Search for Higgs Bosons Beyond the Standard Model

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Photo: Eleni Ntomari

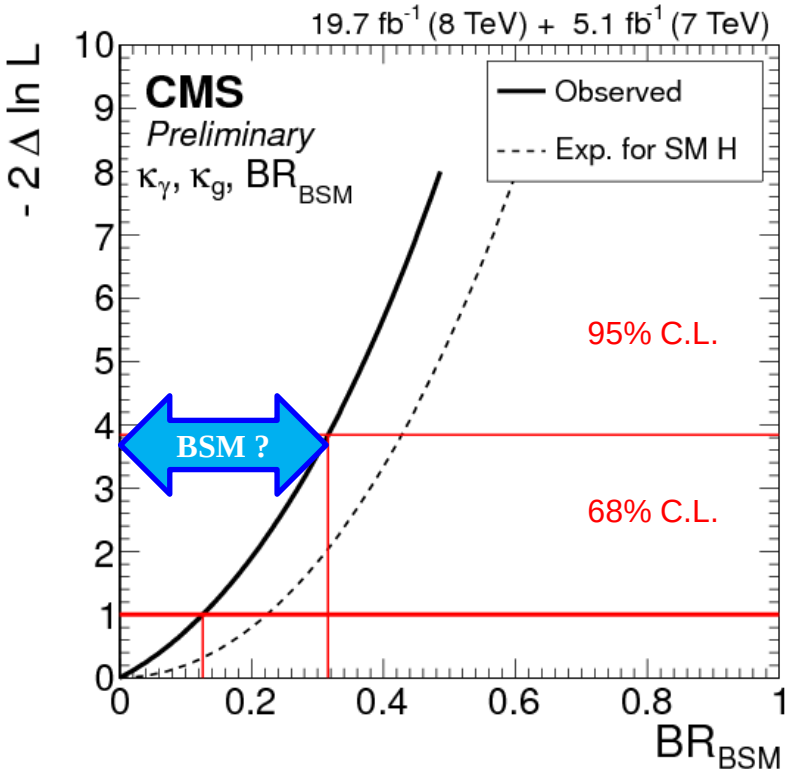
HELMHOLTZ ASSOCIATION

H(125) = Standard Model Higgs?

- Most relevant question after discovery of a Higgs boson at ~125 GeV:
  - structure of the Higgs sector
  - are there additional Higgs bosons?
- At the level of current measurements, the observed state is compatible with the Standard Model Higgs
  - but SM features quadratically divergent self-energy corrections at high energies (Hierarchy problem)
  - many other open questions: dark matter, CP violation in early universe, …
  - ➔ SM very likely incomplete
- Concluding from the Higgs couplings analysis, there is still plenty of room for non-SM decays of the H(125)
  - BR_{BSM}<32% at 95% CL
    - assuming no modification at tree-level

New!

CMS PAS HIG-14-009



Fingerprints of Extended Higgs Sectors

Heavy Neutral Higgs
$\phi \rightarrow \tau\tau$
(N)MSSM

Charged Higgs
$H^+ \rightarrow cs$
(N)MSSM

Invisible Higgs Decays
ZH and VBF
WED* SUSY

Lepton-Flavor Violating Higgs Decays
$H \rightarrow \mu\tau$
2HDM

Resonant Higgs Pair Production
$X \rightarrow H\,H \rightarrow (\gamma\gamma)bb$
(N)MSSM WED*

Discovering <u>any</u> of these would <u>extend</u> the Standard Model

*Warped Extra Dimensions

(N)MSSM Higgs Sectors

- Supersymmetry presents an elegant solution to the quadratic divergences in the Higgs mass corrections → cancellation by super partners
  - requires additional Higgs bosons
- Minimal supersymmetric extension (MSSM) features two complex Higgs doublets
  - ➔ Five physical Higgs bosons
    - three neutral: $\underbrace{\underbrace{h, H}_{\text{CP-even}}}_{\text{denoted } \Phi}$, $\underbrace{A}_{\text{CP-odd}}$
    - two charged: $H^{\pm}$
    - two tree-level parameters: m_A and $\tan\beta$

Usually identify
$h \equiv H(125)$

- Next-to-Minimal Supersymmetric Model (NMSSM): two complex Higgs doublets + additional scalar field
  - seven physical Higgs states, which are mixtures: $\underbrace{h_1, h_2, h_3}_{\text{CP-even}}$, $\underbrace{a_1, a_2}_{\text{CP-odd}}$, $h^{\pm}$

h_1 or $h_2 \equiv H(125)$?

Other Models

- Two-Higgs Doublet Models (2HDM)
  - effective theory; extension of SM by adding a second complex Higgs doublet
  - five Higgs bosons: h, H, A, $H^{\pm}$
  - flavor conservation can be enforced via symmetries
    - four types of 2HDM, depending on the way the Higgs doublets couple
  - MSSM Higgs structure corresponds to a Type II 2HDM
  - flavor-changing Yukawa couplings are in principle possible (Type III models)

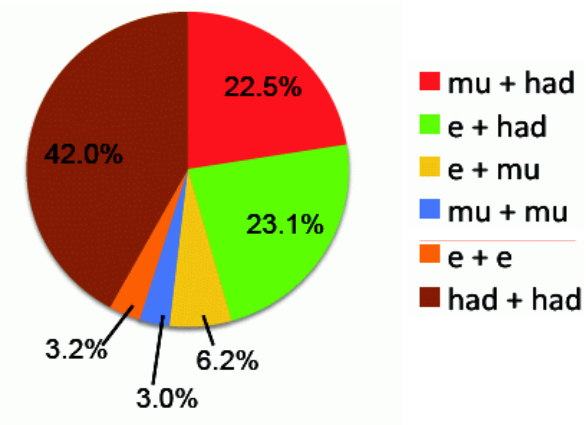
2HDM with natural flavor conservation:

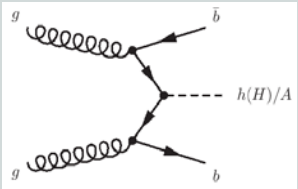
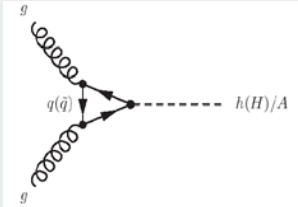
Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

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

- Models inspired by Warped Extra Dimensions (WED, Randall-Sundrum model)
  - predict new heavy particles ($m_X > 2m_H$) that can decay to a pair of Higgs bosons
  - Examples:
    - radion (spin 0)
    - first Kaluza-Klein excitation of the graviton (spin2)

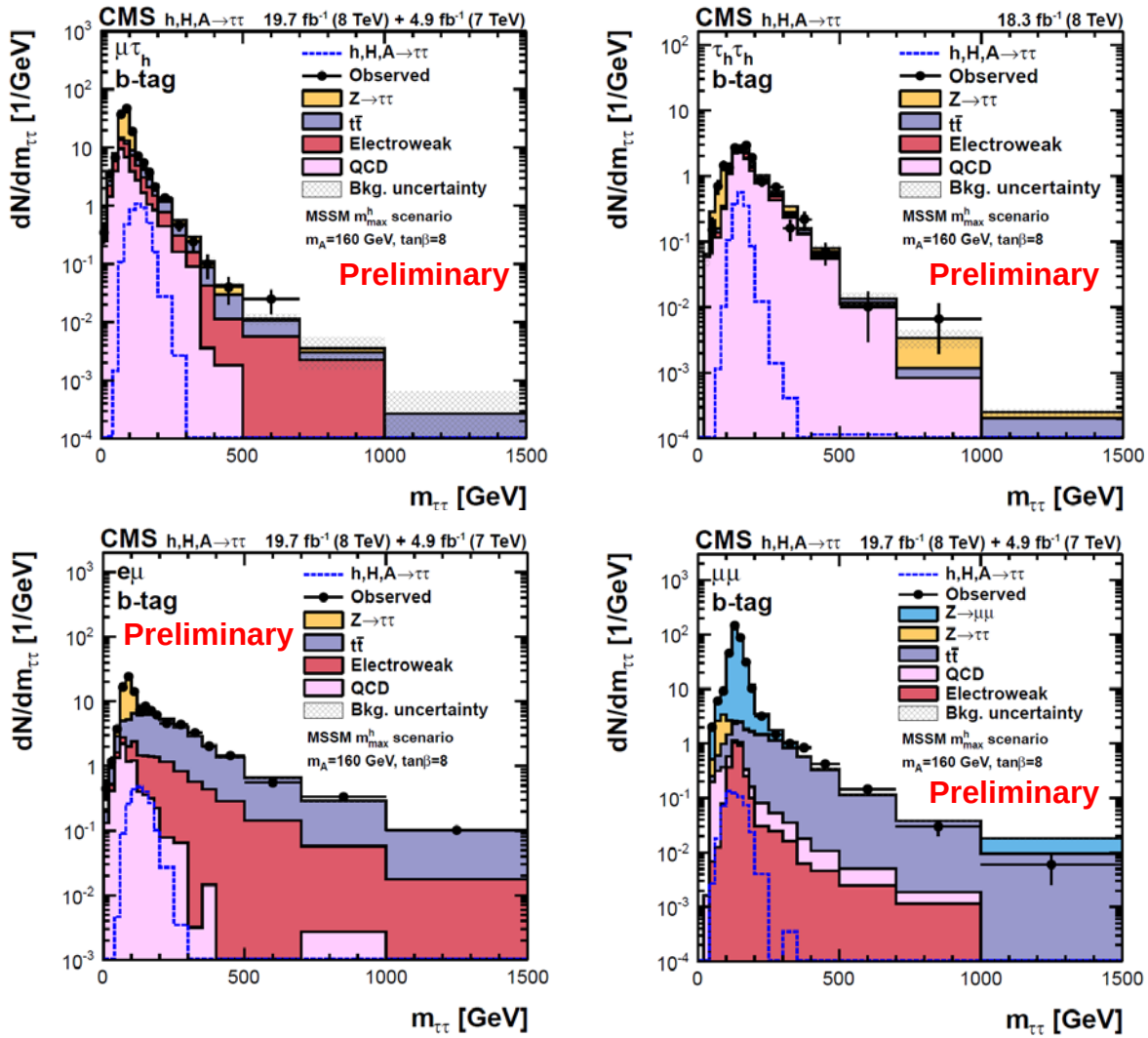
Heavy Neutral $\Phi \rightarrow \tau\tau$



Production mechanisms & event categories	
	B-Tag at least 1 b-tagged jet associated production
	No B-Tag no b-tagged jet gluon-gluon fusion

- Good compromise between relatively large BR and manageable backgrounds
- Analysis covers five of six possible $\tau\tau$ decay patterns: e+μ, e+had, μ+had, had+had, μ+μ
- Production: gg fusion + b-associated
- Mass of τ pair is reconstructed from visible τ decay products and missing E_T
  - maximum likelihood technique
- Main backgrounds (in broad strokes – may differ from channel to channel):
  - **Z→$\tau\tau$:**
    - embedding technique: take Z→$\mu\mu$ from data, replace μ's by simulated τ decays
  - Z→$\mu\mu$: suppress using the distance of closest approach (DCA)
  - $t\bar{t}$ and di-boson
  - QCD multijet, W+jets

Φ → ττ: Mass Distributions (B-tag Category)

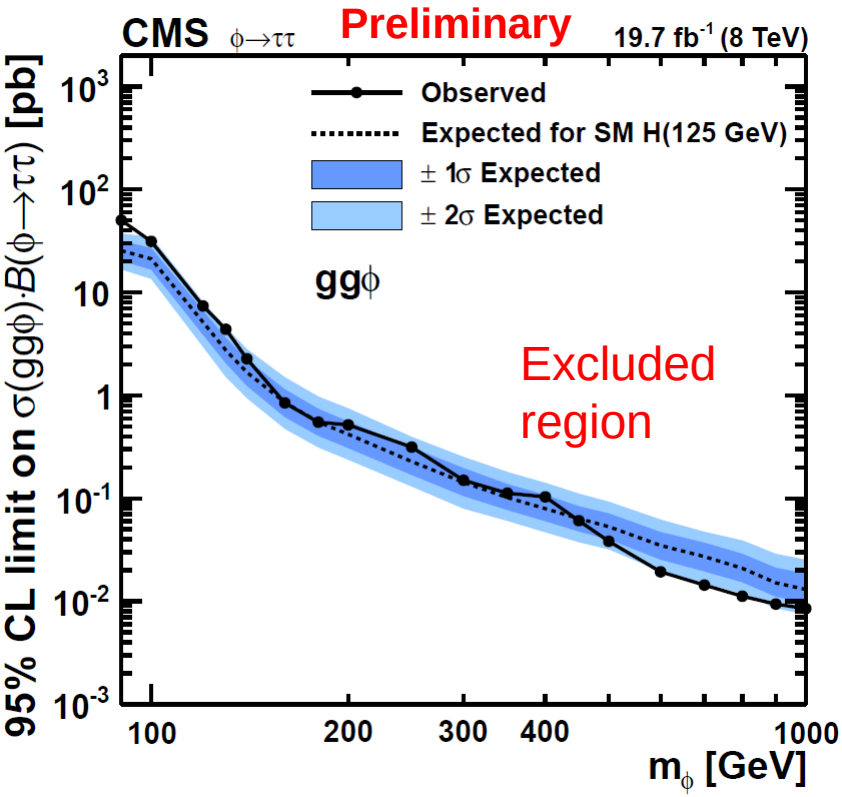


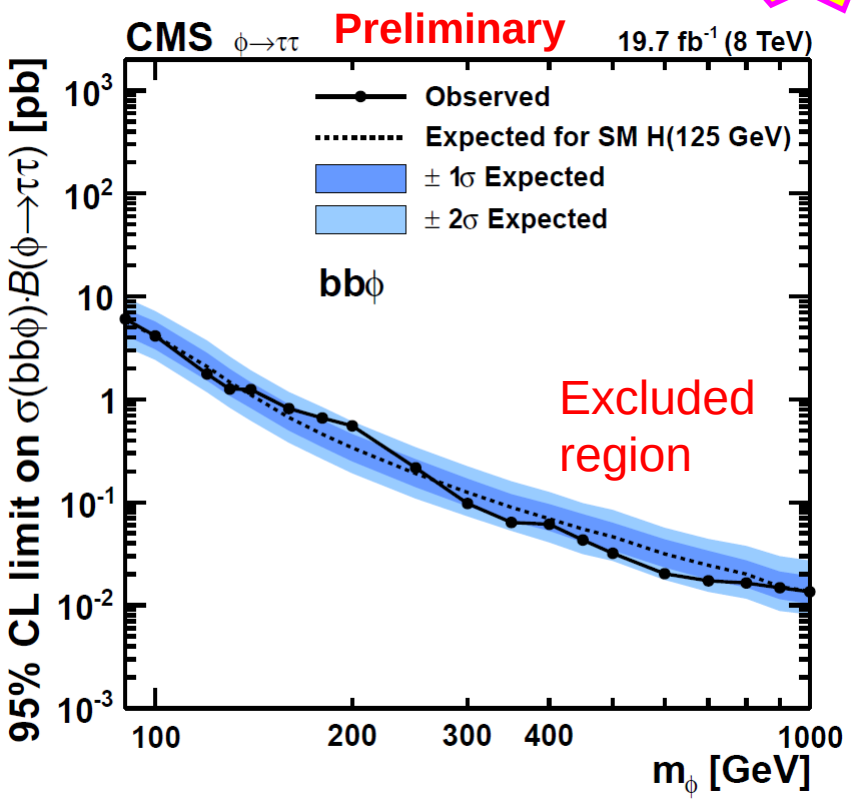
CMS PAS HIG-13-021

- Background compositions differ significantly across the various decay channels
- All distributions well described by background hypothesis

Φ → ττ: Cross Section Limits

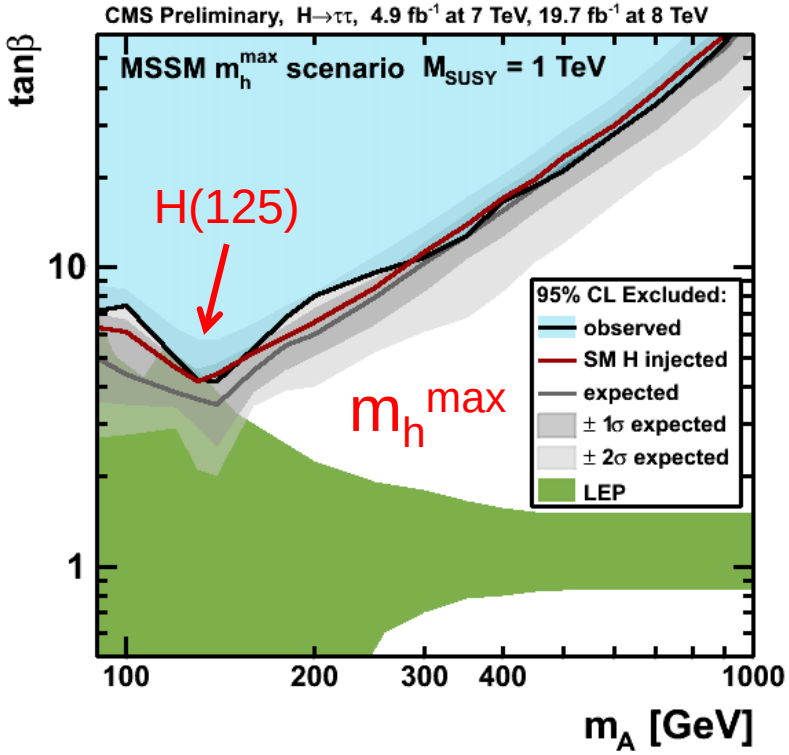
New!

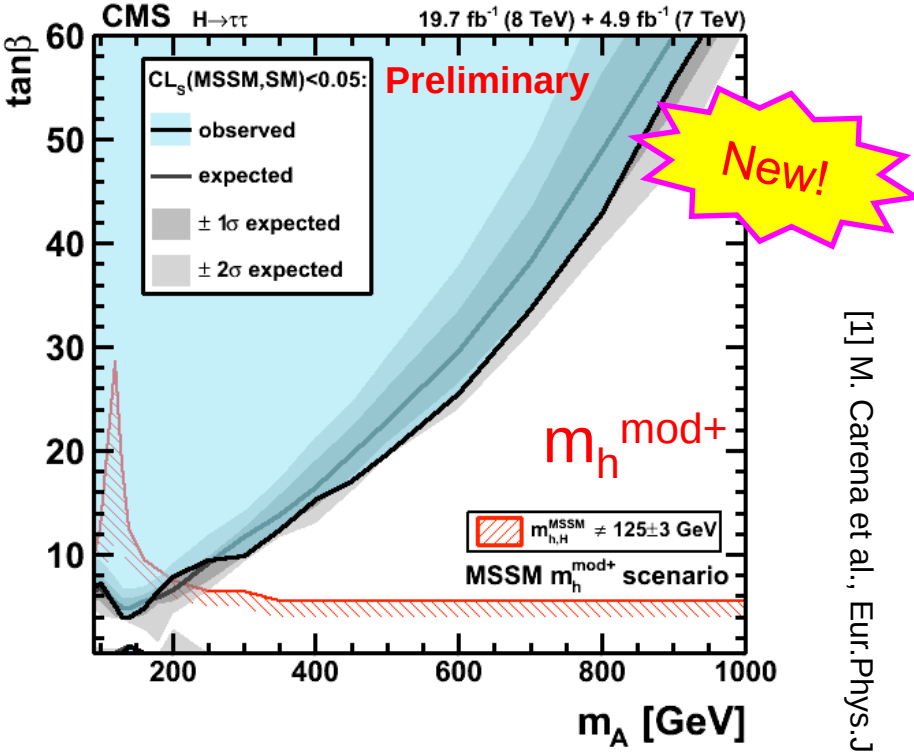




- Separate for the two production mechanisms
- Expected limits take a SM H(125) into account

$\Phi \rightarrow \tau\tau$: MSSM Interpretation





[1] M. Carena et al., Eur.Phys.J. C73, 2552 (2013)

- Very low tan β upper limits (tan β < 5 for m_A<250 GeV !)
  - touching the LEP constraint at low m_A . Presence of H(125) weakens the MSSM limits
- Latest interpretation (right) takes implications of H(125) explicitly into account
- m_h^{mod} scenario [1]: better suited for known mass of H(125), than m_h^{max} scenario

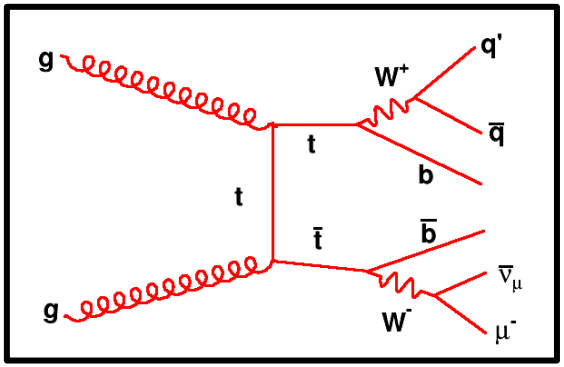
Charged Higgs ($H^+ \rightarrow c\bar{s}$)

CMS PAS HIG-13-035

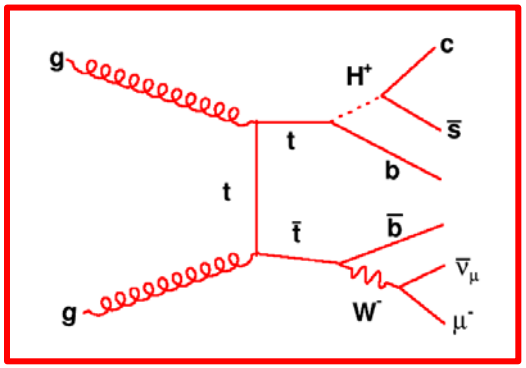
New!

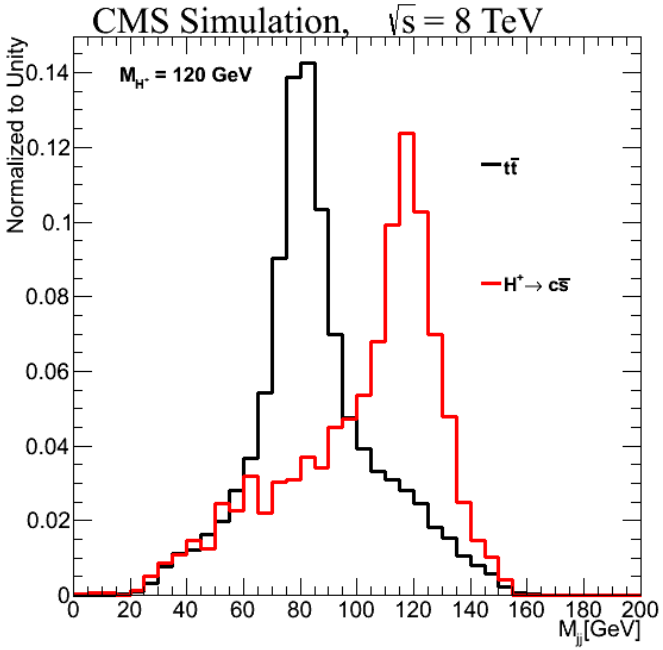
- $H^+ \rightarrow c\bar{s}$ dominant decay mode for tan β<1 and $m(H^+)<m_t$
- Same topology as $t\bar{t}$ decays in lepton + jets channel
  - Search for second peak in the di-jet mass distribution

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



H^+ production in top decays



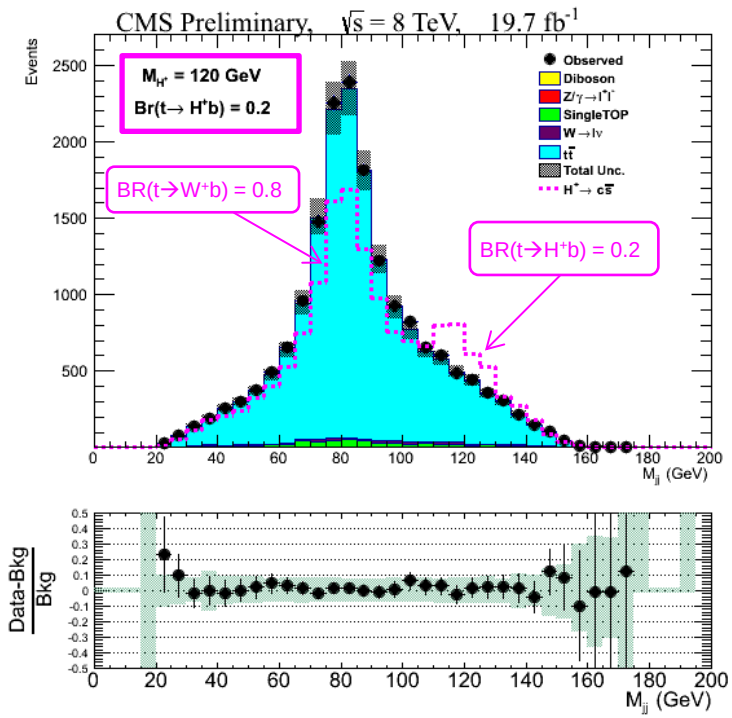


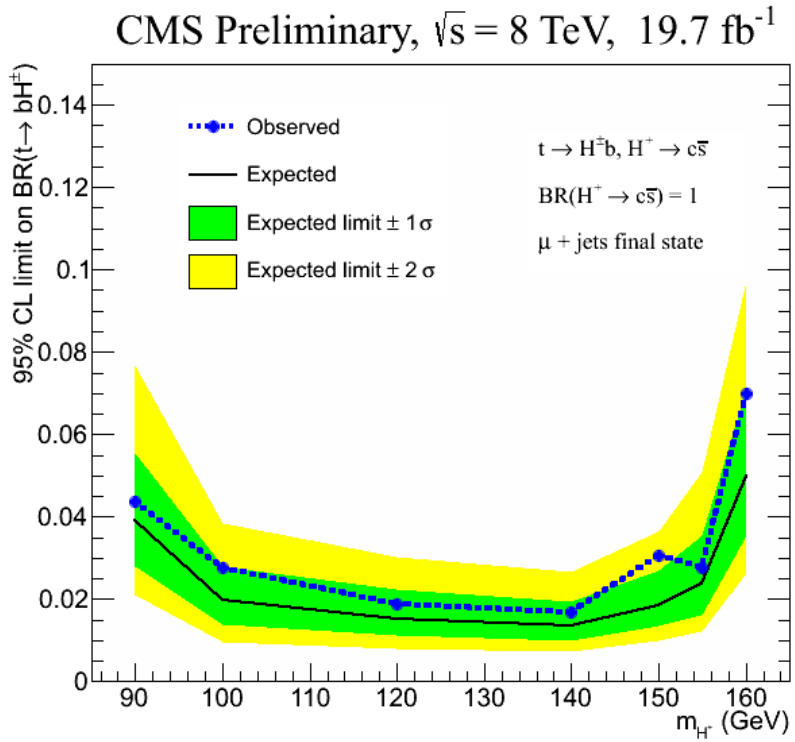
- Event selection:
  - isolated muon, ≥ 4 jets (≥2 b-tagged)
  - E_T^{miss} > 20 GeV → suppress QCD, Z+jets
- M_{jj} : invariant mass of non-b-tagged jets
- Kinematic fit → both top candidates m=172.5 GeV
  - improves mass resolution of $c\bar{s}$ candidate
- Backgrounds: $t\bar{t}$, W/Z+jets, di-bosons, QCD

$H^+ \rightarrow c\bar{s}$ (cont'd)

CMS PAS HIG-13-035

- M_{jj} distribution after kinematic fit → no signal



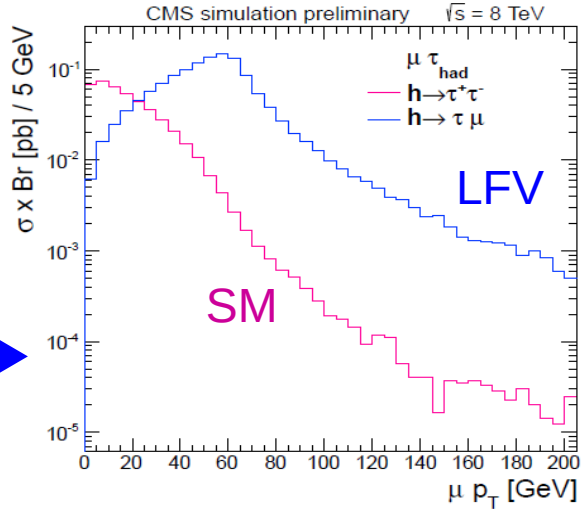


- Determine BR(t→bH⁺) assuming BR($H^+ \rightarrow c\bar{s}$)=100%
  - → observed upper limit of 2-3% in the range 100-150 GeV
  - applies to any BSM resonance with the corresponding production & decay topology

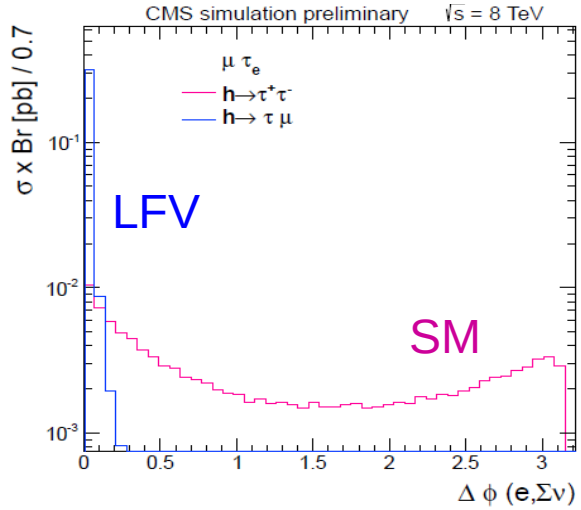
Lepton-Flavor Violating Higgs Decays

CMS PAS HIG-14-005

- Forbidden in the SM, but in principle possible in general 2HDM, composite Higgs and Randall-Sundrum models
  - this search focuses on $H \rightarrow \mu\tau$
  - direct search in $\mu\tau_e$ and $\mu\tau_{had}$ decay modes
  - signatures similar to $H \rightarrow \tau\tau$ searches, but kinematics differ



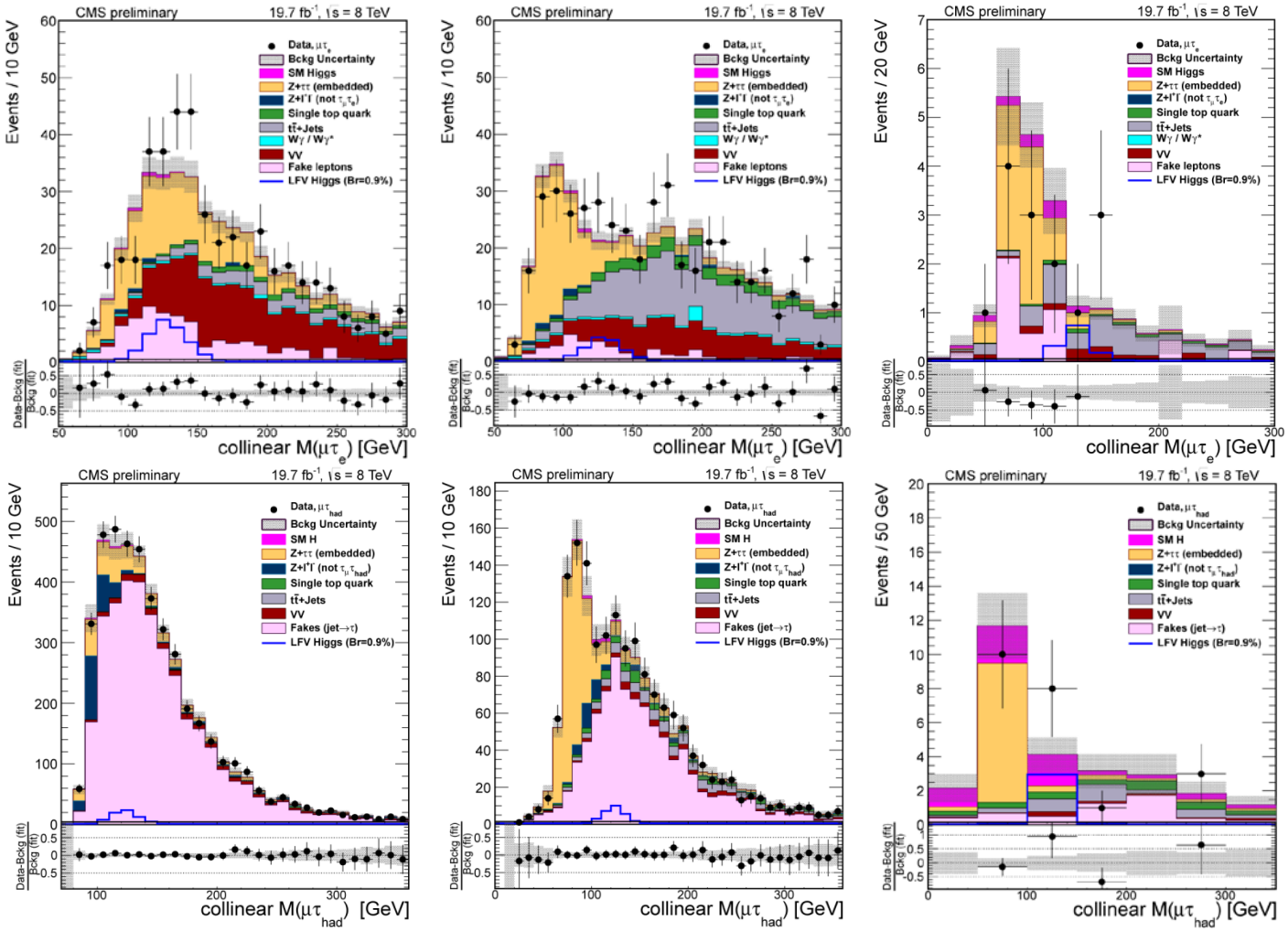
- Selection:
  - isolated muon + isolated electron ($\mu\tau_e$) or hadronic tau candidate ($\mu\tau_{had}$)
  - categorize according to #jets



- Signal variable: "collinear mass", reconstructed from visible decay products

LFV H→μτ Mass Distributions

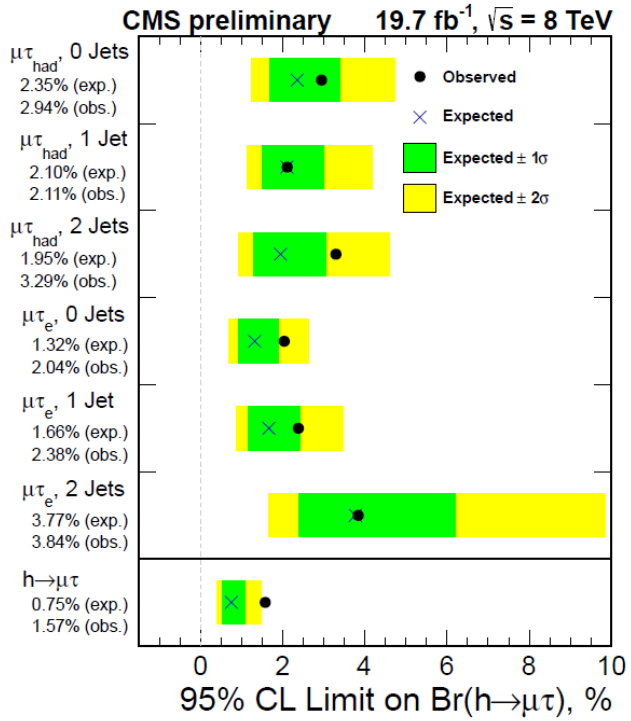
- 0-jet | 1-jet | 2-jet (VBF)

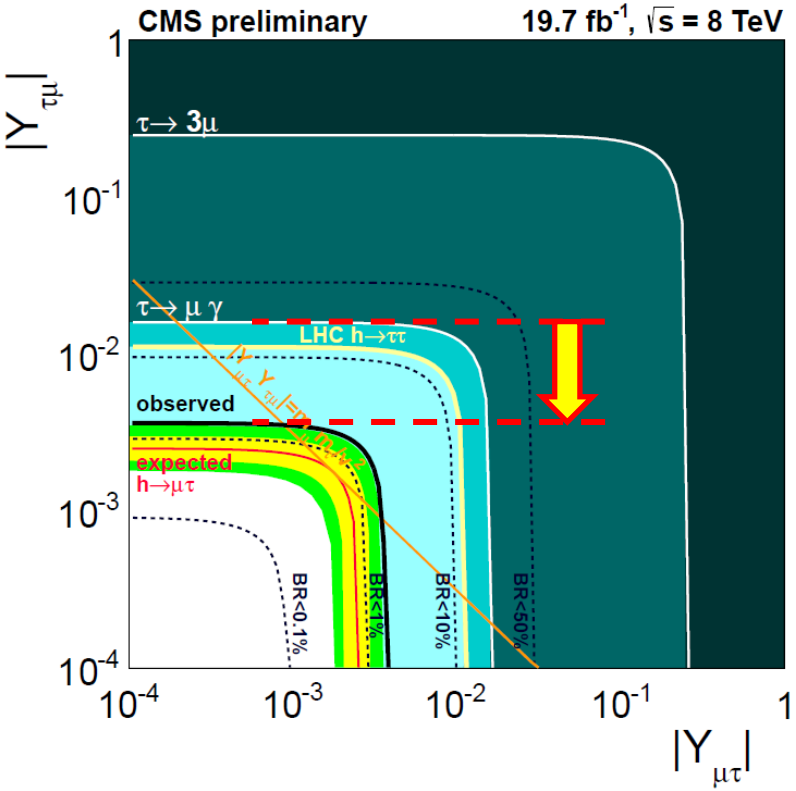


$\mu\tau_e$

$\mu\tau_{had}$

Limits on BR & Yukawa Coupling



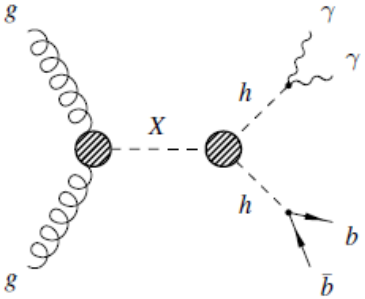


- BR(H→μτ) < 1.57% observed (0.75% exp'td)
  - best fit: BR(H→μτ) $= (0.89^{+0.40}_{-0.37})\%$
- ➔ We observe a mild excess of ~2.5 σ
  - ➔ still compatible with Standard Model

- ➔ Significant improvement (4.4x) wrt. existing indirect measurements
- ➔ Best limits on τ anomalous Yukawa couplings to date

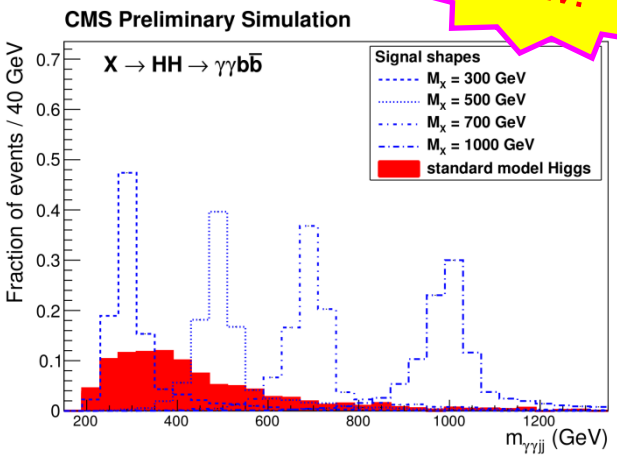
Search for X→HH→(bb)(γγ)

- In the SM, rate of Higgs pair production is very small
- But resonant pair production, motivated by BSM physics, can already be probed with existing dataset
  - heavy (N)MSSM Higgs decaying to pair of H(125)
  - Radion or Kaluza-Klein excitation of graviton (Warped Extra Dimensions)
- Combine H(125) decay channels $b\bar{b}$ (large BR) and $\gamma\gamma$ (good mass resolution)
  - → selections similar to SM analyses
- Mass-constraint fit on $b\bar{b}$ candidate, using known H(125) mass
  - → significant improvement of m_X resolution
  - essential to suppress the SM H→γγ background

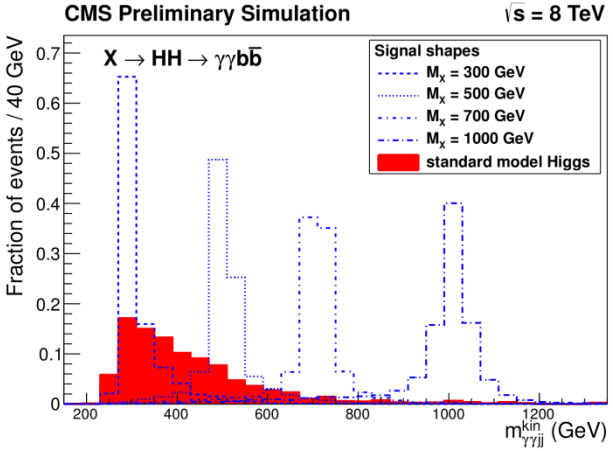


CMS PAS HIG-13-032

New!



no kinematic fit



kinematic fit

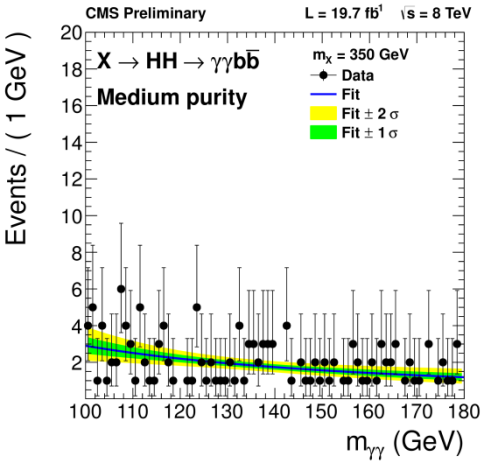
X→HH→(bb)(γγ) (cont'd)

- Signal searched in $m_{\gamma\gamma}$ distribution for low m_X (260—400 GeV), and in $m_{\gamma\gamma jj}^{kin}$ for high m_X (400—1100 GeV)
  - beyond 1100 GeV, increased merging of $b\bar{b}$ pair into single fat jet
- Medium and High Purity selections
  - b-tagging on one or both legs of the di-jet candidate
  - 85 < m_{jj} <155 GeV
  - QCD background low due to required γ's

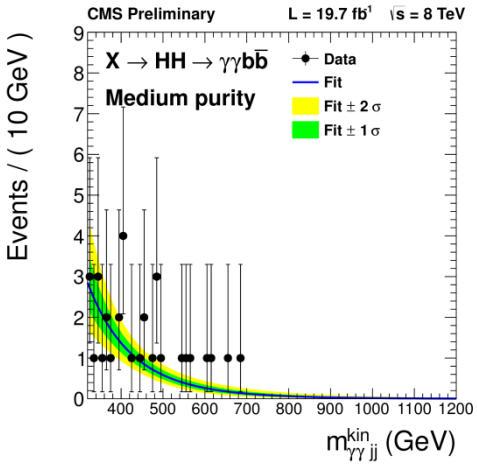
➔ Exclude radions with m<970 GeV for the radion scale Λ_R=1 TeV

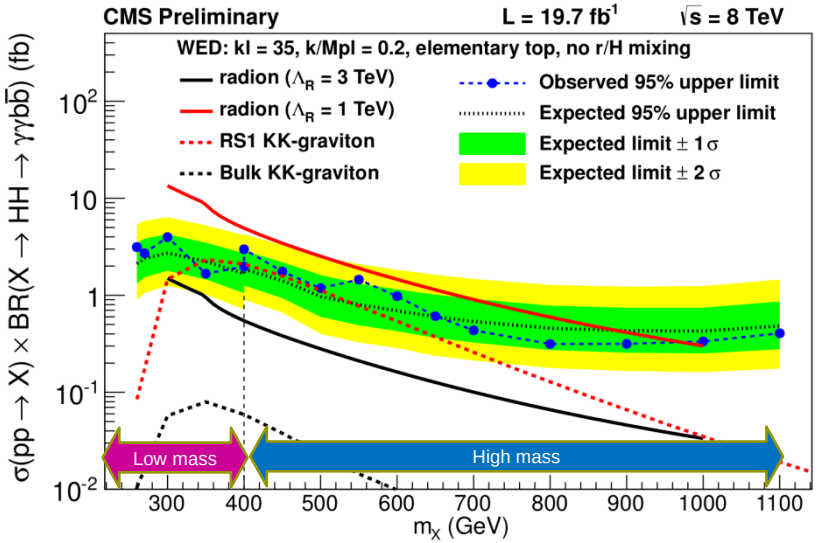
➔ Exclude RS1 KK-graviton in mass range 340—400 GeV.

Low m_X:



High m_X:



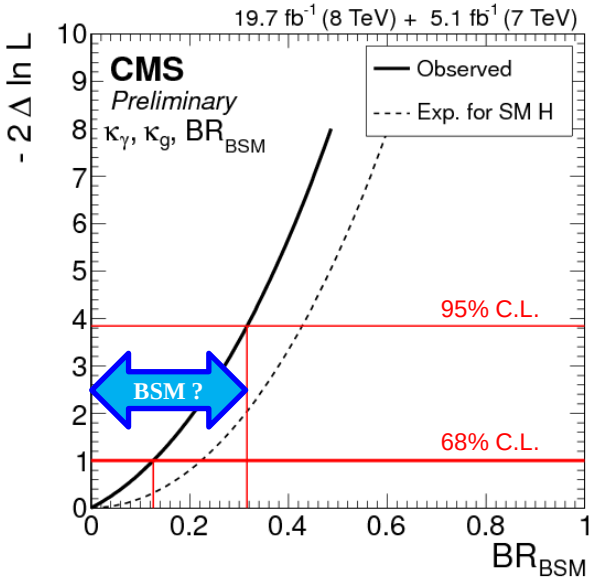


Invisible Higgs Decays

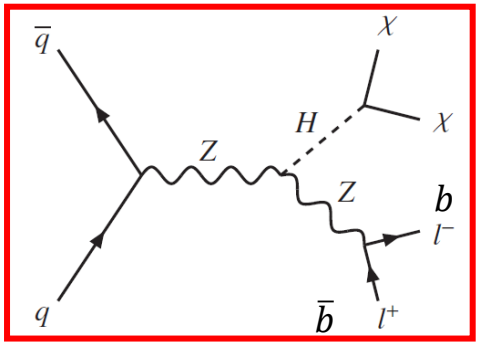
- Invisible Higgs decay modes may be possible through
  - decays to neutralinos (in supersymmetric models)
  - via graviscalars (in models with extra dimensions)
- Analysis of couplings only constrain invisible modes at best to ≤ 32% (assumptions-dependent)
- Can we directly search for invisible Higgs decays?

- Yes, if the Higgs is accompanied by something visible!

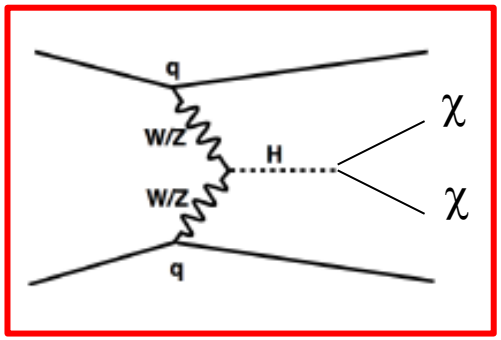
Reminder:



Vector boson-associated production (VH):

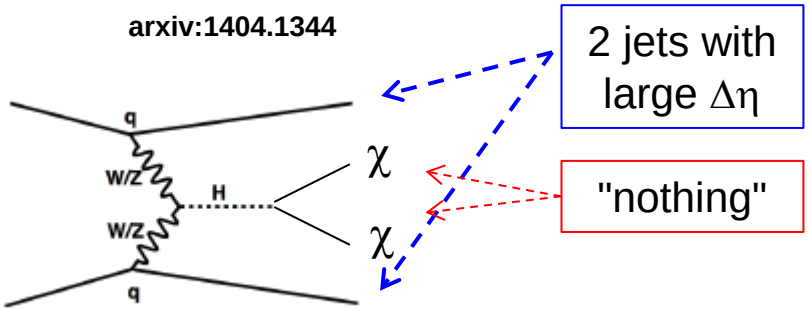


Vector boson fusion (VBF):

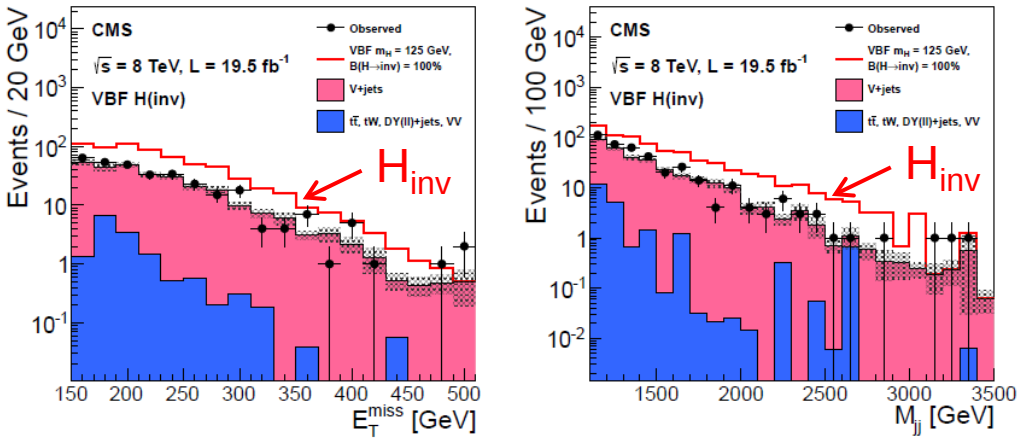


Invisible Higgs (VBF)

arxiv:1404.1344



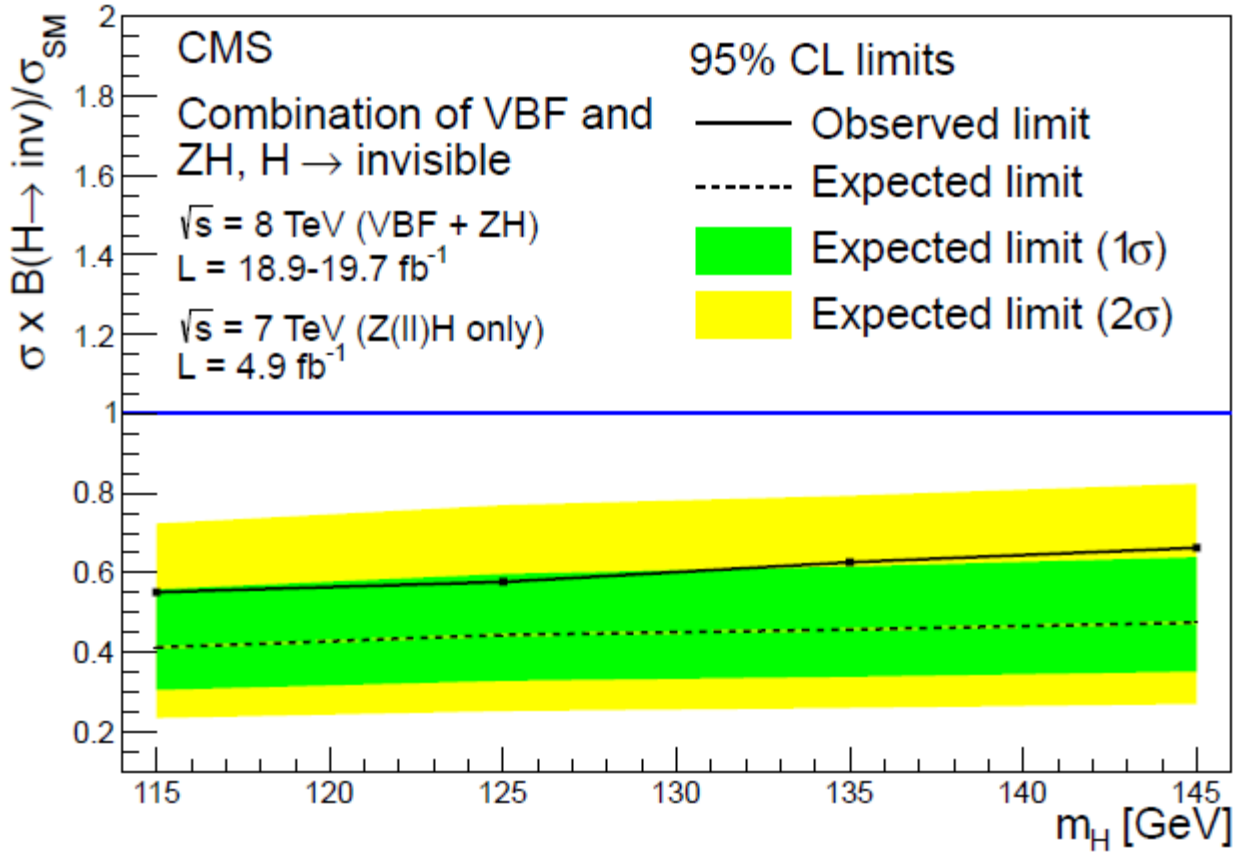
- Cross section in VBF higher than in ZH production
  - signature: two jets + large missing energy
  - central jet veto
- Main background: V+jets, where the vector boson is not seen
  - e.g. Z→νν
  - estimated by selecting Z+jets events in visible decay modes, and removing the Z decay products from the event
- Signal analyzed in variables missing E_T and di-jet mass



➔ Data in good agreement with SM backgrounds

Invisible Higgs Combination

arxiv:1404.1344



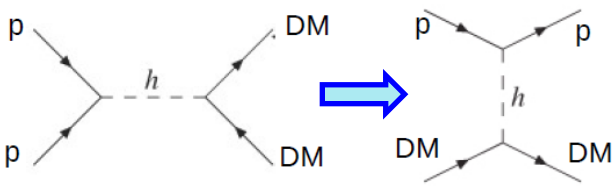
New!

- Invisible BR_{inv}<58% observed (44% expected) for a SM Higgs @ 125 GeV (95% C.L.)

➔ Significant improvement relative to earlier direct searches

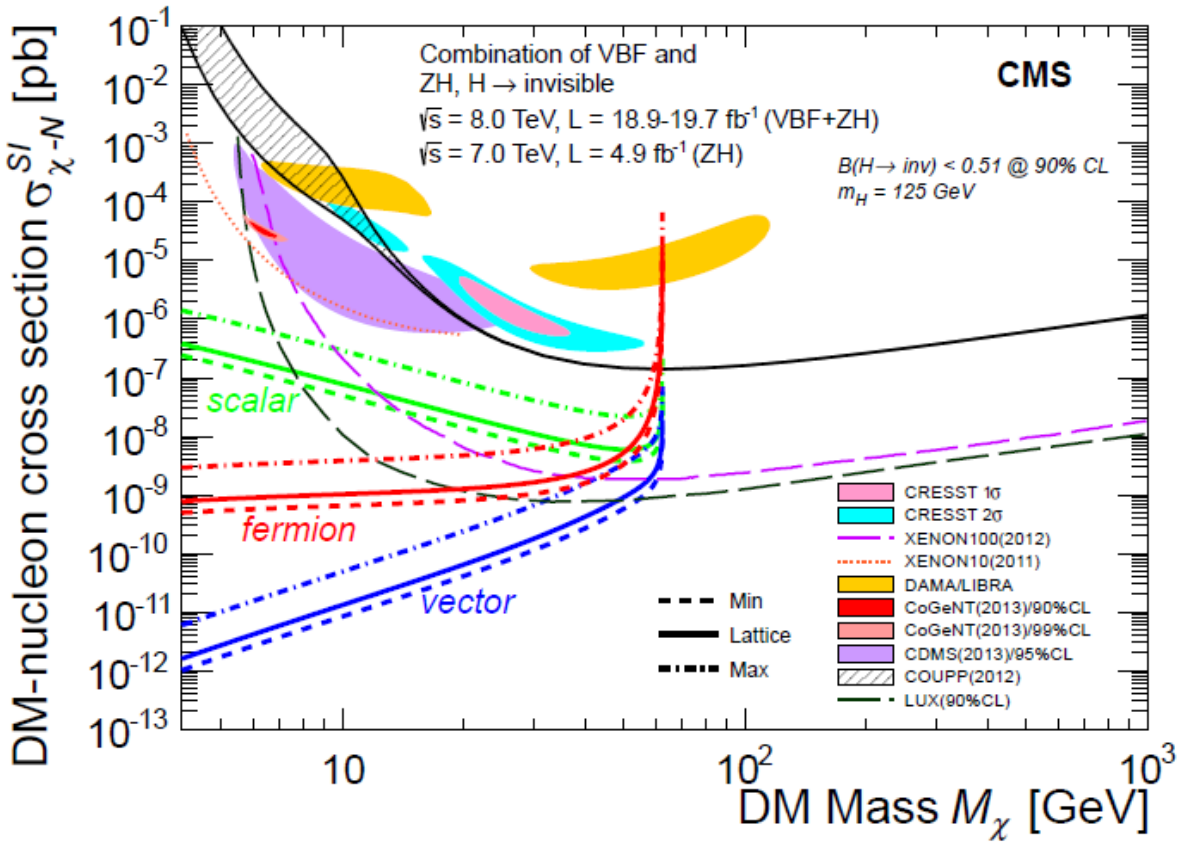
Dark Matter Interpretation

- Higgs-portal model of DM interactions → hidden sector with stable DM particles
  - if mass below $m_H/2$, might contribute to Γ_{inv} of Higgs boson
- Complementary to direct DM-detection, sensitive to DM-nucleon cross section



→ Convert BR_{inv} to DM-nucleon cross section, assuming Γ_{SM} for total Higgs boson decay width
  - three spin assumptions for DM

→ Attractive limits up to $m_H/2$



Summary

- Addressing the fundamental question whether the observed H(125) is just one member of an extended Higgs sector → potential window into New Physics

- Many new results on key signatures:
  - neutral heavy Higgs ($H \to \tau\tau$): closing the lower m_A mass range
    - large m_A and tan β still possible. New interpretation takes H(125) into account
  - charged Higgs ($t \to bH^+$): results in $H^+ \to c\bar{s}$ channel complements $H^+ \to \tau\nu_\tau$ searches
  - lepton flavor violation ($H \to \mu\tau$): considerably improved limits on anomalous Yukawa couplings
  - resonant Higgs pair production ($X \to HH \to (b\bar{b})(\gamma\gamma)$): excludes significant parameter range for radion models
  - invisible Higgs search: new combination gives improved upper limits
    - also interpreted in Higgs-portal model of Dark Matter
- 13 TeV running will further extend the reach, especially towards higher masses, and scrutinize further the properties of the H(125)

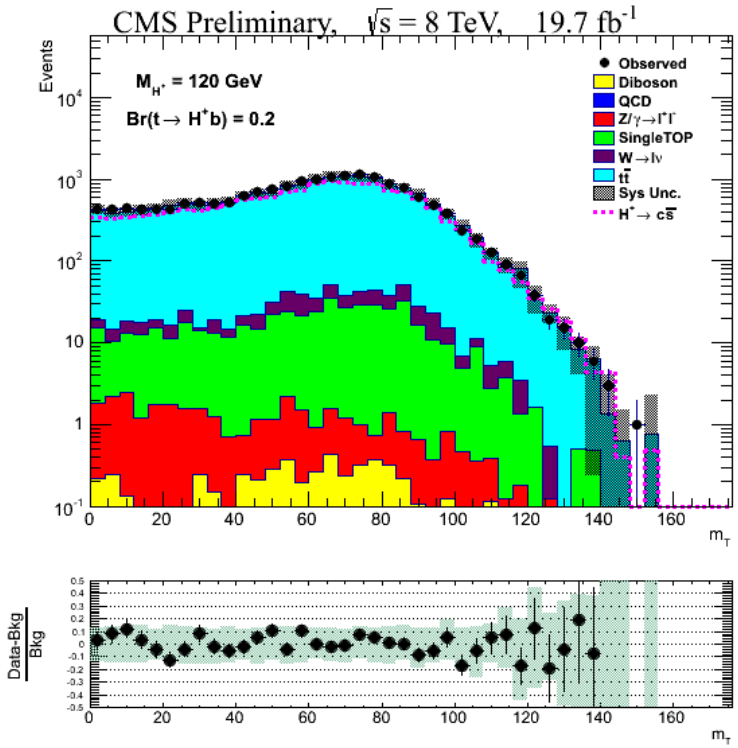
→ A rich research program for the future

Backup

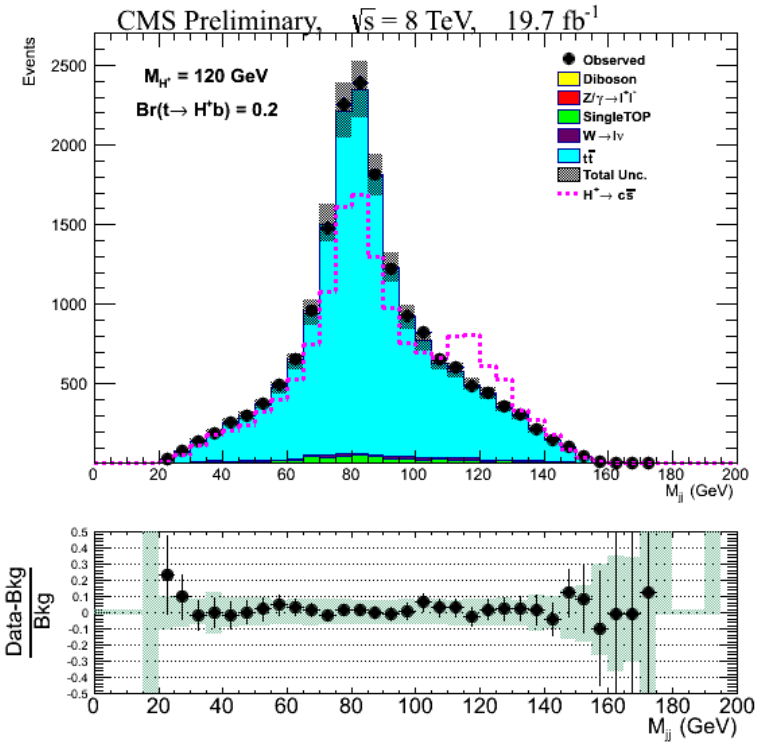
$H^+ \rightarrow c\bar{s}$ (cont'd)

CMS PAS HIG-13-035

- Control distribution: m_T (μ+ E_T^{miss})
  - good description of BG



- M_{jj} distribution after kinematic fit
  - no indication for H^+ signal

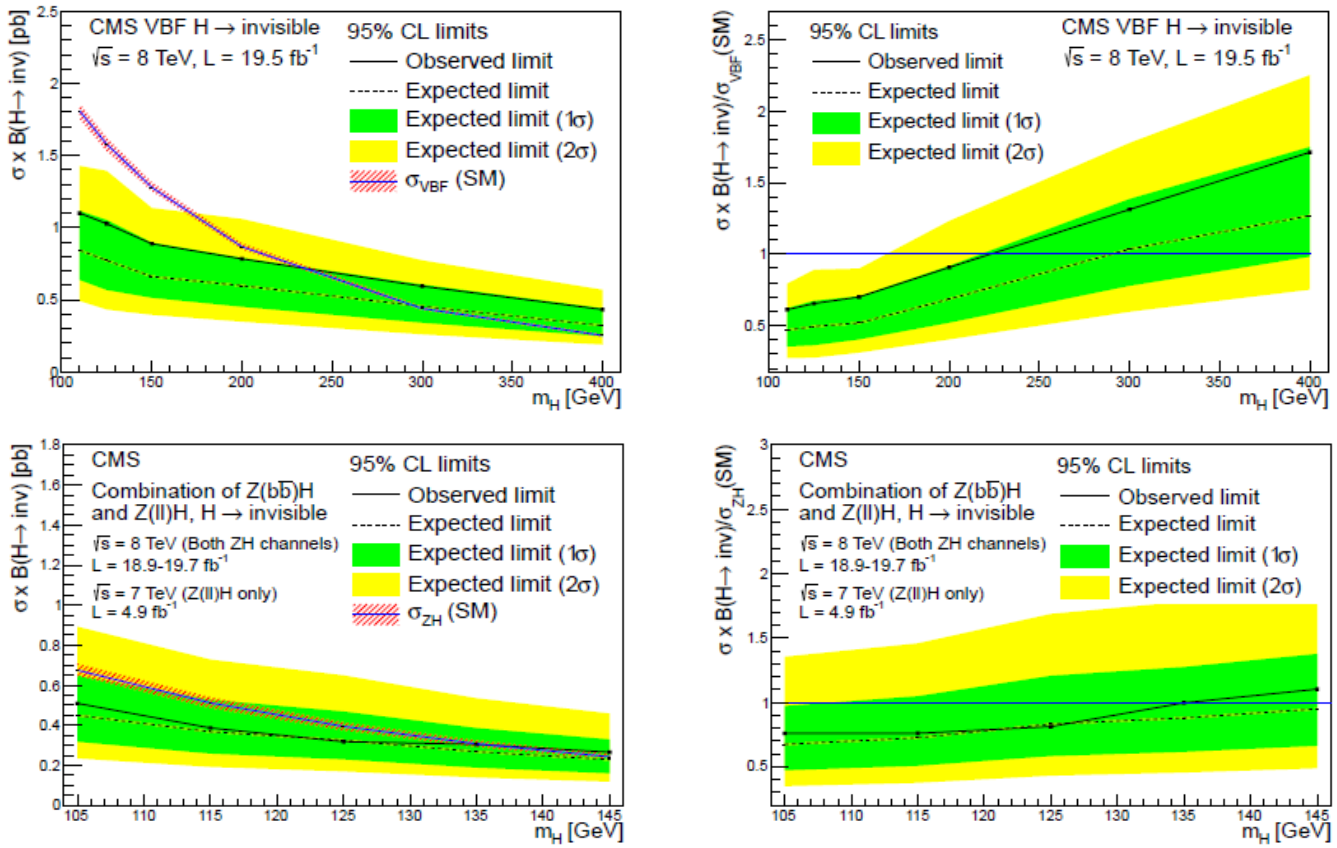


Invisible Higgs (VBF+ZH)

arxiv:1404.1344

σ x BR (absolute):

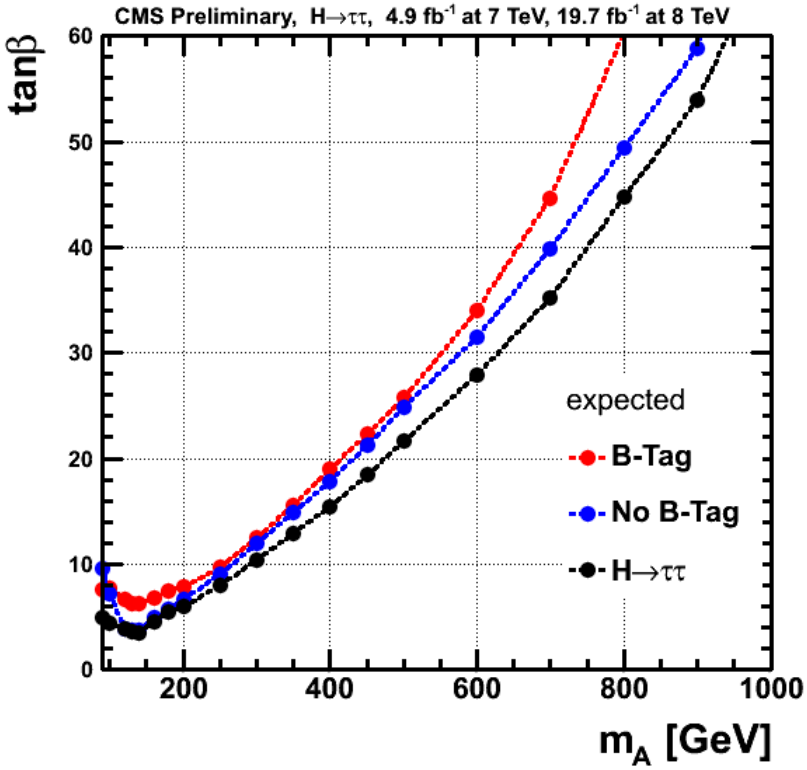
Relative to σ(SM):

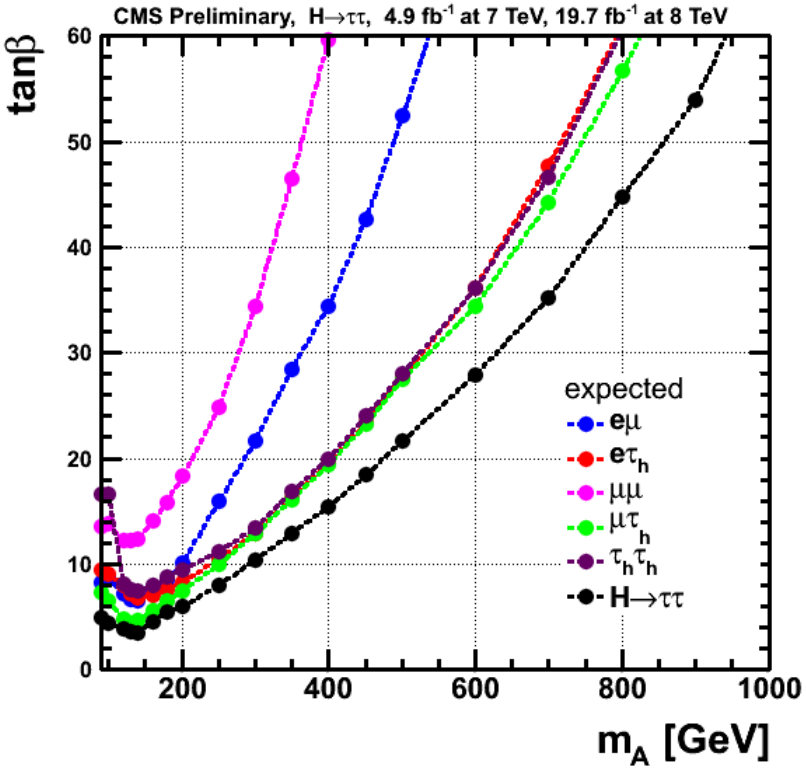


	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$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

- G.C. Branco et al, "Theory and phenomenology of two-Higgs-doublet models", arXiv:1106.0034

$\Phi \rightarrow \tau\tau$: Categories & Channels

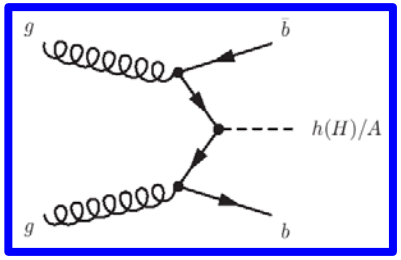


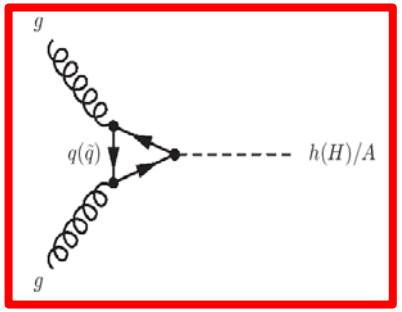


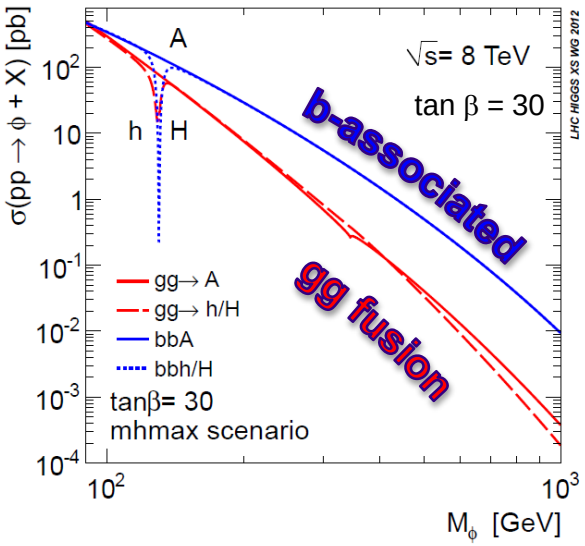
- "No B-Tag" category has slightly higher sensitivity
- Combination of all channels and categories leads to best sensitivity

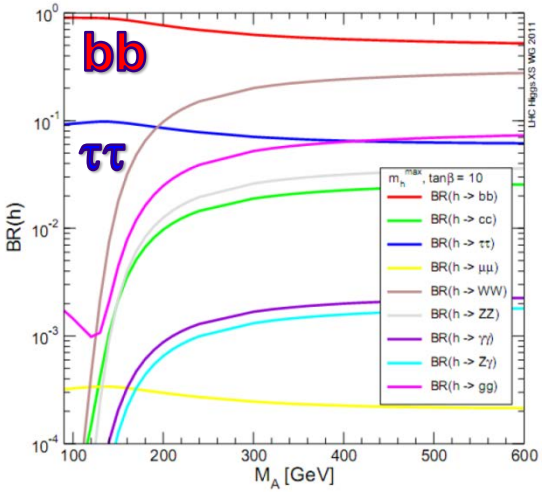
MSSM Higgs: Production & Decay

- Of three neutral MSSM Higgs bosons, must identify one as the "observed" H(125)
  - usually assign the lightest neutral boson: h
  - ~Standard-Model-like properties
- ➔ Look for additional, heavy Higgs bosons H and A
- Cross sections enhanced with increasing tan β
  - Main decay modes: bb (~ 90%) and ττ (~ 10%) for moderately large tan β
  - in contrast to SM Higgs, these decay modes dominate even at large masses



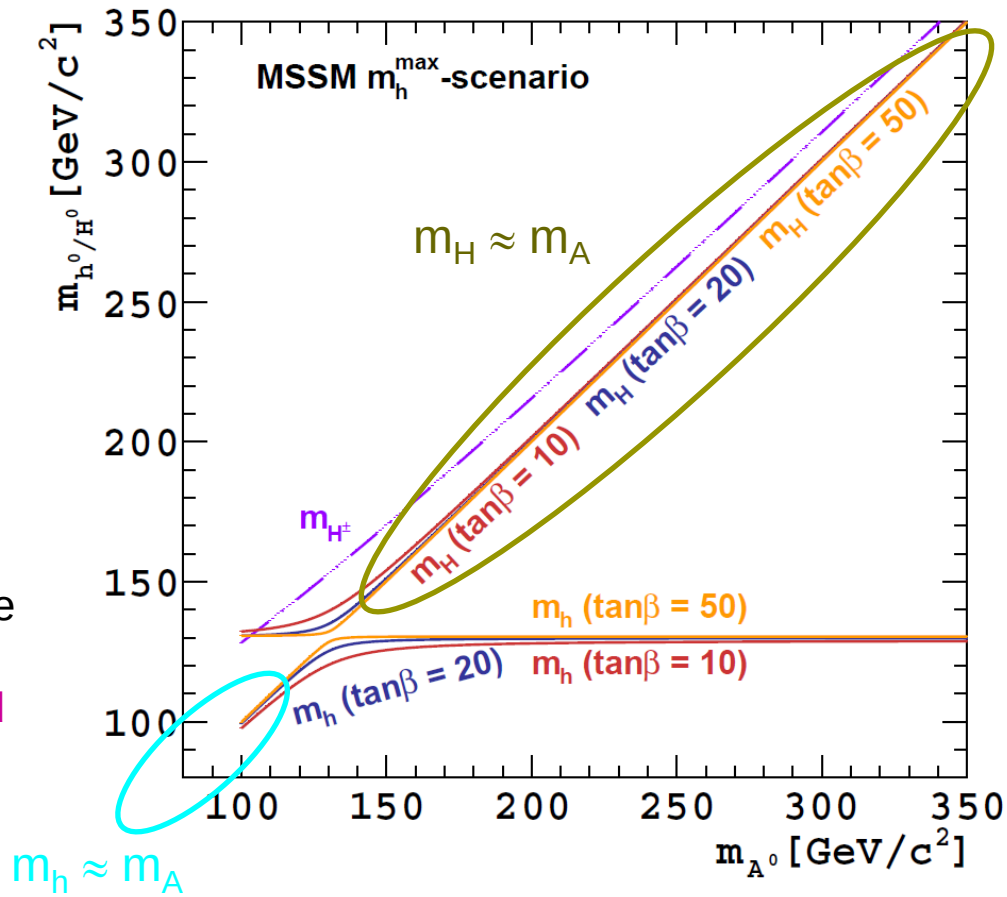






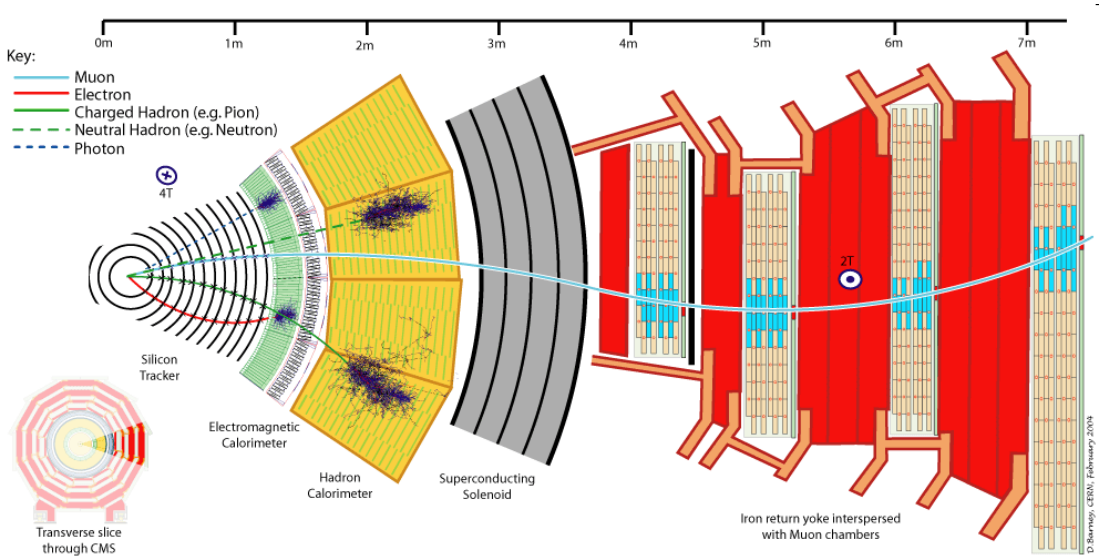
Higgs Masses in the MSSM

- The mass of the CP-odd Higgs boson A is usually ~degenerate with one of the CP-even bosons
  - $m_A \approx m_H$ for $m_A >> m_h^{max}$
  - $m_A \approx m_h$ for $m_A << m_h^{max}$
- With the exception of the $\mu\mu$ channel, this degeneracy cannot be resolved within the mass resolution
  - ➔ visible cross section effectively doubles
- ➔ Together with the effect of the Higgs coupling to b quarks, visible cross sections in b-associated production are typically enhanced by a factor of $\approx 2 \tan^2 \beta$



Reconstruction of Physics Objects

- Particle flow technique for optimized reconstruction of all particles in the event
  - extensive combination of all CMS detector systems



- Muon: matching tracks in inner tracker & muon chambers

- Electron: EM cluster with associated track

- Photon: EM cluster without associated track

- Jet: anti-k_T algorithm applied to particle flow objects

- Tau lepton (had): narrow jet ("hadron + strips" algorithm)

- b-Tagging: combined secondary vertex algorithm (CSV), discriminant based on
  - track impact parameters
  - secondary vertices inside jets

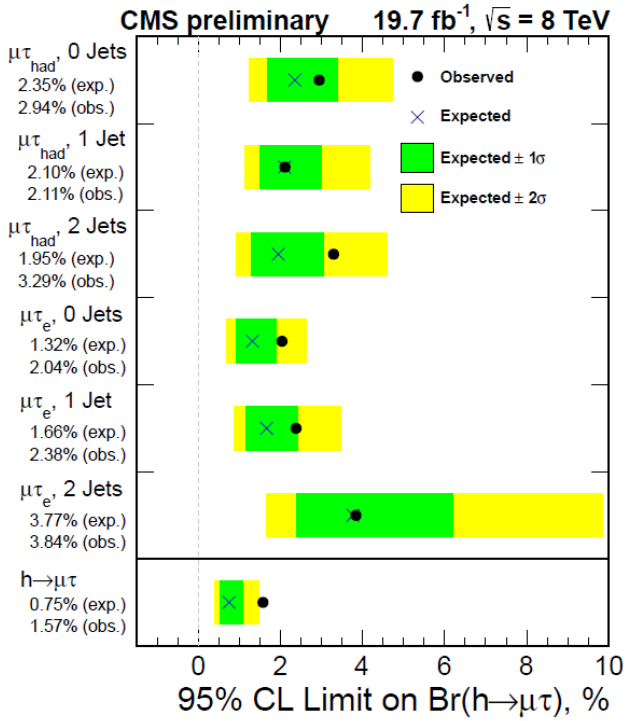
MSSM Benchmark Scenarios

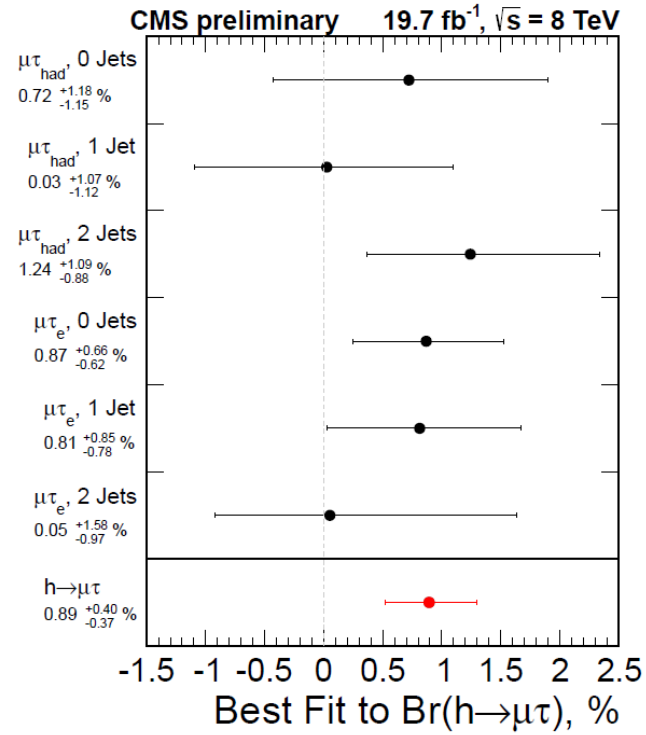
- m_h^{max} : Designed to yield the maximum value of the light MSSM Higgs mass, m_h
  - M_{SUSY} = 1 TeV — common soft-SUSY-breaking squark mass of 3rd generation
  - $X_t = 2M_{SUSY}$ — stop mixing parameter
  - μ = 200 GeV — higgsino mass parameter
  - M_{gluino} = 1500 GeV;
  - M_2 = 200 GeV — gaugino mass parameter
  - $A_b = A_t = A_\tau$ — tri-linear couplings
  - M_3 = 1000 GeV

- m_h^{mod+} : reduced stop mixing parameter to $X_T = 1.5\ M_{SUSY}$ in view of measured H(125), compatible with muon g-2

Proposed by Carena et al., Eur.Phys.J.C73, 2552 (2013)

Limits on the BR





- Expected limit for H→μτ: 0.75% (95% C.L.)
  - observed limit: 1.57%
- We observe a mild excess at ~2.5 σ