Search for non-standard and rare decays of the Higgs boson with the ATLAS detector

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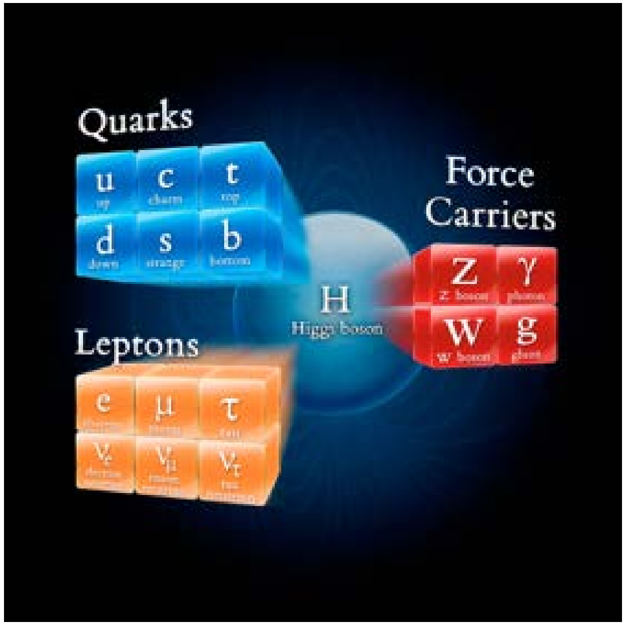
Outline

- Introduction
- Lepton Flavor Violation Higgs decay
- Higgs decay to light scalar
- Higgs decay to light boson
- Invisible Higgs decay
- Other rare decays
- Summary

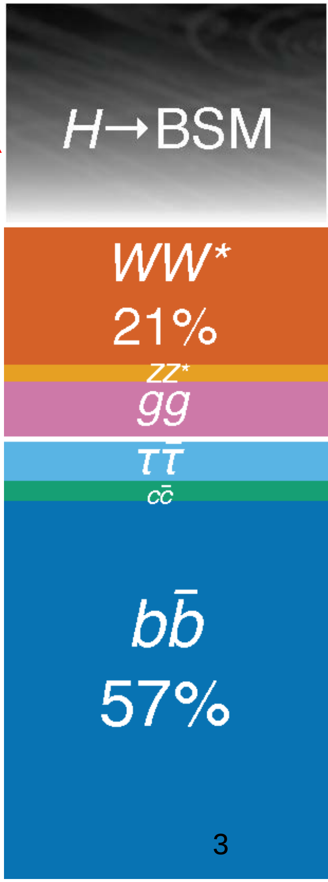


Why rare Higgs decays?

- The discovery of the Higgs boson put an end on the search of the last missing particle of the Standard Model
  - So far, Higgs shows properties consistent with the SM predictions
- However, up-to-date constraints are still relatively loose
  - Possible room for BSM physics
- Higgs decay properties:
  - Dominated by bb, but with small coupling: **O**(0.01)
  - A new coupling of **O**(0.01) could either add a new decay or modify an existing one as much as **O**(10%). B(H → BSM)

Current limit: B(H → BSM) < 34%

10%



- Rare or non SM Higgs decays have yet to be observed
  - May be sensitive to new physics if new Higgs coupling exist
- New Higgs decay would definitively be a BSM signature
- Higgs boson would be a Portal to new physics

Curtin et al. Phys. Rev. D 90, 075004 (2014)
Chang et al. 0801.4554 (2008)
Silveira & Zee, PL B 161 (1985) 136
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR2014

Search for Higgs Lepton Flavor Violation decay

Lepton Flavor Violation in Higgs boson decay

- The Standard Model Higgs boson coupling

$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - \underline{Y_{ij}(\bar{f}_L^i f_R^j)h} + h.c. + \cdots ,$$

Higgs-fermion coupling

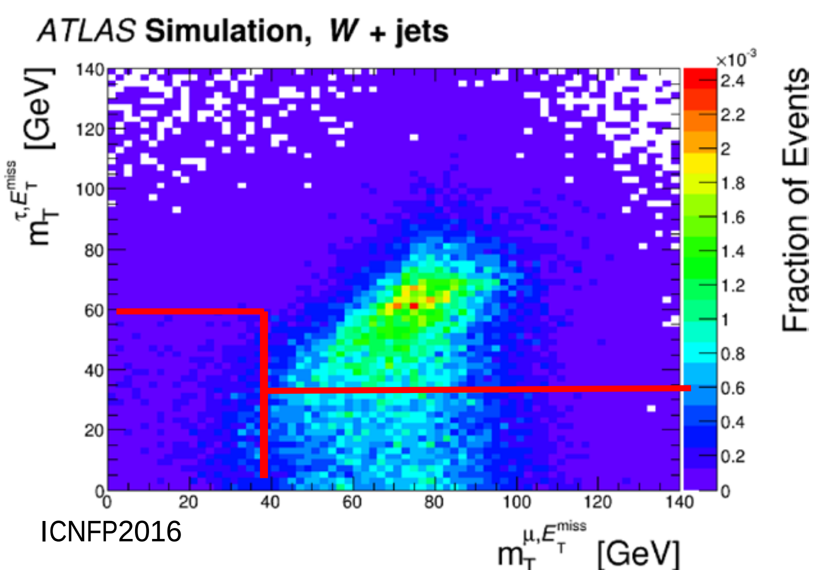
conserves the flavor symmetry (Y_{ij} is diagonal)

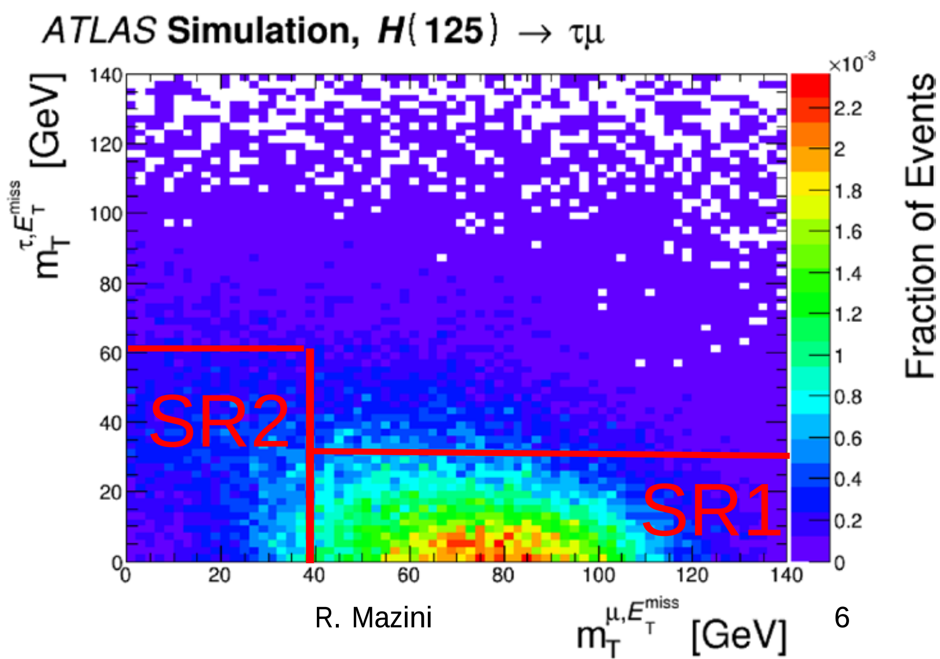
- However, Y_{ij} can be non-diagonal leading to a fermion flavor violation, which would be a strong signature of BSM physics.
  - Naturally occurs in models with more that one Higgs doublet
  - Arises in SUSY, composite Higgs models, RS models, etc.
- Current limit on LFV in muon decay: BR($\mu \rightarrow e\gamma$) < 5.7x10^{-13} @ 90% CL, put a strong constraint on some LFV Higgs decay:
  - BR(H $\rightarrow e\mu$) < $O(10^{-8})$
- But less constraints for decays involving τ lepton
  - BR(H $\rightarrow e\tau / \mu\tau$) < O(10%)
- ATLAS has searched for H $\rightarrow e\tau / \mu\tau$
  - Still Run I results (8TeV)

Example of LFV Higgs decay: $H \rightarrow \mu\tau$

- Search for $H \rightarrow \mu + \tau_{(1 \text{ or } 3 \text{ hadrons})}$ + missing transverse momentum
  - μ and τ with opposite charge
  - $p_T(\mu) > 26$ GeV, $p_T(\tau_{had}) > 45$ GeV
  - $|\eta(\mu) - \eta(\tau_{had})| < 2$
    - High signal efficiency ~ 99% on
- Effective background rejection
- 2 signal regions (SR1, SR2)

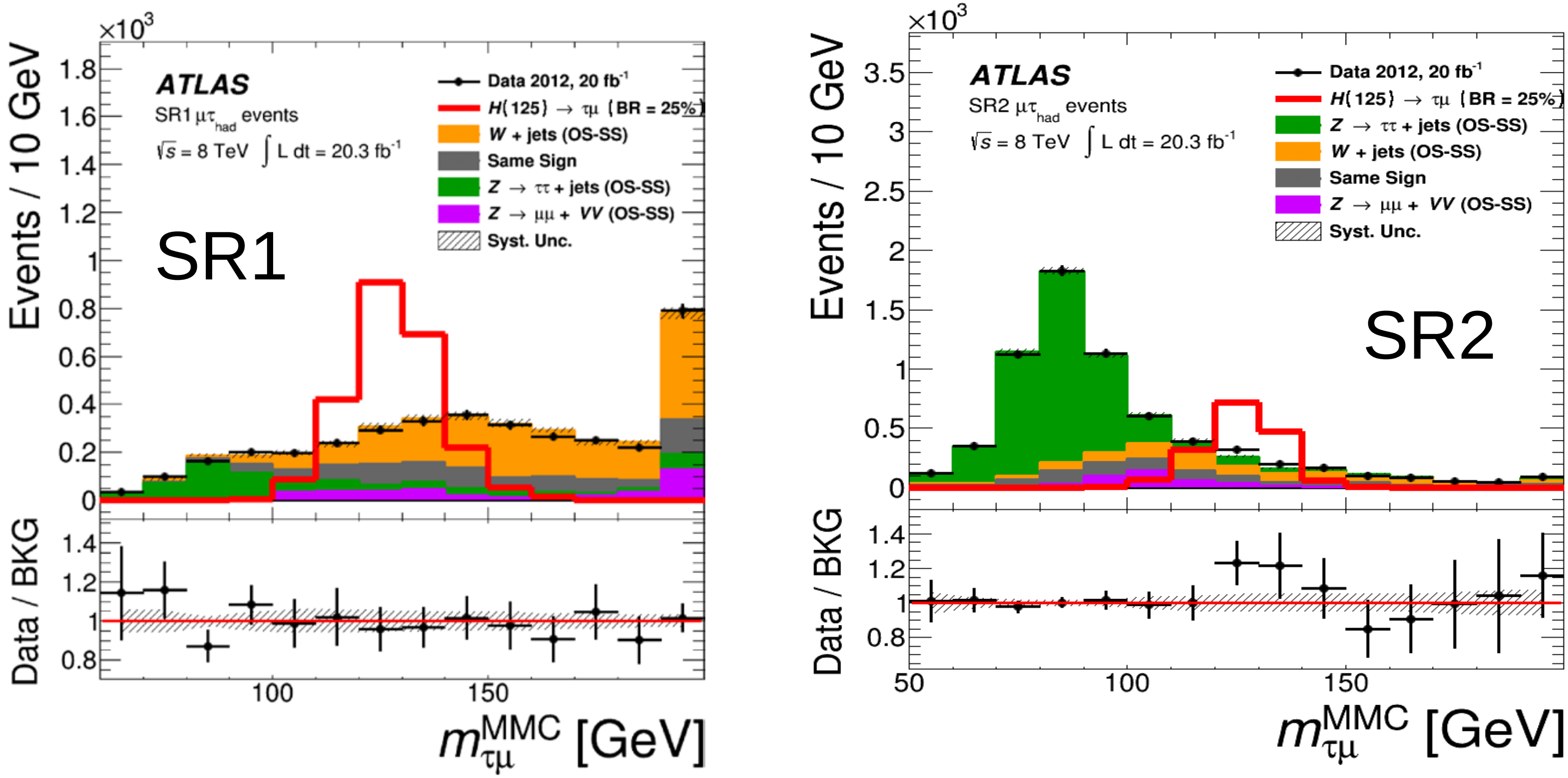
arXiv:1604.07730, JHEP11 (2015)211
Phys. Lett. B 749 (2015) 337





Results for H → $\mu\tau$ searches

arXiv:1604.07730, JHEP11 (2015)211
Phys. Lett. B 749 (2015) 337



- One signal region (SR2) shows 2.2σ excess, but with higher background and lower efficiency

Results for H → $\mu\tau$ searches

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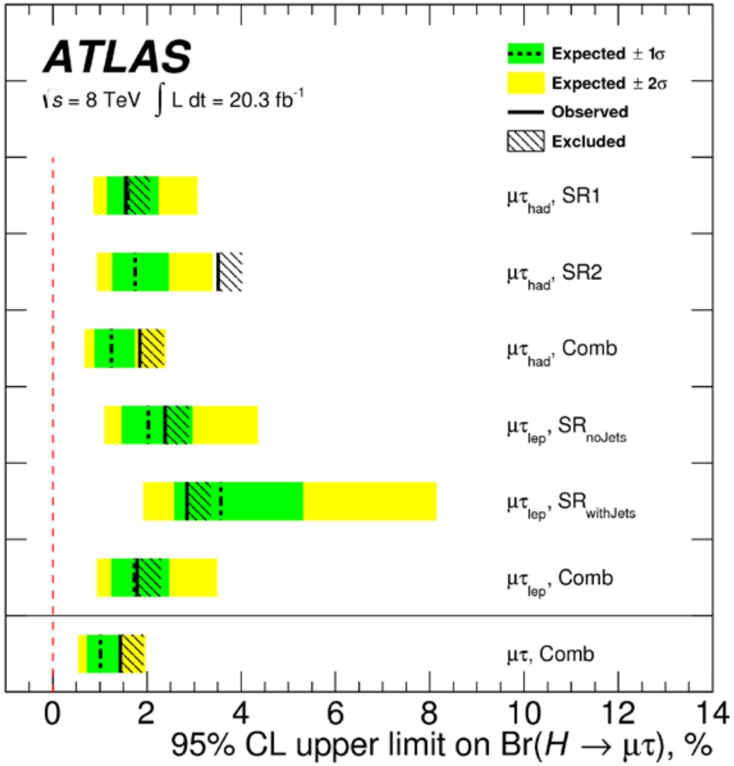


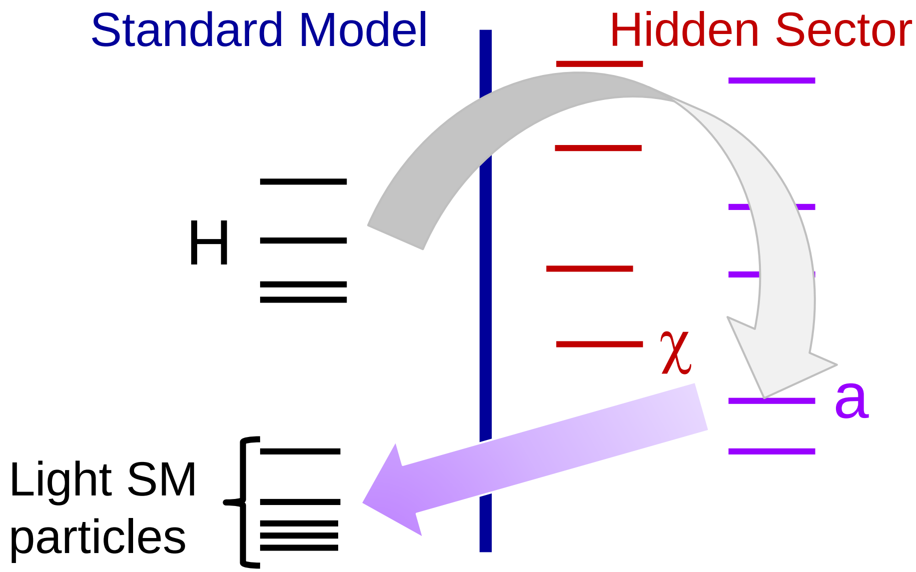
- Observed 95% C.L. upper limits on LFV Higgs decays O(1-2%)
- Combined results show Data is consistent with background within 1.3σ
- Best limit B(H→μτ) = 1.43% @ 95%CL (expected 1.24%)

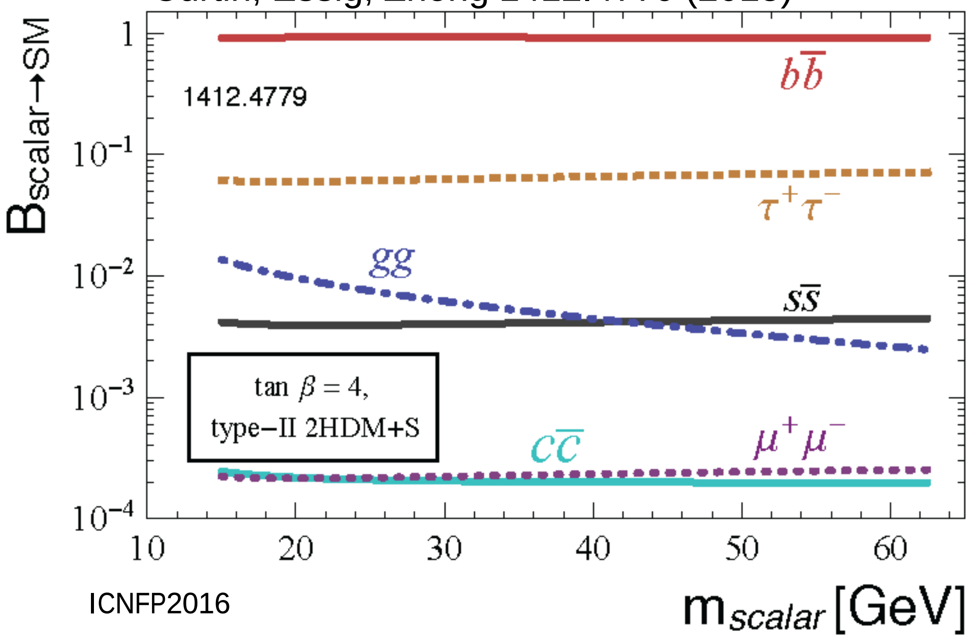
Search for Higgs decays to light scalar “a”

Higgs decay to light scalar

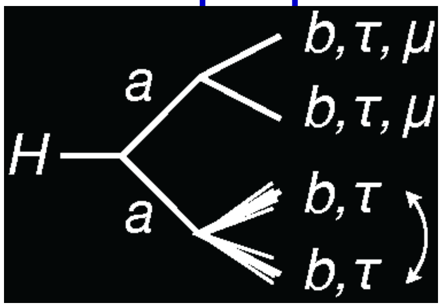
- Many models motivating Higgs portal as a way to explore hidden sector.
- Higgs decays first to hidden sector, with a subsequent decay to SM light particles.
- Many theoretical work, e.g.:

Patt, Wilczek hep-ph/0605188 (2006)
Curtin et al. 1312.4992 (2014)
Curtin, Essig, Zhong 1412.4779 (2015)





- Final state properties:

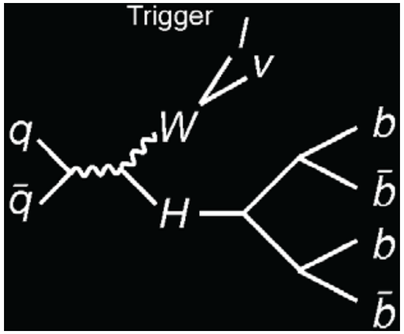


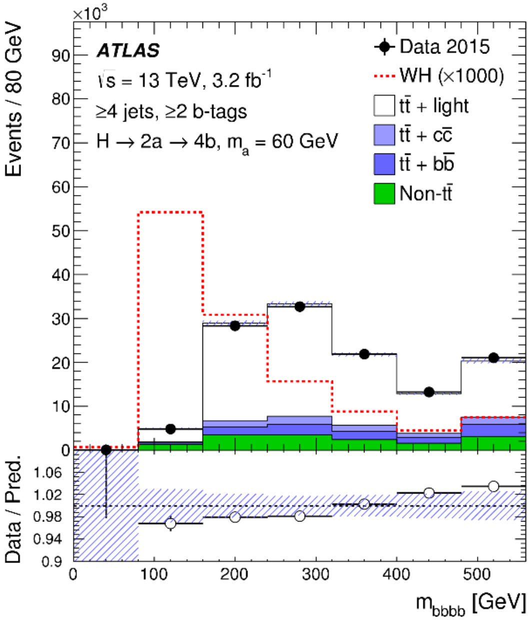
  - Low p_T particles
  - Boosted low p_T b-tagged jets

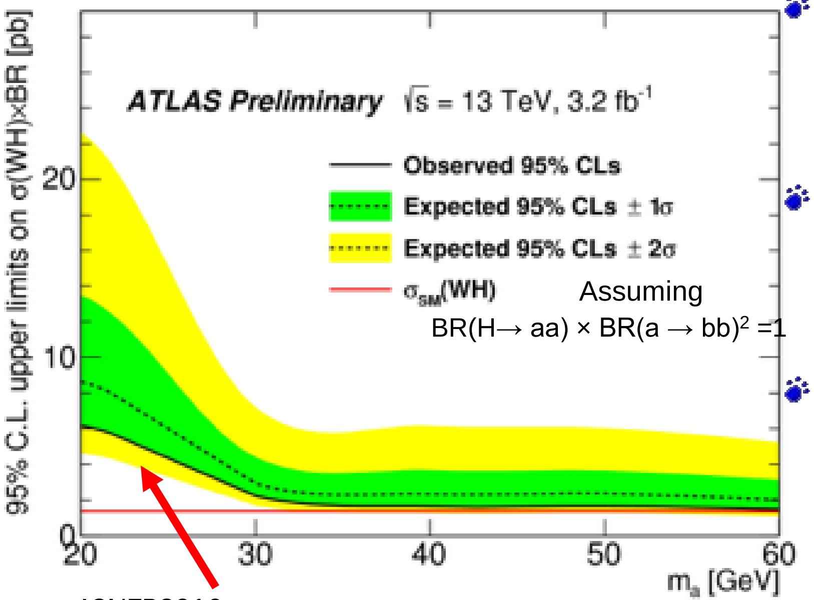
Search for $H \rightarrow aa \rightarrow bbbb$

arXiv:1606.08391

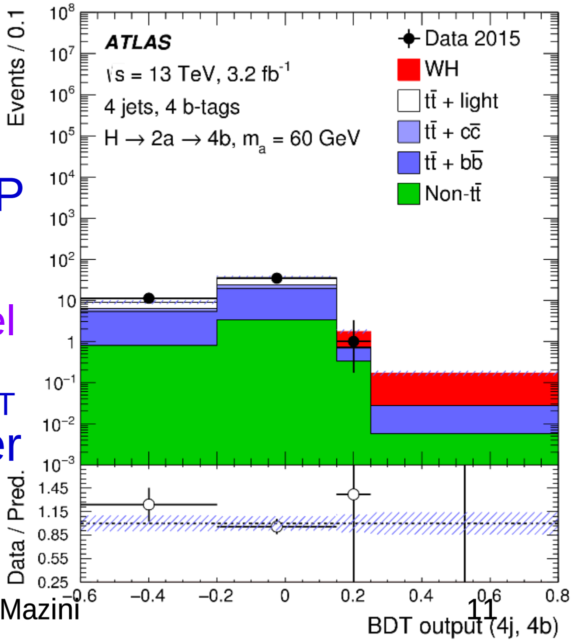
- Focus on WH, with $W \rightarrow e/\mu\nu$ and $H \rightarrow aa \rightarrow bbbb$
  - Final state with 4 b-tagged jets.
  - Low p_T b-jets can be overlapping
- Searches carried out for
  - $20 < m_a < 60$ GeV
- $3.2\ fb^{-1}$ @ 13 TeV







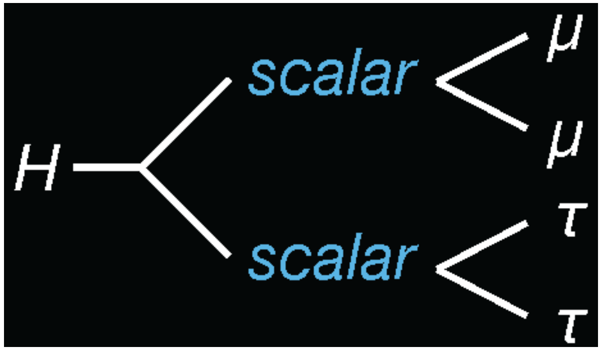
- Upper limits:
  - 6.2pb, m_a=20GeV
  - 1.5pb, m_a=60GeV
- More results for ICHEP
  - More data
  - Other decay channel
- New method for low p_T merged b-jets $\Rightarrow$ better sensitivity for low m_a



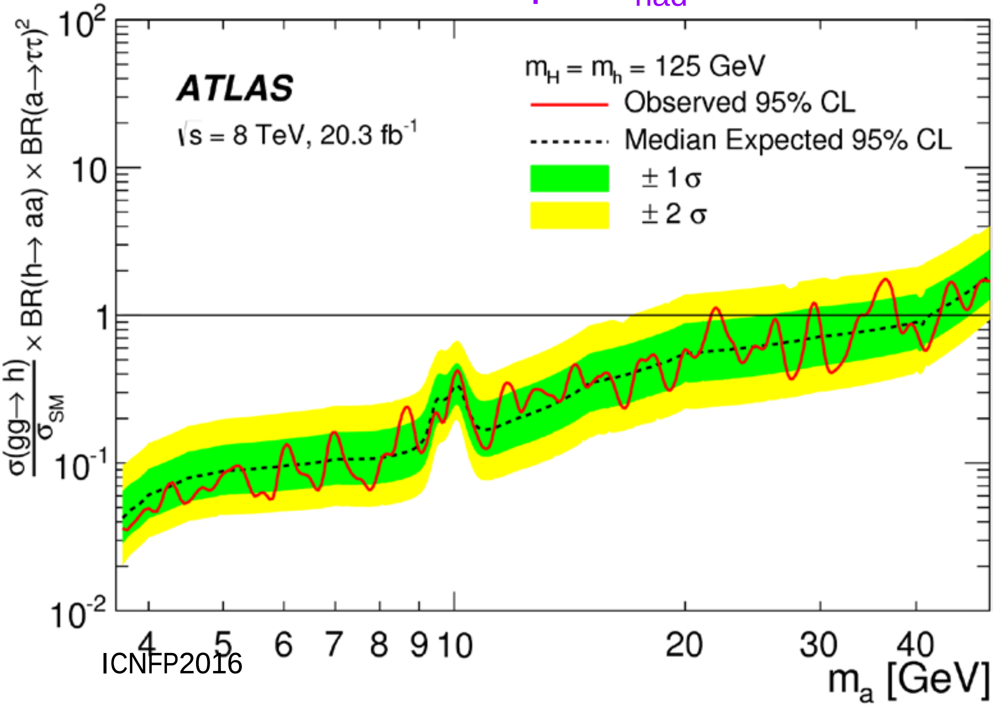
Sensitivity loss at low m_a due to merged jet

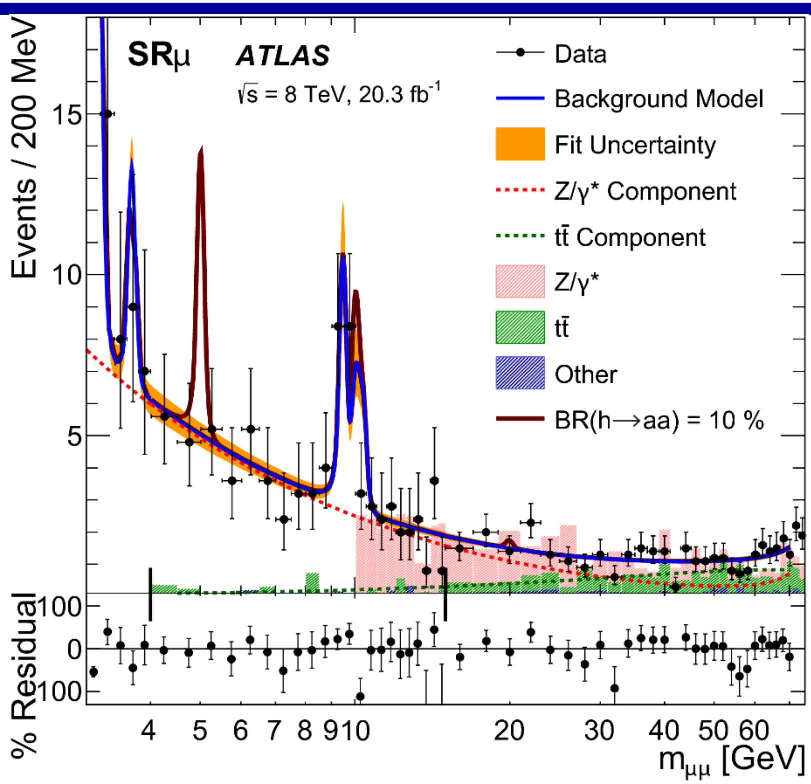
Search for $H \rightarrow aa \rightarrow \mu\mu\tau\tau$

PRD92, 052002 (2015)



- Focus on $H \rightarrow aa$, with:
  - $a \rightarrow \mu\mu$
  - $a \rightarrow \tau\tau \rightarrow e/\mu + \tau_{had}$ ..





- Still 8 TeV results. Searches done in NMSSM context.
- No significant excess for $3.7 < m_{\mu\mu} < 50$ GeV
- Most stringent limit on $H \rightarrow aa$ Is 3.5% for m_a=3.75 GeV

Search for Higgs decays to a light boson

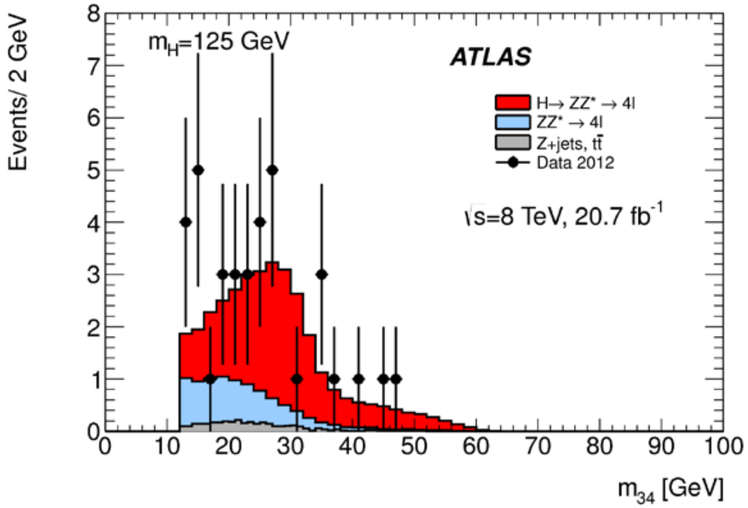
Search for Higgs Decays into New Light Bosons

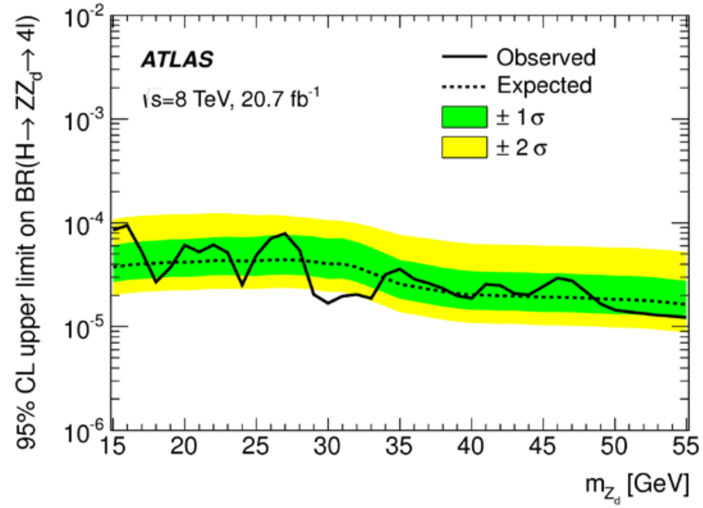
- Some extensions to SM contain dark or hidden sector
- Exotic decay $H \rightarrow 4l$ can be produced via two processes:
  - $H \rightarrow ZZ_d \rightarrow 4l$
    - rate depends on the kinetic or mass mixing between Z_d and Z
    - Results would lead to set upper limit on $B(H \rightarrow ZZ_d \rightarrow 4l)$ and can be translated into upper limits on the kinetic or mass mixing between Zd and Z
  - $H \rightarrow Z_dZ_d \rightarrow 4l$
    - rate depends on the coupling between Z_d and H
    - set upper limit on $B(H \rightarrow Z_dZ_d \rightarrow 4l)$ and can be translated into upper limit on coupling between Z_d and H
- distinctive $4l$ signature could be easily detectable for $m(Z_d)$ > 15 GeV

Search for Higgs Decays into New Light Bosons

Phys. Rev. D 92 (2015) 092001

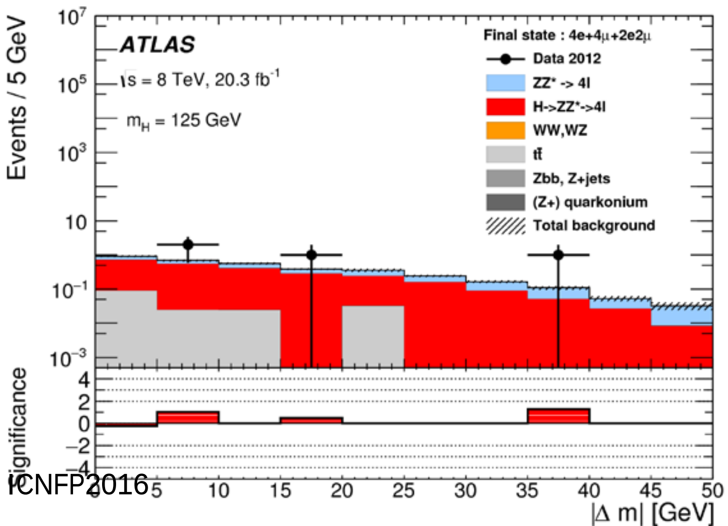
- $H \to ZZ_d \to 4l$

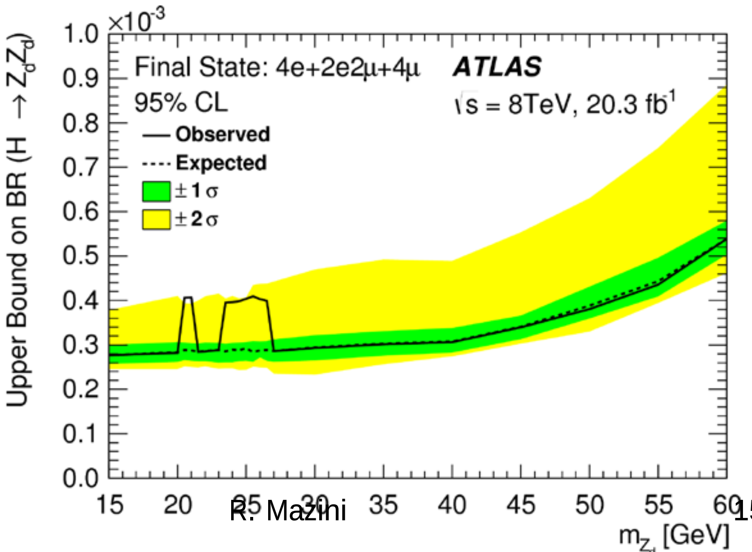




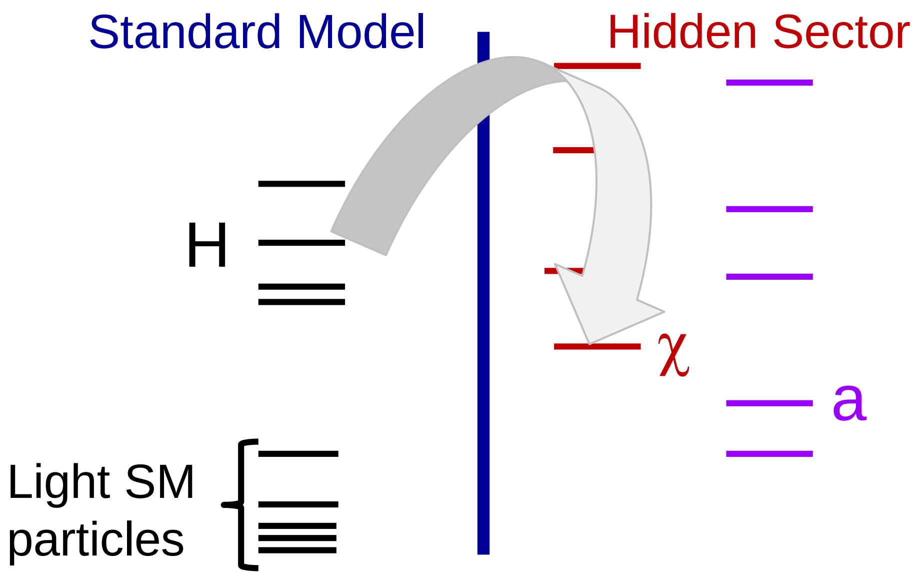
No observed excess for both channels

- $H \to Z_d Z_d \to 4l$





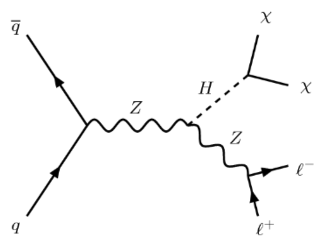
Search for Invisible Higgs decay

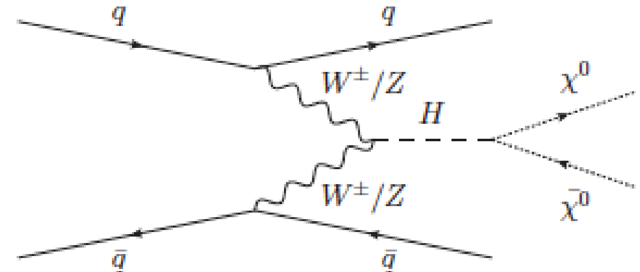


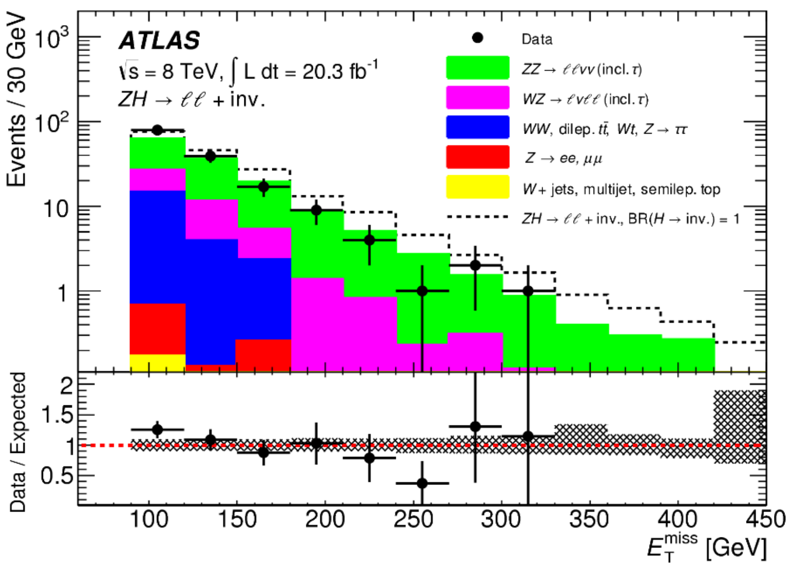
Invisible Higgs @ 8 TeV

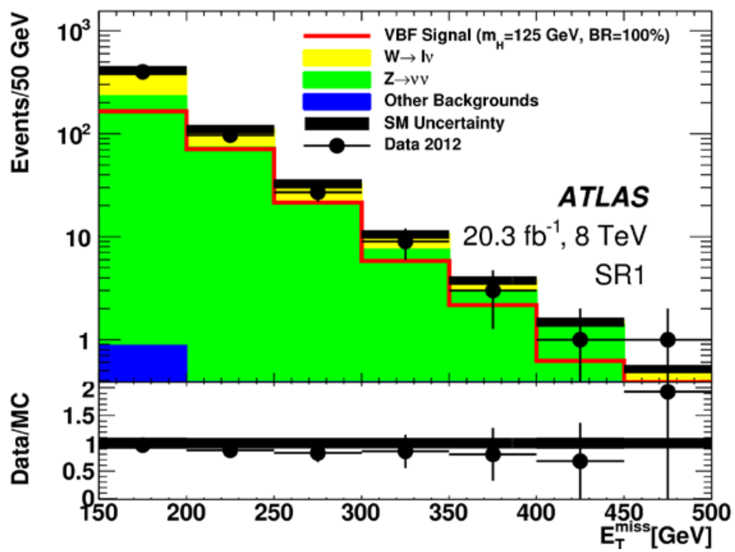
JHEP01(2016)172, JHEP11(2015)206
PRL112, 201802 (2014), EPJ C75 (2015) 337

- Direct searches for **invisible** Higgs decays in the VBF, Z(ll)H and V(jj)H production modes
- Relevant for $m_D<m_H/2$ (m_D : mass of the lightest dark matter candidates)







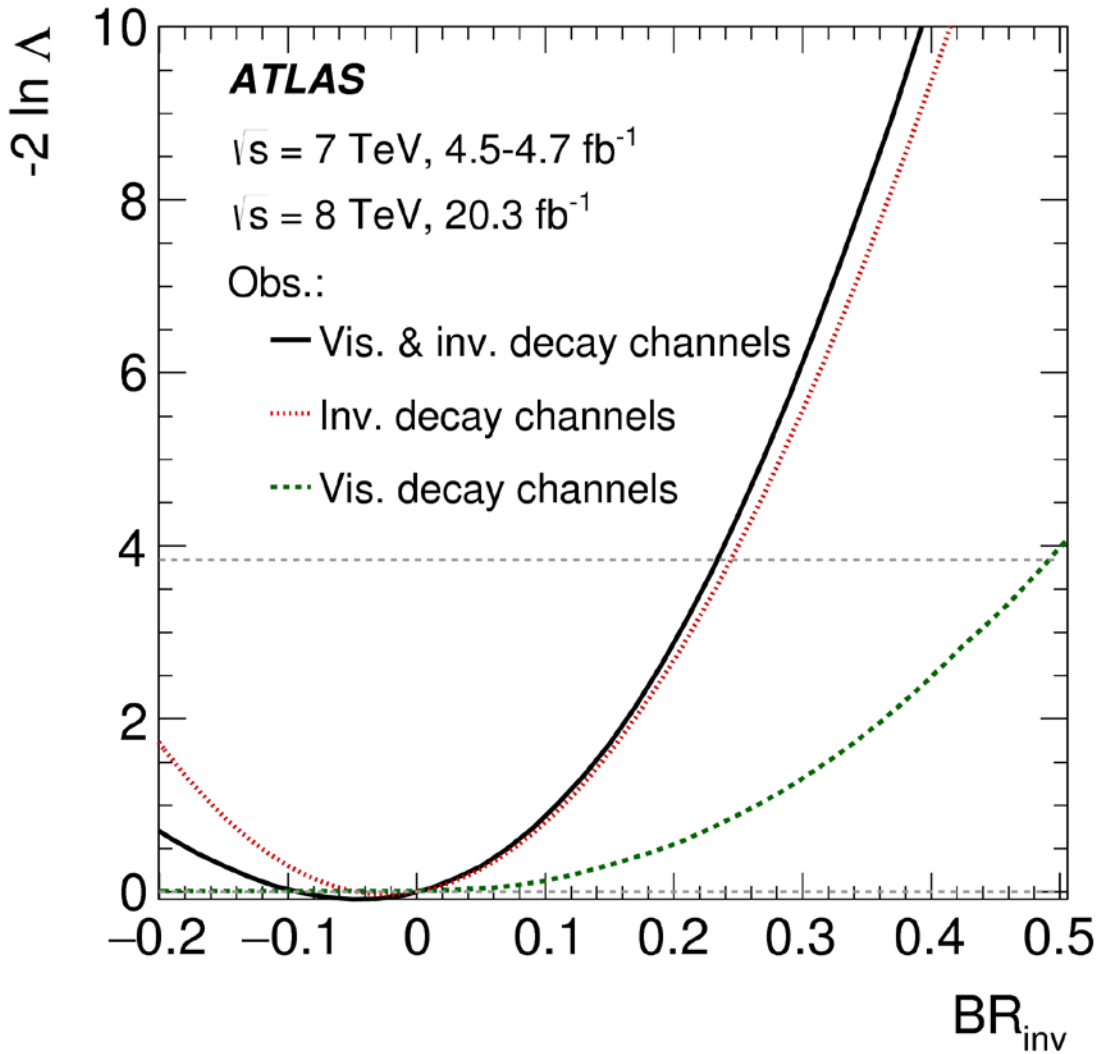


- Combination of these channels yields 95% CL upper limit on: **BR(*H*→inv) < 0.25**

Invisible Higgs @ 8 TeV

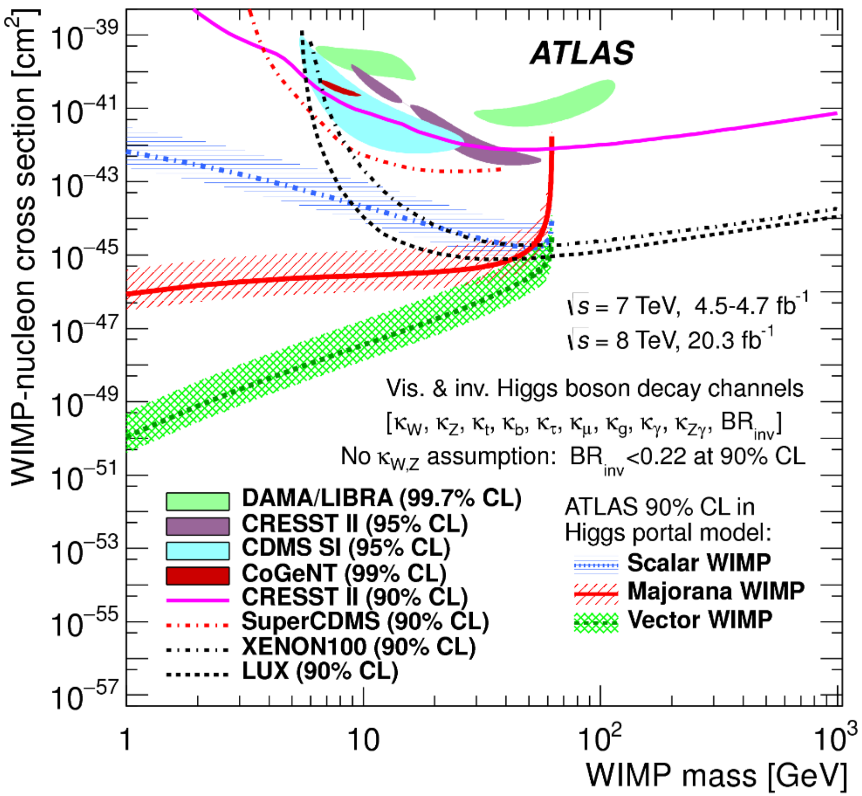
JHEP01(2016)172, JHEP11(2015)206
PRL112, 201802 (2014), EPJ C75 (2015) 337

- Combination of visible and invisible channels gives more stringent limit on **BR(*H*→inv): 0.23 (0.22 of 90% CL)**



DM Higgs Portal

- **Higgs-portal DM scenario:** results from the BR(H→ invisible) limit translated into upper limits on WIMP-nucleon cross section
- Limit on the invisible decay BR is used to constraint the rate of DM-nucleon scattering in model with Higgs portal to DM
  - Scalar, Majorana fermion or vector, with mass < 1/2 Higgs mass, assuming WIMPs account entirely for BR(H→inv)
- Strong constraints on low mass vector and fermions WIMPS



Other rare Higgs decays

Search for H/Z → J/Ψ γ, ϒ(nS) γ

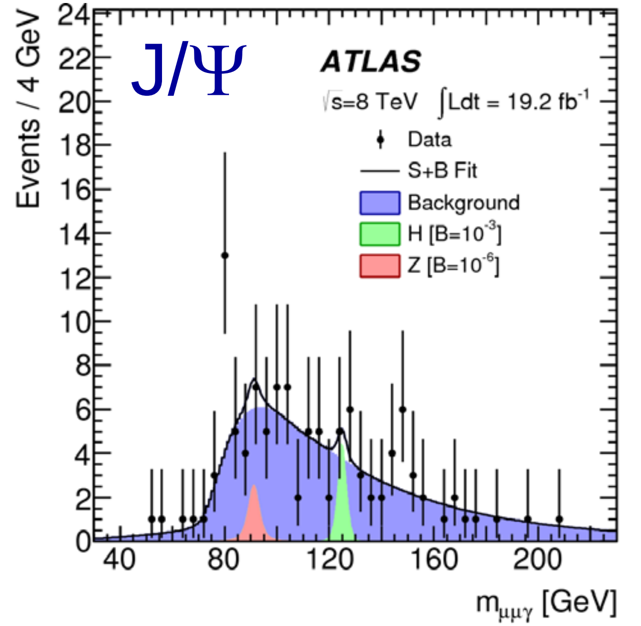
PRL114, 121801 (2015)

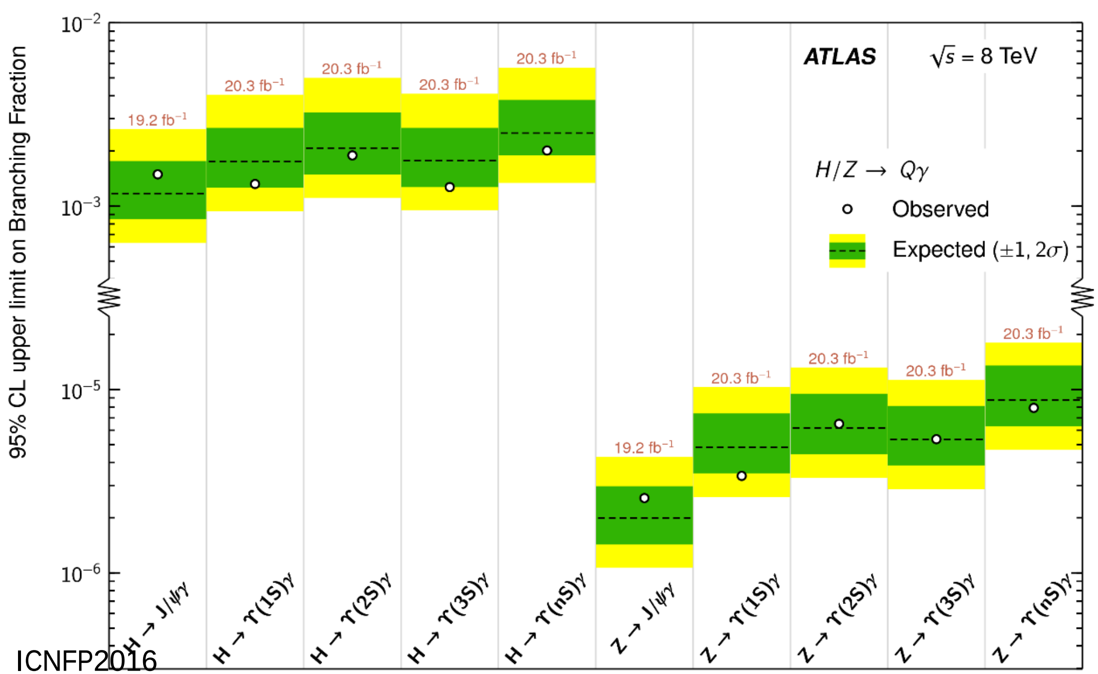
- A very rare decay, involving $Hc\bar{c}$ coupling
  - SM BR($H \to J/\psi\gamma$)=2.8×10^{-6},
  - BR($H \to \Upsilon(nS)\gamma$)=$(6.1,2.0,2.4)\times10^{-10}$

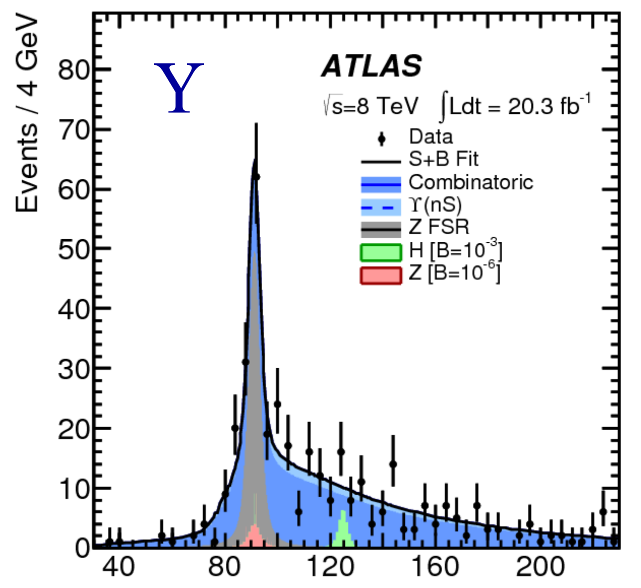
- Only $\mu^+\mu^-\gamma$ final state
- Simultaneous fits performed to $m_{\mu\mu\gamma}$ and $m_{\mu\mu}$

- No significant H/Z → $\mathcal{Q}\gamma$ signal is observed

  BR($H \to J/\psi\gamma$) < 1.5×10^{-3}@95%CL



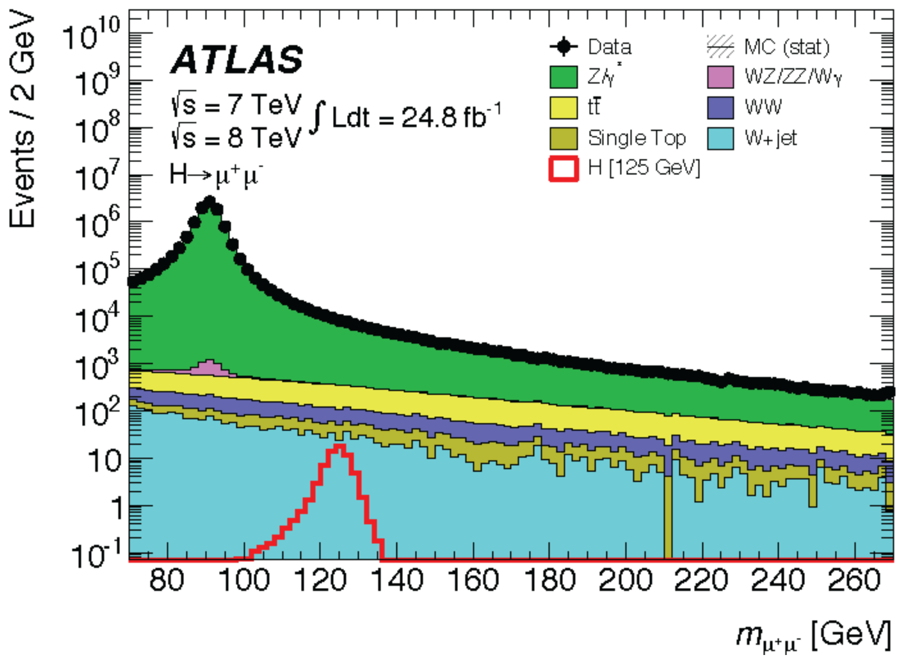


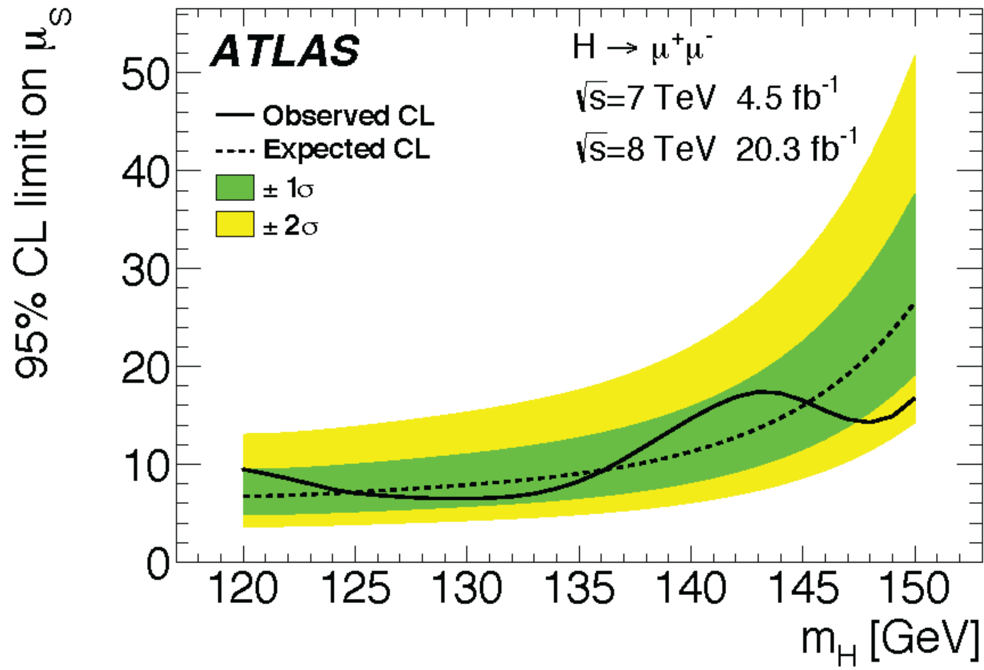


Search for H→μμ decay

- Light-flavor lepton/quark couplings to the Higgs boson provide useful insights to the nature of the Yukawa couplings.
  - May probe the universal or non universal Higgs coupling to fermions.

    ⇒ physics beyond the Standard Model
- ggF & VBF categories, Analytic background modelling.





- $\sigma \times BR < 7.0$ obs (7.2 exp) $(\sigma \times BR)_{SM}$.
- Confirmation of non-universal couplings to fermions, when compared to H→ττ results.

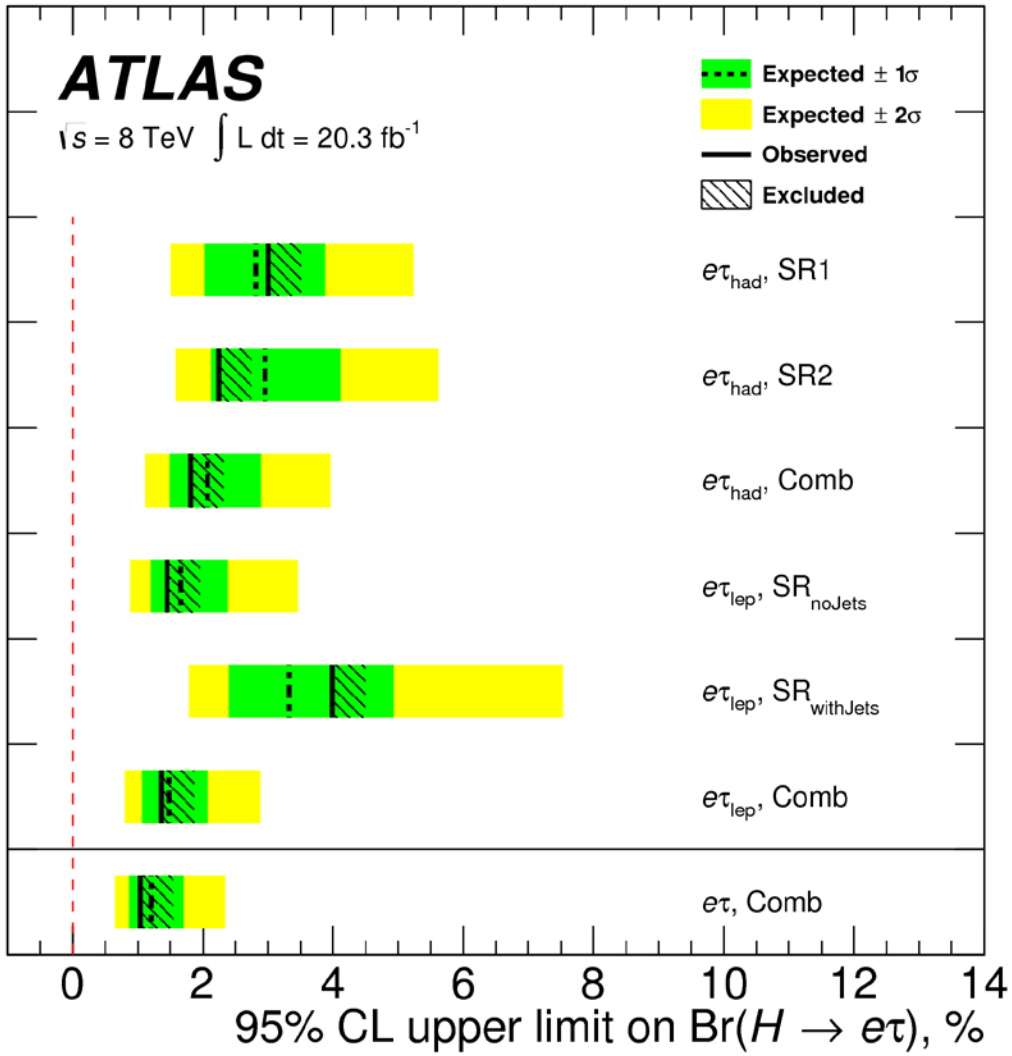
Conclusion

- ATLAS has carried out several direct searches for rare or new Higgs boson decay channels as a probe for BSM physics
  - LFV, light scalar, invisible decays
  - Mostly 8TeV results and some 13 TeV ones.
  - Stringent limits on many branching ratio
- Existing constraints on BSM Higgs decay is “only” 34%
  - Though limits from direct searches for invisible Higgs decay are more stringent:. < 25%
- Significant increase in LHC luminosity for 2016 run, up to 30 fb^{-1}.
  - Higher precision for SM processes ⇒ better estimation for physics backgrounds
  - We should see a significant increase in the sensitivity to many signals
- Many more direct searches are being performed and results are expected soon

Back up

Limits on LFV H → $e\tau$ decay

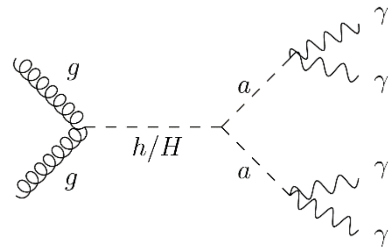
- Run I limits of BR(H → $e\tau$)



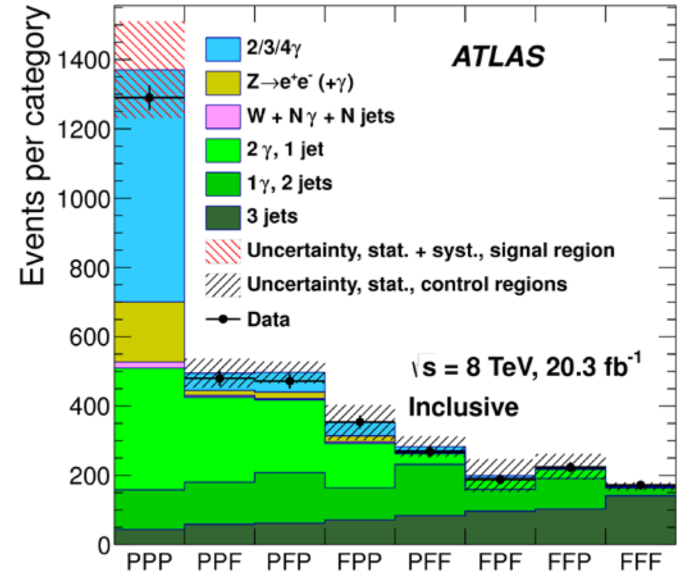
Search for H/a → aa → γγγγ

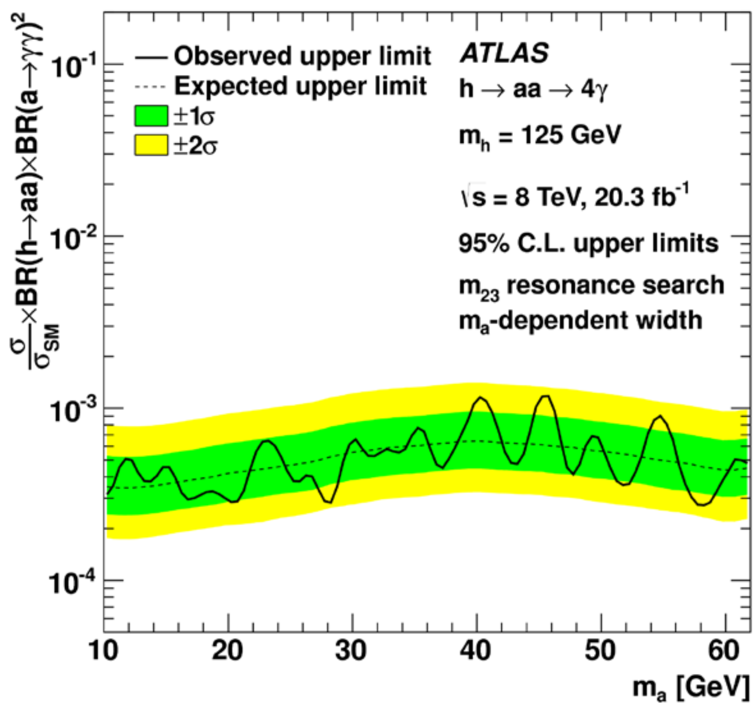
EPJ C76 (4) 1-26 (2016)

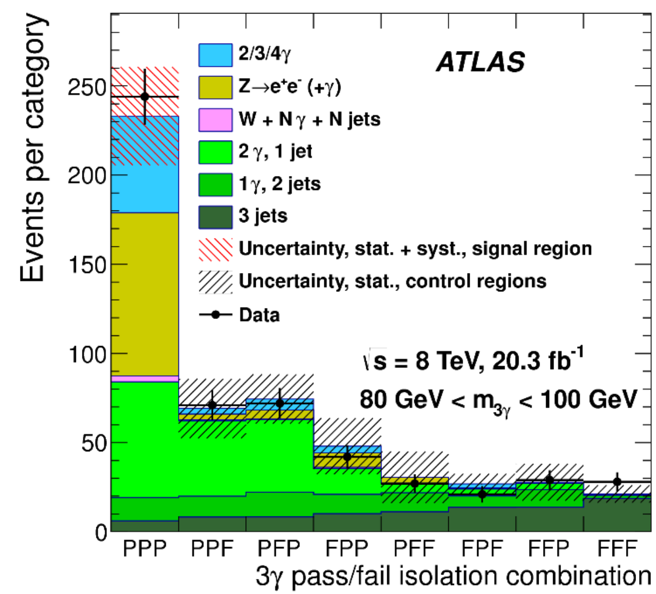
- Looking at events with at least 3 tight photons.



- Signal and Control regions defined with γ's passing (P) or failing (F) isolation requirement.
- BR(h→ aa)xBR(a →γγ)^2 < $10^{-3}\sigma_{SM}$, 10<m_a< 62 GeV







Higgs portal scenario: WIMP-nucleon cross section

WIMP dark matter interacts through Nuclei recoil by Higgs :

$$\sigma^{SI}_{S-N} = \frac{4\Gamma_{inv}}{m_H^3 v^2 \beta} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$$

$$\sigma^{SI}_{V-N} = \frac{16\Gamma_{inv} M_\chi^4}{m_H^3 v^2 \beta (m_H^4 - 4M_\chi^2 m_H^2 + 12 M_\chi^4)} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$$

$$\sigma^{SI}_{f-N} = \frac{8\Gamma_{inv} M_\chi^2}{m_H^5 v^2 \beta^3} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$$

where

VEV: $\sqrt{2}v = 246\text{GeV}$ $\beta_\chi = \sqrt{1 - 4m_\chi^2/m_h^2}$

m_N (proton mass) = 0.939GeV,

f_N (H-nucleon coupling) = 0.33+0.30-0.07