Higgs rare and exotic decays at CMS and ATLAS

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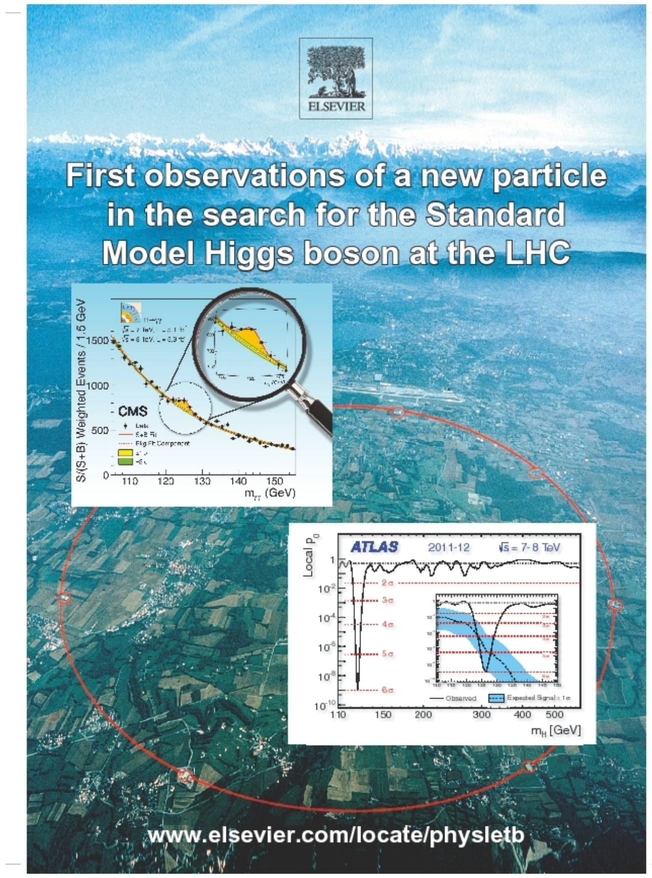
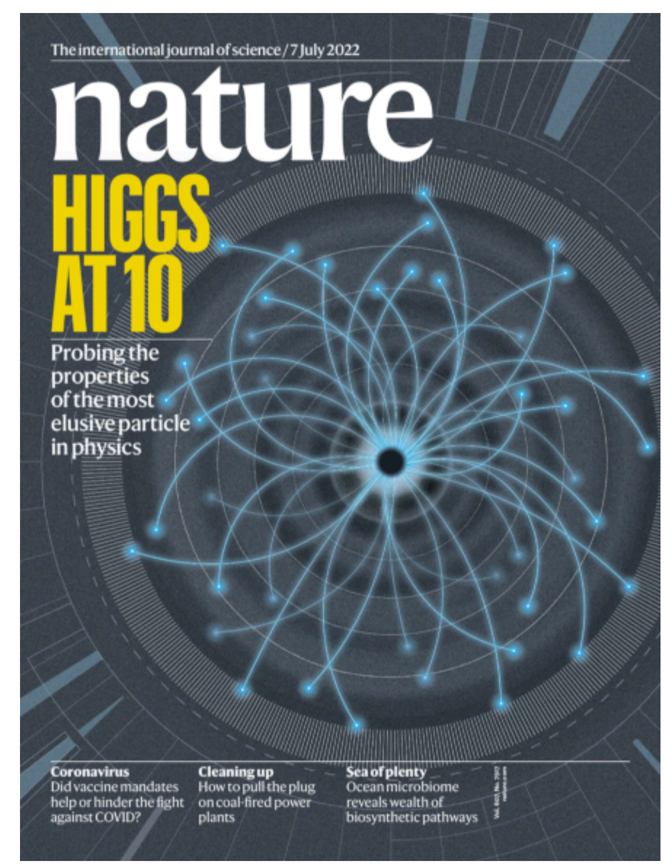
Particle physics is never as exciting as today.

This is largely because of the discovered Higgs boson.

The Higgs boson

- **The Higgs boson** was discovered by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) in 2012
  - a major milestone for particle physics
- It opened a new way to refine our understanding of the electroweak sector
  - many studies of **Higgs boson properties** have been performed
  - deviation from the Standard Model (SM) predictions on Higgs boson properties would provide clue for new physics





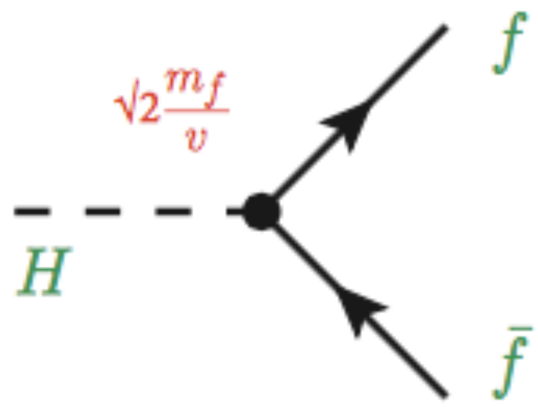
Contents of this talk

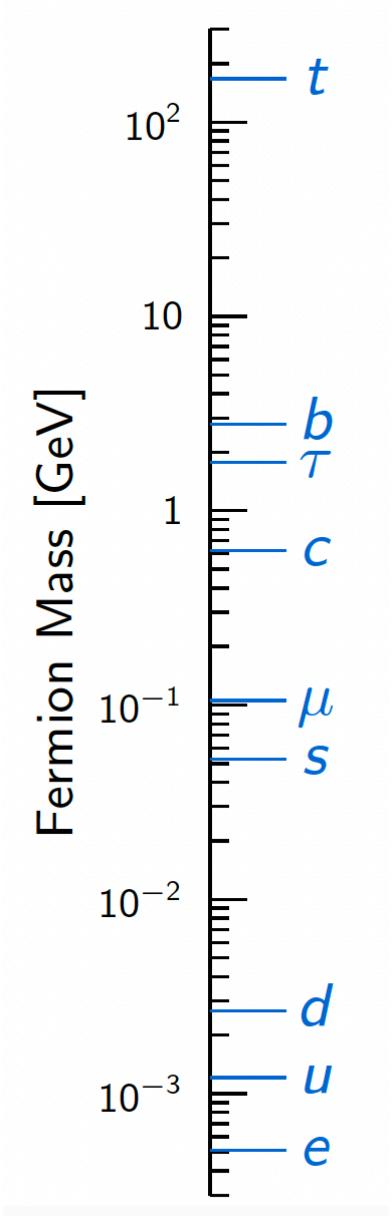
- **Rare and exotic decays of Higgs boson are important portals to new physics**
- **ATLAS and CMS experiments have a large program to study these decays and keep improving sensitivities**
    - Focus on full Run-2 results recently released
- Results of Higgs rare decays
    - $H \to ff$, $H \to ll\gamma$, $H \to$mesons
- Results of Higgs exotic decays
    - $H \to$invisible, lepton flavor violation, $H \to$exotic particles

$H \to ff$

Yukawa couplings

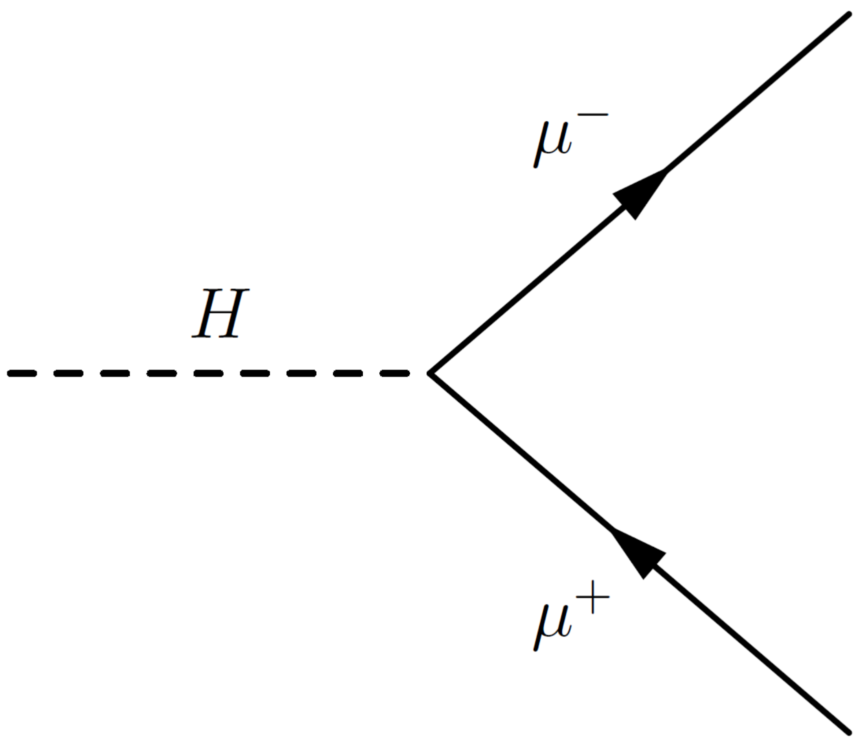
- In Standard Model, Higgs boson couples to fermions (quarks and leptons) through Yukawa interactions
  - **giving masses to quarks and leptons**
- Yukawa interactions are "a new kind of fundamental interaction" -Gavin Salam at LHCP theory summary talk
  - **important to study the Yukawa sector, which may provide important indication for the origin of the fermion mass pattern**
- Experimental signatures: **$t\bar{t}H$ production**, **$H\rightarrow\tau\tau$ decay**, **$H\rightarrow b\bar{b}$ decay**, etc.
  - In SM, Yukawa couplings are proportional to fermion masses; BSM physics can modify coupling strengths





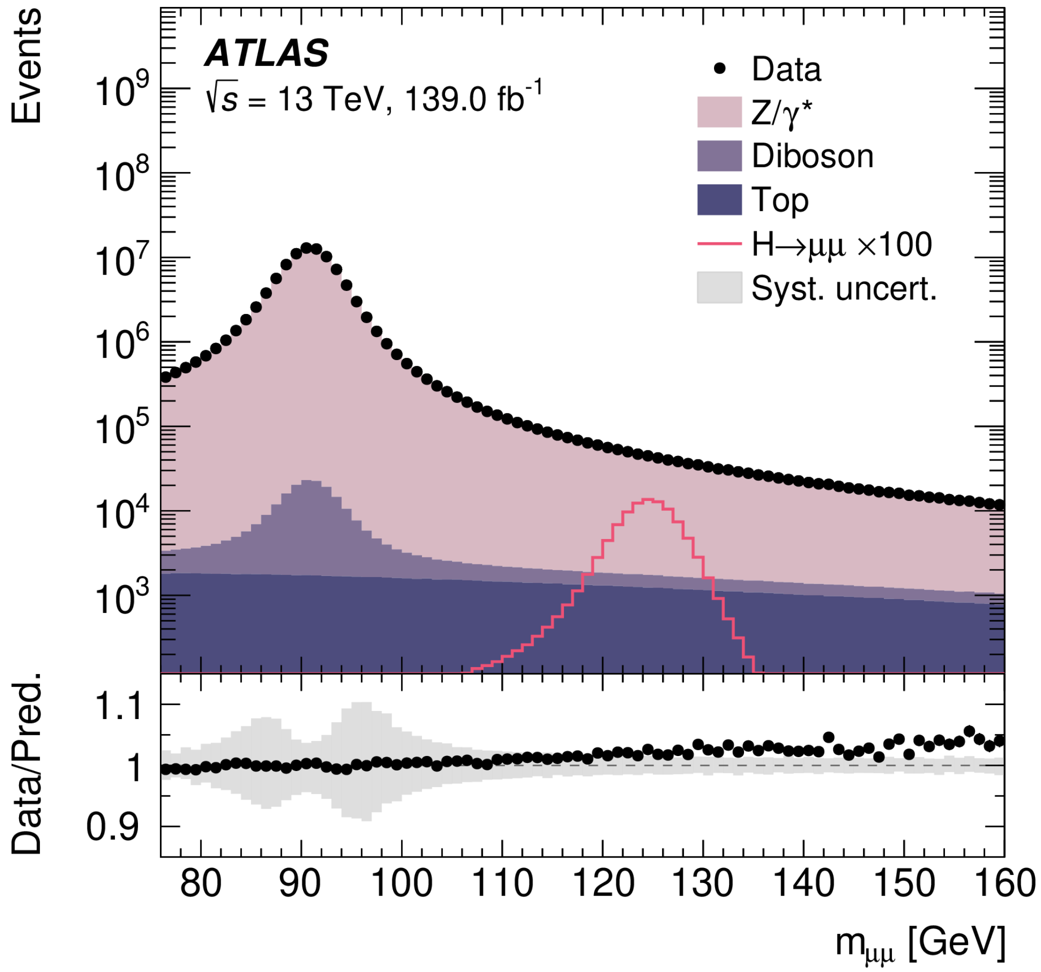
H→$\mu\mu$ decay

- The couplings between the Higgs boson and third-generation fermions (top quark, bottom quark, τ lepton) have already been observed
  - The Higgs couplings with fermions of the other generations have not been established
- The Higgs decay to two muons offers the best opportunity to observe the Higgs couplings with second-generation fermions at the LHC
  - Small branching ratio in SM (2×10^{-4}), physics beyond the SM could modify it

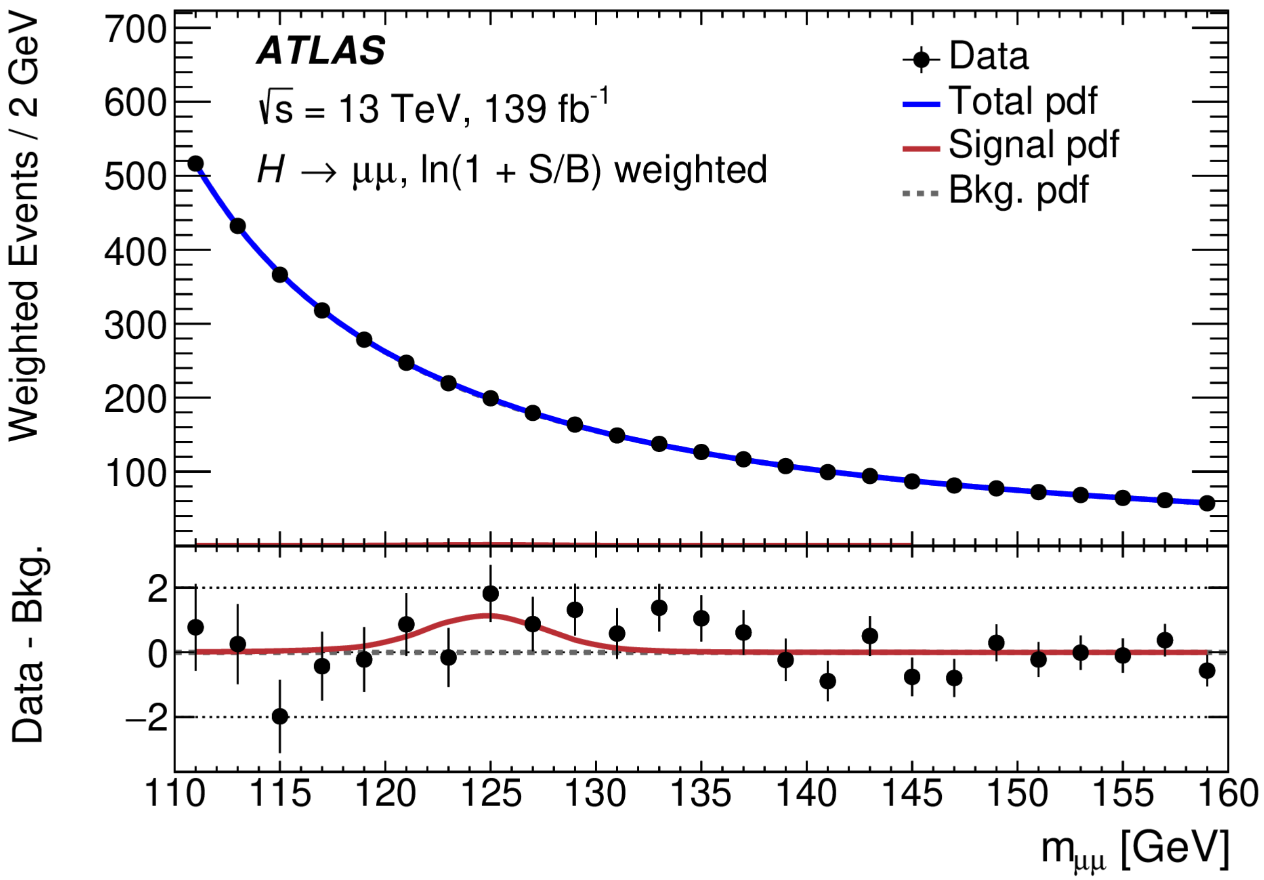


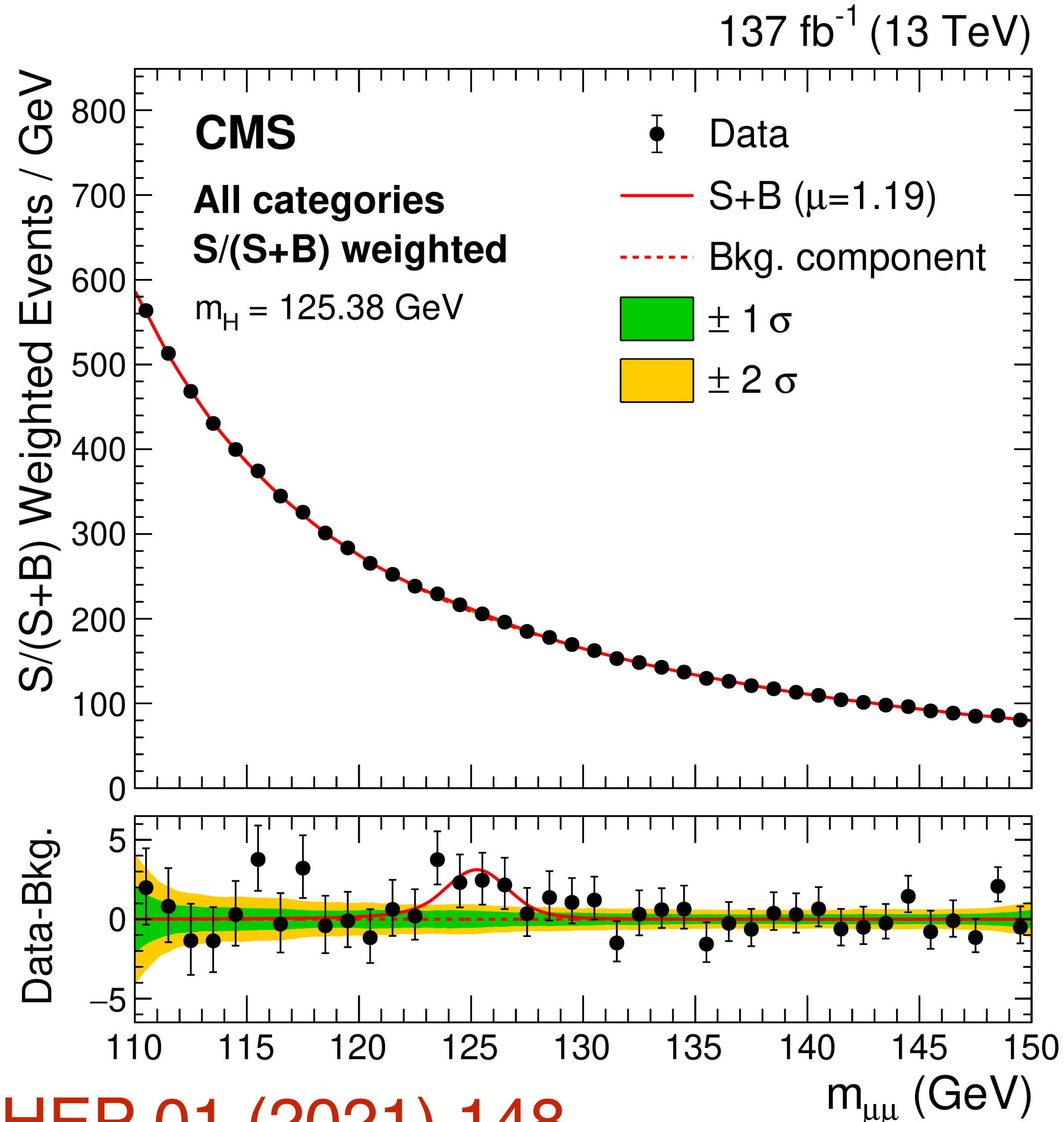
H→$\mu\mu$ decay

- Select events with **two opposite-sign muons**
- The main challenge is a very small signal over background ratio (~0.2% in 120-130 GeV)
  - the dominant background is **Drell-Yan process (Z/γ*→μμ)**
- **MVA-based categories** are defined to target all major Higgs production modes
- **Fit dimuon mass** over all categories; background mass distribution modeled with Core function x Empirical function
  - exception: CMS VBF categories, which fit MVA discriminant and use MC simulation for background modeling



H→$\mu\mu$ decay





Phys. Lett. B 812 (2021) 135980

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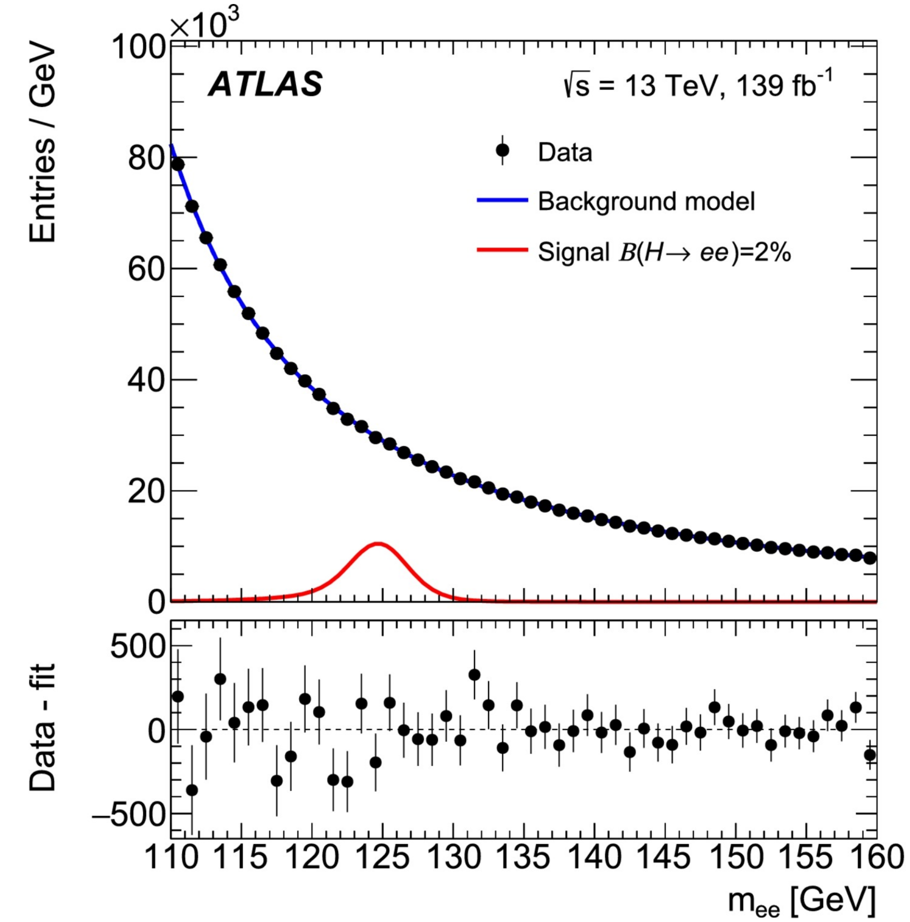
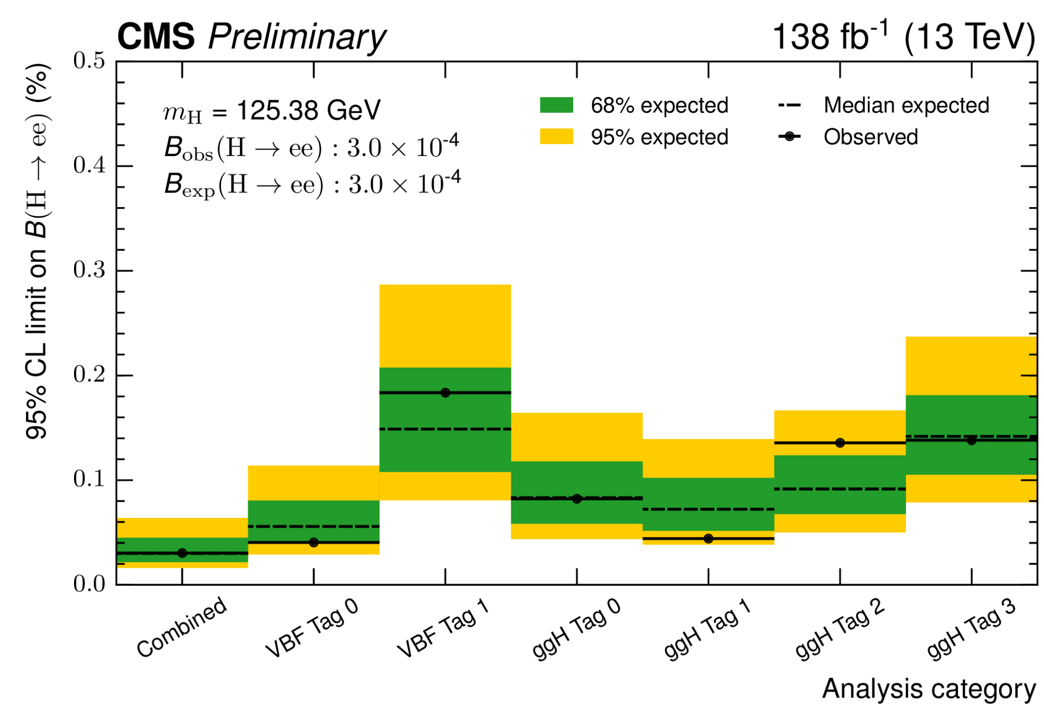
- The observed H→μμ significance in ATLAS full Run 2 result is **2.0σ** (expected 1.7σ)
- The observed H→μμ significance in CMS full Run 2 result is **3.0σ** (expected 2.5σ)
- These results provide **first evidence** for the Higgs couplings to second generation fermions

H→ee decay

- The Higgs decay to two electrons probe Higgs couplings with first generation fermions
  - tiny branching ratio in SM (5x10^{-9})
- Analysis strategy similar to H→μμ analyses
  - ATLAS: BR < 3.6x10^{-4} at 95% CL
  - CMS: BR < 3.0x10^{-4} at 95% CL



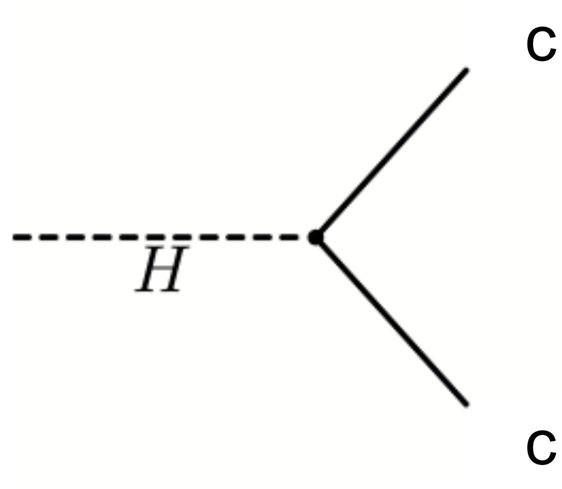


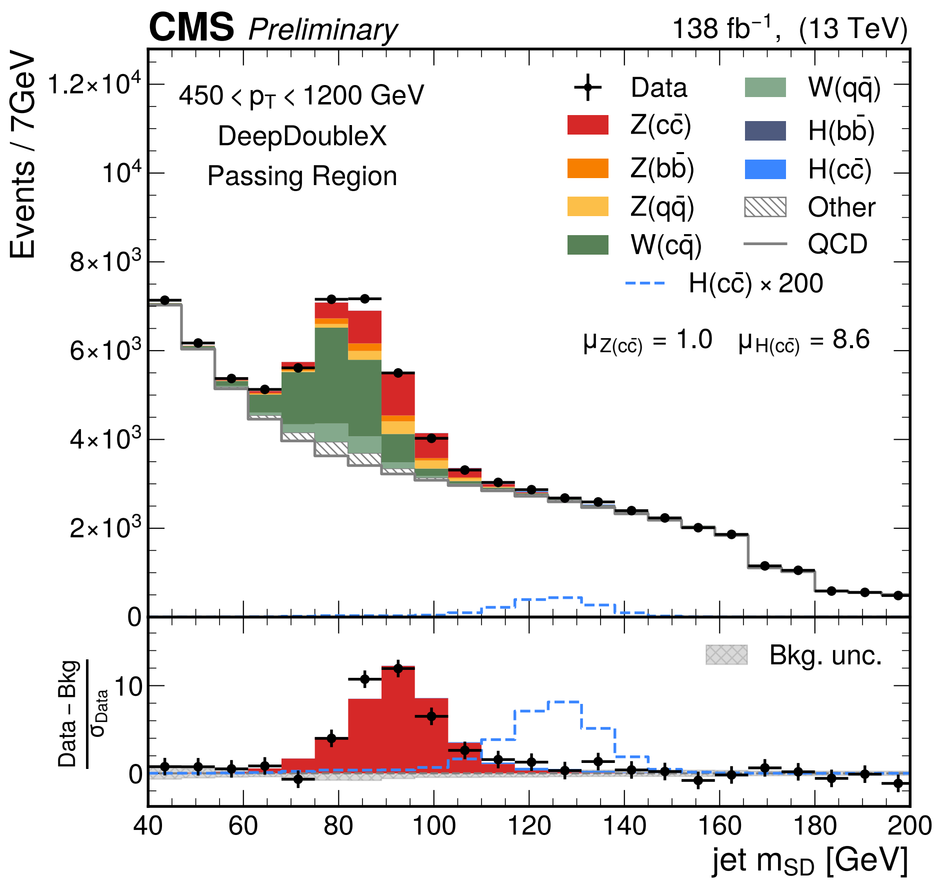
Phys. Lett. B 801 (2020) 135148

CMS-PAS-HIG-21-015

H→cc̄ decay

- **H→cc̄ decay** is currently the main channel to probe Higgs coupling to c quarks
  - branch ratio in SM: 2.8%
- Reconstruct Higgs as two separate small-radius jets (resolved channel) or one large-radius jet (boosted channel)
- Typically large background, tackled by requiring large Higgs pT or associated particles





CMS-PAS-HIG-21-012

Study Higgs boson production with large pT (where some BSM effects are enhanced)

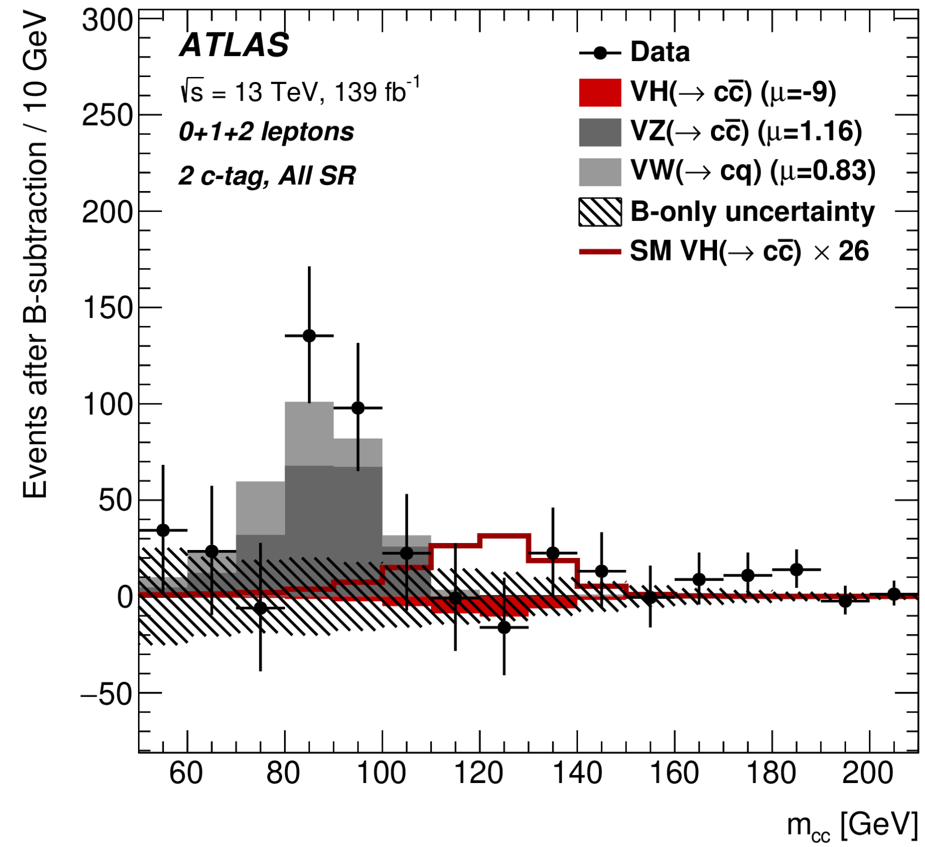
- Higgs reconstructed as single large-radius jet recoiling against a hadronic system
- Main bkg: multi-jet, V+jet
- Inclusive in production modes
- Observed (expected) limit at 95% CL on H→cc̄ signal strength: 45 (38) times SM prediction

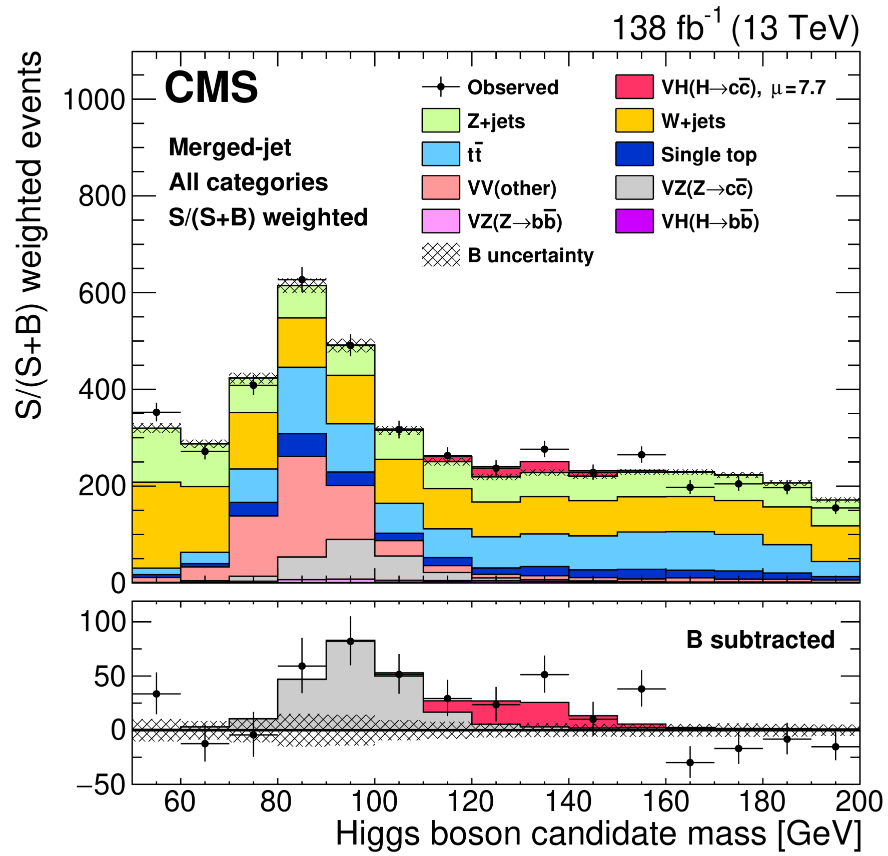
H→cc̄ decay

VH - ATLAS

arXiv:2201.11428

- Tag leptonically decaying W/Z boson
- Main bkg: W/Z+heavy flavor, tt̄
- **Resolved analysis only**
- Observed (expected) limit at 95% CL on H→cc̄ signal strength: 31 (26) times SM prediction
- Constraint on Higgs-charm Yukawa coupling modifier: |Kc| < 8.5





VH - CMS

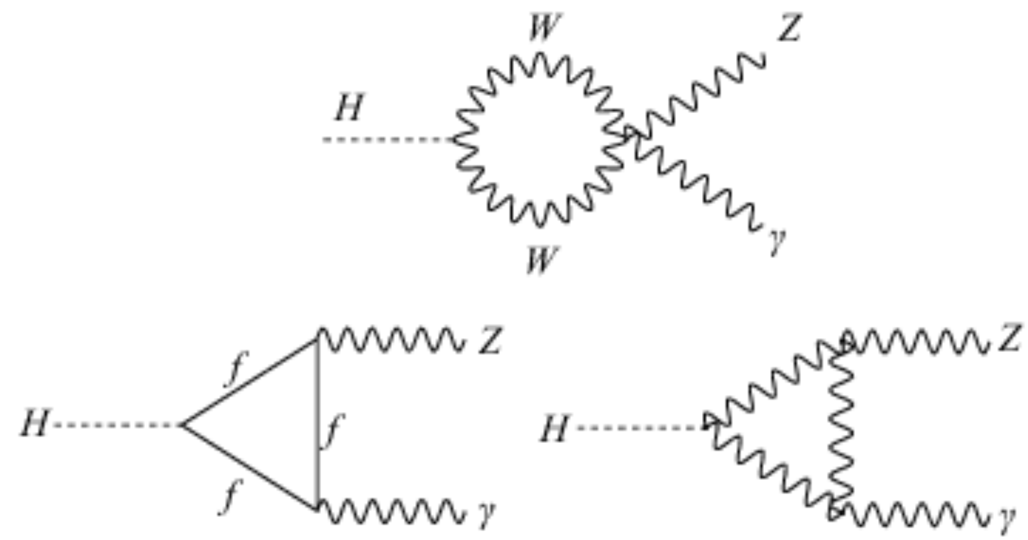
- **Combine both resolved and boosted analyses**
- Boosted analysis benefits from ParticleNet based charm tagging
- Observed (expected) limit at 95% CL on H→cc̄ signal strength: 14 (7.6) times SM prediction
- Constraint on Higgs-charm Yukawa coupling modifier: 1.1 < |Kc| < 5.5

arXiv:2205.05550

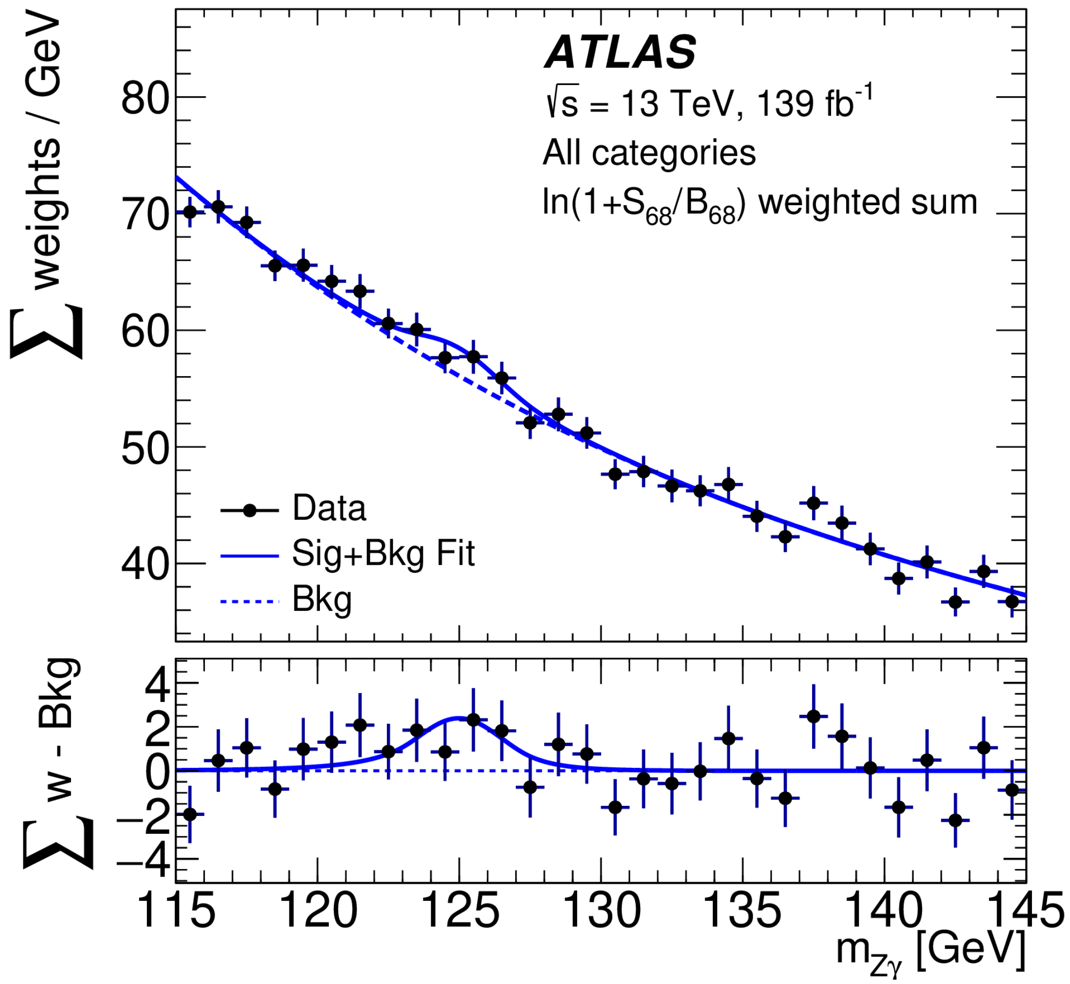
$H \rightarrow ll\gamma$

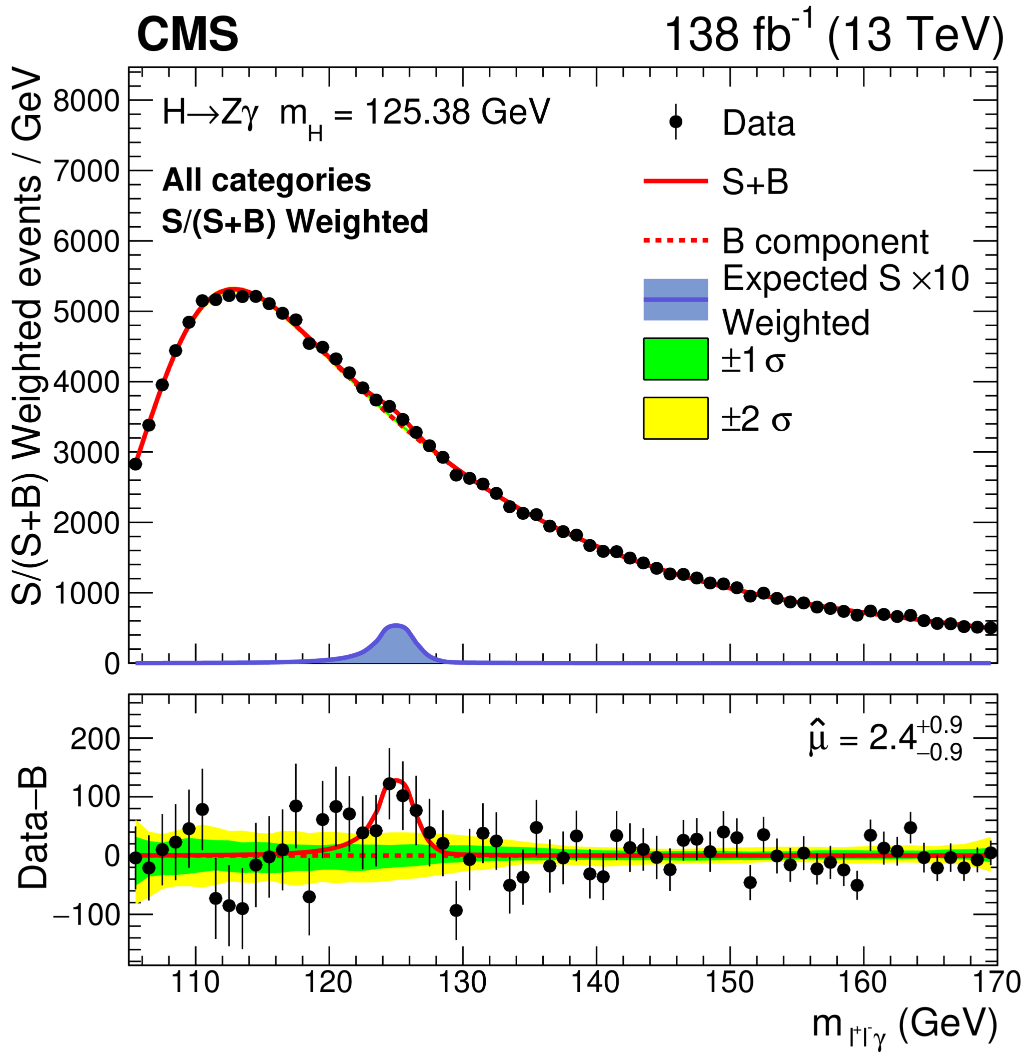
H→Zγ decay

- BSM particles & couplings could be present in the quantum loops
- Difference between H→Zγ decay and H→γγ/H→ZZ decay sensitive to new physics
    - (e.g. Qing-Hong Cao et al. *Phys. Lett. B* 789 (2019) 233)
    - Small branching ratio in SM (1.6×10^{-3}); main bkg: non-Higgs Zγ, Z+jets
- Select events with two leptons (mll ~90 GeV) and one photon and separate them to multiple categories to target various production modes
- Fit in llγ mass distribution over all categories



H→Zγ decay





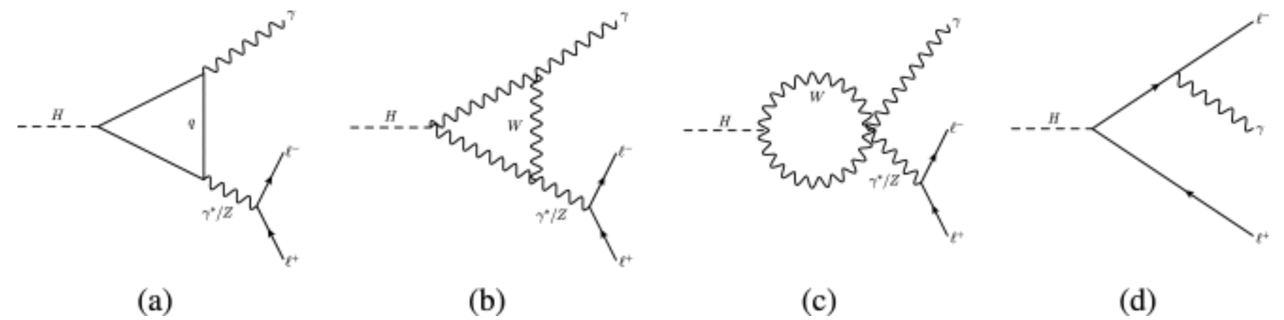
Phys. Lett. B 809 (2020) 135754

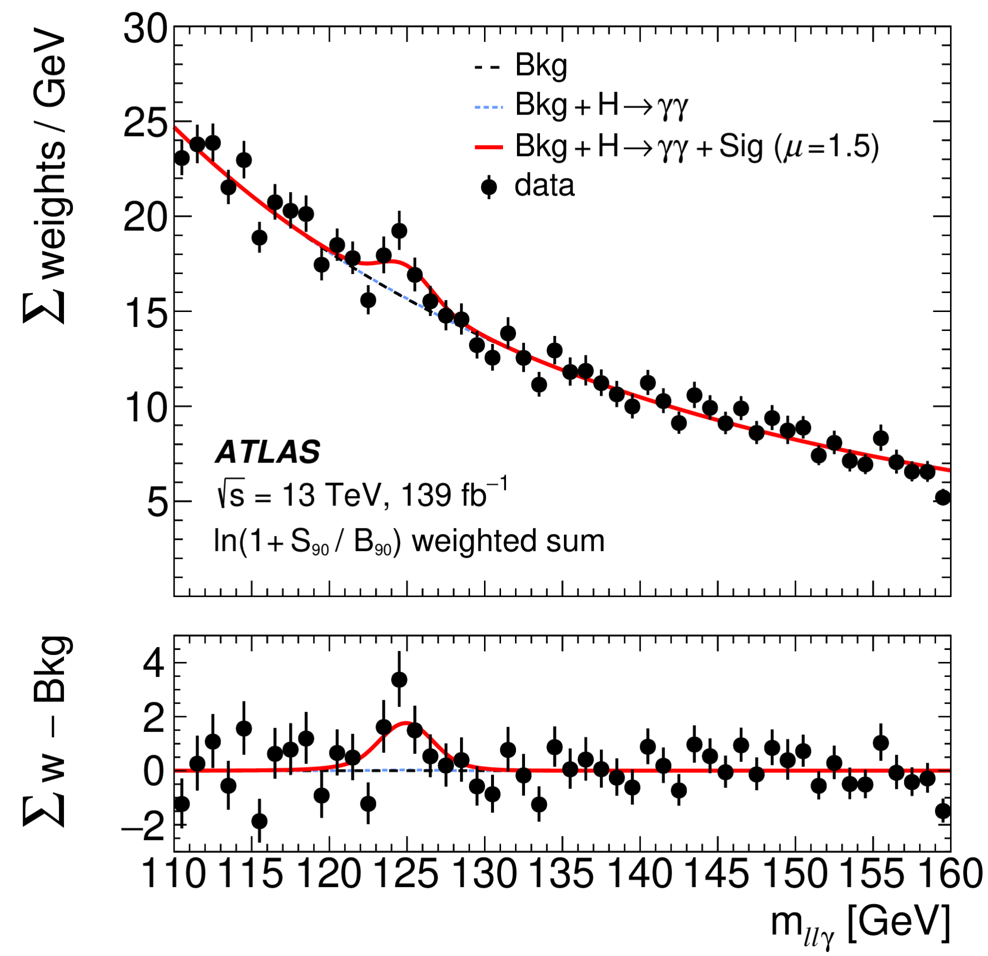
arXiv:2204.12945

- The observed H→Zγ significance in ATLAS full Run 2 result is **2.2σ** (expected 1.2σ)
- The observed H→Zγ significance in CMS full Run 2 result is **2.7σ** (expected 1.2σ)
- Interesting excesses from both experiments

H→γ*γ

- Search for Higgs boson decaying into a photon and a low-mass pair of electrons or muons (m_{ll} < 30 GeV)
- Analyze events in μμ, resolved ee and merged ee channels
  - Dedicated ID and calibration for merged ee channel
- The observed significance in ATLAS full Run 2 result is **3.2σ** (expected 2.1σ) : **first evidence** for this process!





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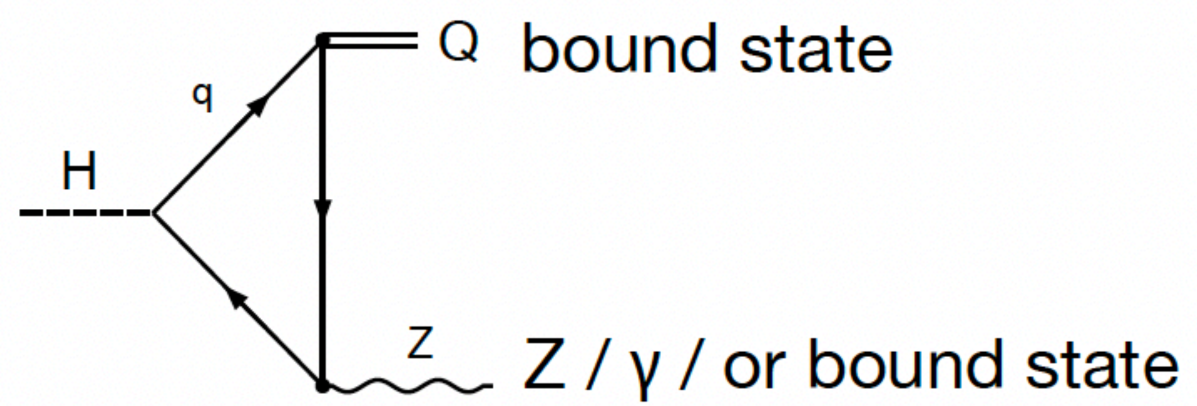
$H \to mesons$

Higgs decays to mesons

- Higgs decays to mesons can be used to study Higgs couplings to light, charm and bottom quarks, as well as new physics in the loops

- Look into associated production to reduce background



Higgs decays to mesons

- The quarkonium decays to two muons leave a clear signature inside the detectors

ATLAS, quarkonium+photon

Decay channel	95% CL_s upper limits: Branching fraction, Higgs boson [10^{-4}] Expected	Higgs boson [10^{-4}] Observed	Z boson [10^{-6}] Expected	Z boson [10^{-6}] Observed	$\sigma \times \mathcal{B}$: Higgs boson [fb] Observed	Z boson [fb] Observed
$J/\psi\,\gamma$	$1.9^{+0.8}_{-0.5}$	2.1	$0.6^{+0.3}_{-0.2}$	1.2	12	71
$\psi(2S)\,\gamma$	$8.5^{+3.8}_{-2.4}$	10.9	$2.9^{+1.3}_{-0.8}$	2.3	61	135
$\Upsilon(1S)\,\gamma$	$2.8^{+1.3}_{-0.8}$	2.6	$1.5^{+0.6}_{-0.4}$	1.0	14	59
$\Upsilon(2S)\,\gamma$	$3.5^{+1.6}_{-1.0}$	4.4	$2.0^{+0.8}_{-0.6}$	1.2	24	71
$\Upsilon(3S)\,\gamma$	$3.1^{+1.4}_{-0.9}$	3.5	$1.9^{+0.8}_{-0.5}$	2.3	19	135

CMS, quarkonium +Z and 2 quarkonium

Process	Observed	Expected	Observed	
Higgs boson channel	Longitudinal	Longitudinal	Unpolarized	Transverse
$\mathcal{B}(H \to ZJ/\psi)$	1.9×10^{-3}	$(2.6^{+1.1}_{-0.7}) \times 10^{-3}$	2.4×10^{-3}	2.8×10^{-3}
$\mathcal{B}(H \to Z\psi(2S))$	6.6×10^{-3}	$(7.1^{+2.8}_{-2.0}) \times 10^{-3}$	8.3×10^{-3}	9.4×10^{-3}
$\mathcal{B}(H \to J/\psi J/\psi)$	3.8×10^{-4}	$(4.6^{+2.0}_{-0.6}) \times 10^{-4}$	4.7×10^{-4}	5.2×10^{-4}
$\mathcal{B}(H \to \psi(2S)J/\psi)$	2.1×10^{-3}	$(1.4^{+0.6}_{-0.4}) \times 10^{-3}$	2.6×10^{-3}	2.9×10^{-3}
$\mathcal{B}(H \to \psi(2S)\psi(2S))$	3.0×10^{-3}	$(3.3^{+1.5}_{-0.9}) \times 10^{-3}$	3.6×10^{-3}	4.7×10^{-3}
$\mathcal{B}(H \to \Upsilon(nS)\Upsilon(mS))$	3.5×10^{-4}	$(3.6^{+0.2}_{-0.3}) \times 10^{-4}$	4.3×10^{-4}	4.6×10^{-4}
$\mathcal{B}(H \to \Upsilon(1S)\Upsilon(1S))$	1.7×10^{-3}	$(1.7^{+0.1}_{-0.1}) \times 10^{-3}$	2.0×10^{-3}	2.2×10^{-3}
Z boson channel				
$\mathcal{B}(Z \to J/\psi J/\psi)$	11×10^{-7}	$(9.5^{+3.8}_{-2.6}) \times 10^{-7}$	14×10^{-7}	16×10^{-7}
$\mathcal{B}(Z \to \Upsilon(nS)\Upsilon(mS))$	3.9×10^{-7}	$(4.0^{+0.3}_{-0.3}) \times 10^{-7}$	4.9×10^{-7}	5.6×10^{-7}
$\mathcal{B}(Z \to \Upsilon(1S)\Upsilon(1S))$	1.8×10^{-6}	$(1.8^{+0.1}_{-0.0}) \times 10^{-6}$	2.2×10^{-6}	2.4×10^{-6}

HDBS-2018-53

arXiv:2206.03525

Higgs decays to mesons

- Bounds states like ϕ and ρ can decay into pairs of kaons and pions, which have good mass resolution at low pT

ATLAS, ϕγ and ργ

Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)\,[\,10^{-4}\,]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \to \phi\gamma)\,[\,10^{-6}\,]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \to \rho\gamma)\,[\,10^{-4}\,]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \to \rho\gamma)\,[\,10^{-6}\,]$	33^{+13}_{-9}	25

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CMS, ϕZ and ρZ

	Observed	Median expected	±68% expected	±95% expected
Isotropic decay	0.36%	0.33%	0.23–0.46%	0.18–0.61%
Z and ϕ longitudinally polarized	0.31%	0.27%	0.20–0.39%	0.15–0.52%
Z and ϕ transversely polarized	0.40%	0.36%	0.26–0.50%	0.19–0.68%

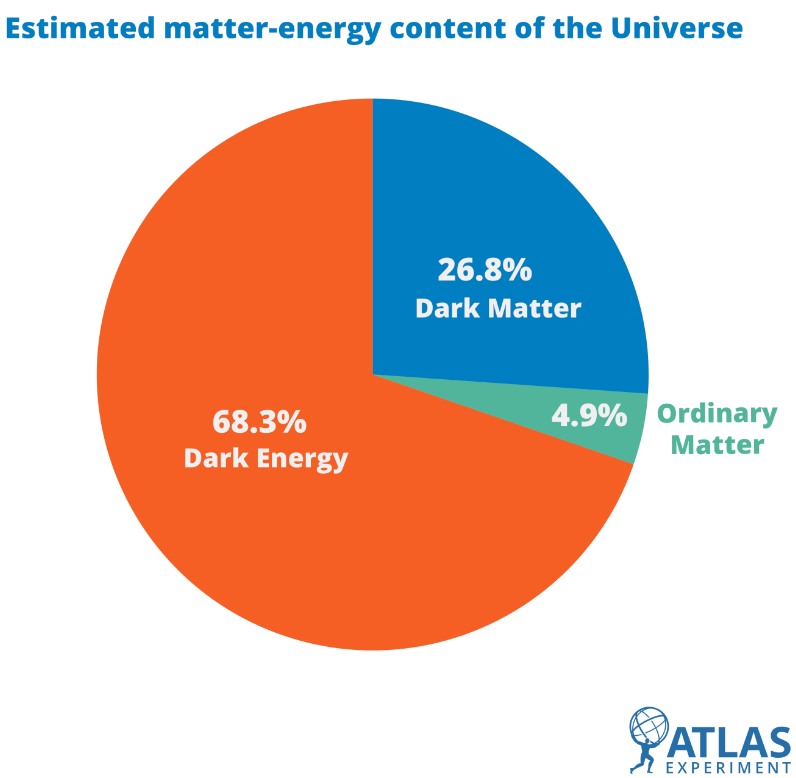
	Observed	Median expected	±68% expected	±95% expected
Isotropic decay	1.21%	0.73%	0.52–1.04%	0.38–1.41%
Z and ρ longitudinally polarized	1.04%	0.63%	0.44–0.89%	0.32–1.20%
Z and ρ transversely polarized	1.31%	0.80%	0.57–1.14%	0.41–1.54%

JHEP 11 (2020) 039

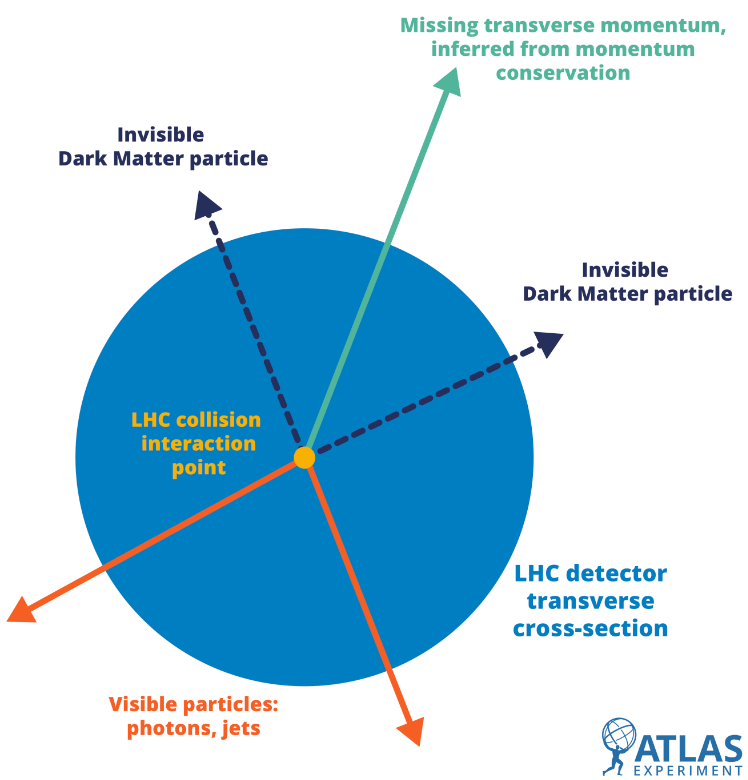
$H \to$ *invisible*

Dark Matter @ LHC

- Dark Matter comprises most of the mass of the Universe according to astrophysics measurements
  - But the nature of Dark Matter remains largely unknown

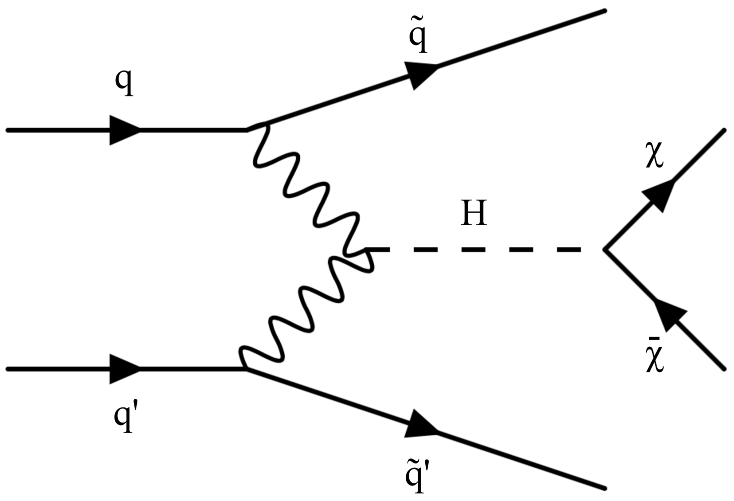


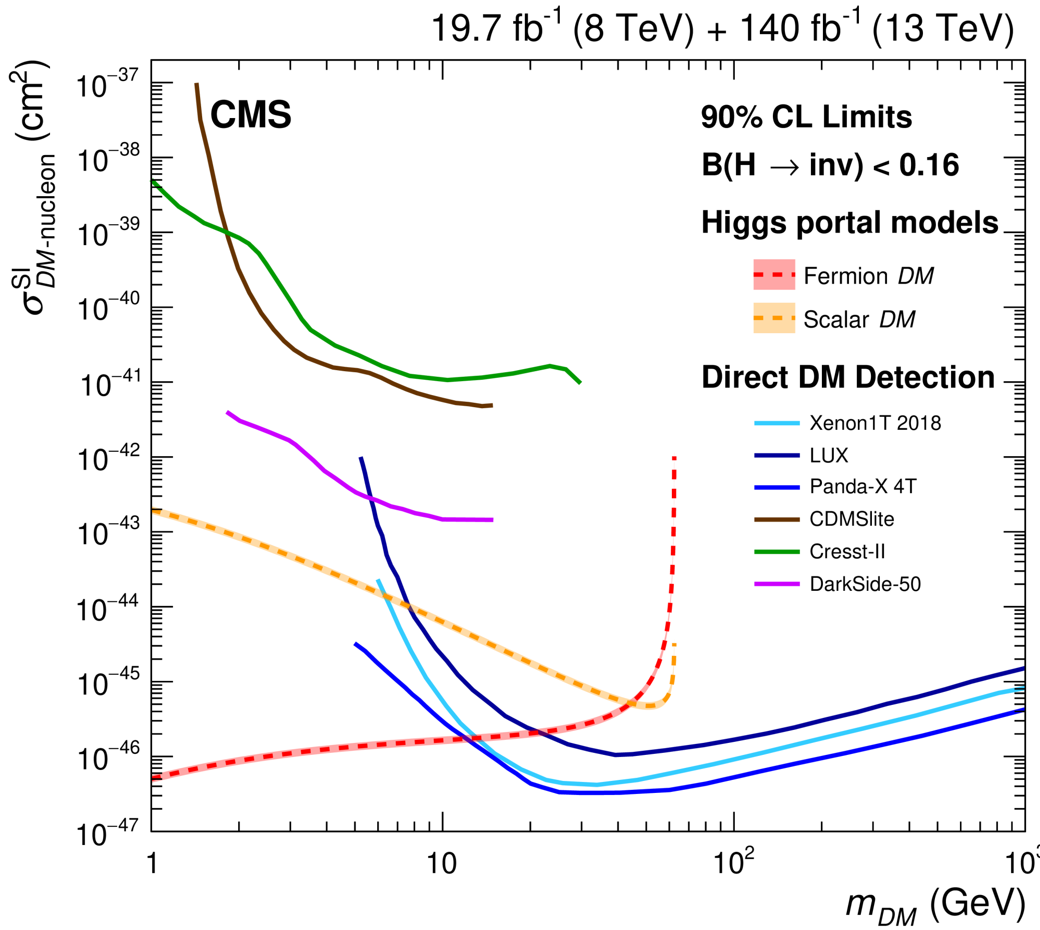
- If Dark Matter has weak interaction with known particles, it can be produced at the LHC
  - They would not leave a visible signature in the detectors
  - Look for visible objects (e.g. jets, photons) plus large missing transverse momentum from Dark Matter



Higgs→invisible Dark Matter search

- The Higgs discovery has opened up a new path to discover Dark Matter. Higgs→invisible decay is favored by so-called "Higgs portal" model
  - where Dark Matter interacts with known particles through the Higgs boson
- VBF channel drives the sensitivity thanks to its cross section and event topology (main background: V+jets).
- Run 2 observed (expected) limits on branching ratios:
  - ATLAS (arXiv:2202.07953): BR < 14.5% (10.3%)
  - CMS (Phys. Rev. D 105 (2022) 092007): BR < 18% (10%)
- Results are interpreted as limit on DM-nucleon scattering in Higgs portal model

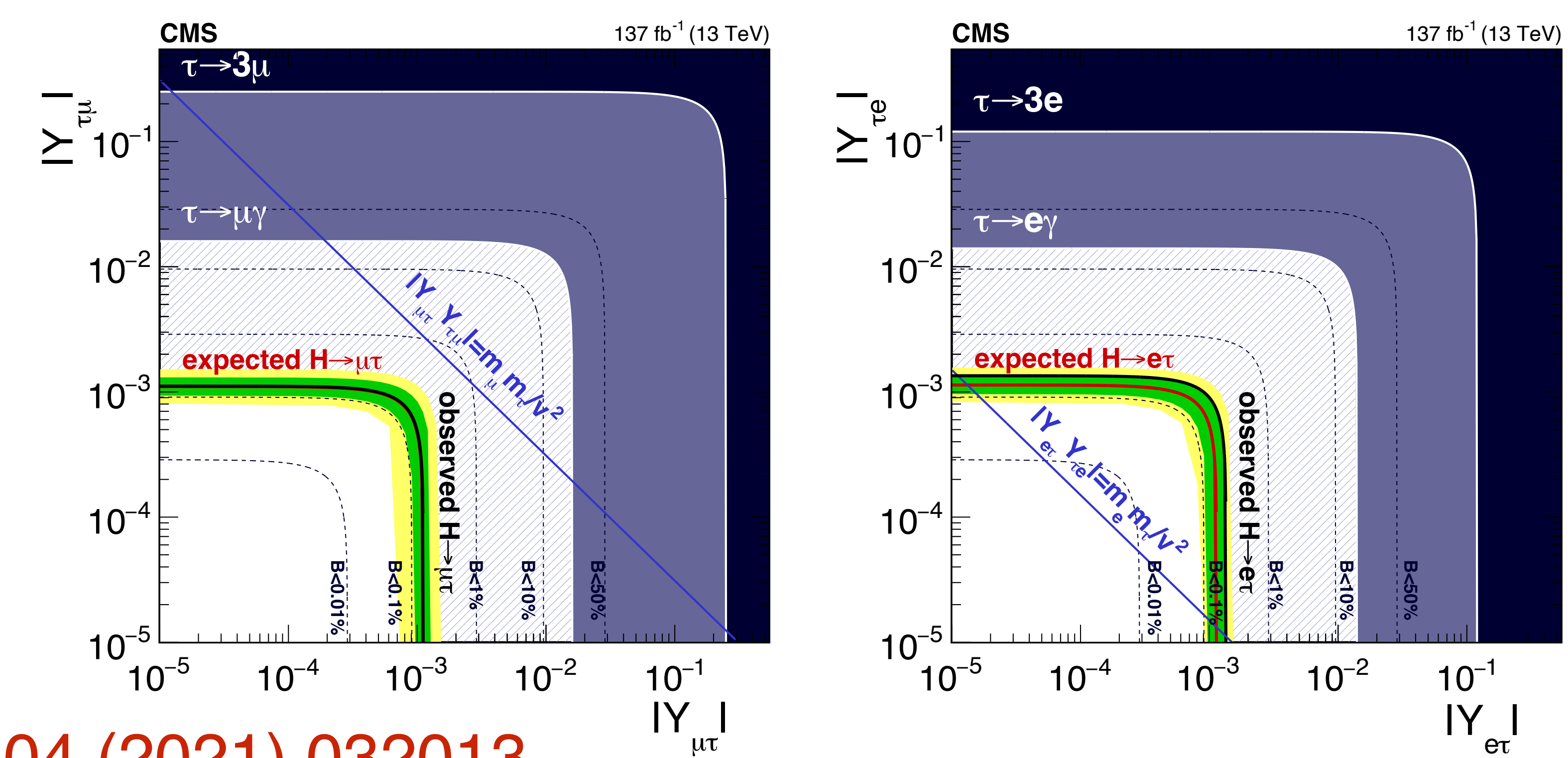




Lepton flavor violation

Lepton flavor violation decays

- H→eμ, H→eτ, or H→μτ decays are forbidden in the SM, but take place through LFV Yukawa couplings $Y_{e\mu}$, $Y_{e\tau}$, or $Y_{\mu\tau}$ arising in two Higgs boson doublet models, composite Higgs models, models with flavor symmetries, extra spatial dimensions, etc.
- Focus on $Y_{e\tau}$ and $Y_{\mu\tau}$ ($Y_{e\mu}$ strongly constrained by μ→eγ)
- Observed (expected) upper limits on branching ratios
  - H→eτ: BR < 0.15% (0.15%) at 95% CL
  - H→μτ: BR < 0.22% (0.16%) at 95% CL
- Limits are used to put constraints on $Y_{e\tau}$ and $Y_{\mu\tau}$



Phys. Rev. D 104 (2021) 032013

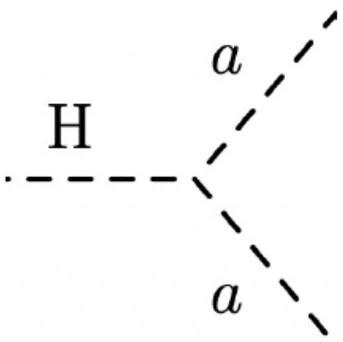
H→exotic particles

Higgs decays to exotic particles

- Extensions to the Standard Model predict Higgs decays to exotic particles, which may decay into SM particles

- ATLAS and CMS have searched for these decay modes in various final states using LHC Run 2 data

H→aa/AA

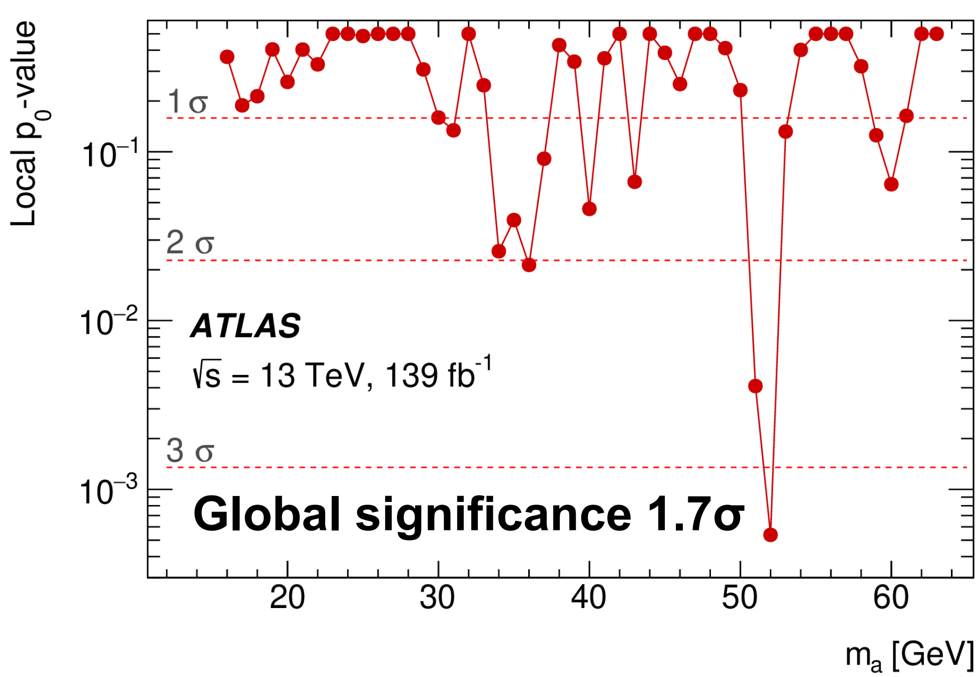


In various BSM models: additional SM-neutral singlet, minimal composite Higgs models, two-Higgs-doublet-like models, axion-like particle, etc.

ATLAS, H→aa→bbμμ

Kinematic likelihood fit is performed exploiting equal invariant masses of bb and μμ

=>m(μμ) is used to constrain m(bb)

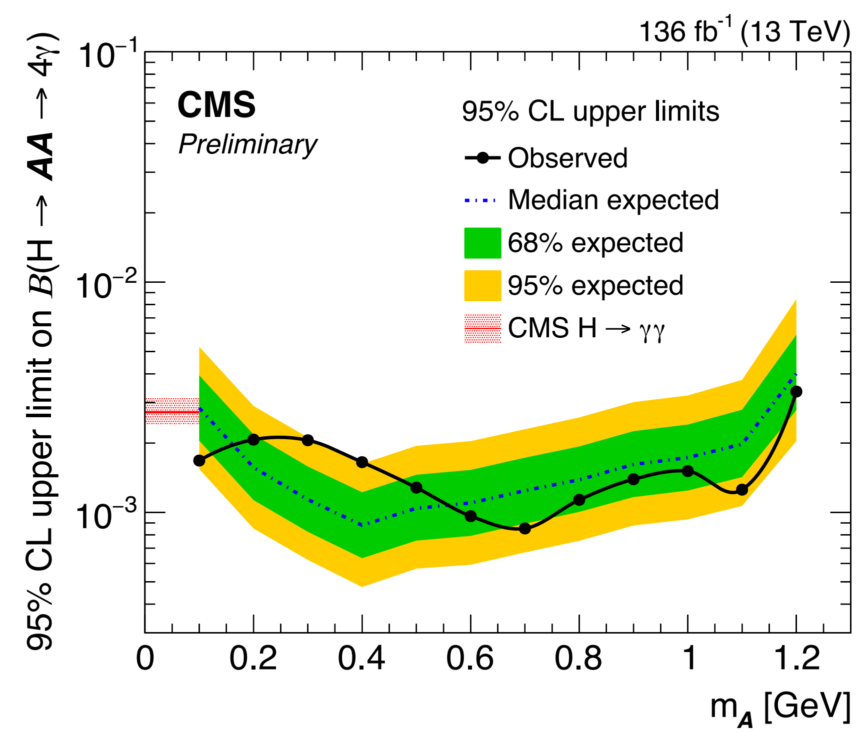


Phys. Rev. D 105, 012006 (2022)

CMS, H→AA→γγγγ

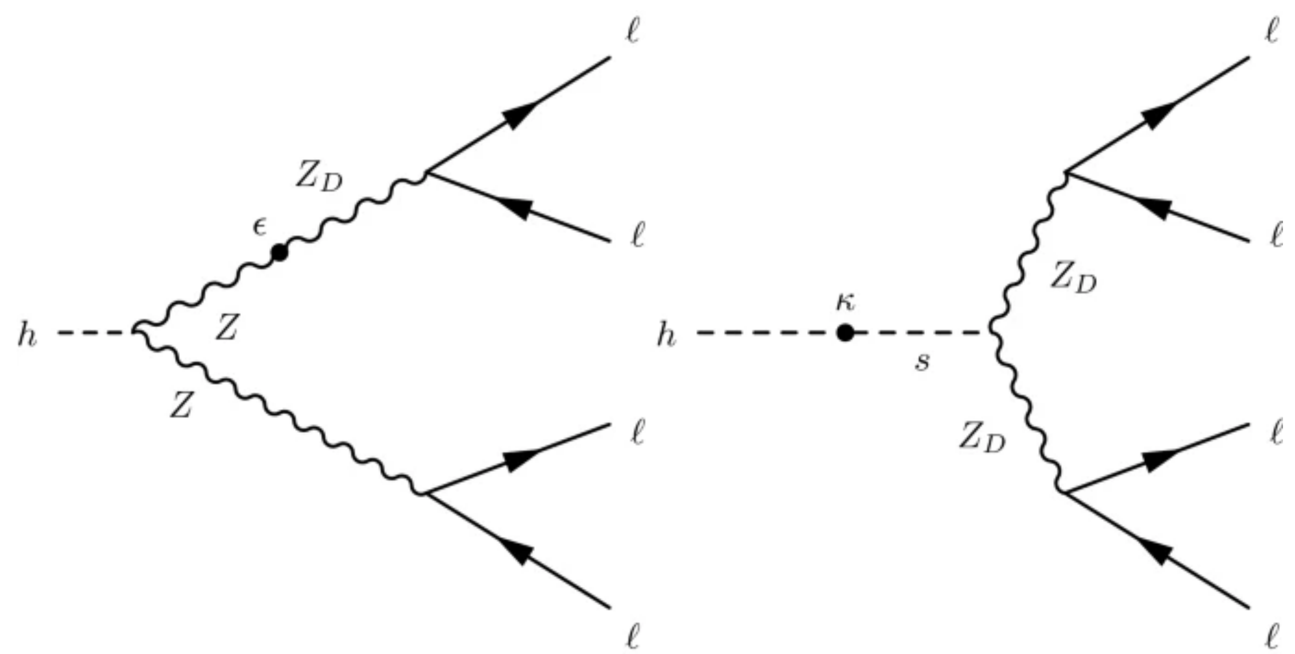
Low-mass, boosted scalar A decays to two highly merged photons, mis-reconstructed as a single photon-like object

=>Dedicated reconstruction using deep learning



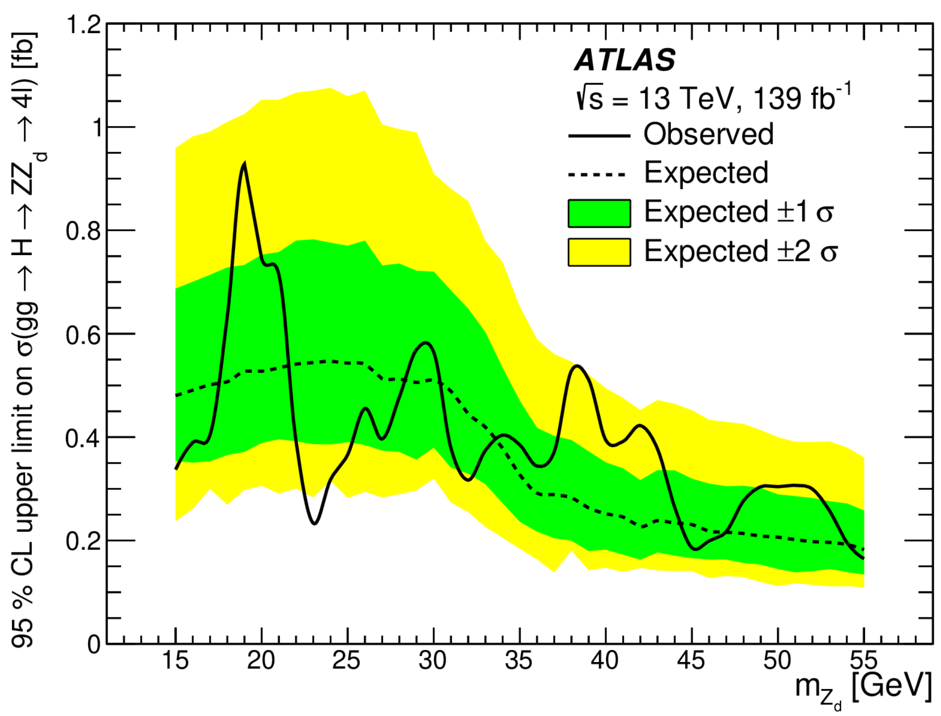
CMS-PAS-HIG-21-016

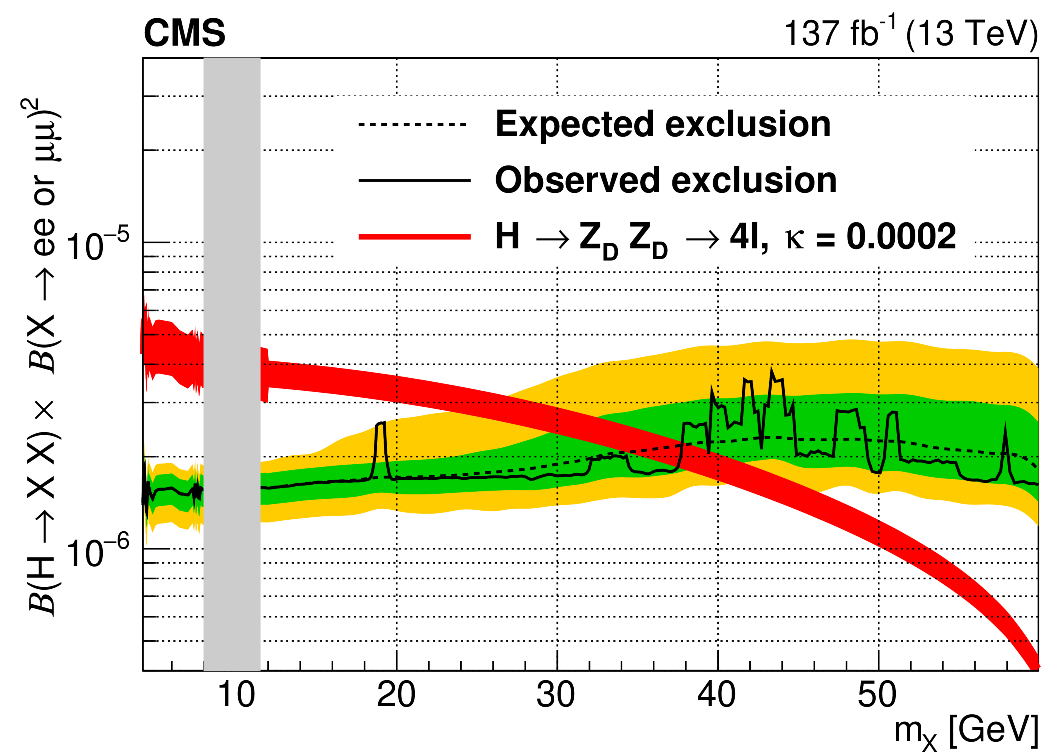
$H\to ZX/XX\to 4l$



In various BSM models: hidden Abelian Higgs Model, axion-like particle, extended Higgs sector, etc.

- Different dilepton mass requirements in ZX and XX selections





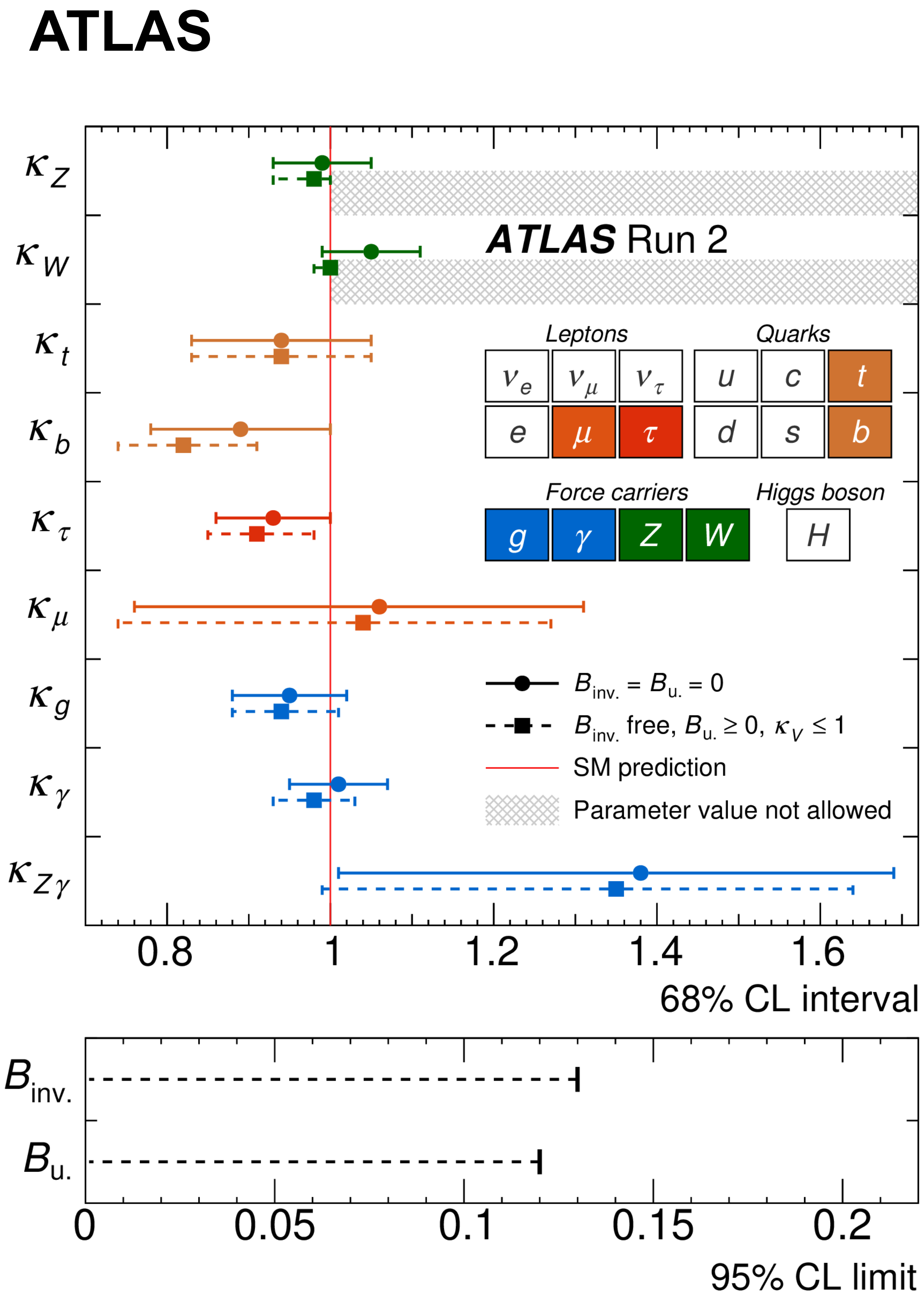
JHEP 03 (2022) 041

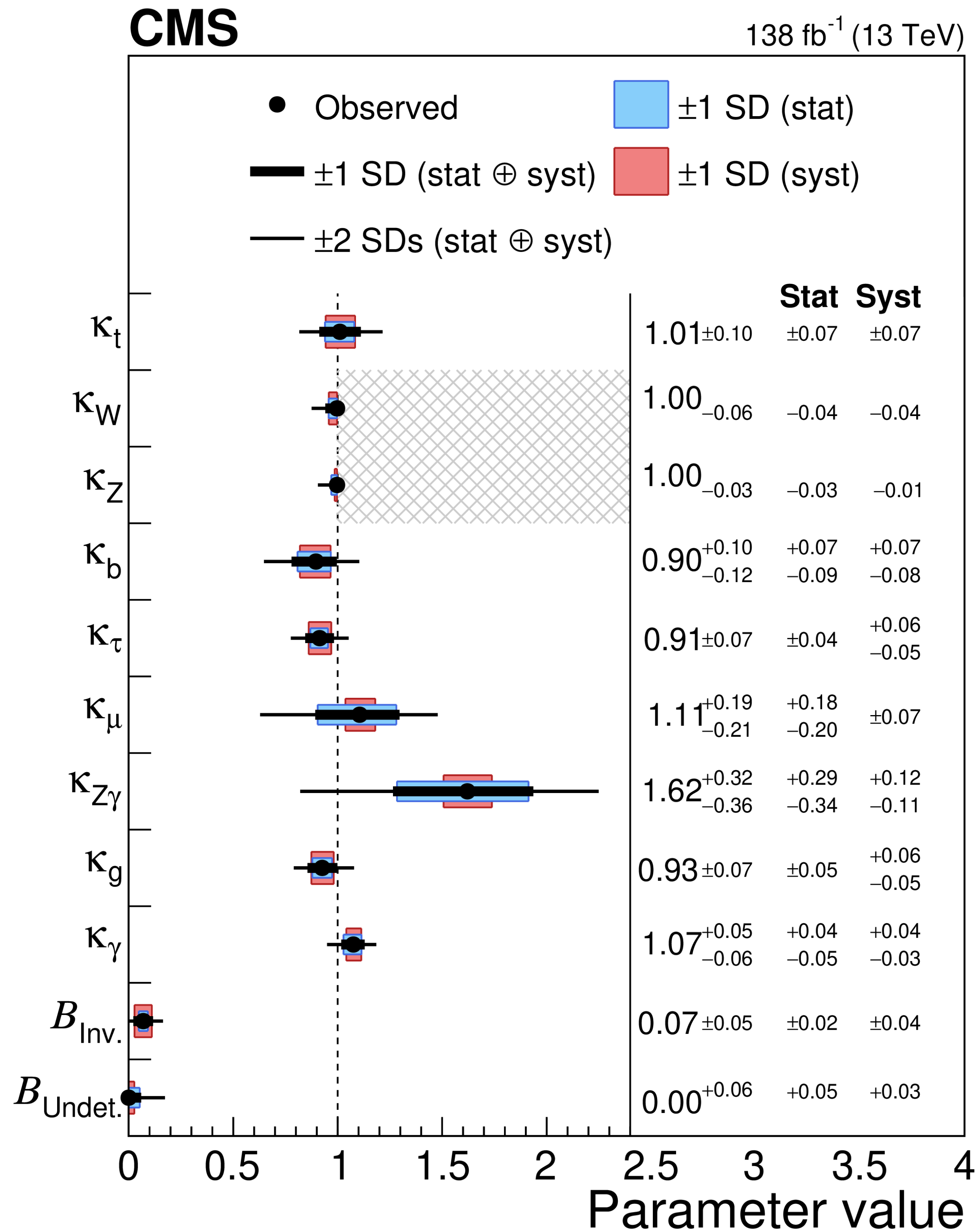
Eur. Phys. J. C 82 (2022) 290

Summary

- **Rare and exotic decays of Higgs boson are important portals to new physics**
- **ATLAS and CMS experiments have a large program to study these decays and keep improving sensitivities**
  - Results are so far consistent with the Standard Model predictions
  - First evidence of $H\rightarrow\mu\mu$ and $H\rightarrow\gamma^{*}\gamma$
- Run 3 is now approaching. **Stay tune for the new results!**

Summary





Nature 607 (2022) 52-59

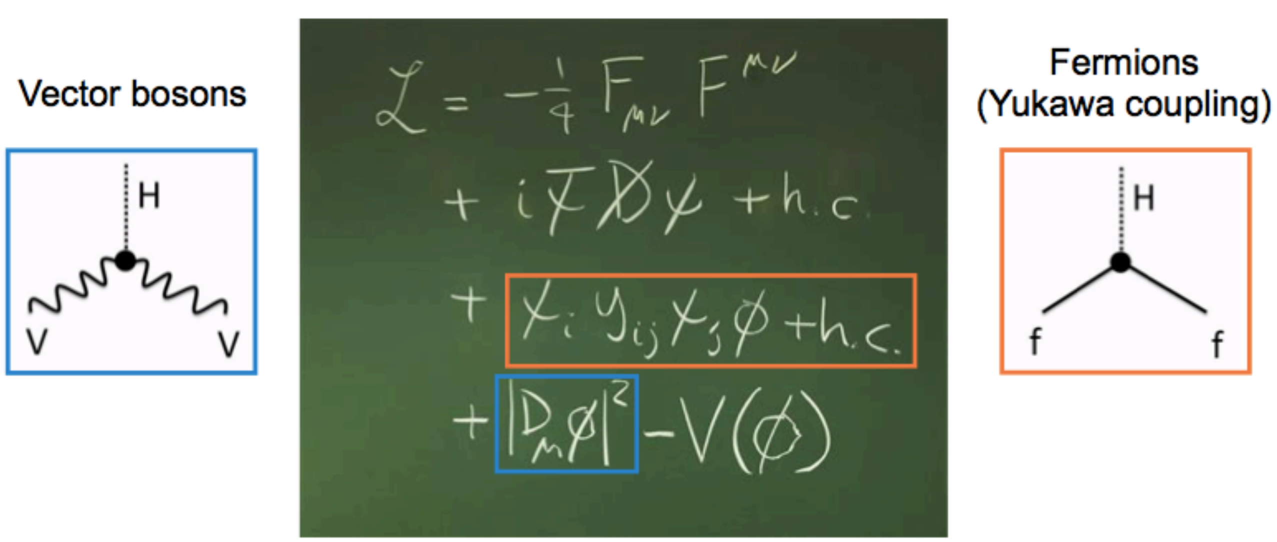
Nature 607 (2022) 60-68

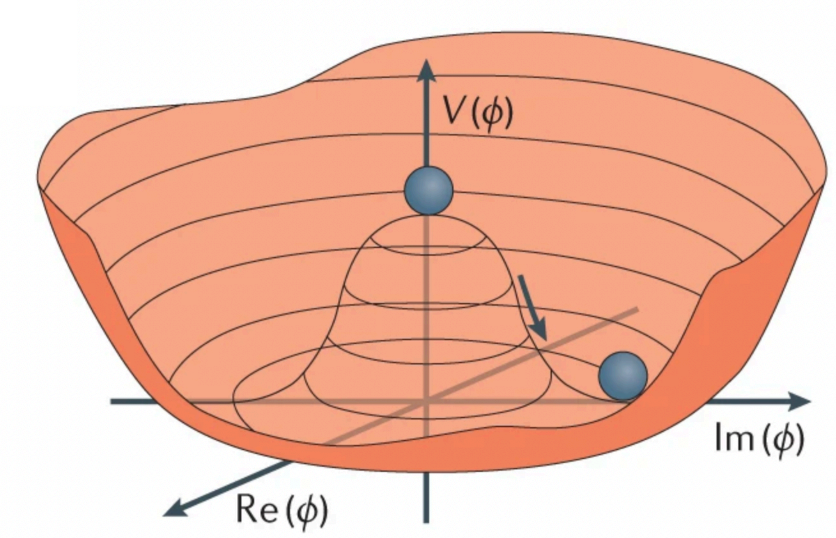
Thank you!

The Higgs boson

- ***In their famous 1964 papers, Professors Robert Brout, François Englert and Peter Higgs proposed a new, massive boson of spin zero to explain how elementary particles – the building blocks of the Universe – get their masses***

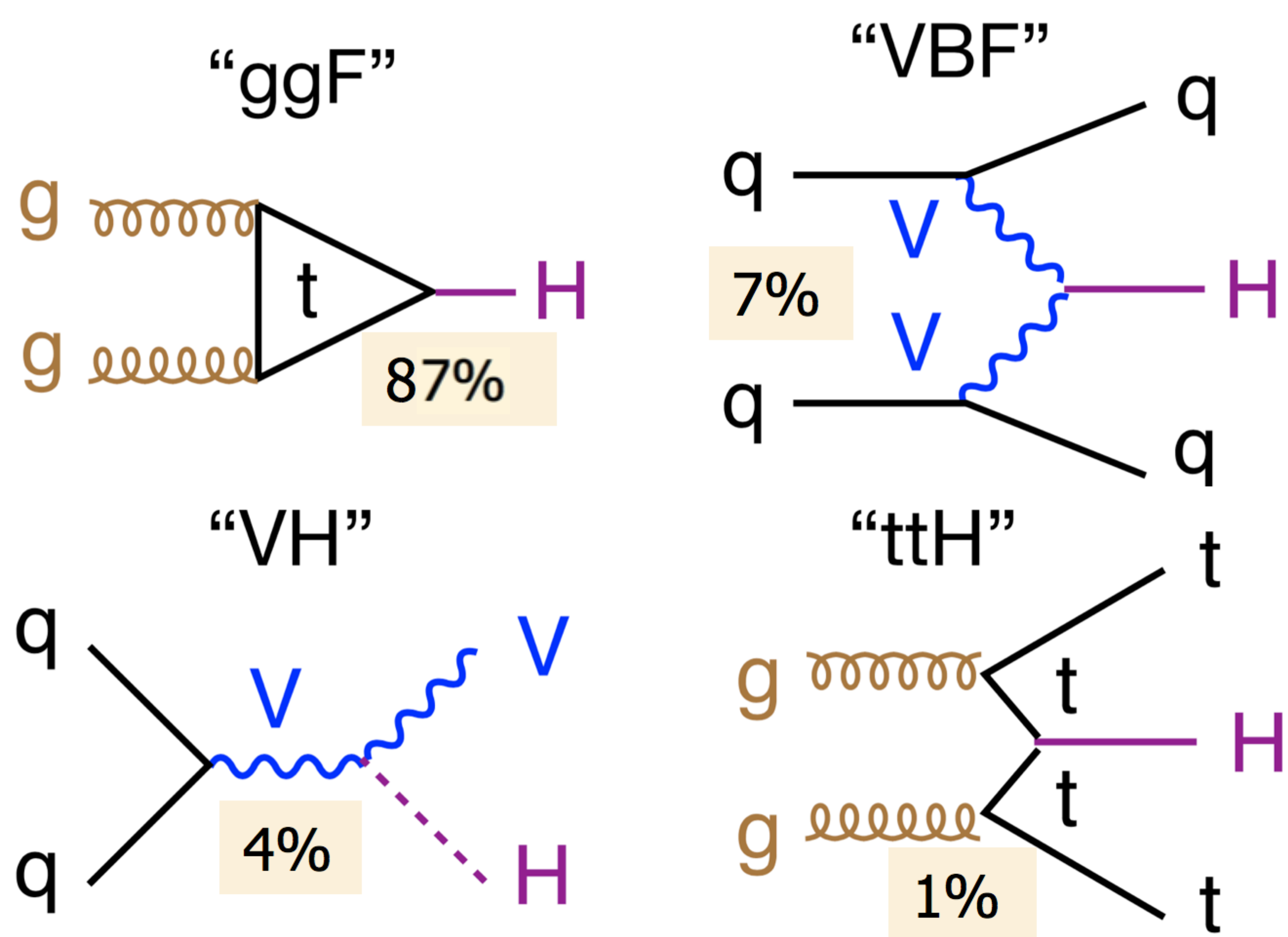
- ***In the universe, there is a Higgs "field" that pervades all of space, turning mass-less particles moving through it into the massive ones***

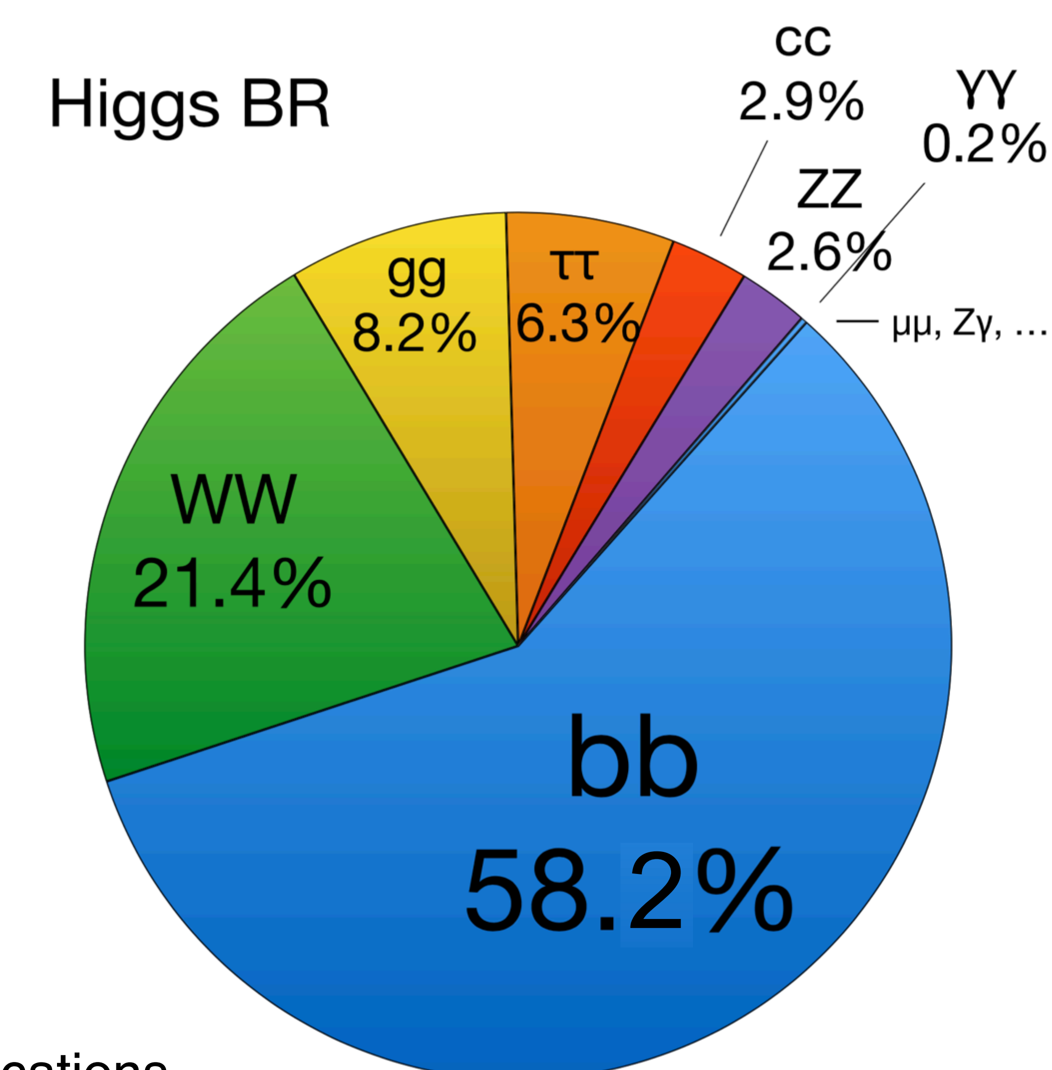




Higgs Boson production and decay modes

- In the Standard Model, the Higgs boson couples to massive bosons and fermions
- These couplings determine the Higgs boson production and decay modes:





Figures from https://msneubauer.github.io with modifications