BSM Higgs, DM, & W' Searches at the LHC

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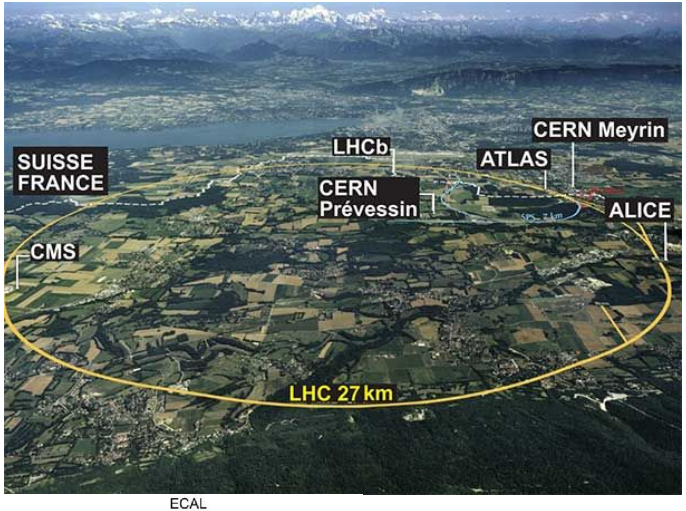
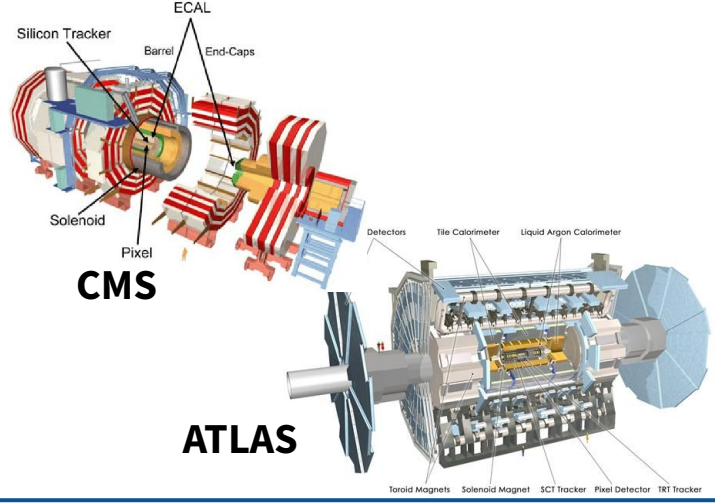
Testing BSM Physics at the LHC

- **LHC** is world's most powerful discovery machine
  - Hope to find hints of BSM physics in direct searches and measurements as well
- Program driven by **BSM** and **experimental results**
  - Explaining unresolved mysteries in SM
    - Hierarchy problem, Unification, Dark matter, neutrino mass, Matter-antimatter asymmetry …
  - Strong hints from measurements
    - μ g-2, B-anomalies, direct detection of DM, cosmological constraints, neutrino oscillation …
- Program driven by **signatures** in detector
  - Trigger and reconstruction algorithm are important
  - Improving techniques (ML) to explore more exotic world
    - Allow us to test new signature, more sensitivity



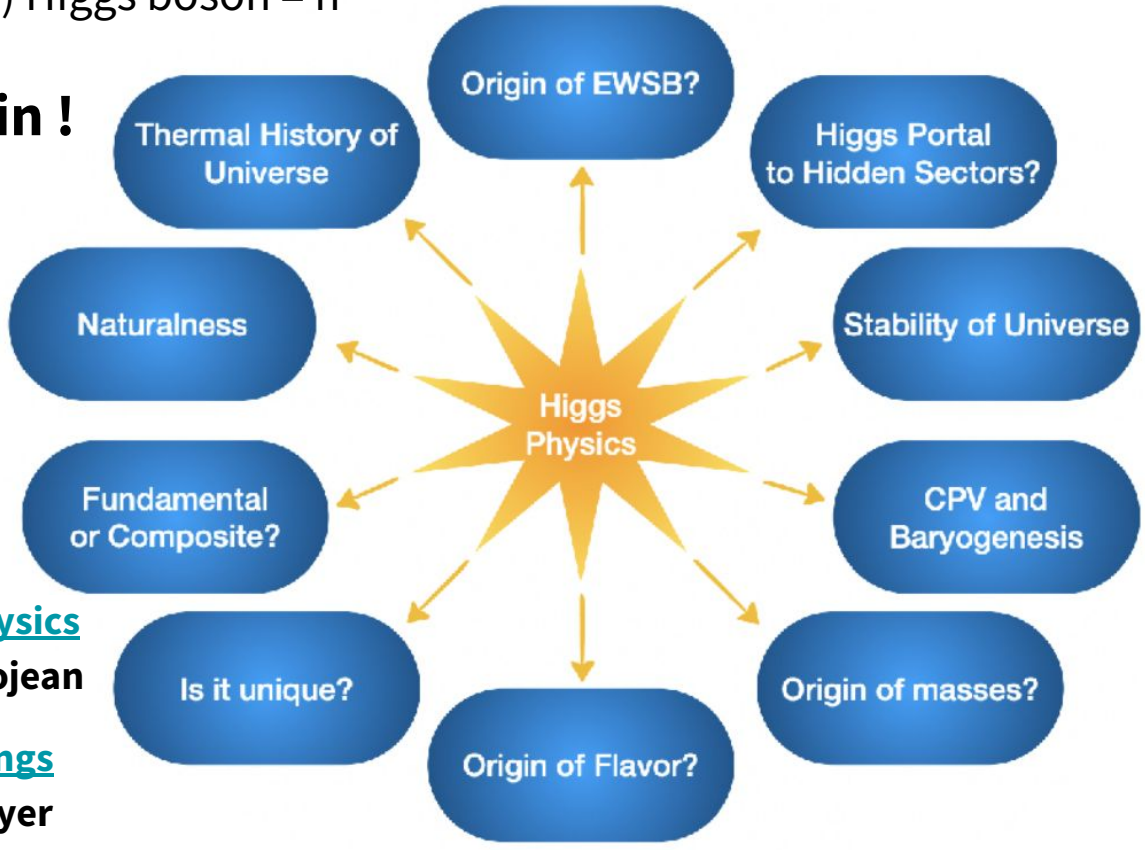


Higgs Physics @ LHC

- In the SM, only 1 complex Higgs doublet is responsible for EWSB :
  One neutral, CP-even (Scalar) Higgs boson = h

But many questions remain !

The Higgs boson is connected to numerous fundamental questions



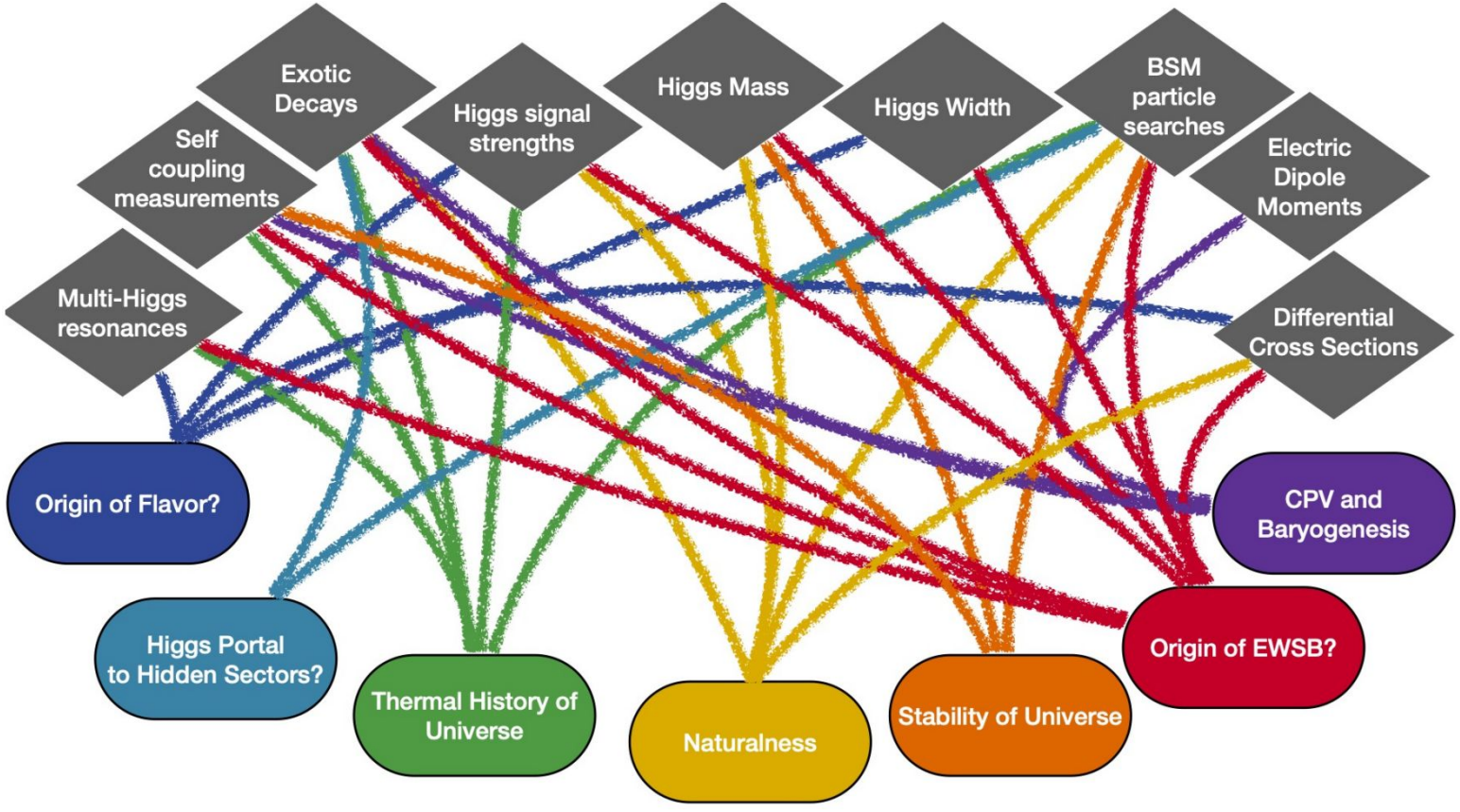
Plenary talk on 12 June

Theoretical Perspectives on Higgs Physics
is covered in the talk by **Christophe Grojean**

BSM Higgs sectors triple Higgs couplings
is covered in the talk by **Sven Heinemeyer**

BSM Higgs @ LHC

- Examples of the interplay between **experimental observables** and **fundamental questions** connected to the Higgs boson



BSM Higgs Models @ LHC

- There are many interesting BSM models to guide us at the LHC:
  Higgs Singlet, 2HDMs, 2HDM+a, Composite Higgs, Higgs portal to Dark matter, FCNC ..

- **Two Higgs Doublet Model (2HDM)** extends BSM Higgs sector to include 2 complex H doublets
  (CP-even) h, H, (CP-odd) A, H^+, H^-
  - Parameter : **mass**, **tanβ** (ratio of vev, v2/v1) , **α** (mixing angle between the h, H)
  - **Type 1** : One doublet couples to V(fermiophobic), one to fermions
  - **Type 2** : MSSM like model, one doublet couples to up-type quark, one to down-type quarks
  - **Type 3** : Lepton-specific model, same coupling to quarks as Type 1 & to lepton as Type 2
  - **Type 4** : Flipped model, same coupling to quarks as Type 2 & to lepton as Type 1

- **2HDM+S :** This model is an extension of 2HDM with an **additional EWK scalar singlet**.

- **Minimal Super Symmetry SM (MSSM)** provides an elegant solution to the hierarchy problem, and potential Dark matter candidate
  - More specific MSSM model **Mh^{125}** fully determined at tree-level by **m_A** and **tanβ**
  - The NMSSM is a particular case of 2HDM+S Type 2.

- In MSSM/2HDM Type 2, the couplings to **b-quarks** and **τ-leptons** are enhanced at high tanβ

How to Search for BSM Higgs @ LHC

- At the LHC, large group of BSM Higgs searches being covered with full Run-2
  - Only a few instructive and very recent results will be showing.

Additional Higgs, neutral H, A
Charged $H^{+/-}$ H^{++}

ATLAS-CONF-2023-035
CMS-PAS-HIG-20-002
ATLAS-PHYS-PUB-2022-043
CMS public Higgs Summary Plot
ATLAS_HDBS-2020-12
ATLAS-CONF-2023-034

The width of the observed resonance is very narrow, small coupling to BSM particles can lead to observable exotic decays of the Higgs boson at the LHC

LFV, h→ ll' arxiv:2302.05225v1, CMS-PAS-HIG-22-002

Light pseudoscalar h→aa CMS-PAS-HIG-22-007, arxiv:2208.01469, arxiv:2209.06197, ATLAS_HDBS-2020-12

h→Invisible, h→ dark photons arxiv:2301.10731, arxiv:2303.01214, ATLAS_HDBS-2019-13, ATLAS-CONF-2023-016

X → HH Searches ATLAS-CONF-2021-052, CMS public Higgs Summary Results

X → HY Searches ATLAS-CONF-2023-031

Many other list can be found in
ATLAS Publication List
CMS Publication List

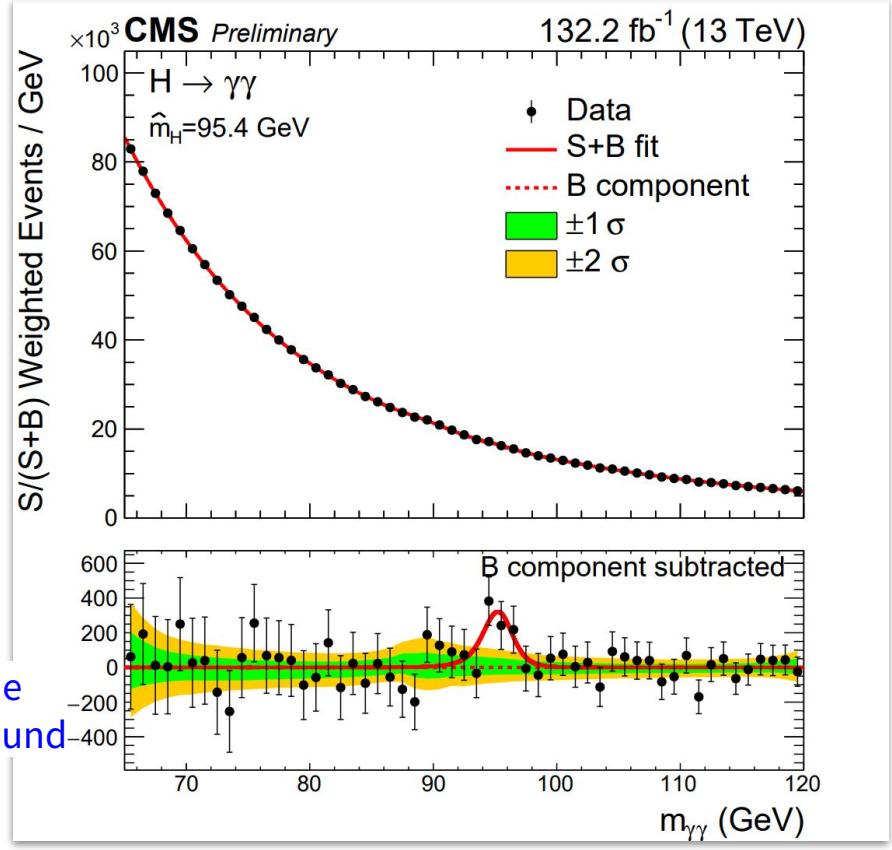
Low mass SM-like H → γγ Search

Is the 125 GeV Higgs the lightest Higgs ?

- Search for SM-like Higgs in di-photon mass spectrum, **70 – 110 GeV**
- Diphoton triggers with p_T > 30, 18 GeV
- Background : SM γγ, dijet, γ+jet, DY(ee)
- Event selection based on BDT photon ID
- Event classes with extra jet & year
- Extract Signal from the Background using a parametric fit to diphoton mass.

A previous CMS result at 8+13 TeV
Local (global) significance of 2.8σ (1.3σ) @ 95.3 GeV.
Phys. Lett. B 793 (2019) 320

Result of a fit of the S+B model under a mass hypothesis of 95.4GeV

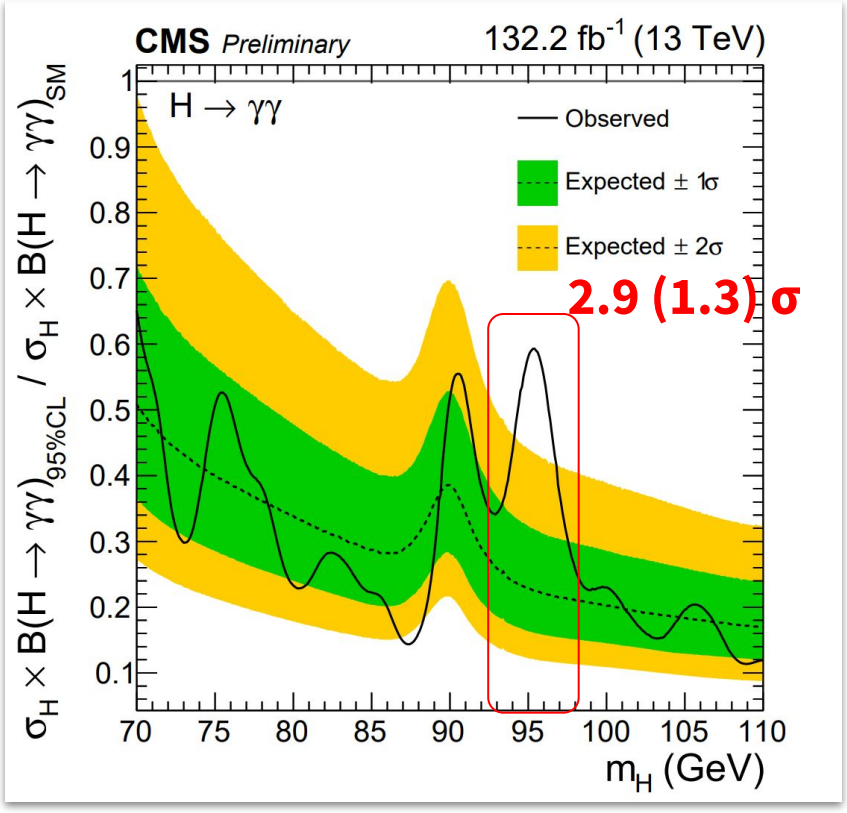


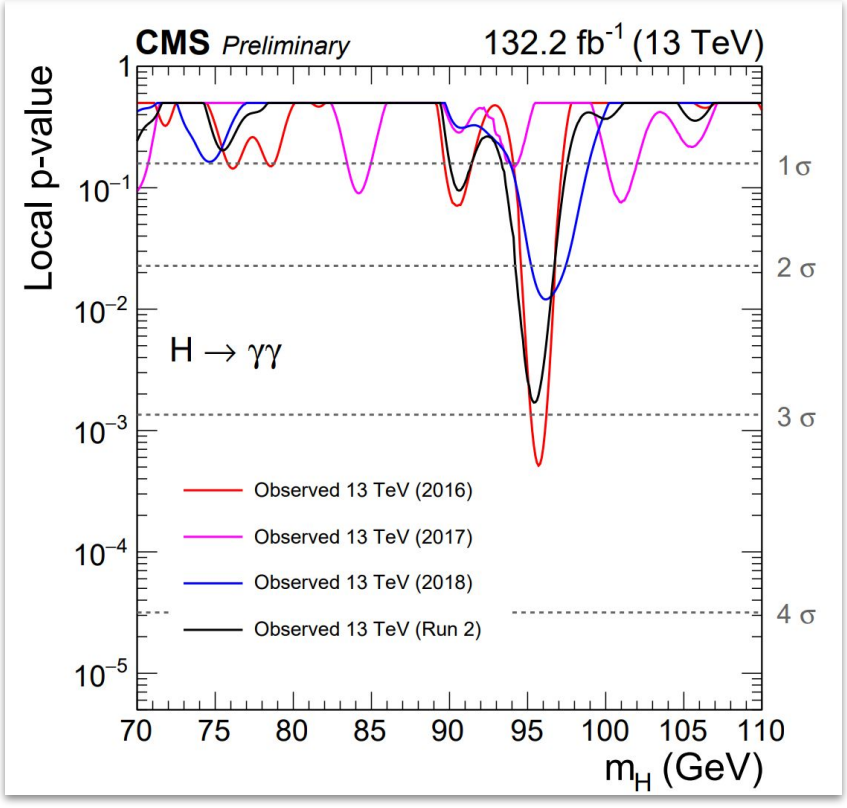
Data after subtracting the fitted background component

Low mass SM-like H → γγ Search

- Maximum observed excess for a mass hypothesis of **95.4 GeV** with local (global) significance of **2.9σ (1.3σ)**.

first result using full Run-2

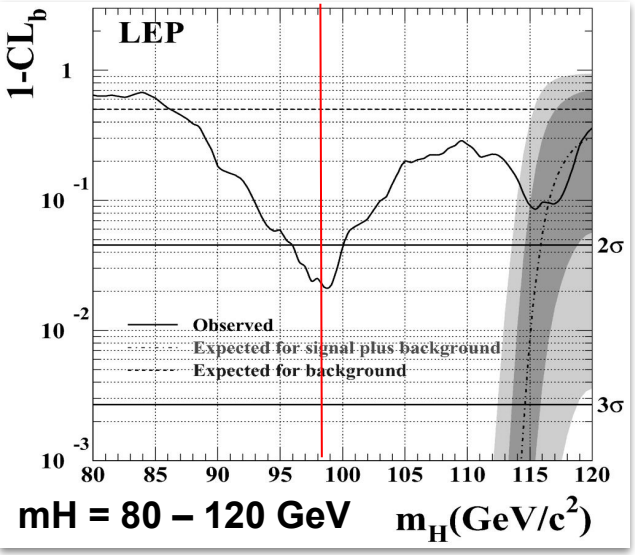




Low mass H → γγ Search

LEP experiment (2003 July)

PLB.565(2003)61-75

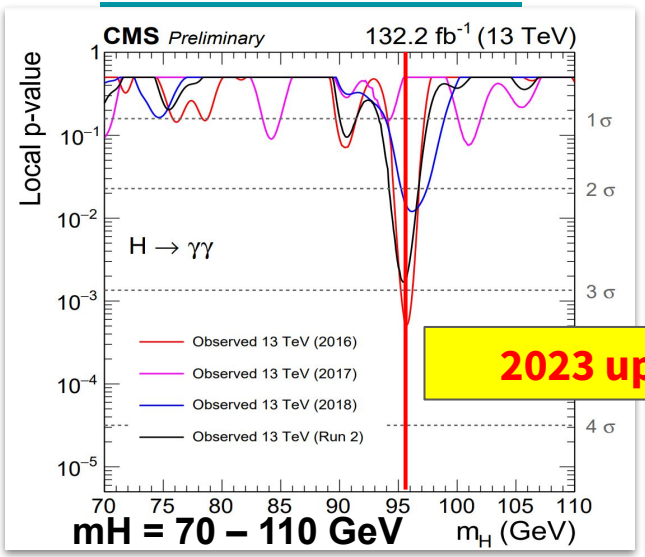


2461 pb^{-1} of e^+e^- collision data @ c.o.m energy = 189–209 GeV

local 2.3 σ @ m_H ≈ 98 GeV

CMS experiment (2023 March)

CMS-PAS-HIG-20-002

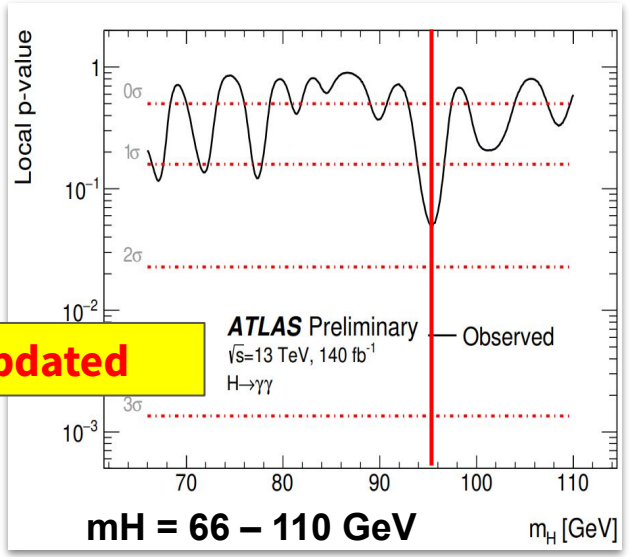


132.2 fb^{-1} of pp collision data @ c.o.m energy = 13 TeV

local 2.9 σ @ m_H ≈ 95.4 GeV

ATLAS experiment (2023 June)!!

ATLAS-CONF-2023-035



2023 updated

140 fb^{-1} of pp collision data @ c.o.m energy = 13 TeV

local 1.7 σ @ m_H ≈ 95.4 GeV

No significant excess with respect to the background-only hypothesis is observed.

LFV H → $e^{\pm}\tau^{\mp}$ / $\mu^{\pm}\tau^{\mp}$ Search

- Search for the **Lepton Flavor Violating** decays of 125 GeV Higgs (eτ, μτ).
- In the SM, Higgs couplings are diagonal Y_{ii}
- The discovery of LFV would suggest a Flavor Structure

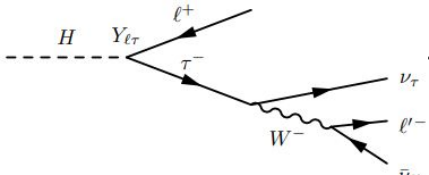
LFV Decay widths

$$\Gamma(H \to \ell^\alpha \ell^\beta) = \frac{m_H}{8\pi}(|Y_{\ell^\alpha \ell^\beta}|^2 + |Y_{\ell^\beta \ell^\alpha}|^2)$$

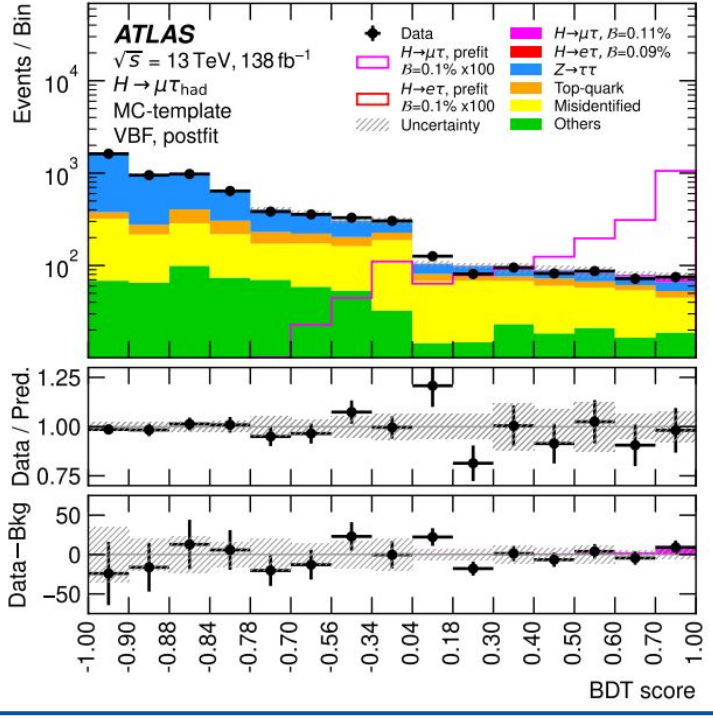
Branching ratios

$$\mathcal{B}(H \to \ell^\alpha \ell^\beta) = \frac{\Gamma(H \to \ell^\alpha \ell^\beta)}{\Gamma(H \to \ell^\alpha \ell^\beta) + \Gamma_{SM}}$$

- Multivariate techniques like BDT and DNN are employed to achieve maximum separation between signal and background to enhance sensitivity

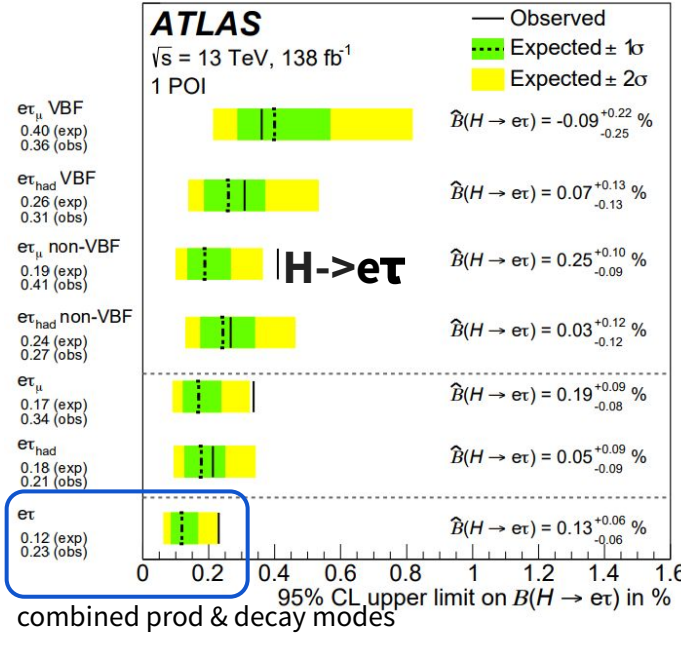


τ→l'ν$^{\nu}$, τ→ hadrons + ν

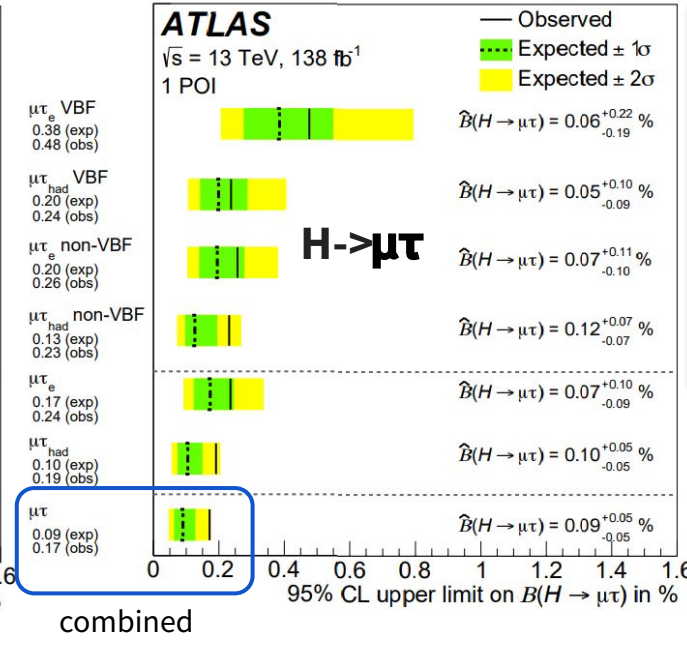


LFV H → $e^{\pm}\tau^{\mp}$ / $\mu^{\pm}\tau^{\mp}$ Search

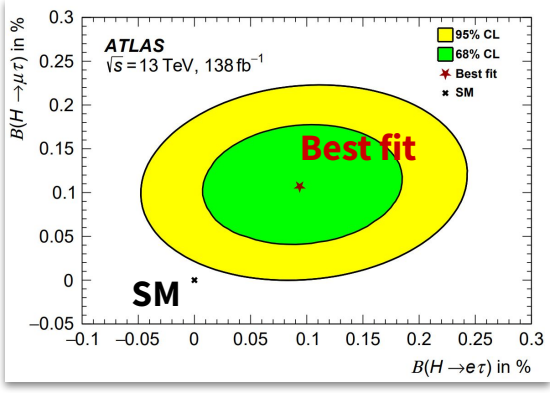
- Observed (expected) limits at 95% CL :
  BR(**H->eτ**)< 0.23 % (0.12 %) & BR(**H->μτ**) < 0.17 % (0.09 %)
- Best-fit BR(**H->μτ**)-BR(**H->eτ**) = (0.2 +/- 0.12)%, compatible with zero within 2.5σ



combined prod & decay modes



combined

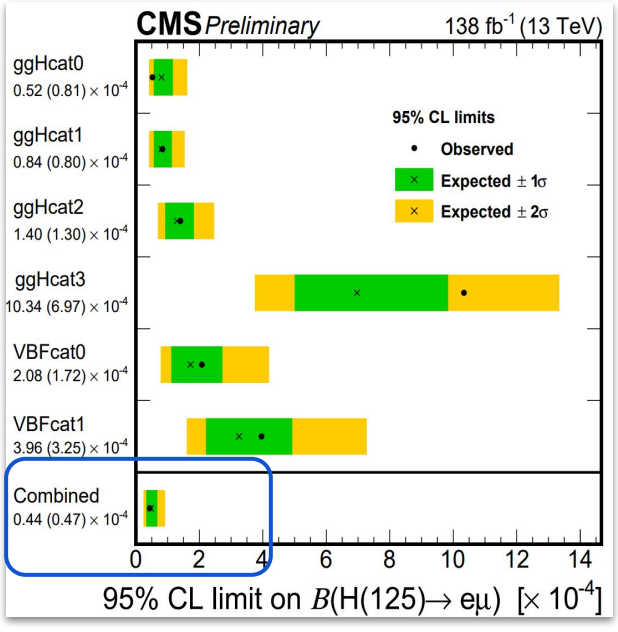


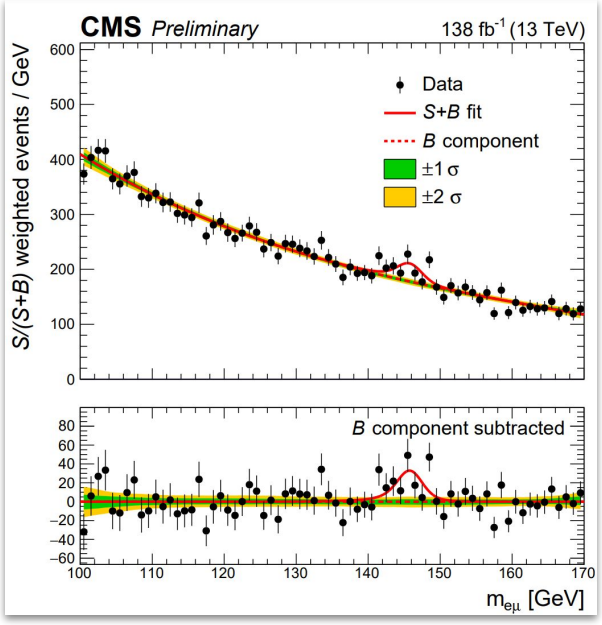
$$\left(\left|Y_{\mu\tau}\right|^2+\left|Y_{\tau\mu}\right|^2\right)=\frac{8\pi}{m_h}\frac{BR(h\to\mu\tau)\Gamma_{SM}}{1-BR(h\to\mu\tau)}$$

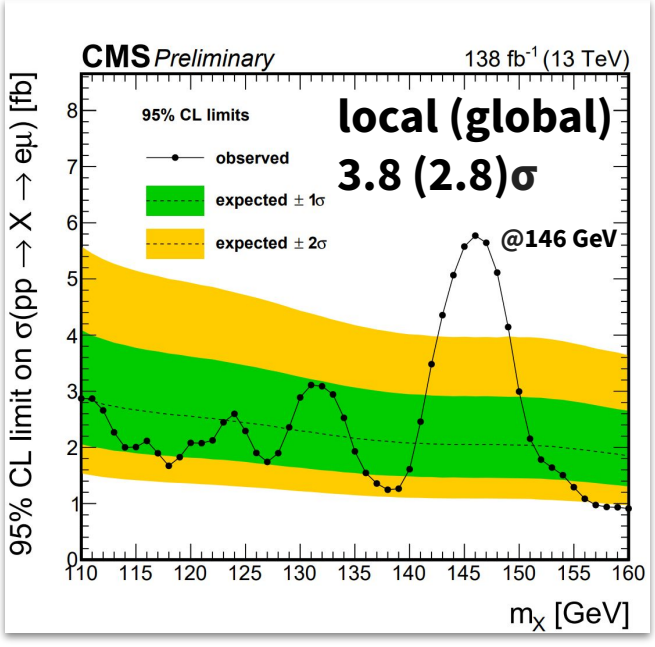
Also, $\sqrt{|Y_{e\tau}|^2+|Y_{\tau e}|^2}$ < 1.4 x 10^{-3} and $\sqrt{|Y_{\mu\tau}|^2+|Y_{\tau\mu}|^2}$ < 1.2 x 10^{-3}

LFV H, X → $e^{\pm}\mu^{\mp}$ Search

- Search for 'both' SM and BSM Higgs boson **H, X→eμ**, where **110 < m_X < 160 GeV**, following a bump hunt strategy.
- Obs (exp) BR: BR(**H_{125}→eμ**) < 0.0044 % (0.0047 %)



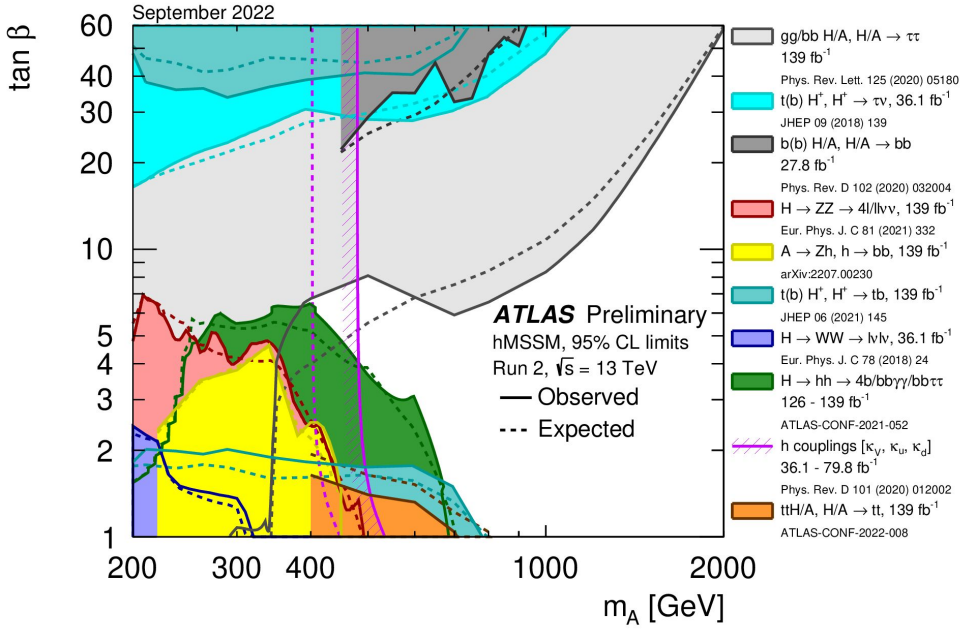


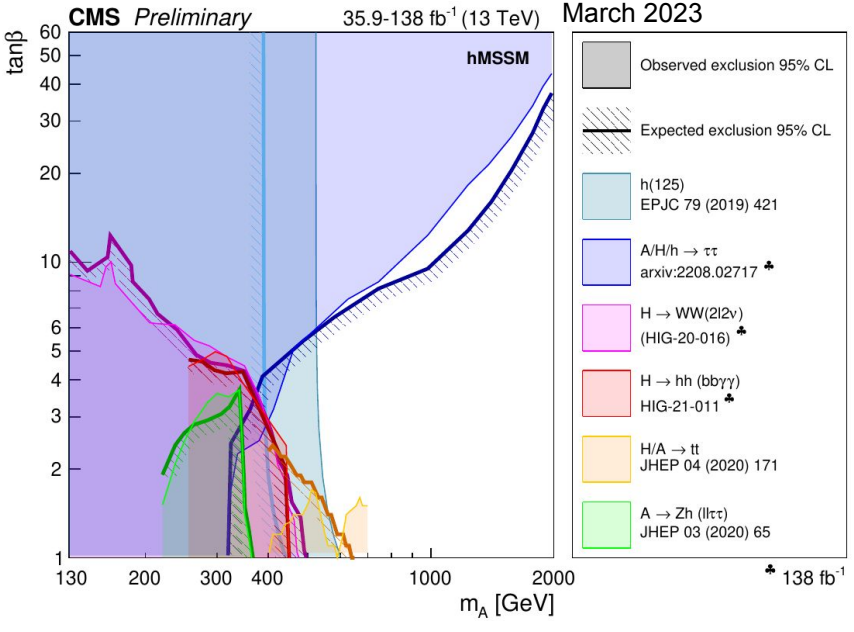


Also, set obs. upper limits on LFV Yukawa coupling : $\sqrt{|Y_{e\mu}|^2 + |Y_{\mu e}|^2} < 1.9 \times 10^{-4}$

Combining into hMSSM

Results for **MSSM Higgs Boson Search :** h_{125} interpreted as lower mass Higgs boson
Regions of the [m_A, tanβ] plane excluded in the hMSSM via direct searches for heavy Higgs boson

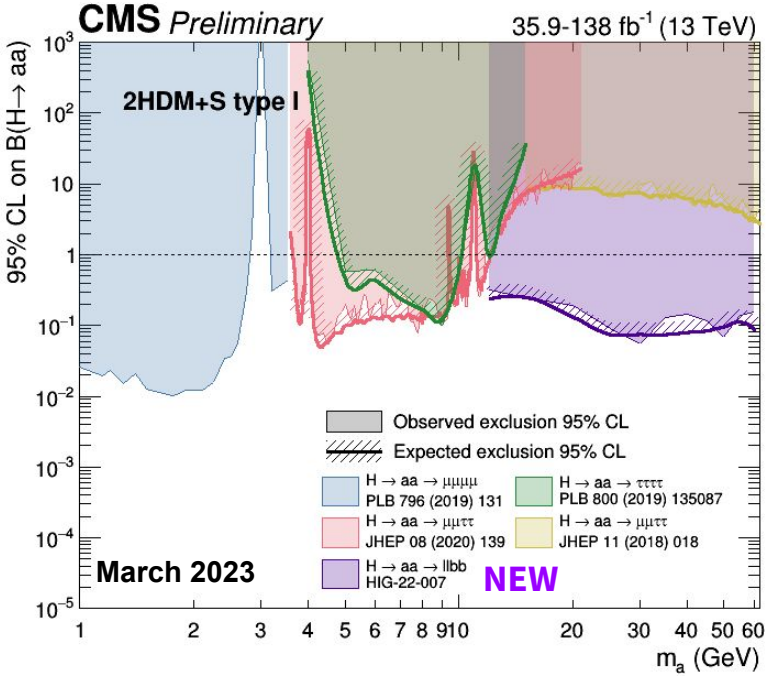


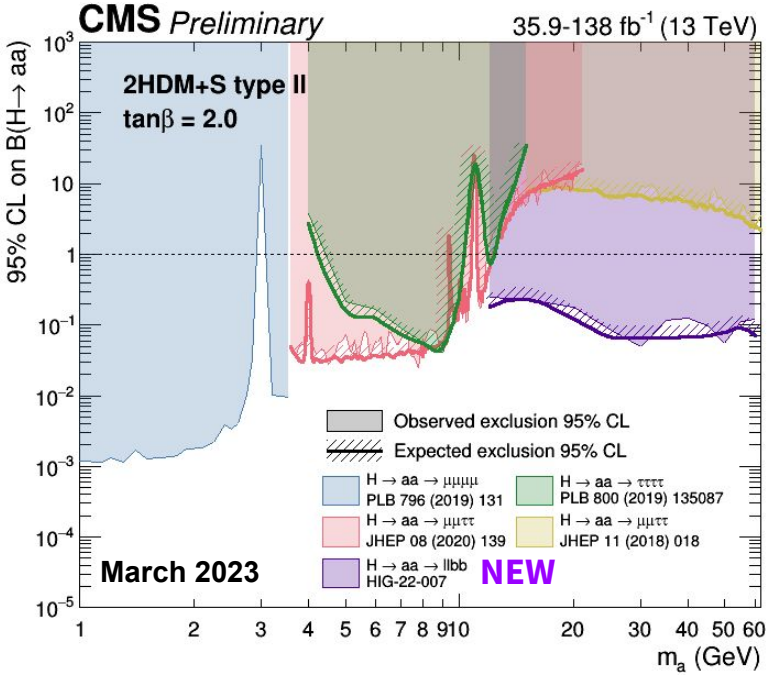


[ATLAS-PHYS-PUB-2022-043]

[CMS public Higgs PAG Summary Plot]

H→aa combining into 2HDM+S



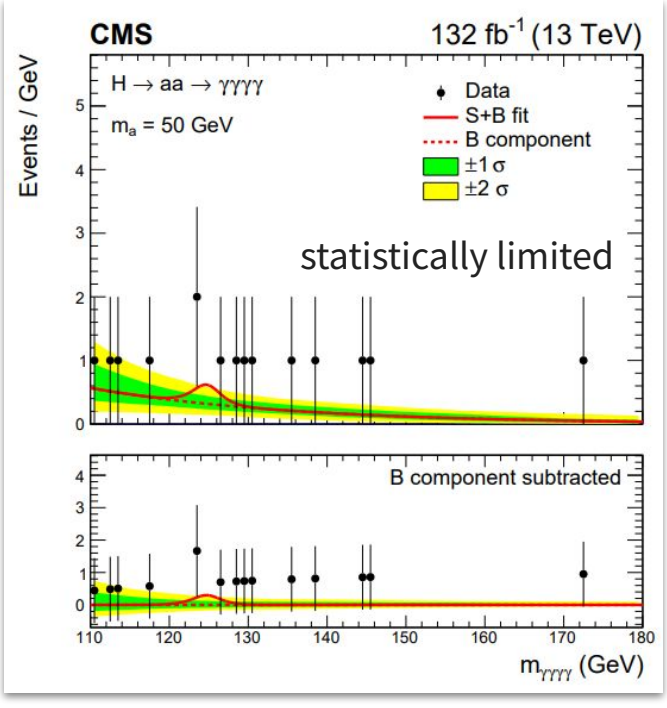


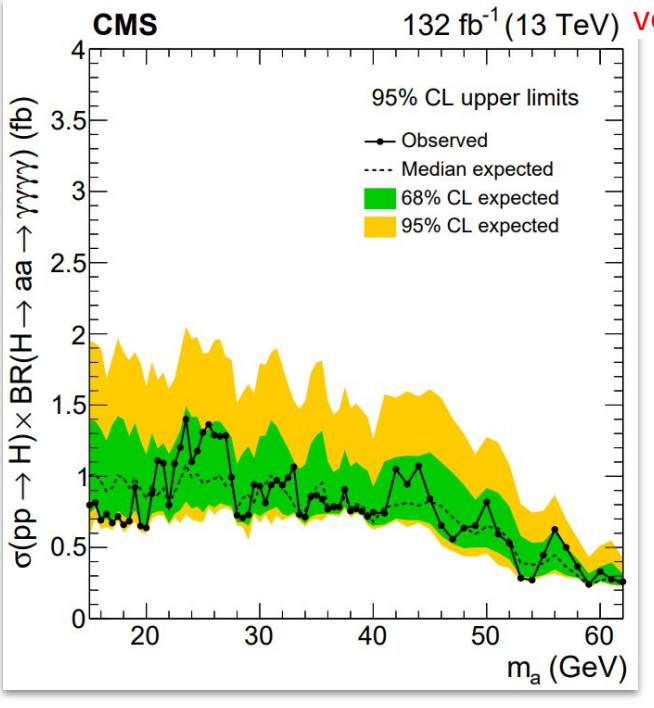
- BR(H→aa) depend on the **Types** and **model parameters**.
- Typically searched **light $M_a < M_H/2$**
- Assuming the S has no direct Yukawa couplings, coupling to fermions are a result of mixing with the Higgs sector.

Exotic decay mode :
SM H → aa search can constraint 2HDM+S that conserve observed features of the SM.

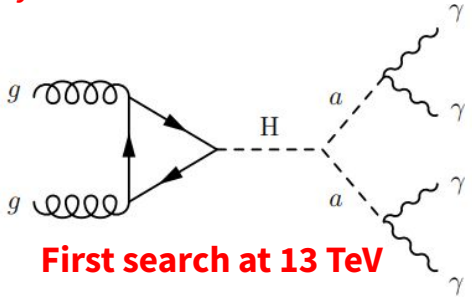
H → aa → 4γ Search

- Search for SM-like H→aa →γγγγ : **well isolated four photons (resolved)**:
- ΔR(γ, γ) or ΔR(γγ, γγ) > 0.2 ⇒ Probes the pseudoscalar mass range **15 < m(a) < 62 GeV**
- To improve sensitivity, train a 4 photon event classifier using variables uncorrelated to m(4γ) and look for a 125 GeV resonance in the m(4γ) spectrum of the signal-like events.





very small contributions from SM



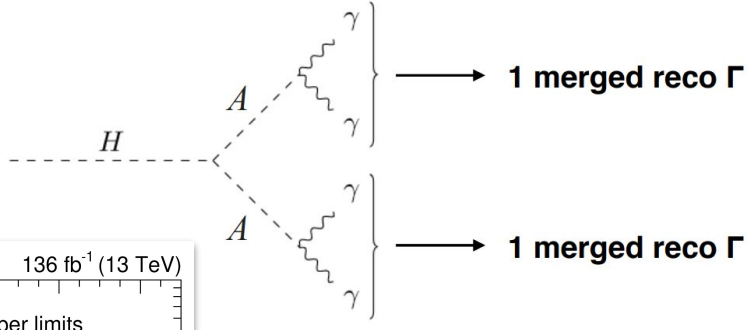
First search at 13 TeV

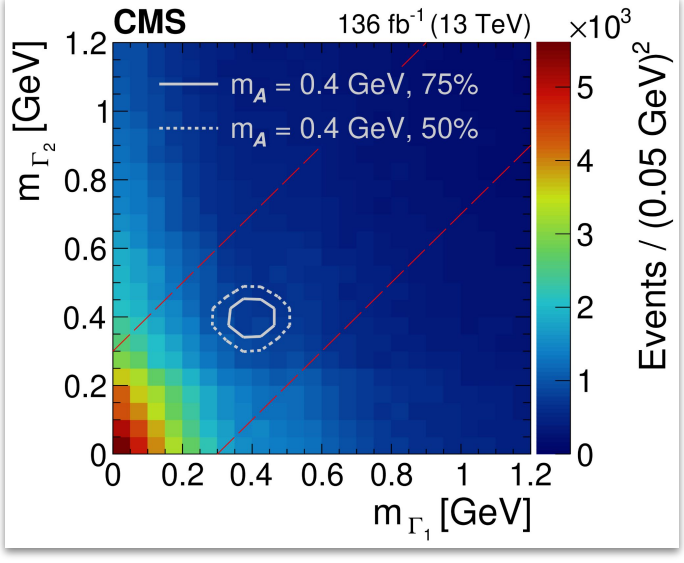
Observed upper limits on cross section range between **0.80 - 0.26 fb**, compared to Higgs production cross section of **52 pb**
BR(H→aa →γγγγ) ~0.001 %

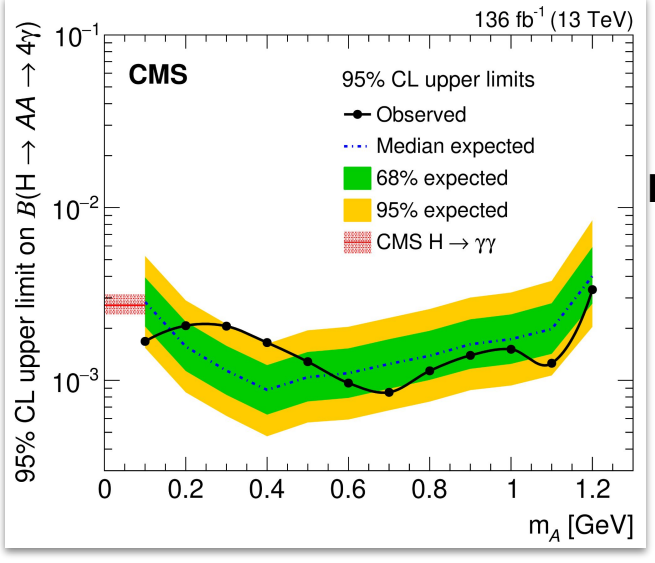
H → aa → 4γ (Merged) Search

- Search for **very low mass pseudoscalars** decaying promptly to a **merged** di-photon
- Probes the pseudoscalar mass range **m(a) < 1.2 GeV**
- Probe merge Γ candidates in the SM H→γγ final state using novel photon reconstruction technique of **end-to-end deep learning**
- Fit 2D distribution of invariant masses $m(\Gamma_1)$ and $m(\Gamma_2)$

*** First search in this topology**







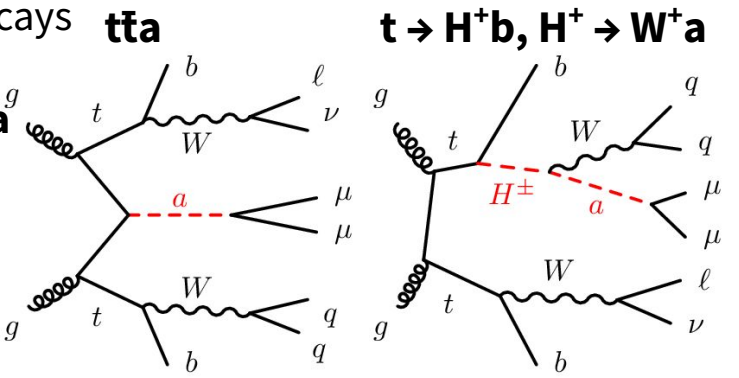
BR(H→aa→4γ) < (0.09–0.33) %

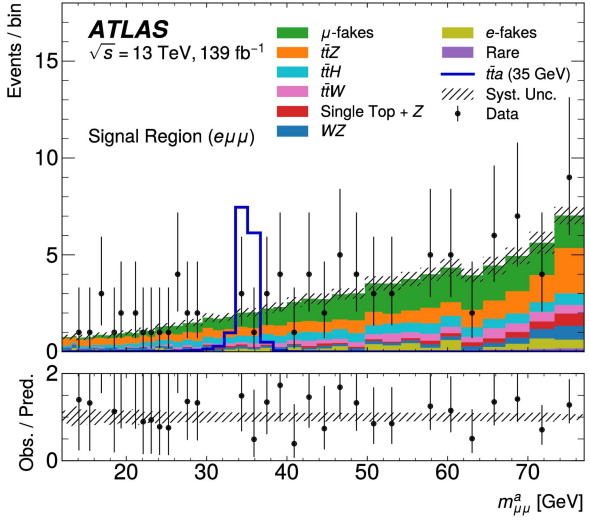
Best constraints for this decay mode in very low mass (0.1 < m < 1.2 GeV)

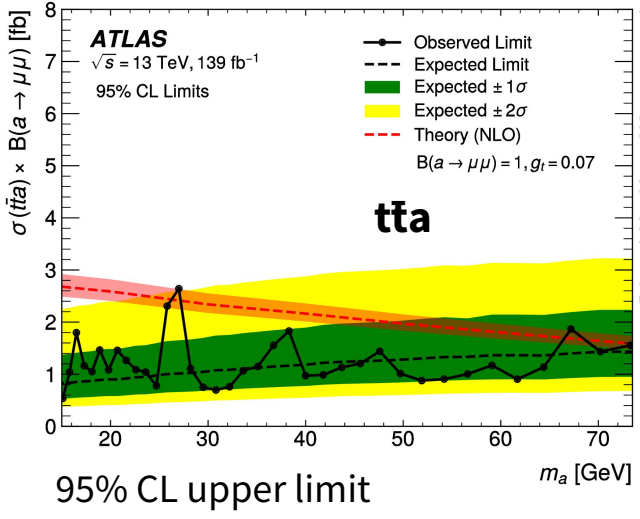
Physics Briefing

Light pseudoscalar a→μμ with tt̄

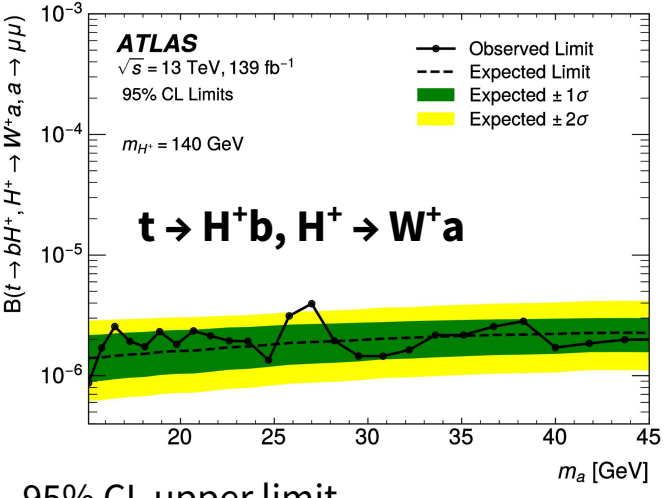
- Search for a **pseudoscalar a** produced with tt, where a decays into clean di-muon (high mass resolution)
- Focus on two direct productions : **tt̄a** , tt̄ with **t → H⁺ → W⁺a**
- Predicted in 2HDM+S, NMSSM, Explain excess of galactic gamma-ray emission.
- **15 < m_a <72 GeV** and **120 ≤ $m_{H^\pm}$≤160 GeV**
- Mild excess at m_a =27 GeV: 2.4σ (local) ⇒ Run-3 data





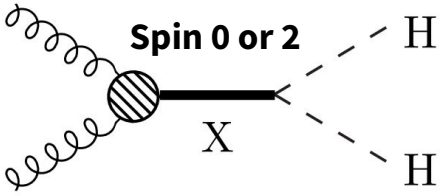


95% CL upper limit
σ(tt̄a)BR(a→ μμ) : (0.5 - 3) fb



95% CL upper limit
σ(t → H⁺b, H⁺→ Wa→μμ):(0.9 - 3.9)x10⁻⁶ fb

Summaries of resonant HH Search

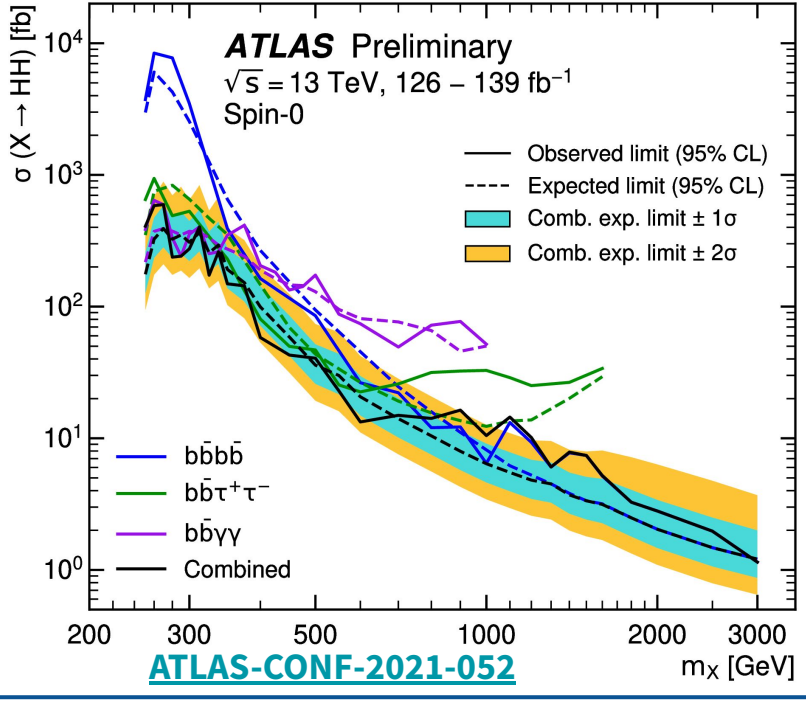


Higgs pair searches (full Run 2) :

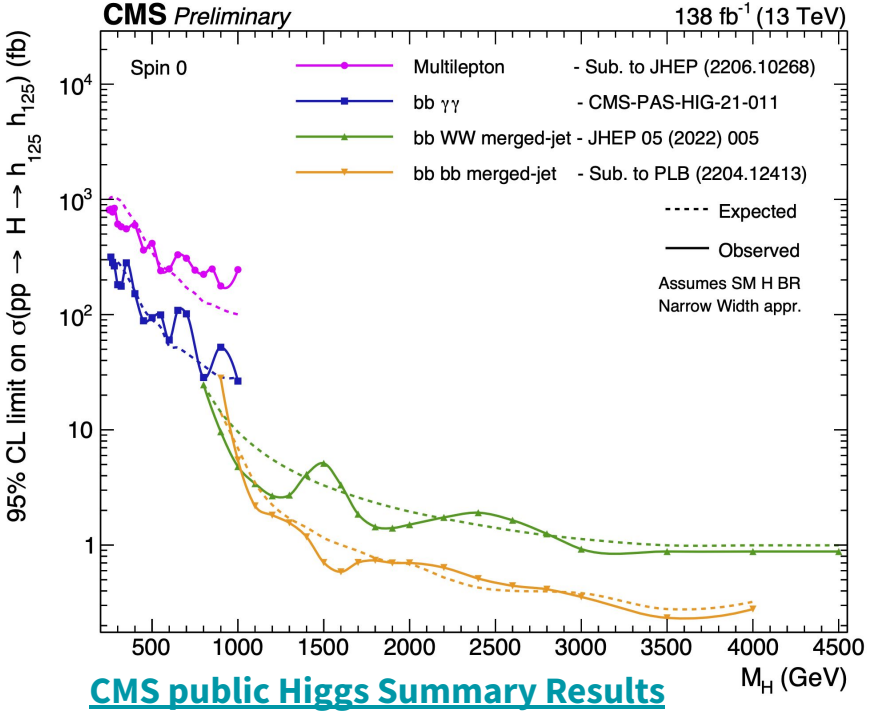
- **bbbb** (ATLAS, CMS), **bbWW** (CMS)
- **bbττ** (ATLAS), **bbγγ** (ATLAS, CMS)
- **WWWW, WWττ, ττττ** (CMS)

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

← Branching Ratio of HH → xxyy



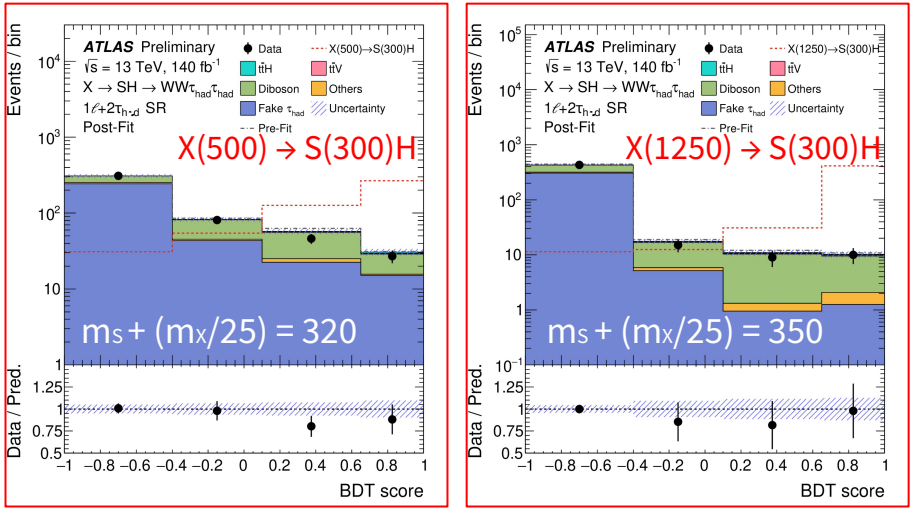
ATLAS-CONF-2021-052

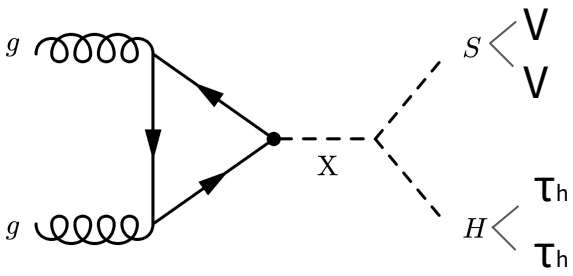


CMS public Higgs Summary Results

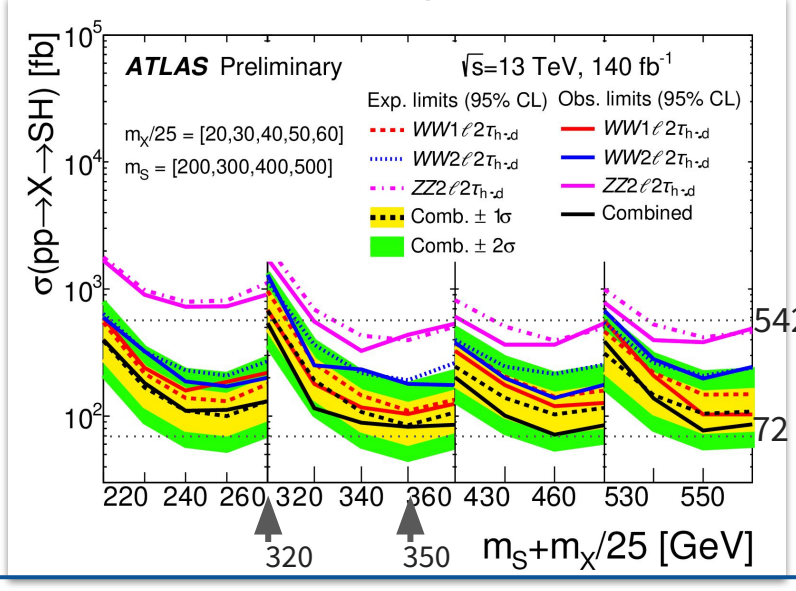
X → SH_{SM} → $VV\tau_h\tau_h$ Search

- Search for heavy scalar X → singlet (S)+ SM Higgs
- Appearing in 2HDM+X, NMSSM
- M_X : 500 - 1500 GeV, M_s : 200 - 500 GeV
- Require :
  H→$\tau_h\,\tau_h$, S →VV → 1 or 2 leptons(= e, μ)
  WW → lνqq' (1l), WW → lνlν (2l), ZZ → llqq, llνν (2l)
- Utilizes BDT discriminant parameterized over M_X
- Fake τ_h measured from DD using CR techniques

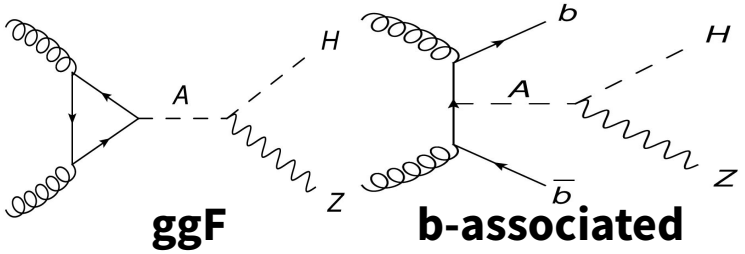




Resulting upper limits @ 95% CL :
σ(pp→X→SH) range : 72 - 542 fb



$A_{heavy} \rightarrow ZH_{heavy} \rightarrow \ell\ell t\bar{t}$, $\nu\bar{\nu}b\bar{b}$ Search

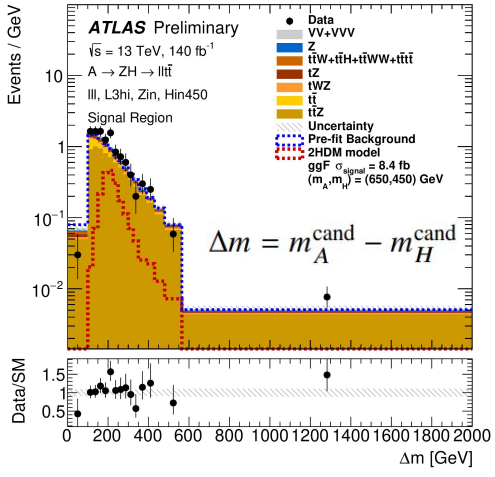


- 2HDM, baryogenesis : CP-odd **M_A > M_H**
- Consider mass ranges:
  M_A > 800 GeV, M_H >350 GeV (2 x Mtop)

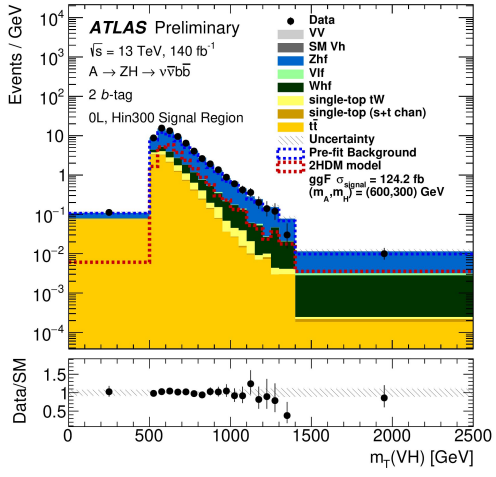
- **lltt Channel** : Z → ll, H → tt (semi-L)
  - 3 leptons : eee, eeμ, eμμ, μμμ
  - ≧ 4 jets and exactly 2 b-tagged

- **vvbb Channel:** Z → νν, H → bb
  - p_T^{miss} > 150 GeV, no charged leptons
  - ≧ 2 jets, exactly 2 b-tagged (ggF)
    or > 2 b-tagged (b-associated)
- Max. local significance of 2.85 σ
  at (M_A, M_H) = (650, 450) GeV for **lltt**

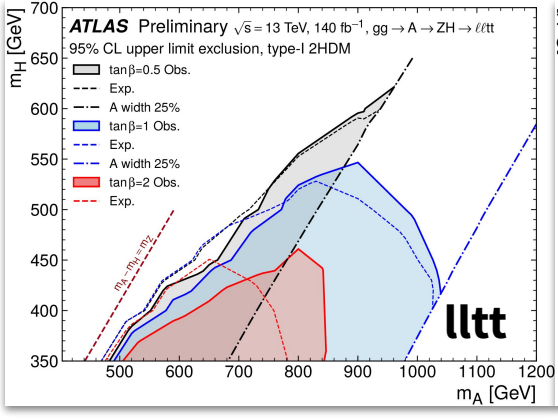
A→ZH→lltt

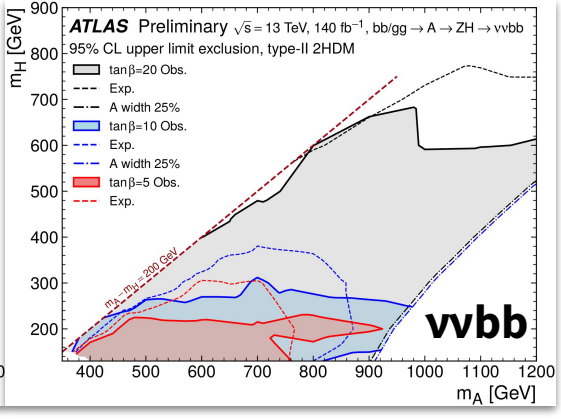


A→ZH→νvbb



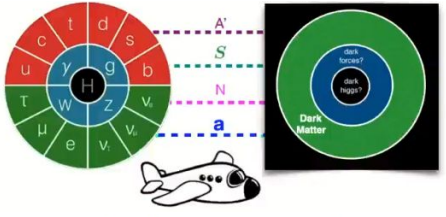
First result in lltt channel & high M(H→bb)





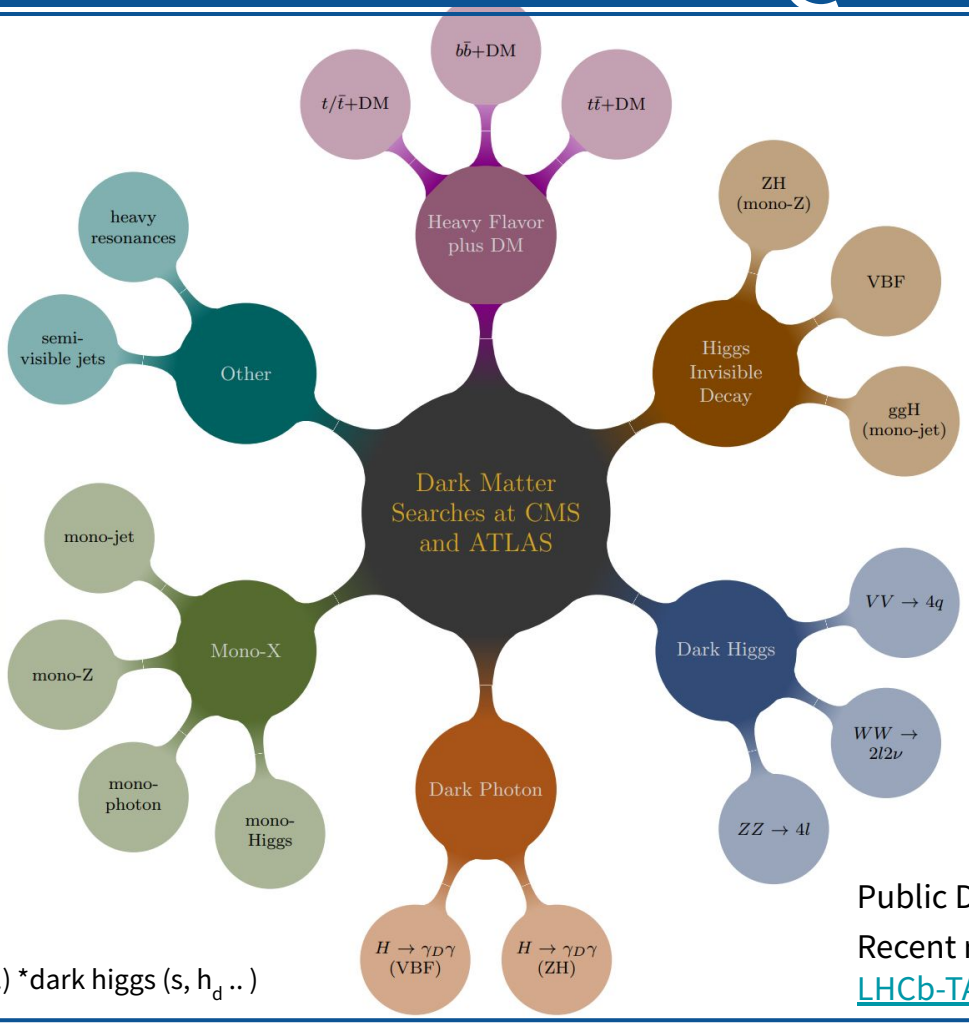
Dark matter Search @ LHC

To extend our searches to unreached scale, we need to add additional particles on the top of dark matter.



Dark sector portals

- dark photon $\epsilon B^{\mu\nu} A'_{\mu\nu}$
- dark scalar H $\kappa |H|^2 |S|^2$
- sterile neutrino $yHLN$
- ALP $g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$



2HDM+a combination
ATLAS-EXOT-2018-064

Summary of Higgs Invisible decay
ATLAS *arxiv:2301.10731*
CMS *arxiv:2303.01214*

mono-Higgs
ATLAS *arxiv:2305.12938*

dark higgs (WW+MET)
CMS-PAS-EXO-21-012

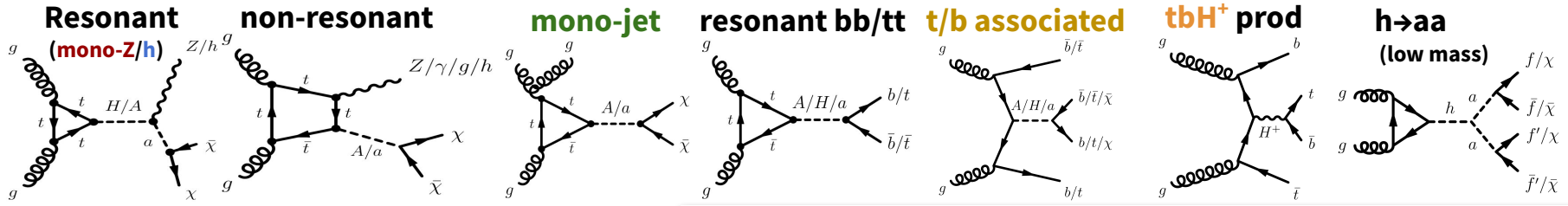
dark photon(ZH→llγA')
ATLAS_HDBS-2019-13

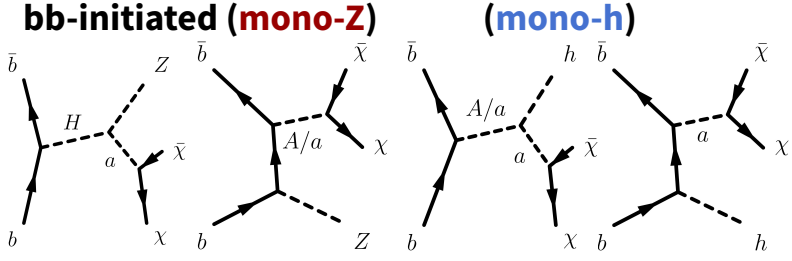
dark higgs dark photon (Z→h$_D$A')
ATLAS-CONF-2023-016

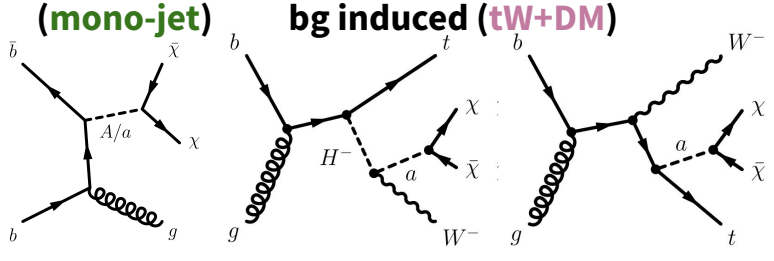
Public DM Results : ATLAS , CMS
Recent results of Dark Sector @ LHCb
LHCb-TALK-2023-060

Stefania Gori *dark photon (A' , γ_d ..) *dark higgs (s, h_d ..)

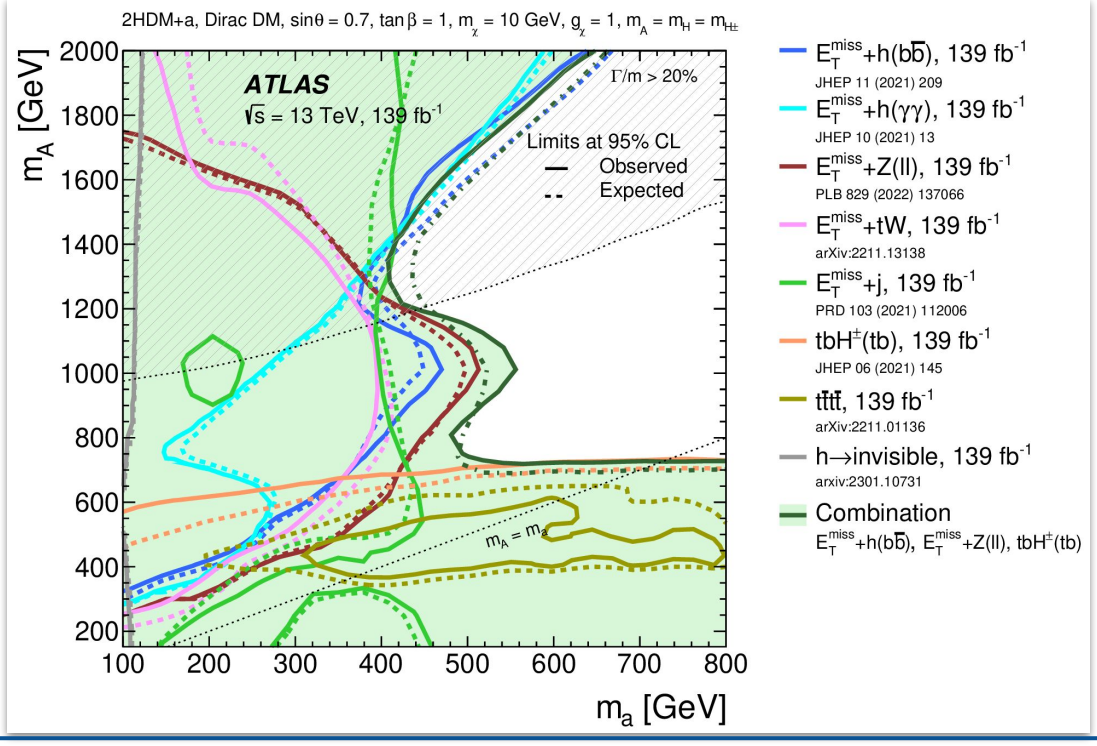
Combination of 2HDM+a DM Searches



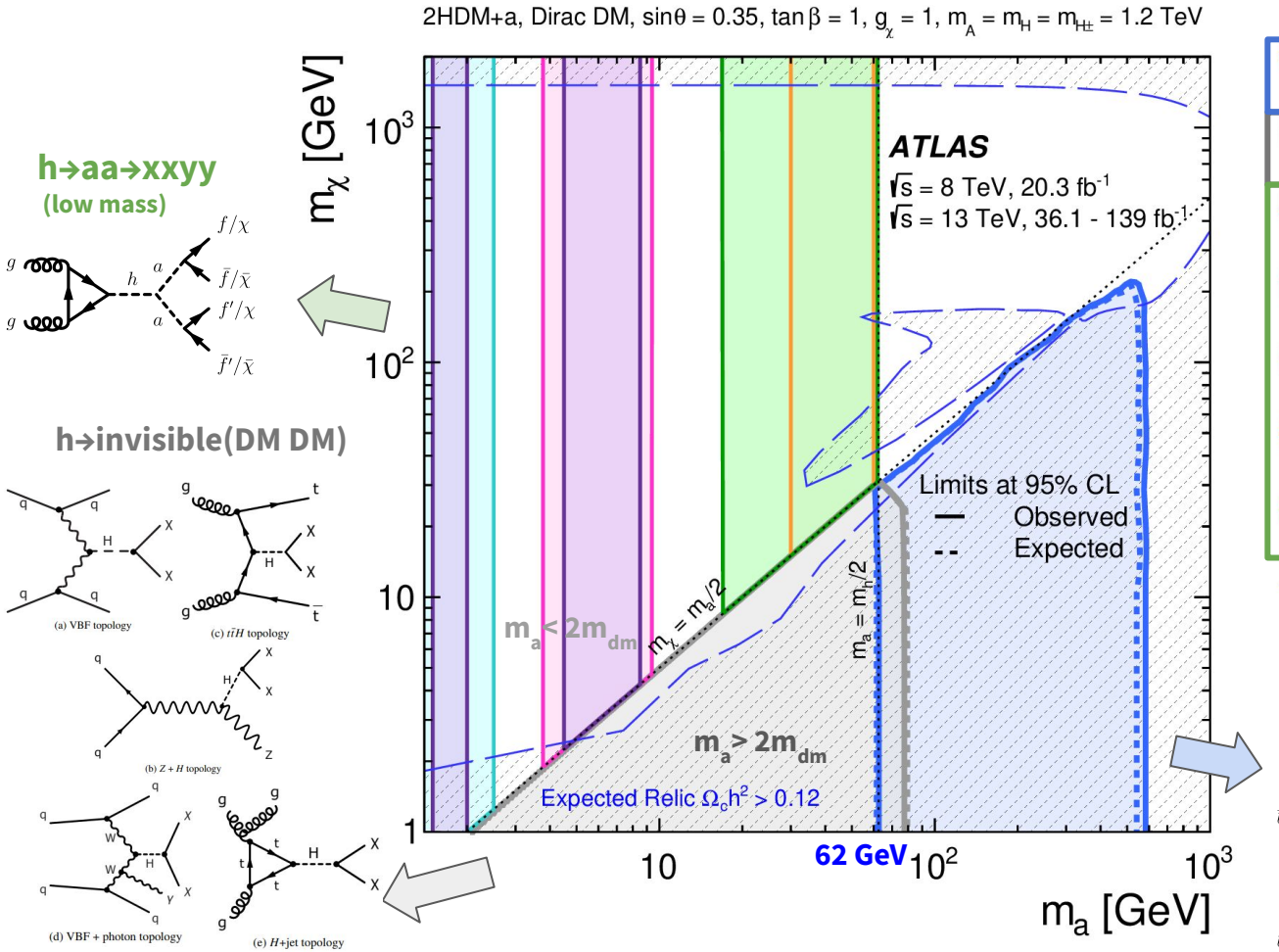




Higgs not only provides mass, it could also serve as a portal into darkness !



Combination of 2HDM+a DM Searches

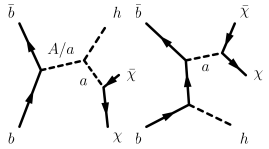


- E_T^{miss}+h(bb̄), 139 fb^{-1} — JHEP 11 (2021) 209
- h→invisible, 139 fb^{-1} — arxiv:2301.10731
- h→aa→μμττ, 20.3 fb^{-1} — PRD 92 (2015) 052002
- h→aa→μμμμ, 36.1 fb^{-1} — JHEP 06 (2018) 166
- h→aa→μμμμ, 139 fb^{-1} — JHEP 03 (2022) 041
- h→aa→bbbb, 36.1 fb^{-1} — JHEP 10 (2018) 031
- h→aa→bbμμ, 139 fb^{-1} — PRD 105 (2022) 012006
- Observed Relic $\Omega_c h^2 = 0.12$

next slide

*first time, including h→ aa searches in this limits

mono-h

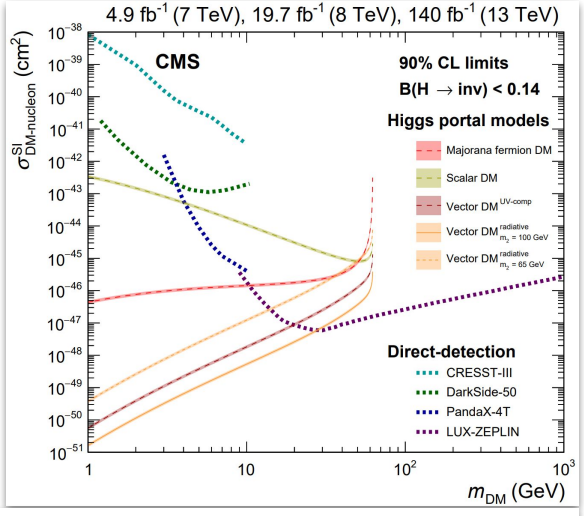


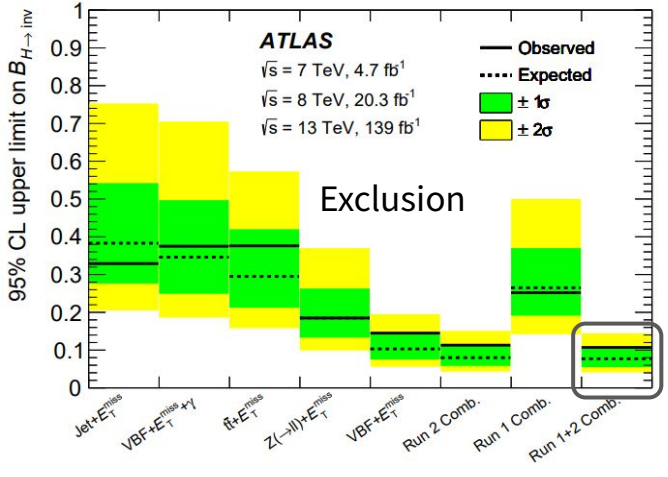
Invisible Higgs decays

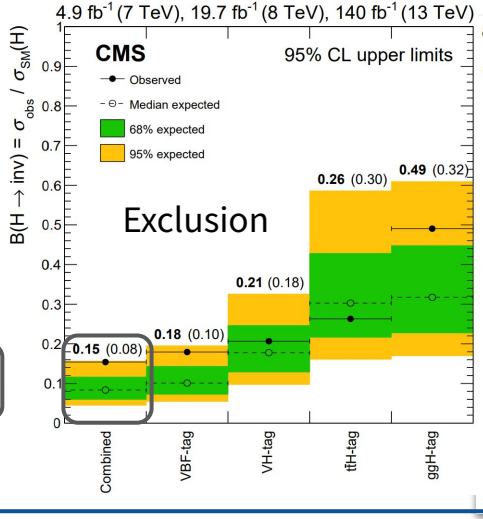
- Search for possible Higgs decay in Dark Matter
- SM expectation BR(H→inv) ~ 0.1 % (given by ZZ* → 4ν)
  ⇒ Enhanced decay in models, where $\mathbf{m_{DM} < m_H/2}$ light enough
- Combination between all the signatures in Run 1+2

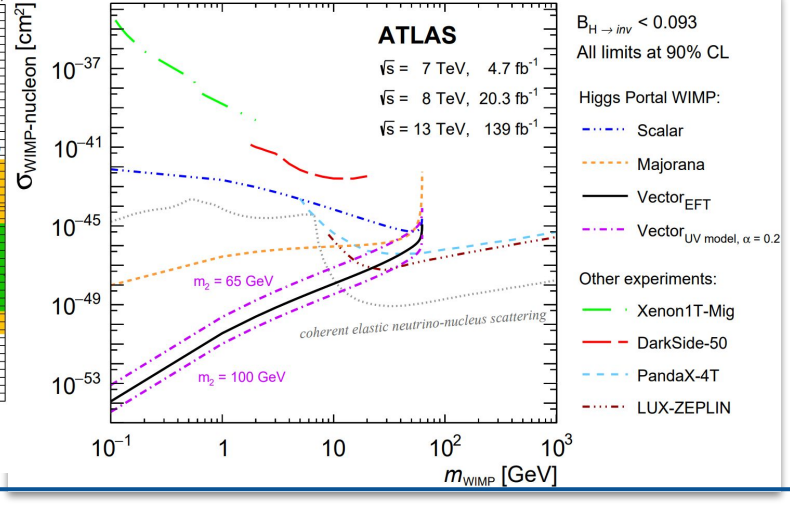
ATLAS : **BR(H→inv) < 10.7%** (7.7 % expected) @ 95% CL
CMS : **BR(H→inv) < 15%** (8 % expected) @ 95% CL

$$B(H \to \text{inv}) = \frac{\Gamma_{\text{inv}}}{\Gamma_{\text{SM}}+\Gamma_{\text{inv}}}$$
$$\Gamma_{\text{SM}} = 4.07\text{MeV}$$



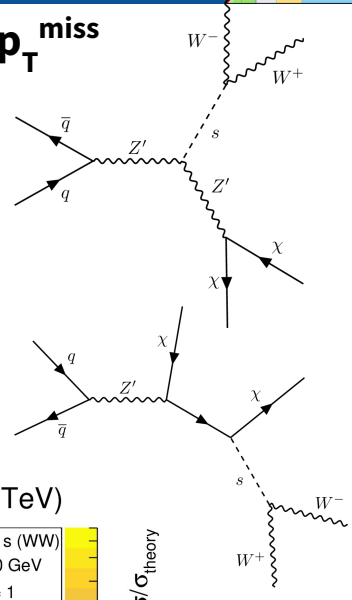




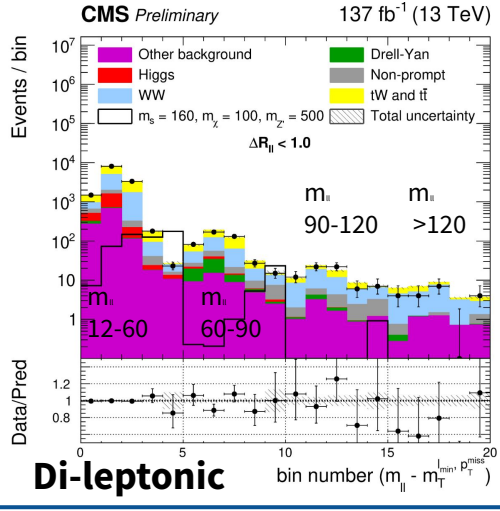


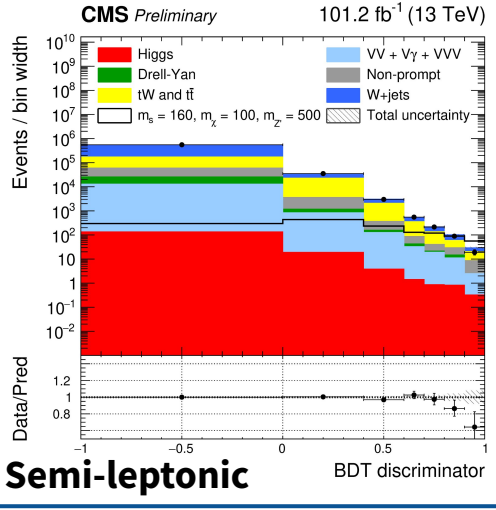
Dark higgs ($Z' \to s\chi\chi$, $s \to W^+W^-$)

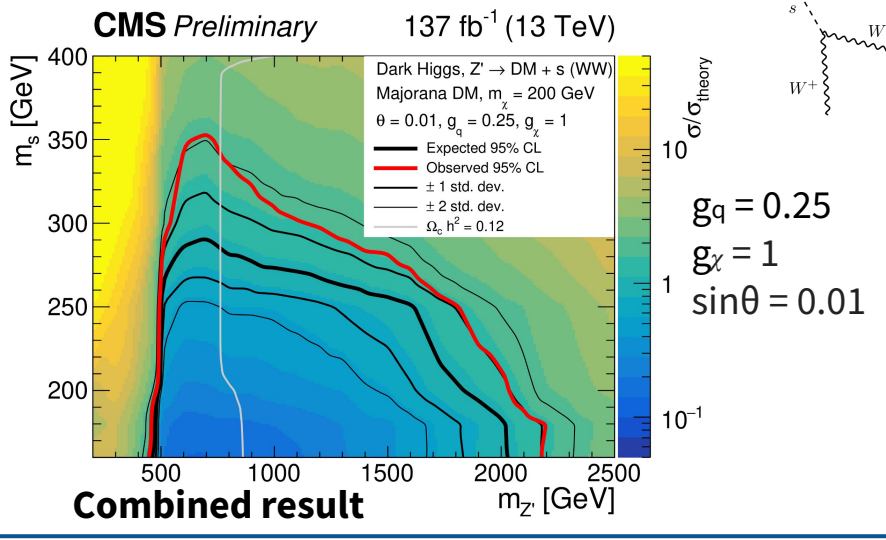
- Search for Dark matter and dark higgs in **WW** (decay of dark Higgs singlet **s**) + $\mathbf{p_T^{miss}}$
- $\mathbf{m_\chi}$ **: 100 – 300 GeV**, $\mathbf{m_{Z'}}$ **: 200–2500 GeV**, $\mathbf{m_s}$ **: 160 –400 GeV** (WW highest BR)
- 2 final states : Di-leptonic (μe, eμ) , Semi-leptonic(1 lep+ ≧ 2jets)
- Discriminators :
  (m_T of subleading lepton and p_T^{miss}- m_{ll}) in di-leptonic channel
  ues BDT in semi-leptonic channel



Most stringent limit for m_{DM} = 200 GeV : m_s < 350 GeV exclude at $m_{Z'}$ = 700 GeV
$m_{Z'}$ < 2200 GeV excludes at m_s = 160 GeV

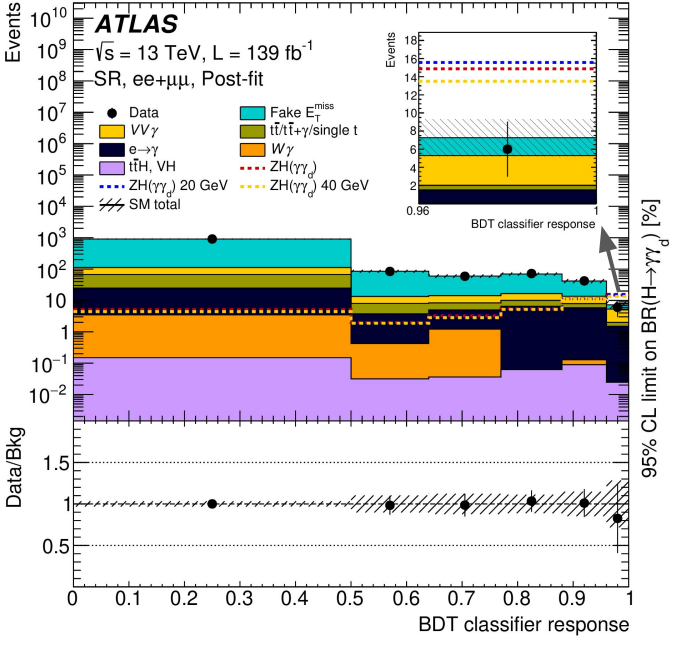


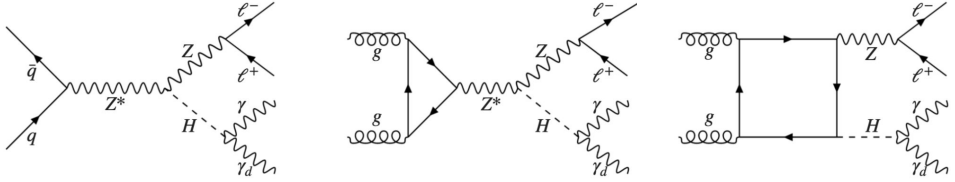




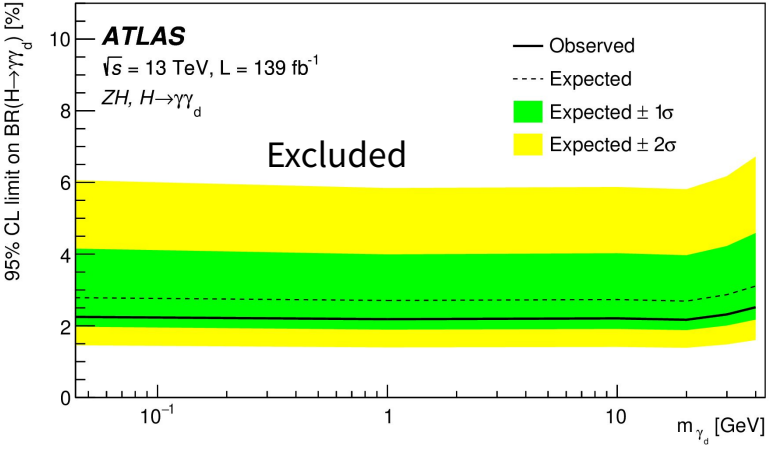
Dark photons Search ($ZH \to ll\gamma\gamma_d$)

- Search for SM Higgs boson decaying into dark photon γ_d in VH production topology. (leptonic)
- Considering the signal with massless/massive γ_d
- A BDT has been used to distinguish signal events from the SM background
- Set constraint on BR ($H \to \gamma\gamma_d$) ~ 2 %





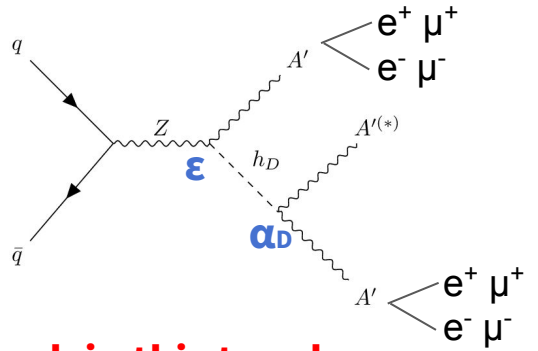
95% CL exclusion limits on BR($H \to \gamma\gamma_d$) for m_{γ_d}



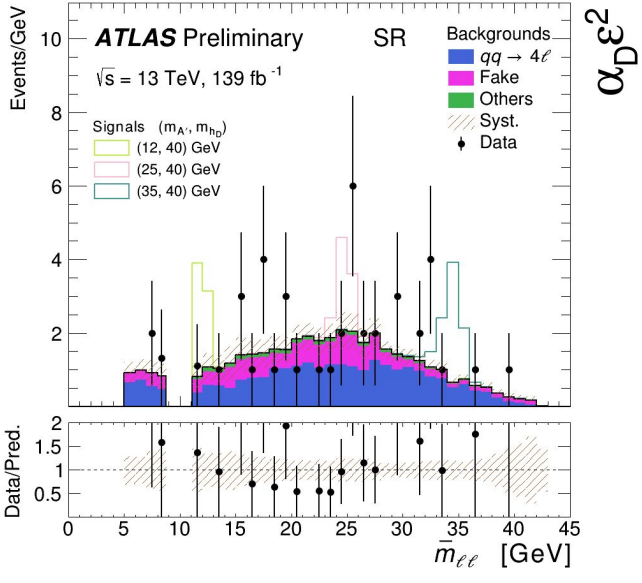
m_{γ_d} [GeV]	$BR(H \to \gamma\gamma_d)^{95\%\,CL}_{obs}$ [%]	$BR(H \to \gamma\gamma_d)^{95\%}_{exp}$ [%]
0	2.28	$2.82^{+1.33}_{-0.84}$
1	2.19	$2.71^{+1.28}_{-0.81}$
10	2.21	$2.73^{+1.31}_{-0.82}$
20	2.17	$2.69^{+1.29}_{-0.81}$
30	2.32	$2.87^{+1.36}_{-0.86}$
40	2.52	$3.11^{+1.48}_{-0.93}$

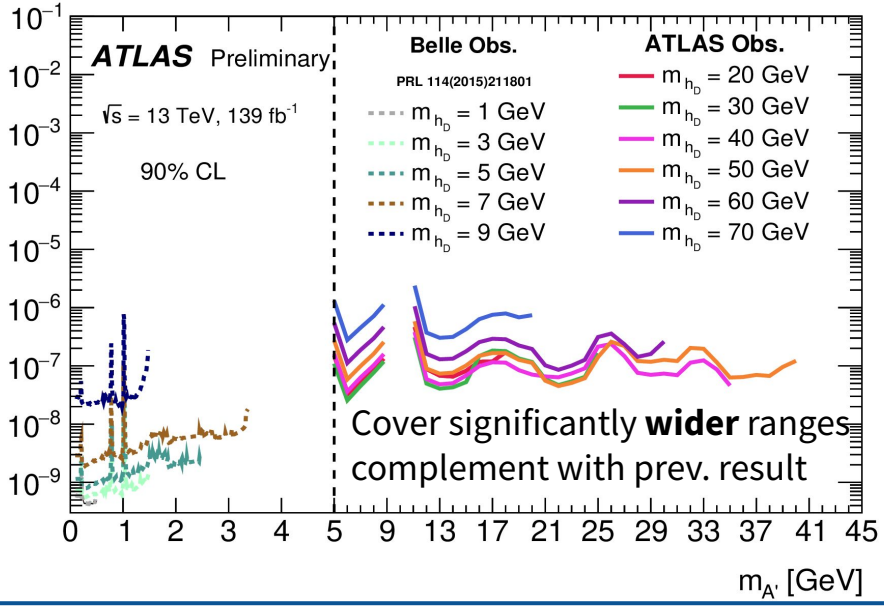
Dark photons Search ($Z \to A' h_D$, $h_D \to A'A'^*$)

- A search for the **dark photon A'** produced in association with the **dark Higgs boson h_D** via **rare SM Z decays**.
- **Higgs strahlung** : sensitive to coupling A'–SM (ε) and A'–h_D (α_D)
- In final state : at least two A's decay into **pairs of leptons**
- Discriminator : average dilepton mass $\bar{m}_{\ell\ell} = (m_{\ell_1\ell_2} + m_{\ell_3\ell_4})/2$
- Focusing on **$m_{A'}$: 5 –40 GeV, m_{hD} : 70 GeV ($m_{hD} > m_{A'}$)**



*** First search in this topology**

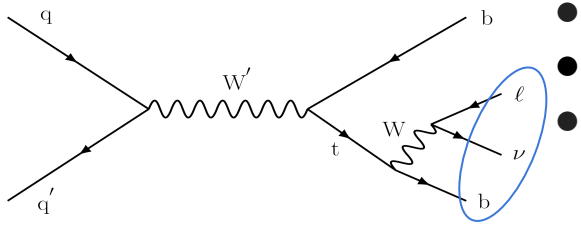




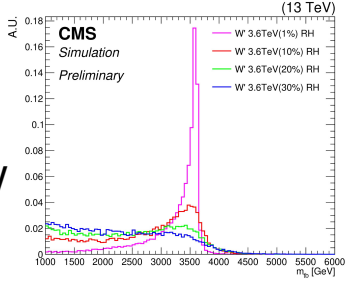
veto
m(ϒ) region
[8.8 –11.1] GeV

W' → tb Search

W'->lnu Search with full Run2 (CMS)
covered on Tue **Parallel: Collider Physics**

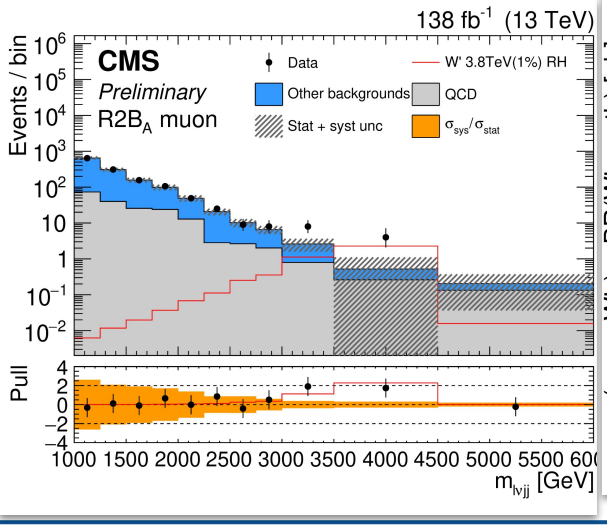


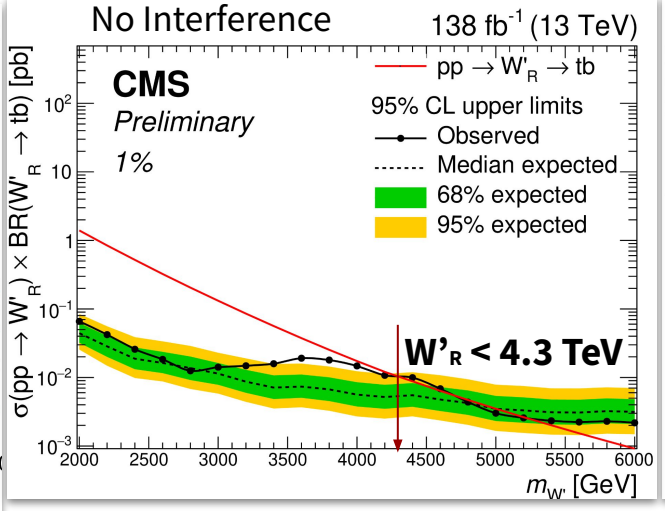
- Search for W' range **2 – 6 TeV** , following a bump hunt strategy in m
- Event with one muon or electron + At least two ak4 jets
- Probe different width scenarios($\Gamma_{W'}/M_{W'}$): 1, 10, 20, 30%
- Categorization based on N_b and b-tagging condition of top jet and W' jet

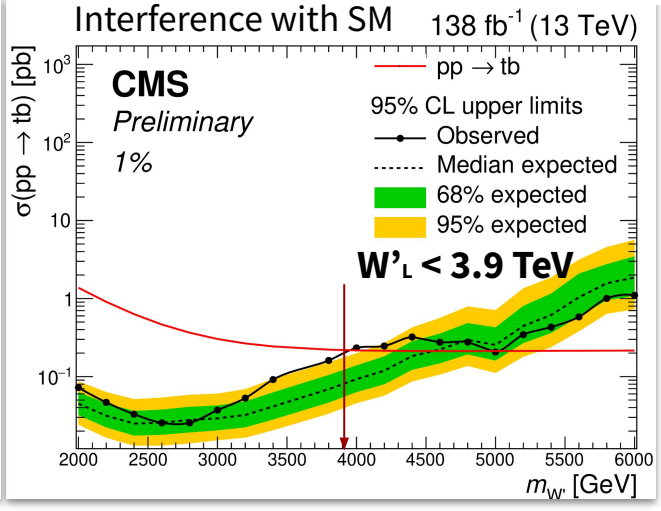


Selecting jet from top decay
M(lvj) closest to top mass
ΔR closest to lepton and subleading

Largest local (global) excess around W'@3.8 TeV
for 1 % width with significance : 2.6 σ (2.0 σ)

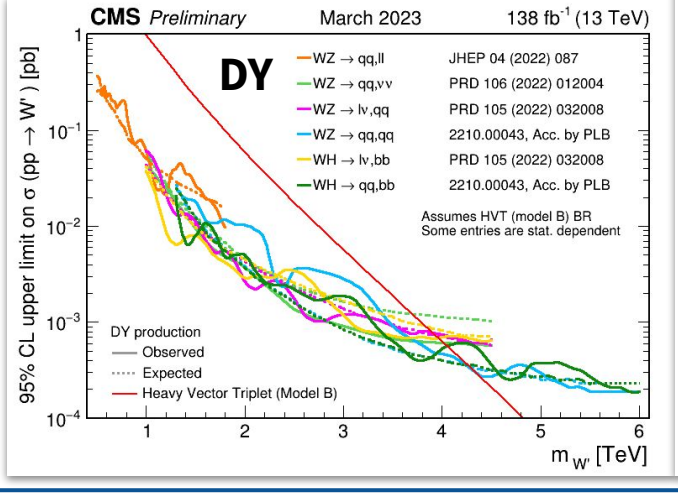


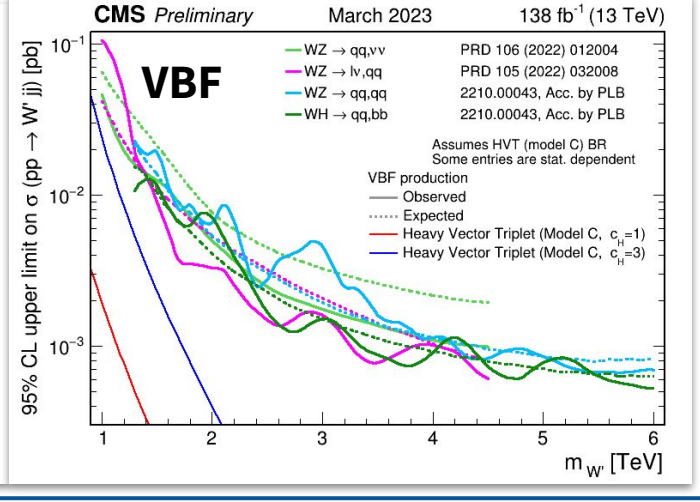


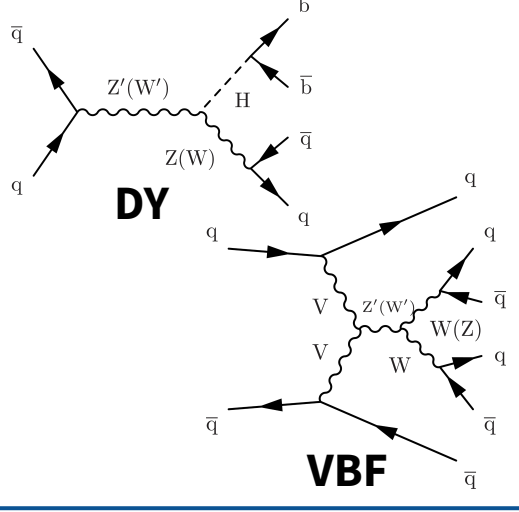


W' → WZ(H) Search


Gauge bosons
SSM $Z' \to \ell\ell$ 2 e, μ – – 139 Z' mass 5.1 TeV 1903.06248
SSM $Z' \to \tau\tau$ 2 τ – – 36.1 Z' mass 2.42 TeV 1709.07242
Leptophobic $Z' \to bb$ – 2 b – 36.1 Z' mass 2.1 TeV 1805.09299
Leptophobic $Z' \to tt$ 0 e, μ ≥1 b, ≥2 J Yes 139 Z' mass 4.1 TeV 2005.05138
SSM $W' \to \ell\nu$ 1 e, μ – Yes 139 W' mass 6.0 TeV 1906.05609
SSM $W' \to \tau\nu$ 1 τ – Yes 139 W' mass 5.0 TeV ATLAS-CONF-2021-025
SSM $W' \to tb$ – ≥1 b, ≥1 J – 139 W' mass 4.4 TeV ATLAS-CONF-2021-043
HVT $W' \to WZ \to \ell\nu qq$ model B 1 e, μ 2 j / 1 J Yes 139 W' mass 4.3 TeV 2004.14636
HVT $W' \to WZ \to \ell\nu \ell'\ell'$ model C 3 e, μ 2 j (VBF) Yes 139 W' mass 340 GeV 2207.00230
HVT $W' \to WH \to \ell\nu bb$ model B 1 e, μ 1-2 b, 1-0 j Yes 139 W' mass 3.3 TeV 2207.00230
HVT $Z' \to ZH \to \ell\ell/\nu\nu bb$ model B 0,2 e, μ 1-2 b, 1-0 j Yes 139 Z' mass 3.2 TeV 2207.00230
LRSM $W_R \to \mu N_R$ 2 μ 1 J – 80 W_R mass 5.0 TeV 1904.12679
ATLAS
$\Gamma/m = 1.2\%$
$g_V = 3$
$g_V c_H = 1, g_f = 0$
$g_V = 3$
$g_V = 3$
$m(N_R) = 0.5$ TeV, $g_L = g_R$
resonances
W', HVT B
▷ W' (2016 combination) PLB 798 (2019) 134952 4.3
▷ W' → WZ → ℓℓqq̄ JHEP 09 (2018) 101 2.7
▶ W' → WZ → νν qq̄ PRD 106 (2022) 012004 4.0
▷ W' → WH → qq̄ττ̄ JHEP 01 (2019) 051 2.6
▶ W' → WZ → qq̄qq̄ 2210.00043, Sub. to PLB 4.4
▶ W' → WH → ℓνqq̄ PRD 105 (2022) 032008 4.0
▶ W' → WZ → ℓνqq̄ PRD 105 (2022) 032008 3.9
▶ R → ZZ → νν qq̄ PRD 106 (2022) 012004 2.9
138 fb⁻¹
96.5 fb⁻¹
36 fb⁻¹
CMS
W'→tb
▷ W' → tb, 1ℓ (RH) $M_{\nu_R} > M_{W'}$ PLB 777 (2018) 39 3.6
▶ W' → tb, 0ℓ, (LH) PLB 820 (2021) 136535 3.4
▶ W' → tb, 0ℓ, (RH) PLB 820 (2021) 136535 3.4


CMS Preliminary March 2023 138 fb⁻¹ (13 TeV)
DY
WZ → qq,ll JHEP 04 (2022) 087
WZ → qq,νν PRD 106 (2022) 012004
WZ → lν,qq PRD 105 (2022) 032008
WZ → qq,qq 2210.00043, Acc. by PLB
WH → lν,bb PRD 105 (2022) 032008
WH → qq,bb 2210.00043, Acc. by PLB
Assumes HVT (model B) BR
Some entries are stat. dependent
DY production
Observed
Expected
Heavy Vector Triplet (Model B)
95% CL upper limit on σ (pp → W') [pb]
m W' [TeV]


CMS Preliminary March 2023 138 fb⁻¹ (13 TeV)
VBF
WZ → qq,νν PRD 106 (2022) 012004
WZ → lν,qq PRD 105 (2022) 032008
WZ → qq,qq 2210.00043, Acc. by PLB
WH → qq,bb 2210.00043, Acc. by PLB
Assumes HVT (model C) BR
Some entries are stat. dependent
VBF production
Observed
Expected
Heavy Vector Triplet (Model C, c_H=1)
Heavy Vector Triplet (Model C, c_H=3)
95% CL upper limit on σ (pp → W' jj) [pb]
m W' [TeV]


q
q̄
Z'(W')
H
b
b̄
Z(W)
q̄
q
DY
V
Z'(W')
W(Z)
V
W
VBF

Conclusion

- A lot of progress in BSM Higgs, W', and DM searches have made with LHC Run-2 datasets with excellent ATLAS and CMS detectors.
- Some of mild excesses worth keeping an eye on, but no convincing sign of BSM physics have shown up yet.
- A special role will be covered by the Higgs boson

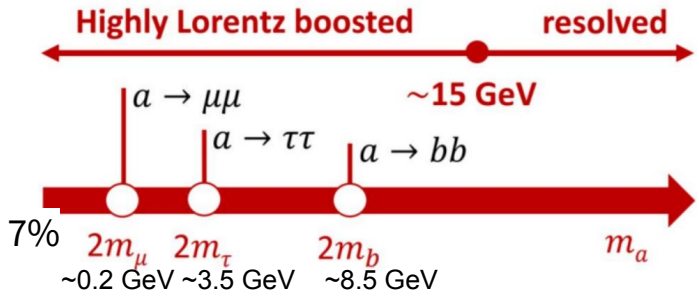
- LHC data will be 2 times in size for Run 3 (2022-2025), and up to 10 times in size for the high-luminosity LHC (expected 2029 -)
- Run 3 will provide a significant boost in statistics to search for New Physics.

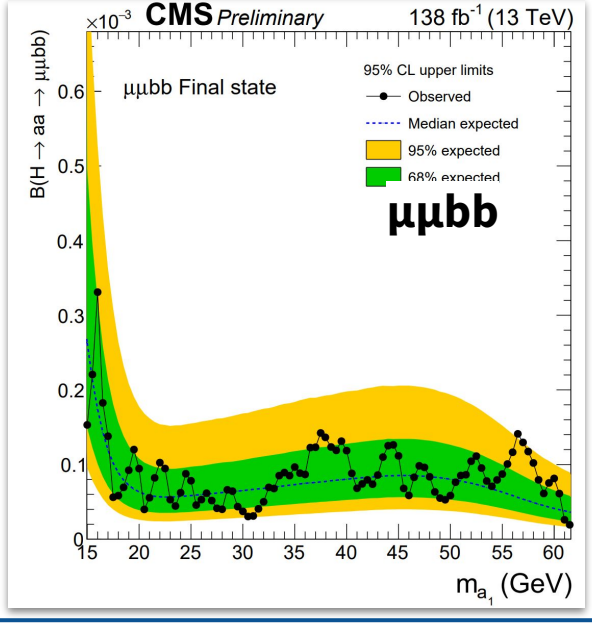
Stay tuned for many more interesting results with Run-2 & Run-3 !!!

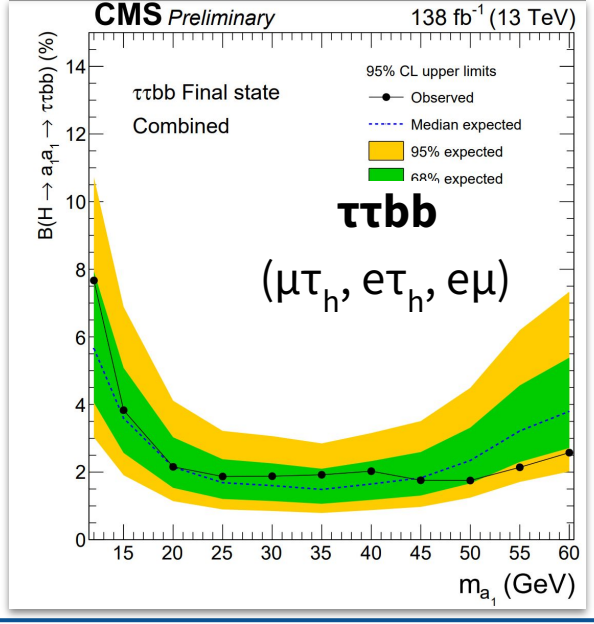
Thank you for your attention

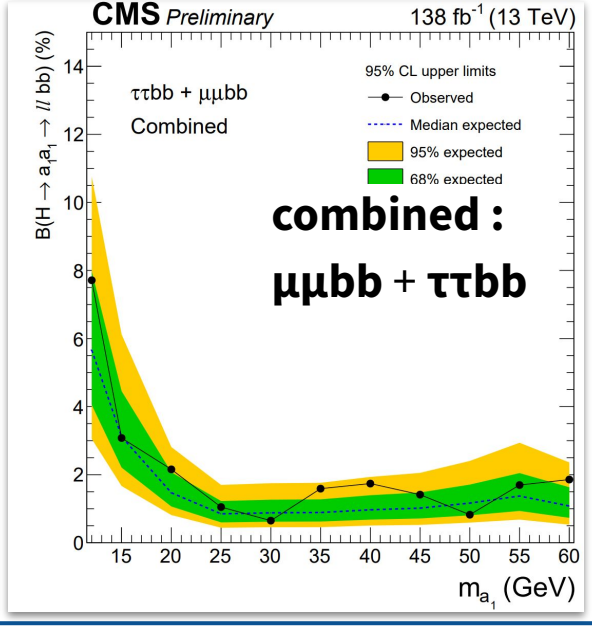
H → aa → μμbb, ττbb Search

- Covers range **15,12 < m(a) < 62 GeV** (Resolved)
- Type-independent limits on BR(H→aa→llbb) in **2HDM+S** are derived combining μμbb + ττbb as a function of $\mathbf{m_a}$
- **μμbb** + **ττbb** combination :
  BR(H→aa) values excluded above 23% (Typ-2 tanβ > 1), (Type-3 tanβ = 2.0), and 15 % (Type-4 tanβ =0.5)









LFV H → $e^{\pm}\tau^{\mp}$ / $\mu^{\pm}\tau^{\mp}$ Search

- **Background**
- The top-quark processes :34%–54% of the total background, $Z \to \tau\tau$: 23% (11%) of the total background in the non-VBF (VBF) SR
- Diboson:19%–32% of the total background, $Z \to \mu\mu$: 2% (sizable on μτ)
- Misidentified : A data-driven method is used → contribution from events having at least one light lepton originating from heavy-flavour decays, photon conversion, a jet or a τh misidentified as a light lepton

Selection	$\ell\tau_{\ell'}$	$\ell\tau_{\text{had}}$
Baseline	exactly $1e$ and 1μ, OS τ_{had}-veto b-veto $p_{\text{T}}^{\ell_1} > 45\ (35)$ GeV MC-template (Symmetry method) $p_{\text{T}}^{\ell_2} > 15$ GeV $30\,\text{GeV} < m_{\ell_1\ell_2} < 150\,\text{GeV}$ $0.2 < p_{\text{T}}^{\text{track}}(\ell_2 = e)/p_{\text{T}}^{\text{cluster}}(\ell_2 = e) < 1.25$ (MC-template) track d_0 significance requirement (see text) $\lvert z_0 \sin\theta\rvert < 0.5$ mm	exactly 1ℓ and $1\tau_{\text{had-vis}}$, OS τ_{had} Tight ID Medium eBDT ($e\tau_{\text{had}}$) b-veto $p_{\text{T}}^{\ell} > 27.3$ GeV $p_{\text{T}}^{\tau_{\text{had-vis}}} > 25$ GeV, $\lvert\eta^{\tau_{\text{had-vis}}}\rvert < 2.4$ $\sum_{i=\ell,\tau_{\text{had-vis}}} \cos\Delta\phi(i, E_{\text{T}}^{\text{miss}}) > -0.35$ $\lvert\Delta\eta(\ell, \tau_{\text{had-vis}})\rvert < 2$
VBF	*Baseline* ≥ 2 jets, $p_{\text{T}}^{j_1} > 40$ GeV, $p_{\text{T}}^{j_2} > 30$ GeV $\lvert\Delta\eta_{jj}\rvert > 3$, $m_{jj} > 400$ GeV	
non-VBF	*Baseline* plus fail *VBF* categorisation – –	 veto events if $90 < m_{\text{vis}}(e, \tau_{\text{had-vis}}) < 100$ GeV

Systematic unvertainties

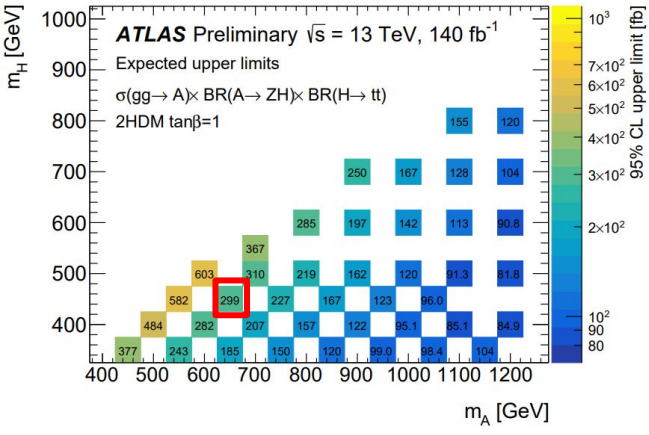
1 POI Source of uncertainty	Impact on observed [10^{-4}] $\hat{\mathcal{B}}(H \to e\tau)$	 $\hat{\mathcal{B}}(H \to \mu\tau)$
Flavour tagging	0.6	0.4
Misidentified background ($\ell\tau_{\text{had}}$)	2.1	1.5
Misidentified background ($\ell\tau_{\ell'}$)	2.9	1.6
Jet and $E_{\text{T}}^{\text{miss}}$	1.1	1.1
Electrons and muons	0.2	0.5
Luminosity	0.6	0.5
Hadronic τ decays	0.9	1.0
Theory (signal)	0.9	0.7
Theory (Z + jets processes)	1.0	1.2
Theory (top-quark processes)	0.3	0.3
Theory (diboson processes)	0.4	0.7
$Z \to \ell\ell$ normalisation	0.2	0.7
Symmetric background estimate	0.2	0.1
Background sample size	4.2	2.4
Total systematic uncertainty	5.3	3.9
Data sample size	2.9	2.7
Total	6.1	4.7

Heavy A → ZH$_{heavy}$ →lltt , ννbb

Table 2: Event selection for the $\ell^+\ell^- t\bar{t}$ channel. SR, CR and VR next to the region name indicate that this region is used as a signal, control or validation region in the fit, respectively.

A→ZH→lltt

Cut	Regions				
	ss (CR)	L3hi_Zout (VR)	Hlo / Hhi (CR)	Hin (SR)	L3lo_Zin (VR)
N leptons	3				
p_T (ℓ_1)	> 27 GeV				
N jets	≥ 4				
N b-jets	2				
$\lvert\eta^{ZH-r.fr.}_{H-cand}\rvert$	$< 2.2 + 0.0004 \cdot m_H^{cand} - 0.0011 \cdot m_A^{cand}$				
p_T (ℓ_3)		> 13 GeV			> 7 GeV & < 13 GeV
Lepton flavour	$ee\mu/\mu\mu e$	$eee/ee\mu/\mu\mu e/\mu\mu\mu$			
OSSF lepton pairs	0	≥ 1			
$\lvert m_Z^{cand} - m_Z\rvert$	< 20 GeV	> 10 GeV & < 20 GeV		< 10 GeV	
$\lvert m_H^{cand} - m_H^{hypo}\rvert$ $m_H^{hypo} < 500$ GeV	-		$> 0.32 \cdot m_H^{hypo}$	$< 0.32 \cdot m_H^{hypo}$	-
$\lvert m_H^{cand} - m_H^{hypo}\rvert$ $m_H^{hypo} > 500$ GeV			$> 0.24 \cdot m_H^{hypo}$	$< 0.24 \cdot m_H^{hypo}$	



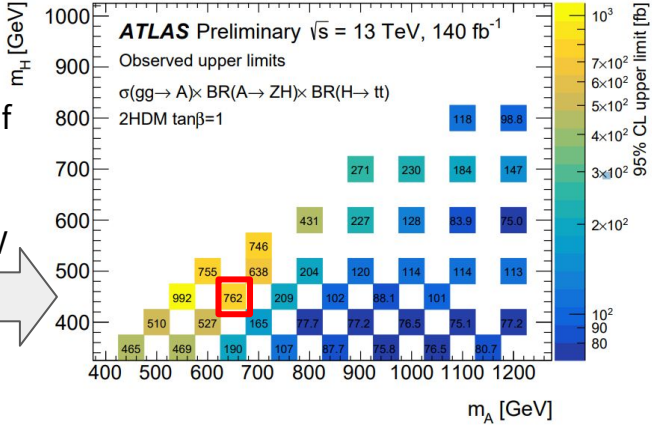
(a) $\ell^+\ell^- t\bar{t}$, $\tan\beta = 1$, expected

Table 3: Event selection for the $\nu\bar{\nu}b\bar{b}$ channel. SR, CR and VR next to the region name indicate that this region is used as a signal, control or validation region in the fit, respectively.

A→ZH→ννbb

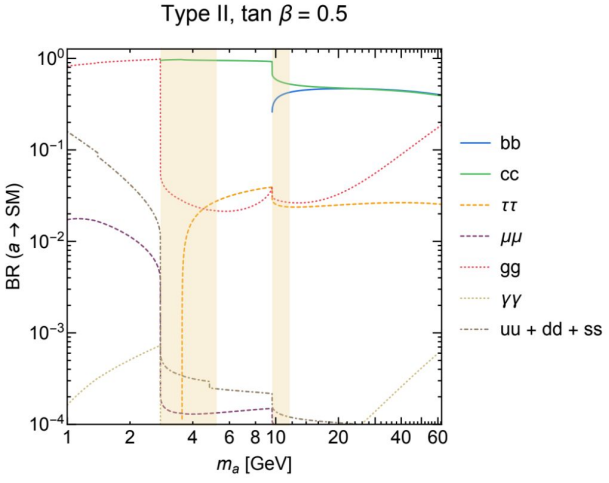
Cut	Regions				
	2L (CR)	eμ (CR)	1L (VR)	Hlo / Hhi (CR)	Hin (SR)
N jets	2-5				
N b-jets	> 2				
m_H^{cand}	> 50 GeV				
N hadronically decaying τ-leptons	0				
$p_T(V)$	> 150 GeV				
$\min_i \Delta\phi(\vec{E}_T^{miss}, \vec{p}_i^{jet})$	$> \pi/10$				
$\Delta R(b_1, b_2)$	< 3.3 (2 b-jets)				
	< 3.5 (≥ 3 b-jets)				
N leptons	2		1		0
Lepton flavour	$ee/\mu\mu$	$e\mu$	e/μ		-
$p_T(\ell_1)$	> 27 GeV				-
$\lvert m_Z^{cand} - m_Z\rvert$	< 10 GeV		-		
$\mathcal{S}_{MET}$	< 5	-	> 3		> 10
m_{top}^{near}	-				> 180 GeV
m_{top}^{far}	-				> 200 GeV
$\lvert m_H^{cand} - m_H^{hypo}\rvert$	-			$> 0.2 \cdot m_H^{hypo}$	$< 0.2 \cdot m_H^{hypo}$

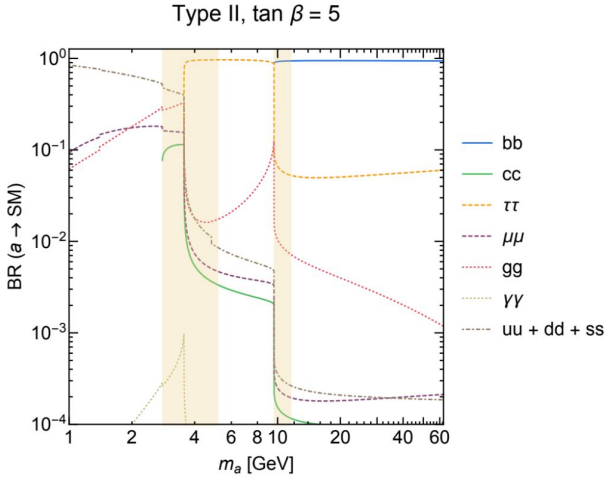
Max. local significance of 2.85 σ at (MA, MH) = (650, 450) GeV for **lltt**



(b) $\ell^+\ell^- t\bar{t}$, $\tan\beta = 1$, observed

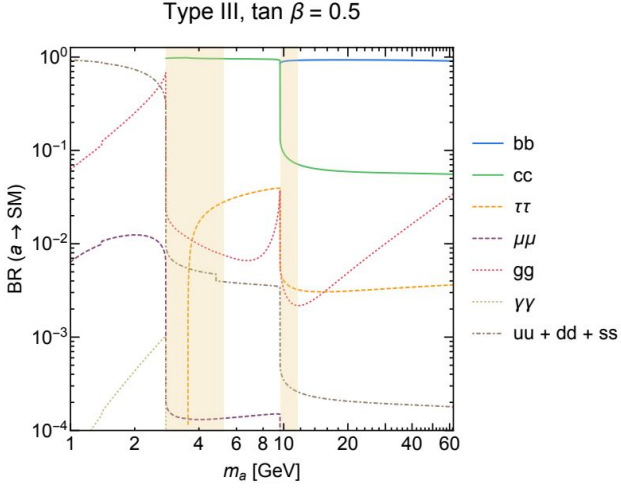
BR(h→aa) in 2HDM+S

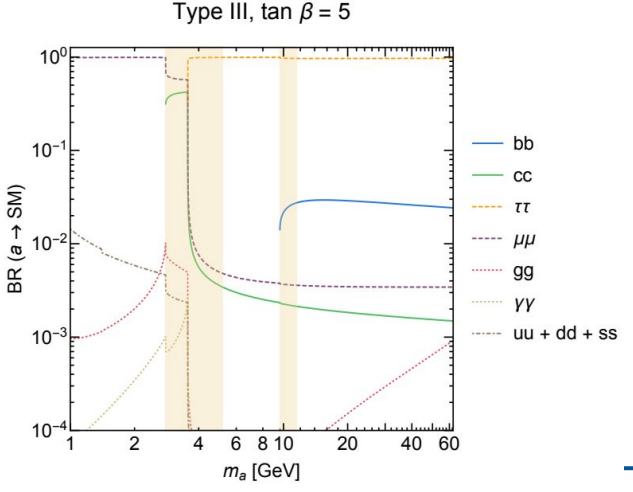




Predicted BR of a→SM

Decays to quarkonia likely invalidate our simple calculations in the shaded regions.





End-to-end DL to reconstruct merging

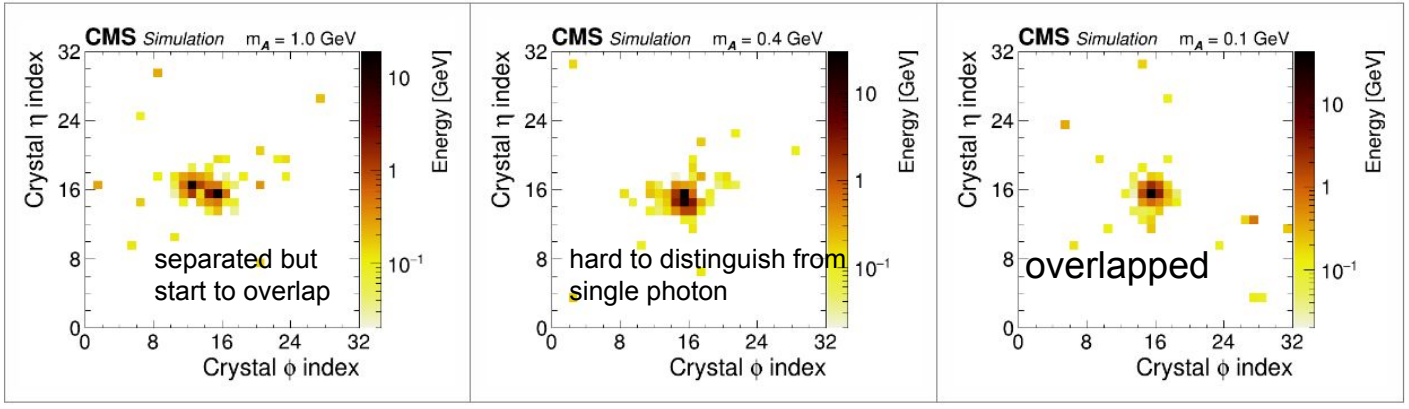


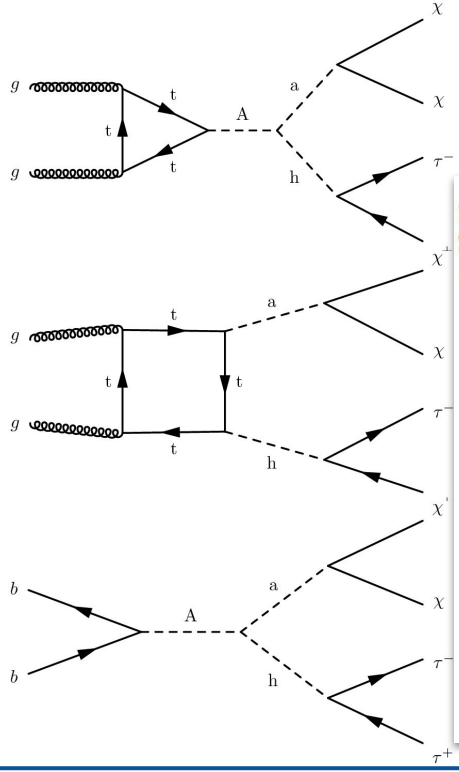
Fig 1. The energy signature of a single A→γγ decay as it would be seen by the CMS ECAL. The energy deposits are indexed by their positions in azimuth (ϕ) and pseudorapidity (η). For ALP masses of mA = 1.0 GeV (left), the two photon clusters are separated but begin to overlap. This merging makes it difficult to distinguish the A→γγ energy pattern from that of a single photon. For mA = 0.4 GeV (middle), the overlap is even stronger, though distinct cluster maxima remain visible. At mA = 0.1 GeV (right), the merging is such that the two photons land in the same crystal. These fully overlapping energy clusters are impossible to distinguish from the cluster of a single photon, except through the use of AI.

End-to-end deep learning : the technique bypasses existing rule-based particle reconstruction methods typically used in high energy physics analyses. It uses minimally processed detector data as input and directly outputs particle properties of interest.

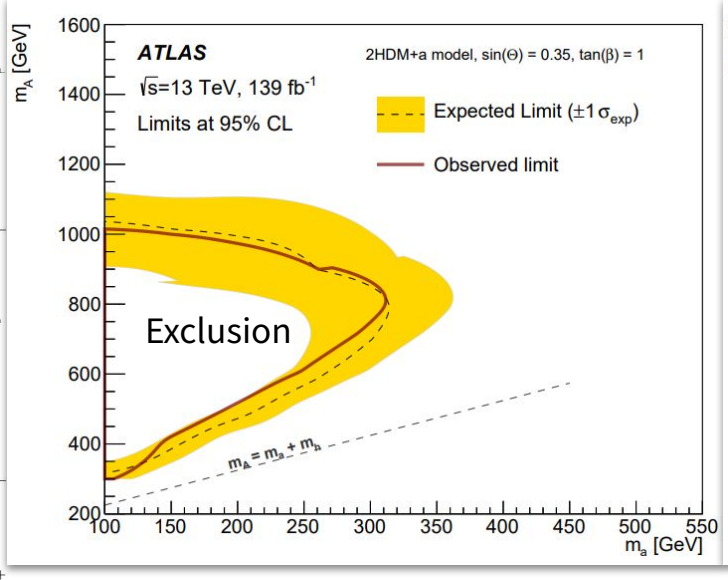
Using inputs that are as unfiltered and informationally rich as possible !

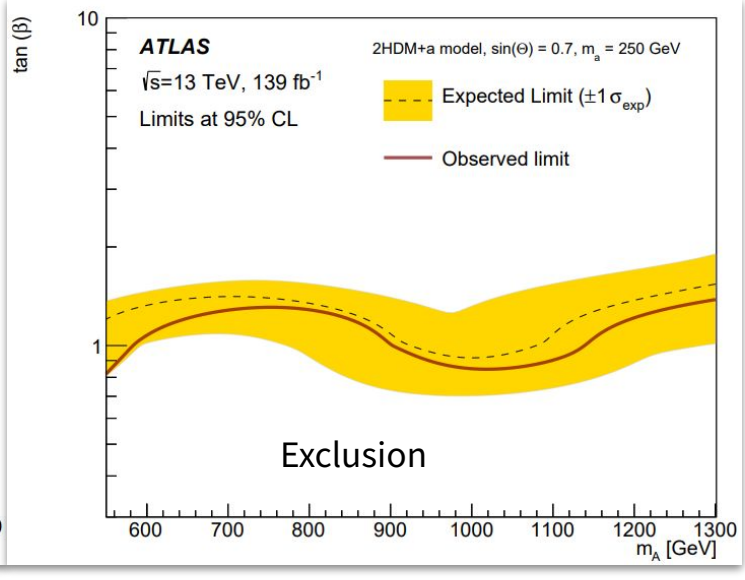
Mono-Higgs Search (A→Ha →ττ χχ)

- Search for dark matter (DM) appears as p_T^{miss} in association with a SM Higgs boson
- In 2HDM+a, pseudoscalar singlet 'a' could be a mediator between SM and DM
- **First exploration of mono-H → ττ signature with hadronically decaying τ_h**

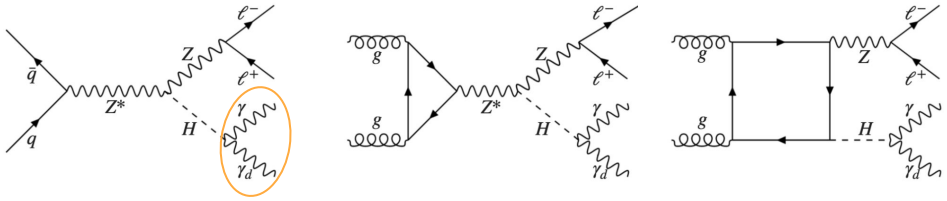


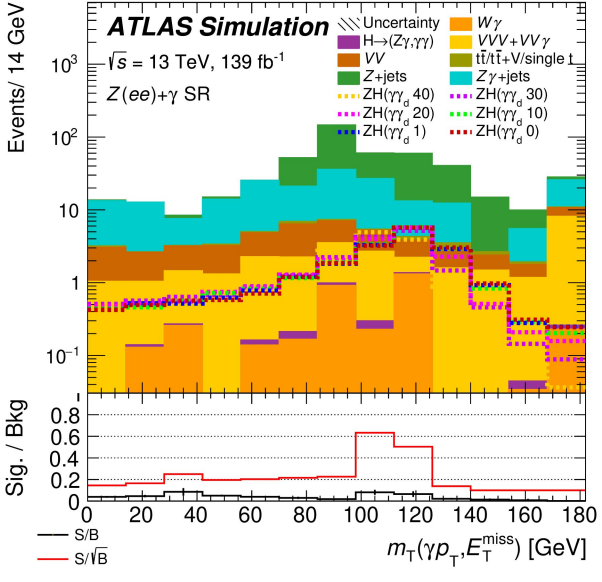
- M_a : 100 – 400 GeV , M_A : 300 –1400 GeV
- σ_{vis} < 0.04 – 0.08 fb
- No significant deviation from the SM prediction is found

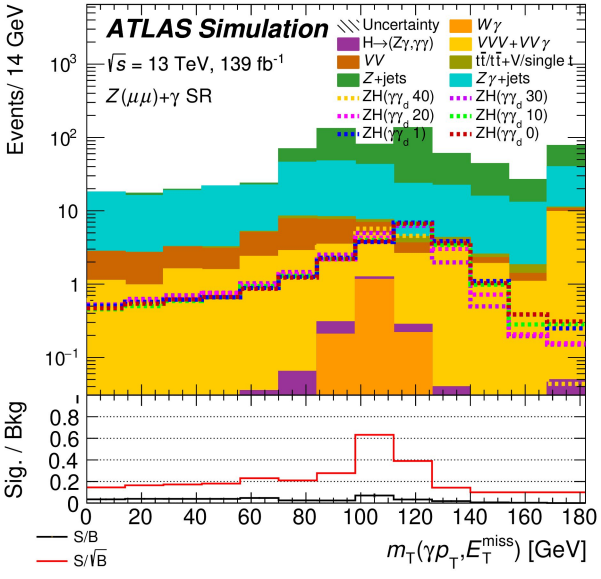


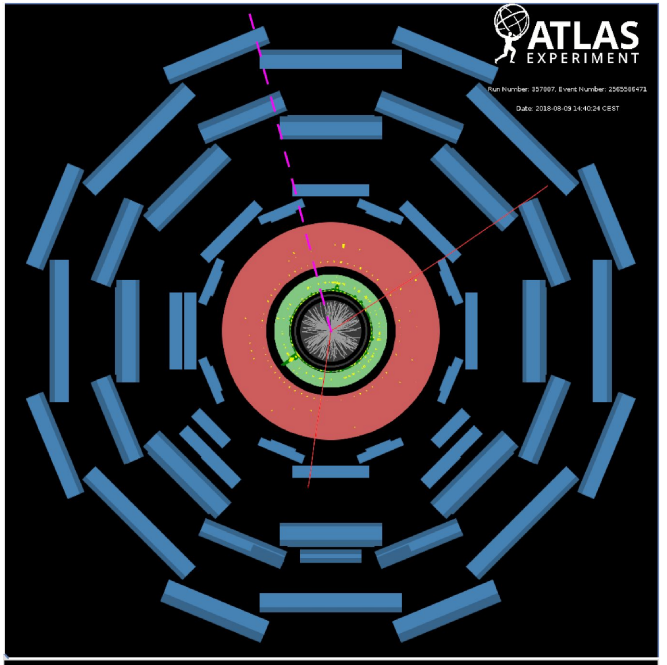


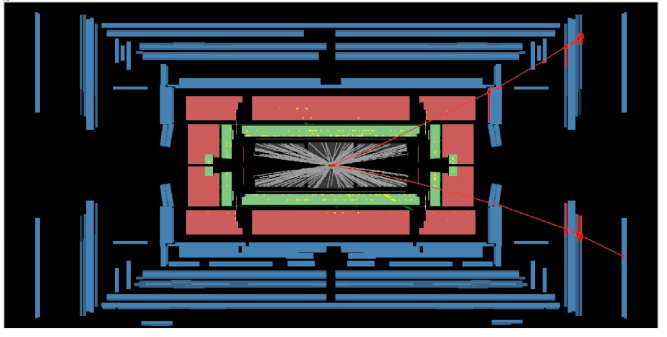
Dark photons Search ($ZH \to ll\gamma\gamma_d$)











BSM Higgs Model

Model	Higgs spectrum	Possible H pair mode from resonant
SM+Real **Singlet** **(RxSM)**	dark phase : h_{SM}, DM , broken phase : h_{SM}, S	DM DM, h_{SM} h_{SM}, S S
SM+2Real **Singlet** **(TRSM)**	broken phase : h_{SM}, H_1, H_2	h_{SM} h_{SM}, H_1 H_1 , H_2 H_2 , **H_1 H_2 ,h_{SM} H_1**
SM+Complex **Singlet** **(CxSM)**	dark phase : h_{SM}, S, DM, broken phase : h_{SM}, H_1, H_2	h_{SM} h_{SM}, S S, DM DM, H_1 H_1 , H_2 H_2 , **H_1 H_2 ,h_{SM} H_1**
2 Higgs **Doublets** **(2HDM)**	CP conserving : h_{SM},H, A	h_{SM} h_{SM}, H H
2 Higgs **Doublets**, **SUSY (MSSM)**	CP conserving : h_{SM},H, A	h_{SM} h_{SM}, not H H (due to constraints)
2 **Doublets**, 3 Higgses Mix **(C2HDM)**	CP violating : h_{SM}, H_1, H_2	h_{SM} h_{SM}, H_1 H_1 , H_2 H_2 , **H_1 H_2 ,h_{SM} H_1**
2 **Doublets, 1 Real Singlet** **(N2HDM)**	h_{SM}, H_1, H_2, A	h_{SM} h_{SM}, H_1 H_1 , H_2 H_2 , **H_1 H_2 ,h_{SM} H_1**
2 **Doublets+1 Complex Singlet** **(2HDM+S)**	h_{SM}, H_1, H_2, A_1, A_2	h_{SM} h_{SM}, H_1 H_1 , H_2 H_2 , **H_1 H_2 , h_{SM} H_1, h_{SM} A_1, A_1H_1 , A_1H_2**
2 Doublets+1 Complex Singlet, SUSY (NMSSM)	h_{SM}, H_1, H_2, A_1, A_2	h_{SM} h_{SM}, H_1 H_1 , **h_{SM} H_1, h_{SM} A_1, A_1H_1** (not H_2 H_2 , **A_1H_2** , **H_1 H_2 due to constraints**)