

Review of Higgs Physics at the LHC - Higgs sectors

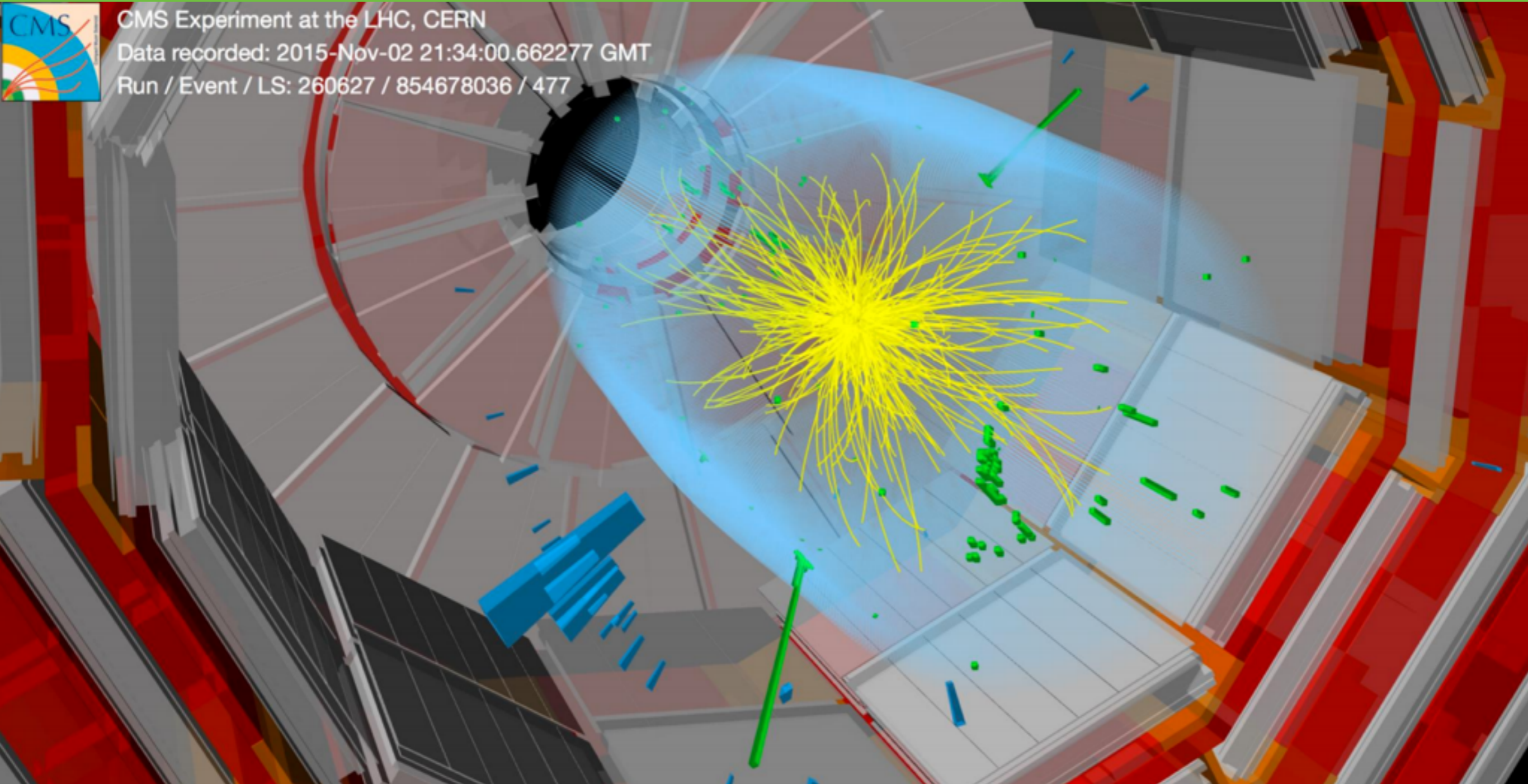
EXTENDED



CMS Experiment at the LHC, CERN

Data recorded: 2015-Nov-02 21:34:00.662277 GMT

Run / Event / LS: 260627 / 854678036 / 477



Markus Klute (MIT)

KITP workshop, April 12, 2016

Experimental Challenges for LHC Run II

EXTENDED

Higgs Sectors

- ◎ **Discussing Higgs bosons that still have to be discovered (or do not exist)**
- ◎ **Large range of models and many, many, many searches at the LHC**
- ◎ **Talk gives an overview and with preference for new or 13 TeV results**

Summary of Run I Higgs Physics

Combined measurement using LHC Run-1 dataset

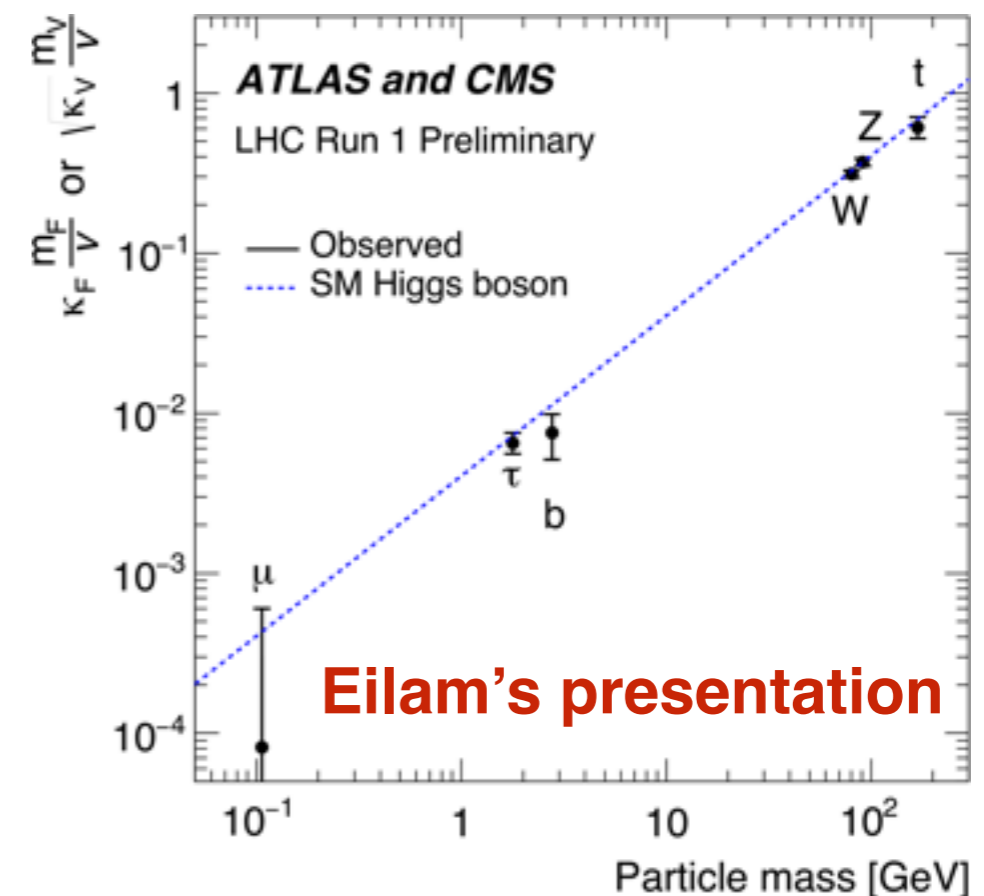
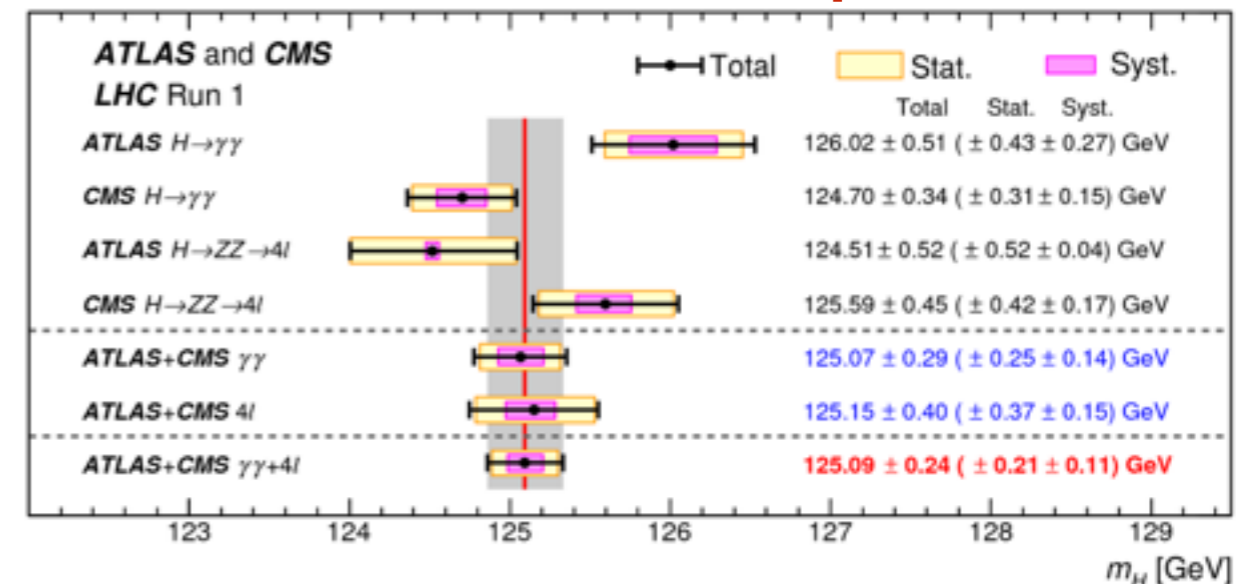
→ $m_H = 125.09 \pm 0.21$ (stat.) ± 0.11 (syst) GeV

→ Precision (0.2%) limited by statistical uncertainty

Established that particle masses and couplings to the Higgs boson relate

No additional Higgs bosons or BSM decays observed

Jim's presentation



Eilam's presentation

EXTENDED

Higgs Sectors

- **Electroweak Singlets**

- ➔ 2nd CP-even boson

- **Two-Higgs Doublet Models (2HDM)**

- ➔ 5 Higgs bosons (H, h, A, H^\pm)

- ➔ MSSM prominent example; hMSSM common benchmark

- **2HDM + singlets**

- ➔ NMSSM prominent example

- ➔ 7 Higgs bosons ($a_1, a_2, h_1, h_2, h_3, H^\pm$)

- **Triplet Models**

- ➔ Adding doubly charged Higgs bosons to 2HDM phenomenology

- **... and more**



generating a catalog

Signatures

- **Neutral Higgs bosons**
 - **Charged Higgs bosons**
 - **Doubly-charged Higgs bosons**
 - **Higgs to Higgs decays**
 - **Di-Higgs processes**
- In case of a discovery, signatures of new Higgs bosons can also be due to other new particles.

Overview of 7/8 TeV Results

○ Neutral Higgs bosons

➔ $H \rightarrow ZZ; H \rightarrow WW; H \rightarrow \gamma\gamma; H \rightarrow Z\gamma; H \rightarrow \tau\tau; H \rightarrow \mu\mu; H \rightarrow bb$

○ Charged Higgs bosons

➔ $H^\pm \rightarrow \tau^\pm \nu; H^\pm \rightarrow cs; H^\pm \rightarrow tb; H^\pm \rightarrow W^\pm Z$

○ Doubly-charged Higgs bosons

➔ $H^{\pm\pm} \rightarrow W^\pm W^\pm; H^{\pm\pm} \rightarrow 4l^\pm$

○ Higgs to Higgs decays

➔ $H \rightarrow ZA; A \rightarrow Zh; H^\pm \rightarrow HW^\pm$

○ Di-Higgs processes

➔ $H \rightarrow hh \rightarrow bb\gamma\gamma; \rightarrow bb\tau\tau; \rightarrow bbbb; \rightarrow \gamma\gamma WW;$

➔ $h \rightarrow aa \rightarrow bb\mu\mu; \rightarrow \mu\mu\mu\mu; \rightarrow \mu\mu\tau\tau; \rightarrow \tau\tau\tau\tau; \rightarrow \gamma\gamma\gamma\gamma;$ **Bill's presentation**

Overview of 13 TeV Results

Neutral Higgs bosons

→ $H \rightarrow ZZ$; $H \rightarrow WW$; $H \rightarrow \gamma\gamma$; $H \rightarrow Z\gamma$;
 $H \rightarrow \tau\tau$

Charged Higgs bosons

→ $H^\pm \rightarrow \tau^\pm \nu$

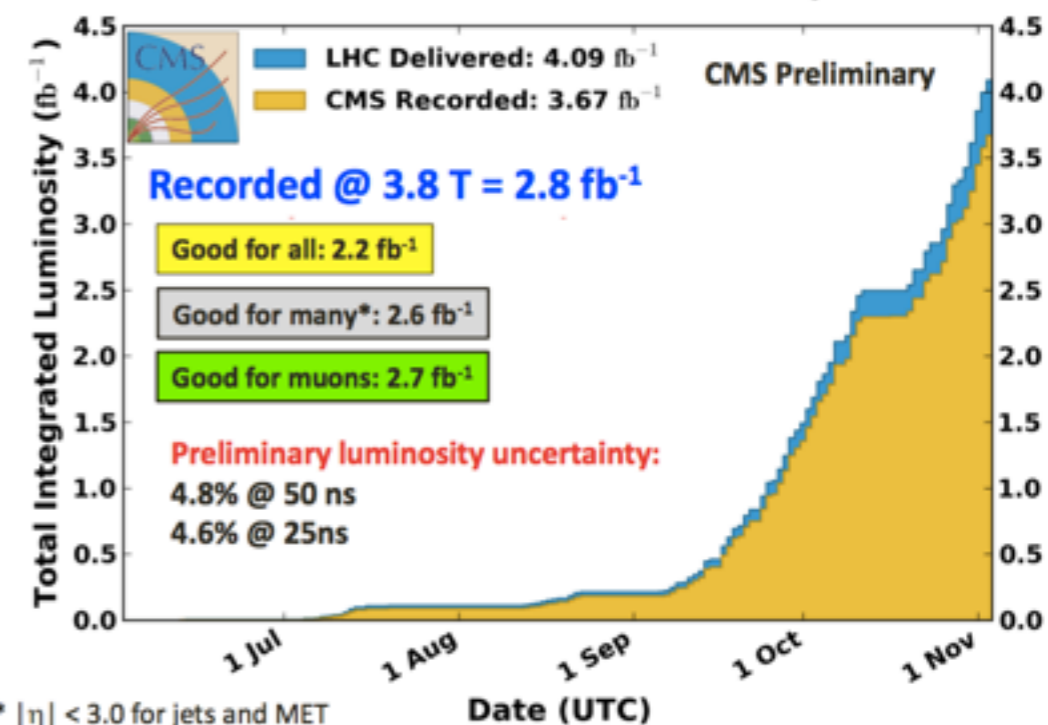
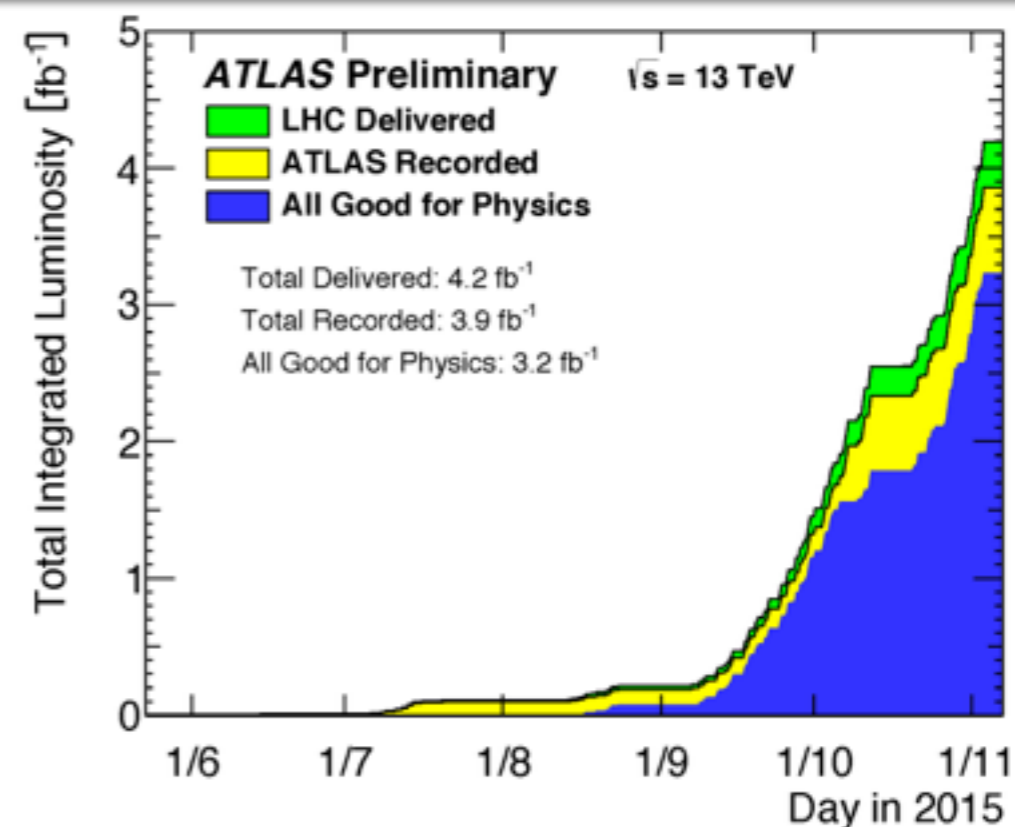
Doubly-charged Higgs bosons

Higgs to Higgs decays

→ $H \rightarrow ZA$; $A \rightarrow Zh$,

Di-Higgs processes

→ $H \rightarrow hh \rightarrow bb\gamma\gamma$; $\rightarrow bb\tau\tau$; $\rightarrow bbbb$;
 $bbWW$



$X \rightarrow \gamma\gamma$

Neutral Higgs?

ATLAS-CONF-2016-016

CMS-PAS-EXO-16-018

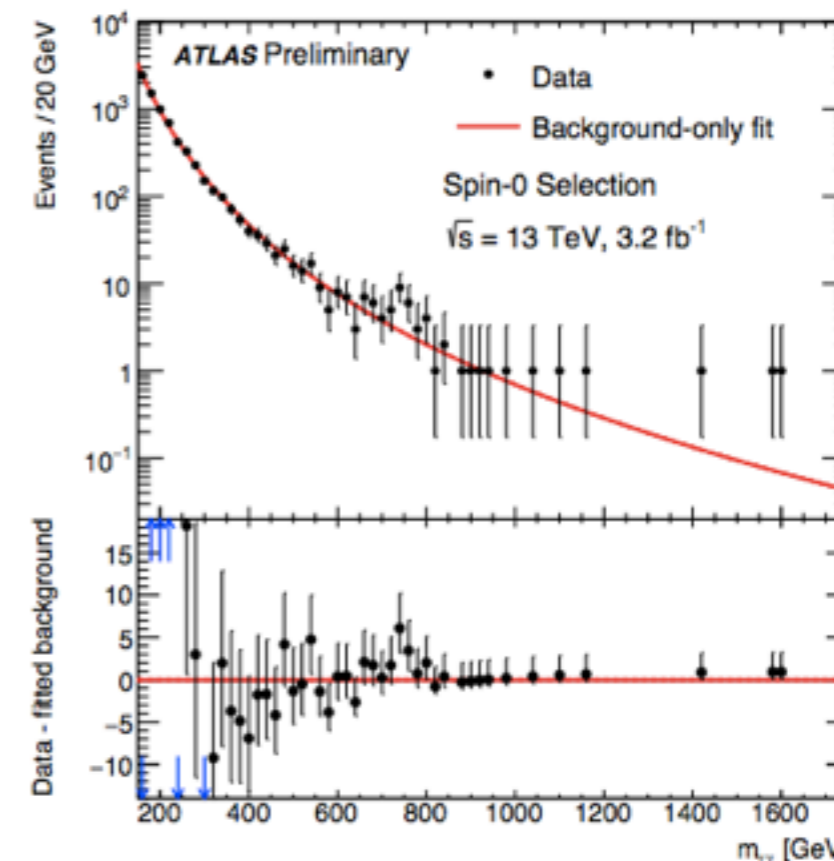
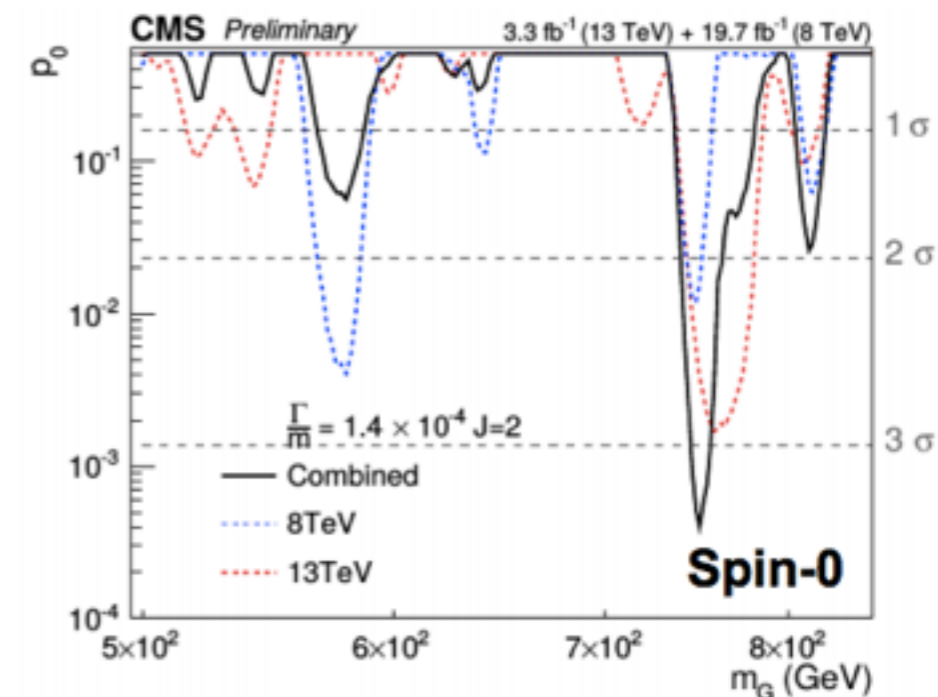
→ Highlights of Run-II presented at Jamboree Dec 15th

- ATLAS and CMS updated studies for Moriond
- Local p-value: 3.4σ for CMS and 3.9σ for ATLAS
- Global p-value: 1.6σ for CMS and 2.0σ for ATLAS
- Cross section $O(10\text{fb})$
- Huge excitement and avalanche of papers (~ 300 and counting)

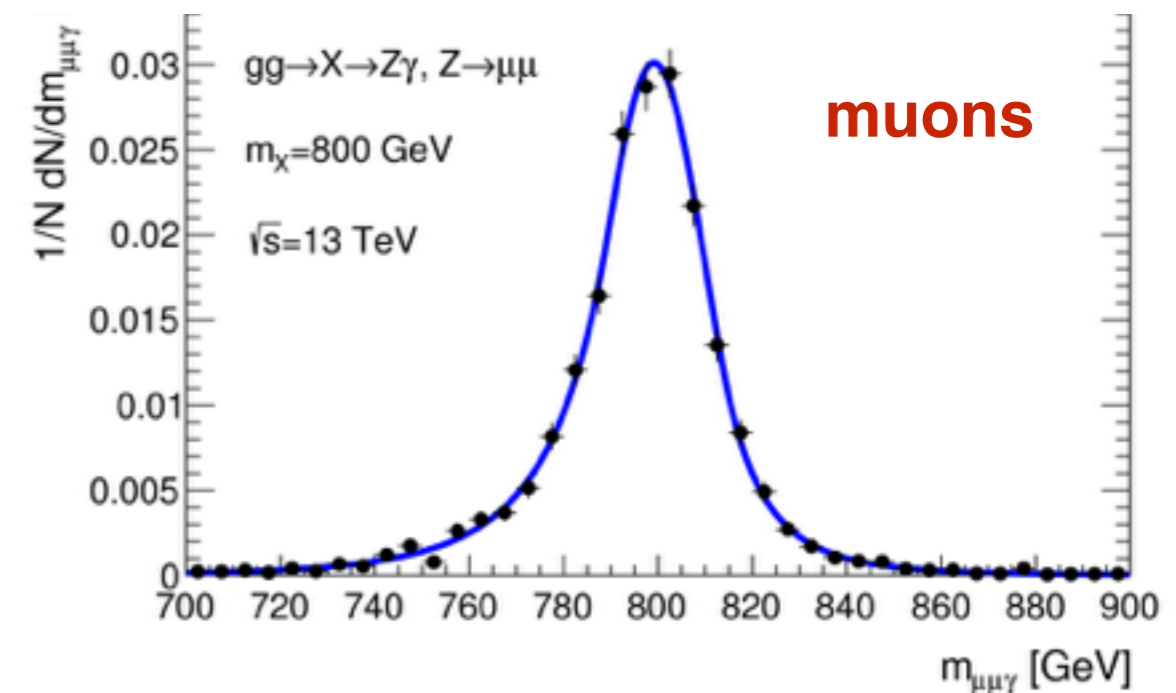
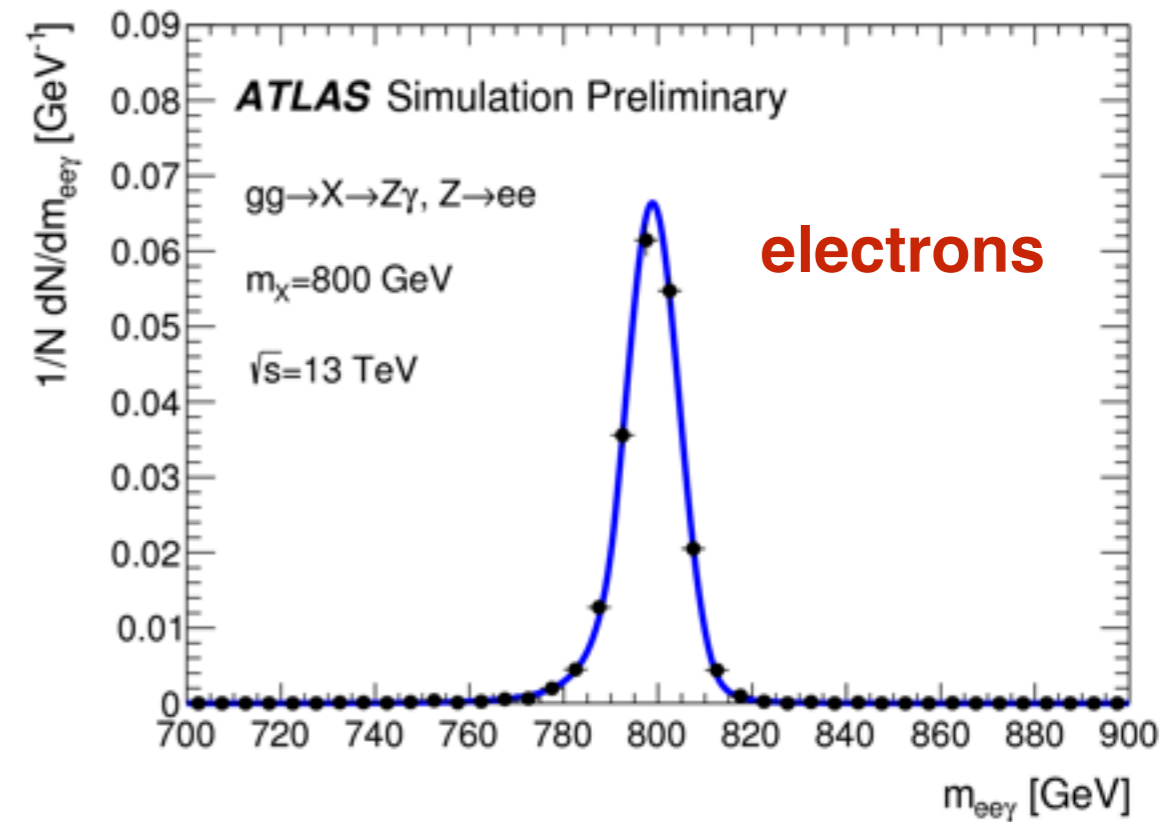
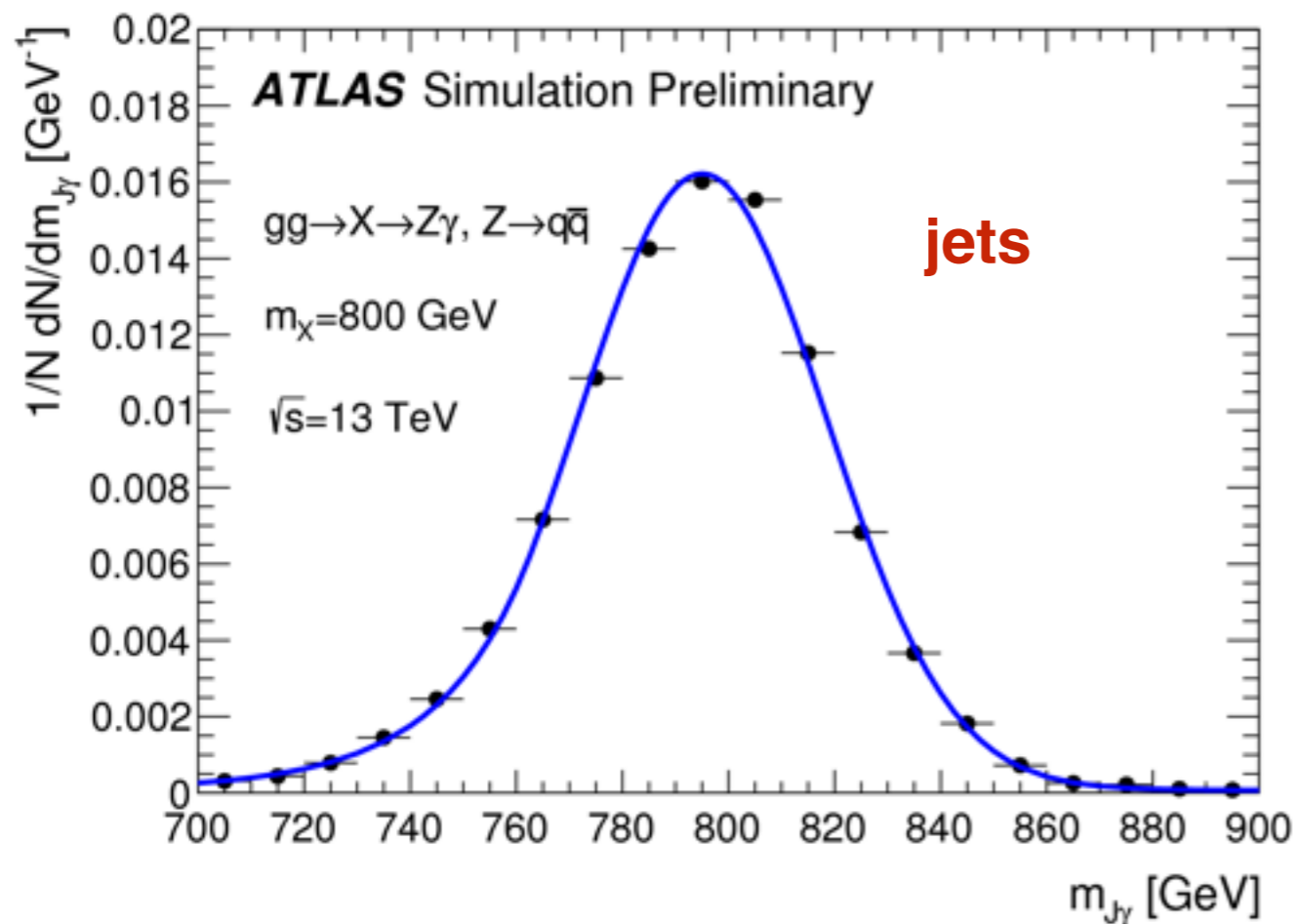
→ 2016 data will show whether or not this is a sign of new physics

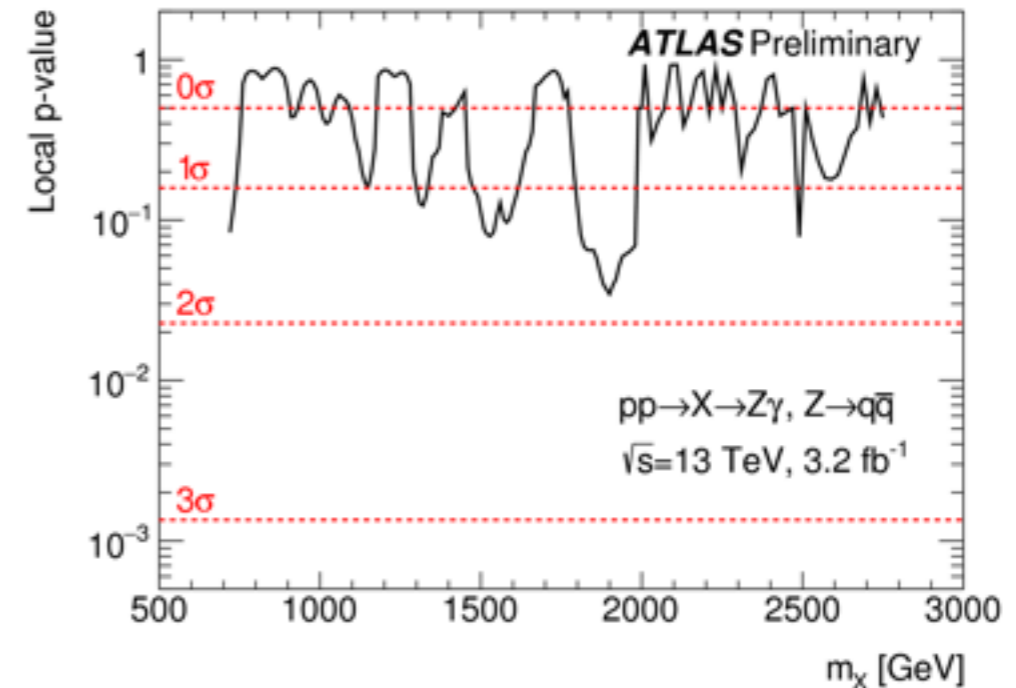
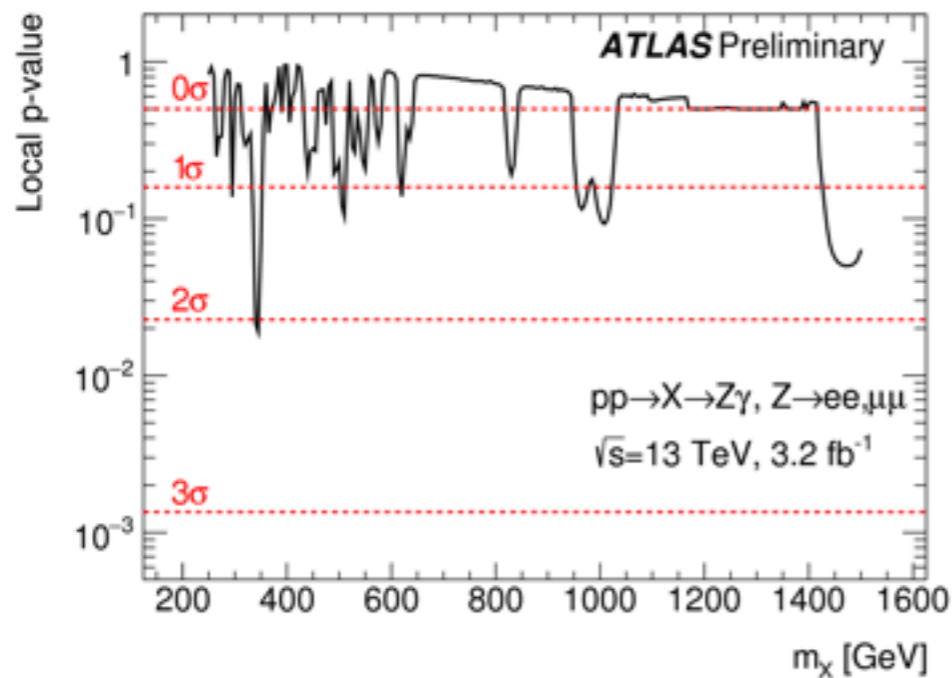
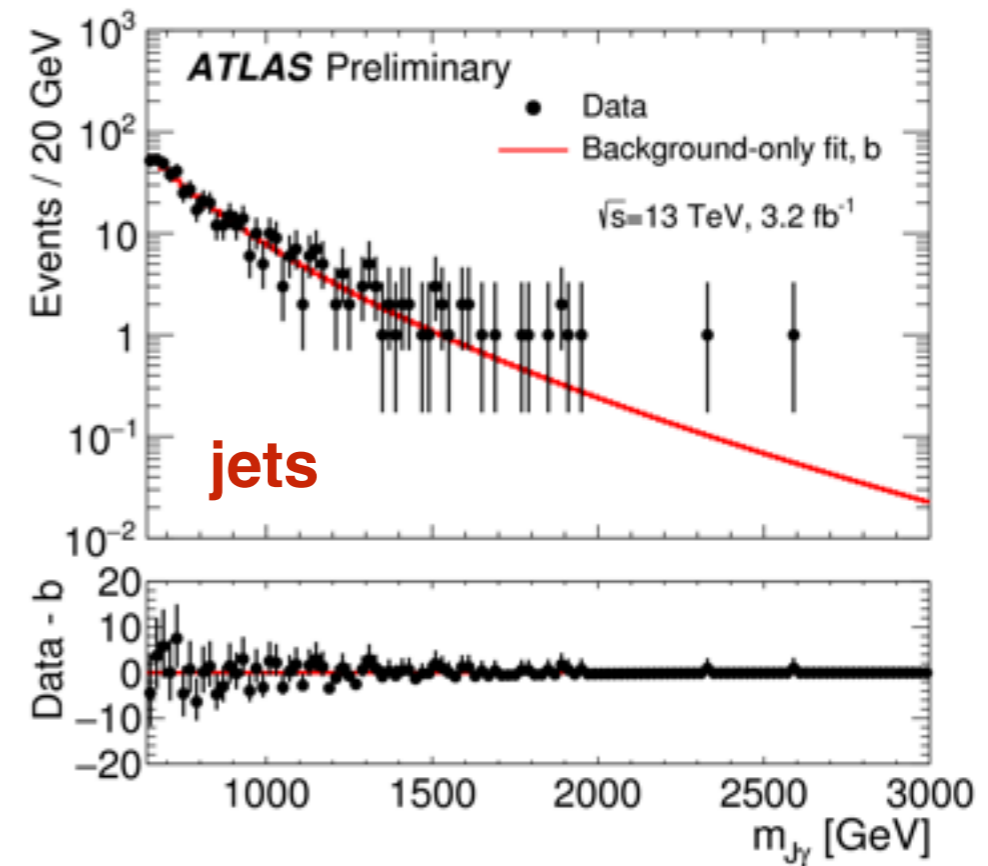
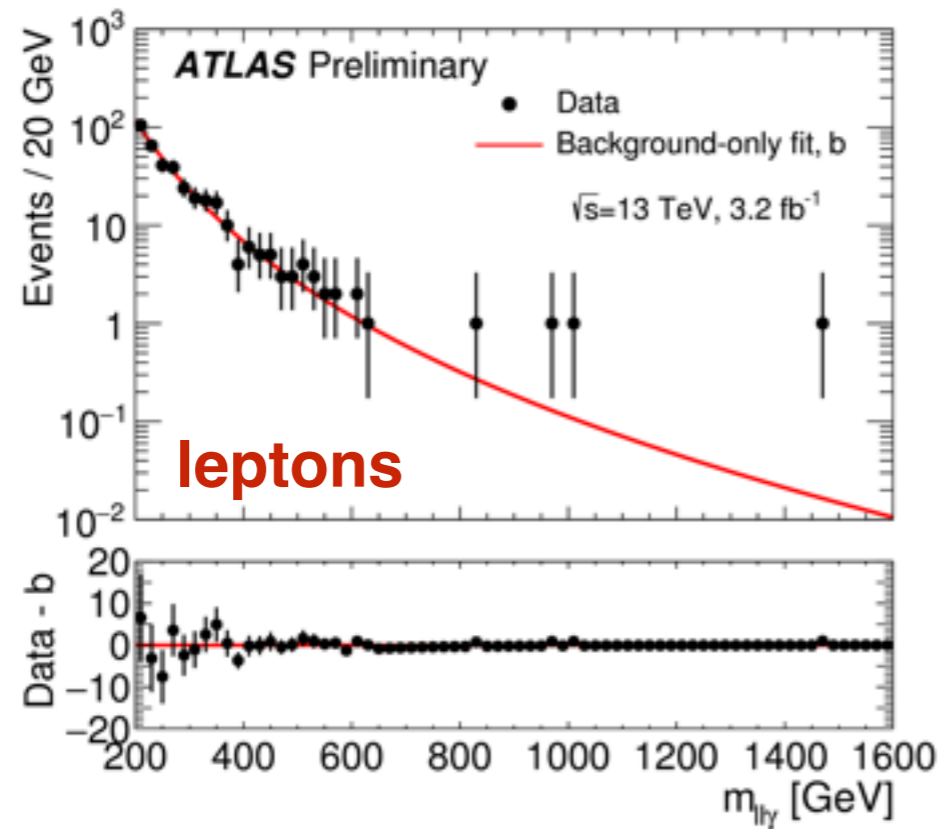
→ Discussion Monday April 18th, 2pm by Nathaniel Craig

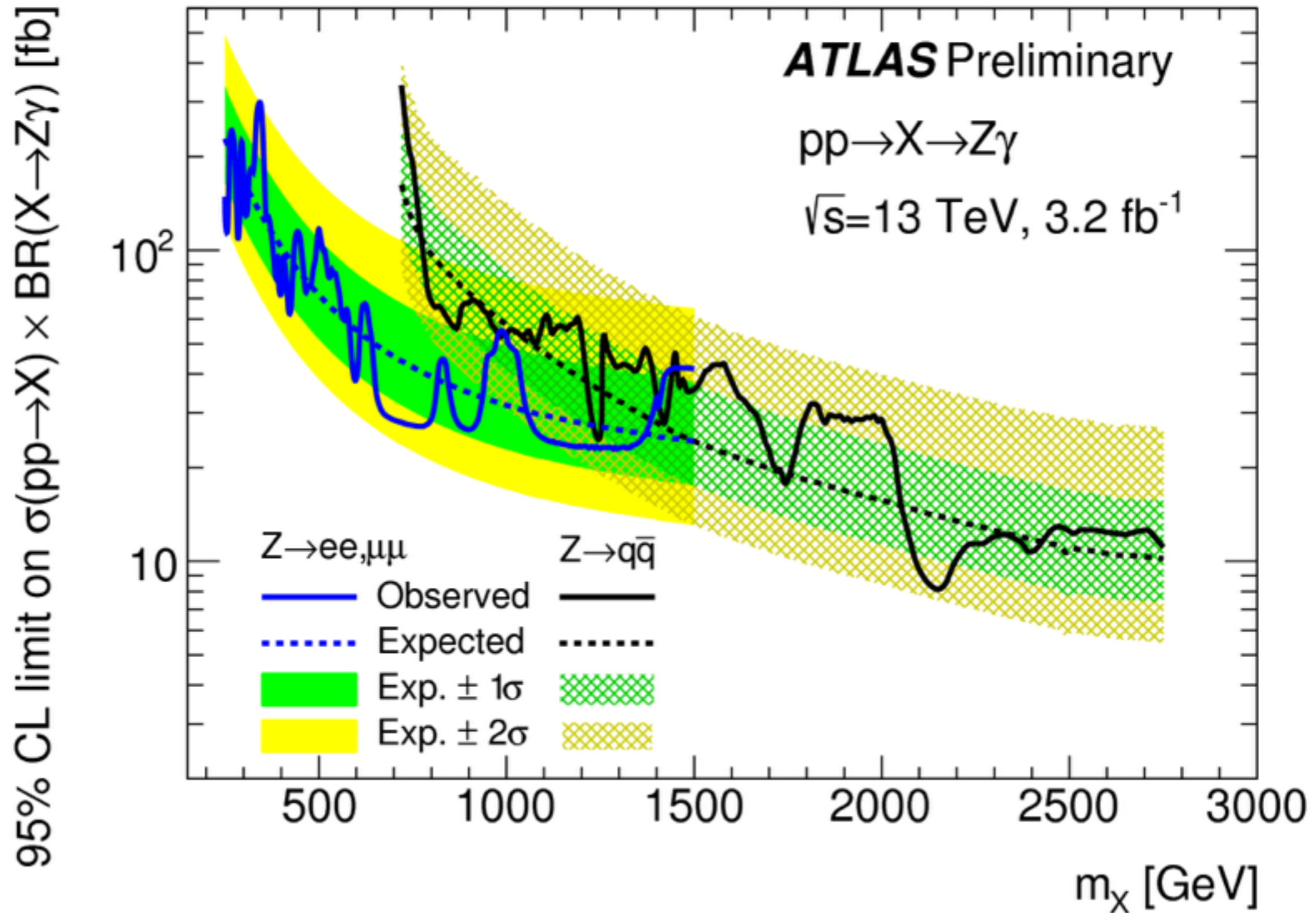
→ Are there hints in other channels?

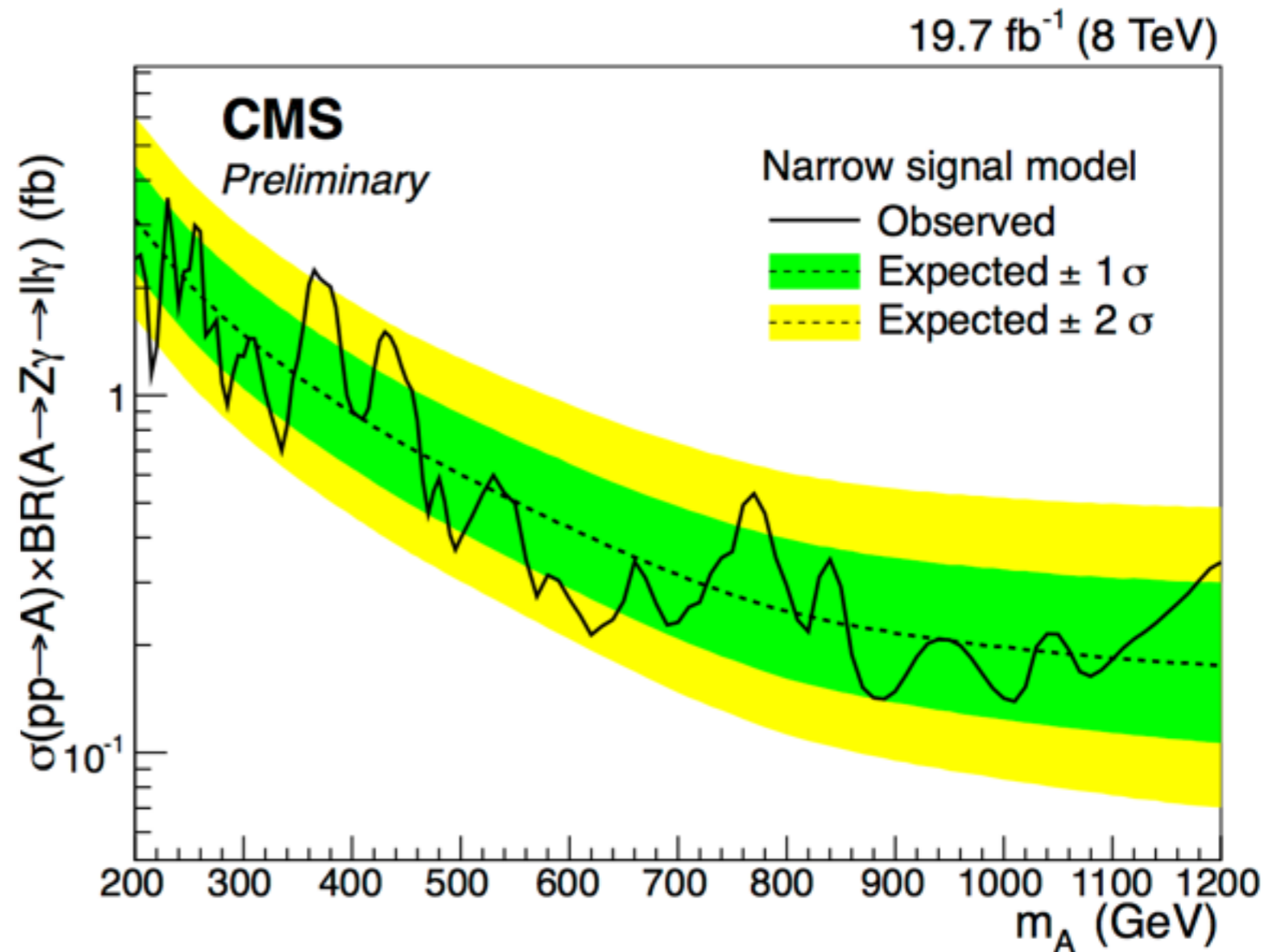
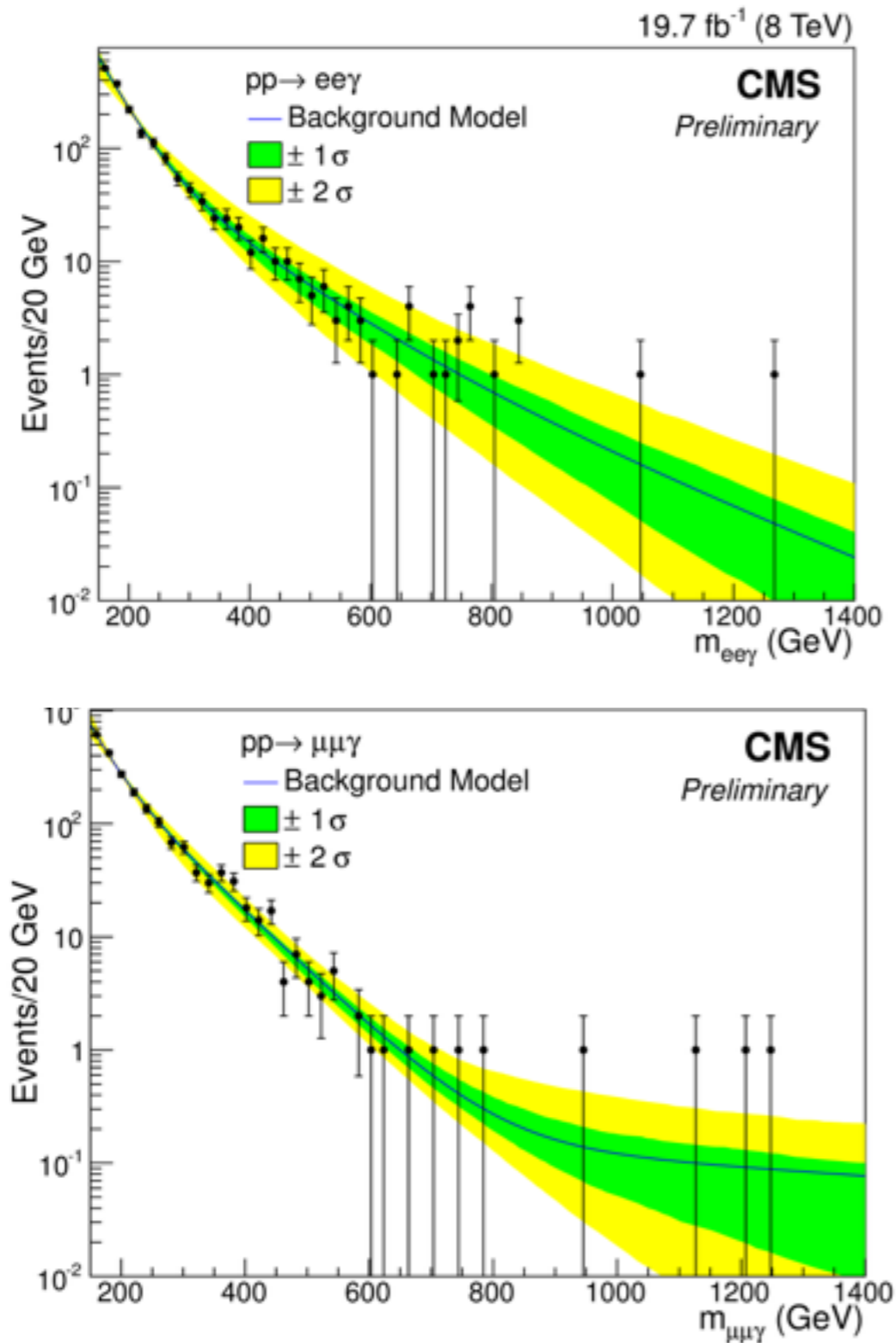


- Search for narrow $Z\gamma$ resonance
- $Z \rightarrow ll$ and $Z \rightarrow qq$ (fat jet) final states used

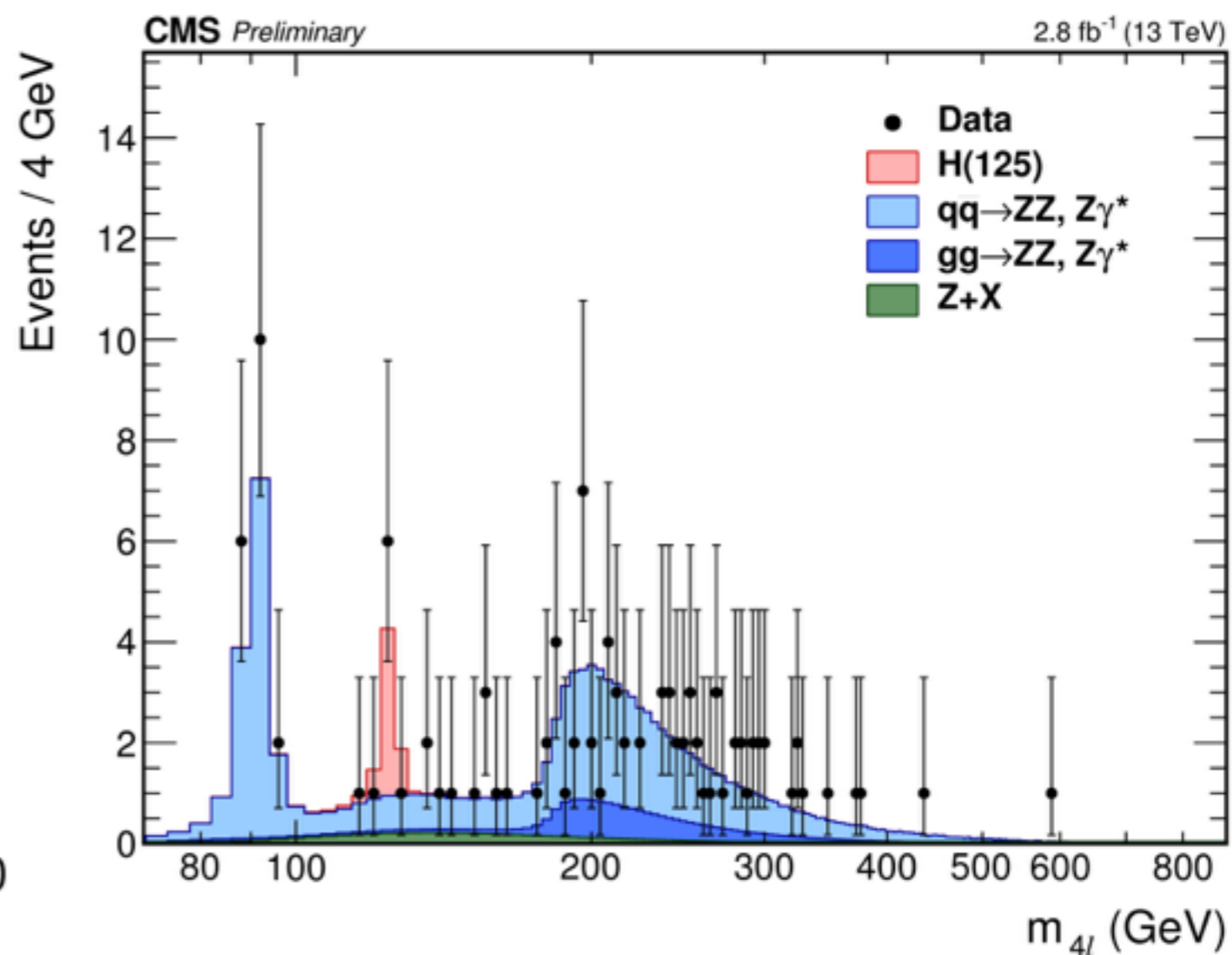
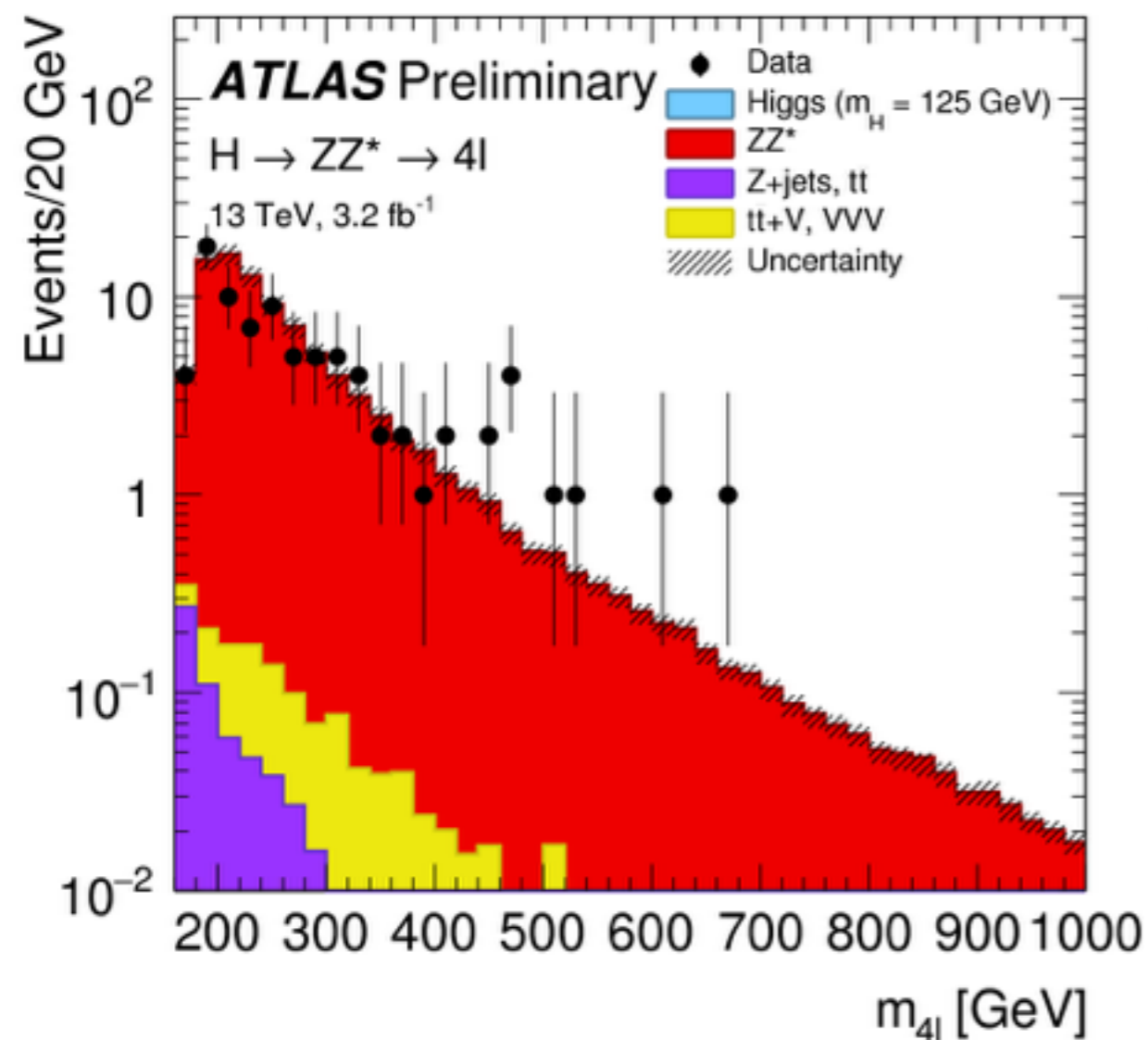




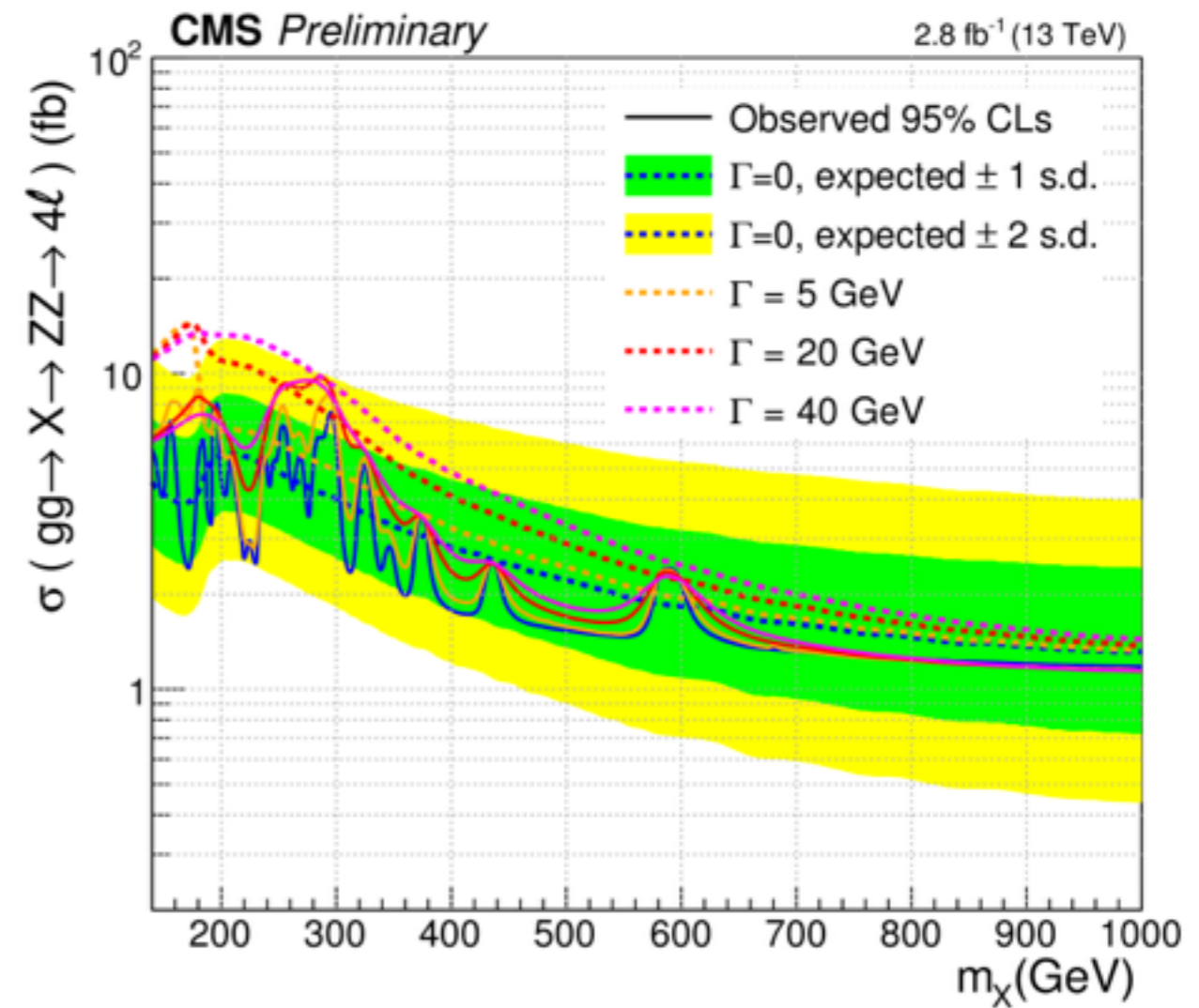
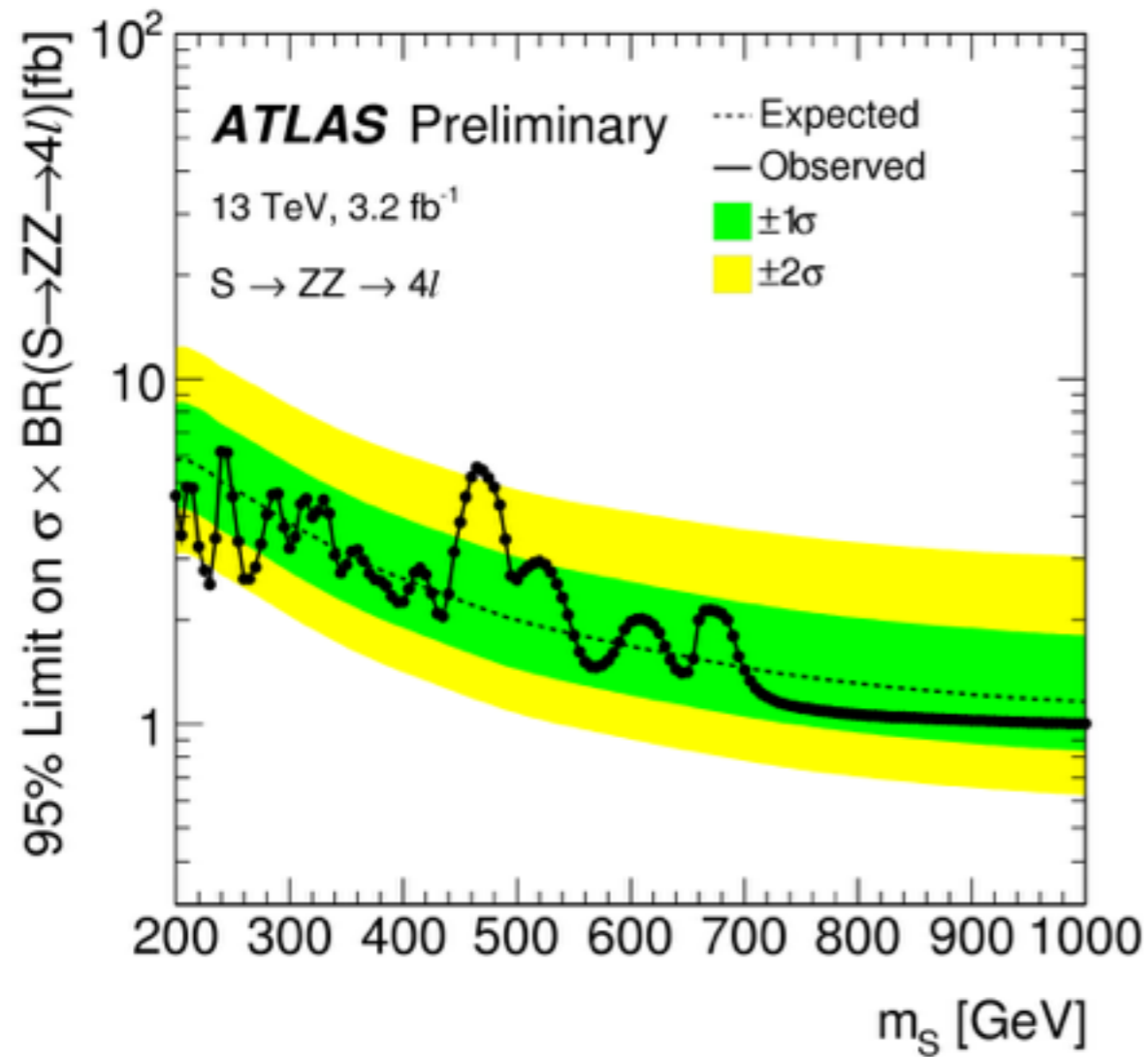




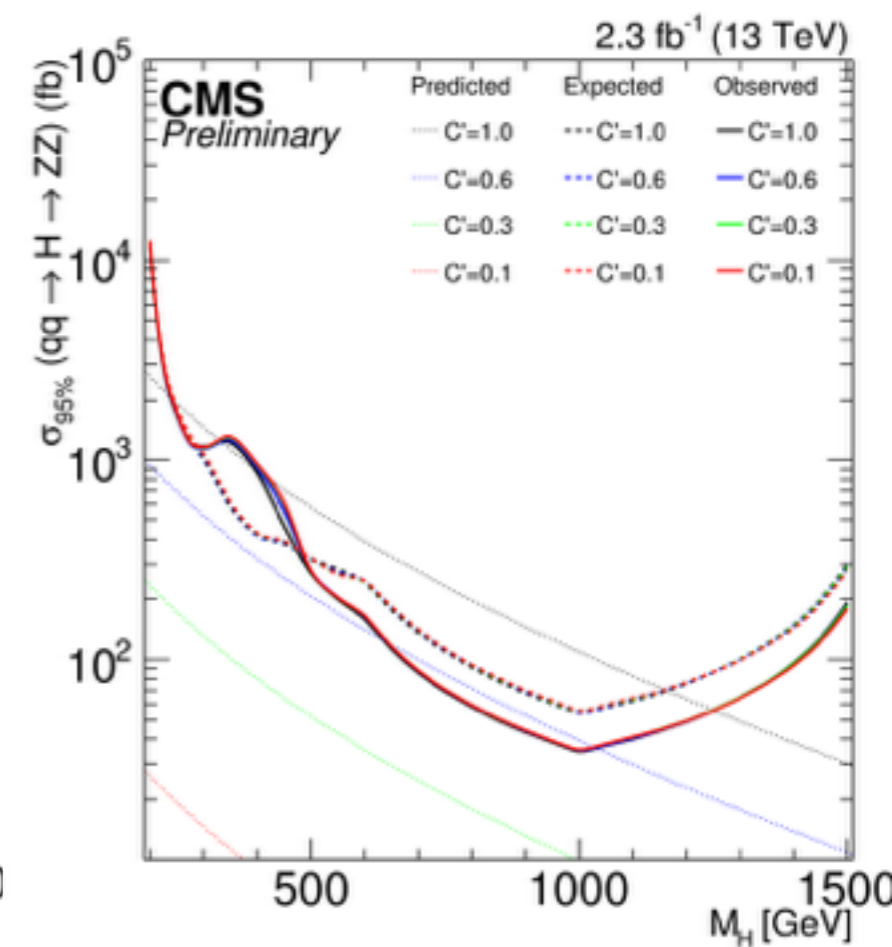
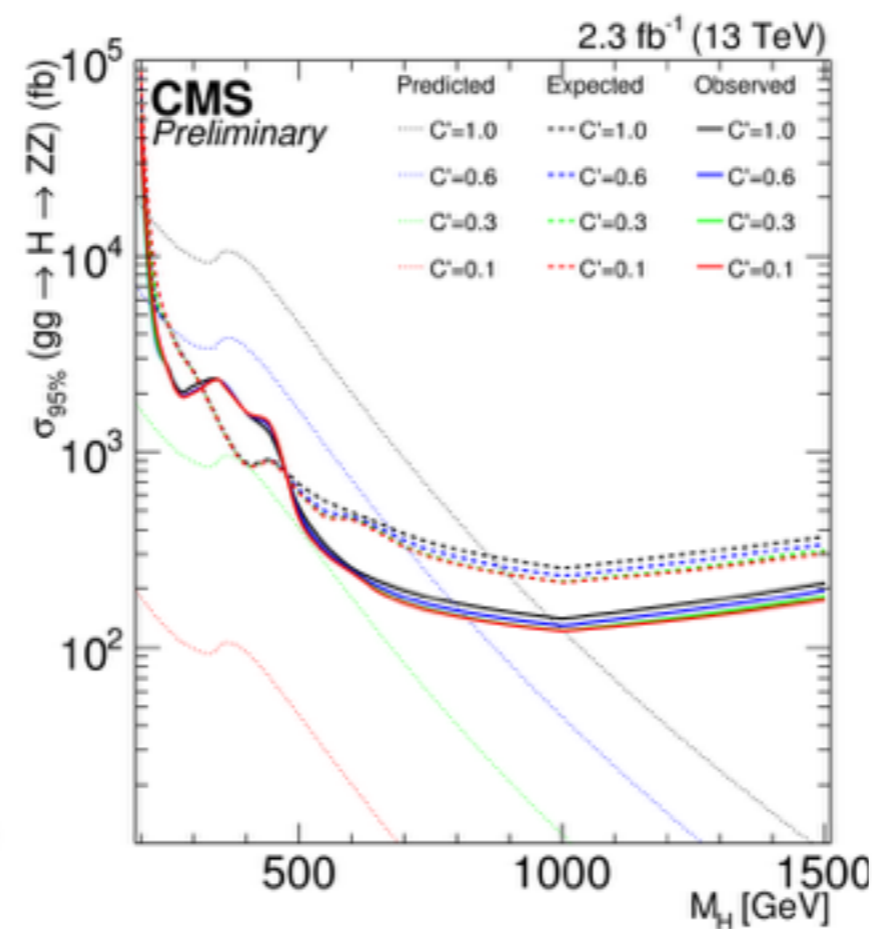
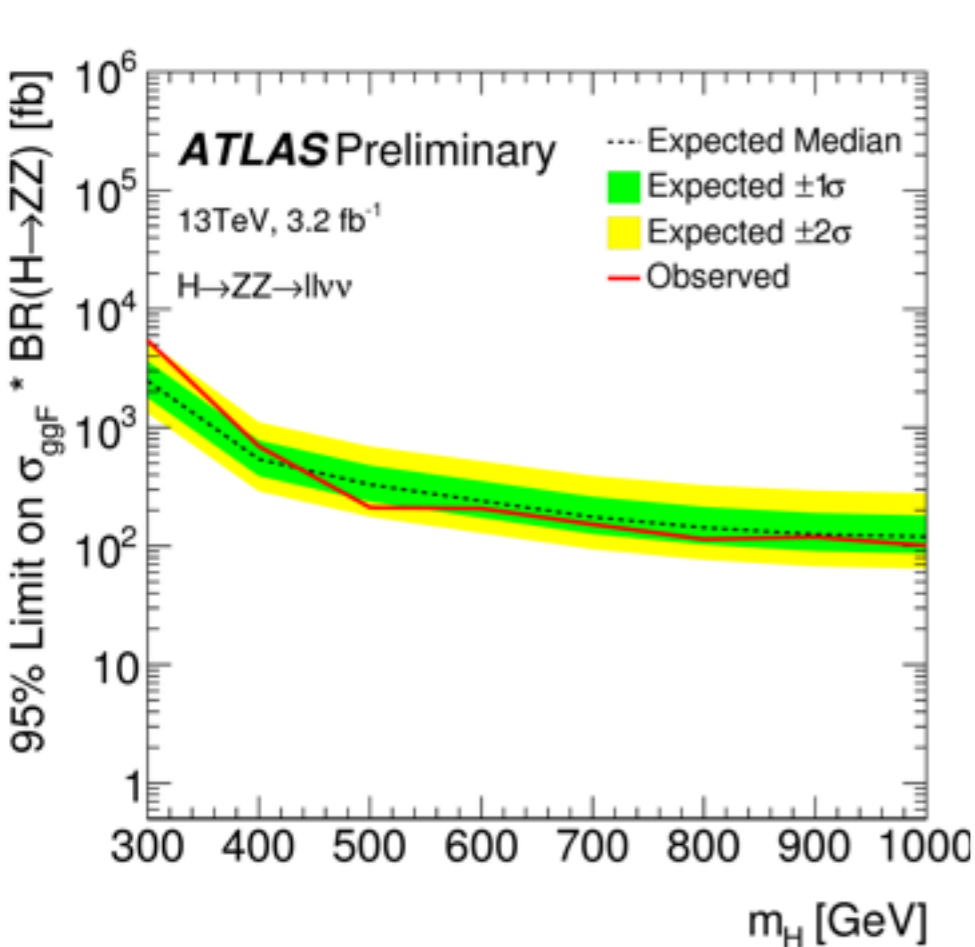
- ◎ $4l$ final state gives clean signature with low background
- ◎ Search for resonances with mass between 140 and 1000 GeV



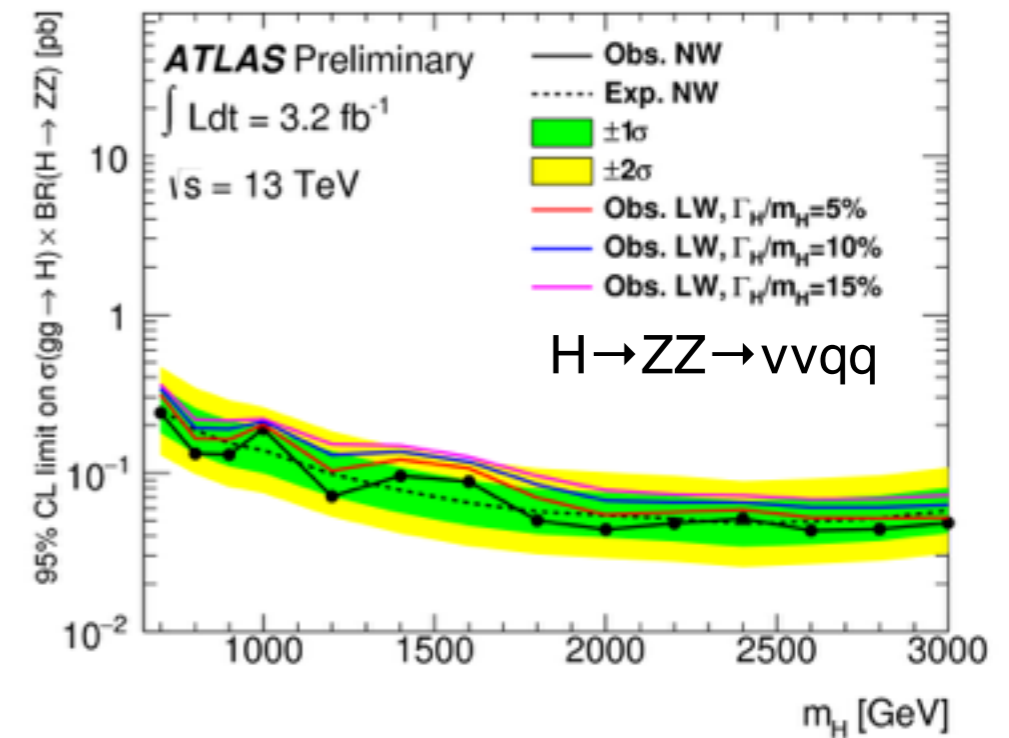
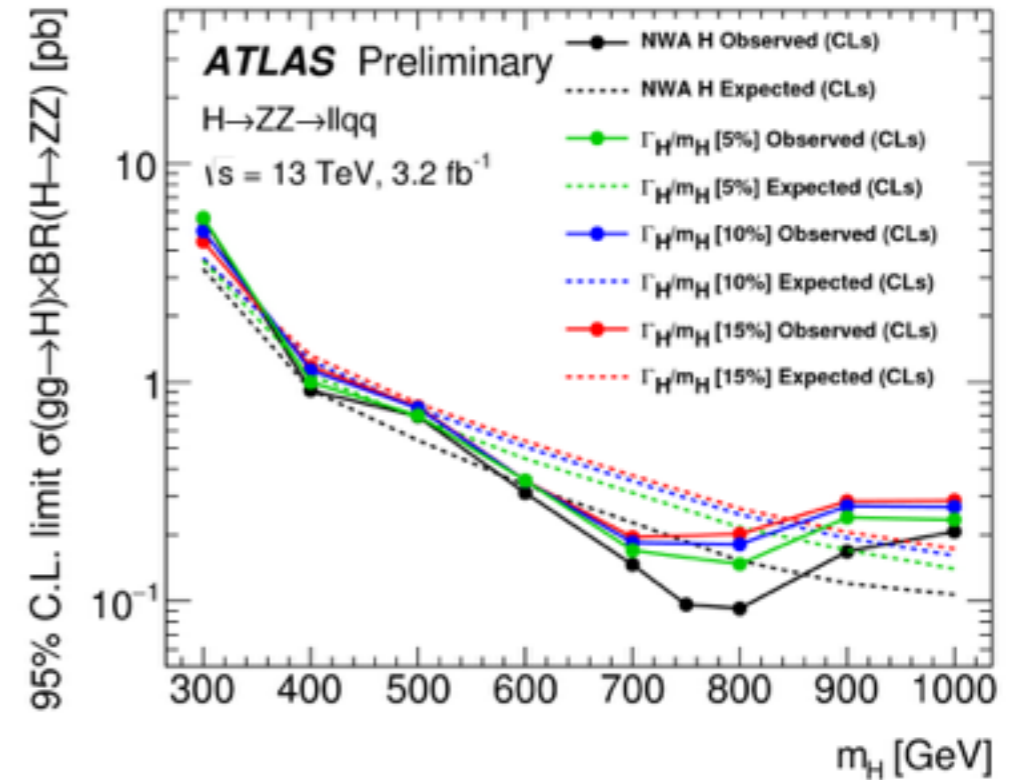
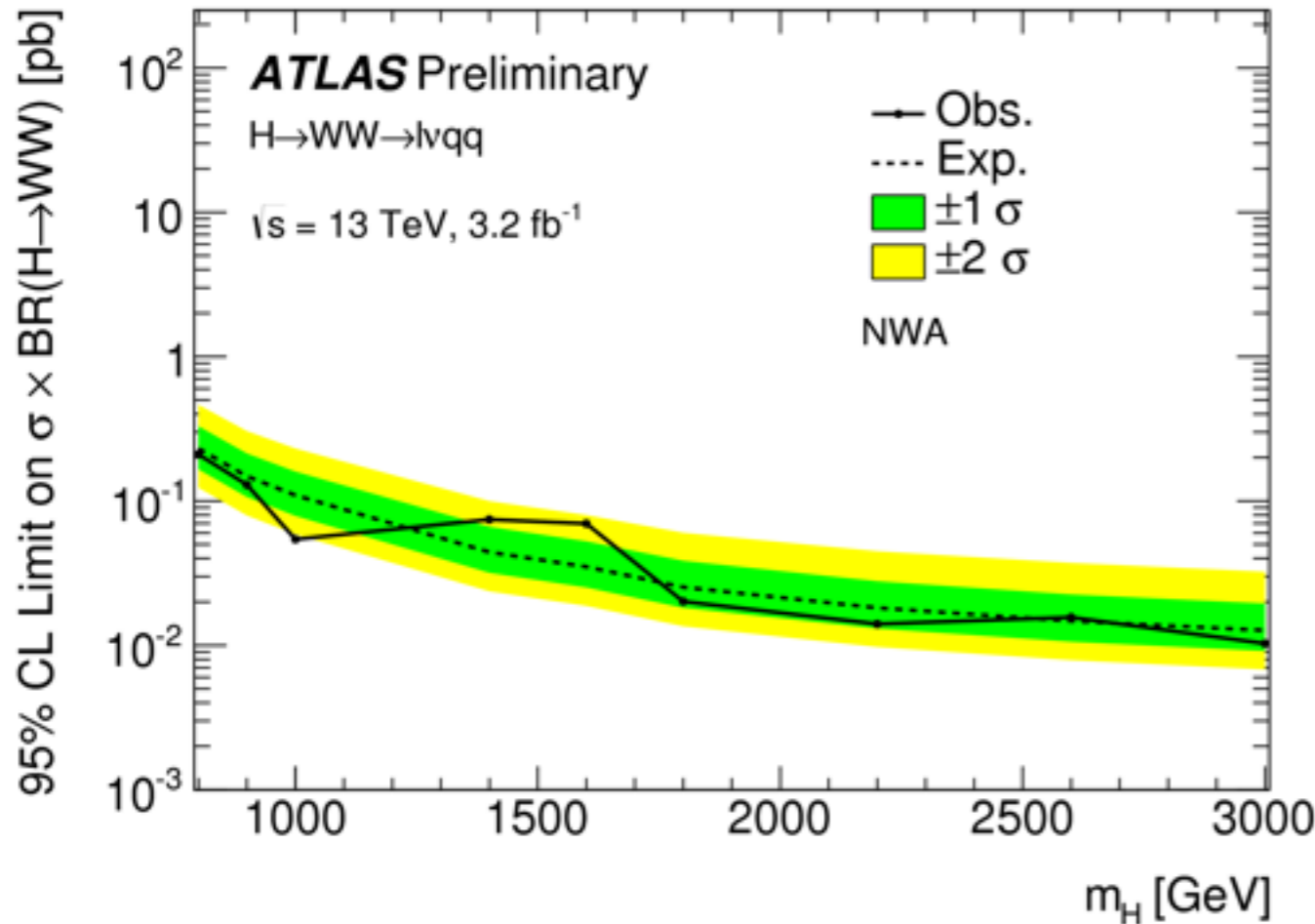
- ⊙ No significant excess
- ⊙ Deficit at 750 GeV



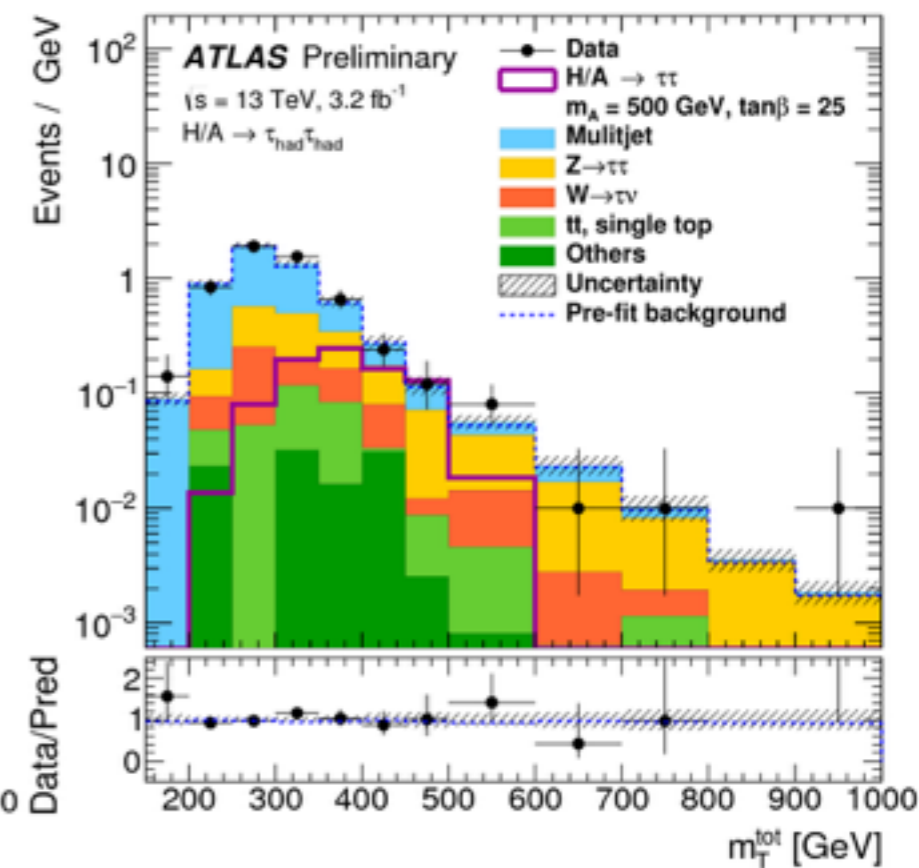
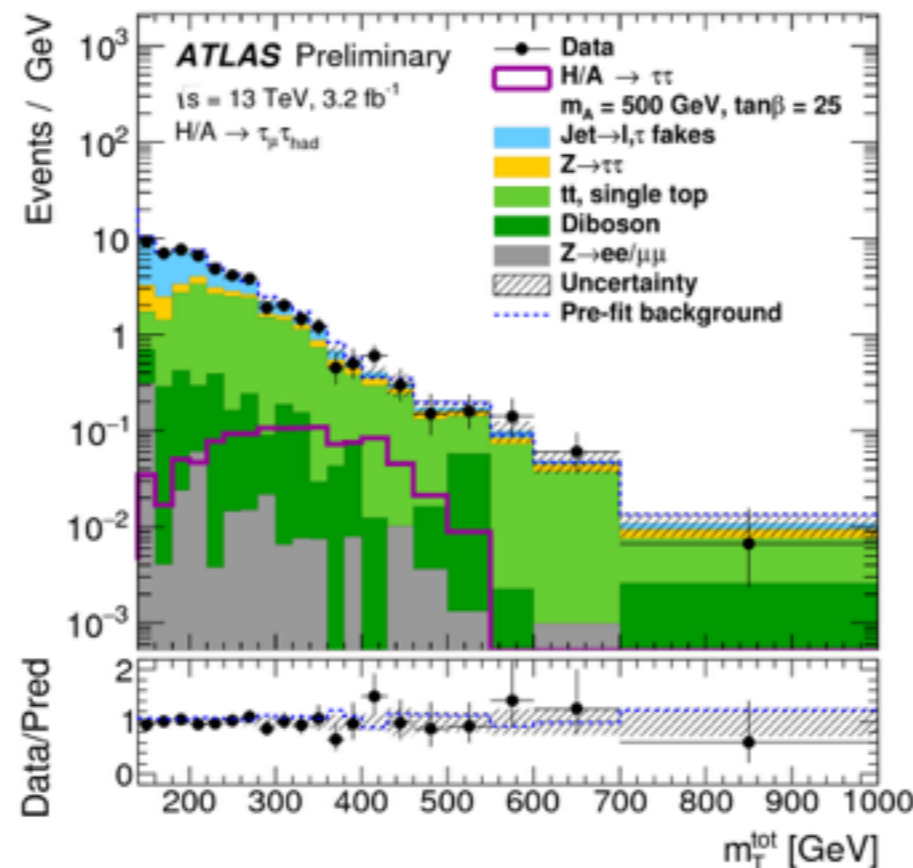
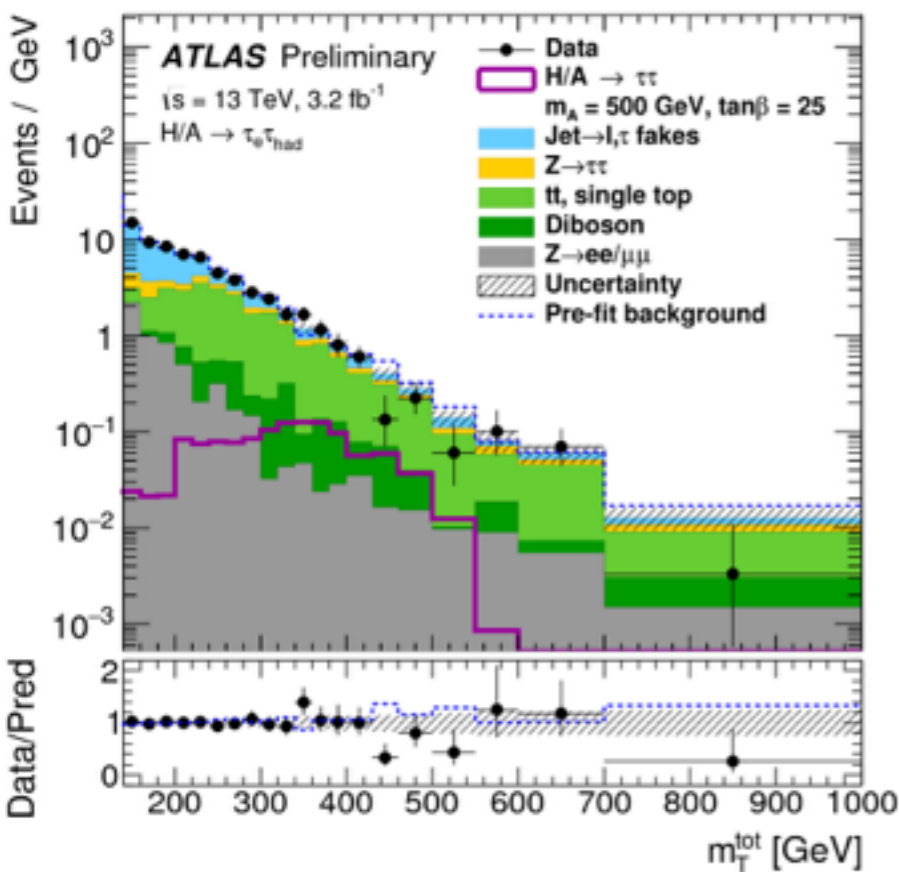
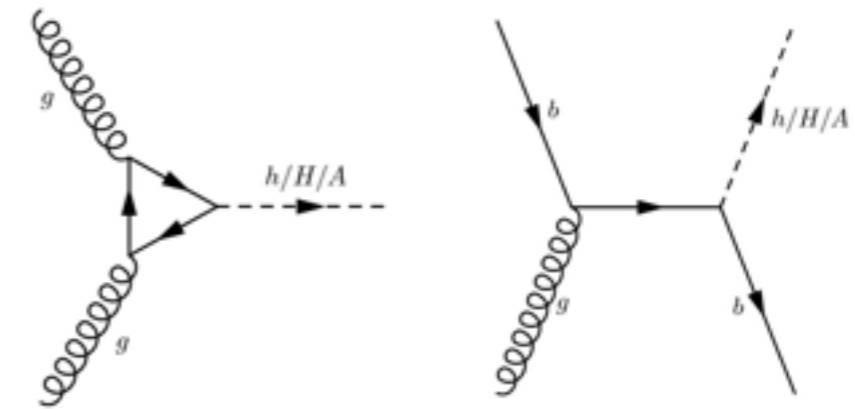
- $H \rightarrow ZZ \rightarrow ll\nu\nu$
- Exploring gF and VBF topology
- Transverse mass used as discriminant variable
- Results interpreted in electroweak singlet models and Type-I and Type-II 2HDM.



- $H \rightarrow WW \rightarrow l\nu qq$, $H \rightarrow ZZ \rightarrow ll qq$, $H \rightarrow ZZ \rightarrow \nu\nu qq$
- Boosted diboson resonances
- Run-I excitement. Excess not confirmed (nor ruled out)
- Search range extends to 3TeV
- Narrow width approximation and widths ranging from 5-15%



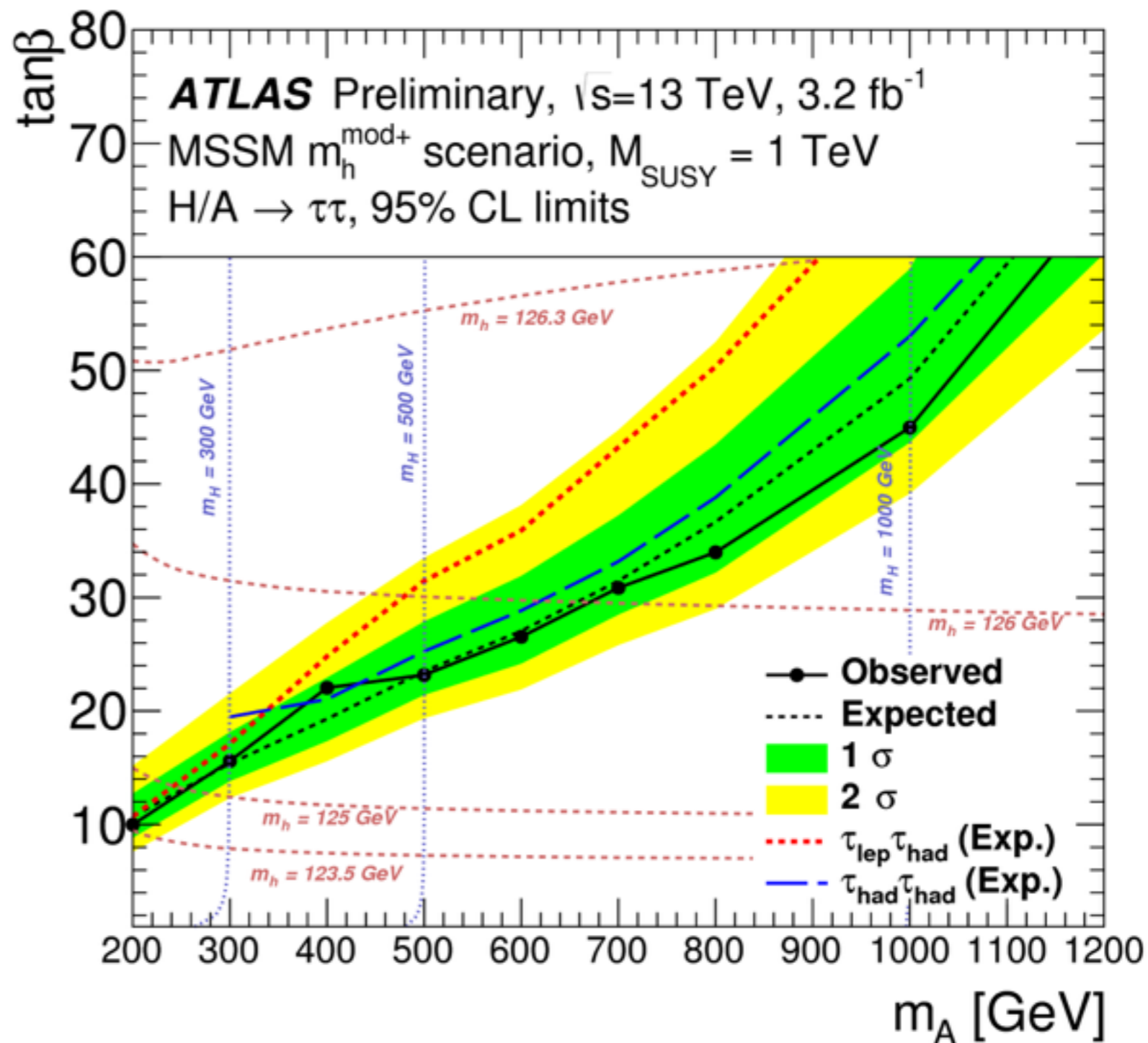
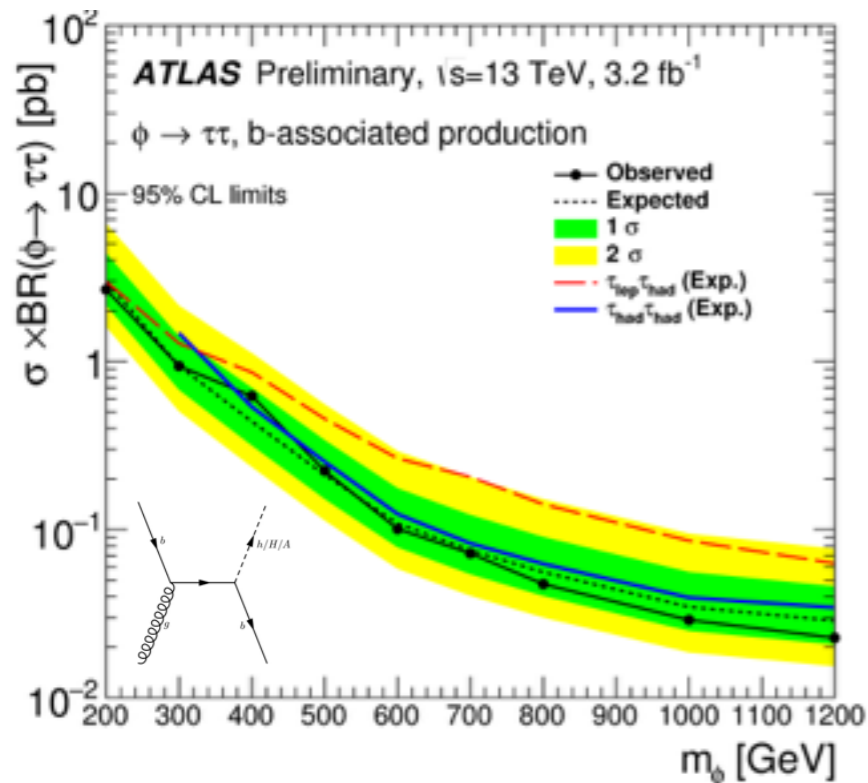
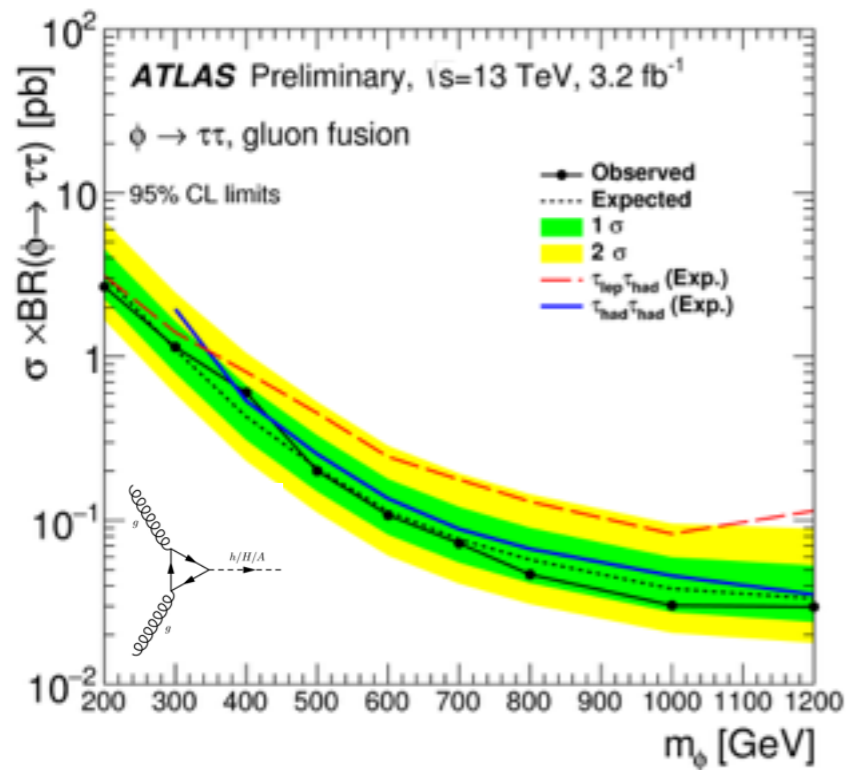
- ⊙ $H \rightarrow \tau\tau$ coupling enhanced in MSSM at high $\tan\beta$
- ⊙ $T_{lep}T_{had}$ and $T_{had}T_{had}$ channels studied
- ⊙ m_T^{total} final discriminant
- ⊙ Separating gF and b-associated production



$X \rightarrow \tau\tau$

Neutral Higgs

ATLAS-CONF-2015-061



- $H^\pm \rightarrow tb$

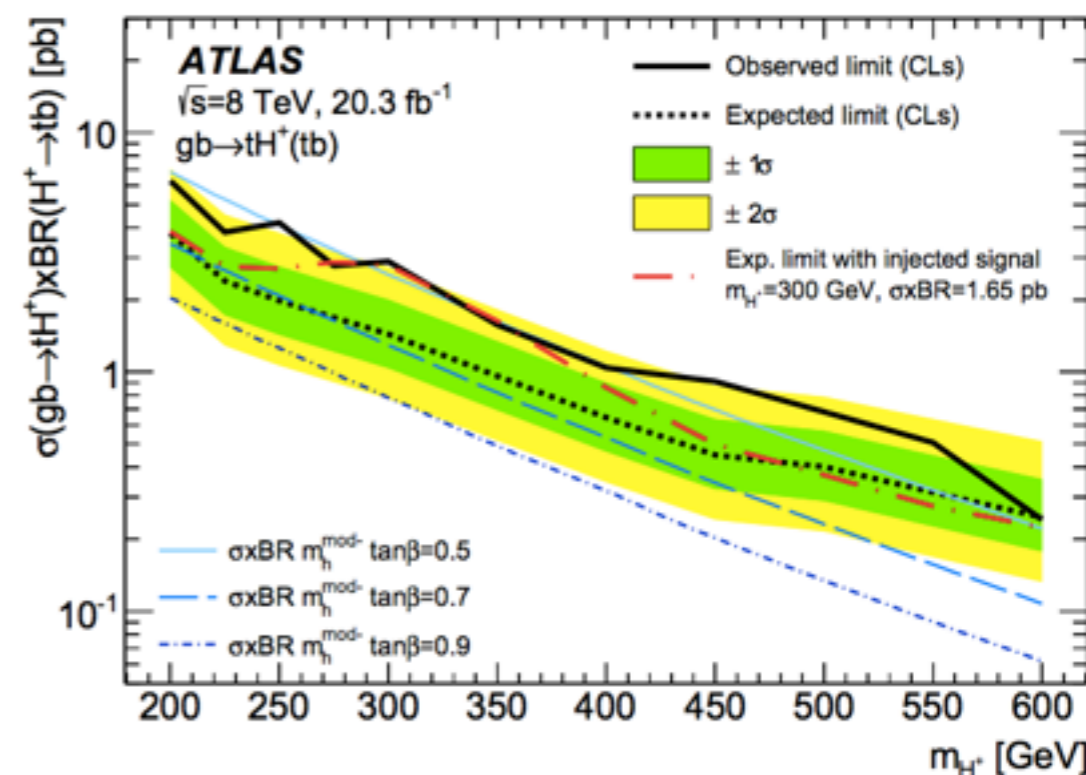
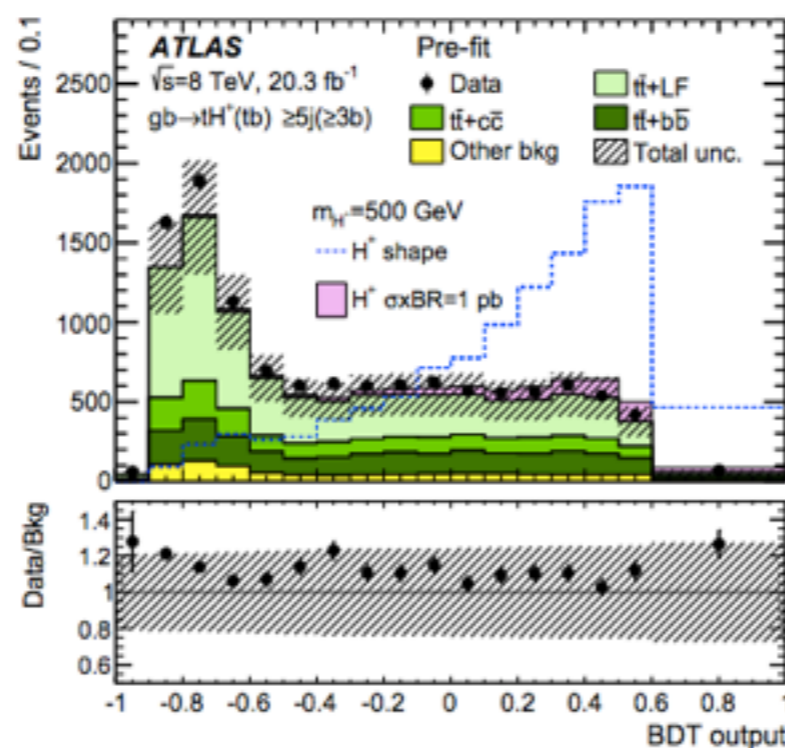
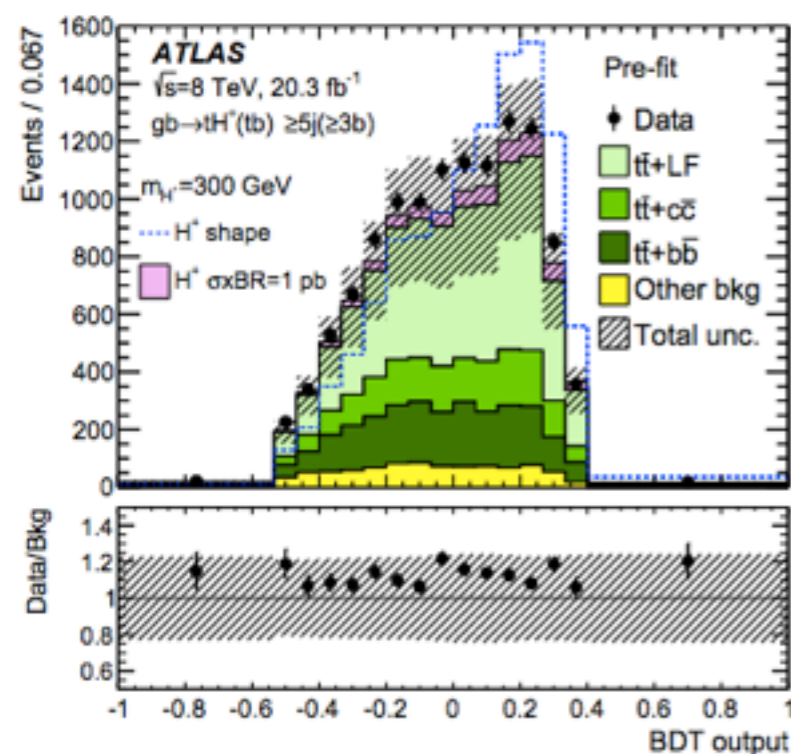
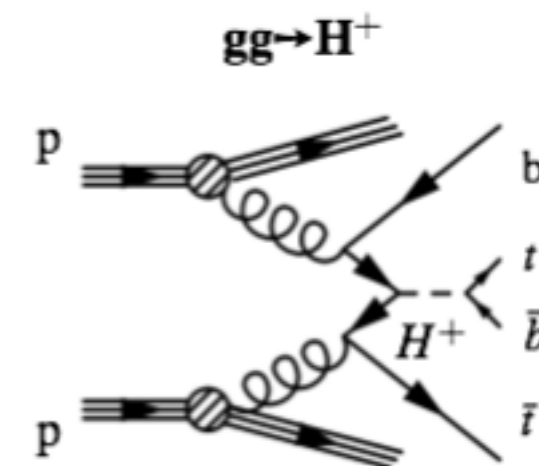
- Production in association with top quark

- Lepton+jets final state

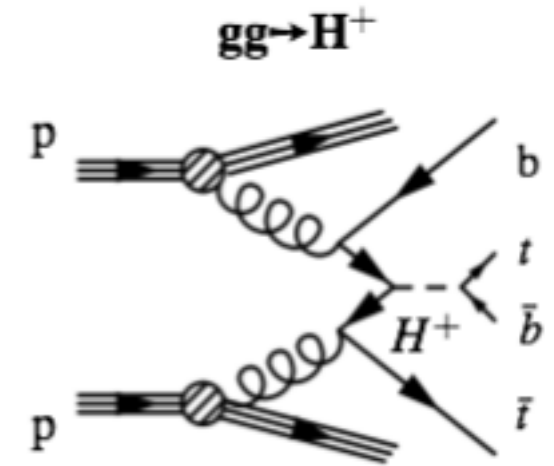
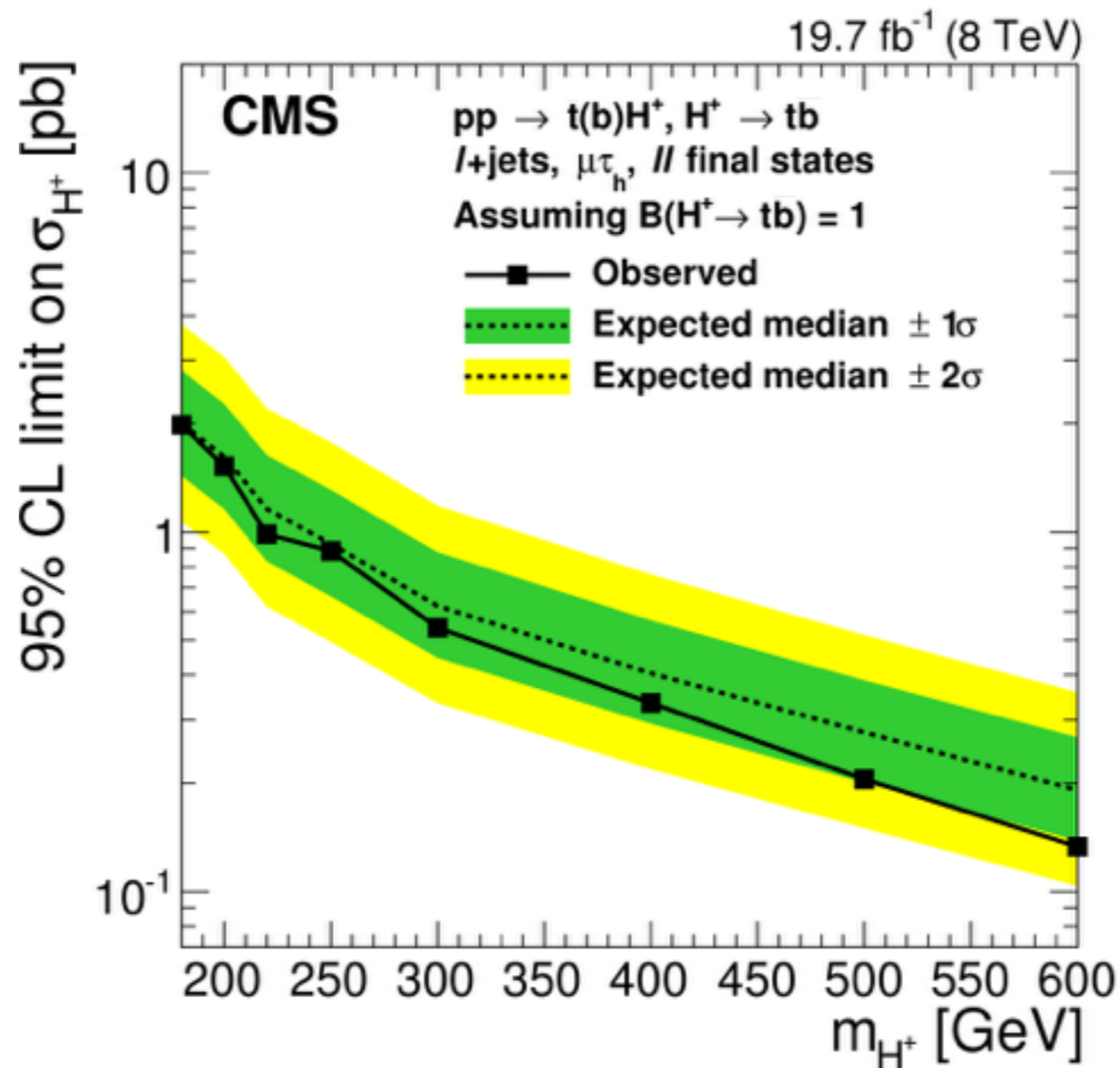
- BDT in signal region with $\geq 5j, \geq 3b$

→ formed with H_T , lead jet p_T , m_{bb} , second Fox-Wolfram moment, and average ΔR between all b-jet pairs

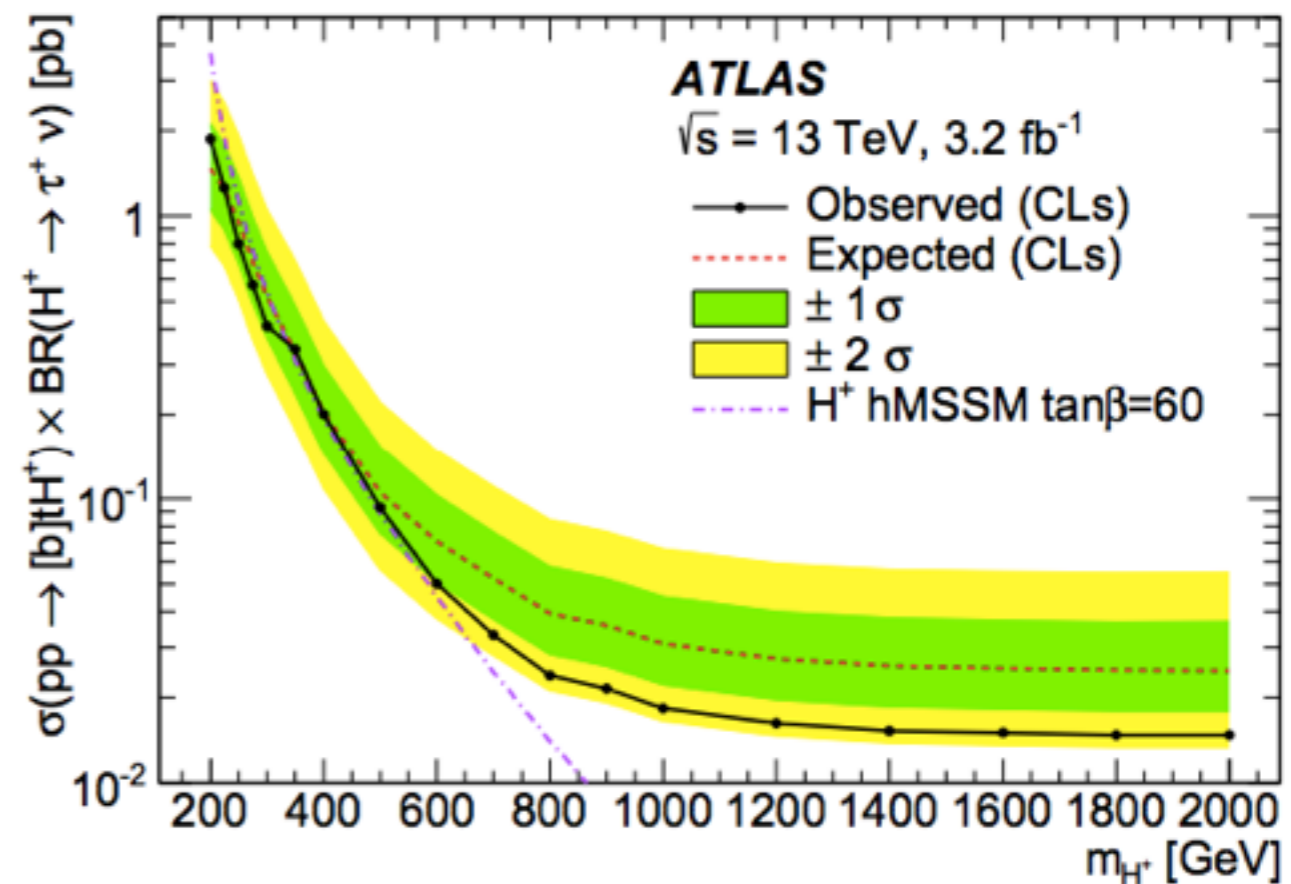
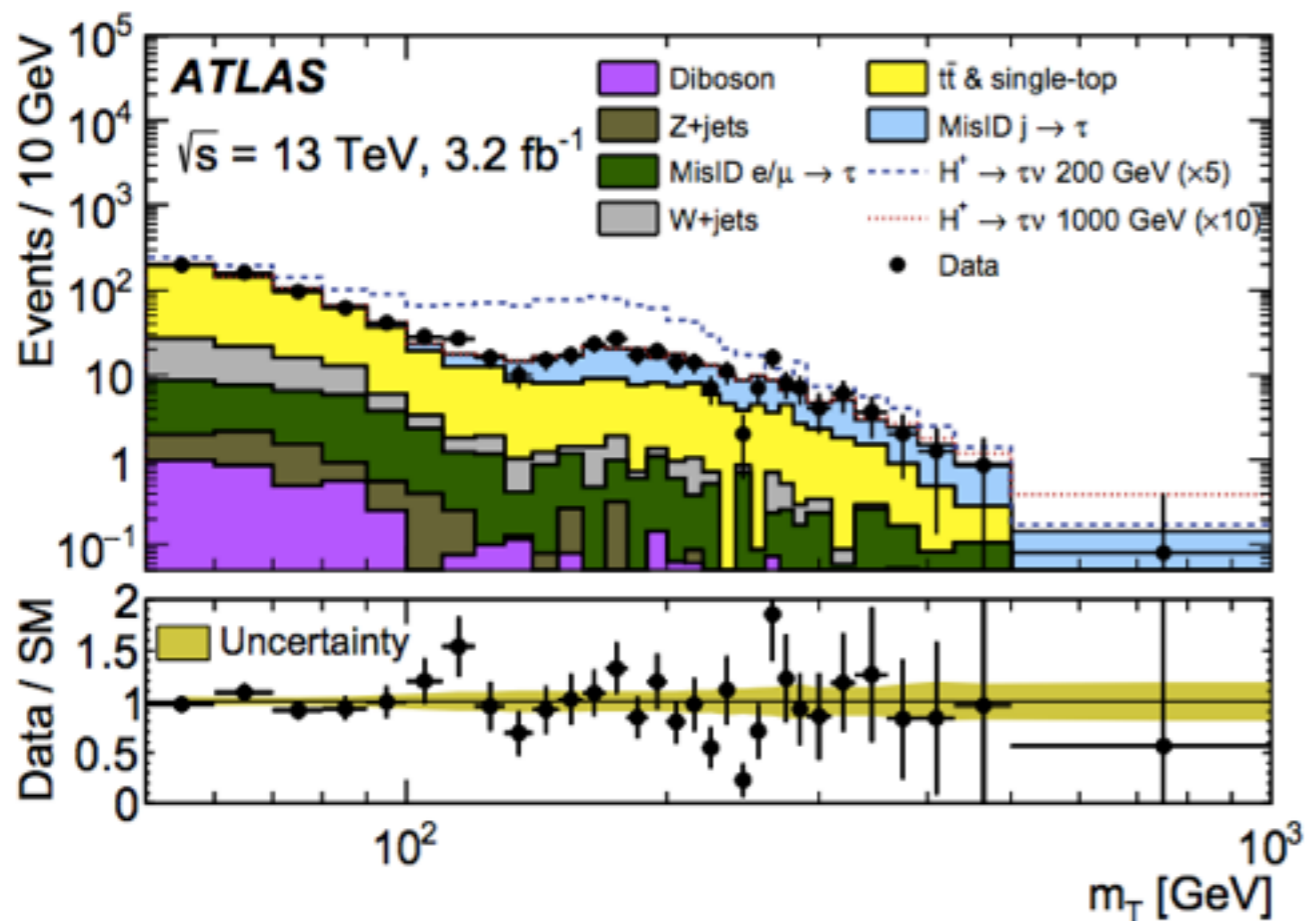
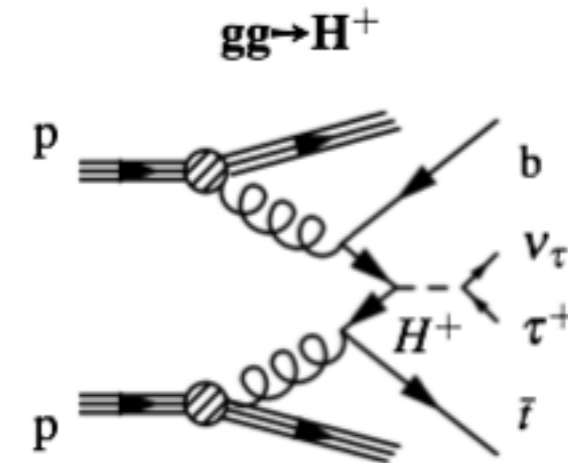
- Observed 2.3-2.4 excess (likely due to background mismodelling)



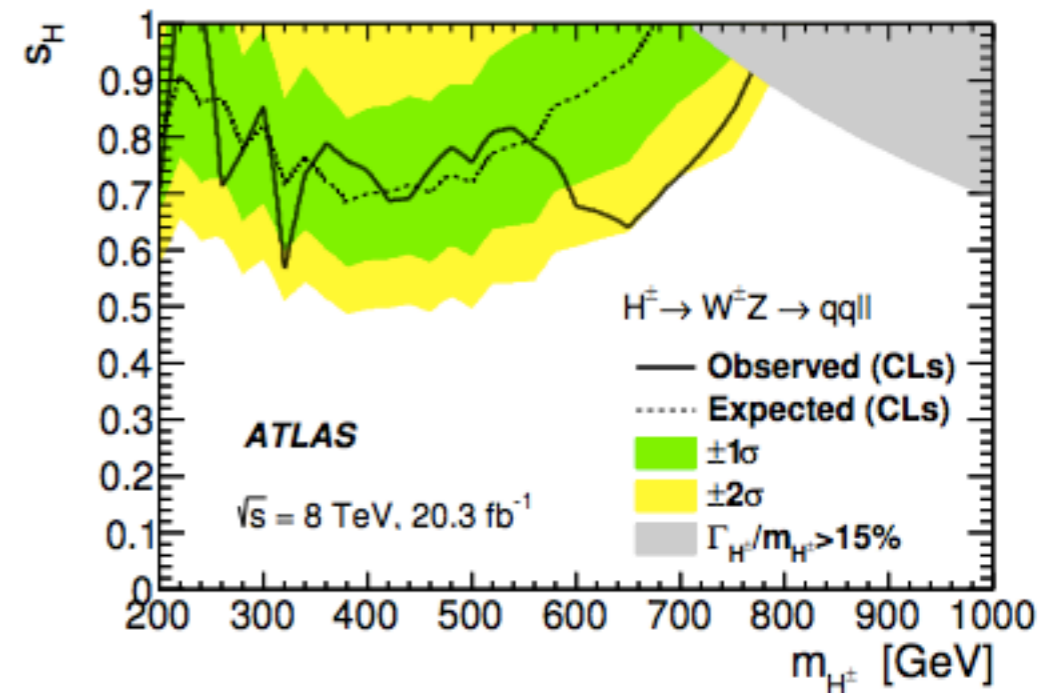
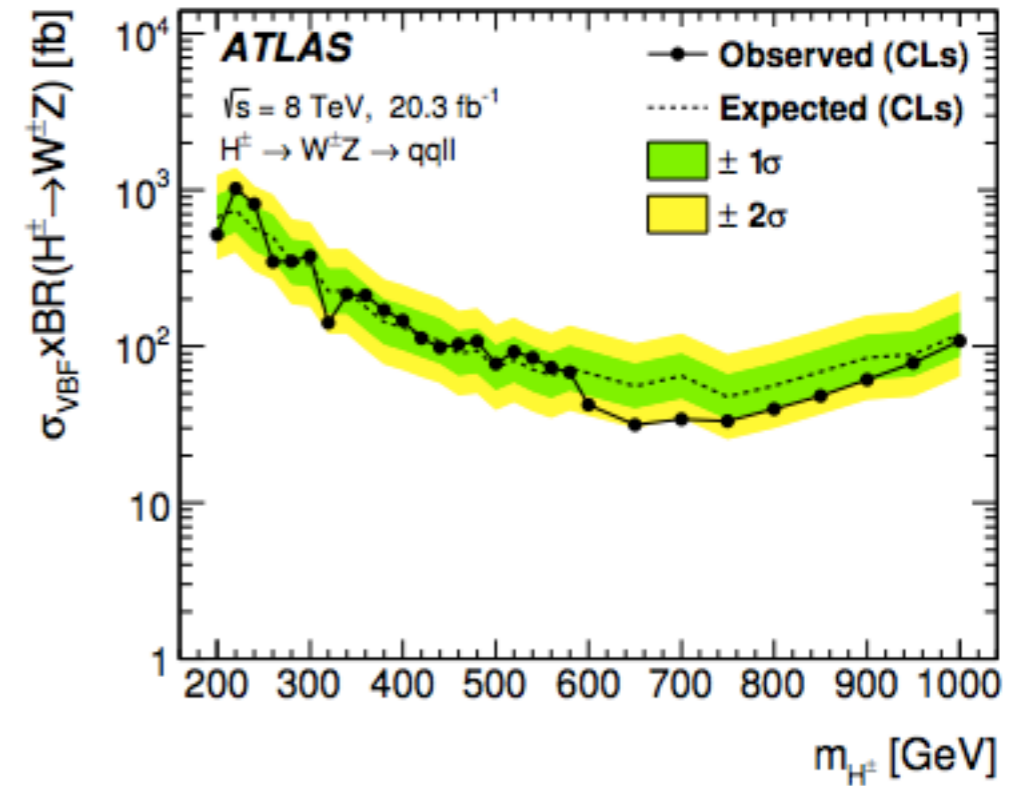
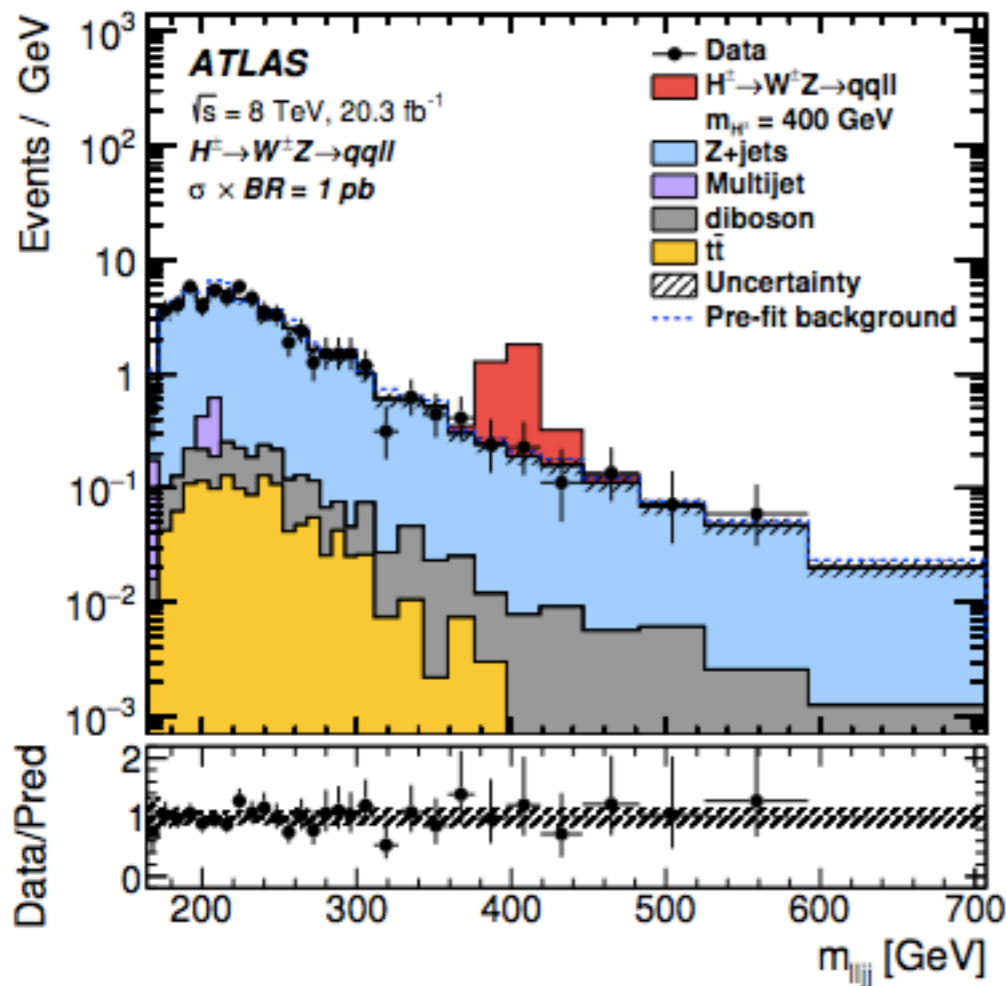
- $H^\pm \rightarrow tb$
- Production in association with top quark
- Lepton+jets, $\mu\tau_{had}$, and 2 lepton final state



- $H^\pm \rightarrow \tau \nu$
- Production in association with top quark
- 8 TeV results by ATLAS and CMS
- Using transverse mass as discriminant



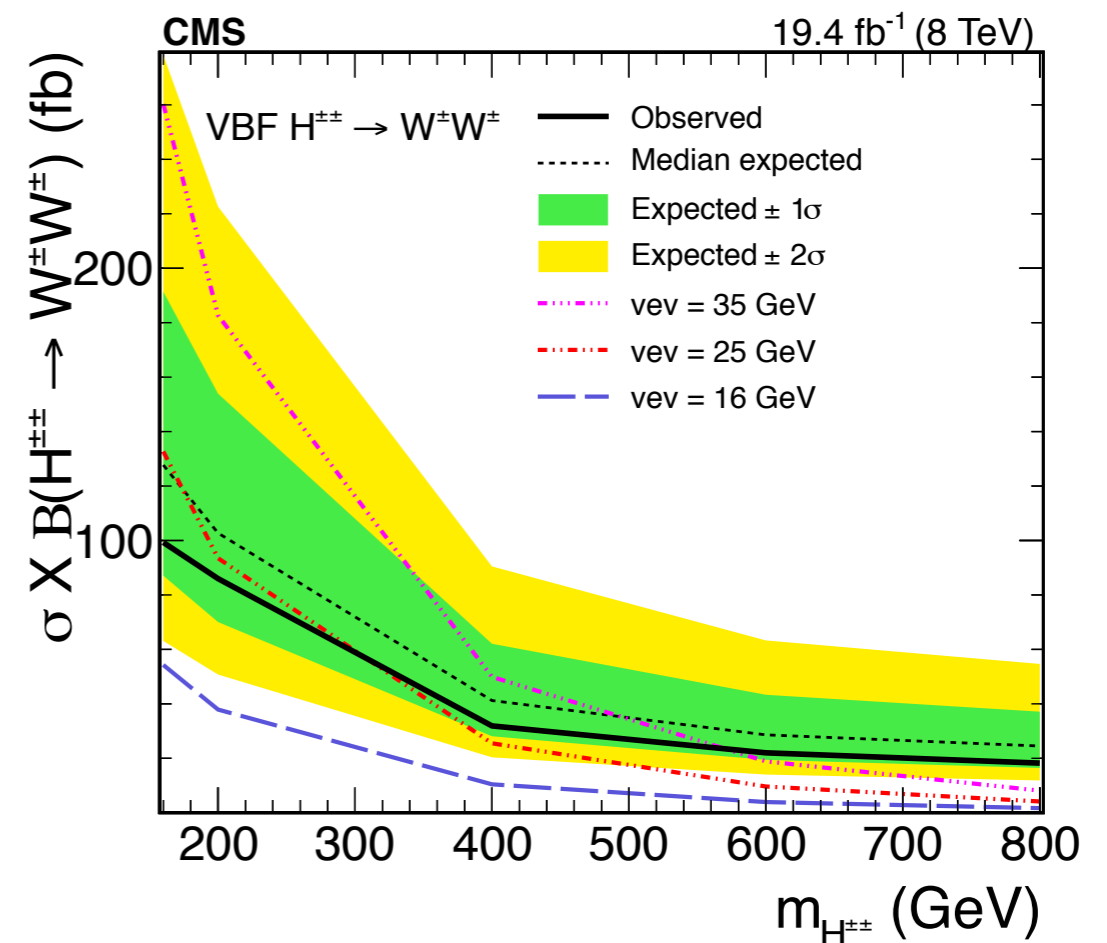
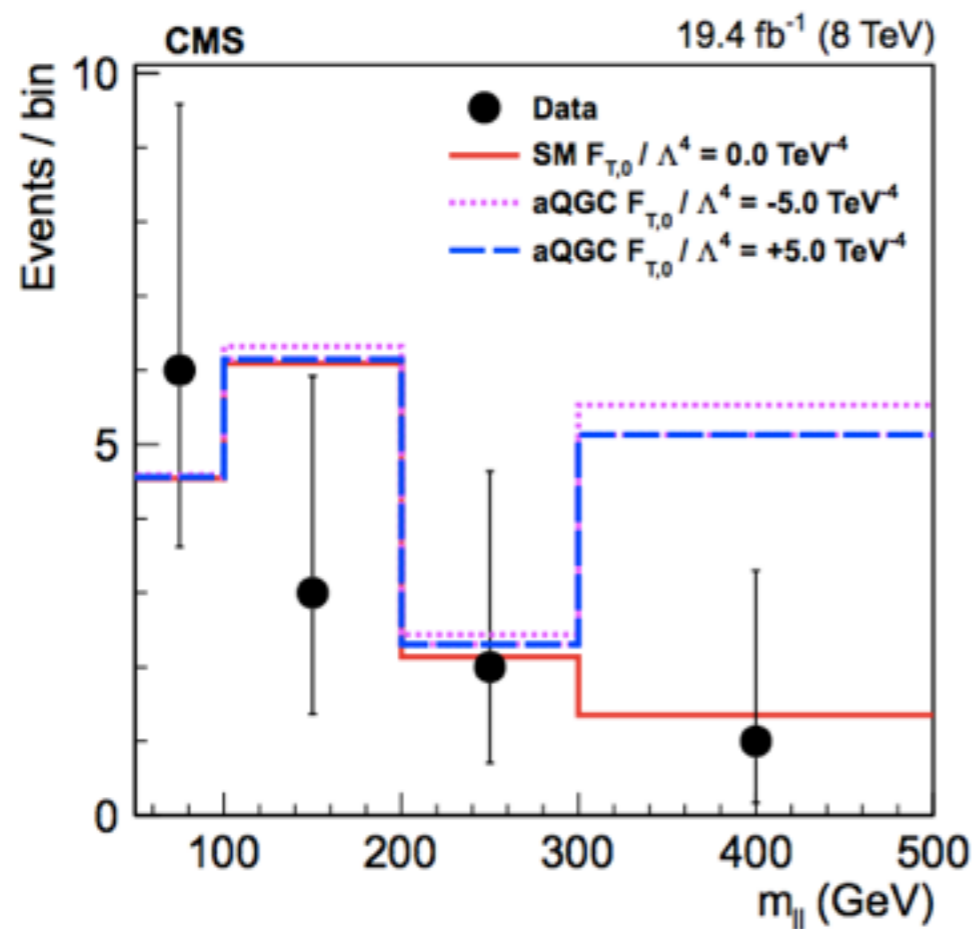
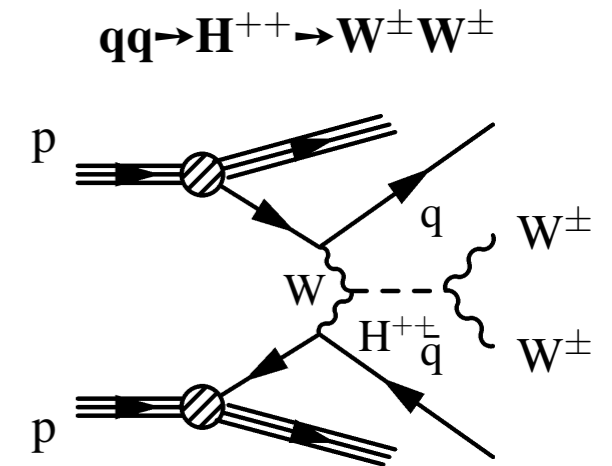
- ⊙ $H^\pm \rightarrow W^\pm Z \rightarrow qq\ell^+\ell^-$ (Vector boson scattering topology)
- ⊙ Fermiophobic charged Higgs bosons
- ⊙ Predictions from Georgi-Machacek (GM) Higgs Triplet Models
- ⊙ Excluding phase-space where large fractions of the W and Z mass are generated by the triplet



$X^\pm \rightarrow WW$ Doubly Charged Higgs

arXiv:1410.6315

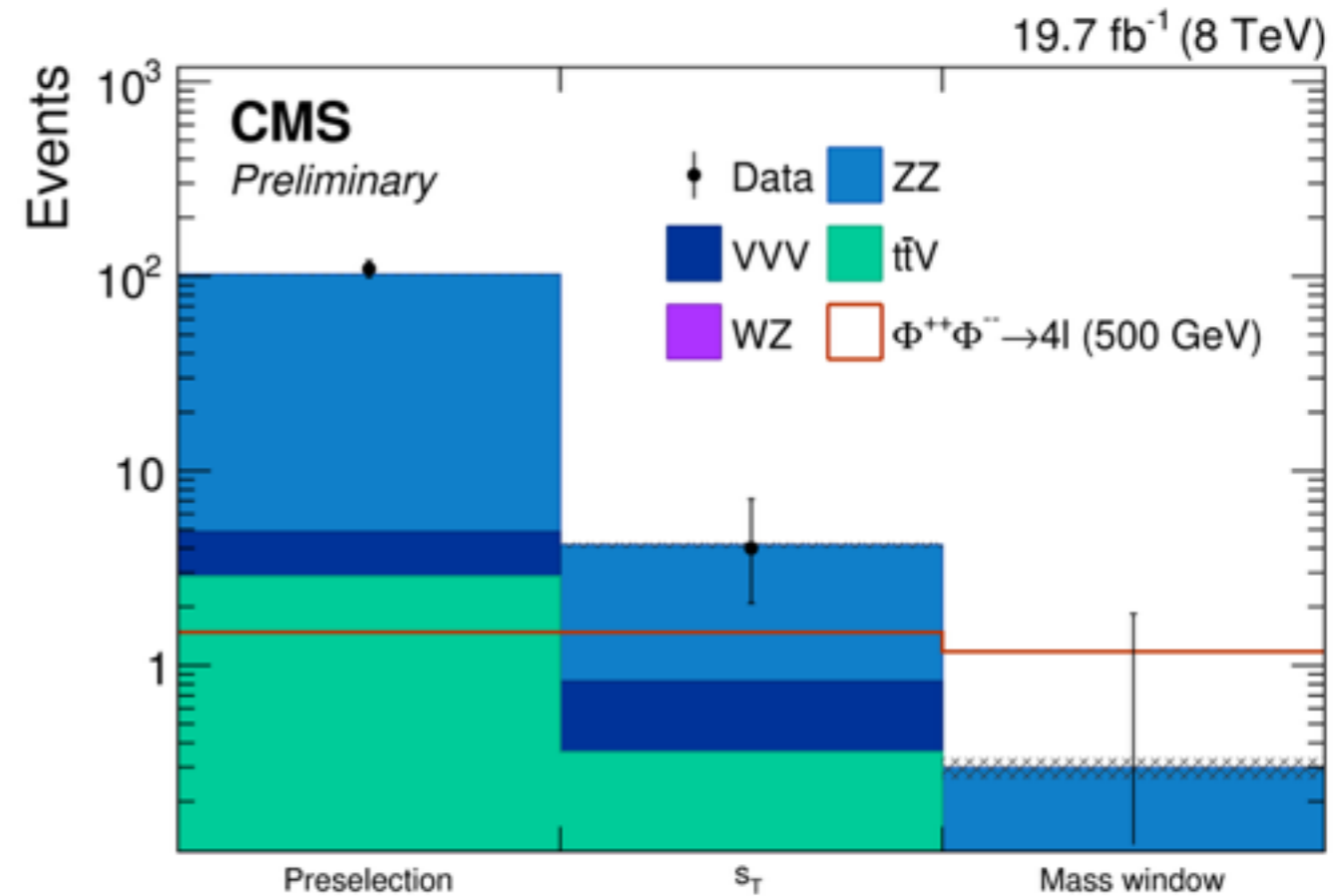
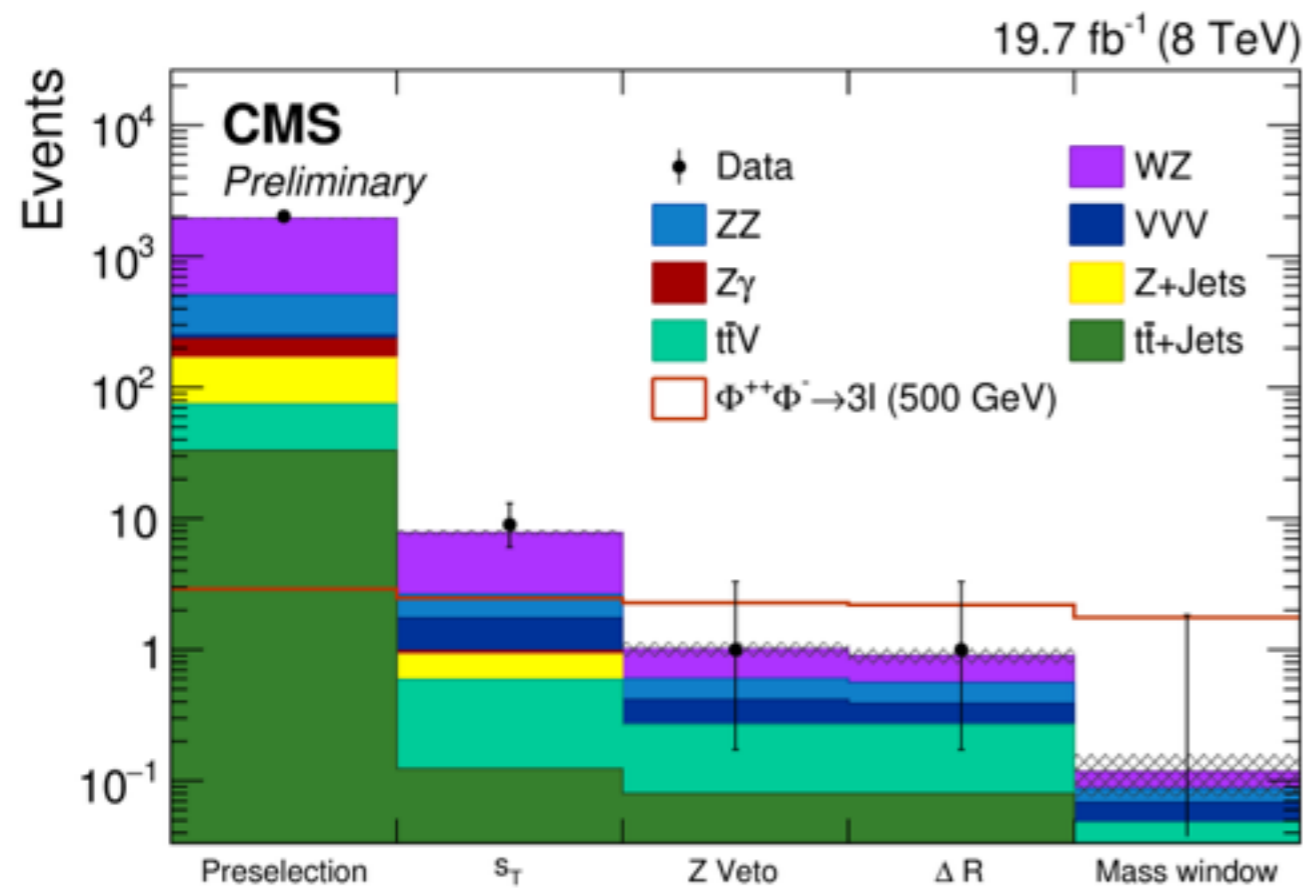
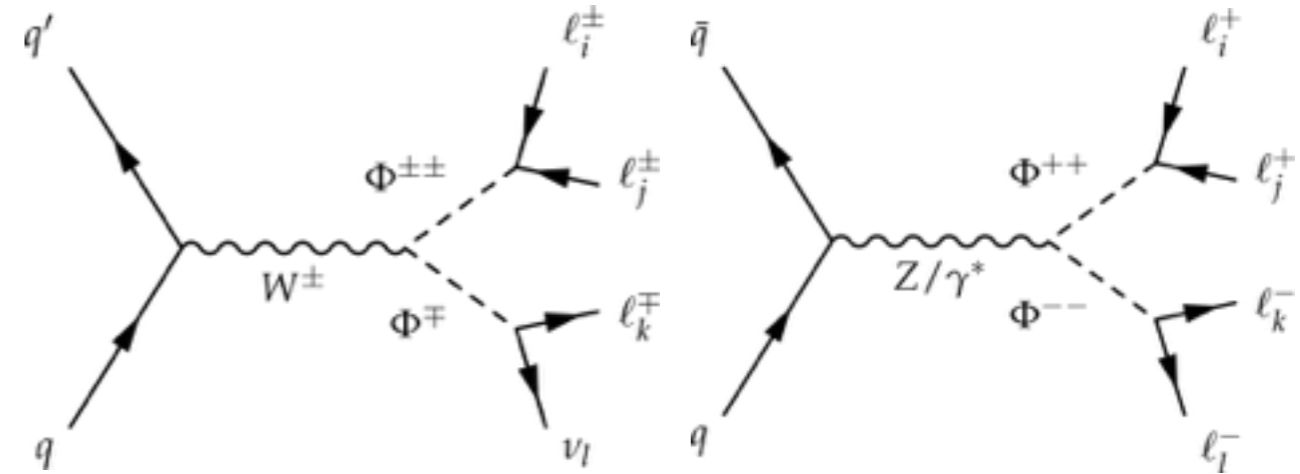
- ◉ $H^{\pm\pm} \rightarrow W^\pm W^\pm \rightarrow l^\pm l^\pm \nu \nu$ (Vector boson scattering topology)
- ◉ Predictions from GM Higgs Triplet Models
- ◉ Spin-off of vector boson scattering measurement



$X^{\pm\pm} \rightarrow 4l$ Doubly Charged Higgs

CMS-PAS-HIG-14-039

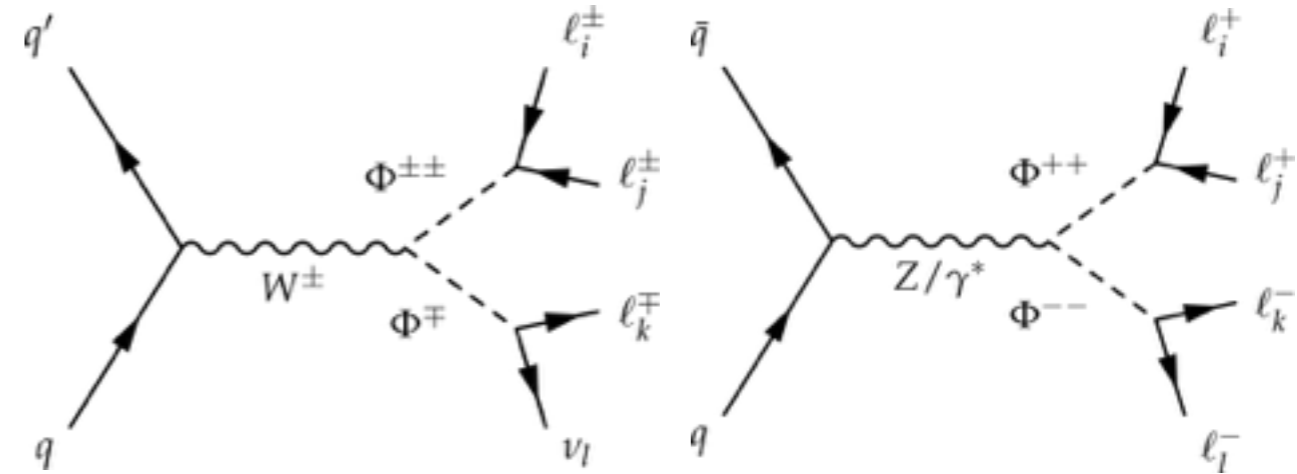
- Search for associated- or pair-production in 3 or 4 lepton final state



$X^{\pm\pm} \rightarrow 4l$ Doubly Charged Higgs

CMS-PAS-HIG-14-039

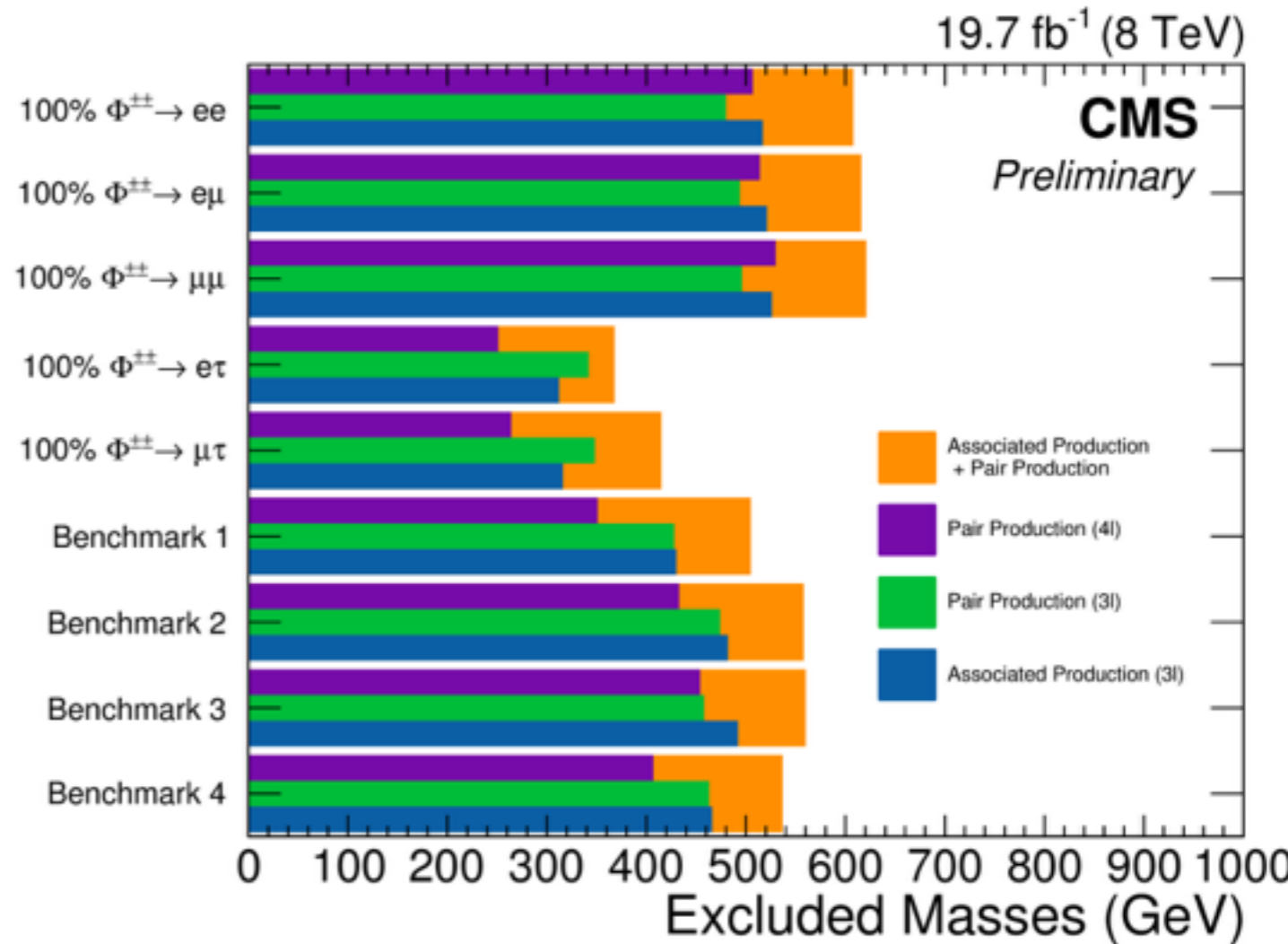
- Search for associated- or pair-production in 3 or 4 lepton final state



$m_\phi = 500 \text{ GeV}$

Channel	Expected Signal		Expected Background	Observed
	AP	PP		
100% $\rightarrow ee$	3.63	5.44	0.28	0
100% $\rightarrow e\mu$	3.87	6.07	0.07	0
100% $\rightarrow \mu\mu$	4.14	7.15	0.04	0
100% $\rightarrow e\tau$	0.79	1.36	1.22	0
100% $\rightarrow \mu\tau$	0.86	2.00	1.16	1

Benchmark Point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	1/2	0	0	1/8	1/4	1/8
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

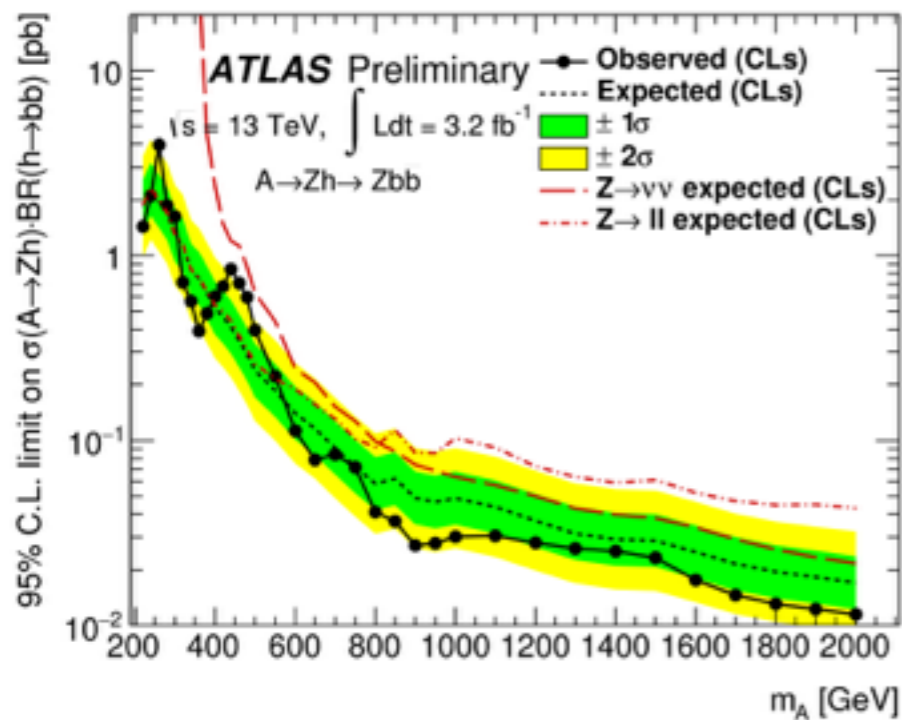


A → Zh Higgs to Higgs decays

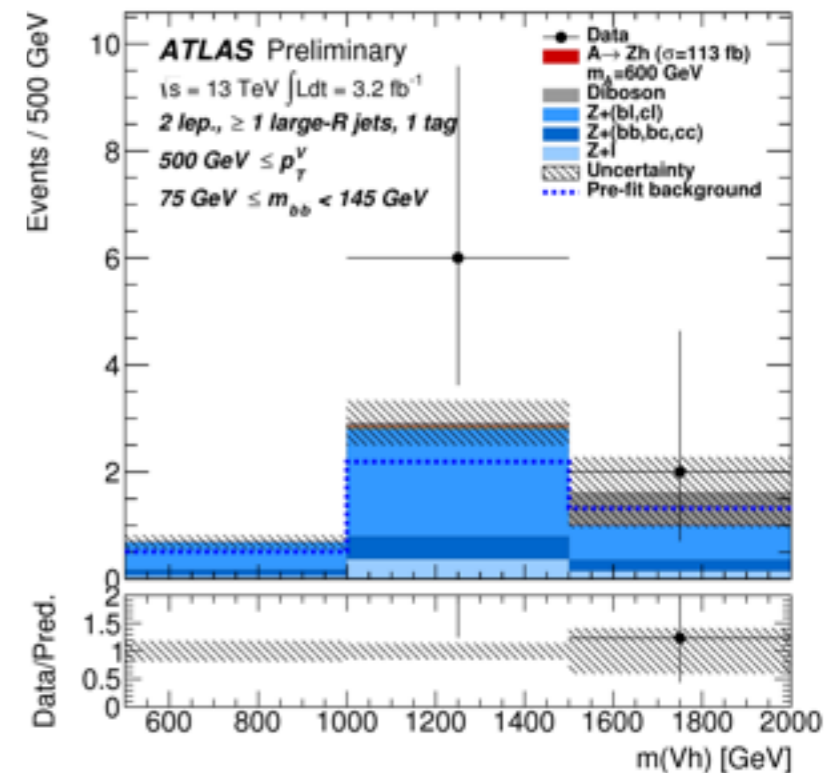
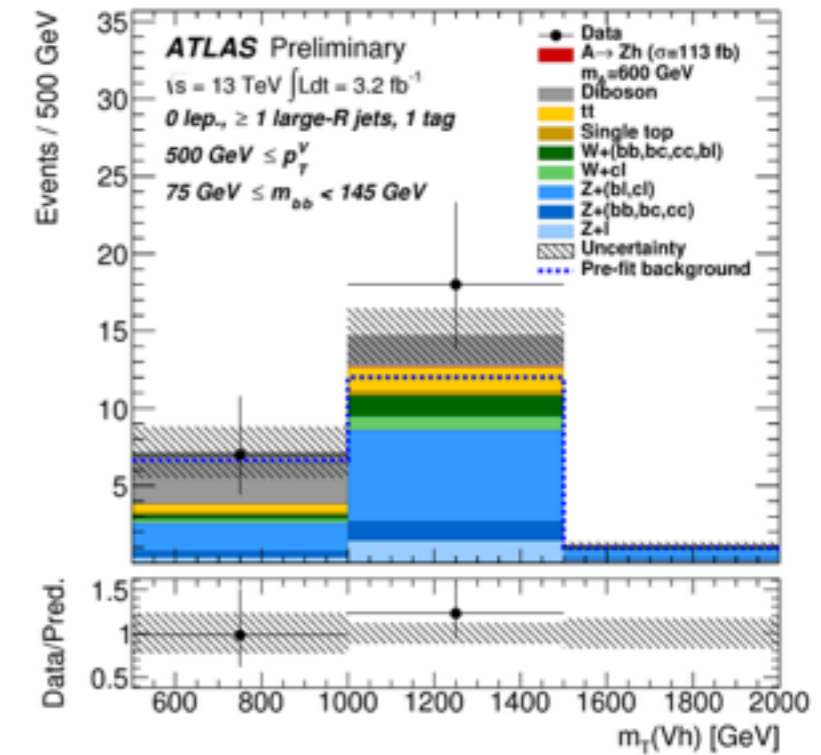
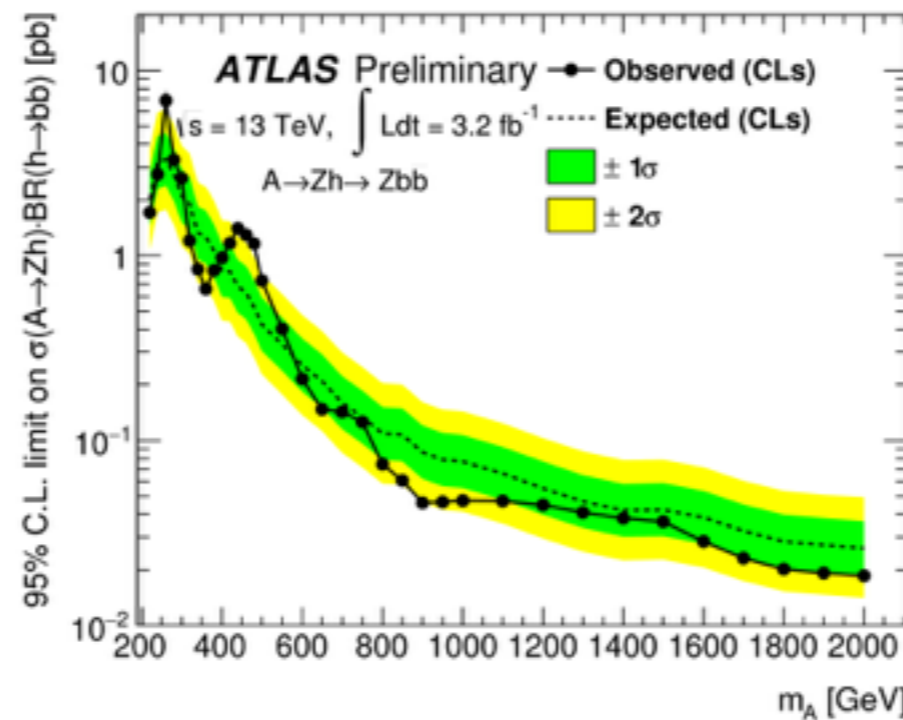
ATLAS-CONF-2016-015

- A → Zh, h → bb, Z → ll/vv
- 4-body mass or transverse mass as discriminant
- Search range $m_A = 200\text{--}2000$ GeV

gluon fusion production



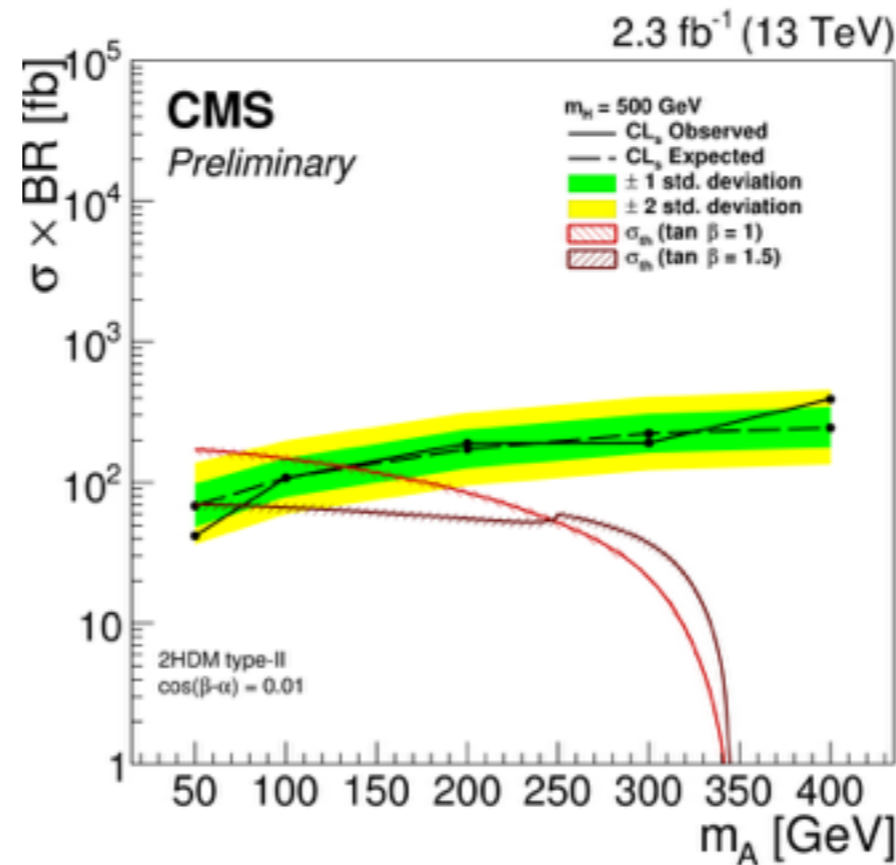
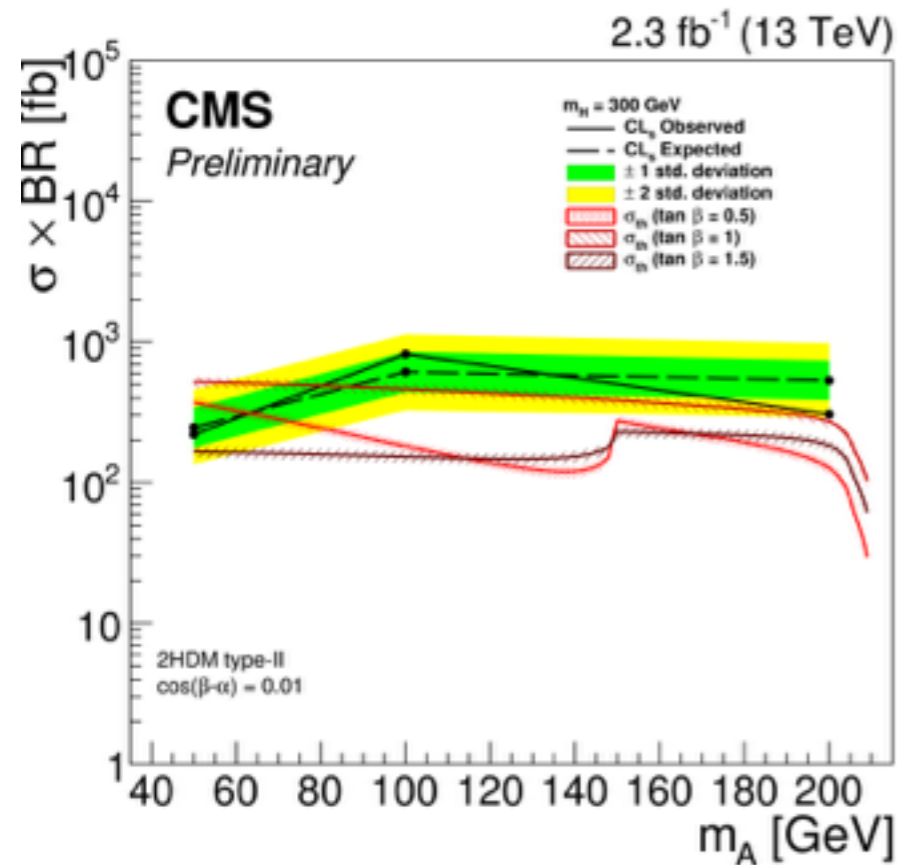
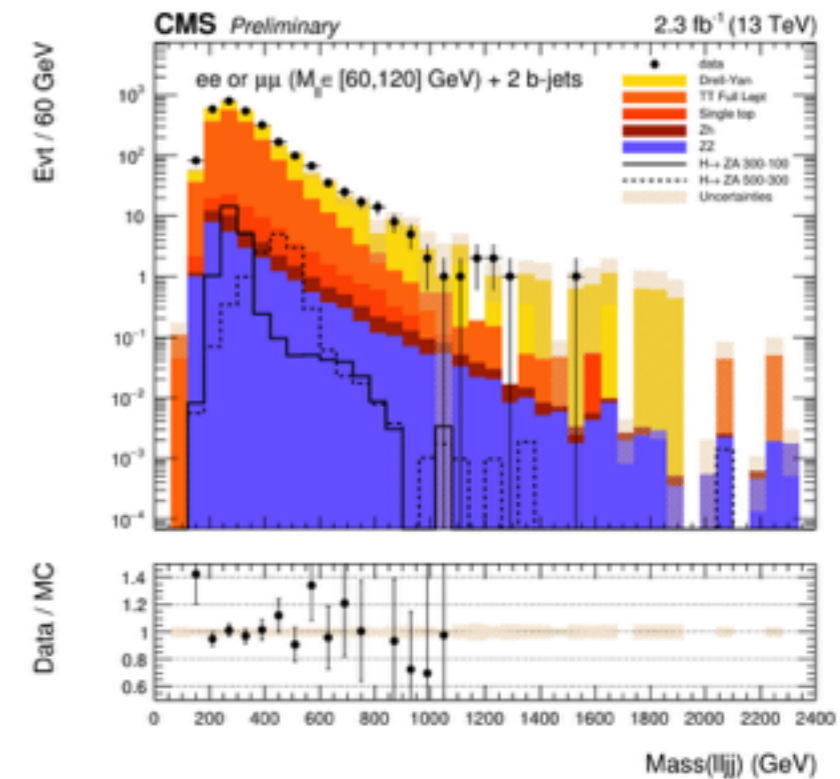
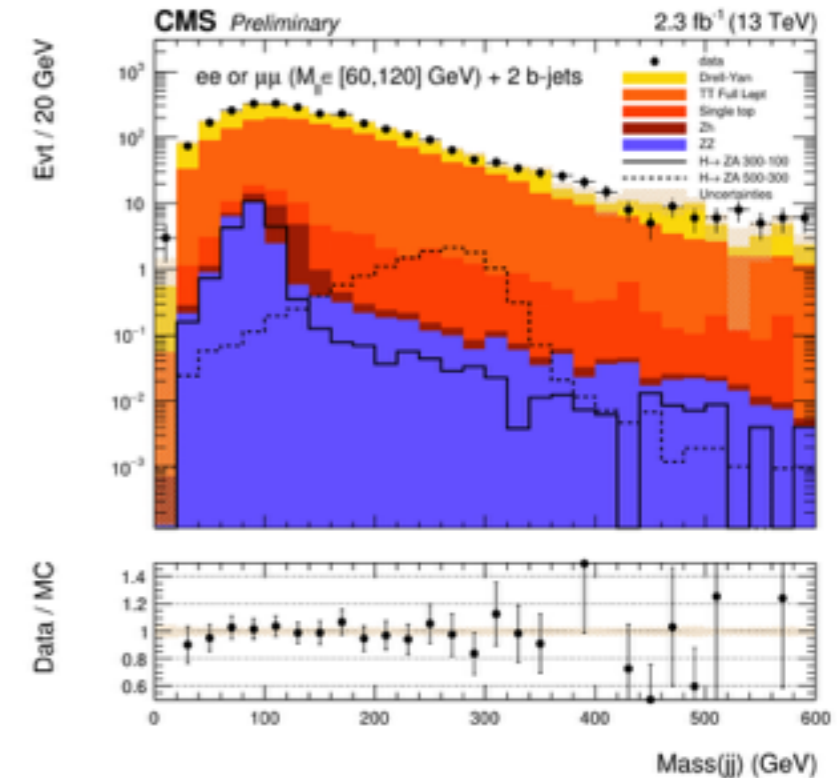
b-associated production



$H \rightarrow ZA$ Higgs to Higgs decays

CMS-PAS-HIG-16-010

- ⊙ $H \rightarrow ZA, A \rightarrow bb, Z \rightarrow ll$
- ⊙ Motivated by 2HDM with twisted custodial symmetry
- ⊙ Signal region defined in $m_{bb} - m_{llbb}$ plane for each $m_H - m_A$ hypotheses
- ⊙ Backgrounds from sideband
- ⊙ Limits on $\sigma \times BR$ for m_H hypotheses as function of m_A



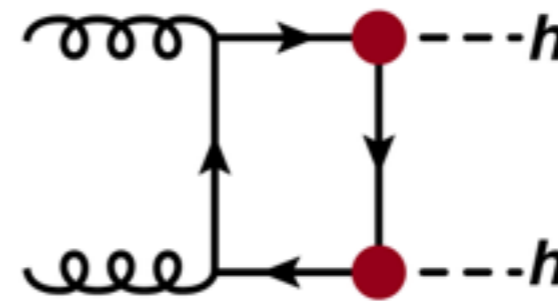
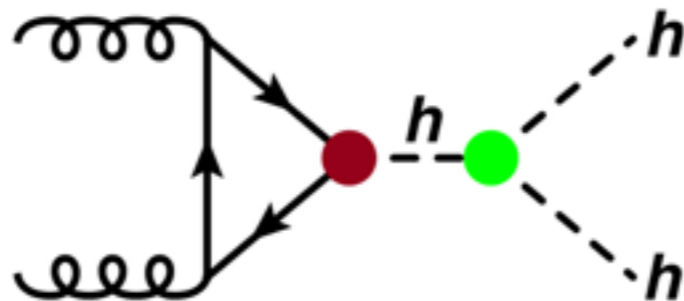
$X \rightarrow hh$ Di-Higgs Production

- Exciting prospects of the HL-LHC and future proton colliders

- a process like di-Higgs production has not been observed in nature
- gluon fusion cross section is only **40.2fb** [NNLO] at 14 TeV
- vector boson fusion cross section is 2fb
- challenging measurement

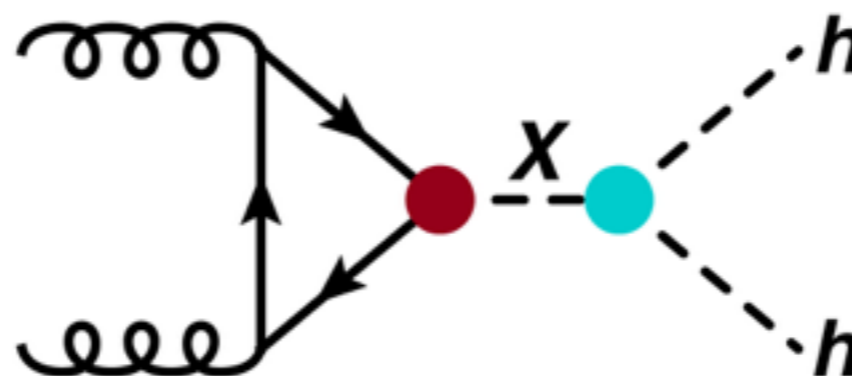
Pierre's (and Heather's) presentation

- Destructive interference in gluon fusion



- Resonant production

- enhance production cross section

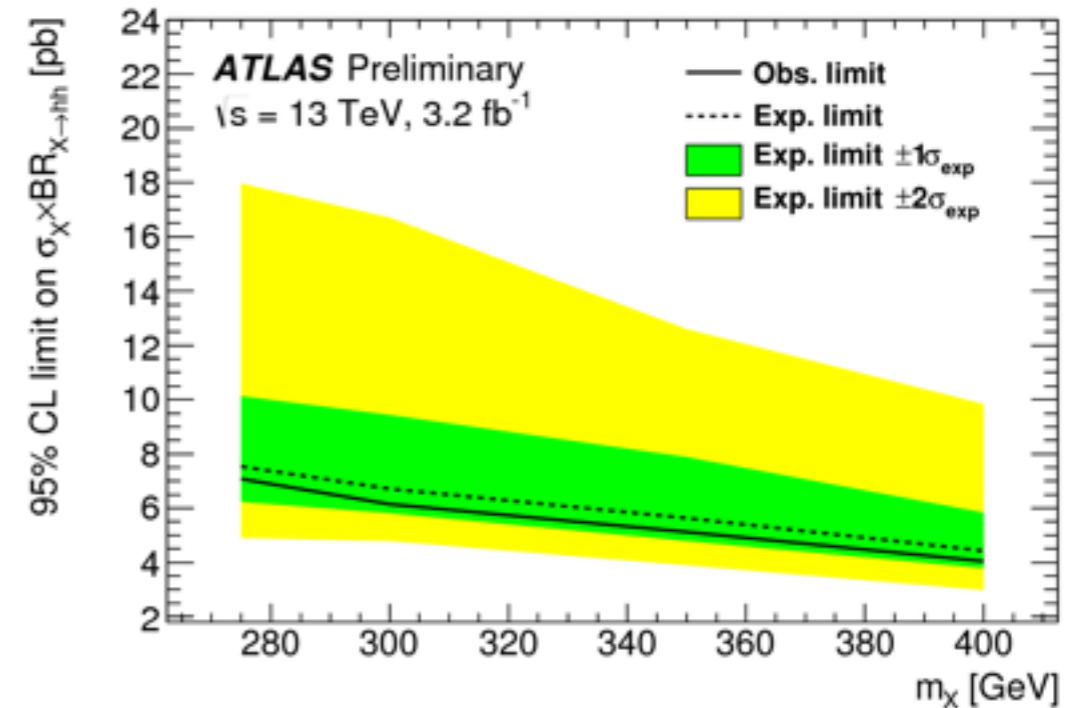
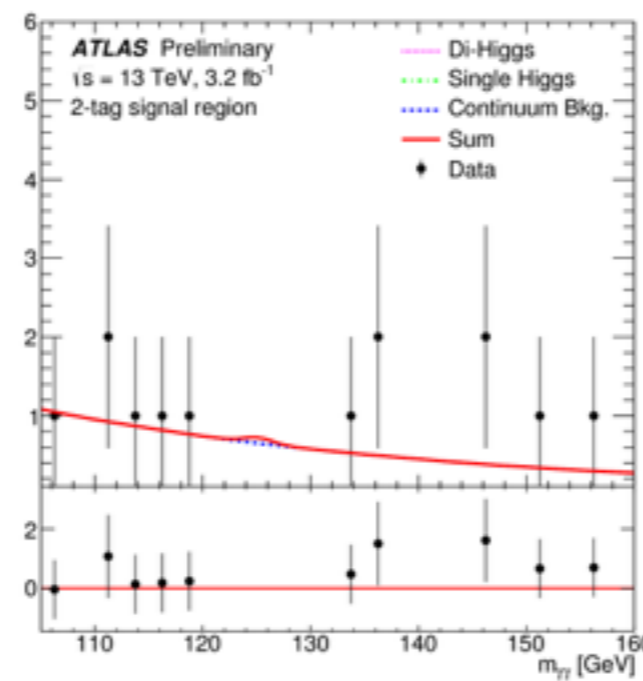
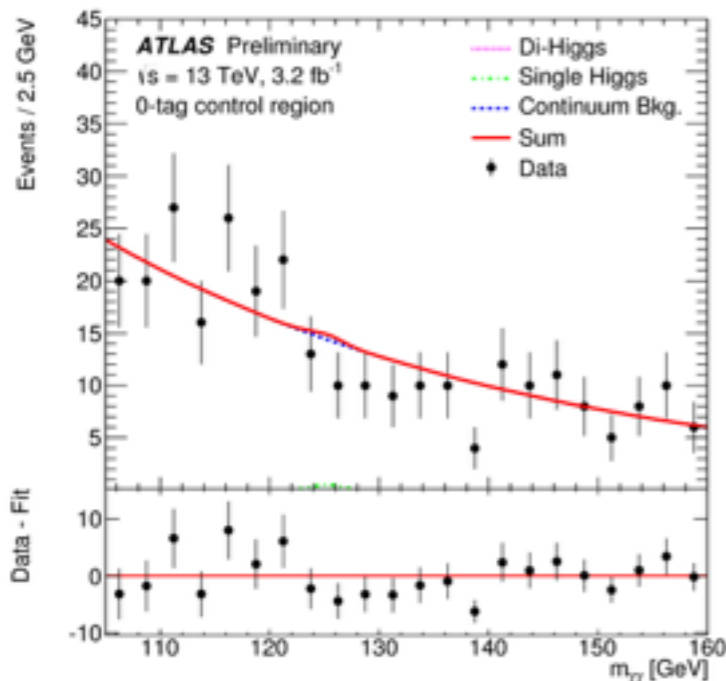
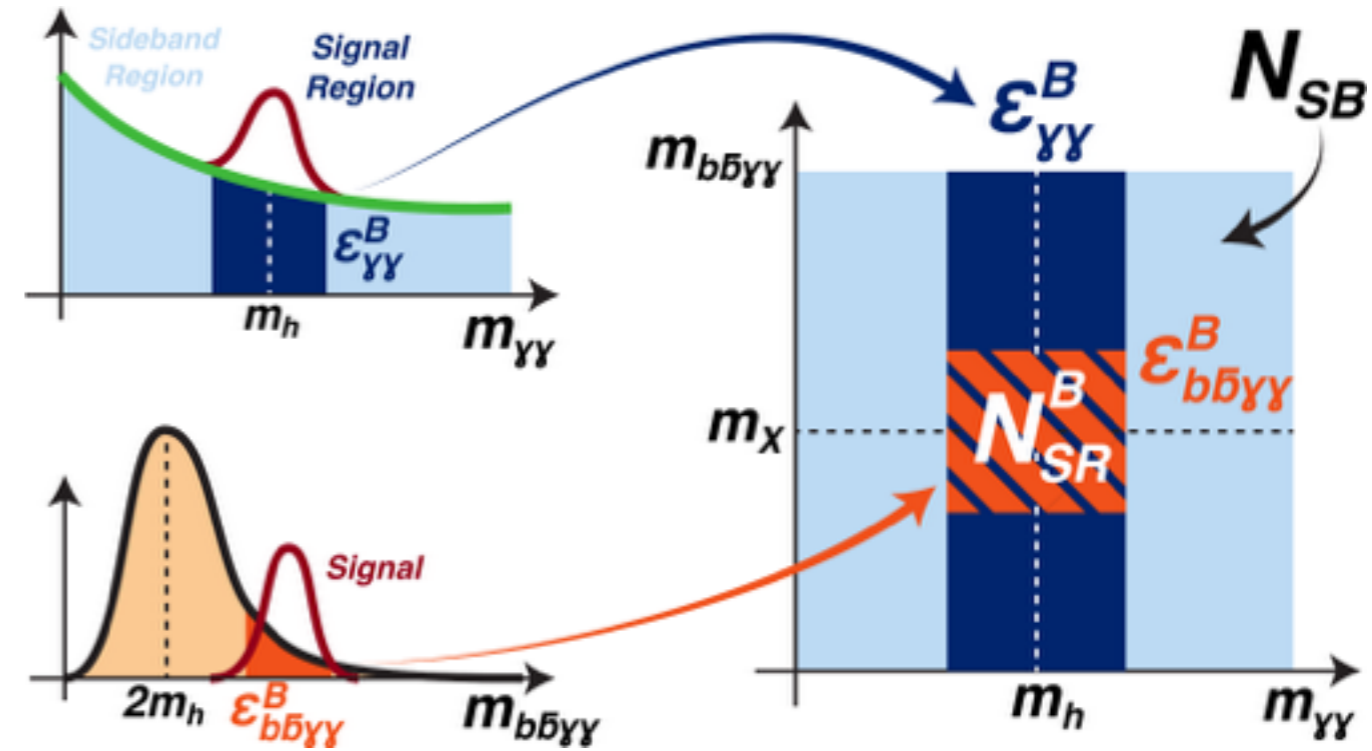


$X \rightarrow hh$ Di-Higgs Production

ATLAS-CONF-2016-004

- $H \rightarrow hh \rightarrow bbyy$
- Background estimation in sideband
- Resonant and non-resonant production considered

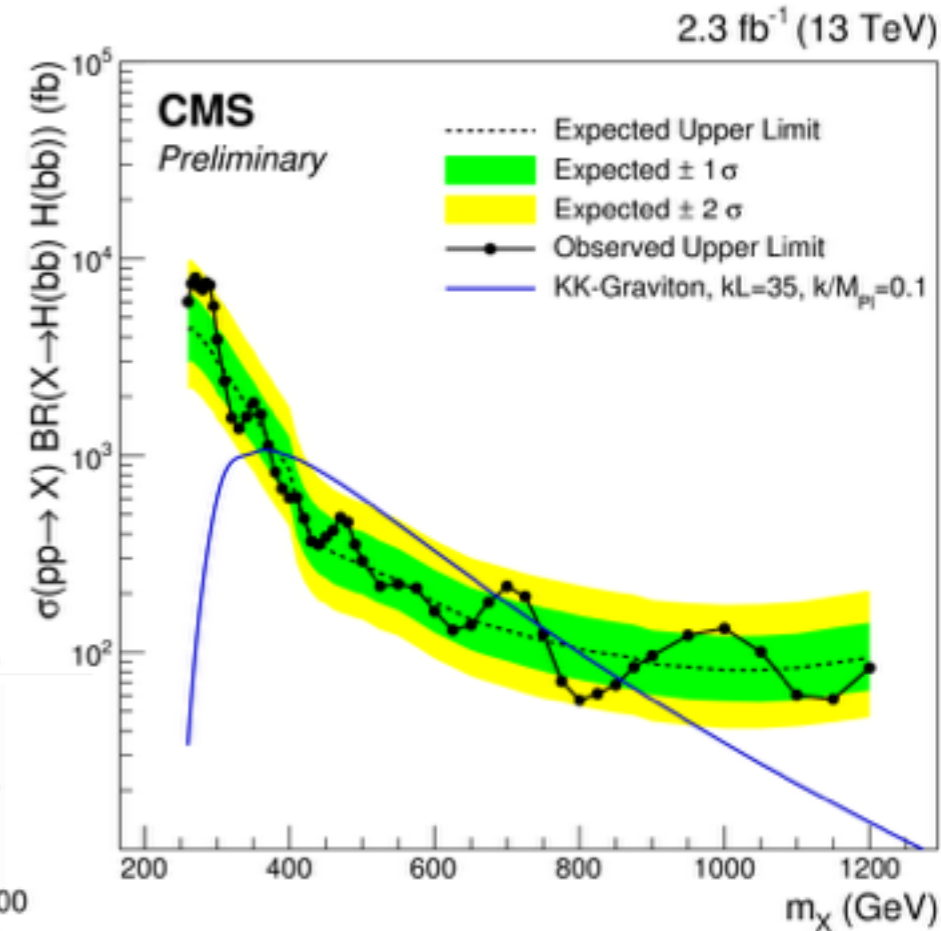
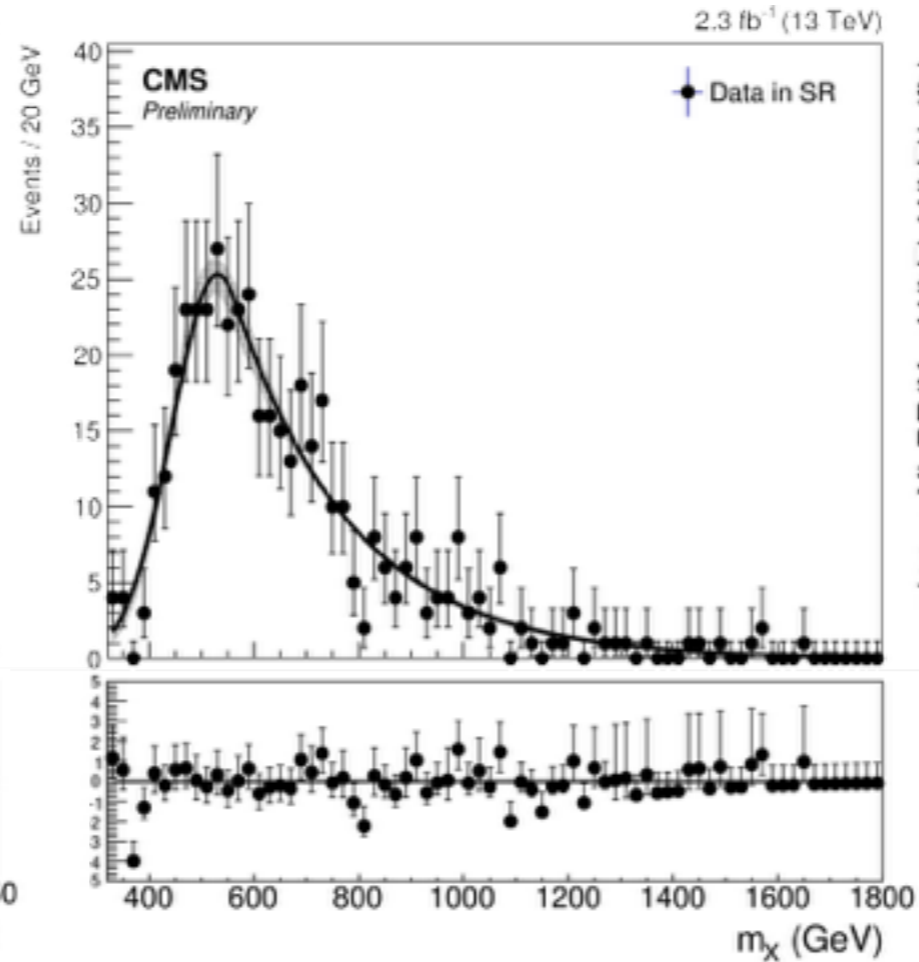
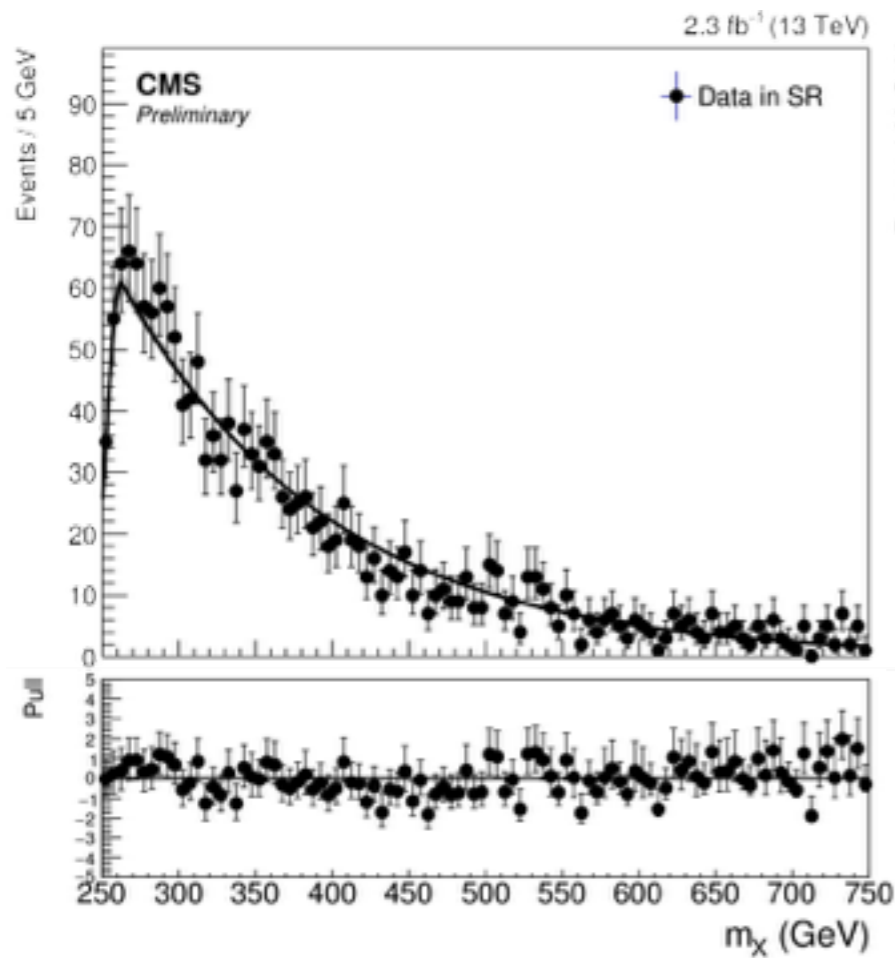
Process	0-tag	2-tag
Continuum background	35.8 ± 2.1	1.63 ± 0.30
SM single-Higgs	1.8 ± 1.5	0.14 ± 0.05
SM di-Higgs	<0.001	0.027 ± 0.006
Observed	27	0



$X \rightarrow hh$ Di-Higgs Production

CMS-PAS-HIG-2016-002

- $H \rightarrow hh \rightarrow bbbb$
- Resonant production considered



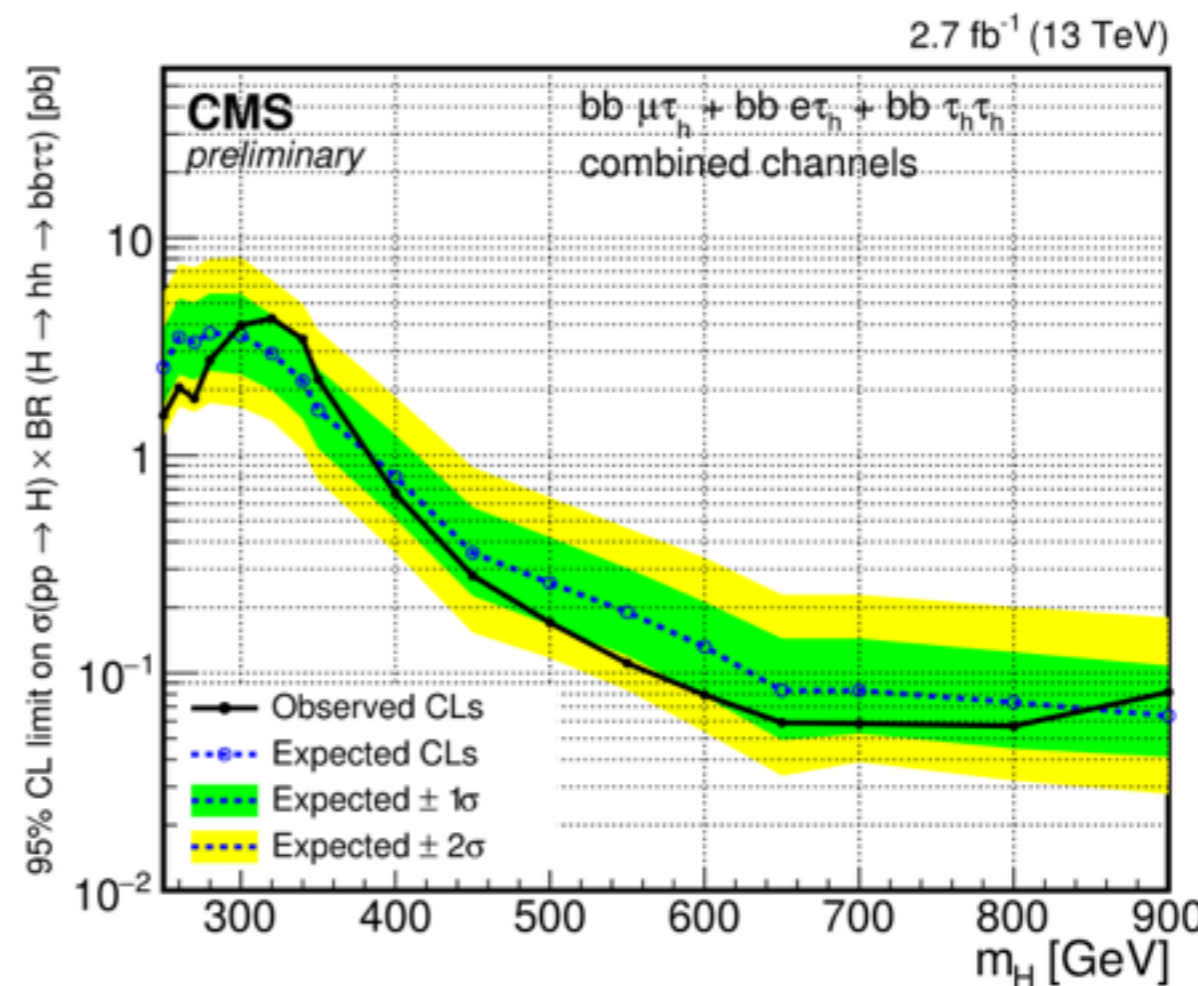
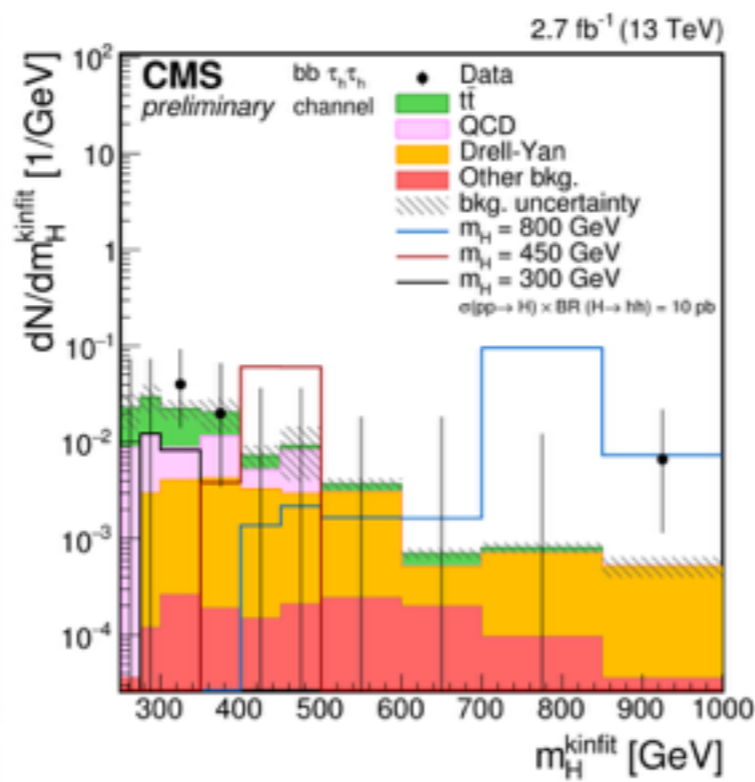
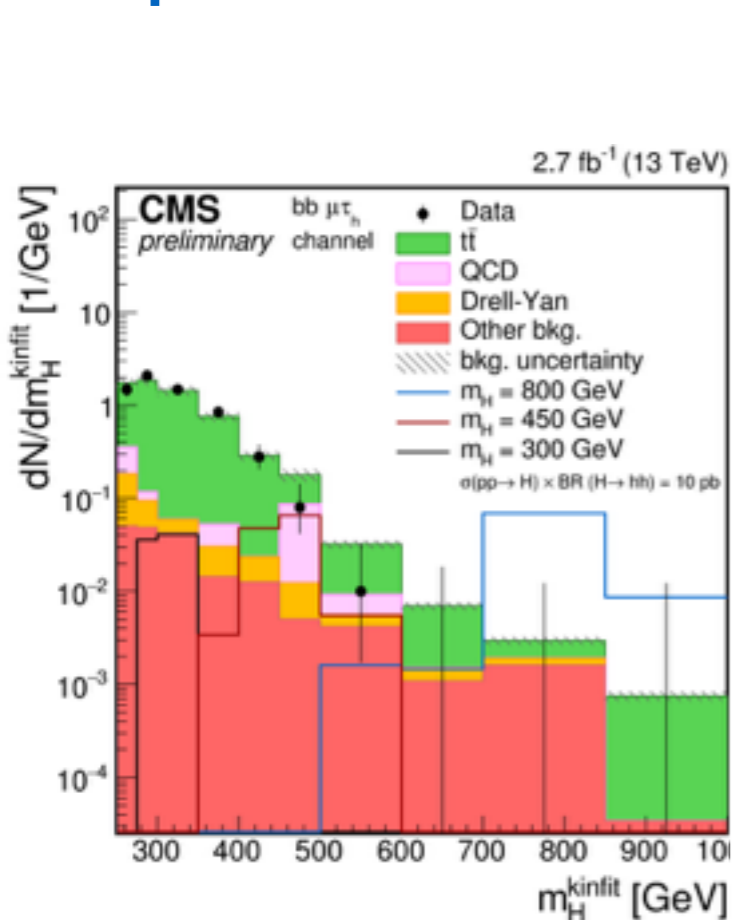
$X \rightarrow hh$

Di-Higgs Production

CMS-PAS-HIG-2016-013
CMS-PAS-HIG-2016-013

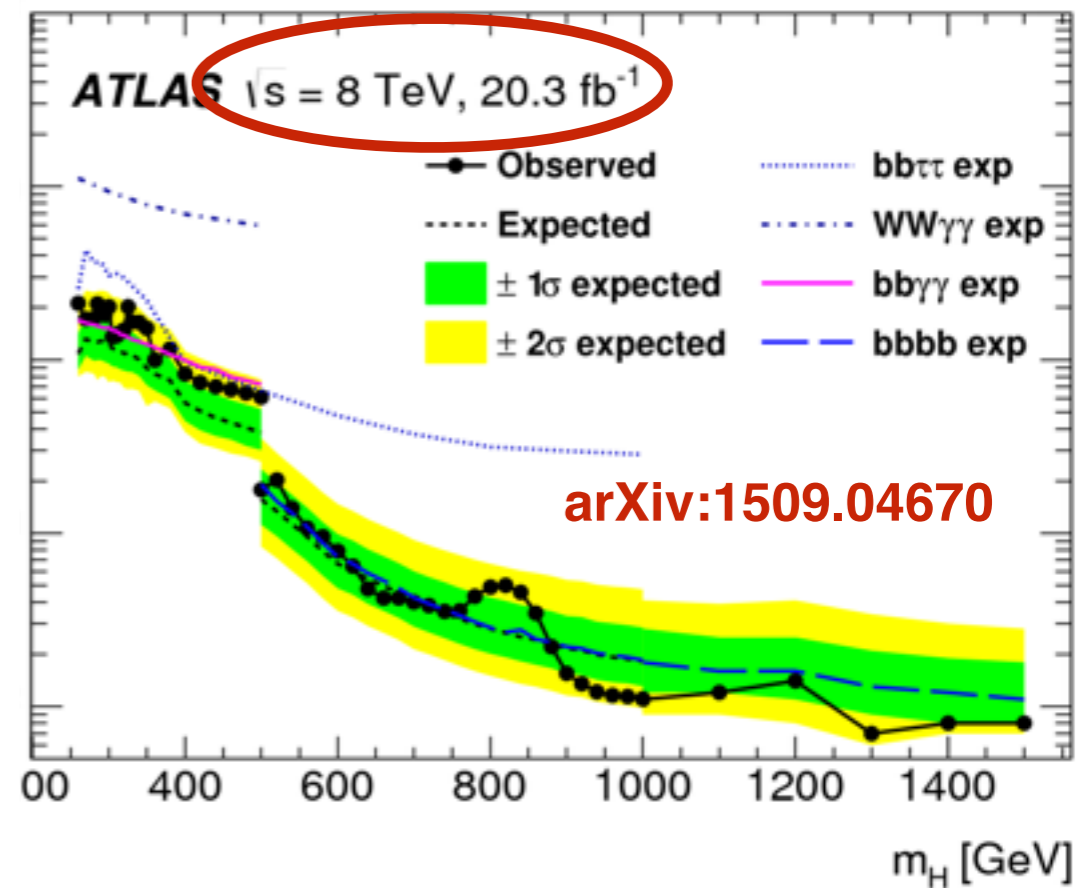
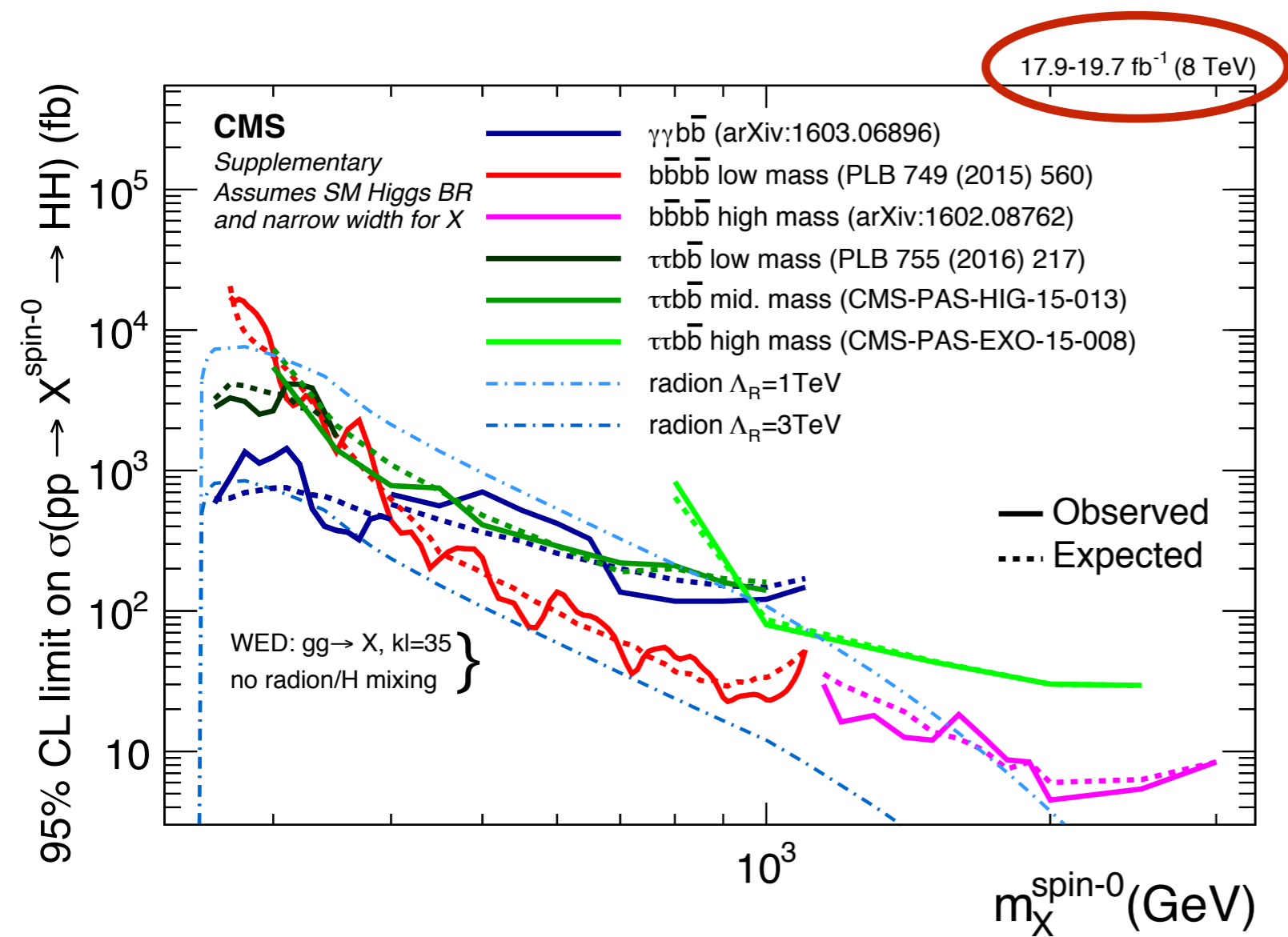
- $H \rightarrow hh \rightarrow bb\tau\tau$
- Using $T_{lep}T_{had}$ and $T_{had}T_{had}$ channels
- Mass variable m_H constructed using kinematic fit
- Resonant and non-resonant production considered

Process	$bb \mu\tau$	$bb e\tau$	$bb \tau\tau$
$t\bar{t}$	203.3 ± 25.4	106.8 ± 13.6	2.2 ± 0.3
QCD	10.0 ± 3.3	4.2 ± 1.8	1.4 ± 1.0
Z+jets	7.2 ± 1.8	2.1 ± 0.5	1.2 ± 0.3
W+jets	1.4 ± 0.1	0.5 ± 0.1	–
single top	5.2 ± 0.5	3.2 ± 0.3	–
di-boson	0.3 ± 0.1	0.11 ± 0.02	0.11 ± 0.02
Total expected background	227.4 ± 25.7	116.9 ± 13.7	4.9 ± 1.1
$m_H = 300 \text{ GeV} - \sigma(pp \rightarrow H) \times BR(H \rightarrow hh) = 1 \text{ pb}$	0.29	0.15	0.07
$m_H = 450 \text{ GeV} - \sigma(pp \rightarrow H) \times BR(H \rightarrow hh) = 1 \text{ pb}$	0.64	0.51	0.62
$m_H = 800 \text{ GeV} - \sigma(pp \rightarrow H) \times BR(H \rightarrow hh) = 1 \text{ pb}$	1.20	0.7	1.6
DATA	224	110	4



$X \rightarrow hh$

Di-Higgs Summary



Summary of BSM searches in Run I

CMS-PAS-HIG-2016-007

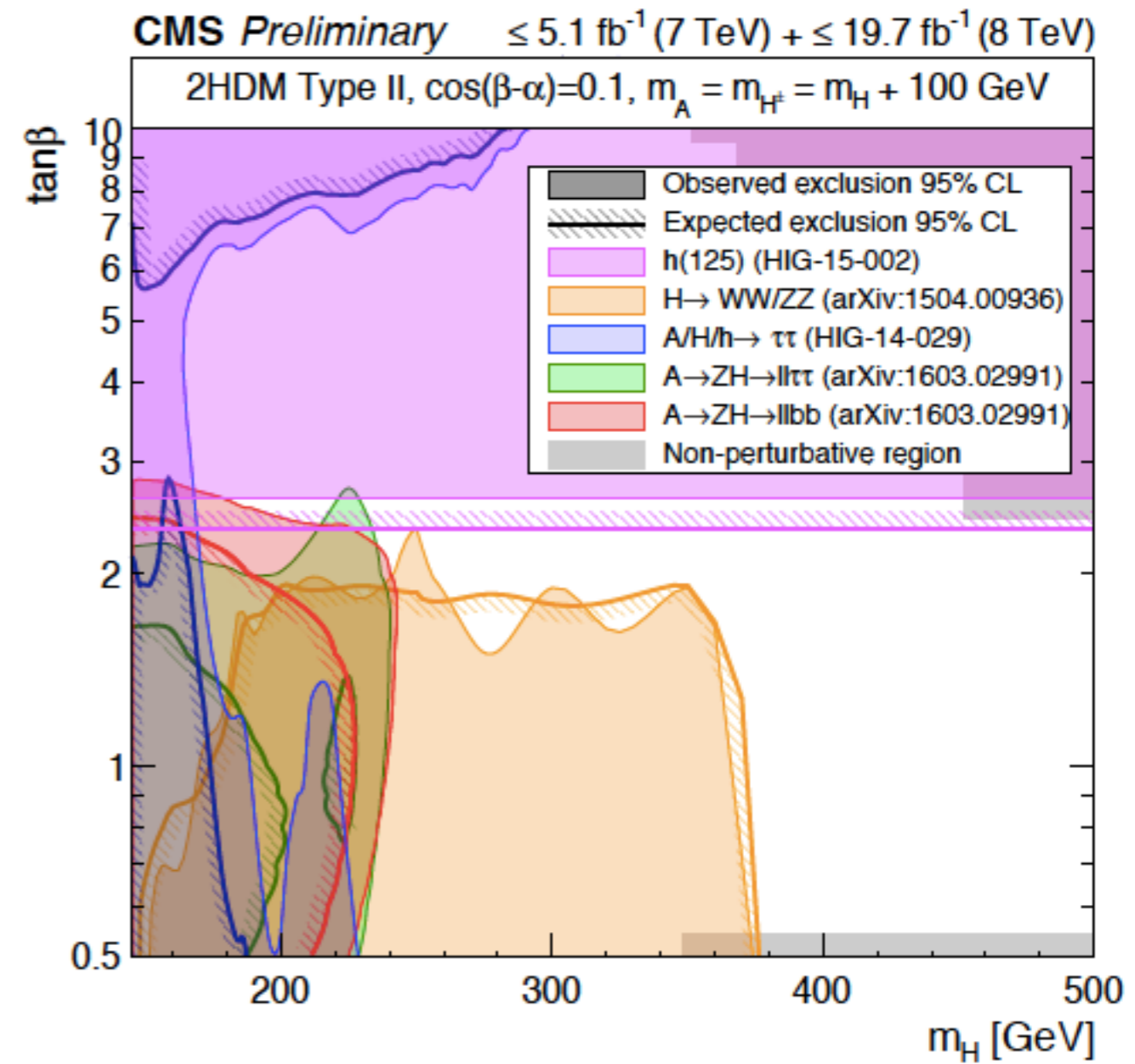
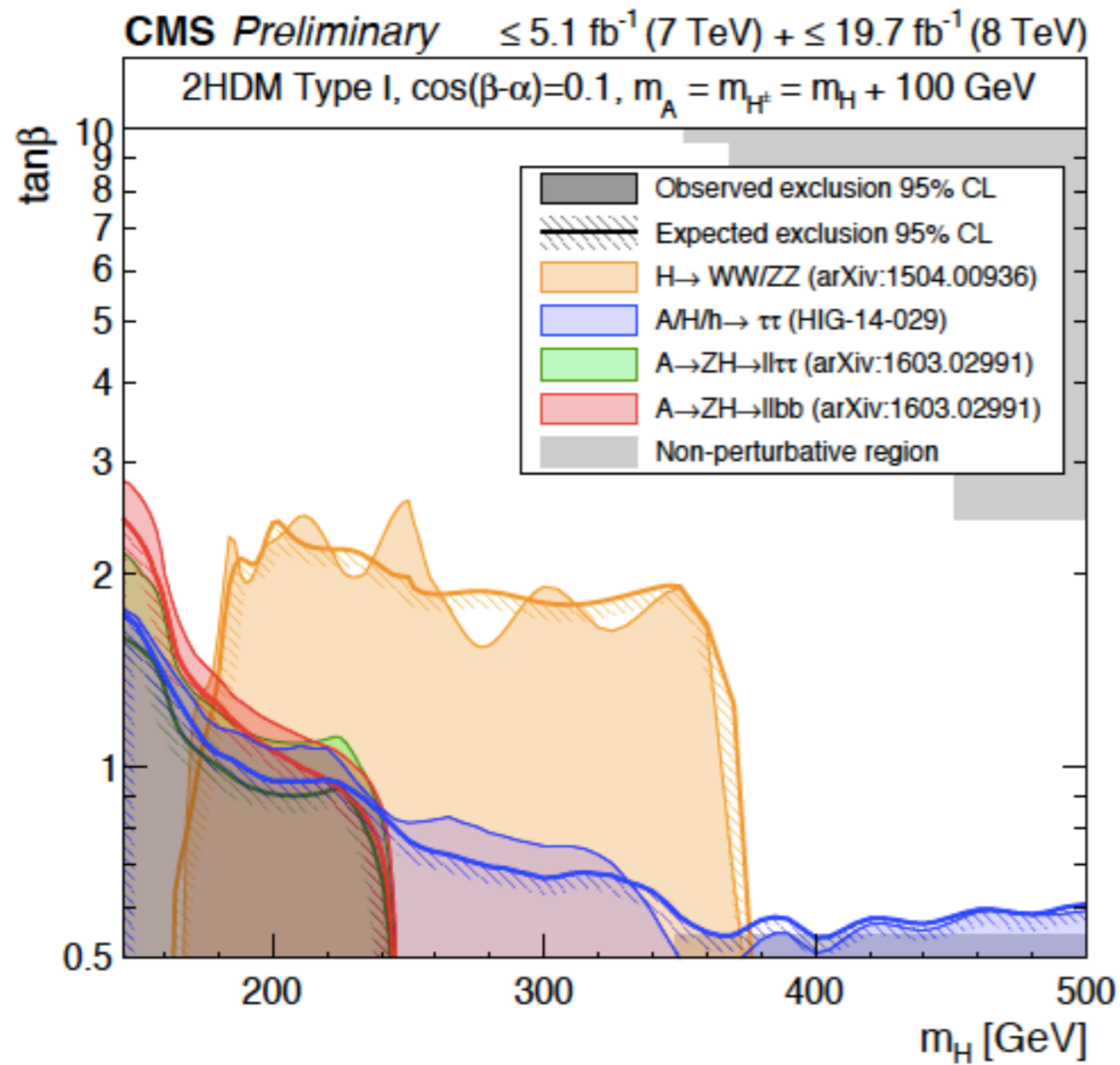
© Two 2HDM and two MSSM benchmarks used in summary

Parameter	Value (type I or type II)	2HDM		hMSSM
		type I	type II/MSSM	
m_h	125.09 GeV			
m_A	$m_H + 100$ GeV			$\frac{s_d + s_u \tan \beta}{\sqrt{1 + \tan^2 \beta}}$
m_{H^\pm}	$m_H + 100$ GeV			$s_u \frac{\sqrt{1 + \tan^2 \beta}}{\tan \beta}$
$\cos(\beta - \alpha)$	0.1	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$	
m_{12}^2	$\max(1 - \tan \beta^{-2}, 0) \cdot \frac{1}{2} \sin(2\beta)(m_A^2 + \lambda_5 v^2)$ <i>m_H and $\tan \beta$ scanned.</i>	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$s_d \sqrt{1 + \tan^2 \beta}$

Constraint/Direct search		2HDM		MSSM	
		<i>type-I</i>	<i>type-II</i>	<i>hMSSM</i>	m_h^{mod+}
Coupling constraint	[23]		☑ [◇]	☑ [◇]	
$A/H/h \rightarrow \tau\tau$	[38]	☑ [◇]	☑ [◇]	☑ [◇]	☑ [*]
$A/H/h \rightarrow \mu\mu$	[42]			☑ [•]	☑ [*]
$A/H \rightarrow bb$	[47]			☑ [•]	☑ [*]
$H^\pm \rightarrow \tau\nu$	[48]				☑ [*]
$H \rightarrow hh(bb\tau\tau) / A \rightarrow Zh(\ell\ell\tau\tau)$	[49]			☑ [◇]	
$H \rightarrow hh(bb\gamma\gamma)$	[50]			☑ [•]	
$H \rightarrow WW/ZZ$	[51]	☑ [•]	☑ [•]	☑ [•]	☑ [•]
$A \rightarrow ZH(\ell\ell bb)$	[52]	☑ [•]	☑ [•]		
$A \rightarrow ZH(\ell\ell\tau\tau)$	[52]	☑ [•]	☑ [•]		

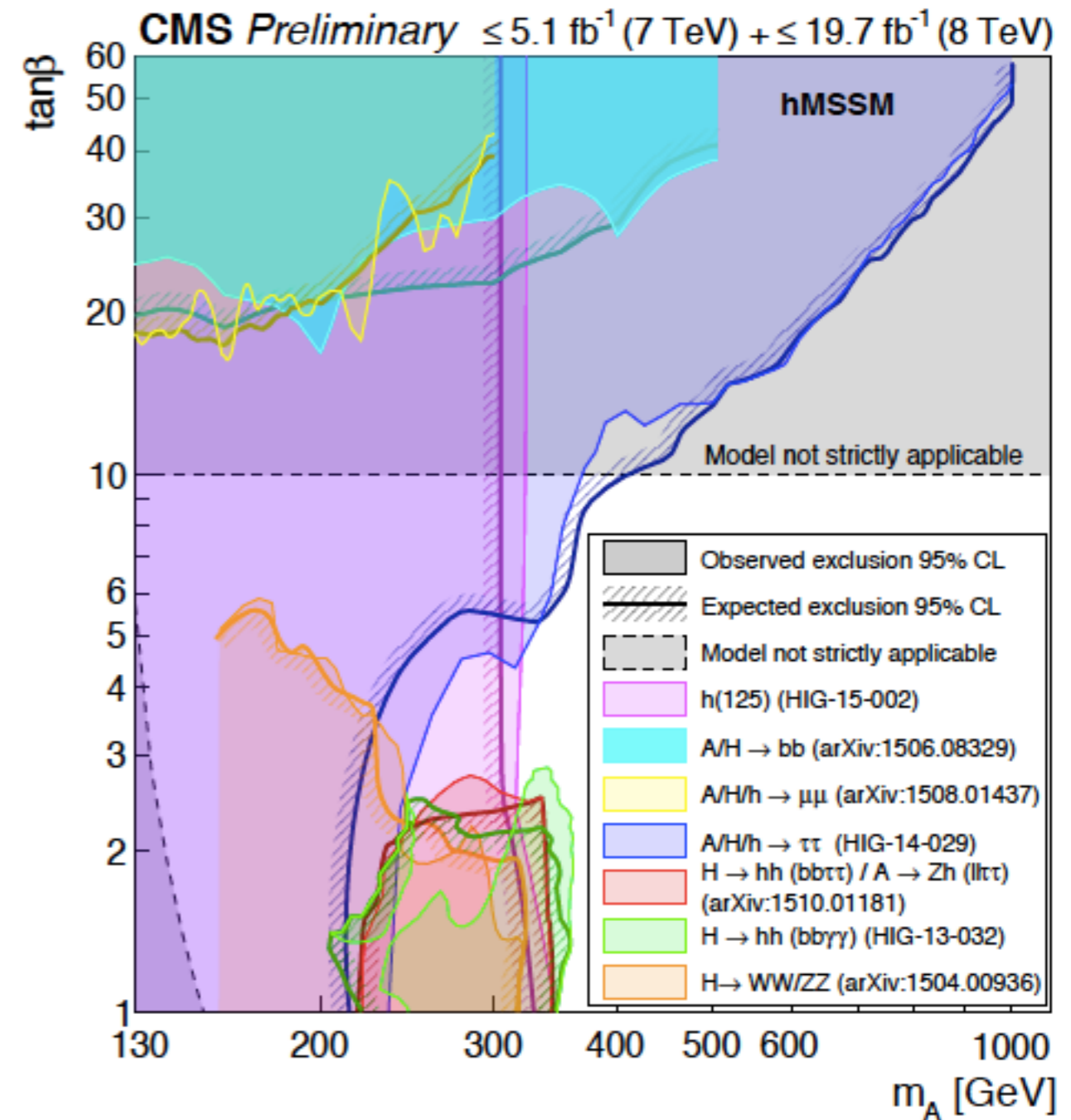
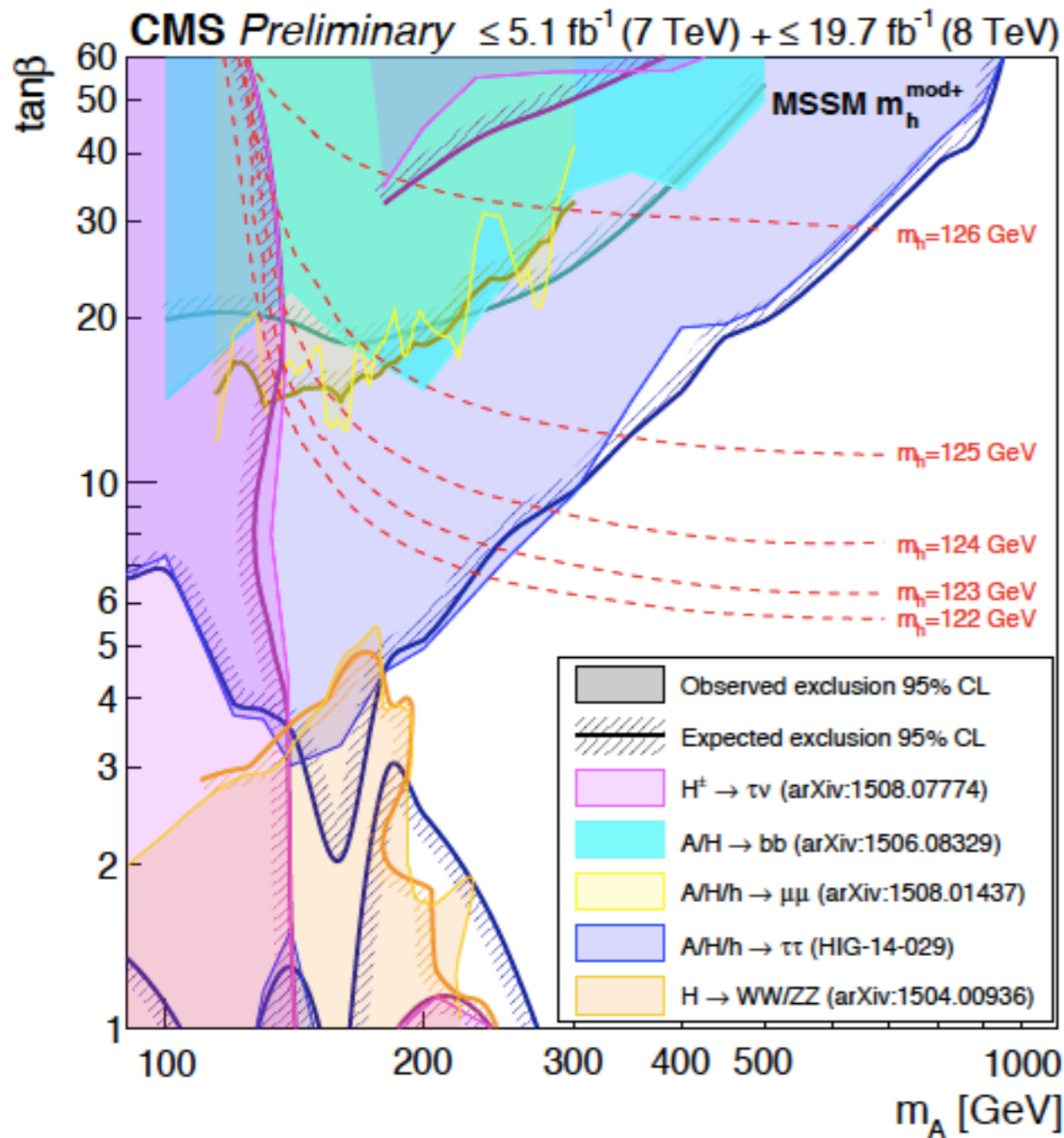
Summary of BSM searches in Run I

CMS-PAS-HIG-2016-007



Summary of BSM searches in Run I

CMS-PAS-HIG-16-007

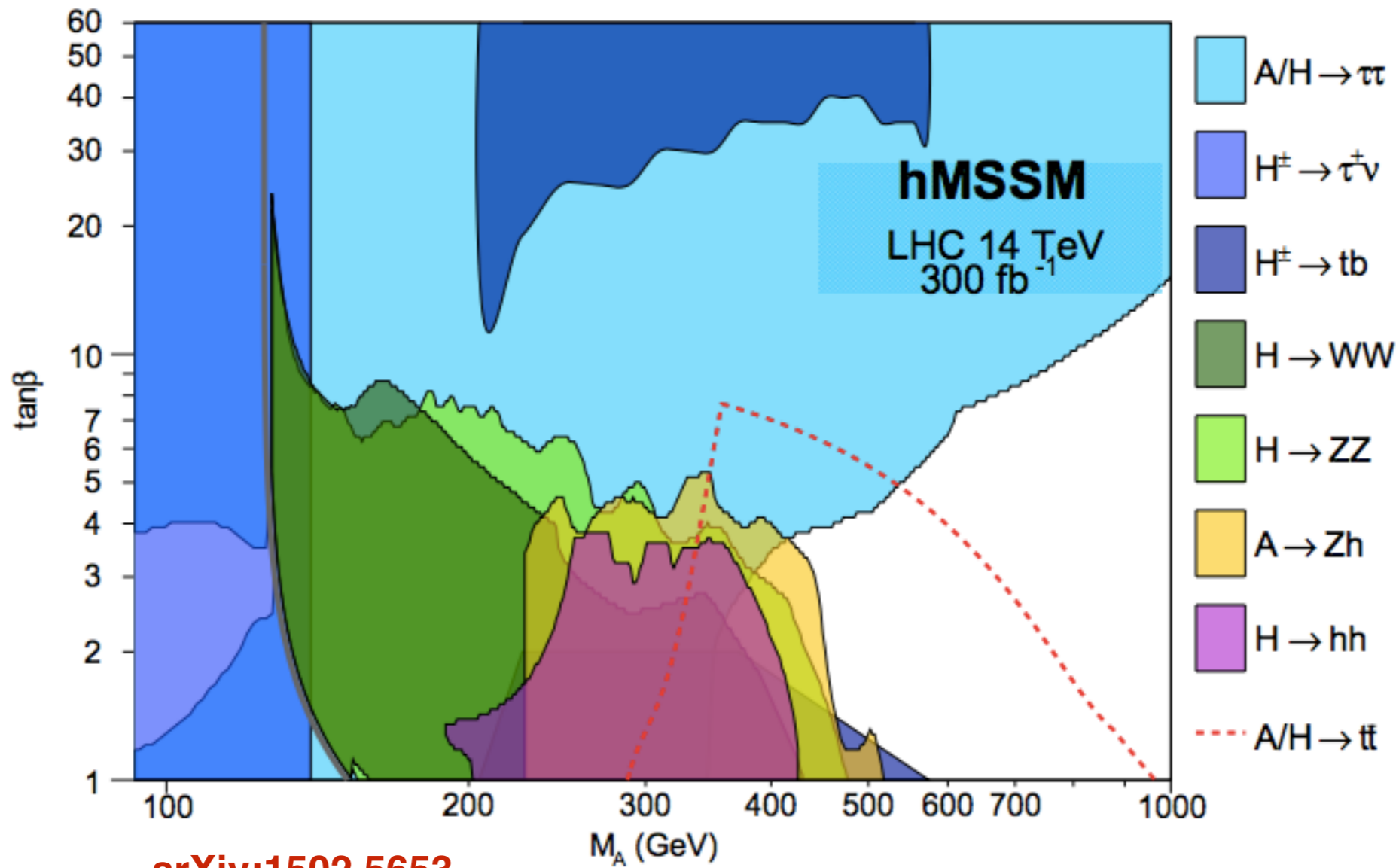


Summary & Conclusion

- **Many LHC searches target extended Higgs sectors**
- **No additional Higgs bosons observed in Run I**
- **Early Run II results extend the sensitivity to high mass resonances**
- **Some intriguing results need more data as judge of new physics**

- **What did we miss?**
 - ➔ Signatures
 - ➔ Public information on analyses
 - ➔ Interpretation of results

Backup



[arXiv:1502.5653](https://arxiv.org/abs/1502.5653)