Higgs boson self-interactions in SM and BSM (ATLAS+CMS)

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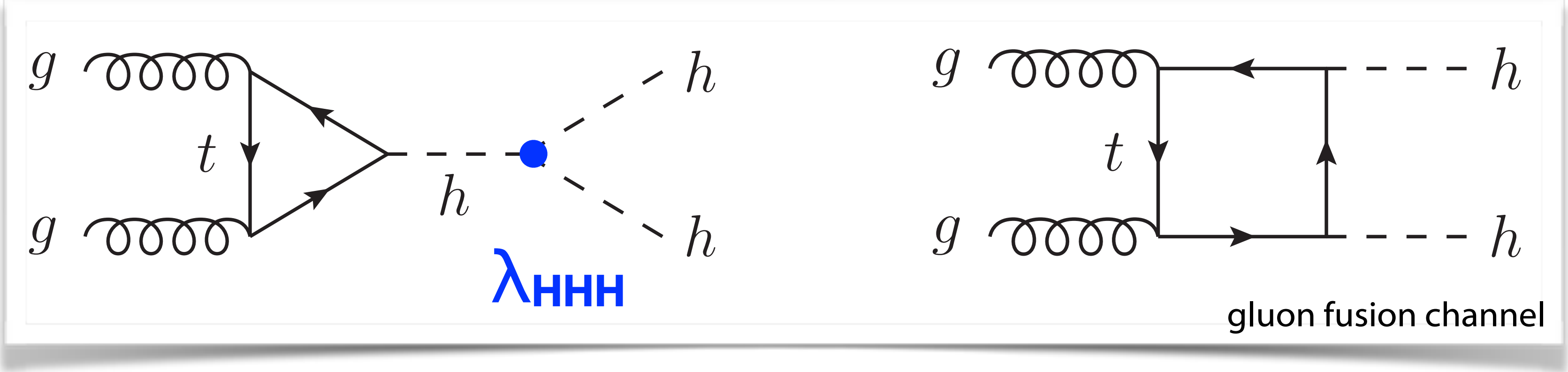
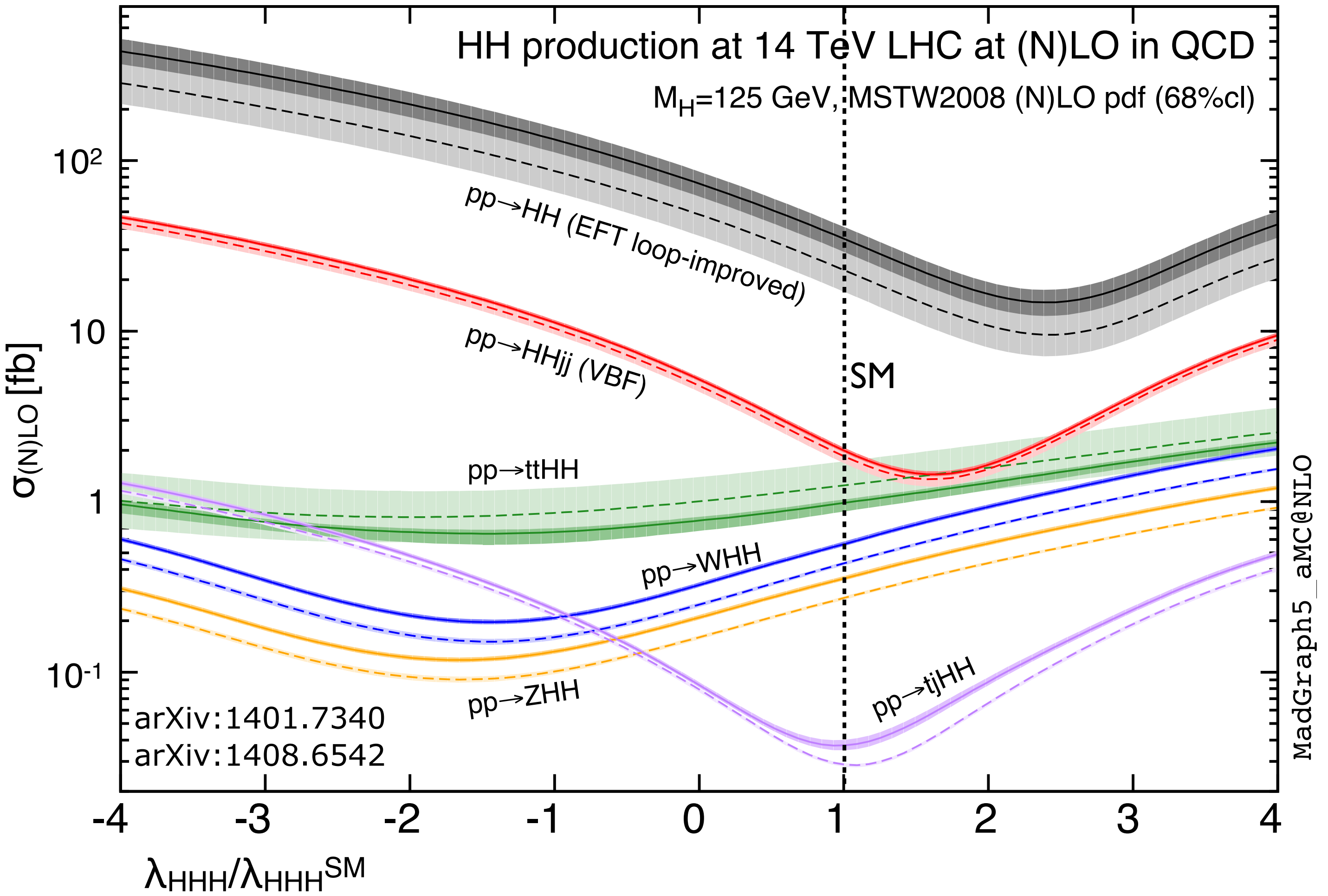
Introduction

Double Higgs boson (hh) production is the principal way to to study the Higgs boson self-interaction extracting the trilinear coupling (λ_{HHH})

→ this is generally considered as an analysis for the HL-LHC





$\sigma_{SM}(gg\rightarrow hh)$

m_h = 125 GeV

√s	σ (fb)
7 TeV	6.85
8 TeV	9.96
13 TeV	34.3
14 TeV	40.7

Preliminary recommendations from the hh group of LHXSWG

Introduction

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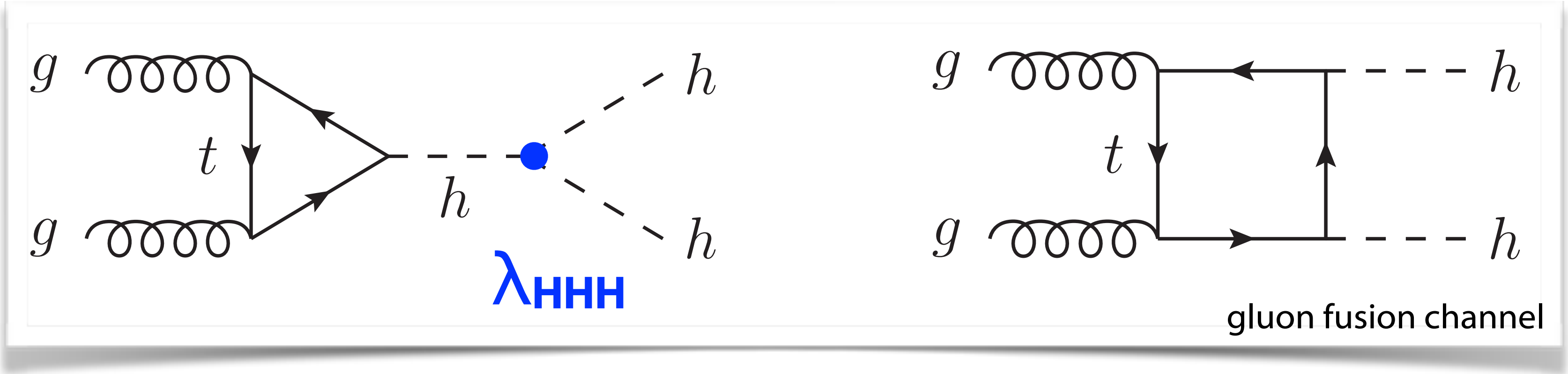


Even if in LHC Run1 we did not have any sensitivity to "measure" Standard Model λ_{HHH} an easy pattern to look for hh are :

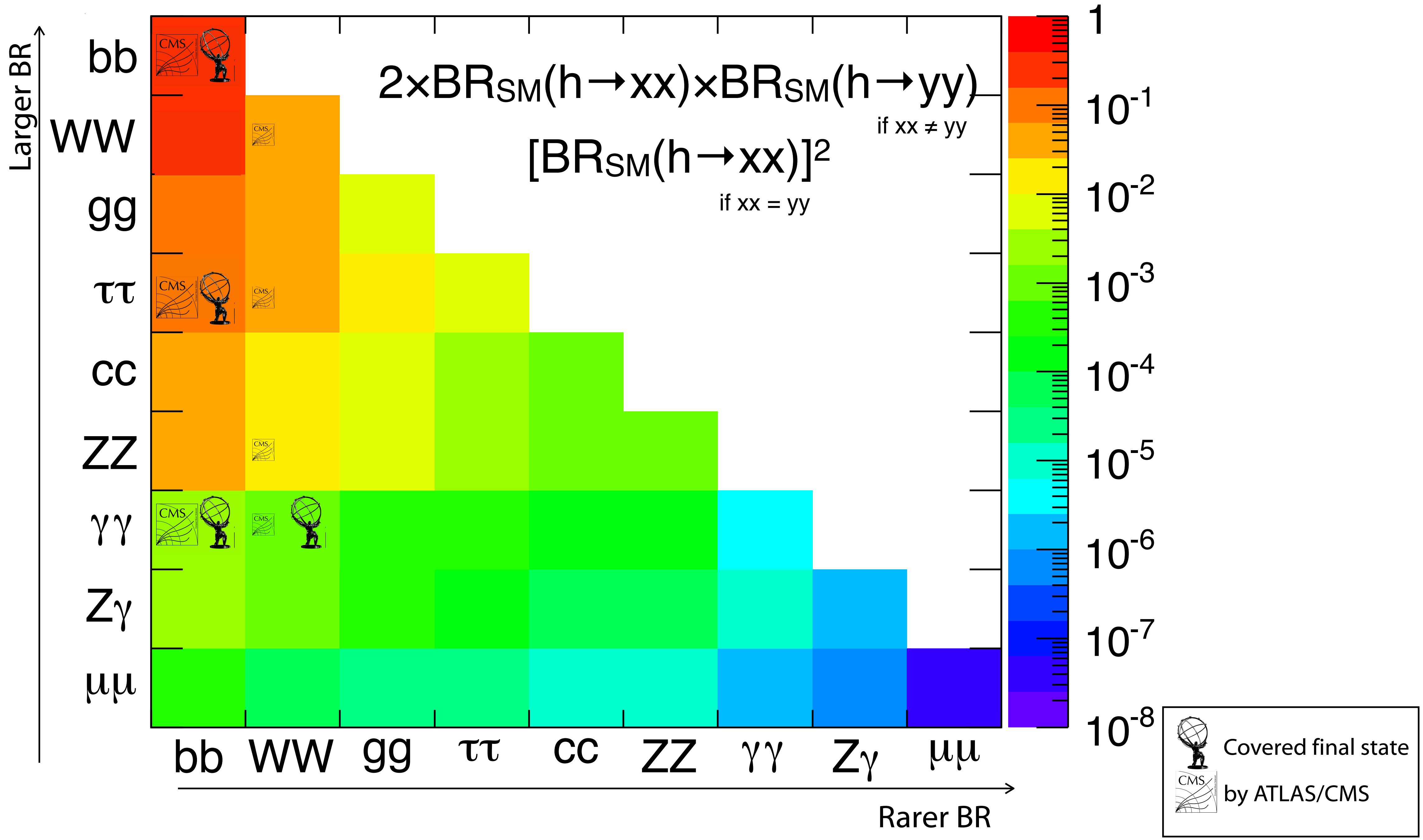
→ resonant production from decay of new exotic particles

→ non-resonant production from SM or from new diagrams increasing the production cross section

- non SM Yukawa couplings
- ttHH interactions
- dimension-6 gluon Higgs operators
- light coloured scalars
- …

Which final states?

Branching ratios and production mechanisms are decoupled effects
Double Higgs boson production has a phenomenologically rich set of final states



→SM branching ratios (for m_h = 125 GeV) are used as first approximation for all the analyses

$(X) \rightarrow hh \rightarrow bbbb$

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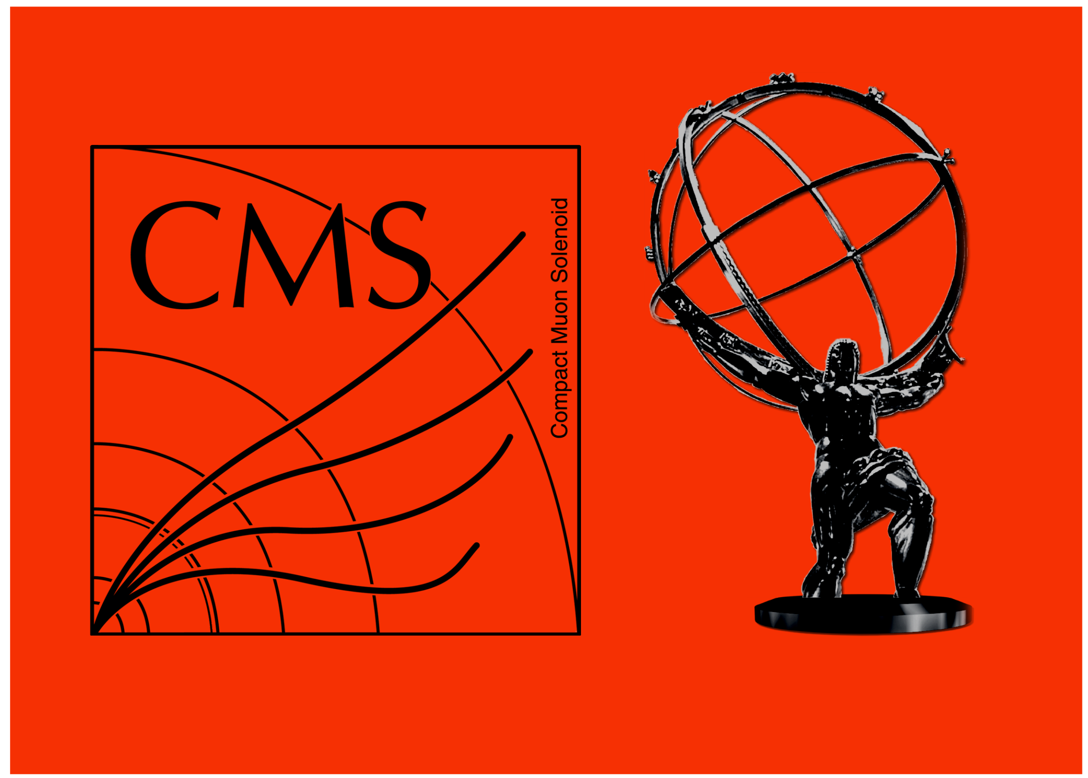
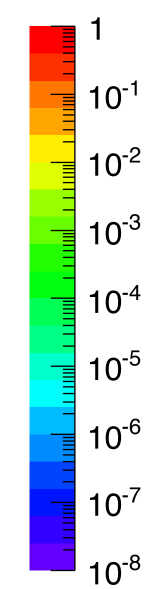
CMS-EXO-12-053



Eur. Phys. J. C (2015) 75:412

$BR_{SM}(hh \rightarrow bbbb) \sim 33.3\%$



(X)→hh→bbbb : resolved analysis

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A model-independent search for a narrow-width resonance in 270-1100 GeV range

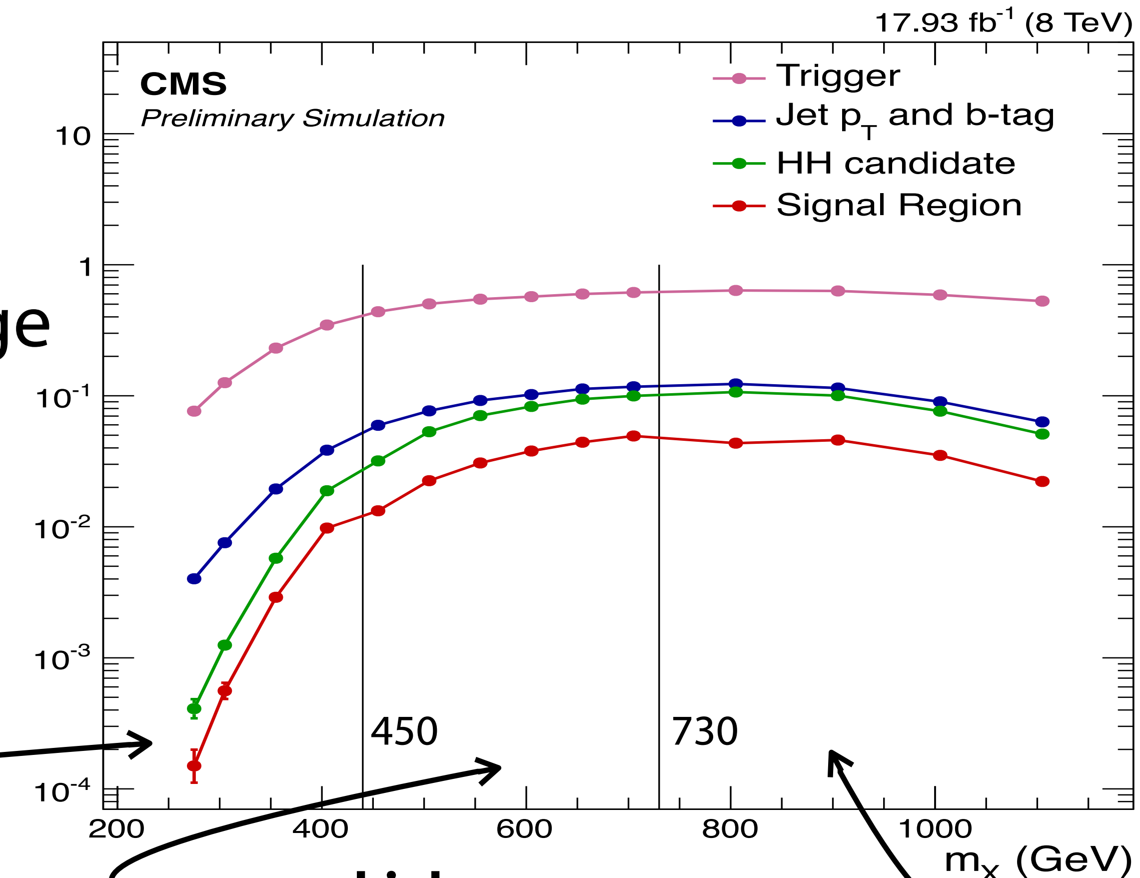
4 anti-k$_T$ ΔR=0.5 b-jets with $p_T > 40$

The kinematic distributions of the decay products vary substantially over the mass range

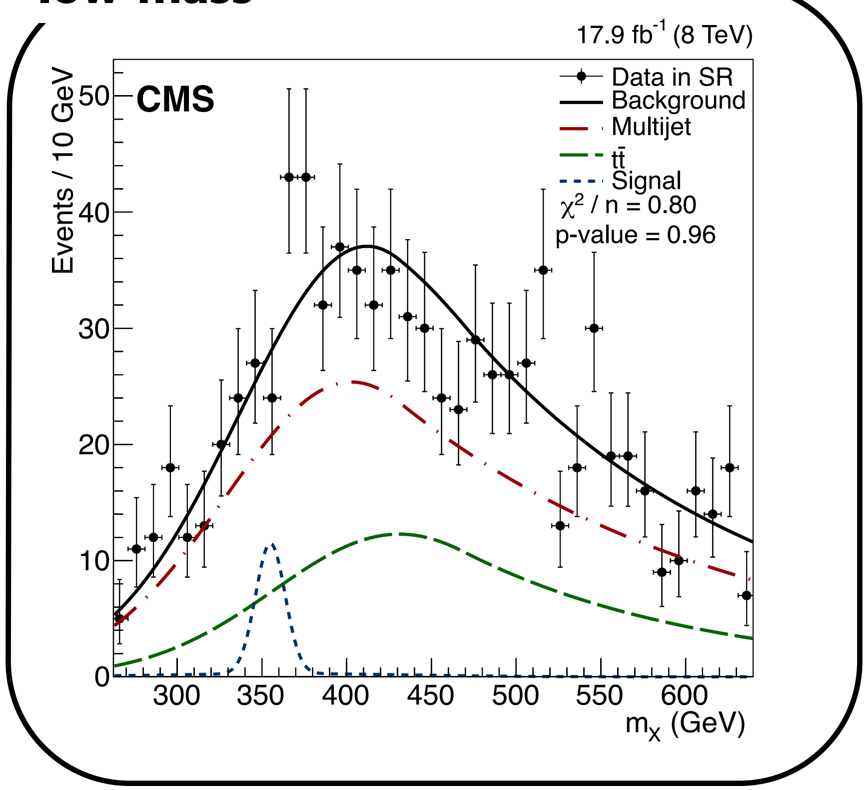
3 kinematical regions

A kinematic fit is performed to improve the mass resolution

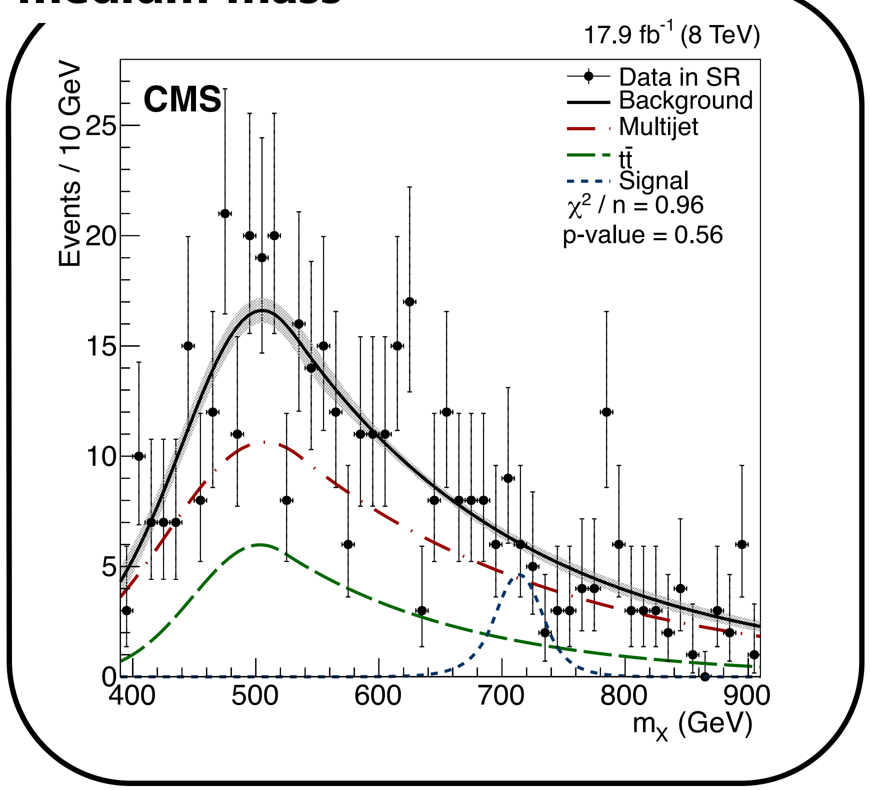
m_X resolution is 4-30 GeV (improves by 20-40%)



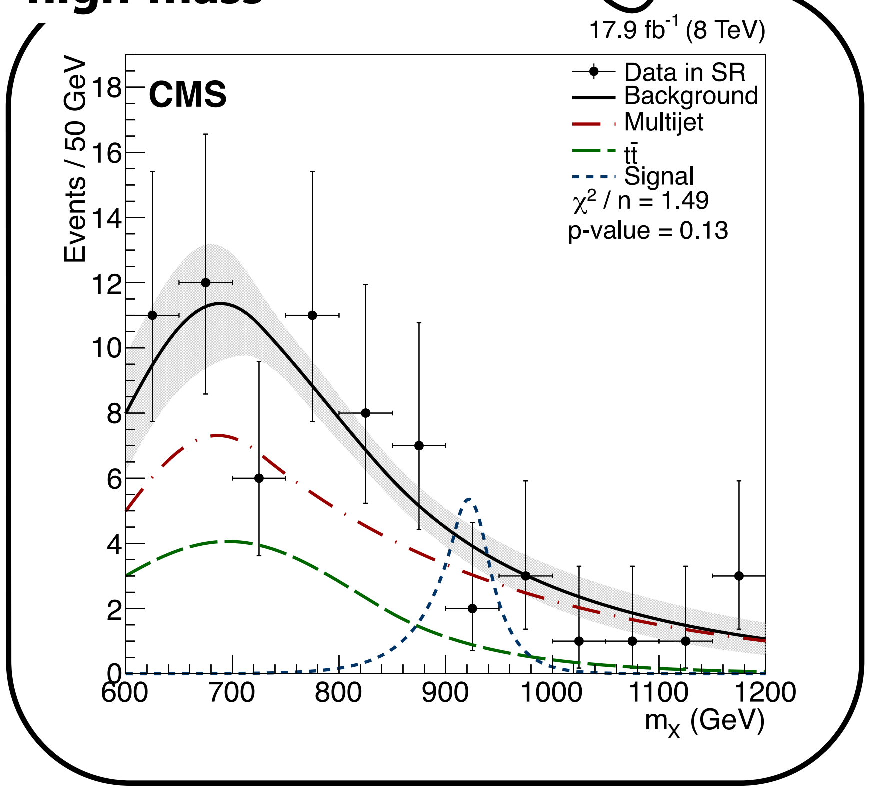
low-mass



medium-mass



high-mass



(X)→hh→bbbb : resolved analysis

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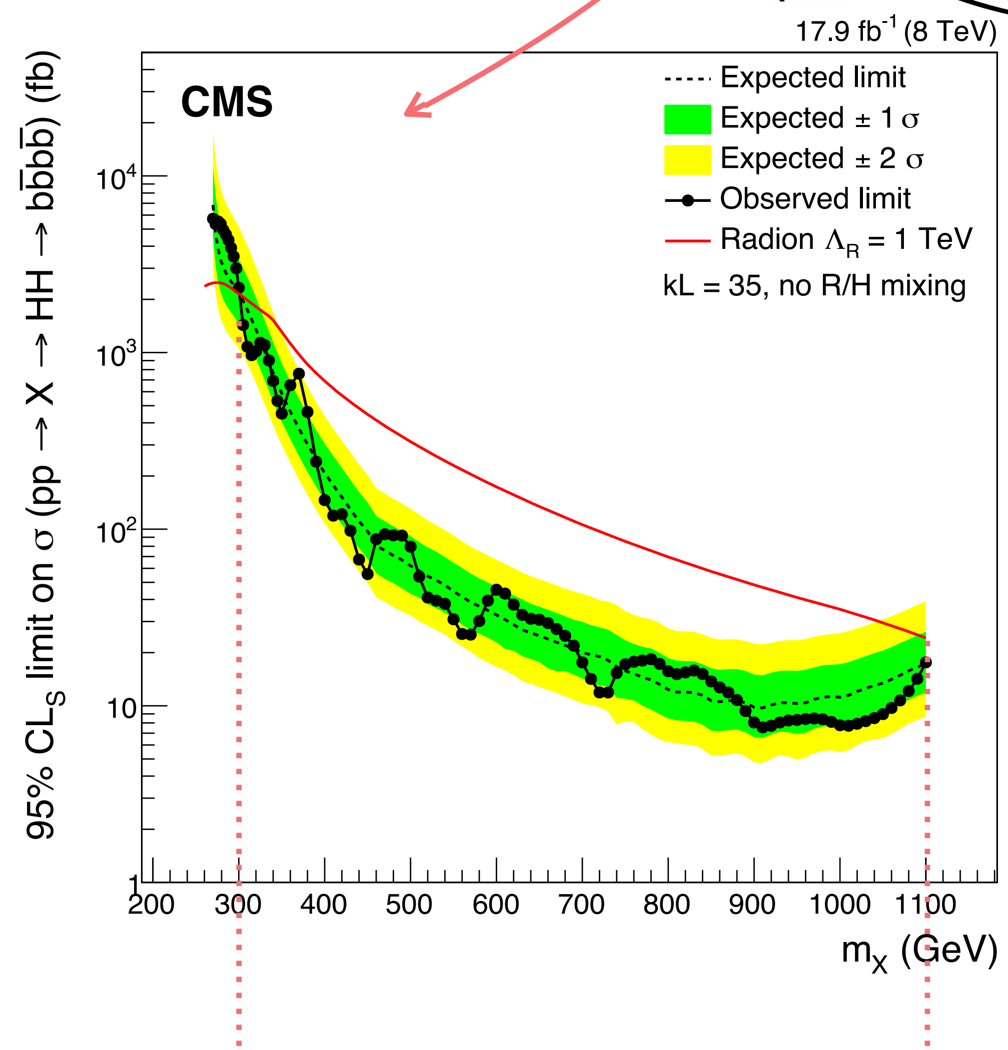
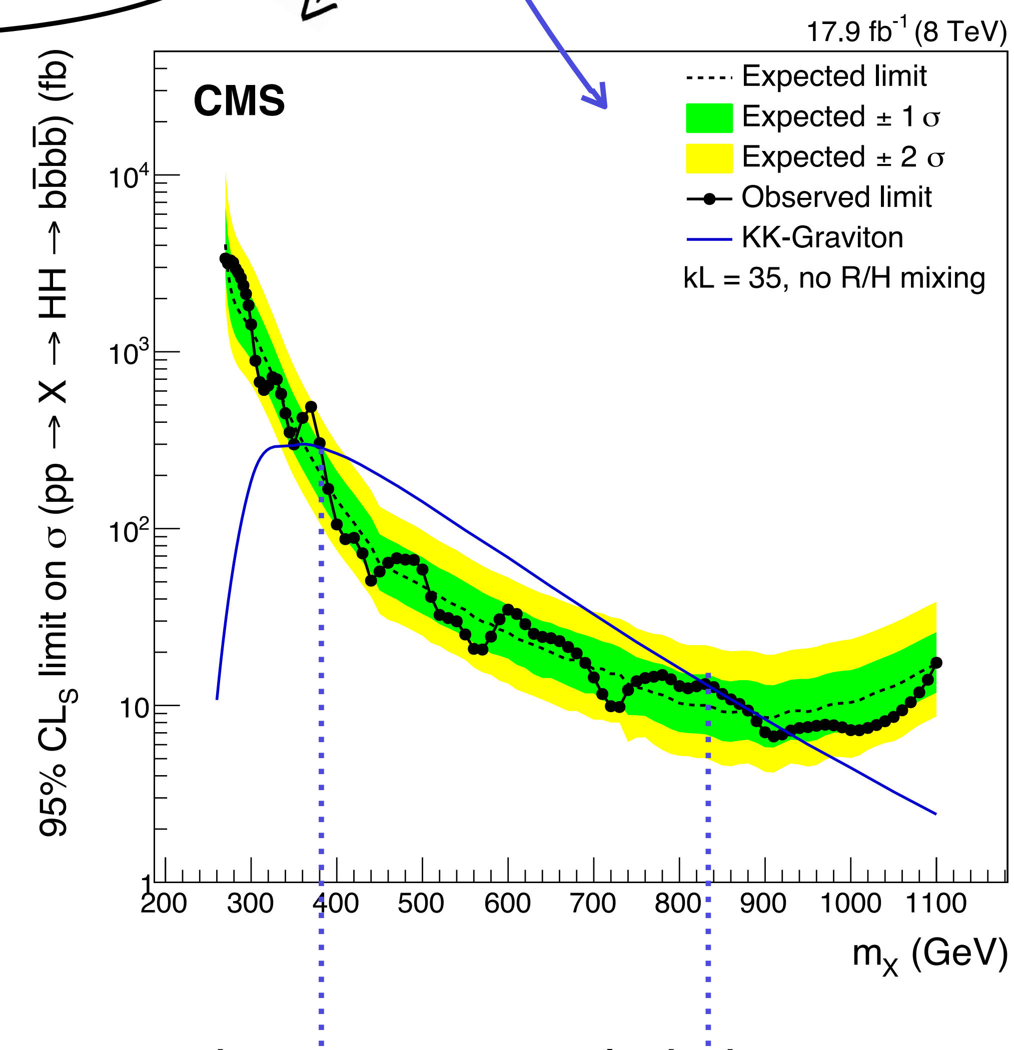
The exclusion limits for **radion** production and **Kaluza–Klein graviton** production

different acceptance
+20-30% signal efficiency



300 and 1100 GeV are excluded at 95% CL



380 and 830 GeV are excluded at 95% CL

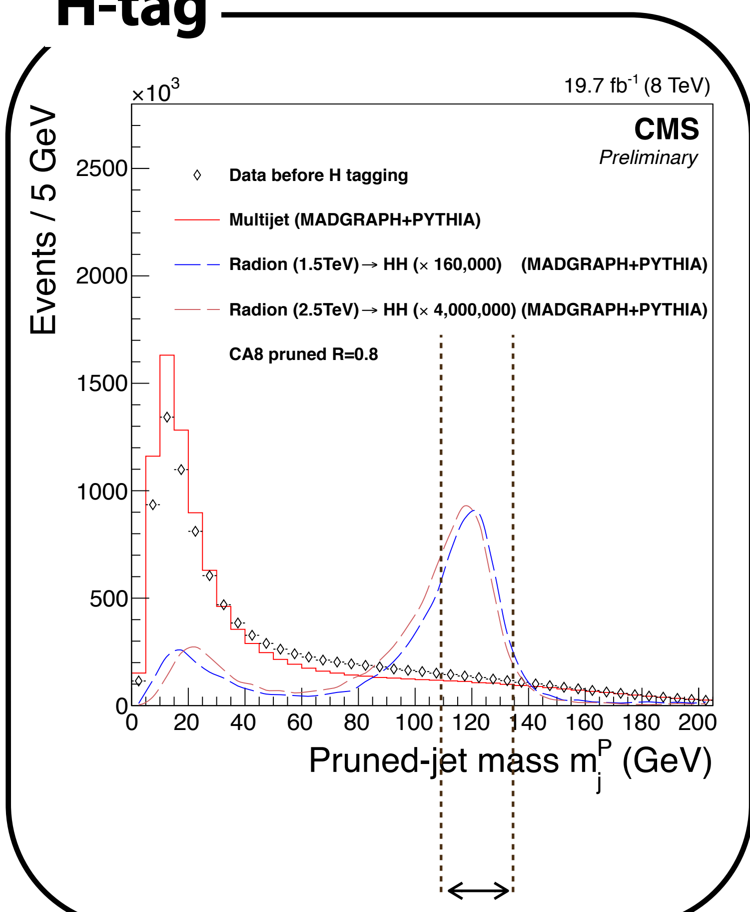
The low mass region sensitivity not enough to probe (N)MSSM predictions

Above $m_X > 1$TeV significant merging takes place

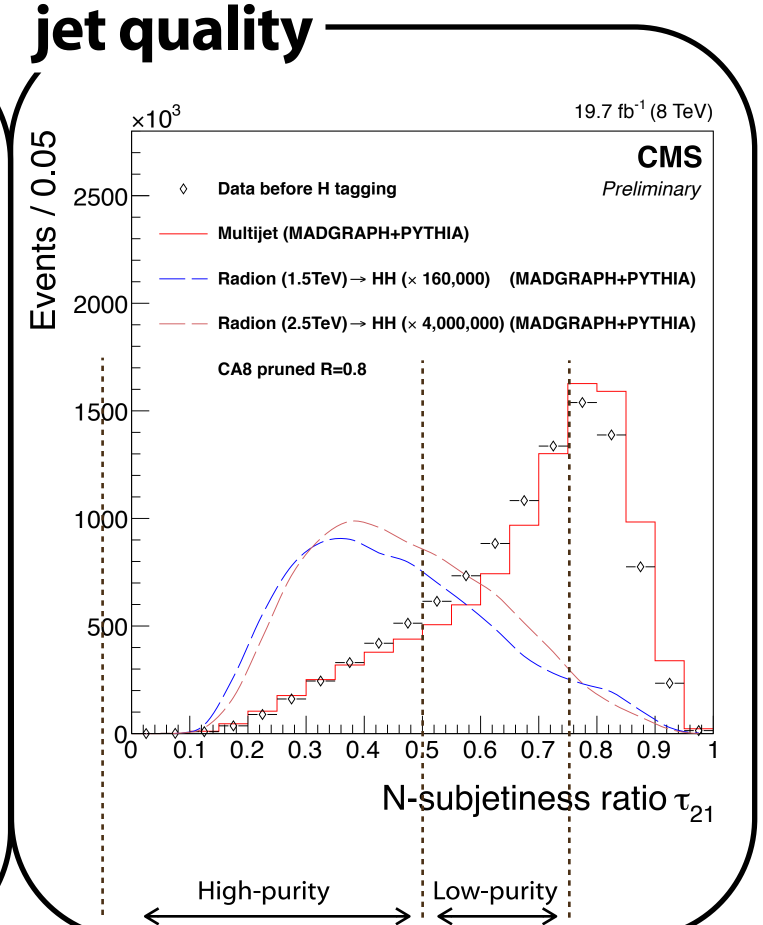
- → one massive jet instead of two resolved b jets
- → jet sub-structure techniques exploited to perform **H-tag** and **jet quality**

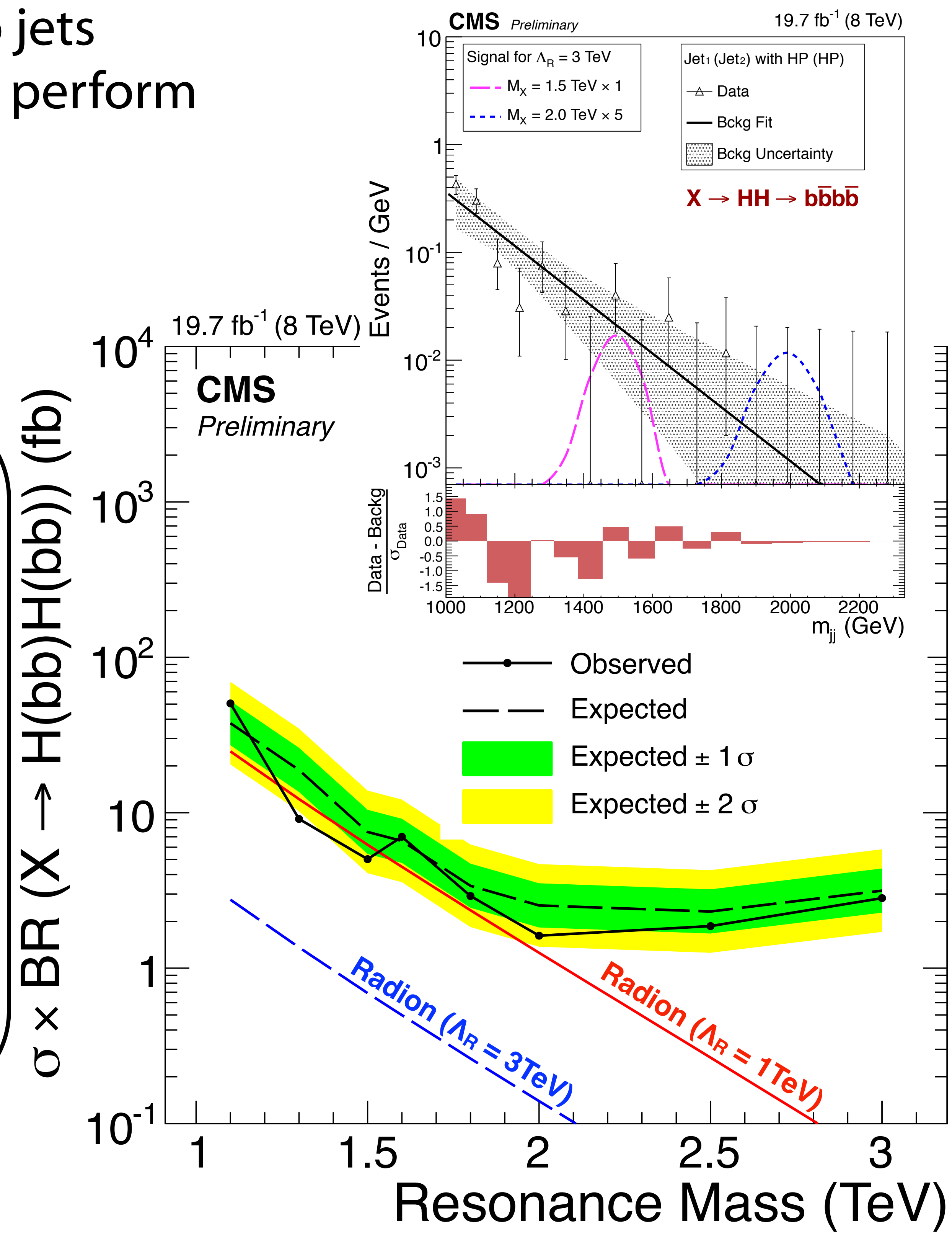
Starting with **2 CA ΔR=0.8** central jets

H-tag



jet quality





(X)→hh→bbbb : resolved analysis

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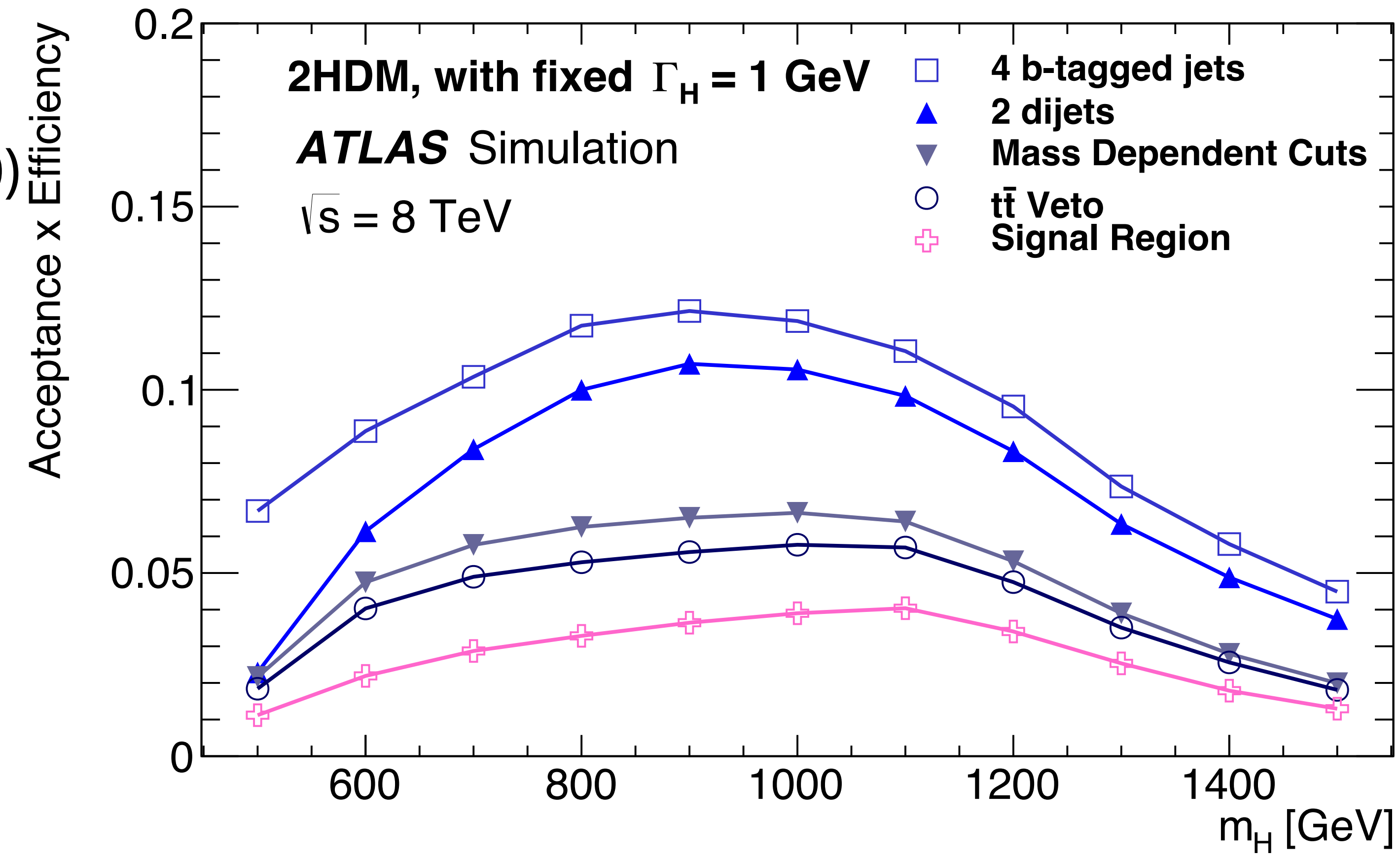
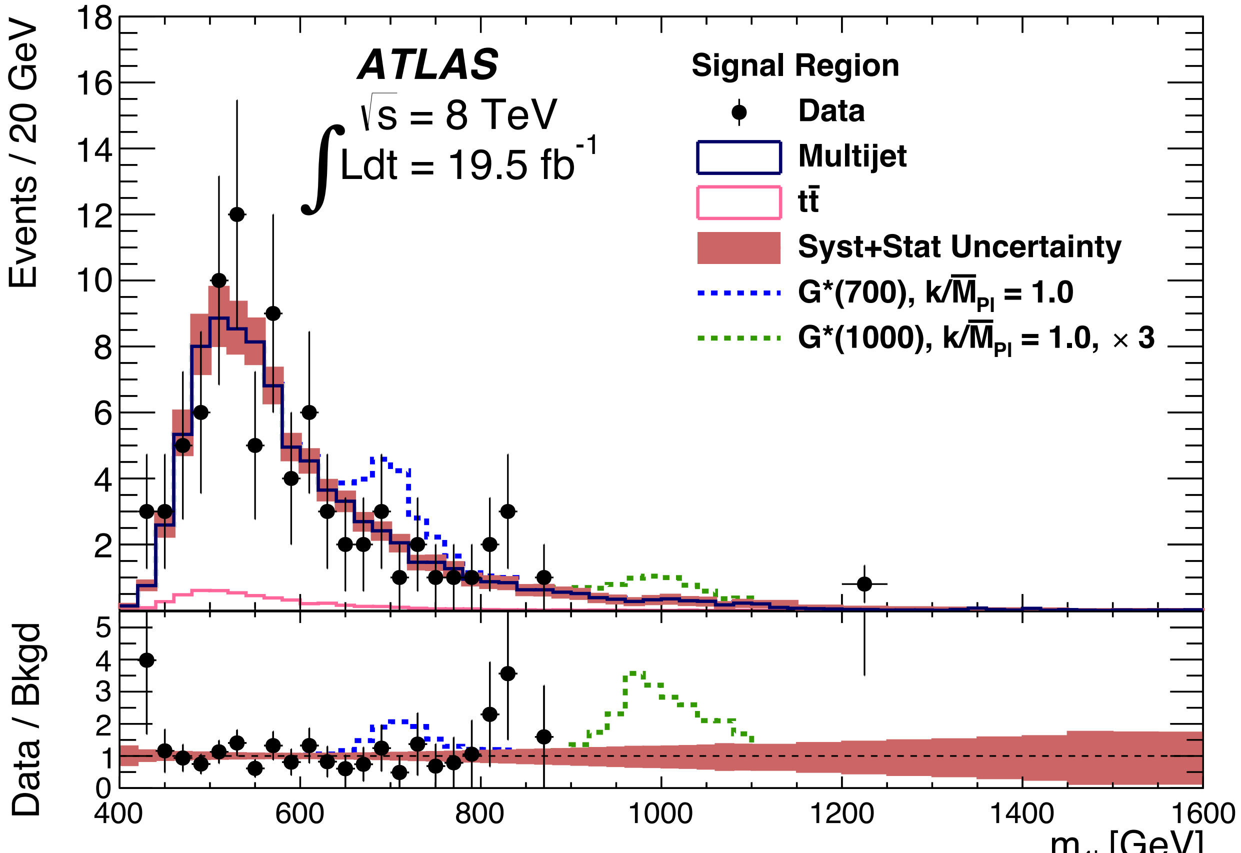
4 anti-k_T ΔR=0.4 b-jets with p_T > 40

- Di-jet system ($p_T^{Sublead}$> 150 && p_T^{Lead} > 200)
- Mass dependent cuts in 3 regions
- tt Veto
- Signal region with mass depended cuts



Background

- Multijet (~95%) from sidebands
- tt yields from data shape from MC



Analysis used to set a limit on the non-resonant SM hh production

(X)→hh→bbbb : boosted analysis

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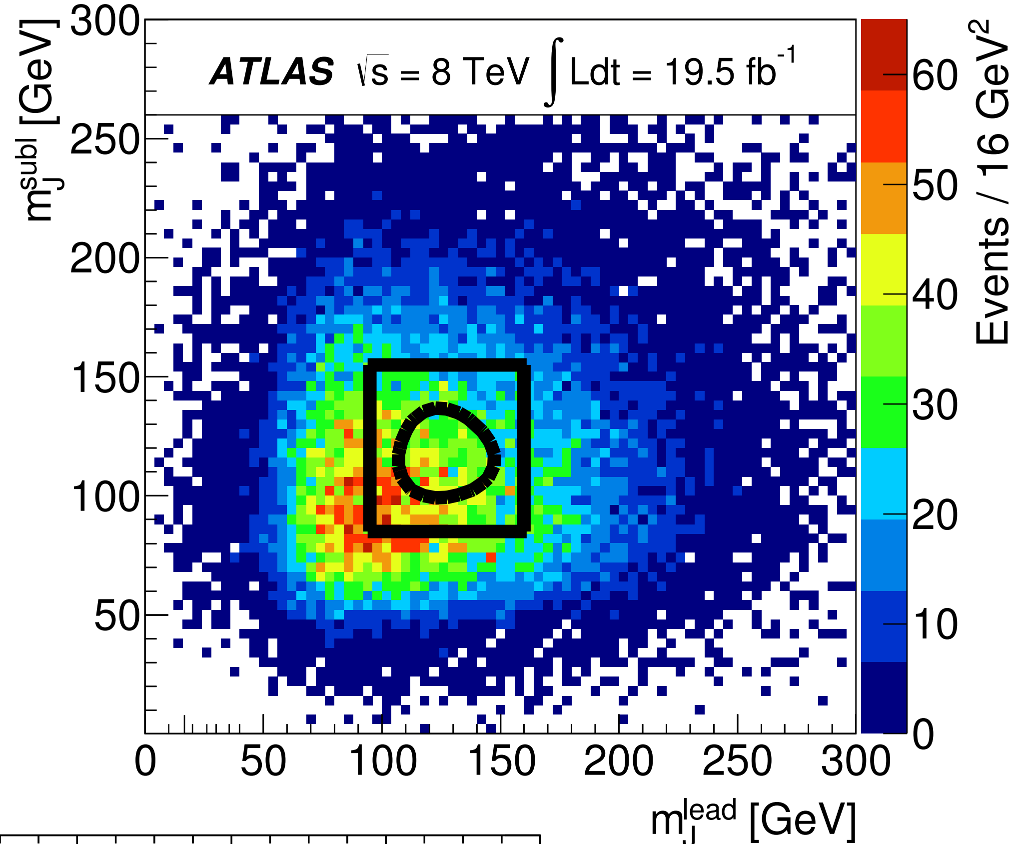
2 anti-k$_T$ ΔR=1.0 jets with p_T > 250 GeV

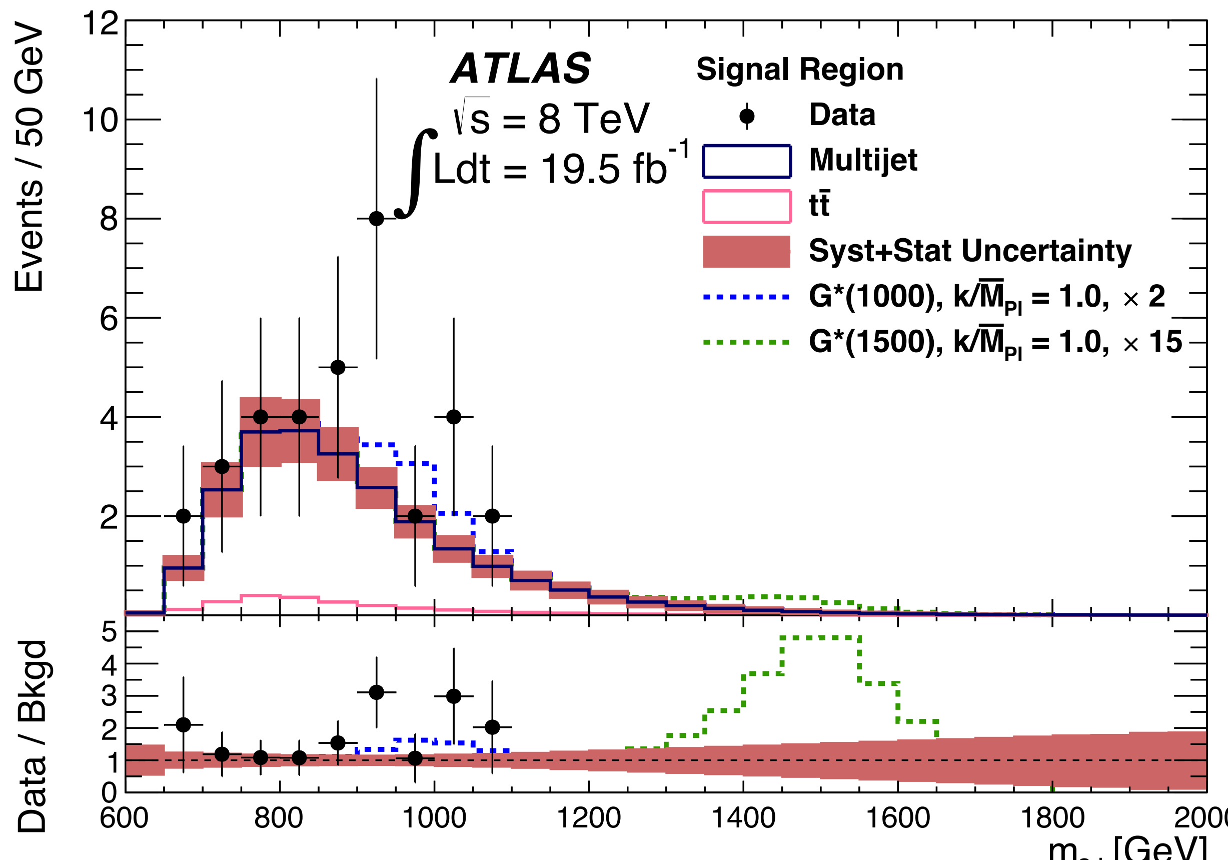
- Trimming to remove pile-up effects
- Track jets b-tag (ΔR=0.3)
- Use jet mass to test Higgs mass compatibility



Background

- Multijet (~90%) from sidebands
- tt yields from data shape from MC

Signal Region



(X)→hh→bbbb : results

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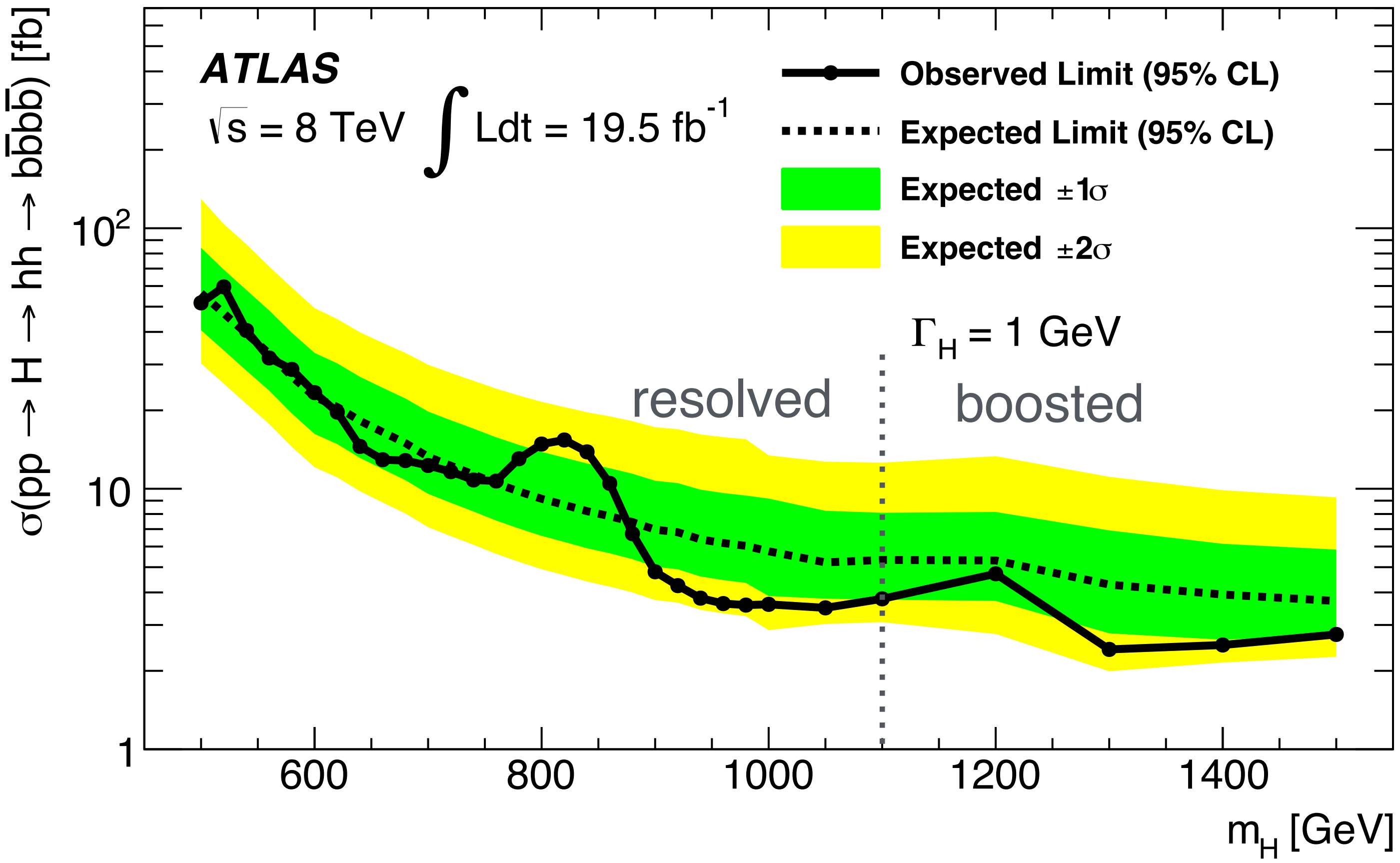
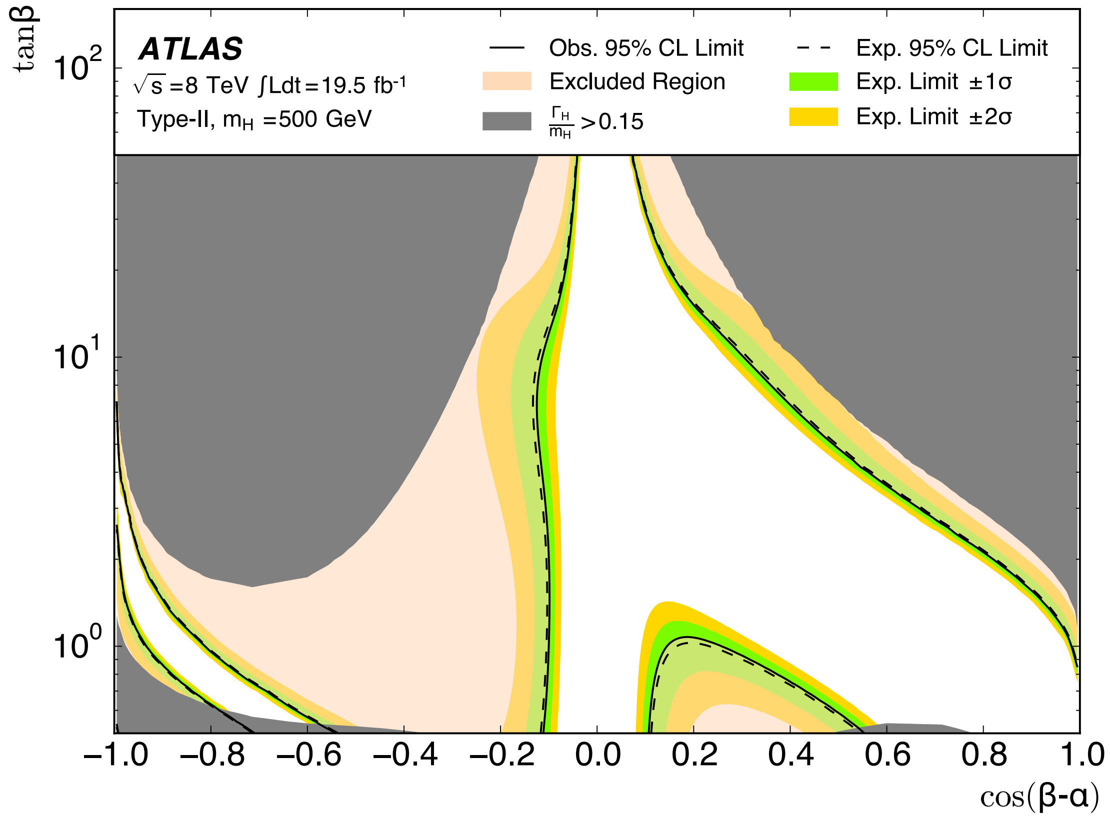
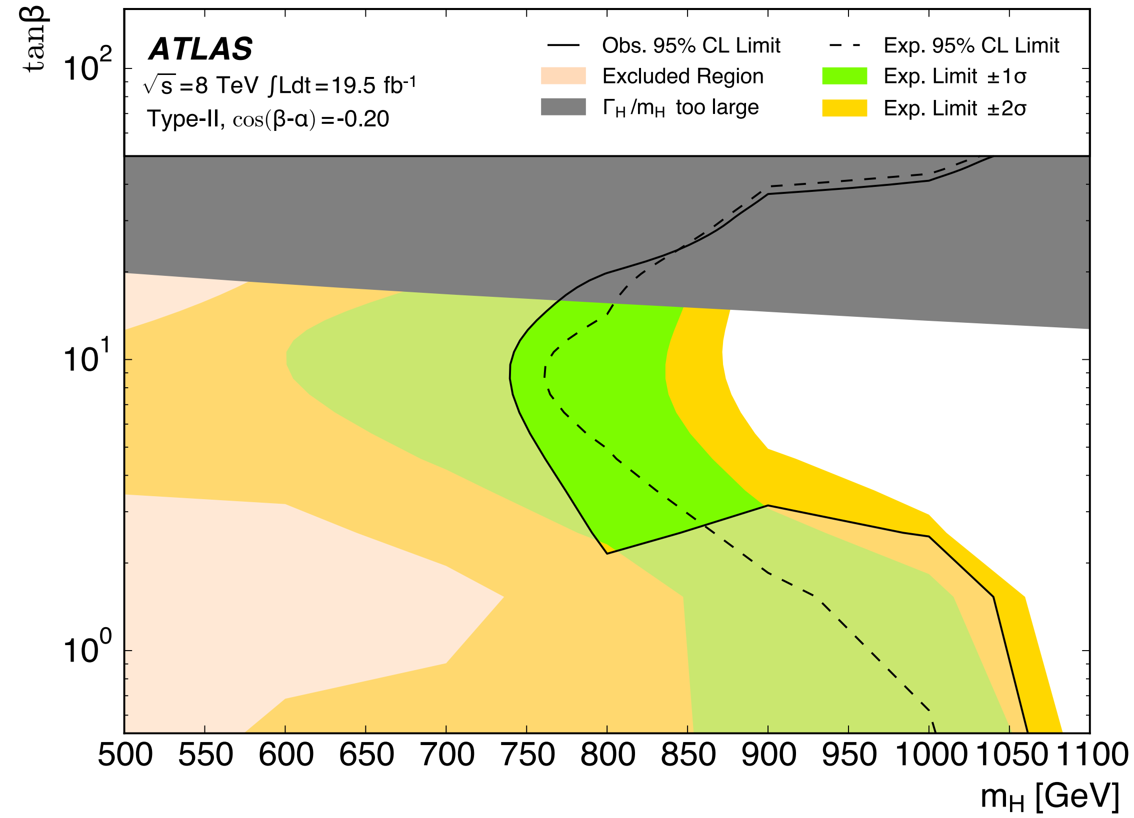
The exclusion limit for pp→H→hh→bbbb with fixed Γ_H=1GeV

A simple combination of the separate limits from the resolved and boosted (performance crossing around 1.1 TeV)



Excluded regions are presented in four 2HDMs (Type-I, Type-II, Lepton-specific, Flipped)



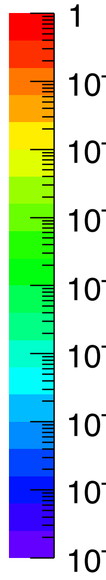


$(X) \rightarrow hh \rightarrow bb\tau\tau$

arXiv:1510.01181

arXiv:1509.04670

$BR_{SM}(hh \rightarrow bb\tau\tau) \sim 7.2\%$



(X)→hh→bb$\tau\tau$

Final states: $\tau_h\tau_h$ $e\tau_h$ $\mu\tau_h$

divided in categories based on number of b-jets (0 or 1 or 2)

Selection largely following the SM H→$\tau\tau$ analysis

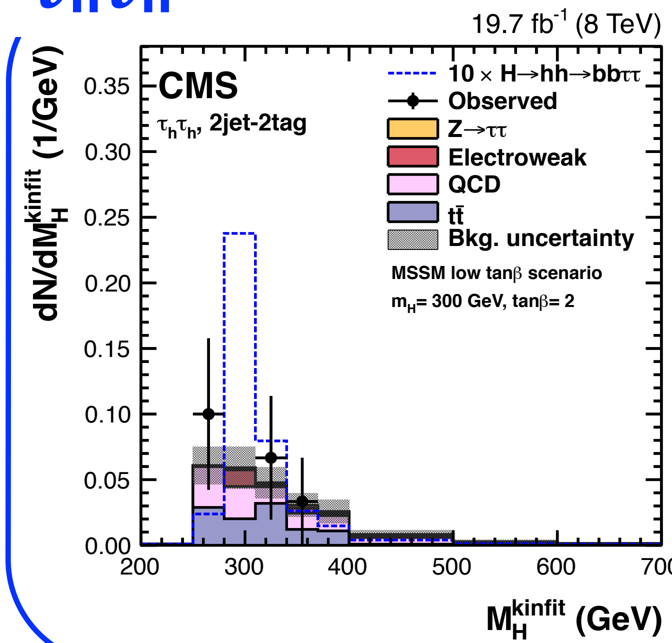
Kinematical fit (M_H^{kinfit}) for M_{hh}

signal-to-background ratio is greatly improved

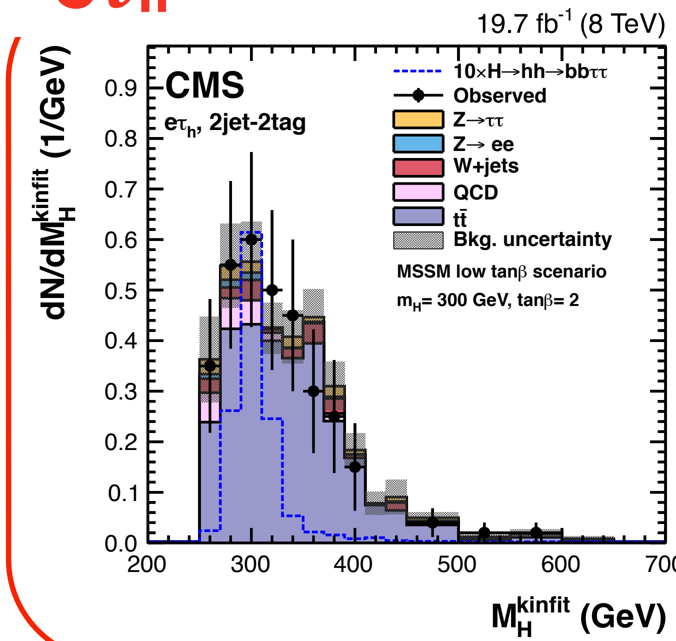
Background (tt,QCD,Z→$\tau\tau$,...)

shapes/yields mainly from data

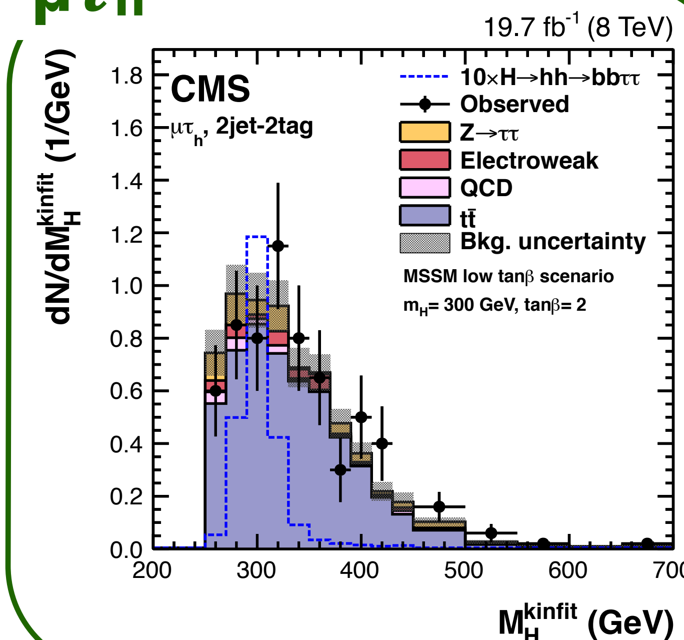
$\tau_h\tau_h$

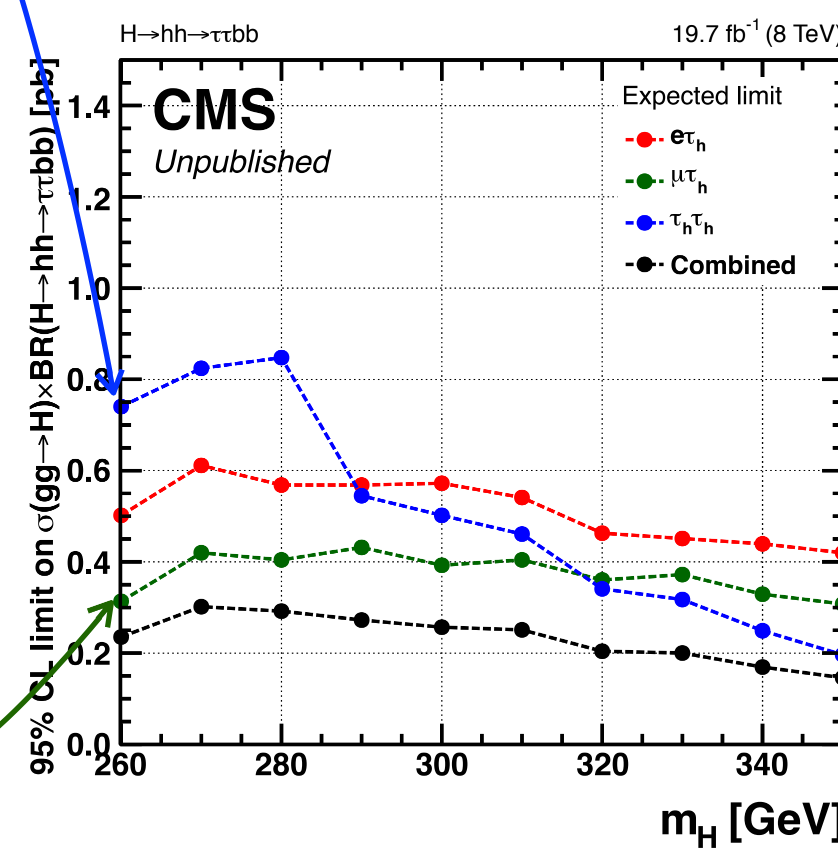


$e\tau_h$



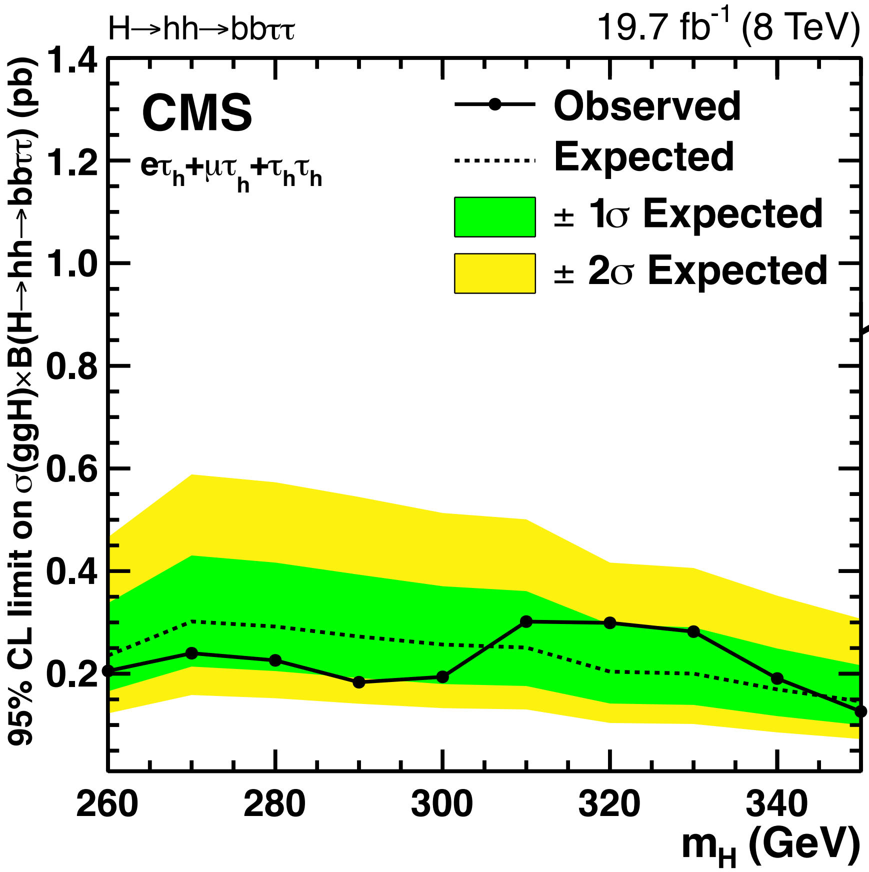
$\mu\tau_h$





Comparison of the expected limits separated by final states

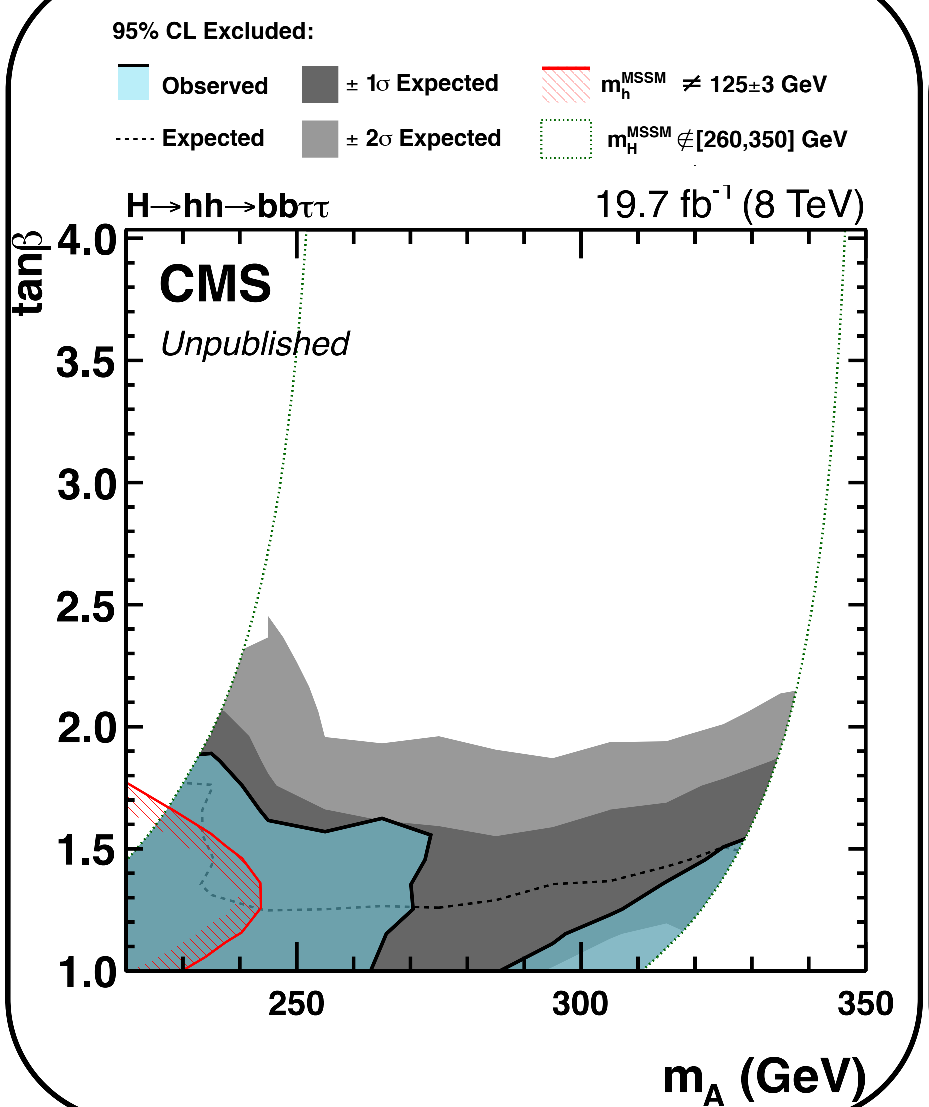
(X)→hh→bbττ: results



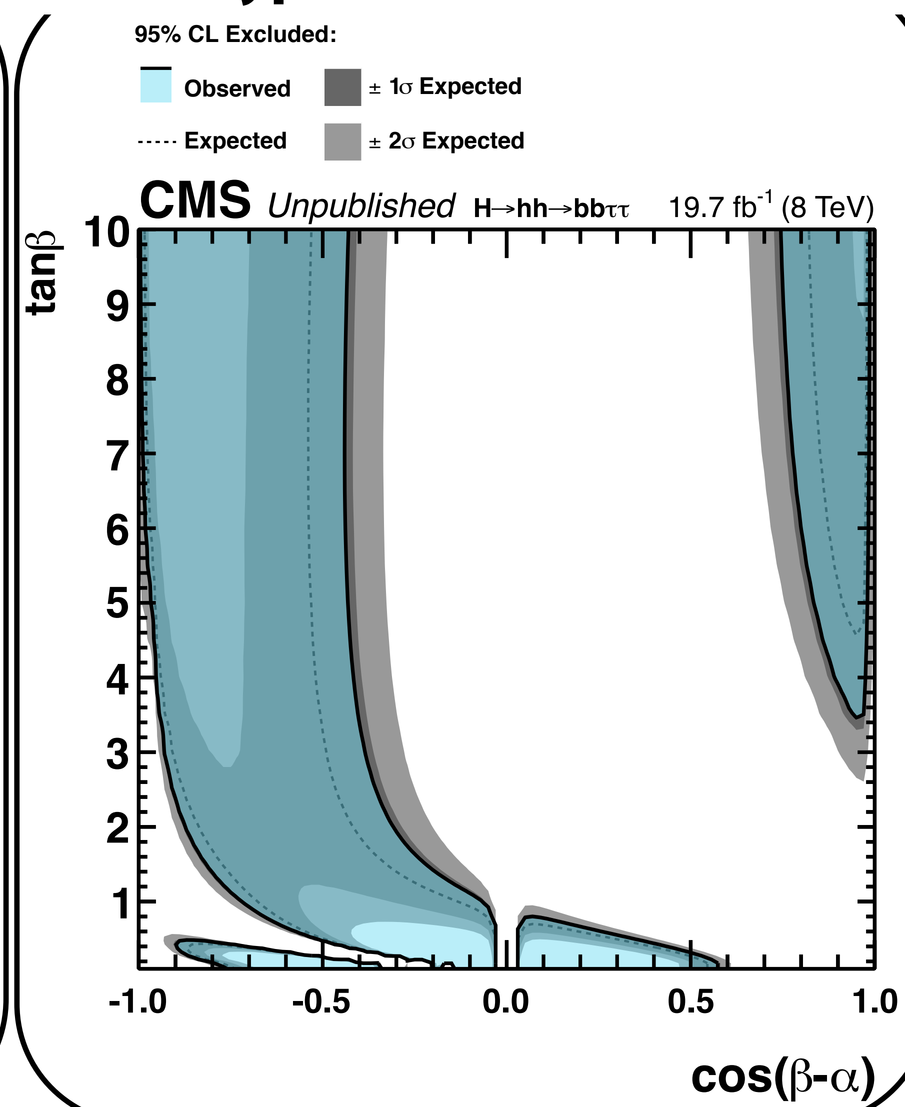
The upper limit at 95% CL on the σ(ggH)×BR(H→hh→bbττ) is re-interpreted in 2HDM Type-II and MSSM models

"low tanβ" scenario: the value of M_{SUSY} is increased until the mass of the lightest Higgs boson is consistent with 125 GeV over a range of low tan β and m_A values

MSSM low tanβ scenario



2HDM Type-II $m_H = m_A = 300$ GeV



(X)→hh→bb$\tau\tau$

Final states: $e\tau_h$ $\mu\tau_h$

divided in categories based on

- $P_T^{\tau\tau}$ (< or > 100 GeV)
- number of b-jets (1 or ≥2)

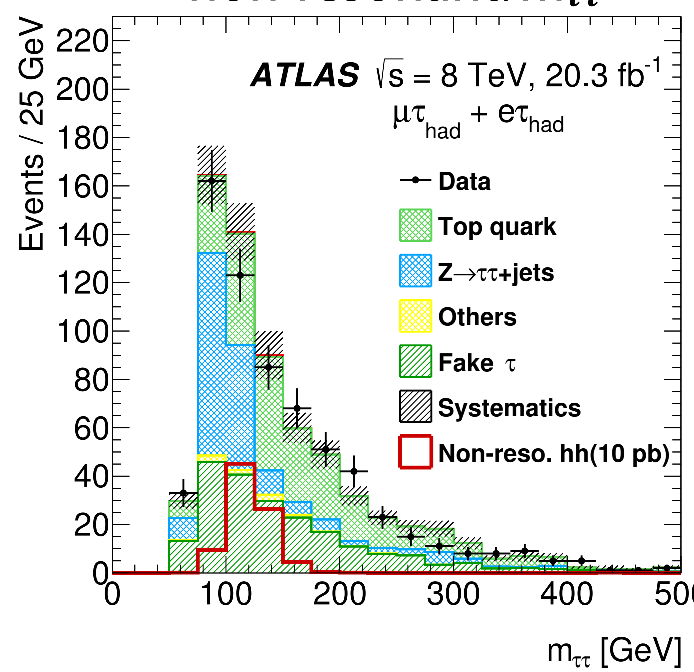
Selection largely following the SM H→$\tau\tau$ analysis

	Process	$n_b \geq 2$ $p_T^{\tau\tau}$ < 100 GeV	$n_b \geq 2$ $p_T^{\tau\tau}$ > 100 GeV
	SM Higgs	0.1 ± 0.1	0.2 ± 0.1
Simulation	Top quark	30.9 ± 3.0	23.6 ± 2.5
	$Z \to \tau\tau$	6.8 ± 1.8	2.6 ± 1.0
Embedded	Fake τ_{had}	13.7 ± 1.9	5.4 ± 1.0
	Others	0.7 ± 1.6	0.2 ± 0.7
“Fake-factor” method	Total background	52.2 ± 8.2	32.1 ± 5.4
	Data	35	35
	Signal m_H = 300 GeV	1.5 ± 0.3	0.9 ± 0.2

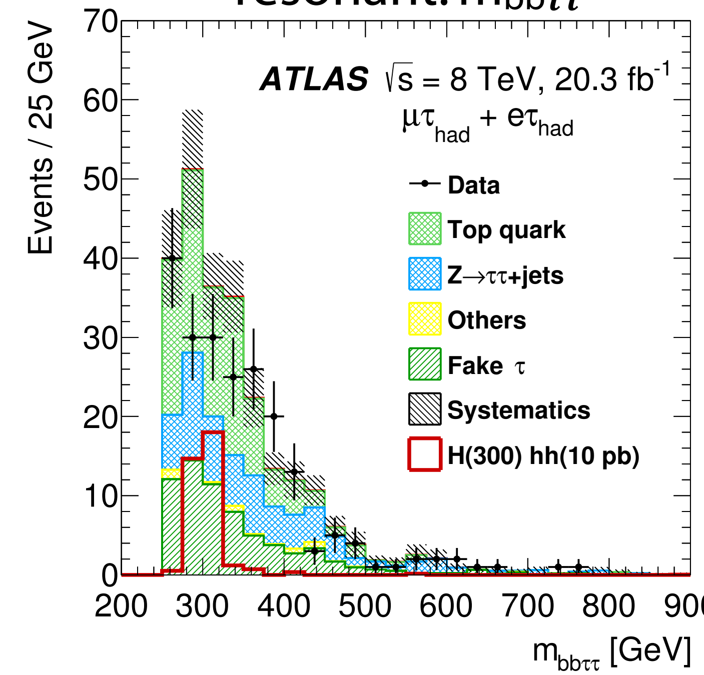
Numbers of events predicted from background and observed in the data

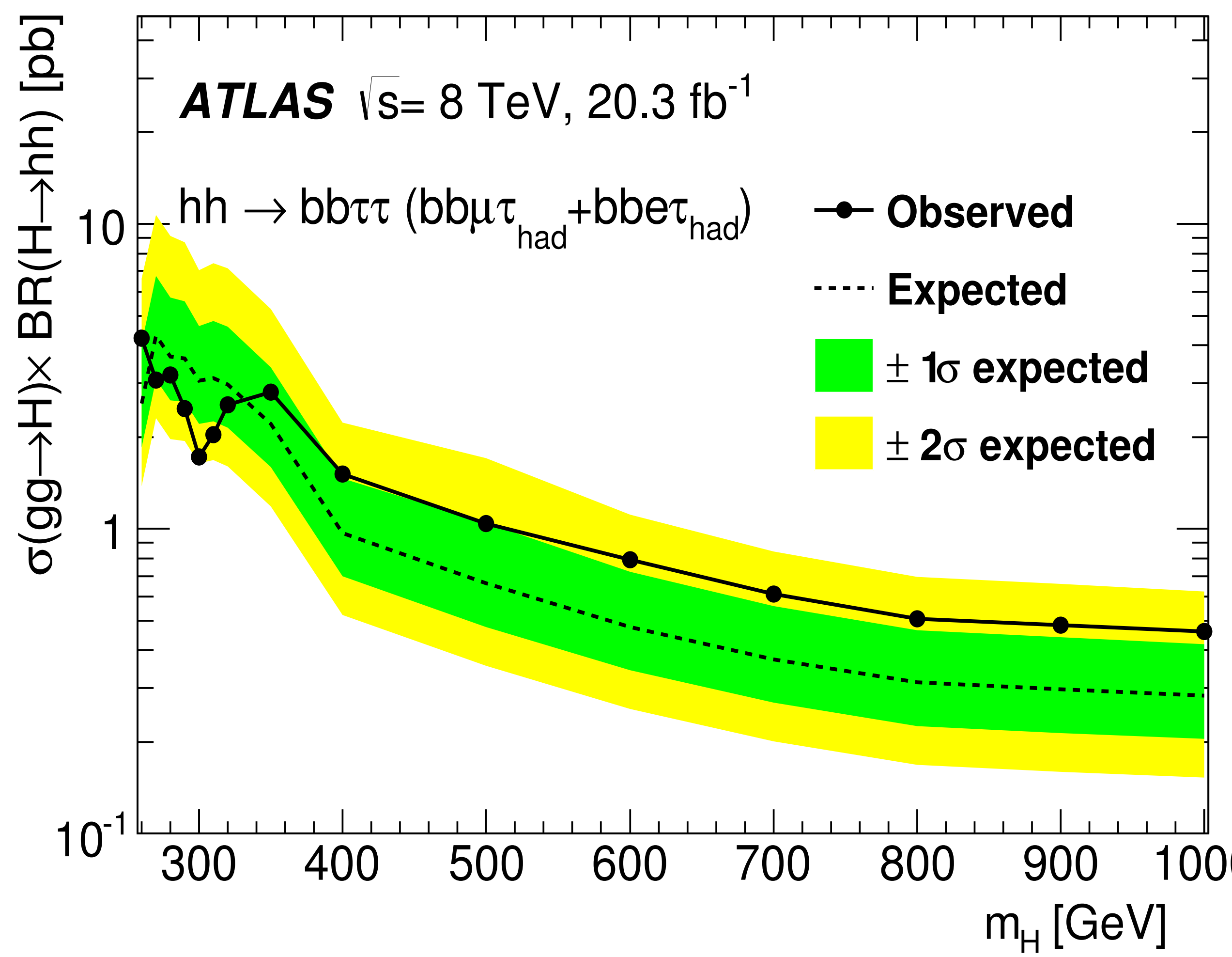
Final discriminants used to extract the signal (1D analysis)

non-resonant: $m_{\tau\tau}$



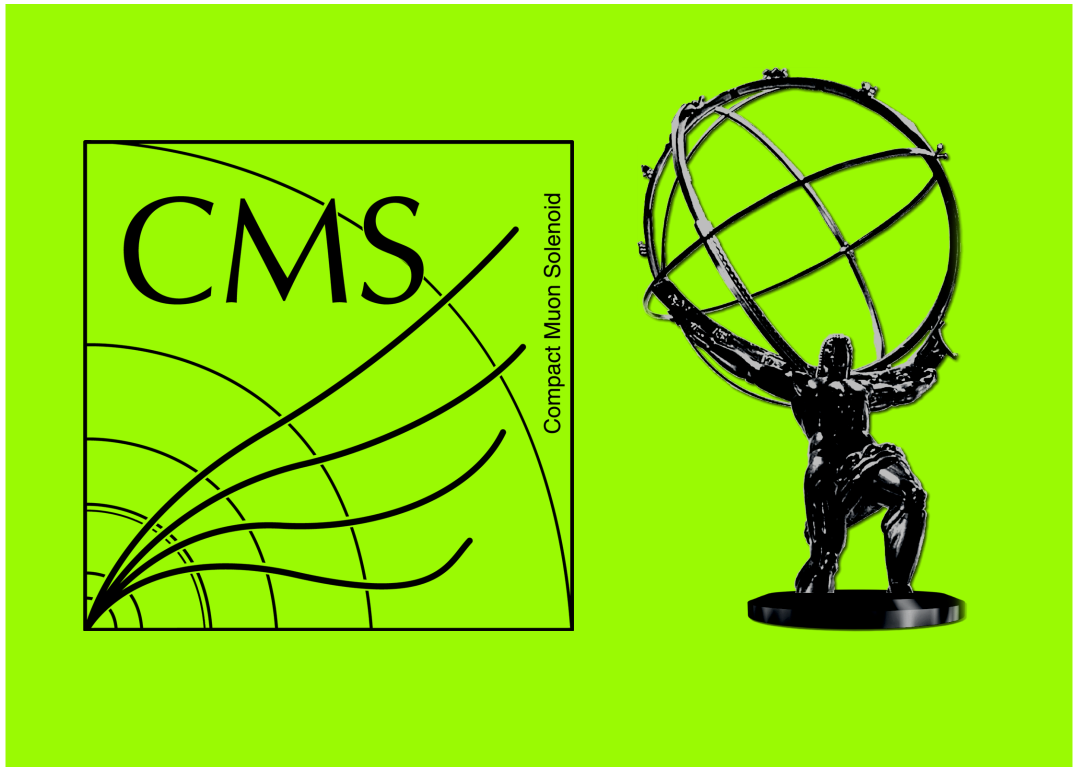
resonant: $m_{bb\tau\tau}$





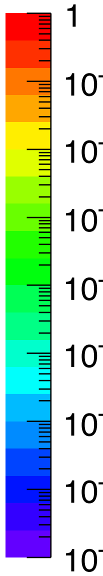
$(X) \rightarrow hh \rightarrow bb\gamma\gamma$

CMS-HIG-13-032



Phys. Rev. Lett. 114, 081802 (2015)

$BR_{SM}(hh \rightarrow bb\gamma\gamma) \sim 0.26\%$



(X)→hh→bb$\gamma\gamma$

Follow SM h→$\gamma\gamma$ analysis

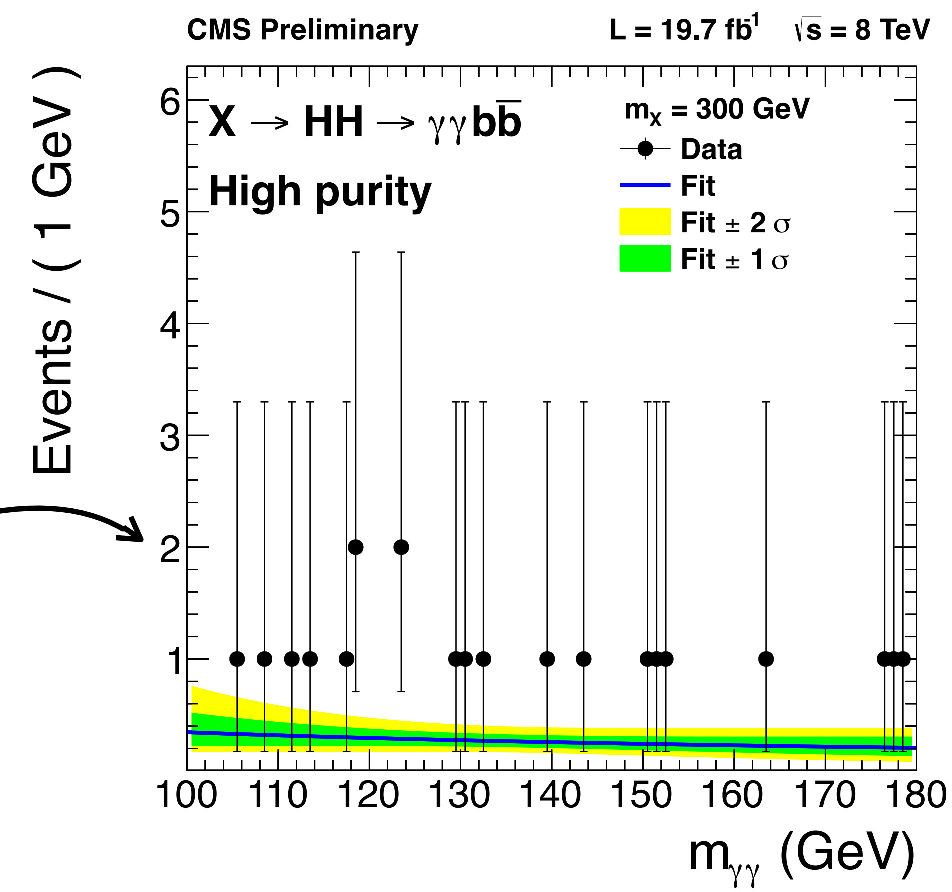
- no Primary Vertex efficiency issue thanks to the hadronic h

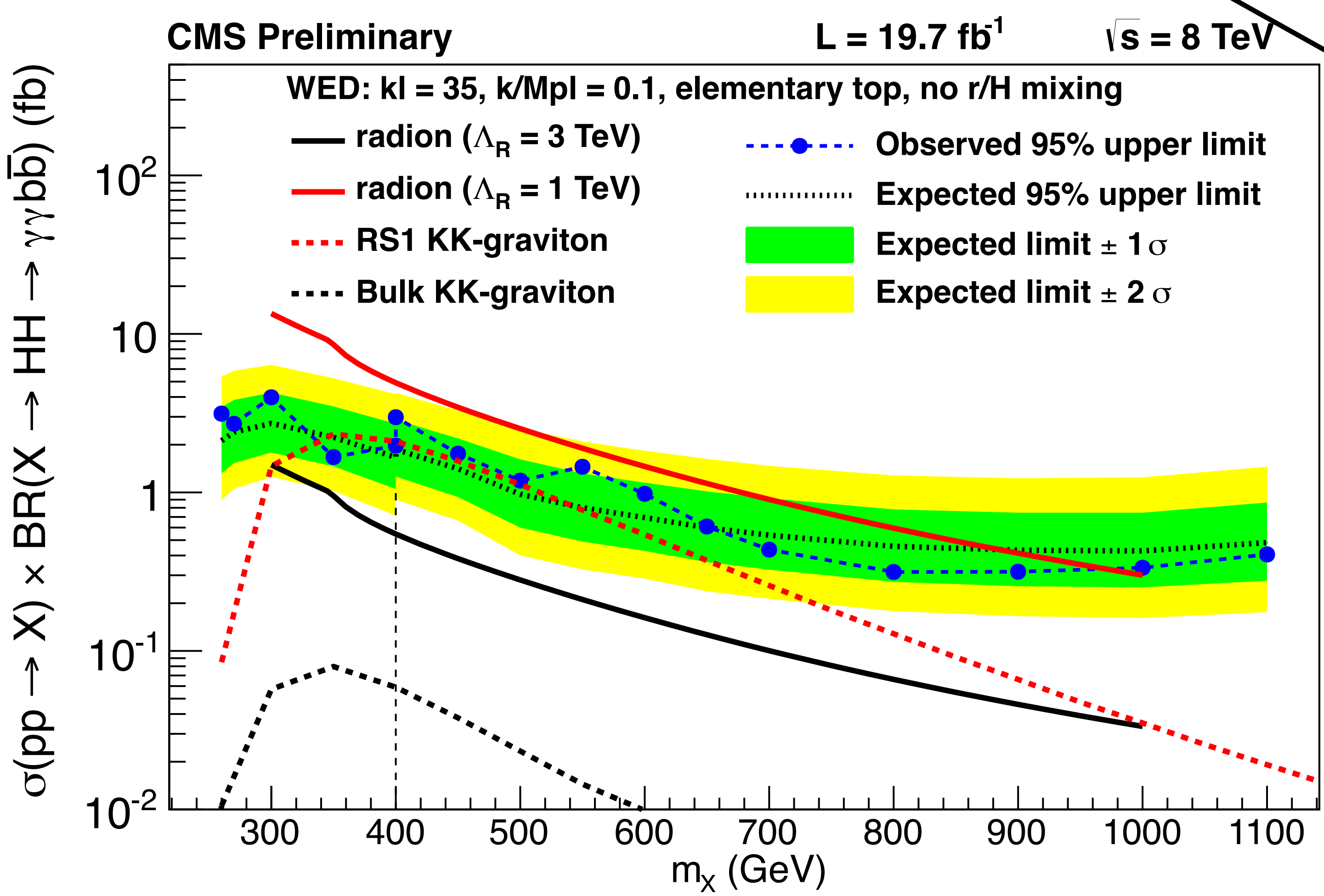
Three categories of events

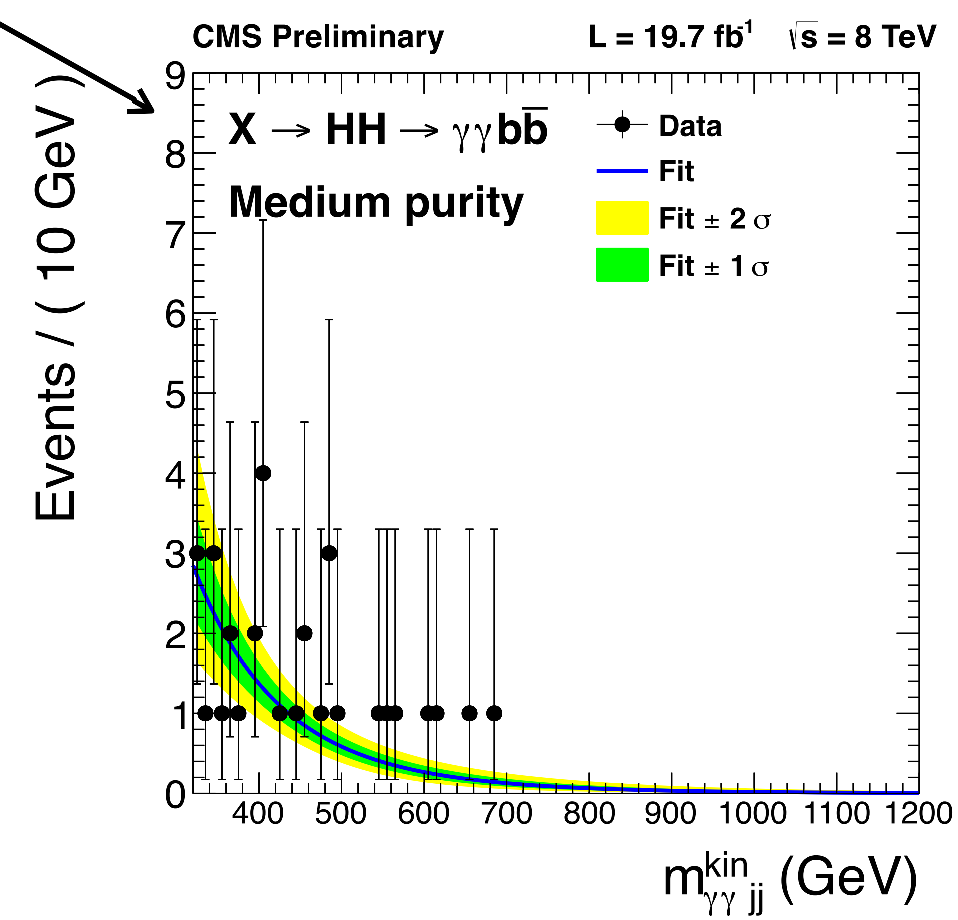
- 0 b-tags: used as control region
- 1 and >=2 b-tags: medium and high purity region

Two ranges of resonances masses

- 260≤m_X≤400 GeV : $m_{\gamma\gamma}$ to extract the signal
- 400<m_X≤1000 GeV : $m^{kin}_{\gamma\gamma jj}$ to extract the signal







(X)→hh→bb$\gamma\gamma$

Phys. Rev. Lett. 114, 081802 (2015)

Follow SM h→$\gamma\gamma$ measurement analysis

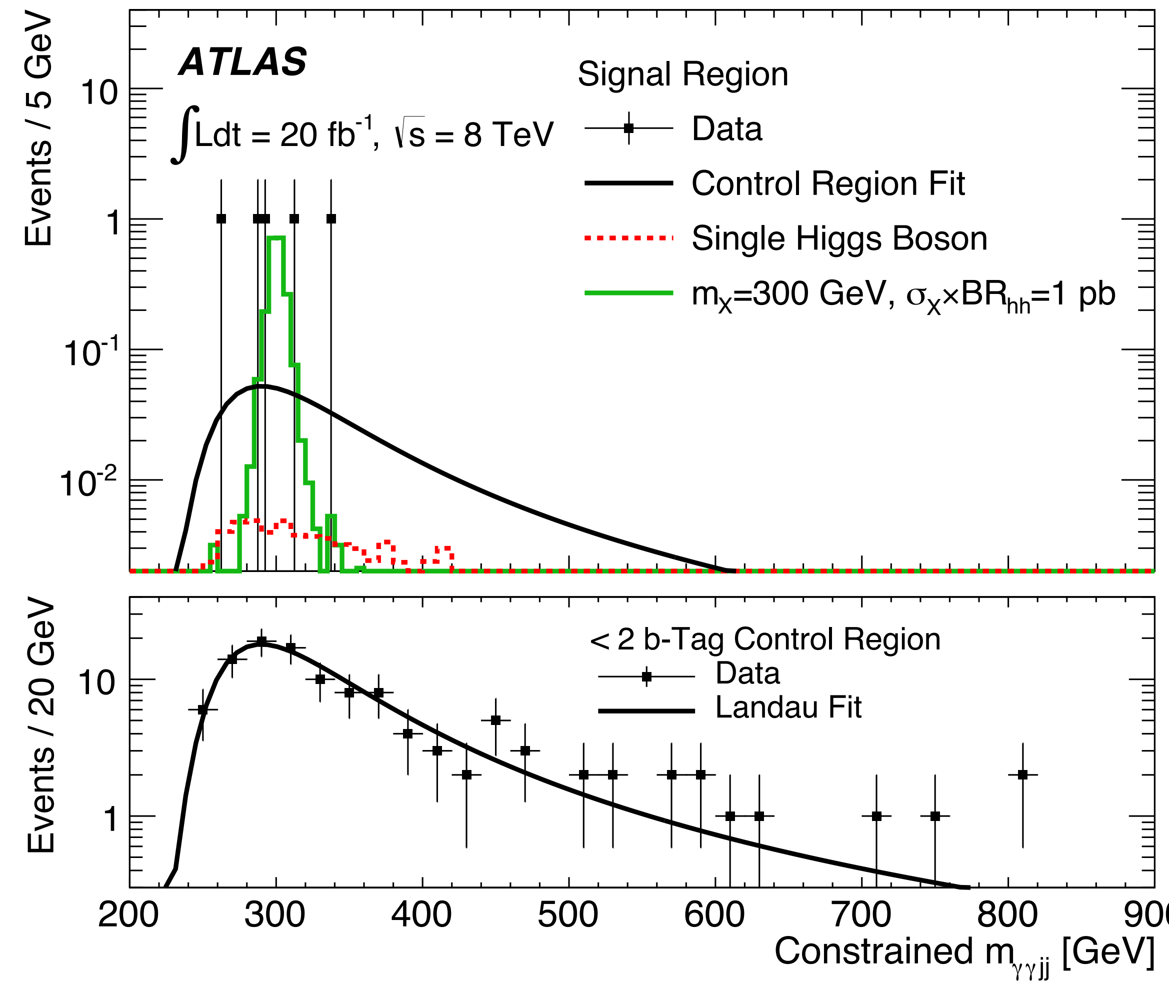
Only one category of events

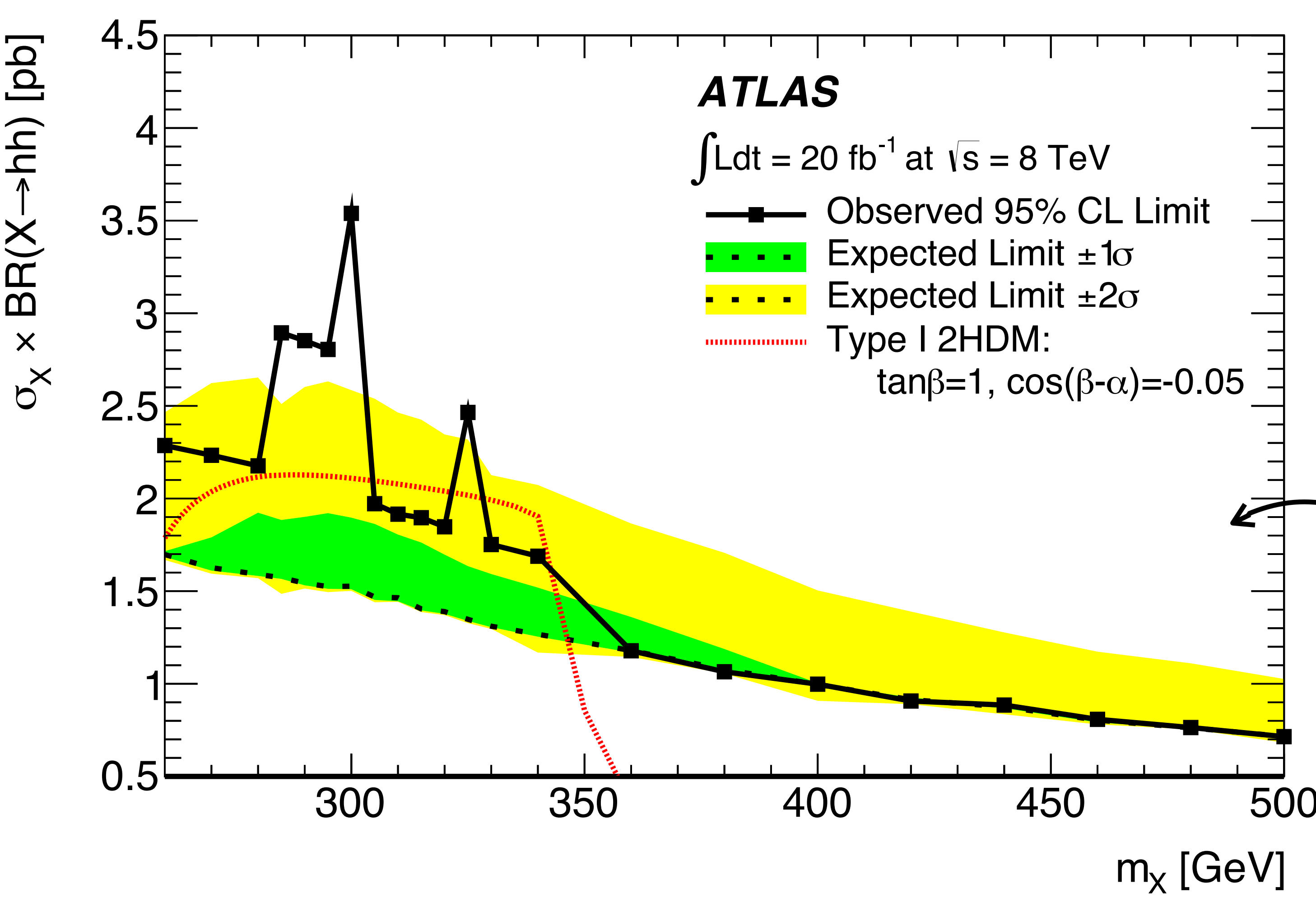
Search for:

→ spin 0 resonances in the 260≤m_X≤500 GeV mass range SM Higgs boson

→ non-resonant pair production

Constrained $m_{\gamma\gamma jj}$ to extract the signal





Limit non-resonant analysis:

Expected: $1.0^{+0.2}_{-0.5}$ pb

Observed: 2.2 pb (2.4σ)

Limit resonant analysis:

1pb in the higher mass region

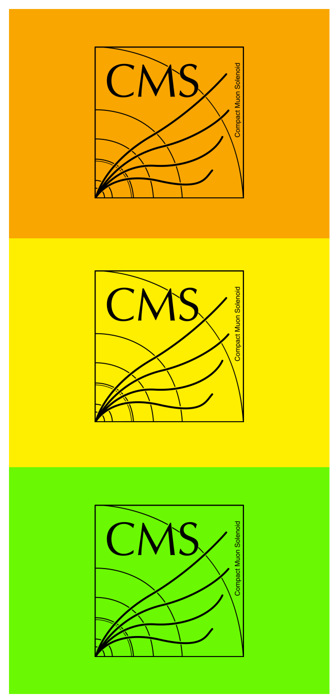
Local excesses below 350 GeV around 3.5 pb

Other channels

Multileptons
Lepton plus photons

(X)→hh→WW$\gamma\gamma$

Phys. Rev. D 90 (2014) 112013



Phys. Rev. Lett. 114, 081802 (2015)

BR$_{SM}$(hh→WW$\gamma\gamma$) ~ 0.1%

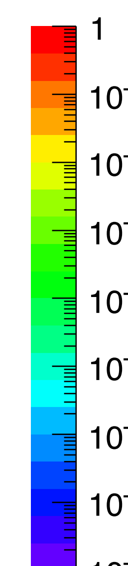
BR$_{SM}$(hh→WWWW) ~ 4.6%

BR$_{SM}$(hh→WW$\tau\tau$) ~ 2.7%

BR$_{SM}$(hh→WW$\gamma\gamma$) ~ 0.1%

… … ….

… … ….

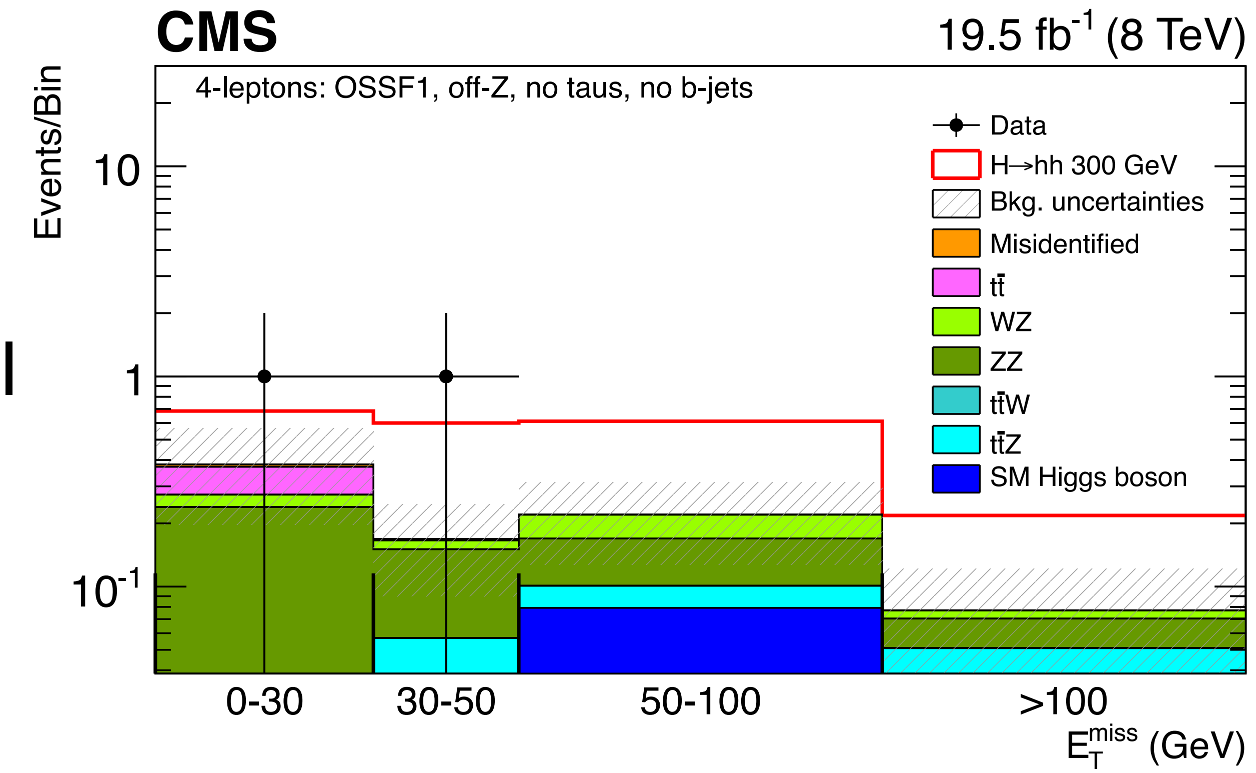


Multileptons / lepton plus photons

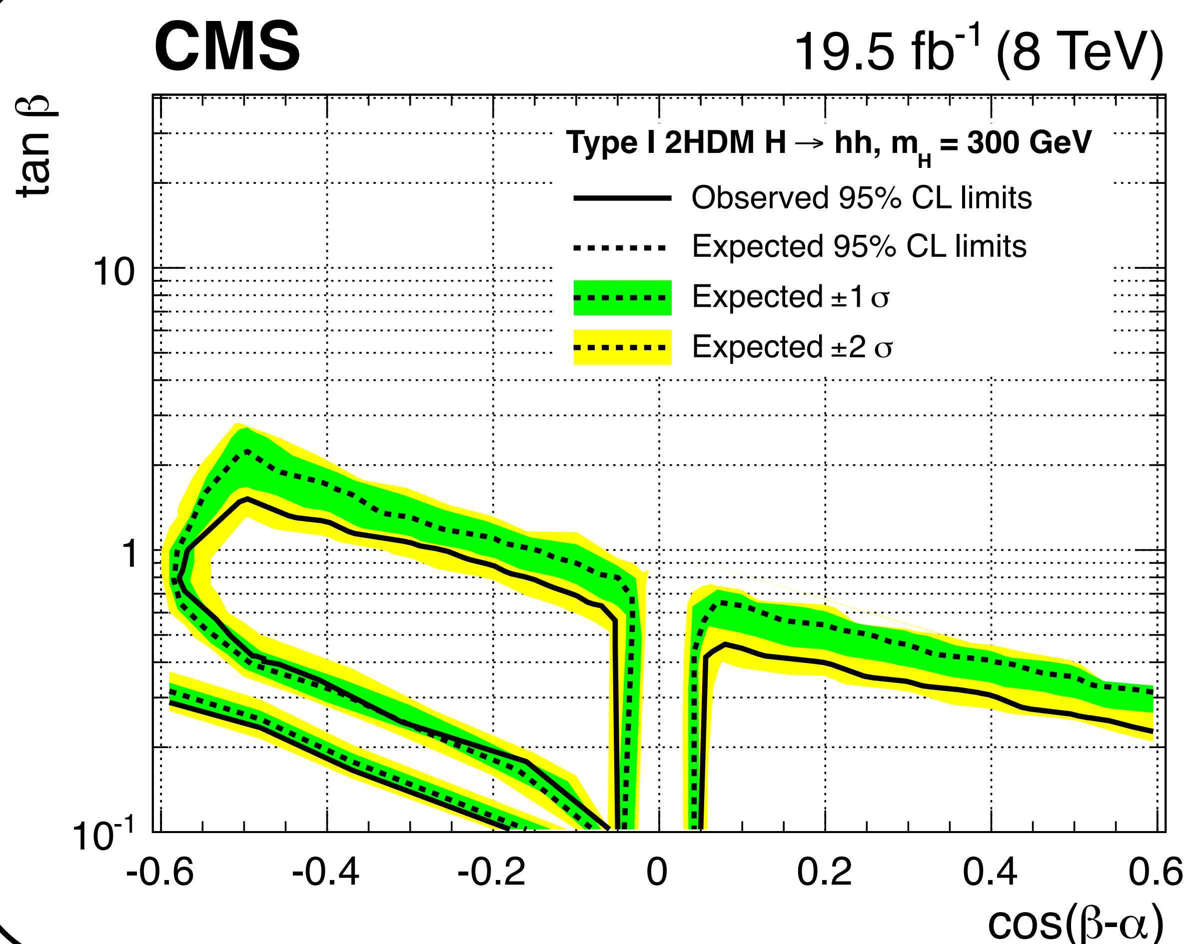
Phys. Rev. D 90 (2014) 112013

>=3 leptons covering 7 final states:
- WWWW, WWZZ, WWττ, ZZZZ, ZZττ, ZZbb, and ττττ

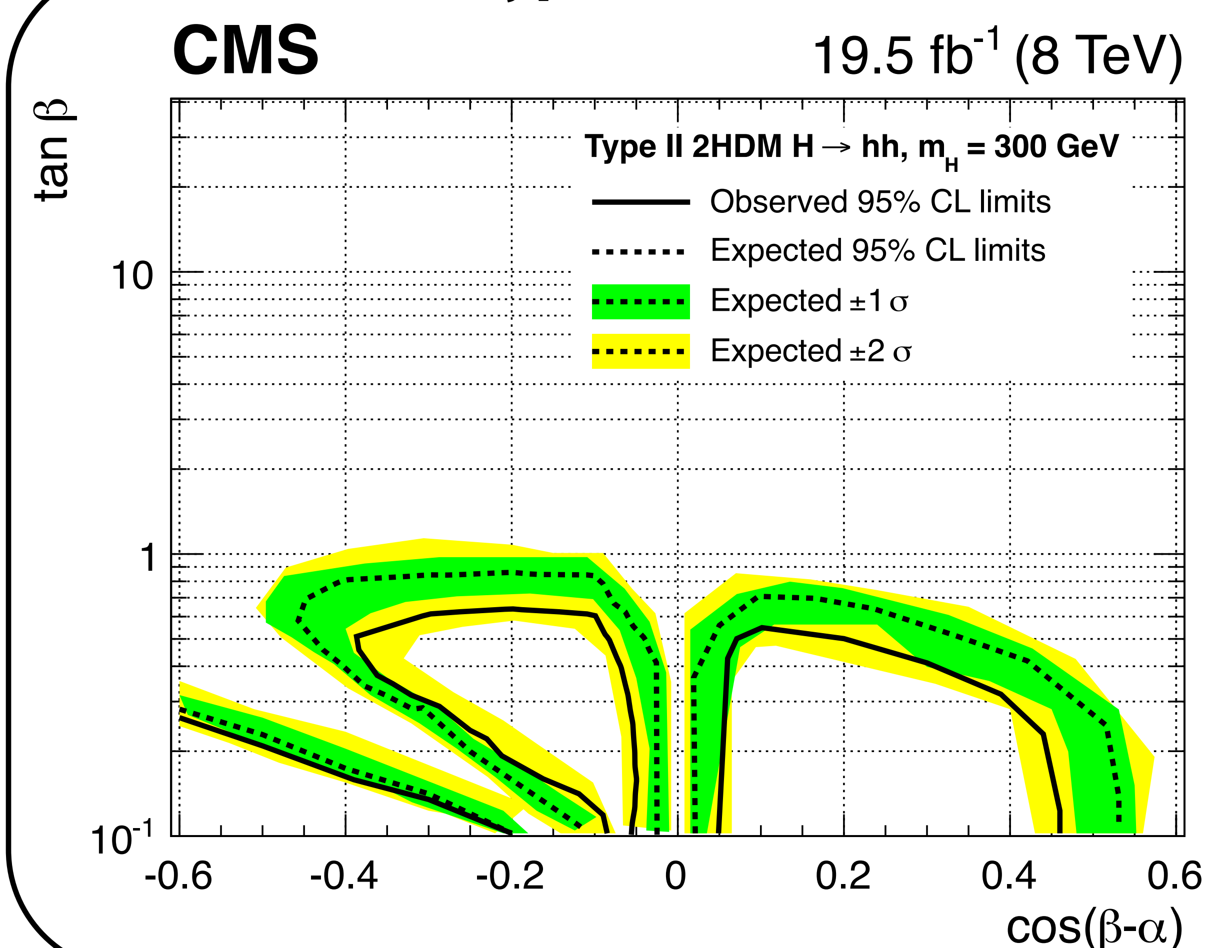
2 photons plus >=1 lepton covering 3 final states:
- $WW\gamma\gamma$, $ZZ\gamma\gamma$, and $\tau\tau\gamma\gamma$



2HDM Type-I m_H = 300 GeV



2HDM Type-II m_H = 300 GeV



(X)→hh→WW$\gamma\gamma$

$\gamma\gamma$ side

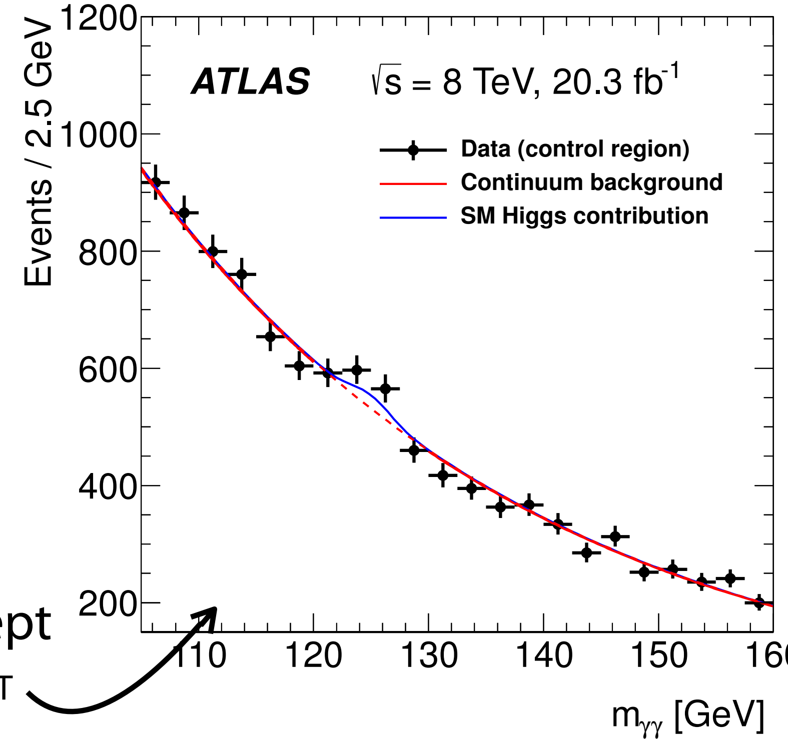
following SM h→$\gamma\gamma$ analysis used to tag the Higgs boson

WW side

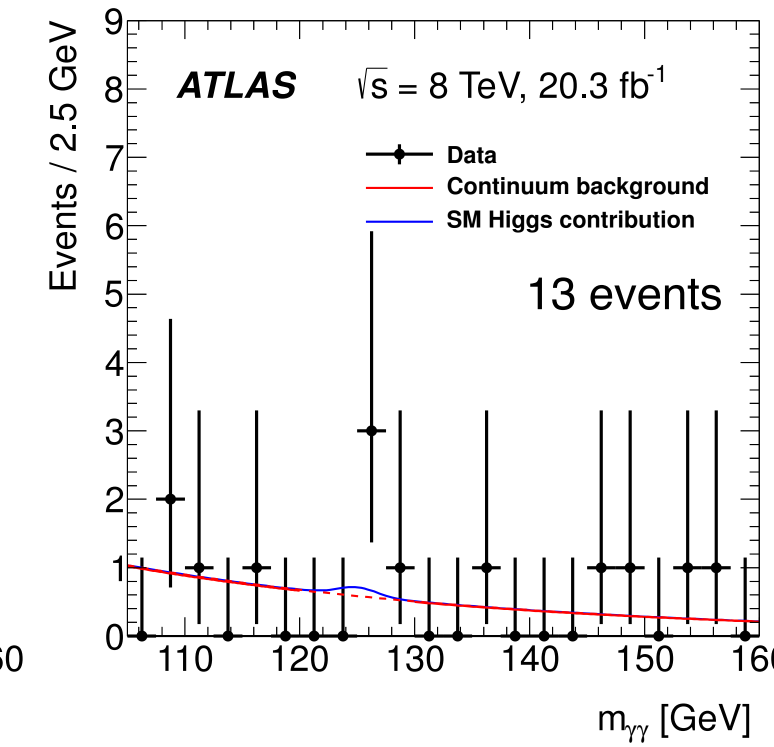
additional lepton+jets (b-tag veto)

All final selections except on the lepton and E^{miss}_T

Relaxed requirements



Final selection

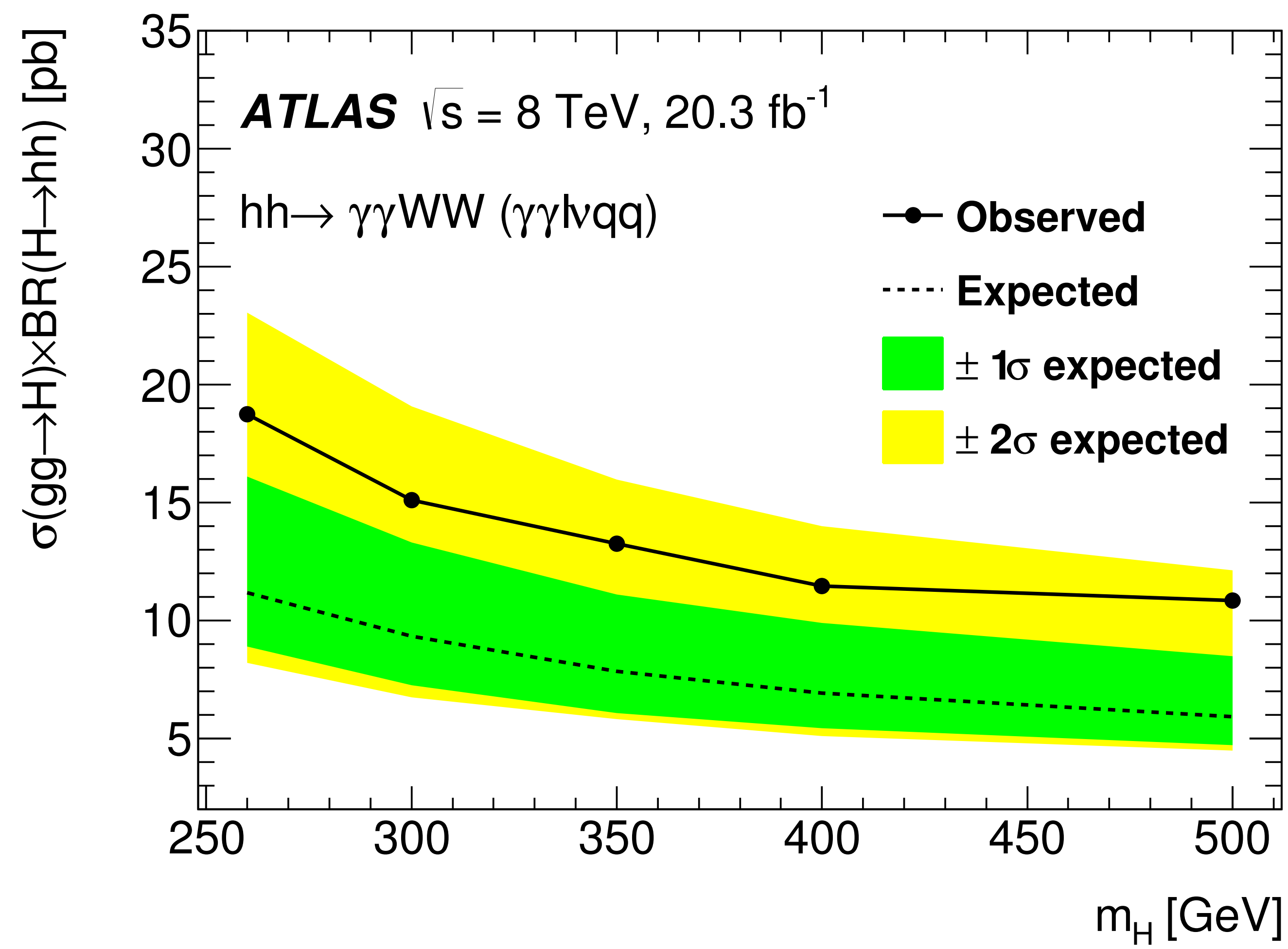


Selection efficiency

→ SM non-resonant 2.9%.

→ resonant production, from 1.7% at 260 GeV to 3.3% at 500 GeV

SM non-resonant p-value of the background-only hypothesis is 3.8% (1.8σ)



Combination

Upper limits

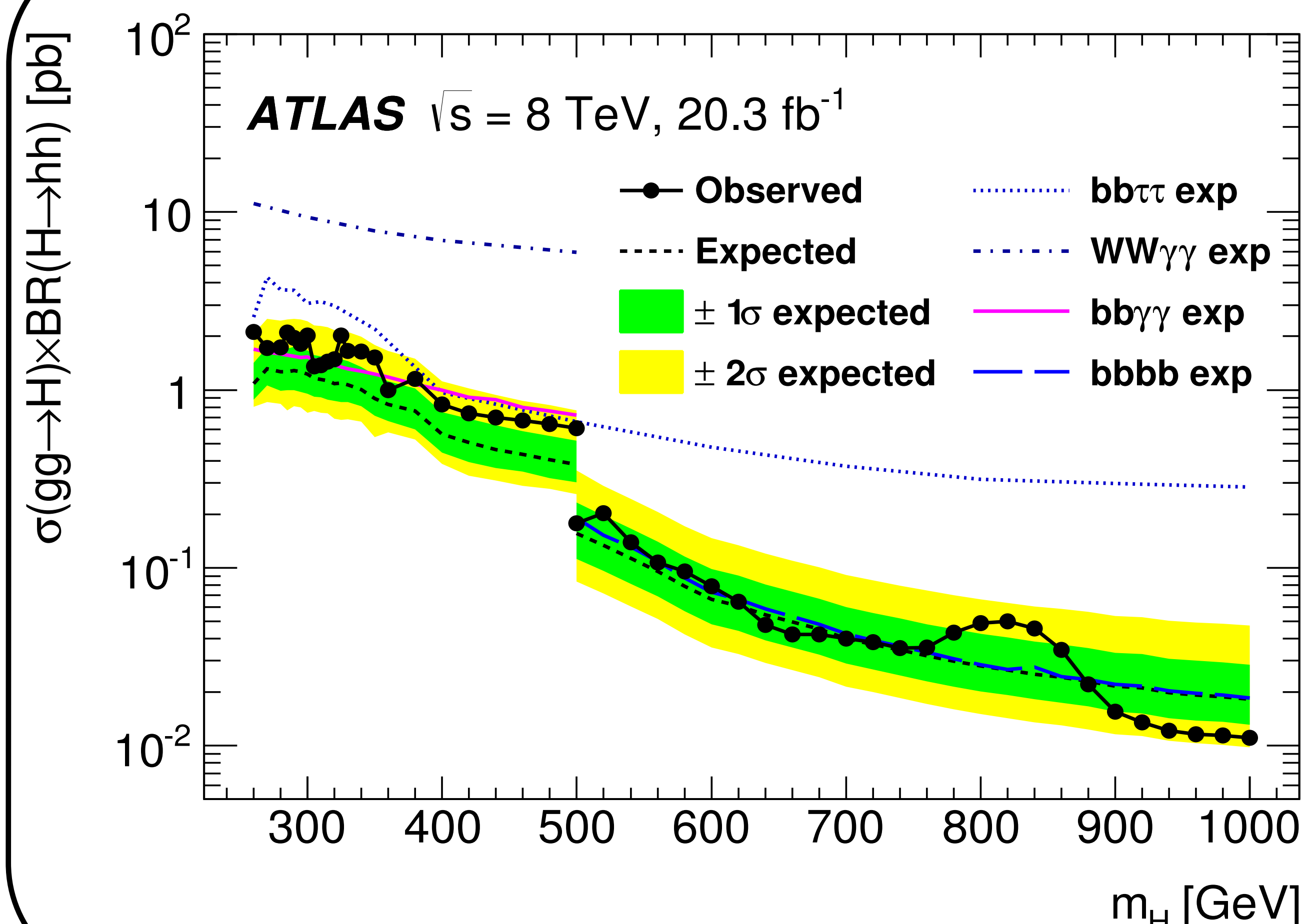
The four individual analyses are sensitive to different kinematic regions of the hh production and decays

hh final state	Nonresonant search Categories	Nonresonant search Discriminant	Resonant search Categories	Resonant search Discriminant	m_H [GeV]
$\gamma\gamma b\bar{b}$	1	$m_{\gamma\gamma}$	1	event yields	260–500
$\gamma\gamma WW^*$	1	event yields	1	event yields	260–500
$b\bar{b}\tau\tau$	4	$m_{\tau\tau}$	4	$m_{bb\tau\tau}$	260–1000
$b\bar{b}b\bar{b}$	1	event yields	1	m_{bbbb}	500–1500

non-resonant

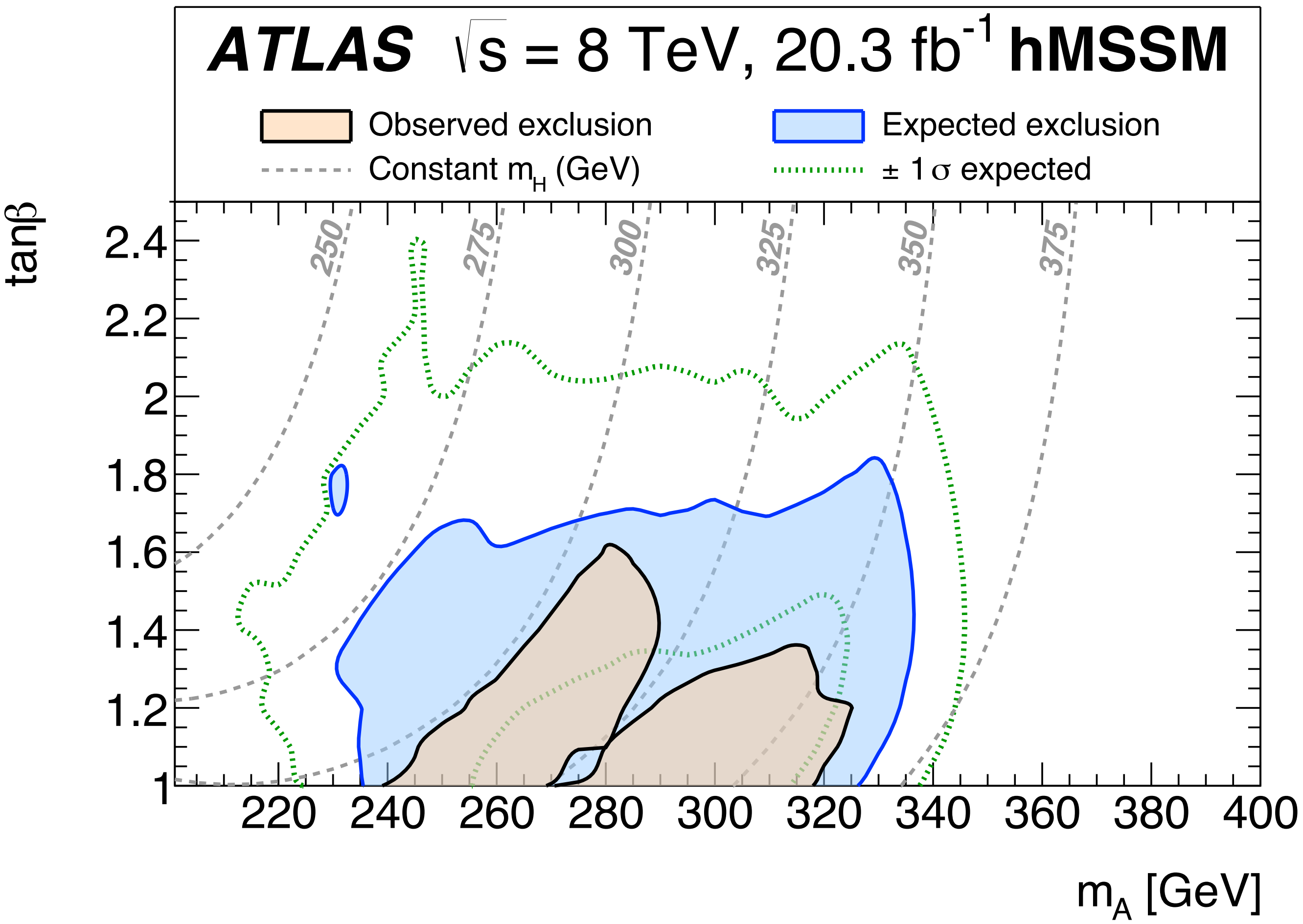
Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
		Upper limit on the cross section [pb]			
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
		Upper limit on the cross section relative to the SM prediction			
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

resonant

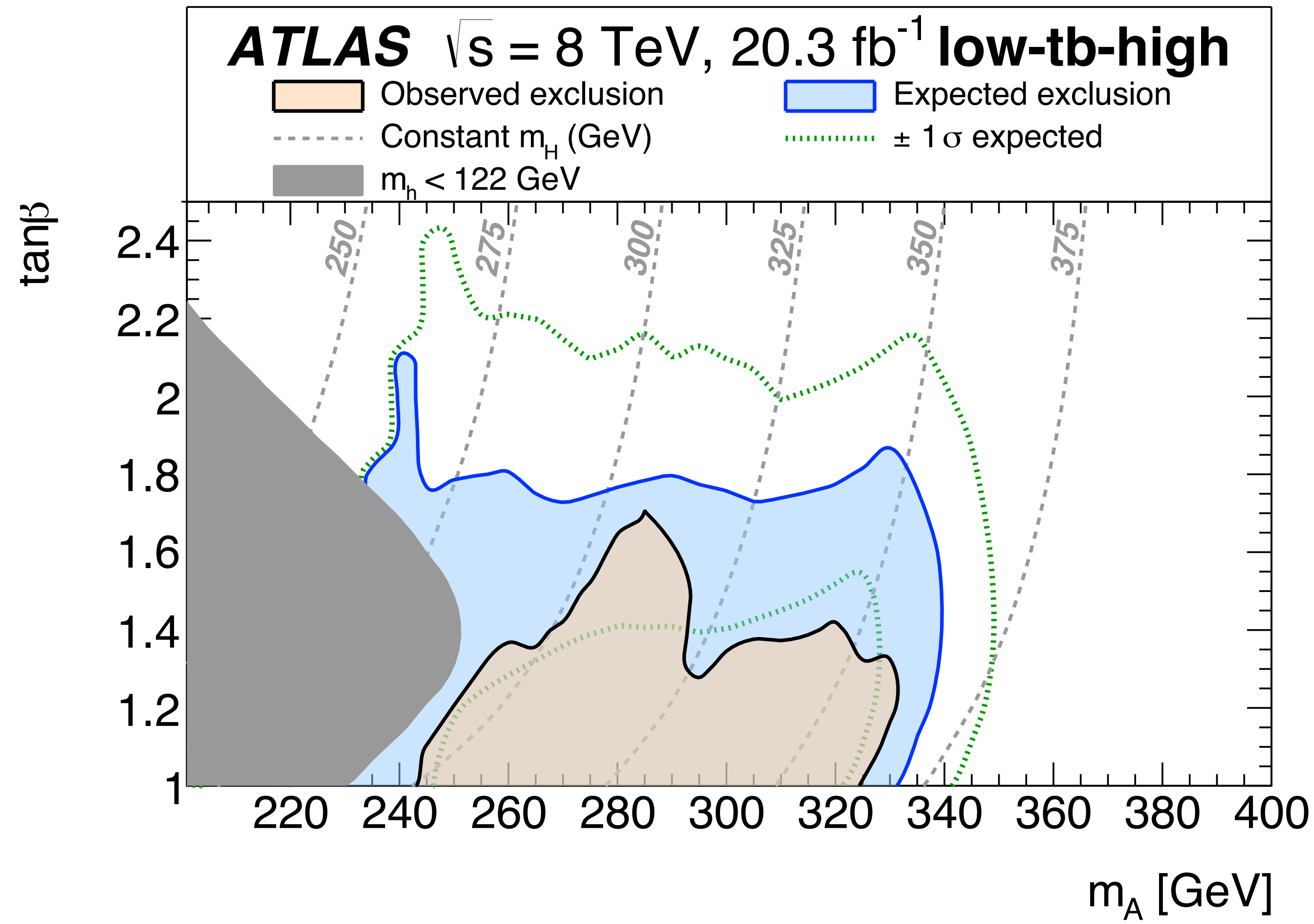


Interpretation

The upper limits on σ(gg→H)×BR(H→hh) can be interpreted as exclusion regions in the (tanβ, mA) plane.



Light CP-even Higgs boson is fixed to 125 GeV in the whole parameter space



Light CP-even Higgs boson mass is not fixed. Gray shaded region the mass of h is inconsistent with the measured value.

Summary

Search for hh final state in Run1 performed by both LHC experiments investigating a large variety of final states

The non-resonant search is far from SM sensitivity (50x SM) but new physics can be probed

Limits on resonant hh set on wide mass range