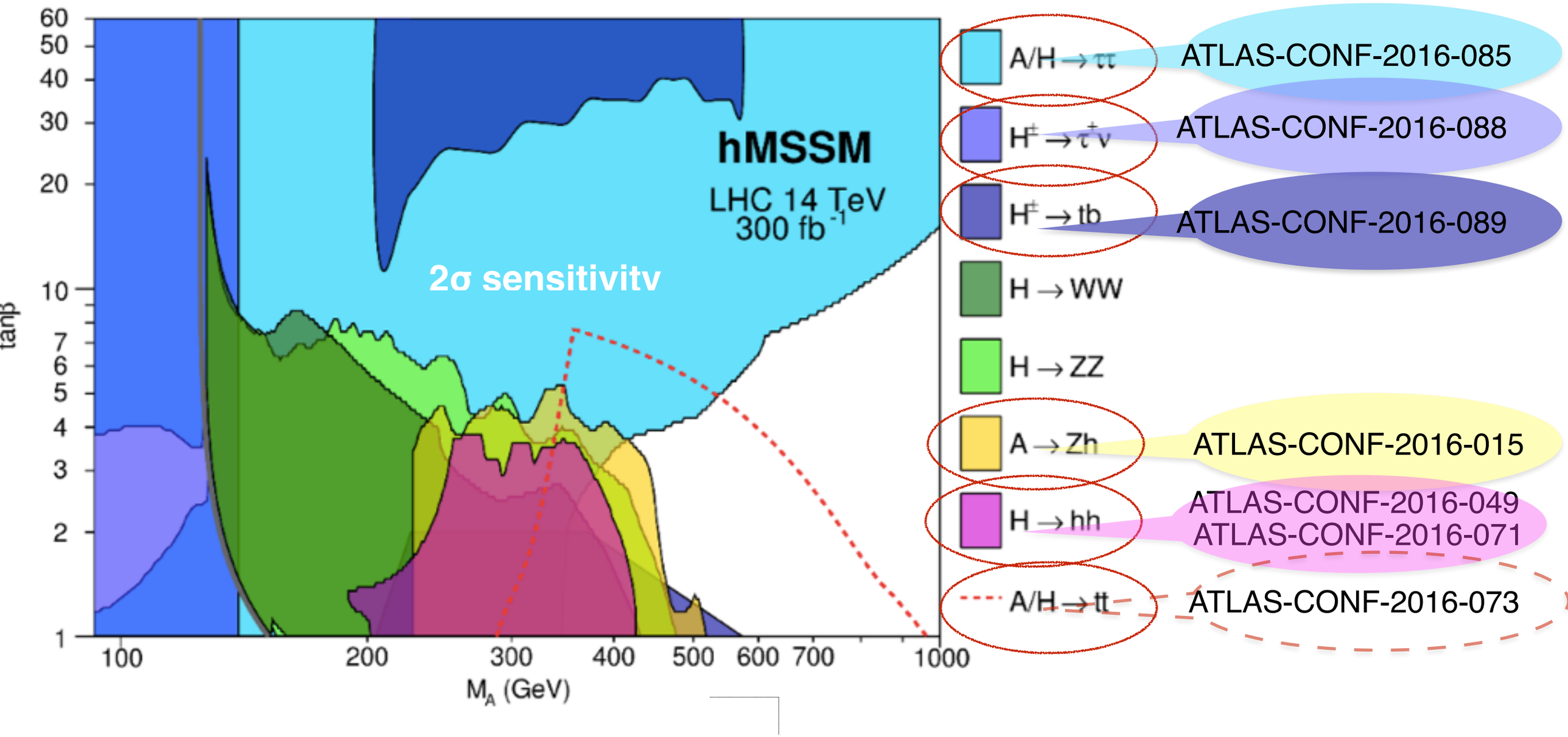
Heavy Higgs searches (MSSM)

Pamela Ferrari (Nikhef)

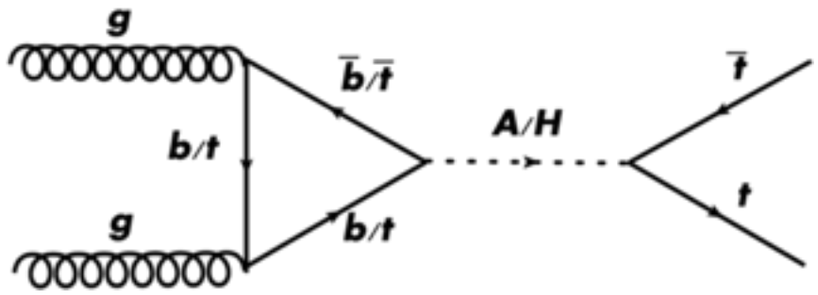
Higgs Coupling 2016

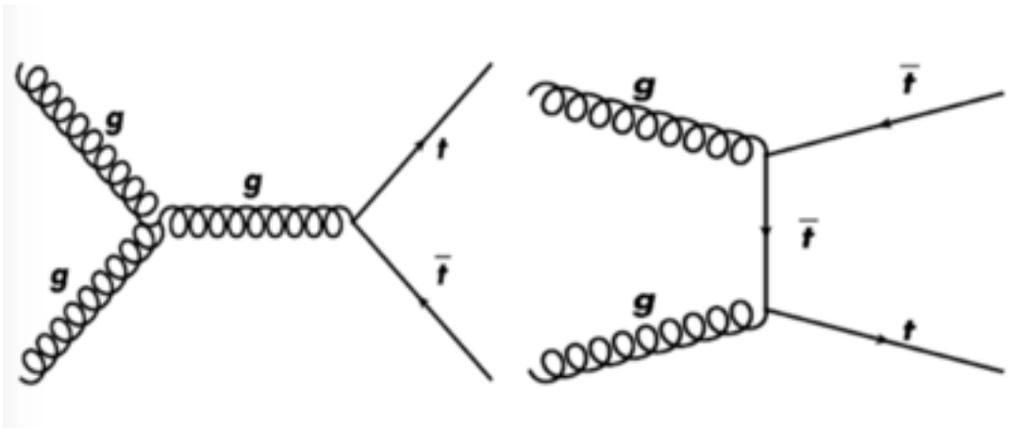
This talk: MSSM high mass Higgses

JHEP06(2015)168 A. Djouadi, et al



H/A→ tt decay @8TeV



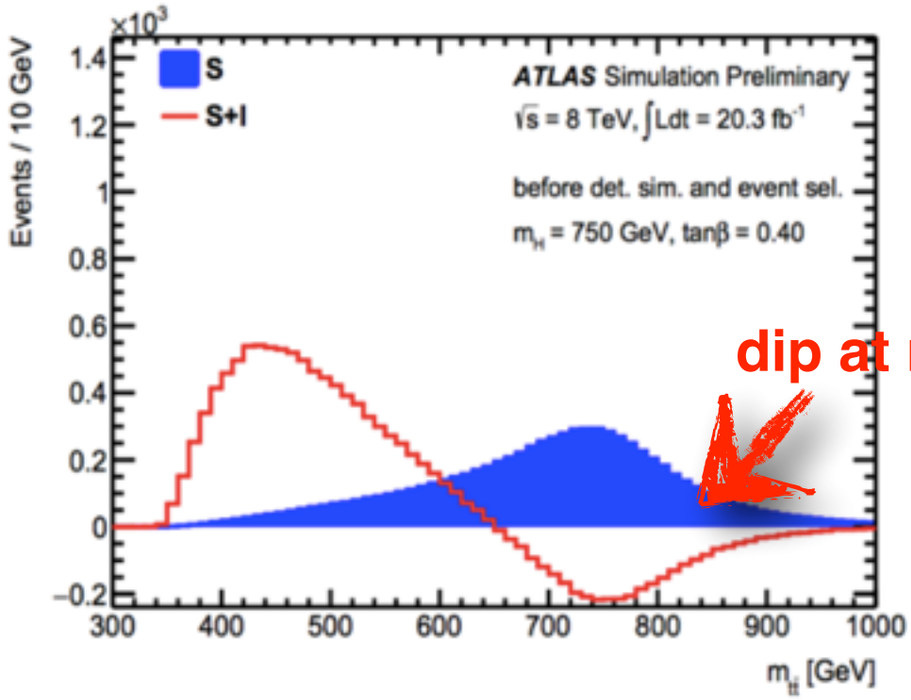


Analysis builds on JHEP **08** (2015) 148

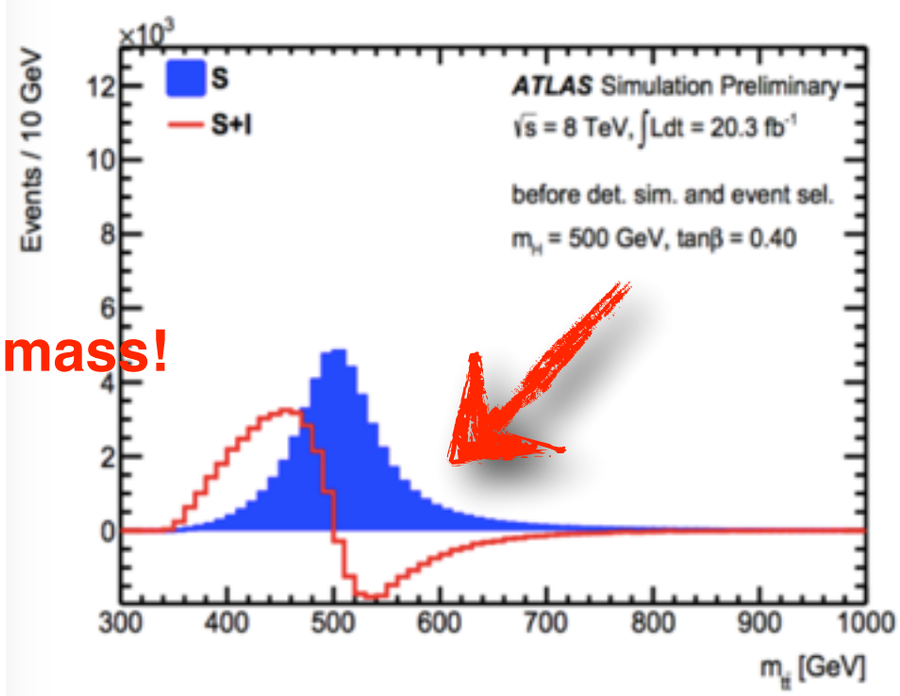
tt semileptonic decays

- mass 400-800 GeV variable width, 2HDM(II)
  Interference with SM tt background considered
  m_h =125 GeV. sin(β-α) =1→SM coupling
- A/H top coupling ~1/tan(β): search most sensitive to low tan(β)

Interference: generator modified to remove the SM $t\bar{t}$ matrix element → S + I contribution on event-by-event basis.



dip at resonance mass!



H/A→ tt decay @8TeV

Event selection:

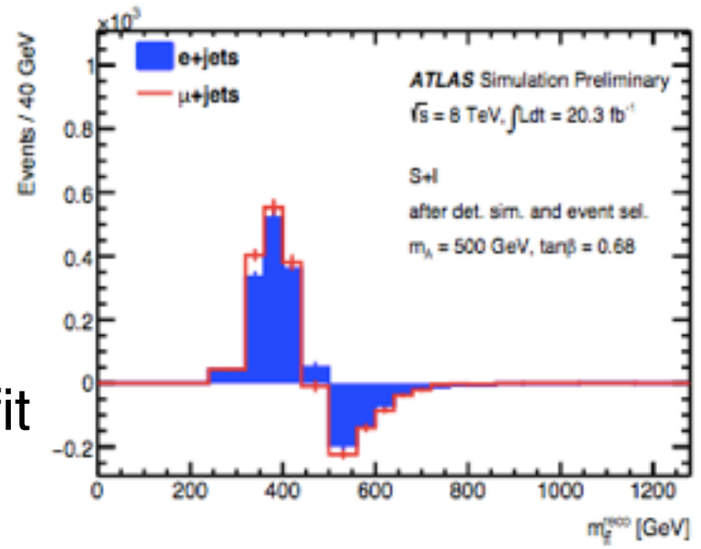
- One high p_T electron or muon;
- MET> 20 GeV, MET+m_{TW}> 60 GeV
- ≥4 high p_T jets, ≥1 b jet (70%eff)

Decay product assignment via χ^2 kin. fit

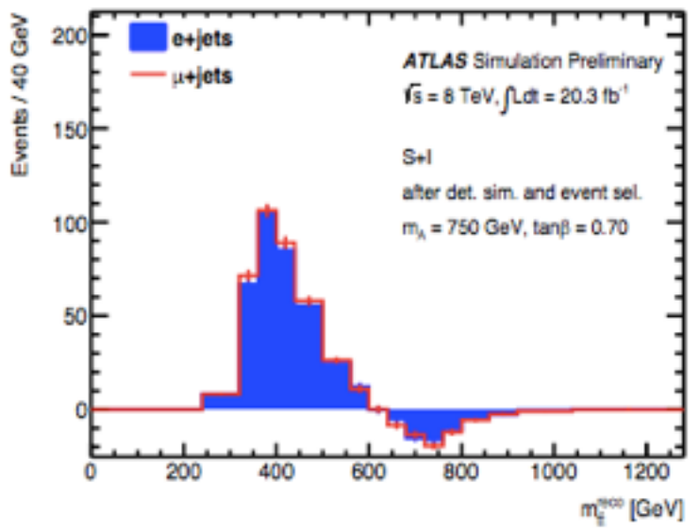
6 categories:

(2 lepton types) x (3 b-tagging categories)

1 b-tag for each top or only to one top quark.



(c) $m_A = 500$ GeV, $\tan\beta = 0.70$

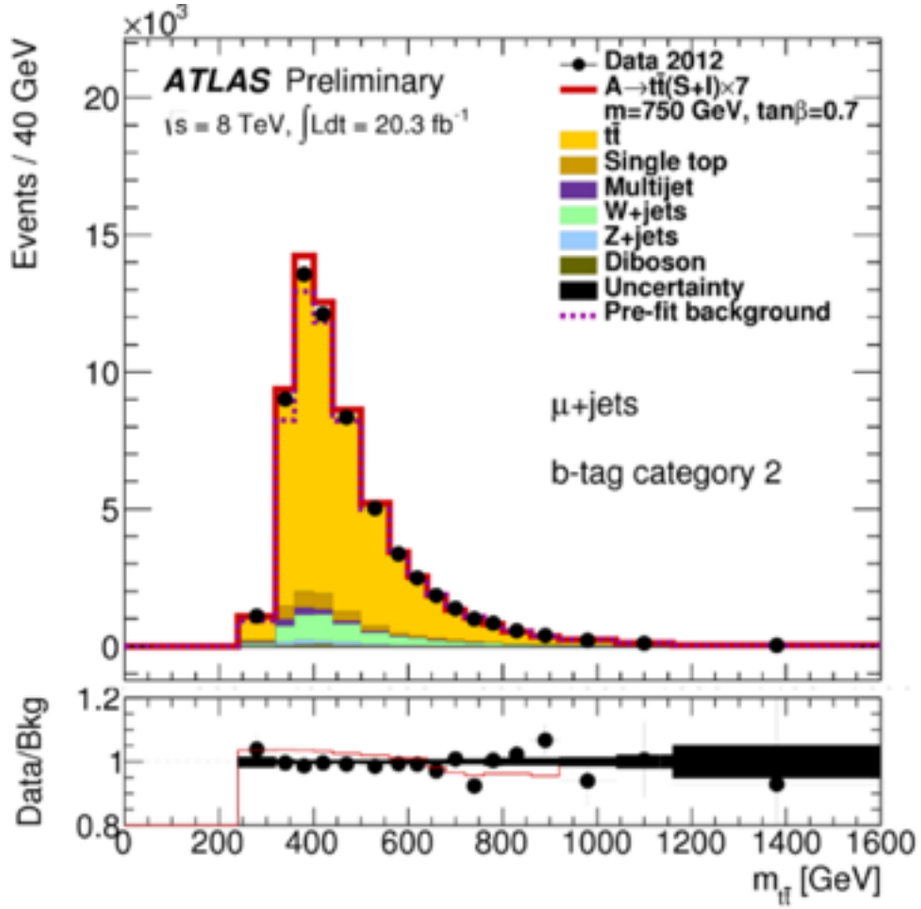


(d) $m_A = 750$ GeV, $\tan\beta = 0.64$

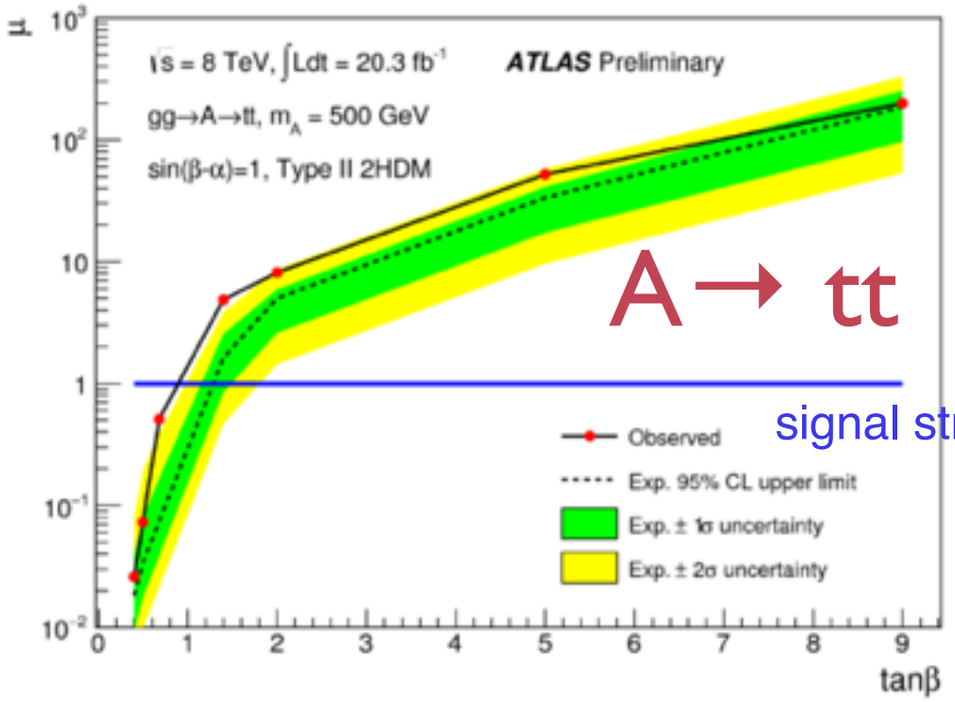
main backgrounds: ttbar, W-jets and multi-jet.

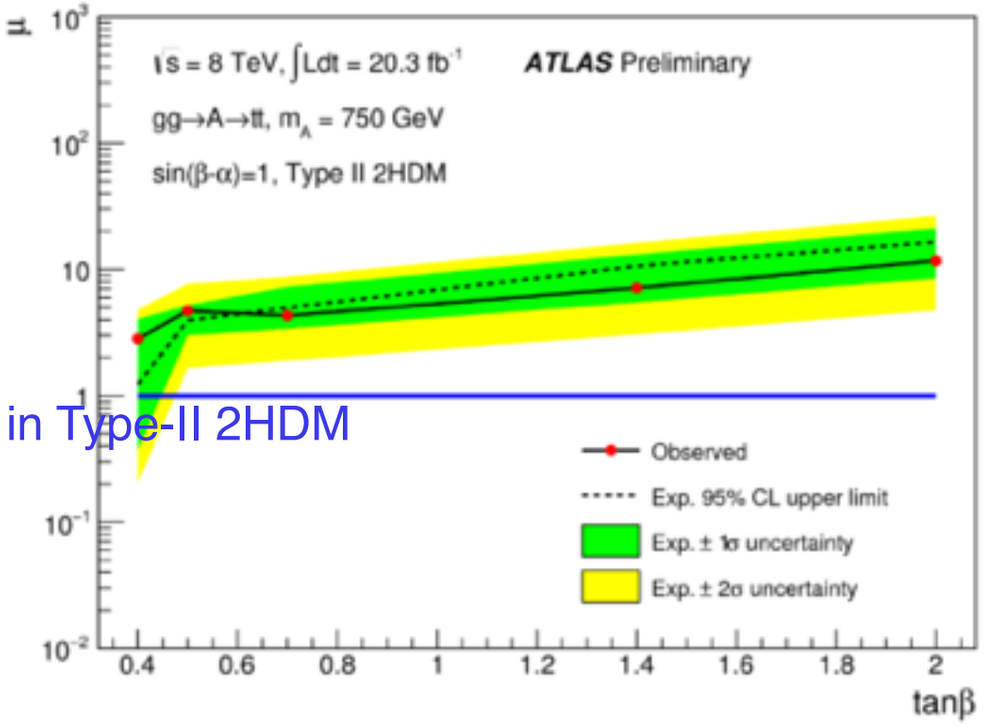
- W+jets SF obtained from data (comparing W boson charge asymmetry with Alpgen) in CR with same selection as SR apart b-tag requirement
- multi-jets normalisation and shape from data with matrix method.

No excess → exclusion limits



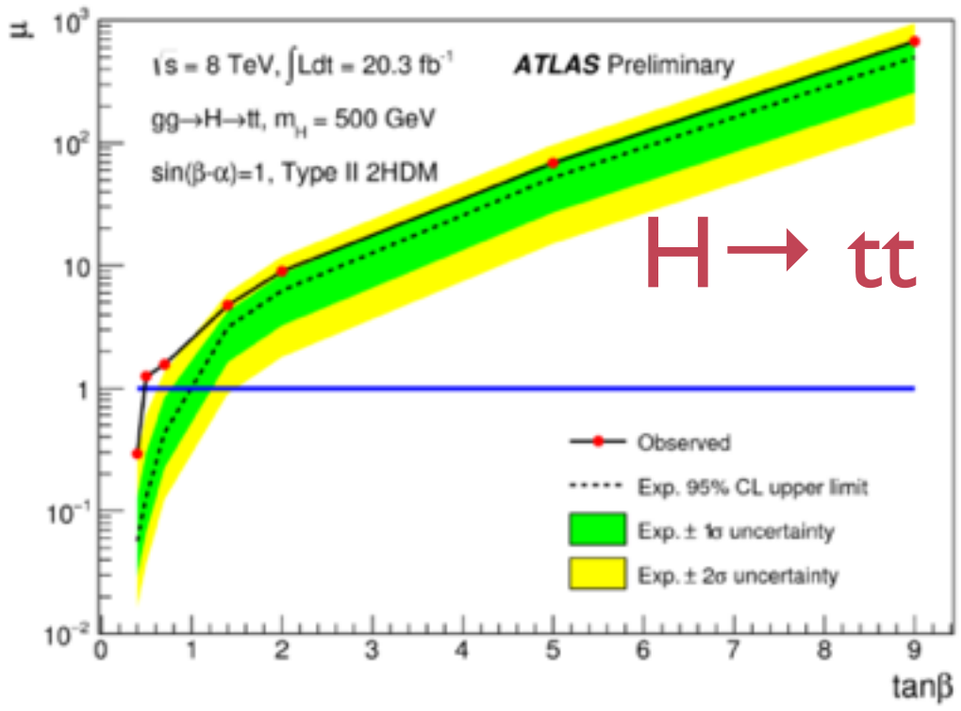
H/A→ tt decay @8TeV

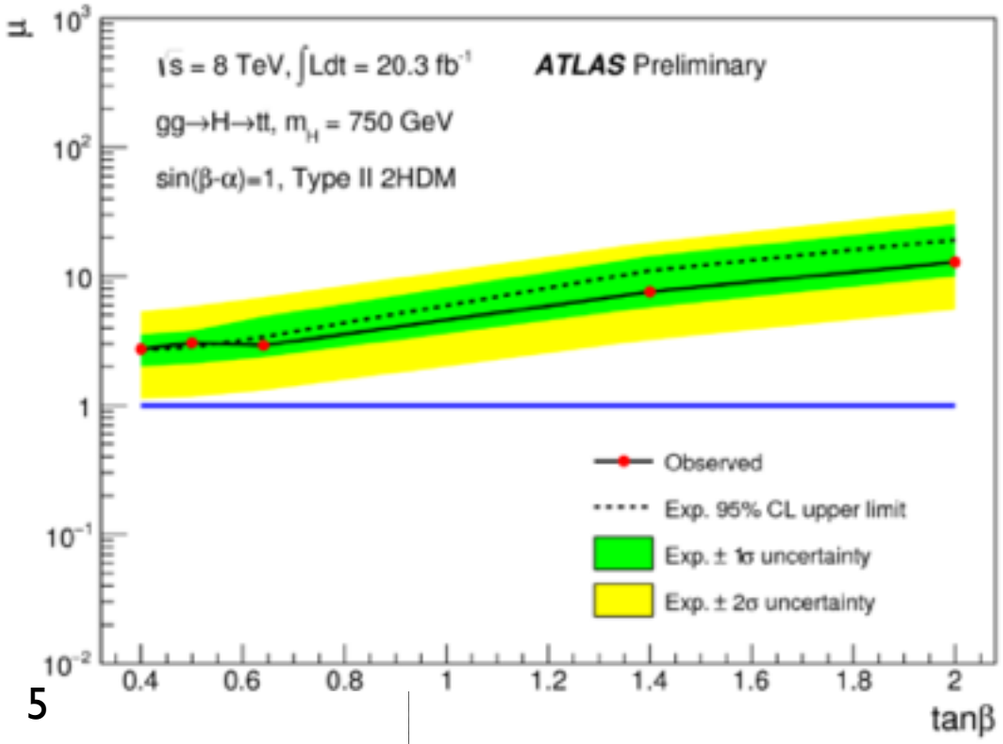




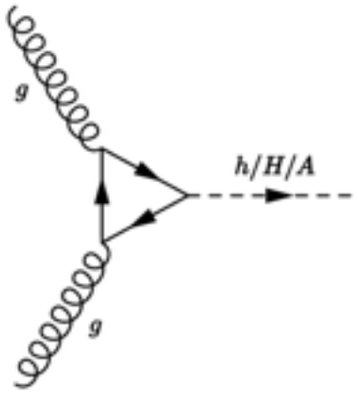
signal strength in Type-II 2HDM

These results show that with more data we will be sensitive to the interesting parameter space values (in particular in the low tan(β) and high mass regions).





$A/H \rightarrow \tau^+\tau^-$

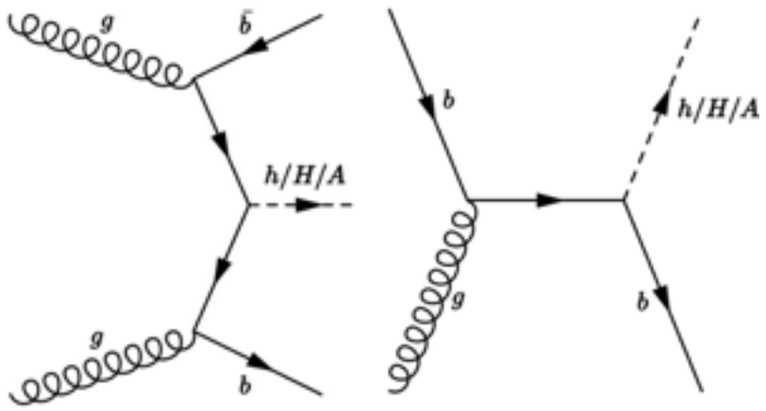


dominant
@ small tan(β),

13.3 fb^{-1} @13 TeV coupling to τ and b enhanced at large tan(β) wrt to SM. Two production modes: ggF and b associated production.

Categories:

- [lep-had , had-had] ⊗[b-tagged, b-veto] + lep-had high E^T_{miss} (>150 GeV)



dominant
@ large tan(β),

	lep had				had had	
	b-veto	b-tag	high MET		b-veto	b-tag
trigger	1 lep > 20-140 GeV	1 lep >20-140 GeV	MET>70-100 GeV	**tau trigger p_T>80 (125 GeV)**	✔	✔
1 PT>30 GeV lepton	✔	✔	✔	**1 medium/1 loose tau**	p_T >110/65 GeV (140/65)	pT>110/65GeV
1 pT>25 GeV tau (medium)	✔	✔	✔	**lepton veto**	✔	✔
E^T_{miss}>150 ($\tau_e\tau_{had}$) $\lvert\vec{p}+\vec{E}T_{miss}\rvert$>150GeV($\tau_\mu\tau_{had}$)			✔			
M_T(e/μ, E^T_{miss})<40 GeV	✔	✔	✔			
Δφ(τ, e/μ) > 2.4	✔	✔	✔	**Δφ(τ1, τ2) > 2.7**	✔	✔
≥1 b-tag (77%)		✔		**≥1 b-tag (70%)**		✔
b-veto (0-btag)	✔				✔	

All have opposite charge requirement+ Z mass veto for $\tau_e\tau_{had}$ channel

A/H→τ+τ- (lep-had)

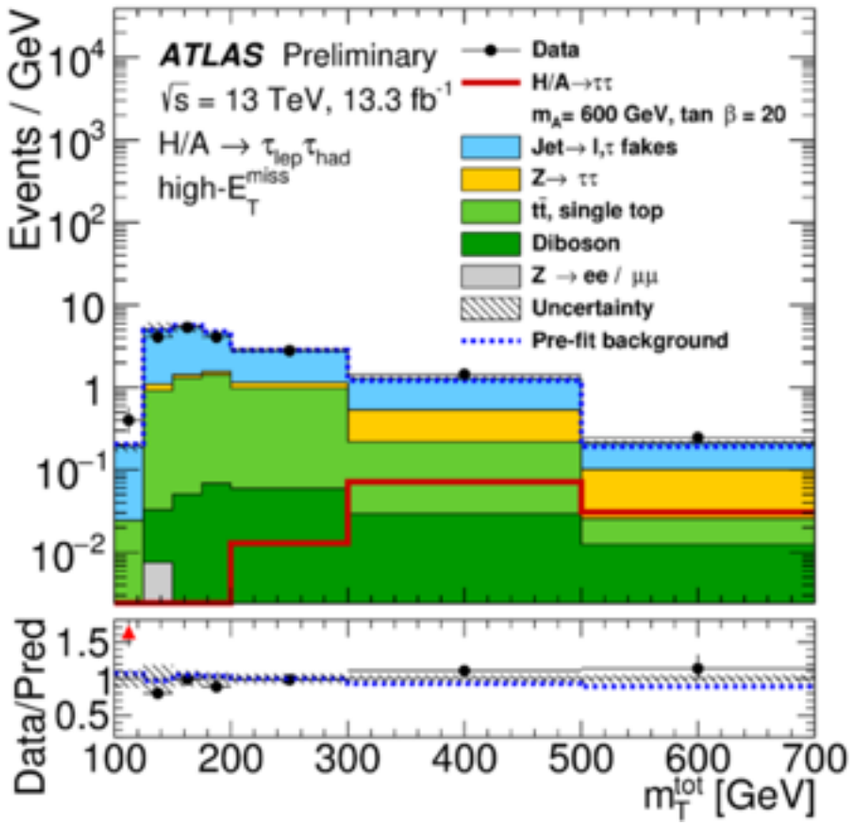
Main backgrounds:
jets misidentified as leptons and τ-> Data Driven

- Fake Factors (FF) for tt and W+jets from W+jets/top CR (obtained reversing $m_T(l, E^{miss})$ requirement)
- Fake Factor for multi-jet (MJ) obtained from QCD CR (e/μ isolation inverted)

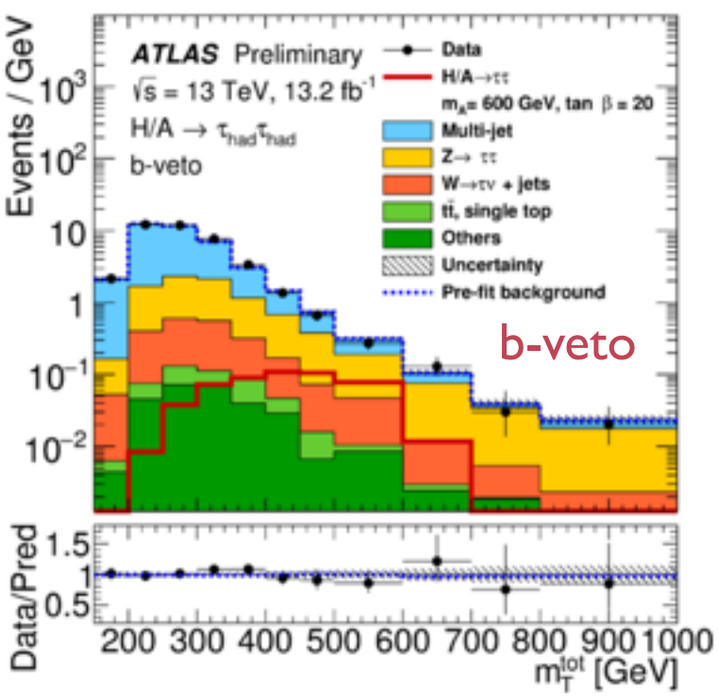
$$FF_{comb} = FF_{MJ} \times rQCD + FF_{W} \times (1\text{-}rQCD)$$

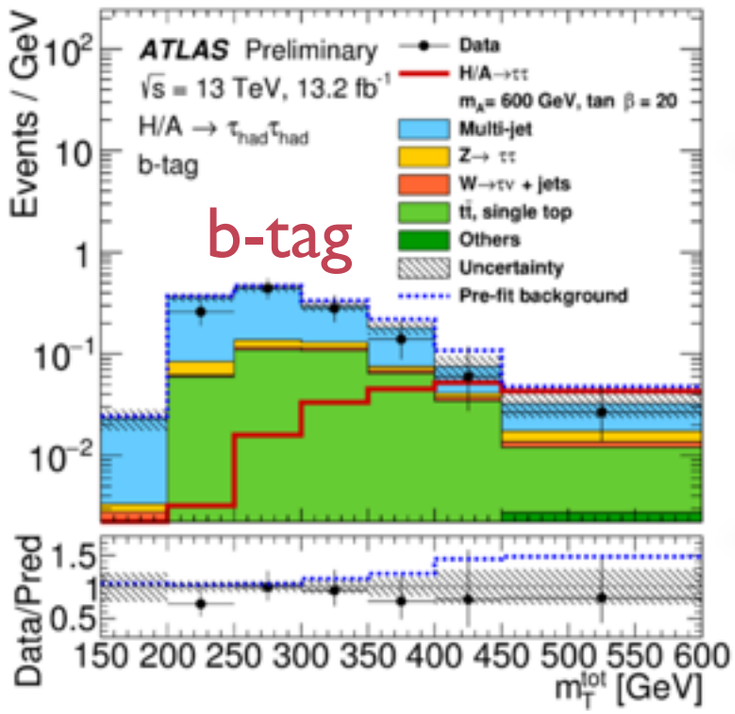
FF are then applied to events passing anti-τ_{had} ID selection

High MET



A/H→τ+τ- (had-had)

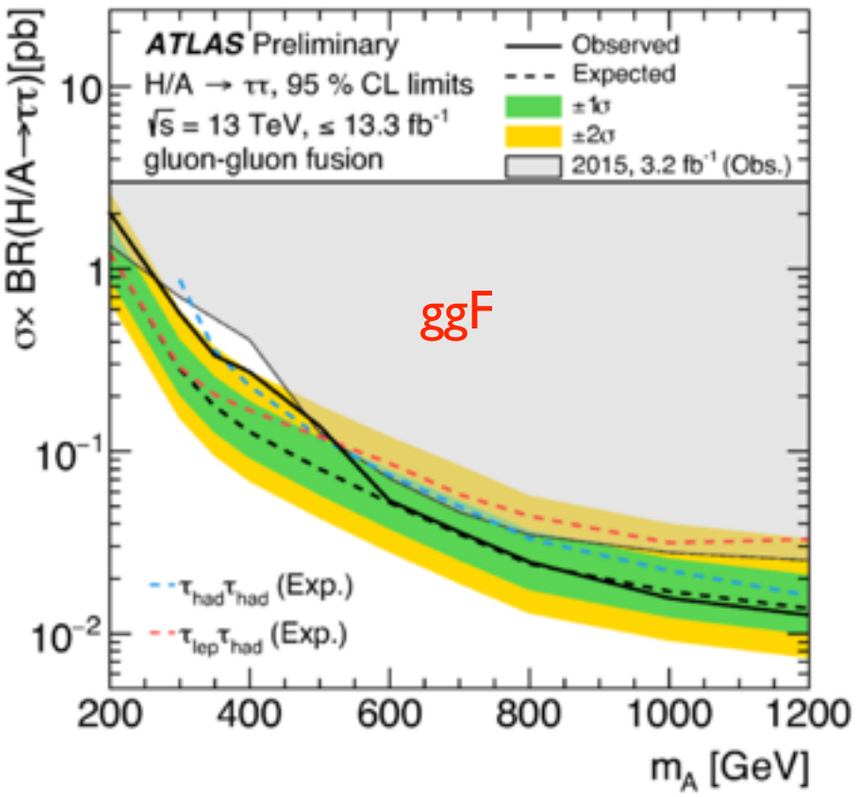


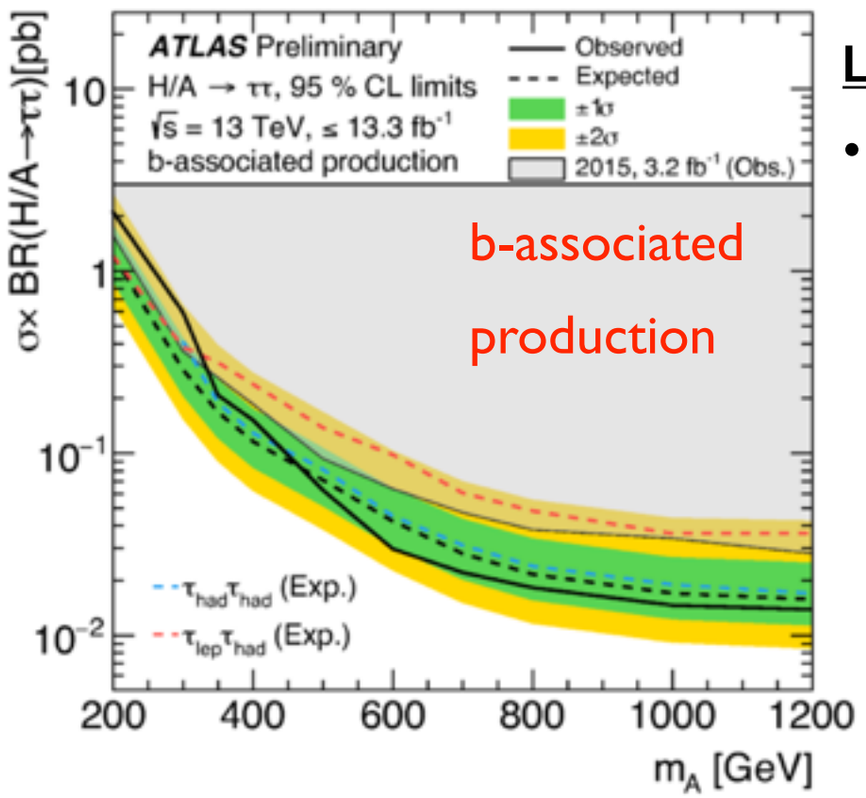


Main Backgrounds

- Multi-jet fake taus Data Driven.
  FF obtained from Multi-jet CR.
  - CR Lead τ anti-id (medium)
  - applied to data events in a CR that has sublead τ anti-ID tau(loose).
- W+jets and tt bkg are also evaluated applying to MC a fake rate from CR.
  -W+jets: 0 b-tag+1μ
  - tt: ≥ 1 b-tag+ 1 μ

$A/H \to \tau^+\tau^-$





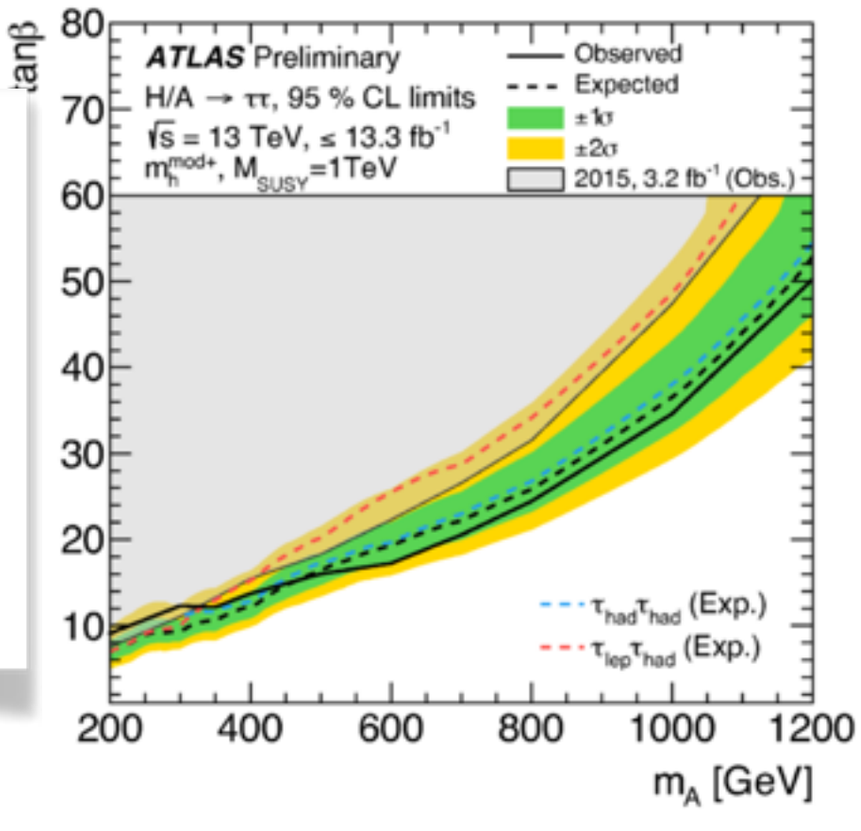
Limits on σ x BR (NWA)

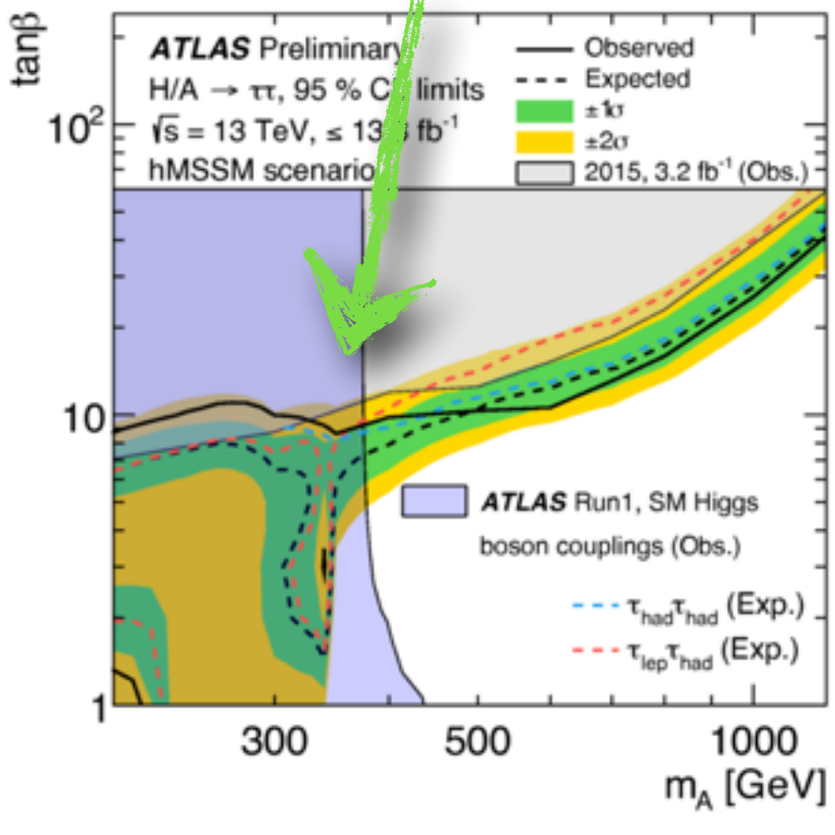
- had-had $M_{A/H}$>300 GeV due to low sensitivity below.

exclusion from 2 pb-14 fb

irregular σ_{ggF} behavior close to A/H→ttbar threshold

hMSSM more stringent exclusion than m_h^{mod+} (because the latter has low mass neutralinos). Some exclusion also for for low tanβ and m_A



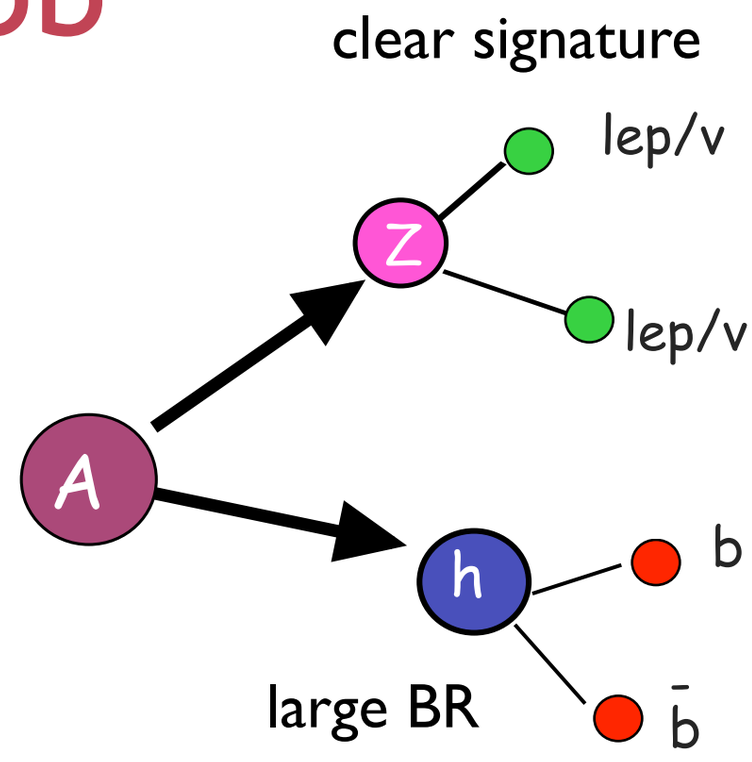


A → Zh → (ll or νν)bb

Search focuses on CP-odd A Narrow Width @13 TeV, 3.2 fb^{-1}

(h→bb SM BR and A width are adapted to 2HDM when needed)

Variable	Low-p_T^Z	High-p_T^Z
Common selection		
p_T^Z [GeV]	<500	≥ 500
$N_{b\text{-tag jet}}$	1,2	1,2
$N_{\text{small-}R\text{ jet}}$	≥2	≥0
$N_{\text{large-}R\text{ jet}}$	≥0	≥1
m_{dijet} or m_{jet} [GeV]	110–140	75–145
0-lepton selection		
E_T^{miss} [GeV]	> 150	–
$\sum_{i=1}^{N_{\text{jet}}=3(2)} p_T^{\text{jet}_i}$ [GeV]	> 150 (120)$^{(*)}$	–
p_T^{miss} [GeV]	> 30	> 30
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\text{miss}})$	$< \pi/2$	$< \pi/2$
$\Delta\phi(\vec{E}_T^{\text{miss}}, h)$	$> 2\pi/3$	$> 2\pi/3$
min[$\Delta\phi(\vec{E}_T^{\text{miss}}$, small-$R$ jet)]	$> \pi/9^{(*)}$	$> \pi/9^{(*)}$
$\Delta\phi(j, j)$	$< 7\pi/9$	–
Number of hadronic taus	0	0
Number of b-tag track-jets not associated to the leading large-R jet	–	0
2-lepton selection		
m_{ee} [GeV]	70–110	70–110
$m_{\mu\mu}$ [GeV]	70–110	55–125
$E_T^{\text{miss}}/\sqrt{H_T}$ [$\sqrt{\text{GeV}}$]	< 3.5	–



Events are categorized:

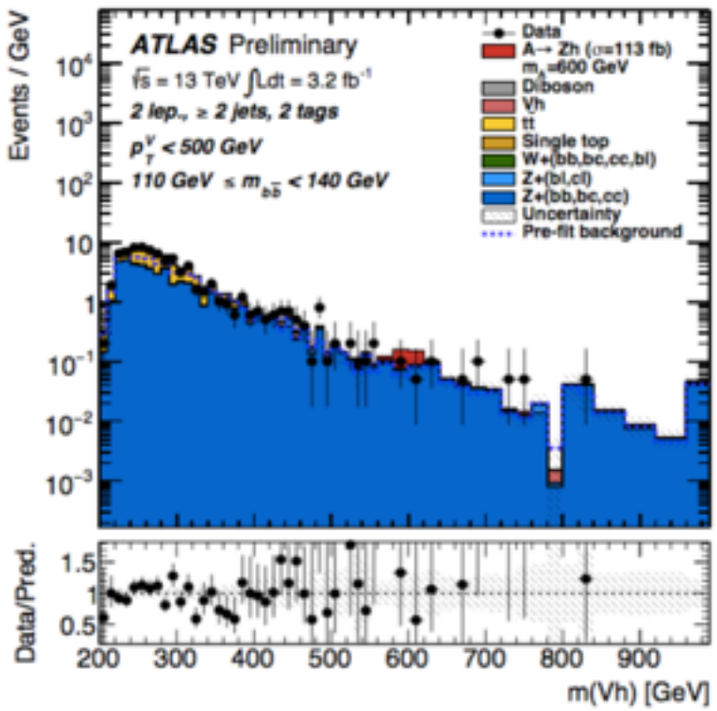
-0- or 2-leptons (MET or single lepton trigger,)

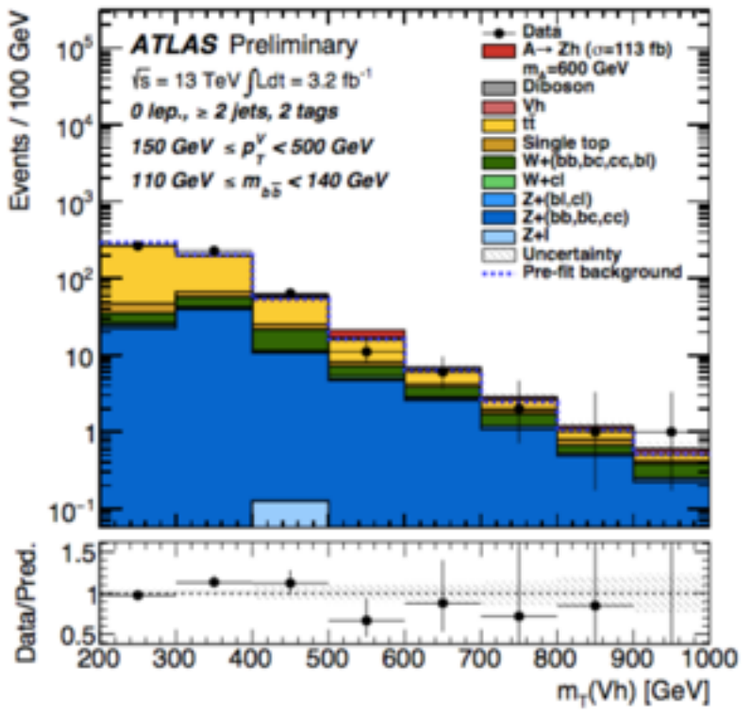
-p_T^Z low/high(<500 GeV), small/fat R-jets used

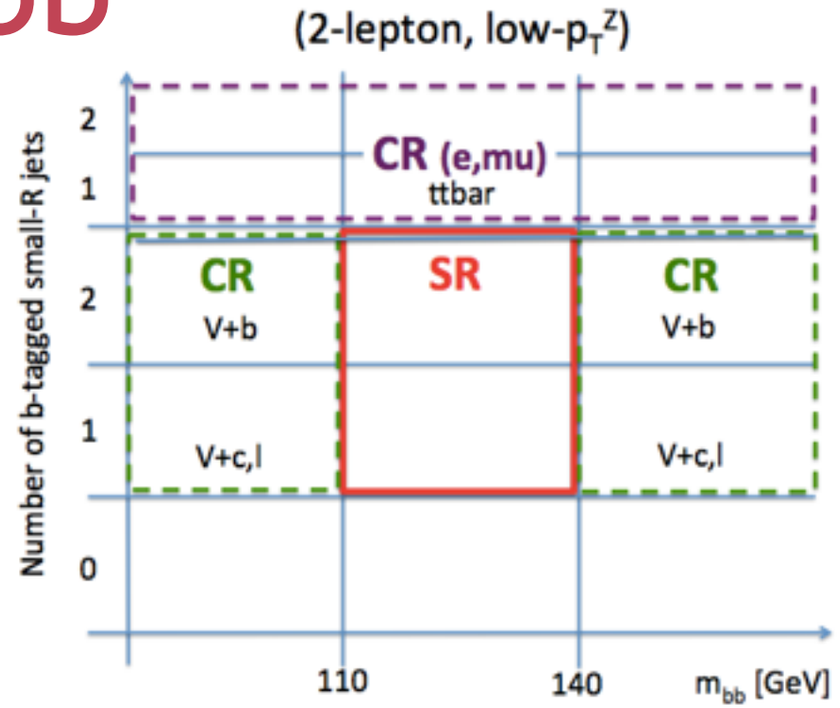
-number of *b*-tagged jets (1-tag or 2-tag).

mjj compatible with mh(125 GeV).

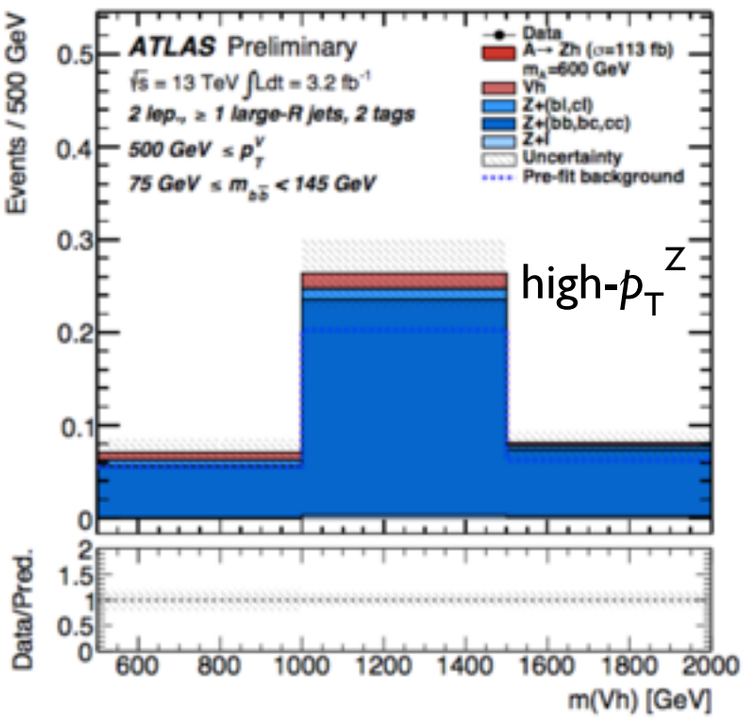
A → Zh → (ll or νν)bb

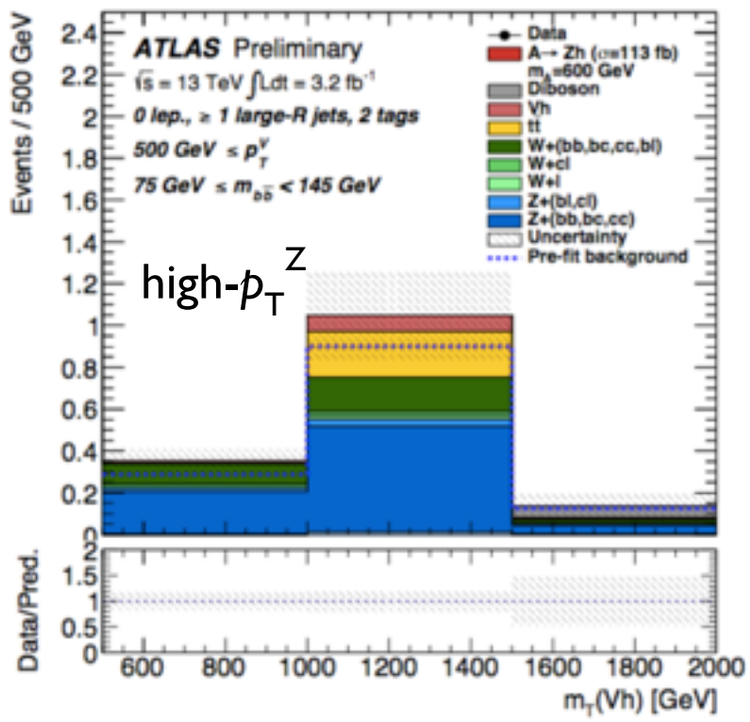






(b) 2-lepton, low-p_{T}^{Z}



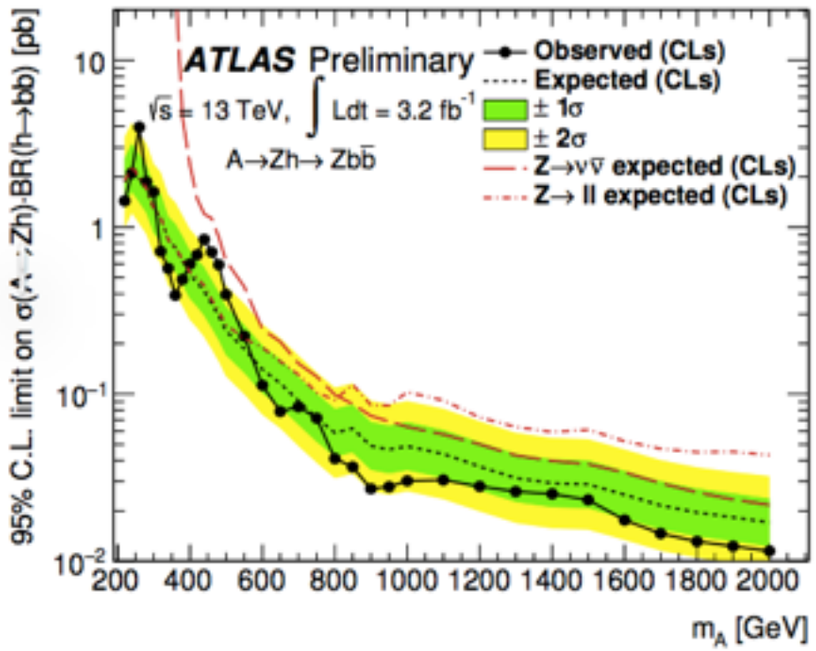


Backgrounds:

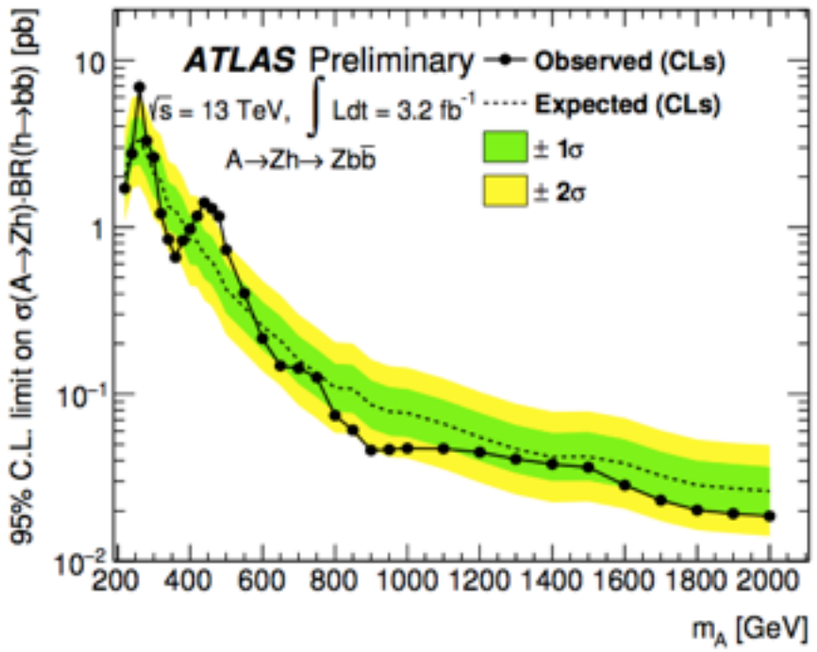
- Z(ll or νν)+b,c,l
  CR outside m(bb) window
- t t background: 2 CR (for 1,2 b-tag) with different flavor eμ final state (in 2 leptons low-p_{T}^{Z})

No significant excess found

A → Zh

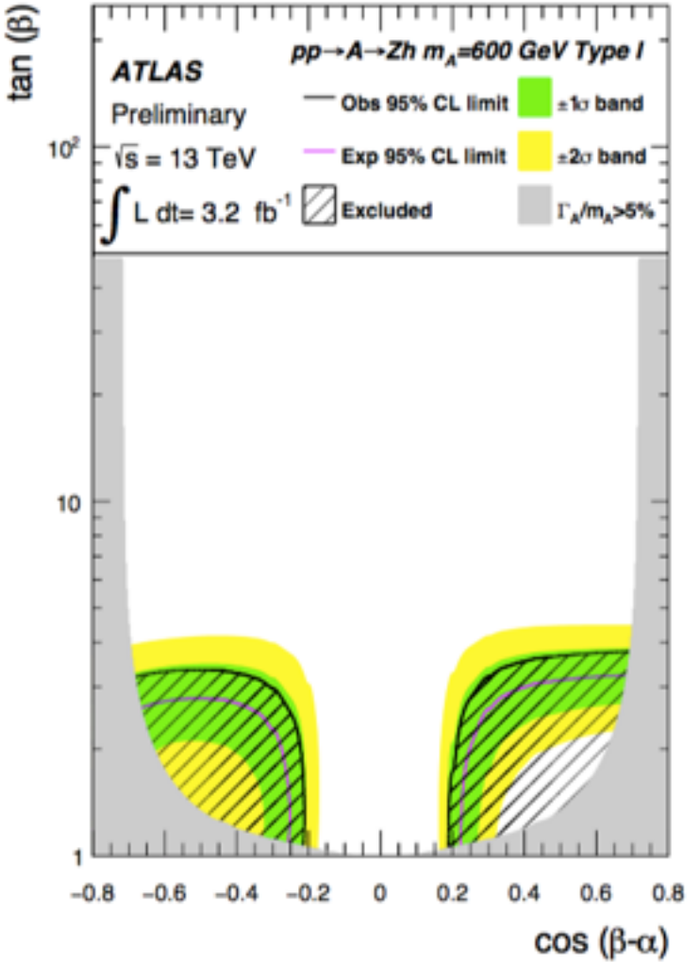


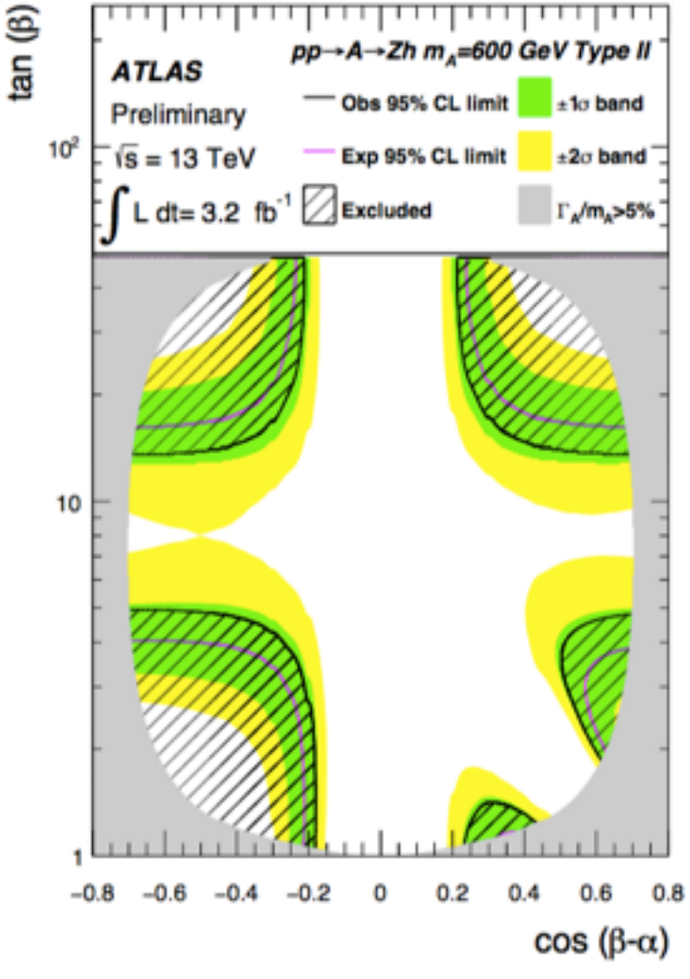
(a) Pure gluon fusion production



(b) Pure *b*-quark associated production

95% CL limits on ggF and b assoc. production





Two upward 2 **σ** fluctuations at m_A=260 and 440 GeV.

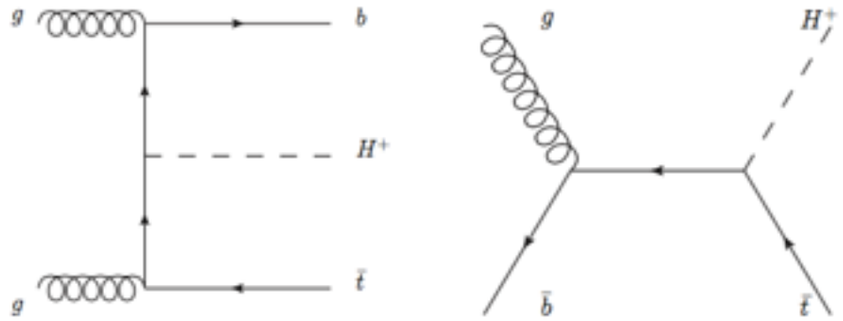
limits on 2HDM(I) and 2HDM(II)

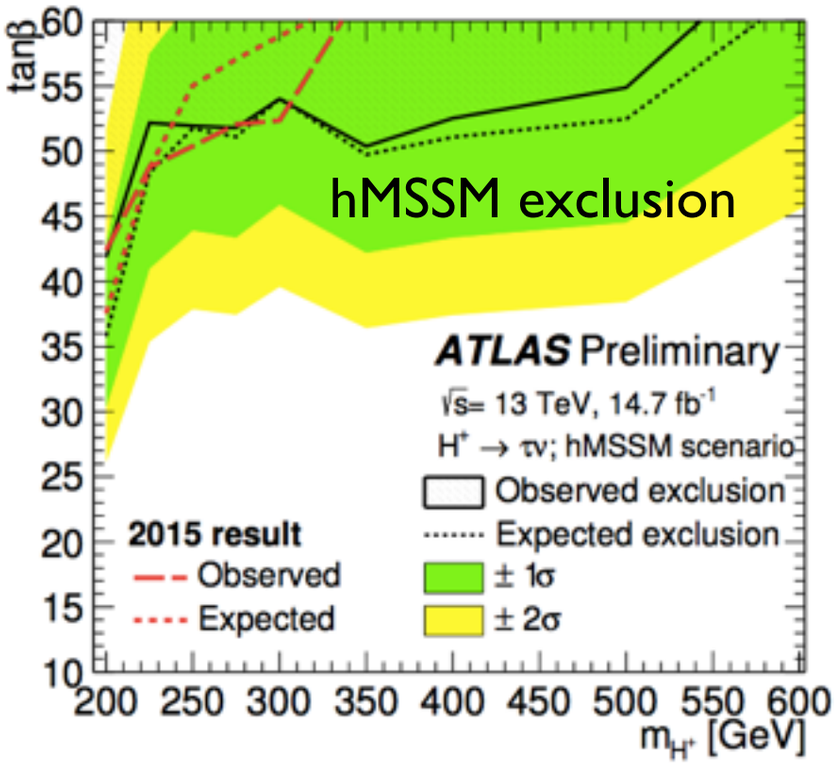
NWA corrected to 2HDM width using relativistic Breit wigner,

Only parameter space points with Γ_A/m_A<5% are considered

Charged Higgs

[more details in parallel talk by A. Ferrari]





$H^{\pm} \rightarrow \tau\nu$: W from top and τ decaying hadronically

Selection: E_{Tmiss}>150 GeV, 1 τ_{had} and ≥3 jets (≥1 b-tag)

Backgrounds:

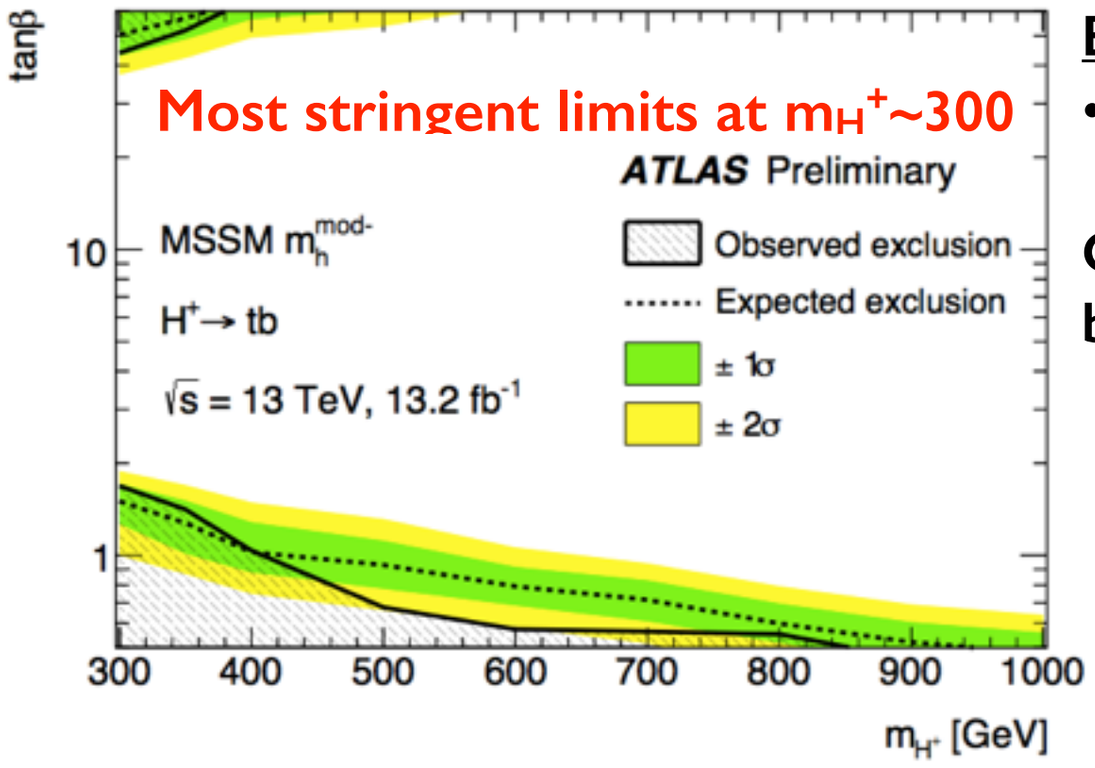
- $W \rightarrow \tau\nu$,tt true τ_{had}, from MC.
- τ_{had} fakes, mainly multi-jet: from data.

$tbH^{\pm}(\rightarrow tb)$: tt semi-leptonic, similar to tth(bb)

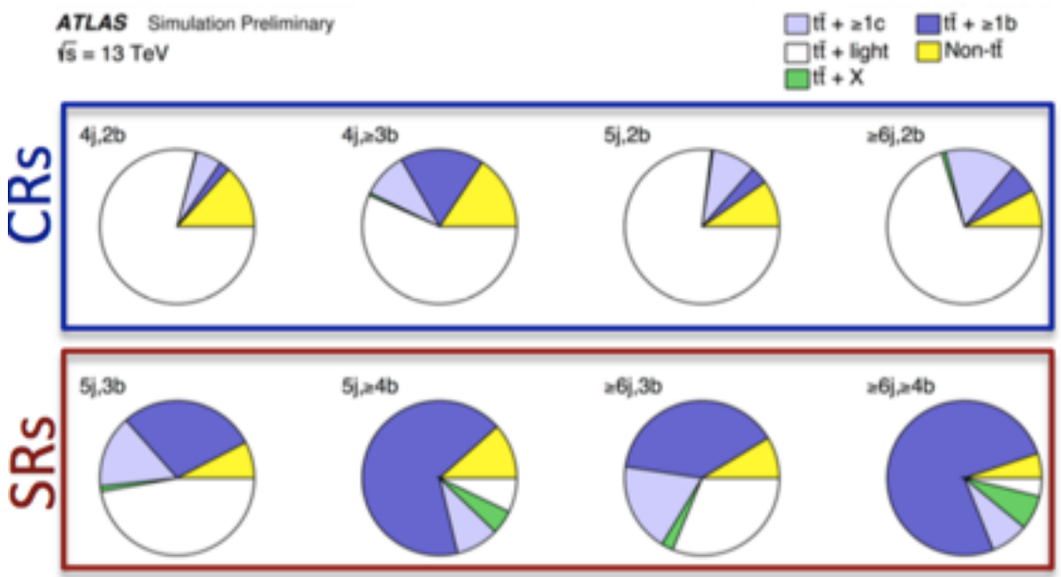
Selection: 1 lepton ≥4jets (≥ 2 b-tagged)

Background:

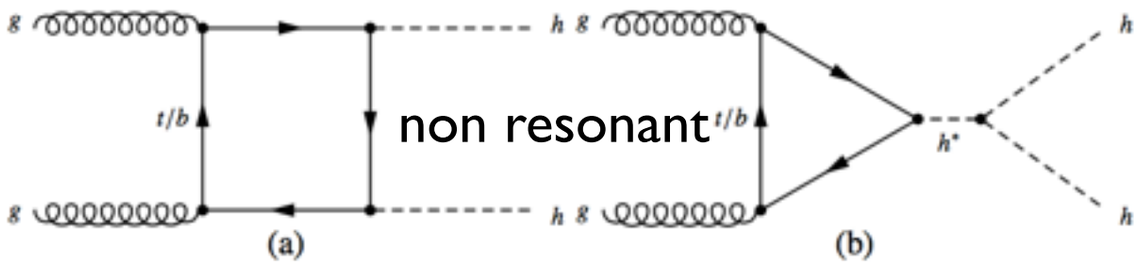
- tt+light (NNLO prediction), tt+≥1c, tt+≥1b free in fit.

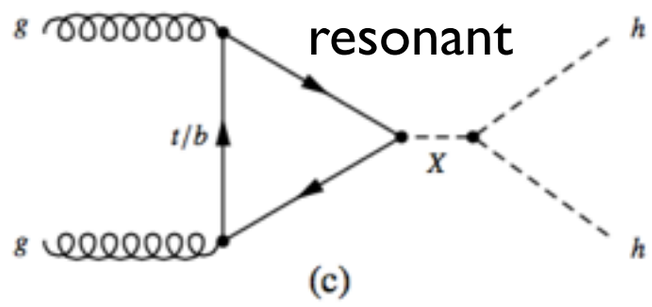


Categorization by n-j and n-b



di-Higgs





SM Di-Higgs production small, enhanced in BSM

- **bbγγ** (@13 TeV 3.2 fb^{-1}) no excess

  (run I 2.4σ excess at 300 GeV)

- **WWγγ (WW→lνqq), @13TeV 13.3 fb^{-1}**
  - 2 photons, $|m_{\gamma\gamma}-m_h|<2\sigma_{\gamma\gamma}$ (1.7 GeV) di-photon continuum from sidebands
  - ≥2 jets (0 b), ≥1/0lepton (SR/CR)

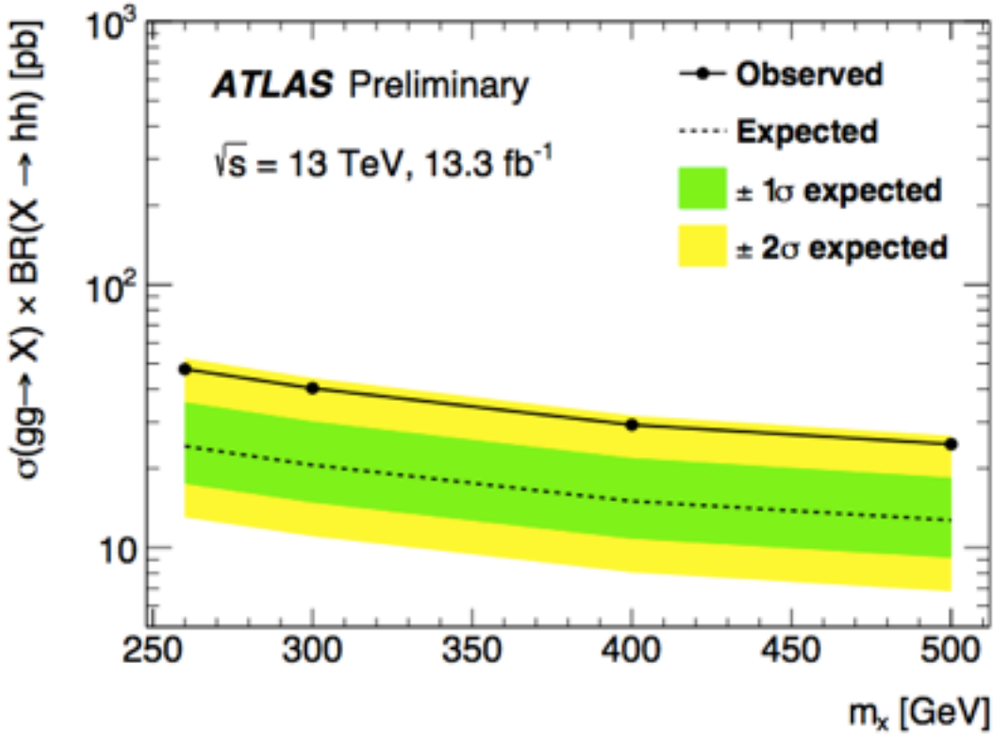
  simple counting experiment: has a slight excess

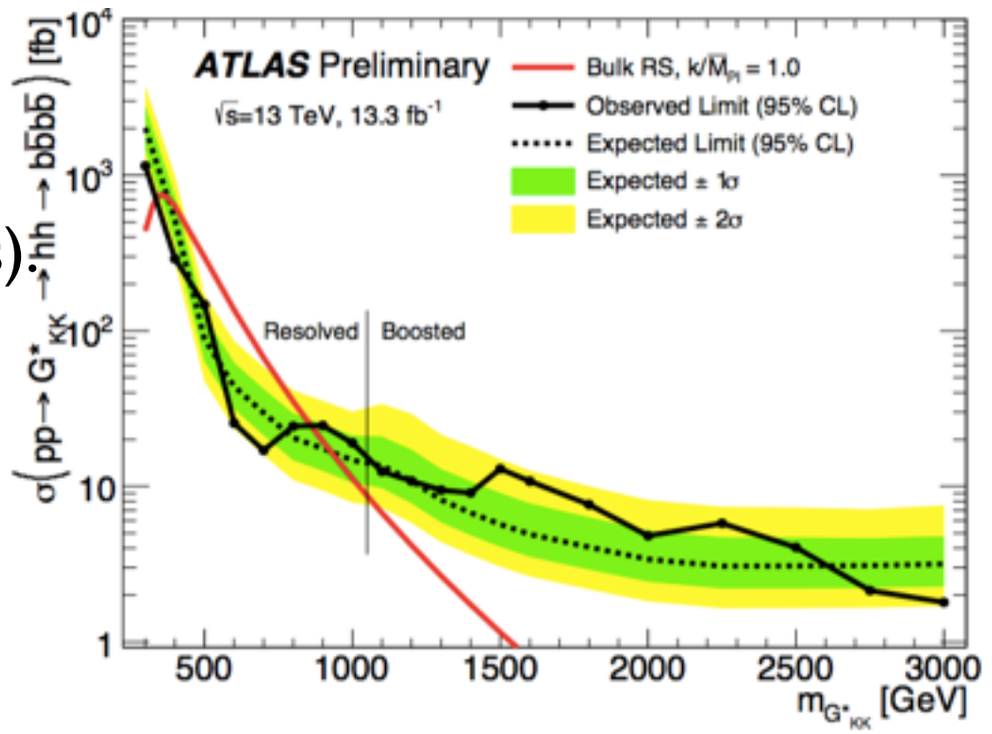
  15 evts obs for 7.88±1.24 exp

- **bbbb, @13TeV 13.3 fb^{-1}**

  resolved/boosted (4 small R/ 2 fat jets associated to b's), m_h(125) constraint used.

  Main Background: multi-jet (~90% depending on channel) obtained from data in mh sidebands





more details in parallel talk by B. Tong

tt+HF final states interpretation

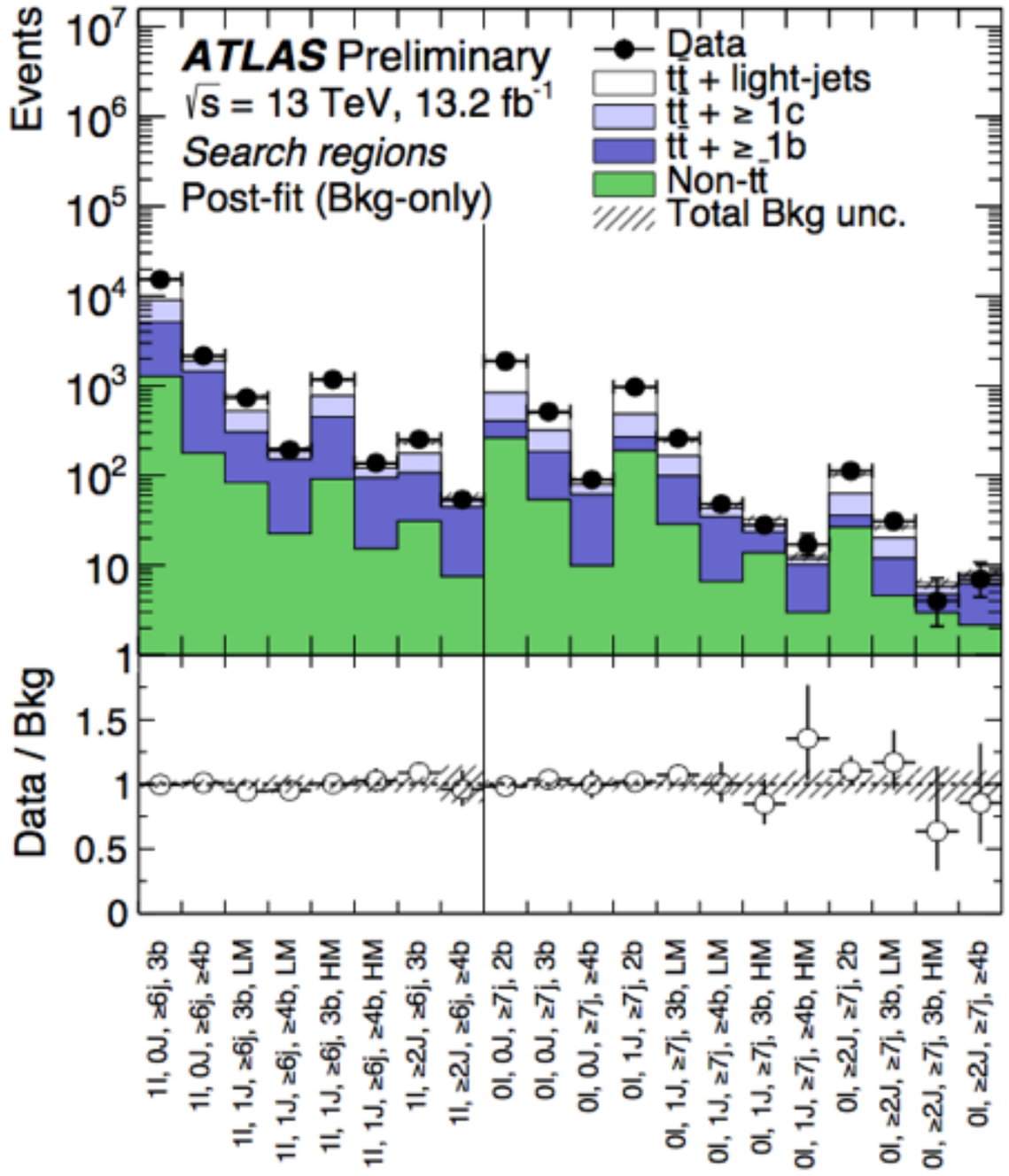
ATLAS-CONF-2016-104

Designed for prod. of 2 vector like top quarks TT→HtHt, HtZt and HtWb, or 4t final state.

Reinterpreted in Higgs sector:

- bbH/A(→tt) or ttH/A(→tt) (complementary to H/A→tt which has negative interference)
- tbH+(→tb)
- **Search Categories:**

0 lepton (E_{Tmiss} trigger)	1 lepton (e/μ trigger)
E_{Tmiss}>200 GeV	E_{Tmiss}>20 GeV
≥6 small Rjets	≥7 small Rjets
2/3/≥4 b-jets (77%)	3/≥4 b jets (77%)
0,1 ≥2 mass-tagged jets (p_T>300 GeV)	0,1 ≥2 mass-tagged jets (p_T>300 GeV)
m_{bb}^{minDR}<100 or >100 GeV LM or HM	m_{Tmin}^{b}<160 or >160 GeV LM or HM



mass-tagged jets (recluster small R_{jet}→Large R_{jets}(R=1))

Contemporary fit in all categories of m_{eff}

(scalar sum of transverse momenta of all objects)

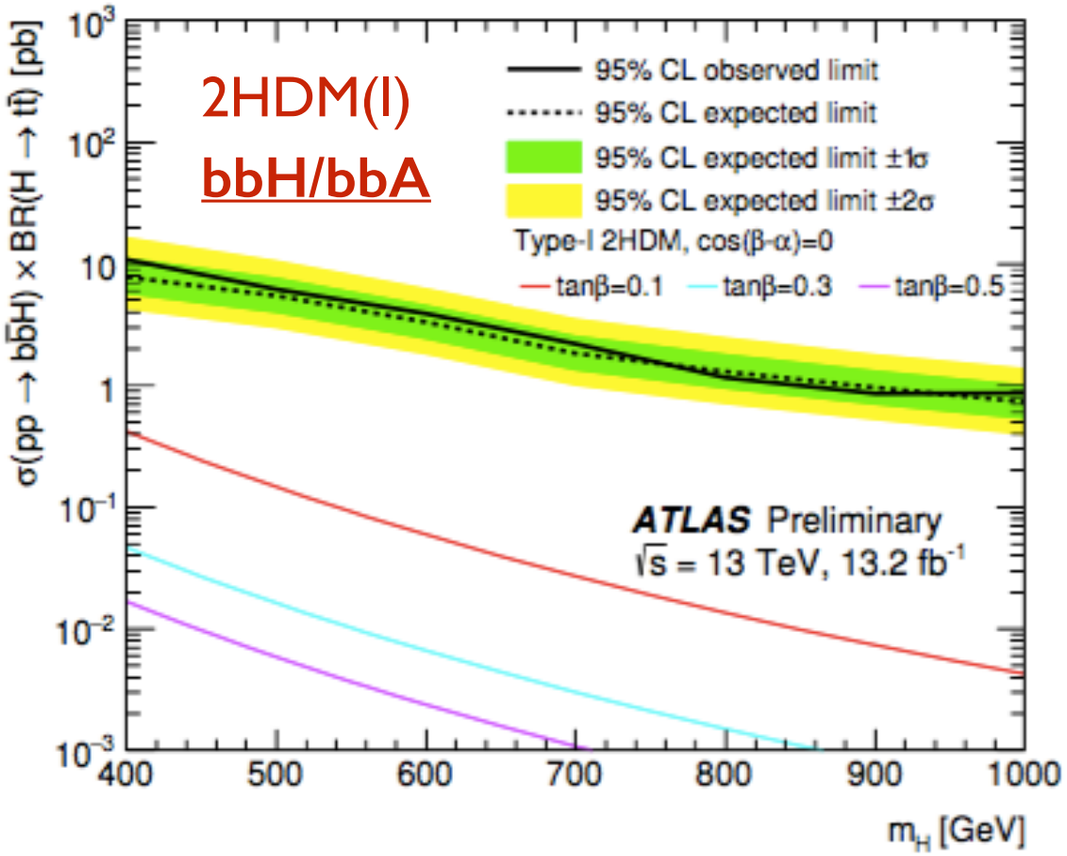
Backgrounds:

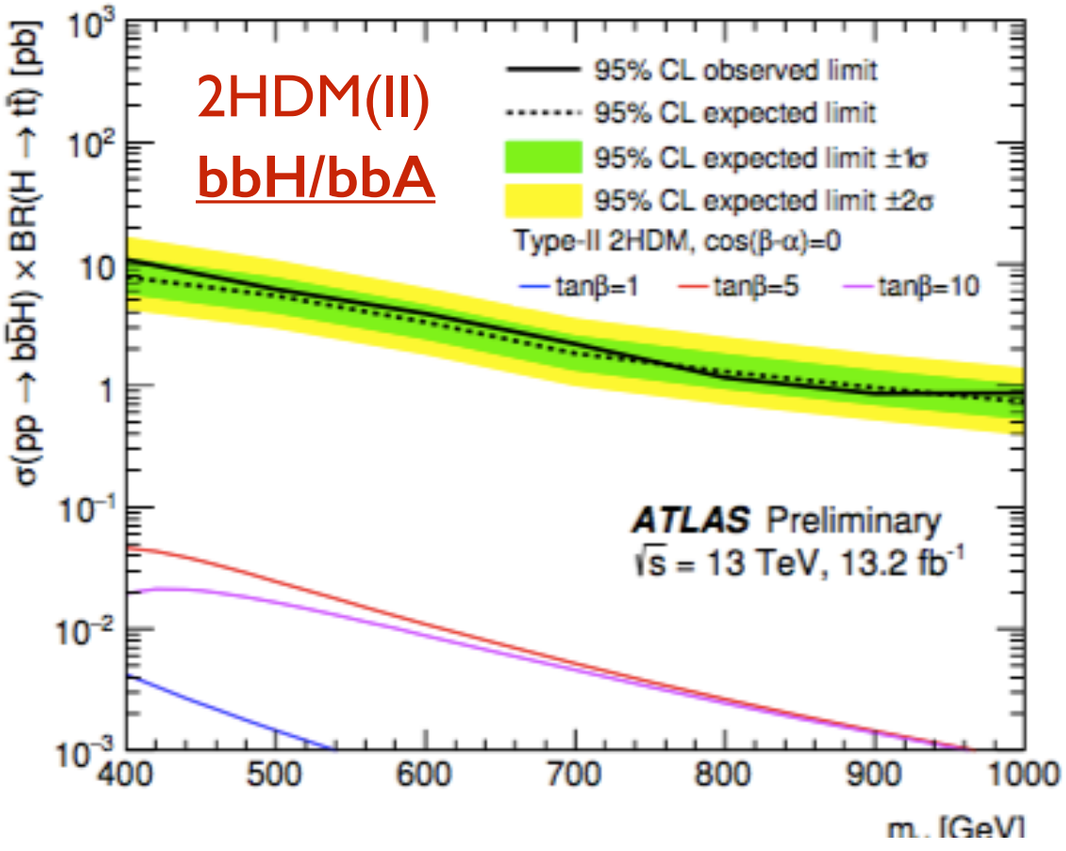
-Search categories with low S/B normalize bkgs

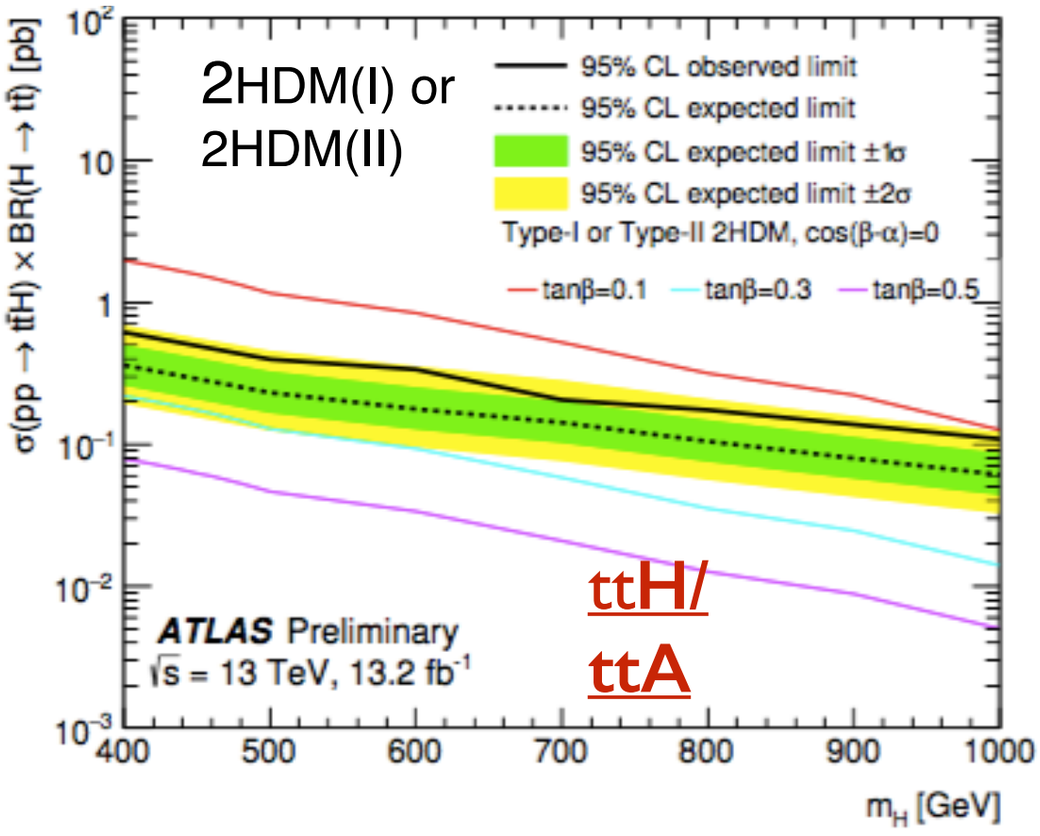
(tt+≥1b underestimated by MC→ free to float)

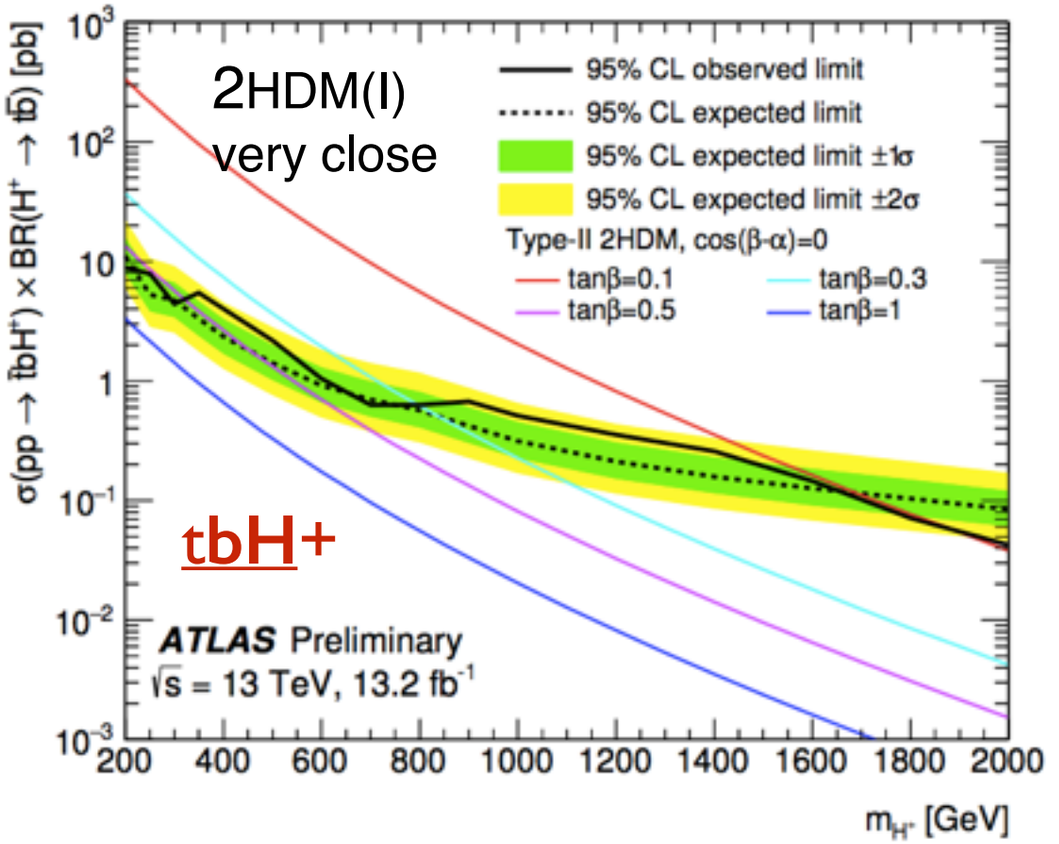
-multi-jet Data Driven Matrix Method

tt+HF Higgs interpretation







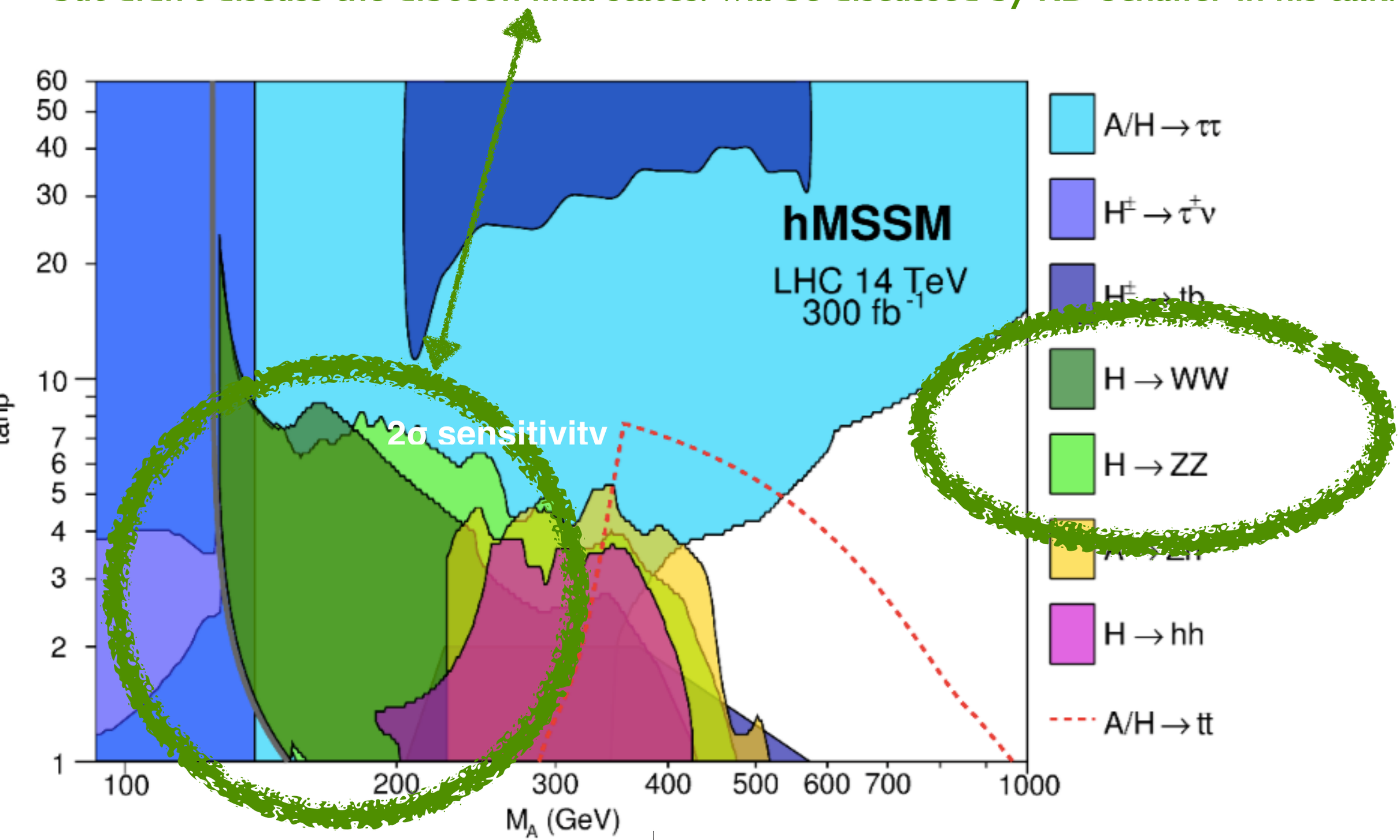


Conclusions

Thoroughly scanning the MSSM phase space

no hint of a signal

but didn't discuss the diboson final states: will be discussed by RD Schaffer in his talk!



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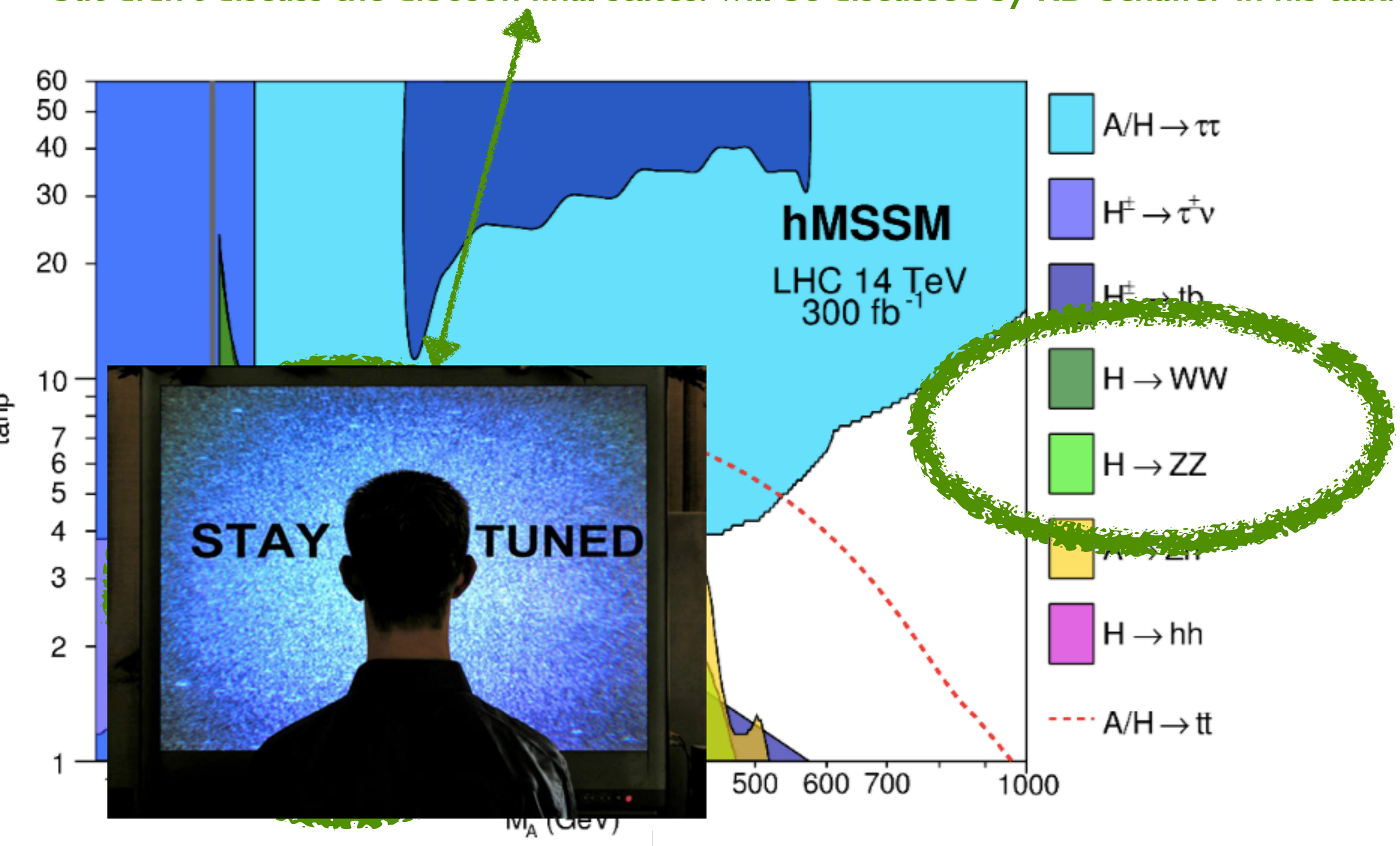
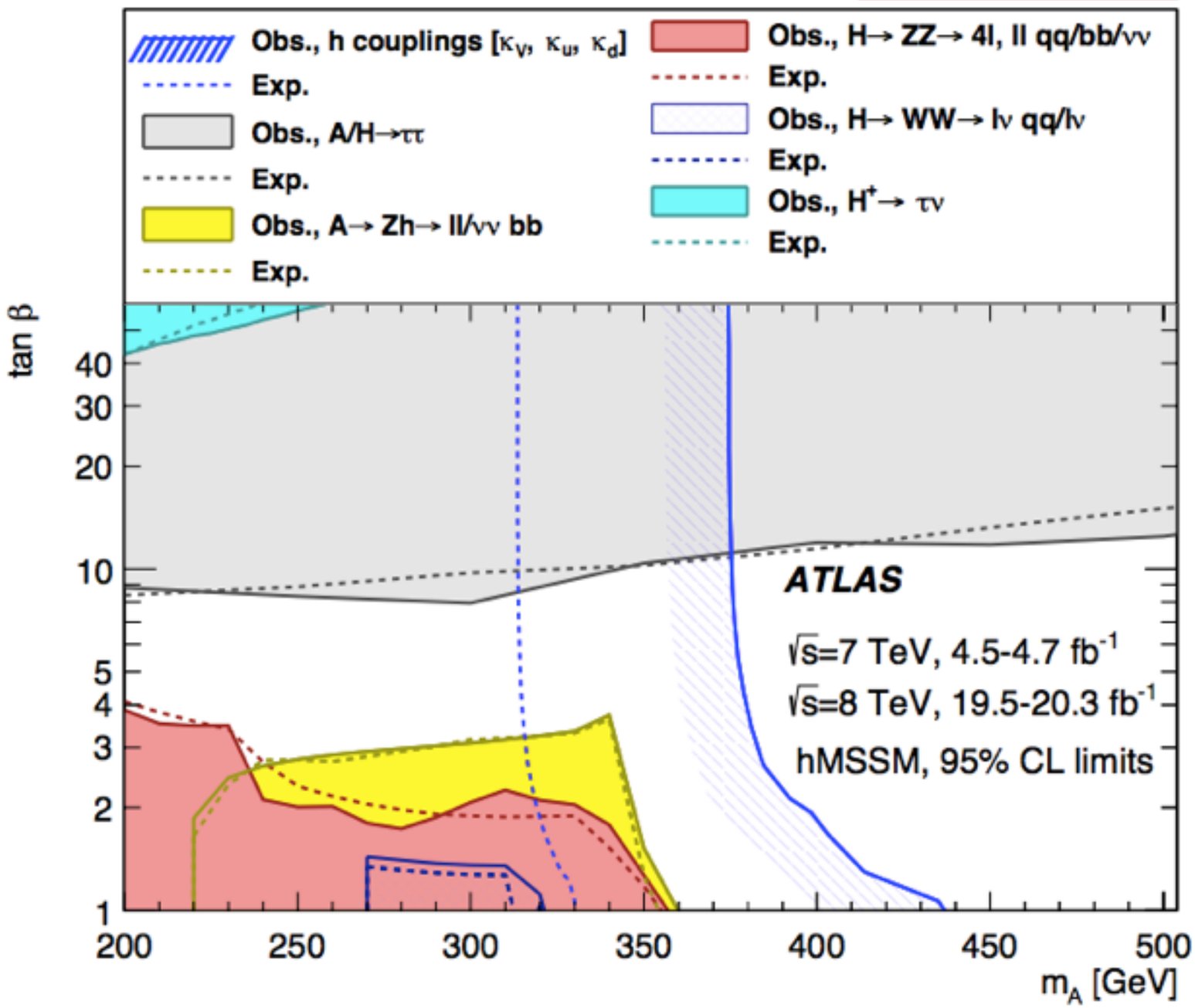


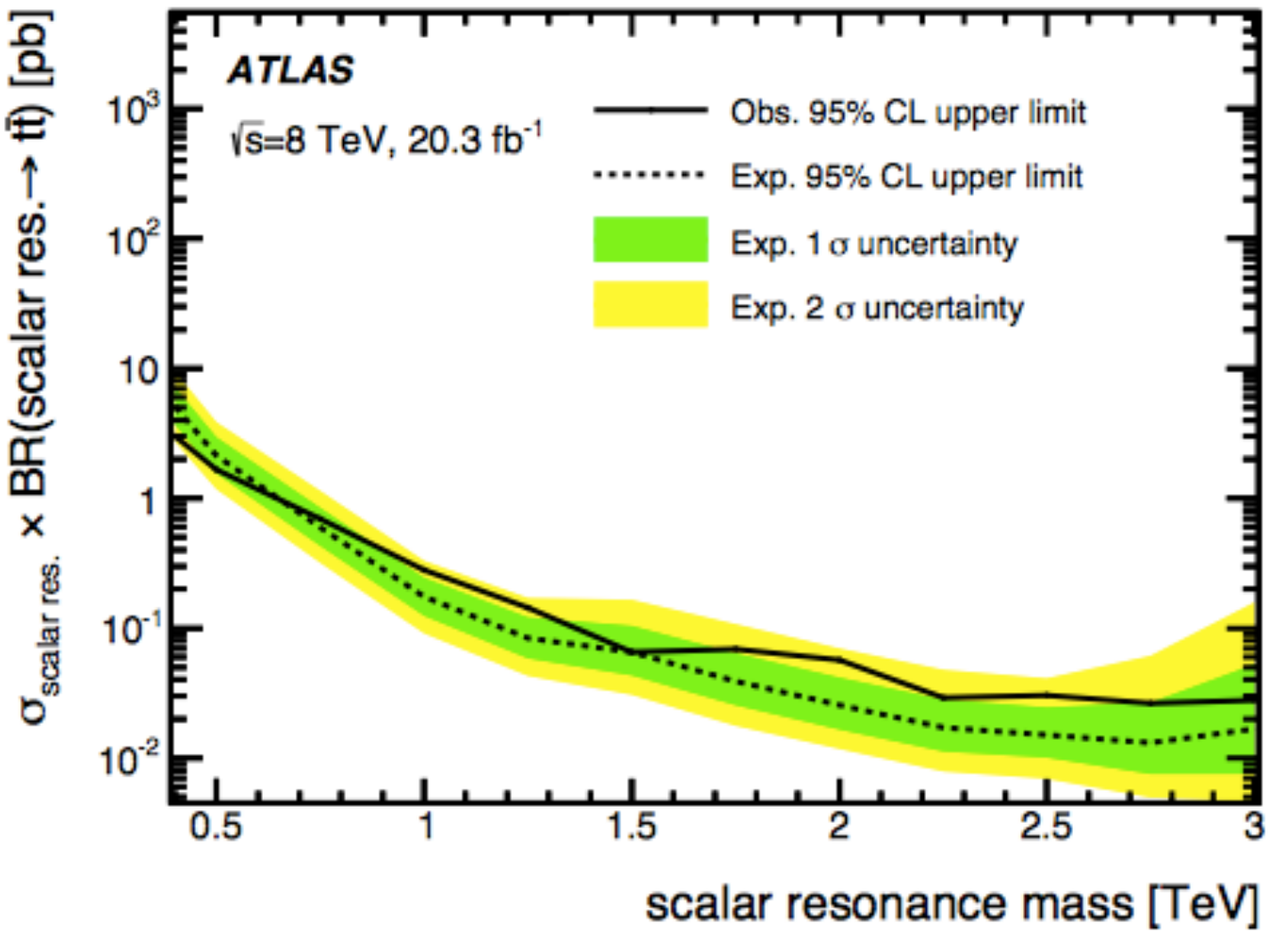
Back-up

MSSM runI

8 TeV



tt analysis at 8 TeV



A/H→τ+τ- (lep-had)

Major backgrounds:
jets misidentified as leptons and τ-> Data Driven

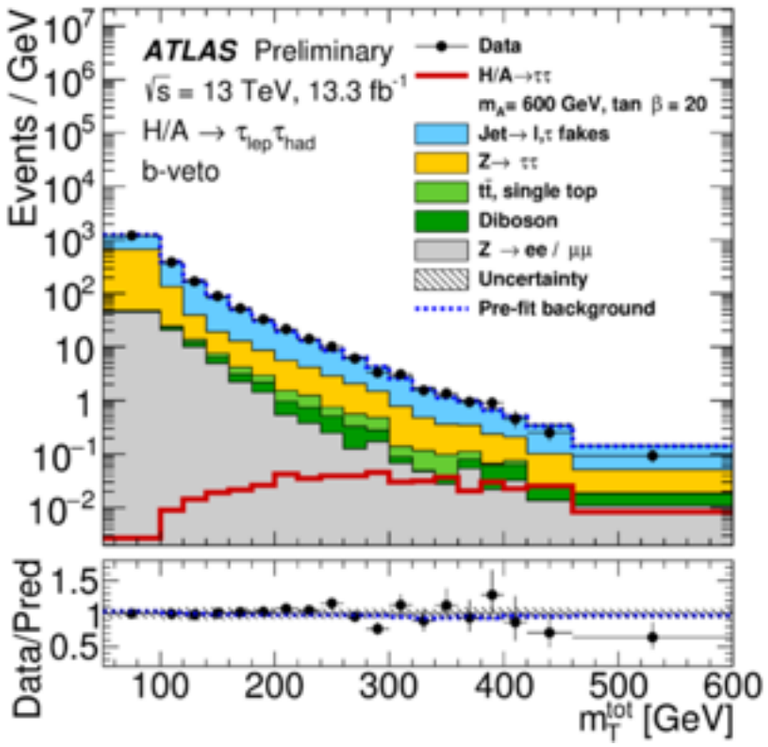
Fake Factors (FF) for tt and W+jets from W+jets/top CR (obtained reversing *m* (l,E^{miss}) requirement)

fake factor for multi-jet (MJ) obtained from QCD CR
(e/mu isolation inverted)

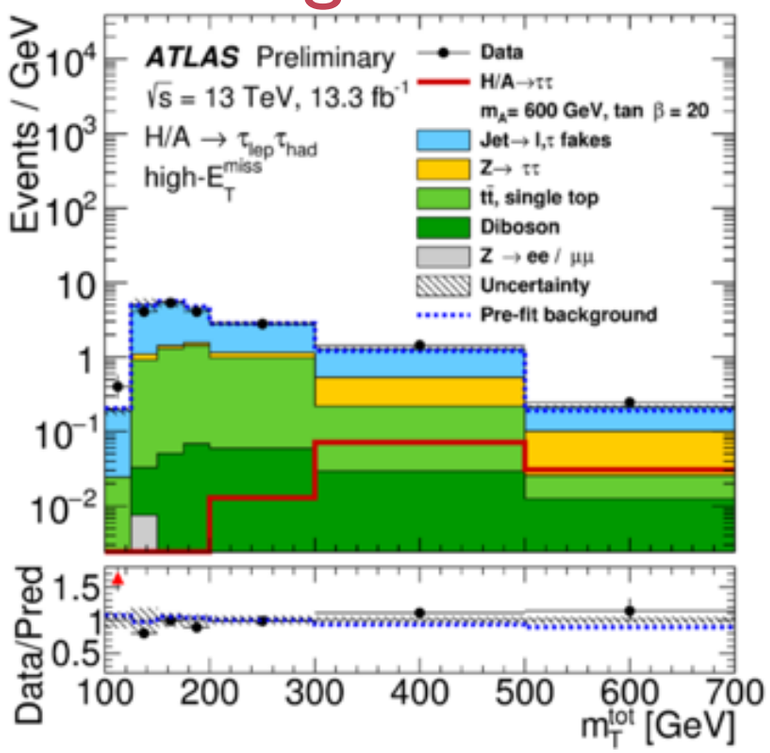
shape and normalization of the bkg estimated this way are corrected in anti-tau ID control region

$$\mathrm{FF(comb)} = \mathrm{FF}(W + \mathrm{jets}/t\bar{t}) \times r_{W/t\bar{t}} + \mathrm{FF(MJ)} \times r_{\mathrm{MJ}}$$

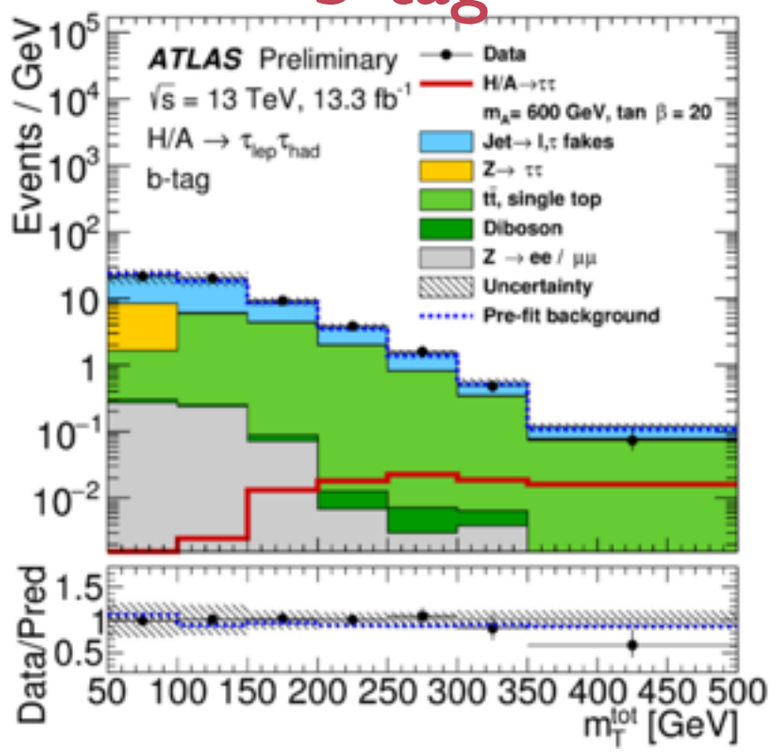
b-veto



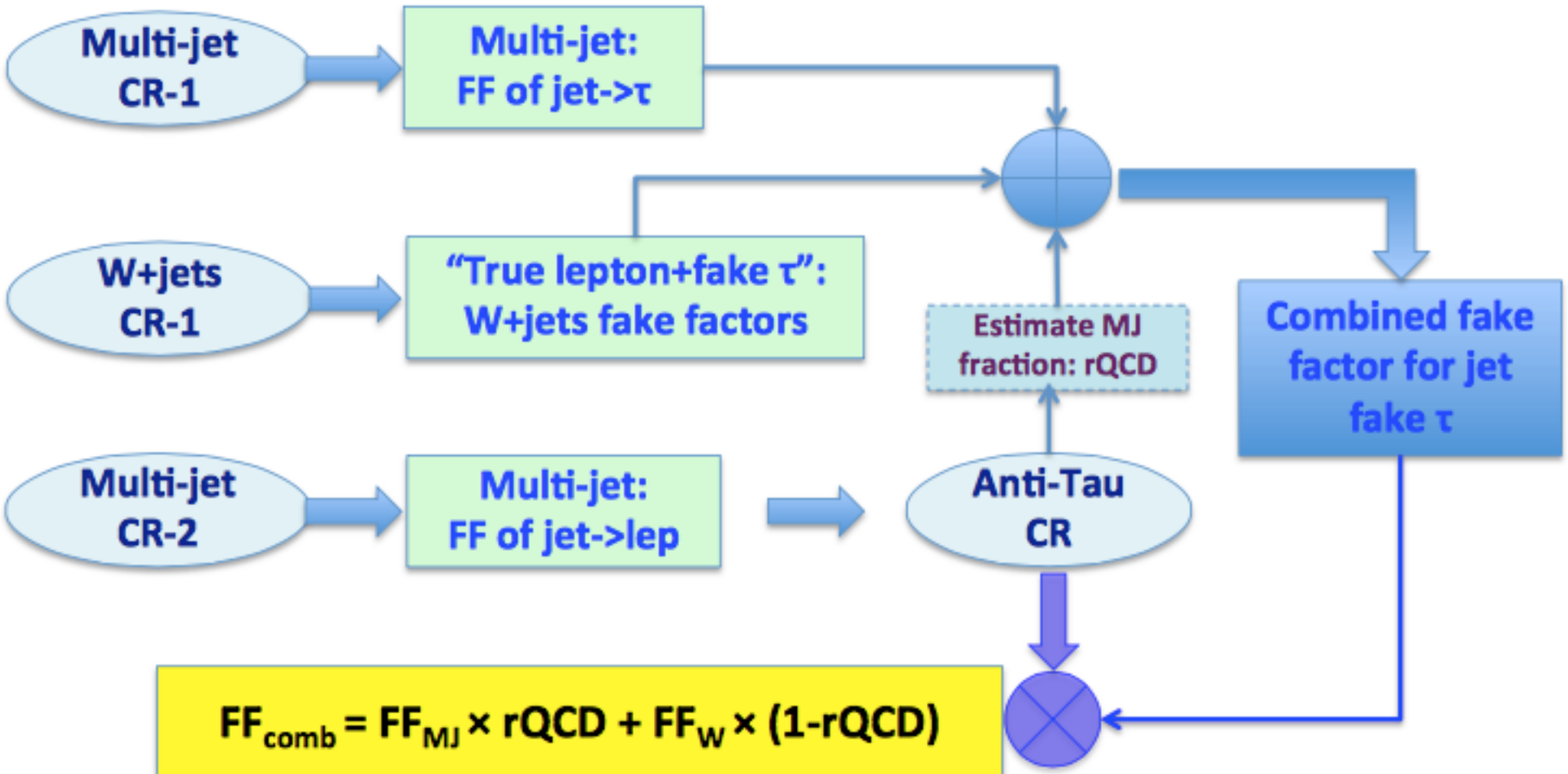
High MET



b-tag



A/H→τ+τ- (lep-had)



Jet fake τ background

- Multi-jet, W+jets, Top, Z+jets, diboson

QCD MJ fraction, rQCD, is measured in MJ enriched control region:

- Single lepton trigger
- N_{lep}=1 without offline iso.
- No loose τ
- MT (l, E_T^{miss}) < 30 GeV

Dedicated rQCD are derived from ehad and muhad in bveto, btag and high MET category.

A/H→τ+τ- (had-had)

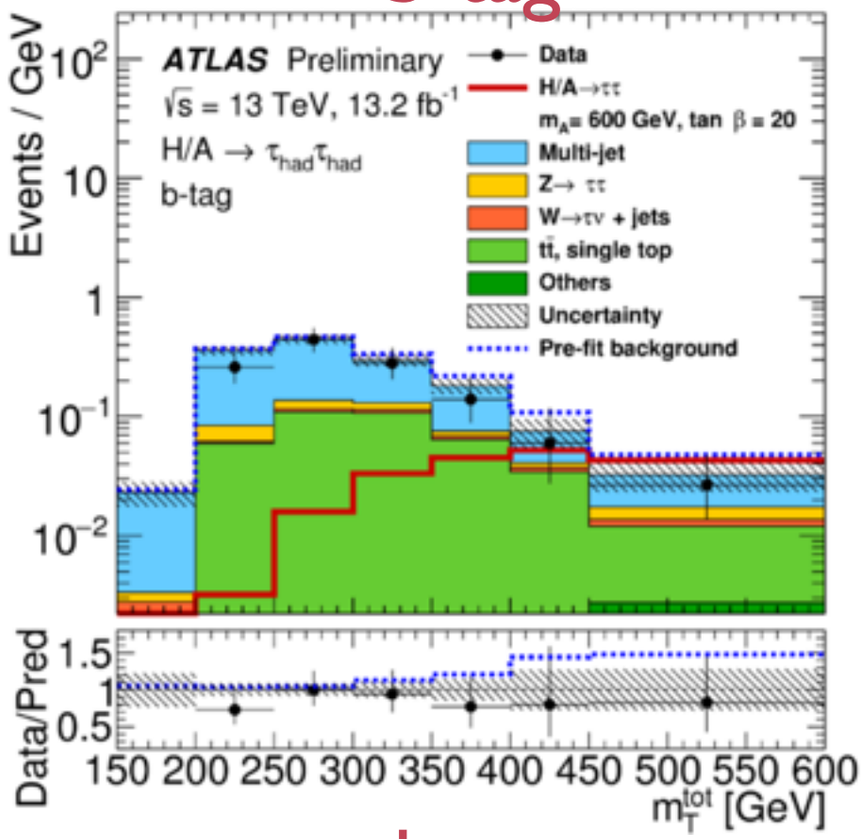
Multi-jet backgrounds faking taus Data Driven

Fake Factors parametrized by pT(τ) and number of tracks of subleading tau, and obtained from Multijet dedicated CR and then applied to
the anti-ID regions to obtain estimates for the signal regions

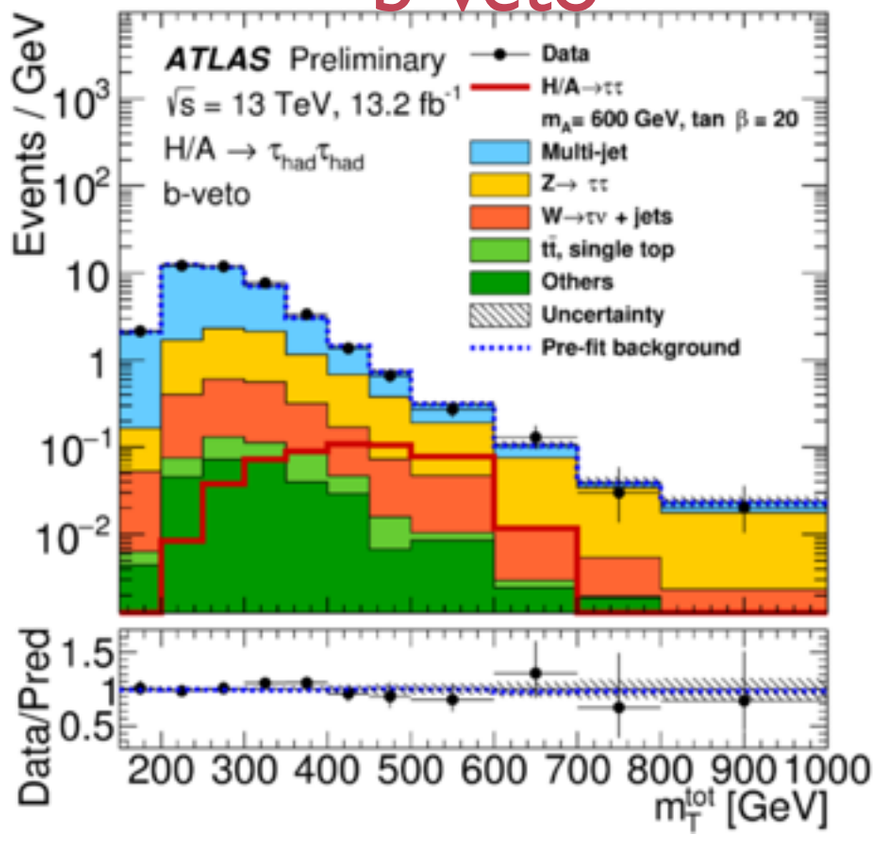
W+jets and tt bkg are also evaluated applying to MC a fake rate obtained from data CR.

No excess observed

b-tag



b-veto



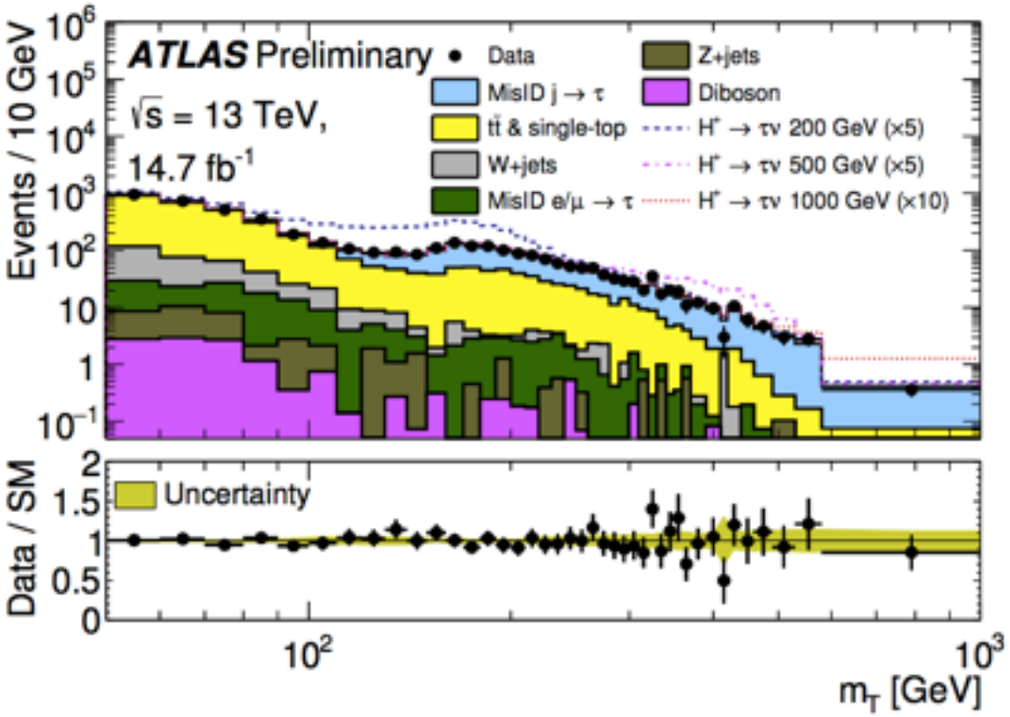
A/H→τ+τ- (systematics)

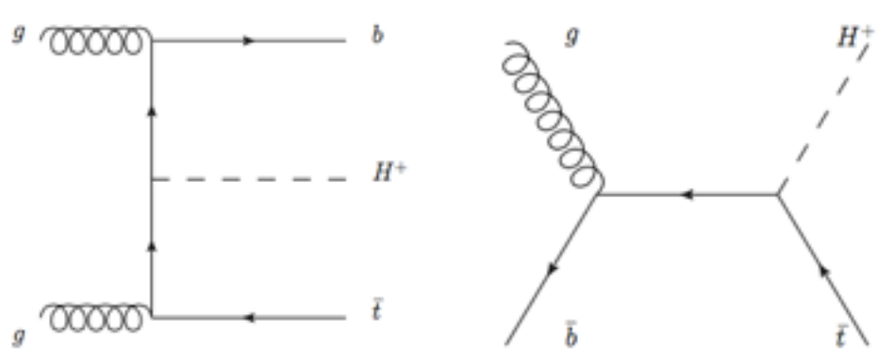
Impact of systematics on the total signal strength in MSSM scan mH=600 GeV tanβ=20

Source of uncertainty	F_- (%)	F_+ (%)
$t\bar{t}$ background parton shower model	−21	+39
$\tau_{\text{had-vis}}$ energy scale, detector modelling	−10	+12
r_{MJ} estimation b-veto region ($\tau_\mu\tau_{\text{had}}$)	− 5	+ 6
r_{MJ} estimation b-veto region ($\tau_e\tau_{\text{had}}$)	− 2.3	+ 3.0
bbH signal cross-section uncertainty	− 3.8	+ 1.6
Multi-jet background ($\tau_{\text{had}}\tau_{\text{had}}$)	− 2.2	+ 2.6
Jet-to-$\tau_{\text{had-vis}}$ fake rate b-veto region ($\tau_{\text{lep}}\tau_{\text{had}}$)	− 1.3	+ 2.9
$\tau_{\text{had-vis}}$ energy scale, in-situ calibration	− 1.4	+ 1.1
r_{MJ} estimation high-$E_{\text{T}}^{\text{miss}}$ region ($\tau_\mu\tau_{\text{had}}$)	− 1.4	+ 1.0
τ trigger (2016)	− 0.5	+ 1.3
Statistics (data and simulation)	−48	+25

Charged Higgs $H^{\pm} \rightarrow \tau\nu$

more details in parallel talk by A. Ferrari





W from top and τ decaying hadronically

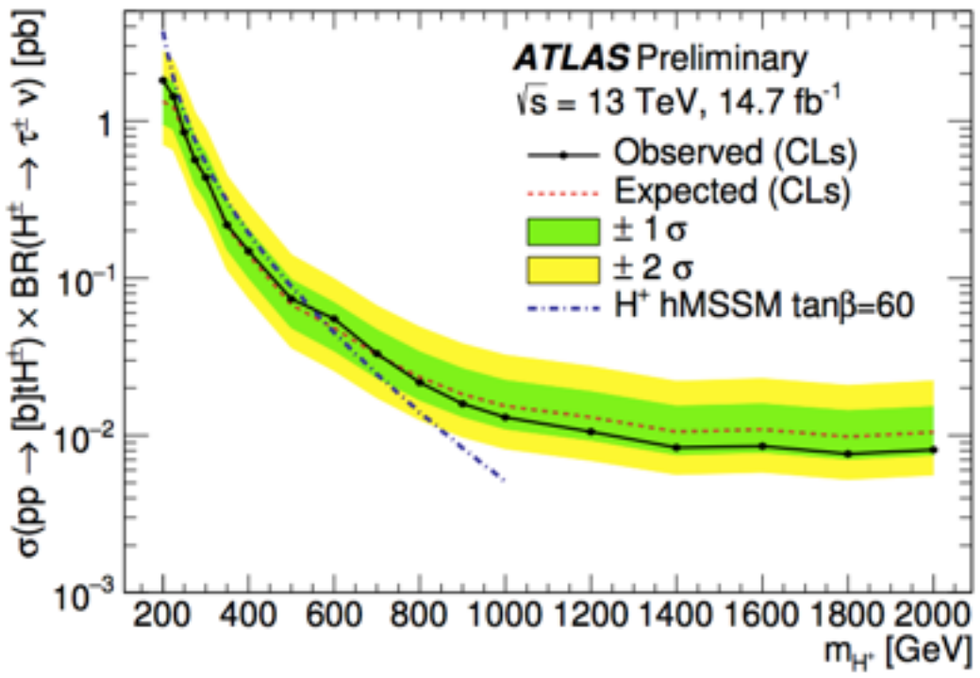
Selection:

- MET trigger, one τ_{had} (p_T>40 GeV), no e or μ,
- MET > 150 GeV, m_T (τ+MET)>50 GeV
- 3 jets (≥1 b-tag) with p_T(j)>25GeV

Backgrounds:

- True τ_{had}: from MC. $W \rightarrow \tau\nu$ (tt) bkg norm. (validated) in CRs with m_T < 100 GeV and 0 and ≥2 b-tags.
- Jet->τ_{had} fakes: mainly multi-jet. Fake Factor from anti-ID selection, as SR but MET<80 GeV and 0 b-tag

improves 3.2 fb^{-1} result within 200 -2000 GeV



Source of systematic uncertainty	Impact on the expected limit (in %) m_{H^+} = 200 GeV	m_{H^+} = 1000 GeV
Experimental		
luminosity	1.5	0.9
trigger	< 0.1	< 0.1
$\tau_{\text{had-vis}}$	1.0	1.4
jet	3.0	0.2
$E_{\text{T}}^{\text{miss}}$	< 0.1	< 0.1
Fake factors	0.8	4.7
Signal and background models		
$t\bar{t}$ modelling	13.2	3.5
H^+ signal modelling	1.4	1.4

Charged Higgs $H^{\pm} \rightarrow tb$

$tbH^{\pm} \rightarrow tb$, tt semi-leptonic, similar to tth(bb)

Categorization of SR and CRs by n-j and n-b

- Single lepton triggers
- 1 lepton p_T > 25 GeV
- ≥4jets p_T >25GeV (≥ 2 b-tagged)

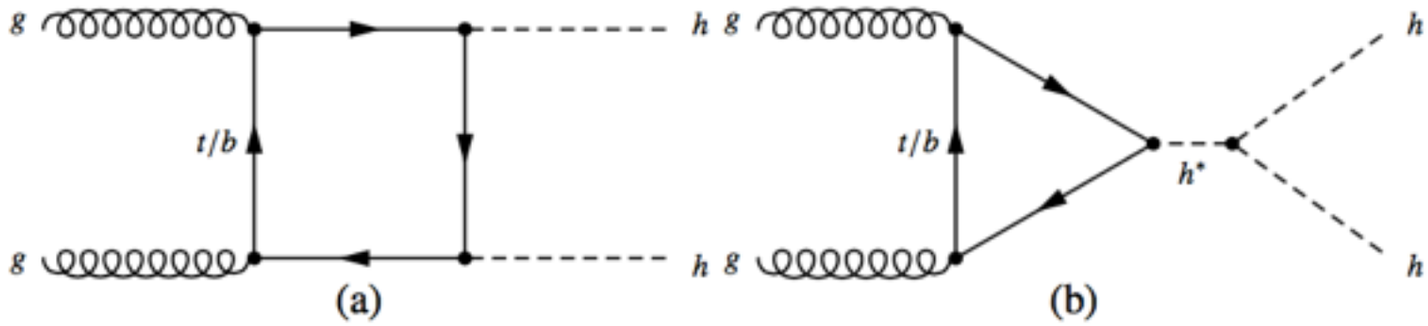
A maximum likelihood fit to all regions is performed using as input a BDTin SR(ΔR_{bb}, $p_T(jet_{lead})$,m_{bb}…) and Hadd (scalar sum of jet pT) in CR

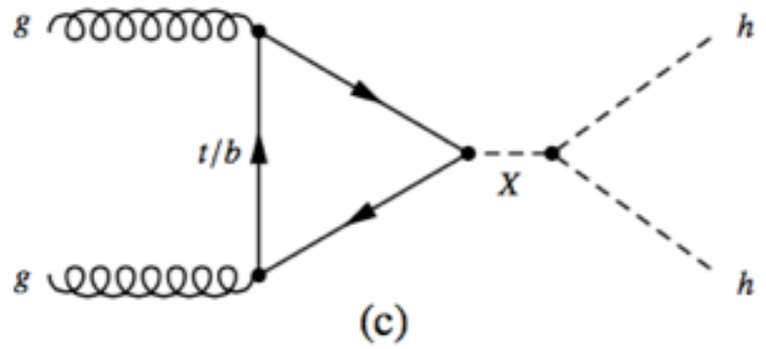
Background:

tt+light (reweighted to NNLO prediction[Top+ +2.0]), tt + ≥c, tt + ≥b (main bkg) free in the fit.

Uncertainty Source	$\Delta\mu(H^+_{300})$		$\Delta\mu(H^+_{800})$	
$t\bar{t}+ \geq 1b$ modelling	+0.53	−0.53	+0.07	−0.07
Jet flavour tagging	+0.30	−0.29	+0.07	−0.07
$t\bar{t}+ \geq 1c$ modelling	+0.23	−0.22	+0.03	−0.03
Background model statistics	+0.19	−0.19	+0.05	−0.05
Jet energy scale and resolution	+0.18	−0.17	+0.03	−0.03
$t\bar{t}$+light modelling	+0.16	−0.16	+0.03	−0.03
Other background modelling	+0.15	−0.14	+0.03	−0.03
Jet-vertex association, pileup modelling	+0.12	−0.11	+0.01	−0.01
Luminosity	+0.12	−0.12	+0.01	−0.01
Light lepton (e, μ) ID, isolation, trigger	+0.01	−0.01	< +0.01	< −0.01
Total systematic uncertainty	+0.72	−0.79	+0.13	−0.11
$t\bar{t}+ \geq 1b$ normalisation	+0.36	−0.36	+0.03	−0.03
$t\bar{t}+ \geq 1c$ normalisation	+0.15	−0.14	+0.02	−0.02
Total statistical uncertainty	+0.44	−0.43	+0.08	−0.08
Total	+0.84	−0.90	+0.15	−0.13

di-Higgs





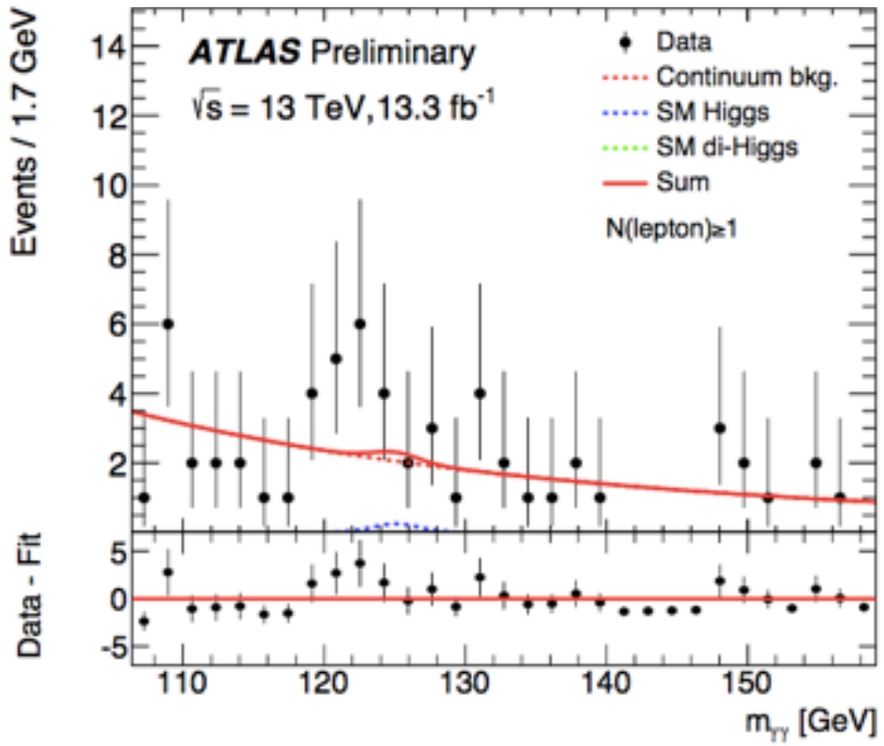
Di-Higgs production is small in the SM, enhanced in BSM both non resonant and resonant.

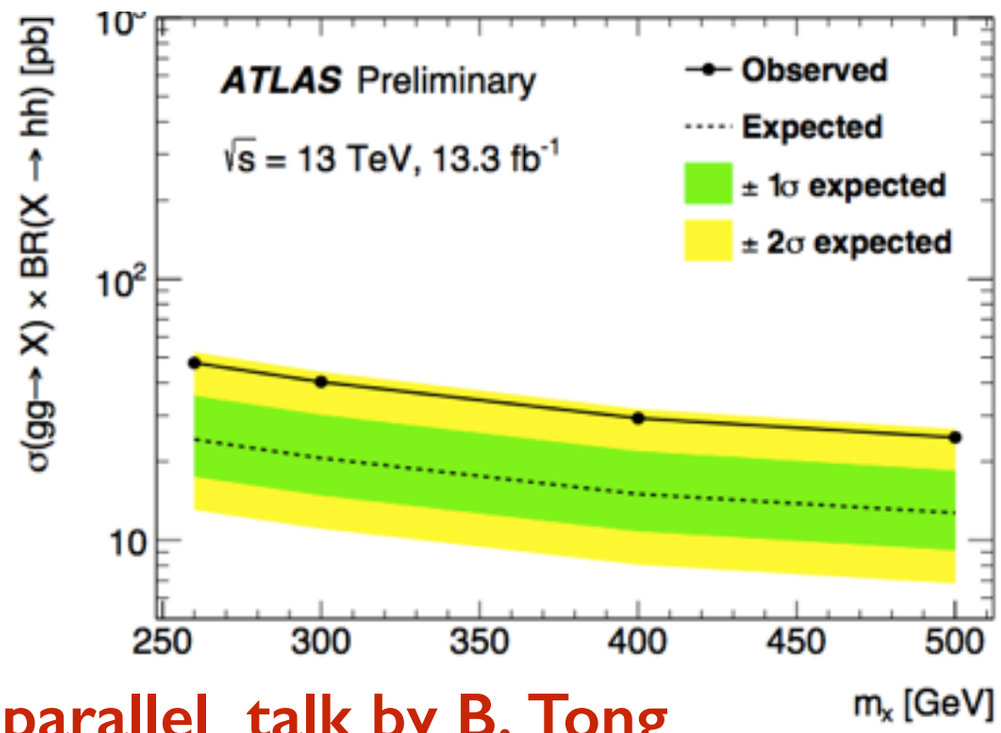
bbγγ (@13 TeV 3.2 fb^{-1})

no excess (run I excess at 300 GeV)

WWγγ (WW→lνqq),

- di-photon triggers, 2 photons (p_T>35/25 GeV) $|m_{\gamma\gamma}-m_h|<2\sigma_{\gamma\gamma}$ (1.7 GeV) sidebands used to extract di-photon continuum
- ≥2 jets, no b-tag
- ≥1lepton (SR), 0 leptons (CR)



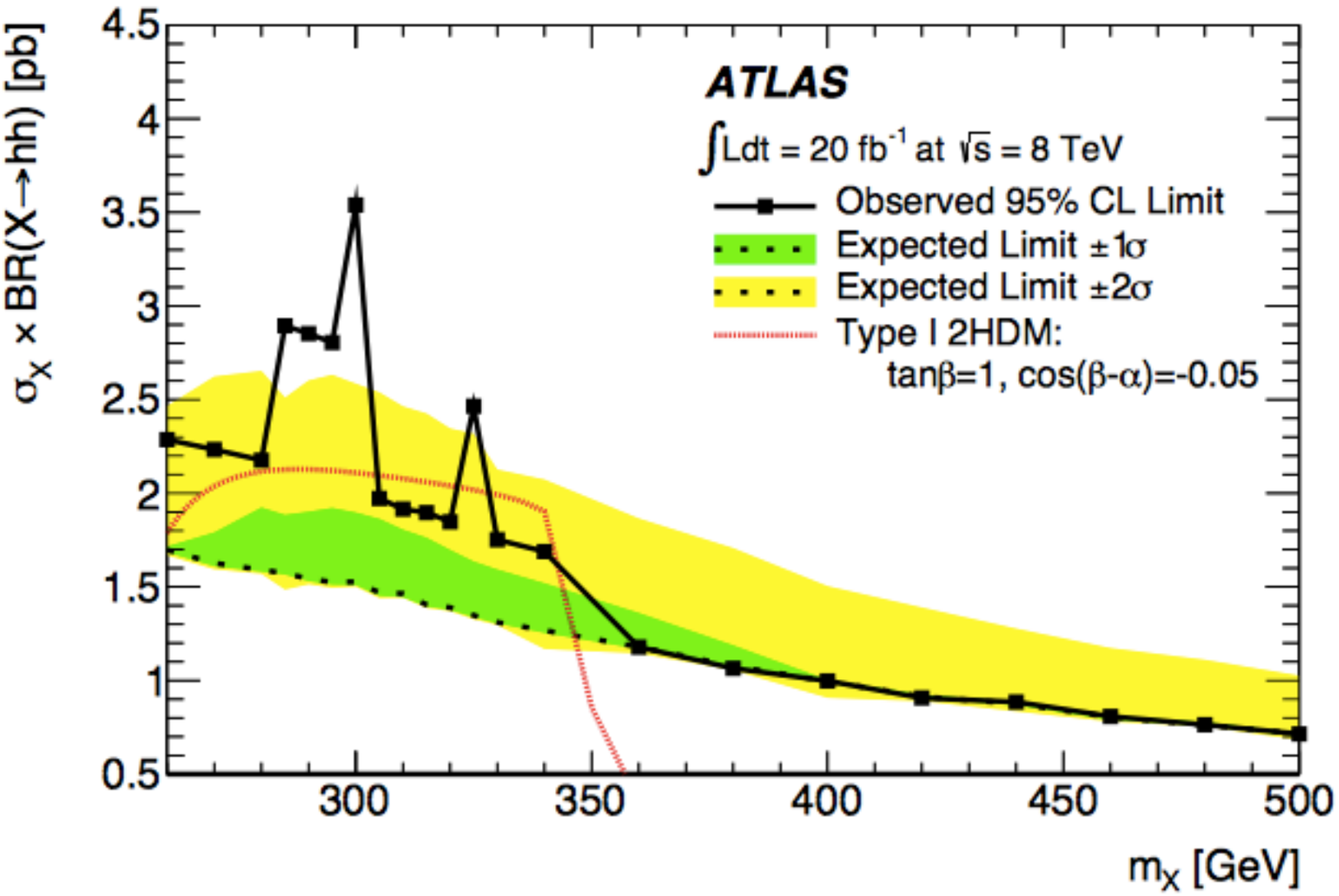


simple counting experiment: has a slight excess

15 evts obs for 7.88±1.24 exp

more details in parallel talk by B. Tong

bb$\gamma\gamma$ analysis at 8 TeV

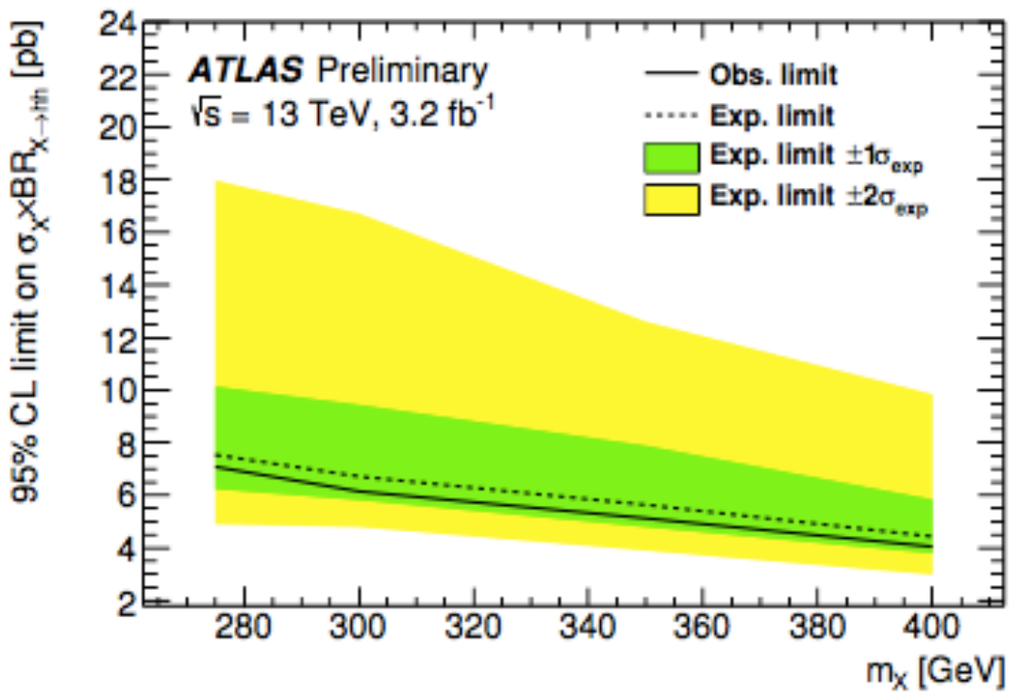


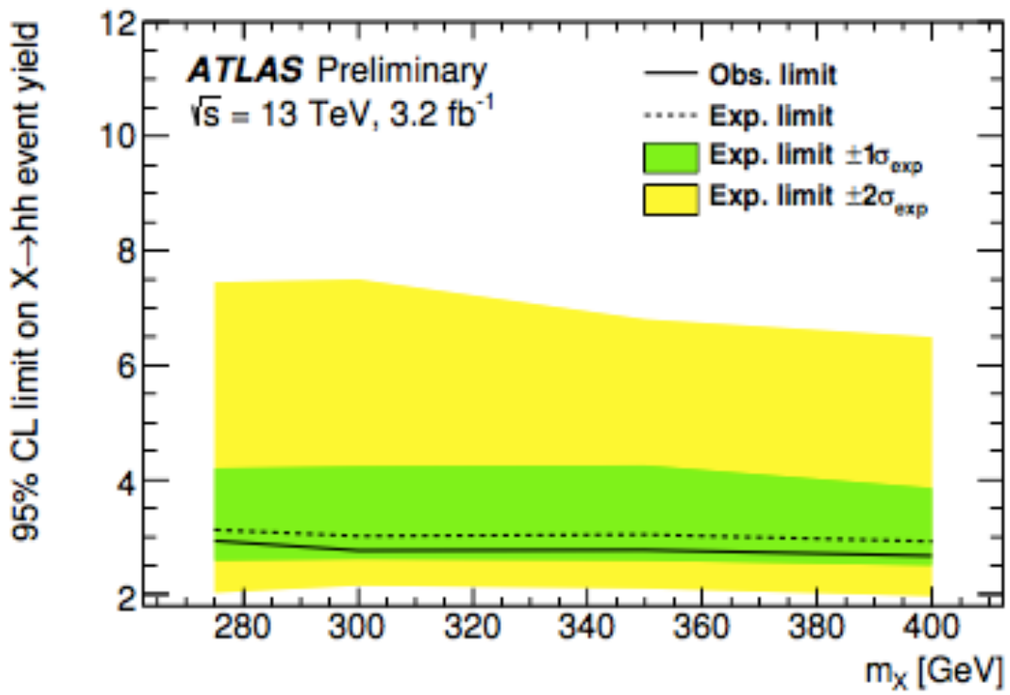
Phys. Rev. Lett. 114 (2015) 081802,
The present result excludes excesses above 3 events at 95% CL. The modest excess presented in Ref. [8] would translate into about 2 events in the 2015 dataset, under the assumption that it was induced by a gluon-initiated state.

bb$\gamma\gamma$ analysis at 13 TeV

Process	0-tag	2-tag
Continuum background	35.8 ± 2.1	1.63 ± 0.30
SM single-Higgs	1.8 ± 1.5	0.14 ± 0.05
SM di-Higgs	<0.001	0.027 ± 0.006
Observed	27	0

Table 1: Number of expected and observed events in the $m_h \pm 2\,\sigma_{m_{\gamma\gamma}}$ mass window in the 0-tag and 2-tag regions in the non-resonant selection, in the 3.2 fb^{-1} of data analysed. For the SM di-Higgs sample, a cross-section of 37.9 fb is assumed,





WWγγ (systematics)

Source of uncertainties		Non-resonant hh	$X \to hh$	Single-h bkg	Cont. bkg
		All numbers are in %			
Luminosity 2015+2016		2.9	2.9	2.9	-
Trigger		0.4	0.4	0.4	-
Pileup re-weighting		0.8	0.2	1.8	-
Event statistics		2.0	1.8	2.7	14.7
Photon	energy resolution	2.0	1.8	1.2	-
	energy scale	4.2	4.1	1.6	-
	identification	4.2	4.2	4.2	-
	isolation	1.0	1.0	1.1	-
Jet	energy resolution	0.8	0.2	8.0	-
	energy scale	3.5	3.5	5.2	-
b-tagging	b-jets	0.06	0.05	5.4	-
	c-jets	0.5	0.5	0.3	-
	light jets	0.4	0.4	0.4	-
	extrapolation	0.006	0.06	0.8	-
Lepton	electron	0.7	0.7	0.7	-
	muon	0.3	0.3	0.6	-
$\epsilon_{\gamma\gamma}$	lepton dependence	-	-	-	7.4
	background modelling	-	-	-	3.8
	sideband definition	-	-	-	1.2
	statistics on $\epsilon_{\gamma\gamma}$	-	-	-	1.3
Theory	PDF	(2.1)	-	2.2	-
	α_S	(2.3)	-	1.5	-
	scale	(6.0)	-	3.7	-
	HEFT	(5.0)	-	-	-
	jet multiplicity	-	-	12.5	-
	BR($h \to \gamma\gamma$)	2.1	2.1	2.1	-
	BR($h \to WW^*$)	1.5	1.5	1.5	-
Total		12.0	8.4	18.6	17.0

di-Higgs (bbbb)

Resolved: 4 b's at 70% eff, (R_{jet} = 0.4), p_{Tjet}> 30 GeV

- pairing uses angles of jets, depends on m_{4j}
- $m_h(125)$ constraint also used.

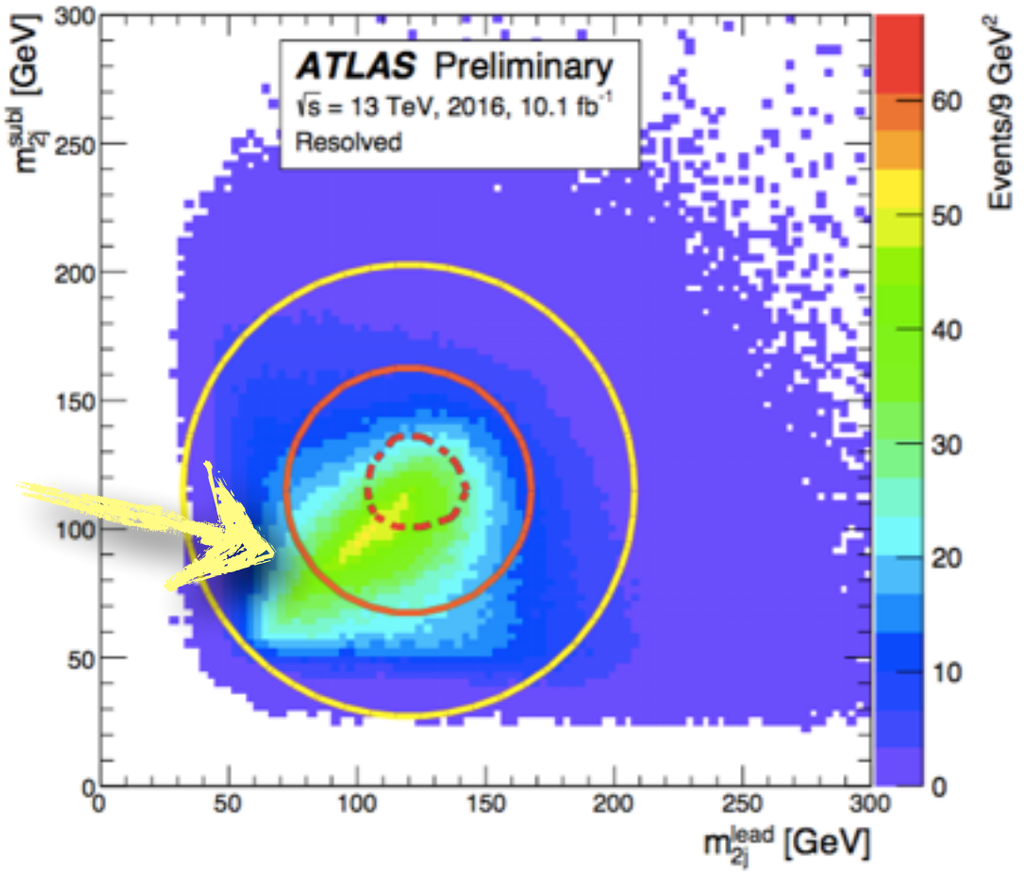
95% of bkg is multijet, obtained from data requiring exactly 2 jets with b-tag and inverting m_h constraint

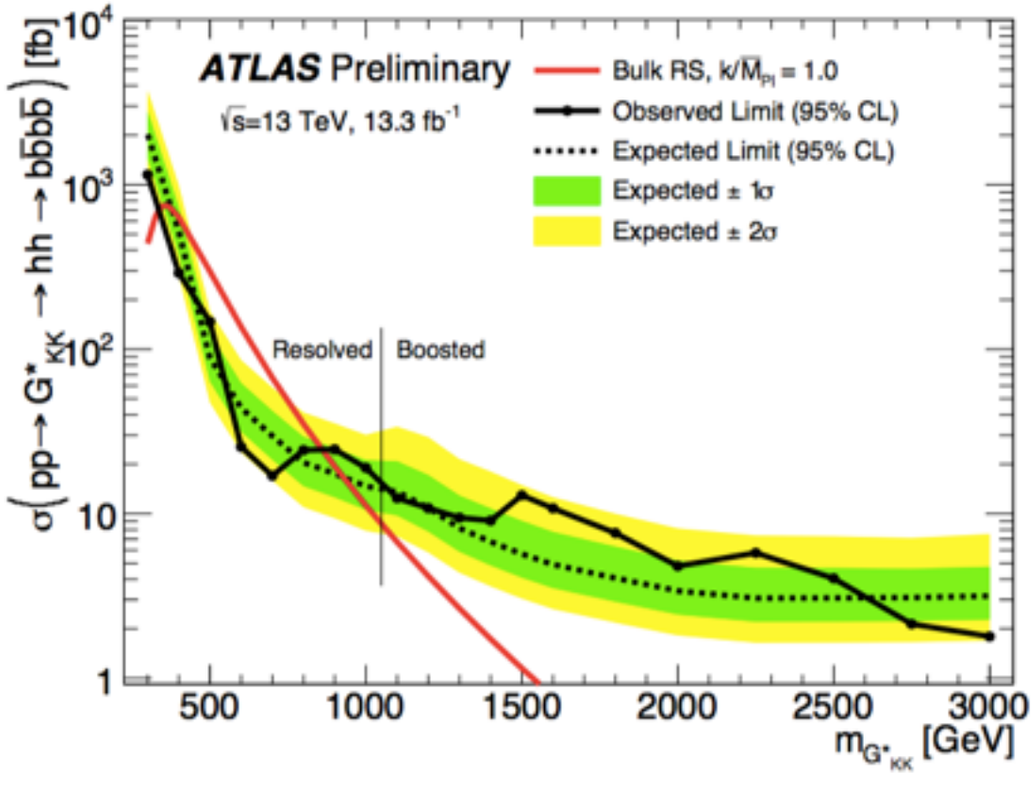
Unresolved:

- 2 fat jets (R_{jet}=1) each associated ≥1b-tag track-jet
- p_{Tj1} p_{Tj2} > 450/250 GeV, $|\eta| < 2.0$, m_J > 50 GeV
  m_J compatible with $m_h(125)$
- 3 categories, 2/3/4 tag: 1 b-tag for each Higgs or 2 on one and 1(2) on the other.

Background: multijet(83-87%) and tt.

Multijet obtained from data in sidebands (no b-tag requirement).
Sideband also provides tt normalization.
For resonant search boosted and resolved are combined.





di-Higgs (bbbb) systematics

Source	2015 Background	2015 SM hh	2015 G^*_{KK} (800 GeV)	2016 Background	2016 SM hh	2016 G^*_{KK} (800 GeV)
Luminosity	–	2.1	2.1	–	3.7	3.7
JER	–	5.7	3.3	–	5.4	3.5
JES	–	6.4	1.3	–	6.6	1.3
b-tagging	–	23	35	–	23	35
Theoretical	–	9.7	4.2	–	9.7	4.2
Multijet	5	–	–	5	–	–
$t\bar{t}$	58	–	–	58	–	–
Total	5.5	26	35	5.5	27	36

Resolved

Source	2-tag-split Background	2-tag-split G^*_{KK} (2 TeV)	3-tag Background	3-tag G^*_{KK} (2 TeV)	4-tag Background	4-tag G^*_{KK} (2 TeV)
Luminosity	-	2.9	-	2.9	-	2.9
JER	-	0.1	-	0.1	-	0.3
JMR	-	12	-	12	-	12
JES/JMS	-	4.5	-	4.2	-	3.3
b-tagging	-	58	-	15	-	38
Theoretical	-	2.7	-	2.3	-	2.4
Bkg Estimate	4.4	-	4.6	-	21	-
Statistical	0.5	1.4	1.1	1.0	1.2	1.3
$t\bar{t}$	1.6	-	4.7	-	10	-
Total Sys	4.7	59	6.6	20	24	40

Unresolved