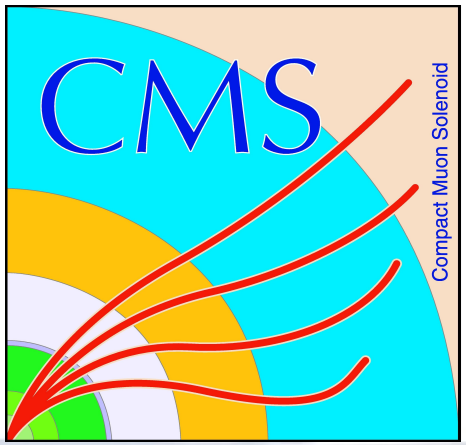
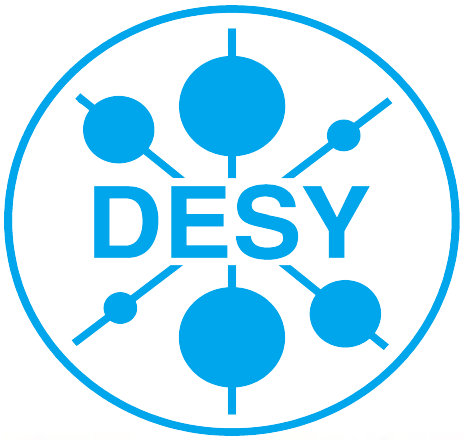
Beyond the Standard Model Higgs Searches at ATLAS and CMS

John Keller (DESY)
on behalf of the
ATLAS and CMS collaborations





Why study BSM Higgs?

- Many open questions from the Standard Model (e.g. naturalness) point to an incomplete understanding of electroweak symmetry breaking.
- Higgs sector in the SM the last to be discovered and among the least understood: plenty of space for surprises!

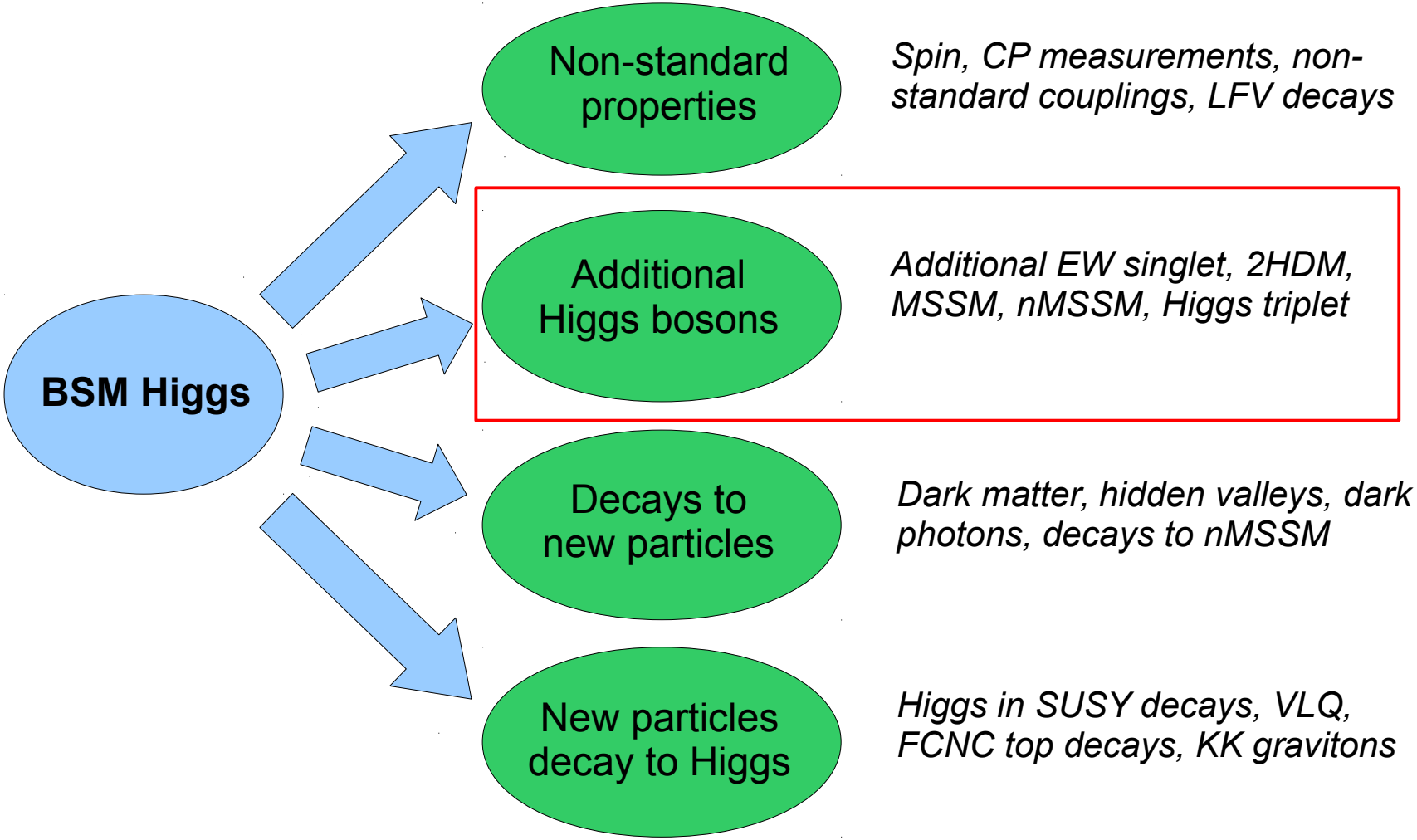
- We have two fantastic (and expensive) detectors and we need to do *something* with them.

Bored Scientists Now Just Sticking Random Things Into Large Hadron Collider

VIDEO: TECH TRENDS
July 8, 2014
VOL 50 ISSUE 27
Science & Technology · Video

(from The Onion)

The BSM Higgs Landscape



- This talk: Focus on additional Higgs states (with overlap).

Topics in this talk

- "BSM cousins" of SM Higgs decays:
  - WW, ZZ, γγ, Zγ, and $\tau\tau$
- Heavy Higgs decaying to light Higgs:
  - Zh, ZH/A, and hh
- Charged Higgs searches:
  - $\tau\nu$, tb, and WZ

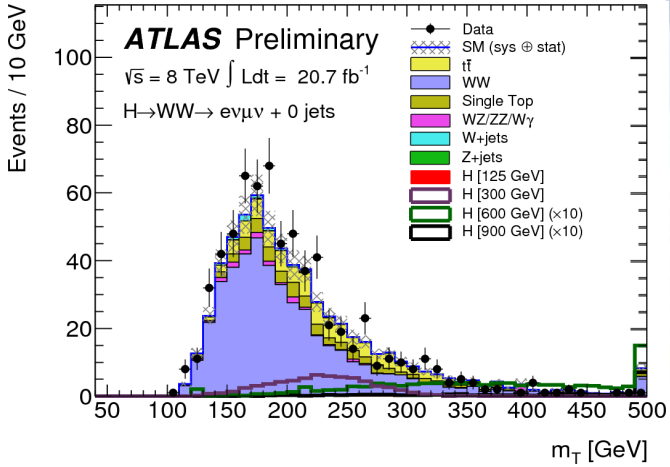
Two Disclaimers

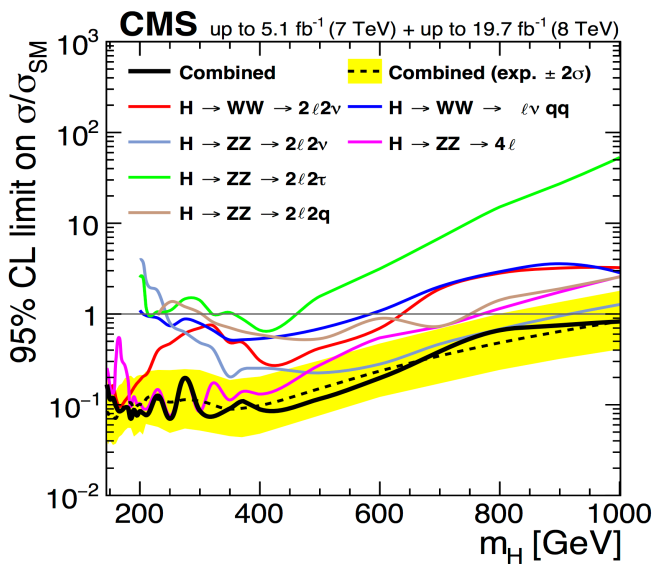
- This is not meant as an exhaustive list.
- The focus is on experimental aspects of the searches with scant attention paid to the theory interpretations.

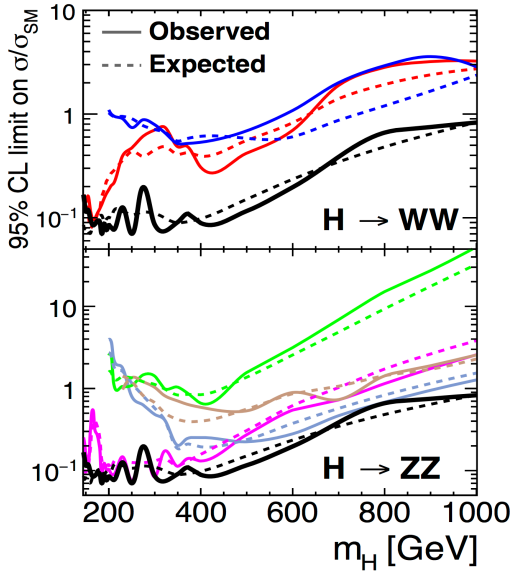
H → WW/ZZ

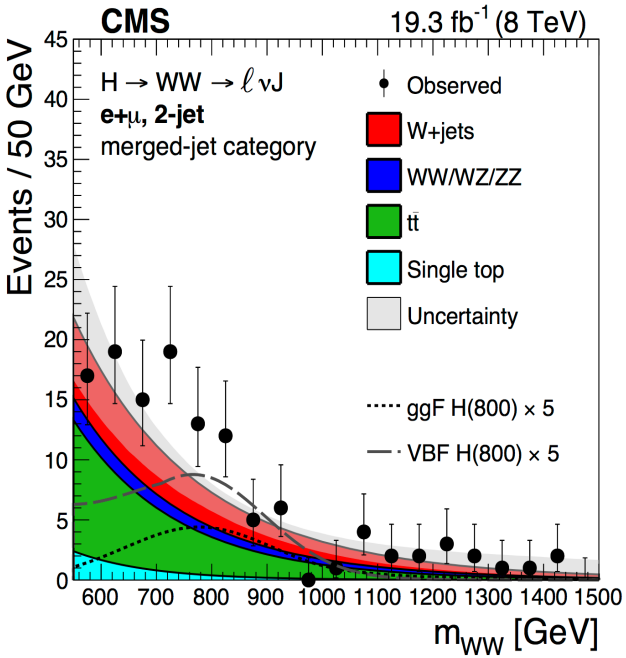
arXiv:1504.00936
ATLAS-CONF-2013-067

- ATLAS: WW→lν*l*ν channels; 0, 1, or 2 jets.
- CMS: WW→lν*l*ν, lν*qq*′; ZZ → llll, ll*νν*, ll*qq*; VBF or un-tagged production.
  - Including b-jets and τ leptons.
- Merged jet categories to target high mass.
- No significant excesses observed.





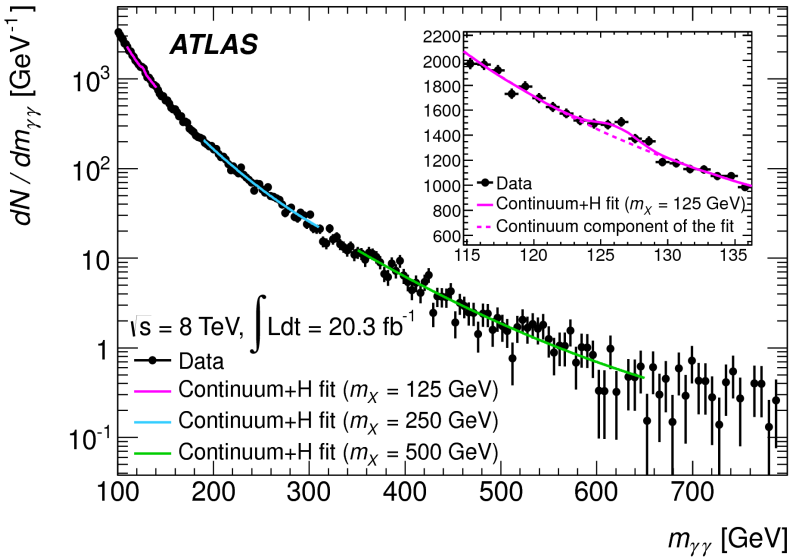


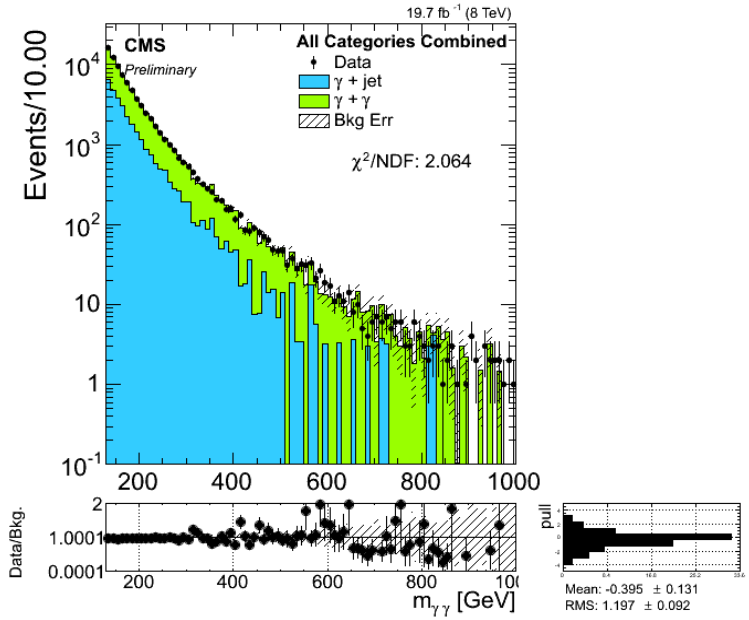


CMS-PAS-HIG-14-006
Phys. Rev. Lett. 113, 171801

New di-photon resonances

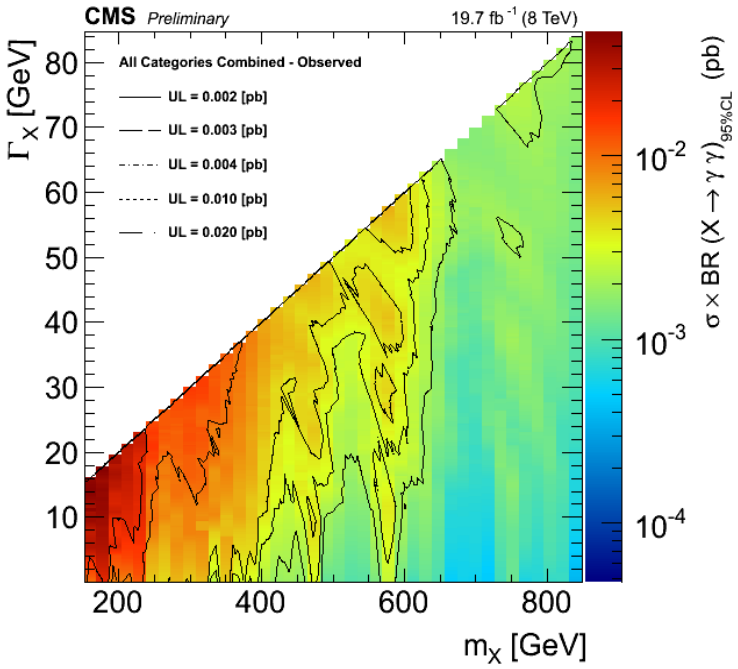
- ATLAS considers both low and high-mass resonances ($65 < m < 600$ GeV).
- At low mass, additional background from Z→ee, mitigated by categorizing based on photon conversion status.
- CMS considers only high mass (150 – 800 GeV).
- 4 categories based on photon rapidity and shower shape.
- Both: fit continuum background in sliding mass window.

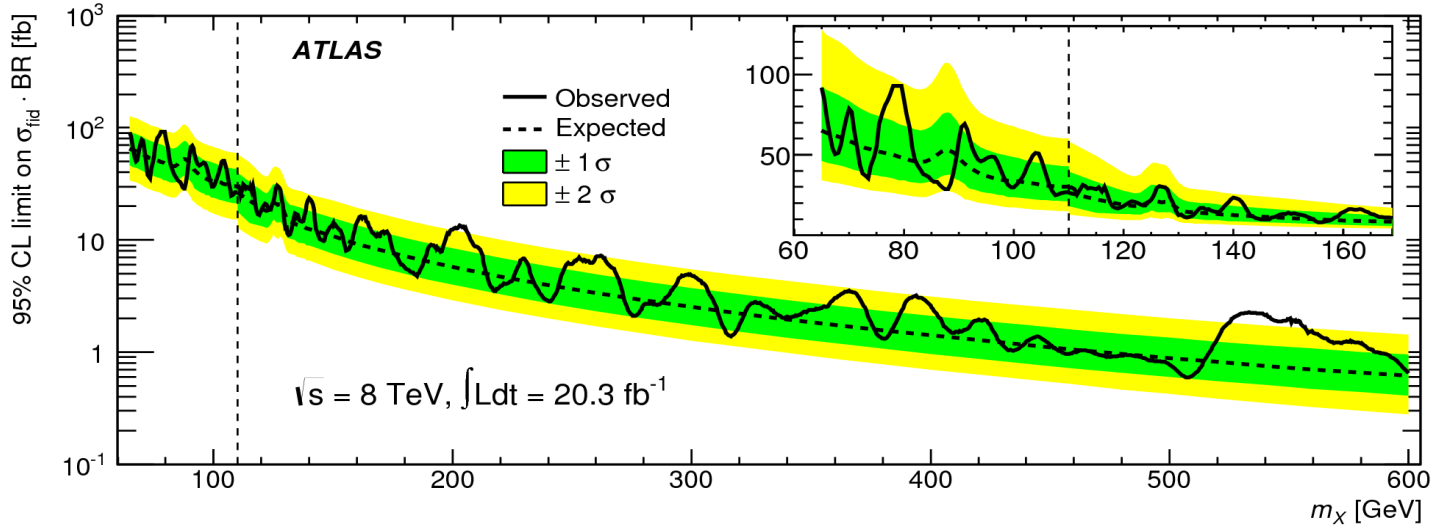




New di-photon resonances

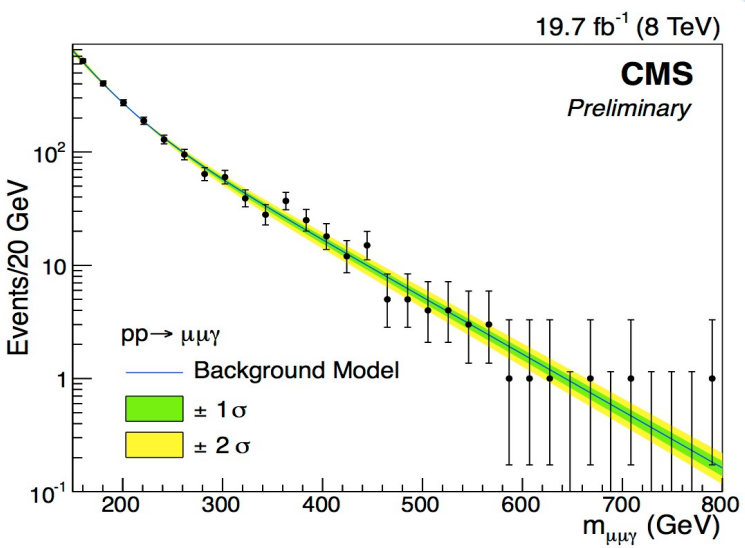
- Neither experiment sees evidence for a signal.
- ATLAS assumes a narrow resonance and sets limits on XS*BR.
- CMS considers widths up to 10% of mass, and sets limits that depend on both mass and width.

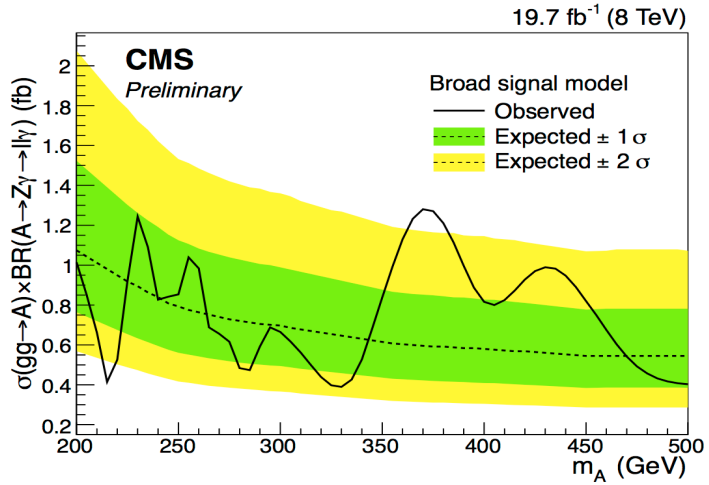


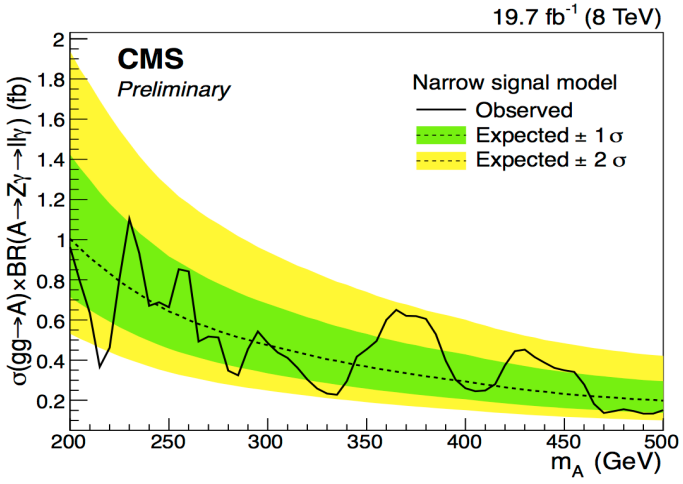


Heavy Higgs → Zγ

- Events selected with two opposite-sign leptons and a photon.
- Backgrounds fit using triple exponential function.
- No excess worth getting excited about.
- Limits set using either broad (width set to SM value) or narrow (width at most 1% of mass) signal model.

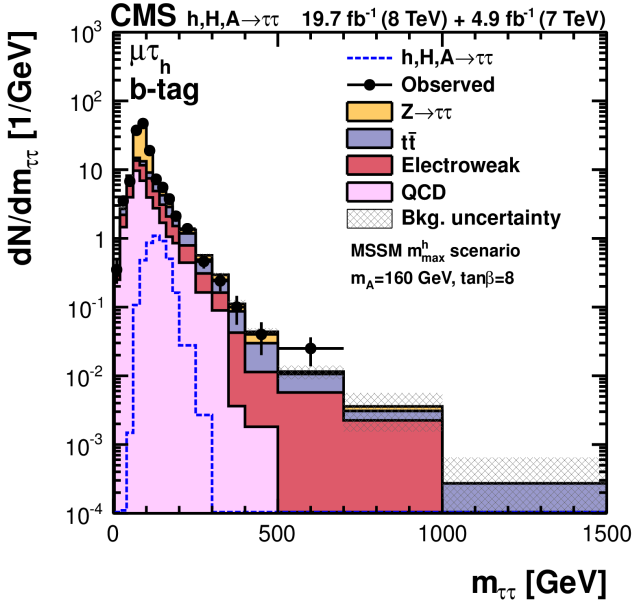


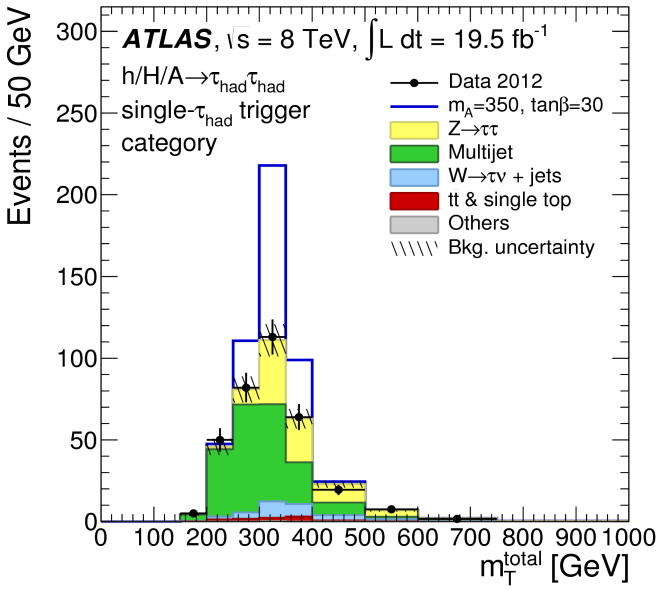




MSSM Higgs → ττ

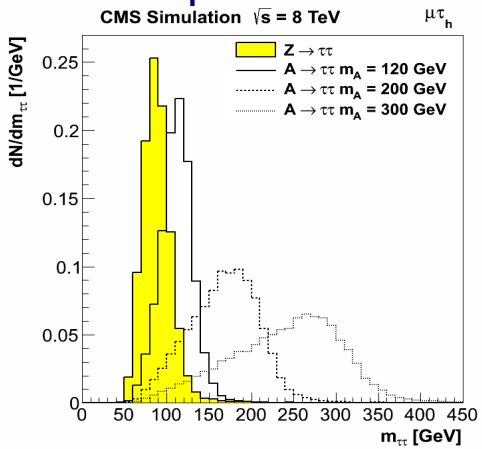
JHEP 10 (2014) 160
JHEP 11 (2014) 056





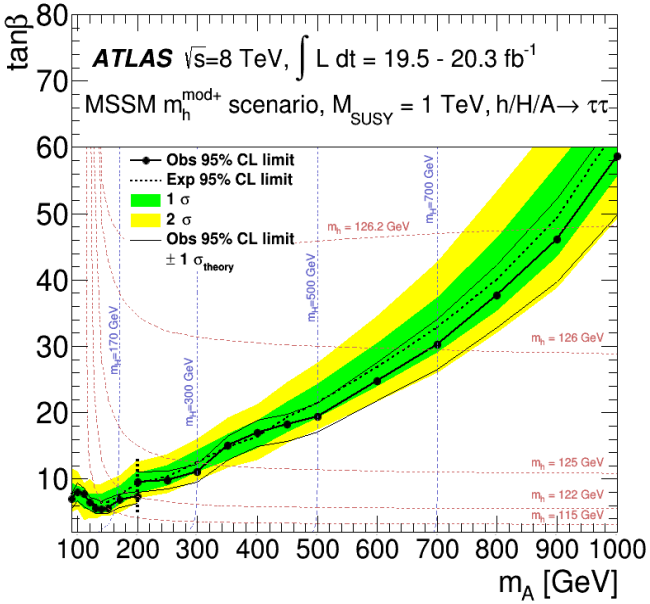
- Almost all di-tau decay modes considered: $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$, and $\mu\mu$ (CMS only).
- ATLAS: dedicated categorization and trigger for high-mass Higgses.
- b-tag and b-veto categories targeting bb and gluon fusion production modes.
  - ATLAS: only at low mass.

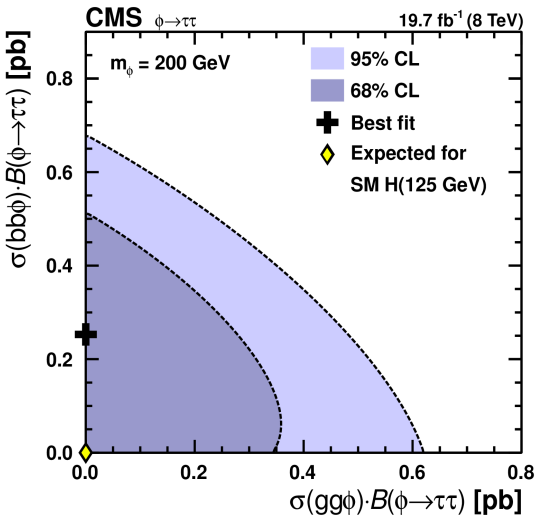
Likelihood-based mass reconstruction to optimize resolution, or m_T^{total} to improve QCD separation.

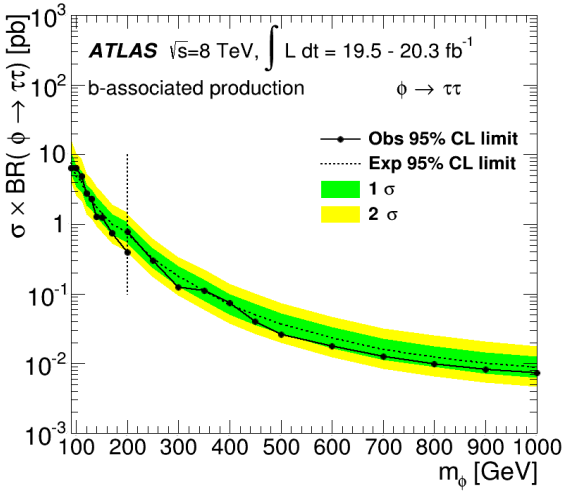


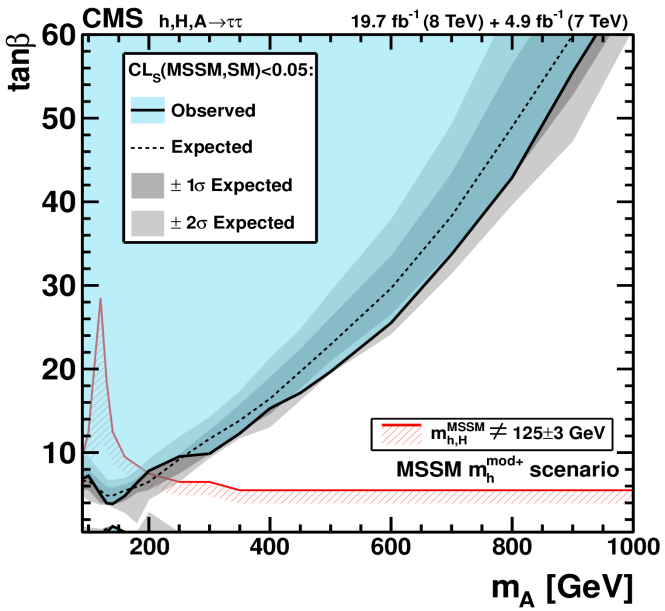
MSSM Higgs → ττ

- No evidence of new physics is seen, but a vast array of interpretations is provided to please any theorist.
  - CMS: 52 limit plots, a record for one search?





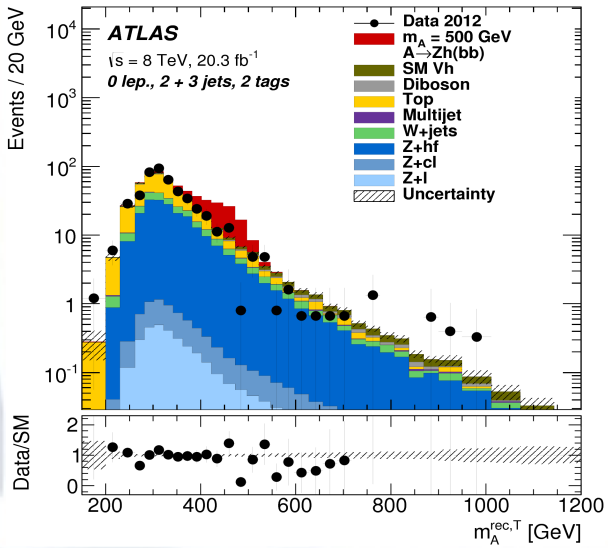


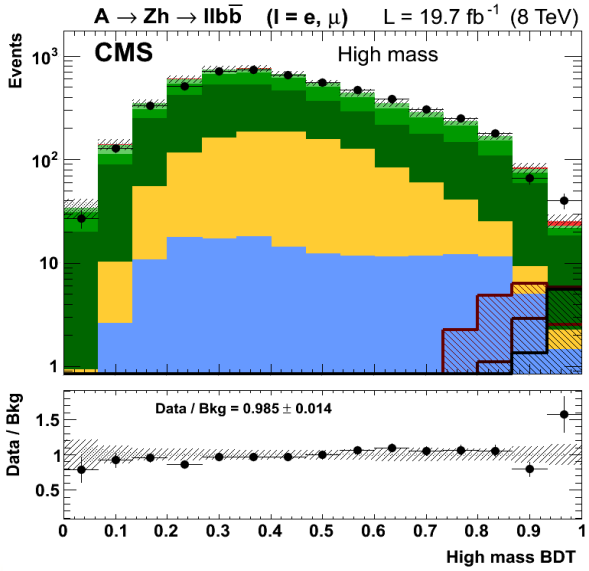


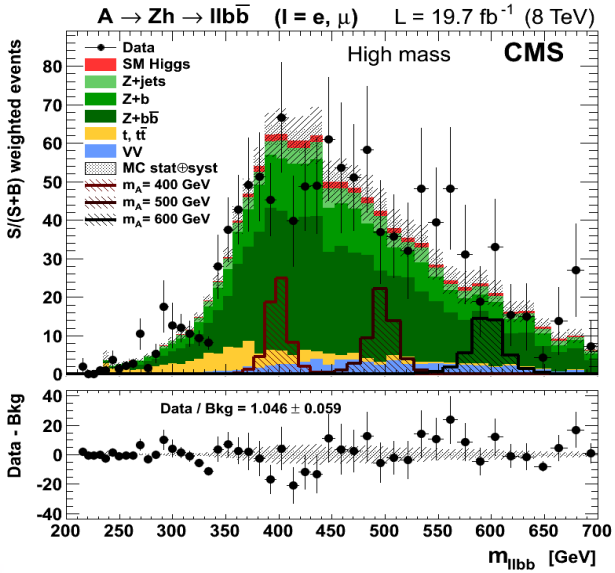
A → Zh (bb)

arXiv:1504.04710
PLB 744 (2015) 163-183

- ATLAS: Fit to reconstructed A boson invariant or transverse mass using llbb and *vv*bb channels.
- CMS: 2-D fit of A mass and BDT discriminant, in three mass regions. Only use llbb channel.
- Both: Use known Higgs mass (125 GeV) to re-scale b-jet transverse momentum.



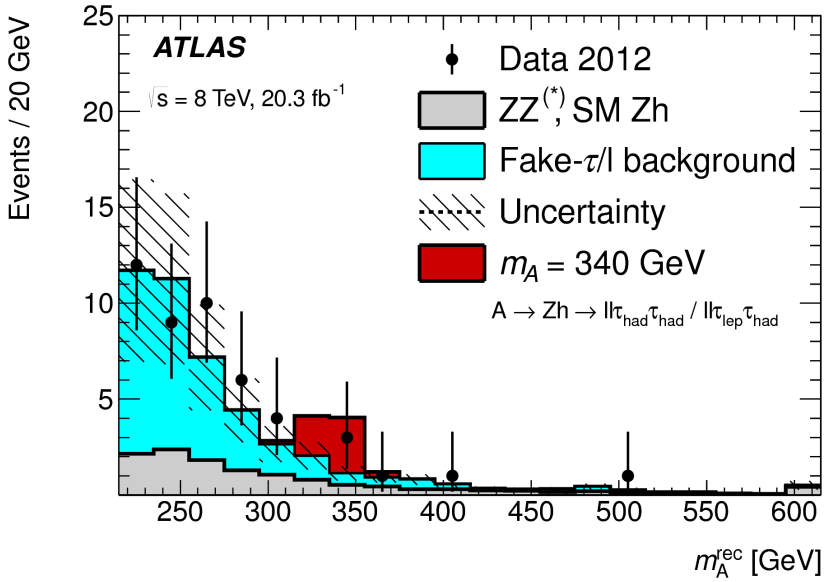


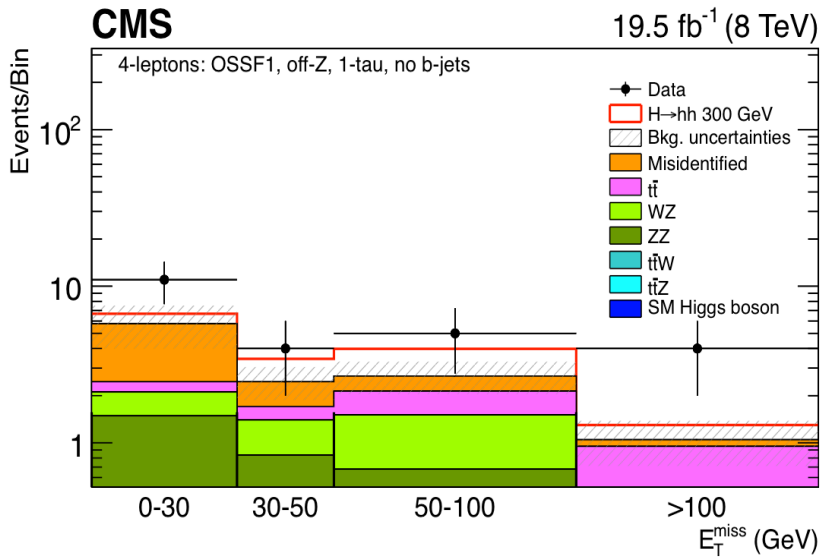


PRD 90 (2014) 112013

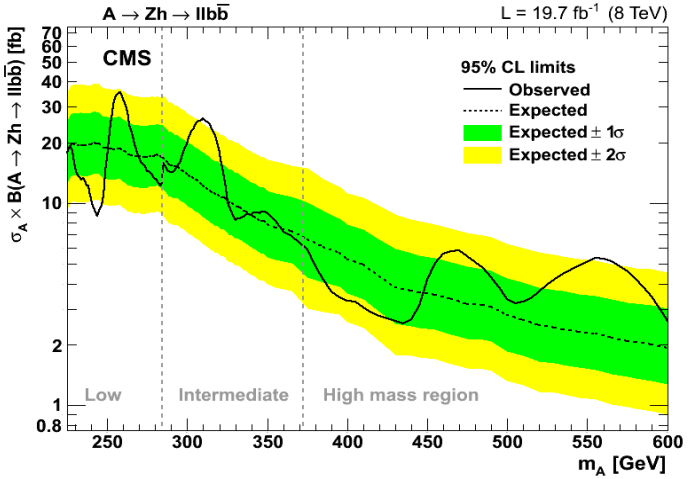
A → Zh (ττ, γγ, leptons)

- ATLAS: Direct search for A → Zh with h decaying to taus.
  - All tau decay modes considered. Fit reconstructed A mass after correcting for known Higgs mass.
- CMS: Event counting in ~160 regions based on # of leptons, taus, photons, b-jets, on- or off-shell Z candidates, and MET.
  - Used for both hh and Zh.
  - Some interesting-looking excesses but a large number of regions.

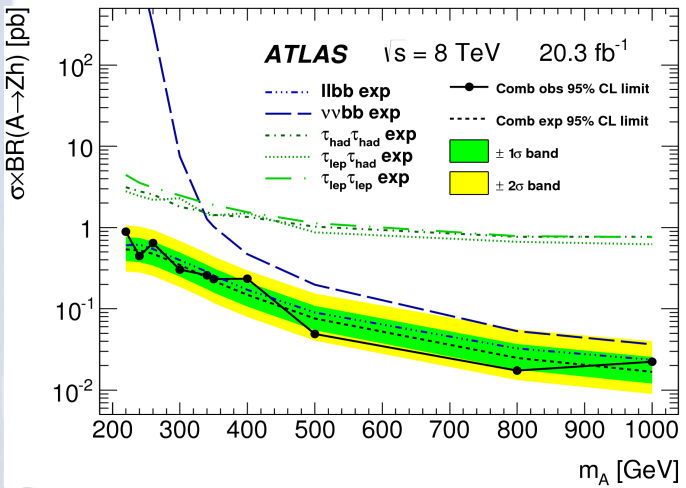


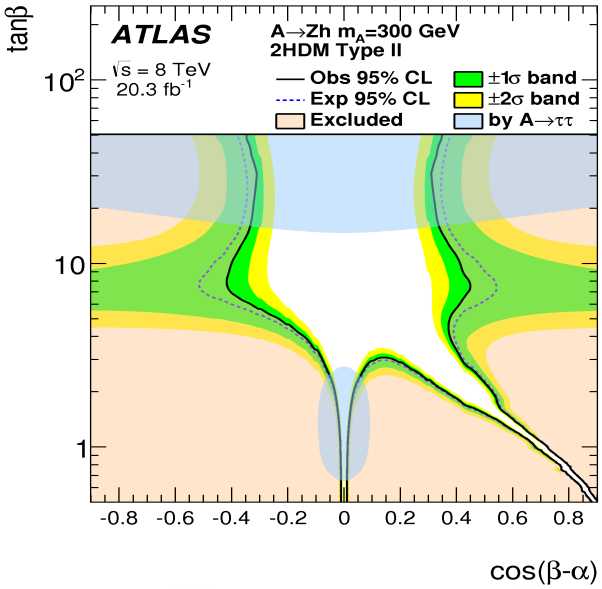


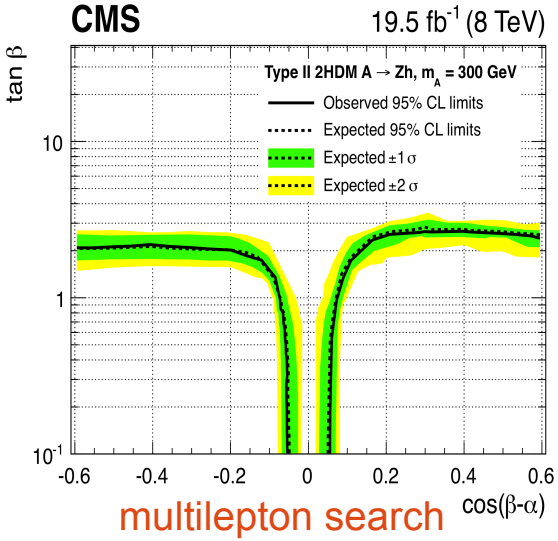
A → Zh: results



- Again no evidence for new Higgs bosons.
- llbb provides most sensitivity assuming SM-like h decays, but other channels important for general 2HDM interpretations.



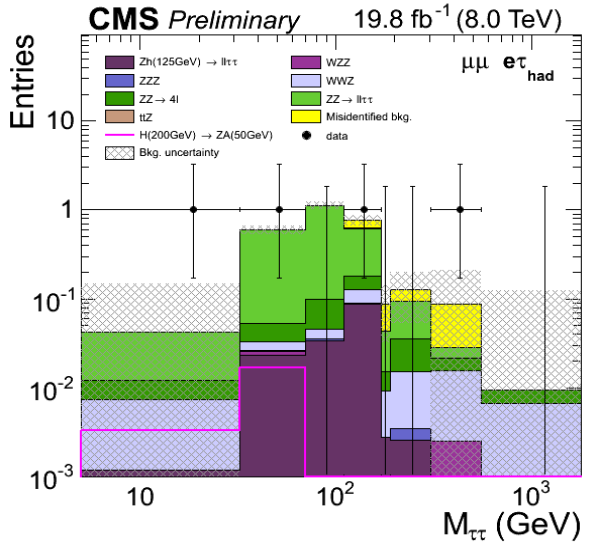


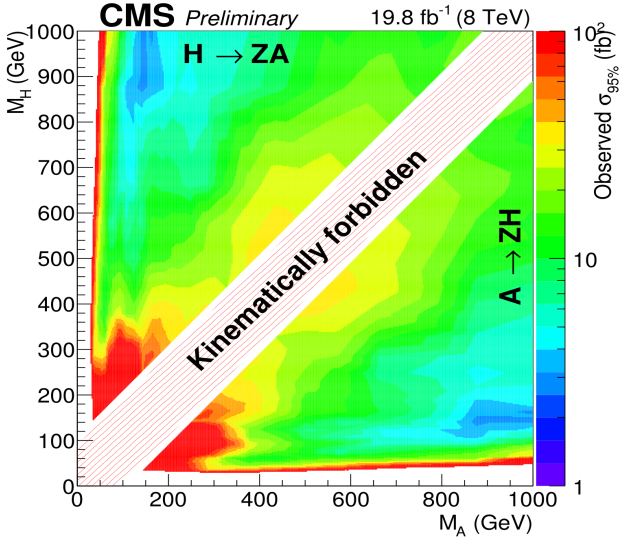


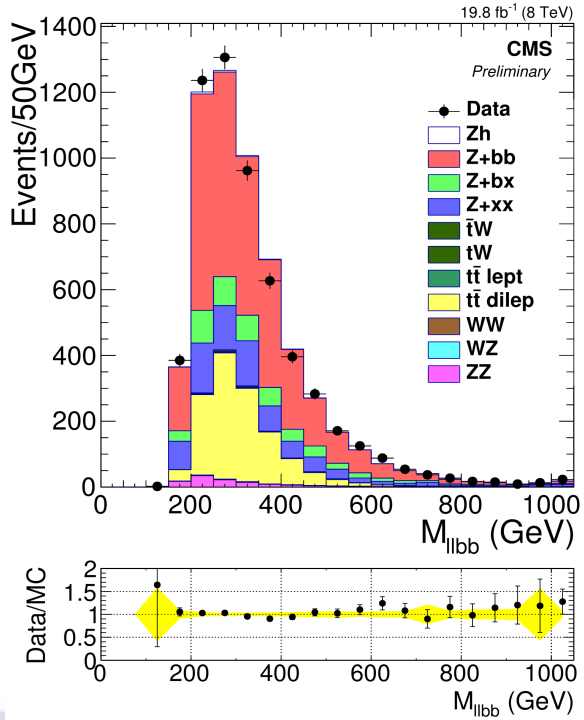
multilepton search

A → ZH or H → ZA

- Similar analyses to A→Zh, but no Higgs mass constraint.
- bb decays: Cut-and-count in 2-D bins of m_{bb} and m_{llbb}.
- $\tau\tau$ decays: Cut-and-count or shape fit using (likelihood-based) $m_{\tau\tau}$.
- bb sees local excess of 2.85σ at (575, 662) and 2.6σ at (93, 286).
  - Less than 2σ after look elsewhere effect.



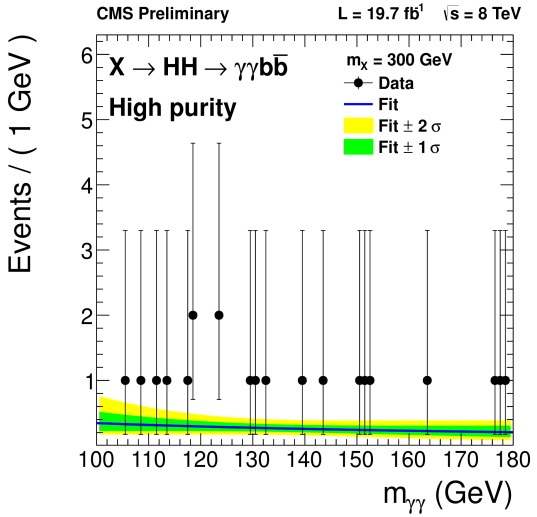


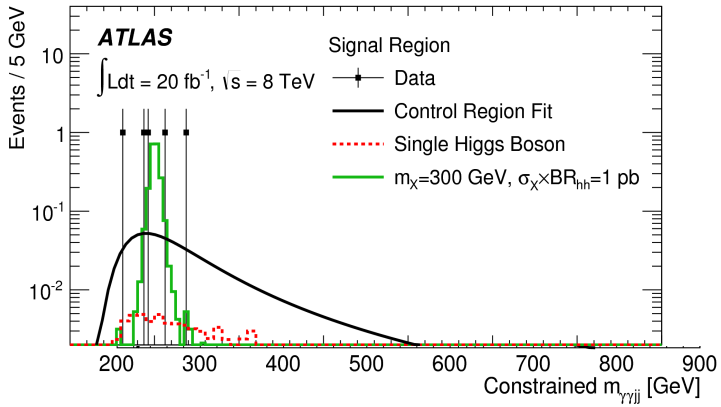


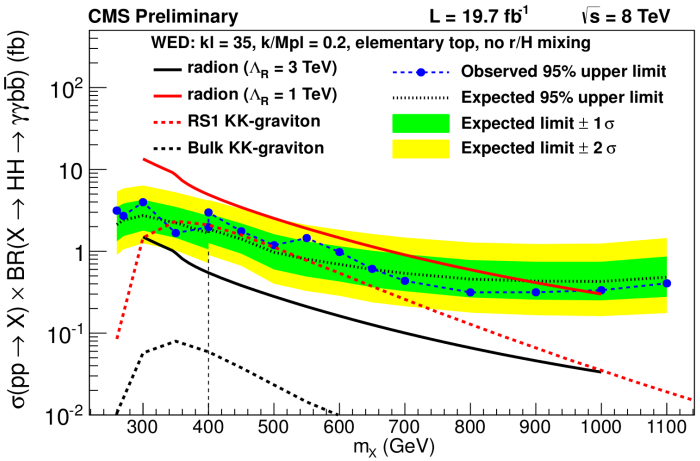
CMS-PAS-HIG-13-032
PRL 114, 081802 (2015)

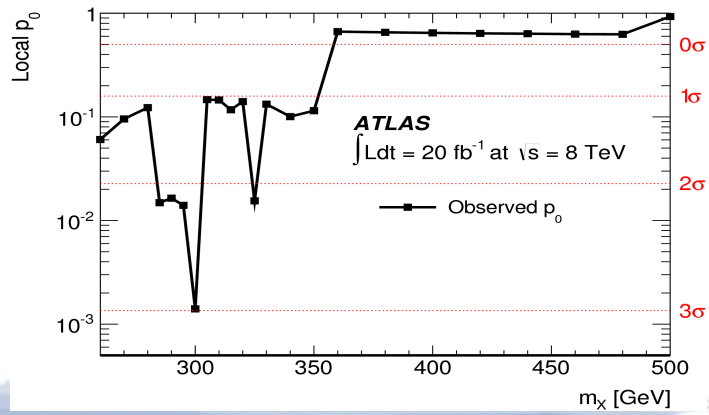
Di-Higgs bbγγ

- Events selected with 2 photons and 2 or 1 (CMS only) b-jets.
- ATLAS: Counting experiment in $m_{\gamma\gamma bb}$ windows.
- CMS: Fit $m_{\gamma\gamma}$ (low mass) or $m_{\gamma\gamma bb}$ (high mass).
- ATLAS sees 3σ (local) excess at 300 GeV, not confirmed by CMS.





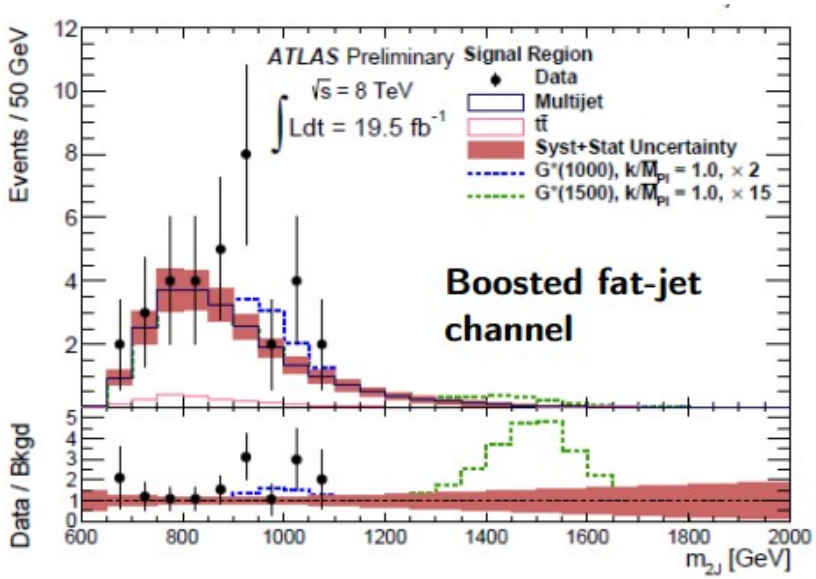


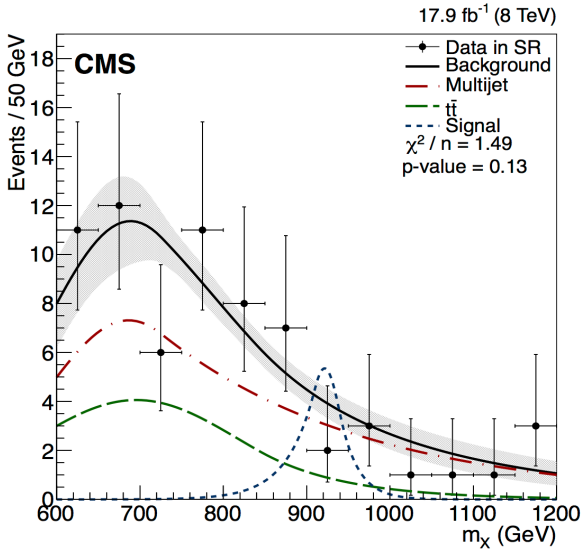


Di-Higgs 4b

arXiv:1503.04114
ATLAS to appear shortly

- Events selected with 4 high-p_T b-jets consistent with two Higgs bosons.
- 4-jet mass fit applying Higgs mass constraints.
- ATLAS extends to high masses using boosted Higgs reconstructed as single fat jets.
  - b-tagging using track sub-jets.

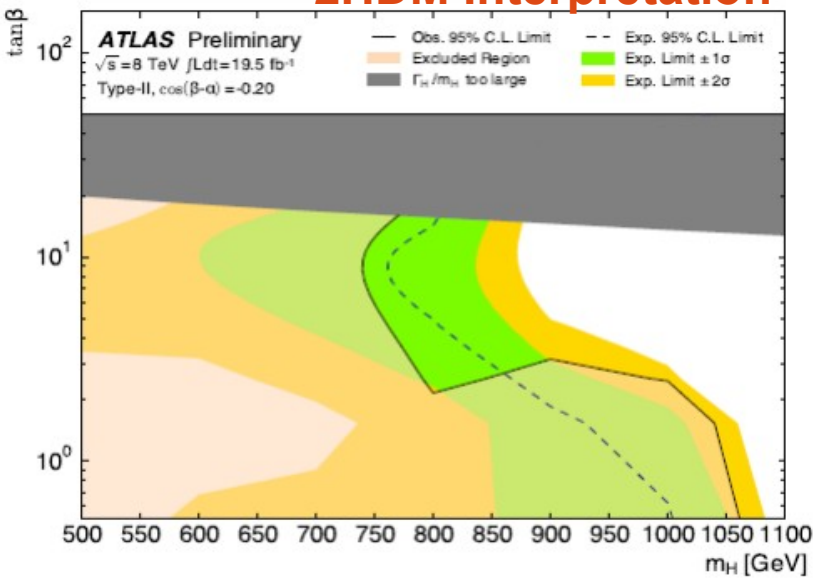


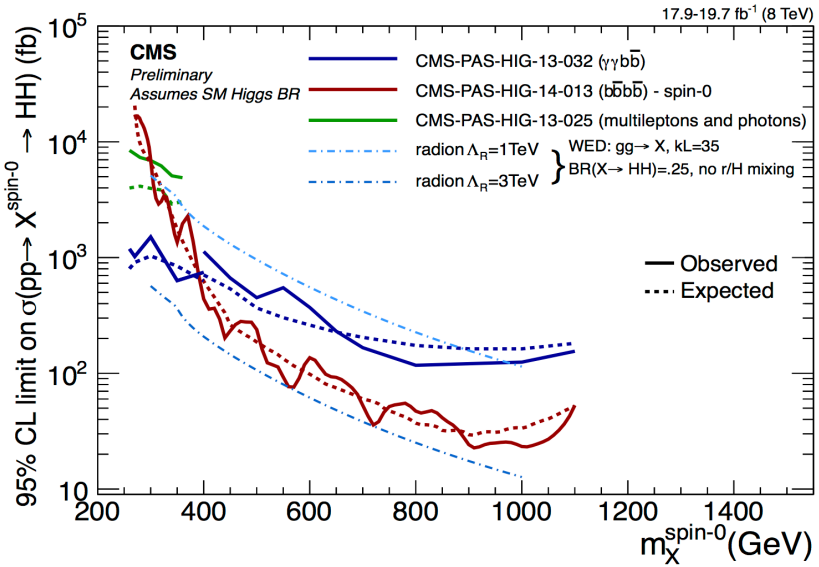


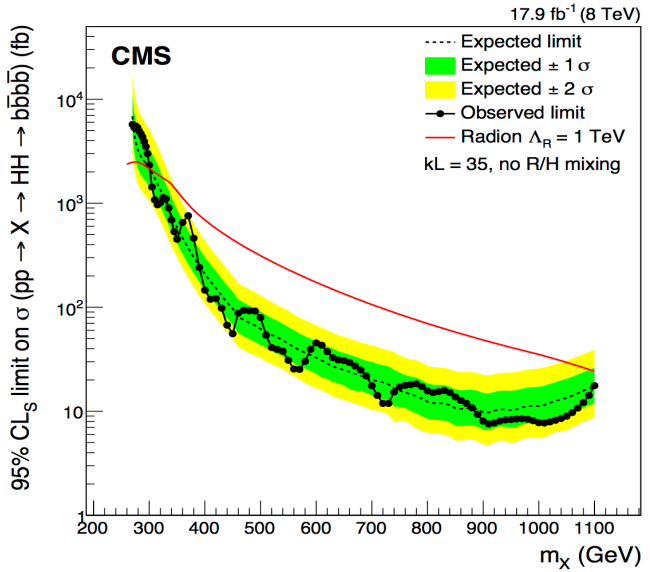
Di-Higgs 4b

- No evidence for di-Higgs resonance is observed.
- 4b dominates sensitivity for high-mass resonances.
- ATLAS boosted analysis: most sensitive above 1100 GeV.

2HDM Interpretation

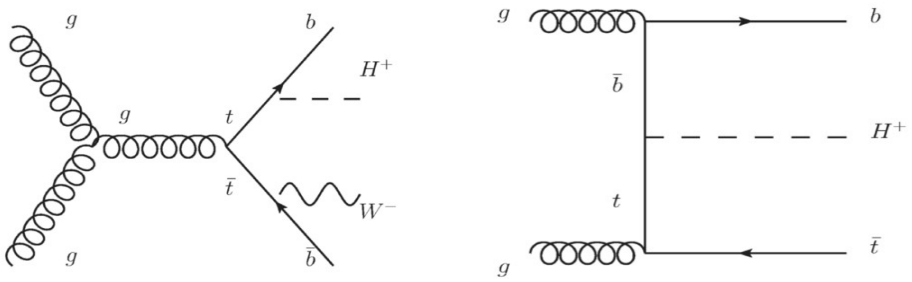




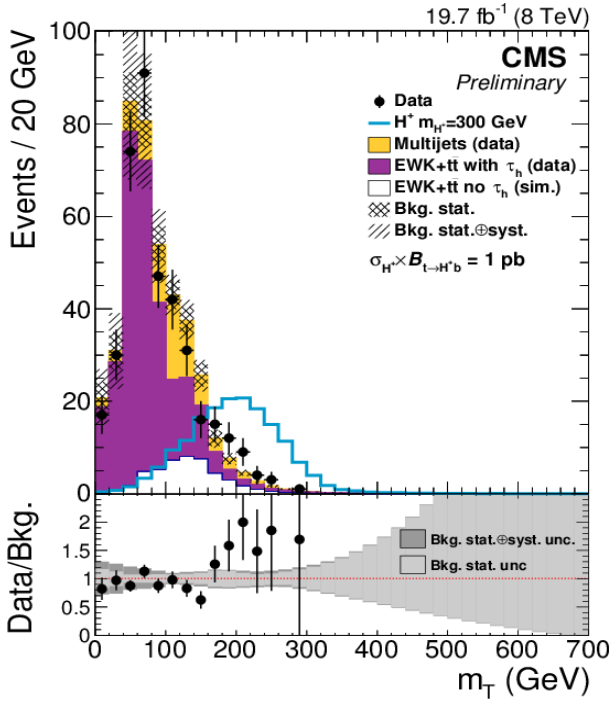


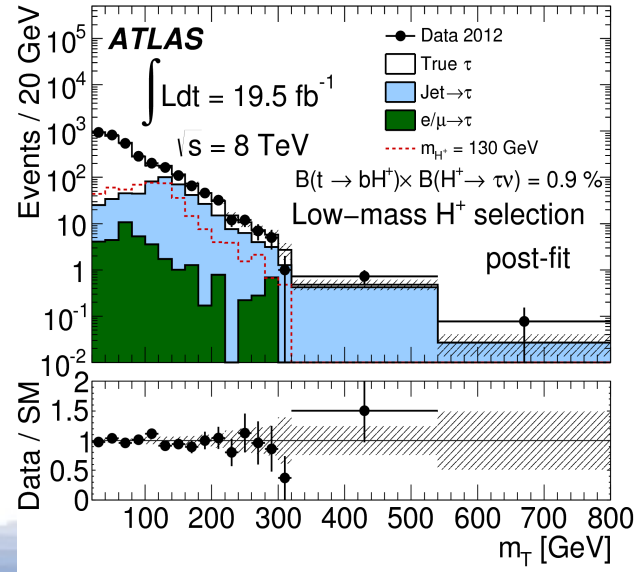
CMS-PAS-HIG-14-020
JHEP 03 (2015) 088

Charged Higgs → $\tau\nu$



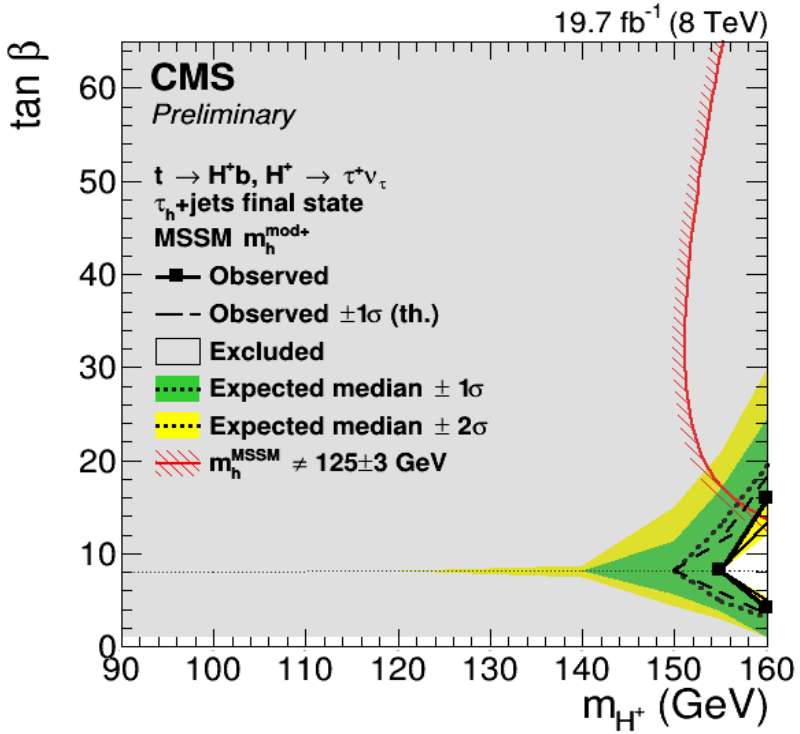
- H^+ produced in top decays (low mass) or with tb (high mass) → same particles in final state.
- Searches performed in fully hadronic channel.
- Separate selections for low and high-mass H^+.
- Backgrounds taken from data using embedded events and τ_{had} fake rates.

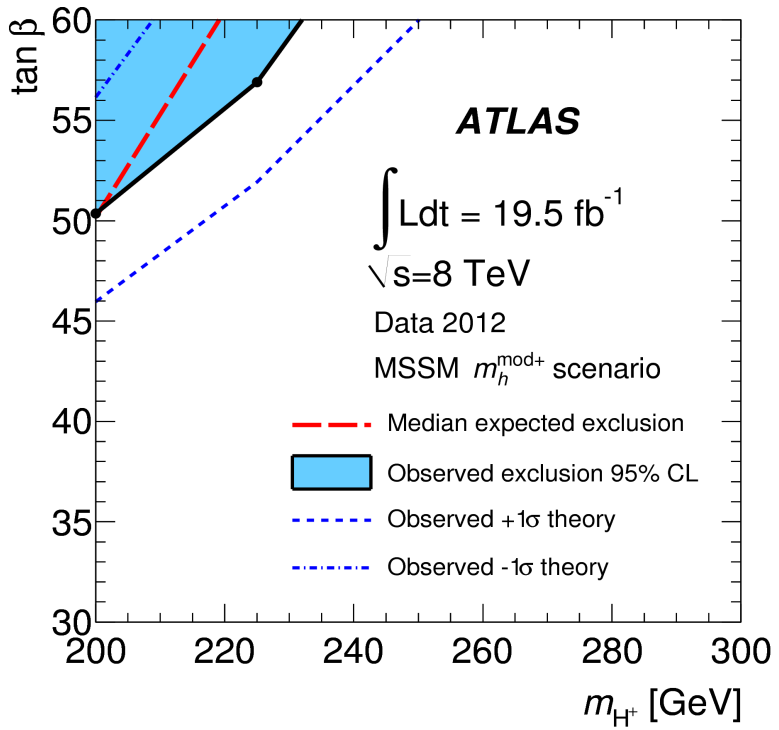




Charged Higgs → $\tau\nu$

- No evidence for charged Higgs is observed.
- The low-mass MSSM is basically dead.
- At high mass the fun is just getting started (but sensitivity to the MSSM in particular is very limited).

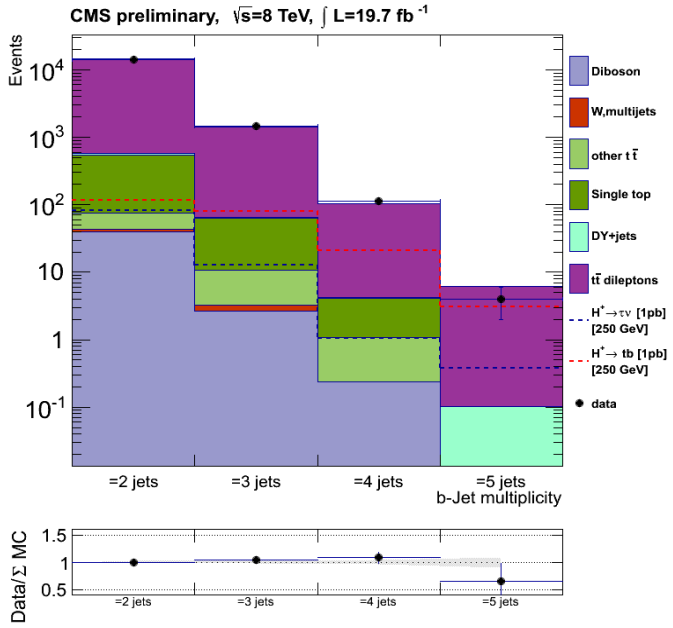


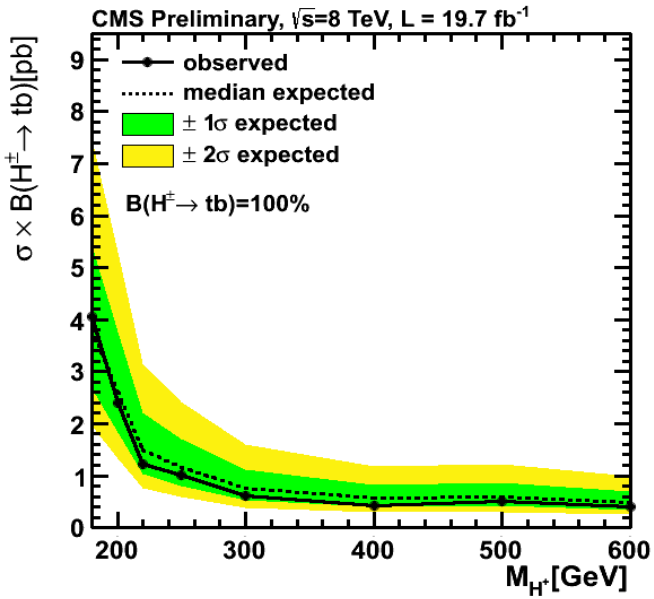


CMS-PAS-HIG-13-026

Charged Higgs → tb

- Events selected in *ee*, *eμ*, *μμ*, and $\mu\tau_h$ final states.
- After simple selection, binned fit performed in number of b-tagged jets.
- No significant excess is observed.
- Limits set on XS*BR, about 1 order of magnitude higher than MSSM values.

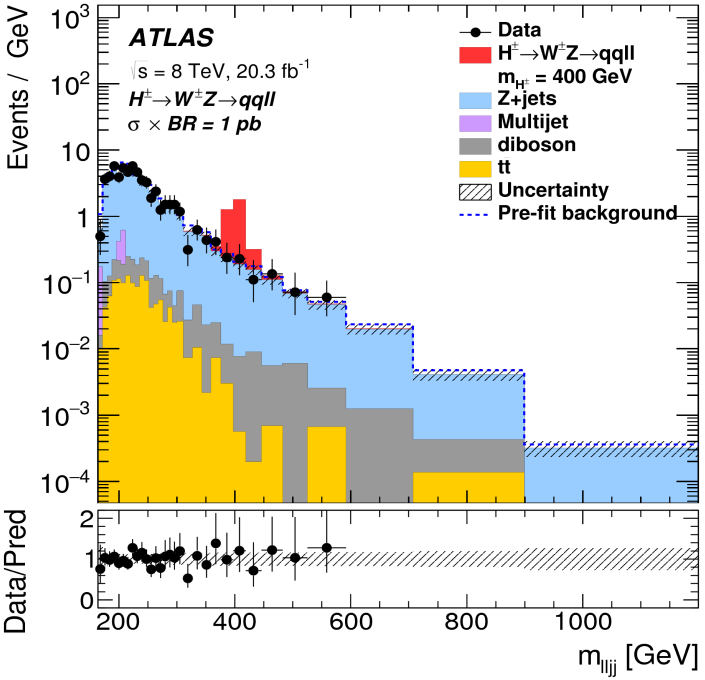




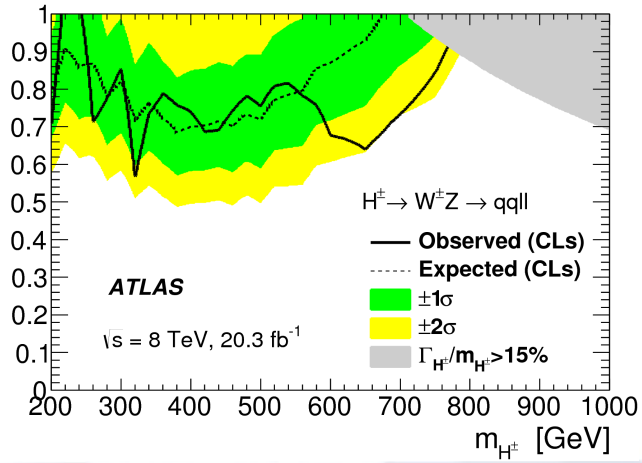
arXiv:1503.04233

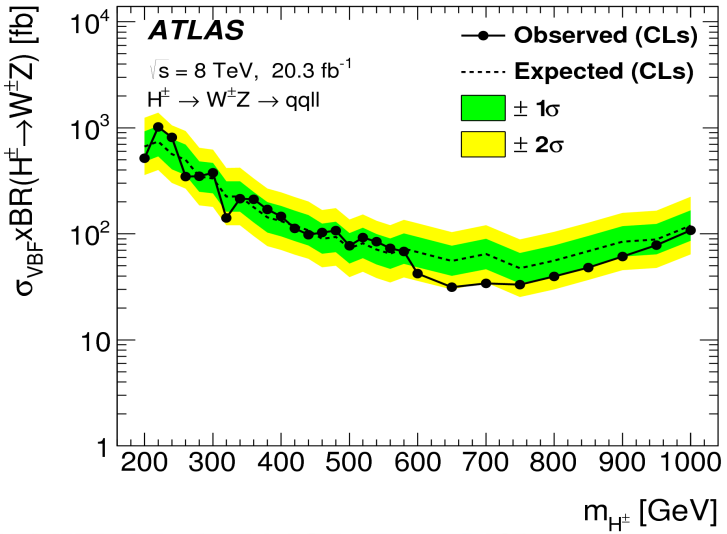
Charged Higgs → WZ

- Enhanced coupling in some Higgs triplet models: production via VBF and decay to WZ.
- W→*qq*' and Z→*ee*/*μμ* decays considered.
- Selection made on VBF "tag" jets, with additional kinematic cuts to reduce Z+jets background.
- No excess is observed.



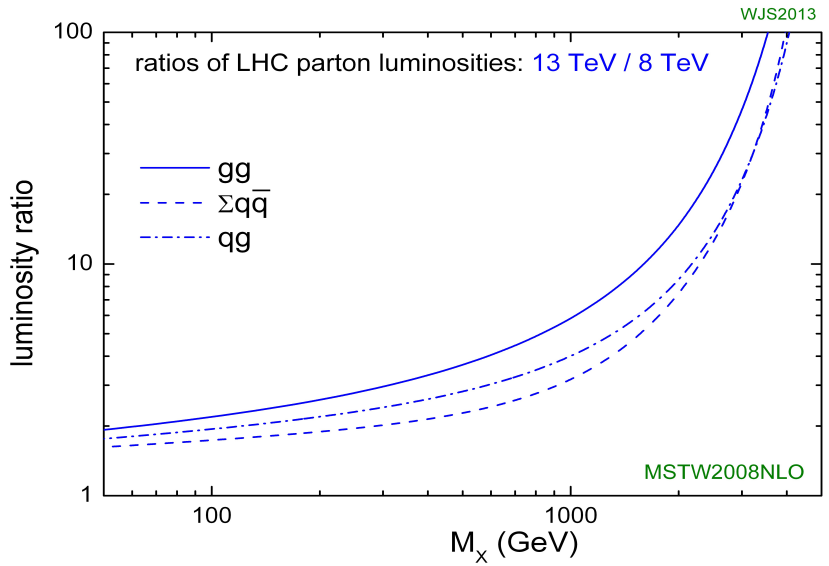
Fraction of W/Z masses from Higgs triplet VEV.





Conclusions

- CMS and ATLAS have searched for and not found a wide-ranging collection of BSM Higgs signatures.
- Results are complementary to precision studies of 125 GeV state as a means of understanding EWSB sector.
- Cross-sections increase rapidly with higher energy: many high-mass states will have improved sensitivity with early data.
- However BSM Higgs searches often use complex objects and final states: Understanding detector performance and backgrounds will be critical.



Beyond the Standard Slides

2HDM parameters

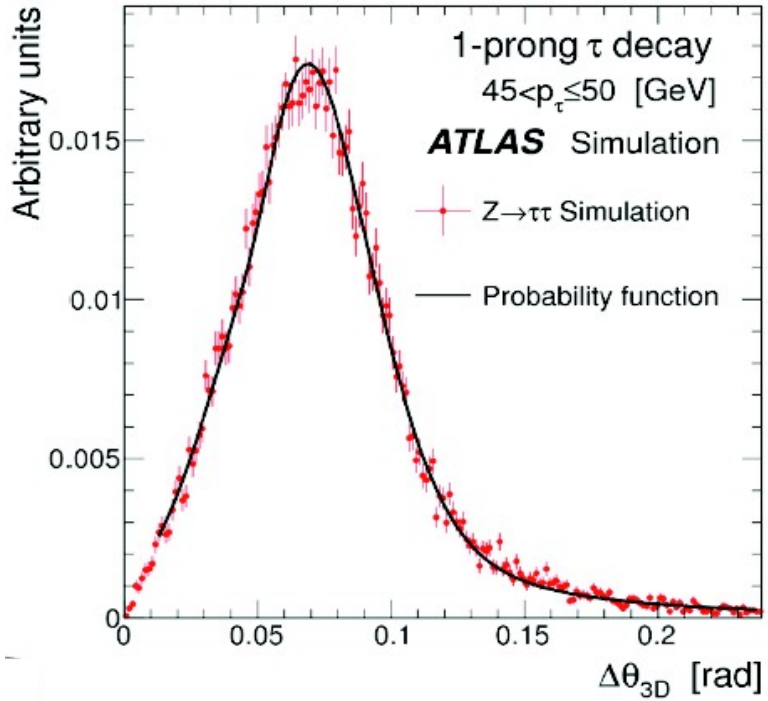
Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

MMC / SVFit

- 4 constraints on mass of di-tau system, but 6-8 unknowns
  - Depending on # of neutrinos in final state

$$
\begin{aligned}
E_x^{\text{miss}} &= p_{\text{miss}_1} \sin\theta_{\text{miss}_1} \cos\phi_{\text{miss}_1} + p_{\text{miss}_2} \sin\theta_{\text{miss}_2} \cos\phi_{\text{miss}_2}, \\
E_y^{\text{miss}} &= p_{\text{miss}_1} \sin\theta_{\text{miss}_1} \sin\phi_{\text{miss}_1} + p_{\text{miss}_2} \sin\theta_{\text{miss}_2} \sin\phi_{\text{miss}_2}, \\
m_\tau^2 &= m_{\text{miss}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{miss}_1}^2 + m_{\text{miss}_1}^2}, \\
&\quad -2p_{\text{vis}_1} p_{\text{miss}_1} \cos\Delta\theta_{\text{vm}_1}, \\
m_\tau^2 &= m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2} \cdot p_{\text{miss}_2}, \\
&\quad -2p_{\text{vis}_2} p_{\text{miss}_2} \cos\Delta\theta_{\text{vm}_2}
\end{aligned}
$$



- Ambiguity resolved by scanning the parameter space, calculating the mass for each point, weighting the solution by the likelihood to come from a tau decay.
- Final di-tau mass is the peak of the resulting distribution.

A.Elagin, P.Murat, A.Pranko, A.Safonov
arXiv:1012.4686 ; NIM A654 (2011) 481