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Beyond the Standard Model Higgs Searches

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On behalf of the ATLAS & CMS Collaborations

Lepton Photon 2013, San Francisco, USA

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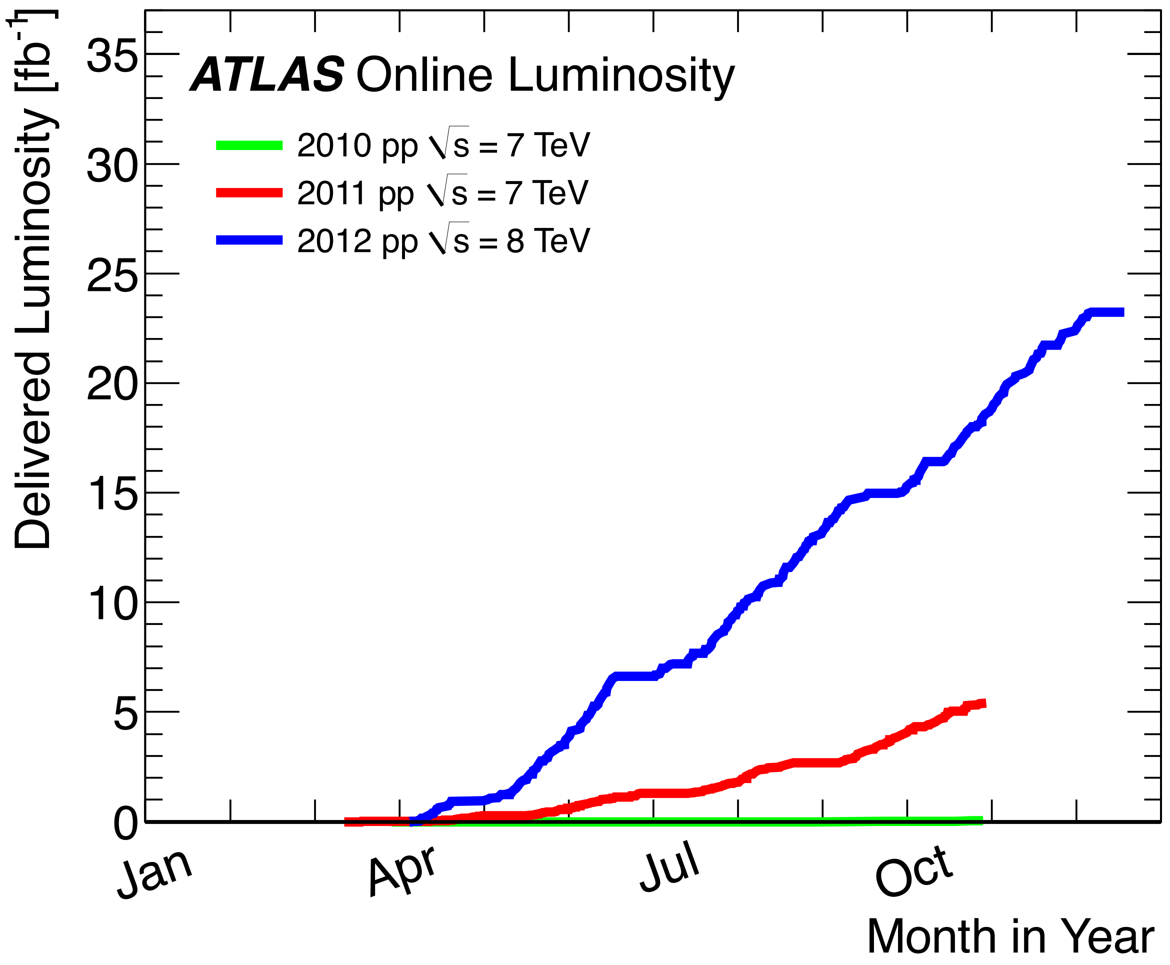
Outline

- Motivation
- Neutral Higgs searches
  - Higgs to tau pairs
  - Higgs to b-quark pairs
  - Heavy Higgs to WW
- Charged Higgs searches
  - H^+ to $\tau\nu$
  - H^+ to $c\bar{s}$
- Summary

Will focus on most recent results



Results possible due to fantastic LHC & detector performance

Why Beyond the SM Higgs?

- Want to test whether the SM Higgs mechanism is solely responsible for mass generation for all particles.
  - Could have additional Higgs fields & hence additional Higgs bosons.
- Various possibilities exist, e.g.:
  - Additional Higgs doublet - realised in SUSY models - connection with addressing the Hierachy problem.
  - Additional singlet fields.
- Additional particles may be accessible at the LHC.

Two Higgs Doublet Models

- Additional Higgs doublet added to the SM:

$$\langle\Phi_1\rangle_0 = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix}, \langle\Phi_2\rangle_0 = \begin{pmatrix} 0 \\ v_2/\sqrt{2} \end{pmatrix}$$

- Different doublets can couple to different quarks & leptons:

Type I: Φ_2 couples to all quarks & charged leptons

Type II: Φ_2 couples to up-type quarks
Φ_1 couples to down-type quarks & charged leptons

MSSM is Type II

- 5 Higgs bosons: h, H, A, $H^{\pm}$
- Important parameters: $\tan\beta = \frac{v_2}{v_1}$ $\sin\alpha$ Rotation angle to diagonalize mass matrix
- BSM Higgs models still very relevant for the observed Higgs boson with m=125 GeV.

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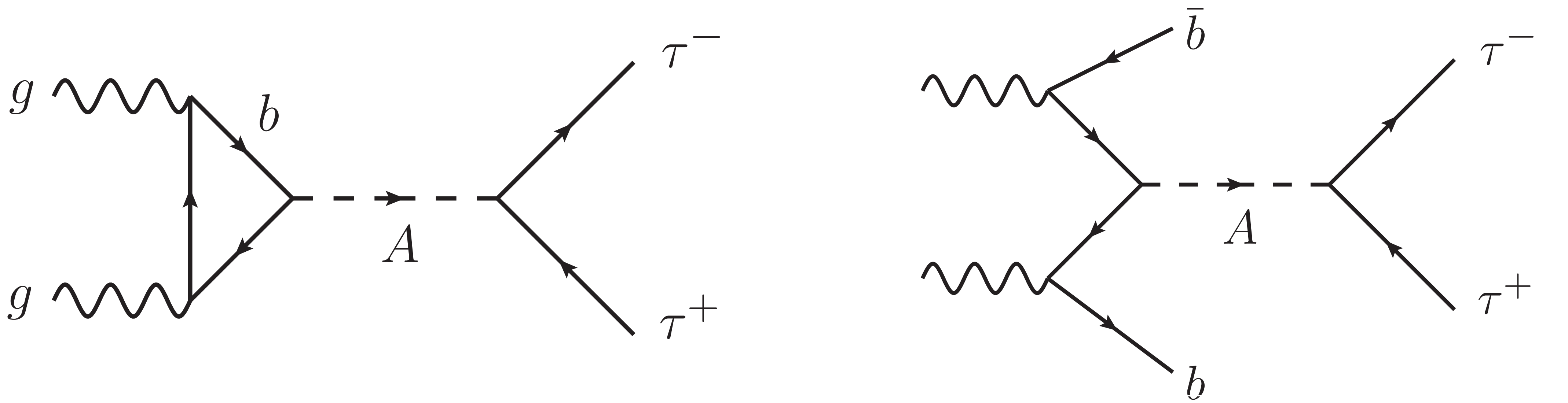
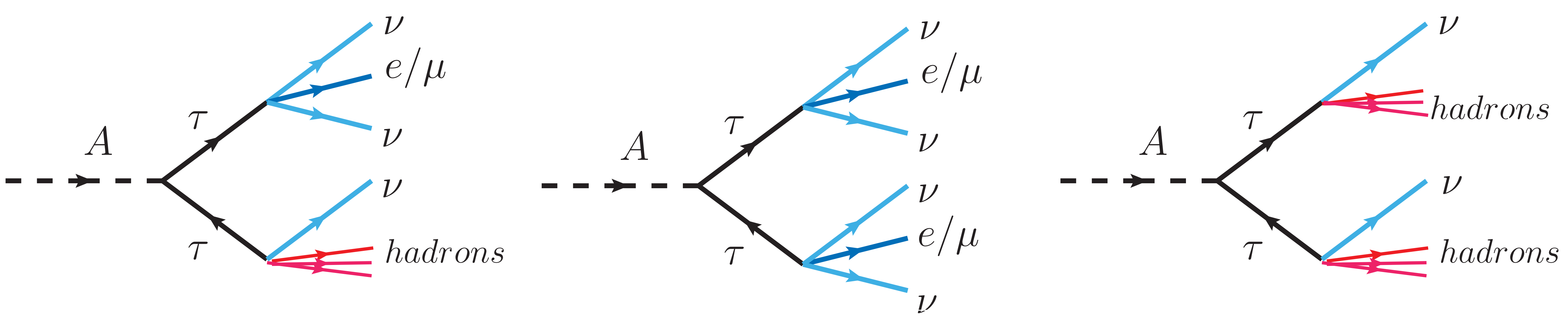
Neutral Higgs Searches

Neutral Higgs to Tau Pairs

- Type II 2HDM (including MSSM) at high tanβ have increased couplings to b-quarks & tau leptons.
  - Increased cross-section for production of e.g. A→**ττ**.



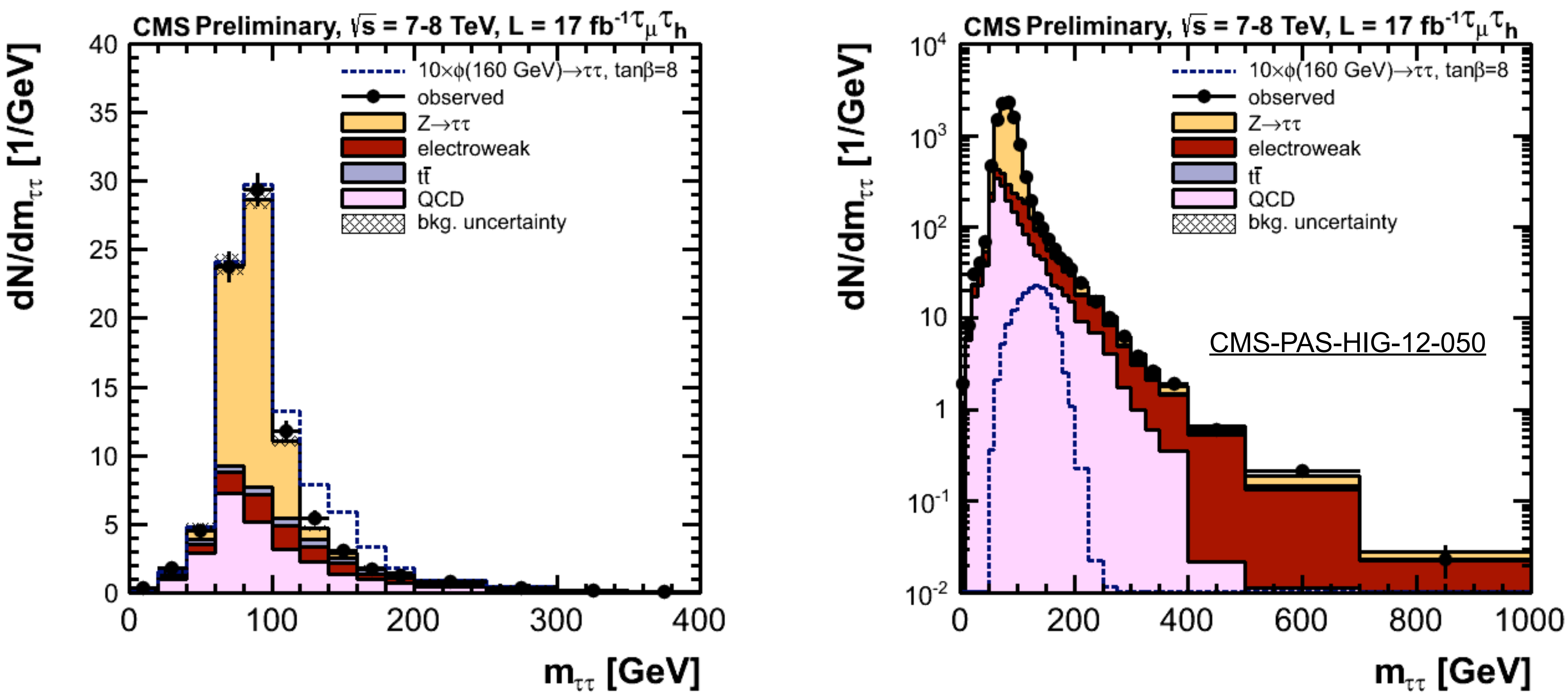
- Experimental signature determined by the tau decays:



Neutral Higgs to Tau Pairs

CMS, 12 fb^{-1} 8 TeV, 5 fb^{-1} 7 TeV
ATLAS, 5 fb^{-1} 7 TeV

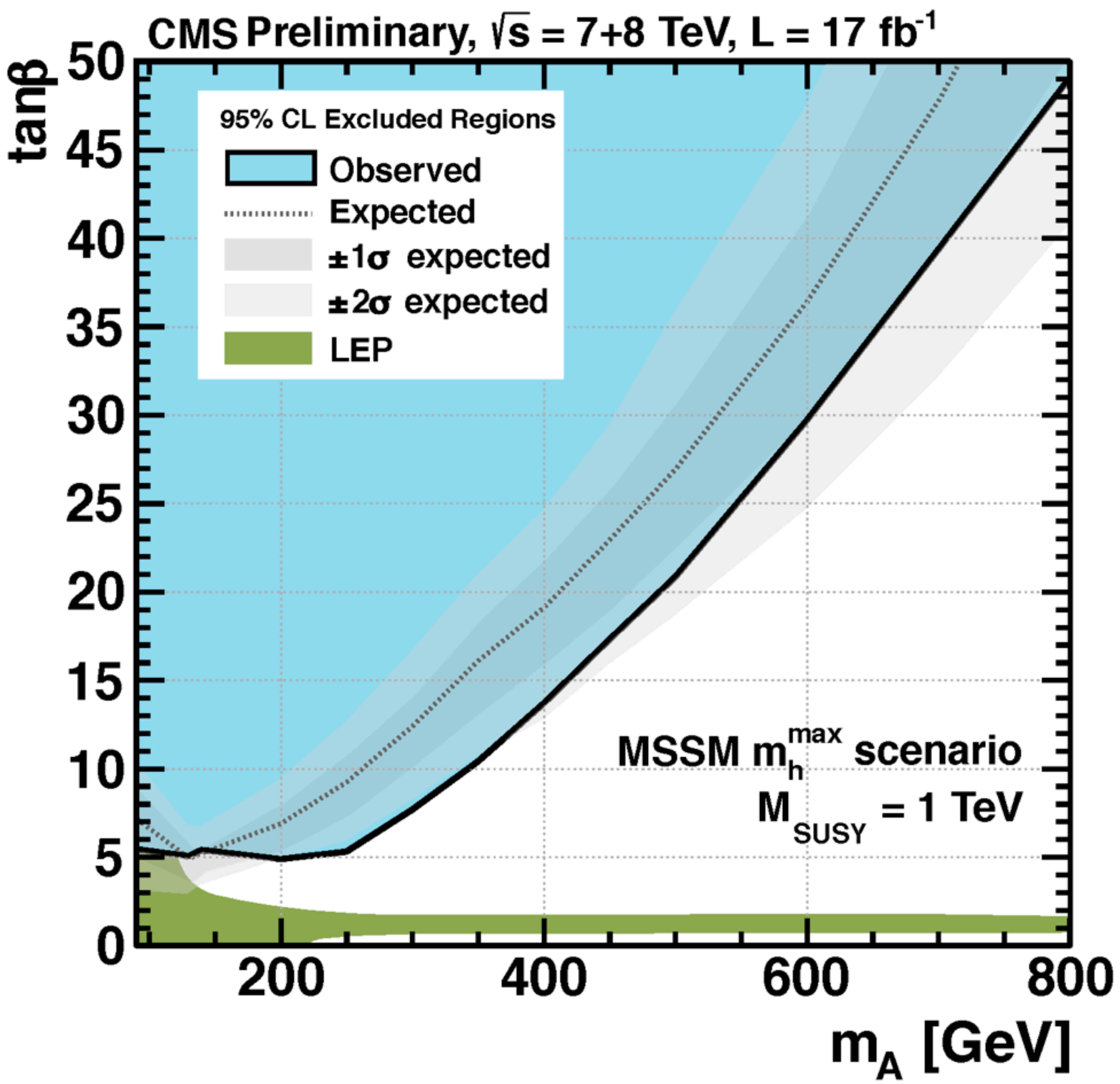
- Main background from $Z\rightarrow\tau\tau$ decays - model using $Z\rightarrow\mu\mu$ from data and replace μ with simulated τ.
- Fit di-tau mass distribution - mass reconstruction is improved by using the measured missing transverse energy.



Neutral Higgs to Tau Pairs

CMS, 12 fb^{-1} 8 TeV, 5 fb^{-1} 7 TeV
ATLAS, 5 fb^{-1} 7 TeV

- Stringent limits on MSSM parameter space in a given benchmark model:



Neutral Higgs to Tau Pairs

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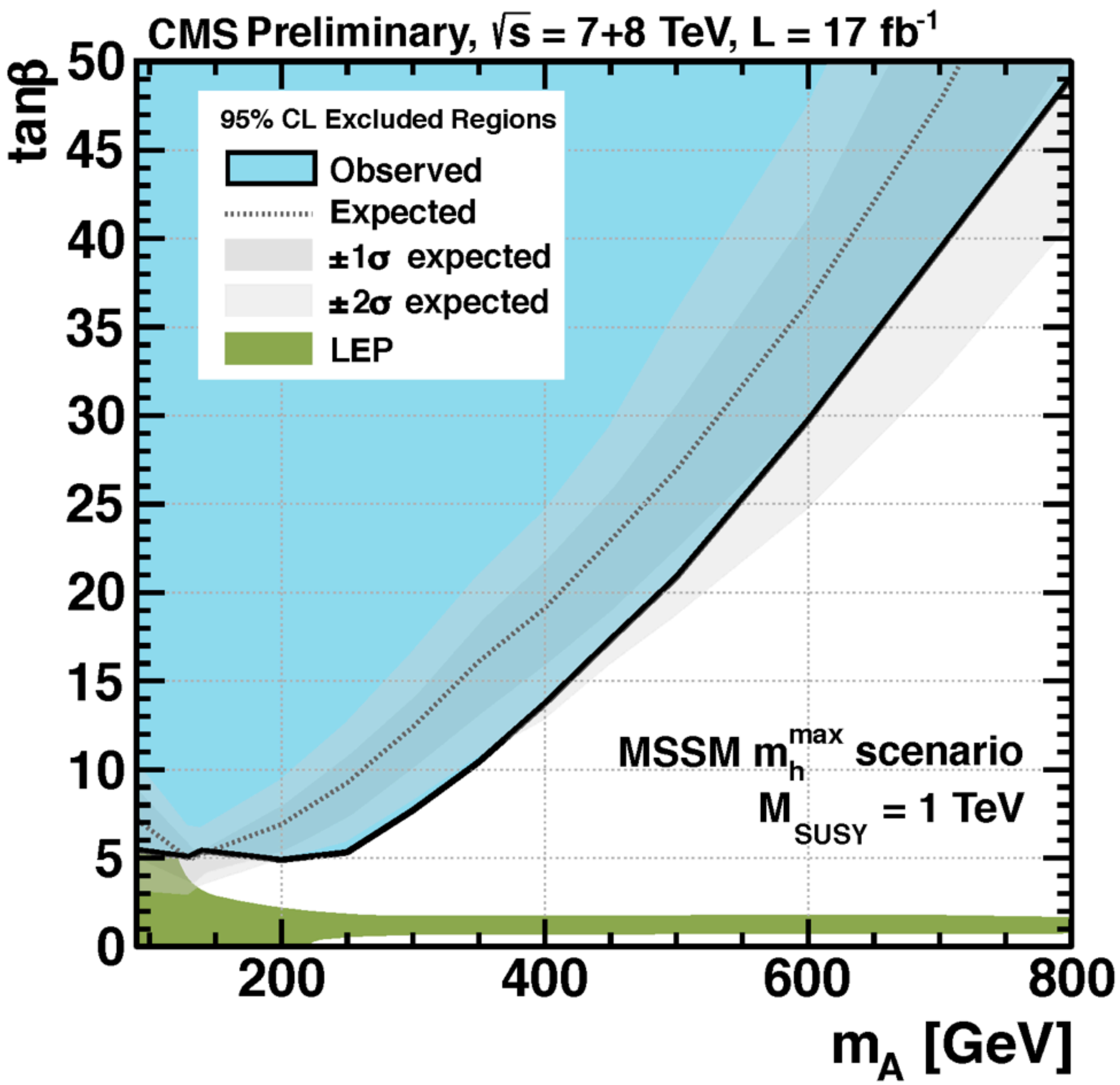

- Important to provide also the model independent cross section limits to allow translation into other BSM Higgs models.

Neutral Higgs to Tau Pairs

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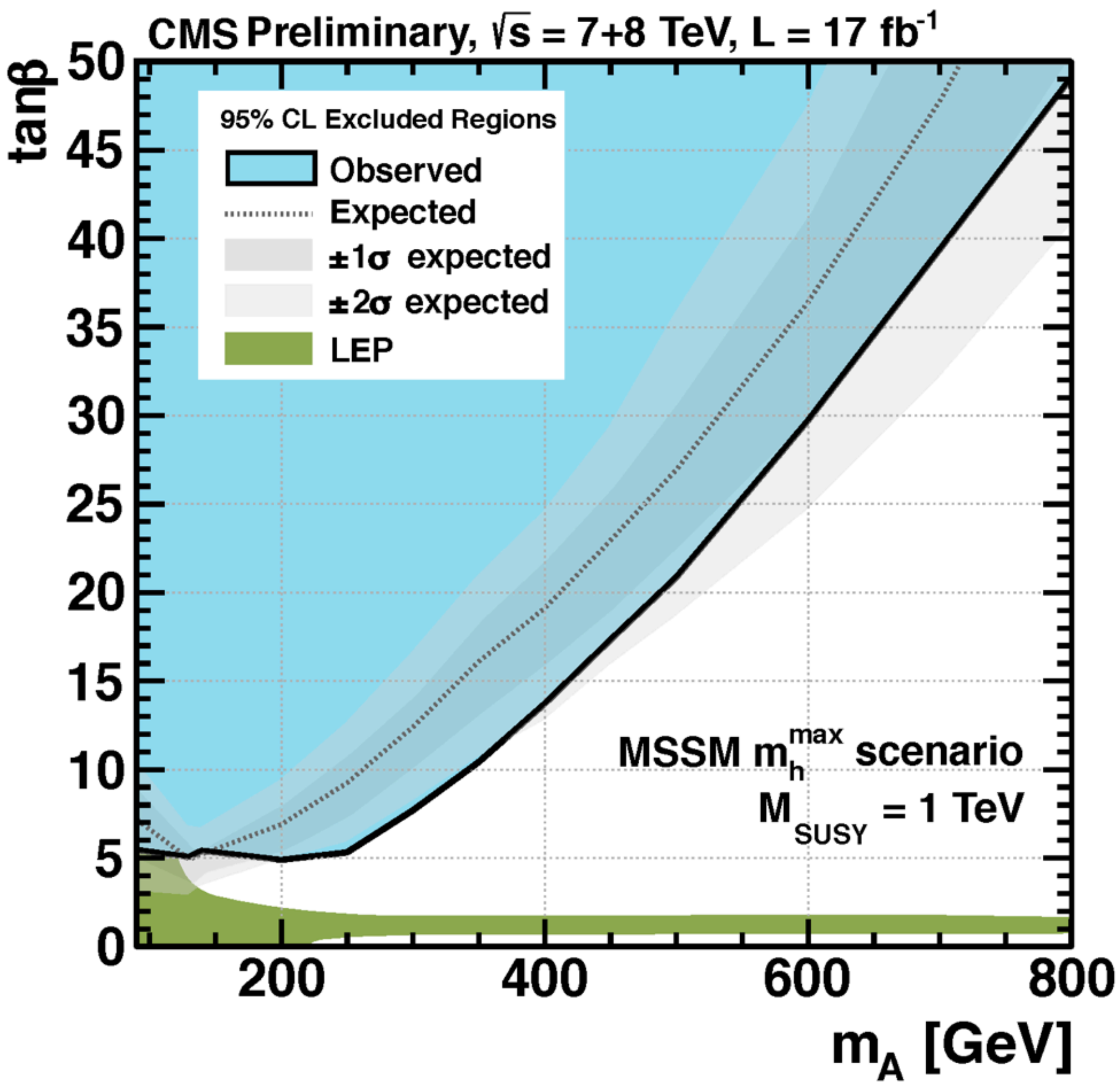
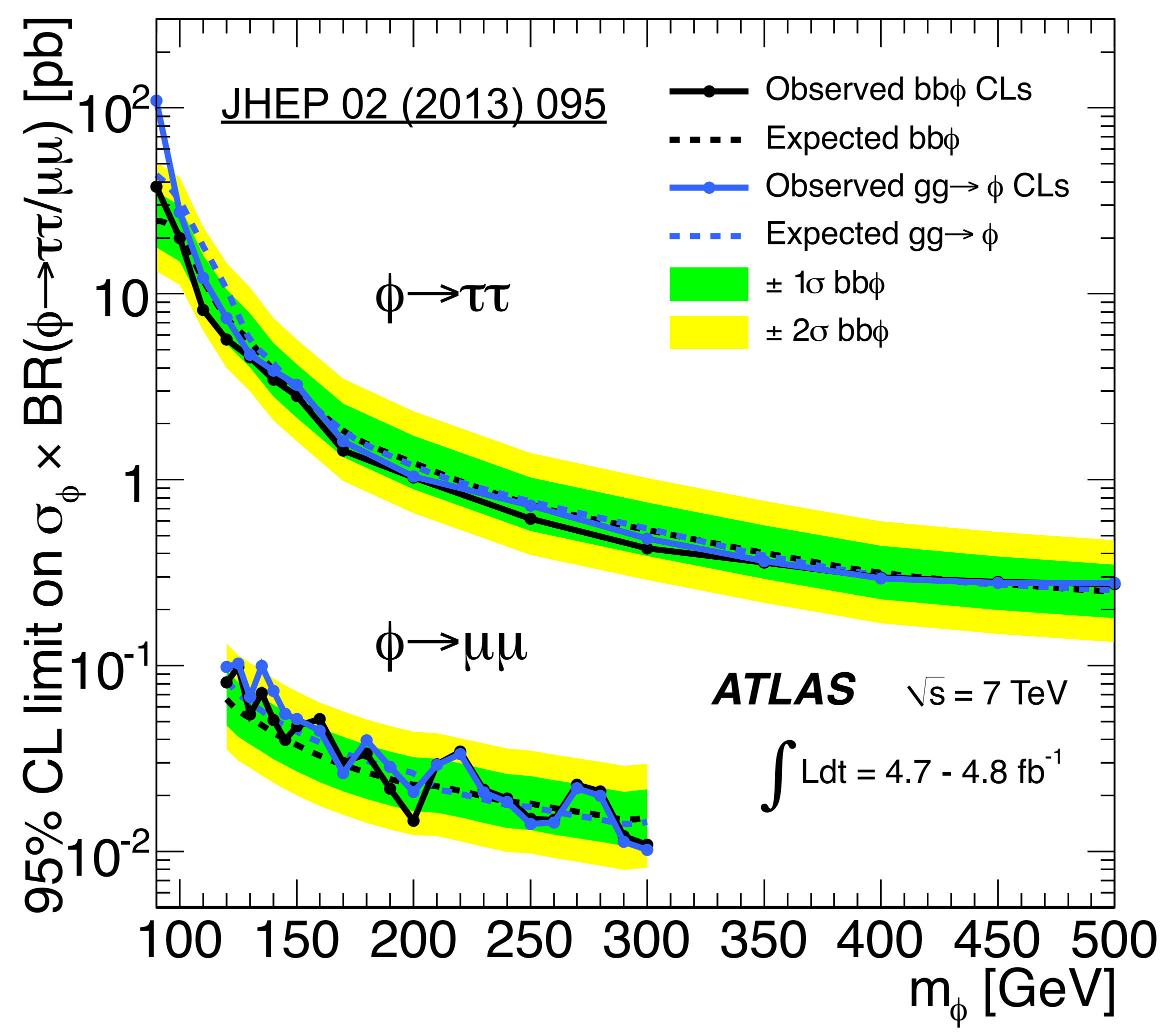
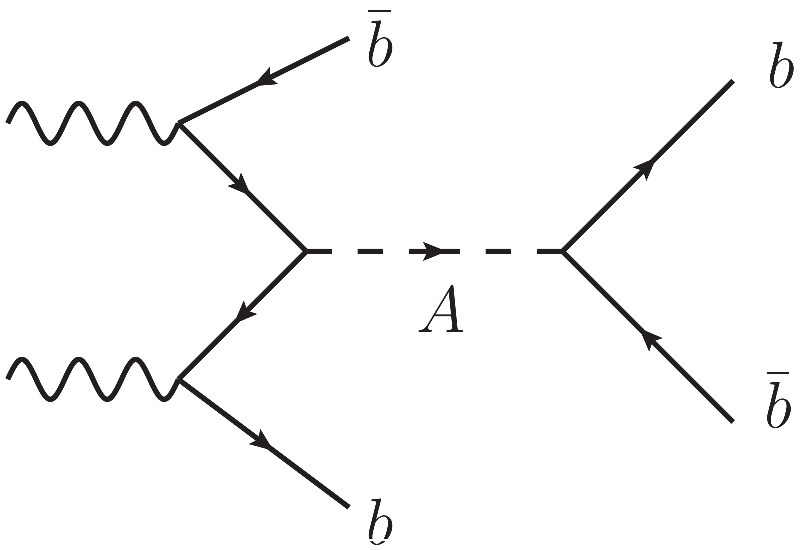




- Important to provide also the model independent cross section limits to allow translation into other BSM Higgs models.

Neutral Higgs to b Quark Pairs

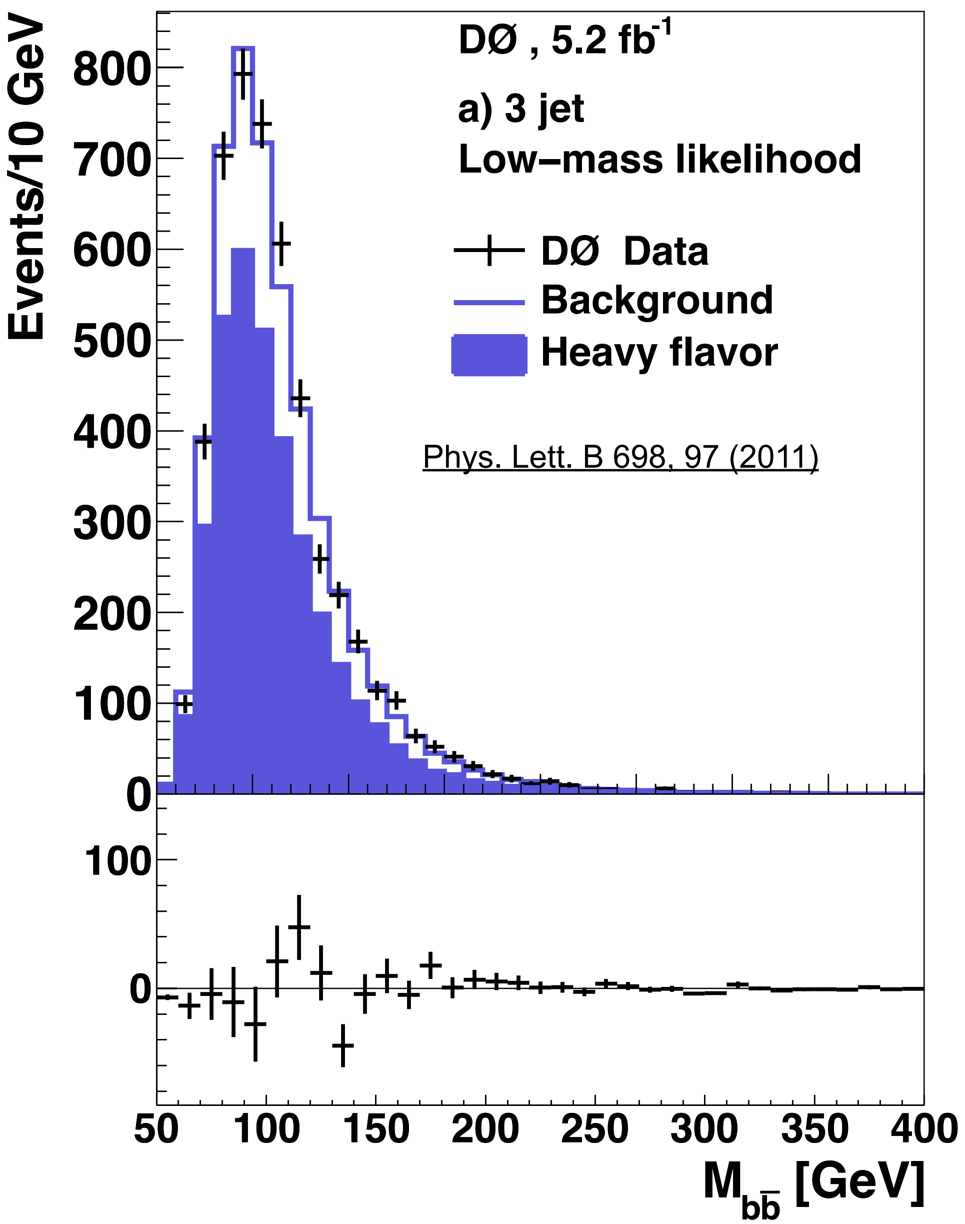
- Type II 2HDM (including MSSM) at high tanβ have increased couplings to b-quarks & tau leptons.
  - Dominant decay mode Higgs to bb can be accessed via associated production:

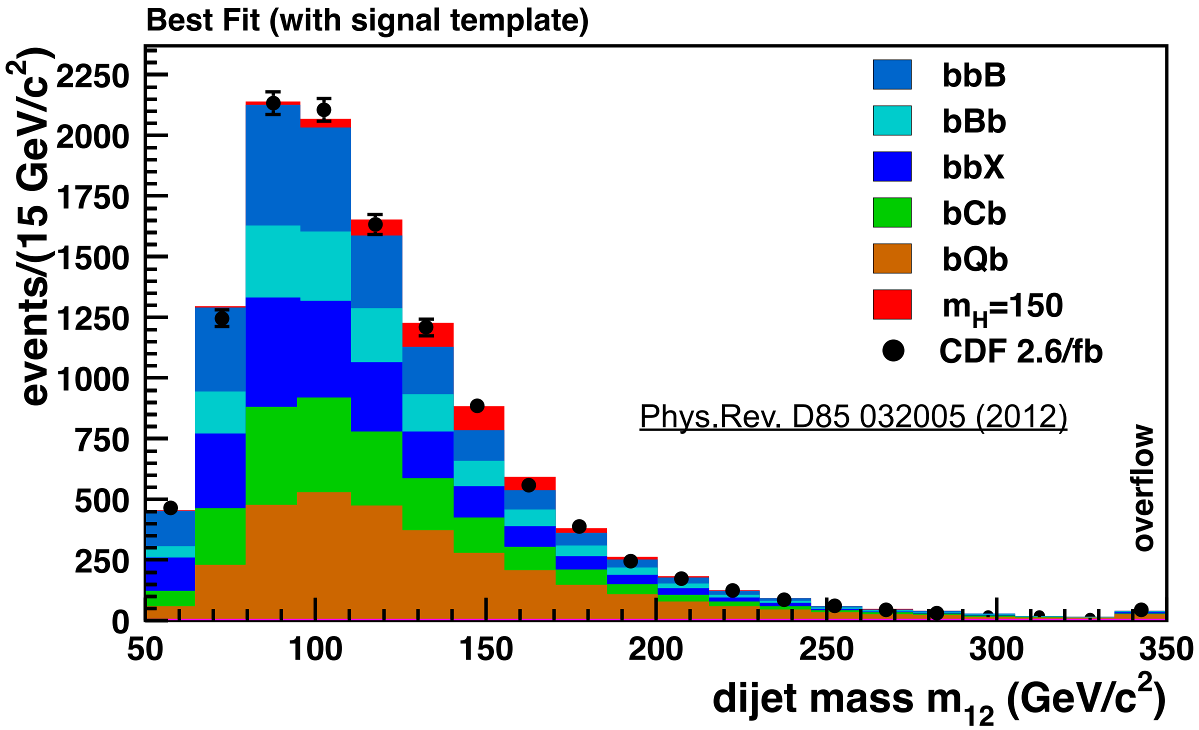


- Challenging final state for the trigger at hadron colliders.
- Background dominated by multijet background sources - estimated using data-driven techniques.

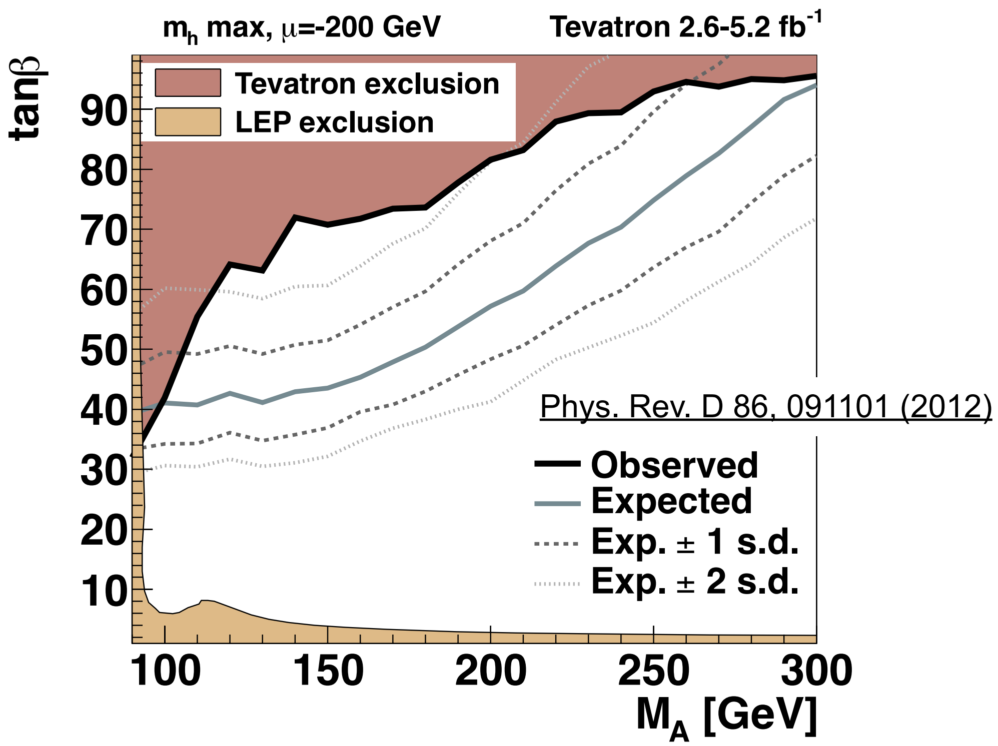
Neutral Higgs to b Quark Pairs

- D0 and CDF analyses both have slight excesses at low mass:





D0 5.2 fb^{-1}
CDF 2.6 fb^{-1}



- Combined significance of ~2 sigma in D0+CDF combination.

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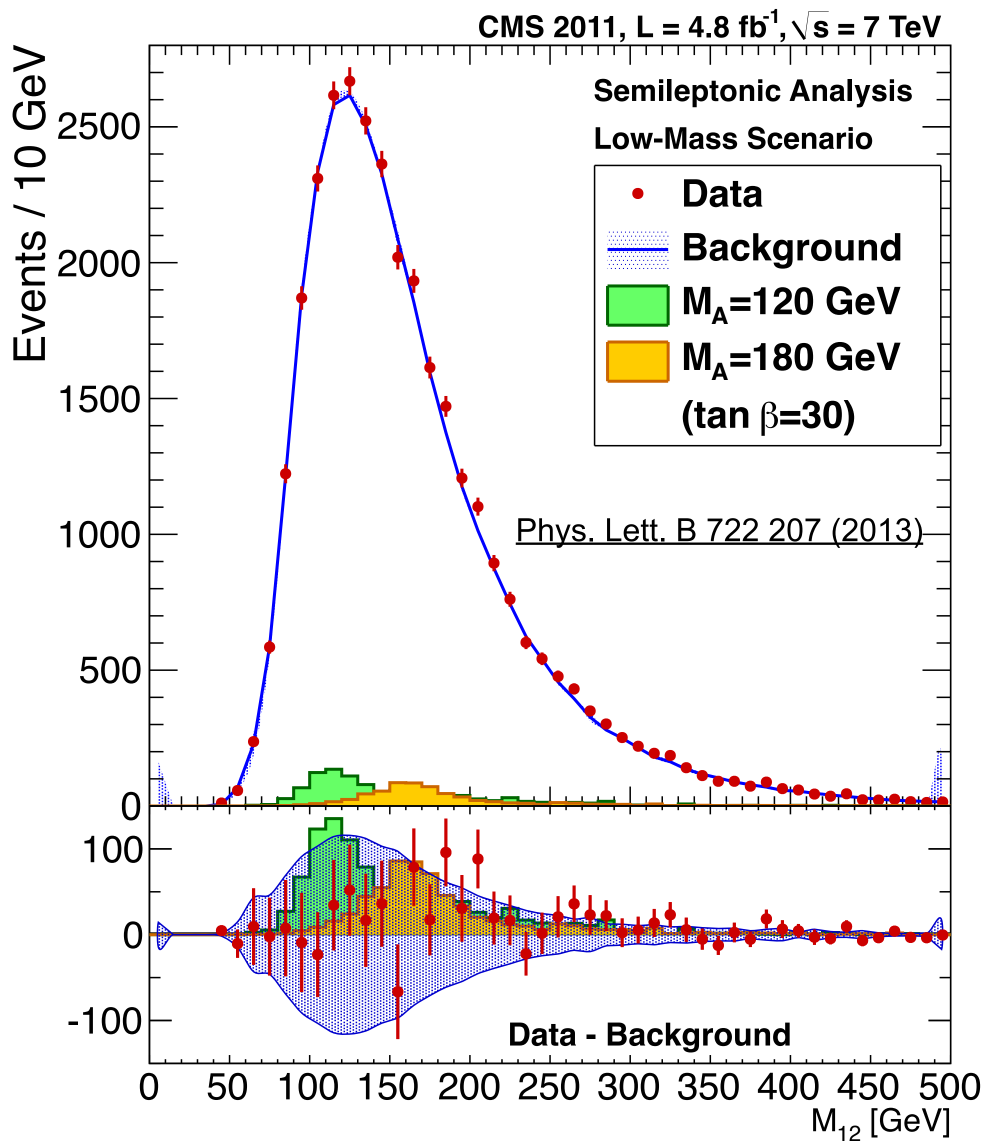
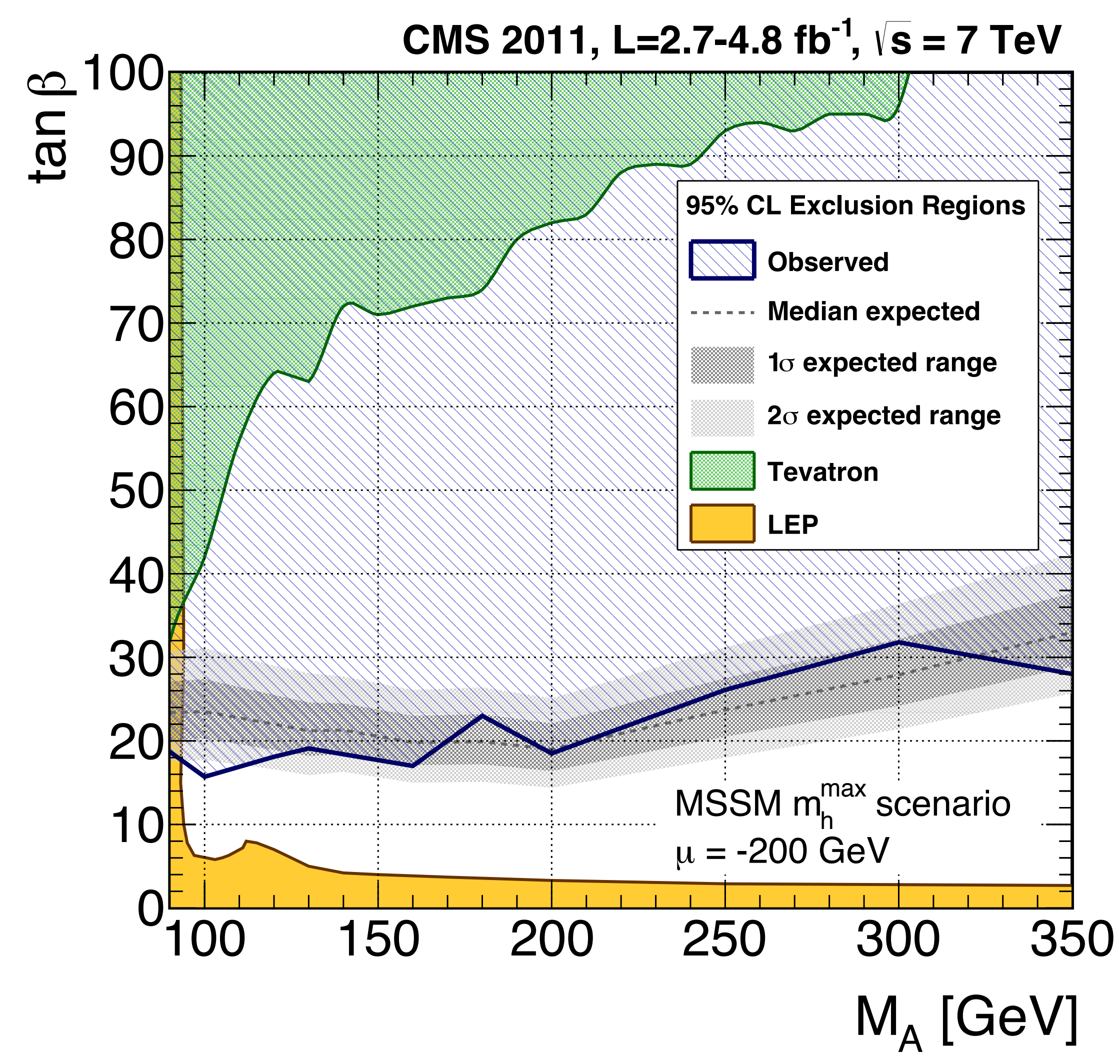
Neutral Higgs to b Quark Pairs

- Recent analysis by CMS in the same final state, using multijet and muon + jet triggers.

CMS 2-5 fb^{-1} 7 TeV



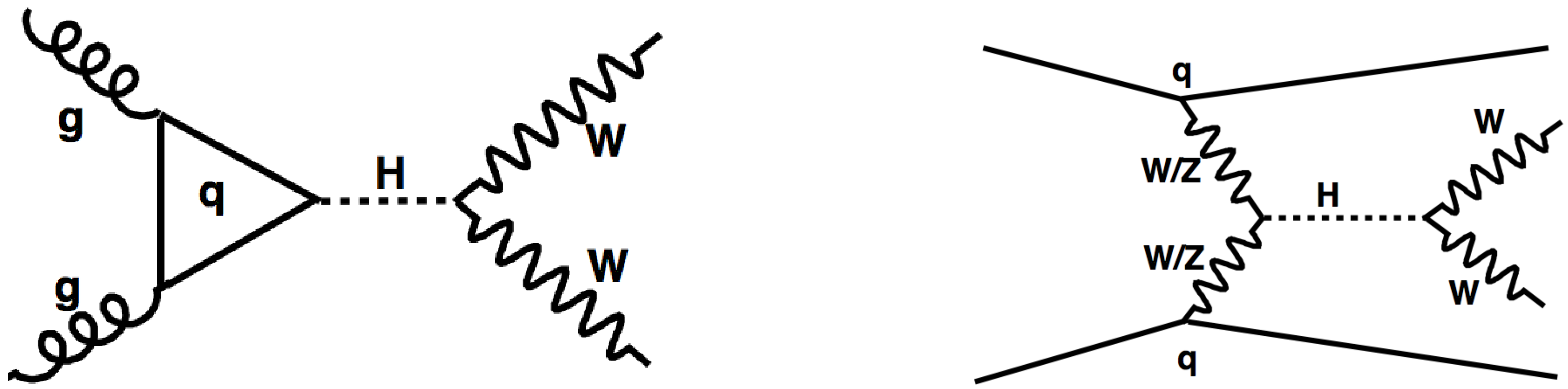


- No significant excess seen - analysis excludes region of MSSM parameter space consistent with Tevatron excess.

Heavy Higgs to WW

ATLAS, 13 fb^{-1} 8 TeV

- 2HDM: Assume 125 GeV Higgs is h and search for H→WW with 130 < m_H < 300 GeV

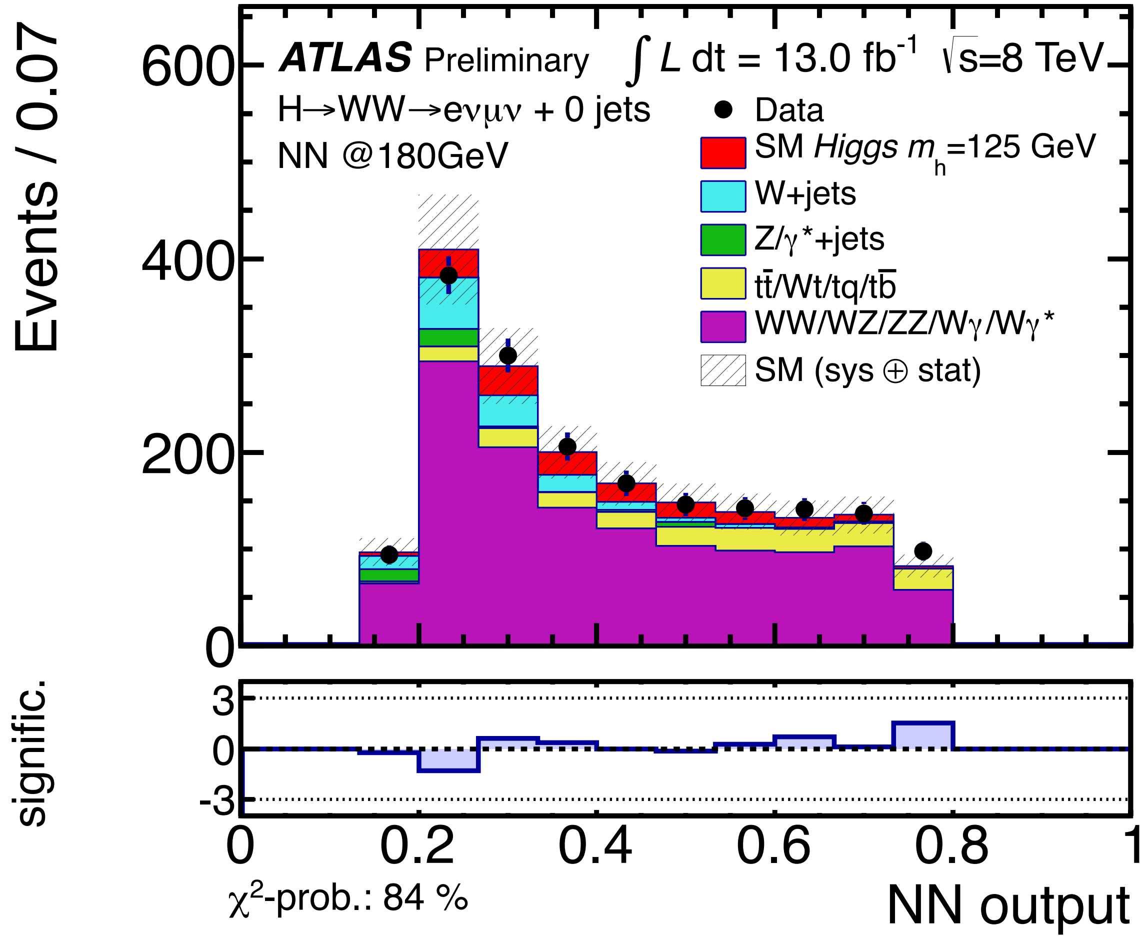


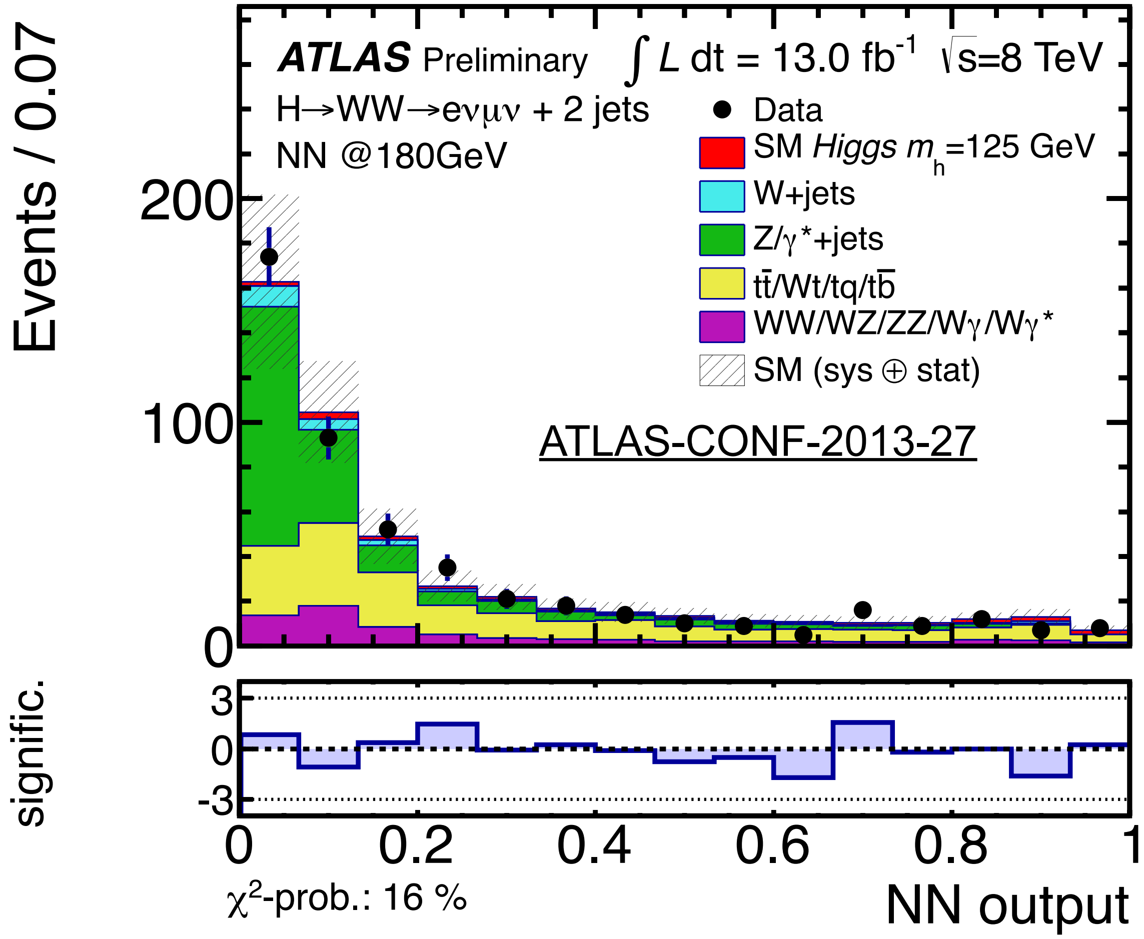
- Analysis selections similar to SM h→WW dilepton analysis with two sub-channels: 0-jet events and 2-jet events.
- Neural networks are then used to separate the Higgs signal from the SM diboson, W/Z+jets & top backgrounds.

Heavy Higgs to WW

ATLAS, 13 fb^{-1} 8 TeV

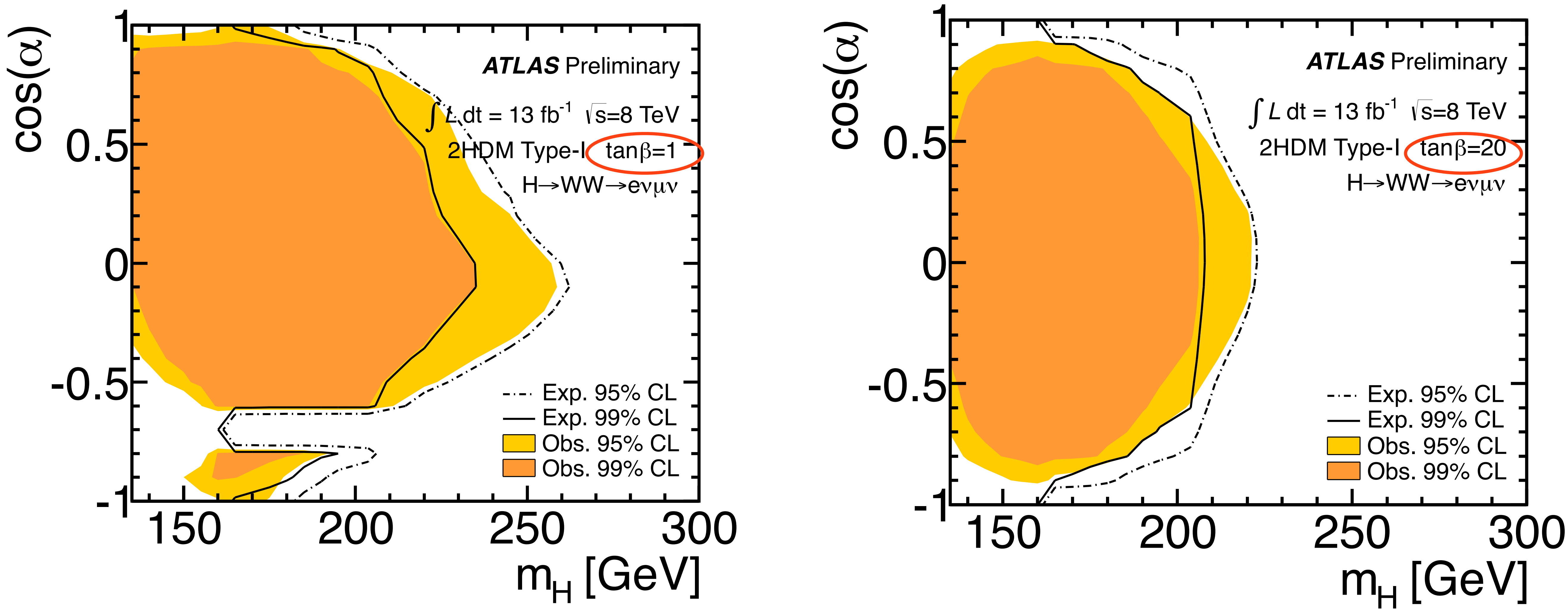
- No excess (other than 125 GeV Higgs!) seen in the signal region:





Heavy Higgs to WW

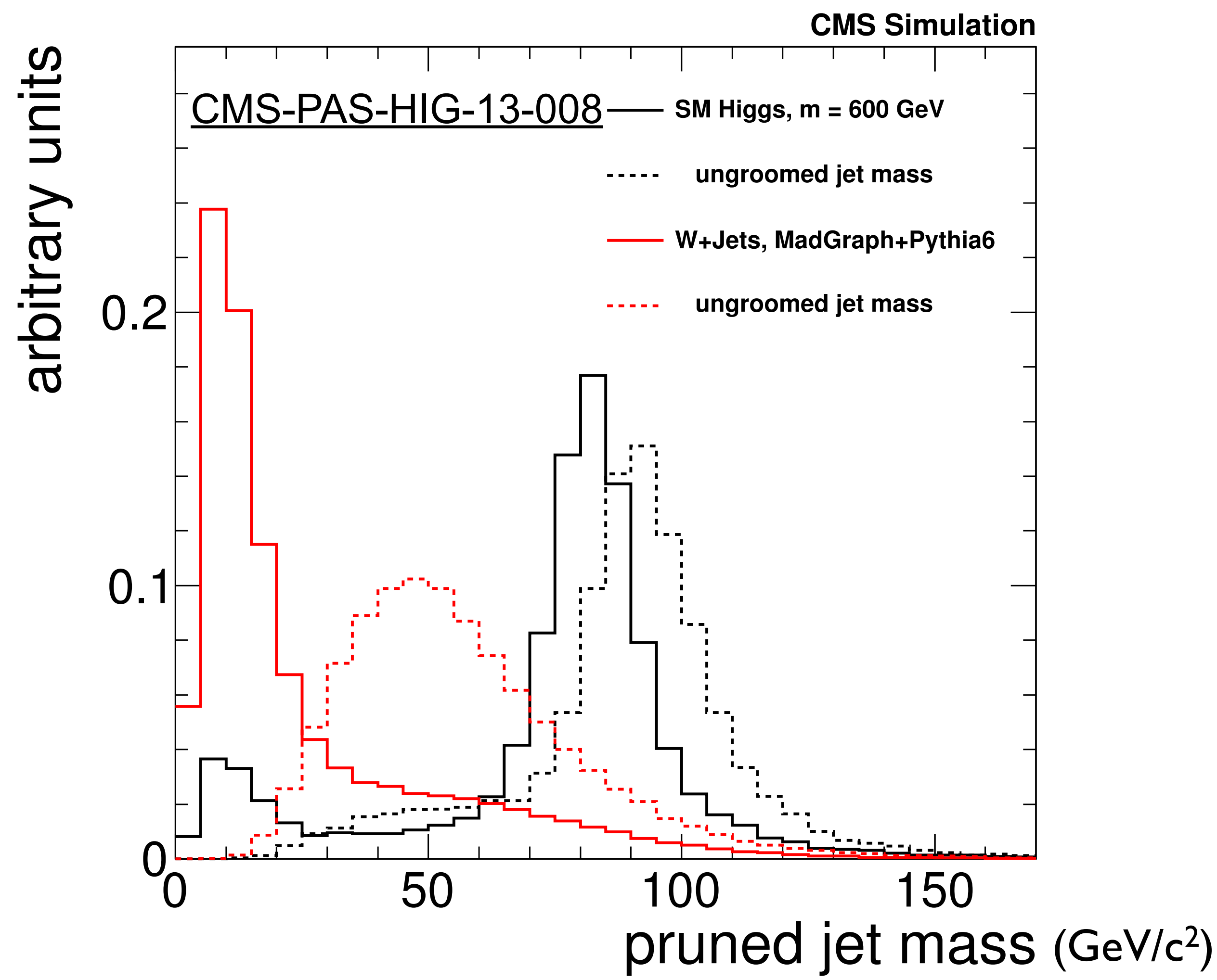
- Results are presented by scanning the angle α & m_H in Type I 2HDM:

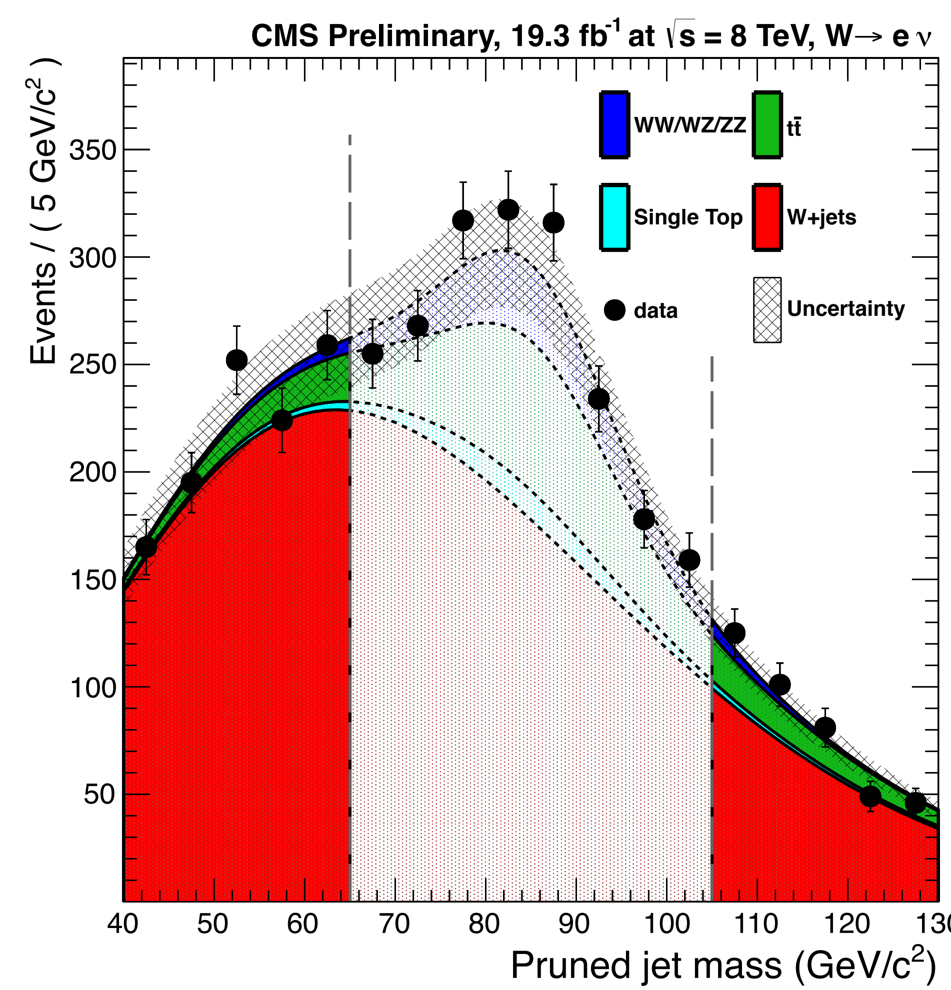


Heavy Higgs to WW

CMS, 19 fb^{-1} 8 TeV

- Search for heavy Higgs 600 GeV < m_H < 1 TeV, use hadronic decay mode of one W boson to maximise sensitivity.
- Higgs decays to high p_T W bosons - identify the hadronic W boson decay in a single large-radius jet, p_T > 200 GeV:

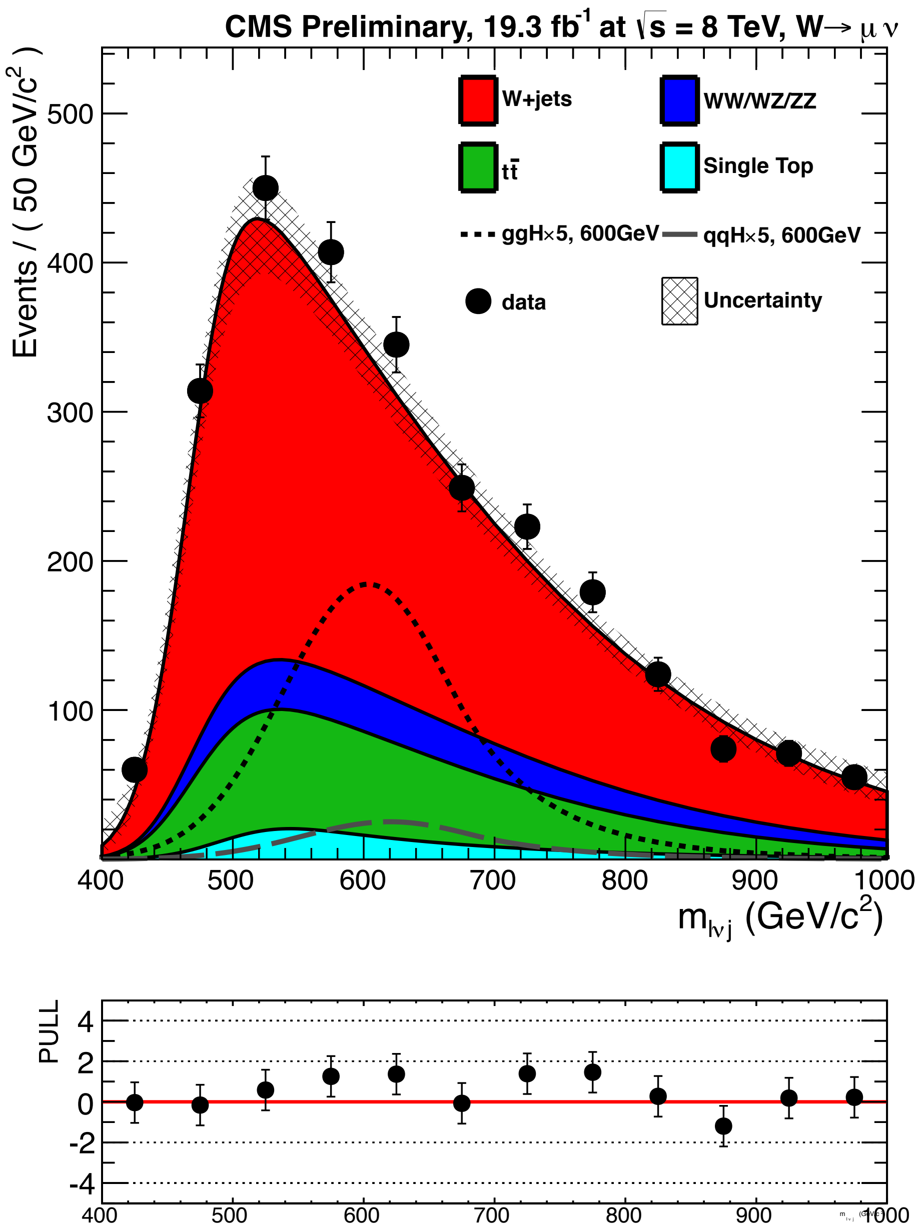


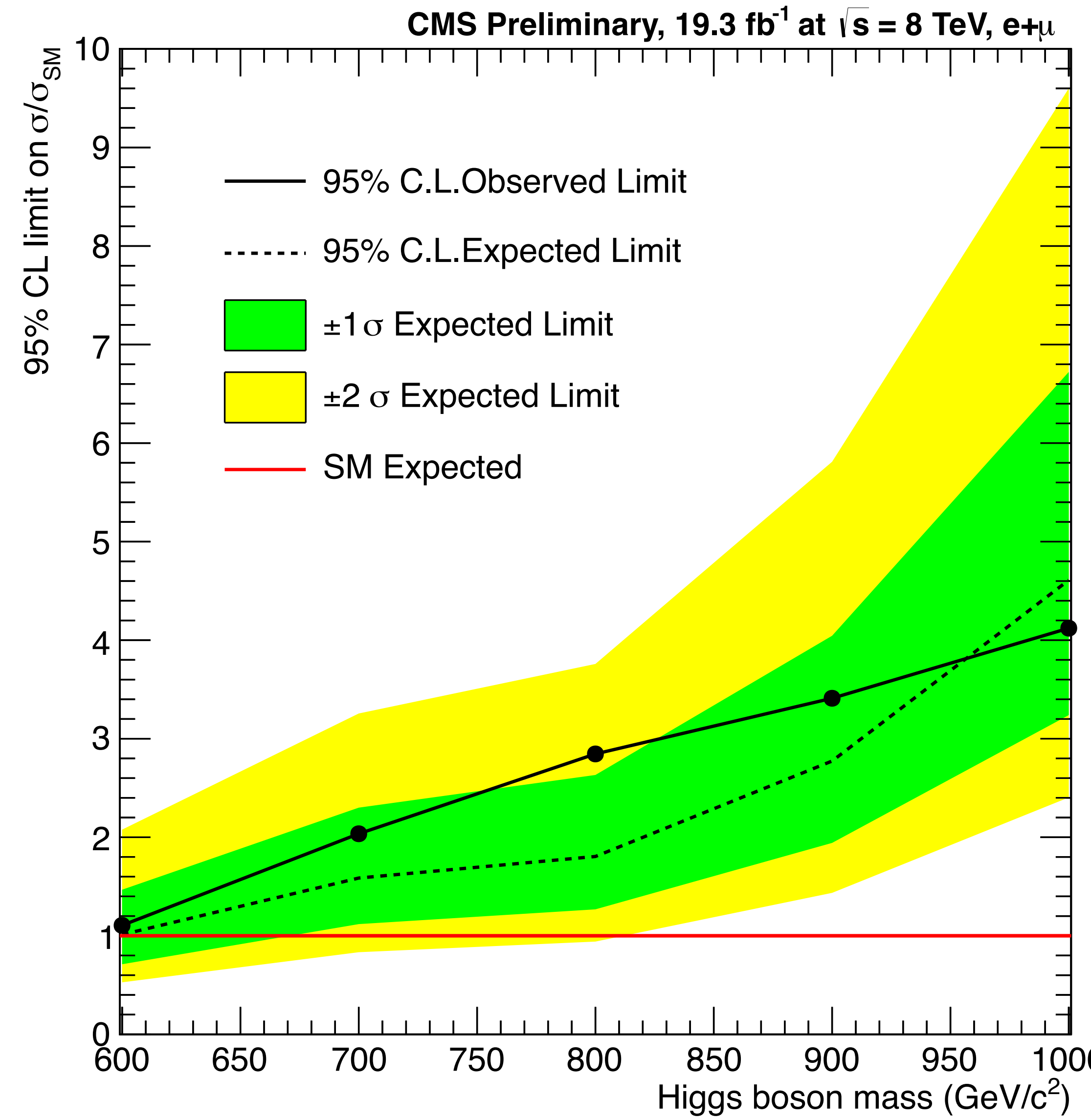


Heavy Higgs to WW

CMS, 19 fb^{-1} 8 TeV

- Search for heavy Higgs using invariant mass of the two reconstructed W bosons:





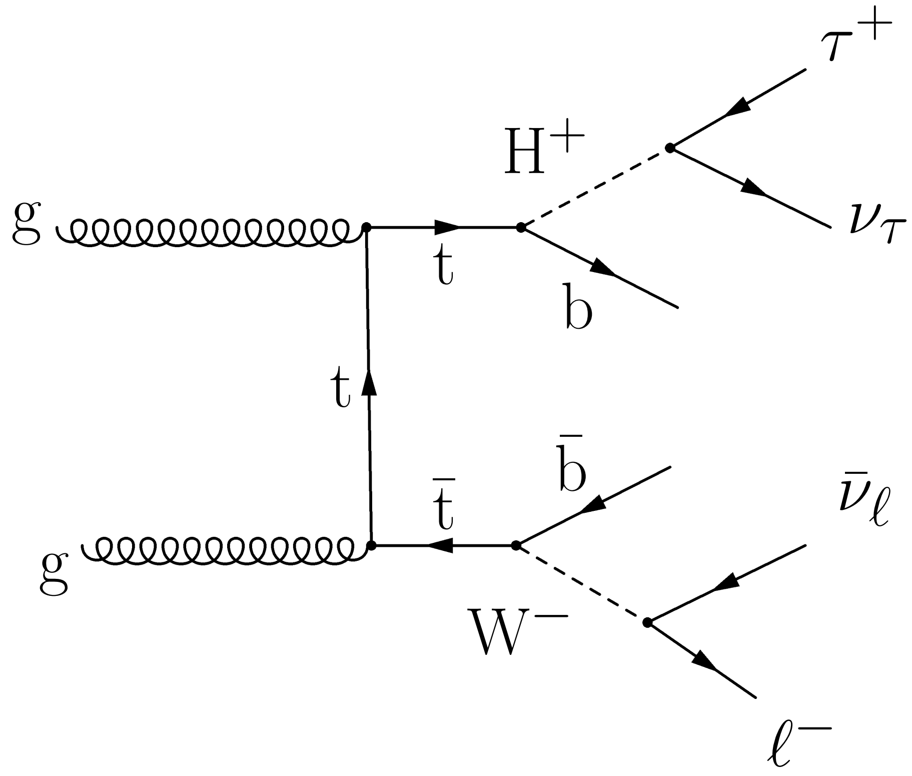
- Limit expressed as ratio to expected SM cross section.

Charged Higgs Searches

Charged Higgs

CMS, 2-5 fb^{-1} 7 TeV
ATLAS, 5 fb^{-1} 7 TeV

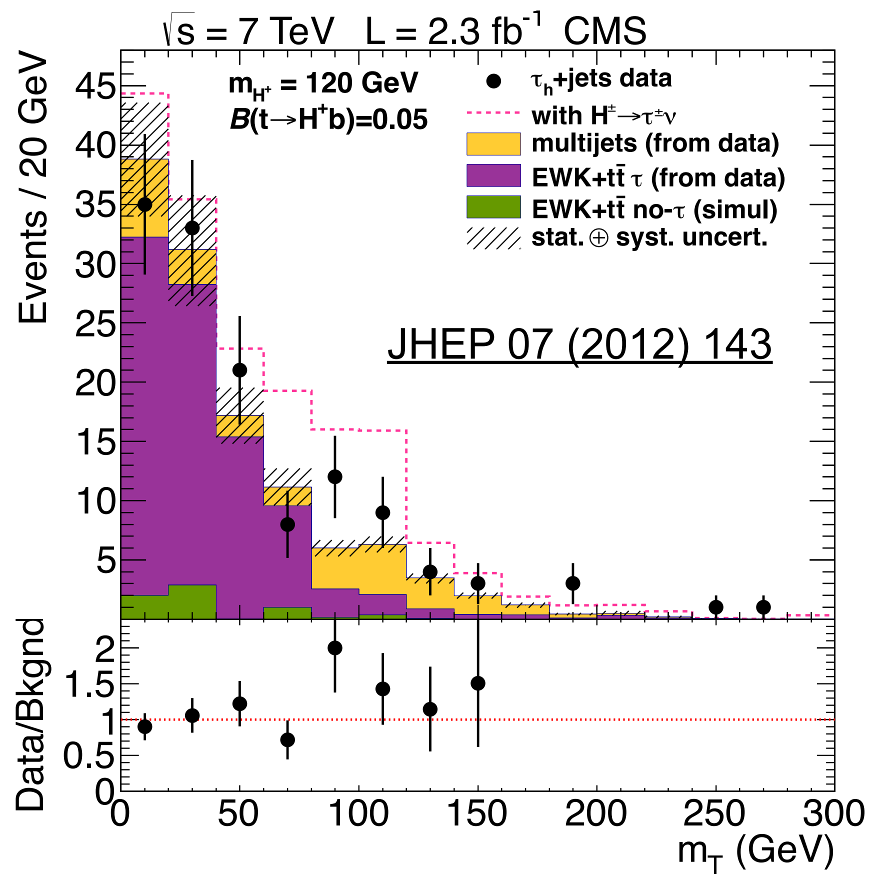
- For $m(H^+) < m(t) - m(b)$, the decay $t \rightarrow H^+ b$ is allowed.
- Decay $H^+ \rightarrow \tau\nu$ favoured, e.g. in MSSM with large tanβ.

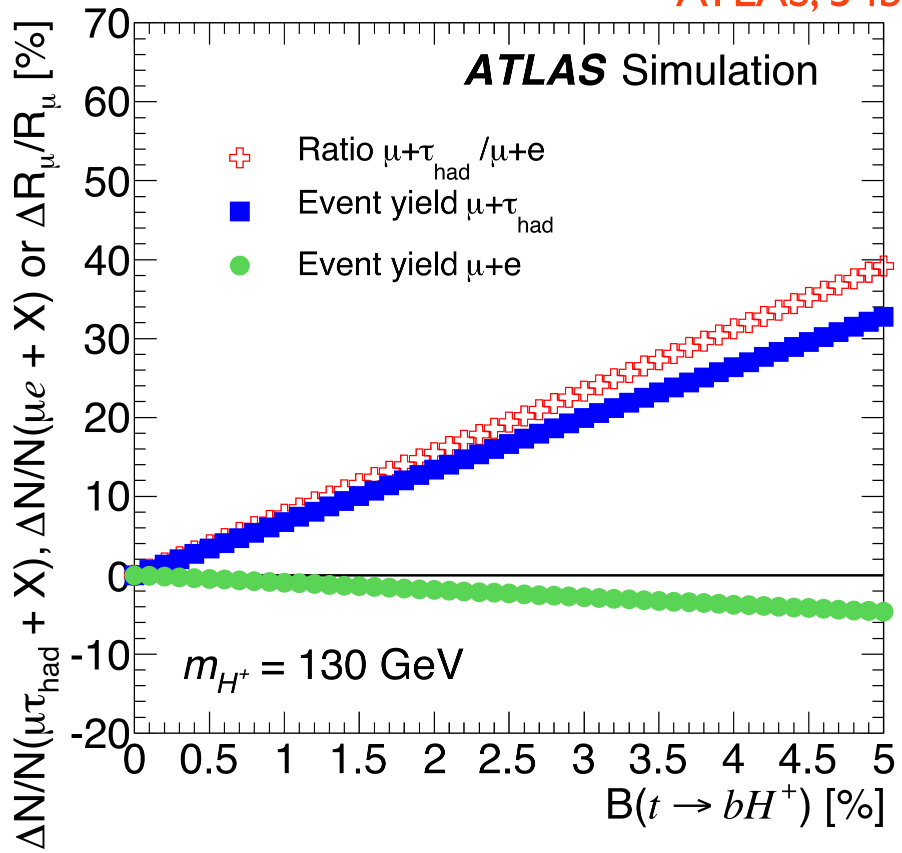


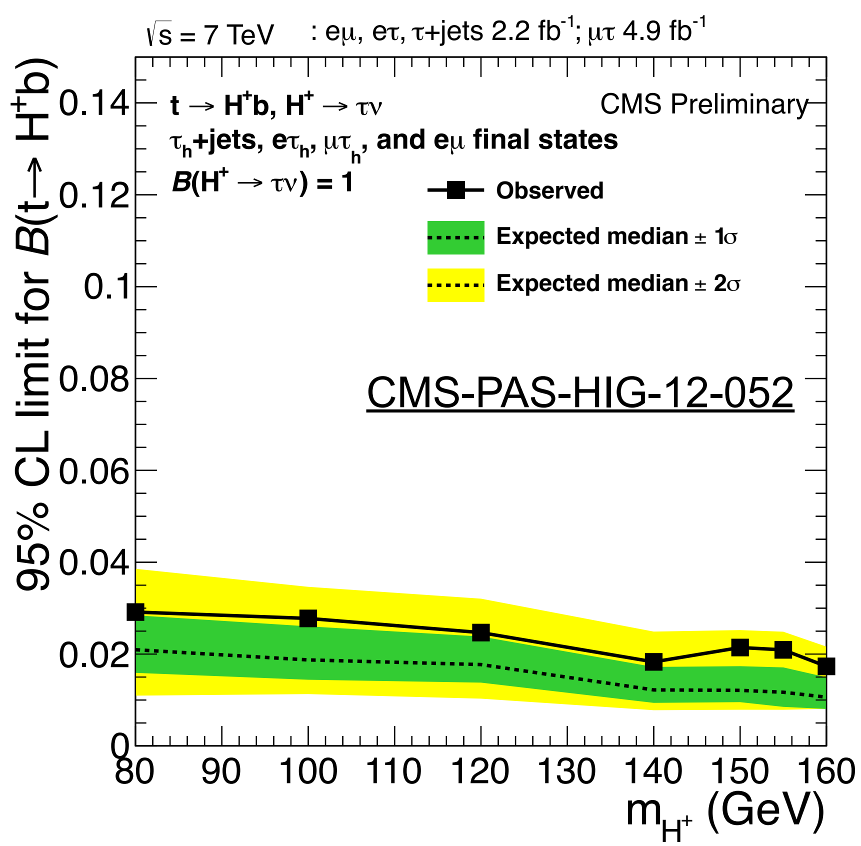
- Both experiments select top-like events with tau decays:
    - Use event yields & exploit kinematic properties - ATLAS & CMS.
    - Measure ratio (e or μ + τ) / (e + μ) - ATLAS.

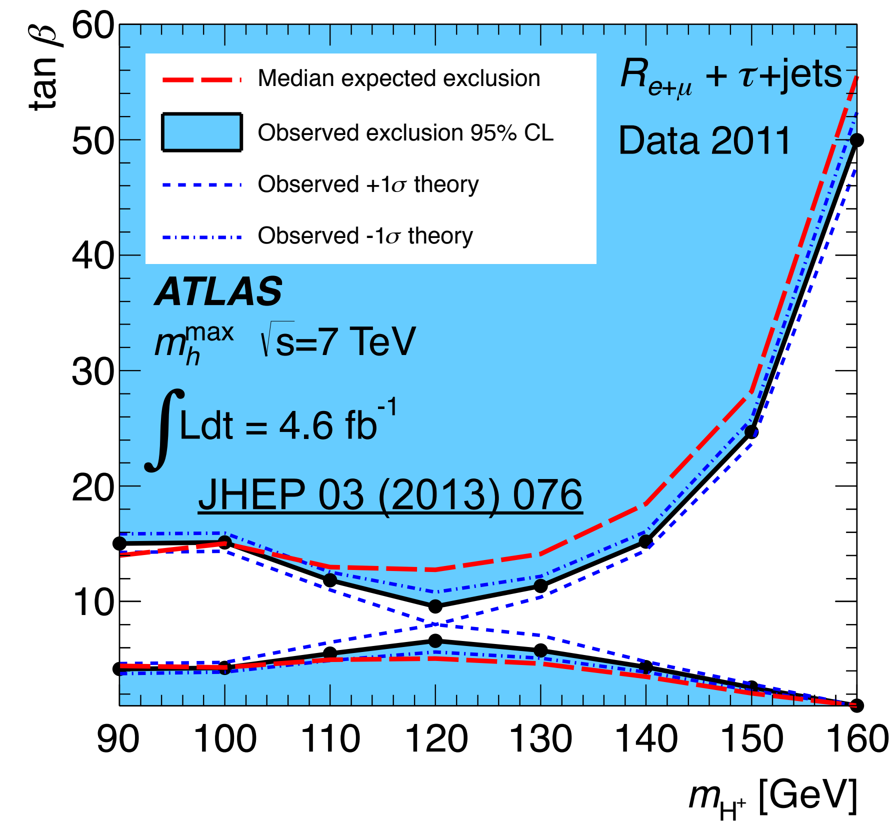
Charged Higgs

CMS, 2-5 fb^{-1} 7 TeV
ATLAS, 5 fb^{-1} 7 TeV





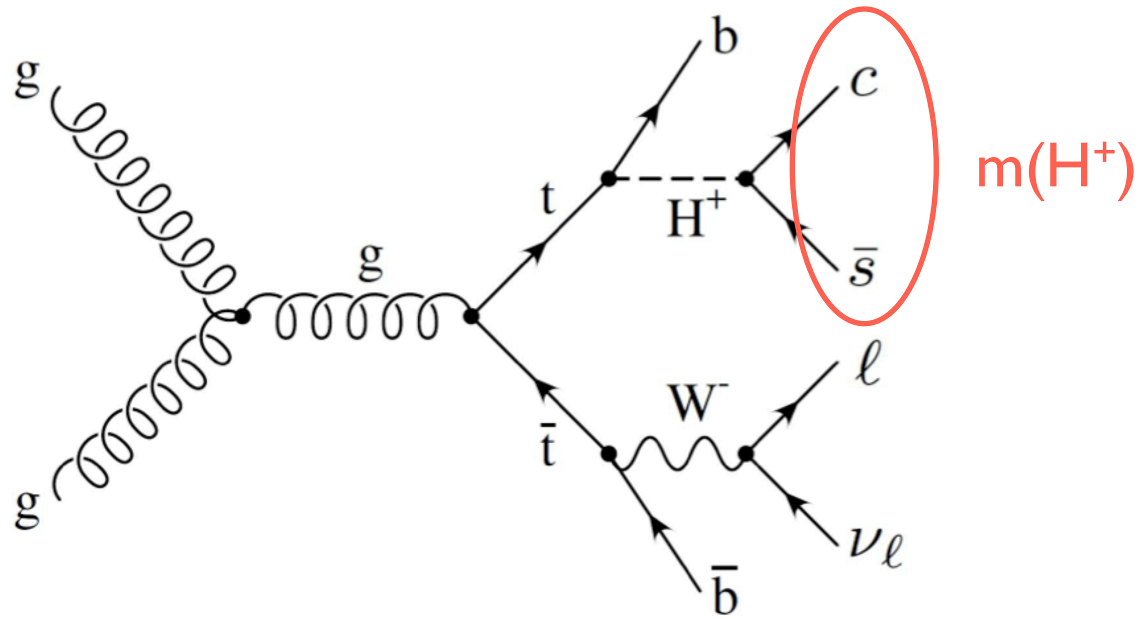


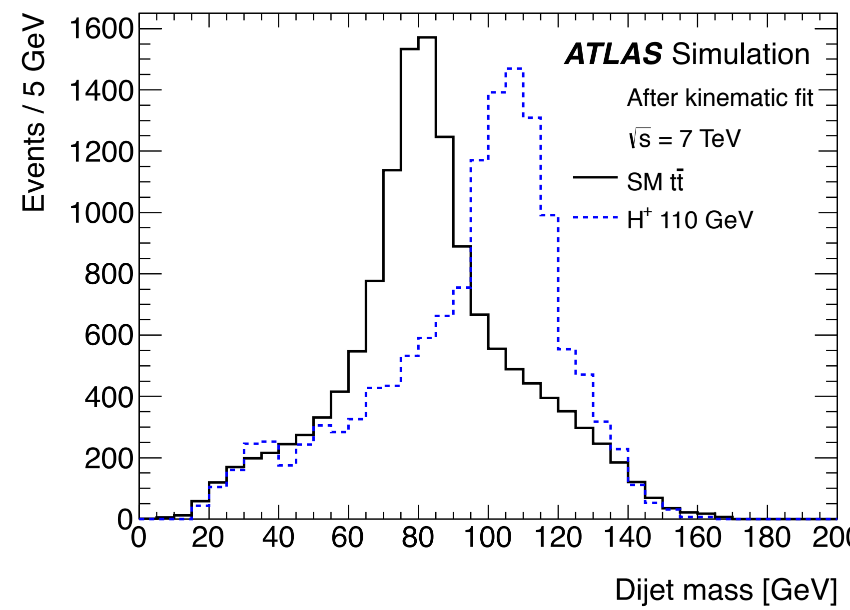


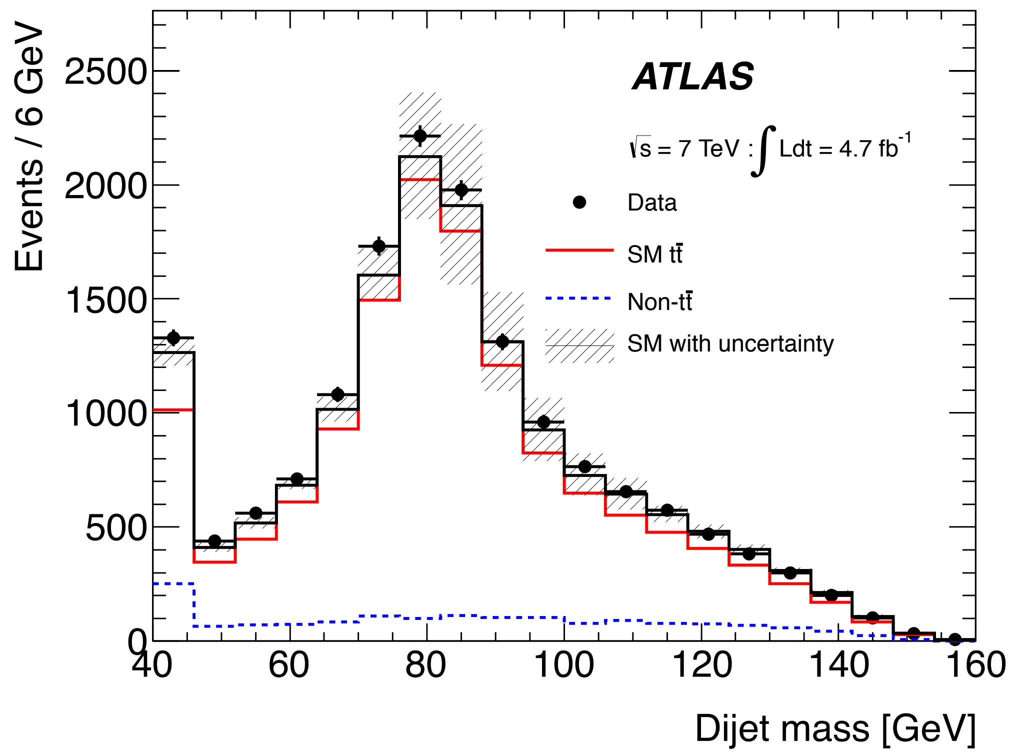
Charged Higgs

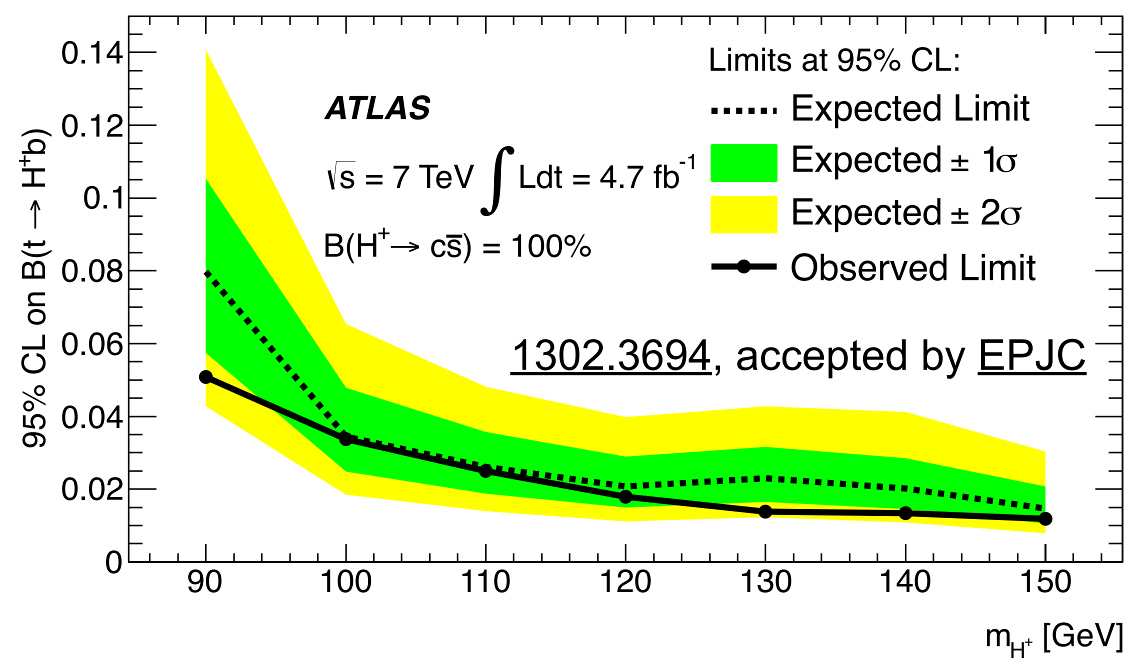
ATLAS, 5 fb^{-1} 7 TeV

- Decay $H^+ \to c\bar{s}$ also possible.
- Search for additional peak in dijet mass spectrum in top events.









Summary

- Active search programme underway at LHC for BSM neutral and charged Higgs bosons.
- No evidence of BSM Higgs found.
- Searches are limiting parameter space available for BSM models.
- Full 8 TeV dataset not fully analysed in most channels.
- Many results still to come - stay tuned.

Backup

Two Higgs Doublet Models

- Different doublets can couple to different quarks & leptons, avoiding flavour changing neutral currents

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

MSSM is Type II

	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	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

$$\xi_h^{VV} \propto \sin(\beta-\alpha)$$
$$\xi_H^{VV} \propto \cos(\alpha-\beta)$$

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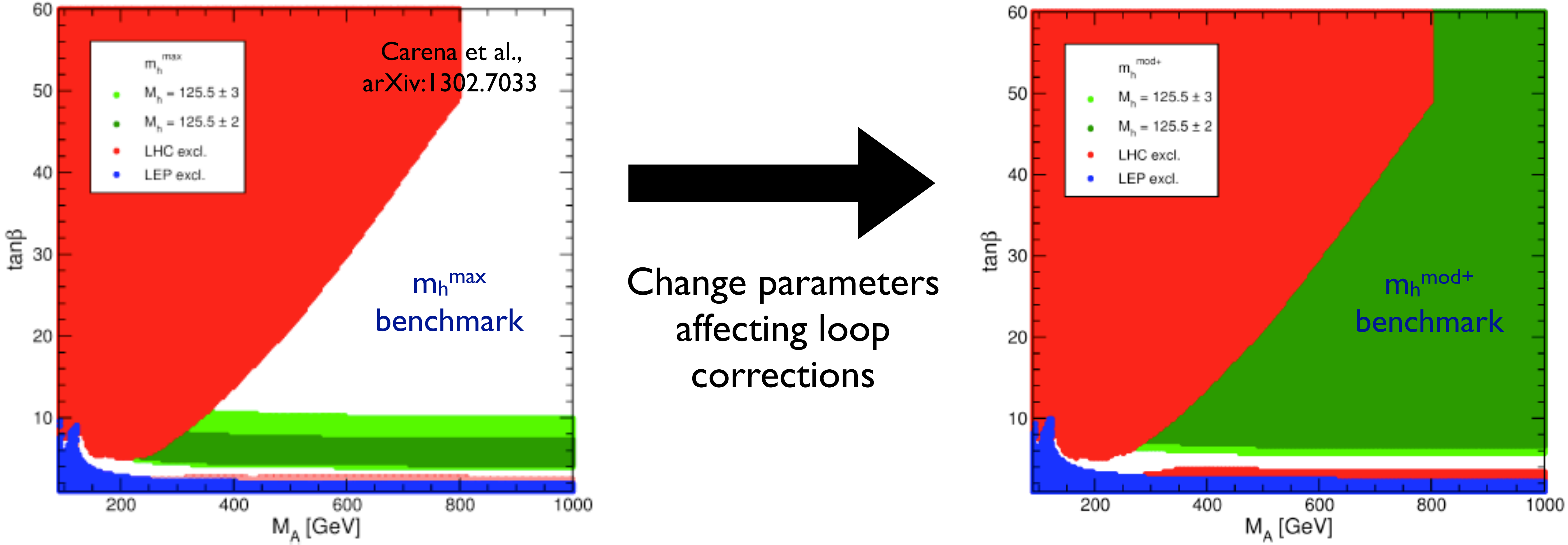
Is this still interesting?

- Many interesting studies on extended Higgs sector in view of the discovery @ 125 GeV, example for MSSM:



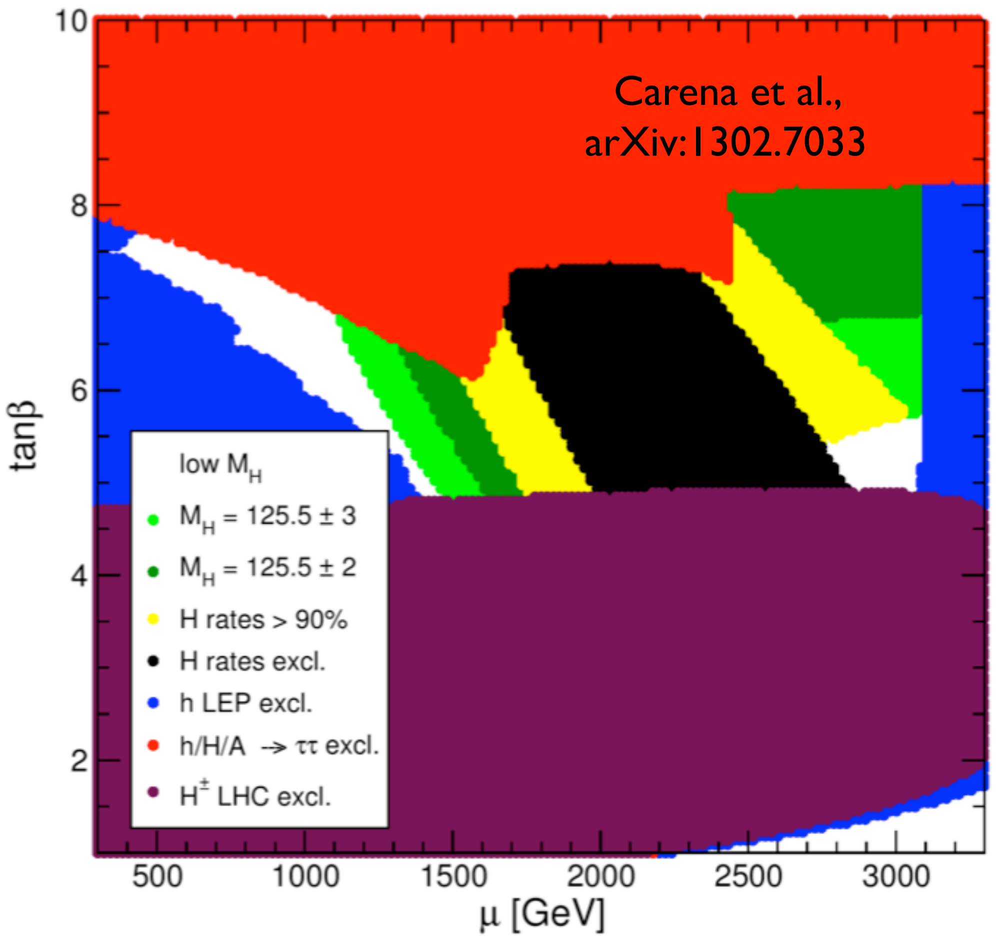
- BSM Higgs models still very relevant for the observed Higgs boson. Given h is SM-like - ‘decoupling’ regime is important:

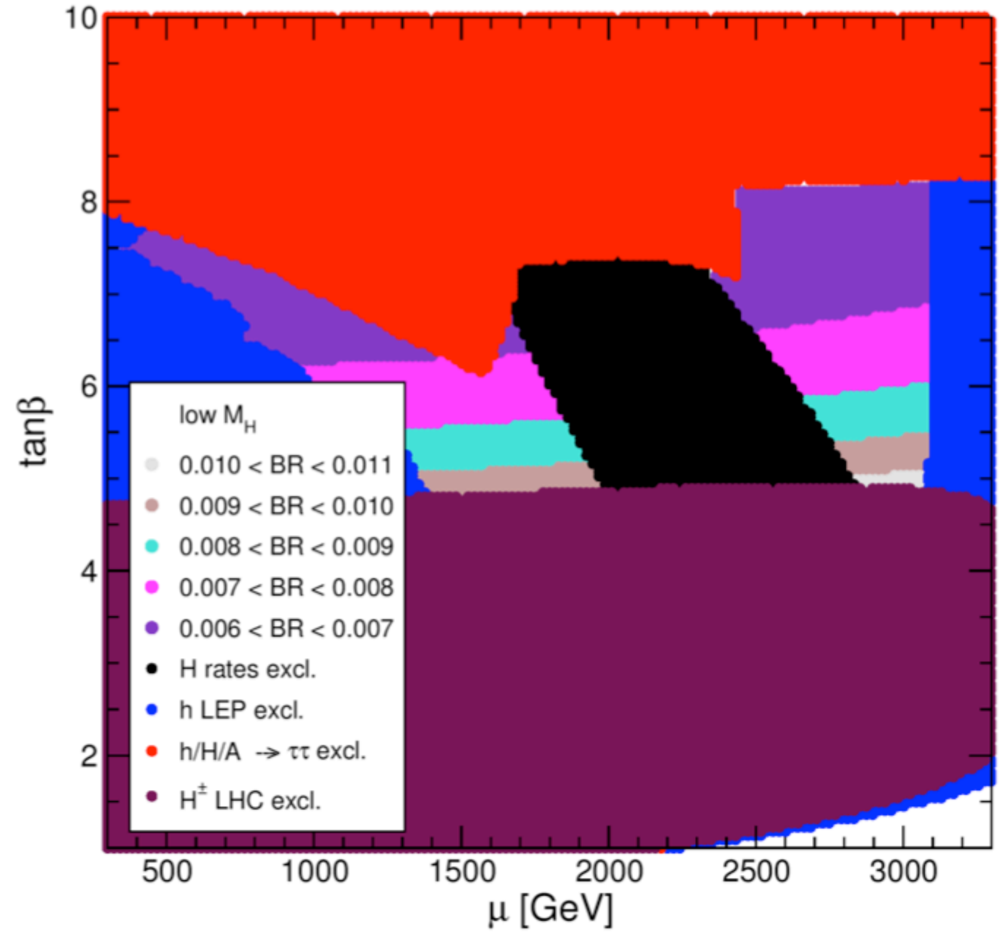
$$m_A, m_H \gg m_h$$

- For MSSM - higher order corrections matter.

Is this still interesting?

- MSSM parameter set with H as the boson discovered at LHC:

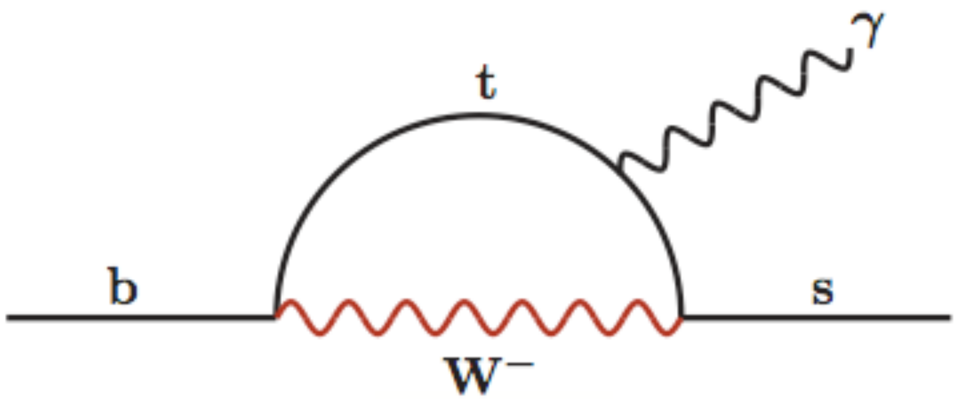


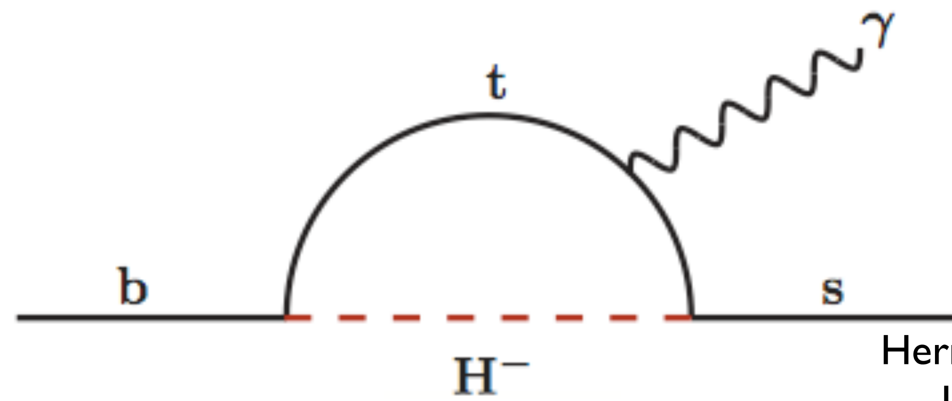


$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_A &= 110 \text{ GeV}, \\
M_{\text{SUSY}} &= 1500 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 2.45\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= 2.9\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b = A_\tau &= A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned}
$$

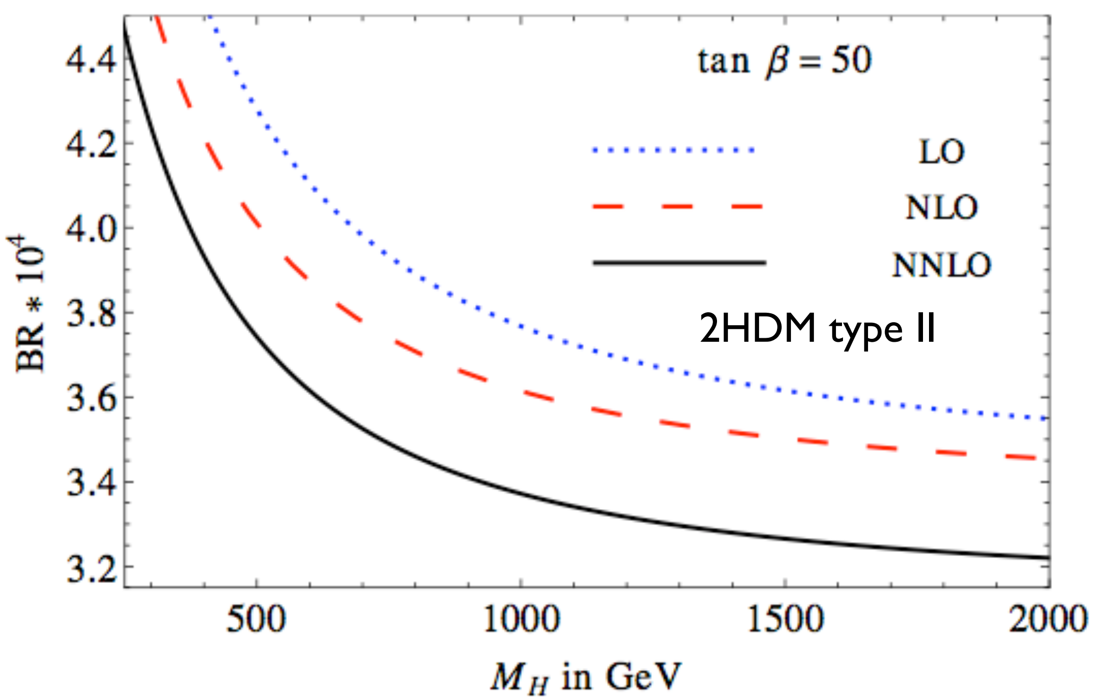
B physics constraints

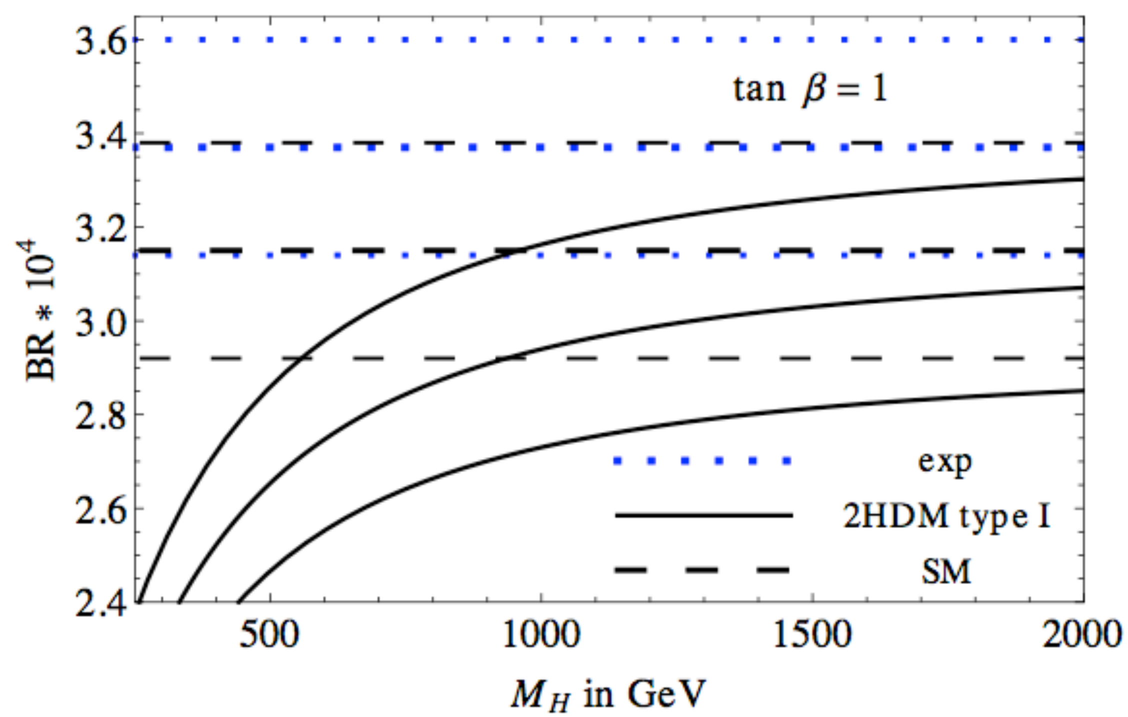
- B physics observables provide constraints on 2HDM, e.g.:





Hermann, Misiak, Steinhauser,
JHEP 1211 (2012) 036



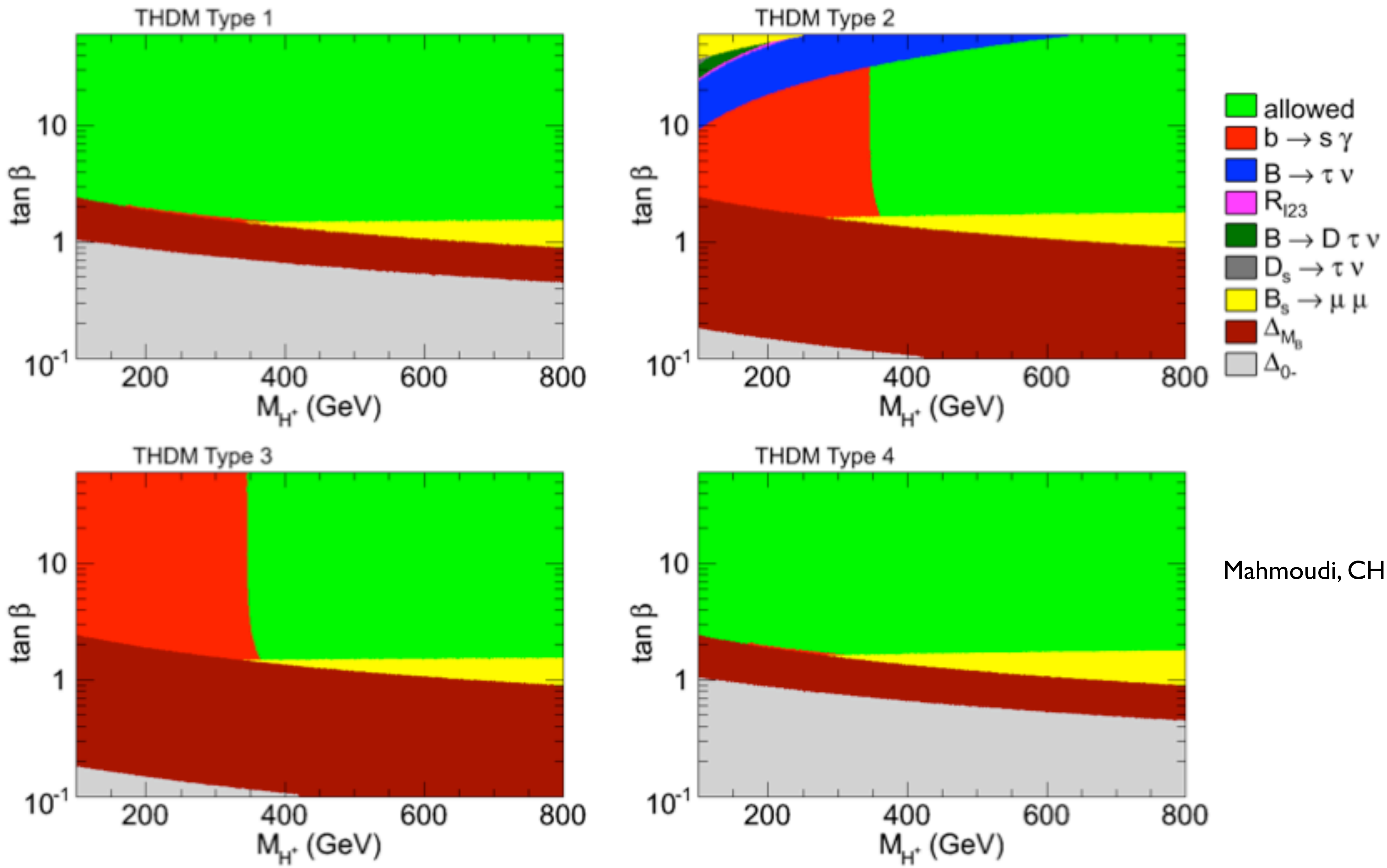


Experimental values (HFAG 2012): $\mathrm{BR}(\bar{B} \to X_s\gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$

- Limits depend on other particles in the loop, e.g. in SUSY models.

B physics constraints

- B physics observables provide constraints on 2HDM:



Mahmoudi, CHiggs 2012

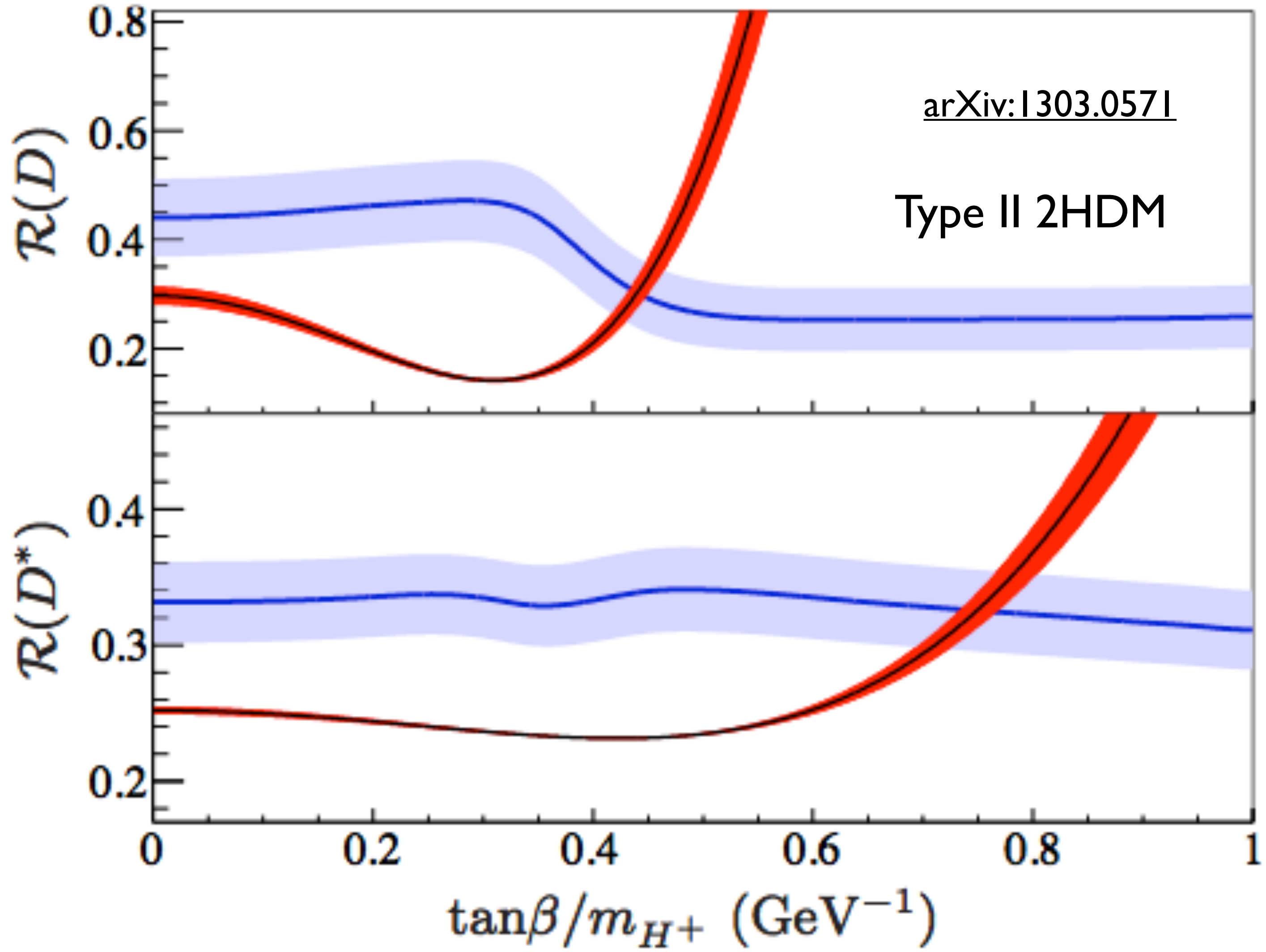
B physics constraints

- BaBar D→$\tau\nu$ measurement:

$$\mathcal{R}(D) = \frac{\mathcal{B}(\overline{B} \to D\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D\ell^-\overline{\nu}_\ell)}, \quad \mathcal{R}(D^*) = \frac{\mathcal{B}(\overline{B} \to D^*\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^*\ell^-\overline{\nu}_\ell)}.$$

$$\mathcal{R}(D)_{\rm exp} = 0.440 \pm 0.072 \quad \mathcal{R}(D^*)_{\rm exp} = 0.332 \pm 0.030,$$
$$\mathcal{R}(D)_{\rm SM} = 0.297 \pm 0.017 \quad \mathcal{R}(D^*)_{\rm SM} = 0.252 \pm 0.003,$$

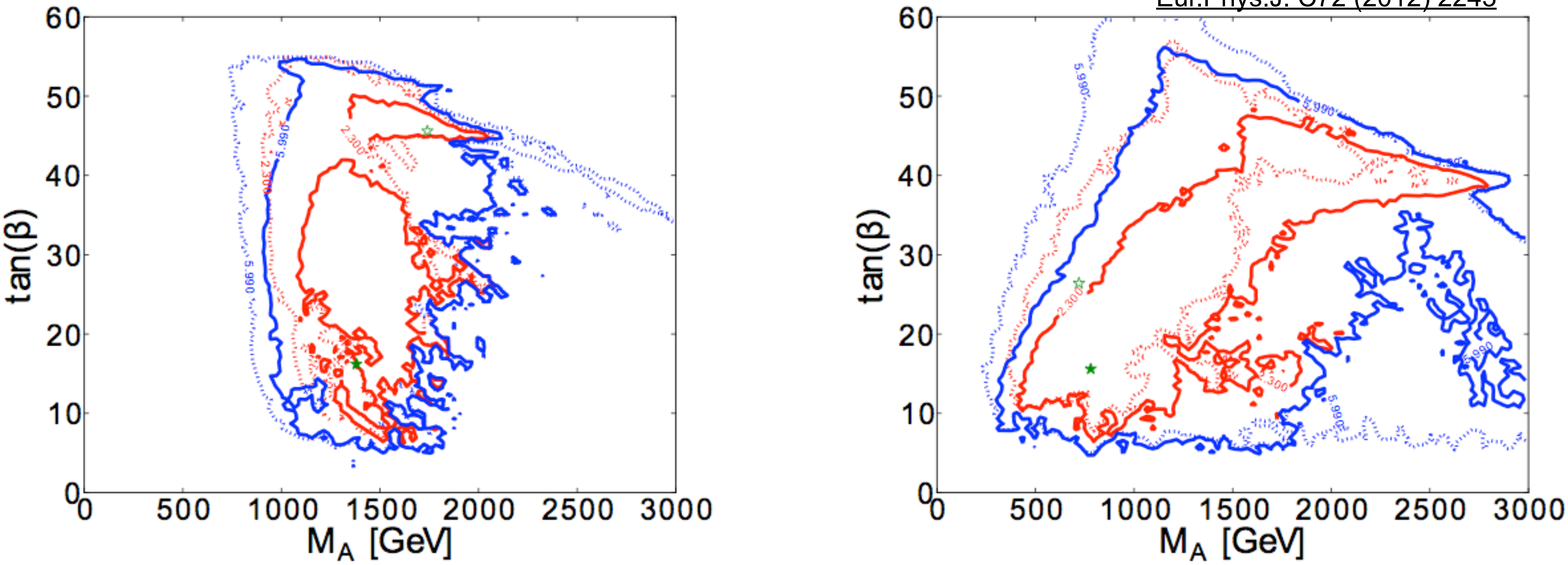
3.4σ from SM



SUSY Parameter Scans

- Parameter scans in CMSSM and NUHM1, including constraints from m_h=125 GeV Higgs, LHC direct searches, $B_s \to \mu\mu$, $(g-2)_\mu$, $b \to s\gamma$, $B \to \tau\upsilon$:

Buchmueller et al., Eur.Phys.J. C72 (2012) 2243



Neutral Higgs to Tau Pairs

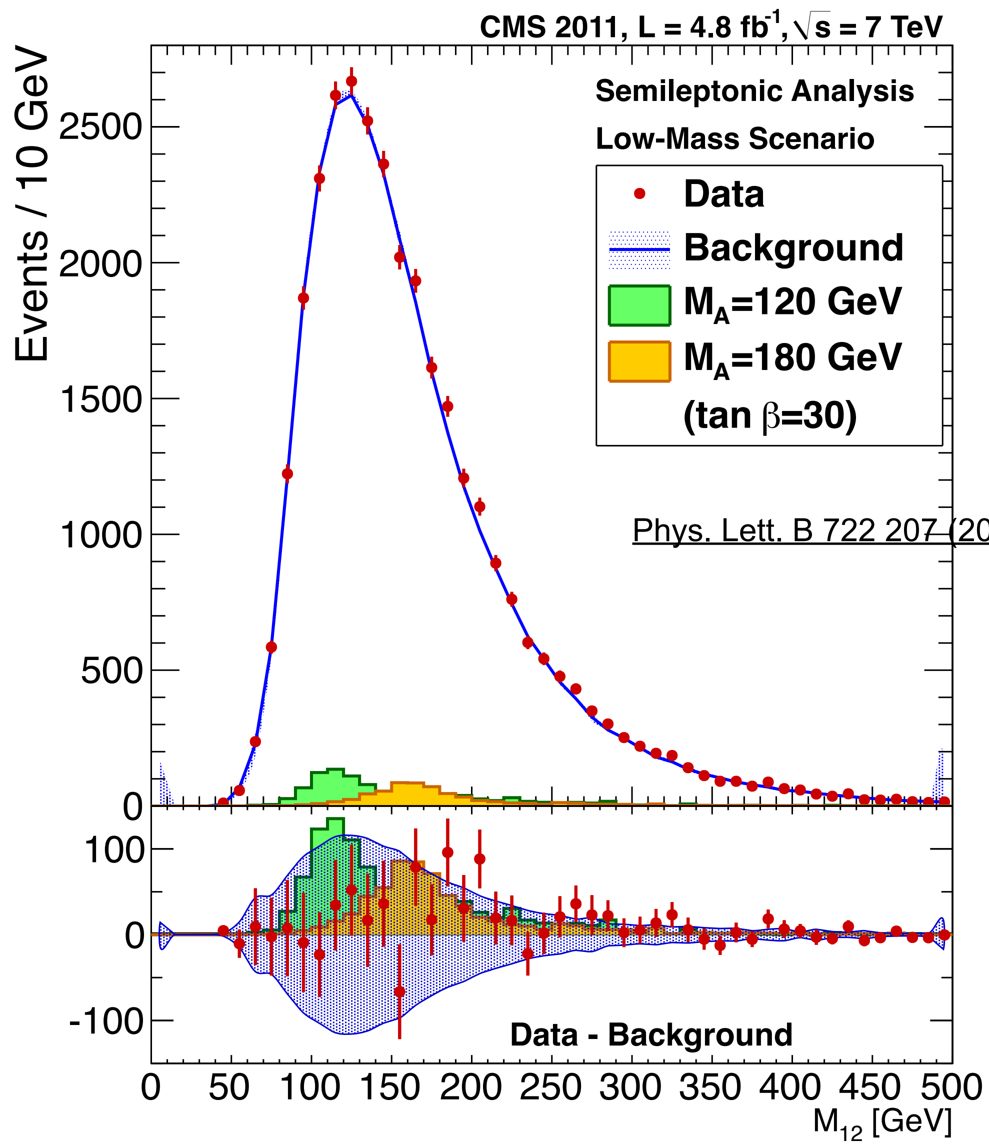
CMS, 12 fb^{-1} 8 TeV, 5 fb^{-1} 7 TeV
ATLAS, 5 fb^{-1} 7 TeV

- ATLAS mass reconstruction (Missing Mass Calculator):
  - Scan over angles between neutrinos & visible tau decay products & weight each mass with PDF from simulation.
  - Resolution of 13-20%.
- CMS mass reconstruction:
  - Maximise likelihood built from measured tau momenta, missing transverse energy, kinematic constraints and expected PDF of tau transverse momentum.
  - Resolution of 15-20%.

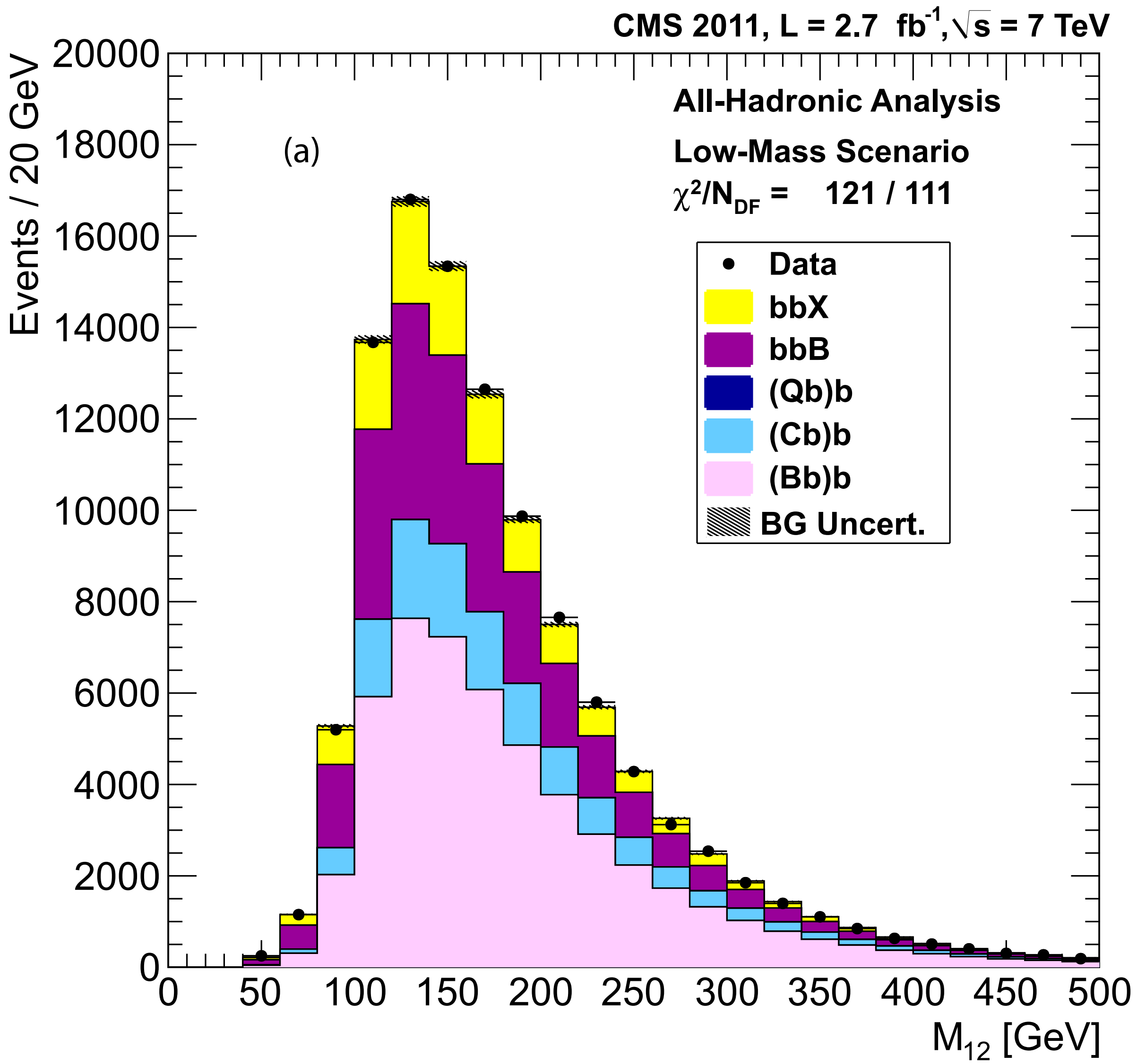
Neutral Higgs to b Quark Pairs

- Recent analysis by CMS in the same final state, using multijet and muon + jet triggers.

CMS 2-5 fb^{-1} 7 TeV



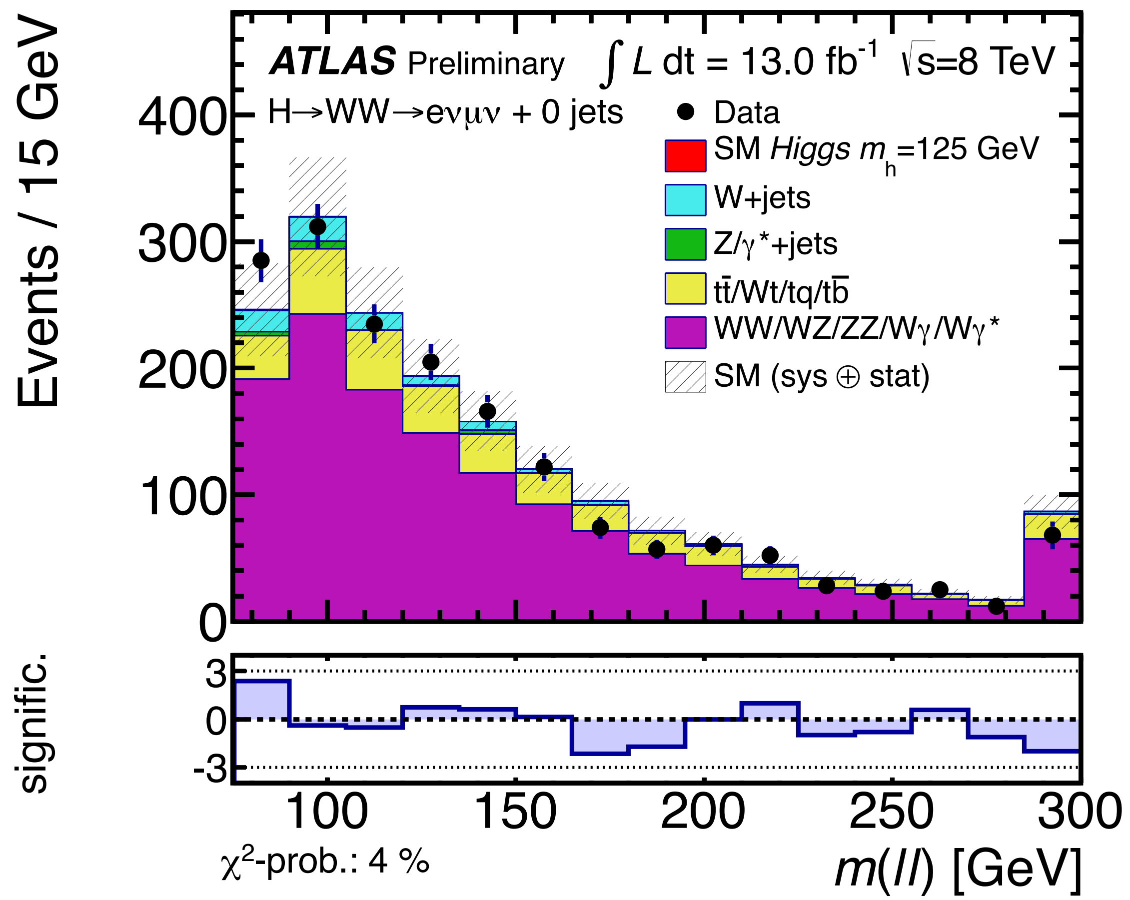
Phys. Lett. B 722 207 (2013)

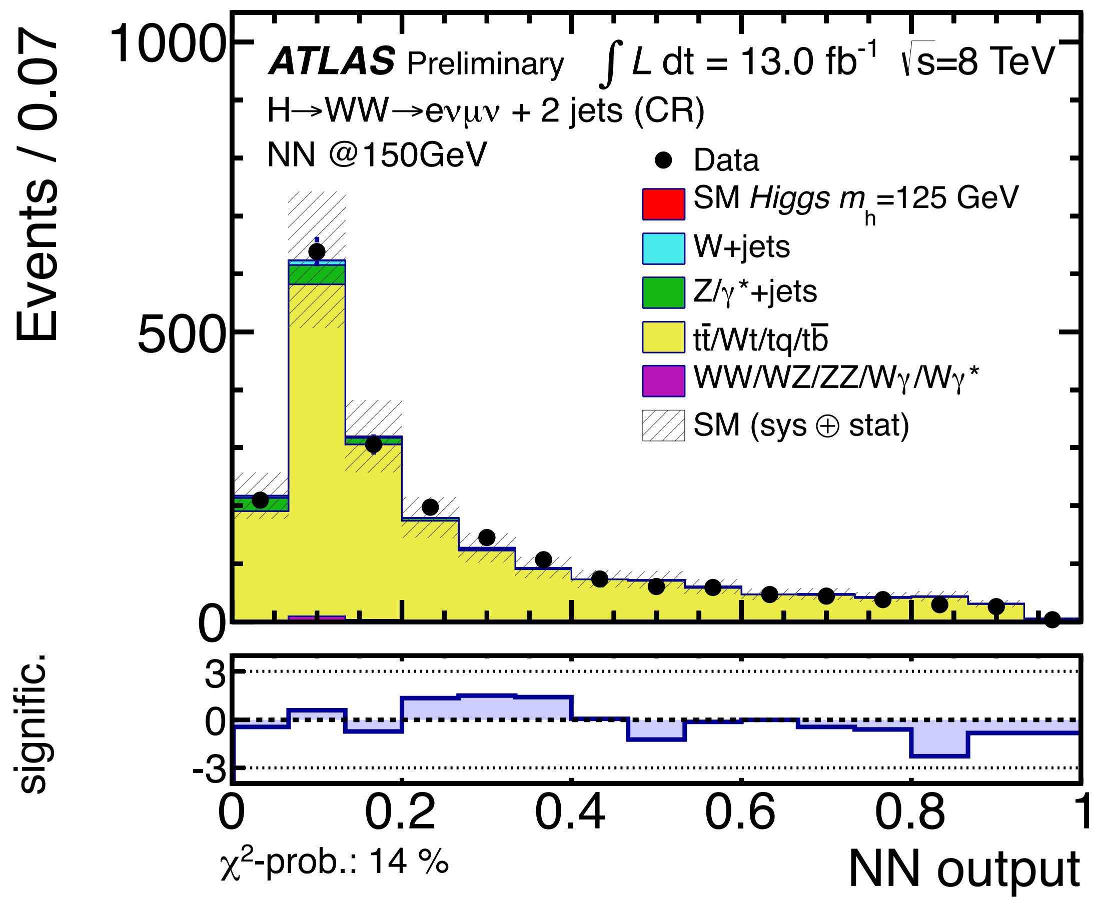


Heavy Higgs to WW

ATLAS, 13 fb^{-1} 8 TeV, 5 fb^{-1} 7 TeV

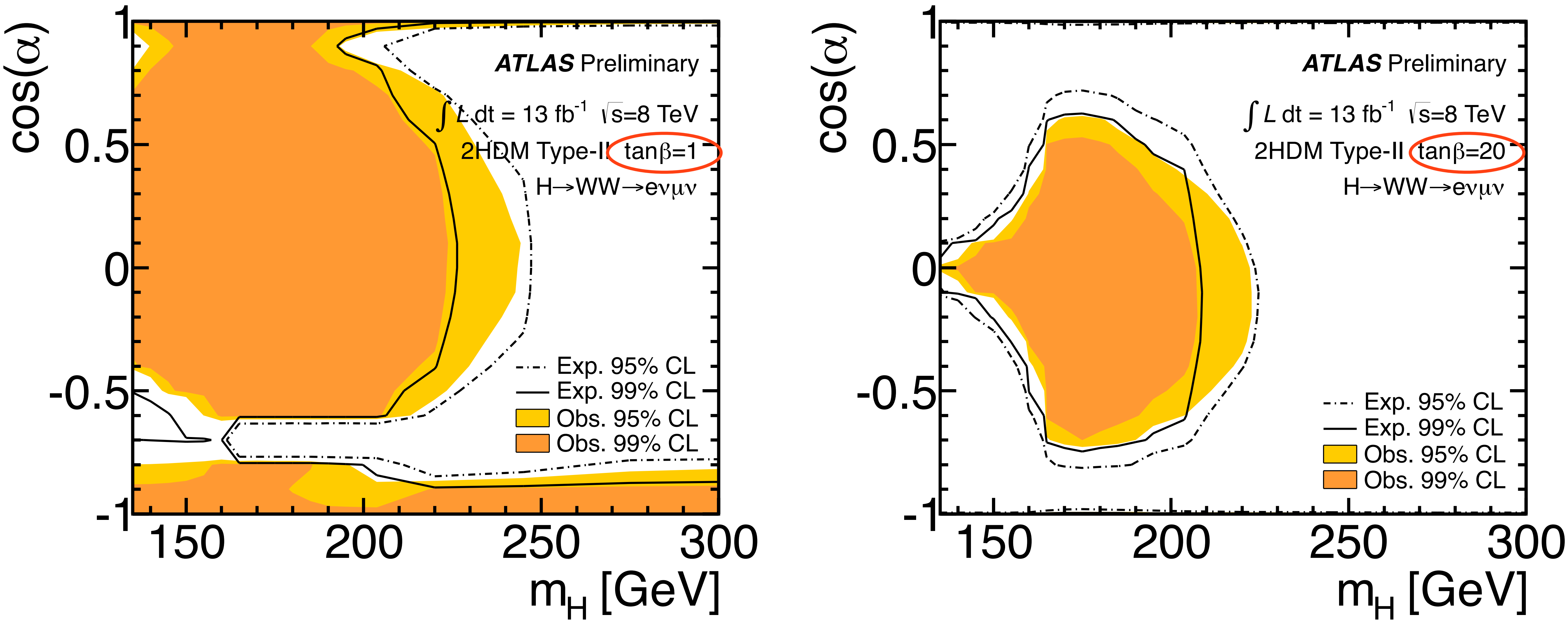
- Background models are tested in diboson & top control regions:





Heavy Higgs to WW

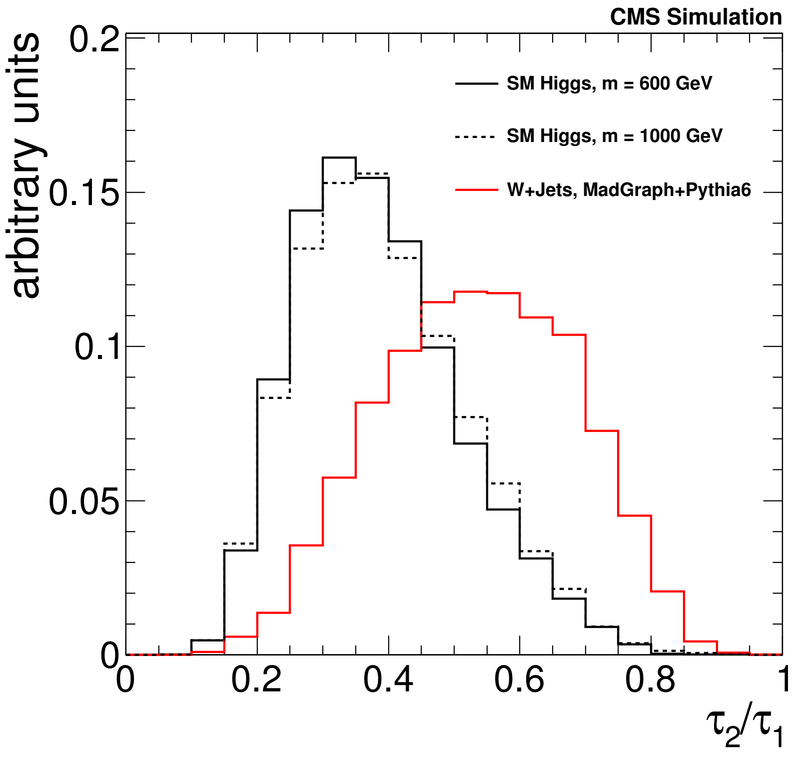
- Results are presented by scanning the mixing angle α & m_H in Type II 2HDM:

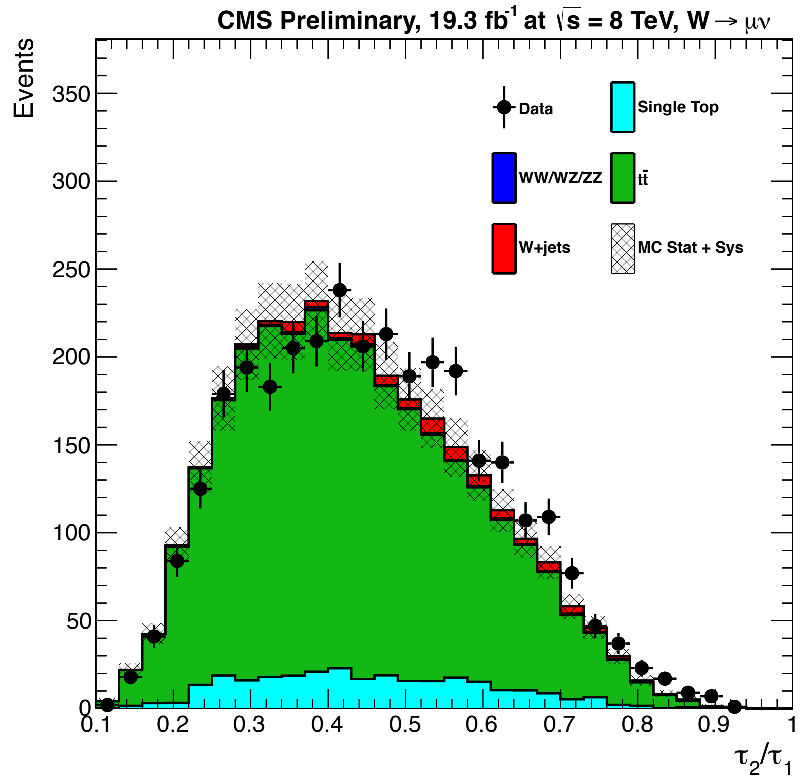


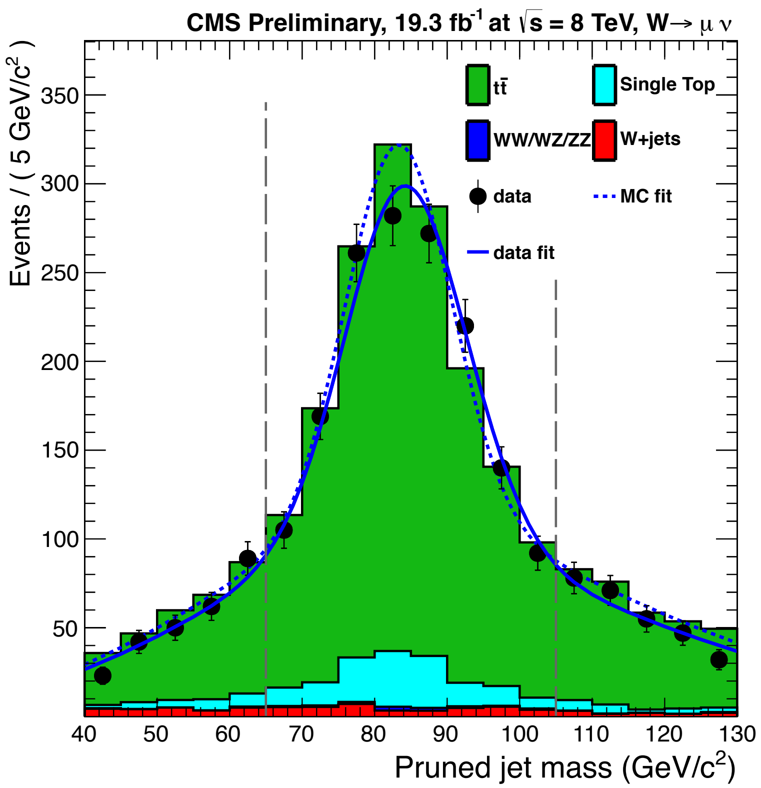
Heavy Higgs to WW

CMS, 19 fb^{-1} 8 TeV

- Control boosted jet finding with top control region:







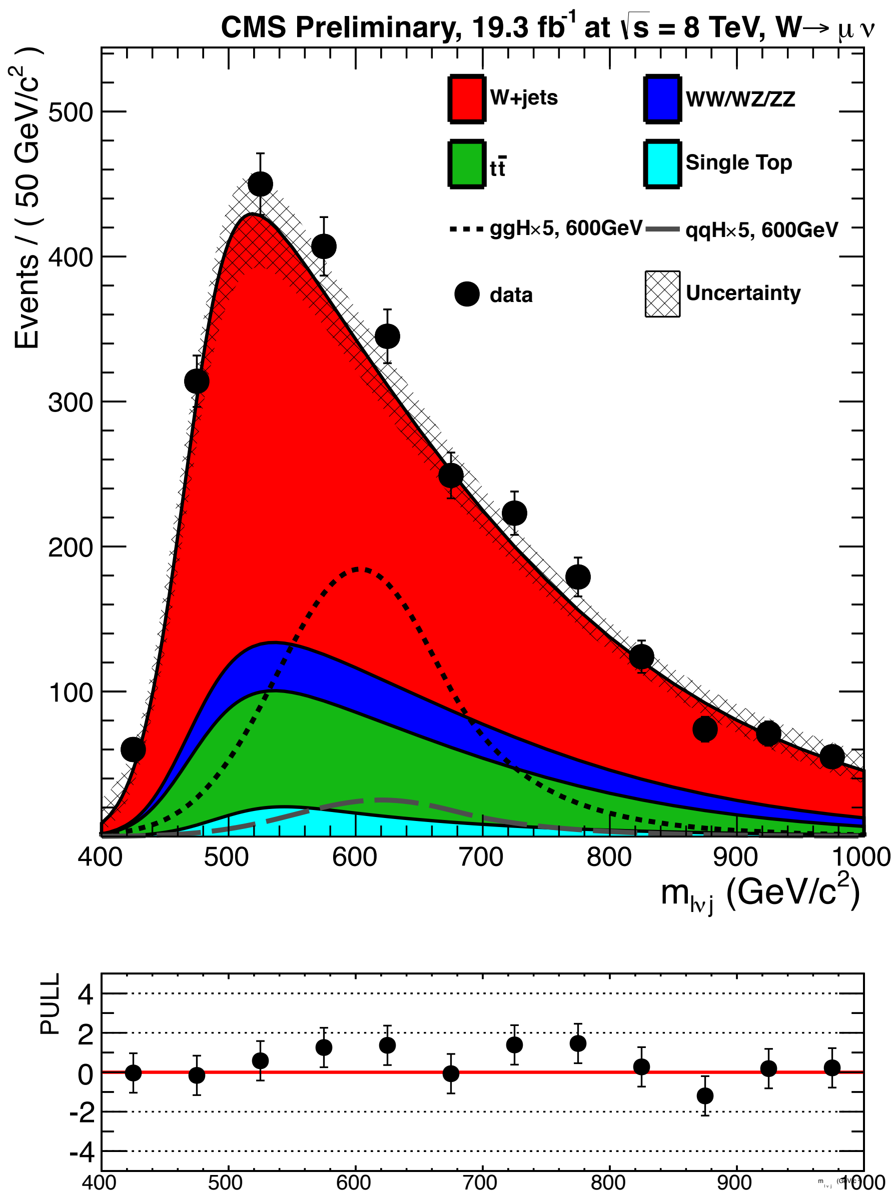
$$\tau_N = \frac{1}{d_0}\sum_i p_{T,i}\min\{(\Delta R_{1,i})^\beta, (\Delta R_{2,i})^\beta, ..., (\Delta R_{N,i})^\beta\}$$

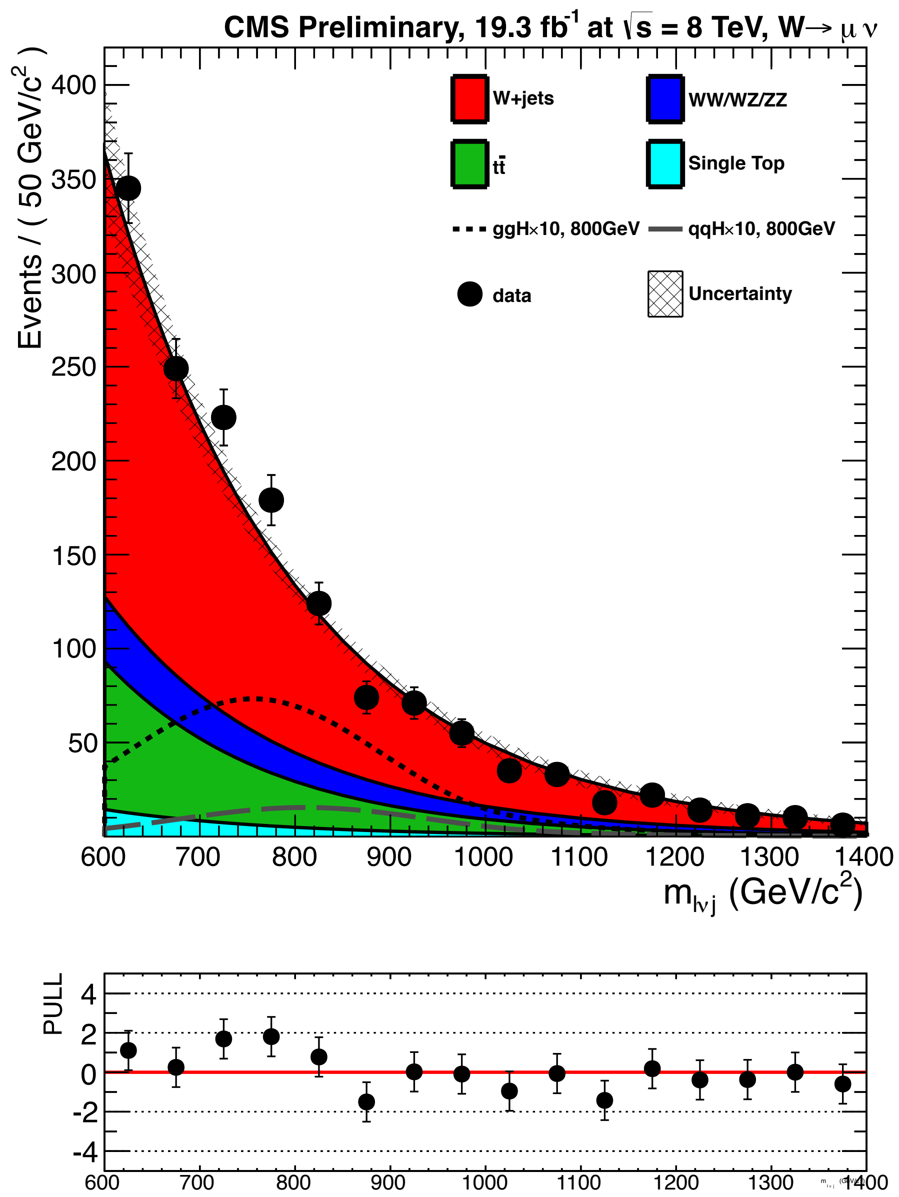
$$d_0 = \sum_i p_{T,i}(R_0)^\beta$$

Heavy Higgs to WW

CMS, 19 fb^{-1} 8 TeV

- Search for heavy Higgs using invariant mass of the two reconstructed W bosons:

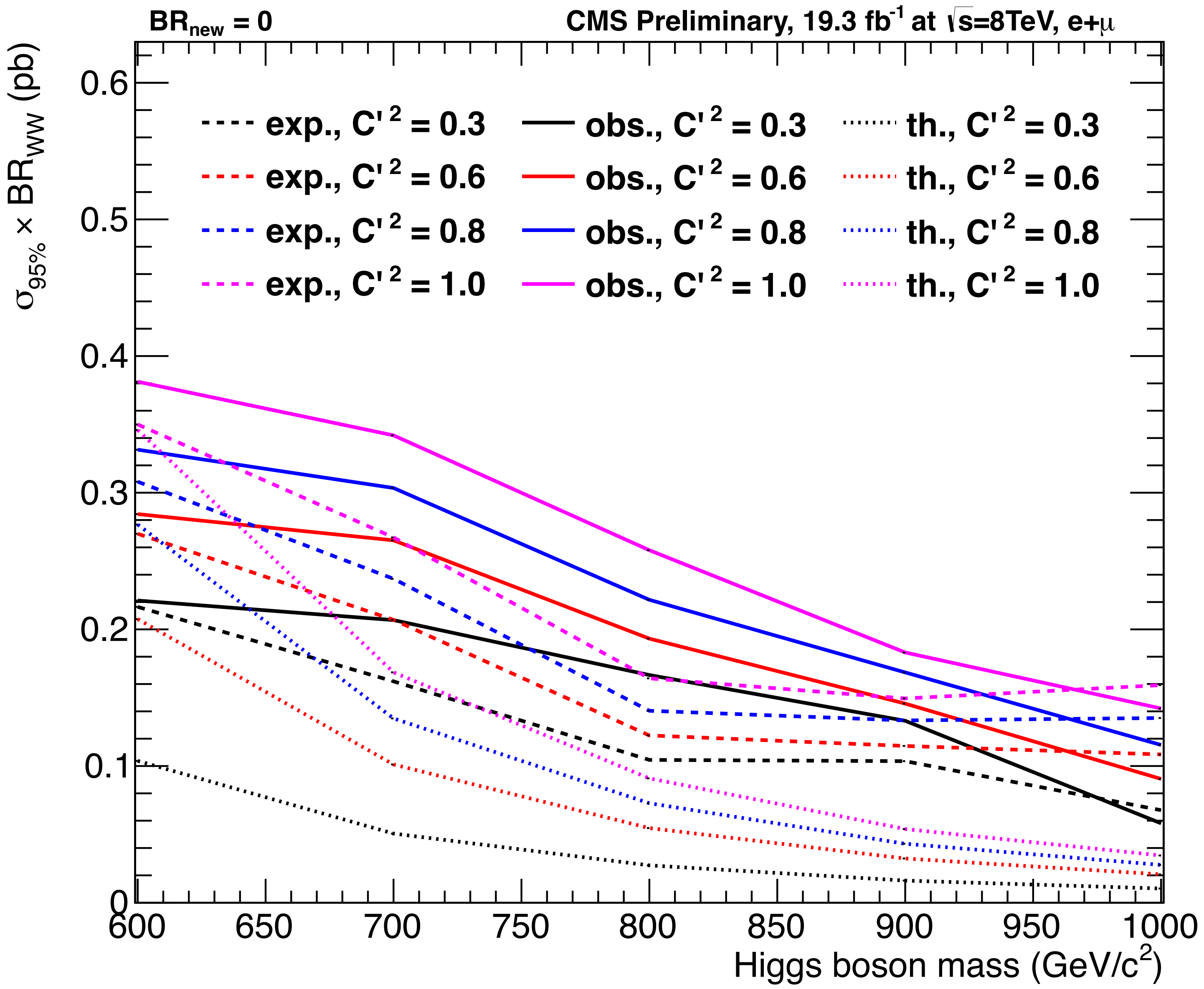




Heavy Higgs to WW

CMS, 19 fb^{-1} 8 TeV

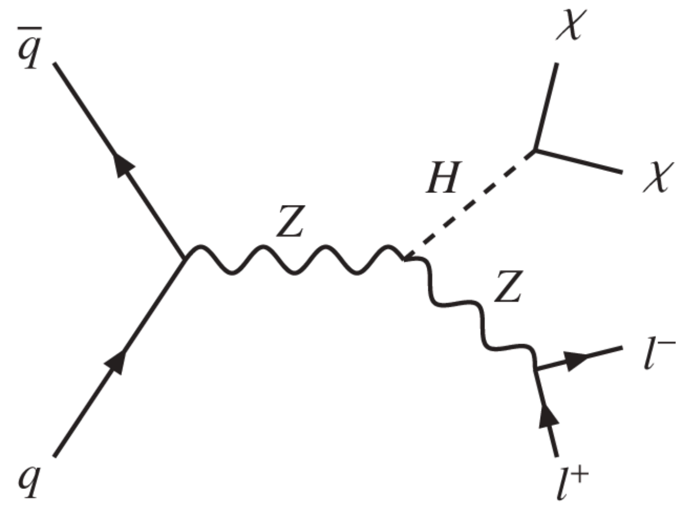
- Interpretation in terms of BSM model with SM Higgs plus an additional EW singlet:



C' - coupling of heavy Higgs relative to SM

Higgs to Invisibles

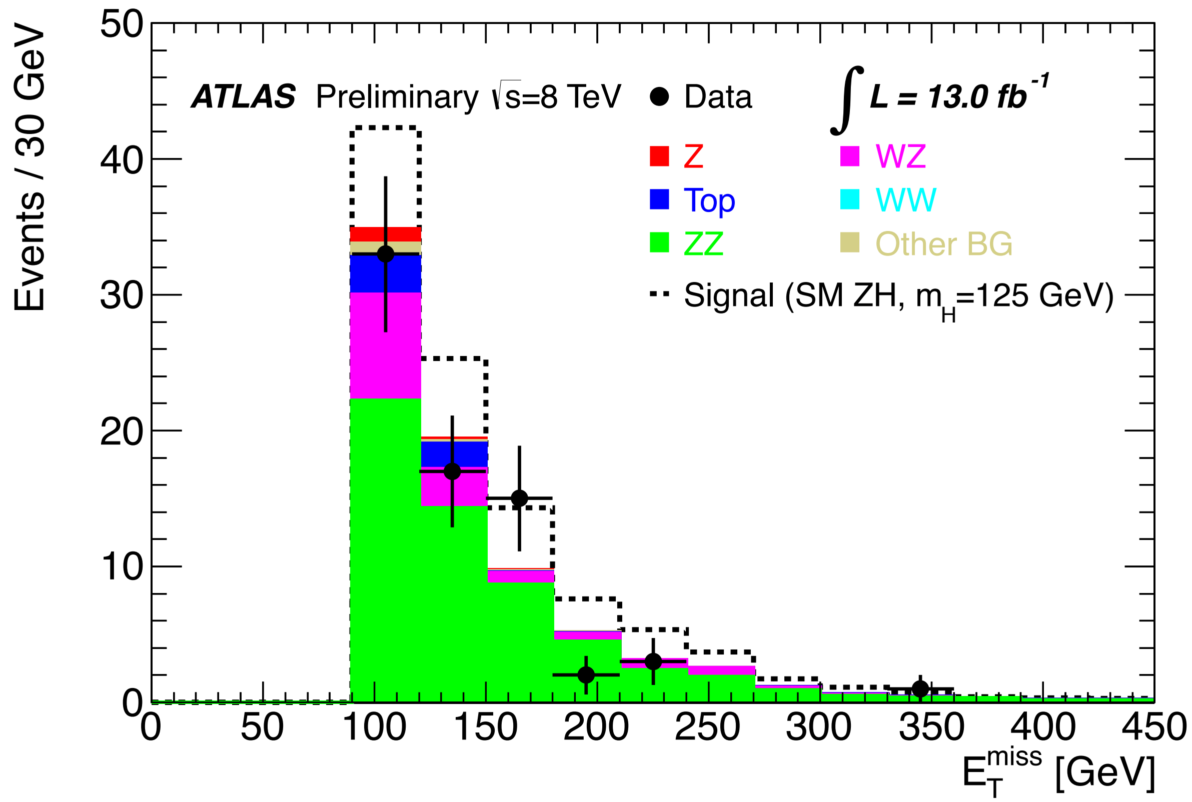
- Search for ZH production, with Higgs decaying to invisible particles:

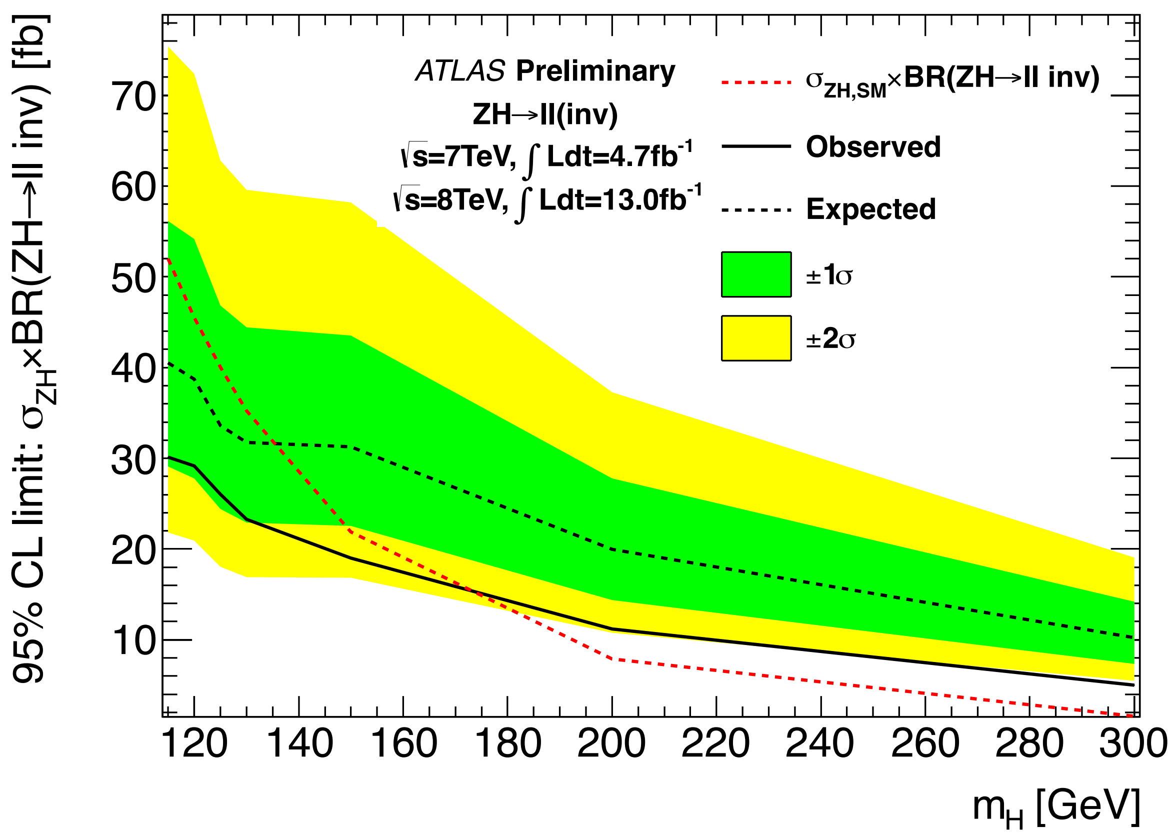


- Analysis requires two high pT leptons from Z and large missing transverse energy.
- Additional kinematic requirements are applied to select events consistent with Higgs recoiling against Z.
- Background dominated by SM WZ & ZZ production.

Higgs to Invisibles

- No significant discrepancy observed:

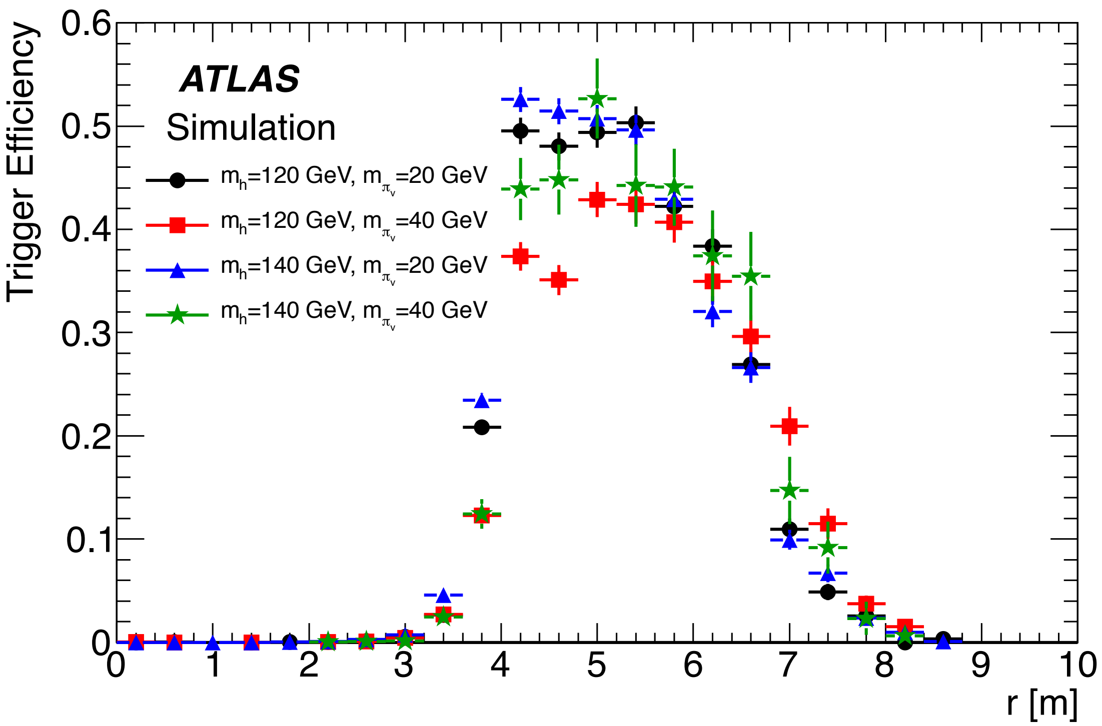


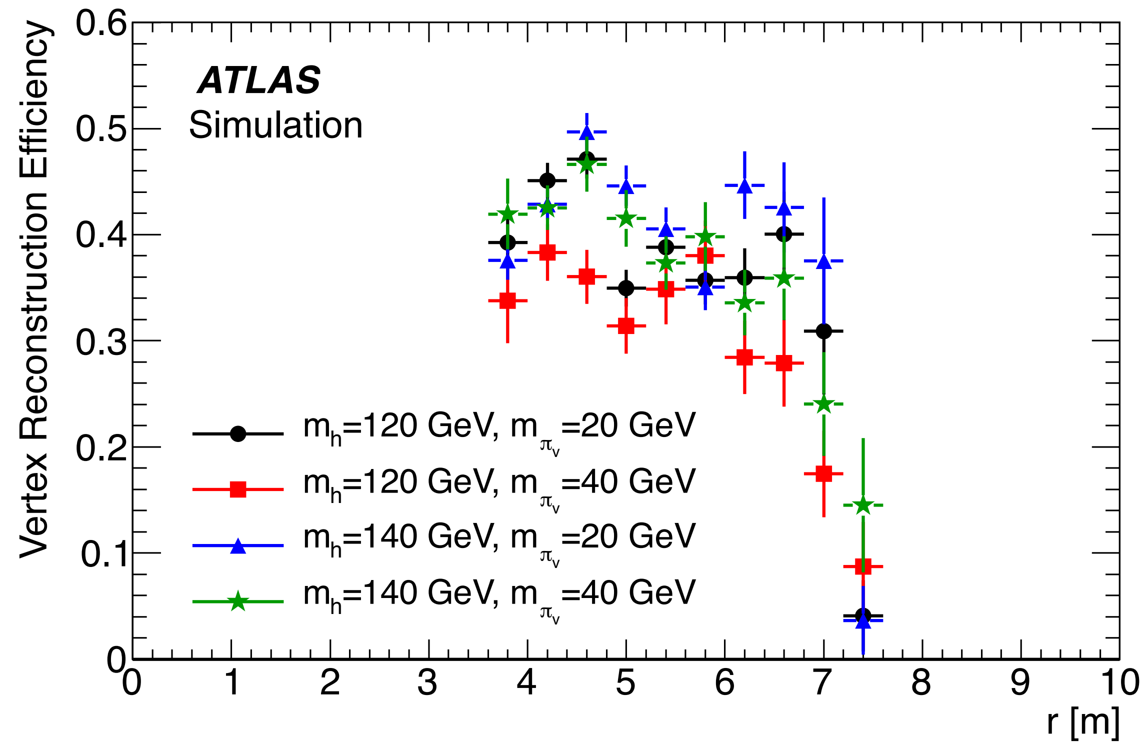


Higgs to Long Lived Particles

ATLAS, 2 fb^{-1} 7 TeV

- Possibility for Higgs bosons to decay into heavy, long lived particles in e.g. Hidden Valley models.
- ATLAS search for $h \rightarrow \pi_v \pi_v$; $\pi_v \rightarrow$fermion pairs.
- Novel trigger using multiple close-by L1 muon signals used.
- Dedicated tracking algorithm in the muon system used to identify vertices outside the calorimeter.





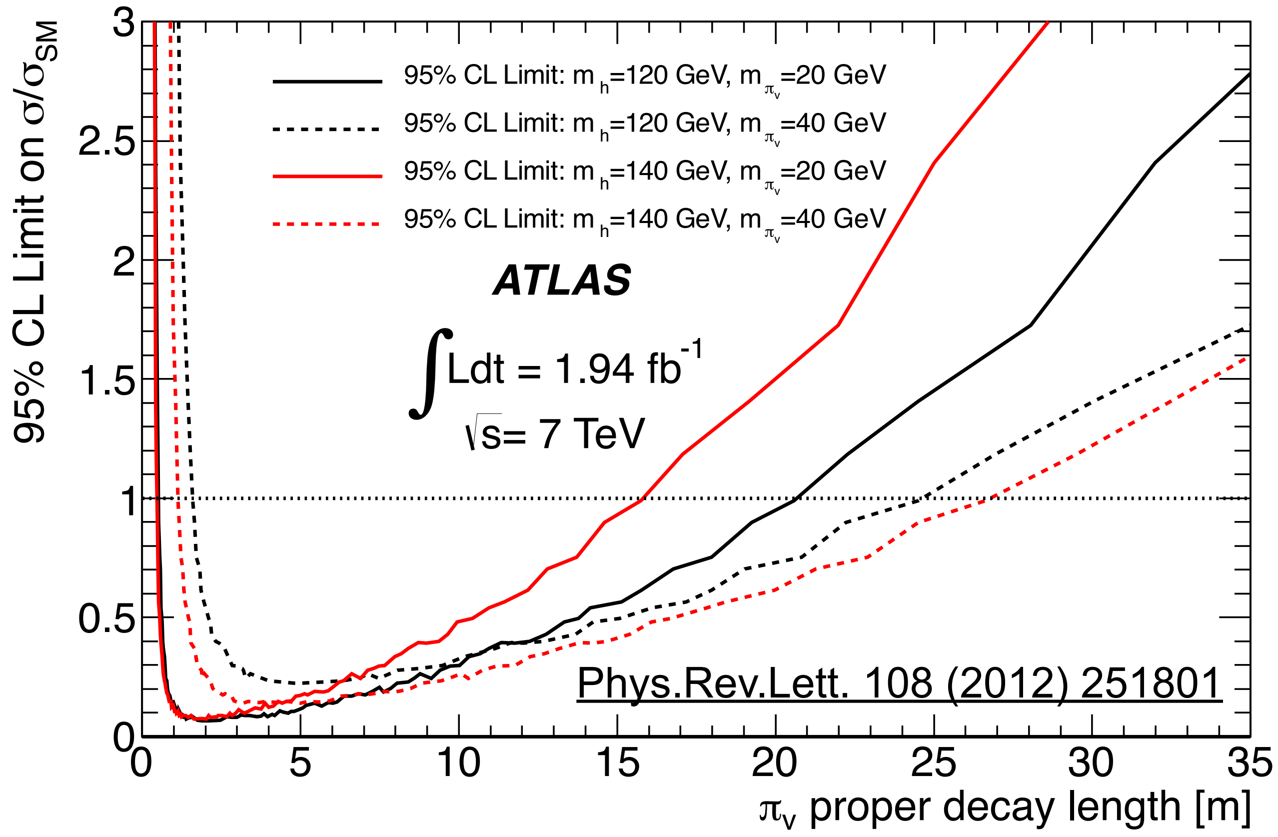
Higgs to Long Lived Particles

ATLAS, 2 fb^{-1} 7 TeV

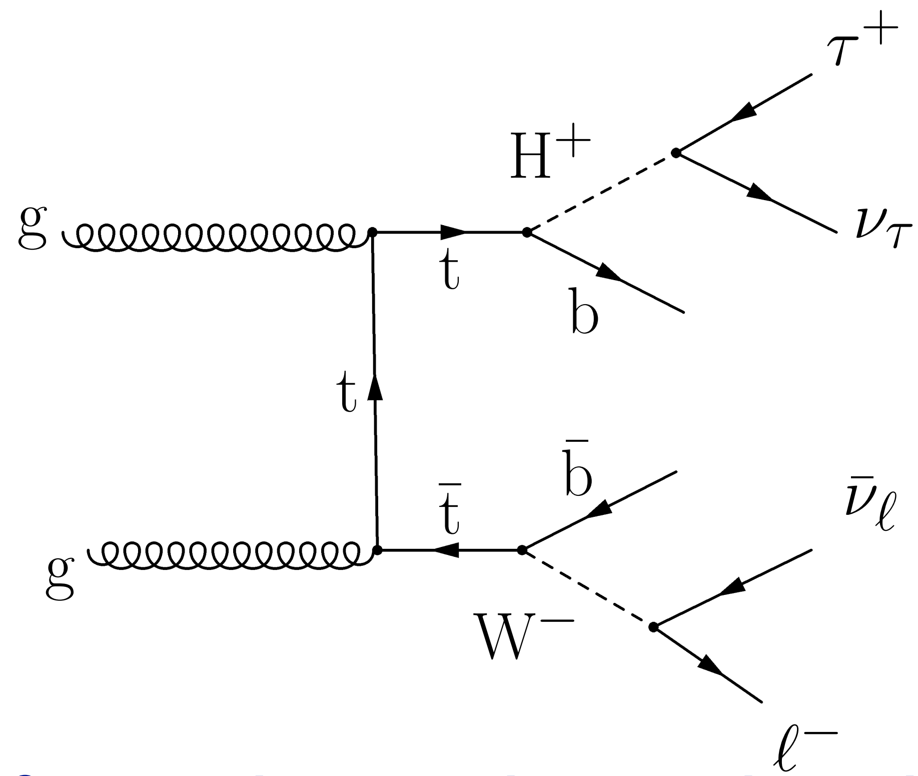
- Final selection requires two reconstructed vertices (ΔR > 2).
- Backgrounds estimated directly from the data:

$$N_{Fake}(2\ \text{MS vertex}) = N(\text{MS vertex,1 trig})*P_{vertex} + N(\text{MS vertex,2 trig})*P_{reco}$$

- No events observed, with 0.03 expected from background.



Charged Higgs

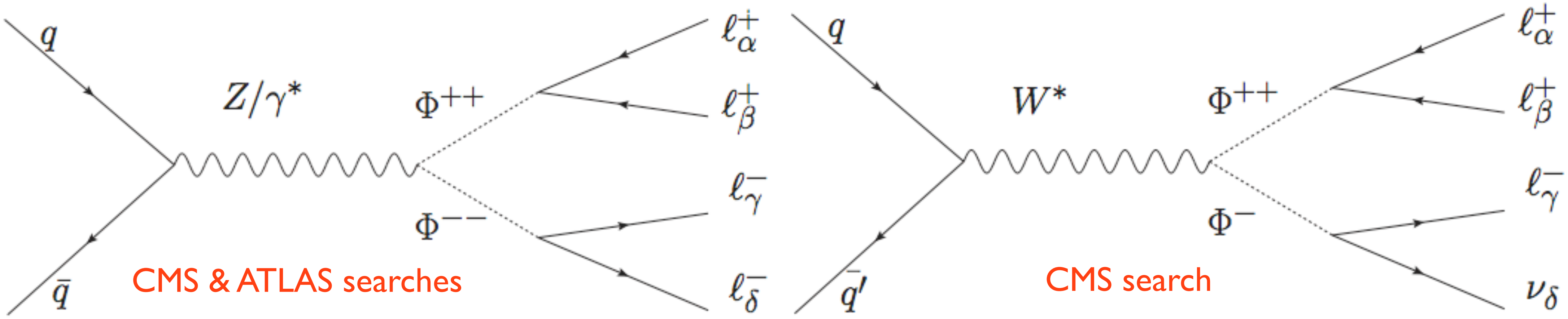


- SM W decay & tau decay determine the final state:
  - τ + jets: $\tau \to$ hadrons, W boson $\to$ hadrons.
  - μ / e + τ: $\tau \to$ hadrons, W boson $\to$ lepton & neutrino.
  - μ / e + μ / e: $\tau \to$ lepton & neutrino, W boson $\to$ lepton & neutrino.

Doubly Charged Higgs

CMS, 5 fb^{-1} 7 TeV
ATLAS, 5 fb^{-1} 7 TeV

- Doubly charged Higgs boson present in models with a scalar triplet, e.g. type II seesaw for neutrino mass generation.



- Striking signature of invariant mass peak in same-sign charge dilepton pairs.
- CMS: Look for three and four lepton events, including possibility of one hadronic tau.
- ATLAS: Look for same-sign dilepton events.

Doubly Charged Higgs

CMS, 5 fb^{-1} 7 TeV

- CMS selections:

Table 2: Selections applied in the three-lepton final states.

Variable	ee, eμ, $\mu\mu$	eτ, $\mu\tau$	$\tau\tau$
$\sum p_T$	$> 1.1 m_\Phi + 60$ GeV	$> 0.85 m_\Phi + 125$ GeV	$> m_\Phi - 10$ GeV or > 200 GeV
$\lvert m(\ell^+\ell^-) - m_Z \rvert$	> 80 GeV	> 80 GeV	> 50 GeV
E_T^{miss}	none	> 20 GeV	> 40 GeV
$\Delta\varphi$	$< m_\Phi / 600$ GeV $+ 1.95$	$< m_\Phi / 200$ GeV $+ 1.15$	< 2.1
Mass window	$[0.9 m_\Phi; 1.1 m_\Phi]$	$[m_\Phi/2; 1.1 m_\Phi]$	$[m_\Phi/2 - 20$ GeV$; 1.1 m_\Phi]$

Table 3: Selections applied in various four-lepton final states.

Variable	ee, eμ, $\mu\mu$	eτ, $\mu\tau$	$\tau\tau$
$\sum p_T$	$> 0.6 m_\Phi + 130$ GeV	$> m_\Phi + 100$ GeV or > 400 GeV	> 120 GeV
$\lvert m(\ell^+\ell^-) - m_{Z^0} \rvert$	none	> 10 GeV	> 50 GeV
$\Delta\varphi$	none	none	< 2.5
Mass window	$[0.9 m_\Phi; 1.1 m_\Phi]$	$[m_\Phi/2; 1.1 m_\Phi]$	none

Doubly Charged Higgs

CMS, 5 fb[-1] 7 TeV

- No excess seen, limits are set:

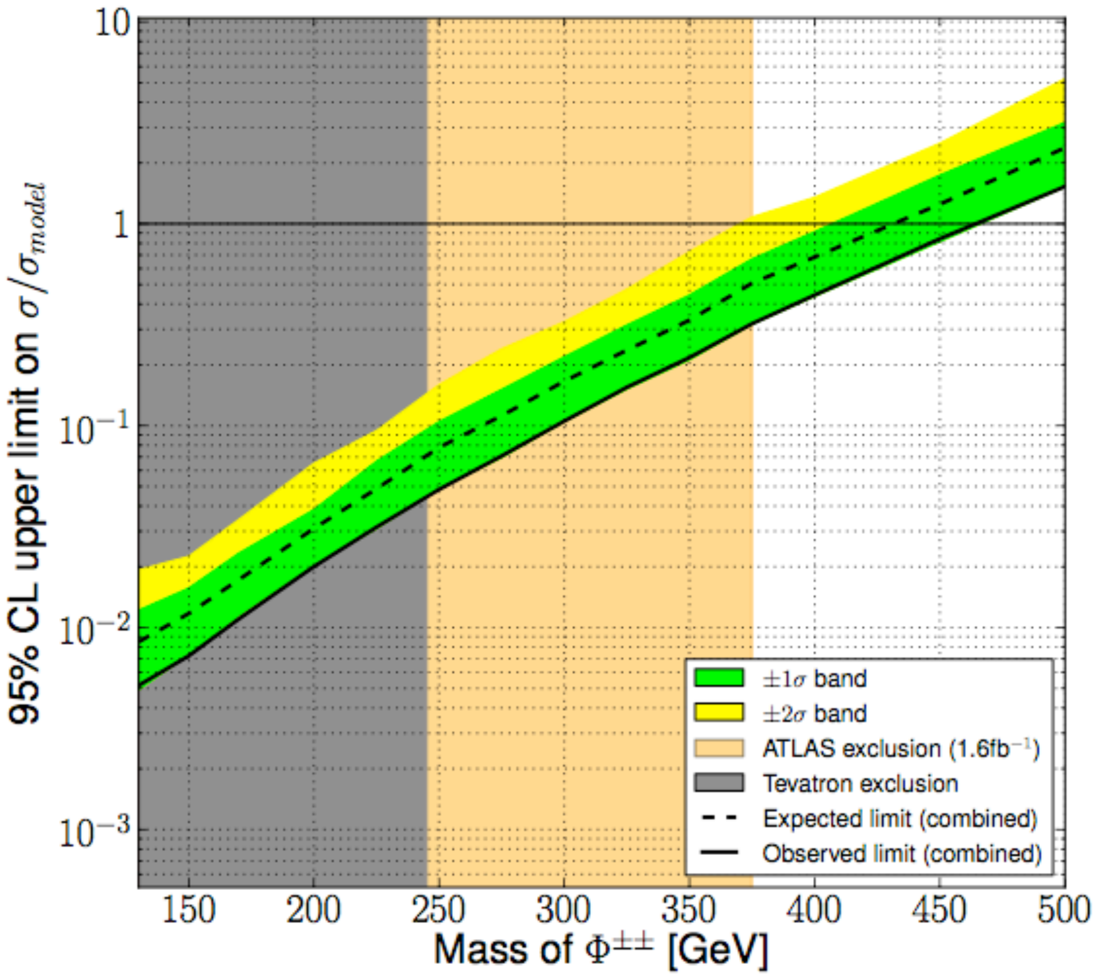


Table 6: Summary of the 95% CL exclusion limits.

Benchmark point	Combined 95% CL limit [GeV]	95% CL limit for pair production only [GeV]
$\mathcal{B}(\Phi^{++} \to e^+e^+) = 100\%$	444	382
$\mathcal{B}(\Phi^{++} \to e^+\mu^+) = 100\%$	453	391
$\mathcal{B}(\Phi^{++} \to e^+\tau^+) = 100\%$	373	293
$\mathcal{B}(\Phi^{++} \to \mu^+\mu^+) = 100\%$	459	395
$\mathcal{B}(\Phi^{++} \to \mu^+\tau^+) = 100\%$	375	300
$\mathcal{B}(\Phi^{++} \to \tau^+\tau^+) = 100\%$	204	169
BP1	383	333
BP2	408	359
BP3	403	355
BP4	400	353

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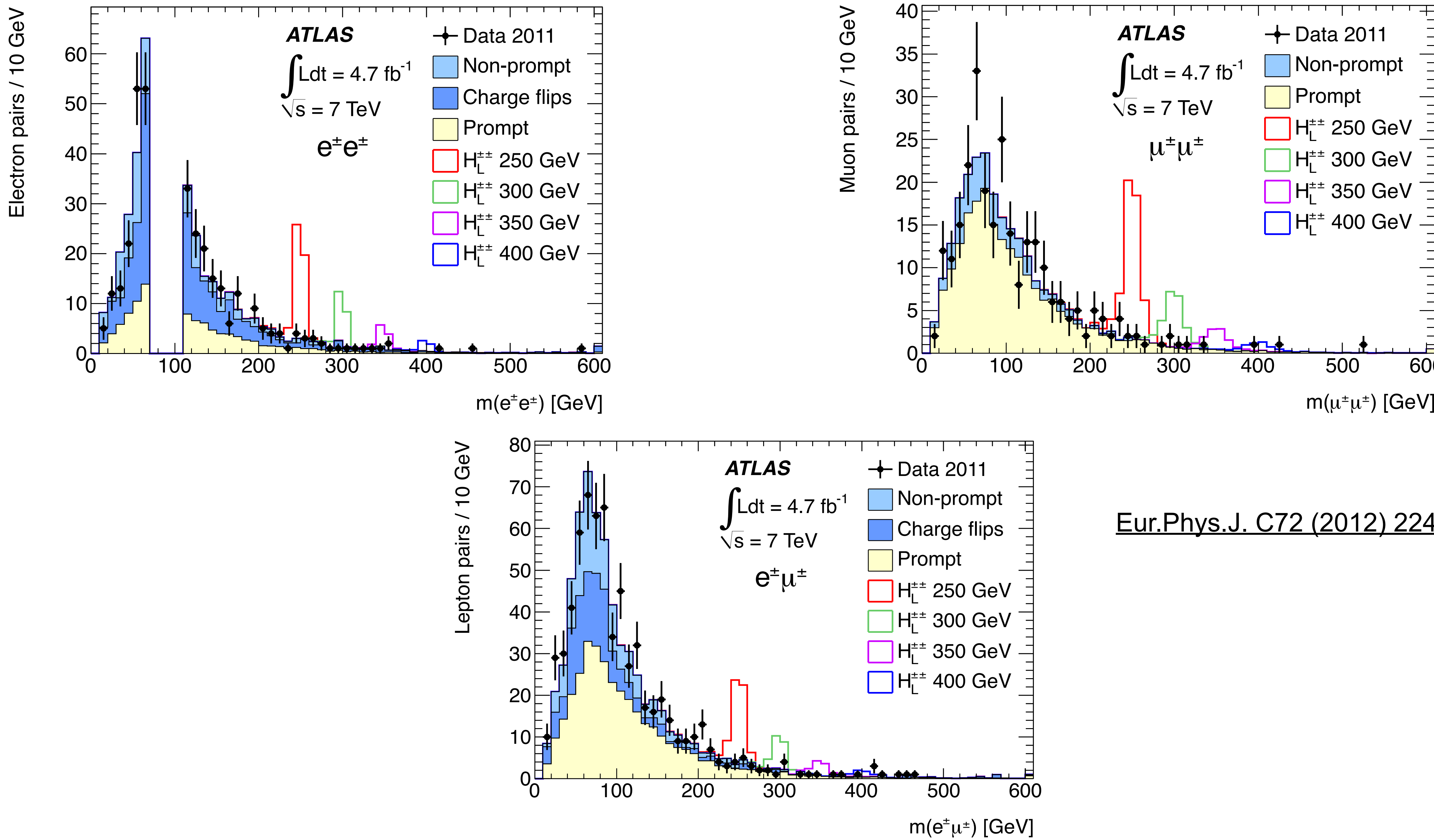
Doubly Charged Higgs

ATLAS, 5 fb^{-1} 7 TeV

- ATLAS selects inclusive same-sign lepton pairs and looks for peak in invariant mass distributions:

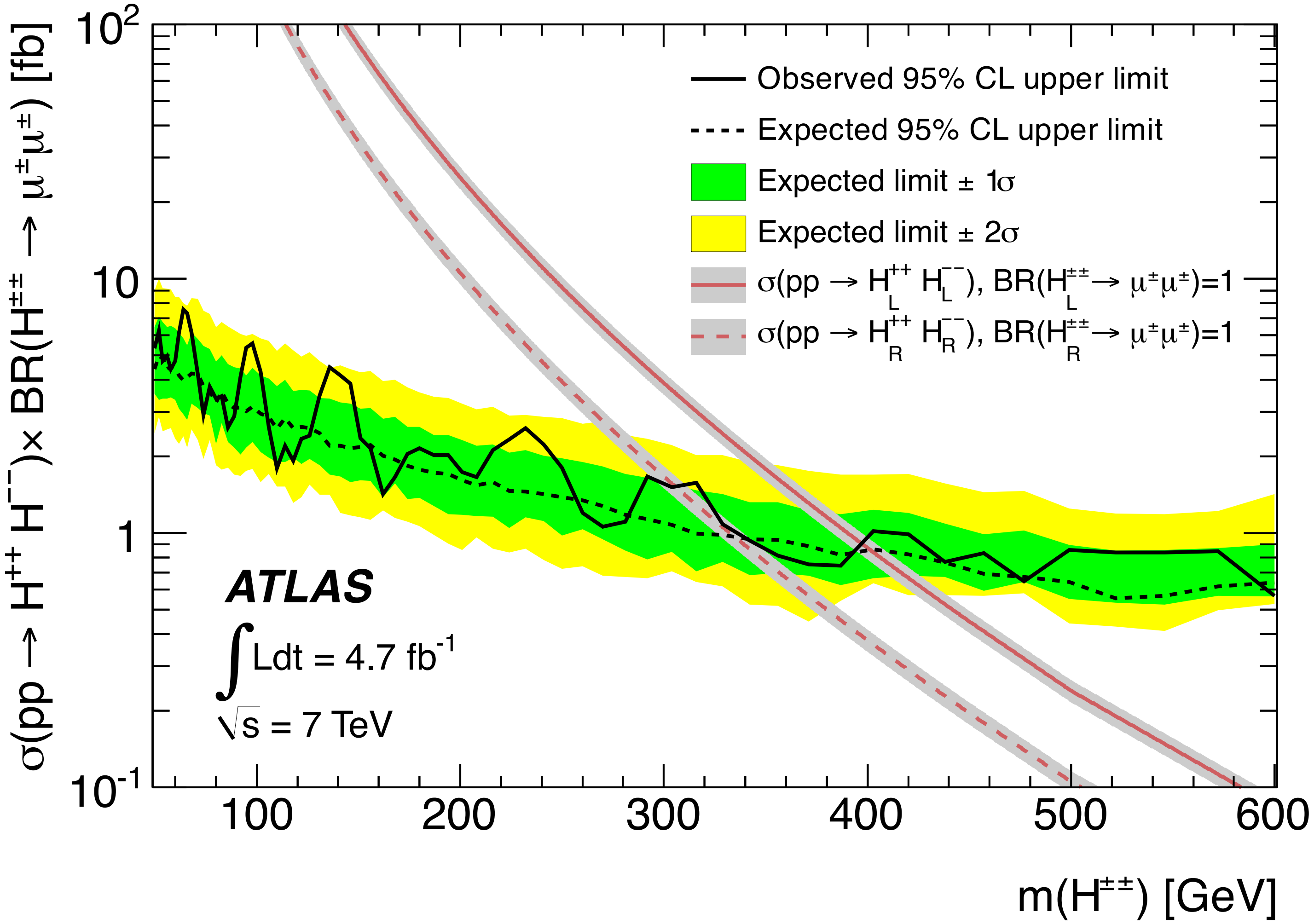


Eur.Phys.J. C72 (2012) 2244

Doubly Charged Higgs

ATLAS, 5 fb^{-1} 7 TeV

- No excess seen, limits are set:

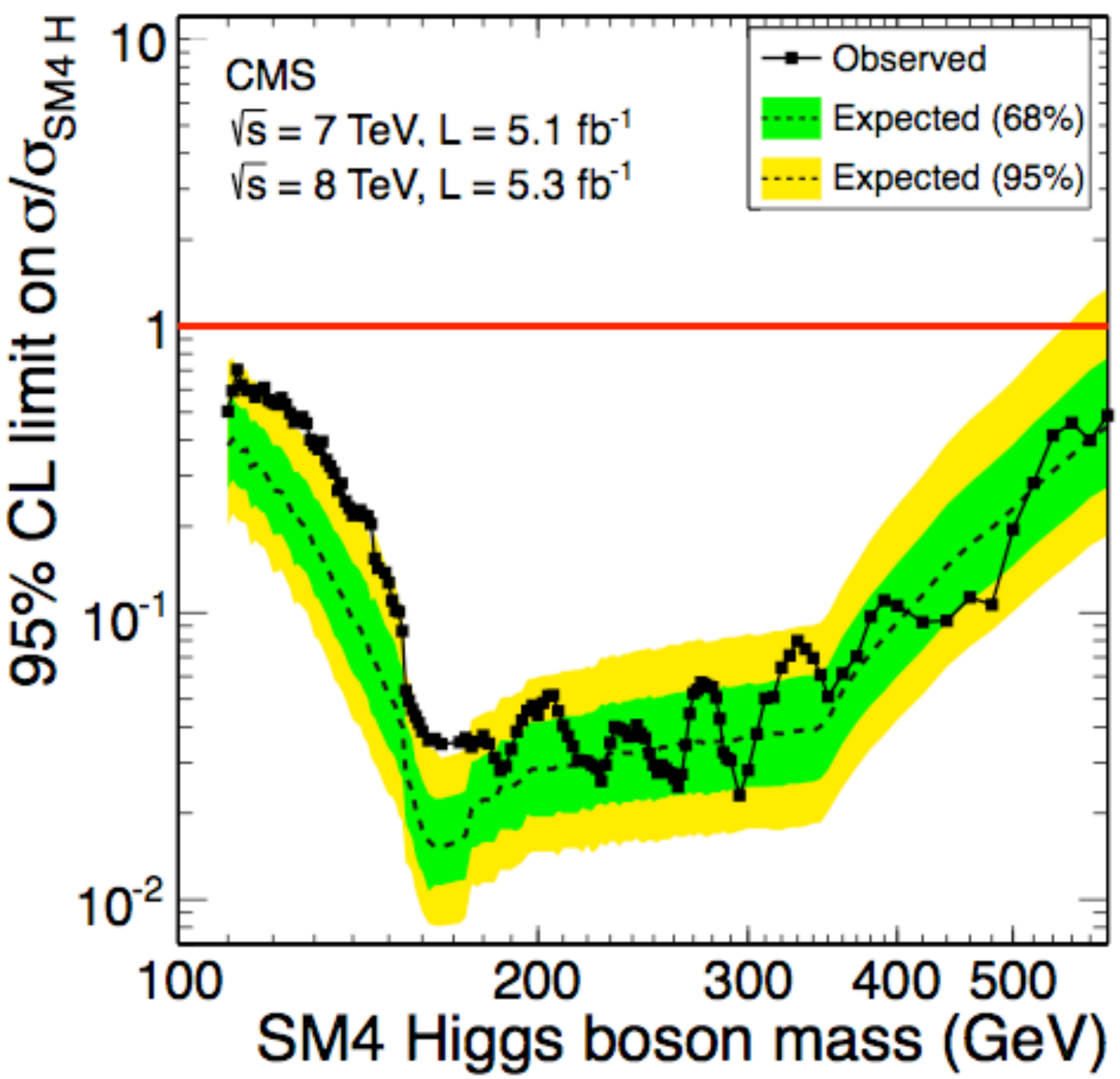


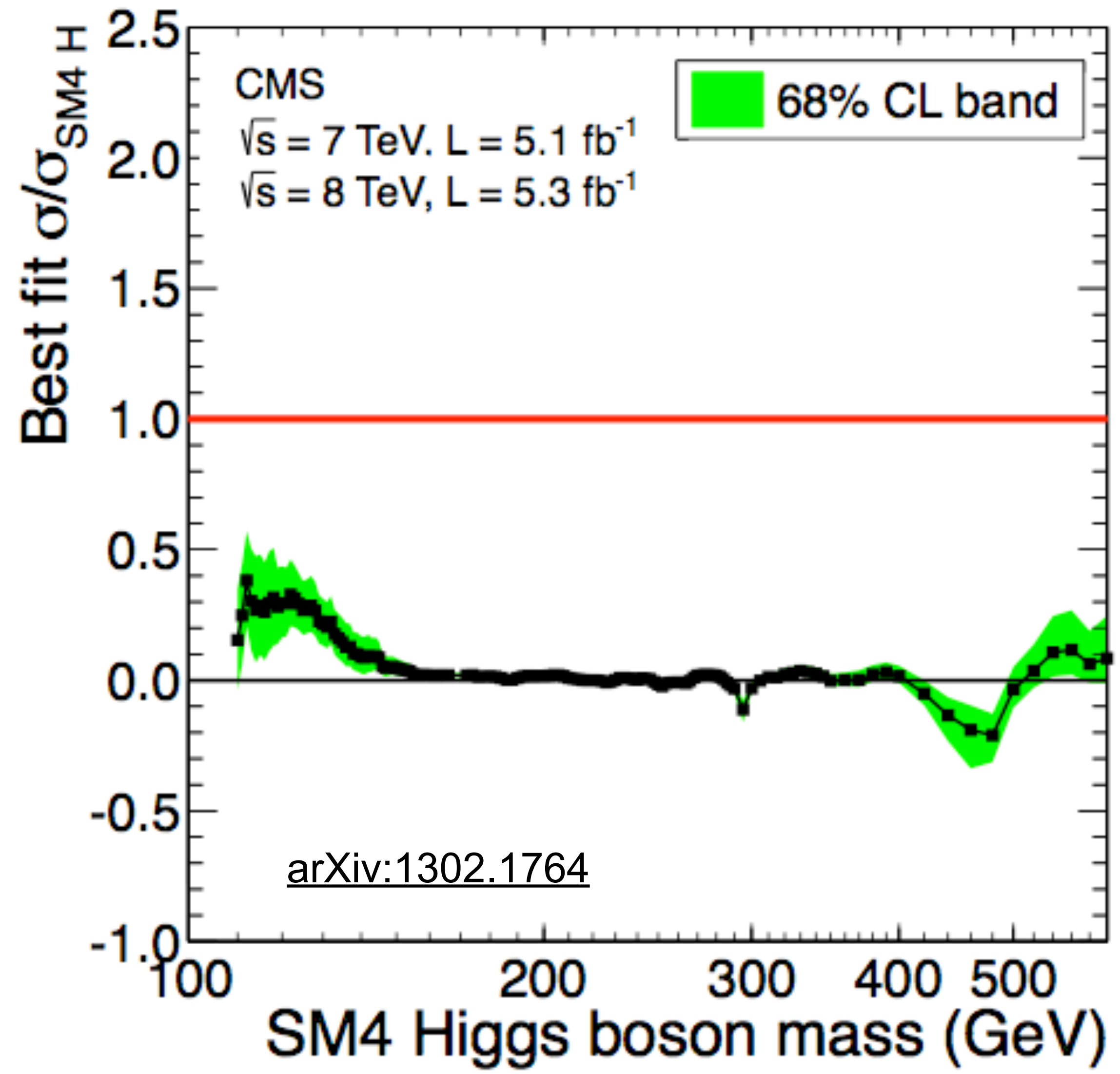
$BR(H_L^{\pm\pm} \to \ell^\pm \ell'^\pm)$	95% CL lower limit on $m(H_L^{\pm\pm})$ [GeV]					
	$e^\pm e^\pm$		$\mu^\pm\mu^\pm$		$e^\pm\mu^\pm$	
	exp.	obs.	exp.	obs.	exp.	obs.
100%	407	409	401	398	392	375
33%	318	317	317	290	279	276
22%	274	258	282	282	250	253
11%	228	212	234	216	206	190

SM with Fourth Generation

CMS, 5 fb^{-1} 7 TeV; 5 fb^{-1} 8 TeV

- CMS re-interpretation of SM Higgs analyses (except $\gamma\gamma$) in context of SM with 4th generation of quarks - observed signal at m=125 GeV has too small rate to be compatible with SM4:



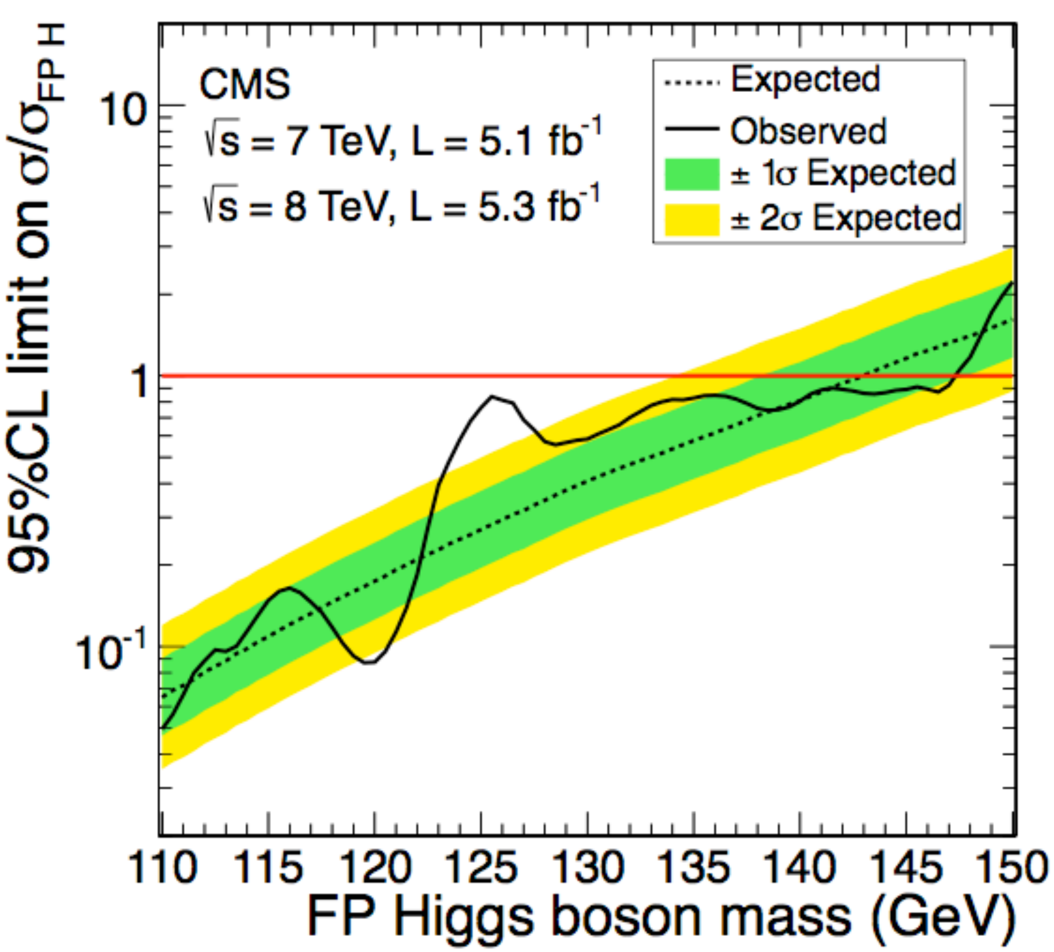


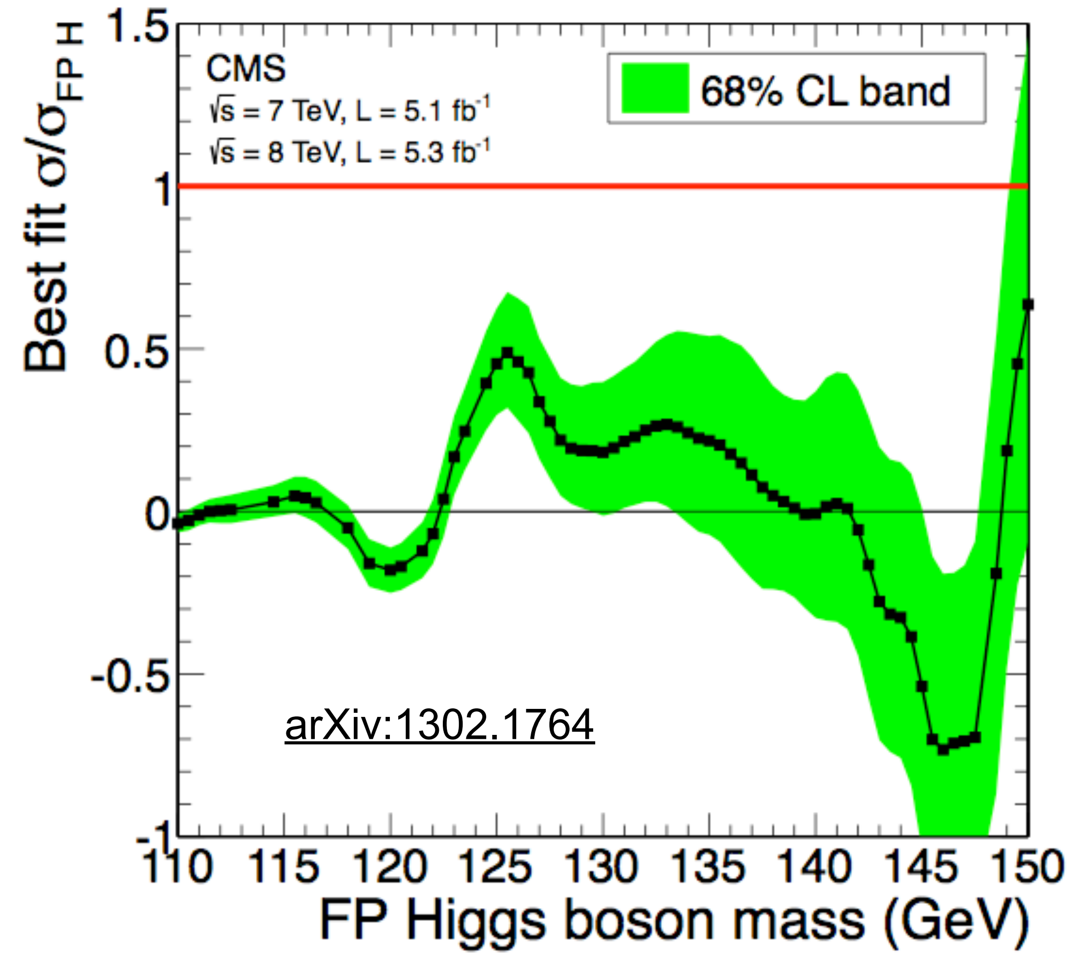
- SM4 Higgs excluded for 110 < m_h < 600 GeV (99% CL).

Fermiophobic Higgs

CMS, 5 fb^{-1} 7 TeV; 5 fb^{-1} 8 TeV

- CMS analysis of $\gamma\gamma$ channel, targeting VH and VBF production modes in context of Fermiophobic Higgs scenario:





- Excess at m=125 GeV too small for Fermiophobic Higgs.
- Fermiophobic Higgs excluded for 110 < m_h < 147 GeV (95% CL).