Non-standard Higgs Interactions & Decays

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Invisible
Exotic
Hidden valley

Introduction

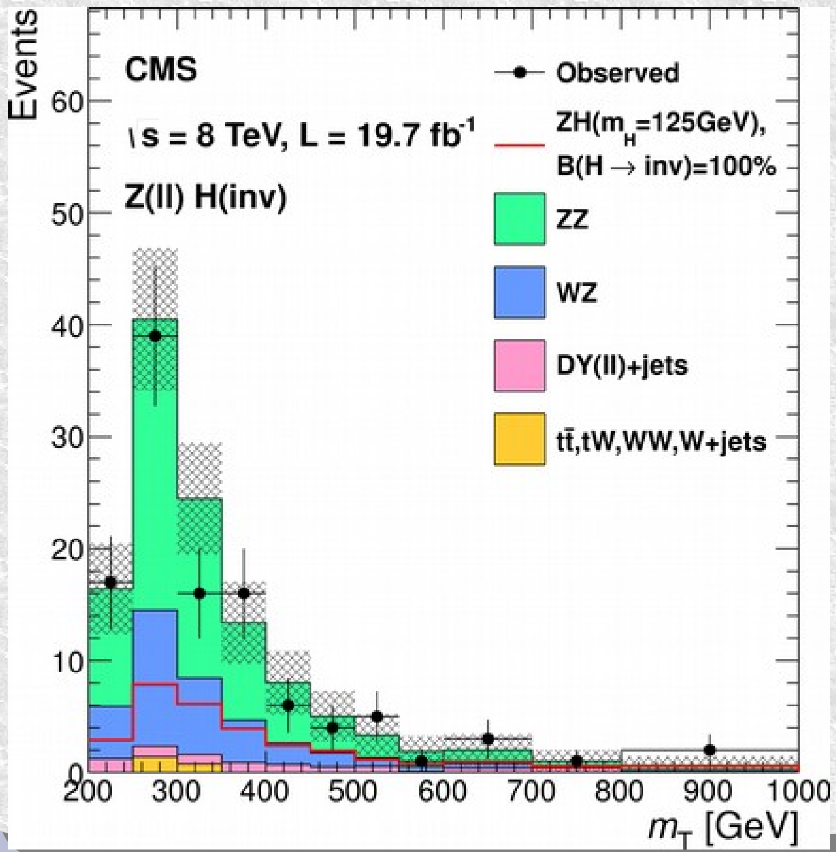
- The Higgs width is very narrow
  - 1000x less than the W,Z
  - Plus the coupling is unique
  - There icould be unknown weakly coupled particles in Higgs decay.
- The analyses discussed here are largely Higgs decay studies
- They benefit from the increase in Higgs σ at 13TeV
  - But with a factor 2 or 3
  - So 2015 data is relatively minor c//f 2012
- Only one result is shown based on 2015 data.

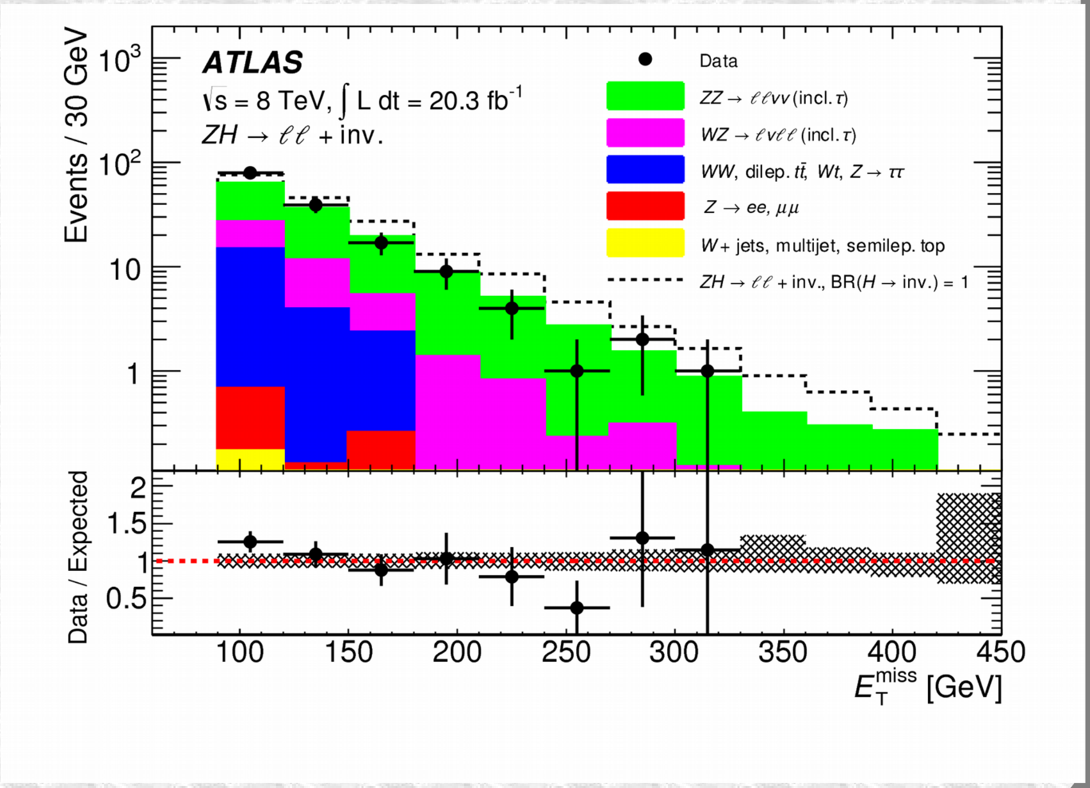
Higgs to invisible: direct

- Dark matter is the most obvious target
- Direct observation means tagging a Higgs production along with the invisible decay
  - ggF is patently impossible
    - i.e. someone shgould work on it!
  - ttH has been suggested in phenomenology, but no experiental results
  - VH gaves a clean experimental signature but low rate
    - Z→ll or W/Z→qq
  - VBF gives the best LHC results

ZH→ invisible

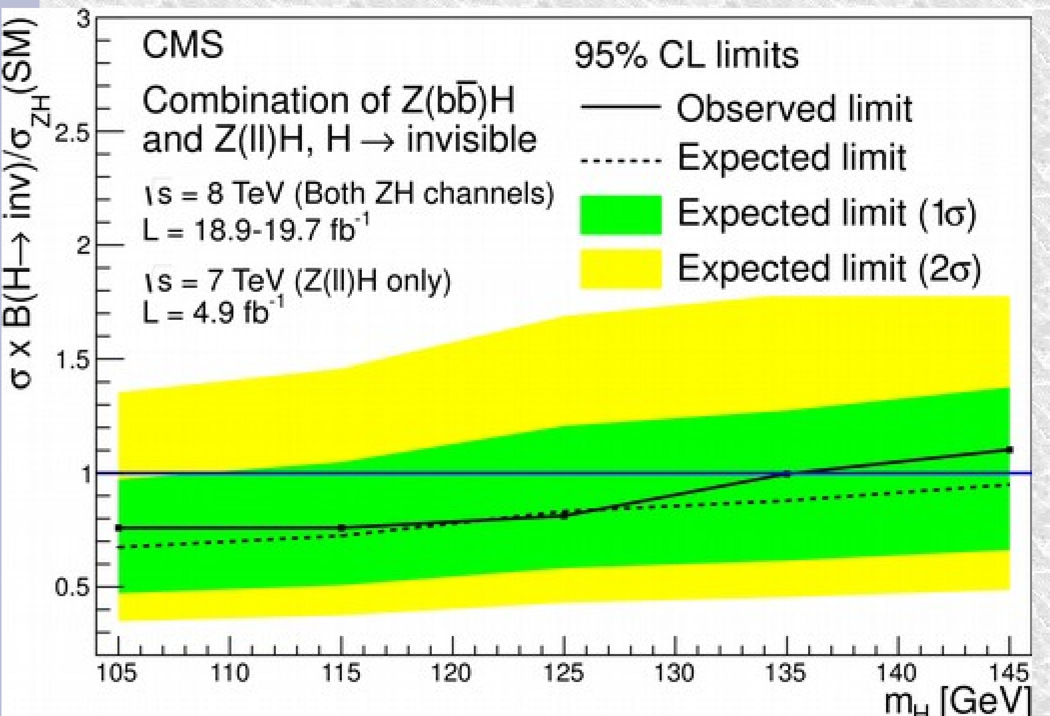
- Z→ll gives clean signal and easy trigger
  - Irreducible background of ZZ→llυυ dominates
  - Similar kinematics of signal and background
  - Low MET threshold helps to maximise rate

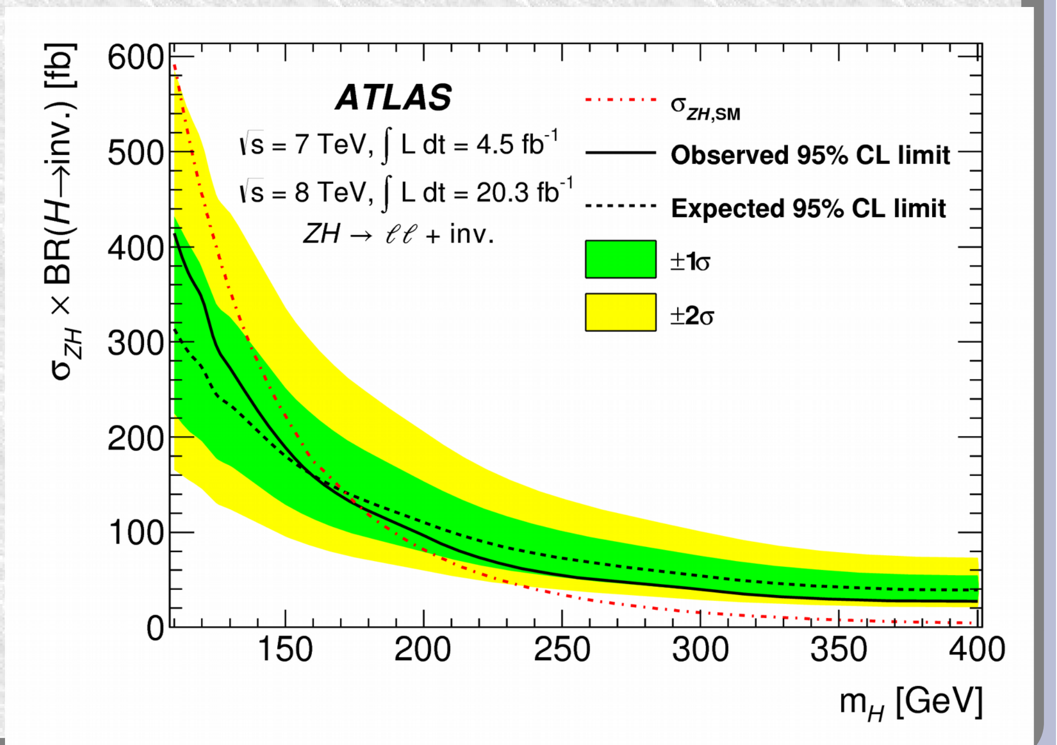




ZH→ ll+invisible results

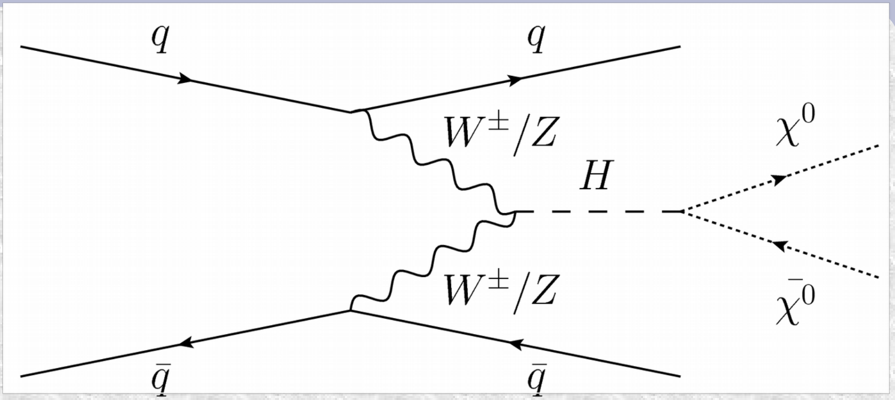
- Nothing surprising seen
- ATLAS set limits of 75% obs (62%) expected
- CMS limits: 83% obs (86% expected)





Higgs to invisible: VBF

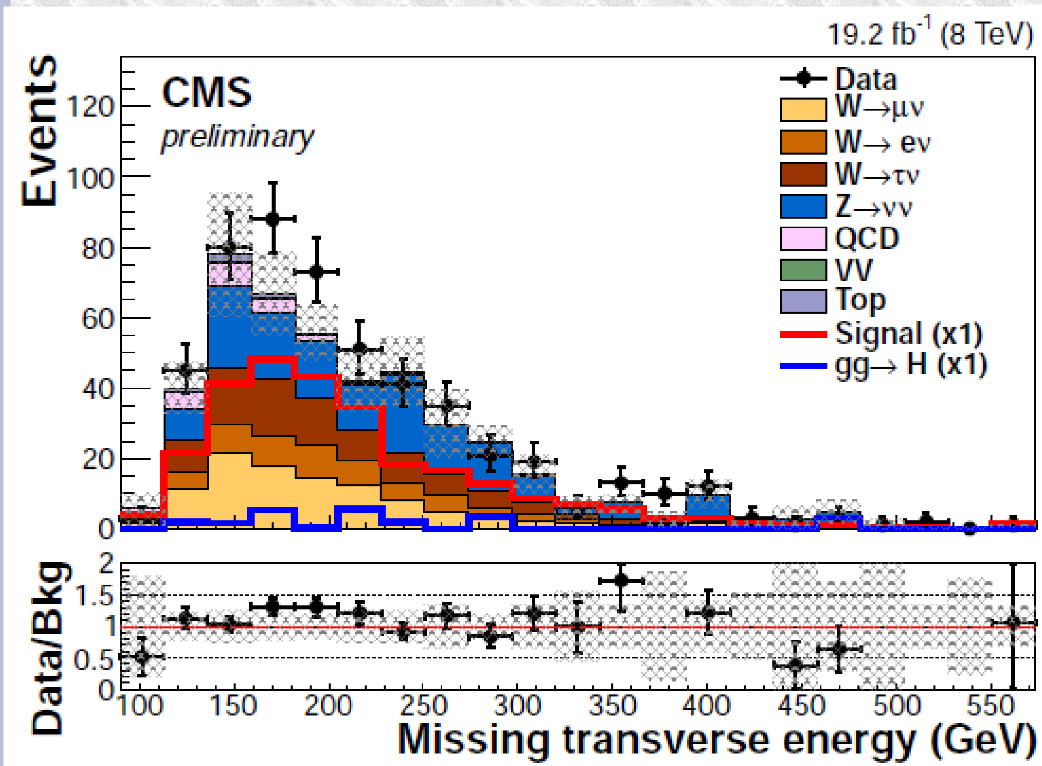
- VBF was essential for the $H \rightarrow \tau\tau$ discovery
  - The high-mass forward jet pair gives an improved s/b

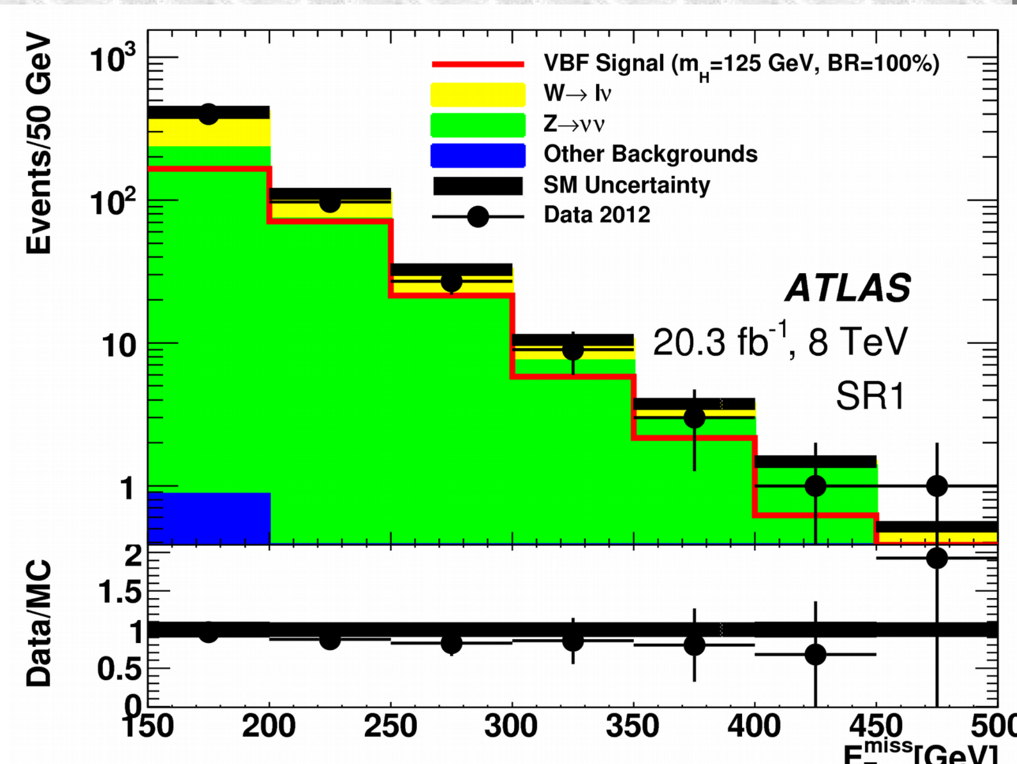


- Tagging the jet pair allows a search for the invisible Higgs decay
  - Much higher cross-section than ZH
  - But not as clean a tag

VBF H to invisible

- Jet pair mass > 1.0TeV (CMS, ATLAS main signal)
- Delta eta cut on tag jets
- Observed (expected) 0.28 (0.31) in ATLAS
- Observed (expected) 0.49 (0.65) in CMS

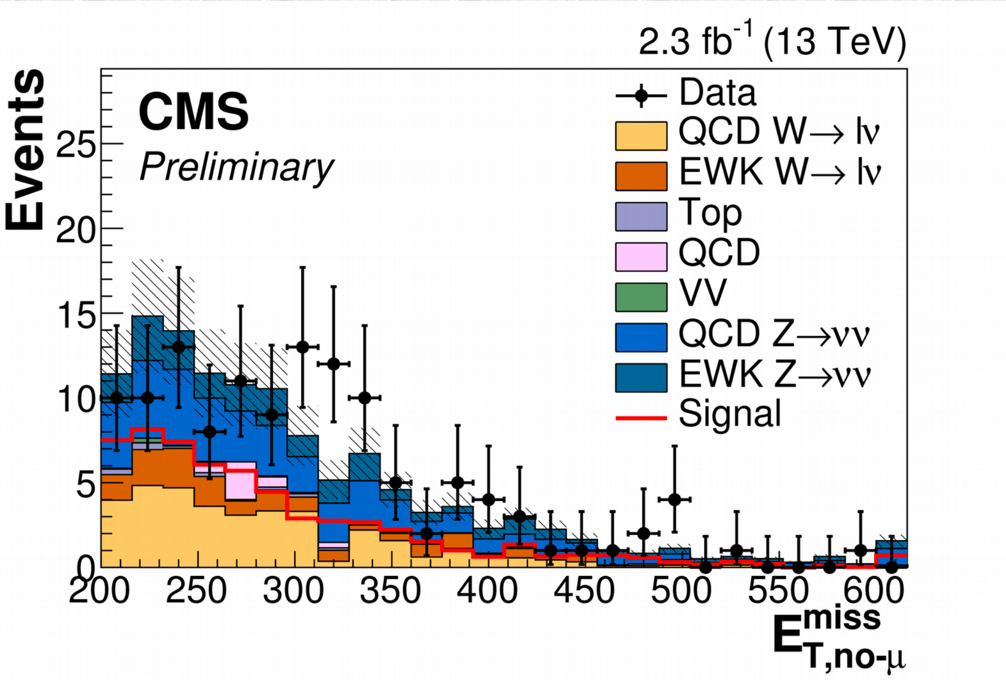




CMS-PAS-HIG-16-0009

CMS VBF H to invisible @ 13 TeV!

- 8 regions of p_T and jet pair mass used for VBF
- Limit set at 69% (62% expected)
  - Brings CMS combined to 32%
- Compare ratios of accepted σ at 13 and 8 TeV
  - Generally below PDFs – preliminary?



	8 TeV	13 TeV	ratio
Z→νν	158	62	3.2
W→ lν	255	51	1.7
Top/qcd/VV	26	6	1.9
Total	439	119	2.2
ggH	23	5.4	1.9
VBF H	273	53.5	1.7

H to invisible summary

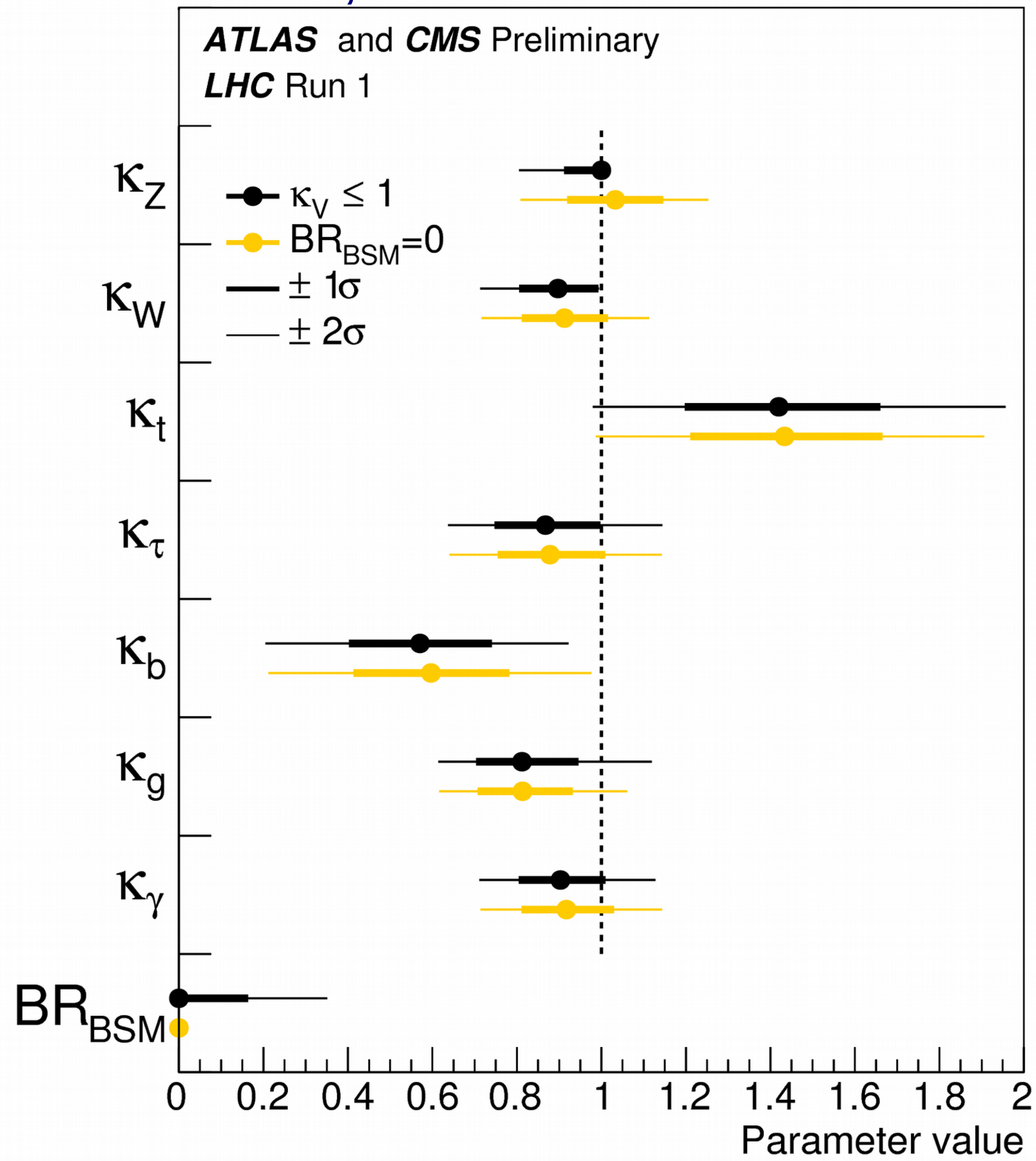
	ATLAS	CMS
ZH	65%	75%
VBF	28%	57%

- Clear lead for the VBF production modes
  - But in run 2 VBF may suffer from pileup
  - And it has harder systematics
    - Can we link W+jets and Z+jets as a control regions?
    - Production kinematics is not identical
- My guess is ZH will be relatively more inportant
- This is a vital search – we have much better evidence for DM than most many in this talk

Higgs to invisible/BSM: indirect

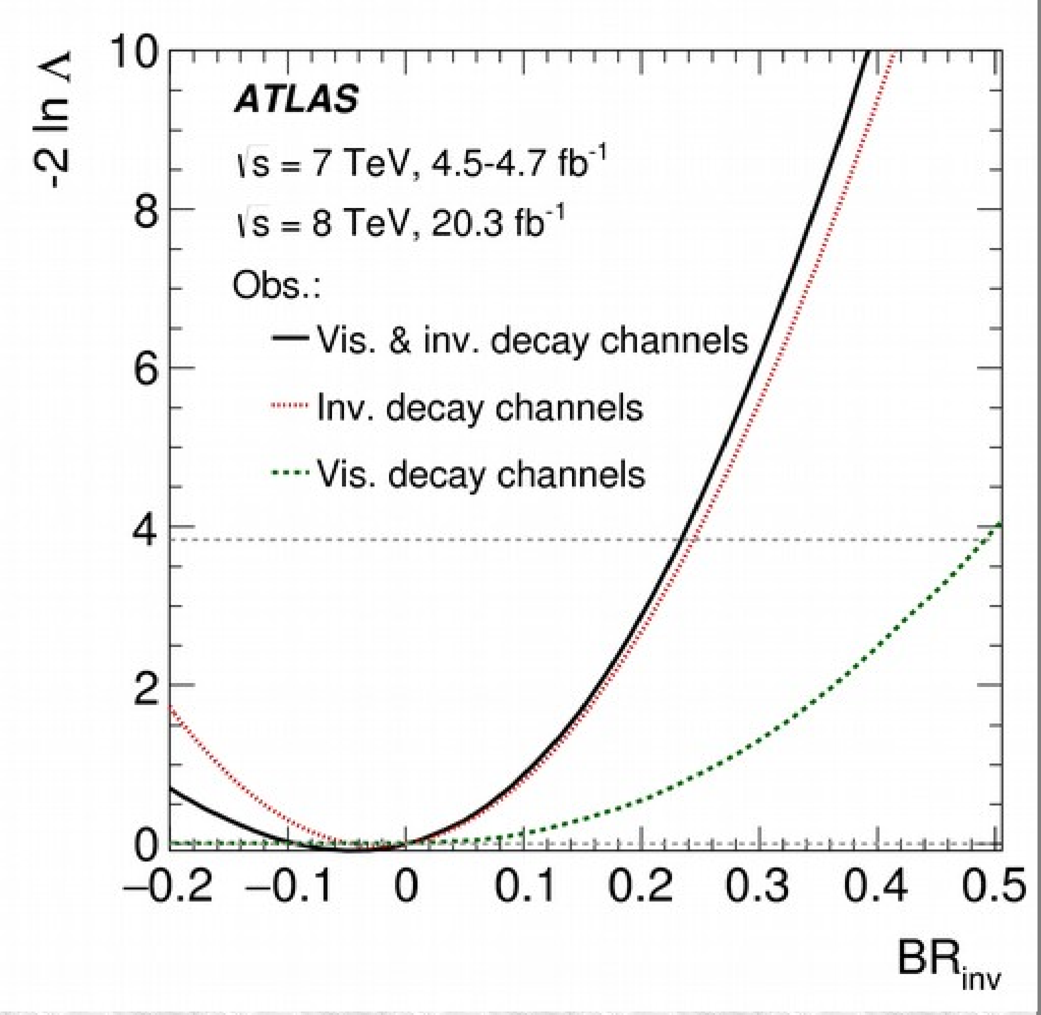
ATLAS-CONF-2015-044, CMS-PAG-HIG-15-002

- Consistency of the Higgs decays in 8 parameter fit, with:
  - κ_V constrained < 1
  - Or Br_{BSM}=0
- It is impressive how *in*sensitive fit is to this
- Upper limit on BSM decay is 0.34 @ 95% CL



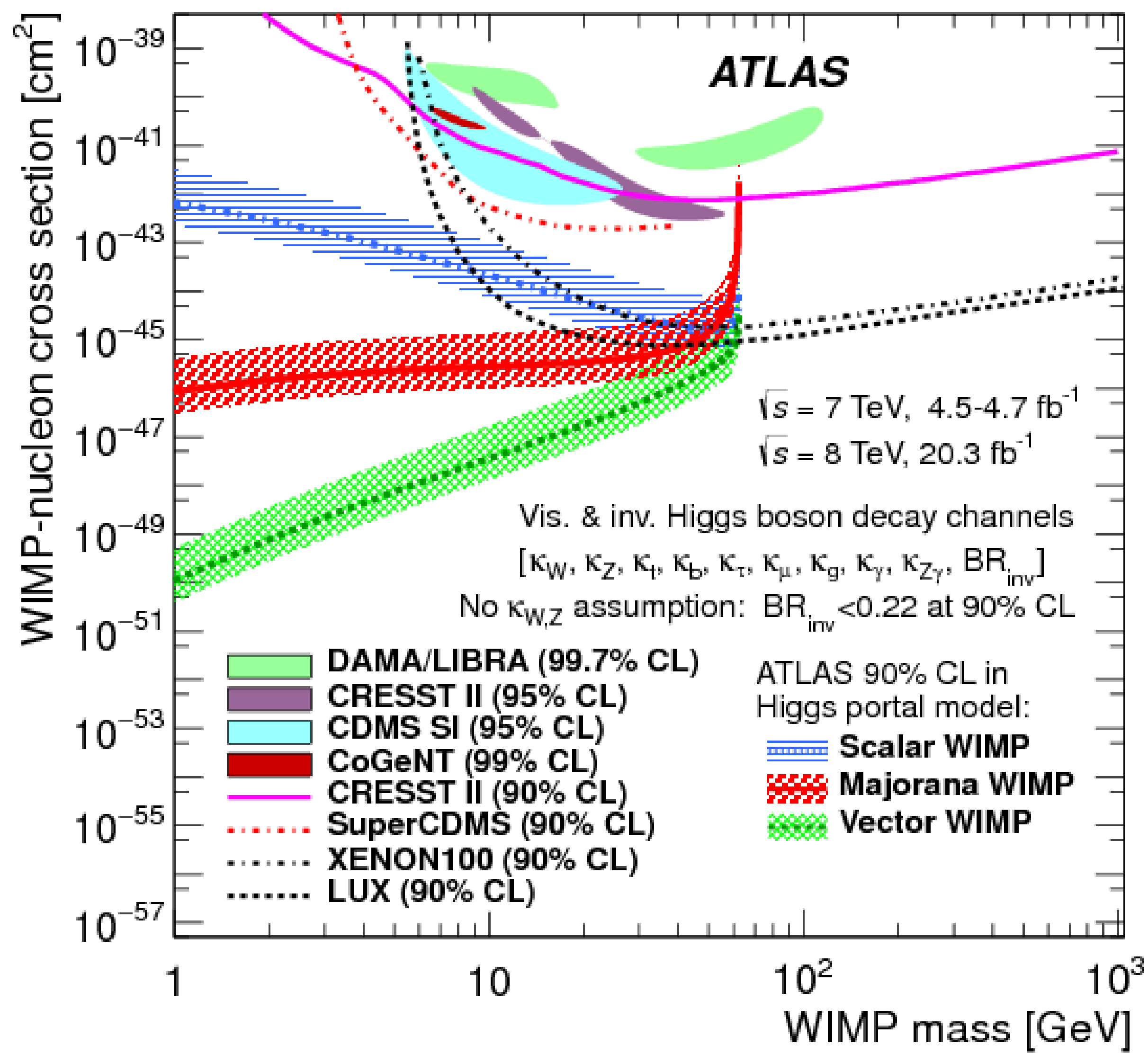
Combined invisible limit

- Direct and indirect constrains on invisible higgs are independent
- Combine for best sensitivity
- Ading visible decays moves BR limit from 25% to 23%
- Plus it is arguably less model depedent – most Brs taken from data,



Higgs invisible v Dark Matter

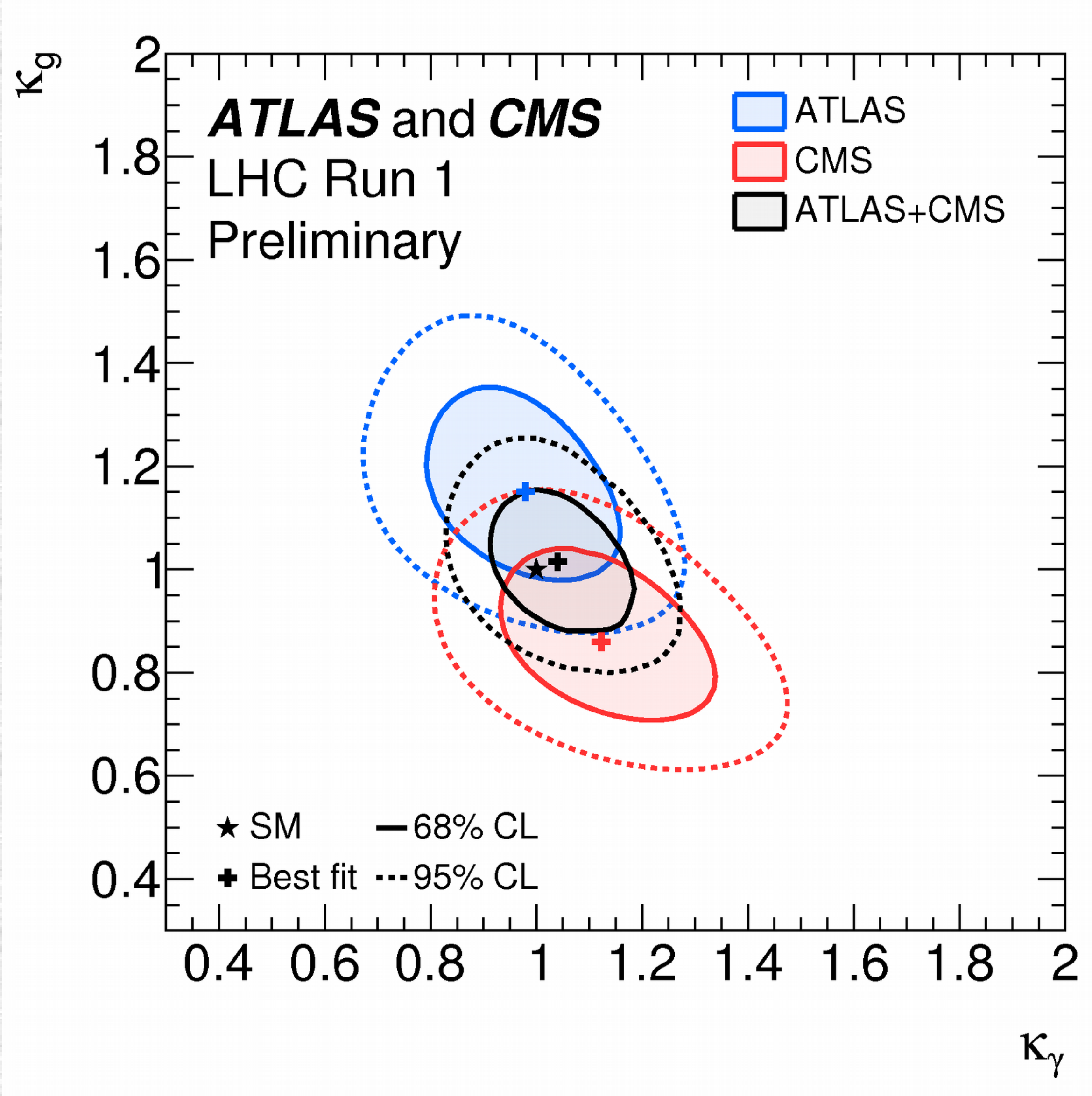
- Interpret dark matter in a 'Higgs portal' model
  - Higgs only SM paricle coupled to DM
- The Spin Independent is very close to this
- Strong constraints for $m_\chi < m_H/2$
  - But χ dependent



Virtual Higgs decays

ATLAS-CONF-2015-044, CMS-PAG-HIG-15-002

- Search for BSM Higgs particle by assuming all SM but allowing arbitrary strength on Higgs loops
  - Despite early γγ final hits the SM nail
- Not a trace of new particles here
  - 4th chiral fermion generations rarely considered now



Next: Visible decays

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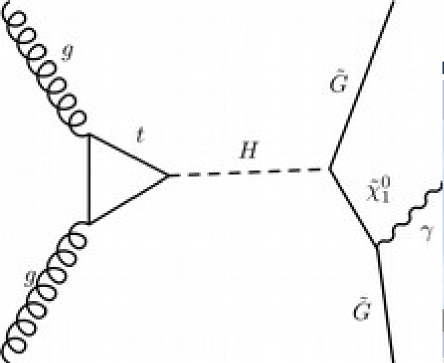

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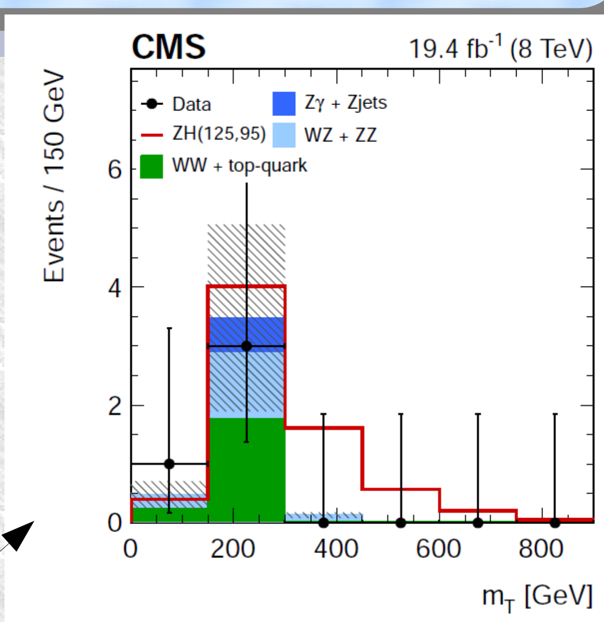
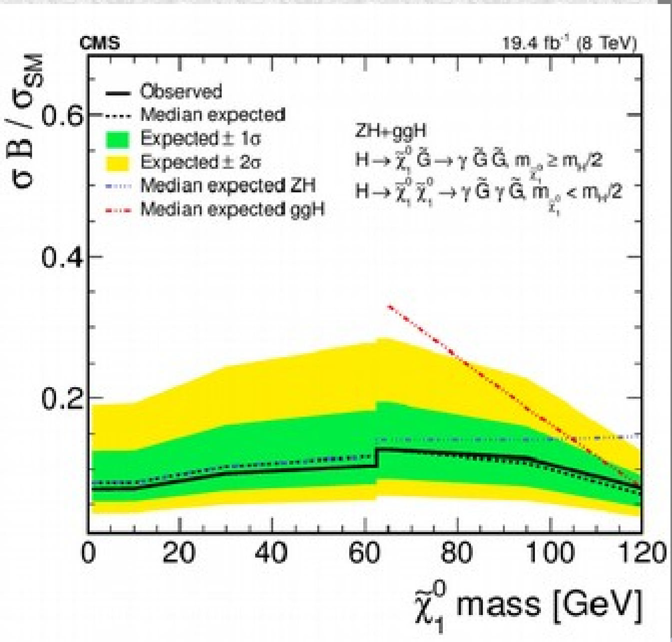
H to γ(s) plus E_T^{miss}

- CMS Searched for a decay to 2 gravitinos and 1/2 γ
  - Decay to pairs of χ_1^0 possible
- Gluon fusion selection
  - E_T^{miss}>40, E_t^{γ}>45 GeV
  - SUSY/Mod.Indep. Variants
- ZH selection
  - p_T^Z>60, E_t^{miss}>60, E_t^{γ}>20 GeV
  - Study mT of Z,γ & E_t^{miss}
- No sign of signal,
- limits are extracted as fn of ET
- e.g.assuming light gravitino

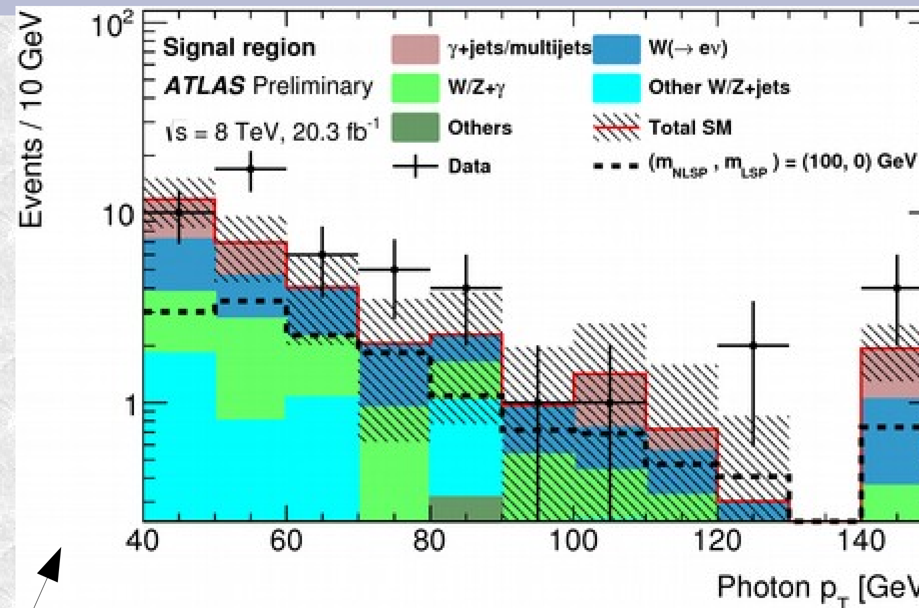


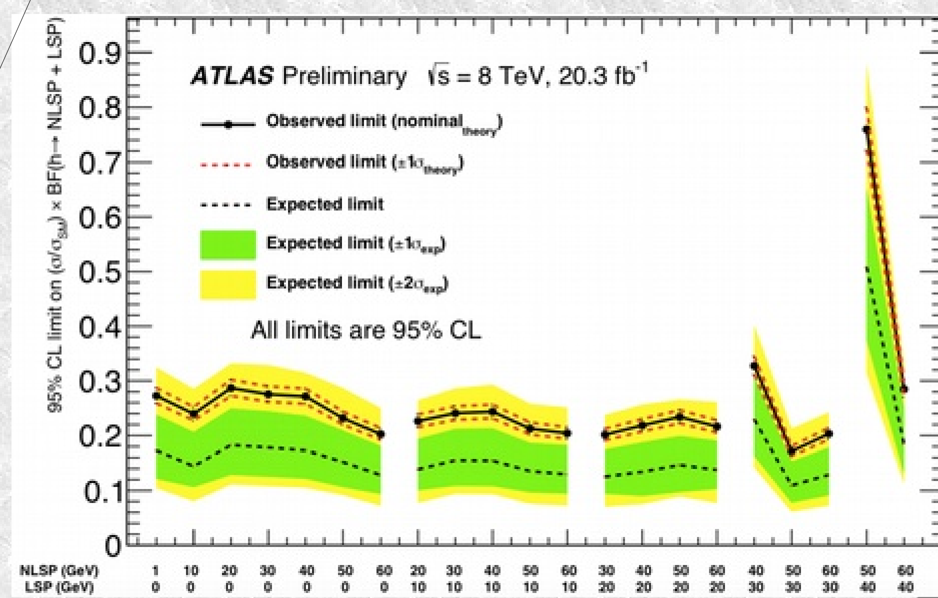


ATLAS-CONF-2015-001

Photon(s)+E_T^{miss}, VBF mode

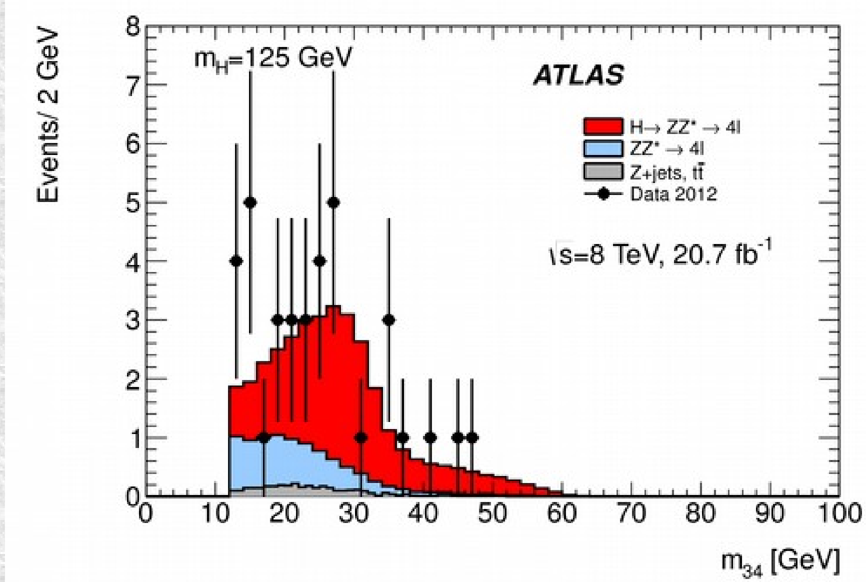
- ATLAS looked in VBF selection
- Trigger on
  - γ>43GeV
  - E_T^{miss} > 60 GeV
- m_{jj}>600, $|\Delta\eta|$<4 VBF tag
  - At most 1 central jet
  - $\Delta\varphi(\gamma, E_t^{miss})$<1.8
  - Diphoton region also used
- Single γ has 1.1σ excess
- Limits on $H \rightarrow (\chi_1^0, G)$ 20% or looser

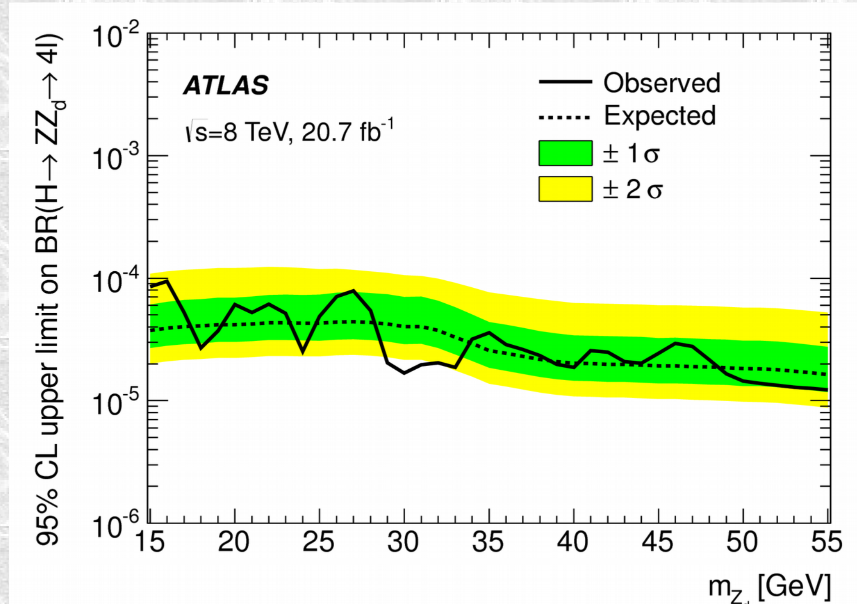




Dark Photons ArXiv:1505.07645

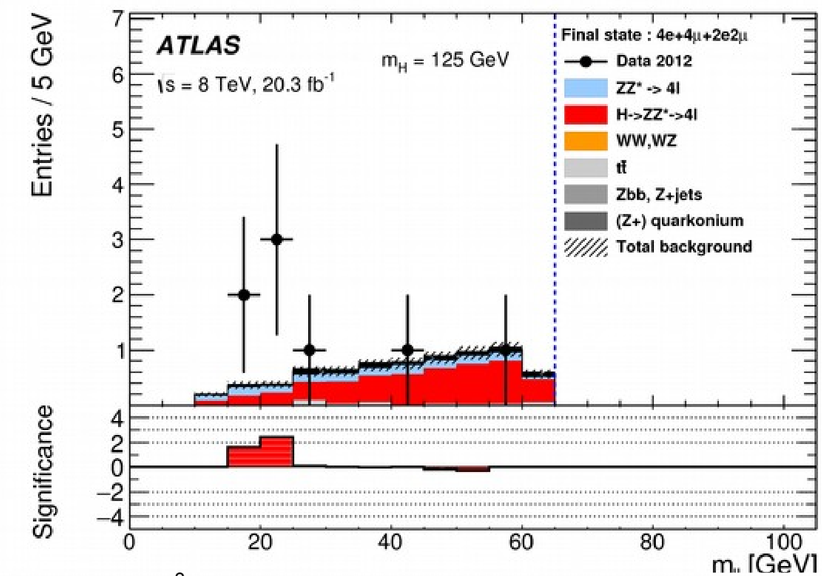
- Dark photon, no EM coupling
  - Might mix with the Z
  - It can decay to lepton pairs
- So $H \rightarrow llll$ might contain $H \rightarrow ZZ$, ZZ_D and/or $Z_D Z_D$ modes
  - Target ZZ_D by using existing search: use m_{34} offshell pair
  - No evidence for Z_D
  - $Br(H \rightarrow ZZ_d \rightarrow llll) < 10^{-4}$
    - $15 < m_{Zd} < 55$

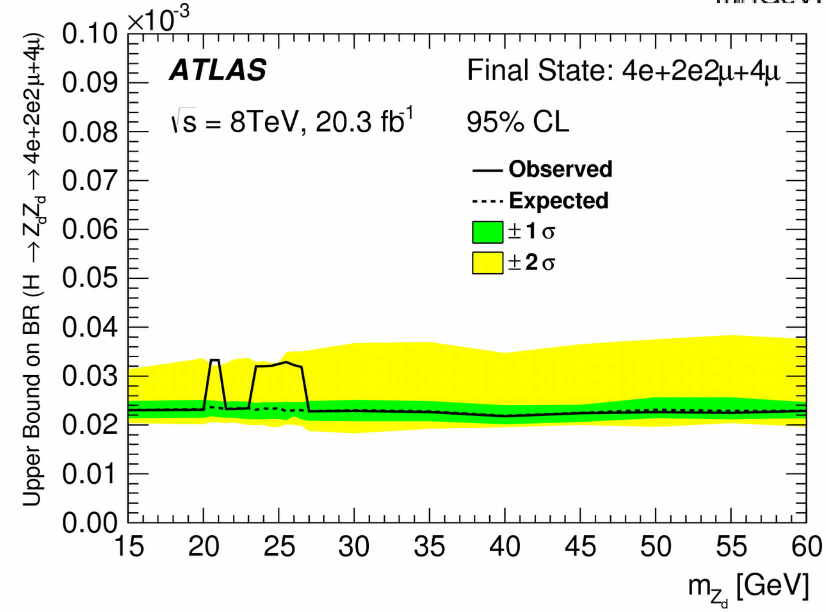


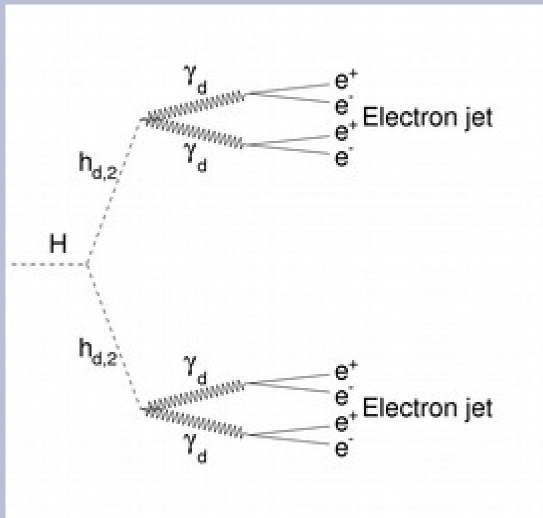


Dark Photons: $Z_d Z_d$

- If target if pair productionb of Z_d start from 4l search, but relax $m_{12} \sim m_Z$
- Search mass spectrum for $Z_D Z_D$ modes
  - 4 events with both pairs below 62.5 GeV
- Constraint of equal pair masses has just 2 events survive
  - $Br(H \rightarrow Z_d Z_d \rightarrow llll) < 3\times10^{-4}$
    - $15 < m_{Zd} < 60$



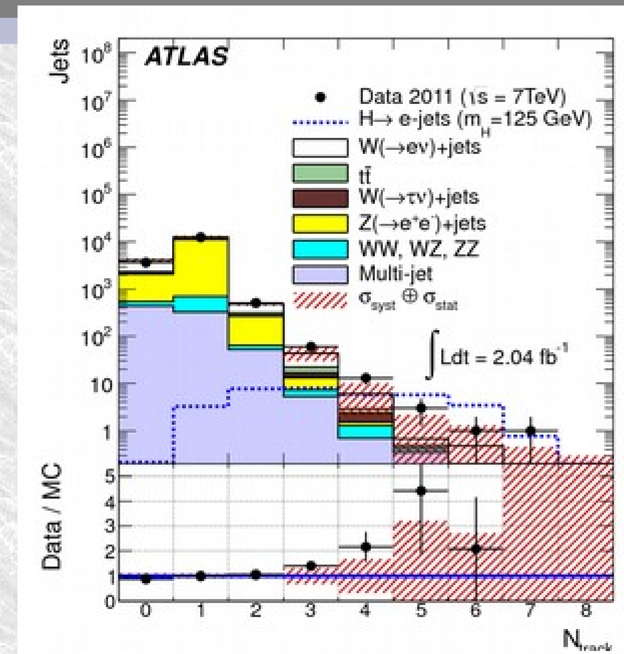


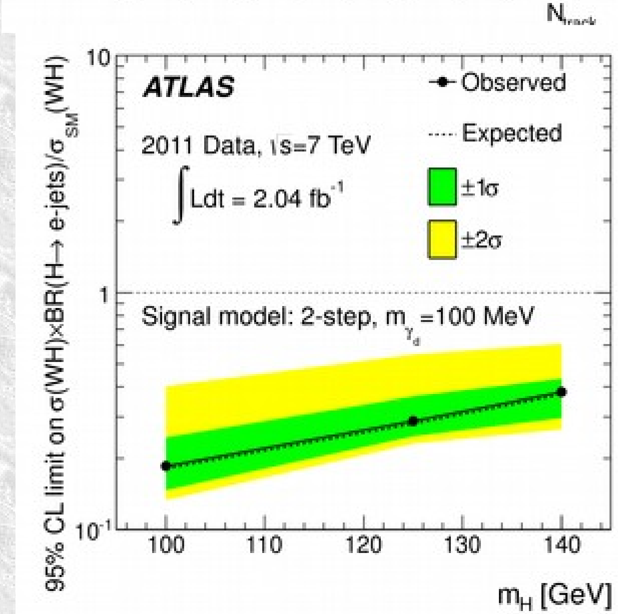


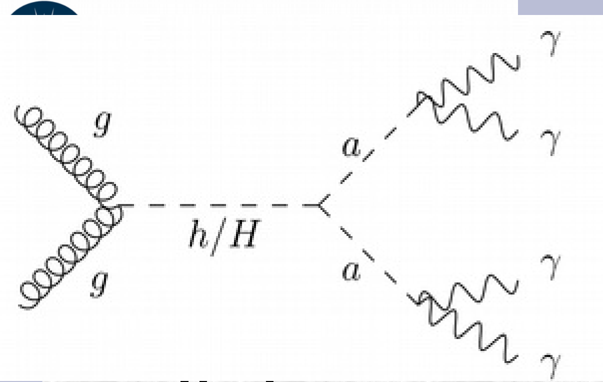
http://arxiv.org/abs/1302.4403

Higgs to electron jets

- The dark sector particles do not have to decay directly to SM
  - This model proposes a chain decay
  - With 2 or even 3 steps
  - Dark photons finally giving ee pairs.
- Analysis uses WH signature
  - $W \rightarrow l\nu$
  - Then 2 jets with >99% EM energy
    - But large numbers of tracks
- Not re-checked with >2fb^{-1}!

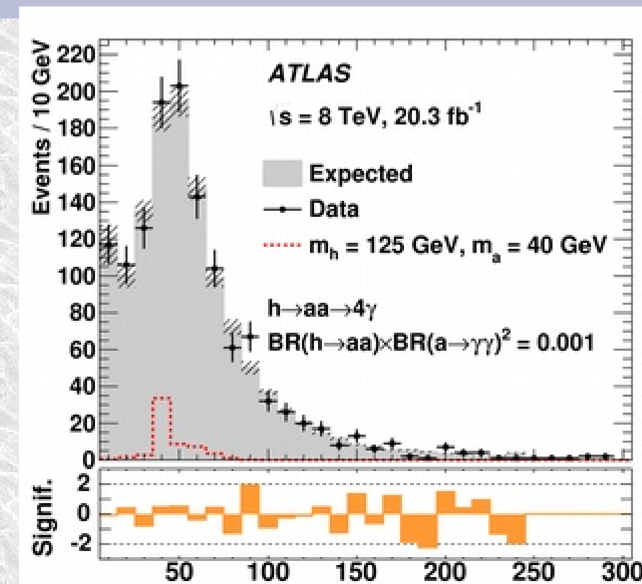


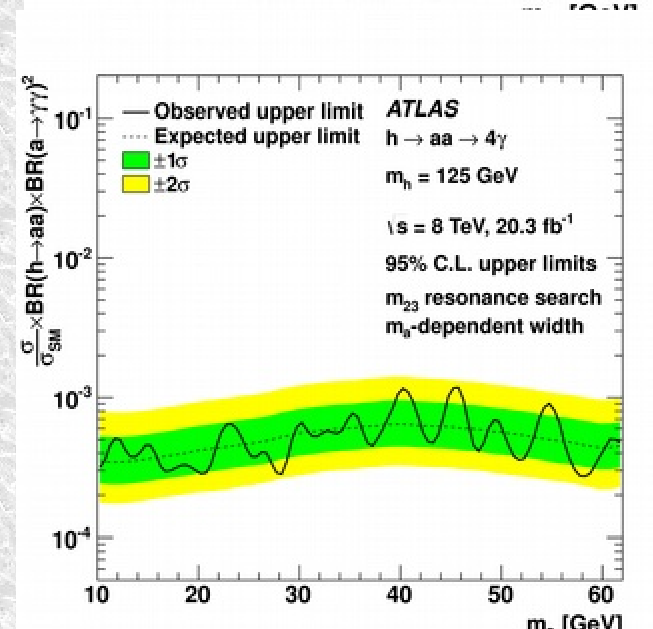




$h \to aa \to \gamma\gamma\gamma\gamma$ arXiv:1509.05051v1

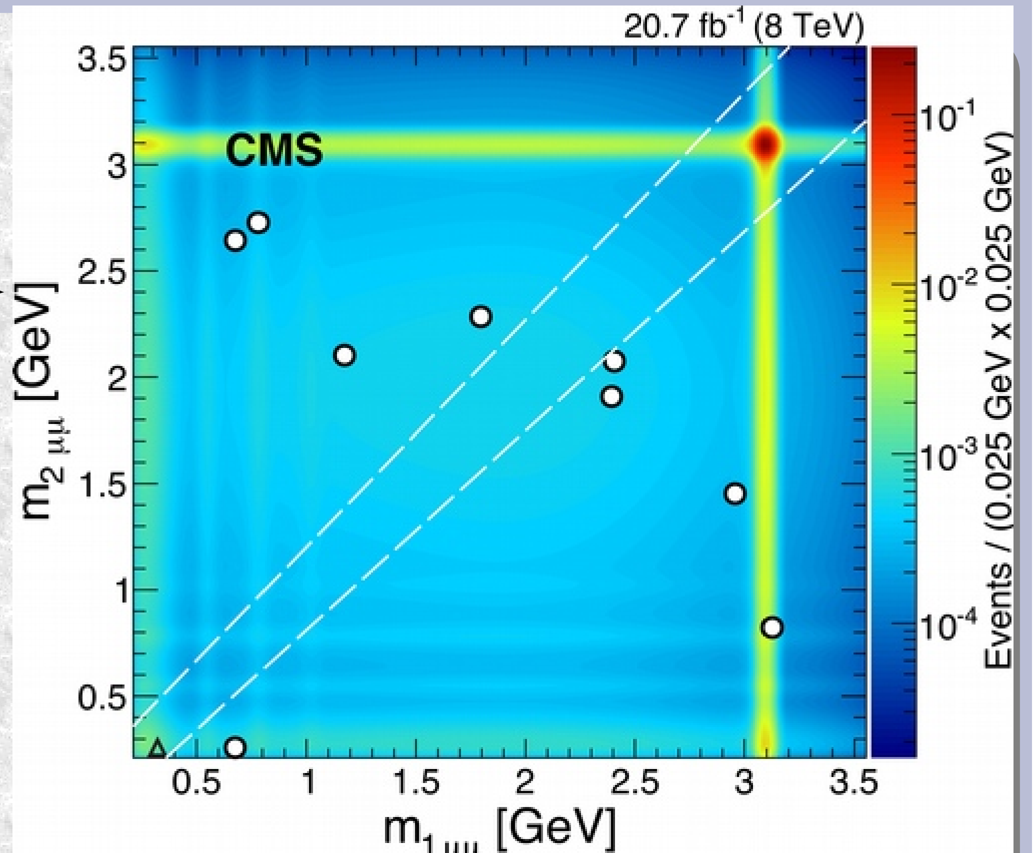
- A light nMSSM a might be produced in $h \to aa$
  - With $a \to \gamma\gamma$ a possible signature
- Select 3 photons
  - $p_T > 17$ GeV for lowest
  - Gives efficient signal reconstruction
    - 4th photon likely soft
- Total 3γ rate sets limits
  - Improve using m_{23} and vary m_a
  - $Br(H \to aa) * Br(a \to \gamma\gamma)^2$ below 10^{-3}
- Is it worth trying 4 photons?

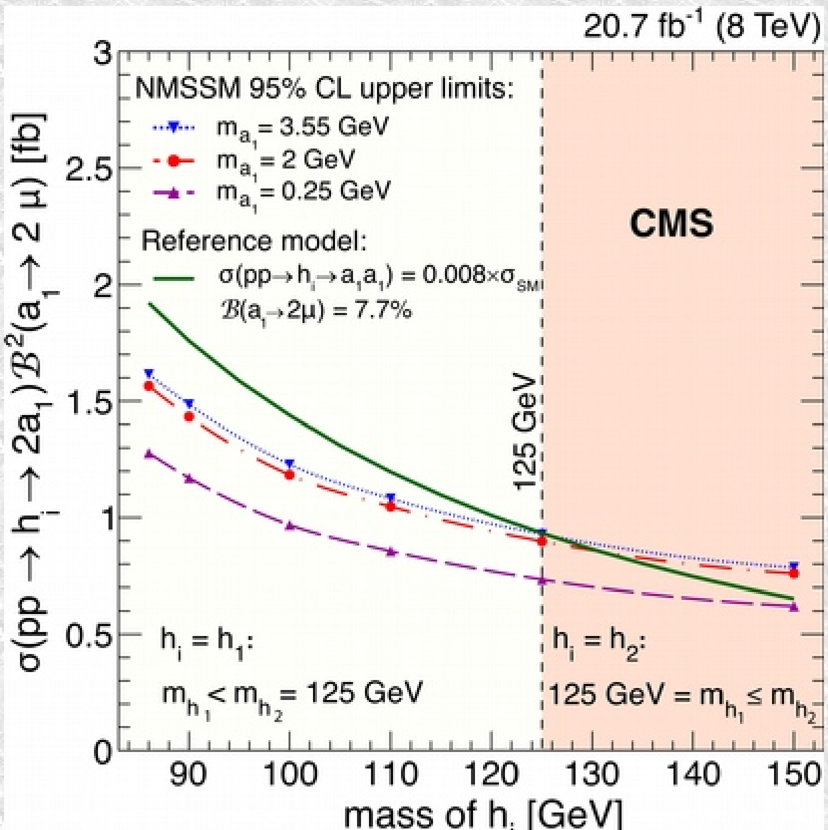




$h \rightarrow aa \rightarrow \mu\mu\mu\mu$ arXiv:1506.00424

- CMS consider $a \rightarrow \mu\mu$
- In $2m_\mu < m_a < 2m_\tau$ window
- No equal mass events

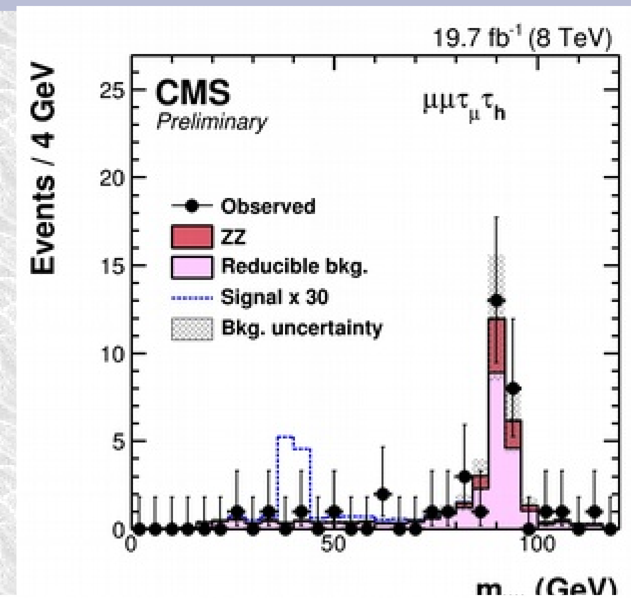


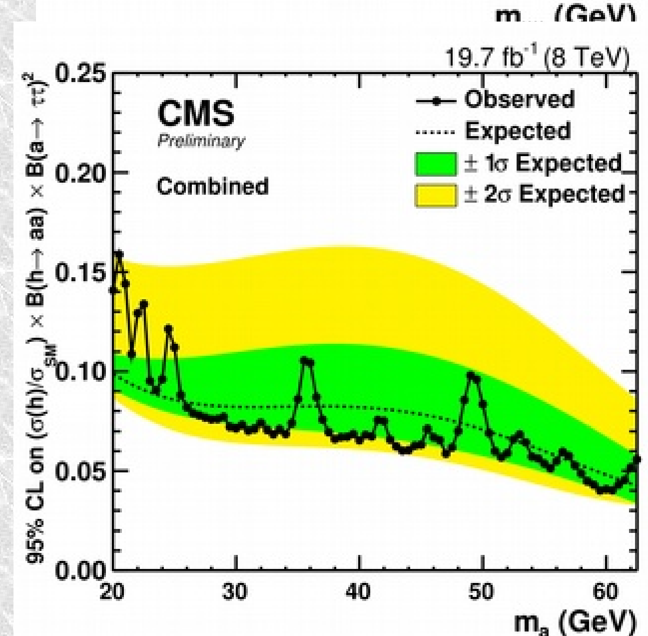


- Limits have little dependence on m_a

$h \rightarrow aa \rightarrow \mu\mu\tau\tau$

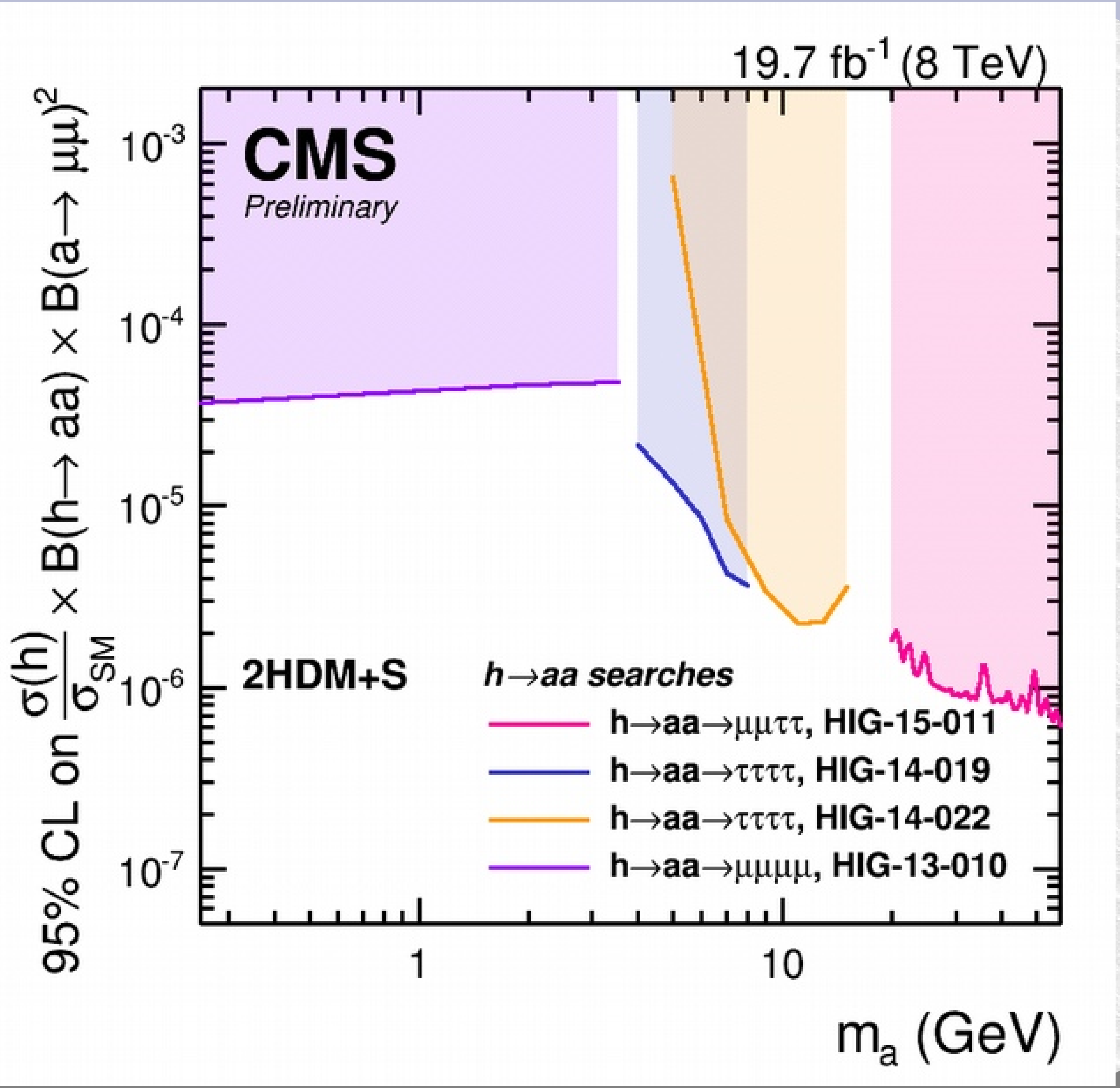
- If $m_a > 2m_\tau$ the τ decay opens
- Analsis uses good μμ mass to identify peak
  - μ p_T>18 (1st) & 5-9 (2nd)
- Identify τ in e/μ/had modes
  - p_T>5-15 GeV
- 19 events observed, 20 expected
- Older results looked for 4-tau mode – no sign of signal





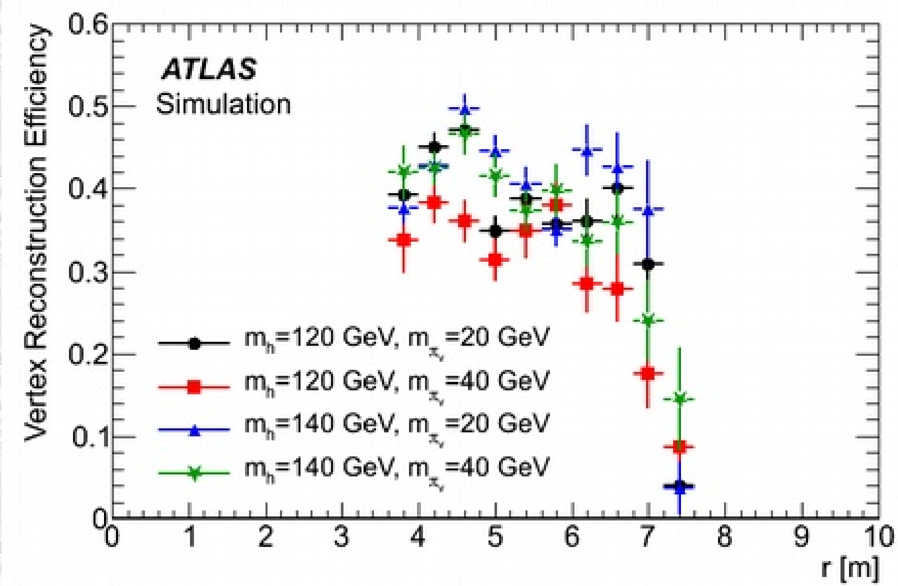
Combining a→μμ and a→ττ

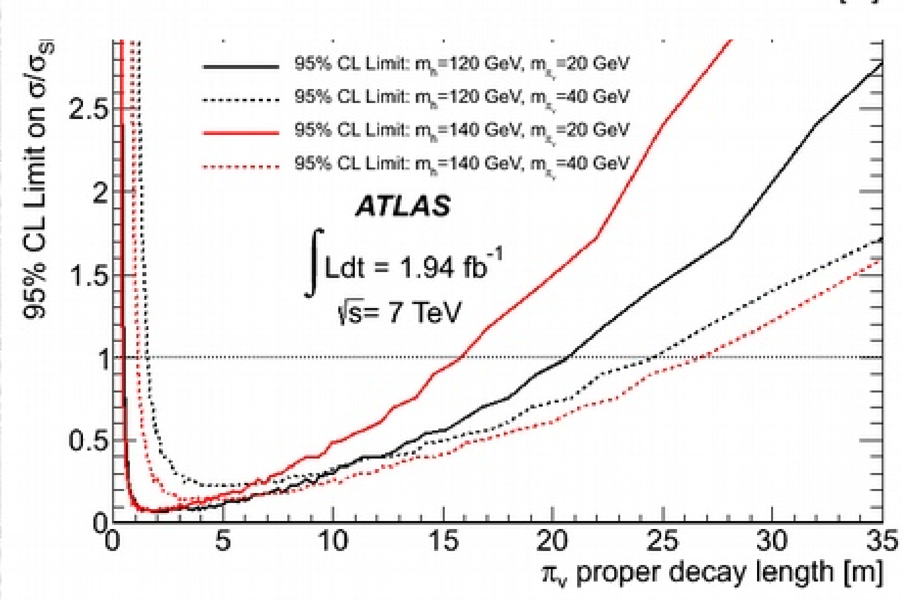
- Combination needs relative rate
  - Here assume given by mass
- Upsilon region is covered by 4τ
- J/ψ and 15-20 not covered
- μμbb mode is also searched for



Higgs to long-lived particles

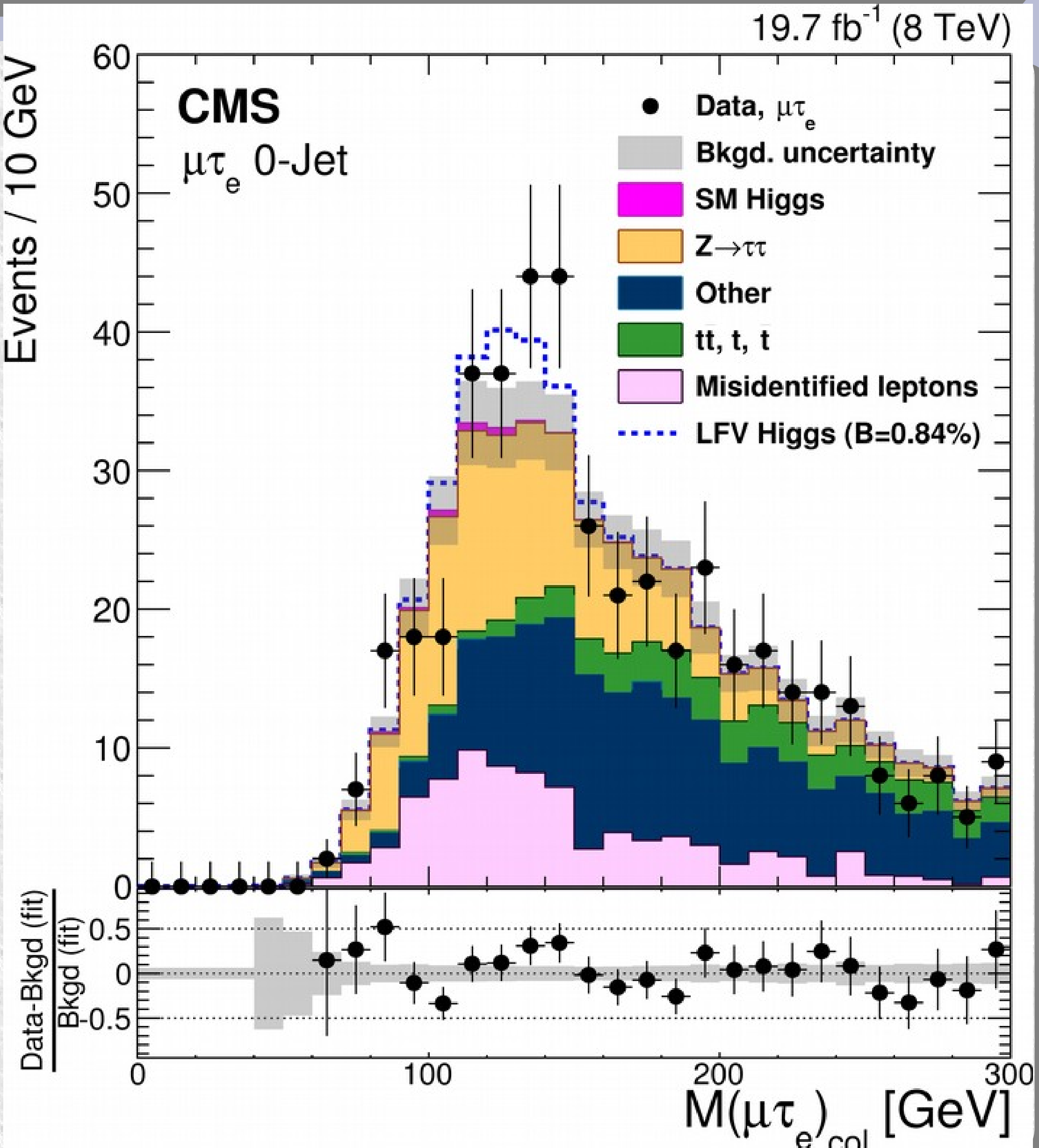
- Hidden sector coupled very weakly to SM?
  - $H \rightarrow \pi_v \pi_v$ with long lived π_v
    - Decaying to bb, cc, ττ
- Here ask for decay in muon spectrometer
  - 4-7m from beam position
  - Veto jets
  - Request 2 collinear vertices
  - 0 events seen
- Limits 10% br at best
  - This is $2 fb^{-1}$ at 7 TeV
- Is metastable a priority?





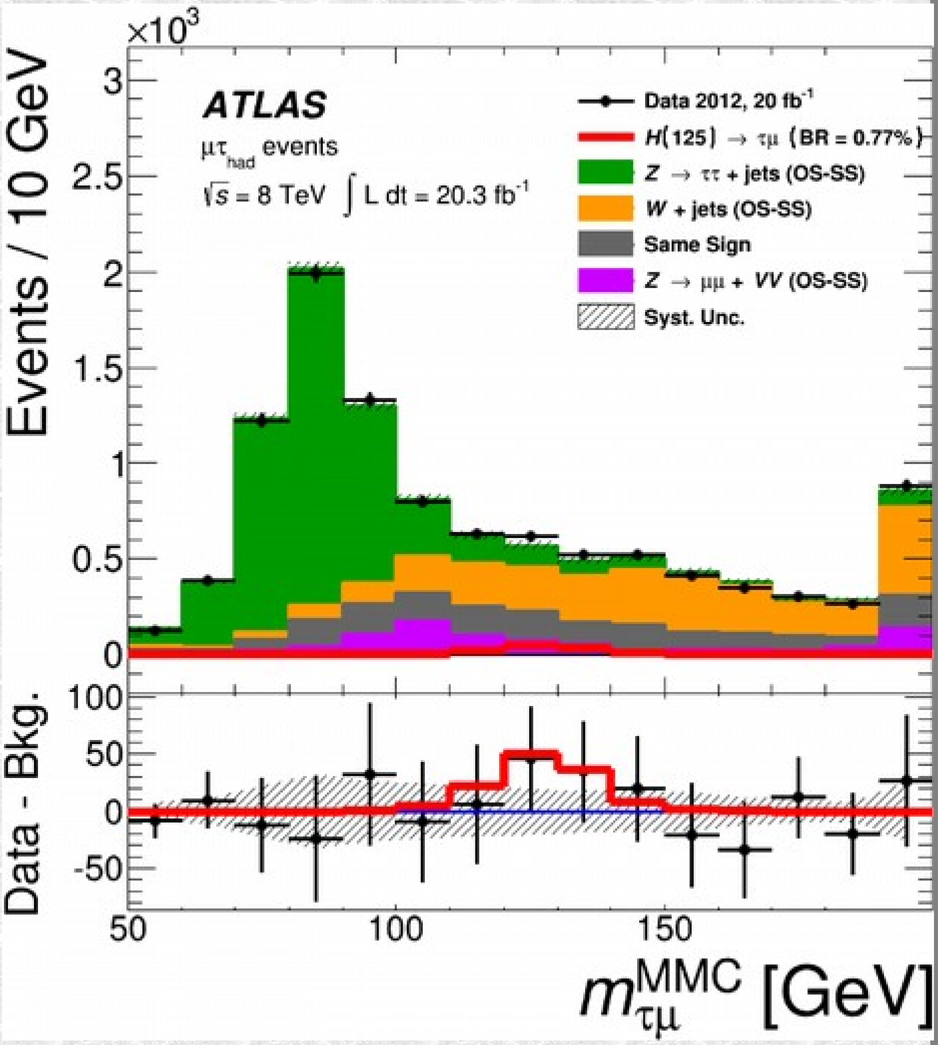
Higgs lepton flavour violation

- $H \rightarrow \mu\tau$ from CMS
  - 0/1/2 jets x τ_e/τ_h
- The most powerful is 0 jets x τ_e
  - Also has the most significant excess
  - Shown right
- Br is 0.84±0.38%



ATLAS LFV

- $H \rightarrow \mu\tau_h$ only
  - Divided into two caregories of mT<,>40 GeV
- They are combined in the plot right:
- Br is 0.77±0.62%
- Remember CMS found the most powerful is 0 jets x τ_e

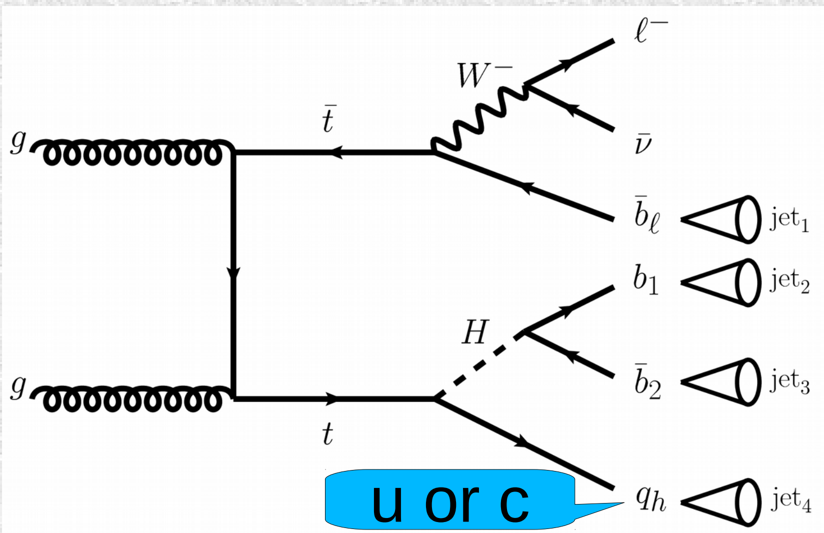


H→τμ LFV

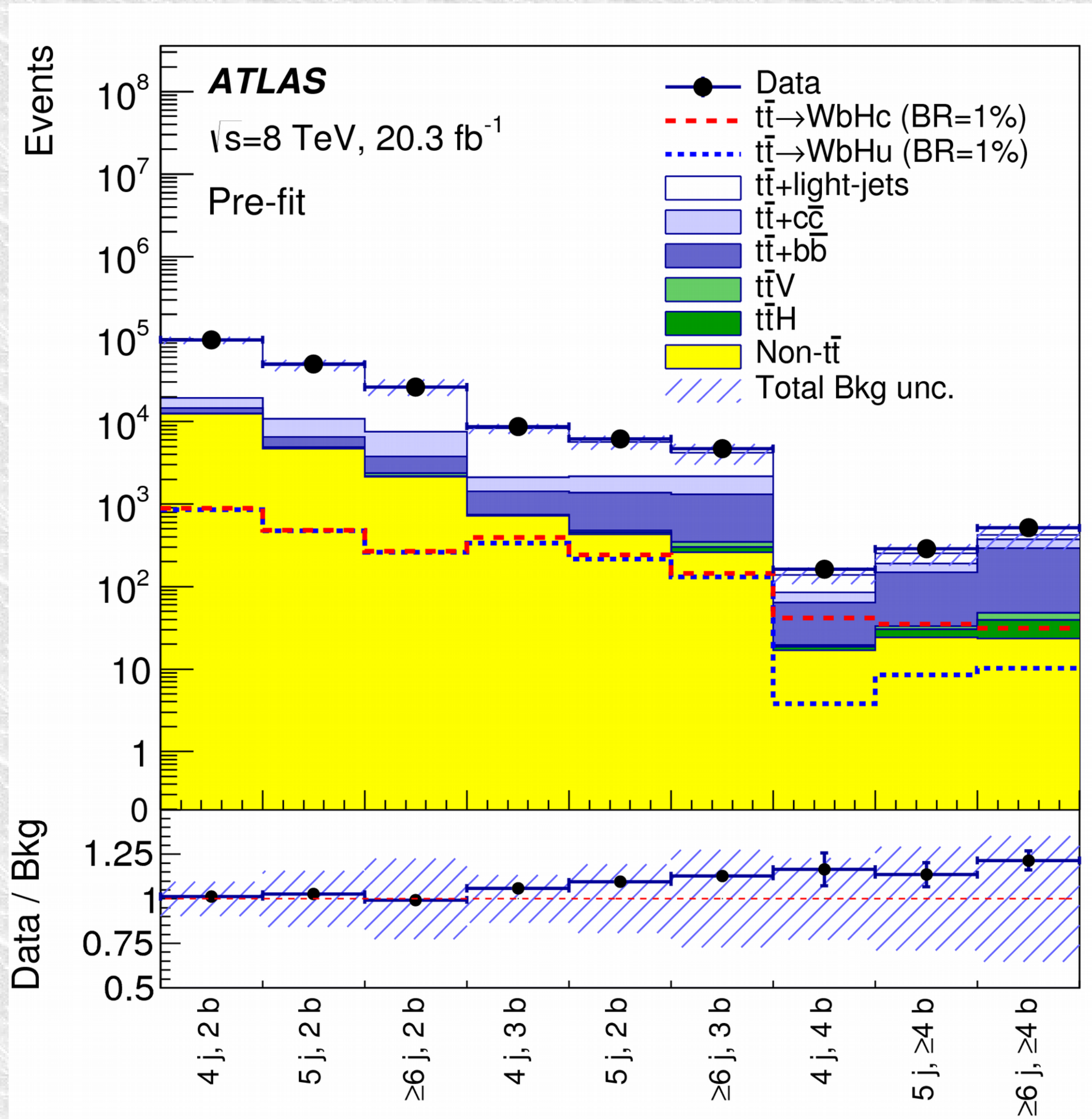
H→ μτ limits	ATLAS		CMS	
	Expected	Observed	Expected	Observed
$\mu\tau_e$	n.a.	n.a.	1.32/1.66/3.77%	2.04/2.38/3.84%
$\mu\tau_h$	1.24%	1.85%	2.34.2.07/2.31%	2.61/2.22/3.68%
Combined	1.24%	1.85%	0.75%	1.51%

- Both ATLAS and CMS have excesses
  - 2.1 sigma in CMS, 1.2sigma in ATLAS
- Clearly a very interesting, but not very significant, excess

FCNC t→Hq; H→bb

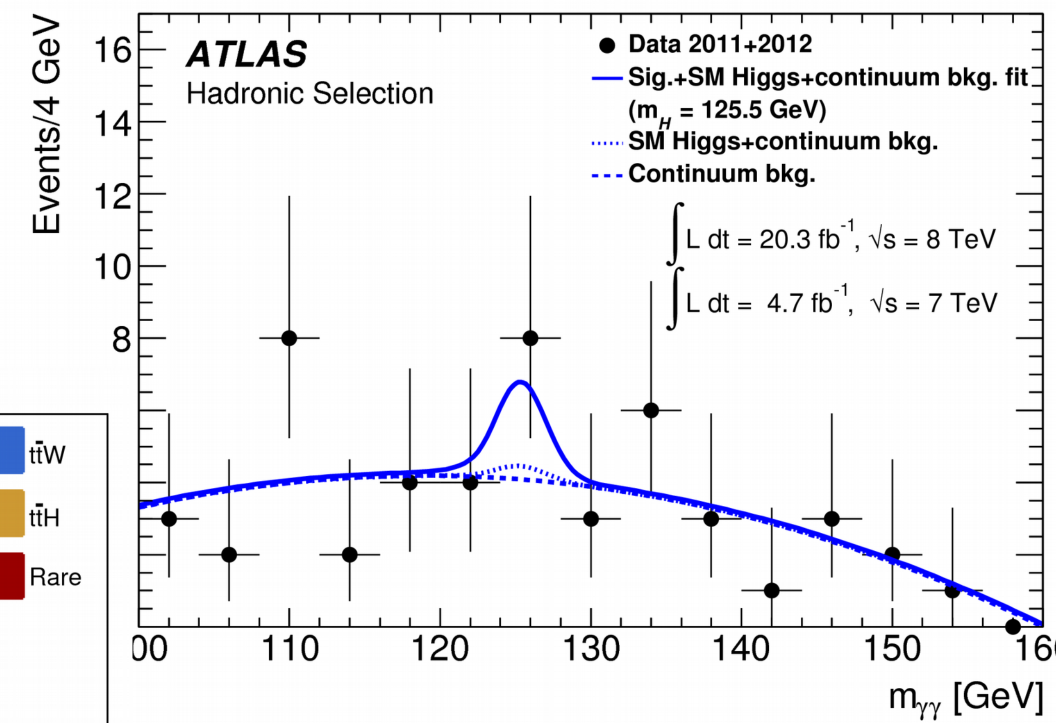


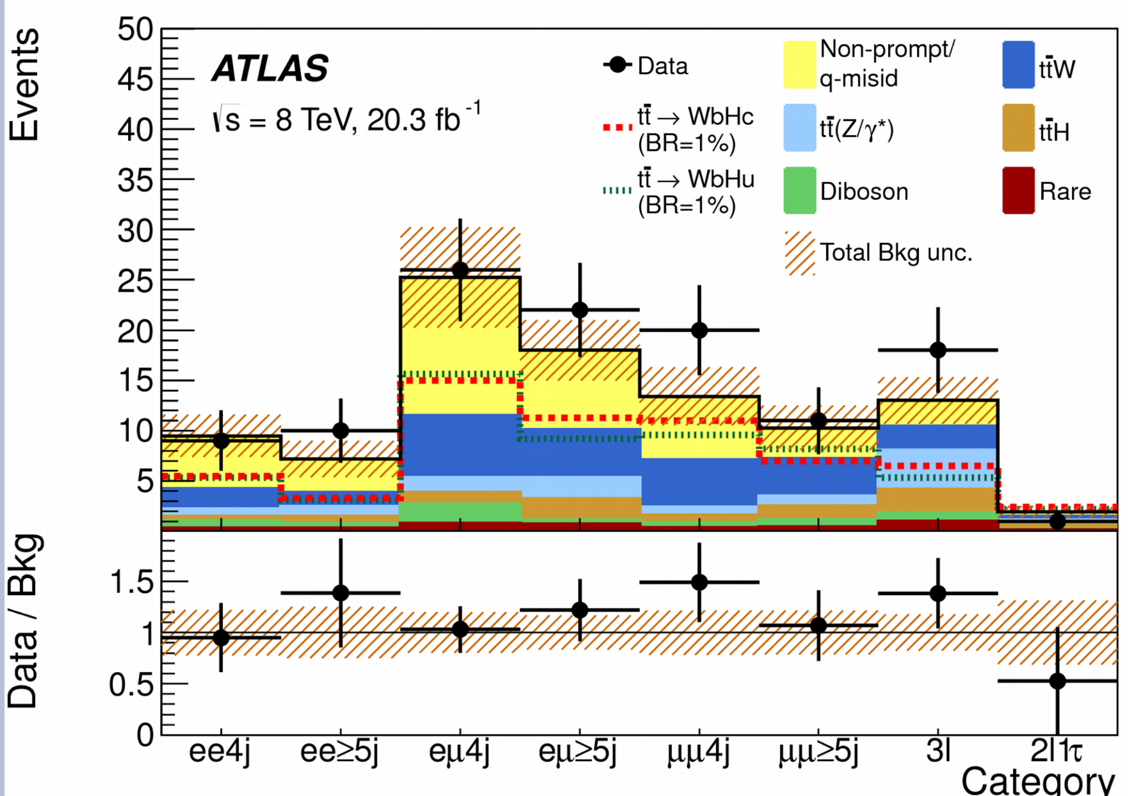
- W→l trigger
- Multiple categories, kinematic discriminant in each discriminant
- 4j, 4b has best s/b for t→cH



FCNC top-Higgs

- Di-photon has hadronic and leptonic top selections





- Multilepton 7 categories of 2/3 leptons, 4/5 jets
- Usually a small excess

CMS FCNC t→Hx

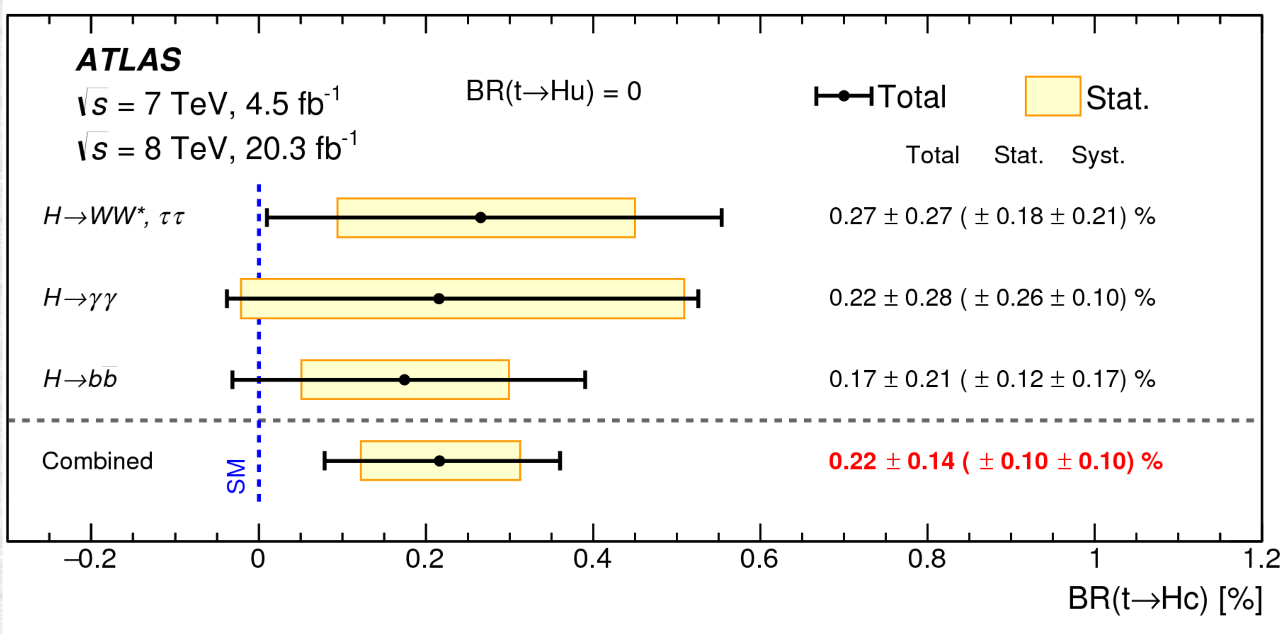
- CMS use H→γγ and multilepton
  - Multiple E_T^{miss} categories used
  - Re-using A→ Zh and H→hh search

Channel	E_T^{miss} (GeV)	N_b	Obs.	Exp.	Sig.
$\gamma\gamma\ell$	(50, 100)	≥1	1	2.3 ± 1.2	2.88 ± 0.39
	(30, 50)	≥1	2	1.1 ± 0.6	2.16 ± 0.30
	(0, 30)	≥1	2	2.1 ± 1.1	1.76 ± 0.24
	(50, 100)	0	7	9.5 ± 4.4	2.22 ± 0.31
	(100, ∞)	≥1	0	0.5 ± 0.4	0.92 ± 0.14
	(100, ∞)	0	1	2.2 ± 1.0	0.94 ± 0.17
$\ell\ell\ell$ (OSSF1, below-Z)	(50, 100)	≥1	48	48 ± 23	9.5 ± 2.3
	(0, 50)	≥1	34	42 ± 11	5.9 ± 1.2
$\ell\ell\ell$ (OSSF0)	(50, 100)	≥1	29	26 ± 13	5.9 ± 1.3
	(0, 50)	≥1	29	23 ± 10	4.3 ± 1.1

Combination of t→Hc

t→ Hc	ATLAS		CMS	
	Expected	Observed	Expected	Observed
H→γγ	0.51%	0.79%	0.81%	0.69%
H→ multilepton	0.54%	0.79%	1.17%	1.28%
H→ bb	0.42%	0.56%	n.a.	
Combined	0.25%	0.46%	0.65%	0.56%

- Small excess in ATLAS
  - <2sigma
- Not confirmed in CMS
  - Though less sensitive



Conclusions: no new physics

- BSM couplings analyses
  - H→BSM Br<34% ATLAS+CMS, κ_V<1 assumed
    - Loops with virtual particles (gg→H,H→γγ) good to 10%
  - H→Invisible Br<25% direct (23% in combination)
- Non-SM couplings of the H_{125} searched for:
  - $Br(H \to Z_{(d)}Z_d \to llll) < (3x)10^{-4}$ for $15 < m_{Zd} < 55$
  - BR $(H \to X \to \gamma_d)$ <30-40% for $m_{\gamma d}$=100MeV: electron jets
  - Br $(H \to aa)$ * $Br(a \to \mu\mu)^2$ below 10^{-4} (to 10^{-6}!) for $0.2 < m_a < 60$
  - Br $(H \to aa)$ * $Br(a \to \gamma\gamma)^2$ below 10^{-3}
  - $H \to \pi_V \pi_V$ long-lived are <50% Br $20 < m_\pi < 40$ $2 < c\tau < 12$m
    - 10% at best points
  - $H \to \chi G/\chi\chi \to$ Ggγ(γ) Br<10% $1 < m_\chi < 120$
- Flavour changing analyses interesting
  - H→μτ, t→Hc both have small excess

Post-conclusions:

- I pray your indulgence for a few slides on
  - $\Gamma(H \to WW)$
    - Dependence on Γ_W
  - ttX
    - A question on modelling

arXiv:1604.01665

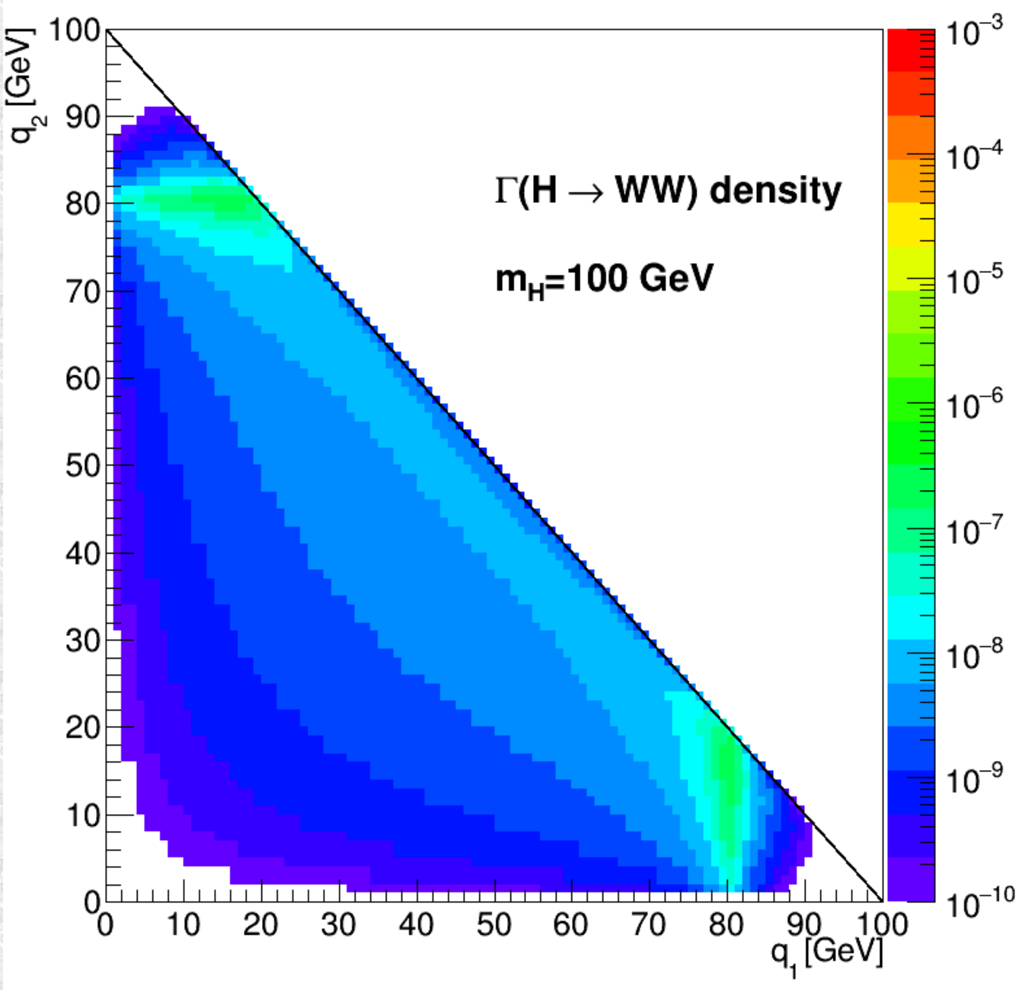
Higgs width to W

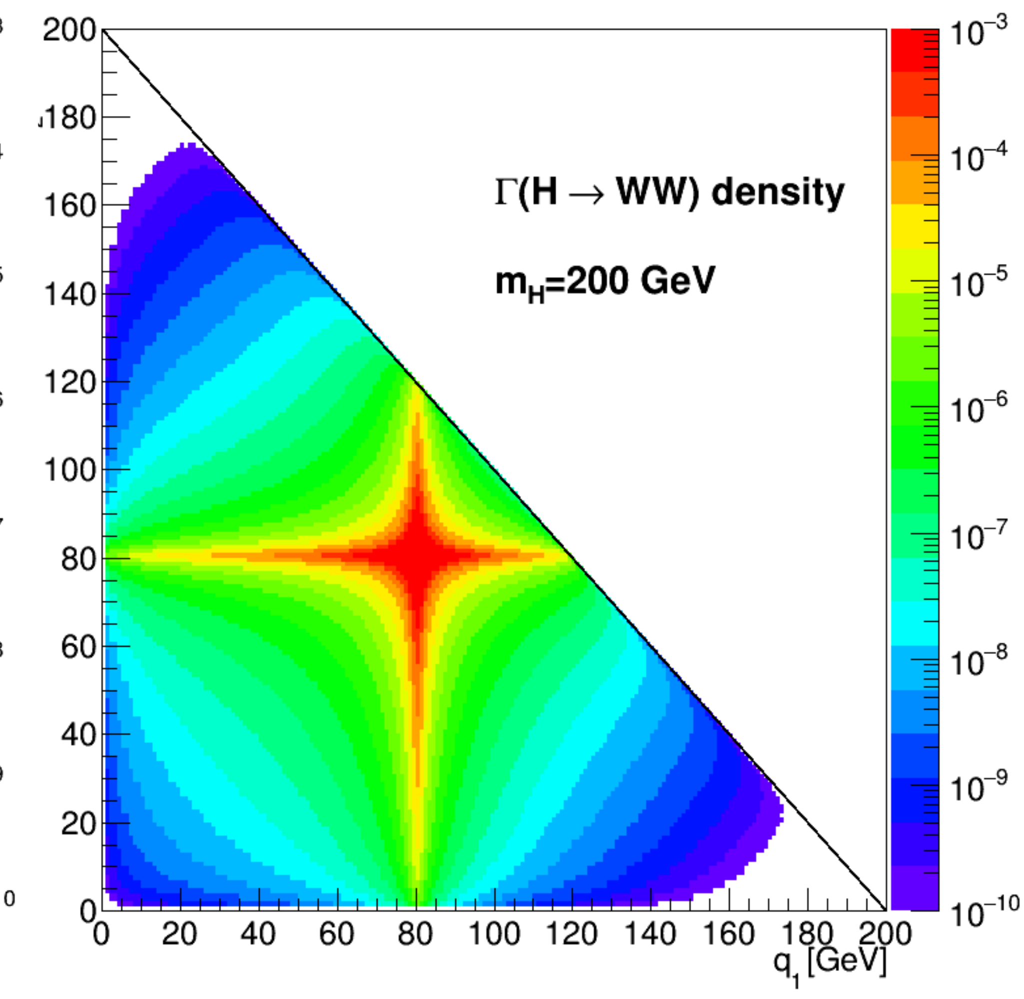
- The Higgs decay width to off-shell dibosons is to LO given by: Djouadi's Anatomy

$$\Gamma(H^0 \to V^* V^*) = \frac{1}{\pi^2} \int_0^{M_{H^0}^2} \frac{dq_1^2 M_V \Gamma_V}{(q_1^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \int_0^{(M_{H^0} - Q_1)^2} \frac{dq_2^2 M_V \Gamma_V}{(q_2^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \Gamma_0$$

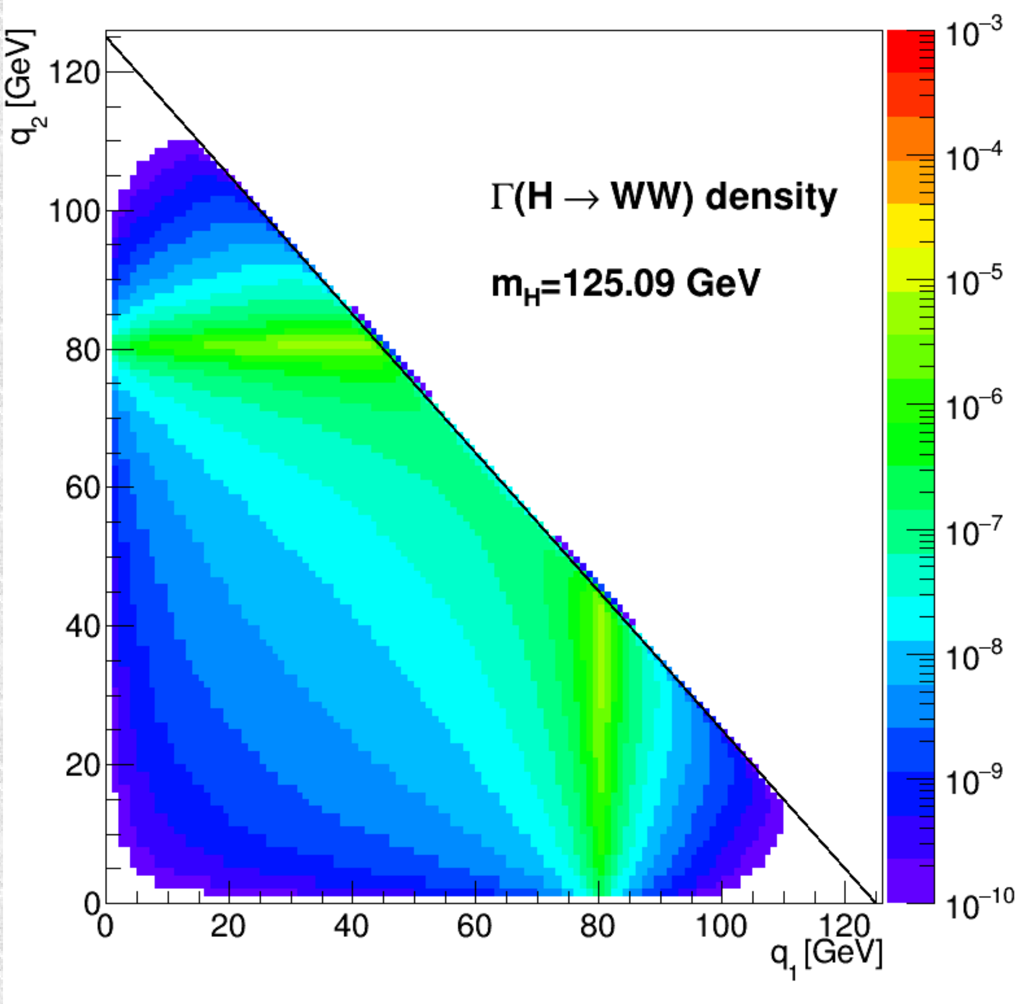
- For the case of one on shell and one off shell this become approximately proportional to one power of the width.
  - Thus the Br H → WW is proportional to the W boson width
  - This is currently known to 2%
  - Not totally negligible in analysing Higgs width

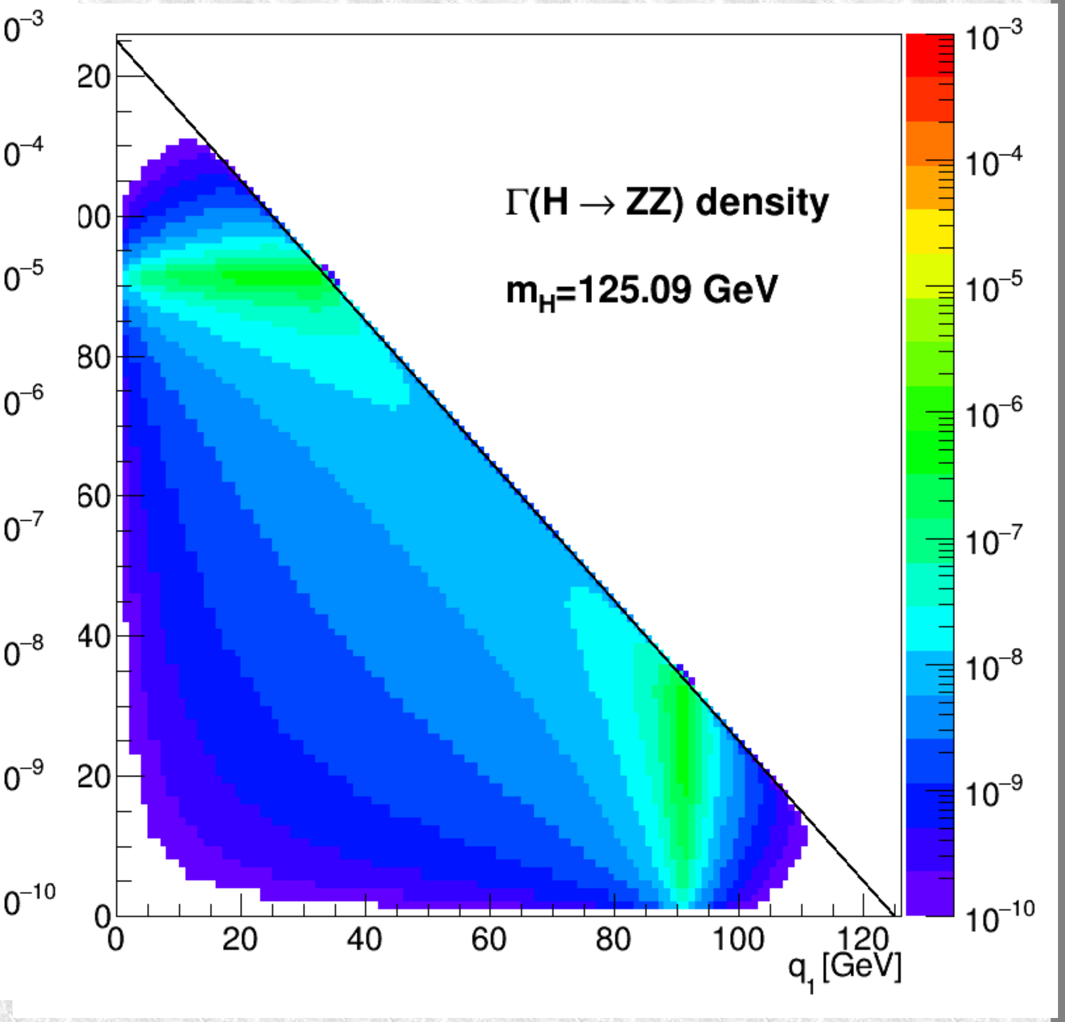
$\Gamma_{WW}(q_1,q_2)$ for m_H=100,200





$\Gamma_{WW/ZZ}(q_1,q_2)$ for m_H=125.09

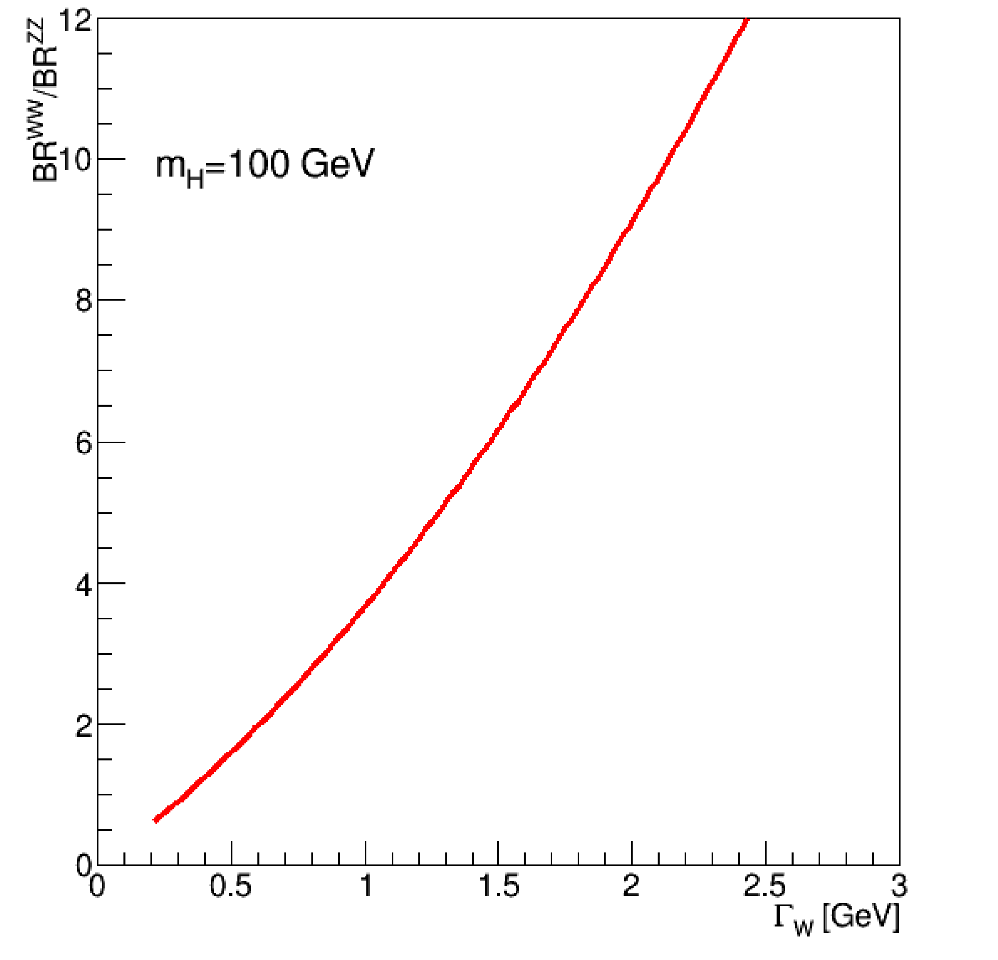


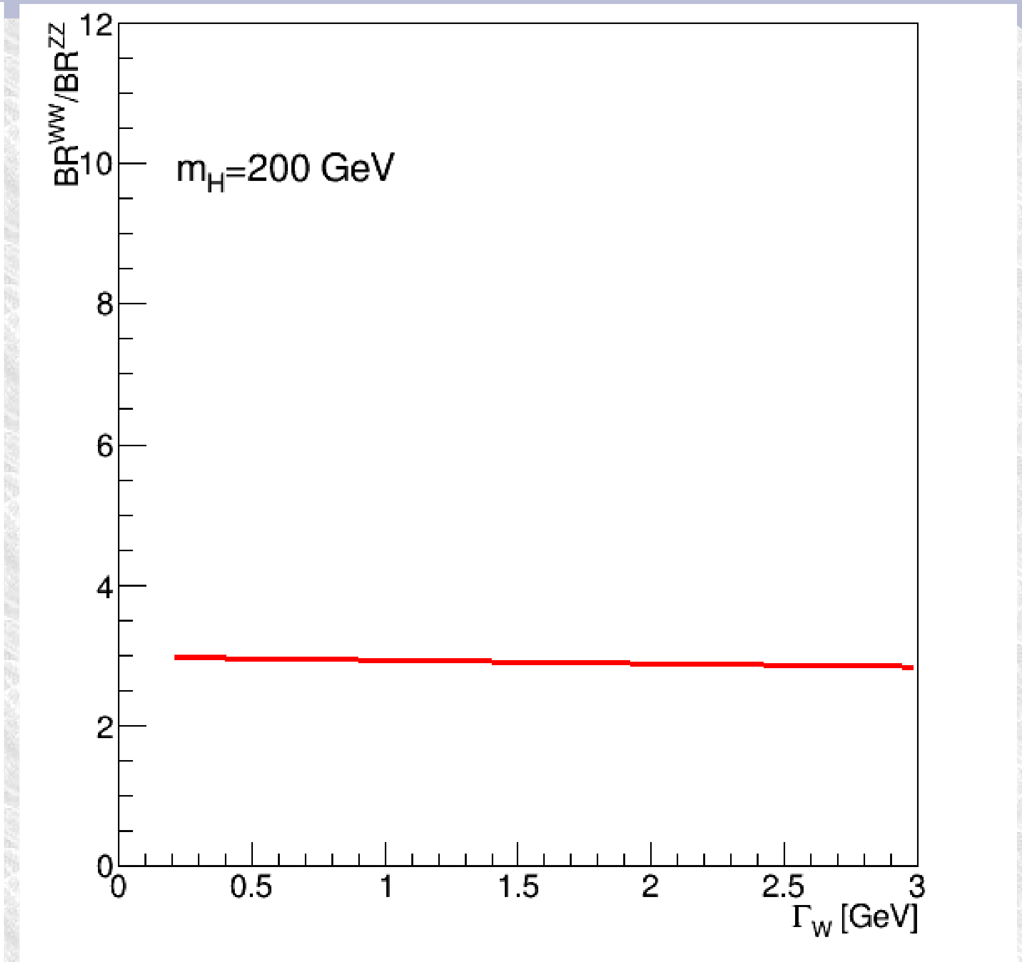


How to interpret?

- Integrate to get the total width:
  - $\Gamma_{WW}|_{lo}$=0.941MeV at 126
  - c/f 0.974MeV in YR3 at the same mass
  - Agreement to 3% (2% for ZZ)
- Now calculate width at 125.09:
  - Γ_{WW}=0.853 MeV at 125.09
- BR(H→WW) must sum over all Brs
  - And LHC does not measure Brs anyway
  - So find Γ_{WW}/Γ_{ZZ}=BR(WW)/BR(ZZ)
  - $BR/BR|_{lo}$=7.99 (c/f 8.07 in YR 3)
- Data ratio is in the LHC CONF on couplings.
  - So find how Br varies with Γ_W

BR ratio v W width

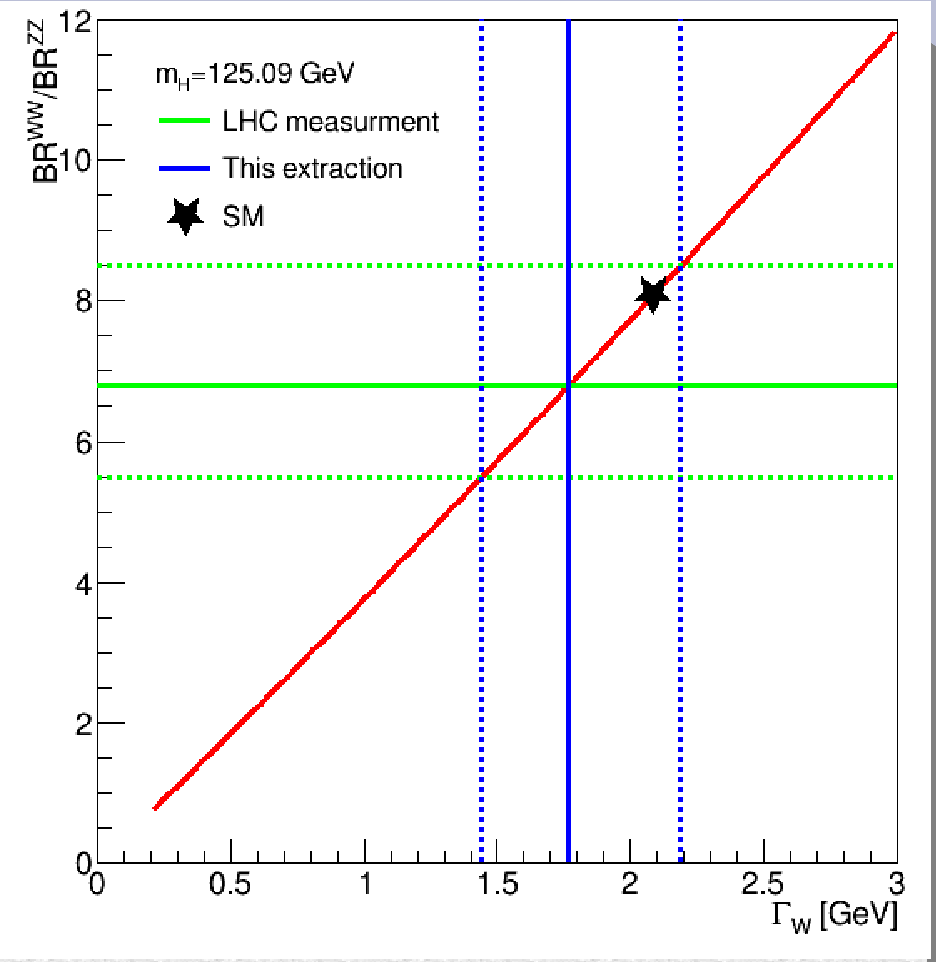




- Quadratic for low mass Higgs, const for 200 Gev
  - Due to 2 or 0 of shell W bosons

BR ratio v W width

- Linear for m_H=125.09
  - One W on shell, the other off.
- Use measured
  $$BR(WW)/BR(ZZ)=6.8^{+1.7}_{-1.3}$$
- Extract
  $$\Gamma_W=1.8^{+0.4}_{-0.3}\,GeV$$
- This can be compared with 2.085±0.042 world average
  - Factor 10 worse
  - But errors will improve



Systematic errors

- Few parametric ingredients:
  - m_Z
  - m_W
  - m_H
  - Γ_Z
  - Γ_H
- None of them contribute significantly
  - Biggest is Γ_Z which is known 20x better than Γ_Z.
- Theoretical uncertainty on $\Gamma(H \rightarrow WW)$ extraction is 0.5%
  - Again, negligible.

Conclusion

- The W boson width should not be ignored in Higgs boson coupling studies
- First LHC measurement of the W boson width!

$$\Gamma_W = 1.8^{+0.4}_{-0.3}\, GeV$$

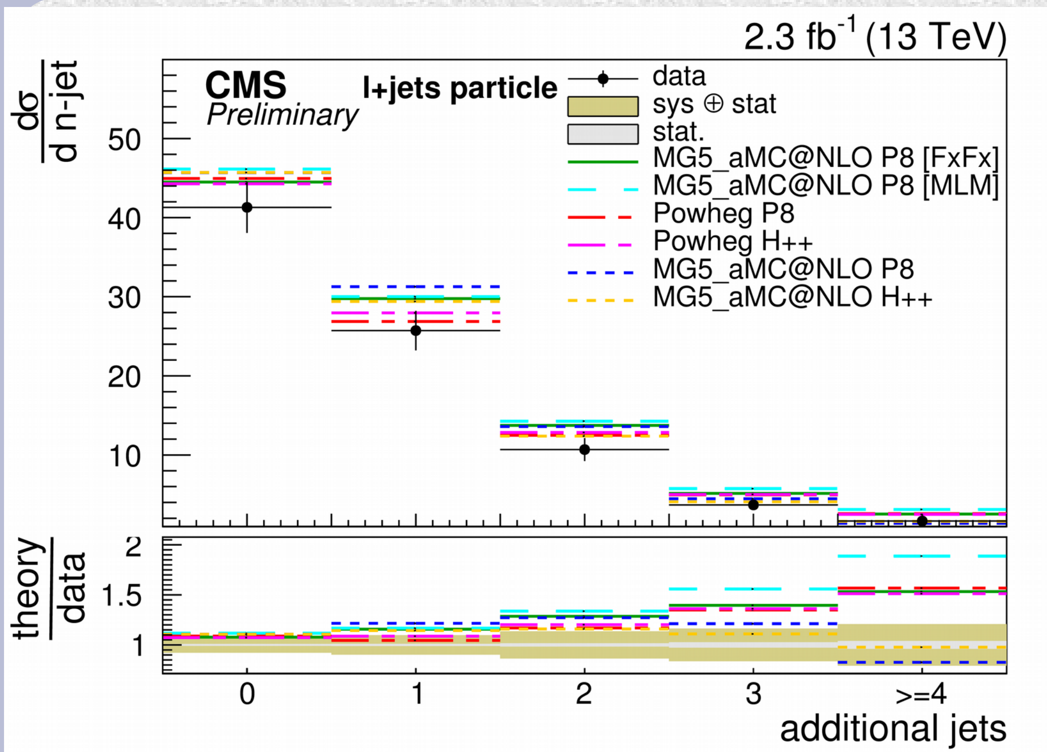
  - From Higgs branching ratios
  - Assumes SM couplings
  - I am asking Higgs/Pc whether I can publish
- Errors comparable to any other experiment
  - Factor 10 off world average
  - But will improve with time
- A proper measurement of the W width is needed to exploit Higgs measurements fully.

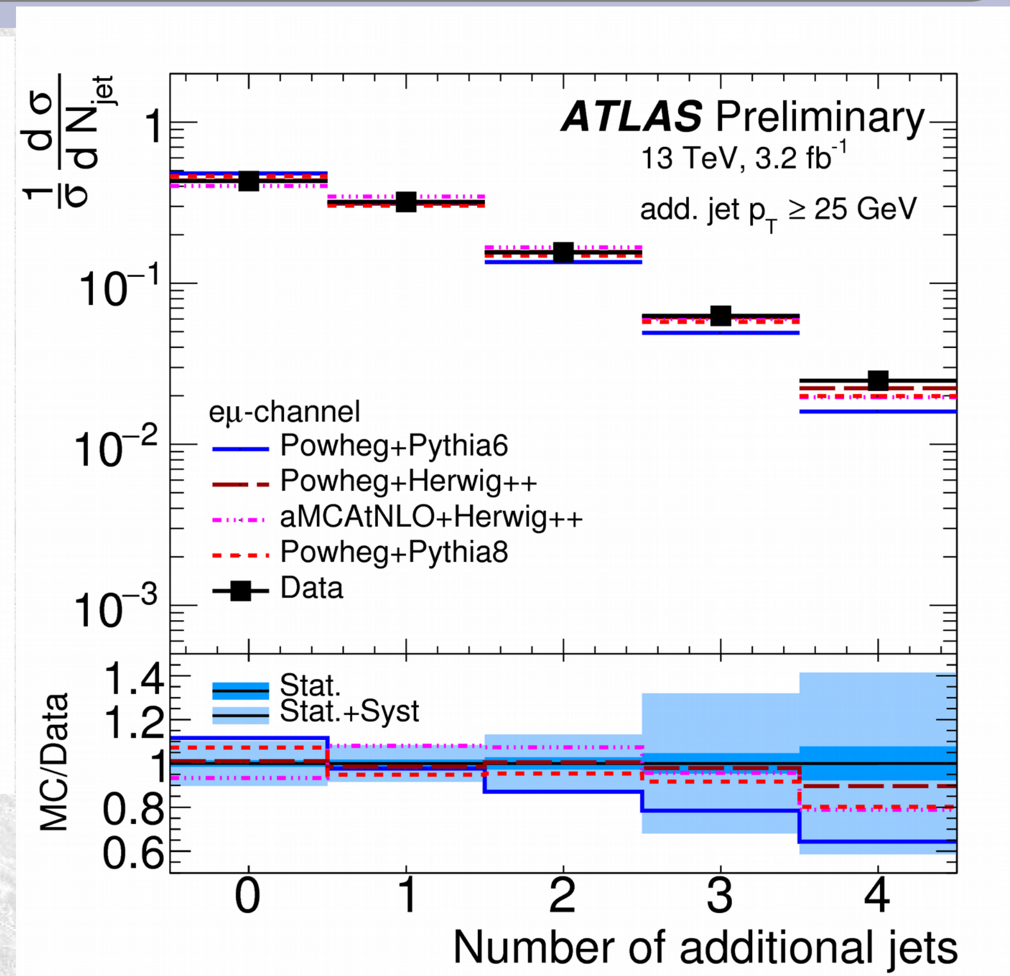
tt + X

- Many searches look for tt plus more
  - ttV, SUSY, vector like quarks, ttH all have seaches where you add leptons or b quarks to a tt system.
  - Modelling is complex, but e.g. ttbb is known at NLO
- So can we confidently predict SM backgrounds to such searches?

$t\bar{t}$ plus jets

CMS-PAS-TOP-16-008



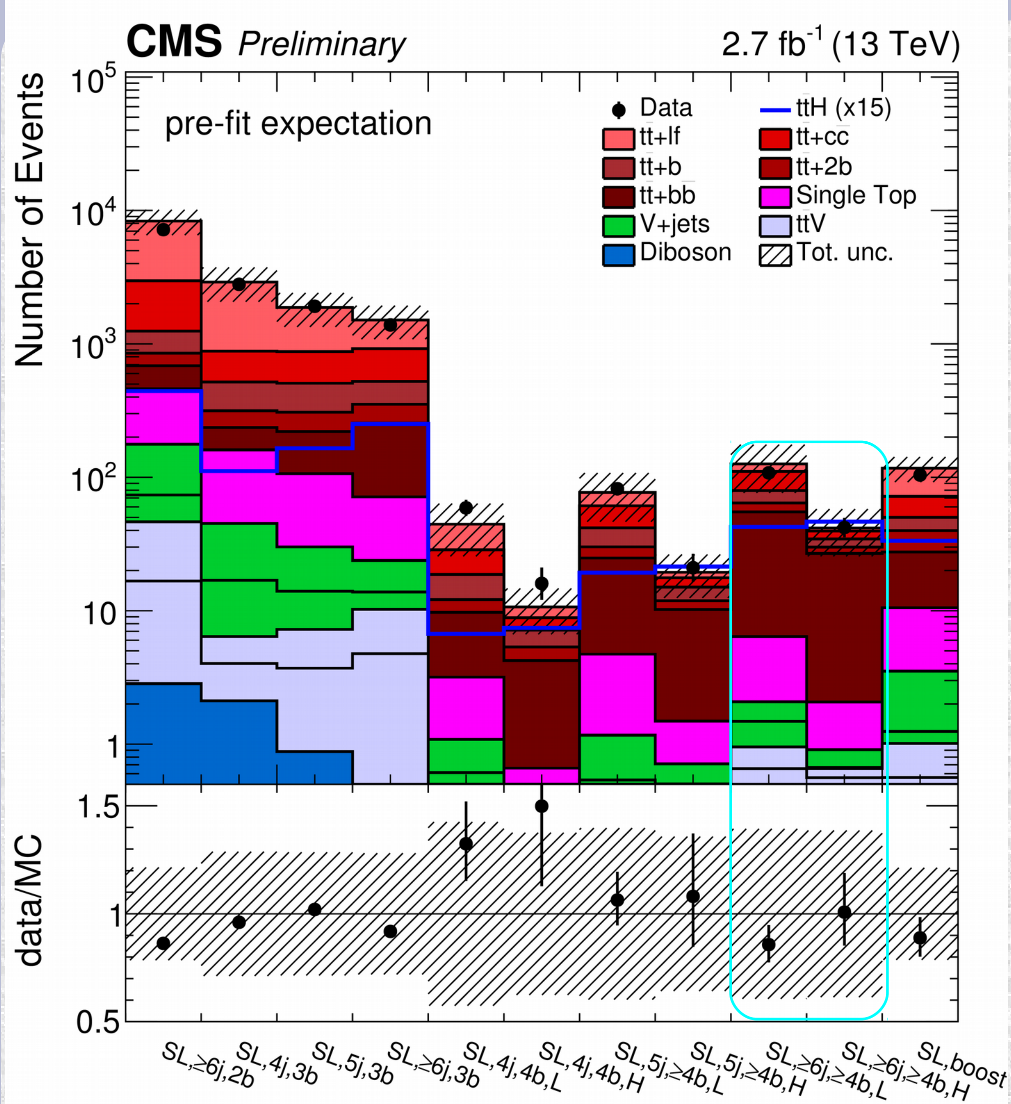


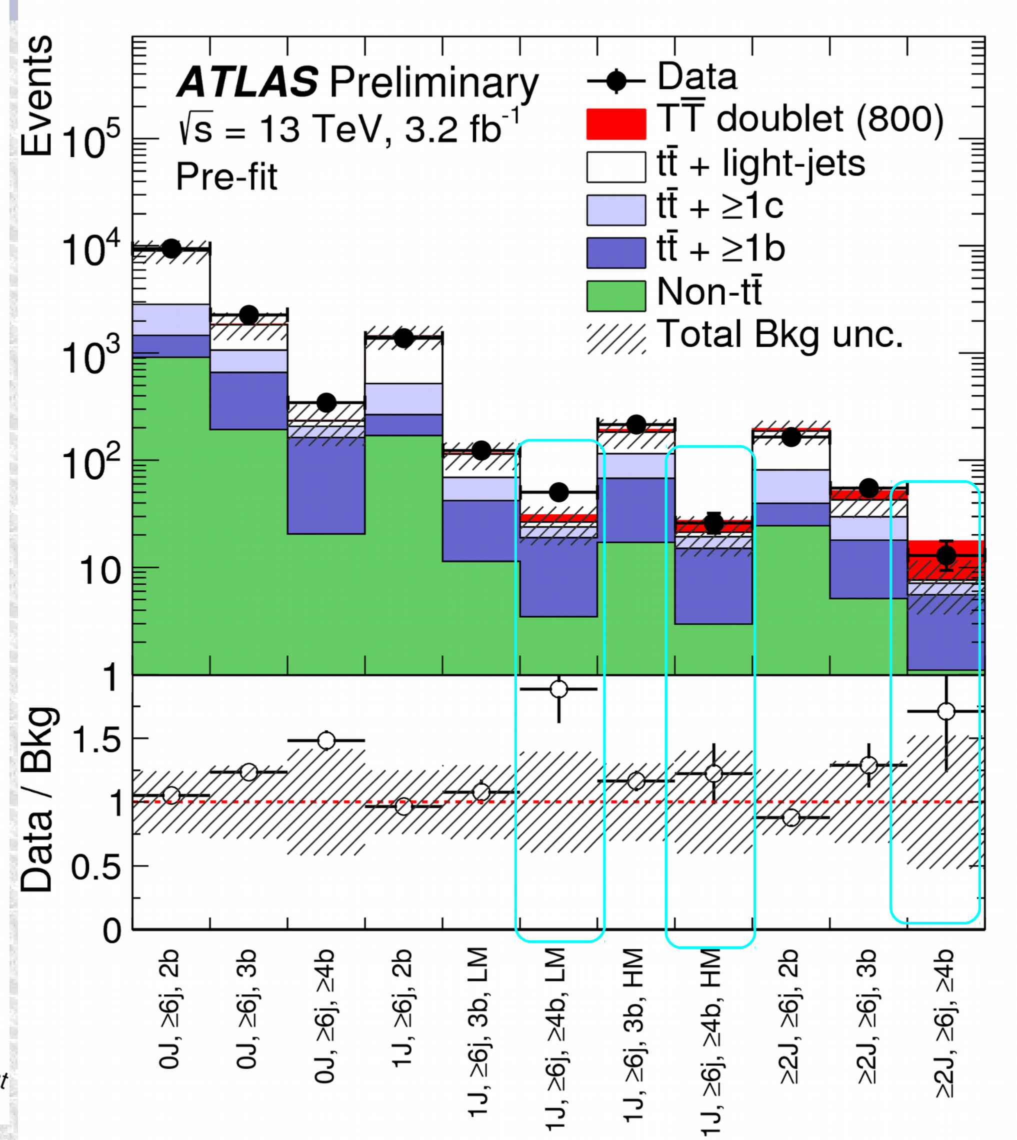
- Excellent to have high quality data on this fast
  - But some work on understanding still...

ATLAS VLQ v CMS ttH

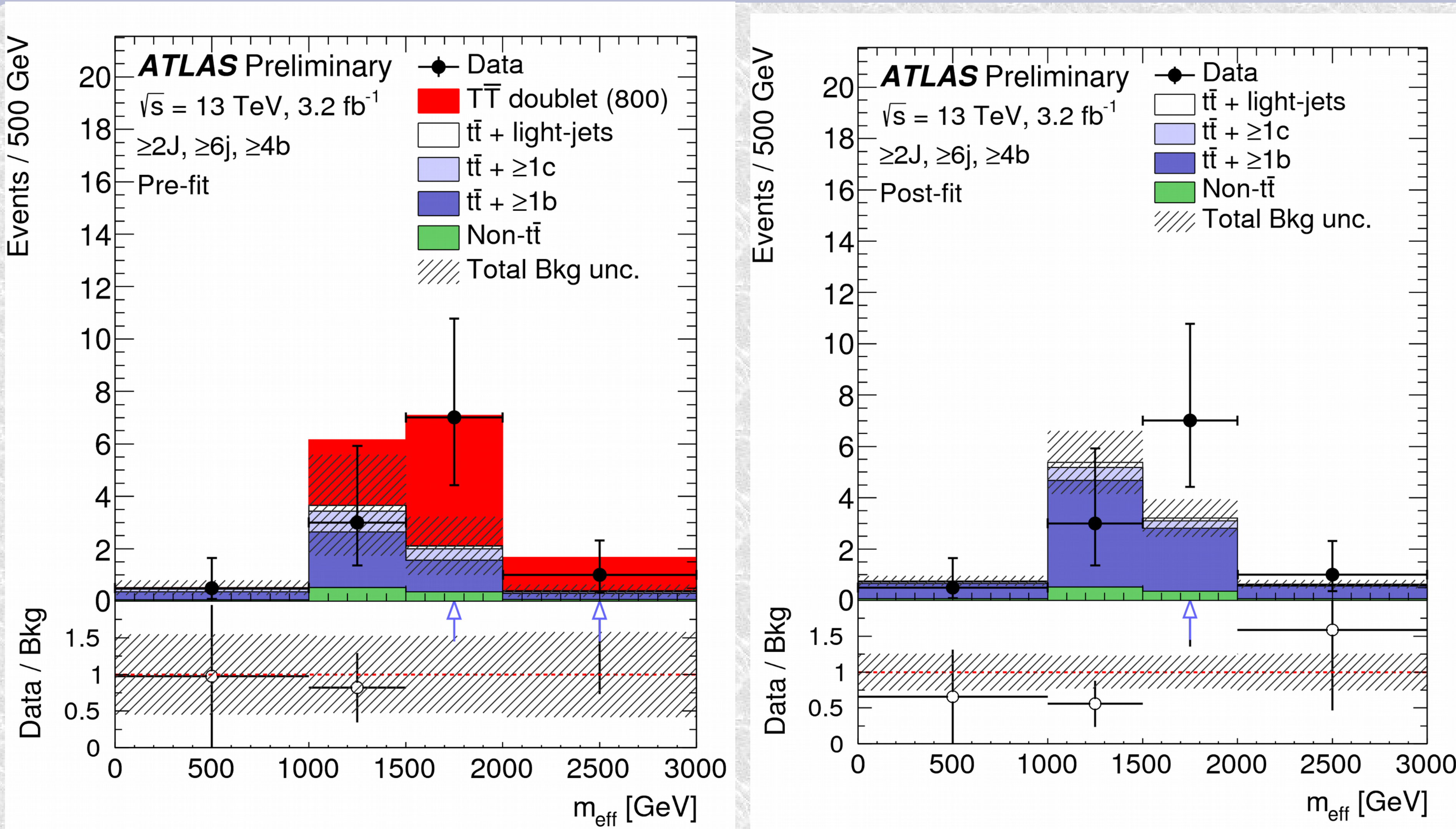
- Both analyses select 1 lepton and at least 4 jets, at least 2 b tagged
- Examine caterogires by numbers of jets, b jets and boosted jet candidates
- ATLAS has problems with ttbb rates
- See 120% - 190% of MC in these regions
- Meanwhile CMS sees expected rate!
  - Modelling of this states is complicated

ATLAS VLQ v CMS ttH



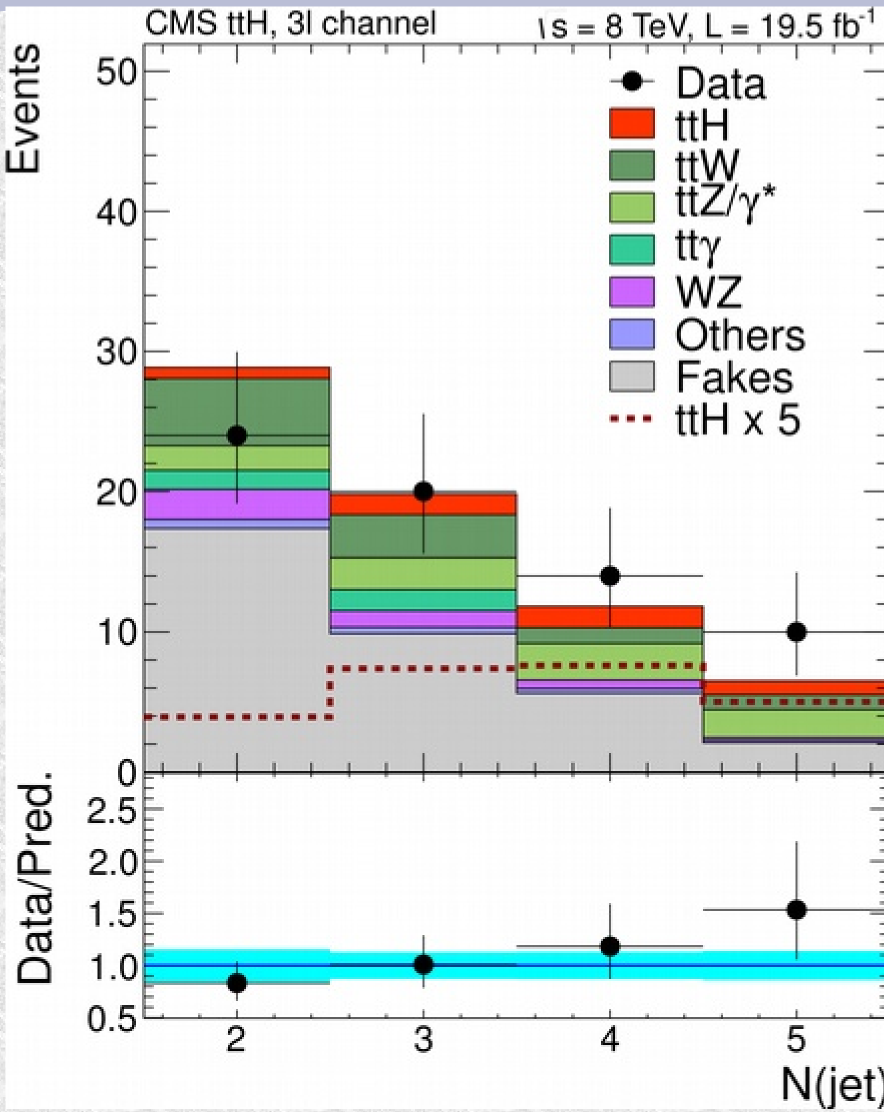


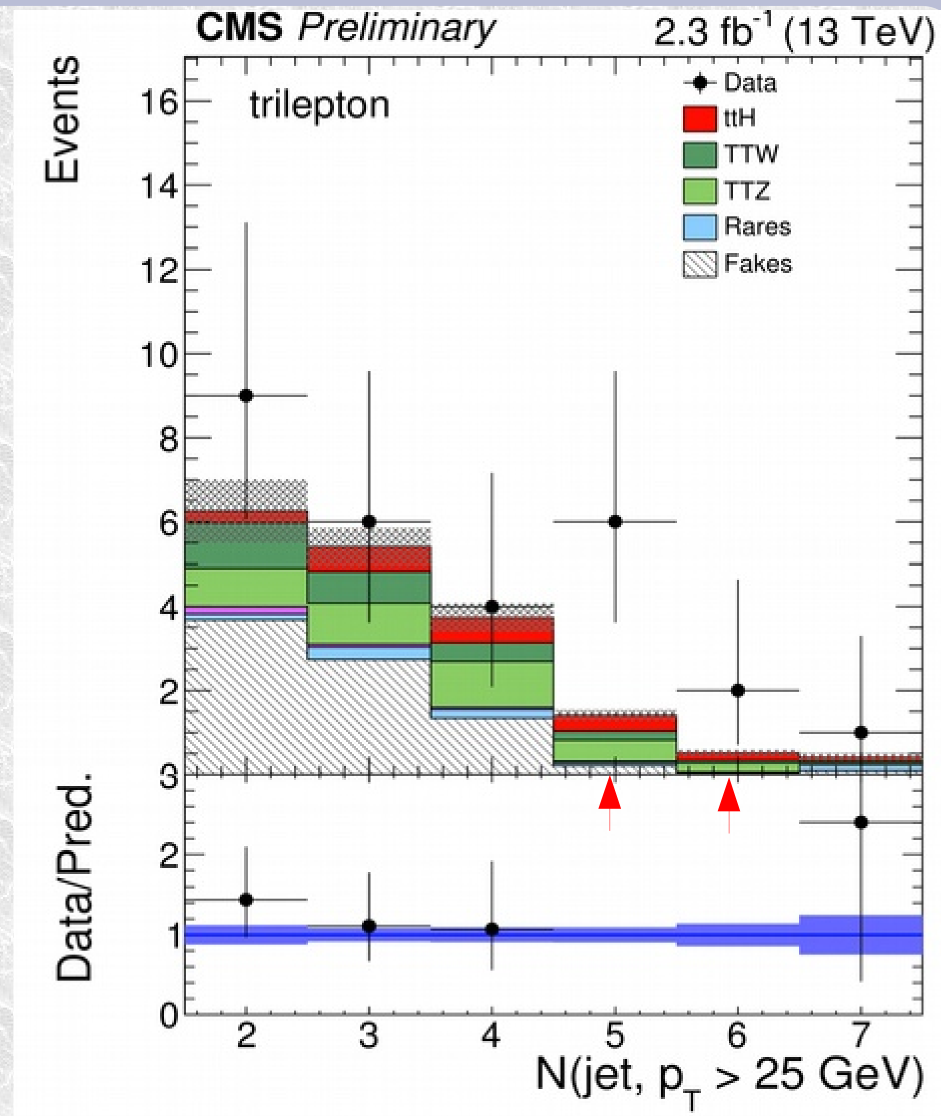
VLQ – 2: 6j4b pre/post fit



- Factor 2 increase in ttbb component to fit data

ttH - multilepton

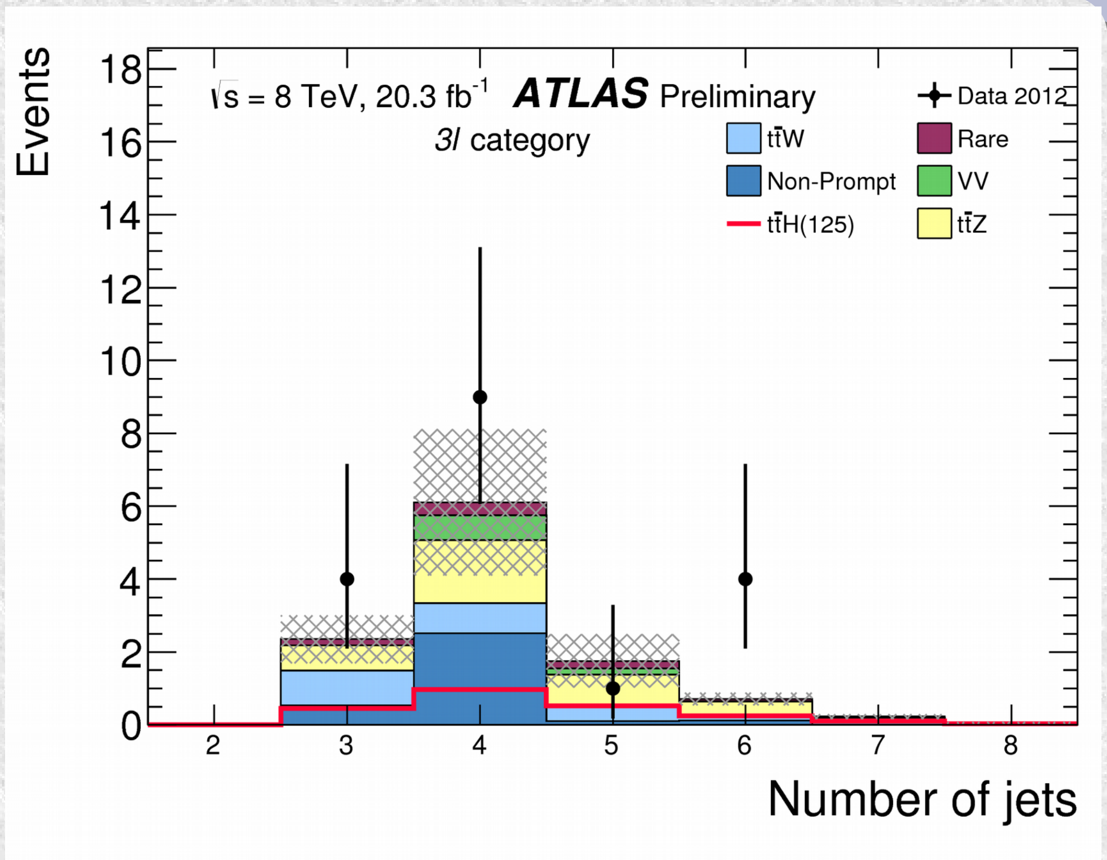




- Excess for 5 jets+ in both years?

ttH

- Multilepton ttH analysis in 2012
  - This channel is 3-leptons and one b jet
  - Plot shows Njets p_T>25GeV
  - Again, factor 2 increase for 5+ jets



tt modelling

- ttbb and tt+leptons are complex systems to model
- tt+jets overall seems reaonably defined
- ttbb:
  - At 13 TeV in CMS looks plausibly modelled
  - In ATLAS there is a factor 2 discrepancy
- Can we treat ttbb shape and rate as independent?
- 3-leptons plus a b
  - Events with 5 or 6 jets have excesses at 8 and 13 TeV in CMS and 8 TeV in ATLAS.
  - Remember: tt+4 jets modelling gets tricky