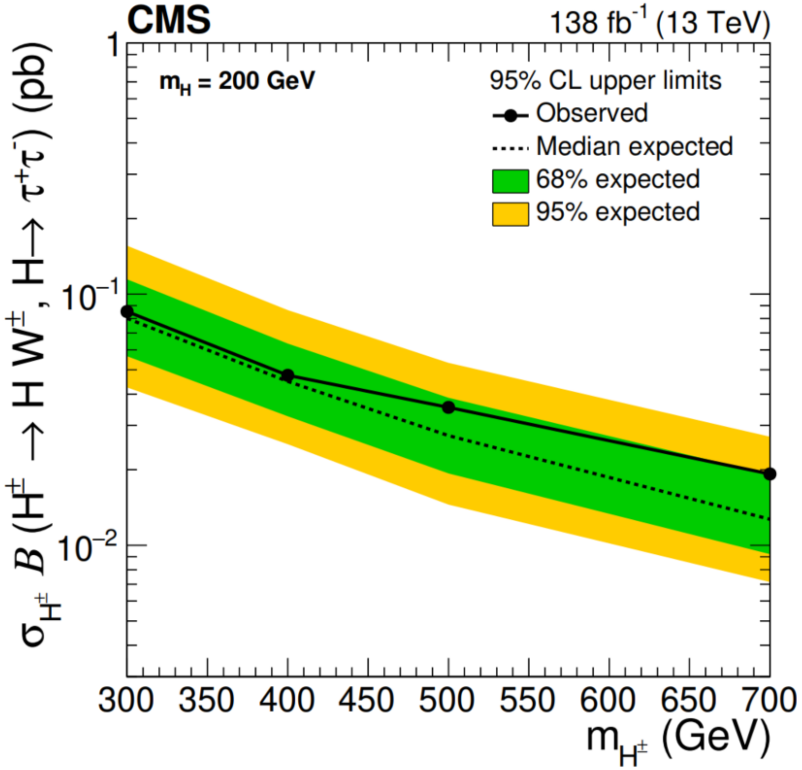












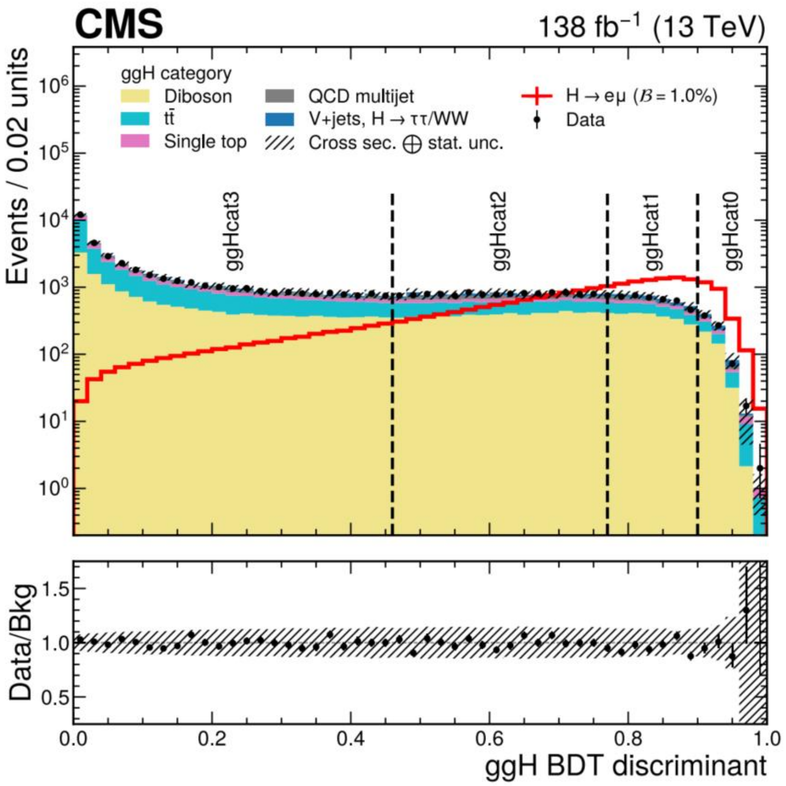
Search for new scalars with di-lepton

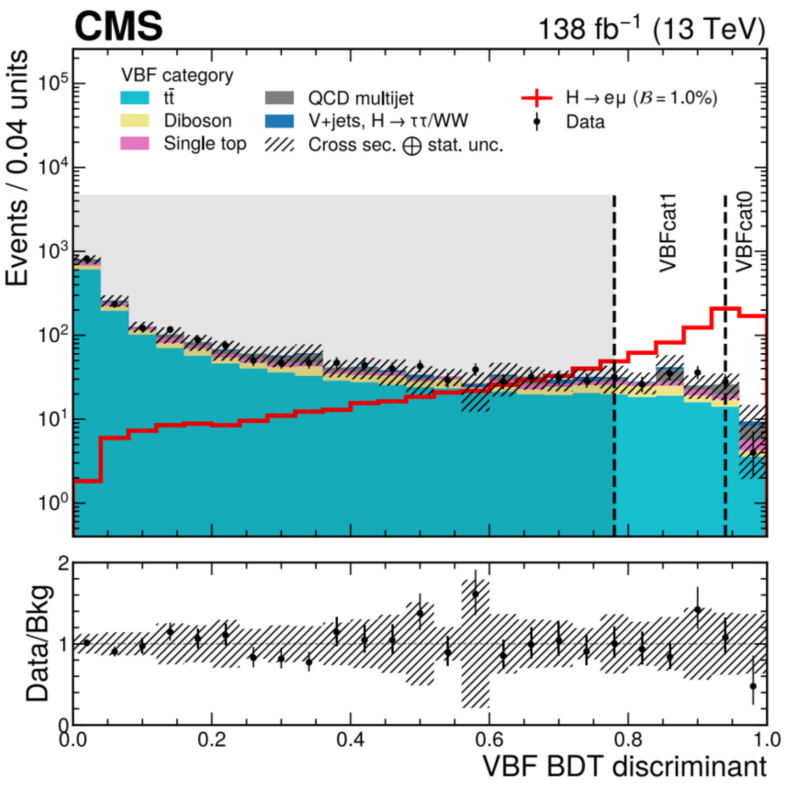
Phys.Rev.D 108(2023)072004

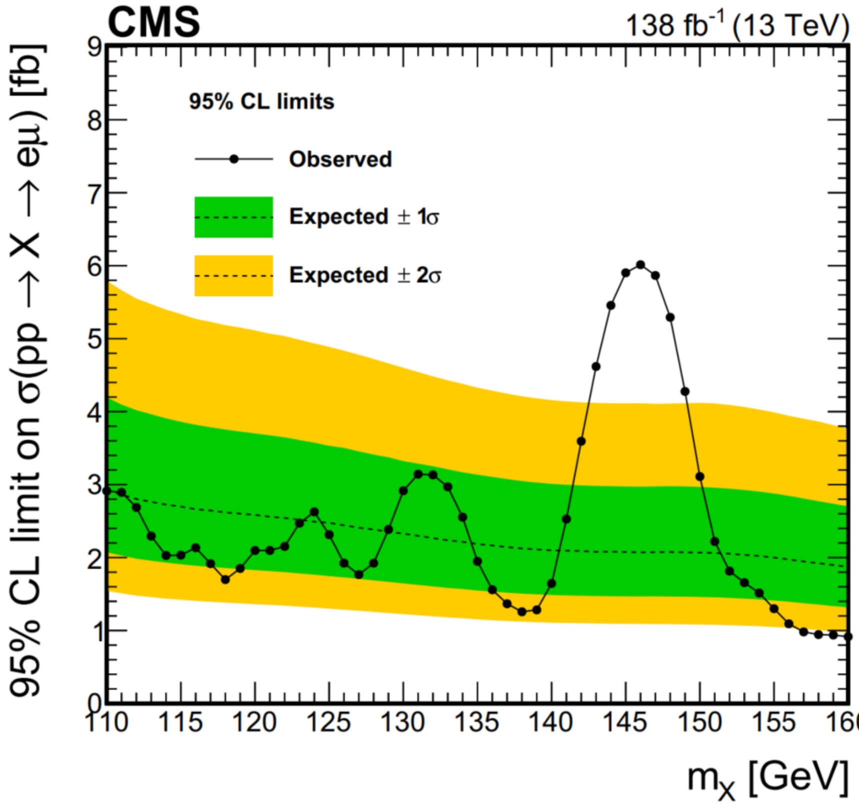
Lepton Flavor Violating $X \rightarrow e\mu$

Type III 2HDM predicts additional scalar bosons X, with LFV decays

$X \rightarrow WW$ dominates when $m_X > 2m_W$, so search in 100-160 GeV. Fitting $m_{e\mu}$ distribution in signal regions (classified by BDT). Largest excess: 3.8σ(2.8σ) local (global) at 146 GeV

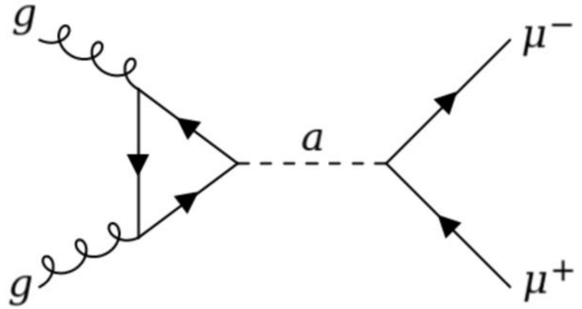




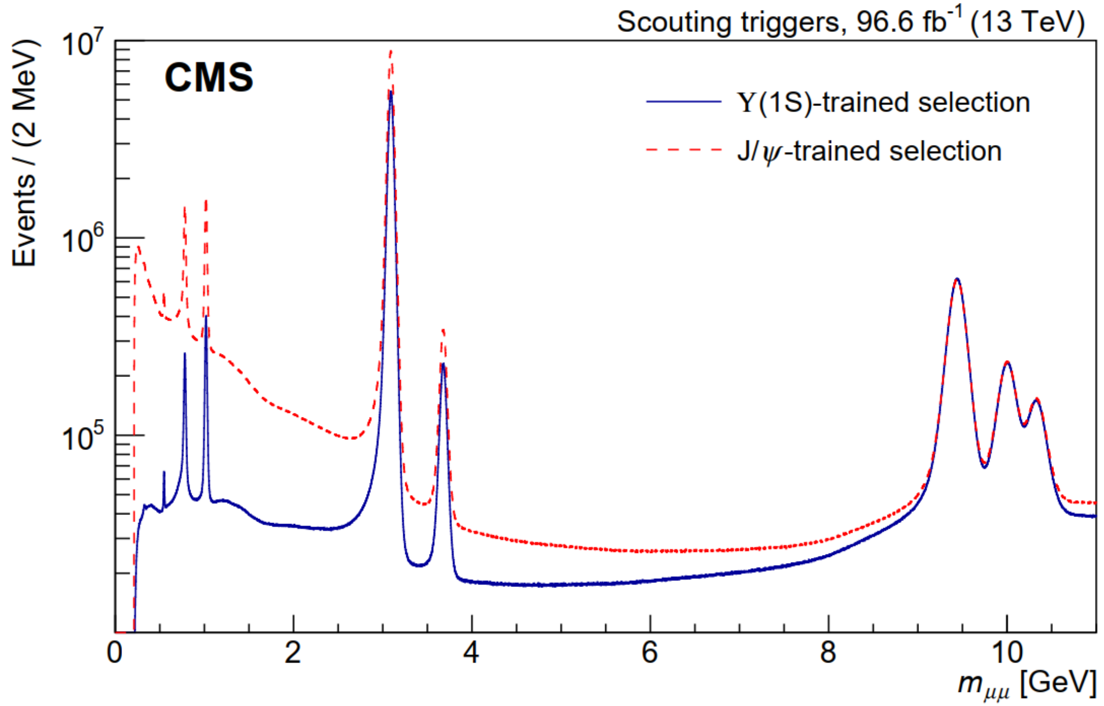


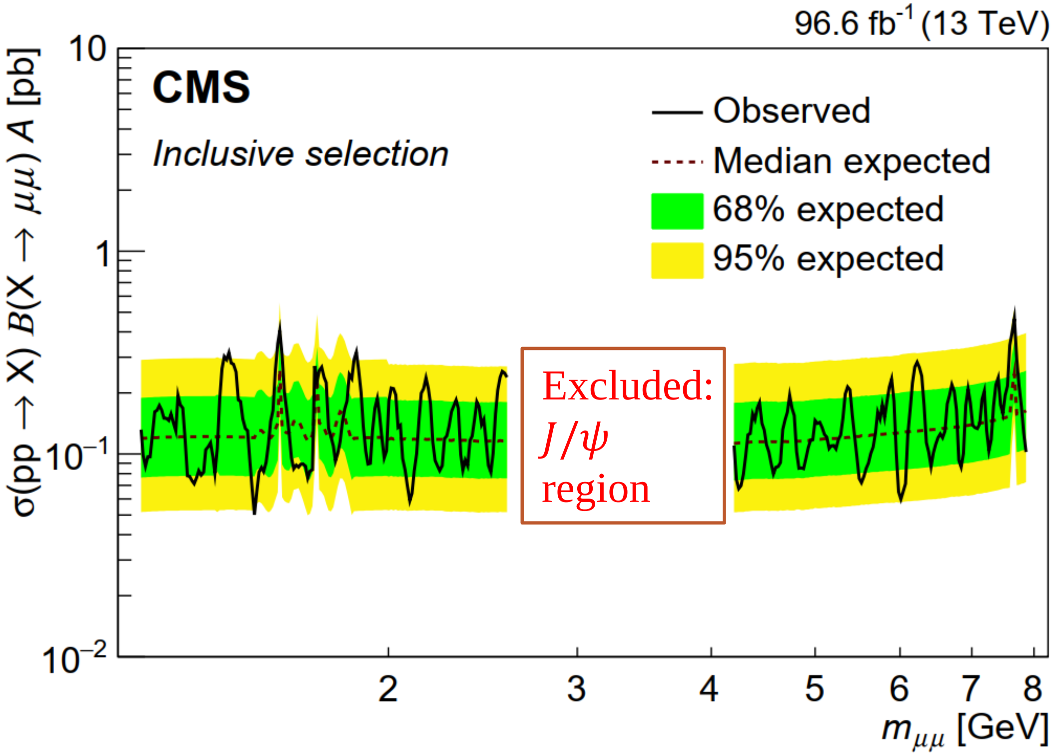
di-muon resonances

arXiv:2309.16003

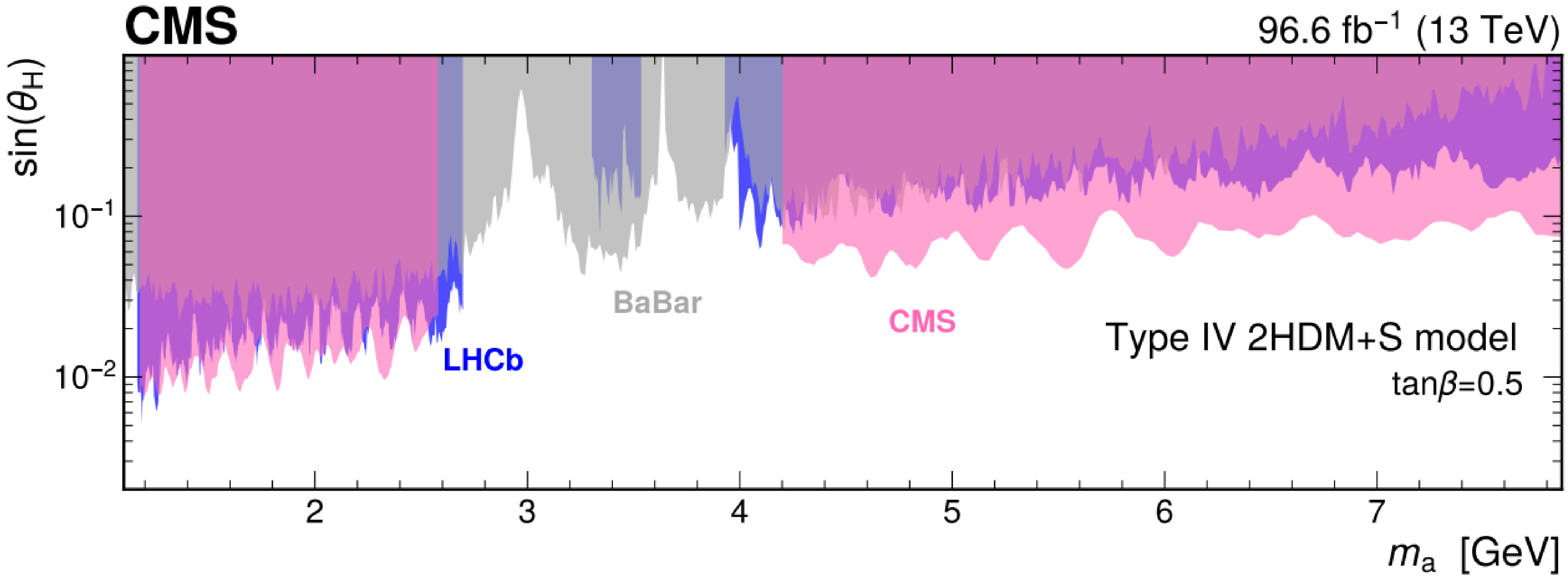


"Scouting" triggers (save limited event info) to access low mass region.
Muon identification based on BDT





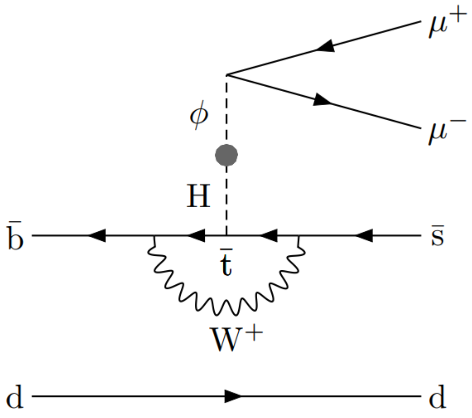
Constraints on 2HDM+S model

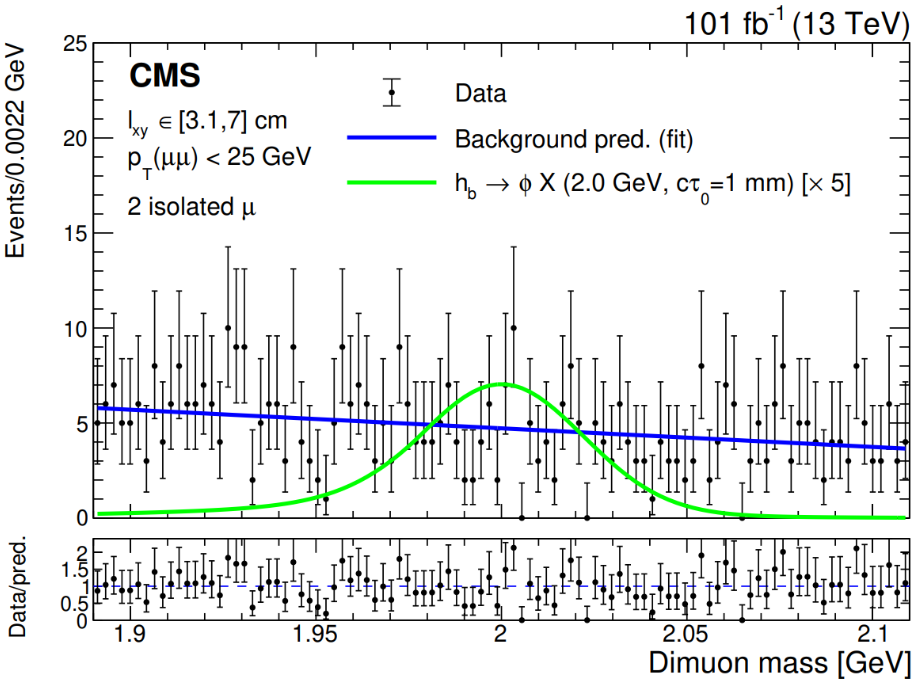


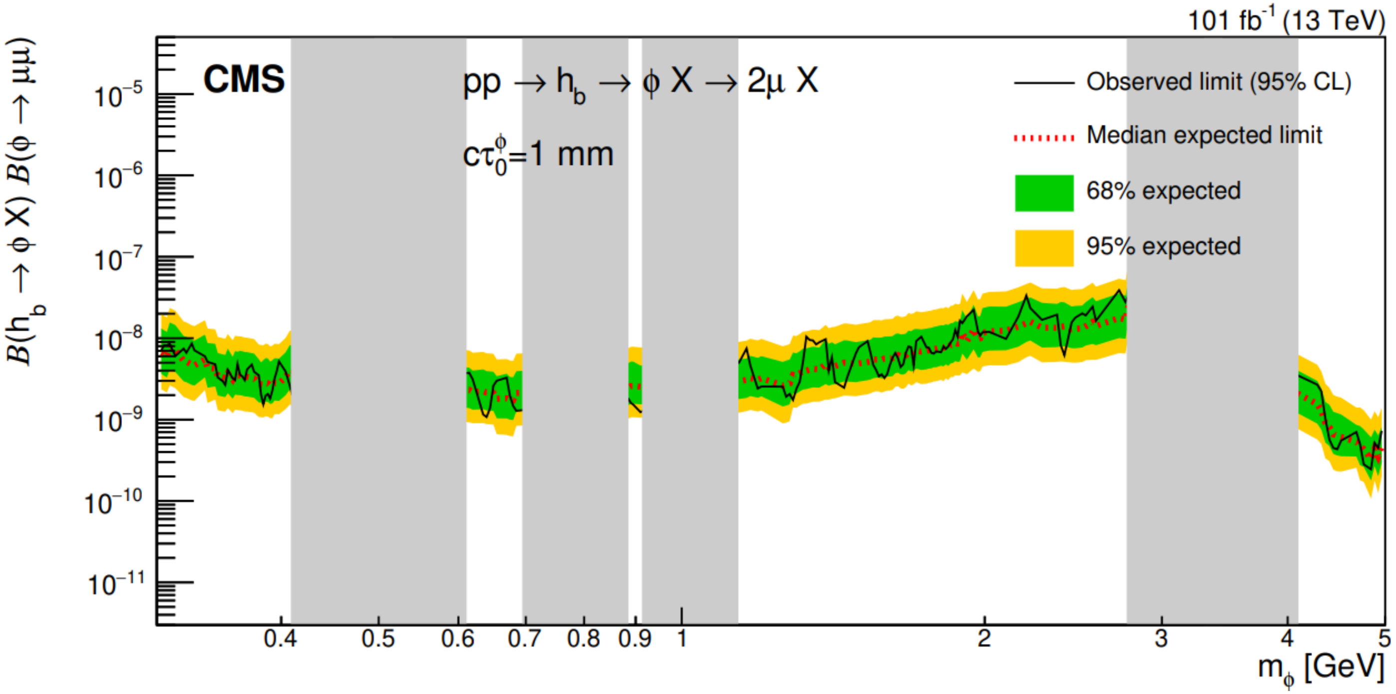
(note: 90% CL)

Long-lived scalar in dimuon

- An "older" result by the dimuon "scouting" triggers
- Scalar ϕ (can be long-lived) emitted in b hadron decay
- Selection: dimuon, l_{xy} < 11 cm (limited by detector acceptance)
- Check dimuon mass spectrum in slices of l_{xy} intervals





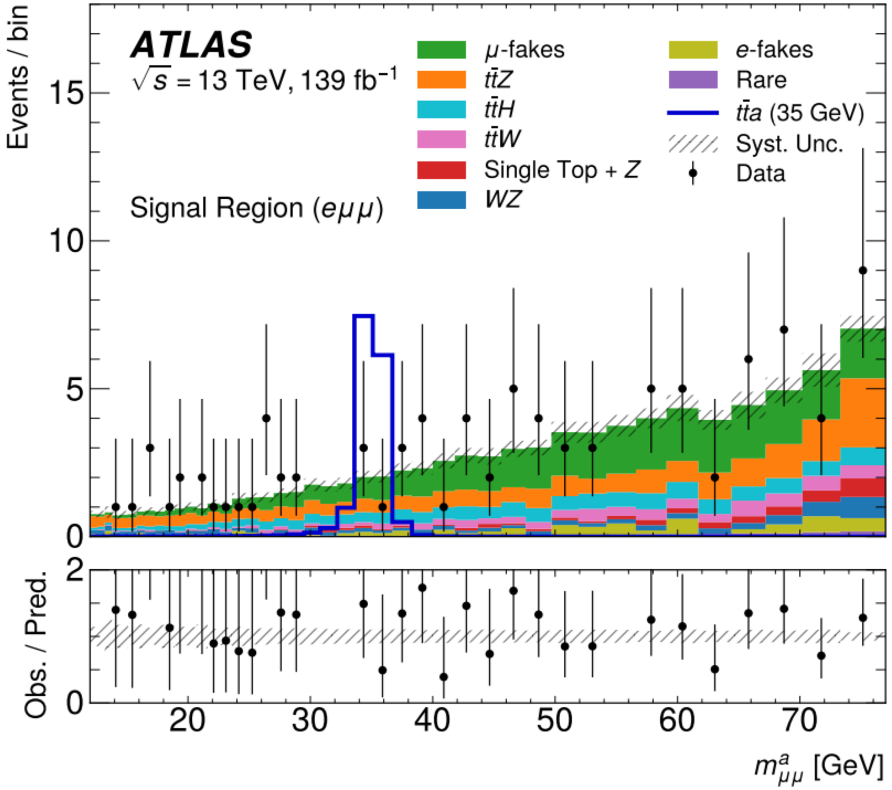


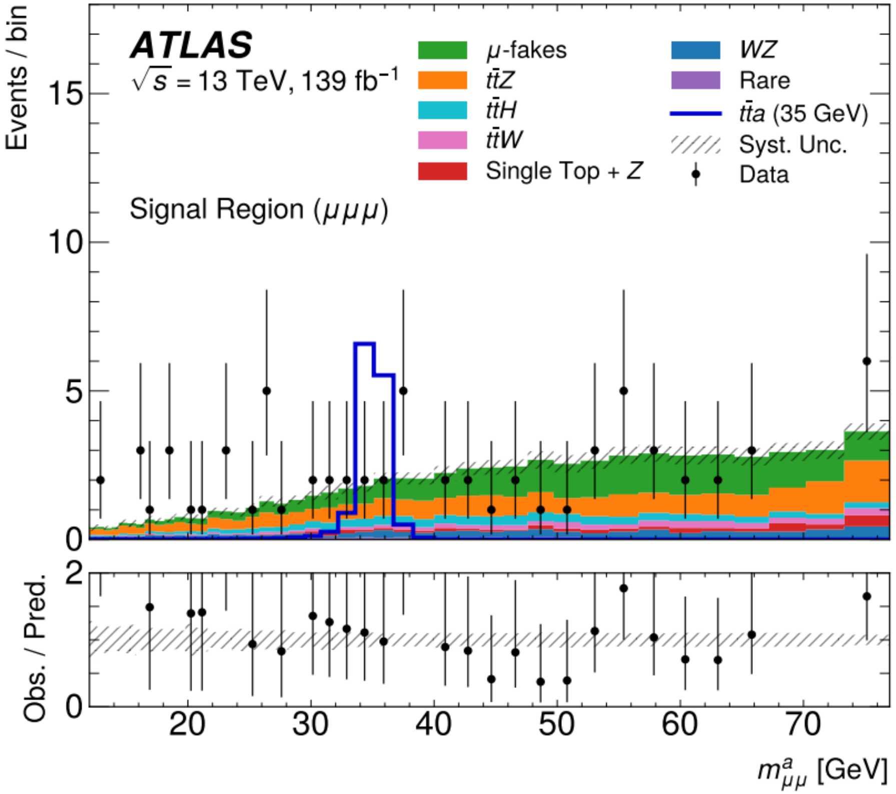
low mass di-muon in $t\bar{t}$ events

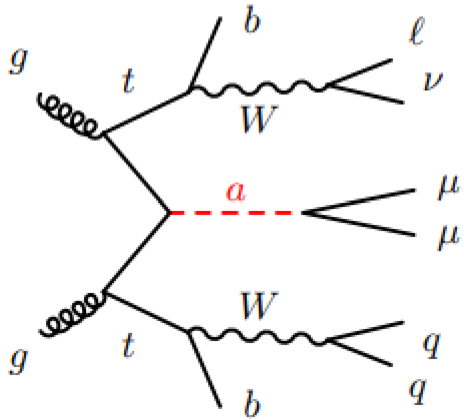
arXiv:2304.14247

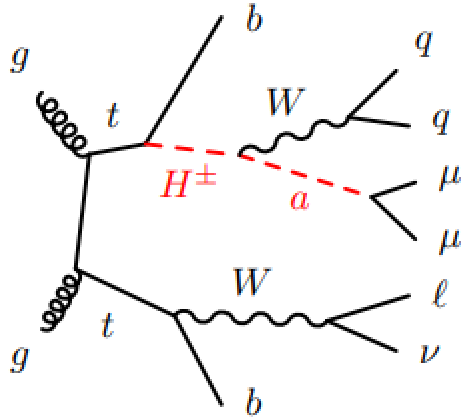
Pseudo-scalar: large coupling with the top quark (two signal processes)

Two signal regions: $e\mu\mu$,$\mu\mu\mu$



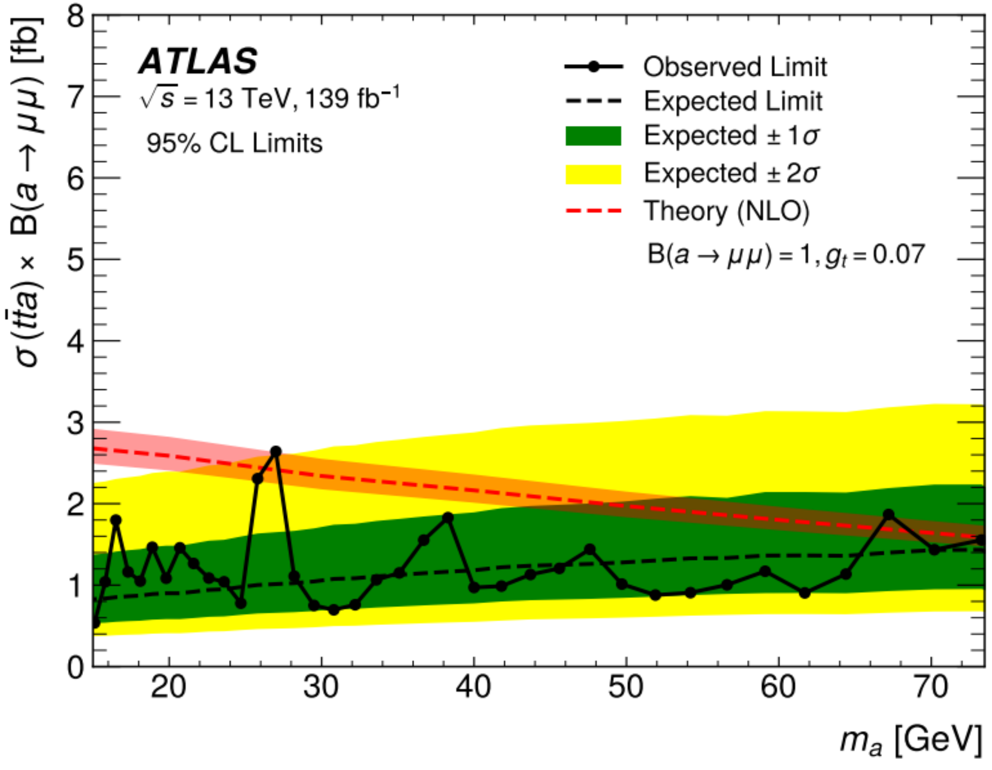


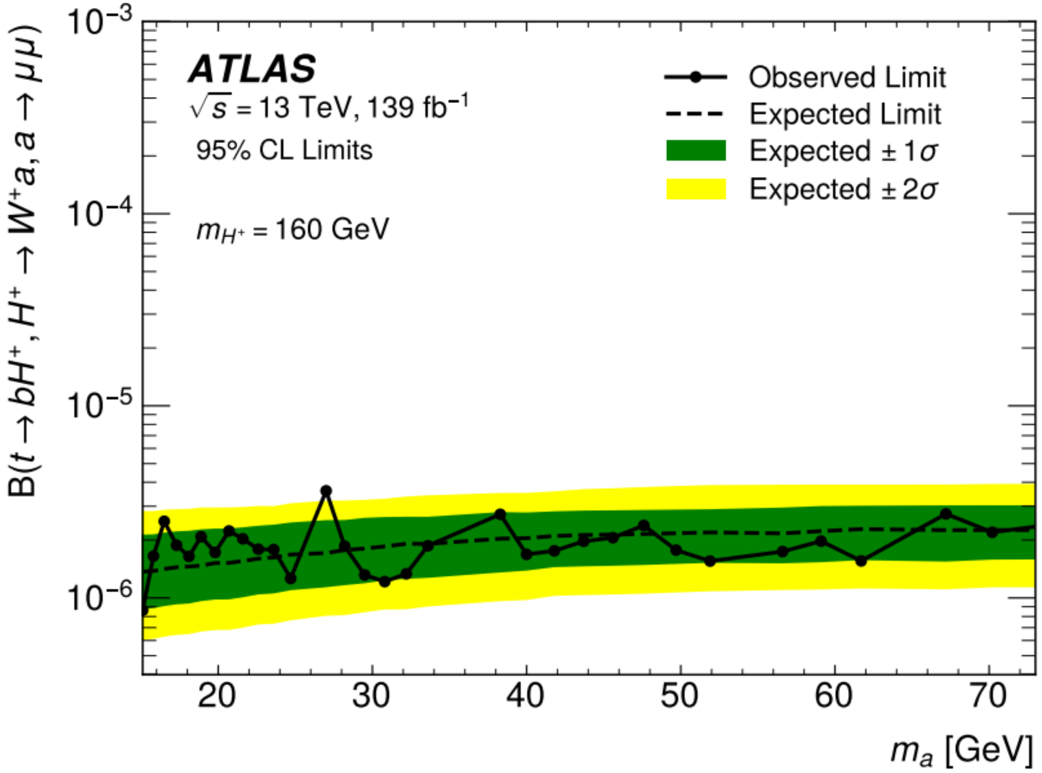




See also talk by Yanhui Ma (BSM 2 parallel session)

Upper limits on cross section times BF





local significance of 2.4σ at 27 GeV

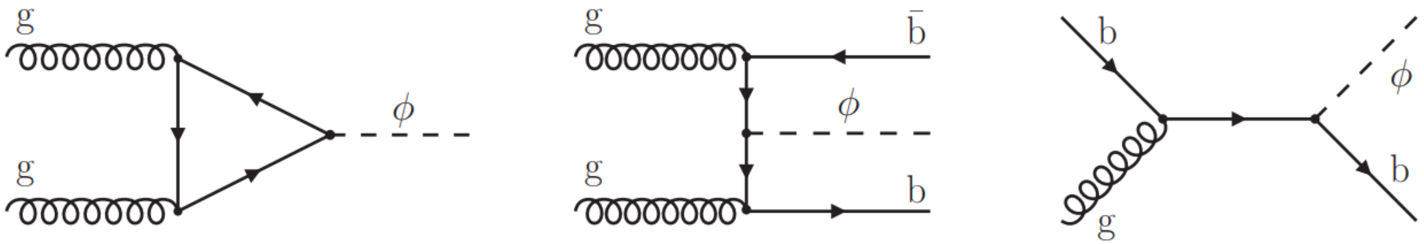
Extra Higgs boson $\phi \rightarrow \tau\tau$

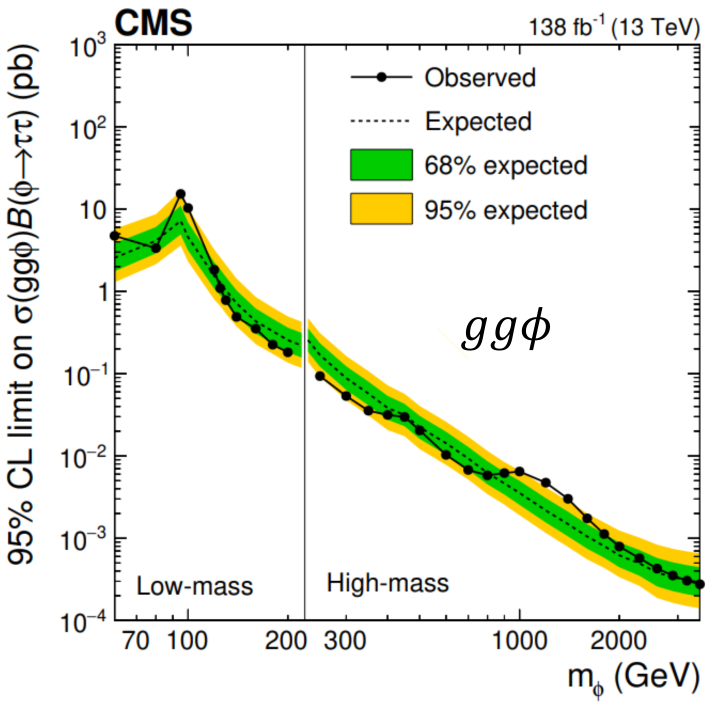
JHEP 07(2023)073

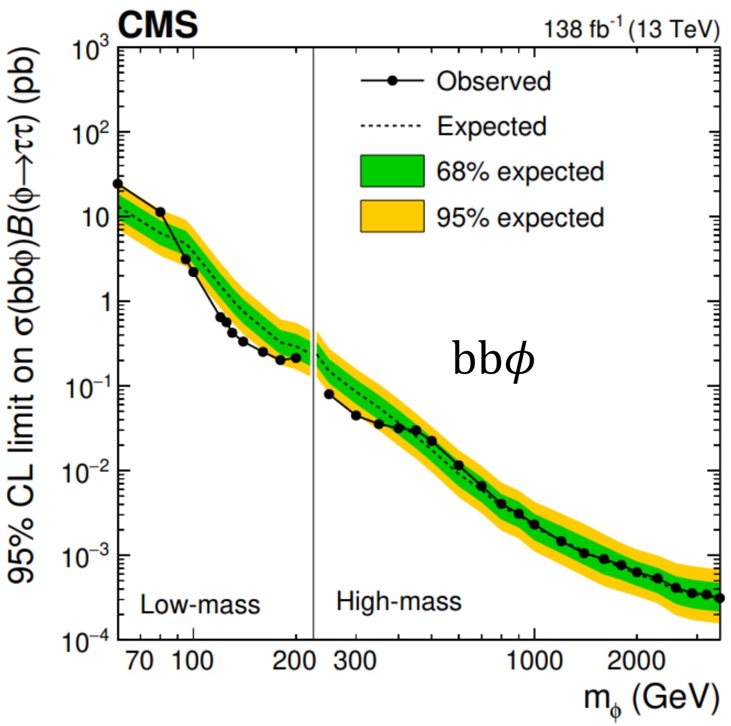
Extra scalar bosons in MSSM(2HDM)

Strategy:

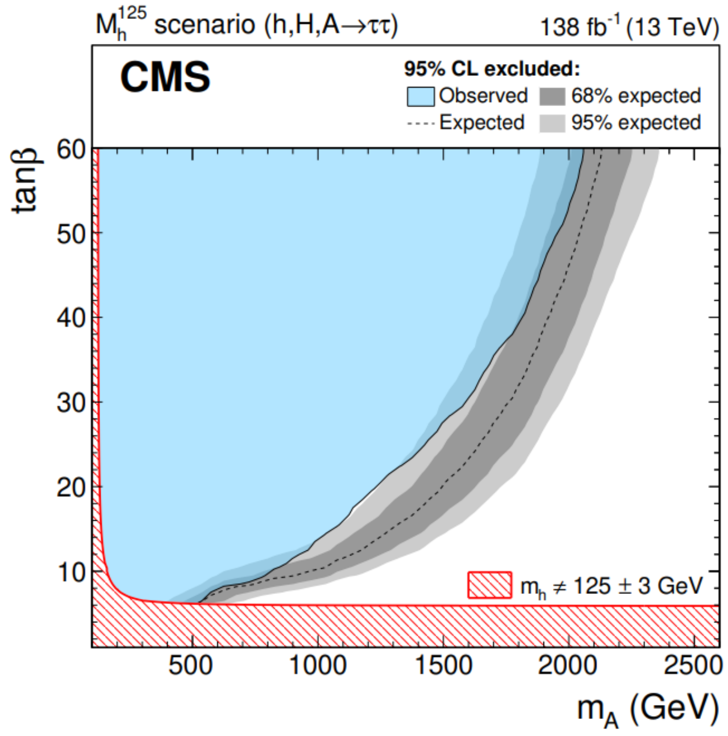
- Fitting m_T in categories for $m_\phi > 250$ GeV
- NN based analysis for $m_\phi < 250$ GeV







MSSM

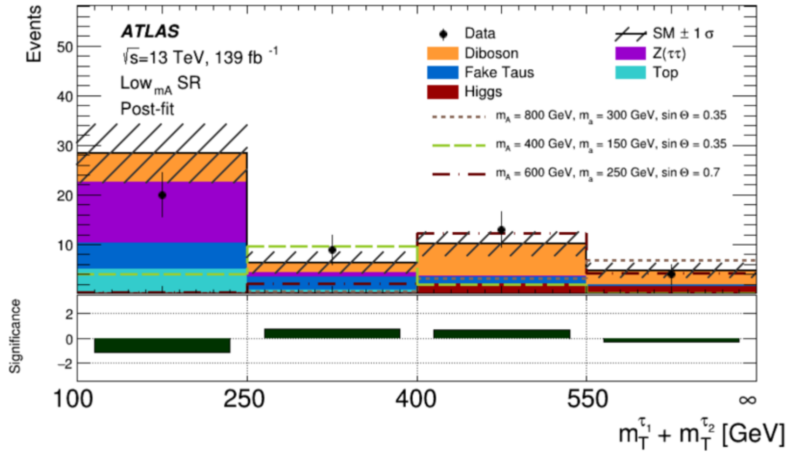


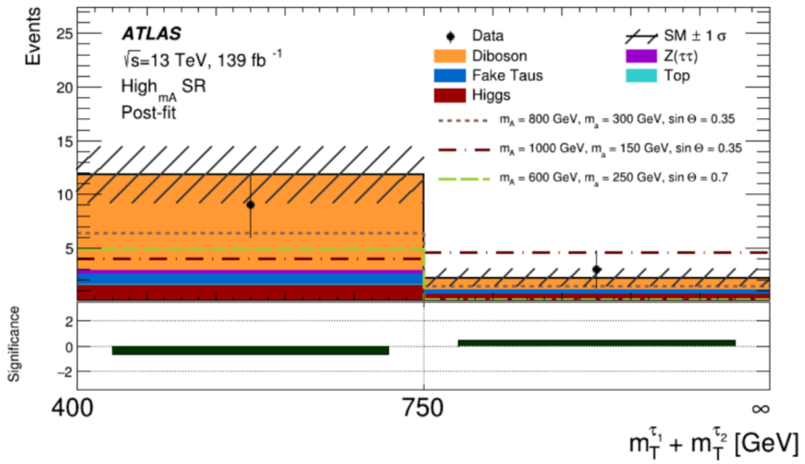
Search for new scalars with complex final states

JHEP 09(2023)189

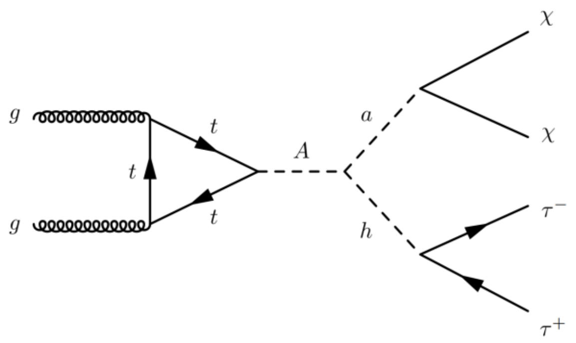
a(invisible) in association with $h \to \tau\tau$

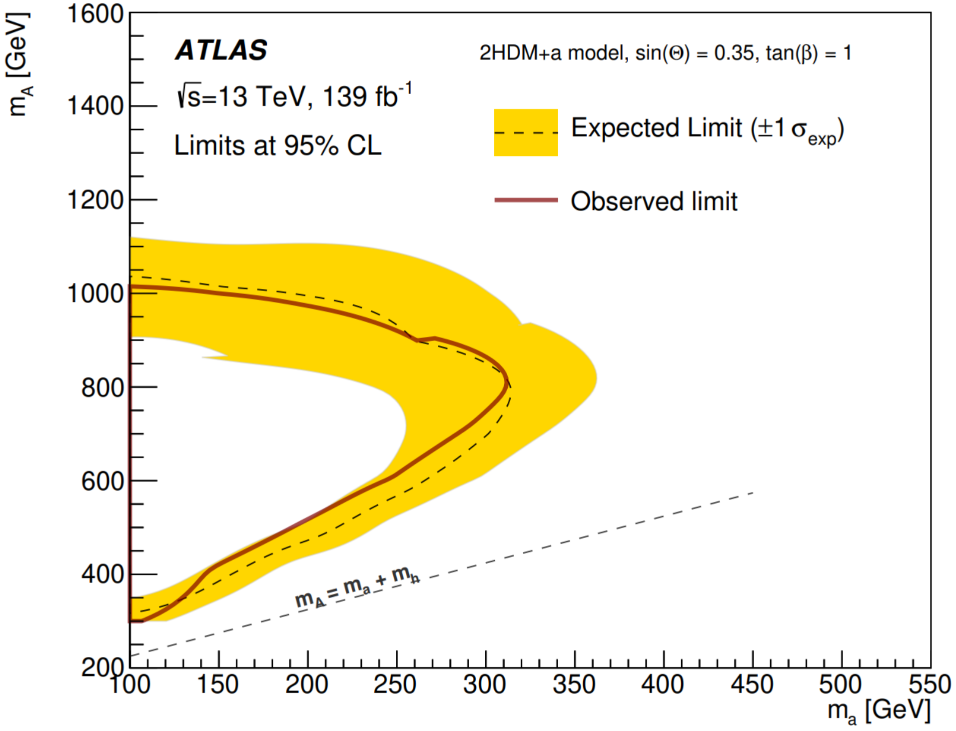
2HDM+a(portal to DM). SR for low m$_A$ and high m$_A$





$$m_{\mathrm{T}}^{\tau_i} = \sqrt{2 p_{\mathrm{T}}^{\tau_i} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi(\tau_i, p_{\mathrm{T}}^{\mathrm{miss}}))}$$



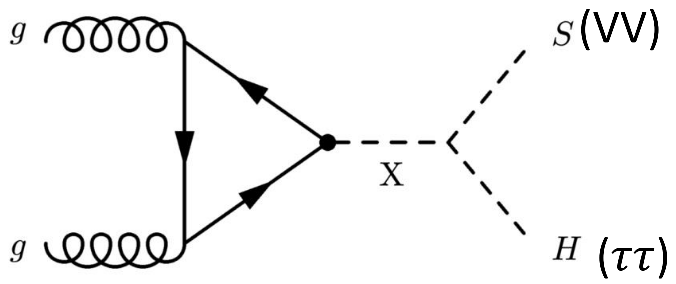


The first exploration of the mono-Higgs signature in hadronic tau pairs in ATLAS, offering sensitivity in low tanβ.

S(VV) in association with $H \rightarrow \tau\tau$

JHEP 10(2023)009

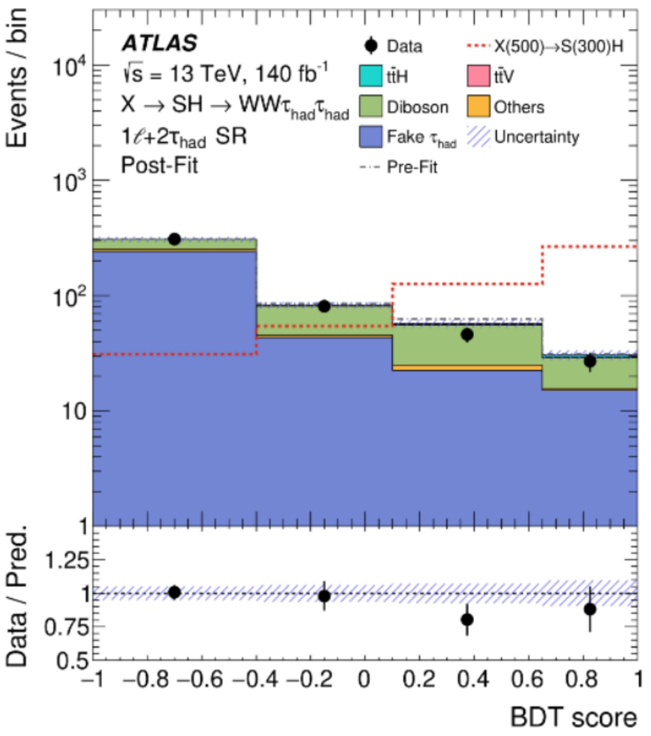
Final state: $2\tau_{\text{had}}$
1/2 l from V

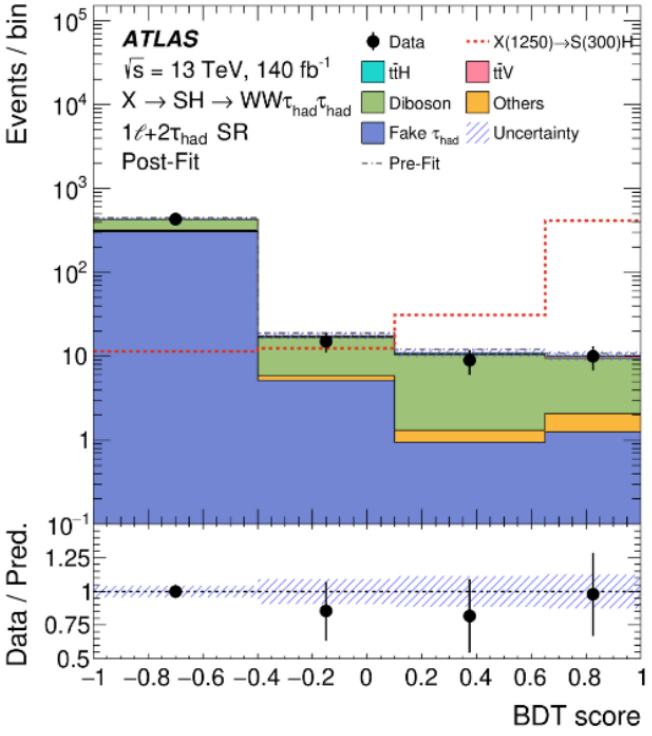


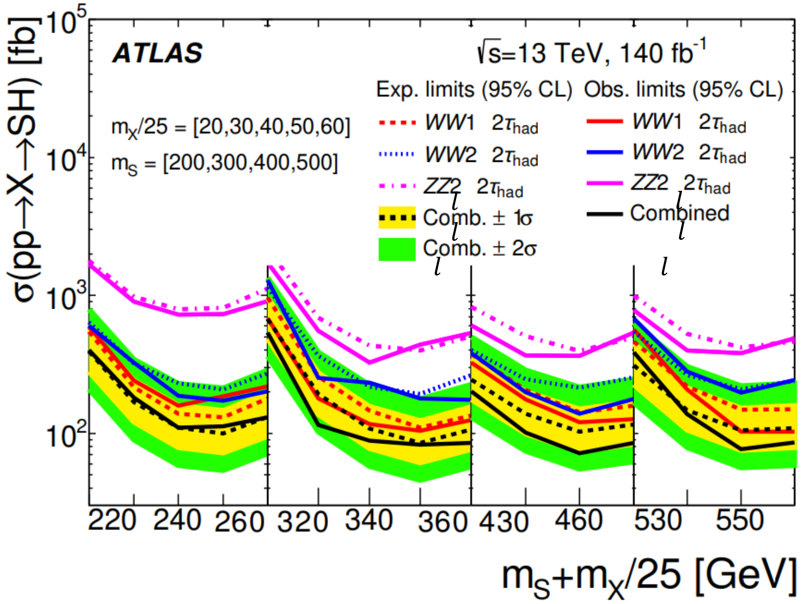
2HDM+S (e.g, NMSSM)

- X→SH,M_X: 0.5-1.5 TeV, M_S: 0.2-0.5 TeV

BDT in each SR to suppress background







More details in talk by Olof LUNDBERG (Di-Higgs 2 parallel session)

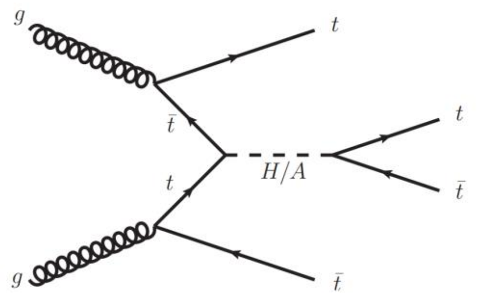
ttH/A →4 top

JHEP 07(2023)203

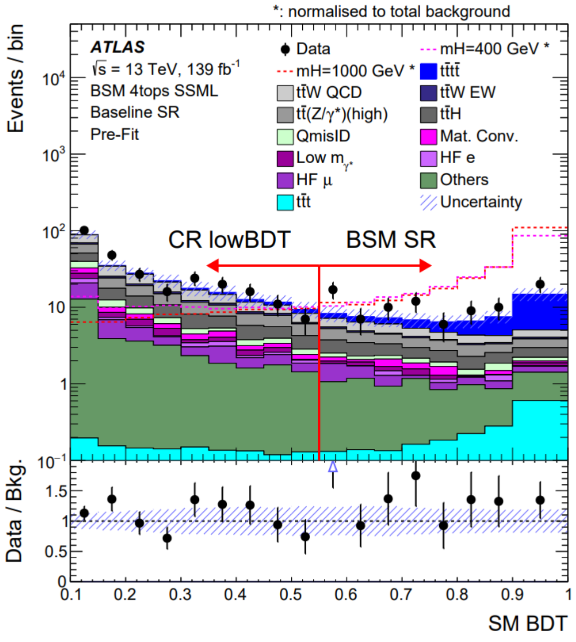
m_H in 400 – 1000 GeV, baseline SR: multi-lepton and jets

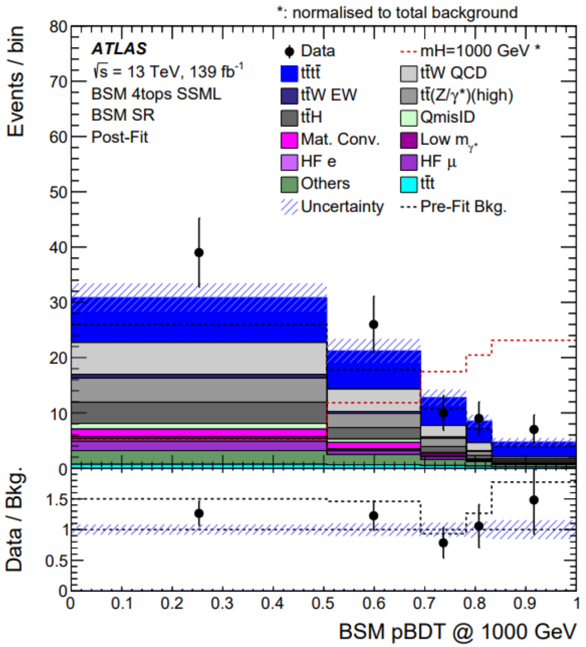
(≥ 6 jets, ≥ 2 b-jets, H_T>500 GeV, same-sign di-lepton+3-lepton)

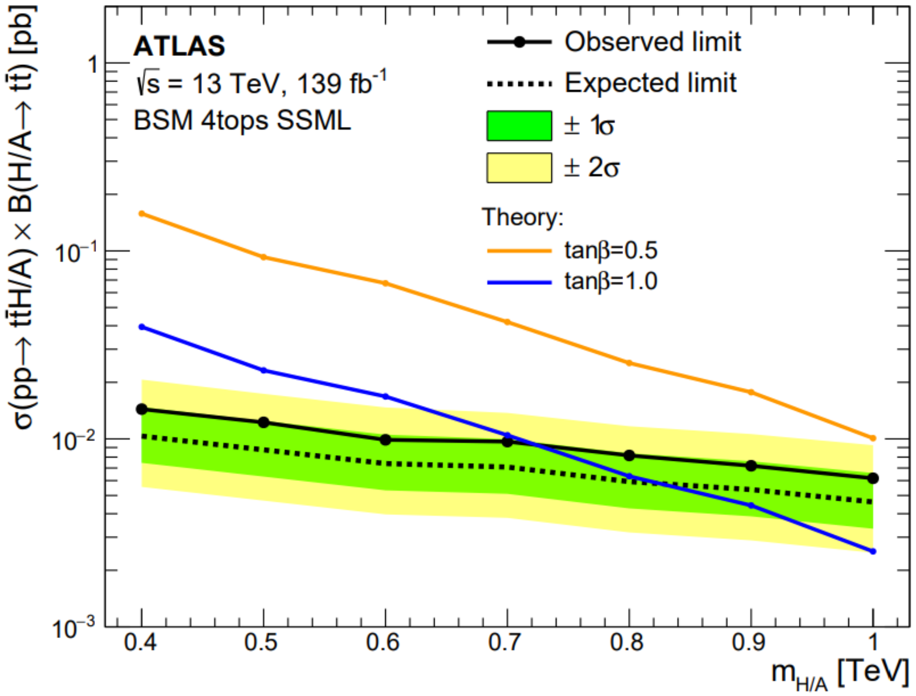
SM BDT (4-top)+BSM (mass-)parameterized BDT



benchmark: 2HDM



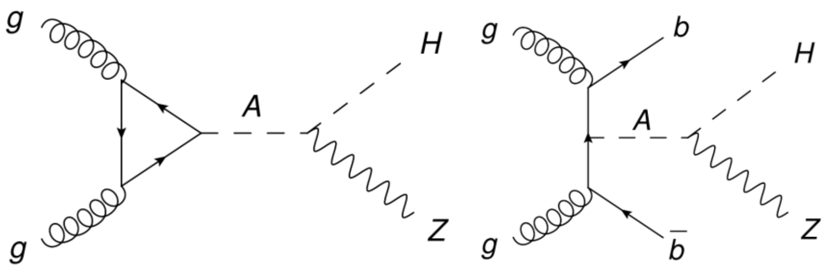




More details in talk by Tom KRESSE (BSM 1 parallel session)

$A \to ZH \to lltt, \nu\nu bb$

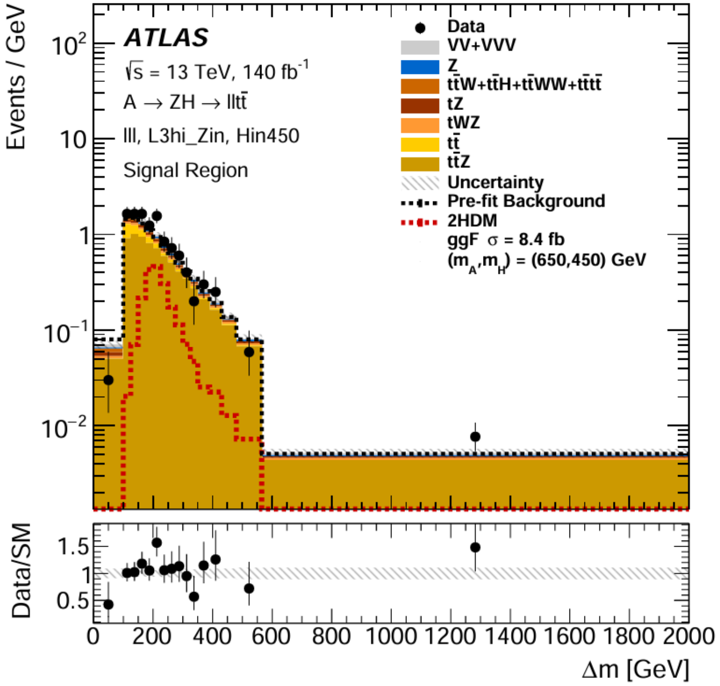
arXiv:2311.04033



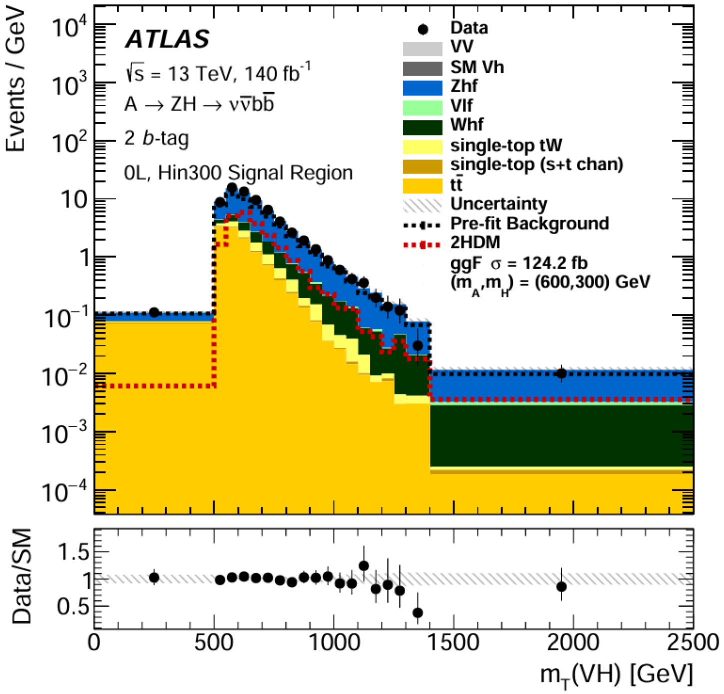
2HDM $m_H \in [130{,}800]$ GeV, $m_A \in [400, 1200]$ GeV

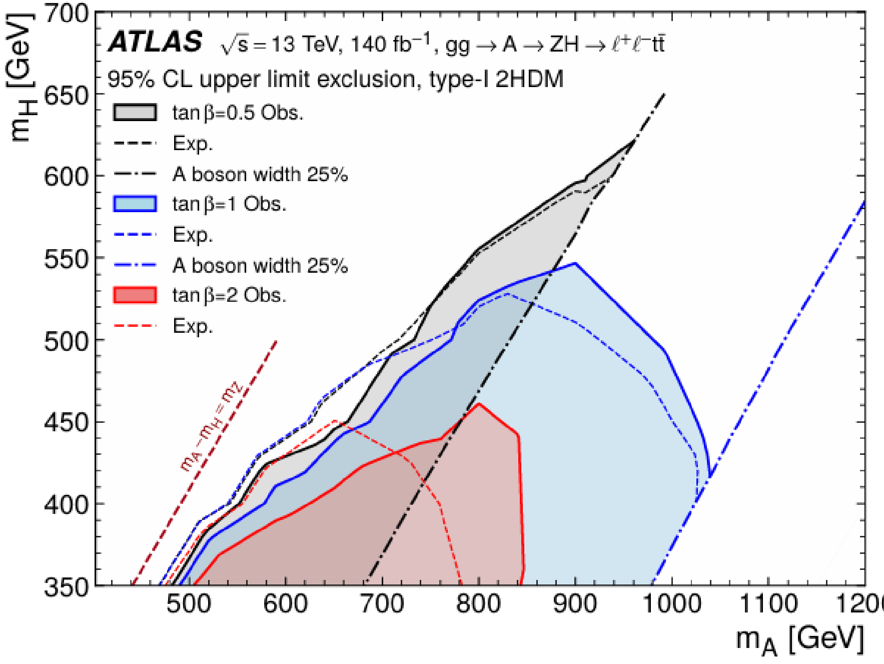
lltt : 3-lepton, 2b-jets, Z mass window, $m(t\bar{t})$ window

$\nu\nu bb$: 2-5 jets, (splits: 2 b-jets, > 2 b-jets), $m(b\bar{b})$ window



$\Delta m = m(lltt) - m(tt)$



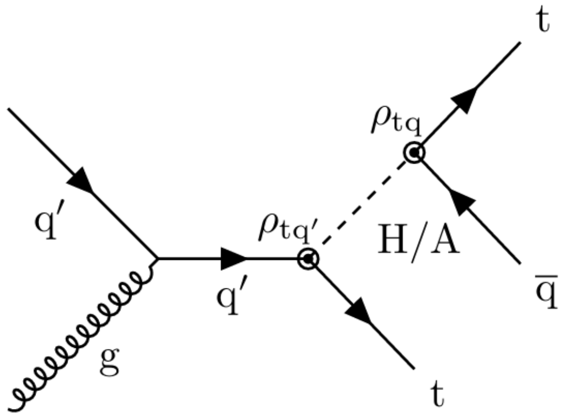


More details in talk by Tom KRESSE (BSM 1 parallel session)

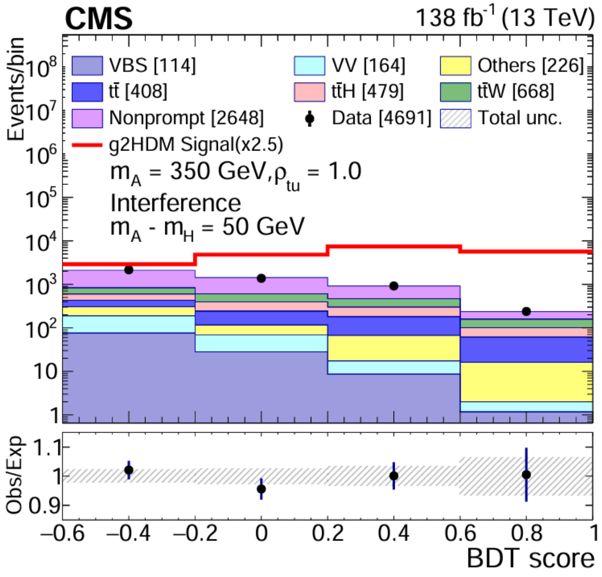
Same-sign top pair production via H/A

arXiv:2311.03261

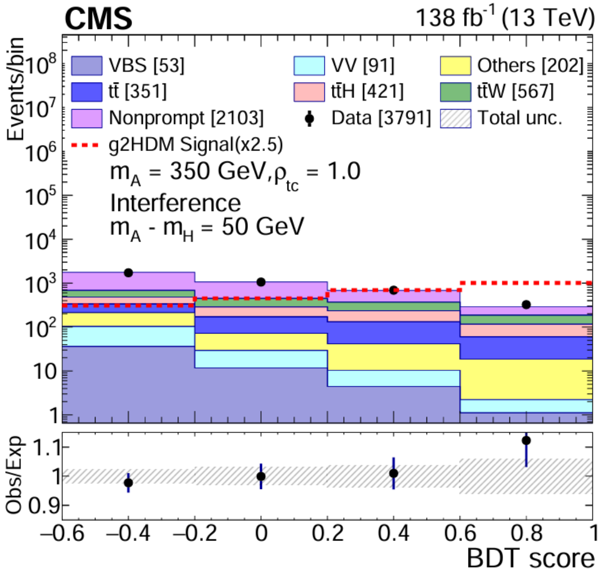
- Benchmark model: Generic 2HDM
- Event selection: same-sign di-lepton, 3 jets
- Signal extraction: BDT based on kinematics and jet flavor-tagging scores



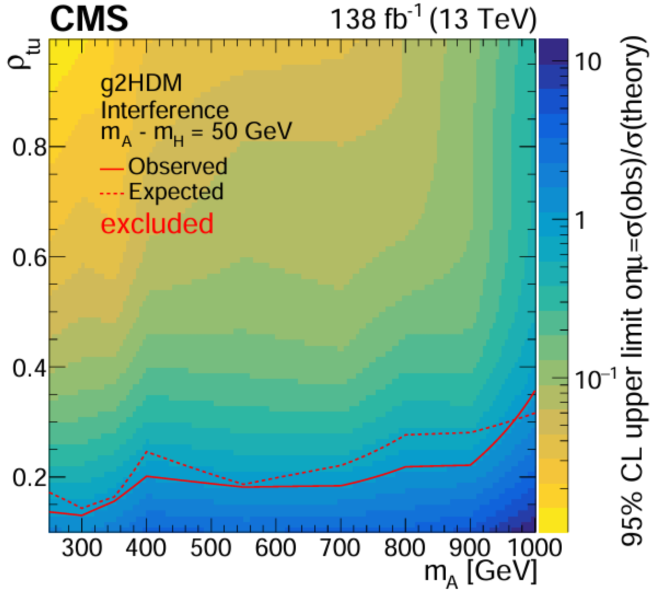
Non-zero ρ_{tu}



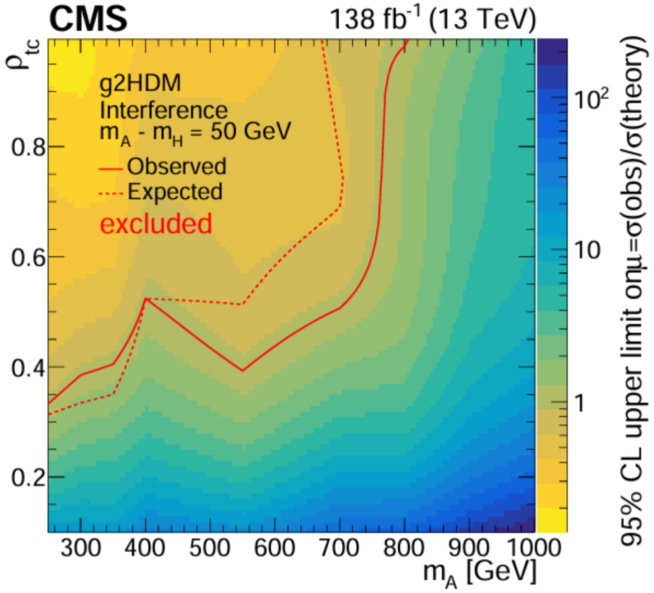
Non-zero ρ_{tc}



ρ_{tu} vs. m_A

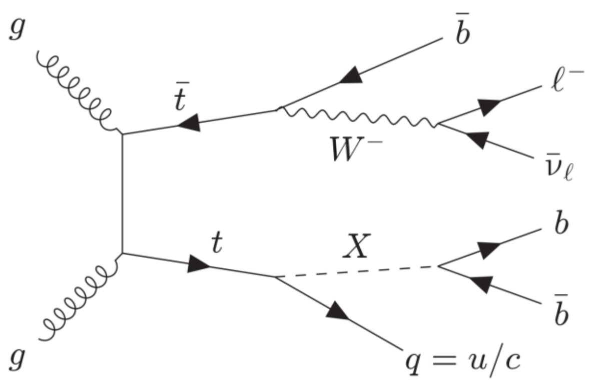


ρ_{tc} vs. m_A



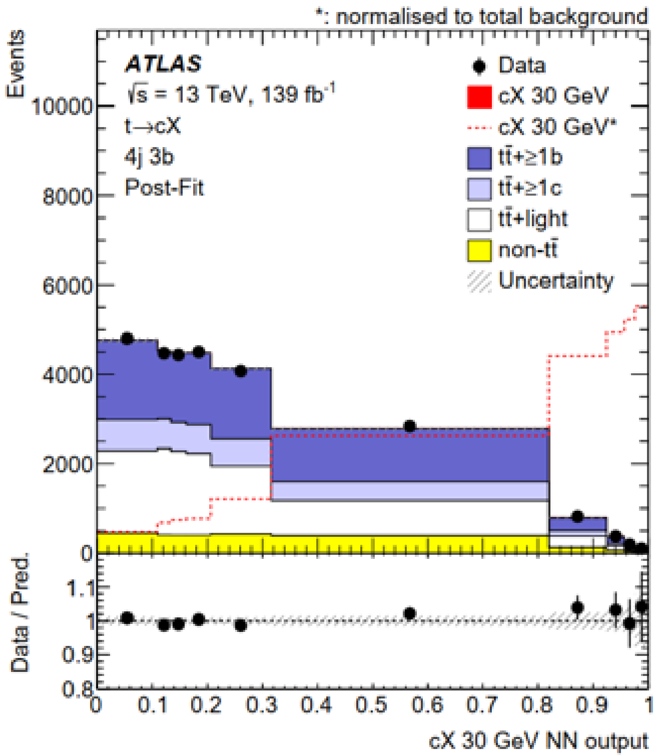
$t \to qX, X \to bb$

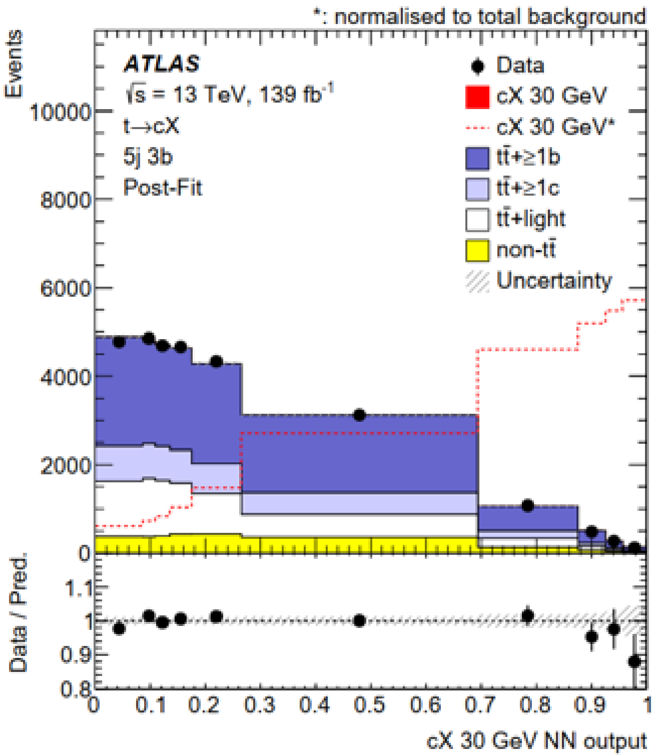
JHEP 07(2023)199

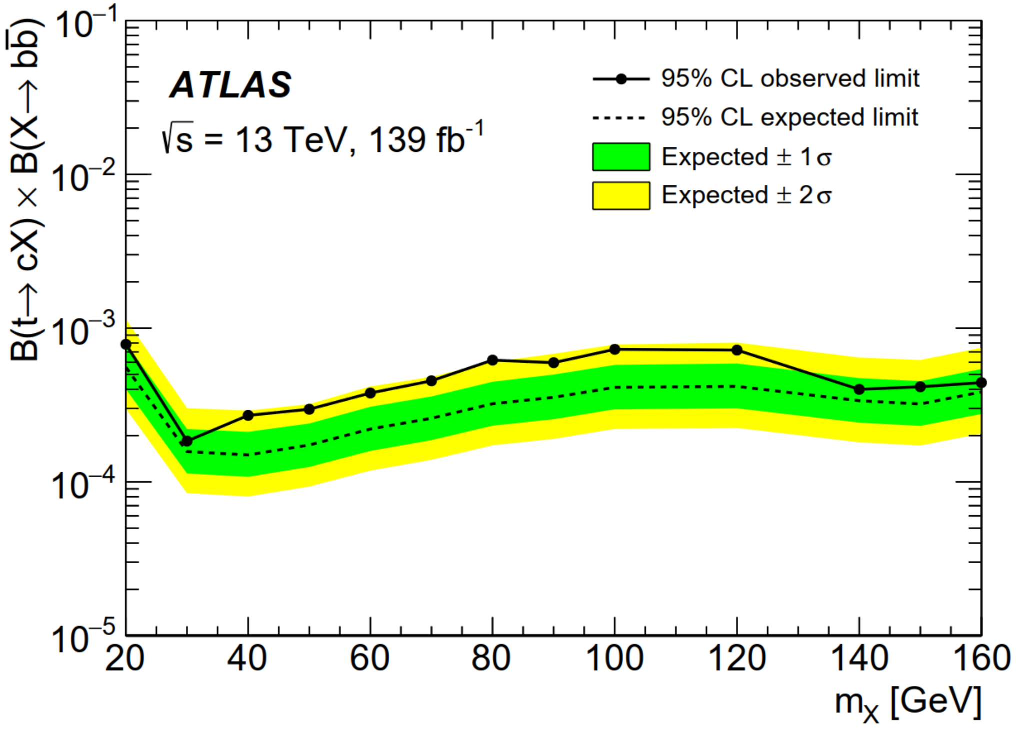


FCNC in top decay

New scalar in 20-160 GeV. SR: 4/5/6j 3b, NN discriminant







More details in talk by Tom KRESSE (BSM 1 parallel session)

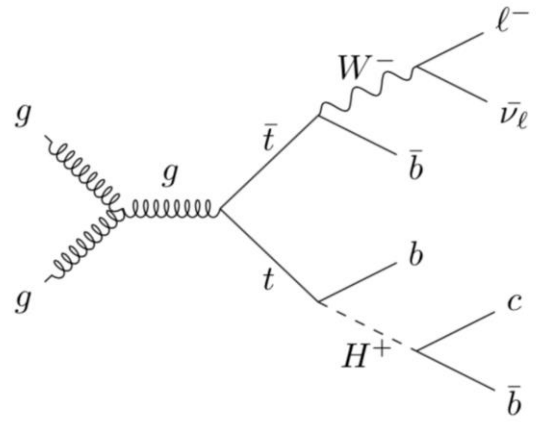
charged Higgs in top decay

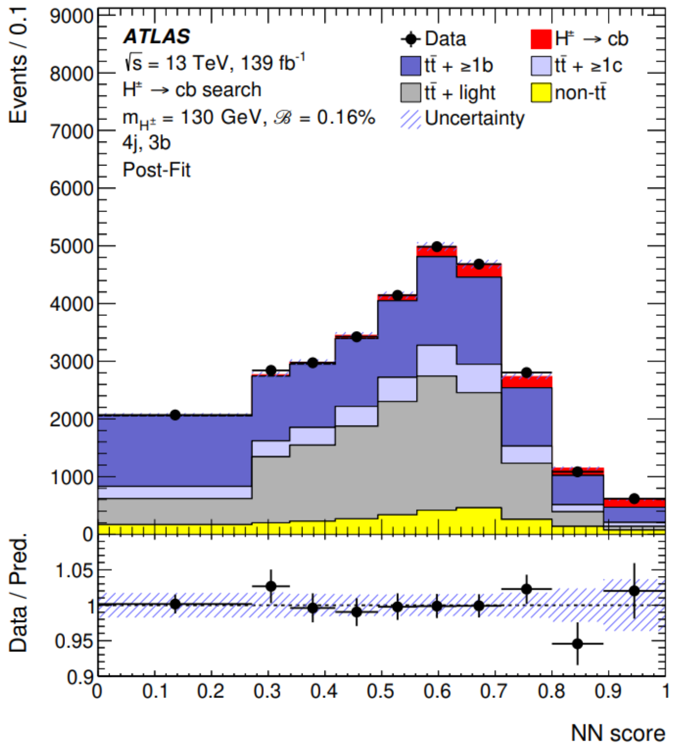
JHEP 09(2023)004

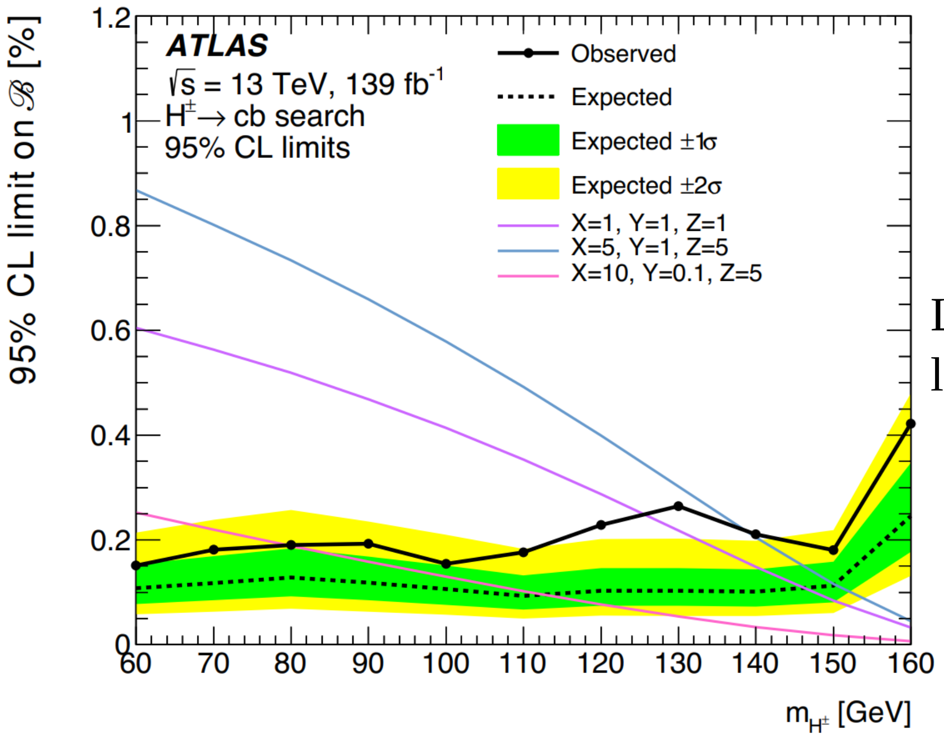
3HDM benchmark predicts 2 charged Higgs, that can be lighter than top quark

Control regions to derive corrections to ttbar modeling

NN as discriminants(10 bins in 3b, 1 bin for >=4b)







Largest excess at $m_{H^\pm}$~ 130 GeV
local (global) significance = $3\sigma(2.5\sigma)$

More details in talk by Yanhui Ma
(BSM 2 parallel session)

Summary and outlook

- Searches for extra scalars (neutral, charged, light, heavy) by CMS and ATLAS
  - with a lot of different final states
  - with a lot of benchmark models
- A few observed excesses (global significances below 3σ). Limits on model parameters derived
- Looking forward to more statistics (Run 3 and HL-LHC)

Some related talks at this conference:

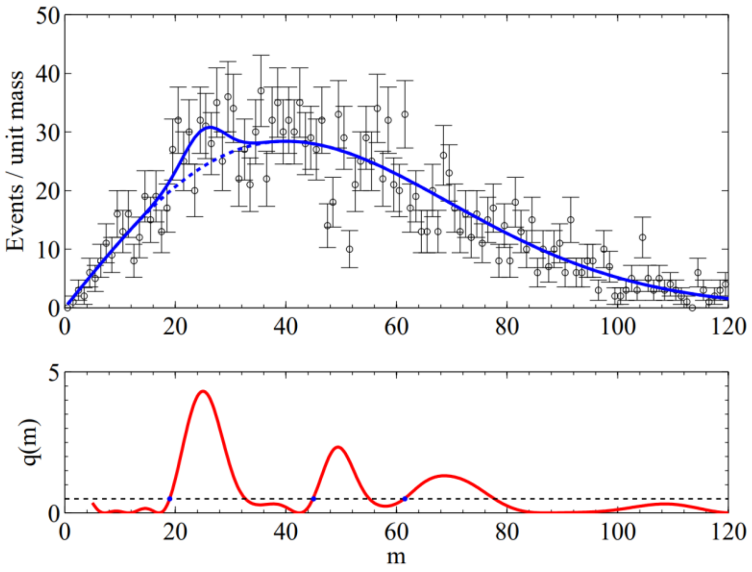
- Searches for additional neutral Higgs bosons in ATLAS, Tom Kresse
- Search for a standard model-like Higgs boson in the mass range between 70 and 110 GeV in $\gamma\gamma$, Muhammad Aamir Shahzad
- Searches for additional heavy Higgs bosons at CMS， Khawla Jaffel
- Searches for singly- and doubly-charged Higgs bosons in ATLAS Yanhui Ma
- Searches for resonances decaying to pairs of bosons in ATLAS, Olof Lundberg
- …

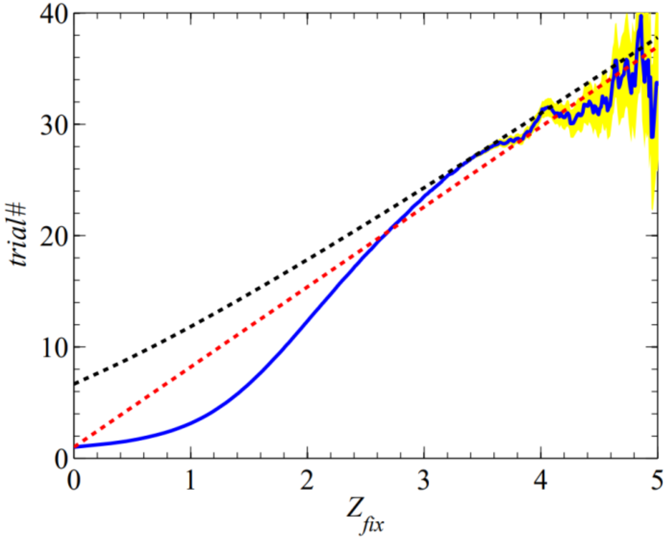
BACK-UP

A few words on Look Elsewhere Effect

arXiv:1005.1891

- LEE:
  - We search for new physics (e.g. a bump) on a (mass) distribution without knowing where it should appear.
  - An excess **anywhere** will be reported as a discovery.
    - In LogLikelihood Ratio test, the effective test statistic is $q(\hat{m}) = \max_m\big(q(m)\big)$, $q(m) = -2\ln\frac{\mathcal{L}(\hat{b})}{\mathcal{L}(\hat{\mu}S(m)+\hat{b})}$,i.e there is a nuisance parameter m for the alternative (signal + background) hypothesis, which is not present in the null (background-only) hypothesis.
    - This (maximization) should be taken into account when deriving the distribution of the test statistic of the null hypothesis (global significance).
    - A toy example: background-only pseudo-experiment. Local fluctuations resemble a mass peak.

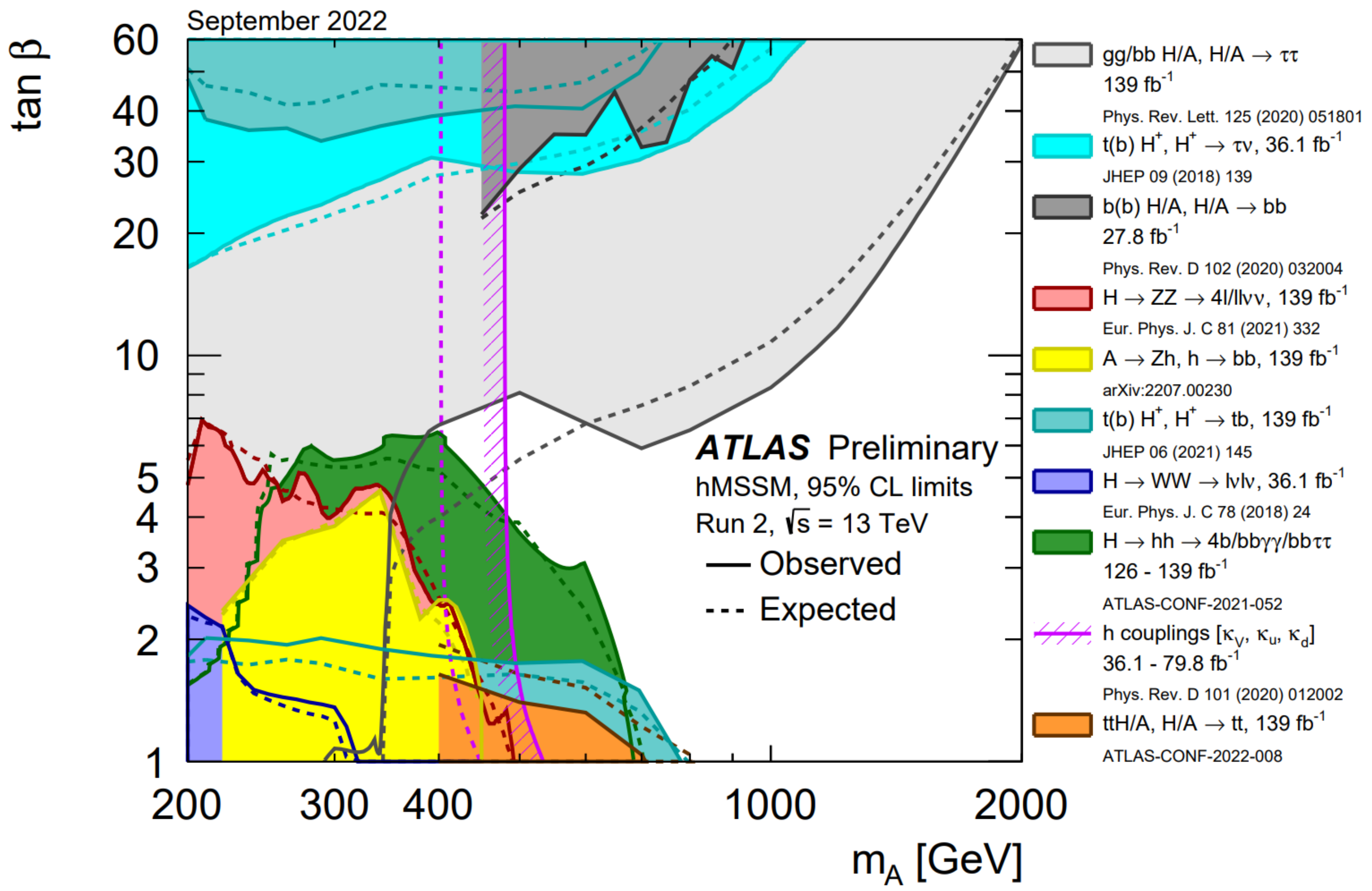




$$\text{trial \#} = \frac{P(q(\hat{m}) > c)}{P(q(m) > c)}$$

hMSSM exclusions

ATL-PHYS-PUB-2022-043



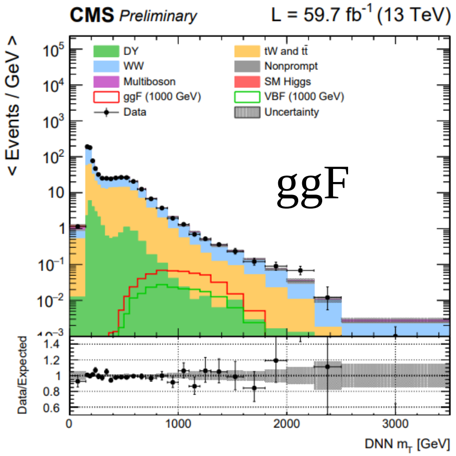
Scenario/Signiture	Experiment	Excess location	Local(global) significance (σ)
$X \to \gamma\gamma$	CMS	$m_{\gamma\gamma}$~95.4 GeV	2.9(1.3)
$X \to \gamma\gamma$	ATLAS	$m_{\gamma\gamma}$~19.4 GeV	3.1(1.5)
$X \to Z\gamma$	ATLAS	$m_{Z\gamma}$~420 GeV	2.3(NA)
$X \to WW$	CMS	m_X~650 GeV(floating f_{VBF})	3.8(2.4)
$H^+ \to WZ$(VBF)	ATLAS	$m(WZ)$~375 GeV	2.8(1.6)
$X \to e\mu$	CMS	$m(e\mu)$~146 GeV	3.8(2.8)
$tta(\mu\mu)$	ATLAS	m_a~27 GeV	2.4(NA)
$gg\phi(\tau\tau)$	CMS	m_ϕ~27 GeV	3.1(2.7)
$X \to HY \to \gamma\gamma bb$	CMS	$M_X = 650$ GeV, $M_Y = 90$ GeV	3.8(2.8)
$X \to HY \to bbbb$	CMS	$M_X = 1$ TeV, $M_Y = 90$ GeV	3.1(0.7)
FCNH($H \to tu$), multi-lep+(b) jets	ATLAS	$M_X = 900$ GeV, $\rho_{tu} = 1.1, \rho_{tc} = 0, \rho_{tt} = 0.6$	2.8(NA)
$H^+ \to WZ$(in top decay)	ATLAS	$M_{H^+} = 130$ GeV	3(2.5)

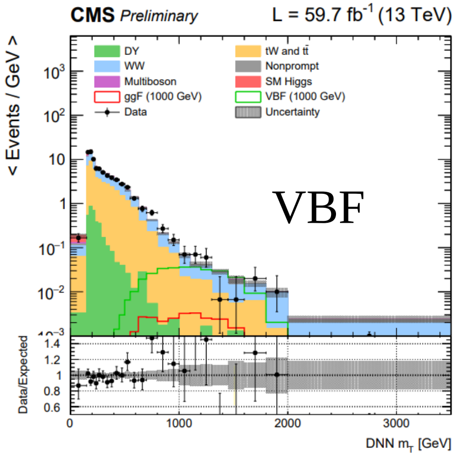
$X \to WW$

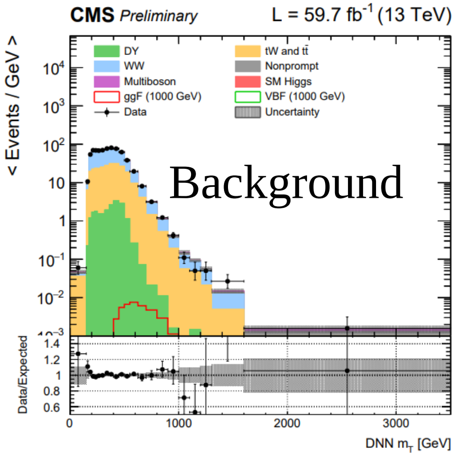
CMS PAS HIG-20-016

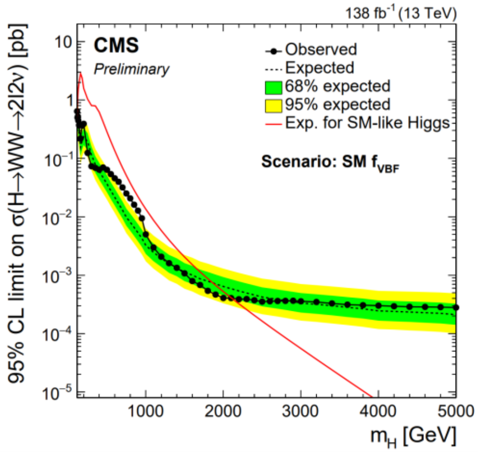
- Consider $e\mu, \mu\mu, ee$ channels
- Control regions to constrain Drell-Yan and top background
- DNN to classify: ggF, VBF and background
- DNN to reconstruct resonance mass(discriminant for statistical analysis)

2018 $e\mu$ data









CMS $X \to WW$ Excesses

Scenario	Mass [GeV]	ggF cross sec. [pb]	VBF cross sec. [pb]	Local signi. [σ]	Global signi. [σ]
SM f_{VBF}	800	0.16	0.057	3.2	1.7 ± 0.2
$f_{VBF} = 1$	650	0.0	0.16	3.8	2.6 ± 0.2
$f_{VBF} = 0$	950	0.19	0.0	2.6	0.4 ± 0.6
floating f_{VBF}	650	2.9×10^{-6}	0.16	3.8	2.4 ± 0.2

Flavor changing Neutral Higgs

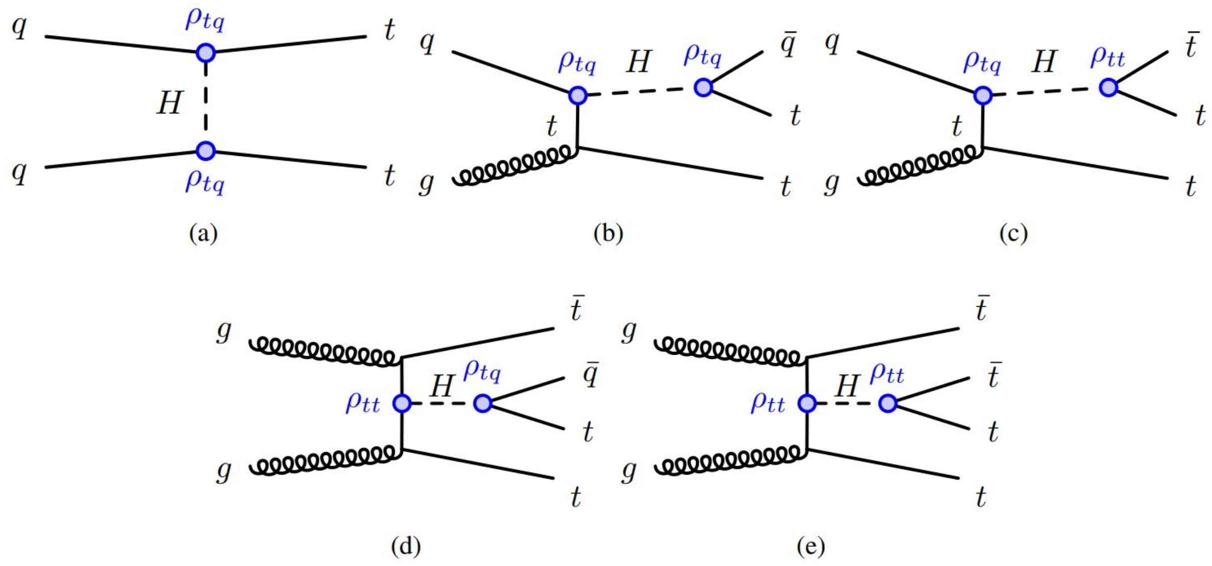
arXiv:2307.14759

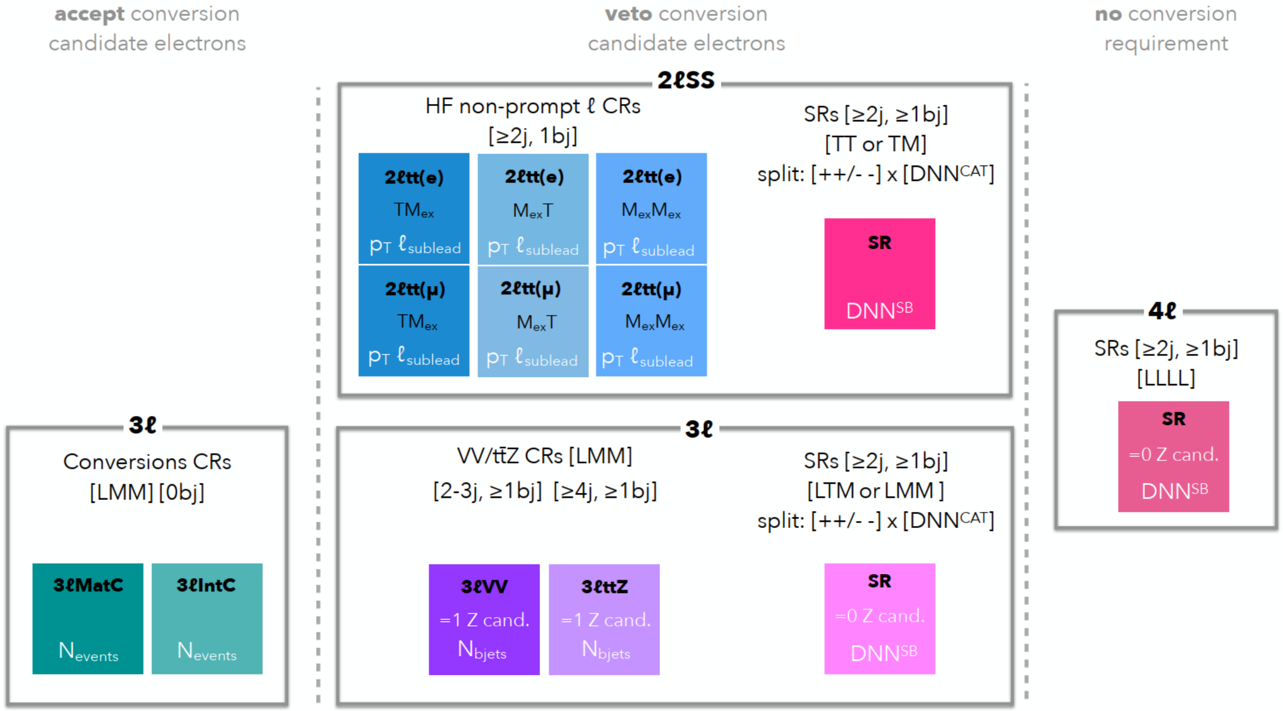
g2HDM (no Z2 symmetry) ➔FCNH couplings

2/3/4 leptons + (b-)jets selection, DNN_{cat}, DNN_{sb}(also for fitting)

L/M/T : Loose/Medium/Tight leptons

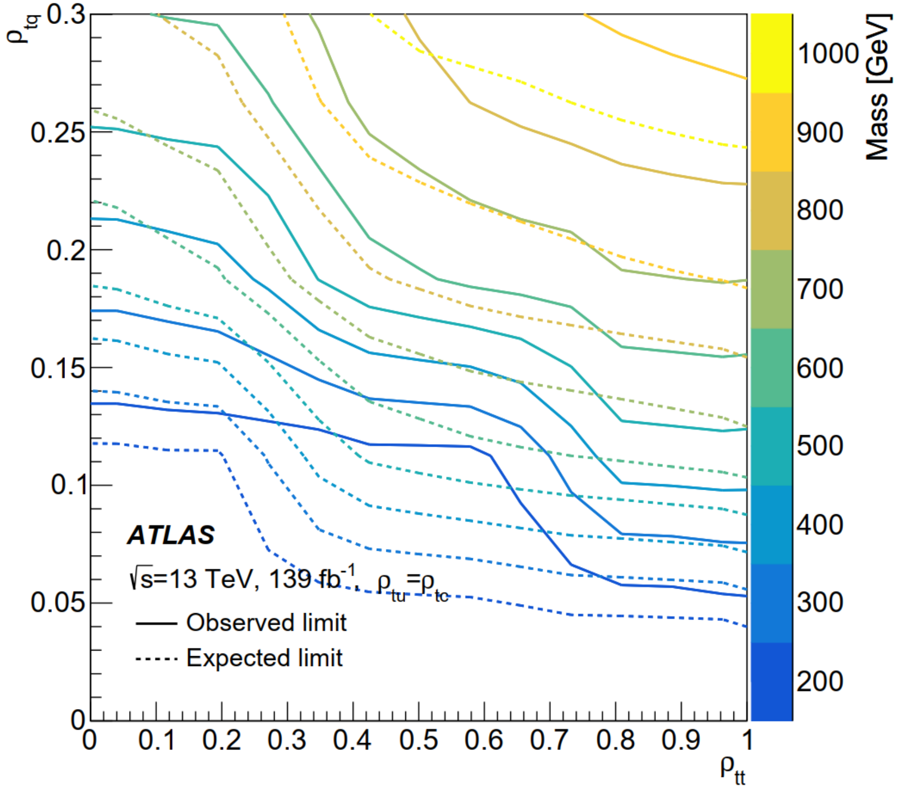
M_{ex}: medium exclusive

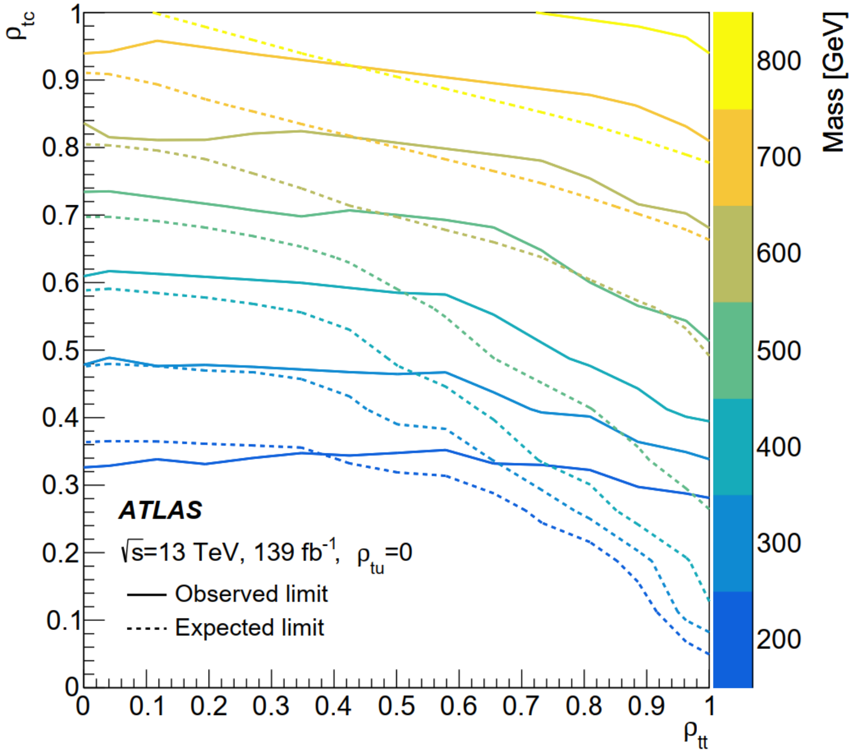




Constraints on couplings

Largest excess: 2.8σ for m_H=900 GeV, $\rho_{tt} = 0.6, \rho_{tc} = 0.0, \rho_{tu} = 1.1$



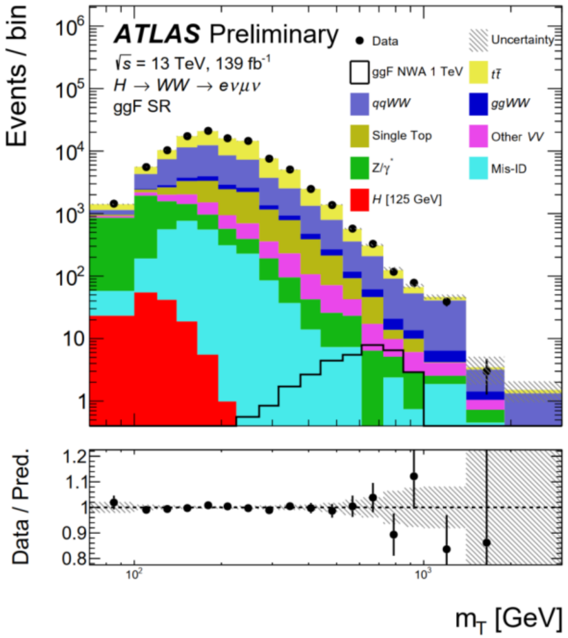


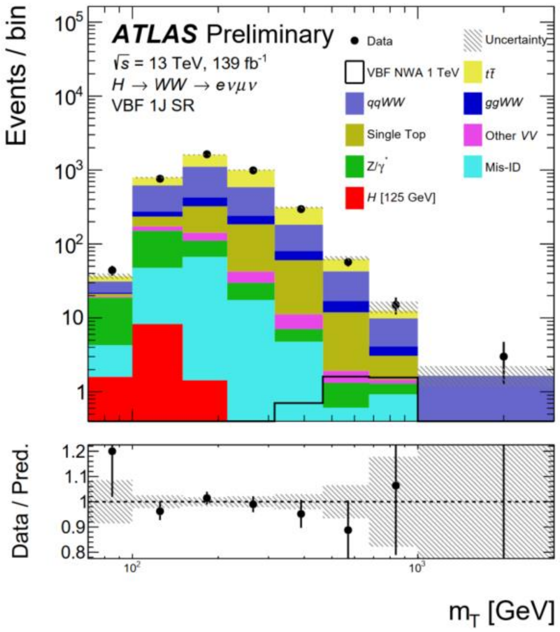
$X \rightarrow WW \rightarrow l\nu l\nu$

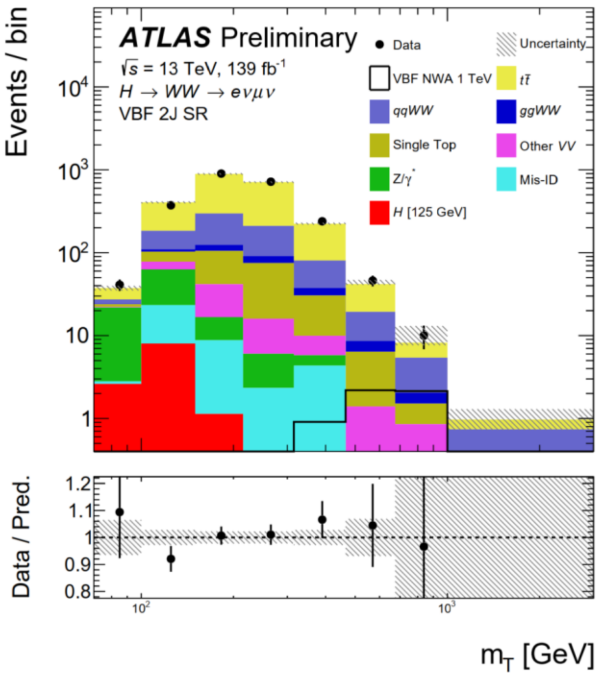
ATLAS-CONF-2022-066

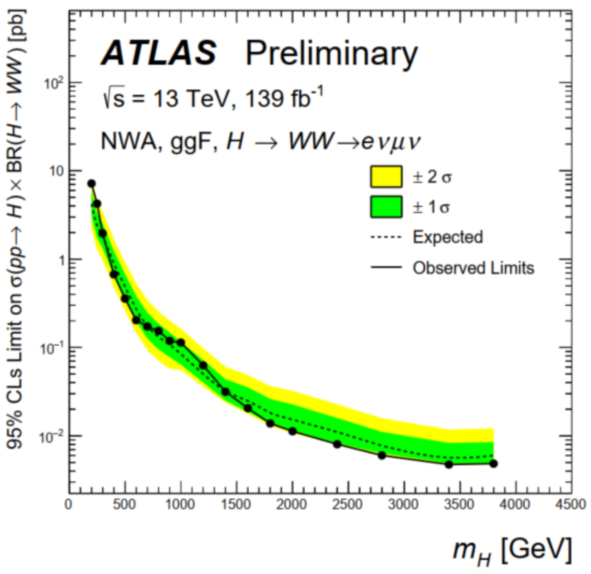
$e\mu$ + MET final state

Transverse mass as discriminant









$WH, H \to WW$

JHEP 07(2023)200

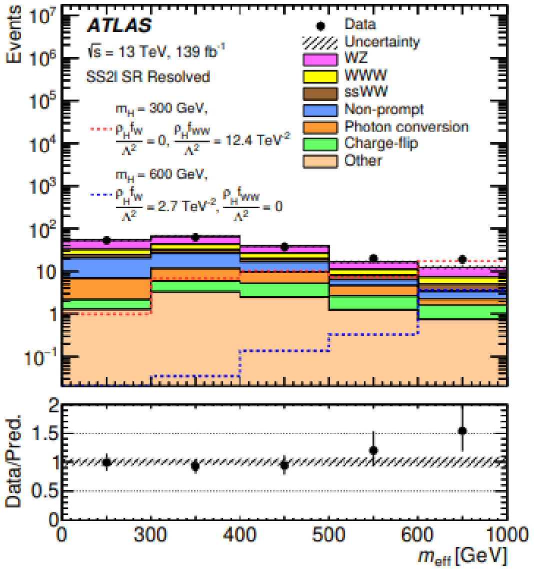
same-sign di-lepton, 2 jets / 1 large-R jet

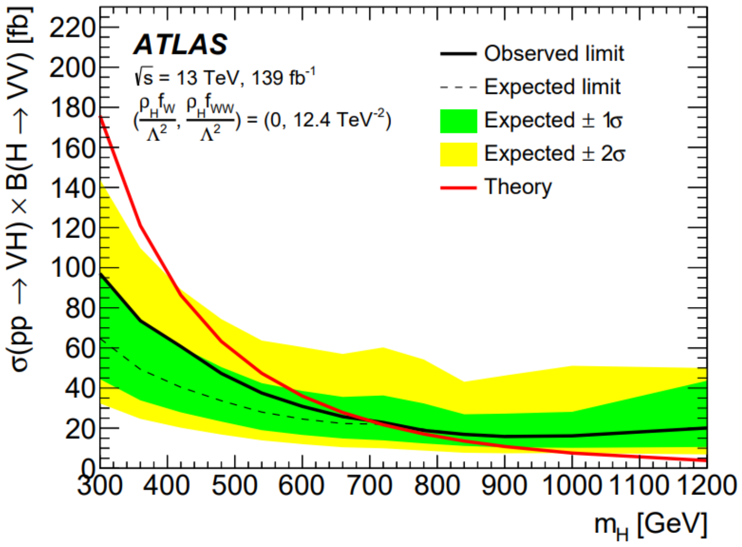
Discriminant by kinematics: m_{eff}

HWW parameterized with EFT

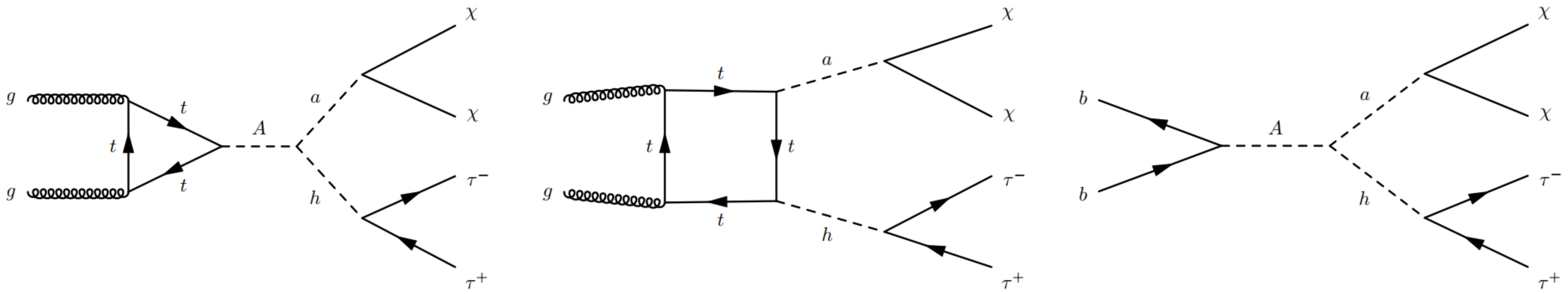
$$\text{boosted category } m_{\text{eff}} = \sum_i p_T^i(\text{lepton}) + p_T(\text{leading J}) + E_T^{\text{miss}},$$

$$\text{resolved category } m_{\text{eff}} = \sum_i p_T^i(\text{lepton}) + p_T(\text{leading j}) + p_T(\text{sub-leading j}) + E_T^{\text{miss}}.$$

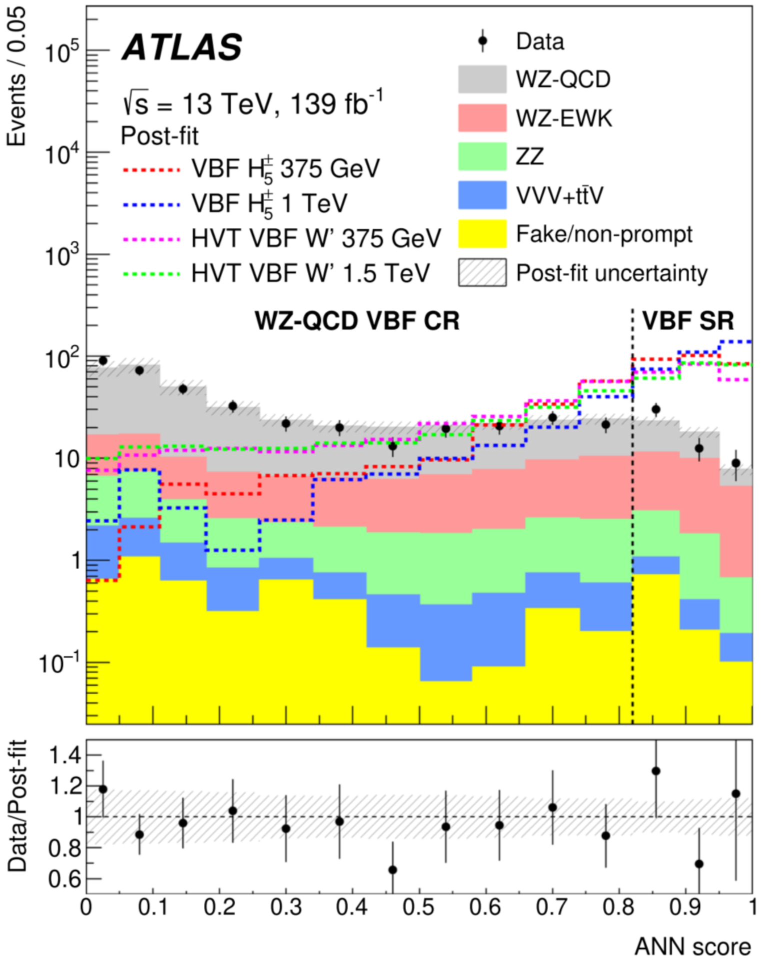




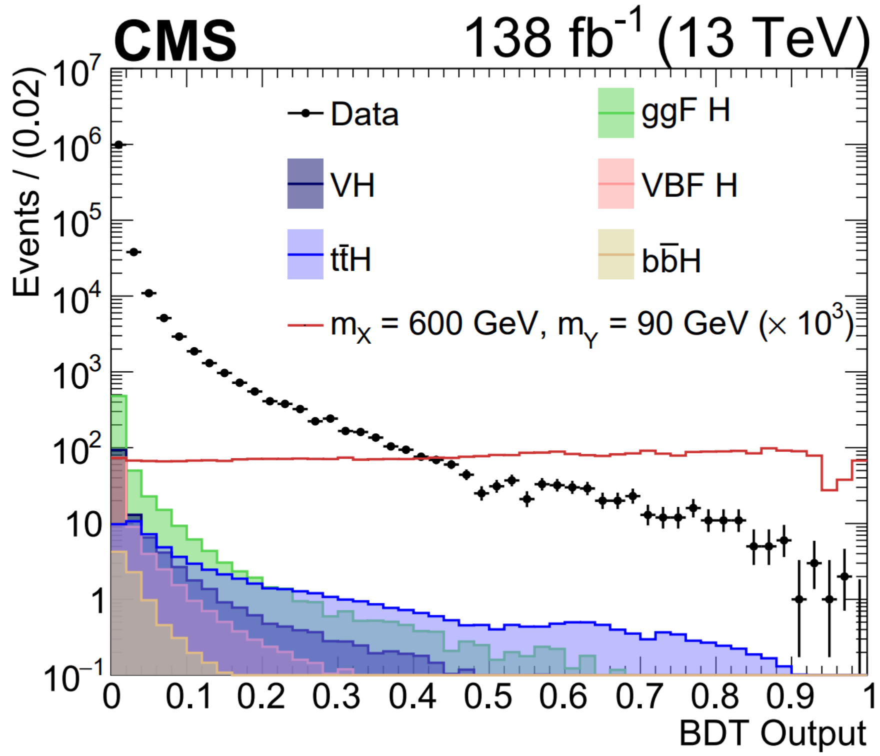
Production mode of 2HDM+a, A→ah



ATLAS $H^+ \rightarrow WZ$ ANN discriminant



CMS $X \rightarrow HY \rightarrow \gamma\gamma bb$ BDT distribution



ATLAS t→H⁺ c analysis CR SR

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)

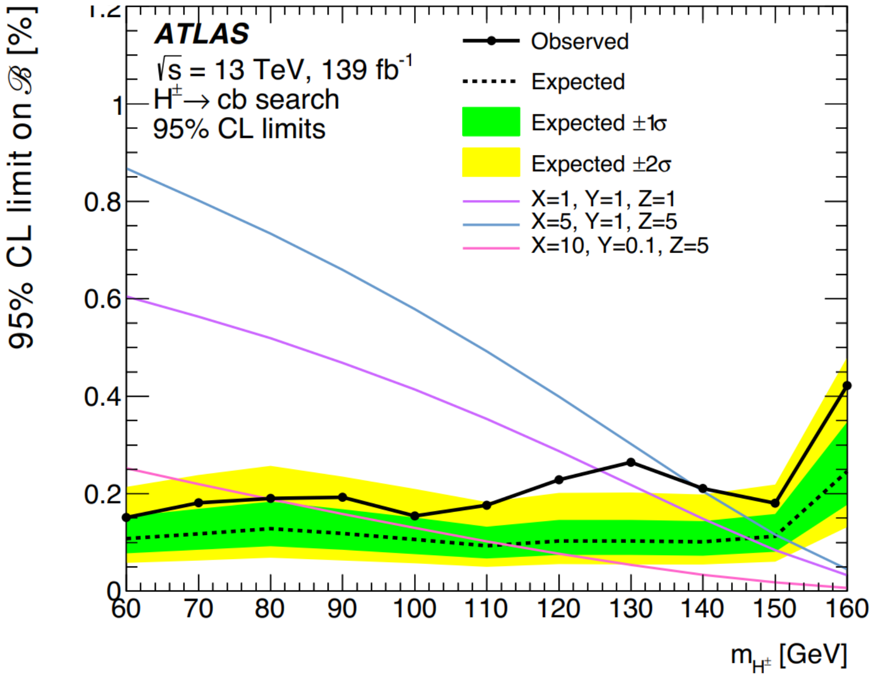
Regions used to derive $t\bar{t}$ correction **Regions for NN training and fit**

Constraints to 3HDM (definition of parameters)

PRD98(2018)115024

$$\mathcal{L}_{H^\pm} = -\left\{ \frac{\sqrt{2}V_{ud}}{v}\overline{u}\,(m_d X P_R + m_u Y P_L)\,d\,H^+ + \frac{\sqrt{2}m_\ell}{v} Z \overline{\nu_L}\ell_R H^+ + H.c. \right\}$$

$$\Gamma(H^\pm \to ud) = \frac{3G_F V_{ud} m_{H^\pm}(m_d^2|X|^2 + m_u^2|Y|^2)}{4\pi\sqrt{2}}$$

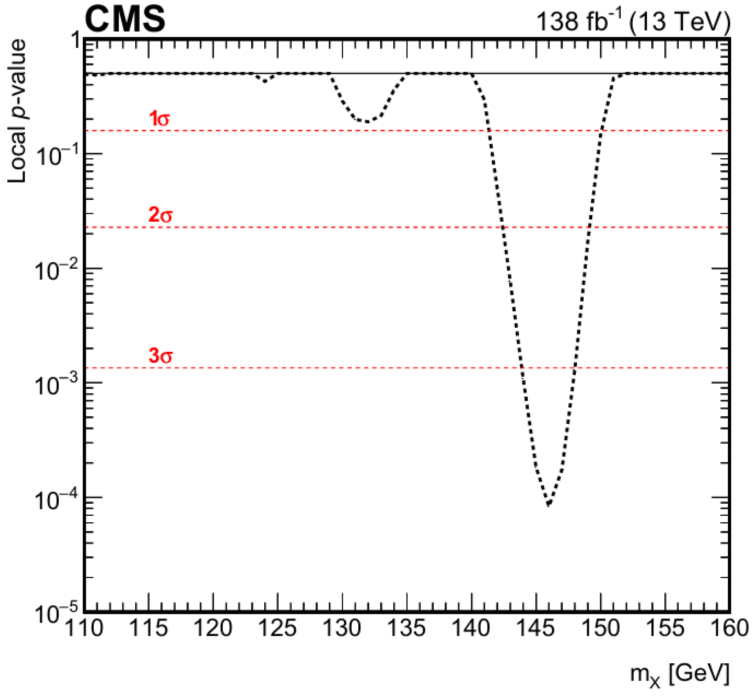


Largest excess at $m_{H^\pm}$~ 130 GeV, local (global) significance = $3\sigma(2.5\sigma)$

CMS X(146 GeV) →$e\mu$ significances

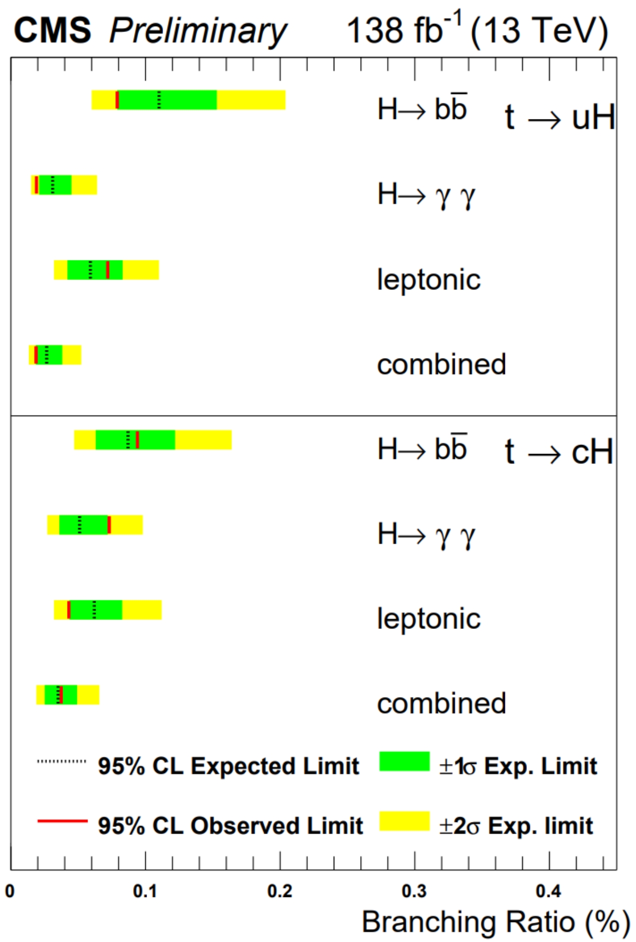
TABLE IV. Observed (expected) 95% CL upper limits, best fit, and local significance in unit of standard deviation (σ) of $\sigma(pp \to X(146) \to e\mu)$ for each individual analysis category and for the combination of all analysis categories.

Category	ggH cat 0	ggH cat 1	ggH cat 2	ggH cat 3	VBF cat 0	VBF cat 1	Combined
Observed limit (fb)	<7.74	<4.70	<11.99	<54.87	<12.56	<22.46	<6.01
Expected limit (fb)	<3.68	<3.57	<5.04	<34.56	<6.56	<12.58	<2.07
Best fit (fb)	$4.16^{+2.10}_{-1.87}$	$1.30^{+1.87}_{-1.78}$	$6.56^{+3.25}_{-3.07}$	$23.46^{+18.17}_{-17.31}$	$5.35^{+3.92}_{-2.96}$	$9.00^{+7.46}_{-6.30}$	$3.89^{+1.25}_{-1.13}$
Local significance (σ)	2.3	0.7	2.2	1.4	2.1	1.5	3.8



$t \to qH$

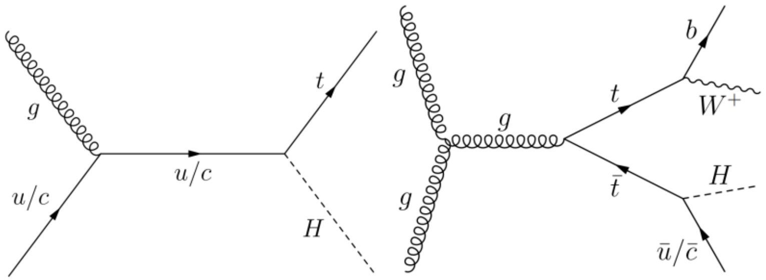
CMS PAS TOP-22-002



Combined limits at 95% CL:

$$BR(t \to uH) < 0.019\%$$

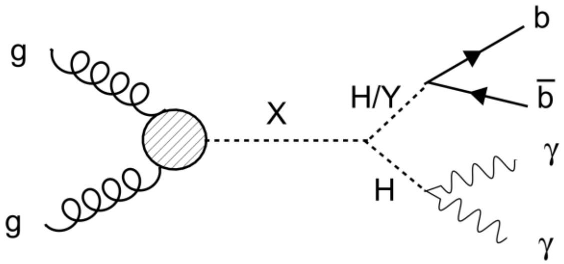
$$BR(t \to cH) < 0.037\%$$



REMOVE??!
COVERED BY
OTHER PLENARY

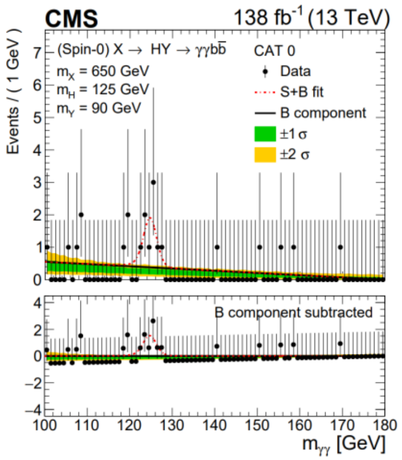
$X \to HY \to \gamma\gamma bb$

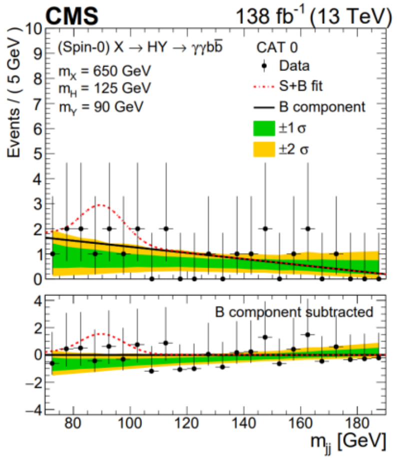
arXiv:2310.01643v1



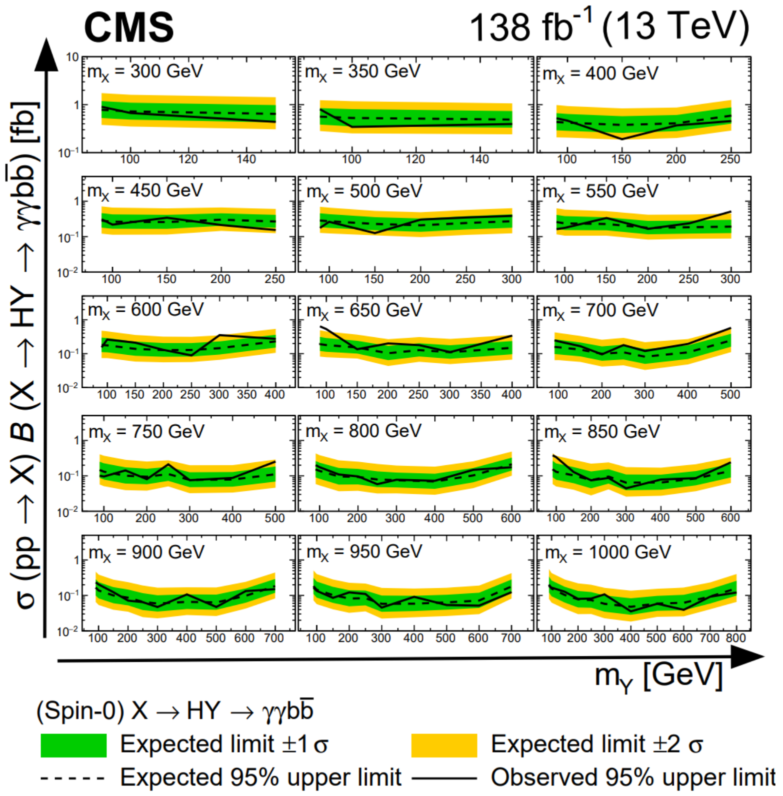
- Resonant production of a scalar (Y) and H(125)
- XGBoost(BDT) trained to categorize SR and to discriminate non-resonant background (inputs: kinematics, object i.d., resolution estimators)
- Resonance selection:
- 2D unbinned maximum likelihood fit on ($m_{\gamma\gamma}$,m_{jj}).

$$\widetilde{M}_X = m_{\gamma\gamma jj} - (m_{\gamma\gamma} - m_H) - (m_{jj} - m_Y)$$





Most significant excess at
$M_X = 650$ GeV, $M_Y = 90$ GeV
$3.8\sigma(2.8\sigma)$ local(global)
LEE:
$M_X \in (300,1000)$ GeV,
$M_Y \in (90,150)$ GeV



REMOVE??!
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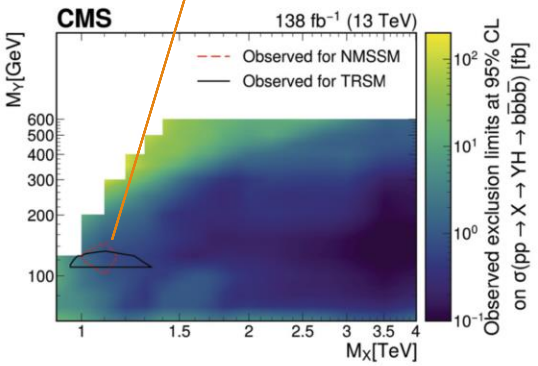
OTHER PLENARY

$X \rightarrow HY \rightarrow bbbb$

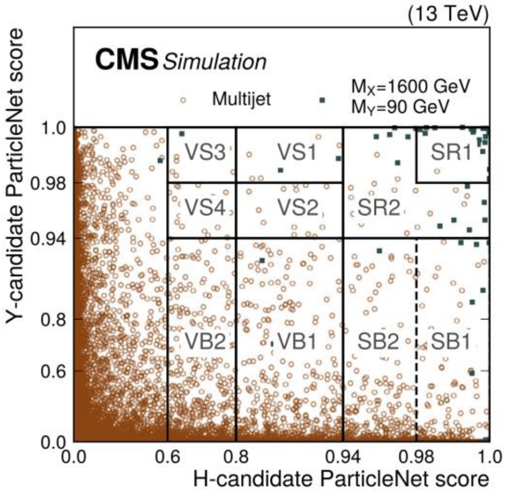
[PLB 842(2023)137392](PLB 842(2023)137392)

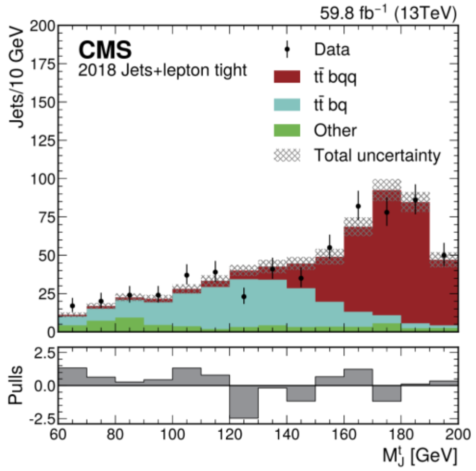
Inside: predicted XS larger than limits

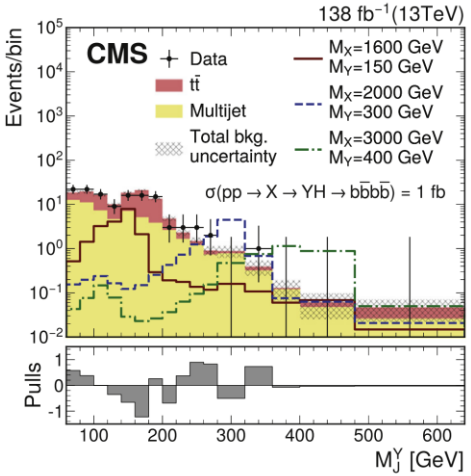


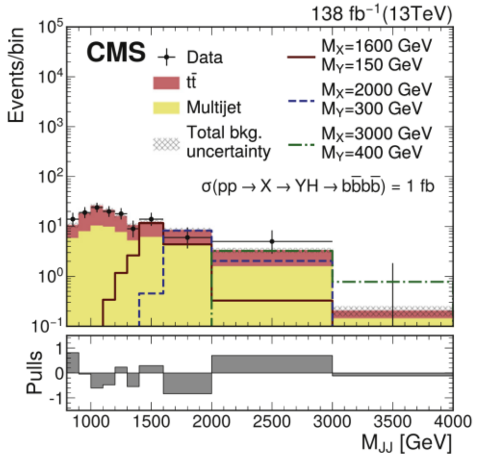
- Both $H(Y) \rightarrow bb$ are reconstructed in merged jets (AK8)
- ParticleNet(Graphic convolutional NN) trained to identify ($R \rightarrow bb$) resonances
- Maximum likelihood fit on (M_{JJ},M_Y) to extract signal

Most significant excess at $M_X = 1.6$ TeV, $M_Y = 90$ GeV $3.1\sigma(0.7\sigma)$ local(global)





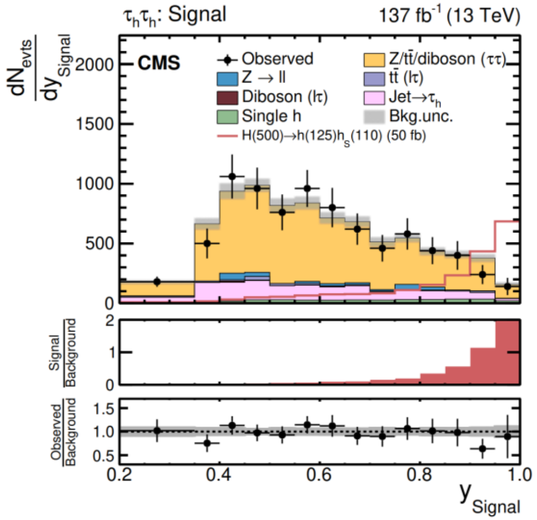


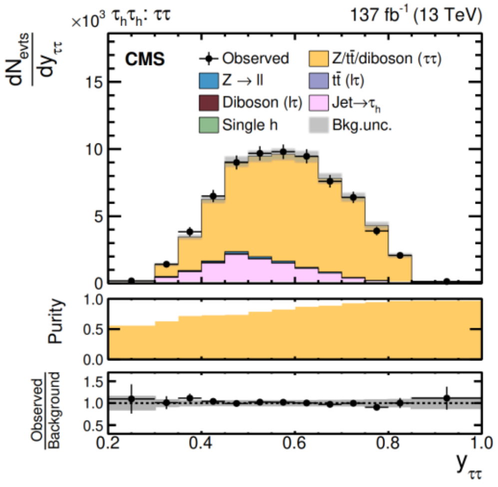


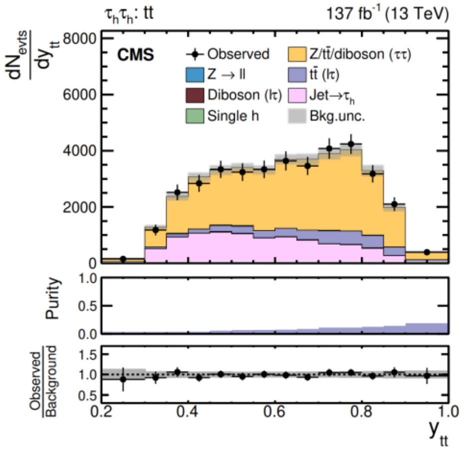
$X \to HY \to \tau\tau bb$

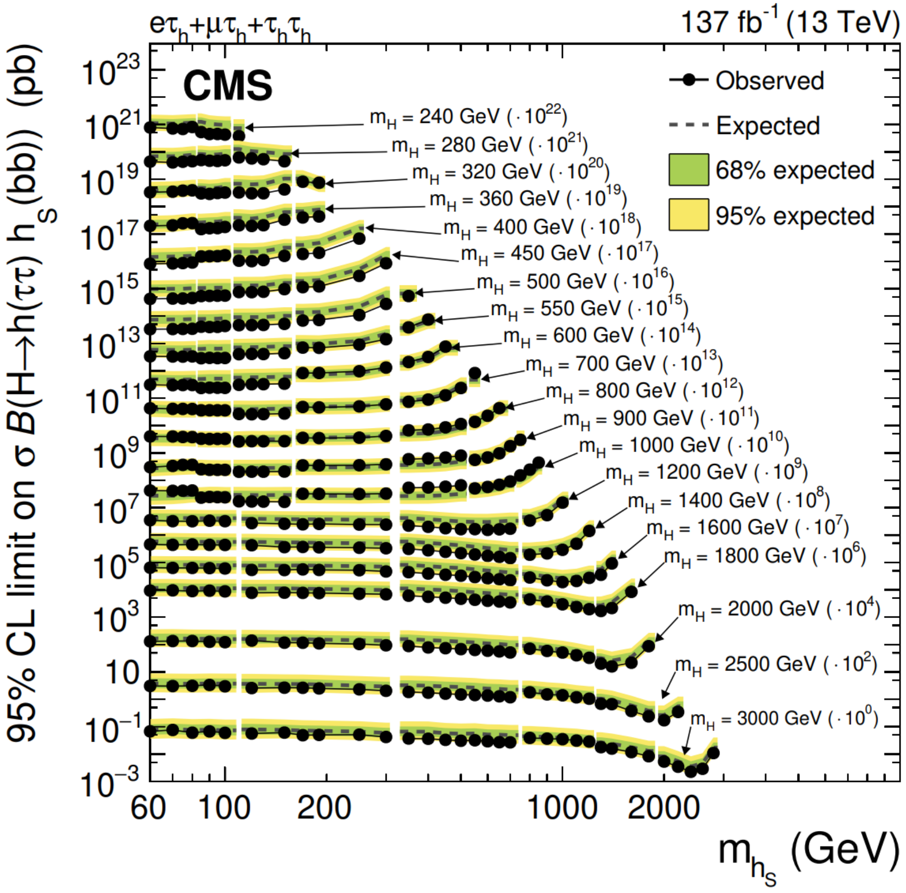
JHEP 11(2021)057

- $H(125) \to \tau\tau, Y \to bb$
- NN multiclassification to split events to 5 classes (1 SR+4 CR)
- Maximum likelihood fit on NN output to extract signal









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$X \to HH \to \tau\tau bb$

JHEP 07(2023)040

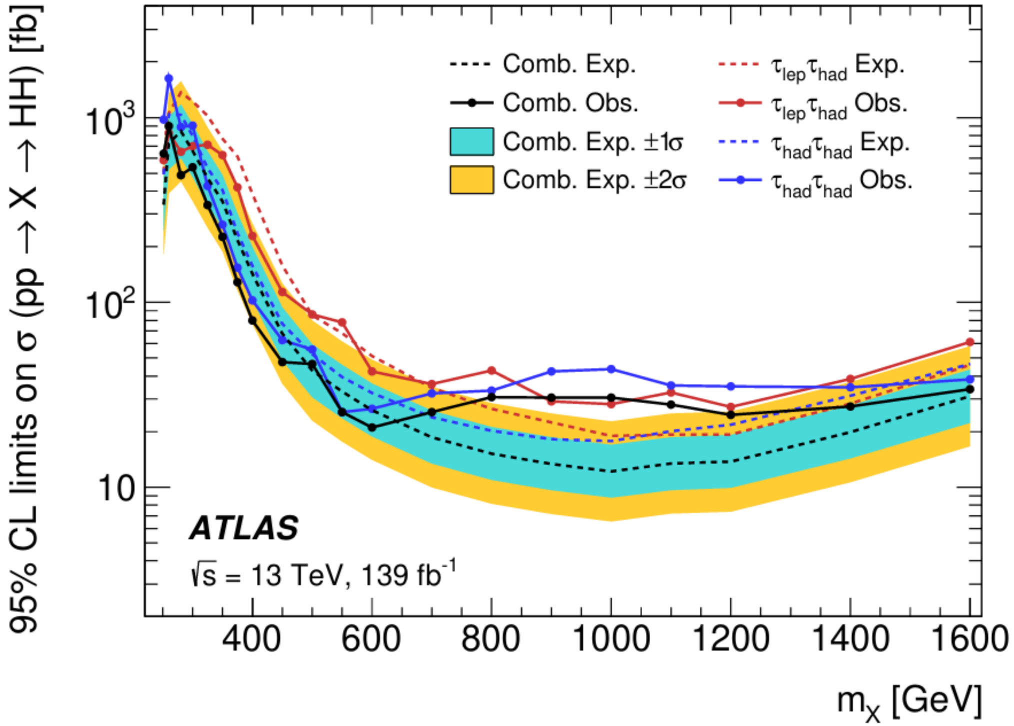
Search for resonant H(125) pair production in ATLAS

(CP-even state X as benchmark)

$m_X \in (251{,}1600)$ GeV

Events categorized by different trigger and tau decay types

Parameterized NN as discriminant



Largest deviation: $3.1\sigma(2.0\sigma)$ at $m_X = 1$ TeV