High-mass Higgs searches at ATLAS and CMS

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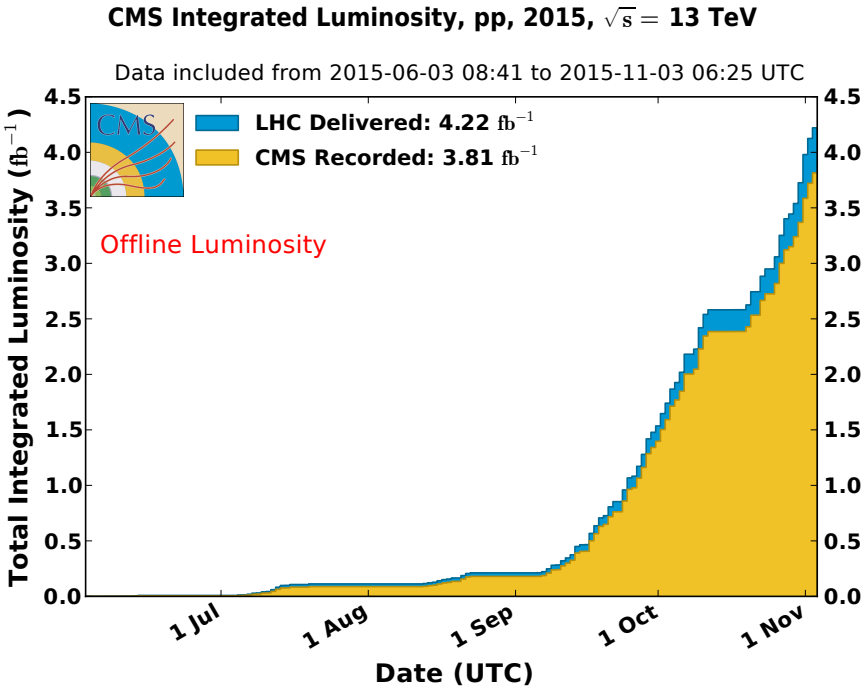
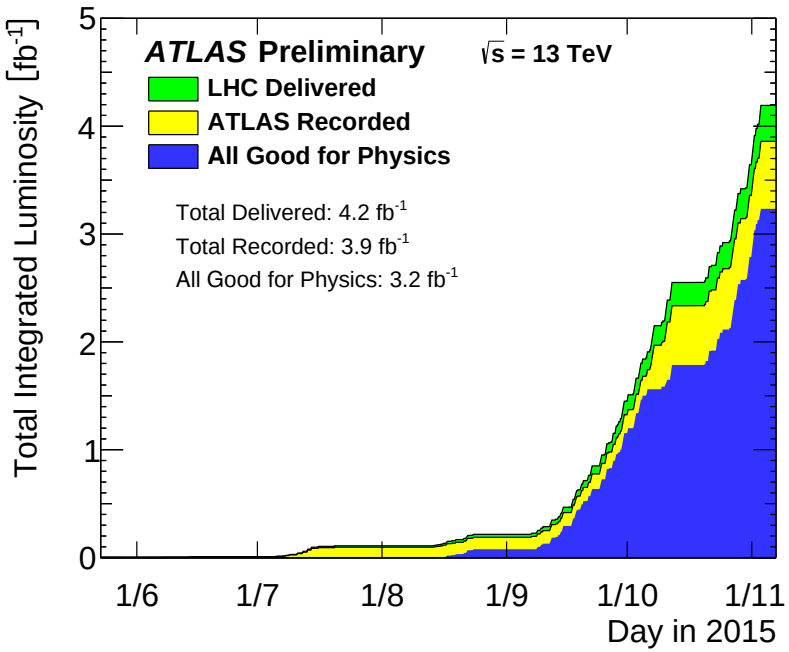
Jul 11, 2016
ICNFP, Crete

- Introduction
- Higgs $\to VV$
- Higgs $\to$ Higgs
- Higgs $\to$ fermions
- Higgs $\to$ invisible
- Summary

Introduction

- Observed Higgs boson very consistent with SM expectations.
- Suspect EW sector of SM may not be complete:
  - Naturalness, dark matter, etc.
- Search for a heavier Higgs-like particle.
- LHC started Run 2 at $\sqrt{s} = 13$ TeV.
- Accumulated ~ 3 fb^{-1} of usable data in 2015.





Some models with heavy Higgs bosons

- Most studied are two simple extensions to the SM:
- Electroweak singlet (EWS)
  - New scalar singlet s that mixes with h.
- 2-Higgs-Doublet Model (2HDM)
  - Extra Higgs doublet.
  - Physical particles h, H, A, $H^{\pm}$.
  - Parameters:
    - ★ Masses: m_h, m_H, m_A, $m_{H^{\pm}}$.
    - ★ VEV ratio of the two doublets: $\tan\beta$.
    - ★ Mixing angle between h, H: α.
    - ★ Potential parameter mixing the two doublets: m_{12}^2.
  - Different ways to couple doublets with other particles; most studied:
    - ★ Type-I: All quarks couple to only one doublet.
    - ★ Type-II: Up-type quarks couple to one doublet, down-type quarks to the other.
  - MSSM is a subset of 2HDM.
  - Numerous MSSM benchmark models:
    - ★ hMSSM, $m_h^{\text{mod}+}$, etc.

Denote the 125 GeV resonance as 'h'; H is a heavier resonance.

Searches covered

All results from 13 TeV 2015 data unless otherwise specified.

Higgs$\to VV$

$H \to ZZ \to 4\ell$
$H \to ZZ \to \ell\ell\nu\nu$
$H \to ZZ \to \ell\ell qq$

Higgs $\to$ fermions

$H^+ \to tb$ [8 TeV]
$H^+ \to \tau\nu$
$H/A \to \tau\tau$

Higgs $\to$ Higgs

$H \to ZA \to \ell\ell bb$
$A \to Zh \to \ell\ell bb/\nu\nu bb$

Invisible Higgs decays

$ZH \to \ell\ell +$ (invisible)
VBF $H \to$ (invisible)

$H \to \gamma\gamma$ covered elsewhere.

Higgs $\rightarrow VV$

- $H \rightarrow ZZ \rightarrow 4\ell$
- $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$
- $H \rightarrow ZZ \rightarrow \ell\ell qq$

Covered in Garabed's talk

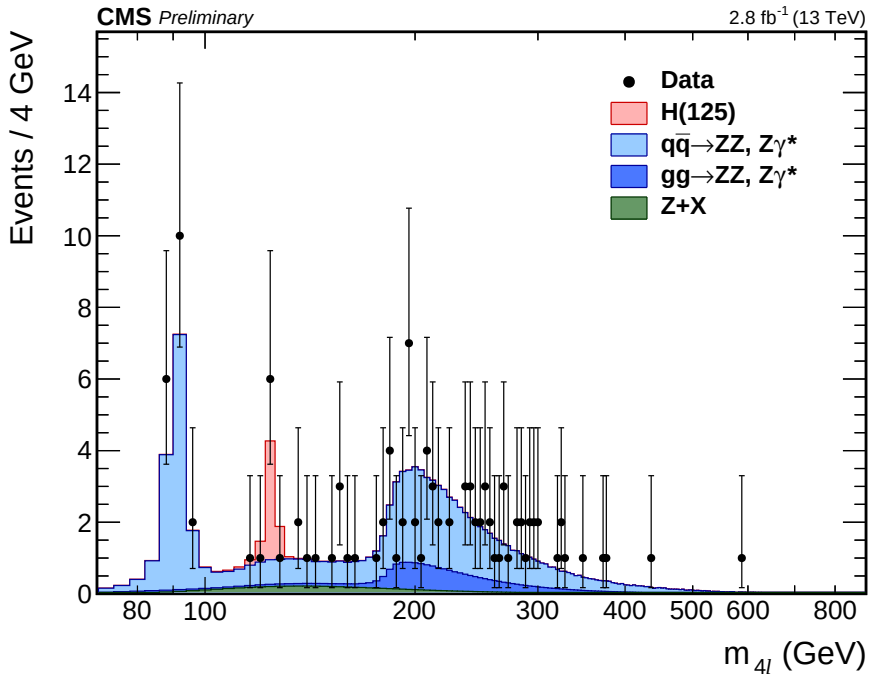
- Merged channels:
  $H \rightarrow VV \rightarrow \nu\nu qq$, $\ell\nu qq$, $\ell\ell qq$, $qqqq$
- $H \rightarrow Z\gamma$

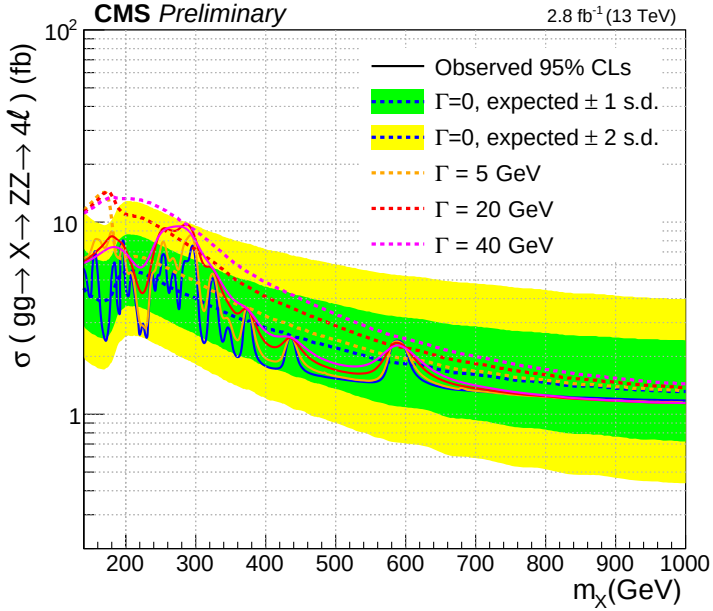
$H \to ZZ \to 4\ell$

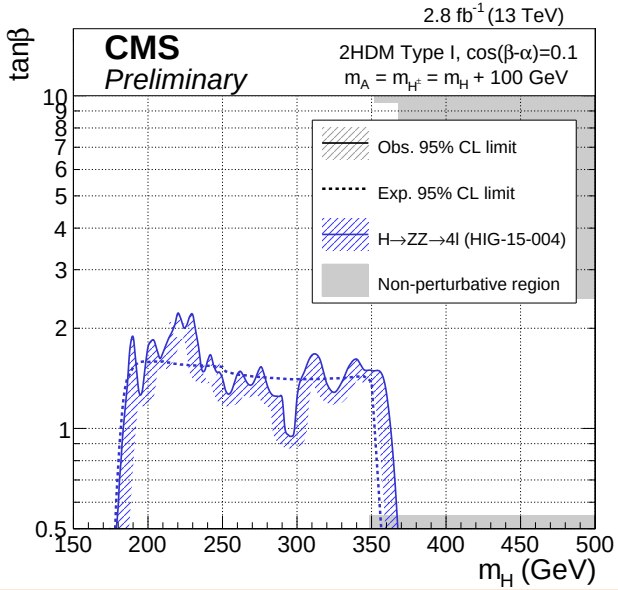
[CMS-PAS-HIG-15-004]

Based on $m_h = 125$ GeV analysis.
2 same-flavor, OS ℓ pairs.
One $40 < m_{\ell\ell} < 120$ GeV;
other $12 < m_{\ell\ell} < 120$ GeV.

BG mostly ZZ, est. from MC







Exclusions for several resonance widths.
Also tan β limits for type-I,II 2HDM.

ATLAS analysis: [ATLAS-CONF-2015-059]

$H \to ZZ \to \ell\ell\nu\nu$

[ATLAS-CONF-2016-012]

Require $Z \to \ell\ell$, large $E_{\mathrm{T}}^{\mathrm{miss}}$, no b-tags.

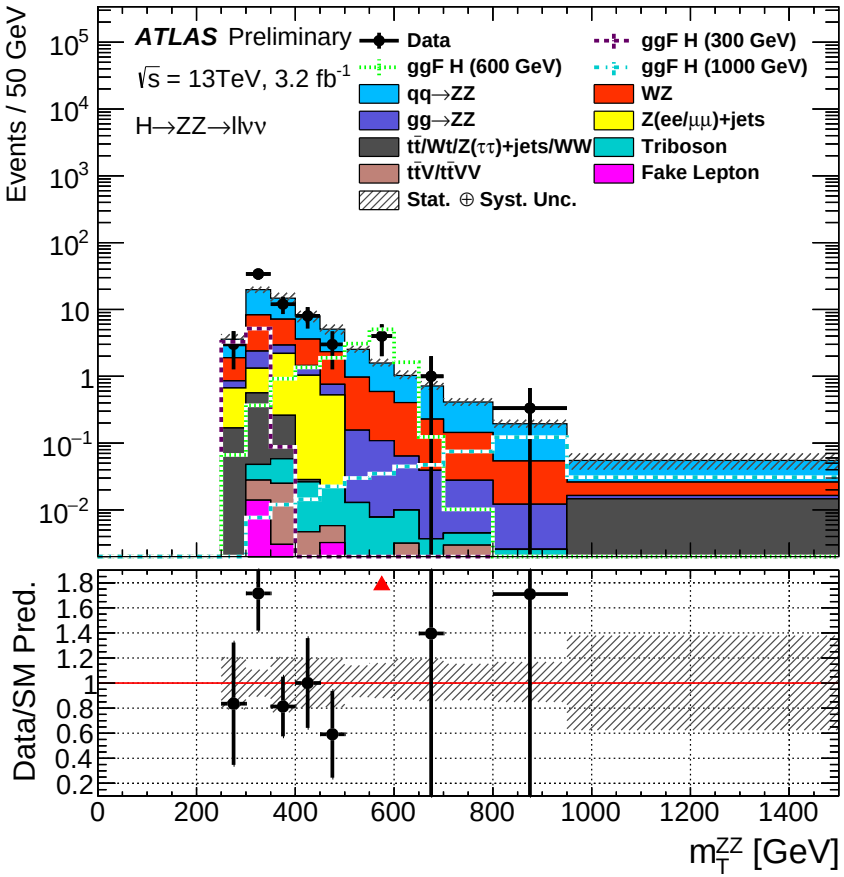
Add'l requirements on $\Delta\phi(Z, E_{\mathrm{T}}^{\mathrm{miss}})$ and p_T^Z.

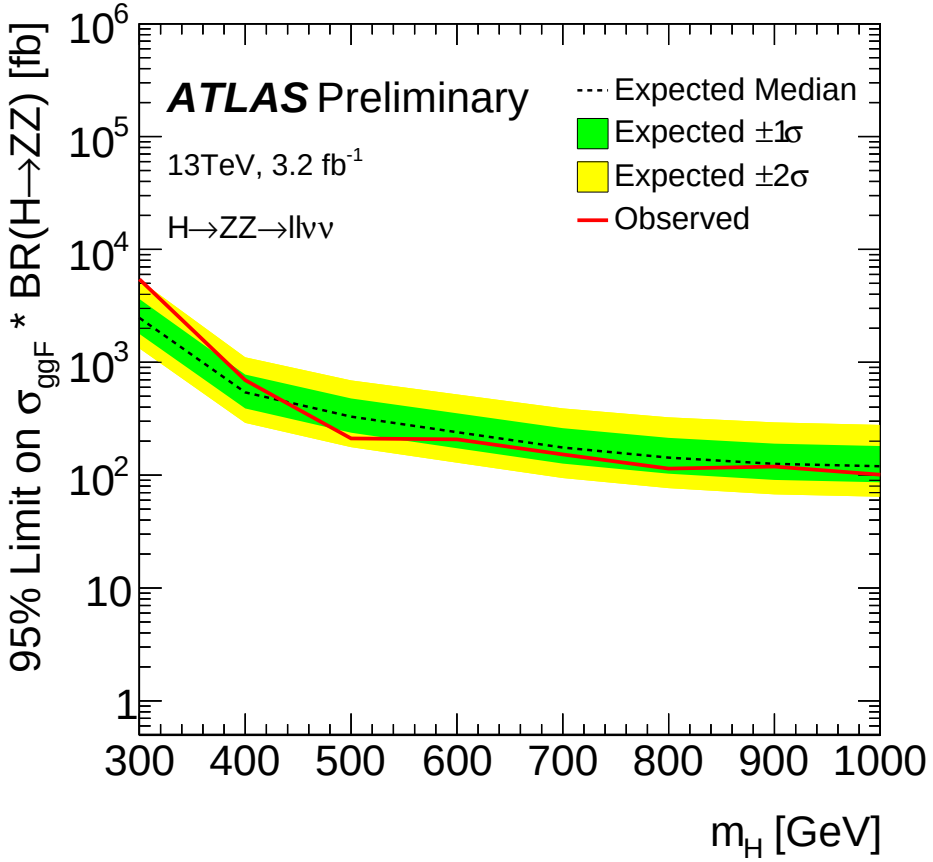
Discriminating variable: $m_T(\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$.

VV: MC

WZ: MC normalized to data

Z + jets: data-driven





CMS analysis: [CMS-PAS-HIG-16-001]

$H \to ZZ \to \ell\ell qq$

[ATLAS-CONF-2016-016]

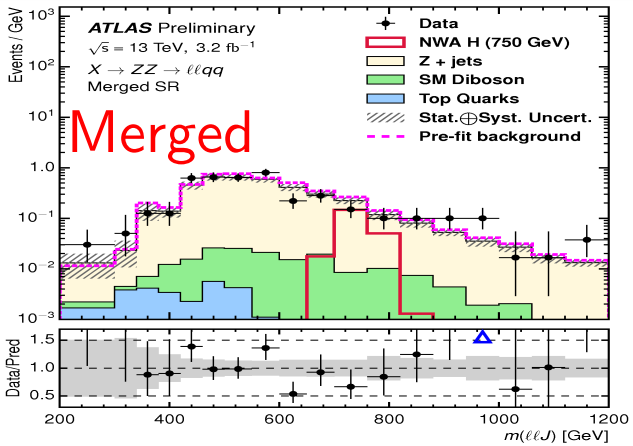
Merged analysis

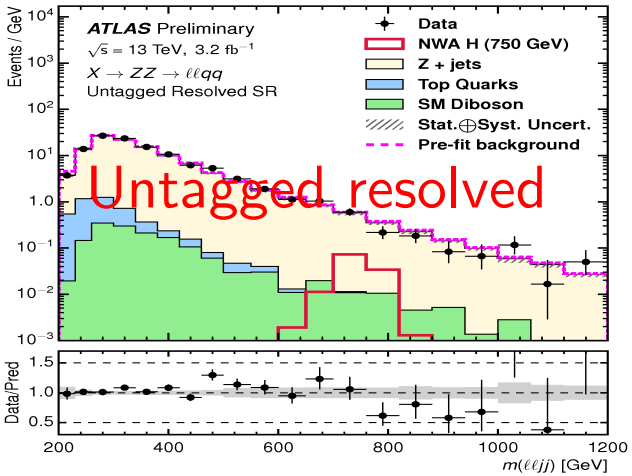
$Z \to \ell\ell$; small $E_{\mathrm{T}}^{\mathrm{miss}}$
large-R Z-tagged jet w/ $p_T > 200$ GeV
$p_T(\ell\ell) > 0.3 m_{\ell\ell}$

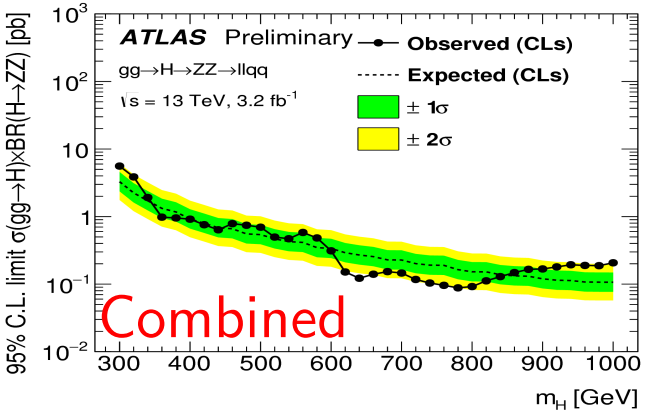
Dominant BG: Z + jets, also $t\bar{t}$.

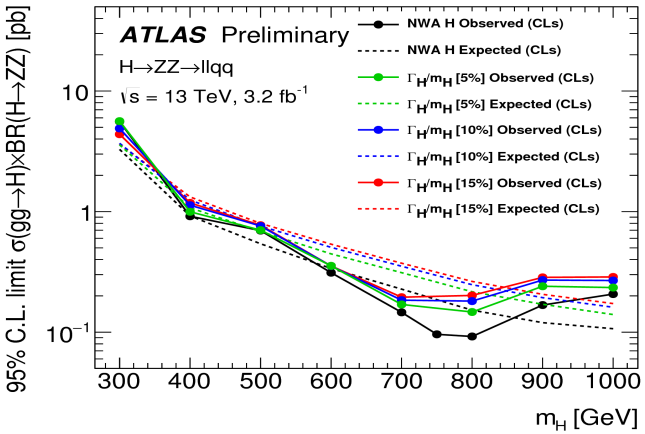
Resolved analysis

$Z \to \ell\ell$; small $E_{\mathrm{T}}^{\mathrm{miss}}$; $2j$ w/ $70 < m_{jj} < 105$ GeV
$\sqrt{p_T^2(\ell\ell) + p_T^2(jj)} > 0.5 m_{\ell\ell jj}$
Tagged ($2b$) and untagged ($< 2b$) categories.









Higgs $\rightarrow$ Higgs

Covered in Xiaohu's and Andrey's talks

- $H \rightarrow hh \rightarrow bb\tau\tau$
- $H \rightarrow hh \rightarrow bb\gamma\gamma$
- $H \rightarrow hh \rightarrow \ell\nu\ell\nu bb$
- $H \rightarrow hh \rightarrow bbbb$

Covered here: analyses involving CP-odd scalar A

- $H \rightarrow ZA \rightarrow \ell\ell bb$
- $A \rightarrow Zh \rightarrow \ell\ell bb/\nu\nu bb$

$H \to ZA \to \ell\ell bb$

[CMS-PAS-HIG-16-010]

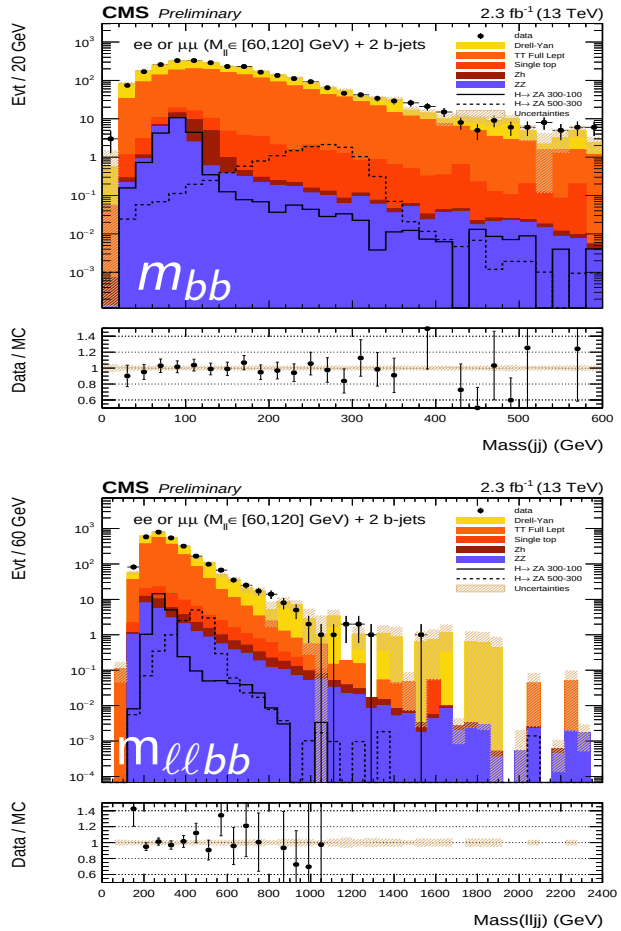
Selection

$Z \to \ell\ell$, 2 b-tags

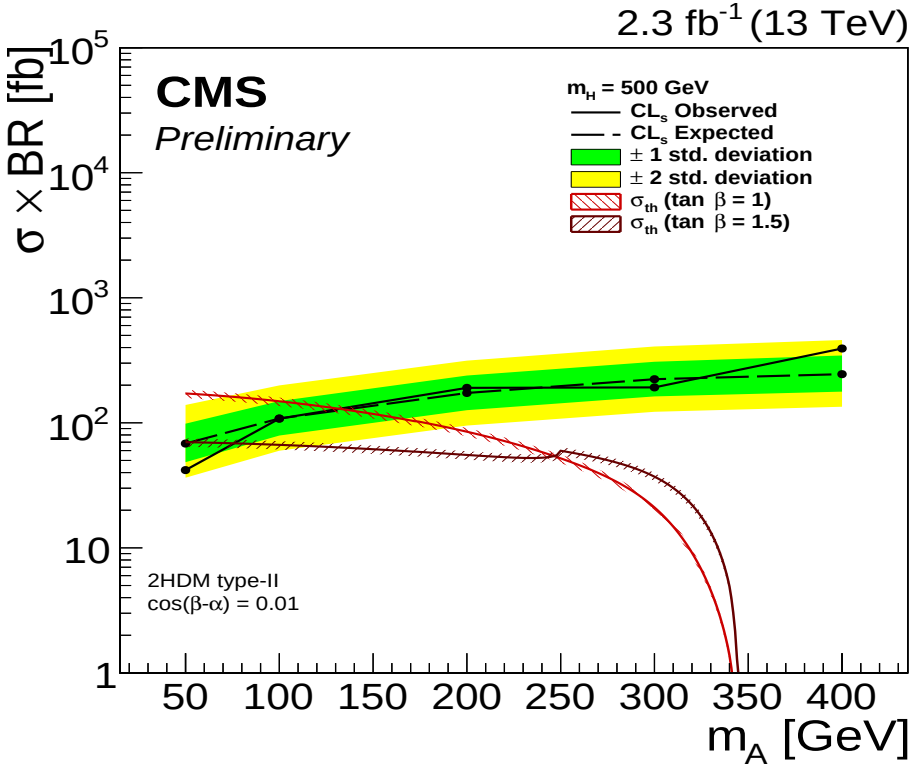
For different hypothesized m_A/m_H pairs: rectangular window in $m_{bb}/m_{\ell\ell bb}$ plane.

Backgrounds

Normalize backgrounds by fitting $m_{\ell\ell}$ outside signal region.



Limits for $m_H = 500$ GeV; also derived for 300 GeV and 800 GeV.



$A \to Zh \to \ell\ell bb/\nu\nu bb$

[ATLAS-CONF-2016-015]

Selection

Either no ℓ and $E_{\mathrm{T}}^{\mathrm{miss}}$
or $Z \to \ell\ell$ and small $E_{\mathrm{T}}^{\mathrm{miss}}$.

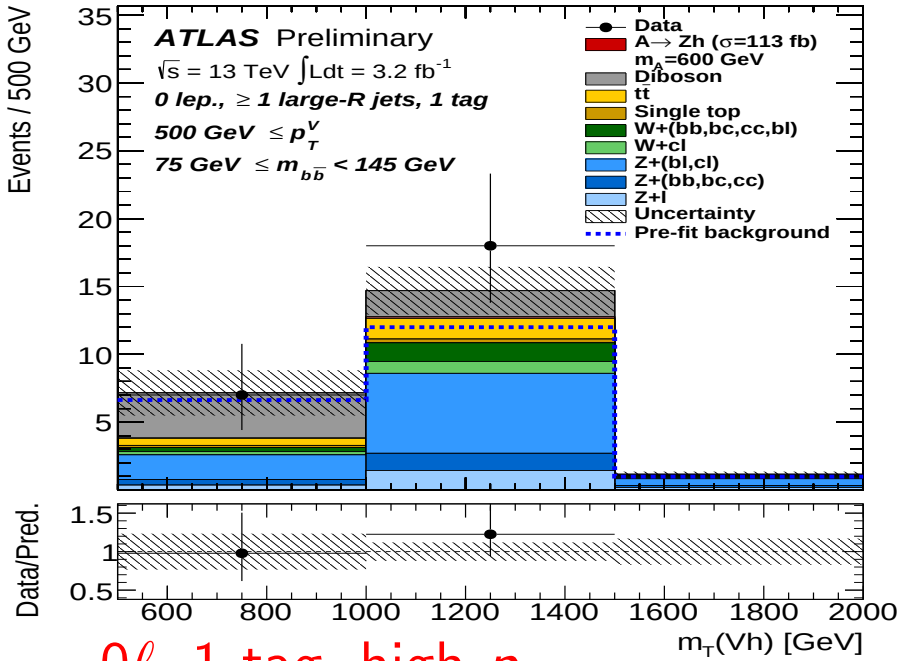
bb either from two small-R jets ($110 < m_{jj} < 140$ GeV) if $p_T^Z < 500$ GeV or a large-R jet ($75 < m_J < 145$ GeV) otherwise.

Either 1 or 2 b-tags.

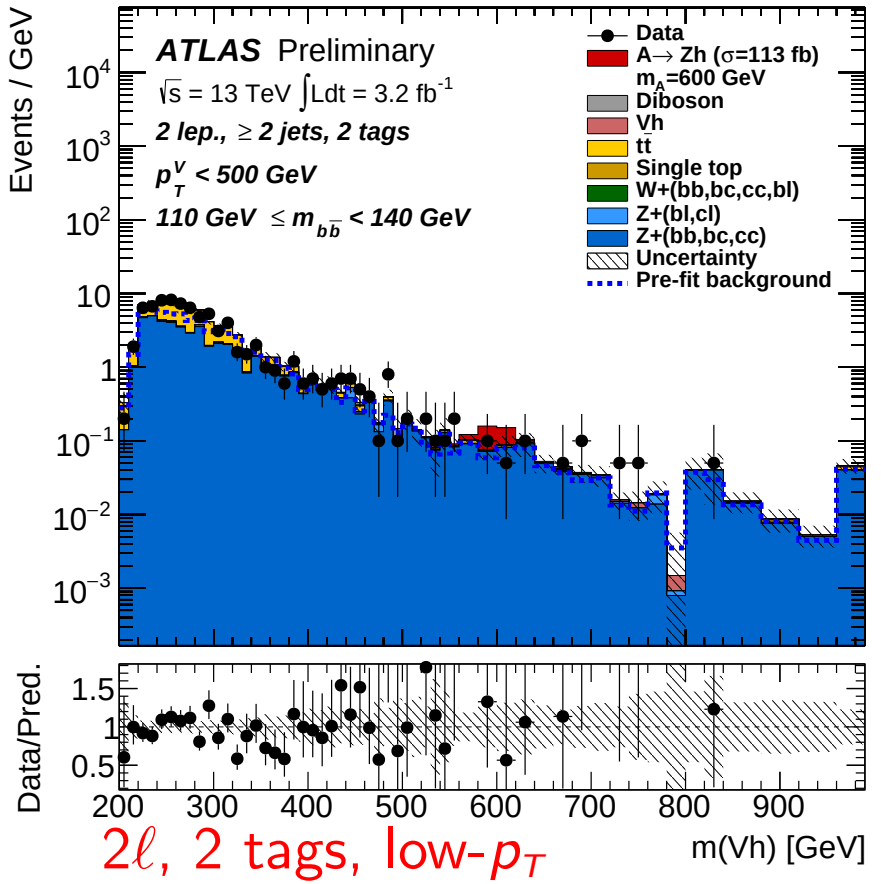
Backgrounds

Shapes from MC. Z + jets, $t\bar{t}$ control regions included in final fit to constrain dominant backgrounds.

Final discriminant: $m(Zh)/m_T(Zh)$.



0ℓ, 1 tag, high-p_T

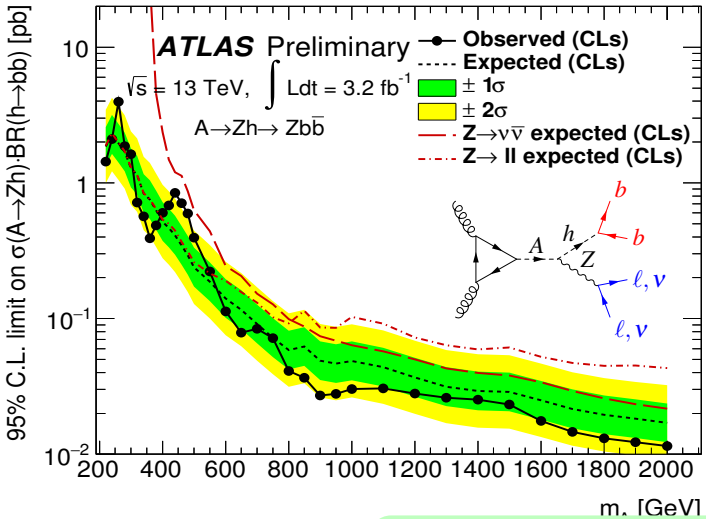


2ℓ, 2 tags, low-p_T

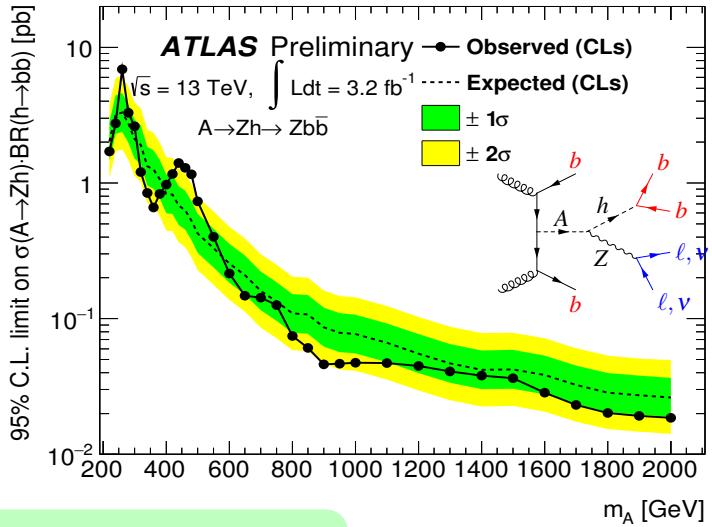
$A \to Zh \to \ell\ell bb/\nu\nu bb$ (2)

[ATLAS-CONF-2016-015]

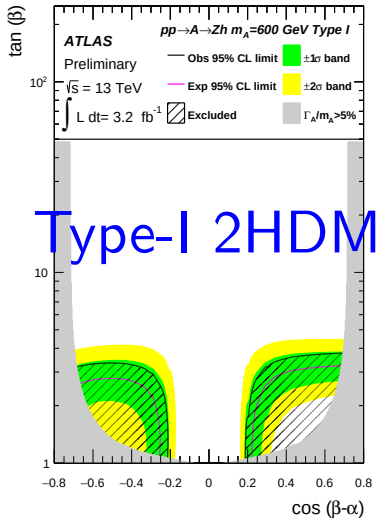
Production via ggf

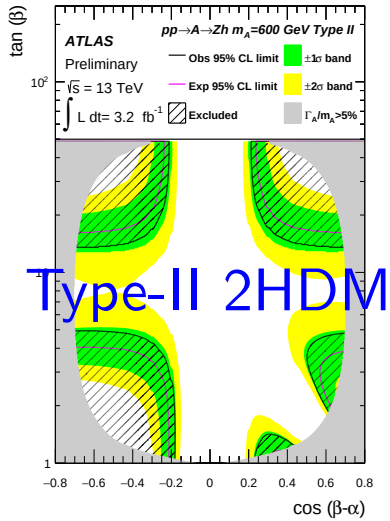


Production w/associated b's



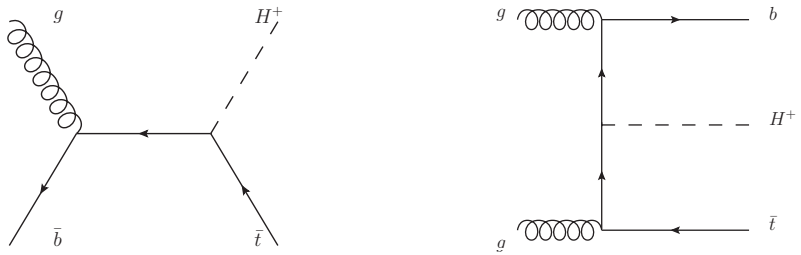
MSSM interpretations ($M_A = 600$ GeV)





Higgs $\rightarrow$ fermions

Charged Higgs production and decay



For $m_{H^+} > m_t$, production is dominantly $pp \rightarrow t(b)H^+$.

- $H^+ \rightarrow tb$
- $H^+ \rightarrow \tau\nu$

Decay is dominantly $H^+ \rightarrow tb$.

But $H^+ \rightarrow \tau\nu$ can be significant for high $\tan\beta$.

Also

$H \rightarrow \tau\tau$

$H^+ \to tb, \tau\nu$ [8 TeV]

[arXiv:1508.07774]

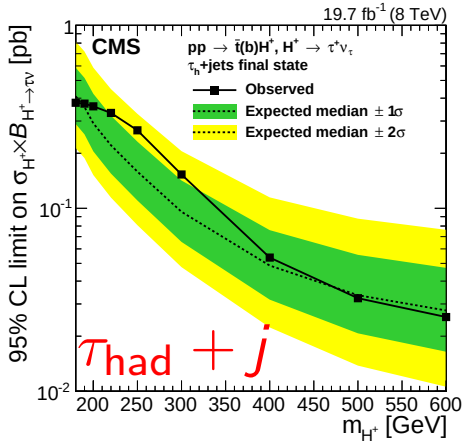
Produced via $pp \to t(b)H^\pm$. Hadronic channel also sensitive to $t\bar{t} \to bH^\pm bH^\pm$, $t\bar{t} \to bH^\pm bW$.

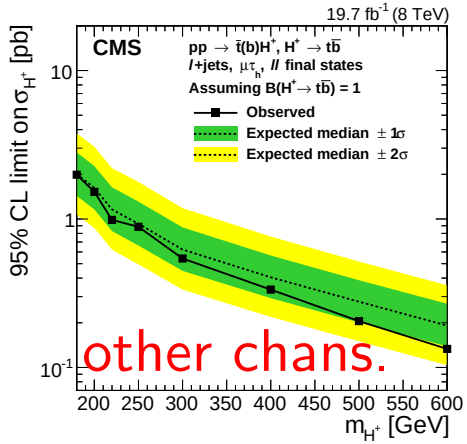
τ_{had} + jets ($\tau\nu$): τ_{had}, $\geq 3j$, $\geq 1b$, no ℓ, angular separations. Extract limit from $m_T(\tau_{\text{had}}, E_{\text{T}}^{\text{miss}})$.
BG: $V + j$, VV, $t \to \tau$: Replace μ in $\mu + j$ with sim. τ
multijet: from data via fake rate; $t\bar{t}$ w/fake τ from MC

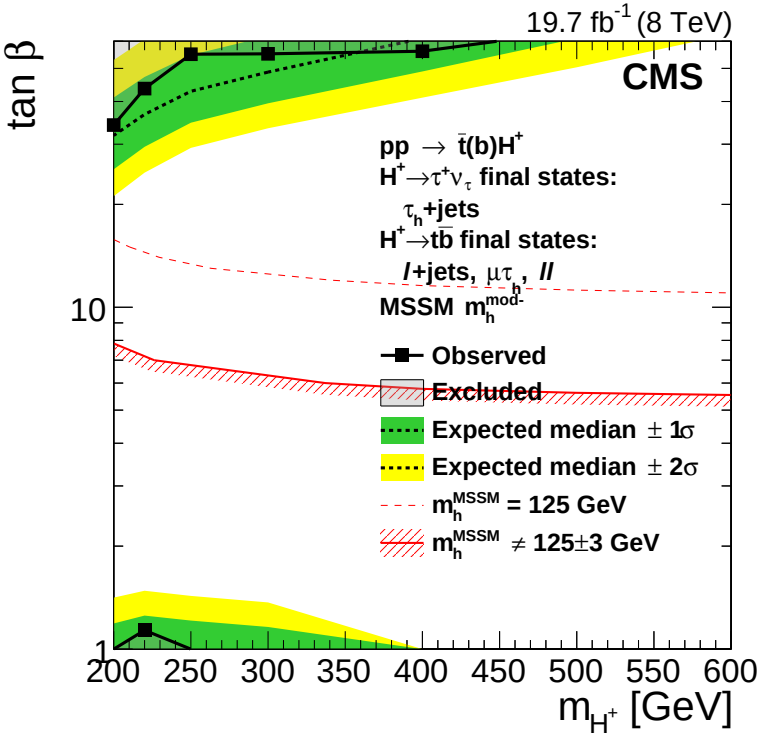
$\ell\ell$ ($tb/\tau\nu$): 2ℓ, $2j$, $E_{\text{T}}^{\text{miss}}$, $\geq 2b$. Extract limit from n_{btag}.
BG: From MC.

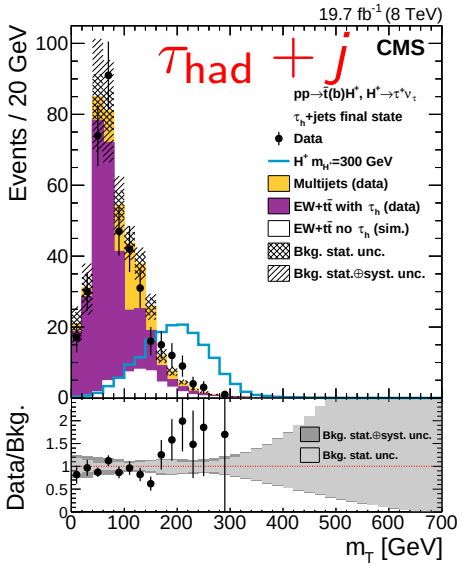
$\mu\tau_{\text{had}}$ ($tb/\tau\nu$): As above with $\mu\tau_{\text{had}}$ instead of 2ℓ and $\geq 1b$.
BG: From MC, with fake-factor for misidentified τ_{had}.

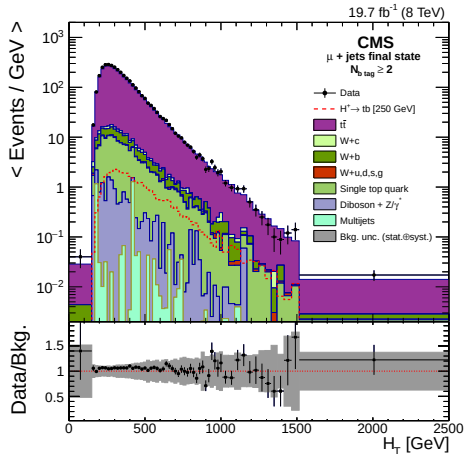
ℓ + jets (tb): ℓ, $E_{\text{T}}^{\text{miss}}$, $2j$, $\geq 1b$. Extract limit from H_T, binned in b-tag multiplicity.
BG: Shapes from MC, normalizations float in fit.











ATLAS tb analysis: [arXiv:1512.03704]

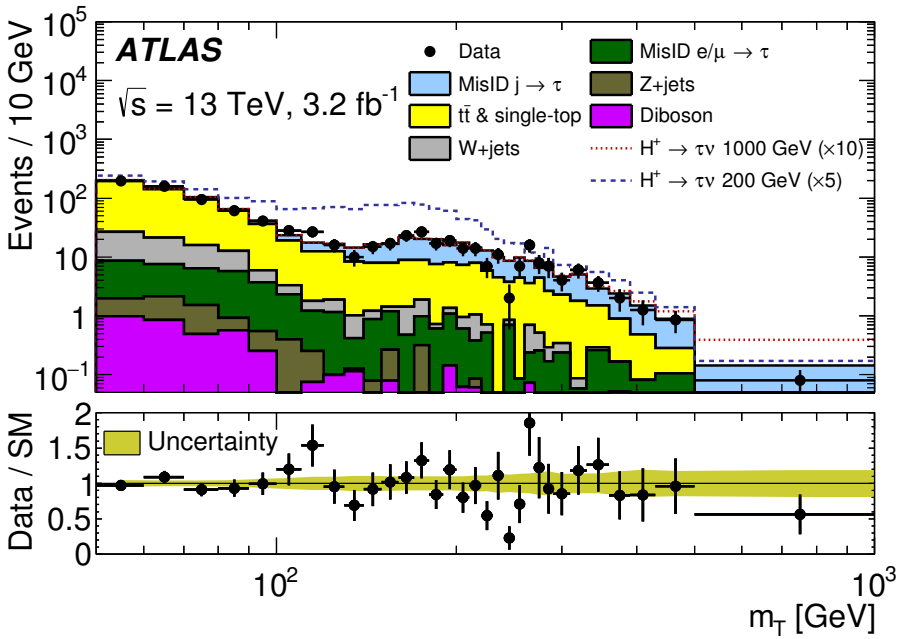
$H^+ \to \tau\nu$

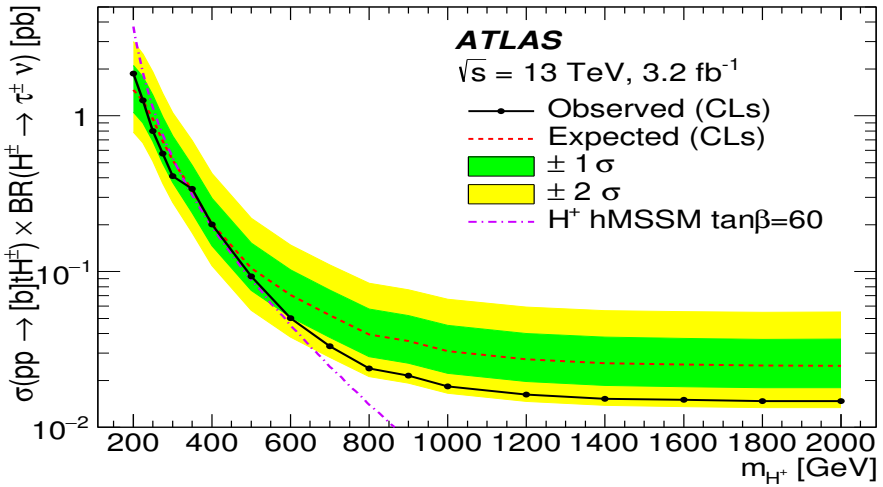
[ATLAS:arXiv:1603.09203]

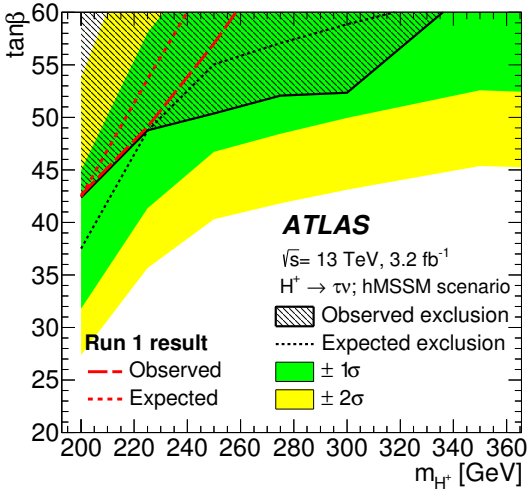
Final state: $(t \to jjb)b\tau_{\text{had}}\nu$

$\geq 3j$, $\geq 1b$, τ_{had}, ℓ veto,
$E_{\text{T}}^{\text{miss}} > 150$ GeV, $m_T > 50$ GeV
Discriminant: $m_T(\tau_{\text{had}}, E_{\text{T}}^{\text{miss}})$

W/Z: shape from MC, norm. to data
Multijet: From data
e,μ faking τ: MC, validated with data







$H/A \to \tau\tau$

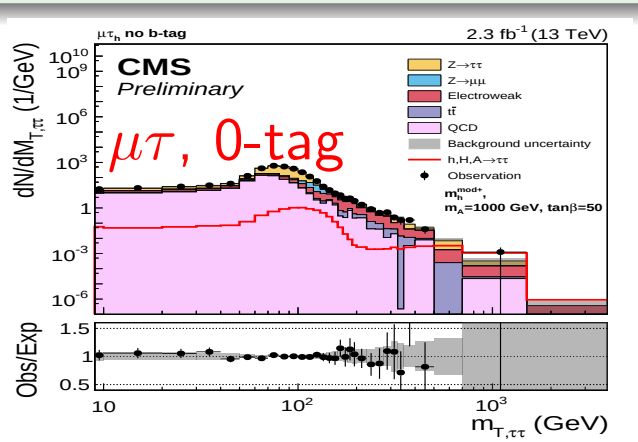
[CMS-PAS-HIG-16-006]

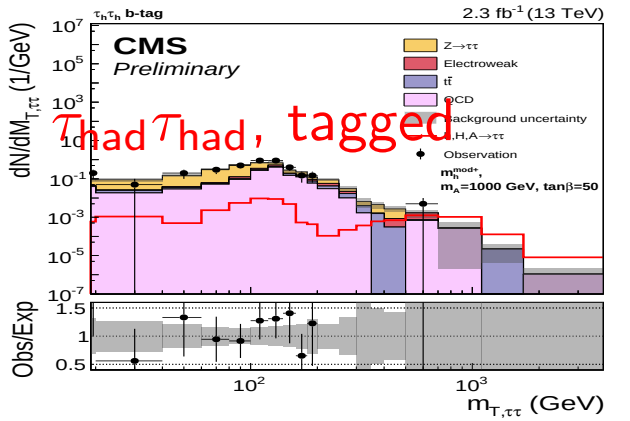
Selection

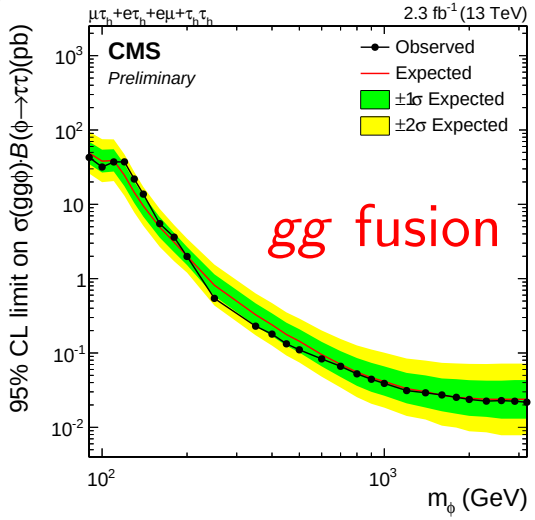
Channels: $\tau_e\tau_{\text{had}}$, $\tau_\mu\tau_{\text{had}}$, $\tau_e\tau_\mu$, $\tau_{\text{had}}\tau_{\text{had}}$.
Candidates are OS and well-separated in ΔR.
$\tau_e\tau_{\text{had}}$, $\tau_\mu\tau_{\text{had}}$: No OS ee or $\mu\mu$ pairs.
$m_T(\ell, E_T^{\text{miss}}) < 40$ GeV $(e) < 30$ GeV (μ).
Topological $t\bar{t}$ rejection in $\tau_e\tau_\mu$.
Categorize: 0-tag, ≥ 1 tag.

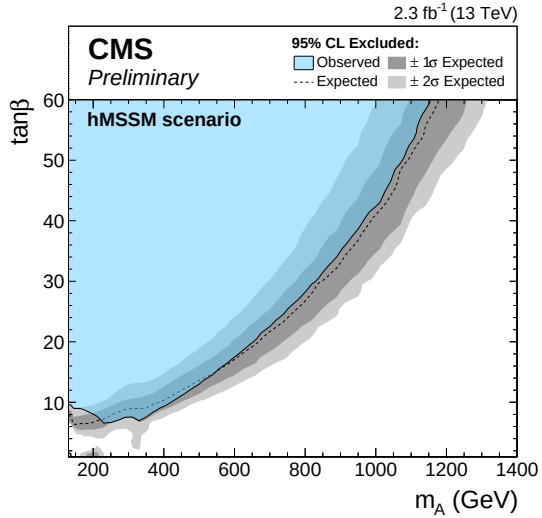
Backgrounds

$Z \to \tau\tau$: MC, cross-checked w/ $Z \to \mu\mu$.
W + jets, multijet: From SS and high-m_T control regions.
$t\bar{t}$: From MC, cross checked in data CRs.









Also results from associated b production and other MSSM benchmarks.

$H/A \to \tau\tau$

[forthcoming pub.]
[ATLAS-CONF-2015-061]

Selection

Either OS $\tau_\ell\tau_{\text{had}}$ (w/$Z \to \ell\ell$ veto) or $\tau_{\text{had}}\tau_{\text{had}}$.
Select on $\Delta\phi$ and $m_T(\tau, \tau_{\text{had},\ell})$.
b-veto (0 tag) and tagged (≥ 1 tag) categories.
Use m_T^{tot} as discriminant.

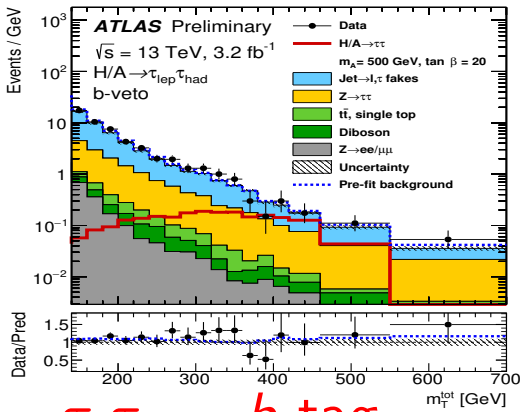
$$(m_T^{\text{tot}})^2 = m_T^2(E_{\text{T}}^{\text{miss}}, \tau_1) + m_T^2(E_{\text{T}}^{\text{miss}}, \tau_2) + m_T^2(\tau_1, \tau_2)$$

Backgrounds

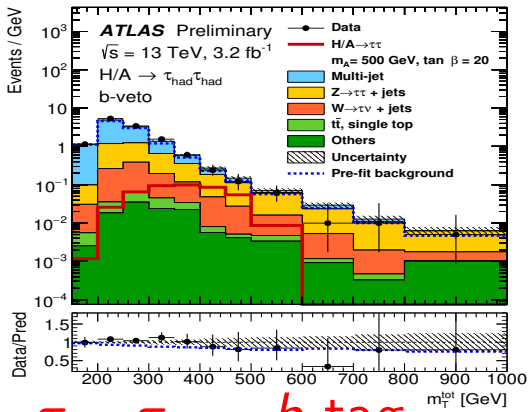
$\tau_\ell\tau_{\text{had}}$: BG w/ true τ/ℓ from MC; misidentified τ/ℓ from fake-factor method.

$\tau_{\text{had}}\tau_{\text{had}}$: Multijet BG from fake-factor method; other BGs from MC with fake factors applied.

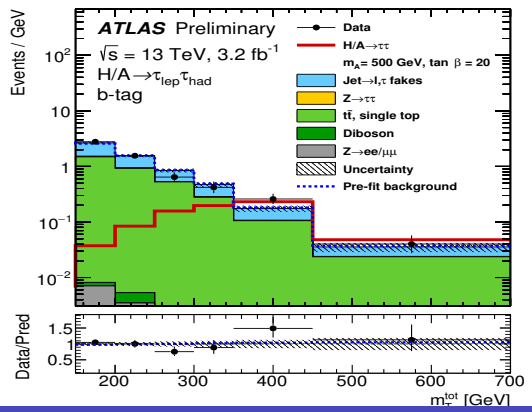
$\tau_\ell\tau_{\text{had}}$, b-veto



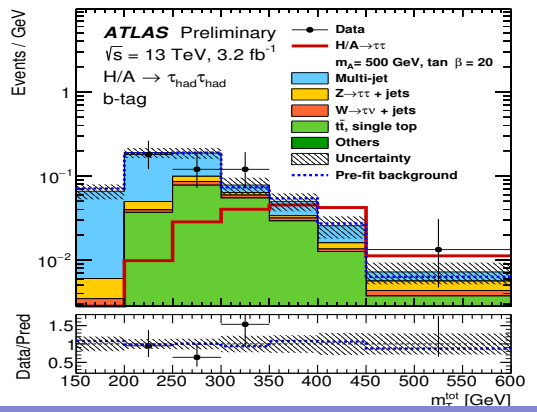
$\tau_{\text{had}}\tau_{\text{had}}$, b-veto

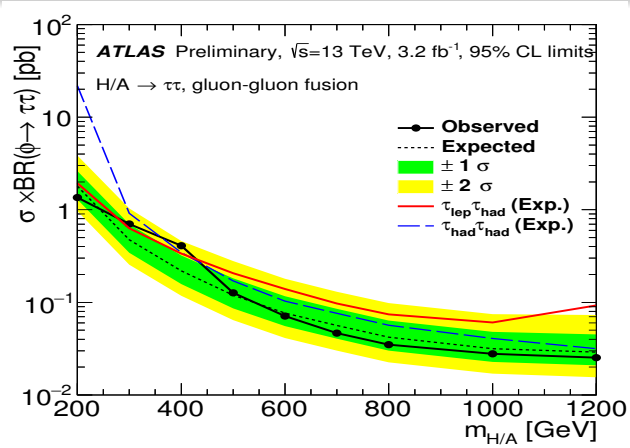


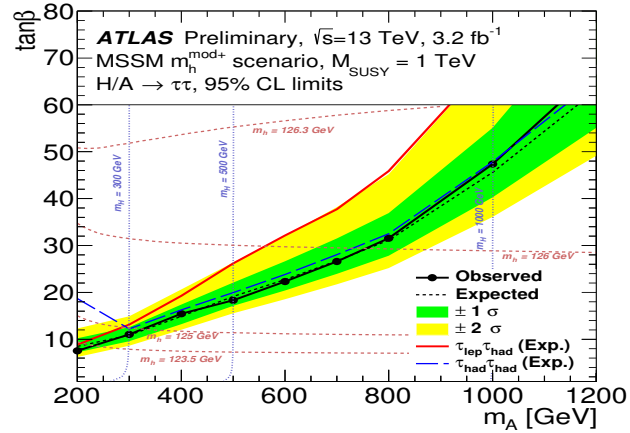
$\tau_\ell\tau_{\text{had}}$, b-tag



$\tau_{\text{had}}\tau_{\text{had}}$, b-tag







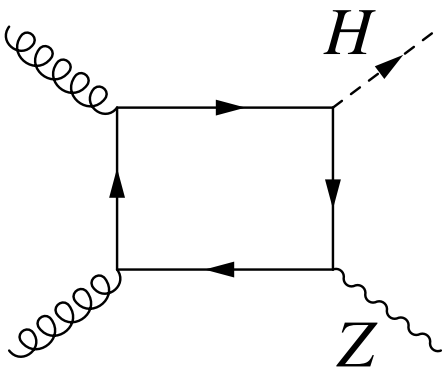
Also associated b production.

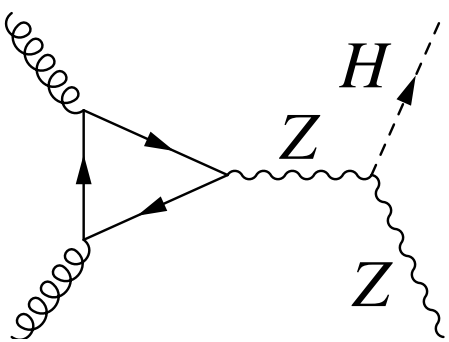
Invisible Higgs decays

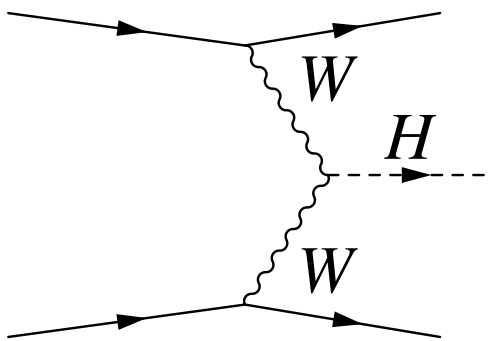
Invisible decays of scalars is a feature of models with SUSY (LSP) or large extra dimensions (graviscalar).

Search for invisibly-decaying heavy scalar.

Tag production of scalar by associated production with Z or by vector boson fusion.







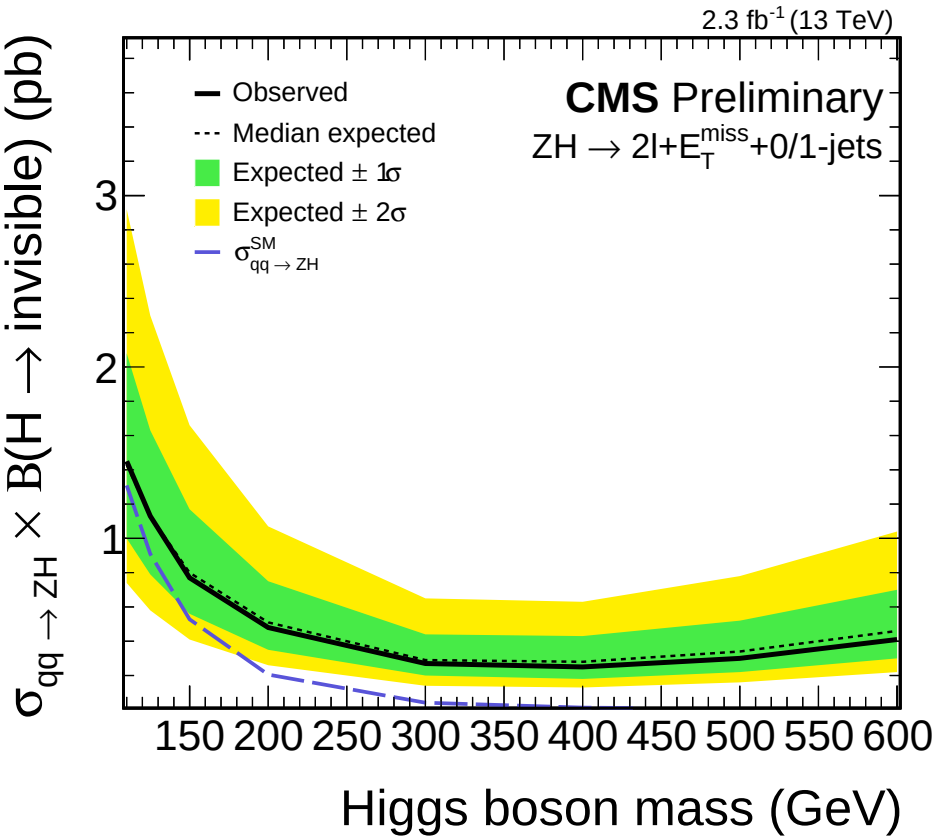
$ZH \to \ell\ell +$ invisible

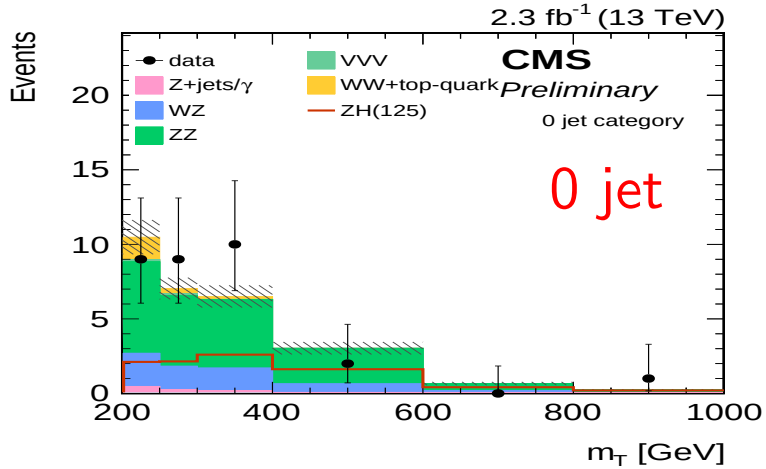
[CMS-PAS-HIG-16-008]

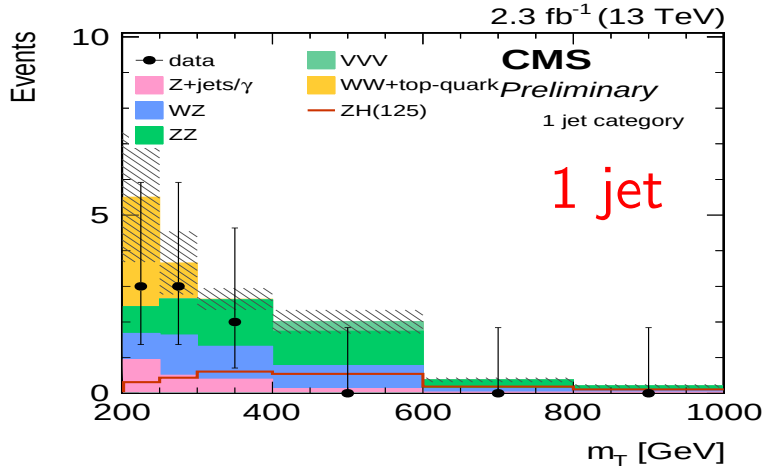
Assume H decays *exclusively* to invisible (LSP, etc). Require $Z \to \ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$.

$Z \to \ell\ell$ w/$p_T^Z > 60$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV, veto leptons, hard jets, b-tags.
Requirements on $\Delta\phi$ and $E_{\mathrm{T}}^{\mathrm{miss}}/p_T^Z$ balance.
0/1-jet bins.

$Z +$ jets: From $\gamma +$ jets
Others: Different-flavor leptons.







$H \to$ invisible [VBF]

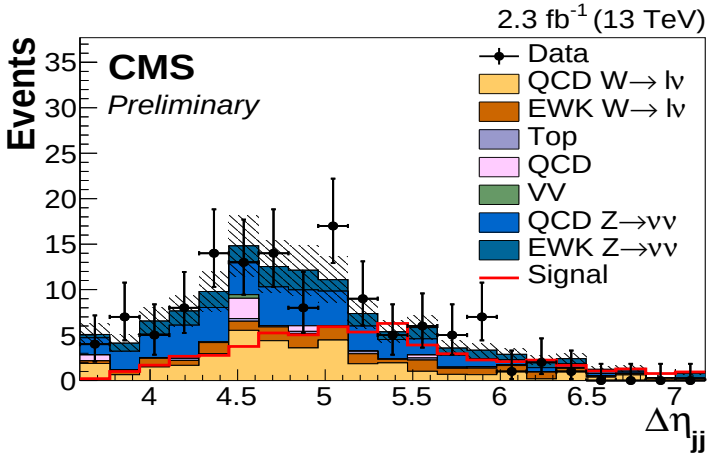
[CMS-PAS-HIG-16-009]

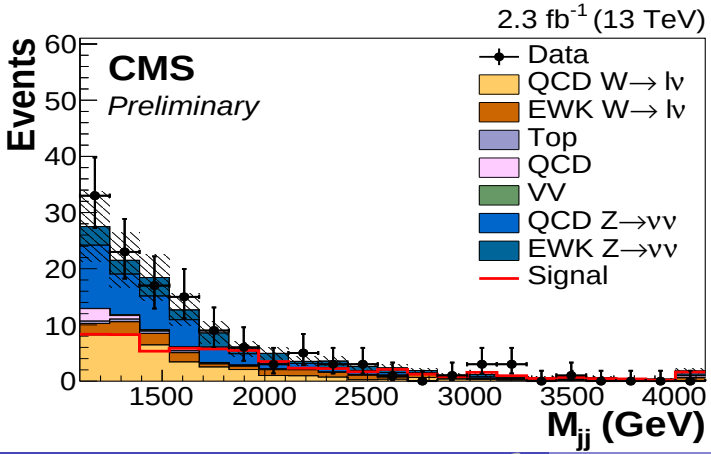
Assume H decays *exclusively* to invisible (LSP, etc). Require VBF jet pair $+E_{\mathrm{T}}^{\mathrm{miss}}$.

$2j$, $\Delta\eta_{jj} > 3.6$, $m_{jj} > 1100$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV, no ℓ,
$\Delta\phi(j, E_{\mathrm{T}}^{\mathrm{miss}}) > 2.3$

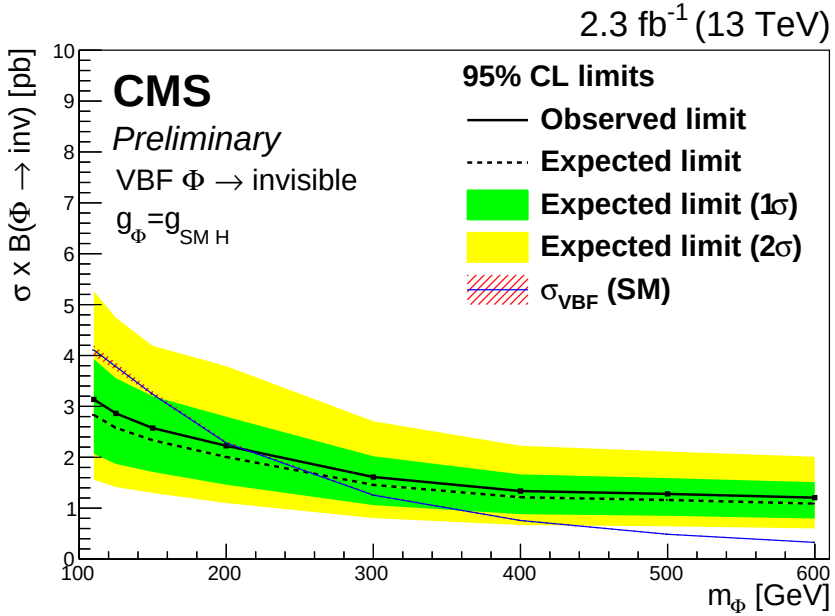
5 control regions

$Z \to \mu\mu$; single-e, μ, or τ;
$\min \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j) < 0.5$



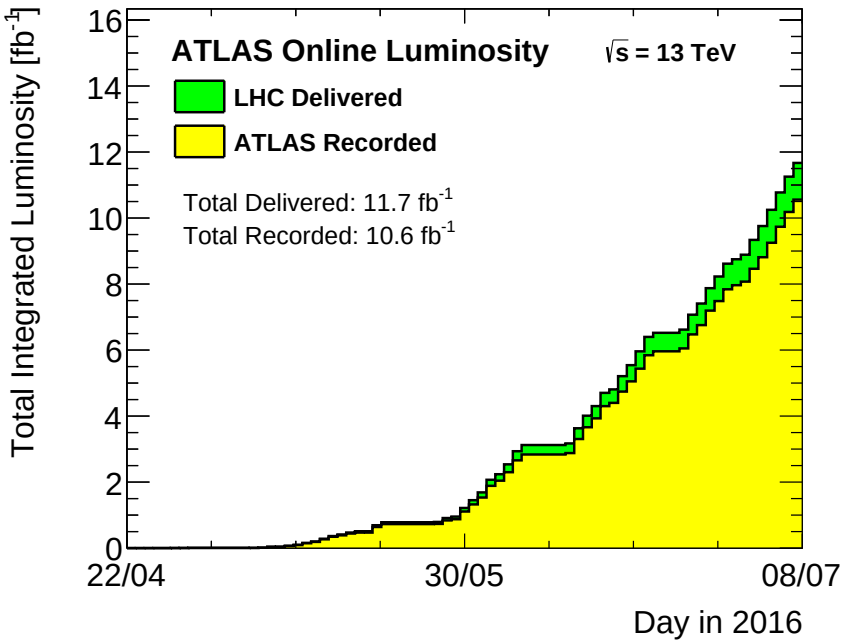


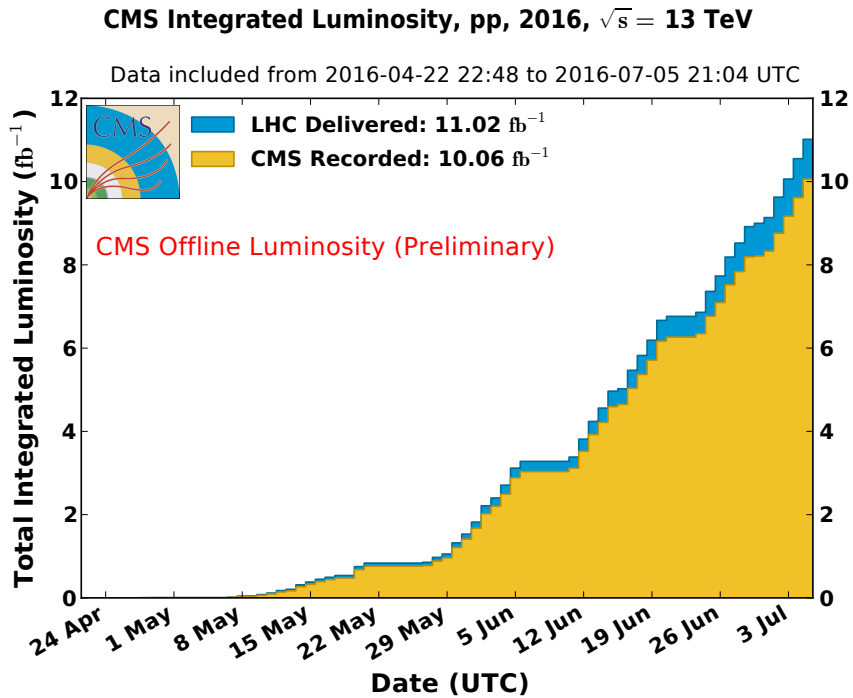
Norm. BG by fitting to CRs; result from counting experiment.



Summary

- Many searches, many channels . . .
  - . . . leave no stone unturned!
- No signal from 2015 data.
- But accumulating more data rapidly.
  - Already have ~ 10 fb^{-1} of data recorded — more than all of 2015!
  - Expect first results from these data at ICHEP.
- Stay tuned!



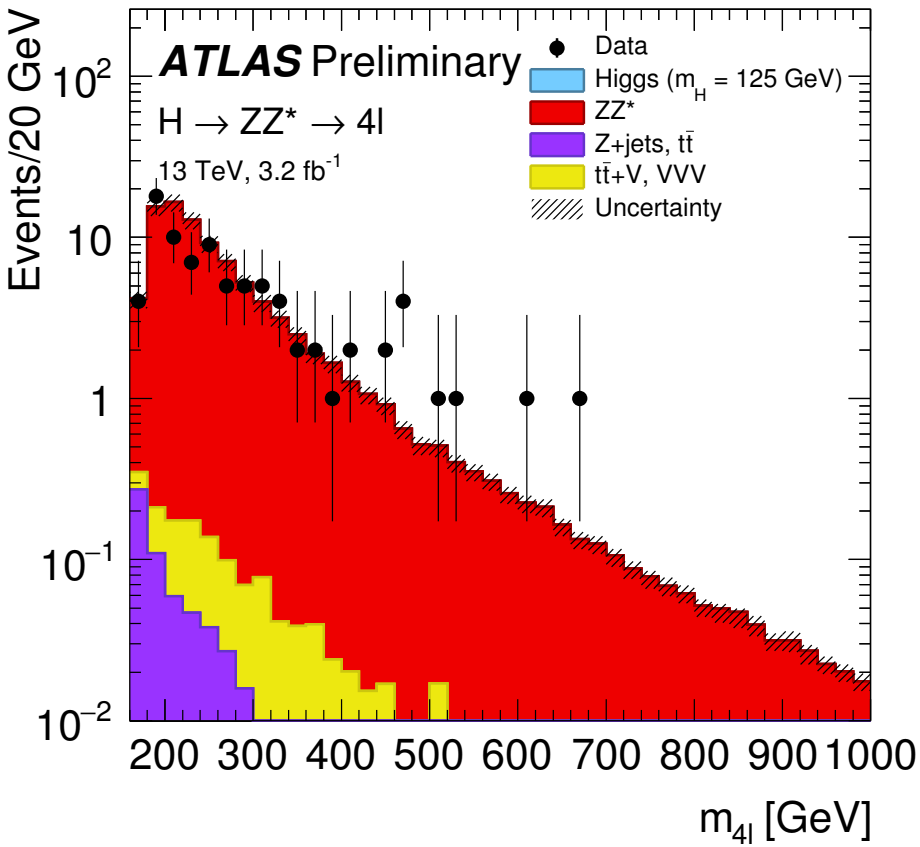


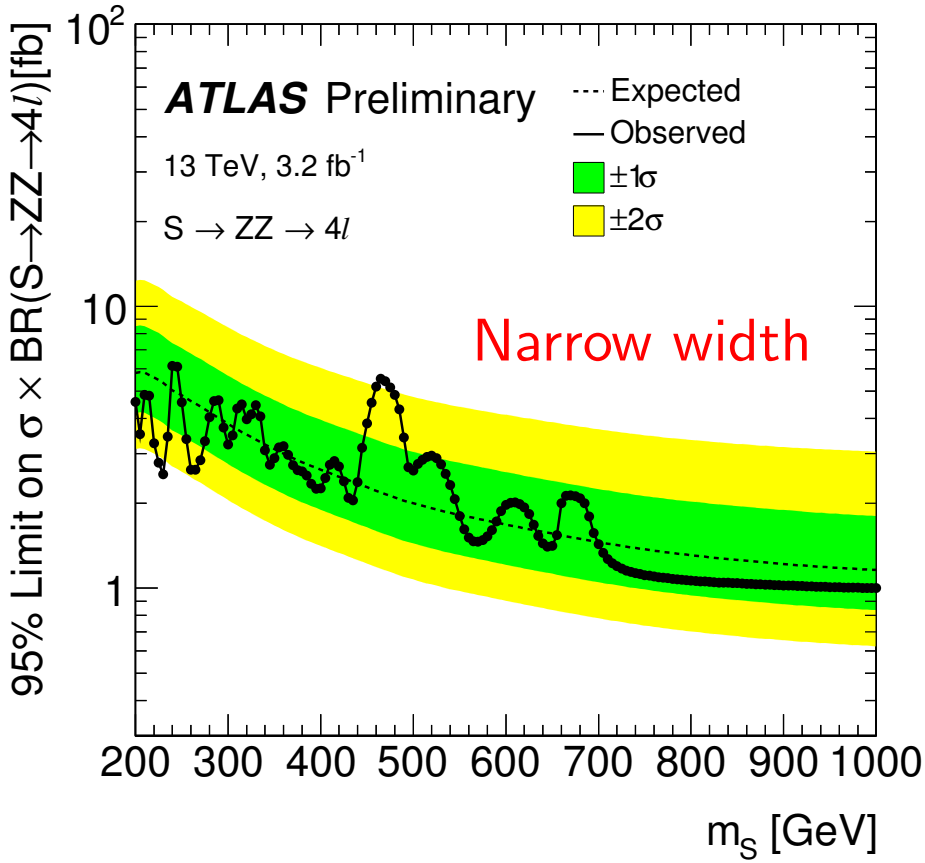
Backup

$H \to ZZ \to 4\ell$

[ATLAS-CONF-2015-059]

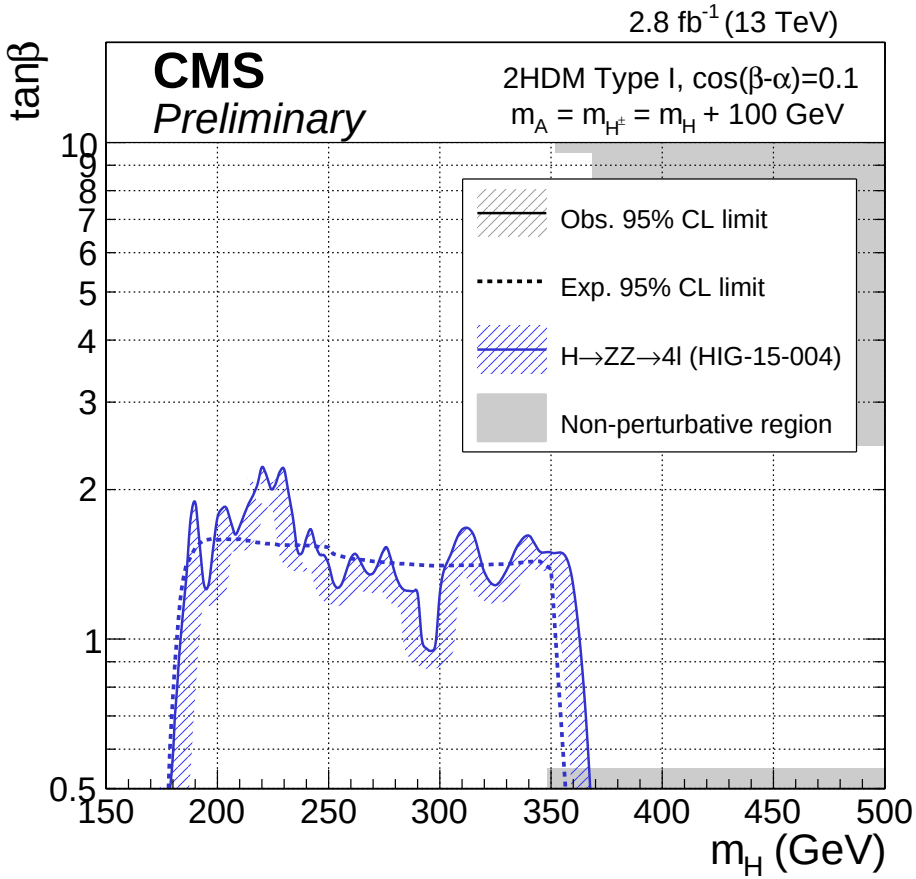
Selection based on $m_h = 125$ GeV analysis

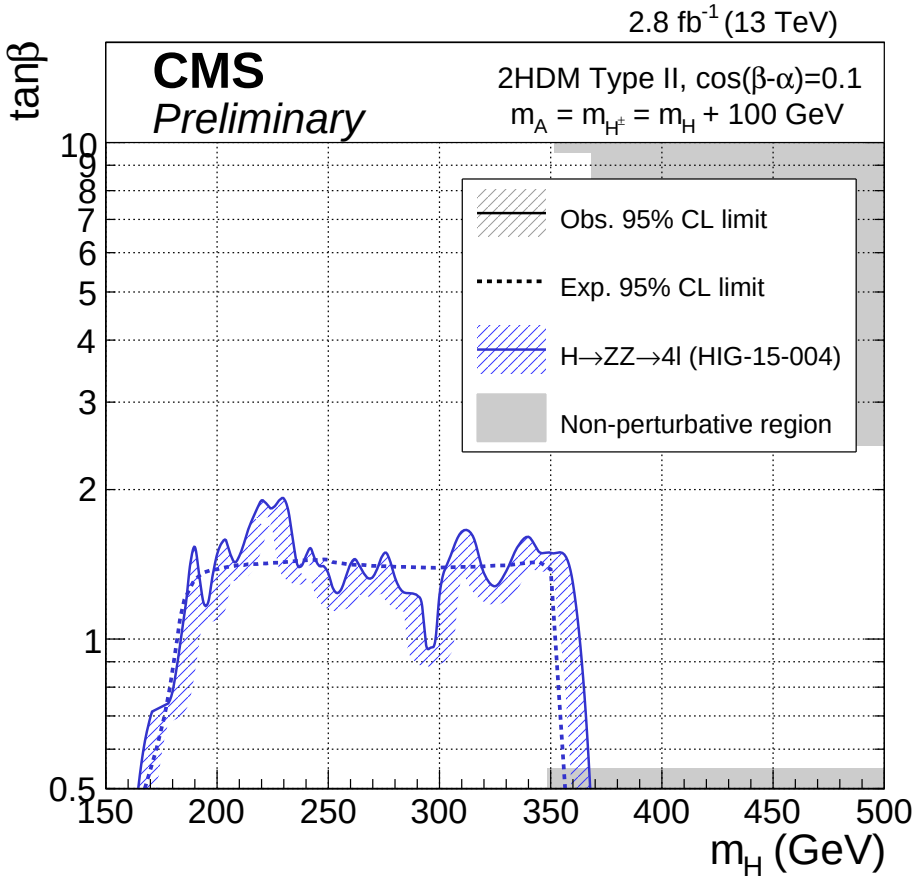




$H \to 4\ell$

[CMS-PAS-HIG-15-004]





$H \to ZZ \to \ell\ell\nu\nu$

[CMS-PAS-HIG-16-001]

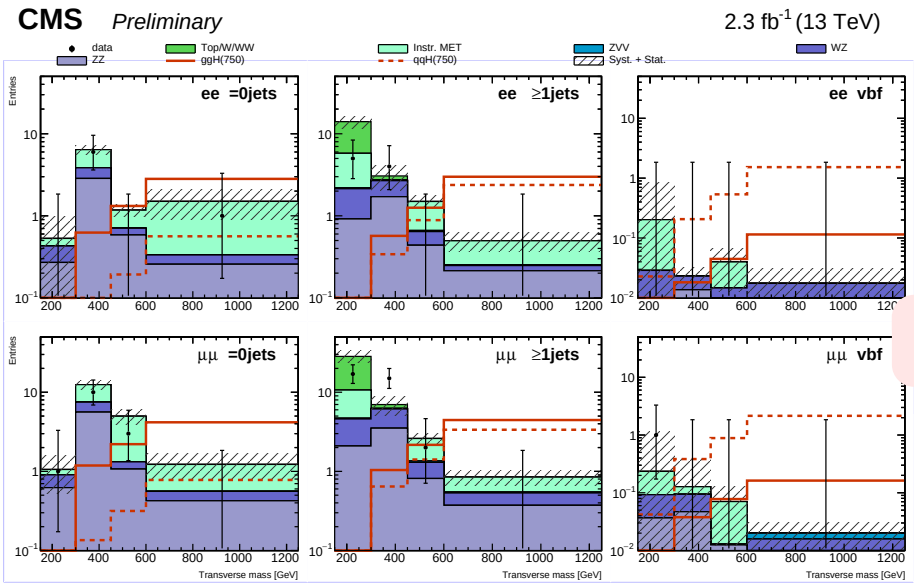
Require $Z \to \ell\ell$, $E_{\mathrm{T}}^{\mathrm{miss}} > 125$ GeV, no b-tags.

3 categories: 0 jet, ≥ 1 jet, and VBF.

(VBF: 0 cent, 2 fwd jets w/$\Delta\eta > 4$, $m_{jj} > 500$ GeV)

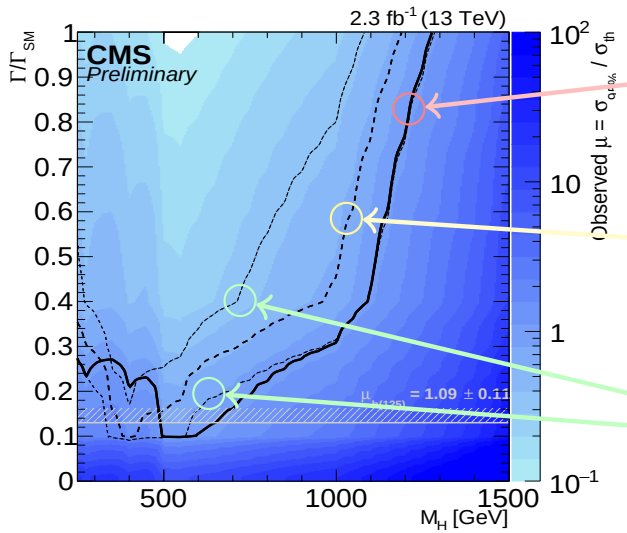
Discriminating variable: $m_T(\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$.

VV BG from MC; Z + jets modelled by $Z + \gamma$.



ATLAS analysis: [ATLAS-CONF-2016-012]

Exclusion of SM-like heavy Higgs as fcn. of m_H and Γ_H. ggF/VBF combined.

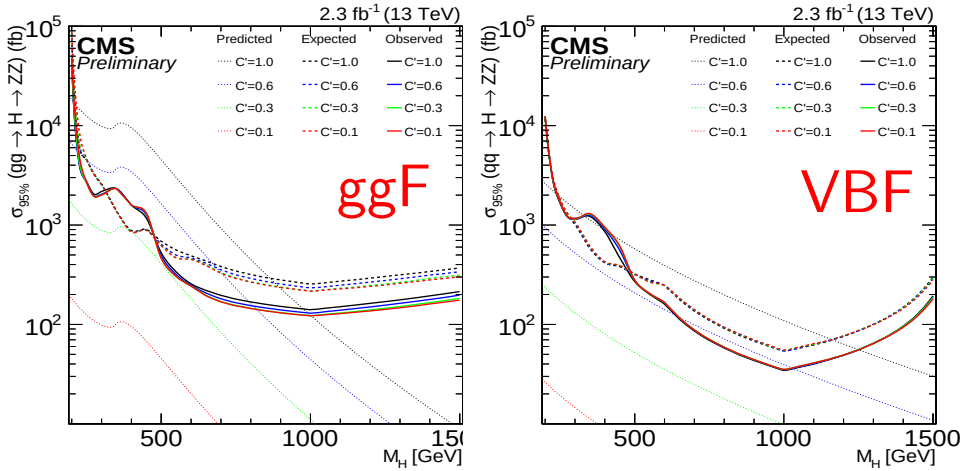


Observed

Expected

$\pm 1\sigma$

Interpret as EWS with mixing parameter C'.

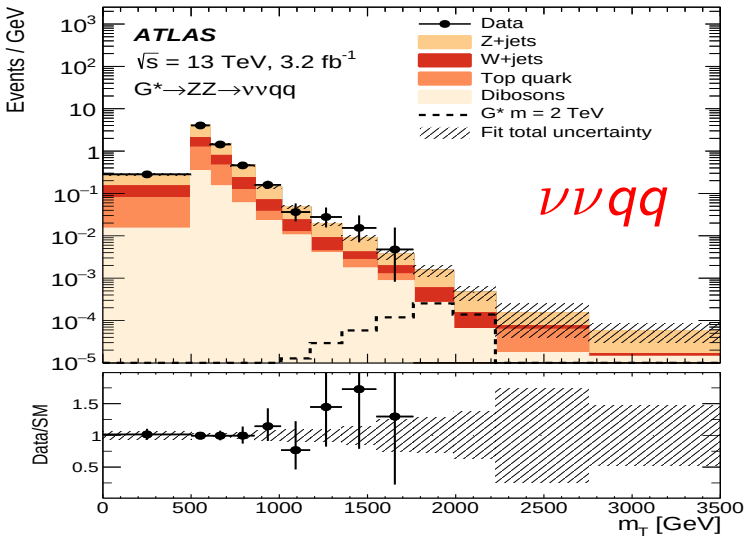


$H \to VV \to XXqq$ (merged)

[arXiv:1606.04833]

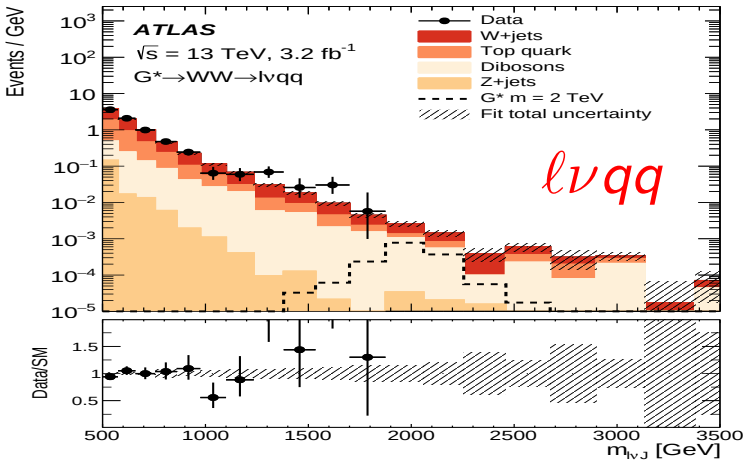
$\nu\nu qq$

No ℓ; $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV; Z-tagged large-R jet
$p_T^{\mathrm{miss}} > 30$ GeV; angular requirements
BG: W/Z + jets, $t\bar{t}$ (shape MC, norm data)



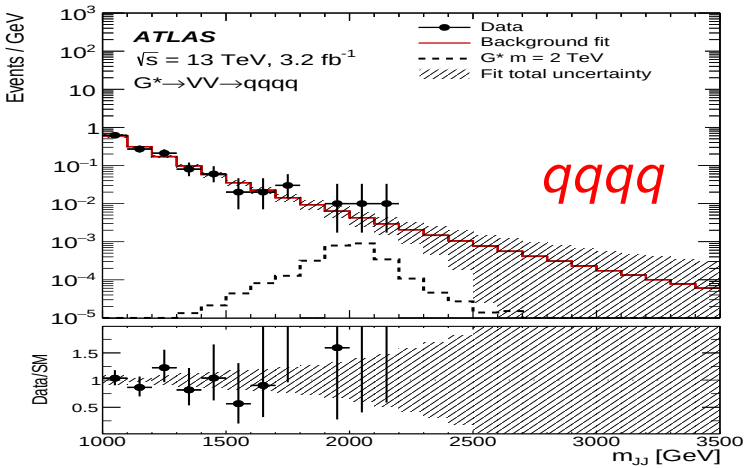
$\ell\nu qq$

1ℓ; $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV; W-tagged large-R jet
$p_{T,J}$ and $p_{T,\ell\nu} > \max(200\ \mathrm{GeV}, 0.4 m_{\ell\nu J})$;
Veto on b-tag close to J
BG: W + jets, $t\bar{t}$ (shape MC, norm data)



$qqqq$

$E_{\mathrm{T}}^{\mathrm{miss}} < 250$ GeV; 2 W/Z-tagged large-R jets
$0\ \ell$; $p_{T,J1/2} > 450/200$ GeV; other topo req.
BG: multijet (analytic fit)

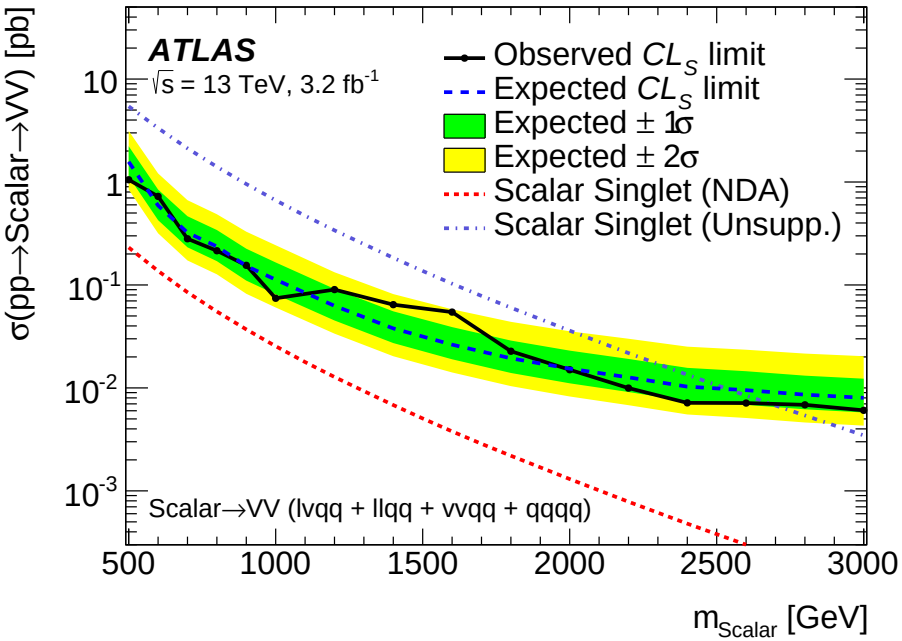


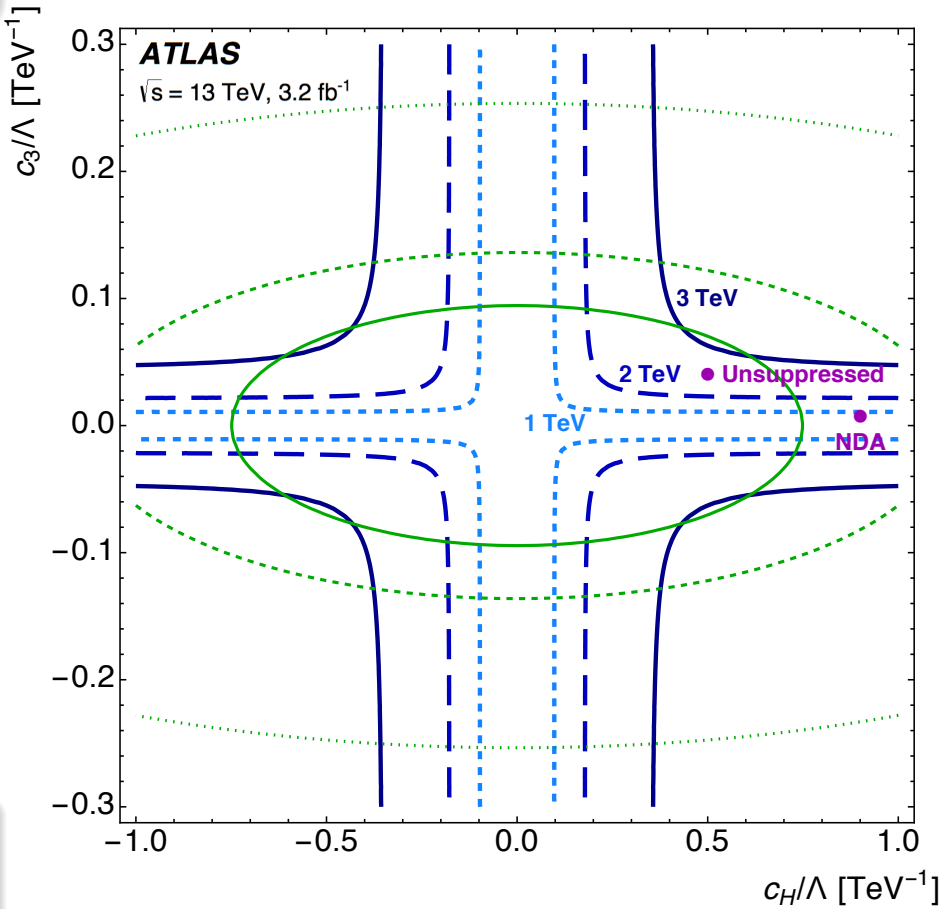
$\ell\ell qq$ similar to previous slide.

$H \to XXqq$ (merged) (2)

[arXiv:1606.04833]

Set combined exclusion limit for narrow scalar resonance to VV.





Interpret as new heavy neutral scalar:

- Λ: energy scale
- c_H: Coupling to SM Higgs.
- c_3: Coupling to gluons.

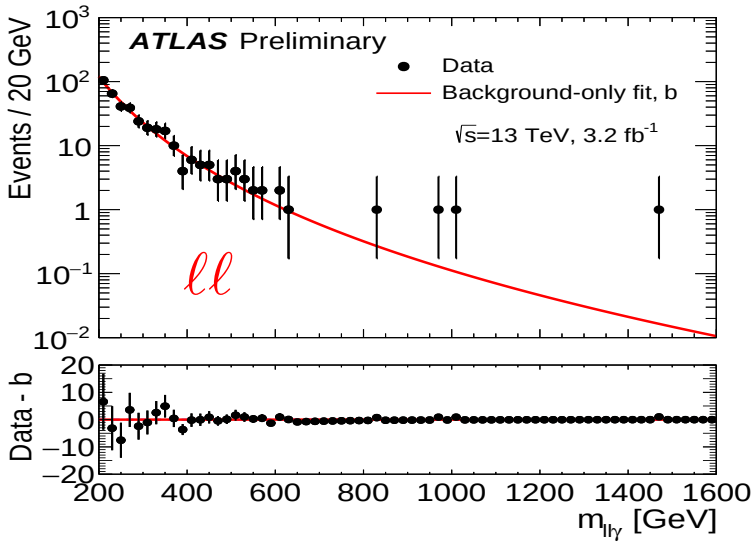
Use naive dimensional analysis (NDA) and unsuppressed benchmarks

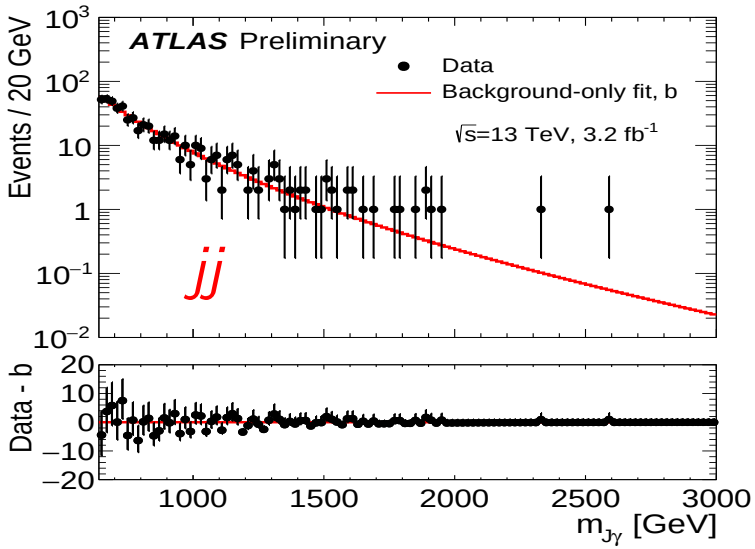
$H \to Z\gamma$

[ATLAS-CONF-2016-010]

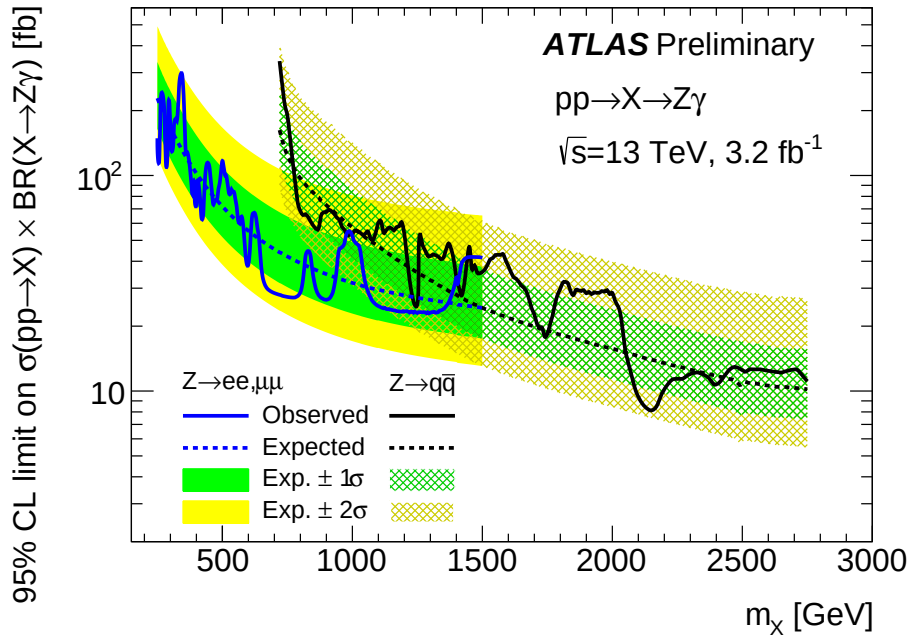
$Z \to ee, \mu\mu + \gamma$ Also $Z \to jj$ using large-R jets ($p_T^\gamma > 250$ GeV)

Plot $m(Z\gamma)$; fit background outside signal region with an analytic function.





Limits for narrow signal width.



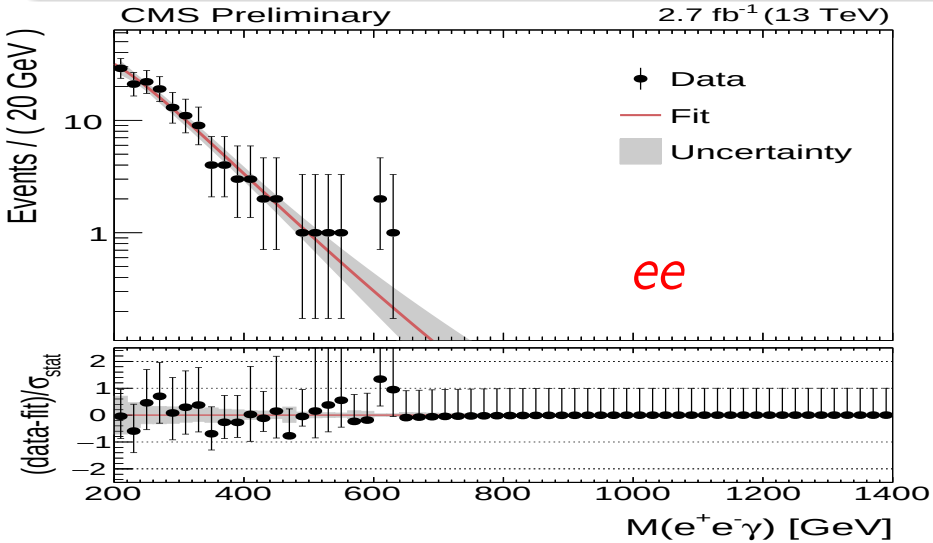
CMS analysis: [CMS-PAS-EXO-16-019]

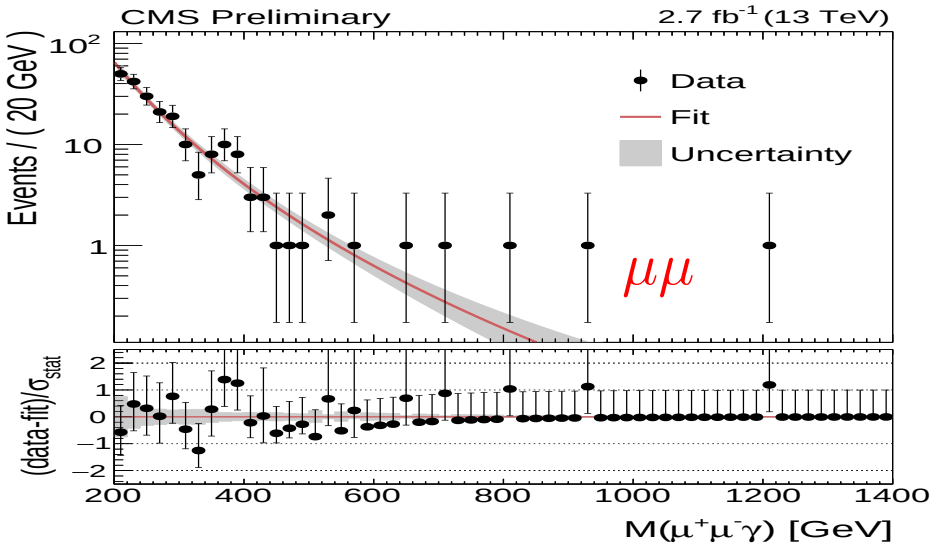
$H \to Z\gamma$

[CMS-PAS-EXO-16-019]

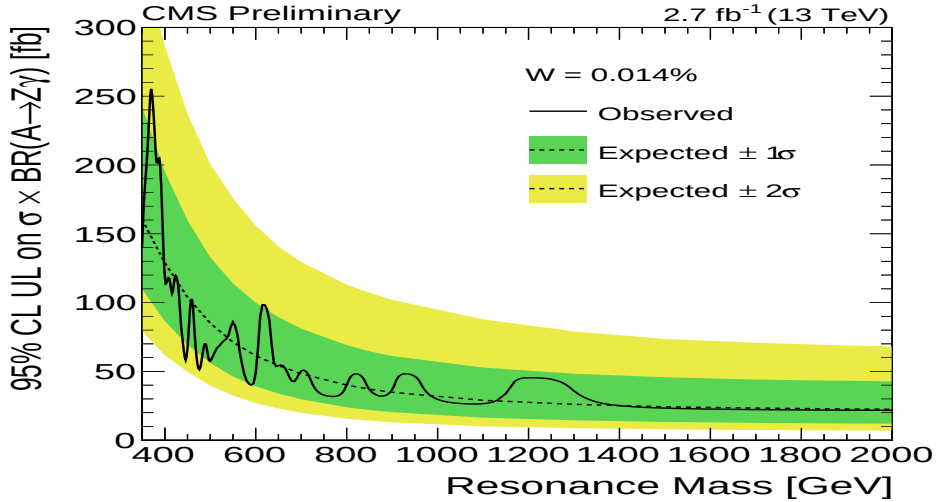
$Z \to ee, \mu\mu + \gamma$

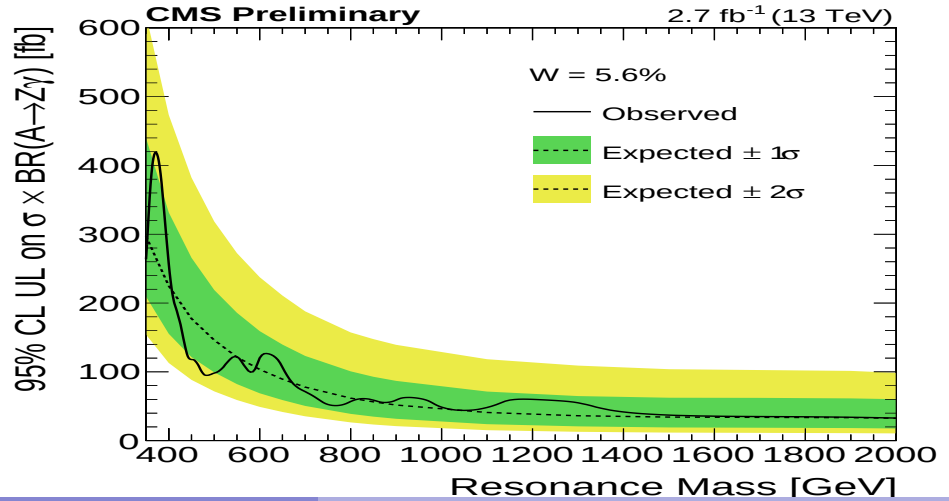
Plot $m(Z\gamma)$; fit background outside signal region with an analytic function.





Limits for two signal widths.





$H \to hh \to bb\tau\tau$

[CMS-PAS-HIG-16-013]

3 channels: $\tau_e\tau_{\text{had}}$, $\tau_\mu\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$.

Selection

2 OS τ's; 2 b-tagged jets

$80 < m_{\tau\tau}, m_{bb} < 160$ GeV

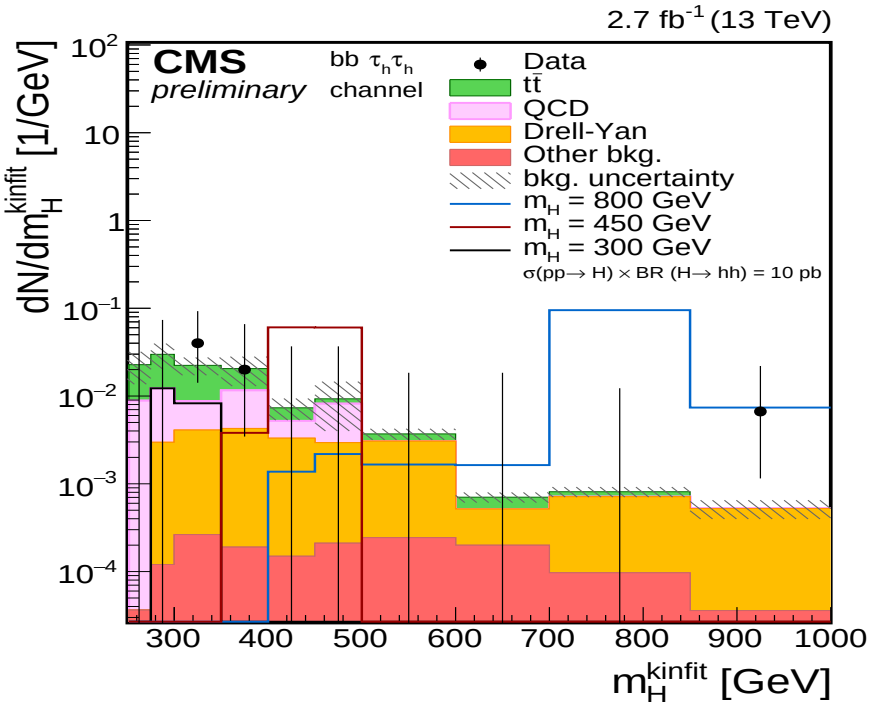
Backgrounds

Z + jets: MC shape, normalized to $\mu\mu$ data

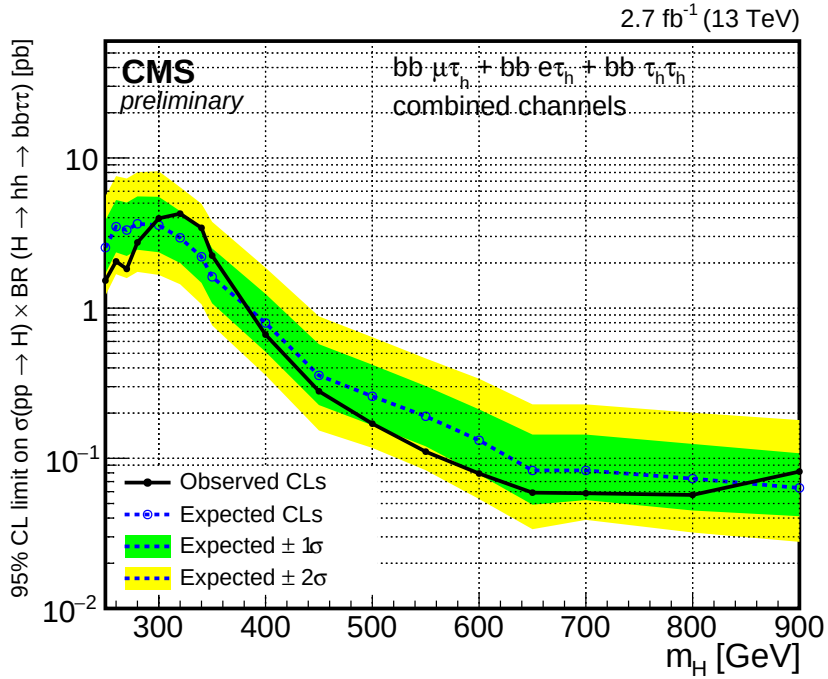
Multijet: From SS data

$t\bar{t}$ + other: MC

Discriminant is $m_{\tau\tau bb}$; found from a kinematic fit.



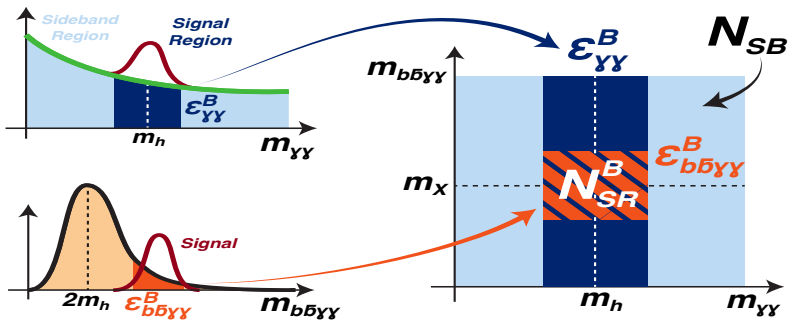
Signal model: Narrow CP-even resonance decaying to hh



$\tau_{\text{had}}\tau_{\text{had}}$ more sensitive at lower m_H.

$H \to hh \to bb\gamma\gamma$

[ATLAS-CONF-2016-004]



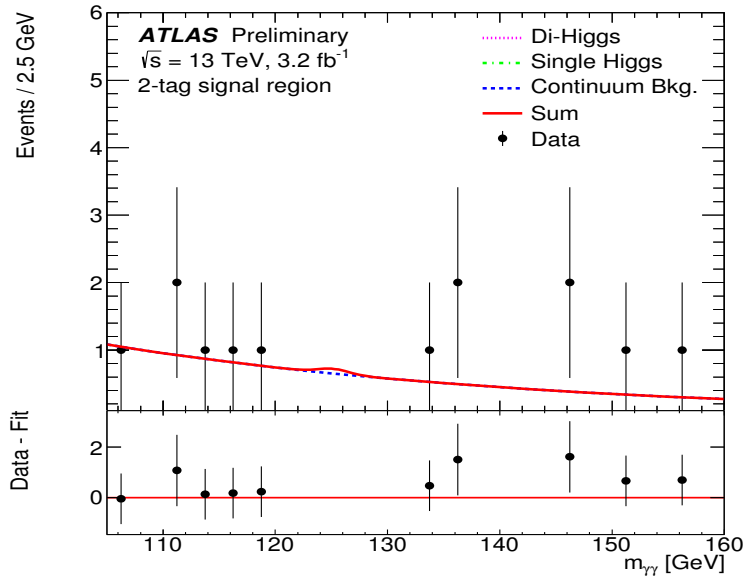
Selection

2 γ; exactly 2 b-tagged jets

$|m_{\gamma\gamma} - m_h|/2 < \sigma(m_{\gamma\gamma})$ [1.55 GeV]

$95 < m_{bb} < 135$ GeV

Final window cut in $m_{\gamma\gamma bb}$ around each hypothesized mass keeping 95% of signal (width 20–50 GeV).

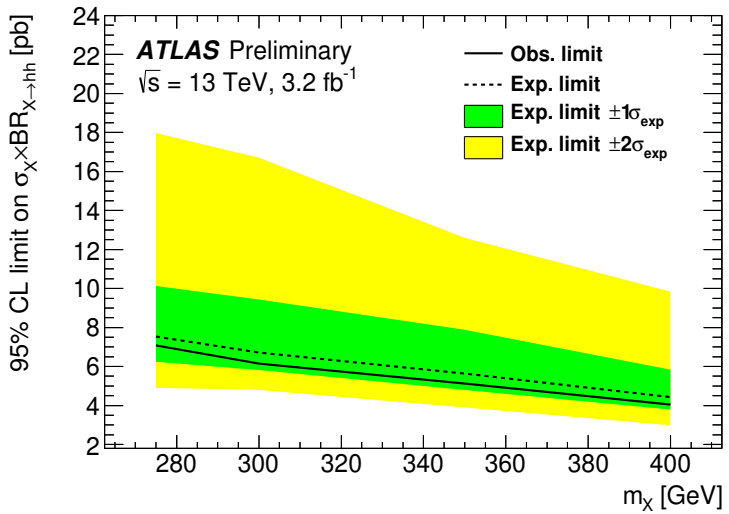


Non-resonant search not covered here.

Backgrounds

From data using sidebands in $m_{\gamma\gamma}$ and $m_{\gamma\gamma bb}$.

Extrapolation to signal region derived from 0-tag sample.



$H \to hh \to \ell\nu\ell\nu bb$

[CMS-PAS-HIG-16-011]

Selection

2 OS leptons; 2 b-tagged jets

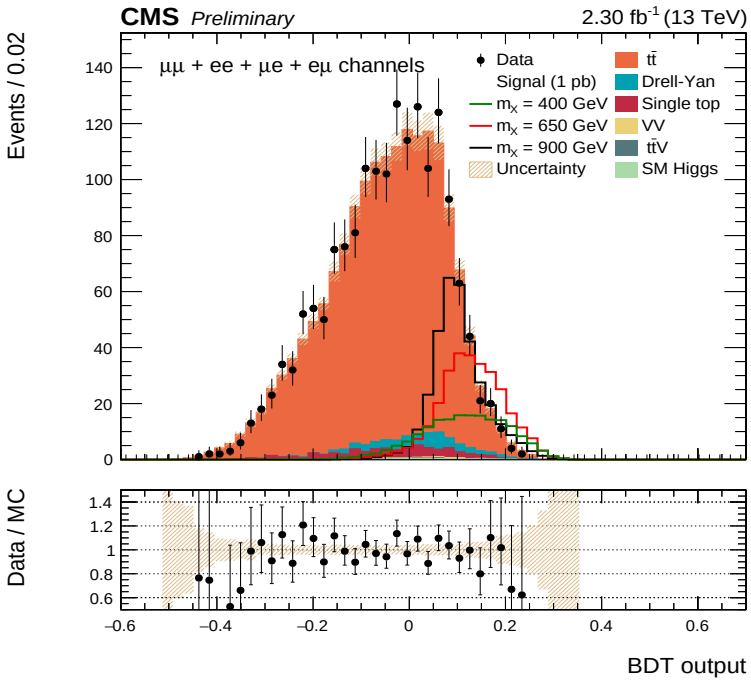
BDT trained at $m_H = 400$ GeV (for $m < 450$ GeV) or $m_H = 650$ GeV.

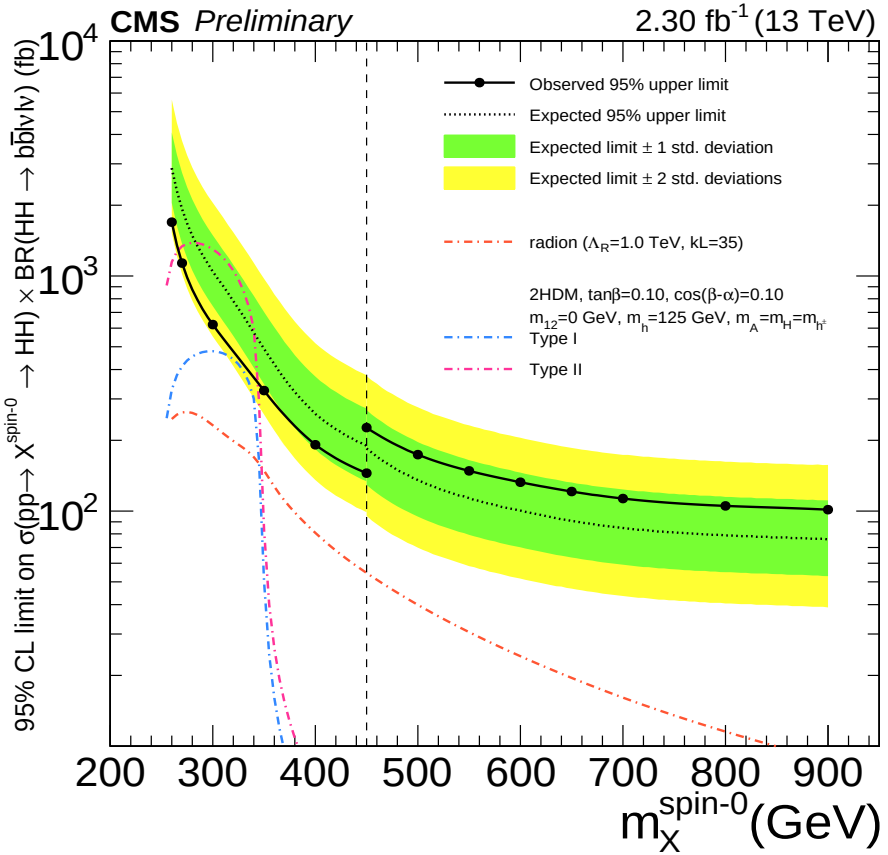
BDT variables

$m_{\ell\ell}$, $\Delta R_{\ell\ell}$, ΔR_{jj}, $\Delta\phi_{\ell\ell,jj}$, $p_T{}^{\ell\ell}$, $p_T{}^{jj}$, $\min \Delta R_{\ell,j}$, M_T

Backgrounds

Fit BDT output to signal+bkg model in 4 bins: signal region plus BDT/m_{jj} sidebands.



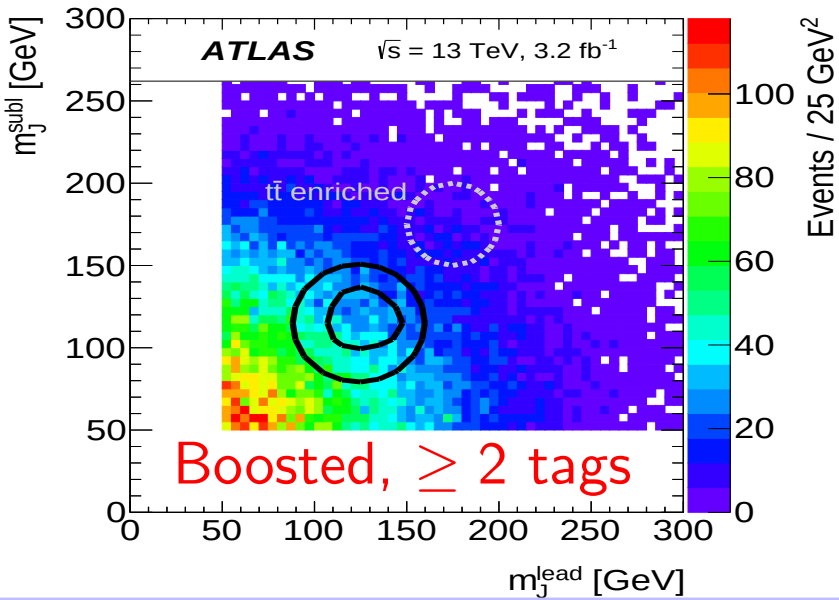


$H \to hh \to bbbb$

[arXiv:1606.04782]

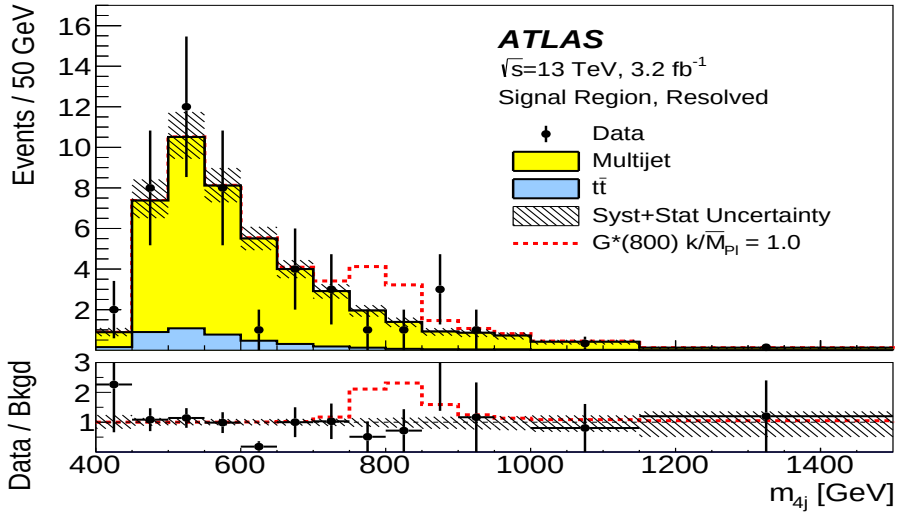
Resolved: 4 b-tagged small-R jets
Boosted: 2 large-R jets w/3 or 4 associated b-tagged track jets
$t\bar{t}$ veto
Mass-dependent requirements on p_T of jet pairs/large-R jets.

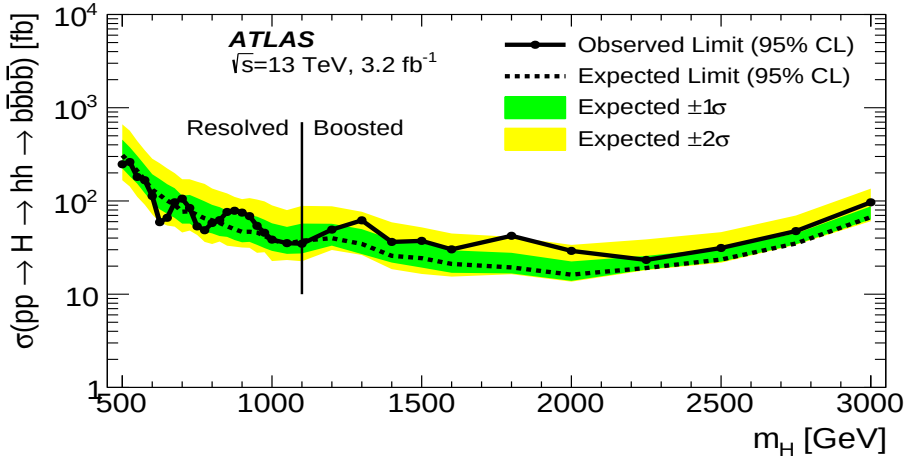
$$\sqrt{\left(\frac{m_{h1}-124\text{GeV}}{0.1m_{h1}}\right)^2+\left(\frac{m_{h2}-124\text{GeV}}{0.1m_{h2}}\right)^2} < 1.6$$



Non-resonant search not covered here.

Multijet: Norm. 2-tag data to 4-tag CR
$t\bar{t}$: Normalize MC to CR





CMS analysis: [CMS-PAS-HIG-16-002]

$H \to hh \to bbbb$

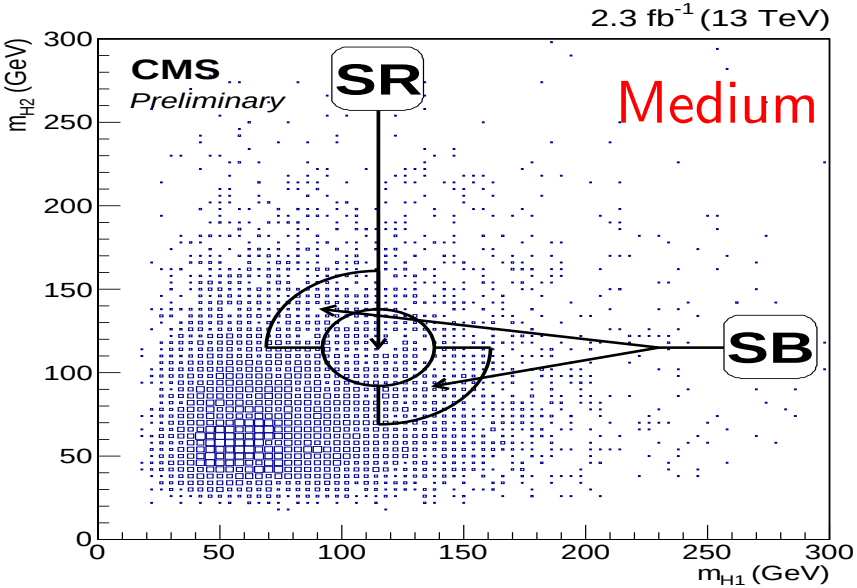
[CMS-PAS-HIG-16-002]

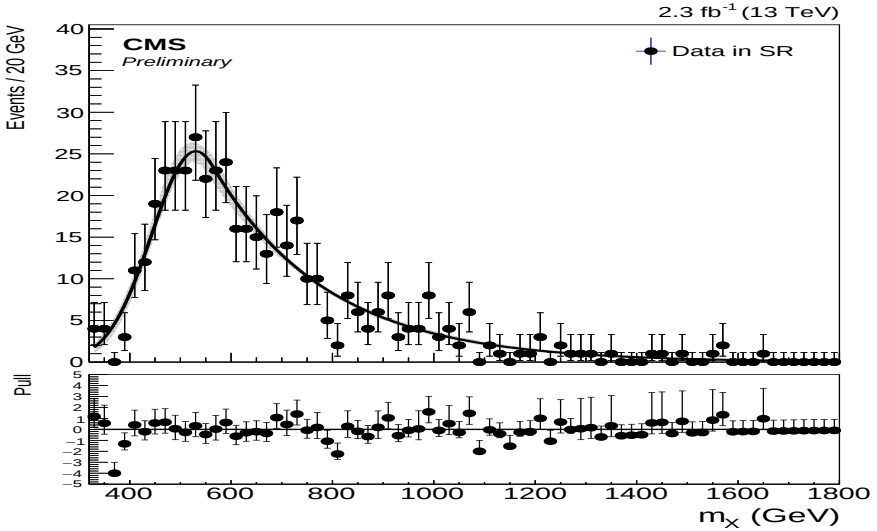
4 b-tagged small-R jets
Low mass (260–400 GeV):
$\sigma_h = 17$ GeV
High mass (400–1200 GeV):
$\sigma_h = 23$ GeV

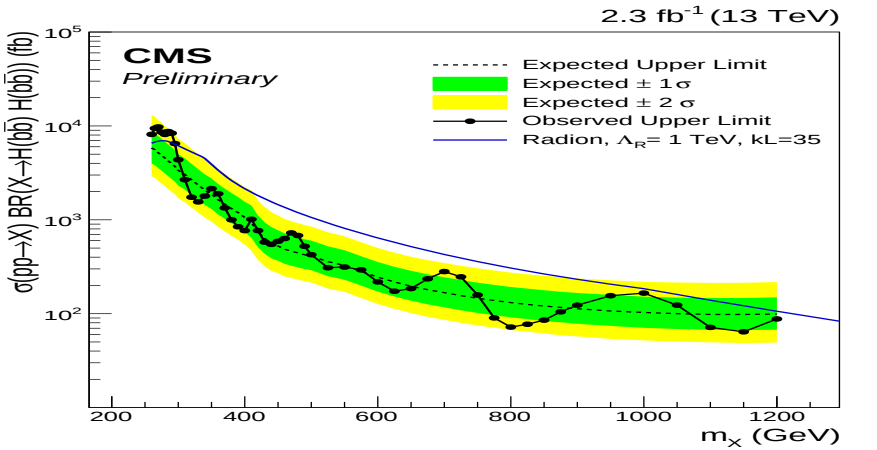
$$\sqrt{\left(\frac{m_{h1}-115\text{GeV}}{\sigma_h}\right)^2 + \left(\frac{m_{h2}-115\text{GeV}}{\sigma_h}\right)^2} < 1$$

Backgrounds

Fit curve to m_{bbbb} from sideband regions.



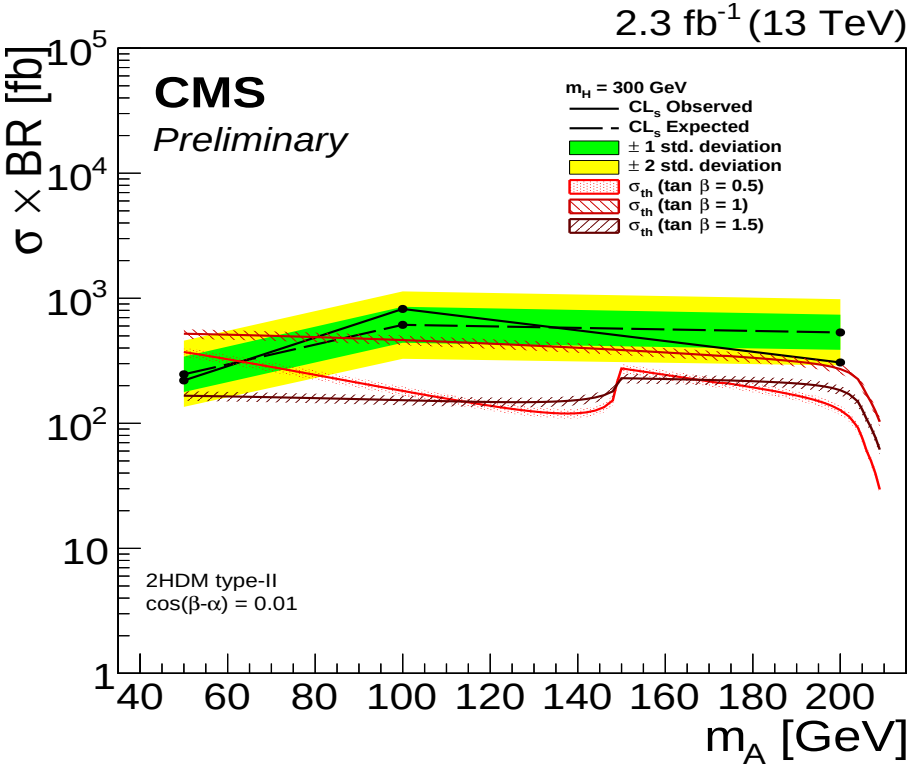




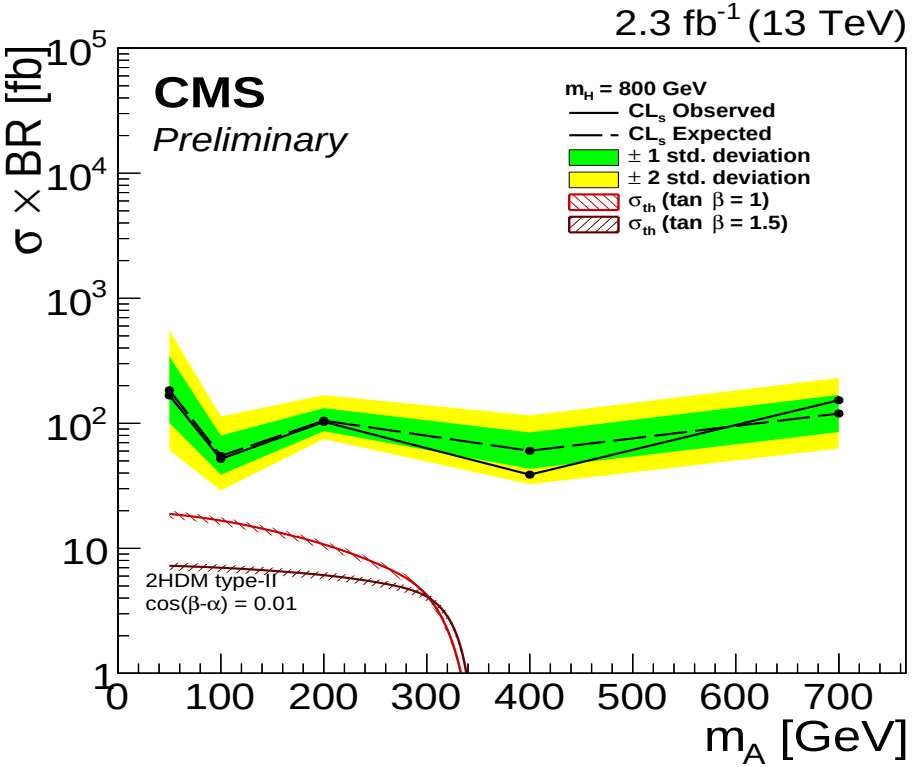
$H \to ZA \to \ell\ell bb$

[CMS-PAS-HIG-16-010]

$m_H = 300$ GeV



$m_H = 800$ GeV



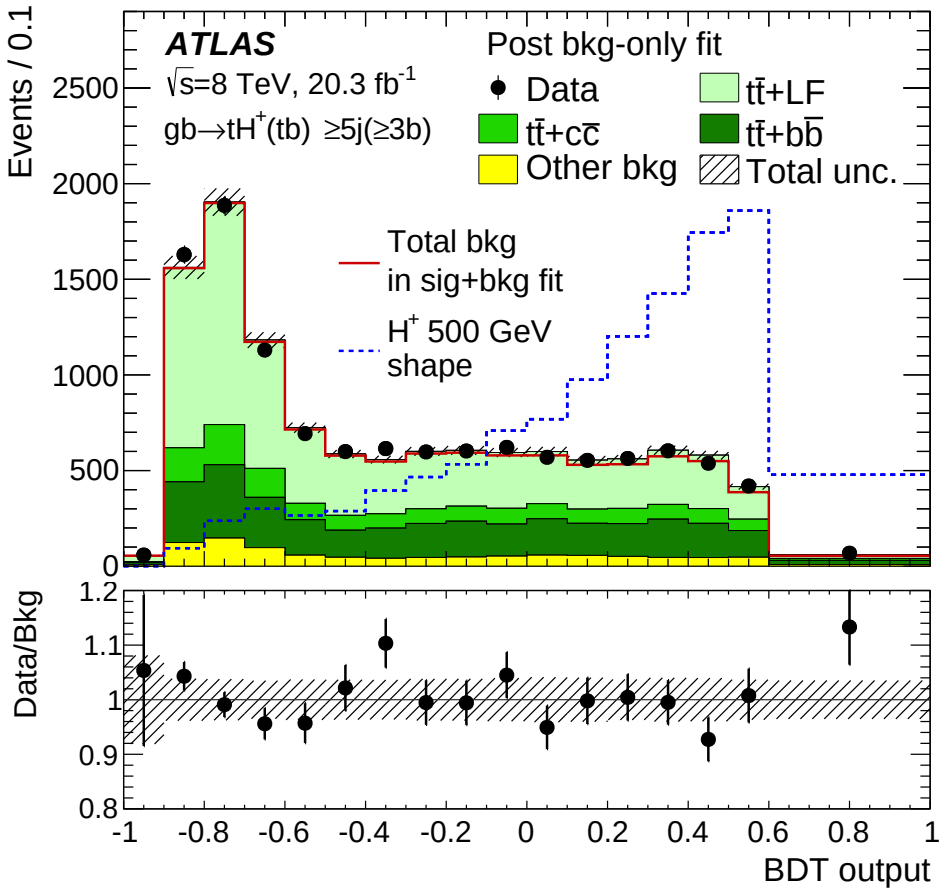
$H^+ \to tb$ [8 TeV]

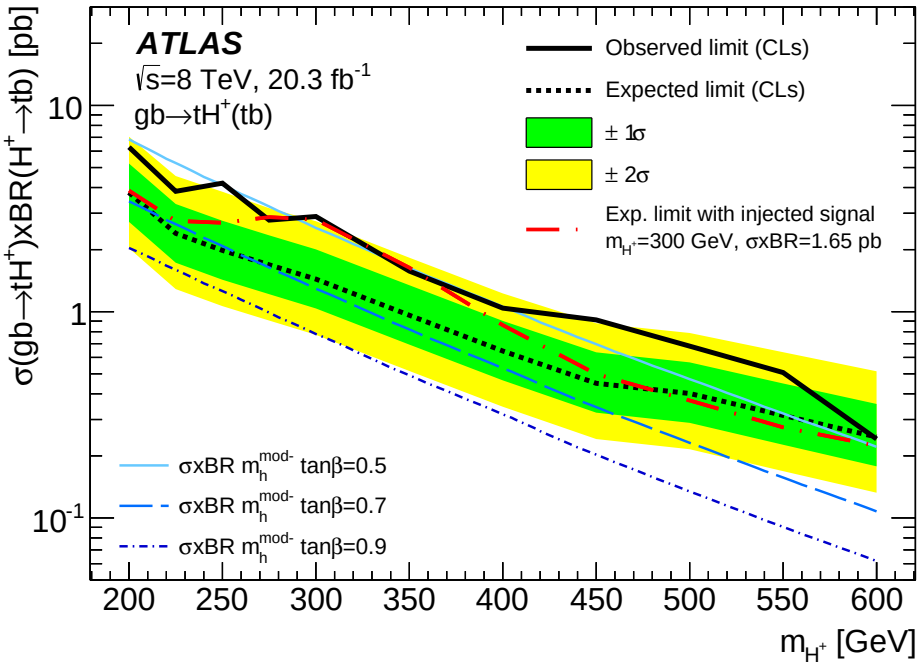
[arXiv:1512.03704]

Search for $t\bar{t} \to \ell +$ jets plus ≥ 1 additional b.
Fit data to 4 CR and one SR:
$5j(2b)$, $4j(\geq 3b)$, $4j(2b)$, $\geq 6j(2b) \to H_T$
$\geq 5j(\geq 3b) \to$ BDT

BDT incl. $p_T(j_1)$, H_T, m_{bb}, $\Delta R(bb)$, 2^{nd} Fox-Wolfram mom.

BG: $t\bar{t}$: MC + data-based p_T-reweight; multijet from data; others from MC.





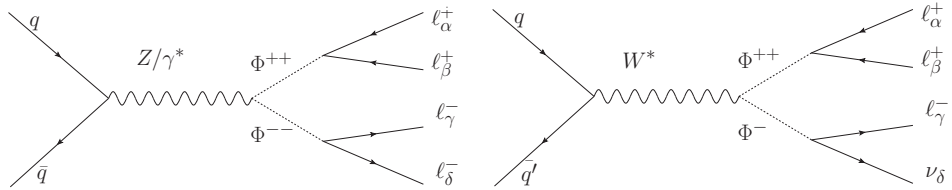
$\Phi^{++} \to \ell^+\ell^+$ [7 TeV]

[arXiv:1207.2666]

Type-II seesaw model for generating neutrino masses includes a scalar triplet with physical particles Φ^{++}, Φ^{+}, Φ^{0}.

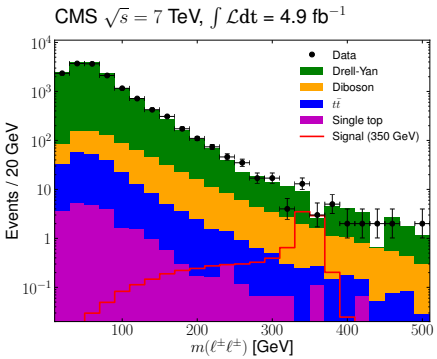
Produced as either $Z/\gamma \to \Phi^{++}\Phi^{--}$ or $W^{+} \to \Phi^{++}\Phi^{-}$.

Primary decay $\Phi^{++} \to \ell^+\ell^+$ (decay to W^+W^+ suppressed for realistic neutrino masses).

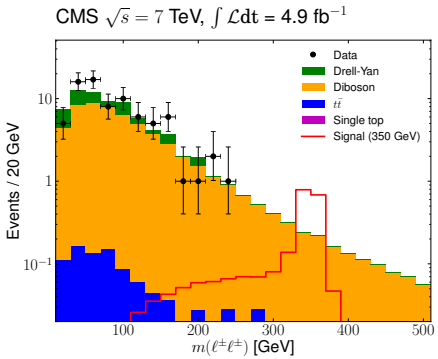


Search in categories $\ell\ell\ell$, $\ell\ell\tau_{\text{had}}$, $\ell\ell\ell\ell$, $\ell\ell\ell\tau_{\text{had}}$, $\ell\ell\tau_{\text{had}}\tau_{\text{had}}$ ($\ell \equiv e, \mu$, flavors may be mixed in a category).

Plot mass of same-sign lepton pairs.



3-lep

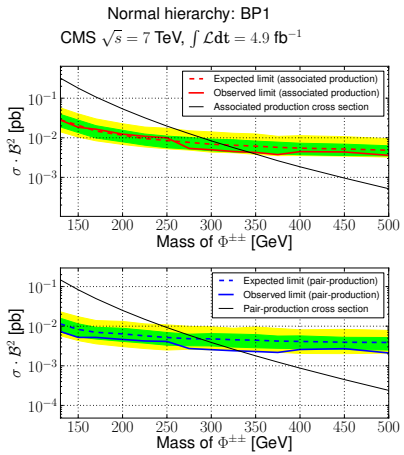


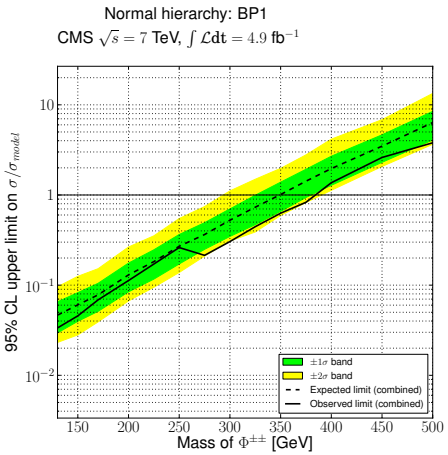
4-lep

Interpret in terms of benchmark points of type-II seesaw model.

BP1: Neutrino sector with a massless neutrino and normal mass hierarchy.

Other benchmark points in paper.





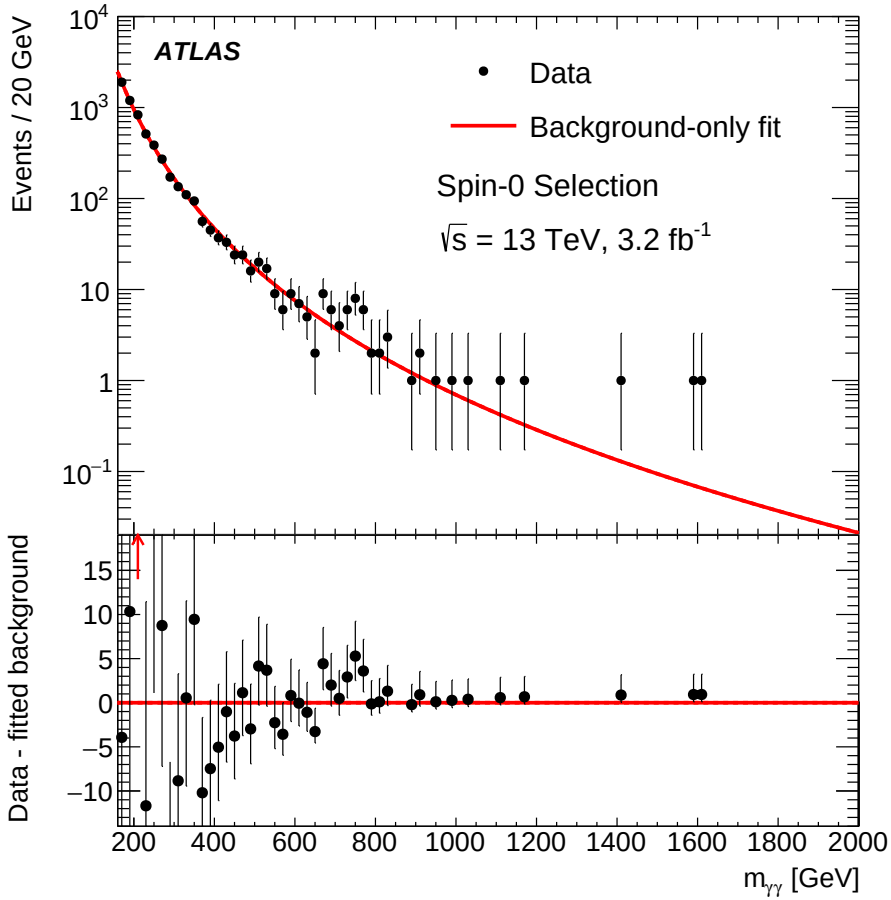
95% CL: $m(\Phi^{++}) > 383$ GeV (BP1)

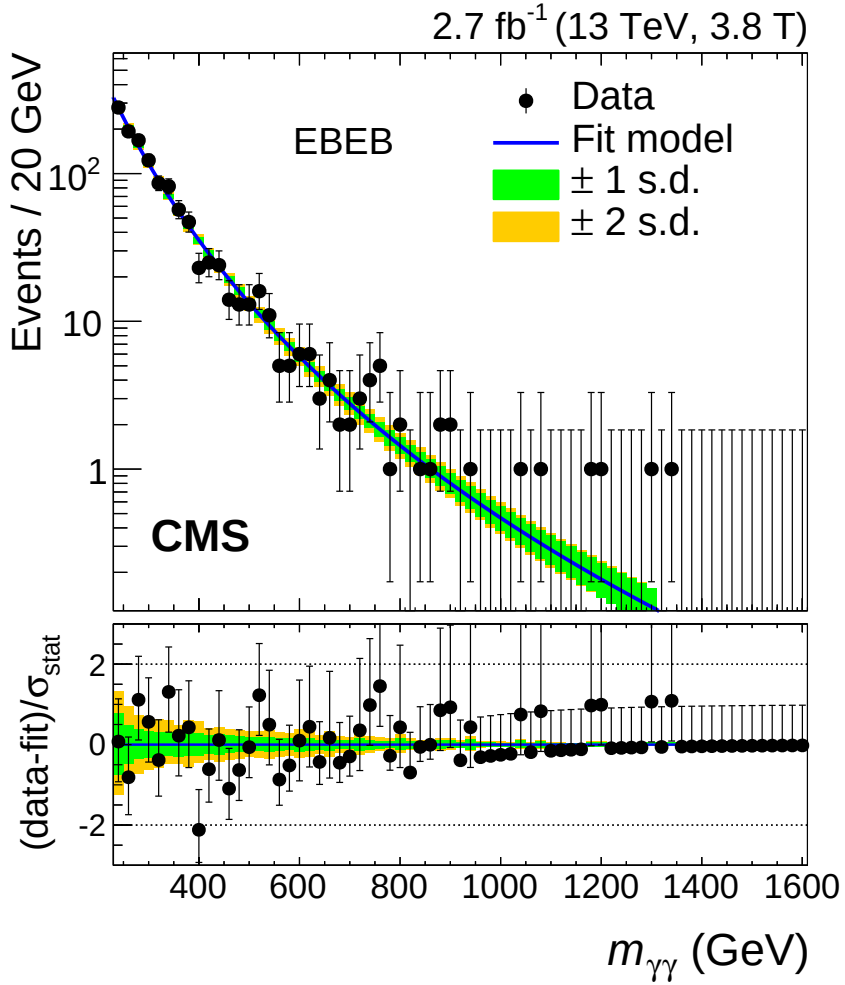
$H \to \gamma\gamma$

[arXiv:1606.03833]
[arXiv:1606.04093]

Select primary vertex using photon pointing and NN discriminant.
$p_T(\gamma) > 55$ GeV; $m_{\gamma\gamma} > 200$ GeV
$p_T(\gamma_1) > 0.4 m_{\gamma\gamma}$; $p_T(\gamma_2) > 0.4 m_{\gamma\gamma}$

$p_T(\gamma) > 75$ GeV
EBEB: Both γ in barrel; $m_{\gamma\gamma} > 230$ GeV
EBEE: 1 barrel γ, 1 endcap γ; $m_{\gamma\gamma} > 330$ GeV
Also categorize on γ shape and B field on/off.

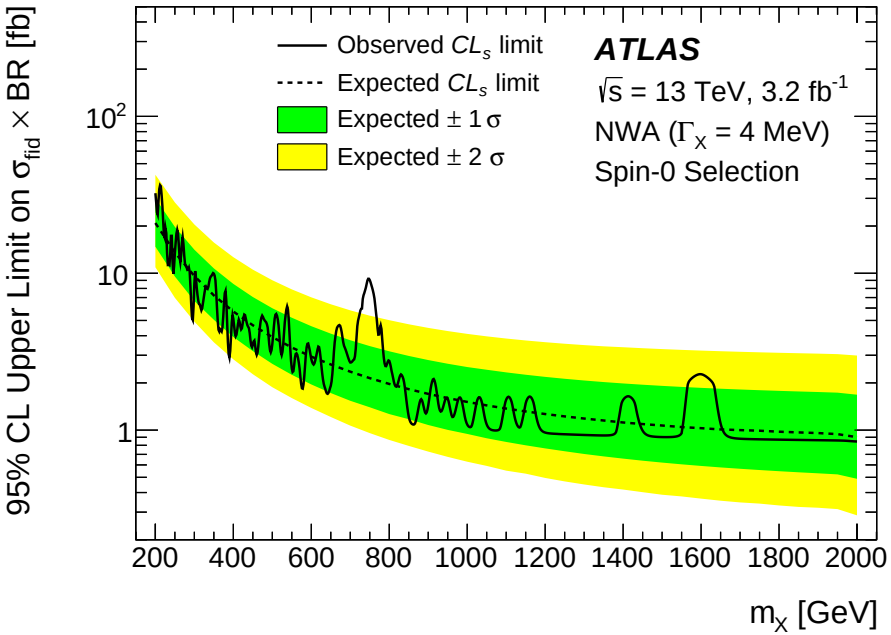




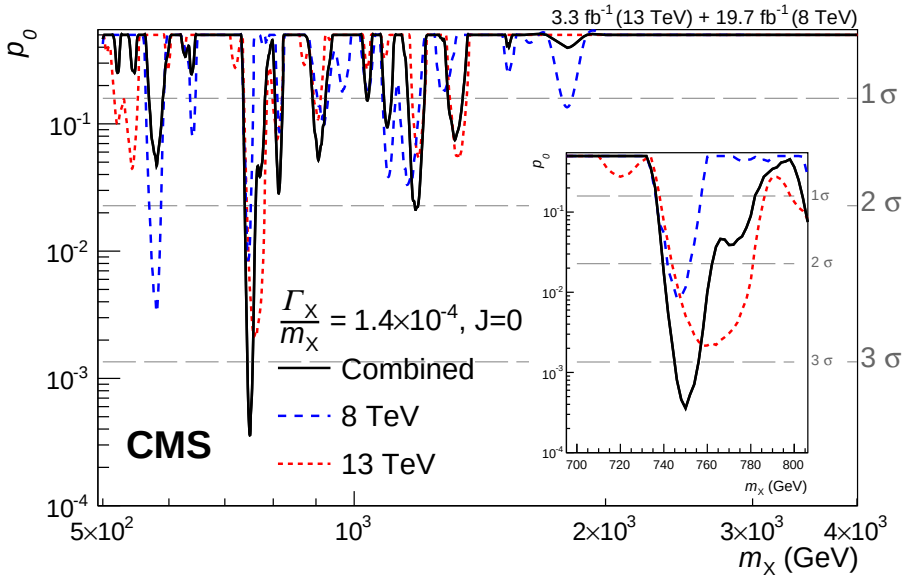
$H \to \gamma\gamma$ (2)

[arXiv:1606.03833]
[arXiv:1606.04093]

Exclusion limits for narrow scalar resonance from 13 TeV data.



p-value plot for a narrow scalar resonance from 8 and 13 TeV data combined.



Results also available for other widths.

$H \to \gamma\gamma$ (3)

[arXiv:1606.03833]
[arXiv:1606.04093]

$m_{\gamma\gamma}$ from 8 TeV data