Rare/Exotic Decays of the Higgs Boson

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On behalf of ATLAS and CMS

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Outline

- Introduction
- Search for H → $e\mu$
- Search for H → $e\tau$
- Search for H → $\mu\tau$
- Search for Higgs decays into new light bosons
- Search for invisible Higgs decays
- Summary

Why Search for Rare/Exotic Decays?

- Discovery of Higgs in 2012 is a crowning achievement of SM
  - SM is simple/elegant but incomplete…
    - why three generations of elementary particles?
    - masses/couplings are free parameters
    - why neutrinos are left-handed?
    - what is the dark matter?
  - ⇨ search for new physics in rare/exotic decays of Higgs
    - rare decays might be more sensitive to new physics contribution
    - exotic decays would be a clear sign of physics beyond SM

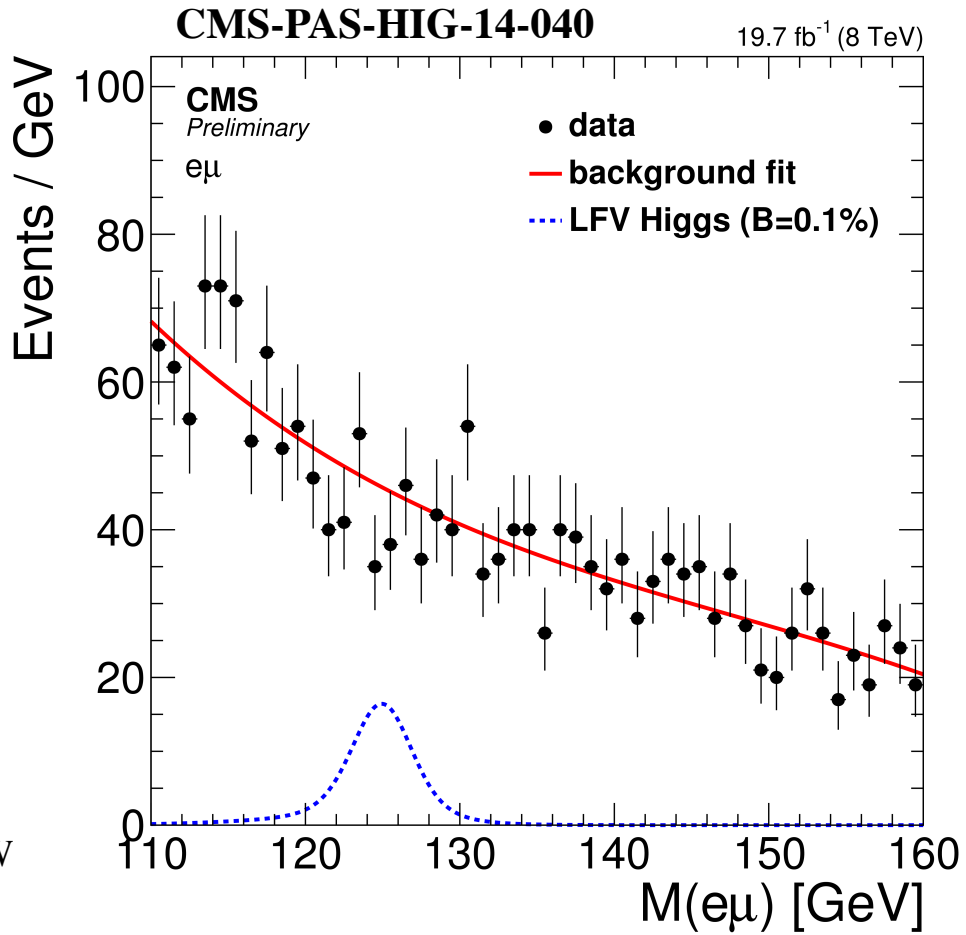
Search for Lepton Flavor Violation

- lepton flavor conservation is an assumption of SM
- no known symmetry associated with lepton flavor conservation
- observation of LFV would revolutionize
  our understanding of particles and fields
  - require a "7σ" signal to claim a discovery?
- discovery of muon 80 years ago started the LFV search industry
  - "best" limit: $B(\mu \to e\gamma) < 5.7 \times 10^{-13}$ @ 90%CL
    - ⇨ $B(\mathrm{H} \to e\mu) < \mathrm{O}(10^{-8})$
  - much less constrained for decays involving τ leptons
    - ⇨ $B(\mathrm{H} \to e\tau/\mu\tau) < \mathrm{O}(10\%)$
    - ⇨ promising venue for discovery

CMS Search for H → $e\mu$

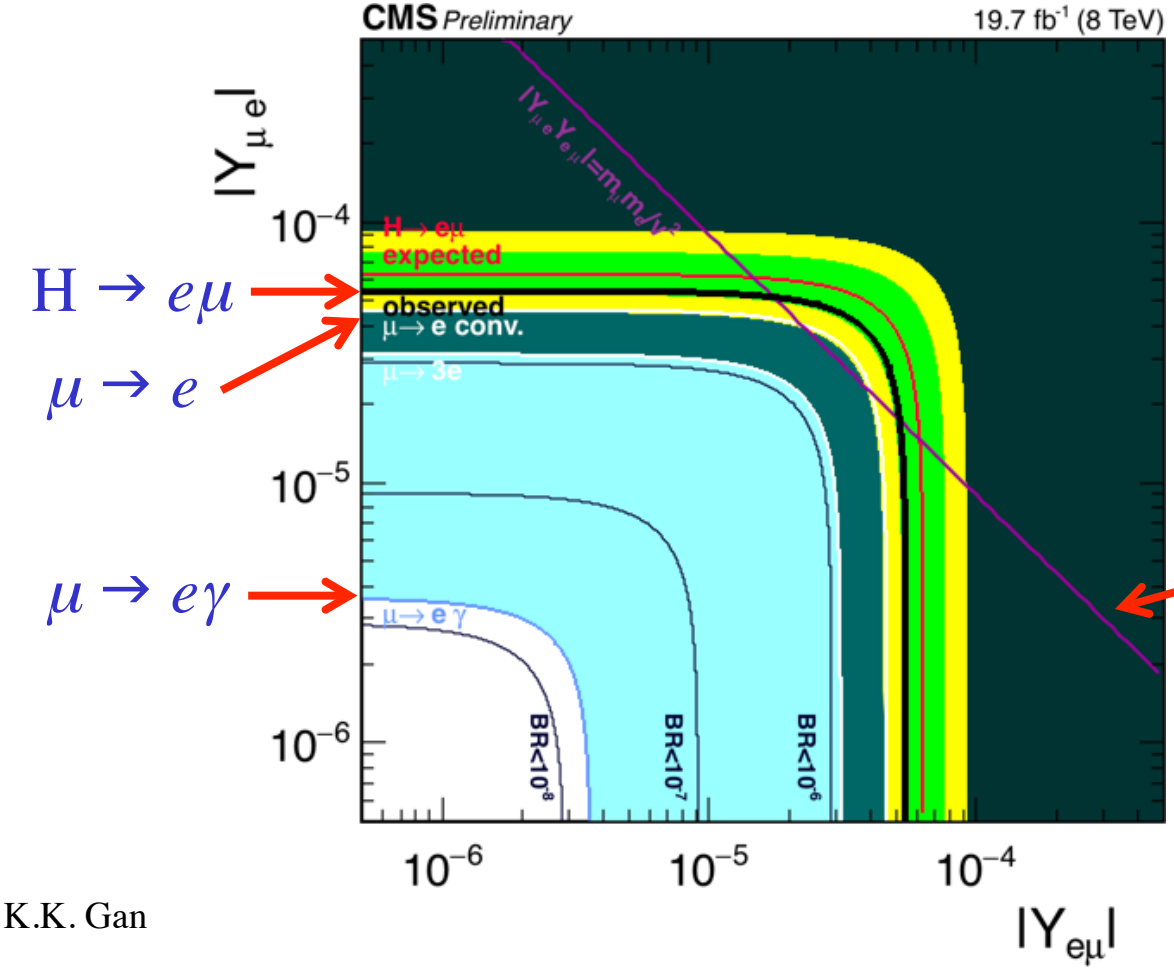
- e and μ have opposite charge
- P_T(lepton) > 20-25 GeV
- missing E_T < 20-30 GeV
- enhance sensitivity to different production processes (VBF, ggF, W/ZH) with different selection criteria for 0, 1, 2 jets
- no significant excess of events

⇨ $B(H \rightarrow e\mu) < 0.036\%$ @ 95% CL



Limits on Lepton-Flavor-Violating Couplings

- direct limits on couplings are less stringent than indirect limits but require no theoretical assumptions



H → $e\mu$

$\mu \to e$

$\mu \to e\gamma$

Naturalness limit

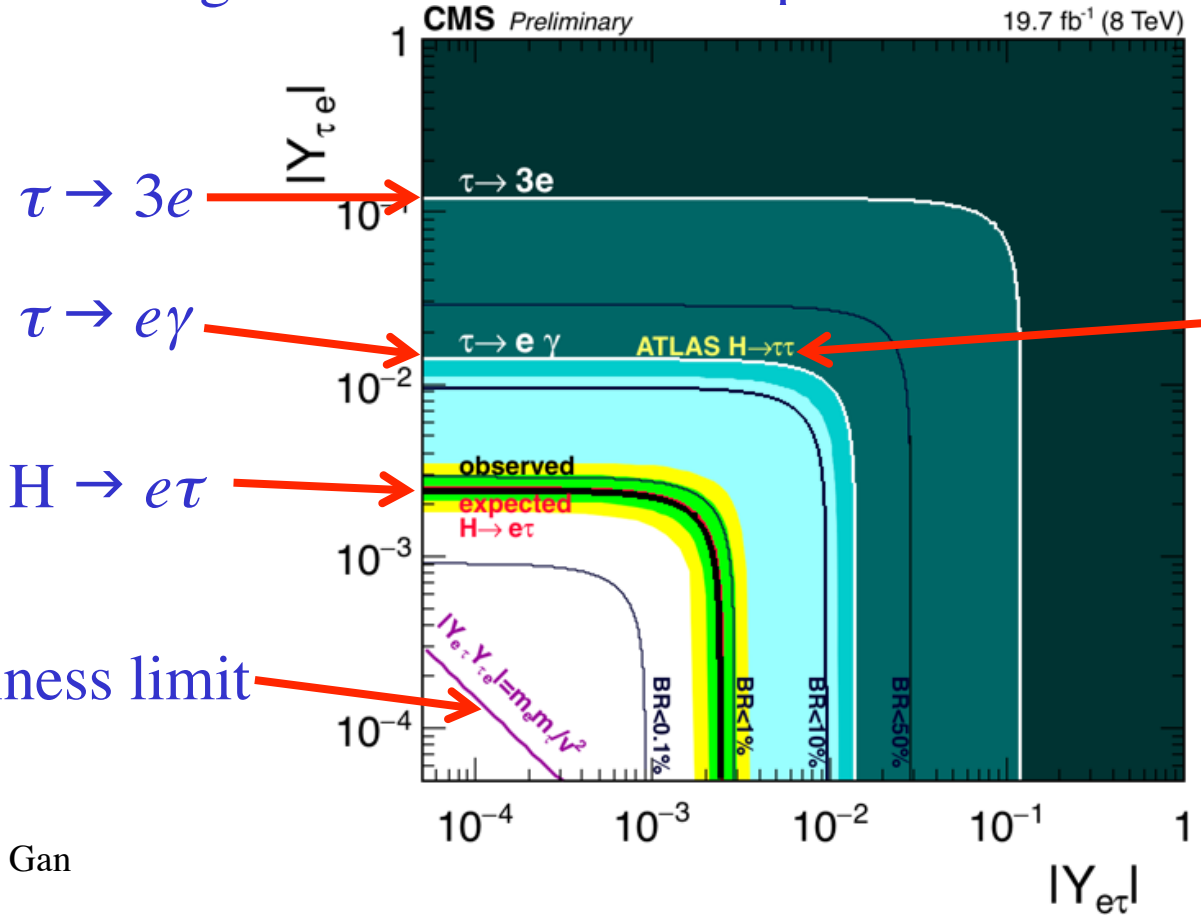
$Y_{e\mu} Y_{\mu e} < m_e m_\mu / v^2$

CMS Search for H → $e\tau$

- Search for H → e + (μ or $h^{\pm}$ + ≤ $2\pi^0$ or $h^{\pm}h^{+}h^{-}$)
- H → e + μ:
  - one isolated e + one isolated μ of opposite charge
- H → e + hadrons:
  - one isolated e + one isolated hadronic τ decay of opposite charge
- enhance sensitivity to different production processes (VBF, ggF, W/ZH) with different selection criteria for 0, 1, 2 jets
- Use collinear mass ($M_{collinear}$) as an estimator of the Higgs mass to discriminate against background
  - use visible τ decay products to approximate ν direction

Limits on Lepton-Flavor-Violating Couplings

- No significant excess of events with $100 < M_{collinear} < 150$ GeV
- $B(H \to e\tau) < 0.70\%$ @ 95% CL
  - ⇨ most stringent direct limits on lepton-flavor-violating couplings



$\tau \to 3e$

$\tau \to e\gamma$

$H \to e\tau$

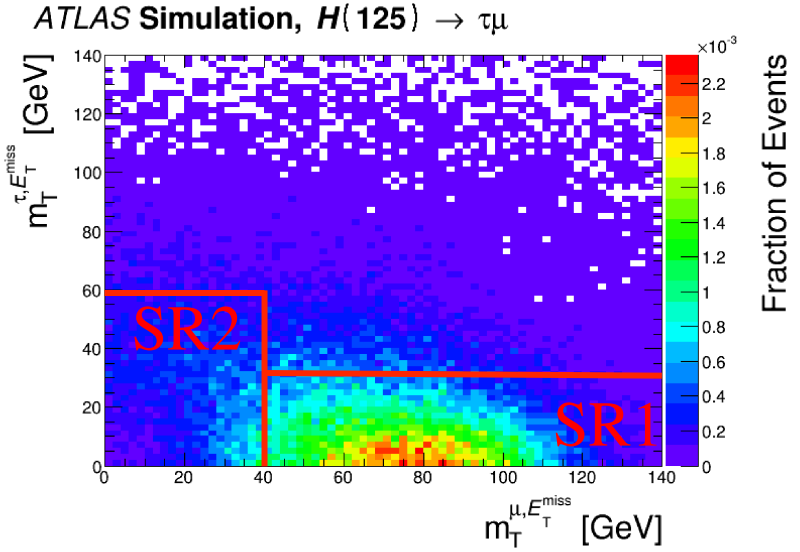
Naturalness limit

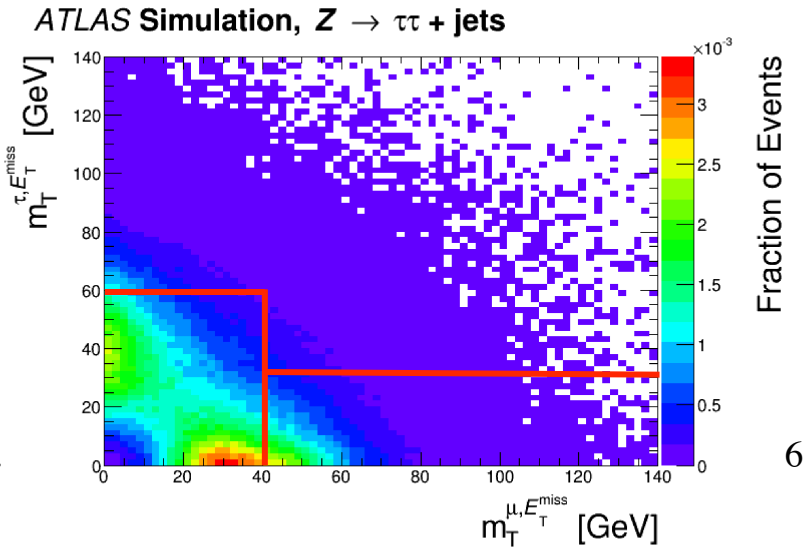
Theoretical interpretation of ATLAS result

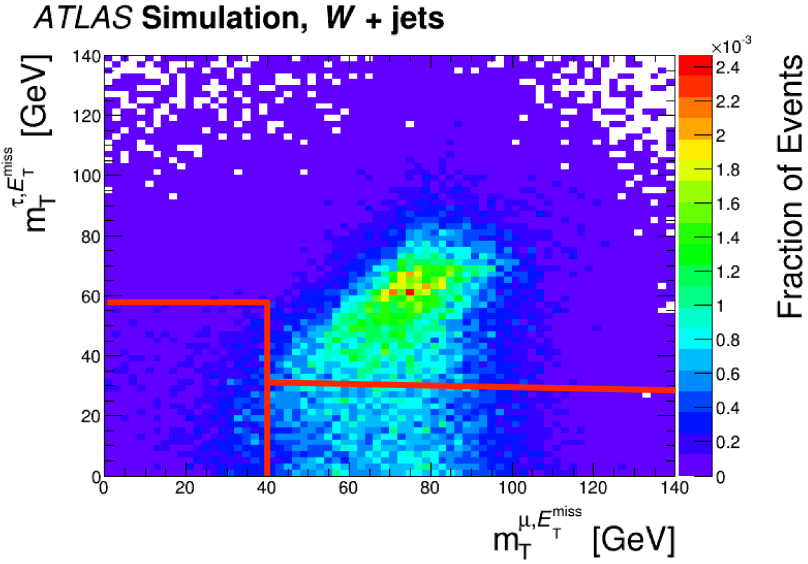
CMS-PAS-HIG-14-040

ATLAS Search for H → $\mu\tau$

- Search for H → μ + (1 or 3 hadrons) + missing transverse energy (E_T)
  - μ and τ_{had} have opposite charge
  - $P_T(\mu) > 26$ GeV
  - $P_T(\tau_{had}) > 45$ GeV
  - $|\eta(\mu) - \eta(\tau_{had})| < 2$
    - high detection efficiency: 99%
    - effective in rejecting W + jets and multi-jet background

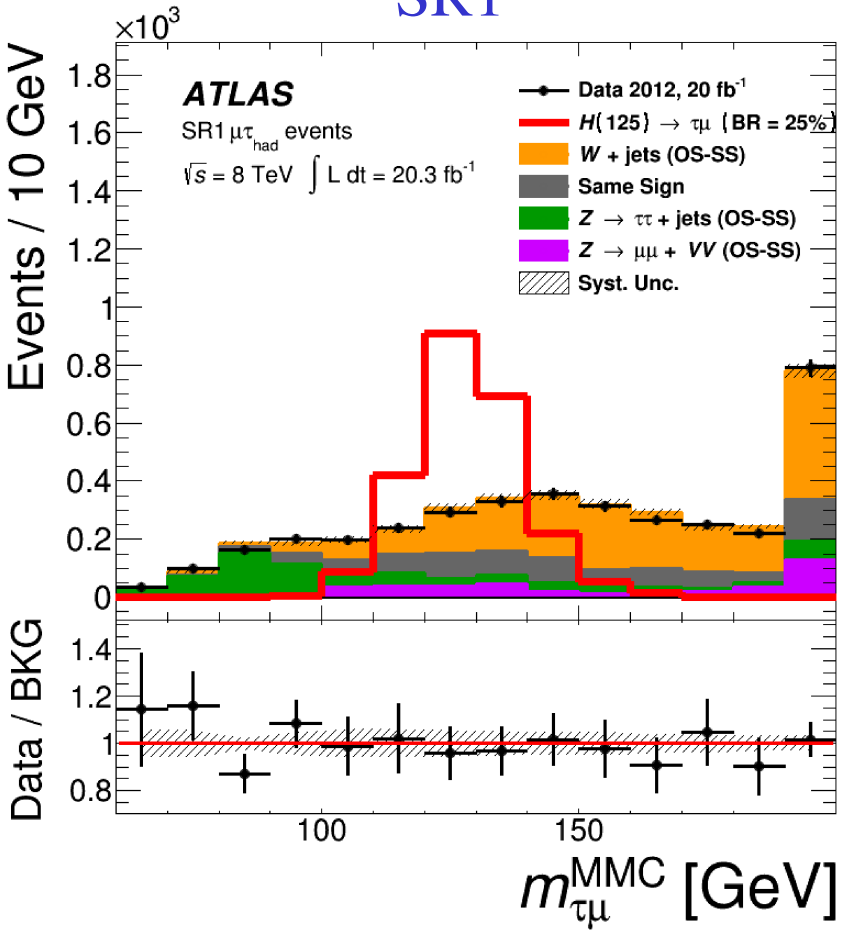




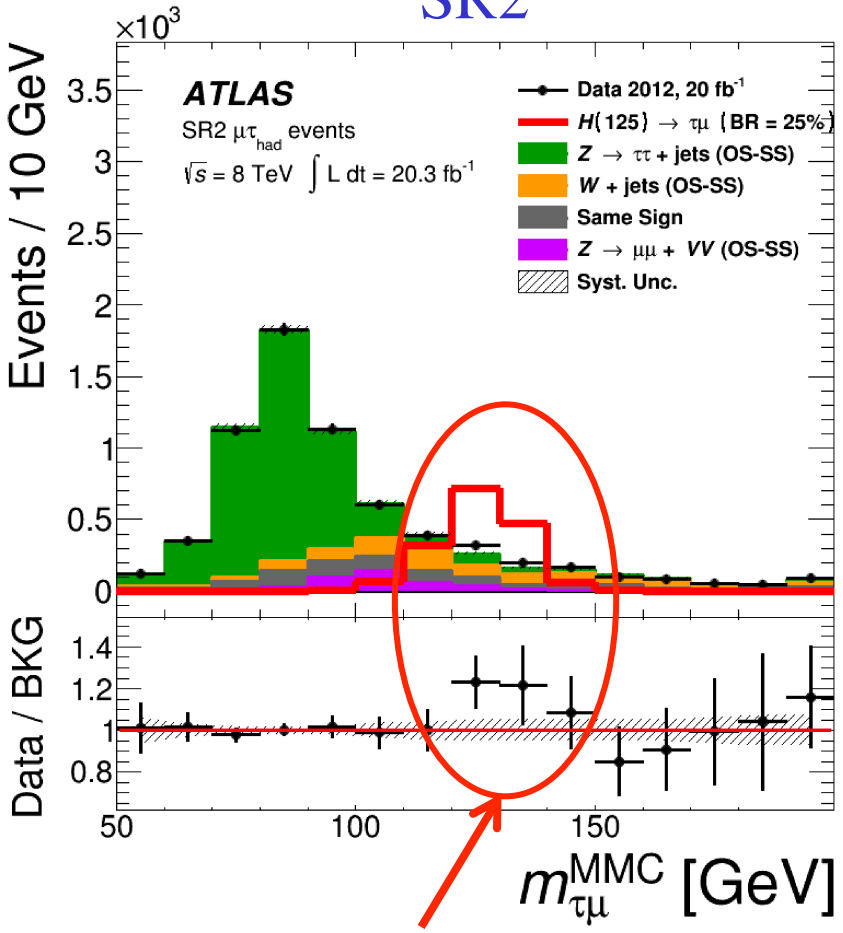


Results of Two Search Regions

SR1



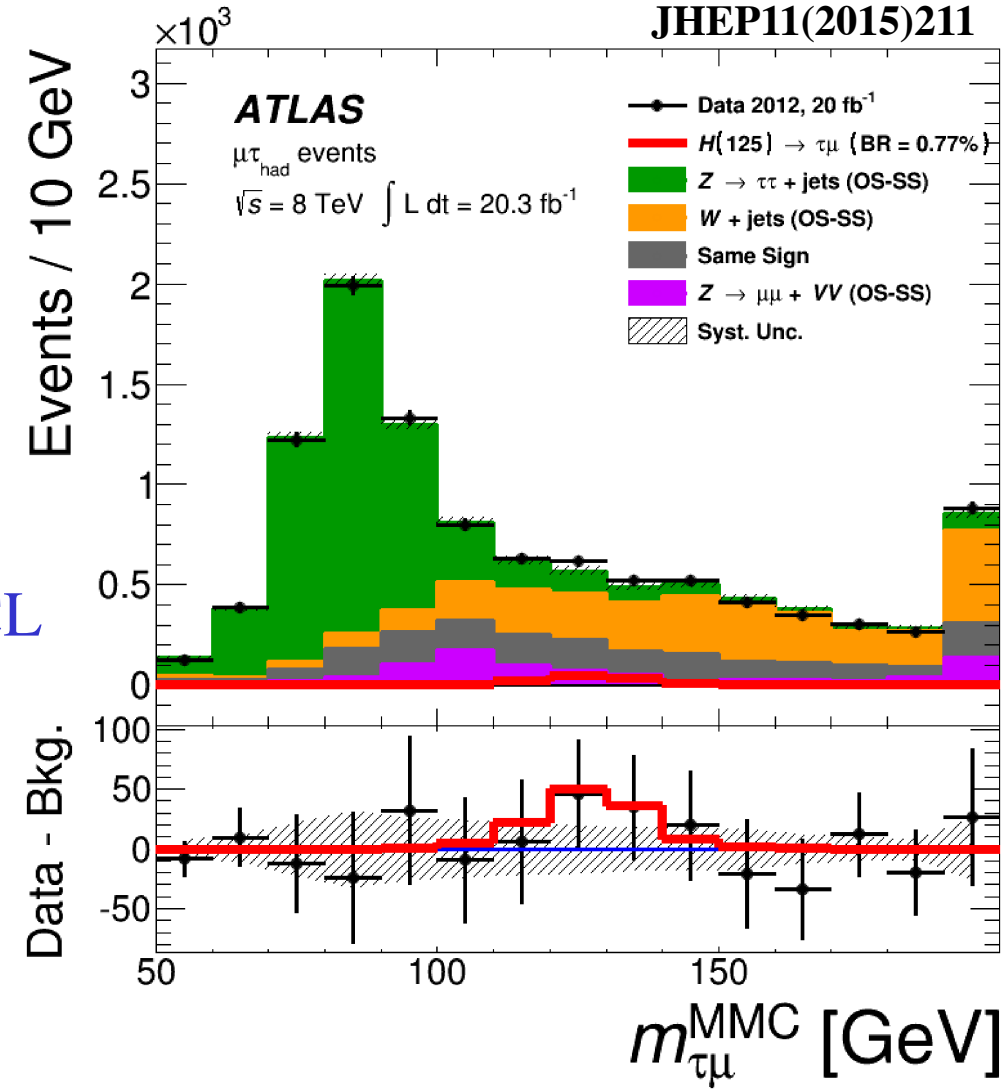
SR2



Lower efficiency
Higher background

Result of Combined Search Regions

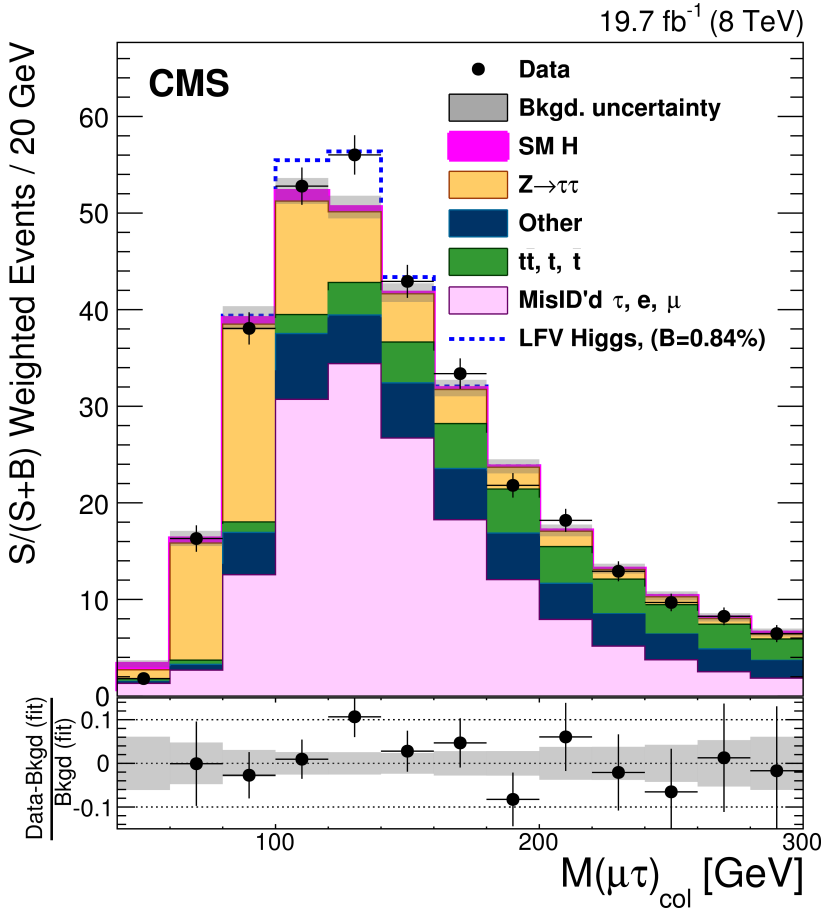
- Data is consistent with background to within 1.3σ
- $B(H \rightarrow \mu\tau) < 1.85\%$ @ 95%CL
  - expected limit: 1.24%

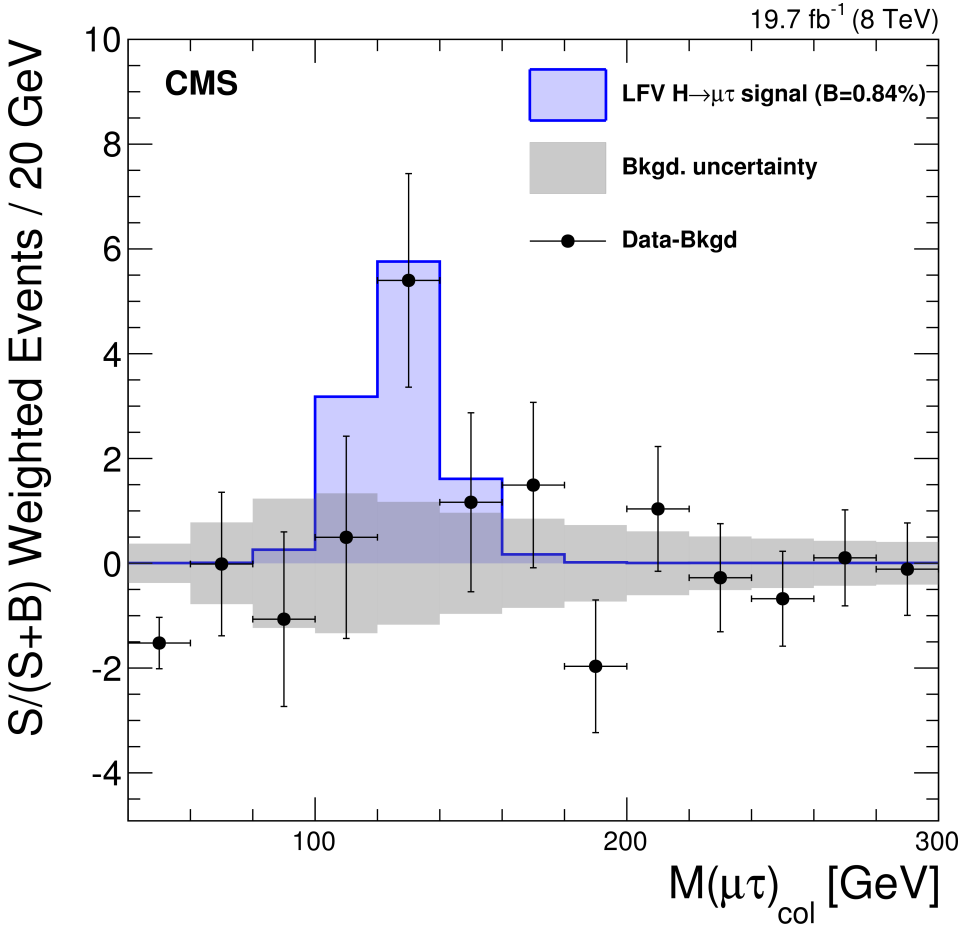


CMS Search for H → $\mu\tau$

- Search for H → μ + (e or $h^{\pm}$ + ≤ $2\pi^0$ or $h^{\pm}h^{+}h^{-}$)
- H → μ + e:
  - one isolated μ + one isolated e of opposite charge
  - main background: $Z \rightarrow \tau\tau$
- H → μ + hadrons:
  - one isolated μ + one isolated hadronic τ decay of opposite charge
  - main background: misidentified τ in W + jets, multiple jets, t-pairs
- enhance sensitivity to different production processes (VBF, ggF, W/ZH) with different selection criteria for 0, 1, 2 jets
- Use collinear mass ($M_{collinear}$) as an estimator of the Higgs mass to discriminate against background
  - use visible τ decay products to approximate ν direction

CMS Search for H → $\mu\tau$





- Mass spectrum has excess of events in one bin near 125 GeV
  - consistency with background only is 2.4σ (p-value = 1%)

Limits on Lepton-Flavor-Violating Couplings

$B(H \to \mu\tau) < 1.51\%$ @ 95% CL

ATLAS: $B < 1.85\%$

⇨ most stringent direct limits on lepton-flavor-violating couplings

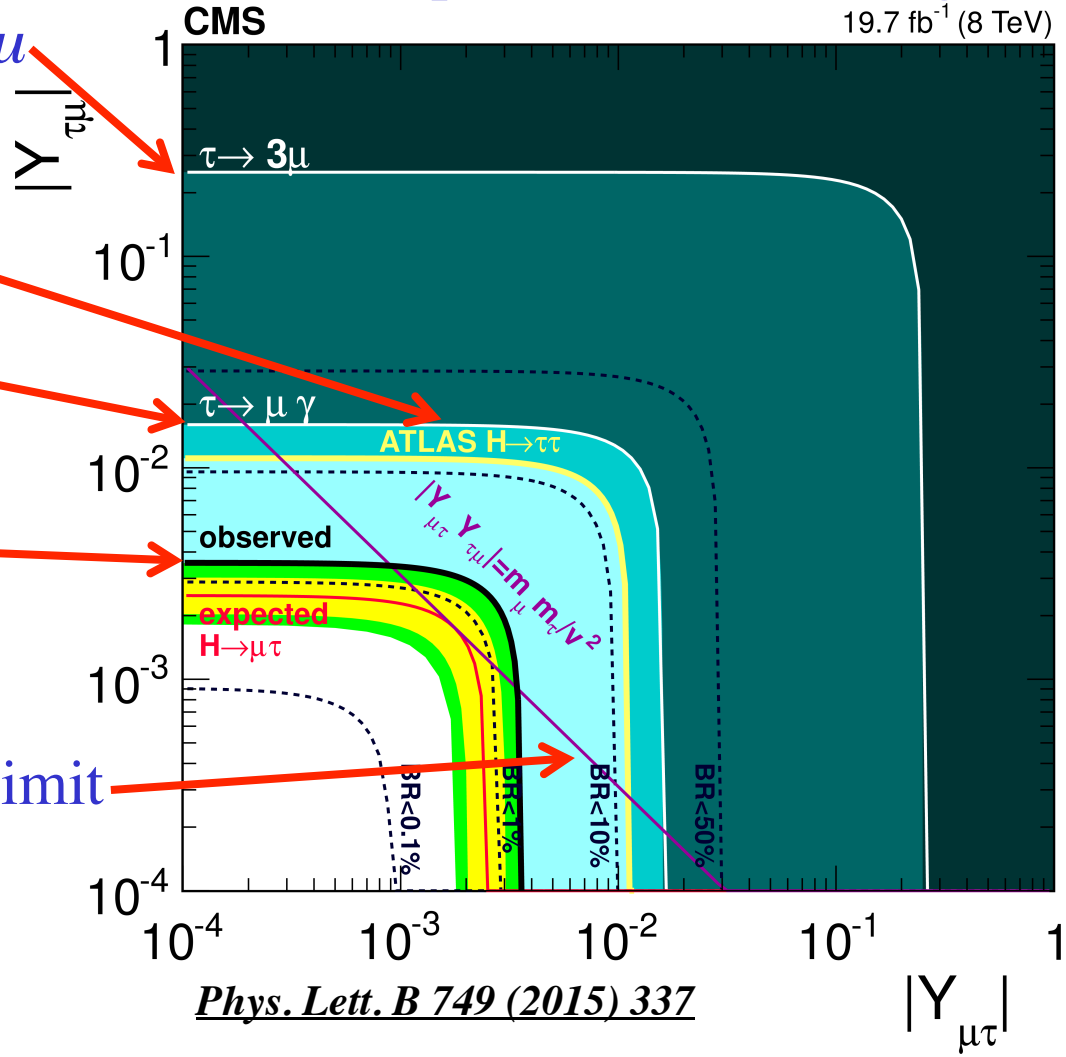
Theoretical interpretation of ATLAS result

$\tau \to 3\mu$

$\tau \to \mu\gamma$

$H \to \mu\tau$

Naturalness limit

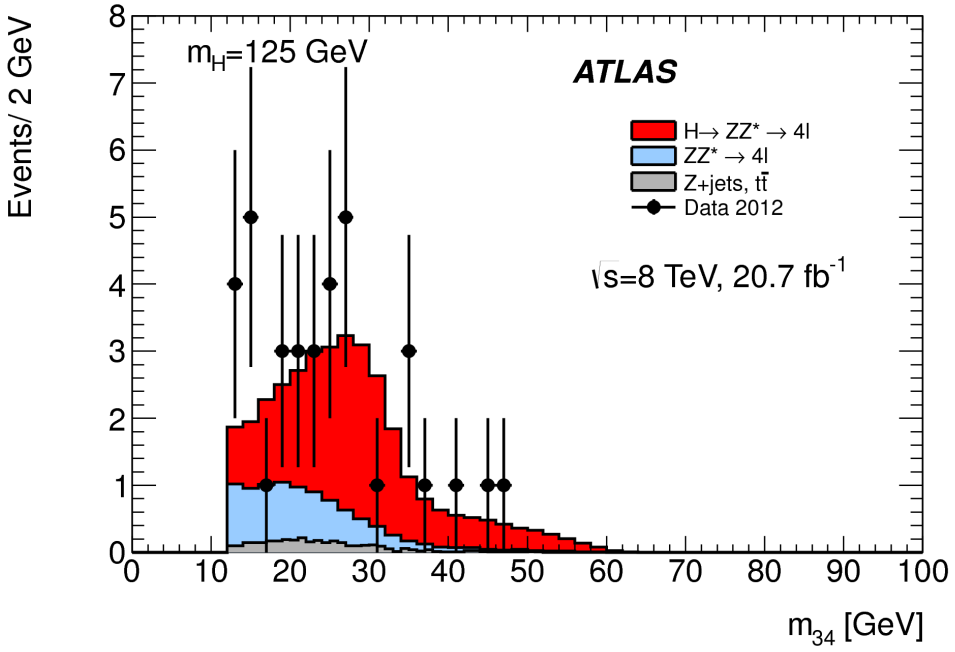


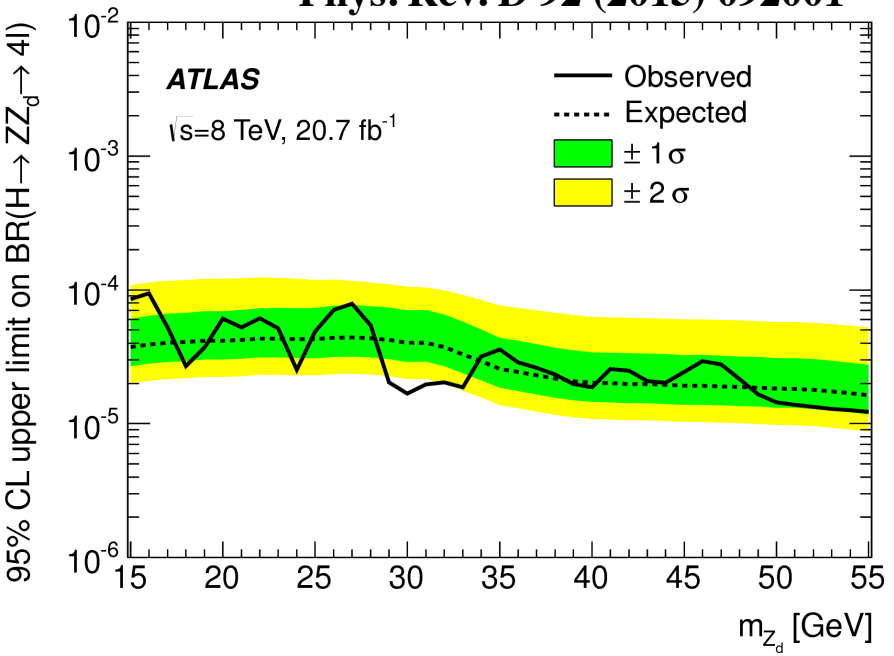
Phys. Lett. B 749 (2015) 337

ATLAS Search for Higgs Decays into New Light Bosons

- Some extensions to SM contain dark or hidden sector
  - provide dark vector boson Z_d that could be dark matter candidate
- Exotic decay H → 4l can be produced via two processes:
  - H → ZZ_d → 4l
    - rate depends on the kinetic or mass mixing between Z_d and Z
  - H → Z_dZ_d → 4l
    - rate depends on the coupling between Z_d and H
  - distinctive 4l signature is readily detectable for $m(Z_d) > 15$ GeV

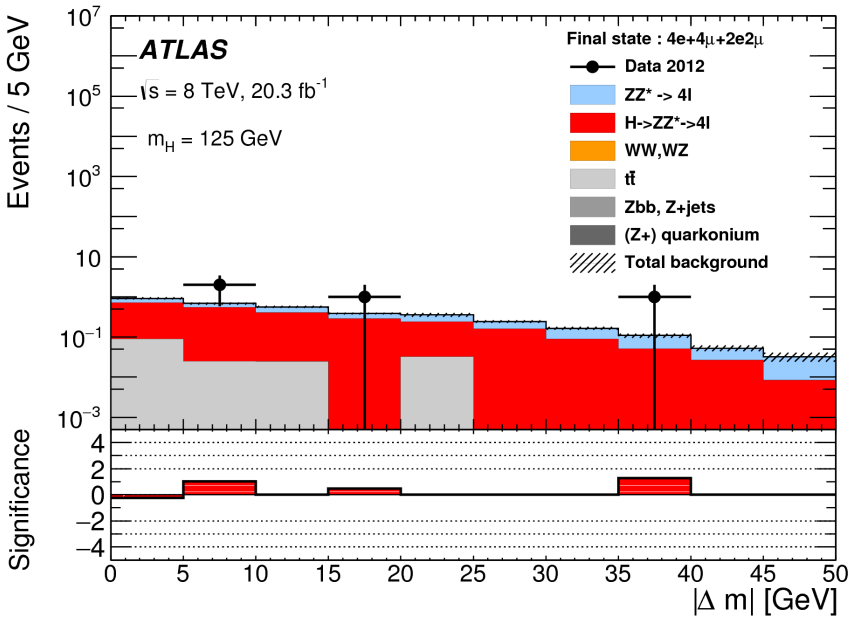
Search for H → ZZ_d → 4l

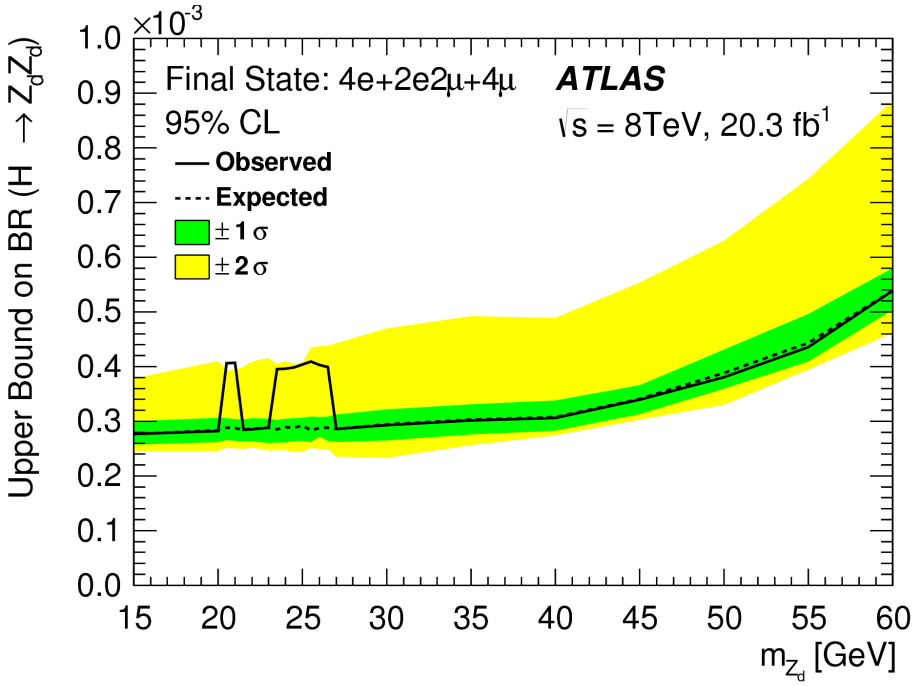




- Search for narrow resonance (m_{34}) recoiling against a Z boson
  - no evidence of an enhancement
  - set upper limit on B(H → ZZ_d → 4l)
  - can be translated into upper limits on the kinetic or mass mixing between Z_d and Z

Search for H → Z_dZ_d → 4l



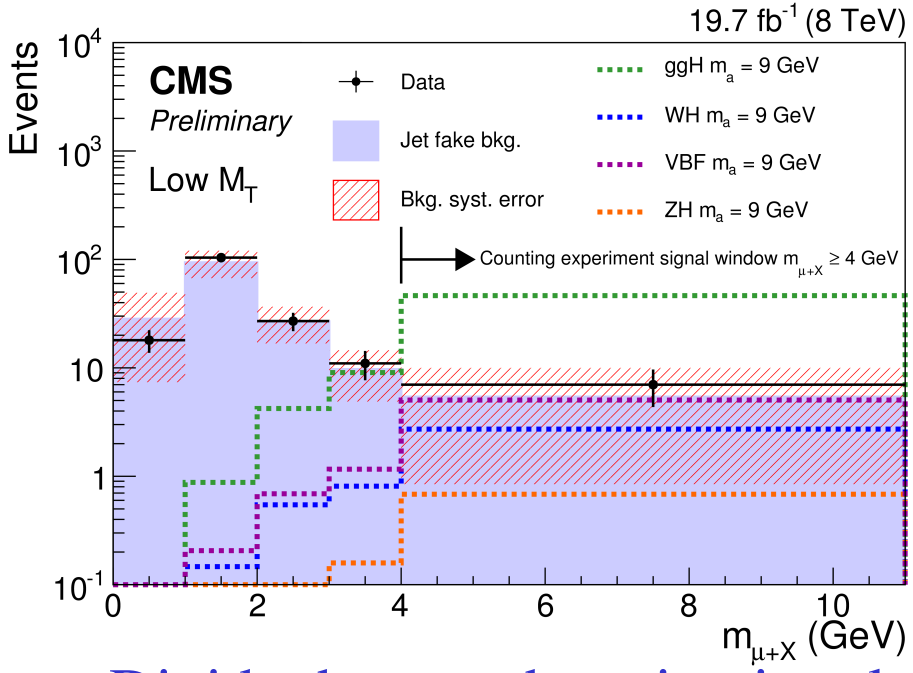


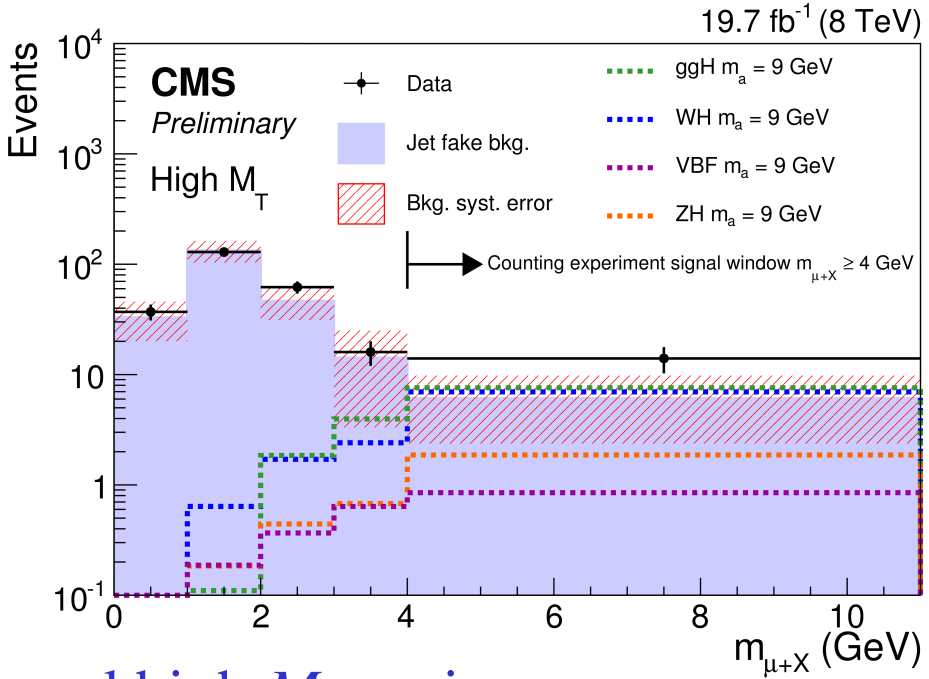
- Search for enhancement in distribution of minimum $\Delta m = |m_{12}-m_{34}|$
  - no evidence of a signal
  - set upper limit on $B(\mathrm{H} \rightarrow Z_dZ_d \rightarrow 4l)$
  - can be translated into upper limit on coupling between Z_d and H

CMS Search for Higgs Decays into New Light Bosons

- Some extensions of SM contain extended Higgs sectors
  - Higgs can decay into a pair of light scalars or pseudo-scalars:
    $H \rightarrow hh \rightarrow 4\tau$ or $H \rightarrow aa \rightarrow 4\tau$
- Higgs production processes used:
  - gluon fusion
  - vector boson fusion
  - vector boson associated production
- Event signature:
  - one isolated high P_T muon to trigger the event
  - relative low mass h or a resulted in highly boosted pair of τ's
    - ⇨ τ's are not very isolated
      - require at least one highly boosted pair of τ's
      - one τ must decay into a muon

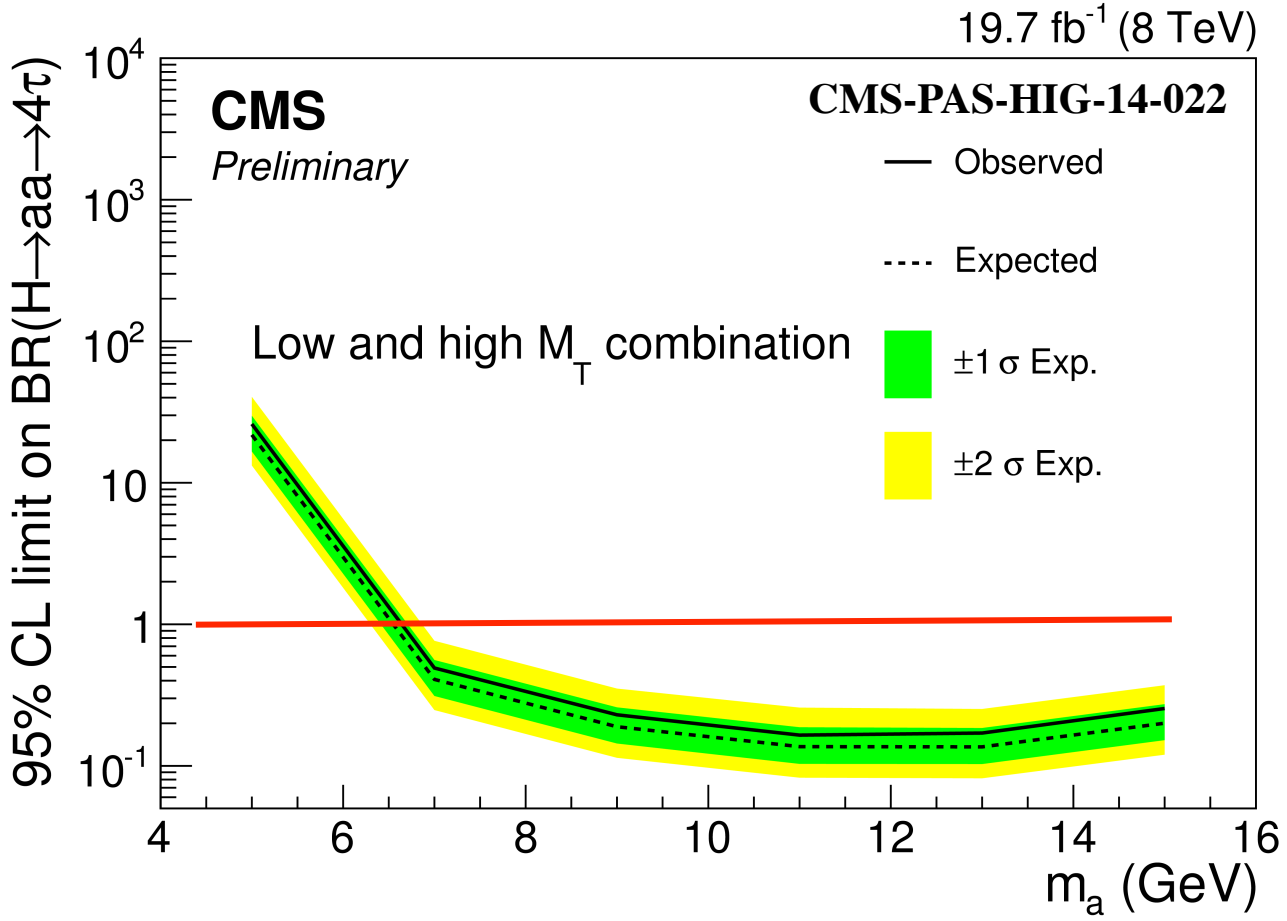
Search for Higgs Decays into New Light Bosons





- Divide the search region into low and high M_T regions
  - high M_T region has enhanced contribution from W associated production
- Search for excess of events with high visible tau-pair mass: $m_{\mu+x} > 4$ GeV
  - no excess of events observed

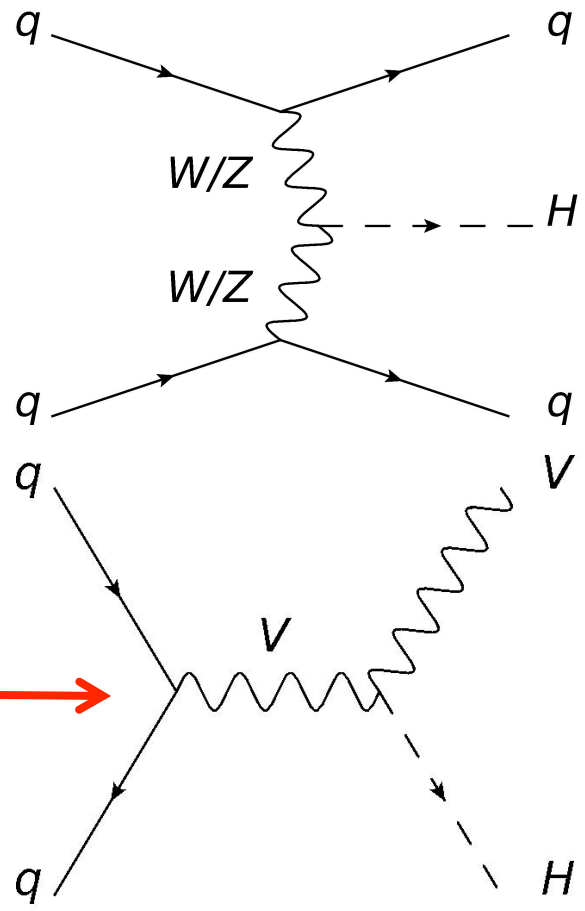
Search for Higgs Decays into New Light Bosons



- $B(H \to aa \to 4\tau) < 50\%$ for $m_a > 7$ GeV at 95% CL
  - $B < 21\%$ for $m_a = 9$ GeV

ATLAS Search for Invisible Decays

- Higgs can decay into "invisible" final state:
  - $B(H \rightarrow ZZ \rightarrow 4\nu) \sim 0.1\%$
- Higgs might decay into dark matter or weakly interacting long-lived/stable particles
- invisible decays of Higgs must be tagged:
  - large missing transverse energy
  - tag with leptons or jets
- search in two production mechanisms:
  - vector boson fusion
    - two jets with large separation in η
    - best sensitivity
  - vector boson associated production



ATLAS Search for Invisible Decays

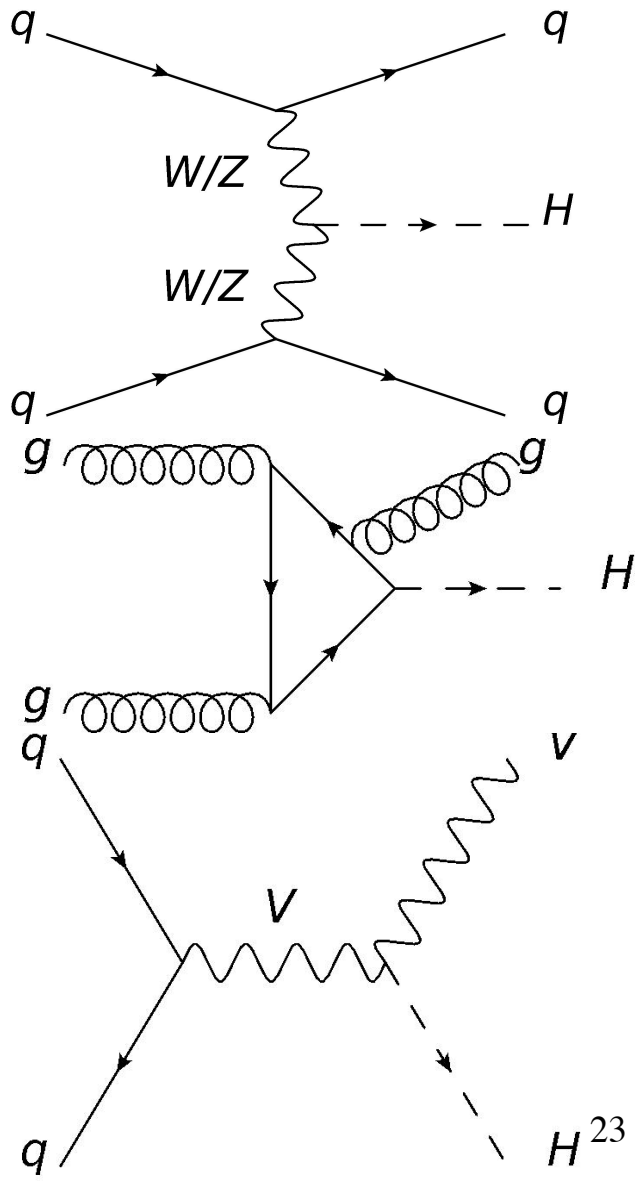
JHEP11(2015)206

Channel	Observed (%)	Expected (%)
VBF	28	31
$Z(ll)$H	75	62
$W/Z(jj)$H	78	86
Combined	**25**	**27**

- $B < 25\%$ @ 95% CL for invisible Higgs decays
- $B < 23\%$ if visible Higgs decays are included
  - more model independent
    - no assumption that vector boson couplings ≤ SM couplings

CMS Search for Invisible Decays

- Vector boson fusion (VBF):
  - large cross section
  - two jets plus large missing E_T
  - large background
- Gluon fusion:
  - 10 x larger cross section than VBF
  - search for mono-jet
- vector boson associated production:
  - small cross section
  - tag with vector boson that decays into jets, lepton or *b*-pairs



CMS Search for Invisible Decays

CMS-PAS-HIG-15-012

Channel	Observed (%)	Expected (%)
VBF	57	40
VH	60	69
ggH	67	71
Combined	**36**	**30**

- No significant excess of events above SM backgrounds
  - ⇨ Set upper limit on cross section normalized to SM cross section
    - < 36% @ 95% CL for invisible Higgs decays

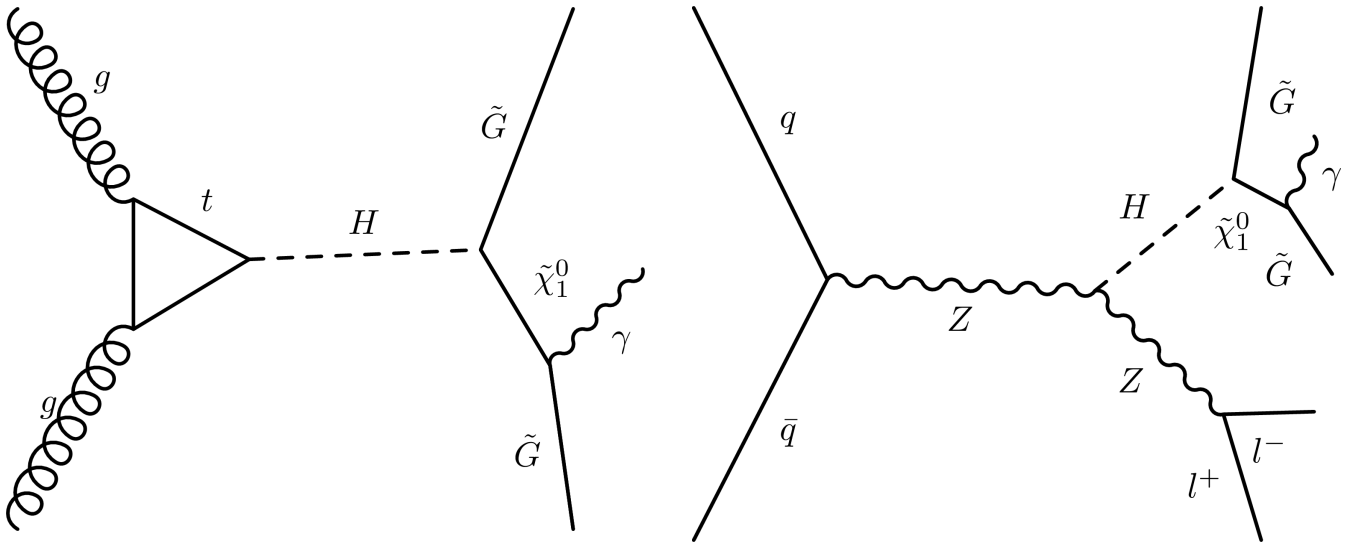
CMS Search for Invisible Decays

- Search for Higgs decays into invisible particles and photons:

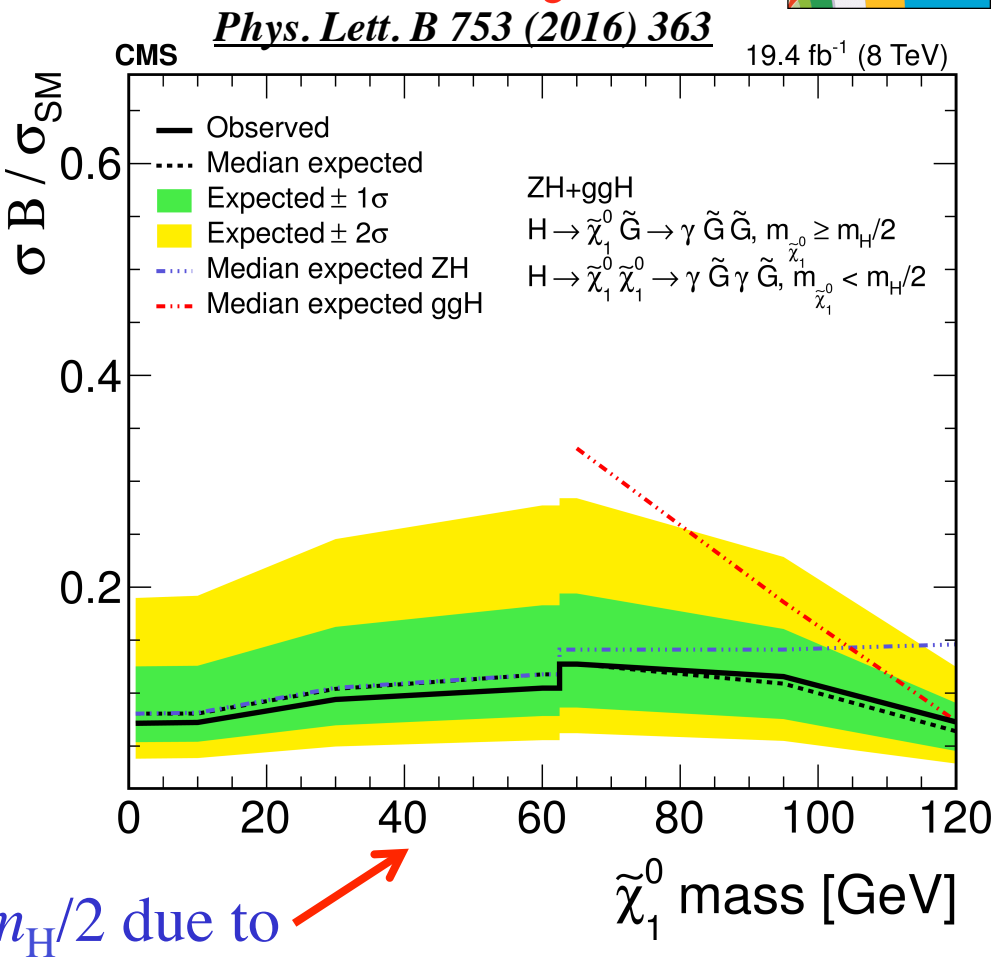
$$m_{\tilde{\chi}_1^0} > \tfrac{1}{2} m_H : \; H \rightarrow \tilde{\chi}_1^0 \tilde{G} \rightarrow \gamma \tilde{G} \tilde{G}$$

$$m_{\tilde{\chi}_1^0} < \tfrac{1}{2} m_H : \; H \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \gamma \tilde{G}$$

- Use Higgs produced in two mechanisms:



Search for Invisible Decays



- ggH has no sensitivity below $m_H/2$ due to missing E_T and photon P_T requirements
- Upper limit on branching fraction is ~10% @ 95% CL

Summary

- No evidence for lepton-flavor-violating Higgs decays:
  - $B(\mathrm{H} \to e\mu) < 0.036\%$
  - $B(\mathrm{H} \to e\tau) < 0.70\%$
  - $B(\mathrm{H} \to \mu\tau) < 1.51\%$
- No evidence for Higgs decays into new light bosons
  - presented here only two of the several searches by ATLAS/CMS
- No evidence for invisible Higgs decays: $B < 23\%$
- Results mostly based on ~20 fb^{-1} at 8 TeV
- Will reach new level of sensitivity to new physics at 13 TeV
  - cross section increases by 2.3x
  - expected to collect 100 fb^{-1} in three years

- CMS paper on H → μτ has received 66 citations…

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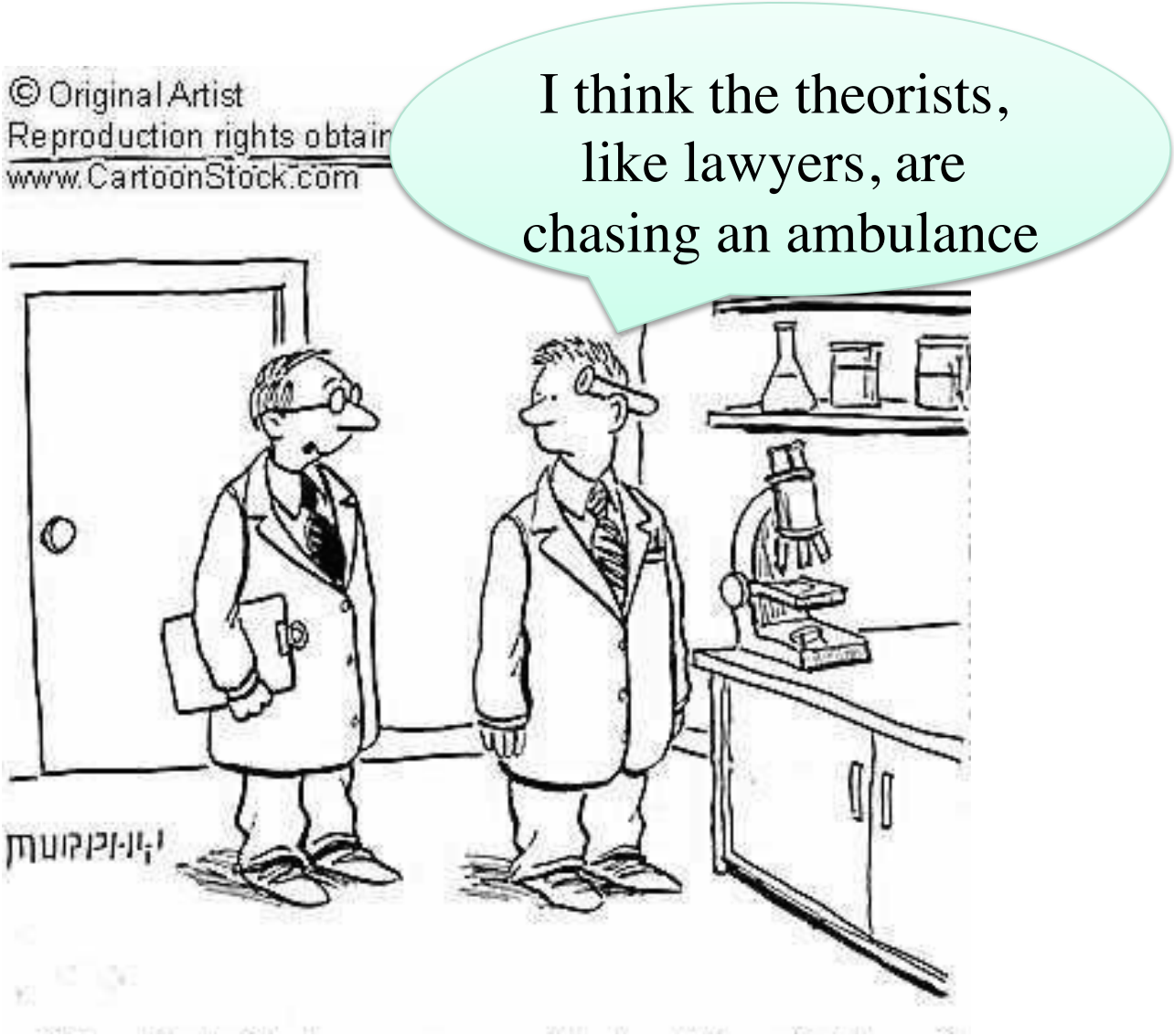

- CMS paper on H → μτ has received 66 citations…