Direct searches for New Physics in Multiboson final states - ATLAS & CMS

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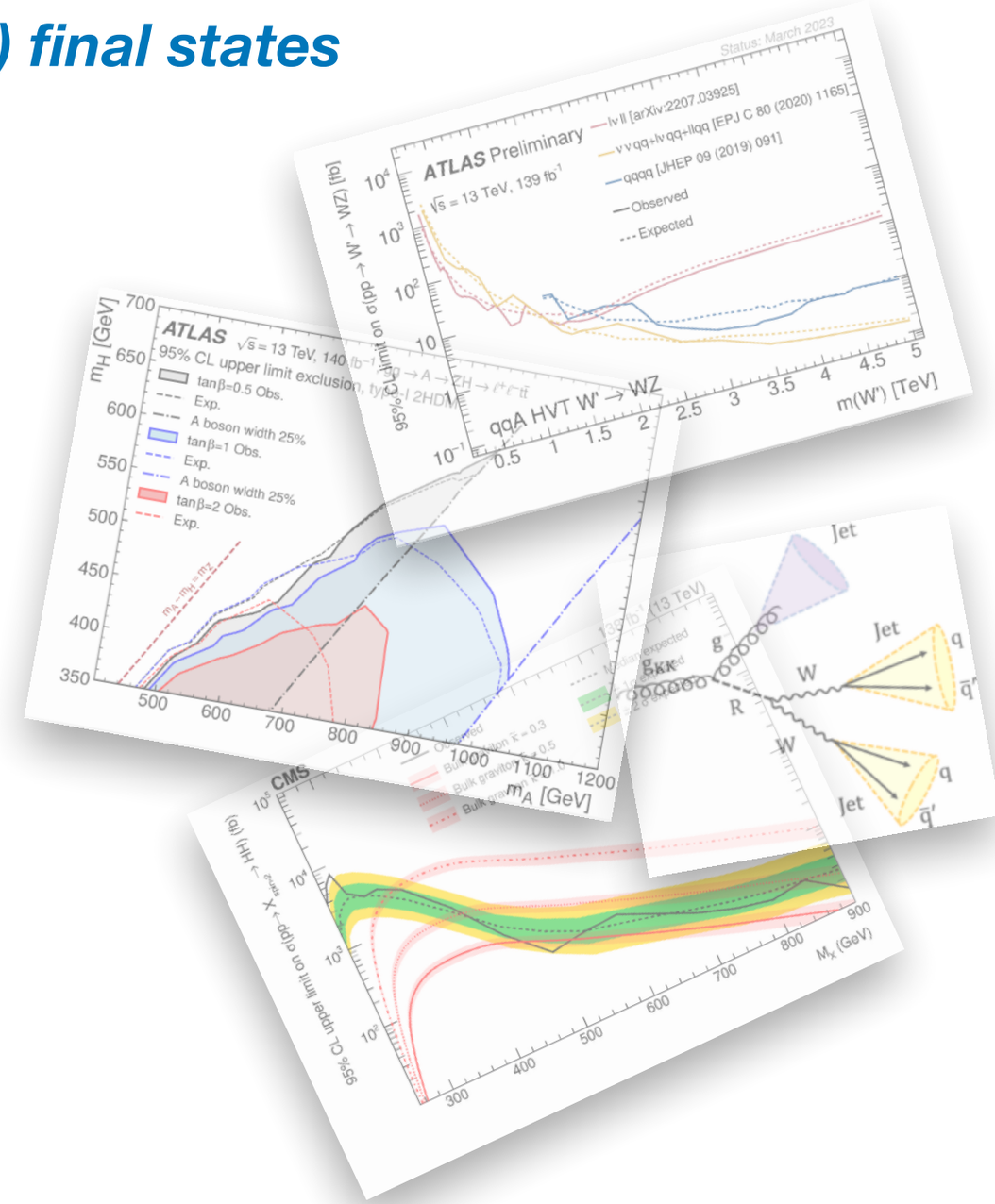
Antonio Giannini
on behalf of the ATLAS & CMS collaborations

Today menu with disclaimer!

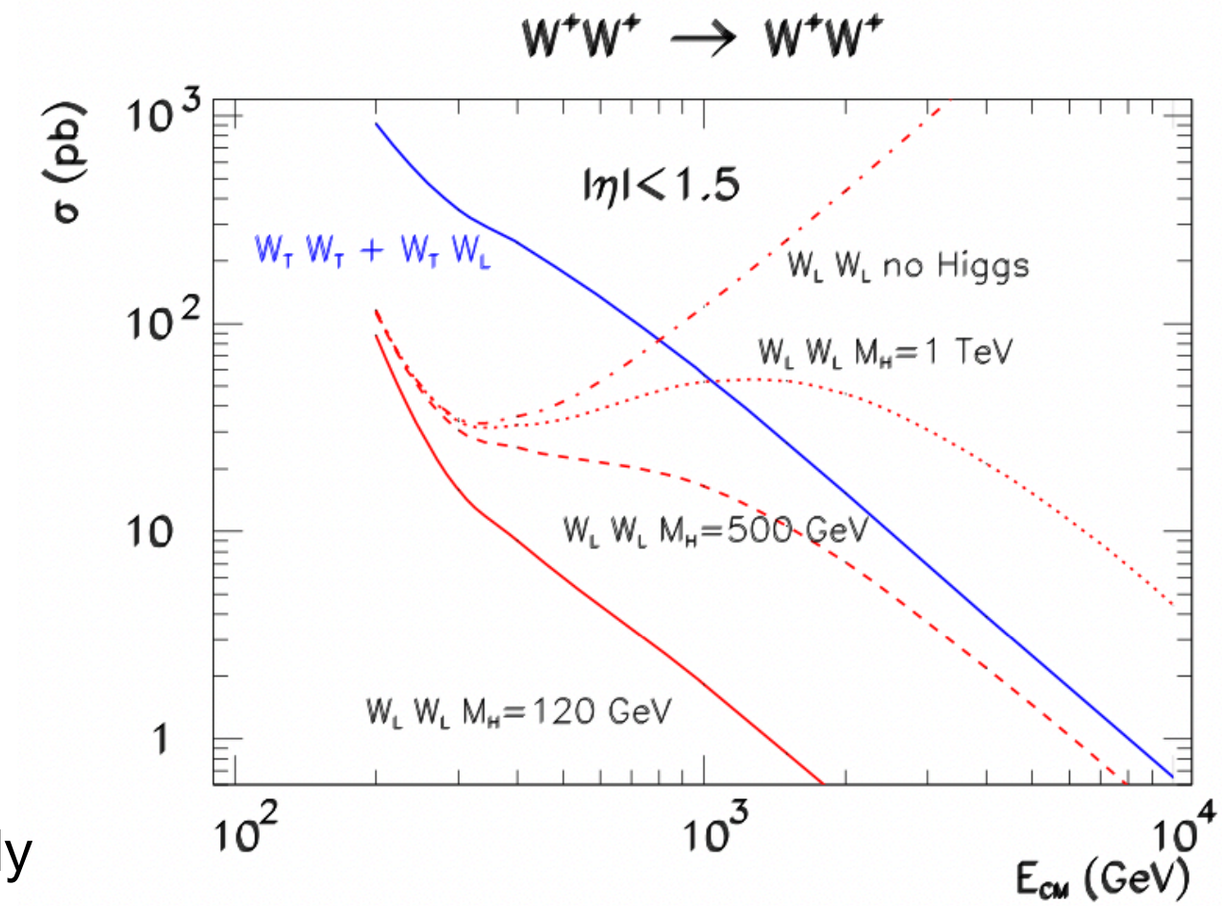
- ***Direct searches in multi bosons (including hh) final states***
- ***Introduction***
  - theory and experimental inputs
  - status of phase spaces and combinations
- ***VV/Vh searches***
  - ssWW/WZ combination
  - cascade searches
  - Vh new channels
  - AZH searches
- ***hh (resonant) searches***
  - VBF hh 4b, bbWW
- ***Sh searches***
  - bb$\gamma\gamma$, VV$\gamma\gamma$, $\gamma\gamma\tau\tau$
- ***Wrap-up***
  - Multi-boson searches w/o bosons
  - Conclusions



After an introduction, I will focus on recent (~few months) results; the selection of searches/topics is given from my personal preference!

Why diboson searches: historical intro

- Diboson interactions are a key process in the LHC program
  - according to the EWK sector the W_LW_L scattering is violating the unitarity at the TeV scale
  - we expected something to happen with the LHC era
- After the Higgs discovery, we can say that the Higgs+EWK sector can mitigate this
  - however, this still needs to be directly confirmed at very high energy
- ***High-energy diboson interactions may still hide new physics!***

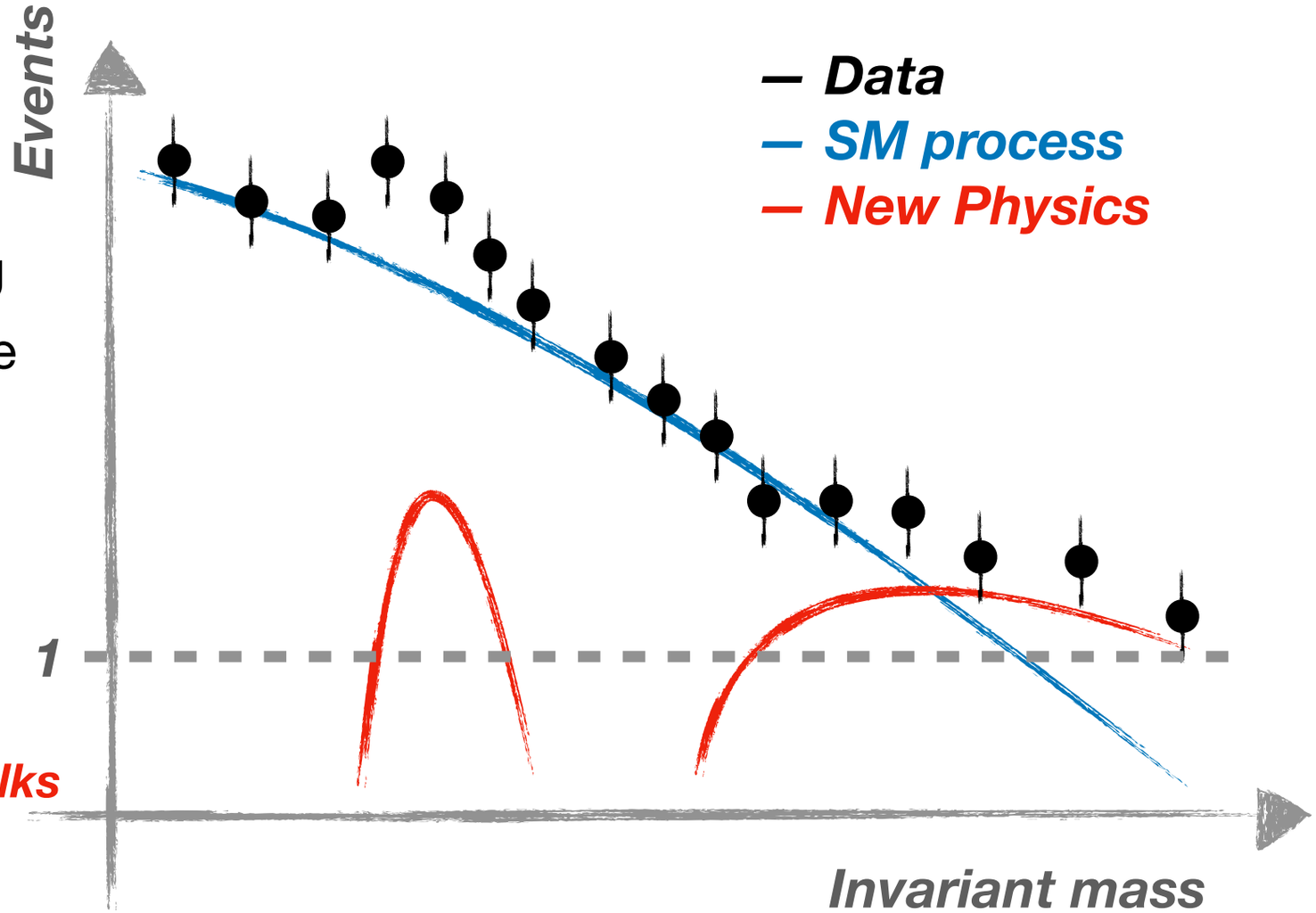


arxiv.1412.8367

Why direct searches

- Diboson and multi-boson is a portal to New Physics (NP)
  - it can manifest as an excess in the SM data as ***narrow*** or ***wide peaks***, or ***deviations in tails***
- Direct searches are a way to analyse the data and look for something new in the data

- Minimal and simplest approach
  - ***theory***: i.e. 1-to-2-bodies decay X —> YZ
  - ***experiment***: a bump hunting in data when modelling of the background or related uncertainties are limiting factors

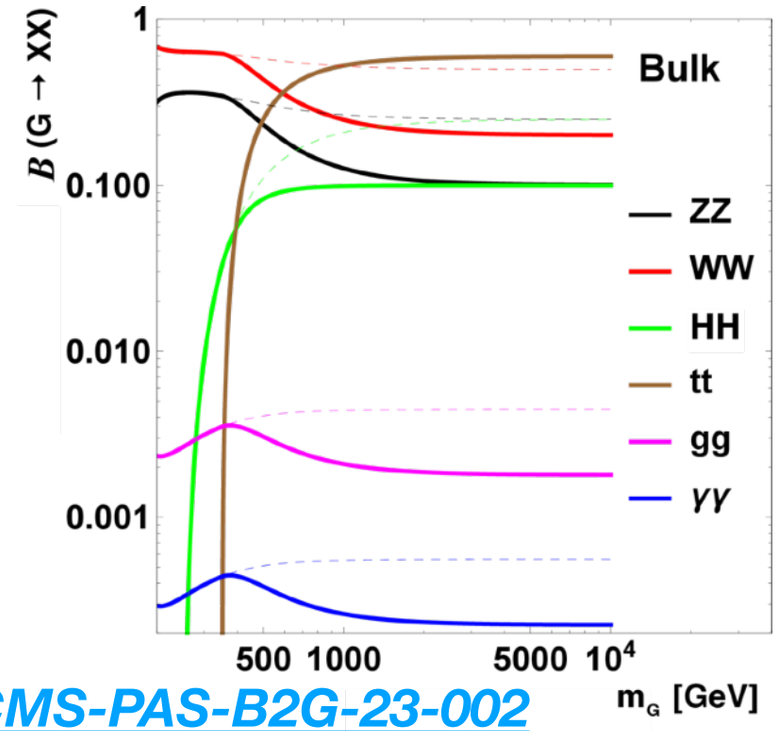


Not covered in this talk:

- ***hh non resonant in Giulia/Garyfallia talks***
- ***tail excesses in Anna/Heshasm talks***
- ***γ associated not covered***

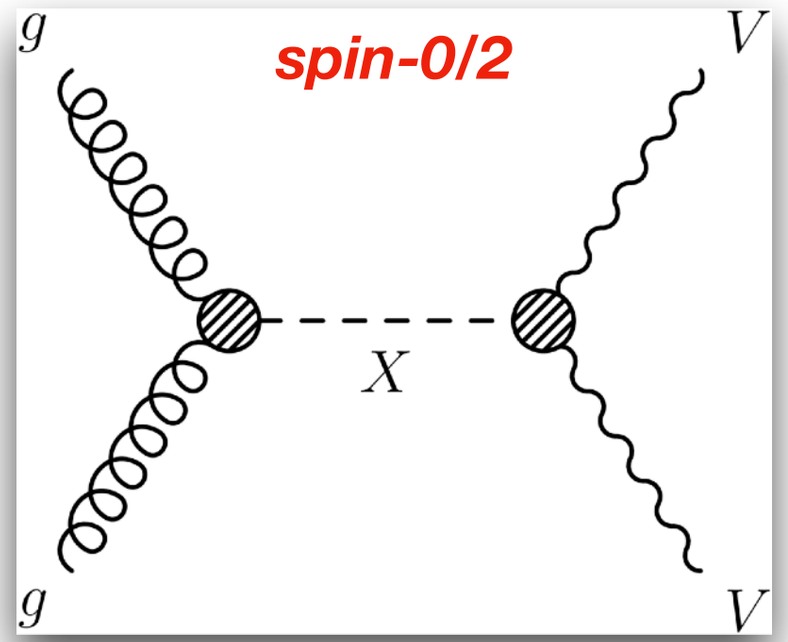
Theoretical models/productions

- Several theoretical models foresee the presence of additional and high mass resonances
  - spin-0 Radion
  - spin-1 Heavy Vector Triplet (HVT)
  - spin-2 Randal Sundrum Graviton
- Each of them can be produced via different production mechanisms

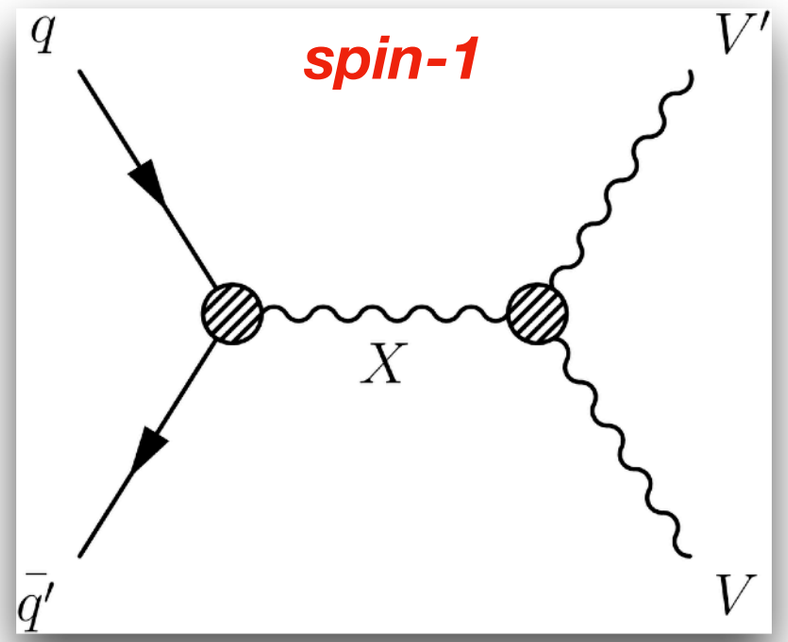


CMS-PAS-B2G-23-002

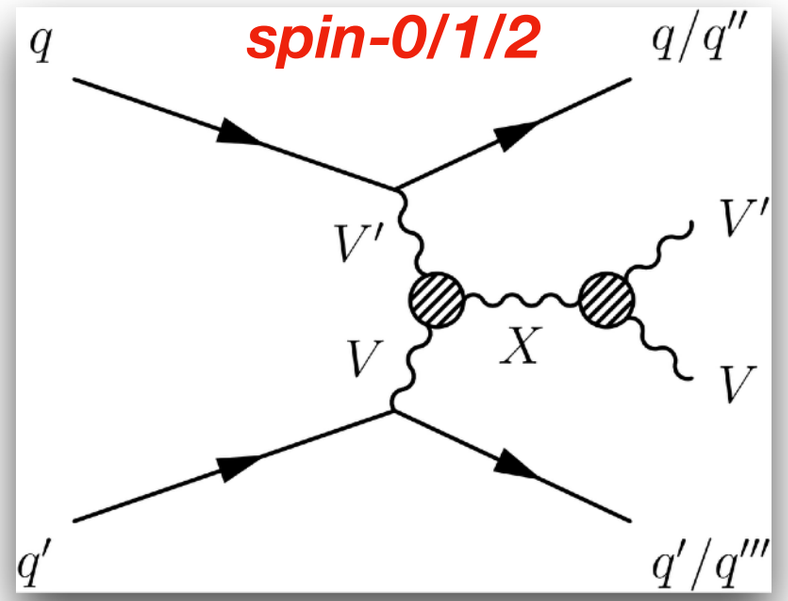
gluon-gluon Fusion (ggF)



Drell-Yan (DY)



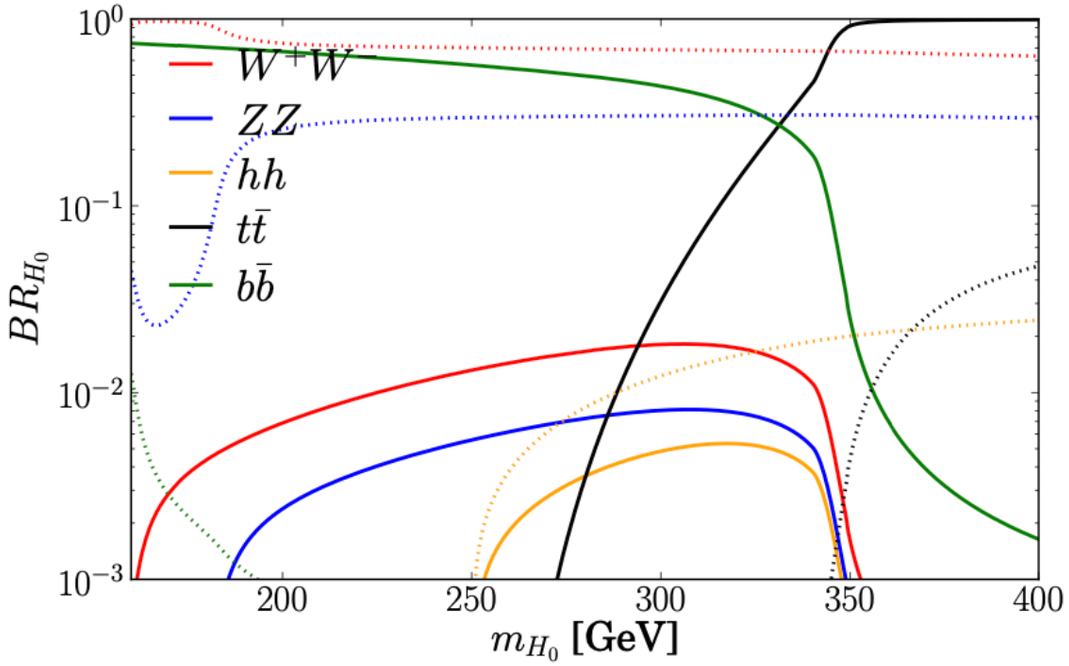
Vector Boson Fusion (VBF)



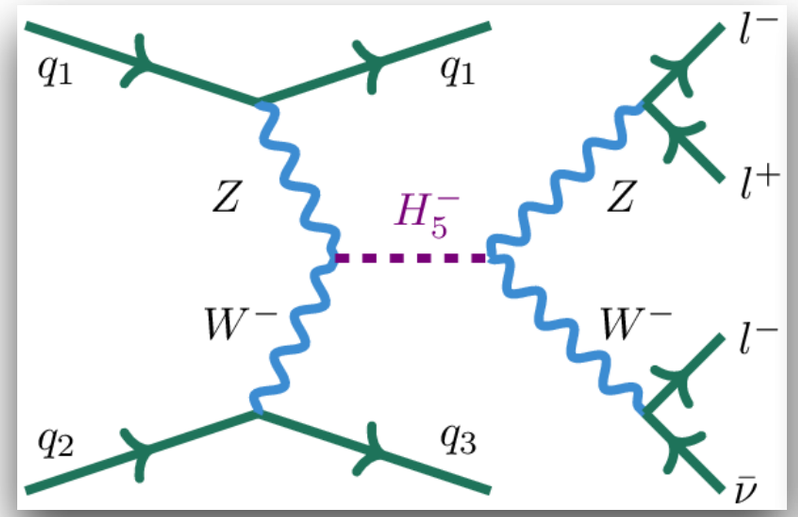
Theoretical models/productions

- During run-2 models exploring the presence of ***additional*** neutral or charged ***high mass higgs*** have been considered
  - charged Georgi Machacek (GM)
  - 2 Higgs Double Model (2HDM)
  - 2HDM + Scalar (2HDM+s)
  - Next-to-Minimal Supersymmetric SM (NMSSM)
- VBF exclusive production mode for GM
- bbA production mode for AZH signatures

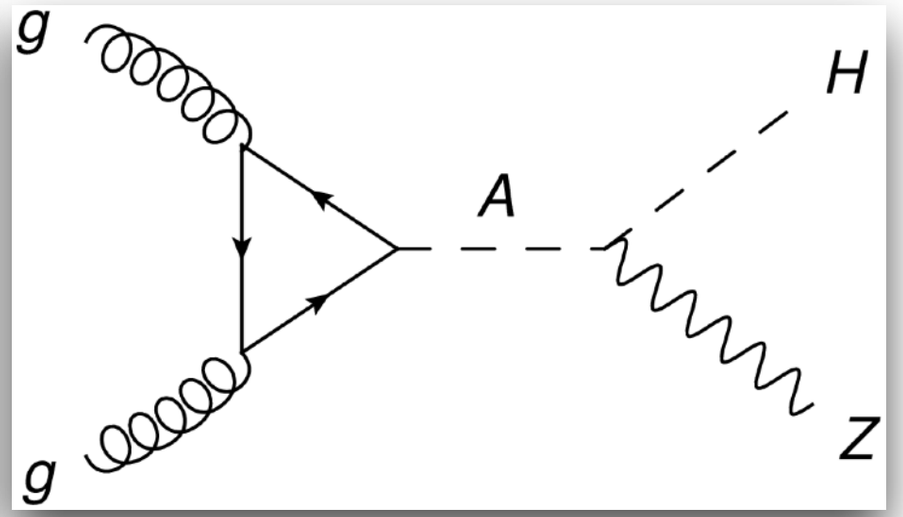
arxiv.1405.5537v1



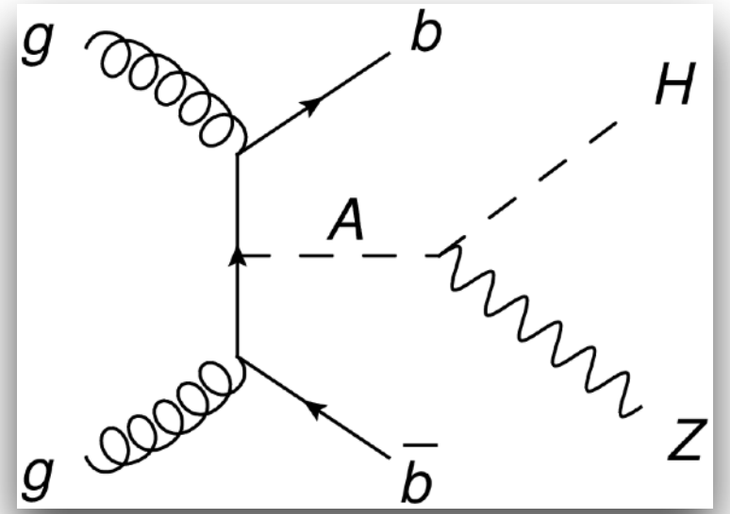
VBF



ggA



bbA



What does "Multibosons" mean

with V = W/Z, h = 125 GeV Higgs, X = BSM

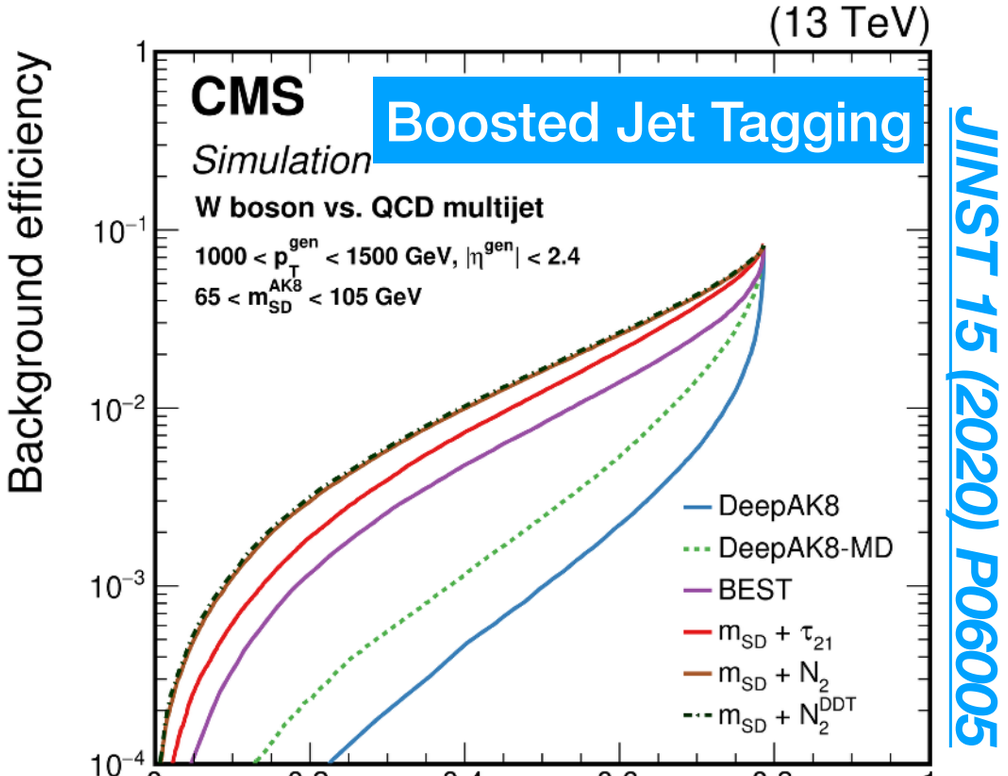
Reference = [ATLAS, CMS]

A new resonance

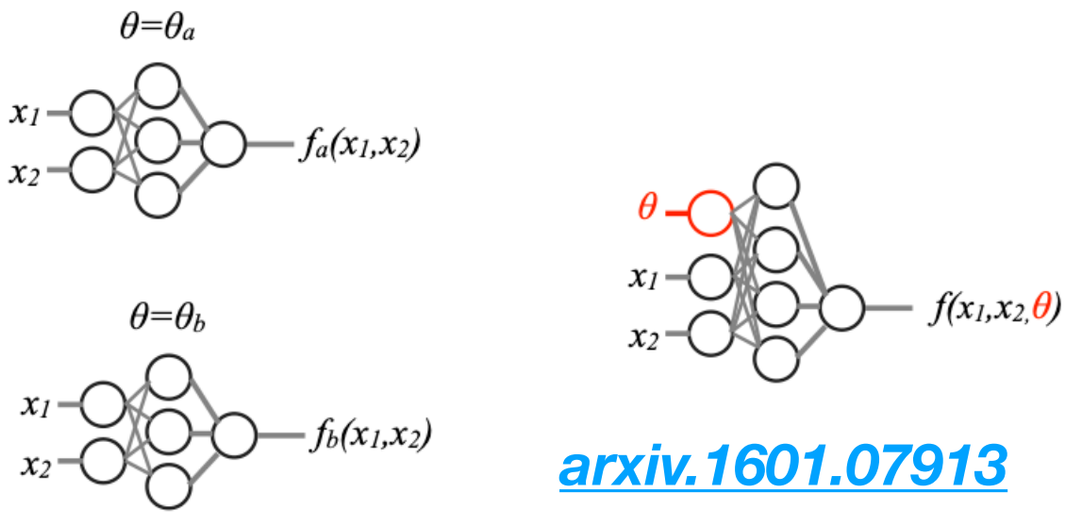
- **VV** — $l\nu l\nu$ [1, 2, 3], $l\nu ll$ [4, 3], $4l/ll\nu\nu$ [5, 6], $llqq$ [7, 8], $l\nu qq$ [7, 9], $\nu\nu qq$ [7, 10], $qqqq$ [11, 12]
- **Vh** — $llbb/\nu\nu bb$ [11, 12], $l\nu bb$ [9], $ll\tau\tau$ [13], $qqbb$ [14, 12], $llcc/vvcc/ll4q/\nu\nu 4q$ [15]
- **VX** — $qqbb$ [16], $ll+X$ [17], $llbb$ [18, 19], $llWW$ [18], $ll\tau\tau$ [20], $\nu\nu bb$ [21], $lltt$ [21, 22]
- **hh** — $bbbb$ [23, 24], $bb\gamma\gamma$ [25], $bb\tau\tau$ [26], $\gamma\gamma\tau\tau$ [27], $bbVV$ [28, 29], $4W/\tau\tau WW/4\tau$ [30]
- **hX** — $bbbb$ [31], $bb\gamma\gamma$ [32, 33], $bb\tau\tau$ [34], $\gamma\gamma\tau\tau$ [35], $VV\tau\tau$ [36], $4W$ [37]
- **XX** — 2-jets (AD) [38, 39], 4-jets [40]
- **VVV/Vhh/VVX** — WWW [41, 42], Vhh [43], WW+jet [44]

Setting the stage: ML & jets

- Recent searches that will be highlighted in the following rely on jets and ML developments over the past years
  - ***aim to improve more and more the physics results w/o waiting for new data***
  - ***new challenges given new phase spaces to explore***

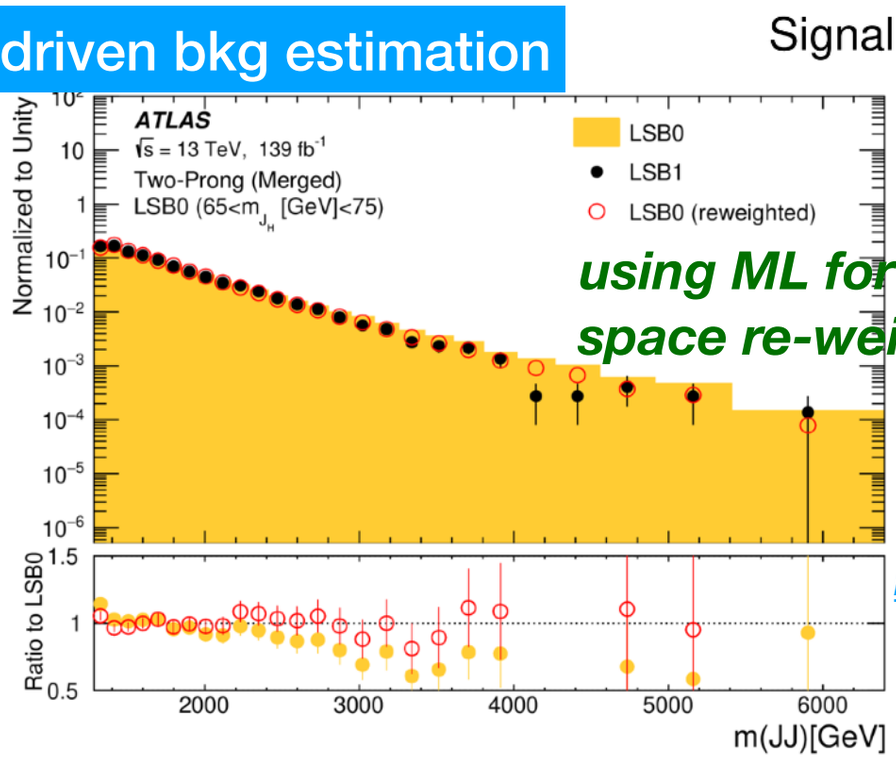


parameterised-DNN to optimise the full signal parameter space



arxiv.1601.07913

Data-driven bkg estimation



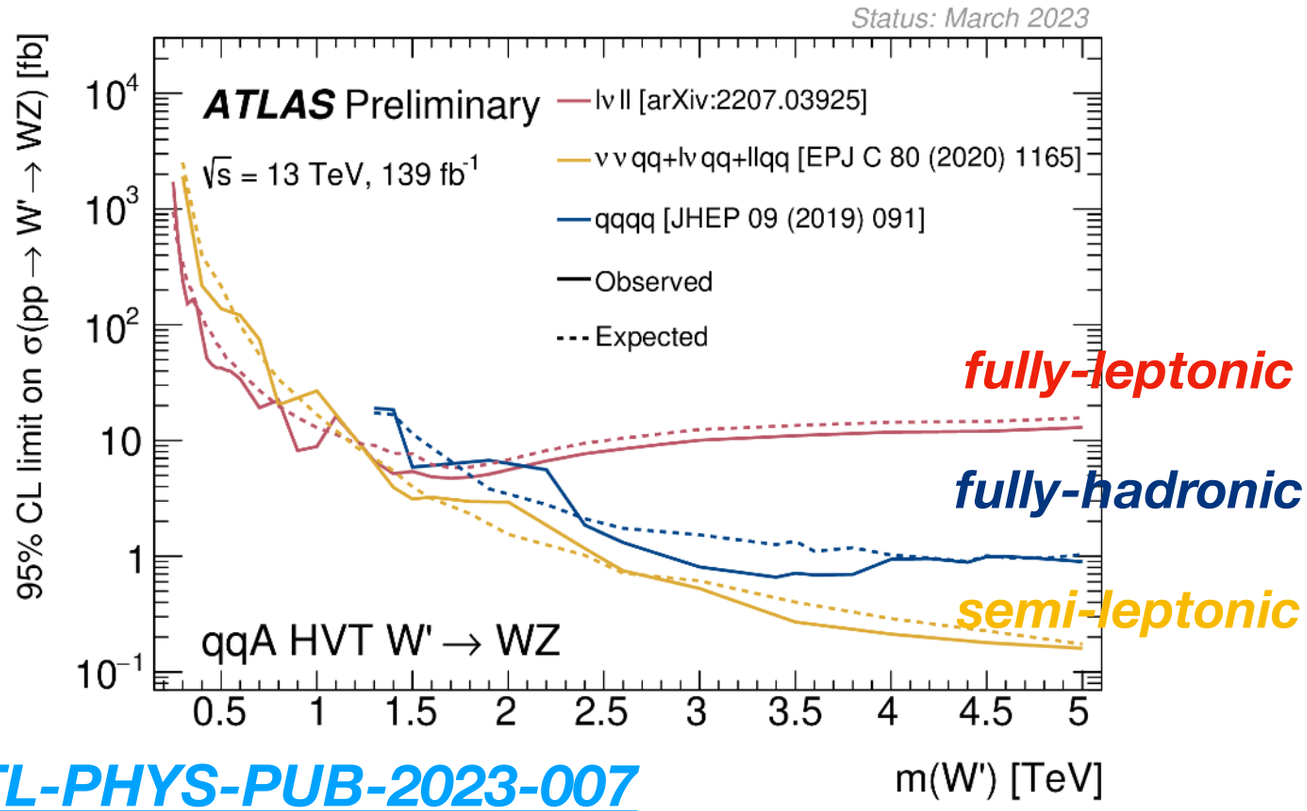
using ML for phase space re-weighting

Phys. Rev. D 108 (2023) 052009

Setting the stage: VV/Vh searches

- Searches performed adding more data and new techniques and channels during run-2
  - all major direct channels covered
  - different production modes covered
- ***Objects tagging***: boson [*JHEP 09 (2019) 091*] and flavour tagging [*Phys. Rev. D 108 (2023) 052009*]
- ***VBF topologies tagging*** [*Eur. Phys. J. C 80 (2020) 1165*, *Eur. Phys. J. C 83 (2023) 633*]
- ***Strategies***: data driven [*Eur. Phys. J. C 81 (2021) 688*] and multi-dimensional fits [*Phys. Lett. B 844 (2023) 137813*]

If interested in dedicated techniques, check them



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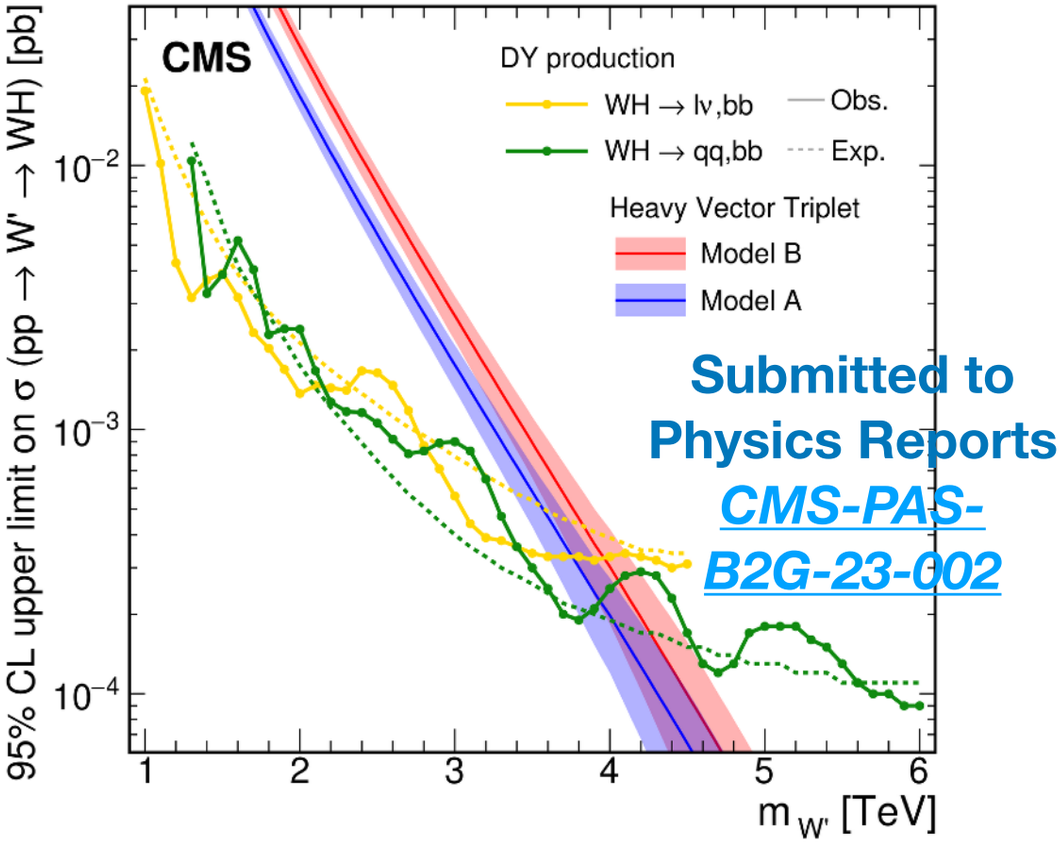


Submitted to Physics Reports

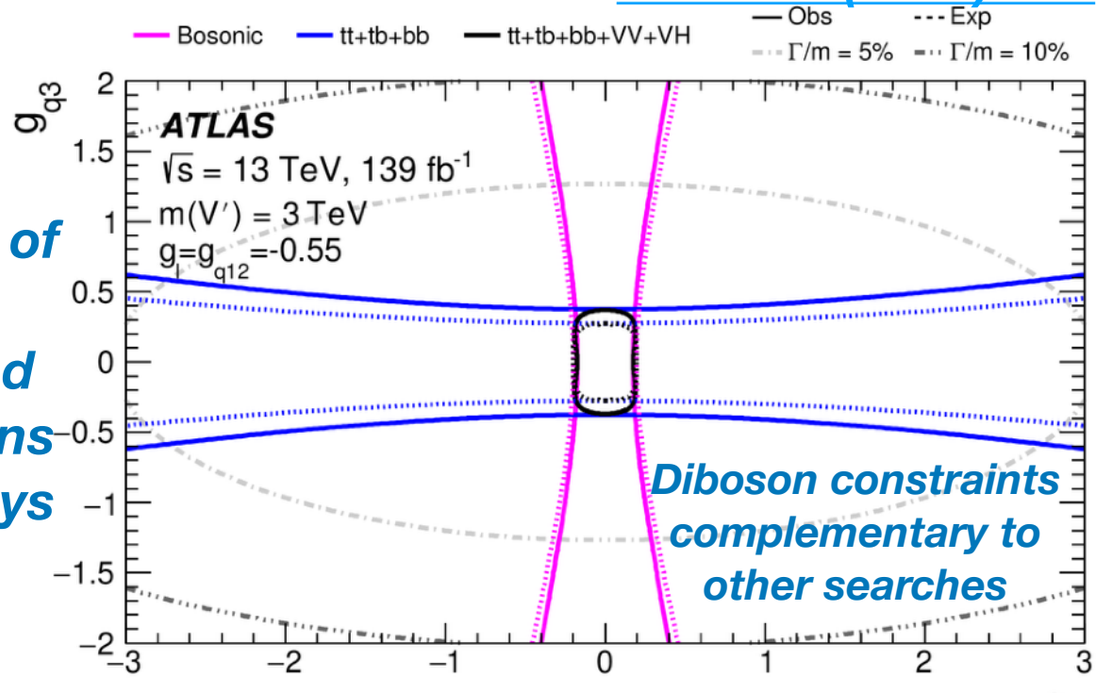
CMS-PAS-B2G-23-002

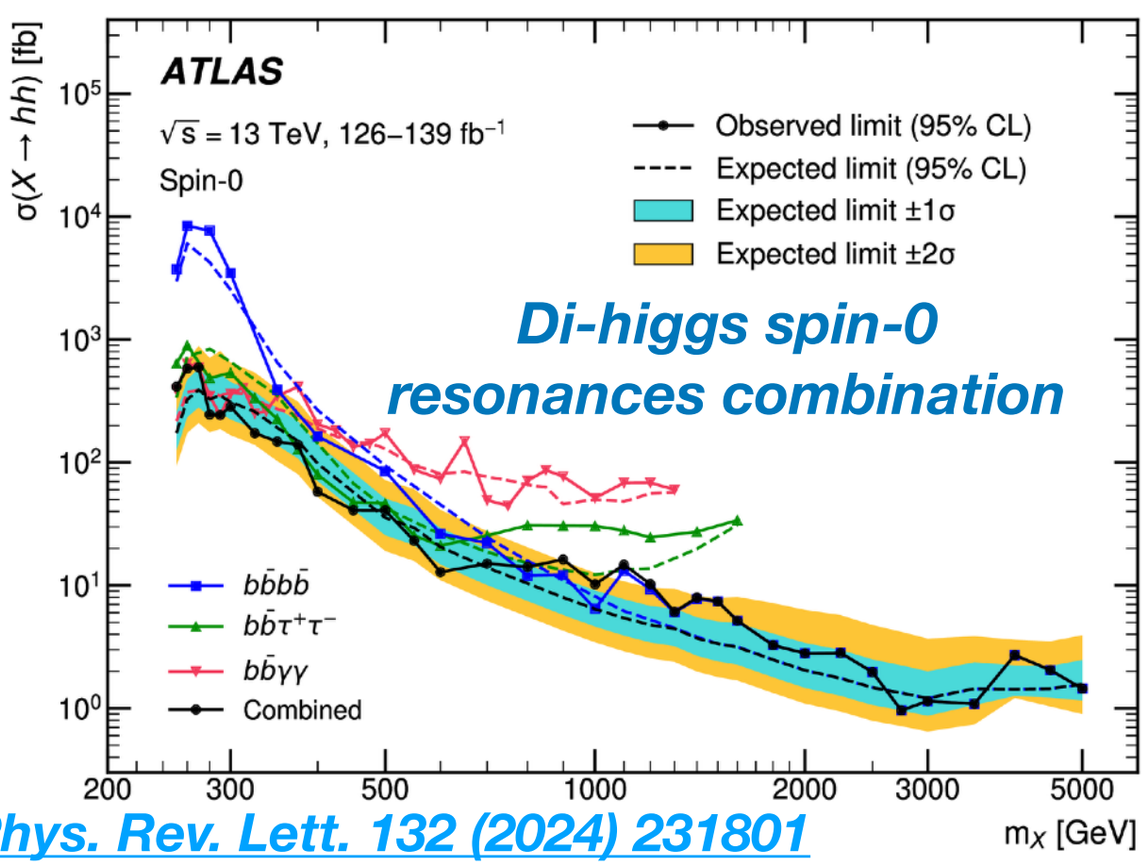
Setting the stage: combinations

- Different channels can be complementary or competitive according to the parameters space
  - ***cover wider phase spaces***
  - ***increase the constraints via statistical combinations***

Combination of VV/Vh channels and 3rd generations leptons decays

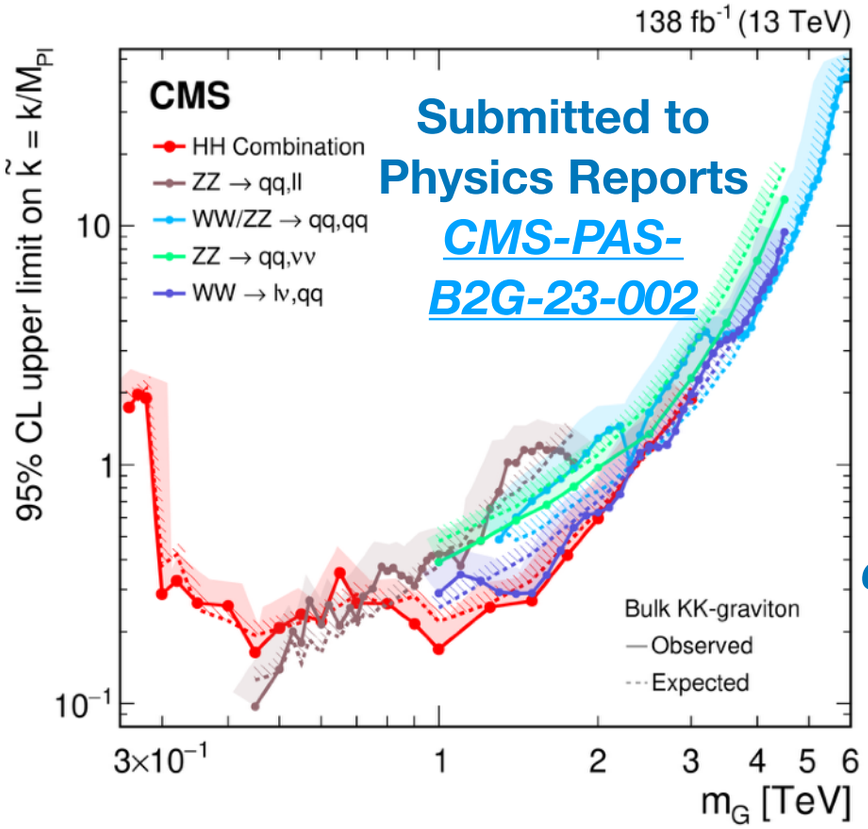
[JHEP 04 (2024) 118]





Di-higgs spin-0 resonances combination

[Phys. Rev. Lett. 132 (2024) 231801]



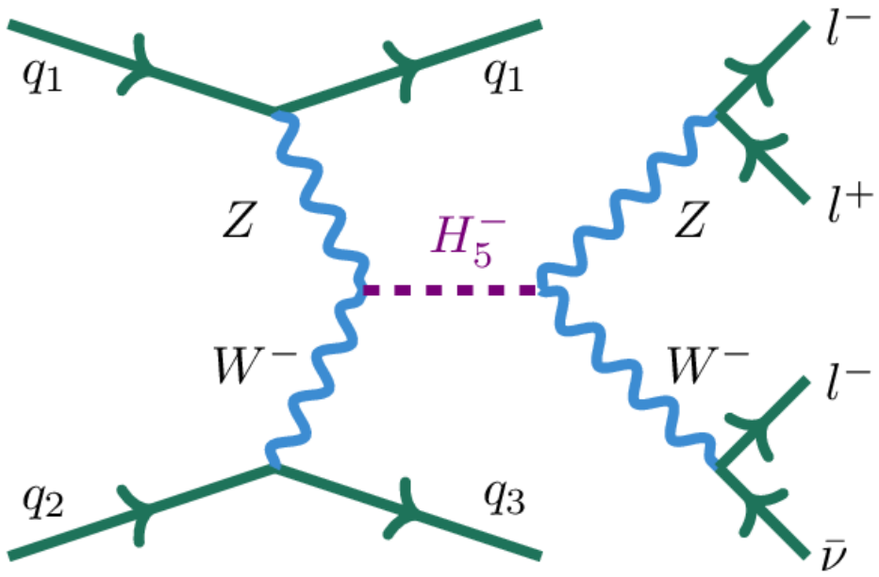
Submitted to Physics Reports

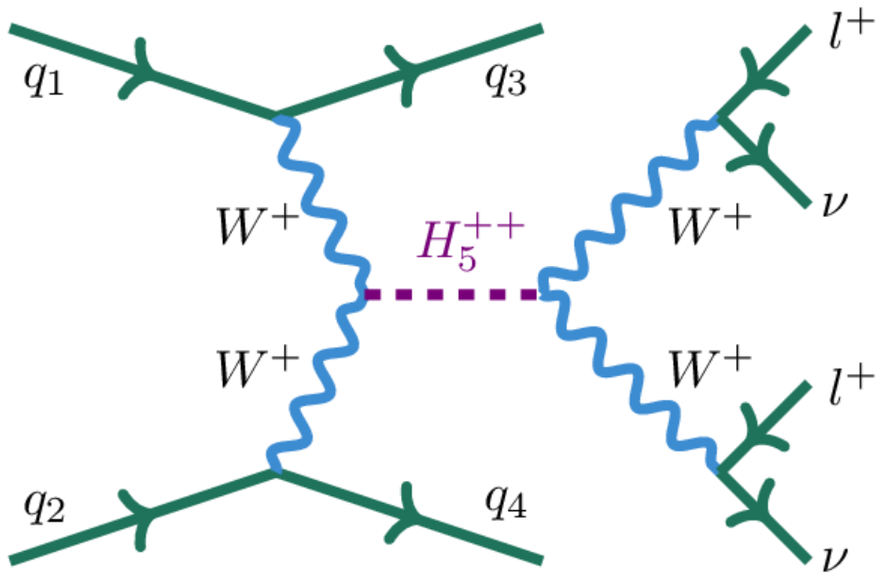
[CMS-PAS-B2G-23-002]

Warped-extra dimension hh combination and overlay with VV channels

GM Charged Higgs searches

- Higgs sector extended by introducing one real and one complex triplet
  - (H^{++}, H^{+}, H^{0}) fermiophobic —> VBF production mode
- sin-ϑ_H handles the contribution of the scalar fields to the W/Z mass
- Recent ATLAS combination of searches published previously:
  - ***WZ lvll*** *Eur. Phys. J. C 83 (2023) 633* and ***ssWW lvlv*** *JHEP 04 (2024) 026*
- CMS also released results in fully leptonic and semi-leptonic channels
  - *Eur. Phys. J. C 81 (2021) 723*, *Phys. Lett. B 798 (2019) 134985*





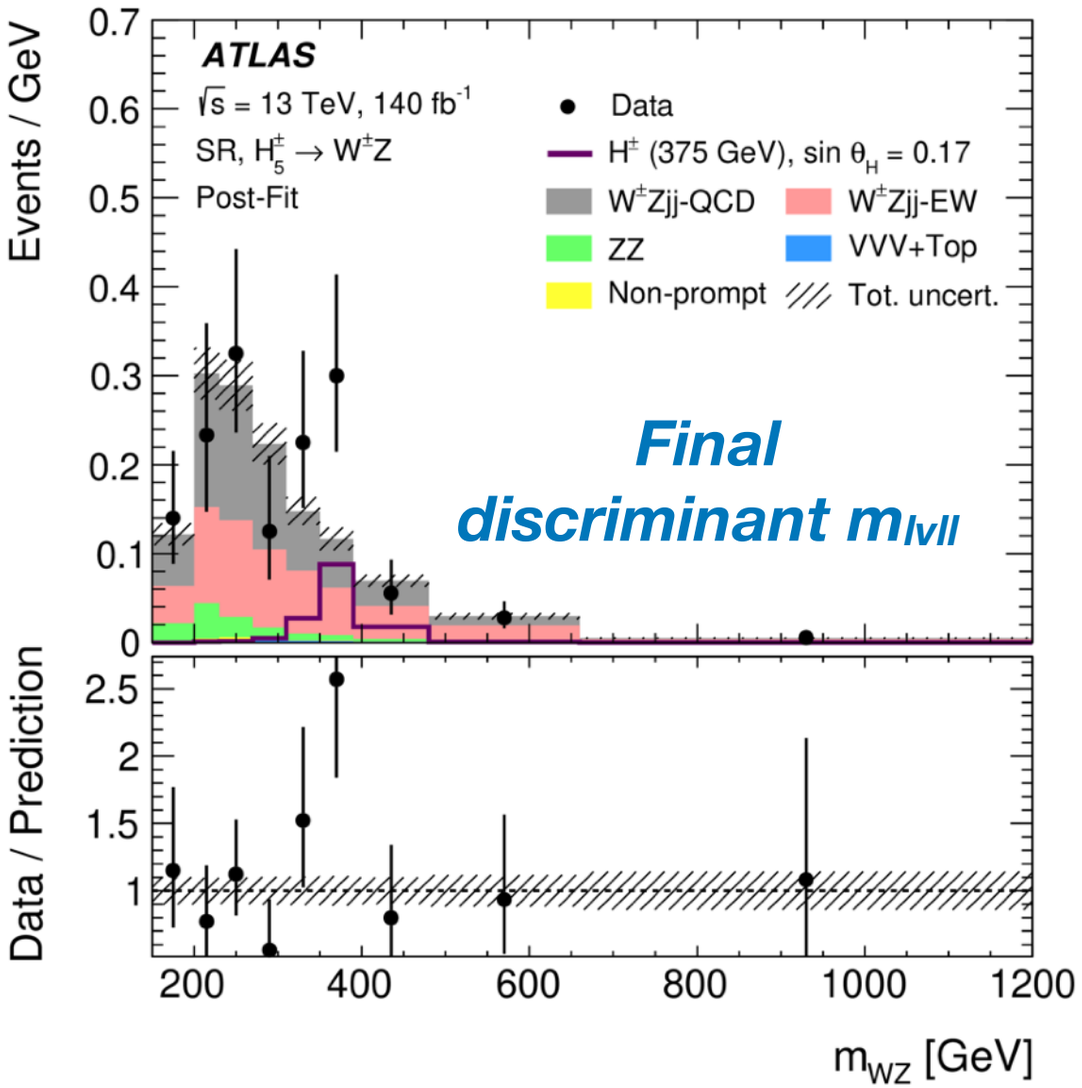
Submitted to Phys. Lett. B

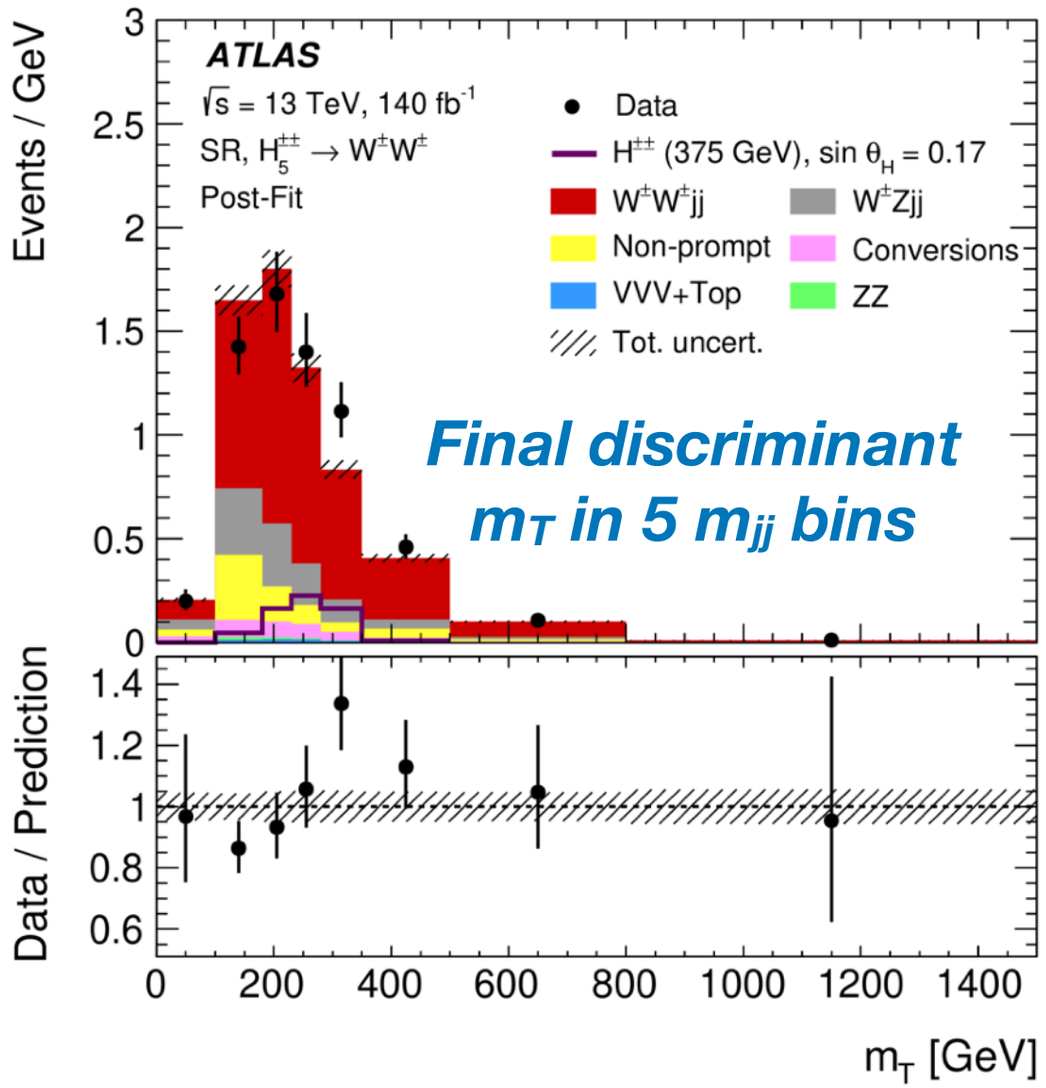
arxiv.2407.10798

The phase space: VBF topology

Submitted to Phys. Lett. B
arxiv.2407.10798

- Distinct signature in the detector:
  - ***VBF production***: forward jets with high invariant mass and angular separation
  - ***diboson system***: 2 or 3 isolated leptons + missing energy
- Phase space mainly dominated by EWK and QCD diboson production



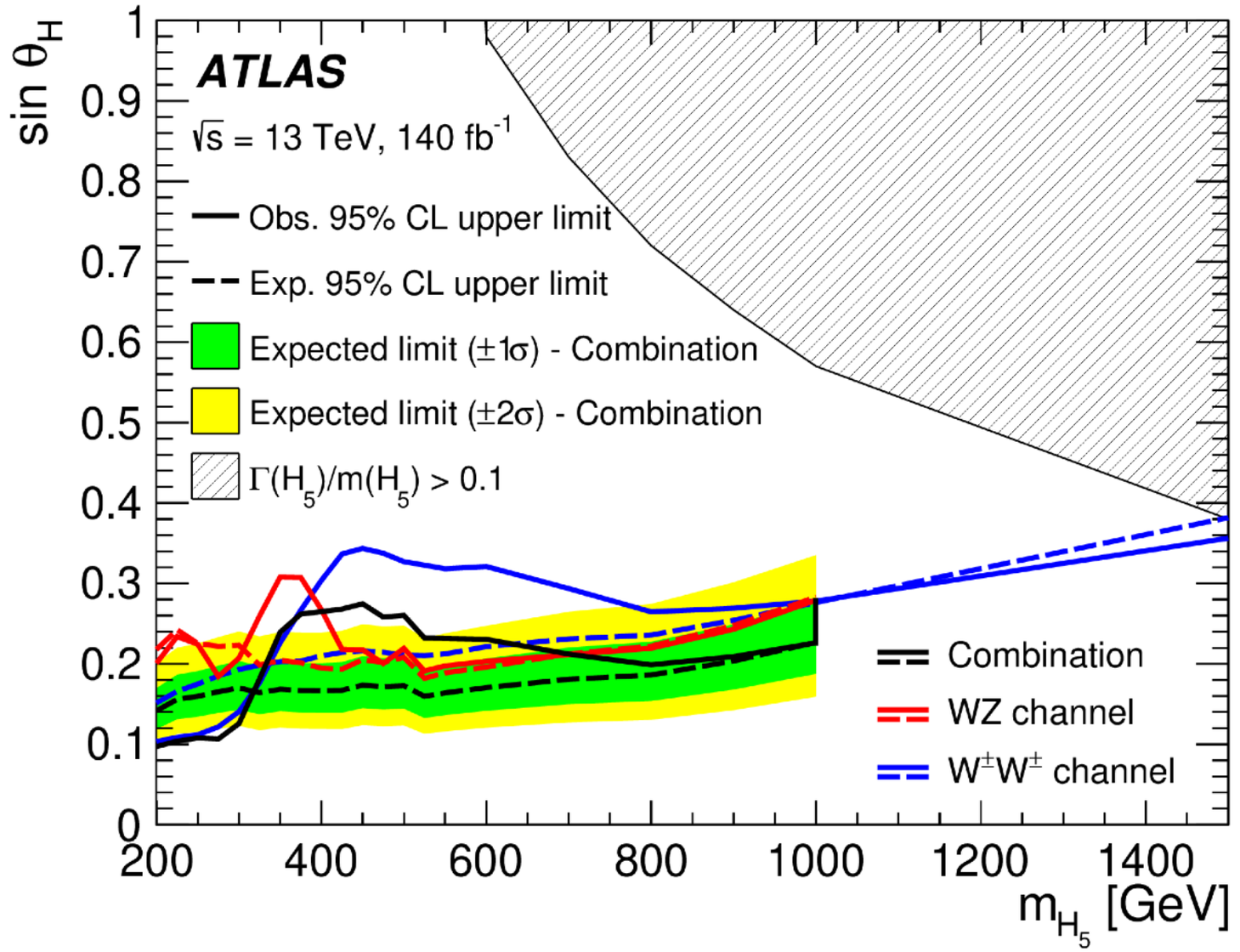


Combination results

Submitted to Phys. Lett. B
arxiv.2407.10798

- Followup on the on the slight excesses that both the individual analyses reported
  - ***WZ 2.8 (1.6) σ @375 GeV and WW 3.2 (2.5) σ @450 GeV***
  - difference can be related to the effect of the detector resolution

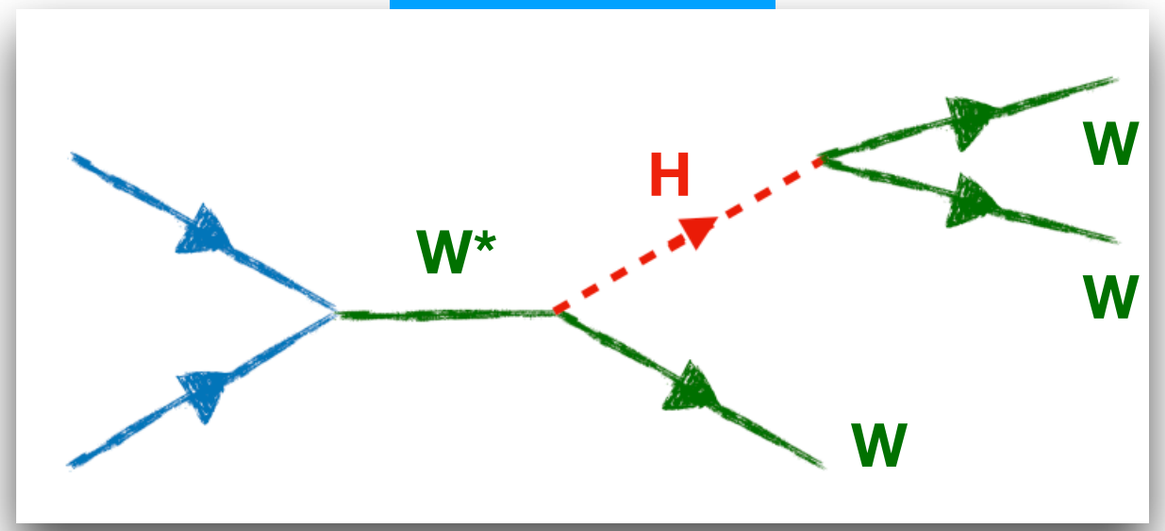
- Largest excess @m_{H5} = 375 GeV
  - local sigma 3.3
  - global sigma 2.5
- Data interpreted as exclusion limits on the sin-ϑ_H as a function of the m_{H5}
  - ***10% to 26% more stringent than the individual analyses***
  - ***10% to 50% stronger than CMS results***



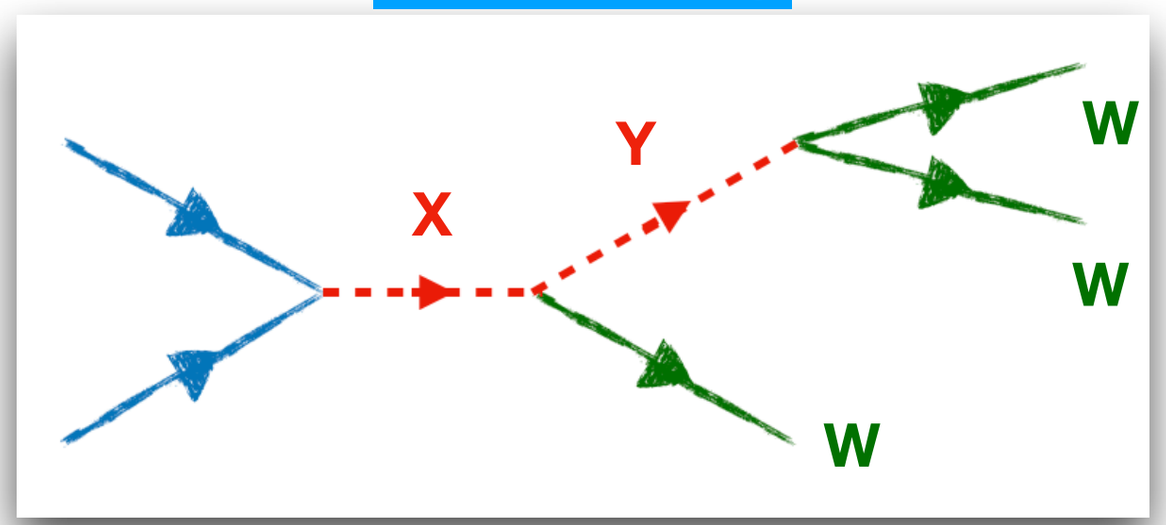
Tri-boson searches: how to

- We have been focusing on diboson signatures and got incredibly amazing results during Run-1/2
  - ***what if NP manifests in other signatures?***
- For example, tri-boson signatures might offer scenarios with lower SM backgrounds
  - "VX" production, with X generic heavy resonance, ATLAS WH —> WWW search *JHEP 07 (2023) 200*
  - Cascade decays, some from CMS see next slide

VX production



Cascade decay

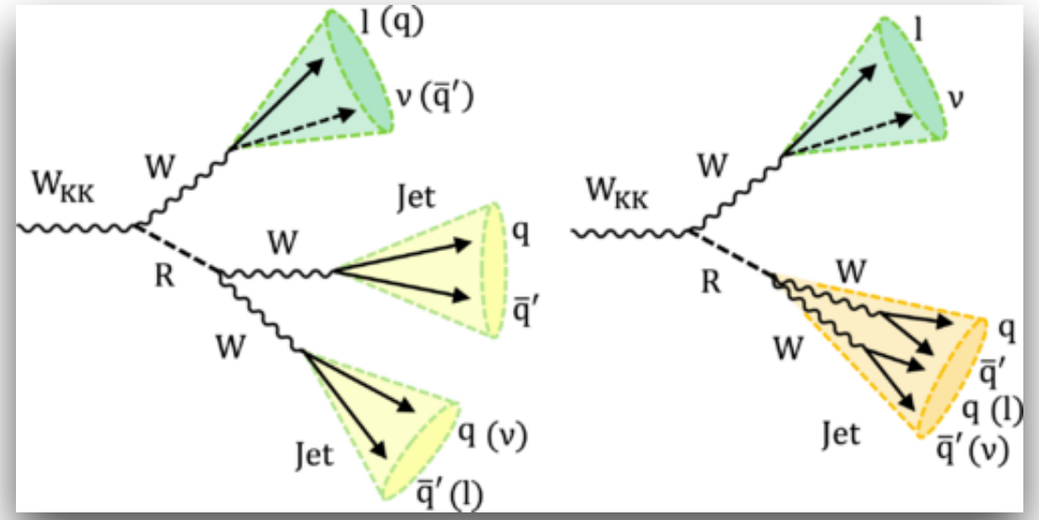


Cascade decays searches

- Can explore a larger phase space looking at 3 jets signatures
  - fully hadronic final states to explore high mass regimes
- ***W_{KK} in tri-bosons final state***
  - lν + 2 x 2-prongs large-R jets or lν + 1 x 4-prongs large-R jet
- ***g_{KK} in tri-jets final state***
  - 2 x 2-prongs large-R jet + 1 gluon-initiated jet

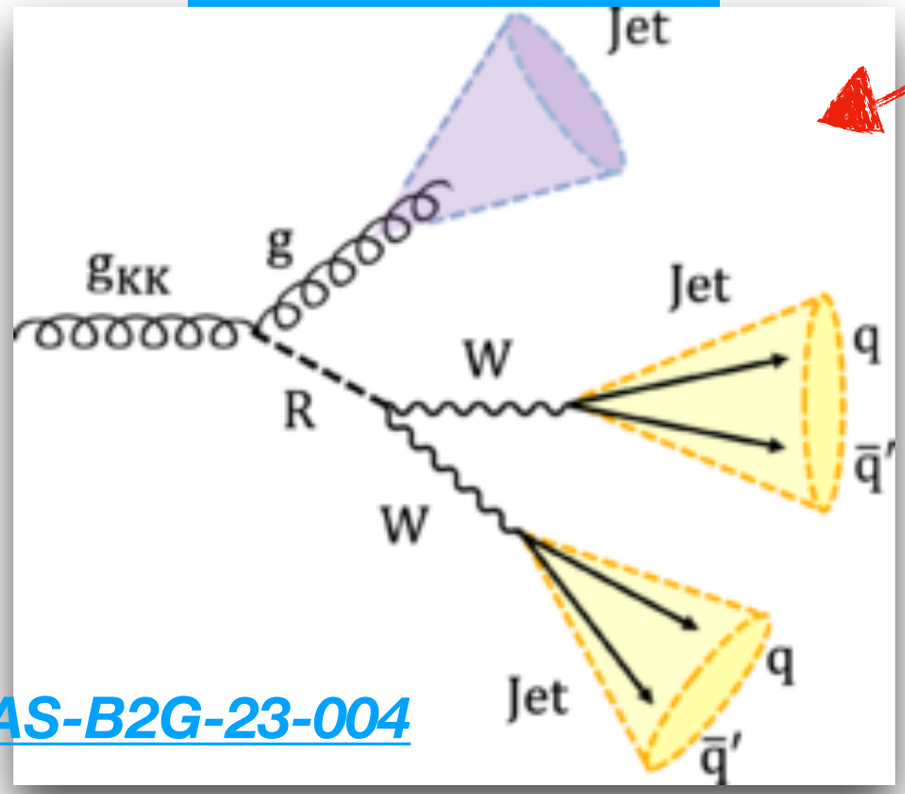
Discussed today

WWW: lνJJ or lvJ signatures



[PhysRevLett.129.021802]

gWW: JJJ signature



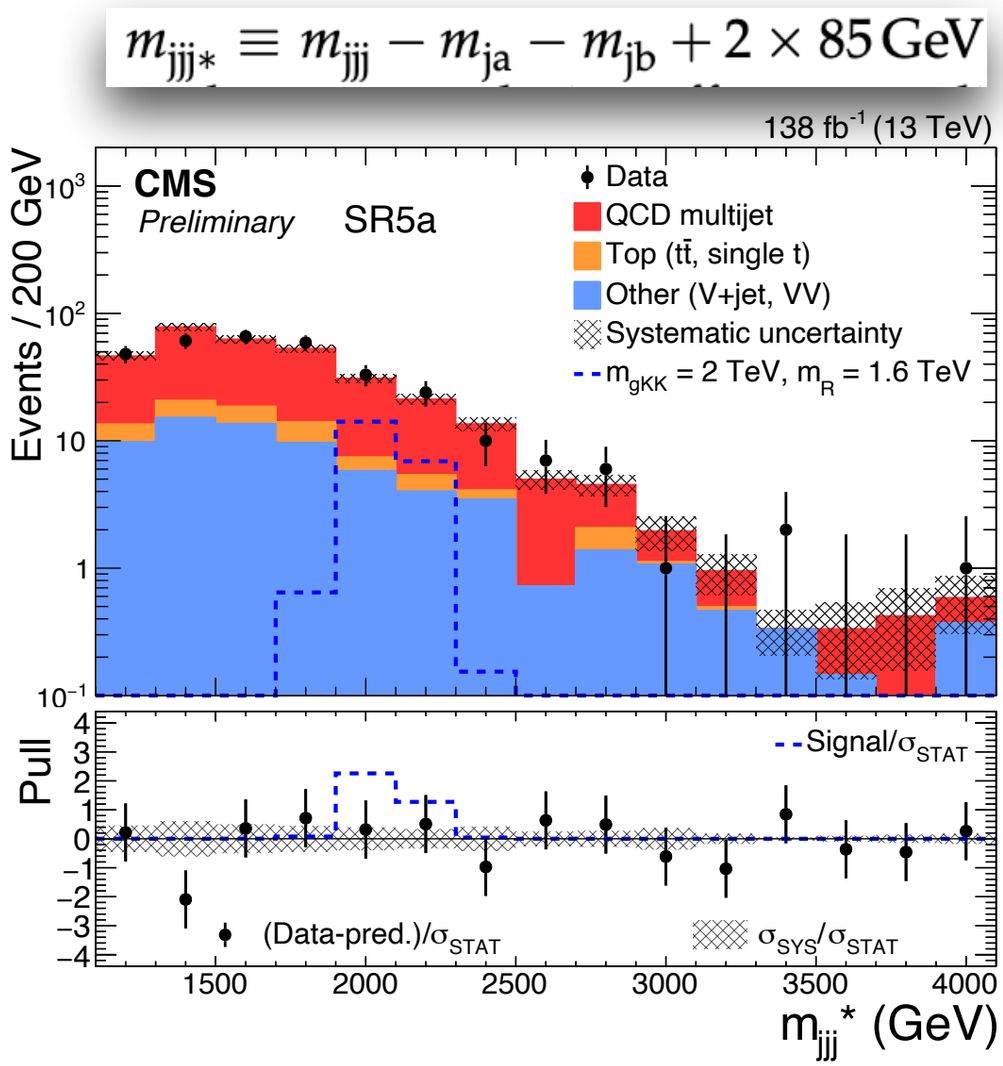
[CMS-PAS-B2G-23-004]

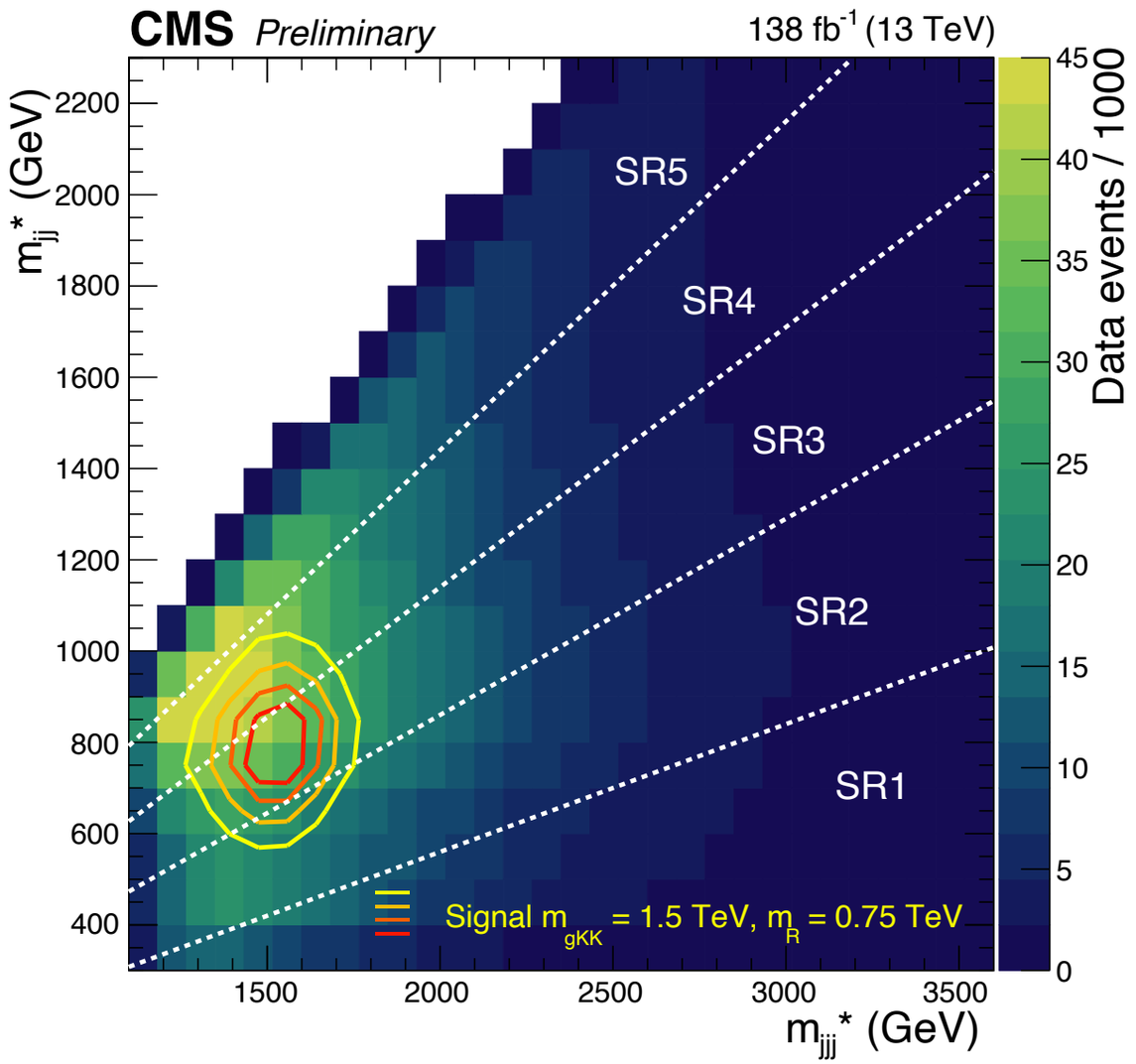
gWW search: challenges

[CMS-PAS-B2G-23-004]

- Sensitive variable: modified invariant mass
  - improve the signals resolution
  - define several SRs to optimise the sensitivity to different mass grid hypotheses
- The main multi-jets background estimated via data driven (ABCD)

$$m_{jjj*} \equiv m_{jjj} - m_{ja} - m_{jb} + 2 \times 85\,\text{GeV}$$

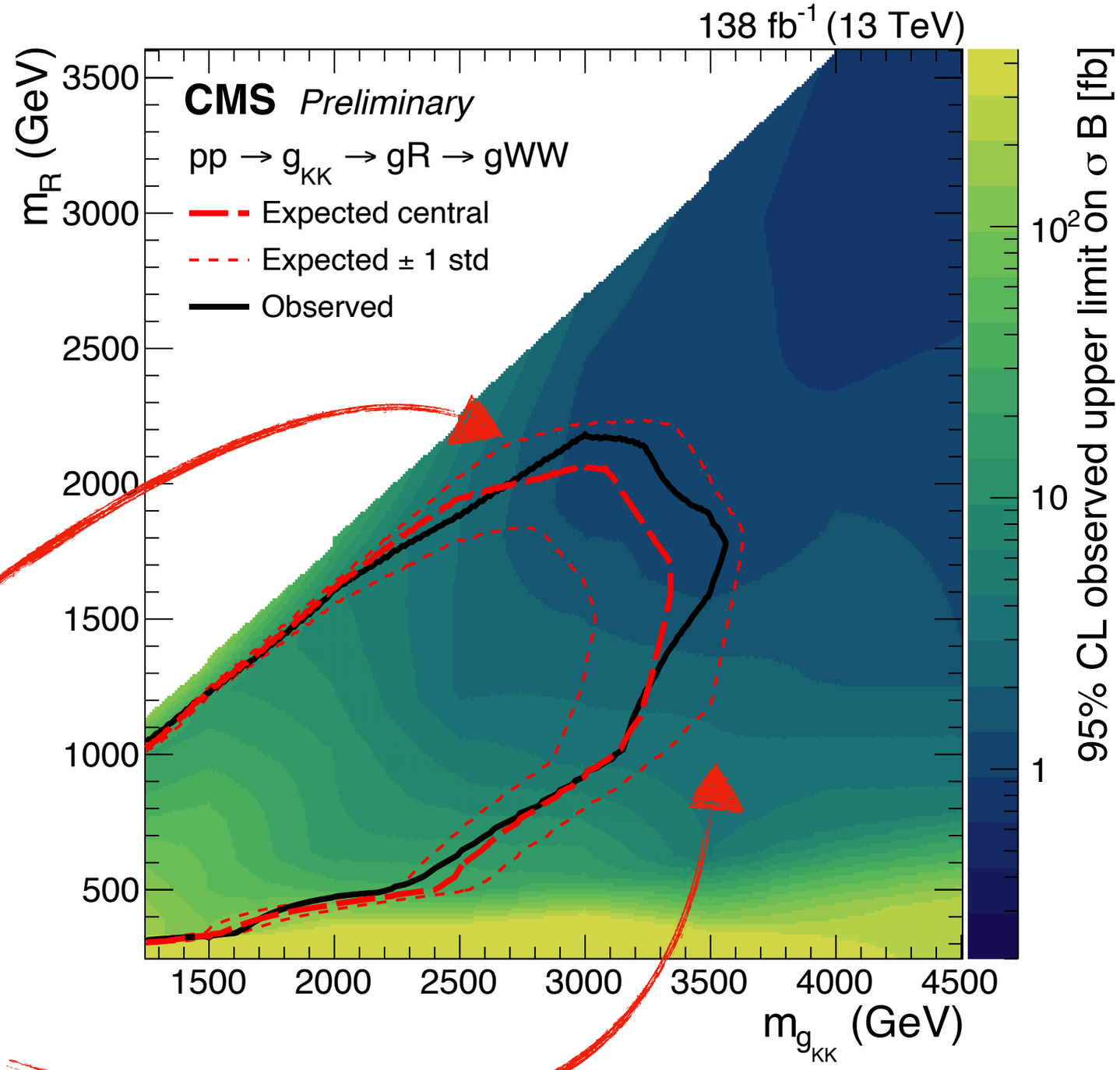




Results on extended WED

CMS-PAS-B2G-23-004

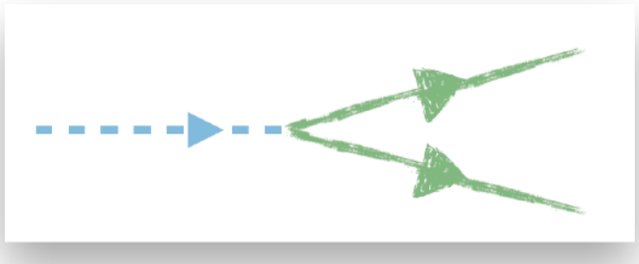
- No significant excess with respect to the SM predictions
- Interpret the results in the context of the ***extended Warped Extra Dimension model***
  - g_{KK} spin-1
  - Radion spin-0
  - set limits on the g_{KK} and R masses



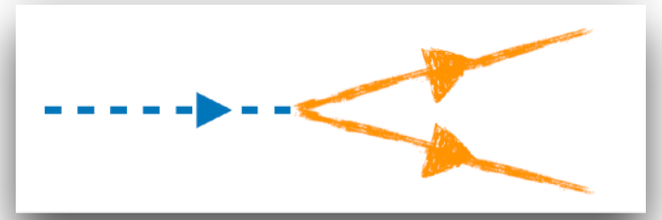
Warped extra dimensions extended model exclusion: g_{KK} up to 3.5 TeV and R up to 2.2

New higgs associated channels

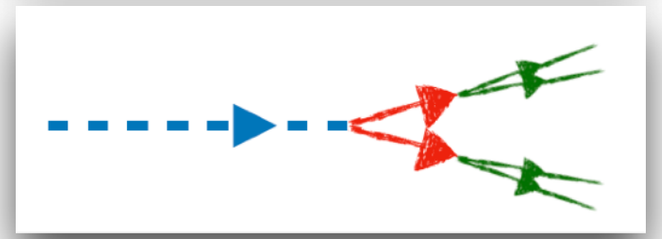
- Historical Vh searches can be extended by looking at new final states
  - e.g. ***Z(ll/vv) h(cc)*** and ***Z(ll/vv) h(VV*—>4q)***
- This is possible thanks to the new and improved jet tagging techniques
- We can explore more final states and get benefits in combinations with previous channels
  - ***note: the Zh —> ZVV* channel in some sense can be another example of tri-boson search!***



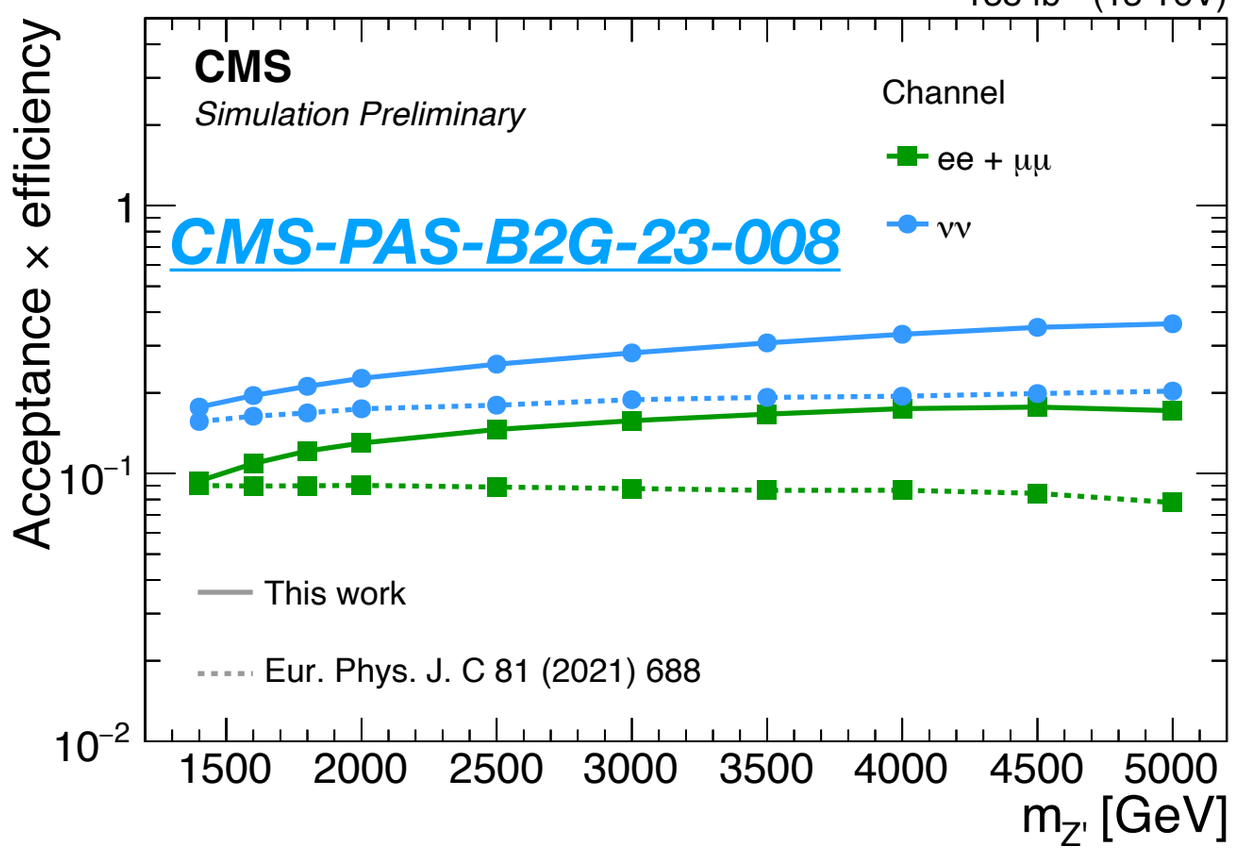
h —> bb



h —> cc



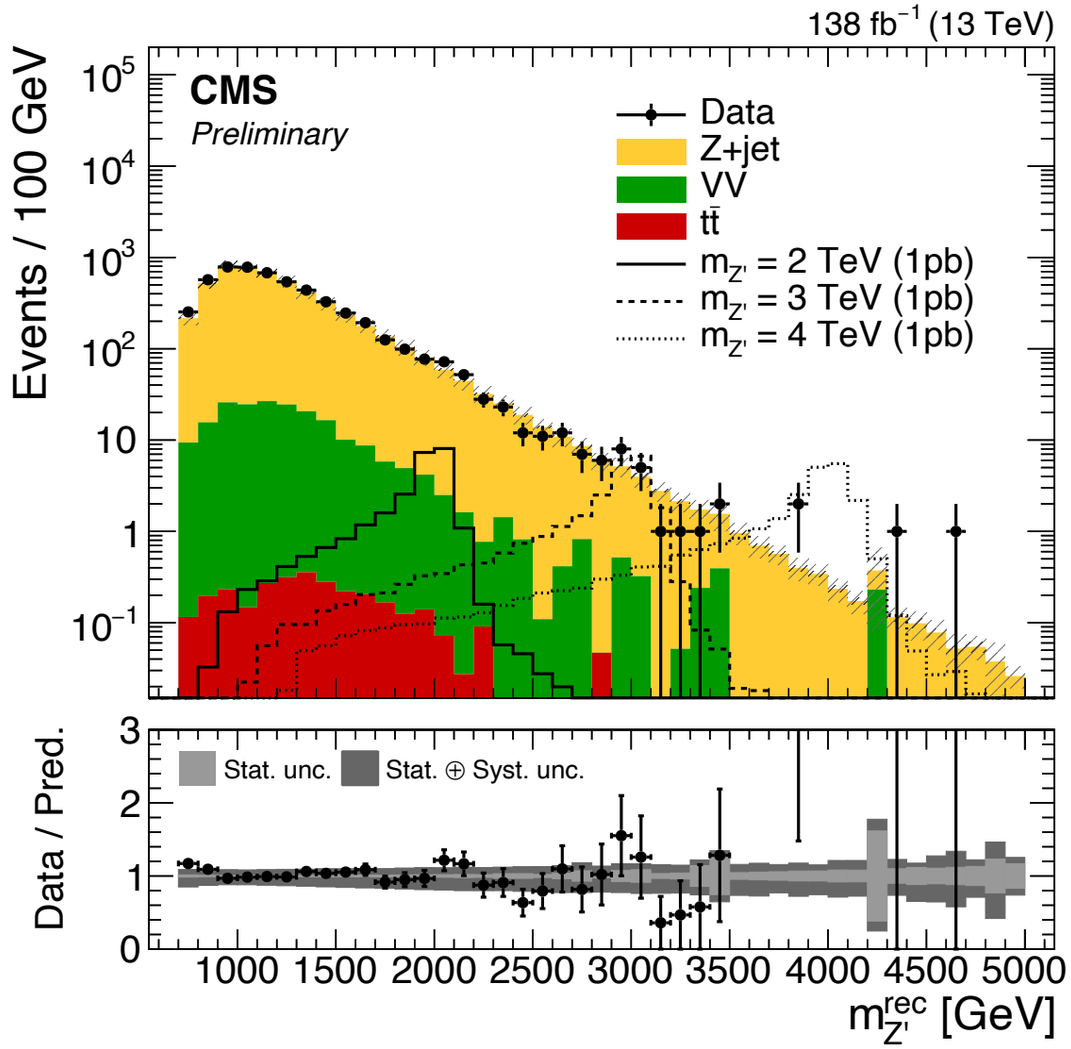
h —> VV* —> 4q

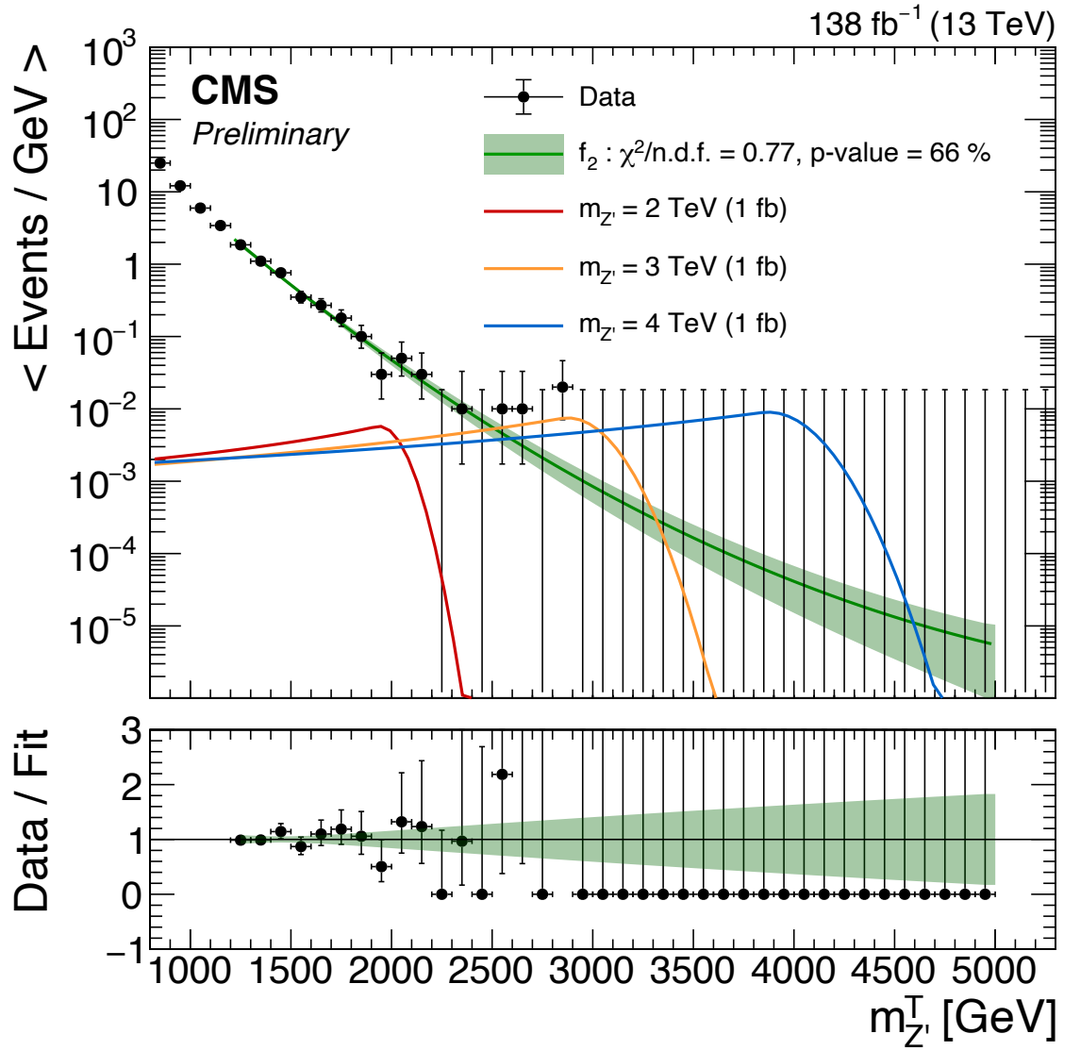


Zh(cc) and Zh(4q) semi-leptonic

CMS-PAS-B2G-23-008

- The SM background is mainly dominated by Z+jets production
  - contamination from W+jets and ttbar in the Z(vv) channel
- Data driven background estimation
  - reduce the amount of MC modelling uncertainties
  - functional form fit to the falling down SM bkg and to signal parameterisation

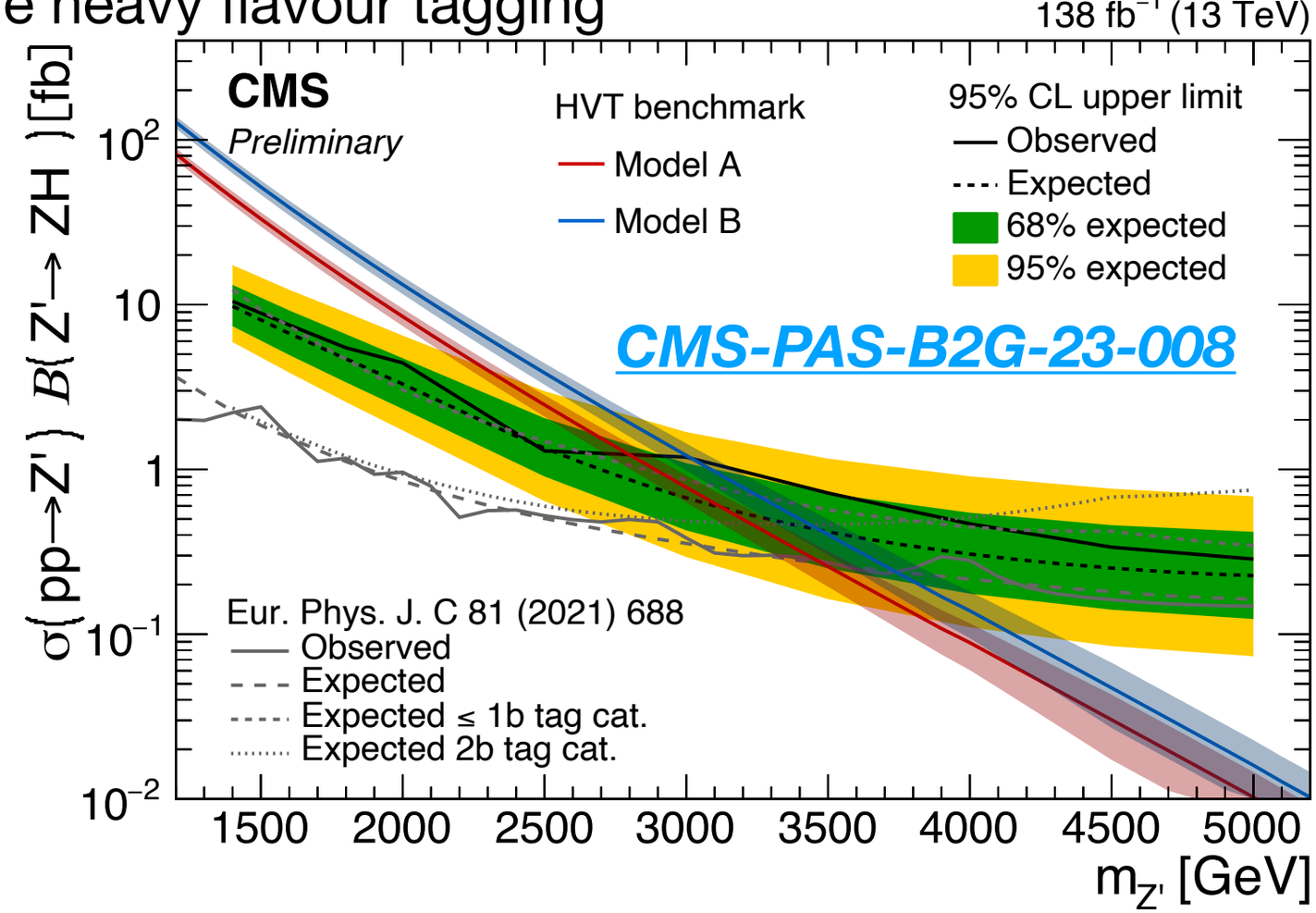




Zh semi-leptonic interpretation

- The data are interpreted in the context of the HVT spin-1 model
  - model-A, $m_{Z'} < 2.8$ TeV
  - model-B, $m_{Z'} < 3.0$ TeV
- The Z($\nu\nu$) channel is dominating over the Z(ll) channel
- Comparison with respect to the baseline Zh(bb) search
  - better sensitivity due to the heavy flavour tagging

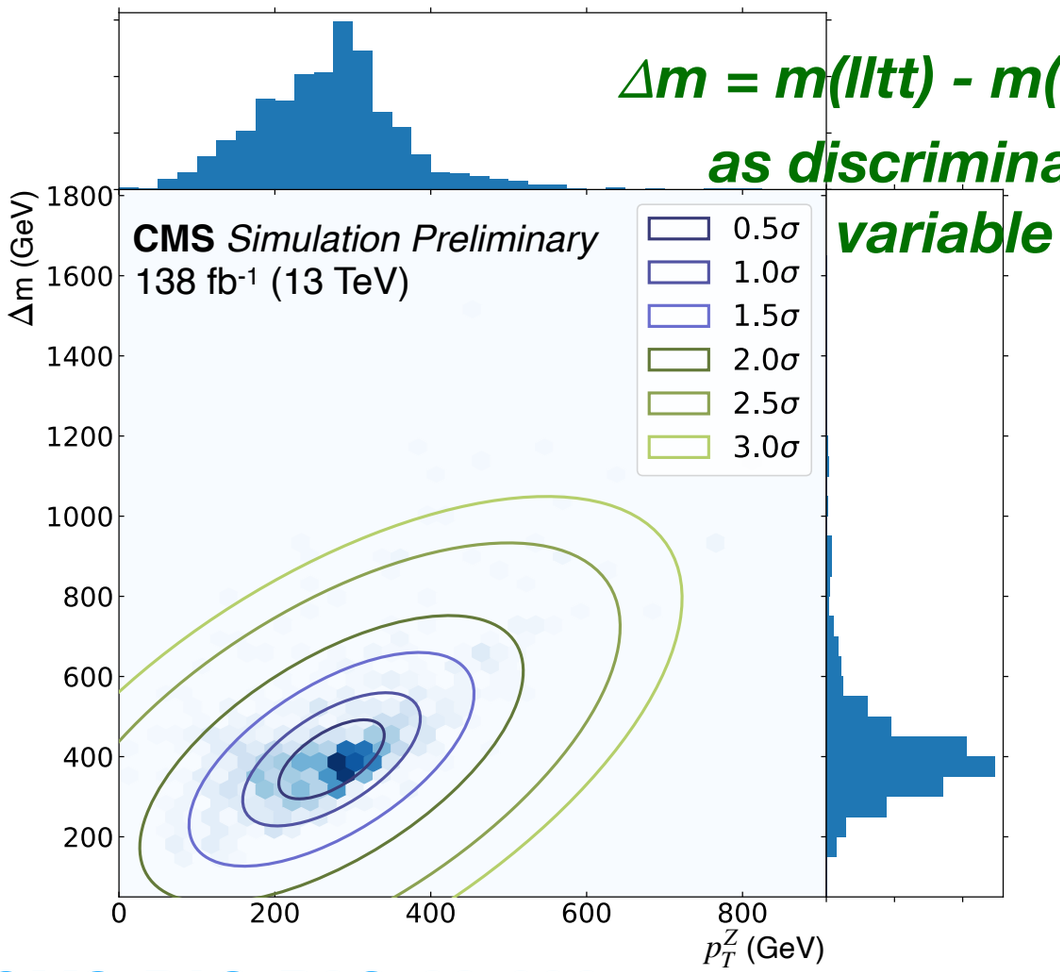
New channels offer the possibility to improve combinations and push for further jet tagging techniques improvements!



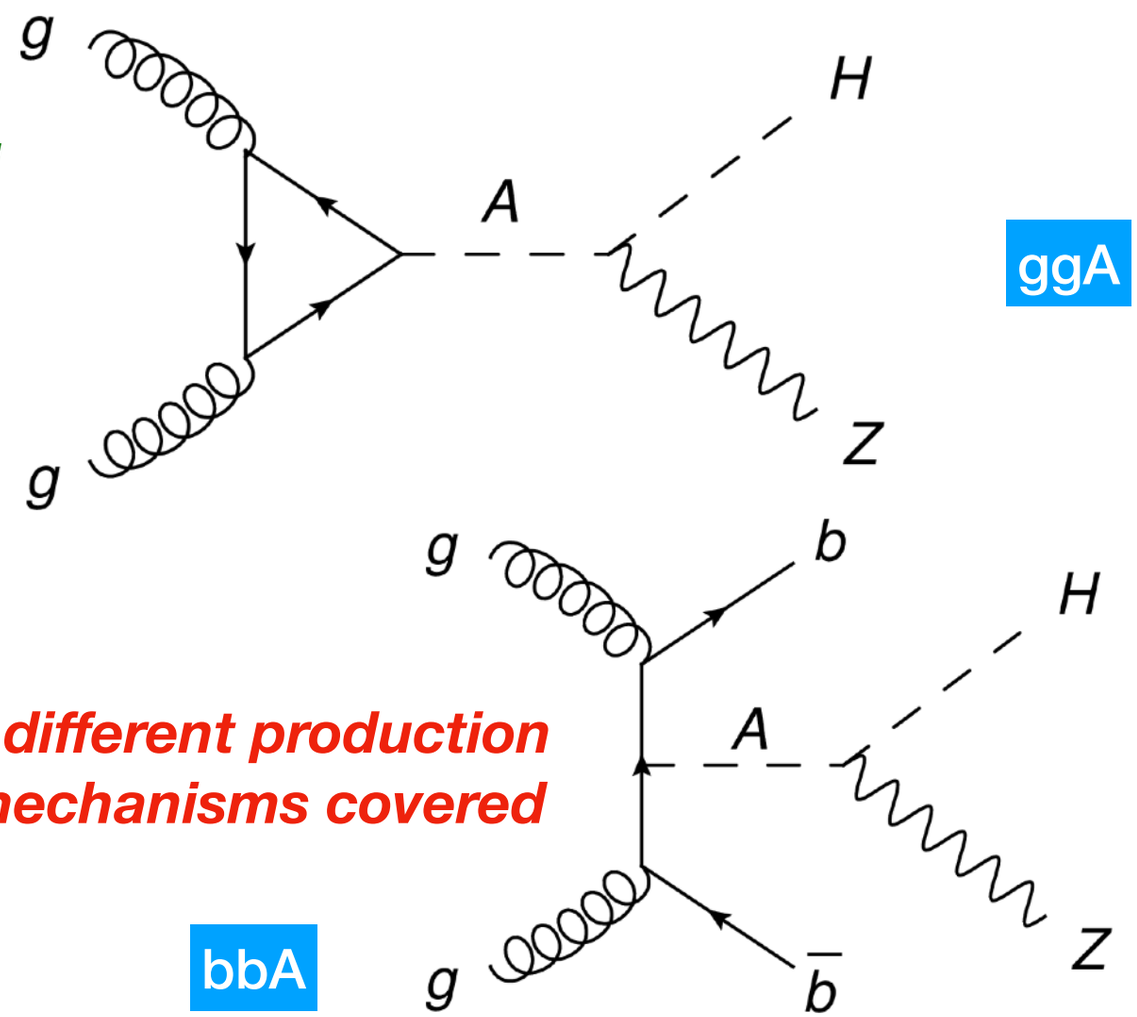
ZH

2HDM: AZH searches

- Explore final states with one SM and one BSM boson
  - Z + high mass Higgs
- 2HDM parameter space
  - new lltt final state to enhance the sensitivity for $m_H > 2*m_{Top}$ with the H —> tt decay being dominant



Δm = m(lltt) - m(tt) used as discriminating variable



2 different production mechanisms covered

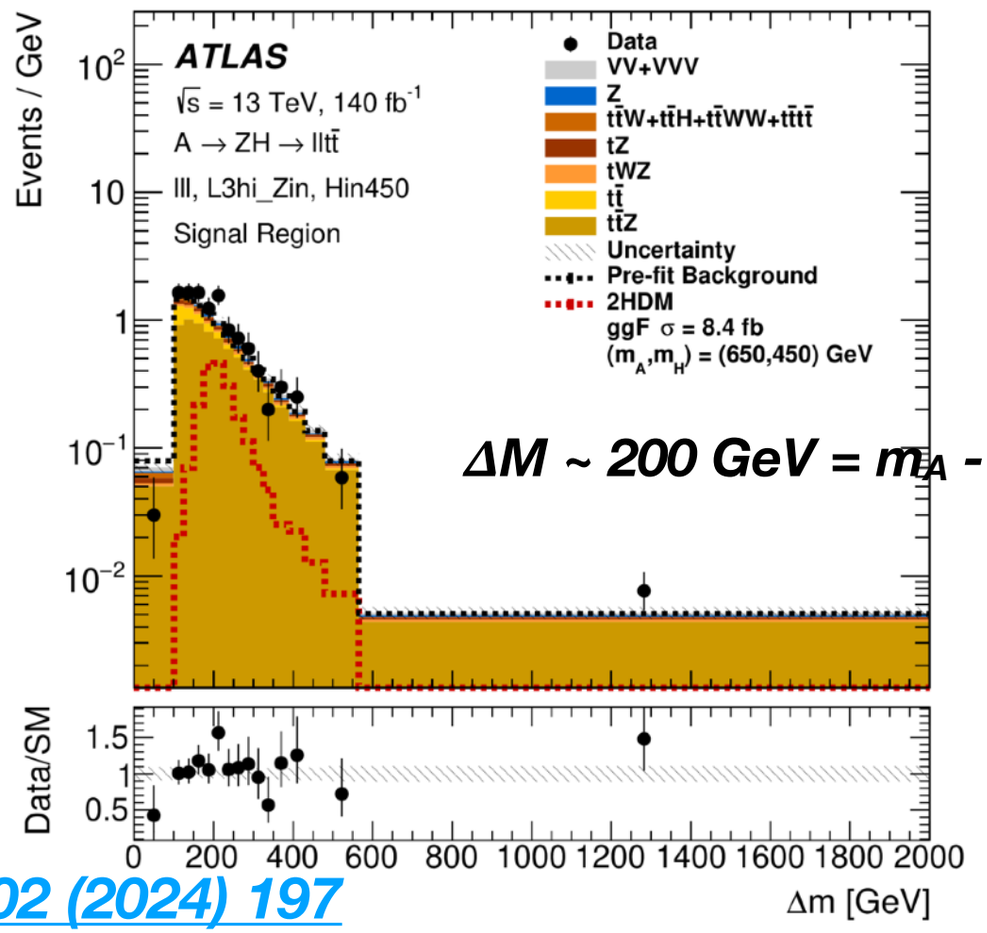
[CMS-PAS-B2G-23-006]

[JHEP 02 (2024) 197]

ZH

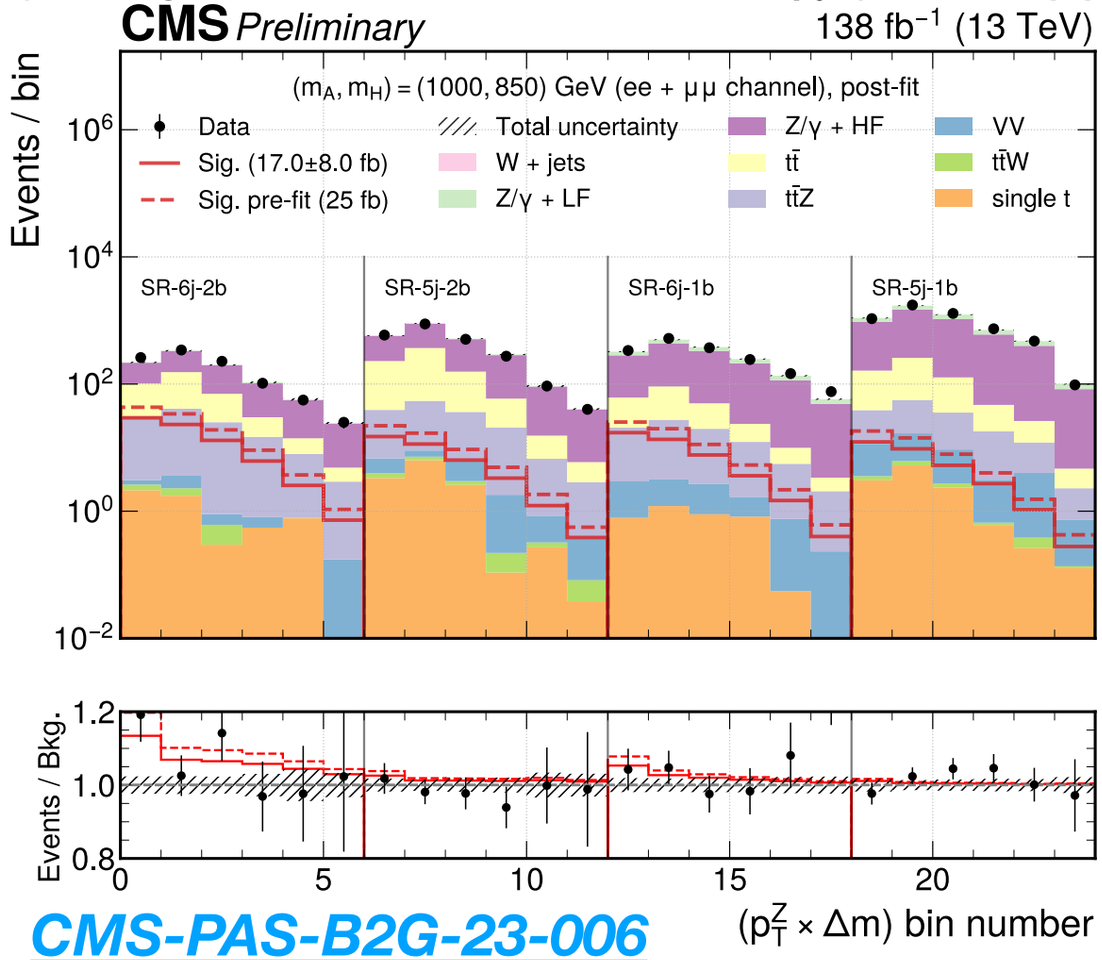
Where to look for

- Recent and exciting results:
  - ***[ATLAS] AZH —> $\nu\nu$bb and lltt, with tt semi-leptonic***
  - ***[CMS] AZH —> lltt, with tt fully hadronic***
- Resolve the final state is challenging given the many objects
  - ***tt semi-leptonic***: t_{lep} over t_{had} pairing, improve resolution by constraining m(lν) and m(qq') systems and m(tt)
  - ***tt fully hadronic***: if more than 5 or 6 jets, jets system that minimise the χ^2(tt—>bqqbqq)



ΔM ~ 200 GeV = m_A - m_H

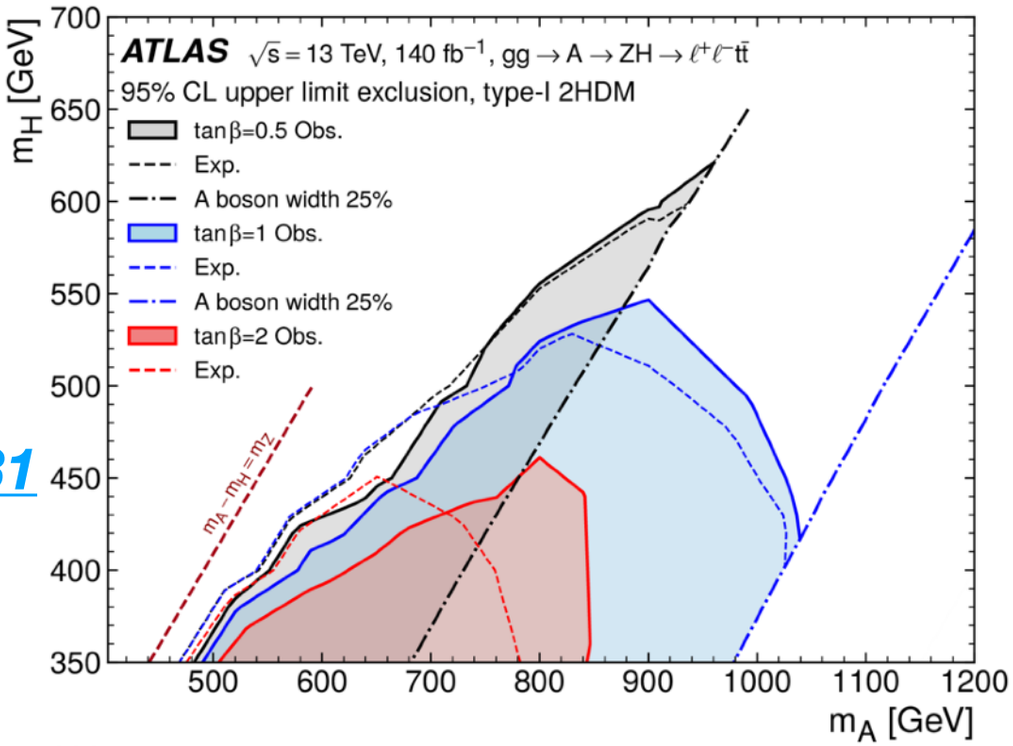
JHEP 02 (2024) 197

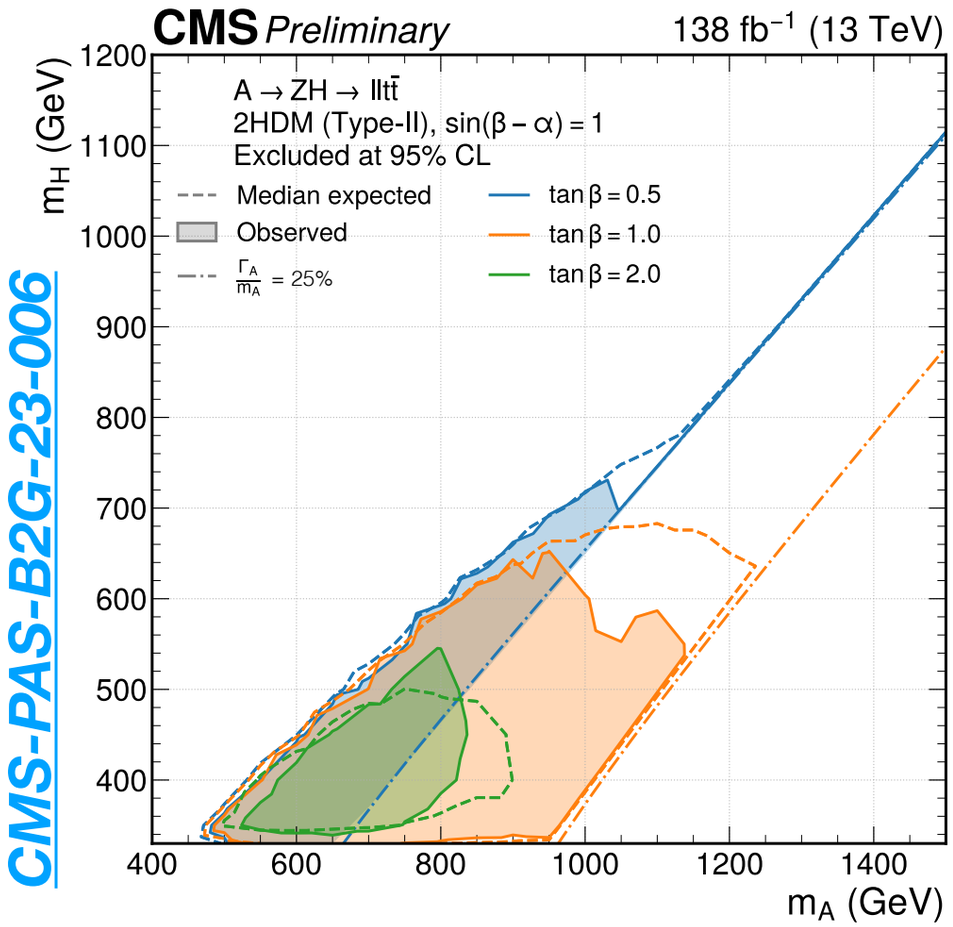


CMS-PAS-B2G-23-006

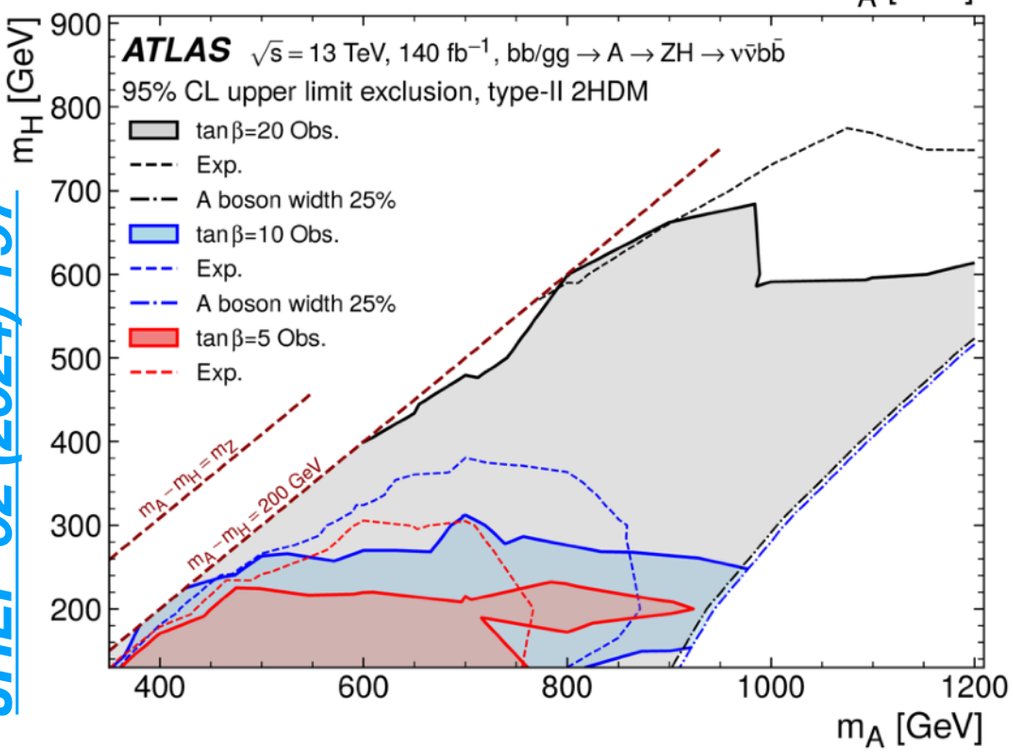
Limits on 2HDM model

- Data interpreted in the context of type-I and type-II 2HDM
  - different tanβ hypotheses
- Most significant excess
  - ATLAS 2.85 σ (local) 2.35 σ (global) @(m_A, m_H) = (650, 450) GeV
  - not confirmed from CMS
- For more, theory "Smoking gun" paper ***arxiv.2309.17431***





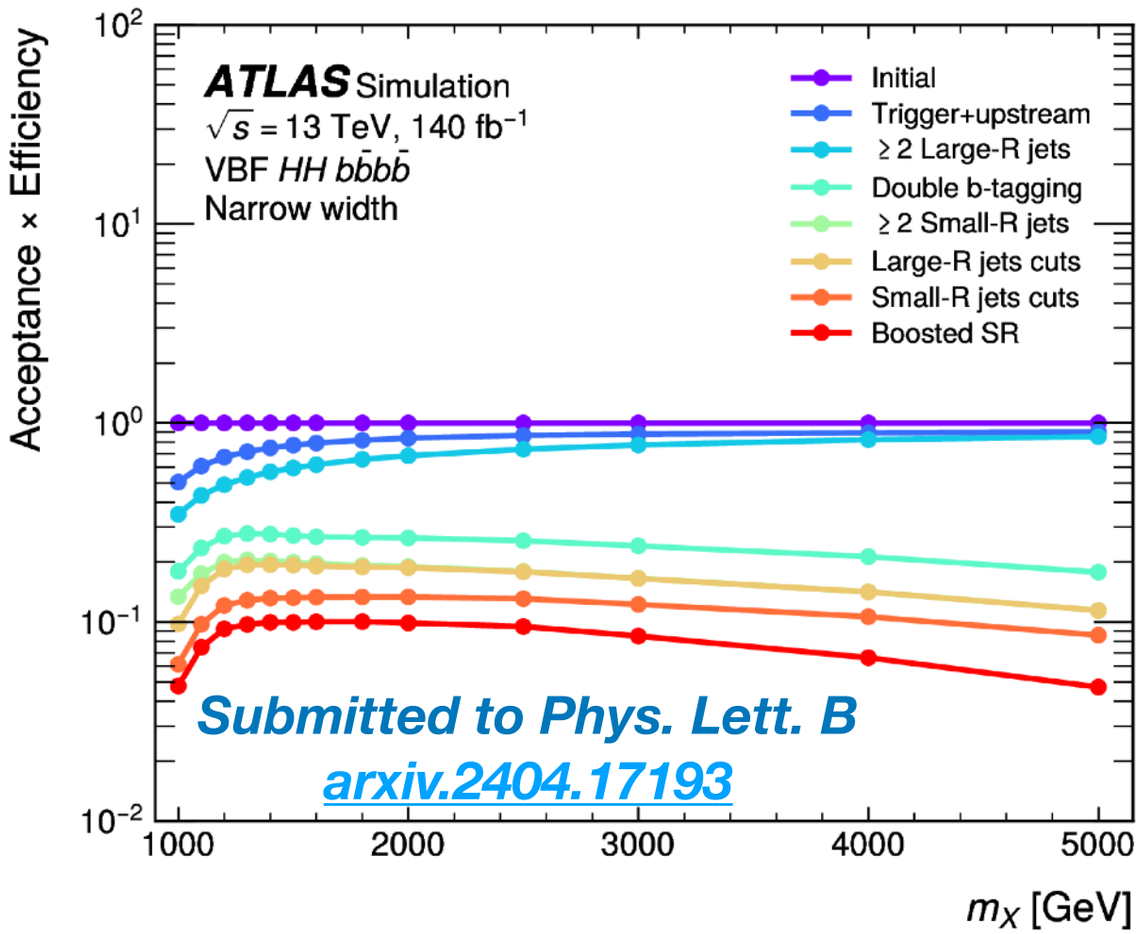
CMS-PAS-B2G-23-006

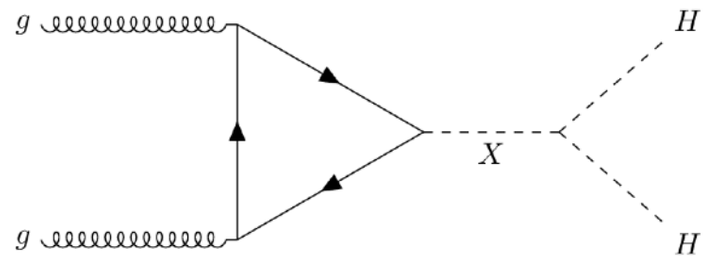


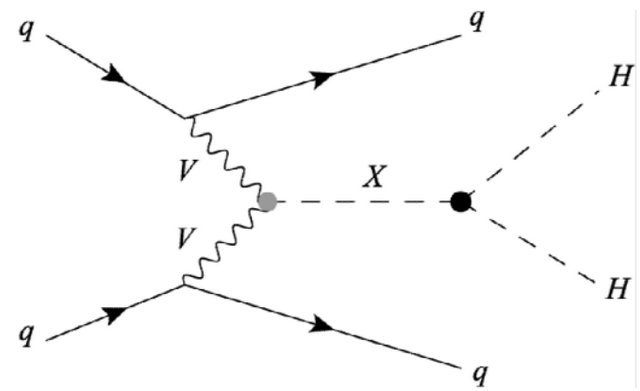
JHEP 02 (2024) 197

hh resonant searches

- Di-higgs signatures offer the possibility to explore the presence of new resonances
  - strongly connection between resonant and non-resonant searches!
- Two new final states recently published
  - VBF 4b (boosted) and bbWW multi-leptons







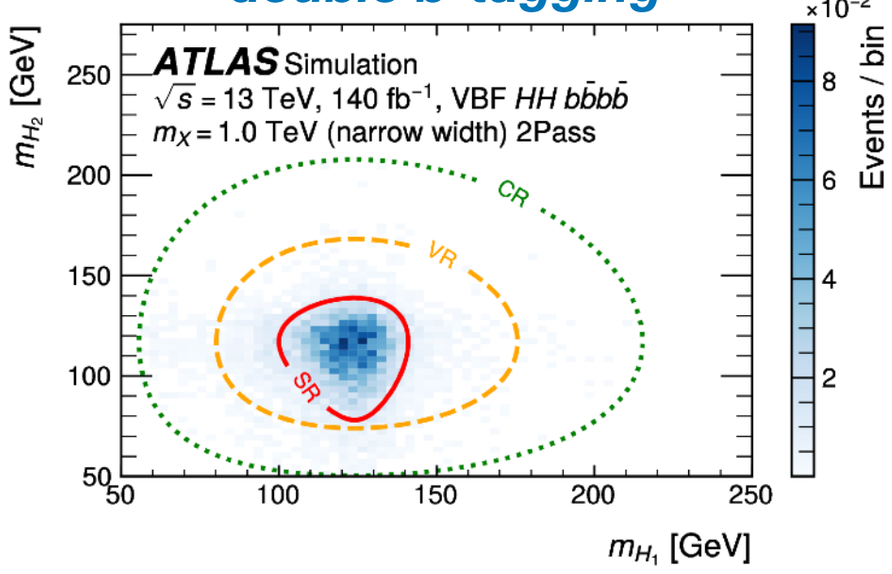
bbWW channel:
1lep (lvqq) and 2lep (lvlv)
second largest combined BR

	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%

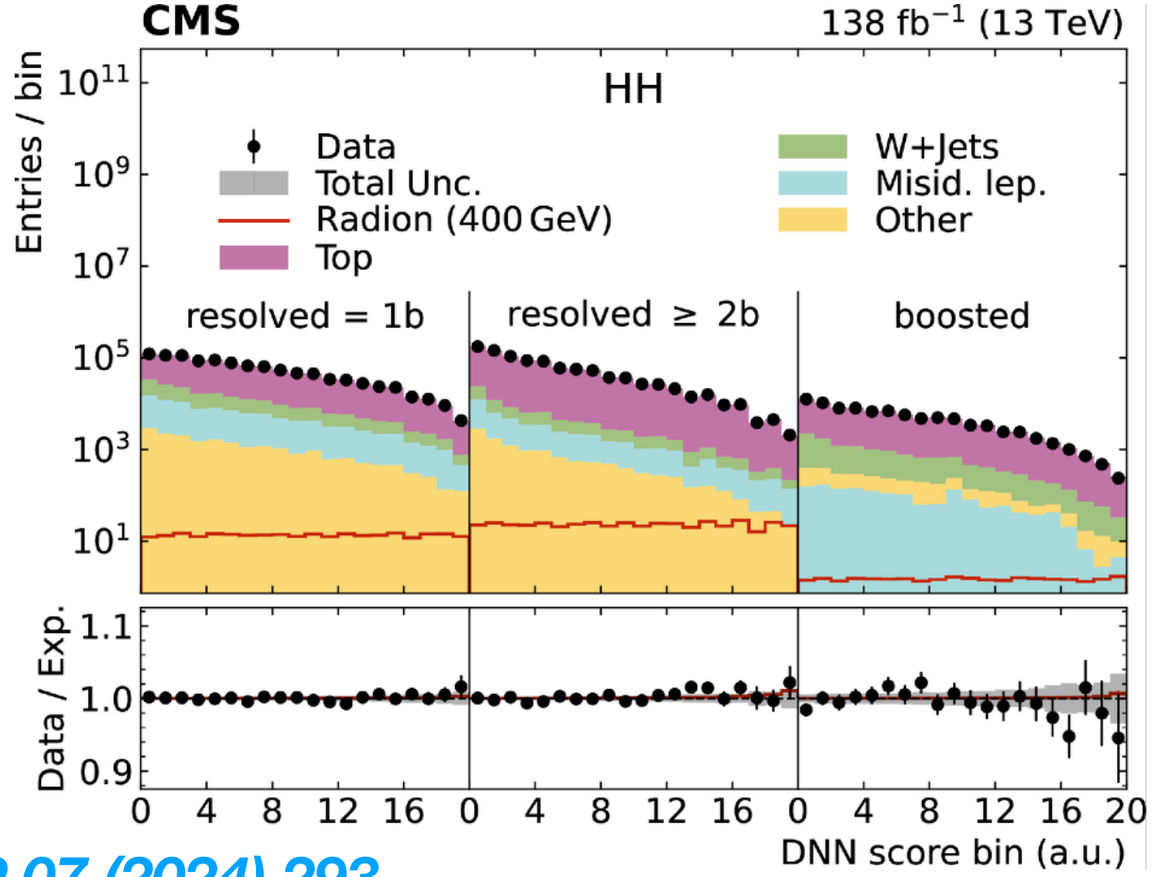
How to estimate the background

- ***Fully hadronic final states***
  - QCD multijets production estimated via data driven technique
- ***Final states with leptons***
  - V+jets and ttbar dominant backgrounds, still possible via MC simulations
- ML techniques to enhance the sensitivity to the signal

SR: two large-R passing double b-tagging

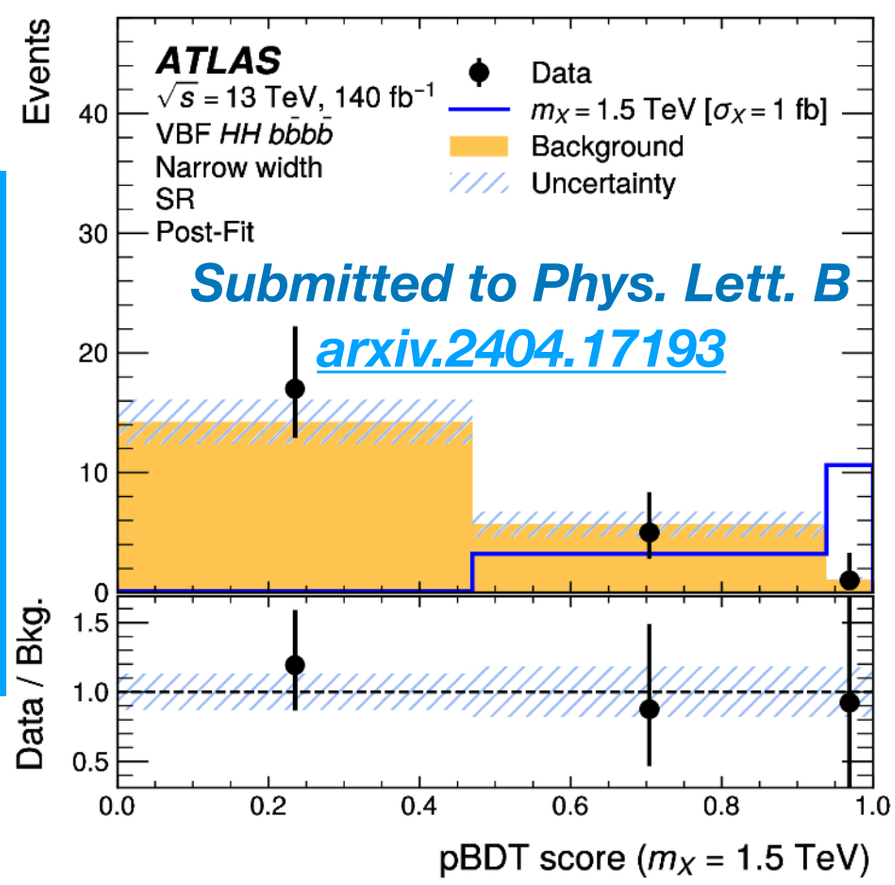


DNN + Lorentz Boost Network as pre-processor



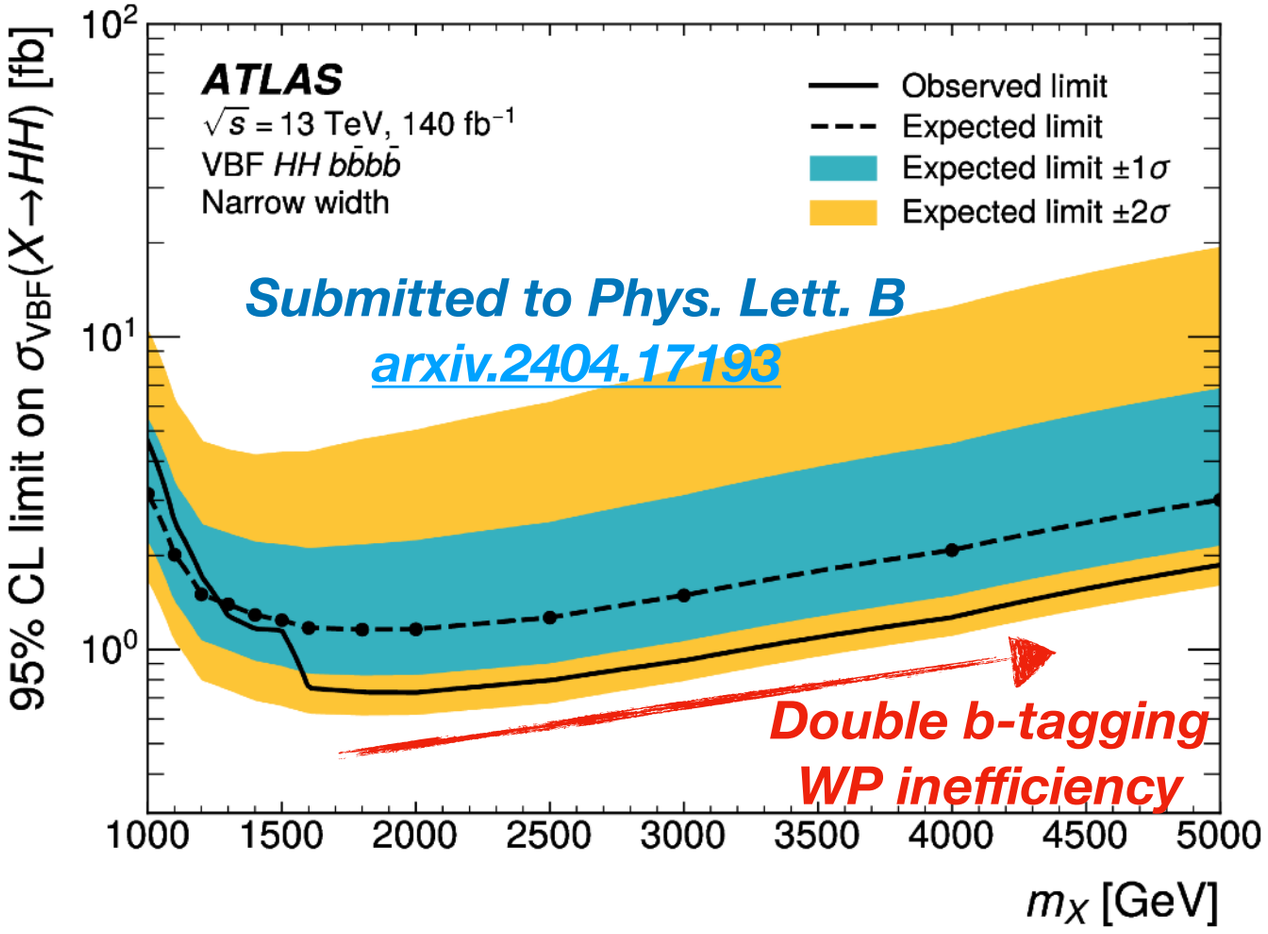
[JHEP 07 (2024) 293](#)

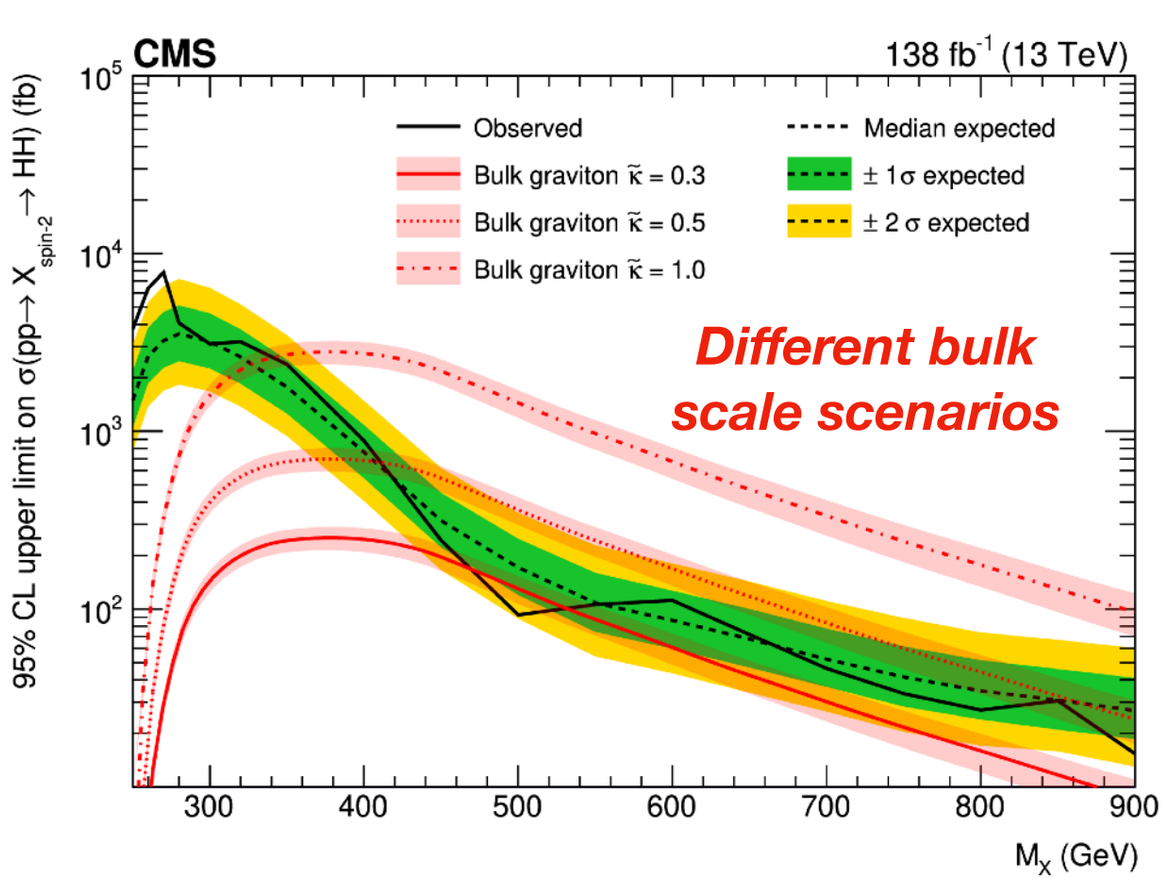
parameterised-BDT



Recent hh results

- Combined fit using the ML output scores
- Data in the SRs are interpreted in the context of new resonances:
  - ***spin-0 narrow and broad width resonance***
  - ***spin-0 radion and spin-2 graviton***
- Upper limits on the X —> hh cross section in complementary mass ranges
  - boosted 4b sensitivity up to high mass
  - bbWW lower mass, competitive with bb$\gamma\gamma$ above 700 GeV

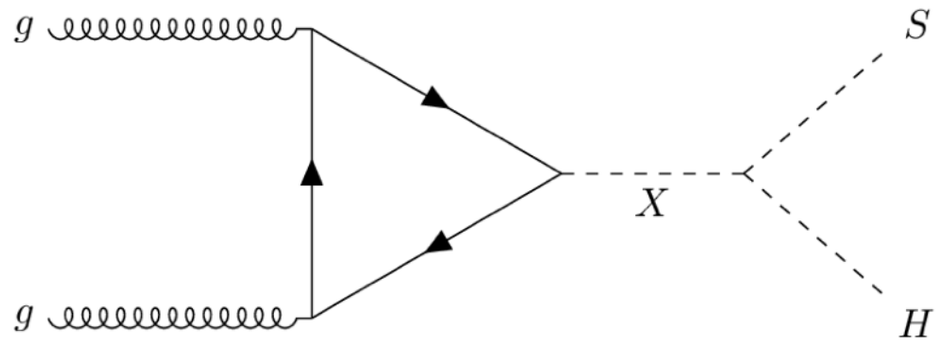




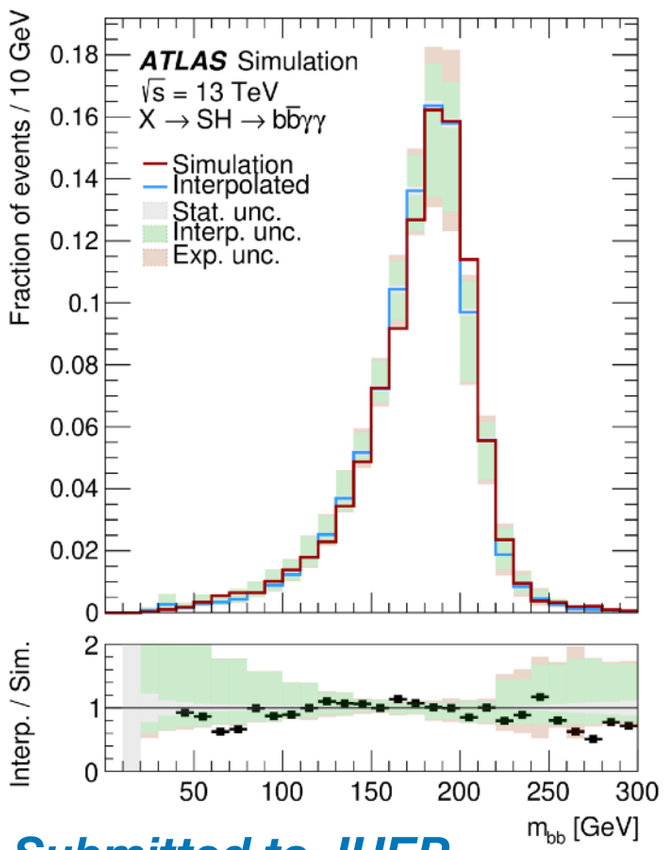
JHEP 07 (2024) 293

Sh resonant searches

- Resonant searches extending the phase space by relaxing the hypothesis on the mass on one of the higgs
  - X —> Sh, different final states covered
- Searches inspired from the 2HDM+S (*arxiv.1808.02667*) or NMSSM models (*Phys. Rep. 496 (2010)*)
- ***Where to look for to catch the signal?***

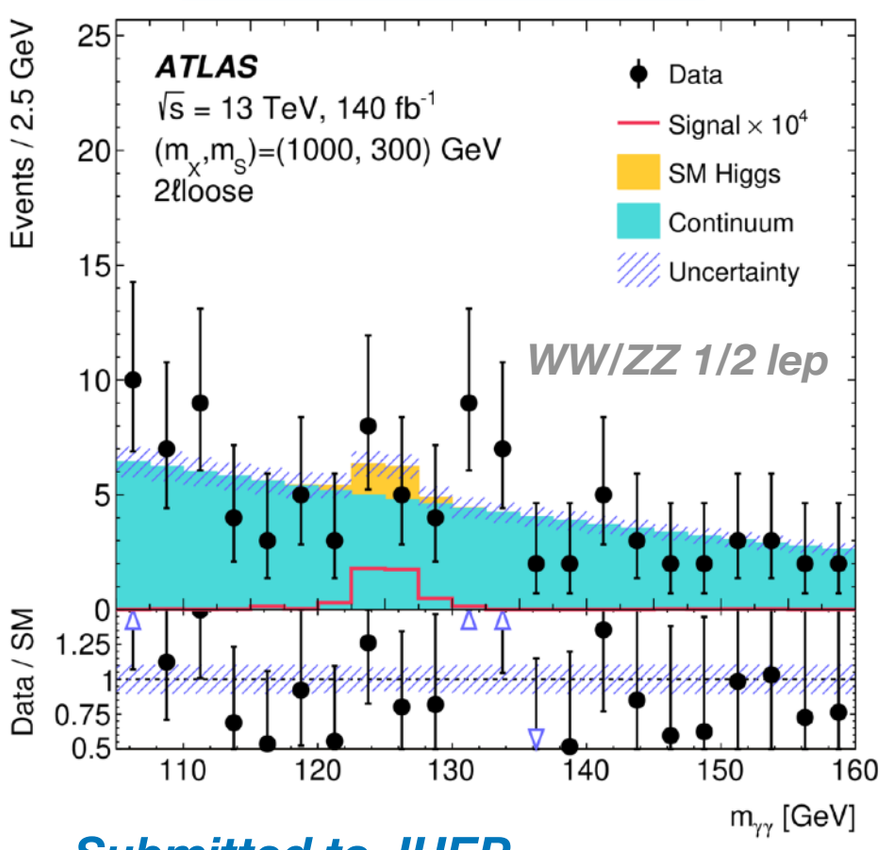


X —> Sh —> bbγγ
m_X < 1 TeV, m_S < 500 GeV



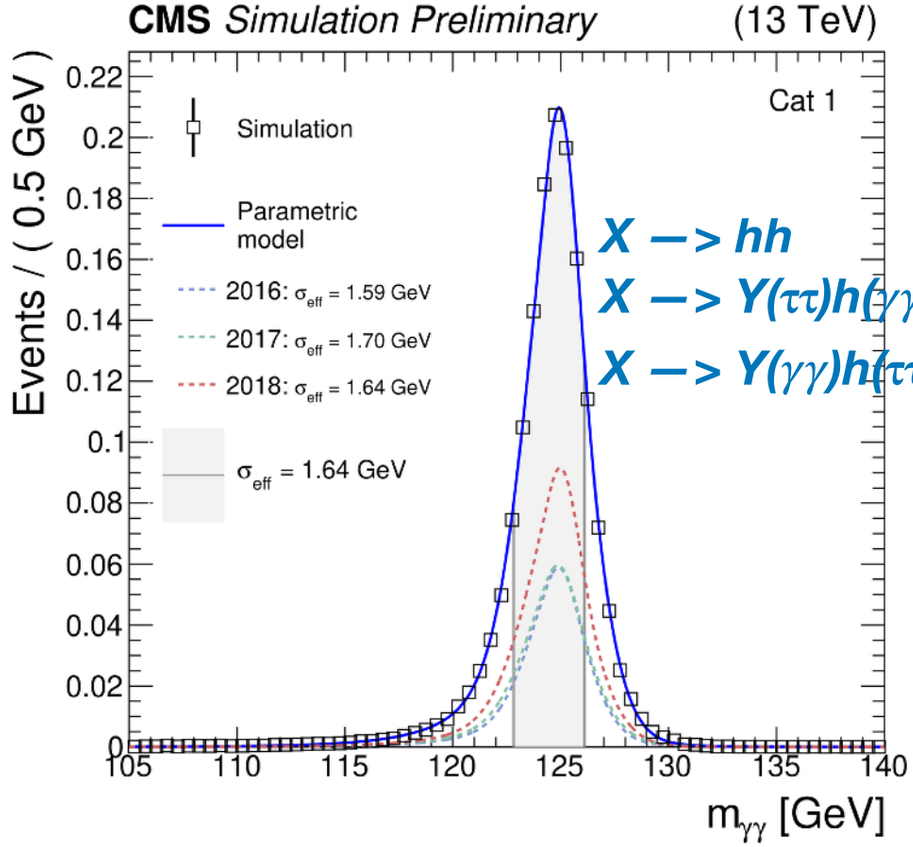
Submitted to JHEP
arxiv.2404.12915

X —> Sh —> VVγγ
m_X < 1 TeV, m_S < 500 GeV



Submitted to JHEP
arxiv.2405.20926

X —> Sh —> γγττ
m_X < 1 TeV, m_S < 800 GeV

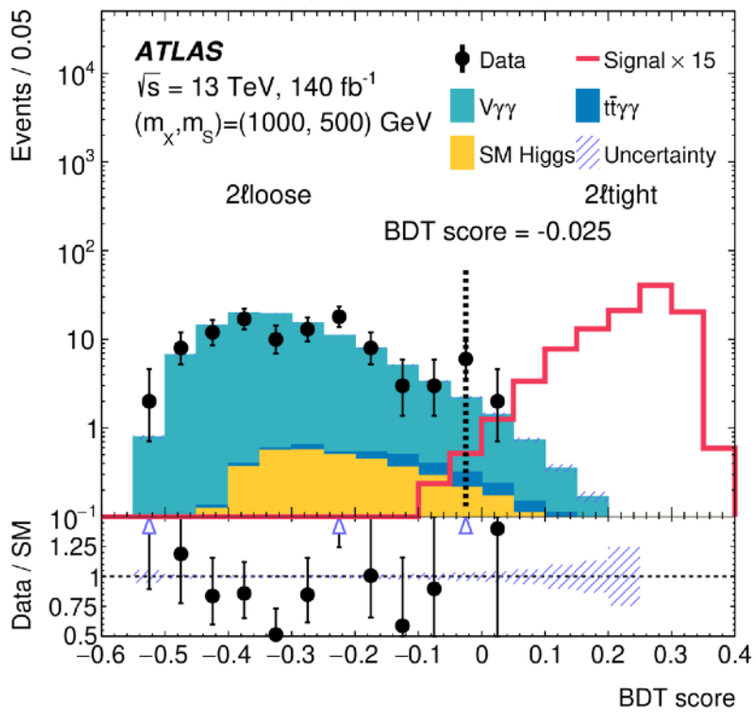


CMS-PAS-HIG-22-012

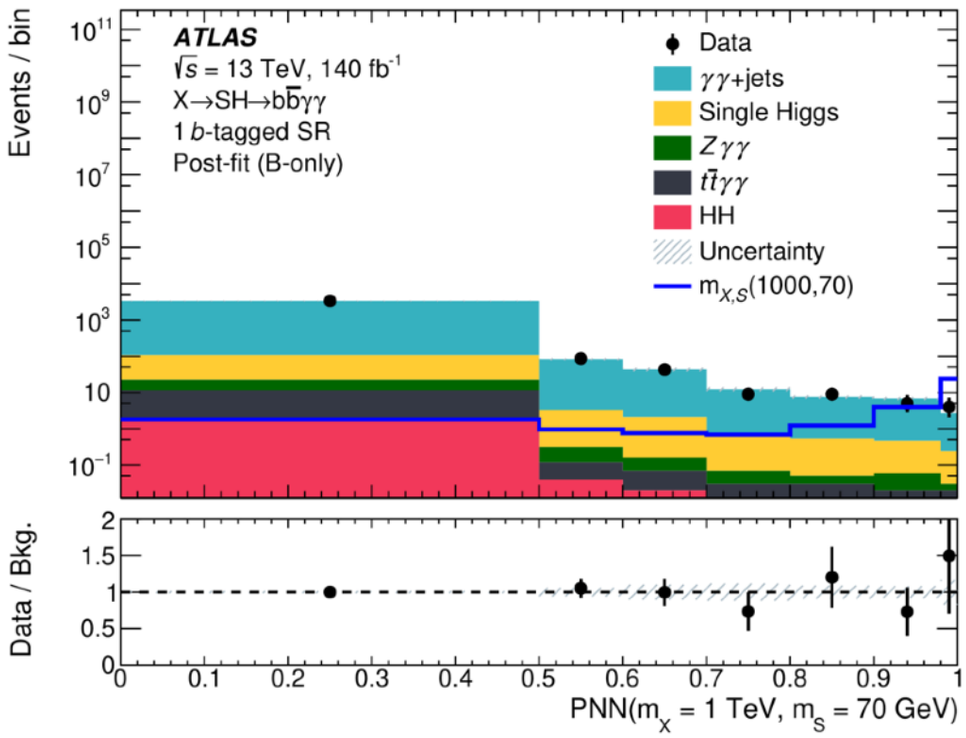
How to enhance the signal

- All these searches rely on ML approaches to enhance the sensitivity to the signal
  - signal peaking in 2 dimensions
  - kinematic variables as input features
- Optimise the discriminant
  - p-DNN (fit) approach for bb$\gamma\gamma$
  - p-DNN for $\gamma\gamma\tau\tau$, used to define categories
  - p-BDT for VV$\gamma\gamma$ due to tighter phase space

VV$\gamma\gamma$ p = (m$_S$)



Submitted to JHEP
arxiv.2405.20926

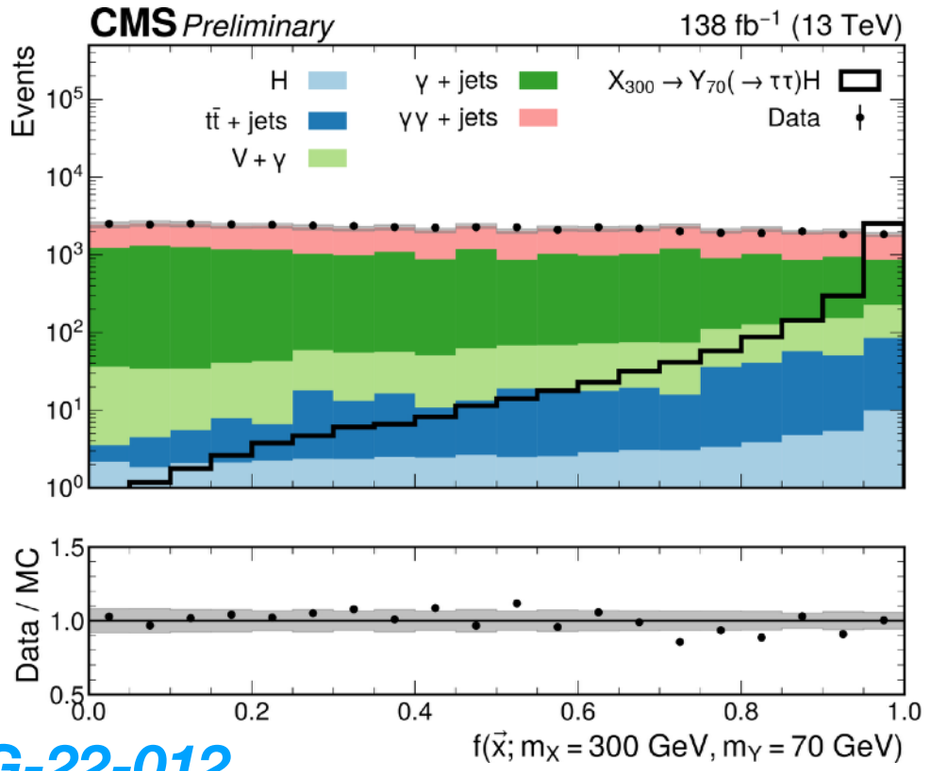


bb$\gamma\gamma$:

p = (mX, mS) 2b SR

p = (mX) 1b SR

Submitted to JHEP
arxiv.2404.12915



$\gamma\gamma\tau\tau$:

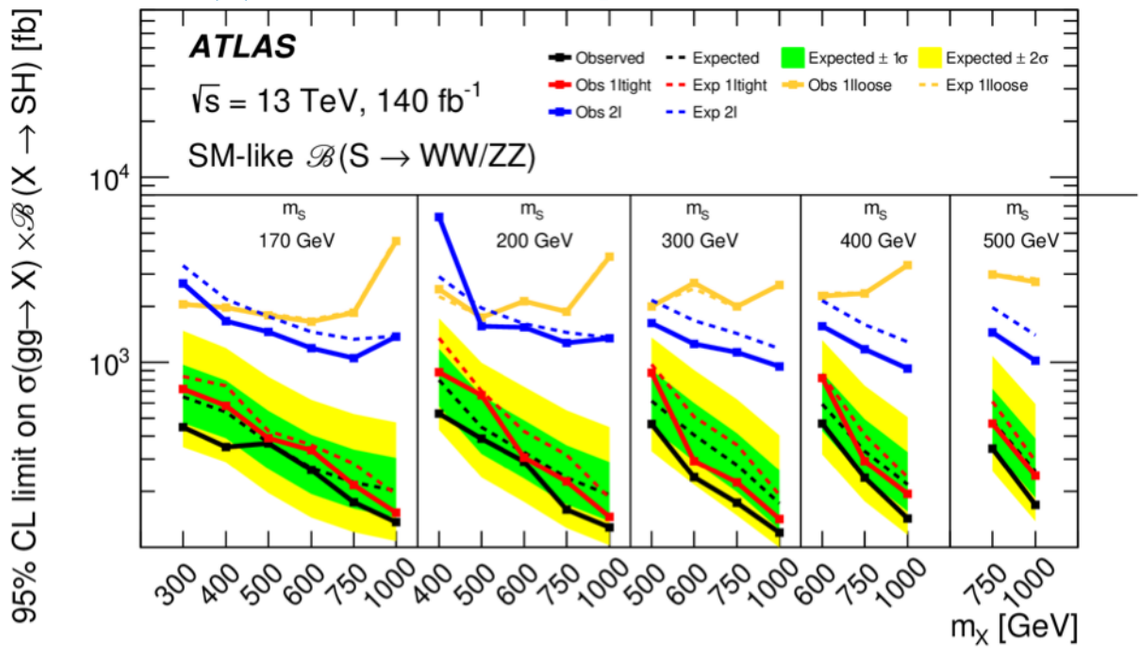
p = (mX, mS)

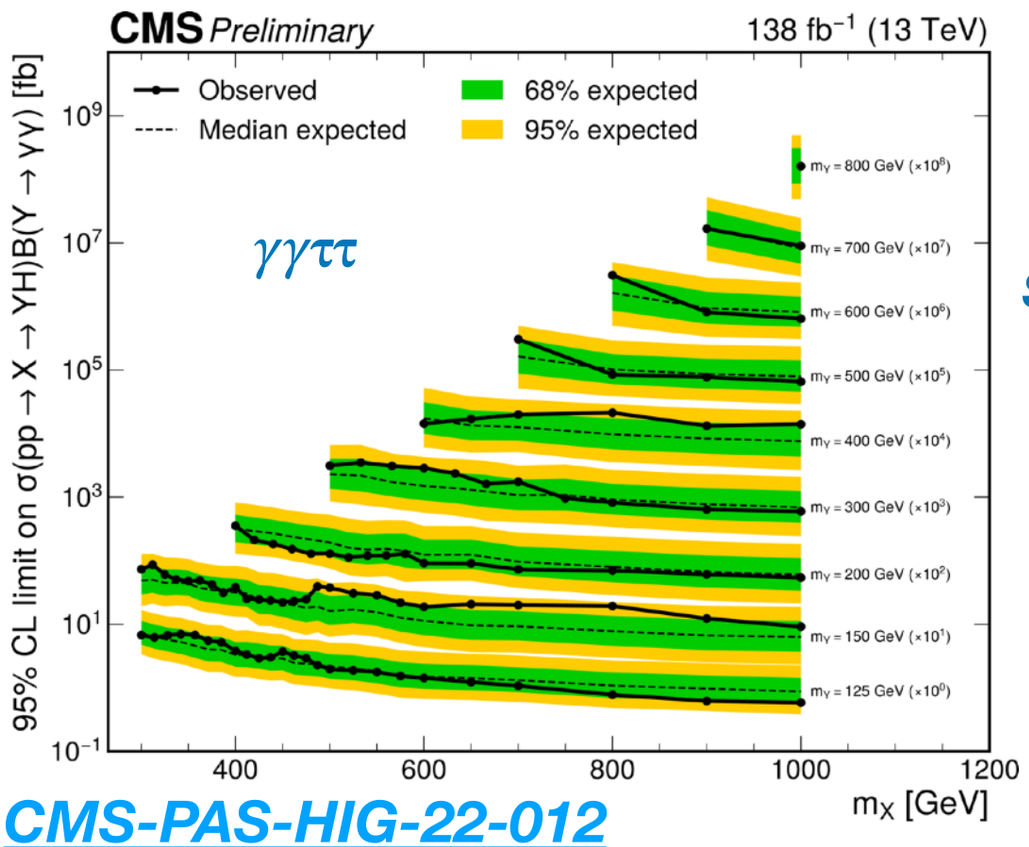
CMS-PAS-HIG-22-012

Limits in 2D space

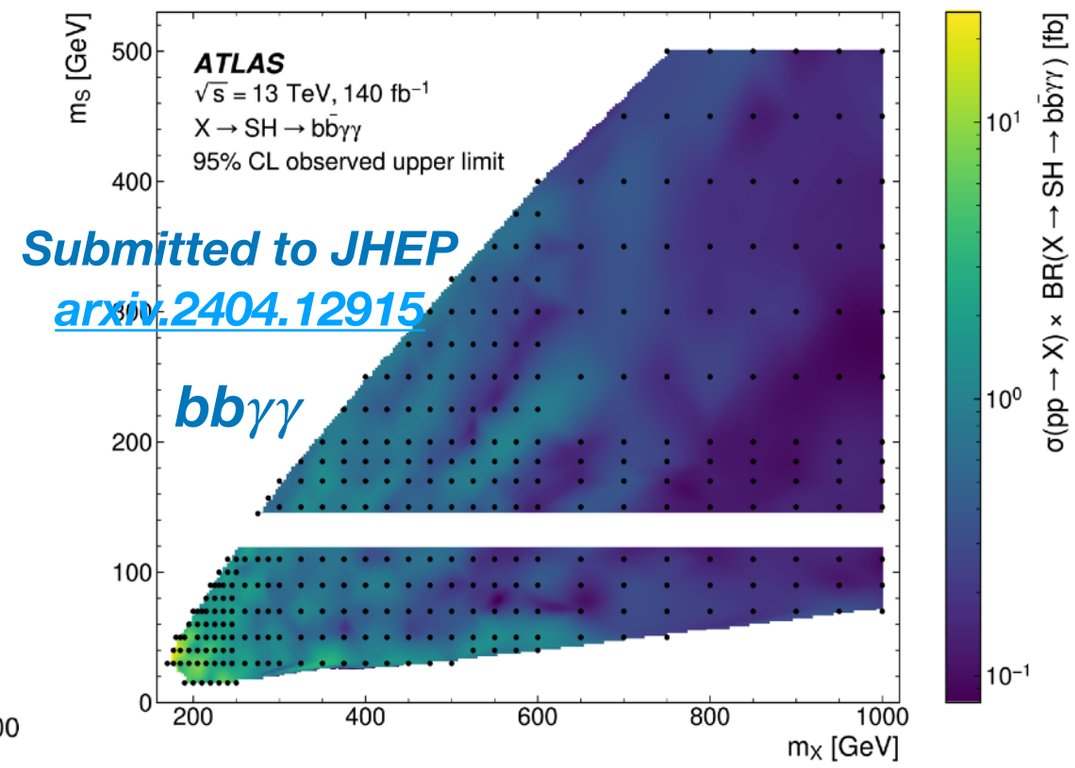
- Combined fit to discriminating variables
  - $m_{\gamma\gamma}$ has better experimental resolution
  - pDNN for the bb$\gamma\gamma$
- Most significant excesses
  - S($\gamma\gamma$)h($\tau\tau$) 3.4σ local @(525, 115) GeV
  - S(bb)h($\gamma\gamma$) 3.5σ local @(575, 200) GeV

VV$\gamma\gamma$: Limits comparable with VV$\tau\tau$





[CMS-PAS-HIG-22-012](#)



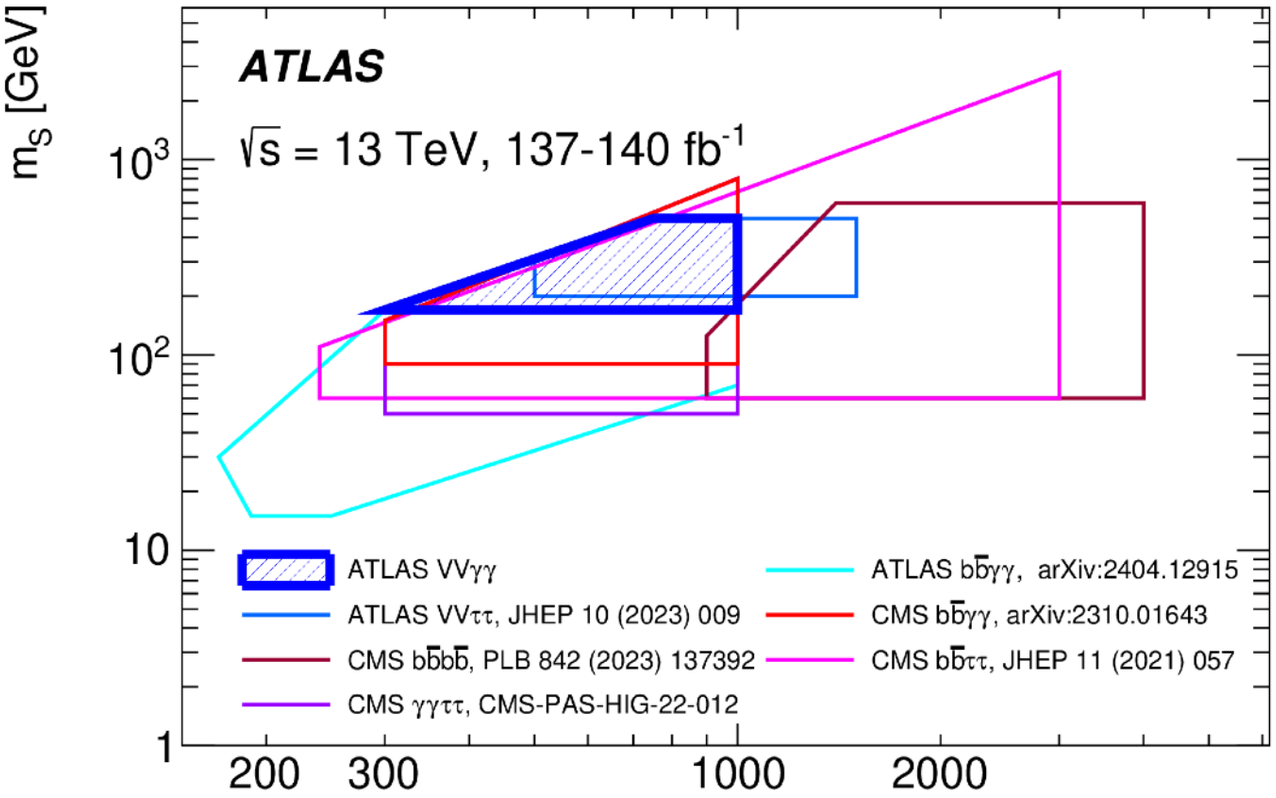
Submitted to JHEP
[arxiv.2404.12915](#)

Submitted to JHEP
[arxiv.2405.20926](#)

Does not confirm 3.8 (2.8) excess from CMS @(650, 90) GeV in the same channel

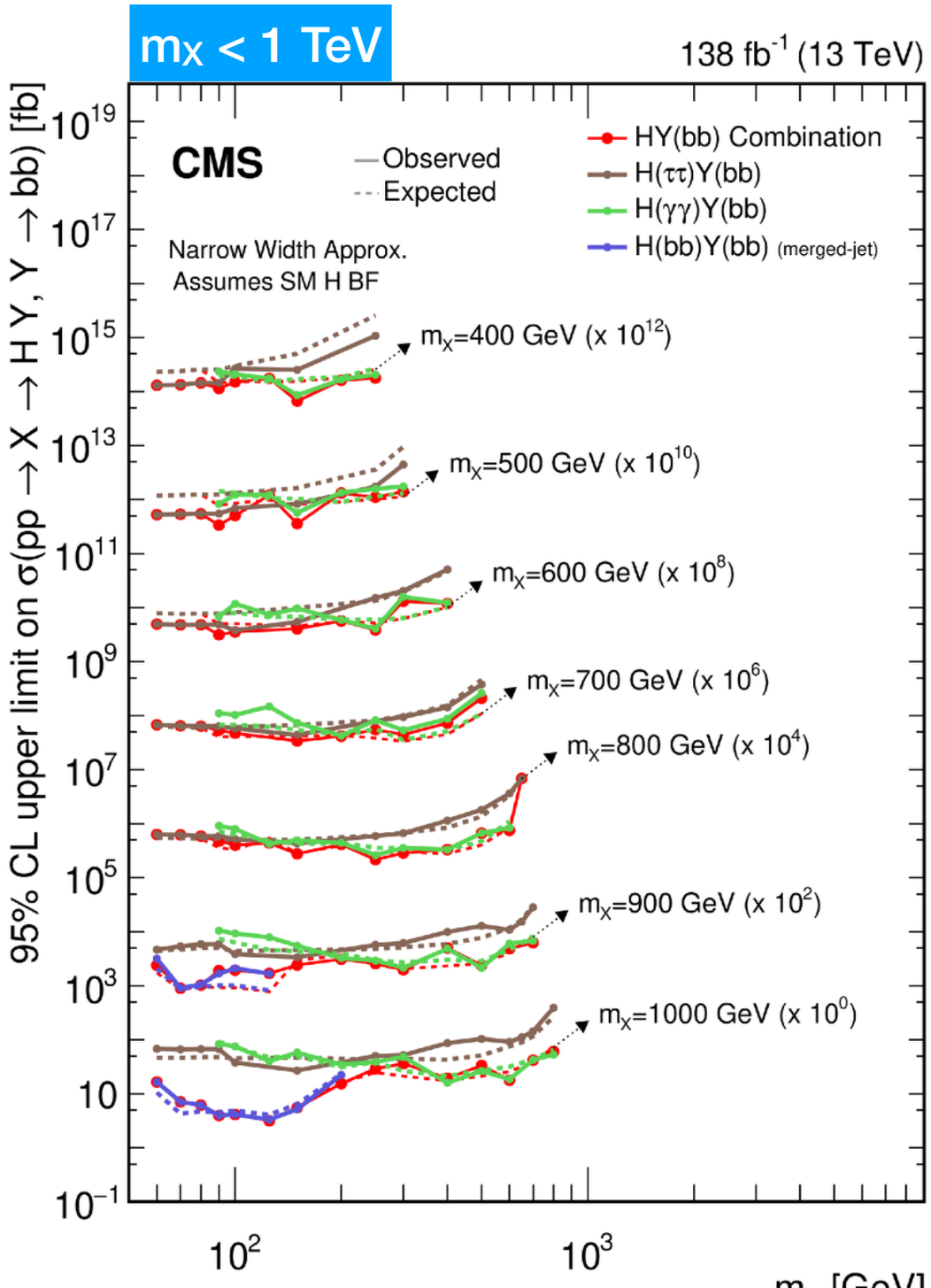
Putting all of them together…

- Cover as much as possible of the parameters space to probe Extended Higgs Sector models
  - complementary ranges
  - benefit in combination of competitive channels



Submitted to JHEP

arxiv.2405.20926

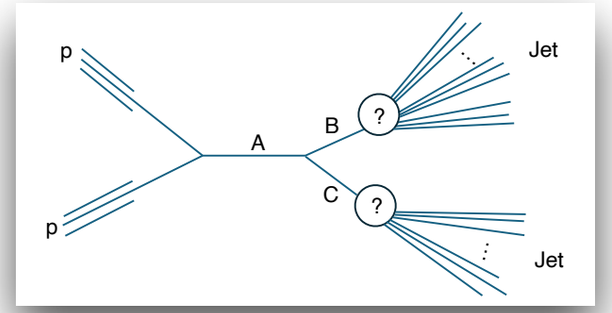


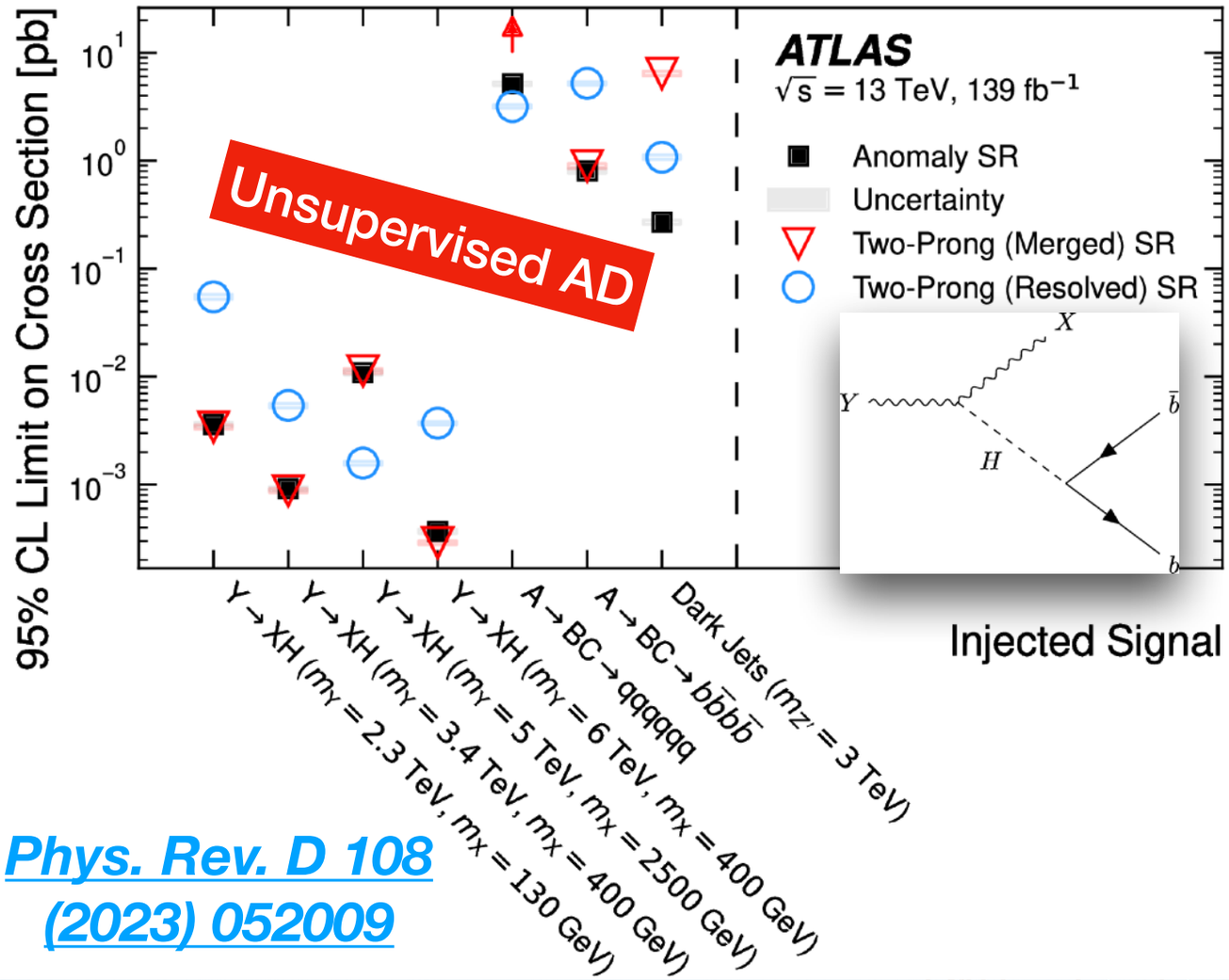
Submitted to Physics Reports

[CMS-PAS-B2G-23-002](CMS-PAS-B2G-23-002)

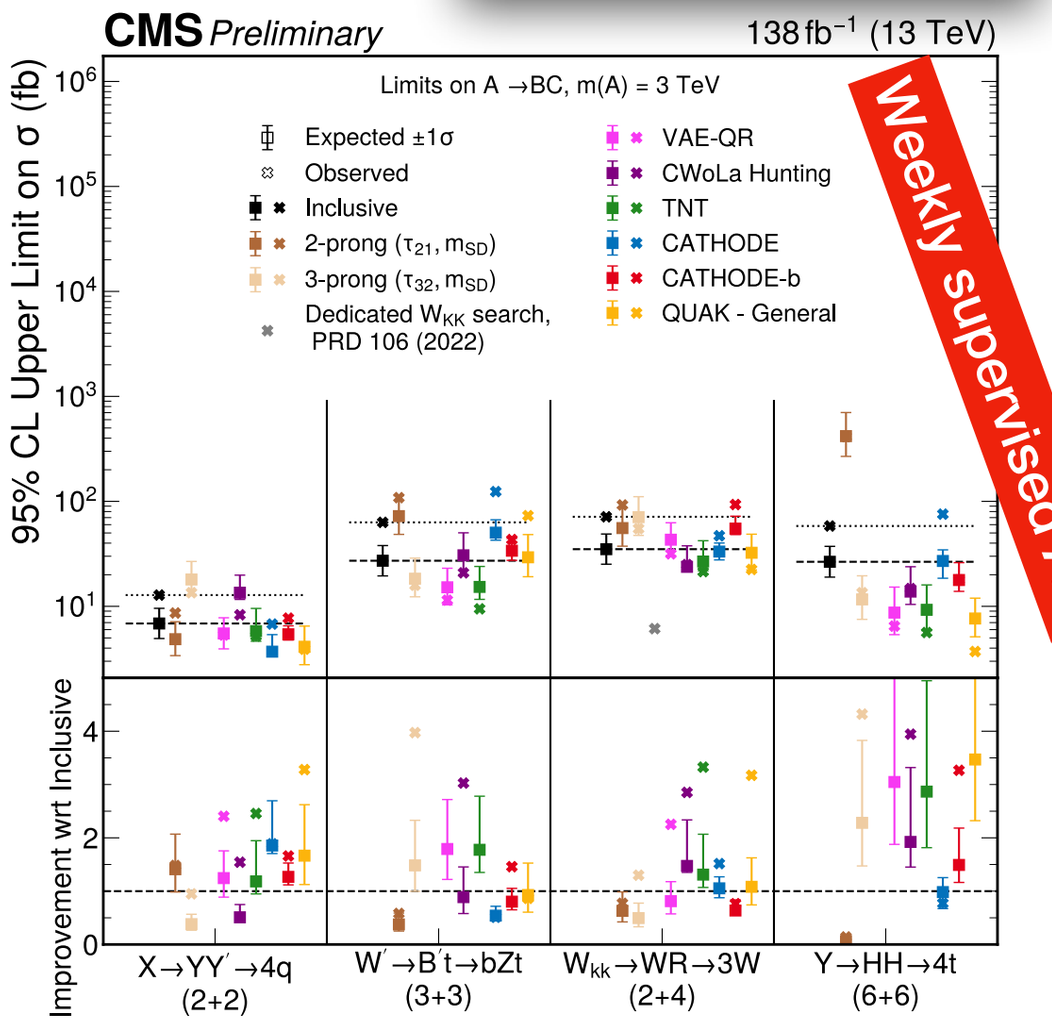
Multi-bosons searches w/o bosons

- Model independent searches in loose phase spaces
  - cover wide and general phase spaces (e.g. 2 high-p_T jets) with minimal theoretical assumptions
- Rely on powerful ML techniques to spot “Anomalies” in the data
  - ***event level***: CWoLa & Co family, ATLAS [***Phys. Rev. Lett. 125 (2020) 131801***] and CMS
  - ***jet level***: Y —> Xh(bb) ATLAS





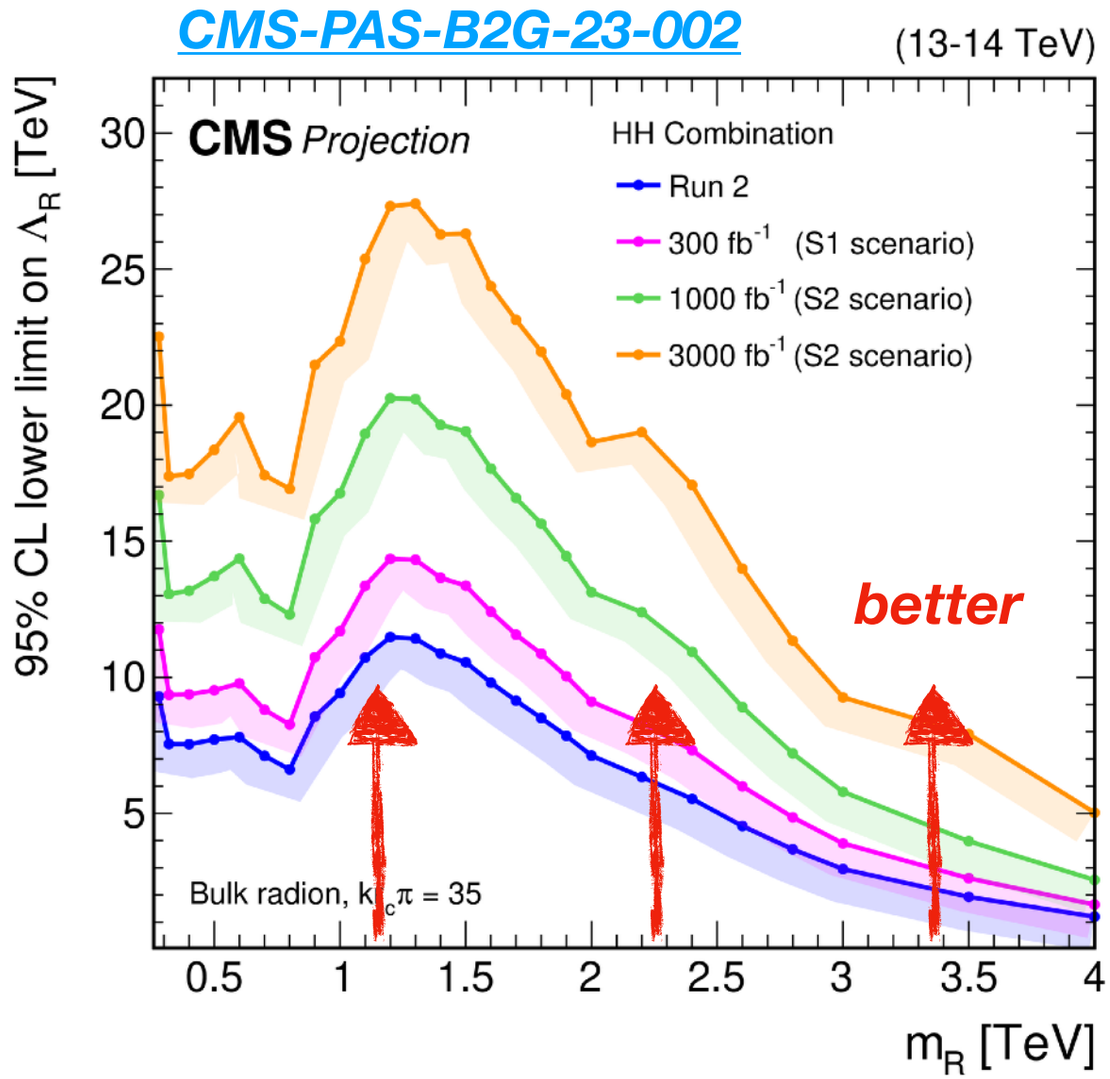
[***Phys. Rev. D 108 (2023) 052009***]



[***CMS-PAS-EXO-22-026***]

Conclusions

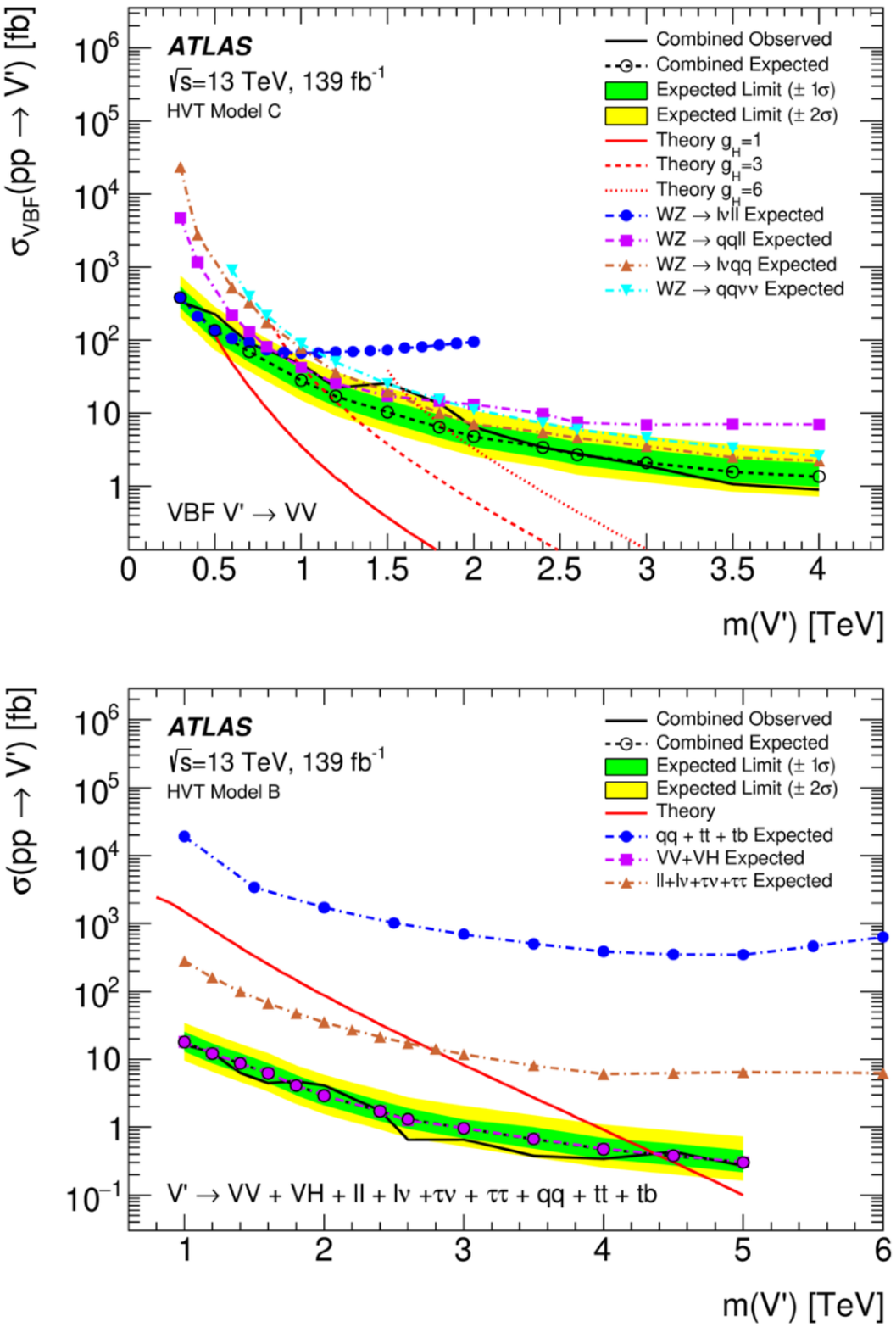
- ***Multiboson searches in ATLAS & CMS with Run-2 data***
  - exploiting combinations of leading channels
  - exploring new signatures and channels
- ***The nature seems behaving as SM predictions***
  - only slight (<~3σ) excesses in some channels
  - keep improving analyses techniques and invest on new ideas to better probe our data
- ***Looking forward for new exciting results with Run-3 data***
  - and start keeping an eye on HL-LHC potentiality!!

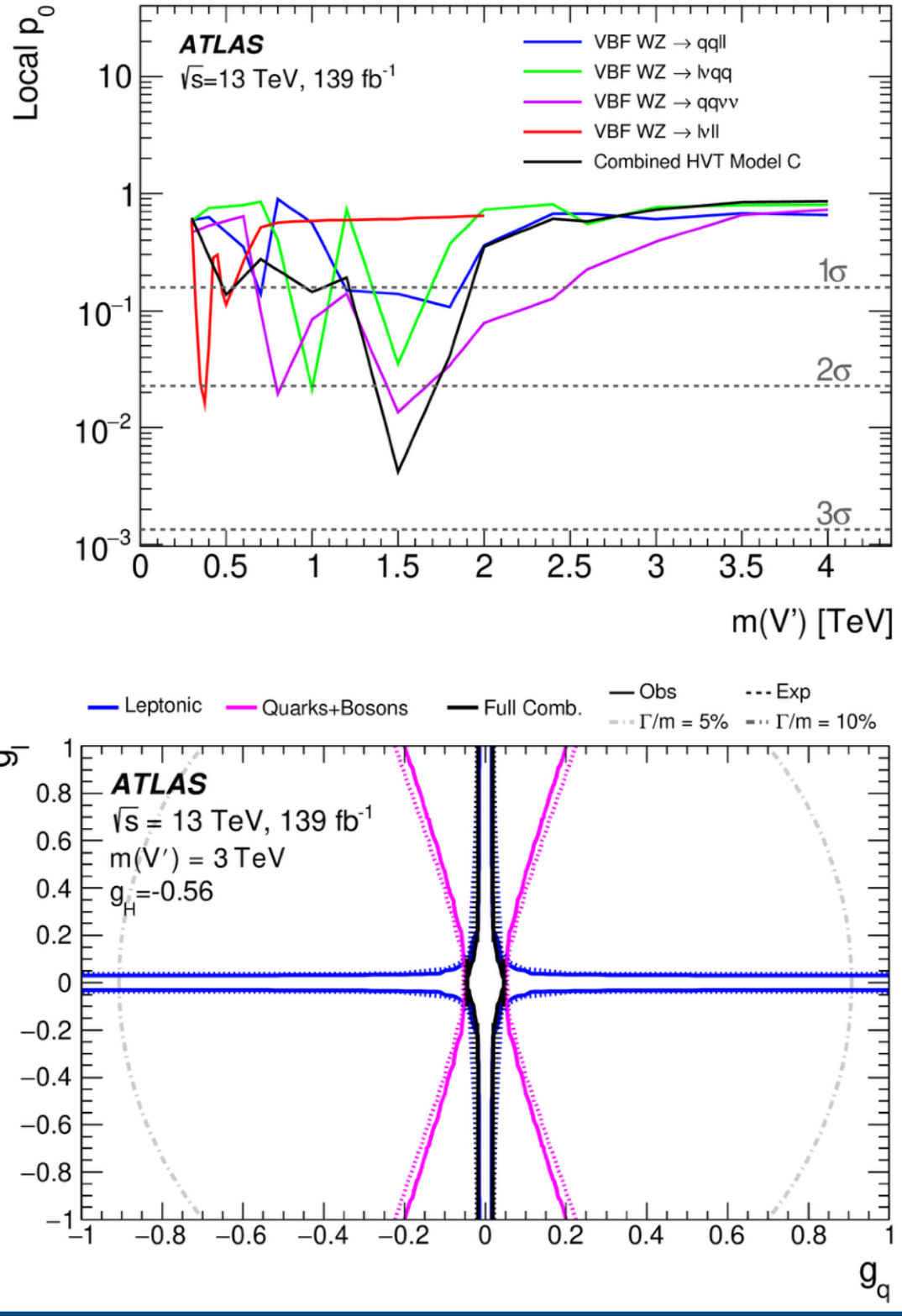


HL projections for exclusion on the Radion Λ_R scale via hh combination

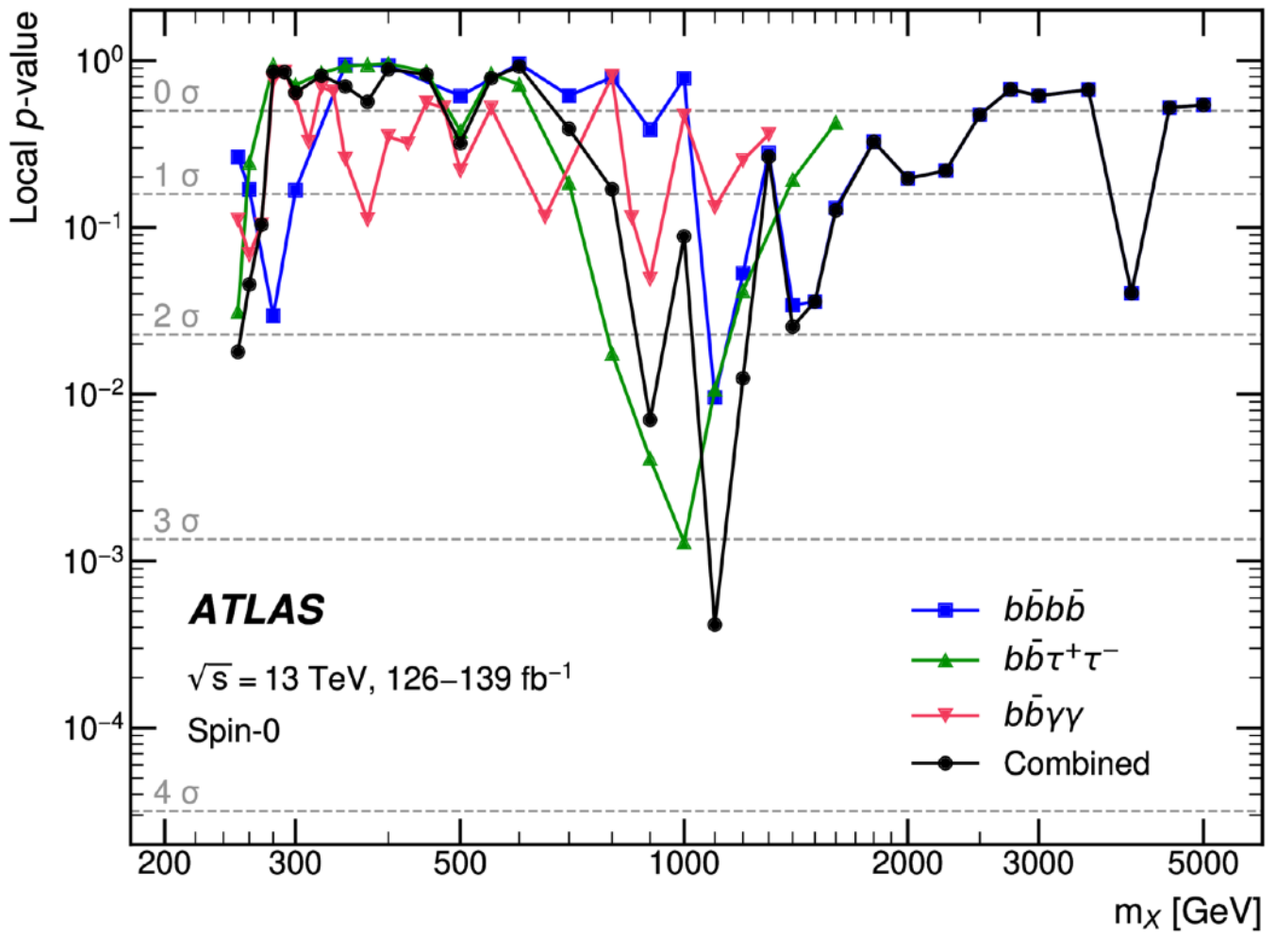
backup

Heavy resonance combo





hh combo


Local p-value
10^0
10^-1
10^-2
10^-3
10^-4
0 σ
1 σ
2 σ
3 σ
4 σ
ATLAS
√s = 13 TeV, 126–139 fb^-1
Spin-0
bb̄bb̄
bb̄τ+τ−
bb̄γγ
Combined
200
300
500
1000
2000
3000
5000
mX [GeV]

Radion model benchmarks

Three types of resonances corresponding to different spins are considered in the search. The first one is a scalar neutral radion, introduced in some bulk RS models to stabilise the radius of the compactified extra dimension r_c [17, 18]. The coupling of the RS radion field to SM fields is inversely proportional to $\Lambda_R = e^{-k\pi r_c}\sqrt{6M_5^3/k}$ [35–37], where M_5 is the five-dimensional Planck mass, and k is the curvature factor. The RS radion events were simulated with $k\pi r_c = 35$ and $\Lambda_R = 3$ TeV [36]. The RS radion couples to SM fermions with a strength proportional to the fermion mass and to SM vector bosons with a strength proportional to the square of the boson mass, similarly to a heavy Higgs boson. However, the RS radion has a much narrower width due to its overall weaker couplings to SM particles. For example, the intrinsic width of a 3 TeV RS radion is approximately 3% of its mass, assuming $\Lambda_R = 3$ TeV. RS radions can be produced through both the ggF and VBF processes at the LHC as shown in Figure 1.

HVT model benchmarks

The second type considered comprises two heavy vector bosons described in the HVT framework [19]: an electrically charged W' boson and an electrically neutral Z' boson produced through the DY and VBF processes. The new heavy vectors couple to the Higgs and the SM gauge bosons via a combination of parameters $g_V c_H$ and to the fermions via the combination $g^2/g_V\ c_F$. The parameter g_V represents the typical strength of the vector boson interaction, while the parameters c_H and c_F are expected to be of the order of unity in most models. Benchmark Model A [19] ($g_V = 1$) is representative of a model of weakly coupled vector resonances in an extension of the SM gauge group where the HVT bosons have comparable decay branching ratios into SM fermions and vector bosons. Model B [19] with $g_V = 3$, is representative of a composite model scenario where the HVT boson couplings to fermions are suppressed. In *Model C*, $g_V = c_H = 1$ and the HVT boson coupling to fermions was set to zero, so that only VBF production is possible. The $W' \rightarrow WZ$ and $Z' \rightarrow WW$ decays were considered in this search.

HVT model benchmarks

For the $q\bar{q}$ processes, the two scenarios emphasize the relative strengths of the g_H and g_f couplings. The first scenario, referred to as model A, reproduces the phenomenology of weakly coupled models based on an extended gauge symmetry [36]. In this case, the couplings are $g_H = -0.56$ and $g_f = -0.55$, with the universal fermion coupling $g_f = g_q = g_\ell$. The second $q\bar{q}$ scenario, referred to as model B, implements a strongly coupled scenario as in composite Higgs models [37] with $g_H = -2.9$ and $g_f = 0.14$.[2] In model B, the V' resonances are broader than in the weakly coupled scenario, model A, but remain narrow relative to the experimental resolution. The relative width of the V' resonances, Γ/m, is below 5% over much of the parameter space explored.

The VBF production scenario is referred to as model C. In this case, the V' resonance's couplings are set to $g_H = 1$ and $g_f = 0$. Therefore, Model C is in a phase-space domain separate from that of model A or B, and assumes no $q\bar{q}$ production.

Gravitons model benchmark

The third benchmark resonance searched for is a spin-2 bulk RS graviton G_{KK} which appears as the first KK excitation of the gravitational field in a bulk RS graviton model [7, 20, 21]. The G_{KK} couplings to light fermions are suppressed and therefore decays into final states involving heavy quarks, Higgs or vector bosons are favoured. The strength of the coupling depends on $k/\overline{M}_{\mathrm{Pl}}$, where k corresponds to the curvature of the warped extra dimension and $\overline{M}_{\mathrm{Pl}}$ is the effective four-dimensional Planck scale. The value of $k/\overline{M}_{\mathrm{Pl}}$ is typically of $O(1)$, and this and the G_{KK} mass are the only two free parameters. The G_{KK} has a mass-dependent width, which is 3.7% of its mass at 500 GeV and 6.4% at 5 TeV for $k/\overline{M}_{\mathrm{Pl}} = 1$. It can be produced through the ggF and VBF processes and decays into WW and ZZ with sizeable branching ratios. The G_{KK} samples were generated with $k/\overline{M}_{\mathrm{Pl}} = 1$.

Extended Warped Extra dimension

Previous searches for triboson and trigluon final states resulting from a two-step cascade decay of a heavy resonance have been performed by the CMS experiment [11–14]. Despite the constraints imposed, a large fraction of the theoretical parameter space remains unexplored. In this paper, we consider the specific EWED model scenario in which only the quantum chromodynamic (QCD) gauge field can propagate into the extended bulk, giving rise to a Kaluza–Klein (KK) gluon g_{KK}. The g_{KK} can decay in a cascade through the lightest scalar R of the theory. In a certain parameter space of the model, the dominant decay mode is $g_{KK} \to gR \to gWW$, which is the focus of this analysis.

In this paper, we probe this scenario performing a search for new physics in the trijet final state. Two of the jets, both arising from the R decay, are identified as originating from Lorentz-boosted hadronic W boson decays using jet substructure techniques. No particular constraints are imposed on the third jet. Figure 1 displays a schematic diagram of the signal process including the cascade decay and the resulting final state probed in this paper. The overall g_{KK} mass range probed is 1.25–4.5 TeV. Within this range, the phase space with a ratio of R and g_{KK} masses of $0.06 \leq m_R/m_{g_{KK}} \leq 0.9$ is considered. However, for $m_R/m_{g_{KK}} < 0.2$ and $m_R/m_{g_{KK}} > 0.8$ the analysis sensitivity is reduced because a significant number of events result in a dijet final state that is not reconstructed. In the former case, the two W bosons are collimated, while in the latter case, the final-state gluon carries relatively little energy. The analysis is based on proton-proton (pp) collision data collected by the CMS experiment during 2016–2018 at a center-of-mass energy of $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$.

2HDM model

Models with extended Higgs sectors often contain an additional Higgs doublet, resulting in the presence of two CP-even (h and H) and one CP-odd (A) neutral Higgs bosons, as well as two charged Higgs bosons ($H^{\pm}$). The phenomenology of these models is generically described by two-Higgs-doublet-models (2HDM) [11, 12], which are defined by the following parameters when assuming CP conservation: the masses of the five Higgs bosons (m_h, m_H, m_A, and $m_{H^{\pm}}$); the ratio of the vacuum expectation values of the two doublets ($\tan\beta$); the mixing angle between the two CP-even Higgs bosons (α); and the soft-breaking term (m_{12}^2). Depending on the coupling of the two doublets to the right-handed quarks and the charged leptons, different types of 2HDM are possible. For example, in type-II models the down-type quarks together with the leptons and the up-type quarks couple to two different Higgs doublets. When $\cos(\beta-\alpha) \to 0$, referred to as the "alignment limit", the properties of the h boson are expected to be identical to those of a SM Higgs boson with the same mass. In this note, h is identified with the observed Higgs boson with a mass of approximately 125 GeV.

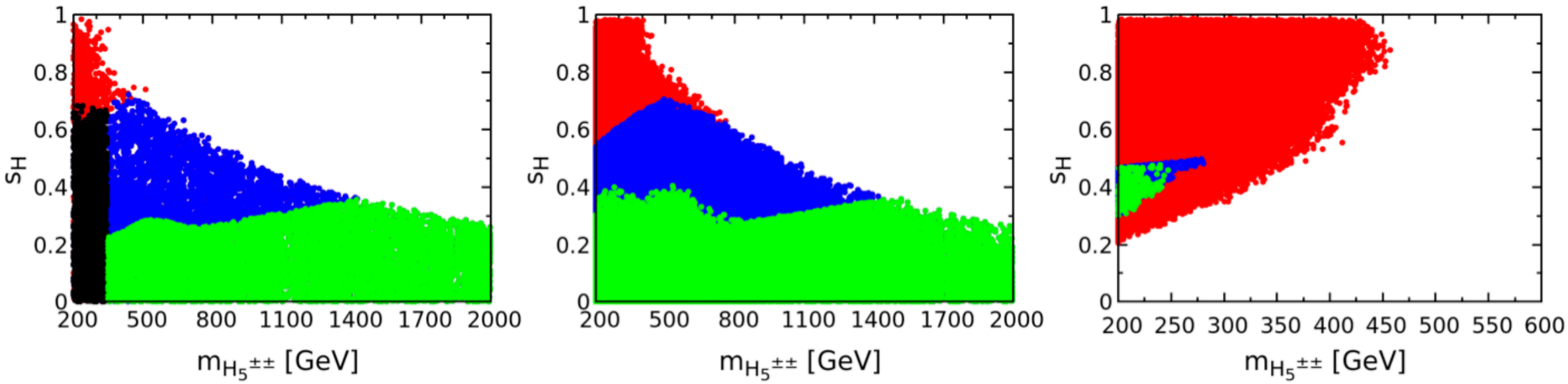
GM model

- The GM introduces two new triplets, ξ and χ
  - it ensures the custodial symmetry at the tree level if the two triplets have the same vev
- Theoretical (perturbative unitarity, vacuum stability and custodial symmetry) and experimental constraints are combined
  - ***https://arxiv.org/abs/2212.11688***

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1,$$

$$v_\chi = v_\xi.$$

$$s_H = \frac{2\sqrt{2}v_\chi}{\sqrt{v_\Phi^2 + 8v_\chi^2}}$$



(a) (b) (c)

Figure 1: Constraints on the $m_{H_5^{\pm\pm}} - s_H$ plane. 1(a),(b) and (c) correspond respectively to the situations of single, double and triple channel decay of H_5^{++}. Red, black and blue regions are excluded by indirect constraints, DY search of H_5^{++} and VBF of H_5^{++} respectively. Green regions are allowed by all constraints.

GM model validity

[LHCHXSWG-2015-001_2.pdf]

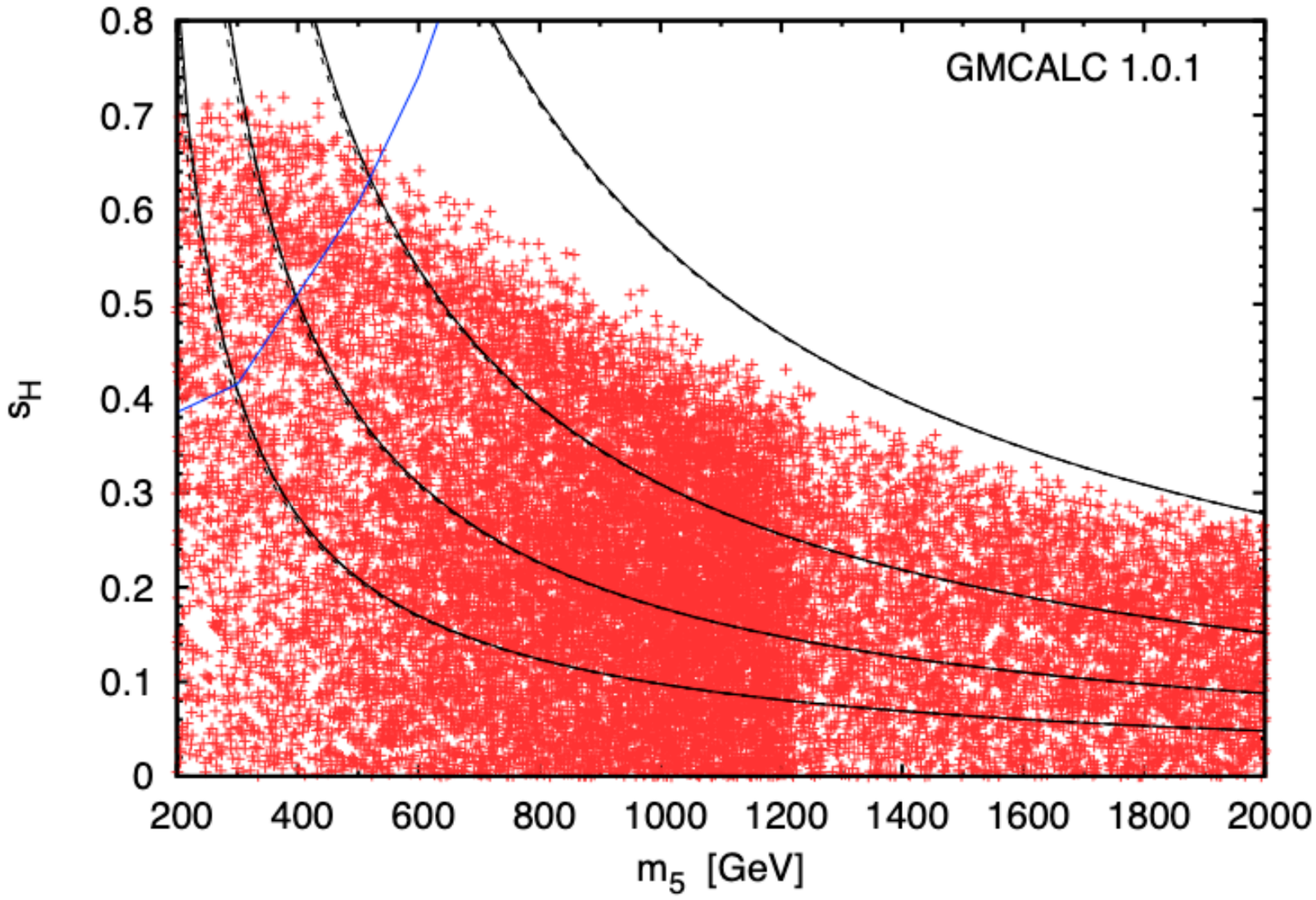
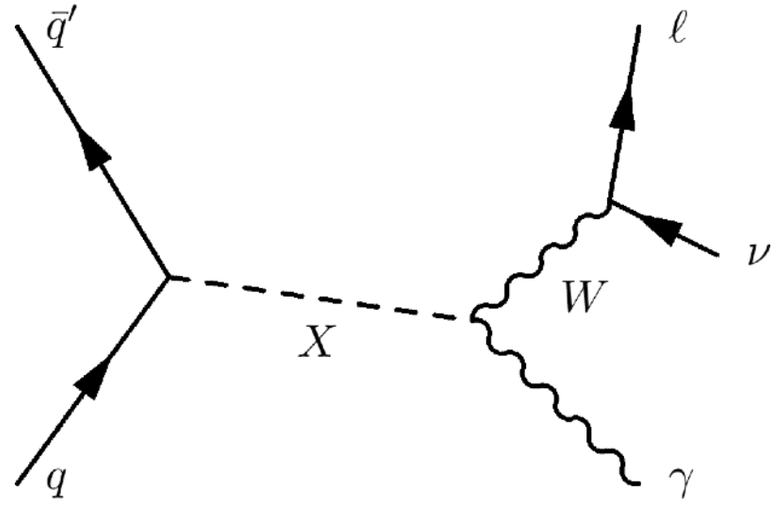


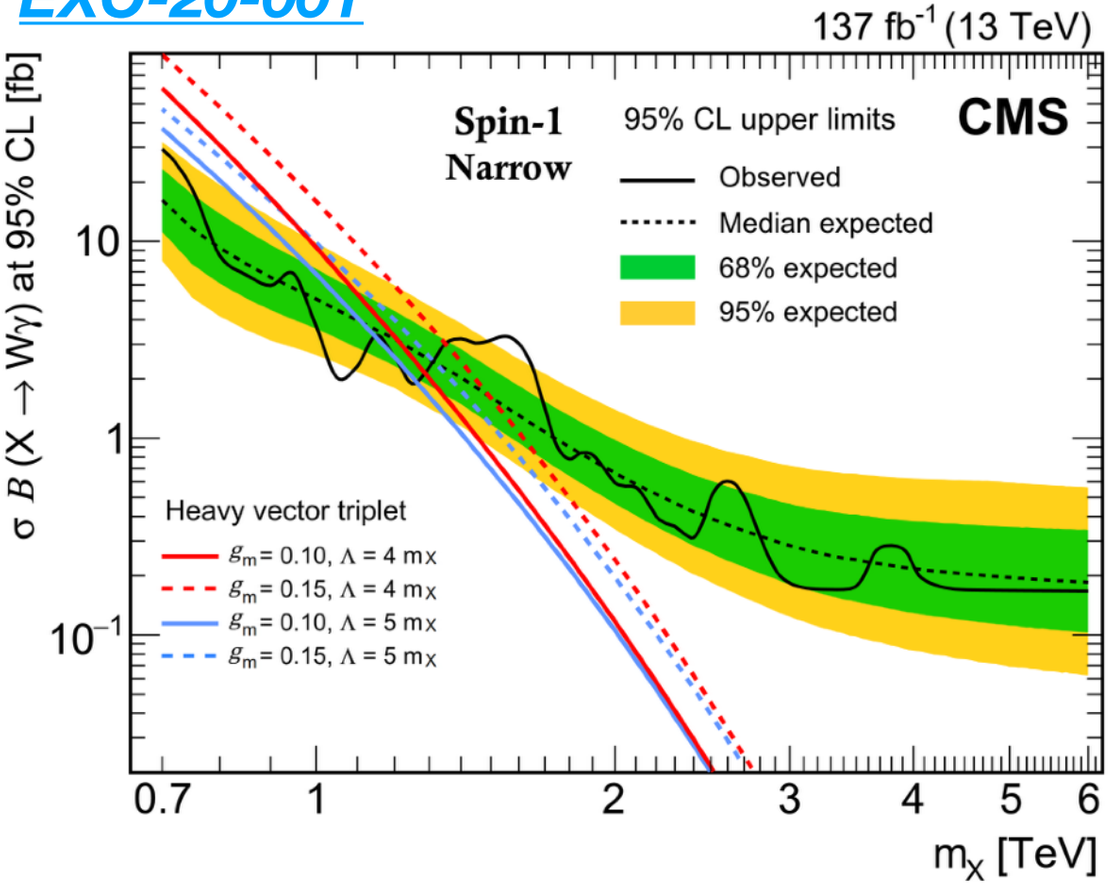
FIG. 1. Allowed ranges of m_5 and s_H after imposing theoretical and indirect experimental constraints on the GM model. The red points are a parameter scan produced using GMCALC 1.0.1 [6]. Contours of the width-to-mass ratio of H_5^0 (solid black lines), $H_5^\pm$ (long-dashed black lines, indistinguishable from the solid lines) and $H_5^{\pm\pm}$ (short-dashed black lines), assuming that $\mathrm{BR}(H_5 \to VV) = 1$. From top to bottom, $\Gamma(H_5)/m_5 = 0.10$, 0.03, 0.01, and 0.003. The recast analysis in Ref. [11], which constrains the doubly-charged scalar H_5^{++}, excludes points above the blue curve.

Vγ searches

- Complementary final states with distinct signature in the detector
- Why leptonic vs hadronic final states?
  - ability to probe different mass ranges
  - slighty excess in hadronic with CMS data



EXO-20-001



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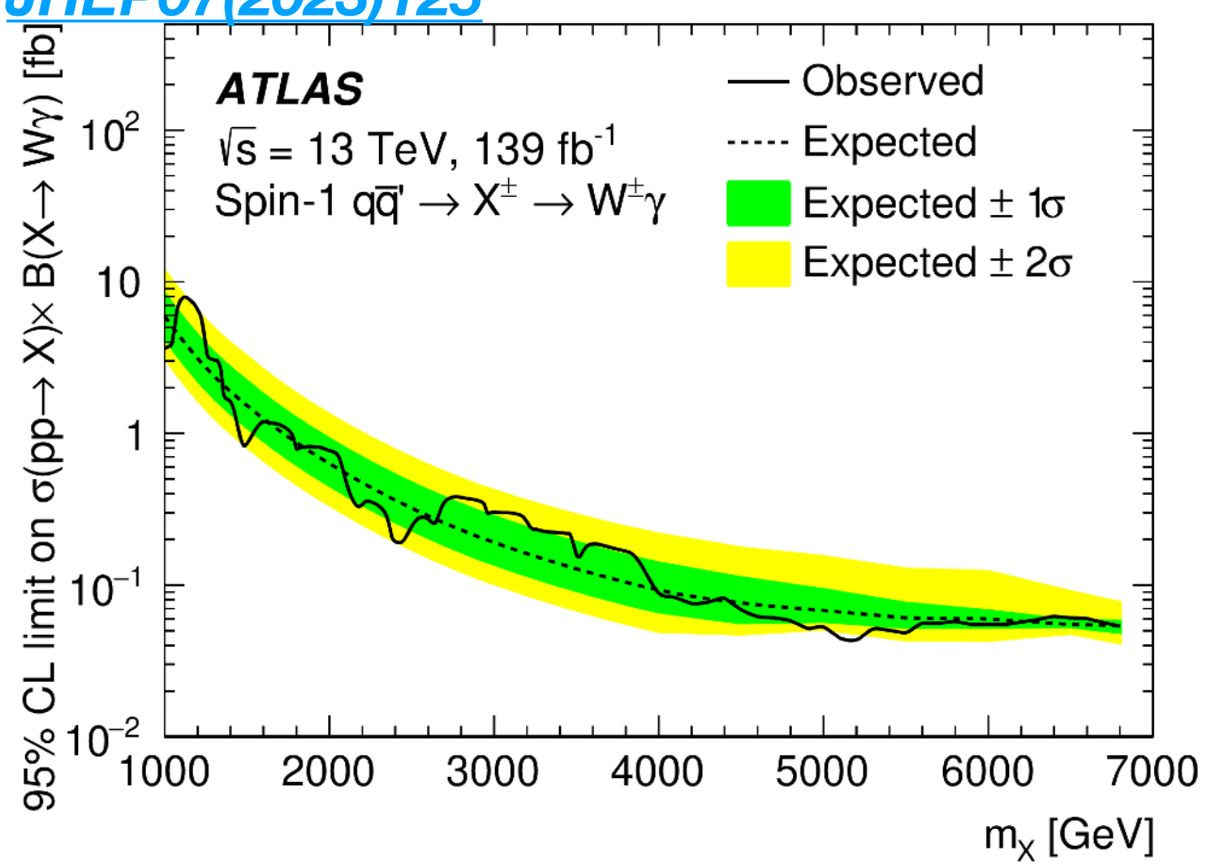
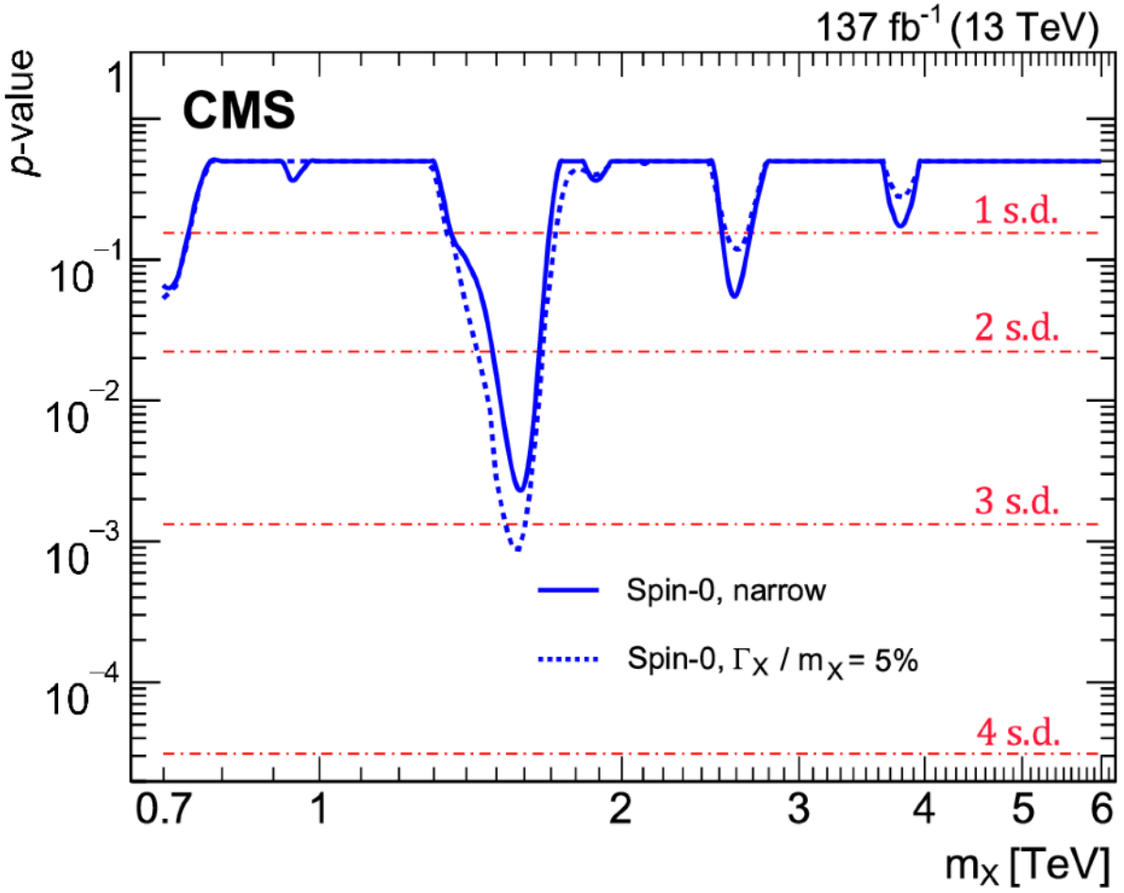
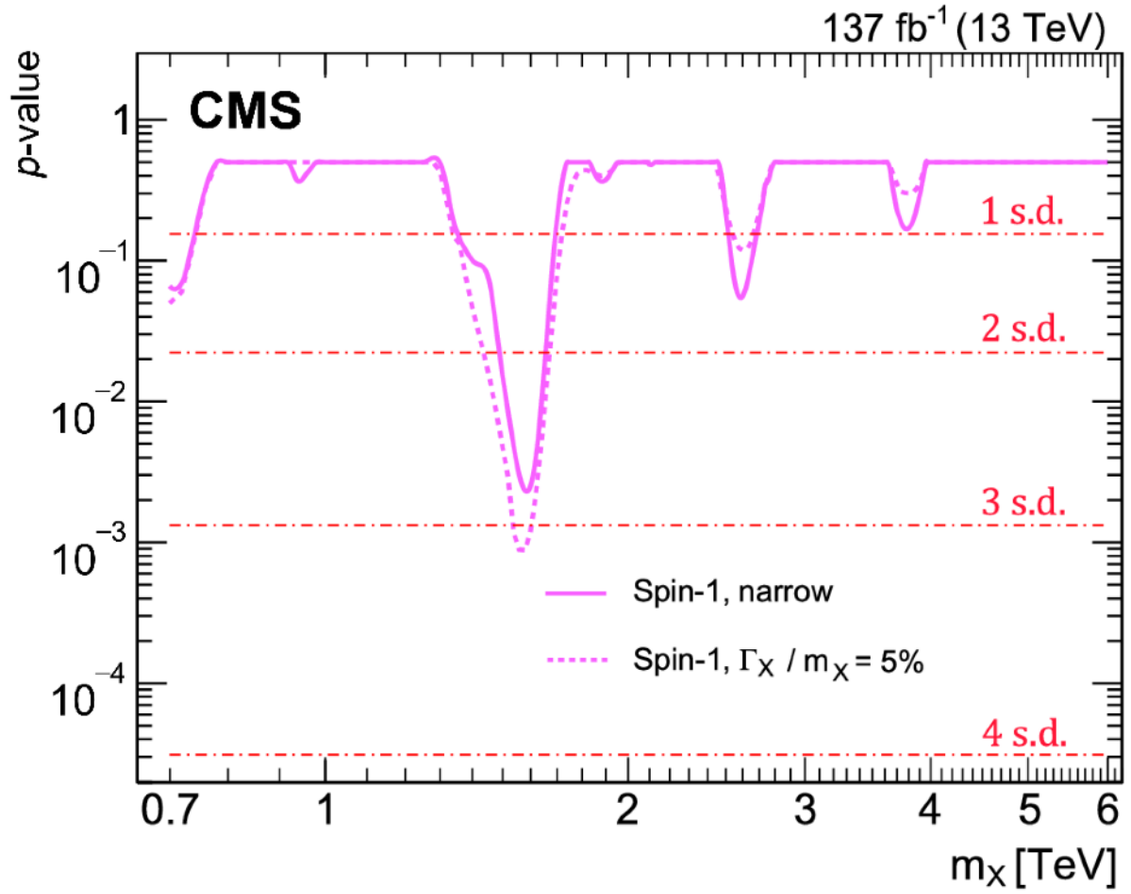
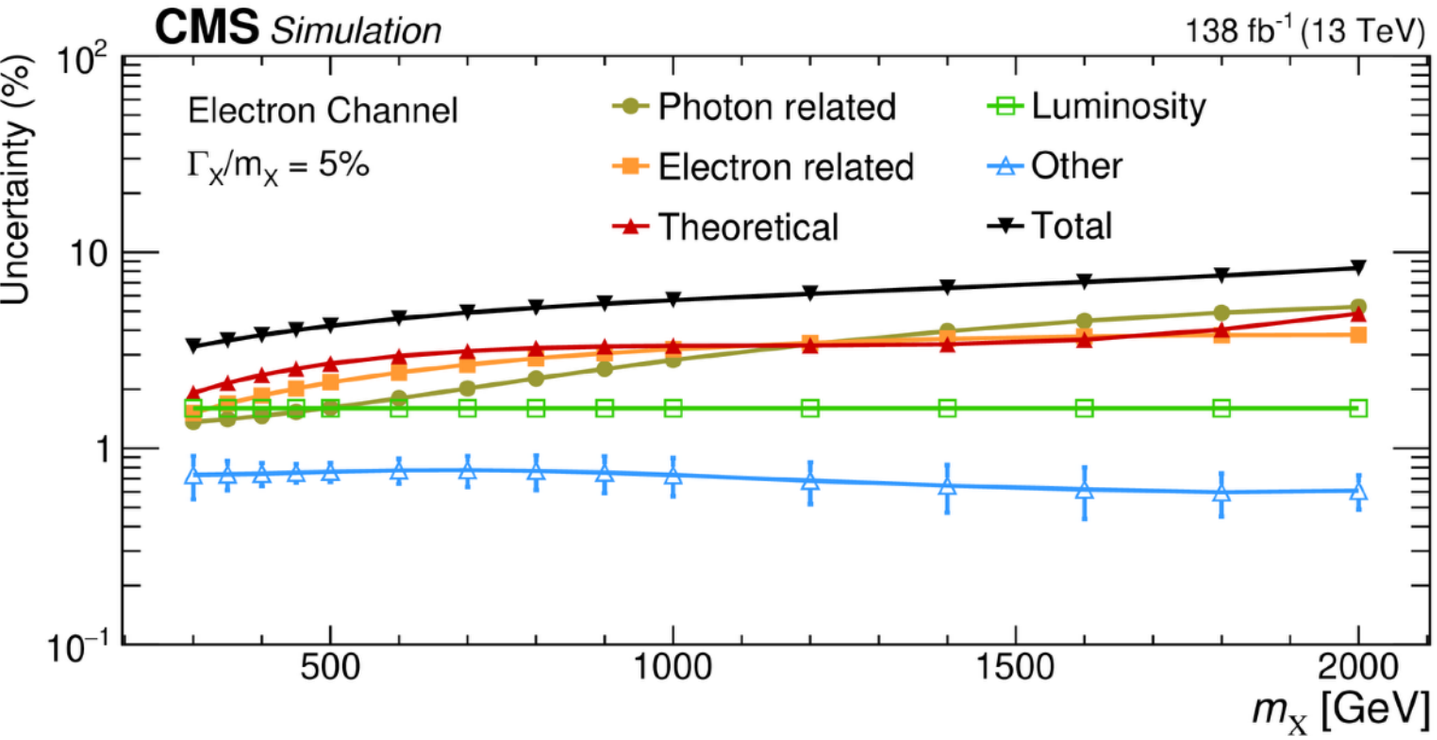
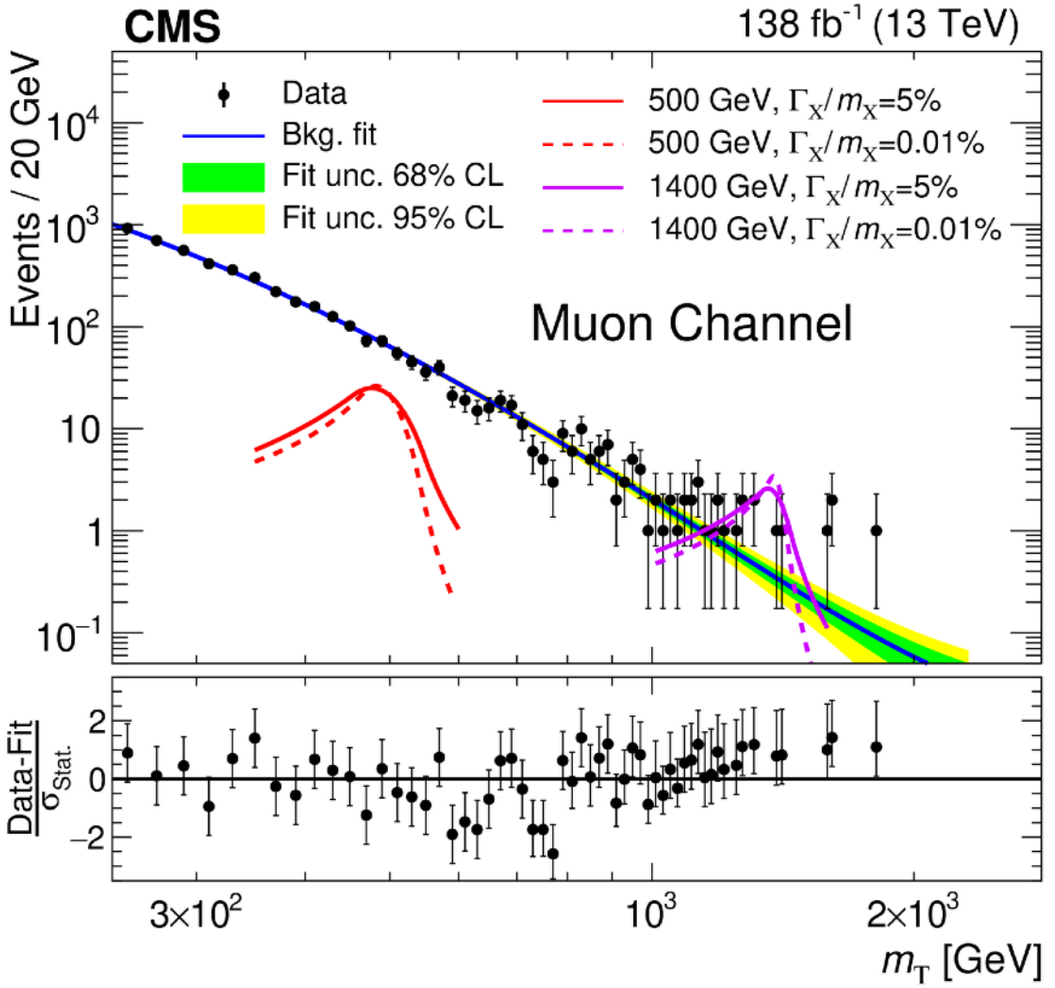



137 fb-1 (13 TeV)
CMS
p-value
1 s.d.
2 s.d.
3 s.d.
4 s.d.
Spin-0, narrow
Spin-0, ΓX / mX = 5%
mX [TeV]

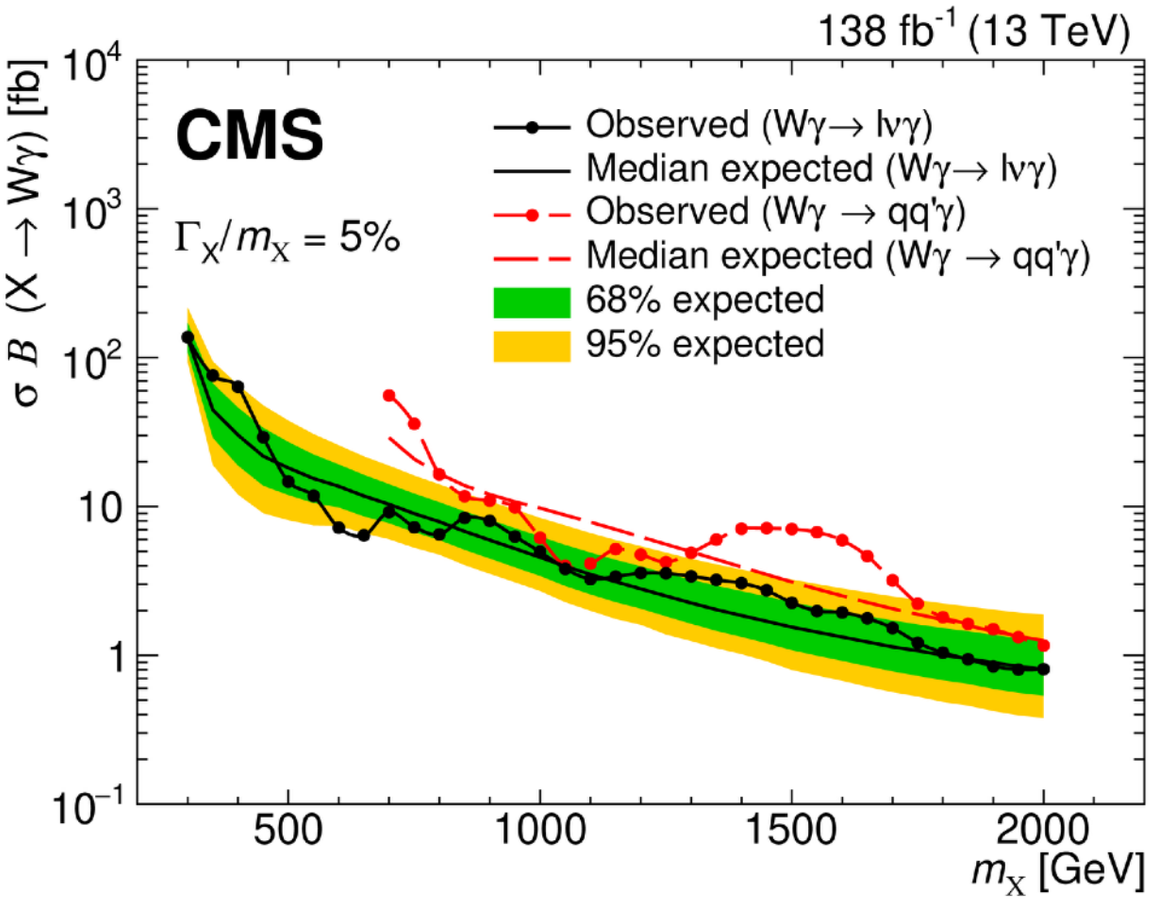

137 fb-1 (13 TeV)
CMS
p-value
1 s.d.
2 s.d.
3 s.d.
4 s.d.
Spin-1, narrow
Spin-1, ΓX / mX = 5%
mX [TeV]

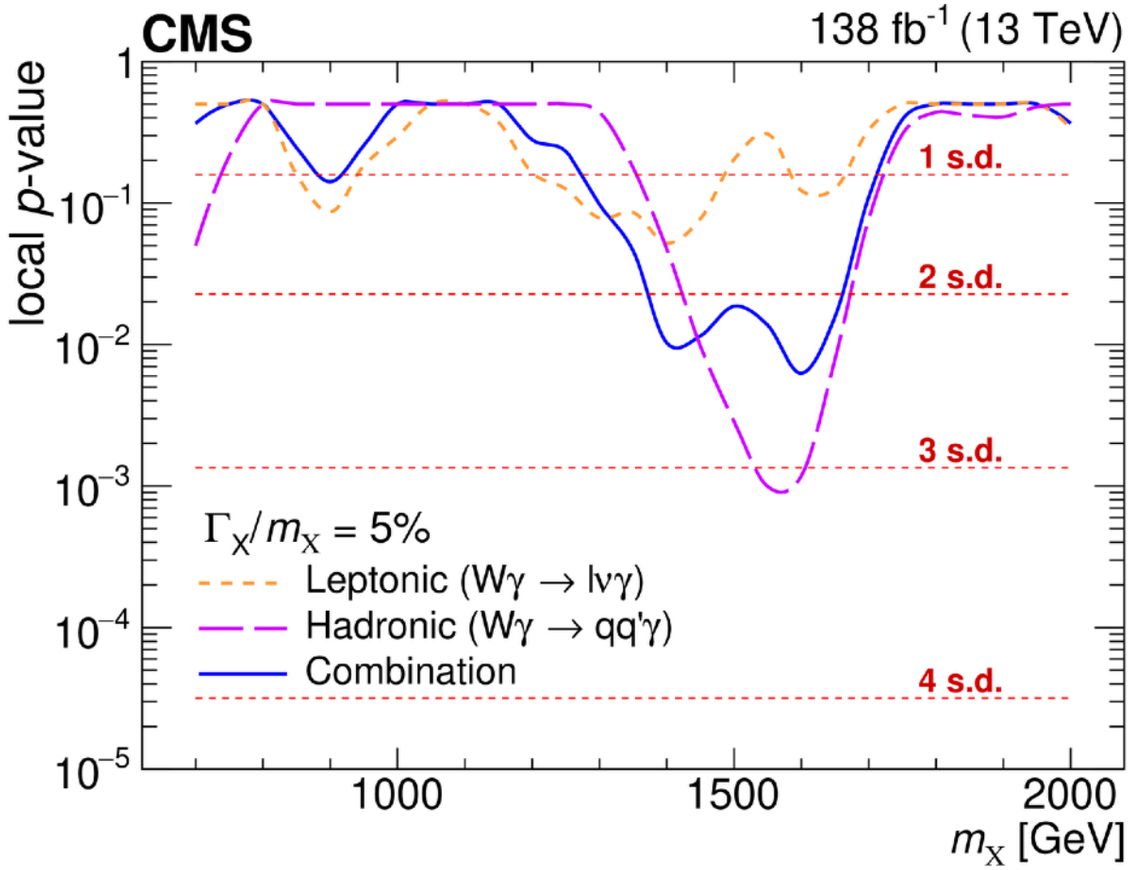
Wγ leptonic search at CMS





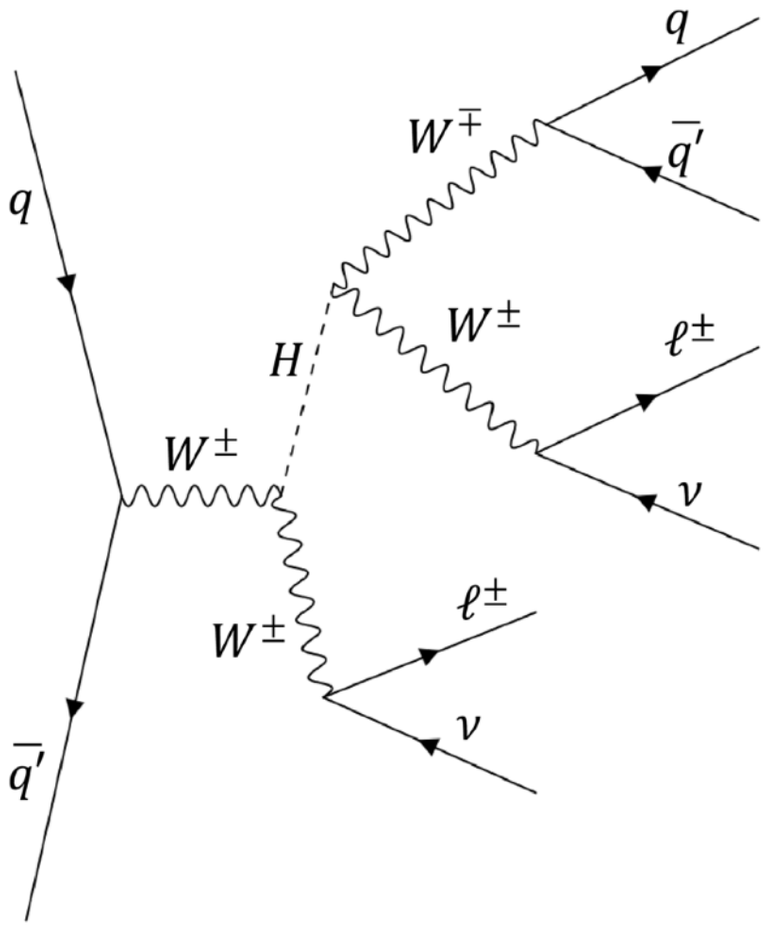
2 is always better than 1

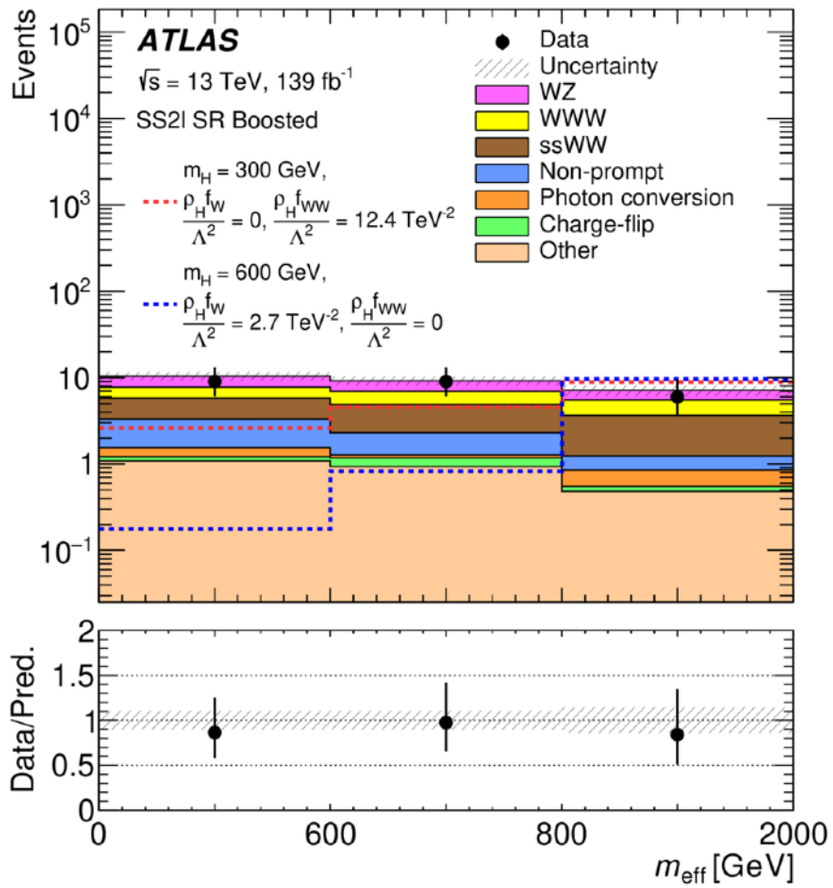


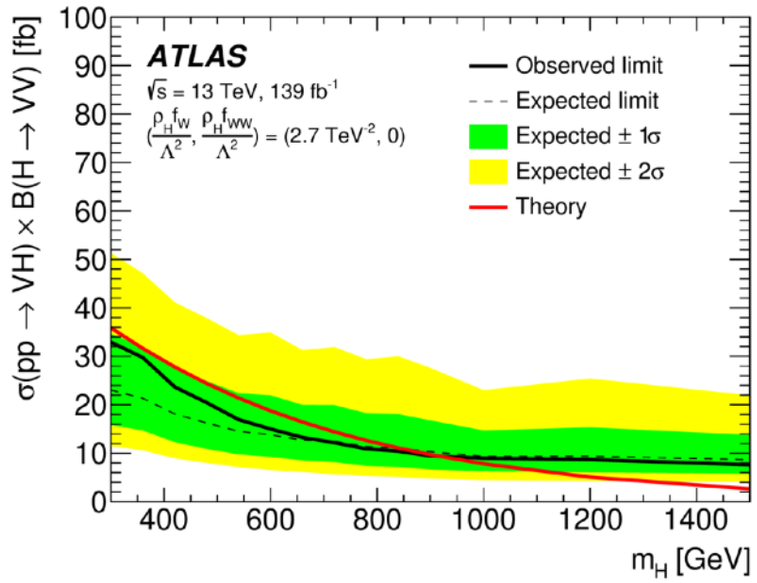


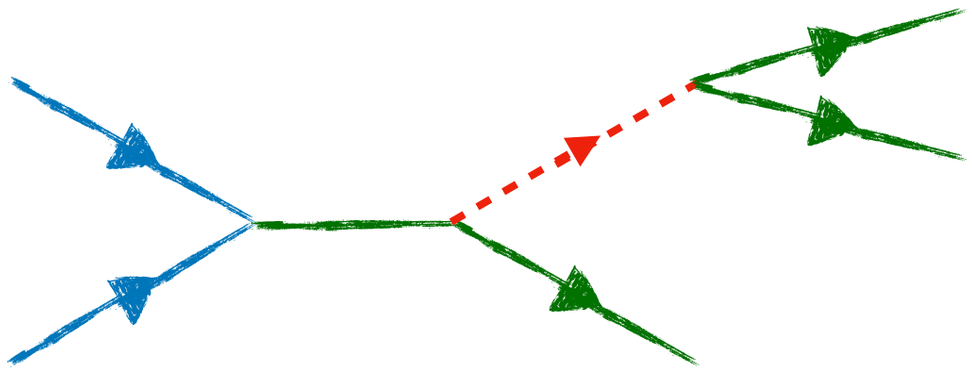
Generic Heavy Higgs search

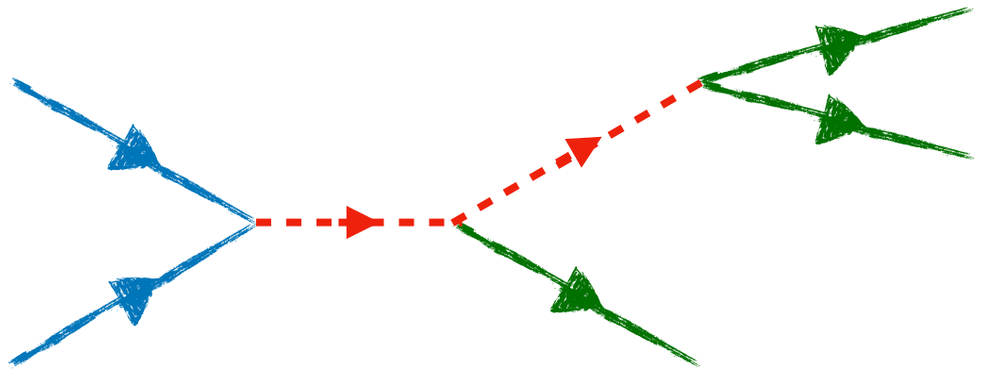
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2019-16/





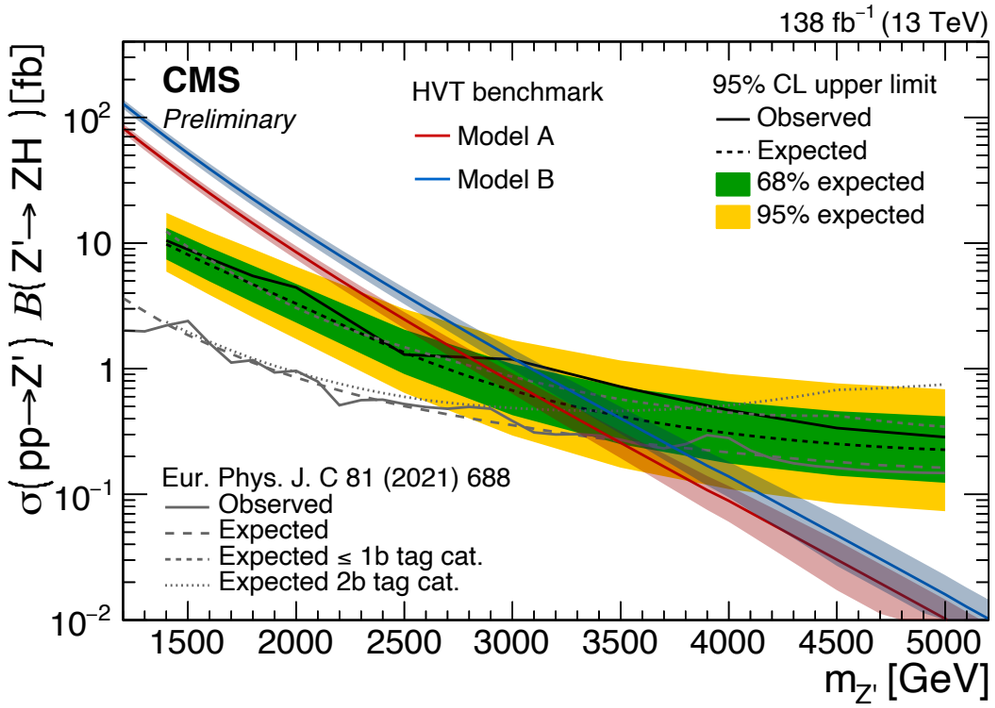






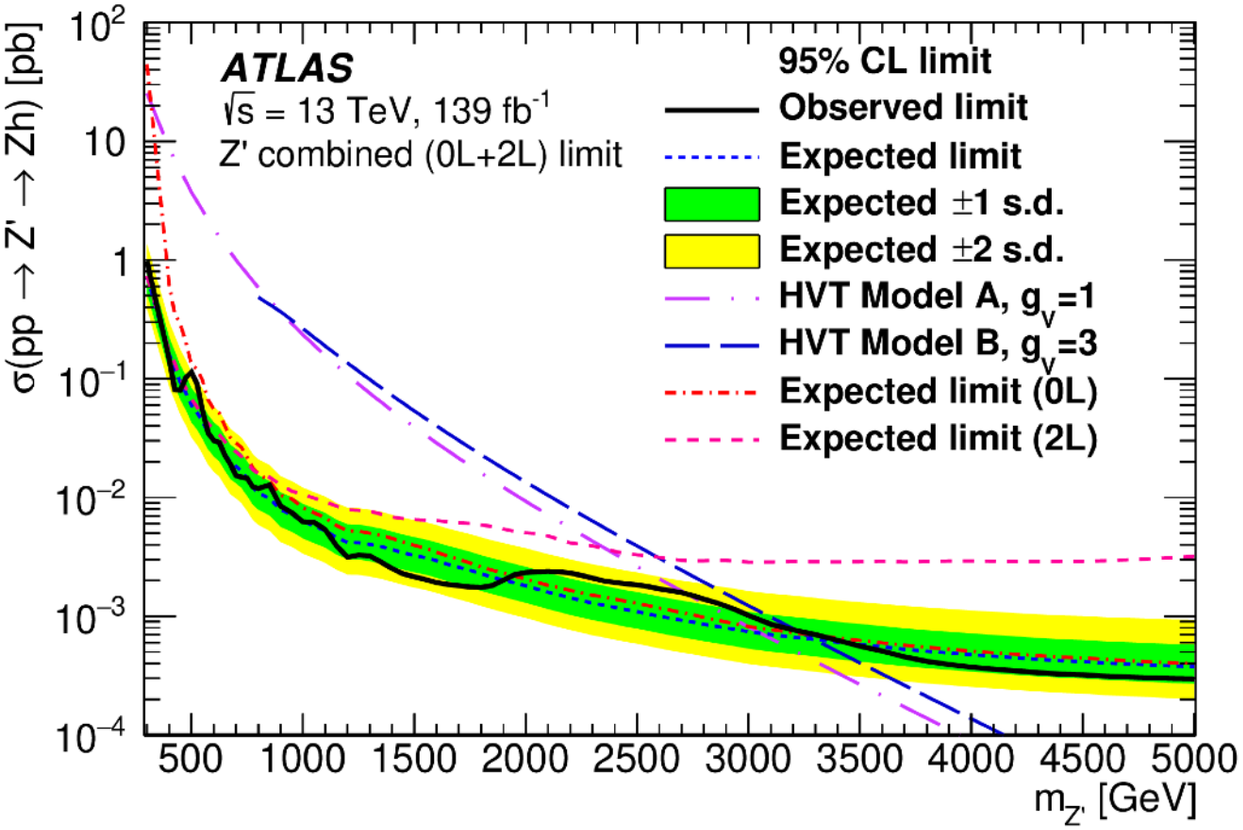
Other Vh channels

CMS, h(cc) and h(4q)



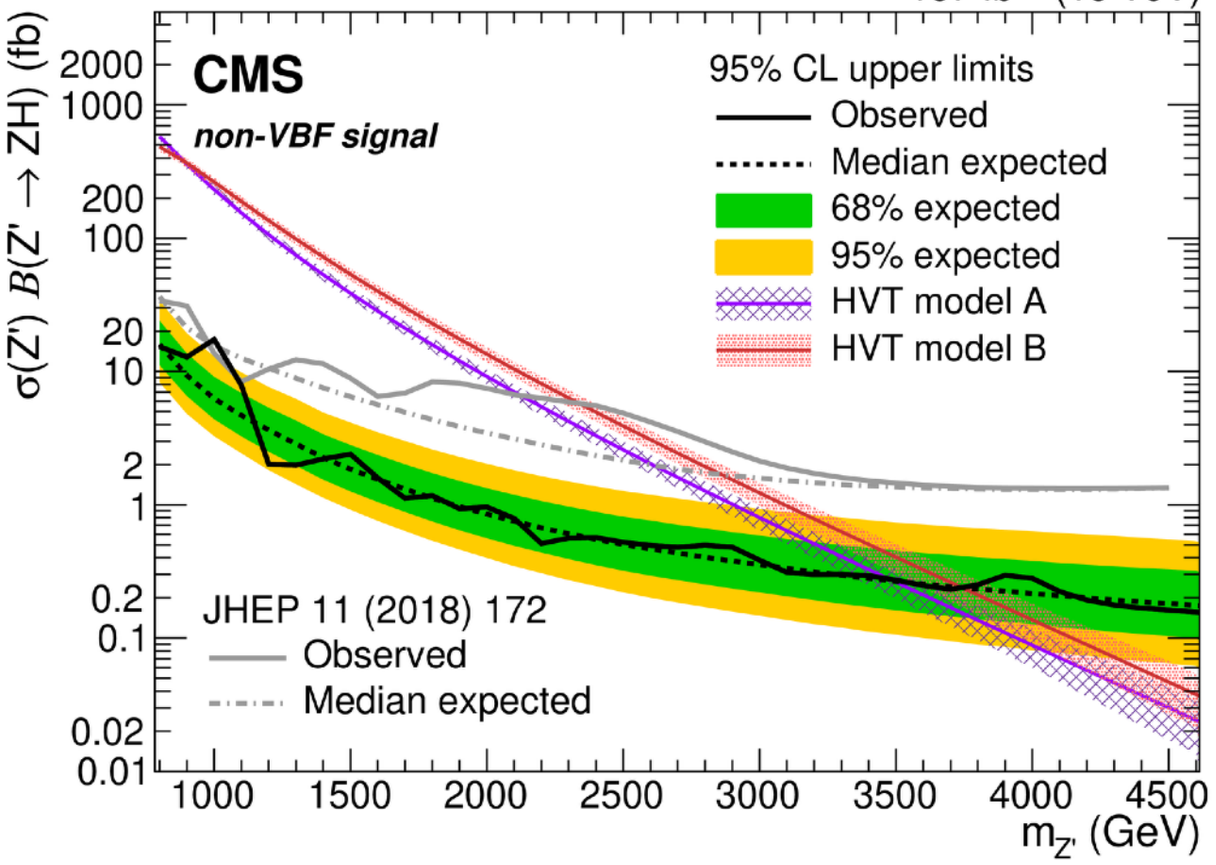
HDBS-2020-19

ATLAS, h(bb)

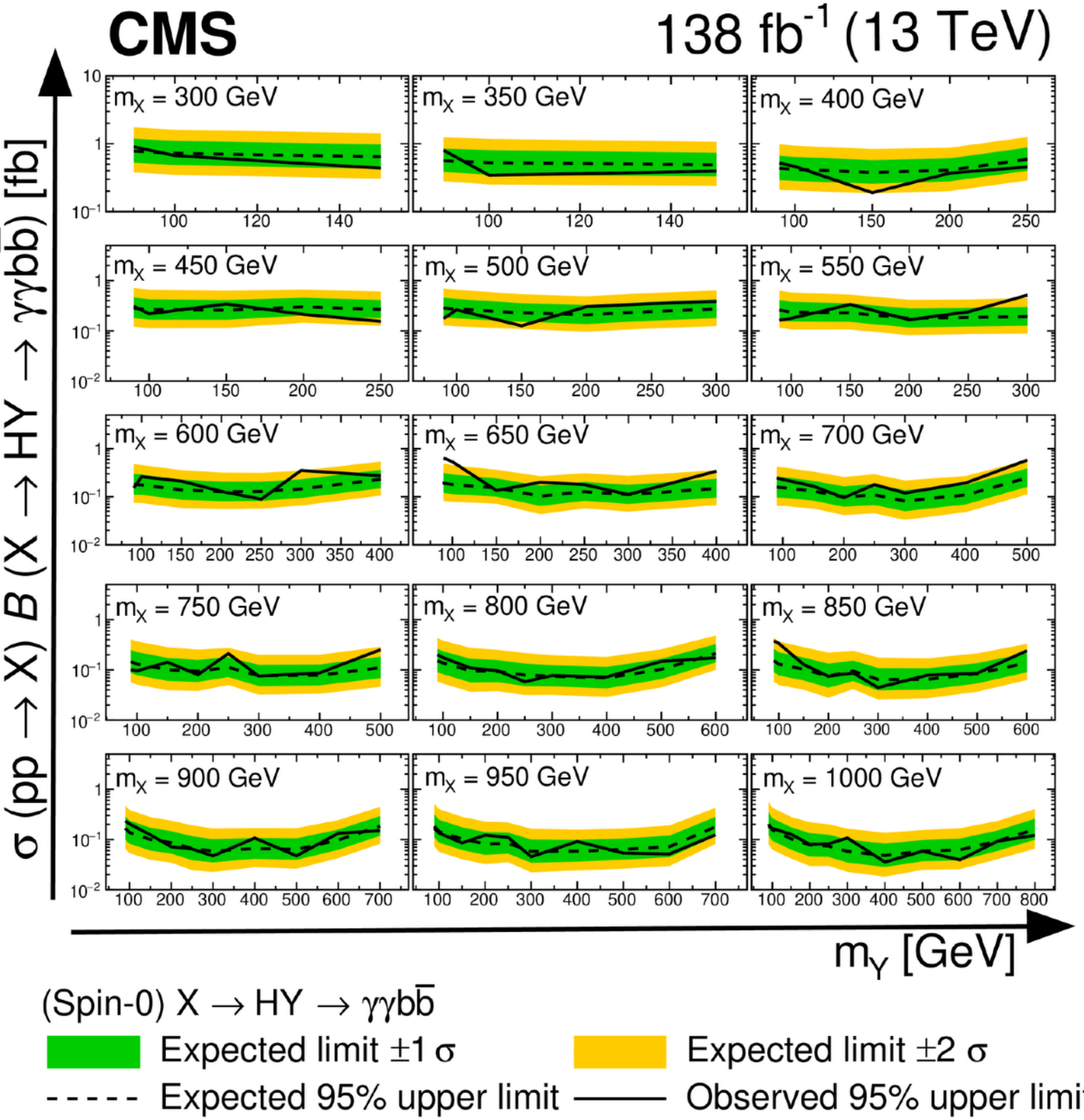


B2G-19-006

CMS, h(bb)

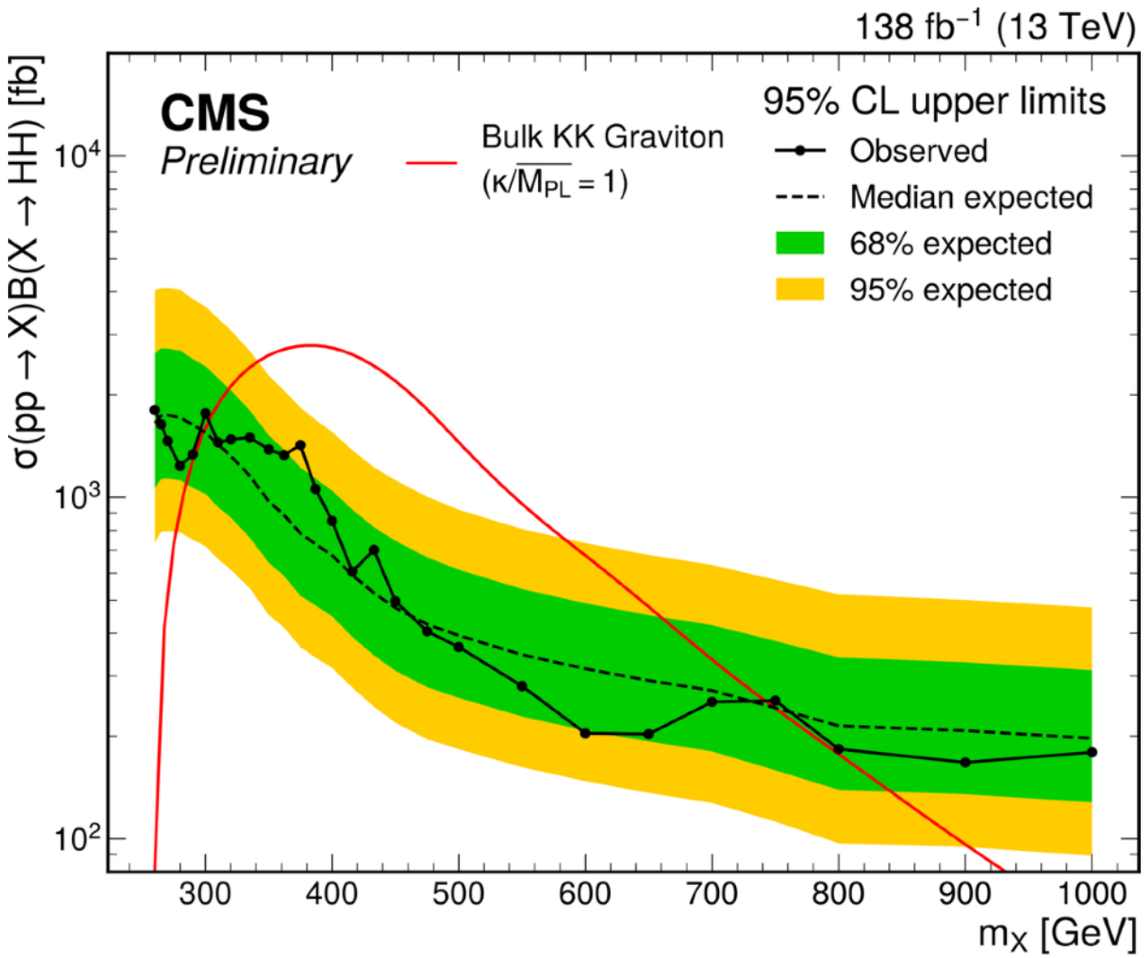


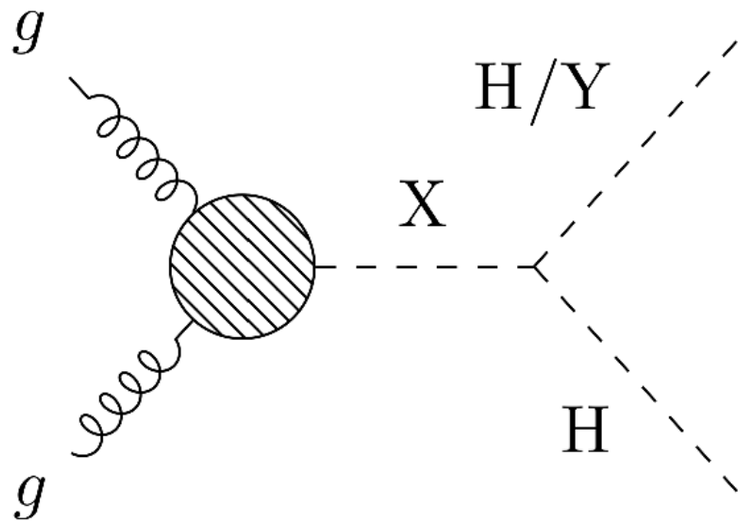
Sh bbyy CMS



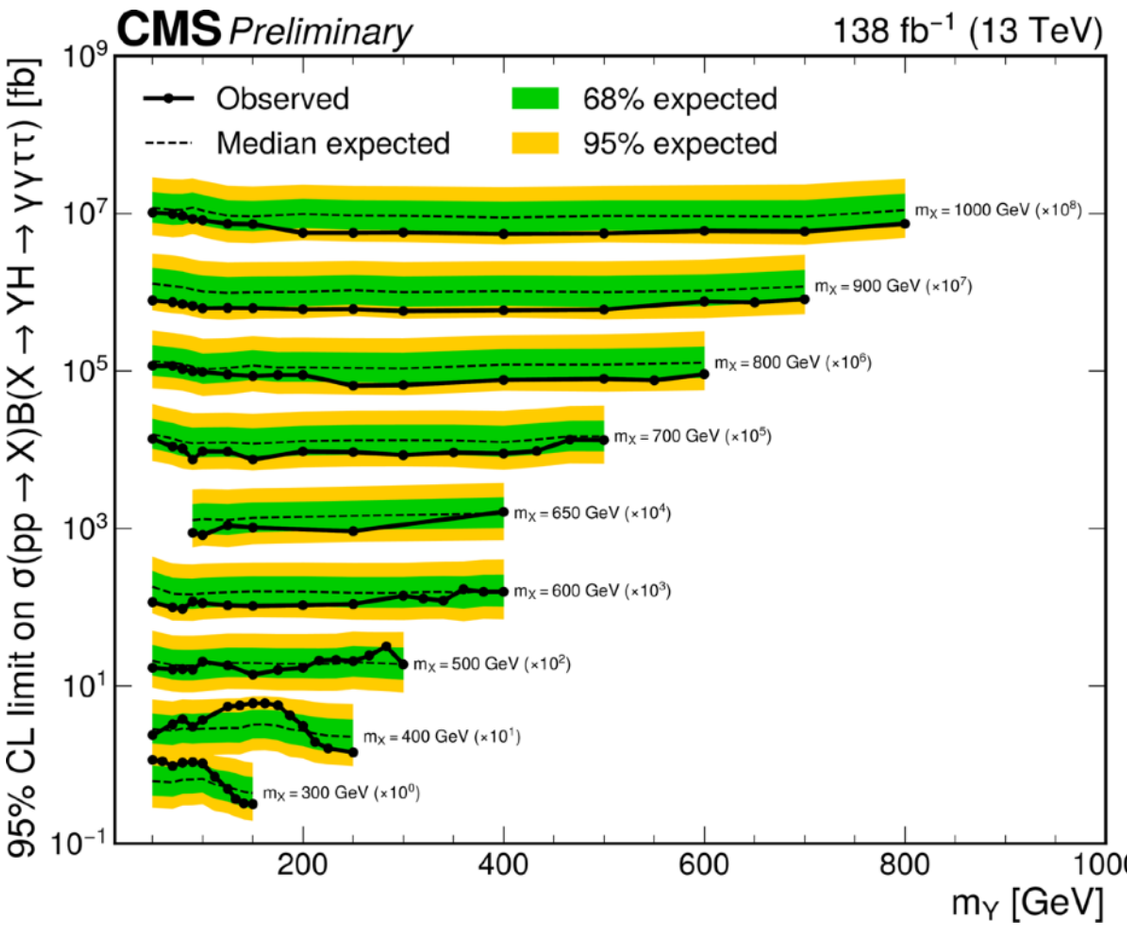
local (global) significance of 3.8 (2.8) standard deviations is observed for mX = 650 GeV and mY = 90 GeV

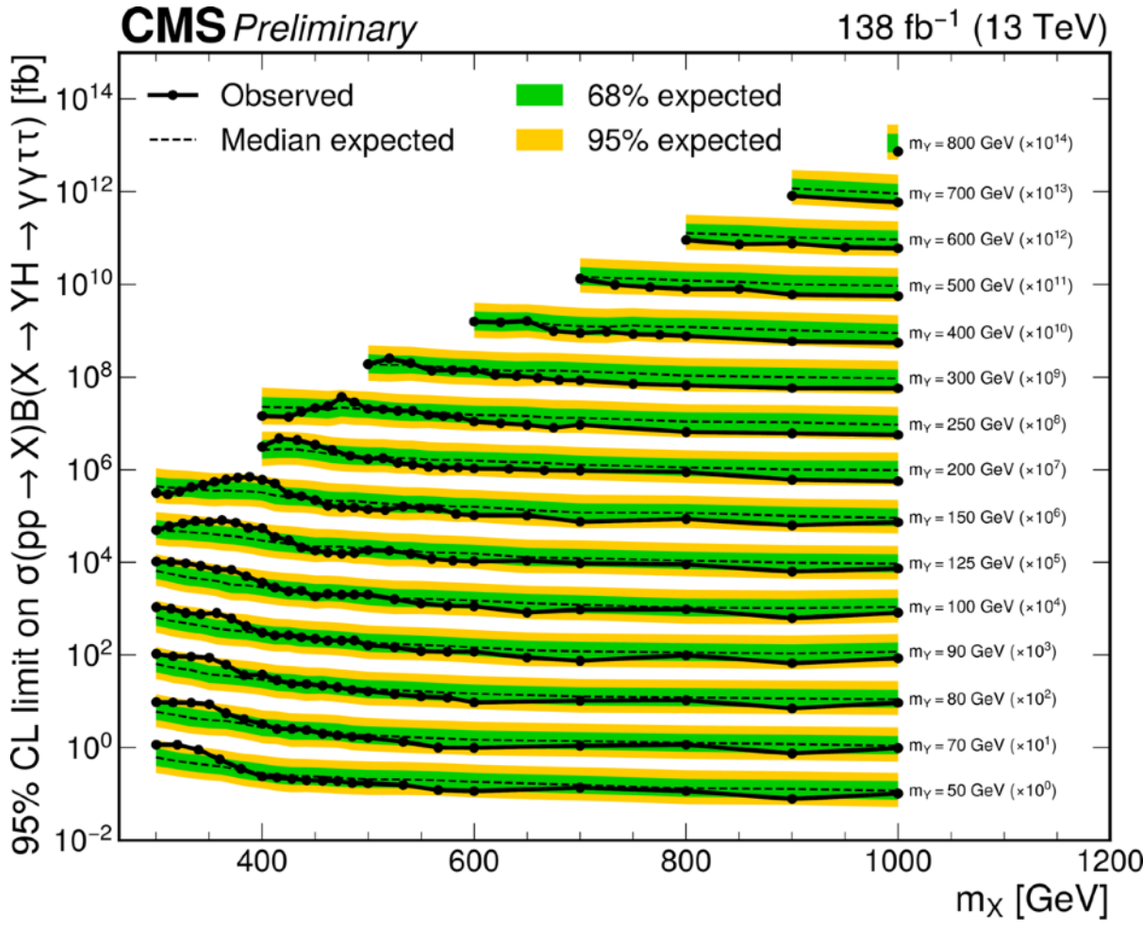
Sh yytautau


138 fb^{-1} (13 TeV)
CMS
Preliminary
Bulk KK Graviton
($\kappa/\overline{M_{PL}} = 1$)
95% CL upper limits
Observed
Median expected
68% expected
95% expected
$\sigma(pp \to X)B(X \to HH)$ [fb]
10^4
10^3
10^2
300
400
500
600
700
800
900
1000
m_X [GeV]

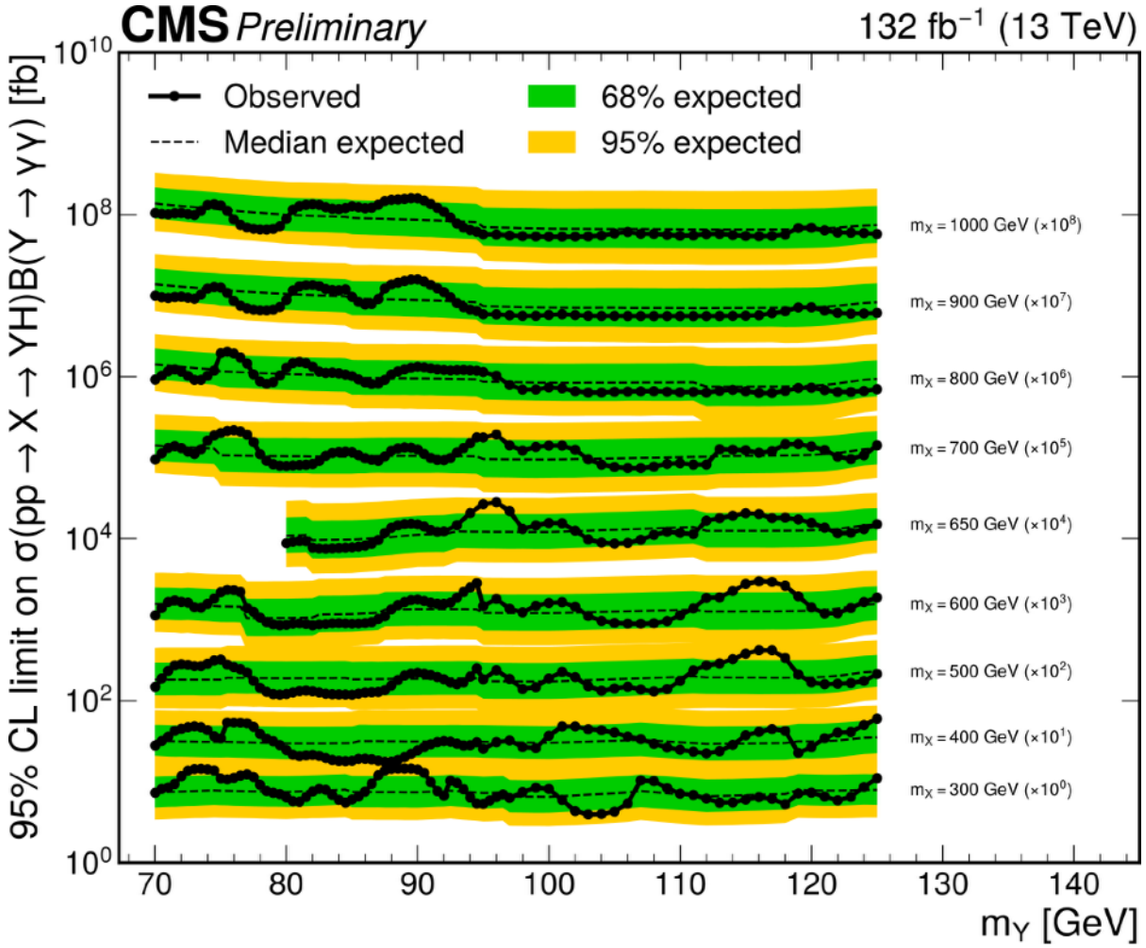

g
g
X
H/Y
H

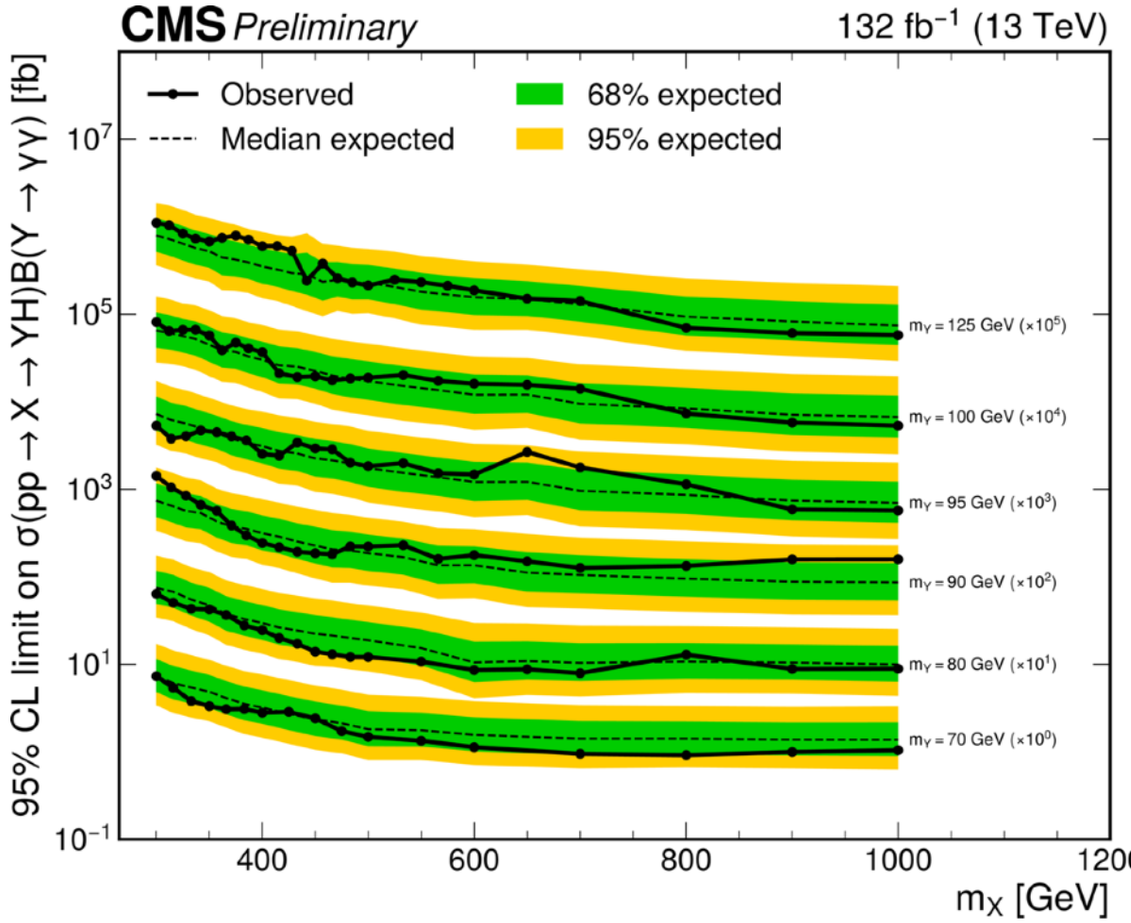
X->Yh -> tautauyy



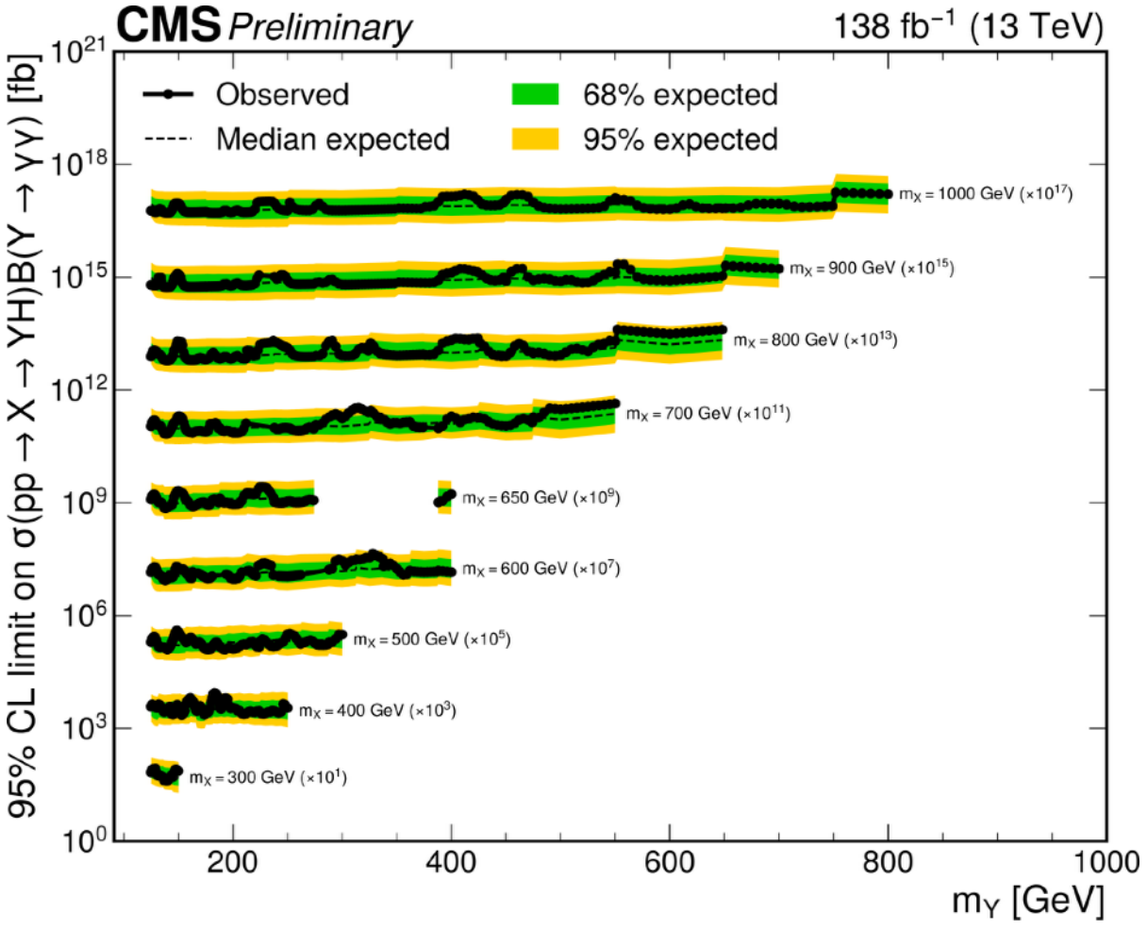


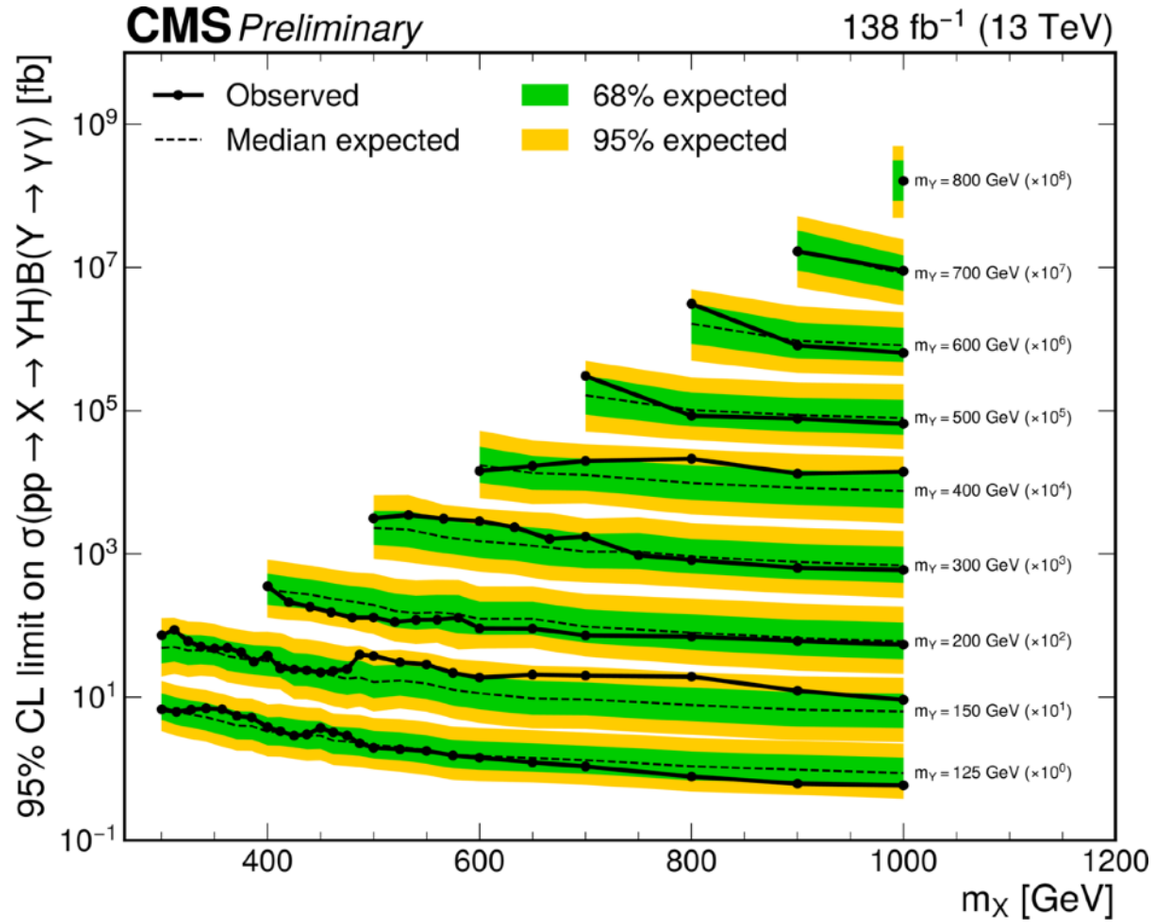
X->Yh -> yytautau, low mass



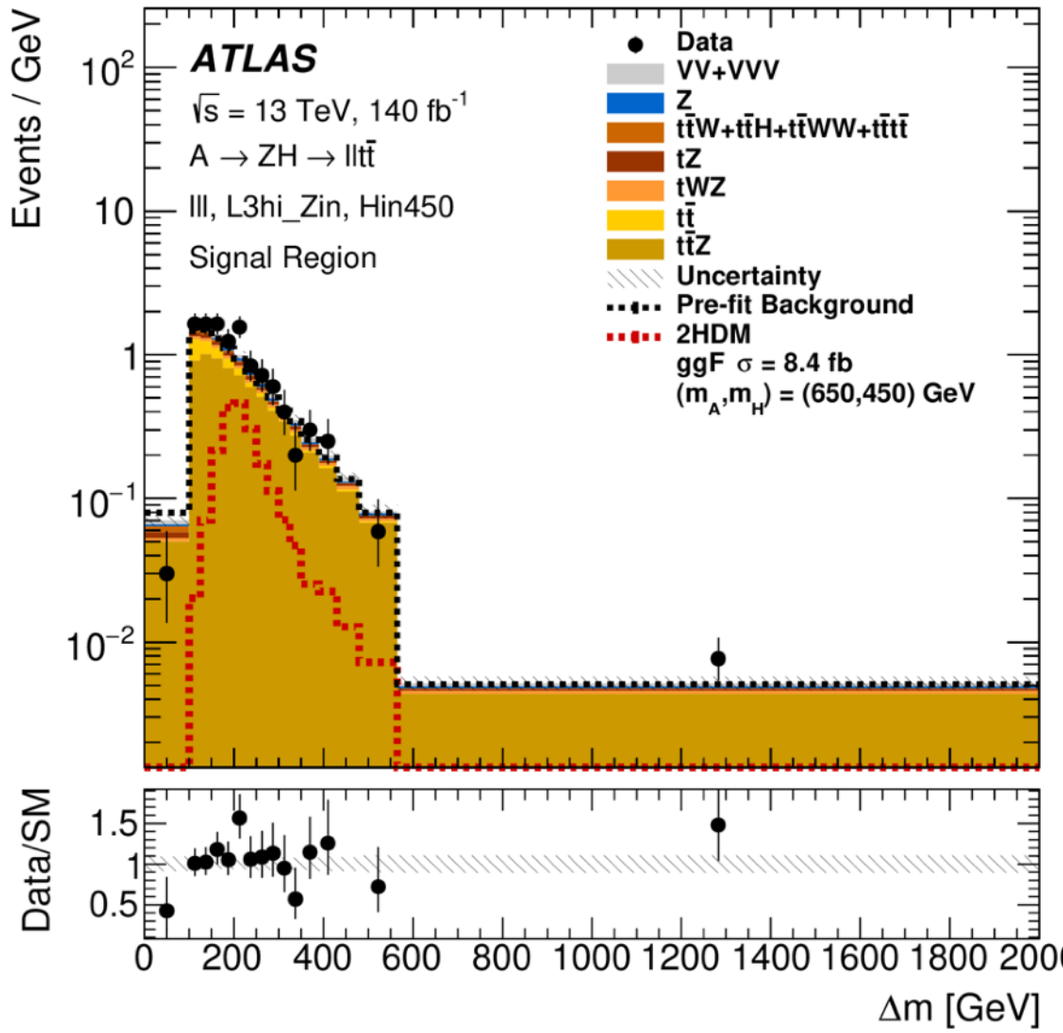


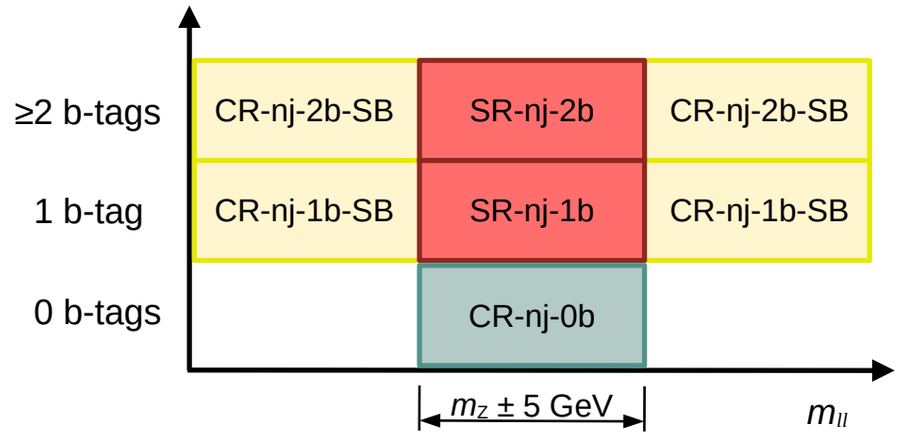
X->Yh -> yytautau, high mass



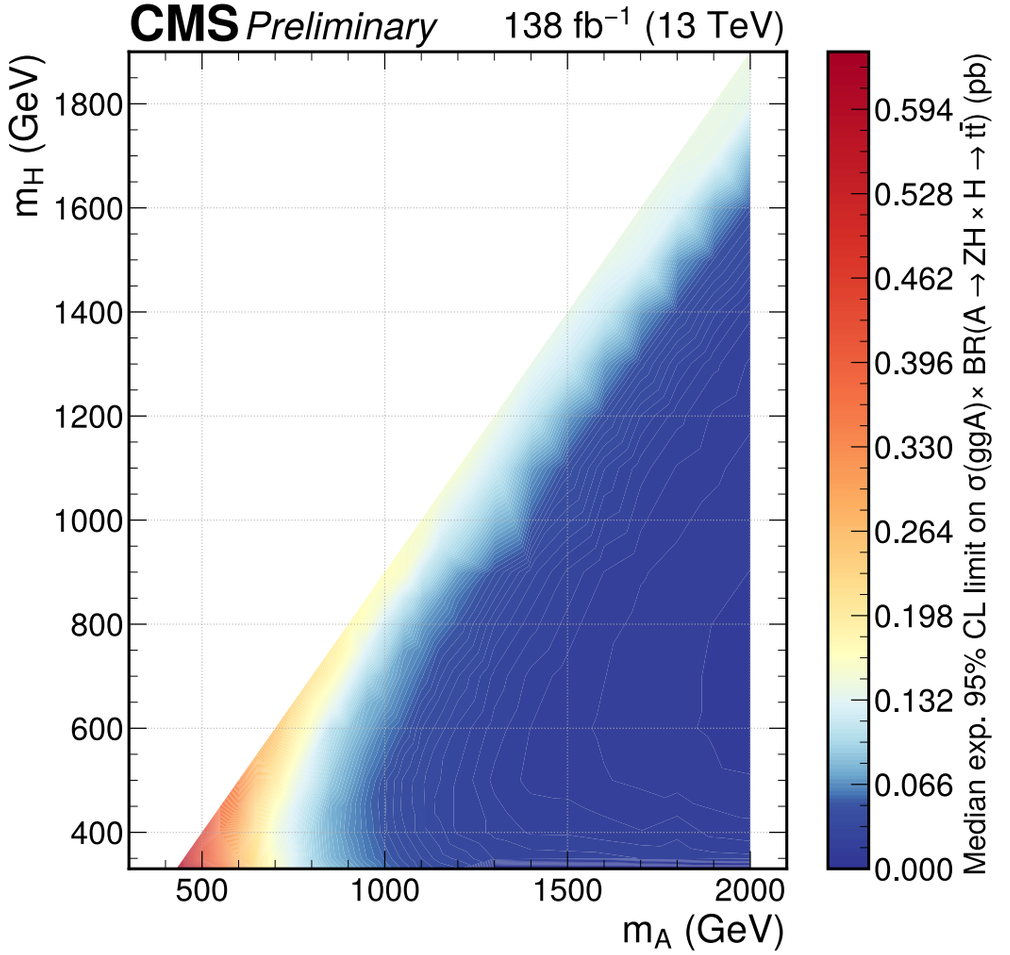


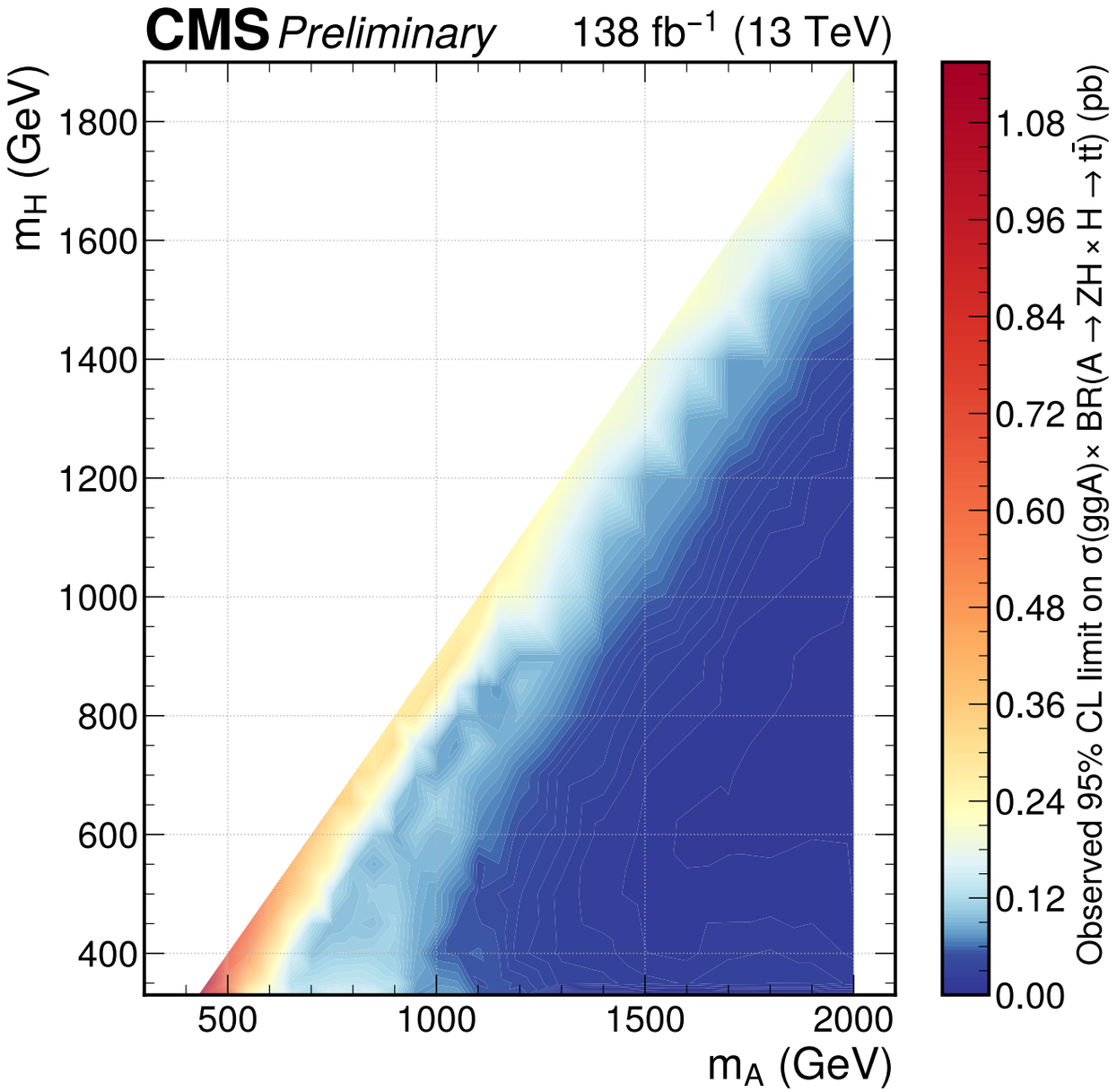
AZh

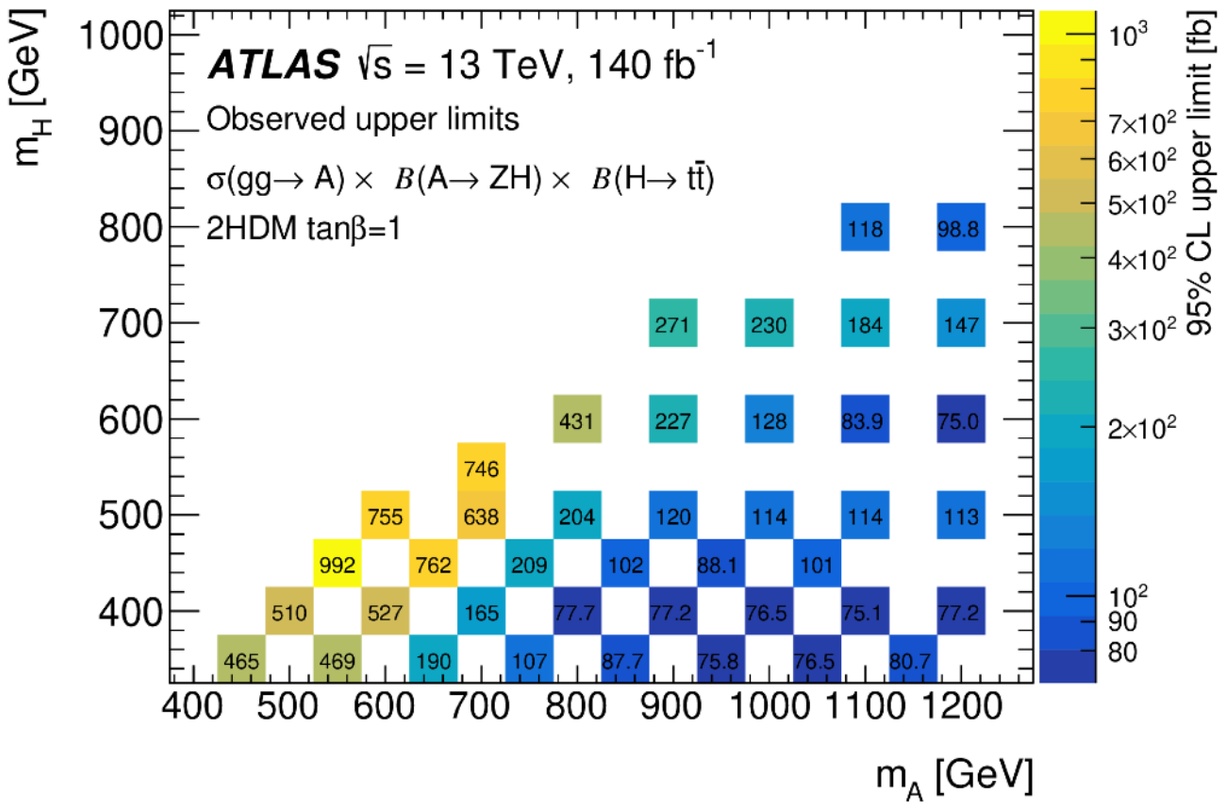

ATLAS
√s = 13 TeV, 140 fb-1
A → ZH → llt̄t̄
lll, L3hi_Zin, Hin450
Signal Region
Data
VV+VVV
Z
t̄t̄W+t̄t̄H+t̄t̄WW+t̄t̄t̄t̄
tZ
tWZ
t̄t̄
t̄t̄Z
Uncertainty
Pre-fit Background
2HDM
ggF σ = 8.4 fb
(mA,mH) = (650,450) GeV
Events / GeV
Data/SM
Δm [GeV]


≥2 b-tags
1 b-tag
0 b-tags
CR-nj-2b-SB
SR-nj-2b
CR-nj-2b-SB
CR-nj-1b-SB
SR-nj-1b
CR-nj-1b-SB
CR-nj-0b
mZ ± 5 GeV
mll

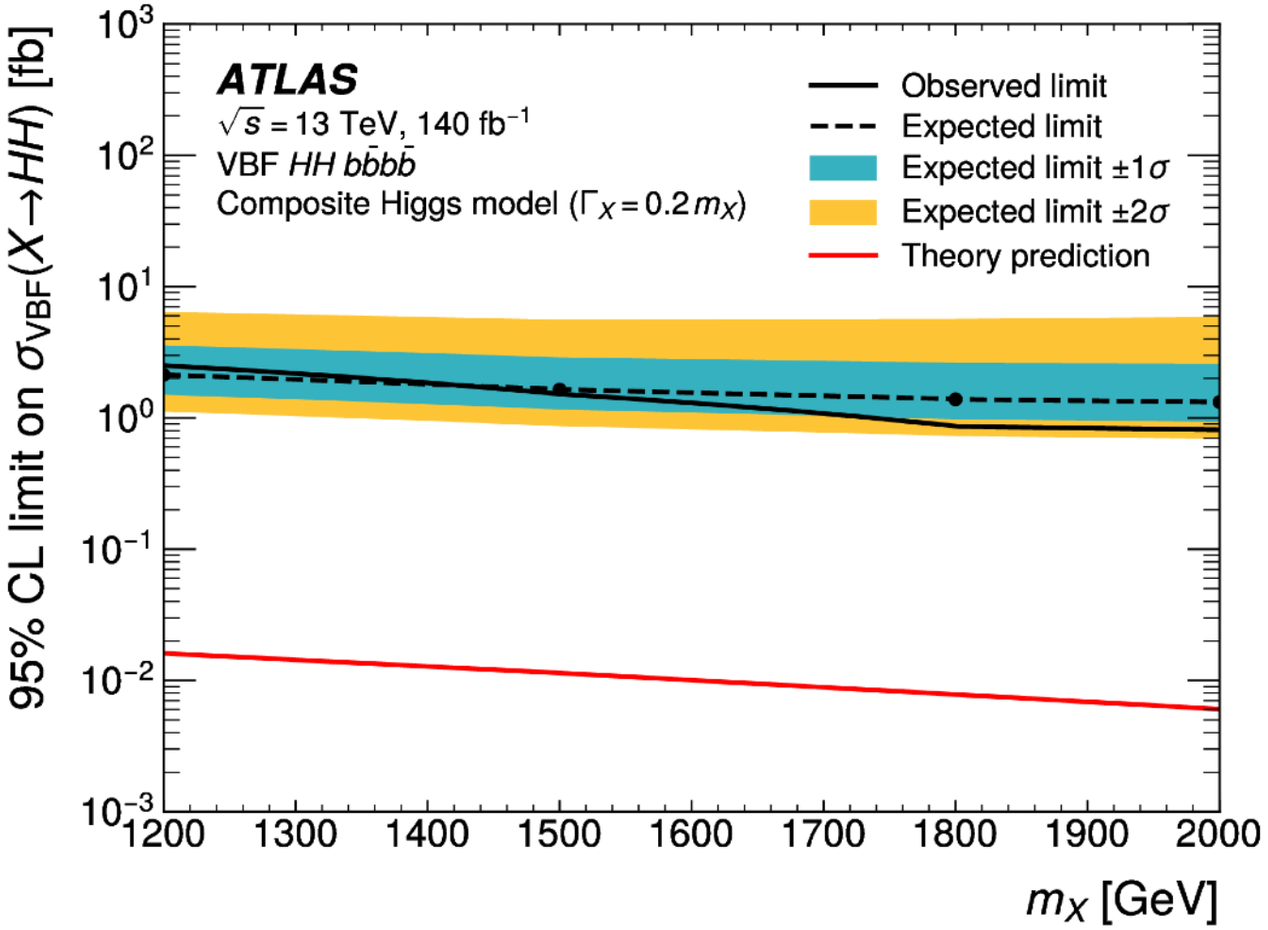
with n = 5, ≥6


CMS Preliminary
138 fb−1 (13 TeV)
mH (GeV)
mA (GeV)
Median exp. 95% CL limit on σ(ggA)× BR(A → ZH × H → t̄t) (pb)

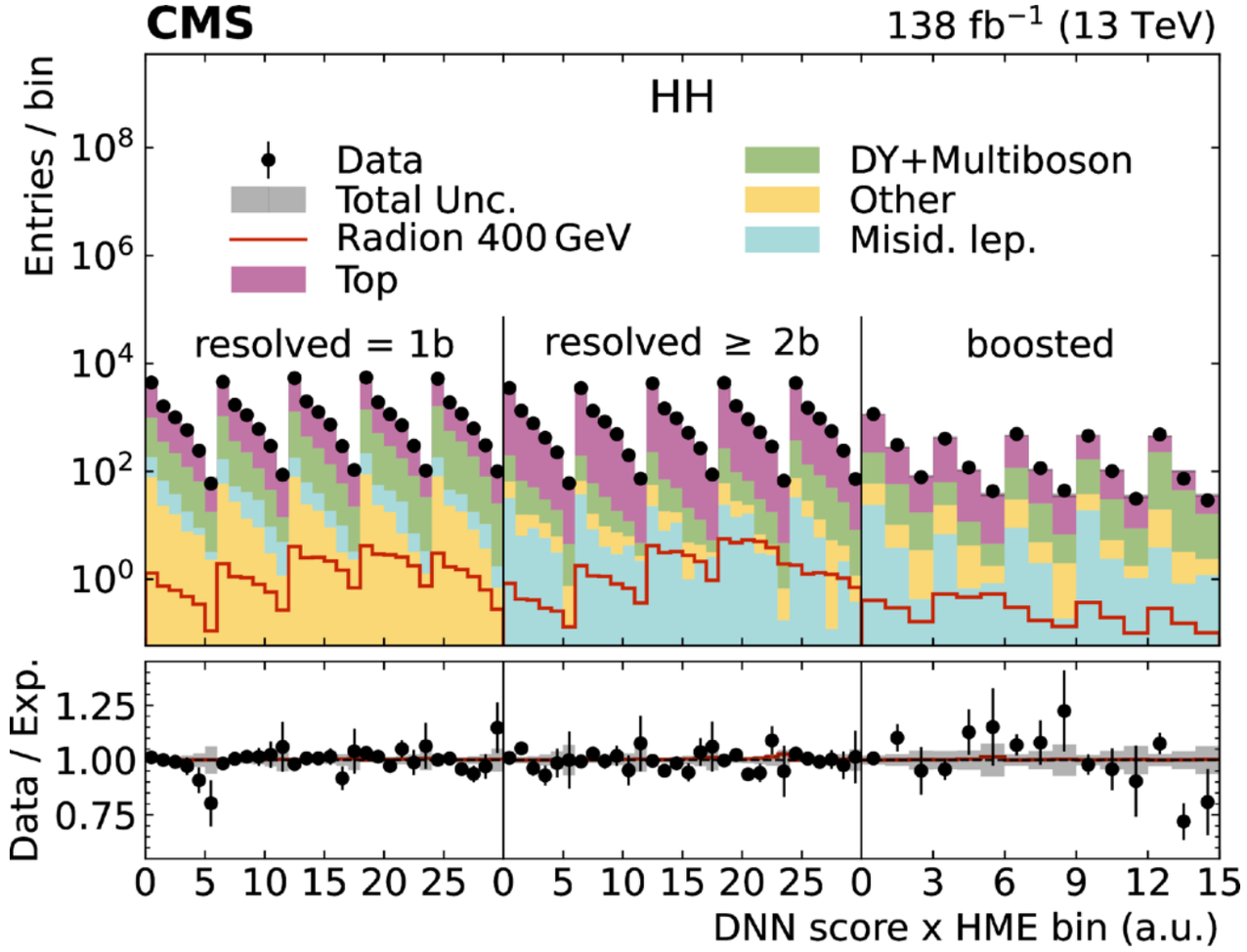

CMS Preliminary
138 fb^{-1} (13 TeV)
m_H (GeV)
1800
1600
1400
1200
1000
800
600
400
500
1000
1500
2000
m_A (GeV)
1.08
0.96
0.84
0.72
0.60
0.48
0.36
0.24
0.12
0.00
Observed 95% CL limit on σ(ggA)× BR(A → ZH × H → tt̄) (pb)

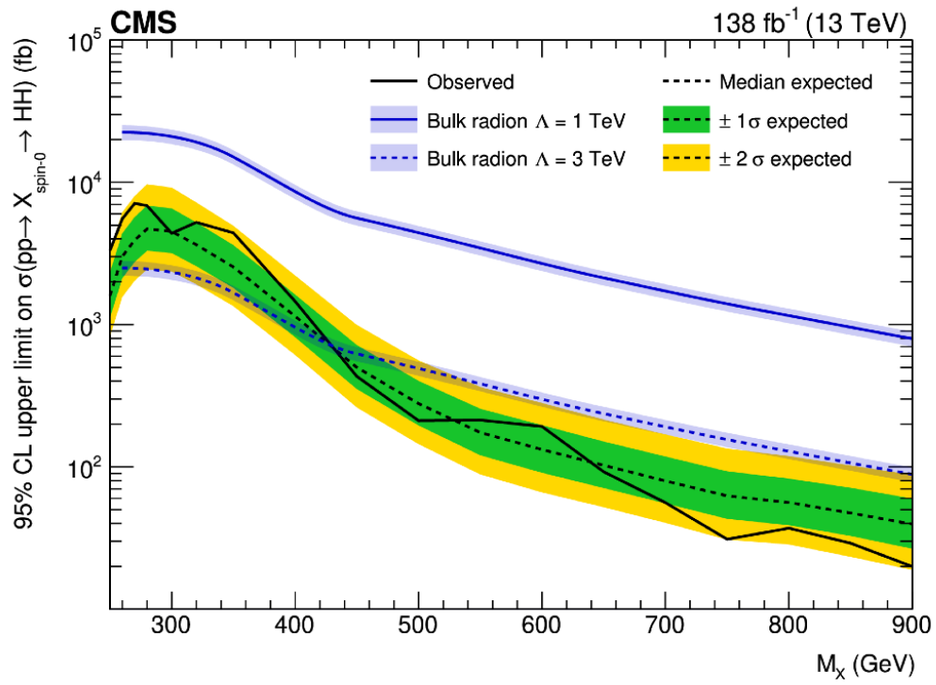

ATLAS √s = 13 TeV, 140 fb^{-1}
Observed upper limits
σ(gg→ A) × B(A→ ZH) × B(H→ tt̄)
2HDM tanβ=1
m_H [GeV]
1000
900
800
700
600
500
400
118
98.8
271
230
184
147
431
227
128
83.9
75.0
746
638
204
120
114
114
113
755
992
762
209
102
88.1
101
510
527
165
77.7
77.2
76.5
75.1
77.2
465
469
190
107
87.7
75.8
76.5
80.7
400
500
600
700
800
900
1000
1100
1200
m_A [GeV]
10^3
7×10^2
6×10^2
5×10^2
4×10^2
3×10^2
2×10^2
10^2
90
80
95% CL upper limit [fb]

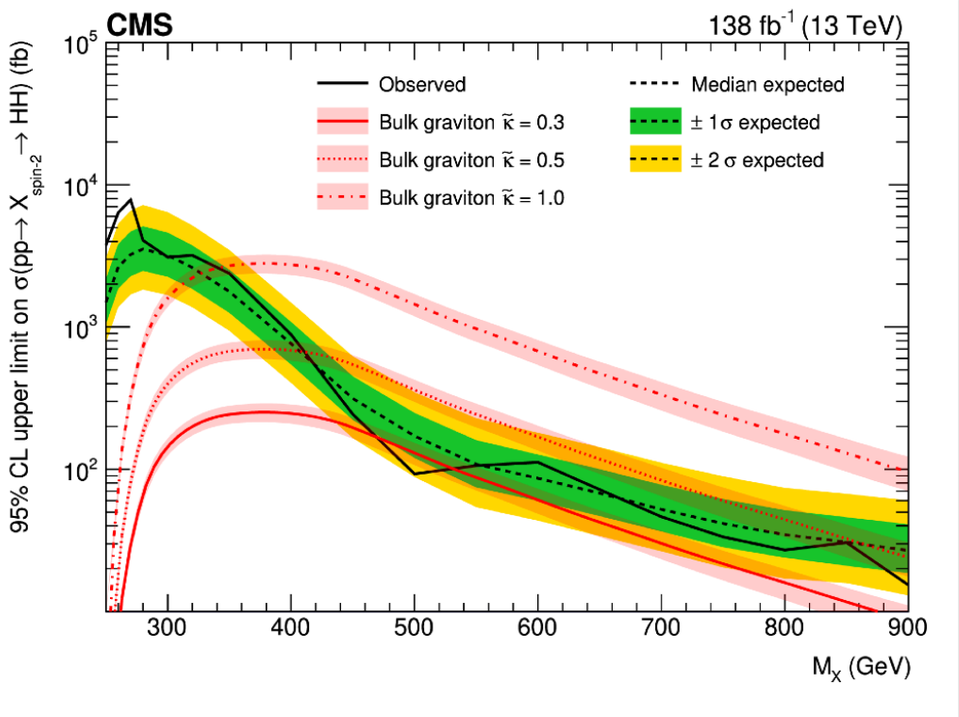
Resonant hh 4b

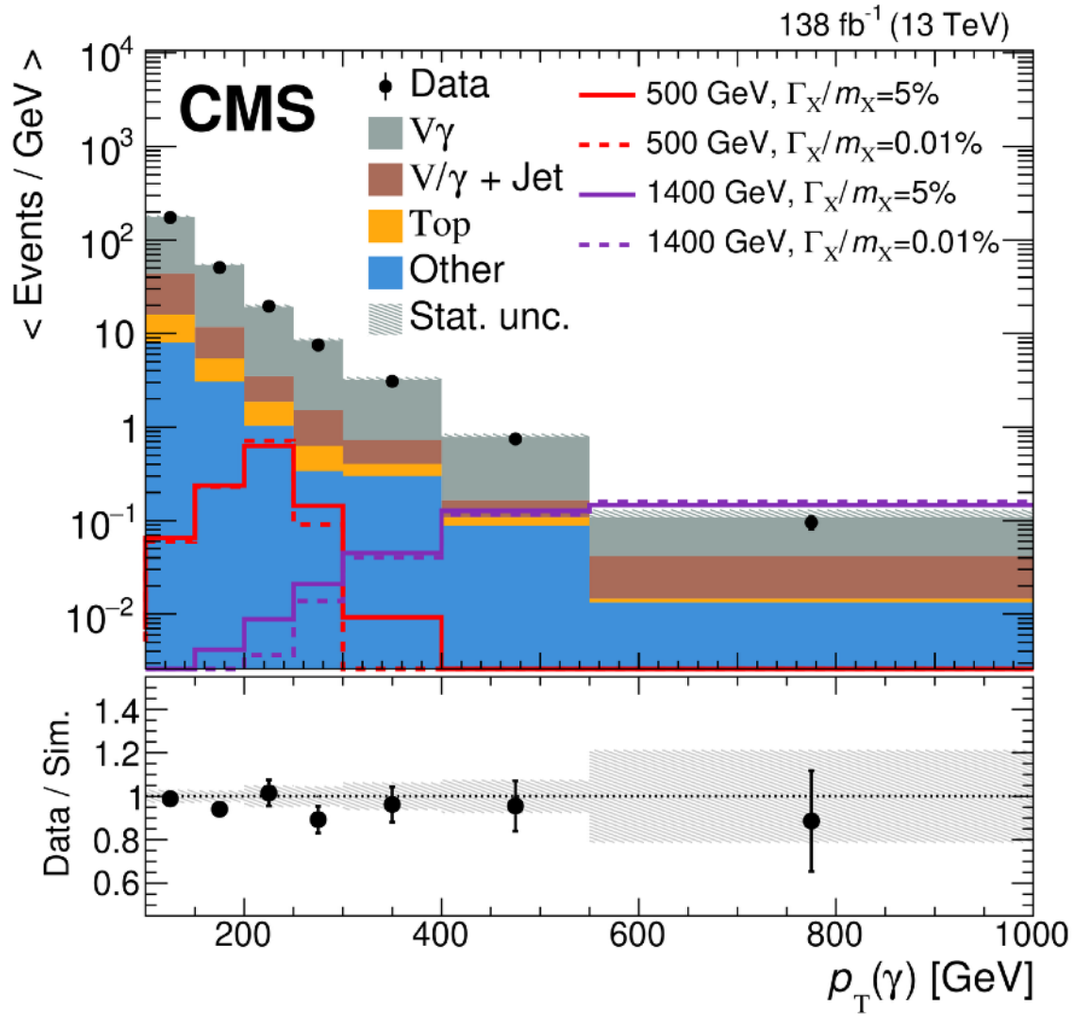


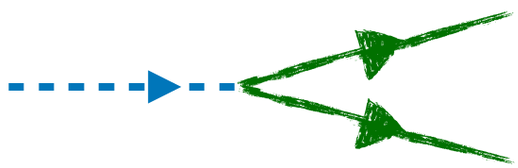
hh bbww

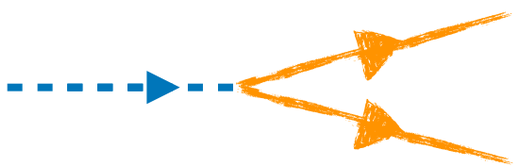

CMS
138 fb^{-1} (13 TeV)
HH
Data
Total Unc.
Radion 400 GeV
Top
DY+Multiboson
Other
Misid. lep.
resolved = 1b
resolved ≥ 2b
boosted
Entries / bin
Data / Exp.
DNN score x HME bin (a.u.)

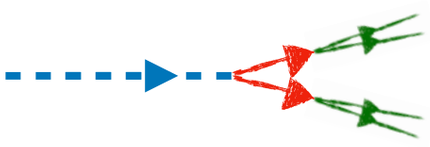

CMS
138 fb^{-1} (13 TeV)
Observed
Median expected
Bulk radion Λ = 1 TeV
± 1σ expected
Bulk radion Λ = 3 TeV
± 2 σ expected
95% CL upper limit on σ(pp→ X$_{spin-0}$ → HH) (fb)
M$_X$ (GeV)

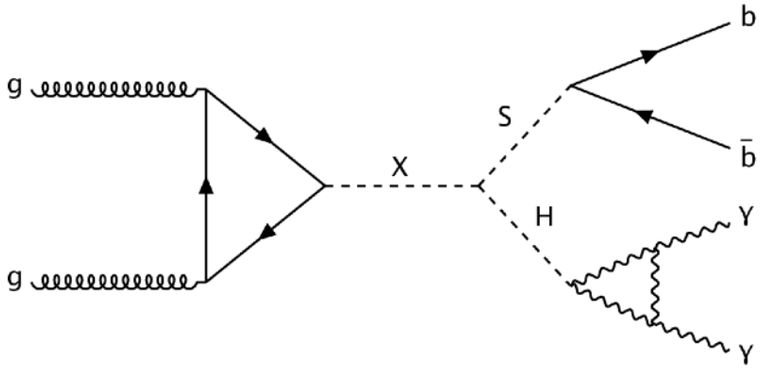

CMS
138 fb^{-1} (13 TeV)
Observed
Median expected
Bulk graviton κ̃ = 0.3
± 1σ expected
Bulk graviton κ̃ = 0.5
± 2 σ expected
Bulk graviton κ̃ = 1.0
95% CL upper limit on σ(pp→ X$_{spin-2}$ → HH) (fb)
M$_X$ (GeV)


138 fb^{-1} (13 TeV)
CMS
Data
Vγ
V/γ + Jet
Top
Other
Stat. unc.
500 GeV, Γ_X/m_X=5%
500 GeV, Γ_X/m_X=0.01%
1400 GeV, Γ_X/m_X=5%
1400 GeV, Γ_X/m_X=0.01%
< Events / GeV >
Data / Sim.
$p_T(\gamma)$ [GeV]





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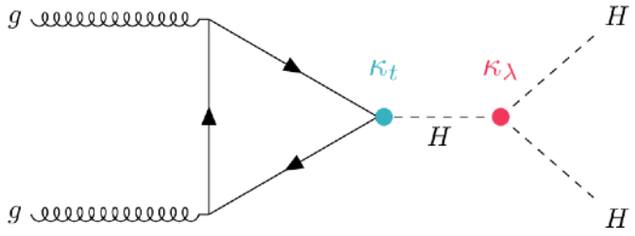
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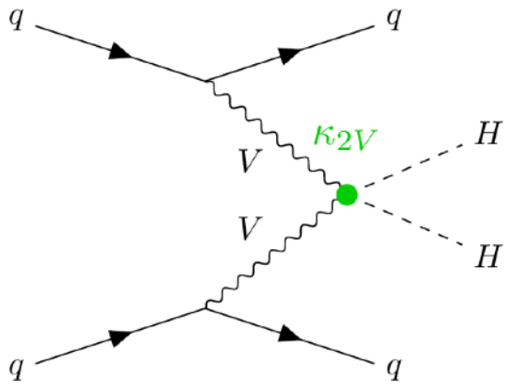
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