Searches for additional Higgs bosons

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on behalf of the CMS and ATLAS collaborations

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Introduction

There is a H (125), all the measured properties consistent with the SM. Why bother?

Short answer: the SM is not perfect

A lot of BSM models, some come with the solution by extending the Higgs sector

- Additional singlet ⇒ one more Higgs boson
- Additional doublets ⇒ 5 Higgs bosons (h, H, A, $H^{\pm}$): 2HDM
- Additional singlet+doublet ⇒ 7 Higgs bosons ($h_{1,2,3}$, $a_{1,2}$, $H^{\pm}$): NMSSM
- Additional triplets …

Run2 Higgs searches so far

Luminosity used in each analysis (fb^{-1})

		CMS	ATLAS
X→ hh	bbWW	36.9	
	bbττ	36.9	
	bbγγ	2.7	3.2
	bbbb	2.3	13.3
	γγWW		13.3
X→ ZZ	llqq	12.9	13.3
	llll	12.9	13.3
	llνν	2.3	13.3
X→ WW	lνlν	2.3	13.2
	lνqq	12.9	13.2
	qqqq	36.9	15.5
X→ Zγ	llγ	12.9	13.3
	qqγ	12.9	3.2
X→ γγ		12.9	15.4

X: general resonances including H

> 30 fb^{-1} | 13-15 fb^{-1} | 2-3 fb^{-1}

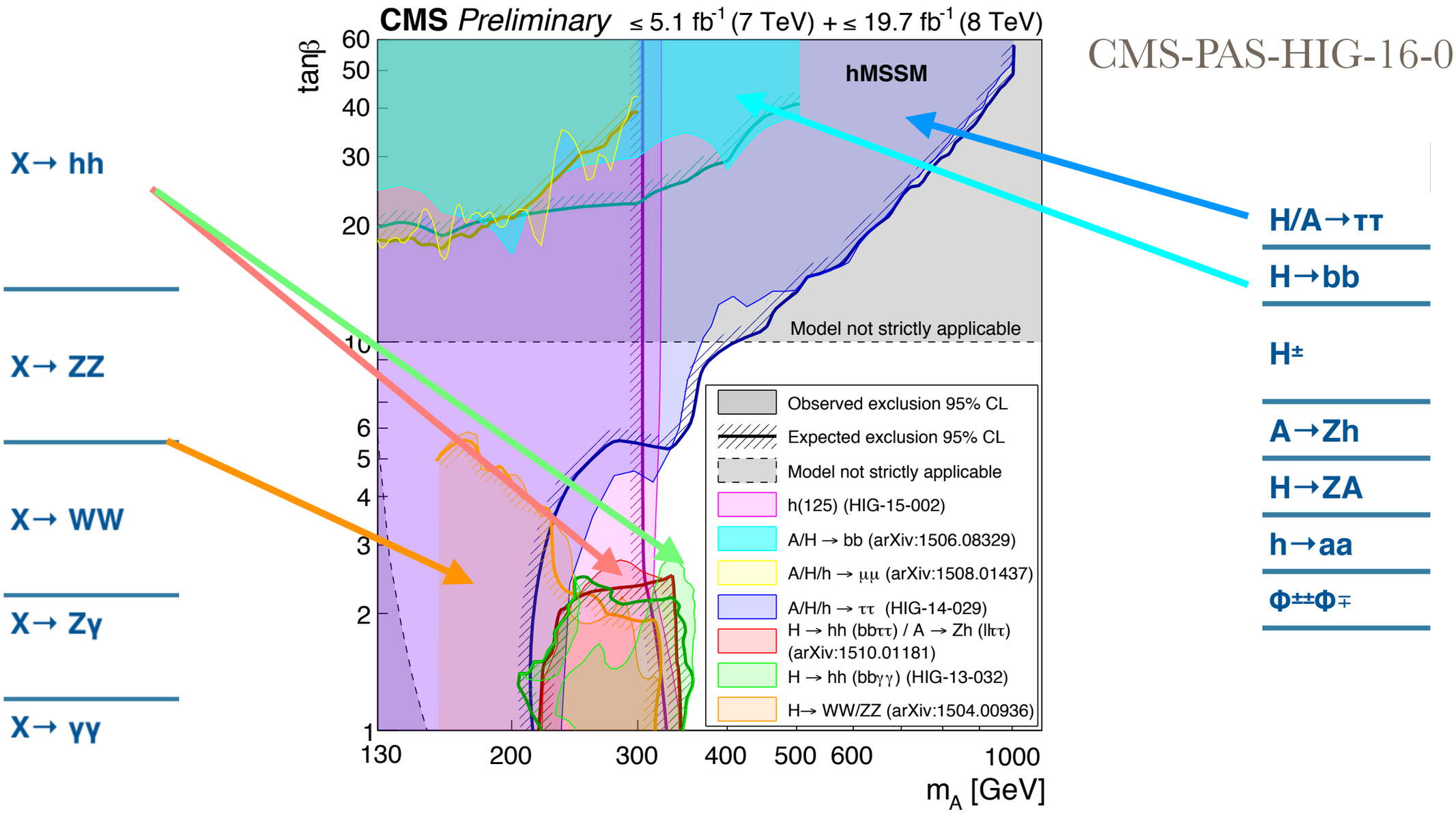
		CMS	ATLAS
H/A→ττ		12.9	13.3
H→bb		2.69	
H±	τν	12.9	14.7
	tb		14.7
	WZ	15.2	
A→Zh	(ll/νν)bb		3.2
H→ZA	llbb	2.3	
h→aa	μμμμ	2.8	
Φ±±Φ∓	llll	12.9	13.9

Most of them model independent
Some specific to 2HDM/NMSSM

Searches, and then?

Run1 example:
interpretation with a specific 2HDM model: hMSSM

CMS-PAS-HIG-16-007



Each search covers quite different phase space

Run2 Higgs searches so far

I will focus on a subset of analyses

		CMS	ATLAS
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L. Morvaj: Diboson searches, 18/05
H. Fox: Results on di-Higgs with ATLAS, 17/05
D. M. Morse: Results on di-Higgs with CMS, 17/05

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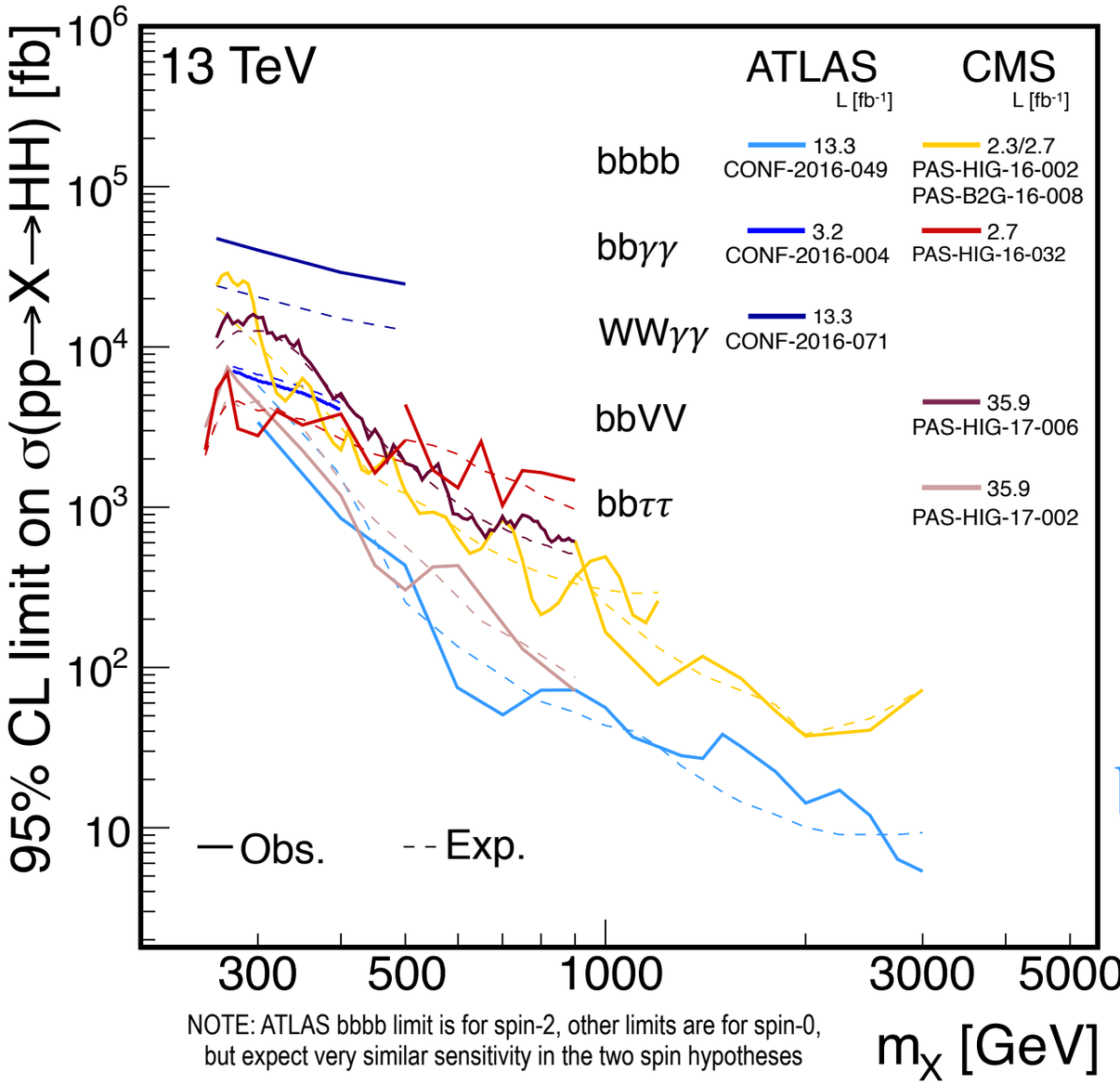
S. Mukherjee: High mass searches, 18/05

Searches for X→ HH

Predicted by: MSSM/2HDM, EW singlet
X: spin0 scalar, narrow width assumption

Low mass region
bbγγ most sensitive

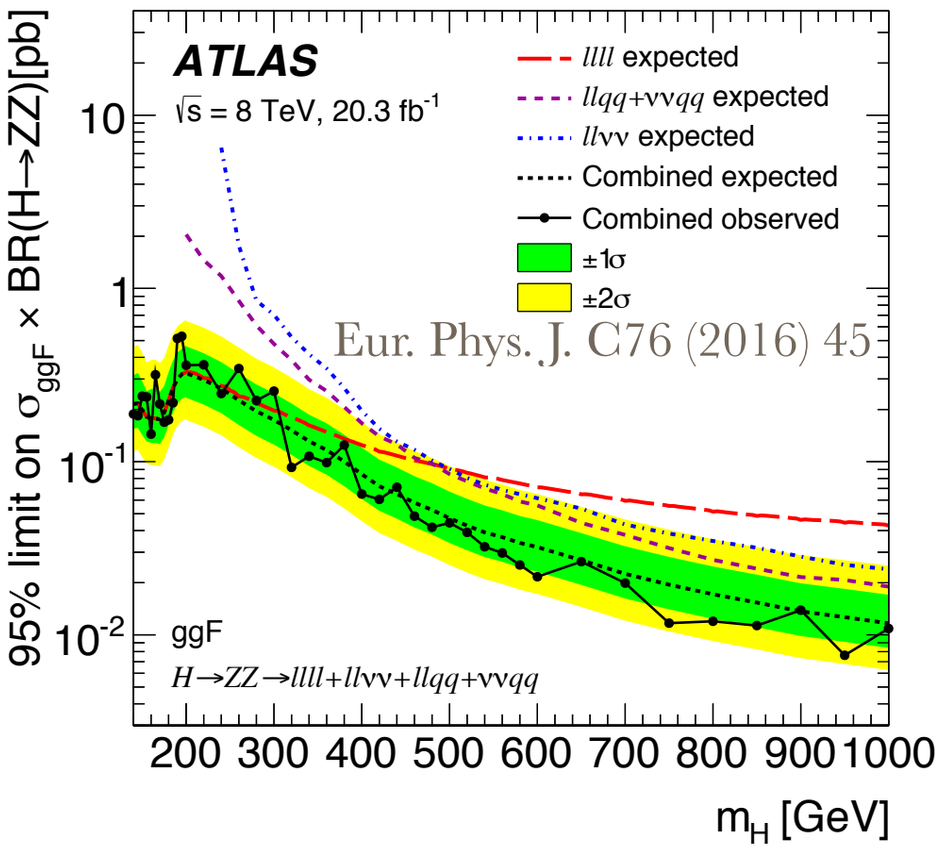


High mass region
bbbb most sensitive

No significant excess

X→ VV searches

- Most BSM models allow X→VV decay
- Such searches usually look for
  - ggH and VBF : XVV coupling → VBF production
  - spin0 scalar, narrow or wide: interference with SM background and H(125)



All final states matter, results from Run1

- X→ZZ :
  - < 500 GeV: 4ℓ
  - 500-600 GeV: 2ℓ2ν, 2ℓ2q
  - >600 GeV 2ℓ2q
- X→WW:
  - < 500 GeV: ℓνℓν
  - > 500 GeV: ℓνqq

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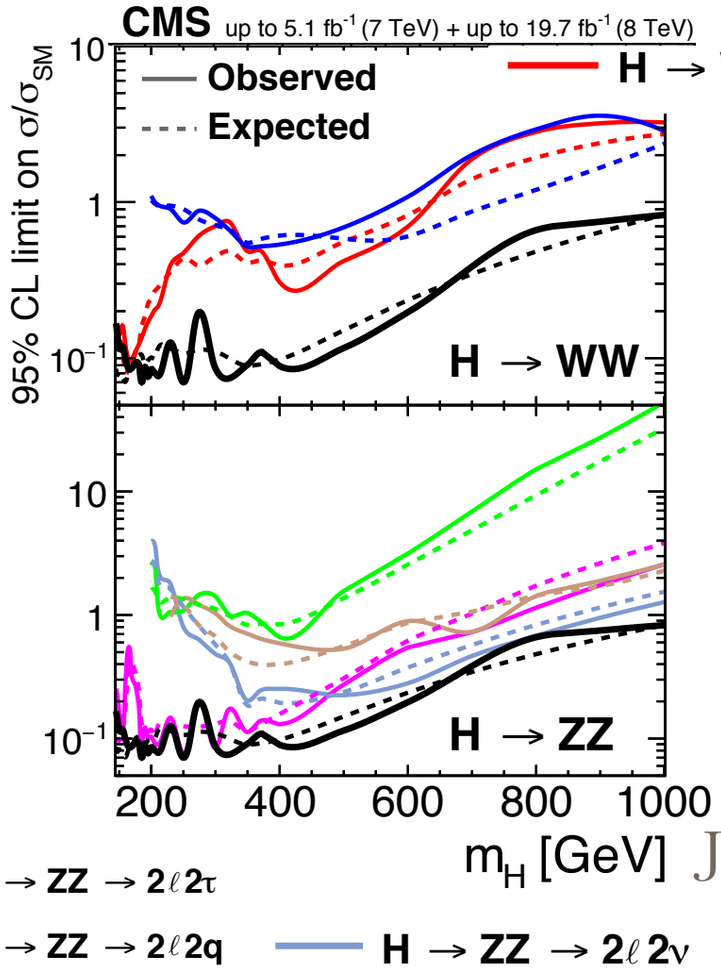

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CMS-PAS-HIG-16-033
ATLAS-CONF-2016-079

X→ ZZ→ 4ℓ (e,μ)

- 2 categories: ggH and VBF
- Parameterized signal shape for m_X and Γ_X
- $m_{4\ell}$ as observable

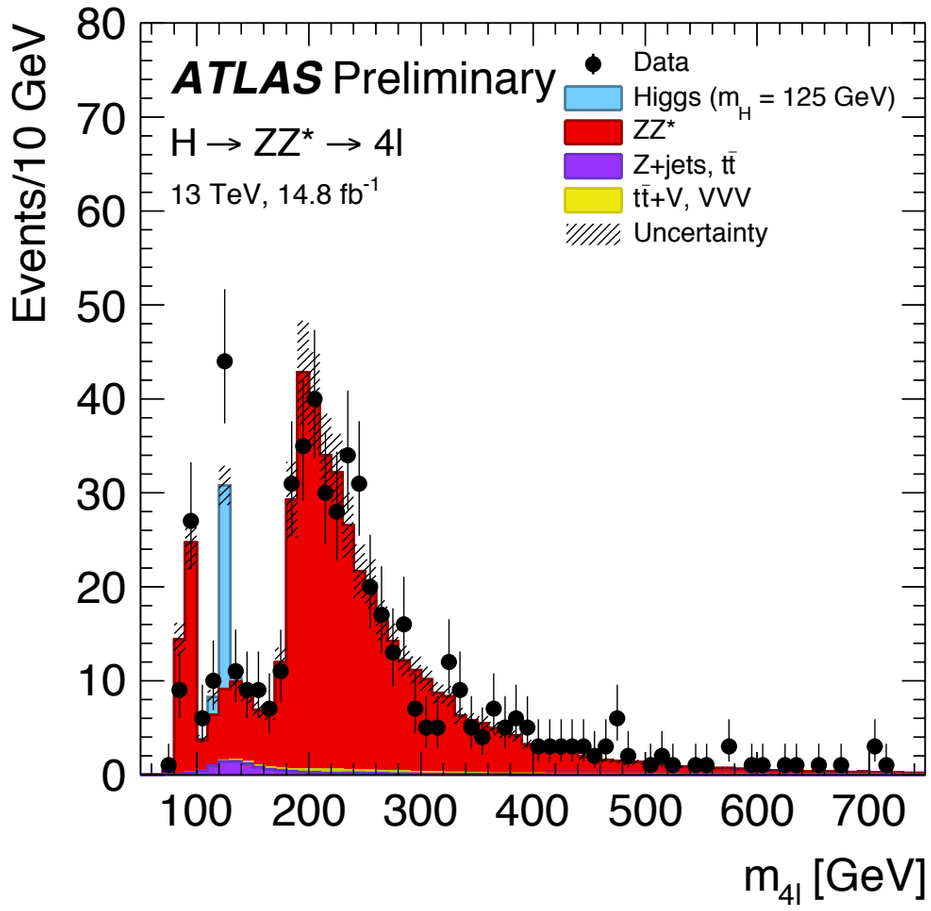
ATLAS

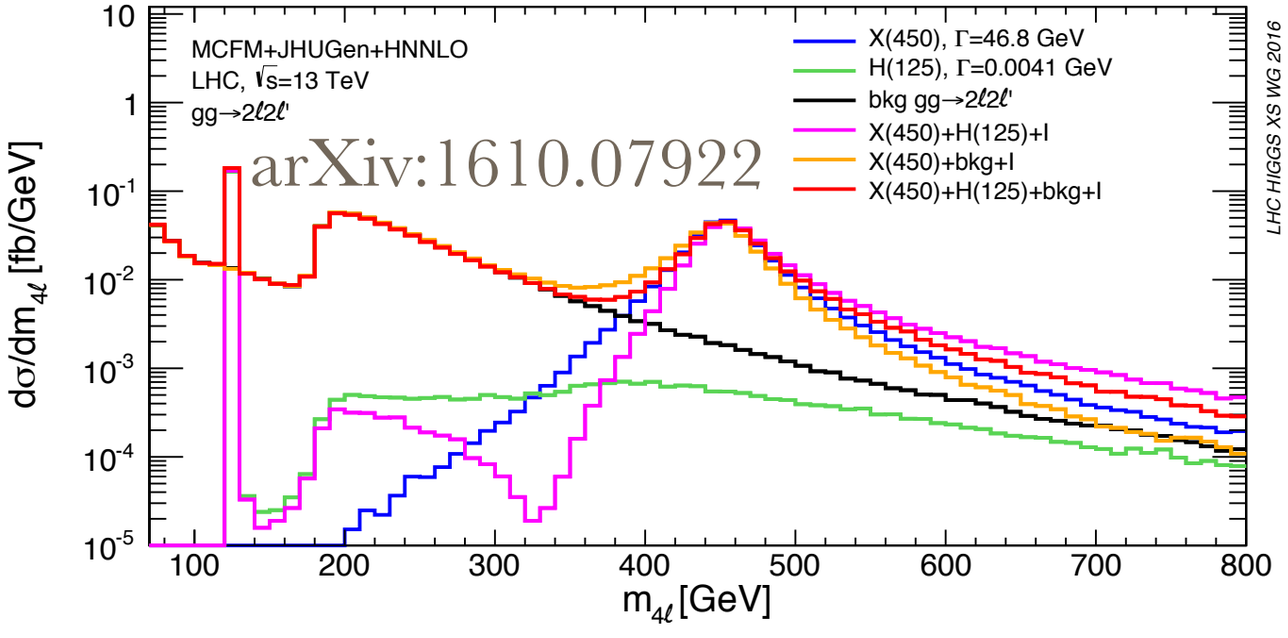
Z-mass constraint on both $\ell\ell$ pairs

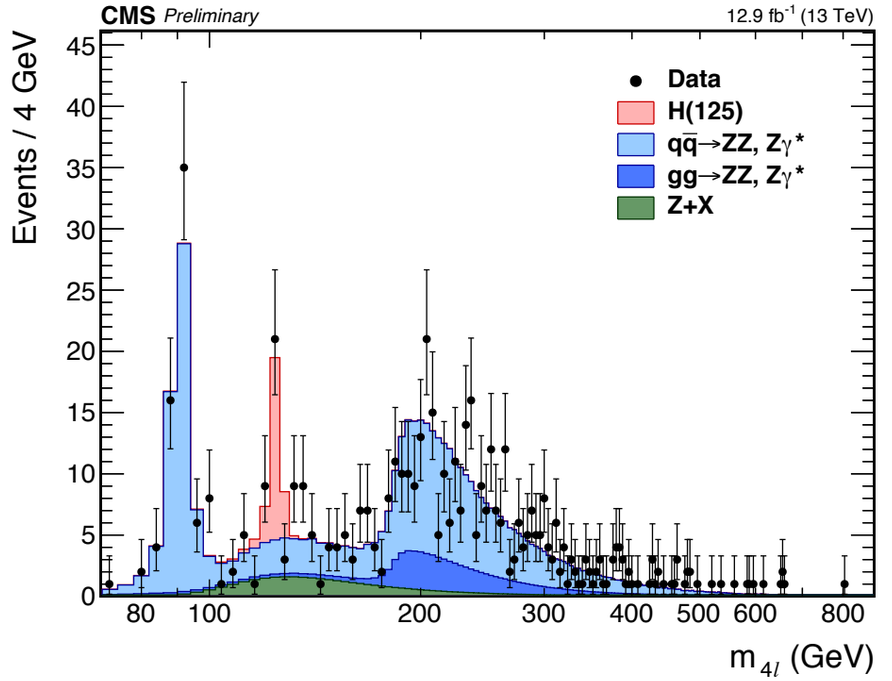
CMS

High-mass region selection optimization

Parameterization of any (m_X, Γ_X) from ggH/VBF with X, H(125) and background interference







CMS-PAS-HIG-16-033
ATLAS-CONF-2016-079

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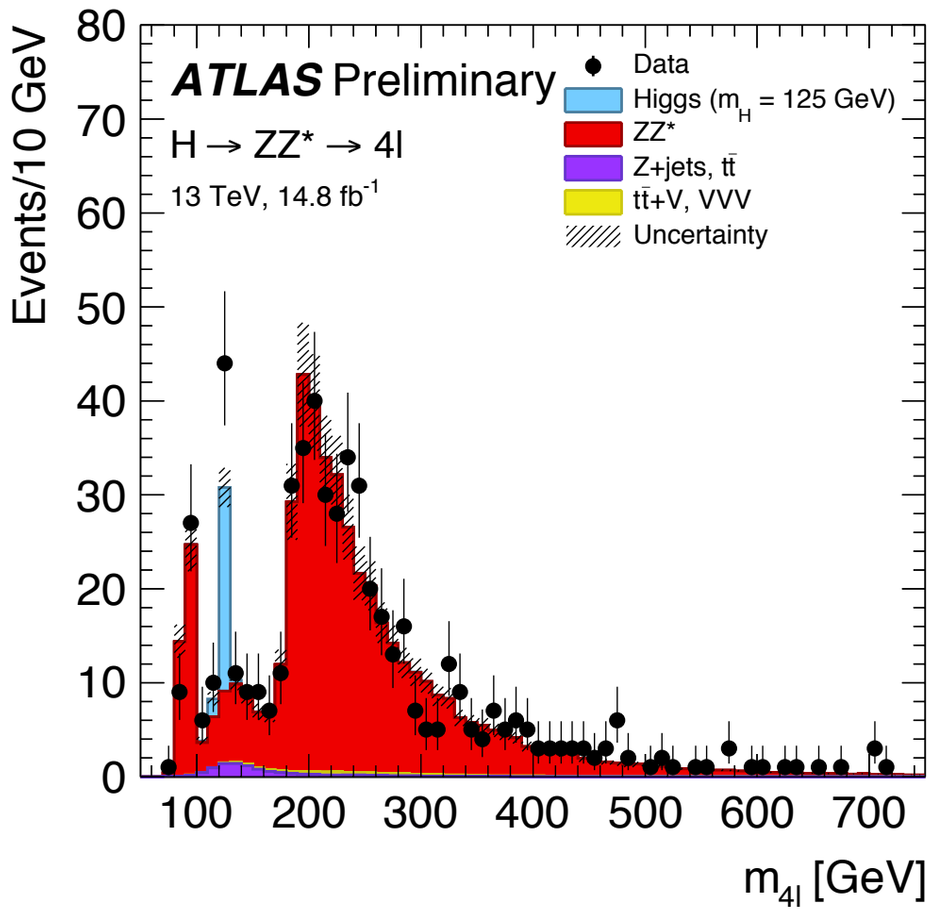
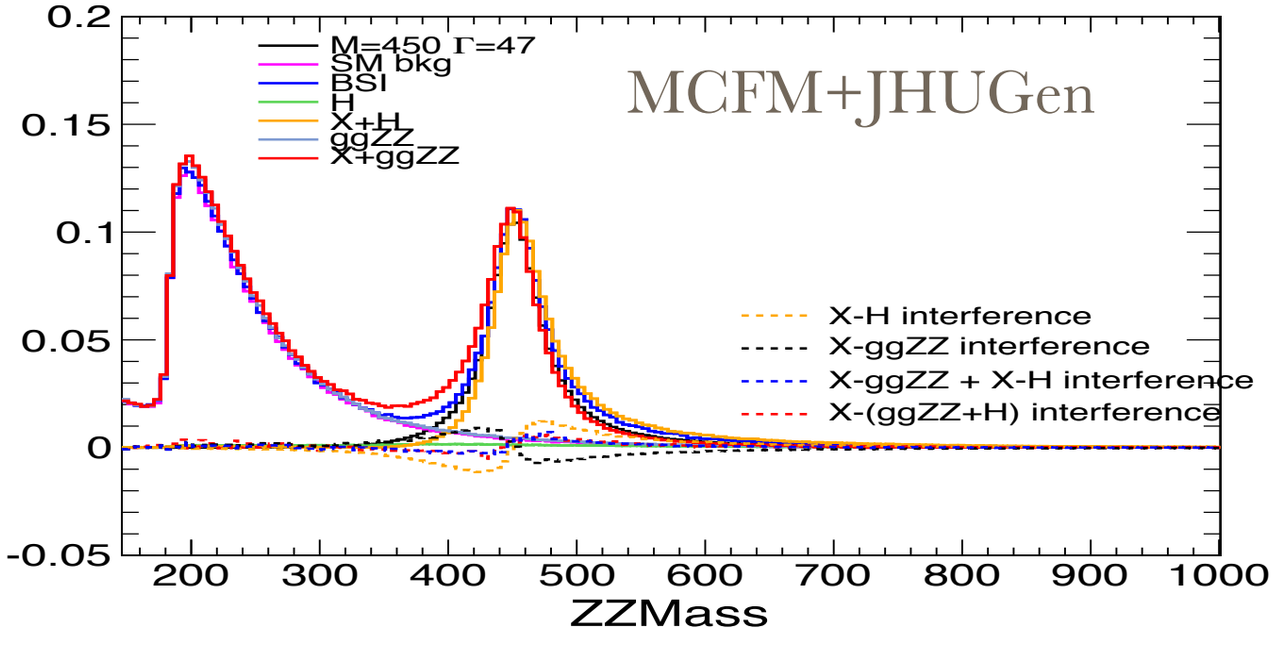
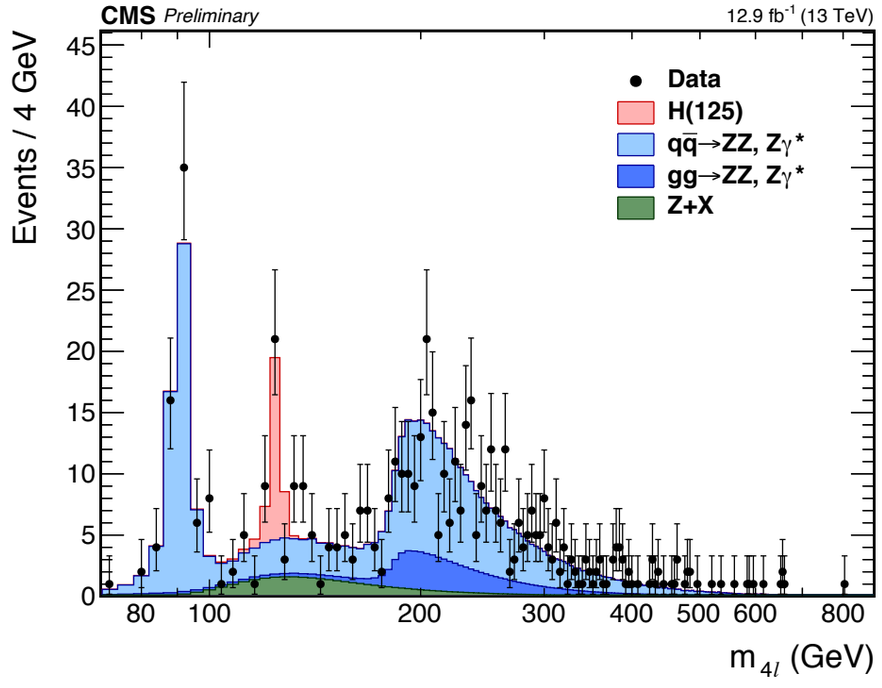


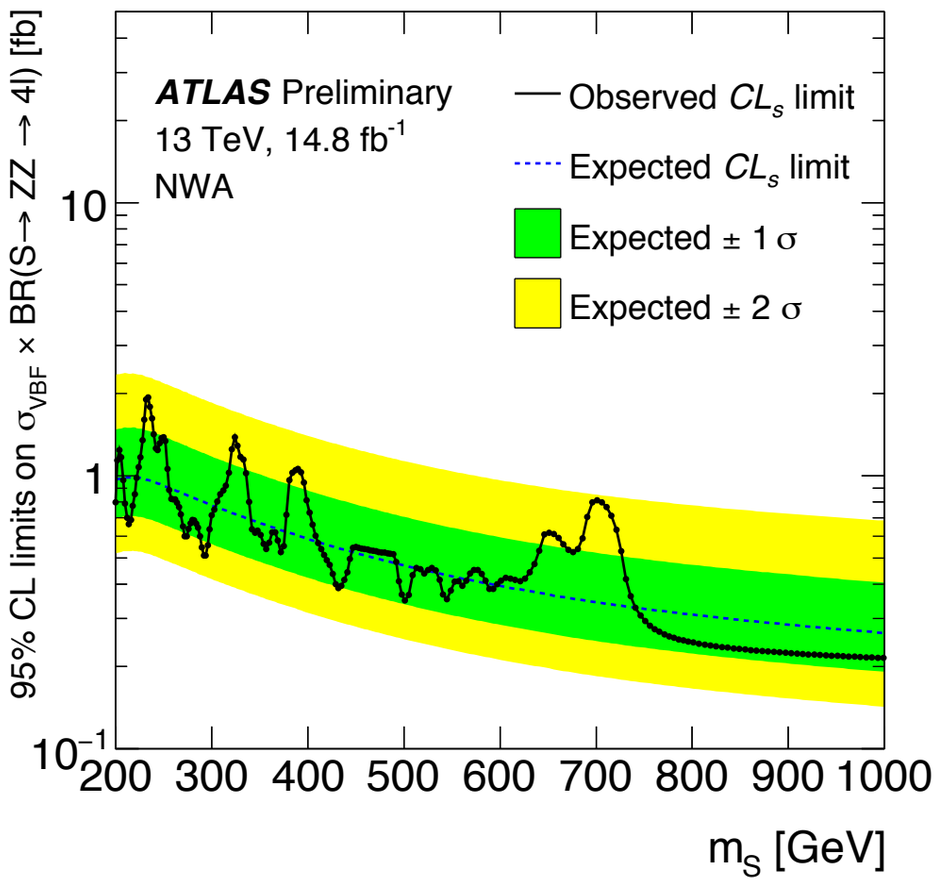




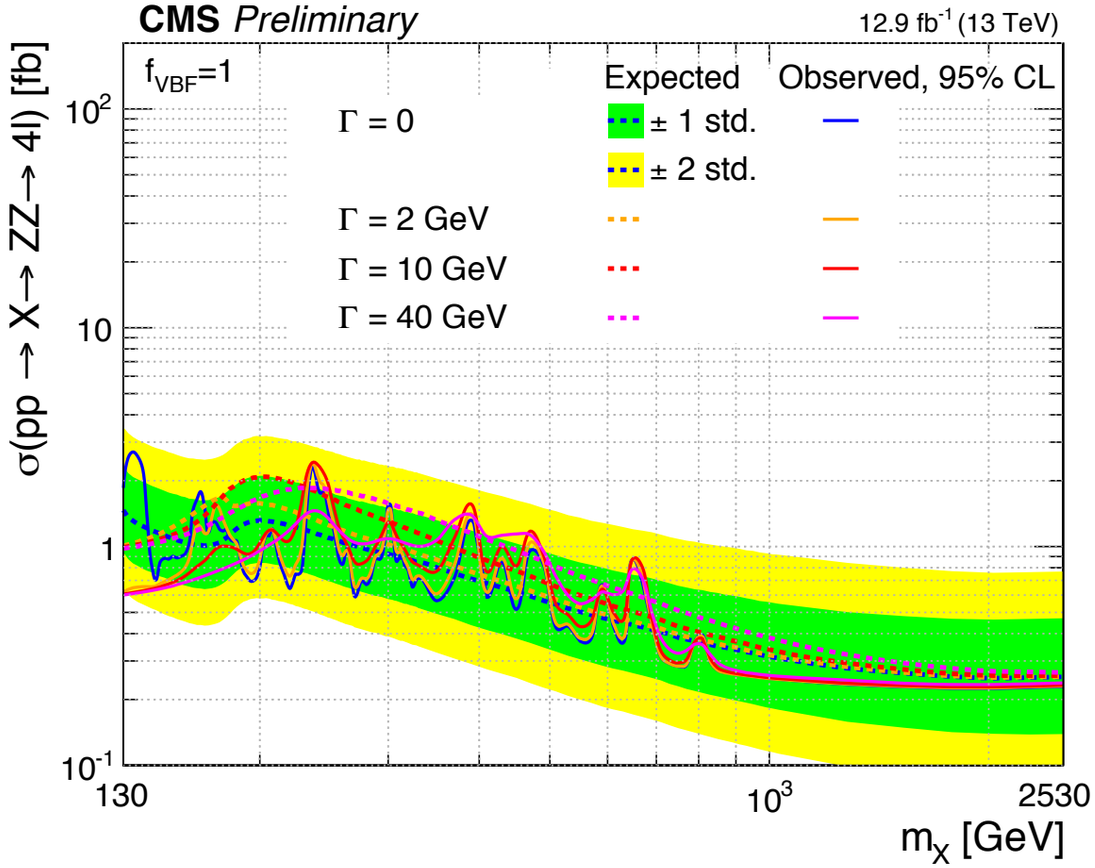
CMS-PAS-HIG-16-033
ATLAS-CONF-2016-079

X→ ZZ→ 4ℓ (e,μ)

- No significant excess, ggH and VBF cross section limit
  - ATLAS: width 0% → 10%, CMS: width 0 → 40 GeV
- Similar sensitivity in ATLAS and CMS



VBF



VBF

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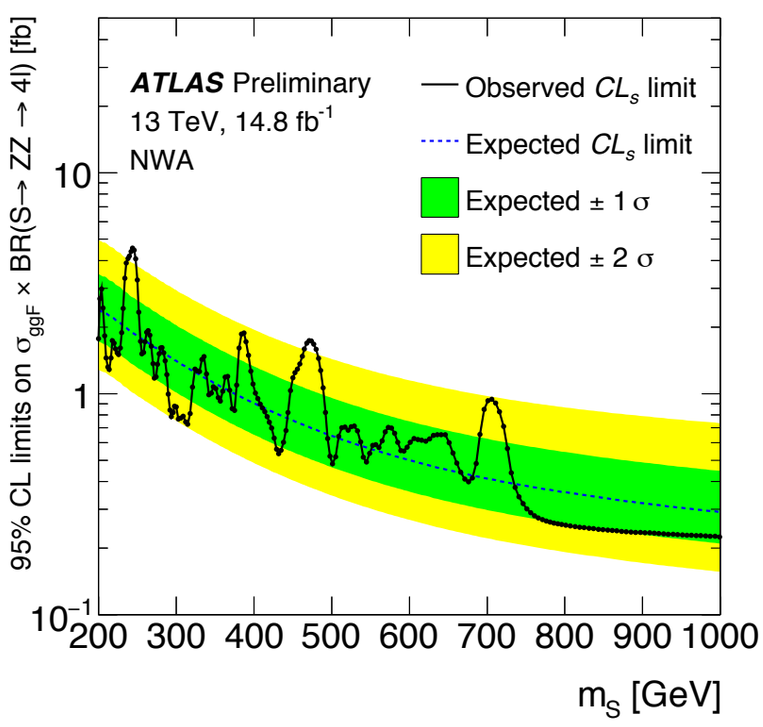
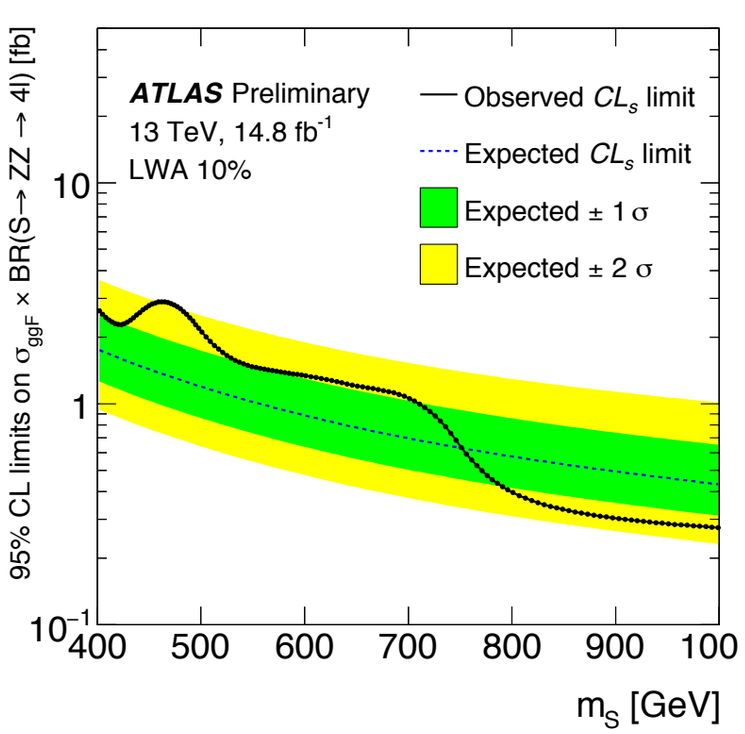
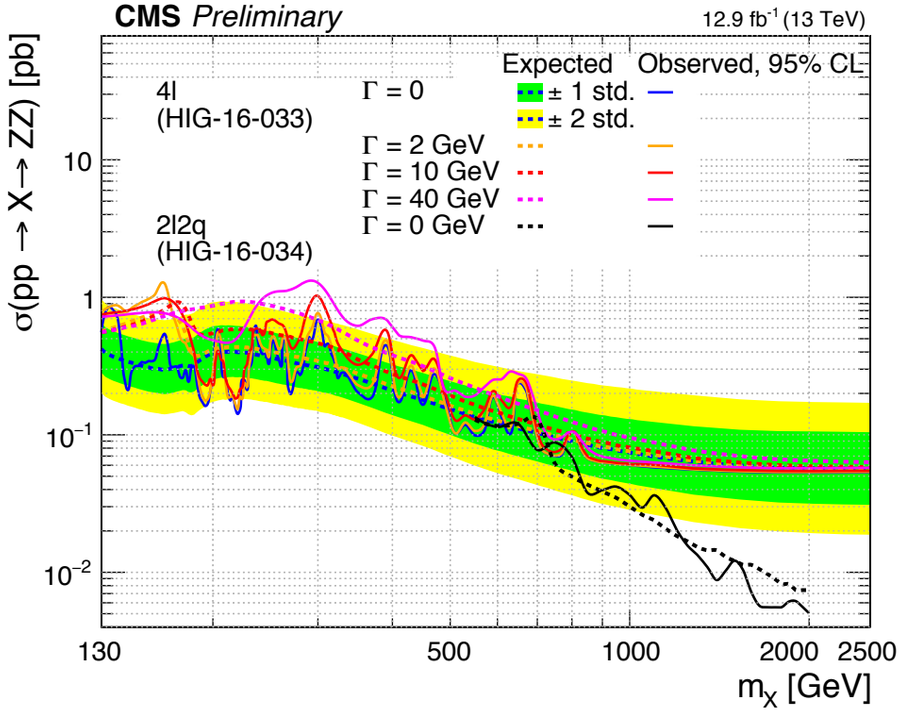


ggH



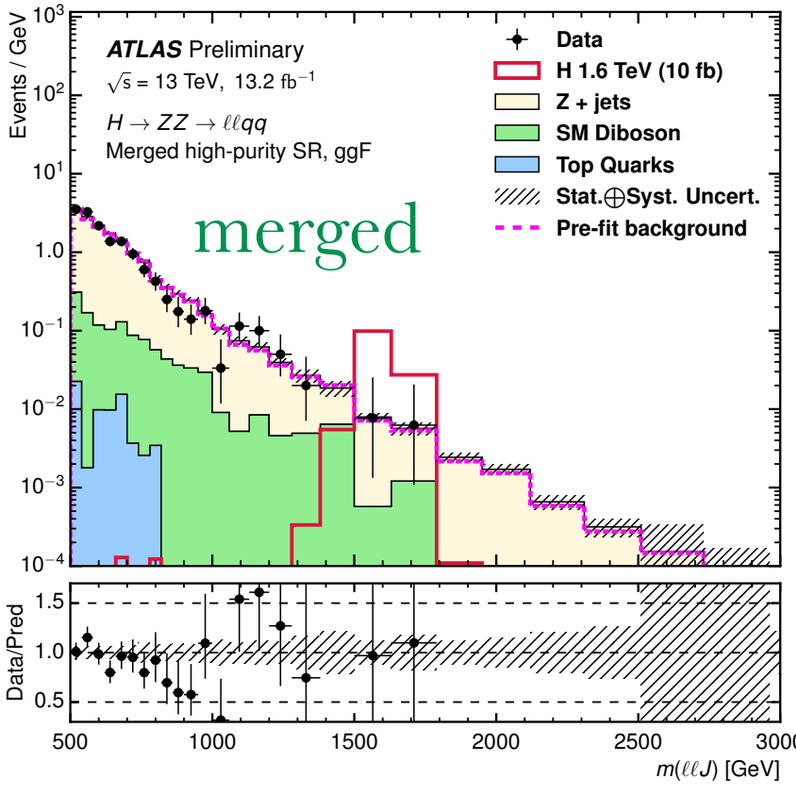
ggH



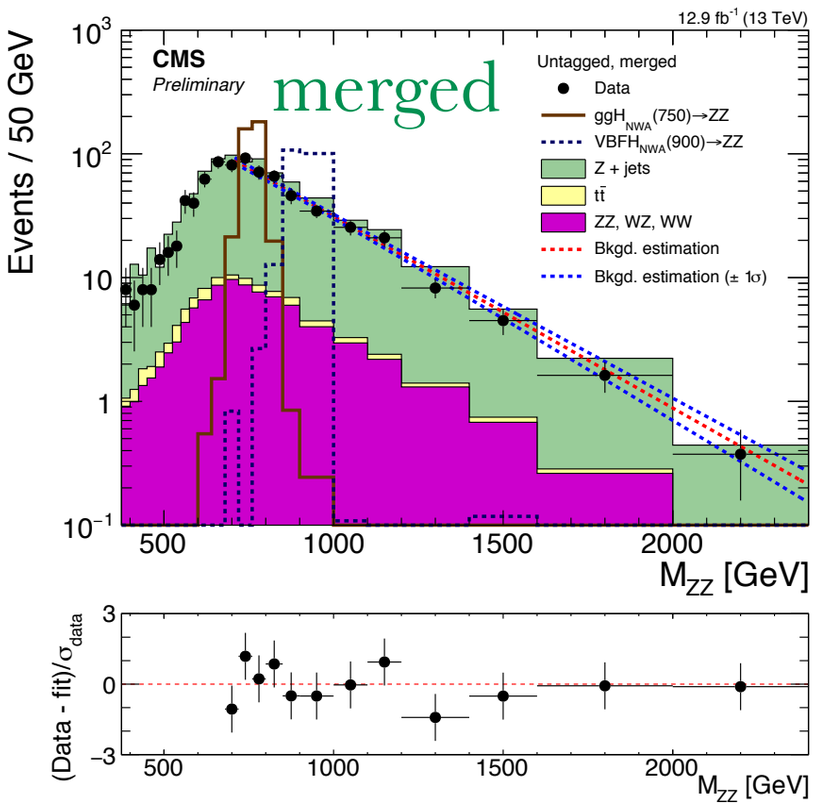
ggH+VBF
f_{VBF} floated

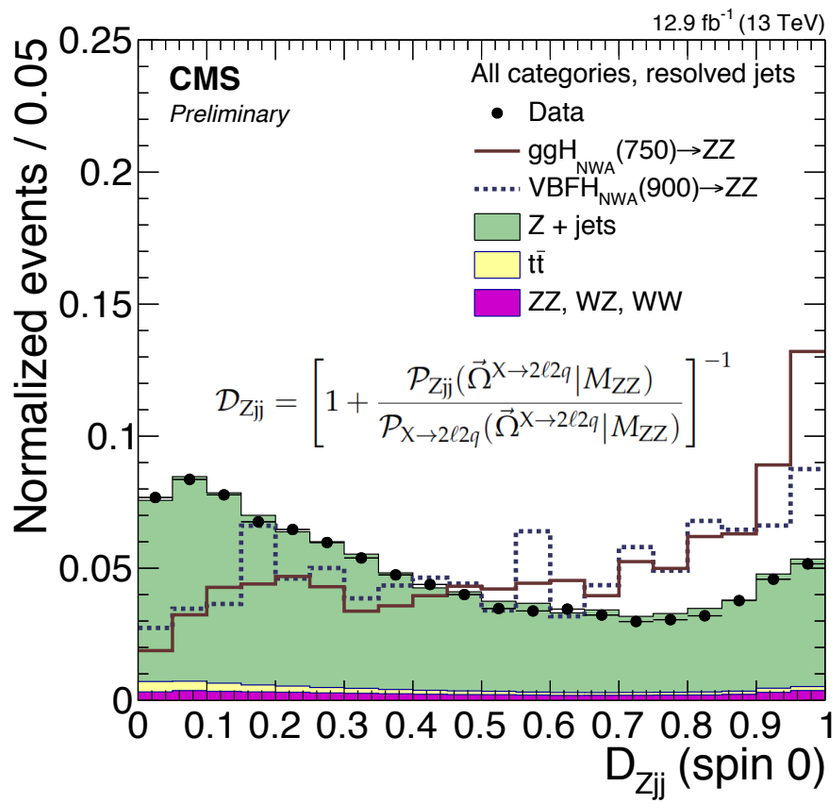
CMS-PAS-HIG-16-034
ATLAS-CONF-2016-082

X→ ZZ→ 2ℓ2q



- Categorization
  - resolved/merged jet: high mass boost topology
  - b-tag/non-tag: large Z→ bb branching ratio
  - VBF/ggH: probe production
- Z mass constraint: improve resolution
- Look for narrow scalar





ATLAS: m_{ZZ} as observable

CMS: matrix element based discriminants (MELA) for:

— VBF/ggH category

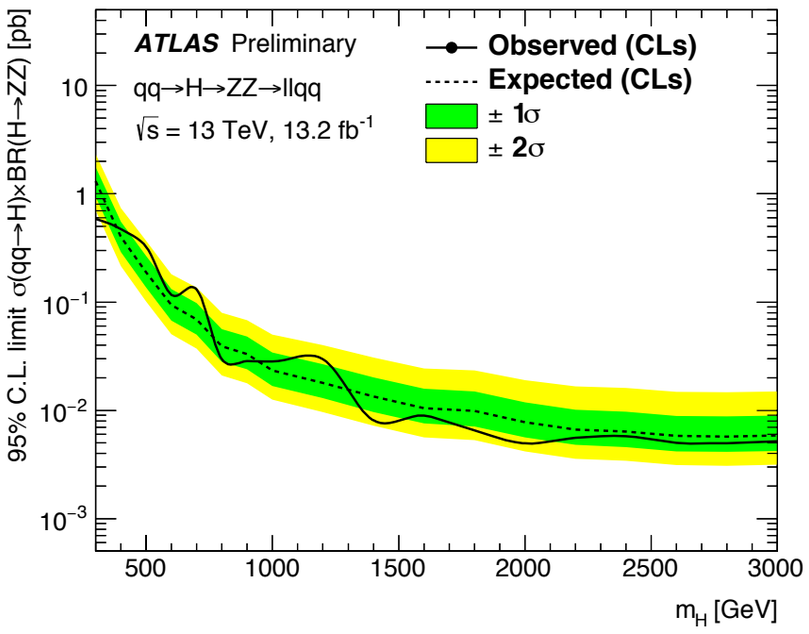
— signal/Z+jet separation

m_{ZZ} vs D_{Zjj}, as observables

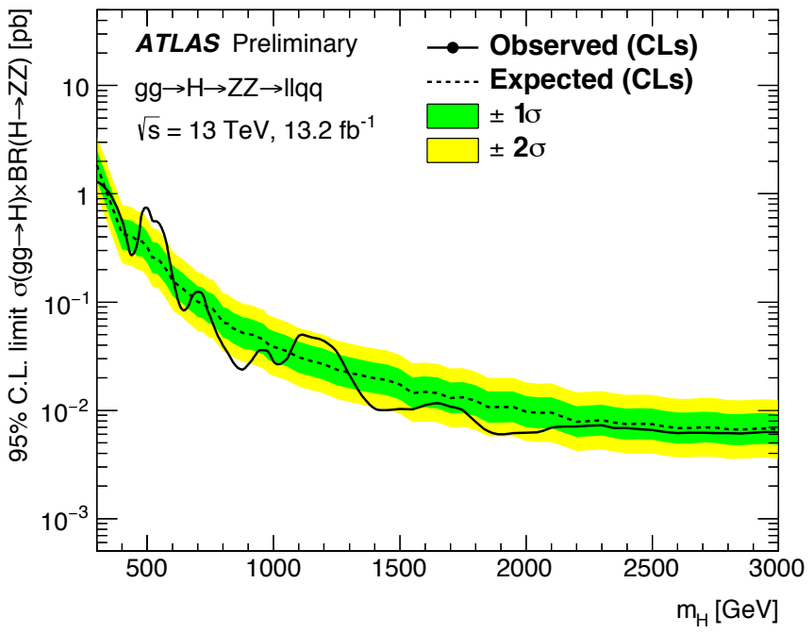
CMS-PAS-HIG-16-034
ATLAS-CONF-2016-082

X→ ZZ→ 2ℓ2q

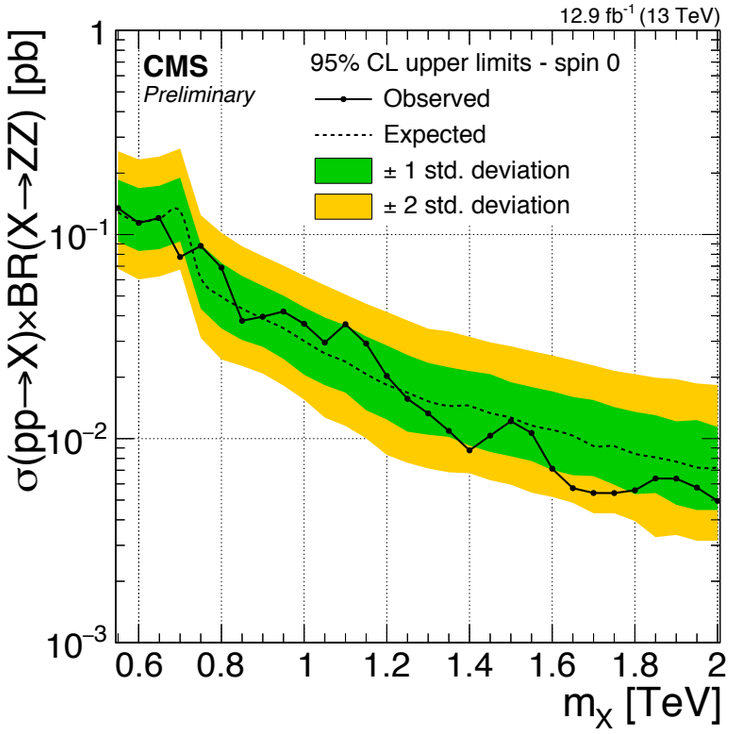
- No significant excess
  - CMS: total cross section limit, VBF/ggH ratio floated
  - ATLAS: ggH and VBF cross section limit



VBF



ggH



ggH+VBF

ATLAS also performed ZZ→ vvqq search with similar sensitivity at high mass

CMS-PAS-HIG-16-001
ATLAS-CONF-2016-056

$X \to ZZ \to 2\ell 2\nu$

- Modified m_T as discriminant $M_T^2 = \left(\sqrt{p_T(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{E_T^{miss\,2} + M_Z^2}\right)^2 - (\vec{p}_T(\ell\ell) + \vec{E}_T^{miss})^2$

ATLAS

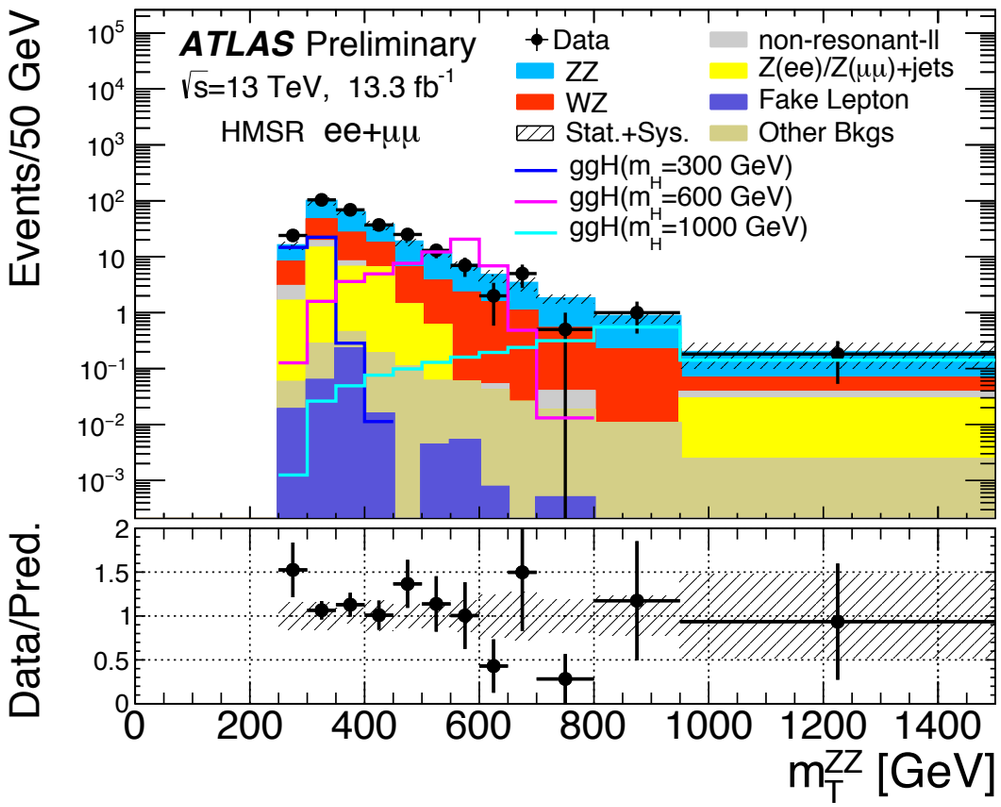
More kinematic cuts to reduce backgrounds

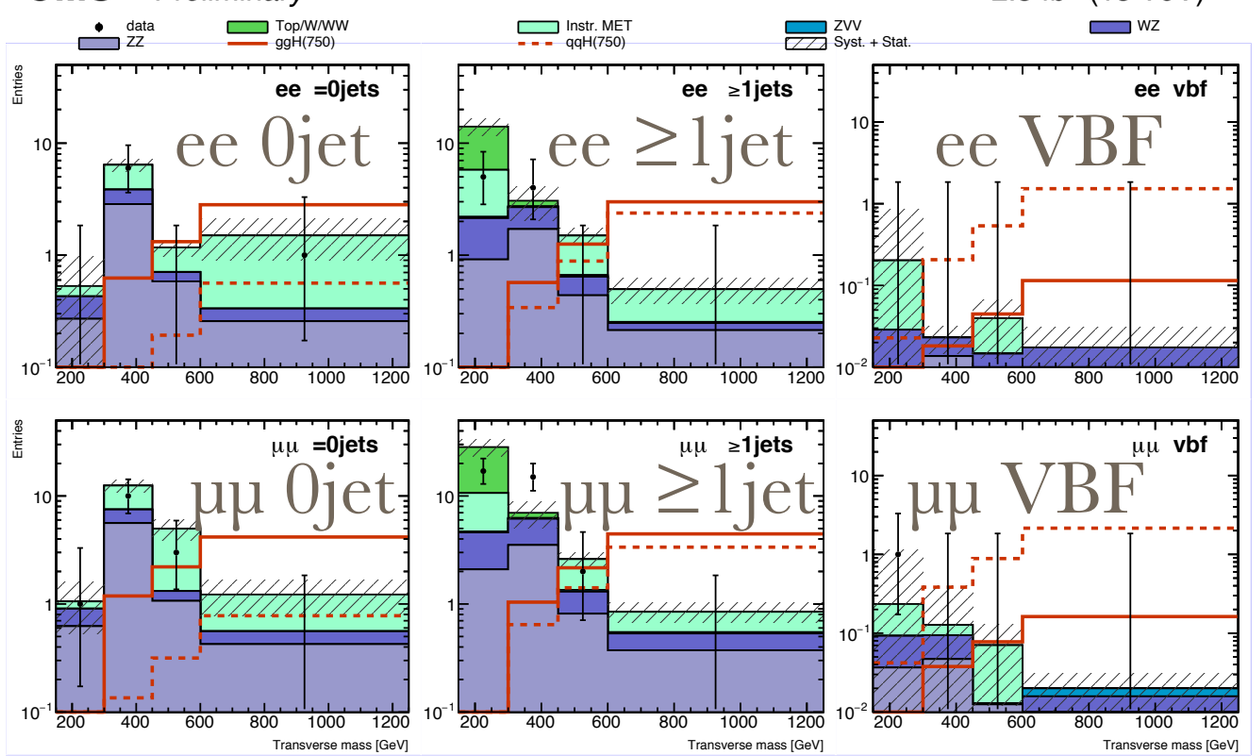
Consider only narrow width ggH

CMS

Consider EWK singlet model

Categories to probe ggH and VBF



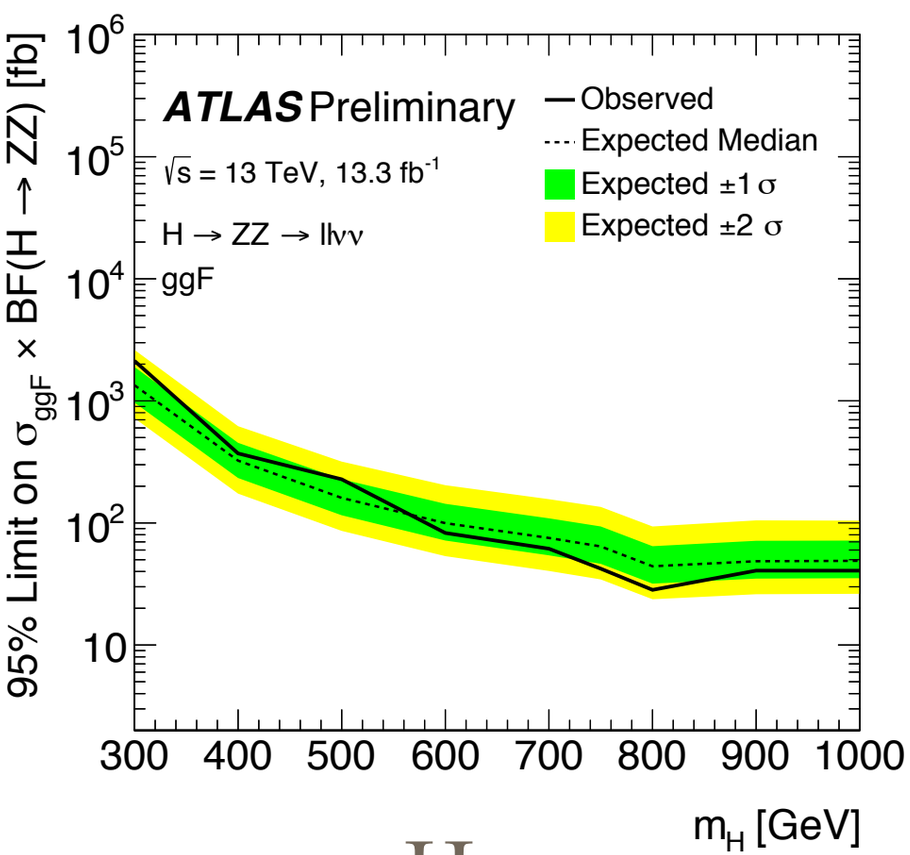


Transverse mass [GeV]

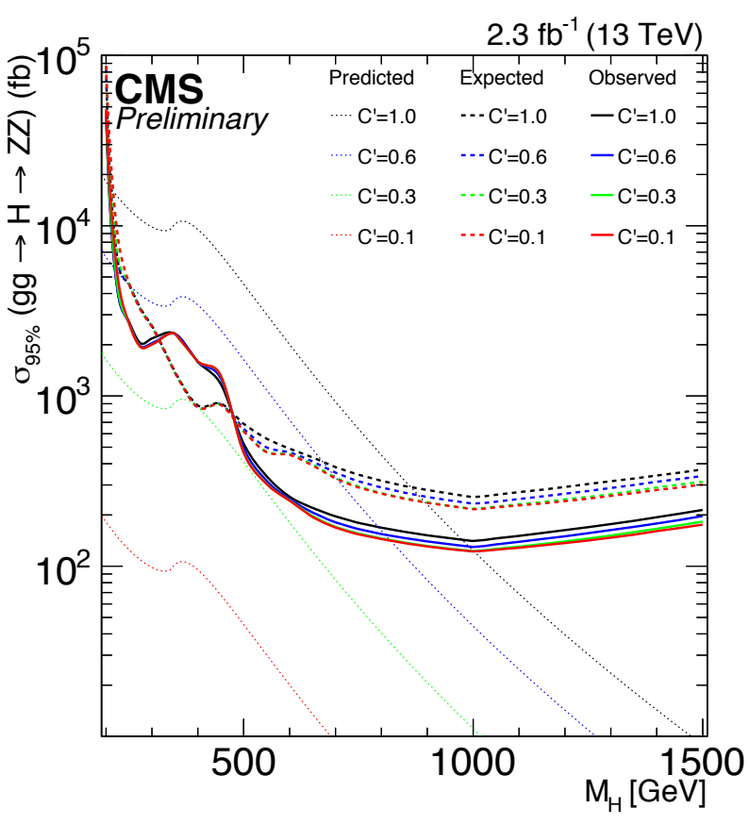
CMS-PAS-HIG-16-001
ATLAS-CONF-2016-056

$X \to ZZ \to 2\ell 2\nu$

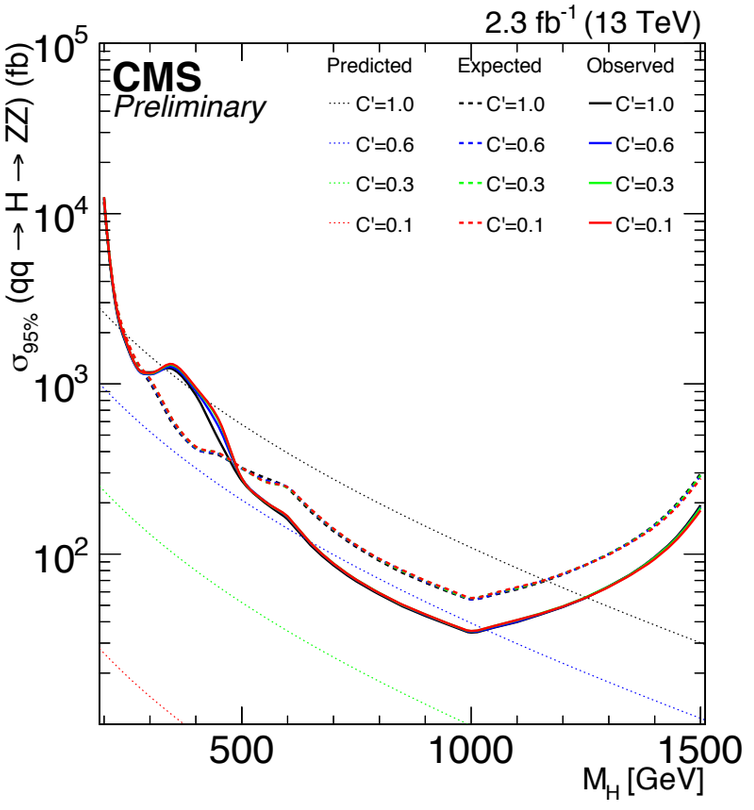
- No significant excess
  - ATLAS: ggH narrow width limit
  - CMS: various EWK singlet scenarios, ggH and VBF cross section limit (interference effect neglected)



ggH



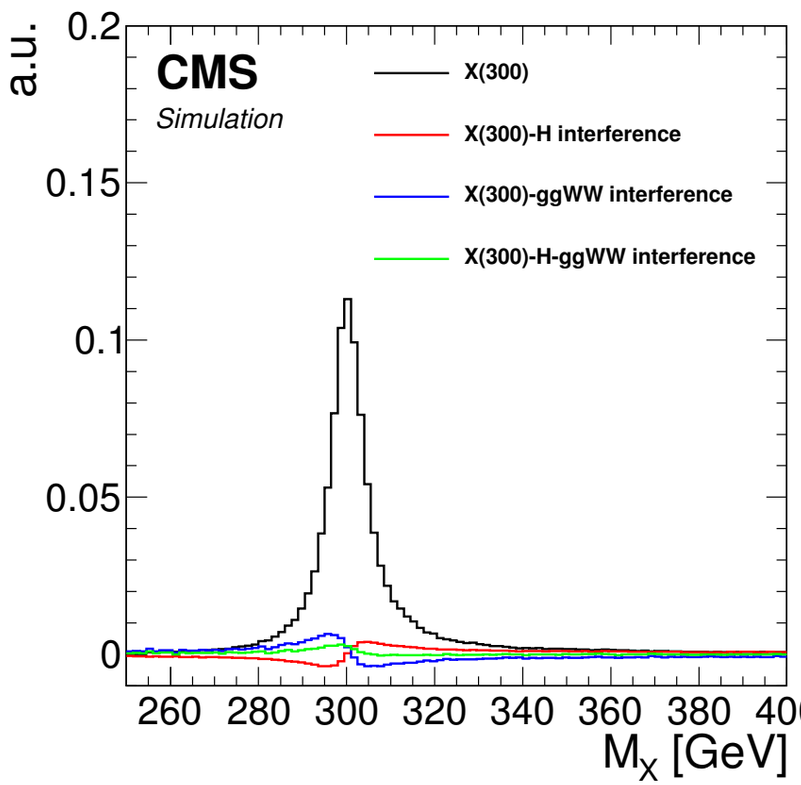
ggH



VBF

CMS-PAS-HIG-16-023
ATLAS-CONF-2016-074

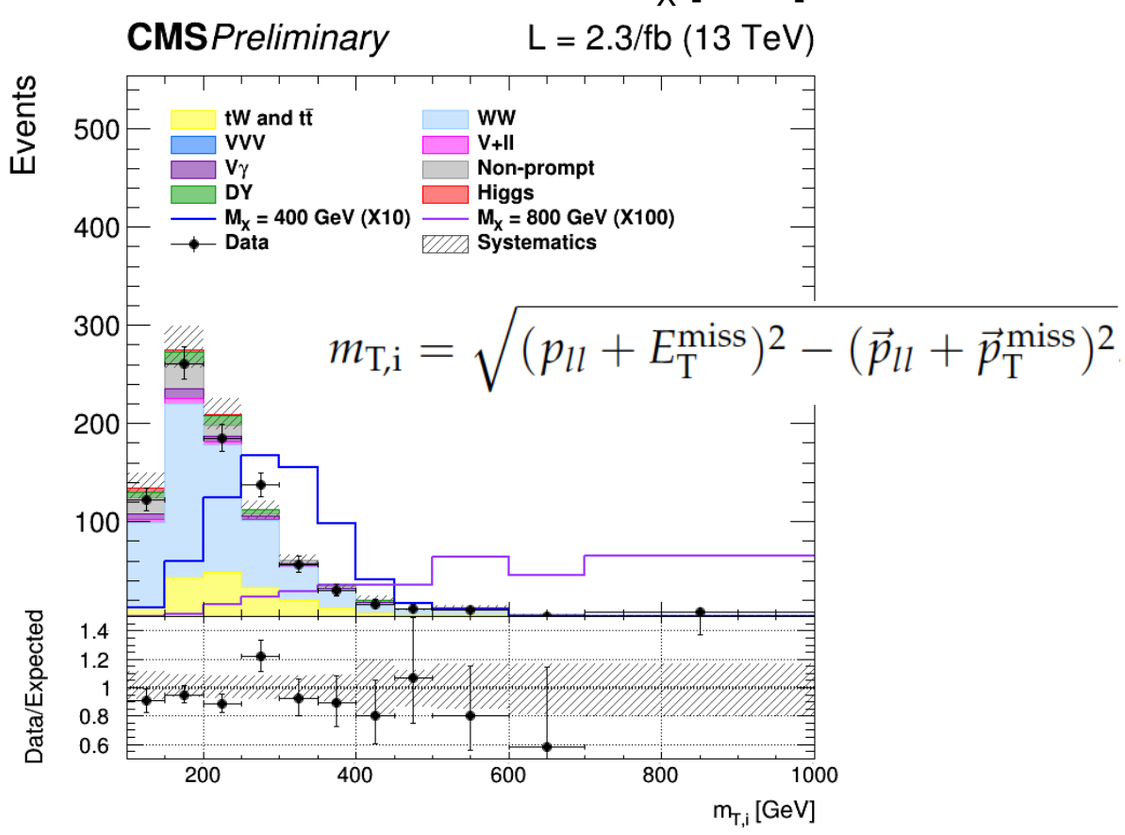
X→ WW→ $\ell\nu\ell\nu$

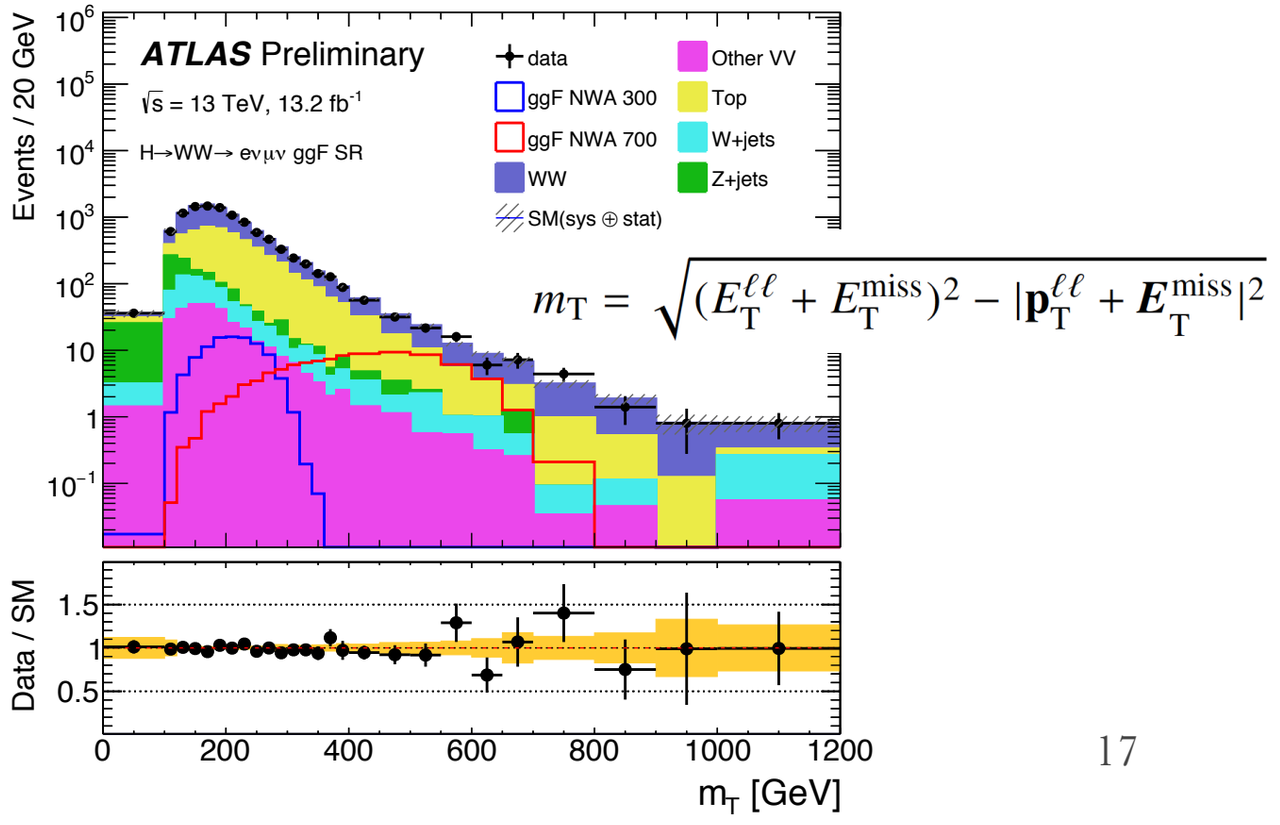


- eμ final state
- ggH, 1 jet, VBF category
- Modified m_T as observable

ATLAS: ggH category inclusive, not only 0 jet events

CMS: interference properly modeled

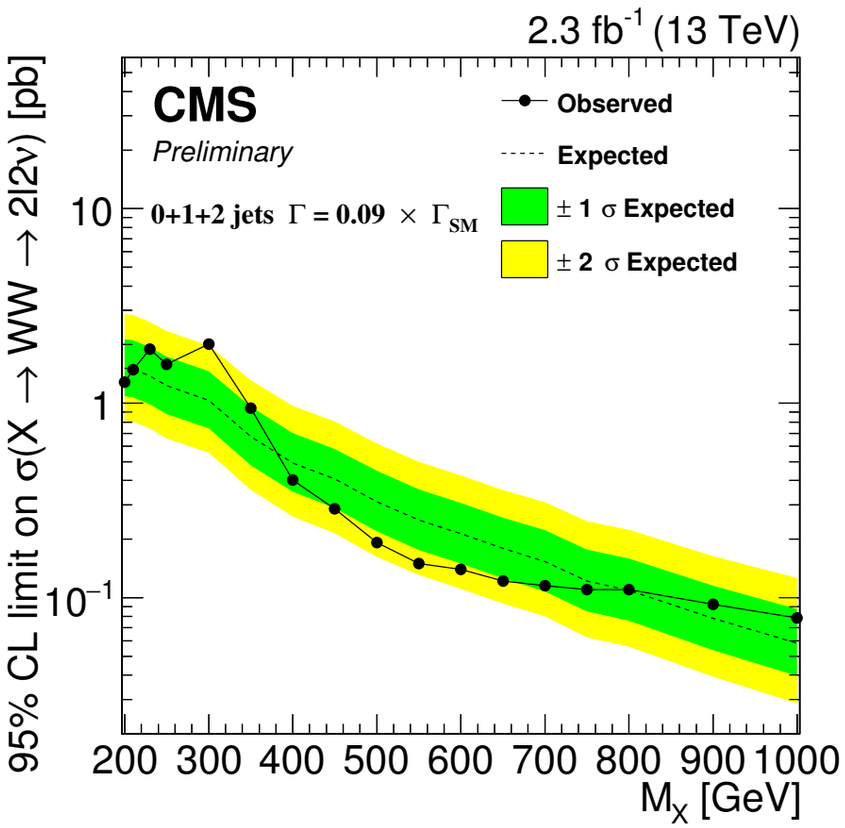


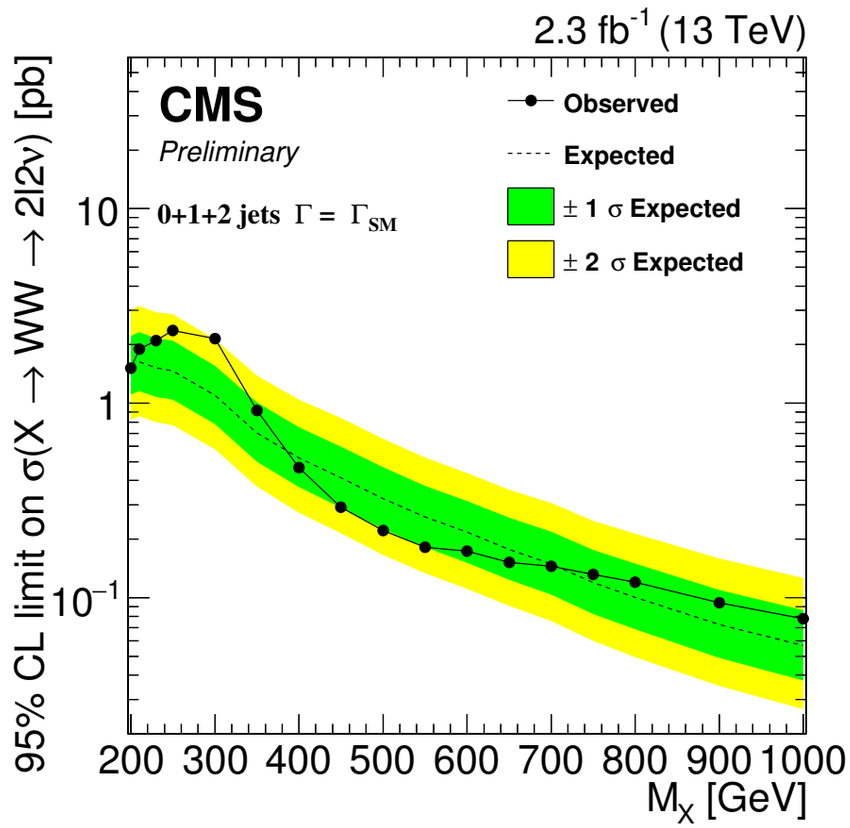


CMS-PAS-HIG-16-023
ATLAS-CONF-2016-074

$X \rightarrow WW \rightarrow \ell\nu\ell\nu$

- No significant excess
  - CMS: total cross section limit, VBF/ggH ratio floated, Γ_X: 0.1 —1 SM Γ_X
  - ATLAS: ggH cross section limit Γ_X: 0% —15% m_X; VBF narrow width





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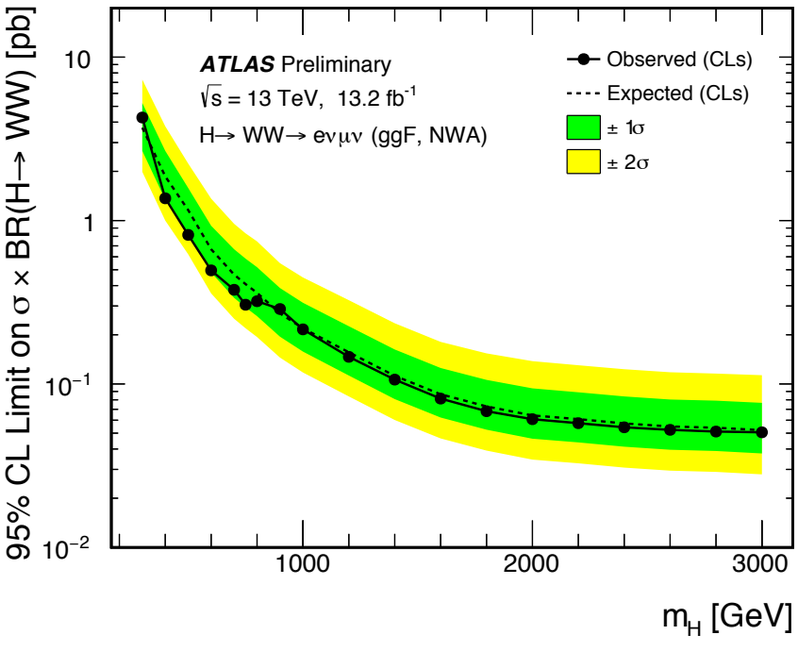
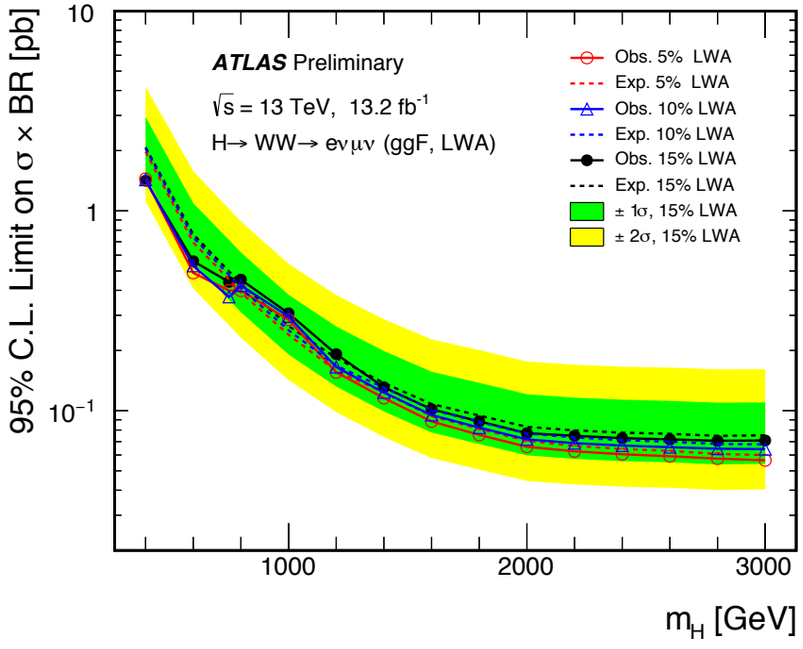
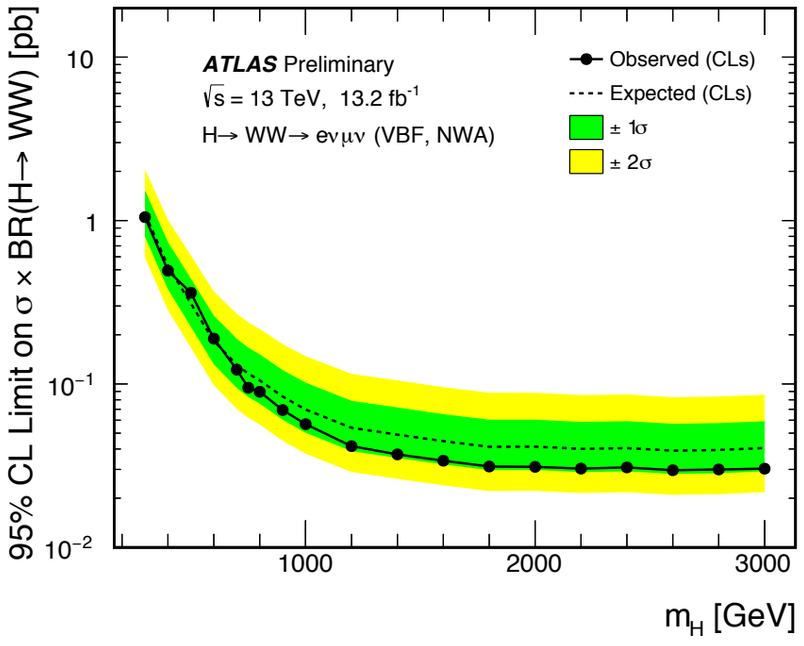


ggH



ggH



VBF

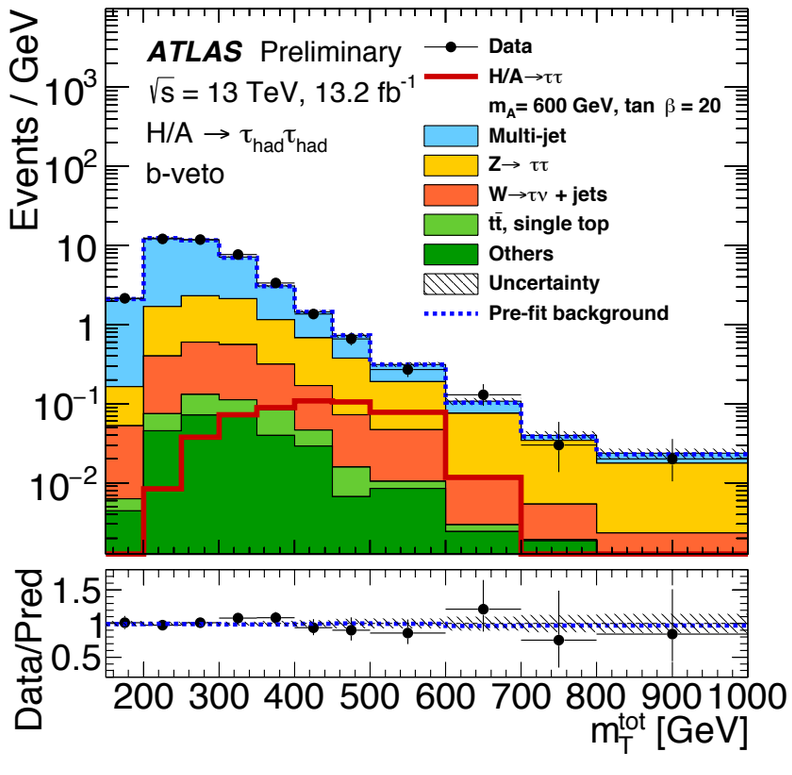
CMS-PAS-HIG-16-037
ATLAS-CONF-2016-085

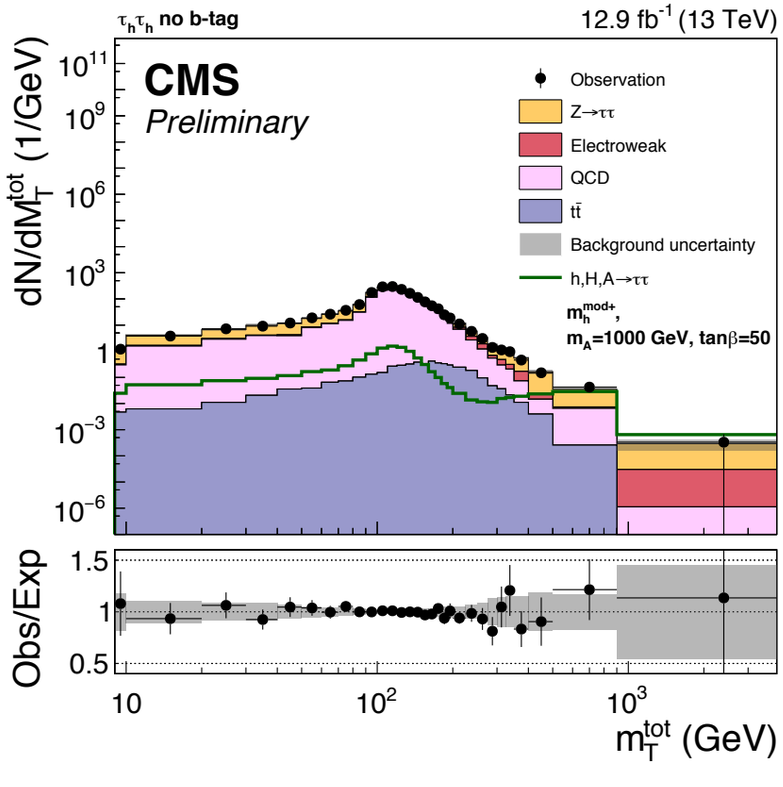
$H/A \rightarrow \tau\tau$

- Particular sensitive to large tanβ in 2HDM
- Produced mainly by ggH and bbH (depend on tanβ)
  - b tag/b veto categories
- (e, μ, τ_h)τ_h final state
- m_T^{tot} as observable $$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_1^{\mathrm{vis}})^2 + m_{\mathrm{T}}(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_2^{\mathrm{vis}})^2 + m_{\mathrm{T}}(\tau_1^{\mathrm{vis}}, \tau_2^{\mathrm{vis}})^2}.$$

ATLAS: additional high E_T^{miss} category, fewer bkg

CMS: include eμ final state

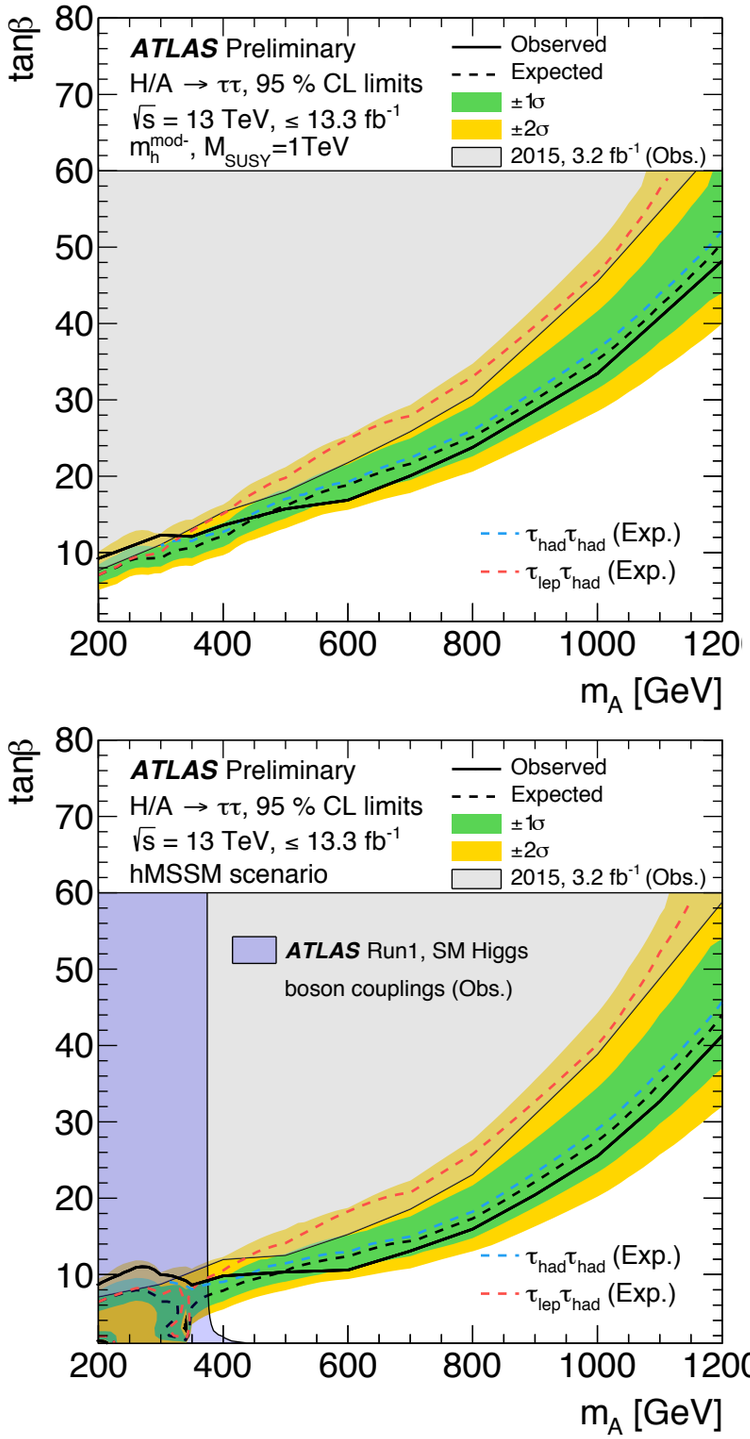


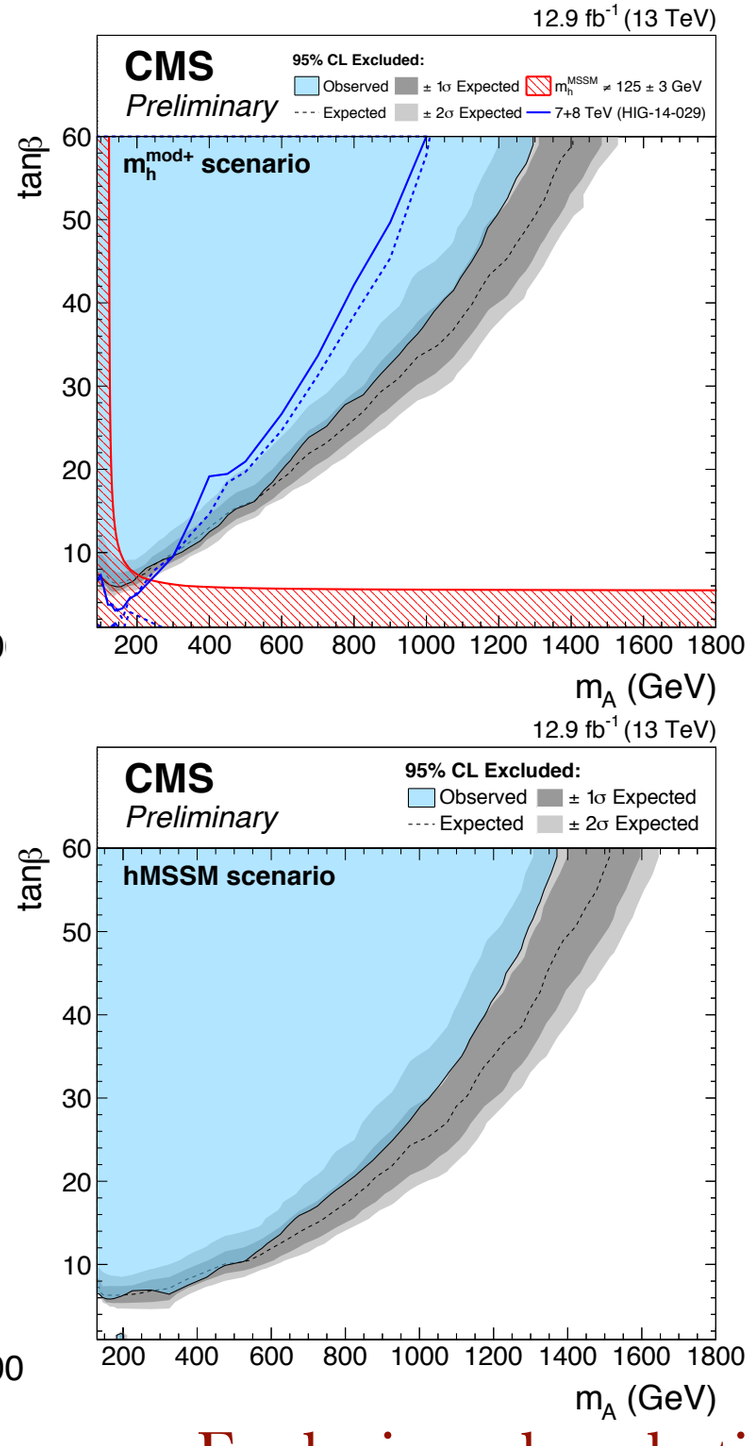


CMS-PAS-HIG-16-037
ATLAS-CONF-2016-085

$H/A \rightarrow \tau\tau$

No significant excess, interpretation with MSSM models





m_h^{mod}
adjusted SUSY parameters
to allow $m_h = 125$

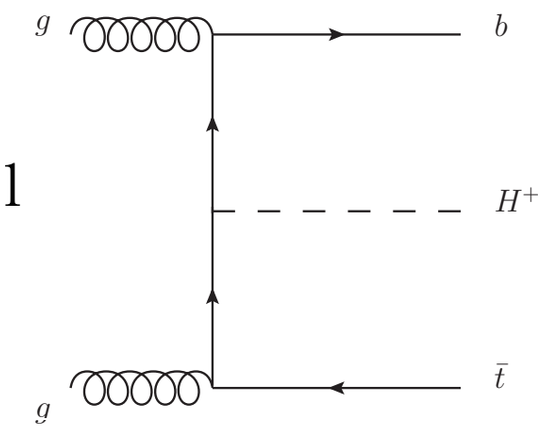
hMSSM
effective theory
input: m_h, not SUSY parameters

Exclusion already tighter than Run1

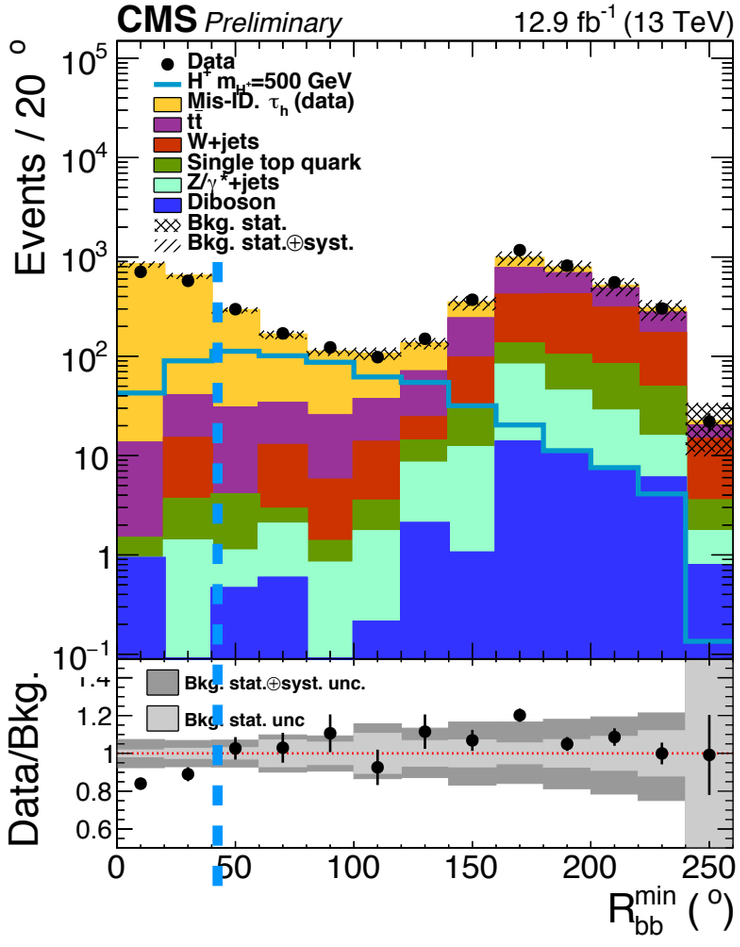
CMS-PAS-HIG-16-031
ATLAS-CONF-2016-088

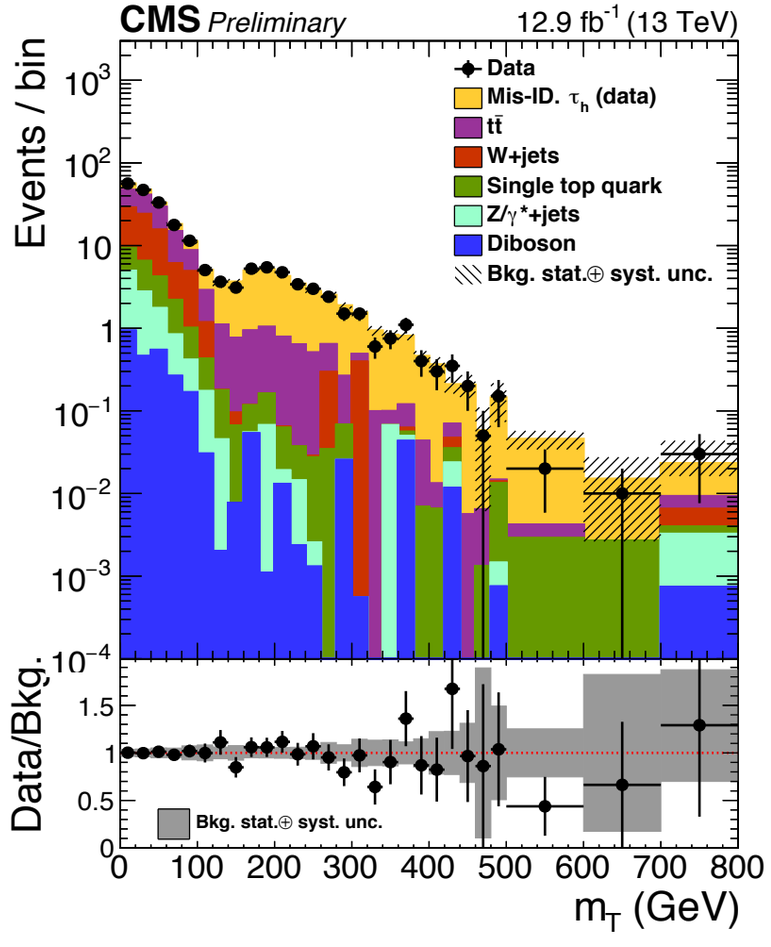
$H^{\pm} \rightarrow \tau\nu$

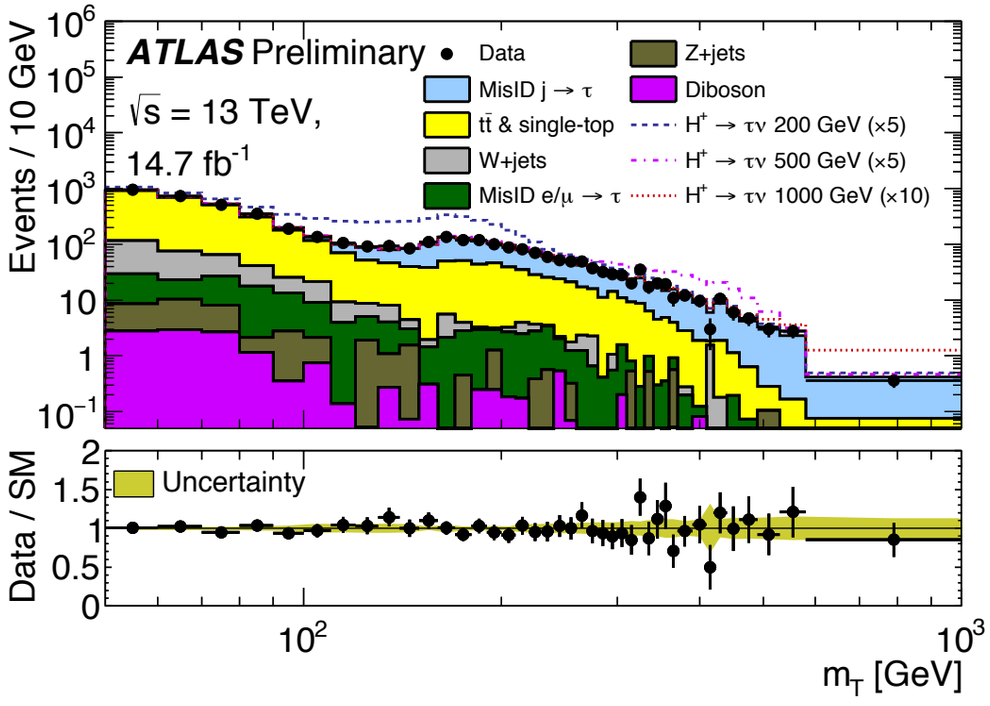
- Predicted by 2HDM, Higgs triplets
- Dominant production tHb ($m_{H^+} > m_t$), $m_{H^+} < m_t$ excluded in Run1
- Full hadronic final state: $\tau_{had,}$ large E_T^{miss}, b-tag jet
- m_T as observable
- CMS: kinematic information to reduce multi-jet



$$R_{bb}^{min} = \min_{j \in j_1..j_3} \sqrt{\Delta\phi(\not{E}_T, j)^2 + (\pi - \Delta\phi(\tau^h, \not{E}_T))^2}$$



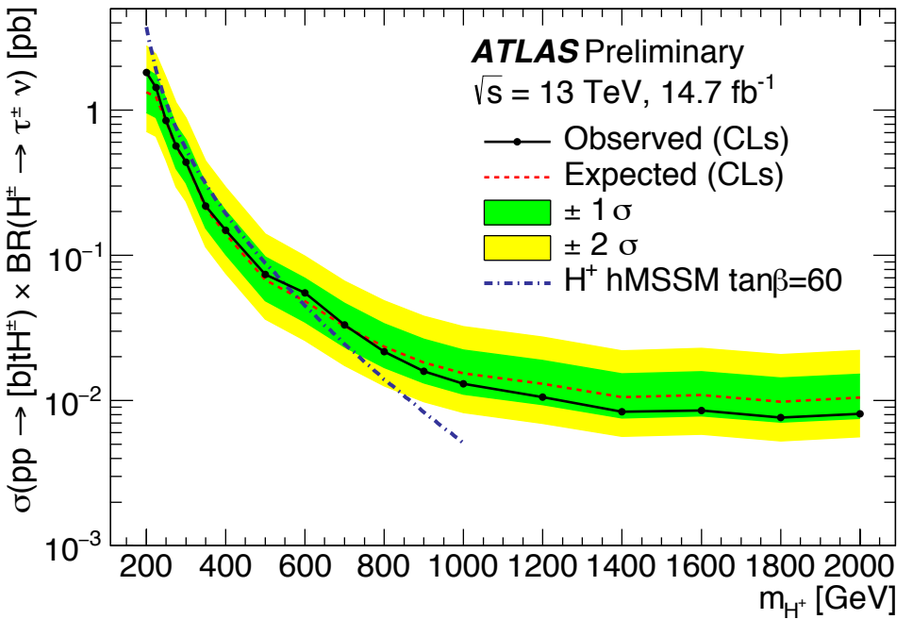


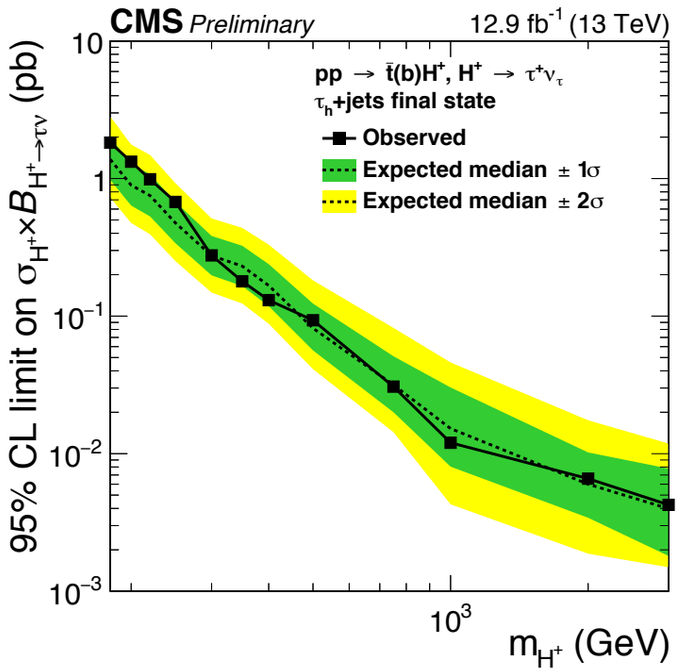


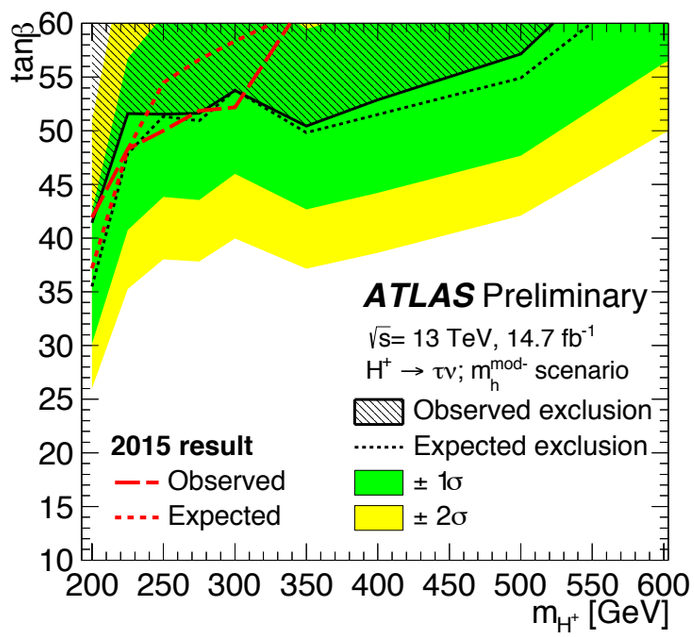
CMS-PAS-HIG-16-031
ATLAS-CONF-2016-088

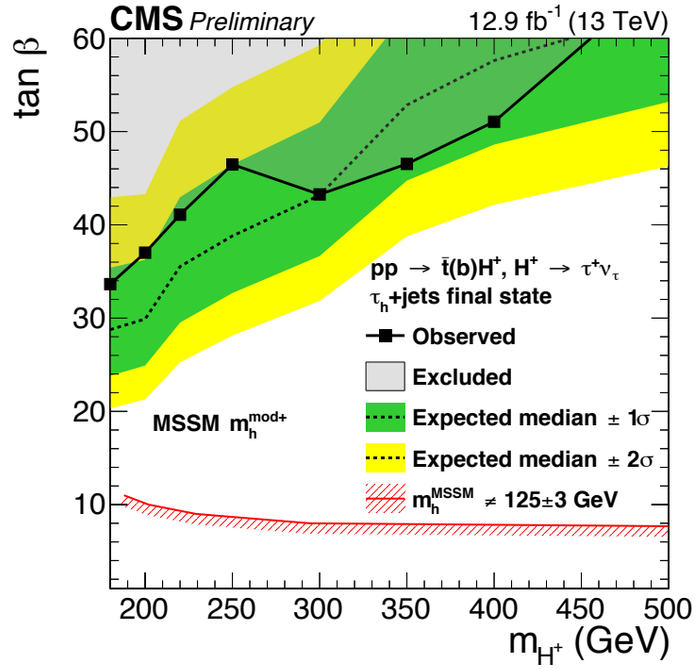
$H^{\pm} \rightarrow \tau\nu$

Cross section limit and interpretation to MSSM models
ATLAS and CMS interpretation in different scenarios





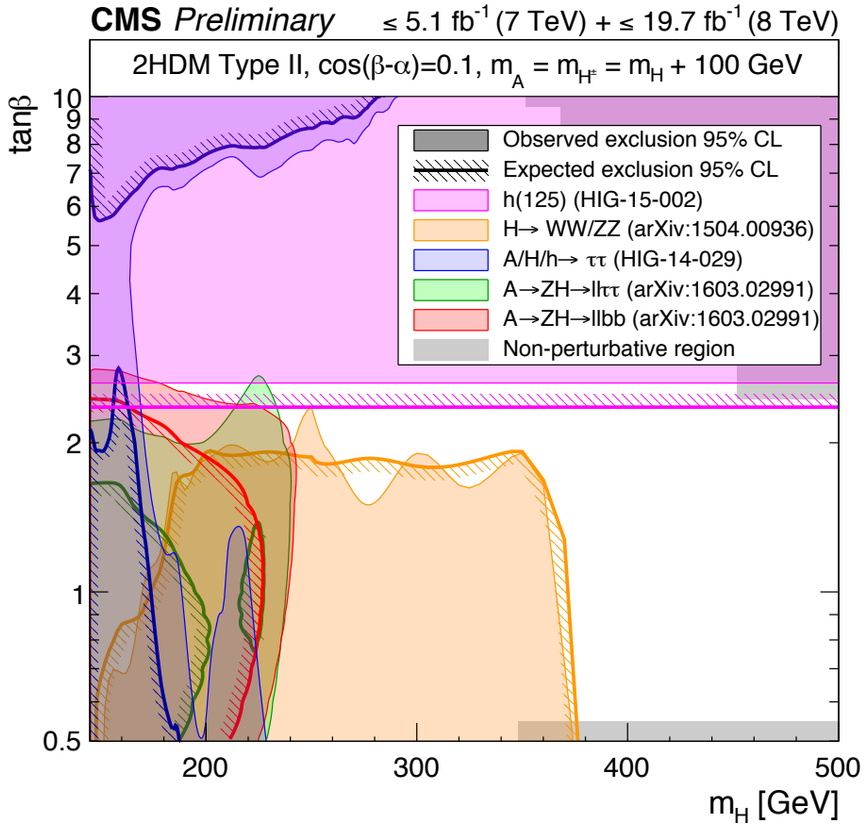


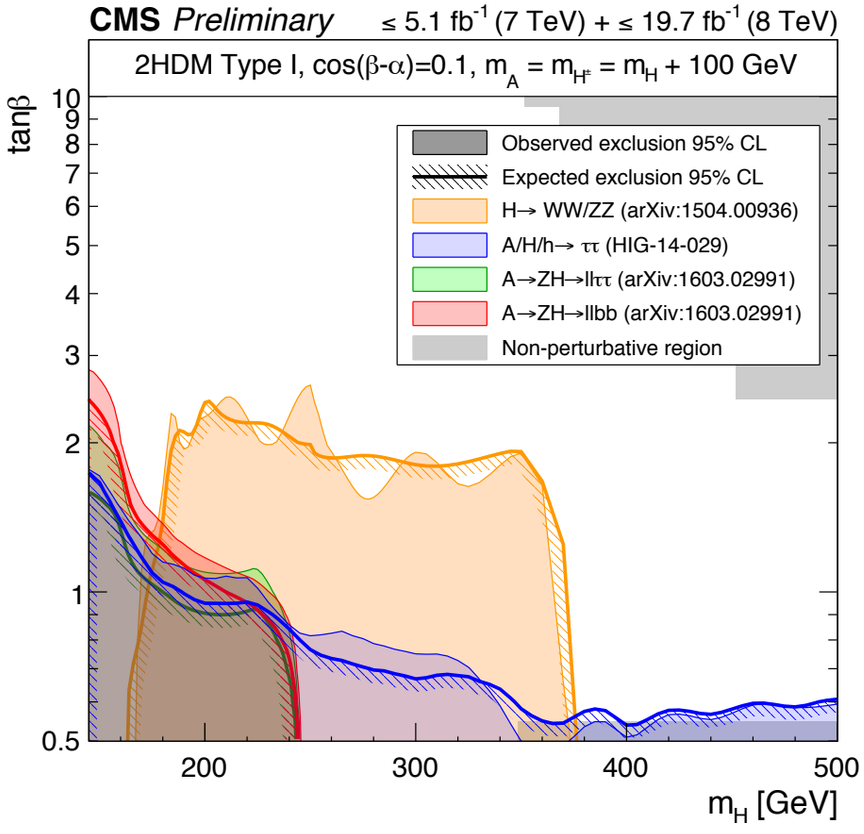


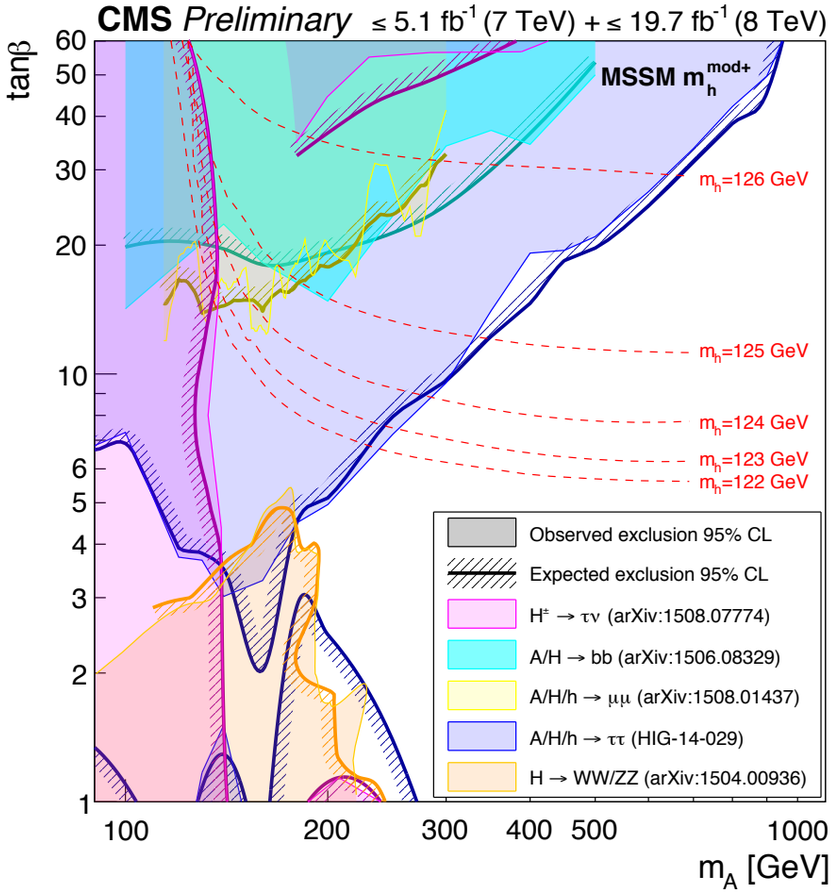
Summary

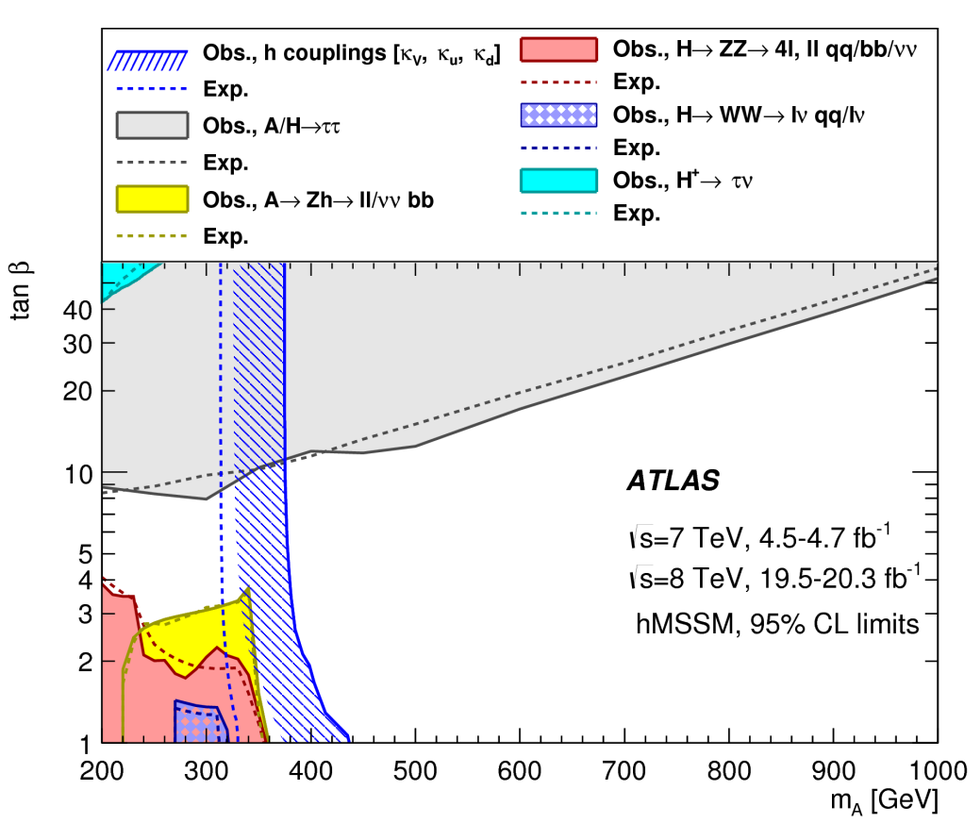
- **A wide range of searches with Run2 data from ATLAS and CMS**
- **Many new development/techniques**
- **No significant excess observed so far**
- **A lot more results to come soon**

Additional slides


CMS Preliminary ≤ 5.1 fb-1 (7 TeV) + ≤ 19.7 fb-1 (8 TeV)
2HDM Type II, cos(β-α)=0.1, mA = mH± = mH + 100 GeV
tanβ
mH [GeV]
Observed exclusion 95% CL
Expected exclusion 95% CL
h(125) (HIG-15-002)
H→ WW/ZZ (arXiv:1504.00936)
A/H/h→ ττ (HIG-14-029)
A→ZH→llττ (arXiv:1603.02991)
A→ZH→llbb (arXiv:1603.02991)
Non-perturbative region


CMS Preliminary ≤ 5.1 fb-1 (7 TeV) + ≤ 19.7 fb-1 (8 TeV)
2HDM Type I, cos(β-α)=0.1, mA = mH± = mH + 100 GeV
tanβ
mH [GeV]
Observed exclusion 95% CL
Expected exclusion 95% CL
H→ WW/ZZ (arXiv:1504.00936)
A/H/h→ ττ (HIG-14-029)
A→ZH→llττ (arXiv:1603.02991)
A→ZH→llbb (arXiv:1603.02991)
Non-perturbative region


CMS Preliminary ≤ 5.1 fb-1 (7 TeV) + ≤ 19.7 fb-1 (8 TeV)
MSSM mhmod+
mh=126 GeV
mh=125 GeV
mh=124 GeV
mh=123 GeV
mh=122 GeV
tanβ
mA [GeV]
Observed exclusion 95% CL
Expected exclusion 95% CL
H± → τν (arXiv:1508.07774)
A/H → bb (arXiv:1506.08329)
A/H/h → μμ (arXiv:1508.01437)
A/H/h → ττ (HIG-14-029)
H → WW/ZZ (arXiv:1504.00936)


Obs., h couplings [κV, κu, κd]
Exp.
Obs., A/H→ττ
Exp.
Obs., A→ Zh→ ll/νν bb
Exp.
Obs., H→ ZZ→ 4l, ll qq/bb/νν
Exp.
Obs., H→ WW→ lν qq/lν
Exp.
Obs., H+→ τν
Exp.
tan β
mA [GeV]
ATLAS
√s=7 TeV, 4.5-4.7 fb-1
√s=8 TeV, 19.5-20.3 fb-1
hMSSM, 95% CL limits

$\underline{m_h^{\text{max}}}$:

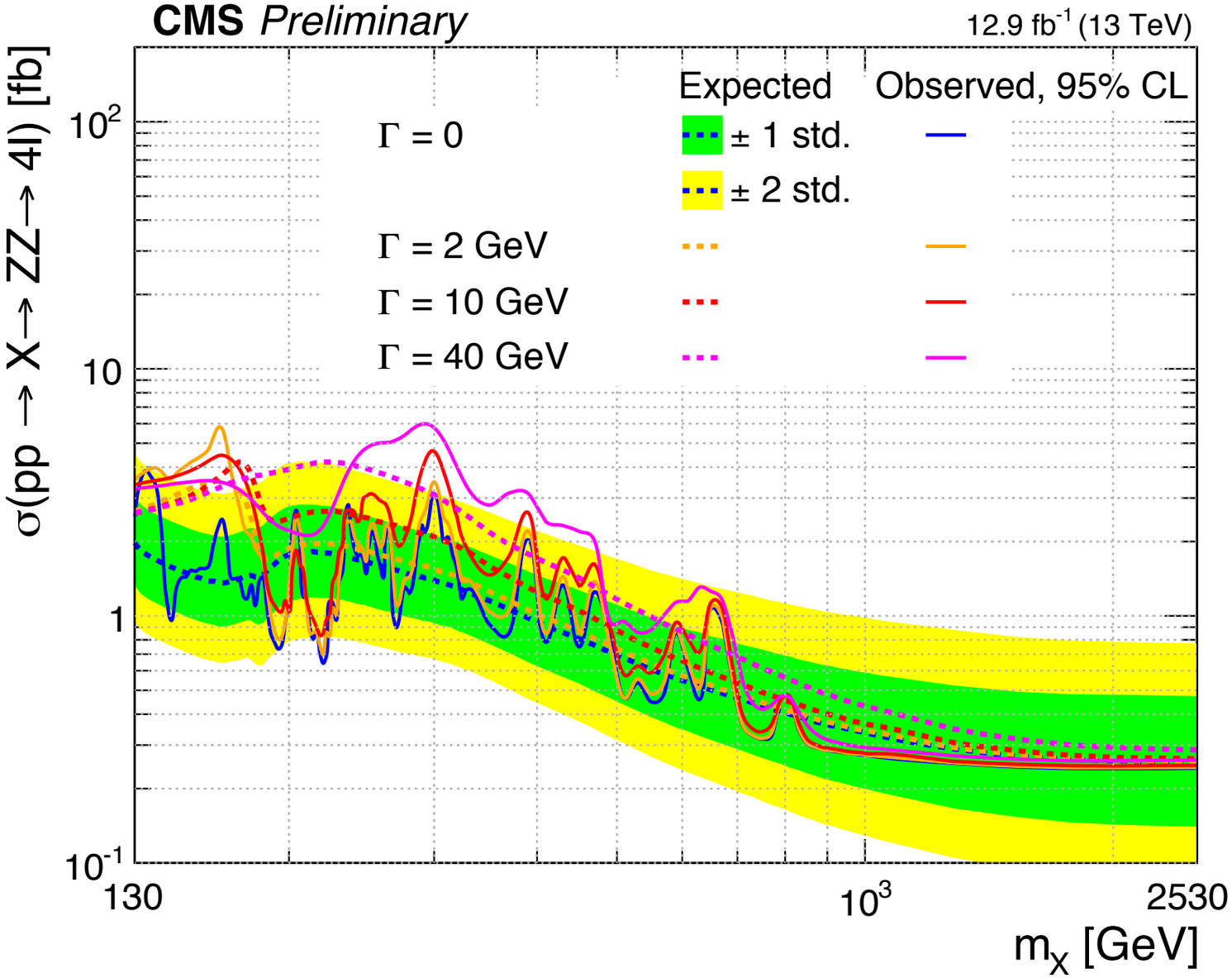
$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 2\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= \sqrt{6}\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned}
$$

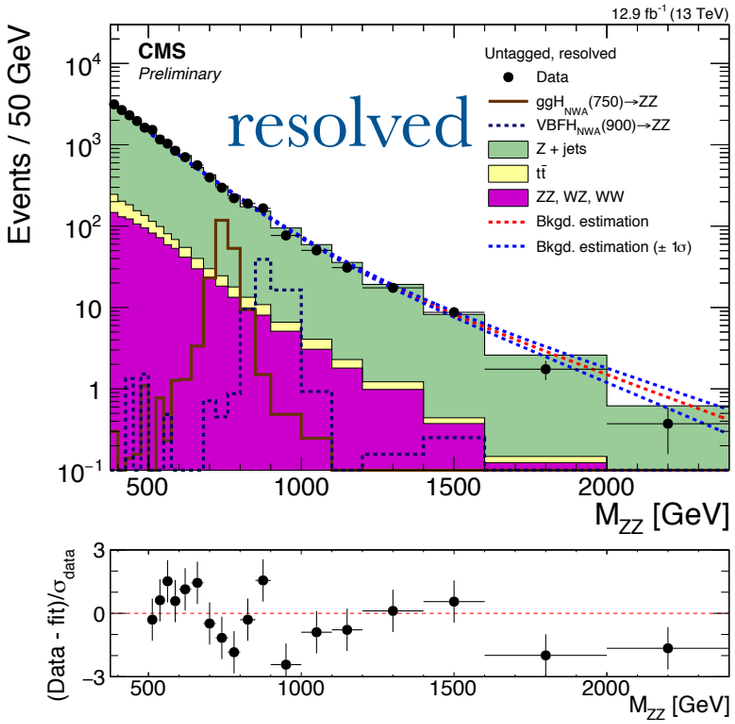
$\underline{m_h^{\text{mod+}}}$:

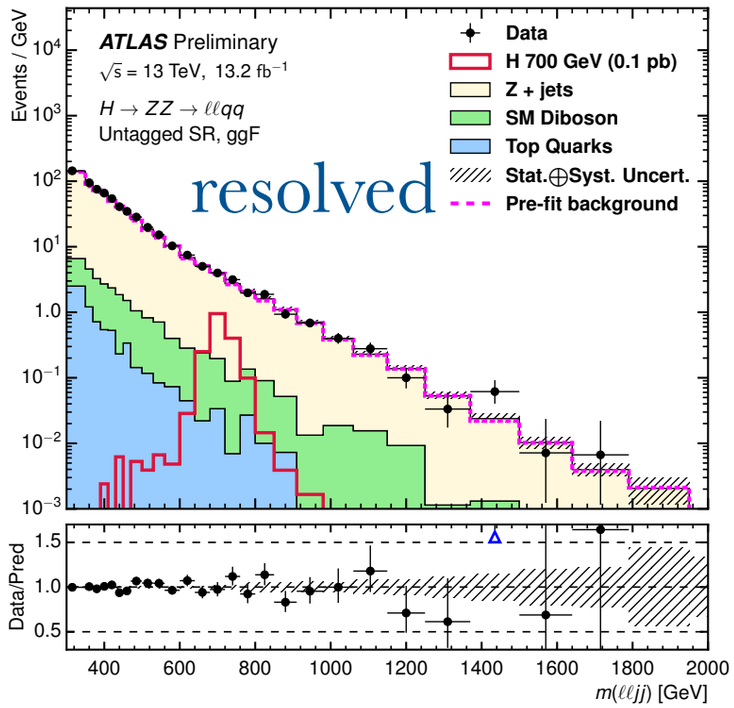
$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 1.5\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= 1.6\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned}
$$

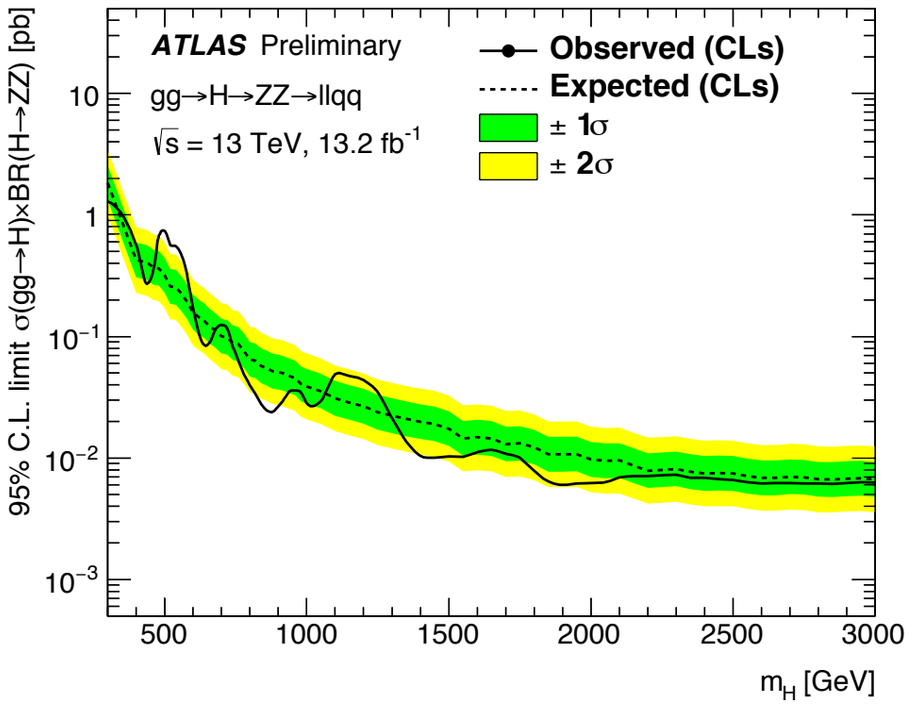
$m_h^{\text{mod-}}$

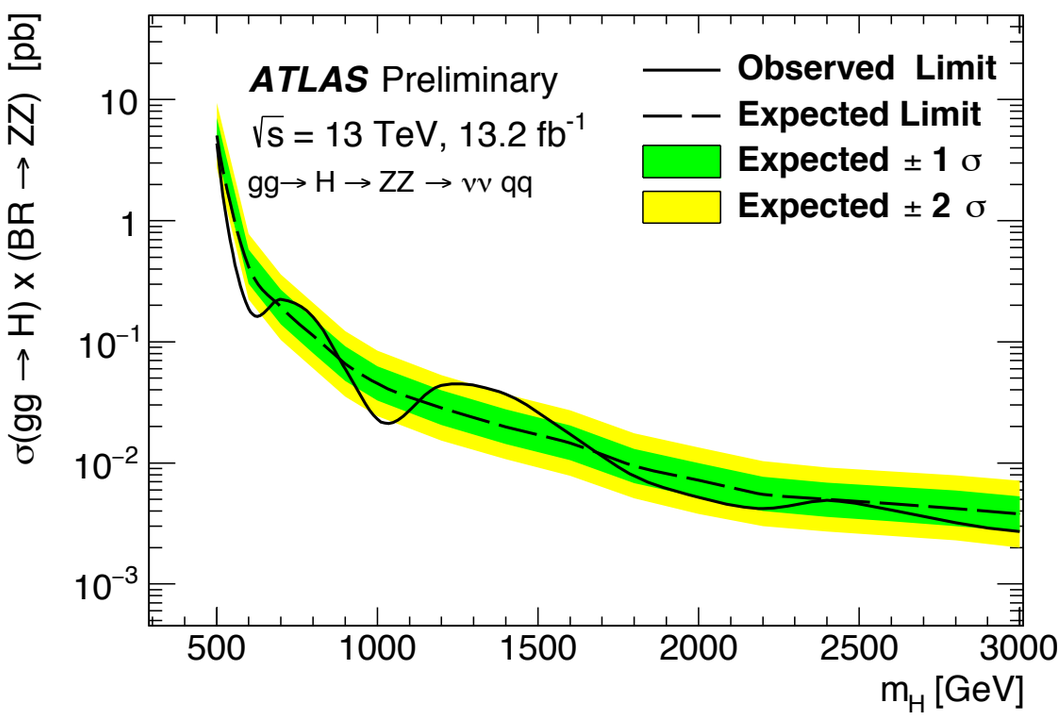
$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= -1.9\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= -2.2\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned}
$$


CMS Preliminary
12.9 fb-1 (13 TeV)
Expected
Observed, 95% CL
Γ = 0
± 1 std.
± 2 std.
Γ = 2 GeV
Γ = 10 GeV
Γ = 40 GeV
σ(pp → X → ZZ → 4l) [fb]
10²
10
1
10⁻¹
130
10³
2530
mX [GeV]

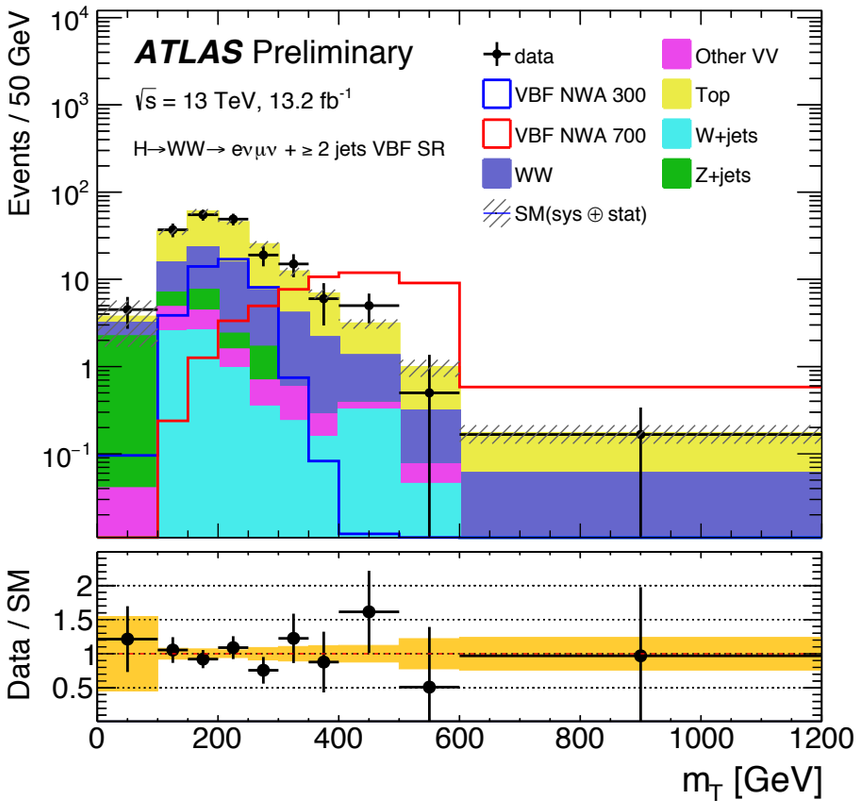

12.9 fb^{-1} (13 TeV)
CMS
Preliminary
resolved
Untagged, resolved
Data
ggH$_{NWA}$(750)→ZZ
VBFH$_{NWA}$(900)→ZZ
Z + jets
tt̄
ZZ, WZ, WW
Bkgd. estimation
Bkgd. estimation (± 1σ)
Events / 50 GeV
M$_{ZZ}$ [GeV]
(Data - fit)/σ$_{data}$

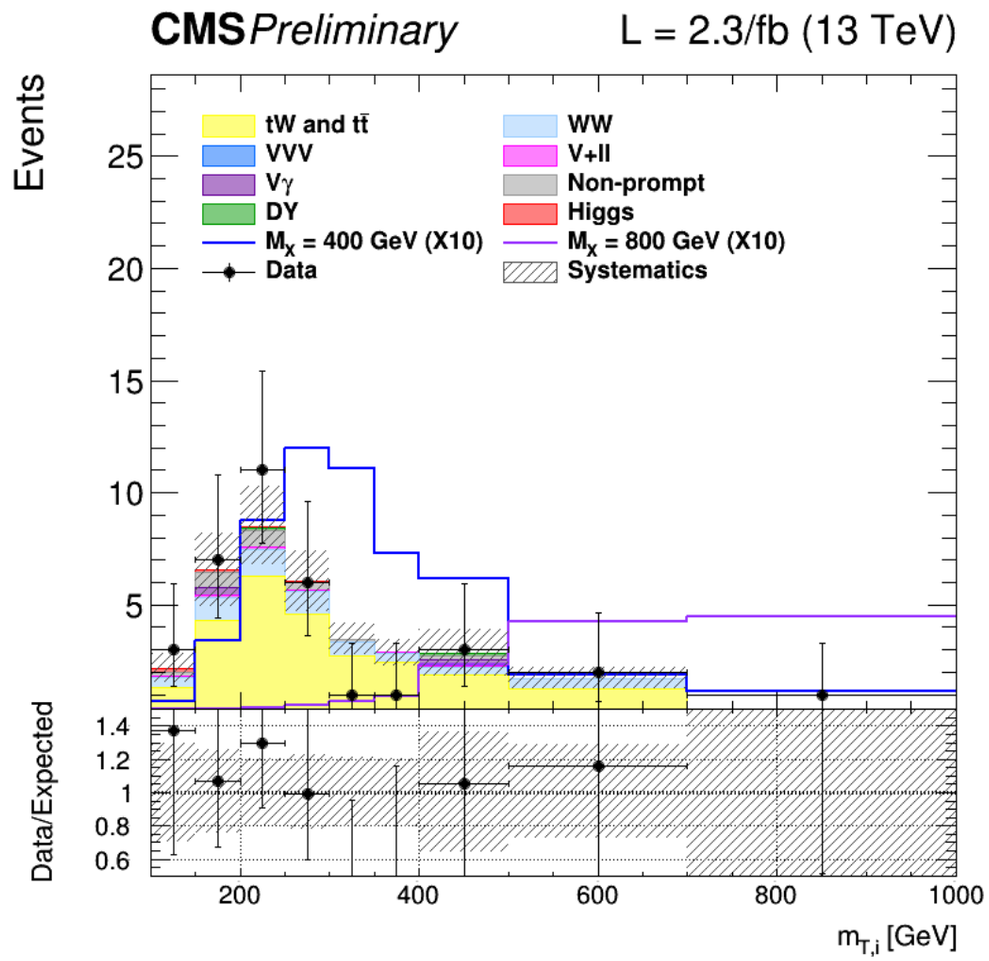

ATLAS Preliminary
√s = 13 TeV, 13.2 fb^{-1}
H → ZZ → ℓℓqq
Untagged SR, ggF
resolved
Data
H 700 GeV (0.1 pb)
Z + jets
SM Diboson
Top Quarks
Stat.⊕Syst. Uncert.
Pre-fit background
Events / GeV
Data/Pred
m(ℓℓjj) [GeV]


ATLAS Preliminary
gg→H→ZZ→llqq
√s = 13 TeV, 13.2 fb^{-1}
Observed (CLs)
Expected (CLs)
± 1σ
± 2σ
95% C.L. limit σ(gg→H)×BR(H→ZZ) [pb]
m$_H$ [GeV]


ATLAS Preliminary
√s = 13 TeV, 13.2 fb^{-1}
gg→ H → ZZ → νν qq
Observed Limit
Expected Limit
Expected ± 1 σ
Expected ± 2 σ
σ(gg → H) x (BR → ZZ) [pb]
m$_H$ [GeV]

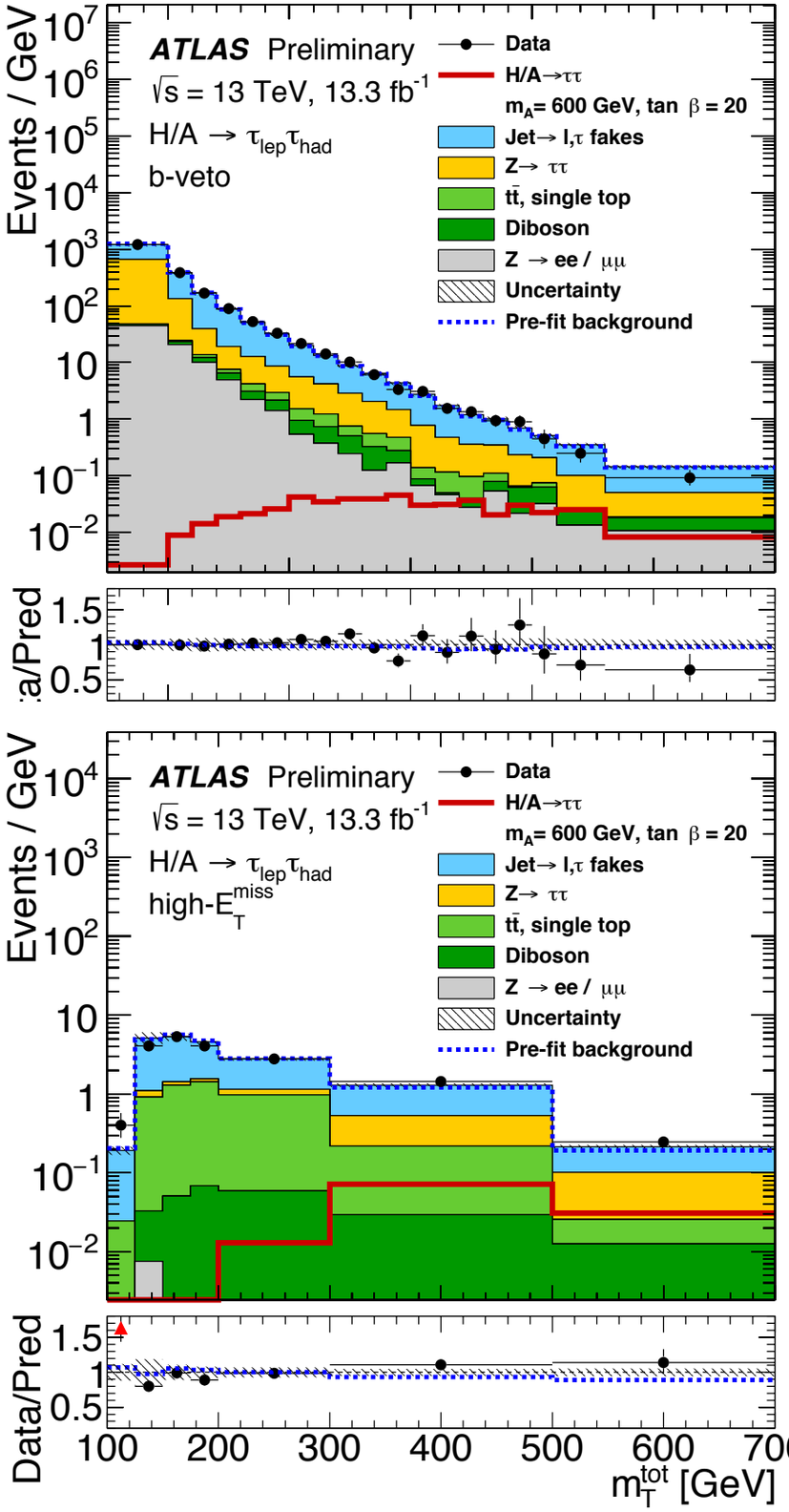
Event Selection		
Exactly one ee or $\mu\mu$ pair		
$p_{\mathrm{T}}(e/\mu) > 30(20)$ GeV for leading (sub-leading) lepton		
Selection	**High Mass**	**Low Mass**
$\lvert m_{ll} - m_Z \rvert$	< 15 GeV	
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 120 GeV	> 90 GeV
$\Delta R_{\ell\ell}$	< 1.8	
$\lvert \Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell\ell}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}}) \rvert$	> 2.7	
$\lvert p_{\mathrm{T}}^{\mathrm{miss,jet}} - p_{\mathrm{T}}^{\ell\ell} \rvert / p_{\mathrm{T}}^{\ell\ell}$	< 0.2	
$\lvert \Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}) \rvert$	> 0.4 $p_{\mathrm{T}}(\mathrm{jet}) > 100$ GeV	> 0.7 $p_{\mathrm{T}}(\mathrm{jet}) > 25$ GeV
$p_{\mathrm{T}}^{\ell\ell}/m_{\mathrm{T}}$	< 0.7	< 0.9
Number of b-jets	$= 0$	

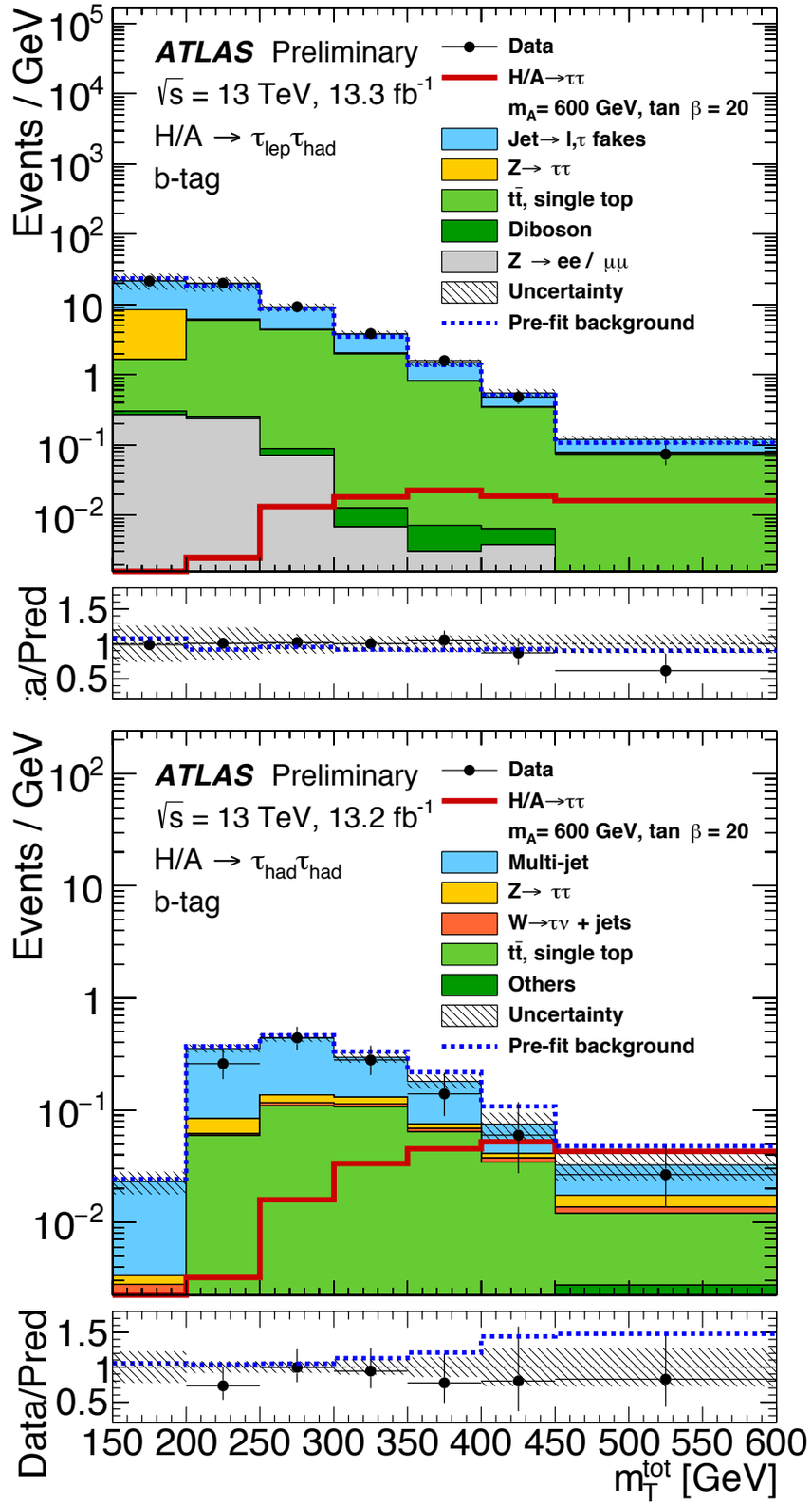

ATLAS Preliminary
√s = 13 TeV, 13.2 fb-1
H→WW→ eνμν + ≥ 2 jets VBF SR
data
VBF NWA 300
VBF NWA 700
WW
SM(sys ⊕ stat)
Other VV
Top
W+jets
Z+jets
Events / 50 GeV
Data / SM
mT [GeV]

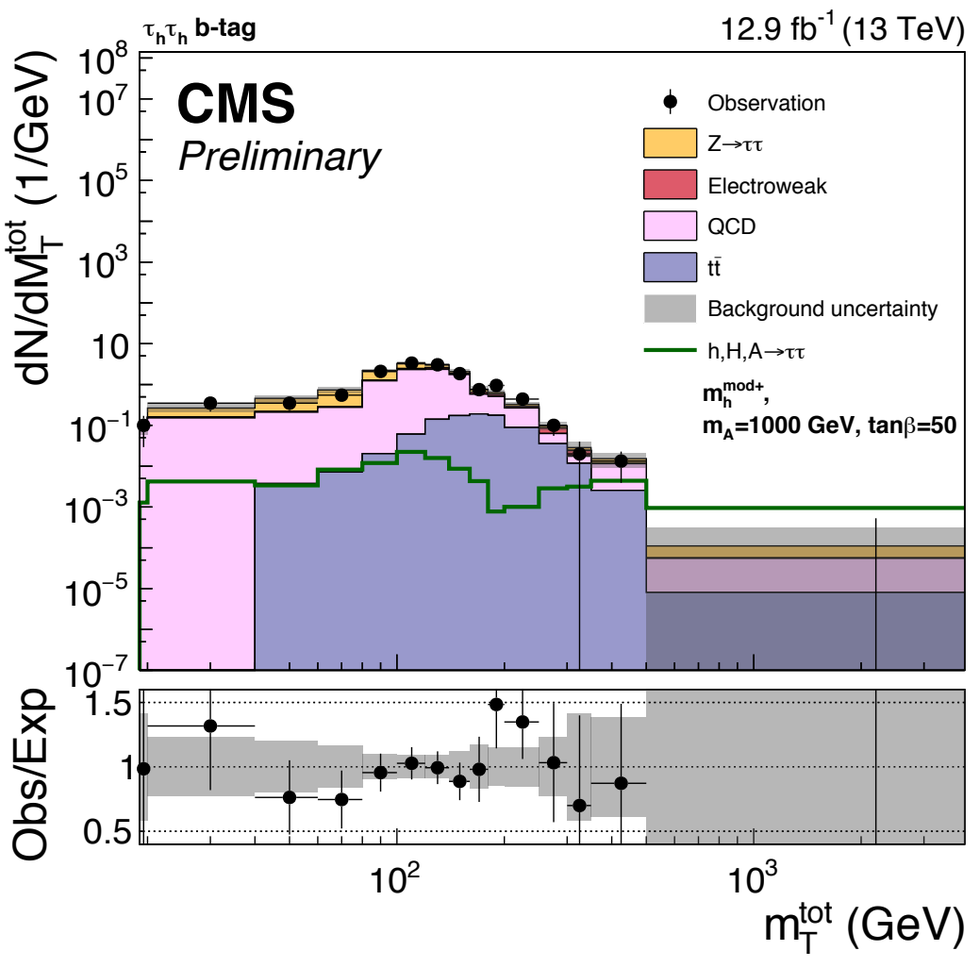

CMS Preliminary
L = 2.3/fb (13 TeV)
tW and tt̄
VVV
Vγ
DY
MX = 400 GeV (X10)
Data
WW
V+ll
Non-prompt
Higgs
MX = 800 GeV (X10)
Systematics
Events
Data/Expected
mT,i [GeV]

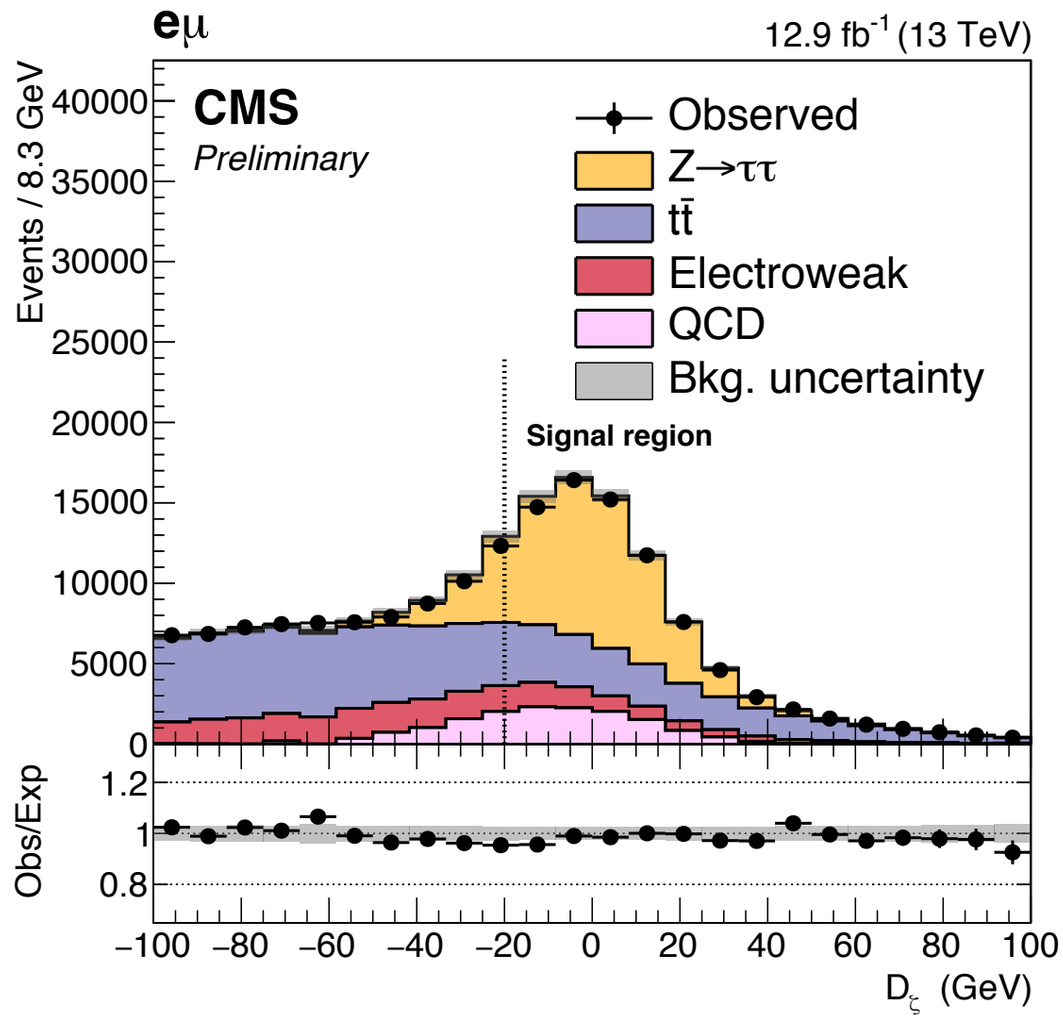
CMS-PAS-HIG-16-037
ATLAS-CONF-2016-085

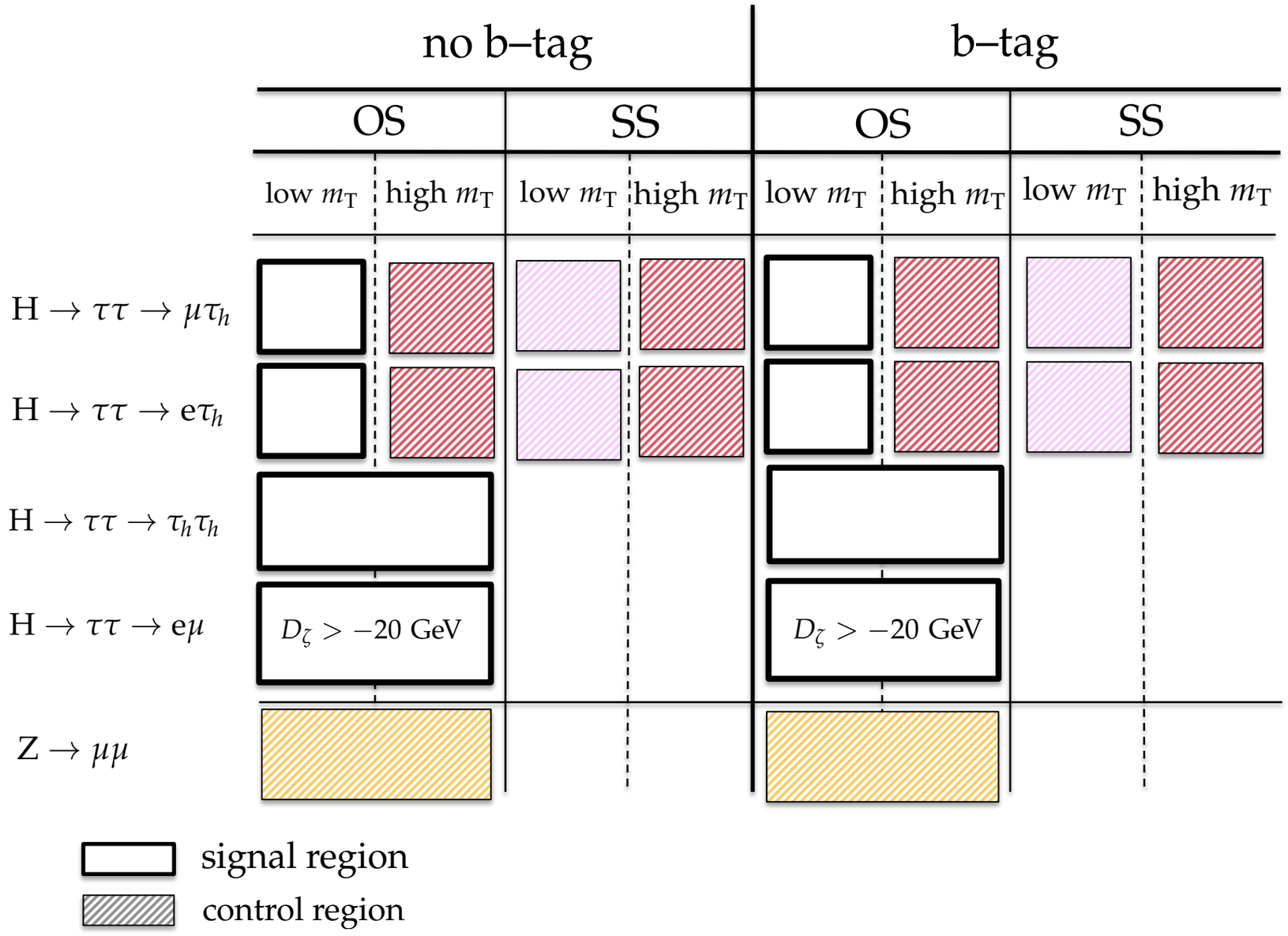
$H/A \to \tau\tau$

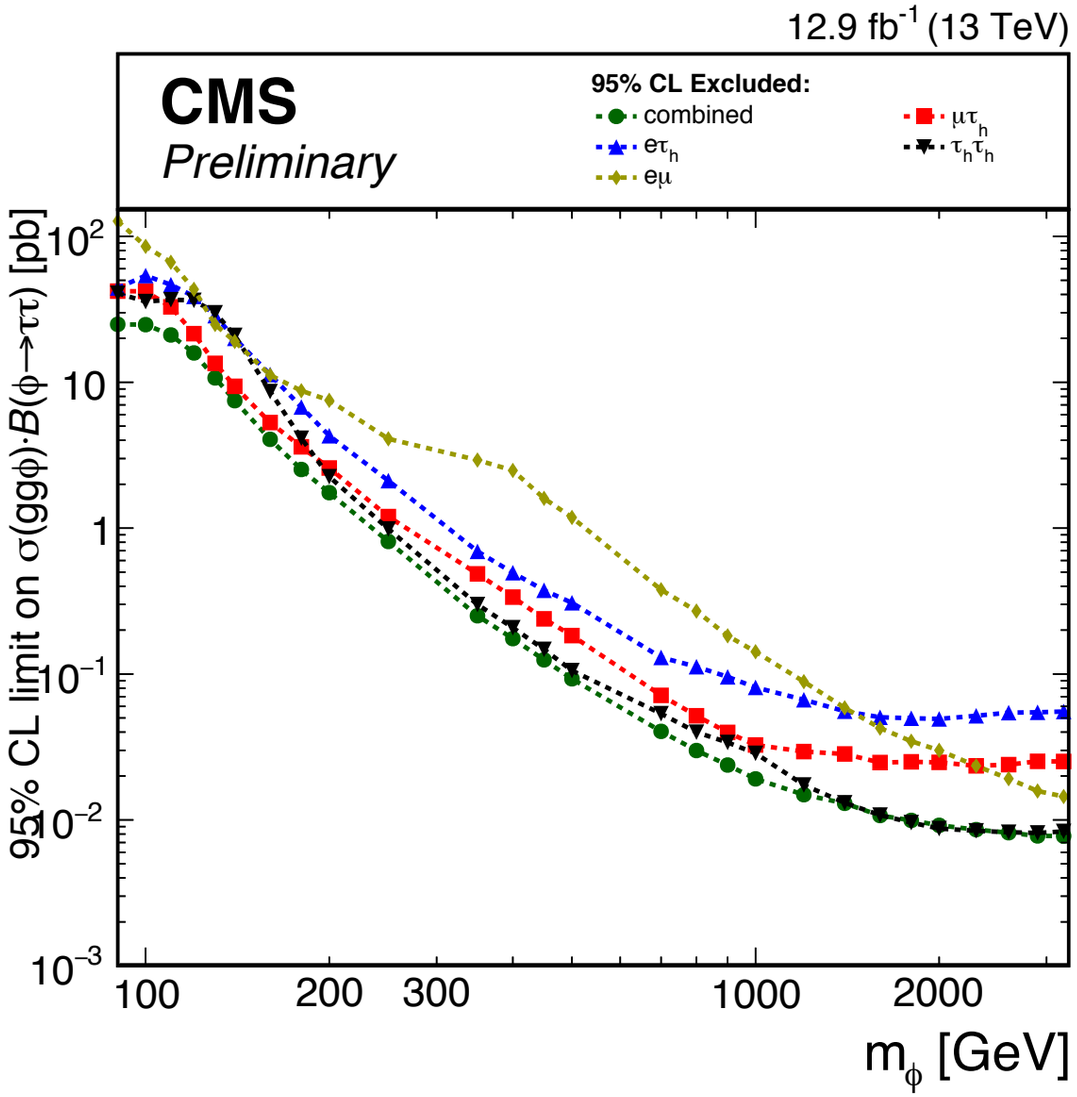


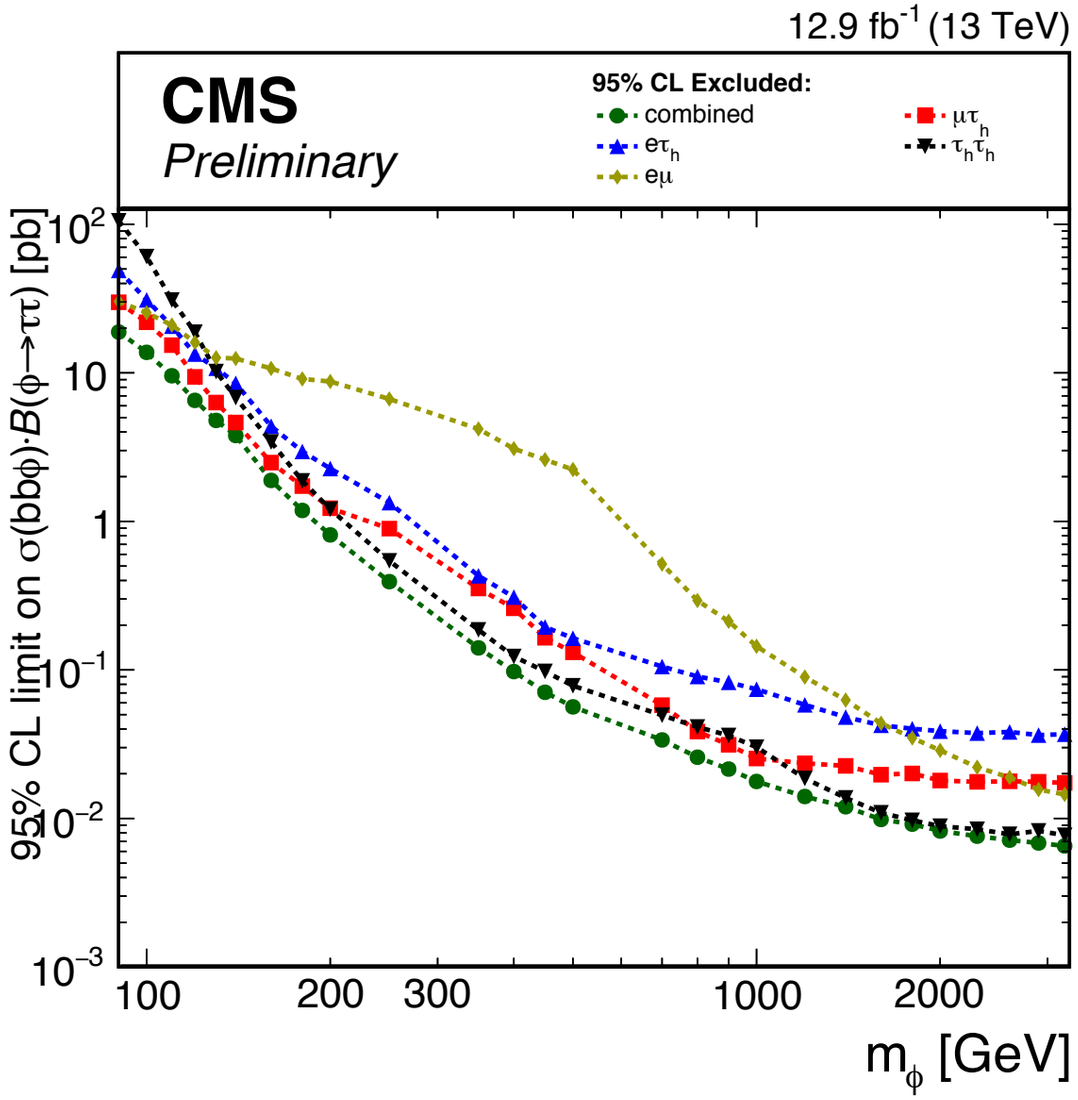



$\tau_h\tau_h$ b-tag
12.9 fb^{-1} (13 TeV)
CMS
Preliminary
Observation
Z→ττ
Electroweak
QCD
tt̄
Background uncertainty
h,H,A→ττ
m_h^{mod+},
m_A=1000 GeV, tanβ=50
dN/dm$_T^{tot}$ (1/GeV)
Obs/Exp
m$_T^{tot}$ (GeV)


eμ
12.9 fb^{-1} (13 TeV)
CMS
Preliminary
Observed
Z→ττ
tt̄
Electroweak
QCD
Bkg. uncertainty
Signal region
Events / 8.3 GeV
Obs/Exp
D$_\zeta$ (GeV)


no b–tag
b–tag
OS
SS
OS
SS
low m_{T}
high m_{T}
low m_{T}
high m_{T}
low m_{T}
high m_{T}
low m_{T}
high m_{T}
$\mathrm{H} \to \tau\tau \to \mu\tau_h$
$\mathrm{H} \to \tau\tau \to \mathrm{e}\tau_h$
$\mathrm{H} \to \tau\tau \to \tau_h\tau_h$
$\mathrm{H} \to \tau\tau \to \mathrm{e}\mu$
$D_\zeta > -20$ GeV
$D_\zeta > -20$ GeV
$\mathrm{Z} \to \mu\mu$
signal region
control region

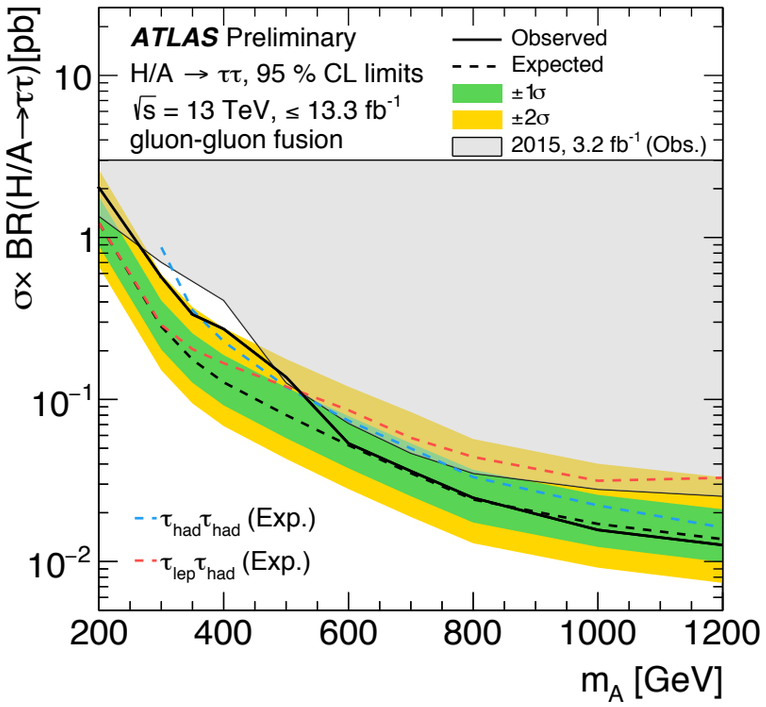

12.9 fb-1 (13 TeV)
CMS
Preliminary
95% CL Excluded:
combined
eτh
eμ
μτh
τhτh
95% CL limit on σ(ggϕ)·B(ϕ→ττ) [pb]
10^2
10
1
10^-1
10^-2
10^-3
100
200
300
1000
2000
mϕ [GeV]

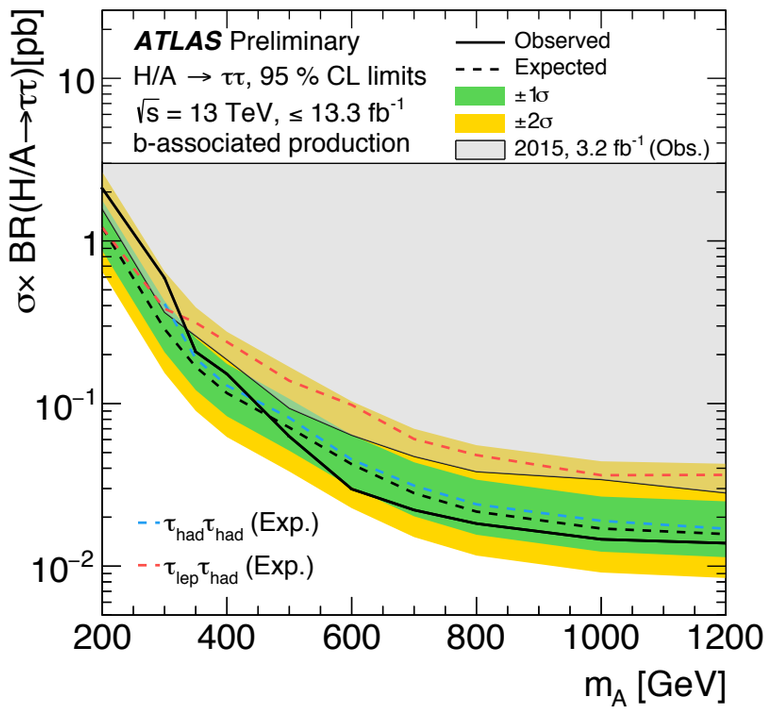

12.9 fb-1 (13 TeV)
CMS
Preliminary
95% CL Excluded:
combined
eτh
eμ
μτh
τhτh
95% CL limit on σ(bbϕ)·B(ϕ→ττ) [pb]
10^2
10
1
10^-1
10^-2
10^-3
100
200
300
1000
2000
mϕ [GeV]

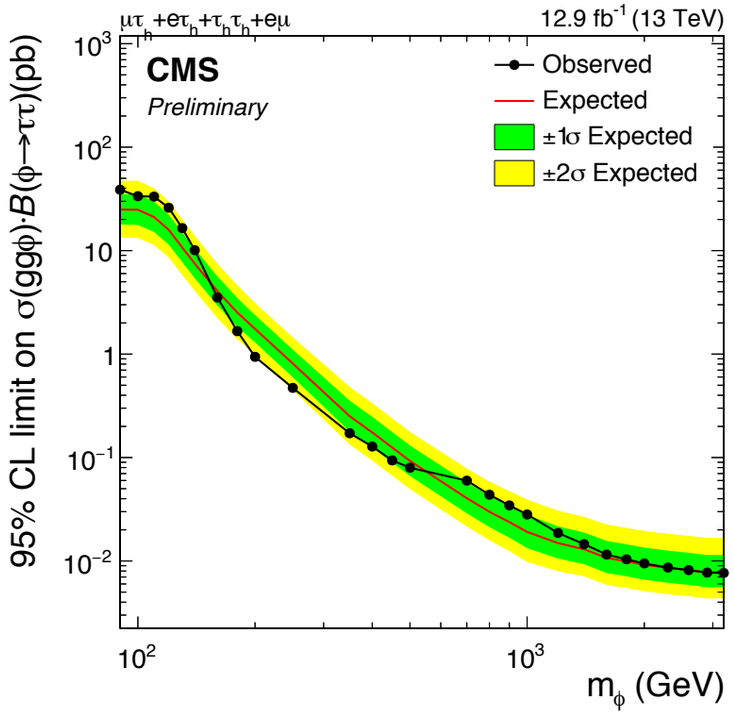
CMS-PAS-HIG-16-037
ATLAS-CONF-2016-085

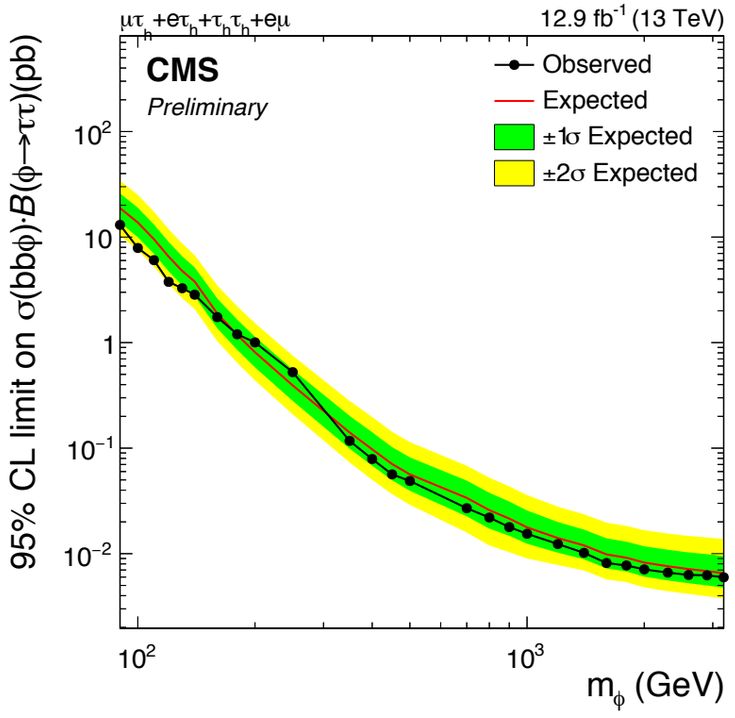
$H/A \to \tau\tau$

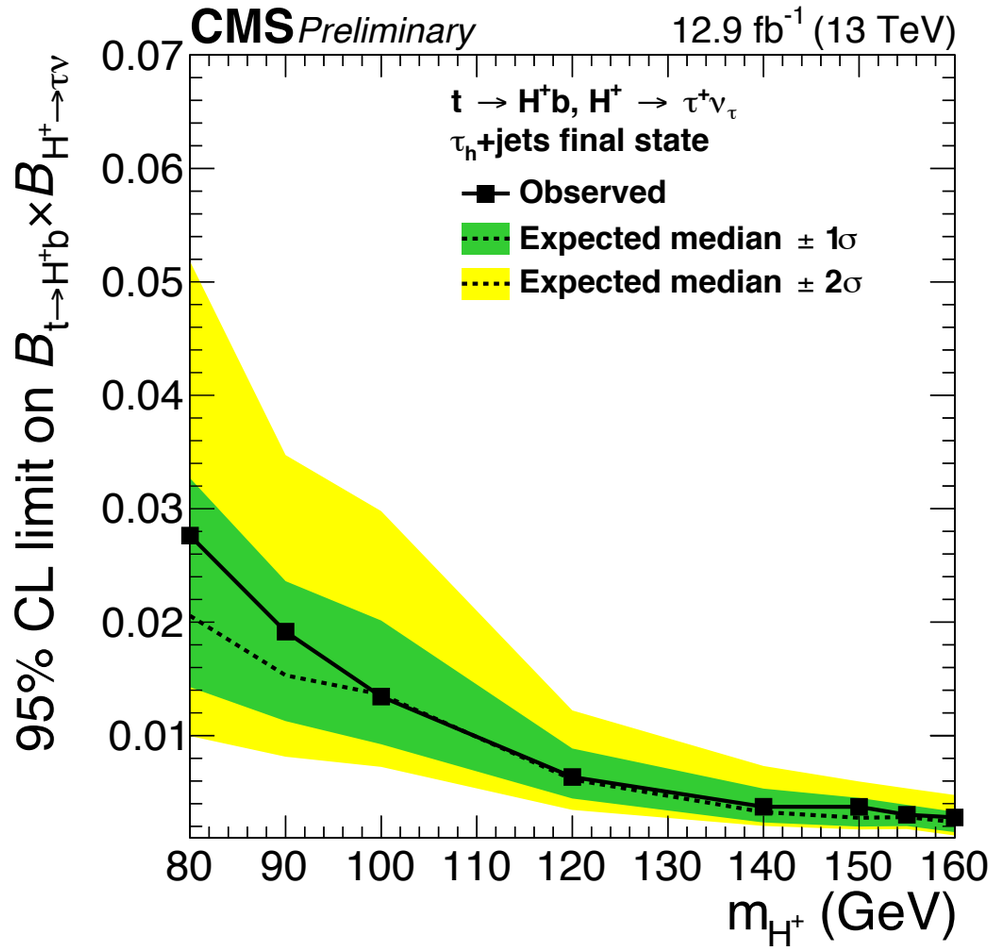
Cross section limit










CMS Preliminary
12.9 fb-1 (13 TeV)
t → H+b, H+ → τ+ντ
τh+jets final state
Observed
Expected median ± 1σ
Expected median ± 2σ
95% CL limit on Bt→H+b×BH+→τν
0.07
0.06
0.05
0.04
0.03
0.02
0.01
80
90
100
110
120
130
140
150
160
mH+ (GeV)