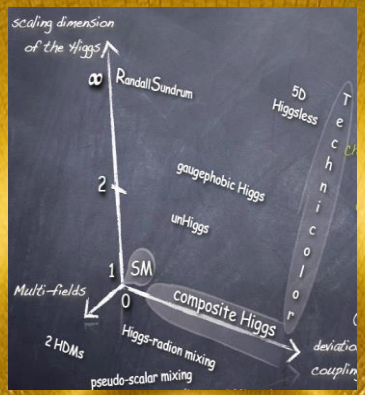
"LHC Run 1 Results: Beyond Standard Model Scalar Boson"

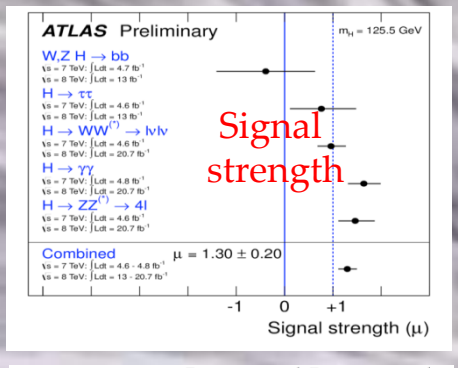
Maxim Titov (CEA Saclay, France)

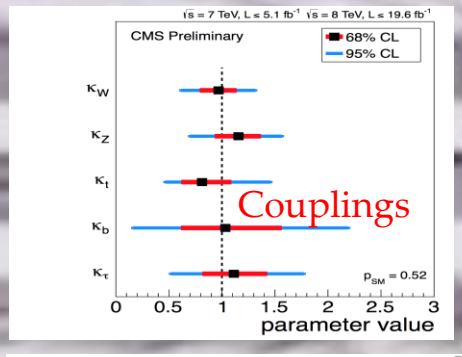
On behalf of the ATLAS and CMS Collaborations

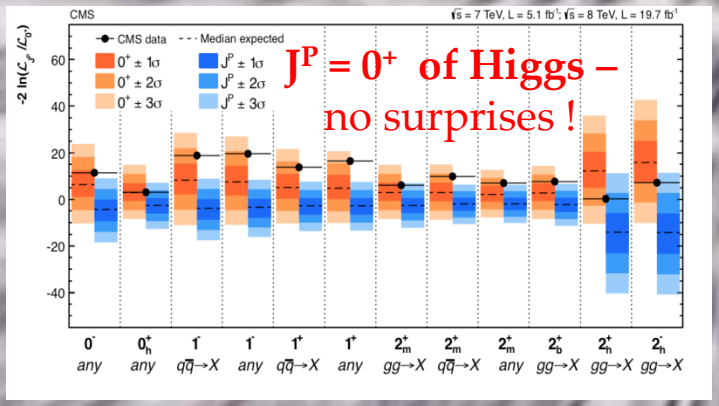


10^{X} Rencontres Du Vietnam "Physics at LHC and Beyond"
Quy Nhon Vietnam, August 10 – 17, 2014

Three Years of Remarkable LHC Operations: First Steps in an Incredible Journey







$J^P = 0^+$ of Higgs – no surprises !

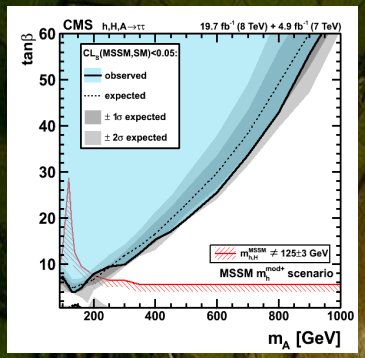
With the discovery of a Higgs boson,
the SM could be completed → and …
it looks very much like "*the SM* Higgs Boson »

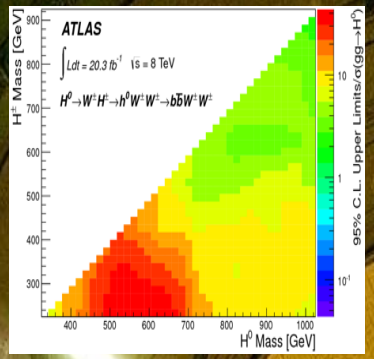
Higgs is a journey, not a destination

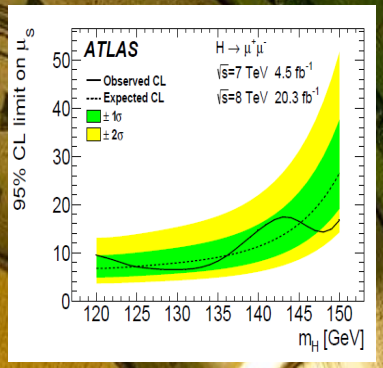
Higgs: A Portal to BSM

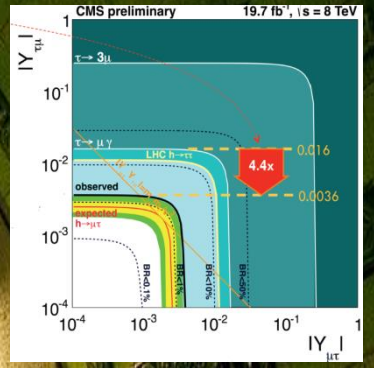
Is the SM Minimal ?
(2HDM/MSSM, NMSSM Models, Multi-Higgs Cascades)

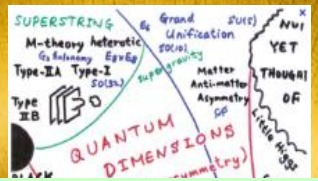
Rare Higgs Modes, FCNC, LFV Higgs Decays, Long-Lived Higgs

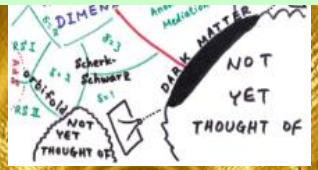




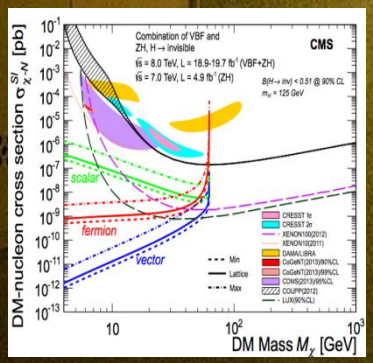


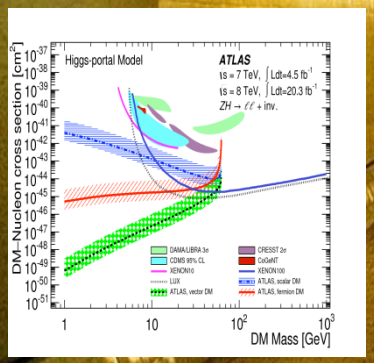




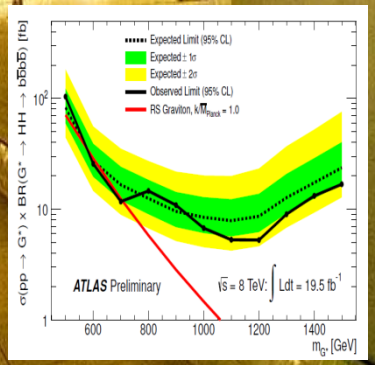


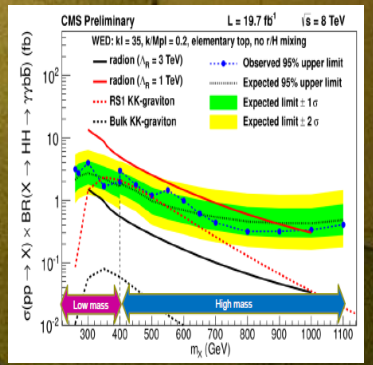
Tool for Discovery - Portal to DM
(invisible decays), hidden sectors





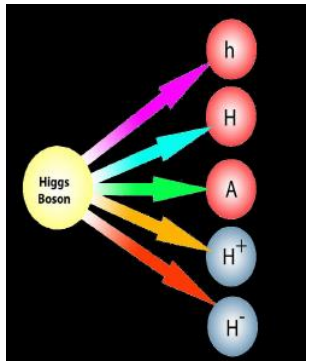
Higgs Boson Pair Production, resonant searches, etc …





Two Higgs Doublet Models (2HDM)

- Effective theory; extension of SM by adding a second complex Higgs doublet



- 5 Higgs Bosons: 2 CP-even neutral bosons: h (light) & H (heavy), 1 CP-odd neutral boson (A) and 2 charged bosons (H±)
- 6 Parameters: m_h, m_H, m_A, $m_{H\pm}$; α = mixing between h and H; $\tan\beta = \langle vev\rangle_u/\langle vev\rangle_d$ satisfying $\langle vev\rangle_u^2 + \langle vev\rangle_d^2 = (246\ \text{GeV})^2$

- Flavor conservation can be enforced via symmetries

- Four types of 2HDM, depending on the way the Higgs doublets couple

Type I: one doublet couples only with vector bosons [Fermiophobic], other only with fermions
Type II: one doublet couples with up-type quarks, other with down-type quarks and leptons [MSSM-like]
Type III: one doublet couples with quarks as in Type I, other with leptons as in Type II [lepton-specific]
Type IV: one doublet couples with quarks as in Type II, other with leptons as in Type I [Flipped]

2HDM with natural flavor conservation:

Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

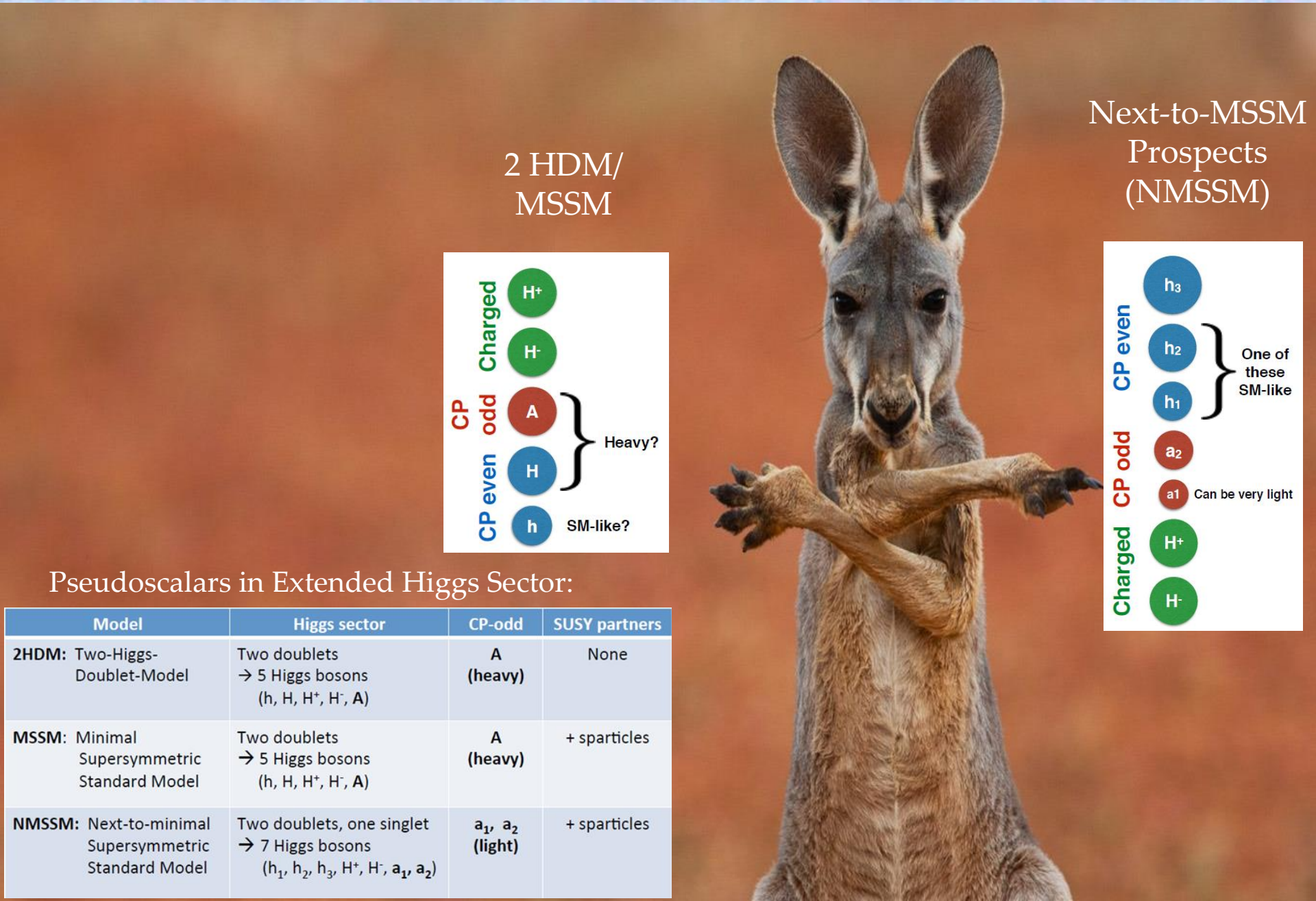
G.C. Branco et al., Phys. Rep. 516 (2012) 1

- MSSM: 2HDM Type II + SUSY sector

- NMSSM: MSSM+1 additional singlet
  → 7 Higgs bosons:
  5 neutral h1, h2, h3 (CP even), a1, a2 (CP odd), 2 charged (H±)

- Flavor-changing Yukawa couplings are in principle possible (Type III models)

Beyond the Standard Model Higgs Sector



2 HDM/
MSSM

Next-to-MSSM
Prospects
(NMSSM)

Pseudoscalars in Extended Higgs Sector:

Model	Higgs sector	CP-odd	SUSY partners
2HDM: Two-Higgs-Doublet-Model	Two doublets → 5 Higgs bosons (h, H, H^+, H^-, **A**)	**A (heavy)**	None
MSSM: Minimal Supersymmetric Standard Model	Two doublets → 5 Higgs bosons (h, H, H^+, H^-, **A**)	**A (heavy)**	+ sparticles
NMSSM: Next-to-minimal Supersymmetric Standard Model	Two doublets, one singlet → 7 Higgs bosons (h_1, h_2, h_3, H^+, H^-, $\mathbf{a_1}, \mathbf{a_2}$)	$\mathbf{a_1}$, $\mathbf{a_2}$ **(light)**	+ sparticles

Summary of 2 HDM / MSSM and NMSSM Searches

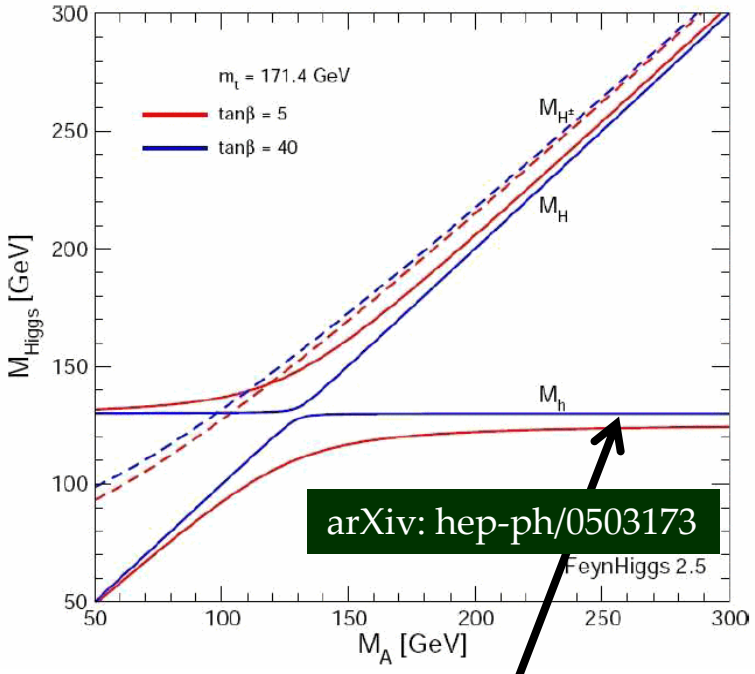
	CMS			ATLAS		
	L(fb^{-1})	Result	Reference	L(fb^{-1})	Result	Reference
	2 HDM Neutral and Charged Higgs:					
$\varphi \rightarrow \tau\tau$	25	m_A – tanβ	arXiv: 1408.3316	20	m_A-tanβ	ATLAS-CONF-2014-049
$\varphi \rightarrow bb$	5	m_A - tanβ	PLB 722, 207 (2013)	-	-	-
$H^+ \rightarrow \tau\nu$+ lep/ $\tau\nu$ +jet	5	Br ($t \rightarrow bH^+$)	CMS-HIG-12-052	5 20	Br ($t \rightarrow bH^+$) m_A-tanβ σ (H+)	JHEP03(2013)076 ATLAS-CONF-2013-090
$H^+ \rightarrow cs$	20	Br ($t \rightarrow bH^+$)	CMS-HIG-13-035	5	Br ($t \rightarrow bH^+$)	EPJC736(2013)2465
	2 HDM Higgs Cascade and Indirect Limits:					
$H \rightarrow W^{\pm}H^{\mp} \rightarrow W^{\pm}W^{\mp}h(bb)$	-	-	-	20	$m(H^+)$-$m(h^0)$	PRD89,032002(2014)
$H \rightarrow hh$, $A \rightarrow Zh$	20	tan β – cos (β–α)	CMS-HIG-13-025	-	-	-
Indirect limits $\gamma\gamma, VV, \tau\tau, bb$	-	-	-	25	tan β – cos (β–α)	ATLAS-CONF-2014-010
	NMSSM Neutral Bosons; Doubly Charged Higgs:					
$h1 \rightarrow 2a1 \rightarrow 4\mu$	21	σxBR($a \rightarrow 4\mu$)	CMS-HIG-13-010	-	-	-
$h1 \rightarrow a1 \rightarrow 2\mu$	1	σxBR($a \rightarrow 2\mu$)	PRL109,121801(2012)	0.04	σxBR($a \rightarrow 2\mu$)	ATLAS-CONF-2011-020
$h1 \rightarrow 2a1 \rightarrow 4\gamma$	-	-	-	5	σxBR($a \rightarrow 4\gamma$)	ATLAS-CONF-2012-079
Doubly charg $\Phi^{++} \rightarrow l^+l^+$	5	σxBR($\Phi^{++} \rightarrow l^+l^+$);	EPJC 72 (2012) 2189	1.5	σxBR($\Phi^{++} \rightarrow l^+l^+$);	PRD85,032004(2012)

*Results discussed in the talk (marked in magenta)

MSSM Landscape of the BSM Higgs Searches

Five Higgs Boson in MSSM:

→ CP-even (h, H); CP-odd (A), $H^{+/-}$: assume 125 GeV is light CP-even Higgs in 2HDM ?



In m_h^{max}: $m_h \approx 130$ GeV.

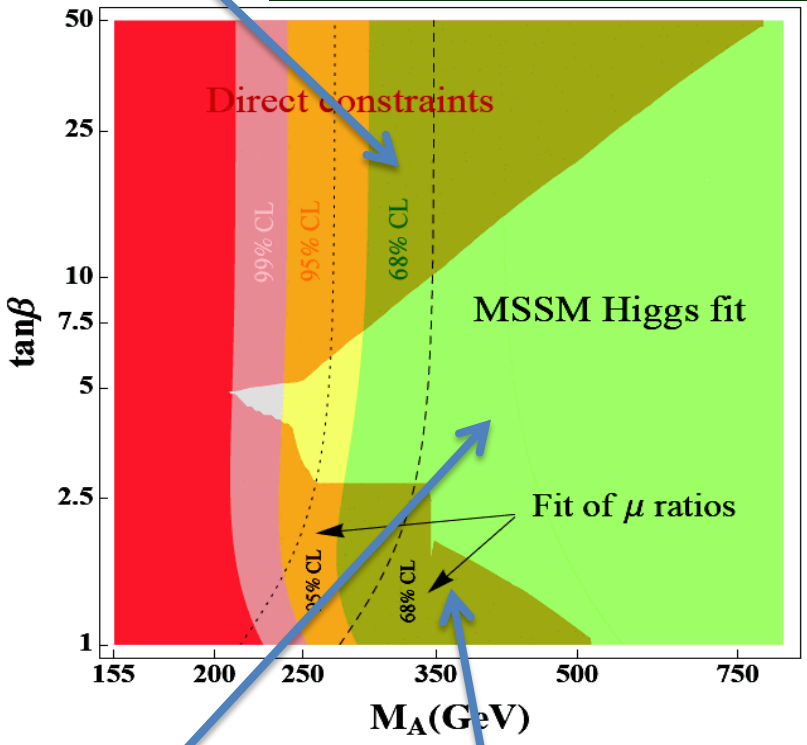
→ Move to new scenarios with $m_h \approx 125$ GeV.

6 New MSSM Benchmark Scenarios:

- Proposed by M. Carena et al., Eur. Phys. J. C73, 2552(2013)
- Each addressing certain phenomenology

- High tan β : $\phi \to \tau\tau$, $\phi \to \mu\mu$; $H^+ \to \tau\nu$, tb

A. Djouadi et al., arXiv: 1307.5205



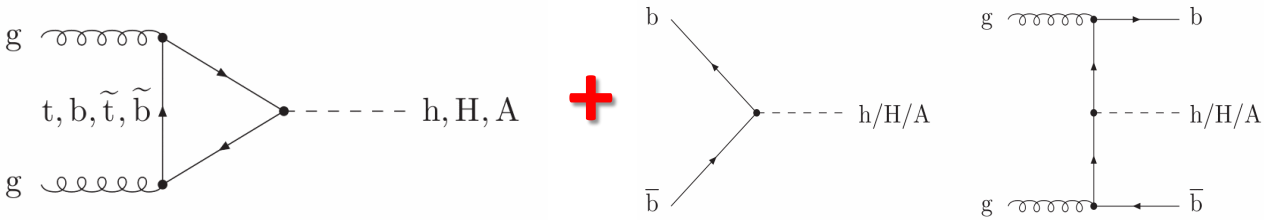
- Intermediate tanβ:

$H/A \to \chi_i^0\chi_j^0$, $\chi_i^+\chi_j^-$; $H^+ \to \chi_i^+\chi_j^0$

- Low tan β: $A \to Zh$; $H \to hh$, tt; $H^+ \to cs$, cb, τν, tb, Wh

Neutral MSSM Higgs Boson φ(h, H, A) Searches

Production via gluon fusion (b-, t- loops) and associated b-quark annihilation



- 2 HDM and Fermions: enhanced coupling to b-quarks and τ-leptons

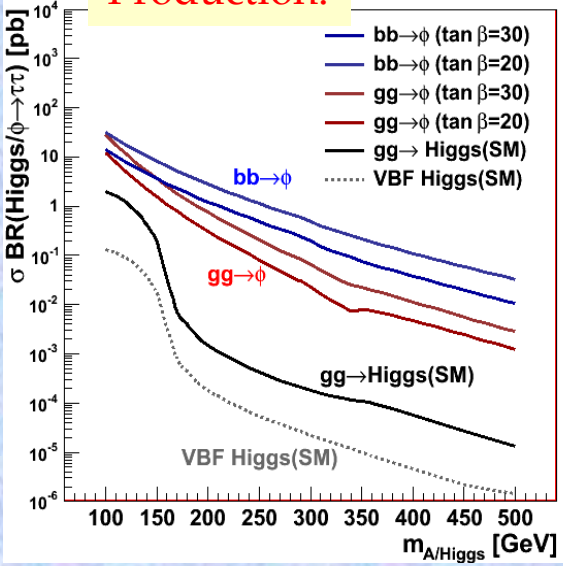
  ($g^{MSSM}_{b\bar{b}H} = \tan\beta \cdot g^{SM}_{b\bar{b}H}$ ➔ production rate enhanced × $\tan^2\beta$); associated production dominant

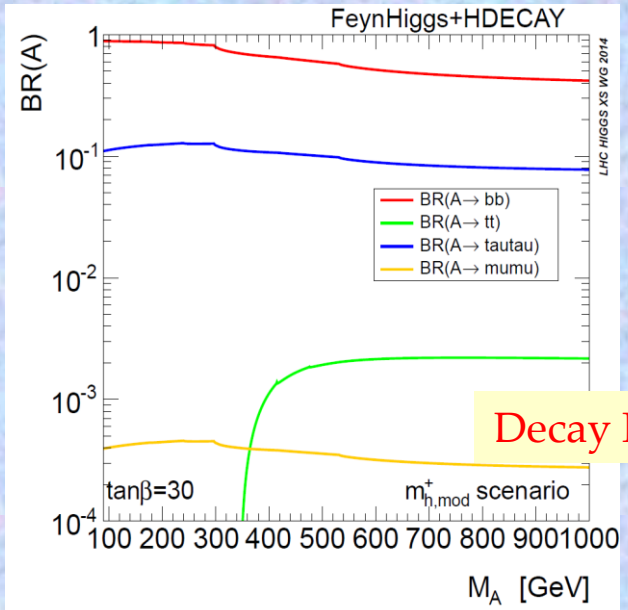
  - small-moderate tanβ: gluon-fusion production is dominant
  - high tanβ: b-associated production is enhanced

- Decay Modes: bbar (90%), ττ (10%), μμ (0.04%)

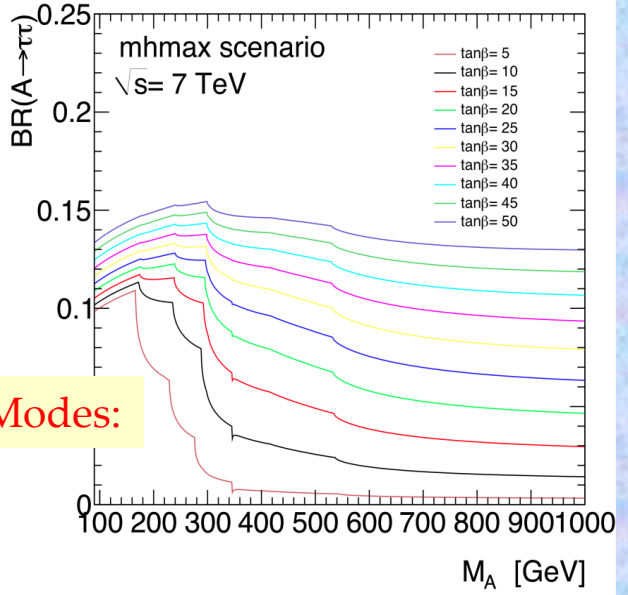
Coll.	Channel	Dataset	Cite
CMS	ττ	25fb-1(7+8TeV)	CMS-PAS-HIG-13-021
ATLAS	ττ/μμ	5fb-1(7TeV)	JHEP02(2013)095
LHCb	ττ	1fb-1(7TeV)	JHEP05(2013)132
D0	ττ+bb	5-7fb-1(2TeV)	PLB 710, 569 (2012)
D0+CDF	bb	3-5fb-1(2TeV)	PRD 86, 091101 (2012)
CMS	bb	3-5fb-1(7TeV)	PLB 722, 207 (2013)

Production:





Decay Modes:



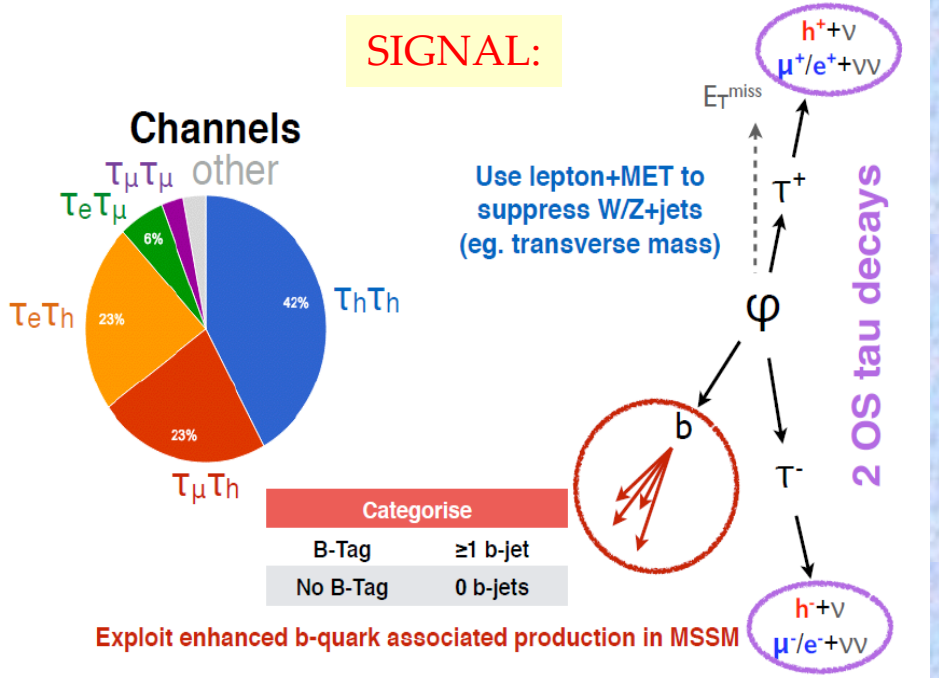
Neutral MSSM Higgs Boson φ(h, H, A) Searches

- Cover five of six possible ττ decay patterns: $\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, $\tau_{had}\tau_{had}$, $\tau_e\tau_\mu$, $\tau_\mu\tau_\mu$
- Split events into b-tag and no-b-tag categories

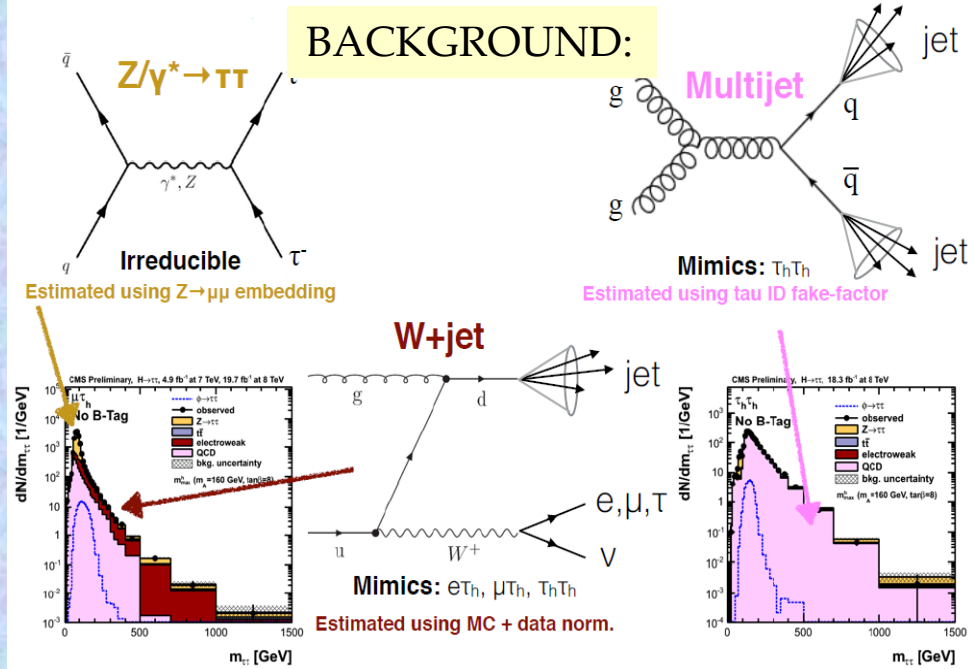
	ATLAS	CMS
Channels	$\tau_h\tau_h, e\tau_h, \mu\tau_h, e\mu$ (94%)	$\tau_h\tau_h, e\tau_h, \mu\tau_h, e\mu, \mu\mu$ (97%)
Categories	ll, lh: b-tag / b-veto lh high-mass: incl. hh: single-/di-tau trigger	all channels: b-tag / no b-tag
Discriminant	ll, lh: di-tau mass taking missing energy into account (MMC) hh: total transverse mass	all channels: di-tau mass taking missing energy into account (SVFit)

- Dilepton: sensitive at low mass where hadronic background is large
- Semi-leptonic: sensitive at wide range of masses
- Hadronic: sensitive at high mass:hadronic bkg. decreases

SIGNAL:



BACKGROUND:

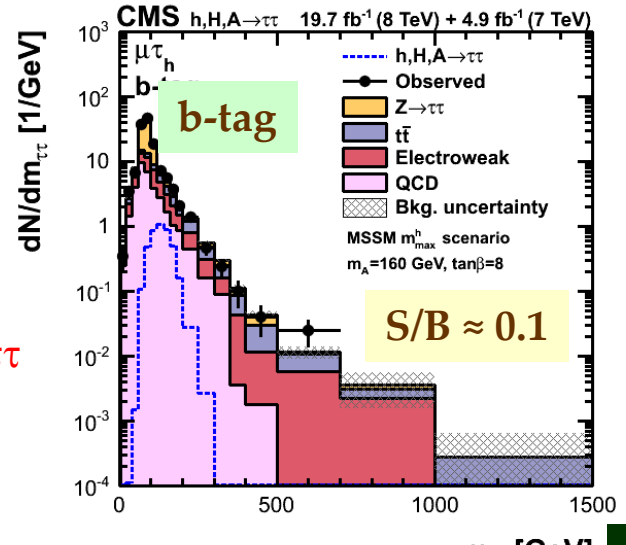


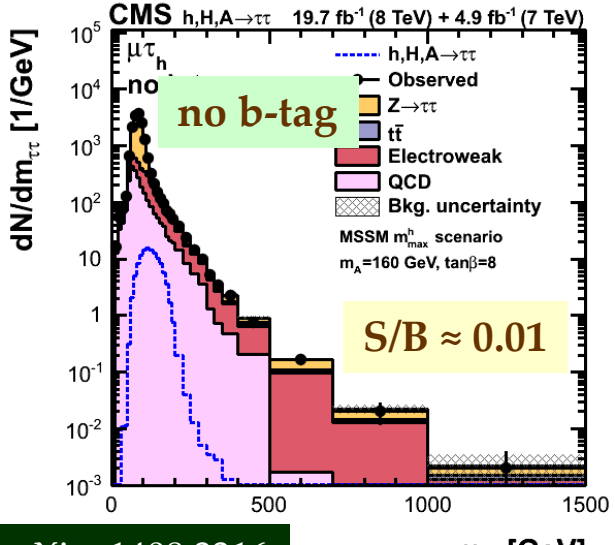
Neutral MSSM Higgs Boson φ(h,H,A) → ττ Search

- Di-tau mass reconstruction (SVFit) based on likelihood method using e/μ/τ momenta and E_T^{miss} information

J. Phys. Conf. Ser. 513(2014)022035

- Analysis is similar to SM H → ττ but optimized for different production mechanisms and Higgs boson masses



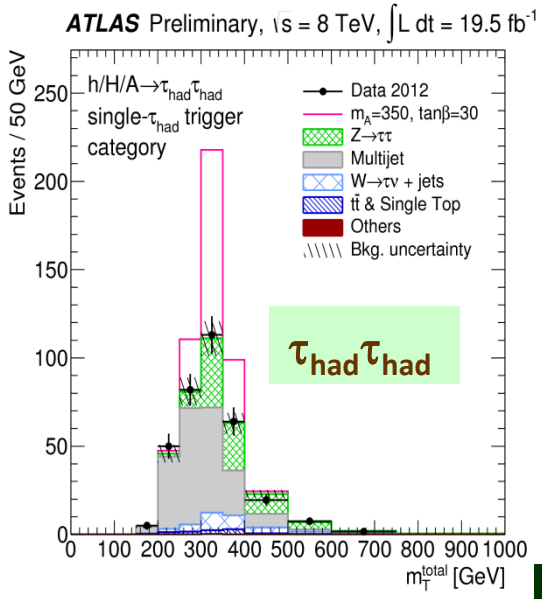


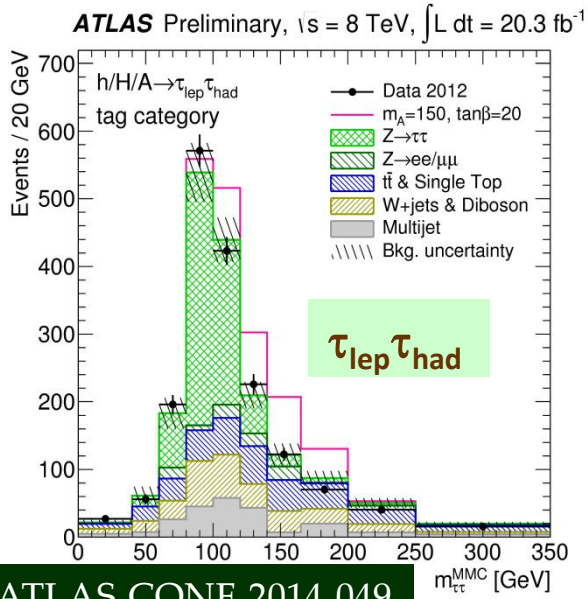
arXiv: 1408.3316

- Missing Mass Calculation (MMC) method based on lepton/tau momenta and E_T^{miss} information

NIMA654(2011) 481

- Separate optimizations in $\tau_{lep}\tau_{had}$ channel for the high- and low- mass
  → best sensitivity at high mass
  - $\tau_{lep}\tau_{lep}$ and $\tau_{lep}\tau_{had}$ channels combined for m_A<200 GeV
  - $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels combined for m_A≥200 GeV





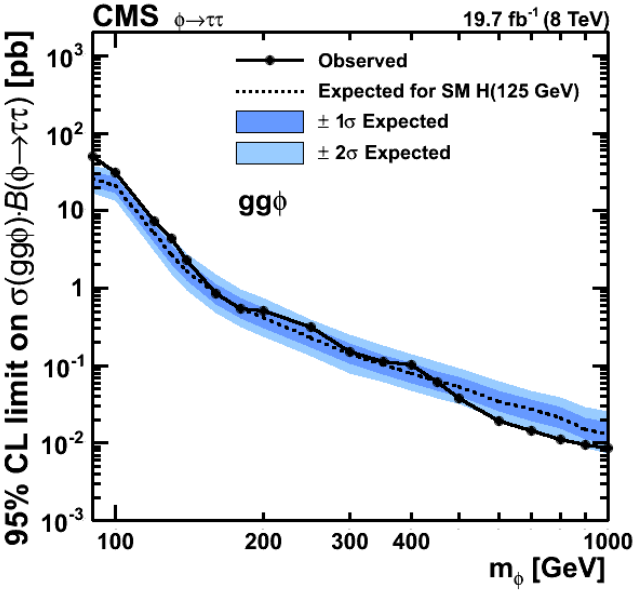
ATLAS-CONF-2014-049

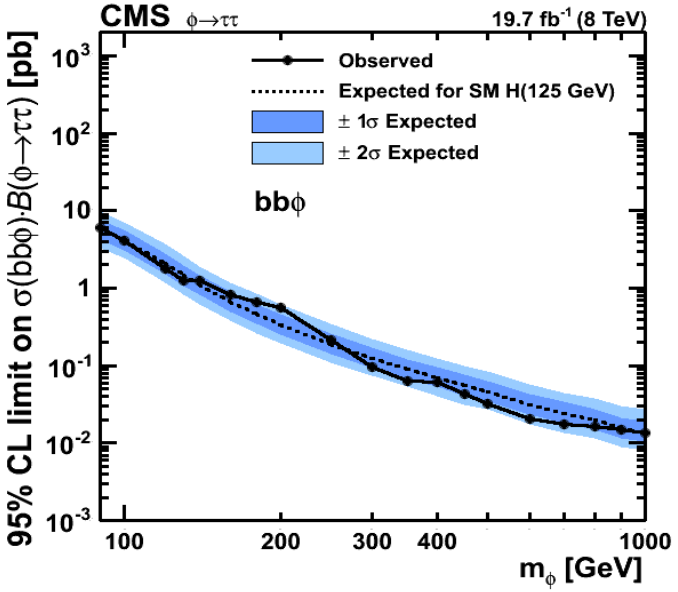
Model-Independent Limits: Neutral Higgs Boson φ → ττ Searches

- No evidence of signal beyond the SM found
- Separate for gluon-fusion and b-associate production mechanisms

  → Calculate σ*BR limit on one process while the other is left floating freely

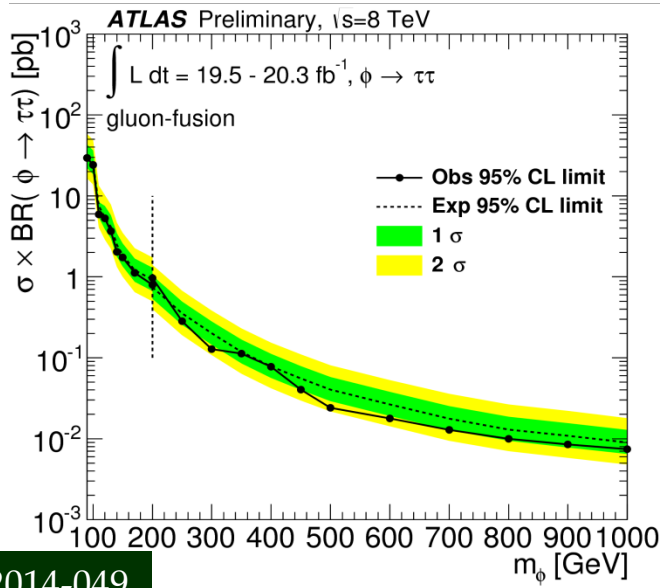
arXiv: 1408.3316

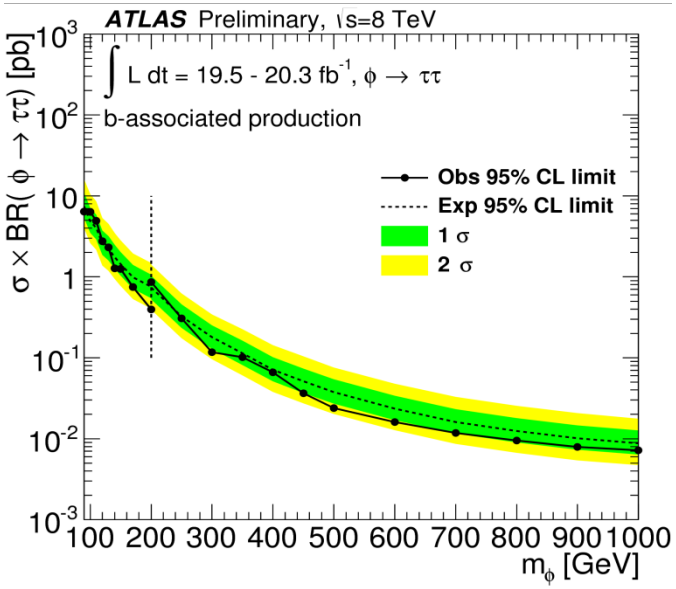




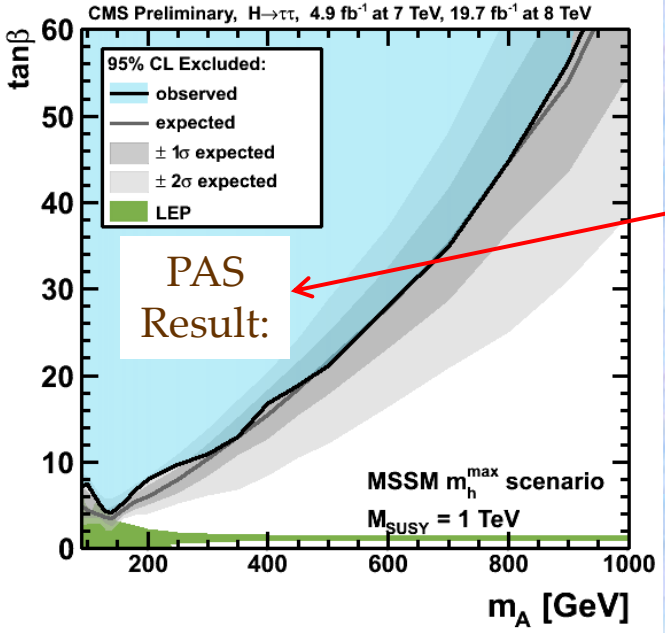
- Excluded σ×BR ranges from > 29 pb (> 6.4pb) at m_φ = 90 GeV to > 7.4pb (>7.2pb) at m_φ =1000GeV for ggF (b-associated) mechanisms
- Model-independent σ×BR limits achieve limits down to ~10fb at high mass

ATLAS-CONF-2014-049





φ(h, H, A) → ττ: MSSM Interpretation



Model-Dependent Interpretation: Statistical Approaches

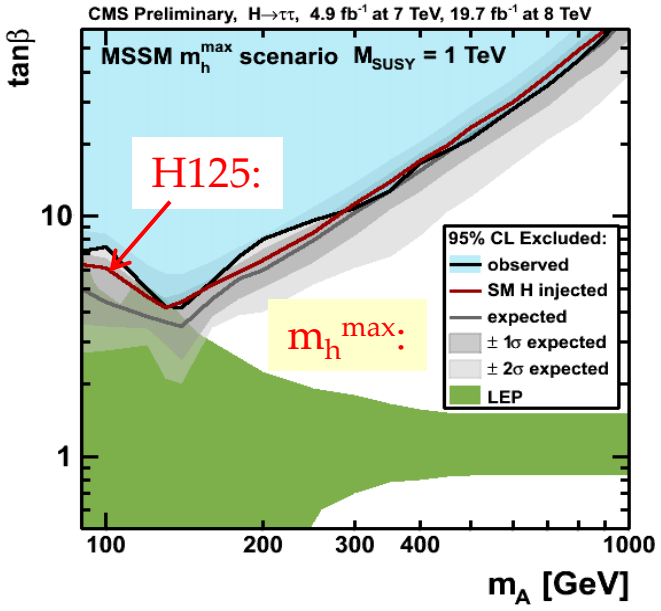
- Old Approach:

  - Test MSSM vs background only (h+H+A+BG) vs (BG)
  - New discovered particle was not taken into account

- New Approach:

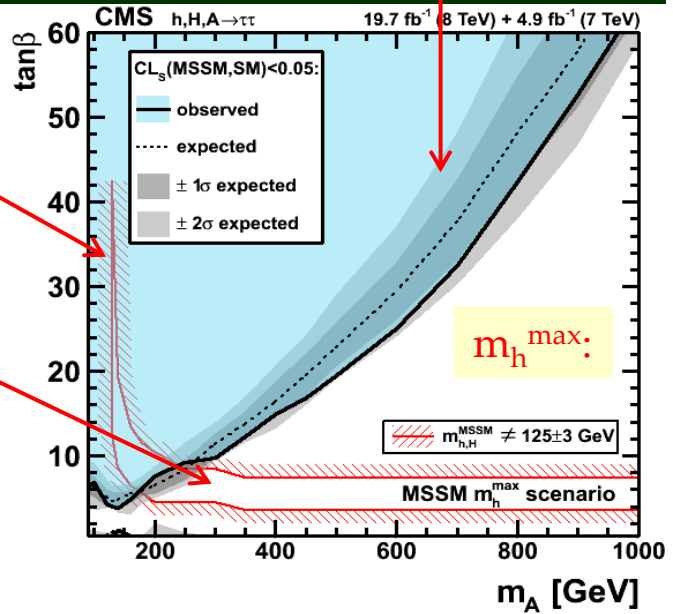
  - Take into account the discovered Higgs boson at 125 GeV
  - Hypothesis test of MSSM vs SM: (h+H+A+BG) vs (h_{SM}+BG)
  - Presence of h(125) weakens the MSSM limits

https://twiki.cern.ch/twiki/bin/viewauth/CMS/Hig13021PaperTwiki



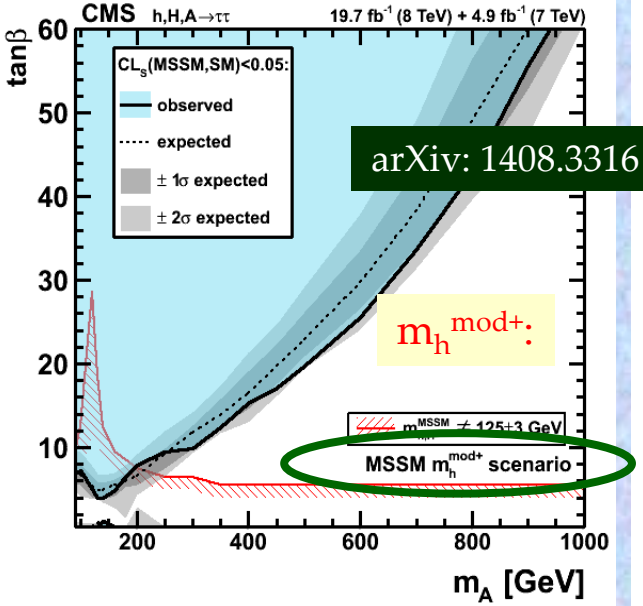
Incompatible with 125 + 3 GeV mass constraint

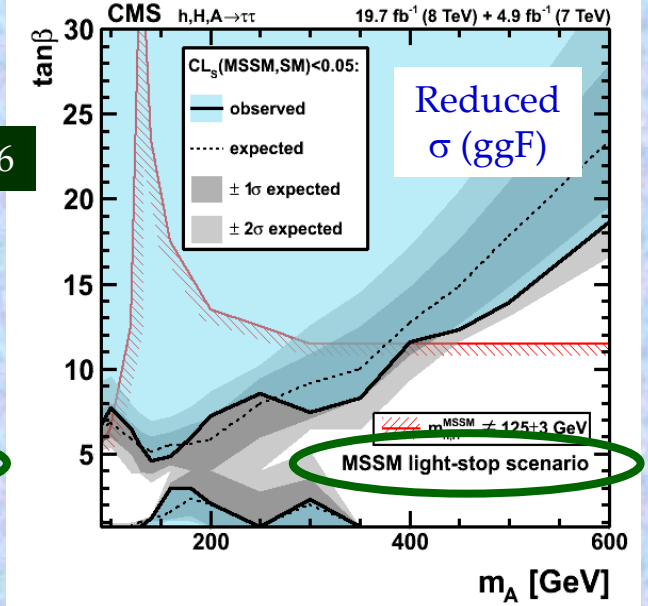
m_h^{max} scenario is in agreement with the Higgs-like state only in a relatively small strip in the M_A–tan β plane at low tan β

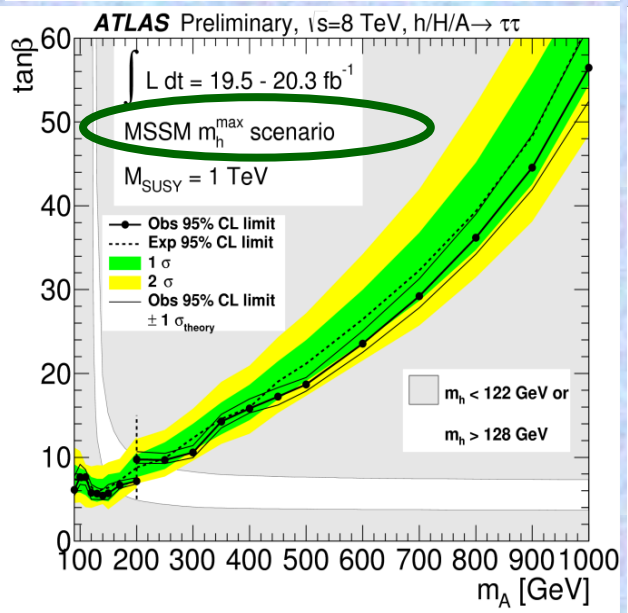


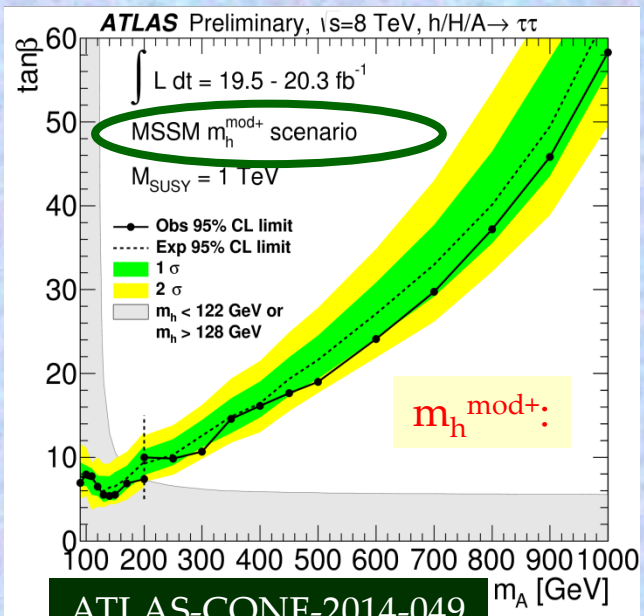
M(A) – tanβ Exclusion Limits: MSSM Benchmark Scenarios

- Very low tan β upper limits (tan $\beta < 5$ for $m_A <$ 250 GeV → touching the LEP constraint at low m_A
- m_A-tanβ exclusions in new benchmark scenarios (arXiv:1302.7033)
- m_h^{mod} scenario much better suited for mass of h(125), than m_h^{max} scenario









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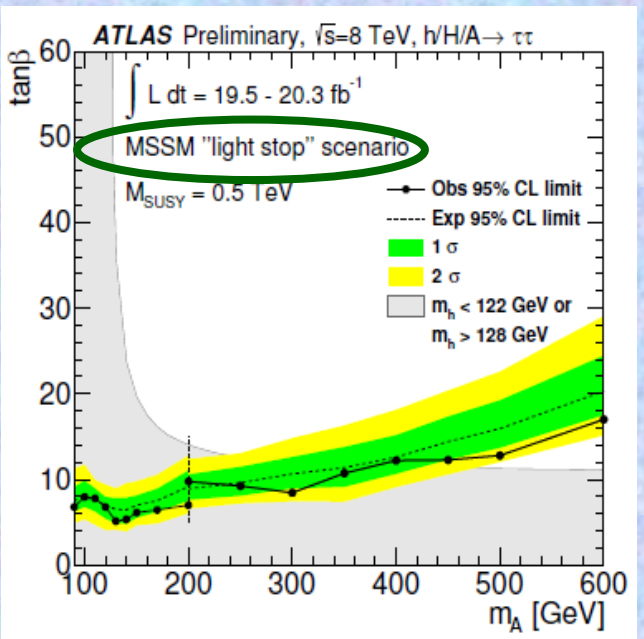
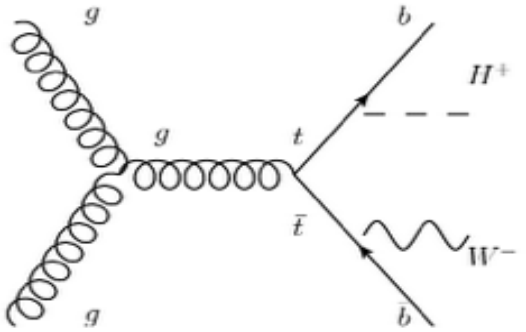


Charged MSSM Higgs Boson Searches

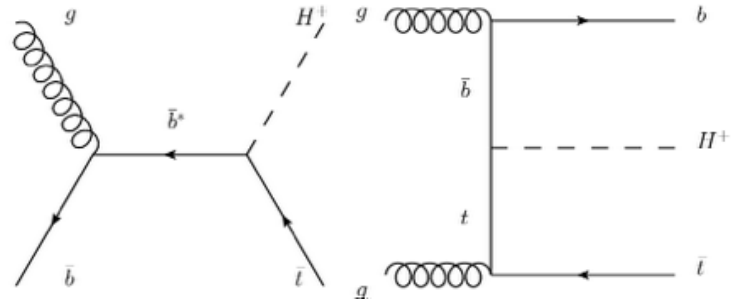
Relation between m_{top} and $M_{H\pm}$ dictates both production mode and decay channels

- Decay via H+ → τν / cs / tb, depending on m(H+) and tan β
- τ / b / top reconstruction play a central role in the searches



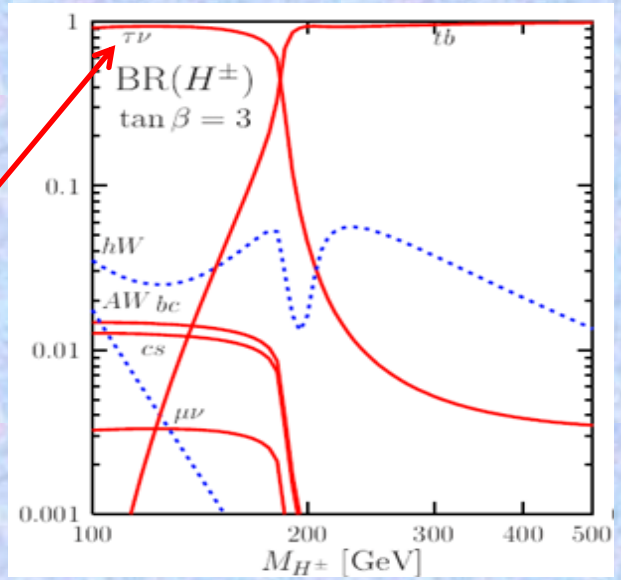
Low mass H± ($M_{H\pm} < m_{top}$):
Final state: H±bWb

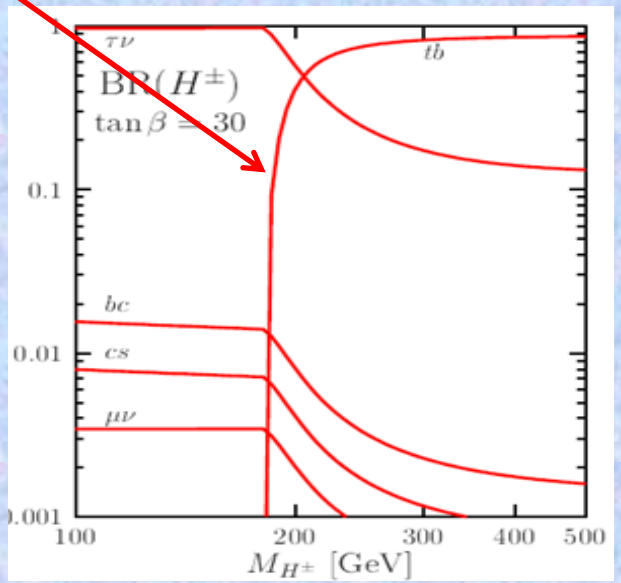
Dominant Decays:
- tanβ > 3: B(H+ → τν)~90%
- tanβ < 1: B(H+ → cs)~70%



Heavy ($M_{H\pm} > m_{top}$):
Final state: tH±

- H± → tb dominant
- H± → τν can be sizeable





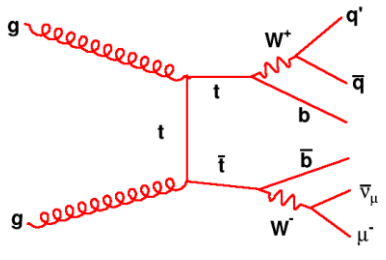
Coll.	Channel	Dataset	Cite
ATLAS	**τν+jets**	**20fb-1(8TeV)**	**ATLAS-CONF-2013-090**
ATLAS	τν+lep	5fb-1(7TeV)	JHEP03(2013)076
ATLAS	cs	5fb-1(7TeV)	EPJC 73 6 (2013) 2465
CMS	τν+lep/jet	5fb-1(7TeV)	CMS-PAS-HIG-12-052
CDF	cs	2fb-1(2TeV)	PRL 103, 101803 (2009)
D0	tb	1fb-1(2TeV)	PRL 102, 191802 (2009)

Charged Higgs Boson Searches (H+ → cs)

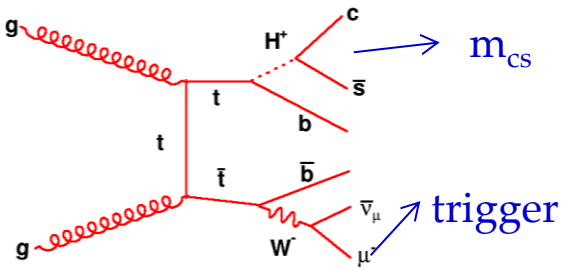
H+ → ***cs*** dominant decay mode for tan β<1 and m(H+)<m_{top}

Same topology as $t\bar{t}$ decays in lepton + jets channel
→ Search for second peak in di-jet mass distribution

SM $t\bar{t}$ semi-leptonic



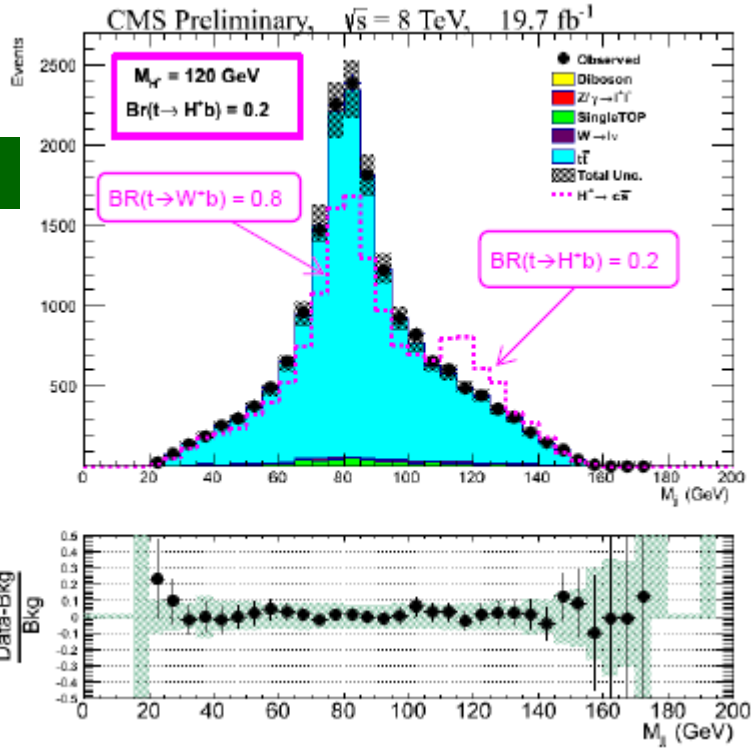
H+ production in top decays



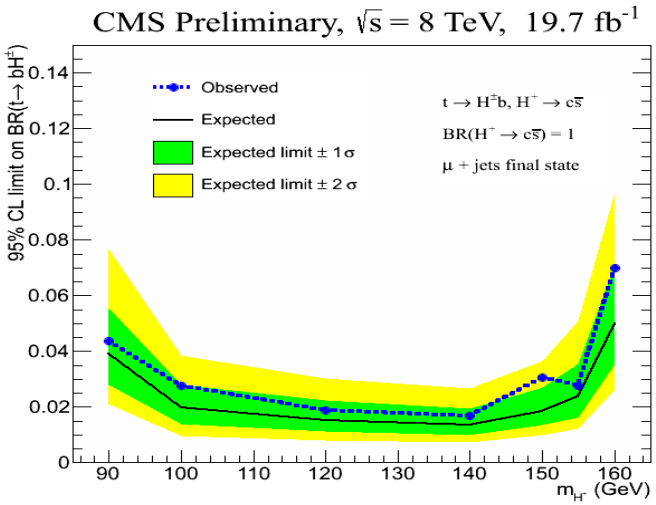
➢ Kinematic fit of both top candidates m=172.5 GeV → improves mass resolution of ***cs*** candidate (WH separation)

➢ Bkgs.: $t\bar{t}$, W/Z+jets, di-bosons, QCD

❖ Mjj (invariant mass of non-b-tagged jets) distribution after kinematic fit → no signal



Light charged Higgs search mH+ < m_{top} :
Determine BR(t→bH+) assuming BR(H+→ ***c***s)=100%



CMS-PAS-HIG-13-035

95% CL:

BR < 1.7 - 7.0% Observed

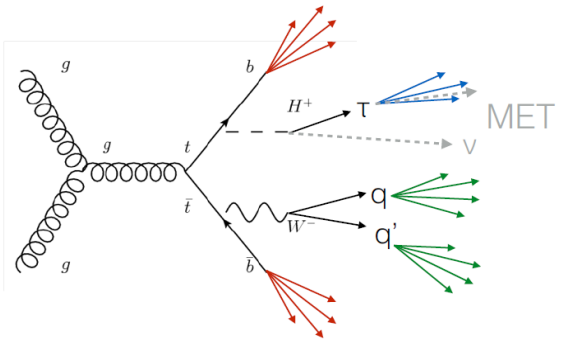
BR < 1.5 – 5.0% expected

Applies to any BSM resonance with the corresponding production & decay topology

Charged Higgs Boson Searches (H+ → τν)

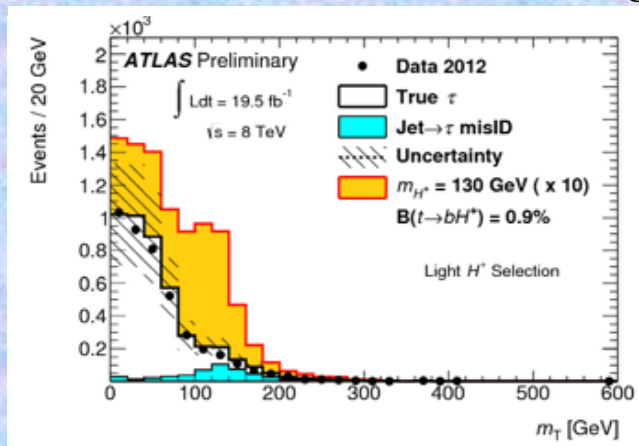
H+ → τν +jets (light and heavy H+)

- 1τ, ≥4 jets (≥1 b-jet), no leptons, large MET;

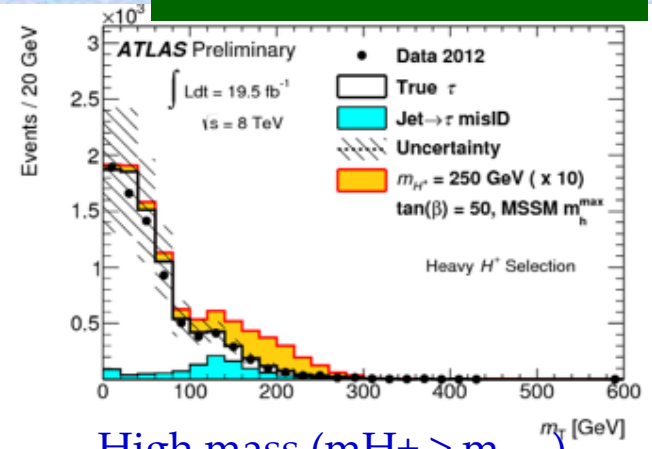


- Look for excess in τ-MET transverse mass distribution
- SM ttbar dominant background

ATLAS-CONF-2013-090



Low mass (mH+ < m top)



High mass (mH+ > m top) (looser selection)

Model-independent limits:

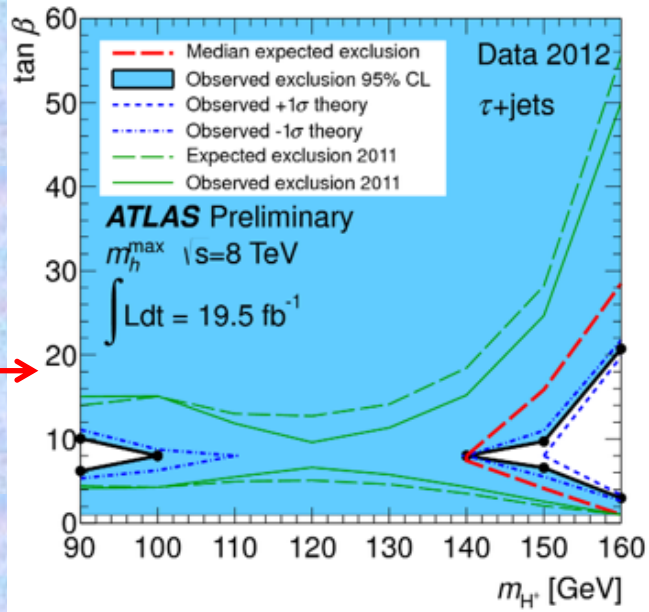
- Light H+:

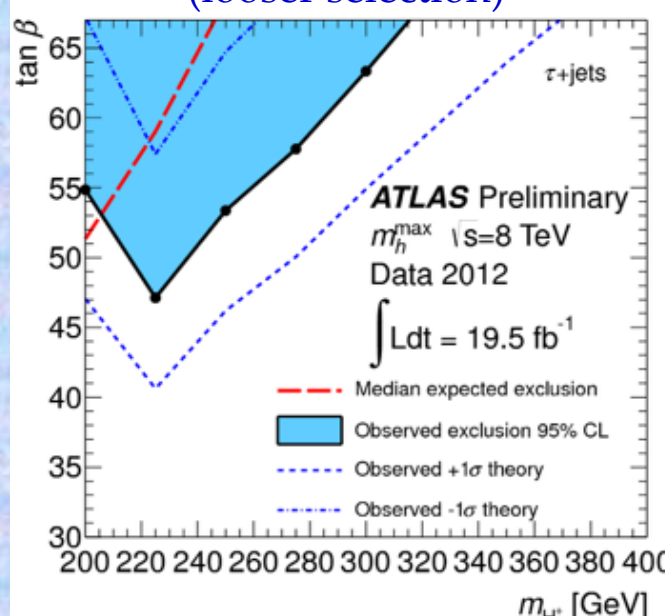
BR ($t \to H^+ b$)=0.24–2.1%
for 90<m_{H^+}<160 GeV

- Heavy H+:

$\sigma(H^+)$=0.017–0.9 pb
for 180< m_{H^+}<600 GeV

Results interpreted in MSSM mhmax scenario

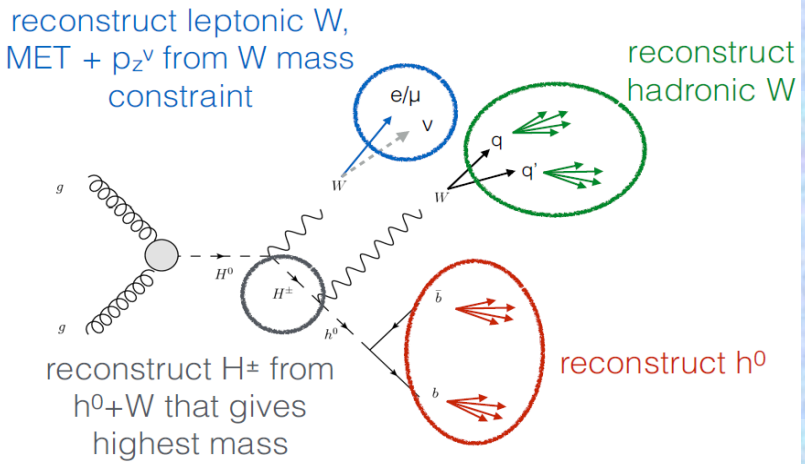




- ongoing searches: heavy H+ → tb

2HDM Higgs Cascade: Searches for Charged Higgs Boson

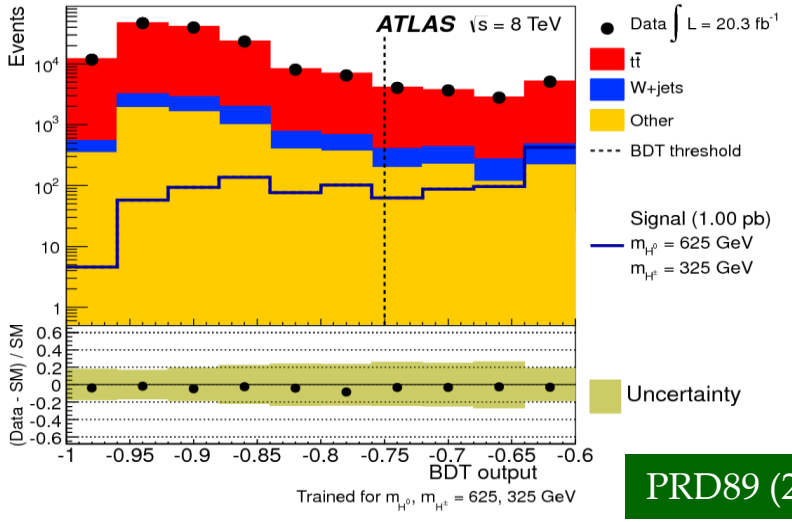
2 HDM phenomenology allow for cascade decays: $H \to W^{\pm} H^{\mp} \to W^{\pm} W^{\mp} h \to W^{\pm} W^{\mp} bb$



- No particular model assumed
- CP-odd (A) too heavy to participate in decay chain
- Only consider gluon fusion production

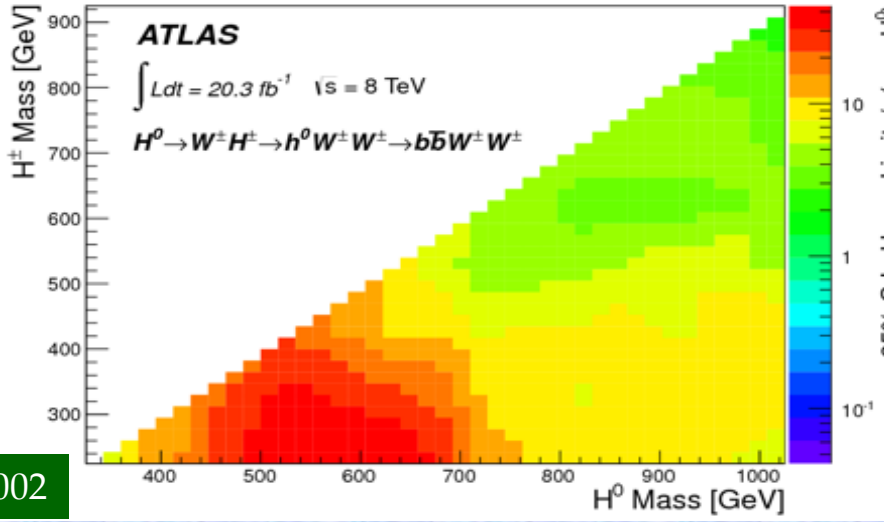
- h0 (125 GeV) is the SM Higgs Boson
  → exploit h→bb decay to gain statistics
- Drawback: same final state as tt semileptonic (l+jets) → use MVA to discriminate against bkg.
- Produce limits in the (mH,mH±) plane

BDT output trained at 36 (m_{H0}; m_{H+}) mass points →kinematic difference between Higgs cascade and top-pair production



PRD89 (2014) 032002

- Upper limits : larger than theoretical (SM-like) H^0 Cross-section
- Approaching SM pred. in high-mass region



2 HDM Higgs Cascade: Searches for H→ hh and A→ Zh

h (126) is the SM-like Higgs boson:

- **H→hh** dominant in $2m_h < m_H < 2m_{top}$
- **A→Zh** dominant in $m_h + m_z < m_H < 2m_{top}$

Exclusive search in various final states:

- Multileptons: ≥ 3 leptons; 0 or 1 τ_{had}
- Diphotons: = 2 photons; at least one lepton

Leptons	Photons	OSSF pairs	Hadronic τ	b-tag
4	0	0, 1 or 2	0 or 1	0 or 1
3	0	0 or 1	0 or 1	0 or 1
2	2	0 or 1	0	-
1	2	-	0	-
1	2	-	1	-
0	2	-	1 or 2	-

H→hh: CMS-PAS-HIG-13-025

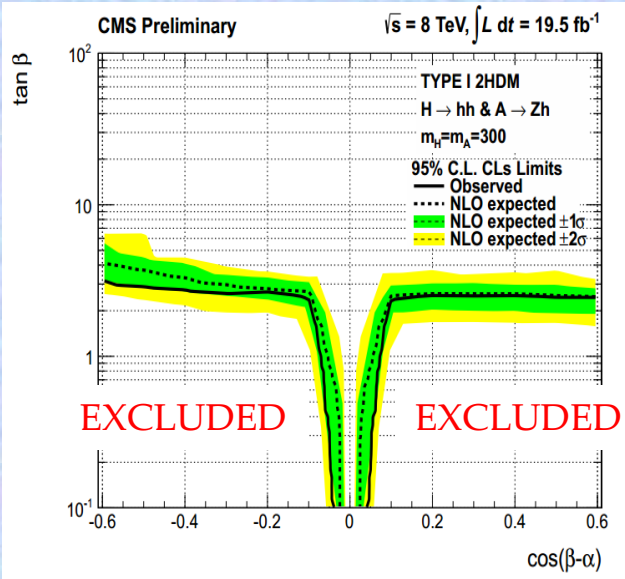
	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau\tau$	$h \to bb$	$h \to \gamma\gamma$
$h \to WW^*$	✓	✓	✓	X	✓
$h \to ZZ^*$	-	✓	✓	✓	✓
$h \to \tau\tau$	-	-	✓	X	✓
$h \to bb$	-	-	-	X	X
$h \to \gamma\gamma$	-	-	-	-	X

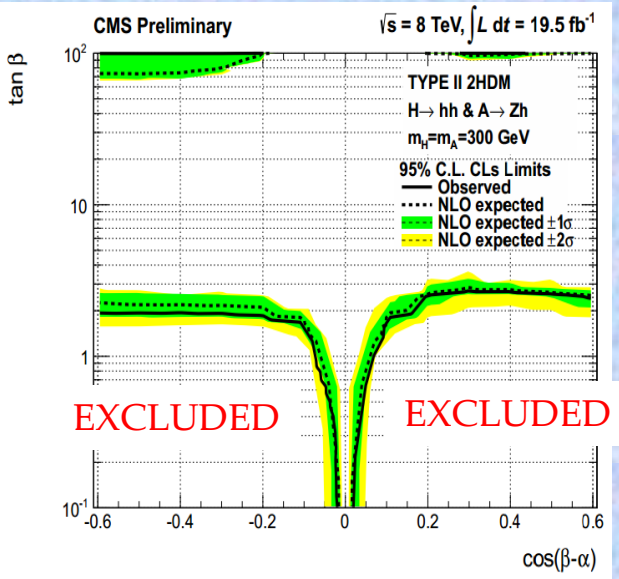
H→Zh:

	$h \to WW^*$	$h \to ZZ^*$	$h \to \tau\tau$	$h \to \gamma\gamma$
$Z \to ll$	✓	✓	✓	✓
$Z \to qq$	X	✓	X	X
$Z \to \nu\nu$	X	✓	X	X

- Use SuShi + 2HDMC to calculate cross sections and BRs from theory
- Translate limits on σ*BR in limits on α and β (determine cross-section and BRs for H and A production/decays)
- cos(β -α) = 0: Decoupling limit: h behaves like in SM

Direct Constrants: on 2 HDM (Type I and Type II) Models





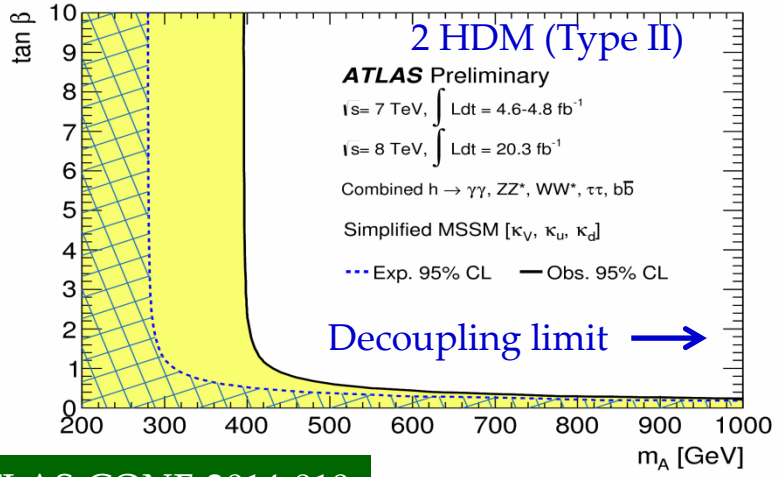
Reinterpretation of h(126) Couplings in 2 HDM Model

- Parameterize difference in Higgs couplings w.r.t. SM (production/decay rates in γγ,ZZ,WW,ττ, bb interpret in each type of **2HDM)**

- Assume Higgs decay kinematics not significantly altered and h(126) - light CP-even neutral Higgs

- Rescaling rates according to k_i for the SM production modes (bbH included as correction scaling with the square of b-quark coupling)
- Extracting from k_i information on tanβ and cos(β-α)

Coupling scale factors for light CP-even Higgs can be written as function of m_A &tanβ



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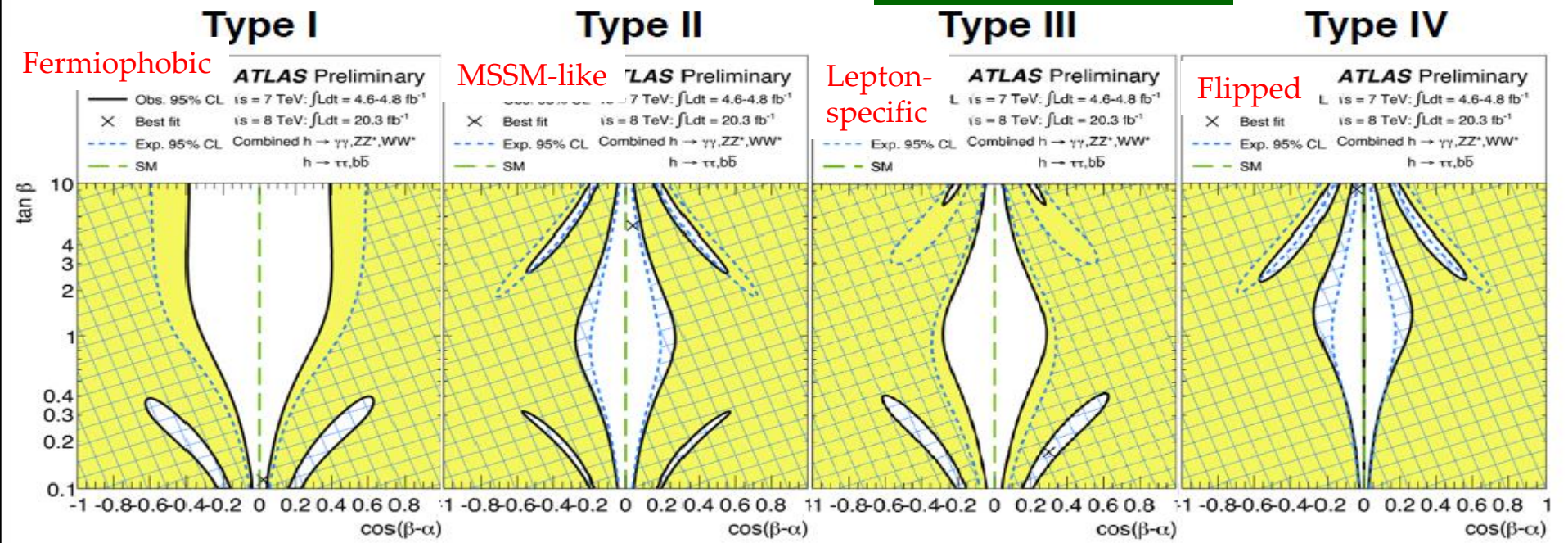
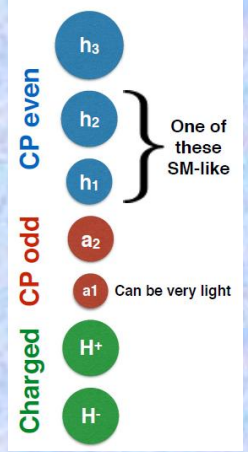


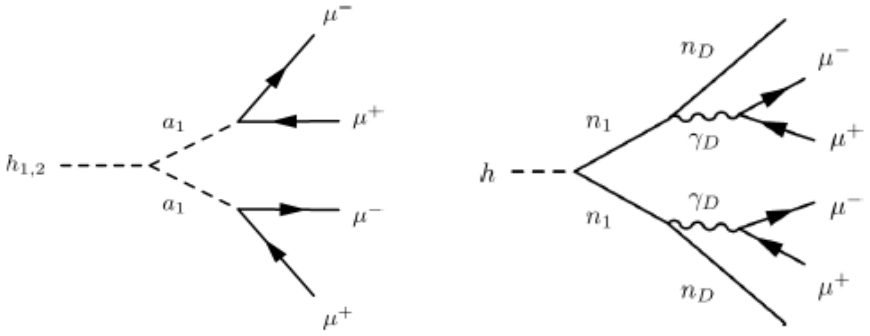
Higgs Sector in NMSSM

NMSSM: additional gauge singlet w. r. t. MSSM → further extend Higgs sector: 1 additional CP-even and 1 additional CP-odd wrt MSSM

Larger phenomenology: additional particles can be very light (neutral scalars with $m_h < 125$ not excluded in NMSSM)

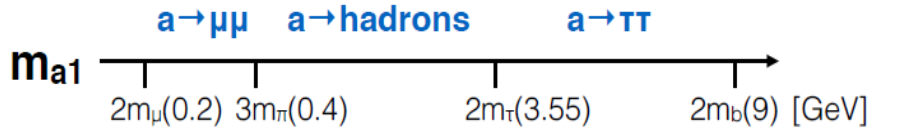


Motivated by two model interpretations:

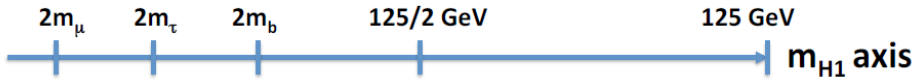


❖ **NMSSM:**
- $h_{1,2}$ (SM-like Higgs) decays to 2 a_1 (*CP*-odd)
- BR(a1→μμ) sizeable, if 2mμ<ma1<2mτ

❖ **Dark SUSY:**
- h→2n_1→2n_D2γ_D→2n_D4μ
- n_1 - lightest neutralino, n_D -dark neutralino, γ_D - dark photon
- BR(γ_D →μμ) up to 45% depending on γ_D mass



Coll.	Channel	m_a range [GeV]	Dataset	Cite
CMS	h→2a→4μ	0.25 - 3.55	21fb-1(8TeV)	CMS-PAS-HIG-13-010
D0	h→2a→4μ/2μ2τ	0.2 - 20	4fb-1(2TeV)	PRL 103, 061801 (2009)
ATLAS	h→2a→4γ	0.1 - 0.4	5fb-1(7TeV)	ATLAS-CONF-2012-079
CMS	a→2μ	5.5 -14	1fb-1(7TeV)	PRL 109, 121801 (2012)
CDF	t→H+b→Wa(→ττ)b	4 - 9	3fb-1(2TeV)	CDF Note 10104



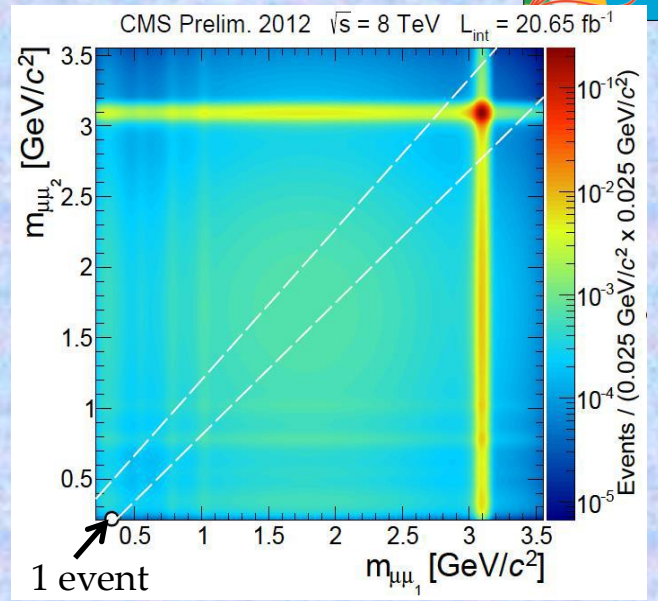
- $2m_\mu < m_{h1} < 2m_\tau$: $h_1 \rightarrow a_1a_1 \rightarrow 4\mu + X$
- $2m_\tau < m_{h1} < 2m_b$: $h_2 \rightarrow h_1h_1 \rightarrow 4\tau + X$
- $2m_b < m_{h1} < 125/2$ GeV: $h_2 \rightarrow h_1h_1 \rightarrow \tau\tau bb + X$, $Wh_2 \rightarrow h_1h_1 \rightarrow bbbb$
- $125/2$ GeV $< m_{h1} < 125$ GeV: $h_3 \rightarrow h_2h_1 \rightarrow WWbb$

Neutral NSSM Higgs Boson Searches: h → 2a +X → 4μ + X

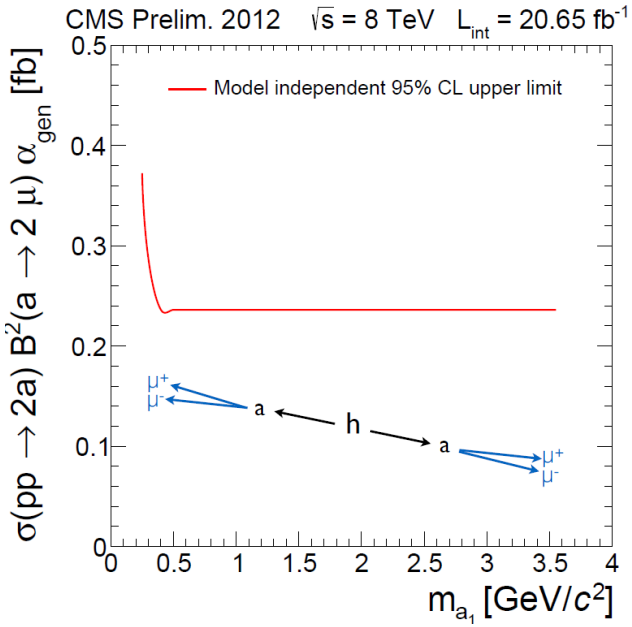
- Search for pair production of a new light boson from the decay of a SM-like Higgs boson:

- NMSSM: substantial BR $a \to \mu\mu$ if $2m_\mu < m_a < 2m_\tau$
  h → 4μ +X final state is explored
- Background dominated by bb and J/ψ pair production
- 1 event observed in signal region, compatible with bkg. prediction 3.8 ± 2.1
- Limit obtained for $0.25 < m_a < 3.55$ GeV, $m_h > 86$ GeV
- Search interpreted for NMSSM, dark-SUSY models as well as model-independent

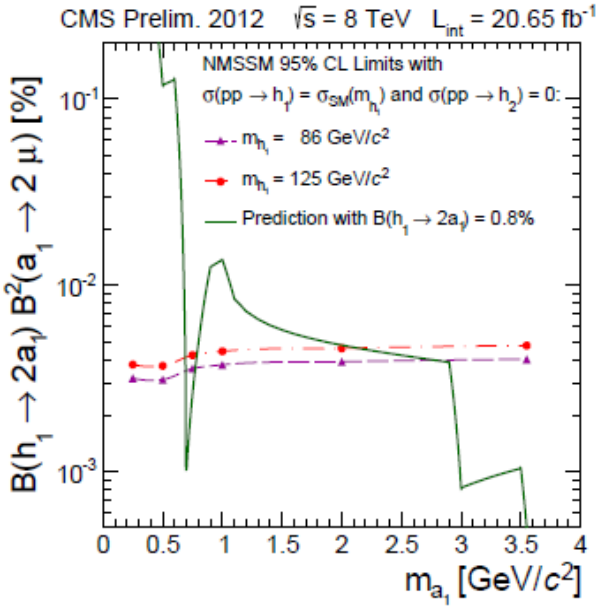
CMS-PAS-HIG-13-010



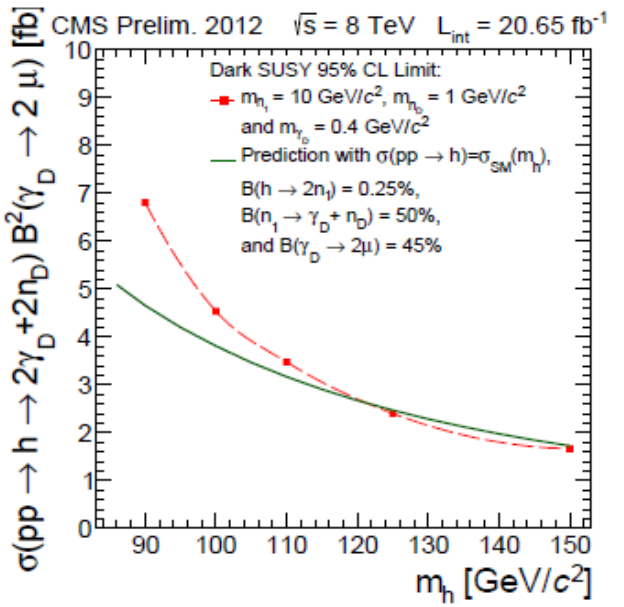
Model - Independent Limit:



nMSSM Interpretation:



Dark SUSY Interpretation:



Summary of Rare, FCNC, LFV and Invisible Higgs Decays

	CMS			ATLAS		
	L(fb^{-1})	Result	Reference	L(fb^{-1})	Result	Reference
	Rare SM Higgs Decays:					
$h \rightarrow \mu\mu$	25	$\mu\,(\sigma/\sigma_{SM}) < 7.4$	CMS-HIG-13-007	25	$\mu\,(\sigma/\sigma_{SM}) < 7.2$	arXiv: 1406.7663
$h \rightarrow Z\gamma$	25	$\mu\,(\sigma/\sigma_{SM}) < 10$	arXiv: 1307.5515	25	$\mu\,(\sigma/\sigma_{SM}) < 11$	arXiv: 1402.3051
$h \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma$	20	$\mu\,(\sigma/\sigma_{SM}) < 10$	CMS-HIG-14-003	-	-	-
	FCNC, Lepton Flavour Violating and Exotic Higgs Decays:					
$t \rightarrow cH$	20	BR($t \rightarrow cH$) < 0.56 %	CMS-HIG-13-034 CMS-HIG-14-001	25	BR($t \rightarrow cH$) < 0.83 %	arXiv: 1403.6293
$H \rightarrow \tau\mu$	20	BR ($H \rightarrow \tau\mu$) < 1.57%	CMS-HIG-14-005	-	-	-
$\Phi \rightarrow \pi_V\pi_V$ (long-lived)	-	-	-	25	σxBR vs. decay length	ATLAS-CONF-2014-041
	Invisible Higgs Decays:					
Z(ll) – H(inv)	25	BR (inv) < 0.58	arXiv: 1404.1344	25	BR(inv)< 0.75	PRL112,201802(2014)
Z(bb)– H(inv)				-	-	-
VBF – H(inv)				-	–	-

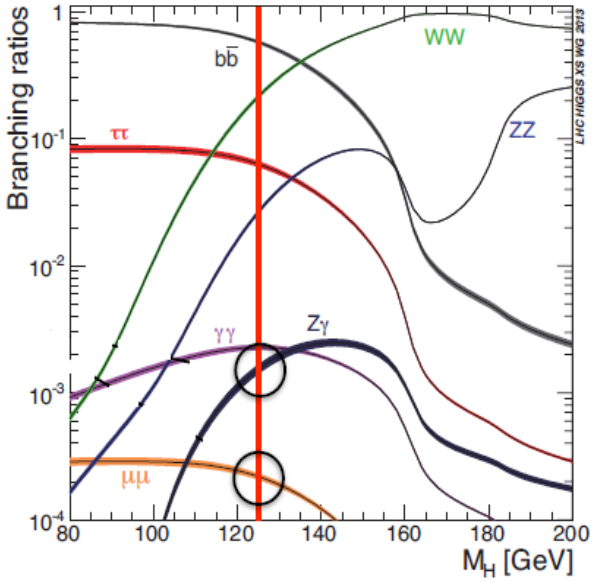
*Results discussed in the talk (marked in magenta)

- Searches for particles with long lived signatures at colliders → see talk Rachel Christine Rosten
- Comparison of collider and non-collider DM results → see talk Phat Srimanobhas

Rare SM Higgs Decays

Rare Higgs decays as probes of new couplings and SM extensions (may enhance SM branching ratios)

Decay mode	Limit (σ/σ_{SM})@125 GeV	
	CMS	ATLAS
$h\to\gamma^*\gamma\to\mu\mu\gamma$	< 10	-
$h\to Z\gamma$	< 10	< 11
$h\to\mu\mu$	< 7.4	< 7.2



❖ **H→μμ**
- SM BR @125 GeV ≃ 2×10^{-4}
- probes directly 2nd generation Higgs fermion coupling

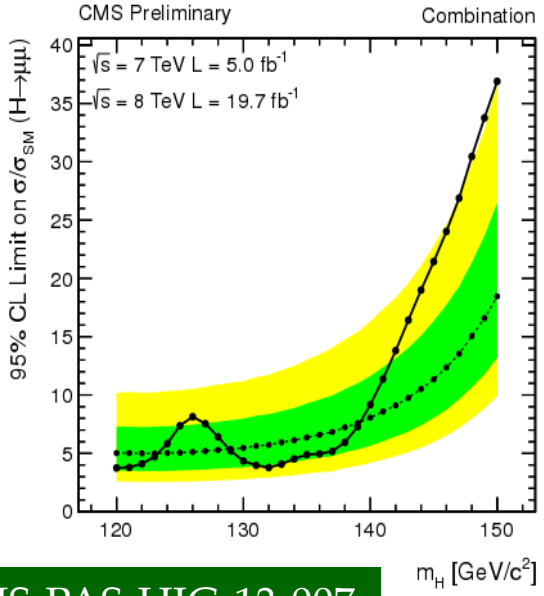
❖ **H→Zɣ/ɣ*ɣ**
- SM BR @125 GeV ≃ 1×10^{-4} (Z→ee,μμ)
- constrains new particle contributions in loops

φ(h,H,A) → μμ Final State:

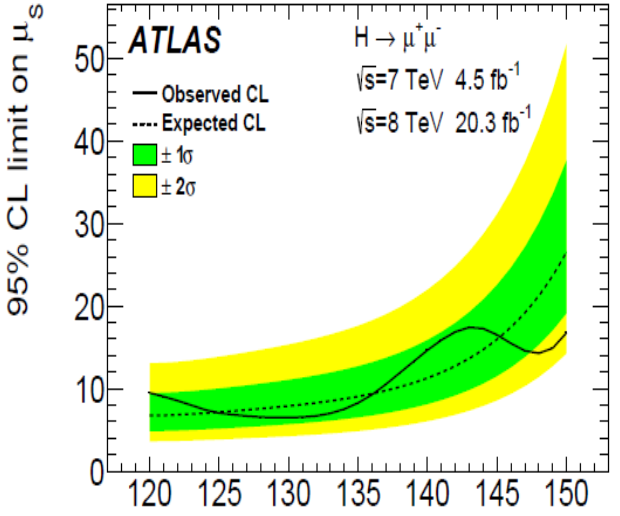
- Clean signature - μμ resonance
- Main backgrounds: Z/ɣ*, tt, WW

- Categorization of events
  - mass resolution
  - production ggF/VBF mechanism

- tan β can be extracted from the signal mass $M_{A0} = M_{\mu^+\mu^-}$ and its width ($\Gamma_{\mu^+\mu^-}$)



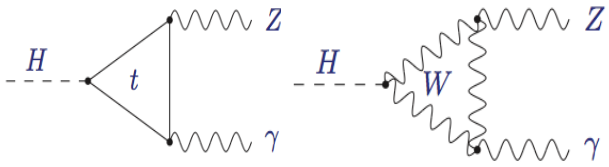
CMS-PAS-HIG-13-007

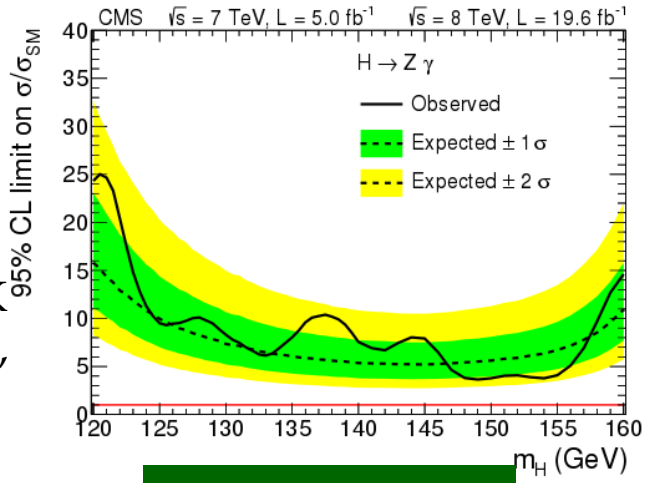


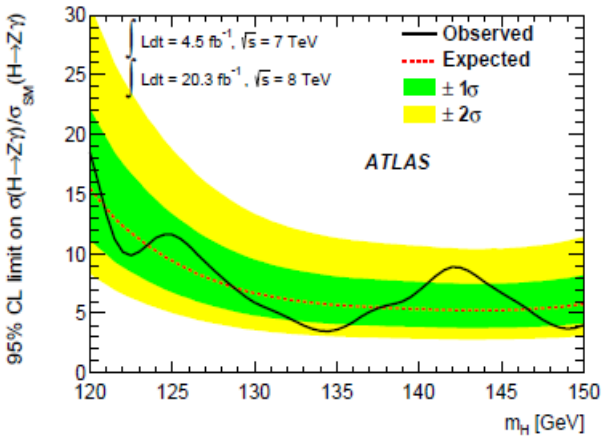
arXiv: 1406.7663

Rare SM Higgs Decays

❖ h→Zγ Final State: sensitive to BSM contributions in loops → e.g. composite Higgs





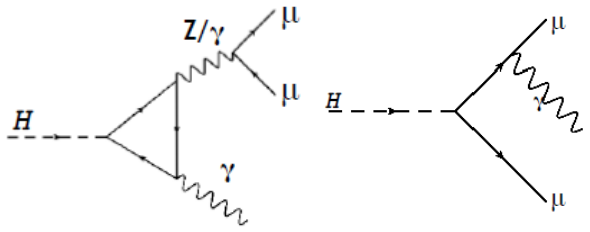


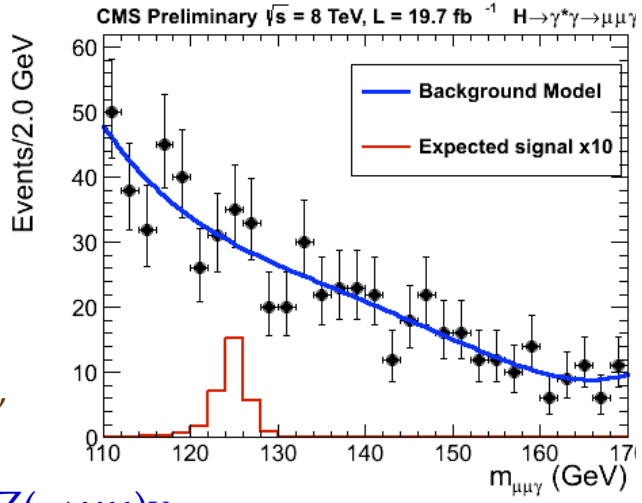
- μμγ and eeγ final states
- Main backgrounds: Zγ EWK production, FSR in Z→*ll* decays, jets (mis)identified as photon in Z+jets events
- m(llγ) use to extract limits

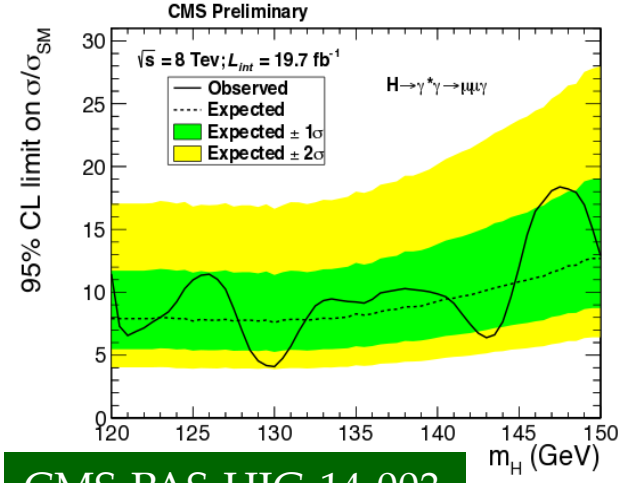
PLB726(2013) 587

PLB732(2014) 8

❖ h→γ*γ→μμγ Final State: Sensitive to BSM loop/tree level processes → e.g. new resonances







- "Dalitz decay": internal conversion of γ* into μμ
- $m_{\mu\mu} < 20$ GeV to separate γ* γ from Zγ
- Similar sensitivity as in H → Z(→μμ)γ

CMS-PAS-HIG-14-003

2 HDM Higgs and FCNC

Coll.	Dataset	Cite
ATLAS	25fb-1(7+8TeV)	arXiv:1403.6293 [hep-ex]
CMS	20fb-1(8TeV)	CMS-PAS-HIG-13-034

- FCNC highly suppressed in SM due to GIM mechanism → can be relaxed in BSM

- LHC: Large tt cross section and large top-coupling to Higgs: for t->cH possible new physics rate higher than SM by ~10^{10}-10^{12}

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}

FCNC: t → cH Decays

CMS-PAS-HIG-13-034

Searches done using ttbar topology:

- Reinterpretation of searches:

- Diphoton: CMS-PAS-HIG-13-025 (H→hh, A→Zh)
- Multilepton: CMS-PAS-SUS-13-002

B(t→Hc)<0.56% (0.65%)

Used to place limit on coupling

$g_{tHc} < 0.14$ (observed)

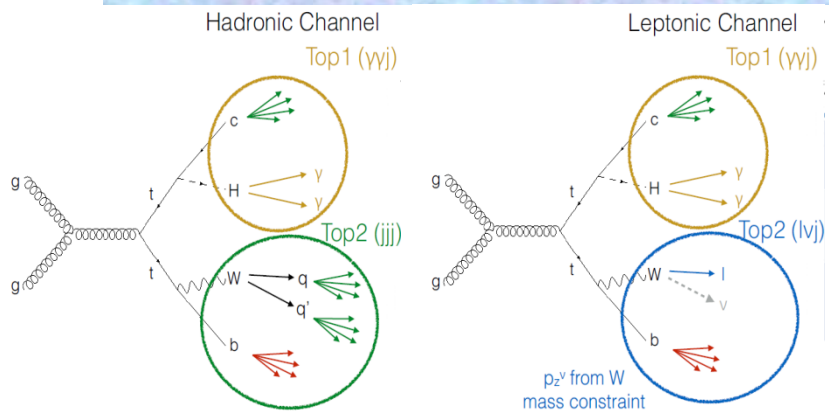
Combine most sensitive categories for stat. interpretation:

- Multileptons: 3 leptons (no hadronic tau), no opposite-sign same-flavour pair (OSSF) or an OSSF and a b-tag
- Sensitivity improved by diphoton channel b -tag

Higgs Decay Mode	observed	expected	1σ range
$H \to WW^*$ ($\mathcal{B} = 23.1\,\%$)	1.58 %	1.57 %	(1.02–2.22) %
$H \to \tau\tau$ ($\mathcal{B} = 6.15\,\%$)	7.01 %	4.99 %	(3.53–7.74) %
$H \to ZZ^*$ ($\mathcal{B} = 2.89\,\%$)	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons (WW^*, $\tau\tau$, ZZ^*)	1.28 %	1.17 %	(0.85–1.73) %
$H \to \gamma\gamma$ ($\mathcal{B} = 0.23\,\%$)	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons	0.56 %	0.65 %	(0.46–0.94) %

Study of Top-Higgs Coupling (tHq): $tHq \to bW \to l\nu\, q(H \to \gamma\gamma)$ CMS-PAS-HIG-14-001

2 HDM Higgs: FCNC (t → qH) Decays



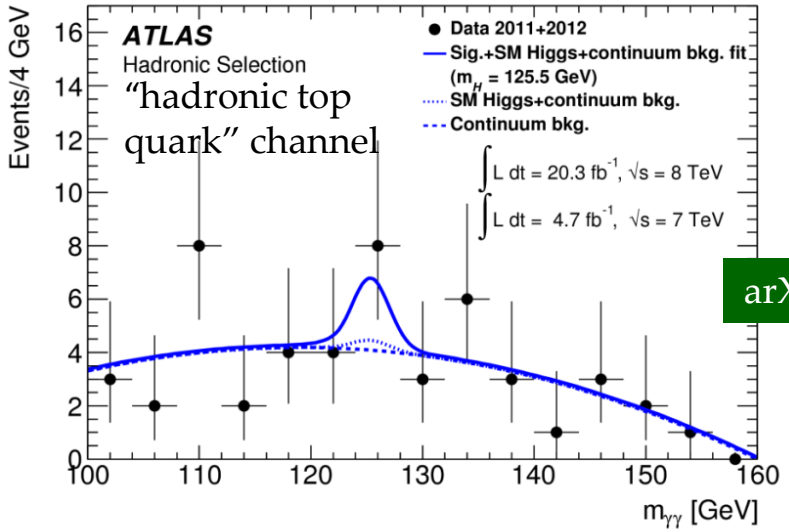
In 2 HDM Type III model (without flavor conservation)
The c(u)H coupling is present at tree level

Search for FCNC t → qH done in top-pair events:

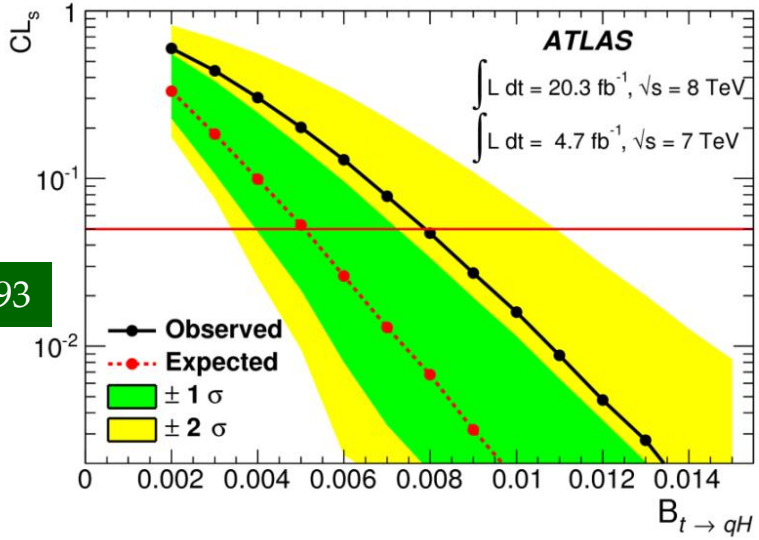
$$tt \rightarrow b(W \rightarrow ff)\ q(H \rightarrow \gamma\gamma)$$

FCNC: t->qH, where H->γγ
Other t->bW, both leptonic & hadronic W decays used

Search for excess in $M_{\gamma\gamma}$ mass spectrum



CLs as a function of the FCNC branching ratio



arXiv: 1403.6293

Limit on Br (t→cH): **B(t→Hc)< 0.83%** (0.53%)

Observed (expected)

Limit on Higgs Yukawa coupling

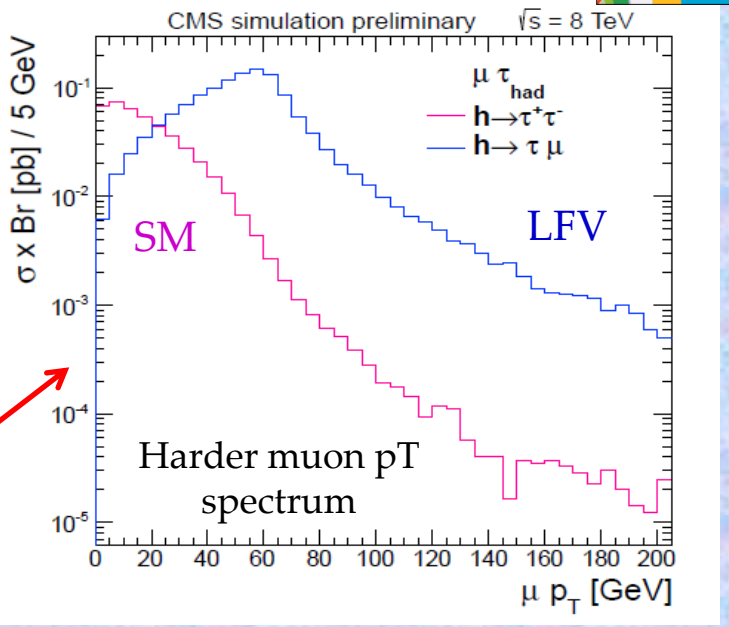
$$\lambda_{tcH} < 0.17\ (0.14)$$

$$\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17$$

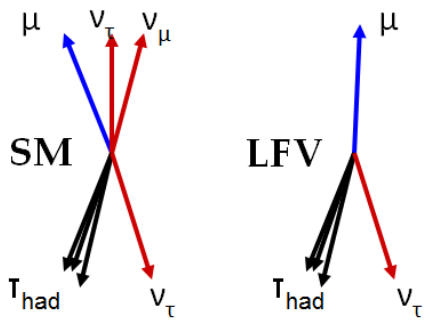
Equally sensitive to tuH and tcH:

Searches for Lepton Flavor Violating Higgs Decays

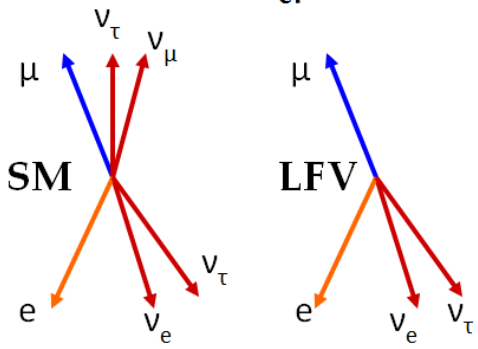
- Forbidden in the SM; naturally occur in 2HDM, composite Higgs, and Randall-Sundrum models
- Previous best limit from indirect searches: B(H→μτ)<10% → reinterpretation of ATLAS H→ττ searches and from τ→μγ (arXiv:1209.1397)
- Can do better with the first dedicated search: H →$\mu\tau_e$ and H→ $\mu\tau_{had}$ (within current LHC reach)
- Similar strategy as for H→ττ (but kinematics differ)

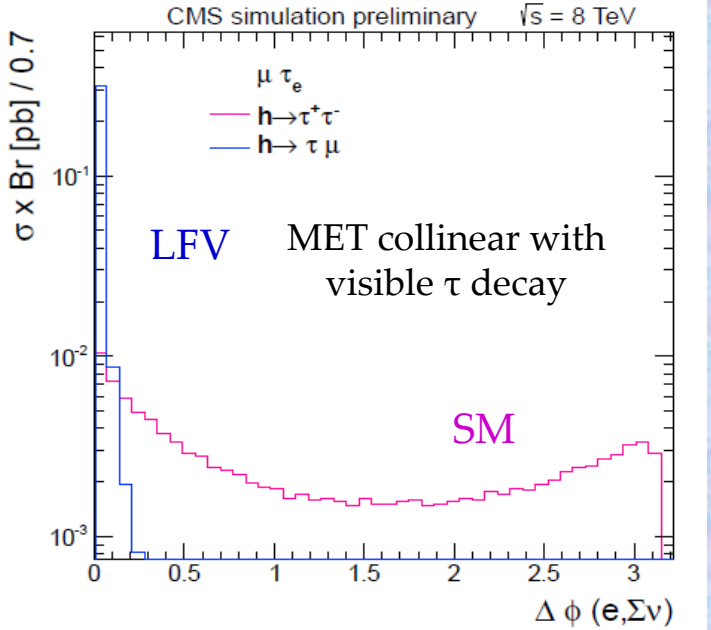


Search for H → $\tau_{had}\mu$



Search for H → $\tau_e\mu$

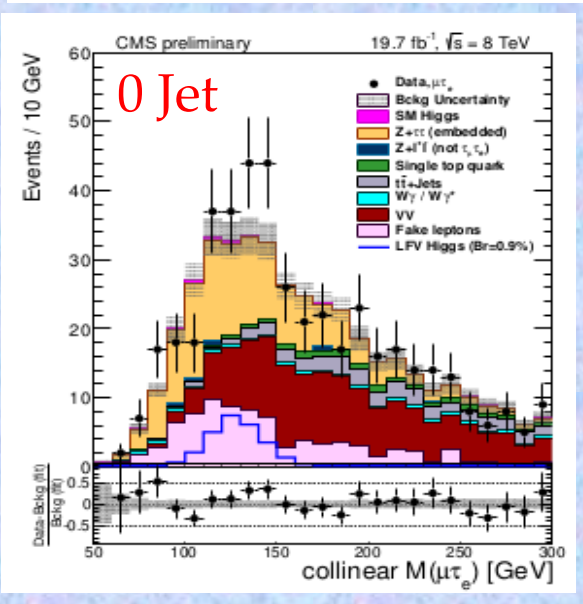


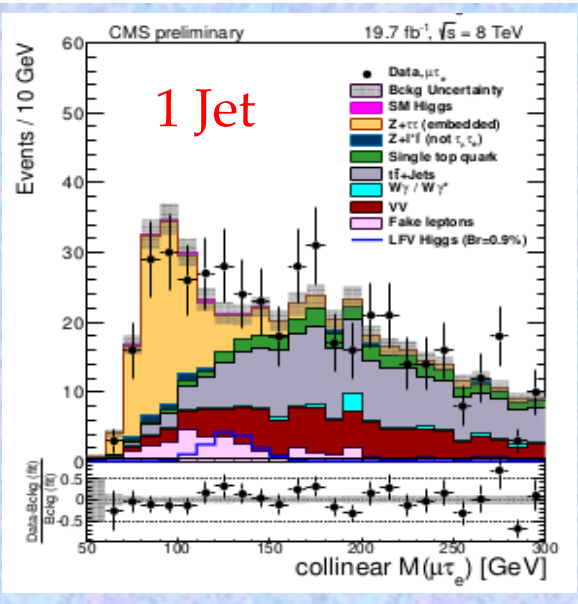


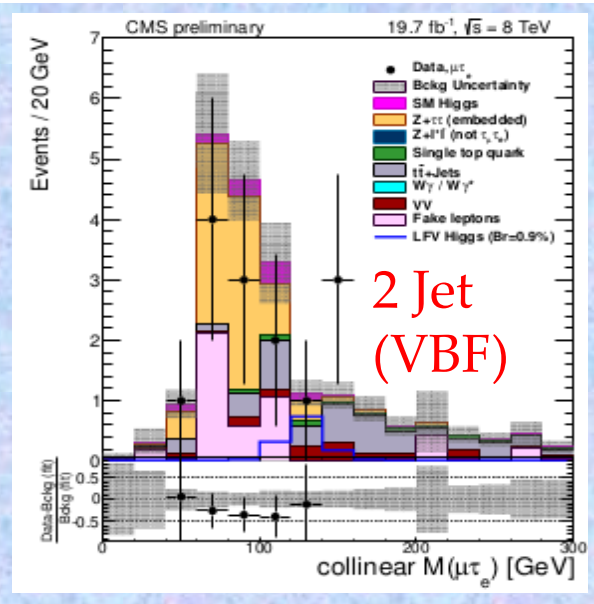
- Exploit collinearity between tau and MET
- Signal variable: "collinear mass", reconstructed from visible decay products

LFV Couplings: Search for H → τμ

- Selection: isolated muon + isolated electron ($\mu\tau_e$) or hadronic tau candidate ($\mu\tau_{had}$)
- Categorize according to number of jets

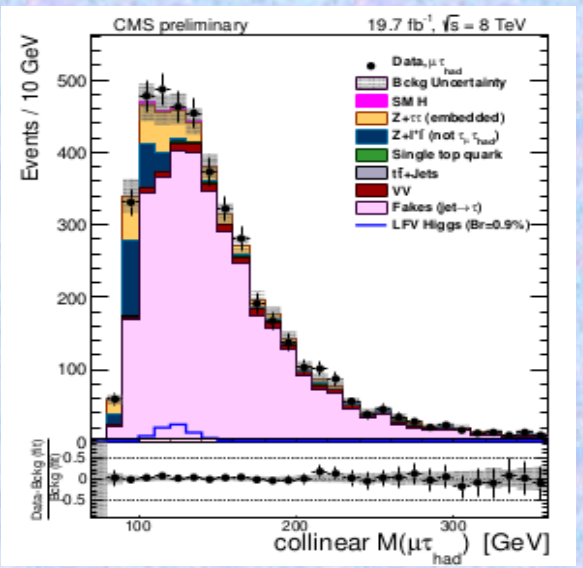


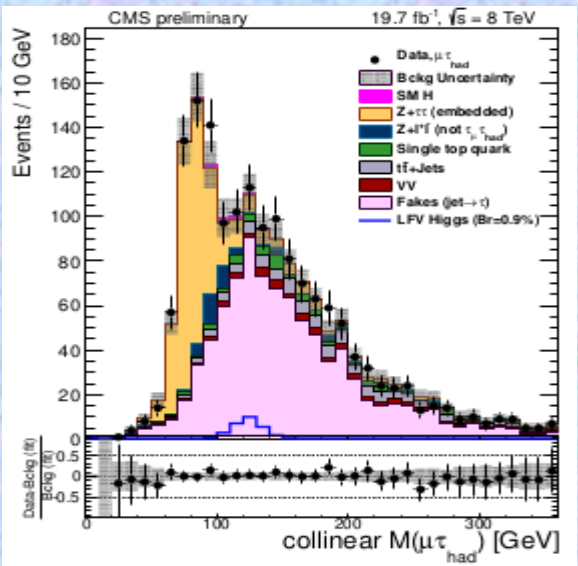


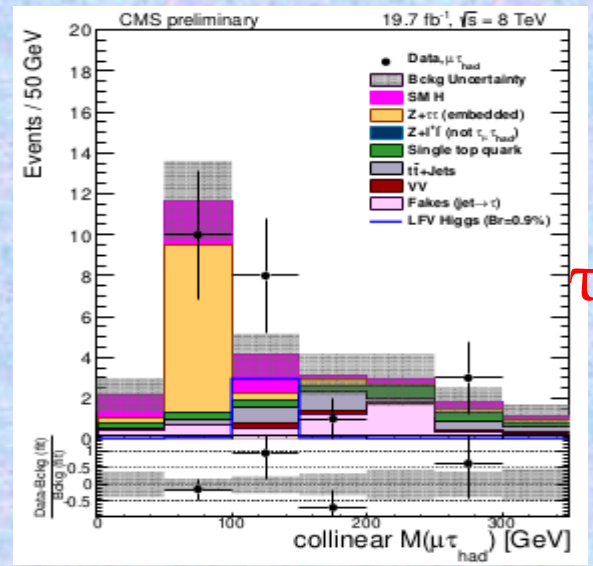


$\tau_e\mu$

CMS-PAS-HIG-14-005

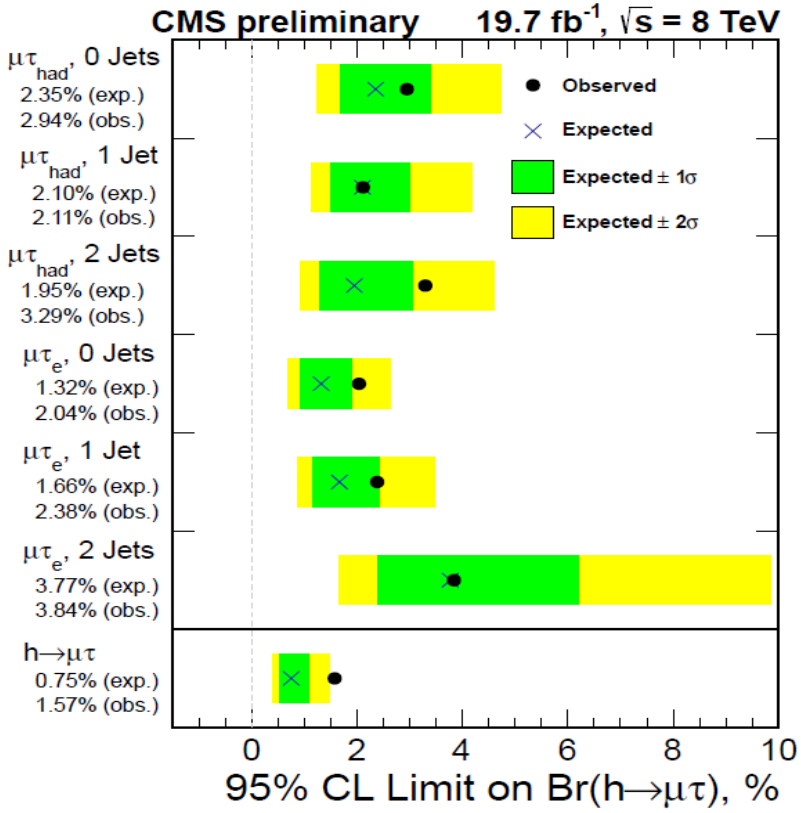






$\tau_{had}\mu$

Limits on Br (H → τμ) and Yukawa Coupling



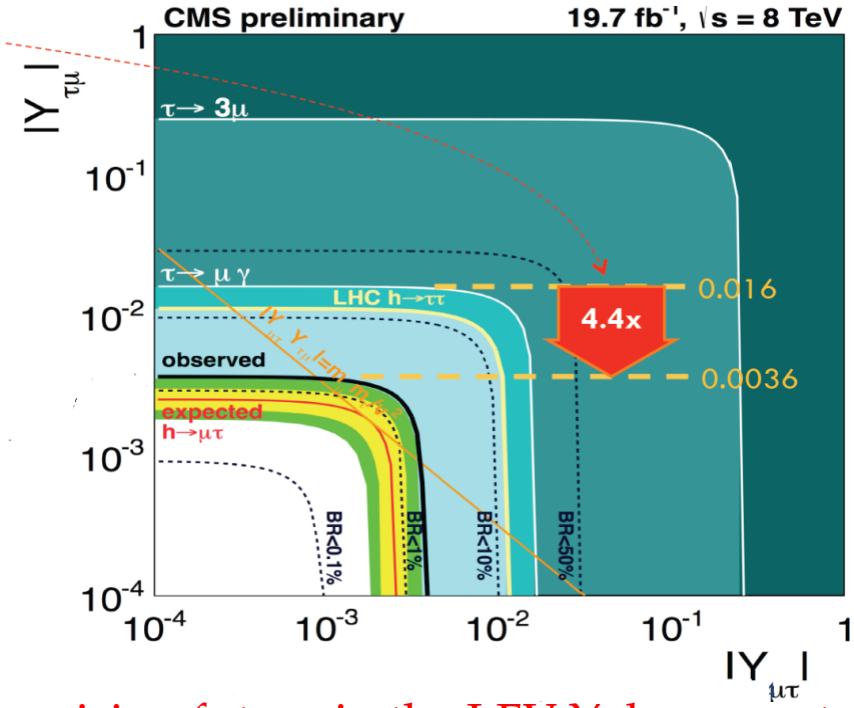
- BR (H → τμ) < 1.57% @ 95 CL observed
(expected B(H → μτ) < (0.75 ± 0.38)%)

- Best fit: B(H → μτ) = (0.89±0.40)%

Mild excess in data at the level of 2.5σ
→ still compatible with the SM

CMS-PAS-HIG-14-005

Constraint on B(H → μτ) interpreted in terms of LFV Higgs Yukawa couplings



Promising future in the LFV Yukawa sector

- Significant improvement (4.4x) wrt. indirect measurements

- Previous best limit from τ→μγ: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 0.016$
- Observed limit: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 0.0036$

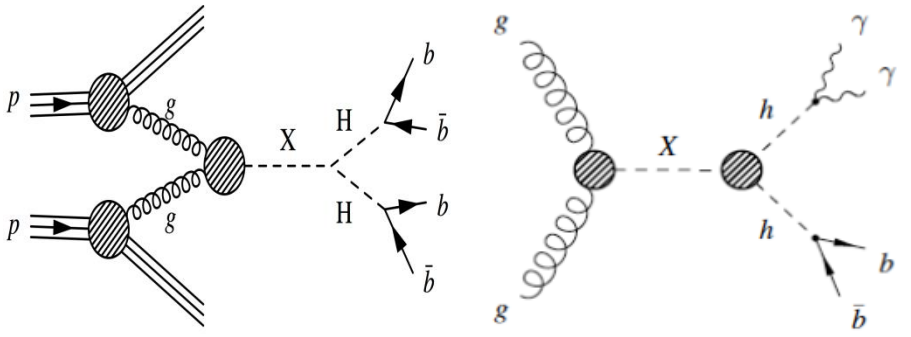
Best limits on τ anomalous Yukawa couplings to date

Alternative models

	CMS			ATLAS		
	L(fb^{-1})	Result	Reference	L(fb^{-1})	Result	Reference
	Higgs Boson Pair Production (resonant, non-resonant)					
hh → γγbb	20	σxBR, radion, graviton	CMS-HIG-13-032	20	σxBR, 2 HDM	arXiv: 1406.5053
hh → bbbb	18	σxBR, radion, graviton	CMS-HIG-14-013	20	σxBR, graviton	ATLAS-CONF-2014-005
	Resonant Searches (Extended Higgs sector):					
X→ γγ	20	Mass range: 150-850 GeV	CMS-HIG-14-006	20	Mass range: 65-600 GV	arXiv: 1407.6583

Higgs Boson Pair Production (X → hh)

- SM: rate of Higgs pair production is very small
- BSM (rate of resonant hh production enhanced):
  - Heavy(N)MSSM Higgs: H → h(125)h(125)
  - Radion or Kaluza-Klein excitation of graviton (Warped Extra Dimensions)



Model Independent Analysis → results interpreted in terms of spin-0 (radion) or spin-2 (KK graviton):

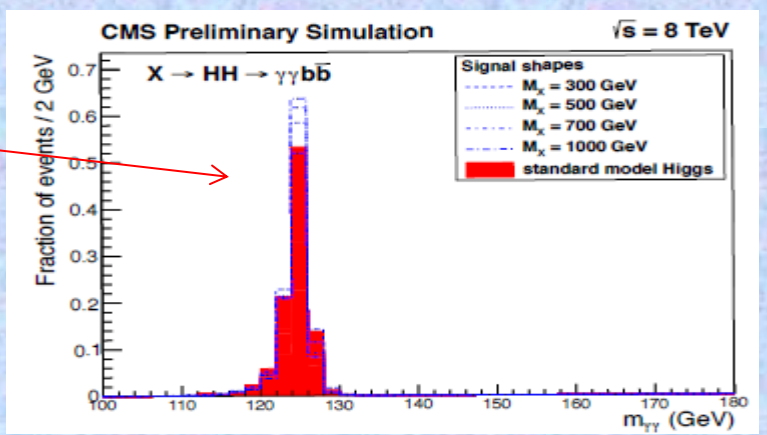
- hh →γγbb: large BR(H → bbar), low bkg., good mass resolution (H → γγ)

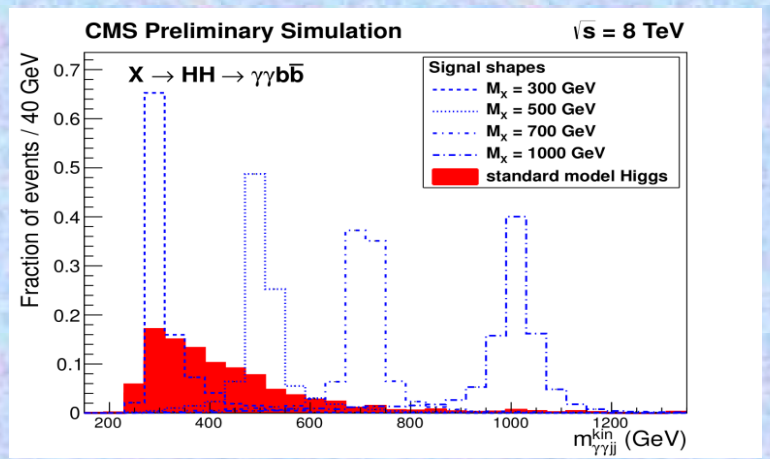
ATLAS (260-550 GeV):
- Non resonant: fit to inbunned $m_{\gamma\gamma}$
- Resonant production : counting experiemnt

CMS (260-1100 GeV):
- Low mass (m_X<400 GeV) →fit to $m_{\gamma\gamma}$ spectrum
- High mass (mX<400 GeV) → fit to the $m_{\gamma\gamma jj}$

- hh→ bbbb: Increased sensitive at high mass

ATLAS/CMS: 4b-tagged jets, veto ttbar events





Search for Higgs Boson Pair Production: hh → (γγ)(bb) Final State

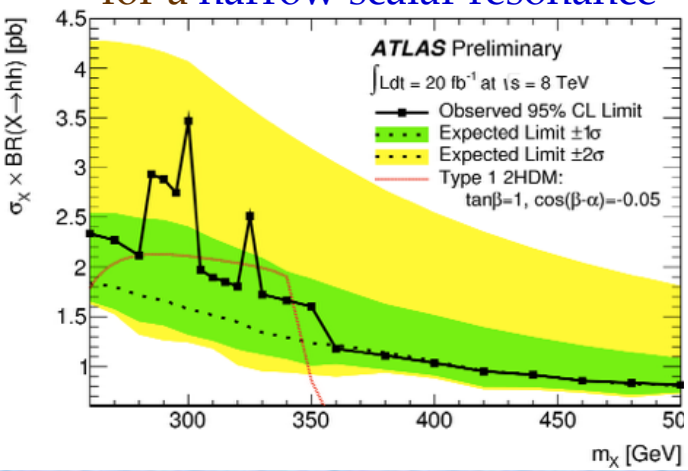
ATLAS: non-resonant and resonant (2 HDM model)

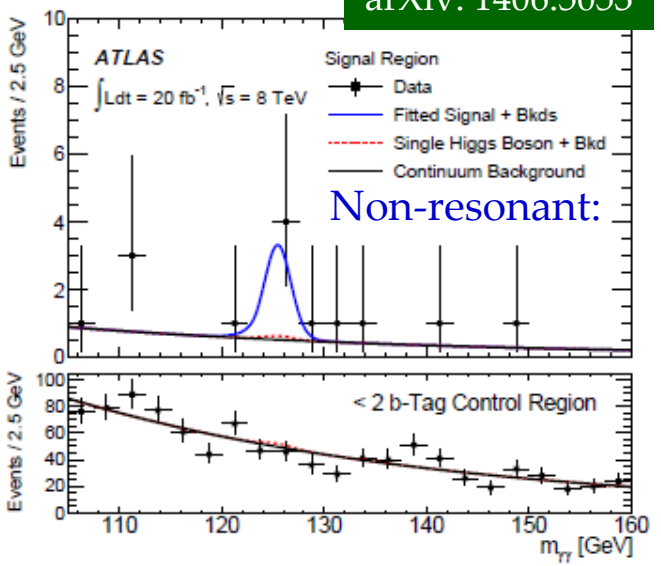
arXiv: 1406.5053

Spin-0 benchmark,
$260 < m_X < 500$ GeV

- Resonant : 2.1σ max. deviation (incl. LEE)
- Non-resonant (assuming SM Br(h)): σ<2.2 pb obs. (1.0 exp.)

95 % CL on σ x BR vs. m_X for a narrow scalar resonance





CMS: resonant search (KK-graviton and radion)

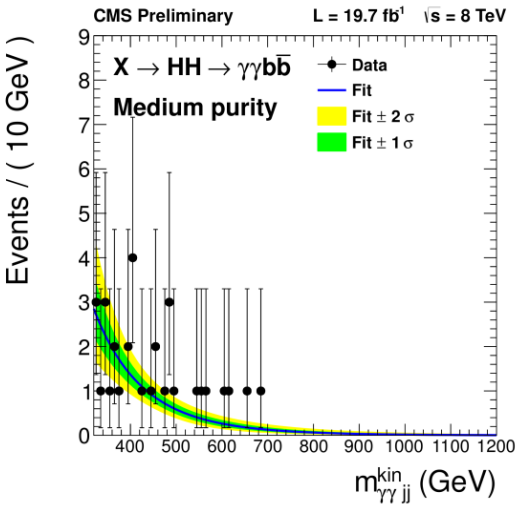
CMS-PAS-HIG-13-032

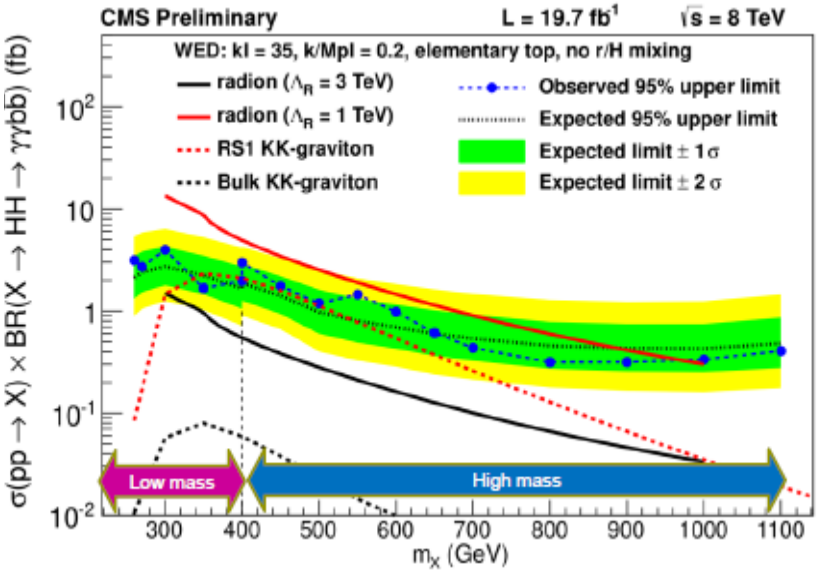
Spin-0 (2) benchmarks
$260 < m_X < 1100$ GeV

Exclude:

- Radions : m_X<970 GeV; radion scale Λ_R=1 TeV
- RS1 KK-graviton : mass range 340< m_X<400 GeV.

No deviation w.r.t. SM





Search for X → hh → (bb)(bb) Final State

ATLAS searches:

- TeV resonance decaying into pair of SM Higgs bosons

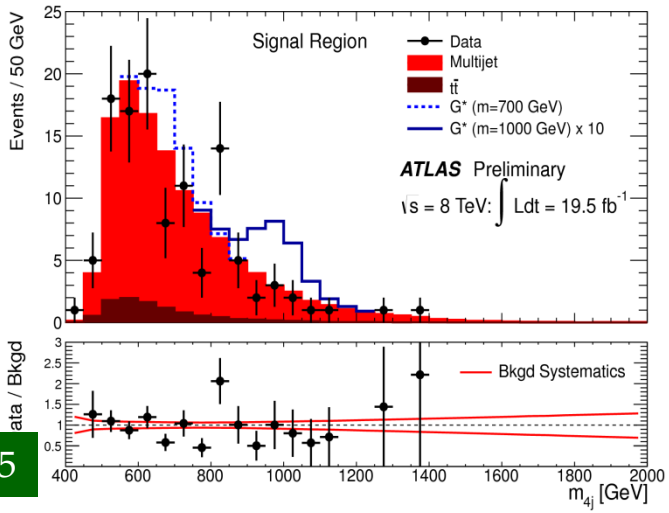
- KK Graviton

Excluded:

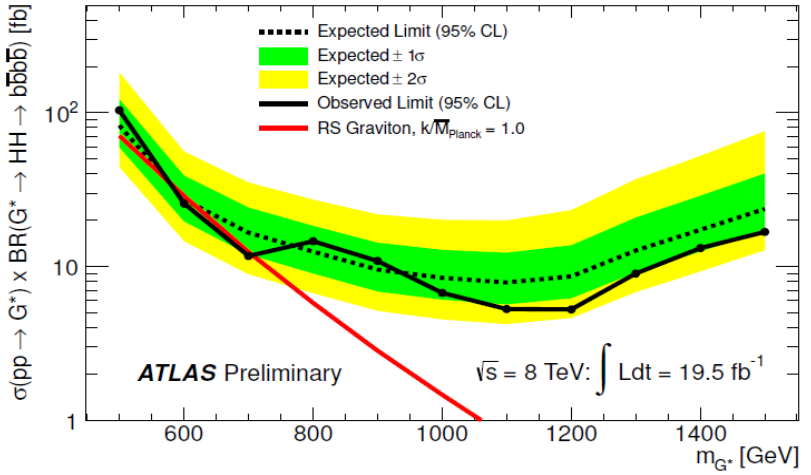
$590 < m_X < 710$ GeV

ATLAS-CONF-2014-005

Signal region (m_{4j}) mass
(90% bkg. From multijet +10% ttbar)



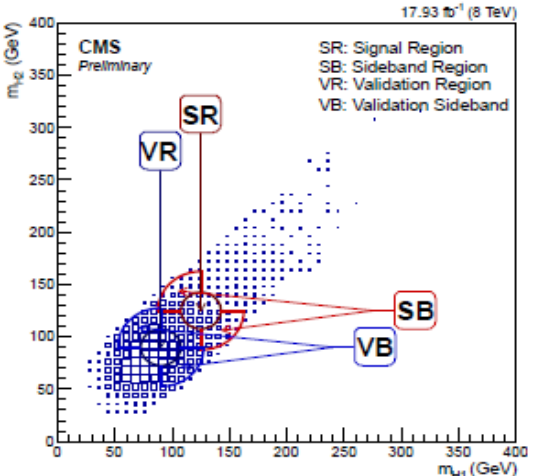
95 % CL on σ x BR vs. m_X
for a KK excitation of graviton

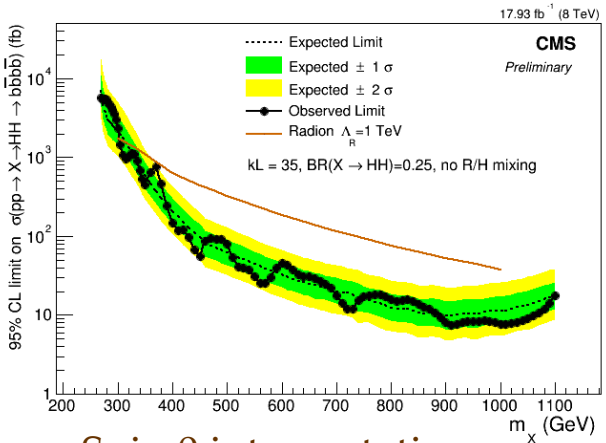


CMS Searches → see Conference Poster Caterina Vernieri

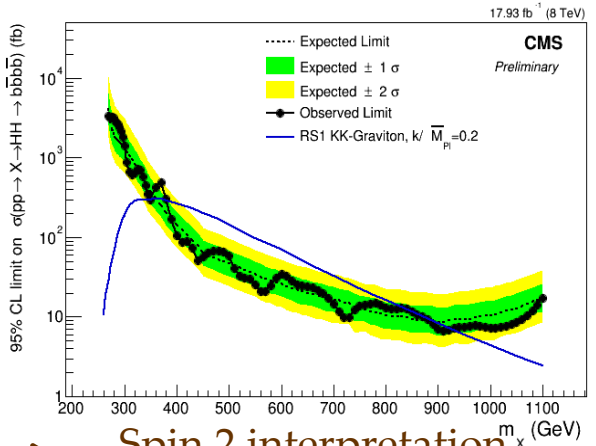
CMS-PAS-HIG-14-013

m_{H1} vs m_{H2} (after b-tag)





Spin 0 interpretation →



Spin 2 interpretation

+20-30% signal efficiency

We Have to Exploit All Opportunities !!!

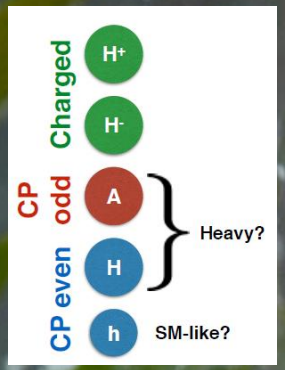
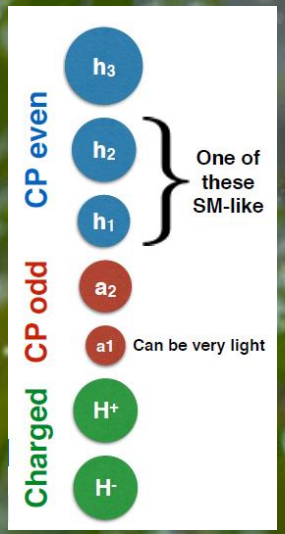
- Run I ATLAS/CMS searches covered a large range of BSM Higgs boson signatures

→ narrowing the the phase space for the (N)MSSM models

- LHC is the discovery machine

→ the adventure in the TeV energy regime has just begun

Run II will open new horizons for an exciting future Higgs Physics program

… Preparing for the LHC Restart …

« Dreaming for the BSM Future … »