The Standard Model Higgs and beyond

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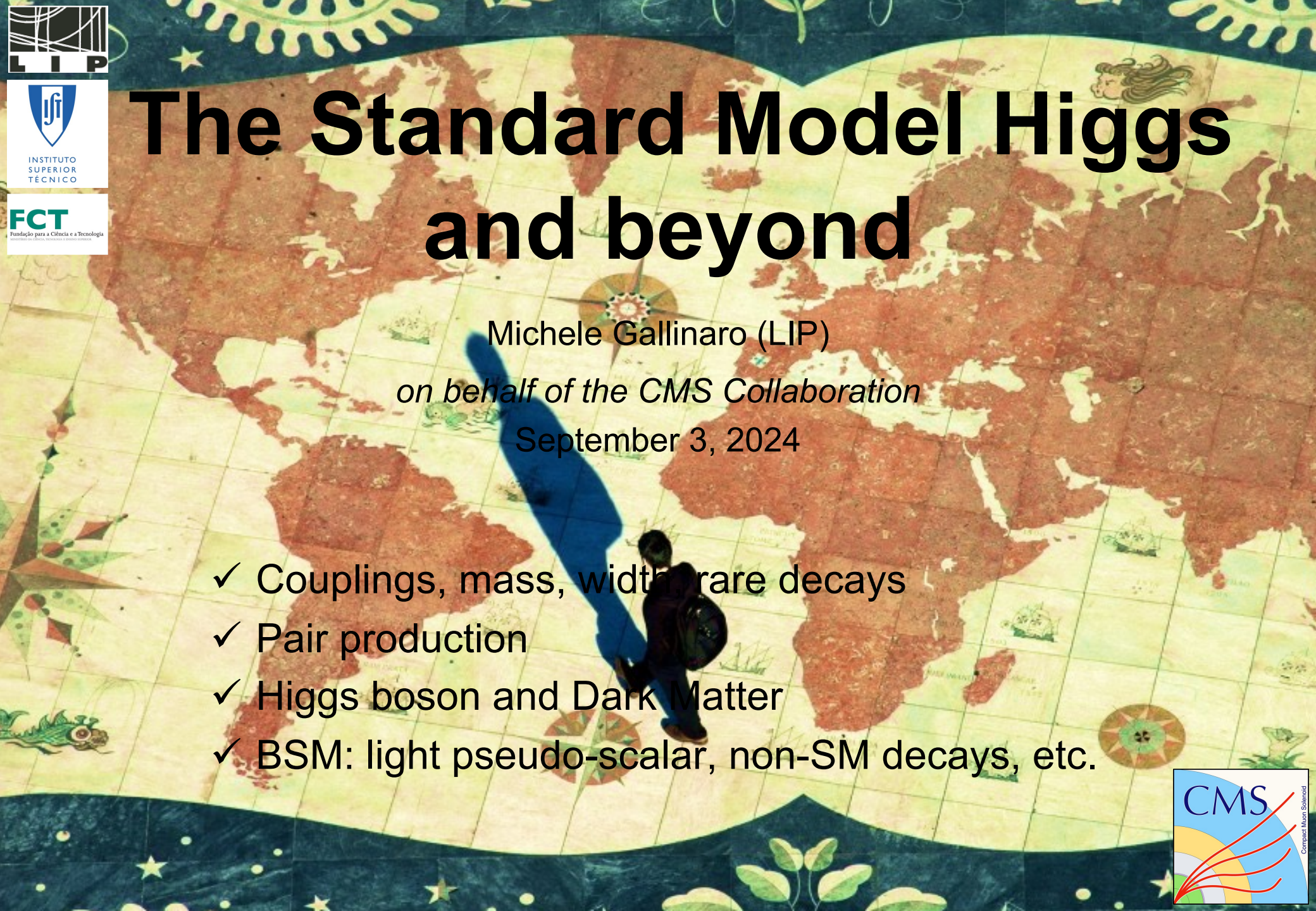
on behalf of the CMS Collaboration

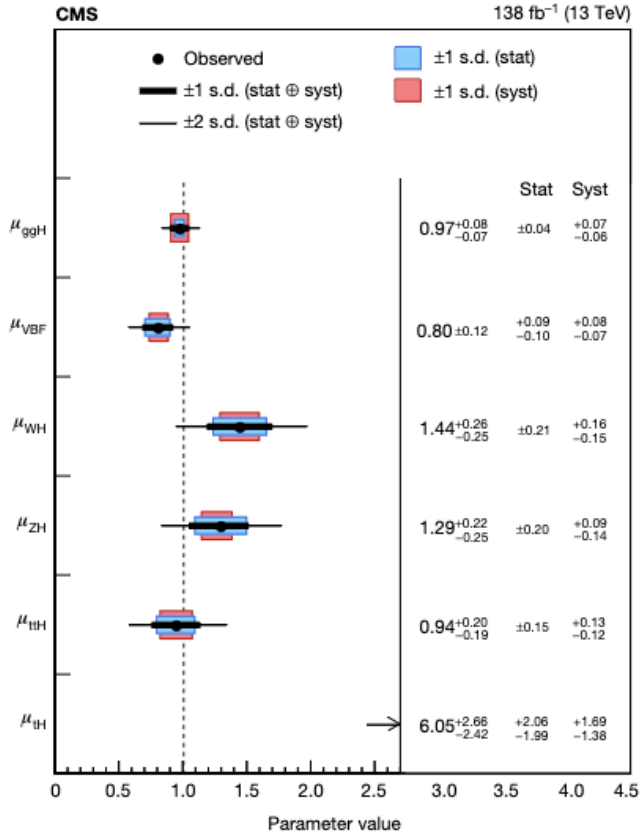
September 3, 2024

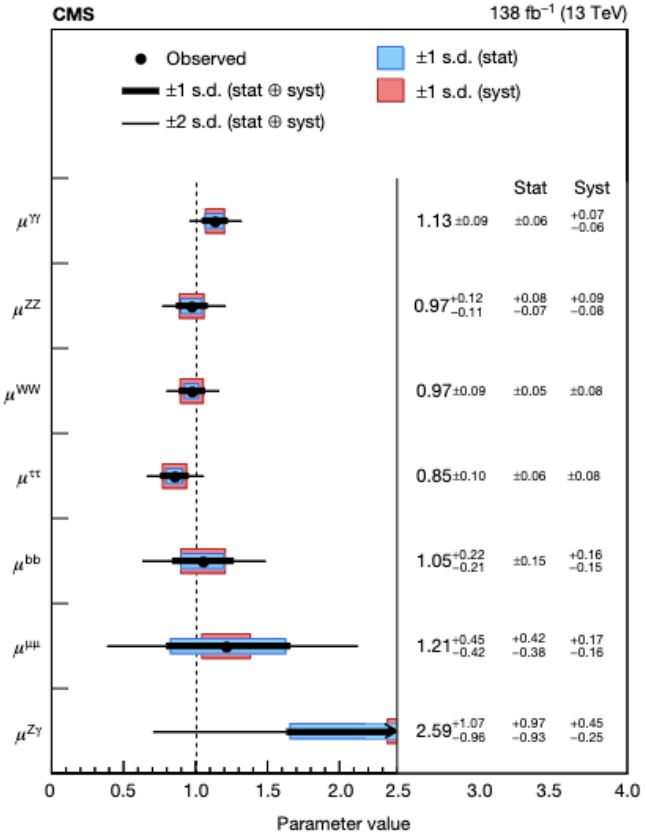


- ✓ Couplings, mass, width, rare decays
- ✓ Pair production
- ✓ Higgs boson and Dark Matter
- ✓ BSM: light pseudo-scalar, non-SM decays, etc.

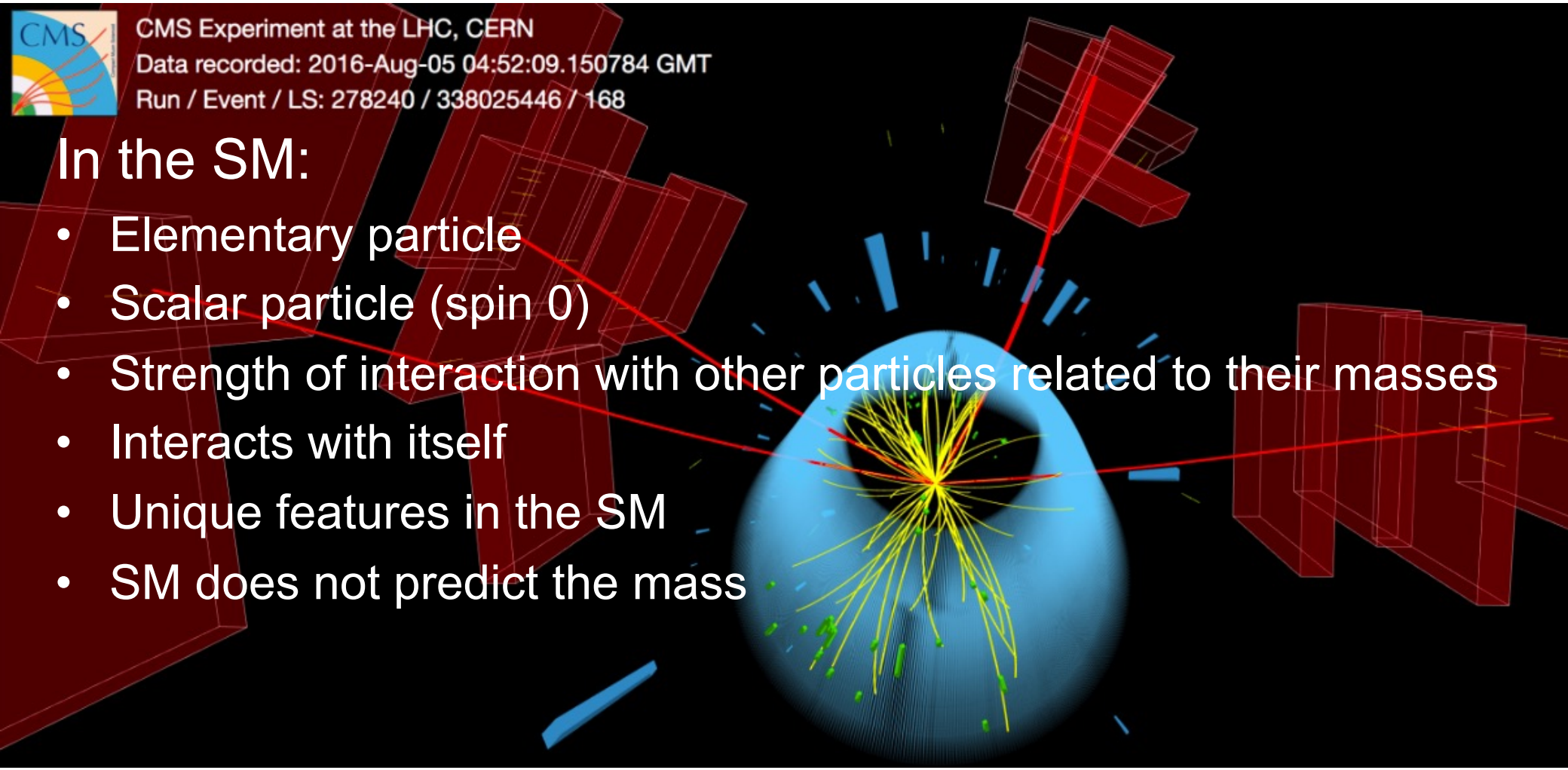
Introduction

- The Higgs boson discovery marked LHC Run 1
- Run 2 and Run 3 are eras of precision measurements
- Wide variety of final states explored
  - Each channel probes different phase space and brings complementary information
- All main decay modes have been measured (>5σ)





The Higgs boson



In the SM:

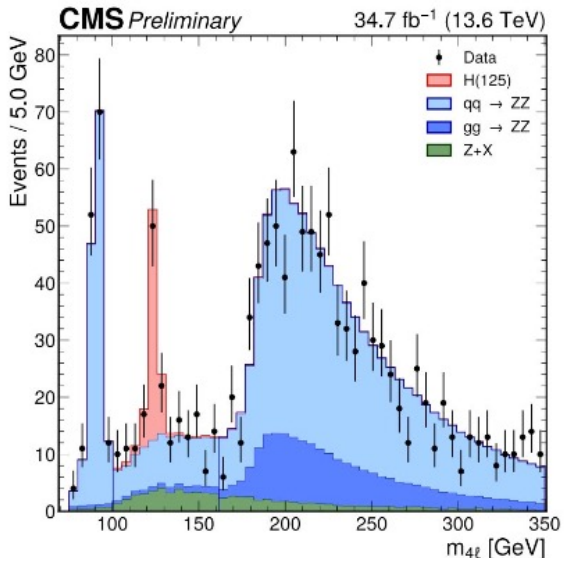
- Elementary particle
- Scalar particle (spin 0)
- Strength of interaction with other particles related to their masses
- Interacts with itself
- Unique features in the SM
- SM does not predict the mass

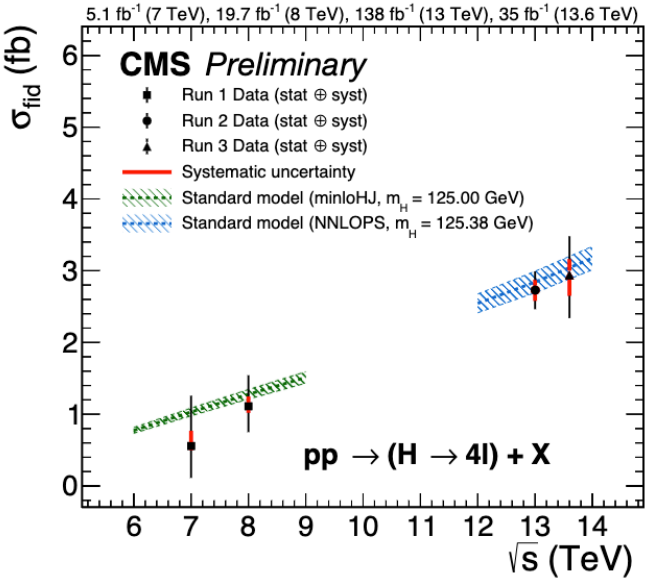
Only a few events ⇒ aim at exploring its properties

Higgs boson in Run3

CMS-PAS-HIG-23-014, CMS-PAS-HIG-24-013

- 5 main decay channels
  - ZZ, $\gamma\gamma$, WW, $\tau\tau$, bb
  - Most accurate measurements in $\gamma\gamma$ and ZZ
- Progress since Higgs discovery (July 2012)
  - Observation in boson and fermion channels
  - Precise mass measurement (~125 GeV)
  - Improving precision of coupling measurements
  - Differential distributions
  - 2nd generation fermions
  - Study of rare decays
- A long journey ahead



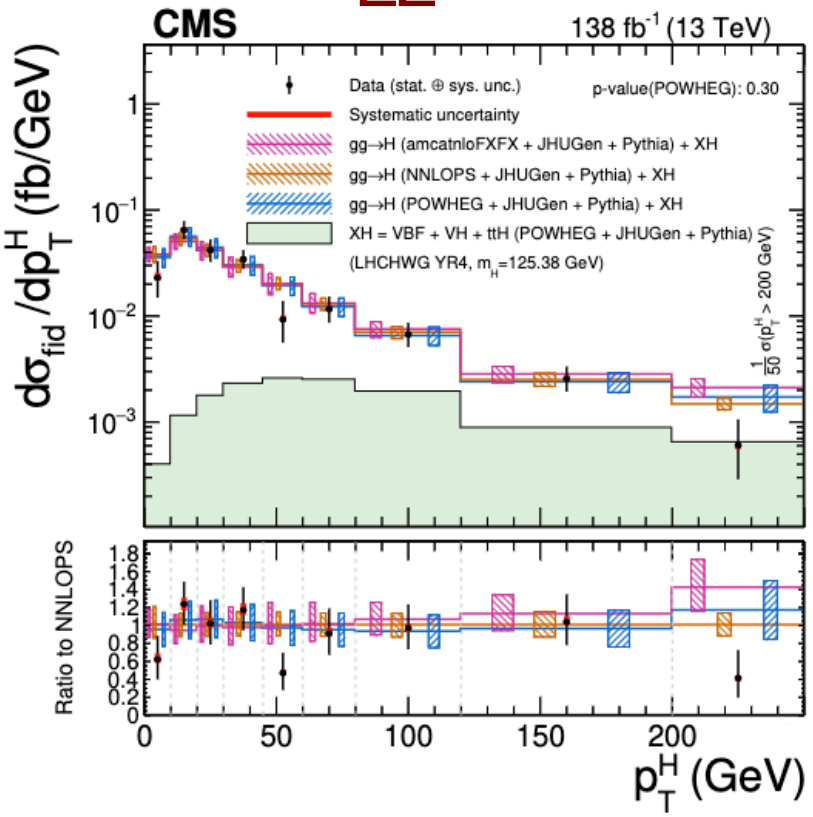


Differential distributions

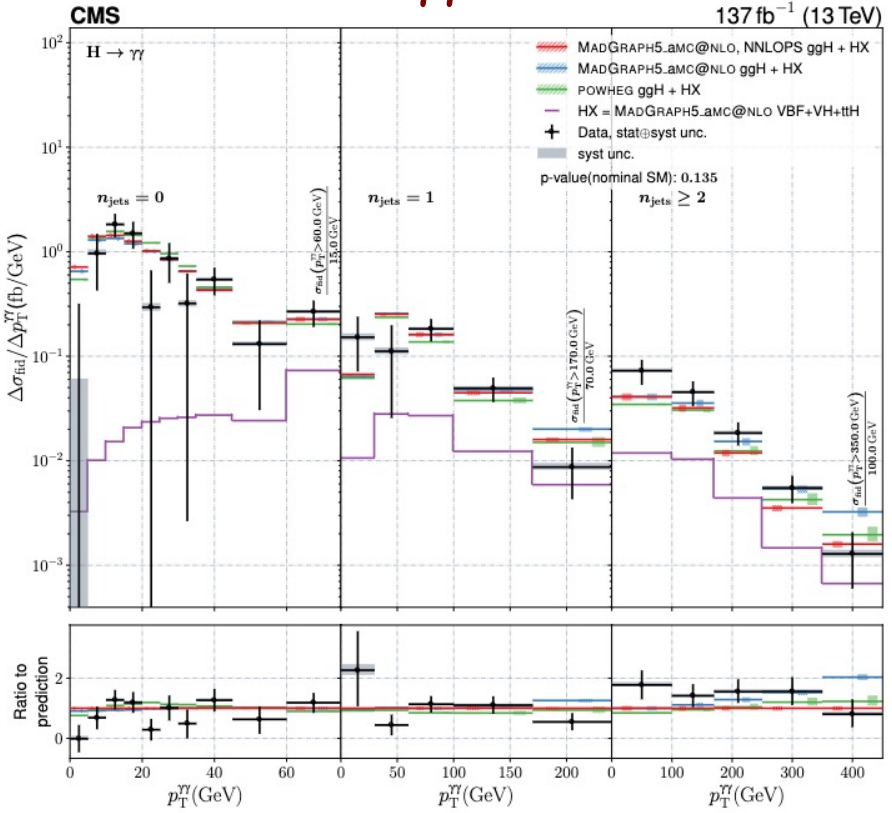
arXiv:2305.07532, arXiv:2208.12279

- 1-D and 2-D variables measured in several channels
- BSM effects can be enhanced in tails of distributions
- Good agreement of data with predictions

ZZ

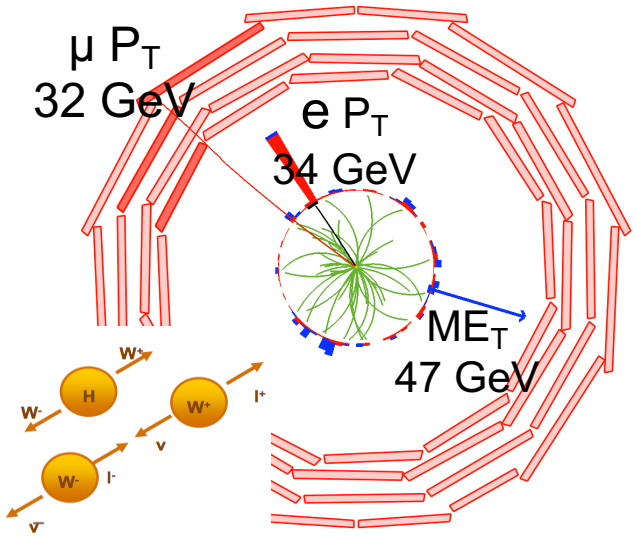


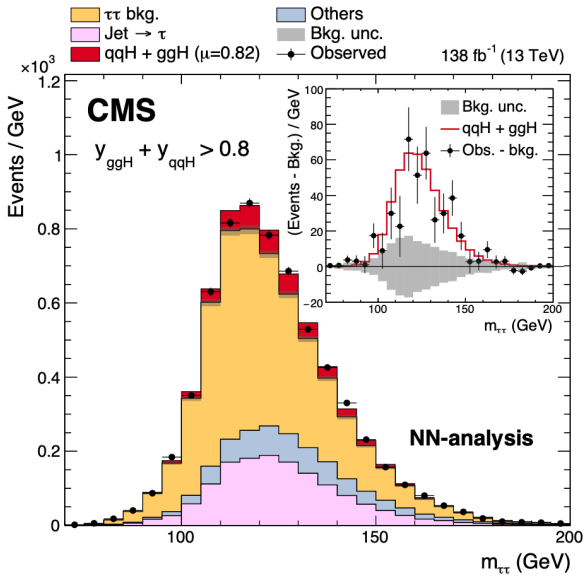
γγ

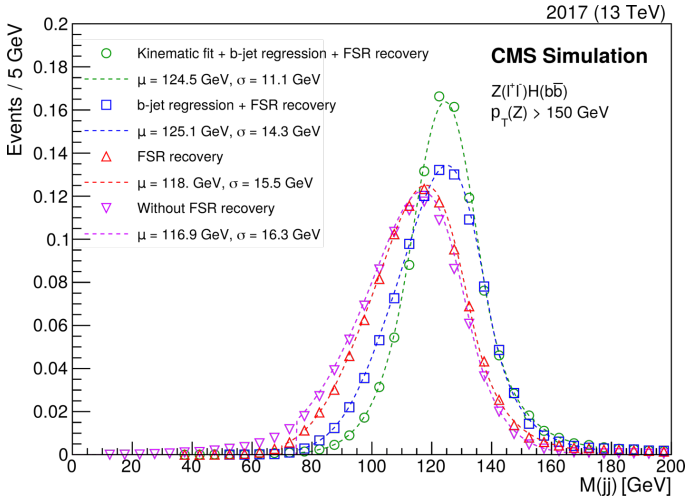


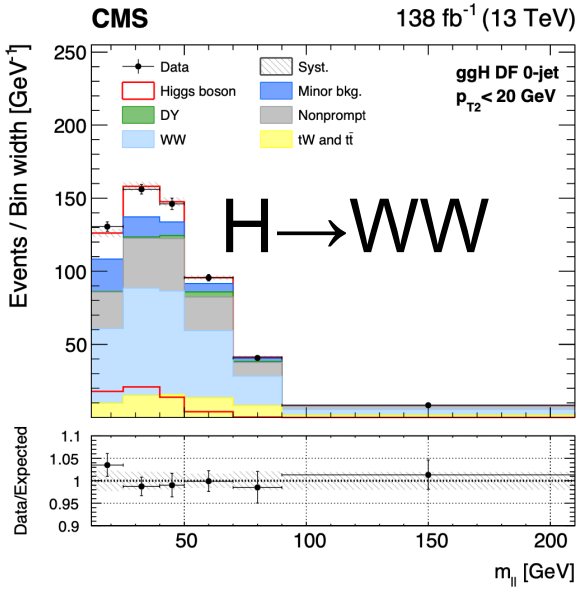
Low mass-resolution channels

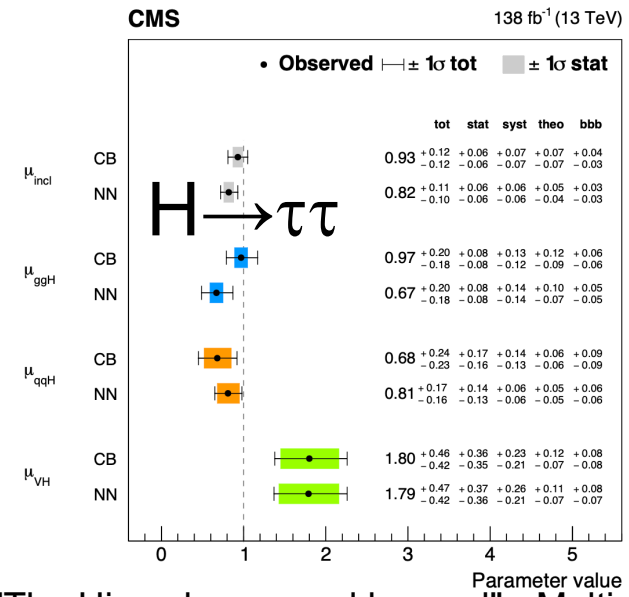
arXiv:2206.09466, arXiv:2204.12957, arXiv:2312.07562

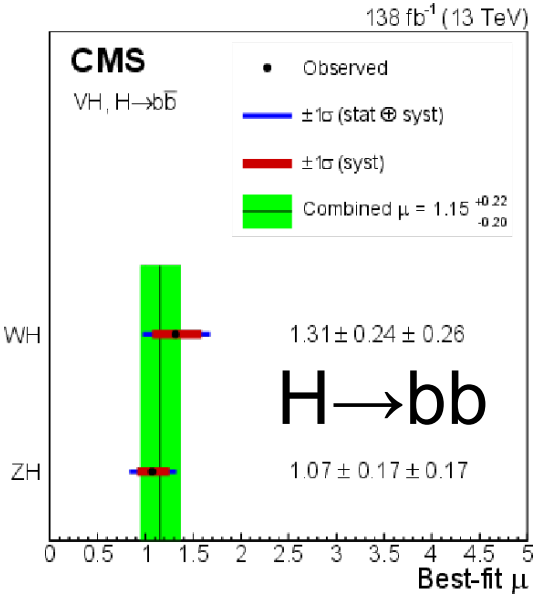








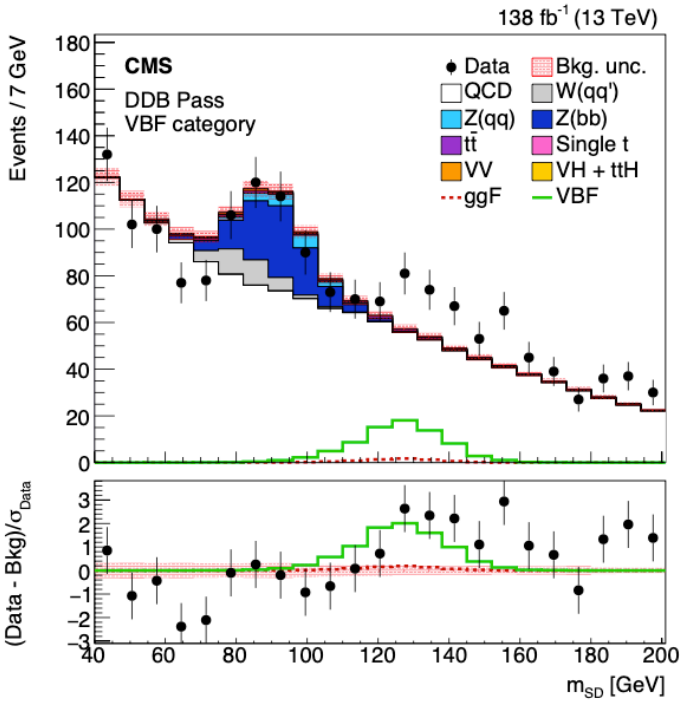


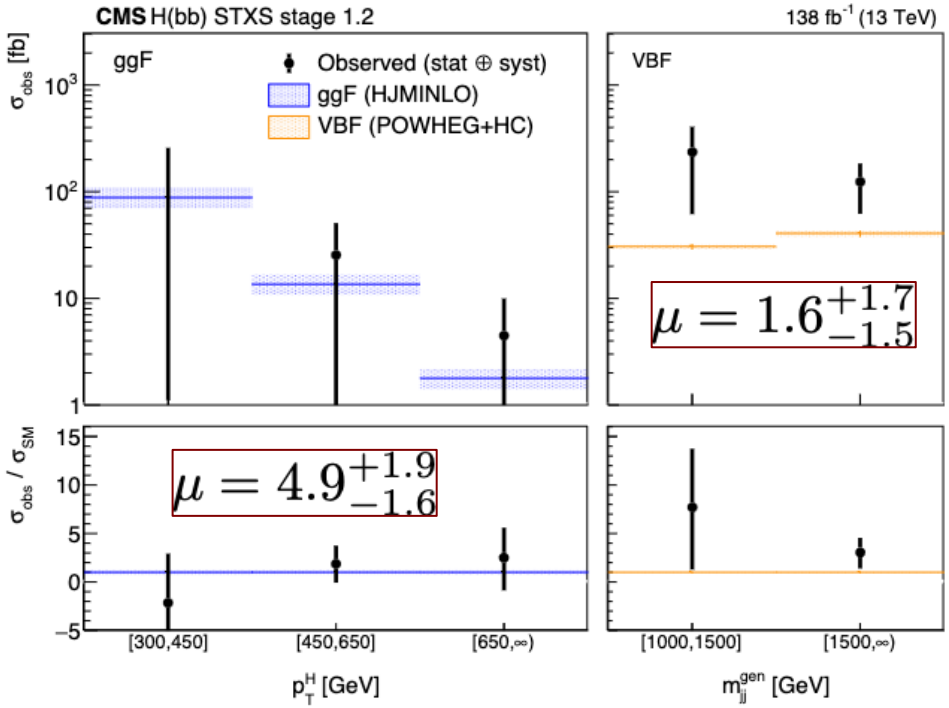


Boosted H→bb

arXiv:2407.08012

- Search for boosted Higgs (p_T>450 GeV) via VBF and ggF
  - Higgs identified by 2-prong substructure (large R jet), multi-variate jet tagger
  - Relative ggF contribution expected to decrease as p_T ↗ (>450GeV)
  - Jets are used to distinguish VBF vs ggF production
- Cross sections measured in bins of m_{jj} and p_T

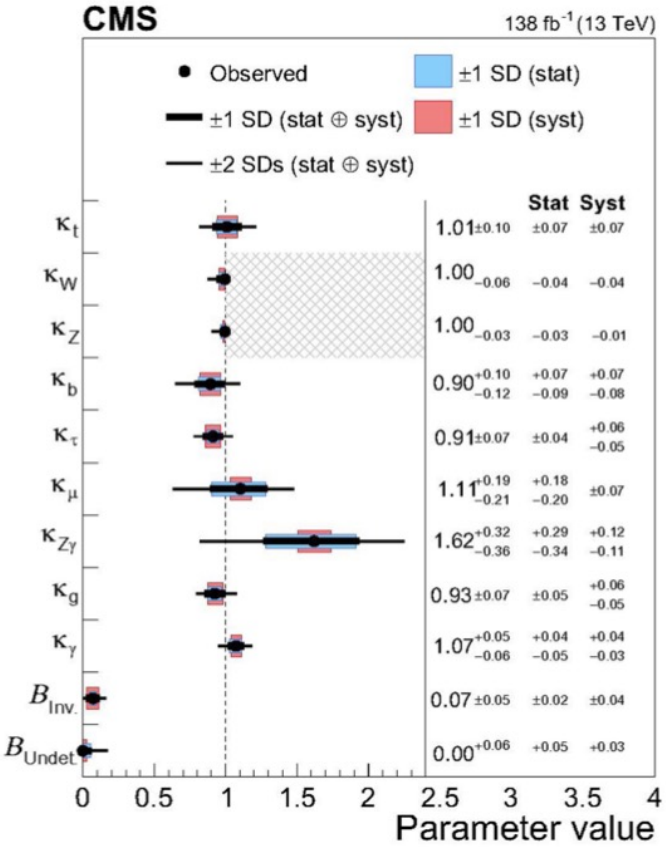




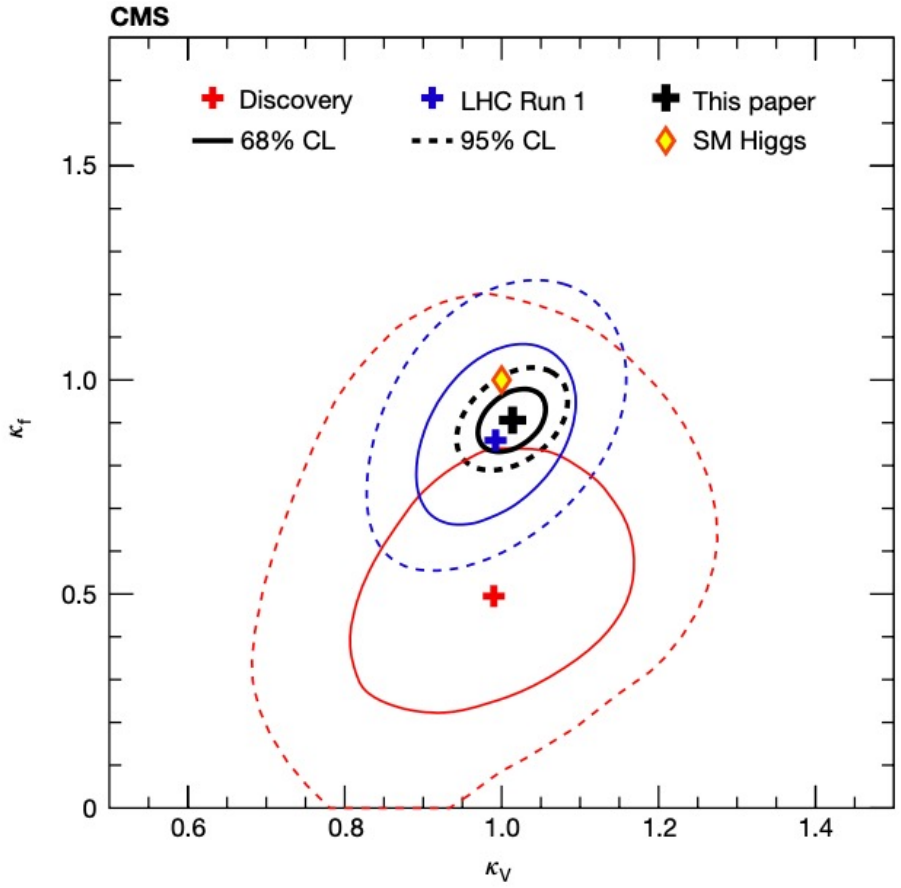
Couplings

Nature 607(2022)60

BSM physics in the loop



Vector and fermion couplings



BR_{inv} < 0.18 (0.10) at 95% C.L. (assuming $\kappa_V \leq 1$)

BR_{undet} includes non-standard decays, visible or invisible

⇒Results in agreement with SM (k_V=k_F=1)

Rare decays: H→μμ, cc

JHEP 01(2021)148, arXiv:2205.0550, arXiv:2211.14181

Study couplings to 2nd generation

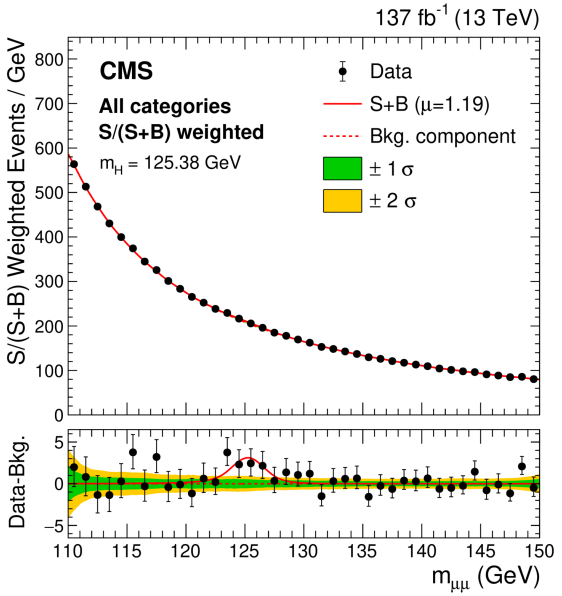
- H→μμ
  - Most sensitive category is VBF channel
  - Obs.(exp.): 3.0 σ (2.5σ)
- H→cc
  - Low cross section, need c-tagging
  - Use resolved (2jets) and merged (1jet),
  - Use ML and large jet substructure for tagging and classification
  - Validate using VZ production:

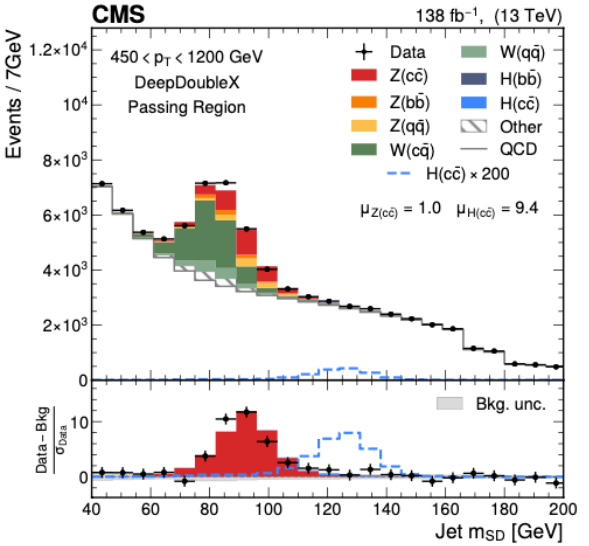
$$\mu_{VZ(cc)} = 1.01^{+0.23}_{-0.21}\ (5.7\sigma)$$

  - Set limits

$$\sigma\,(\mathrm{VH})\,\mathcal{B}\,(\mathrm{H}\to\mathrm{c\bar{c}}) < 0.94\,\mathrm{pb}$$

$$1.1 < |\kappa_c| < 5.5\ (|\kappa_c| < 3.4)$$





Coupling vs mass

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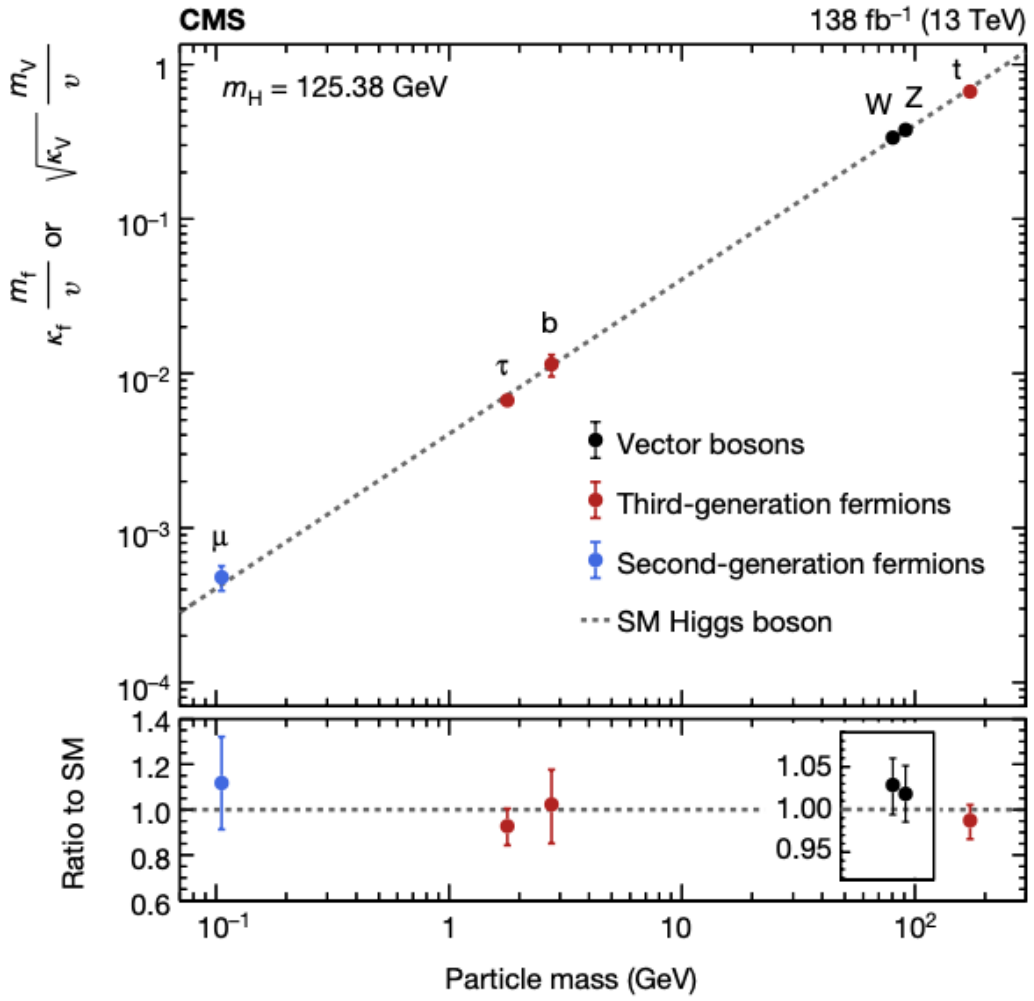
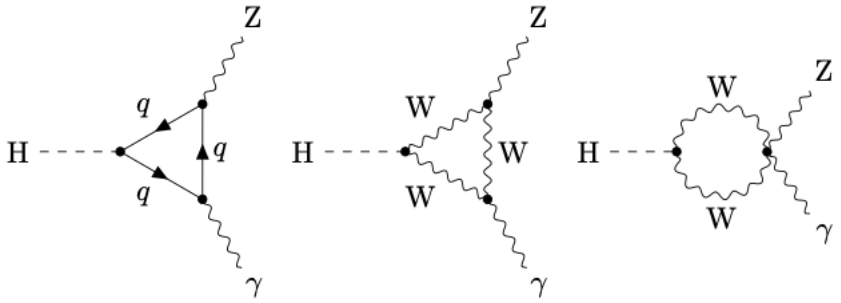


Rare decays: Z+photon

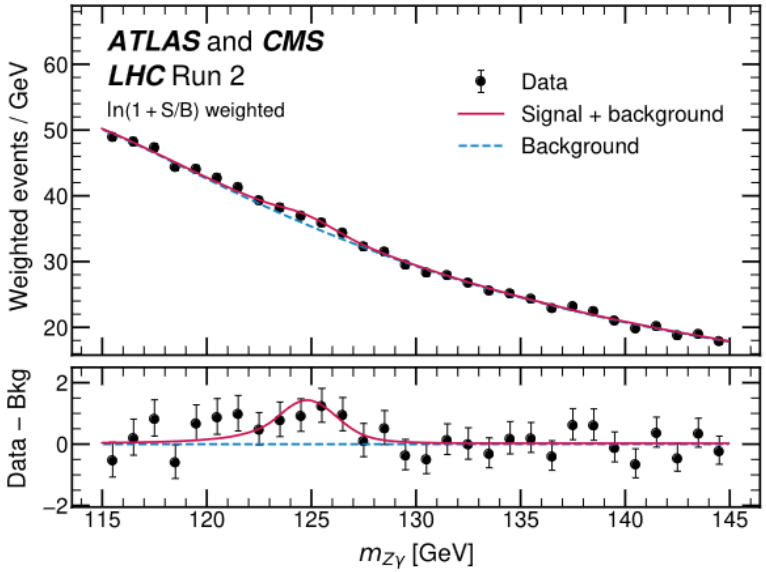
arXiv:2204.12945, PRL 132 021803

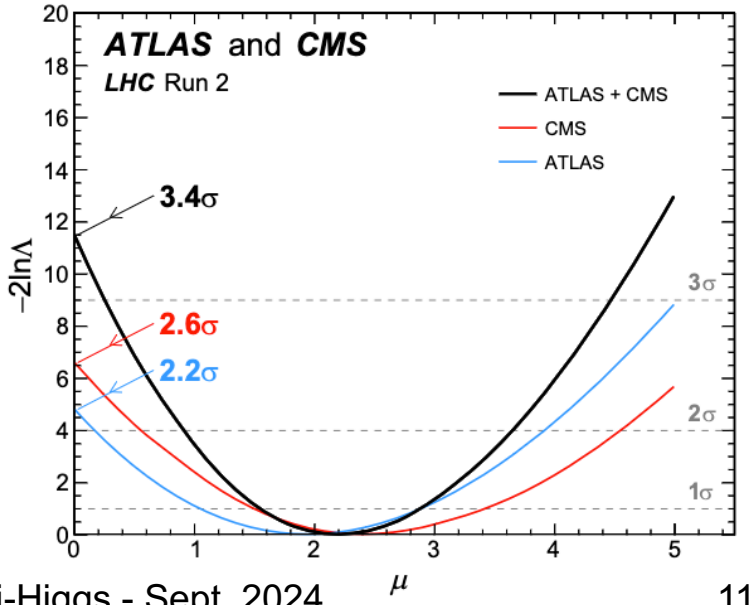
- New particles may contribute to internal loops
- Exploit different production modes
  - Tag Z⟶ℓℓ (ℓ=e,μ): most accessible experimentally

$$\sigma(\mathrm{pp} \rightarrow \mathrm{H})\mathcal{B}(\mathrm{H} \rightarrow \mathrm{Z}\gamma) = 0.21 \pm 0.08\,\mathrm{pb}$$



⇒ significance of 3.4σ (ATLAS+CMS)

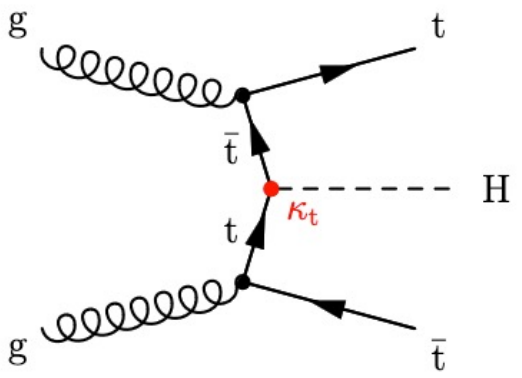


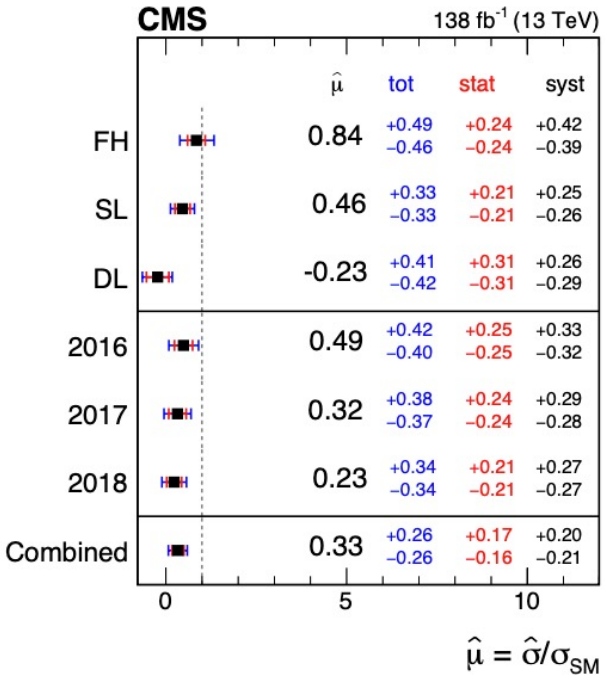


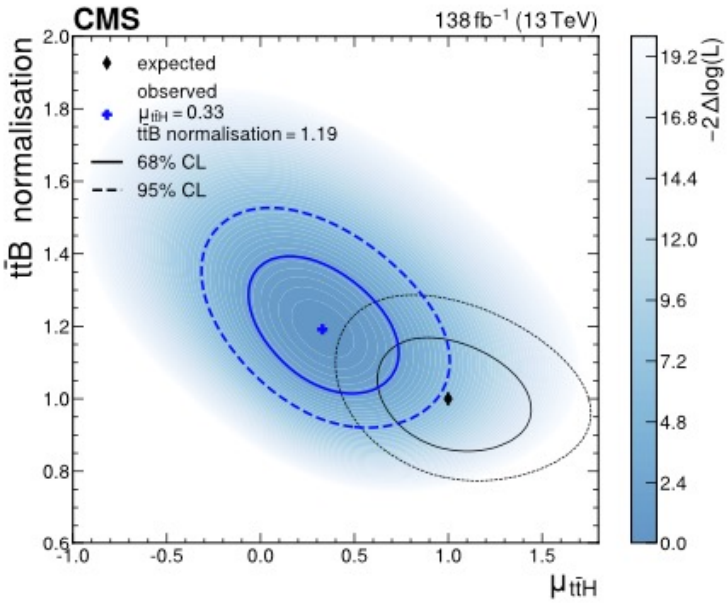
Higgs+Top: ttH(bb)

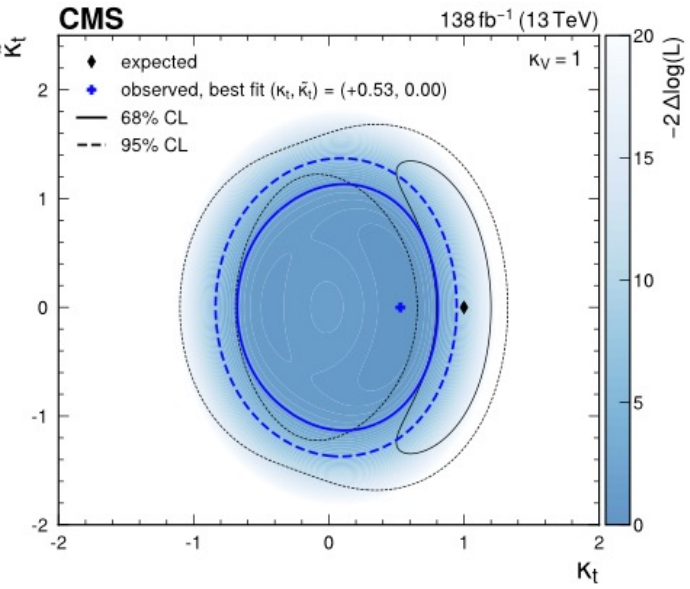
arXiv:2407.10896

- ttH offers direct access to top-H coupling
  - Higgs produced in association with one (tH) or two (ttH) top quarks in final states with electrons, muons
  - Study H→bb decays
  - Challenging due to irreducible bkg from ttbb
- Model-independent, signature-based





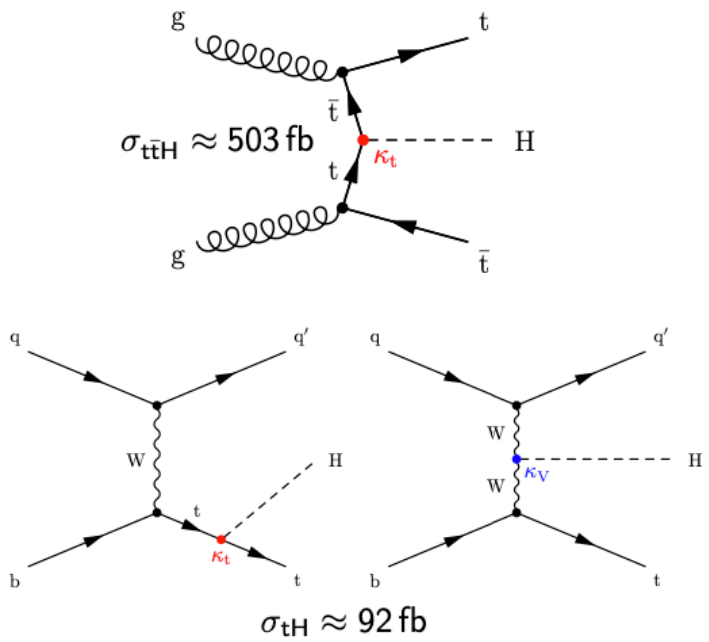


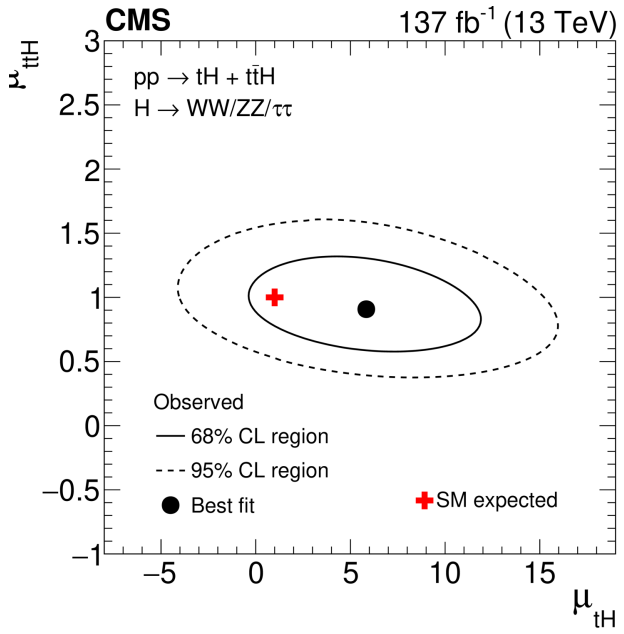


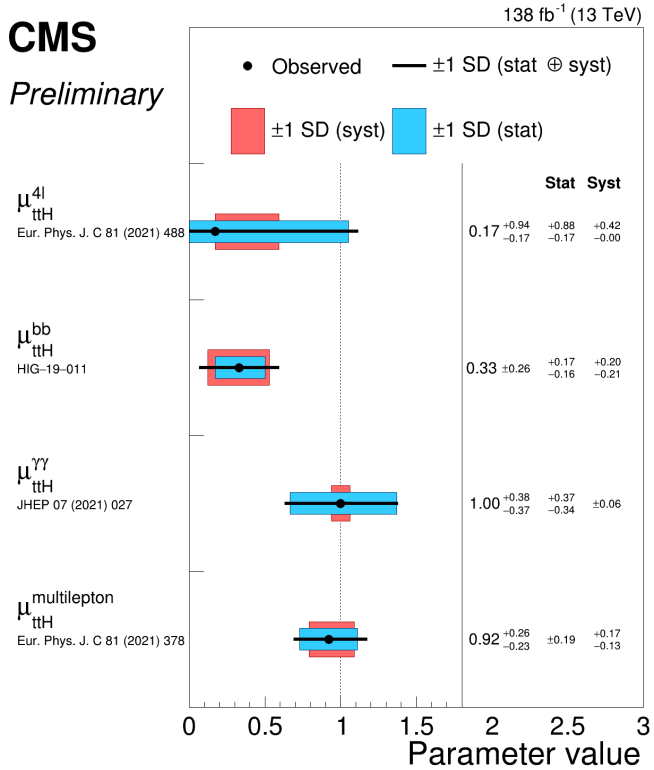
Higgs+Top: tH, ttH (cont.)

arXiv:2011.03652, CMS summary

- Crucial to SM tests and BSM searches
- Direct access to top-Higgs coupling
  - Also sensitive to CP-odd contributions in top-H coupling
- Challenge: small cross section wrt bkg
- tH and ttH production in many final states

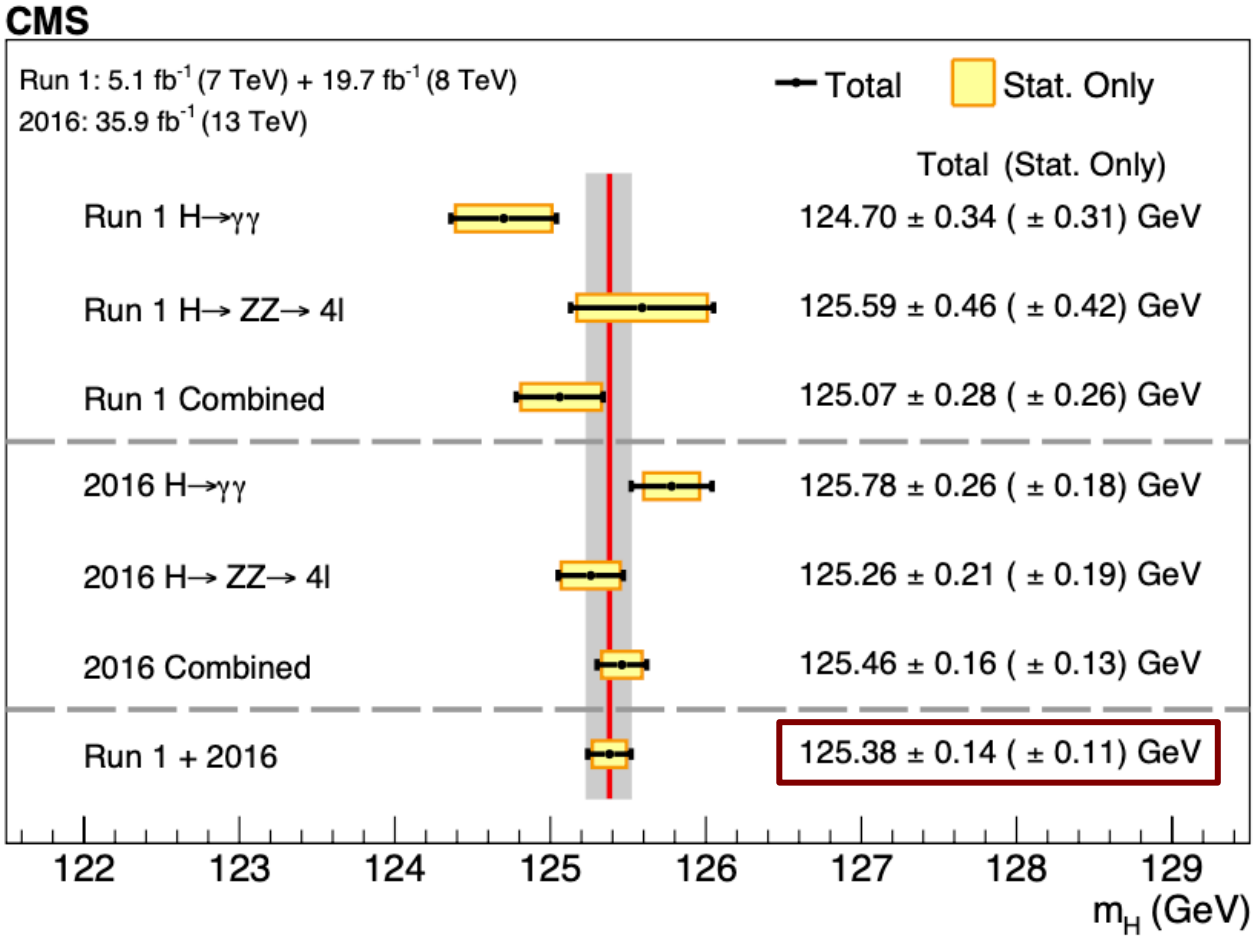






Higgs boson mass

PLB 805(2020)135425



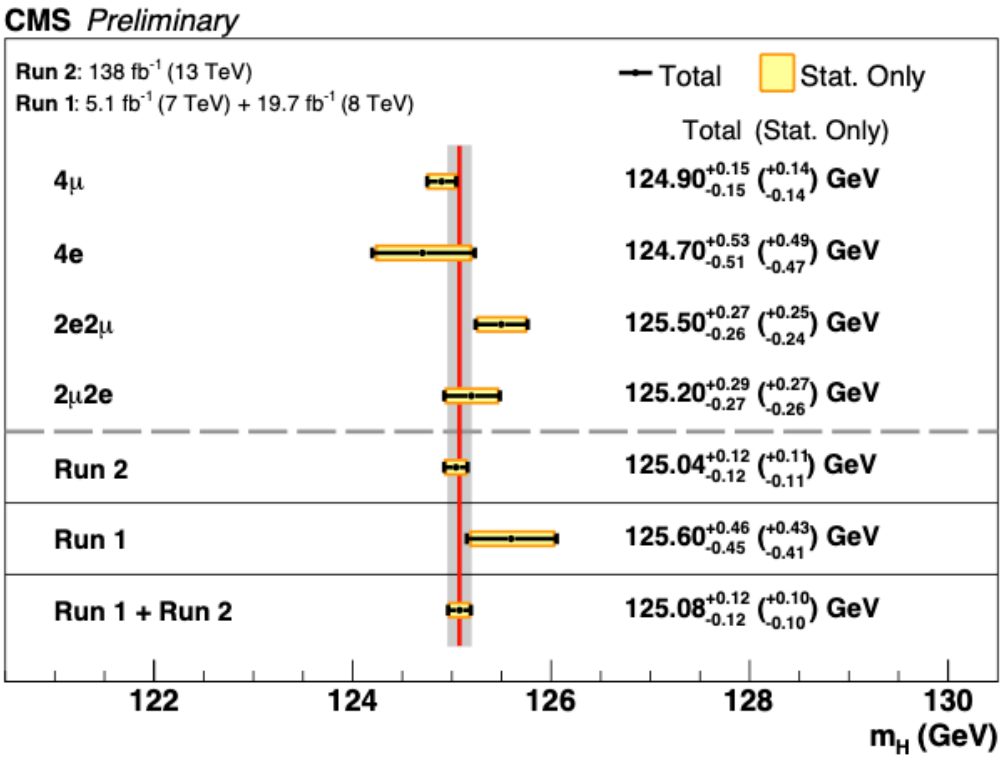
- Most accurate measurement in the $\gamma\gamma$ and 4ℓ channels
- Precision driven by statistics
  - soon energy scale and resolution systs will become dominant
- Some measurements still based on partial Run2 datasets

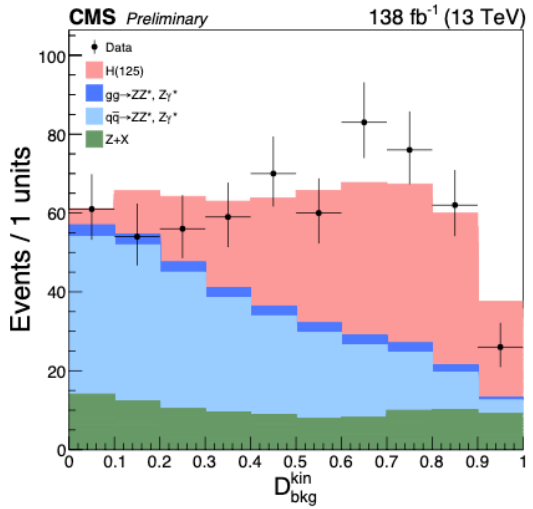
Uncertainty 140 MeV (0.11%)

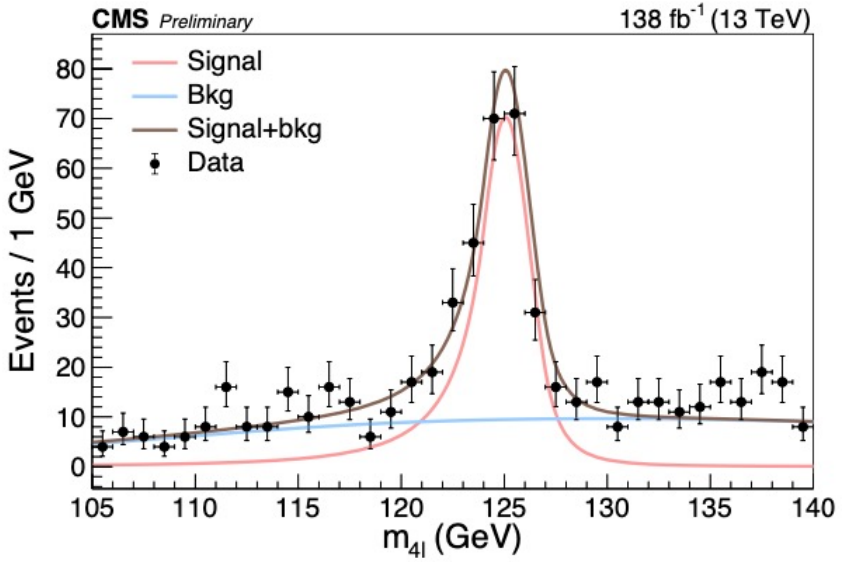
Higgs mass and width

arXiv:2202.06923, CMS-HIG-21-019

- H(4ℓ) small BR (1.24×10^{-4}) but clean final state
- Improved m_H measurement through better detector calibration, understanding of systematics
- Most precise single-channel measurement to date
  - precision at per-mille level







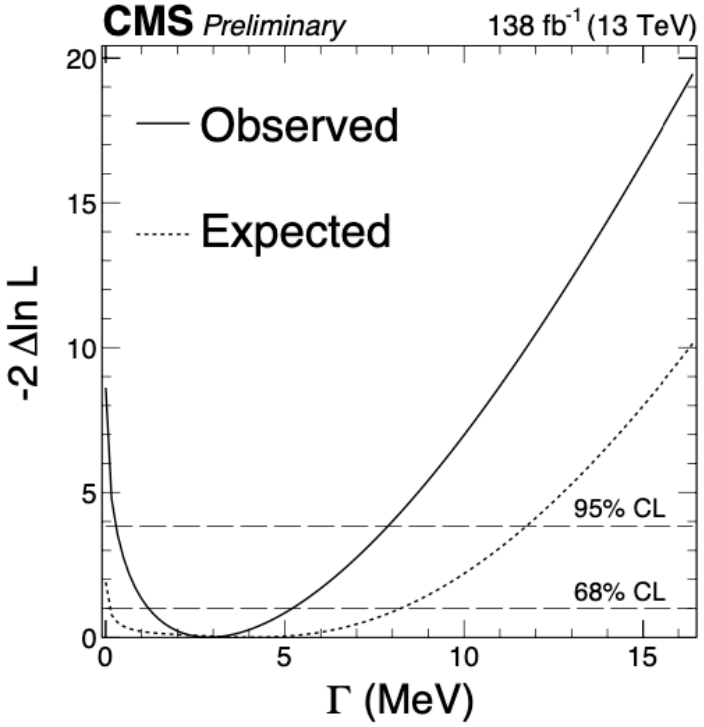
Higgs mass and width (cont.)

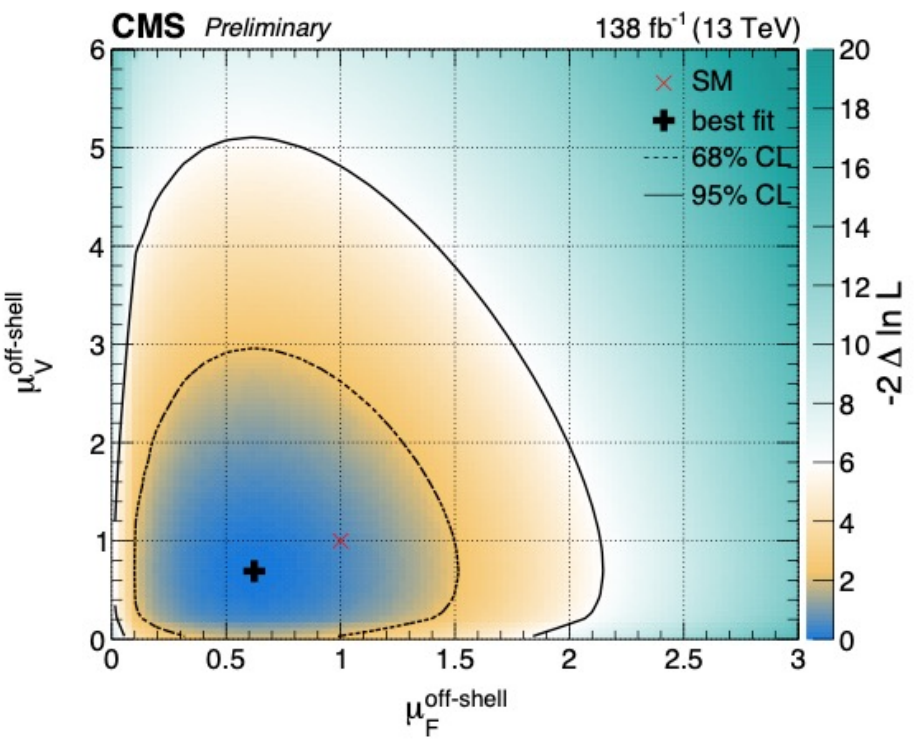
arXiv:2202.06923, CMS-HIG-21-019

- Couplings and width sensitive probes to BSM
  - Total width of 4.1MeV too small to measure directly
- Measure width by using off-shell production/decay: H(ZZ)
- Off-peak to on-peak ratio proportional to Γ_H

$$\frac{\sigma^{\text{off-shell}}_{\text{vv}\to\text{H}\to 4\ell}}{\sigma^{\text{on-shell}}_{\text{vv}\to\text{H}\to 4\ell}} \propto \Gamma_{\text{H}}$$

$$\Gamma_{\text{H}} = 2.9^{+2.3}_{-1.7}\,\text{MeV}$$





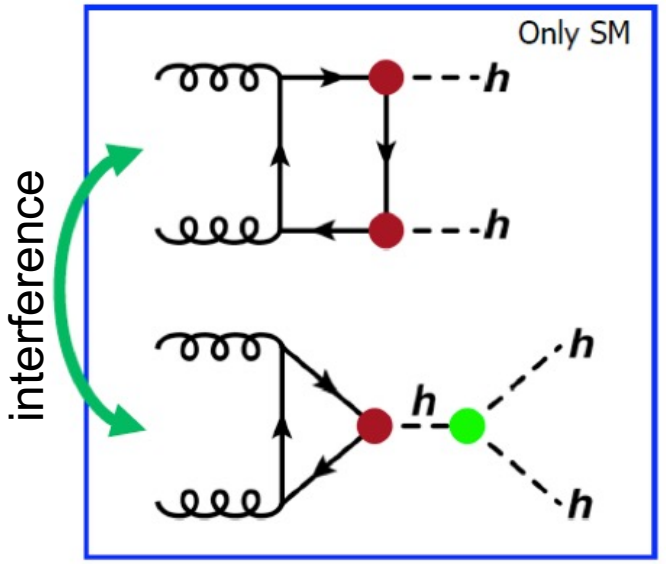
di-Higgs searches

- Self-coupling measurement
- Destructive interference in SM
  - Could be altered in BSM
  - If constructive, it could be large enhancement
- In SM, only σ=31fb at 13 TeV
- Study different final states

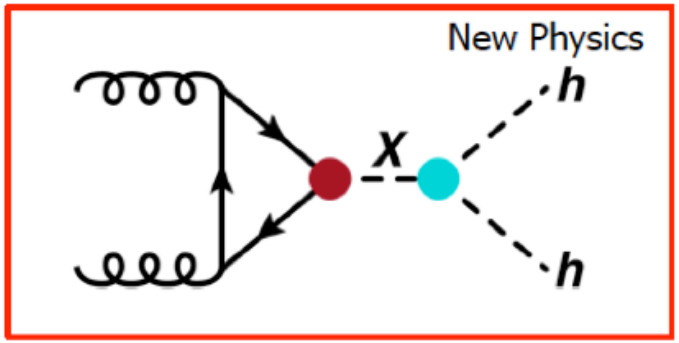
(X→)hh→		BR	Mass scale
	bbbb	34%	High
	bbττ	7.3%	
	bbWW	27%	
	bbγγ	0.26%	Low

$$V(h) = V_0 + \underbrace{\frac{1}{2}m_H^2 h^2}_{\text{Mass Term}} + \underbrace{\lambda_{hhh} v h^3}_{\text{HH production}} + \underbrace{\frac{1}{4}\lambda_{hhhh} h^4}_{\text{HHH production}}$$

non-resonant production

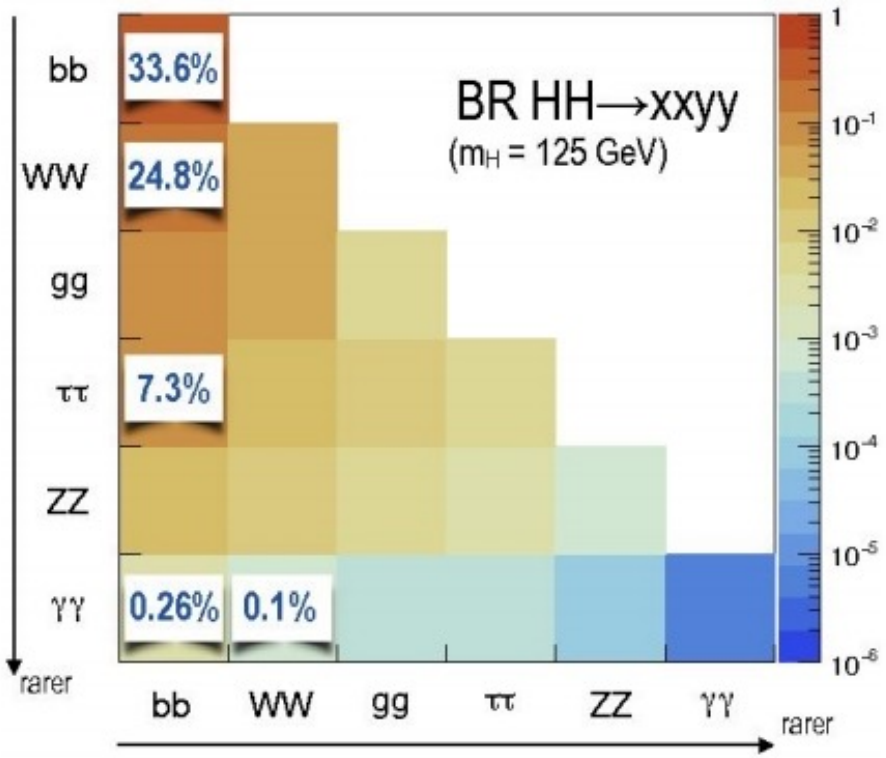


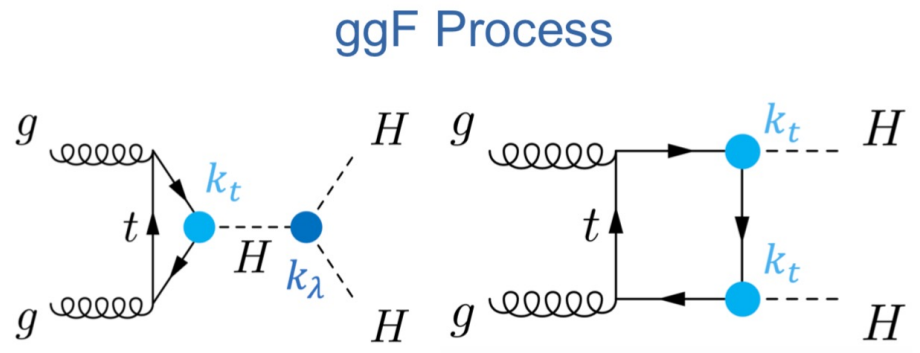
resonant production

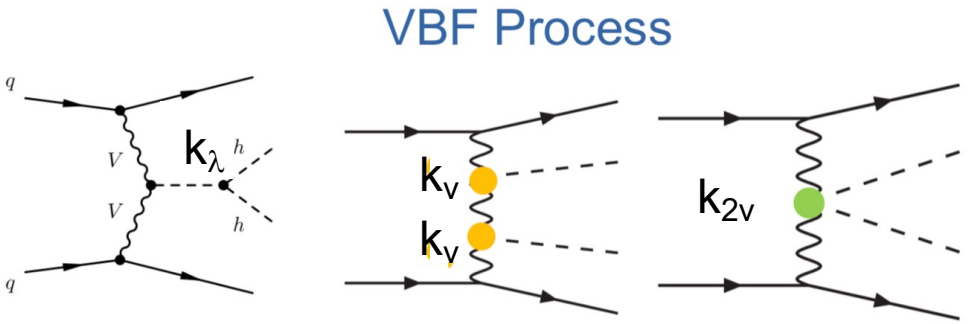


HH: Non-resonant production

- Higgs pair production @13 TeV
  - ggF σ=31 fb
  - VBF σ=1.7 fb
- Test non-resonant BSM models with anomalous couplings





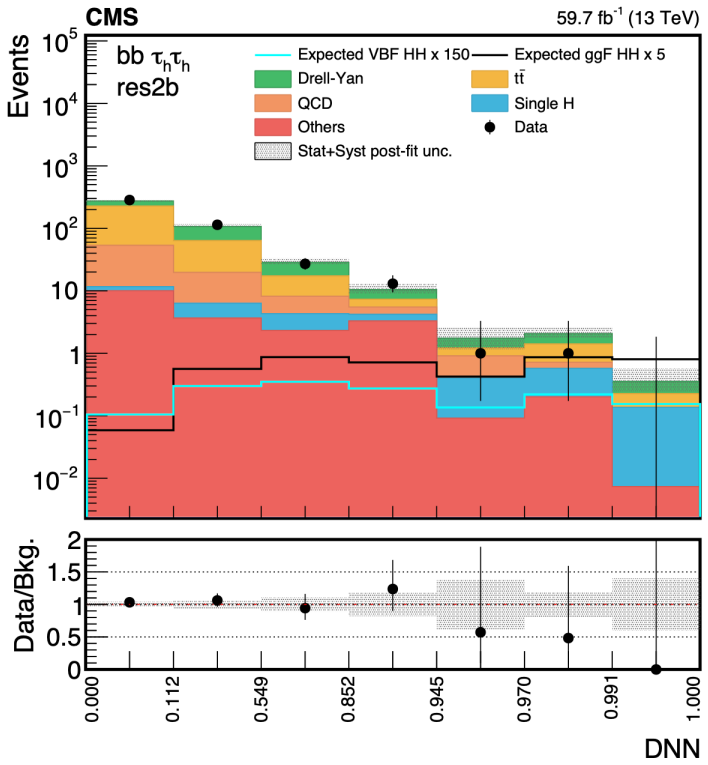


What is new in HH searches

arXiv:2206.09401, CMS-B2G-21-001

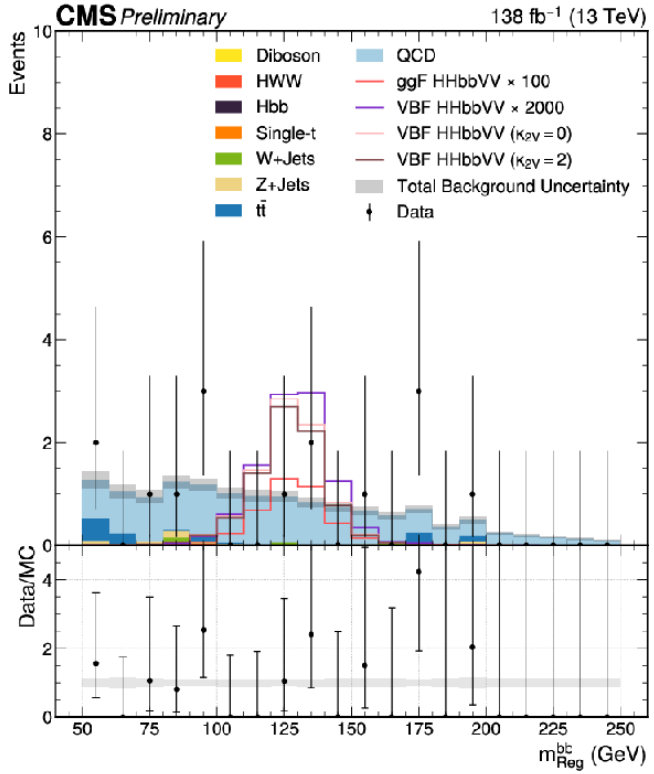
- Results are better (x2-3) than 2016 results alone after scaling for luminosity

Extensive use of ML tools



DNN score for resolved ggHH(bbττ) category

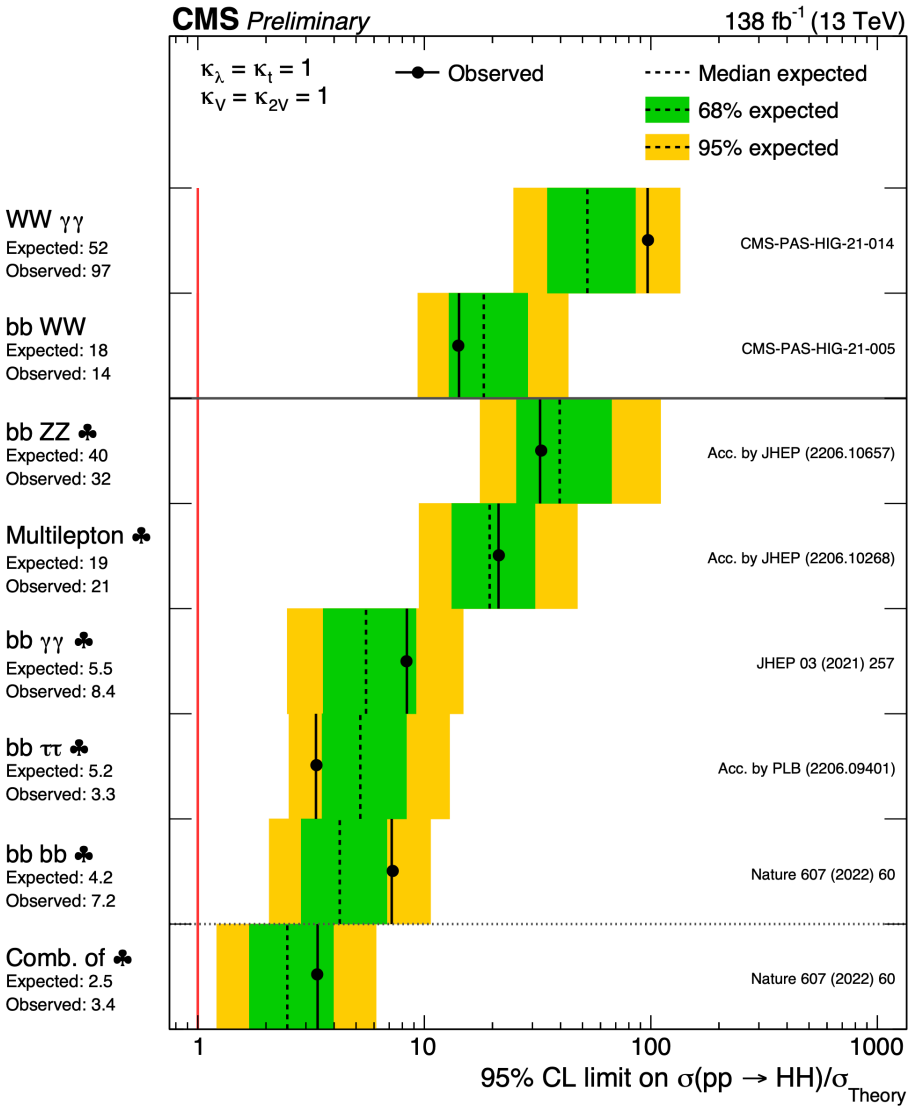
Boosted topologies

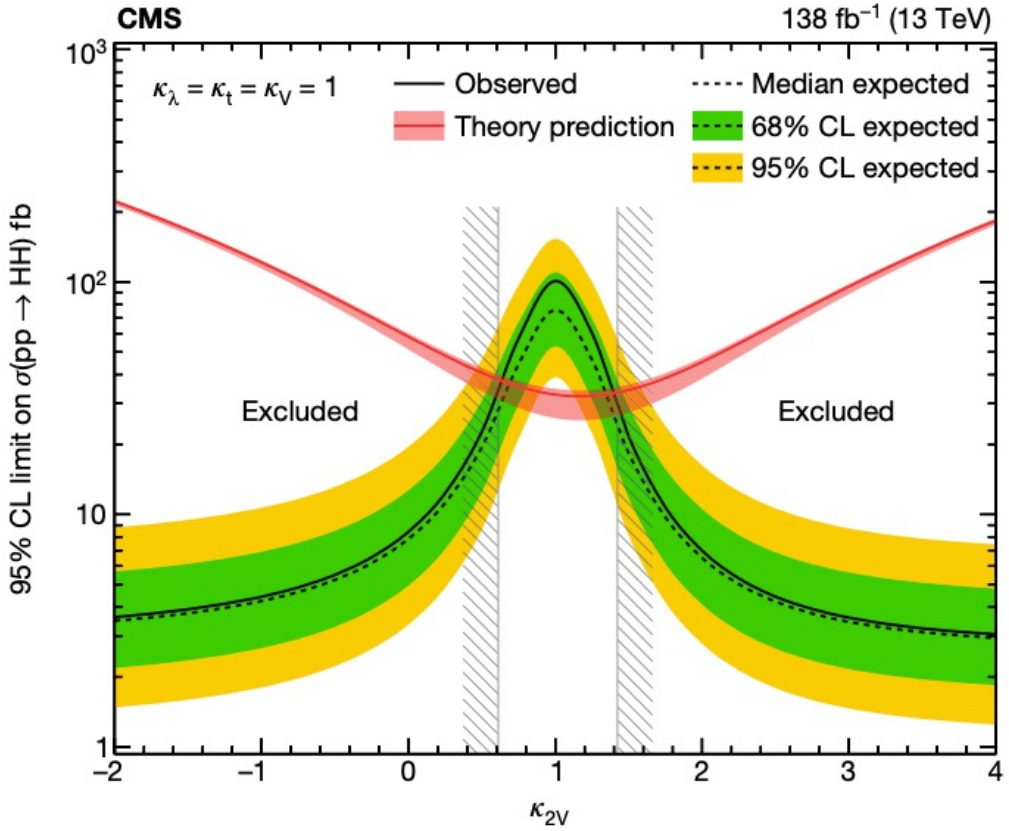


Regressed mass of one AK8 jet in a HH(VVbb) boosted category

HH: Results

Nature 607(2022)60



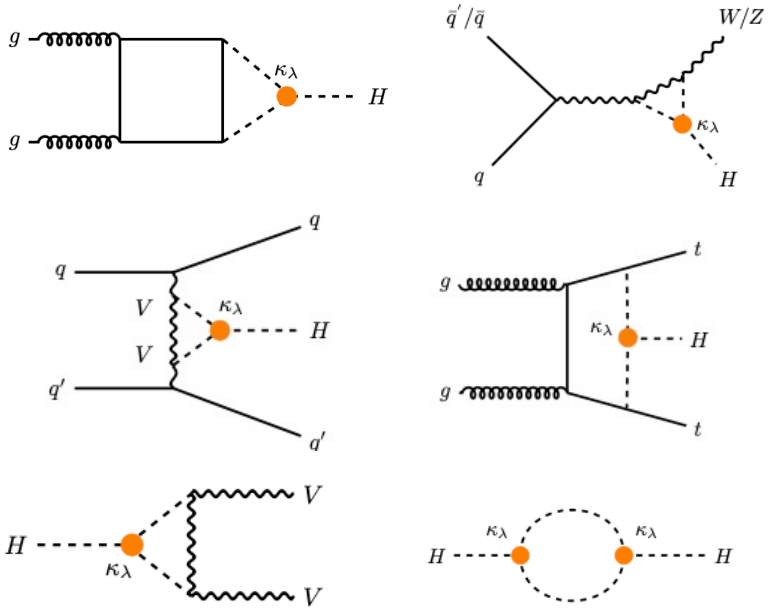


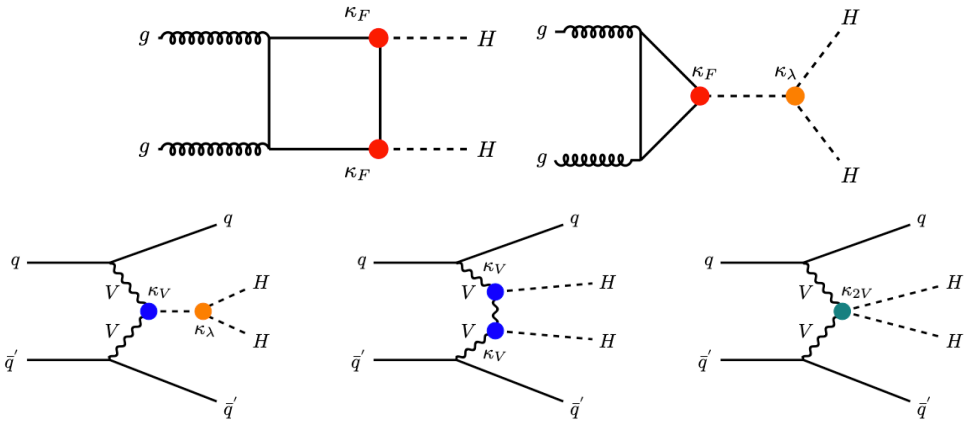
Combined sensitivity:

- $k_\lambda \in [-1.24, 6.49]$
- $k_{2V} \in [0.67, 1.38]$

Self-coupling: H and HH

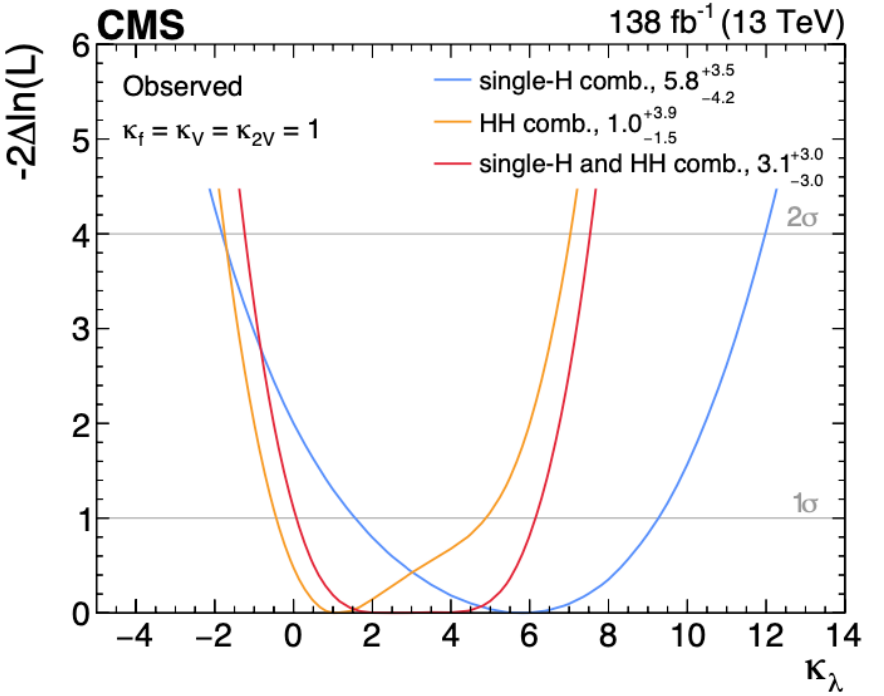
arXiv:2407.13554





- Set constraints on H self-coupling
- Use H and HH results:
  - HHVV coupling (k_{2V}) affects VBF HH mechanism
  - H: Use NLO EWK corrections

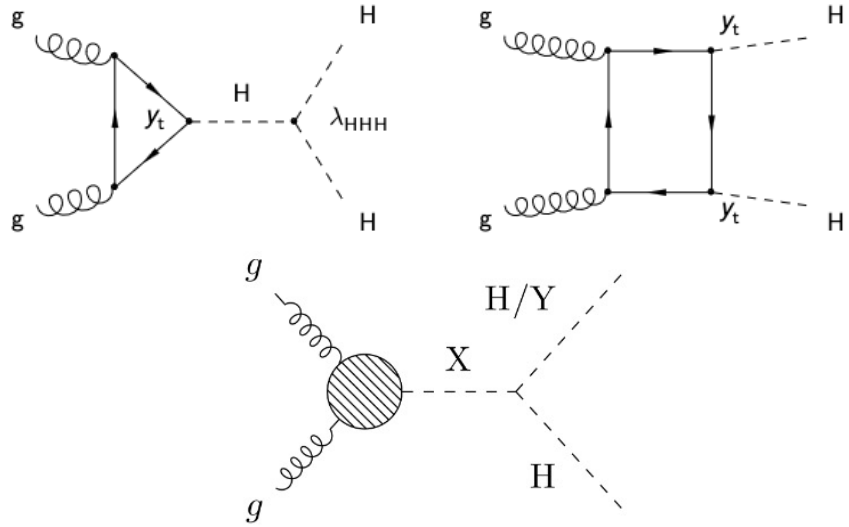
$\Rightarrow k_\lambda \in [-1.2, 7.5]$ @95%CL



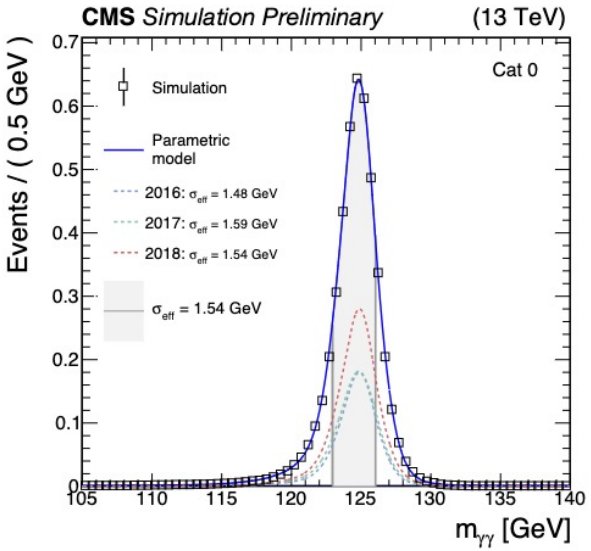
HH: Resonant searches

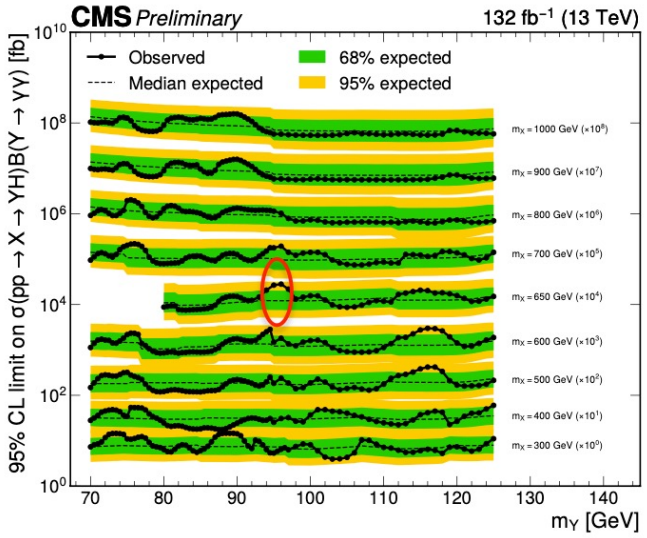
CMS-HIG-22-012

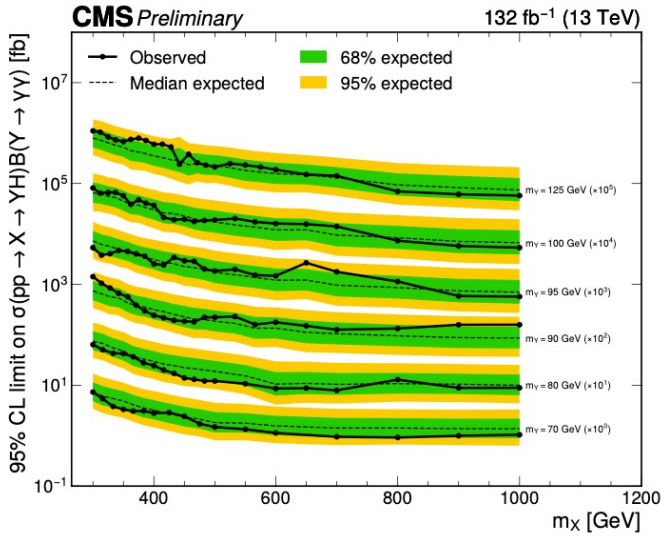
- $X \to YH(\tau\tau\gamma\gamma)$
- Probe additional heavy scalar
  - Clean exp. signature w/good mass resolution: $\gamma\gamma$
  - Perform fits to $m_{\gamma\gamma}$
- Set limits on HH resonant production
  - Max deviation 3.4(0.1)σ for m_Y~95GeV, m_X=650GeV
- Non resonant: self-coupling, $k_\lambda \in [-13,18]$



low mass: $X \to Y(\gamma\gamma)H(\tau\tau)$

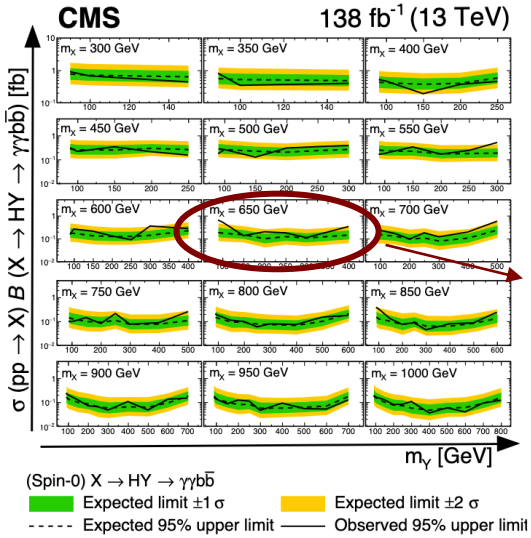




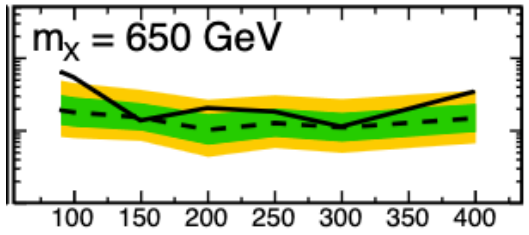


Consistency with SM

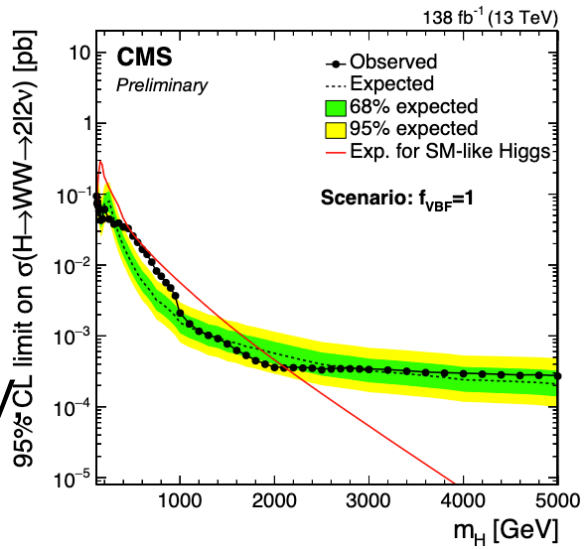
arXiv:2310.01643, CMS-HIG-20-016, arXiv:2208.02717, CMS-HIG-20-002



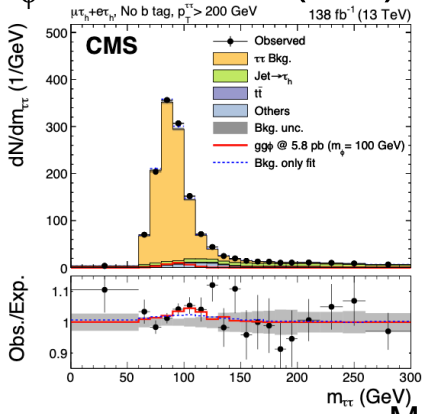
X→Y(bb)H(γγ) for
m_X=650GeV,
m_Y=90GeV, 3.8(2.8)σ

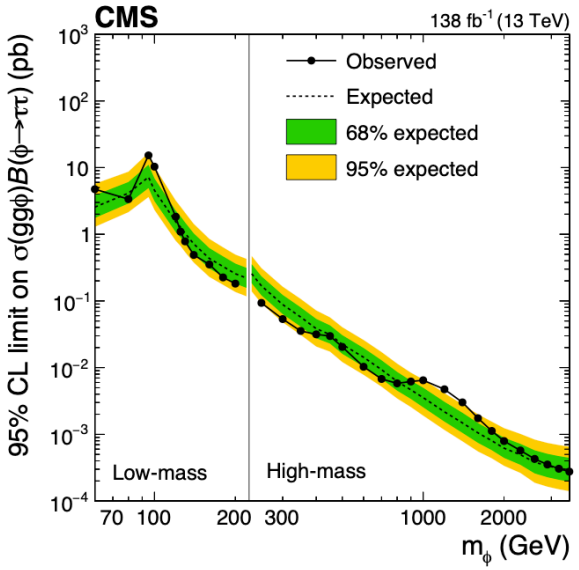


Heavy Higgs:
X→WW (2ℓ2ν)
at m_X=650GeV
3.8(2.6)σ

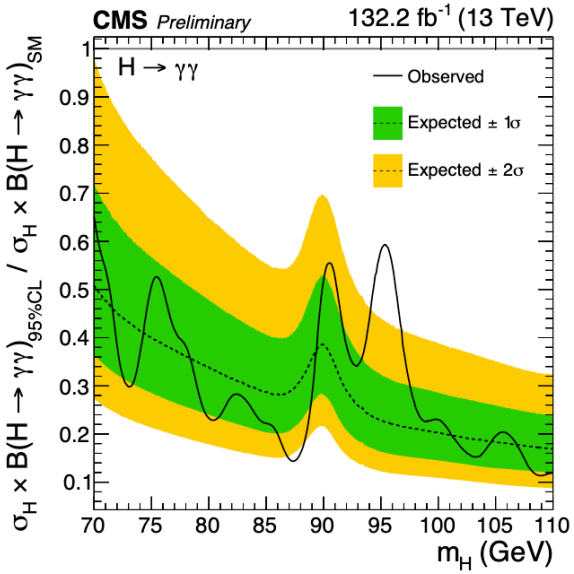


Scalar: ϕ→ττ
m_ϕ~100GeV 3.1(2.7)σ
m_ϕ~1TeV, 2.8(2.2)σ



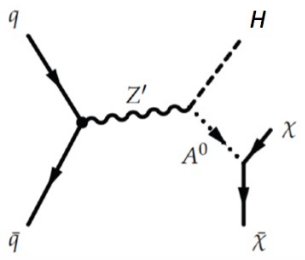


Light Higgs:
$h\to\gamma\gamma$ at
m_h~95GeV,
2.9(1.3)σ

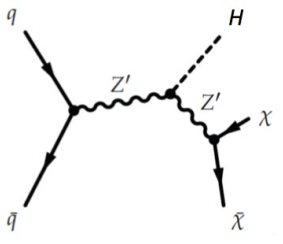


DM searches with Higgs bosons

- Higgs as portal to Dark sector
  - New massive particle mediates the Higgs-DM interaction
- H(125) may mix with new dark mediators
  - DM particles could get mass through Higgs mechanism
- Study scenarios where Higgs is involved

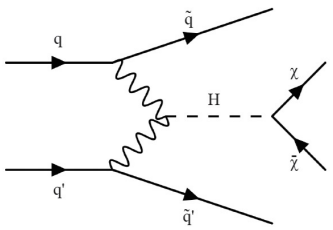


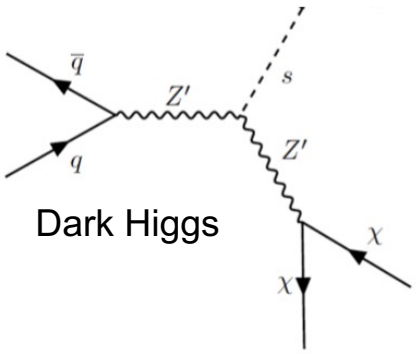
Z' – 2HDM



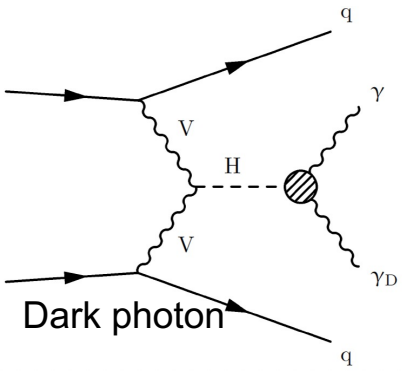
Z' – baryonic

Invisible Higgs





Dark Higgs



Dark photon

Mono-Higgs

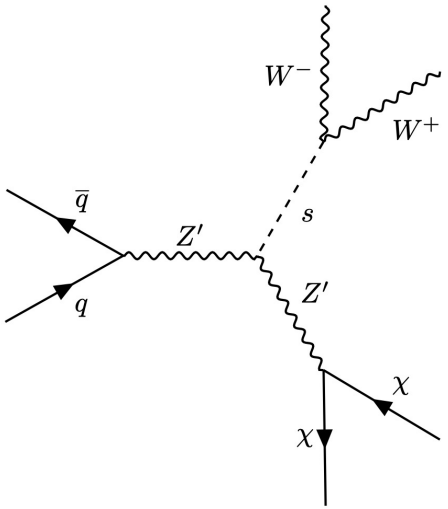
- Generic search: pp→H+MET
- ISR suppressed due to small coupling to H
- Signature: Higgs+MET ⇒ H used as a tag
- Final states (WW,ZZ,bb,ττ,γγ)

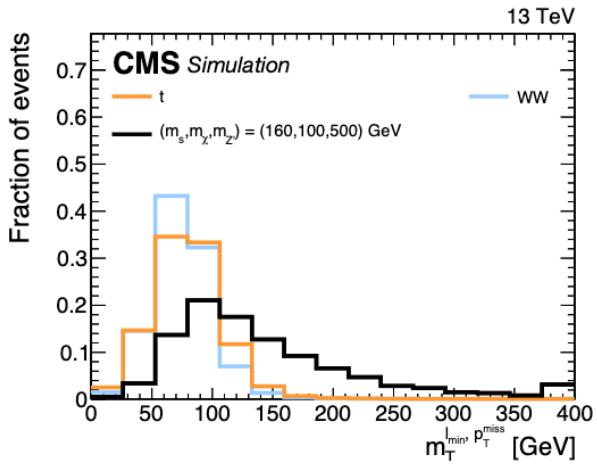
Dark Higgs & Dark photon

arXiv:2310.12229, arXiv:1908.02699, arXiv:2009.14009, arXiv:2405.13778

Dark Higgs

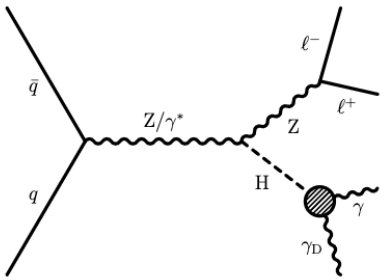
- DM particle acquire mass through interaction with a dark Higgs (s)
- WW decay dominates for m_s>160GeV
  - leptonic final state (2ℓ2ν, 2ℓ2q)
- Observable: m_T(ℓ,MET)

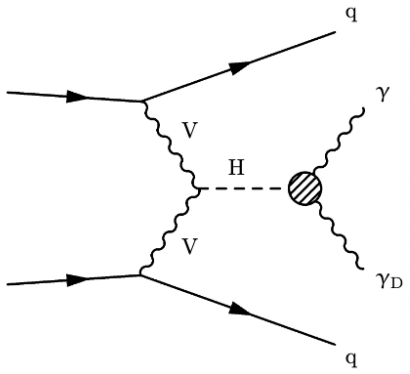


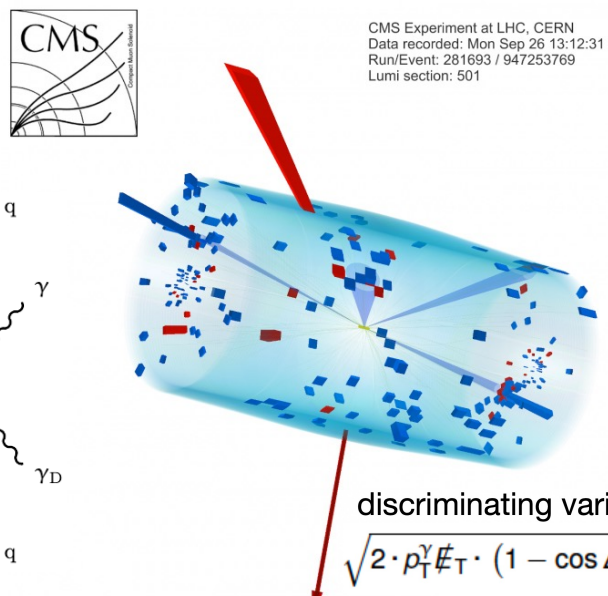


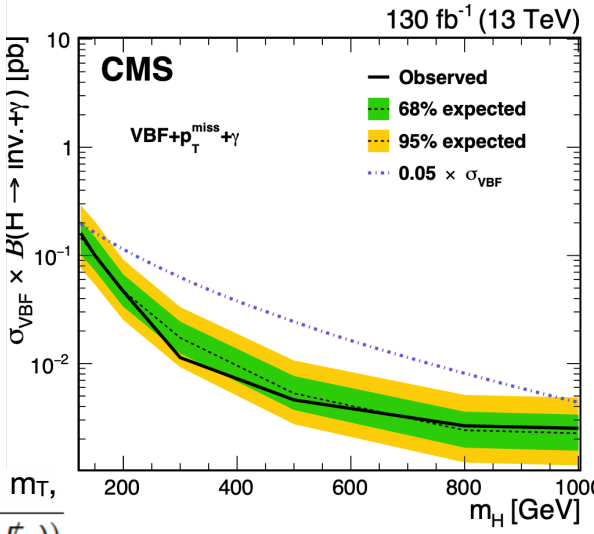
Dark photon

- Search in ZH & VBF events







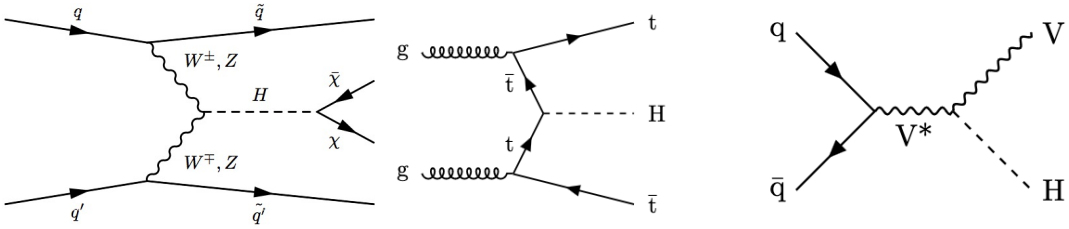


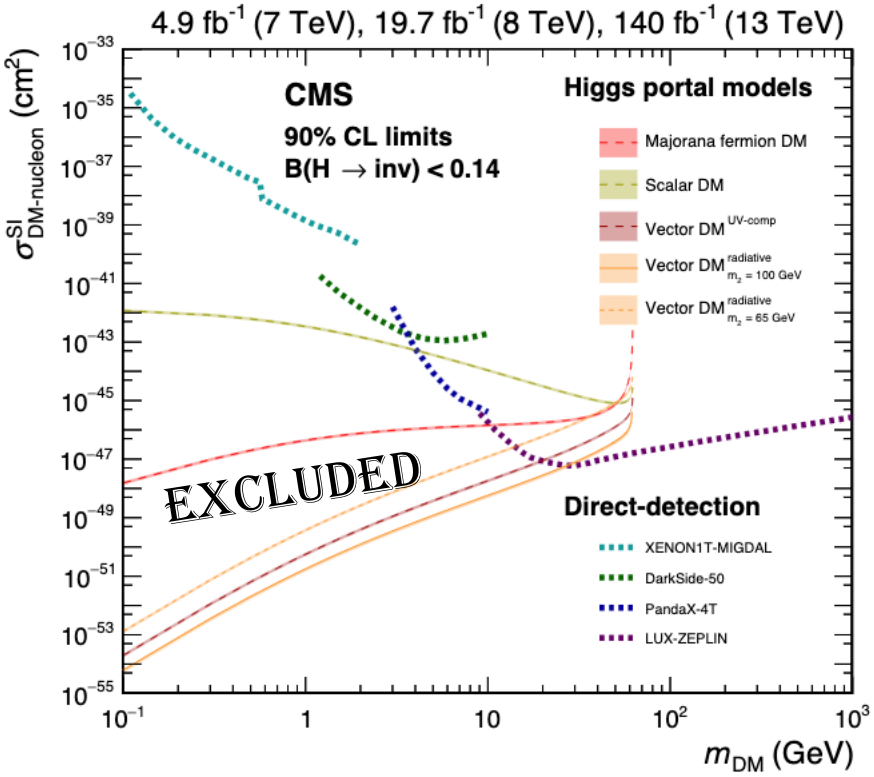
DM: Higgs invisible decays

arXiv:2201.11585, arXiv:2303.01214

- In the SM, BR(H→inv) is ~0.1%
- Search for Higgs invisible decays in VBF and associated production
  - Select large MET and 2-jet events with large $\Delta\eta(jj)$
  - Fit to dijet invariant mass distributions
- Combination of ggH, V(jj)H, and Z($\ell\ell$)H, ttH production modes
- Set limits on DM models
  - Upper limits: 0.15(0.08exp)@95%CL
- Limits interpreted in the context of Higgs portal models

⇒ Competitive limits for low-mass DM candidates

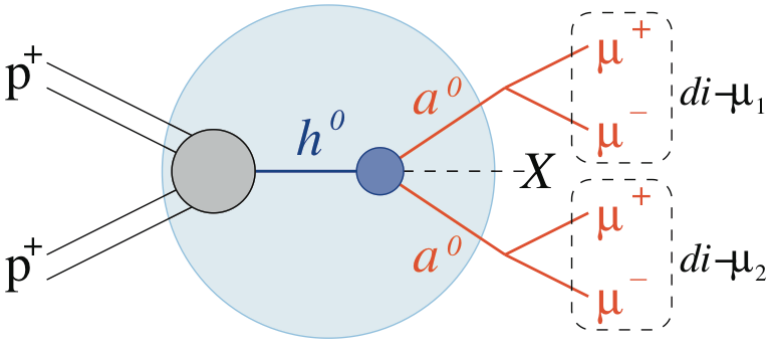




non-SM Higgs decay: h→aa→4X

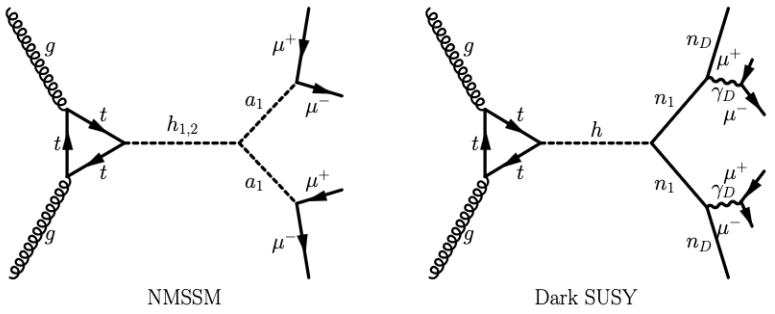
arXiv:2407.20425, arXiv:2403.10341

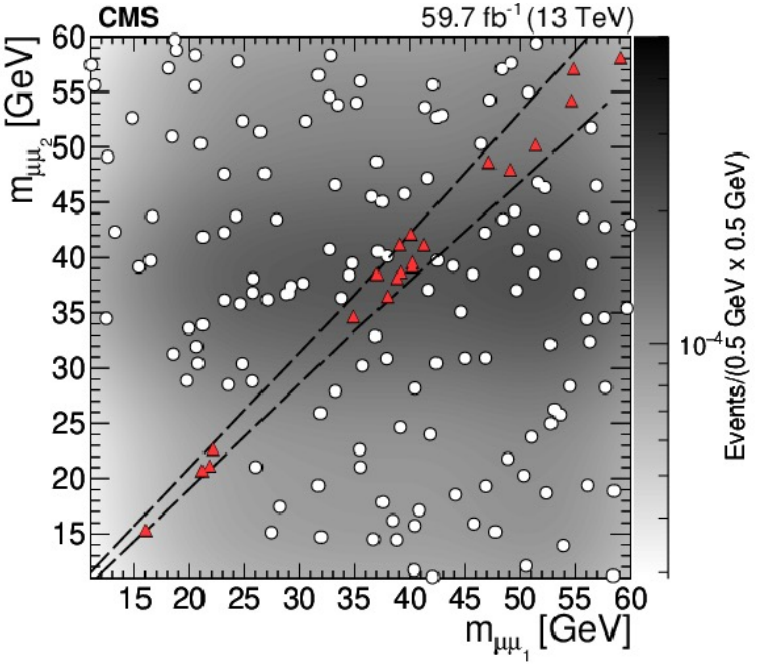
- Explore non-SM decays of a Higgs boson (h)
  - Higgs boson (h) can be SM or not
  - include production of two new light boson (a^0)
- Search for generic Higgs decays: h→2a+X→4μ+X
  - Require two dimuon pairs with consistent masses
  - Limits on production rates, benchmark models
- (similar search: 4b final state)



Results interpreted in NMSSM and dark SUSY

- Dark SUSY: h decay to pair of neutralinos (n_1): LSP
- NMSSM: add a complex singlet field (1 CP-even+1 CP-odd boson)

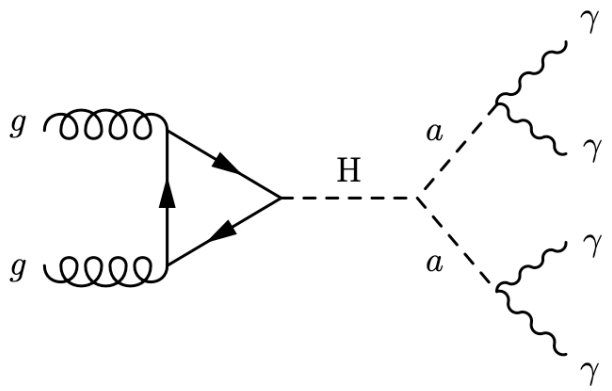




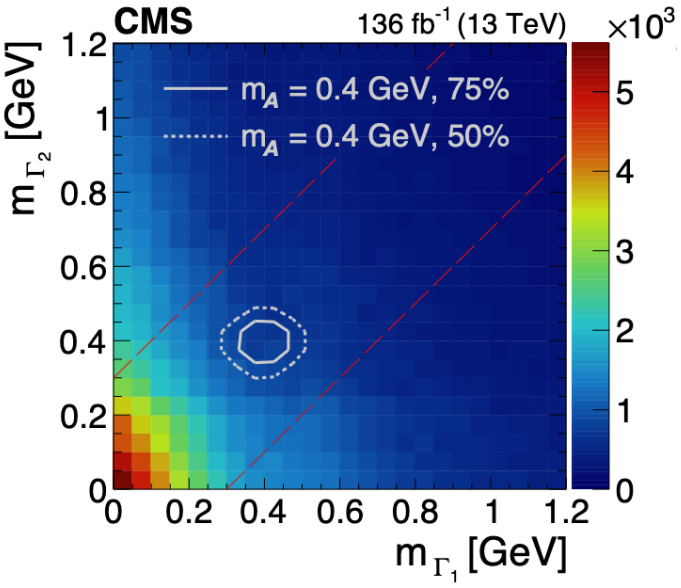
Exotic: H→AA→4γ

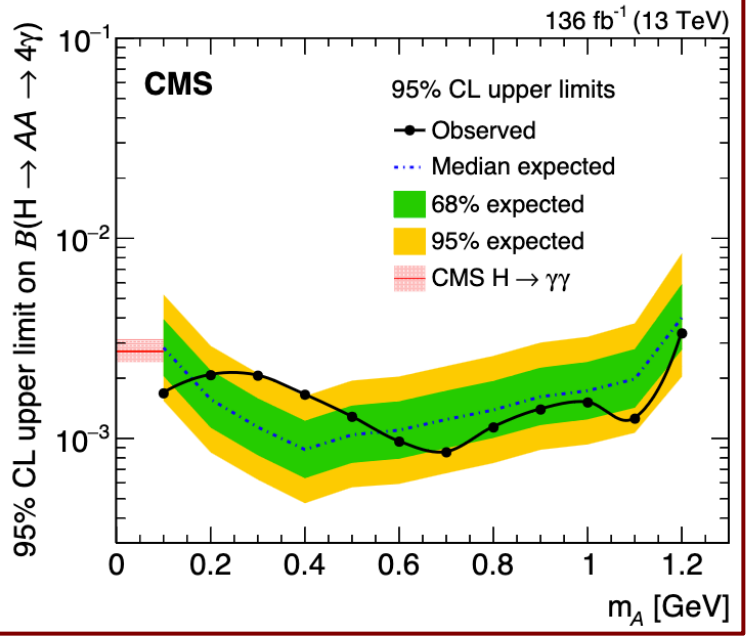
arXiv:2209.06197, arXiv:2208.01469

- Exotic Higgs decay to light pseudo-scalar A
  - Motivated in BSM extensions (ALPs, DM, etc)
  - Merged γγ reconstructed as single γ-like object
  - Resolved and boosted topologies
- Model-independent search

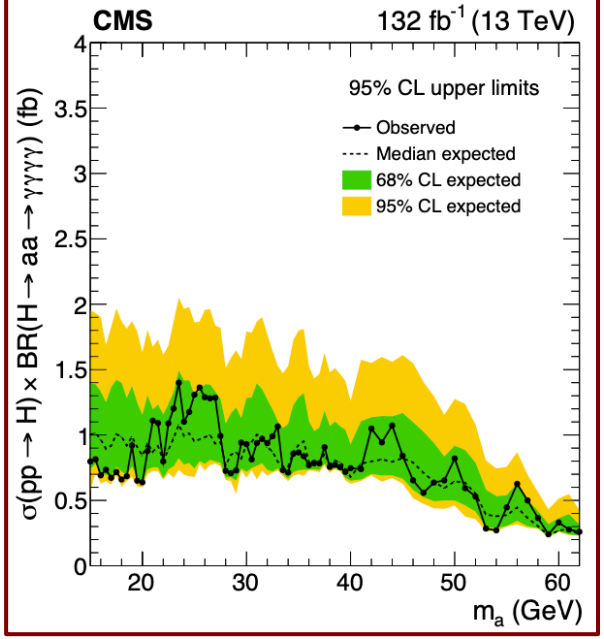


boosted





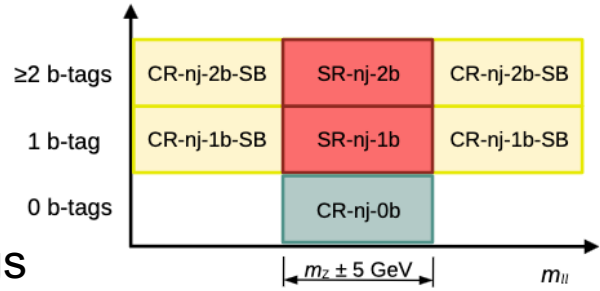
resolved



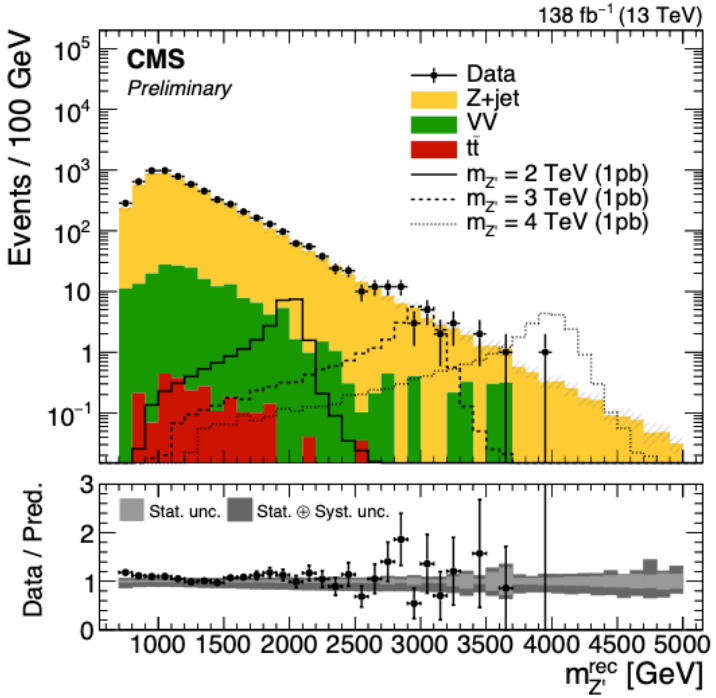
Heavy resonance search: ZH

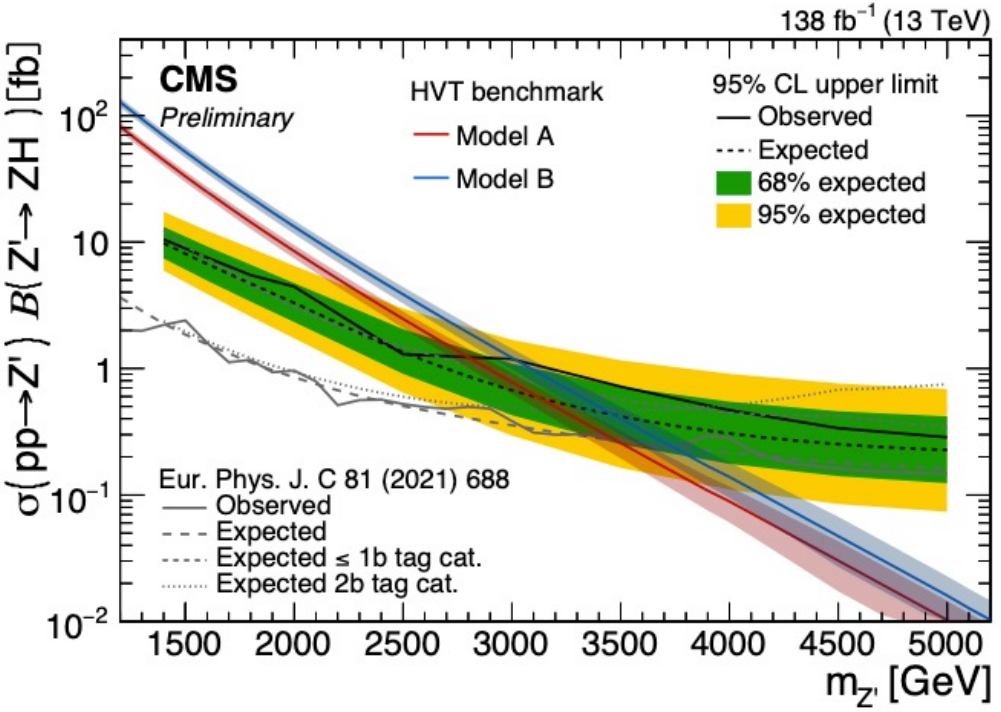
CMS-B2G-23-008, B2G-23-006

- Search for heavy resonance: Z(ℓℓ)H
  - H → cc or VV(4q)
  - H as AK8 jet recoiling against Z
  - Jet substructure to discriminate vs bkg (DNN)
  - H→ttbar
  - Event categories: leptons, b-tags



- Reconstruct invariant mass of ZH system



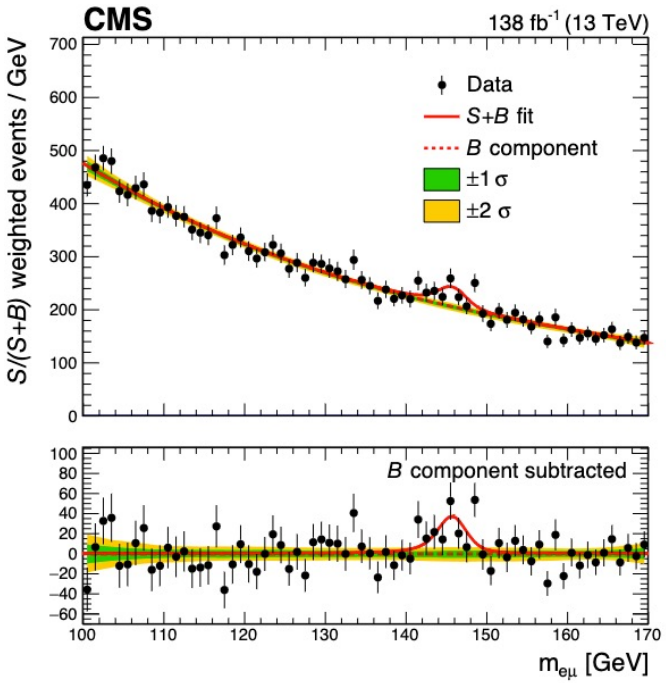


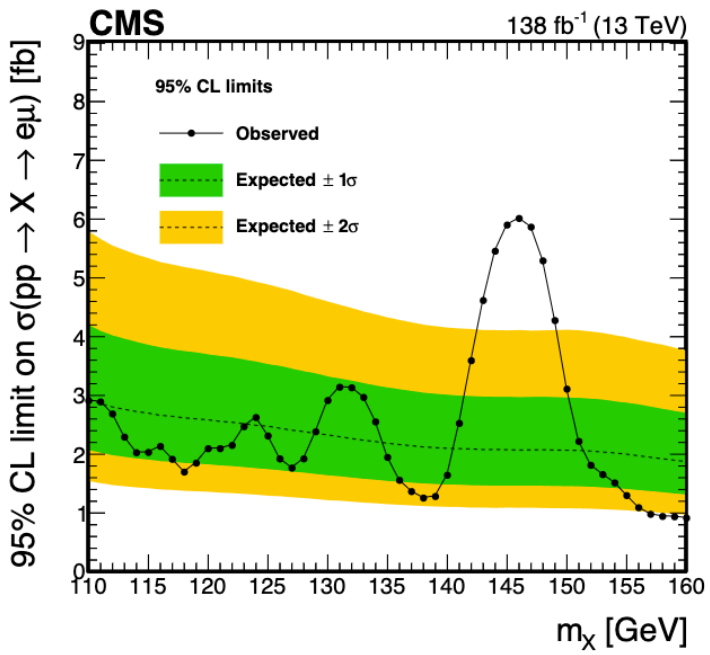
LFV in Higgs decays

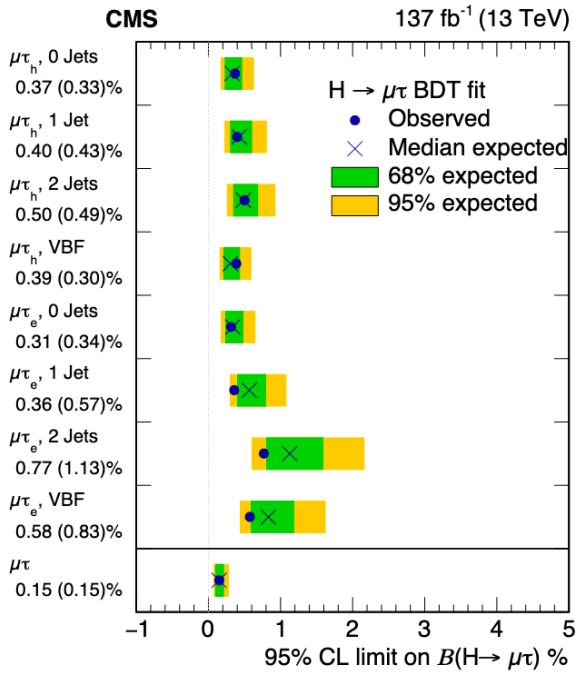
arXiv:2105.03007, arXiv:2305.18106

- Some BSM models allow for LFV Higgs decays
- Search for H→eτ, eμ, μτ final states
- Categories: N_{jet}, lepton kinematics
  - N_{jet} to target ggH and VBF production
- Largest excess at $m_{e\mu}$=146GeV, 3.8(2.8)σ

	Observed (expected) upper limits (%)	Best fit branching fractions (%)	Yukawa coupling constraints
$H \to \mu\tau$	<0.15 (0.15)	0.00 ± 0.07	$< 1.11\,(1.10) \times 10^{-3}$
$H \to e\tau$	<0.22 (0.16)	0.08 ± 0.08	$< 1.35\,(1.14) \times 10^{-3}$



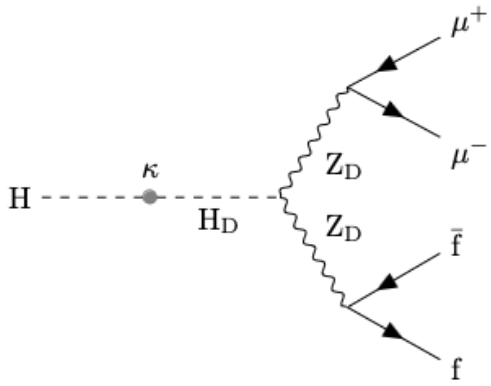


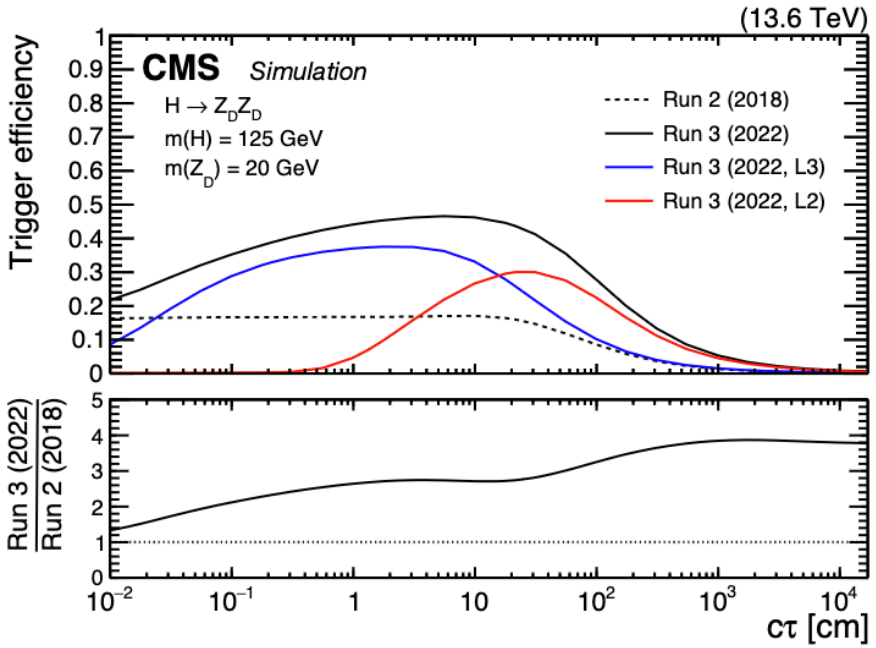


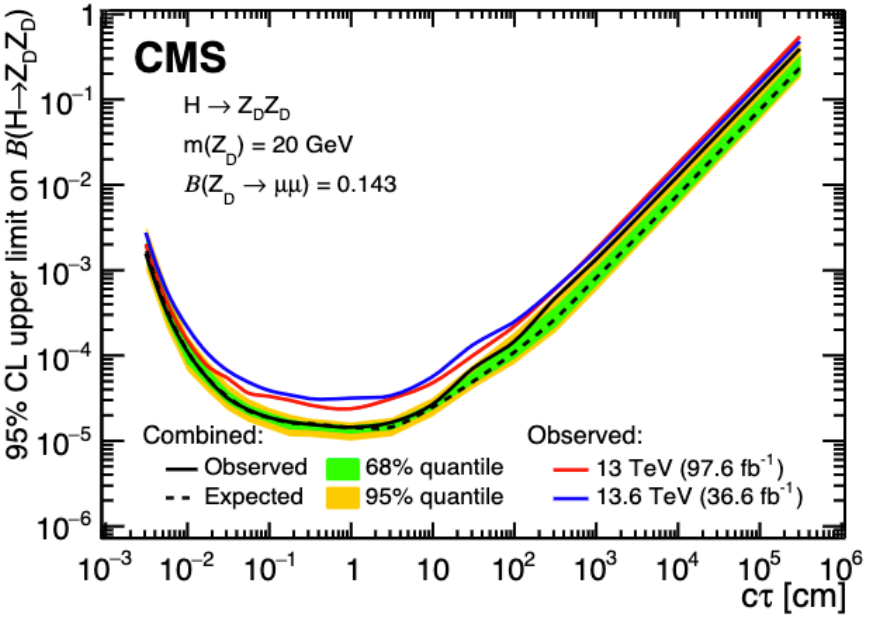
Long-lived: Higgs portal

arXiv:2402.14491

- Production of long-lived dark photons Z_D via Higgs portal
- H-H_D mixing with parameter κ
- Higgs decaying to long-lived scalars
  - Scalars decay to fermion final states in the muon chambers
  - Displaced dimuon originating from secondary vertex
- Resulting bounds are interpreted in context of LL decays







Run 3 improvements: The present

CMS-DP-2023-050, CMS-DP-2024-064

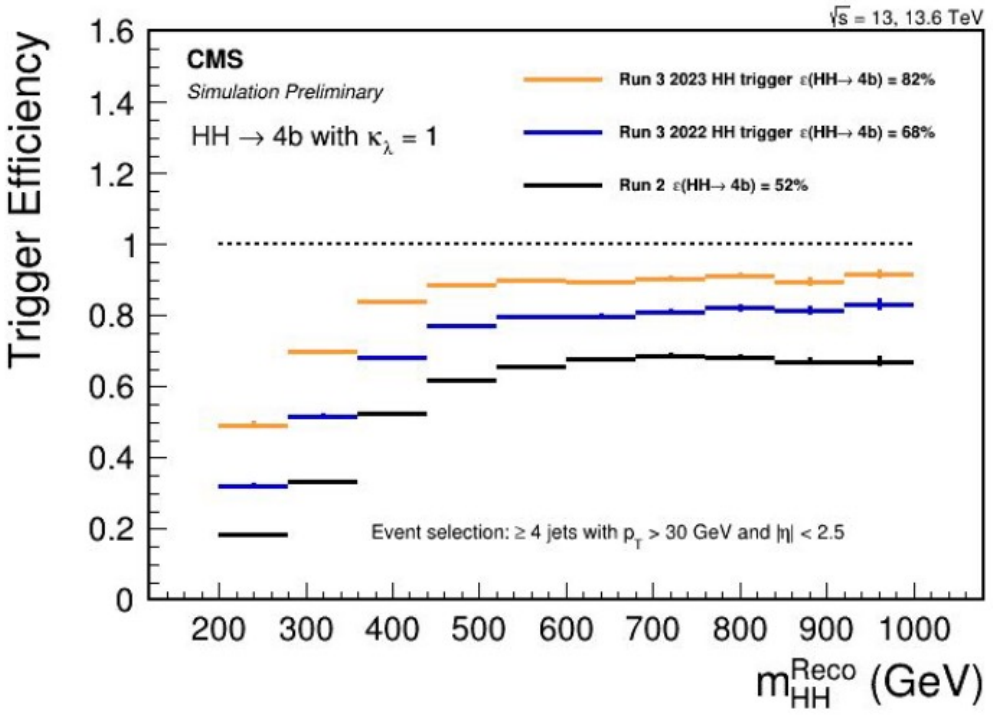
Trigger:

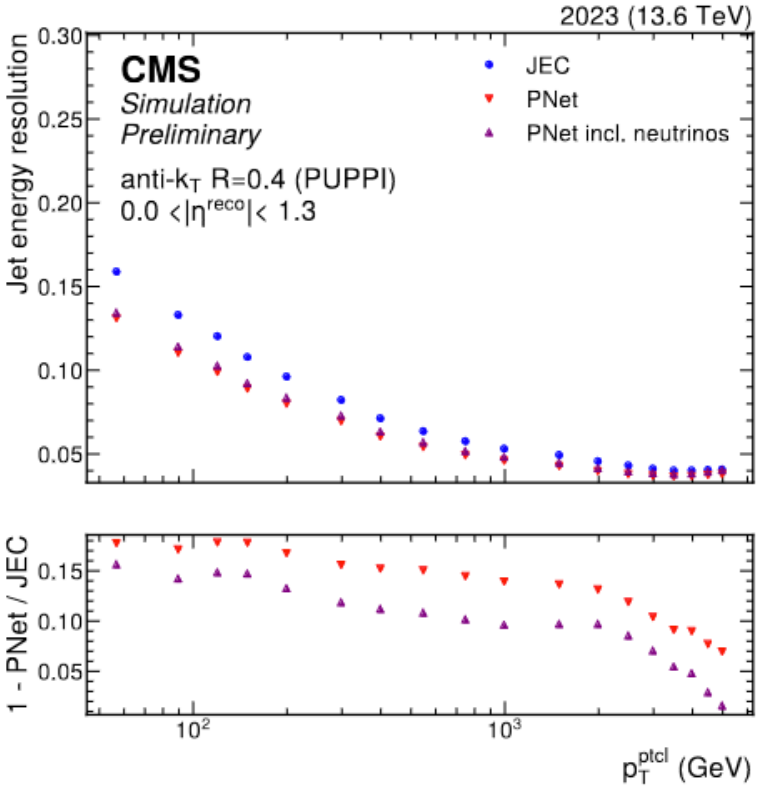
- ML (ParticleNet, DeepTau)
- Added data streams (“parking”)
- Lower p_T threshold (4b, bbττ)

Reconstruction:

- Jet p_T regression (ParticleNet)

⟹ Improves resolution ~15%

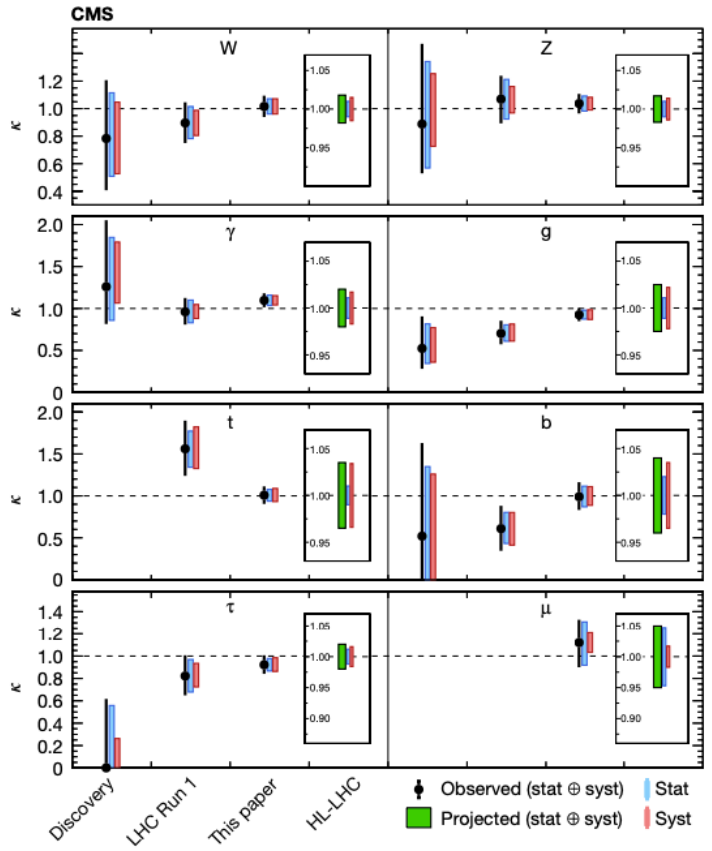


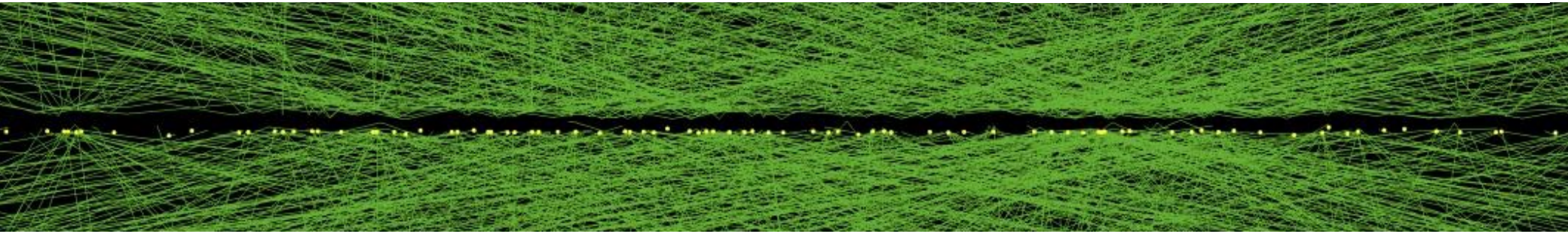


Looking ahead

Nature 607(2022)60

- Precision of measurements improved
- BSM scenarios may provide only small deviations
- More Higgs bosons expected in Run3 and HL-LHC
  - harsher experimental conditions
  - Improved/new detectors





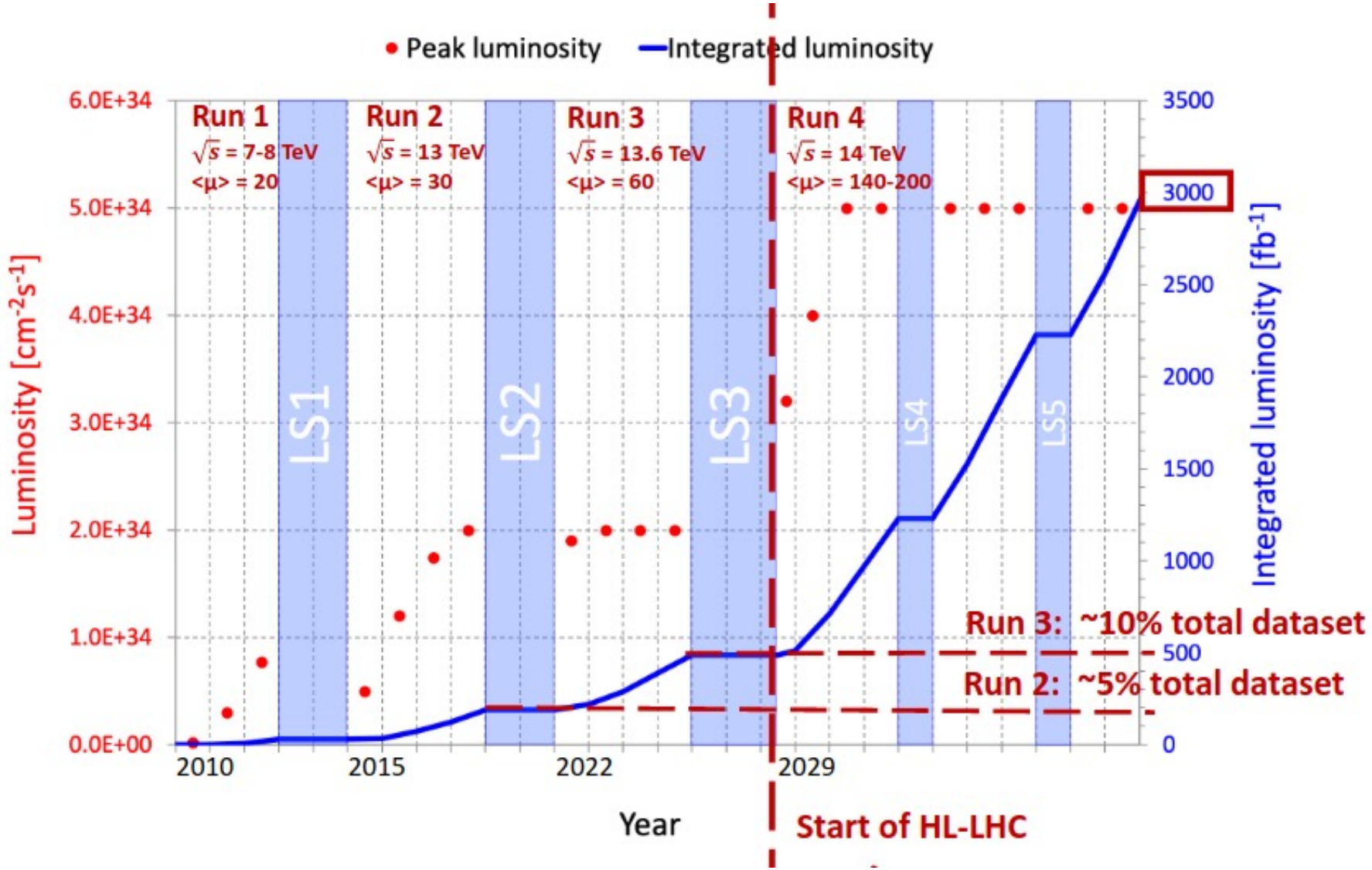
Summary

- From discovery to precision
- Latest results on Higgs studies:
  - Properties, couplings, HH, BSM
  - Improved analysis techniques and new tools crucial to enhance sensitivity beyond statistics
  - No clear signal, a few deviations
- Great progress in the first 10+ years
- Large samples to be collected
  - Run3 ongoing
  - Preparations for HL-LHC at full speed

⇒ Rare processes and precise measurements as BSM probe

…and crack the code of Nature

Stay tuned!

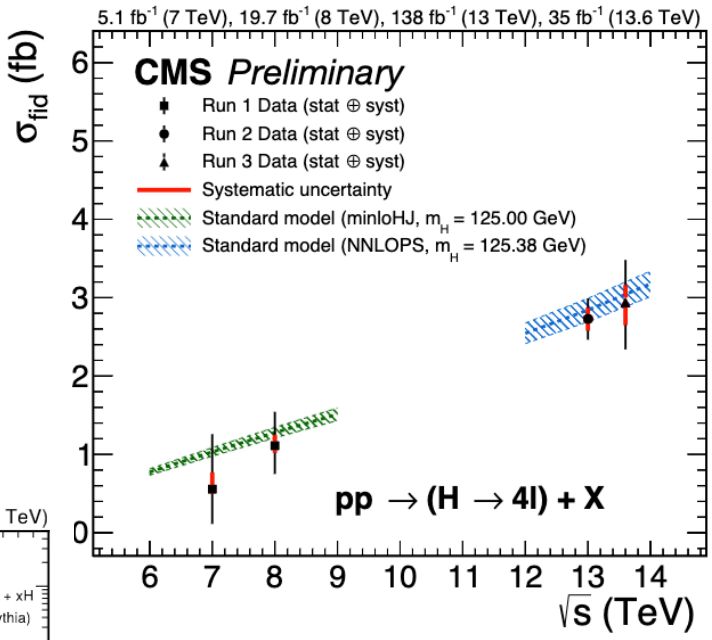

Peak luminosity
Integrated luminosity
Run 1
√s = 7-8 TeV
<μ> = 20
Run 2
√s = 13 TeV
<μ> = 30
Run 3
√s = 13.6 TeV
<μ> = 60
Run 4
√s = 14 TeV
<μ> = 140-200
LS1
LS2
LS3
LS4
LS5
Luminosity [cm⁻²s⁻¹]
Integrated luminosity [fb⁻¹]
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
3500
3000
2500
2000
1500
1000
500
0
2010
2015
2022
2029
Year
Run 3: ~10% total dataset
Run 2: ~5% total dataset
Start of HL-LHC

backup

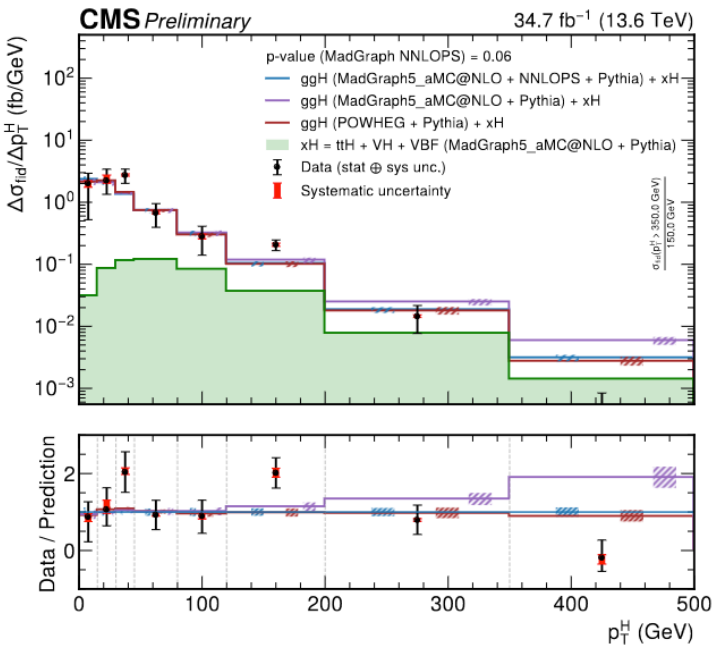
Run 3: $\gamma\gamma$ and ZZ

CMS-HIG-24-013, CMS-HIG-24-014

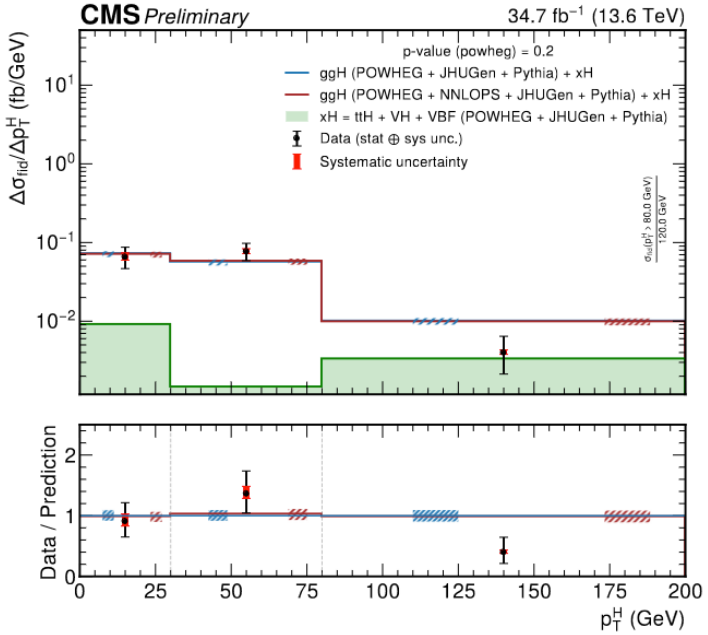
- Inclusive and differential distributions



$\gamma\gamma$

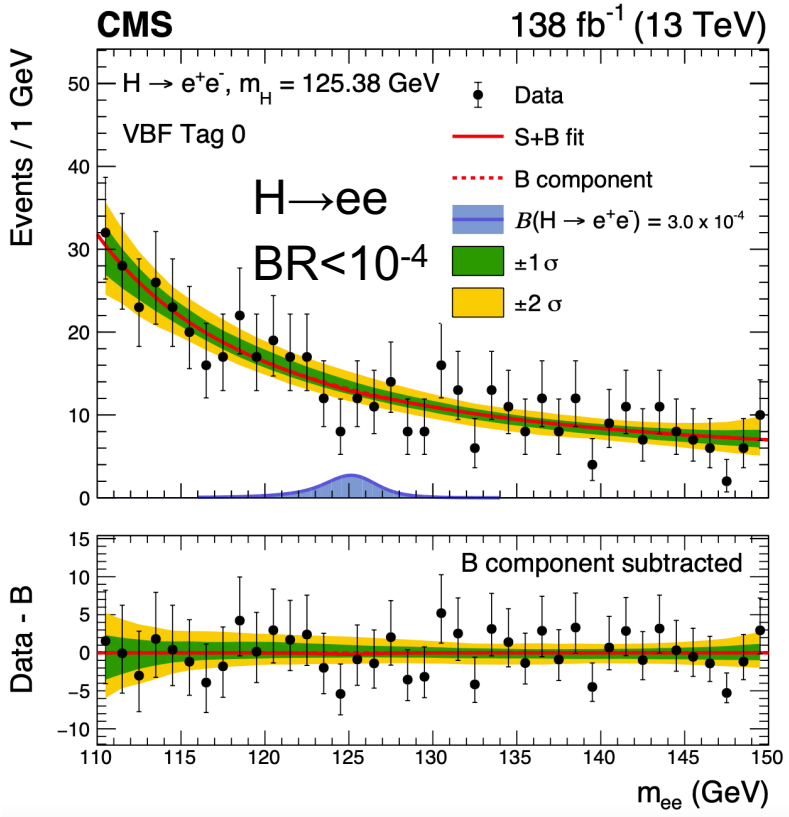


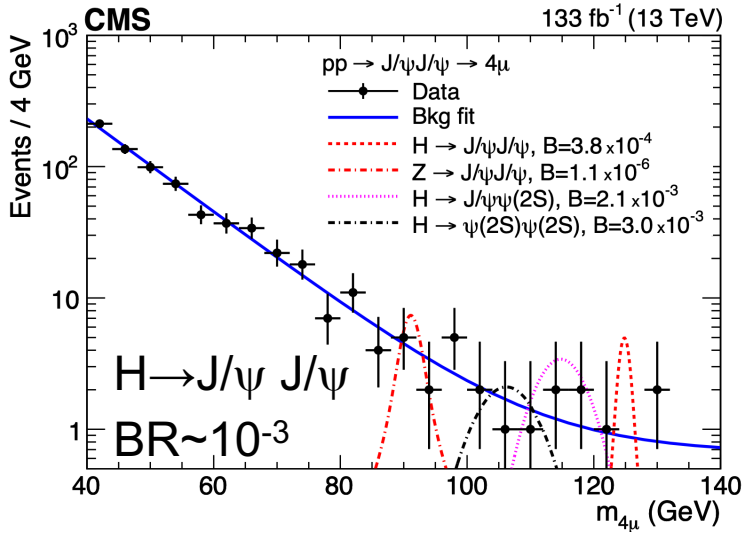
ZZ

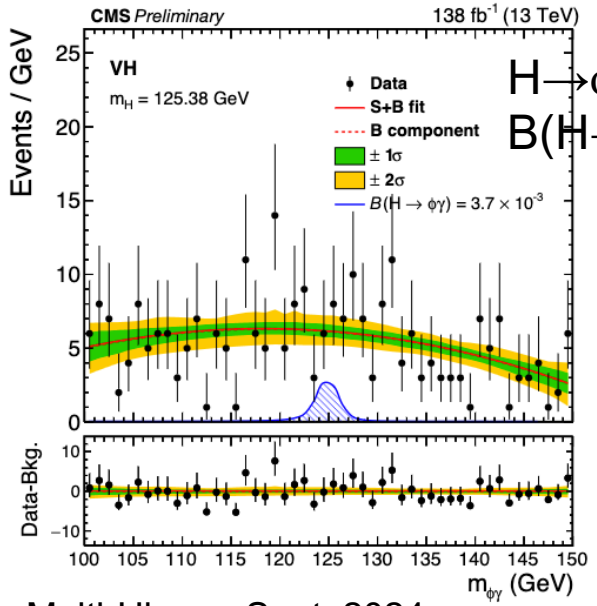


Search for rare decays

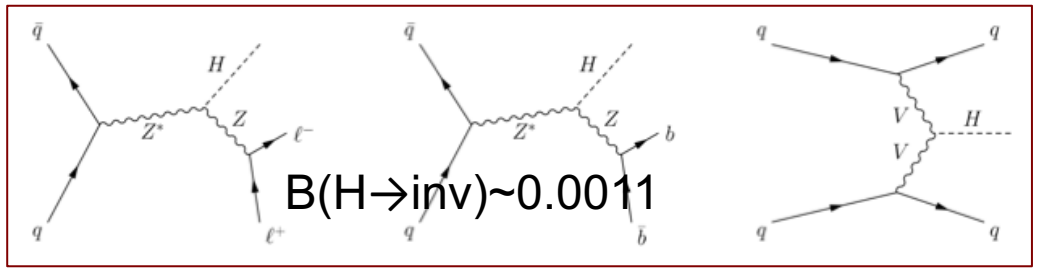
arXiv:2208.00265, arXiv:2206.03525, CMS-HIG-23-005







H→invisible (difficult at LHC)



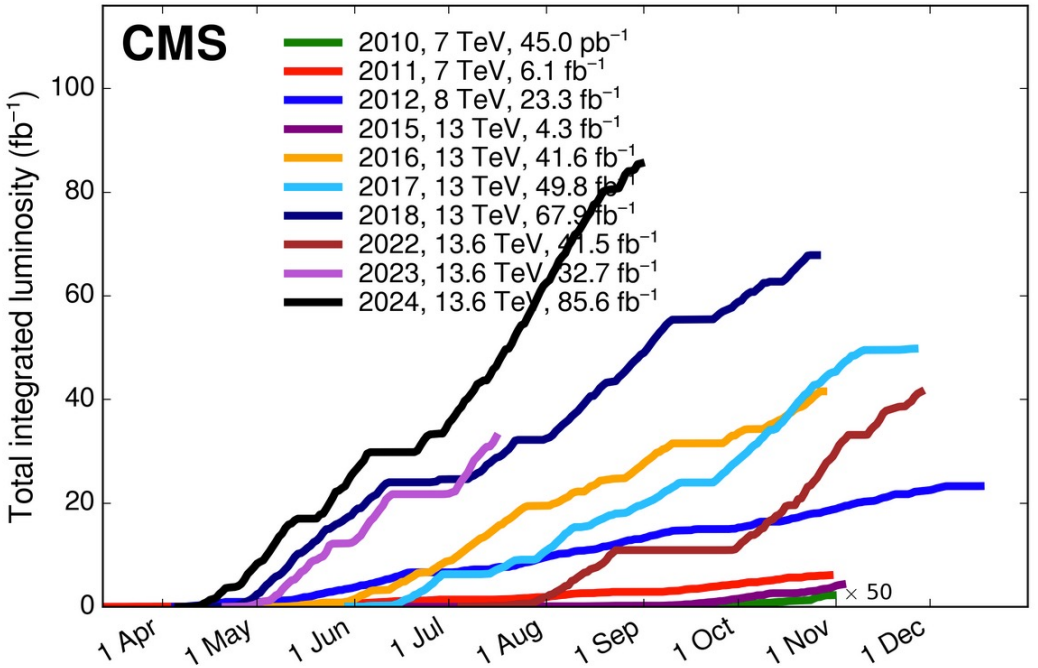
Excellent LHC performance!

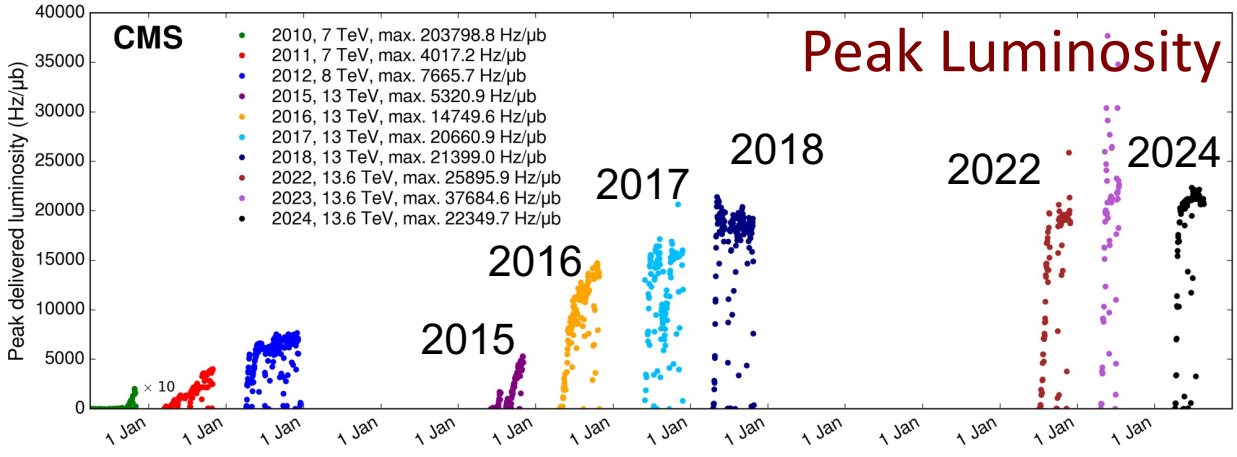
Currently pp collisions @13.6TeV

- Excellent performance: data-taking efficiency, data quality, performance of LHC
- Luminosity (Run2): delivered ~163/fb, recorded ~150/fb

Excellent performance

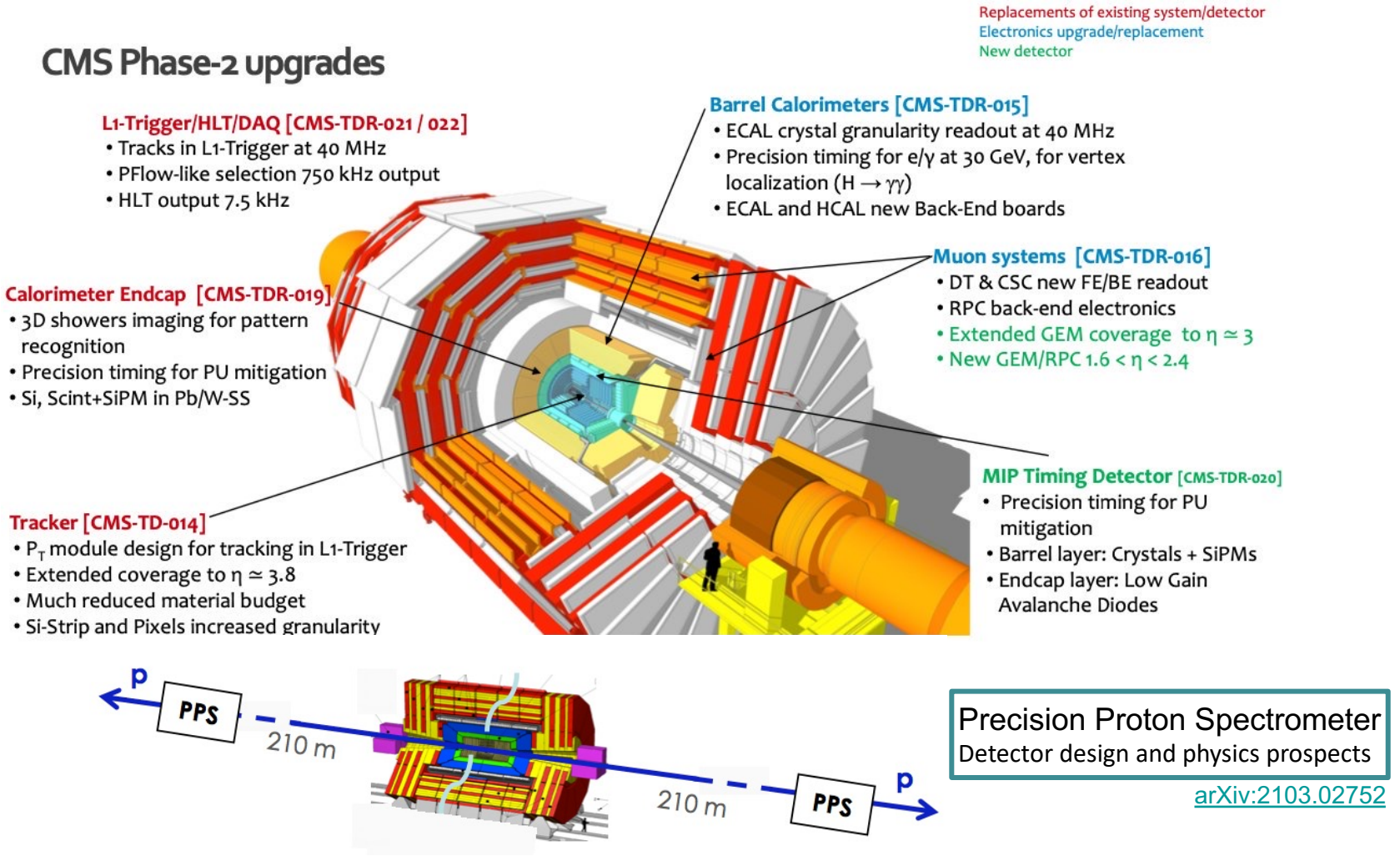
- Fast commissioning
- Good recording efficiency >94%
- Peak luminosity ~2.1x10^{34}sec^{-1}cm^{-2}
- Pileup ~52 (2023)
- Deadtime negligible at highest luminosity (factor of 2 higher than design)





Detector Upgrades

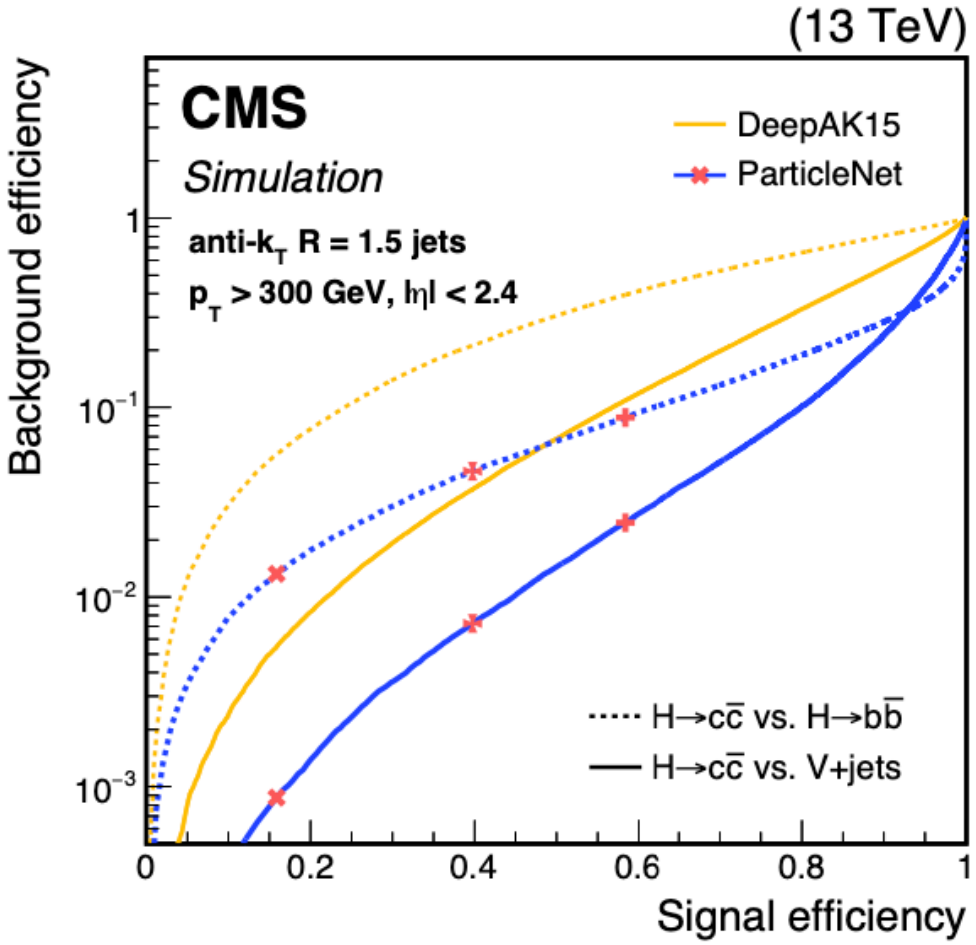
The HL-LHC will provide an integrated luminosity of 3000 fb^{-1} over 10 years of operation. It will present many technological challenges. Preparing new detectors and upgrading current ones.



Precision Proton Spectrometer
Detector design and physics prospects
arXiv:2103.02752

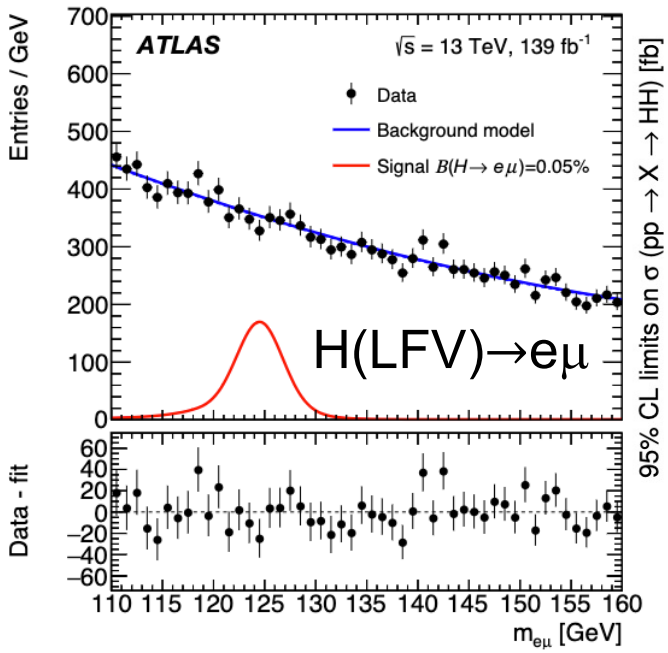
Charm tagging

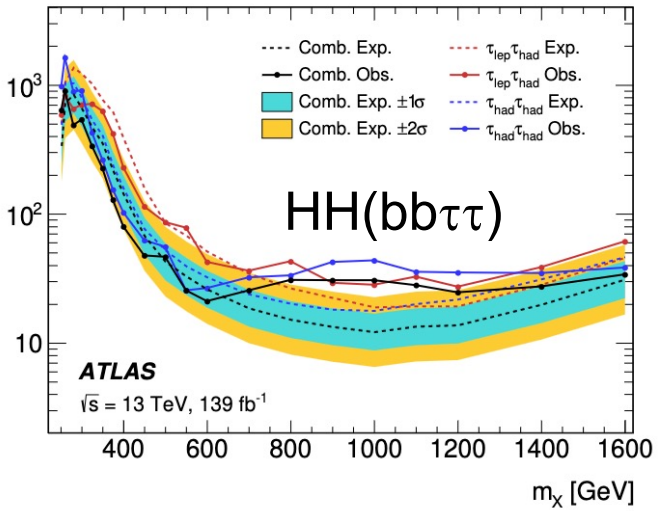
- ParticleNet: Use of PF and secondary vertices associated to large-R jets
- Exploits jet substructure, flavor, pileup with GNN
- Regression algorithm to improve mass reconstruction

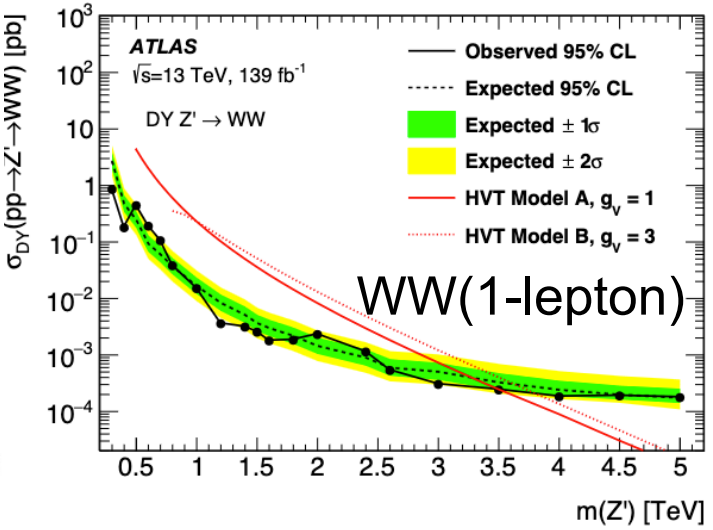


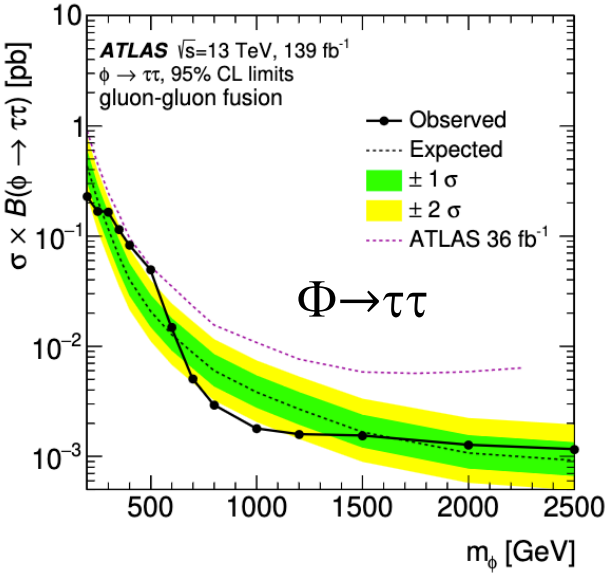
From ATLAS

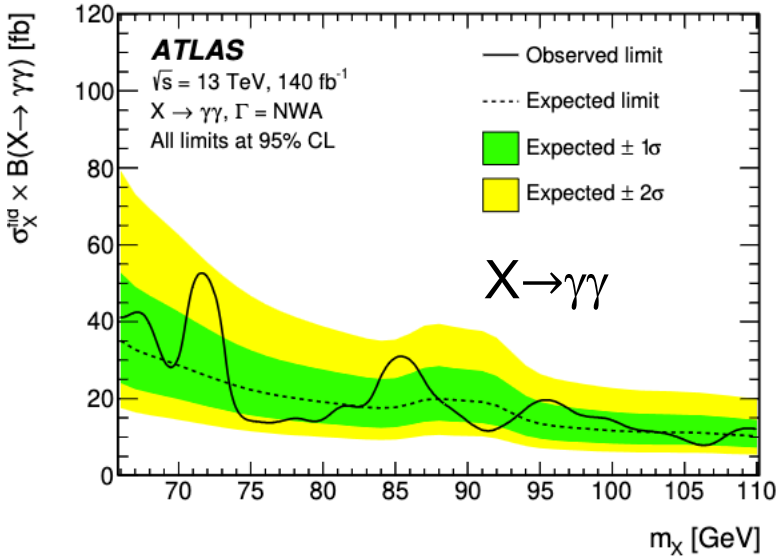
arXiv:1909.10235, arXiv:2209.10910,arXiv:2004.14636, arXiv:2407.07546, arXiv:2002.12223







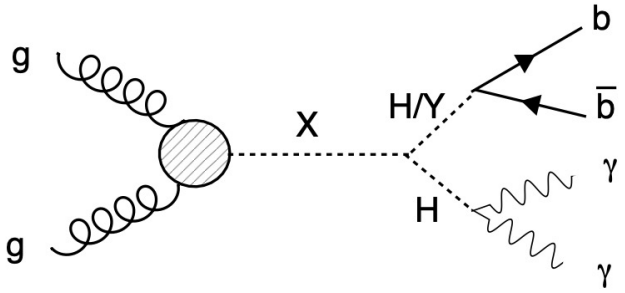




Resonant: X→HH→bbγγ

arXiv:2310.01643

Search for a resonance decaying to two scalars

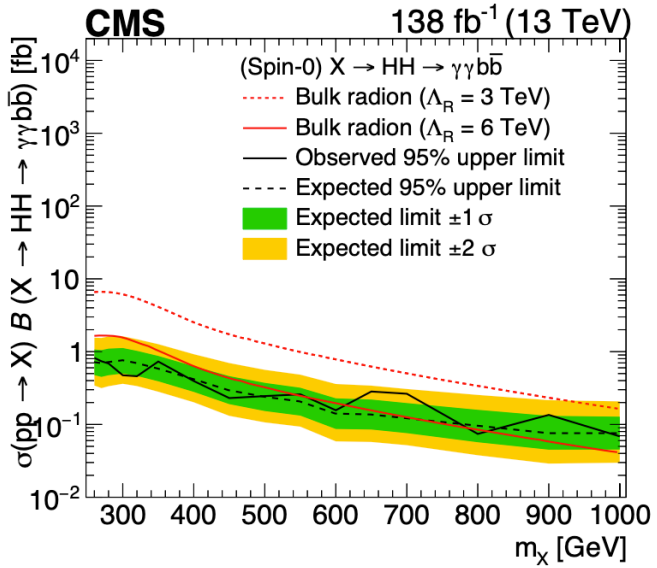


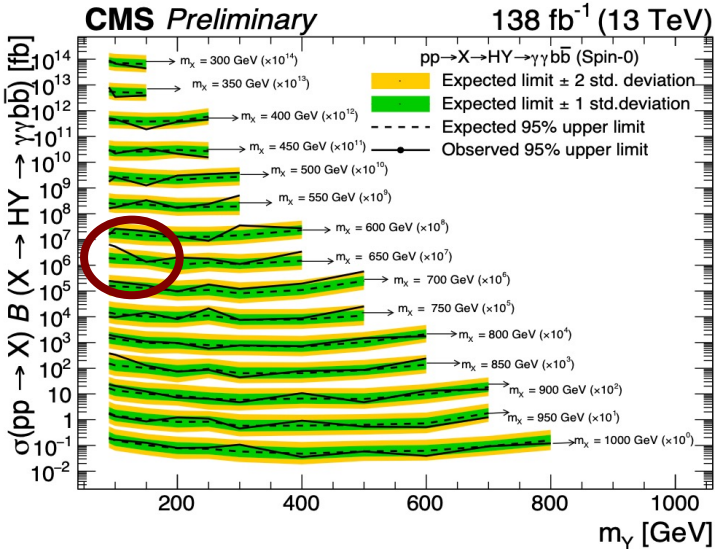
HH

- BDT to reject non-resonant γ(γ)+jets bkg
- b-jets tagged using DNN
- 2D fit of $m_{\gamma\gamma}$ vs m_{jj}
- No significant excess observed

HY

- Consider H→γγ and Y→bb
- Largest excess for m_Y=90GeV, m_X=650GeV
- Local(global) significance 3.8(2.8)σ



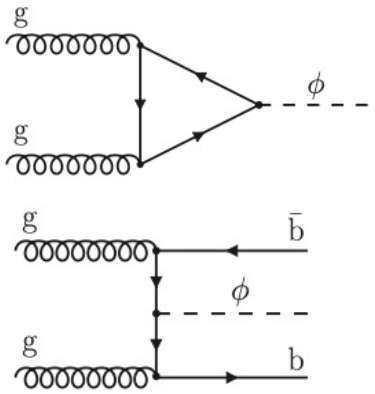


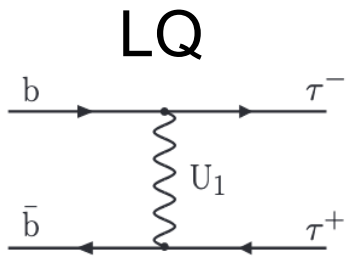
Neutral MSSM Higgs

PLB793(2019)320, arXiv:2208.02717

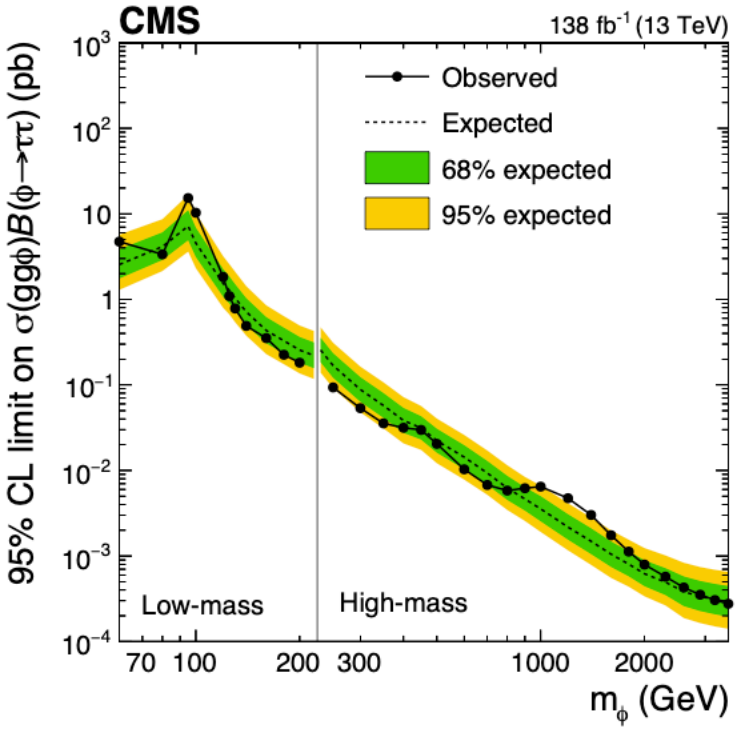
- Enhanced couplings of MSSM Higgs to down-type fermions (large tanβ)

⇒increased BR to τ leptons and b-quarks





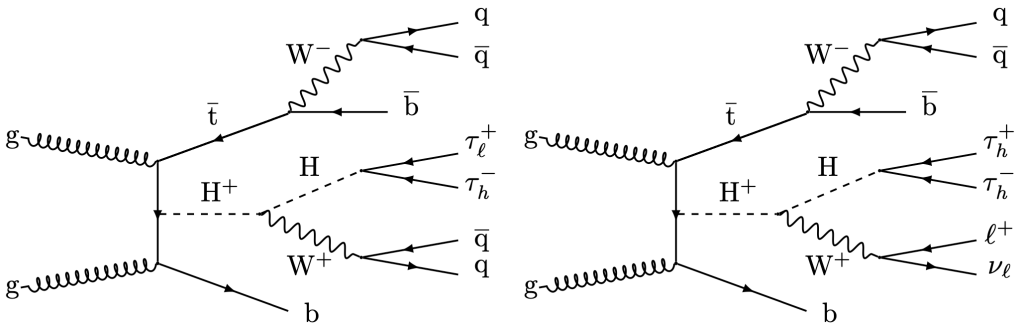
- Search for neutral MSSM Higgs boson
- 4 final states used: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$
  - Reconstruct tau-pair invariant mass
  - Signal extracted from m_T^{tot} distribution
  - Split in b-tag/no b-tag categories to enhance sensitivity
- Main backgrounds: $Z\rightarrow\tau\tau$, QCD/W+jets, DY, ttbar
- Some fluctuations over bkg expectations
  - Two excesses: 100GeV and 1.2TeV
  - Local(global) significance 3.1(2.7)σ@100GeV
  - 2.8(2.4)σ@1.2TeV

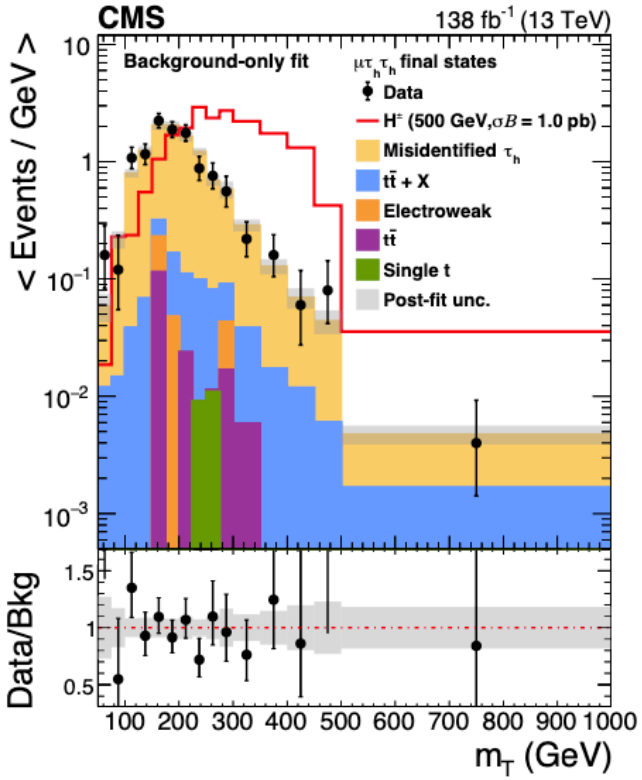


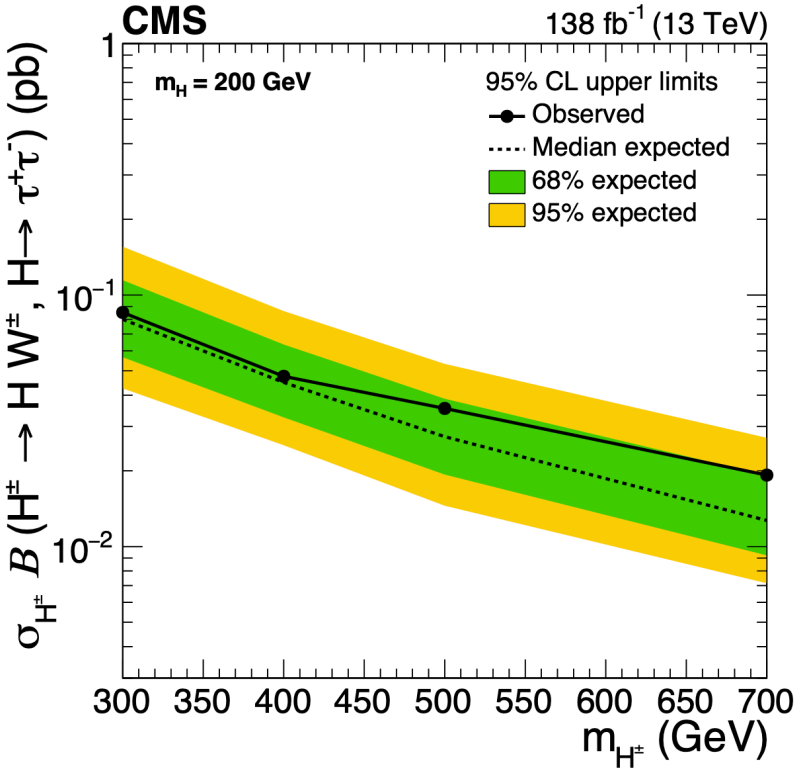
Charged Higgs

arXiv:2207.01046

- Search for a $H^{\pm}$ decaying to a heavy neutral Higgs boson H and a W
- Produced in association with top quark
  - discriminating variables: m_T, BDT discr.
- Data consistent with SM expectations







Charged Higgs (cont.)

EPJC 81(2021)723

- Search for charged Higgs in GM model: H^+ and H^{++}
- Search for resonant production
  - Only fermiophobic H^+ considered
  - Require 2/3 leptons
  - Good bkg description of data in SR