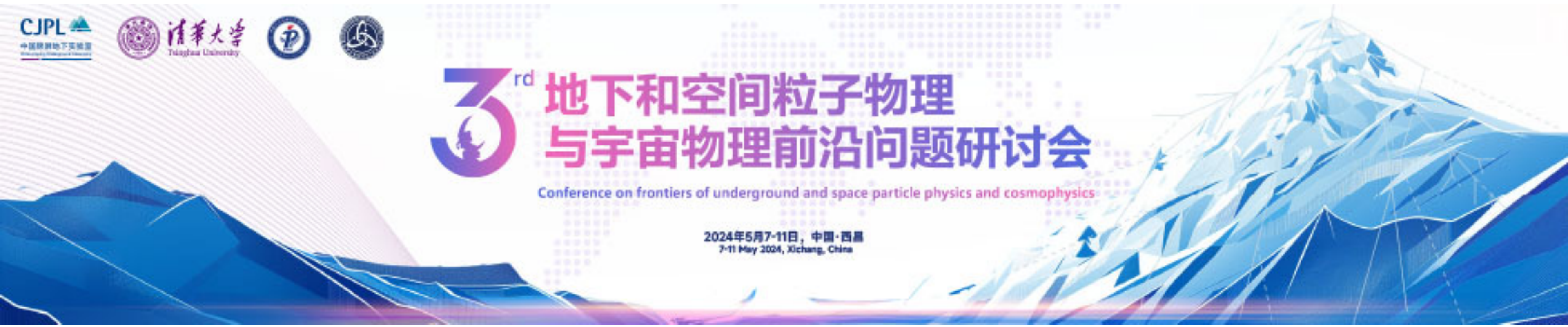


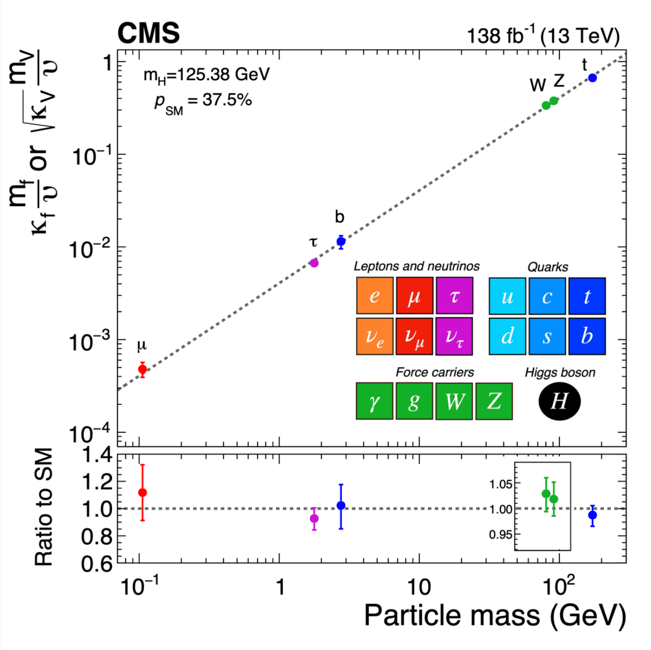
Searches for Dark Sector States in Exotic Higgs Boson Decays at the LHC

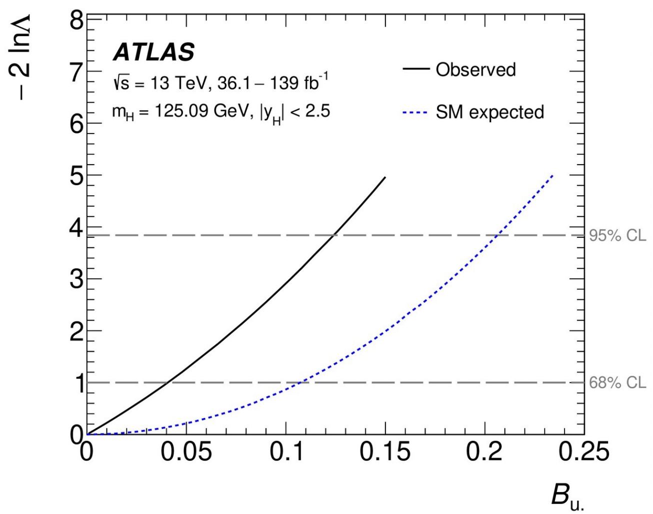
Mingshui Chen (IHEP Beijing）

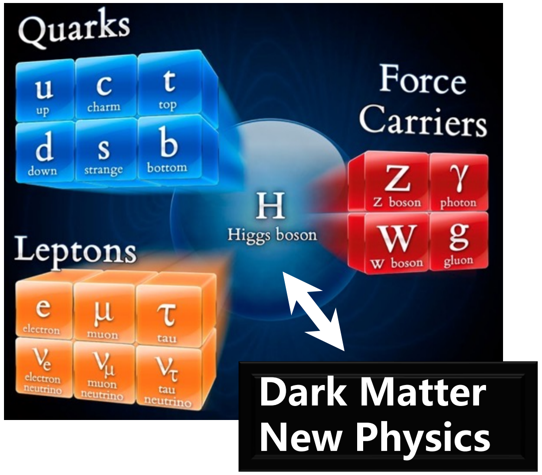
Introduction

Nature 607 (2022) 60-68
Nature 607 (2022) 52-59

- Higgs discovery in 2012, last building block discovered
- Since then, ATLAS and CMS recorded 30 times more Higgs bosons, more precise measurements
  - Data in agreement with SM predictions, so far
- Still plenty of rooms for the Higgs boson to connect with BSM







room for “left-out” decays (“undetected”)

Dark Sector

- **Dark Sector as "New Physics" beyond the SM, could couple to the SM very weakly**

Standard Model ⟷ **Dark Sector**

mediators

(+ gravity)

Need new force / interaction to connect SM to Dark Sector

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})}$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j$$

Vector portal [Okun; Galison & Manohar; Holdom; Foot et al]

Higgs portal [Patt & Wilczek]

Neutrino portal

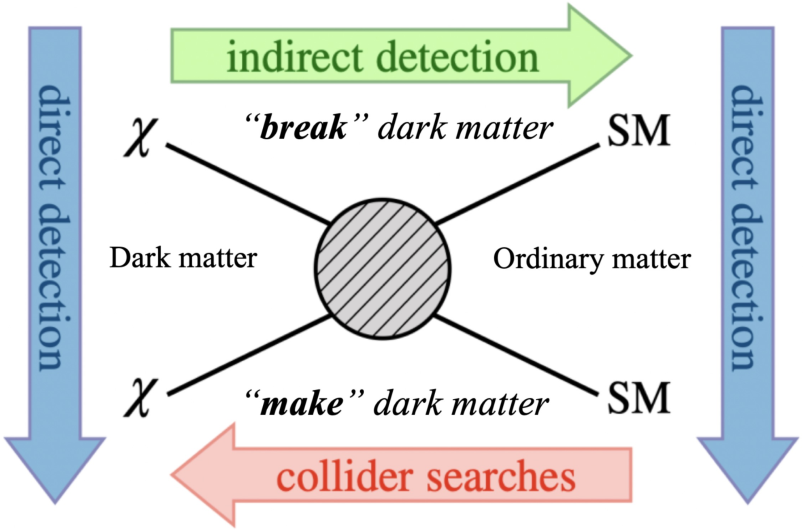
$$+ \frac{1}{f_a} \left(\mathrm{tr}(G\tilde{G}) + c_F F\tilde{F} + c_\psi \partial_\mu j^\mu_{A\psi} \right) a + \mathcal{O}(\mathrm{dim} \geq 5)$$

Axion portal [Weinberg, Wilczek, KSVZ, DFSZ]

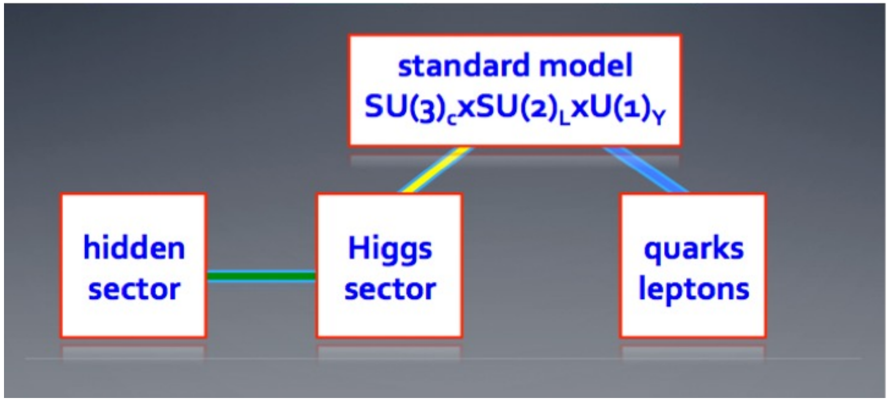
The Higgs Portal

Phys. Rev. D 90, 075004 (2014)

- **All Higgs-BSM connections could be revealed in Higgs measurements.**
  - **Higgs is the key to new physics.**
- **Exotic Higgs boson decays have been proposed as a way to search for evidence of new physics**
  - **To measure the coupling strengths between the SM and the dark sector**



e.g. Higgs decays to invisible



e.g. Higgs decays to dark photons, (pseudo-)scalars, axion-like-particles

Higgs to invisible

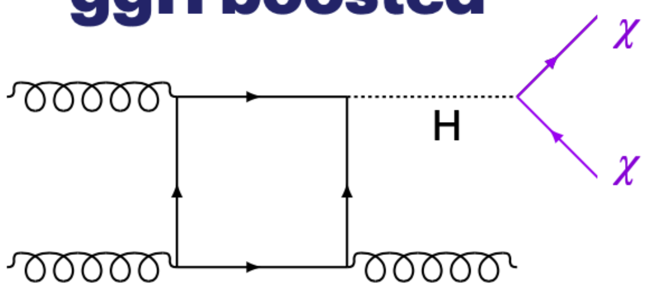
- SM H$\rightarrow$invisible only via H$\rightarrow$ZZ*$\rightarrow$4$\boldsymbol{\nu}$ with B_{inv} of ~0.1%
- Some Dark Sector particle χ, neutral and stable over the range of the detector
  - Could have mass from Higgs mechanism
  - Its mass $m_{\chi} < m_H/2$ such that H->$\chi\chi$
  - $\Rightarrow$ B_{inv} is significantly enhanced
- Signature: significant missing transverse momentum from the Higgs decay
- Identify through visible particles recoiling against the Higgs boson

Higgs to invisible

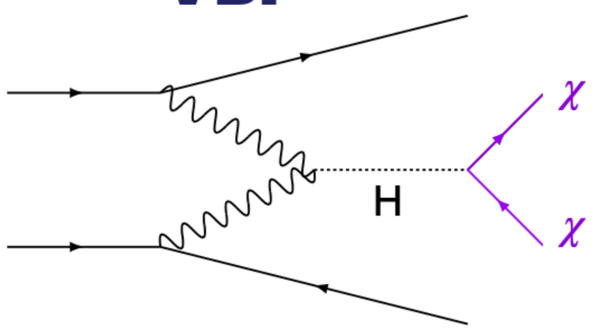
- **ATLAS and CMS probe all production modes**

ATLAS	Phys.Rev.D 103 (2021) 11, 112006	JHEP 08 (2022) 104 Eur.Phys.J.C 82 (2022) 2, 105	Phys.Lett.B 829 (2022) 137066	arXiv:2211.05426
CMS	JHEP 11 (2021) 153	Phys.Rev.D 105 (2022) 092007	CMS-PAS-HIG-21-007 Eur.Phys.J.C 81 (2021) 1, 13 JHEP 11 (2021) 153	CMS-PAS-HIG-21-007 JHEP 05 (2020) 032 Eur. Phys. J. C 81 (2021) 3

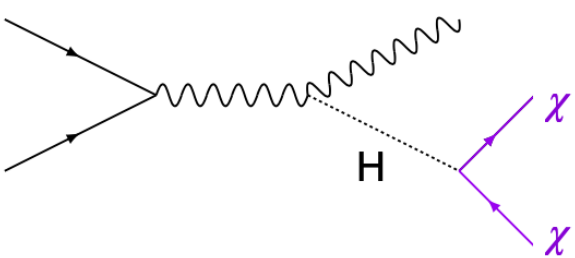
ggH boosted



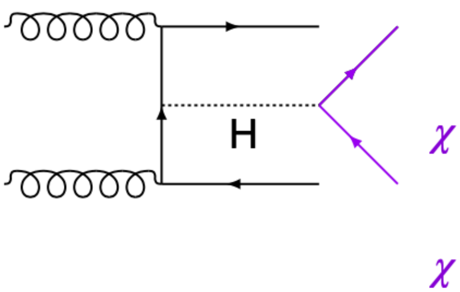
VBF



Associated production



ttH

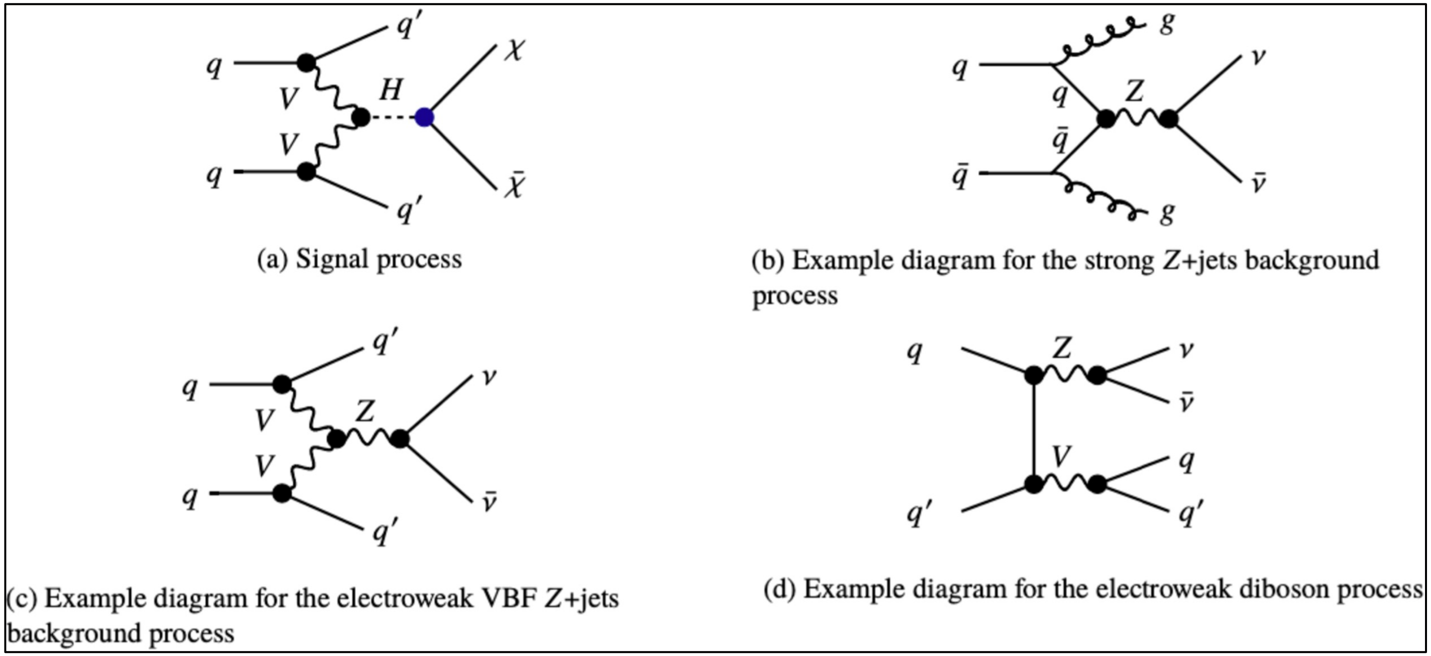


VBF Higgs to invisible

The **VBF** production mechanism drives the overall sensitivity in the direct search for invisible decays of the Higgs boson, thanks to its large production cross section and distinctive event topology

- **2 jets with large angular separation $\Delta\eta_{jj}$ and large invariant mass m_{jj}**
- High missing transverse momentum (trigger constraint) → reject QCD
- Low | $\Delta\phi_{jj}$ | → reject QCD

⇒ Main remaining backgrounds: Z(νν) + jets and W(lν) + jets



(a) Signal process

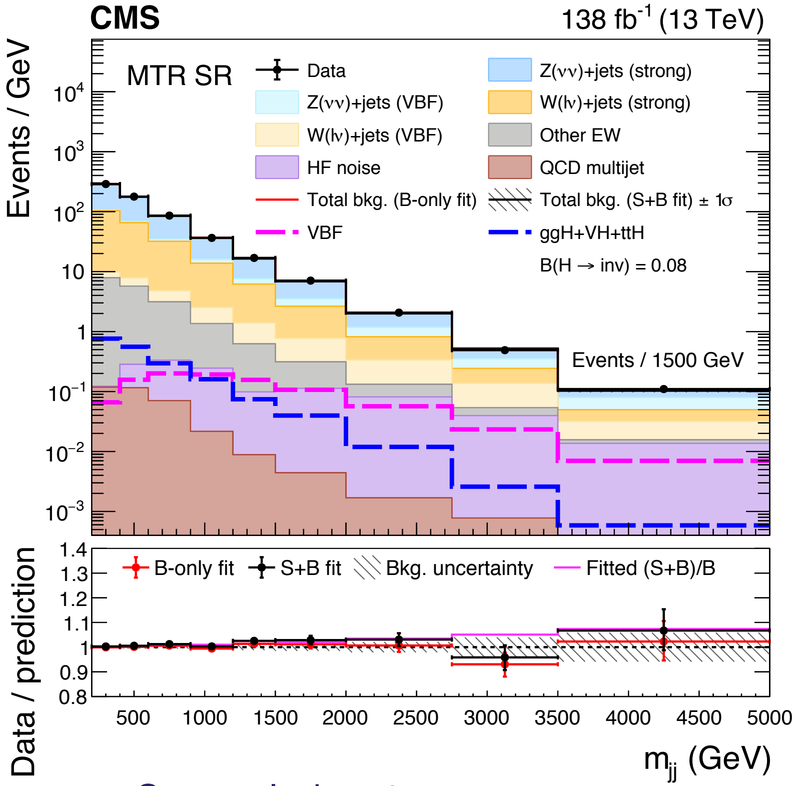
(b) Example diagram for the strong Z+jets background process

(c) Example diagram for the electroweak VBF Z+jets background process

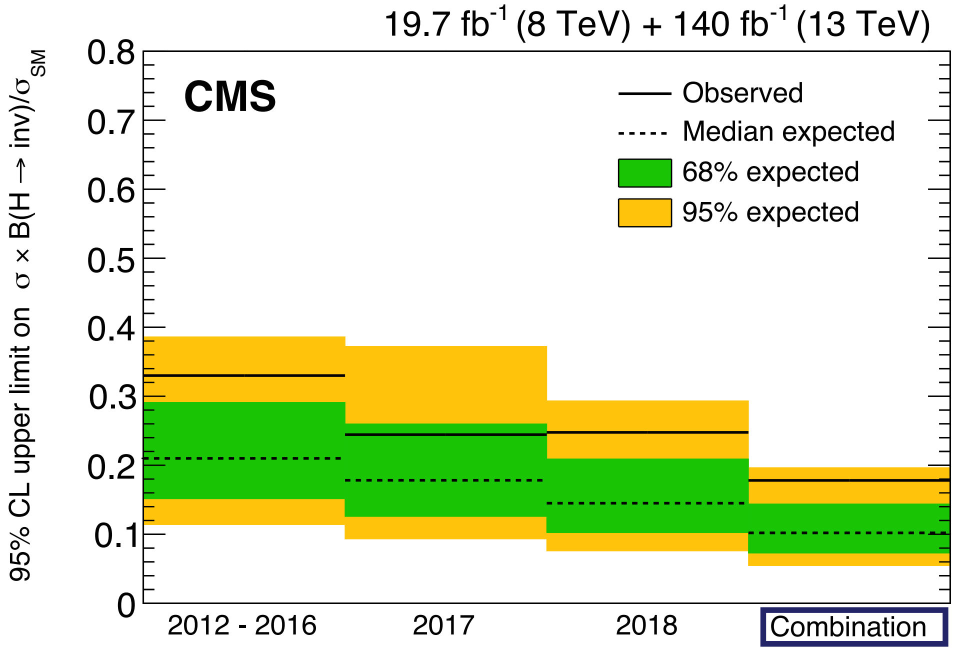
(d) Example diagram for the electroweak diboson process

VBF Higgs to invisible

ATLAS: JHEP 08 (2022) 104
CMS: PRD 105 (2022) 092007



One analysis category



UL on Br(H→inv) @ 95% C.L

CMS : 0.18 (0.10 exp.)

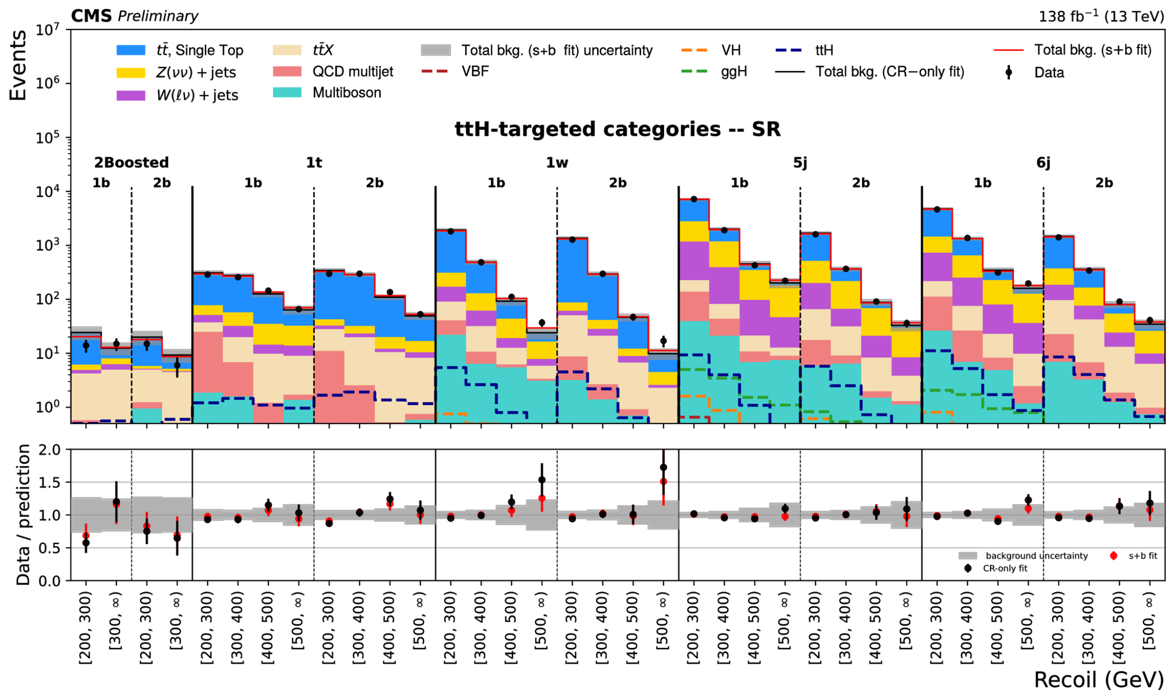
ATLAS : 0.15 (0.10 exp.)

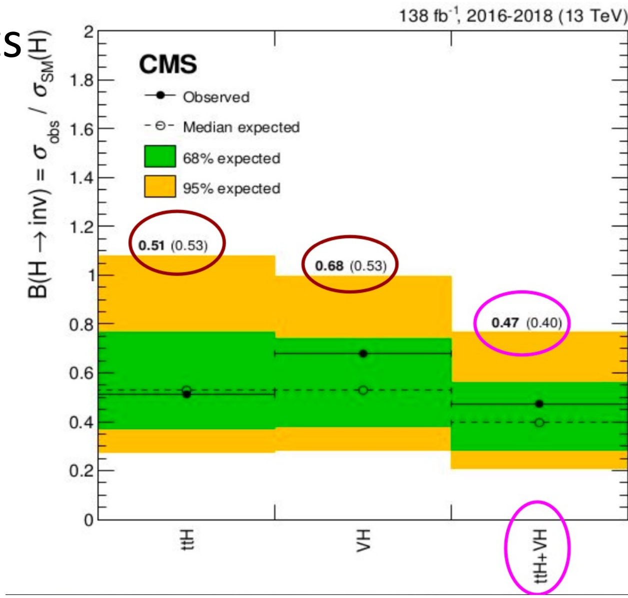
Higgs to invisible: ttH and VH

CMS: Eur.Phys.J.C 83 (2023) 933
ATLAS: Eur.Phys.J.C 83 (2023) 503

Fully hadronic final state

- tt and V decay hadronically
- Categorization based on resolved and boosted regimes
- Main backgrounds: tt + jets and W + jets and Z(νν̄)+jets
- No excess of events above the estimated backgrounds





UL on Br(H⟶inv) @ 95% C.L

ttH : 0.51 (0.53 exp.)

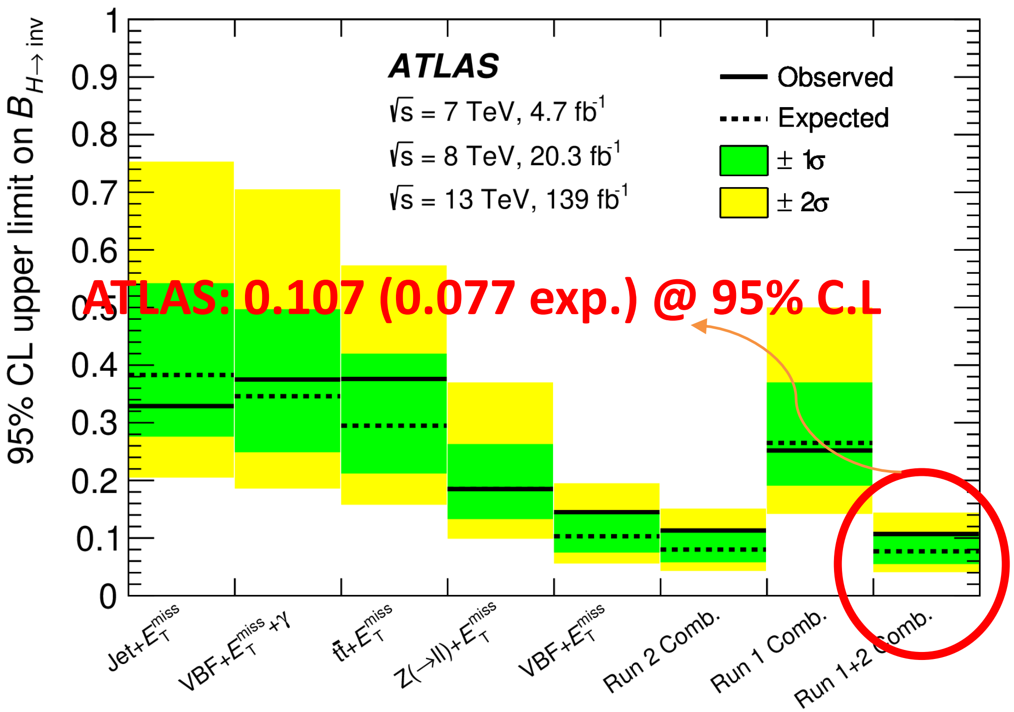
VH : 0.68 (0.53 exp.)

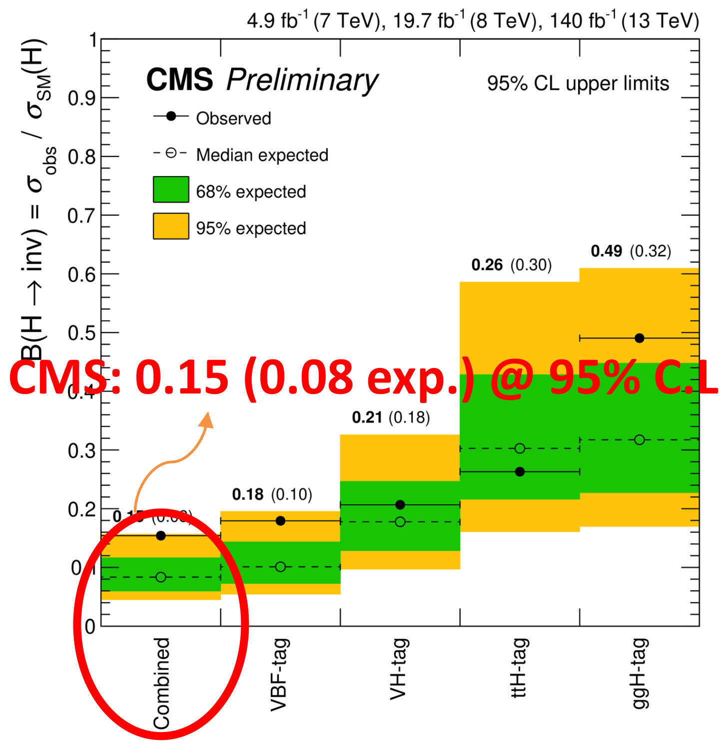
ttH+VH : 0.47 (0.40 exp.)

Higgs to invisible: combination

CMS: Eur.Phys.J.C 83 (2023) 933
ATLAS: PLB 842 (2023) 137963

- Adding ttH, VH and ggH production modes improves a bit

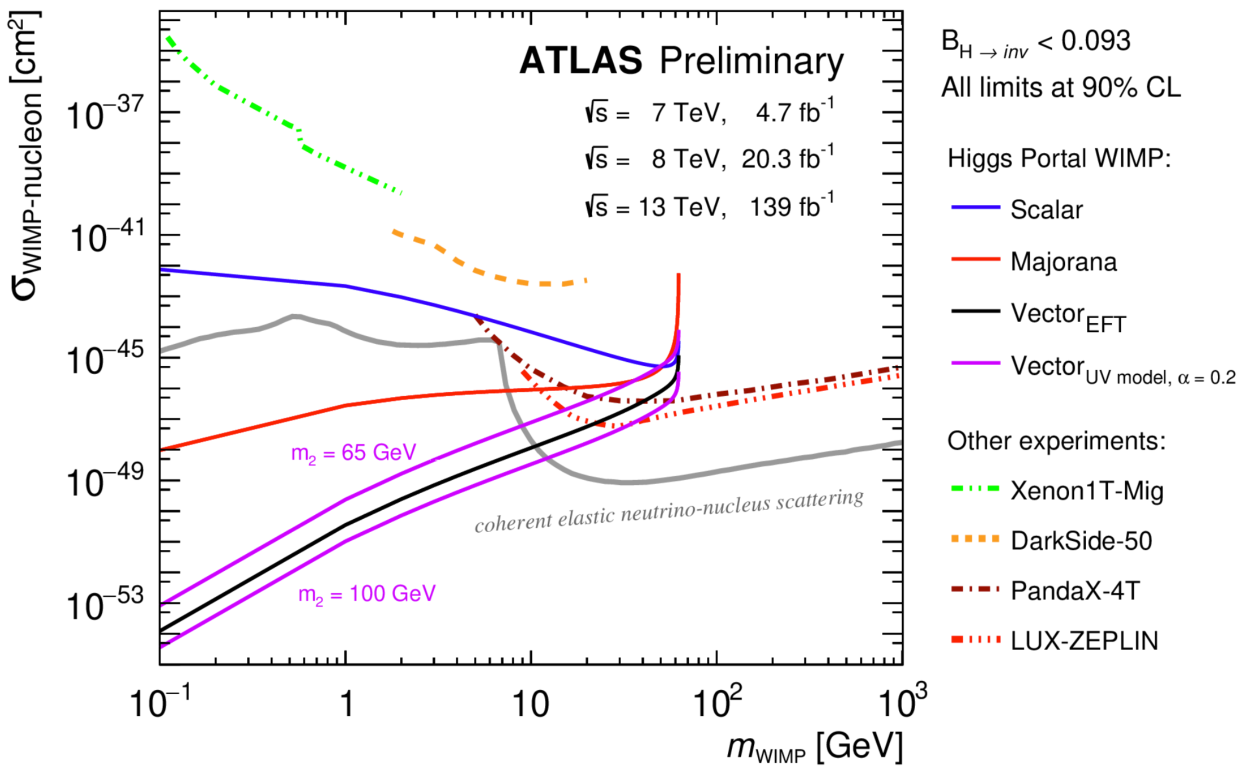




Interpretations

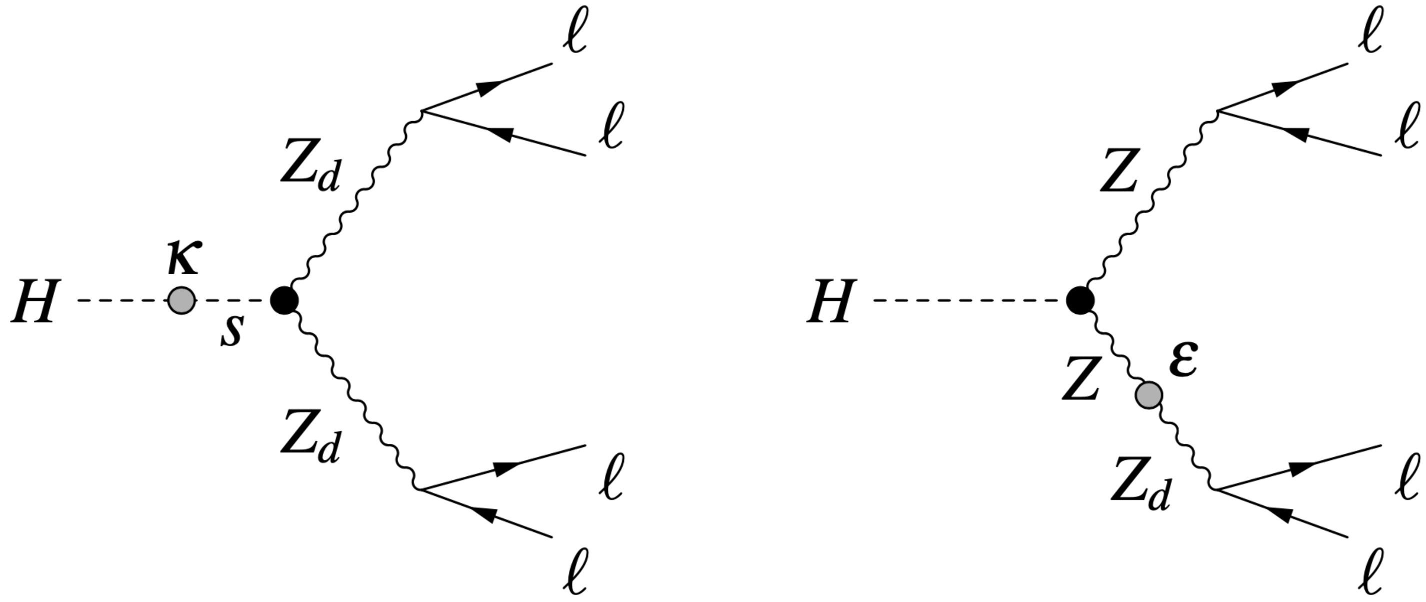
CMS: Eur.Phys.J.C 83 (2023) 933
ATLAS: PLB 842 (2023) 137963

- Convert the BR(H → inv) limit to the limit on **spin independent DM-nucleon elastic scattering cross section**
  - Complementary to direct detection results
- Assume several WIMP (weakly interacting massive particle) hypotheses:
  - Scalar, Majorana fermion, vector



Higgs decays to dark photons

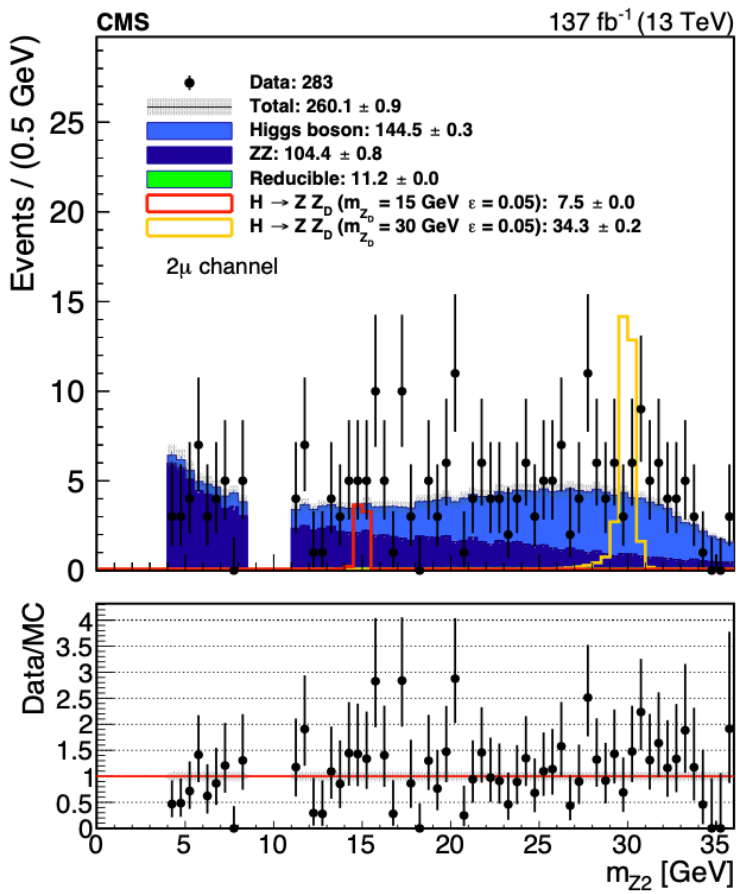
- Many SM extensions include a U(1) dark gauge symmetry with gauge boson Z_d mixing with SM Higgs via κ and with hypercharge gauge boson via ε
  - Gives rise to $H \to Z_d Z_d$ and $H \to Z Z_d$
  - Z_d has significant decays to ll (~ 0.2–0.3)

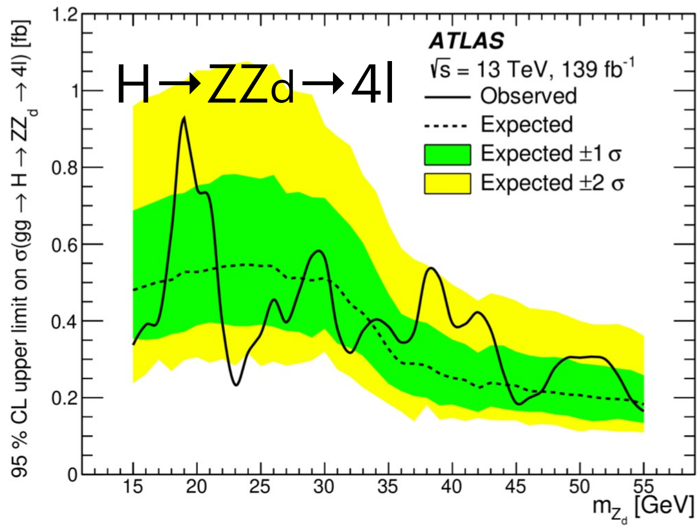


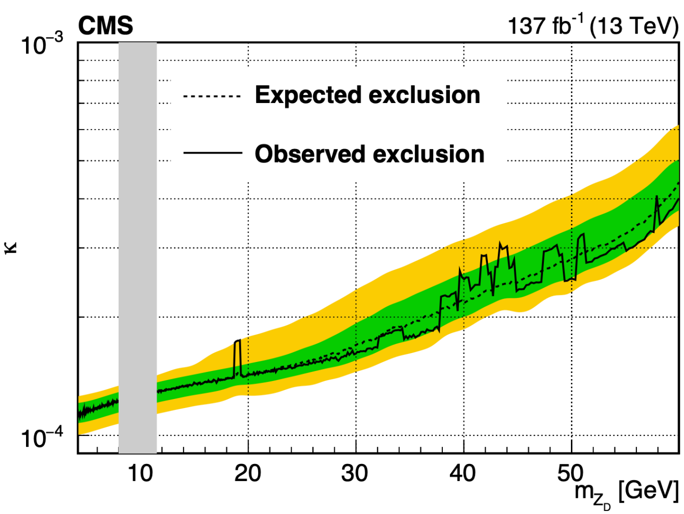
$H\to Z_dZ_d/ZZ_d\to 4l$

ATLAS: JHEP 03 (2022) 041
CMS: EPJC 82 (2022) 290

- Very clean final state, results can be interpreted in various theoretical models
  - Hidden Abelian Higgs Model, Axion-Like Particle, Extended Higgs sector

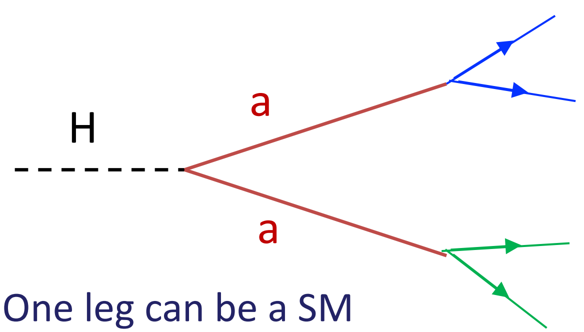




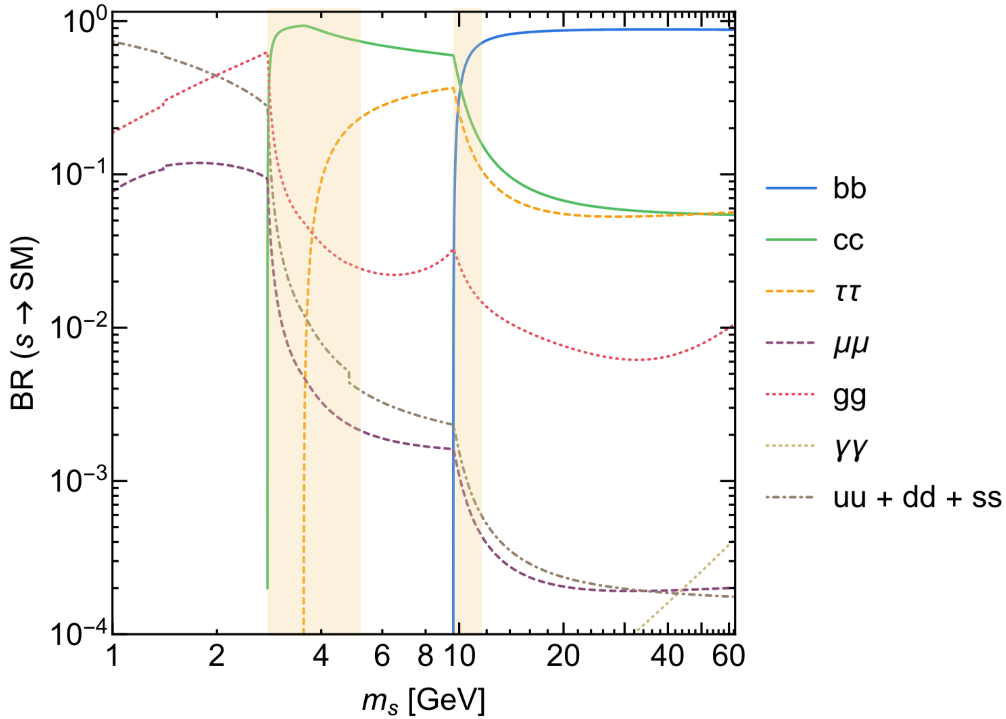


Higgs decays to pseudoscalars

- Many extensions to the SM include Higgs boson decays via one or two hypothetical on-shell new (pseudo)scalar(s) decaying to a pair of SM particles
  - Branching ratio of the new particle a to other particles depend on the model



One leg can be a SM particle as the Z boson

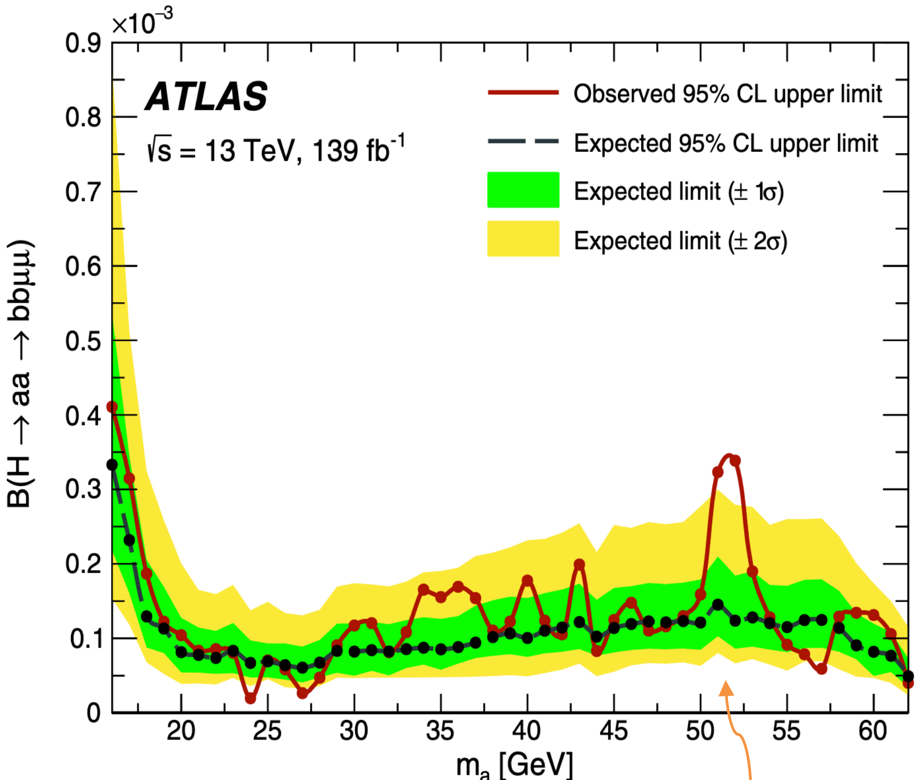


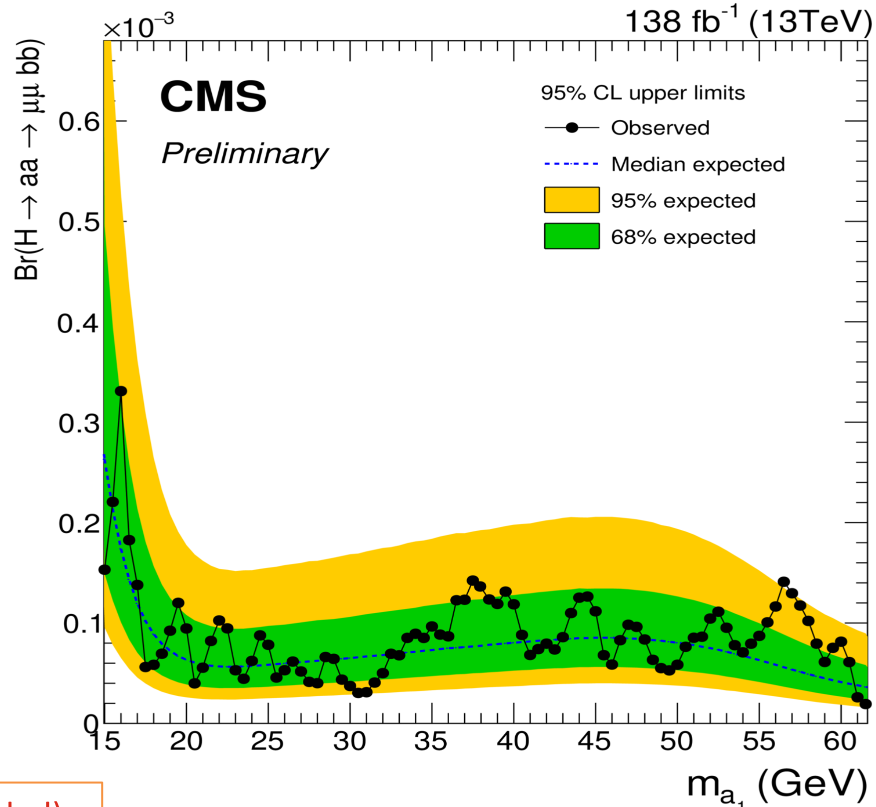
Predicted decay branching ratios of pseudoscalar to SM particles in Type I 2HDM+S (arxiv:1312.4992)

H→aa→bbμμ

ATLAS: PRD 105 (2022) 012006
CMS-PAS-HIG-21-021

- The largest Br(aa→μμbb) for large tanβ in 2HDM+S type III
- Kinematic likelihood fit is performed exploiting equal invariant masses of bb and μμ
  - Excellent m(μμ) resolution is used to constrain m(bb)



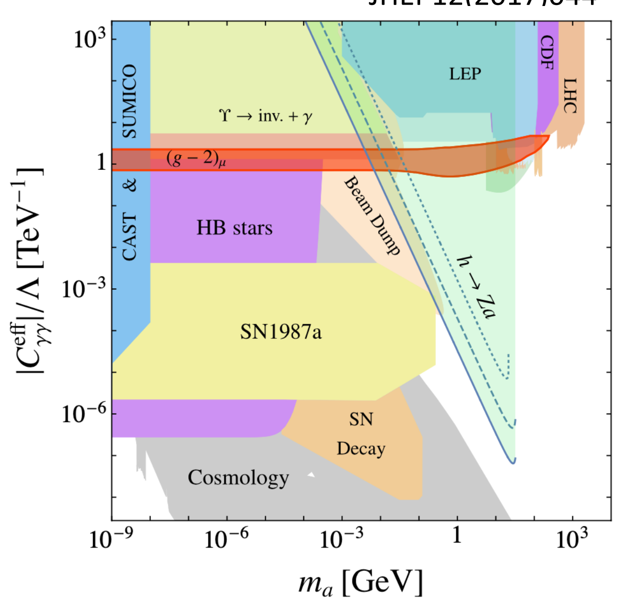


3.3σ (1.7σ) local (global) significance at 52 GeV

Higgs decays to Axion-Like-Particles

- **Axions**: pseudoscalar particles, originally proposed to answer strong CP problem in QCD
  - Extension of the SM with an additional, spontaneously broken, global chiral symmetry
- **ALPs** are gauge singlets under SM, coupling to SM fermions
  - Enhanced coupling to photons can contribute to anomalous muon magnetic moment
  - Constraints on the ALP mass and coupling to photons derived from various experiments

JHEP12(2017)044



- Search channels: h→aa and h→Za
  - Effective couplings:

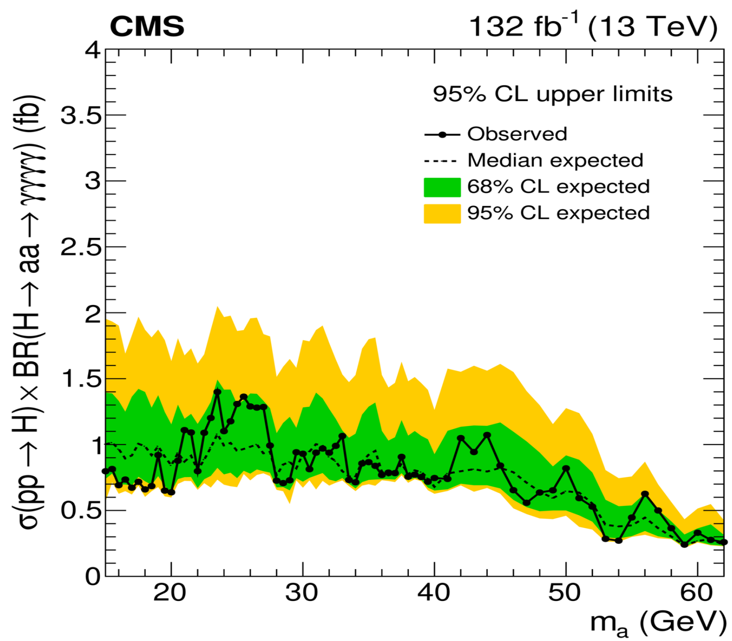
$$C_{Zh}^{eff}/\Lambda \text{ and } C_{\gamma\gamma}^{eff}/\Lambda$$

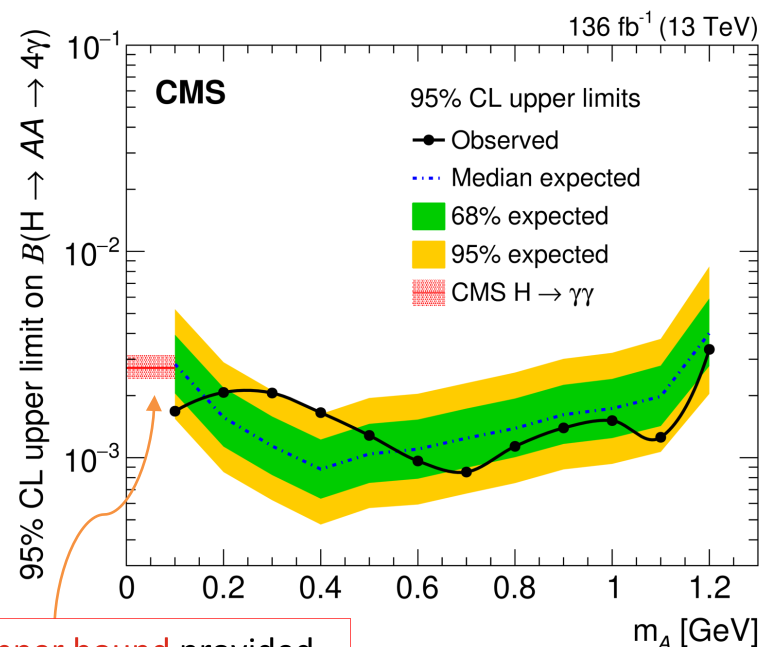
H→aa→4γ

CMS: arXiv:2208.01469
CMS: arXiv:2209.06197

- Searches for a with mass **above 15 GeV,** final-state photons **resolved**

- **Low-mass, boosted** scalar A decays to two highly **merged photons**, mis-reconstructed as a single photon-like object
→ Dedicated reconstruction of collimated di-γ using deep learning



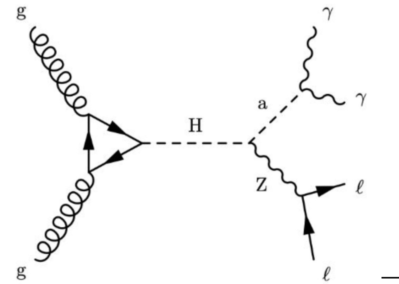


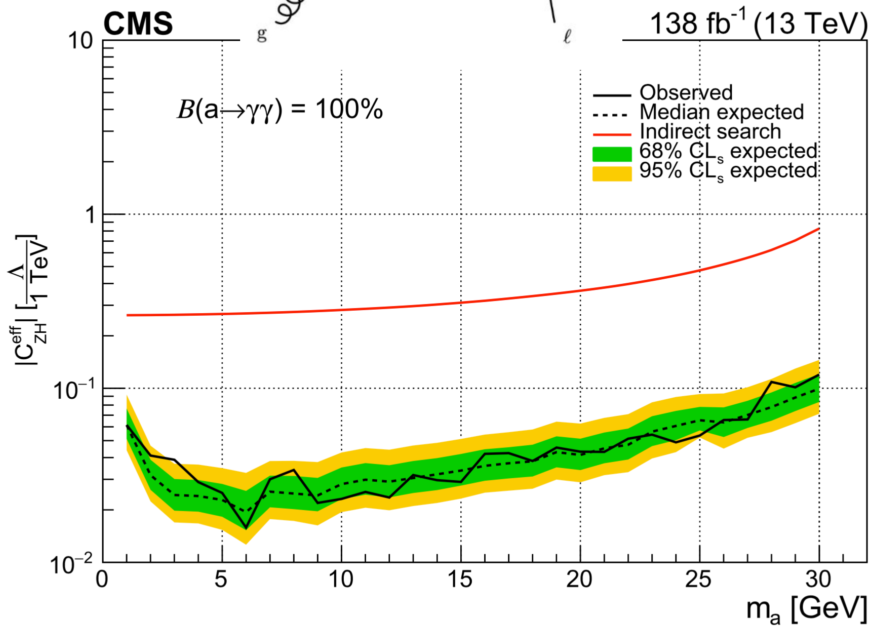
Upper bound provided by SM H→γγ

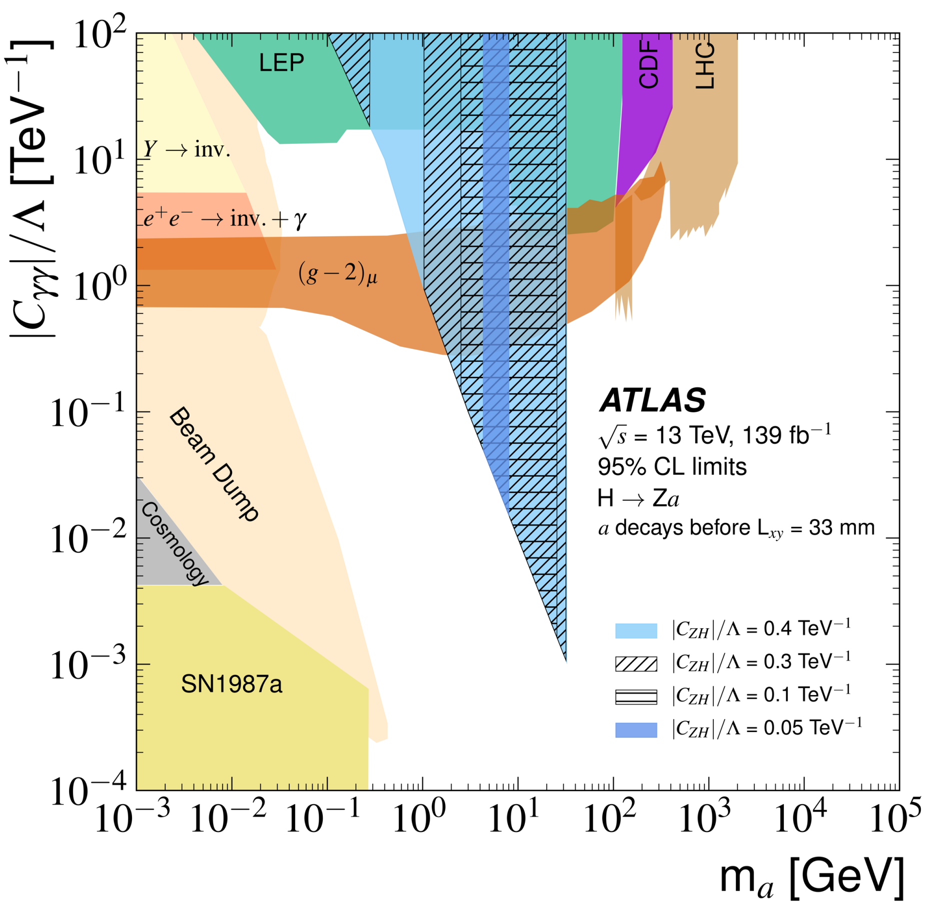
H→Za→2l2γ

PLB 848 (2024) 138536
PLB 852 (2024) 138582

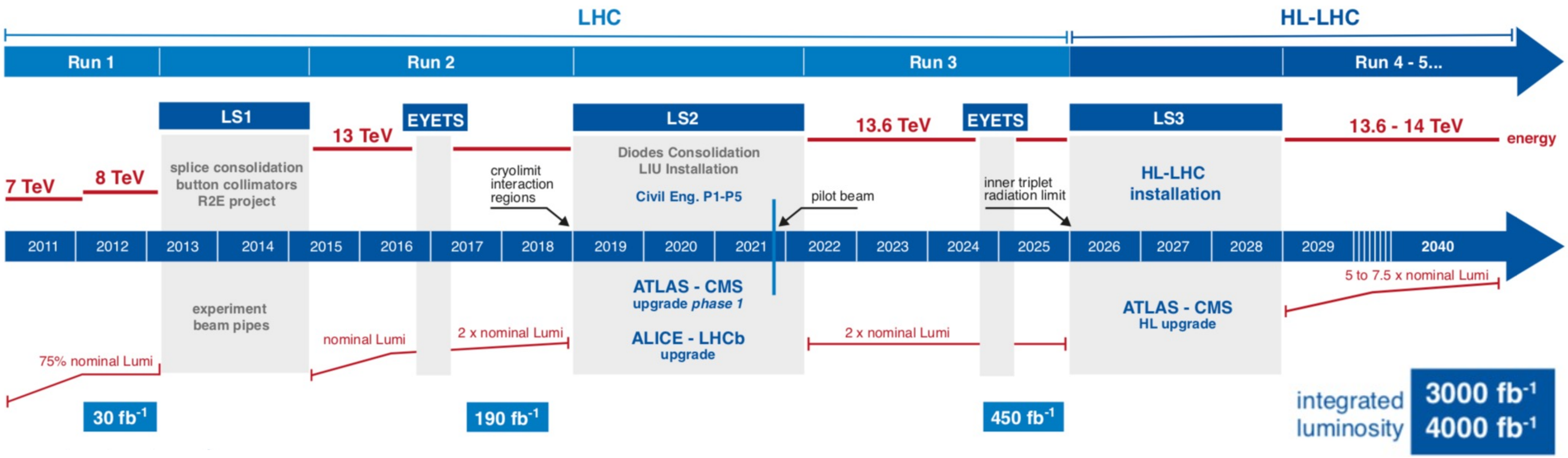
- On-shell Higgs boson and Z boson, $m_a = m_H - m_Z$ ~< 30 GeV
- Final state contains a lepton pair from Z decay and one (merged) or two (resolved) photons from a



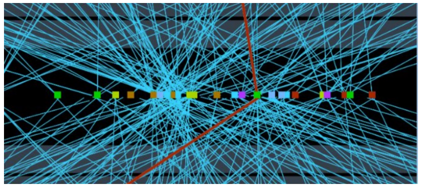




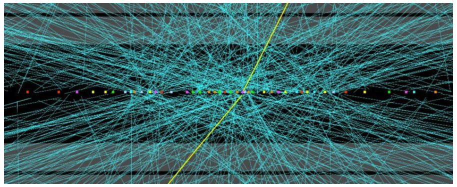
Towards HL-LHC



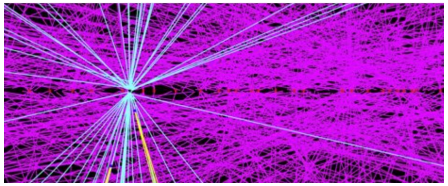
Run 2



Run 3



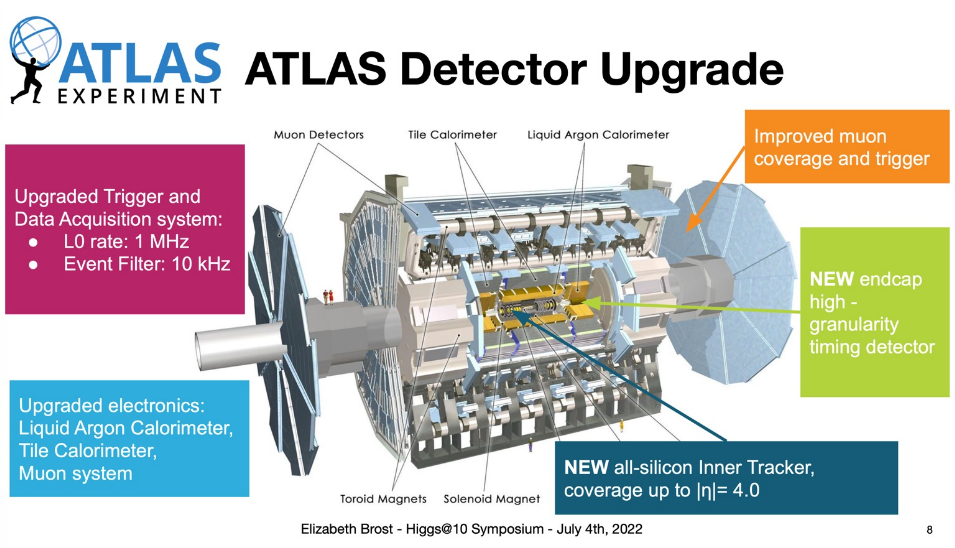
Run 4-6

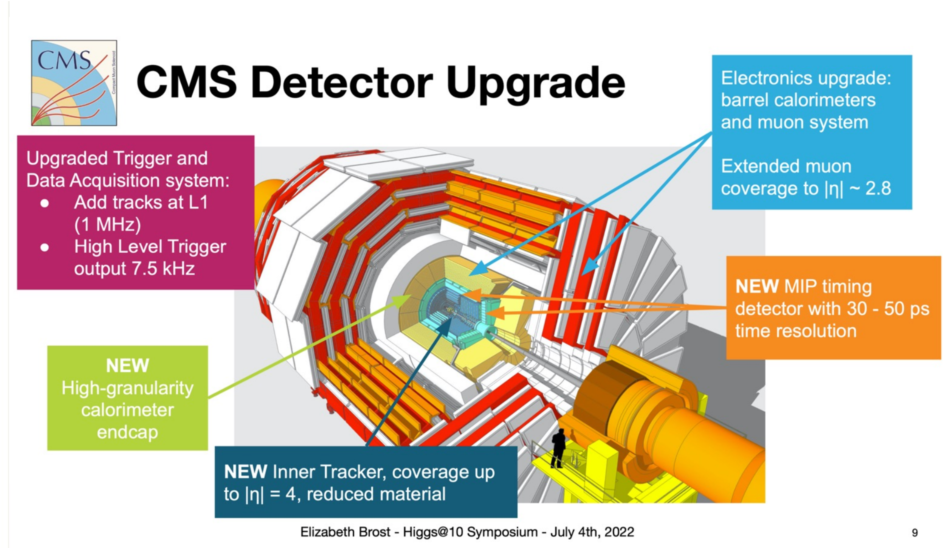


- **Total HL-LHC dataset (3000-4000 fb^{-1}) will be 20 times more data than what has been analyzed.**
  - ~180M Higgs bosons produced per experiment!
- **Mean Pileup will increase from ~30@Run2 to ~200@HL-LHC**

→ detector irradiation, higher detector occupancy, higher trigger rates

Experiment Upgrades for the HL-LHC





The harsh conditions at the HL-LHC will challenge the experiments in all areas, and will require improvements to:

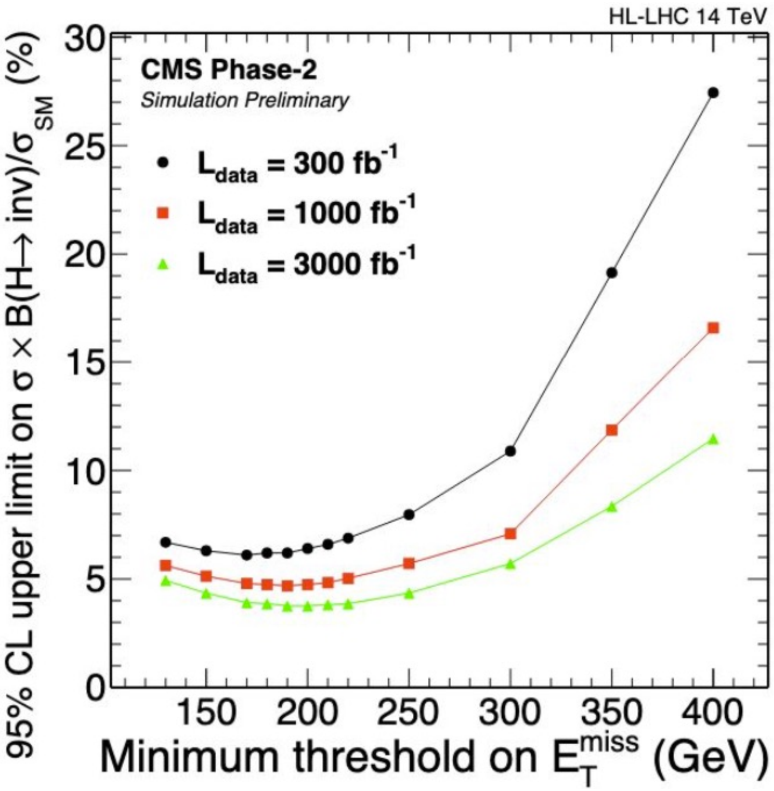
- Detectors themselves
- Trigger menu and hardware
- Event reconstruction
- Software & computing
- Physics analysis techniques

With the planned and ongoing upgrades, the detector and trigger performance after phase 2 upgrades, are supposed to be comparable to or better than Run 2

Projections of H→invisible at HL-LHC

H → invisible searches rely on the MET trigger, significantly more difficult with more pileup

- CMS search in VBF events: BR(H→invisible) < 3.8%, for MET > 190 GeV



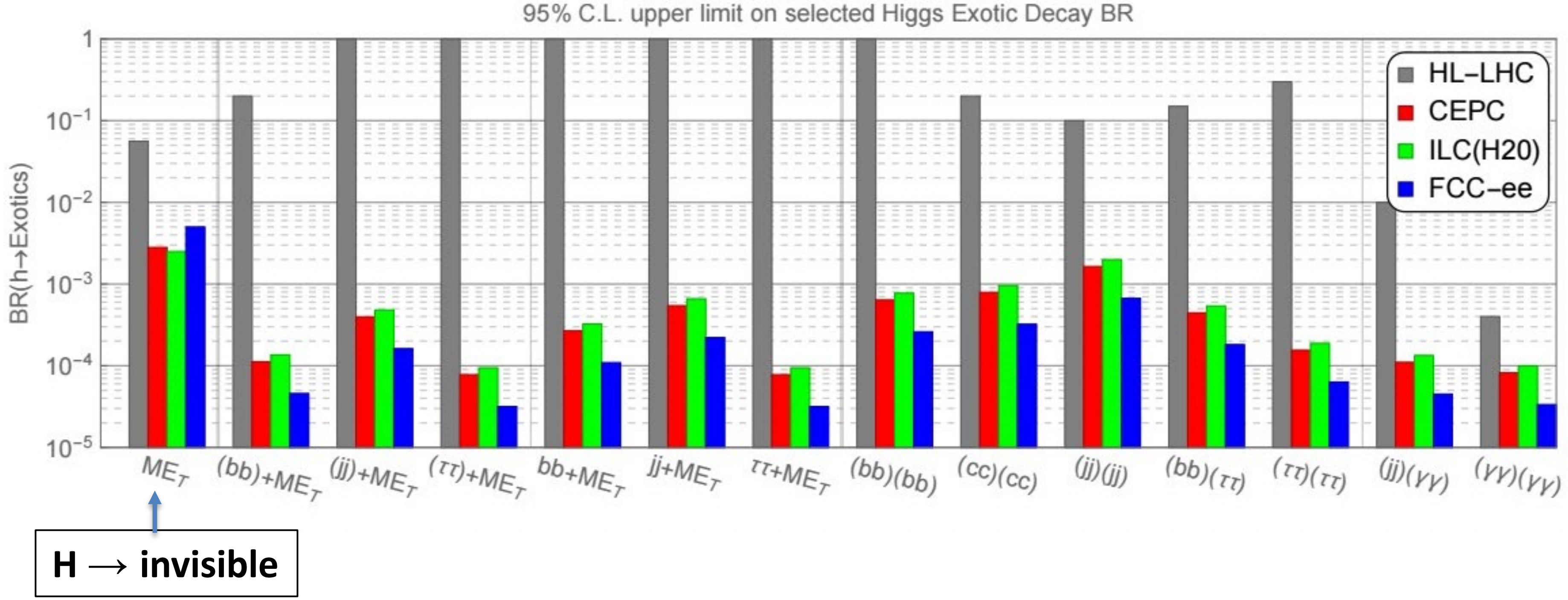
CMS-PAS-FTR-18-016

- **ATLAS+CMS VBF+VH** combination gives **BR(H→invisible) < 2.5%**

CERN-2019-007

Prospects at future colliders

arXiv:1612.09284



Lepton colliders show great advantage for decays that are very challenging at the LHC, such as Higgs decays into jets and Higgs decays with missing energy

- Orders of magnitude improvement for the constraints on such exotic branching fractions

Summary

- No significant sign of exotic Higgs decays seen in the LHC data yet
  - **Though some small deviations need to be verified with more data**
- These searches push the limits of our understanding of physics beyond the Standard Model
  - **And they provide an opportunity to discover new physics**
- Stay tuned for more exciting results as we enter the LHC Run 3 era!

Thank you!