Search for Higgs boson pair production in events with two bottom quarks and two tau leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

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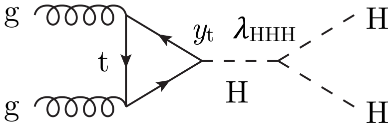
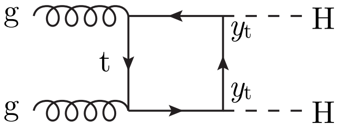
Overview

HH production in the SM



Trilinear coupling



Box Diagram

Destructive Interference

HH production in the SM

$$V(\phi) = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2,$$

$$\mu = -\frac{1}{2}M_H^2, \quad \lambda = \frac{M_H^2}{v^2}$$

$$\phi \to \frac{1}{\sqrt{2}}(v + H)$$

$$\downarrow$$

$$\lambda_{HHH} = \frac{3M_H^2}{v}$$

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$$\downarrow$$

$$\boxed{\lambda_{HHH} = \frac{3M_H^2}{v}}$$

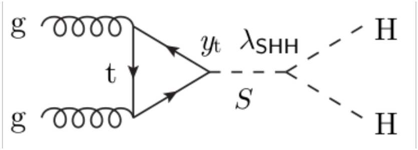
SM Prediction!

BSM HH production

Non-Resonant Production

$$\lambda_{HHH} \neq \frac{3M_H^2}{v} \quad \text{, for any mass range}$$

Resonant Production



Resonance for $p^2 \sim M_S^2$

BSM HH production - EFT approach

$$\mathcal{L} = \mathcal{L}_{SM} + \left(c_g \frac{H}{v} + c_{gg} \frac{H^2}{v^2} \right) \frac{g_s^2}{4} G^A_{\mu\nu} G^A_{\mu\nu}$$
$$- \frac{H}{v} m_t k_t y_t \bar{t}t - \frac{H^2}{2v^2} c_2 \bar{t}_i t_i + k_\lambda \lambda_{HHH} H^3$$

Coefficients

- k_t : y_t / y_t^{SM}: top yukawa coupling multiplicative deviation from SM
- k_λ : $\lambda_{HHH} / \lambda_{HHH}^{SM}$: Higgs trilinear coupling multiplicative deviation from SM
- c_2 : top pair coupling to Higgs pair
- c_g : gluon pair coupling to single Higgs
- c_{gg} : gluon pair coupling to Higgs pair

Why use the $bb\tau\tau$ channel?

(One of) the most sensitive

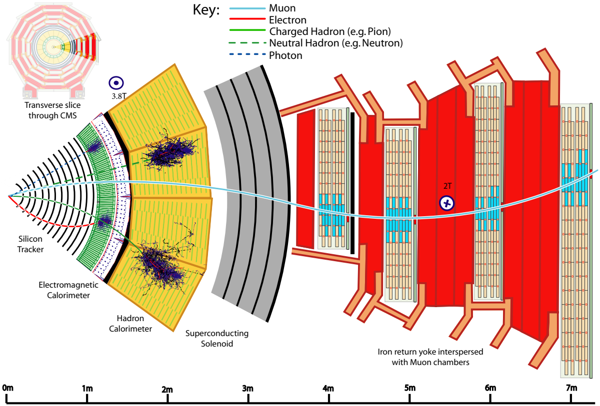
Sizeable branching ratio (7.3%) + small background contribution

$\downarrow$

sensitive channel for HH pair production

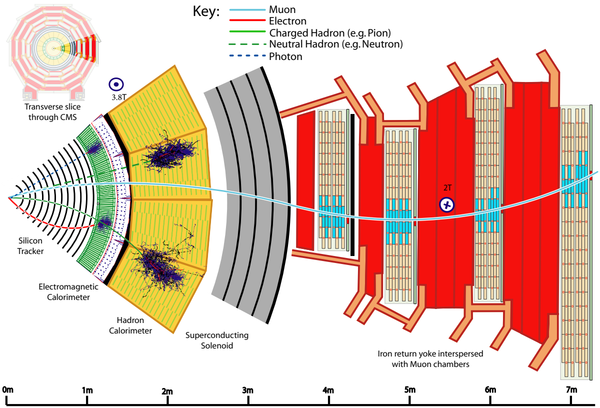
Name	Decay mode	$\mathcal{B}$ [%]
τ_e	$\tau^- \rightarrow e^- \overline{\nu}_e \nu_\tau$	17.8
τ_μ	$\tau^- \rightarrow \mu^- \overline{\nu}_\mu \nu_\tau$	17.4
τ_h	$\tau^- \rightarrow h\, \nu_\tau$	63.0
	Other modes with hadrons	1.8

Particle Flow - $\mu^{\pm}$



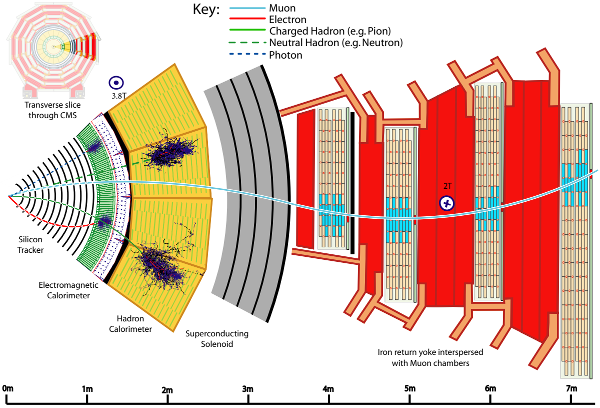
p_{μ} reconstructed from track curvature

Particle Flow - $e^{\pm}$



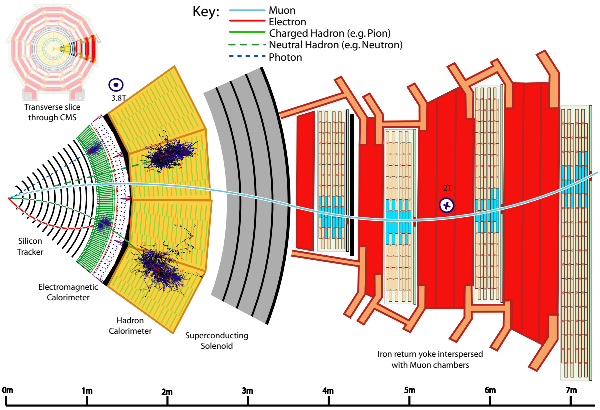
E_e reconstructed from tracker, ECAL, and Bremsstrahlung

Particle Flow - $h^{\pm}$



$E_{h^{\pm}}$ from tracker, ECAL, and HCAL

Particle Flow - h^0



E_{h^0} from ECAL, and HCAL

Complex Objects: Jets

Algorithms

1. Particle Flow
2. anti-k_T

Jets are clustered with different radii ("AK4" and "AK8")

$$p_{\text{jet}} = \sum \vec{p_i}$$

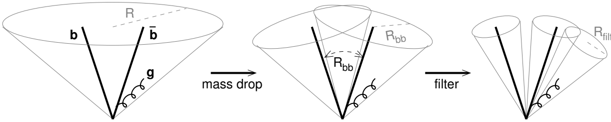
(within 5 to 10 % of true momentum)

Complex Objects: Jets

Algorithms

1. Particle Flow
2. anti-k_T
3. soft drop

AK8 jets' invariant mass is corrected by iteratively decomposing the jet



Complex Objects: Jets

Algorithms

1. Particle Flow
2. anti-k_T
3. soft drop
4. Hadron plus strips

Identifies τ decay mode

Reconstructed	Generated		
	$\tau^- \to h^- \nu_\tau$	$\tau^- \to h^- \pi^0 s\, \nu_\tau$	$\tau^- \to h^- h^+ h^- \nu_\tau$
$\tau^- \to h^- \nu_\tau$	0.89	0.16	0.01
$\tau^- \to h^- \pi^0 s\, \nu_\tau$	0.11	0.83	0.02
$\tau^- \to h^- h^+ h^- \nu_\tau$	0.00	0.01	0.97

π^0s denotes 1 or more π^0

Complex Objects: Jets

Algorithms

1. Particle Flow
2. anti-k_T
3. soft drop jet grooming
4. hadrons plus strips

Jet corrections from simulation data and confirmed *in situ*

Identifying $\tau_h\tau_\ell$

Trigger

e or μ in final state

Requirements for the selected events

- $p_T > 23\ (27)$ GeV and $|\eta| < 2.1$ for μ (e)
- $p_T > 20$ GeV and $|\eta| < 2.3$ for τ_h
- $I^{\text{rel}} < 0.15\ (0.10)$ for μ (e)
- "medium" working point of multivariate isolation discriminant $\rightarrow$ 60% signal efficiency, and $0.1 \sim 1\%$ jet misidentification.
- tracks of e, μ, τ_h compatible with primary vertex
- Discriminants to rule out e and μ reconstructed as τ_h candidates

Identifying $\tau_h \tau_h$

Trigger

Two τ_h candidates

Requirements for the selected events

- $p_T > 45$ GeV and $|\eta| < 2.1$
- "medium" working point of multivariate isolation discriminant $\rightarrow$ 60% signal efficiency, and $0.1 \sim 1\%$ jet misidentification.

Additional requirements for all final states

- both τ leptons must carry opposite charges
- Only one isolated e or μ to reduce Z/γ^* background

Identifying bb

Requirements

2 AK4 jets with $p_T > 20$ GeV and $|\eta| < 2.4$

Resolved and Boosted

Resonant production of $m_S > 700$ GeV: overlapping jets
Jets are reconstructed as 2 AK4 and 1 AK8
If:

- AK8 invariant mass > 30 GeV
- $p_T > 170$ GeV
- geometrically compatible

Then:
Boosted
Else:
Resolved

Separation between signal and $t\bar{t}$ background
($t\bar{t}$ is more spatially separated: no overlapping)

Signal Region and Discriminating Observables

$m_{\tau\tau}$: Reconstructed from SVfit
(combines kinematics from the two visible leptons and $p_{\mathrm{T}}^{\mathrm{miss}}$)

"Resolved": m_{bb} estimated from the 2 AK4 jet candidates

$$\frac{(m_{\tau\tau} - 116\mathrm{GeV})^2}{(35\mathrm{GeV})^2} + \frac{(m_{bb} - 111\mathrm{GeV})^2}{(45\mathrm{GeV})^2} < 1$$

"Boosted": m_{bb} estimated from the AK8 jet candidate

$$80 < m_{\tau\tau} < 152\mathrm{GeV}$$
$$90 < m_{bb} < 160\mathrm{GeV}$$

Signal efficiency: 80%, background reduction: 85%

Boosted Decision Trees

Training for $\tau_h\tau_e$ and $\tau_h\tau_\mu$

Further discriminates signal *vs.* background for “resolved” events

Training Regions

- Resonant production w/ $m_S \leq 350$ GeV and Non-Resonant
- Resonant production w/ $m_S > 350$ GeV

Discriminating Variables

- $m_{\mathrm{HH}}^{\mathrm{KinFit}}$: Kinematic Fit to m_{HH}
- m_{T2}(“stransverse mass”): largest parent particle mass compatible with kinematics

Signal Efficiency

65% - 95% depending on m_S

Background rejection

90% (70%) for (non-)resonant

Background Estimation

Process	Generator
$t\bar{t}$ production	POWHEG 2.0
$Z/\gamma^* \to \ell\ell$	MADGRAPH5_aMC@NLO 2.3.2
QCD multijet	estimated from data
single top production	POWHEG 2.0
SM single H production	MADGRAPH5_aMC@NLO 2.3.2
$W+$ jets	MADGRAPH5_aMC@NLO 2.3.2
diboson production	MADGRAPH5_aMC@NLO 2.3.2
Resonant HH production	MADGRAPH5_aMC@NLO 2.3.2
Non-Resonant HH production	MADGRAPH5_aMC@NLO 2.3.2

$Z/\gamma^* \to \ell\ell$ is imperfect at LO $\to$ corrected from data

Systematic Uncertainties

- Imperfect Knowledge of detector response
- Discrepancies between simulation and Data
- Limited knowledge of the background and signal processes

Shape Uncertainties: affect the distribution

- Kinematics of $t\bar{t}$ background: $< 1\%$
- Limited number/statistical fluctuations of multijet background: $< 7\%$
- τ_h and jet energy scales - correlated with normalization uncertainties

Normalization Uncertainties

Systematic uncertainty	Value	Processes
Luminosity	2.5%	all but multijet, $Z/\gamma^* \to \ell\ell$
Lepton trigger and reconstruction	2-6%	all but multijet
τ energy scale	3-10%	all but multijet
Jet energy scale	2-4%	all but multijet
b tag efficiency	2-6%	all but multijet
Background cross section	1-10%	all but multijet, $Z/\gamma^* \to \ell\ell$
$Z/\gamma^* \to \ell\ell$ SF uncertainty	0.1-2.5%	$Z/\gamma^* \to \ell\ell$
Multijet normalization	5-30%	multijet
Scale unc.	$+4.3\%/-6.0\%$	signals
Theory unc.	5.9%	signals

Results

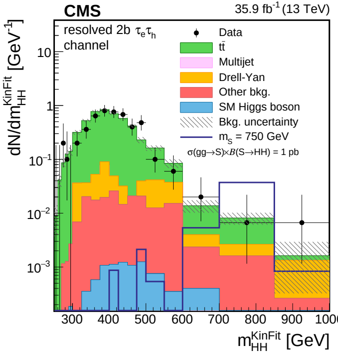
Signal tell-tales

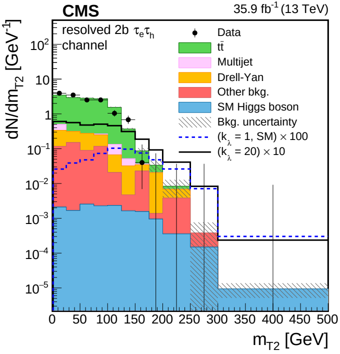
Resonant production: Localized excess in $m_{\mathsf{HH}}^{\mathsf{KinFit}}$ distribution
Non-Resonant production: Excess in the tails of m_{T2} distribution

No evidence for HH pair production

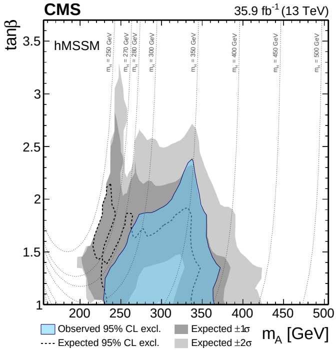
Upper Limit: 95% asymptotic confidence limits
Interpretation as exclusion plots for hMSSM
Interpretation as exclusion plots for BSM couplings (EFT approach)

Results - Distributions

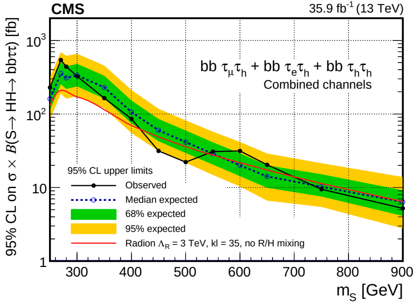




Results- $95\% CL_s$ and hMSSM

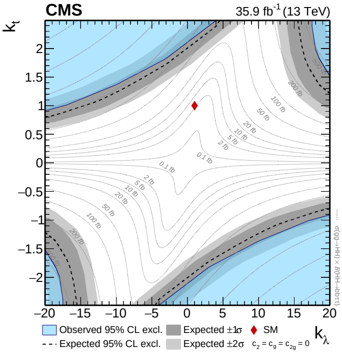


Exclusion plot for hMSSM in the $\tan\beta - M_A$ plane

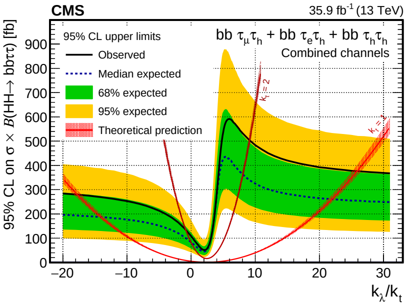


Upper limit of the HH resonant production cross-section as a function of M_S

Results- $95\% CL_s$ and EFT



Exclusion plot for BSM couplings assuming $c_g = c_{gg} = c_2 = 0$



Upper limit of HH production cross-section as a function of k_λ / k_t

Summary

- Results compatible with the expected SM background contribution
- No evidence for signal $\rightarrow$ upper limits at the 95% confidence level
- Resonant Production: narrow resonance of mass $m_S \in [250, 900]$ GeV
- hMSSM context: $m_A \in [230, 360]$ GeV and $\tan\beta \lesssim 2$ is excluded at 95% CL
- EFT: 95% CL on HH σ as a function of k_λ and k_t
- Observed (expected) CL: 30 (25) times the SM prediction
- Highest sensitivity achieved so far for SM HH production at the LHC

Thank You

Back Up

The stransverse mass

Signal

$$pp \to HH + X \to (b + \bar{b}) + (\tau^+ + \tau^-) + X$$

Dominant Background

$$pp \to \bar{t}t + X \to (b + W^+) + (\bar{b} + W^-) + X$$
$$\to (b + \tau^+ + \nu_\tau) + (\bar{b} + \tau^- + \bar{\nu}_\tau) + X$$

m_{T2}: mass-bound variable

$A' \to B' + C'$ B visible

$A \to B + C$ C invisible

$m_A = m_{A'}$

greatest lower bound on $m_A = m_{A'}$ given kinematic constraints

The stransverse mass

	signal	backgrounds			
σ [fb]	hh	$bbWW$	$bb\tau\tau$	$bb\tau\tau$ ew.	S/B
Before cuts	13.89	10792	2212	82.3	1.06×10^{-3}
trigger	1.09	1966	372	15.0	0.463×10^{-3}
event sel.	0.248	383.0	43.7	2.08	0.578×10^{-3}
$m(\tau^+\tau^-)$	0.128	107.4	16.0	0.789	1.02×10^{-3}
$m(b\bar{b})$	0.093	29.1	4.03	0.351	2.79×10^{-3}
$p_{\mathrm{T},b\bar{b}}$	0.041	0.480	0.247	0.079	0.050
m_{T2}	0.034	0.194	0.204	0.074	0.072

b-tagging

Combined Secondary vertex algorithm: b jets vs multijet
Resolved: medium working point $\rightarrow$ b-tagged
$\rightarrow$ 2 groups:
2b (best sensitivity)
1b1j (increases signal acceptance)
Boosted: loose working point for both AK4 jets $\rightarrow$ b-tagged

Working points

medium:	$\sim 60\%$ efficiency	$\sim 1\%$ misidentification
loose:	$\sim 80\%$ efficiency	$\sim 10\%$ misidentification