BSM Higgs Searches at the LHC and Tevatron

Justin Griffiths

University of Texas Arlington

On behalf of the ATLAS, CMS, D0 and CDF experiments

- Motivation for Exotic/BSM Higgs Searches
- Searches for Invisible Higgs Decays
- Overview of MSSM Higgs Searches highlighting recent results from ATLAS and CMS
- A look at NMSSM Scenarios in which the newly discovered Higgs could decay to undiscovered bosons
- A brief look at other Exotic Searches
  - Hidden Valley, Displaced Vertices, FCNC Searches with the Higgs Boson.

UT AR MAVERICKS

ATLAS

Current Higgs Couplings

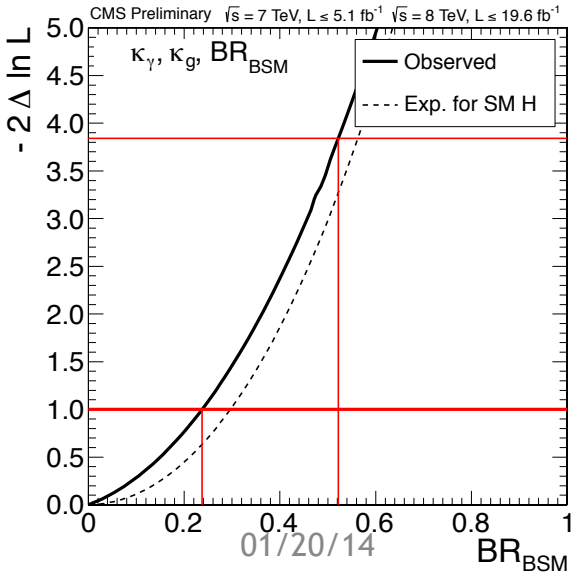
- Since the discovery of the Higgs, coupling measurements were performed and are consistent with a SM Higgs, but there is still significant room for non-SM decays.

	BR_{BSM} < xx	
	68% CL	***95% CL***
CMS	***0.24***	***0.52***
ATLAS	***0.33***	***0.6***

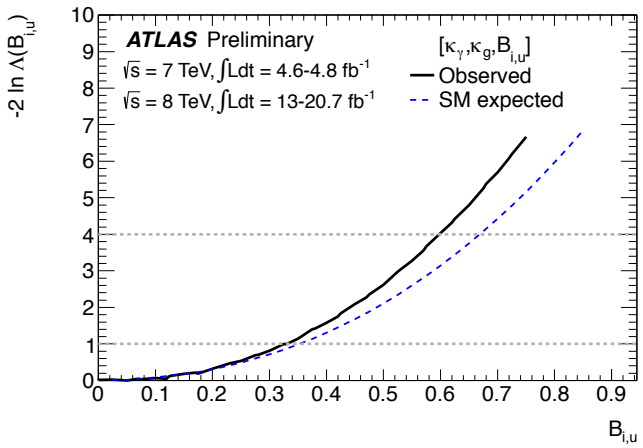
$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{inv.,undet.})}\Gamma_H^{SM}$$

- Single Resonance at 125.5 GeV
- Zero-Width Approximation
- New particle is CP-even
- More Details on methodology:
  - arXiv:1209.0040
  - arXiv:1101.0593
  - arXiv:1201.3084
- See Michela BIGLIETTI's talk

CMS-PAS-HIG-13-005

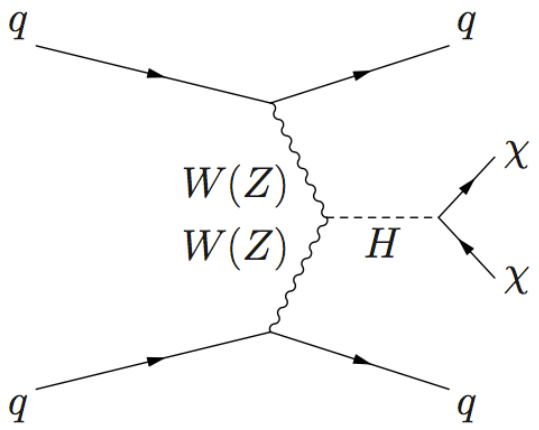


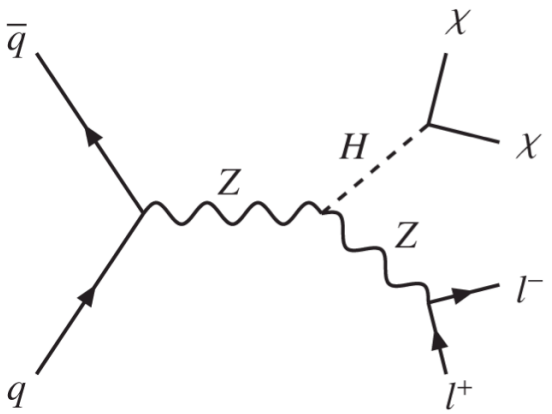
ATLAS-CONF-2013-034



Higgs to Invisible

- The observation of a significant branching ratio for H→Invisible would provide evidence for new physics beyond the SM.
  - SUSY (often) predicts a stable neutral lightest SUSY particle (LSP)
  - Some Extra dimension theories predict graviscalars
- Searches performed in:
  - VBF: CMS
  - ZH: ATLAS and CMS
- The main backgrounds in ZH include:
  - ZZ→2ℓ2ν Irreducible background ~70%
  - WZ→ℓν2ℓ 20-25% of background
  - Other backgrounds include: *WW*, top, *W*/*Z* +jets
- The main backgrounds in VBF include:
  - (*Z*→*νν*)+jets (*W*→*ℓν*)+jets and QCD multijet events





Higgs to Invisible (ZH)

ATLAS-CONF-2013-011 CMS-PAS-HIG-13-018

	ATLAS Selection	CMS Selection
E_T^{miss}	90 GeV	110 GeV
$\Delta\varphi(\ell\ell, E_T^{miss})$	> 2.6	> 2.6
$\lvert E_T^{miss}-p_T^{\ell\ell}\rvert/p_T^{\ell\ell}$	< 0.2	< 0.2
No Jets	> 20 GeV; $\lvert\eta\rvert$ < 2.5	> 30 GeV

- Backgrounds estimated by:
  - Dominant *ZZ* and *WZ* backgrounds estimated using simulation and normalized to their NLO Cross Section.
  - *Z* background estimated in *γ*+jets events in CMS and an ABCD method in ATLAS.
  - Remaining backgrounds are estimated in a *eμ* Control Region.
- Final discriminating variable used in analyses were m_T(MET, $\ell\ell$)(CMS) and MET (ATLAS).

Higgs to Invisible (VBF) CMS

- Triggering is a challenge since there are no leptons to trigger on. A dedicated VBF trigger along with E_T^{miss} was used.

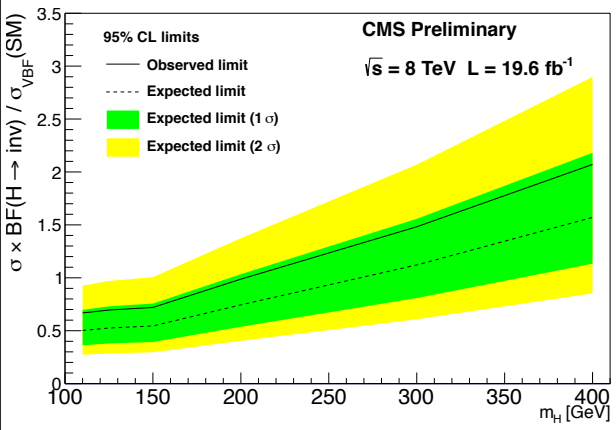
CMS-PAS-HIG-13-013

	Trigger Threshold	Offline Threshold
Jet p_T [GeV]	*40*	*50*
$\|\Delta\eta\|$	*3.5*	*4.7*
M_{jj} [GeV]	*800*	*1100*
E_t^{miss} [GeV]	*65*	*130*

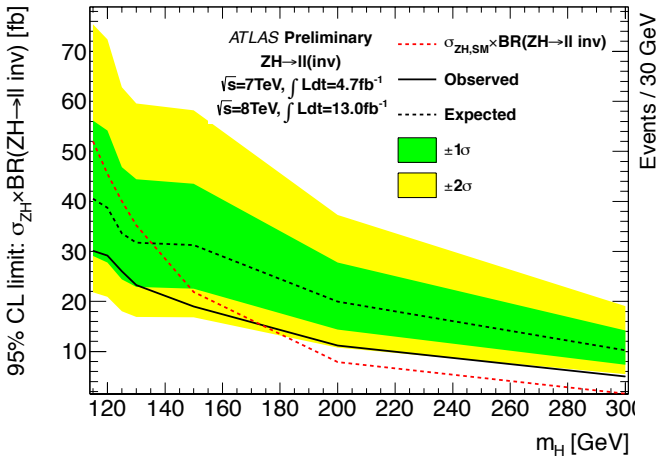
- Backgrounds estimated by:
  - *W/Z*+jets estimated from data using visible Control regions
  - QCD multijet estimated with an ABCD
  - Remaining backgrounds estimated using simulation

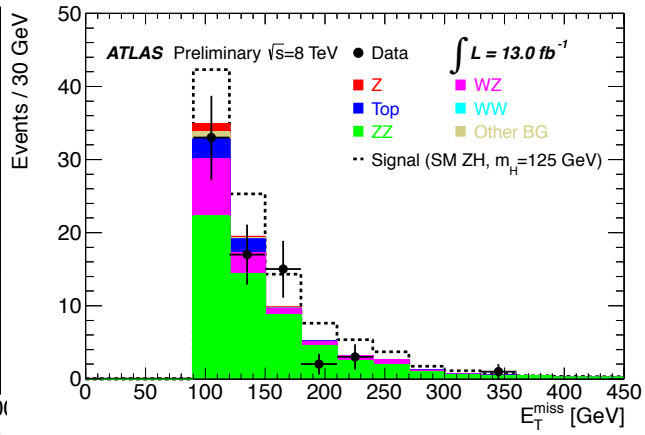
Invisible Higgs Results

CMS VBF H→ Invisible



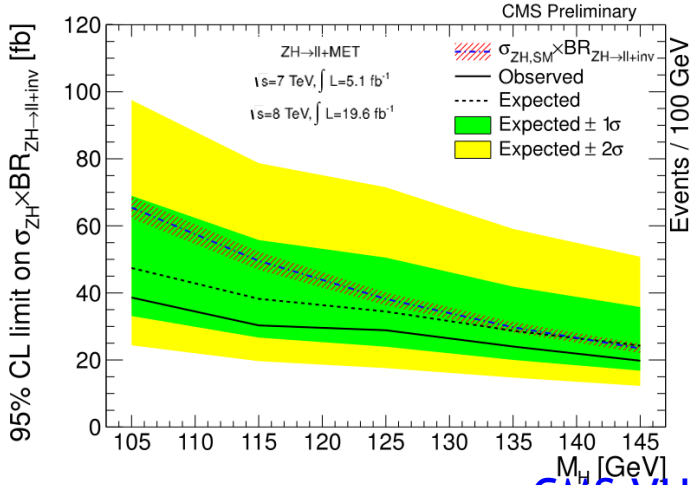
ATLAS VH→ Invisible

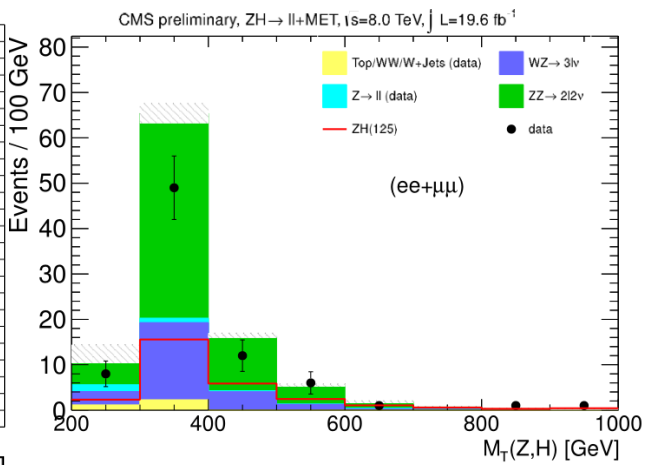




Observed LImits

Limits (BR)	VBF	ZH
ATLAS		*65%*
CMS	*65%*	*75%*





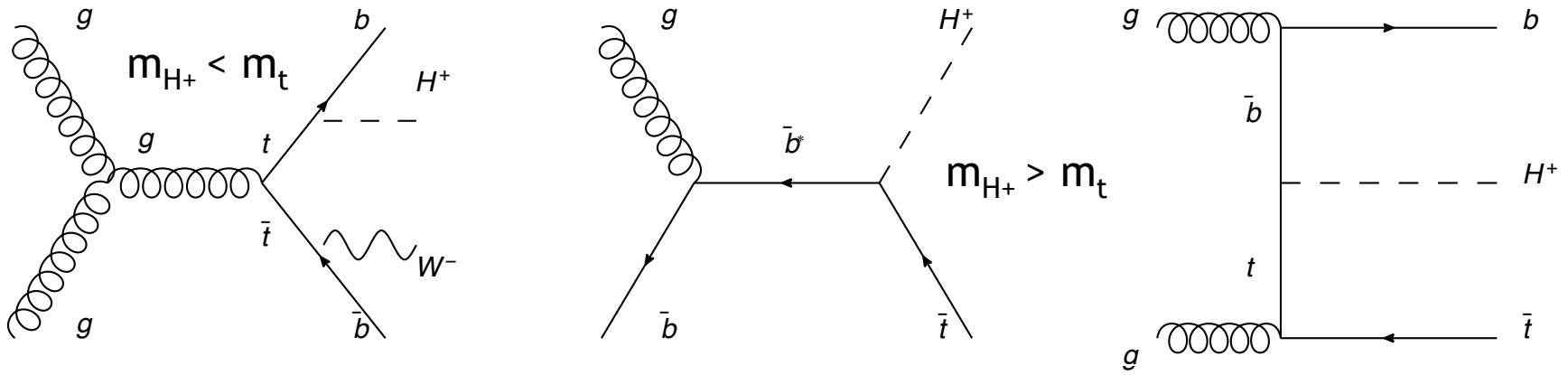
CMS VH→ Invsible

MSSM Searches

Signature	ATLAS (fb^{-1})	CMS (fb^{-1})	Tevatron (fb^{-1})
$\varphi \to \tau\tau$	4.7	4.9+19.7	1.8(CDF)+2.2(D0)
$\varphi \to \mu\mu$	4.7		
$\varphi \to bb$		4.8	2.6(CDF)+5.2(D0)
$H^+ \to \tau^+\nu$	19.5	4.9	
$H^+ \to t\bar{b}$			0.9 (D0)

- Supersymmetry offers a solution to the hierarchy problem.
- Minimal Supersymmetric Standard Model (MSSM) is an extension to the SM that introduces two higgs doublets resulting in 5 Higgs: CP-even (H, h), CP-odd (A), and two Charged Higgs.
  - Neutral Higgs often denoted φ
- At tree level, the Higgs sector of MSSM can be described by two parameters: the m_A and tan(β). At high values of tan(β), couplings to down-type fermions are enhanced motivating searches in the bb $\tau\tau$ final states.
- ATLAS, CMS, and the Tevatron experiments have performed multiple MSSM searches. The more recent ATLAS $H^+ \to \tau^+\nu$ result and the CMS neutral $H \to \tau\tau$ results will be summarized here. In addition the D0 $H^+ \to tb$ search will also be shown

Search for $H^+ \rightarrow \tau^+\nu$ in ATLAS



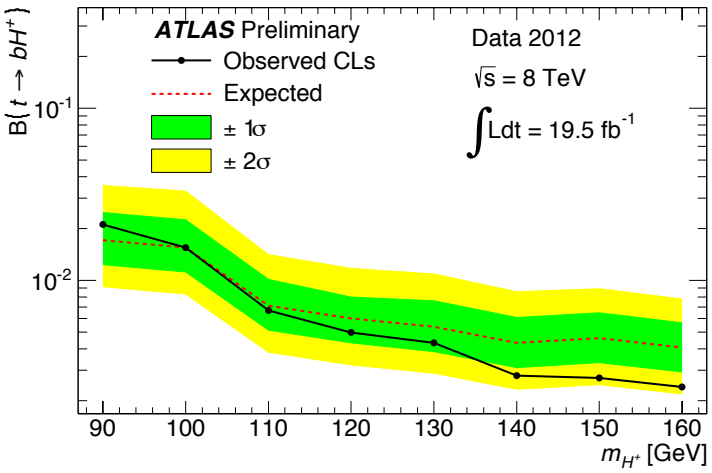
- ATLAS searched for a charged Higgs ($90 < m_{H+} < 600$ GeV)
  - $m_{H+} < m_t$; Searching for a charged higgs in top decays.
  - $m_{H+} > m_t$; Searching for a charged higgs produced in association with a top.
- Final state: $H^+ \rightarrow \tau^+\nu \rightarrow \tau_h\nu\nu$, ($\tau_h$ hadronically decaying tau) and the top quark decays hadronically
- The main backgrounds include:
  - $t\bar{t}$ events, W/Z+jets, single top, and QCD multijet
- Backgrounds are classified in 4 groups based on what object is identified as the τ_h candidate: A true τ_h, an electron, a muon, or a jet.
- This last background is estimated from data using a matrix method while all other backgrounds are estimated using simulation.

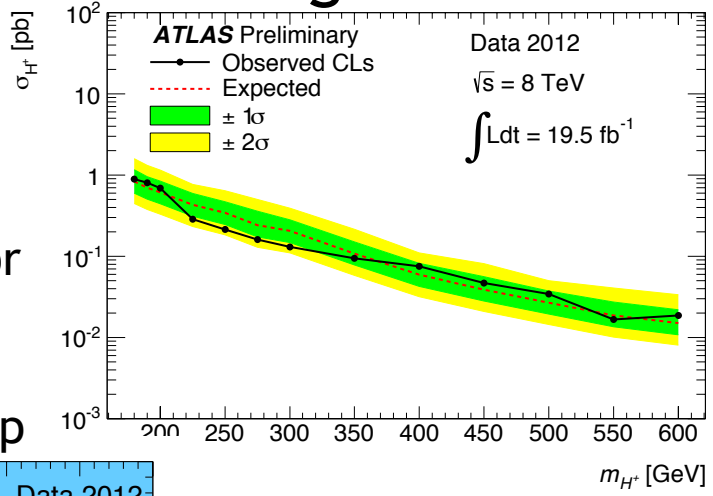
Search for $H^+ \rightarrow \tau^+\nu$ in ATLAS

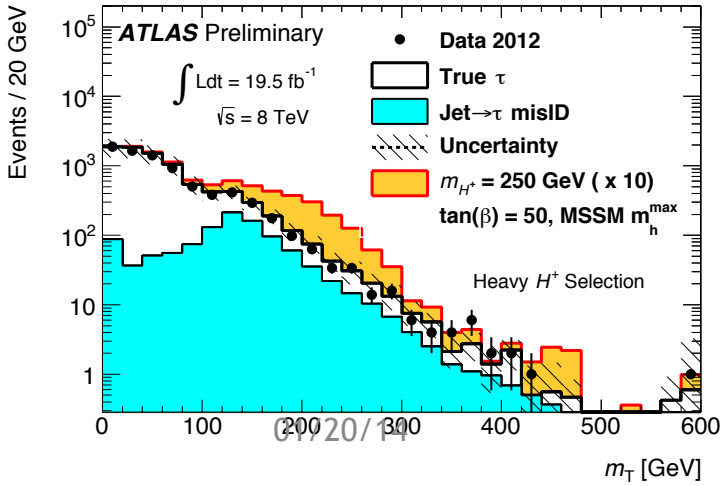
- The final $m_T(\tau_h, E_T^{miss})$ is used as the discriminating variable in the final fit.
- No excess was observed over the mass range scanned, so limits were set.

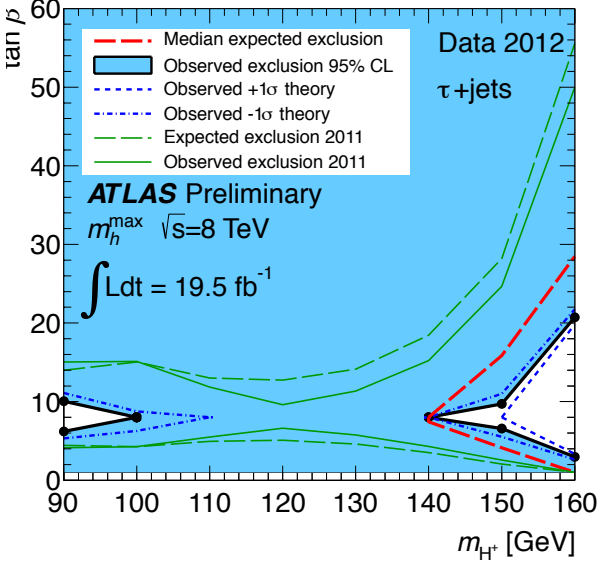
Left: limit on B(t→H)

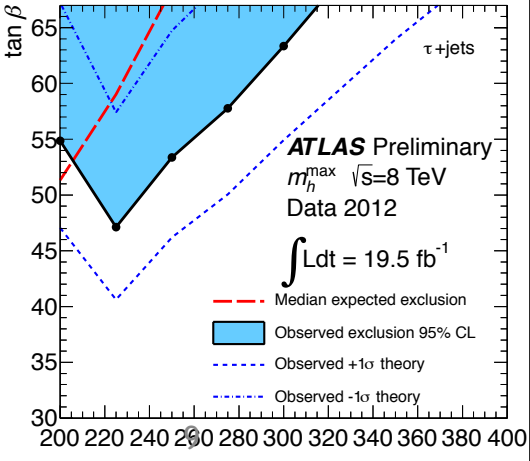
Right: limit on σ for a Charged Higgs produced in association with top





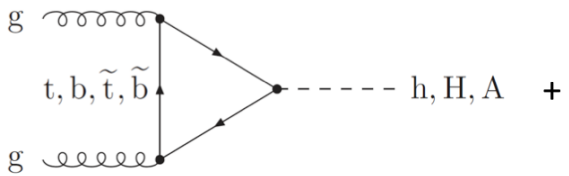






Search for MSSM h/H/A→ττ in CMS

- 2 main Production Processes:



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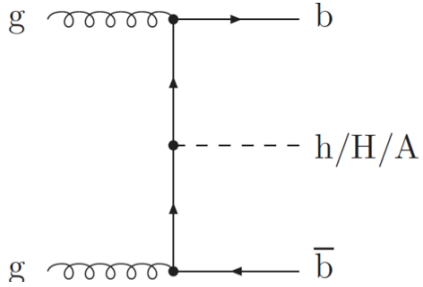
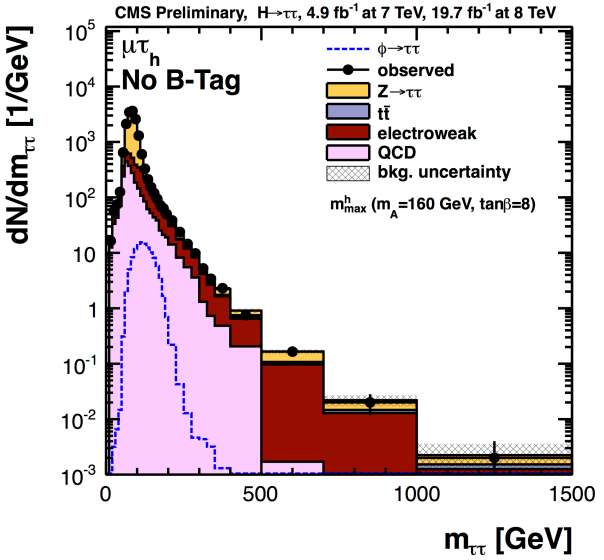


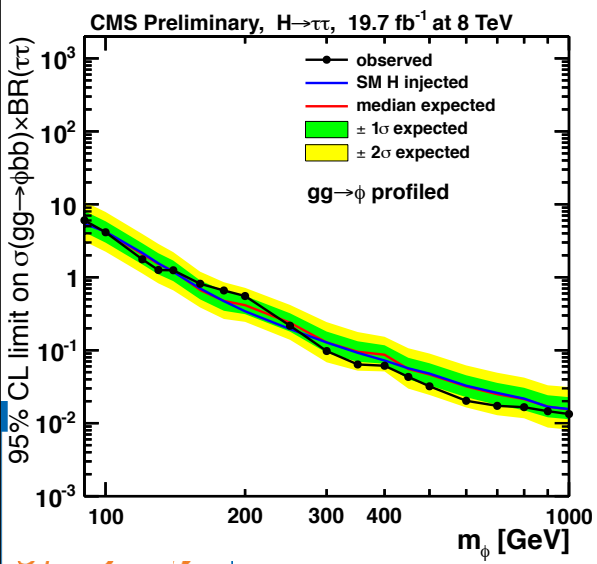
- Cross-section increases ~tan β²

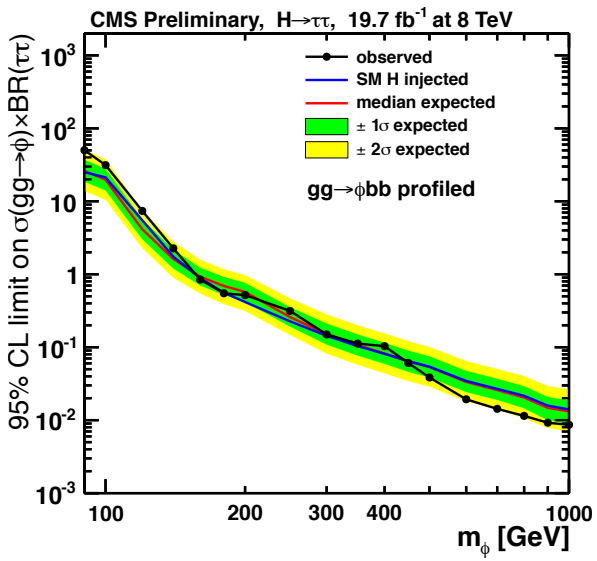
- CMS searched for a neutral Higgs using the entire 7+8 TeV data set in 5 possible ττ decay modes and two production modes:
  - $e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$, and $\tau_h\tau_h$
  - b-tagged and non-b-tagged categories
- The main background: Z→ττ estimated using Z→μμ events from data where the reconstructed muons are replaced by simulated and reconstructed tau decays.
- Other significant backgrounds: QCD multijet estimated in data, W/Z+jets, $t\bar{t}$, and dibson.
- The final ττ invariant mass is reconstructed using a maximum likelihood which attempts to compute a ditau mass which is most compatible with the visible momentum of the tau decay products. The resulting tau-pair mass distribution is consistent with the true invariant mass with a resolution of 15-20%. (MMC)

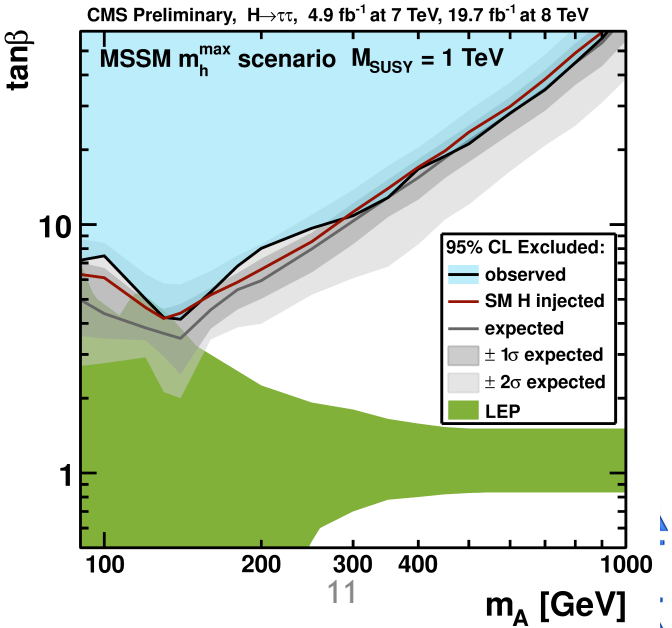
Search for MSSM h/H/A→ττ in CMS

- Fit is performed using the reconstructed ττ mass as input. The fit is performed simultaneously:
  - In all 5 ττ final states
  - In b-tagged and non-b-tagged production modes





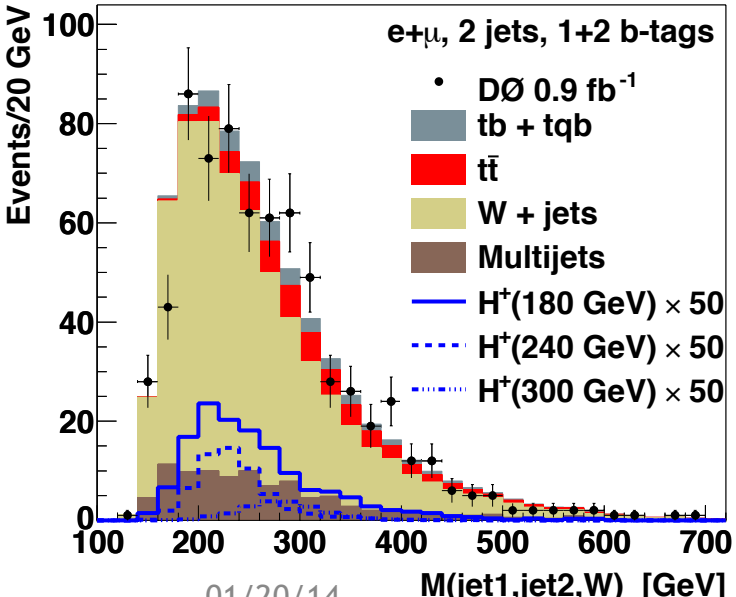


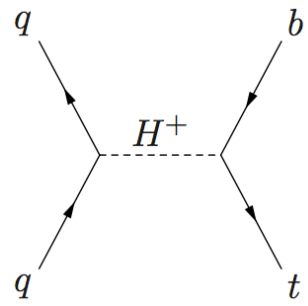


$H^+ \to t\bar{b} \to \ell\nu b\bar{b}$ Search at D0

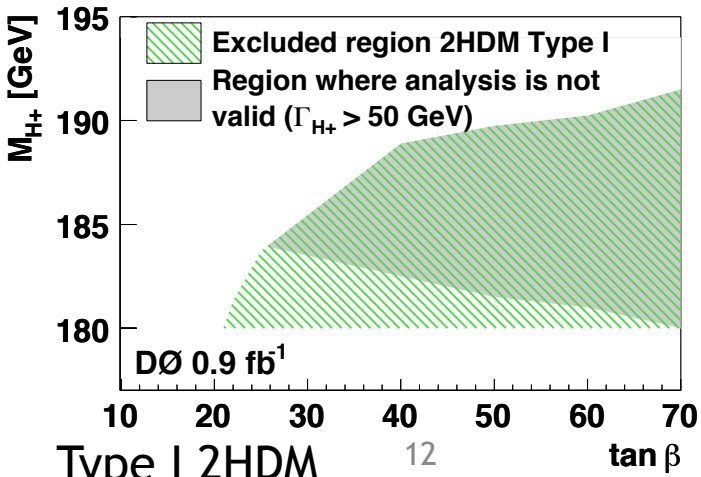
- D0 performed a search for a heavy Charged Higgs ($180 < m_{H^+} < 300$ GeV) in 0.9 fb^{-1} of data.
- The main backgrounds W+jets, $t\bar{t}$, single top were modeled with simulation while QCD Multijet background was estimated from data
- The discriminating variable is the invariant mass of the W and two b-jets.
- The 2D exclusion plane is only shown for the Type I 2HDM since the analysis was not as sensitive in the TYPE II and III 2HDM models.

Type III 2HDM





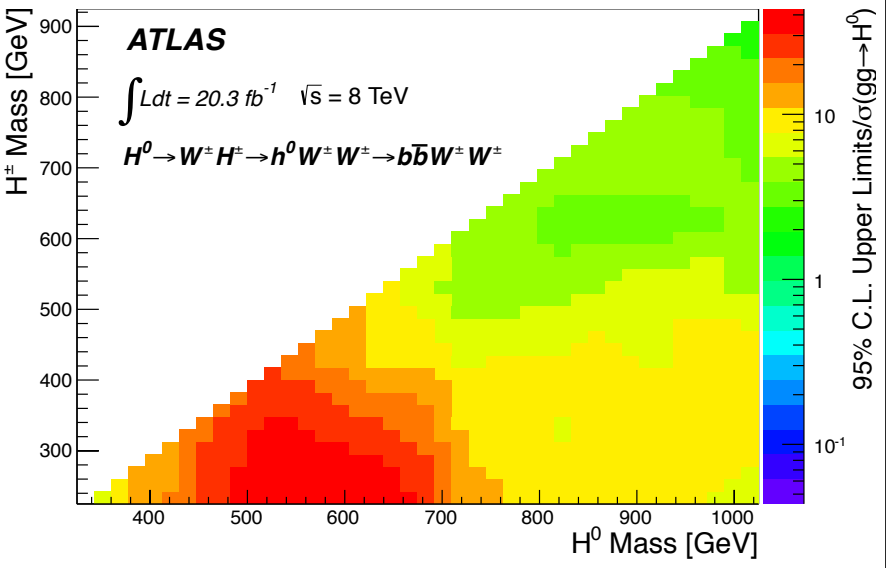
PRL 102, 191802 (2009)

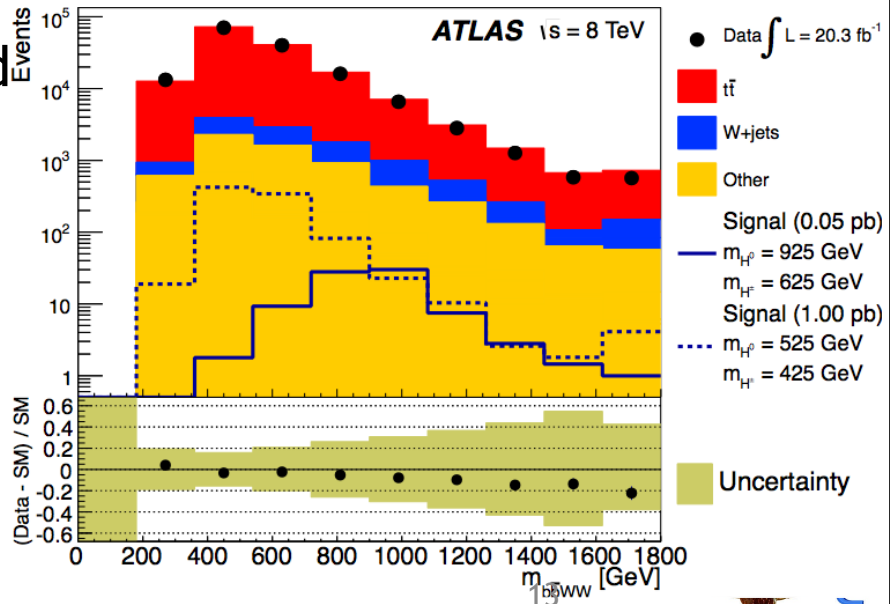


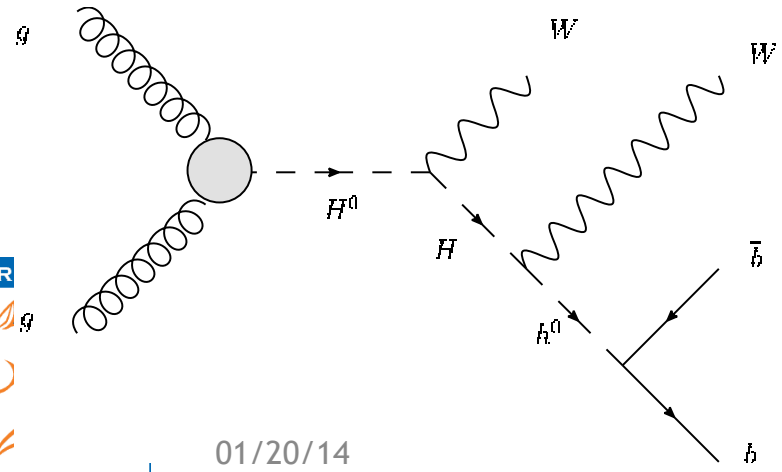
Type I 2HDM

Higgs Cascade searches at ATLAS and CDF

- ATLAS and CDF have searched for heavy Higgs cascade.
  - $H0 \rightarrow H^+W^- \rightarrow W^+W^-h^0 \rightarrow jj\ell\nu b\bar{b}$
- The main background is $t\bar{t}$.
  - CDF enhances S/B with constraints on m_{H0} and m_{H+} and used the $m(b\bar{b})$ as discriminating variable.
  - ATLAS uses a BDT: m_{H0}, m_{H+}, and h_0, $\Delta R(b, \bar{b})$, and candidate top quark masses. The number of events that pass the BDT threshold is used to set limits.

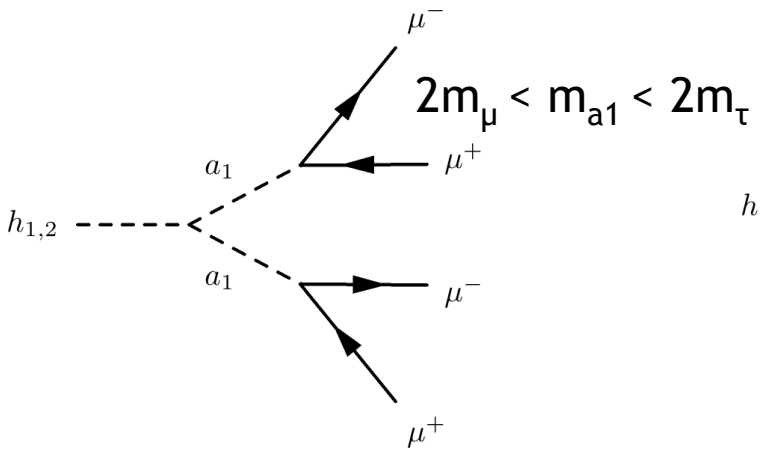


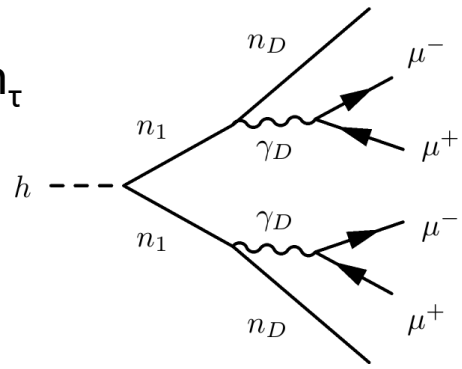




NMSSM Searches

- NMSSM provides a solution to the μ problem in MSSM and introducing a new gauge singlet field under $U(1)_{PQ}$ symmetry in the Higgs sector of the superpotential.
  - A total of 7 Higgs are now possible, 3 CP-even ($h_{1,2,3}$), 2 CP-odd ($a_{1,2}$) and two charged Higgs bosons.
- Searches have been performed at ATLAS, CMS, Babar, Tevatron, and LEP
- CMS searched for a Higgs boson decaying to two new CP-od bosons that subsequently decayed to muons utilizing the entire 8 TeV data set.





Dark-SUSY
[1, 2, 3]

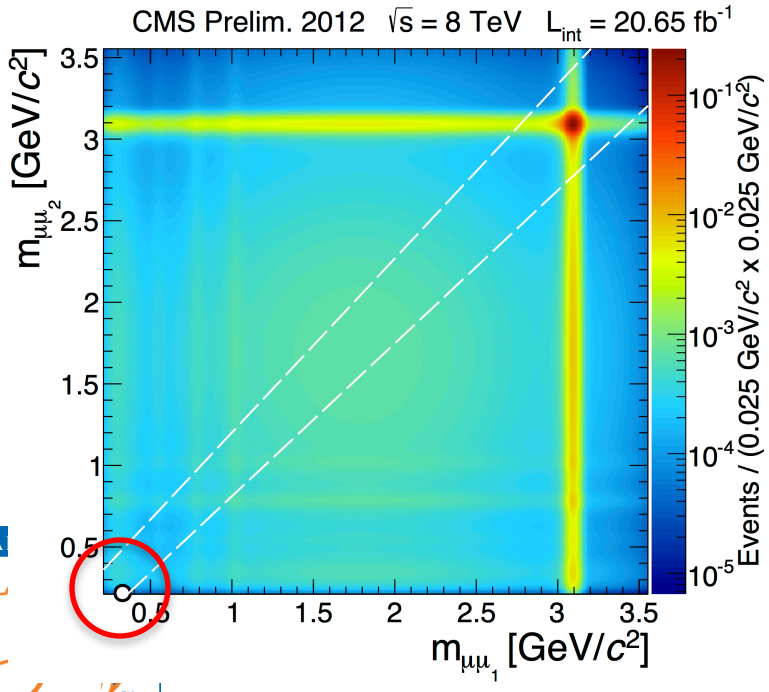
NMSSM h→2a+X→4μ+X CMS

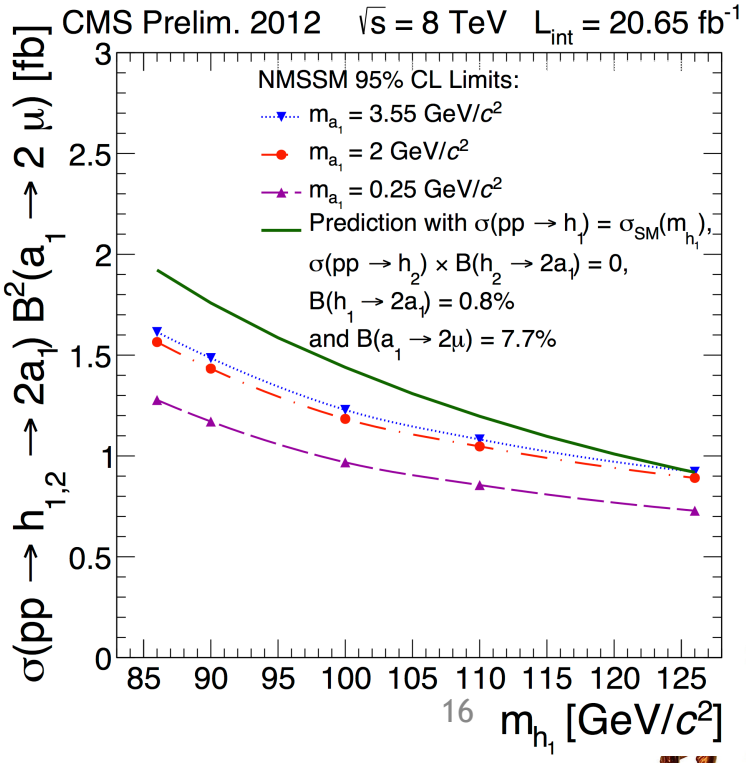
- Four muons with pT > 8 GeV are required with one of the muons having at least 17 GeV (trigger-constraint).
- Opposite signed muons are paired and required to have $m_{\mu\mu} < 5$ GeV and are consistent with the same vertex. Two pairs of muons are then required to have a consistent mass and come from the same pp vertex:
  - $|z_{\mu\mu1}-z_{\mu\mu2}| < 1$ mm

  and be isolated from other activity in the event.
- Main backgrounds:
  - b mesons, estimated in background rich control regions.
  - Direct J/ψ production, estimated with Pythia8 and scaled to data
  - other SM backgrounds negligible

NMSSM h→2a+X→4μ+X CMS

- 1 event passed all signal selections with a predicted background of 3.8±2.1 events.
- Limits were derived in the context of NMSSM (shown), Dark-SUSY, and in a model independent manner.





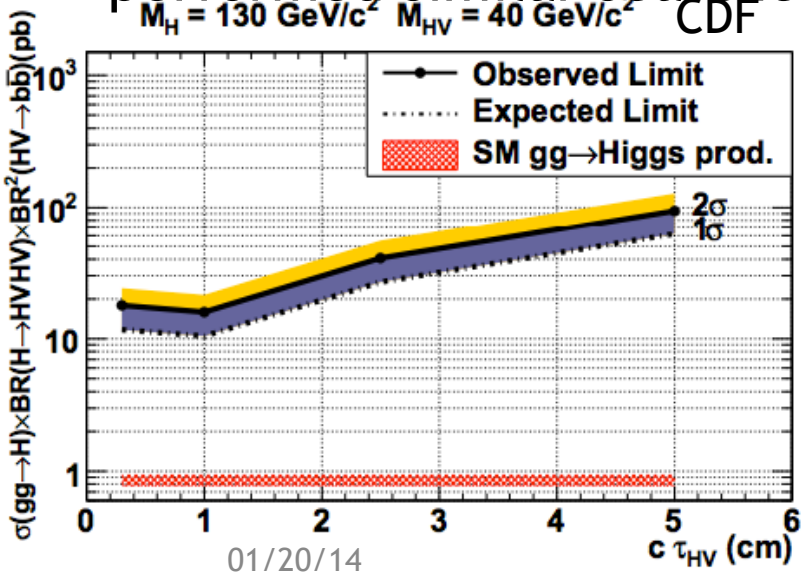
Other MSSM and NMSSM Searches

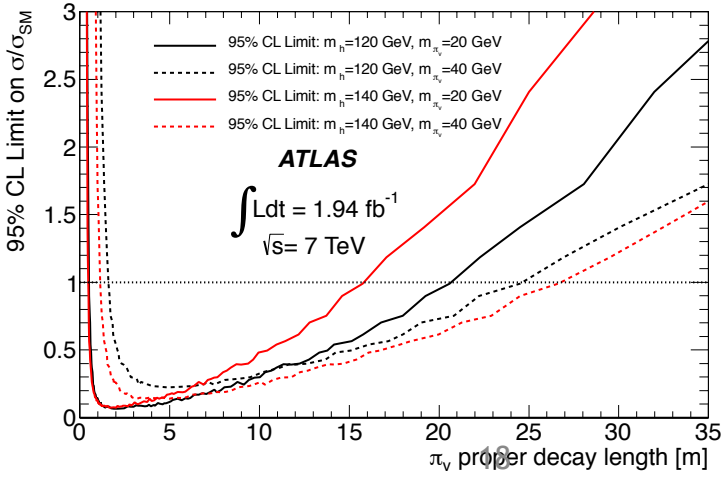
- No significant excess observed in the following.
- ATLAS performed two searches in 2010/2011 Data:
  - $a \to \mu\mu$ 36 pb^{-1}
  - $H \to aa \to 4\gamma$ 4.9 fb^{-1}
  - $H^+ \to c\bar{s}$ 0.36 fb^{-1}
- CMS has performed in 7 TeV data
  - $a \to \mu\mu$ different mass range for a: [5.5-8.7] and [11.5,14] GeV
- D0 performed a search:
  - $H \to aa \to \mu\mu\mu\mu / \mu\mu\tau\tau$

Hidden Valley, Long Lived Particle searches

- There are multiple scenarios in which a Higgs boson could decay to particles that couple weakly to the SM. For example:
  - $H \rightarrow \pi_v \pi_v$

  where the π_v are Hidden Valley neutral particles that have displaced fermion/anti-fermion vertices.
- ATLAS performed a search for displaced vertices in its Muon Spectrometer using 1.94 fb^{-1} of 7 TeV data. CDF and D0 performed similar searches.





FCNC in top Decays t->cH in ATLAS

- ATLAS and CMS searched for a Flavor Changing Neutral Current in top decays:
  - $t \rightarrow cH$
- $t \rightarrow cH(Z)$ processes are forbidden at tree level in the SM and highly suppressed at higher orders. The presence of signal would signify new physics beyond the SM.
- ATLAS considered scenarios with $H \rightarrow \gamma\gamma$.
- CMS considered scenarios with $H \rightarrow WW/ZZ/\tau\tau$ in part of a more generalized ≥ 3 lepton SUSY search.
- No significant excess was observed in either analysis so limits on the branching ratio $t \rightarrow cH$ of 0.83% (ATLAS) and 1.28% (CMS) were derived.

Summary

- Although at the moment the newly discovered Higgs boson appears to be SM-like, there is still potential for new physics beyond the SM.
  - Based on our current coupling measurements from CMS and ATLAS, there is still the possibility for Higgs physics beyond the Standard Model.
- Many searches have been performed at the LHC and at the Tevatron. So far, no evidence for exotic decays have been observed.

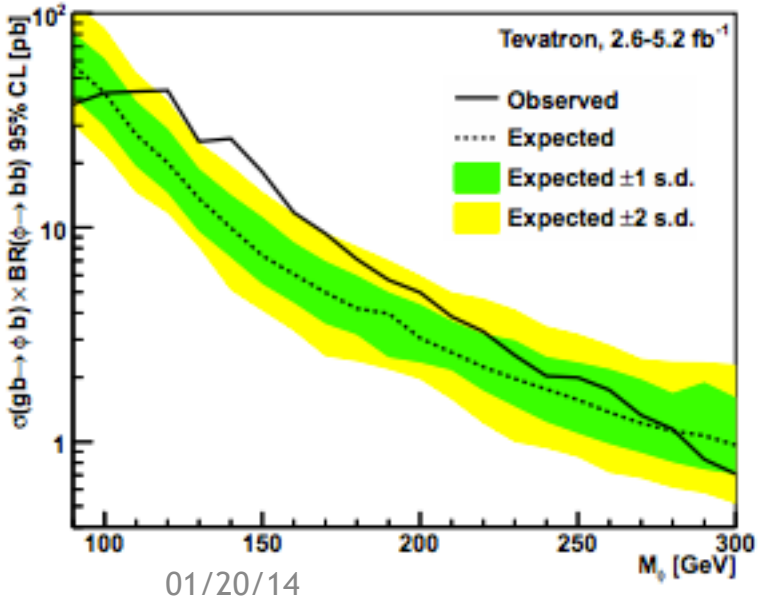
BACKUP

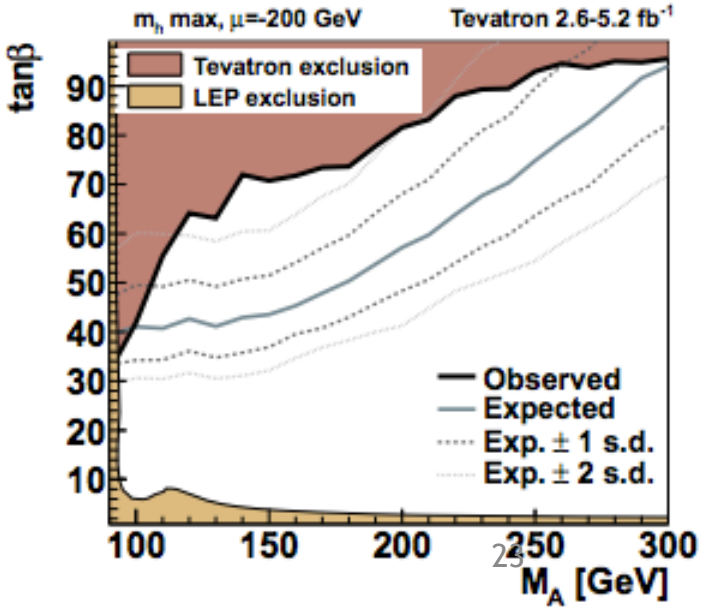
Higgs Discovery

- In July 2012, the discovery of a Higgs-like boson was jointly announced by the ATLAS and CMS collaborations.
  - The decay channels with the highest significance where the $H \rightarrow ZZ$ and $\gamma\gamma$.
- Since then, both experiments have further confirmed that this particle is indeed SM-Higgs like
  - Evidence observed in the WW and $\tau\tau$ final states
  - ggF, VBF, VH, and ttH production modes have all been studied and σ/σ_{SM} consistent with 1.
- Combined Higgs searches from CDF and D0 at the Tevatron yield a 3σ observed excess for a 125 GeV Higgs.
- So far detailed coupling studies have been performed by both experiments. No significant deviations from the SM have been observed.
  - ATLAS and CMS have shown that the new particle is most consistent with a 0^+ particle.

MSSM Searches at the Tevatron

- The most recent result from the Tevatron still only covers half of the total luminosity 2.6(5.2) fb^{-1} at CDF(D0)
- The search looks for a neutral Higgs produced in association with one or more b-quarks that decays to b quarks.
- The main background is from QCD multijet events





FCNC in top Decays t->cH in ATLAS

- Theoretical values of FCNC top decays in the Standard Model and other Models.

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}