Searches for an **extended Higgs sector**

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UCLouvain, CP3, and FNRS
for ATLAS & CMS collaborations

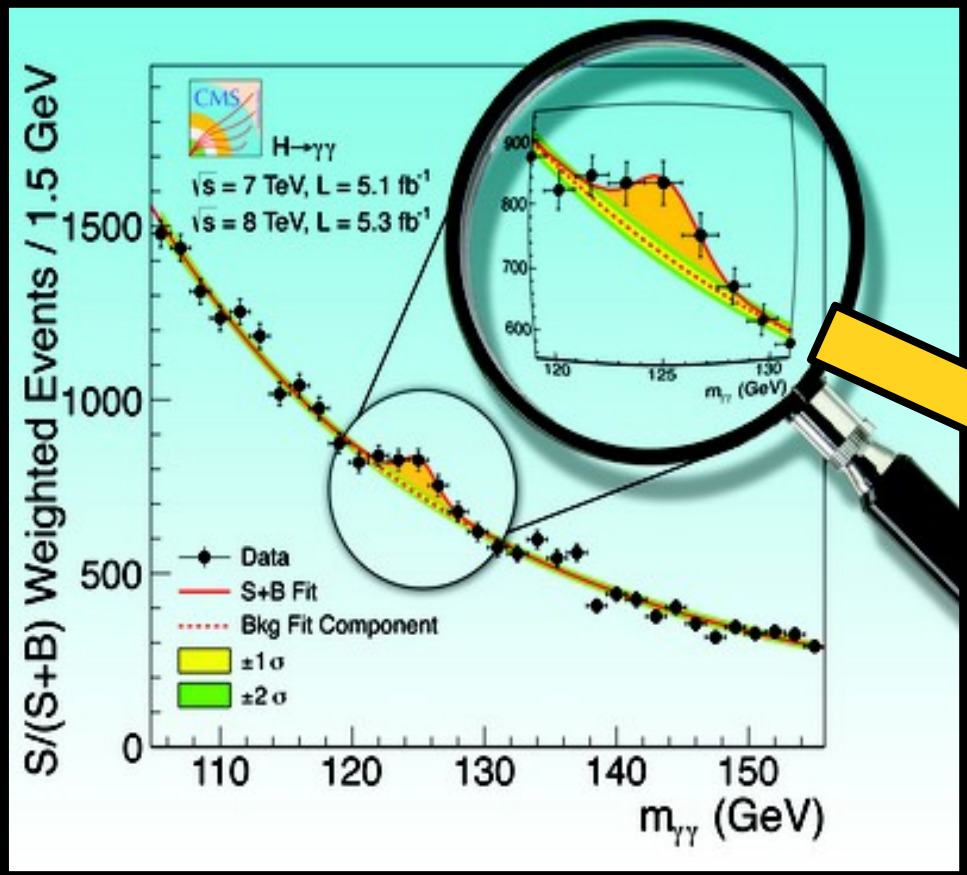
Higgs Tasting Workshop
15th – 21st May, Benasque, Spain

fnrs LA LIBERTÉ DE CHERCHER
UCL
ATLAS
CMS

You might have heard about the "Big discovery"!

4 July 2012:

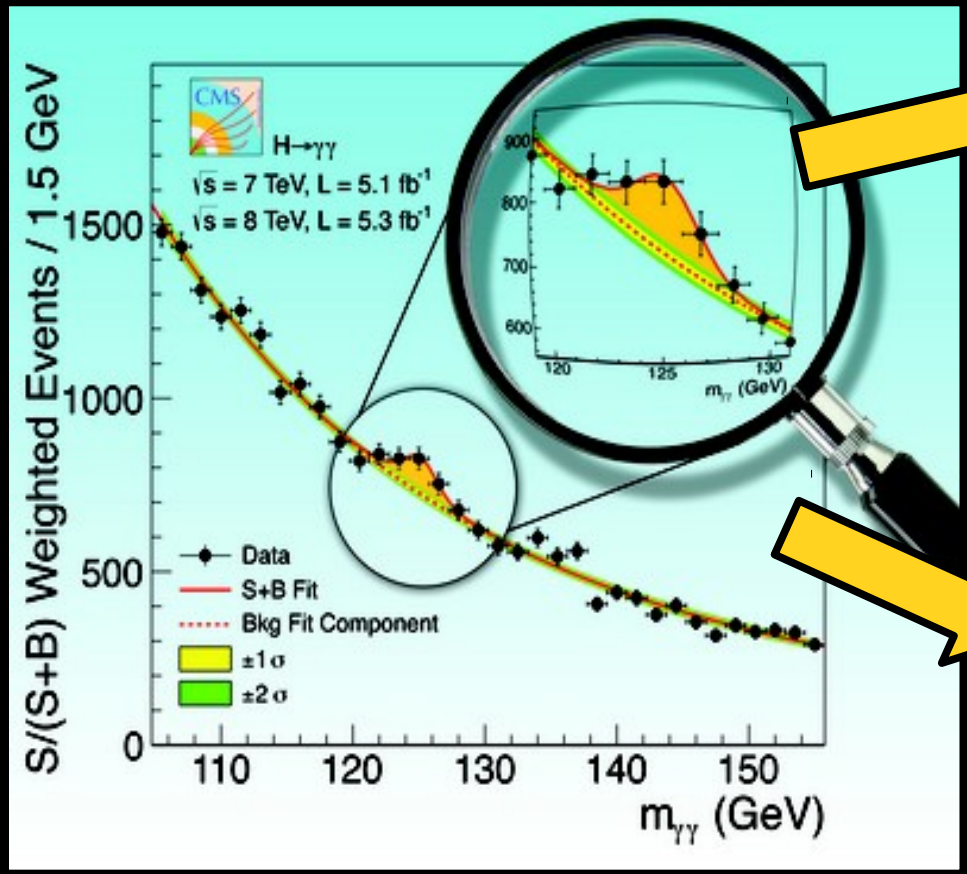
Something IS there



However the Question was:

Is it REALLY you Sir?!

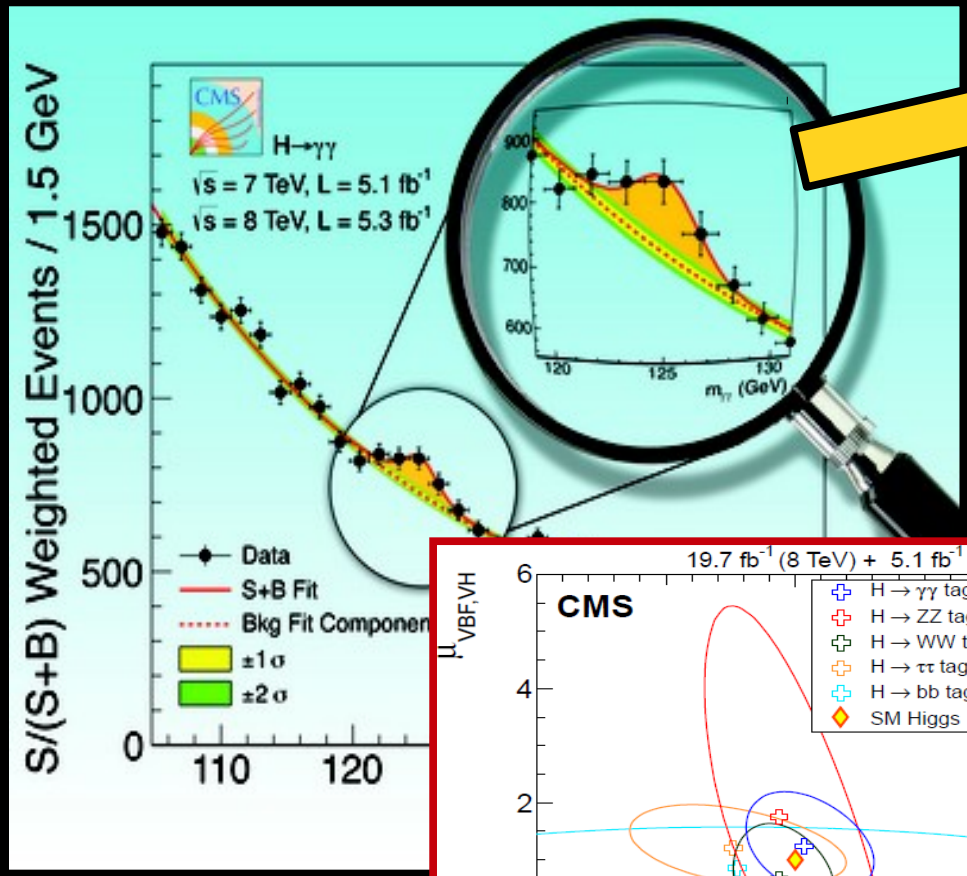
And the beginning of a long journey …



Does it behave as we expect, Standard-Model-wise?

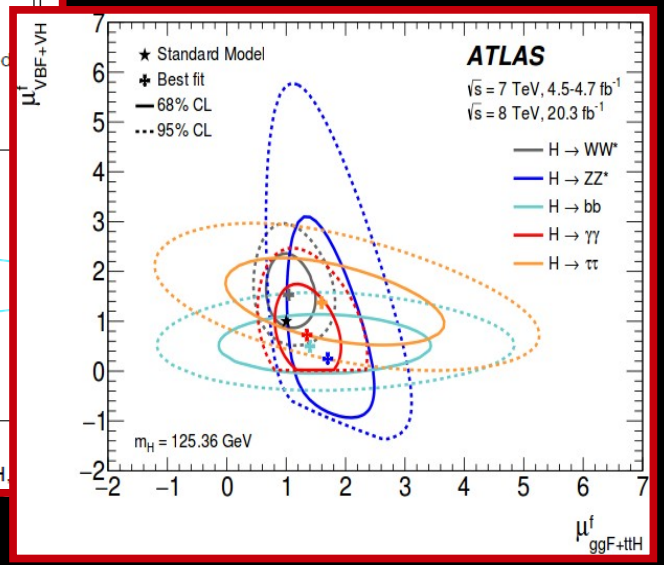
Could it be e.g. one of many Higgs's expected in beyond Standard Model?

And the beginning of a long journey …



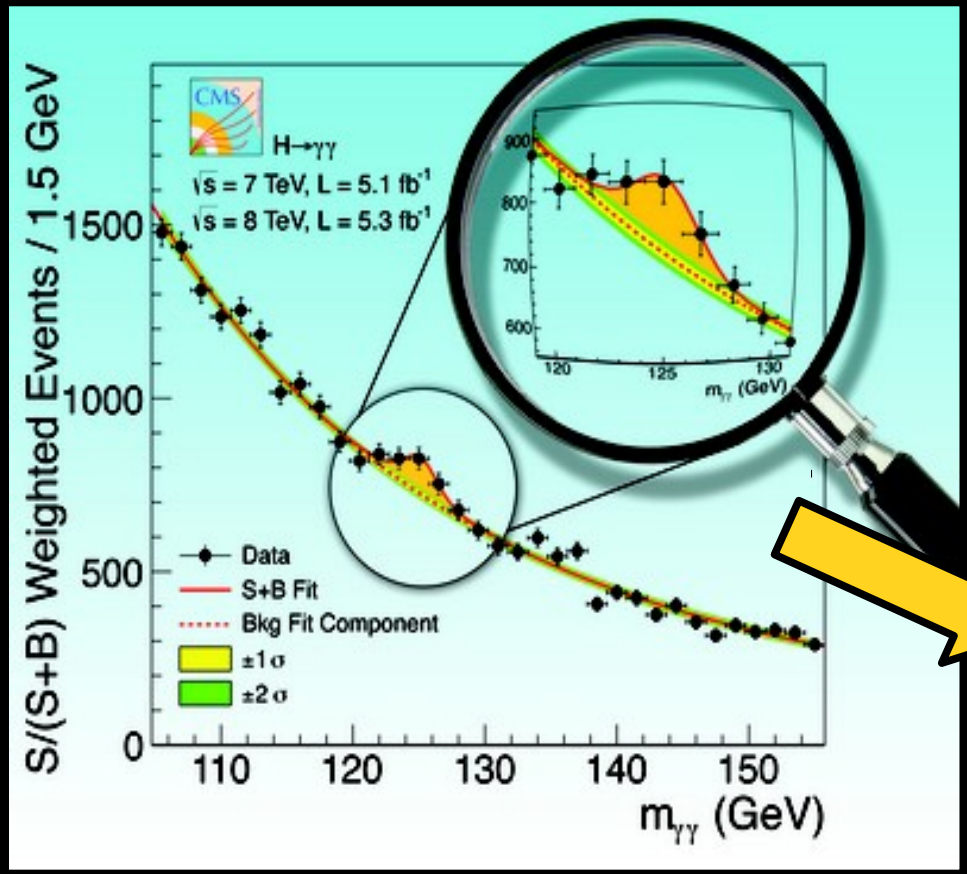
Does it behave as we expect, Standard-Model-wise?

It's VERY SM like!!



+ …

And the beginning of a long journey …



Still YES!

With uncertainties in measurements, still room for it to connect to BSM

Could it be e.g. one of many Higgs's expected in beyond Standard Model?

Where to look?

Measurements

Couplings – Differential

- Main modes: $h \to ZZ$, WW, $\gamma\gamma$ $\tau\tau$, bb
- Lower rate: $\mu\mu$, $Z\gamma$, ee, …
- Challenging (at LHC): $s\bar{s}$, $c\bar{c}$, gg
- Couplings: gg$h$, qq$h$, Vh, t$\bar{t}h$, tq$h$, b$\bar{b}h$

Direct searches

- Additional Higgs bosons: NMSSM, 2HDM, $h^{\pm\pm}$, …
- FCNH: $t \to ch$ …
- In decays of new particles: $\tilde{\chi}^{\pm}_1 \tilde{\chi}^0_2 \to W^{\pm}\tilde{\chi}^0_1 h\, \tilde{\chi}^0_1$
- Rare SM h decays: either SM-forbidden or highly SM-suppressed
- Di-h production: rare SM or in decay of new states
- …

Where to look?

- Focus on the latest results, mainly 13 TeV
- Many Run I studies
  - Need more data at 13 TeV to be competitive
  - *Example:* Higgs rare decays
- Check them all in ATLAS and CMS public pages

Direct searches

- Additional Higgs bosons: NMSSM, 2HDM, $h^{\pm\pm}$, …
- FCNH: $t \rightarrow ch$ …
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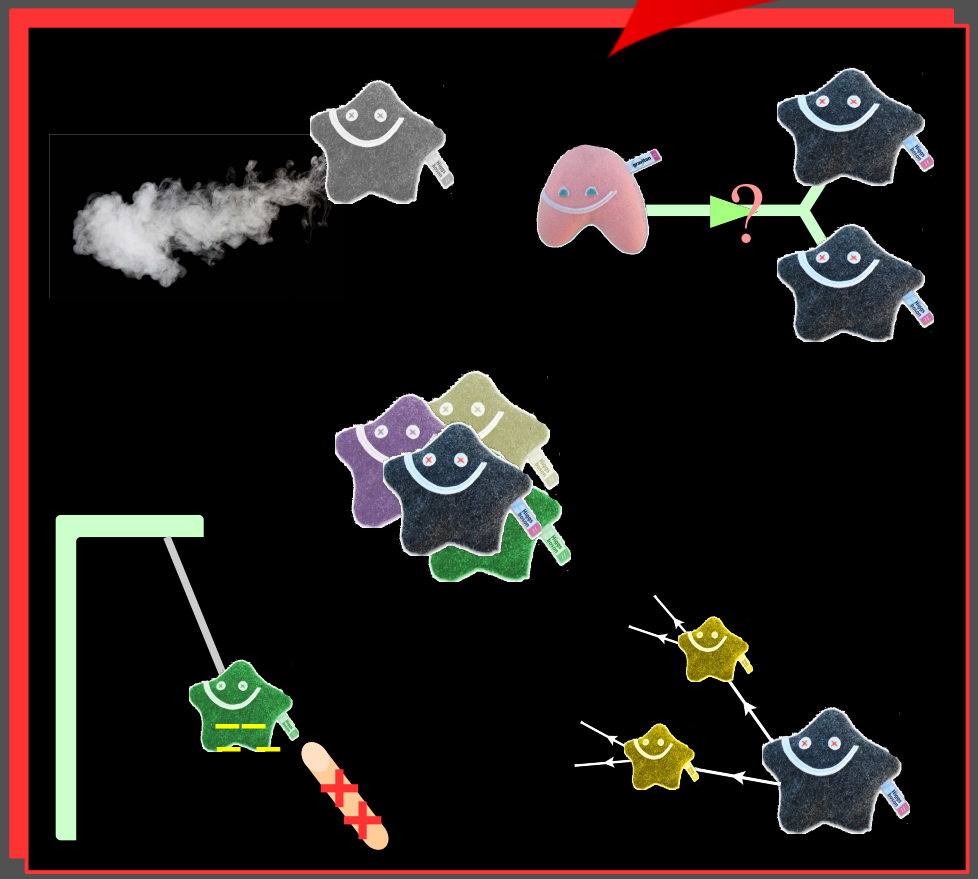
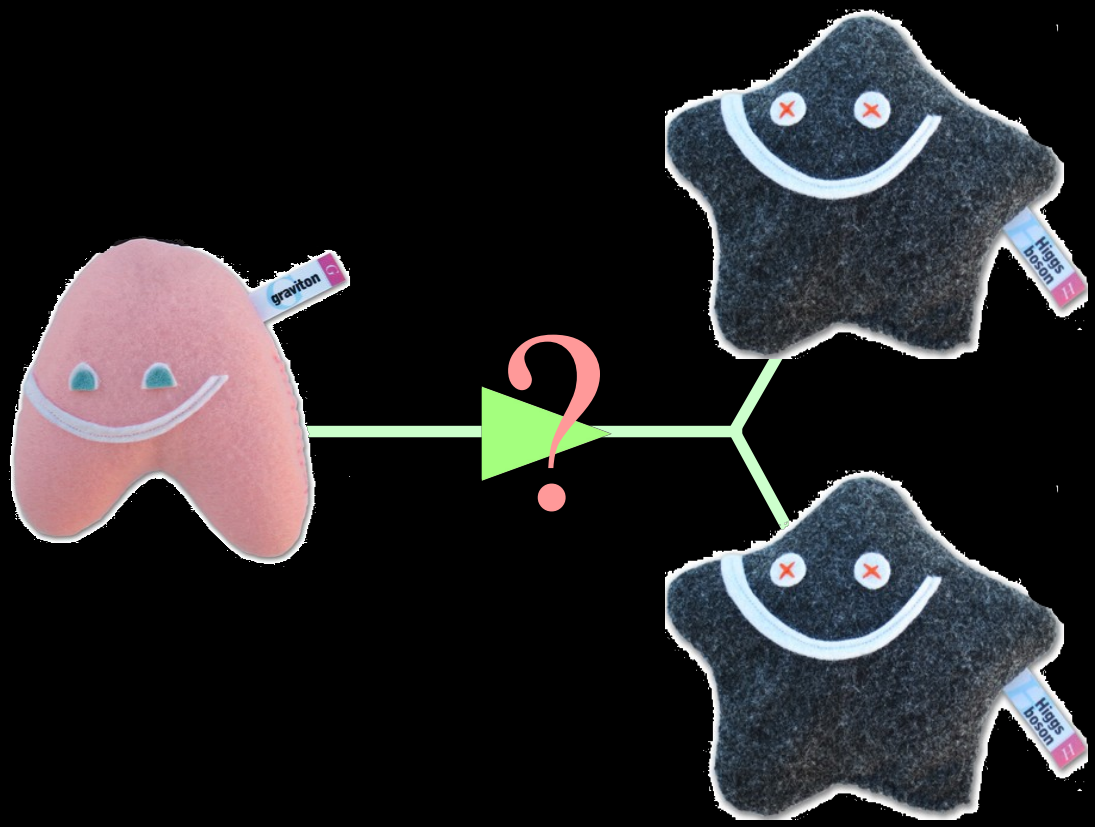
Where to look?



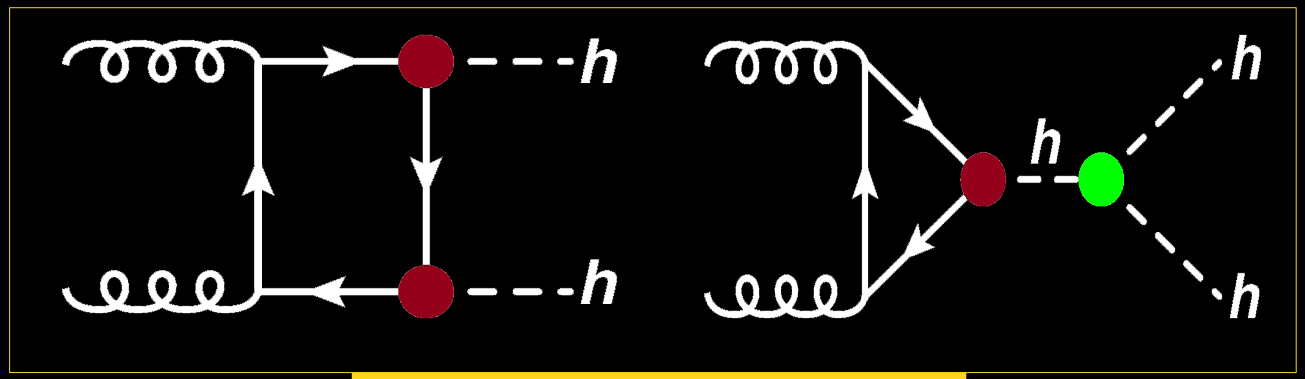
Outline

- Di-*h* production
- Additional Higgs bosons
- Exotic *h* decays
- Invisible Higgs
- Charged Higgs

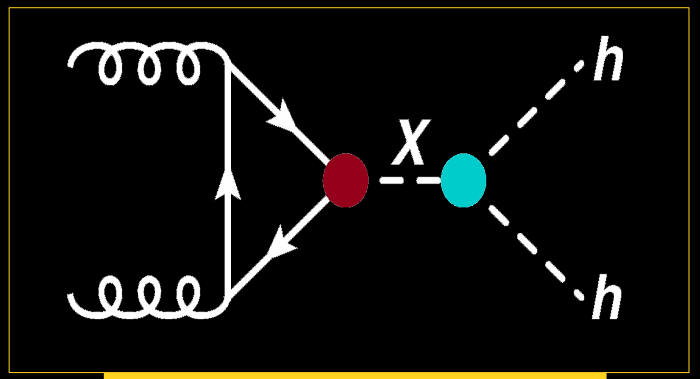


DI-HIGGS PRODUCTION

Di-*h* production



- Probing 3-*h* coupling
- SM suppressed
- BSM in couplings

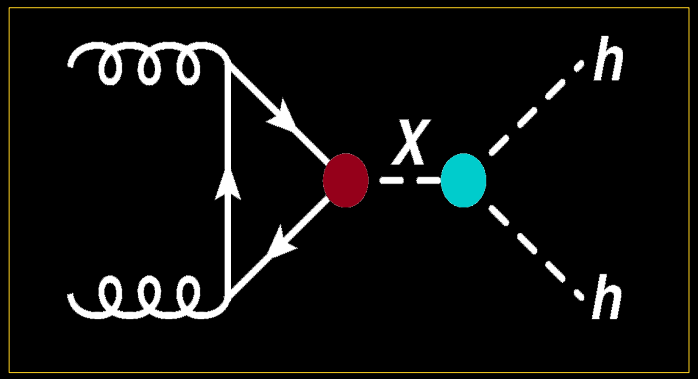


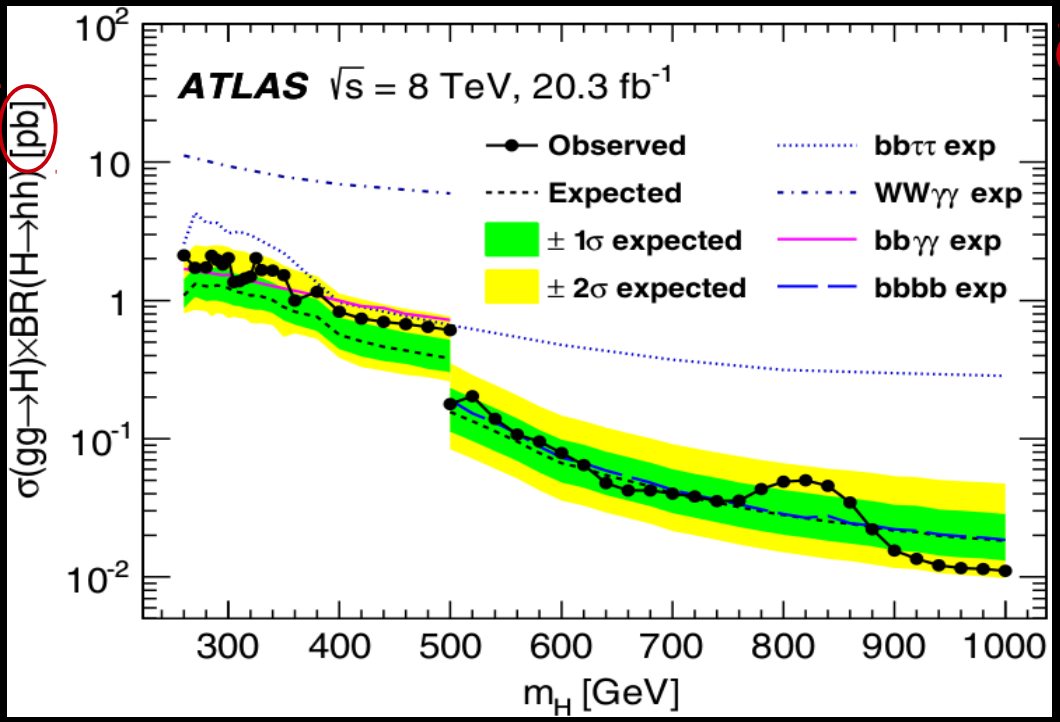
- X is spin-2 or 0
- Heavy Higgs, KK modes in RS models, …

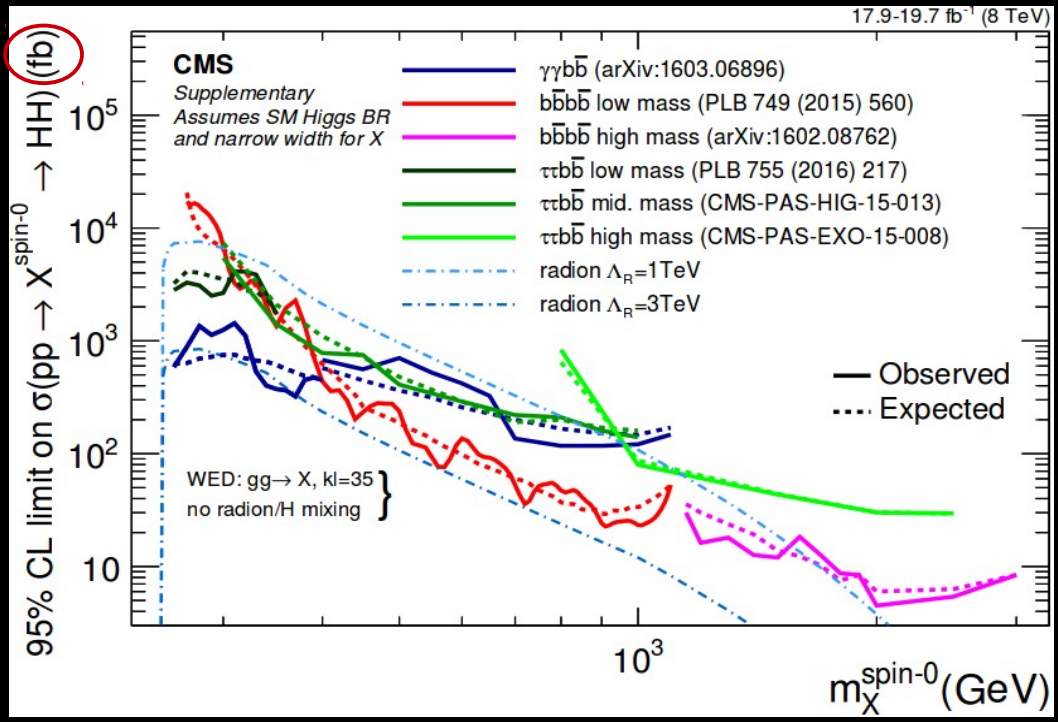
h decay products

Di-*h* production

Wide range of searches with Run I collisions





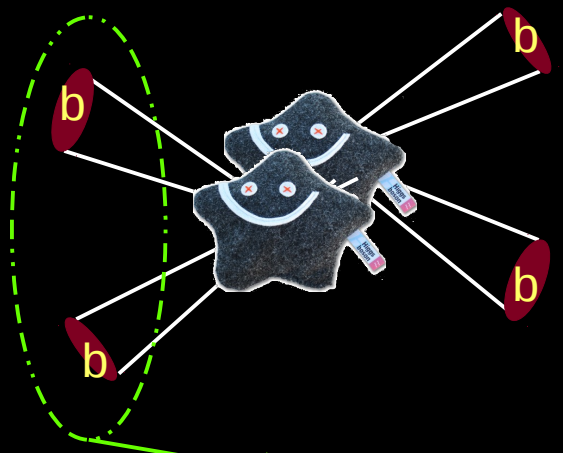


Phys. Rev. D 92, 092004 (2015)

Higgs PAG Summary Plots

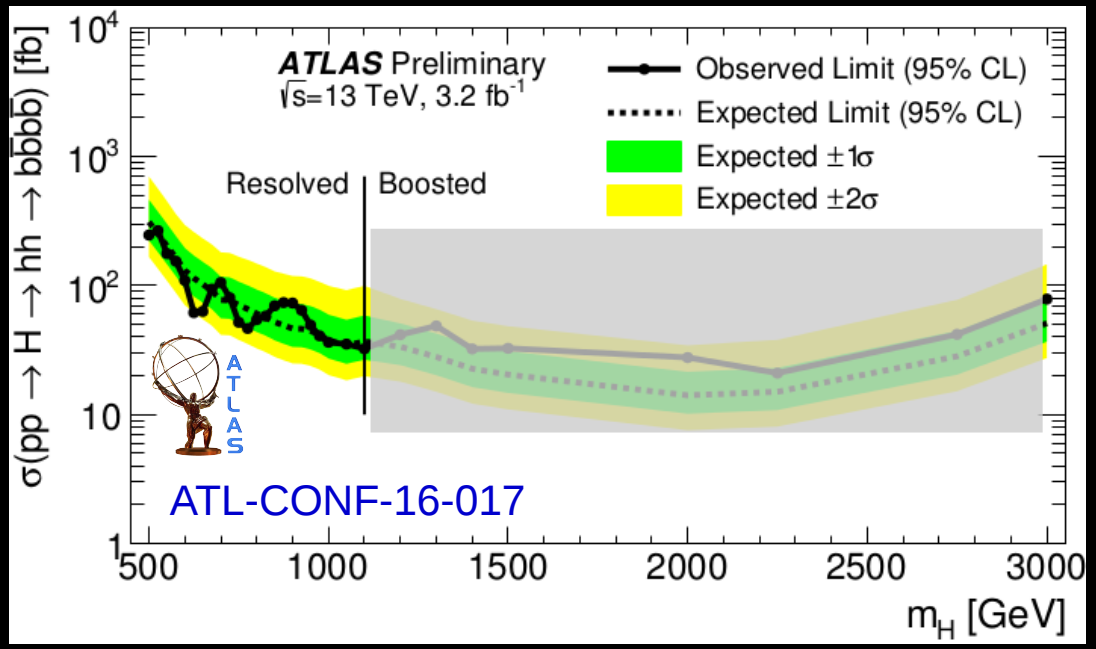
Di-*h* production: $b\bar{b}b\bar{b}$ 13 TeV *(resolved)*

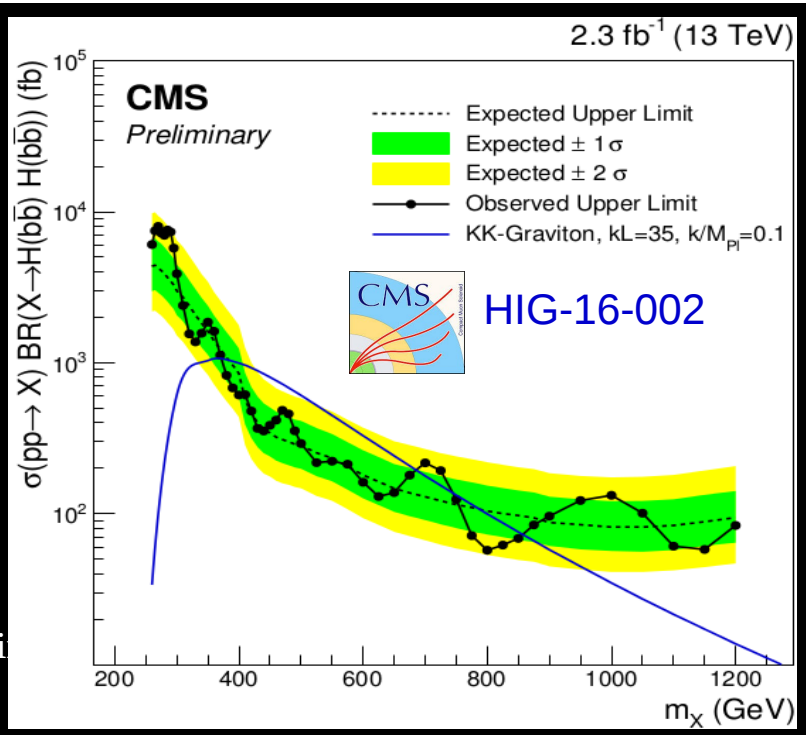
At least 4 b jet



compatible with *h*

Backgrounds from data in control regions
- Exploiting the "2b-*h*" compatibility
- Also events with 2 b-jets for ATLAS





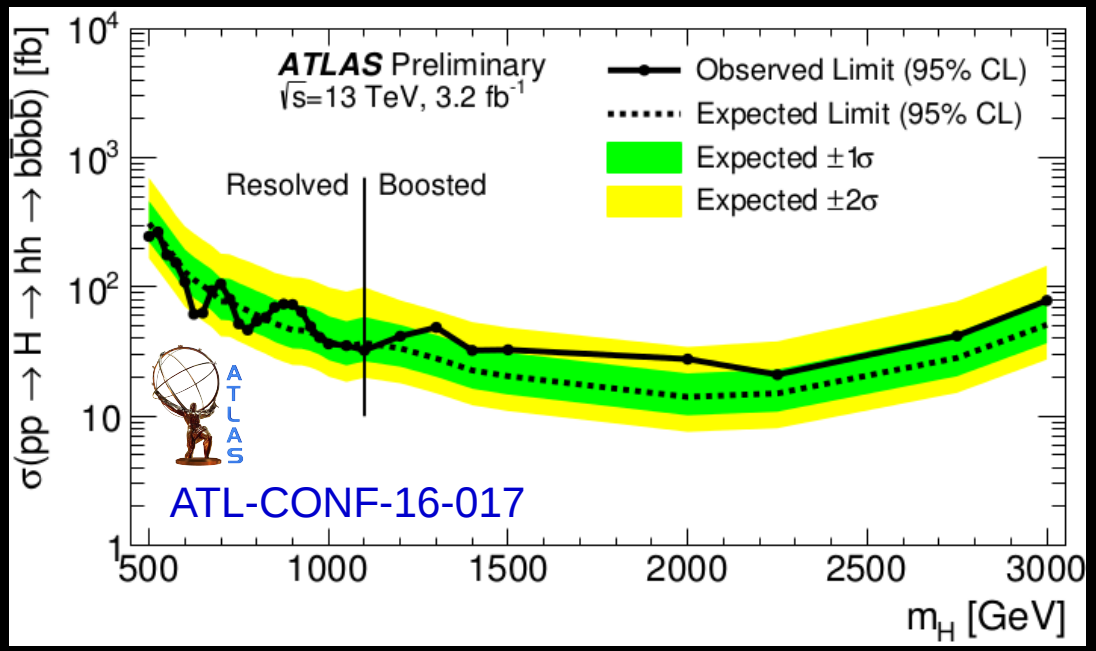
Di-*h* production: $b\bar{b}b\bar{b}$ 13 TeV *(boosted)*

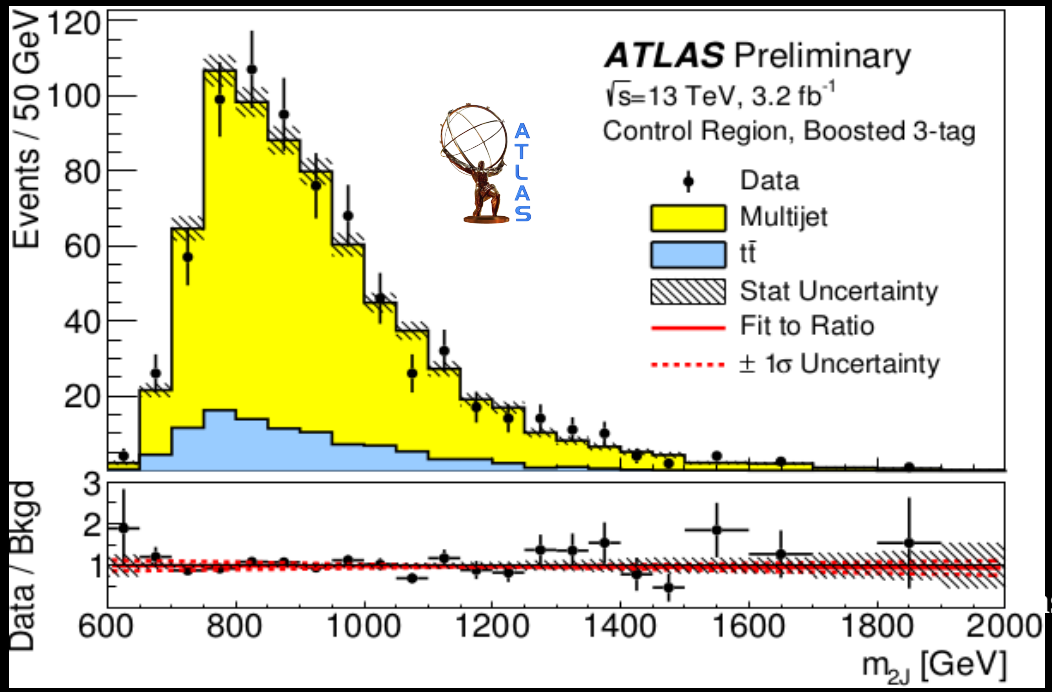
2 large-R jets

$250 < p_T < 1500$ GeV

Compatible with m_h

4-b or 3-b associated

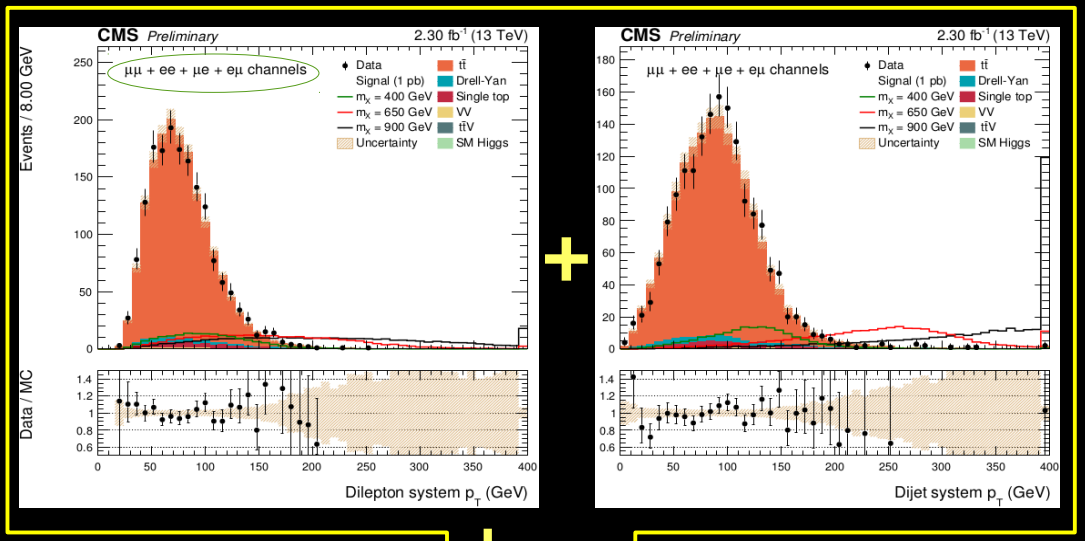




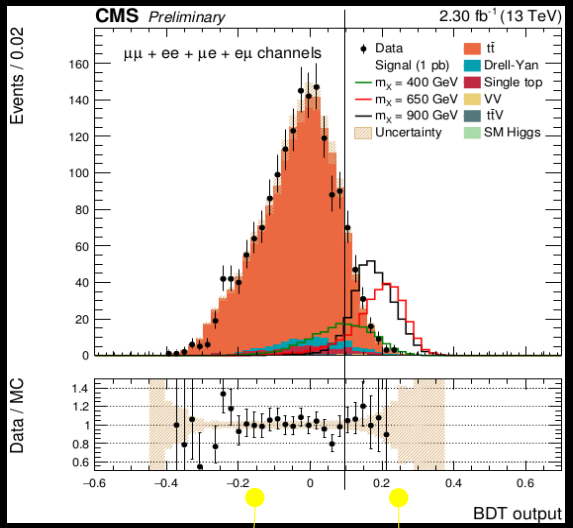
Main systematics

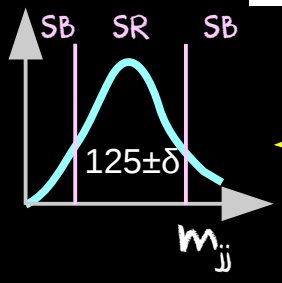
- Resolved
  - JES, b-tag – ATLAS
  - Trigger, b-tag – CMS
- Boosted:
  - JMS/JMR, b-tag
  - 4-tag QCD norm.

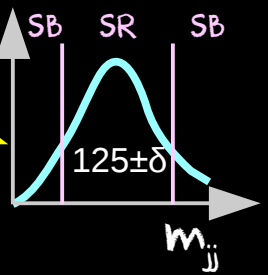
Di-*h* production: $b\bar{b}W^+W^-$ ($\ell\nu\ell\nu$) 13 TeV



+ ...

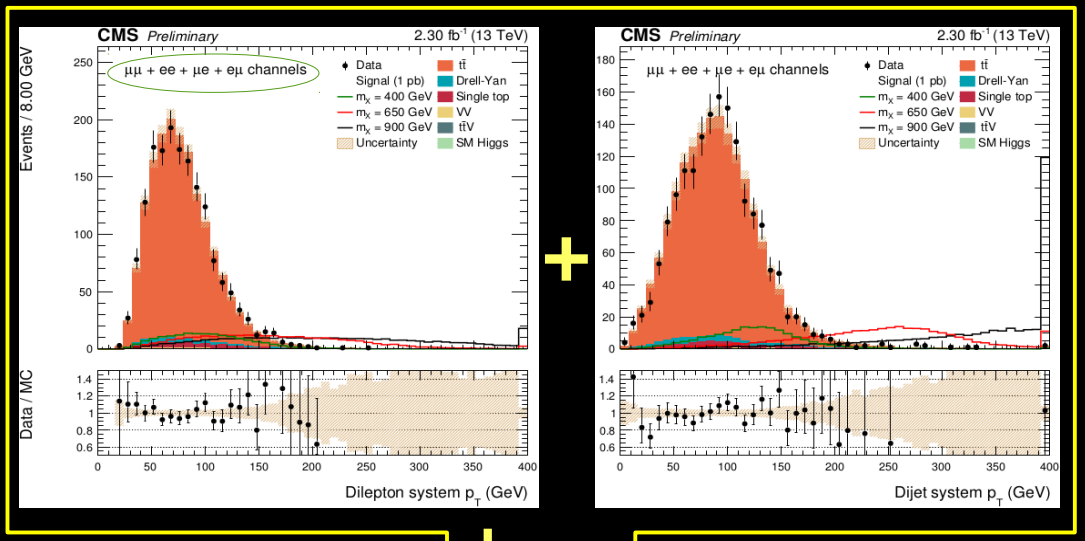






HIG-16-011

Di-*h* production: $b\bar{b}W^+W^-$ ($\ell\nu\ell\nu$) 13 TeV



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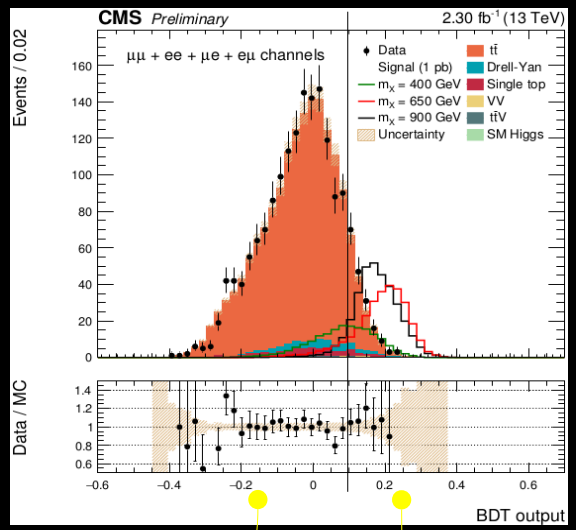
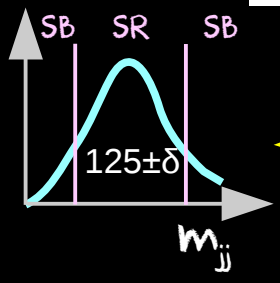
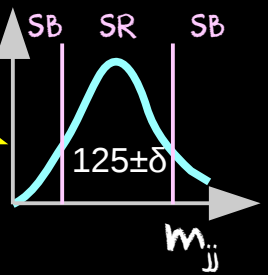
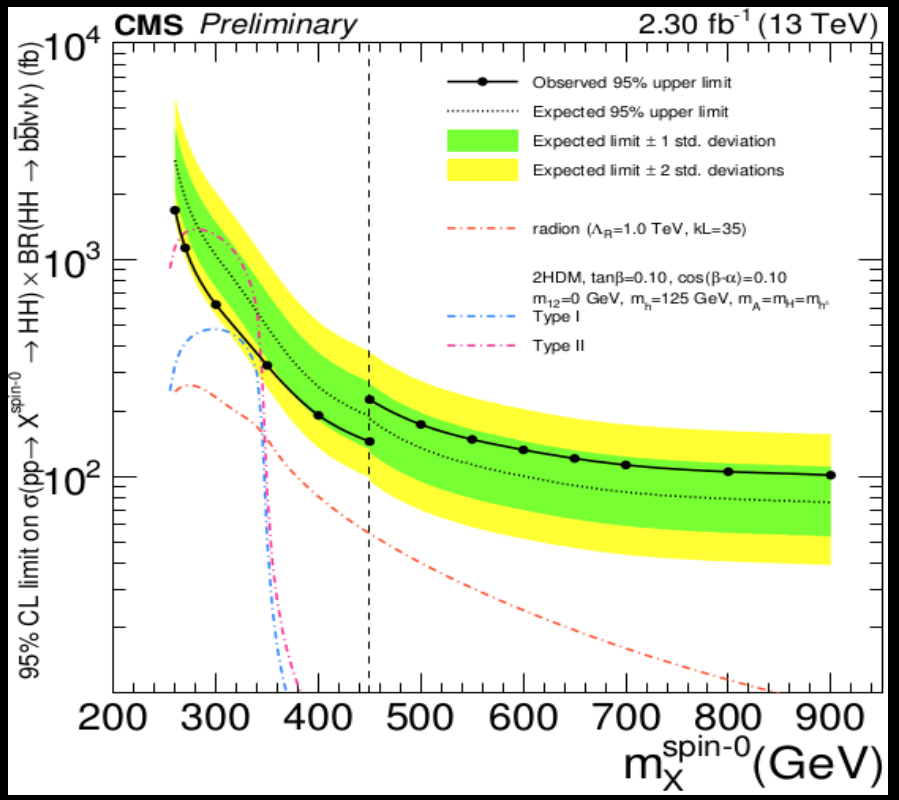








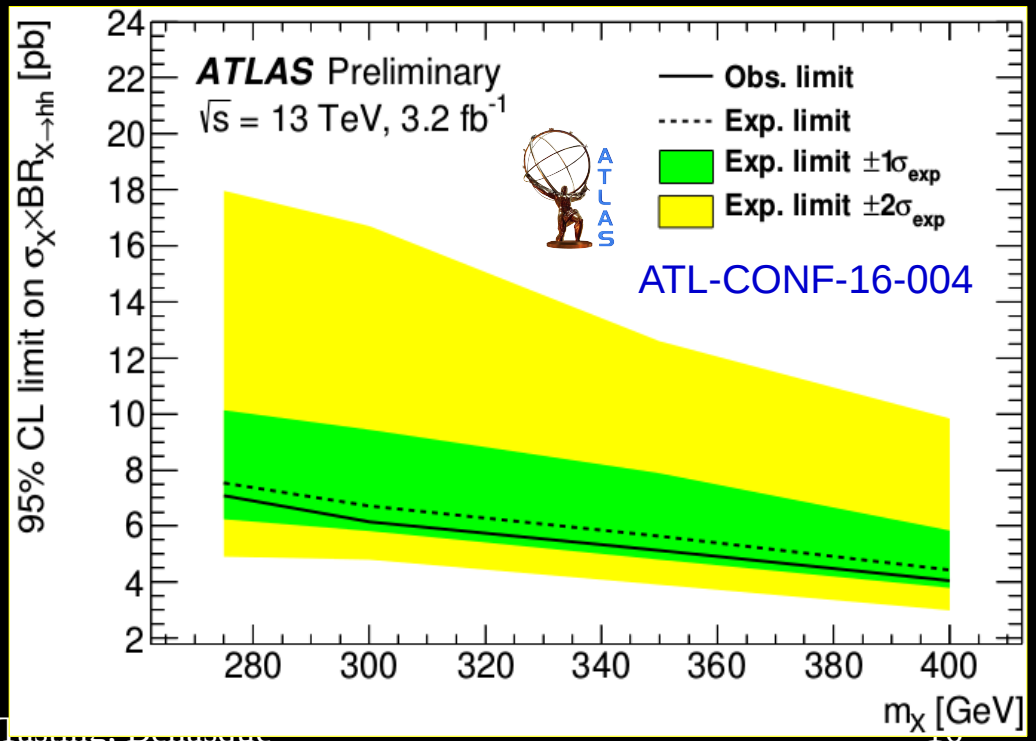
HIG-16-011

Di-*h* production: $b\bar{b}\gamma\gamma$ 13 TeV

- 2 high p_T photons
- 2 b-jets with $m_{b\bar{b}} \sim m_h$

resonant

Counting experiment
- $m_{\gamma\gamma} \sim m_h$
- $m_{bb\gamma\gamma}$ window with $\varepsilon_{sig.} = 95\%$



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- 2 b-jets with $m_{b\bar{b}} \sim m_h$

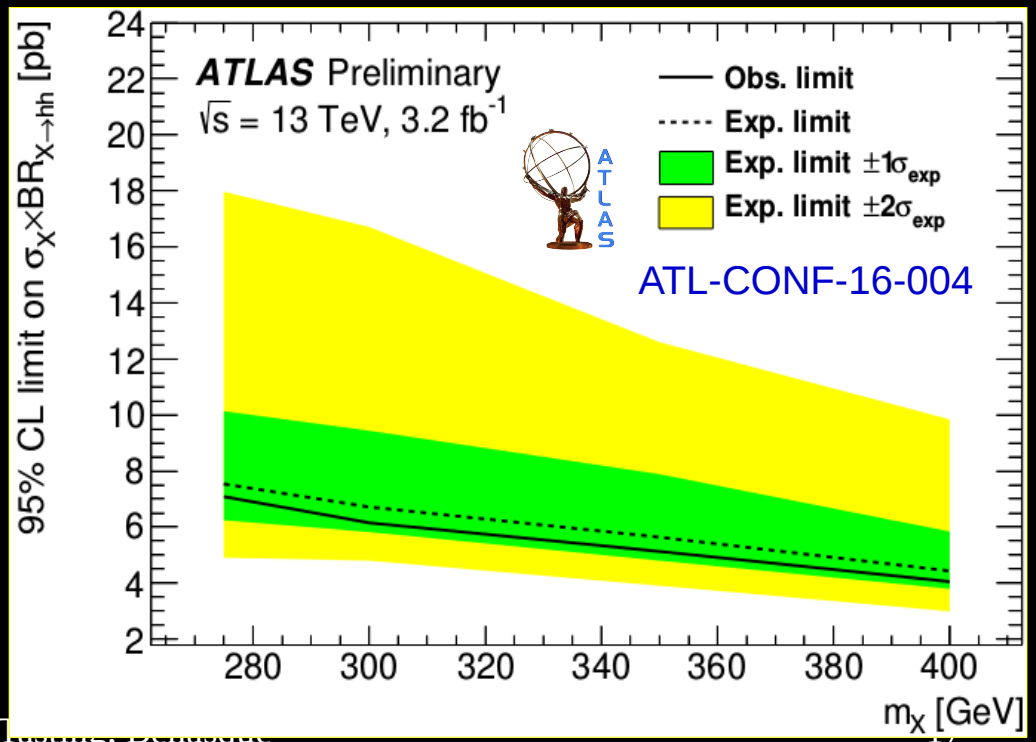
resonant

Counting experiment
- $m_{\gamma\gamma} \sim m_h$
- $m_{bb\gamma\gamma}$ window with $\varepsilon_{sig.} = 95\%$

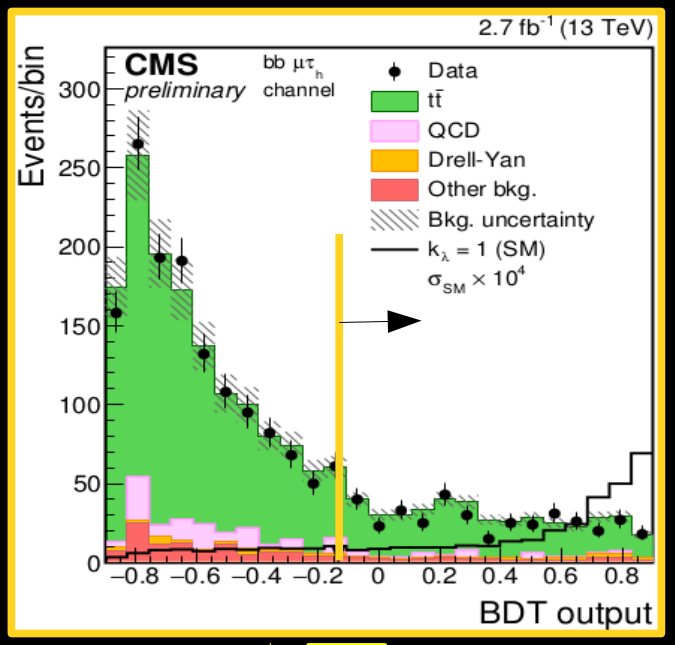
Non-res.

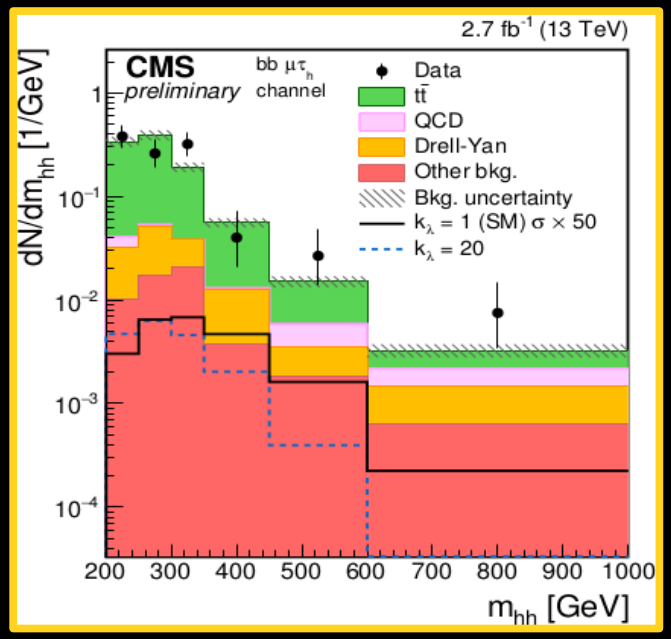
Fit to $m_{\gamma\gamma}$ in 2-b and 0-b regions
- Parametric signal from MC
- Parametric bkg. from data

Upper limit at 95% CL:
$\sigma < 3.9$ (5.4) pb obs. (exp.)

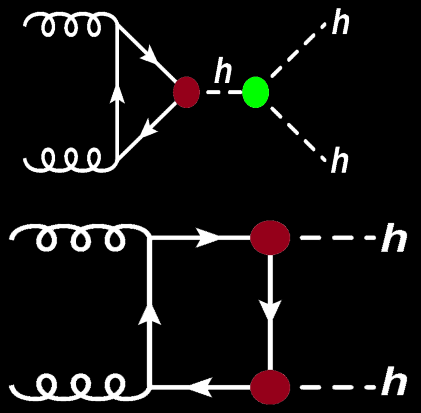


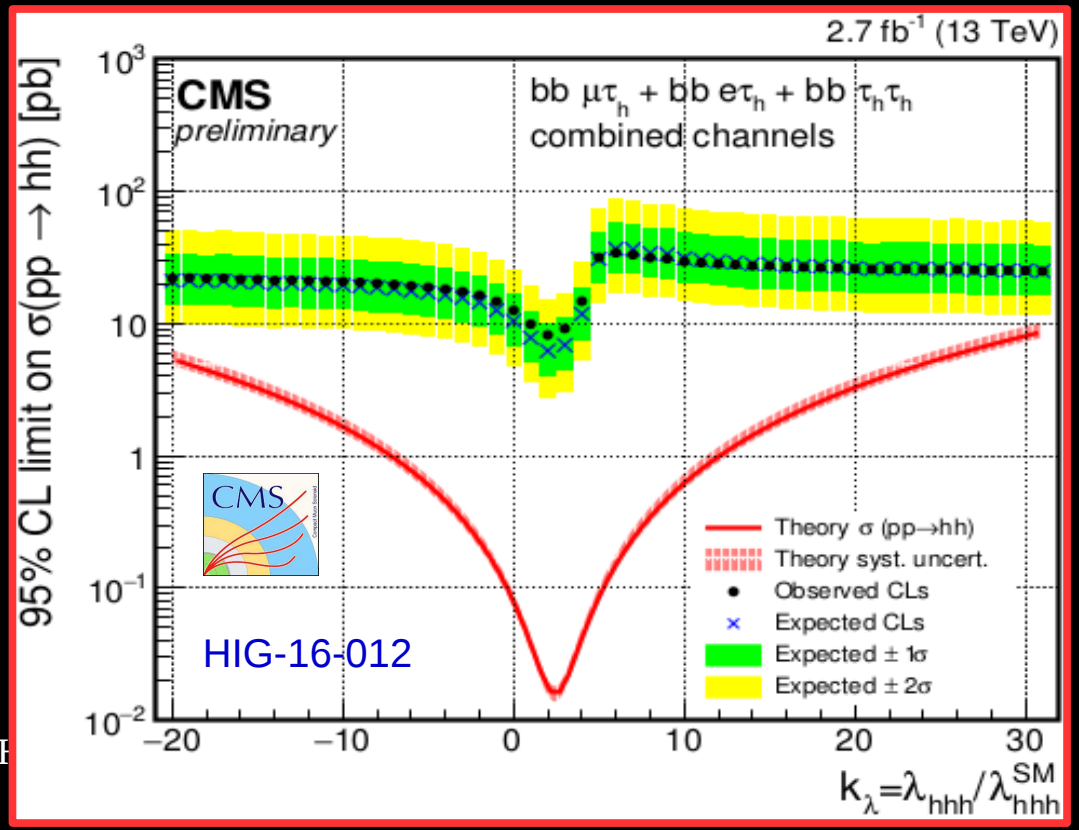
Di-*h* production: $b\bar{b}\tau\bar{\tau}$ 13 TeV





- $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$
- BDT in $\ell\tau_h$ against $t\bar{t}$
- Main backgrounds from data





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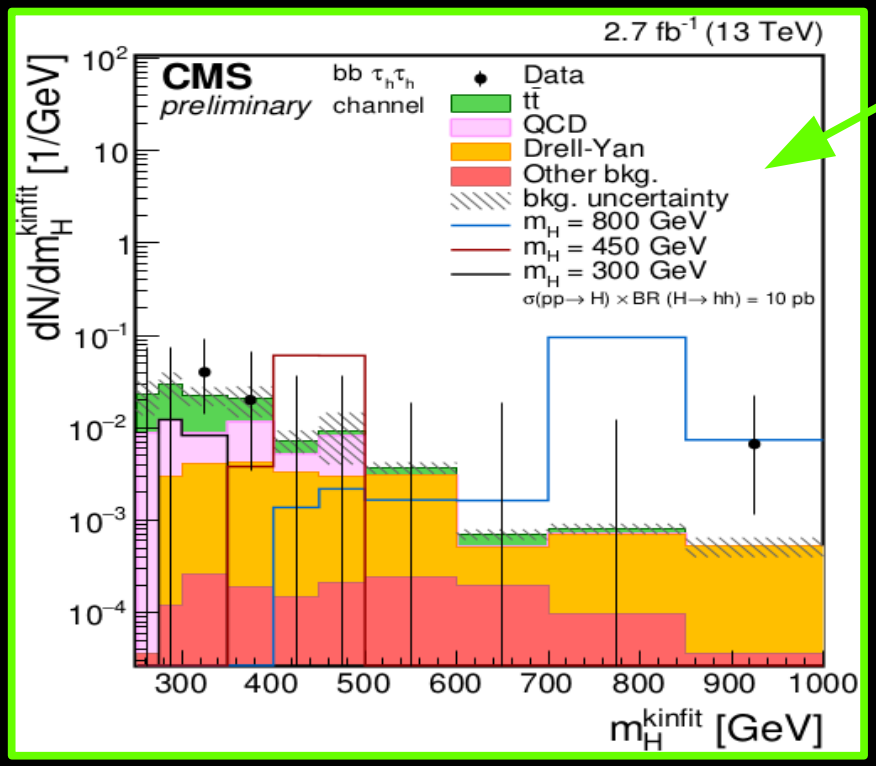
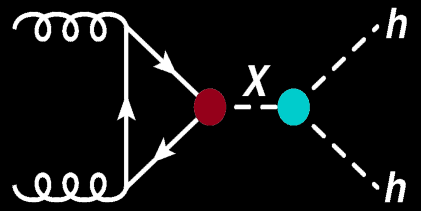
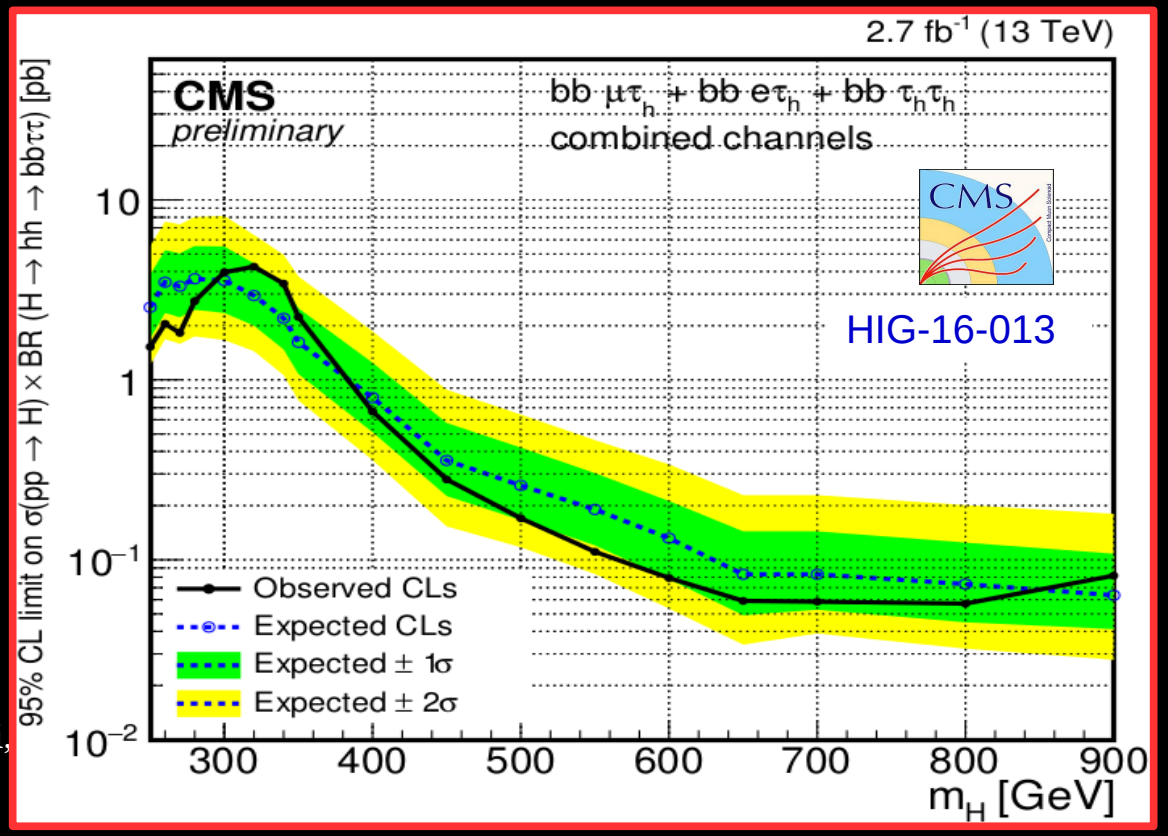
Di-*h* production: $b\bar{b}\tau\bar{\tau}$ 13 TeV



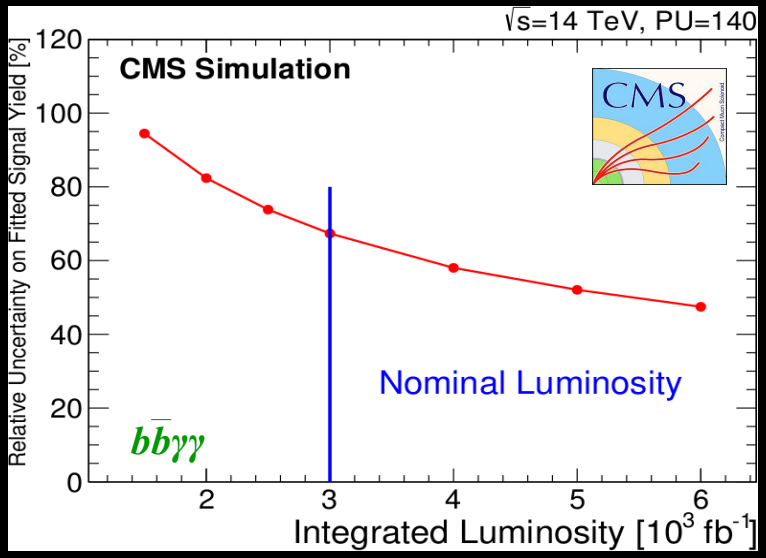
- $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$
- Kin. fit with X → *hh* hypothesis
- Main backgrounds from data

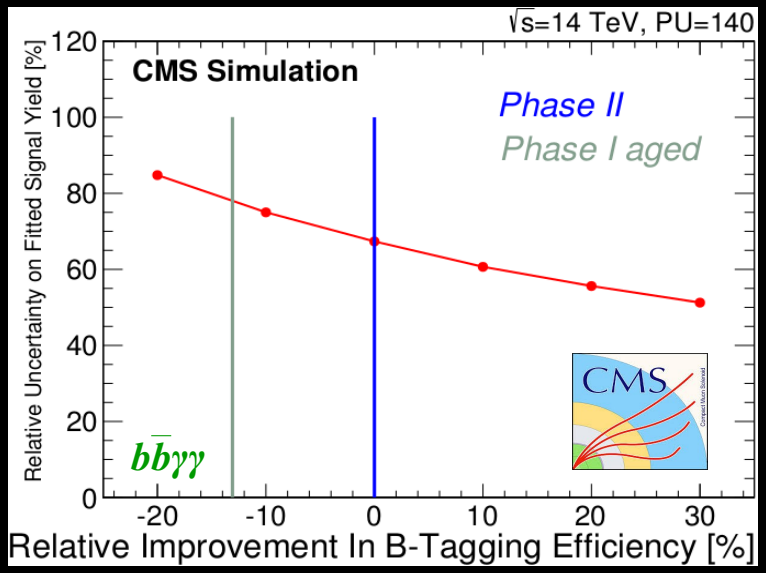


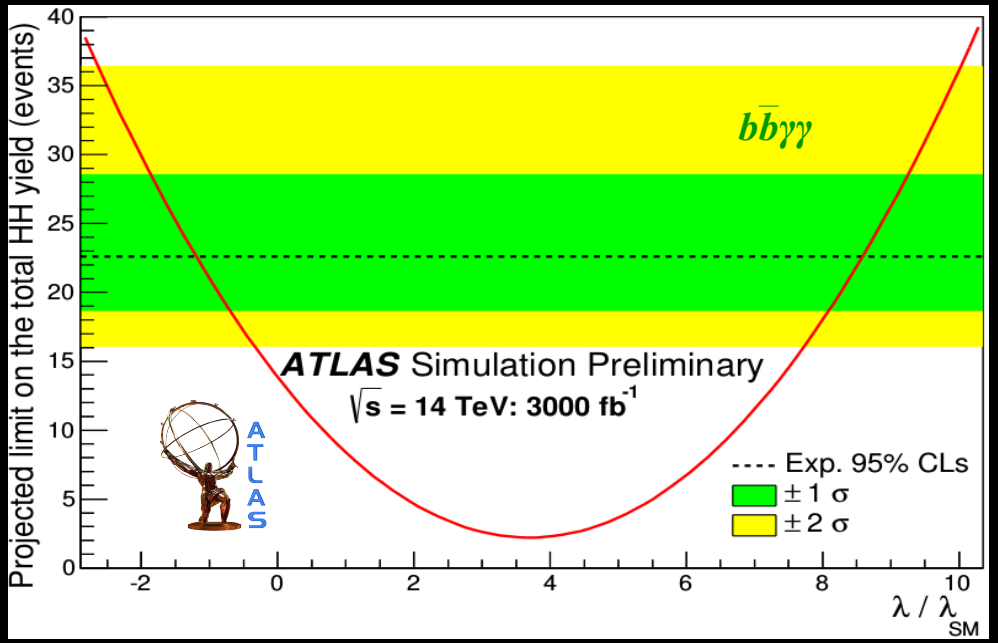


A. Jafari,

Di-*h* production: towards HL-LHC







See also ATL-2015-046 for $b\bar{b}\tau\tau$

Expected significance: **1.3 σ**

- Improve identification performances
- Analysis techniques
- Additional final states
  - Beneficial also for Run II data

Expected significance, inc. $b\bar{b}\tau\tau$: **1.9 σ**

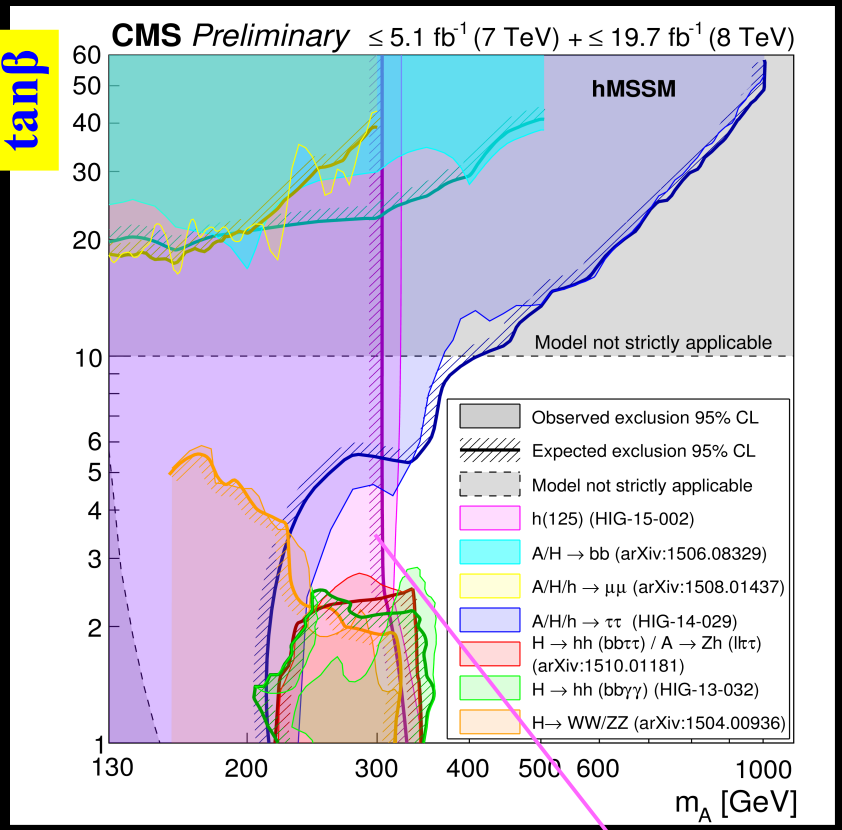
ADDITIONAL HIGGS BOSONS

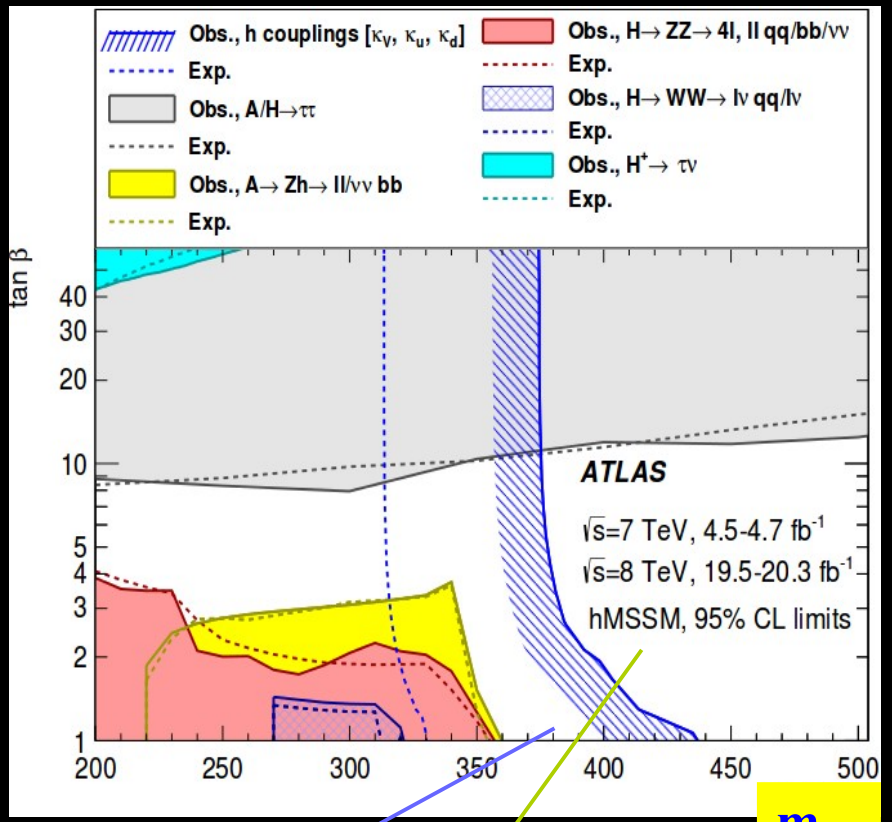
In the framework of 2HDM, NMSSM, …

Additional Higgs bosons

A Run I summary: Searches and measurements

HIG-16-007





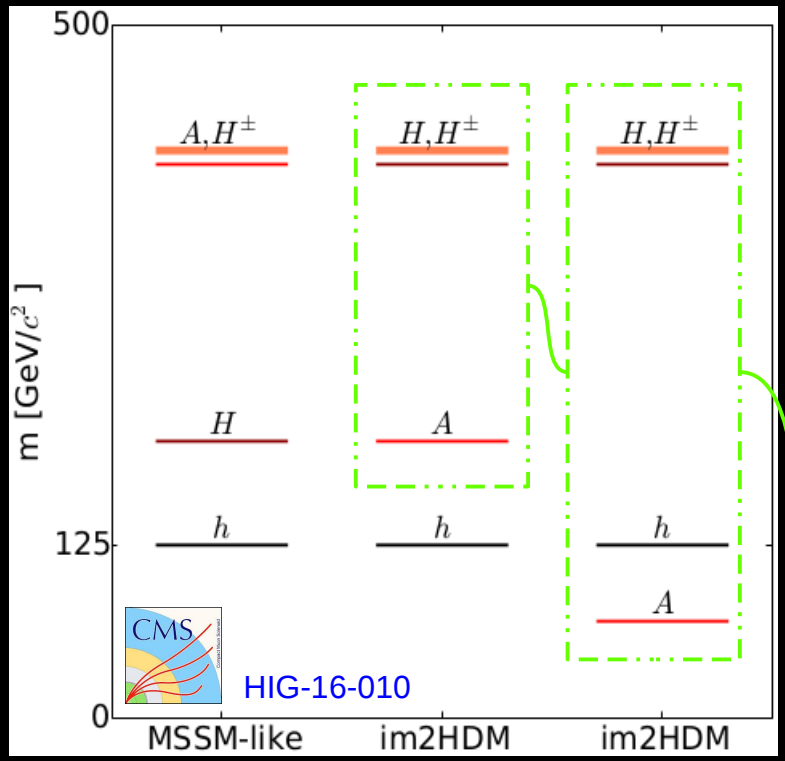
JHEP11(2015)206

Couplings fit

Could be reached by $t\bar{t}$

Interpretation in Type I-II are available in HIG-16-007

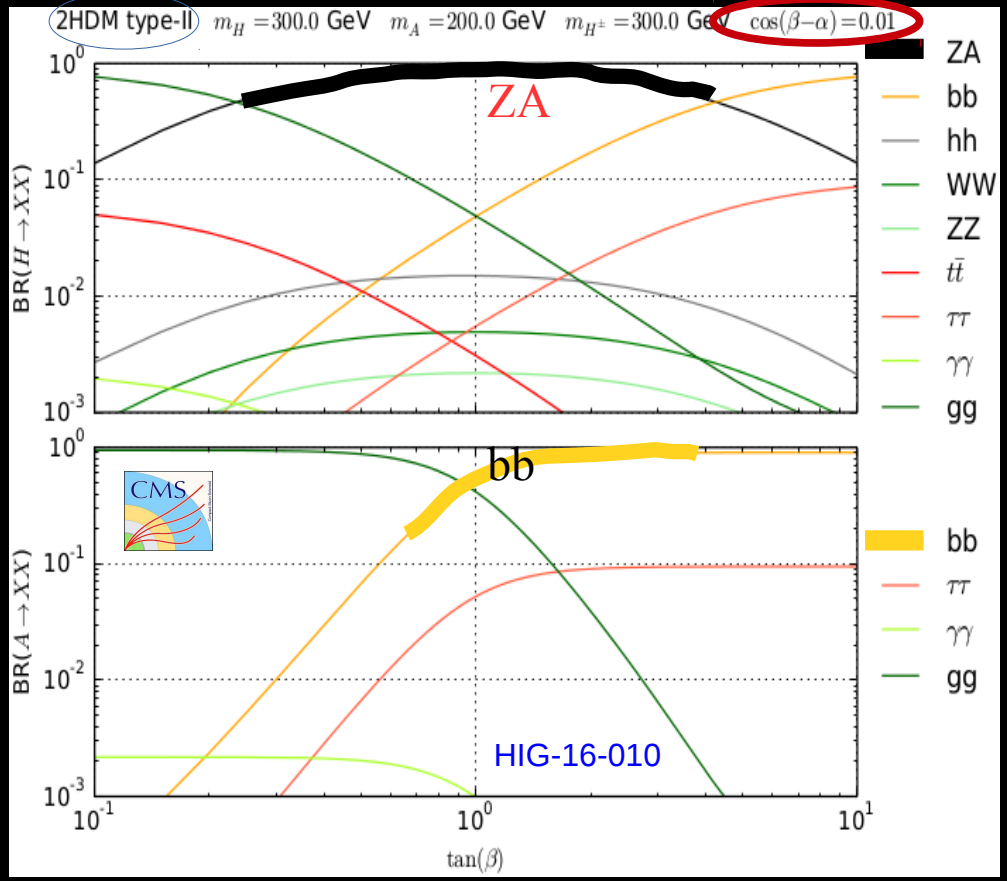
Additional Higgs bosons



H → ZA

No H → VV

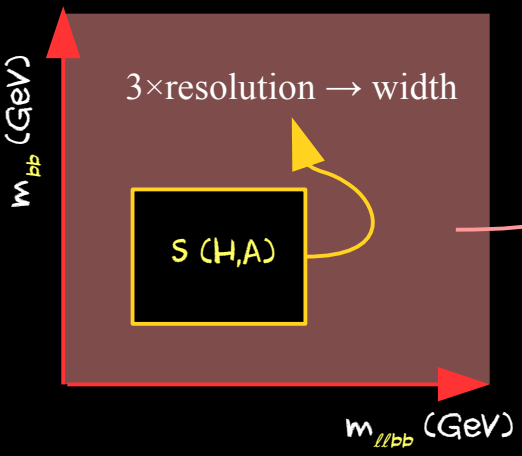
Favored by *h*(125) couplings



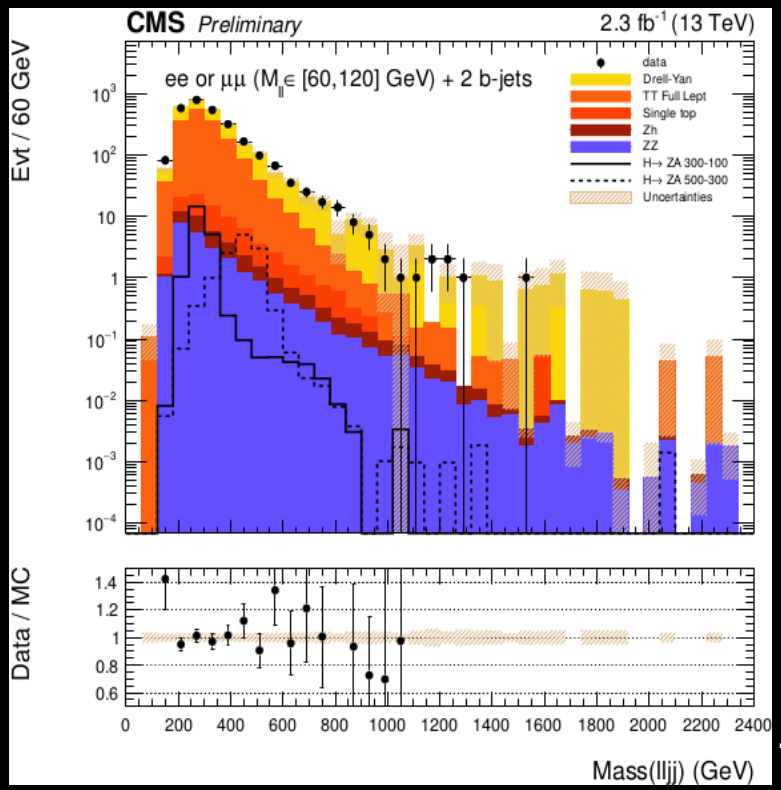
$H_{(1,2)}$ couplings to SM fermions

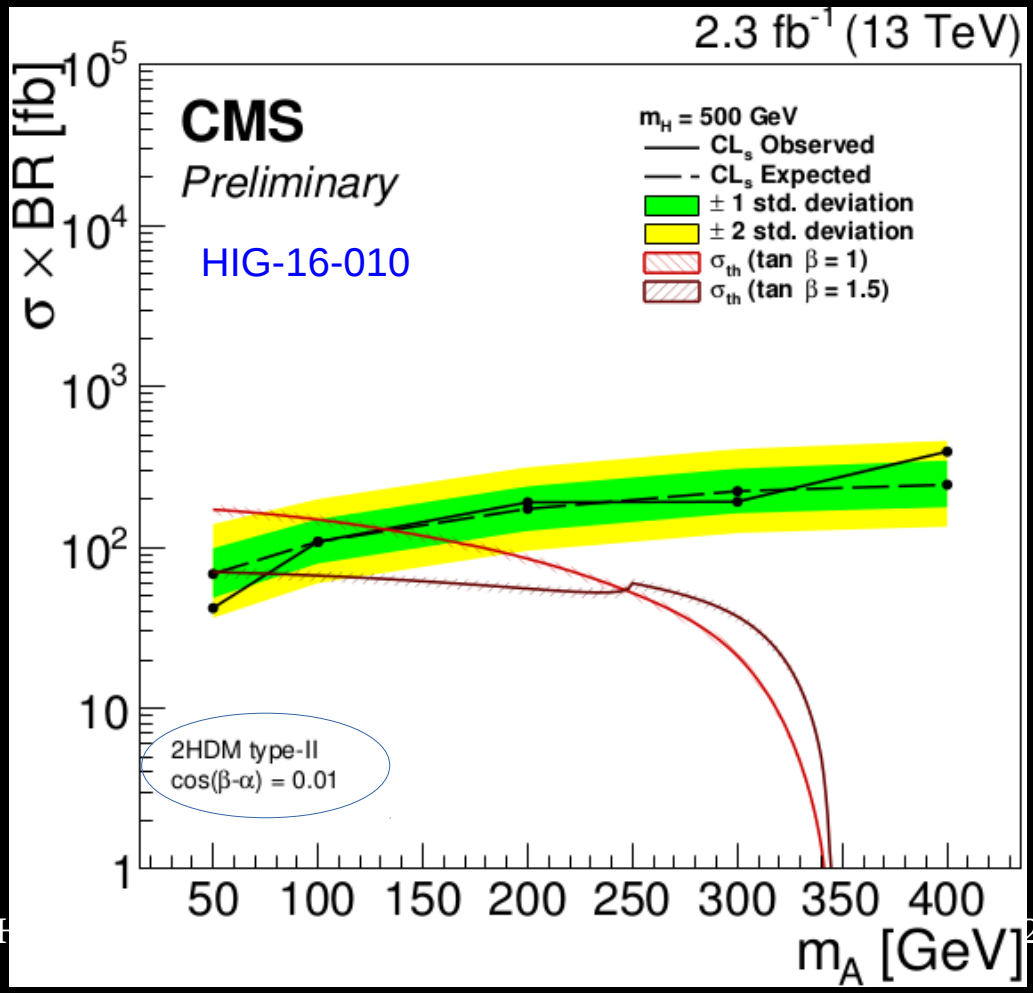
2HDM	Type			
	I	II	III	IV
Up q	H_1	H_1	H_1	H_1
Down q	H_1	H_2	H_1	H_2
Lepton	H_1	H_2	H_2	H_1

H → ZA: $A \to b\bar{b}$, $Z \to \ell^-\ell^+$ 13 TeV

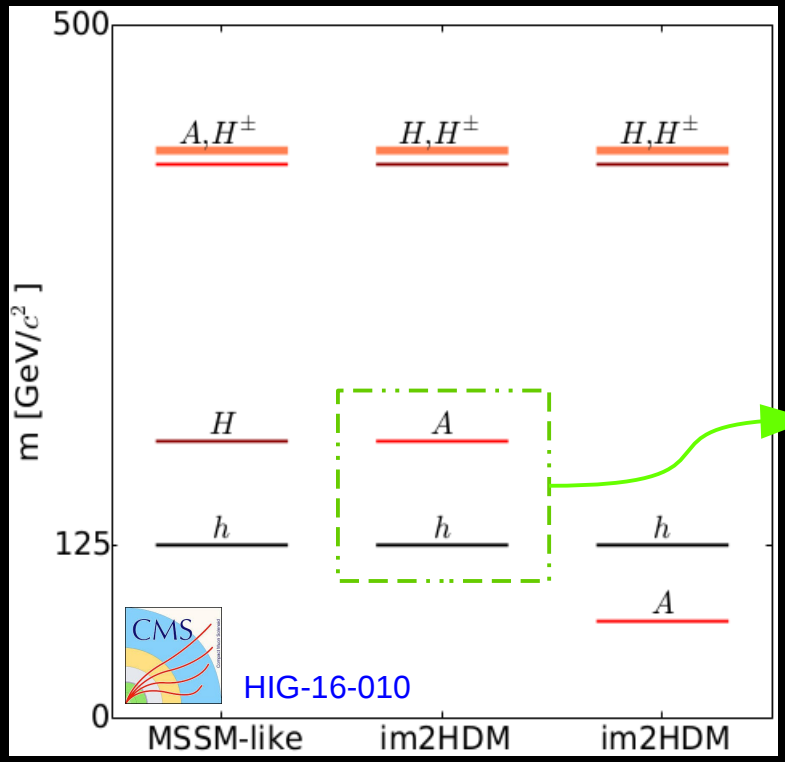


- $m_{\ell\ell}$ compatible with m_Z
- Backgrounds
  - Normalized with a fit to $m_{\ell\ell}$ in control regions

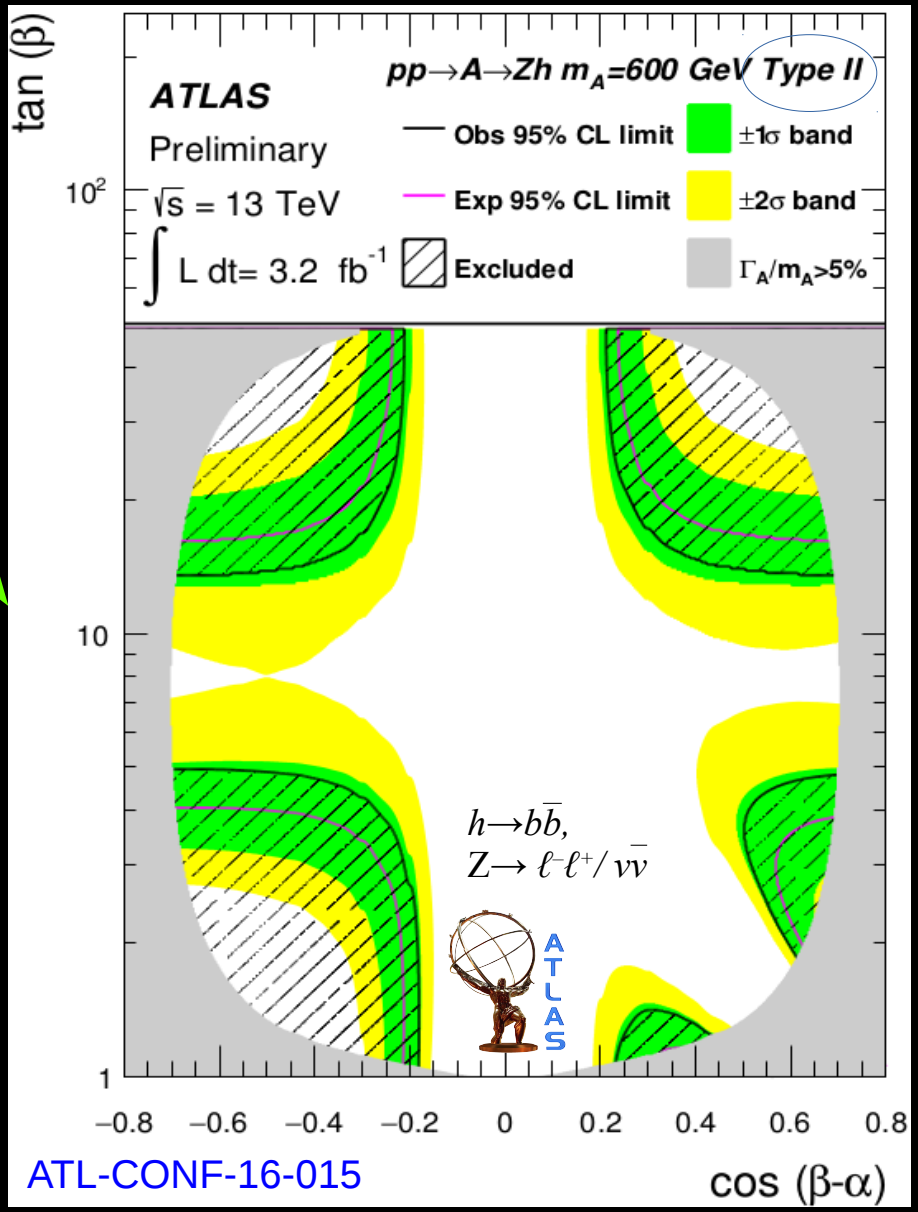




Additional Higgs bosons



$A \rightarrow Zh$



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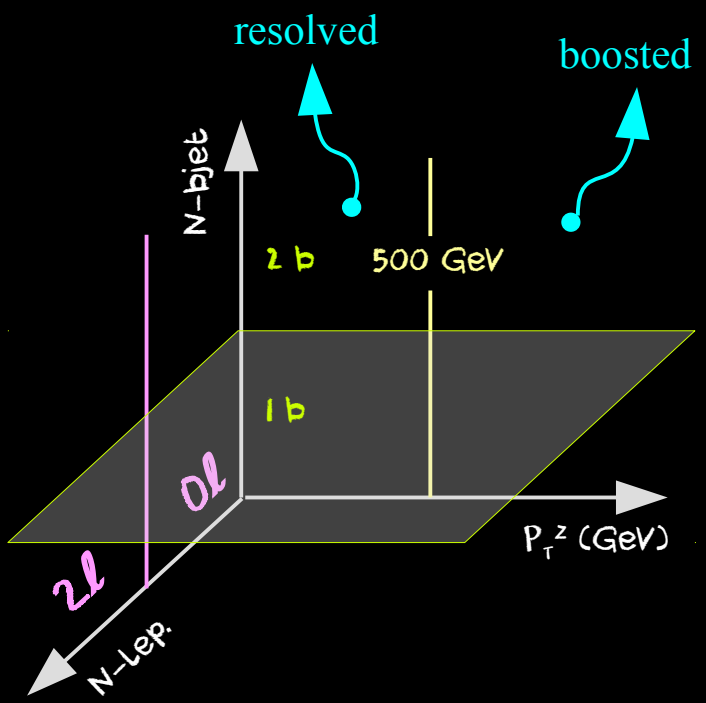
Lepton	H_1	H_2	H_2	H_1

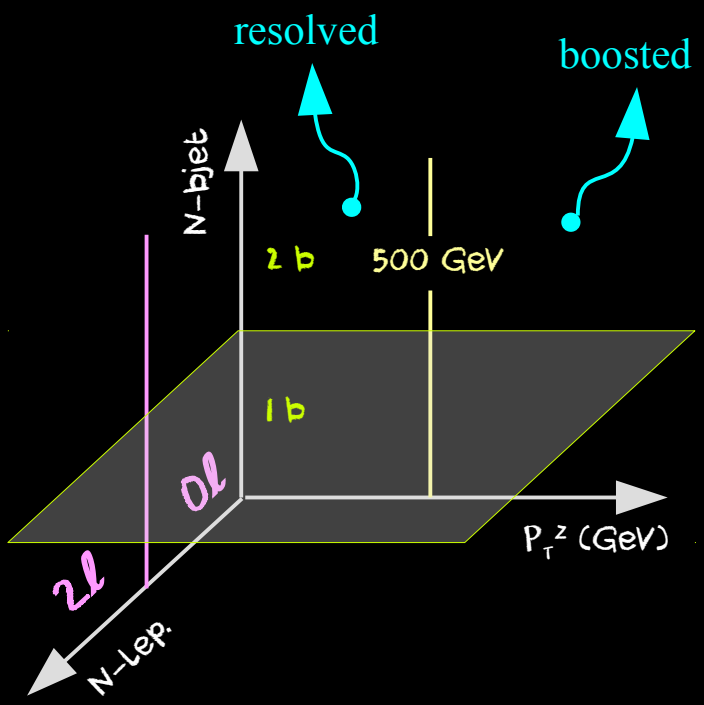
$A \rightarrow Zh$: $h \rightarrow b\bar{b}$, $Z \rightarrow \ell^-\ell^+ / \nu\bar{\nu}$ 13 TeV



- Resolved: ≥ 2 small-R jets, m_{jj} compatible with m_h
- Boosted: ≥ 1 large-R jet, m_j compatible with m_h
- 2 lepton: $m_{\ell\ell}$ compatible with m_Z

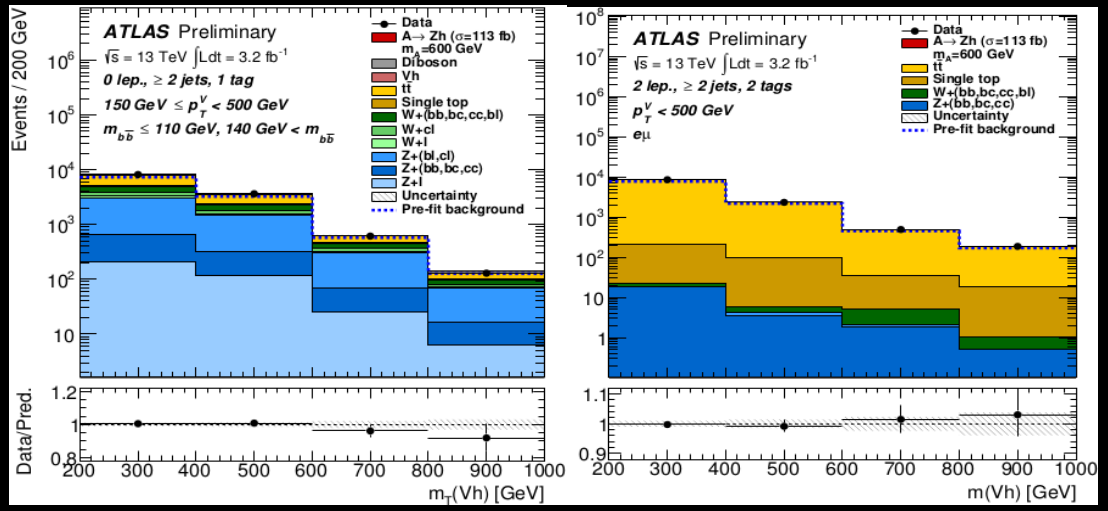
ATL-CONF-16-015

A → Zh: $h \to b\bar{b}$, $Z \to \ell^-\ell^+ / \nu\bar{\nu}$ 13 TeV



- Resolved: ≥ 2 small-R jets, m_{jj} compatible with m_h
- Boosted: ≥ 1 large-R jet, m_j compatible with m_h
- 2 lepton: $m_{\ell\ell}$ compatible with m_Z

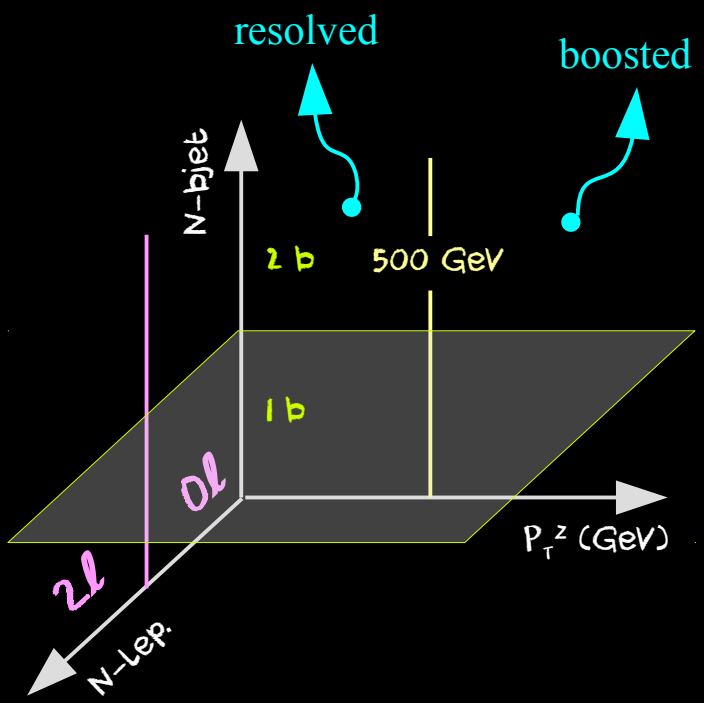
- Backgrounds: control regions included in the fit
  - V+jets: side band in m_{jj}
  - $t\bar{t}$: eμ sample, 2ℓ, low p_T^Z

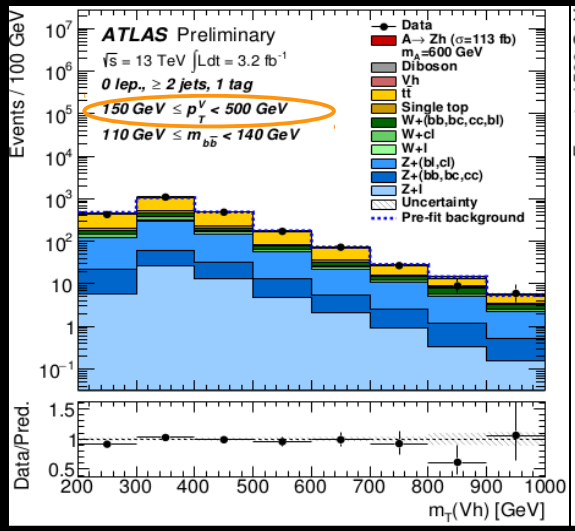


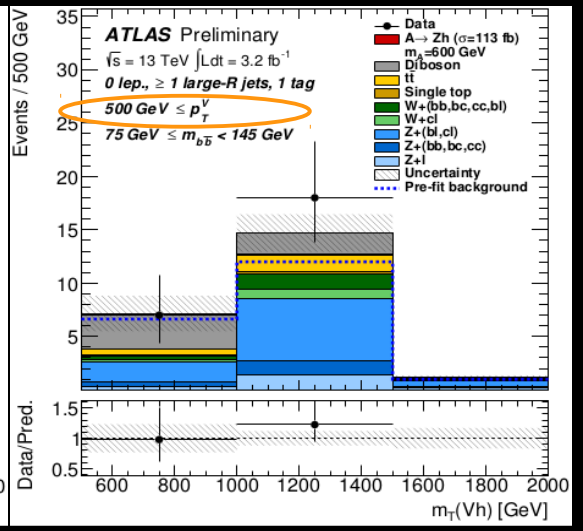
- Search variables:
  - 2ℓ: m(Z*h*)
  - 0ℓ: m_T(Z*h*)

ATL-CONF-16-015

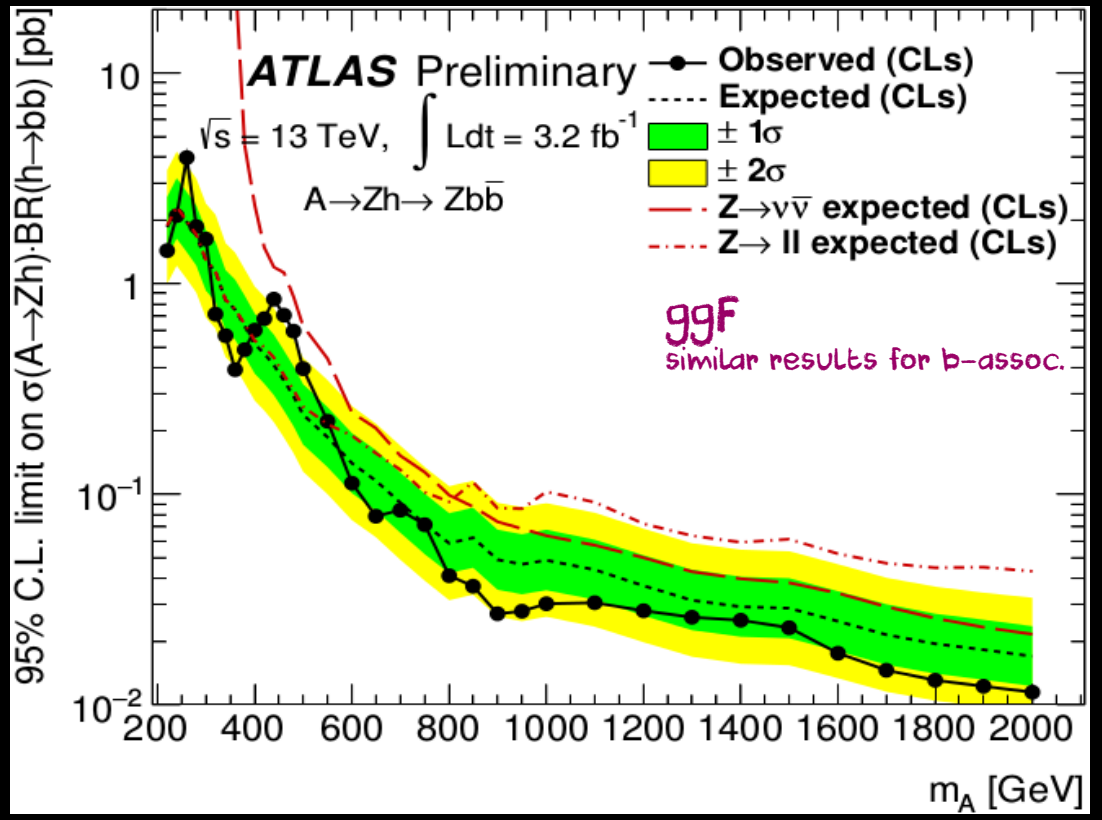
$A \to Zh$: $h \to b\bar{b}$, $Z \to \ell^-\ell^+ / \nu\bar{\nu}$ 13 TeV





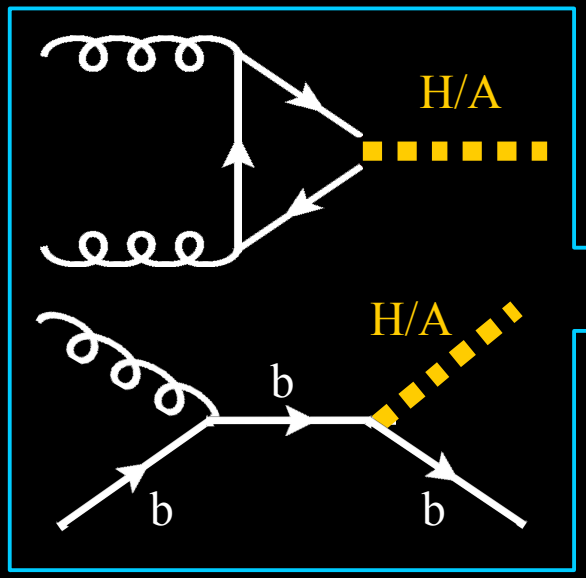


- Search variables:
  - 2ℓ: m(Zh)
  - 0ℓ: m_T(Zh)



ATL-CONF-16-015

MSSM H/A: $H/A \to \tau\bar{\tau}$ 13 TeV



$H/A \to \tau_\mu \tau_h,\ \tau_e \tau_h,\ \tau_h \tau_h$

Backgrounds

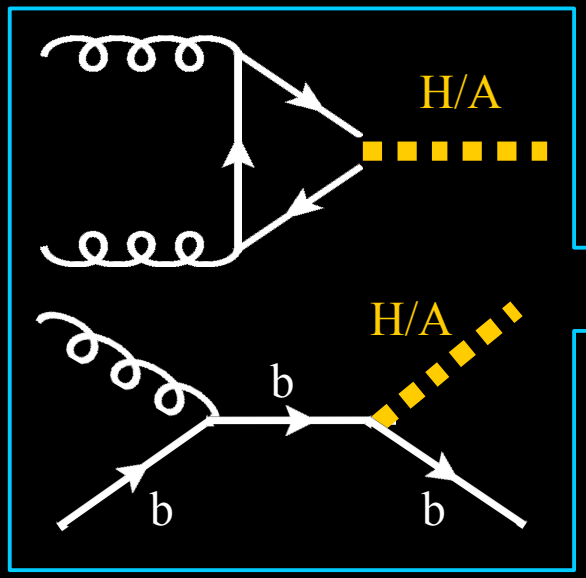
"Jet $\to \tau_h$": fake factor method in data

$Z \to \ell\ell$ (in $\tau_\ell \tau_h$): corrected using Z-peak region data

Search variable: $m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1) + m_T^2(E_T^{miss}, \tau_2) + m_T^2(\tau_1, \tau_2)}$

ATL-CONF-15-061

MSSM H/A: $H/A \to \tau\bar{\tau}$ 13 TeV

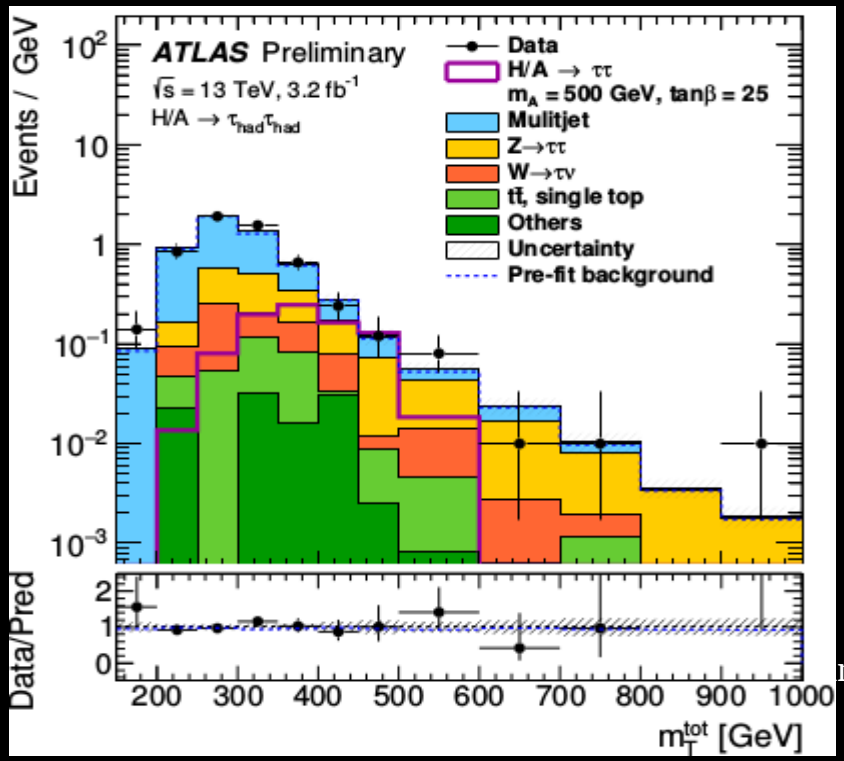


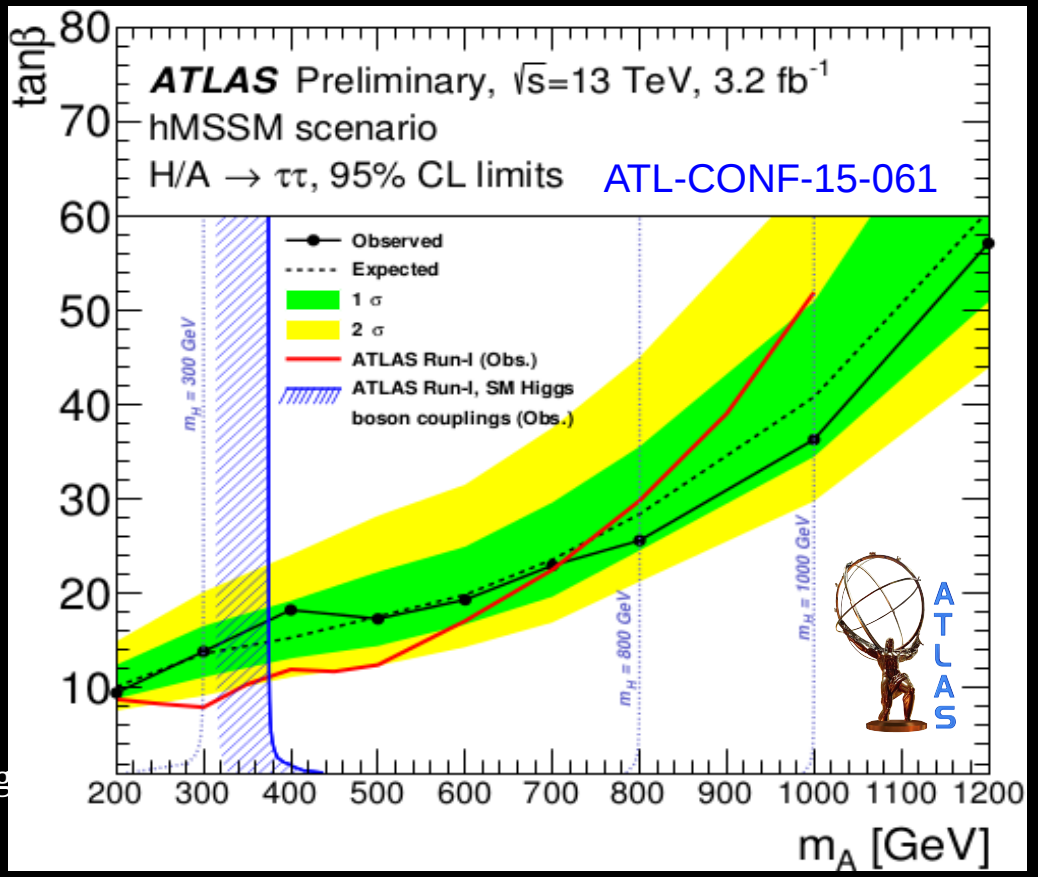
$H/A \to \tau_\mu\tau_h,\ \tau_e\tau_h,\ \tau_h\tau_h$

Backgrounds

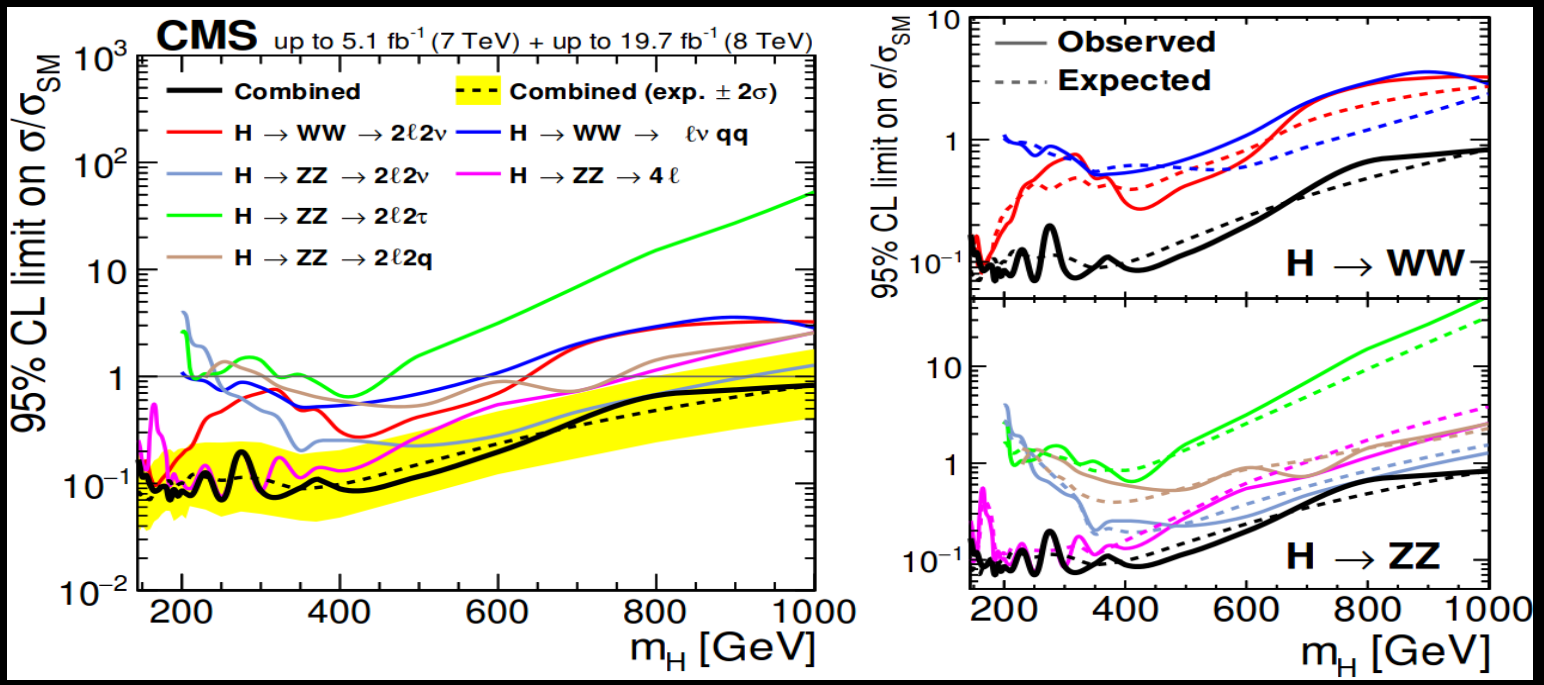
"Jet $\to \tau_h$": fake factor method in data

$Z \to \ell\ell$ (in $\tau_\ell\tau_h$): corrected using Z-peak region data

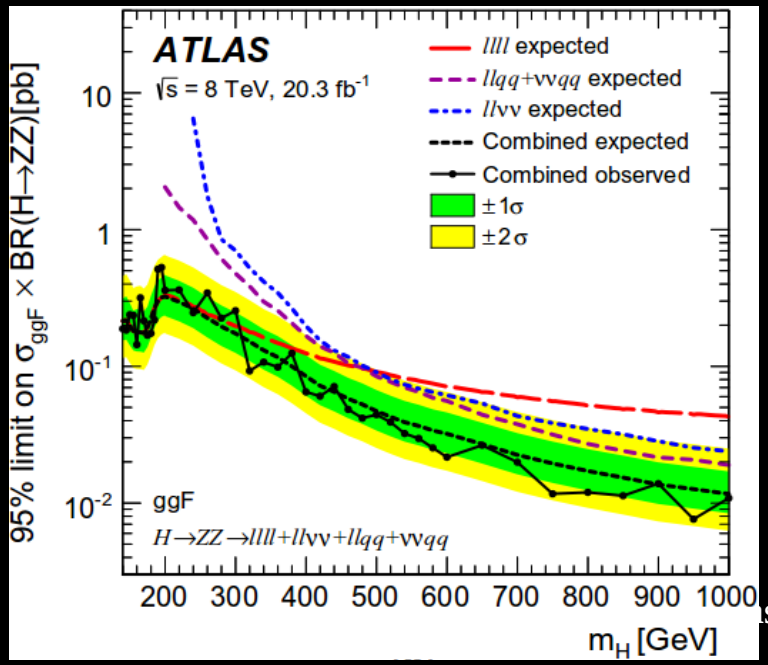




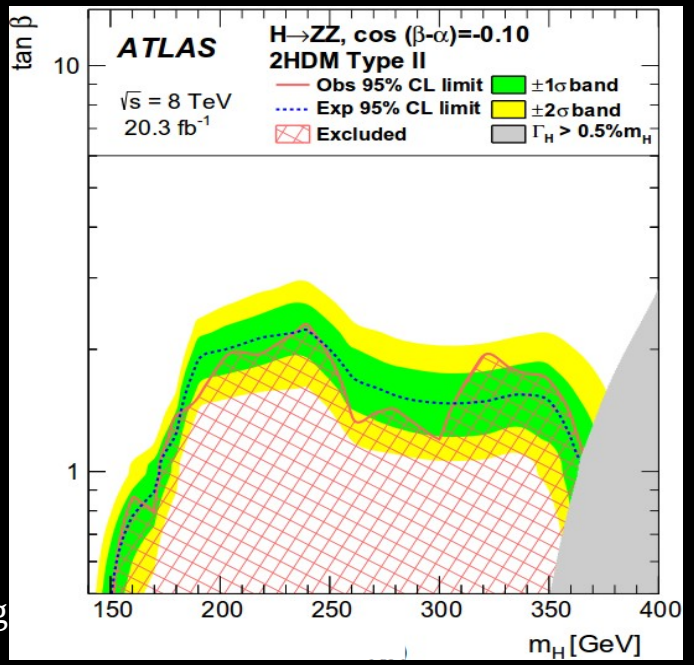
New H boson to *ZZ/WW*



arXiv:1504.00936 [hep-ex]



Eur. Phys. J. C 76 (2016)



New H boson to $ZZ \to \ell^-\ell^+ \nu\bar{\nu}$ 13 TeV

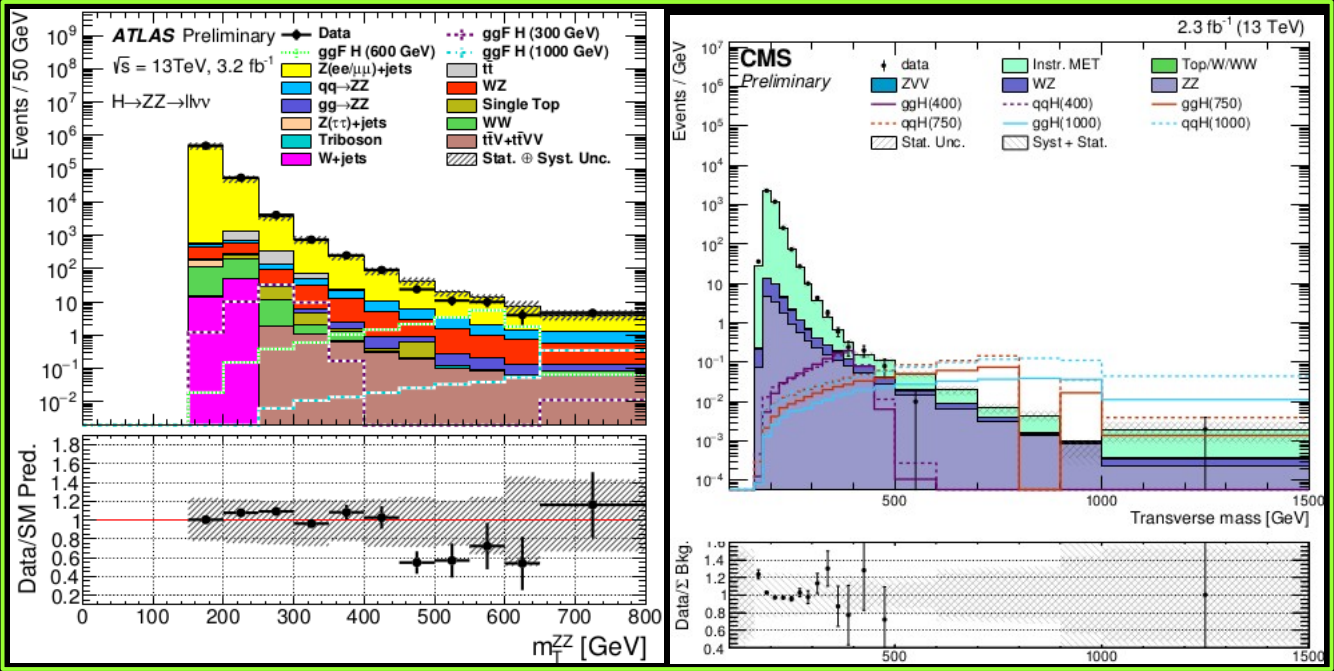
- $\ell^-\ell^+$ compatible with Z
- Large missing E_T
- No b-jet → against $t\bar{t}$
- CMS: 0, ≥ 1 b, VBF

Search variable

$$m_T^{(ZZ)} = \left(\sqrt{|p_T^{ll}|^2 + m_{ll}^2} + \sqrt{|E_T^{miss}|^2 + m_Z^2}\right)^2 - \left(\vec{p}_T^{\,ll} + \vec{E}_T^{\,miss}\right)^2$$

Backgrounds

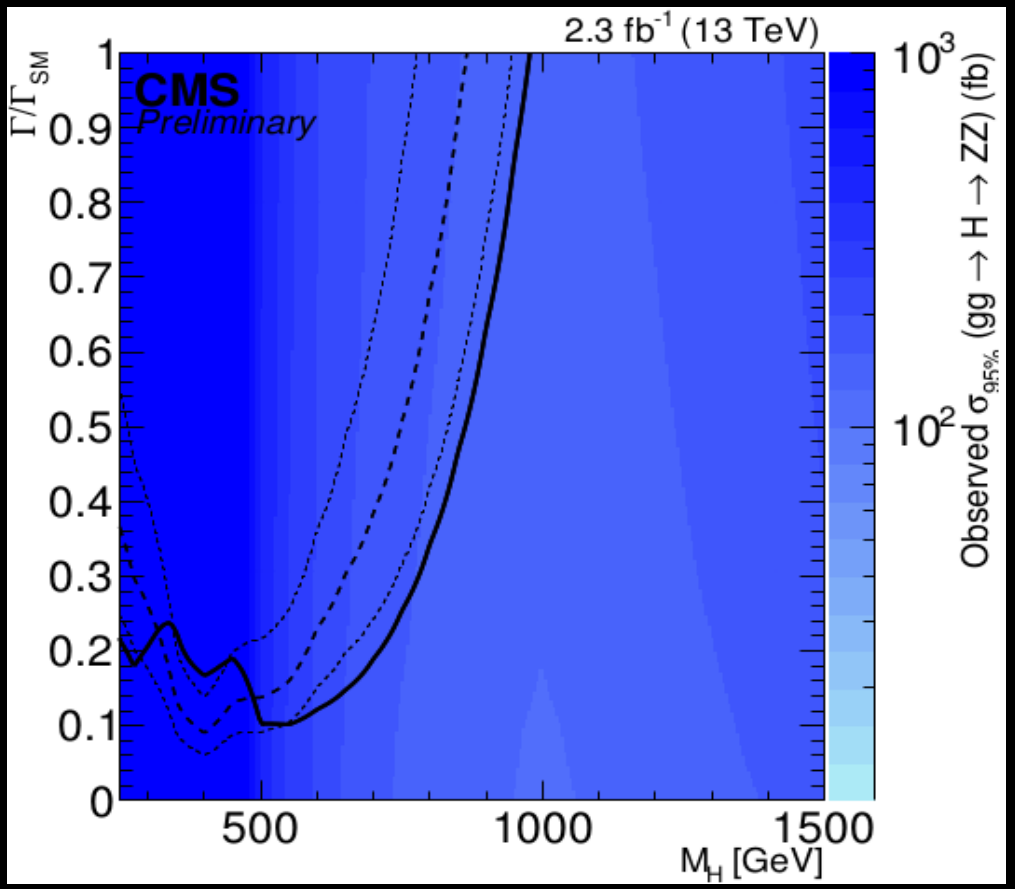
- $WW, t\bar{t}, \ldots$: from eμ CR
- Z+jets:
  - ATLAS: yield from data, shape from MC
  - CMS: γ+jets data
- WZ:
  - ATLAS: from 3ℓ data
  - CMS: MC

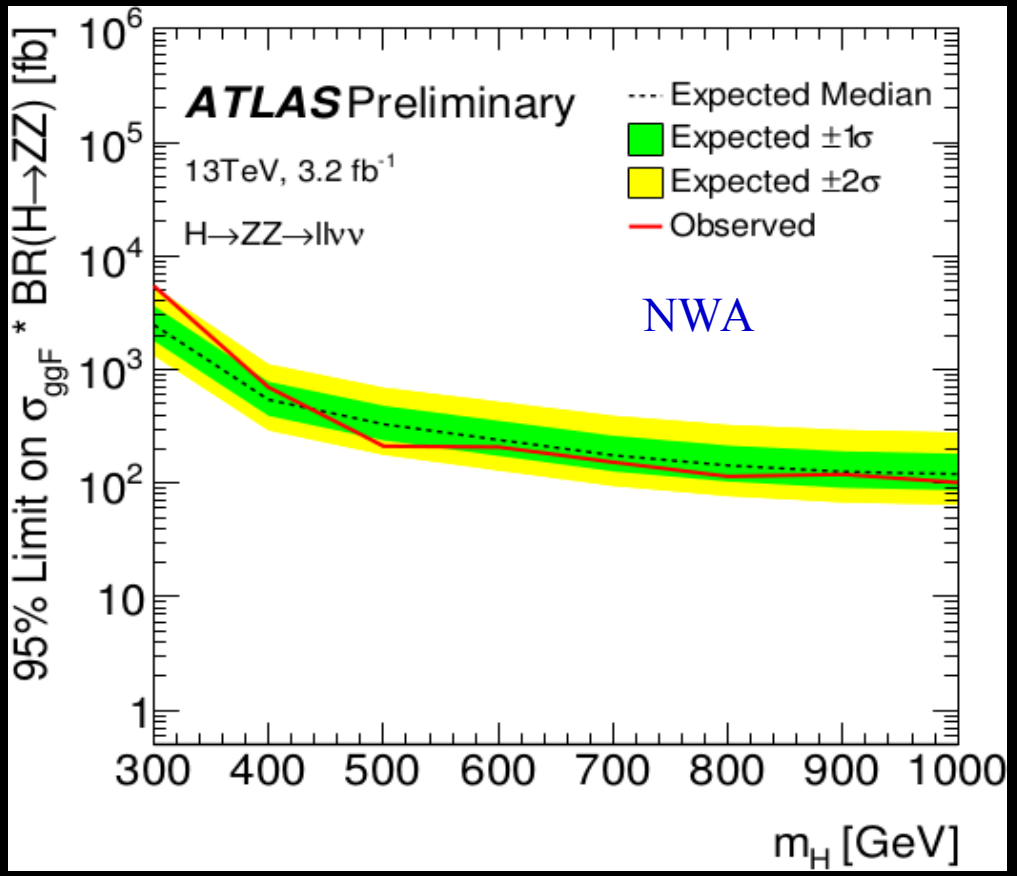


ATL-CONF-16-012

HIG-16-001

New H boson to $ZZ \to \ell^-\ell^+ \nu\bar{\nu}$ 13 TeV

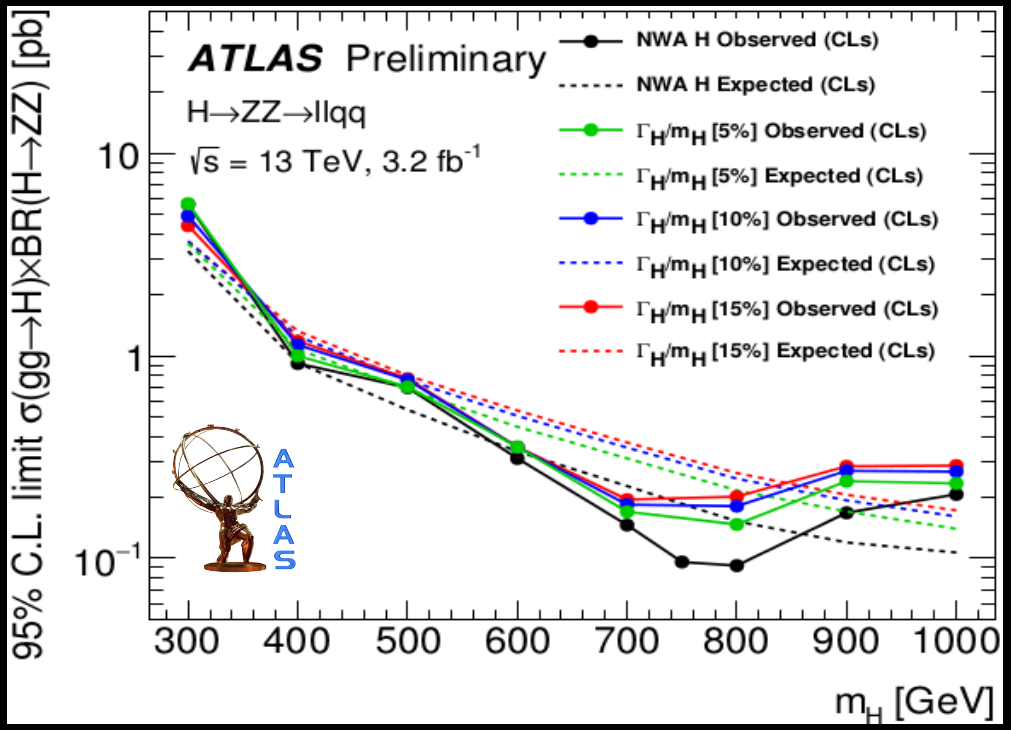


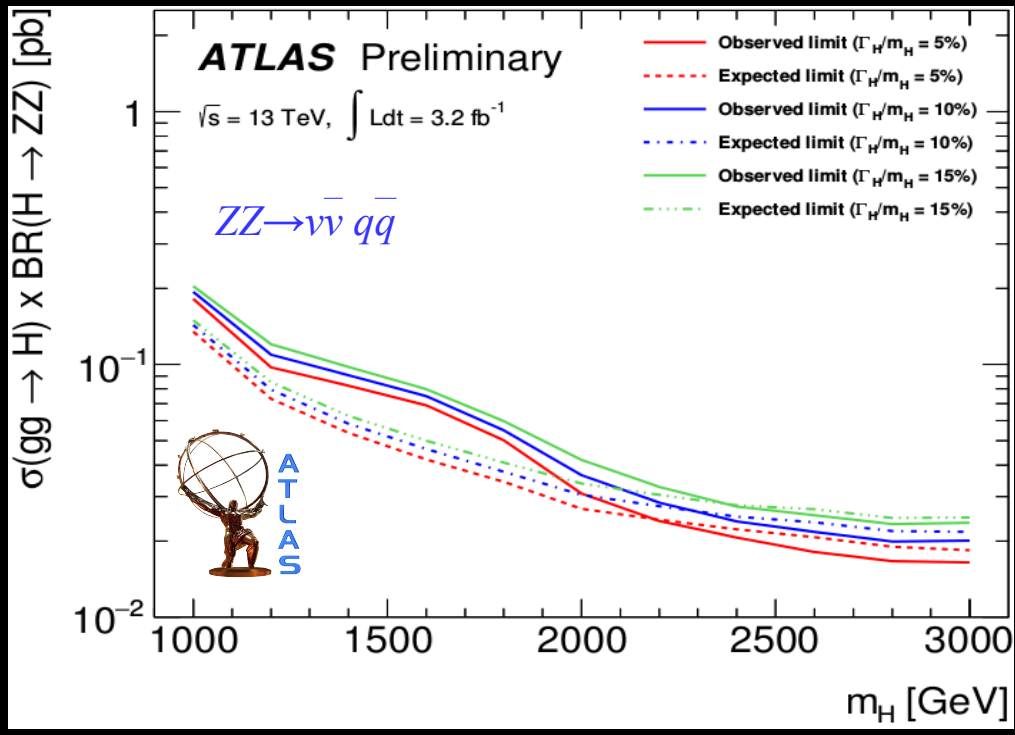


HIG-16-001

ATL-CONF-16-012

New H boson to $ZZ \to (\ell^-\ell^+/\nu\bar{\nu})\, q\bar{q}$ 13 TeV





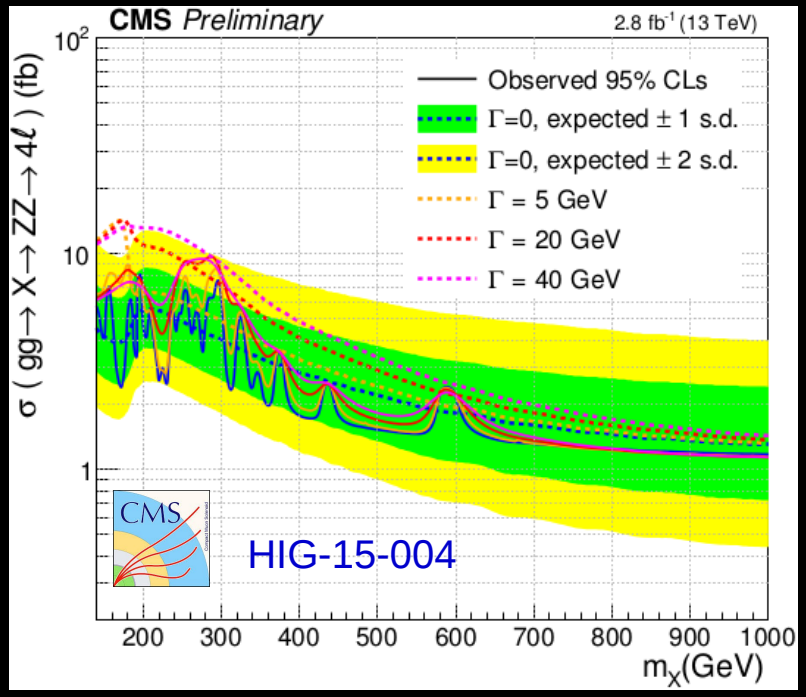
- Boosted:
  - Z-tagged jet
  - Search over $m_{\ell\ell J}$ distribution
- Resolved:
  - 2-b and less-b regions
  - Search over $m_{\ell\ell jj}$

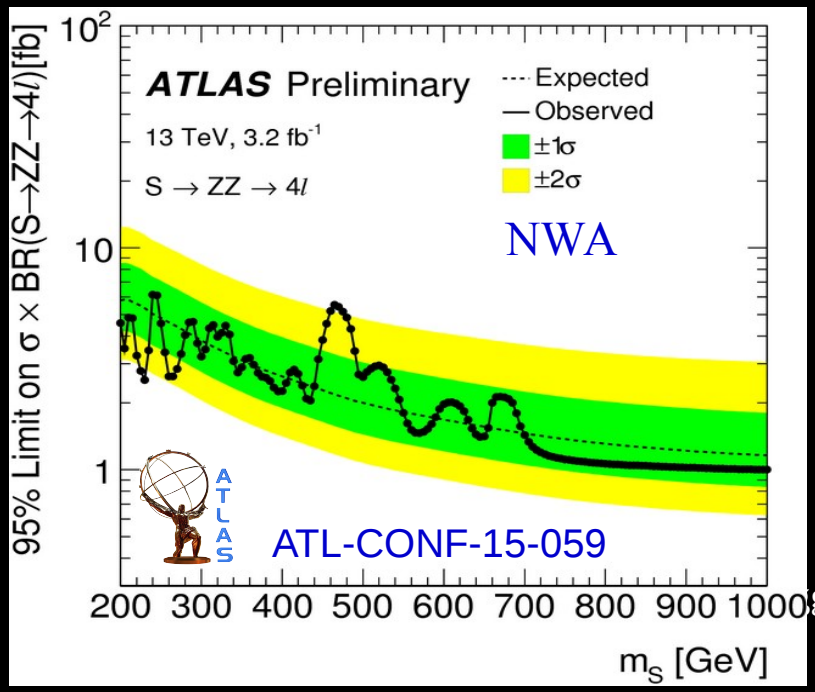
ATL-CONF-16-016

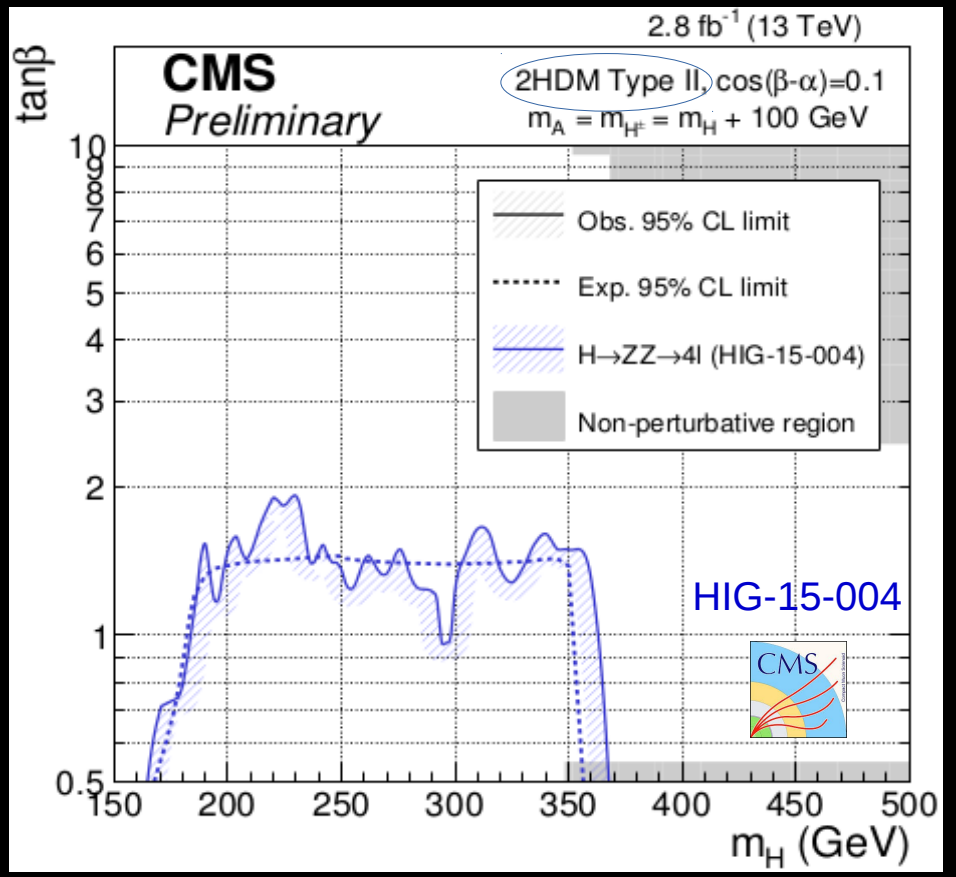
- Boosted:
  - Z-tagged jet
  - Large missing E_T
  - Search over $m_T(E_T^{miss}, J)$ distribution

ATL-CONF-15-068

New H boson to $ZZ \to \ell^-\ell^+\ell^-\ell^+$ 13 TeV





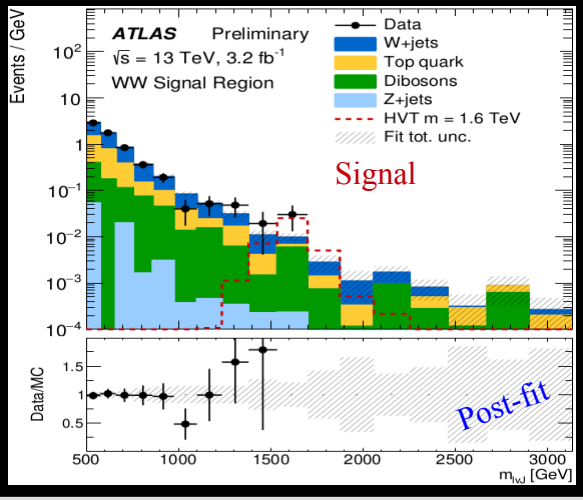


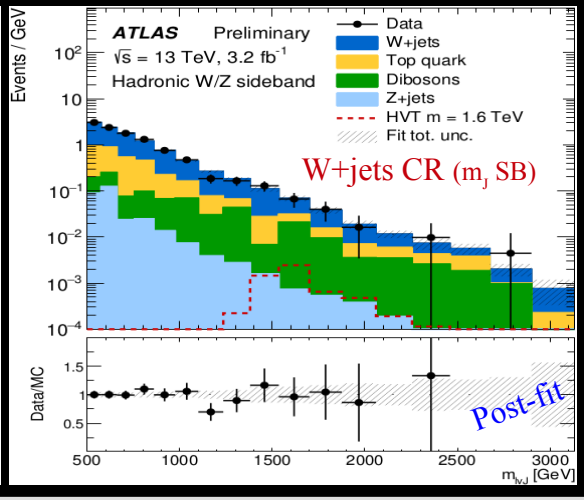
Using the sample of the SM Higgs analysis in search for a resonance

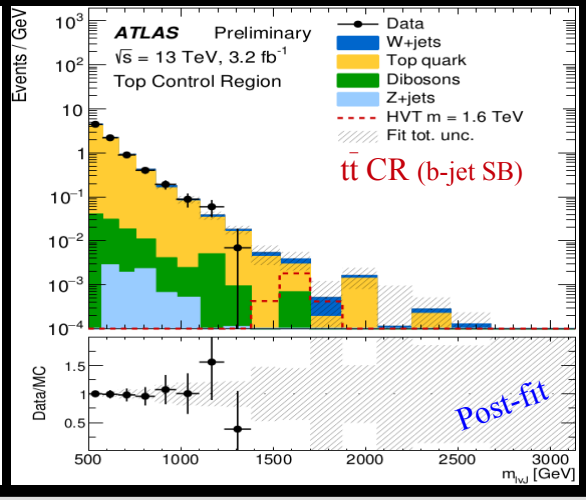
New H boson to $WW \rightarrow \ell\nu qq'$ 13 TeV

Boosted W → qq': W-tagged jet, $m_J \sim m_W$

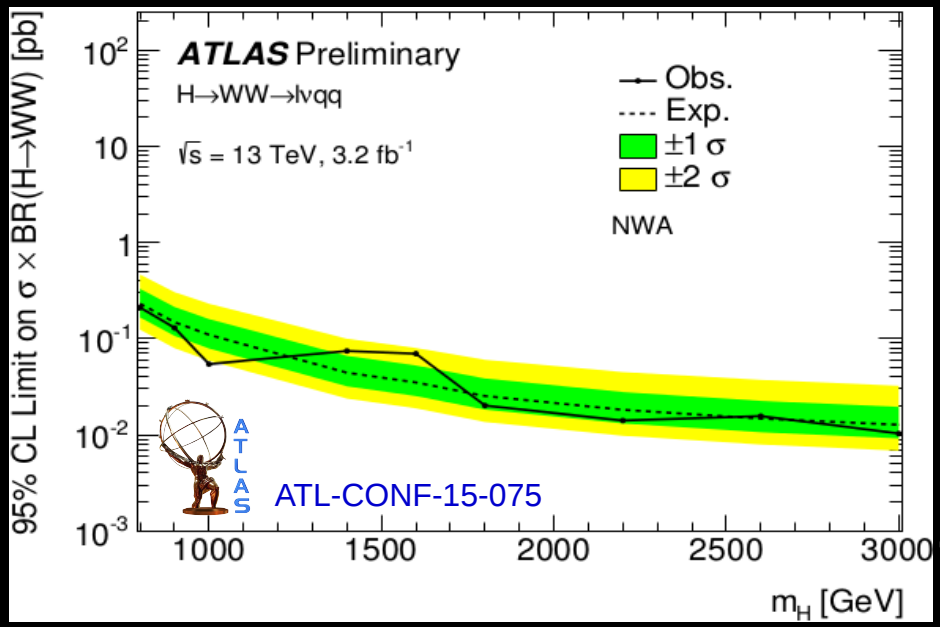
Search over $m_{\ell\nu J}$ distribution

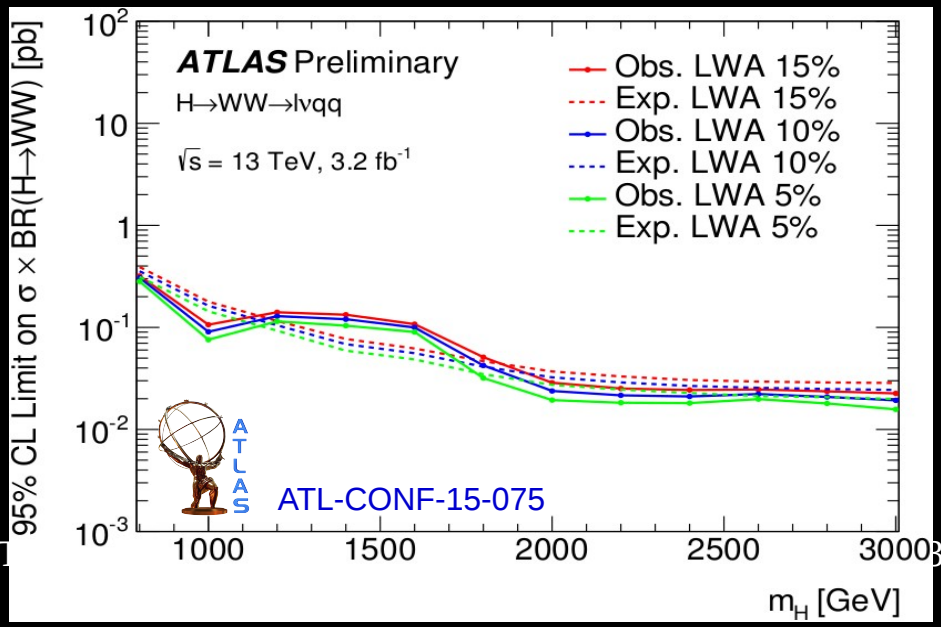




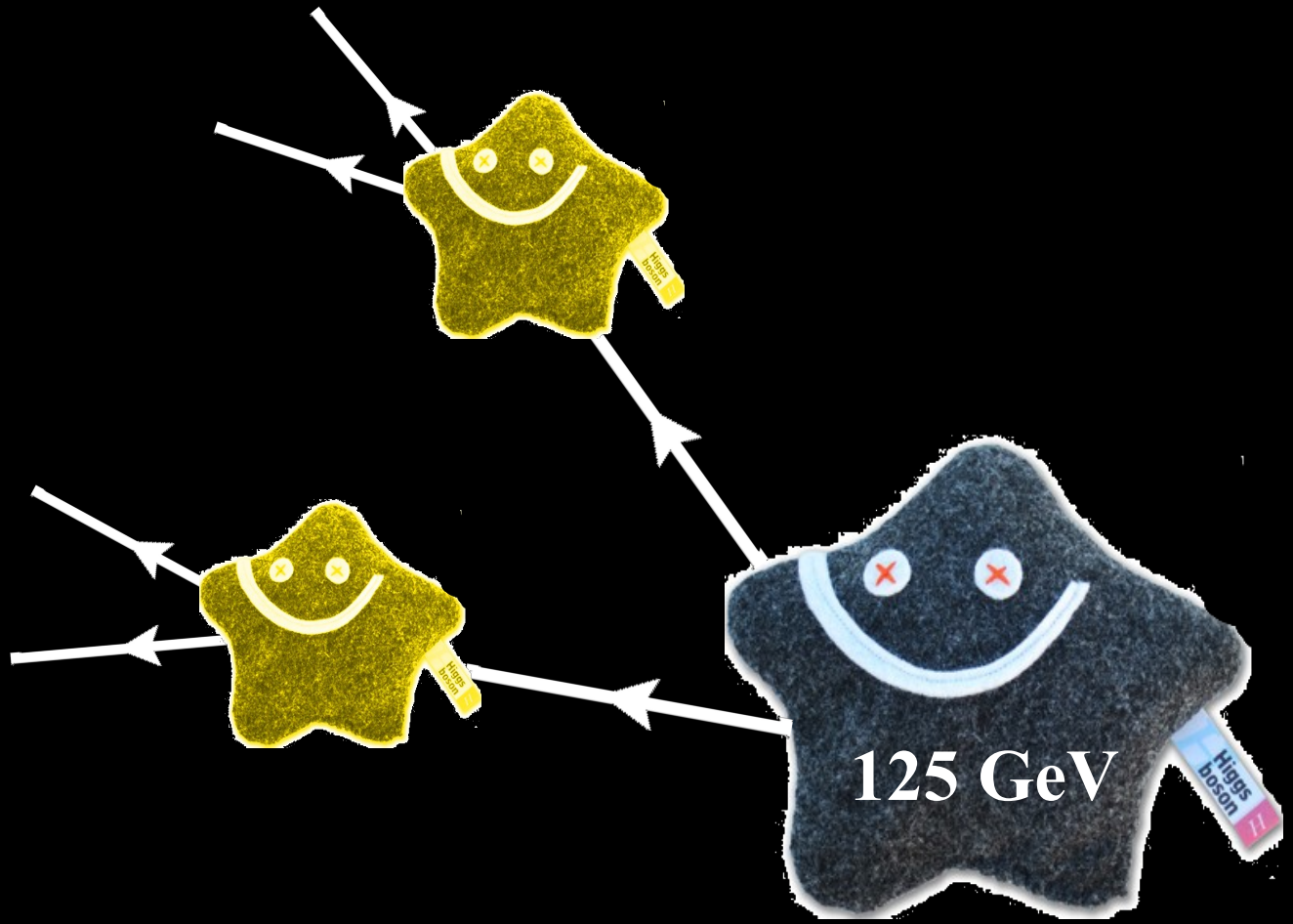


Simultaneous fit

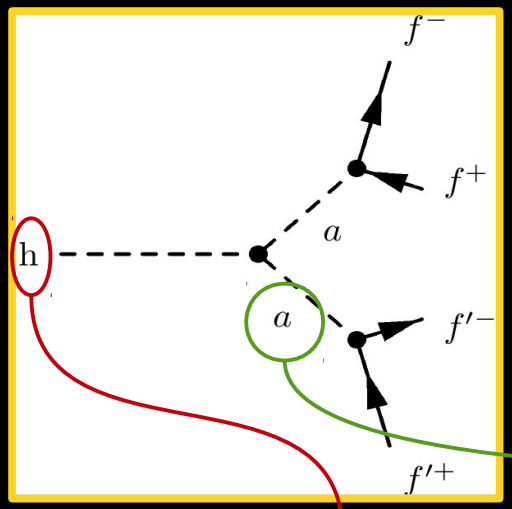




Γ > 15% mostly excluded



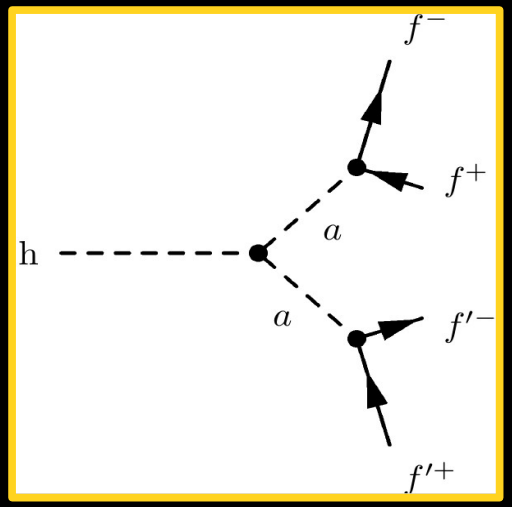
HIGGS EXOTIC DECAYS



- LHC Run I: BR(h→ BSM) < 0.34
  - A lot of room for rare & exotic decays of *h*
- Well motivated in the framework of NMSSM, 2HDM+S, …

A pseudoscalar, interacts with fermions via mixing with Higgs

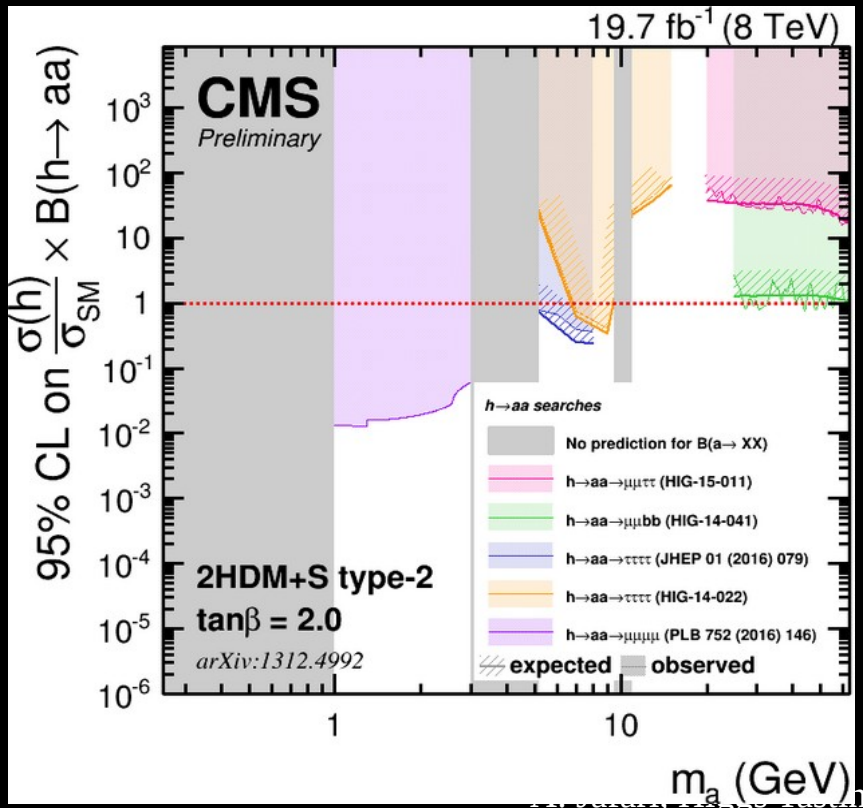
One of the light CP-even Higgs in the model identified as h(125)

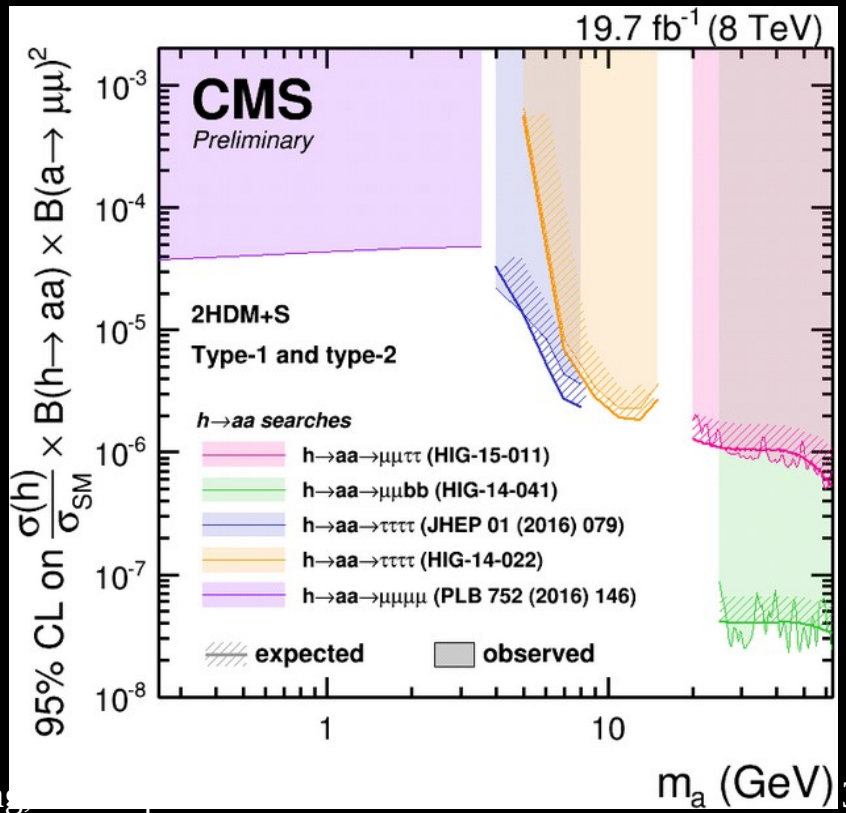


- LHC Run I: BR(h→ BSM) < 0.34
  - A lot of room for rare & exotic decays of *h*
- Well motivated in the framework of NMSSM, 2HDM+S, …

Explored final states:

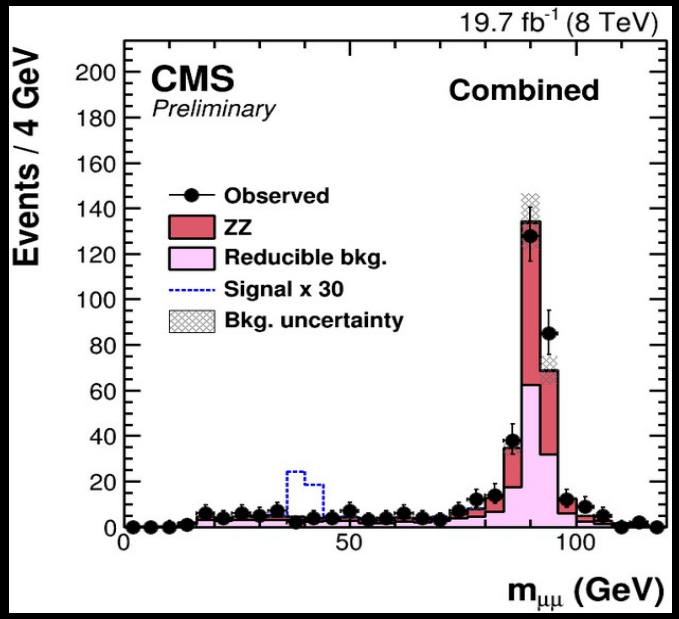
- ATLAS: 2μ2τ (Phys. Rev. D92 (2015) 052002), 4γ (CERN-PH-EP-2015-187)
- CMS: 2μ2b (HIG-14-041), 4μ (CMS:Phys. Lett. B 752 (2016) 221), 2μ2τ (HIG-15-011), 4τ (HIG-14-022, JHEP 01 (2016) 079)

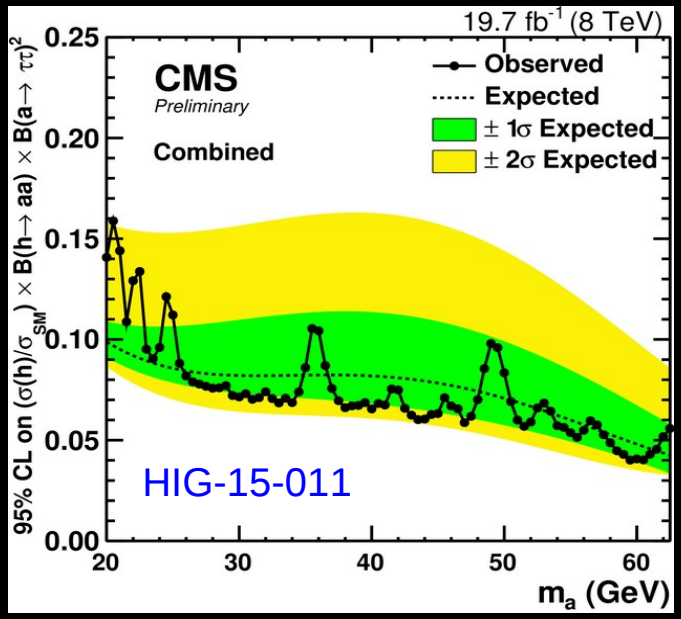


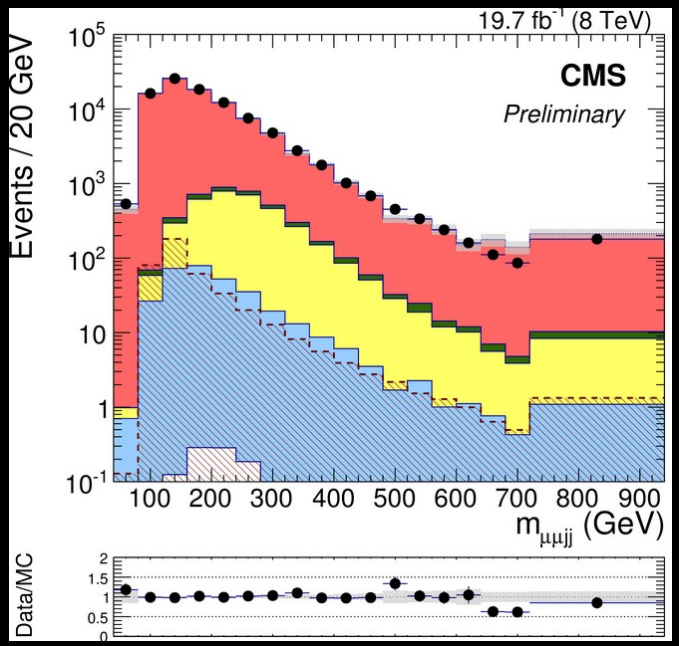


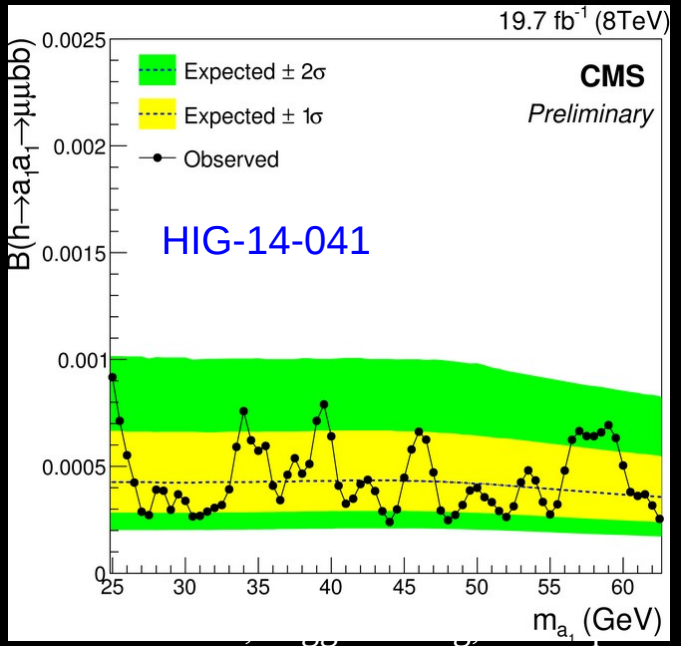
Highly benefit from the upcoming large Run II data sample

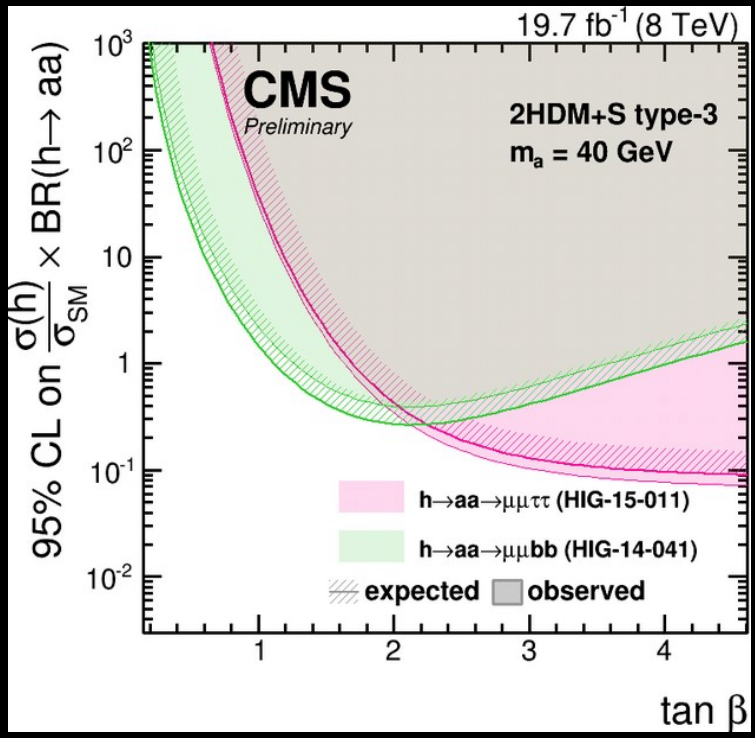
Exotic *h* decays: $h \to aa \to (2b/2\tau)2\mu$ 8 TeV







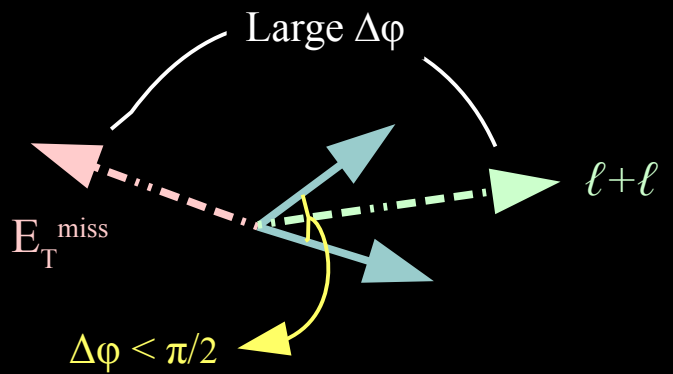




Inspired from Phys. Rev. D 90, 075004 (2014)

INVISIBLE HIGGS

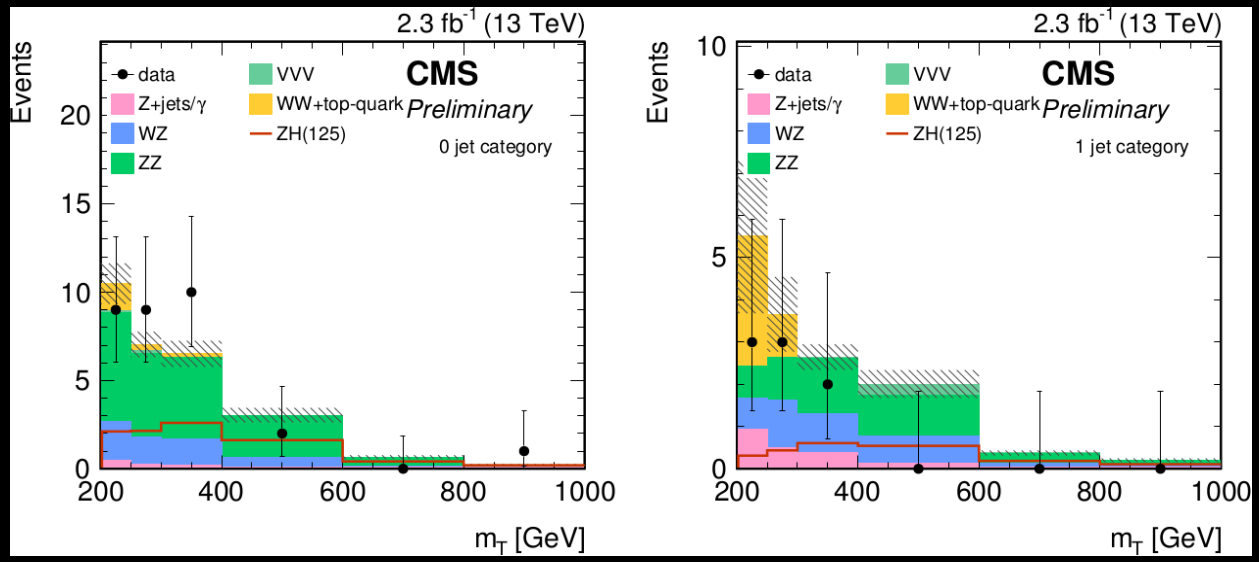
Invisible Higgs: $ZH \to \ell^-\ell^+ + Inv.$ 13 TeV

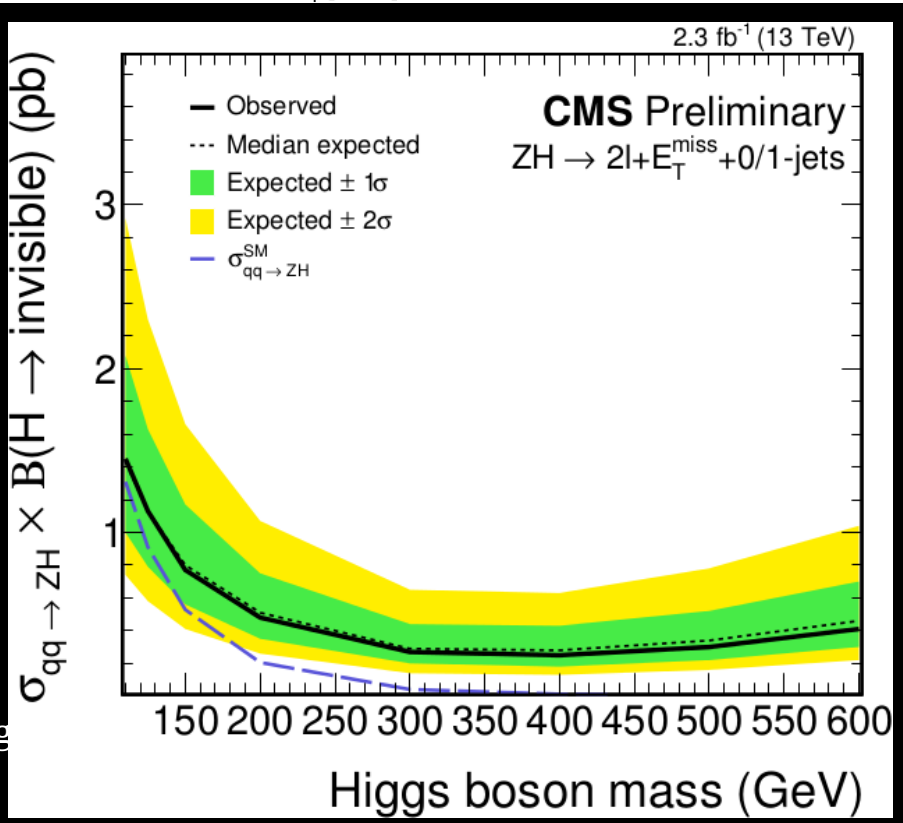


- 2 leptons compatible with Z
- Large E_t^{miss}
- 0-jet and 1-jet categories
- Search variable: m_T

Background

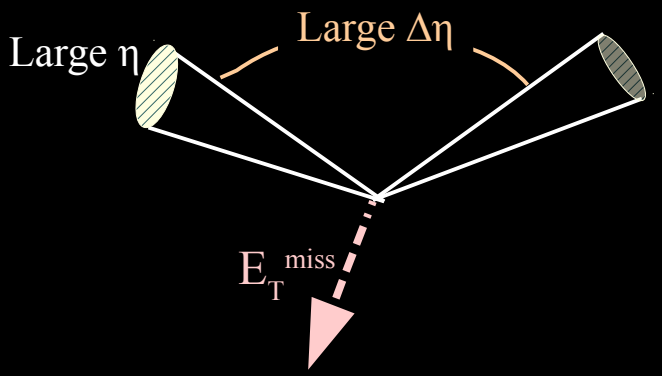
- Z+jets from γ+jets data
- Non-resonant from eμ





HIG-16-008

Invisible Higgs: *VBF H →Inv.* 13 TeV



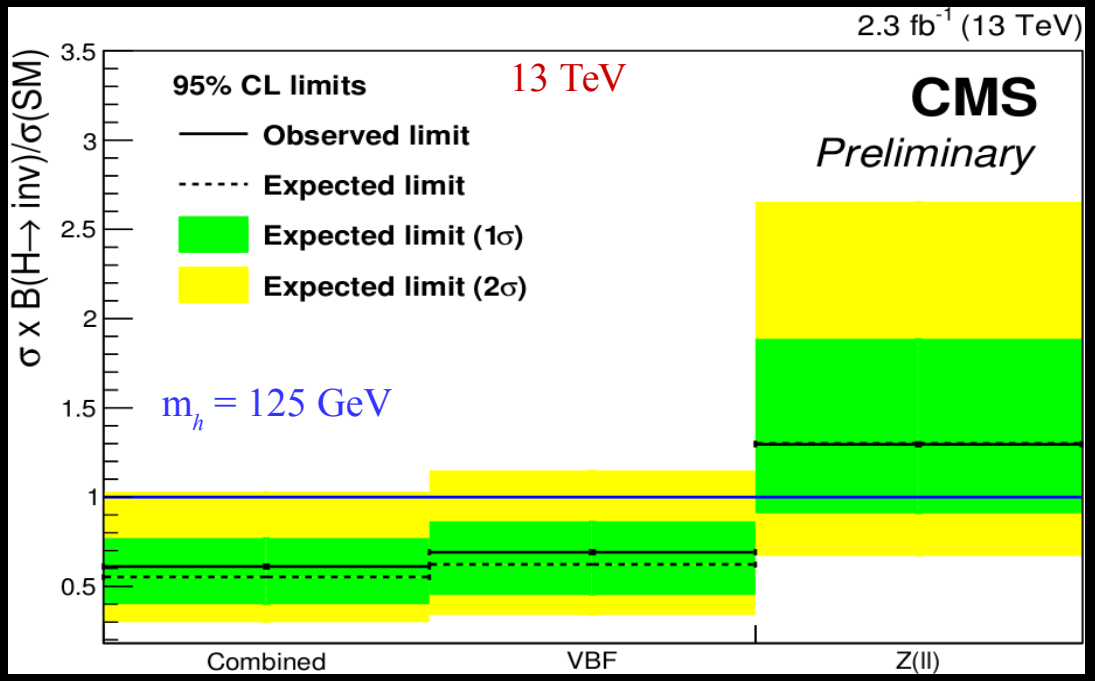
- 2 high p_T jets, large m_{jj}
- Large E_t^{miss}, well separated from jets

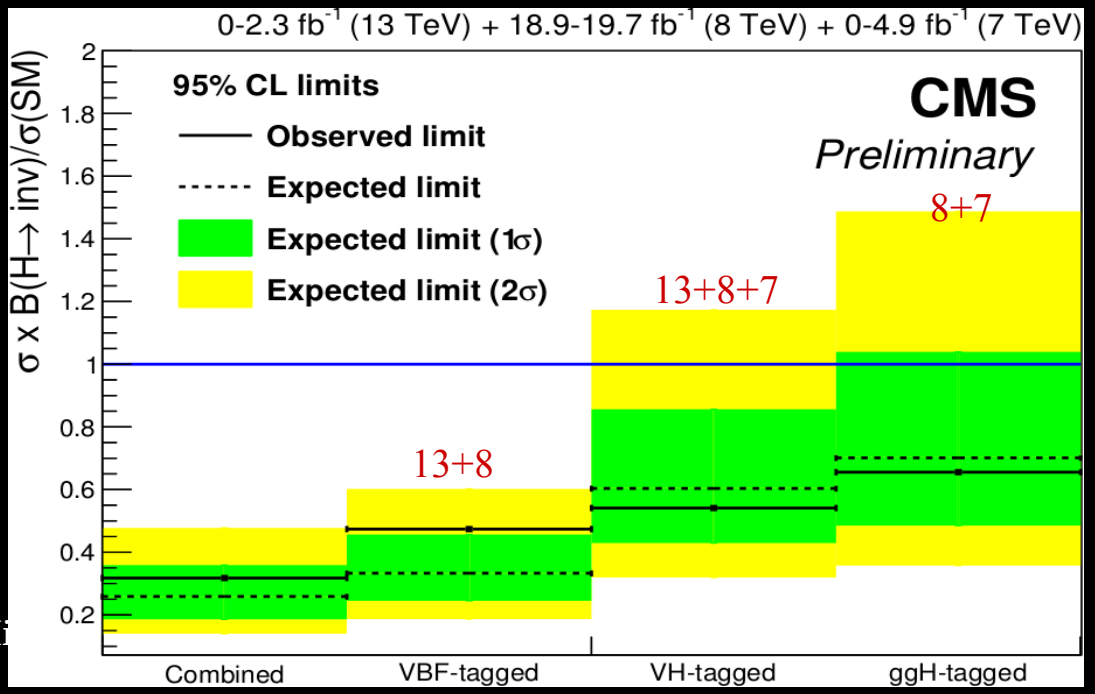
Background

- From control regions
  - Z(ℓℓ), W(ℓυ), QCD

Search strategy

- Simultaneous fit in all regions
- Counting experiment

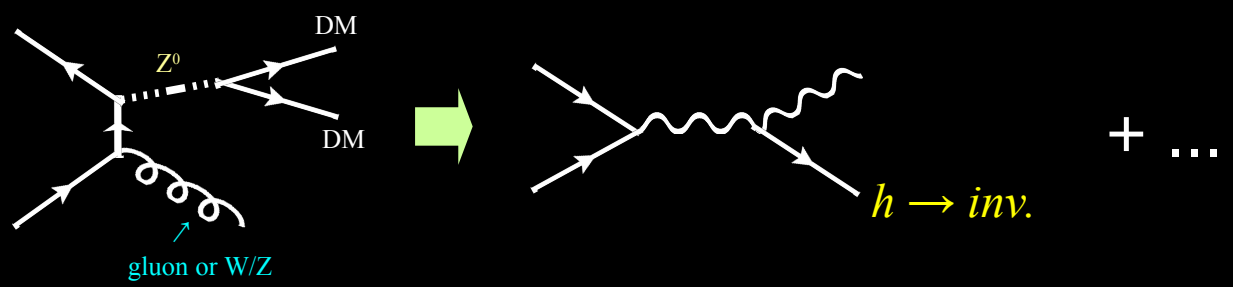




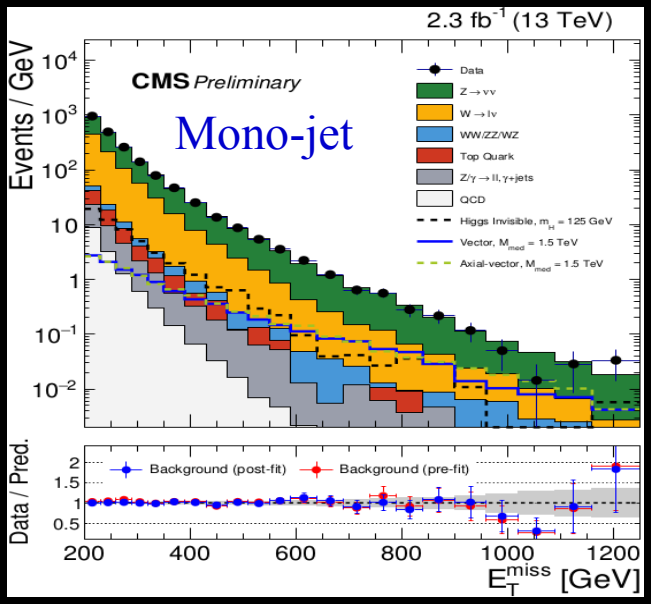
HIG-16-009

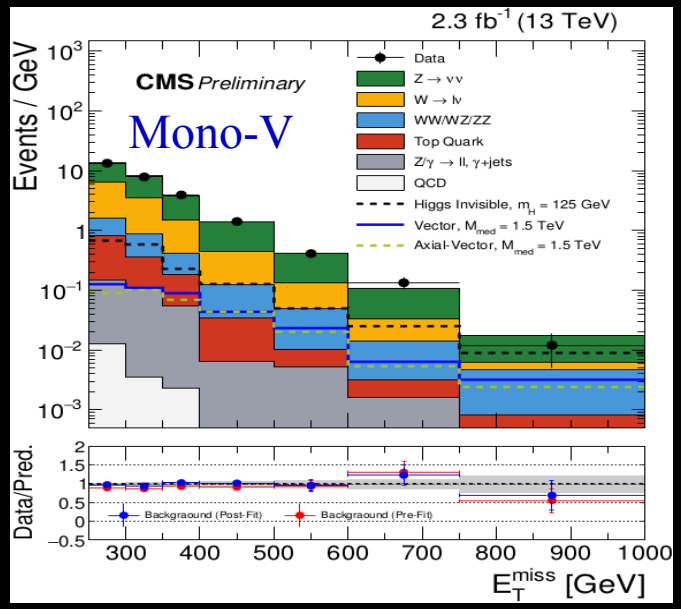
A. Jafari, Hi

Invisible Higgs: in DM searches 13 TeV



- Mono-jet & mono-V
- Single jet (V-tagged)
- Large E_T^{miss}, search variable
- 10 mutually exclusive CR's for Z(νν)/W(ℓν)+jets





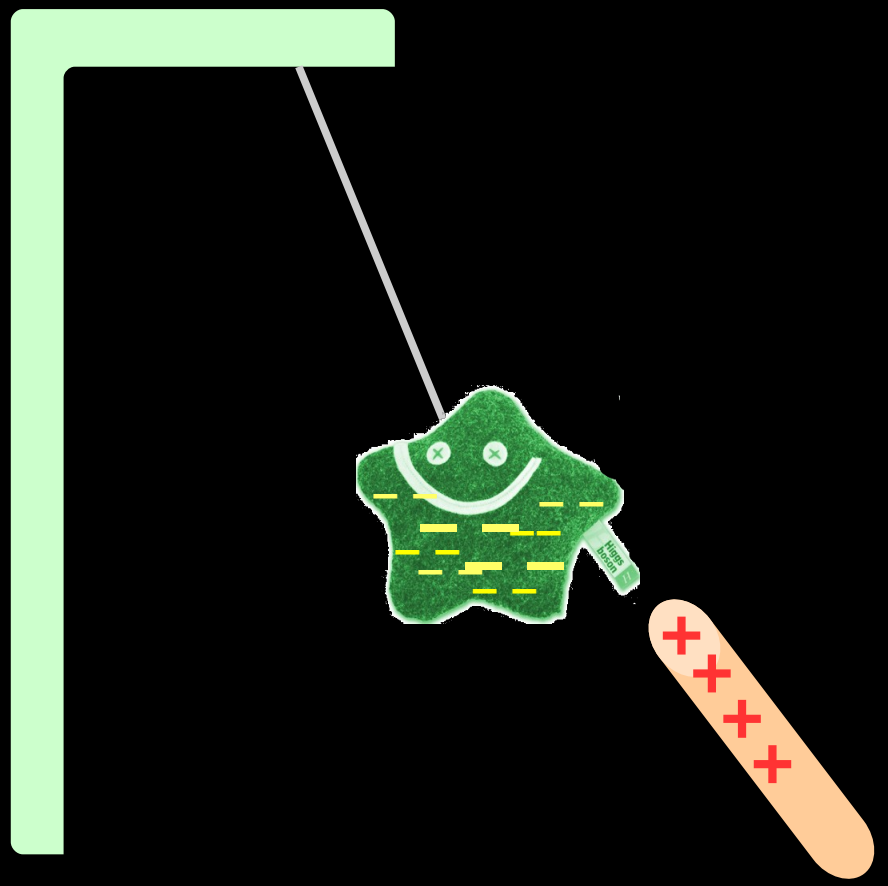
Simultaneous fit to signal regions and CR's:

- MC transfer factors to relate SR & CR yields
- Theory diff. σ_Z/σ_W is used

CMS

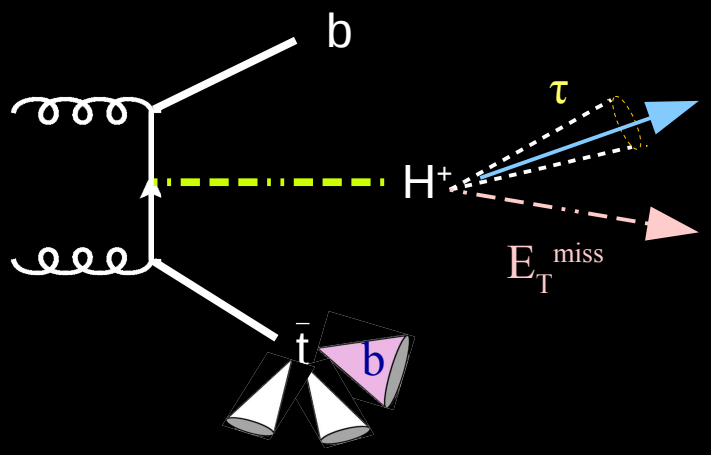
HIG-16-013

Category **$\sigma \times Br(h \to Inv) / \sigma_h$**	Exp. (Obs.) sensitivity	1σ range	Expected signal composition
Monojet	1.11 (1.46)	[0.76-1.64]	66% ggH, 25% VBF, 5% WH, 4% ZH
Mono-V	1.43 (1.04)	[1.02-2.10]	40% ggH, 7% VBF, 33% WH, 20% ZH
Mono-V + monojet	0.84 (0.85)	[0.59-1.22]	-



CHARGED HIGGS

Charged Higgs: $H^{\pm} \rightarrow \tau^{\pm}\upsilon$ 13 TeV



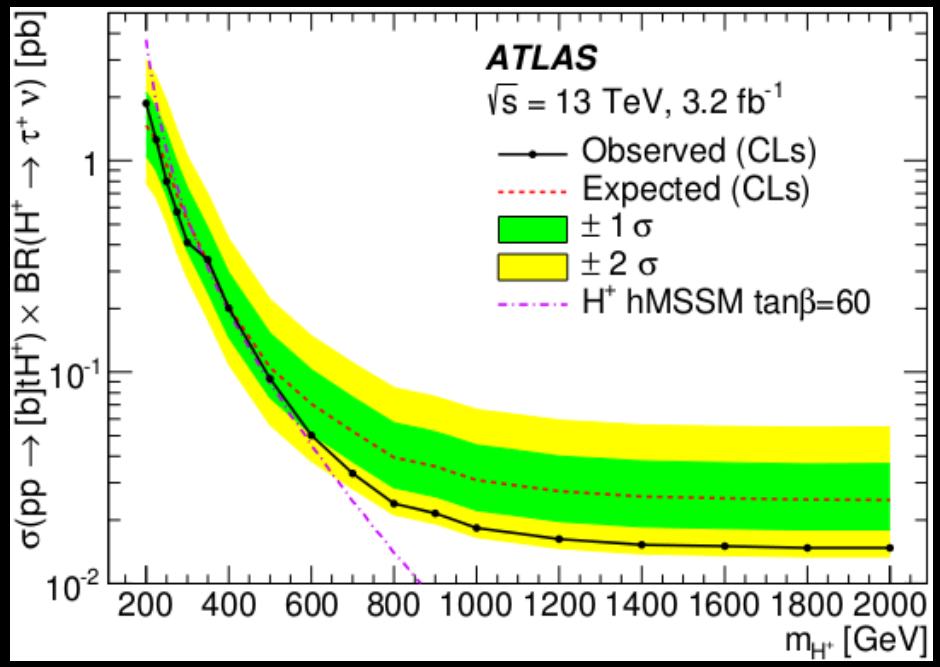
- One hadronic τ
- At least 3 jets, at least 1 b
- Large E_t^{miss}, large m_T^W

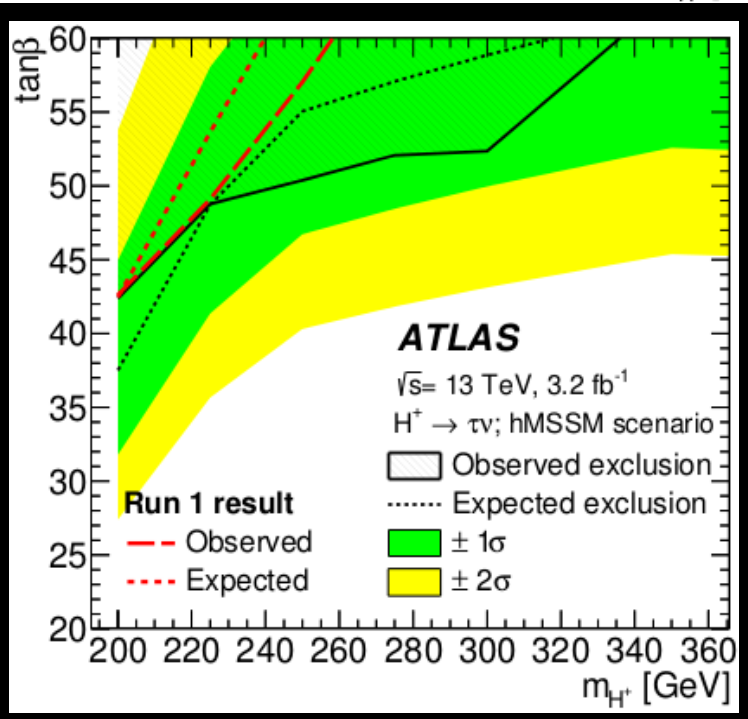
Background

- "Jet→ τ" fake rate from data
- W/$t\bar{t}$ in τυ corrected/validated in CR's with 0 or 2 b jets

Search strategy

- Fit to m_T distribution





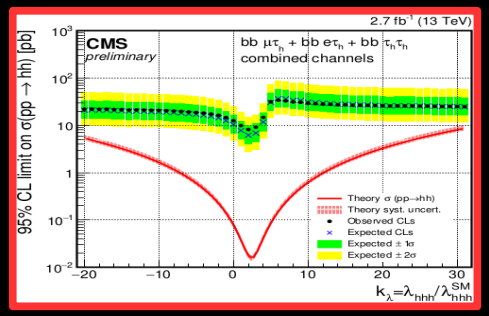
arXiv:1603:09203

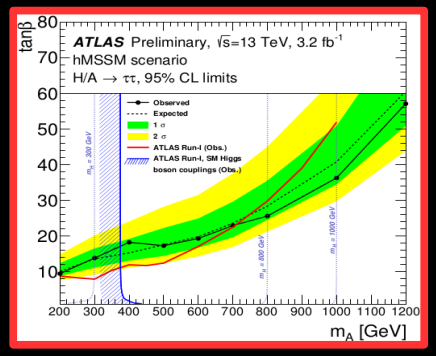
Summary

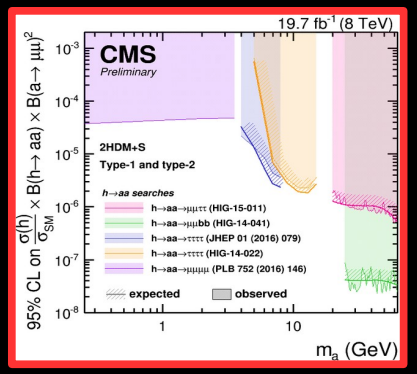
- LHC Higgs discovery is accompanied by a big question:

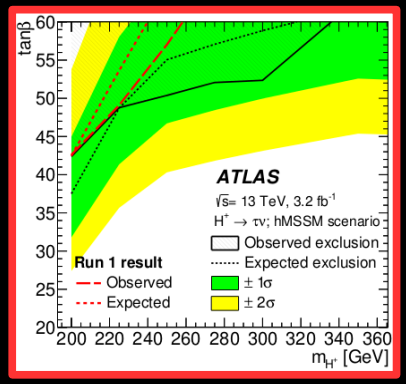
  Is this Higgs connected to BSM? How?!

- ATLAS and CMS have looked into many possibilities
  - Only a subset reviewed here!!









. . .

- Prospects for HL-LHC are also being studied
- Still many areas are not fully explored

  Benefits from more LHC data at higher energy
- Efforts are ongoing with the current data

STAY TUNED!!

BACKUP

Di-*h* production: $b\bar{b}b\bar{b}$ 13 TeV *(boosted)*

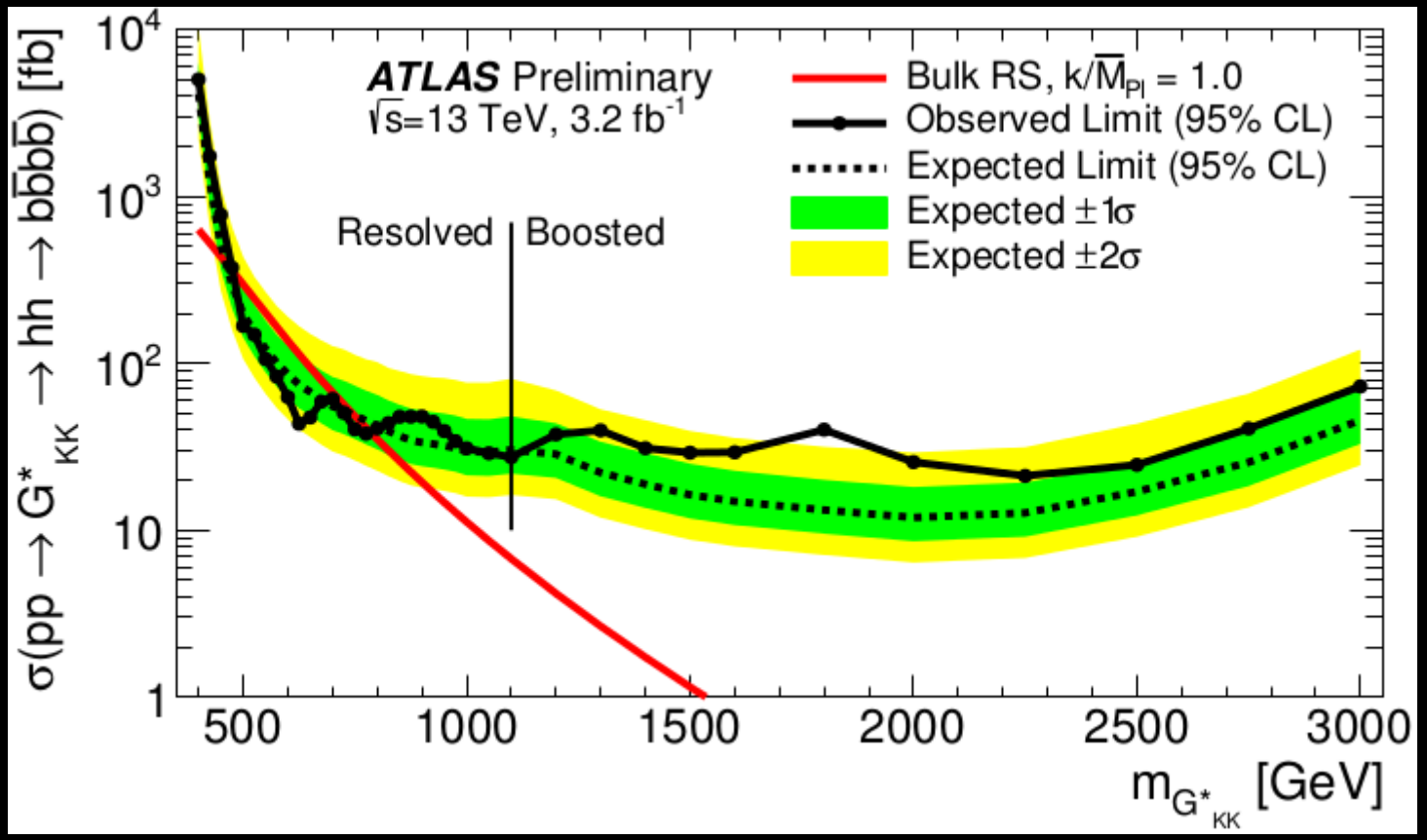
- 3-tag and >= 4-tag samples
- QCD shape from 2-tag sample with parametric tail

- QCD and ttbar from template fit

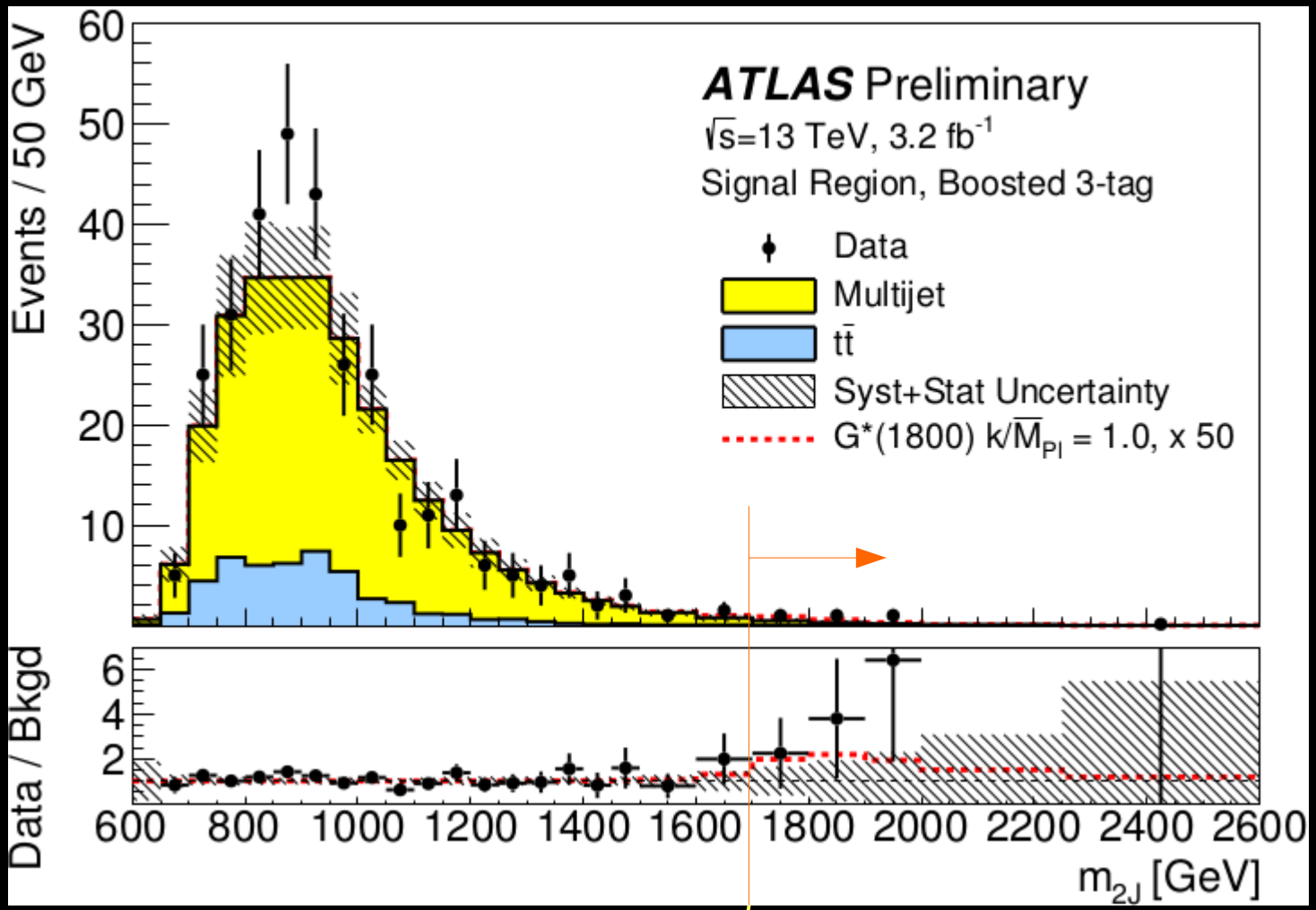
$$N_{\text{bkg}}^{3(4)-\text{tag}} = \mu_{\text{Multijet}} N_{\text{Multijet}}^{2-\text{tag}} + \alpha_{t\bar{t}} N_{t\bar{t}}^{3(4)-\text{tag}} + N_{Z+jets}^{3(4)-\text{tag}}$$

ATL-CONF-16-017

Di-*h* production: $b\bar{b}b\bar{b}$ 13 TeV *(boosted)*



Di-*h* production: $b\bar{b}b\bar{b}$ 13 TeV *(boosted)*



2.0 σ local significance for G^*_{KK} with $k/M_{pl} = 1$

Di-*h* production: $b\bar{b}b\bar{b}$ 13 TeV *(resolved)*

Combinatorics: pairs maximizing b-tag value
mass dependent cuts on p_T and η of dijets

$$p_{\mathrm{T}}^{\mathrm{lead}} > \begin{cases} 400\ \mathrm{GeV} & \text{if } m_{4j} > 910\ \mathrm{GeV}, \\ 200\ \mathrm{GeV} & \text{if } m_{4j} < 600\ \mathrm{GeV}, \\ 0.65 m_{4j} - 190\ \mathrm{GeV} & \text{otherwise}, \end{cases}$$

$$p_{\mathrm{T}}^{\mathrm{subl}} > \begin{cases} 260\ \mathrm{GeV} & \text{if } m_{4j} > 990\ \mathrm{GeV}, \\ 150\ \mathrm{GeV} & \text{if } m_{4j} < 520\ \mathrm{GeV}, \\ 0.23 m_{4j} + 30\ \mathrm{GeV} & \text{otherwise}, \end{cases}$$

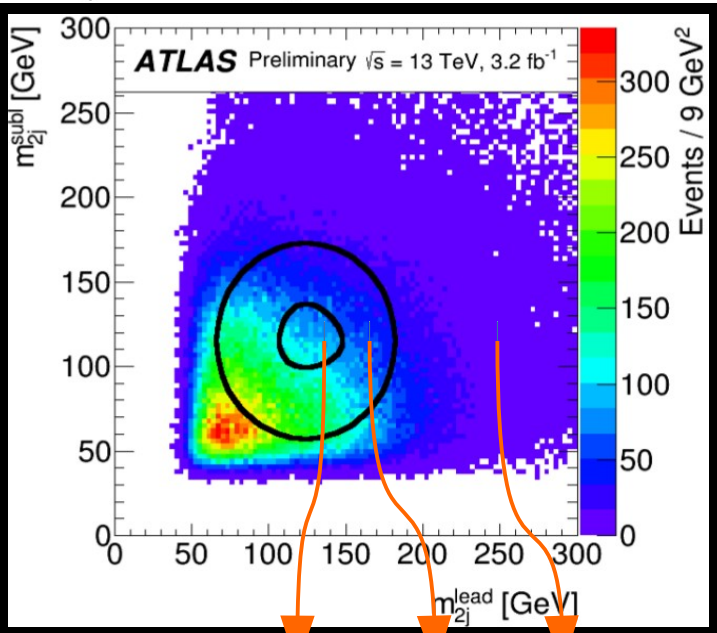
$$|\Delta\eta_{\mathrm{dijets}}| < \begin{cases} 1.0 & \text{if } m_{4j} < 820\ \mathrm{GeV}, \\ 1.6 \times 10^{-3} m_{4j} - 0.28 & \text{otherwise}. \end{cases}$$

Trigger: 1 – 2 b-tag

Reject ttbar:

$$X_{tt} = \sqrt{\left(\frac{m_W - 80.4\,\mathrm{GeV}}{0.1\, m_W}\right)^2 + \left(\frac{m_t - 172.5\,\mathrm{GeV}}{0.1\, m_t}\right)^2} > 3.2$$

Inverted cut: CR to estimate ttbar yield



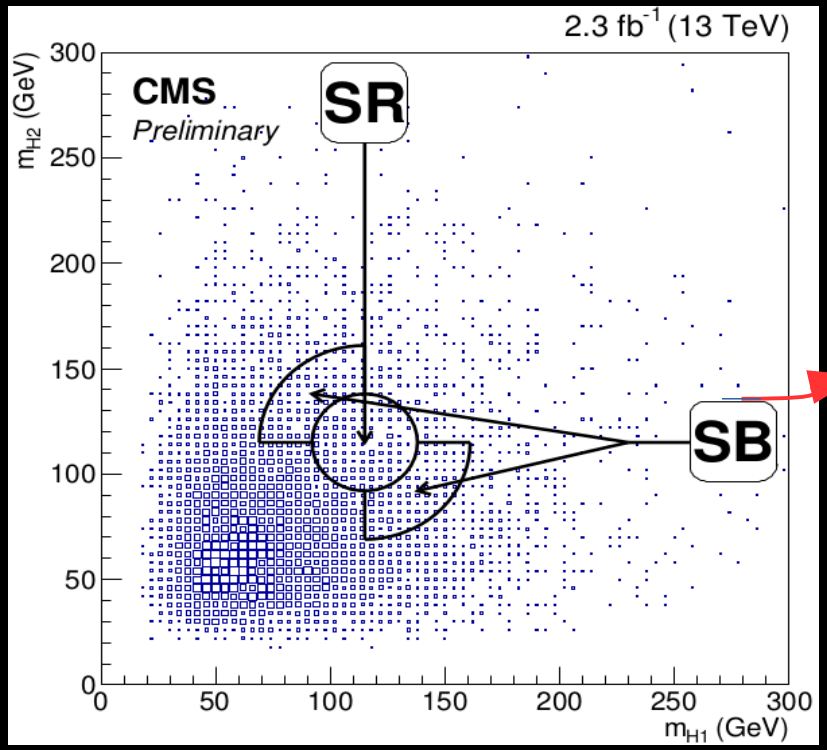
Shape and yield corrections for QCD:

$$\mu_{\mathrm{Multijet}} = \frac{N_{\mathrm{Multijet}}^{4\text{-tag}}}{N_{\mathrm{Multijet}}^{2\text{-tag}}} = \frac{N_{\mathrm{data}}^{4\text{-tag}} - N_{t\bar{t}}^{4\text{-tag}} - N_{Z+jets}^{4\text{-tag}}}{N_{\mathrm{data}}^{2\text{-tag}} - N_{t\bar{t}}^{2\text{-tag}} - N_{Z+jets}^{2\text{-tag}}},$$

Systematics: b-tag, JES

Di-*h* production: $b\bar{b}b\bar{b}$ 13 TeV *(resolved)*

Recalibrate the b-jet energy using Higgs



Trigger: 4j2b, 4j3b

Parametric model for backgrounds

- Used to model background
- In 2-b-jet region, the method is validated

Dominant systematics:
Trigger, b-tag

$$\chi^2 = \left(\frac{m_{H1} - 115\ \text{GeV}}{\sigma_H}\right)^2 + \left(\frac{m_{H2} - 115\ \text{GeV}}{\sigma_H}\right)^2$$

Optimized for the best sensitivity

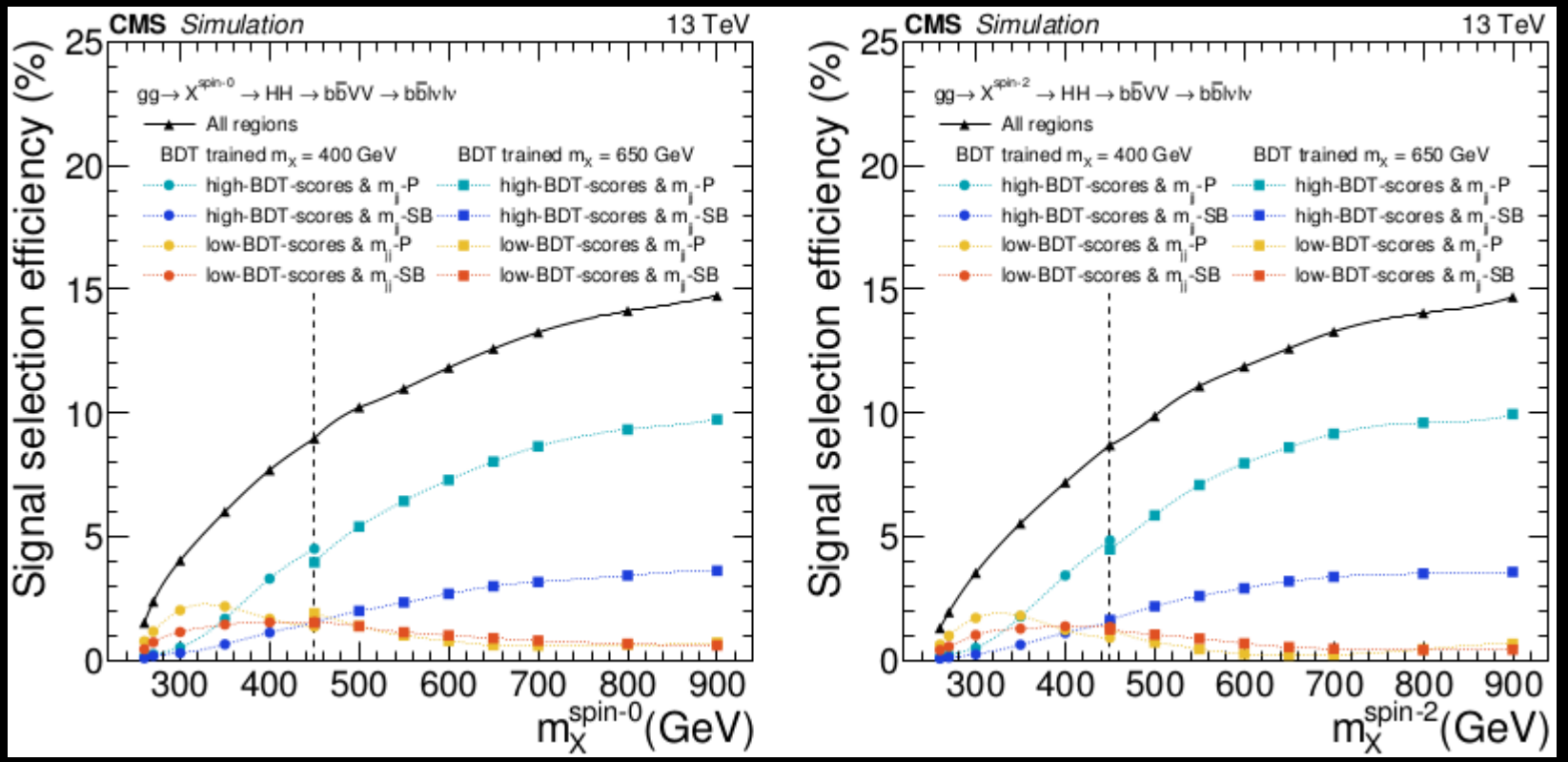
Averaged mean over the range

HIG-16-002

Di-*h* production: $b\bar{b}W^+W^-$ ($\ell\nu\ell\nu$) 13 TeV

- Two different BDT trainings below and above 450 GeV
- Similar training for spin 0 and spin 2
- Dominant systematics: trigger, b-tagging, ttbar background

HIG-16-011



Di-*h* production: $b\bar{b}\gamma\gamma$ 13 TeV

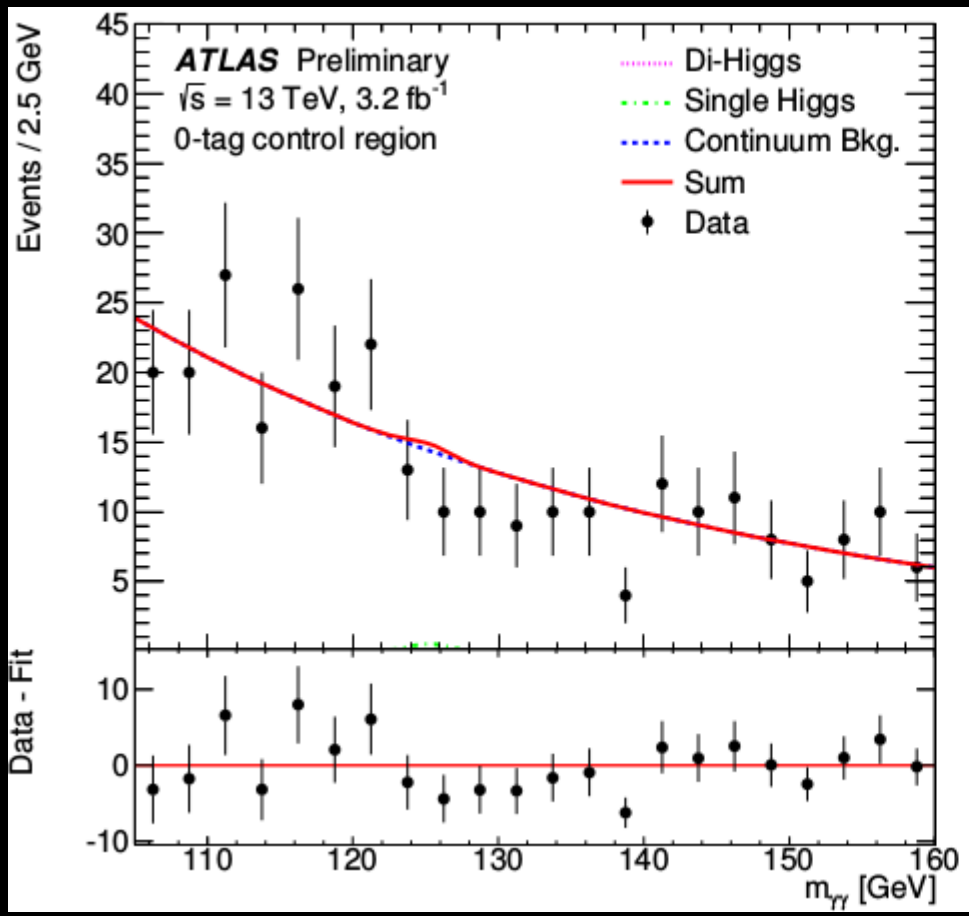
ATL-CONF-16-004

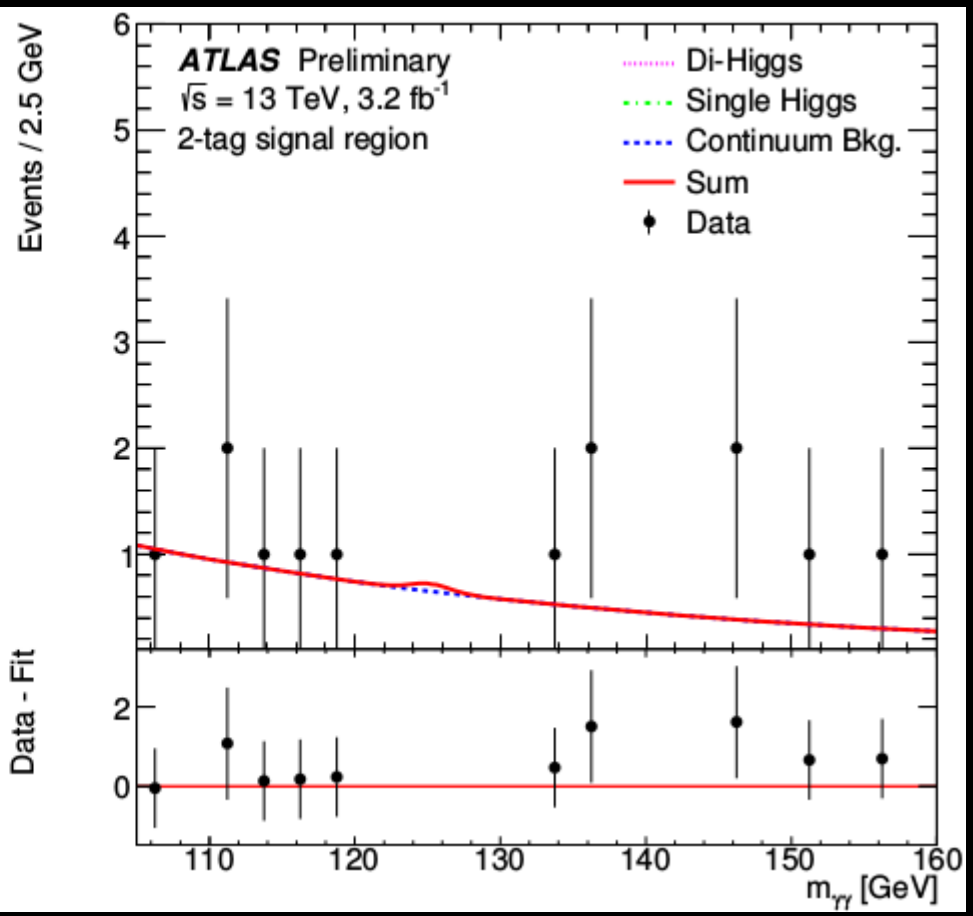
- b-jet recalibration with Higgs mass
- Non-resonant bkg. shape:
  - exp. fit to $m_{\gamma\gamma}$ distribution in $m_{\gamma\gamma}$ side band
- Resonant bkg yield:
  - Estimation from side-band in $m_{\gamma\gamma}$ with efficiencies from 0-tag CR → systematics for 0-tag – 2-tag transfer
- Stat. limited ...

$$N_{SR}^{B} = N_{SB}\frac{\varepsilon_{m_{\gamma\gamma}}^{B}}{1-\varepsilon_{m_{\gamma\gamma}}^{B}}\varepsilon_{m_{b\bar{b}\gamma\gamma}}^{B}$$

Di-*h* production: $b\bar{b}\gamma\gamma$ 13 TeV

ATL-CONF-16-004





Di-*h* production: $b\bar{b}\tau\bar{\tau}$ 13 TeV

- QCD yield:
  - From SS where SS/OS ratio is obtained from non-iso sample
- QCD shape:
  - From SS non-iso sample
- Systematics: b-jet and τ identification, Q^2 scale

HIG-16-012

Non-resonant

HIG-16-013

Resonant

$A \to Zh$: $h \to b\bar{b}$, $Z \to \ell^-\ell^+ / \nu\bar{\nu}$ 13 TeV

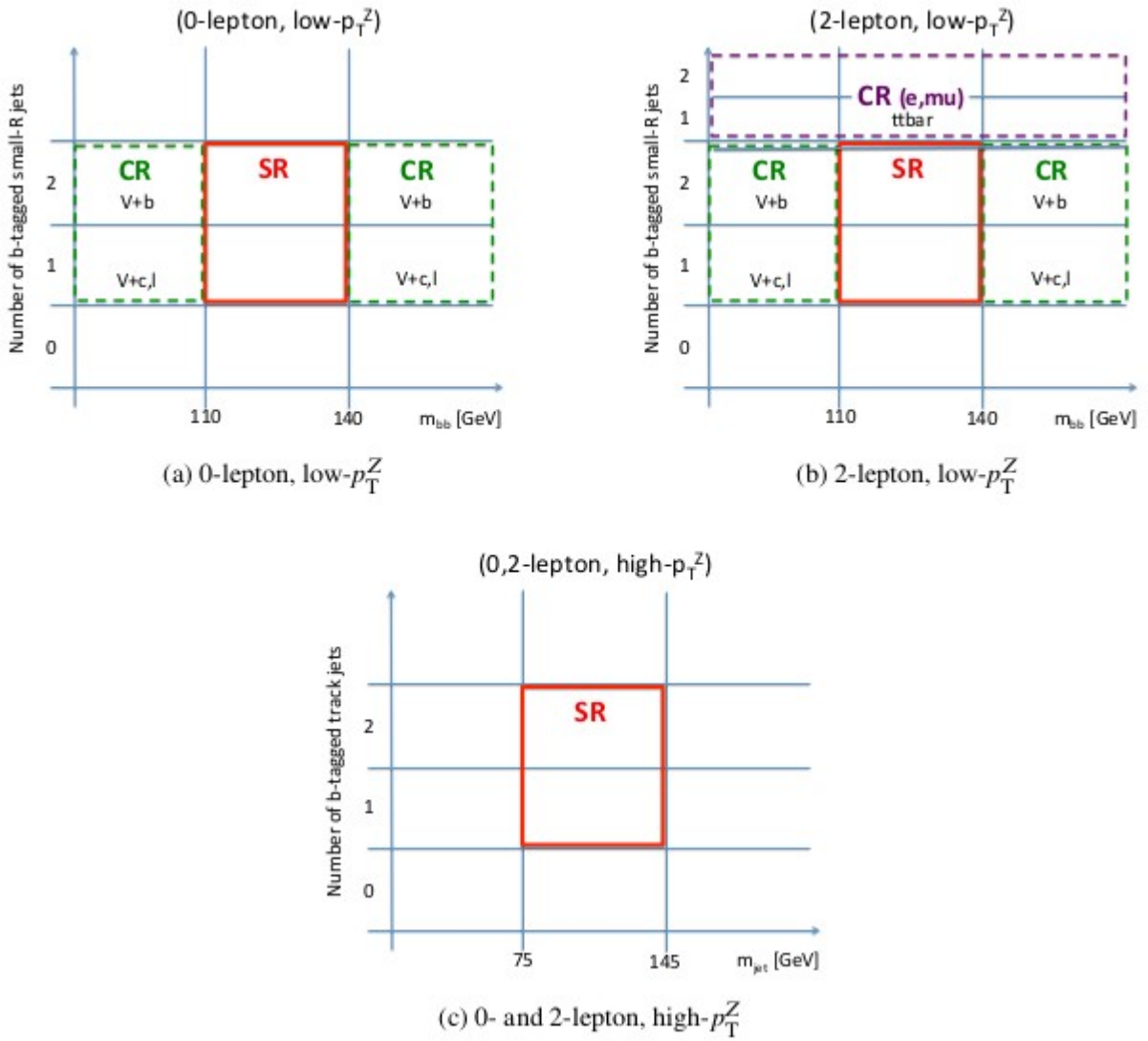
ATL-CONF-16-015

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		
$E_{\mathrm{T}}^{\text{miss}}$ [GeV]	> 150	–
$\sum_{i=1}^{N_{\text{jet}}=3(2)} p_{\mathrm{T}}^{\text{jet}_i}$ [GeV]	> 150 (120)$^{(*)}$	–
$p_{\mathrm{T}}^{\text{miss}}$ [GeV]	> 30	> 30
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\text{miss}}, \vec{p}_{\mathrm{T}}^{\text{miss}})$	$< \pi/2$	$< \pi/2$
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\text{miss}}, h)$	$> 2\pi/3$	$> 2\pi/3$
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\text{miss}}, \text{small-}R\text{ jet})]$	$> \pi/9^{(*)}$	$> \pi/9^{(*)}$
$\Delta\phi(j,j)$	$< 7\pi/9$	–
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
$E_{\mathrm{T}}^{\text{miss}}/\sqrt{H_{\mathrm{T}}}$ [$\sqrt{\text{GeV}}$]	< 3.5	–

$A \to Zh$: $h \to b\bar{b}$, $Z \to \ell^-\ell^+ / \nu\bar{\nu}$ 13 TeV

- Muon recalibration using Z in both high and low p_T^Z
- Jet recalibration using Higgs mass in low p_T^Z

ATL-CONF-16-015



(a) 0-lepton, low-p_T^Z

(b) 2-lepton, low-p_T^Z

(c) 0- and 2-lepton, high-p_T^Z

Systematics:

- JES, JMR, JMS, b-tagging
- Signal modeling and background

New H boson to $ZZ \to \ell^-\ell^+ \nu\bar{\nu}$ 13 TeV

ABCD method for Z+jets yield

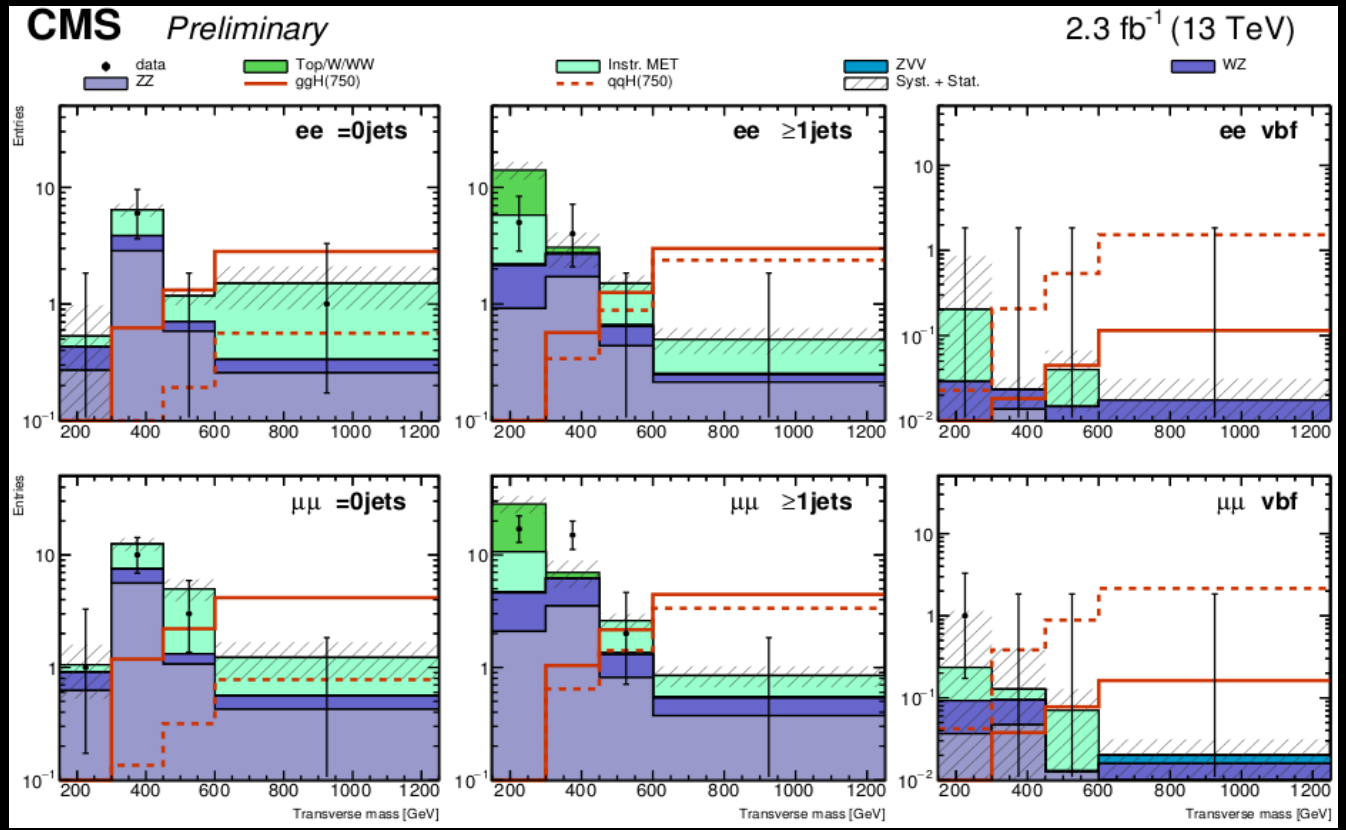
ATL-CONF-16-012

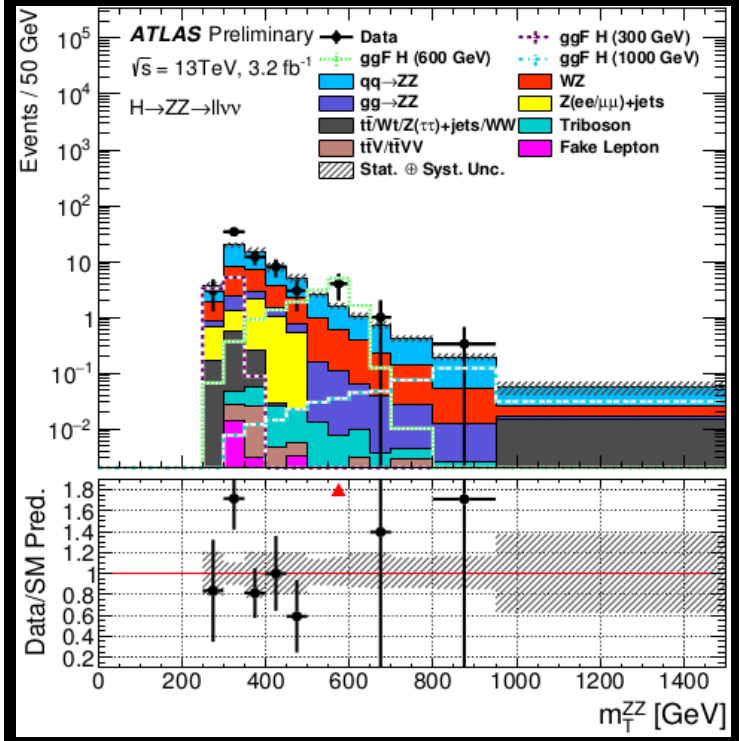
The Z + jets background is estimated from data by comparing the signal region (A) with two-dimensional sideband regions in which requirements on the fractional p_{T} difference (B), $\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell\ell}, \vec{E}_{\mathrm{T}}^{\,\mathrm{miss}})$ (C) or both variables (D) are reversed. The m_{T}^{ZZ} distributions in the signal and those three sideband regions after the dilepton mass requirement are shown in Figure 4. Since the variables $\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell\ell}, \vec{E}_{\mathrm{T}}^{\,\mathrm{miss}})$ and the fractional p_{T} difference are uncorrelated, an estimate of the number of background events in the signal region is given by $N_{\mathrm{A}}^{\mathrm{est}} = N_{\mathrm{C}}^{\mathrm{obs,sub}} \times (N_{\mathrm{B}}^{\mathrm{obs,sub}} / N_{\mathrm{D}}^{\mathrm{obs,sub}})$.

New H boson to $ZZ \to \ell^-\ell^+ \nu\bar{\nu}$ 13 TeV

Better sensitivity with VBF and ggF jet selection

Both flavors combined





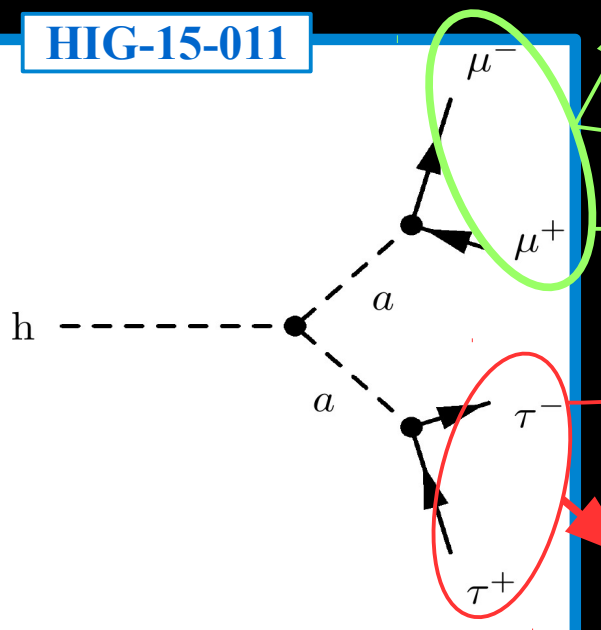
HIG-16-001

ATL-CONF-16-012

New H boson to $WW \rightarrow \ell\nu qq'$ 13 TeV

QCD from a fit to m_T with shape from non-iso, non-id control region

HIG-15-011



$m_a \in [20,62.5]$ GeV

Higgs production
ggF, VBF, Vh

All tau final states
except μμ

$h \rightarrow aa \rightarrow 2\mu 2\tau$

Di-muon trigger

Search variable: $m_{\mu\mu}$

$$\frac{|m_{\mu\mu} - m_{\tau\tau}|}{m_{\tau\tau}} < 0.8$$

All τ final states except $\tau_\mu \tau_\mu$

$|\, m_{\mu\mu\tau\tau} - 125 \,| < 25$ GeV

b-jets vetoed

CMS

HIG-15-011

Signal

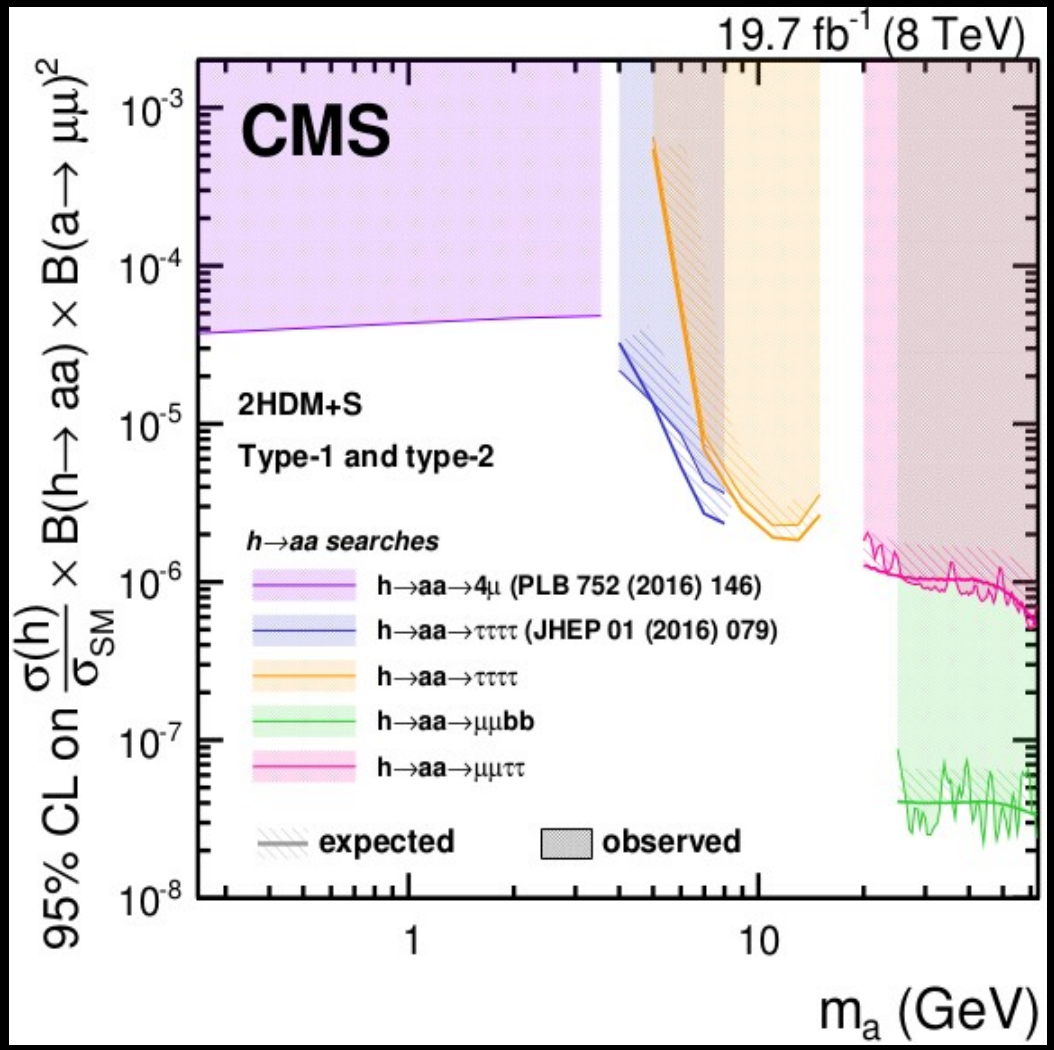
- Parametric model,
  - Voigt with or w/o Gauss component based on final state
  - Interpolated to regions w/o simulations (closure checked)

Background

- Modeled with Bernstein
  - ZZ: irreducible, estimated from MC
  - Fake τ/μ/e: reducible, estimated from control data
    - Fake rate method in p_T bins for yields
    - Shape from SS region

$Br(h \rightarrow aa) \times Br(a \rightarrow \mu\mu)^2$

Type I-II



All types

$$\frac{\Gamma(a \rightarrow \mu\mu)}{\Gamma(a \rightarrow \tau\tau)} = \frac{m_\mu^2 \sqrt{(1-2m_\mu/m_a)}}{m_\tau^2 \sqrt{(1-2m_\tau/m_a)}}$$

Type I - II

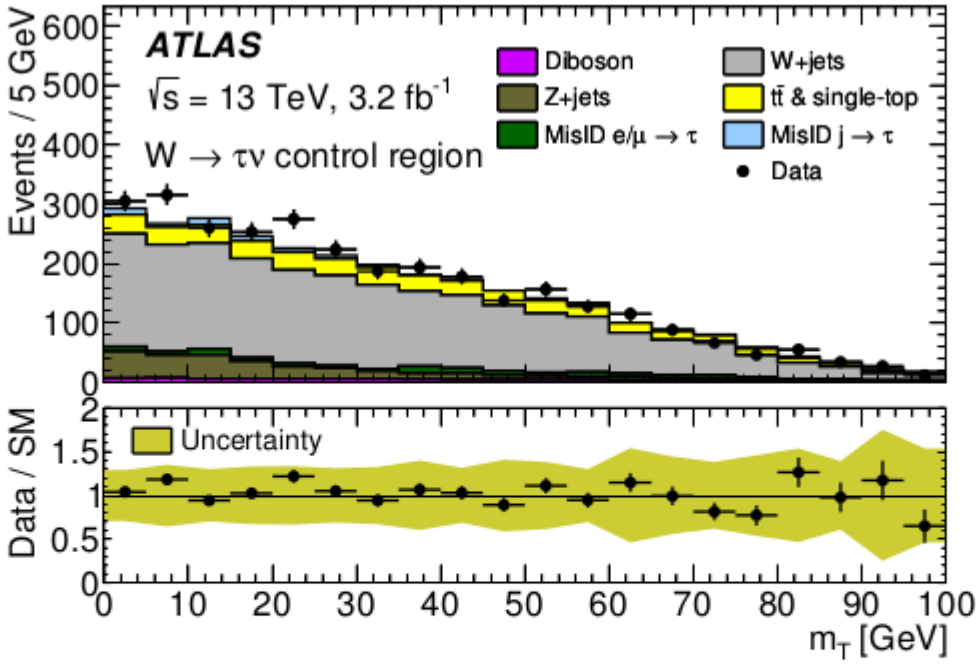
$$\frac{\Gamma(a \rightarrow \mu\mu)}{\Gamma(a \rightarrow bb)} = \frac{m_\mu^2 \sqrt{(1-2m_\mu/m_a)}}{3m_b^2 \sqrt{(1-2m_b/m_a)} \times \textit{QCD Corr.}}$$

Invisible Higgs: *VBF H →Inv.* 13 TeV

QCD CR: inverting $\Delta\varphi$ (E_T^{miss},jets)

HIG-15-011

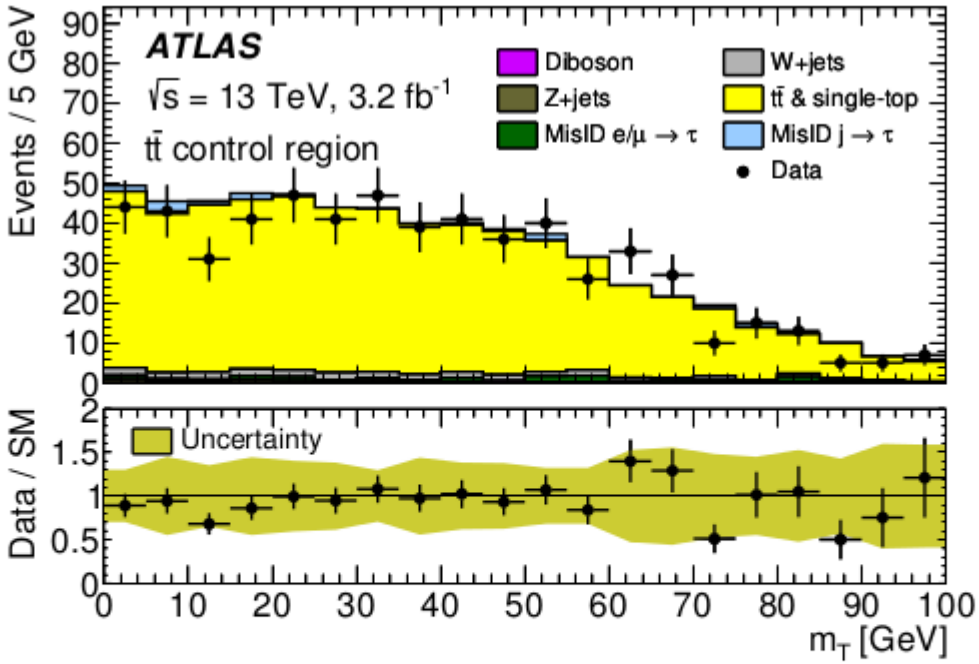
Charged Higgs: $H^{\pm} \rightarrow \tau^{\pm} \upsilon$ 13 TeV



arXiv:1603:09203

Figure 3: Distribution of m_{T} in the control region enriched with $W \rightarrow \tau\nu$ events, which differs from the nominal event selection by the requirements that $m_{\mathrm{T}} < 100$ GeV and that the number of b-tagged jets be zero. The $W \rightarrow \tau\nu$ background is normalised to the data through an overall scale factor. The total (statistical and systematic) uncertainties in the SM prediction are shown in the lower plot.

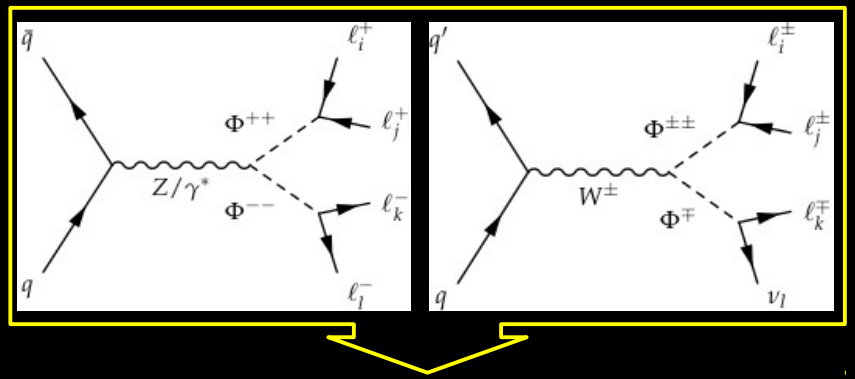
Charged Higgs: $H^{\pm} \rightarrow \tau^{\pm} \upsilon$ 13 TeV



arXiv:1603:09203

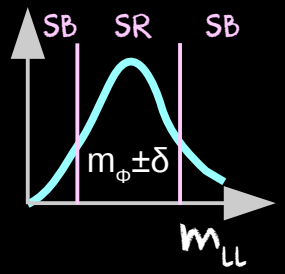
Figure 4: Distribution of m_{T} in the control region enriched with $t\bar{t}$ events, which differs from the nominal event selection by the requirements that $m_{\mathrm{T}} < 100$ GeV and that the number of b-tagged jets be at least two. The total (statistical and systematic) uncertainties in the SM prediction are shown in the lower plot.

Double-charged Higgs: $H^{\pm\pm} \to \ell^-\ell^-\ell^+\ell^+$ 8 TeV



- Explains neutrino masses
  - SM + scalar triplet $\Phi^{\pm\pm}$, $\Phi^{\pm}$, Φ^0

- No lepton flavor conservation
- $\Phi \to ee, \mu\mu, e\mu, e\tau, \mu\tau$
- 3ℓ and 4ℓ final states

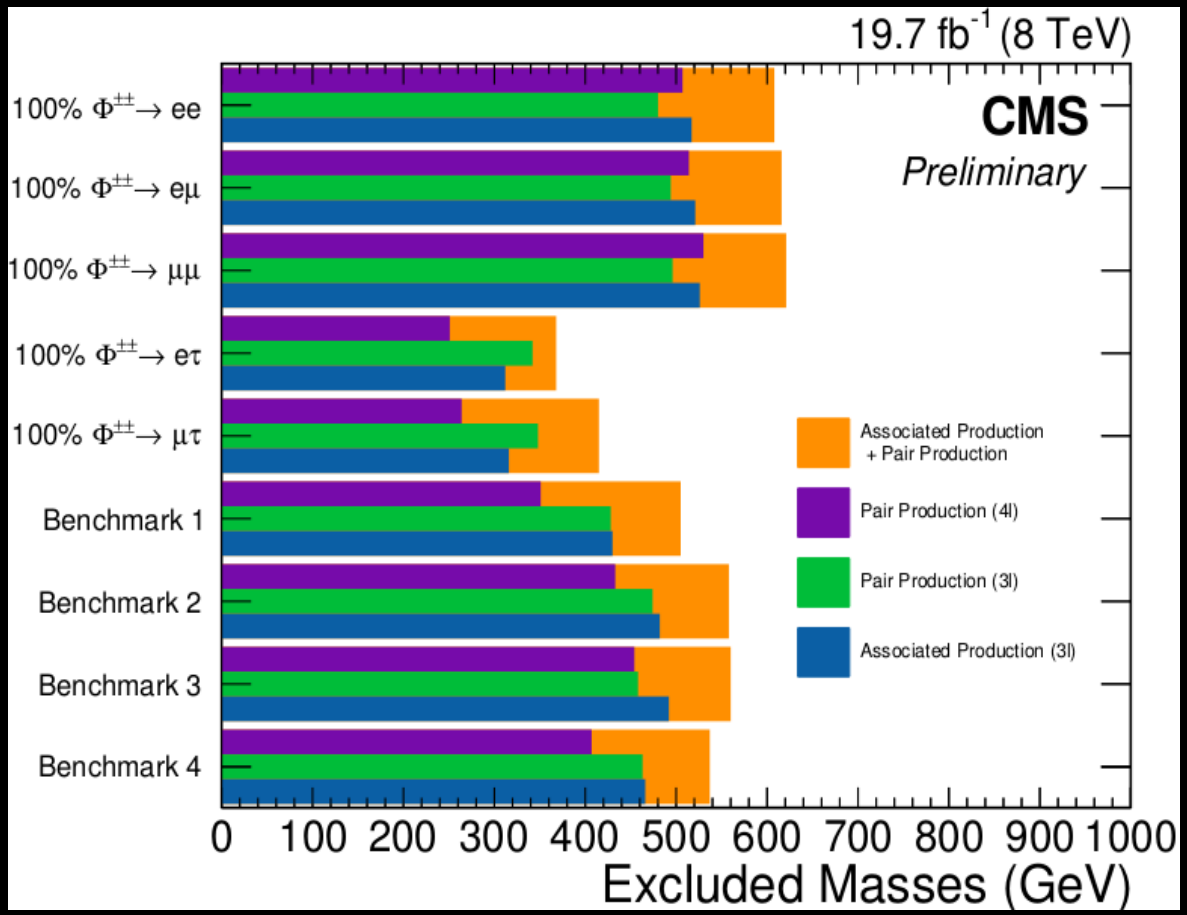


Background

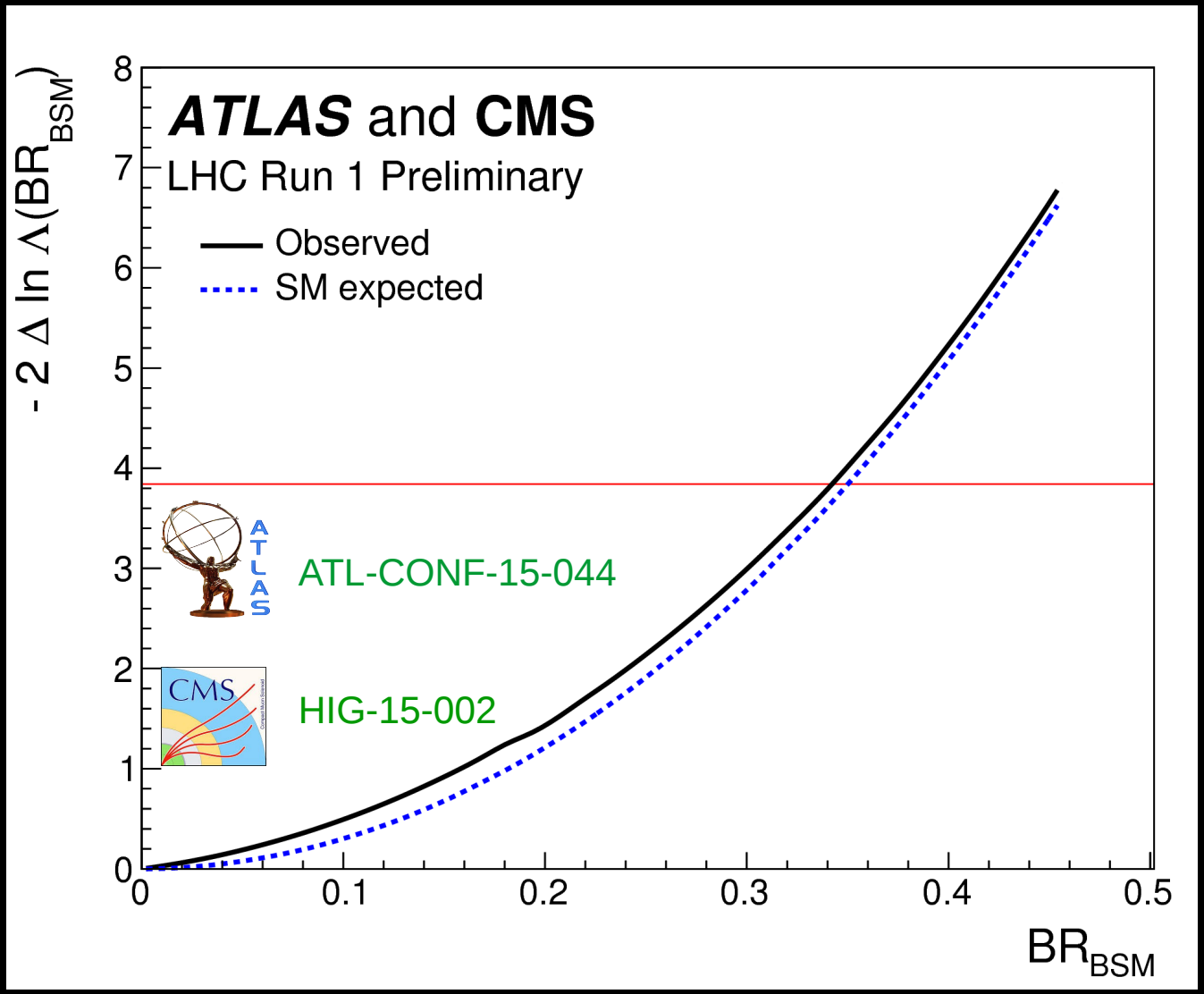
- WZ/ZZ from side band in m_Φ
- Validated in CR's

Search strategy

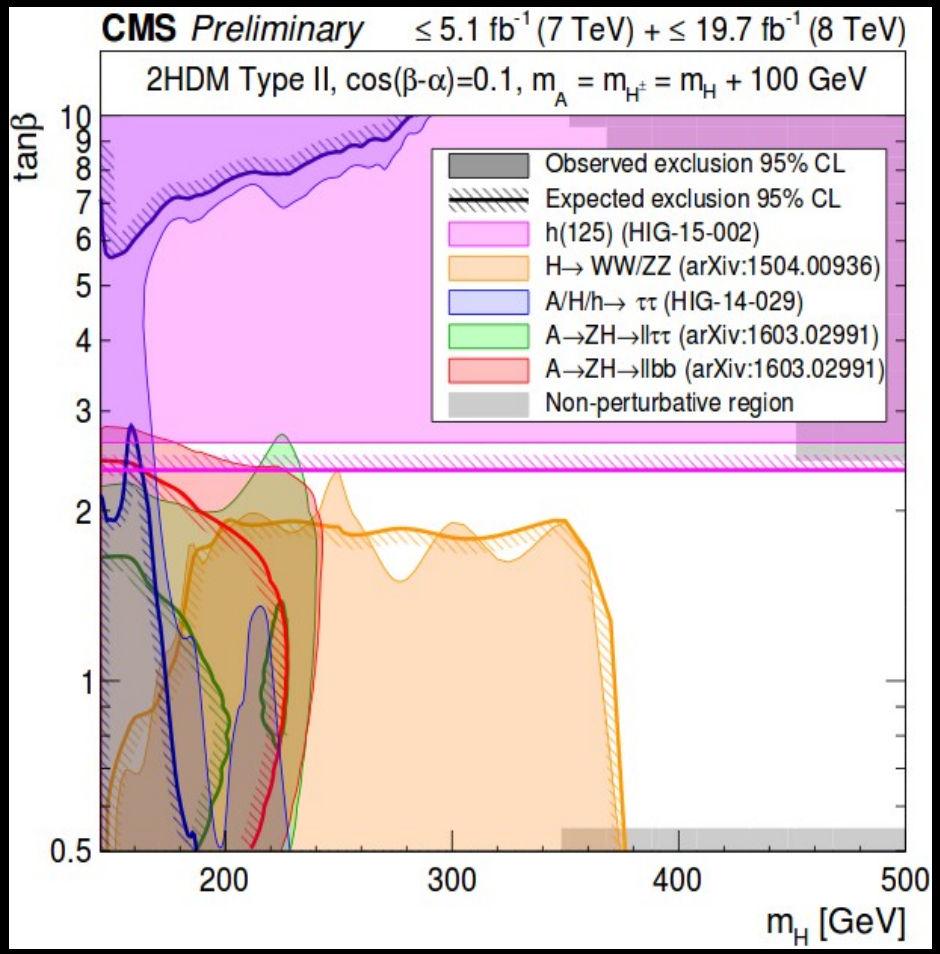
- Counting experiment

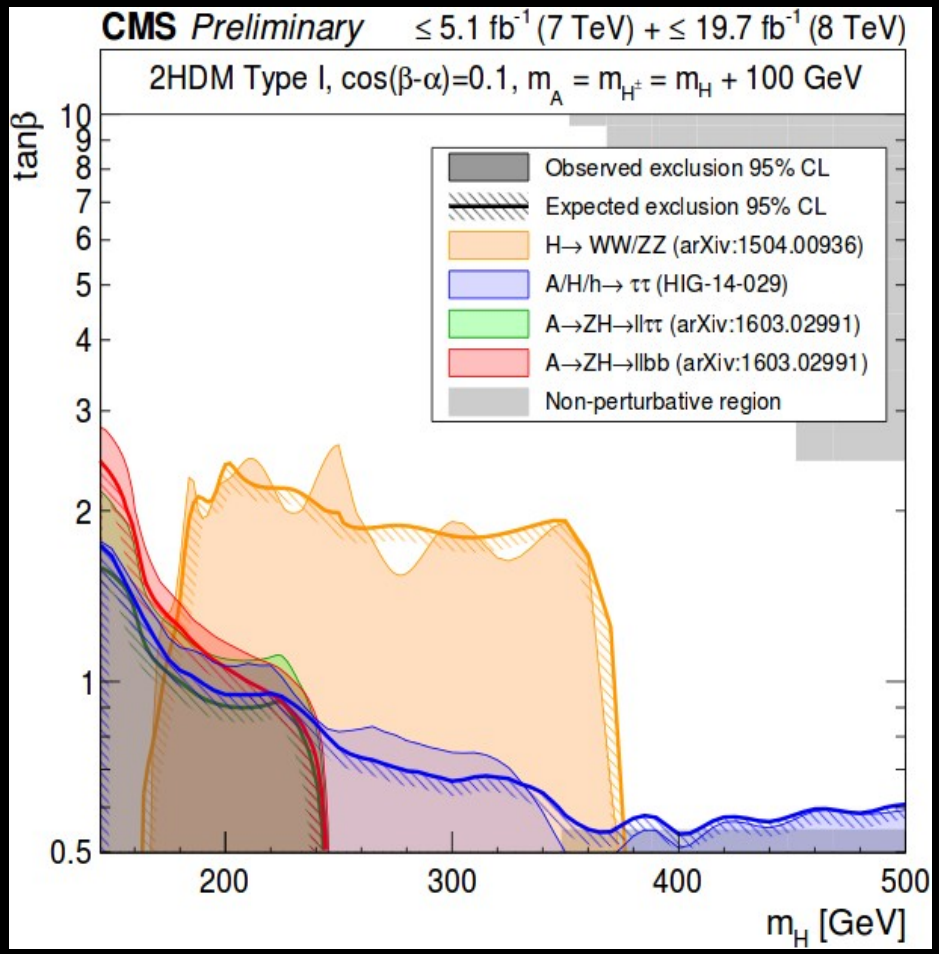


HIG-14-039



- Allowed non-SM loop couplings with additional BSM contribution to Higgs width.
- $\kappa_V \leq 1$


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

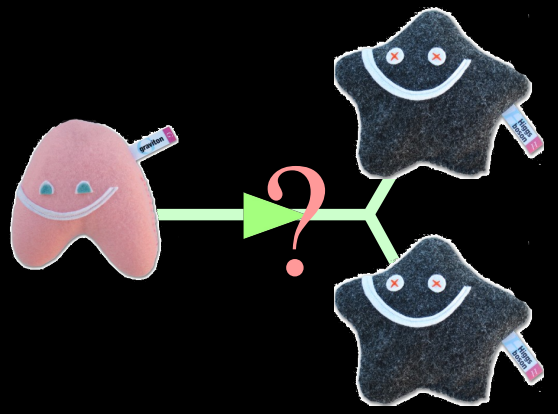

CMS Preliminary ≤ 5.1 fb-1 (7 TeV) + ≤ 19.7 fb-1 (8 TeV)
2HDM Type I, cos(β-α)=0.1, mA = mH± = mH + 100 GeV
tanβ
mH [GeV]
Observed exclusion 95% CL
Expected exclusion 95% CL
H→ WW/ZZ (arXiv:1504.00936)
A/H/h→ ττ (HIG-14-029)
A→ZH→llττ (arXiv:1603.02991)
A→ZH→llbb (arXiv:1603.02991)
Non-perturbative region

HIG-16-007

	2HDM		hMSSM
	type I	type II/MSSM	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$s_d\sqrt{1+\tan^2\beta}$

HIG-16-007

- *Many other channels could be covered*
- *More boosted analyses*
- *...*



13 TeV	Resolved	Boosted	Limit
4b	9 – 0.05 pb	0.05 – 0.1pb	$\sigma \times Br$
bbWW	11 – 0.1 pb	–	$\sigma \times Br$
bbγγ	7.5 – 4 pb	–	σ
bbττ	5 – 0.09 pb	–	$\sigma \times Br$

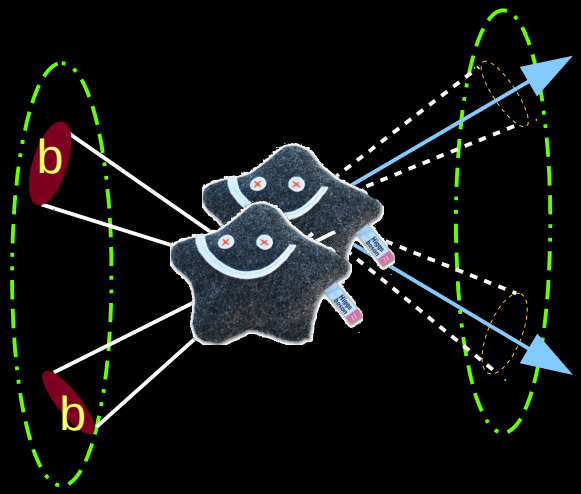
TENTATIVE SUMMARY
ON RESONANCES

- *More sensitive with boosted jets*
- *Other channels could be covered*
- *Results from one experiments could be cross checked with the other*
- *…*

13 TeV	Resolved	Boosted	Limit
$H \rightarrow ZZ \rightarrow \ell\ell\upsilon\upsilon$	4 – 0.1 pb	–	–
$H \rightarrow ZZ \rightarrow \ell\ell qq$	5 – 0.5 pb		–
$H \rightarrow ZZ \rightarrow \upsilon\upsilon qq$	–	0.2 – 0.03 pb	–
$H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$	0.005 – 0.002 pb	–	$Z \rightarrow \ell\ell$ inc.
$H \rightarrow WW \rightarrow qq\ell\upsilon$	–	0.3 – 0.03 pb	–

TENTATIVE SUMMARY

ON H → VV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