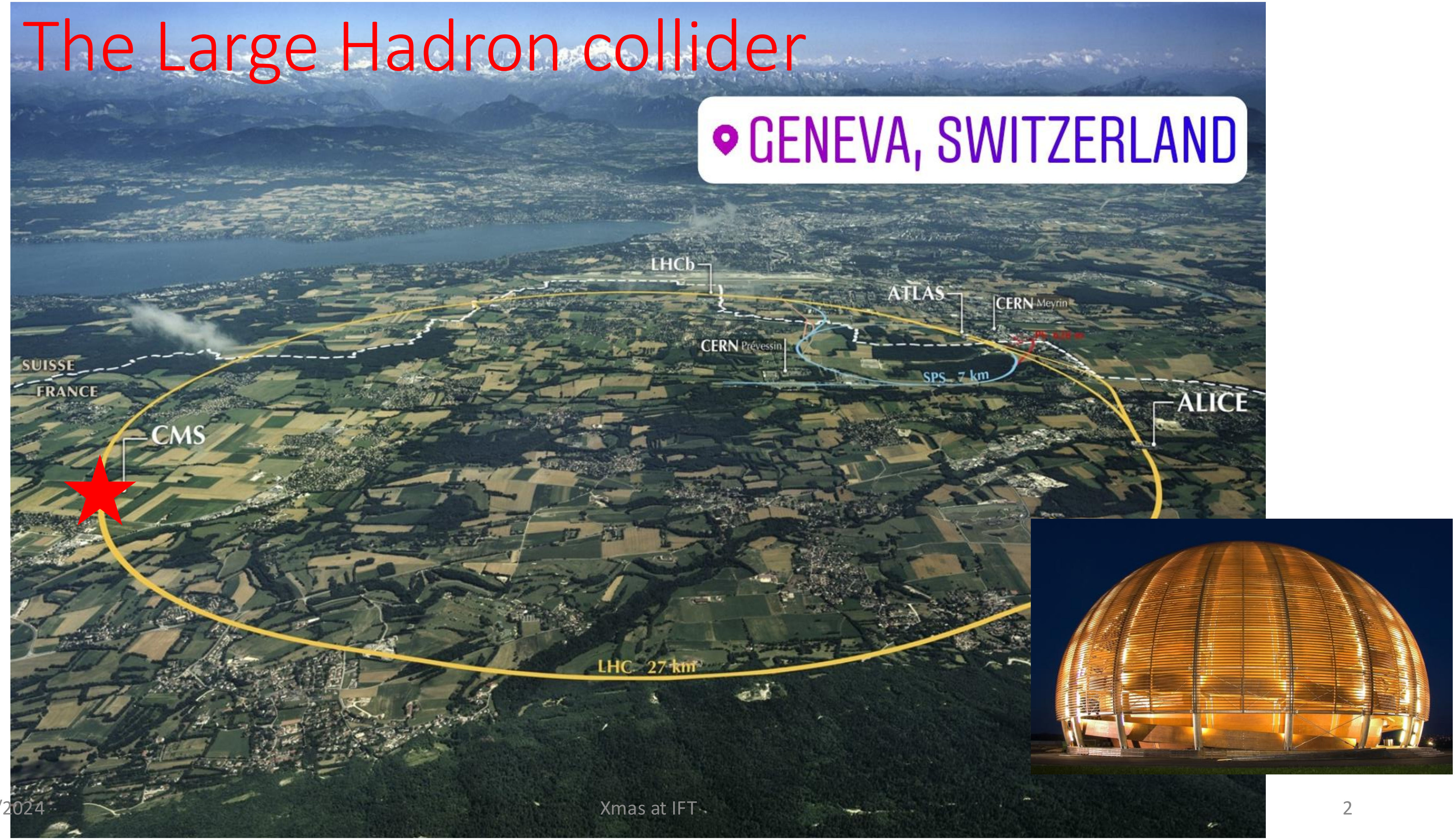
Searches in the Higgs sector at the LHC

...from the CMS point of view

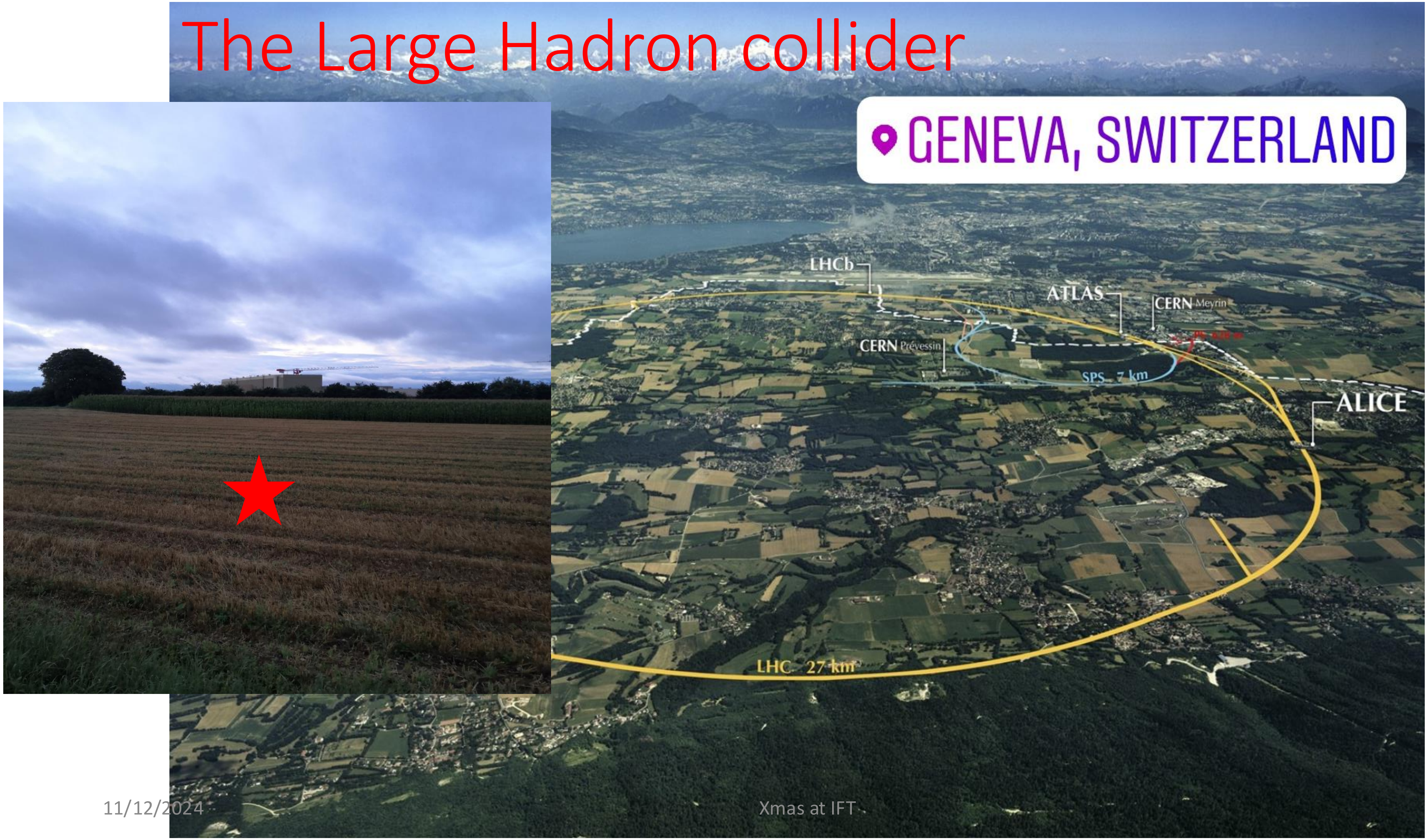
30th IFT Xmas Workshop, December 2024

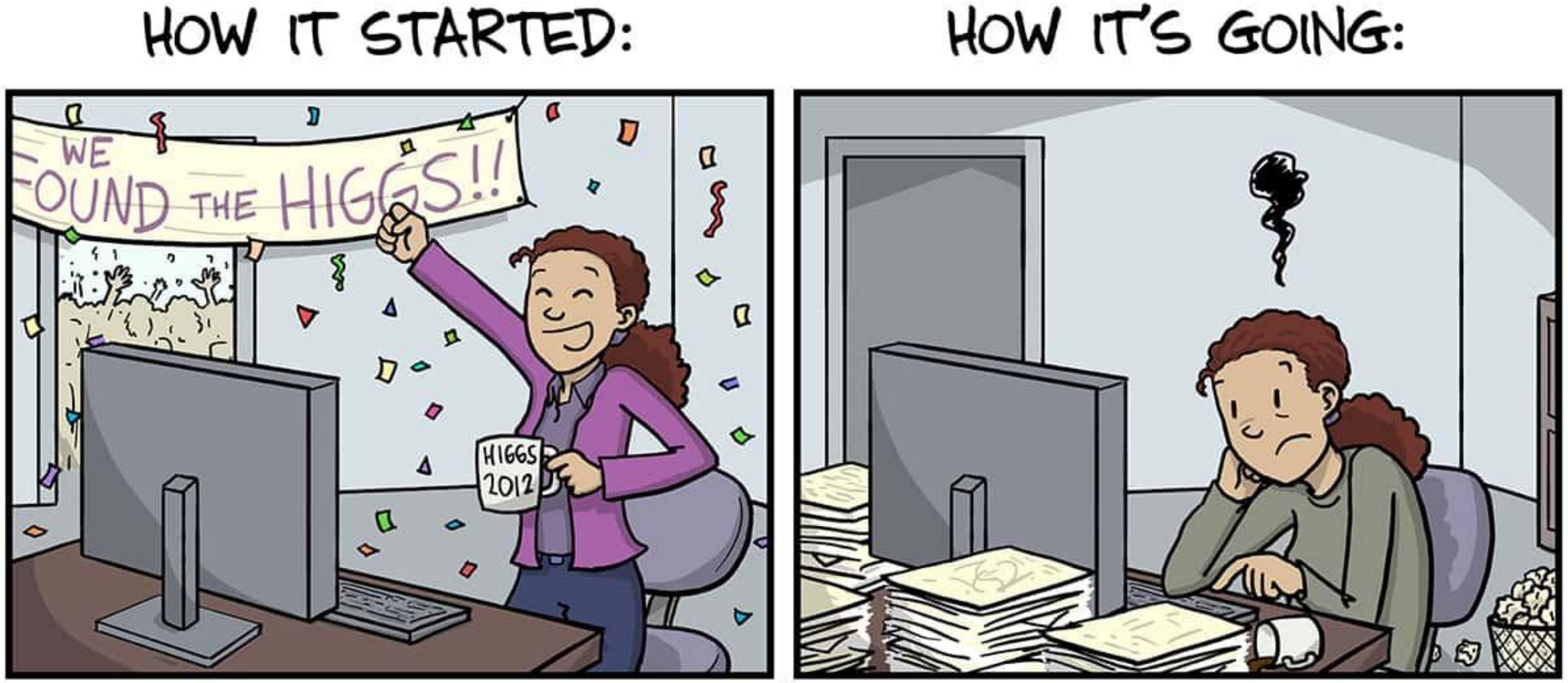
Agni Bethani

The Large Hadron collider

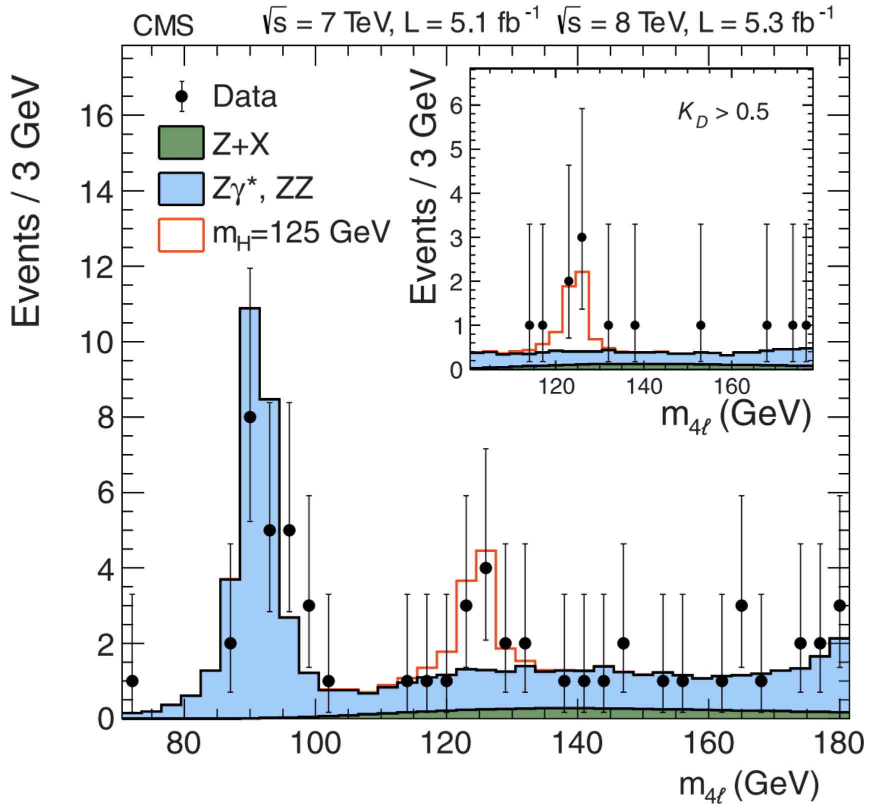


The Large Hadron collider



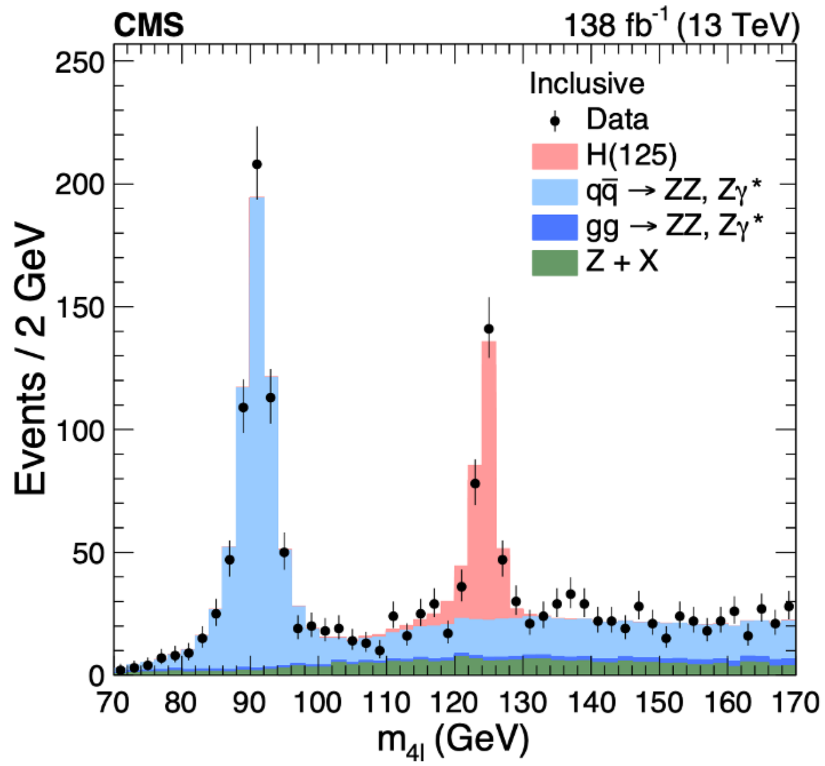

HOW IT STARTED:
WE FOUND THE HIGGS!!
HIGGS 2012
HOW IT'S GOING:

HOW IT STARTED:



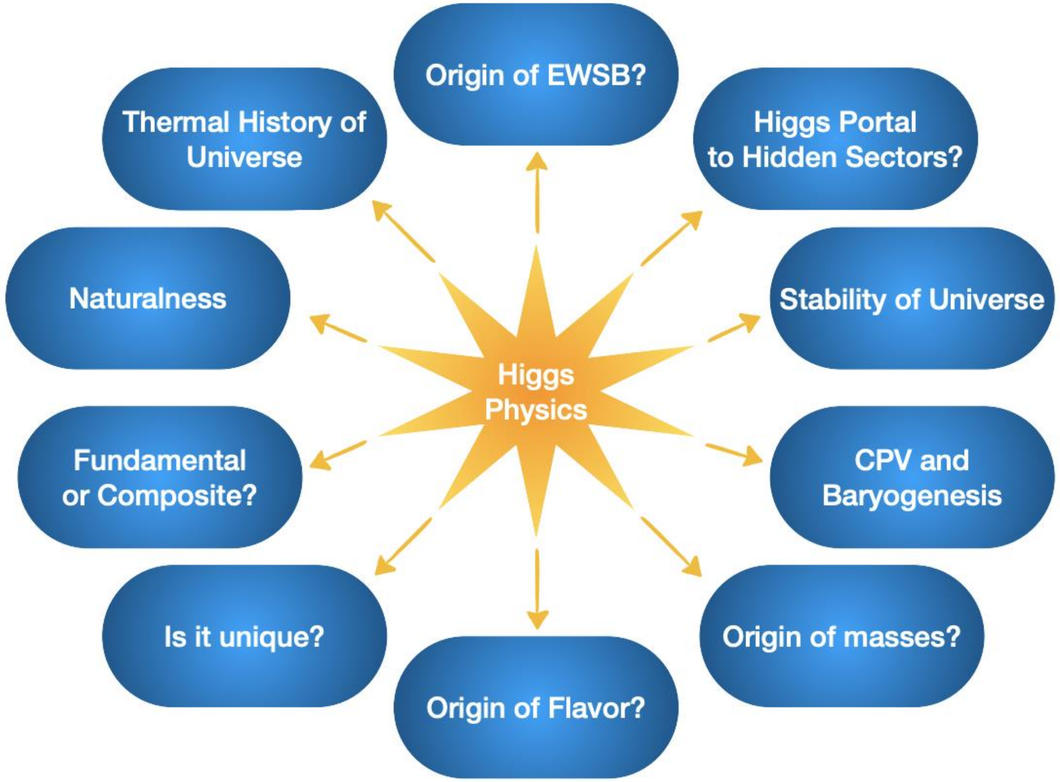
[Physics Letters B, Volume 716, Issue 1](Discovery paper)

HOW IT'S GOING:

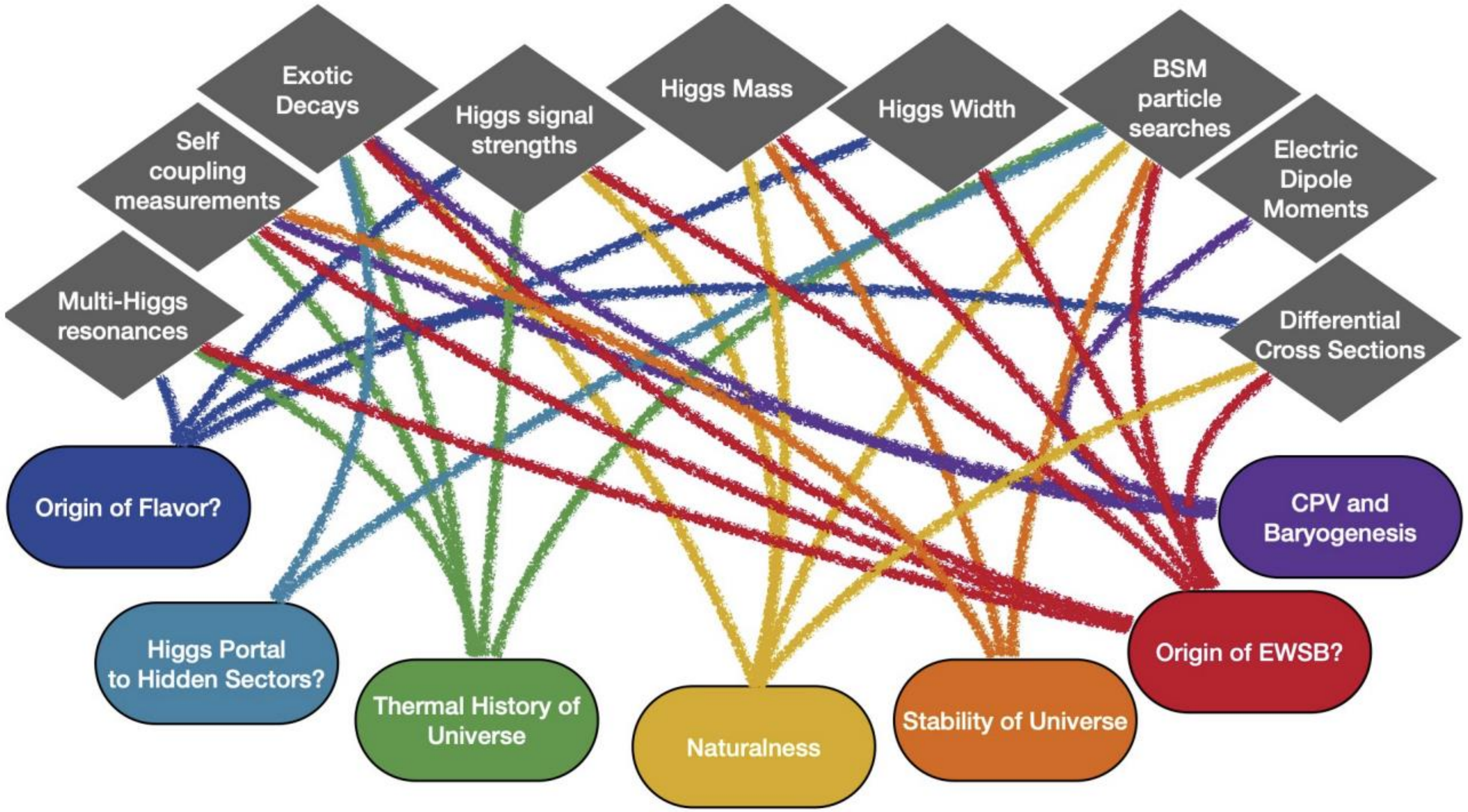


https://arxiv.org/abs/2409.13663

Why study the Higgs sector?



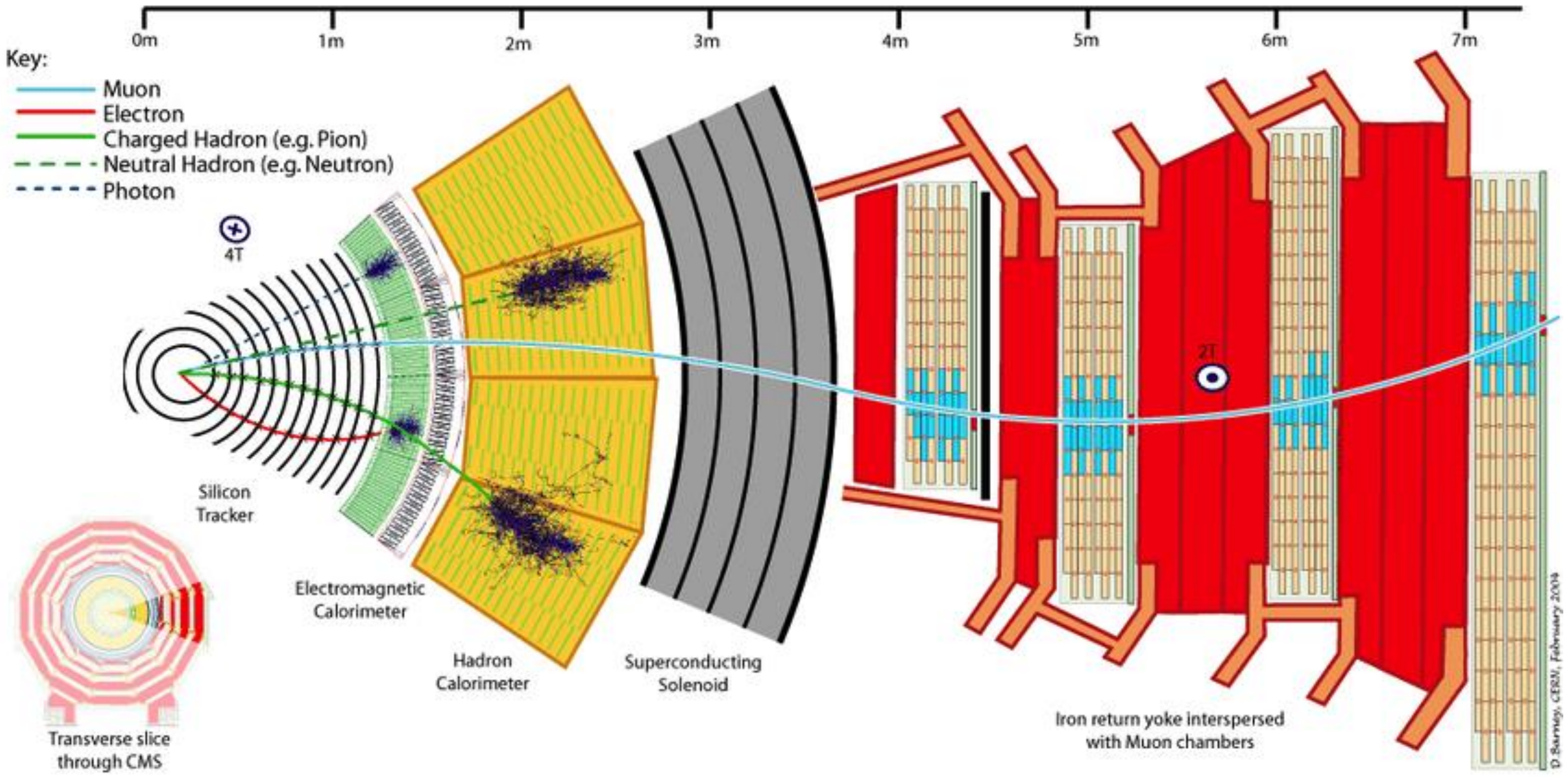
Why study the Higgs sector?



The CMS detector

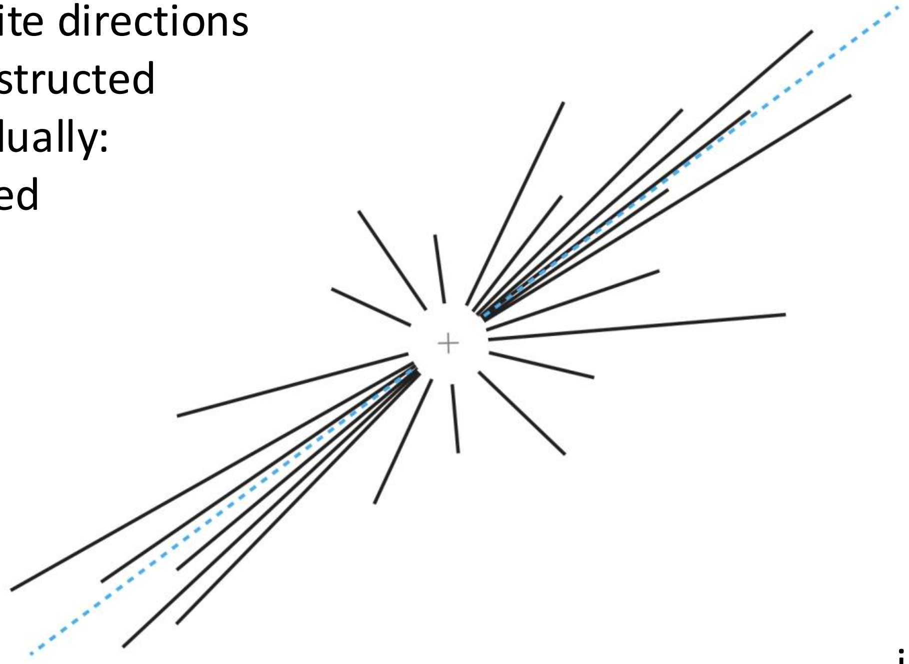
ATLAS does a very similar job!

- One of the experiments along the Large Hadron Collider in the Geneva
- b-jets are really important for Higgs physics due to the large BR,
  H->bb BR 0.6
- information from the inner tracker are used to identify b-jets

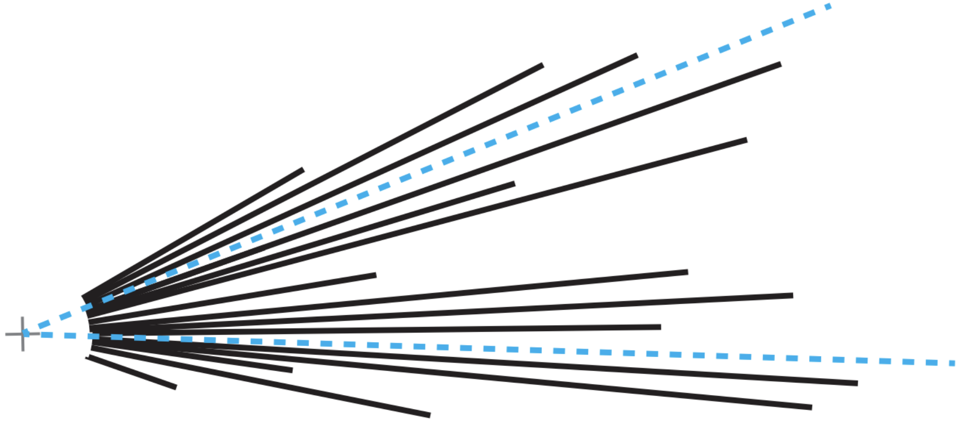


Resolved and boosted topologies

Decay products in
opposite directions
Reconstructed
individually:
resolved



Decay products collinear (or almost)
Reconstructed as one object:
boosted

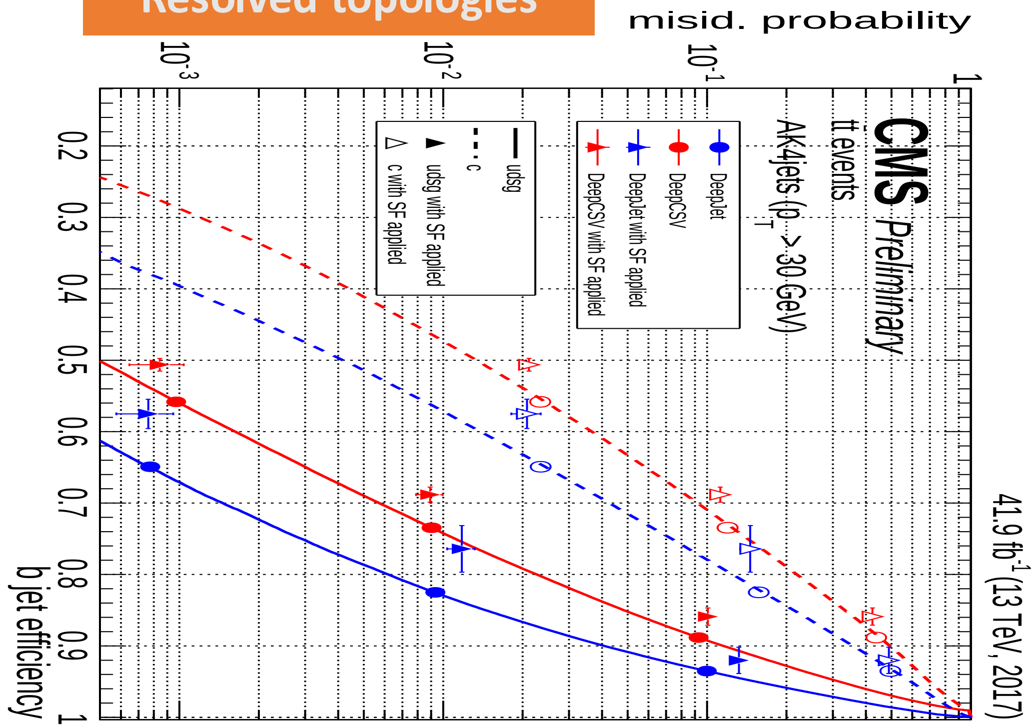


jets, b-jets and hadronic τ decays

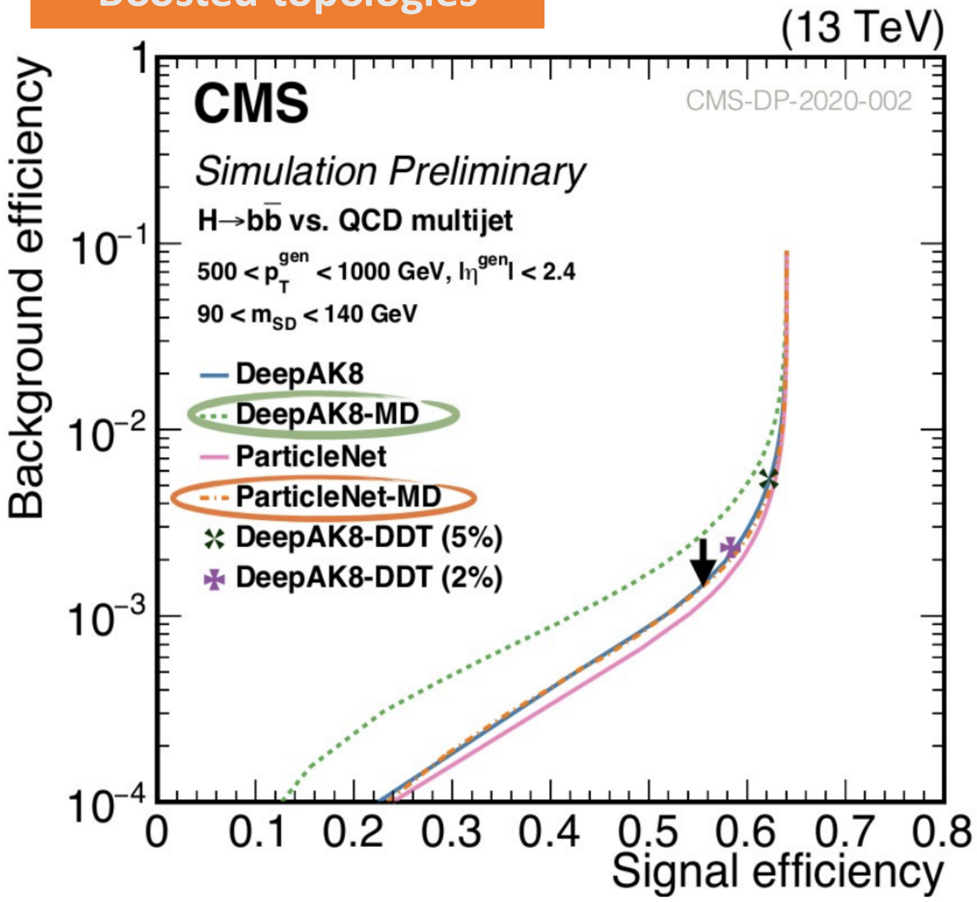
b-jet tagging performance

ParticleNet:
Cutting edge b-tagging algorithm for boosted topologies.
Outperforms DeepAK8 x 2

Resolved topologies



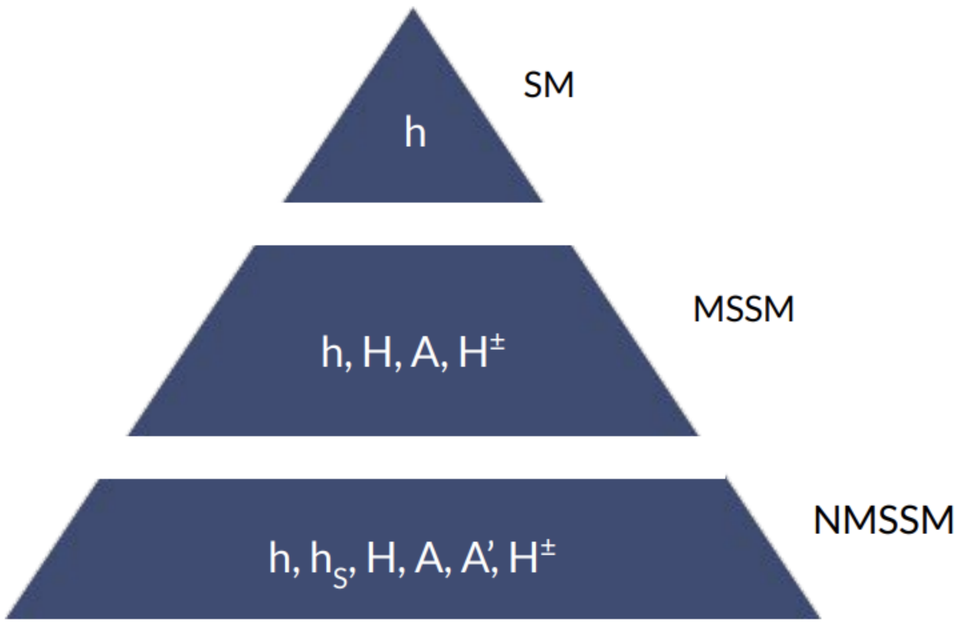
Boosted topologies



Machine learning abundantly applied here!
All algorithms on this slide are based neural networks (NN)

Extended Higgs sectors

- In the Standard Model the Higgs sector is one complex doublet
- SM+ Singlet
  - Minimal extension
  - Mixing with SM doublet=> modified couplings
- Two Higgs doublet model (2HDM)
  - e.g. MSSM
  - Very popular, rich phenomenology
  - Type I, II etc depending on how the doublet interacts with fermions
- 2HDM+Singlet
  - e.g NMSSM
  - Combines benefit from the two above
  - Rich phenomenology, several mixing angles, modified couplings, forbidden decays, multiple scalars

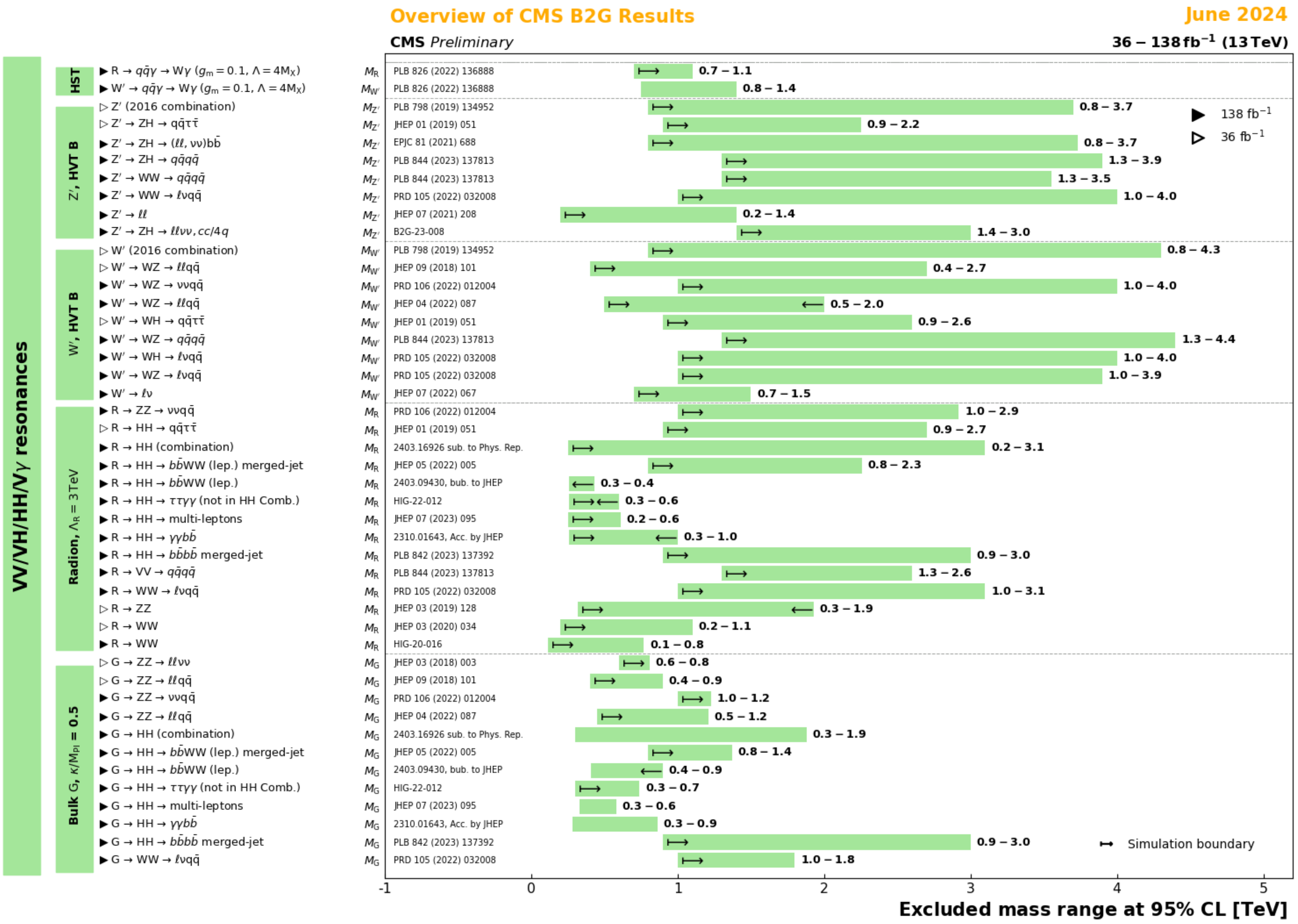


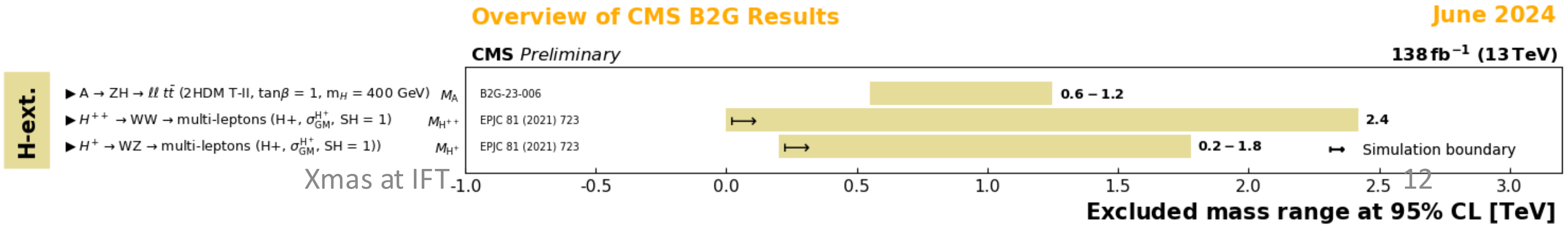
Long list of searches!!

This is not the full list…

I will only talk about select few today, as examples

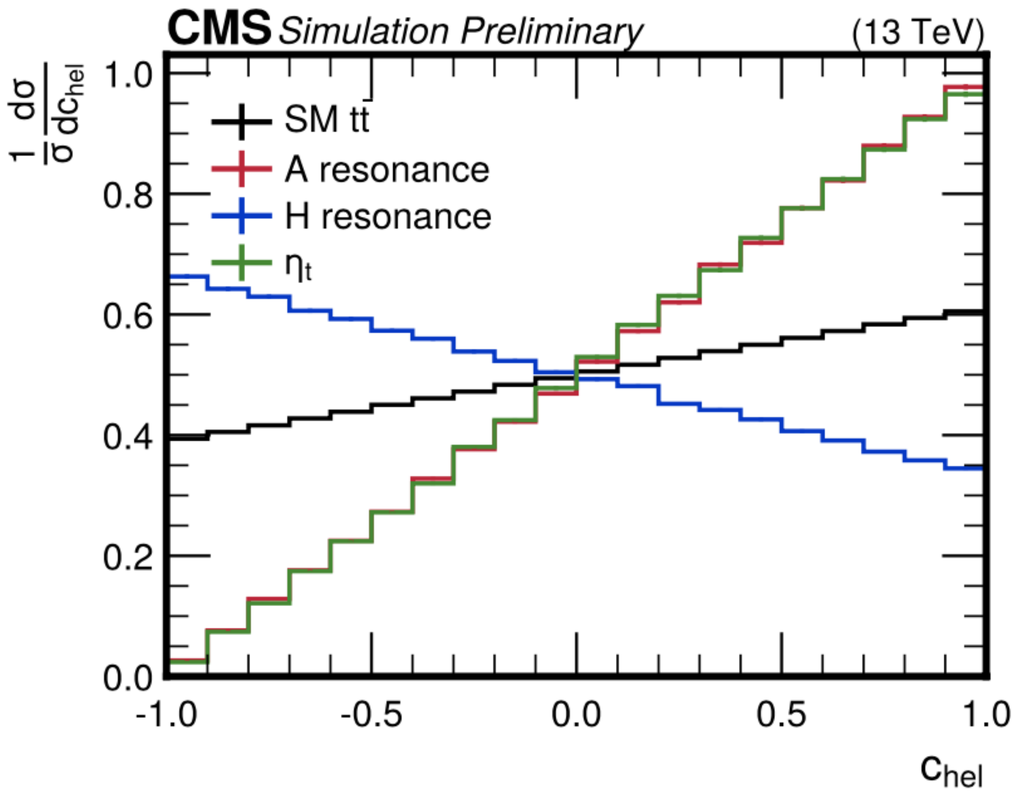
General categories
- Heavy Higgs searches
- Light Higgs searches
- Higgs pair production
- X->VH

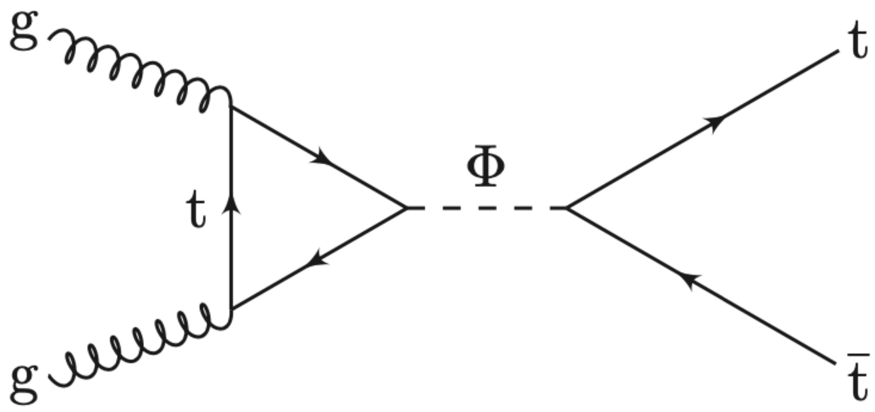


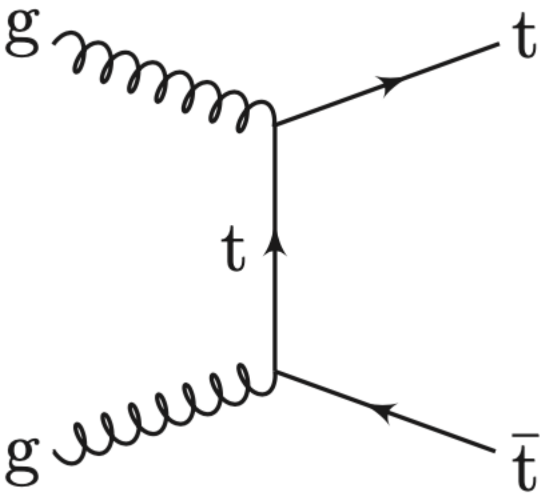


H->tt

- pQCD description of background
- top decay allows to exploit angular observables
  => different tt spin states



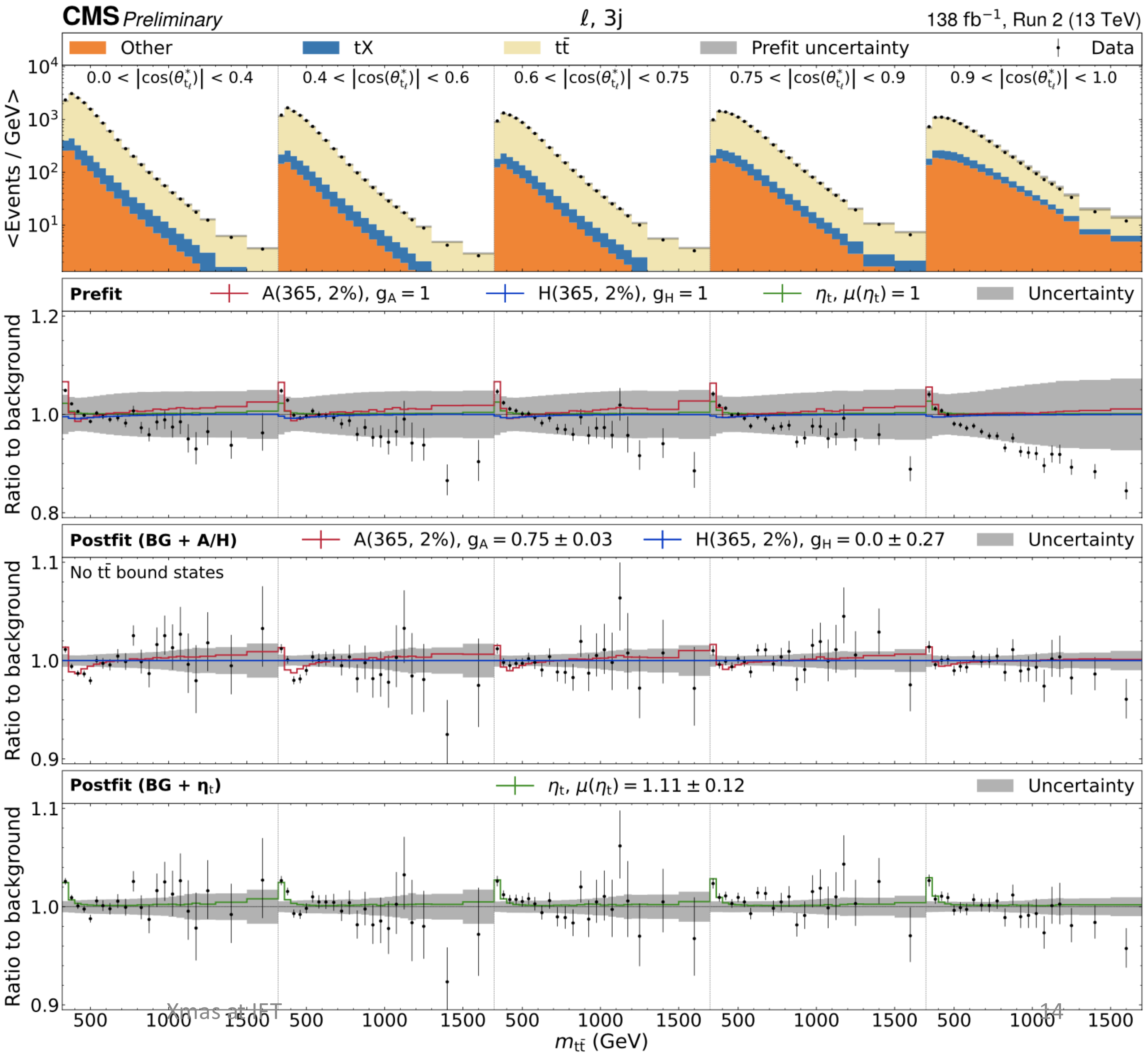




https://cds.cern.ch/record/2911775

H->tt

- Excess of events> 5 sigma with respect to bkg-only
- Pseudoscalar is more compatible than scalar
- Excess compatible with bound state η_t with σ=7.1pb +/-11%



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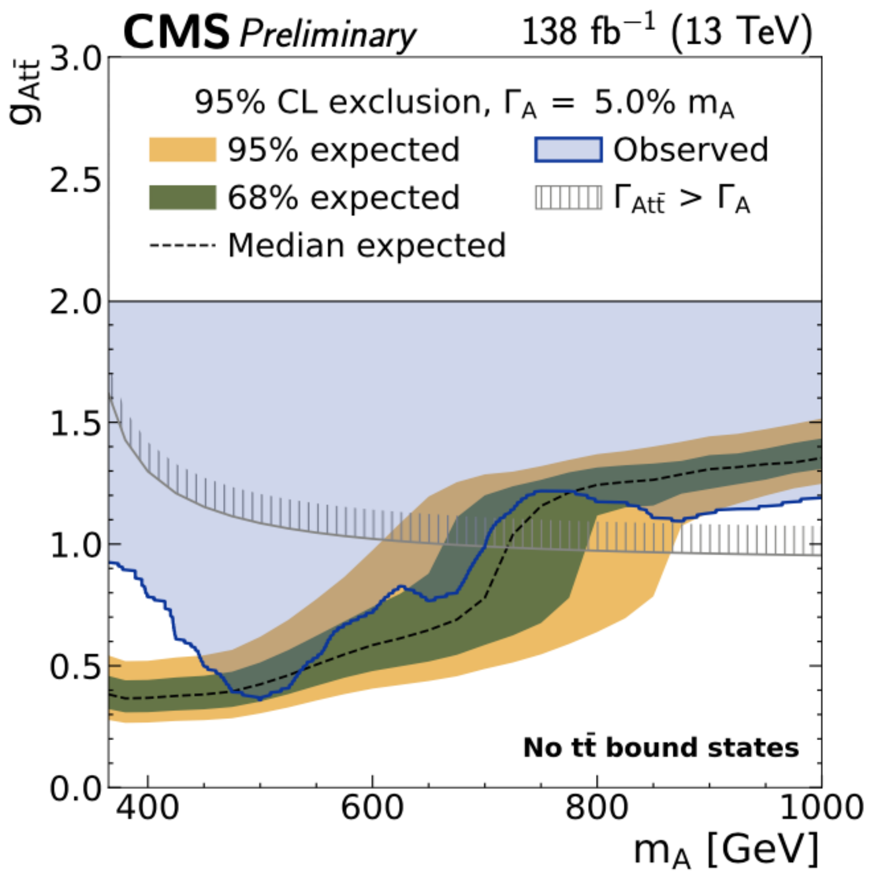
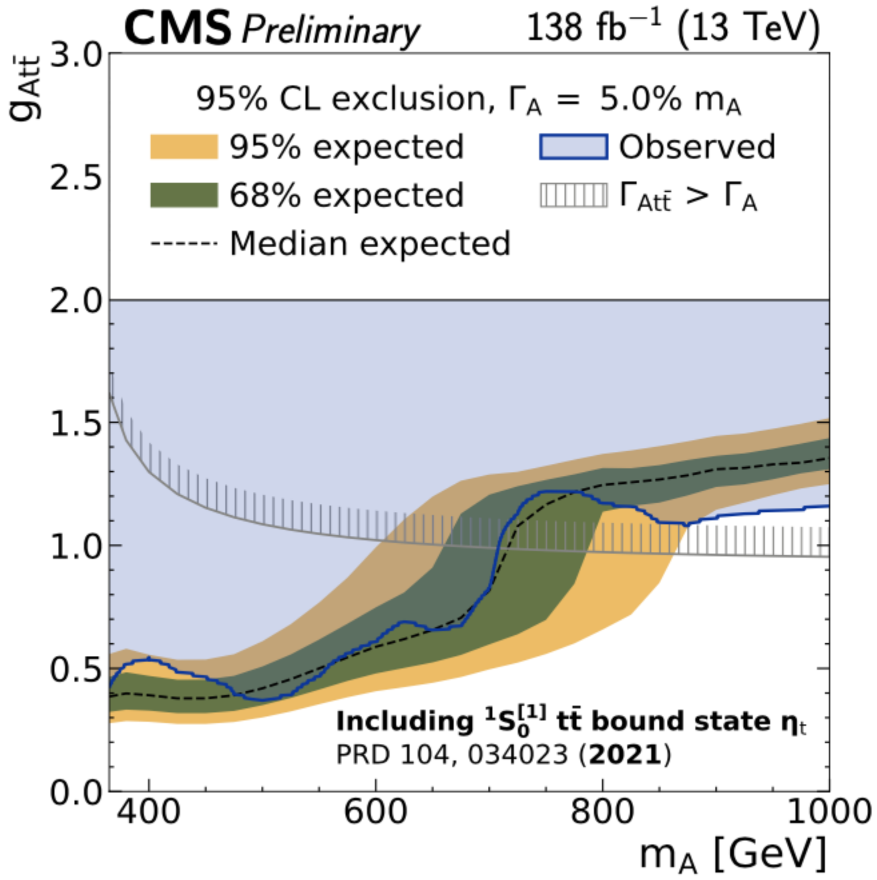
H->tt





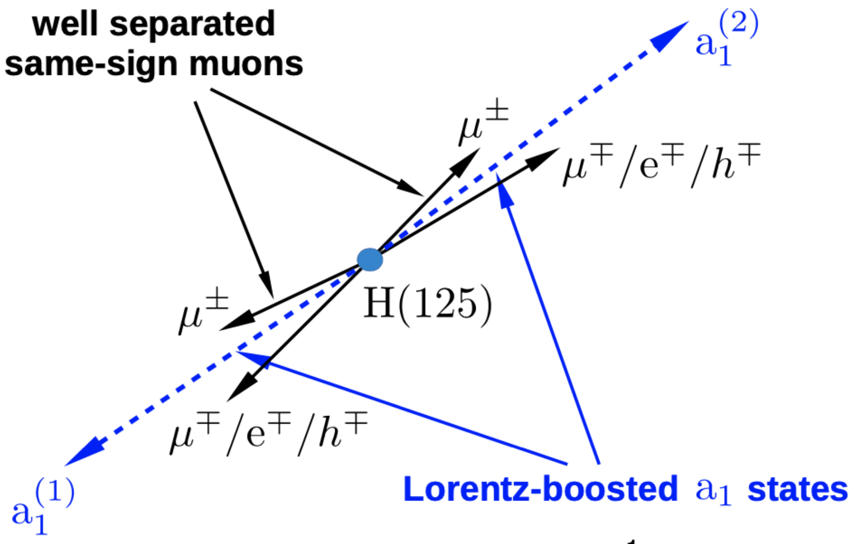
https://cds.cern.ch/record/2911775

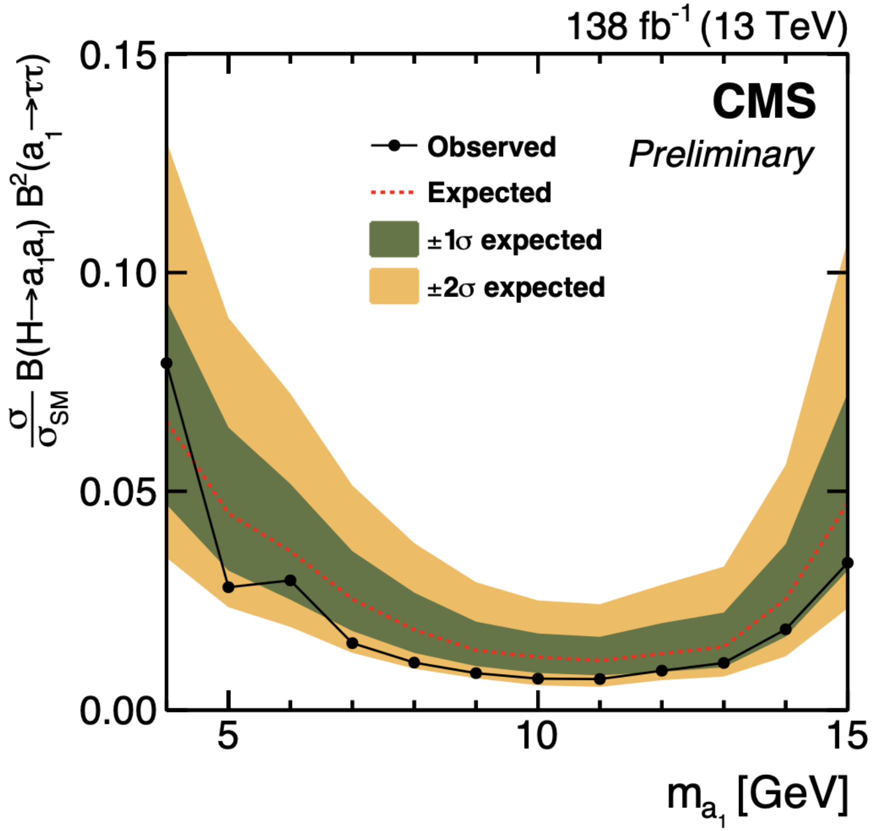
exclusion limits on the coupling of pseudoscalar or scalar bosons to top quarks
Φ mass 365−1000 GeV, width 0.5−25%

H->aa->4τ/2τ+2μ

- a from 4 to 15 GeV
- specialized analysis strategy to identify highly Lorentz-boosted muon or tau lepton pairs with overlapping decay products
- Both 4τ and 2τ+2μ combined to extract limits relative to BR a->4τ
  a BR to fermions linear with m_a
- Various 2HDM+S models examined

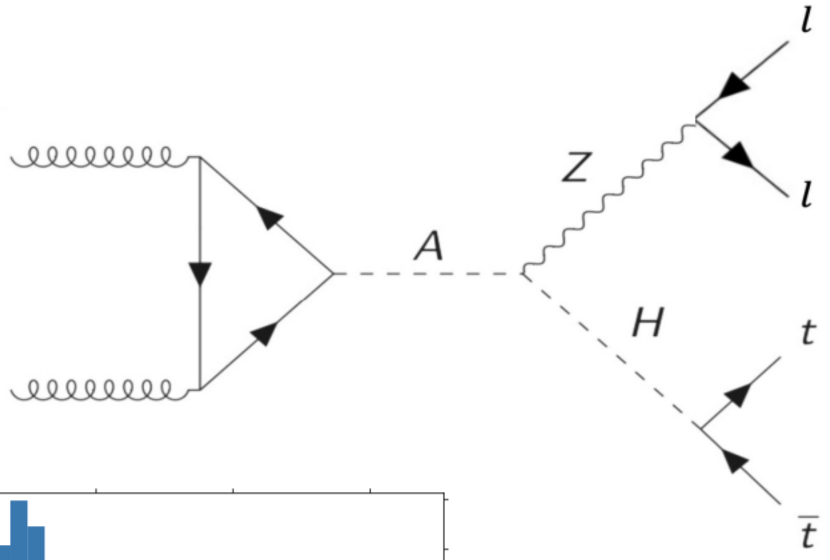
https://cds.cern.ch/record/2911497

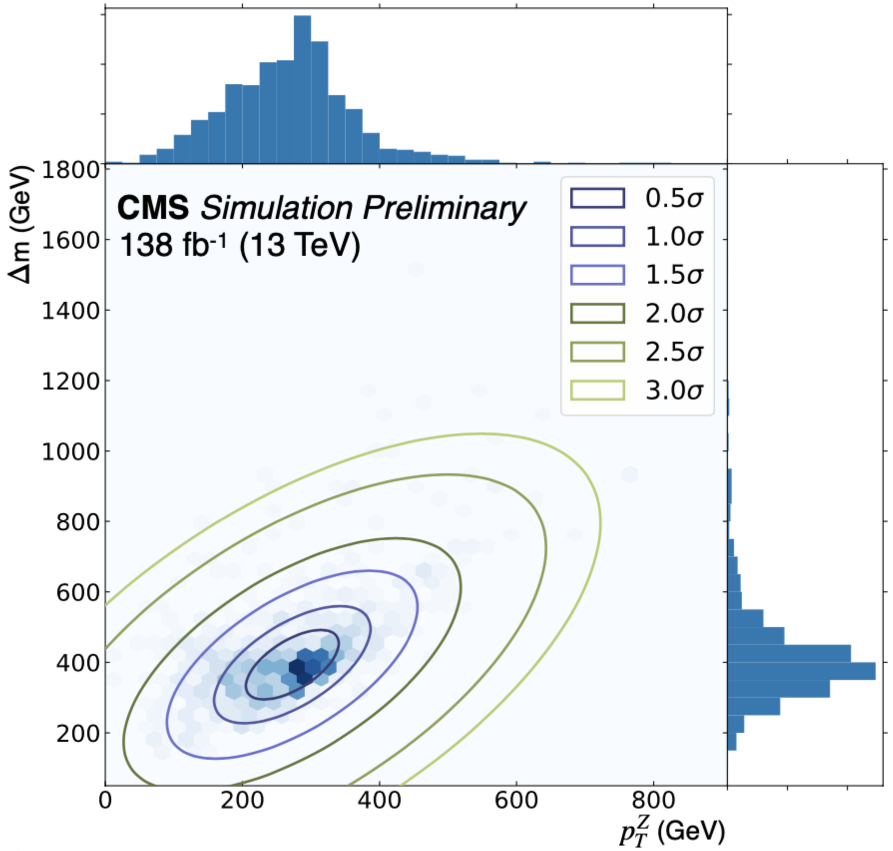




A->ZH->lltt

- mA > mH + mZ,
  - the decay A →ZH dominant in a wide range of the 2HDM
- mH> 400 GeV
  - the decay H →tt dominant
- ATLAS excess
  - (mA, mH) = (650, 450) GeV with a local significance of 2.85 SD

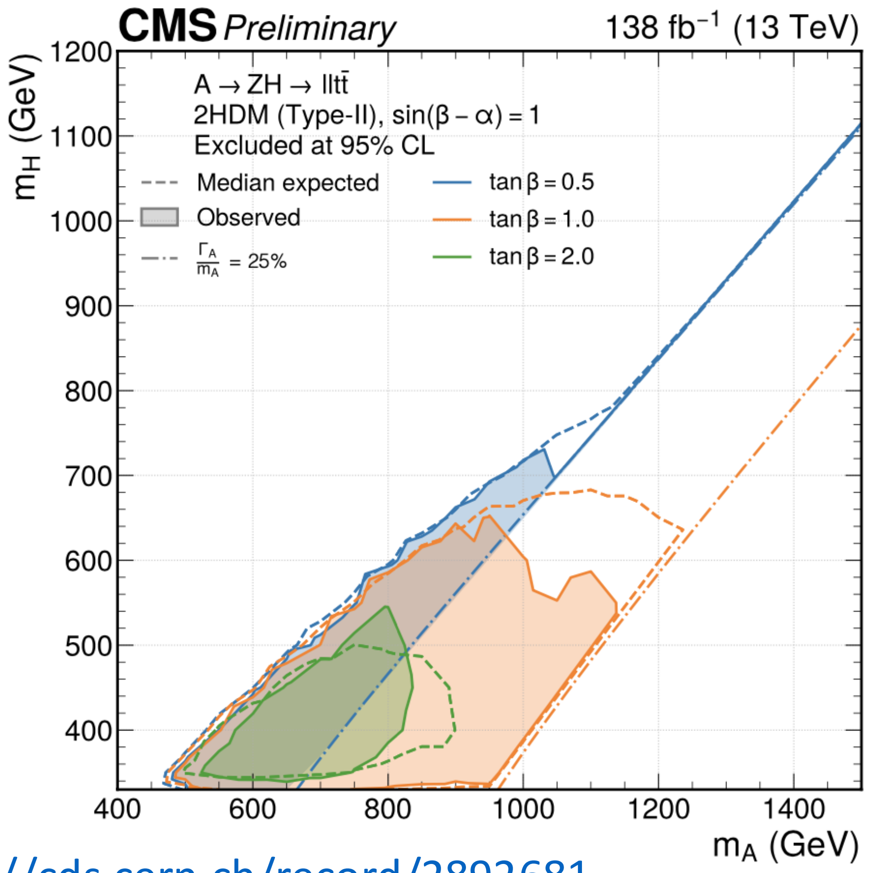


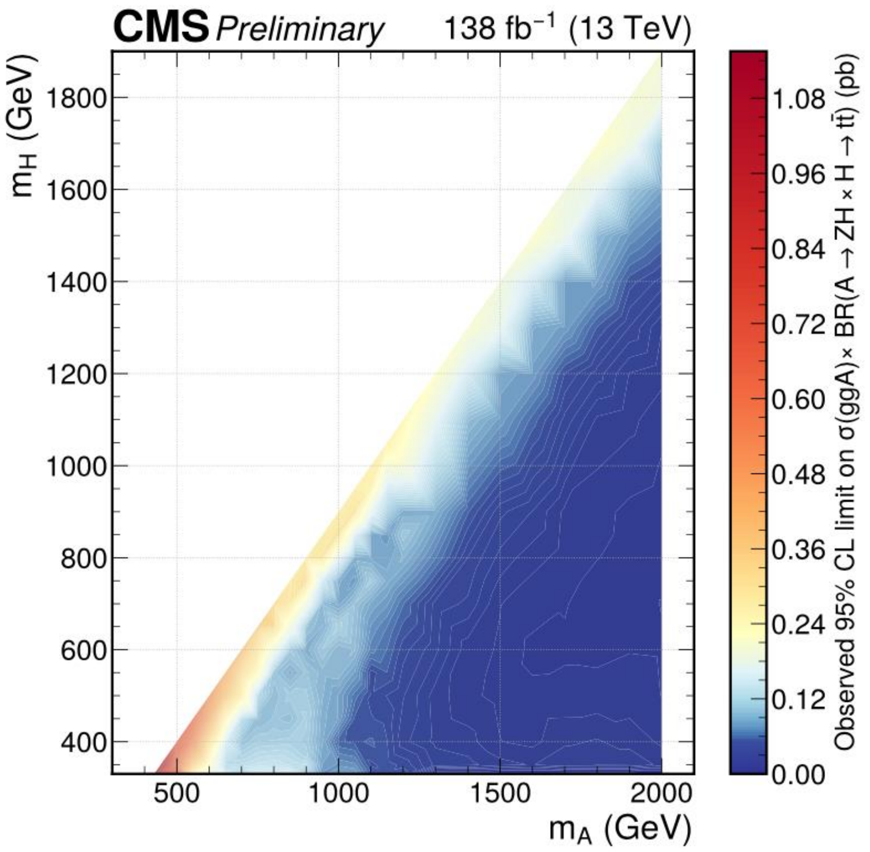


https://cds.cern.ch/record/2892681

A->ZH->lltt

Does not confirm the excess seen by ATLAS
2HDM interpretations





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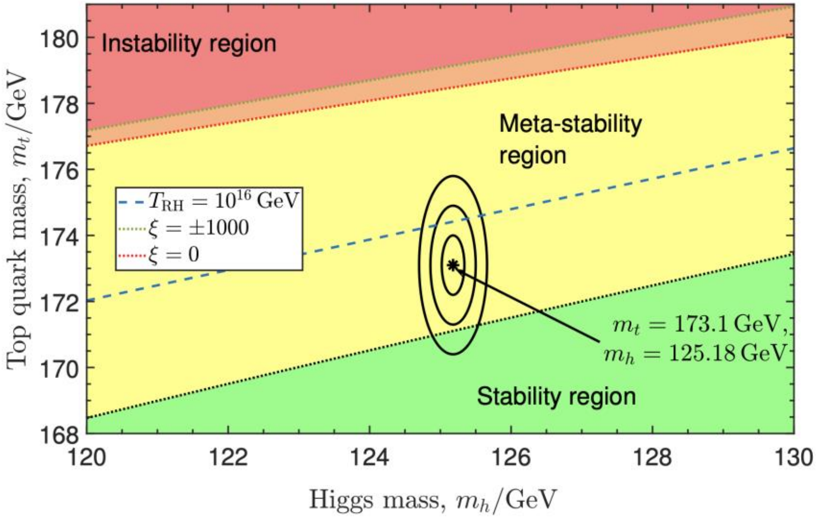
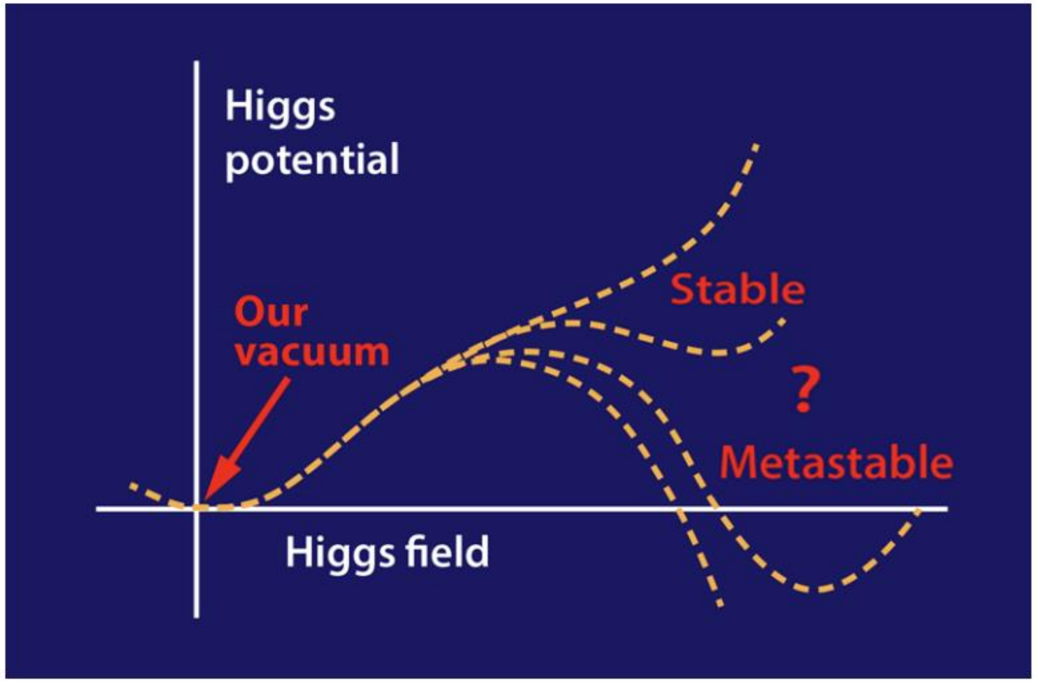
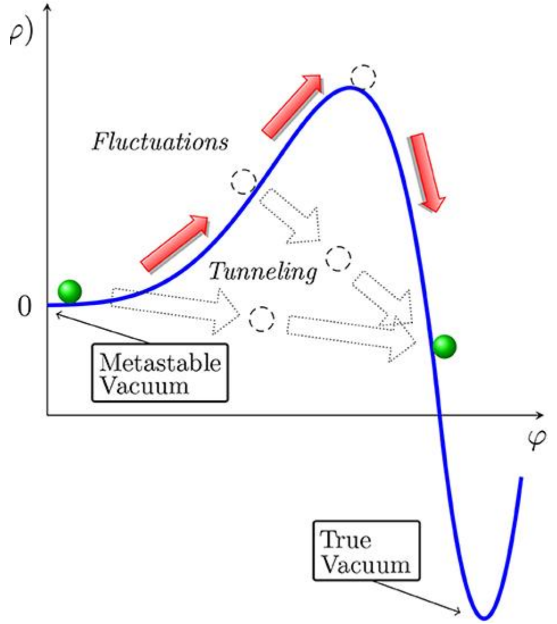
The Higgs potential



- The least explored part of the Standard Model!
- The Higgs sector is sensitive to new physics BSM
- Cosmological consequences:
  - Inflation
  - Vacuum stability
  - Baryogenesis
  - …?

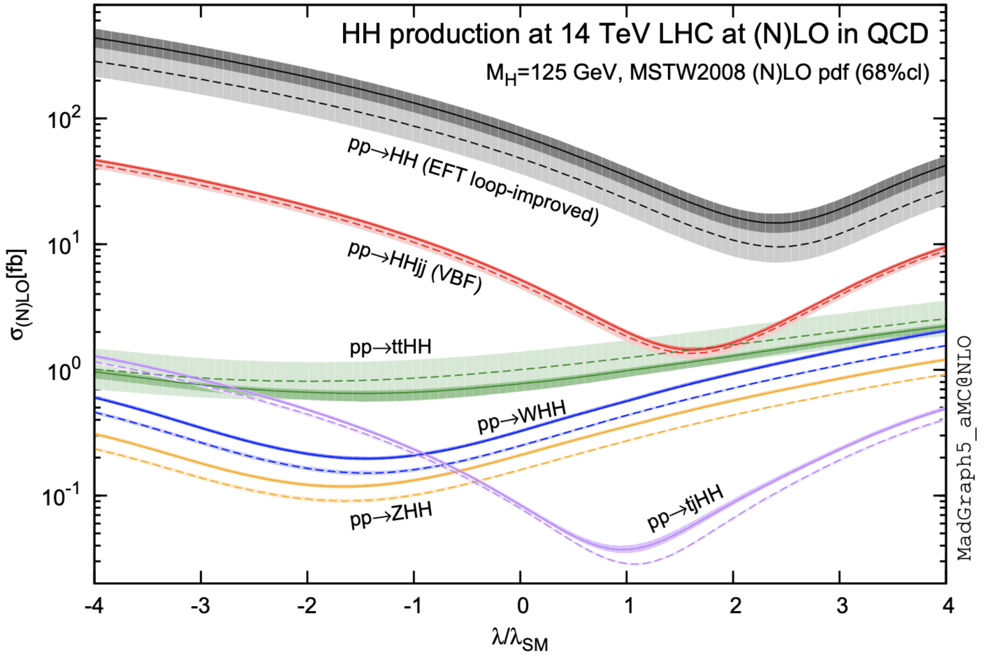


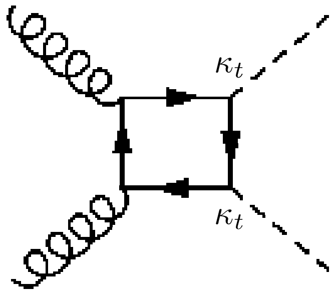


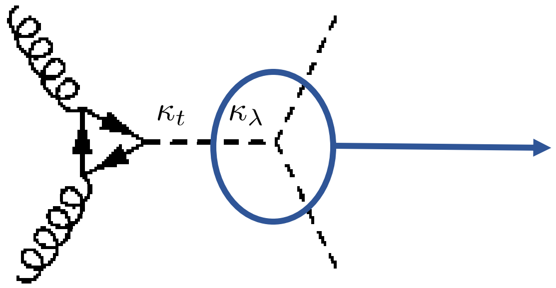
"If the Universe was infinitely old, even an arbitrarily low vacuum decay rate would be incompatible with our existence." https://doi.org/10.3389/fspas.2018.00040

Double Higgs production at the LHC (SM)

- At the LHC dominant production mechanism for SM double Higgs production is gluon fusion (ggf)
- Other productions such as VBF and VHH also possible; σ is much smaller
- The “box” and “triangle” diagrams interact destructively
- SM cross-section very small !!
  (~1000 times smaller than single Higgs production)

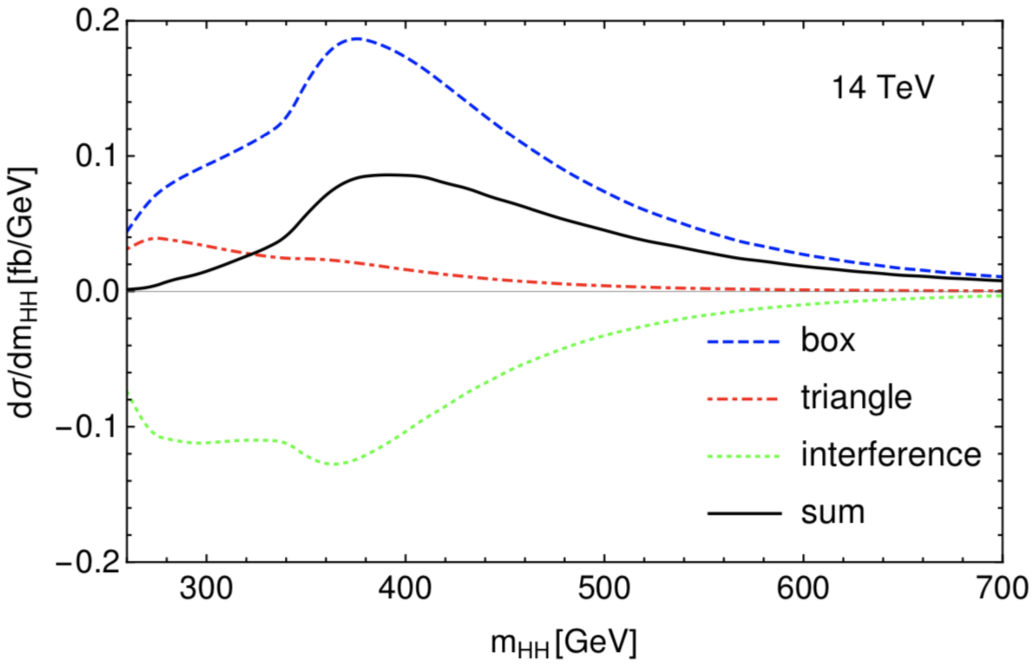


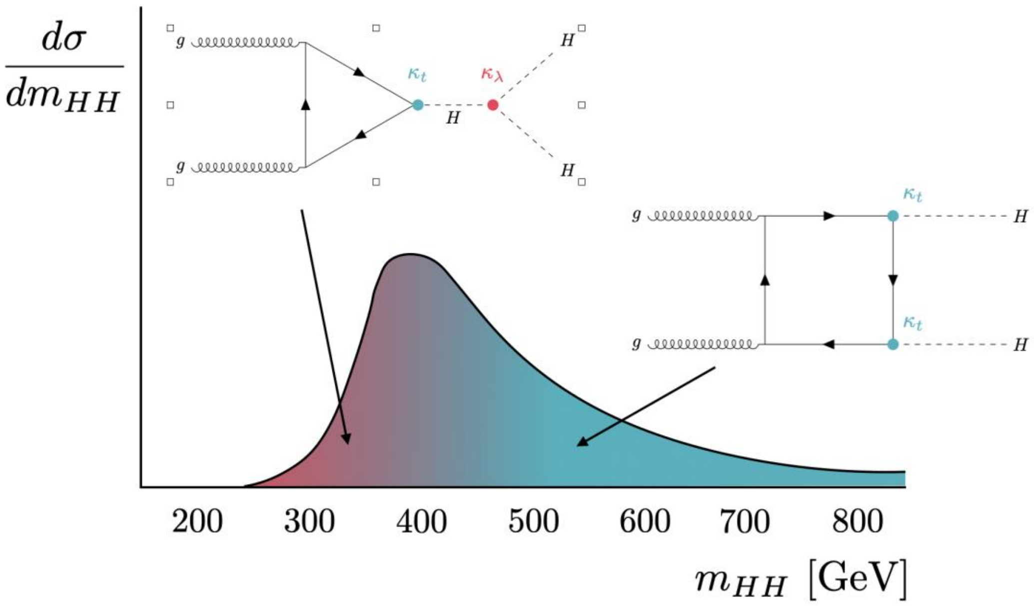




Higgs trilinear coupling

Double Higgs production at the LHC (SM)



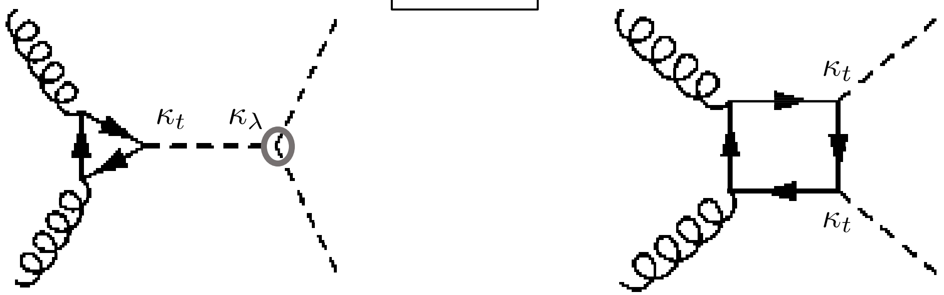


Graphic by Katherine Leney

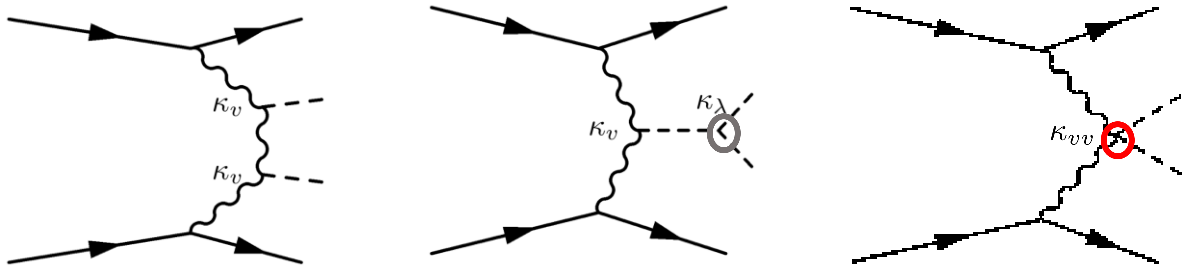
Higgs trilinear coupling

Higgs pair production

ggF

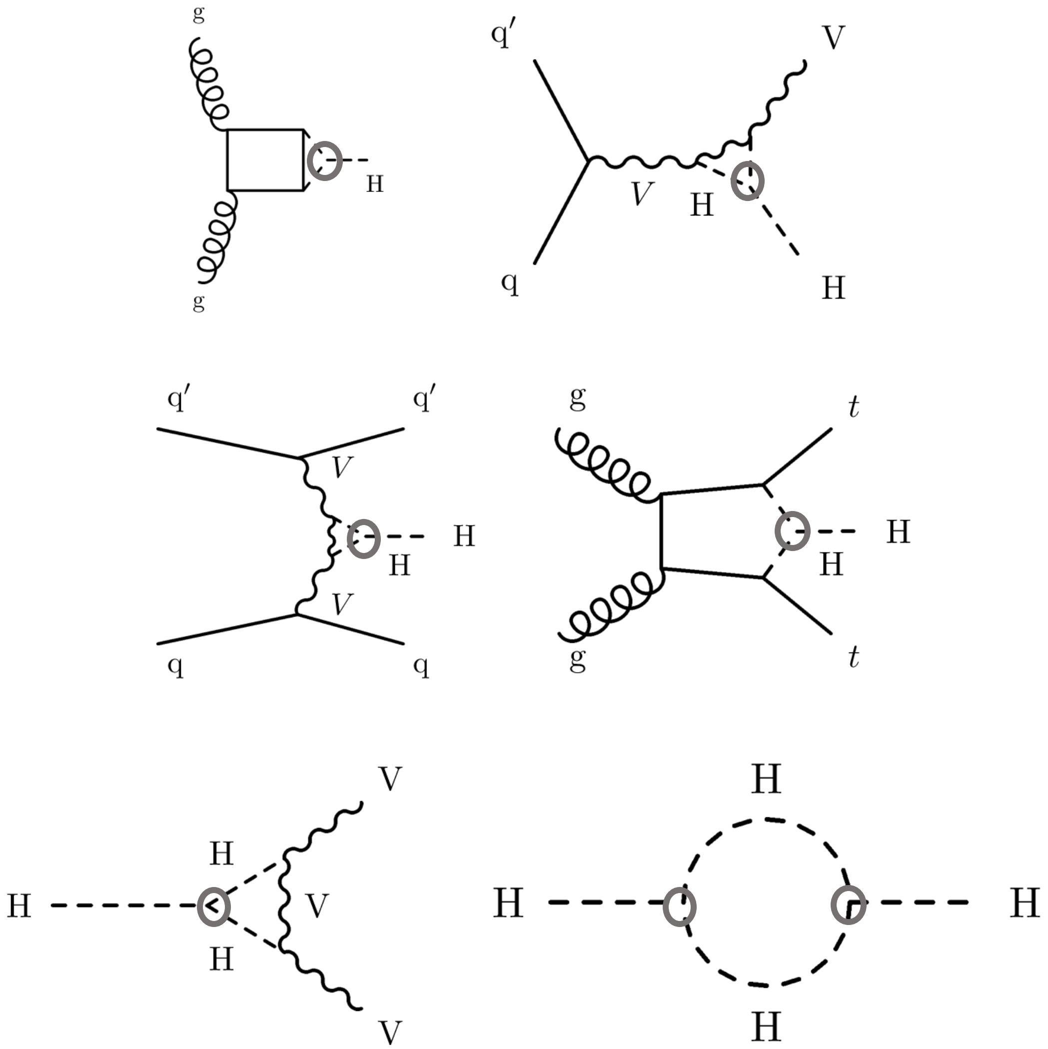


VBF



Sensitivity to κ_λ via single Higgs production

NLO corrections in H->VV decay and Higgs boson propagator

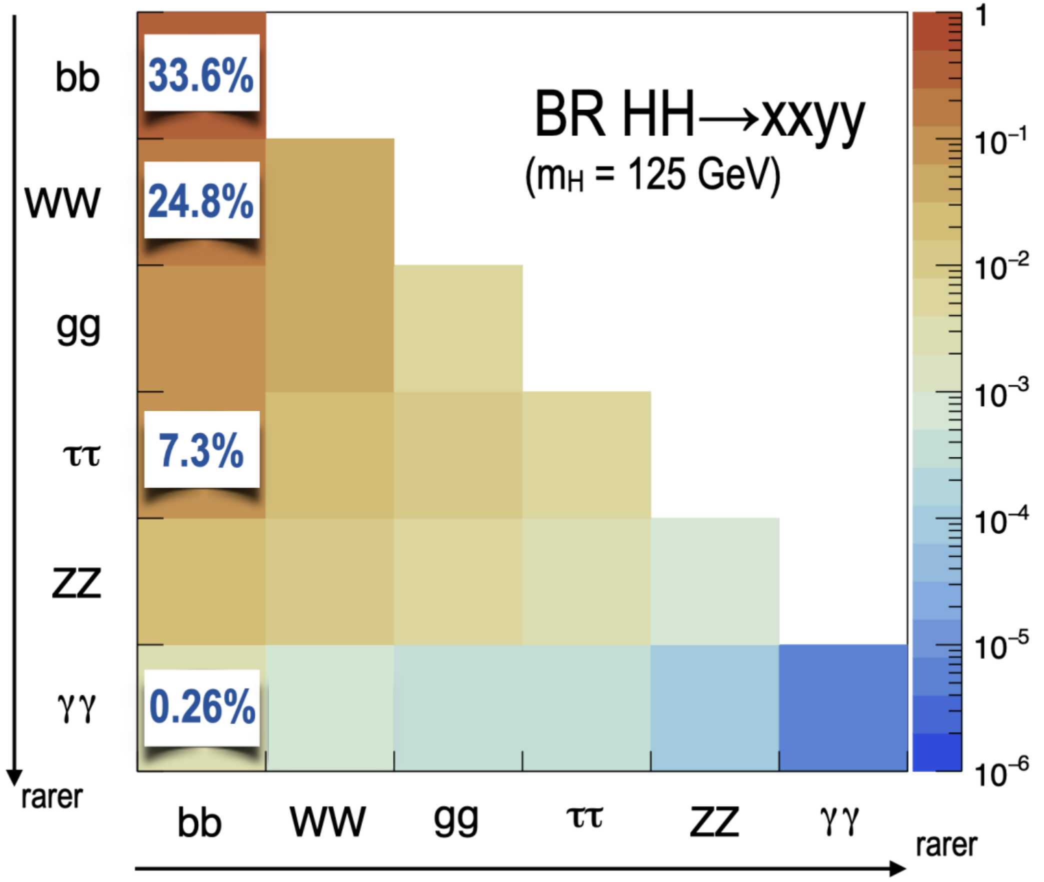


HH decays:

bbbb:
the highest branching fraction, large multijet background

bbWW(bbVV):
Second largest branching fraction
Large background. Final states with at least one lepton cleaner.

Multilepton(WW*WW*, WW*ττ, and ττττ):
Many different signatures, clean leptonic final states, no b-tagging needed



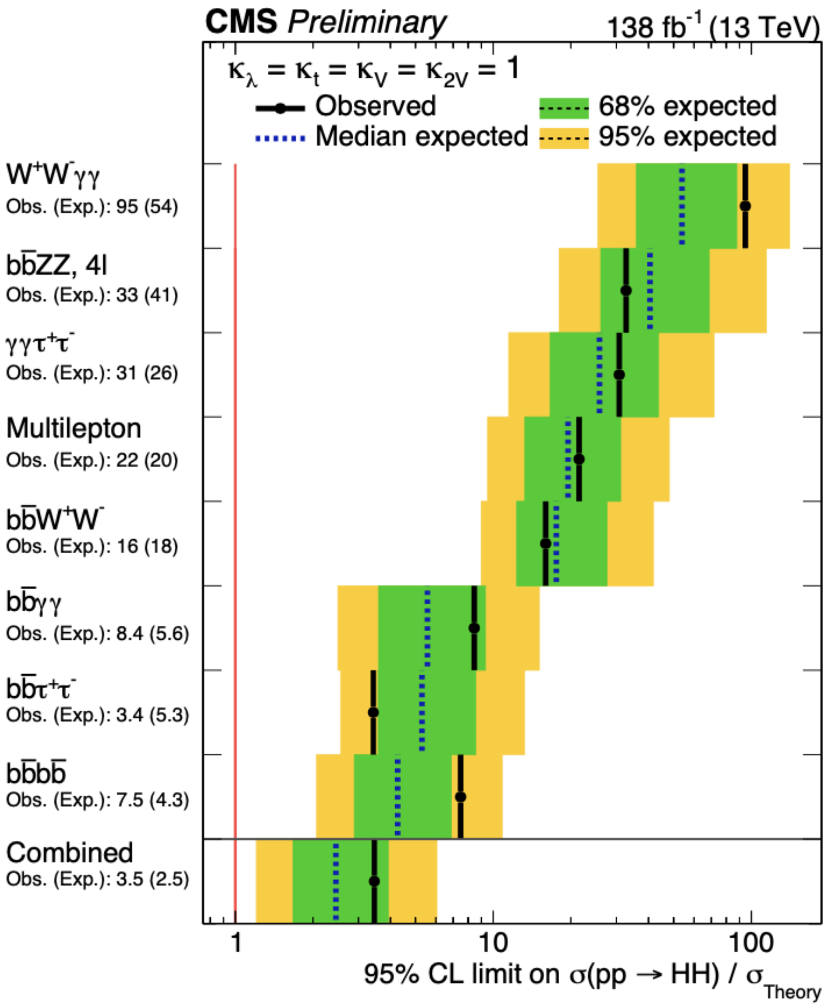
bbττ:
relatively large branching fraction, cleaner final state

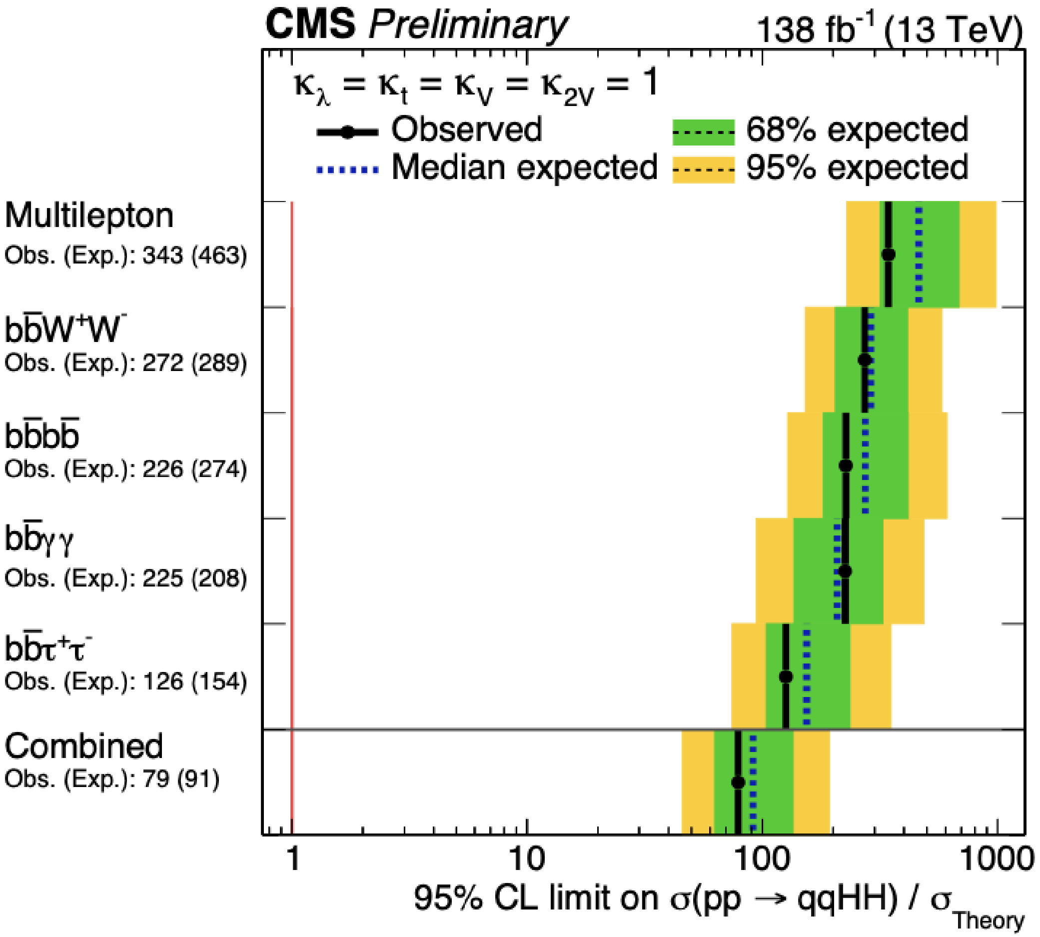
bbγγ:
very small branching fraction, clean signal extraction due to the narrow h → γγ mass peak

WWγγ:
Clean γγ peak, leptonic final states or jets

ττγγ:
best of ττ and γγ. Small BR

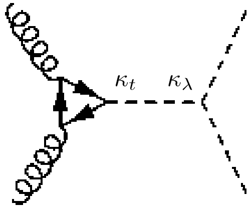
Higgs pair production cross-section

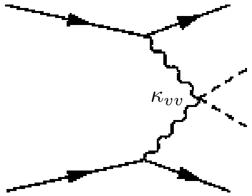


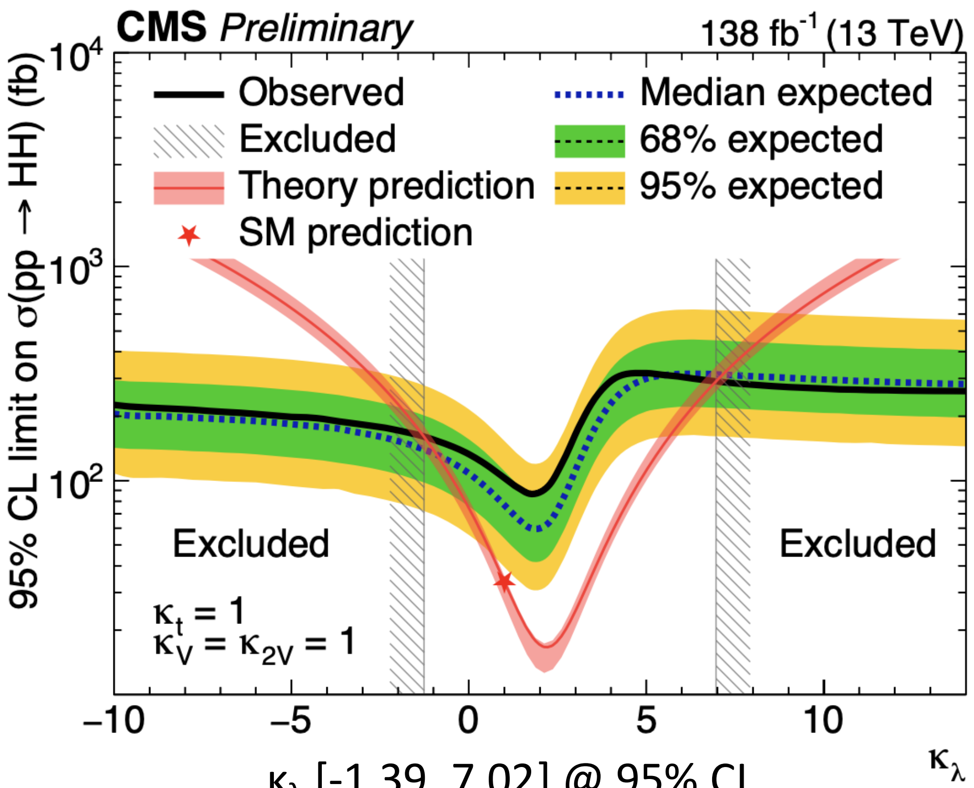


HIG-20-011

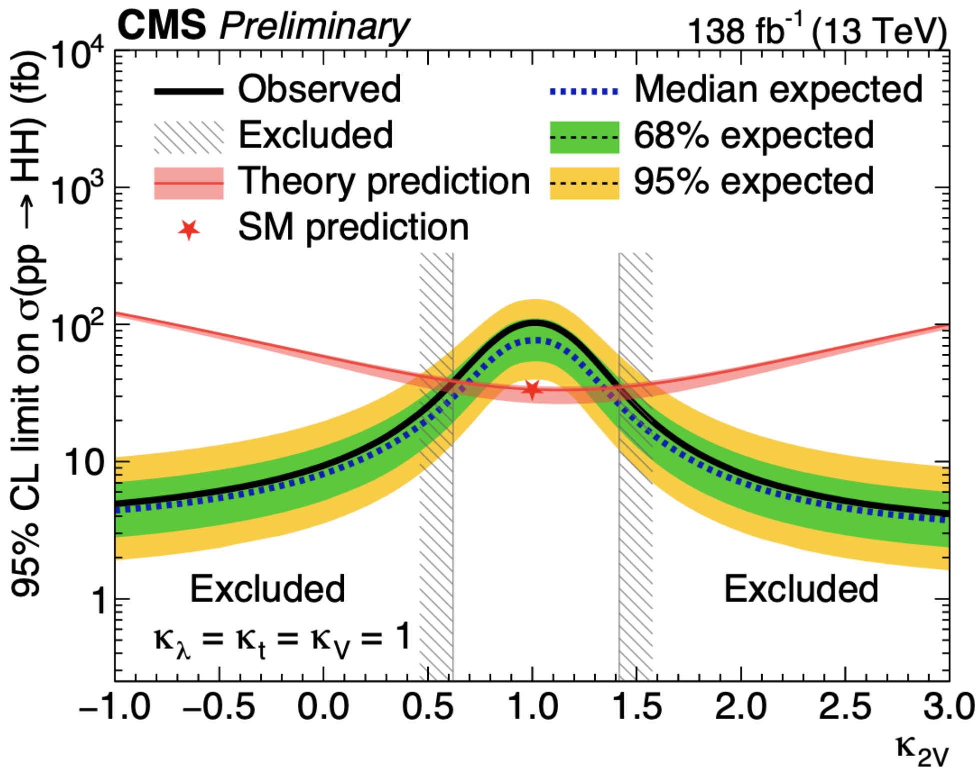
Constraints of Higgs couplings from HH







κ_λ [-1.39, 7.02] @ 95% CL

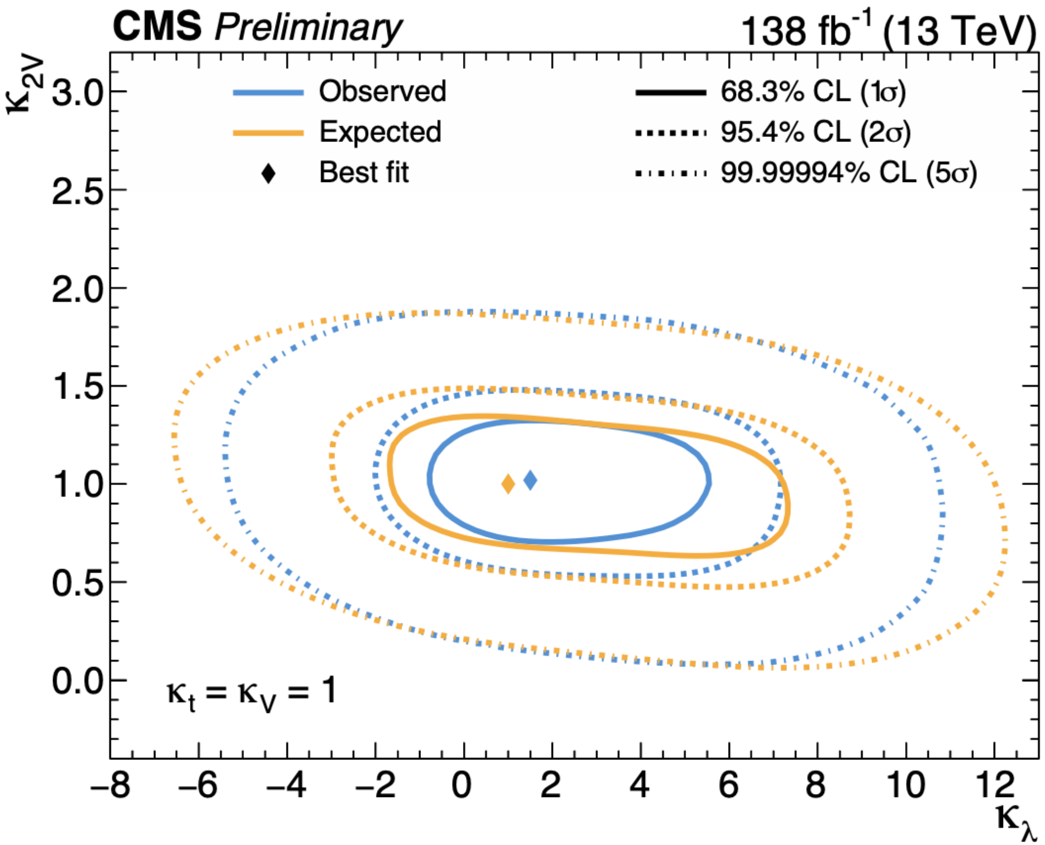


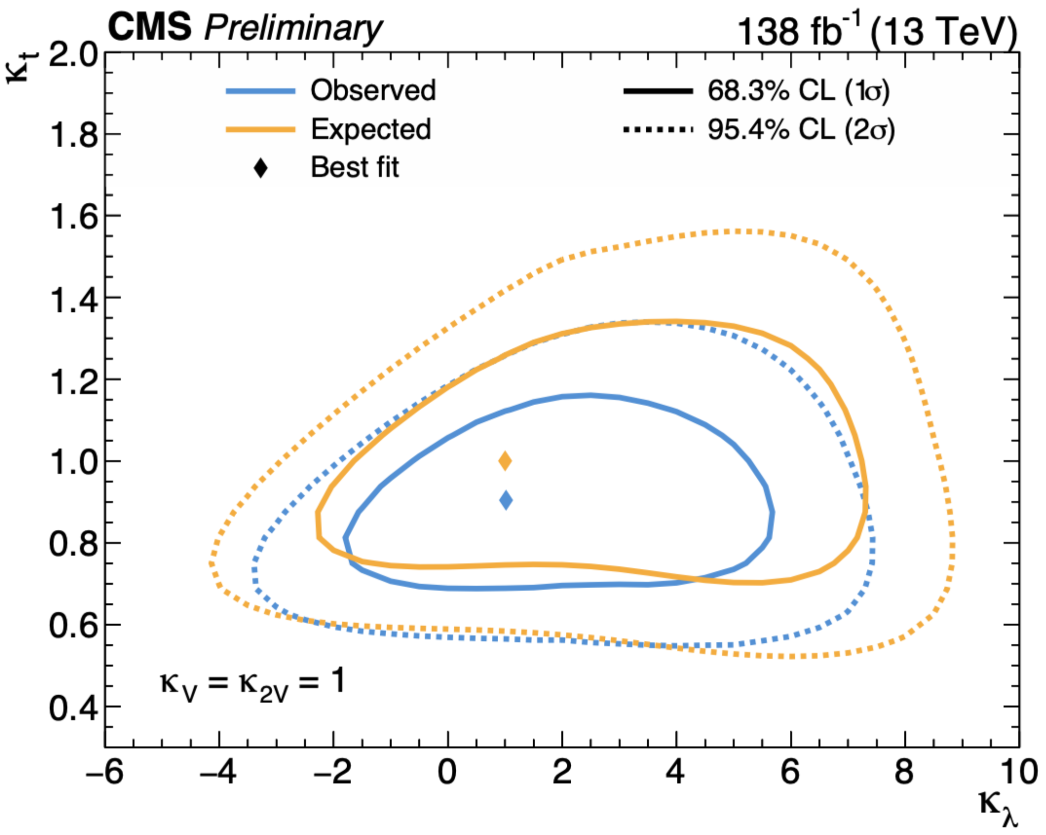
κ_{2v} [0.62, 1.42] @95% CL

Assuming κt=κv=1, κvv=0 is excluded at a CL higher than 99.99%.

HIG-20-011

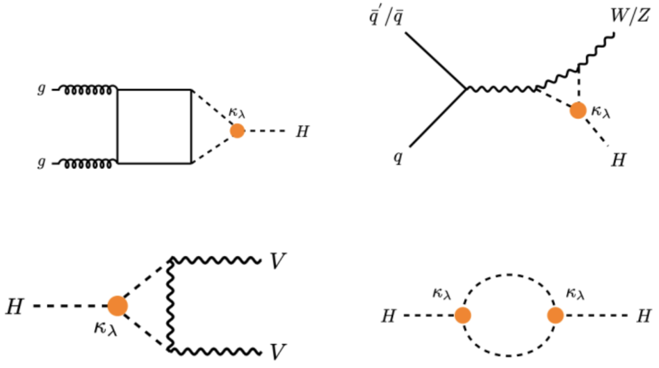
Higgs trilinear coupling





[HIG-20-011]

Single and double Higgs searches



Simultaneously constrain

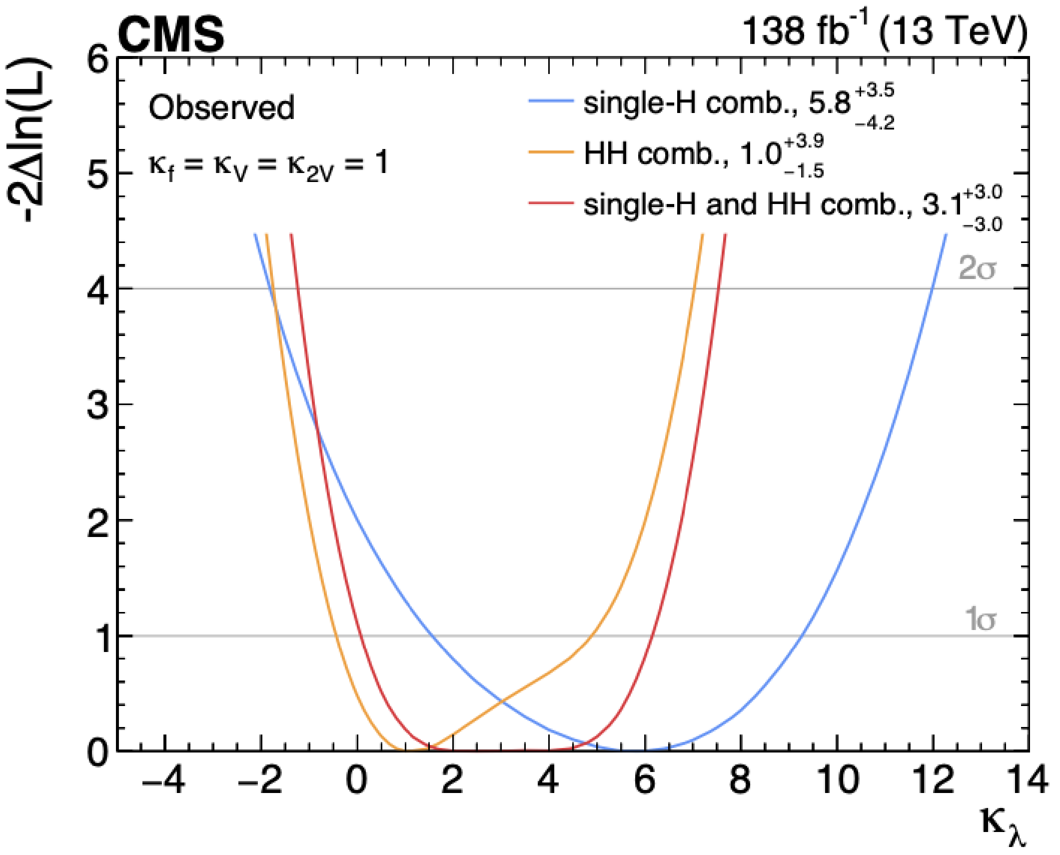
- Higgs boson trilinear self-coupling
- Higgs boson couplings to fermions and to vector bosons.

Analysis	Integrated luminosity (fb^{-1})	Maximum granularity	References
$H \to 4l$	138	STXS 1.2	[34]
$H \to \gamma\gamma$	138	STXS 1.2	[35,none]
$H \to WW$	138	STXS 1.2	[37]
$H \to$ leptons ($t\bar{t}H$)	138	Inclusive	[38]
$H \to b\bar{b}$ (ggH)	138	Inclusive	[39]
$H \to b\bar{b}$ (VH)	77	Inclusive	[40,41]
$H \to b\bar{b}$ ($t\bar{t}H$)	36	Inclusive	[42]
$H \to \tau\tau$	138	STXS 1.2	[43]
$H \to \mu\mu$	138	Inclusive	[44]

Analysis	Int. luminosity (fb^{-1})	Targeted production modes
$HH \to \gamma\gamma b\bar{b}$	138	ggHH and qqHH
$HH \to \tau\tau b\bar{b}$	138	ggHH and qqHH
$HH \to 4b$	138	ggHH, qqHH and VHH
$HH \to$ leptons	138	ggHH
$HH \to WWb\bar{b}$	138	ggHH and qqHH

https://arxiv.org/abs/2407.13554

Single and double Higgs searches



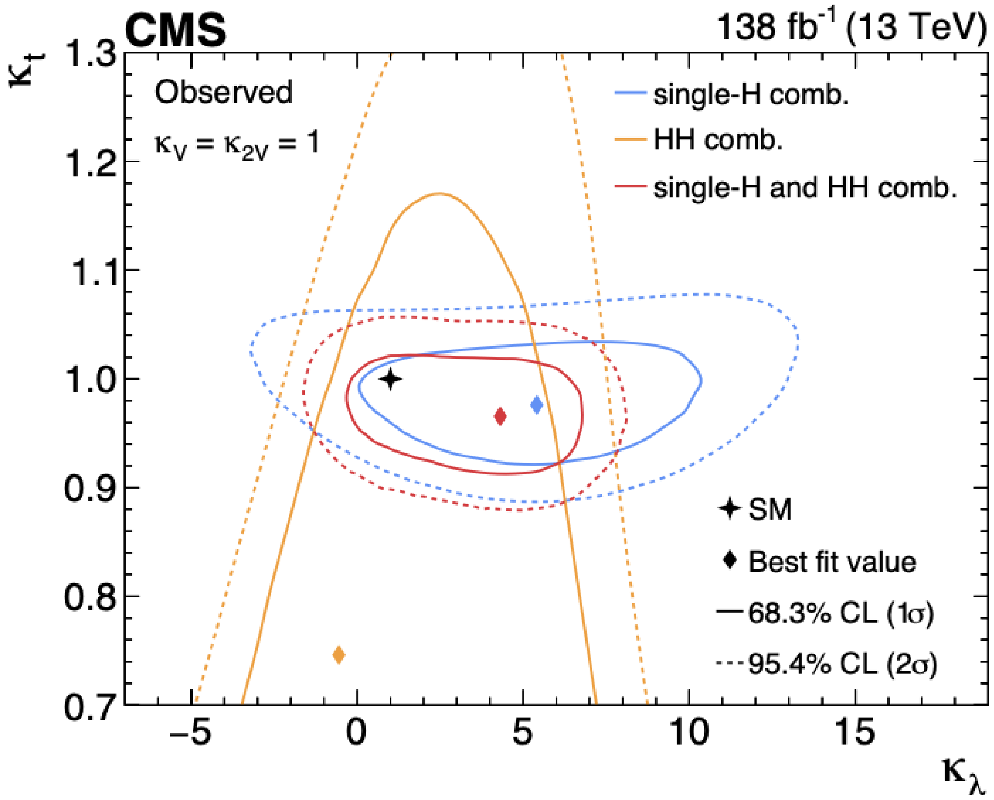
CMS

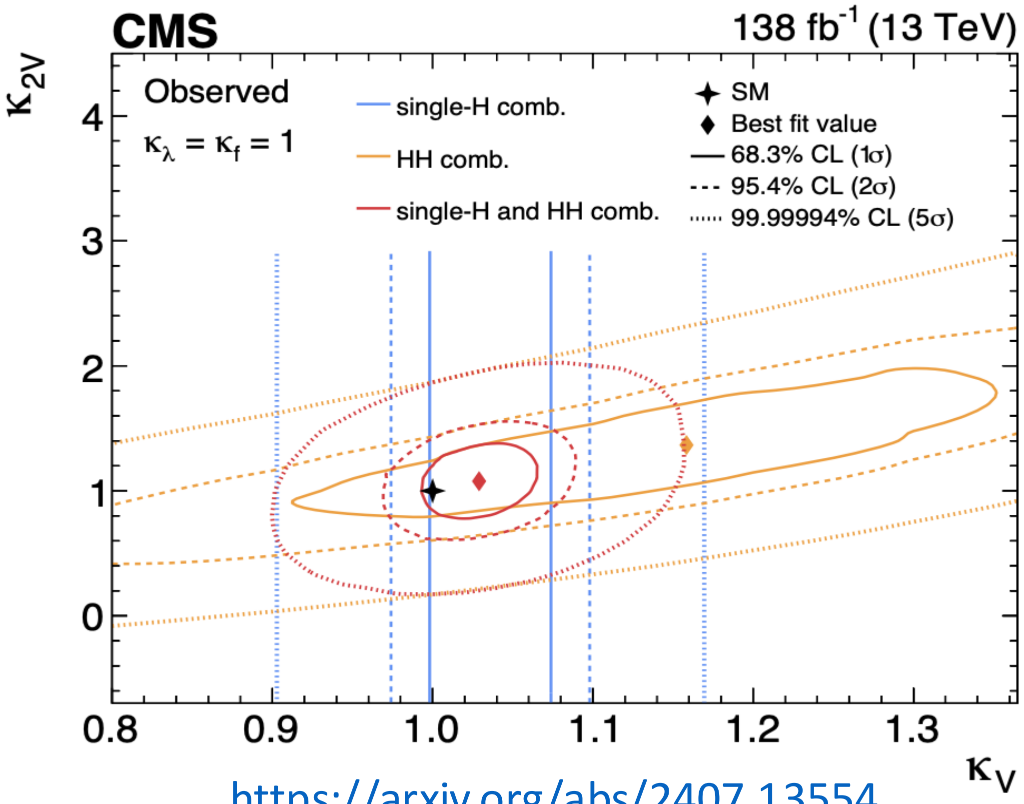
Hypothesis	Best fit ±1σ Expected	Best fit ±1σ Observed	95% CL interval Expected	95% CL interval Observed
Other couplings fixed to SM	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$	[−2.0, +7.7]	[−1.2, +7.5]
Floating ($\kappa_V, \kappa_{2V}, \kappa_f$)	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$	[−2.2, +7.8]	[−1.7, +7.7]
Floating ($\kappa_V, \kappa_t, \kappa_b, \kappa_\tau$)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$	[−2.3, +7.7]	[−1.4, +7.8]
Floating ($\kappa_V, \kappa_{2V}, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$	[−2.3, +7.8]	[−1.4, +7.8]

- Single H prefers positive κλ
- Allowing other coupling to float doesn't affect the constraints a lot. We can measure κλ without assumptions!

https://arxiv.org/abs/2407.13554

Single and double Higgs searches



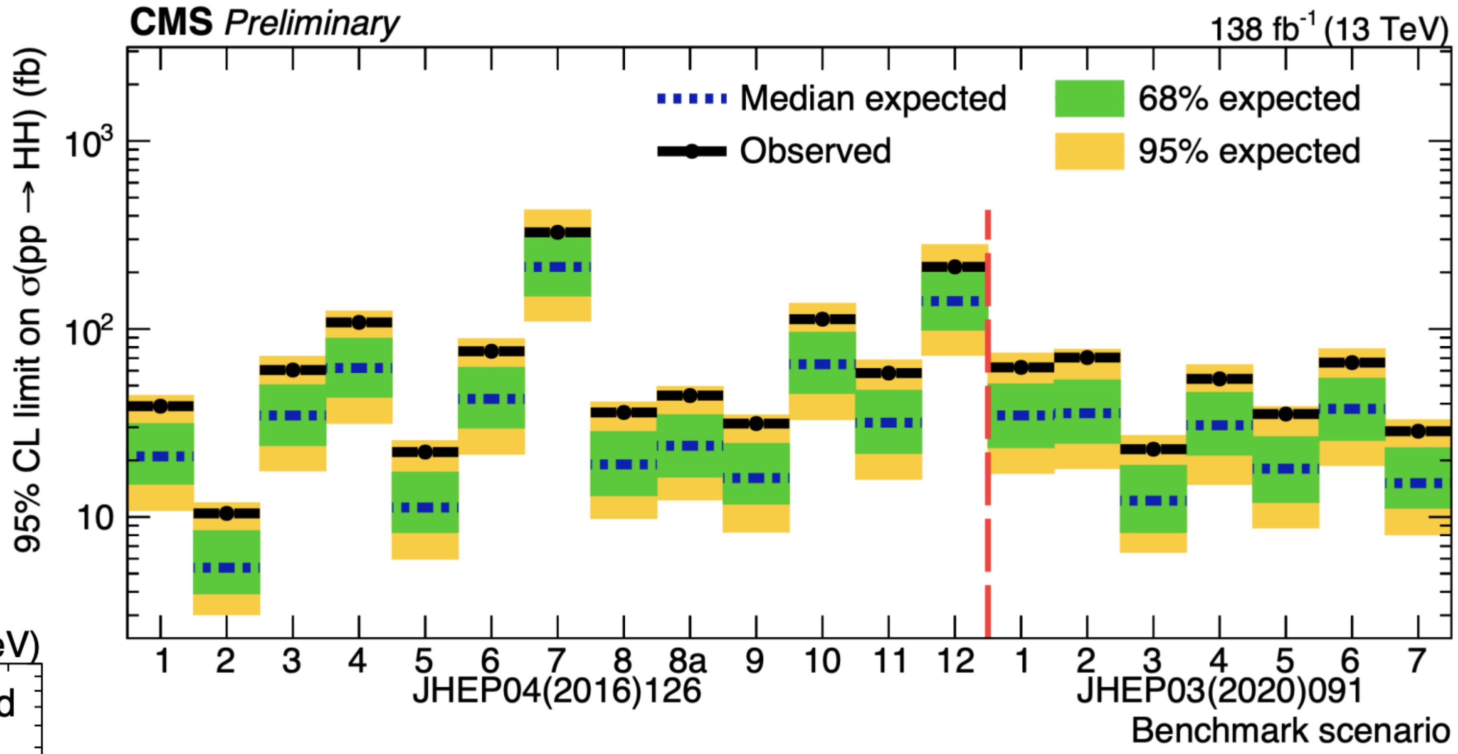


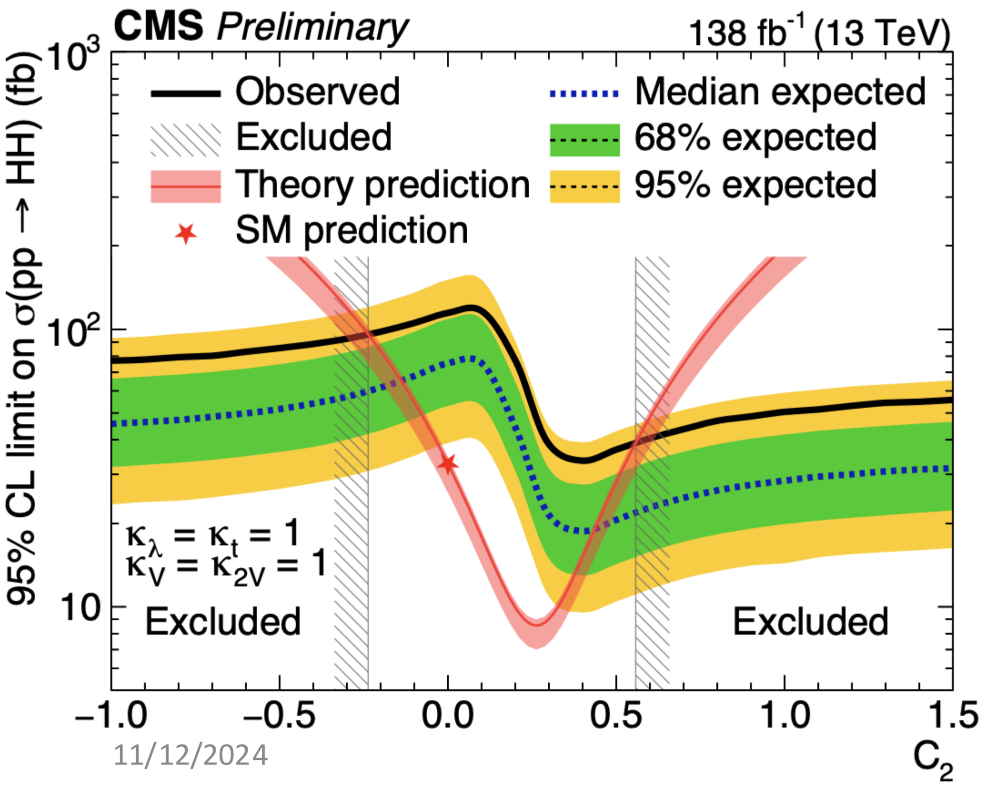
https://arxiv.org/abs/2407.13554

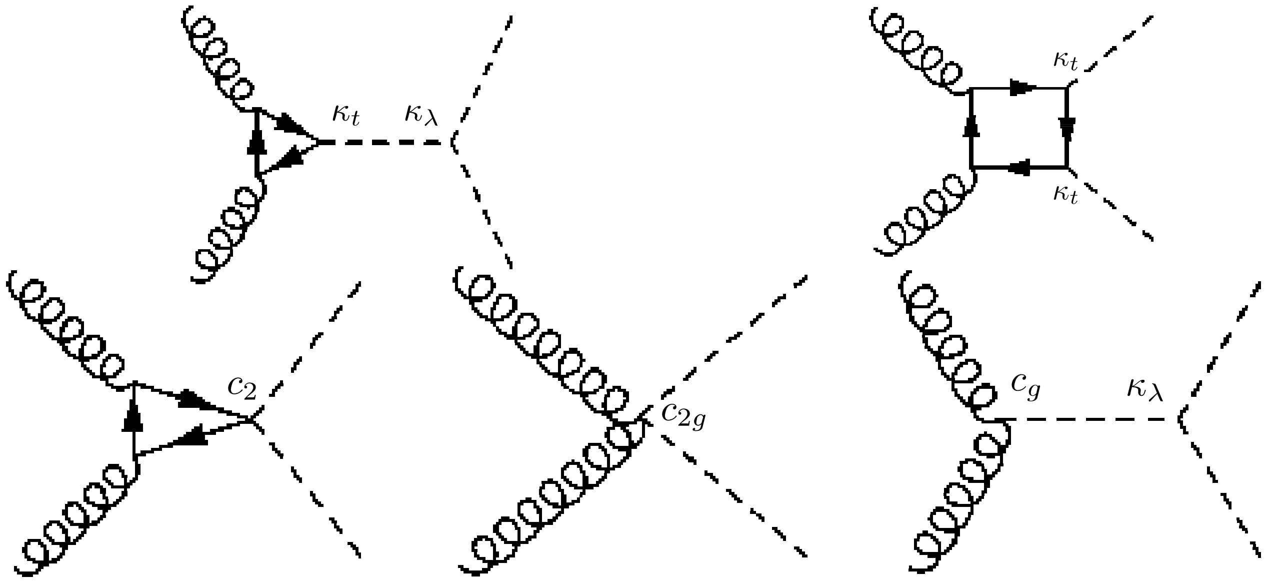
- Adding the H constraints on κt and κv bring enormous improvement to 2D countours!

HH anomalous couplings [HIG-20-011]

- HEFT parametrisation
- Benchmarks combinations of the coupling modifiers (κ_λ , κ_t , c_2 , c_g , c_{2g})

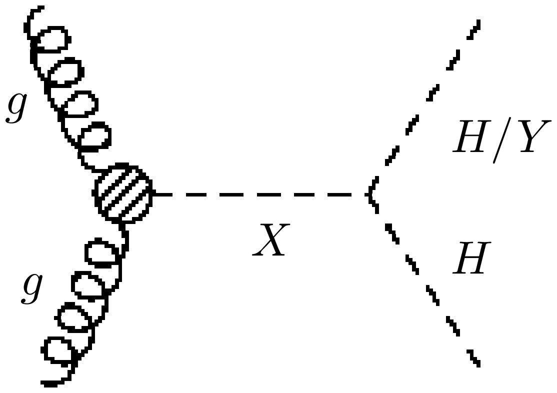


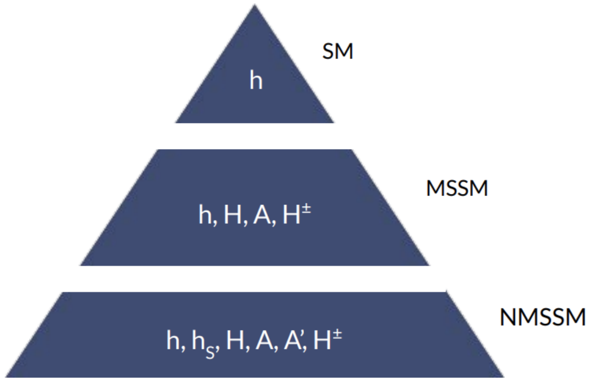


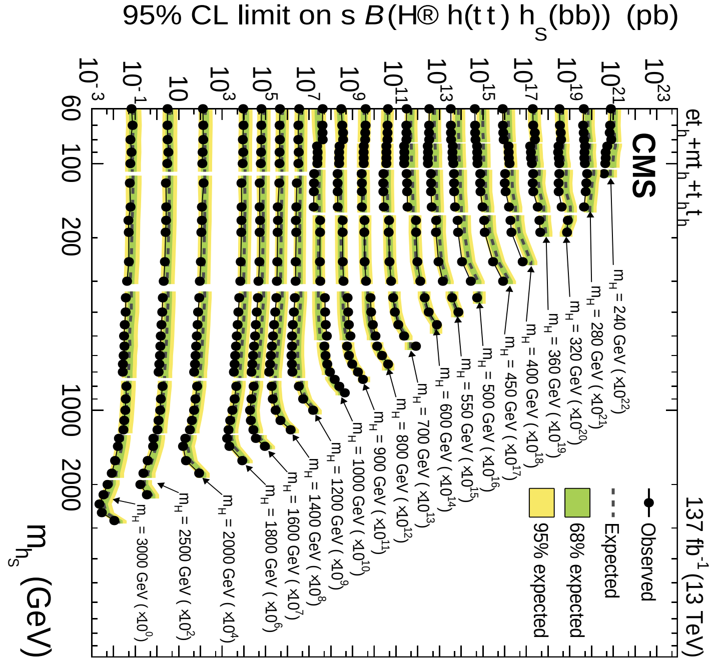


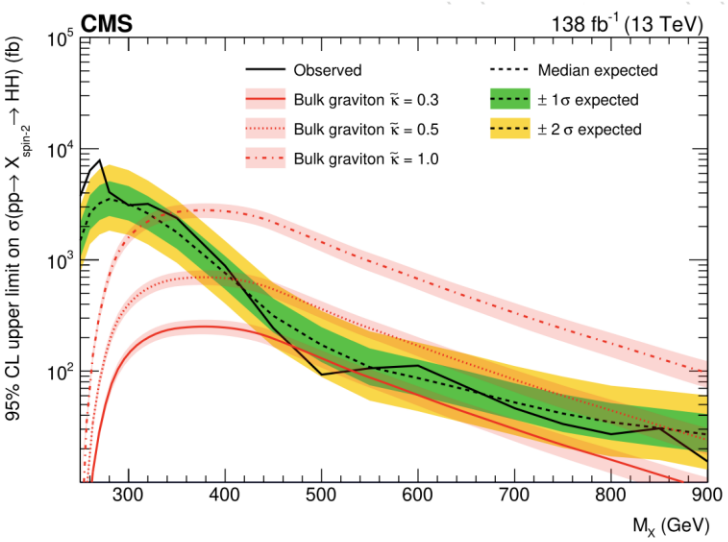
HH/YH searches in CMS

- Searches for heavy resonances
  - X→HH
  - X →YH
- In Run 2 only narrow width (~10%) resonances with:
  - spin 0
    such as a radion, or heavy Higgs in models with extended Higgs sector, e.g. 2HDM
  - spin 2
    such as a KK graviton in Randal-Sundrum model
  - Some model dependent interpretations
- Mass range:
  250 GeV to 4500 GeV
- No interference effects considered









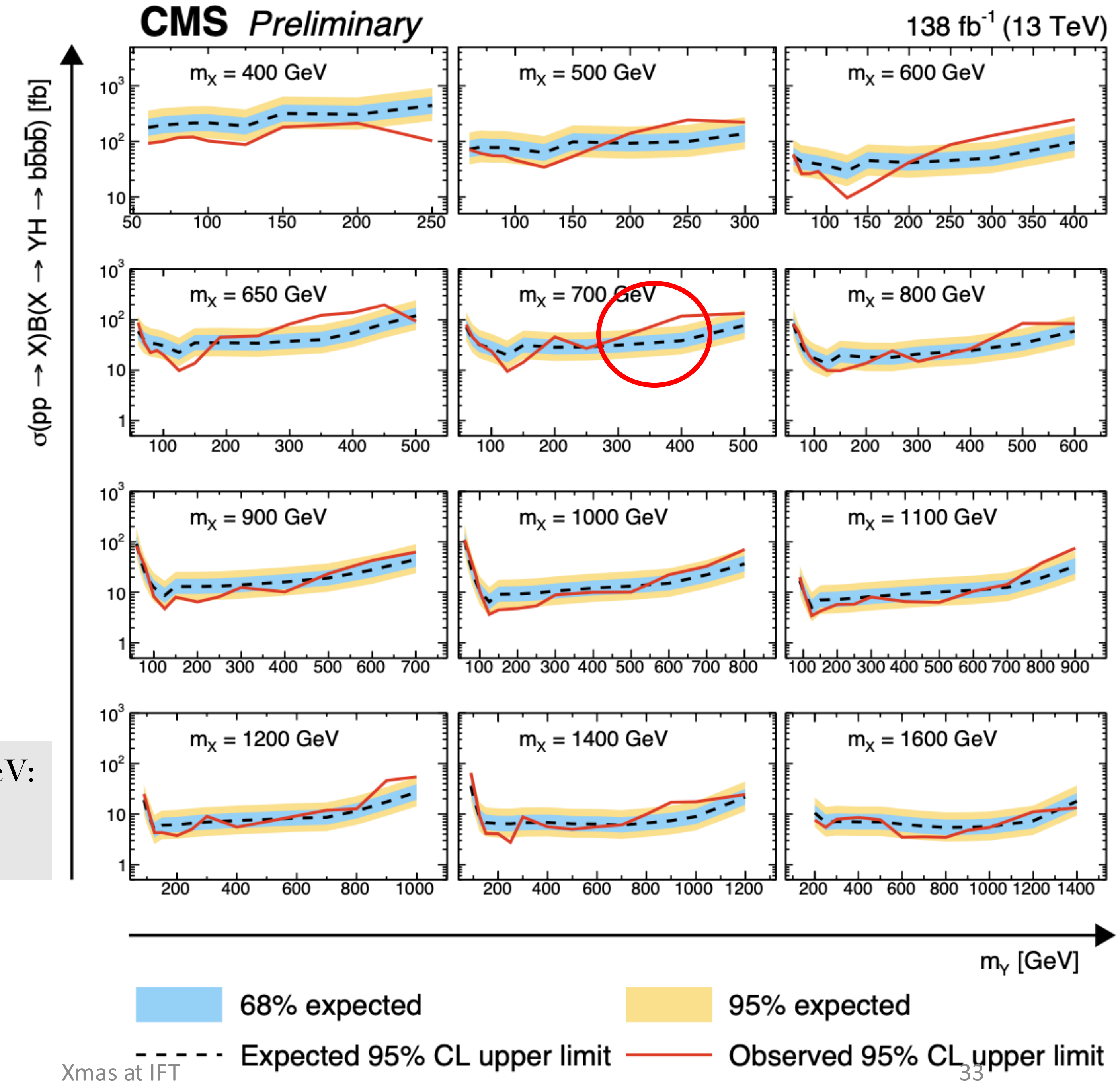
https://link.springer.com/article/10.1007/JHEP11(2021)057

https://link.springer.com/article/10.1007/JHEP07(2024)293

H->YX->4b [HIG-20-012]

- HH and HY
- X in HH search 400–1400 GeV
- X in HY search 400-1600 GeV
  - Y mass range being 60–1400 GeV

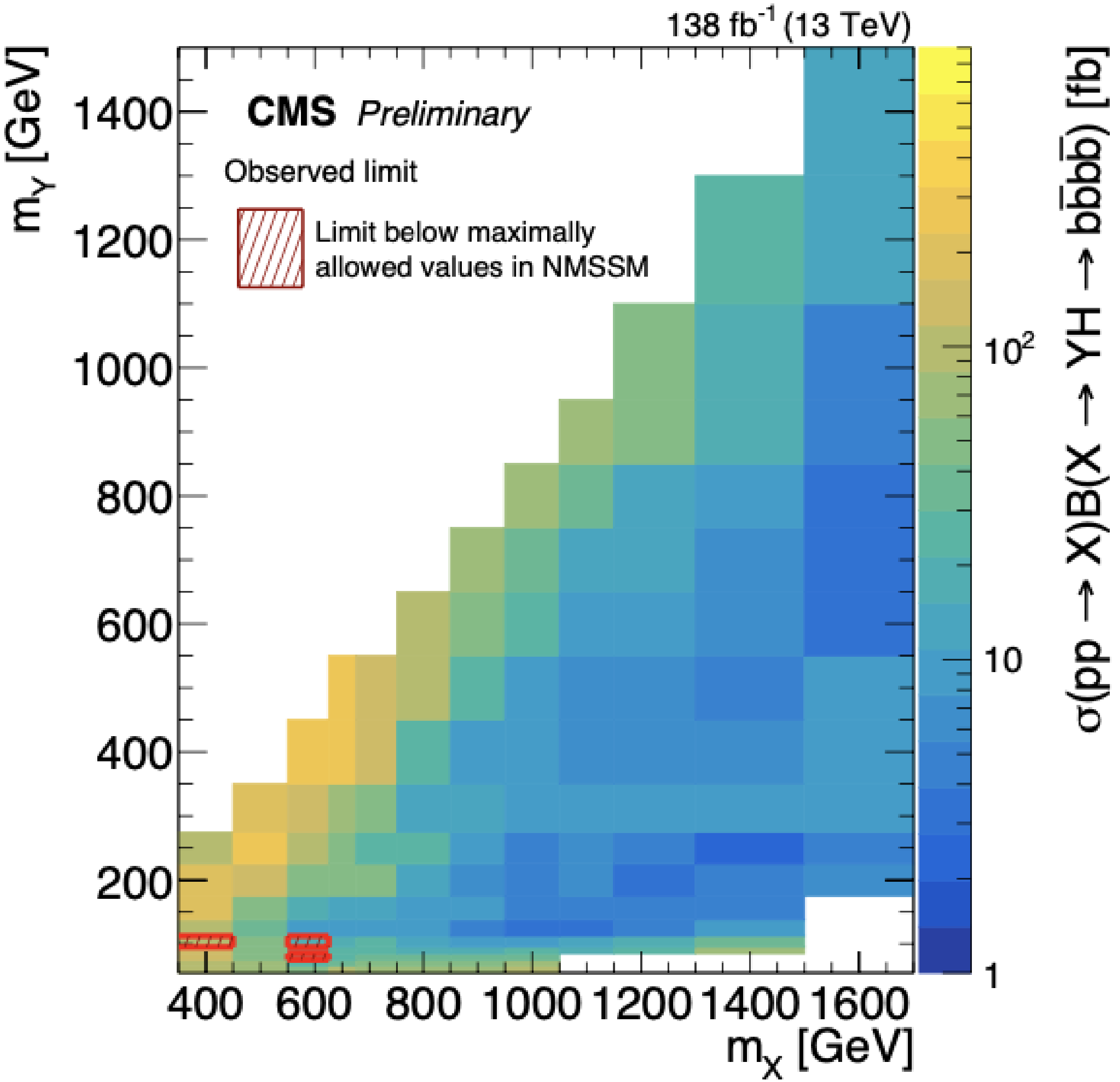
Excess at X700GeV, Y400GeV:
4.1σ (local)
2.8σ (global)



H->YX->4b

HIG-20-012

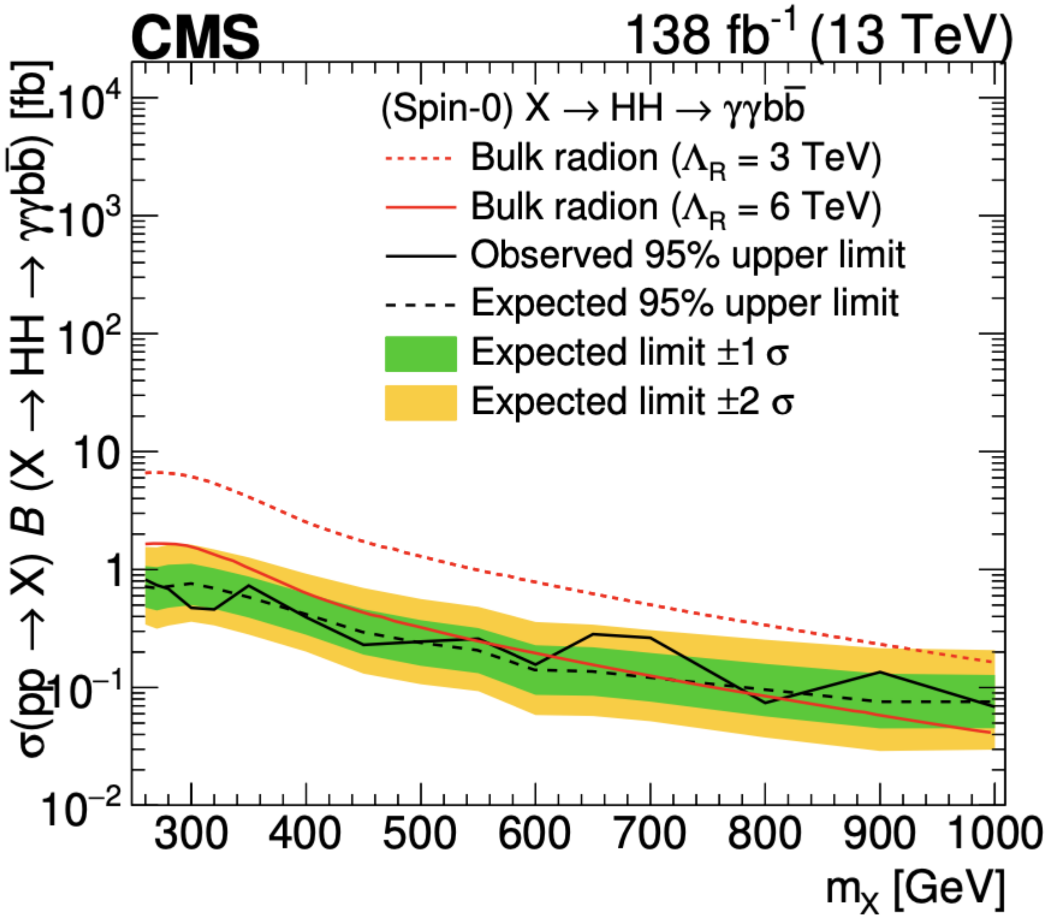
- HH and HY
- X in HH search 400–1400 GeV
- X in HY search 400-1600 GeV
  - Y mass range being 60–1400 GeV
- Interpretation in the context of NMSSM



HY → bbγγ

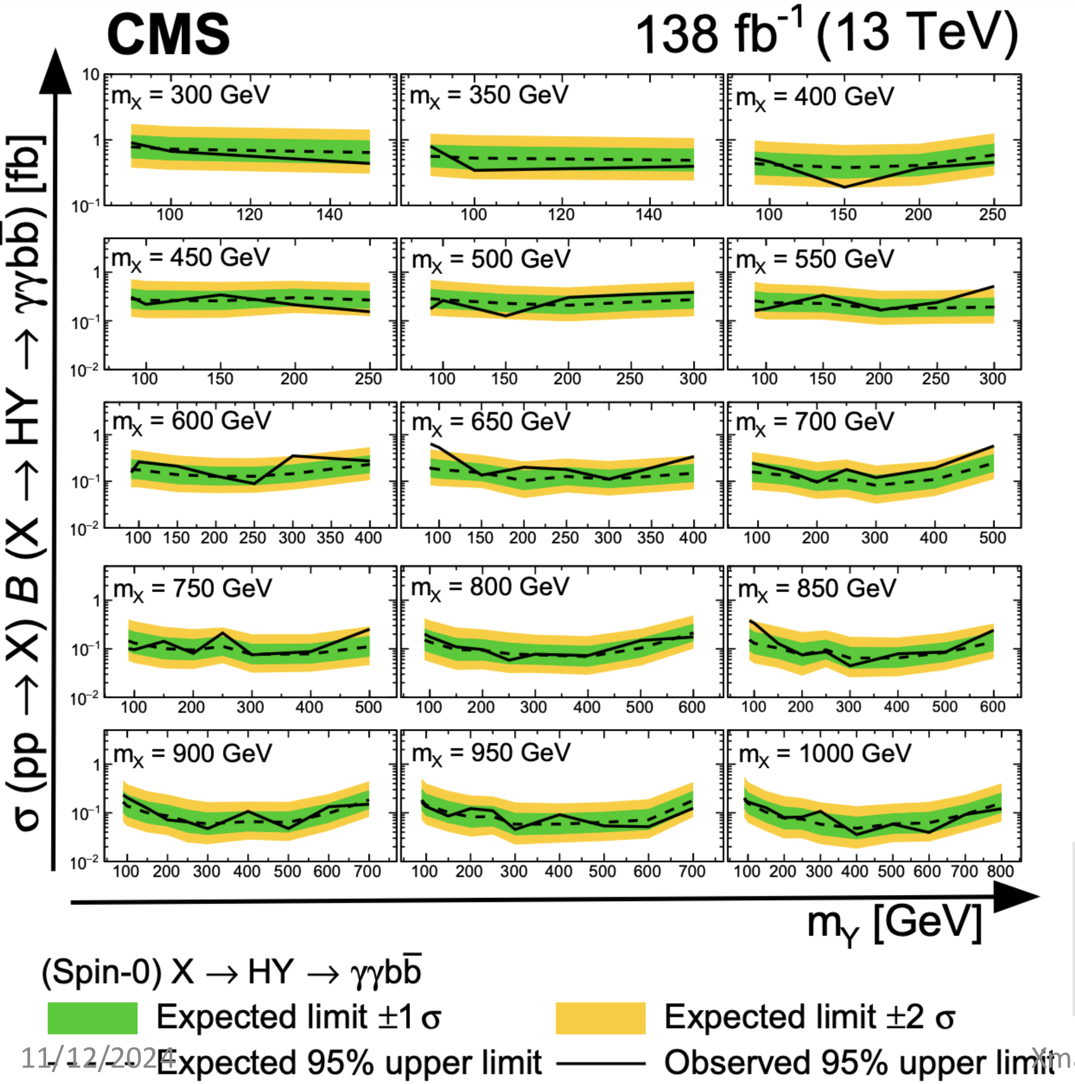
https://link.springer.com/article/10.1007/JHEP05(2024)316

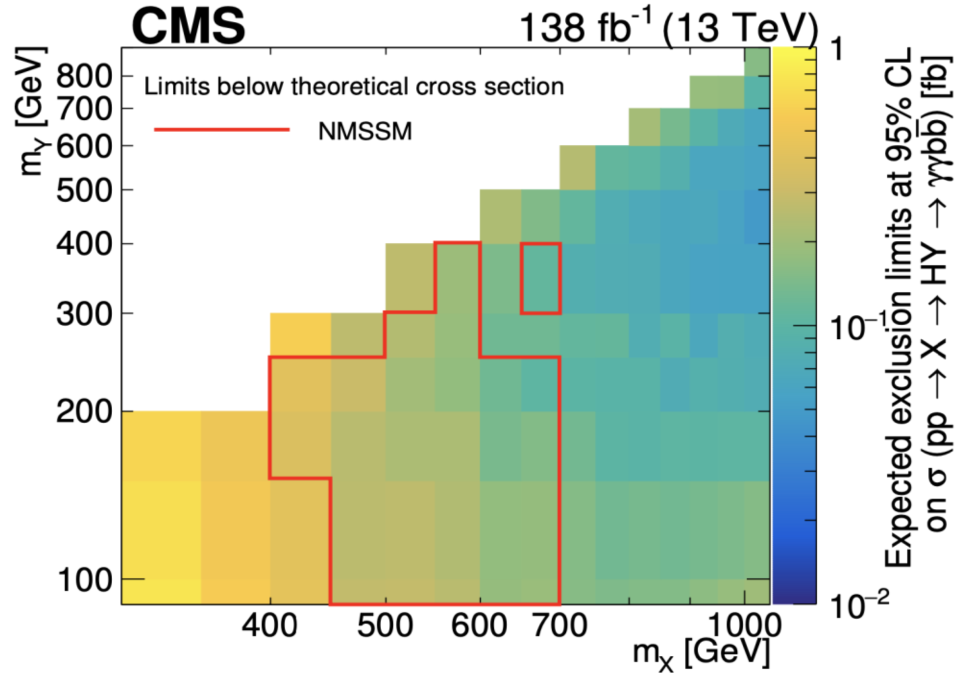
- HH and HY
- X in HH search 260–1000 GeV
- X in HY search 300–1000 GeV
  - Y mass range being 90–800 GeV



https://link.springer.com/article/10.1007/JHEP05(2024)316

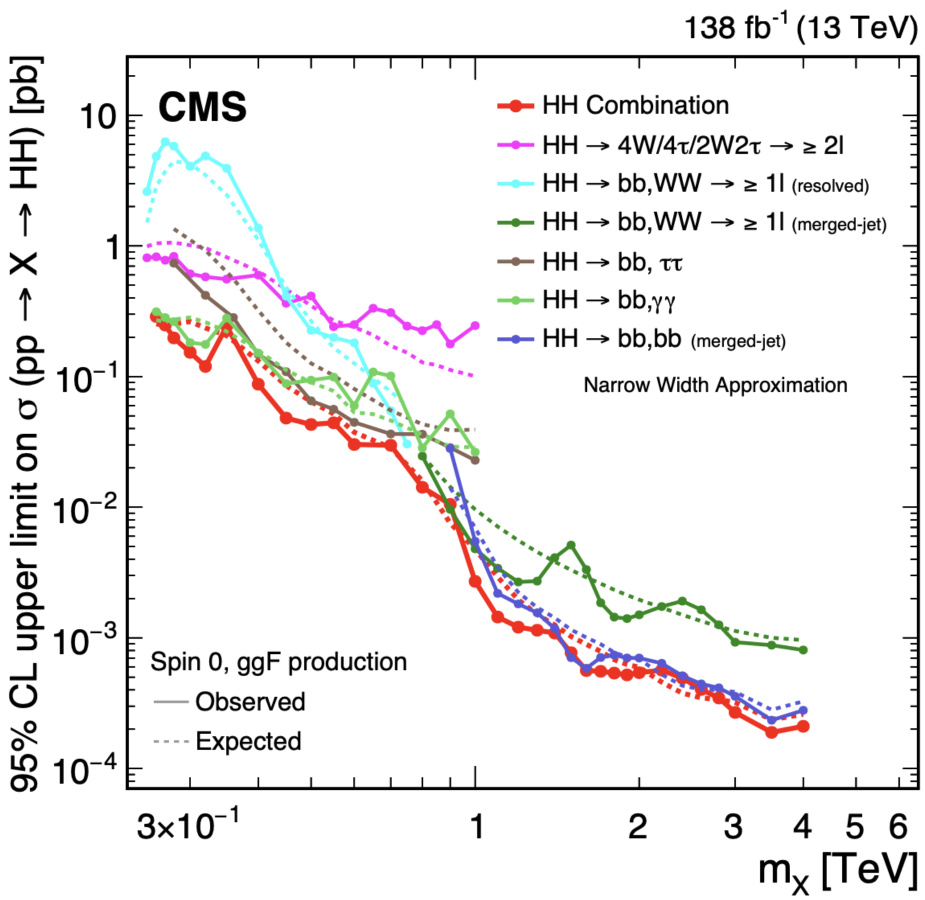
HY → bbγγ

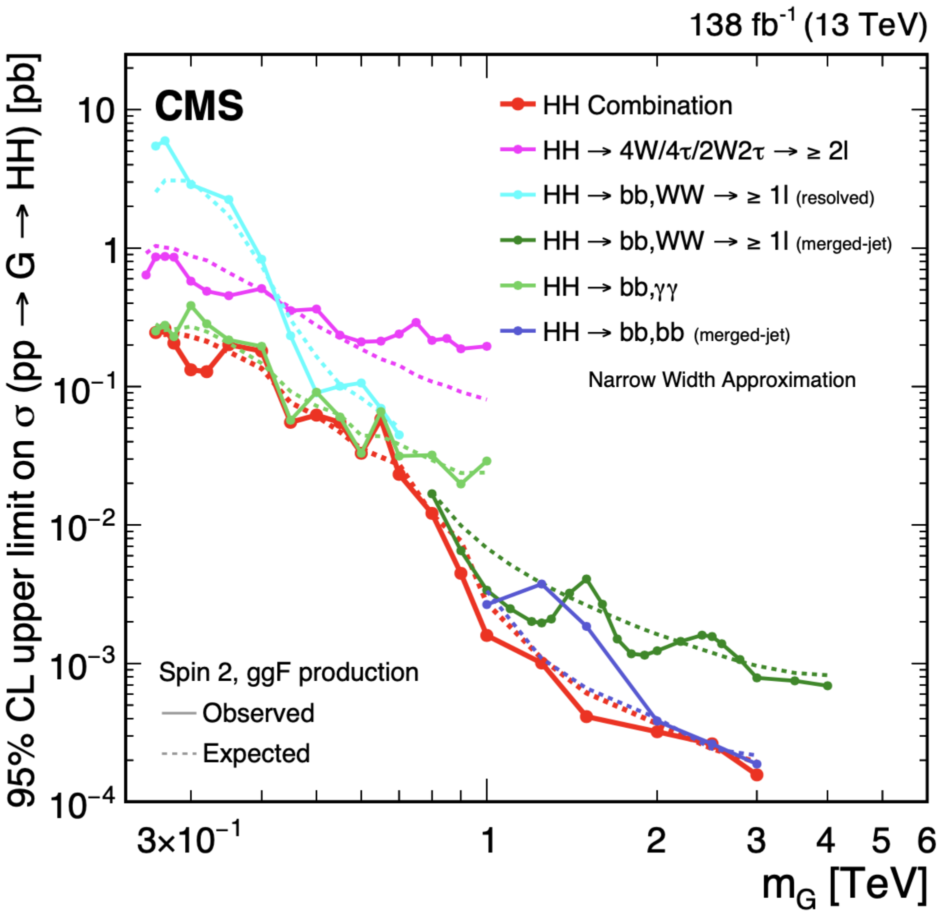




Excess at X650GeV,Y90GeV:
3.8σ (local)
2.8σ (global)

Summary and combination of HH searches





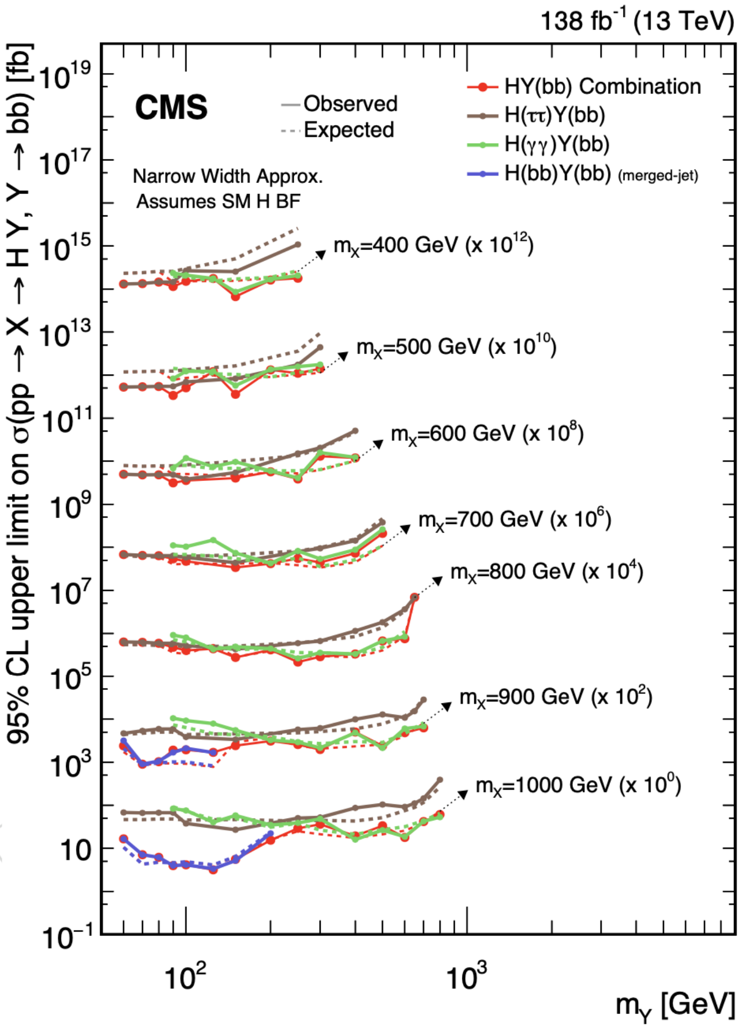
https://arxiv.org/abs/2403.16926

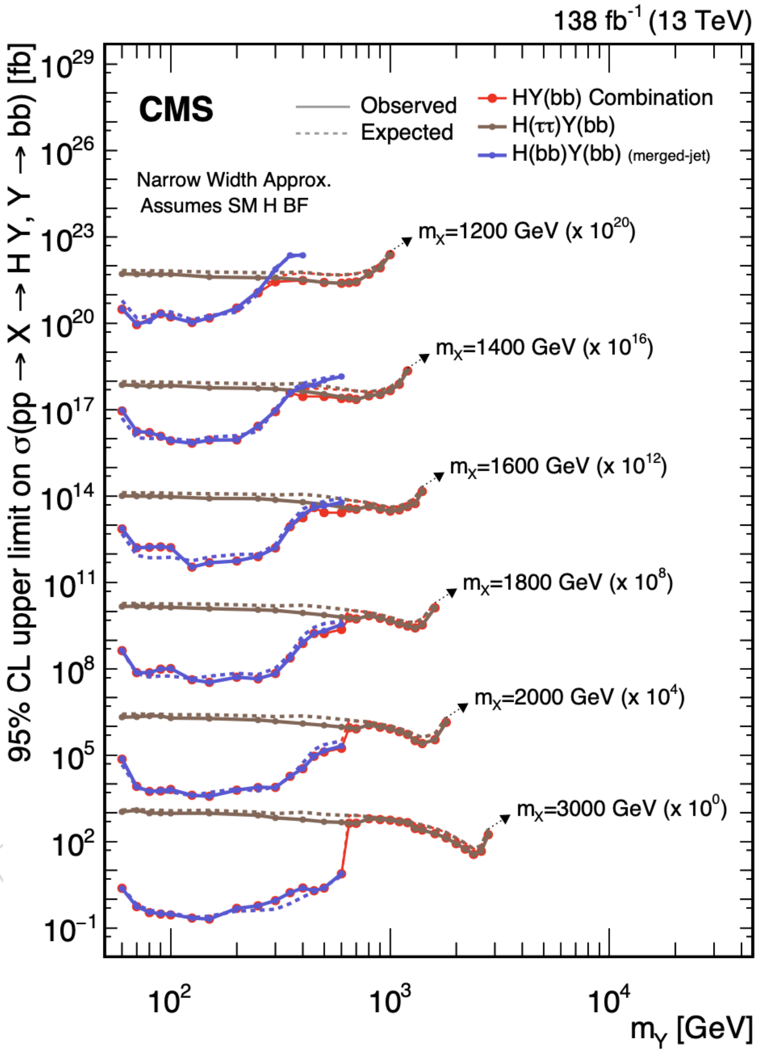
Review on HH,YH and ZH searches

Accepted by Phys. Rept.

Summary and combination of YH searches

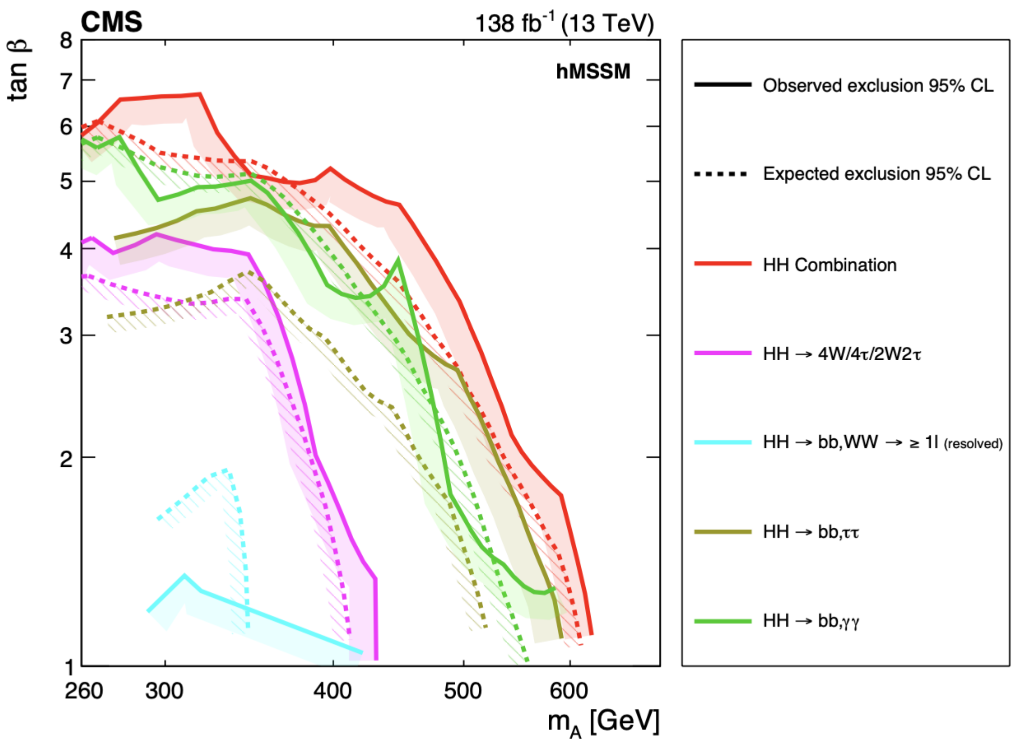
https://arxiv.org/abs/2403.16926

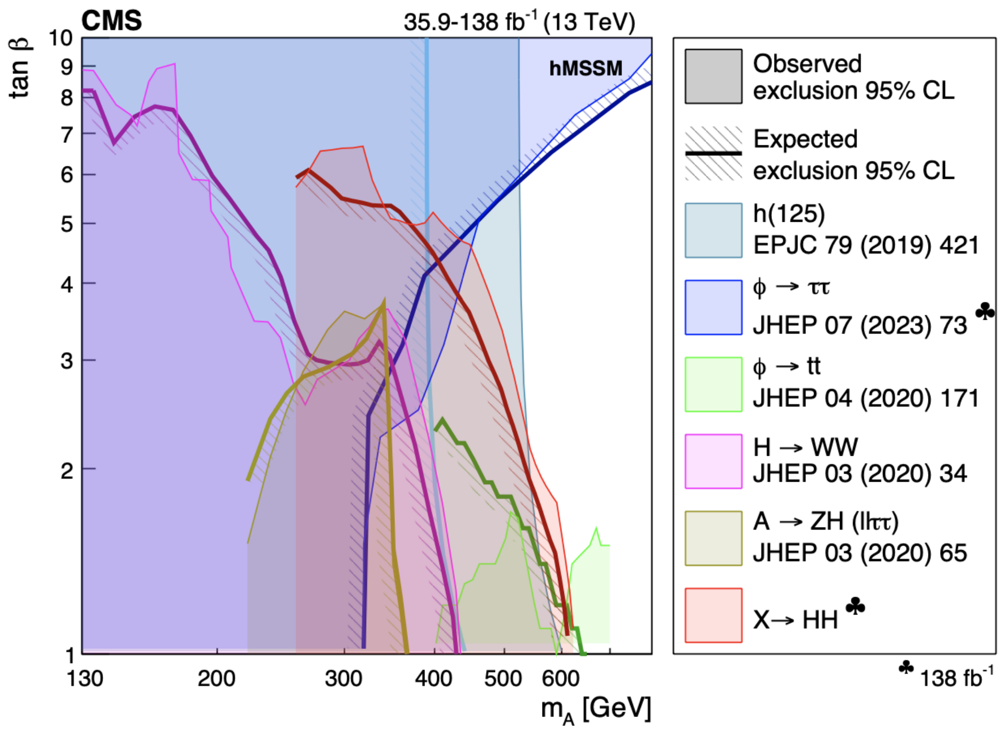




Model dependent results: hMSSM

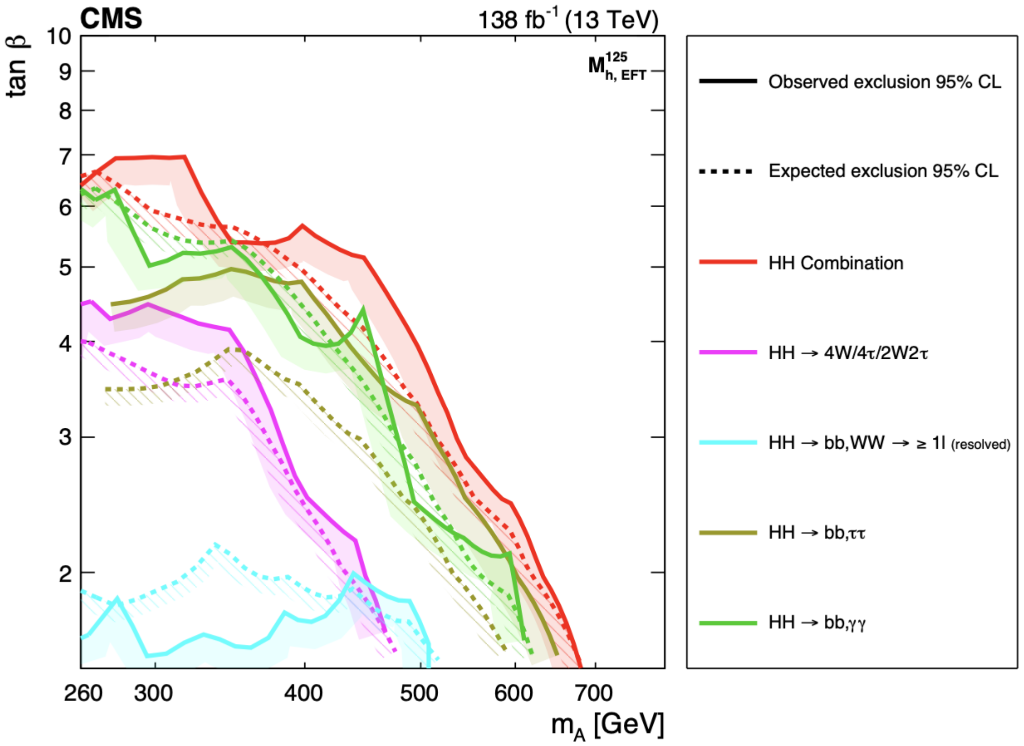
https://arxiv.org/abs/2403.16926

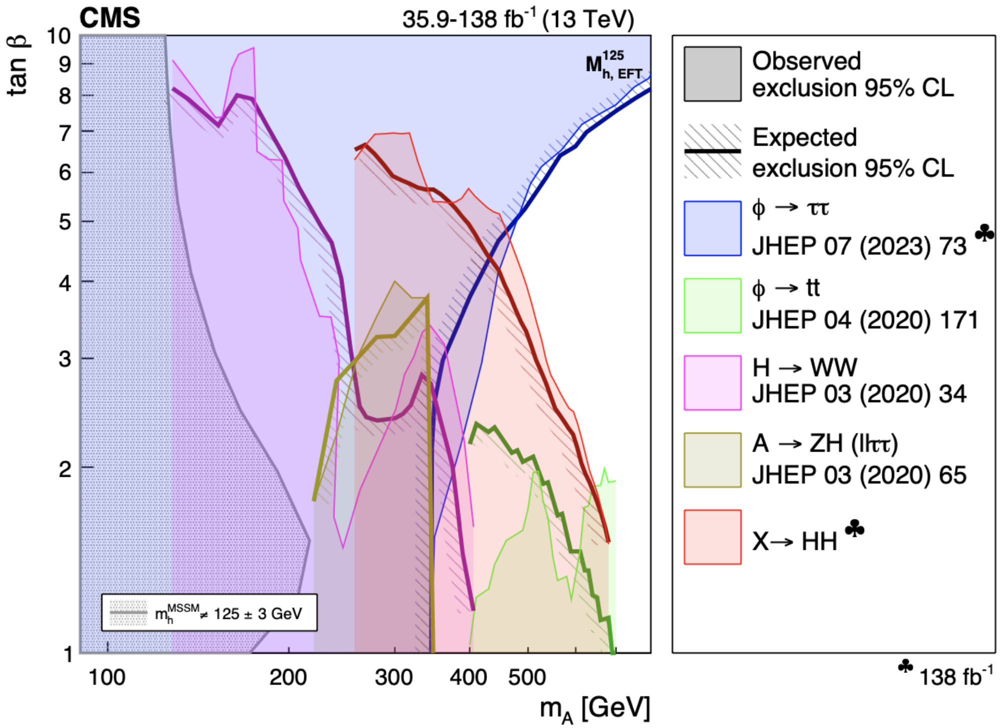




Model dependent results: Mh EFT

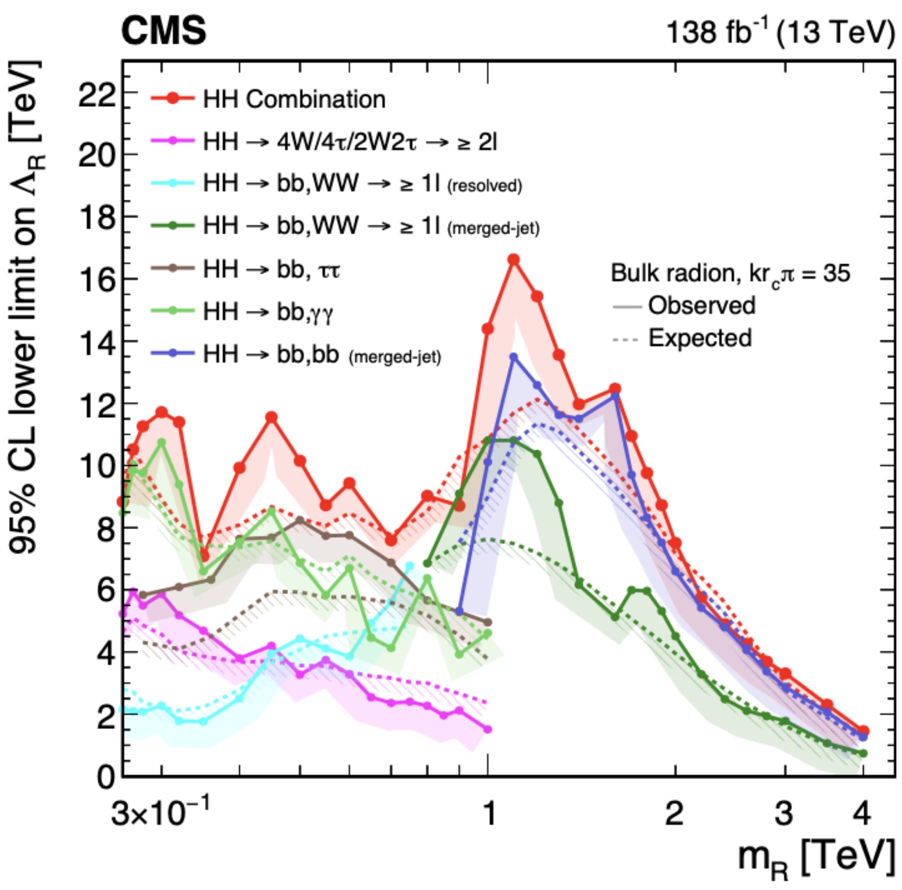
https://arxiv.org/abs/2403.16926

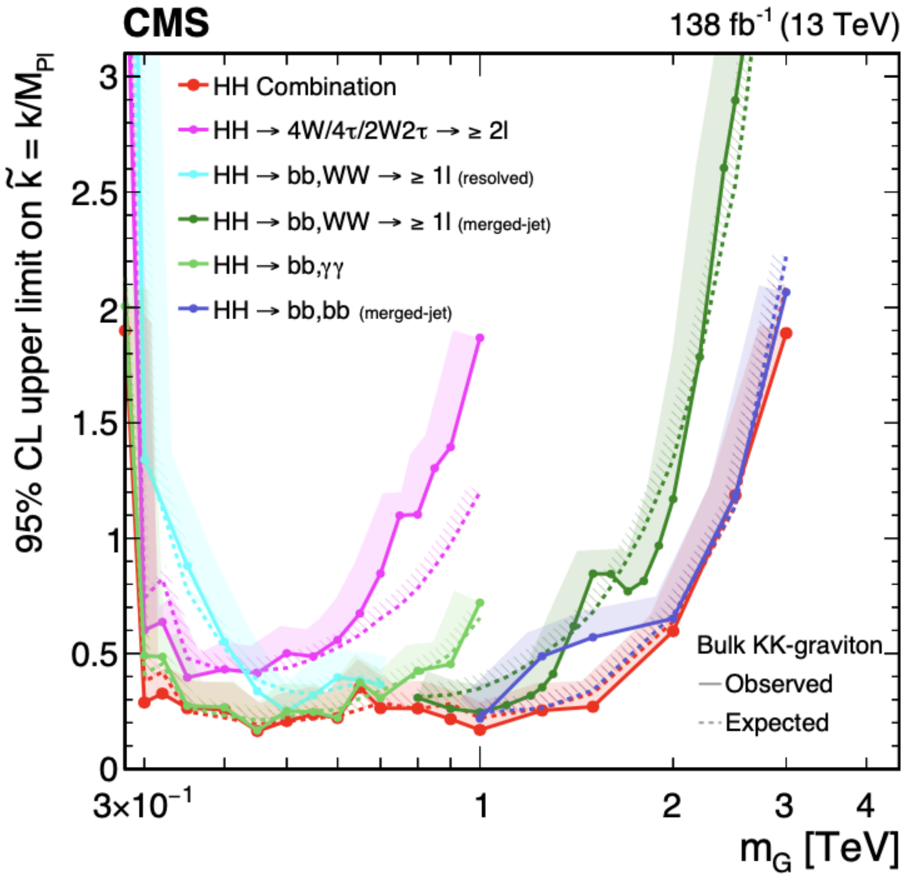




Model dependent results: warped extra dimensions

https://arxiv.org/abs/2403.16926

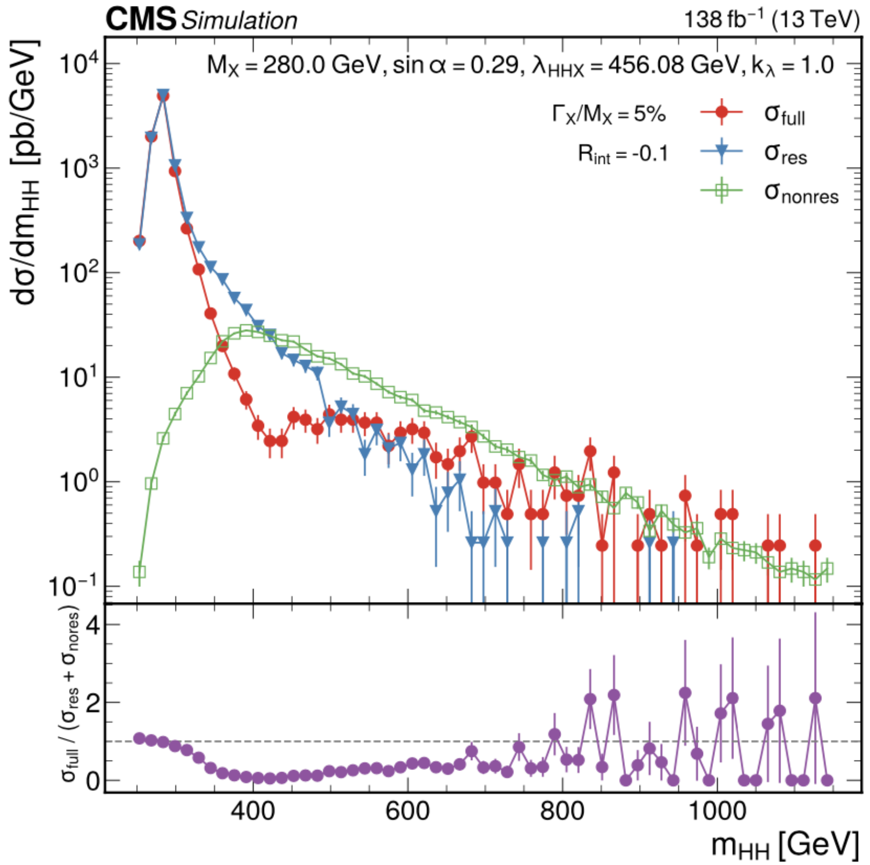




Narrow width approximation

https://arxiv.org/abs/2403.16926

- HH and YH analyses make use of the NWA
- Interference with non-resonant HH can be either constructive or destructive
- May have nonnegligible effect in exclusion limits
- Benchmark:
  Simplified scenario based on the real-singlet model
  Chosen to have the smallest number of additional free parameters
  (λ_{HHX}, sinα, M_X, κλ=1)
- Model dependent!!! Take it with a grain of salt
  But it shows that we need to take this into account in the future.



$$R_{\text{int}} = \frac{\sigma^{\text{full}} - \left(\sigma^{\text{resonant-only}} + \sigma^{\text{nonresonant}}\right)}{\sigma^{\text{resonant-only}} + \sigma^{\text{nonresonant}}}.$$

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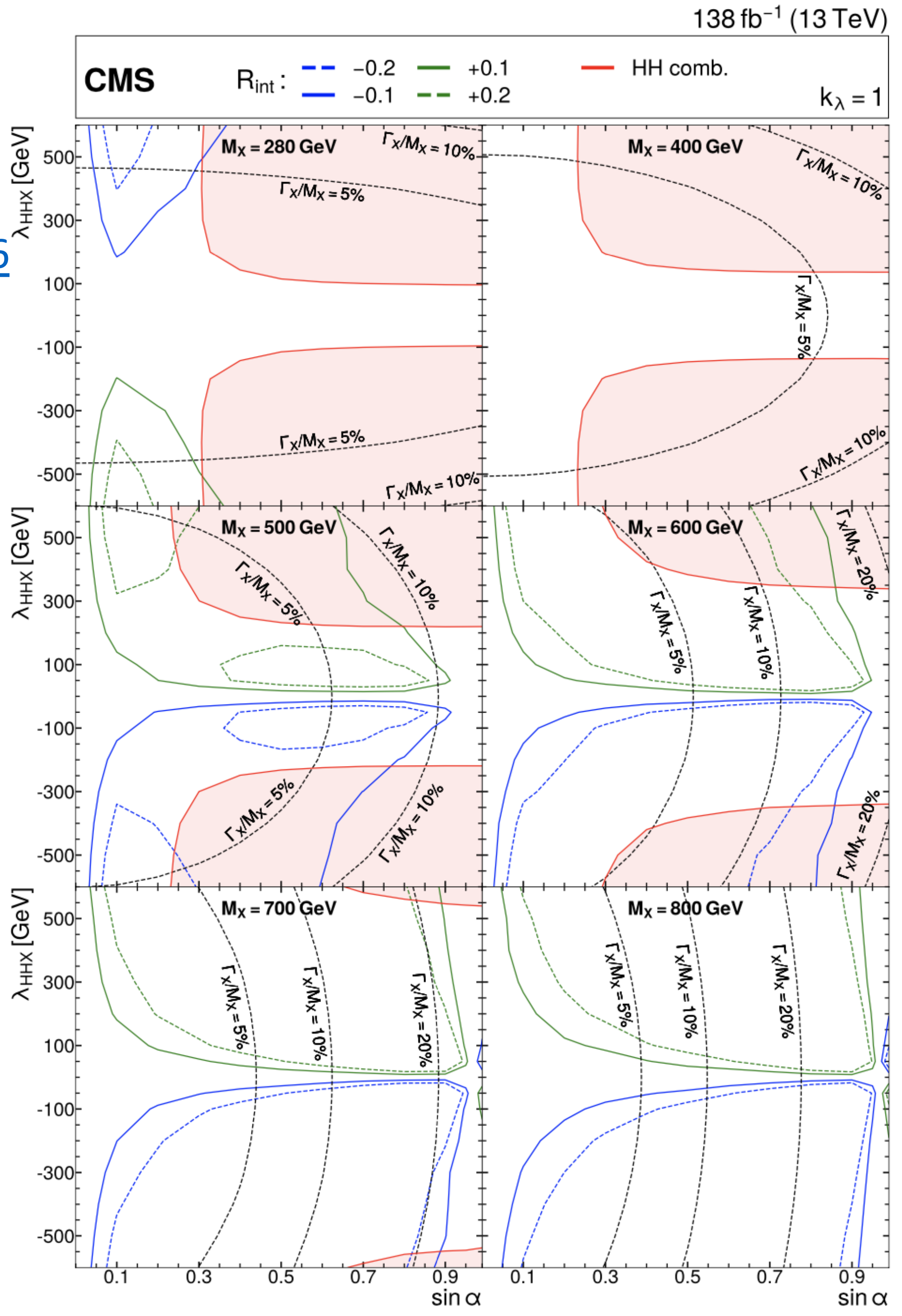


(HL-)LHC timeline

HL-LHC projections

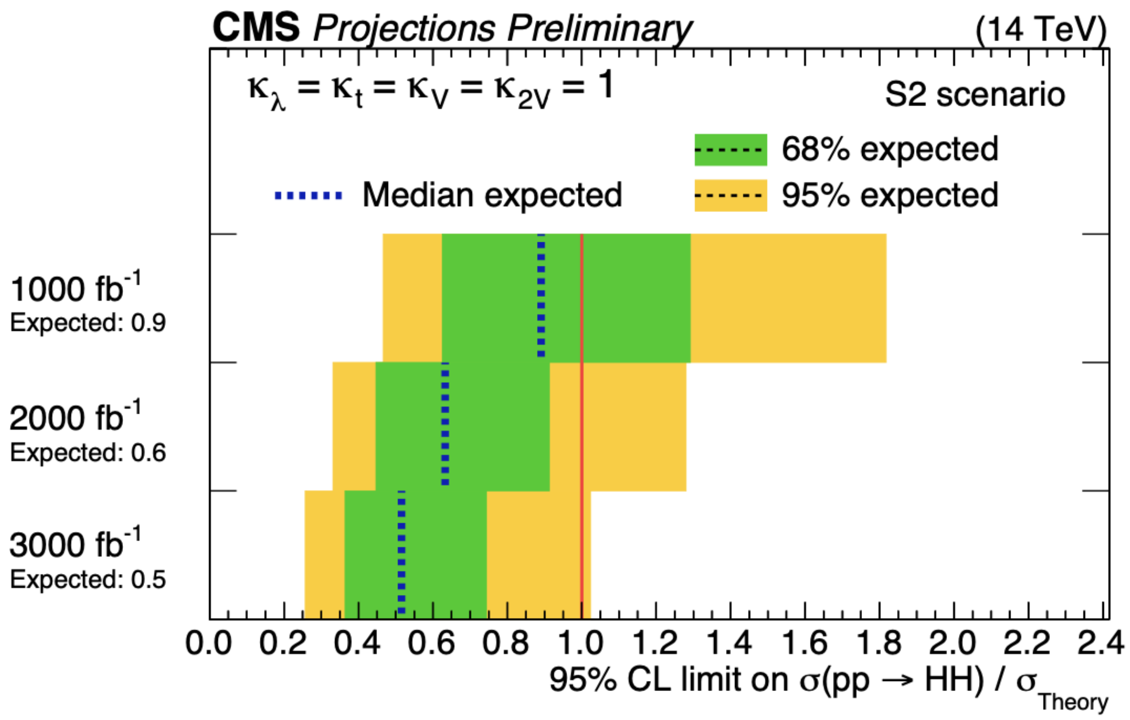
HIG-20-012

- HL-LHC is planned to start in 2029
- 3000 fb^{-1} (maybe even 4000 fb^{-1})
- center-of-mass energy of 14 TeV
- 140 (200) PU baseline (ultimate) scenario.
- bbττ, bbγγ, bbbb(boosted)

- S1
  - systematics same as Run2
  - conservative
- S2
  - Systematic uncertainties halved
  - Datadriven/statistical uncertainties scaled with lumi
  - no MC statistical uncertainties

HL-LHC projections

HIG-20-012



	Significance (σ) at 2000 fb^{-1}		Significance (σ) at 3000 fb^{-1}	
	S2	Stat. only	S2	Stat. only
$b\bar{b}b\bar{b}$ resolved jets	1.0	1.3	1.4	1.6
$b\bar{b}b\bar{b}$ merged jets	1.7	1.7	2.0	2.1
$b\bar{b}\tau\tau$	1.7	1.9	2.1	2.3
$b\bar{b}WW$	0.6	0.8	0.7	0.9
$b\bar{b}\gamma\gamma$	1.8	1.9	2.2	2.3
Combination	3.2	3.6	3.8	4.3

- We could have discovery at the end of HL-LHC!
- Historically projections are always conservative
- We already know of improvements that will benefit the HH results and some are in place already for Run3

After 1000 fb-1 of data we will be sensitive to μ=1

Summary

- Searches for additional scalars
  - Heavy
  - Light
  - 2HDM, NMSSM and more
- Searches for Higgs pairs
  - non-resonant (brand new!)
  - resonant HH and HY
- Looking ahead:
  - Run3:
    - promising improvements expected.
    - More thorough investigations and interpretations
  - Discovery at HL-LHC??