Rare and Exotic Higgs Decays

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LHCP CONFERENCE 2019

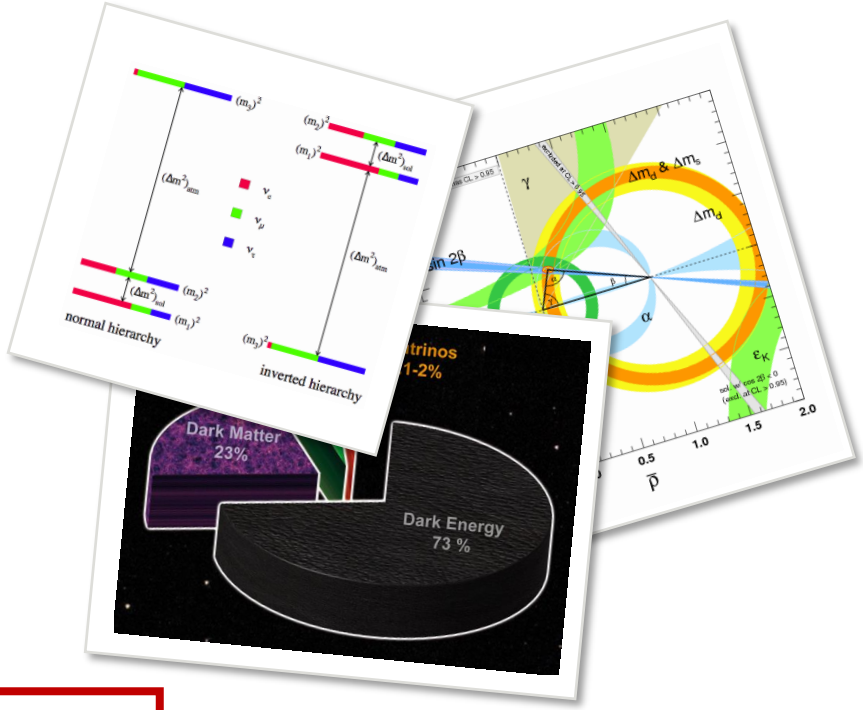
Theoretical Motivations

- The **discovery of a new boson** consistent with the Standard Model (SM) Higgs boson has **completed the SM theory**

- Nevertheless, this theory **cannot address** several **crucial issues**

Direct evidence from observation:
- existence of neutrino masses
- existence of dark matter and dark energy
- matter-antimatter asymmetry

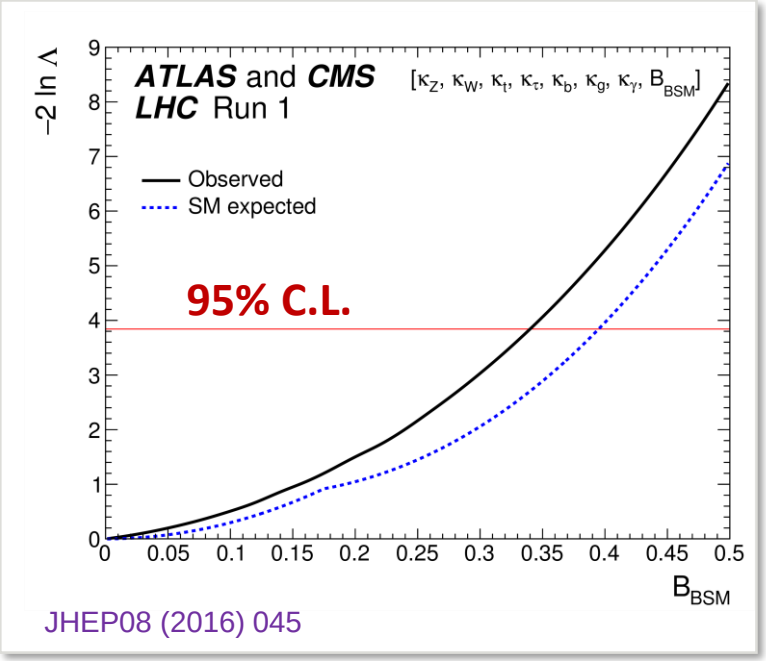
Conceptual problems in the SM:
- the large number of free parameters
- the "hierarchy problem“
- the coupling unification



Strong indications that the SM is only a low-energy expression of a more global theory

Exotic Decays of the Higgs Boson

- The **SM Higgs** boson has a **very narrow width** (~4 MeV): current limits still allow for **additional contributions** from **BSM decays**
- **Constraints** on new physics are still **relatively loose** (Run 1 limit $\mathcal{B}(H \to BSM) < 34\%$)
- Possibilities to **detect BSM physics** in the scalar sector:
  - **Direct evidence** through observation of BSM decays of the H boson
  - **Indirect evidence** through observation of deviations in the couplings of the H boson



JHEP08 (2016) 045

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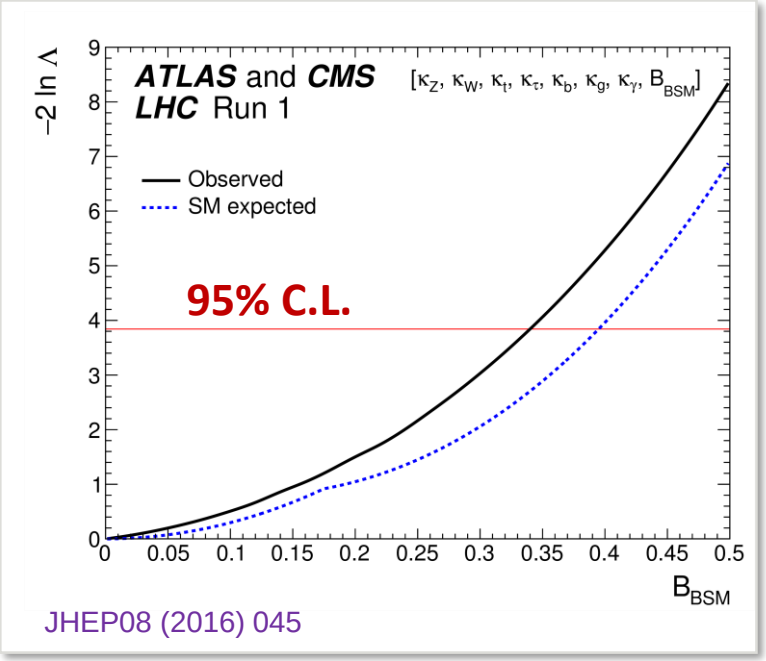
  - **Indirect evidence**

  → precision limited, slowly increase with data



JHEP08 (2016) 045

Search for BSM Physics in Higgs Decays

- Search for Higgs boson **decays** to **SM particles**:
  - Very **rare decays** predicted by the SM
    - An excess on these channels would be an indication of BSM physics
  - **Decays not allowed** in the SM
    - Lepton flavor violating Higgs decays

- Search for Higgs boson **decays** to **non-SM particles**:
  - **Invisible** Higgs boson **decays**, with H produced via ggF, VBF, VH or ttH (H → invisible)
  - Higgs boson **decays** to **light pseudoscalars/scalars** (H → aa), decaying to SM particles

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ATLAS EXPERIMENT **Phys. Lett. B 786 (2018) 134**

CMS **CMS-HIG-18-025**

ATLAS EXPERIMENT **ATLAS-CONF-2019-013**

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ATLAS EXPERIMENT **CERN-EP-2019-046**

CMS **CMS-HIG-17-023**

CMS **CMS-HIG-18-008**

CMS **CMS-EXO-19-007**

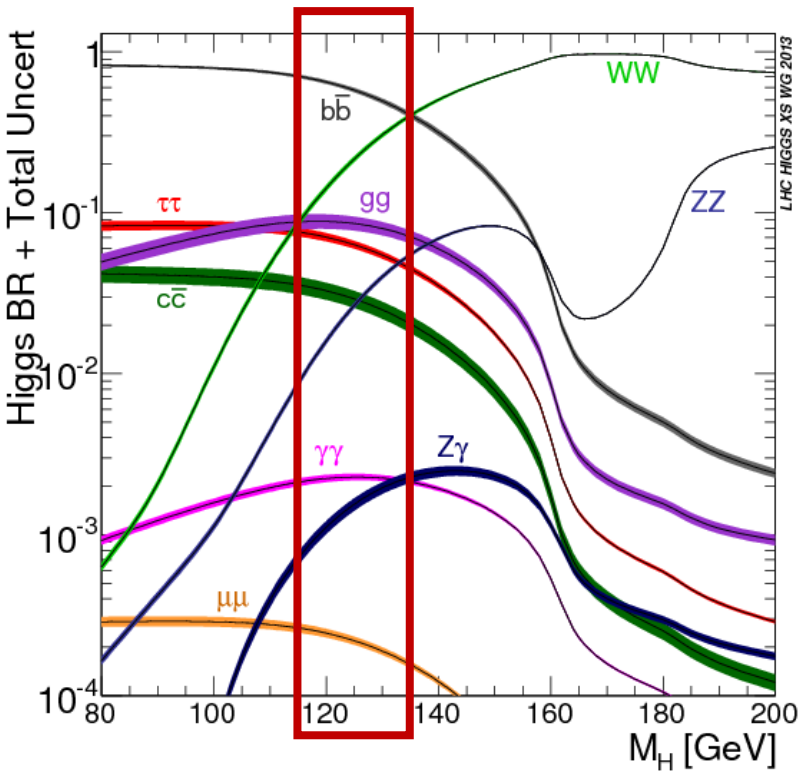
ATLAS EXPERIMENT **Phys. Lett. B 790 (2019) 1**

CMS **CMS-PAS-HIG-18-006**

MOST RECENT RESULTS SHOWN: MANY OTHERS AVAILABLE

Rare Decays

- Important to look at **all** the possible **decay channels** of Higgs boson at the LHC
- Some of them, with **very small branching fraction**, have **yet to be observed**
- Rare decay rates can **deviate from** SM **expectations** and be enhanced as predicted in several **BSM models**



CHANNEL	BR (SM)
$H \to ZZ \to 4\nu$ ($H \to$ inv)	$\sim 1 \times 10^{-3}$
$H \to \mu\mu$	$\sim 2 \times 10^{-4}$
$H \to Z\gamma \to \ell\ell\gamma$	$\sim 1 \times 10^{-4}$
$H \to J/\psi\gamma$	$\sim 3 \times 10^{-6}$
$H \to \Upsilon\gamma$	$\sim 5 \times 10^{-9}$
$H \to \Upsilon\Upsilon$	$\sim 2 \times 10^{-9}$
$H \to J/\psi\ J/\psi$	$\sim 1.5 \times 10^{-10}$

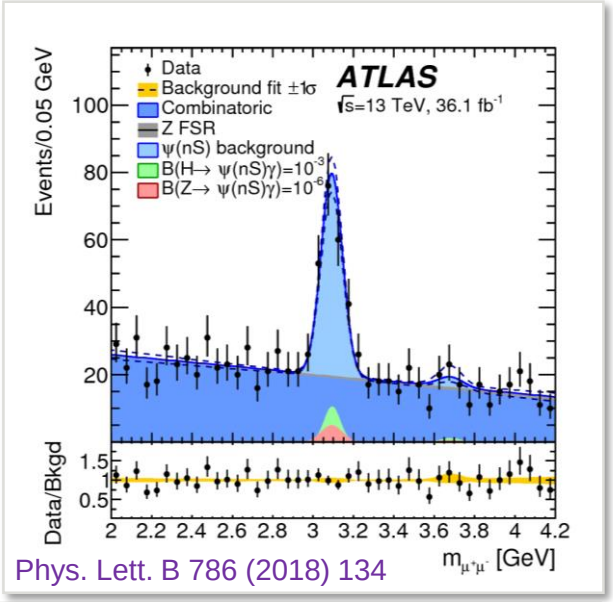
Rare Decays: H → J/ψγ - Υγ

- H → $\mathcal{M}$γ (with $\mathcal{M}$ J^{pc}= 1^{--}) decays provide a clean probe of the **charm and bottom quark Yukawa couplings**
- Focus on the **clean** ψ(nS)/Υ(nS) → **$\mu^+\mu^-$** decays and target high rate **inclusive H and Z production**
- Limits able to **exclude** H → $\mathcal{M}$γ **BR at 10^{-4}**

CHANNEL	BR (SM)
H →J/ψγ	~3× 10^{-6}
H → Υγ	~5 × 10^{-9}

Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to J/\psi\,\gamma)\,[\,10^{-4}\,]$	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \to \psi\,(2S)\,\gamma)\,[\,10^{-4}\,]$	$15.6^{+7.7}_{-4.4}$	19.8
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.4}_{-1.4}$	4.9
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)\,[\,10^{-4}\,]$	$6.2^{+3.0}_{-1.7}$	5.9
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.5}_{-1.4}$	5.7

Phys. Lett. B 786 (2018) 134



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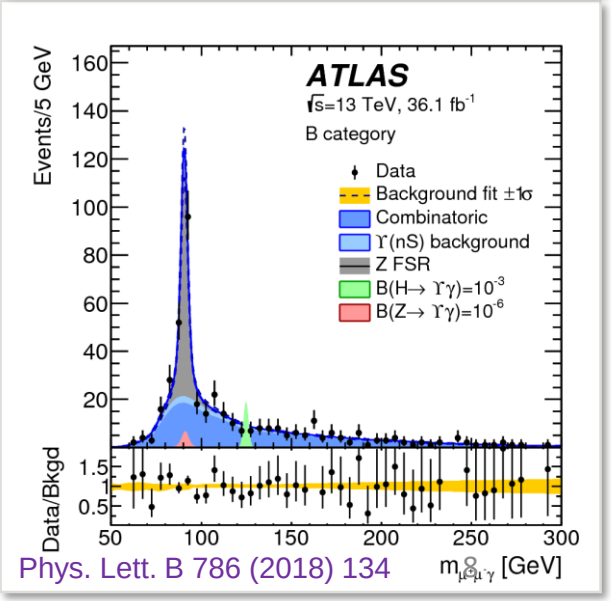
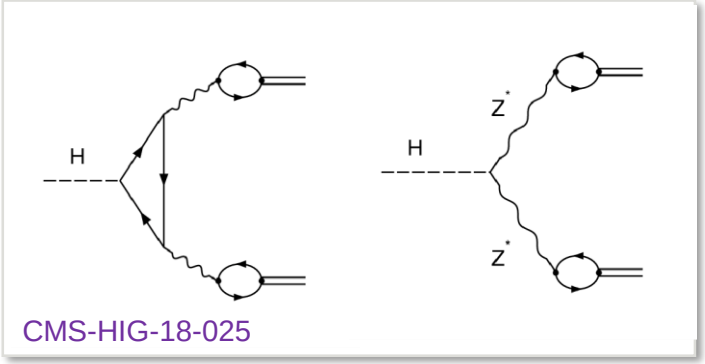


Phys. Lett. B 786 (2018) 134

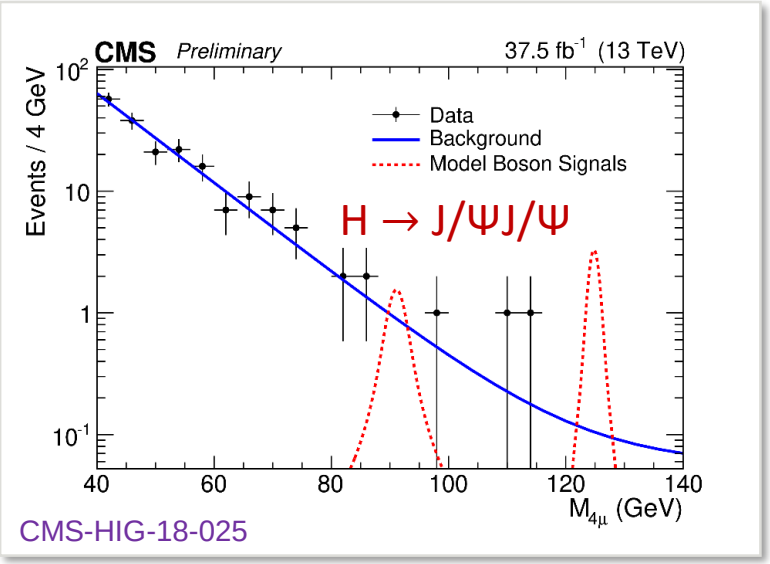
Rare Decays: H → J/ψJ/ψ - ΥΥ

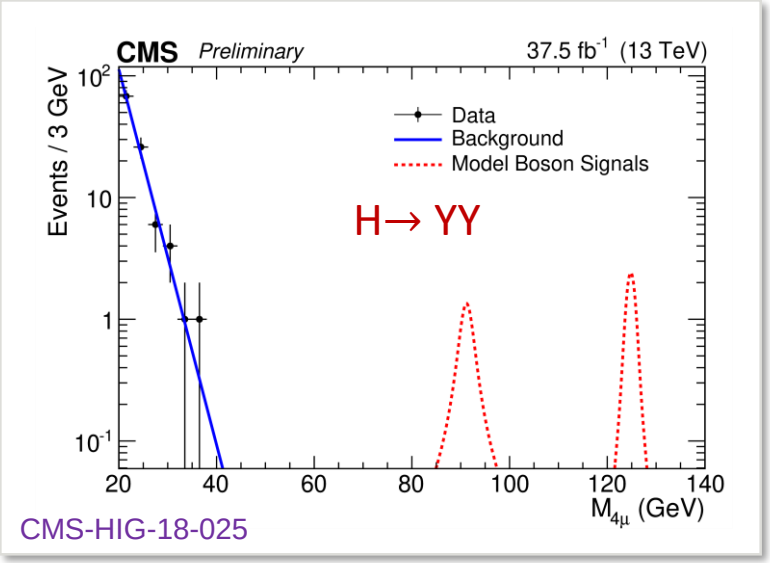
- Almost **background-free**
  ➡ sensitivity scales with luminosity
- **4-muon** final state: very **clean signature** with **narrow intermediate** resonant **states**
- **Dedicated triggers**: 2μ ($m_{J/\psi}$), 3μ (m_{Υ})



CHANNEL	BR (SM)
H → ΥΥ	~2 × 10^{-9}
H →J/ψ J/ψ	~1.5 × 10^{-10}

Exclusion Limits at 95%	observed	expected
$\mathcal{B}(\mathrm{H} \to \mathrm{J}/\psi\mathrm{J}/\psi) \times 10^3$	1.8	$1.8^{+0.2}_{-0.1}$
$\mathcal{B}(\mathrm{H} \to \mathrm{YY}) \times 10^3$	1.4	1.4 ± 0.1





LF Violating Decays: H → eτ - μτ

- **Lepton flavor violating** Higgs boson decays in decays are **forbidden** in the SM
- Search for **H → eτ** and **H → μτ** in 4 signal regions ($\ell\tau_{\ell'}$, $\ell\tau_{had}$, VBF, non-VBF)
- **BDT algorithms** used to enhance the **signal** separation **from** the **background**
- **Main backgrounds**: Z → ττ, top-quark processes, backgrounds from mis-identified objects

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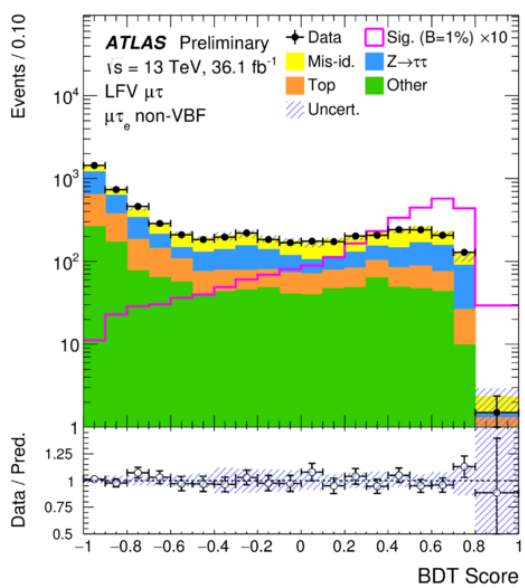

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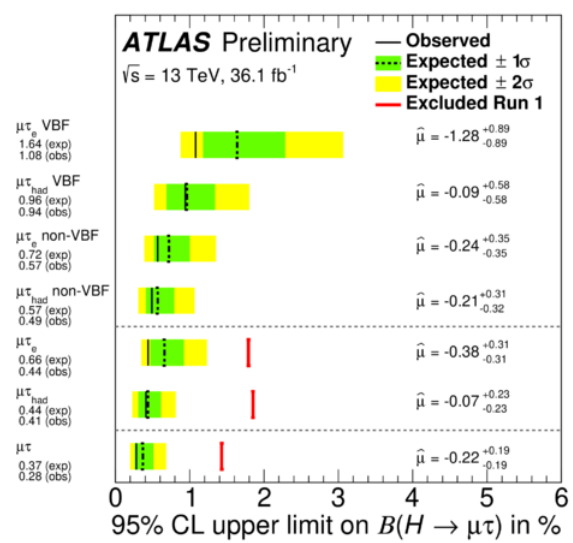
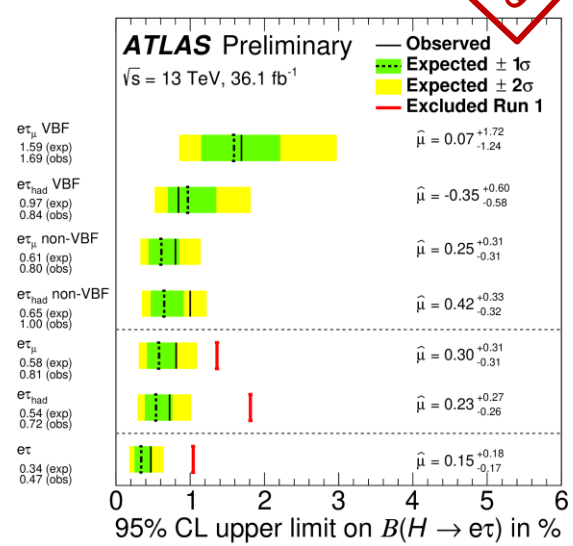
H → μτ



ATLAS-CONF-2019-013

< 0.28% obs.

H → eτ



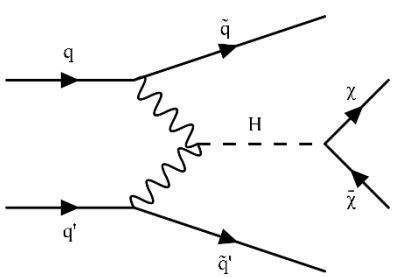
ATLAS-CONF-2019-013

< 0.47% obs.

Higgs To Invisible Searches

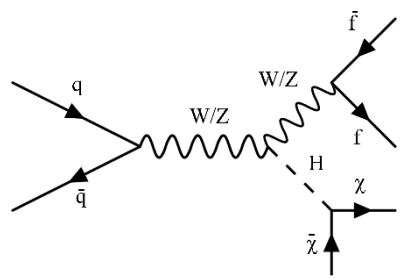
- In the SM, **H → invisible** only via **H → ZZ* → 4ν** with **BR of 0.1%**
- **Rate** for invisible decays significantly **enhanced** in several **BSM scenarios**
- The 125 GeV boson could be a **portal** between a **dark sector** and the SM sector
- All the main **Higgs production modes** can be used to probe its coupling with "invisible" particles
- All searches characterized by **large p_T^{miss}** (DM particles escape detection)
- The Higgs boson **recoils against a visible system** used to distinguish between production modes

CMS and **ATLAS**



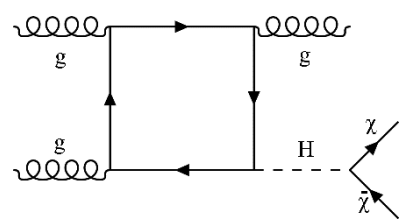
VBF

CMS and **ATLAS**



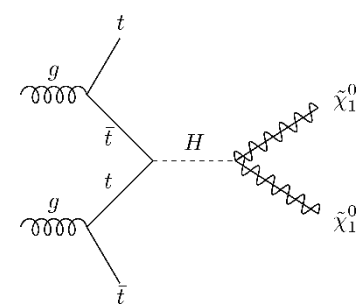
VH (V→ $\ell\ell$, qq')

CMS



ggH + jet

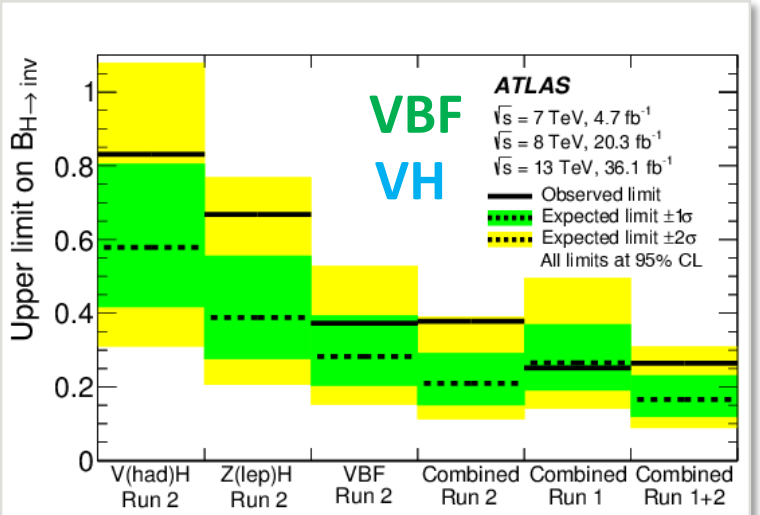
CMS



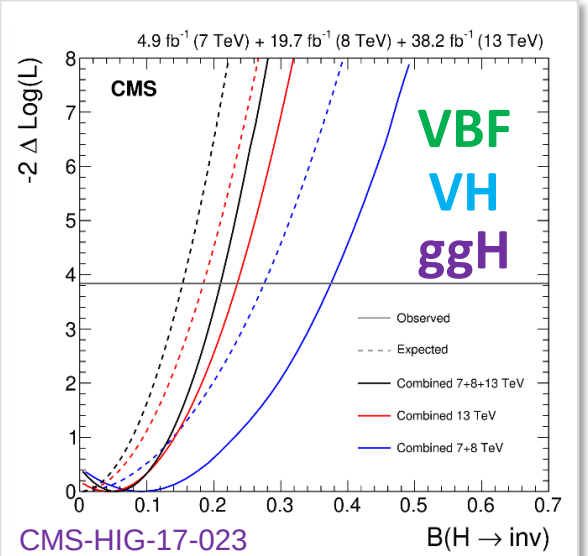
ttH

Higgs To Invisible Searches

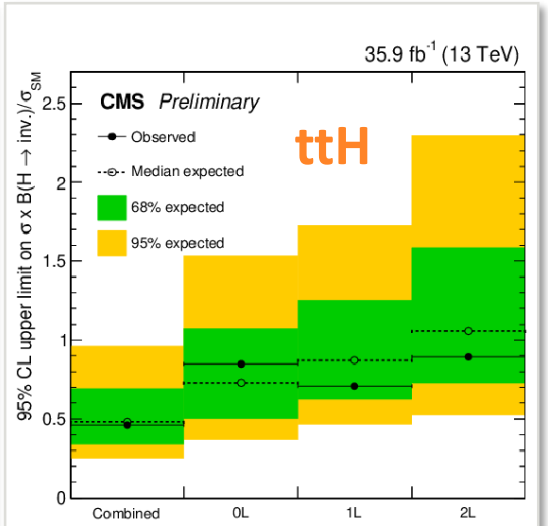
- Both ATLAS and CMS performed
  - A **combination** of the **different production modes** of 2016 measurements, assuming SM production cross sections
  - A **combination** of **Run 1 + Run 2** analyses
- Current upper limits are:
  - $\mathcal{B}(H \to inv)$ < **0.26(0.17)** observed (expected) at 95% CL (**ATLAS**)
  - $\mathcal{B}(H \to inv)$ < **0.19(0.15)** observed (expected) at 95% CL (**CMS**)



CERN-EP-2019-046



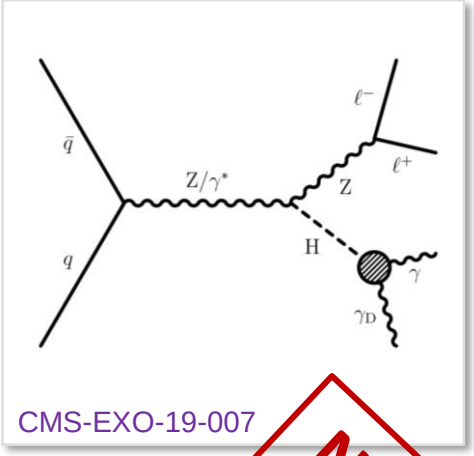
CMS-HIG-17-023



CMS-HIG-18-008

Search for Dark Photons in ZH Decays

- **Massless dark photon** that couples to Higgs boson*
  - γ_D is a dark photon, which is **undetected** (large p_T^{miss})
- Two opposite-sign same-flavor **leptons** and a **photon**
- **Background** from **data-based method** and **simulation**
- m_T (transverse mass of p_T^{miss} and photon system) and $|\eta^\gamma|$ used in the **fit**



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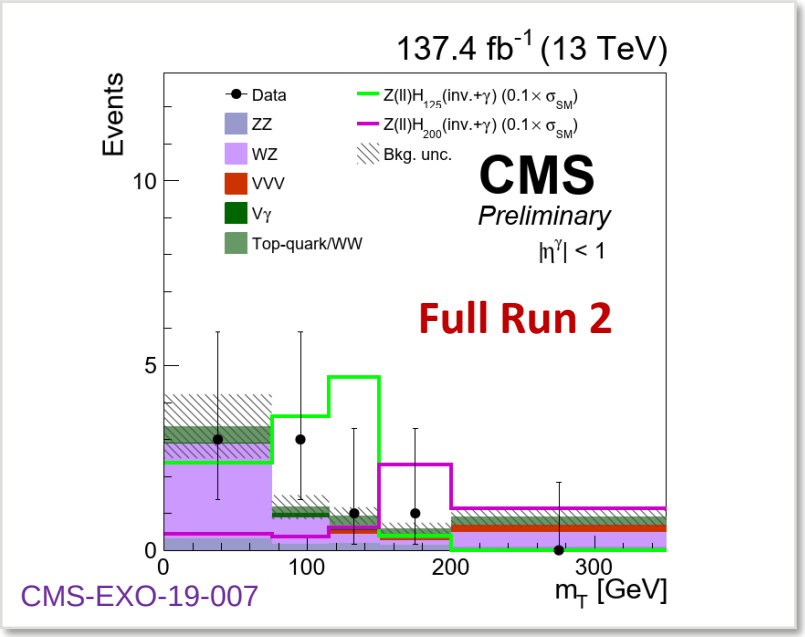
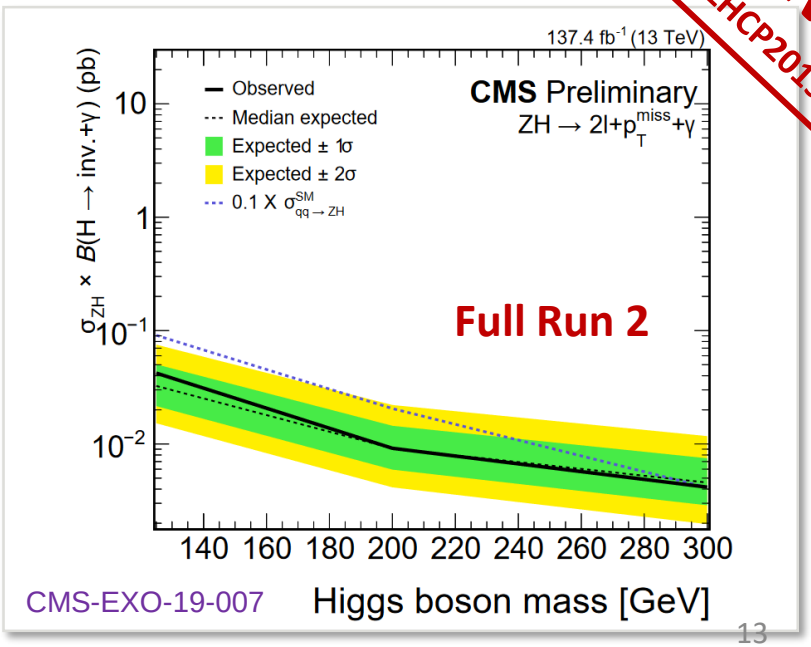
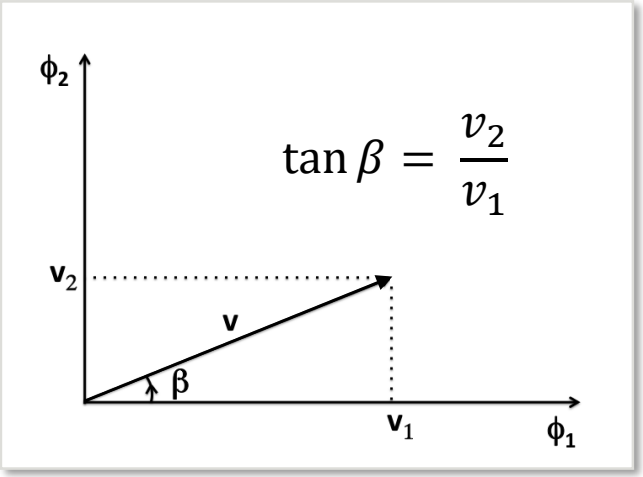




*https://arxiv.org/abs/1603.01377

Exotic Decays in 2HDMs

- **Two-Higgs-doublet models** are simple extensions of the SM introducing **two doublets** of scalar fields (ϕ_1 and ϕ_2) in the SM Lagrangian
- After symmetry breaking, **five physical states are left** (h, H, A and $H^{\pm}$ bosons)
- **Four types**, according to different patterns of **quark and lepton couplings**
- **Further extension** 2HDM+S: possible search for **H** $\rightarrow$ $\boldsymbol{aa}$ (a pseudoscalar)
- Exotic decays still **consistent** with all the **LHC measurements** so far



2HDM	u-type	d-type	lepton
Type I	ϕ_2	ϕ_2	ϕ_2
Type II	ϕ_2	ϕ_1	ϕ_1
Type III	ϕ_2	ϕ_2	ϕ_1
Type IV	ϕ_2	ϕ_1	ϕ_2

Final States of H → aa Decays

$a \to bb$

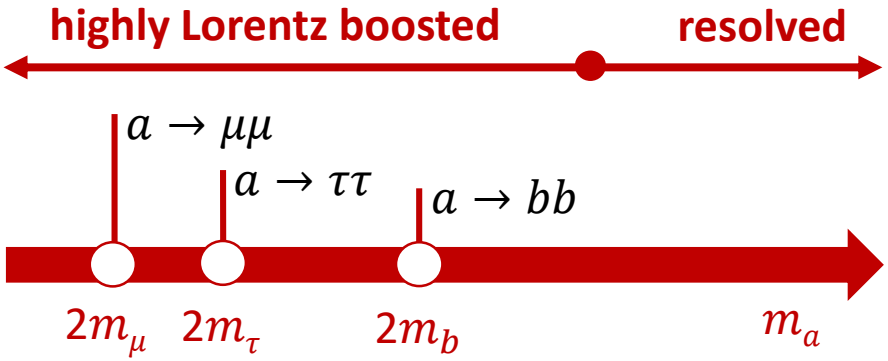
- ✓ **Large BR**
- ✗ Hard to trigger
- ✗ Low identification efficiency
- ✗ High p_T thresholds
- ✗ Large jet-backgrounds

$a \to \tau\tau$

- ✓ **Large BR**
- ✓ Possible to **trigger** on leptonic τ decays
- ✗ Low τ_h identification efficiency, with high p_T thresholds (> 20 GeV)

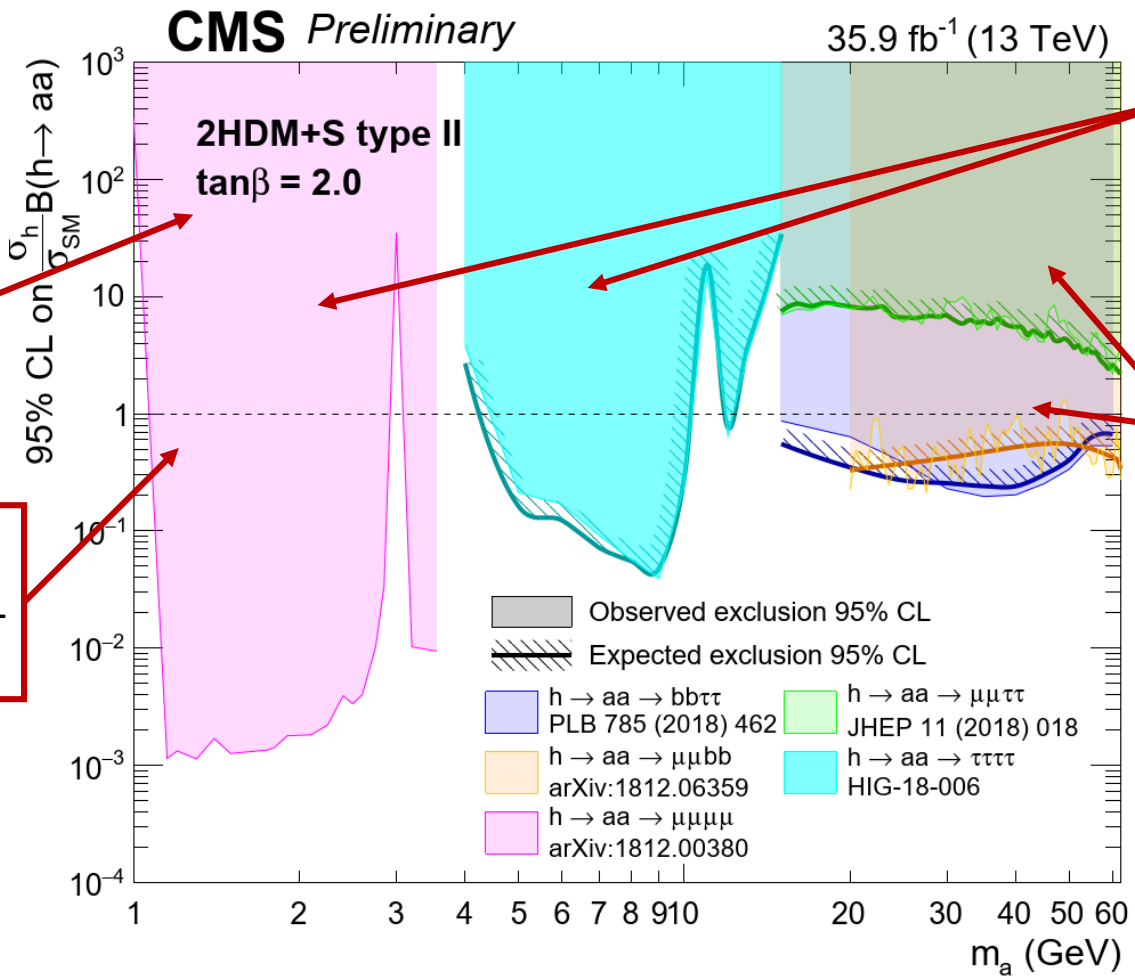
$a \to \mu\mu$

- ✓ Excellent **mass resolution**
- ✓ Easy to trigger
- ✓ Easy identification, with low p_T
- ✓ Open for any m_a>$2m_\mu$
- ✗ Low BR



With **SM-like couplings**: $\mathcal{B}(a \to bb) \sim 9\,\mathcal{B}(a \to \tau\tau) \sim 1700\,\mathcal{B}(a \to \mu\mu)$

Higgs Exotic Decays



Boosted reconstruction techniques

Model dependency

Well separated decay products

Sensitivity to $\mathcal{B}(h \to aa) = 1$ if $\sigma_h = \sigma_{SM}$

NEW @LHCP2019

Higgs Exotic Decays

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2018-045/

$h \to aa \to 2\mu 2\tau$
(Run I)
arXiv: 1505.01609

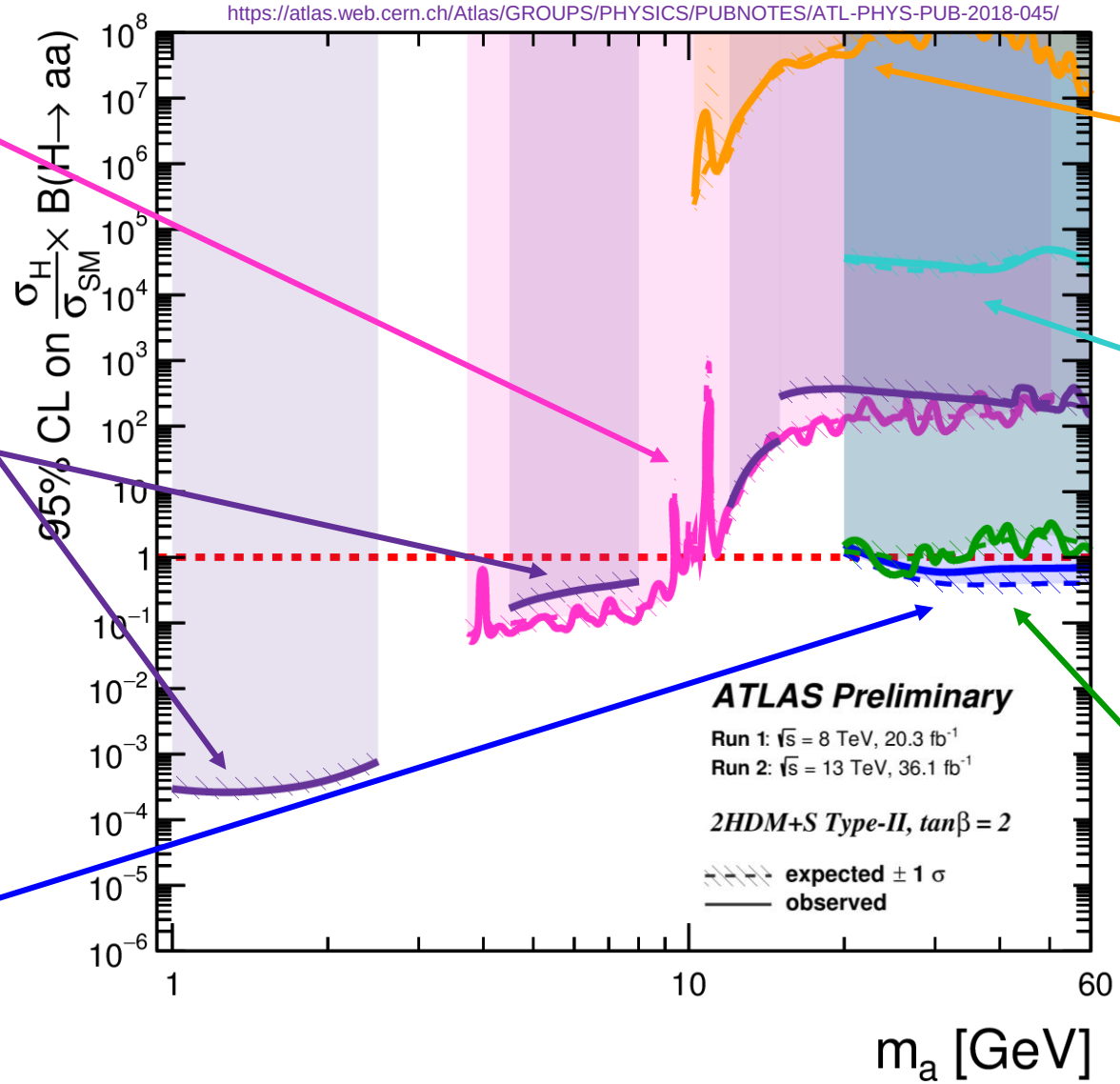
$h \to aa \to 4\gamma$
(Run I)
arXiv: 1509.05051

$h \to aa \to 2\gamma 2j$
(Run 2)
arXiv: 1803.11145

$h \to aa \to 4\mu$
(Run 2)
arXiv: 1802.03388

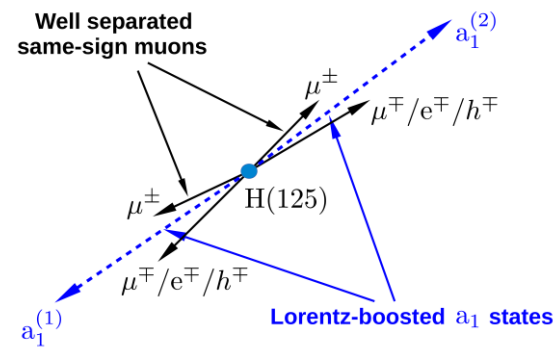
$h \to aa \to 2b2\mu$
(Run 2)
arXiv: 1807.00539

$h \to aa \to 4b$
(Run 2)
arXiv: 1806.07355



Exotic Decays: H → aa → 2μ2τ/4τ

- **Highly boosted a** boson, non-isolated muons
- 4 GeV < m_a < 15 GeV
- Selection: SS μ pair + two 1-prong τ decays (OS wrt nearest μ)
- **Main background**: QCD multijet events
- **2D search** in ($m_{\mu 1,\,trk1}$, $m_{\mu 2,\,trk2}$) plane
- **Reduced sensitivity** as **topology** becomes **resolved**
- **Improves** Run 1 CMS limits by up to a **factor 10**



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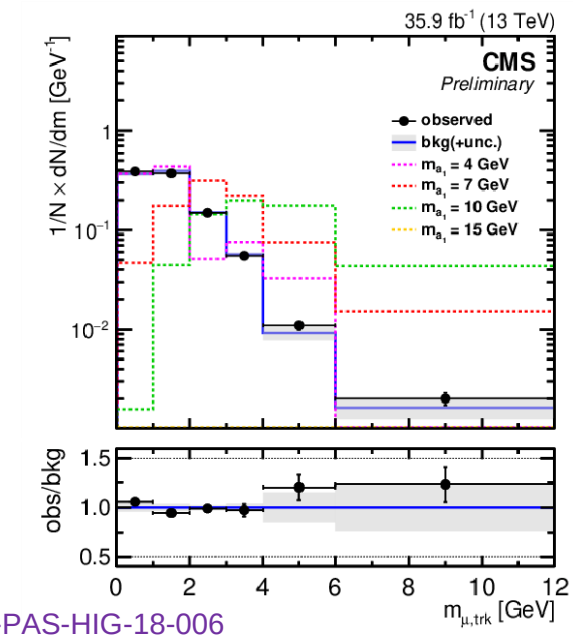

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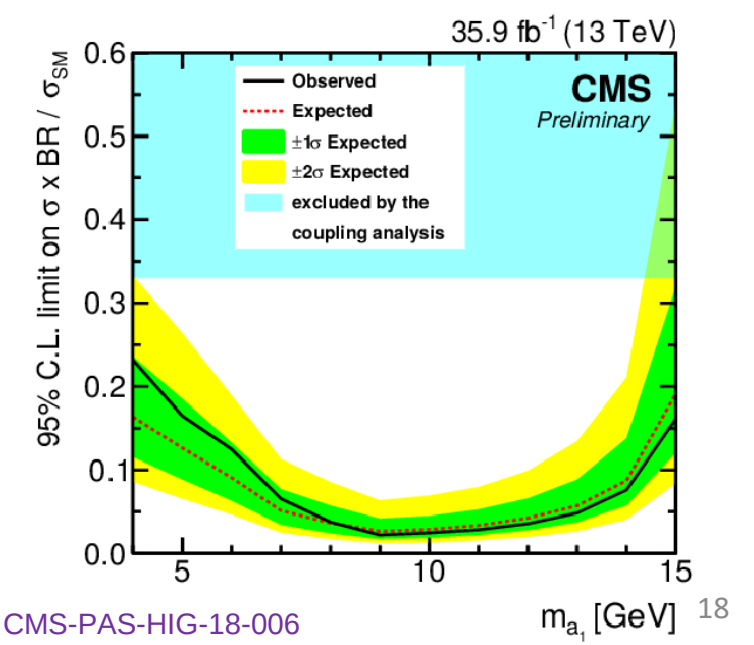
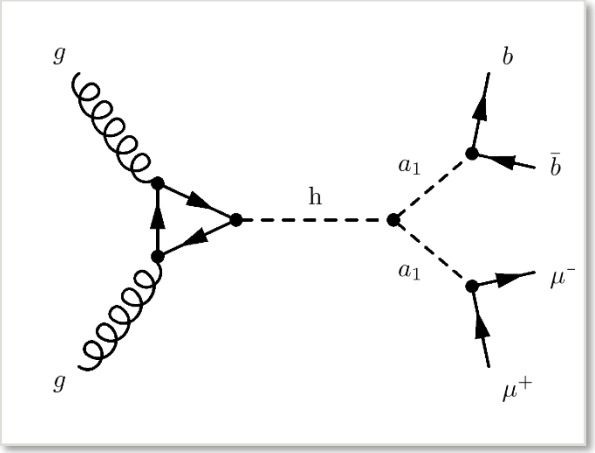
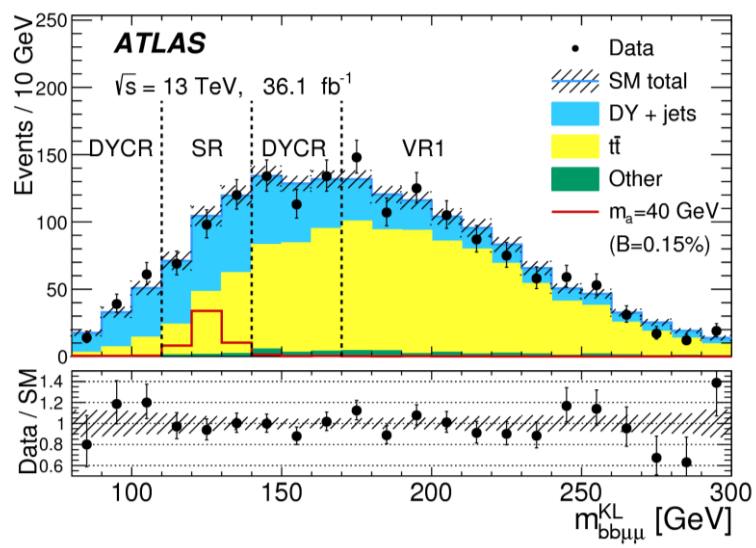


CMS-PAS-HIG-18-006

Exotic Decays: H → aa → 2b2μ

- Clean **di-muon signature** used for triggering and precision mass reconstruction
- $m_{\mu\mu}$ **resolution** 10 times **better** than m_{bb}
- $m_{\mu\mu}$ and b-jet energies inputs of a **kinematic fit**
  - $m_{bb\mu\mu}$ **resolution improved** by a factor of 2
- 18 GeV < m_a < 62 GeV,
- **Main backgrounds** estimated from **CRs** in **data**





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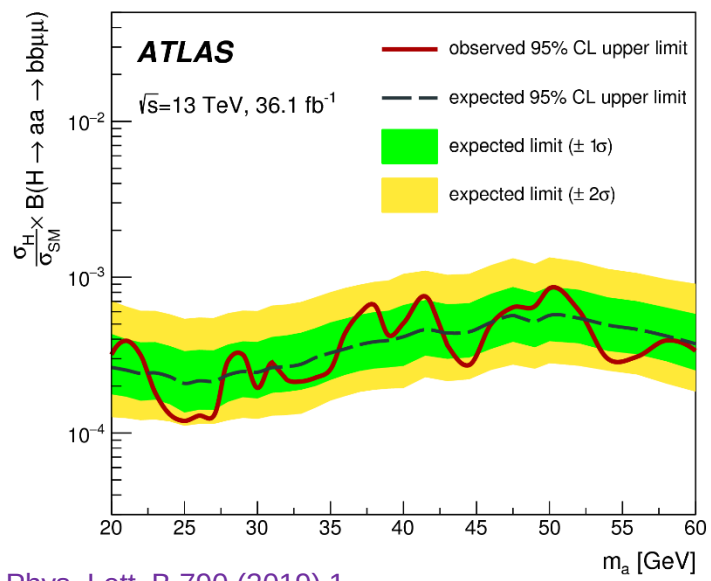

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Conclusions

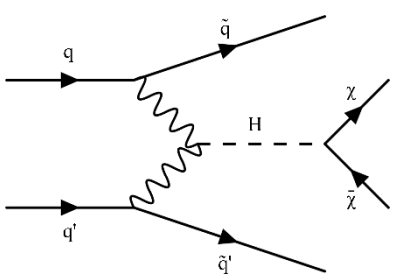
- The **Scalar Sector of the SM** is a favored place to look for **new physics effects**
- **LHC data** are **sensitive** to some theoretical models (2HDM, NMSSM…)
- **No** significant **deviations from SM** predictions yet observed
- We have **just started** to extract the physics **potential of the 13 TeV** dataset
- We have a **comprehensive view** of the potential of the main channels from the **Run1 experience**
- **Feedback** with **theory community** fundamental to keep interest in exploring these signatures

Backup

Higgs To Invisible Searches

- **most sensitive** mode
- **2-jets** with **large $\Delta\eta_{jj}$** and **m_{jj}**
- E_T^{miss} > 250 (180) GeV
- $\Delta\eta_{jj}$ > 1 (4.8)
- Veto leptons and jets
- Signal extracted by **fitting m_{jj}**
- Main bkg: Z(vv)+jets and W+jets (QCD and EW prod)

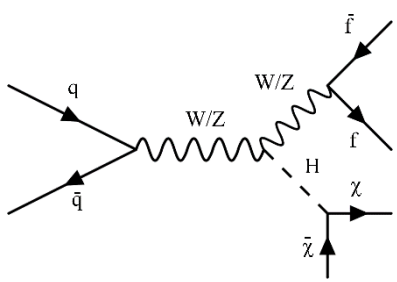
CMS and **ATLAS**



VBF

- **E_T^{miss} + 2-leptons** from Z or **high p_T jets** from V(qq')
- Signal extracted by fitting **BDT classifier** (**E_T^{miss}**)
- Main bkg: ZZ, WZ and residuals from WW and top backgrounds

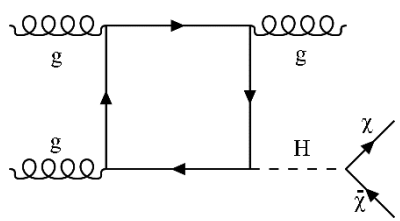
CMS and **ATLAS**



VH (V→ $\ell\ell$, qq')

- **Large p_T^{miss} + high p_T central jet**
- E_T^{miss} > 250 GeV
- At least one jet p_T > 100 GeV, |η| < 2.4
- Veto leptons and jets
- Overlap with VBF and V(qq)H removed
- Signal extracted by **fitting p_T^{miss}**
- Main bkg: Z(vv)+jets and W+jets

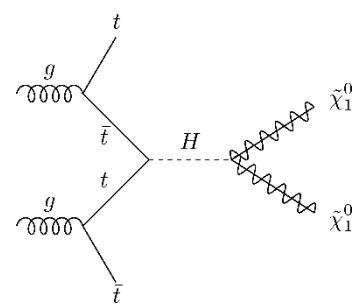
CMS



ggH + jet

- Reinterpretation of **stop searches**
- **0L/1L/2L + (b) jets + p_T^{miss}**
- Signal extracted by **counting data** event in SR
- Main bkg: W+jets, Z+jets, tt, single top

CMS



ttH